

# Instrumental Variable Identification of Dynamic Variance Decompositions\*

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**Abstract:** Macroeconomists often estimate impulse response functions using external instruments (proxy variables) for the shocks of interest. However, existing methods do not answer the key question of how important the shocks are in driving macro aggregates. We provide tools for doing inference on variance decompositions in a general semiparametric moving average model, disciplined only by the availability of external instruments. The share of the variance that can be attributed to a shock is partially identified, albeit with informative bounds. Point identification of most parameters, including historical decompositions, can be achieved under much weaker assumptions than invertibility, a condition imposed in conventional Structural Vector Autoregressive (SVAR) analysis. In fact, external instruments make the invertibility assumption testable. To perform inference, we construct partial identification robust confidence intervals. We illustrate our methods using (i) a structural macro model and (ii) an empirical study of the importance of monetary policy shocks.

*Keywords:* external instrument, impulse response function, invertibility, proxy variable, variance decomposition. *JEL codes:* C32, C36.

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# 1 Introduction

Empirical macroeconomists increasingly seek to estimate impulse response functions using easily interpretable and credible identification approaches. For example, local projections (LPs) have become a popular direct regression-based alternative to Structural Vector Autoregressions (SVARs).<sup>1</sup> Additionally, instrumental variable (IV, also known as proxy variable) methods are now routinely used to conduct structural analysis under plausible identifying assumptions.<sup>2</sup> Several recent papers have combined these two ideas, yielding an appealingly semiparametric method, LP-IV, with a transparent framework for identification.<sup>3</sup>

However, researchers often care not just about impulse responses – they also want to know how *important* different shocks are in driving economic fluctuations. In theoretical and applied macroeconomics, shock importance is usually quantified through variance decompositions and historical decompositions. Variance decompositions measure the fraction of the overall (unconditional or forecast) variance of a variable that can be attributed to each of the shocks, while historical decompositions measure the contributions of each shock to observed fluctuations at specific points in time. These decompositions have served as key tools for discerning between competing business cycle theories since [Kydland & Prescott \(1982\)](#).<sup>4</sup> Conveniently, in conventional SVAR analysis, identifying the impulse response functions also identifies the underlying shocks (and thus their importance). In contrast, in the semiparametric LP-IV setting, the extent to which external instruments are informative about variance/historical decompositions has been an open question, to our knowledge. Applied researchers have thus faced an unfortunate dilemma between a need to quantify the importance of shocks and the desire to avoid imposing a restrictive SVAR structure or assuming that shocks are directly observed without error.

In this paper, we show precisely to what extent the data are informative about the importance of shocks in a general linear dynamic model disciplined by IVs. Our model allows for an unrestricted moving average structure of shock transmission, consistent with

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<sup>1</sup>Jordà (2005); Angrist et al. (2018).

<sup>2</sup> Stock (2008); Stock & Watson (2012); Mertens & Ravn (2013); Gertler & Karadi (2015); Stock & Watson (2016); Caldara & Kamps (2017).

<sup>3</sup>Mertens (2015); Ramey (2016); Barnichon & Brownlees (2018); Stock & Watson (2018).

<sup>4</sup>For example, variance decompositions have been used to quantify the importance of productivity shocks (King et al., 1991), monetary shocks (Romer & Romer, 1989; Christiano et al., 1999), investment shocks (Justiniano et al., 2010), news shocks (Schmitt-Grohé & Uribe, 2012), financial shocks (Jermann & Quadrini, 2012; Christiano et al., 2014), and sentiment shocks (Angeletos et al., 2018). Cochrane (1994) and Smets & Wouters (2007) perform comprehensive shock accounting exercises.

essentially all linearized structural macroeconomic models. Assuming only validity of the instruments, we derive sharp – and informative – *bounds* on variance decompositions. *Point identification* of most parameters of interest, including historical decompositions, can be achieved under a further assumption that the shock of interest is recoverable from the infinite past, present, and future values of the endogenous macro variables. This requirement is substantially weaker than the often questionable invertibility requirement of SVAR analysis – the ability to recover structural shocks only from past and present macro variables. In fact, we show that the availability of an external IV makes the invertibility assumption *testable*. Finally, to perform inference, we develop easily computable, partial identification robust confidence intervals for variance decompositions and other objects of interest.

We adopt the LP-IV model of [Stock & Watson \(2018\)](#), which, although linear, is semiparametric in the sense that we allow for a completely general infinite moving average structure for the transmission of shocks to observed variables.<sup>5</sup> Our sole assumption on the IVs is the usual exclusion restriction – the IVs correlate with the shock of interest, but not with the other macro shocks. Importantly, we allow the number of underlying exogenous shocks to be unknown and potentially exceed the number of observed endogenous variables. Unlike standard SVAR models, we do not restrict the shocks to be *invertible*, i.e., spanned by past and current (but not future) values of the observed endogenous variables. [Stock & Watson \(2018\)](#) show in this setting that *relative* impulse responses can be point-identified through simple two-stage least squares regressions, but these do not pin down the *scale* of the shock of interest, which is crucial for identifying variance/historical decompositions.

In this baseline LP-IV model, we show that variance decompositions are only partially identified, albeit with informative bounds. Hence, even with an infinite sample, it would be impossible to pinpoint the exact importance of the shock of interest. Intuitively, the challenge is that we do not know the signal-to-noise ratio in the IV equation *a priori*. We show, however, that the data are informative about this ratio. Specifically, the identified set of the variance decomposition is an interval, with nontrivial lower and upper bounds computable from the joint spectral density of the macro variables and the IV. The bounds depend on the strength of the external IV and the informativeness of the observed macro variables about the shock of interest. We consider several variance decomposition concepts that are popular in applied work, including forecast variance decompositions.

As the LP-IV model does not assume *a priori* that shocks are invertible, we are able

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<sup>5</sup>This Structural Vector Moving Average Model has been analyzed recently from a Bayesian viewpoint by [Barnichon & Matthes \(2018\)](#) and [Plagborg-Møller \(2018\)](#), although with little emphasis on IVs.

to sharply characterize the extent to which the data are informative about the “degree” of invertibility. Inference about invertibility is useful for gauging the ability of VAR models to perform valid structural analysis and for distinguishing between different classes of structural models, such as models with anticipated versus surprise shocks. The *degree* of invertibility of a shock is given by the  $R^2$  in an (infeasible) regression of the shock on past and current values of the endogenous variables. We show that this  $R^2$  measure is partially identified. In particular, the distribution of the data is inconsistent with invertibility if and only if the IV Granger-causes the observed endogenous variables. Without invertibility, the popular SVAR-IV estimator, which uses IVs to partially identify conventional SVARs, is inconsistent.<sup>6</sup>

Although the baseline model is partially identified, we additionally provide assumptions that guarantee point identification of certain variance decompositions and the degree of invertibility. A novel finding is that point identification obtains if the shock of interest is *recoverable*, i.e., spanned by the infinite past, present, and future of the endogenous macro variables. This assumption also yields point identification of historical decompositions. The recoverability condition – although restrictive – is satisfied in certain classes of macro models, such as news and noise shock models, and it is substantially weaker than the invertibility condition that is automatically, if unintentionally, assumed in SVAR analysis. In particular, recoverability obtains if there are as many observed variables as shocks – a necessary, but not sufficient condition for invertibility. Still, we stress that researchers do not need to adopt any auxiliary assumptions to *partially* identify variance decompositions.

To make our identification analysis practically useful, we develop partial identification robust confidence intervals for all objects of interest. In a first step, the researcher estimates a reduced-form VAR jointly in the macro variables and IVs. To be clear, this step merely uses the reduced-form VAR as a convenient tool for approximating the second moments of the data; it does not assume an underlying *structural* VAR model with invertible shocks.<sup>7</sup> The second step then constructs sample analogues of our population partial identification bounds and inserts these into the confidence procedure of [Imbens & Manski \(2004\)](#) and [Stoye \(2009\)](#). We construct confidence intervals both for the unknown parameters and for the identified sets. We prove that our confidence intervals have asymptotically valid frequentist coverage under weak *nonparametric* conditions on the data generating process. We also discuss a test

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<sup>6</sup>The SVAR-IV estimator was developed by [Stock \(2008\)](#), [Stock & Watson \(2012\)](#), and [Mertens & Ravn \(2013\)](#). We characterize the population bias of SVAR-IV under non-invertibility in Online Appendix B.3.

<sup>7</sup>We view the reduced-form VAR step as a dimension reduction technique, to address finite-sample concerns about unrestricted local projections raised by [Kilian & Kim \(2011\)](#). It is straight-forward to base inference on other first-step estimators of the joint spectrum of the data.

of invertibility that has power against all falsifiable noninvertible alternatives.

We illustrate the usefulness of our identification bounds through the lens of the well-known structural business cycle model of [Smets & Wouters \(2007\)](#). We assume that the econometrician observes aggregate output, inflation, and a short-term policy interest rate, but she does not exploit the underlying structure of the model for inference. We separately consider external instruments for three different shocks: a standard monetary policy shock, a forward guidance (anticipated monetary) shock, and a technology shock. These three shocks vary greatly in terms of their degree of invertibility and recoverability, and we show that invertibility-based (e.g., SVAR) identification of the latter two shocks is severely biased. Nevertheless, our partial identification bounds are informative in all cases. This result is particularly striking for the technology shock, since the macro aggregates provide little information about the short- or medium-run cycles of this shock.

Finally, we apply our method to U.S. data and show that monetary shocks account for at most a moderate fraction of the forecast variance of output growth and inflation. We use the specification of [Gertler & Karadi \(2015\)](#), whose external instrument is constructed from changes in interest rate futures during short time windows around Federal Open Market Committee announcements. Unlike [Gertler & Karadi \(2015\)](#), we do not assume invertibility (i.e., SVAR structure) since we find that the data reject this assumption. At all forecast horizons, our partial identification robust 90% confidence intervals rule out that the monetary shock contributes more than 31% of the forecast variance of output growth and more than 8% of the forecast variance of inflation. Moreover, monetary shocks do not contribute substantially to short-run fluctuations in a non-default-related corporate bond spread. Thus, the upper bounds on shock importance are informative despite the weak identifying assumptions.

LITERATURE. A growing literature has provided inference tools for the LP-IV model, although variance/historical decompositions have been neglected. External IVs relax the assumption that the shock in a local projection is directly observed (or consistently estimable). Theoretical results on LP-IV estimation of impulse response functions were established by [Mertens \(2015\)](#), [Ramey \(2016\)](#), [Ramey & Zubairy \(2017\)](#), [Barnichon & Brownlees \(2018\)](#), [Jordà et al. \(2018\)](#), and [Stock & Watson \(2018\)](#). These papers identify *relative* impulse responses (e.g., the responses of the macro variables to a shock which raises the first variable by 1 unit). We go further and derive the identified set of all LP-IV model parameters.

Our identification results for variance decompositions generalize several results in the literature. Variance decompositions are frequently reported in SVAR analysis, where identi-

fication is straight-forward due to the invertibility assumption (Kilian & Lütkepohl, 2017, Ch. 4). Stock & Watson (2018) assume invertibility of all shocks to identify forecast variance decompositions and historical decompositions in an LP-IV model; we substantially strengthen this result by showing that recoverability of the shock of interest is sufficient to yield point identification of some of these objects. Our results are complementary to Gorodnichenko & Lee (2017), who consider finite-sample inference on what we call the “forecast variance ratio” in local projection models where the shock is assumed to be directly observed.

A key attraction of the LP-IV framework is that it allows for noninvertible shocks, unlike the standard SVAR model. Noninvertibility is now known to occur in many classes of structural models where economic agents observe better information than the econometrician, such as models with news shocks, private signals, or measurement error. Hence, the issue has received a lot of attention in the SVAR literature (see references in Plagborg-Møller, 2018, Sec. 2.3). Stock & Watson (2018) develop an LP-IV-based test of noninvertibility. Our contribution in this area is to sharply characterize the identified set for the *degree* of invertibility of the shocks, which in turn shows under what conditions the distribution of the data is consistent with invertibility. These conditions are related to Granger causality, as in the SVAR settings studied by Giannone & Reichlin (2006) and Forni & Gambetti (2014).

The concept of “recoverability” has precursors in the SVAR literature. Our definition of recoverability has independently been proposed by Chahrour & Jurado (2018). Their generic framework does not specifically consider the LP-IV model, where the recoverability assumption is testable, as we show. As discussed below, recoverability is formally equivalent to recovering shocks from *dynamic* rotations of reduced-form VAR errors, as used by Lippi & Reichlin (1994), Mertens & Ravn (2010), and Forni et al. (2017a,b).

Our confidence interval procedure applies the generic methods for interval-identified parameters developed by Imbens & Manski (2004) and Stoye (2009). Our analysis is distinct from and complementary to the literature on inference in sign-identified SVARs (Giacomini & Kitagawa, 2015; Granziera et al., 2017; Gafarov et al., 2018).

OUTLINE. Section 2 defines the LP-IV model and the parameters of interest. Section 3 contains our main identification results. Section 4 interprets the results through the lens of a structural macro model. Section 5 develops confidence intervals. Section 6 contains the empirical application. Section 7 concludes. Appendix A provides inference formulas and proofs of our main results. A supplementary appendix and Matlab code are available online.<sup>8</sup>

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<sup>8</sup>[https://scholar.princeton.edu/mikkelpm/decomp\\_iv](https://scholar.princeton.edu/mikkelpm/decomp_iv)

## 2 Model and parameters of interest

We begin by defining the Local Projection Instrumental Variable (LP-IV) model and its parameters of interest. The LP-IV model allows for an unrestricted linear shock transmission mechanism and, unlike standard SVAR analysis, does not assume shocks to be invertible, i.e. spanned by current and past (but not future) values of the observed endogenous variables. We assume the availability of valid external IVs (proxy variables) – variables that correlate with the shock of interest, but not with the other shocks. Although the model we study is equivalent with the framework in [Stock & Watson \(2018\)](#), our parameters of interest are entirely different: They study relative impulse responses, whereas we study variance decompositions, historical decompositions, and the degree of invertibility.

**MODEL.** We start out by describing the LP-IV model’s semiparametric assumptions on shock transmission and the instrument exclusion restrictions. For notational clarity, we assume throughout that all time series below have mean zero and are strictly non-deterministic.

First, we specify the weak assumptions on shock transmission to endogenous variables.

**Assumption 1.** *The  $n_y$ -dimensional vector  $y_t = (y_{1,t}, \dots, y_{n_y,t})'$  of observed macro variables is driven by an unobserved  $n_\varepsilon$ -dimensional vector  $\varepsilon_t = (\varepsilon_{1,t}, \dots, \varepsilon_{n_\varepsilon,t})'$  of exogenous economic shocks,*

$$y_t = \Theta(L)\varepsilon_t, \quad \Theta(L) \equiv \sum_{\ell=0}^{\infty} \Theta_\ell L^\ell, \quad (1)$$

where  $L$  is the lag operator. The matrices  $\Theta_\ell$  are each  $n_y \times n_\varepsilon$  and absolutely summable across  $\ell$ .  $\Theta(x)$  is assumed to have full row rank for all complex scalars  $x$  on the unit circle.

The  $(i, j)$  element  $\Theta_{i,j,\ell}$  of the moving average coefficient matrix  $\Theta_\ell$  is the *impulse response* of variable  $i$  to shock  $j$  at horizon  $\ell$ . The  $j$ -th column of  $\Theta_\ell$  is denoted by  $\Theta_{\bullet,j,\ell}$  and the  $i$ -th row by  $\Theta_{i,\bullet,\ell}$ . The full-rank assumption guarantees a nonsingular stochastic process. This condition requires  $n_\varepsilon \geq n_y$ , but – crucially – we do not assume that the number of shocks  $n_\varepsilon$  is known. The model is semiparametric in that we place no *a priori* restrictions on the coefficients of the infinite moving average, except to ensure a valid stochastic process. In particular, we do not impose the usual invertibility conditions that point-identify  $\Theta(L)$  in reduced-form time series analysis. It is well known that the infinite-order Structural Vector Moving Average model (1) is consistent with discrete-time Dynamic Stochastic General Equilibrium (DSGE) models as well as stable SVAR models for  $y_t$ . However, the appeal of LP-IV analysis is that it does not require any specific underlying structure.



Second, we assume the availability of one or more external IVs for the shock of interest.<sup>9</sup> We specify the shock of interest to be the first one,  $\varepsilon_{1,t}$ . Each of the  $n_z$  IVs  $z_t = (z_{1,t}, \dots, z_{n_z,t})'$  are assumed to correlate with the first shock but not the other shocks, after controlling for lagged variables: For all  $i = 1, \dots, n_z$ ,

$$E(\tilde{z}_{i,t}\varepsilon_{1,t}) \neq 0, \quad E(\tilde{z}_{i,t}\varepsilon_{j,t}) = 0, \quad j = 2, 3, \dots, n_\varepsilon, \quad (2)$$

where  $\tilde{z}_{i,t}$  is the population residual from projecting  $z_{i,t}$  on all lags of  $\{z_t, y_t\}$ . The key exclusion restrictions are that the shock of interest  $\varepsilon_{1,t}$  is the only contemporaneous shock to correlate with the IVs. This is a strong assumption that must be carefully defended in applications. Ramey (2016) and Stock & Watson (2018) survey the extensive applied literature that has constructed plausibly valid external IVs for various shocks. In Online Appendix B.2 we discuss how our analysis changes if the exclusion restriction is relaxed.

Using linear projection notation, we can equivalently express the IV exclusion restrictions (2) as follows.  $\|\cdot\|$  refers to the Euclidean norm.

**Assumption 2.** *The IVs  $z_t = (z_{1,t}, \dots, z_{n_z,t})'$  satisfy*

$$z_t = \sum_{\ell=1}^{\infty} (\Psi_\ell z_{t-\ell} + \Lambda_\ell y_{t-\ell}) + \alpha \lambda \varepsilon_{1,t} + \Sigma_v^{1/2} v_t, \quad (3)$$

where  $\Psi_\ell$  is  $n_z \times n_z$ ,  $\Lambda_\ell$  is  $n_z \times n_y$ ,  $\lambda$  is an  $n_z$ -dimensional vector normalized to unit length ( $\|\lambda\| = 1$ ) and with its first nonzero element being positive,  $\alpha \geq 0$  is a scalar, and  $\Sigma_v$  is a symmetric positive semidefinite  $n_z \times n_z$  matrix. The elements of  $\Psi_\ell$  and  $\Lambda_\ell$  are absolutely summable across  $\ell$ , and the polynomial  $x \mapsto \det(I_{n_z} - \sum_{\ell=1}^{\infty} \Psi_\ell x^\ell)$  has all its roots outside the unit circle.

The scale parameter  $\alpha$  (along with the residual variance-covariance matrix  $\Sigma_v$ ) measures the overall strength of the IVs, while the unit-length vector  $\lambda$  determines which IVs are stronger than others. We emphasize that the linearity of equation (3) is not a structural assumption; it arises from a linear projection (as in the “first stage” of cross-sectional IV).<sup>10</sup>

Finally, since we restrict attention to identification from second moments, we assume

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<sup>9</sup>If instruments are not available, the model (1) is severely underidentified (Lippi & Reichlin, 1994).

<sup>10</sup>We allow for lagged values of  $z_t$  and  $y_t$  on the right-hand side of (3) because this is precisely enough to ensure that the LP-IV model is untestable (using second moments) in the case of a single IV, cf. Proposition 1 below. The model with multiple instruments is testable, as further discussed in Section 3.3. If lagged terms can be excluded *a priori*, it presents no difficulties for identification or inference.



that the structural shocks and IV disturbances are jointly i.i.d. standard Gaussian.

**Assumption 3.**

$$(\varepsilon_t', v_t')' \stackrel{i.i.d.}{\sim} N(0, I_{n_\varepsilon+n_z}), \quad (4)$$

where  $I_n$  denotes the  $n$ -dimensional identity matrix.

We adopt the Gaussianity assumption strictly for notational convenience. We could instead have assumed white noise shocks and phrased all our results using linear projection notation.<sup>11</sup> We will drop the Gaussianity assumption when considering inference in [Section 5](#). The mutual orthogonality of the shocks is the standard assumption in empirical macroeconomics. The sole meaningful restriction is that we only consider identification from the second-moment properties of the data, as is standard in the applied macro literature (and without loss of generality for Gaussian data).

Note that we have normalized the variances of all shocks to 1, without loss of generality, as this simplifies our notation. [Stock & Watson \(2018\)](#) study the same LP-IV model as us, but they instead normalize certain impact impulse responses to equal 1, while letting the the shock variances be unrestricted. Hence, when [Stock & Watson](#) discuss identification of “impulse responses”, this translates into our notation as identification of *relative* impulse responses of the type  $\Theta_{i,1,\ell}/\Theta_{1,1,0}$ . The choice of normalization of course does not matter for the identification analysis.

Note also that [Assumptions 1 to 3](#) together imply that the  $(n_y + n_z)$ -dimensional data vector  $(y_t', z_t')'$  is strictly stationary.

**INVERTIBILITY AND RECOVERABILITY.** We now define invertibility, the degree of invertibility, and recoverability.

The shock  $\varepsilon_{1,t}$  is said to be *invertible* if it is spanned by past and current (but not future) values of the endogenous variables  $y_t$ :  $\varepsilon_{1,t} = E(\varepsilon_{1,t} \mid \{y_\tau\}_{-\infty < \tau \leq t})$ . Invertibility of all structural shocks is assumed automatically by SVAR models, but the condition may or may not hold in a given moving average model (1), depending on the impulse response parameters  $\Theta_\ell$ . A sufficient condition for invertibility of all shocks is that  $n_\varepsilon = n_y$  and the polynomial  $x \mapsto \det(\Theta(x))$  has all its roots outside the unit circle. In many structural macro models, at least some of the shocks cannot be recovered from only past and current observed macro variables, i.e., the moving average representation is noninvertible. For example, this is

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<sup>11</sup>Simply replace conditional expectations by linear projections and replace conditional variances by variances of projection residuals.

often the case in models with news (anticipated) shocks or noise (signal extraction) shocks. Furthermore, if the number of structural shocks  $n_\varepsilon$  strictly exceeds the number of endogenous variables  $n_y$ , it is impossible for all shocks to be invertible.

A continuous measure of the *degree* of invertibility is the  $R^2$  value in a population regression of the shock on past and current observed variables. More generally, define

$$R_\ell^2 \equiv \frac{\text{Var}(\varepsilon_{1,t}) - \text{Var}(\varepsilon_{1,t} \mid \{y_\tau\}_{-\infty < \tau \leq t+\ell})}{\text{Var}(\varepsilon_{1,t})} = 1 - \text{Var}(\varepsilon_{1,t} \mid \{y_\tau\}_{-\infty < \tau \leq t+\ell})$$

as an  $R^2$  measure of invertibility of the shock of interest using data up to time  $t + \ell$ . If the shock is invertible in the sense of the previous paragraph, then  $R_\ell^2 = 1$  for all  $\ell \geq 0$ . If  $R_\ell^2 < 1$  for some  $\ell \geq 0$ , then the model is noninvertible and thus no SVAR model could generate the impulse responses  $\Theta(L)$ , although the model may be *nearly* consistent with an SVAR structure if the  $R^2$  values are close to 1, as we discuss further in Online Appendix B.3 (Sims & Zha, 2006, pp. 243–245; Forni et al., 2018; Wolf, 2018). For noninvertible models, a plot of  $R_\ell^2$  for  $\ell = 0, 1, 2, \dots$  reveals how quickly the econometrician learns about the structural shock over time. To illustrate, we derive the  $R_\ell^2$  value for an MA(1) model in Online Appendix B.4.

A weaker condition than invertibility is that the shock of interest is *recoverable* from all leads and lags of the endogenous variables – that is, if  $E(\varepsilon_{1,t} \mid \{y_\tau\}_{-\infty < \tau < \infty}) = \varepsilon_{1,t}$ , or equivalently if  $R_\infty^2 = 1$ .<sup>12</sup> This property will become important when we consider assumptions that guarantee point identification.

VARIANCE DECOMPOSITIONS. Variance decompositions are the key parameters of interest in this paper. We now define several variance decomposition objects, including forecast variance decompositions (either conditioning on past observables or on past shocks) and a frequency-specific unconditional variance decomposition.

We consider two forecast variance decomposition concepts. First, define the *forecast variance ratio* (FVR) for the shock of interest for variable  $i$  at horizon  $\ell$  as

$$FVR_{i,\ell} \equiv 1 - \frac{\text{Var}(y_{i,t+\ell} \mid \{y_\tau\}_{-\infty < \tau \leq t}, \{\varepsilon_{1,\tau}\}_{t < \tau < \infty})}{\text{Var}(y_{i,t+\ell} \mid \{y_\tau\}_{-\infty < \tau \leq t})} = \frac{\sum_{m=0}^{\ell-1} \Theta_{i,1,m}^2}{\text{Var}(y_{i,t+\ell} \mid \{y_\tau\}_{-\infty < \tau \leq t})}$$

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<sup>12</sup>Chahrouh & Jurado (2018) independently propose this definition. Recoverability is formally equivalent to the assumption that the structural shock is spanned by current and *future* reduced-form forecast errors  $u_t \equiv y_t - E(y_t \mid \{y_\tau\}_{-\infty < \tau \leq t-1})$ . Such *dynamic rotations* of  $u_t$  have been exploited for identification by Lippi & Reichlin (1994), Mertens & Ravn (2010), and Forni et al. (2017a,b).

The FVR measures the reduction in the forecast variance that would come from knowing the entire path of future realizations of the first shock. The larger this measure is, the more important is the first shock for forecasting variable  $i$  at horizon  $\ell$ . The FVR is always between 0 and 1. An unappealing feature, however, is that the FVR conflates two different sources of uncertainty: fundamental forecasting uncertainty (uncertainty related to future shock realizations) and noninvertibility-induced uncertainty (uncertainty related to imperfect knowledge about *past* shocks).<sup>13</sup> This means that, when  $\varepsilon_{1,t}$  is noninvertible, the FVR does not equal 1 even if  $\varepsilon_{1,t}$  is solely responsible for driving the  $i$ -th variable in equation (1).

The second variance decomposition concept is the *forecast variance decomposition* (FVD) for the shock of interest for variable  $i$  at horizon  $\ell$ ,

$$FVD_{i,\ell} \equiv 1 - \frac{\text{Var}(y_{i,t+\ell} \mid \{\varepsilon_\tau\}_{-\infty < \tau \leq t}, \{\varepsilon_{1,\tau}\}_{t < \tau < \infty})}{\text{Var}(y_{i,t+\ell} \mid \{\varepsilon_\tau\}_{-\infty < \tau \leq t})} = \frac{\sum_{m=0}^{\ell-1} \Theta_{i,1,m}^2}{\sum_{j=1}^{n_\varepsilon} \sum_{m=0}^{\ell-1} \Theta_{i,j,m}^2}. \quad (5)$$

The FVD measures the reduction in forecast variance that arises from learning the path of future realizations of the shock of interest, supposing that we already had the history of structural shocks  $\varepsilon_t$  available when forming our forecast. Because the econometrician generally does not observe the structural shocks directly, the FVD is best thought of as reflecting forecasts of economic agents who observe the underlying shocks. The FVD always lies between 0 and 1, purely reflects fundamental forecasting uncertainty, and equals 1 if the first shock is the only shock driving variable  $i$  in equation (1). The software package Dynare reports FVDs after having estimated a DSGE model.

While the FVR and FVD concepts generally differ, they coincide in the case where all shocks are invertible, since in that case the information set  $\{y_\tau\}_{-\infty < \tau \leq t}$  equals the information set  $\{\varepsilon_\tau\}_{-\infty < \tau \leq t}$ . This explains why the SVAR literature has not made the distinction between the two concepts.<sup>14</sup>

For completeness, we also consider the frequency-specific unconditional variance decomposition (VD) of Forni et al. (2018, Sec. 3.4). The VD for variable  $i$  over the frequency band  $[\omega_1, \omega_2]$  is given by

$$VD_i(\omega_1, \omega_2) \equiv \frac{\int_{\omega_1}^{\omega_2} |\Theta_{i,1}(e^{-i\omega})|^2 d\omega}{\sum_{j=1}^{n_\varepsilon} \int_{\omega_1}^{\omega_2} |\Theta_{i,j}(e^{-i\omega})|^2 d\omega}, \quad 0 \leq \omega_1 < \omega_2 \leq \pi, \quad (6)$$

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<sup>13</sup> $\text{Var}(y_{i,t+\ell} \mid \{y_\tau\}_{-\infty < \tau \leq t}) = \sum_{m=0}^{\ell-1} \Theta_{i,\bullet,m} \Theta'_{i,\bullet,m} + \text{Var}\left(\sum_{m=\ell}^{\infty} \Theta_{i,\bullet,m} \varepsilon_{t+\ell-m} \mid \{y_\tau\}_{-\infty < \tau \leq t}\right)$ .

<sup>14</sup>Forni et al. (2018) point out the bias caused by noninvertibility when estimating the FVD using SVARs.

where  $\Theta_{i,j}(L)$  is the  $(i, j)$  element of the lag polynomial  $\Theta(L)$ .  $VD_i(\omega_1, \omega_2)$  is the percentage reduction in the variance of  $y_{i,t}$  – after passing the data through a bandpass filter that retains only cyclical frequencies  $[\omega_1, \omega_2]$  – caused by entirely “shutting off” the shock of interest  $\varepsilon_{1,t}$ . The software package Dynare automatically reports  $VD_i(0, \pi)$  after solving a DSGE model.

**HISTORICAL DECOMPOSITION.** The *historical decomposition* of variable  $y_{i,t}$  at time  $t$  attributable to the shock of interest is defined as  $E(y_{i,t} | \{\varepsilon_{1,\tau}\}_{-\infty < \tau \leq t}) = \sum_{\ell=0}^{\infty} \Theta_{i,1,\ell} \varepsilon_{1,t-\ell}$ .

### 3 Identification

This section presents our main results on instrumental variable identification of variance decompositions and the degree of invertibility. For exposition, we start by deriving results for a static version of the LP-IV model. We then turn to the general dynamic model, which applies the static results to the frequency domain representation of the data. The dynamics involve additional nuances in characterizing the informativeness of the macro aggregates for the shock at all frequencies. Our main results assume availability of a single external IV for the shock of interest. We then show that identification analysis in a model with multiple IVs for the same shock can be reduced to the single-IV case.

#### 3.1 Static model

We use an illustrative static model to motivate why variance decompositions are partially identified in the general case but can be point-identified under additional assumptions. Although the static model does not capture all the nuances of the dynamic LP-IV model, it provides useful intuition for the general case.

**MODEL.** The static model with a single IV assumes<sup>15</sup>

$$\begin{aligned} y_t &= \Theta_0 \varepsilon_t, \\ z_t &= \alpha \varepsilon_{1,t} + \sigma_v v_t, \\ (\varepsilon'_t, v_t)' &\overset{i.i.d.}{\sim} N(0, I_{n_\varepsilon+1}), \end{aligned}$$

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<sup>15</sup>While the static model is primarily intended for gaining intuition, the results in this subsection are directly relevant for SVAR analysis with an external IV. In that framework,  $y_t$  would be the reduced-form VAR residuals, which are a linear function of the vector  $\varepsilon_t$  of contemporaneous structural shocks. Textbook SVAR analysis further assumes that  $n_\varepsilon = n_y$ , so the model is identified up to an orthogonal rotation matrix.

where  $\Theta_0$  is  $n_y \times n_\varepsilon$ , and  $\alpha, \sigma_v \geq 0$  are scalars. To avoid singularity, we assume that  $\Theta_0$  has full row rank, so in particular  $n_\varepsilon \geq n_y$ .

Since the static model is nothing but a multivariate classical measurement error model, we can apply ideas from that literature to bound variance decompositions. However, our parameters of interest are not regression coefficients as in [Klepper & Leamer \(1984\)](#). Instead, we essentially seek lower and upper bounds on the  $R^2$  in an infeasible regression of  $y_{i,t}$  on  $\varepsilon_{1,t}$ . We may proceed as follows. First, the  $R^2$  value from a regression of  $y_{i,t}$  on  $z_t = \alpha\varepsilon_{1,t} + \sigma_v v_t$  understates the importance of the shock  $\varepsilon_{1,t}$ , due to attenuation bias.<sup>16</sup> Second, the  $R^2$  from a regression of  $y_{i,t}$  on  $E(z_t | y_t) = \alpha E(\varepsilon_{1,t} | y_t)$  overstates the importance of the shock  $\varepsilon_{1,t}$ , due to bias caused by regressing on the “fitted value”  $E(\varepsilon_{1,t} | y_t)$ .

We now turn this intuition into formal results on the identification of variance decompositions and the degree of invertibility. In the static case, the degree of invertibility of the shock  $\varepsilon_{1,t}$  is fully summarized by the static projection  $R^2$ , defined as

$$R_0^2 = 1 - \text{Var}(\varepsilon_{1,t} | y_t) = \Theta'_{\bullet,1,0} \text{Var}(y_t)^{-1} \Theta_{\bullet,1,0}.$$

As for variance decompositions, the static model does not distinguish between the FVR, FVD, and VD, and we can restrict attention to one-step prediction:

$$FVD_{i,1} = 1 - \frac{\text{Var}(y_{i,t} | \varepsilon_{1,t})}{\text{Var}(y_{i,t})} = \frac{\Theta_{i,1,0}^2}{\text{Var}(y_{i,t})}.$$

**PARTIAL IDENTIFICATION.** We now show that the impulse response functions, the degree of invertibility, and variance decompositions are all identified up to a scalar multiple. This factor of proportionality is interval-identified, with nontrivial and informative lower and upper bounds. Since the data are i.i.d., identification in this model relies solely on contemporaneous covariance calculations.

It is immediate that *absolute* impulse responses  $\Theta_{i,1,0}$  to the shock of interest are identified up to the scale parameter  $\alpha$ :

$$\text{Cov}(y_t, z_t) = \alpha \Theta_{\bullet,1,0}. \tag{7}$$

In particular, *relative* responses are point-identified, cf. [Stock & Watson \(2018\)](#). Since the vector  $\Theta_{\bullet,1,0}$  is identified up to scale  $\alpha$ , the degree of invertibility  $R_0^2$  is identified up to the

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<sup>16</sup>A related argument appears in [Gorodnichenko & Lee \(2017, Appendix D\)](#).

multiple  $\frac{1}{\alpha^2}$ , and the FVDs of different variables  $i$  are identified up to the same multiple  $\frac{1}{\alpha^2}$ :

$$R_0^2 = \frac{1}{\alpha^2} \text{Cov}(y_t, z_t)' \text{Var}(y_t)^{-1} \text{Cov}(y_t, z_t), \quad FVD_{i,1} = \frac{1}{\alpha^2} \frac{\text{Cov}(y_{i,t}, z_t)^2}{\text{Var}(y_{i,t})}. \quad (8)$$

Which values of the scale parameter  $\alpha$  are consistent with the distribution of the data  $w_t = (y_t', z_t)'$ ? First, the equation defining the IV  $z_t$  implies

$$\alpha^2 \leq \text{Var}(z_t) \equiv \alpha_{UB}^2. \quad (9)$$

The boundary case  $\alpha = \alpha_{UB}$  corresponds to  $\text{Var}(\varepsilon_{1,t} | z_t) = 0$ , i.e., perfect instrument strength. Second, we find

$$\alpha_{LB}^2 \equiv \text{Var}(E(z_t | y_t)) = \alpha^2 \text{Var}(E(\varepsilon_{1,t} | y_t)) \leq \alpha^2 \text{Var}(\varepsilon_{1,t}) = \alpha^2, \quad (10)$$

where the inequality uses that “the total sum of squares exceeds the explained sum of squares”. The boundary case  $\alpha = \alpha_{LB}$  corresponds to  $\text{Var}(\varepsilon_{1,t} | y_t) = 0$ , i.e., the observed macro aggregates  $y_t$  are perfectly informative about the hidden shock (invertibility).

It is not hard to show (and it follows from our general results below) that the bounds (9) and (10) on  $\alpha^2$  are *sharp*, in the following sense: Given any positive semidefinite variance-covariance matrix for  $w_t = (y_t', z_t)'$ , and given any value of  $\alpha^2$  in the interval between the bounds (9) and (10), we can construct a static model with the given value of  $\alpha$  and which matches the given  $\text{Var}(w_t)$  (we just have to choose  $\Theta_0$  and  $\sigma_v$  appropriately).

The width of the identified set  $[\alpha_{LB}^2, \alpha_{UB}^2]$  for  $\alpha^2$  depends on the degree of invertibility and the strength of the instrument. The interval is never empty, and it collapses to a point only in the knife-edge case of a perfectly informative instrument *and* invertibility of the first shock. Generically,  $\alpha$  – and so impulse responses, FVDs, and the degree of invertibility – are only partially identified, but with useful bounds that limit the range of admissible values.

We interpret the identified set for  $\frac{1}{\alpha^2}$  by expressing it in terms of the (unknown) model parameters (recall that our parameters of interest are identified up to  $\frac{1}{\alpha^2}$ , cf. (8)):

$$\left[ \underbrace{\frac{\alpha^2}{\alpha^2 + \sigma_v^2}}_{\text{instrument strength}} \times \frac{1}{\alpha^2}, \quad \underbrace{\frac{1}{R_0^2}}_{\text{invertibility}} \times \frac{1}{\alpha^2} \right].$$

The lower bound is more informative (i.e., larger and closer to the true  $\frac{1}{\alpha^2}$ ) when the instrument is stronger in the sense of a higher signal-to-noise ratio. The upper bound is

more informative (i.e., smaller and closer to the true  $\frac{1}{\alpha^2}$ ) when the model is closer to being invertible for the shock of interest.

Having partially identified  $\alpha$ , we obtain identified sets for the FVD, absolute impulse responses, and the degree of invertibility. By scaling the identified set for  $\frac{1}{\alpha^2}$ , we find the identified set for  $FVD_{i,0}$ :

$$\left[ \underbrace{\frac{1}{\text{Var}(z_t)} \times \frac{\text{Cov}(y_{i,t}, z_t)^2}{\text{Var}(y_{i,t})}}_{\frac{\alpha^2}{\alpha^2 + \sigma_v^2} \times FVD_{i,0}}, \underbrace{\frac{1}{\text{Var}(E(z_t | y_t))} \times \frac{\text{Cov}(y_{i,t}, z_t)^2}{\text{Var}(y_{i,t})}}_{\frac{1}{R_0^2} \times FVD_{i,0}} \right].$$

Instrument informativeness and invertibility thus map one-to-one into the width of the identified set for the FVD. The identified set for the absolute impulse response  $\Theta_{i,1,0}$  can similarly be obtained by scaling the identified set for  $\frac{1}{\alpha}$ , cf. (7), while the identified set for the degree of invertibility  $R_0^2$  can be obtained by scaling the identified set for  $\frac{1}{\alpha^2}$ .<sup>17</sup>

**SUFFICIENT CONDITIONS FOR POINT IDENTIFICATION.** Although the baseline model is partially identified, point identification obtains under a variety of auxiliary assumptions.

First, assume that the shock of interest is recoverable, which in the static model is the same as invertibility:  $E(\varepsilon_{1,t} | y_t) = \varepsilon_{1,t}$ , or equivalently  $R_0^2 = 1$ . Then  $\alpha^2$  equals the lower bound in (10); we can then identify the impulse responses  $\Theta_{\bullet,1,0}$  from the covariance relationship (7), and  $\sigma_v$  from  $\text{Var}(z_t)$ . Hence, all objects of interest are point-identified under the recoverability assumption. A stronger condition than recoverability is that there are as many shocks as variables,  $n_\varepsilon = n_y$ . This condition implies that  $\Theta_0$  is square and invertible, so *all* shocks are recoverable, and point identification follows.

Second, point identification obtains if the instrument is assumed to be perfect, i.e.,  $\sigma_v = 0$ . In that case the shock  $\varepsilon_{1,t}$  is effectively observed by the econometrician and all parameters can be identified directly from regressions of  $y_{i,t}$  on  $z_t$  (local projections). Equivalently, the true  $\alpha$  equals the upper bound in (9), and then all derivations follow as before.

## 3.2 General dynamic model

We now present our main identification results for the general dynamic model, applying the logic of the static model frequency-by-frequency to the frequency domain representation of the data. The main theoretical result is that, exactly as in the static model, the identified

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<sup>17</sup>The identified set for  $R_0^2$  always contains 1, i.e., we can never reject invertibility in the static model.



set for the scale parameter  $\alpha$  is an interval with informative bounds. From this result we derive identified sets for the main objects of interest: the degree of invertibility and variance decompositions. Relative to the static case, the dynamic case involves additional challenges in characterizing the informativeness of the data for the hidden shock at all frequencies.

We maintain [Assumptions 1 to 3](#) throughout, but for the moment, we carry out the analysis for the case of a single IV ( $n_z = 1$ ), leaving the generalization to [Section 3.3](#). That is,  $z_t$  is a scalar and  $\lambda = 1$  in equation (3). We write  $\Sigma_v^{1/2} = \sigma_v \geq 0$ , a scalar.

**PRELIMINARIES.** For the identification analysis, it will prove convenient to define and work with the IV projection residual

$$\tilde{z}_t \equiv z_t - E(z_t \mid \{y_\tau, z_\tau\}_{-\infty < \tau < t}) = \alpha \varepsilon_{1,t} + \sigma_v v_t. \quad (11)$$

We have thus removed any dependence on lagged observed variables, and  $\tilde{z}_t$  is serially uncorrelated by construction.

Next, we need to define our notation for spectral density matrices. For any two jointly stationary vector time series  $a_t$  and  $b_t$  of dimensions  $n_a$  and  $n_b$ , respectively, define the  $n_a \times n_b$  cross-spectral density matrix function ([Brockwell & Davis, 1991](#), Ch. 4 and 11)

$$s_{ab}(\omega) \equiv \frac{1}{2\pi} \sum_{\ell=-\infty}^{\infty} e^{-i\omega\ell} \text{Cov}(a_t, b_{t-\ell}), \quad \omega \in [0, 2\pi].$$

This object is well-defined if the autocovariance function of  $(a'_t, b'_t)'$  is absolutely summable. For any vector time series  $a_t$ , we denote its spectrum by  $s_a(\omega) \equiv s_{aa}(\omega)$ .

Just like identification in the static case proceeded through the variance-covariance matrix of the data, identification in the general dynamic model will rely heavily on the joint spectrum for  $w_t = (y'_t, \tilde{z}'_t)'$  implied by the LP-IV model, i.e., equations (1), (4), and (11). This joint spectrum is given by

$$s_w(\omega) = \begin{pmatrix} s_y(\omega) & s_{y\tilde{z}}(\omega) \\ s_{y\tilde{z}}(\omega)^* & s_{\tilde{z}}(\omega) \end{pmatrix} = \frac{1}{2\pi} \begin{pmatrix} \Theta(e^{-i\omega})\Theta(e^{-i\omega})^* & \alpha\Theta(e^{-i\omega})e_1 \\ \alpha e_1' \Theta(e^{i\omega})' & \alpha^2 + \sigma_v^2 \end{pmatrix}, \quad \omega \in [0, 2\pi], \quad (12)$$

where  $e_1$  is the unit vector with 1 as the first element and zeros elsewhere, an asterisk denotes complex conjugate transpose, and the matrix polynomial  $\Theta(\cdot)$  was defined in equation (1). Note the similarity between the spectrum  $s_w(\omega)$  and the covariance structure in the static model in [Section 3.1](#). The main difference is that in the dynamic setting we have a matrix

at each frequency  $\omega \in [0, 2\pi]$ .

RELATIVE IMPULSE RESPONSES. As in the static model, *absolute* impulse responses to the first shock are identified up to the scale parameter  $\alpha$ :

$$\text{Cov}(y_t, \tilde{z}_{t-\ell}) = \alpha \Theta_{\bullet, 1, \ell}. \quad (13)$$

Thus, *relative* impulse responses  $\Theta_{i, 1, \ell} / \Theta_{11, 0}$  are point-identified, as shown by [Stock & Watson \(2018\)](#) and others.

SCALE PARAMETER. We now show that, exactly as in the static case, the identified set for  $\alpha$  is an interval with informative bounds. Although  $\alpha$  itself is not a parameter of primary interest, it is key to identification of variance decompositions and the degree of invertibility.

Just as in the static case, the variance of the instrument provides the upper bound:

$$\alpha^2 \leq \text{Var}(\tilde{z}_t) \equiv \alpha_{UB}^2. \quad (14)$$

As in the static model, the boundary case  $\alpha = \alpha_{UB}$  corresponds to perfect IV informativeness.

To derive the lower bound, we apply the argument from the static case to the joint spectrum of the data at every frequency. Define first the projections of  $\tilde{z}_t$  and  $\varepsilon_{1,t}$ , respectively, onto all lags and leads of the endogenous variables  $y_t$ :

$$\begin{aligned} \tilde{z}_t^\dagger &\equiv E(\tilde{z}_t \mid \{y_\tau\}_{-\infty < \tau < \infty}), \\ \varepsilon_{1,t}^\dagger &\equiv E(\varepsilon_{1,t} \mid \{y_\tau\}_{-\infty < \tau < \infty}). \end{aligned} \quad (15)$$

Then, for every  $\omega \in [0, 2\pi]$ ,

$$s_{\tilde{z}^\dagger}(\omega) = \alpha^2 s_{\varepsilon_1^\dagger}(\omega) \leq \alpha^2 s_{\varepsilon_1}(\omega) = \alpha^2 \times \frac{1}{2\pi}, \quad (16)$$

which is the frequency-domain analogue of the conditional variance inequality (10) in the static case.<sup>18</sup> Hence, we obtain the lower bound

$$\alpha^2 \geq 2\pi \sup_{\omega \in [0, \pi]} s_{\tilde{z}^\dagger}(\omega) \equiv \alpha_{LB}^2. \quad (17)$$

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<sup>18</sup>[Brockwell & Davis \(1991, Remark 3, p. 439\)](#) show that  $s_{\tilde{z}^\dagger}(\omega) = s_{y\tilde{z}}(\omega)^* s_y(\omega)^{-1} s_{y\tilde{z}}(\omega)$  and  $s_{\varepsilon_1^\dagger}(\omega) = s_{y\varepsilon_1}(\omega)^* s_y(\omega)^{-1} s_{y\varepsilon_1}(\omega)$ . Since the joint spectrum is positive semidefinite,  $s_{\varepsilon_1}(\omega) \geq s_{\varepsilon_1^\dagger}(\omega)$  for all  $\omega$ .

This lower bound generalizes the lower bound (10) in the static model. Intuitively, in the static case a small value of  $\alpha$  requires  $y_t$  and  $\tilde{z}_t$  to be nearly independent. In the dynamic case, a small value of  $\alpha$  requires  $\tilde{z}_t$  to be nearly unpredictable by  $y_t$  at *every* frequency  $\omega$ , e.g., both in the long run and at business cycle frequencies. The boundary case  $\alpha = \alpha_{LB}$  corresponds to the observed macro aggregates being perfectly informative about the hidden shock  $\varepsilon_{1,t}$  at *some* frequency  $\bar{\omega} \in [0, \pi]$ , i.e., the projection residual  $\varepsilon_{1,t} - \varepsilon_{1,t}^\dagger$  has a spectral density  $s_{\varepsilon_{1,t} - \varepsilon_{1,t}^\dagger}(\omega) = s_{\varepsilon_{1,t}}(\omega) - s_{\varepsilon_{1,t}^\dagger}(\omega)$  that vanishes at frequency  $\bar{\omega}$ .

The main theoretical result of this paper is that the above bounds  $\alpha_{LB}^2, \alpha_{UB}^2$  are *sharp*.

**Proposition 1.** *Let there be given a joint spectral density for  $w_t = (y_t', \tilde{z}_t)'$ , continuous and positive definite at every frequency, with  $\tilde{z}_t$  being unpredictable from  $\{w_\tau\}_{-\infty < \tau < t}$ . Choose any  $\alpha \in (\alpha_{LB}, \alpha_{UB}]$ . Then there exists a model of the form (1), (4), and (11) with the given  $\alpha$  such that the spectral density of  $w_t$  implied by the model matches the given spectral density.*

In words, the distribution of the data allows us to conclude that  $\alpha^2$  lies in the identified set  $[\alpha_{LB}^2, \alpha_{UB}^2]$ , but the data cannot rule out any values of  $\alpha^2$  in this interval. The proposition does not cover the knife-edge case  $\alpha = \alpha_{LB}$  due to economically inessential technicalities.

The width of the identified set for depends on the application, although the set is never empty. To interpret the identified set, we express it in terms of the (unknown) model parameters. Analogously to the static case, the identified set for  $\frac{1}{\alpha^2}$  equals

$$\left[ \underbrace{\frac{\alpha^2}{\alpha^2 + \sigma_v^2}}_{\text{instrument strength}} \times \frac{1}{\alpha^2}, \quad \underbrace{\frac{1}{2\pi \sup_{\omega \in [0, \pi]} s_{\varepsilon_{1,t}^\dagger}(\omega)}}_{\text{informativeness of data for shock}} \times \frac{1}{\alpha^2} \right].$$

The lower bound of the identified set for  $\frac{1}{\alpha^2}$  is larger (and closer to the true  $\frac{1}{\alpha^2}$ ) when the instrument is stronger in the sense of a higher signal-to-noise ratio. The upper bound of the identified set for  $\frac{1}{\alpha^2}$  is smaller (and closer to the true  $\frac{1}{\alpha^2}$ ) when the data are more informative about the shock of interest at least at *some* frequency. Similar to the static case, the identified set for  $\frac{1}{\alpha^2}$  does not collapse to a point unless the instrument is perfect *and* there exists a frequency  $\bar{\omega}$  for which the data are perfectly informative about the frequency- $\bar{\omega}$  cyclical component of the shock.

To further interpret  $\alpha_{LB}^2$ , we derive a lower bound to this object that is explicitly tied to the degree of recoverability/invertibility. First, we have

$$\alpha_{LB}^2 = 2\pi \sup_{\omega \in [0, \pi]} s_{\tilde{z}^\dagger}(\omega) \geq \int_0^{2\pi} s_{\tilde{z}^\dagger}(\omega) d\omega = \text{Var}(\tilde{z}_t^\dagger). \quad (18)$$

The far right-hand side above depends on the degree of recoverability of the shock:

$$\text{Var}(\tilde{z}_t^\dagger) = \text{Var}(E(\tilde{z}_t | \{y_\tau\}_{-\infty < \tau < \infty})) = \alpha^2(1 - \text{Var}(\varepsilon_{1t} | \{y_\tau\}_{-\infty < \tau < \infty})) = \alpha^2 \times R_\infty^2.$$

An even lower bound on  $\alpha_{LB}^2$  is given by

$$\text{Var}(E(\tilde{z}_t | \{y_\tau\}_{-\infty < \tau \leq t})) = \alpha^2(1 - \text{Var}(\varepsilon_{1t} | \{y_\tau\}_{-\infty < \tau \leq t})) = \alpha^2 \times R_0^2.$$

Thus, if the shock is close to being invertible – or more generally, recoverable –  $\alpha_{LB}^2$  will be close to  $\alpha^2$ . As mentioned above,  $\alpha_{LB}^2$  will in fact be close to  $\alpha^2$  as long as the  $y_t$  process is highly informative about the  $\varepsilon_{1,t}$  process at *some* frequency. For example, the observed macro variables  $y_t$  may not perfectly reveal the short-run fluctuations of an unobserved technology shock, so recoverability fails ( $R_\infty^2 < 1$ ); yet a long-lag two-sided moving average of GDP growth may well approximate the low-frequency cycles of the technology shock. See [Section 4](#) for a concrete example.

**DEGREE OF INVERTIBILITY.** The identified set for the degree of invertibility at horizon  $\ell$  follows directly from the identified set for  $\alpha^2$ , since

$$R_\ell^2 = 1 - \text{Var}(\varepsilon_{1,t} | \{y_\tau\}_{-\infty < \tau \leq t+\ell}) = \frac{1}{\alpha^2} \times \text{Var}(E(\tilde{z}_t | \{y_\tau\}_{-\infty < \tau \leq t+\ell})),$$

and the variance on the right-hand side above is point-identified. Now similarly define

$$\tilde{R}_\ell^2 \equiv 1 - \frac{\text{Var}(\tilde{z}_t | \{y_\tau\}_{-\infty < \tau \leq t+\ell})}{\text{Var}(\tilde{z}_t)} = \frac{\text{Var}(E(\tilde{z}_t | \{y_\tau\}_{-\infty < \tau \leq t+\ell}))}{\text{Var}(\tilde{z}_t)}$$

as the (point-identified)  $R^2$  in a population regression of  $\tilde{z}_t$  on lags and leads of  $y_\tau$  up to time  $\tau = t + \ell$ . Then the identified set for the degree of invertibility  $R_\ell^2$  at horizon  $\ell$  equals

$$\left[ \underbrace{\tilde{R}_\ell^2}_{\frac{\alpha^2}{\alpha^2 + \sigma_v^2} \times R_\ell^2}, \underbrace{\frac{\text{Var}(\tilde{z}_t)}{2\pi \sup_{\omega \in [0, \pi]} s_{\tilde{z}^\dagger}(\omega)} \times \tilde{R}_\ell^2}_{\frac{1}{2\pi \sup_{\omega \in [0, \pi]} s_{\varepsilon_1^\dagger}(\omega)} \times R_\ell^2} \right]. \quad (19)$$

This identified set implies conditions under which the distribution of the observable data is consistent with invertibility or recoverability.

**Proposition 2.** *Assume  $\alpha_{LB}^2 > 0$ . The identified set for  $R_0^2$  contains 1 if and only if the*

instrument residual  $\tilde{z}_t$  does not Granger cause the macro observables  $y_t$ . The identified set for  $R_\infty^2$  contains 1 if and only if the projection  $\tilde{z}_t^\dagger$  is serially uncorrelated.

According to [Proposition 2](#),  $\varepsilon_{1,t}$  is certain to be noninvertible if and only if  $\tilde{z}_t$  Granger causes  $y_t$ . Moreover,  $\varepsilon_{1,t}$  is certain to be non-recoverable if and only if  $\tilde{z}_t^\dagger$ , defined in [\(15\)](#), is serially correlated at some lag.

VARIANCE DECOMPOSITIONS. We now turn to the identification of variance decompositions, the main parameters of interest. The identified sets for the FVR and FVD defined in [Section 2](#) are different. For the FVR, simply observe that

$$FVR_{i,\ell} = \frac{\sum_{m=0}^{\ell-1} \Theta_{i,1,m}^2}{\text{Var}(y_{i,t+\ell} \mid \{y_\tau\}_{-\infty < \tau \leq t})} = \frac{1}{\alpha^2} \times \frac{\sum_{m=0}^{\ell-1} \text{Cov}(y_{i,t}, \tilde{z}_{t-m})^2}{\text{Var}(y_{i,t+\ell} \mid \{y_\tau\}_{-\infty < \tau \leq t})}.$$

Hence, as in the static case, the identified set for  $FVR_{i,\ell}$  equals the identified set for  $\frac{1}{\alpha^2}$ , scaled by the (point-identified) second fraction on the far right-hand side above. In particular, the upper bound on the FVR depends on the informativeness of the macro variables for the shock of interest. Hence, adding more variables to the vector  $y_t$  of endogenous observables leads to a weakly narrower identified set (in relative terms, since the estimand itself changes if  $y_t$  is changed).

The identified set for the FVD requires more work. Intuitively, the (point-identified) full forecasting variance  $\text{Var}(y_{i,t+\ell} \mid \{y_\tau\}_{-\infty < \tau \leq t})$  conflates pure forecasting uncertainty (which enters the denominator of the FVD) and invertibility-related uncertainty (which does not). We thus need to bound the contribution of pure forecasting uncertainty. The following proposition summarizes our results.

**Proposition 3.** *Let there be given a joint spectral density for  $w_t = (y_t', \tilde{z}_t)'$  satisfying the assumptions in [Proposition 1](#). Given knowledge of  $\alpha \in (\alpha_{LB}, \alpha_{UB}]$ , the largest possible value of the forecast variance decomposition  $FVD_{i,\ell}$  is 1 (the trivial bound), while the smallest possible value is given by*

$$\frac{\sum_{m=0}^{\ell-1} \text{Cov}(y_{i,t}, \tilde{z}_{t-m})^2}{\sum_{m=0}^{\ell-1} \text{Cov}(y_{i,t}, \tilde{z}_{t-m})^2 + \alpha^2 \text{Var}(\tilde{y}_{i,t+\ell}^{(\alpha)} \mid \{\tilde{y}_\tau^{(\alpha)}\}_{-\infty < \tau \leq t})}. \quad (20)$$

Here  $\tilde{y}_t^{(\alpha)} = (\tilde{y}_{1,t}^{(\alpha)}, \dots, \tilde{y}_{n_y,t}^{(\alpha)})'$  denotes a stationary Gaussian time series with spectral density  $s_{\tilde{y}^{(\alpha)}}(\omega) = s_y(\omega) - \frac{2\pi}{\alpha^2} s_{y\tilde{z}}(\omega) s_{y\tilde{z}}(\omega)^*$ ,  $\omega \in [0, 2\pi]$ . Expression [\(20\)](#) is monotonically decreasing

in  $\alpha$ , so the overall lower bound on  $FVD_{i,\ell}$  is attained by  $\alpha = \alpha_{UB}$ ; in this boundary case we can represent  $\tilde{y}_t^{(\alpha_{UB})} = y_t - E(y_t \mid \{\tilde{z}_\tau\}_{-\infty < \tau \leq t})$ .

The upper bound on the  $\ell$ -period-ahead FVD is always 1, for any  $\ell \geq 1$ . This is achieved by a model in which all shocks, except the first one, only affect  $y_t$  after an  $\ell$ -period delay.

The expression for the lower bound (20) has a simple interpretation. Even if  $\alpha$  is known, the denominator  $\text{Var}(y_{i,t+\ell} \mid \{\varepsilon_\tau\}_{-\infty < \tau \leq t})$  of the FVD is not identified due to the lack of information about shocks other than the first. Although we can upper-bound this conditional variance by the denominator of the FVR, this upper bound is not sharp. Instead, to maximize the denominator, as much forecasting noise as possible should be of the pure forecasting variety, and not related to noninvertibility. For all shocks except for  $\varepsilon_{1,t}$ , this is achievable through a Wold decomposition construction (Hannan, 1970, Thm. 2'', p. 158). Given  $\alpha$ , we know the contribution of the first shock to  $y_t$ ; the residual after removing this contribution has the distribution of  $\tilde{y}_t^{(\alpha)}$ , as defined in the proposition. If  $\alpha$  is not known, the smallest possible value of the lower bound (20) is attained at the largest possible value of  $\alpha$ , namely  $\alpha_{UB}$ , for which  $\varepsilon_{1,t}$  contributes the least to forecasts of  $y_t$ .

Analogously to the FVR, the frequency-specific variance decomposition  $VD_i(\omega_1, \omega_2)$  is interval-identified with informative lower and upper bounds. This follows from

$$VD_i(\omega_1, \omega_2) = \frac{1}{\alpha^2} \times \frac{\int_{\omega_1}^{\omega_2} |s_{y_i \bar{z}}(\omega)|^2 d\omega}{\int_{\omega_1}^{\omega_2} s_{y_i}(\omega) d\omega},$$

where  $s_{y_i \bar{z}}(\omega)$  is the  $i$ -th element of  $s_{y \bar{z}}(\omega)$ , cf. equations (6) and (12).

**ABSOLUTE IMPULSE RESPONSES.** The identified set for the *absolute* impulse response  $\Theta_{i,1,\ell}$  is obtained by scaling the identified set for  $\frac{1}{\alpha}$ , cf. equation (13). This generalizes existing results on *relative* impulse responses, as discussed above (Stock & Watson, 2018).

**SUFFICIENT CONDITIONS FOR POINT IDENTIFICATION.** Although we have shown that partial identification analysis is informative in the general model, we now give a variety of sufficient conditions that ensure point identification of  $\alpha$  and thus the FVR, VD, and degree of invertibility. We also discuss identification of historical decompositions. **Proposition 3** showed that even point identification of  $\alpha$  is insufficient to point-identify the FVD, although a sharp and informative lower bound can be computed.

The first set of sufficient conditions relates to the informativeness of the macro aggregates  $y_t$  for the hidden shock  $\varepsilon_{1,t}$ . In this category, our weakest condition for point identification is

that the data  $y_t$  is perfectly informative about  $\varepsilon_{1,t}$  at *some* frequency, i.e., the spectral density of the projection residual  $\varepsilon_{1,t} - \varepsilon_{1,t}^\dagger$  vanishes at some frequency  $\bar{\omega}$ . Then  $\alpha = \alpha_{LB}$ , so the FVR, VD, and degree of invertibility are identified. This assumption is not testable. A stronger but more easily interpretable identifying assumption is recoverability, i.e.,  $\varepsilon_{1,t}^\dagger \equiv E(\varepsilon_{1,t} \mid \{y_\tau\}_{-\infty < \tau < \infty}) = \varepsilon_{1,t}$ . This assumption is testable, cf. [Proposition 2](#). Under recoverability, we have both  $\alpha = \alpha_{LB}$  and  $\tilde{z}_t^\dagger = \alpha \varepsilon_{1,t}$ . Recoverability is a restrictive assumption, but at least it is a meaningfully weaker requirement than invertibility in many economic applications, as discussed further in [Section 4](#). In fact, recoverability is implied by the usual SVAR assumption that there are as many shocks as variables,  $n_\varepsilon = n_y$ .<sup>19</sup> Our proof of [Proposition 1](#) shows how restrictive this assumption really is:  $\alpha$  is partially identified with the same sharp bounds as above even if we know that the number of shocks  $n_\varepsilon$  can be at most  $n_y + 1$ . Thus, no identifying power is gained from the knowledge that the number of shocks is “small”, unless that means  $n_\varepsilon = n_y$ .

Point identification can also be achieved by assuming that the instrument is perfect, i.e.,  $\sigma_v = 0$ . Then  $\tilde{z}_t = \alpha \varepsilon_{1,t}$  and identification proceeds in accordance with the logic behind local projections ([Jordà, 2005](#); [Gorodnichenko & Lee, 2017](#)). This assumption is not testable.

Under either recoverability or perfect instrument informativeness, we can point-identify the historical decomposition corresponding to the identified shock, cf. the definition in [Section 2](#). This object is identified because both the impulse responses and the time series of the shock itself are identified, as argued above.

### 3.3 Extension: multiple instruments

We now argue that identification analysis in the model with multiple IVs for the shock of interest ( $n_z \geq 2$ ) can be reduced to the single-IV setting without loss of generality.

The multiple-IV model is testable, unlike the single-IV model. As in the single-IV case, define the projection residual

$$\tilde{z}_t \equiv z_t - E(z_t \mid \{y_\tau, z_\tau\}_{-\infty < \tau < t}) = \alpha \lambda \varepsilon_{1,t} + \Sigma_v^{1/2} v_t. \quad (21)$$

Online Appendix B.1 shows that the testable implication of the multiple-IV model is that the cross-spectrum  $s_{y\tilde{z}}(\omega)$  has a rank-1 factor structure. The validity of the multiple-IV model can be rejected if and only if this factor structure fails.

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<sup>19</sup>Since we have ruled out singularities,  $n_\varepsilon = n_y$  implies that  $\Theta(L)^{-1}$  is a well-defined two-sided lag polynomial ([Brockwell & Davis, 1991](#), Thm. 3.1.3), so that  $\varepsilon_t = \Theta(L)^{-1} y_t$  and *all* shocks are recoverable.



When the multiple-IV model is consistent with the distribution of the data, identification analysis can be reduced to the single-IV case in [Section 3.2](#). Specifically, [Online Appendix B.1](#) shows that (i)  $\lambda$  is point-identified, and (ii) the identified sets for  $\alpha$ , variance decompositions, and the degree of invertibility are the same as the identified sets that exploit only the scalar instrument

$$\check{z}_t \equiv \frac{1}{\lambda' \text{Var}(\tilde{z}_t)^{-1} \lambda} \lambda' \text{Var}(\tilde{z}_t)^{-1} \tilde{z}_t. \quad (22)$$

Intuitively,  $\check{z}_t \propto E(\varepsilon_{1,t} \mid \tilde{z}_t)$ . Because  $\check{z}_t$  is a linear combination of all  $n_z$  instruments, the identified sets are narrower than if we had used any one instrument  $z_{k,t}$  in isolation.

In [Online Appendix B.2](#) we consider the more general case of multiple instruments being correlated with *multiple* structural shocks. In particular, we allow the instrument set to be correlated with a pre-specified number of structural shocks and then bound the forecast variance contribution of this combination of shocks to the macro aggregates of interest. The derived bounds would for example be informative in the application of [Mertens & Ravn \(2013\)](#), who use two external IVs plausibly correlated with two latent tax shocks.

## 4 Illustration using a structural macro model

We use the workhorse business cycle model of [Smets & Wouters \(2007\)](#) to illustrate the informativeness of our partial identification bounds on the degree of invertibility and variance decompositions. We show how the width of the identified sets depends on the strength of the instrument and the informativeness of the macro variables for the unknown shock. Given our choice of observables, the model's monetary policy shock is nearly invertible, so standard SVAR methods would deliver reasonable identification of this shock. In contrast, invertibility is a very poor approximation when identifying the effects of forward guidance (anticipated monetary) shocks or of technology shocks. Nevertheless, our sharp bounds on variance decompositions and the degree of invertibility are informative for all three shocks.

For clarity, we focus entirely on population bounds in this section, assuming the spectral density of the data is known. The econometrician uses our LP-IV techniques and does not exploit the underlying structure of the model.

We stress that the purpose of this section is merely to illustrate the workings of our identification bounds in an economically interpretable setting. Hence, we deliberately consider a small number of observable variables. Our results below are necessarily sensitive to the set of observables, as shown through robustness checks in [Online Appendix B.5](#). However, we caution against the belief that the use of a large number of observable variables will

automatically guarantee that shocks are recoverable (or invertible) in realistic applications.<sup>20</sup>

MODEL. We employ the [Smets & Wouters \(2007\)](#) model. Throughout, we parametrize the model according to the posterior mode estimates of [Smets & Wouters \(2007\)](#).<sup>21</sup> Following the canonical trivariate VAR in the empirical literature on monetary policy shock transmission, we assume the econometrician observes aggregate output, inflation, and the short-term policy interest rate. These macro aggregates are all stationary in the model, so they should be viewed as deviations from trend. The model features seven unobserved shocks, so not all shocks can be invertible.

The econometrician observes a single external instrument  $z_t$  for the shock of interest  $\varepsilon_{1,t}$ :

$$z_t = \alpha \varepsilon_{1,t} + \sigma_v v_t.$$

We normalize  $\alpha = 1$  throughout and compute identified sets for two different degrees of informativeness of the external instrument,  $\frac{1}{1+\sigma_v^2} \in \{0.25, 0.5\}$ . We do not attach any specific economic interpretation to the IV in the context of the [Smets & Wouters \(2007\)](#) model.

We separately consider three different shocks of interest: a monetary shock, a forward guidance shock, and a technology shock. With our set of observables, the monetary shock is nearly invertible, but the others are not. The forward guidance shock is instead nearly recoverable, whereas only the *long-run* cycles of the technology shock can be accurately recovered from the data. Nevertheless, we show that partial identification analysis is informative about the effects of all three shocks.

MONETARY SHOCK. We first consider identification of monetary policy shocks. These are defined as shocks to the serially correlated disturbance in the model’s Taylor rule.

The monetary shock is nearly invertible in our parametrization. Specifically, the collection of all past and current values of the observable macro variables explain a fraction  $R_0^2 = 0.8705$  of the variance of the shock, as shown by [Wolf \(2018\)](#).<sup>22</sup> The infinite past, present, and *future*

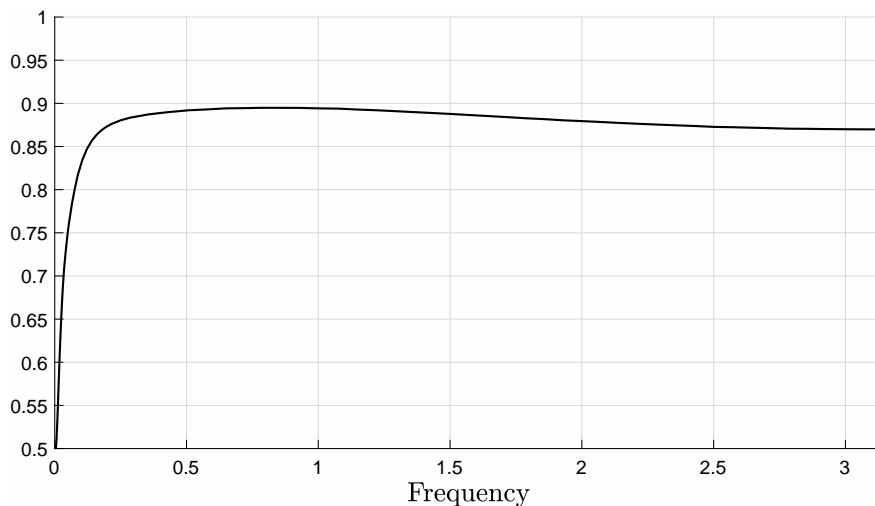
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<sup>20</sup>Although most DSGE models in the literature feature a small number of shocks for simplicity, in reality the addition of new observables will likely contaminate the analysis with additional nuisance shocks (including, but not limited to, measurement error). While the recoverability assumption may in some settings be justified from a theoretical standpoint, it should not be taken for granted.

<sup>21</sup>Our implementation of the Smets-Wouters model is based on Dynare replication code kindly provided by Johannes Pfeifer. The code is available at <https://sites.google.com/site/pfeiferecon/dynare>.

<sup>22</sup>[Wolf \(2018\)](#) argues that the  $R_0^2$  of monetary policy shocks is robustly high because such shocks uniquely move nominal interest rates and inflation in opposite directions.

MONETARY SHOCK: SPECTRAL DENSITY OF BEST 2-SIDED LINEAR PREDICTOR



**Figure 1:** Scaled spectral density  $2\pi s_{\varepsilon_1^\dagger}(\cdot)$  of the best two-sided linear predictor of the monetary shock. A frequency  $\omega$  corresponds to a cycle of length  $\frac{2\pi}{\omega}$  quarters.

of the observables yield only slightly sharper identification, with  $R_\infty^2 = 0.8767$ . [Figure 1](#) shows the spectral density  $s_{\varepsilon_1^\dagger}(\cdot)$  of the two-sided best linear predictor of the monetary shock based on all macro variables. The data are essentially equally informative about medium and high frequencies of the monetary shock, whereas the long-run cycles of the shock cannot be accurately recovered from the data. At the peak of the spectral density, the observables explain a fraction 0.8958 of the variance of that particular cyclical component of the monetary shock; hence,  $\alpha_{LB} = \sqrt{0.8958} = 0.9465$ , which is close to the truth of 1.

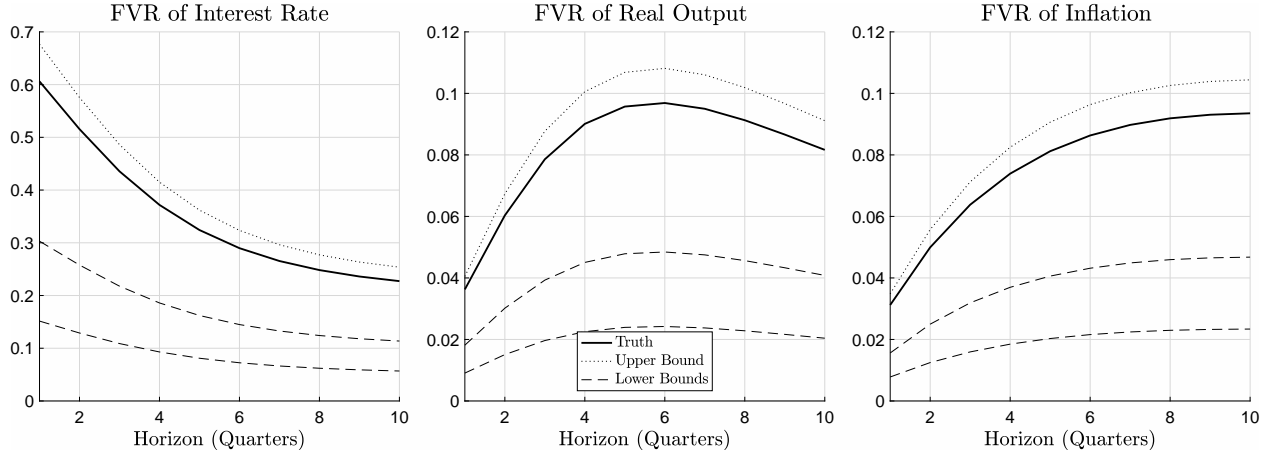
Because the shock is nearly invertible, the upper bounds of the identified sets for the forecast variance ratios are close to the truth, while the lower bounds depend on the informativeness of the IV. [Figure 2](#) displays the identified set of the FVR at different forecast horizons.<sup>23</sup> The upper and lower bounds are proportional to the true FVRs. The lower bound scales one-for-one with instrument informativeness, while the upper bound scales one-for-one with the maximal informativeness of the data for the shock across frequencies. The upper bounds are thus close to the true FVRs in this application with a near-invertible shock. The informativeness of the lower bounds depends entirely on the strength of the IV.

For FVDs, the lower bound of the identified set also depends on the informativeness of the IV, while the upper bound always equals the trivial value 1. [Figure 3](#) depicts the

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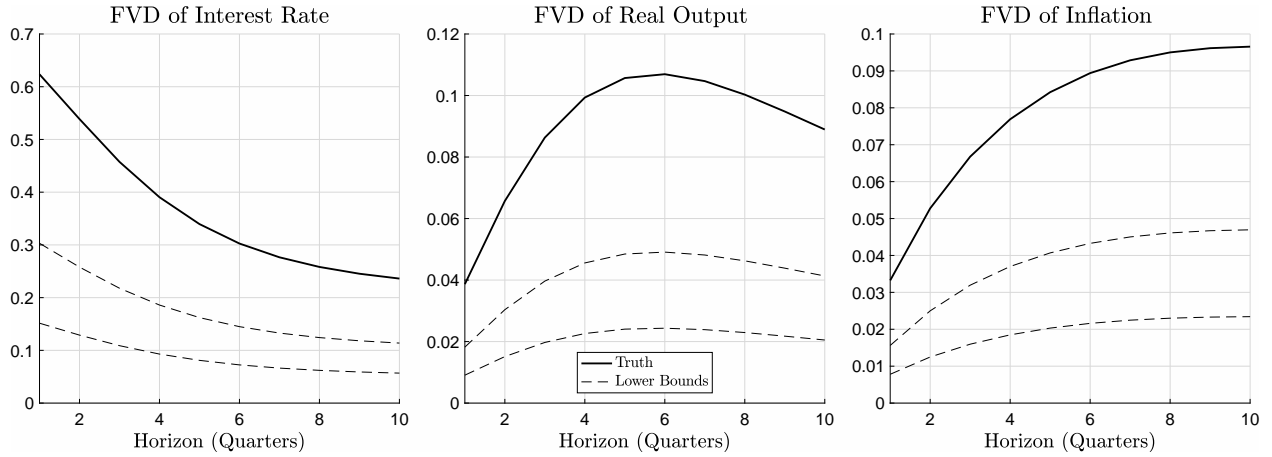
<sup>23</sup>Throughout this paper, the identified sets for FVRs are constructed horizon by horizon. However, the *joint* uncertainty about FVRs at different horizons is caused by uncertainty about the single parameter  $\alpha$ .

### MONETARY SHOCK: IDENTIFIED SET OF FVRs



**Figure 2:** Horizon-by-horizon identified sets for FVRs up to 10 quarters. The two lower bounds are for  $\frac{1}{1+\sigma_v^2} = 0.25$  (lower dashed line) and  $\frac{1}{1+\sigma_v^2} = 0.5$ .

### MONETARY SHOCK: IDENTIFIED SET OF FVDs

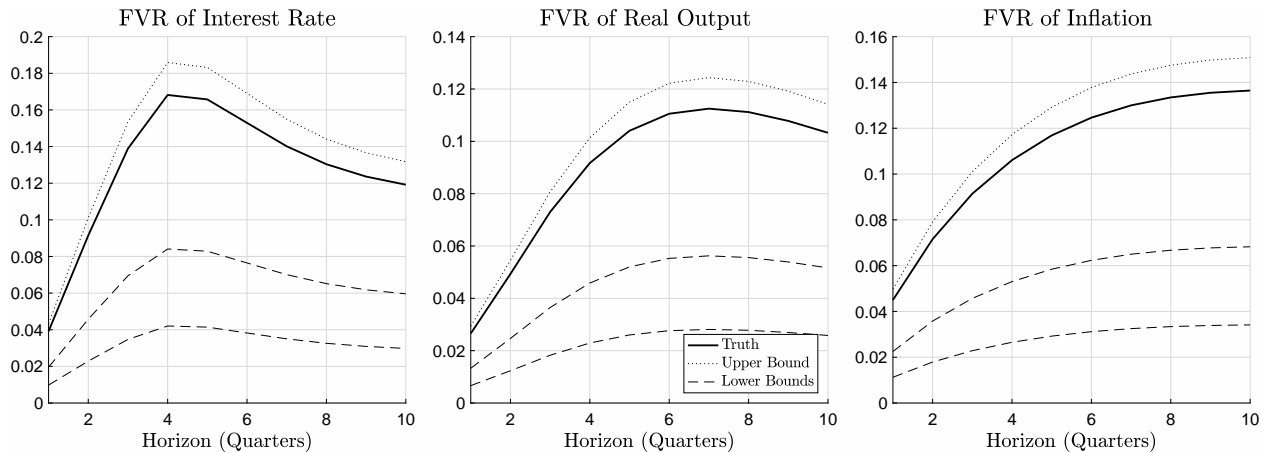


**Figure 3:** Horizon-by-horizon identified sets for FVDs up to 10 quarters. The two lower bounds are for  $\frac{1}{1+\sigma_v^2} = 0.25$  (lower dashed line) and  $\frac{1}{1+\sigma_v^2} = 0.5$ . Upper bound not shown.

identified sets for FVDs, omitting the trivial upper bound. The lower bound is now not simply proportional to the true FVD, due to the intricacies of bounding the denominator of the FVD. In this application, the lower bound is nevertheless approximately equal to the true FVD scaled by instrument informativeness  $\frac{1}{1+\sigma_v^2}$ .

Due to the near-invertibility of the shock, SVAR-IV identification of the monetary shock would only be slightly biased (Forni et al., 2018; Wolf, 2018). This, however, is not the case for the next two shocks we consider.

## FORWARD GUIDANCE SHOCK: IDENTIFIED SET OF FVRs



**Figure 4:** Horizon-by-horizon identified sets for FVRs up to 10 quarters. The two lower bounds are for  $\frac{1}{1+\sigma_v^2} = 0.25$  (lower dashed line) and  $\frac{1}{1+\sigma_v^2} = 0.5$ .

FORWARD GUIDANCE SHOCK. We now modify the model to include forward guidance shocks, a type of news shock. A forward guidance shock is identical to a monetary shock, except it is anticipated two quarters in advance by economic agents.<sup>24</sup>

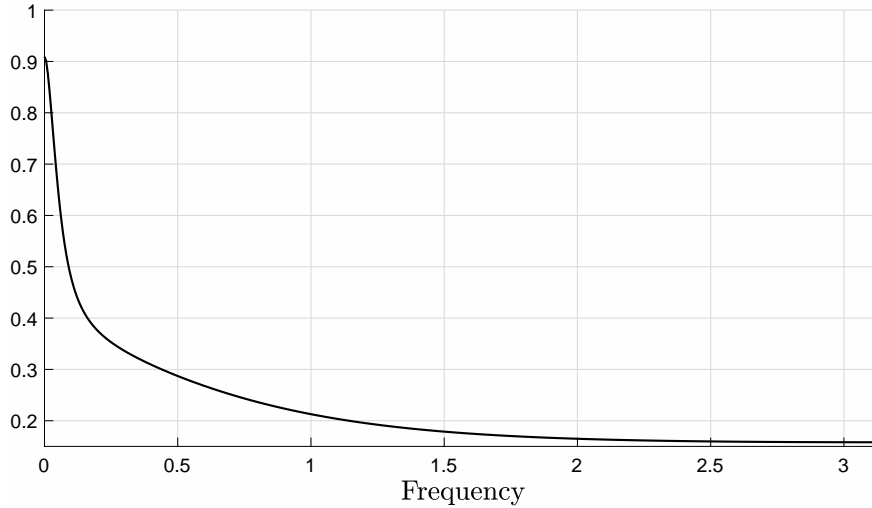
As is common with news shocks, the forward guidance shock is highly noninvertible but approximately recoverable. The wedge between information contained in the infinite past and information contained in the entire time series of observables is sizable: Contemporaneous informativeness is limited, with  $R_0^2 = 0.0792$ , but looking two quarters ahead basically returns us to the level of informativeness for the standard monetary shock, with  $R_2^2 = 0.8731$  and  $R_\infty^2 = 0.8813$ . Intuitively, on impact, all macro aggregates move in the same direction, suggesting to the econometrician that the economy was probably buffeted by a demand shock. But two quarters from now, when the anticipated innovation finally hits, the interest rate response suddenly switches sign, sending a strong signal that in fact a monetary policy shock – and not some other kind of demand shock – had occurred. This is one example of why, with news shocks, the incremental bite of two-sided analysis can be substantial.

Despite the high degree of noninvertibility, the identified sets for the FVRs of the forward guidance shock are as informative as those for the monetary shock, as shown in Figure 4. This demonstrates that our partial identification analysis is not only robust to noninvertibility – its quantitative usefulness does not depend on the degree of invertibility *per se*. In stark contrast,

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<sup>24</sup>Formally, we implement forward guidance by changing the baseline Smets & Wouters (2007) model so that the monetary shock has time subscript  $t - 2$  instead of  $t$ .

TECHNOLOGY SHOCK: SPECTRAL DENSITY OF BEST 2-SIDED LINEAR PREDICTOR



**Figure 5:** Scaled spectral density  $2\pi s_{\varepsilon_1^\dagger}(\cdot)$  of the best two-sided linear predictor of the technology shock. A frequency  $\omega$  corresponds to a cycle of length  $\frac{2\pi}{\omega}$  quarters.

identification that incorrectly imposes invertibility (e.g., SVARs) would overstate variance decompositions by a factor of  $1/0.0792 \approx 13$  (!).<sup>25</sup> Recoverability-based identification would err by a more modest factor of  $1/0.8813 \approx 1.13$ .

TECHNOLOGY SHOCK. Finally, we consider identification of technology shocks, defined as an innovation to the autoregressive process of total factor productivity.

Unlike the monetary and forward guidance shocks, the technology shock is far from recoverable, using our baseline set of observables; nevertheless, our bounds remain informative. In the model, the technology shock is much more important in accounting for low-frequency cycles of the data than it is for high-frequency cycles. The degrees of invertibility and recoverability are low:  $R_0^2 = 0.2007$  and  $R_\infty^2 = 0.2209$ . However, the data are very informative about the lowest-frequency cycles of the technology shock, as shown in Figure 5. As a result,  $\alpha_{LB}^2 = 0.9092$  is close to the true value of 1, and the upper bounds of our identified sets for FVRs and the degree of invertibility (not shown) yield tight identification. In contrast, identification that incorrectly imposes either invertibility or recoverability of the shock overstates the FVR by a factor of about 5.

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<sup>25</sup>To be exact, standard SVAR-IV methods would overstate *impact* impulse responses by a factor of  $1/\sqrt{0.0792} \approx 3.6$  and so impact variance decompositions by a factor of 13. Subsequent impulse responses would not be proportional to true responses, due to the imposed VAR dynamics (Stock & Watson, 2018). We state formal results on the bias of SVAR-IV under noninvertibility in Online Appendix B.3.

## 5 Inference

To make the identification analysis practically useful, we develop partial identification robust confidence intervals and tests. In a first step, the researcher estimates a reduced-form VAR model, which is then used in a second step to derive sample analogues of our population bounds. Using the general partial identification confidence procedures of [Imbens & Manski \(2004\)](#) and [Stoye \(2009\)](#), we construct confidence intervals for both the parameters and for the identified sets. We also discuss a test of invertibility. The confidence intervals are shown to be asymptotically valid under nonparametric regularity conditions. Finally, we show through simulations that the LP-IV confidence intervals perform well in finite samples.

We assume the availability of a single instrument  $z_t$  for notational simplicity. The generalization to multiple instruments is straight-forward, as discussed in [Section 3.3](#).

**REDUCED-FORM VAR.** We assume that the second-moment properties of the data are captured by a reduced-form VAR in  $(y'_t, z_t)'$ . The lag length  $p$  is initially assumed to be finite and known, but this is relaxed below. Thus, assume that there exist  $(n_y + 1) \times (n_y + 1)$  matrices  $A_\ell$ ,  $\ell = 1, 2, \dots, p$ , and a symmetric positive definite  $(n_y + 1) \times (n_y + 1)$  matrix  $\Sigma$  such that the spectral density of  $W_t \equiv (y'_t, z_t)'$  is given by

$$s_W(\omega) = \left( I_{n_y+1} - \sum_{\ell=1}^p A_\ell e^{-i\omega\ell} \right)^{-1} \Sigma \left( I_{n_y+1} - \sum_{\ell=1}^p A_\ell e^{-i\omega\ell} \right)^{-1*}, \quad \omega \in [0, 2\pi],$$

and such that all roots of the polynomial  $x \mapsto \det(I_{n_y+1} - \sum_{\ell=1}^p A_\ell x^\ell)$  are outside the unit circle. Let  $\vartheta \equiv (\text{vec}(A_1)', \dots, \text{vec}(A_p)', \text{vech}(\Sigma)')'$  denote the collection of true reduced-form VAR parameters, and let  $\hat{\vartheta} \equiv (\text{vec}(\hat{A}_1)', \dots, \text{vec}(\hat{A}_p)', \text{vech}(\hat{\Sigma})')'$  denote the least-squares estimators. Under standard conditions, we have  $T^{1/2}(\hat{\vartheta} - \vartheta) \xrightarrow{D} N(0, \Omega)$ , where  $T$  is the sample size, and the asymptotic variance  $\Omega$  can be estimated consistently by  $\hat{\Omega}$ , say ([Kilian & Lütkepohl, 2017](#), Ch. 2.3).

Although not essential to our approach, we assume a reduced-form VAR structure for three reasons. First, VARs are known to be able to approximate any spectral density function arbitrarily well as the VAR lag length tends to infinity. Second, the VAR structure facilitates the development of a test of invertibility. Third, VAR-based inference amounts to applying our population calculations from [Section 3](#) to a spectrum of a particular functional form (namely a VAR spectrum with the particular estimated parameters  $\hat{\vartheta}$ ). All inequalities satisfied in the population must then also hold in any finite sample, thus guaranteeing



nonempty identified sets, for example (up to numerical error, but not statistical error). The advantages of the VAR approach notwithstanding, we remark that one could in principle use any well-behaved estimator of the spectrum of  $(y'_t, z'_t)'$ .

While we here assume a finite VAR lag length for expositional simplicity, Online Appendix B.7 proves that our VAR-based inference strategy is asymptotically valid under *nonparametric* regularity conditions, provided that the VAR lag length  $p = p_T$  used for estimation diverges with the sample size  $T$  at an appropriate rate. That is, the inference strategy is valid even if the true data generating process (DGP) is a possibly non-Gaussian VAR( $\infty$ ). In practice, we suggest estimating the lag length  $p$  by information criteria or likelihood ratio tests. We emphasize that assuming a reduced-form VAR is less restrictive than doing SVAR-IV inference: We do not assume that the reduced-form VAR residuals span the true structural shocks  $\varepsilon_t$ . For example, we continue to allow the number of structural shocks to possibly exceed the number of variables in the VAR.

**INVERTIBILITY TEST.** It is straight-forward to test for invertibility of the shock of interest using the estimated reduced-form VAR. We showed in [Proposition 2](#) that the distribution of the data is consistent with invertibility of  $\varepsilon_{1,t}$  if and only if  $\tilde{z}_t$  does not Granger cause  $y_t$ . Granger non-causality of  $\tilde{z}_t$  for  $y_t$  is equivalent with Granger non-causality of  $z_t$  for  $y_t$ . A test of the Granger non-causality null hypothesis amounts to a test of the exclusion restrictions that lags of  $z_t$  do not enter the reduced-form VAR equations for  $y_t$ . This test has power against all Granger causal alternatives, so it has power against all falsifiable noninvertible alternatives by [Proposition 2](#).<sup>26</sup>

**CONFIDENCE INTERVALS.** We now construct partial identification robust confidence intervals for identified sets and for the true parameters. Here we rely heavily on the inference methods pioneered by [Imbens & Manski \(2004\)](#) and refined by [Stoye \(2009\)](#).

We start by defining notation. Given the reduced-form VAR model, all identified sets derived in [Section 3.2](#) are of the form  $[\underline{h}(\vartheta), \bar{h}(\vartheta)]$ , where  $\underline{h}(\cdot)$  and  $\bar{h}(\cdot)$  are continuous functions mapping the VAR parameter space into the real line, and such that  $\underline{h}(\cdot) \leq \bar{h}(\cdot)$ . A (pointwise) consistent estimator of the identified set  $[\underline{h}(\vartheta), \bar{h}(\vartheta)]$  is then given by the plug-in interval

$$[\underline{h}(\hat{\vartheta}), \bar{h}(\hat{\vartheta})].$$

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<sup>26</sup>[Stock & Watson \(2018\)](#) develop an LP-IV invertibility test which directs power against alternatives with impulse response functions that differ substantially from the invertible null. They do not discuss whether their test has power against all falsifiable noninvertible alternatives.

Let  $\hat{\Delta} \equiv \bar{h}(\hat{\vartheta}) - \underline{h}(\hat{\vartheta})$  denote the width of the estimate of the identified set. Assume  $\underline{h}(\cdot)$  and  $\bar{h}(\cdot)$  are continuously differentiable at the true VAR parameters  $\vartheta$  with  $1 \times \dim(\vartheta)$  dimensional Jacobian functions  $\dot{\underline{h}}(\cdot)$  and  $\dot{\bar{h}}(\cdot)$ . Define the standard errors of  $\underline{h}(\hat{\vartheta})$  and  $\bar{h}(\hat{\vartheta})$ ,

$$\hat{\sigma} \equiv \sqrt{T^{-1} \dot{\underline{h}}(\hat{\vartheta}) \hat{\Omega} \dot{\underline{h}}(\hat{\vartheta})'}, \quad \hat{\bar{\sigma}} \equiv \sqrt{T^{-1} \dot{\bar{h}}(\hat{\vartheta}) \hat{\Omega} \dot{\bar{h}}(\hat{\vartheta})'},$$

and their correlation,

$$\hat{\rho} \equiv \frac{T^{-1} \dot{\underline{h}}(\hat{\vartheta}) \hat{\Omega} \dot{\bar{h}}(\hat{\vartheta})'}{\hat{\sigma} \times \hat{\bar{\sigma}}}.$$

Finally, let  $\Phi(\cdot)$  denote the standard normal cumulative distribution function.

We now construct a confidence interval for the entire identified set. The interval

$$\left[ \underline{h}(\hat{\vartheta}) - \Phi^{-1}(1 - \beta/2) \hat{\sigma}, \bar{h}(\hat{\vartheta}) + \Phi^{-1}(1 - \beta/2) \hat{\bar{\sigma}} \right] \quad (23)$$

is a (pointwise) asymptotically valid level- $(1 - \beta)$  confidence interval for the identified set  $[\underline{h}(\vartheta), \bar{h}(\vartheta)]$ . That is, the above interval contains the *entire* identified set in at least  $100(1 - \beta)\%$  of repeated experiments, asymptotically. This follows from the delta method and the arguments of [Imbens & Manski \(2004\)](#).

Next, we construct a confidence interval for the true parameter of interest. By definition of the identified set, the true parameter is contained in  $[\underline{h}(\vartheta), \bar{h}(\vartheta)]$ , but we know nothing else about the true parameter. Although the interval (23) trivially has asymptotic coverage of at least  $1 - \beta$  for the true parameter, [Imbens & Manski \(2004\)](#) showed that it is possible to develop a narrower interval with the same property. As in [Stoye \(2009, p. 1305\)](#), define the two scalars  $\hat{c}, \hat{\bar{c}}$  as the minimizers of the objective function

$$\hat{\sigma} \times \hat{c} + \hat{\bar{\sigma}} \times \hat{\bar{c}},$$

subject to the two constraints

$$\begin{aligned} \Pr \left( -\hat{c} \leq U_1, \hat{\rho} U_1 \leq \hat{\bar{c}} + \frac{\hat{\Delta}}{\hat{\sigma}} + \sqrt{1 - \hat{\rho}^2} \times U_2 \right) &\geq 1 - \beta, \\ \Pr \left( -\hat{c} - \frac{\hat{\Delta}}{\hat{\sigma}} - \sqrt{1 - \hat{\rho}^2} \times U_2 \leq \hat{\rho} U_1, U_1 \leq \hat{\bar{c}} \right) &\geq 1 - \beta. \end{aligned}$$

Here the probabilities are taken solely over the distribution of  $(U_1, U_2)'$ , which is bivariate

standard normal. The above minimization problem is easy to solve numerically, cf. [Stoye \(2009, Appendix B\)](#). Given these definitions, the interval

$$\left[ \underline{h}(\hat{\vartheta}) - \hat{c} \times \hat{\underline{\sigma}}, \bar{h}(\hat{\vartheta}) + \hat{c} \times \hat{\bar{\sigma}} \right]$$

is a (pointwise) asymptotically valid level- $(1 - \beta)$  confidence interval for the true parameter. Again, this result follows from the delta method and the results in [Stoye \(2009\)](#), who builds on [Imbens & Manski \(2004\)](#).<sup>27</sup>

To implement the above confidence interval procedures, the researcher needs to compute the VAR estimator  $\hat{\vartheta}$ , the asymptotic variance matrix estimate  $\hat{\Omega}$ , the bound estimates  $\underline{h}(\hat{\vartheta})$  and  $\bar{h}(\hat{\vartheta})$ , and the derivatives of the bounds  $\dot{\underline{h}}(\hat{\vartheta})$  and  $\dot{\bar{h}}(\hat{\vartheta})$ . [Appendix A.1](#) provides formulas for the bounds and derivatives in terms of the VAR parameters. A simple bootstrap implementation is also available, see below.

We now discuss how to resolve the complication that the upper bound of the identified sets for  $\frac{1}{\alpha^2}$ ,  $R_0^2$ , the FVR, and the VD may not be continuously differentiable in the VAR parameters. The issue arises because  $\alpha_{LB}^2$  is given by the maximum of a certain function, cf. [\(17\)](#). When this function has multiple maxima at the true VAR parameters (e.g., when the spectral density of  $\tilde{z}_t^\dagger$  is flat, as in the recoverable case), continuous differentiability of  $\alpha_{LB}^2$  in the VAR parameters  $\vartheta$  may fail ([Gafarov et al., 2018](#)). In this case, delta method inference will be unreliable. As a remedy, we suggest replacing the maximum  $\alpha_{LB}^2 = 2\pi \sup_{\omega \in [0, \pi]} s_{\tilde{z}^\dagger}(\omega)$  in all our bounds with the smaller average value  $\text{Var}(\tilde{z}_t^\dagger) = \int_0^{2\pi} s_{\tilde{z}^\dagger}(\omega) d\omega$ , cf. the inequality [\(18\)](#). The latter object is continuously differentiable in the VAR parameters, so inference using the above methods is unproblematic. Use of the non-sharp bound does lead to a power loss, but the loss is small if the shock  $\varepsilon_{1,t}$  is close to being recoverable.<sup>28</sup> Note that continuous differentiability of the bounds for the FVD obtains without modifications.

Our confidence intervals are pointwise valid in both senses of the word. First, we focus on constructing a confidence interval for each parameter of interest separately, as opposed to capturing the joint uncertainty of several parameters at once. Second, our asymptotics are pointwise in the true parameters; we do not derive the coverage under the worst-case

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<sup>27</sup>We do not require that the VAR parameters are *uniformly* asymptotically normal, since we only develop pointwise valid confidence intervals, as discussed further below.

<sup>28</sup>More generally, we can lower-bound  $\alpha_{LB}^2$  by  $\int_0^{2\pi} r(\omega) s_{\tilde{z}^\dagger}(\omega) d\omega$ , where  $r(\cdot)$  is a nonnegative function such that  $\int_0^{2\pi} r(\omega) d\omega = 2\pi$ . If the researcher has prior information about the frequencies  $\omega$  at which  $y_t$  is particularly informative about  $\varepsilon_{1,t}$ , then  $r(\omega)$  can be chosen to weight these frequencies more heavily. This yields a more informative bound than  $\text{Var}(\tilde{z}_t^\dagger)$ , while preserving continuous differentiability.

data generating process.<sup>29</sup> In particular, we ignore finite-sample issues caused by weak instruments, i.e.,  $\alpha_{LB} \approx 0$ . We also ignore the familiar parameter-on-the-boundary issue that may arise if one of the population bounds is at the boundary of its parameter space (this issue can also arise in standard SVAR inference on variance decompositions).

**BOOTSTRAP IMPLEMENTATION.** The calculation of derivatives in the confidence interval formulas above is obviated by the bootstrap. Suppose we bootstrap the estimator  $\hat{\vartheta}$  (Kilian & Lütkepohl, 2017, Ch. 12). Then we can compute  $\hat{\sigma}$  as the bootstrap standard deviation of  $\underline{h}(\hat{\vartheta})$ ,  $\hat{\sigma}$  as the bootstrap standard deviation of  $\bar{h}(\hat{\vartheta})$ , and  $\hat{\rho}$  as the bootstrap correlation of  $\underline{h}(\hat{\vartheta})$  and  $\bar{h}(\hat{\vartheta})$ . By plugging into the same confidence interval formulas as above, we achieve the same (pointwise) asymptotic coverage probability as the delta method confidence intervals, provided an appropriate bootstrap consistency condition holds.

**SIMULATION STUDY.** Online Appendix B.8 presents a simulation study of the LP-IV bootstrap confidence intervals for parameters and identified sets. We consider a variety of structural VARMA DGPs, including a non-invertible one. We find that the finite-sample coverage rates of our confidence intervals are close to the nominal level throughout, except when parameter-on-the-boundary issues cause over-coverage. In particular, the LP-IV confidence intervals have at least as accurate coverage as corresponding SVAR-IV confidence intervals for invertible DGPs, and of course perform much better in the non-invertible case.

## 6 Empirical application

To illustrate our inference procedure, we study the importance of monetary shocks in U.S. data. We use the empirical setting of Gertler & Karadi (2015), whose external instrument for the monetary shock is obtained from high-frequency financial data. Using an SVAR-IV approach, Gertler & Karadi (2015) estimated impulse responses to a 20 basis point shock in the short-term interest rate, but they did not consider the *importance* of the monetary shock using variance decompositions. Caldara & Herbst (2018) compute FVDs for a similar specification, but their analysis also assumes an SVAR model. We find that invertibility (i.e.,

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<sup>29</sup>The Imbens & Manski (2004) and Stoye (2009) procedures are designed to control coverage uniformly over the width of the identified set. We do not discuss uniform asymptotics here because this seems to require bounding the magnitude of the largest eigenvalue of the VAR polynomial away from 1, in which case the width of the identified set (for all our objects of interest) would also be bounded away from zero. Hence, in this case, the uniform asymptotic validity of the confidence procedures is a trivial matter.

SVAR structure) is rejected by the data. Happily, our LP-IV confidence intervals confirm the conclusions in [Caldara & Herbst \(2018\)](#) that monetary shocks contribute at most moderately to fluctuations in output growth and inflation, as well as to financial stress in the short run.

Our specification follows [Gertler & Karadi \(2015\)](#) except that we do not impose a SVAR structure. We consider four endogenous macro variables  $y_t$ : output growth (log growth rate of industrial production), inflation (log growth rate of CPI inflation), the Federal Funds Rate, and the Excess Bond Premium of [Gilchrist & Zakrajšek \(2012\)](#), a measure of the non-default-related corporate bond spread. The external IV  $z_t$  is constructed from changes in 3-month-ahead futures prices written on the Federal Funds Rate, where the changes are measured over short time windows around Federal Open Market Committee monetary policy announcement times.<sup>30</sup> Data are monthly from January 1990 to June 2012. The Akaike Information Criterion selects  $p = 6$  lags in the reduced-form VAR we use for inference. We employ a homoskedastic recursive residual VAR bootstrap with 10,000 draws.<sup>31</sup>

The data reject invertibility. [Table 1](#) shows point estimates and 90% confidence intervals for the identified sets of the degree of invertibility and the degree of recoverability. We also show partial identification robust 90% confidence intervals for these parameters themselves, cf. [Section 5](#). Since the confidence sets for the degree of invertibility exclude 1, we can reject invertibility at the 10% level.<sup>32</sup> The data are consistent, however, with moderately large values of the degree of invertibility  $R_0^2$ , as well as with very small values. The data are also consistent with small values of the degree of recoverability  $R_\infty^2$ .<sup>33</sup>

The monetary shock accounts for a small to moderate fraction of the forecast variance of output growth and inflation, and of the Excess Bond Premium at short horizons. [Figure 6](#) shows partial identification robust confidence intervals for the forecast variance ratio of the

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<sup>30</sup>See [Gertler & Karadi \(2015\)](#) for details on the construction of the IV and a discussion of the exclusion restriction. [Nakamura & Steinsson \(2018\)](#) argue that the monetary shock identified using this IV partially captures revelation of the Federal Reserve’s superior information about economic fundamentals. [Online Appendix B.2](#) shows that our FVR bounds can generally be interpreted as bounding the importance of the particular linear combination of shocks that tend to hit during FOMC announcements.

<sup>31</sup>All empirical results reported in this section, including unreported confidence intervals for the FVR parameters themselves, can be produced in about 6 minutes per 1,000 bootstrap draws, using Matlab R2017b without parallelization on a personal laptop with 1.60 GHz processor and 8 GB RAM.

<sup>32</sup>As discussed in [Section 5](#), this amounts to testing whether the IV Granger causes the other variables in the reduced-form VAR. [Online Appendix B.6](#) provides p-values for such tests. [Stock & Watson \(2018\)](#) fail to reject invertibility in the [Gertler & Karadi \(2015\)](#) specification, apparently because they use a smaller lag length of 4 in their Granger causality tests.

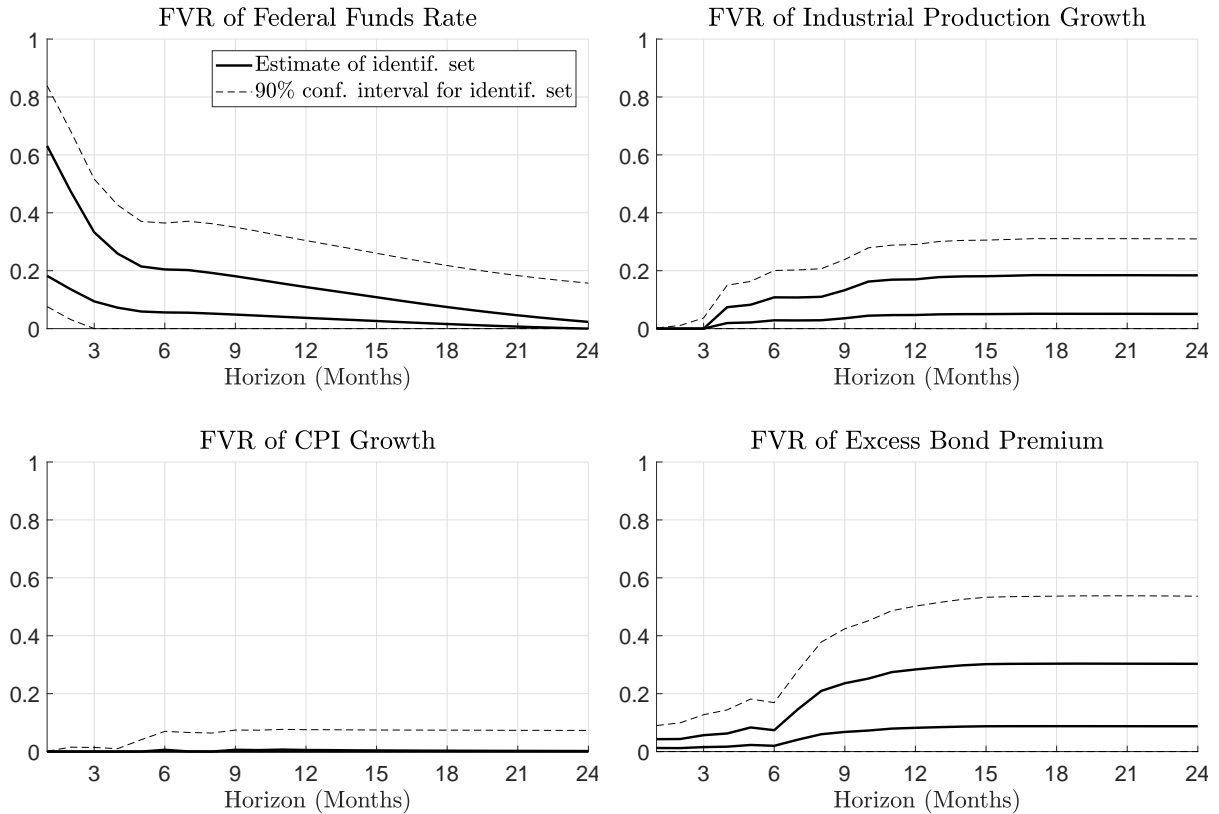
<sup>33</sup>As discussed in [Section 5](#), we base inference on a slightly conservative lower bound for  $\alpha$ , so our confidence intervals for  $R_\infty^2$  include 1 by construction.

EMPIRICAL APPLICATION: DEGREE OF INVERTIBILITY/RECOVERABILITY

$R_0^2$	Estimate of IS	[0.197, 0.687]
	Conf. int. for IS	[0.090, 0.877]
	Conf. int. for param.	[0.117, 0.828]
$R_\infty^2$	Estimate of IS	[0.283, 1.000]
	Conf. int. for IS	[0.186, 1.000]
	Conf. int. for param.	[0.207, 1.000]

**Table 1:** 90% confidence intervals for the degree of invertibility  $R_0^2$  and the degree of recoverability  $R_\infty^2$ , along with point estimates and 90% confidence intervals for the identified sets of these parameters. IS = identified set. All numbers are bootstrap bias corrected. Upper bound of IS for  $R_\infty^2$  equals 1 by construction.

EMPIRICAL APPLICATION: FORECAST VARIANCE RATIOS



**Figure 6:** Point estimates and 90% confidence intervals for the identified sets of forecast variance ratios, across different variables and forecast horizons. For visual clarity, we force bias-corrected estimates/bounds to lie in  $[0, 1]$ .

four endogenous macro variables with respect to the monetary shock. We report point estimates and confidence intervals for the identified sets (at each horizon separately); these intervals happen to be similar to the confidence intervals for the parameters themselves in this application. Because we compute Hall’s asymmetric bootstrap confidence interval, which has a built-in bias correction, some of the intervals and bias-adjusted point estimates go negative.<sup>34</sup> At all forecast horizons, the 90% confidence intervals rule out FVRs above 31% for output growth and 8% for inflation.<sup>35</sup> At forecast horizons up to 6 months, we can rule out that the monetary shock accounts for more than 18% of the forecast variance of the Excess Bond Premium. However, we cannot rule out that the monetary shock is an important contributor to medium- or long-run forecasts of the bond premium. On the other hand, we cannot rule out that the monetary shock is completely unimportant either, for essentially all variables and forecast horizons.

The application illustrates that LP-IV inference can be informative about important questions, in addition to being robust to violations of dubious identification assumptions such as invertibility (here rejected by the data) and the availability of a noise-less IV (an untestable assumption). We obtain tight upper bounds on forecast variance ratios, despite the finding by [Stock & Watson \(2018\)](#) that standard errors for LP-IV-estimated impulse response functions are large in this application. Since our analysis arguably weakens the identifying restrictions used in previous papers, it is reassuring that the finding of a modest role for monetary shocks in driving real output and inflation is in line with the existing literature ([Ramey, 2016](#), Sec. 3; [Caldara & Herbst, 2018](#)).<sup>36</sup>

## 7 Conclusion

We expand the toolkit of the LP-IV approach to causal inference in macroeconometrics. LP-IV has recently become a popular method for estimating impulse response functions by exploiting interpretable exclusion restrictions, without imposing invertibility or functional form assumptions on shock transmission. However, existing methods did not allow researchers to quantify the importance of individual shocks. We fill this gap by providing identification

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<sup>34</sup>This could be avoided by using Efron’s percentile interval, but bias correction is desirable in VAR contexts ([Kilian & Lütkepohl, 2017](#), Ch. 12). Our qualitative conclusions are not sensitive to the bias correction.

<sup>35</sup>Our upper bounds are even tighter if we run our analysis on the pre-crisis 1990–2006 sample.

<sup>36</sup>For completeness, Online Appendix B.6 provides forecast variance decompositions implied by an estimated SVAR-IV model, although the latter is rejected by the data.



results and inference techniques for variance decompositions, historical decompositions, and the degree of invertibility. Our partial identification robust confidence interval procedure is computationally straight-forward and relies on familiar methods for delta method or bootstrap inference in reduced-form VARs. The informativeness of our partial identification bounds does not depend on the degree of invertibility of the shocks *per se*, but rather on the strength of the instrument and the informativeness of the macro variables for *some* short-, medium-, or long-run cycles of the shock of interest. In contrast, the validity of SVAR-IV analysis relies on the testable assumption that the shock of interest is nearly invertible (Forni et al., 2018). Finally, we show that if researchers are willing to assume that the shock of interest is recoverable – a substantively weaker assumption than invertibility – most objects of interest are point-identified.

Our work points to several potential future research directions. First, to simplify the practical econometric procedure, our inference strategy relies on a slightly conservative identification bound that does not exploit the shape of the entire spectrum; it would be interesting to improve on this. Second, one could construct simultaneous (rather than pointwise) confidence bands for, say, forecast variance decompositions at multiple horizons. Third, future research should explore inference issues caused by parameters on the boundary, weak instruments, or near-unit roots. Fourth, our analysis imposed stationarity, but cointegration properties could be relevant for forecast variance decompositions of data in levels. Finally, one could perform Bayesian inference on the identified sets of the structural parameters.

# A Appendix

## A.1 Formulas for implementing the confidence intervals

Here we provide formulas needed to construct the partial identification robust confidence intervals in [Section 5](#). Assume the spectrum of  $W_t = (y'_t, z'_t)'$  has VAR structure as in [Section 5](#). We now show how to compute the interval bounds from the reduced-form VAR parameters  $\vartheta = (\text{vec}(A_1)', \dots, \text{vec}(A_p)', \text{vech}(\Sigma))'$ .

PREPARATIONS. We first map the reduced-form VAR parameters  $\vartheta$  into the various variances and covariances needed to compute our objects of interest. In principle, it is possible to directly compute these mappings from  $\vartheta$  using standard VAR formulas. However, we prefer working with the vector moving average representation, as outlined below. Our first objective is then to map the VAR representation into a VMA representation

$$W_t = B(L)e_t,$$

where

$$B(L) = \sum_{\ell=0}^{\infty} B_{\ell}L^{\ell}, \quad e_t \stackrel{i.i.d.}{\sim} N(0, I_{n_W}),$$

and  $n_W \equiv n_y + 1$ . This is achieved by setting

$$B_0 = \Sigma^{\frac{1}{2}}, \quad B_h = \sum_{\ell=1}^h A_{\ell}B_{h-\ell}, \quad h \geq 1,$$

where  $A_{\ell} = 0_{n_W \times n_W}$  for  $\ell > p$ . In practice, we truncate this recursion at some large  $\hat{p}$ , and set  $B_h = 0_{n_W \times n_W}$  for  $h > \hat{p}$ . For each  $h$ , denote the top  $n_y \times n_W$  block of the  $n_W \times n_W$  matrix  $B_h$  by  $B_{y,h}$ , and write  $B_y(L) = \sum_{\ell=0}^{\infty} B_{y,\ell}L^{\ell}$  for the entire lag polynomial. Then

$$y_t = B_y(L)e_t.$$

Let  $B_{\bar{z}}$  be the bottom row of  $B_0$ , so that

$$\tilde{z}_t = B_{\bar{z}}e_t.$$

BOUNDS FOR  $\alpha$ . To compute the bounds for  $\alpha$ , we need the quantities

$$\alpha_{UB}^2 = \text{Var}(\tilde{z}_t), \tag{24}$$

$$\alpha_{LB}^2 = 2\pi \max_{\omega \in [0, \pi]} s_{y\tilde{z}}(\omega)^* s_y(\omega)^{-1} s_{y\tilde{z}}(\omega), \quad (25)$$

$$\text{Var}(\tilde{z}_t^\dagger) = 2 \int_0^\pi s_{y\tilde{z}}(\omega)^* s_y(\omega)^{-1} s_{y\tilde{z}}(\omega) d\omega. \quad (26)$$

For the upper bound (24), we have

$$\text{Var}(\tilde{z}_t) = B_{\tilde{z}} B_{\tilde{z}}' \equiv \Sigma_{\tilde{z}}.$$

For the lower bound (25),

$$\begin{aligned} s_y(\omega) &= B_y(e^{-i\omega}) B_y(e^{-i\omega})^*, \\ s_{y\tilde{z}}(\omega) &= \sum_{\ell=0}^{\hat{p}} \Sigma_{y,\tilde{z},\ell} e^{-i\omega\ell}, \end{aligned}$$

where

$$\Sigma_{y,\tilde{z},\ell} \equiv \text{Cov}(y_t, \tilde{z}_{t-\ell}) = B_{y,\ell} B_{\tilde{z}}'.$$

In practice, we compute the maximum in (25) by grid search.

Rather than explicitly computing the integral (26), we note that we can approximate  $\text{Var}(\tilde{z}_t^\dagger) = \text{Var}(E(\tilde{z}_t | \{y_\tau\}_{t-\infty < \tau < t+\infty}))$  arbitrarily well as  $M \rightarrow \infty$  by

$$\text{Var}(E(\tilde{z}_t | \{y_\tau\}_{t-M \leq \tau \leq t+M})) = \Sigma_{\tilde{z},y,(M,M)} \Sigma_{y,(M,M)}^{-1} \Sigma_{\tilde{z},y,(M,M)}',$$

where  $\Sigma_{\tilde{z},y,(M,M)}$  is the covariance vector of  $\tilde{z}_t$  and  $(y'_{t+M}, \dots, y'_t, \dots, y'_{t-M})'$ , and  $\Sigma_{y,(M,M)}$  is the full variance-covariance matrix of  $(y'_{t+M}, \dots, y'_t, \dots, y'_{t-M})'$ . For any given  $M$ , we can construct these matrices from

$$\text{Cov}(\tilde{z}_t, y_{t+h}) = \begin{cases} B_{\tilde{z}} B_{y,h}' & \text{if } h \geq 0, \\ 0 & \text{otherwise,} \end{cases}$$

and

$$\text{Cov}(y_t, y_{t-h}) = \sum_{\ell=0}^{\hat{p}} B_{y,\ell} B_{y,\ell+h}'.$$

**BOUNDS FOR  $R_0^2$ .** The only missing ingredient to computing the identified set for the degree of invertibility is  $\text{Var}(\tilde{z}_t | \{y_\tau\}_{-\infty < \tau \leq t})$ . We can approximate this quantity arbitrarily well as  $M \rightarrow \infty$  by

$$\text{Var}(\tilde{z}_t | \{y_\tau\}_{t-M \leq \tau \leq t}) = \Sigma_{\tilde{z}} - (\Sigma'_{y,\tilde{z},0}, 0_{1 \times n_y M}) \Sigma_{y,(M)}^{-1} (\Sigma'_{y,\tilde{z},0}, 0_{1 \times n_y M})',$$

where  $\Sigma_{y,(M)}$  is the full variance-covariance matrix of  $(y'_t, y'_{t-1}, \dots, y'_{t-M})'$ .

**BOUNDS FOR  $R_\infty^2$ .** The only missing ingredient to computing the identified set for the degree of recoverability is  $\text{Var}(\tilde{z}_t \mid \{y_\tau\}_{-\infty < \tau < \infty})$ . We can approximate this quantity arbitrarily well as  $M \rightarrow \infty$  by

$$\text{Var}(\tilde{z}_t \mid \{y_\tau\}_{t-M \leq \tau \leq t+M}) = \Sigma_{\tilde{z}} - \Sigma_{\tilde{z},y,(M,M)} \Sigma_{y,(M,M)}^{-1} \Sigma'_{\tilde{z},y,(M,M)},$$

where all objects were already defined above.

**BOUNDS FOR FVR.** To compute the identified set for  $FVR_{i,\ell}$ , we need  $\text{Cov}(y_t, \tilde{z}_{t-h})$  as well as  $\text{Var}(y_{i,t+\ell} \mid \{y_\tau\}_{-\infty < \tau \leq t})$ . The first object was discussed above, and the second object is well approximated for large  $M$  by<sup>37</sup>

$$\begin{aligned} \text{Var}(y_{i,t+\ell} \mid \{y_\tau\}_{t-M \leq \tau \leq t}) &= \text{Var}(y_{i,t}) - (\text{Cov}(y_{i,t+\ell}, y_t), \dots, \text{Cov}(y_{i,t+\ell}, y_{t-M})) \Sigma_{y,(M)}^{-1} \\ &\quad \times (\text{Cov}(y_{i,t+\ell}, y_t), \dots, \text{Cov}(y_{i,t+\ell}, y_{t-M}))', \end{aligned}$$

where  $\Sigma_{y,(M)}$  was defined above.

**BOUNDS FOR FVD.** To compute the overall lower bound for the FVD, we need  $\text{Var}(\tilde{y}_{i,t+\ell}^{(\alpha_{UB})} \mid \{\tilde{y}_\tau^{(\alpha_{UB})}\}_{-\infty < \tau \leq t})$ . As before, we approximate this by  $\text{Var}(\tilde{y}_{i,t+\ell}^{(\alpha_{UB})} \mid \{\tilde{y}_\tau^{(\alpha_{UB})}\}_{t-M \leq \tau \leq t})$  for large  $M$ . The same formula used above for  $\text{Var}(y_{i,t+\ell} \mid \{y_\tau\}_{t-M \leq \tau \leq t})$  applies, where covariances are obtained from

$$\text{Cov}(\tilde{y}_{i,t+\ell}^{(\alpha_{UB})}, \tilde{y}_t^{(\alpha_{UB})}) = \text{Cov}(y_{t+\ell}, y_t) - \frac{1}{\alpha_{UB}^2} \sum_{m=0}^{\infty} \text{Cov}(y_t, \tilde{z}_{t-m-\ell}) \text{Cov}(y_t, \tilde{z}_{t-m})'.$$

The sum can be truncated when the contribution of additional terms is small.

**REMARKS.** Our computations require two truncation choices: the maximal VMA horizon  $\hat{p}$ , and the maximal prediction horizons  $M$ . In all codes, we set these truncation parameters large enough to leave results unaffected by further increases.<sup>38</sup> Derivatives of all parameters with respect to  $\vartheta$  can be computed by finite differences or automatic differentiation.

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<sup>37</sup>In our computations for this paper we use the Kalman filter to compute the conditional variance, but there is little difference in numerical accuracy or speed relative to the formula stated here.

<sup>38</sup>Our choices of truncation parameters therefore differs according to the application, depending on the persistence of the studied processes.

## A.2 Proofs of main results

### A.2.1 Auxiliary lemma

**Lemma 1.** *Let  $B$  be an  $n \times n$  Hermitian positive definite complex-valued matrix and  $b$  an  $n$ -dimensional complex-valued column vector. Let  $x$  be a nonnegative real scalar. Then  $B - x^{-1}bb^*$  is positive (semi)definite if and only if  $x > (\geq) b^*B^{-1}b$ .*

Please find the proof in Online Appendix B.9.1.

### A.2.2 Proof of **Proposition 1**

Let  $\alpha$  and the spectrum  $s_w(\omega)$  be given. Define the  $n_y$ -dimensional vectors

$$\bar{\Theta}_{\bullet,1,\ell} = \alpha^{-1} \text{Cov}(y_t, \tilde{z}_{t-\ell}), \quad \ell \geq 0,$$

and the corresponding vector lag polynomial

$$\bar{\Theta}_{\bullet,1}(L) = \sum_{\ell=0}^{\infty} \bar{\Theta}_{\bullet,1,\ell} L^\ell.$$

Since  $\alpha^2 \leq \alpha_{UB}^2$ , we may define  $\bar{\sigma}_v = \sqrt{\text{Var}(\tilde{z}_t) - \alpha^2}$ . Since  $\alpha^2 > \alpha_{LB}^2$ , **Lemma 1** implies that

$$s_y(\omega) - \frac{2\pi}{\alpha^2} s_{y\tilde{z}}(\omega) s_{y\tilde{z}}(\omega)^* = s_y(\omega) - \frac{1}{2\pi} \bar{\Theta}_{\bullet,1}(e^{-i\omega}) \bar{\Theta}_{\bullet,1}(e^{-i\omega})^*$$

is positive definite for every  $\omega \in [0, 2\pi]$ . Hence, the Wold decomposition theorem (**Hannan, 1970**, Thm. 2'', p. 158) implies that there exists an  $n_y \times n_y$  matrix lag polynomial  $\tilde{\Theta}(L) = \sum_{\ell=0}^{\infty} \tilde{\Theta}_\ell L^\ell$  such that<sup>39</sup>

$$s_y(\omega) - \frac{1}{2\pi} \bar{\Theta}_{\bullet,1}(e^{-i\omega}) \bar{\Theta}_{\bullet,1}(e^{-i\omega})^* = \frac{1}{2\pi} \tilde{\Theta}(e^{-i\omega}) \tilde{\Theta}(e^{-i\omega})^*, \quad \omega \in [0, 2\pi].$$

Thus, the following model for  $w_t = (y'_t, \tilde{z}'_t)'$  generates the desired spectrum  $s_w(\omega)$ :

$$\begin{aligned} y_t &= \bar{\Theta}_{\bullet,1}(L) \bar{\varepsilon}_{1,t} + \tilde{\Theta}(L) \tilde{\varepsilon}_t, \\ \tilde{z}_t &= \alpha \bar{\varepsilon}_{1,t} + \bar{\sigma}_v \bar{v}_t, \end{aligned}$$

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<sup>39</sup>We can rule out a deterministic term in the Wold decomposition because a continuous and positive definite spectral density satisfies the full-rank condition of **Hannan (1970, p. 162)**.

$$(\bar{\varepsilon}_{1,t}, \tilde{\varepsilon}'_t, \bar{v}_t)' \stackrel{i.i.d.}{\sim} N(0, I_{n_y+2}).$$

Note that the construction requires only  $n_\varepsilon = n_y + 1$  shocks,  $\bar{\varepsilon}_{1,t} \in \mathbb{R}$  and  $\tilde{\varepsilon}_t \in \mathbb{R}^{n_y}$ .  $\square$

### A.2.3 Proof of Proposition 2

IDENTIFIED SET FOR  $R_0^2$ . If the identified set contains 1, then there must exist an  $\bar{\alpha} \in [\alpha_{LB}, \alpha_{UB}]$  and i.i.d., independent standard Gaussian processes  $\bar{\varepsilon}_{1,t}$  and  $\bar{v}_t$  such that (i)  $\tilde{z}_t = \bar{\alpha} \times \bar{\varepsilon}_{1,t} + \bar{v}_t$ , (ii)  $\bar{v}_t$  is uncorrelated with  $y_t$  at all leads and lags, and (iii)  $\bar{\varepsilon}_{1,t}$  lies in the closed linear span of  $\{y_\tau\}_{-\infty < \tau \leq t}$ . This immediately implies the “only if” statement.

For the “if” part, assume  $\tilde{z}_t$  does not Granger cause  $y_t$ . By the equivalence of Sims and Granger causality,  $\tilde{z}_t^\dagger = E(\tilde{z}_t \mid \{y_\tau\}_{-\infty < \tau < \infty}) = E(\tilde{z}_t \mid \{y_\tau\}_{-\infty < \tau \leq t})$ . Note that the latter best linear predictor is white noise since, for any  $\ell \geq 1$ ,

$$\begin{aligned} \text{Cov}(E(\tilde{z}_t \mid \{y_\tau\}_{-\infty < \tau \leq t}), y_{t-\ell}) &= \text{Cov}(\tilde{z}_t, y_{t-\ell}) - \text{Cov}(\tilde{z}_t - E(\tilde{z}_t \mid \{y_\tau\}_{-\infty < \tau \leq t}), y_{t-\ell}) \\ &= 0 - 0, \end{aligned}$$

using the fact that  $\tilde{z}_t$  is a projection residual. In conclusion, the best linear predictor  $\tilde{z}_t^\dagger$  of  $\tilde{z}_t$  given  $\{y_\tau\}_{-\infty < \tau < \infty}$  depends only on  $\{y_\tau\}_{-\infty < \tau \leq t}$  and it has a constant spectrum. From the expression for  $\alpha_{LB}^2$ , we get that  $\alpha_{LB}^2 = \text{Var}(E(\tilde{z}_t \mid \{y_\tau\}_{-\infty < \tau \leq t}))$ , which further yields  $\alpha_{LB}^2 = \text{Var}(\tilde{z}_t) \tilde{R}_0^2$ . Hence, expression (19) implies that the upper bound of the identified set for  $R_0^2$  equals 1.

IDENTIFIED SET FOR  $R_\infty^2$ . The upper bound of the identified set for  $R_\infty^2$  equals 1 if and only if  $2\pi \sup_{\omega \in [0, \pi]} s_{\tilde{z}^\dagger}(\omega) = \tilde{R}_\infty^2 \text{Var}(\tilde{z}_t)$ , and the right-hand side equals  $\text{Var}(\tilde{z}_t^\dagger) = \int_0^{2\pi} s_{\tilde{z}^\dagger}(\omega) d\omega$ . But we have  $\sup_{\omega \in [0, \pi]} s_{\tilde{z}^\dagger}(\omega) = \frac{1}{2\pi} \int_0^{2\pi} s_{\tilde{z}^\dagger}(\omega) d\omega$  if and only if  $s_{\tilde{z}^\dagger}(\omega)$  is constant in  $\omega$  almost everywhere, i.e.,  $\tilde{z}_t^\dagger$  is white noise.  $\square$

### A.2.4 Proof of Proposition 3

Please see Online Appendix B.9.3.

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