

SPRING: A Spectral-Level Framework for Strong-Field Tests with Gravitational-Wave Ringdowns

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What is SPRING?

SPRING

Spectral-level

Infer remnant parameters
through ringdown spectrum

Pre-merger-informed

Use pre-merger information
to inform the amplitude priors

RINGdown inference

Keep the spectral inference
theory-agnostic

A reusable interface between ringdown data and strong-field theories

Roadmap

1. Ringdown spectroscopy & motivation

Why the spectrum? How is SPRING different from conventional inference?

2. The SPRING framework

Pre-merger information $\rightarrow$ spectral likelihood $\rightarrow$ theory interpretation

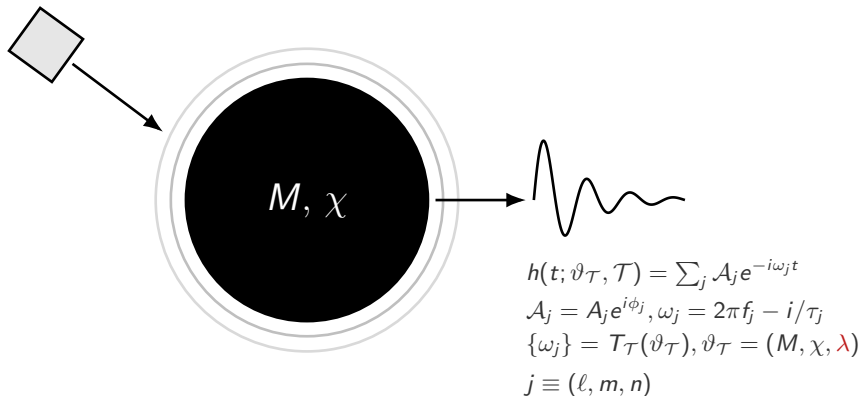
3. Applications & validation

GW250114 and controlled injection studies

4. Beyond Kerr: a spectral-manifold view

Joint spectral geometry for future non-Kerr tests

Ringdown spectroscopy



The ringdown spectrum encodes the properties of the remnant spacetime.

How should theory enter the inference?

Conventional approach

$$\begin{aligned} &(\vartheta_{\mathcal{T}}, \mathcal{T}) \\ &\Downarrow \\ &h(t; \vartheta_{\mathcal{T}}, \mathcal{T}) \xleftrightarrow{\text{compare}} d_{\text{RD}} \\ &\Downarrow \\ &p(\vartheta_{\mathcal{T}} \mid d_{\text{RD}}, \mathcal{T}) \end{aligned}$$

*Theory enters before comparison with data.
Data and theory are compared at the waveform
level.*

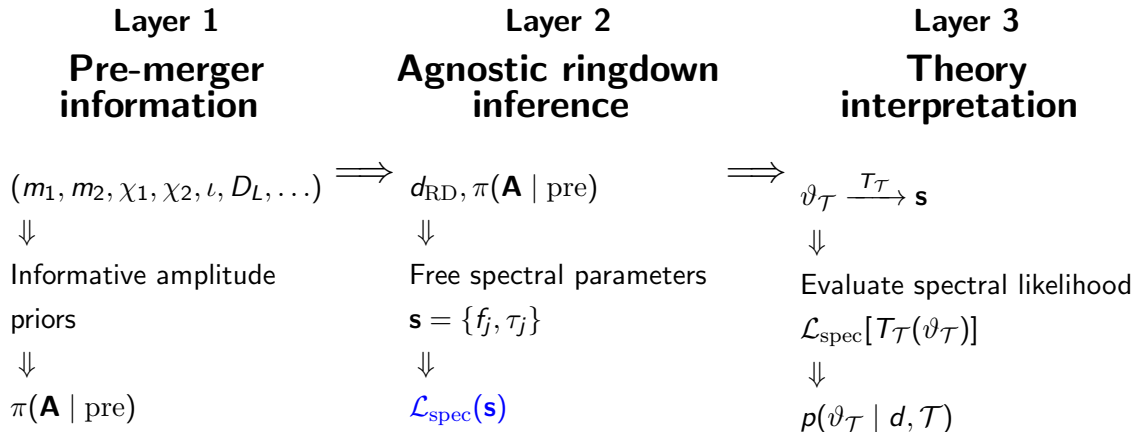
SPRING

$$\begin{aligned} &\mathbf{s} = \{f_j, \tau_j\} \\ &\Downarrow \\ &h_{\text{RD}}(t; \mathbf{s}) \xleftrightarrow{\text{compare}} d_{\text{RD}} \\ &\Downarrow \\ &\mathcal{L}_{\text{spec}}(\mathbf{s}) \end{aligned}$$

Theory enters here

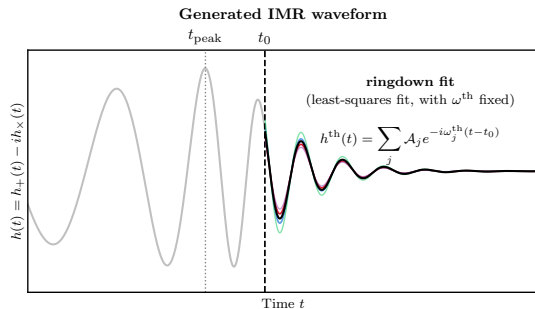
$$\begin{aligned} &\vartheta_{\mathcal{T}} \xrightarrow{T_{\mathcal{T}}} \mathbf{s} \\ &\Downarrow \\ &p(\vartheta_{\mathcal{T}} \mid d_{\text{RD}}, \mathcal{T}) \propto \mathcal{L}_{\text{spec}}[T_{\mathcal{T}}(\vartheta_{\mathcal{T}})] \pi(\vartheta_{\mathcal{T}}) \end{aligned}$$

How does SPRING work?



The spectral likelihood $\mathcal{L}_{\text{spec}}$ is the interface between observation and theory.

Layer 1: Pre-merger-informed amplitude priors



Pre-merger information

component masses, spins, inclination, distance



IMR waveform reconstruction



Expected mode excitation A_j^{exp}



Informative amplitude priors

$$\pi(\mathbf{A} \mid \text{pre})$$

Pre-merger information provides more informative priors for the ringdown mode amplitudes.

Layer 2: Theory-agnostic spectral inference

Agnostic ringdown model

$$h_{\text{RD}}(t) = \sum_j A_j e^{-t/\tau_j} \cos(2\pi f_j t + \phi_j)$$

analytic marginalization
over A_j, ϕ_j
 $\implies$

Amplitudes

$$A_j, \phi_j$$

pre-merger informed

Spectrum

$$f_j, \tau_j$$

free with broad priors

Spectral likelihood

$$\mathbf{s} = \{f_j, \tau_j\}$$

$\Downarrow$

$$\mathcal{L}_{\text{spec}}(\mathbf{s})$$

Retains the joint information and correlations between the spectral parameters.

The data determine the spectrum before any specific gravity theory is imposed.

Layer 3: From spectrum to theory

Theory prediction

$$\vartheta_{\mathcal{T}} \xrightarrow{T_{\mathcal{T}}} \mathbf{s}_{\mathcal{T}}$$

$$\mathbf{s}_{\mathcal{T}} = \{f_j(\vartheta_{\mathcal{T}}), \tau_j(\vartheta_{\mathcal{T}})\}$$

$\Downarrow$

$$\mathcal{L}_{\text{spec}}[\mathbf{s}_{\mathcal{T}}]$$

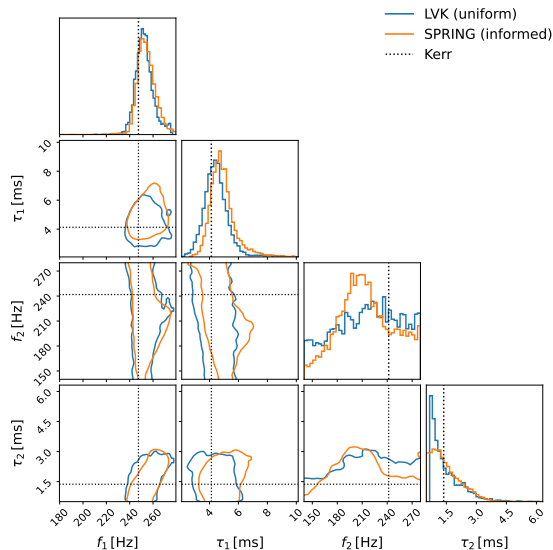
Parameter inference

$$\implies p(\vartheta_{\mathcal{T}} \mid d, \mathcal{T}) \propto \mathcal{L}_{\text{spec}}[T_{\mathcal{T}}(\vartheta_{\mathcal{T}})] \pi(\vartheta_{\mathcal{T}})$$

Infer remnant or theory parameters
without re-analyzing the ringdown data.

The same spectral likelihood can be reused for different theoretical models.

GW250114: agnostic two-mode spectral inference with SPRING



What changes?

Dominant mode:

Broadly consistent

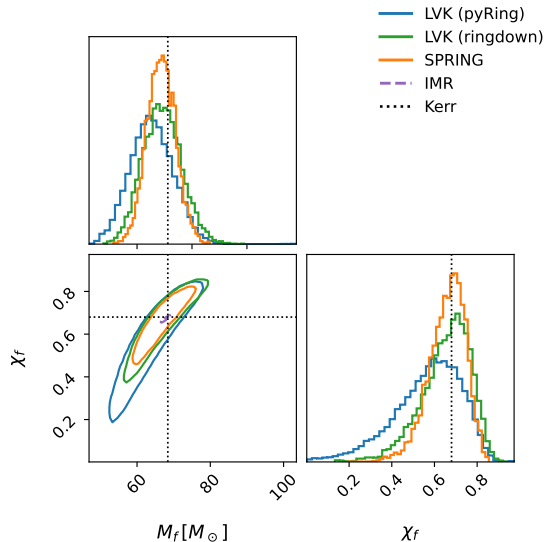
Subdominant mode:

More informative f_2

Pre-merger information changes the spectral inference through the amplitude priors.

LVK reference: [arXiv:2509.08099](https://arxiv.org/abs/2509.08099)

GW250114: Kerr remnant inference



Two inference routes

LVK

Kerr-constrained ringdown templates

$$d_{\text{RD}} \longrightarrow (M_f, \chi_f)$$

SPRING

Theory-agnostic spectrum with pre-merger-informed amplitudes

$$d_{\text{RD}} \longrightarrow \mathcal{L}_{\text{spec}}(\mathbf{s}) \longrightarrow (M_f, \chi_f)$$

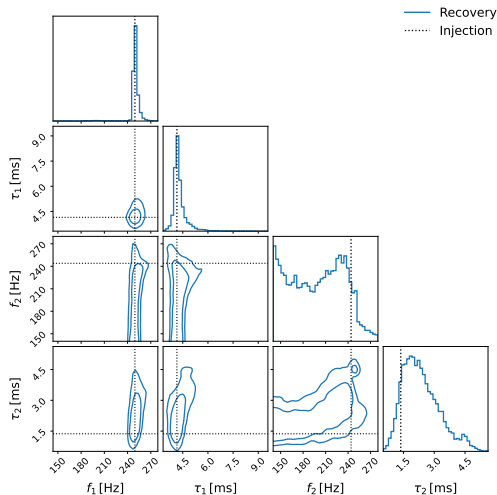
Result

Consistent with both the LVK ringdown analyses and the IMR estimate, with tighter SPRING constraints.

SPRING: Controlled injection and recovery

Injection: *SXS:BBH:0305*, $(\ell, m) = (2, \pm 2)$ only, ringdown SNR = 100

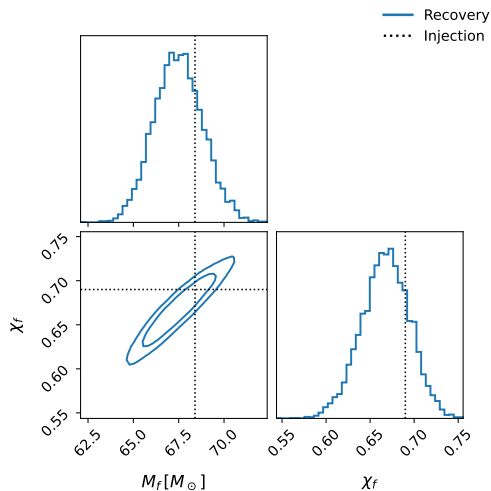
Spectral recovery



Kerr mapping



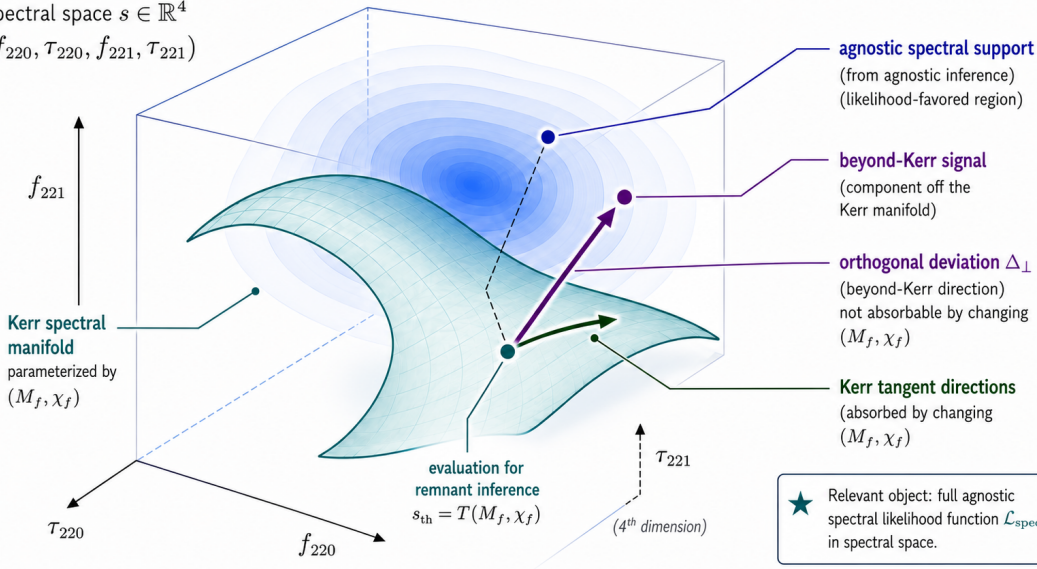
Remnant recovery



High-dimensional spectral space

spectral space $s \in \mathbb{R}^4$

$(f_{220}, \tau_{220}, f_{221}, \tau_{221})$



Take-home messages

- ▶ **Pre-merger information** provides more informative priors for the ringdown mode amplitudes.
- ▶ **SPRING separates spectral inference from theory interpretation** through a reusable joint spectral likelihood.
- ▶ The same spectral information can be used for **remnant inference and future beyond-Kerr tests**.

From data to spectrum, and from spectrum to theory.

Thanks for listening!

Happy to take questions

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