Institute of High Energy Physics
Chinese Academy of Sciences

Not Quite Black Holes and Gravitational Wave Echoes

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Based on collaborations with Bob Holdom, Ufuk Aydemir, Di Wu, Niayesh Afshordi, Pengyuan Gao, Ximeng Li

Outline

- **Not Quite Black Holes**
  - Why not quite black holes?
  - Theoretical candidates for not quite black holes

- **Gravitational wave echoes**
  - Current search strategies and results
  - Model-independent search for characteristic QNMs of echoes

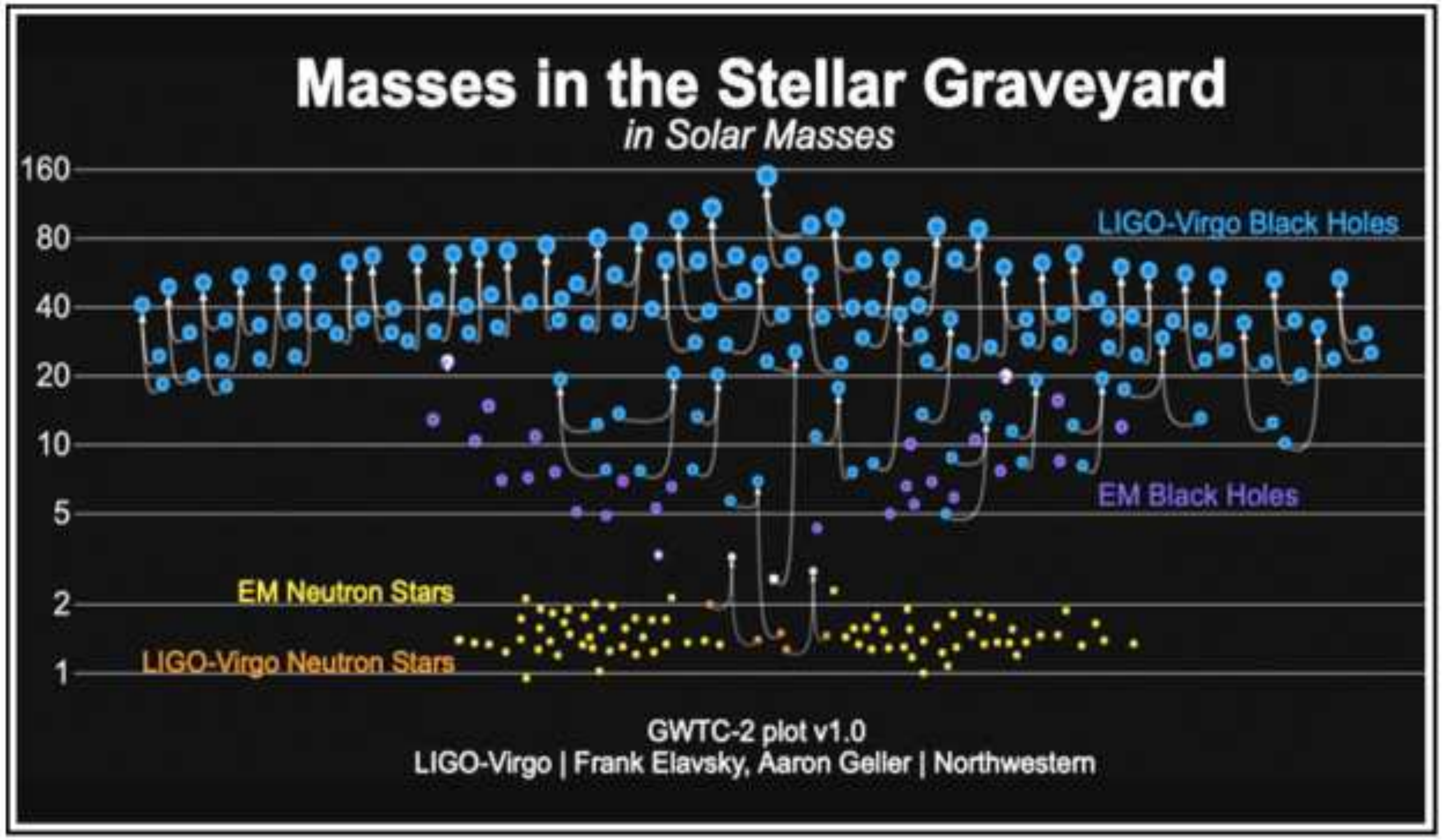
- **Summary**

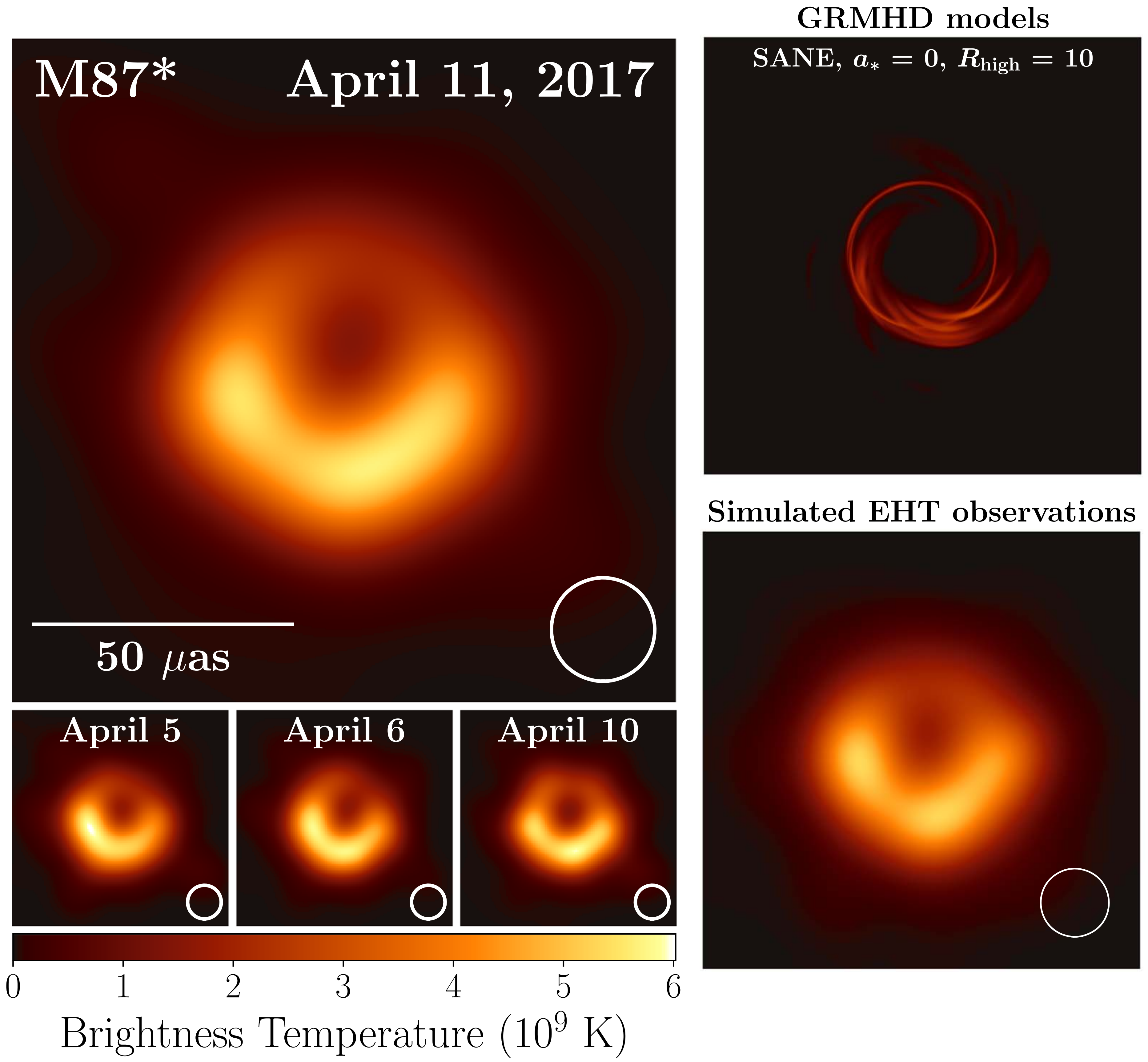
Not Quite Black Holes

So far all observations identified with black holes show a nice agreement with the GR prediction in a wide range of masses, e.g. from a few solar mass to 10^9 solar mass

gravitational wave signals from compact binary coalescence

first image of supermassive compact objects





Q: are astrophysical black holes really what GR predicts?

> "The discoveries of this year's Laureates have broken new ground in the study of compact and supermassive objects. But **these exotic objects still pose many questions that beg for answers and motivate future research**. Not only **questions about their inner structure**, but also **questions about how to test our theory of gravity under the extreme conditions in the immediate vicinity of a black hole**"
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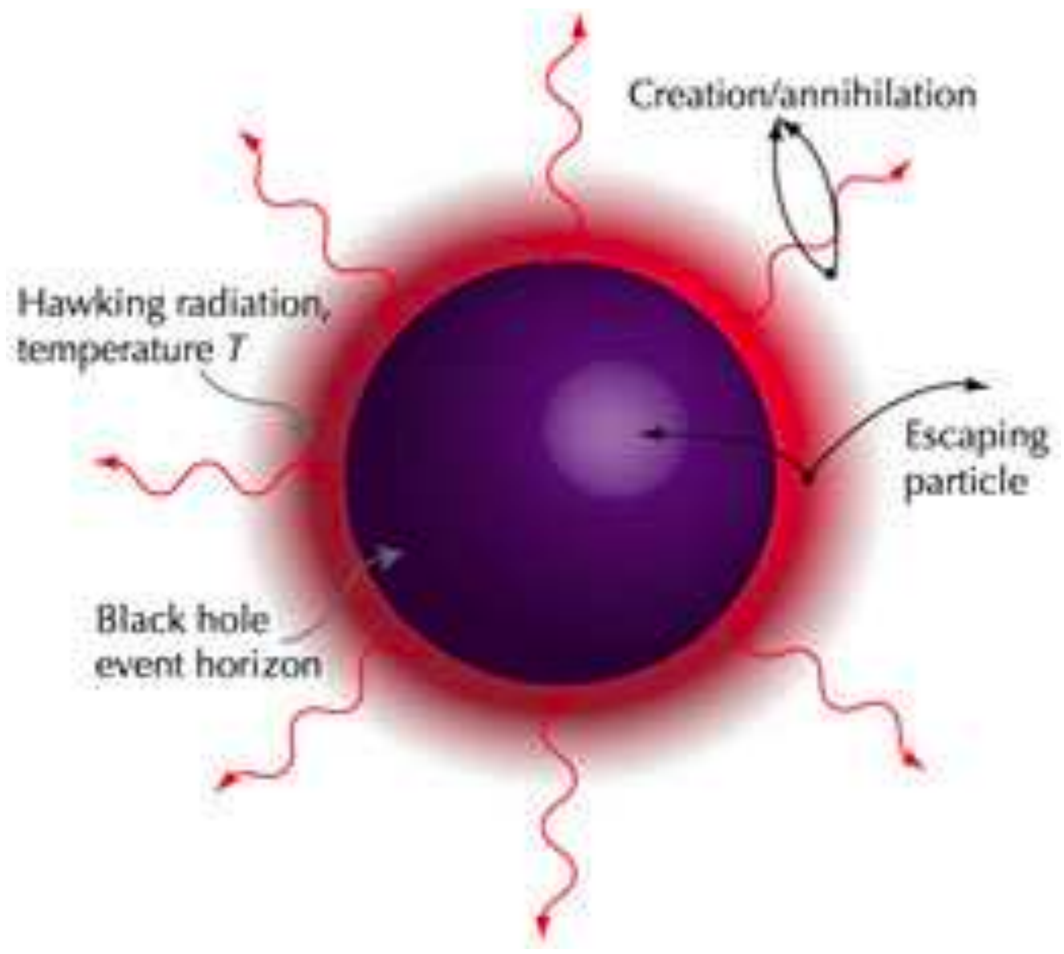
A: maybe they are *not quite black holes*, i.e. ***horizonless* ultracompact objects**?

Quantum black hole as horizonless objects

✦ Theoretical motivations

- Black hole thermodynamics (i.e. entropy area law), and information loss problems for evaporating black holes
- Quantum black holes may feature strong deviations around horizon, or even be *horizonless*
- Potential links to quantum gravity effects



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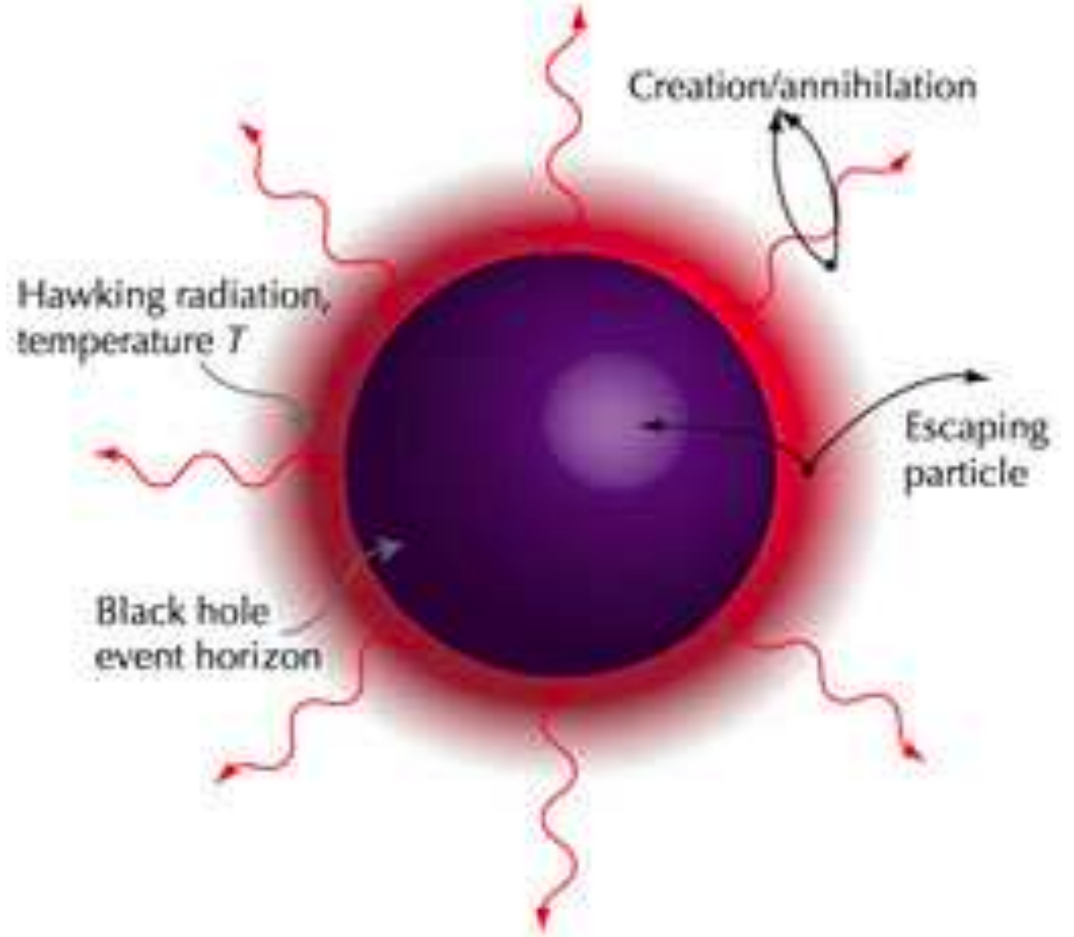
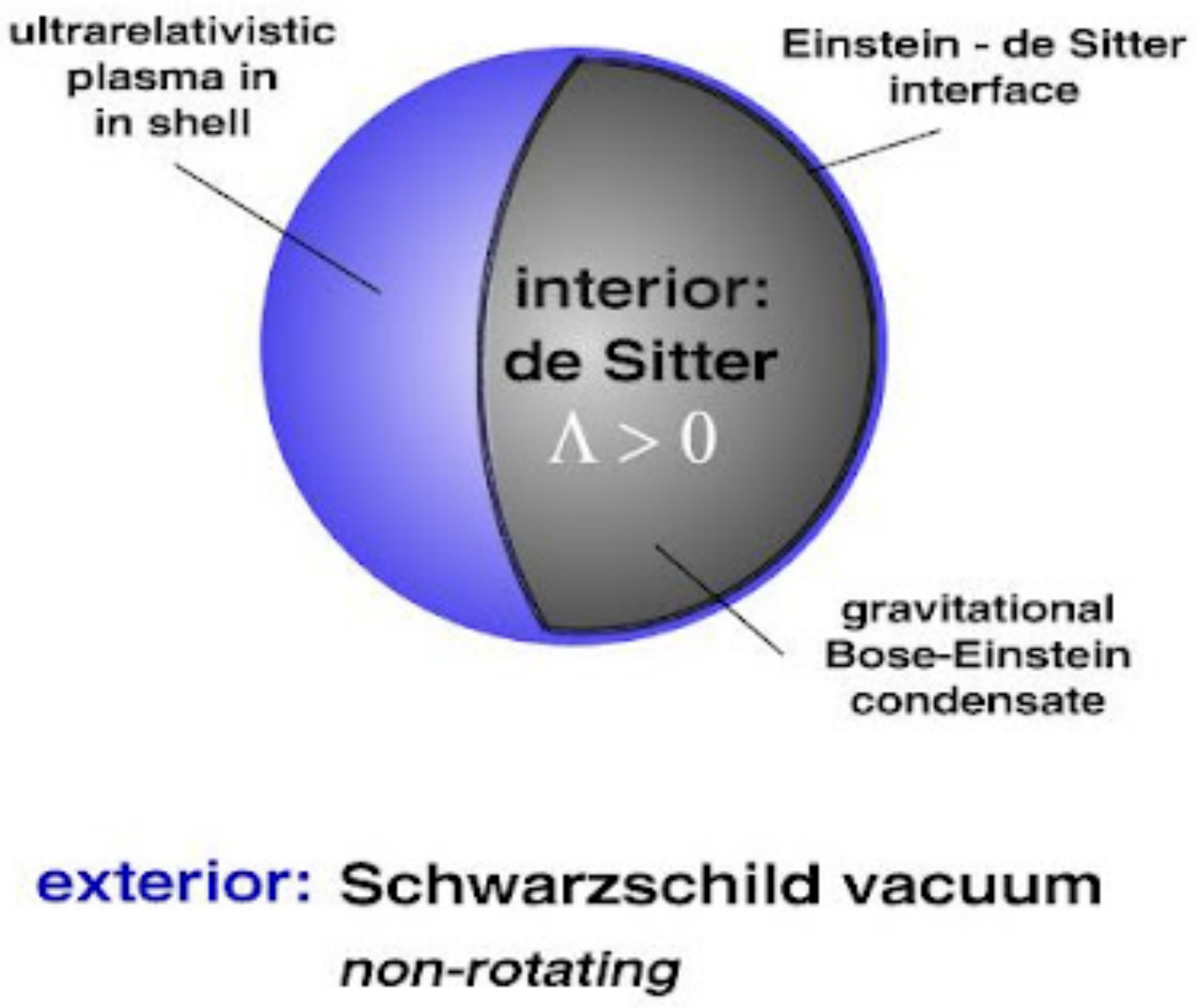


Exotic matter + GR

Gravastars: a black hole mimicker in GR, characterized by a de Sitter interior and thin shell of matter at the would-be horizon

[Mazur and Mottola, gr-qc/0109035]

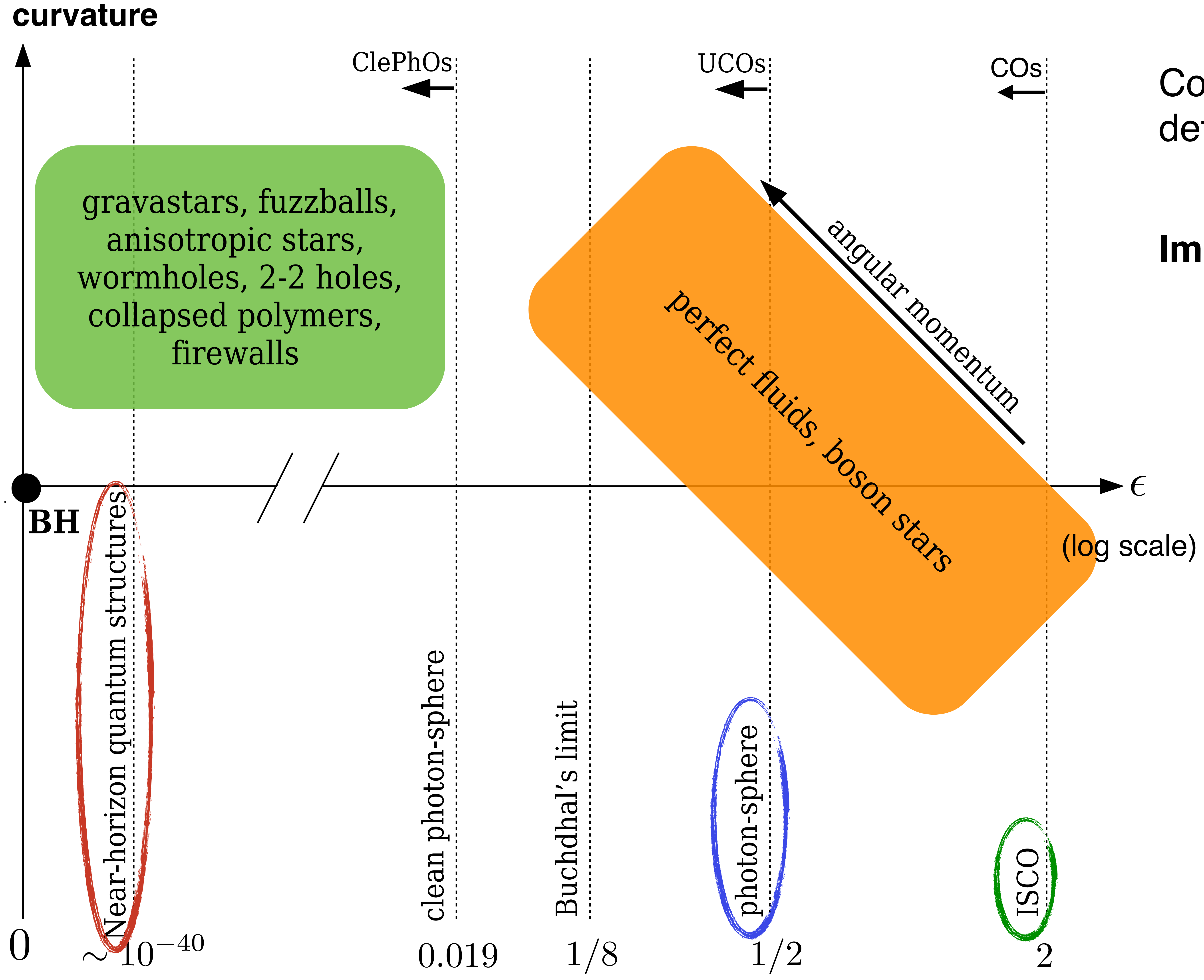


String theory

Classical BH spacetime as an approximation of **quantum fuzzball states**, which stops to apply somewhere outside of the would-be horizon

[Mathur, Fortsch. Phys. 53 (2005)]

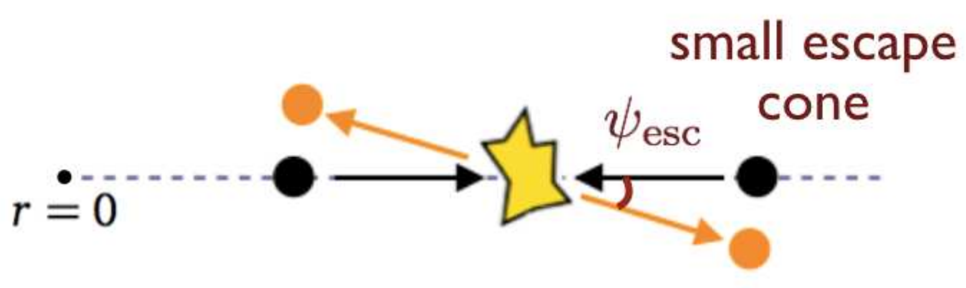
Observation evidence of compact objects (COs)



Considering a compact object with radius r_0, we may define a **compactness parameter** as: $\varepsilon = (r_0 - r_H) / r_H$

Important length scales for astronomical observations:

- **ISCO:** inner-most stable orbit for massive particles, crucial for accretion physics
- **Photon-sphere:** unstable photon orbit (m=0), crucial for black hole shadows and prompt ringdown of GW observation
- **Near-horizon regime:** due to large redshift, this regime difficult to "see" using EMs, but could be "heard" via GWs



$$\sin \psi_{\rm esc} = 3M\sqrt{3 f_0}/r_0$$
$$f_0 = 1 - 2M/r_0.$$

- **Event horizon:** one-way membrane

[Cardoso and Pani, Living Rev. Rel. 22 (2019)]

Key questions to explore in the remainder of the talk:

- Are there concrete theoretical models for ultra-compact objects, where $\varepsilon \to 0$ can be achieved without *fine-tuning*?
- How can we *efficiently* detect near-horizon corrections through GW observations, despite the *large theoretical uncertainties*?

An interesting candidate in quadratic gravity

- **Features**: black hole like exterior + narrow transition region + novel high curvature interior

- **Key ingredients**: quadratic gravity (Weyl tensor term) + a compact matter source (e.g. thermal gas)

$$S_{\mathrm{CQG}} = \frac{1}{16\pi}\int d^4x\,\sqrt{-g}\,\left(m_{\mathrm{Pl}}^2 R - \alpha C_{\mu\nu\alpha\beta}C^{\mu\nu\alpha\beta} + \beta R^2\right)$$

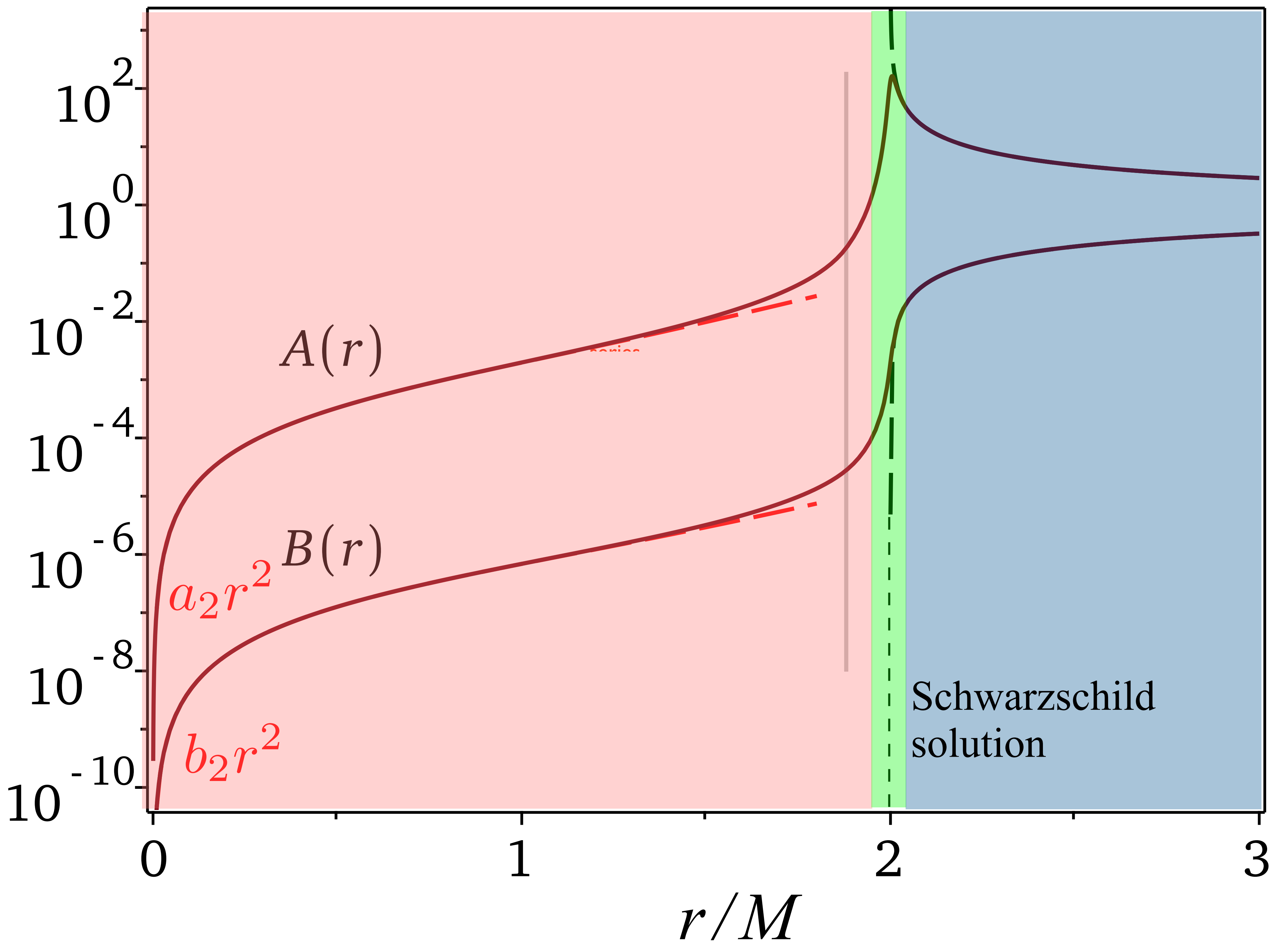
- Mass ranges from the minimum to arbitrarily heavy

- Novel **high curvature interior** leads to interesting connections to **black hole thermodynamics**

[Holdom, **JR**, PRD 95 (2017); Holdom, arXiv:1905.08849; **JR**, PRD 100 (2019)]

horizonless 2-2-hole

$$ds^2 = -B(r)dt^2 + A(r)dr^2 + r^2 d\theta^2 + r^2\sin^2\theta\, d\phi^2$$



Quadratic Gravity

✦ **Quantum Quadratic Gravity:** an old candidate of quantum gravity

$$S_{\rm QQG} = \int d^4x \sqrt{-g} \left(\frac{1}{2}\mathcal{M}^2 R - \frac{1}{2f_2^2} C_{\mu\nu\alpha\beta}C^{\mu\nu\alpha\beta} + \frac{1}{3f_0^2} R^2 \right)$$

generalize GR with all quadratic curvature terms

- **Perturbatively renormalizable and asymptotically free** [Stelle, PRD 16 (1977)]; [Fradkin, Tseytlin, NPB 201 (1982)] …
- But, at the price of "the ghost problem": maybe tackled by quantum corrections?

  e.g. Lee-Wick theory, PT symmetry, modified probability interpretation, "fakeon"; QCD analogy [Holdom, **JR**, PRD 93 (2016)], …

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✦ **Classical Quadratic Gravity:** an approximation of QQG at small and large curvatures

$$S_{\rm CQG} = \frac{1}{16\pi}\int d^4x \sqrt{-g}\left(m_{\rm Pl}^2 R - \alpha C_{\mu\nu\alpha\beta}C^{\mu\nu\alpha\beta} + \beta R^2\right)$$

✦ Strong coupling: $\alpha, \beta \sim \mathcal{O}(1)$, $\lambda_i \sim \ell_{\rm Pl}$ (one scale)

✦ Weak coupling: $\alpha, \beta \gg 1$, $\lambda_i \gg \ell_{\rm Pl}$ (solar system tests)

- In contrast to the standard view in EFT, this perspective allows considering solutions containing both small and large curvature regions without higher order terms

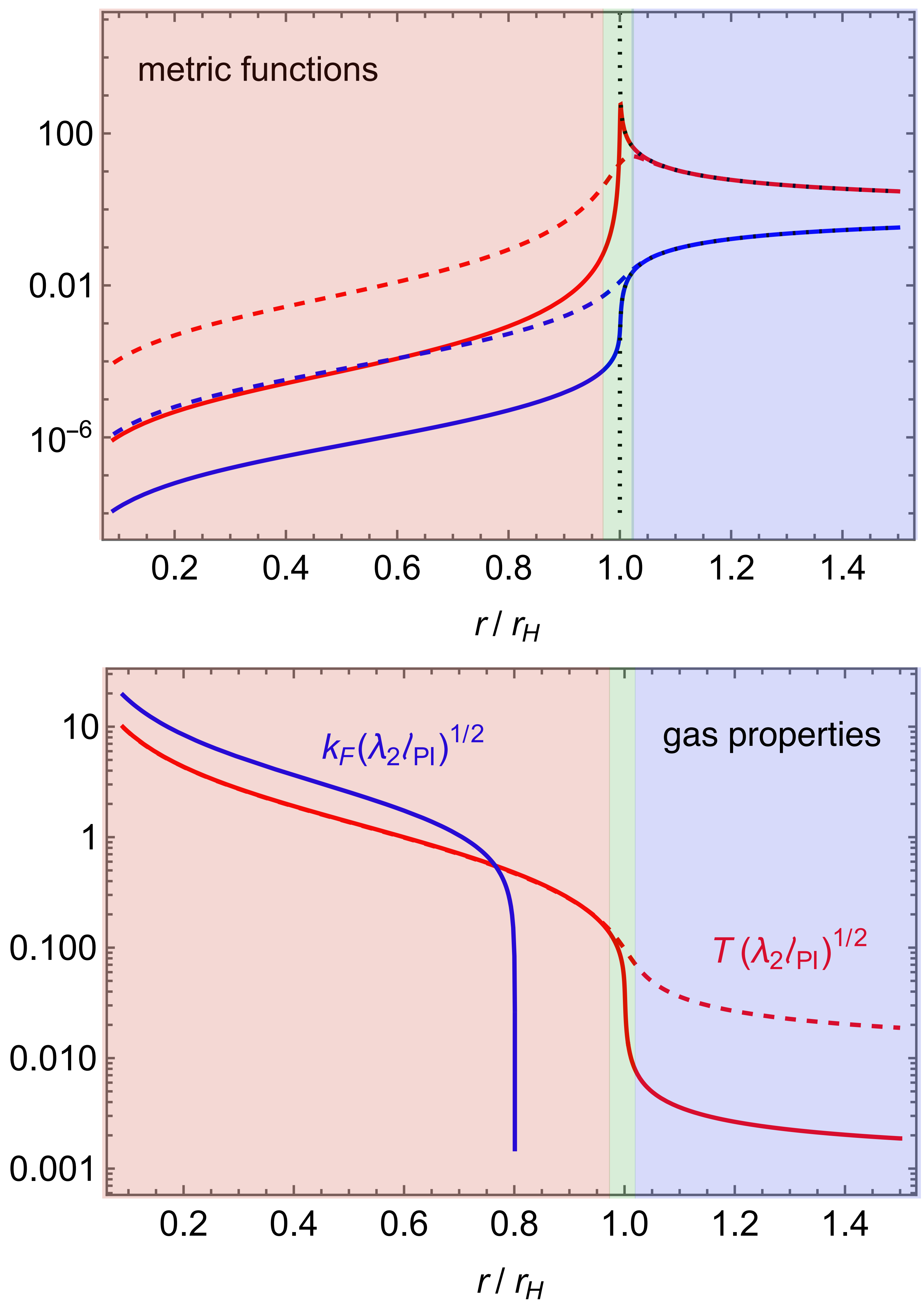
Appealing features for typical 2-2-holes

Mass considerably larger than the minimum $M_{\min} \sim m_{\text{Pl}}^2 \lambda_2$

- **Narrow transition region:** compactness parameter $\varepsilon \sim 1/M^2$ drops quickly for increasing M

- **Novel interior:** a novel scaling associated with quadratic curvature term, yielding a small radial proper length $\sim \lambda_2 << r_H$ ("holography")

$$\bar{A}(\bar{r}) = A(r)\frac{r_H^2}{\lambda_2^2}, \quad \bar{B}(\bar{r}) = B(r)\frac{r_H^2}{\lambda_2^2}, \quad \bar{T}(\bar{r}) = T(r)\sqrt{\lambda_2 \ell_{\text{Pl}}} \qquad (T \rightarrow k_F)$$



[Holdom, PLB 830 (2022); Aydemir, **JR**, CQG 40 (2023)]

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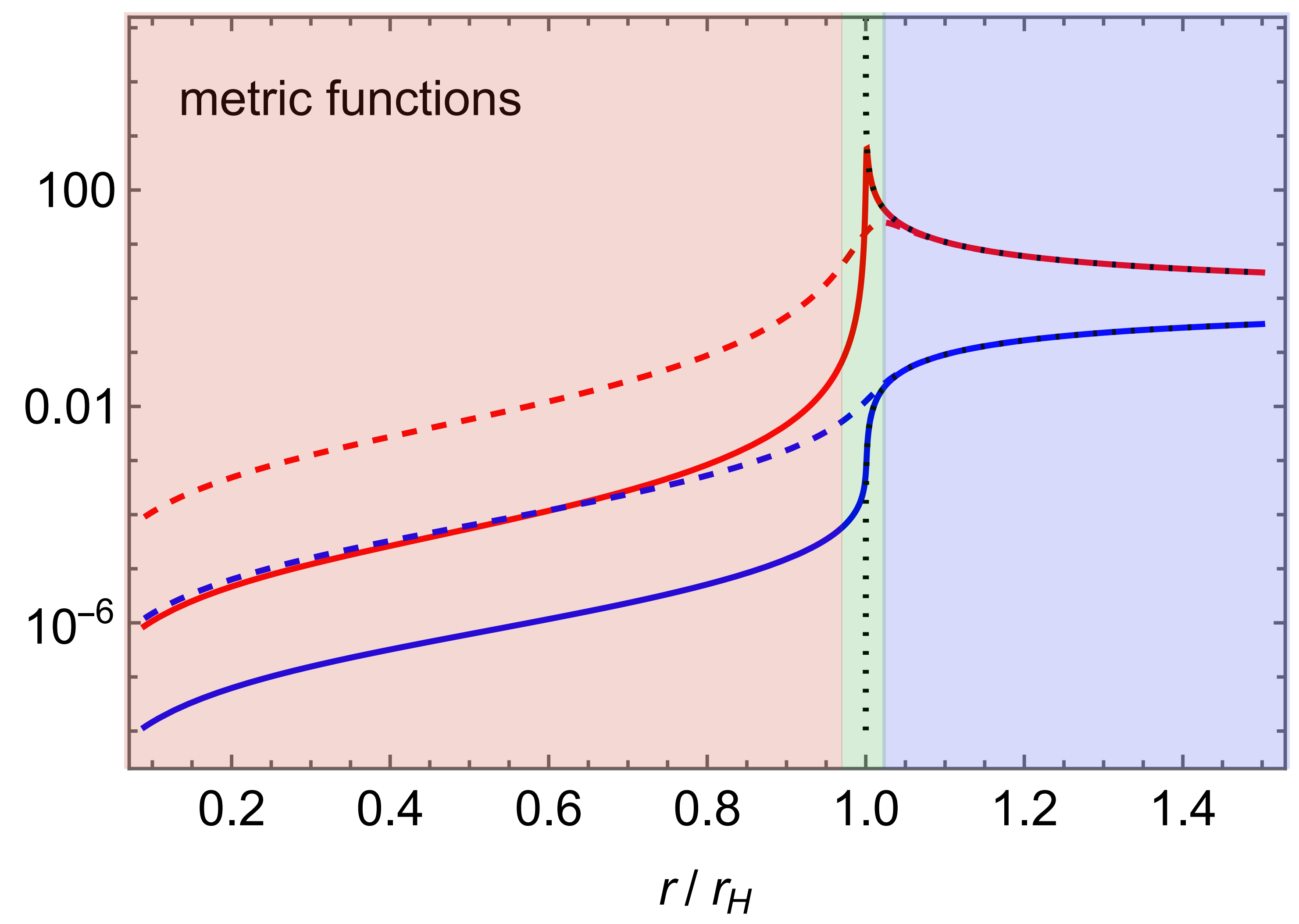
- **Uniform hole properties:** insensitive to matter sources

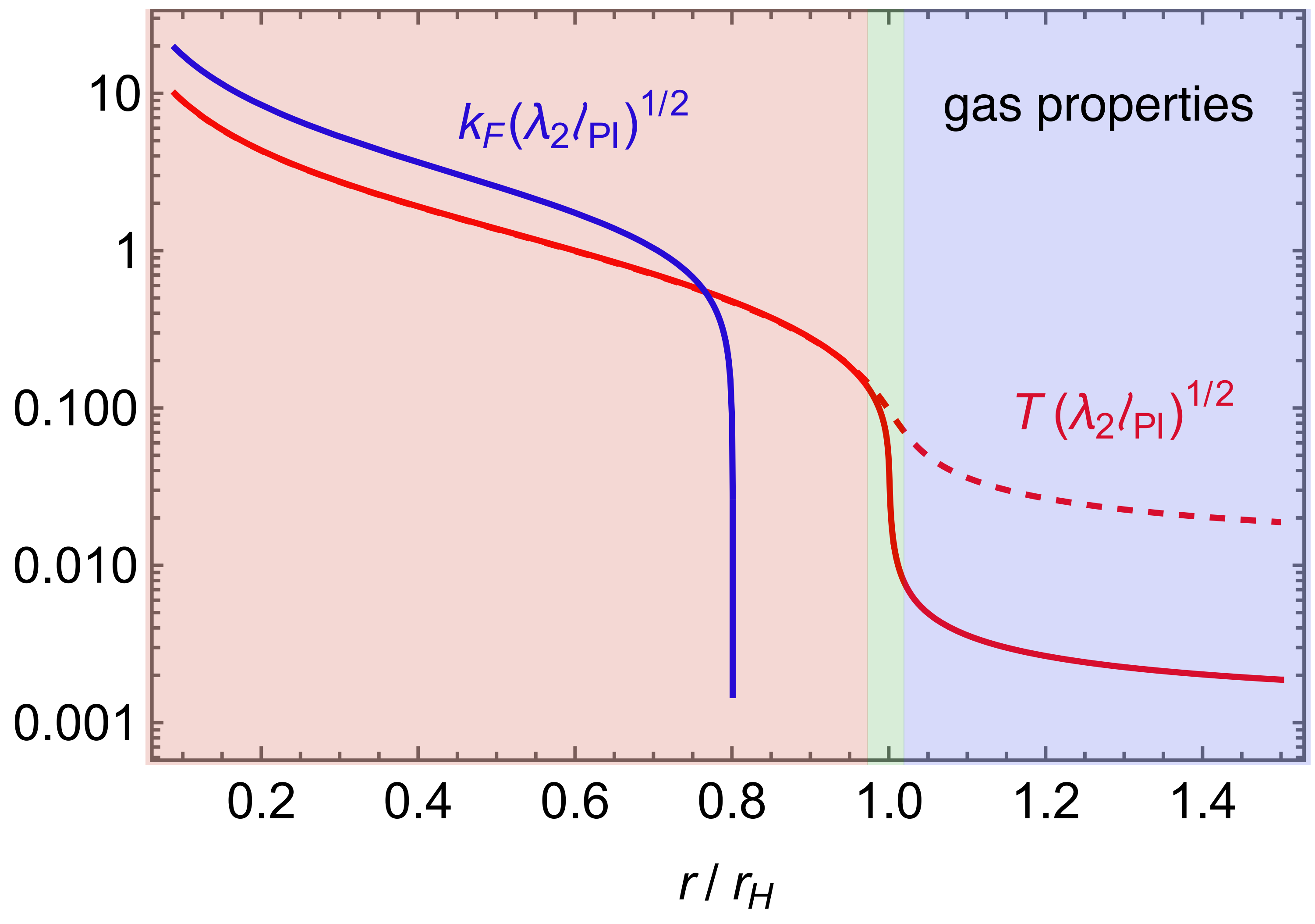
- **Intriguing thermodynamics**

• BH-like behavior emerges: $T_\infty \propto \mathcal{N}^{-1/4}\left(\frac{M_{\rm min}}{m_{\rm Pl}}\right)^{1/2} T_{\rm BH}, \quad S \propto \mathcal{N}^{1/4}\left(\frac{M_{\rm min}}{m_{\rm Pl}}\right)^{-1/2} S_{\rm BH}$

• High curvature effects captured by "thermodynamic volume" $V_{\rm th}$

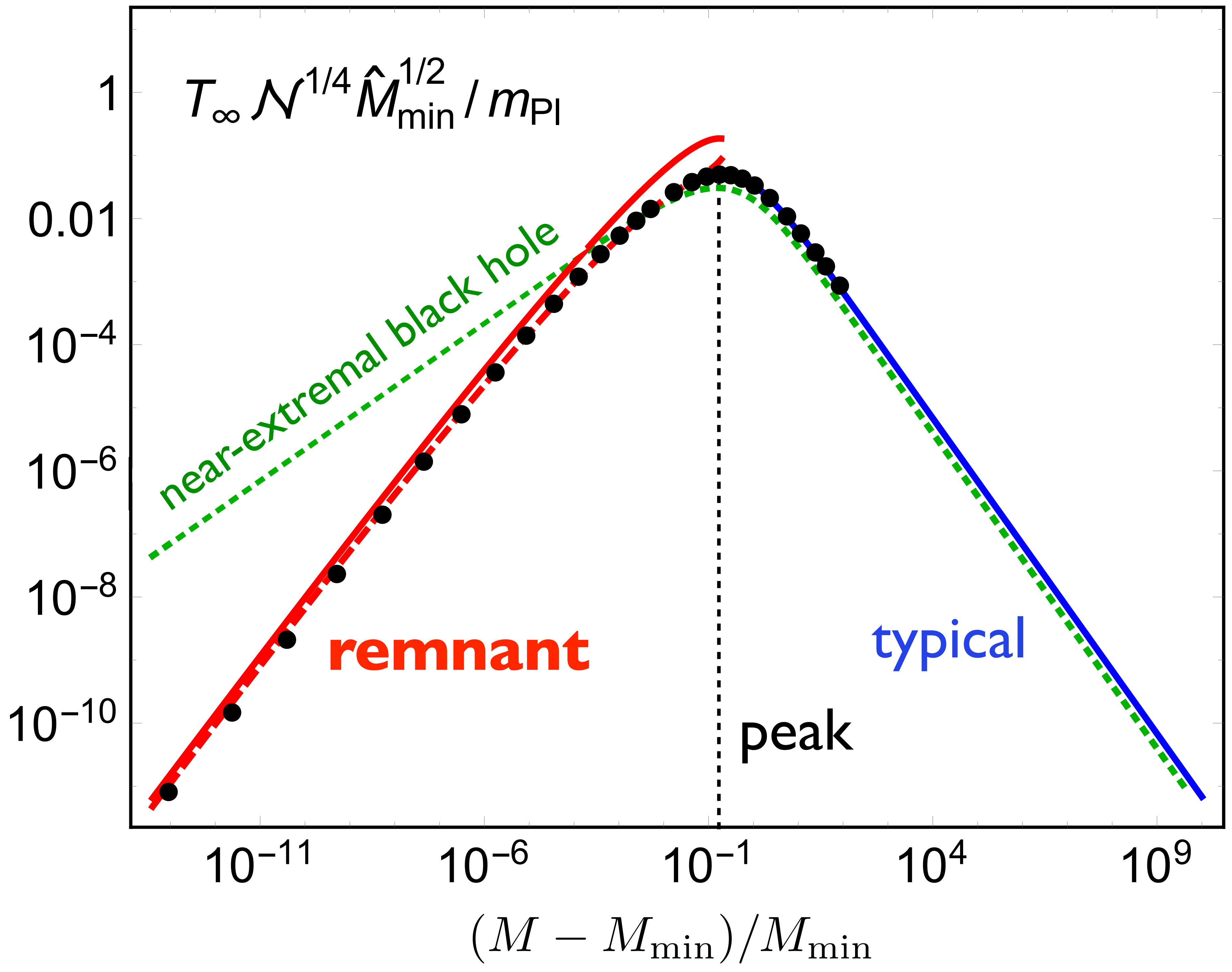
$$\mathrm{d}U = T_\infty \mathrm{d}S - p_\infty \mathrm{d}V_{\rm th} + \mu_\infty \mathrm{d}N$$
$$\mathrm{d}M - \mathrm{d}U = p_\infty\left(\mathrm{d}V_{\rm th} - \mathrm{d}V_{\rm geo} B(R)^{-3/2}\right)$$
$$\Rightarrow \quad \frac{U}{M} \approx \frac{3}{8}, \quad dM \approx \underbrace{T_\infty dS}_{\text{photon gas}} + \underbrace{\mu_\infty dN}_{\text{cold Fermi gas}}$$





[Holdom, PLB 830 (2022); Aydemir, **JR**, CQG 40 (2023)]

Primordial 2-2-hole serve as dark matter



- 2-2-hole starts by radiating like a black hole until entering the remnant stage with reduced power, which can account for DM
- Fundamental parameter $M_{\rm min}$ determines both the remnant mass and the evaporation rate

Typical thermal 2-2-hole ($M \gg M_{\rm min}$)

Anomalous features of black hole thermodynamics emerge from novel high curvature interior. Negative heat capacity and entropy area law

$$T_\infty \propto \mathcal{N}^{-1/4} \left(\frac{M_{\rm min}}{m_{\rm Pl}}\right)^{1/2} T_{\rm BH}, \quad S \propto \mathcal{N}^{1/4} \left(\frac{M_{\rm min}}{m_{\rm Pl}}\right)^{-1/2} S_{\rm BH}$$

Thermal 2-2-hole remnant ($M \sim M_{\rm min}$)

Thermodynamically more like a normal star sourced by radiation. Positive heat capacity and "normal entropy"

$$T_\infty \propto \mathcal{N}^{-1/4} \left(\frac{M_{\rm min}}{m_{\rm Pl}}\right)^{-3/2} \Delta M \left(\ln \frac{M_{\rm min}}{\Delta M}\right)^{7/4}, \quad S \propto \left(\frac{r_a}{\ell_{\rm Pl}}\right)^{3/4}$$

$$\Delta M = M - M_{\rm min}$$

[**JR**, PRD 100 (2019)]

Present observations for 2-2-hole remnants

Present observations determined mainly by the remnant mass M_{min}

- **Large remnants:** conventional PBH search through gravitational interaction
- **Small remnant: a distinctive phenomenon associated with remnant mergers**

Present observations for 2-2-hole remnants

Present observations determined mainly by the remnant mass $M_{\rm min}$

- **Large remnants:** conventional PBH search through gravitational interaction
- **Small remnant: a distinctive phenomenon associated with remnant mergers**

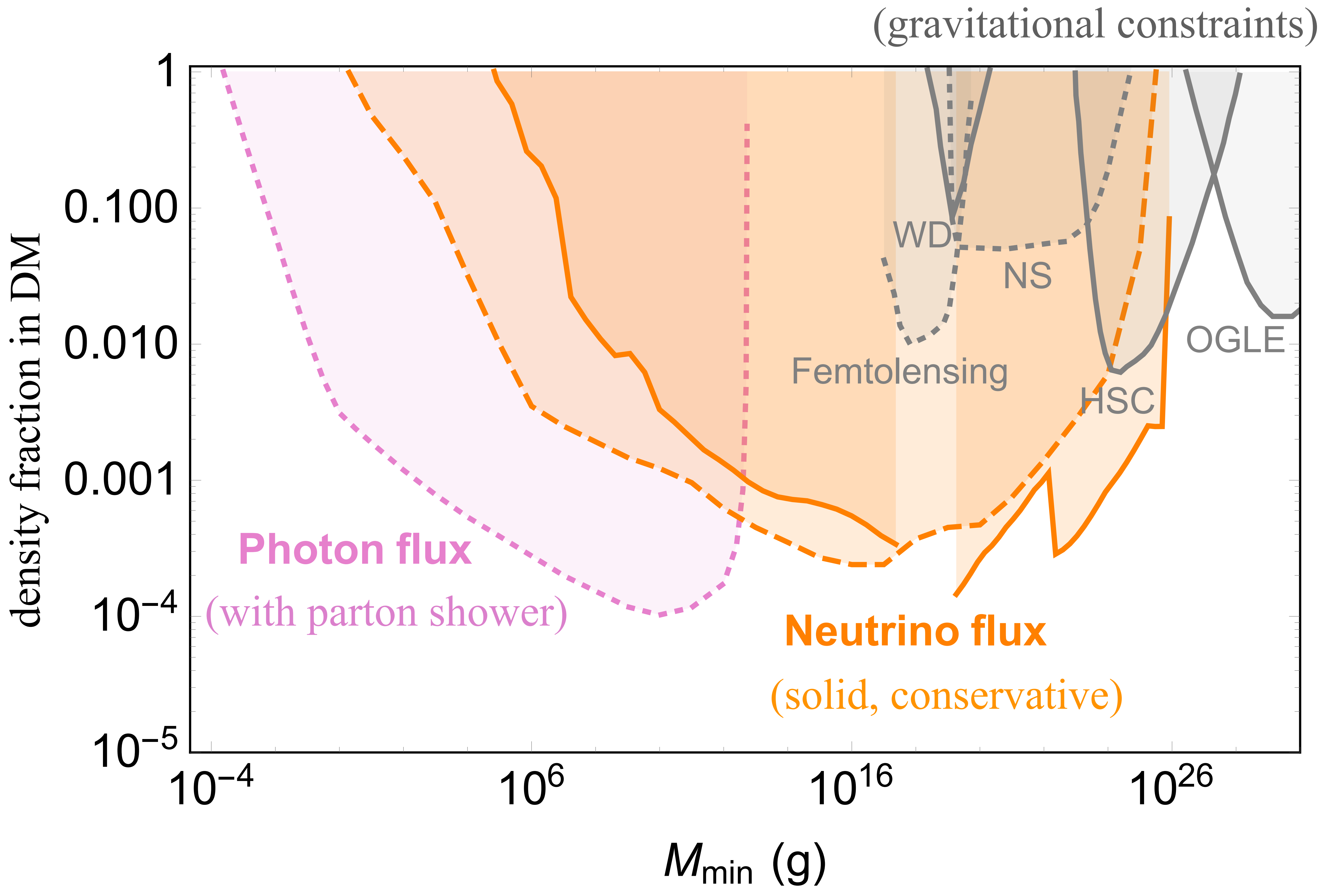
Remnant merger product acquires very high T

$$M_{\rm merger} = 2M_{\rm min} > M_{\rm peak}$$

$$T_{\infty,\rm merger} = 1.9 \times 10^{15} \mathcal{N}^{-1/4} \left(\frac{M_{\rm min}}{\rm g}\right)^{-1/2} \ {\rm GeV}$$

Excess energy ($\sim M_{\rm min}$) released — source of **high-energy astro-physical particles**

Observations of photon and neutrino flux place strong constraints



[Aydemir, Holdom, **JR**, PRD 102 (2020)]

Scalarized 2-2-holes

- **Scalarization:** light scalar sourced exclusively in the strong gravity regime due to a "phase-transition like" phenomenon, i.e. non-trivial scalar profiles inside/around NSs or BHs
    - Spontaneously scalarization in scalar-tensor theories [Damour and Esposito-Farèse 1992; 1993; 1996; Shao *et al.* 2017, PRX; …]
    - Finite density effects for QCD axion inside NSs [Hook and Huang 2018, JHEP; Zhang *et al.* 2021, PRL]

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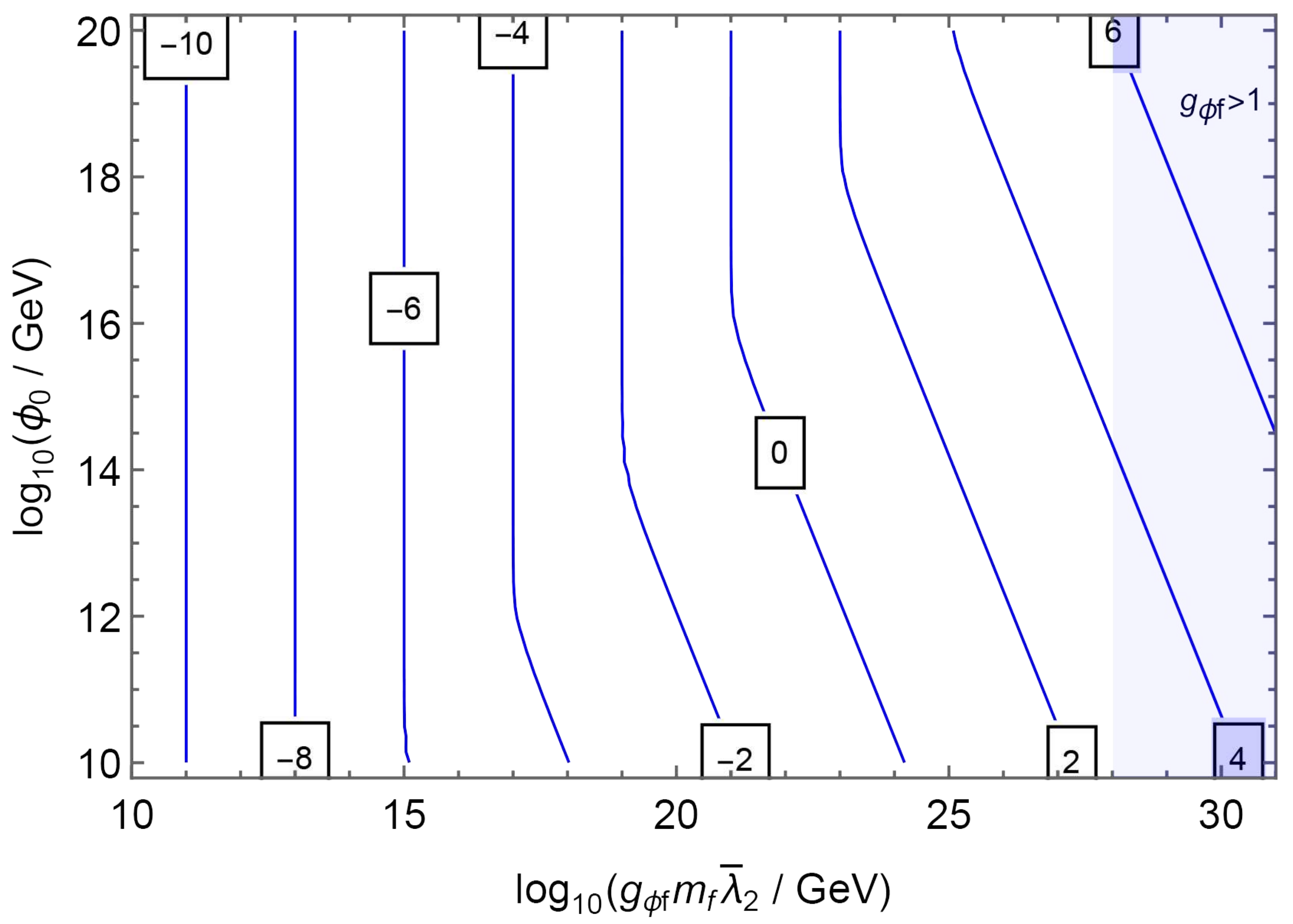
- **Novel mechanism for 2-2-holes:** high-temperature (density) gases inside offer a promising avenue for generating non-trivial scalar profile for minimal scalar models [Li, **JR**, PRD 109 (2024)]

- **Distinctive features of scalarized 2-2-holes**

2-2-hole interior: $T \sim \frac{m_{\rm Pl}}{\sqrt{\bar{\lambda}_2}}\bar{T},\ \bar{F} \approx g_{\phi f}\bar{\lambda}_2 \frac{m_{f,0}}{\phi_0}\bar{T}^2 \qquad \bar{\lambda}_2 = \frac{\lambda_2}{\ell_{\rm Pl}} \gg 1$

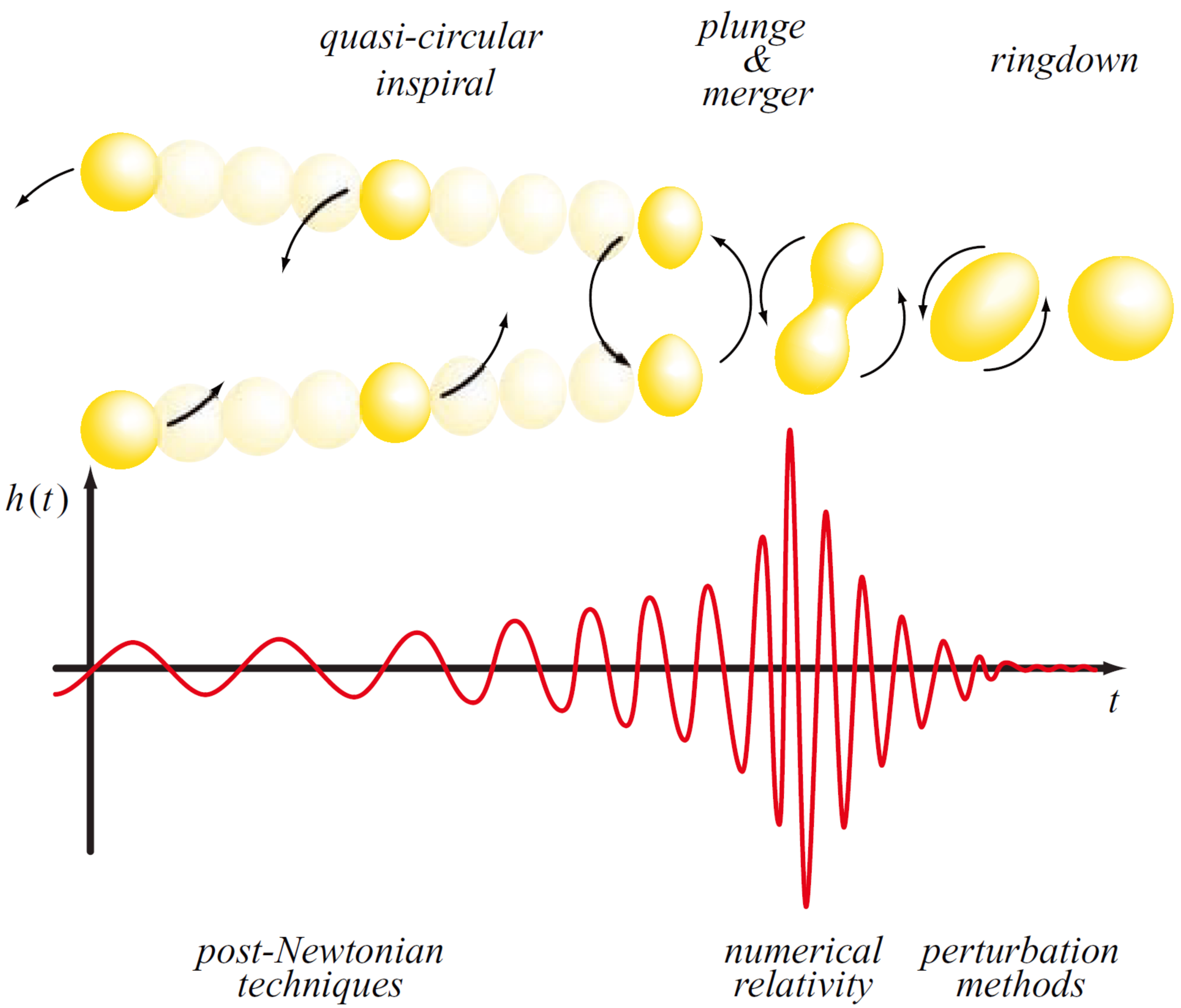
- The ratio γ ~ O(1) can be achieved if the scalar field couples to a new heavy fermion, i.e. $\bar{\lambda}_2 \sim 10^{12},\ g_{\phi f} \lesssim 1,\ m_{f,0} \sim 10^{10}\,\mathrm{GeV}$
- The ratio γ is independent of the 2-2-hole mass, setting it apart from other mechanisms
- Potential GW observations: coalescence time, dephasing

scalar charge-to-mass ratio γ



Gravitational wave echoes

Postmerger echoes: a smoking gun signal

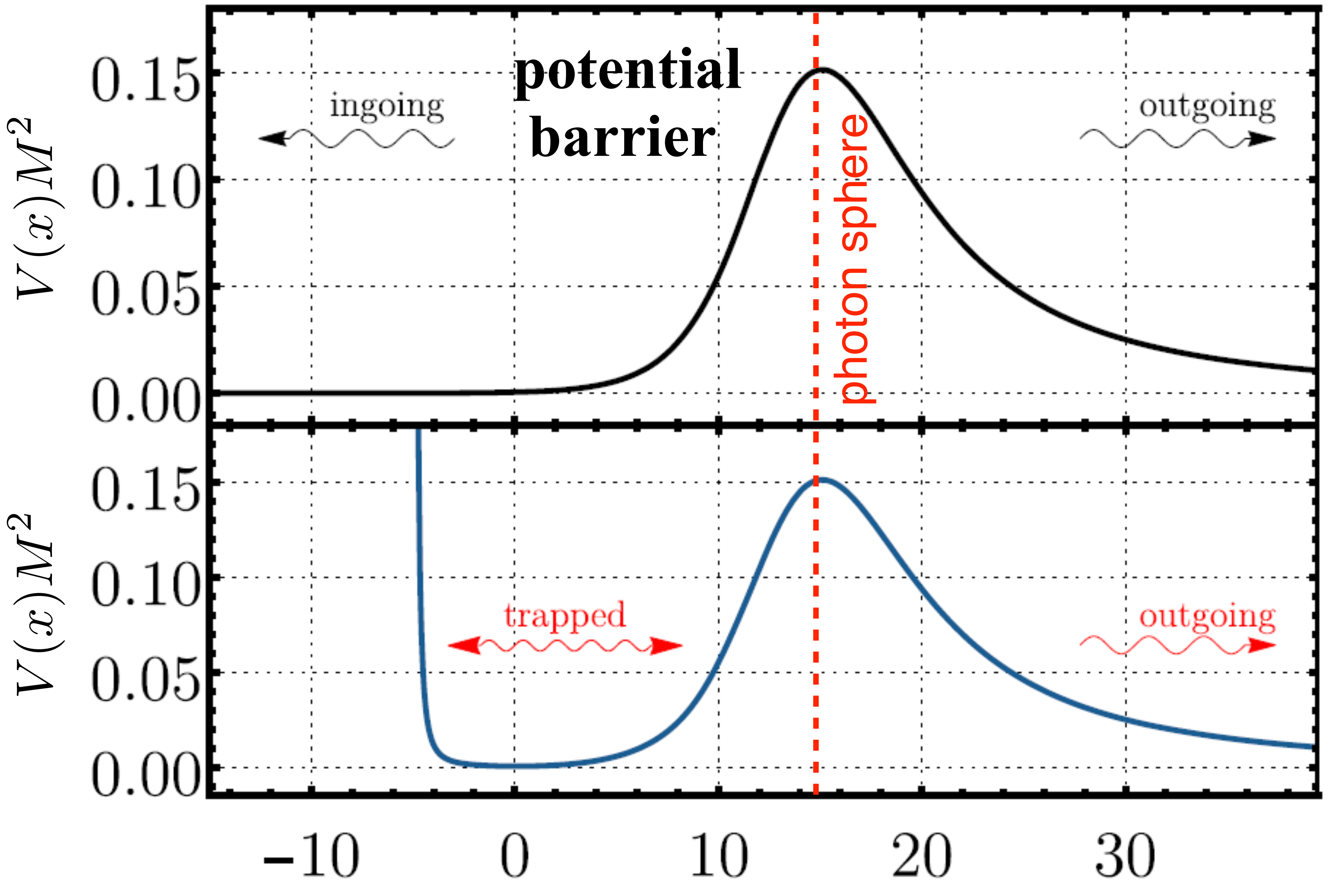


- GR prediction for inspiral-merger-ringdown confirmed by GW observations of ~100 CBC events
- BUT, current observations can't directly probe near-horizon regime, i.e. the ringdown fundamental mode only probe the photosphere [Vitor, Franzin, Pani, PRL 116 (2016)]
- Near-horizon corrections, due to large redshift, generate additional signals that appear later in ringdown
- Postmerger echoes arise when the purely ingoing condition is modified, serving as a smoking gun signal. [Cardoso, Hopper, Macedo, Palenzuela, Pani, PRD 94 (2016)]
- This motivates a deep search of the long-duration postmerger data

Postmerger echoes: a simple picture

UCOs behave as **leaky cavities** with two effective boundaries

$$\left(\partial_x^2 + \omega^2 - V(x)\right)\psi_\omega(x) = S(x,\omega)$$



(near-horizon corrections “heard” via “*QM tunneling*”)

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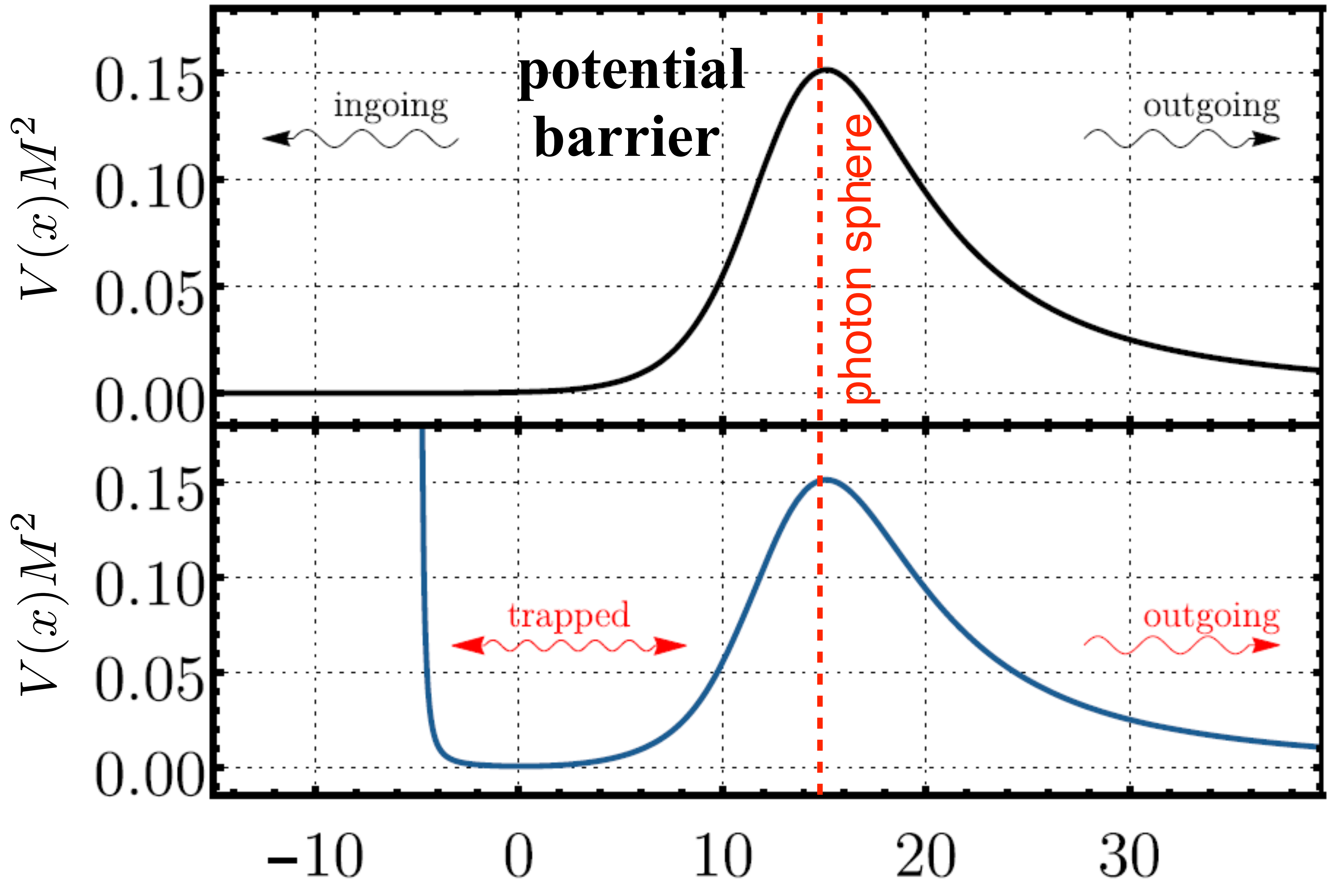

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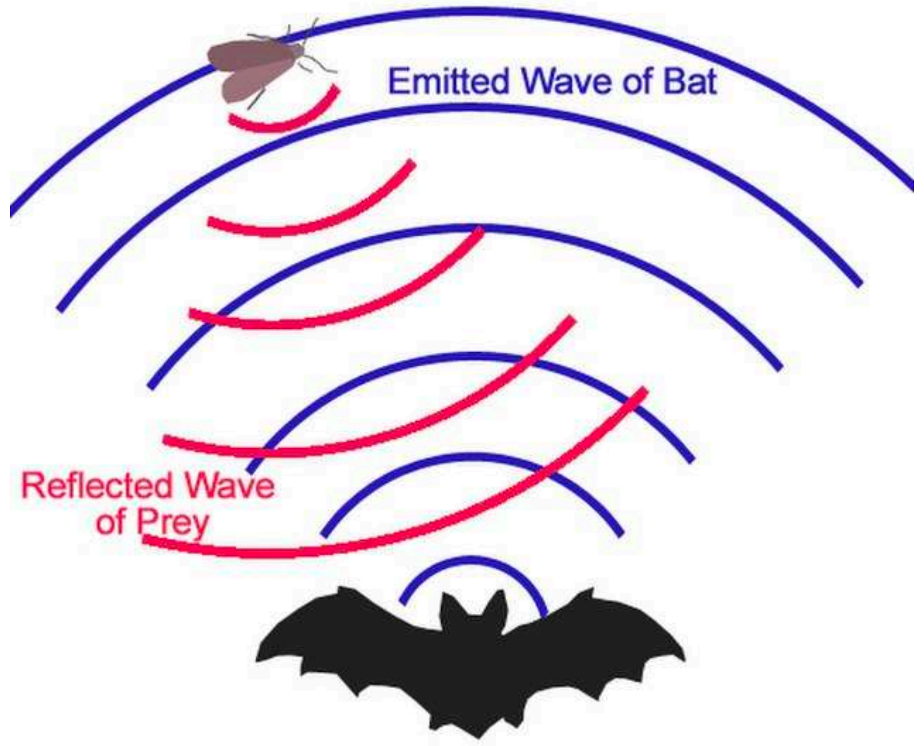
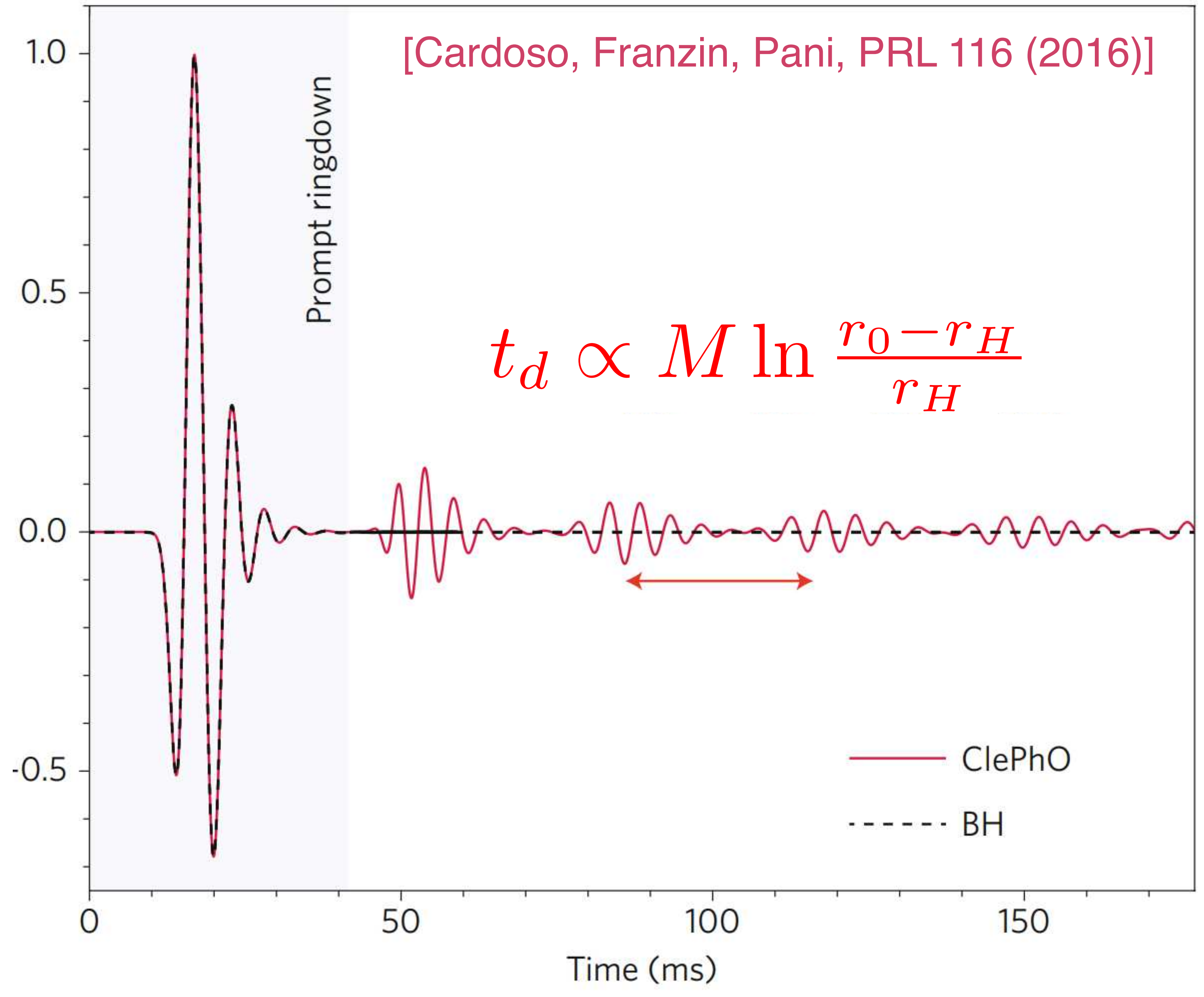


initial perturbation reflected repeatedly between two boundaries

Generate **quasi-periodic GW signal** with a nearly constant **time delay t_d**

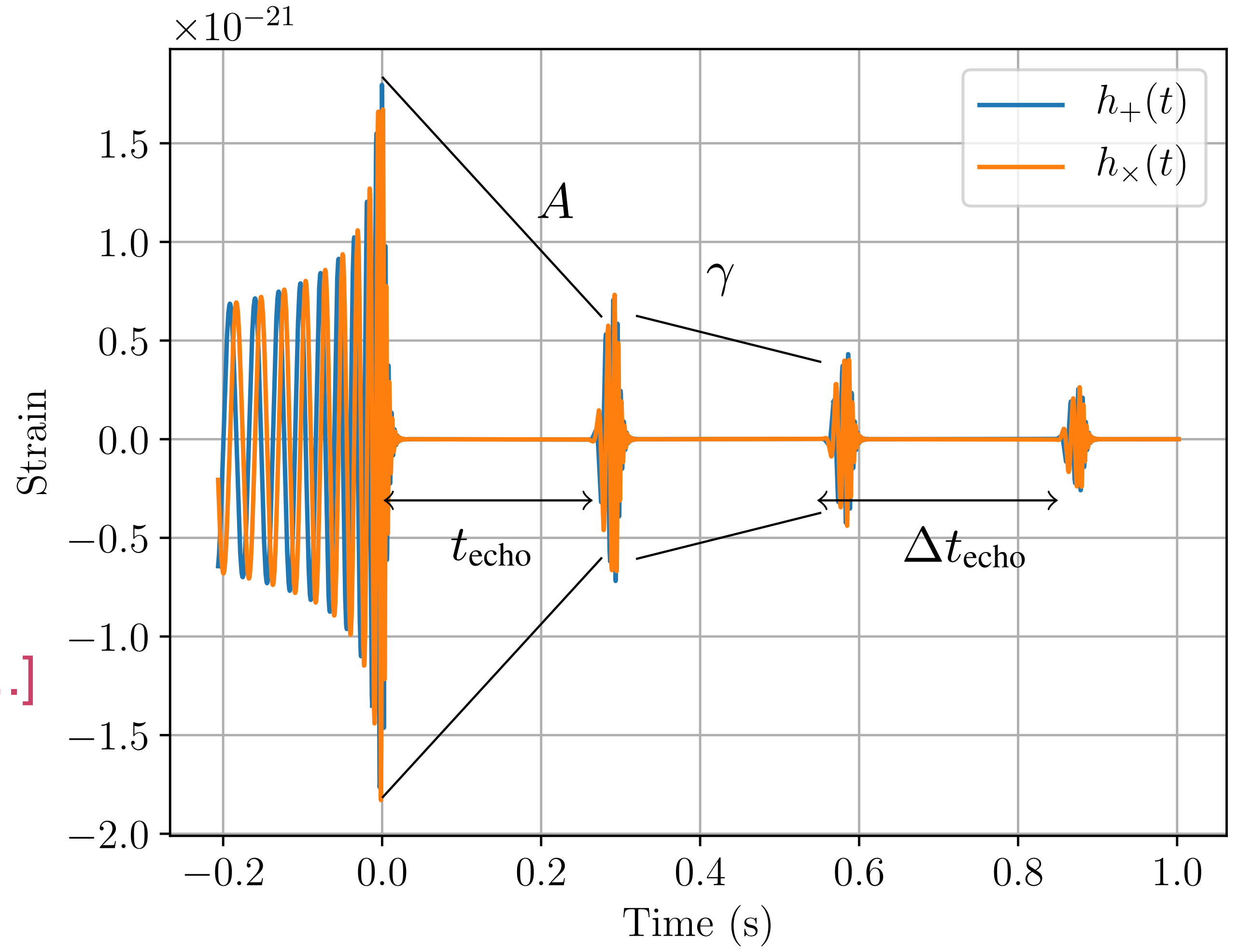
Planck scale deviation detectable: log-dependence of t_d on the interior surface position

$\ln(l_{\rm Pl}/r_H) \sim \mathcal{O}(100)$ (stellar mass BHs)



Template-based search: waveform uncertainties

Matched filtering: requiring a careful modeling of the echo waveform; sensitive to phase difference between the signal and template



- Phenomenological waveform model [Abedi, Dykaar, and Afshordi, PRD 96 (2017)]

  Too simple: repeated ringdown with constant time delay and damping

- Perturbative calculation for truncated Kerr black holes

  [Nakano et al., PTEP 2017 (2017), Maggio et al., PRD 100 (2019), Xin et al. PRD 104 (2021), Ma et al., PRD 105 (2022)….]

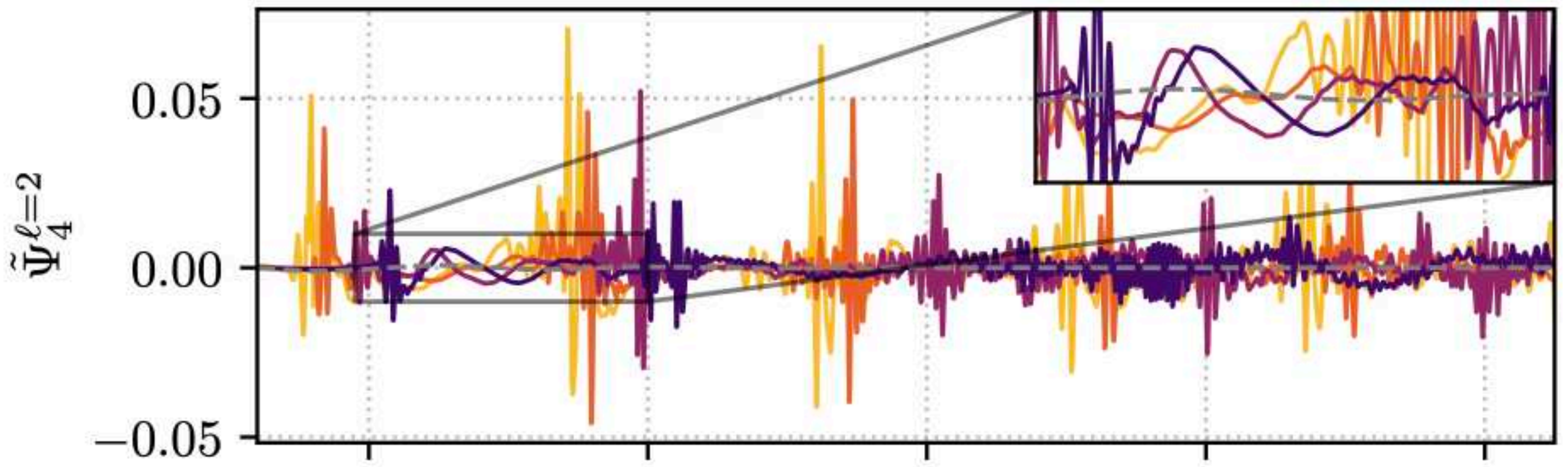
  There remain uncertainties even for such a simply toy model…

- Calculation in the "fuzzball" paradigm [Ikeda et al., PRD 104 (2021)]

  Unclear how to average over numerical simulations of test fields on different microstate geometries

- Numerical simulation for boson stars [Siemonsen, arXiv:2404.14536]

  Complicated waveform: there are both high and low frequency components



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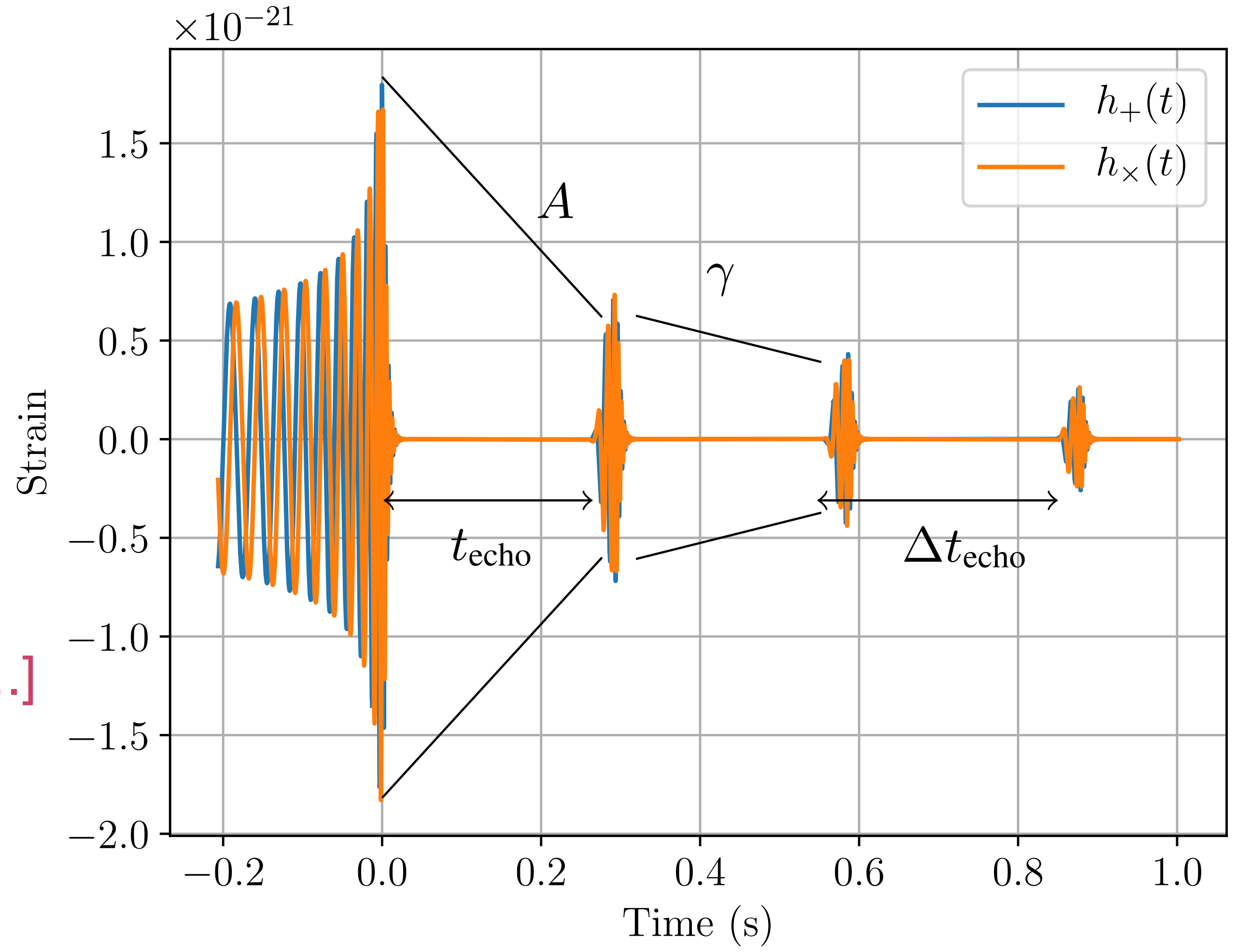

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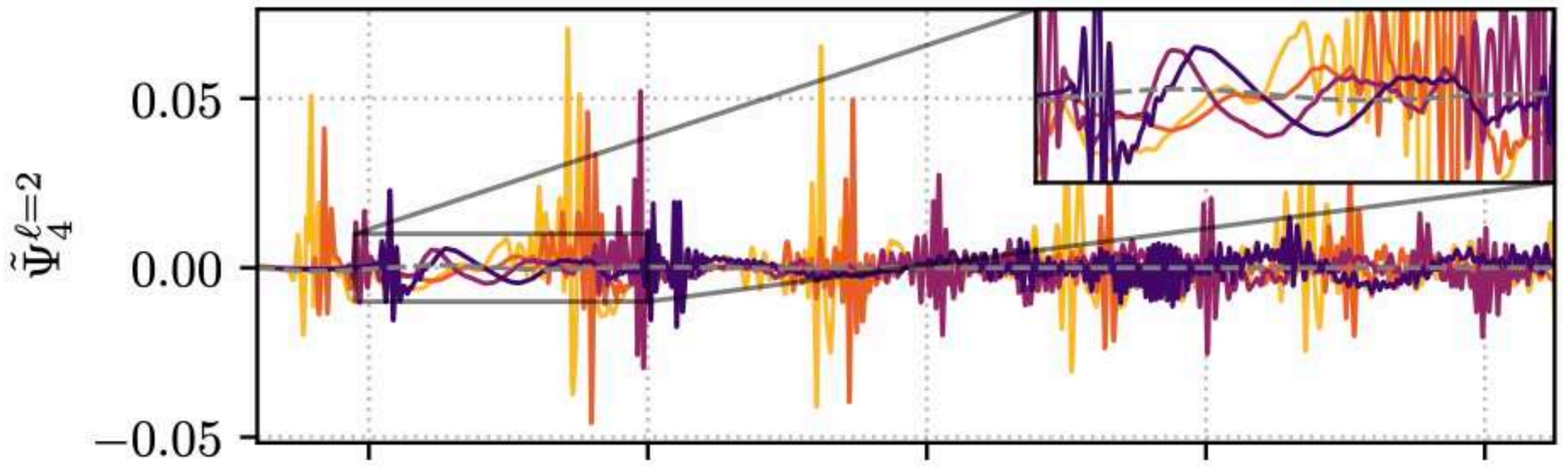


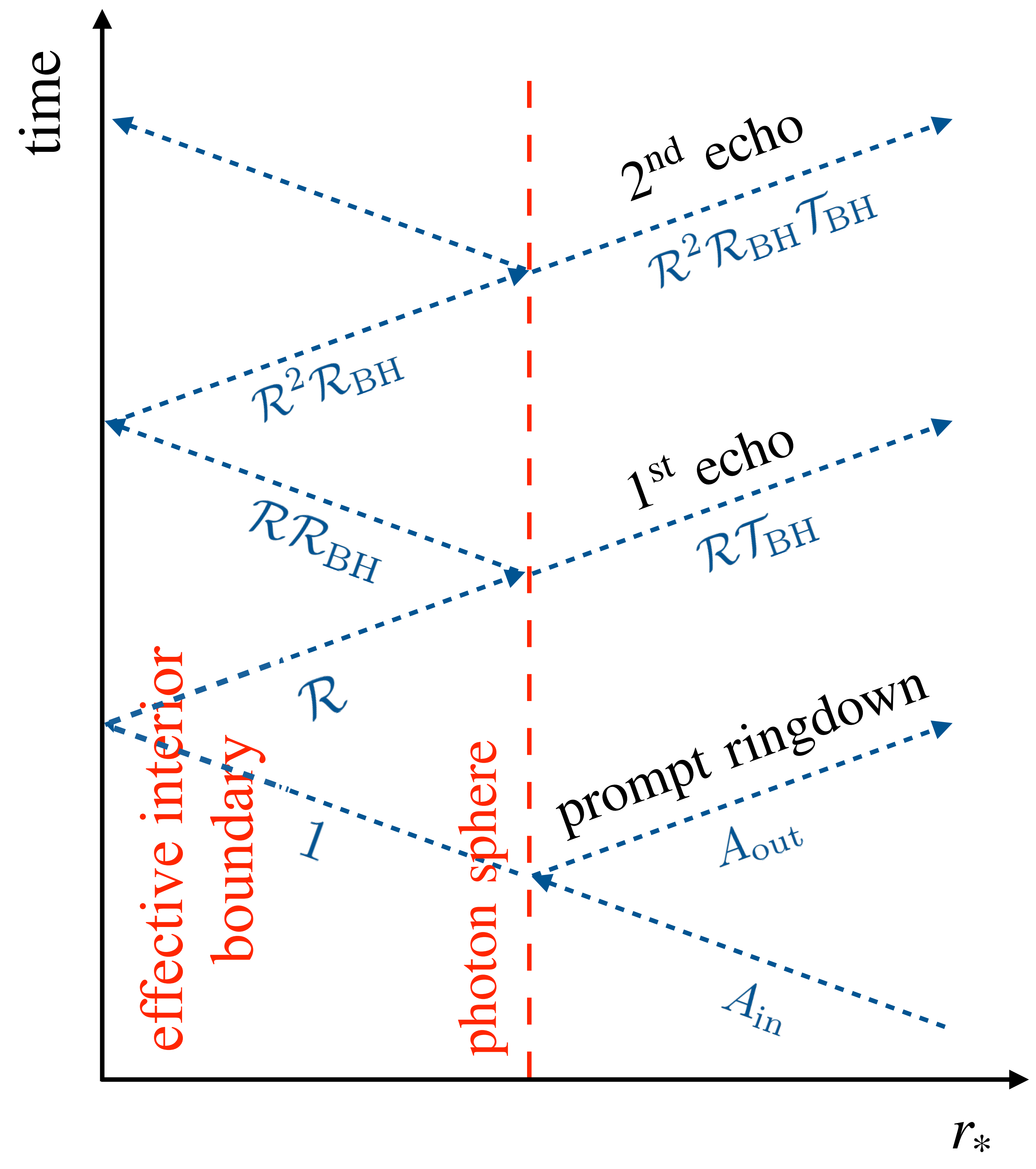
Template-based search is powerful for the targeted signal, but it quickly **loses sensitivity** if the waveform is affected by **large theoretical uncertainties**

Generic construction of echo waveform

Considering a truncated Kerr black hole,

$$h_{\text{echo}}(\omega) = \mathcal{P}(\omega) h_{\text{eff}}(\omega), \quad \mathcal{P}(\omega) = \frac{R_{\text{BH}}(\omega) R_{\text{wall}}(\omega)}{1 - R_{\text{BH}}(\omega) R_{\text{wall}}(\omega)} .$$

- $P(\omega)$: relies on the properties of UCOs, e.g. potential shape close to inner boundary, interior boundary condition vary strongly with models
- $h_{\text{eff}}(\omega)$: encodes the initial condition/source dependence, e.g. out-going pulse from the inside, infalling particle…; may not be intimately related to the BH ringdown signal



LVK collaboration on echo search

LSC-Virgo-KAGRA Observational Science White Paper (Summer 2021 edition)

	LSC-Virgo-KAGRA Observational Science Working Group			
	Burst	CBC (compact binaries)	Continuous Wave	Stochastic Background
Highest priority	Search for short-duration GW bursts (both online and offline)	Responding to exceptional compact binary coalescence detections	Targeted searches for high-interest known pulsars, e.g. Crab, Vela	Searches for an isotropic stochastic GW background
	Search for long-duration GW bursts	Cataloging detections of coalescence of neutron star and black hole binaries and their meaured parameters	Narrow-band searches for high-interest known pulsars	Directional searches for anisotropic stochastic GW backgrounds
	Responding to exceptional GW burst and multi-messenger detections	Characterizing the astrophysical distribution of compact binaries	Directed searches for high-interest point sources, e.g. Cassiopeia A, Scorpius X-1	Detector characterization, data quality, and correlated noise studies specific to SGWB searches
	Searches without templates from GWs from binary black holes	Testing General Relativity with compact binaries	All-sky searches for unknown sources, either isolated or in binary systems	All-sky all-frequency search for unmodeled persistent sources
	GW burst signal characterization	Low-latency searches to enable multimessenger astronomy	Long-transient searches for emission from nearby post-merger neutron stars	SGWB implications and modeling
		Multimessenger search for CBC-GRB coincidences	Follow-up searches of any promising candidates found by other searches	Development of python SGWB search pipeline
		Measuring the properties of extreme matter, e.g. the neutron star equation of state	Detector characterization, data preparation, scientific software maintenance	
		Determination of the Hubble constant		

Op-3.2 Tests of General Relativity R&D (Short Term)

Short-term research and development on tests of general relativity using compact binary coalescences.

TASK Op-3.2-B(ii): PROBING THE NEAR-HORIZON STRUCTURE

Develop and improve searches for echoes and other features that probe the near-horizon structure of the merger remnant, **using template-based and model-agnostic approaches**

Op-3.11 O3b and O4 Strong-Field Tests of General Relativity

Subject GR to a battery of tests based on observed CBC signals, ranging from tests of strong field dynamics to tests of the nature of gravitational waves, using events in the O3b and O4 catalogs.

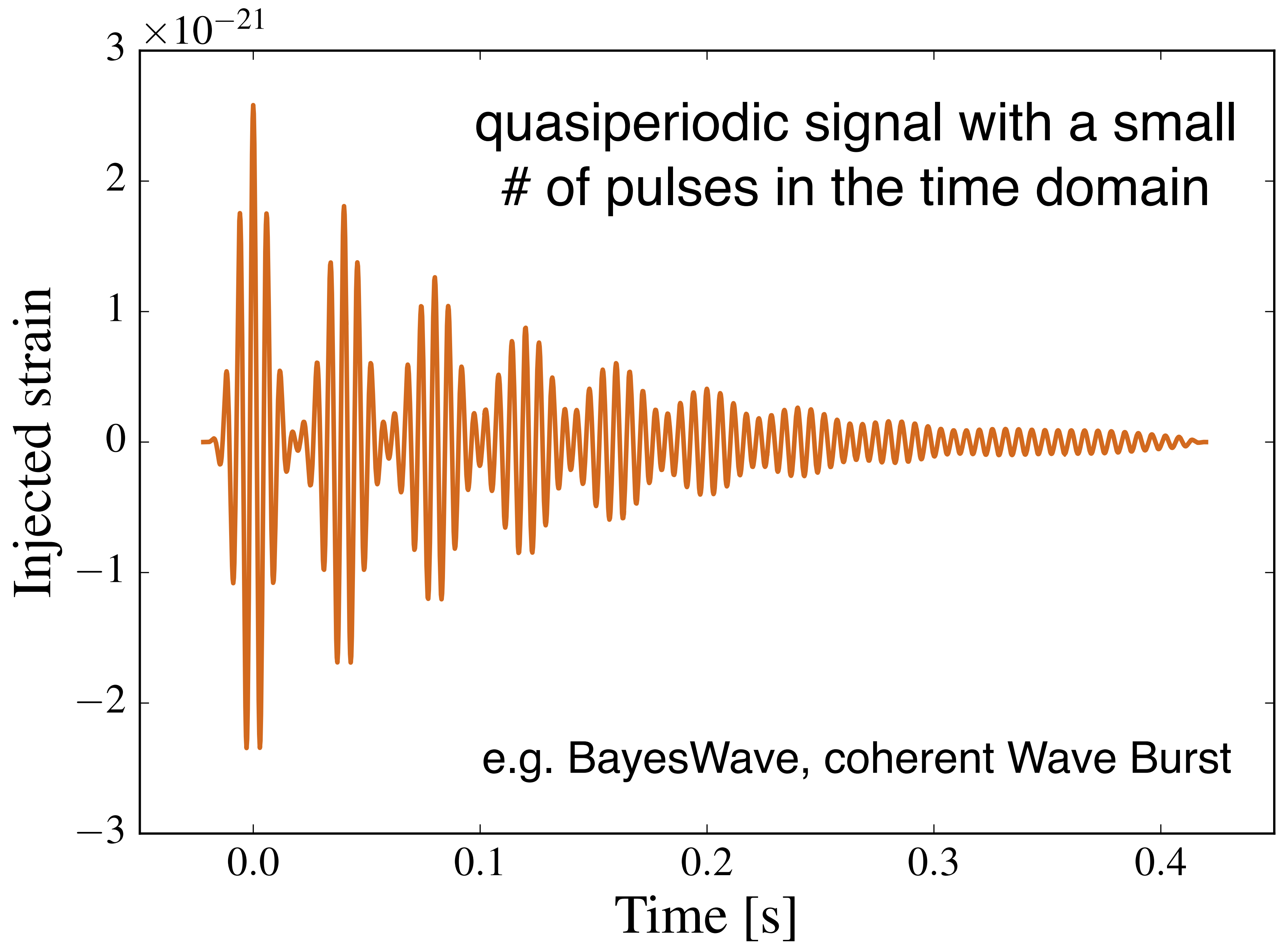
TASK Op-3.11-C(ii): PROBING THE NEAR-HORIZON STRUCTURE

Search for near-horizon effects such as late-time echoes using template-based and model-independent approaches.

Model-independent search of echoes

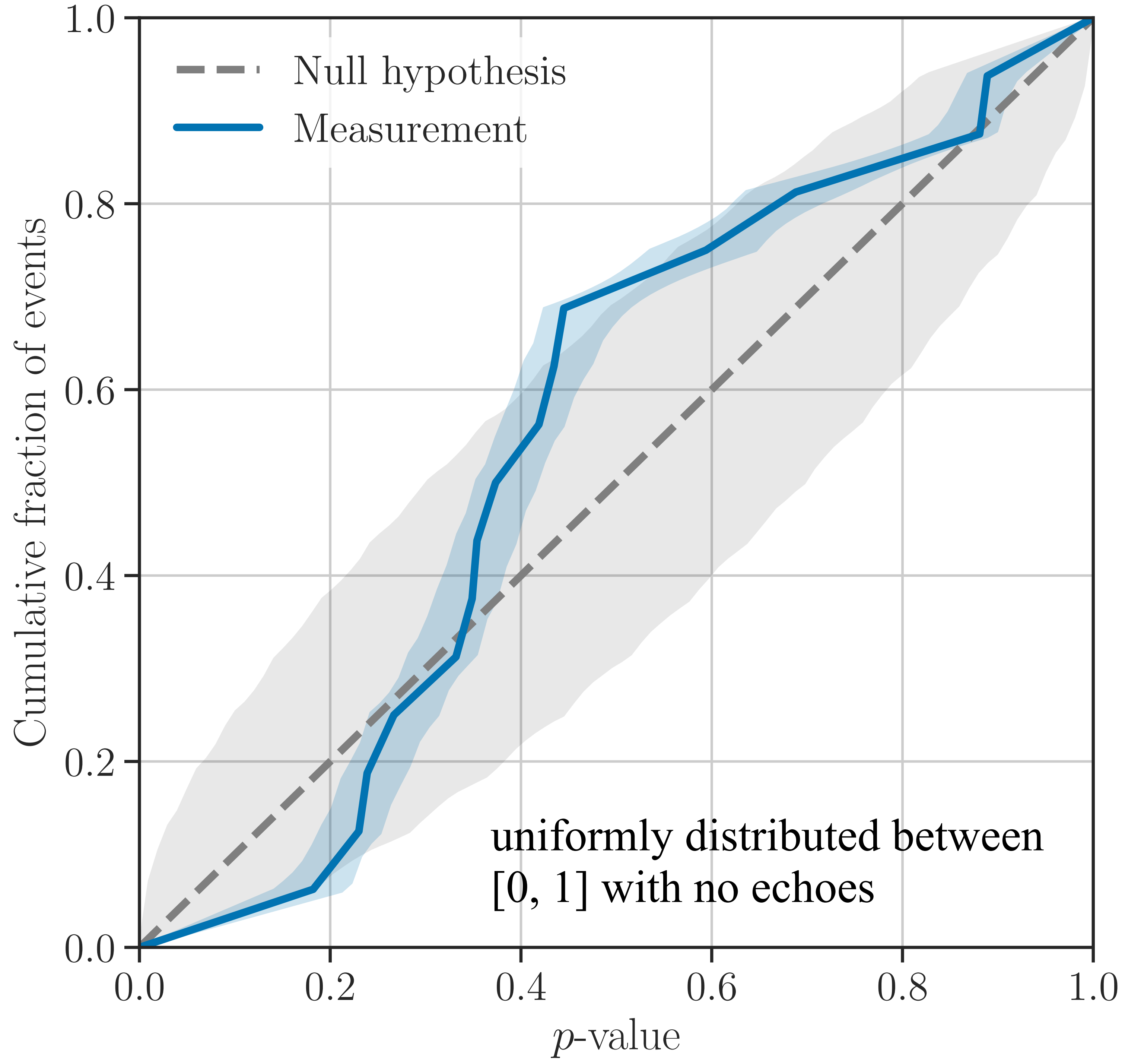
Model-independent searches: target the characteristic features independent of model-specific details

Present methods: target rapidly damped pulses in the case of a *weak reflection (high frequency)*



No clear evidence for postmerger echoes from O1-O3

Event	*p*-value
GW191109_010717	0.35
GW191129_134029	0.35
GW191204_171526	0.37
GW191215_223052	0.23
GW191216_213338	0.88
GW191222_033537	0.89
GW200115_042309	0.44
GW200129_065458	0.33
GW200202_154313	0.43
GW200208_130117	0.24
GW200219_094415	0.18
GW200224_222234	0.59
GW200225_060421	0.69
GW200311_115853	0.42
GW200316_215756	0.27



p-vale for signal to noise Bayes Factor and the distribution

[Tsang et al., Phys. Rev. D 98 (2018); Phys. Rev. D 101 (2020); Miani, et al., arXiv:2302.12158; Abbott et al. [LIGO Scientific, VIRGO and KAGRA], arXiv:2112.06861]

Looking for the characteristic QNMs

"QM black hole seismology": in the case of a *strong reflection*, it is preferable to view echoes as a superposition of long-lived and quasi-periodic QNMs of UCOs

$$h_{\rm echo}(\omega) = \underbrace{h_{\rm eff}(\omega)}_{\text{source/initial condition}} \frac{R_{\rm BH}(\omega)R_{\rm wall}(\omega)}{1-R_{\rm BH}(\omega)\underbrace{R_{\rm wall}(\omega)}_{\text{interior reflection}}} = \sum_{n=1}^{N} A_n e^{i\delta_n} e^{-i\omega t_n} \frac{-i}{(\omega-\omega_n)-i/\tau_n}$$

$$t_d(\omega_n - m\Omega_H) \approx 2\pi n, \quad \text{(quasi-periodic)}$$

$$t_d/\tau_n \approx -\ln \mathcal{R}_{\rm eff}(\omega_n)\,. \quad \text{(long-lived)}$$

($\mathcal{R}_{\rm eff}(\omega) = \mathcal{R}_{\rm BH}(\omega)\mathcal{R}_{\rm wall}(\omega) \sim 1$)

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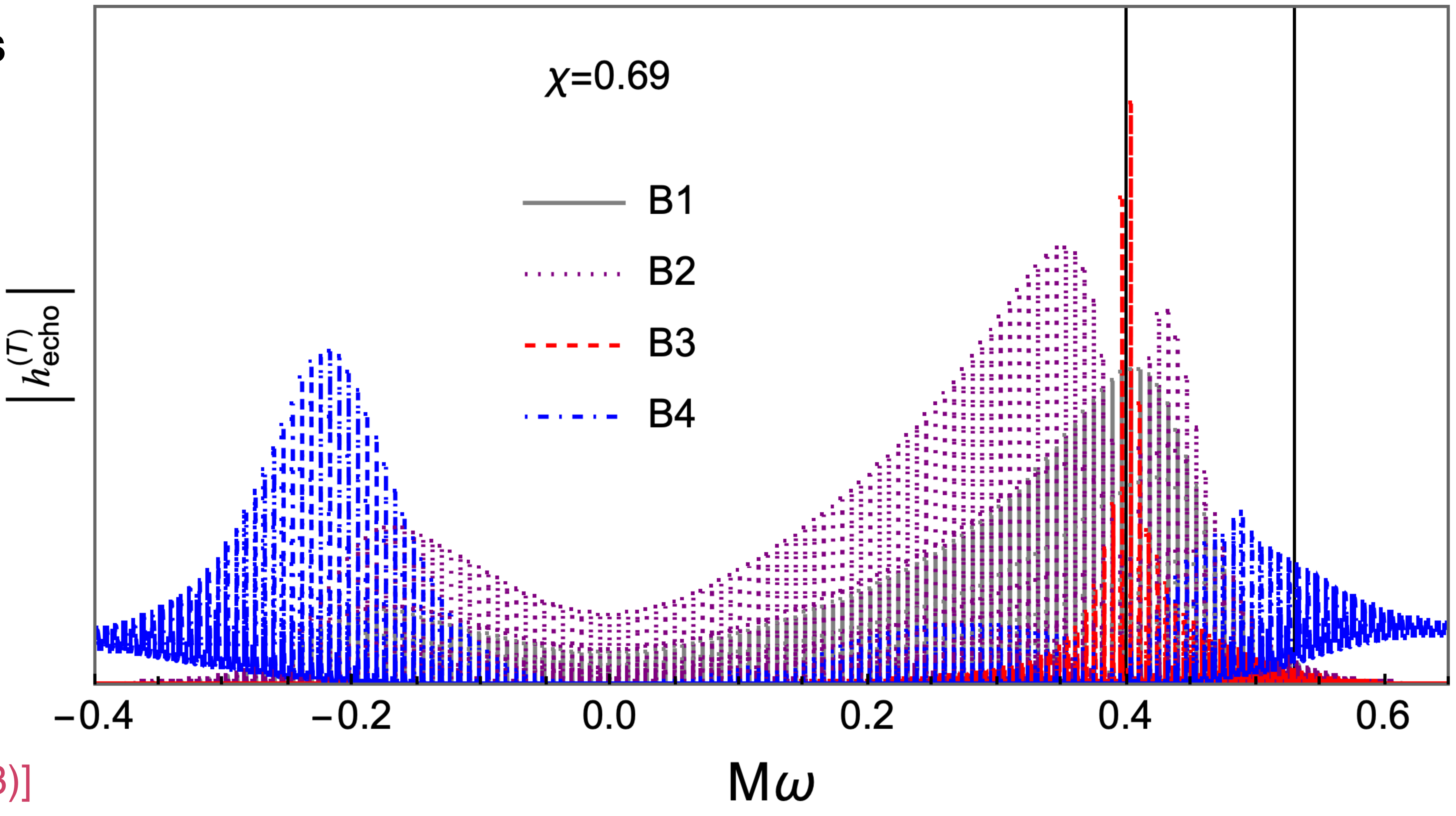
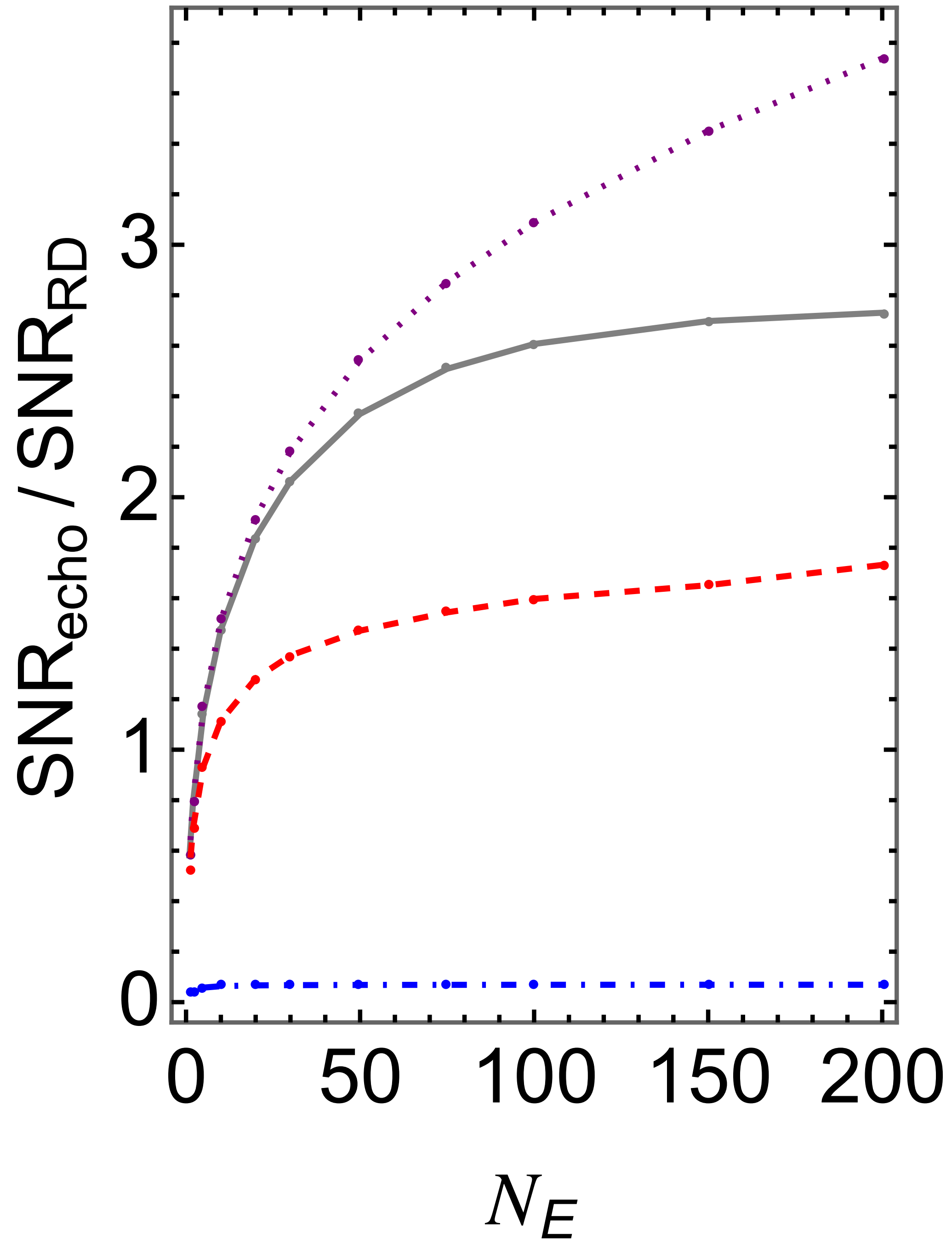
($\mathcal{R}_{\rm eff}(\omega) = \mathcal{R}_{\rm BH}(\omega)\mathcal{R}_{\rm wall}(\omega) \sim 1$)

Complementary benchmarks

— test the algorithm's ability to detect diverse echo signal

- ***R*$_{\rm wall}$:** "damping 2-2-holes", "Boltzman reflection"
- ***h*$_{\rm eff}$:** "initial pulse from inside", "infalling particles"

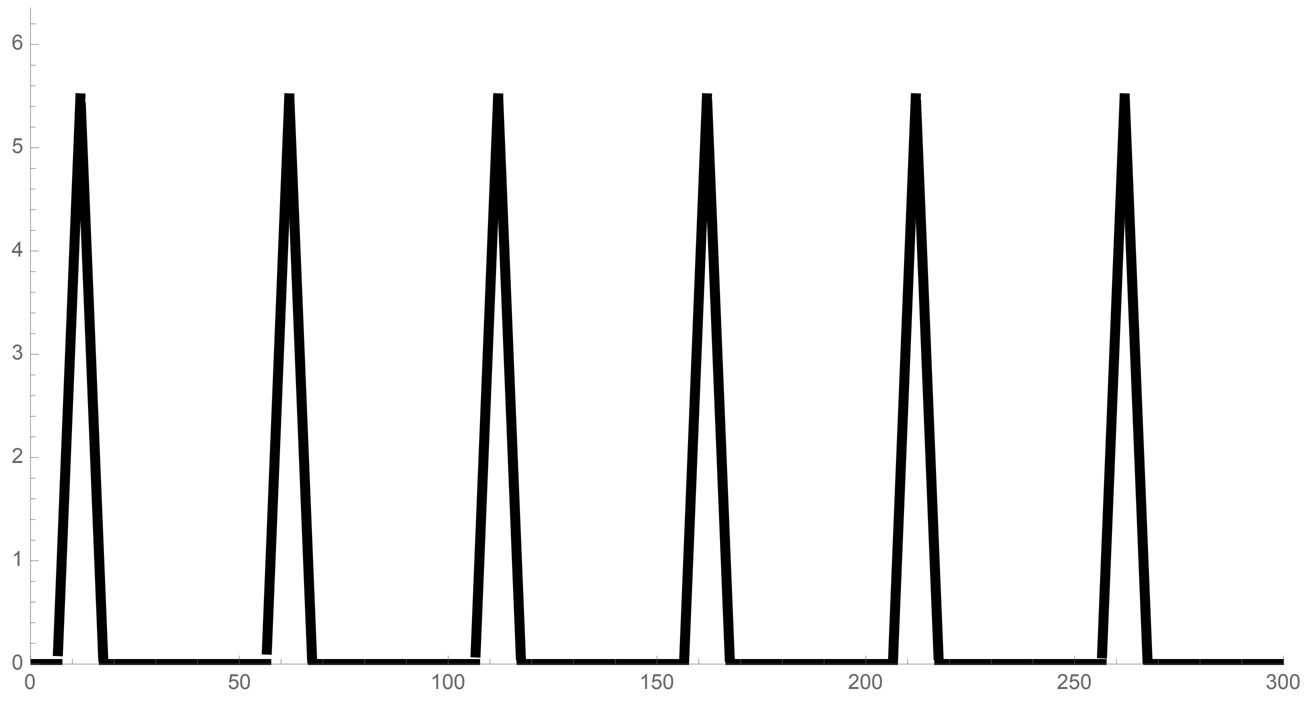




[Wu, Gao, **JR**, Afshordi, PRD 108 (2023)]

QNMs search with no phase information

- **Search template:** periodic and uniform echo waveform (UniEw) [Conklin, Holdom, **JR**, PRD 98 (2018)]



QNMs position/average spacing: $f_0, \Delta f \approx 1/t_d$

QNMs average amplitude: A_{comb}

QNMs average width: f_w

Frequency band: $f_{\min},\ f_{\max}$

- Frequentist search for QNMs amplitude: **tentative evidences** reported [Holdom, PRD 101 (2020)]

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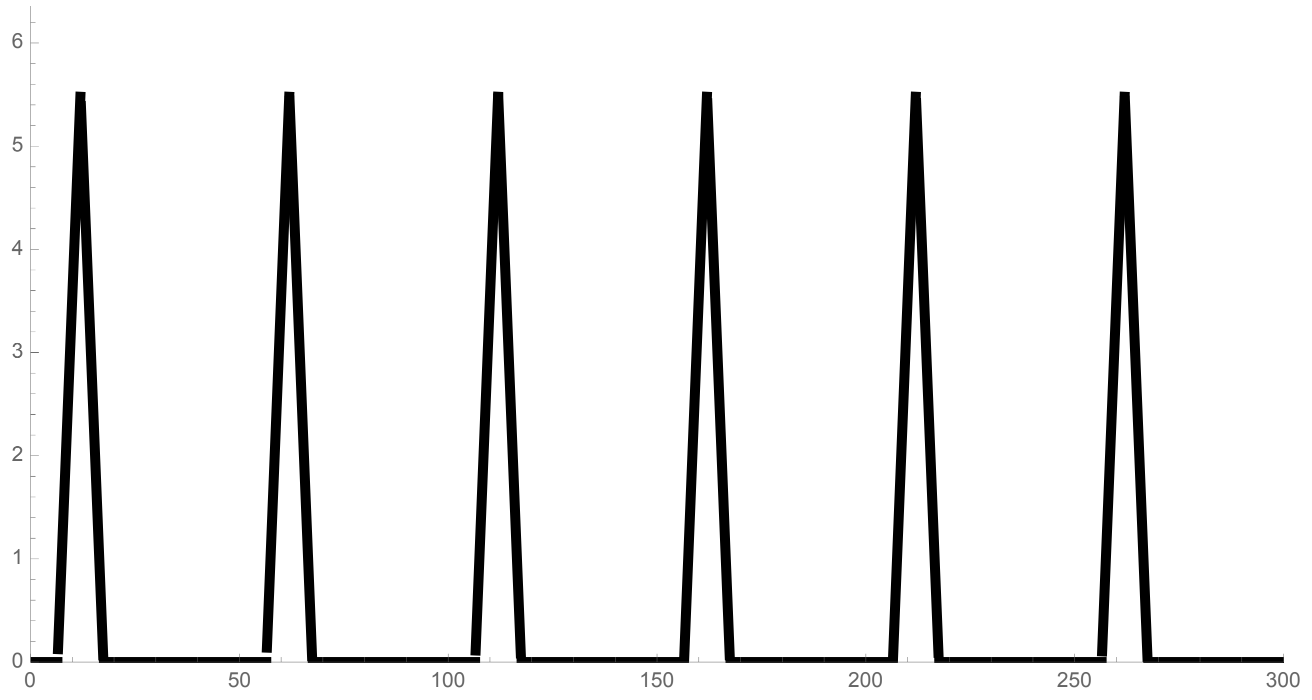

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✦ Frequentist search for QNMs amplitude: **tentative evidences** reported [Holdom, PRD 101 (2020)]

✦ **Bayesian search for QNMs with no phase:** phase-marginalized likelihood [**JR**, Wu, PRD 104 (2021)]

$$\ln \frac{L(d|\theta)}{L(d|0)} = \underbrace{\sum_j \ln I_0\left(4\, df \frac{|d_j||h_j|}{P_j}\right)}_{\text{overlapping term}} - \frac{1}{2}\underbrace{\sum_j 4\, df \frac{|h_j|^2}{P_j}}_{\text{optimal SNR}}$$

$$\ln I_0(x) = \begin{cases} x - \frac{1}{2}\ln(2\pi x), & x \geq 2, \\ \frac{1}{4}x^2, & x < 2. \end{cases}$$

loose sensitivity to signal below the noise level

- Log-Bayes factor used to compare different models
- Inferred UniEw parameters encode essential properties of QNMs

QNMs search with relative phase information

- **More refined treatment of QNM phase** $h^{(T)}(f) = \sum_n A_n e^{i\delta_n} e^{-i2\pi f t'_n} \frac{1 - e^{-T_n/\tau_n} e^{i2\pi(f-f_n)T_n}}{2\pi(f-f_n) - i/\tau_n}$

$$\arg(h^{(T)}(f)) \approx \underbrace{\arg\left(\frac{1 - \mathrm{e}^{-T_n/\tau_n}\mathrm{e}^{\mathrm{i}2\pi(f-f_n)T_n}}{\mathrm{i}2\pi(f-f_n) + 1/\tau_n}\right)} + \underline{(\delta_n - 2\pi f t'_n)} \qquad \text{for } f \sim f_n$$

1) share the same info with the amplitude

2) dominant contribution to the relative phase

roughly a constant
(narrow mode)

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1) share the same info with the amplitude

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roughly a constant (narrow mode)

- **New likelihood:** coherently combine frequency bins belonging to one QNM by marginalizing **the overall phase** for each QNM

$$\ln \mathcal{L}_{\text{new}} = \sum_{n=1}^{N} \underbrace{\ln I_0\left(\left|\sum_{j\in n} \frac{d_j h_j^*}{\tilde{P}_j}\right|\right)} - \frac{1}{2}\sum_{j=1}^{\mathcal{N}} \frac{|h_j|^2}{\tilde{P}_j} \quad \textbf{v.s.} \quad \ln \mathcal{L}_{\text{old}} = \sum_{j=1}^{\mathcal{N}} \underbrace{\ln I_0\left(\frac{|d_j||h_j|}{\tilde{P}_j}\right)} - \frac{1}{2}\sum_{j=1}^{\mathcal{N}} \frac{|h_j|^2}{\tilde{P}_j}$$

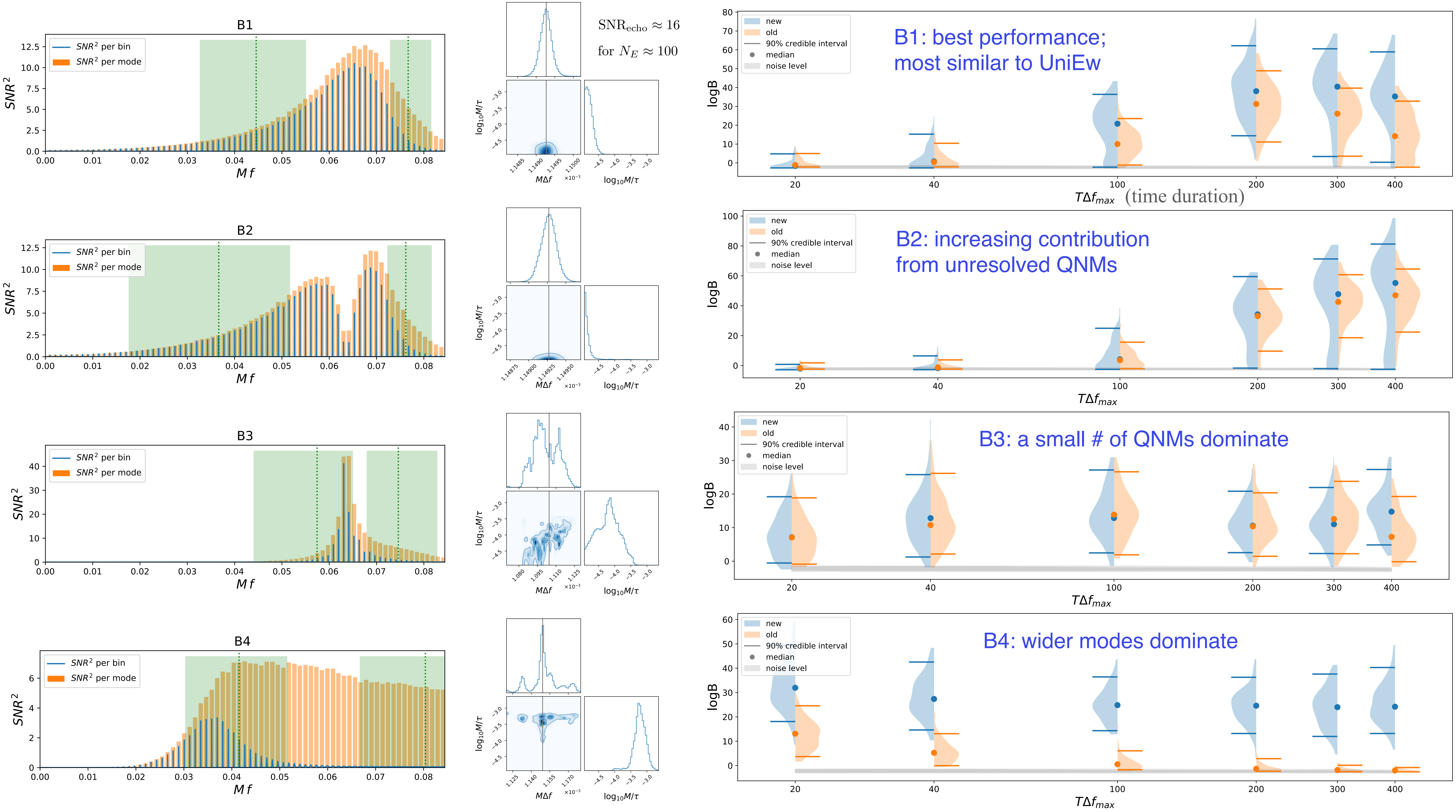
sensitive to **SNR per mode**

sensitive to **SNR per bin**

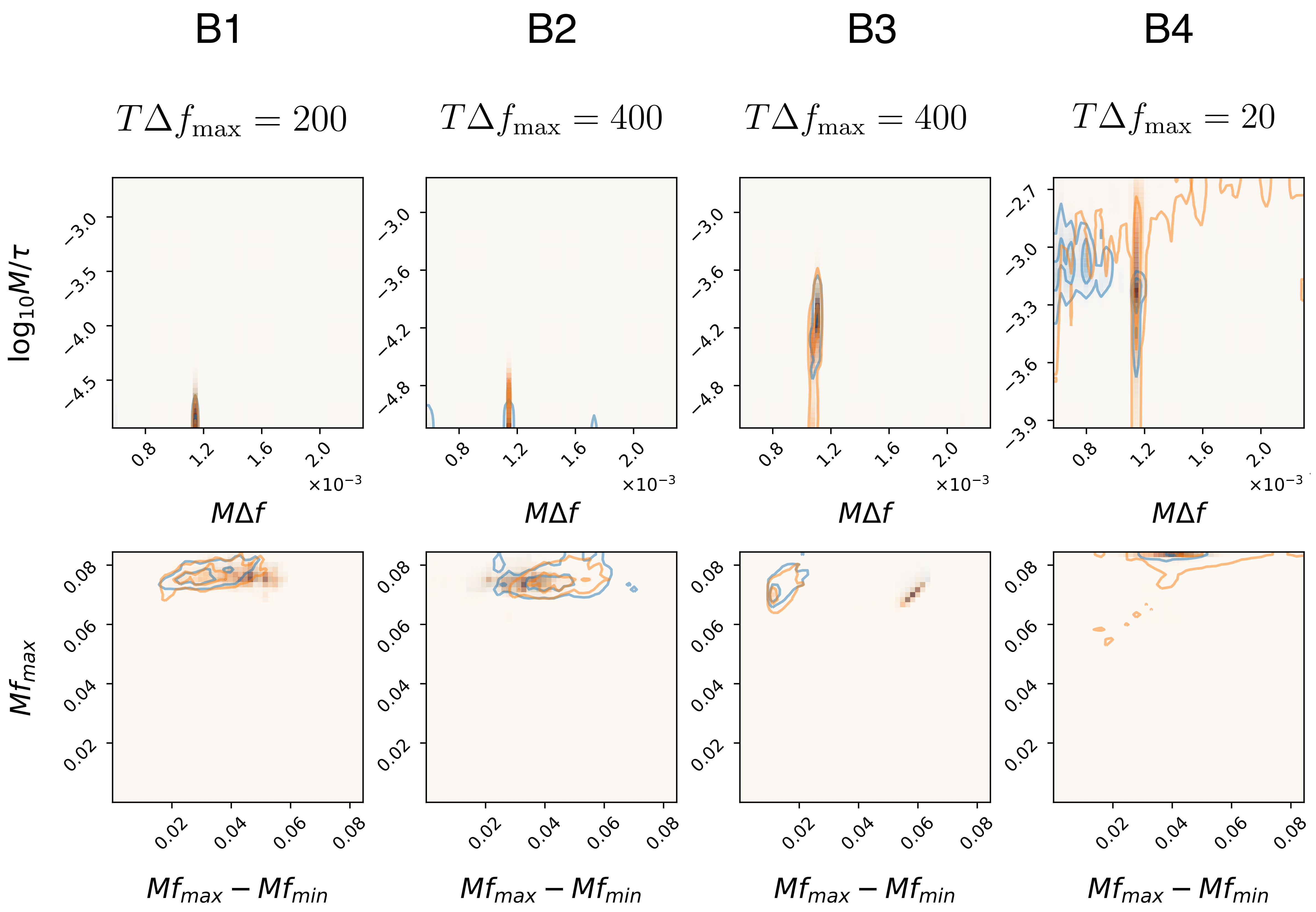
[Wu, Gao, **JR**, Afshordi, PRD 108 (2023)]

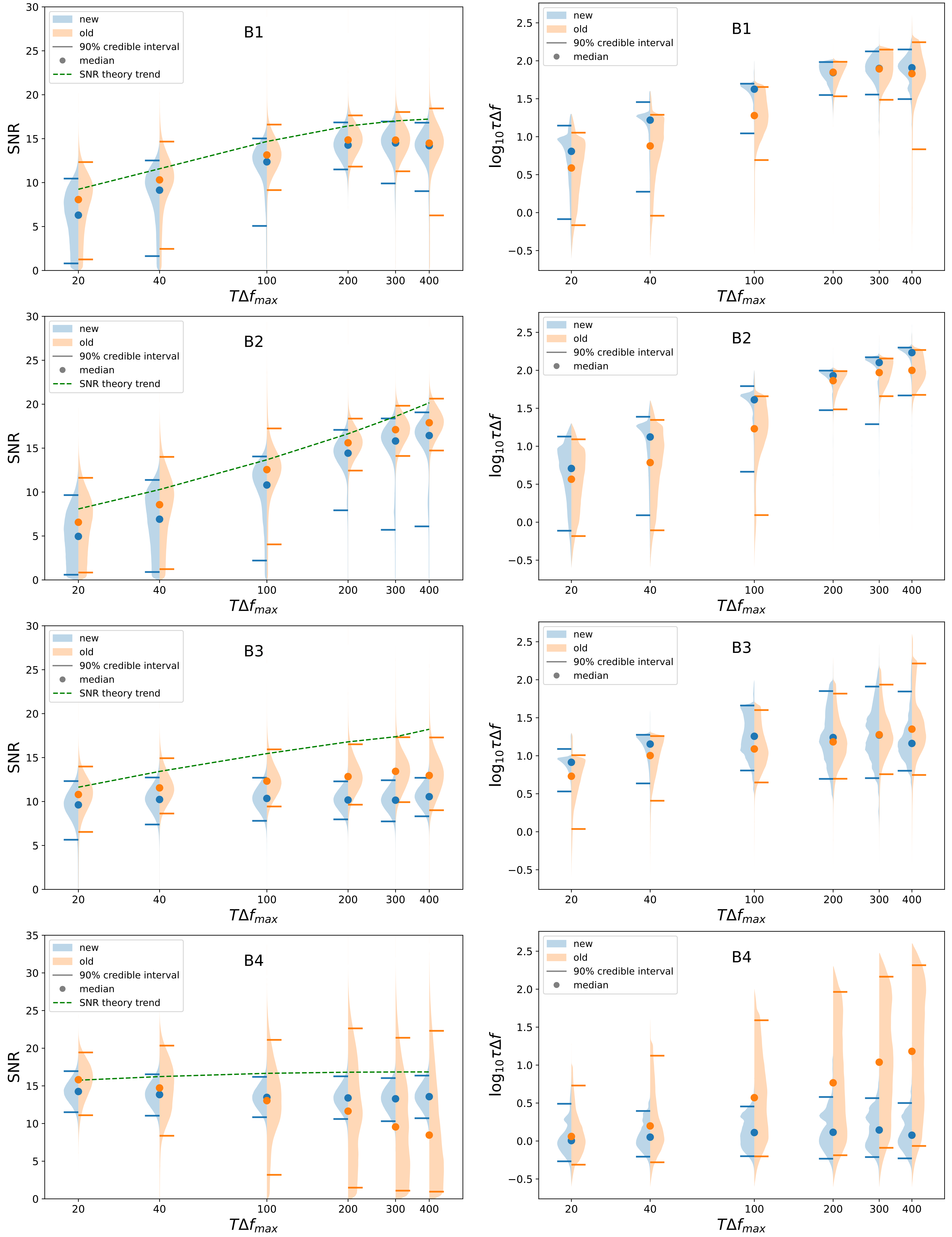
Validation: echo benchmarks + Gaussian noise

Wu, Gao, **JR**, Afshordi, PRD 108 (2023)



Additional search results



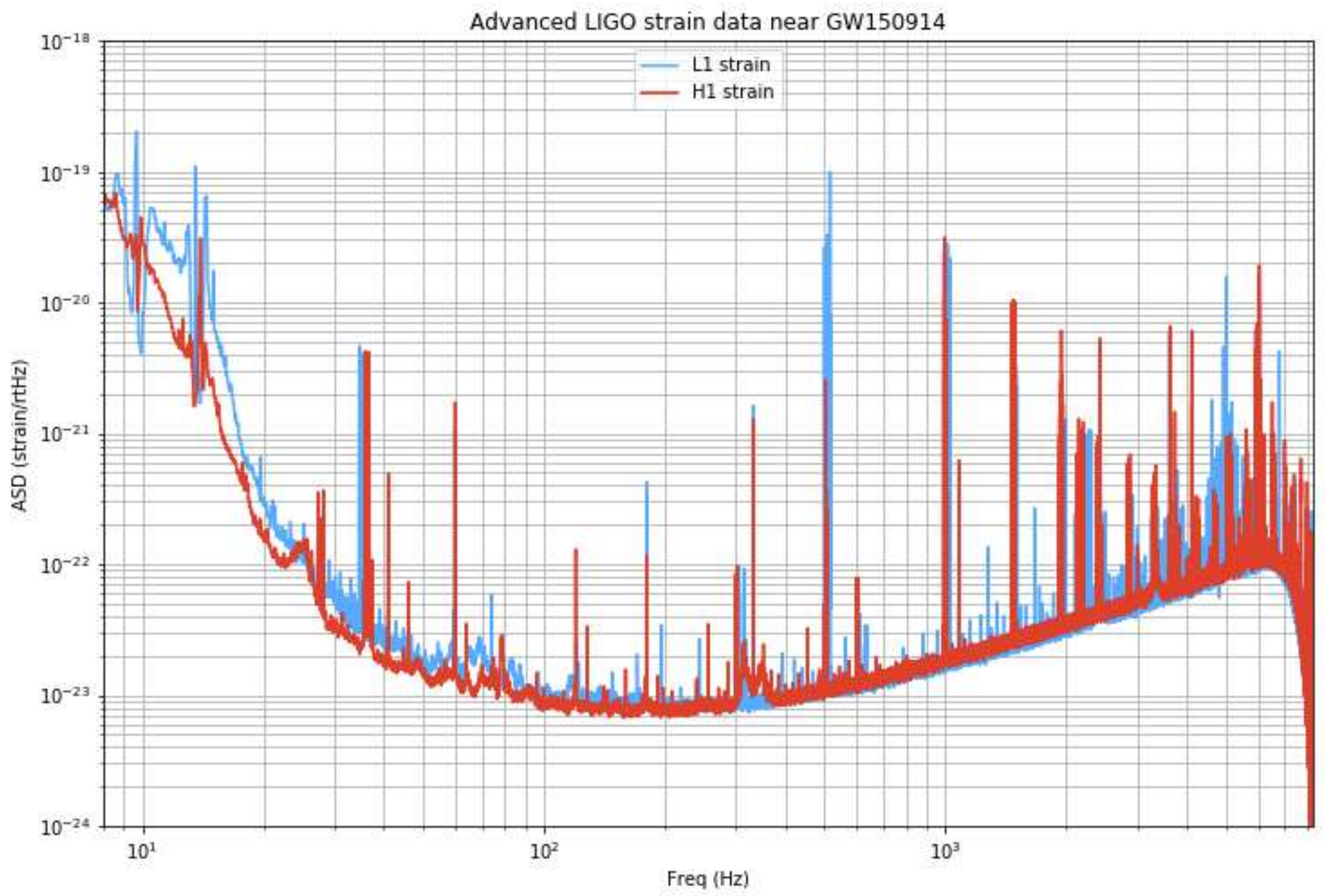


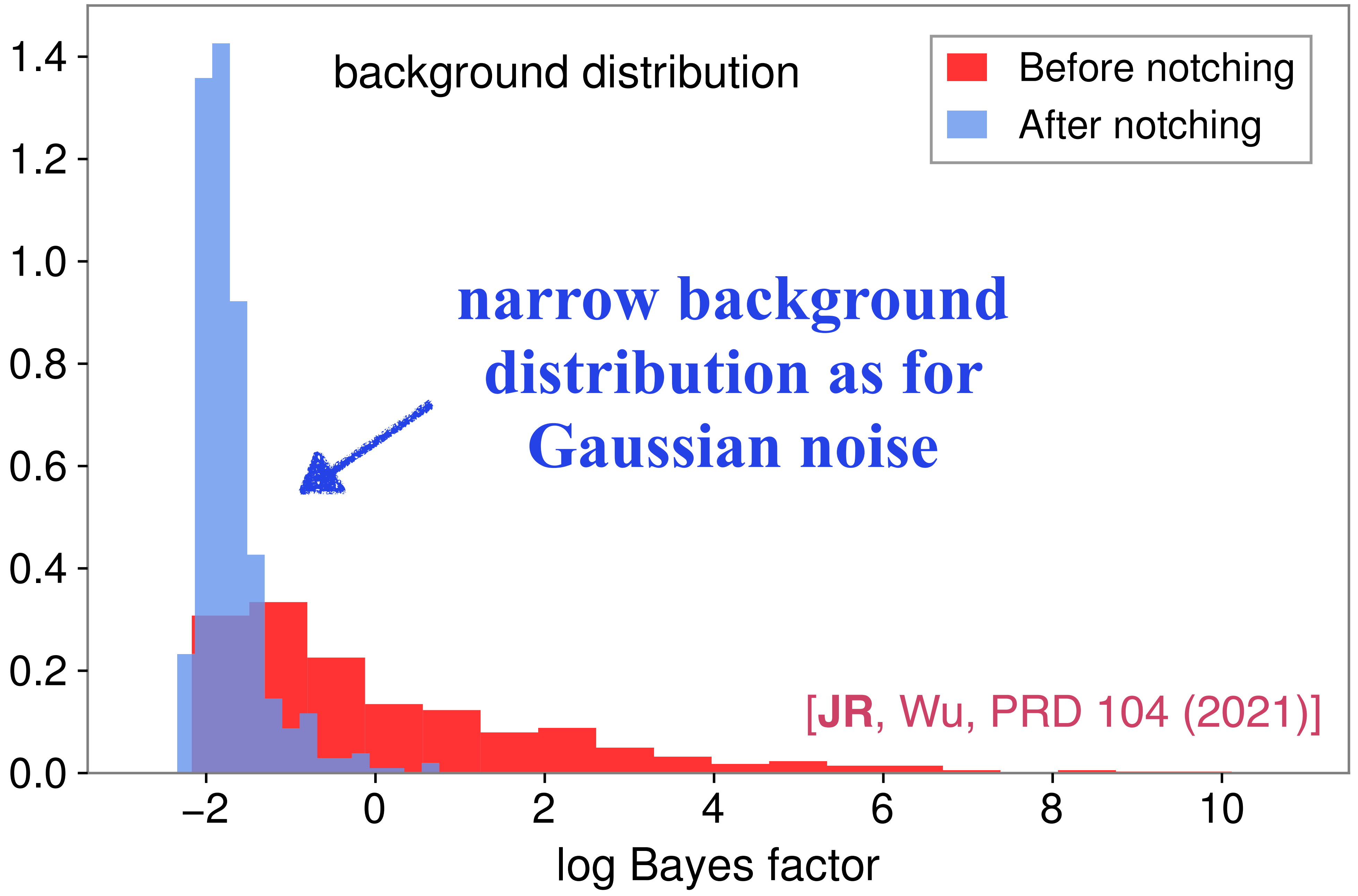
- B1,B2,B3: average spacing (~1/ t_d) determined up to O(0.01%), while others determined up to O(10%)
- Spacing-to-width radio offers a reliable estimate of the average reflection (1/| ln$R_{\rm eff}$|) for sufficiently large T
- B4 distinct: wide modes captured, strong evidence for the signal but parameter estimation poor

LIGO data search

- **Follow-up search for confirmed event:** background estimation with data preceding merger (time slides method); signal search with data right after merger

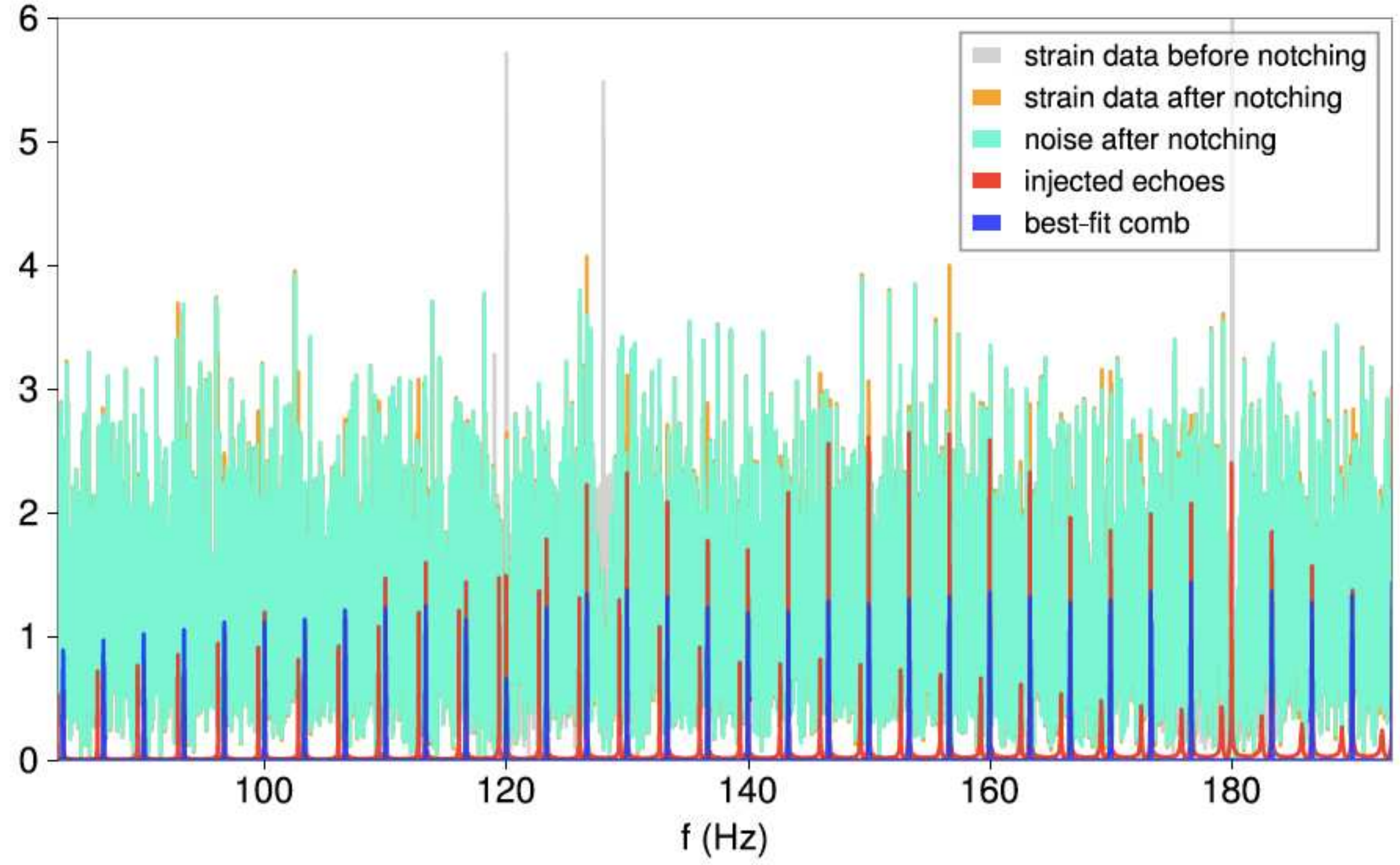
- **Non-Gaussian artifacts:** notch-out large spectral lines due to instrumental disturbances. O1 strain data polluted by a large number lines, while background distribution is well behaved after notching-out a few large lines

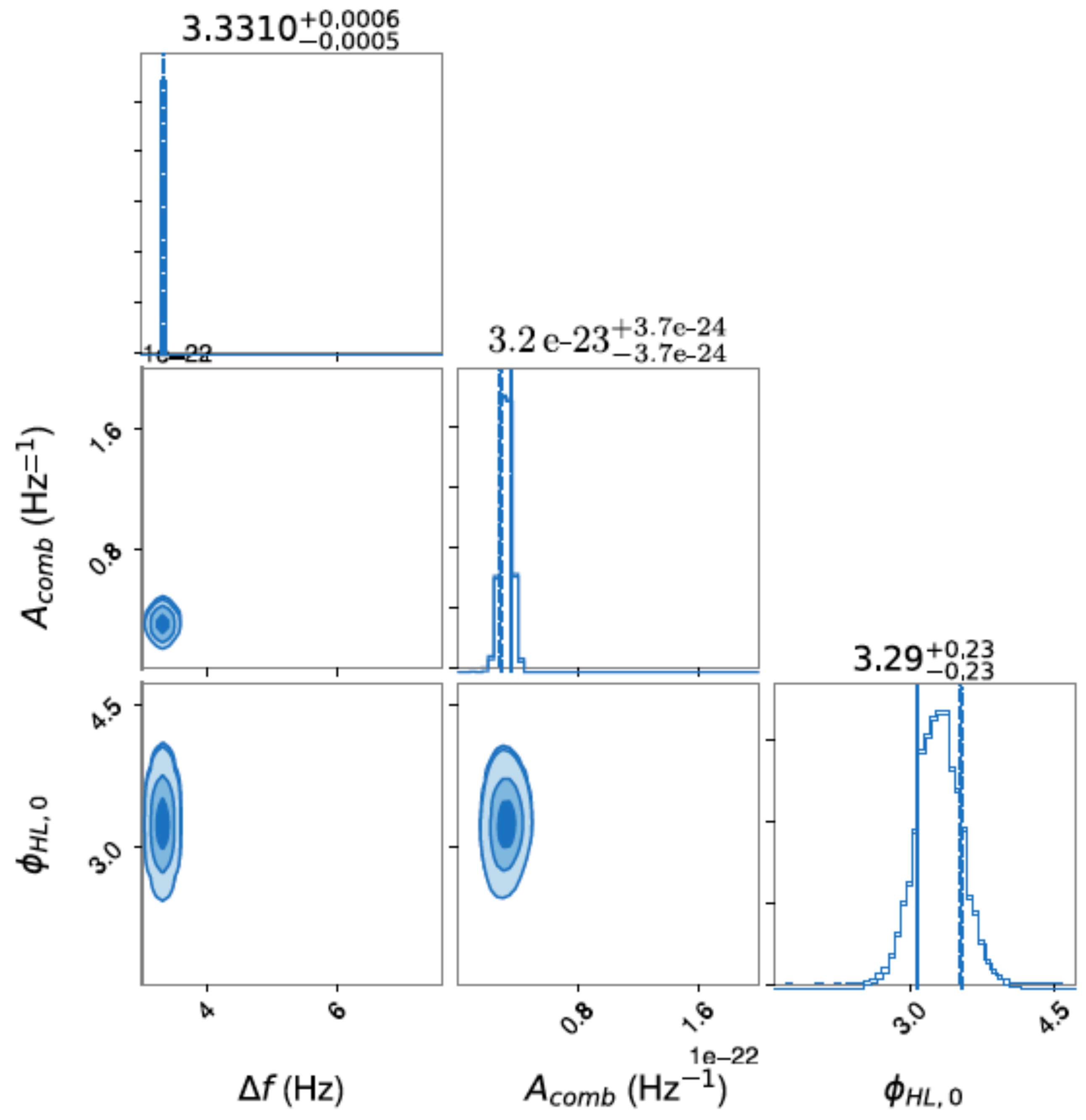




LIGO real data search

- **Echo signal injections in LIGO O1 data:** large instrumental lines properly mitigated, signal detection probability not much influenced even when some QNMs get removed





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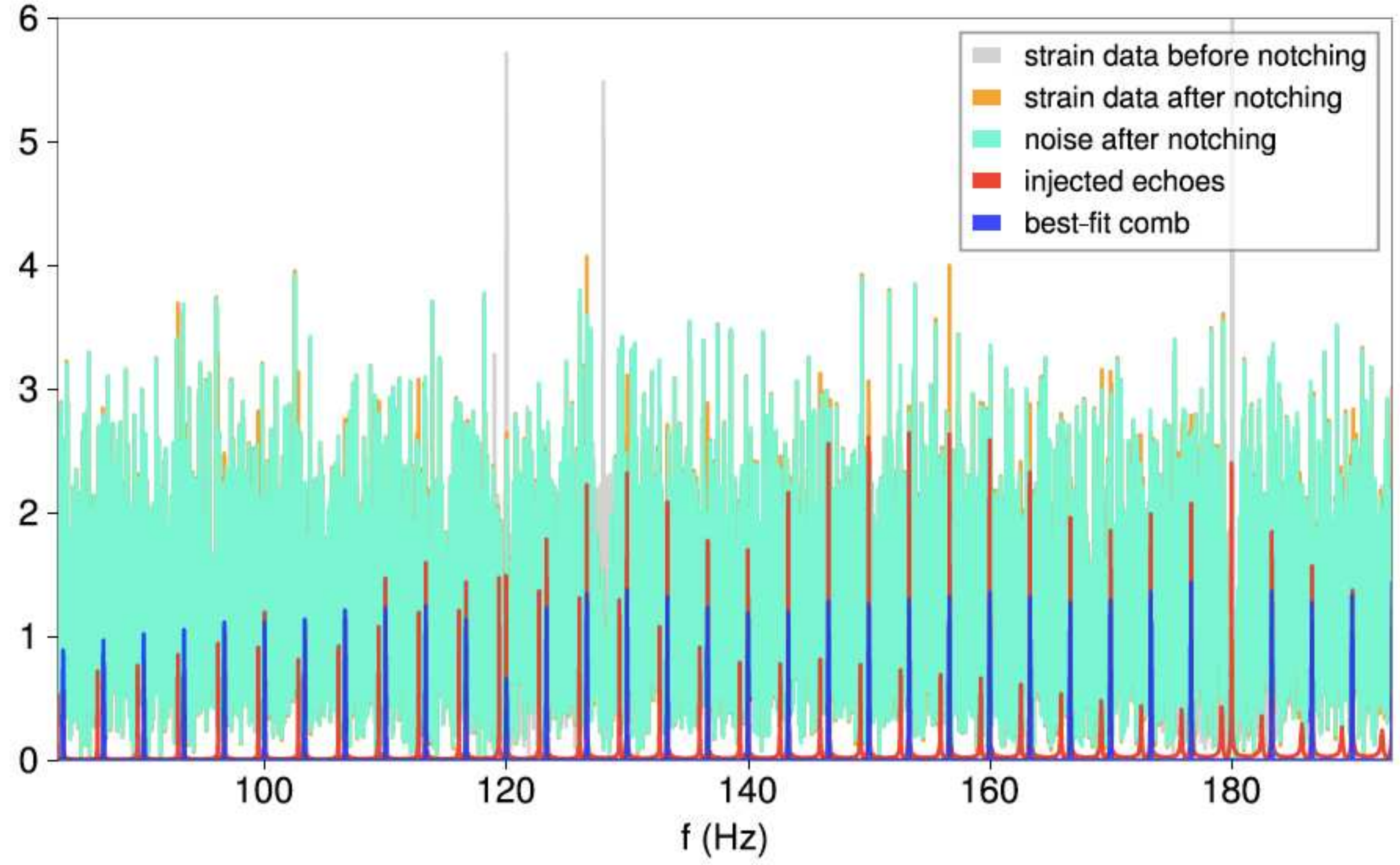
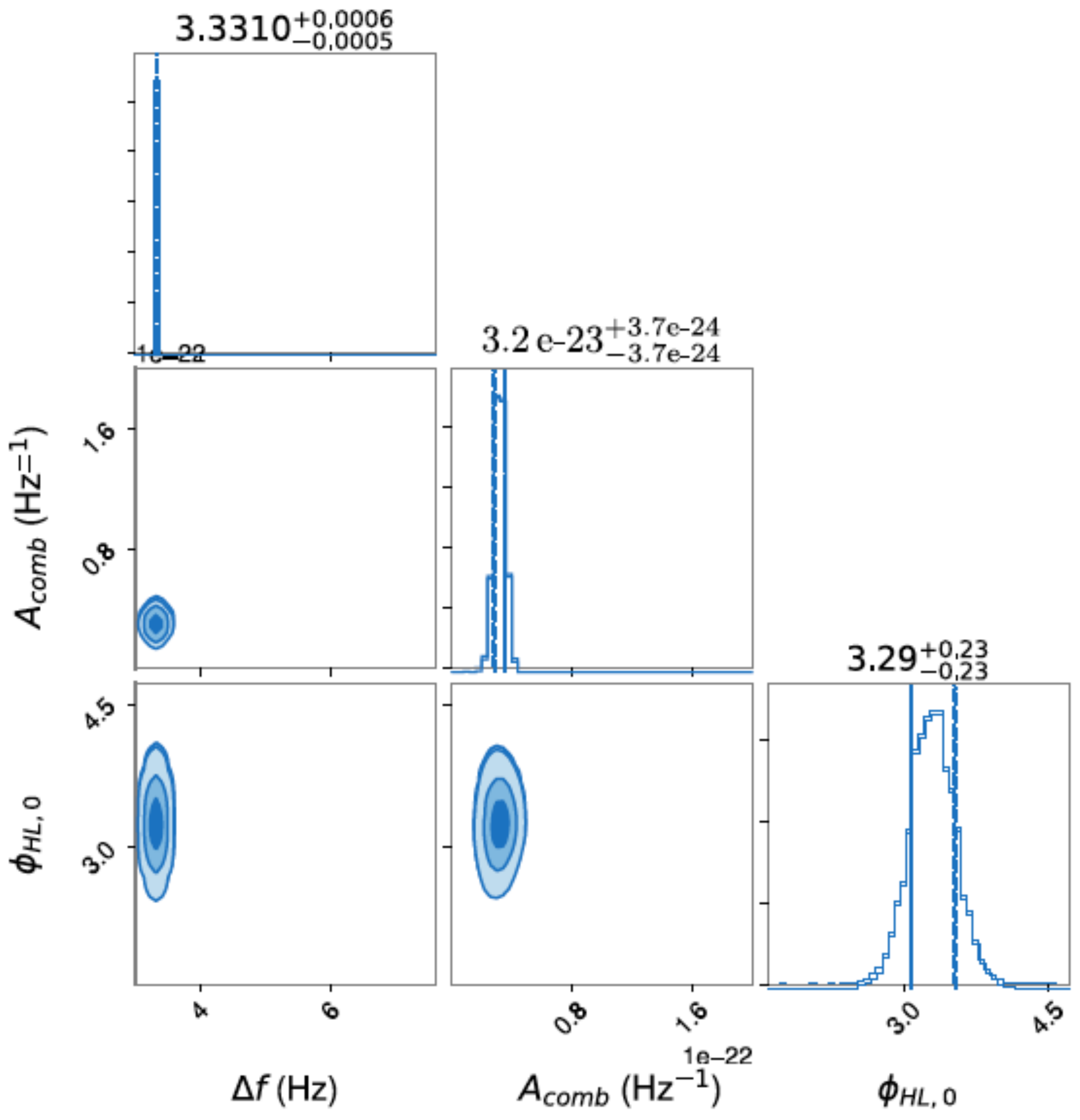




- NO clear evidence for GW150914 and GW151012 with the *old likelihood* [**JR**, Wu, PRD 104 (2021)]

(unfortunately, *tentative evidence* reported in [Holdom, PRD 101 (2020)] not found)

- Search on LVK O2 and O3 data with *both likelihoods* ongoing [**JR**, Wu, Zhang, in progress]

Summary

> "With the increase in GW and multi-messenger data anticipated in this decade… We are therefore on the threshold of transforming BH physics from a theoretical conundrum to a subject of observational science, with potentially far-reaching implications for the foundations of physics, including the quantum nature of gravity"
>
> Snowmass2021 Cosmic Frontier White Paper: Fundamental Physics and Beyond the Standard Model

- Planck-scale physics could naturally manifest just beyond the horizon scale r_H around macroscopic holes, playing a crucial role for not quite black holes. This may lead to intriguing thermodynamic behaviors and significant phenomenological implications.

- Gravitational wave echoes provide a promising way to probe tiny deviations just outside r_H. Developing model-independent search methods for these echoes is crucial. The primary observable, the time delay, can be accurately inferred by searching for quasi-periodic and long-lived QNMs. Stay tuned!

Thank You!

Ghost Problem in Quantum Quadratic Gravity

Classically the spectrum has a *massive, spin-2 ghost* (vacuum instability or unitarity problem), indicating theoretical inconsistency. **BUT, quantum effects may change the story**:

1) remove ghost in perturbative theory, i.e. Lee-Wick theory, PT symmetry… CERN workshop 2019: https://indico.cern.ch/event/740038

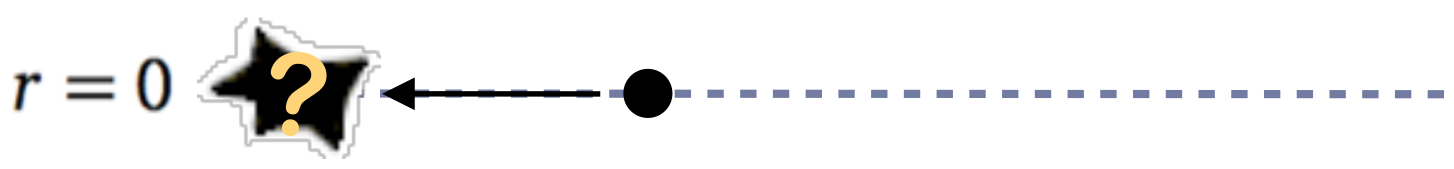
2) remove ghost by strong interaction associated with f_0, f_2 in analogy to QCD [Holdom, **JR**, PRD 93 (2016)]

	QCD	QQG $(\mathcal{M} \lesssim \Lambda_{\rm QQG})$
UV behavior	perturbatively renormalizable, asymptotically free	
Strong scale	gauge coupling strong at $\Lambda_{\rm QCD}$	gravitational couplings strong at $\Lambda_{\rm QQG}$
Nonperturbative effects	the perturbative gluon removed from the physical spectrum and a mass gap developed as controlled by $\Lambda_{\rm QCD}$	$\mathcal{M}=0$: the massless graviton pole emerges as the only light state in the physical spectrum (with would-be ghost removed)
IR effective description	color singlet states described by Chiral Lagrangian	massless graviton described by GR with the derivative expansion, $m_{\rm Pl} \sim \Lambda_{\rm QQG}$

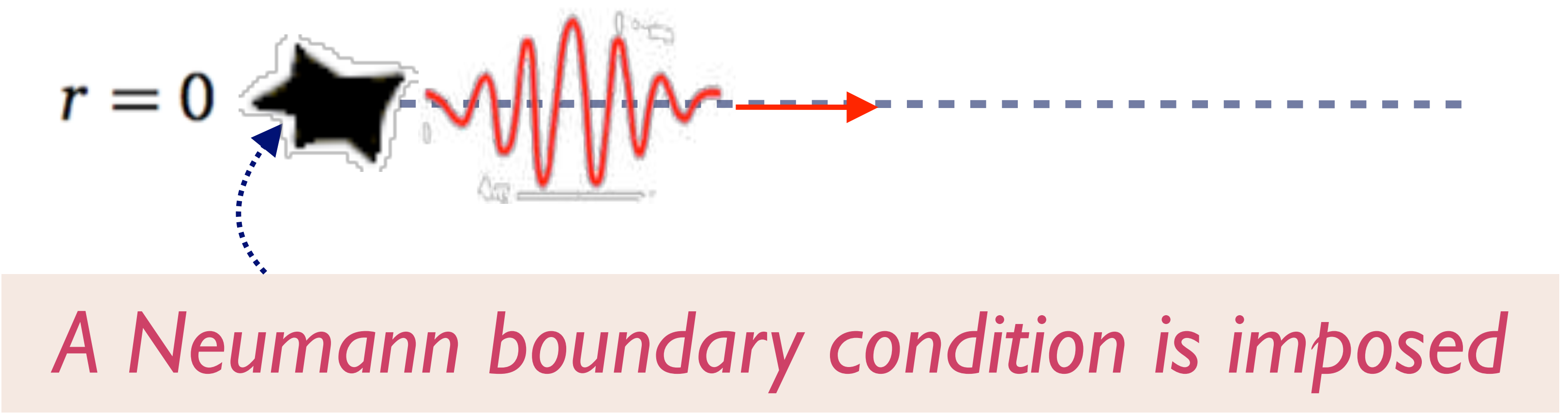
GR emerges as the low energy effective theory!

Timelike curvature singularity for 2-2-holes

Geodesic incompleteness?



May appear regular as probed by finite energy wave-packets?



- The initial value problem of the wave equation is well-posed if A has a **unique** positive self-adjoint extension Wald, JMP. 21, 2802 (1980); Ishibashi,Wald, CQG. 20, 3815 (2003);Horowitz, Marolf, PRD 52, 5670 (1995) Ishibashi, Hosoya, PRD 60, 104028 (1999)

KG equation: $$\partial_t^2\psi_l = \frac{B}{A}\partial_r^2\psi_l + \frac{B}{A}\left(\frac{2}{r} + \frac{B'}{2B} - \frac{A'}{2A}\right)\partial_r\psi_l - B\frac{l(l+1)}{r^2}\psi_l \equiv \mathbb{A}\psi_l$$

- Near the 2-2-singularity, all waves behave like the s-wave on a nonsingular spacetime. **Only one solution has finite energy.**

Spacetime	$A(r)$	$B(r)$	$\psi_{l1}(r,t)$	$\psi_{l2}(r,t)$
2-2-hole	r^2	r^2	1	r^{-1}
star	r^0	r^0	r^l	$r^{-(l+1)}$

Thermodynamics in curved background

- ✦ Thermodynamics of self-gravitating systems usually explored in GR, i.e. deriving equilibrium equation from maximum entropy principle, finding exact relation to *M*
- ✦ Beyond GR, for laws governing the global thermodynamic quantities, we may directly generalize the conventional thermodynamics. The curved spacetime effects are encoded in ***the thermodynamic volume V_{th}*** [Aydemir, **JR**, CQG 40 (2023)]

First law in literature	Conventional first law
$dM = T_\infty dS - p_\infty B(R)^{-3/2}\, dV_{geo}$ (*M* is the physical/ADM mass)	$dU = T_\infty dS - p_\infty dV_{th}$ (*U* is total gas internal energy)
$V_{geo} = \int_0^R \sqrt{A}\, d^3r$	$V_{th} = \int_0^R \sqrt{\frac{A(r)}{B^3(r)}}\, d^3r$

- **Self-gravitating photon gas in GR**: U/M>0.64, ε>1, dV_{geo} non-negligible
- **Thermal 2-2-hole**: U/M=3/8, ε~0, dV_{th} responsible for dM-dU, d$M \approx T_\infty$ dS (similar to BH)

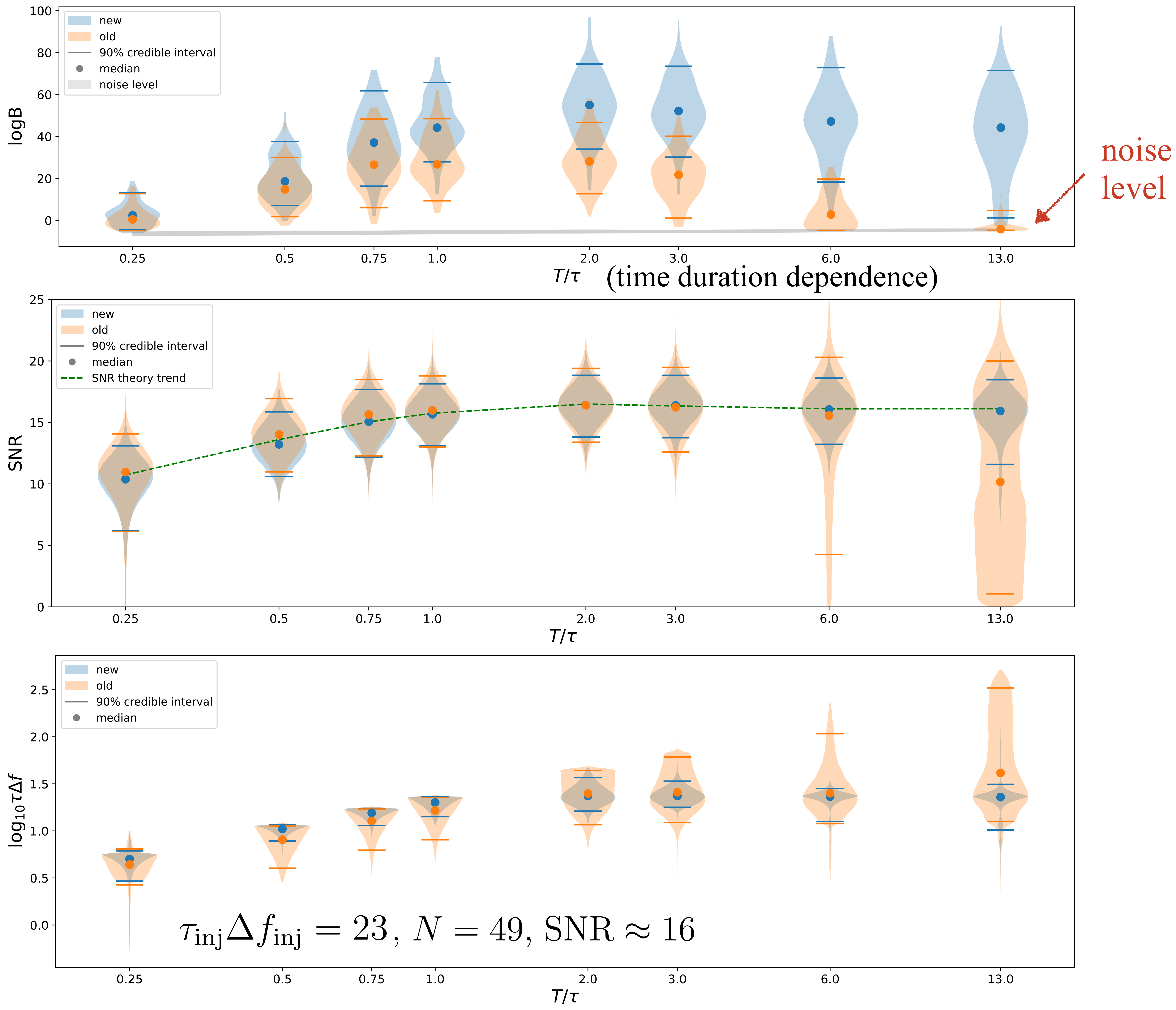
Comparison of two likelihoods

UniEw injections into Gaussian noise
(four parameters Bayesian search)

- two likelihoods are comparable in low resolution limit (T$\lesssim\tau$)
- new likelihood avoids time duration dependence in high resolution limit (T$\gtrsim\tau$)
- new likelihood is insensitive to the QNM shape, e.g. width/height, as T increases
- overall posterior of recovered SNR trace the injected value well

  $p(\theta|d) = \sum_{k=1}^{\mathcal{N}} p(\theta|d_k)p(d_k)$ with $p(d_k) = 1/\mathcal{N}$
- overall posterior of spacing-to-width ratio provides info of combined reflectivity, i.e.

  $\tau_n \Delta f \approx 1/|\ln \mathcal{R}_{\rm eff}(f_n)|$



Validation with echo waveform benchmarks

- Use **UniEw** to capture the dominant contribution in real QNMs spectrum
- For a given benchmark, we inject the waveform in 100 Gaussian noise realizations, analyze the resulting data with a series of time duration $\{T_i\}$
- For each data sample, we conduct a six-parameter Bayesian search with the two likelihoods
- Using two likelihoods help capture different subsets of QNM, increase the detection probability for echoes

Summary of parameter settings

Parameters	Priors and scan values
$M\Delta f$	uniform in $[\bar{R}/\eta_{\rm max}, \bar{R}/\eta_{\rm min}]$
q_0	uniform in $[0, 1]$
A	uniform in $[10^{-2}, 10]\langle\tilde{P}\rangle^{1/2}$
$1/\tau$	log-uniform in $[1/T, \Delta f_{\rm max}]$
$f_{\rm min}, f_{\rm max}$	uniform in $[f_{\rm cut}, f_{\rm RD}]$ with $f_{\rm max} - f_{\rm min} > 10\Delta f$
$T\Delta f_{\rm max}$	$\{20, 40, 100, 200, 300, 400\}$
$n_{\rm liv}$	$\{1000, 1000, 1000, 2000, 2000, 2000\}$

$\eta_{\rm max} = 4$, and $\eta_{\rm min} = 1$

$f_{\rm cut} = 0$ for Gaussian noise

$M f_{\rm RD} = 0.243 - 0.184(1-\chi)^{0.129}$

GWE search parameter setting

- **UniEw parameters:** spacing $\Delta f = 1/t_d$, shift f_0, amplitude A_{comb}, frequency band (f_{min}, f_{max})

$$\frac{t_d}{M} \approx 2\eta\left(\ln\frac{M}{\ell_{Pl}}\right)[1+(1-\chi^2)^{-1/2}], \qquad \frac{\Delta f}{\mathrm{Hz}} \approx \frac{\bar{R}}{\eta}, \qquad \bar{R} \approx 583\frac{M_\odot}{M}\frac{2}{1+(1-\chi^2)^{-\frac{1}{2}}},$$

- **Response parameters:** relative amplitude A_{HL}, relative phase $\phi_{HL,j} = \phi_{HL,0} - 2\pi f_j \Delta t_{HL}$

Parameters	GW150914	GW151012	
Δf	Uniform in [3.0, 7.6] Hz	Uniform in [3.5, 14.3] Hz	(Planck length — proper Planck length)
f_0	Uniform in [0, 1]	Uniform in [0, 1]	
A_{comb}	Uniform in $[10^{-25}, 2\times10^{-22}]$ Hz^{-1}	Uniform in $[10^{-25}, 2\times10^{-22}]$ Hz^{-1}	
f_{min}	Uniform in [50, 154] Hz	Uniform in [50, 230] Hz	
f_{max}	Uniform in [189, 275] Hz	Uniform in [289, 433] Hz	(around BH ringdown frequency)
$\phi_{HL,0}$	Uniform in $[\pi/2, 3\pi/2]$	Uniform in $[\pi/2, 3\pi/2]$	
f_w	Fixed at $11/T$	Fixed at $11/T$	
A_{HL}	Fixed at 1	Fixed at 1	(relative amplitude)
Δt_{HL}	Fixed at 6.9×10^{-3} s	Fixed at -0.6×10^{-3} s	(time lag from main event search)
T	Scan over [13.2, 30.9, 48.6, 66.3] s	Scan over [7.0, 23.8, 40.6, 57.4] s	(T/t_d around 100-200)
Constraints	$f_{max} - f_{min} > 10\Delta f$	$f_{max} - f_{min} > 15\Delta f$	(include a sufficiently large # of resonances)
Line origin	Power mains, OMC length dither	Power mains, OMC length dither, calibration lines, violin modes	
Threshold	[5, 5, 6, 6] for increasing T	[5, 5, 5.5, 5.5] for increasing T	