Institute of High Energy Physics
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Gravitational wave echoes search with combs

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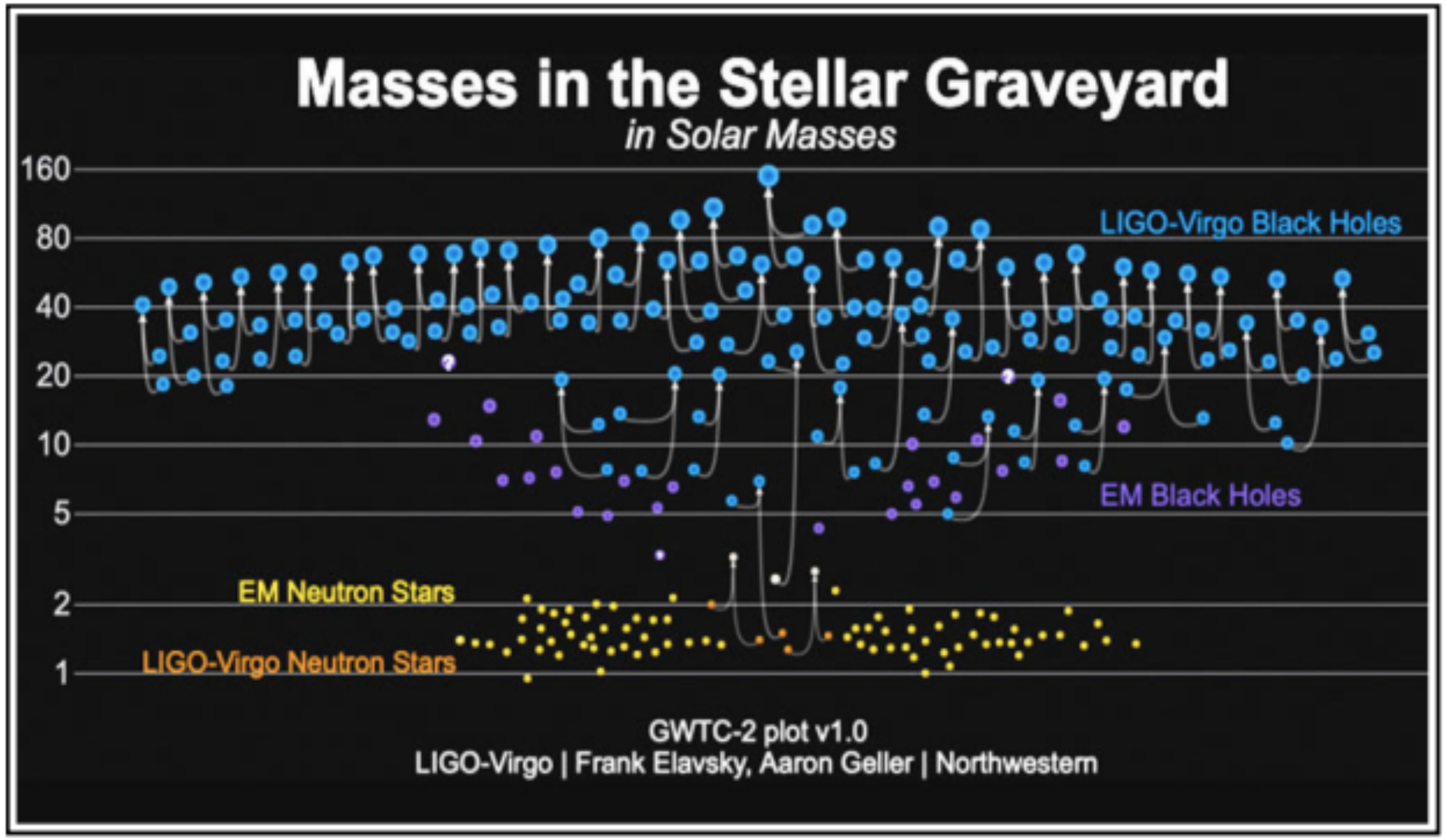
第十五届TeV物理工作组学术研讨会

July 20, 2021

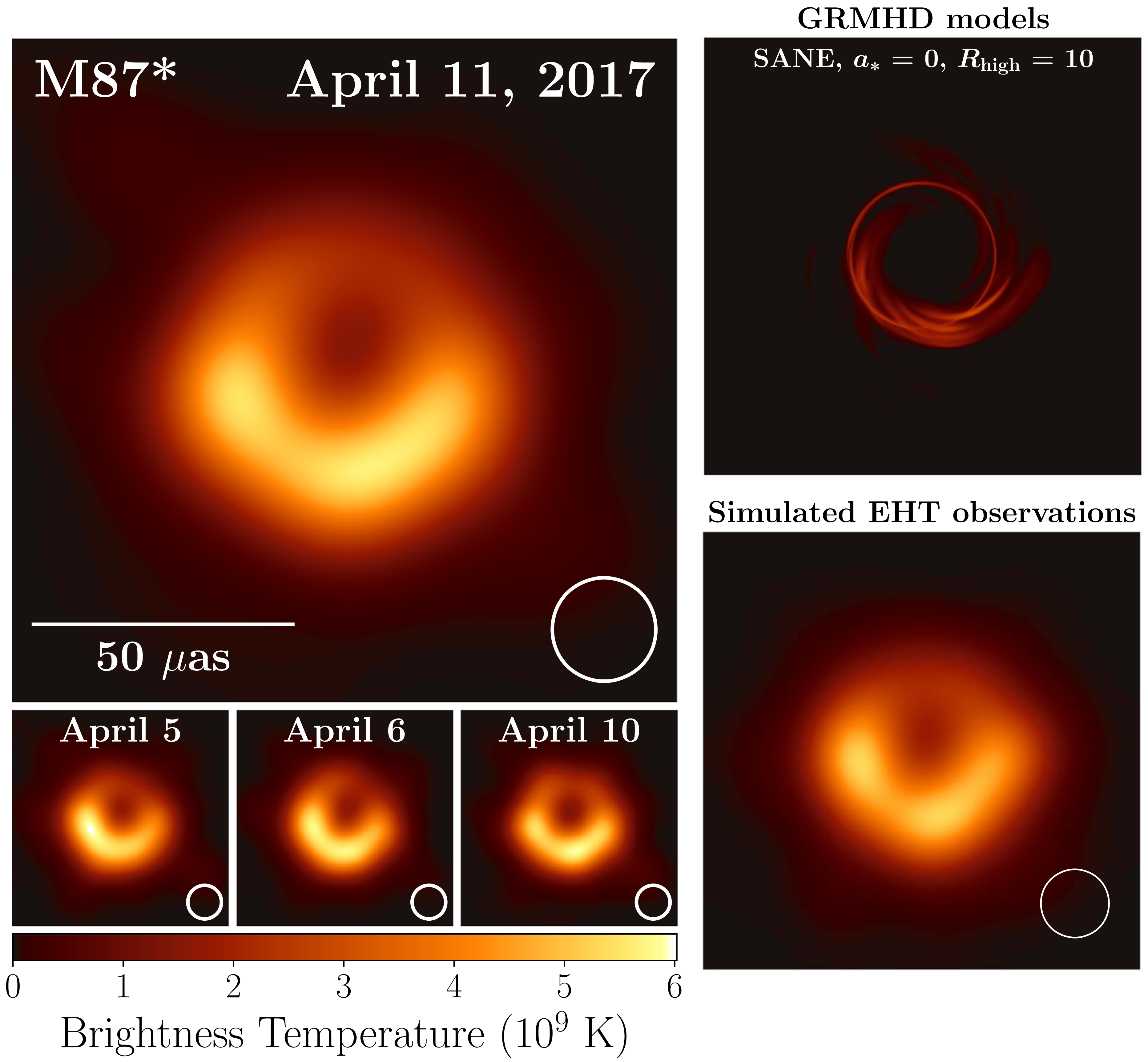
JR, Di Wu, arXiv: 2107.*****

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**"

— David Haviland, chair of the 2020 Nobel Committee for Physics

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A: Maybe they are horizonless ultracompact objects?

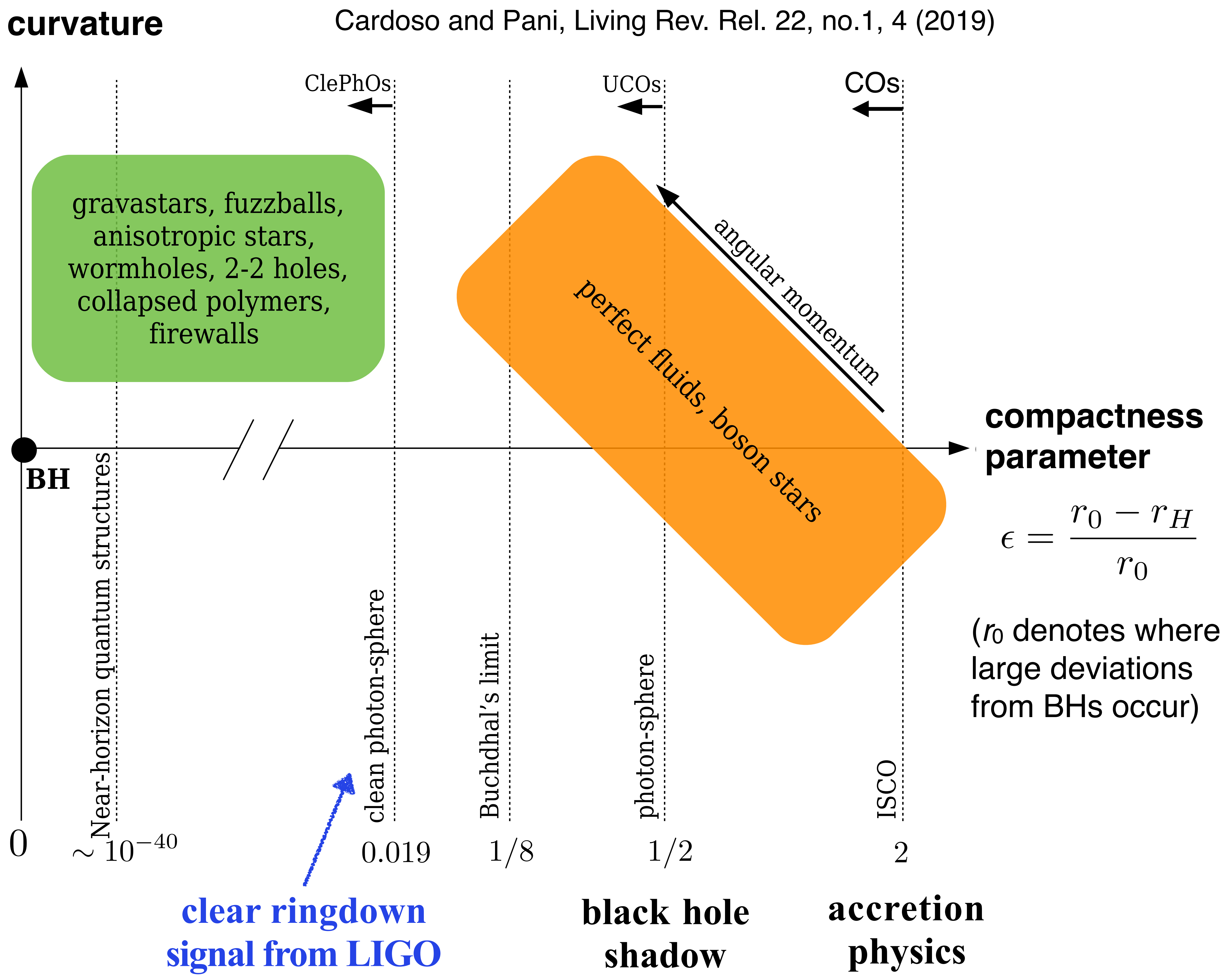
- Theoretically motivated by resolution of information loss paradox
- Observationally near-horizon corrections not much constrained

Classification of Compact Objects (COs)

- **UCOs**: not difficult to achieve in GR

- **ClePhOs**: r_0 well within photon-sphere; require either exotic forms of matter or modified gravity

- **UCOs as generic black hole mimickers**? Have to exist for a wide range of masses



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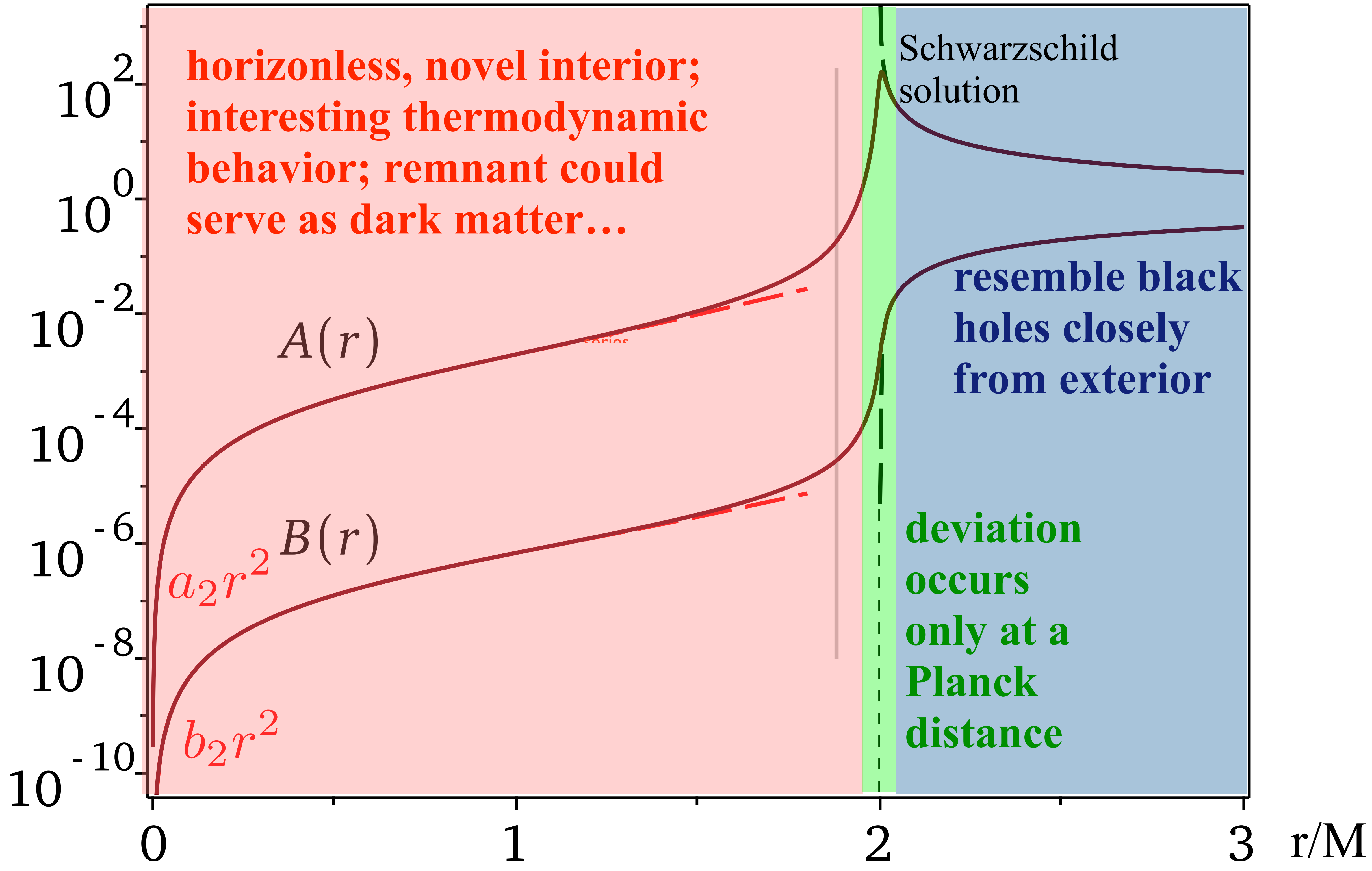
2-2-holes in quadratic gravity

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



Holdom, **JR**, PRD 95, no.8, 084034 (2017); **JR**, PRD 100, no.12, 124012 (2019)

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- **Tell ClePhOs apart from black holes?** Horizonless ClePhOs may allow waves to be reflected out; gravitational wave echoes may provide a smoking gun signal for near-horizon corrections

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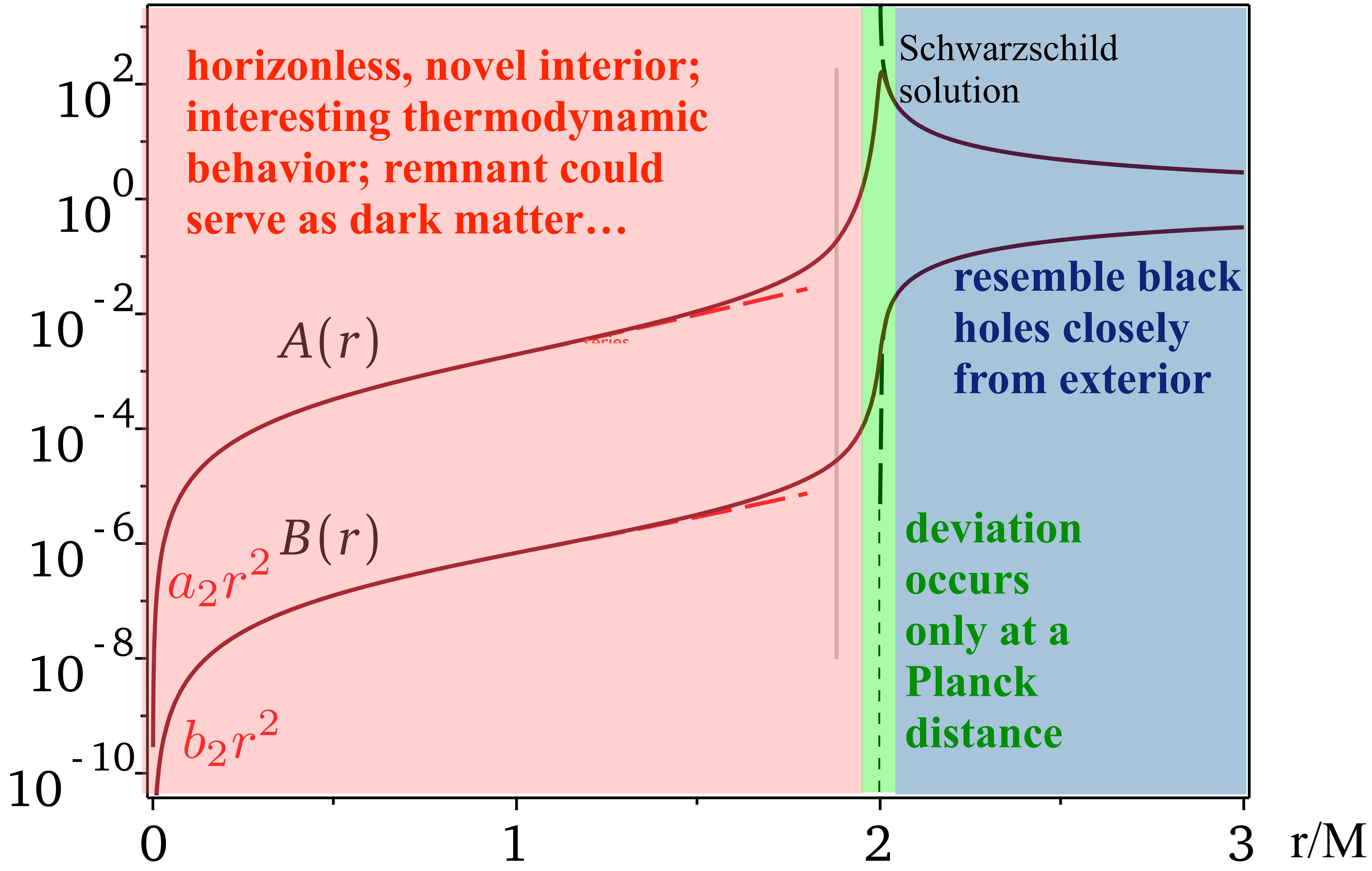

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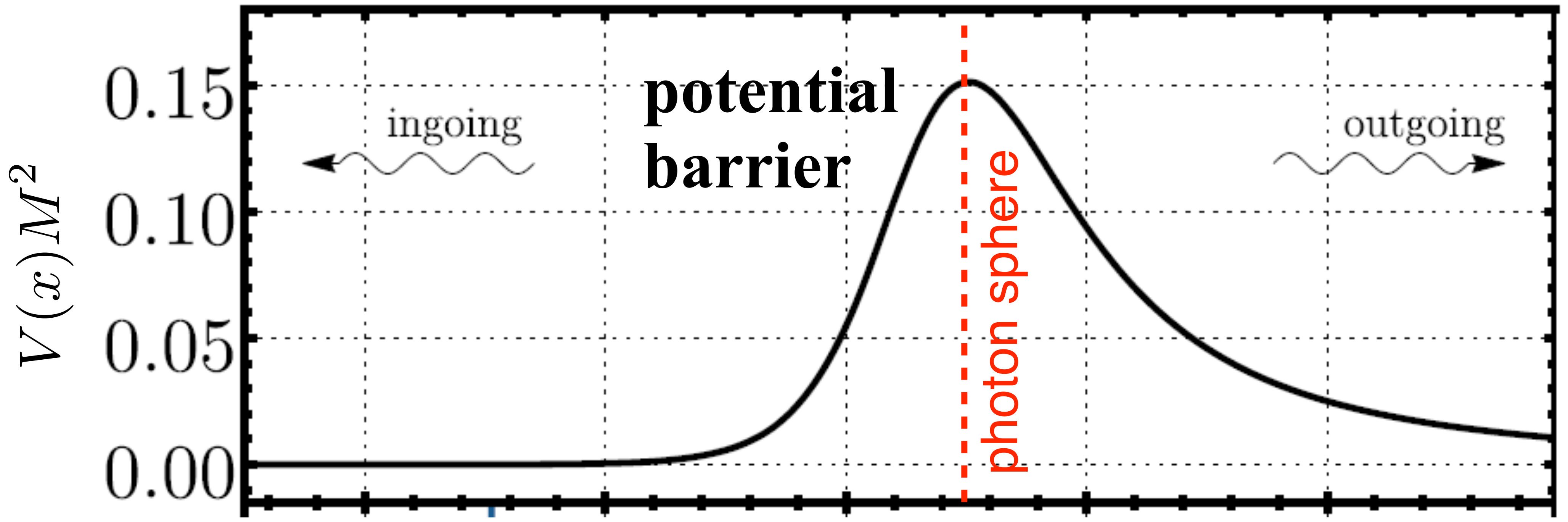
Gravitational wave echoes

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



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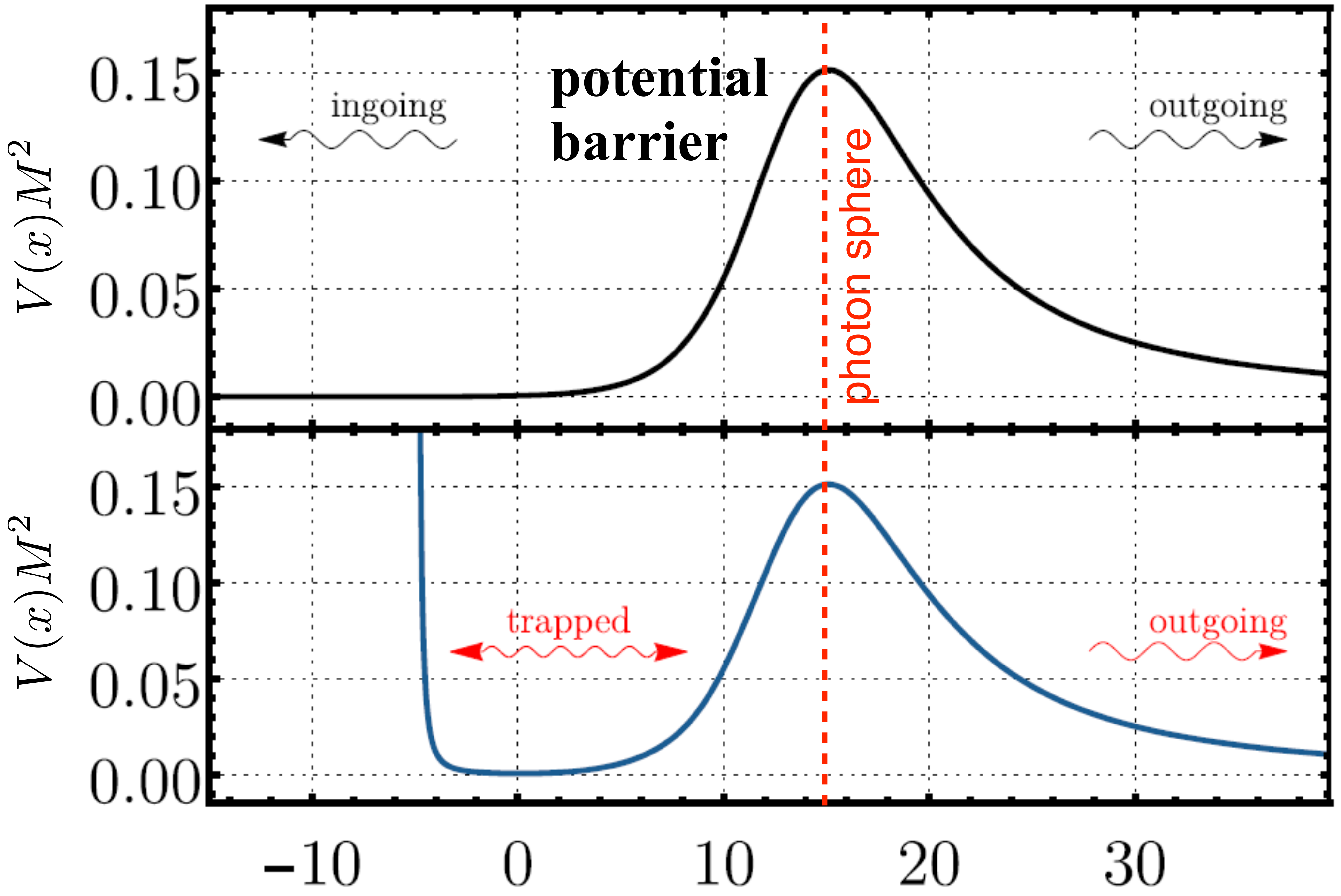
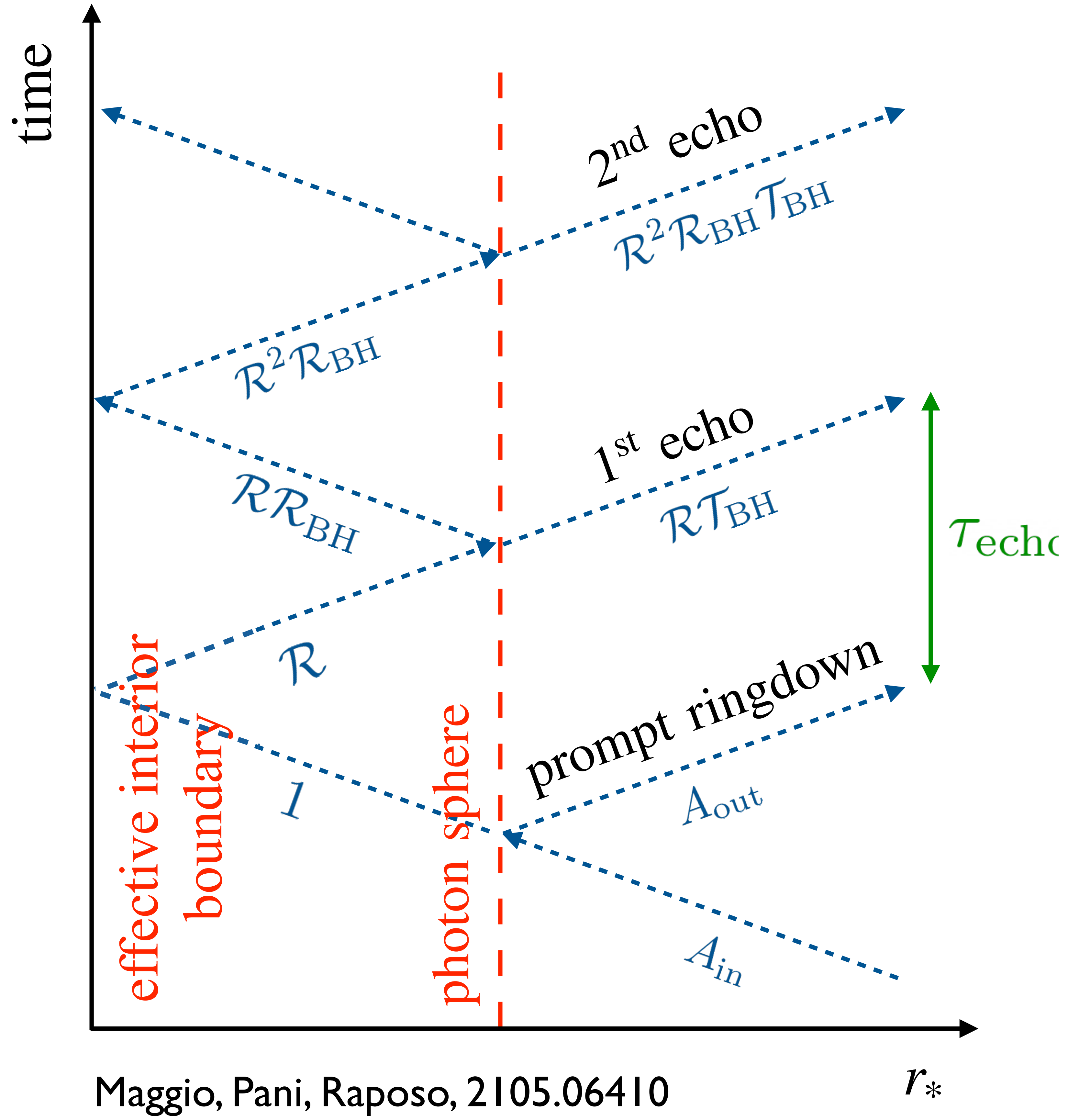




Maggio, Pani, Raposo, 2105.06410

Horizonless UCOs behave as leaky cavities, and echoes are caused by repeated and damped reflections between two boundaries

Quasi-periodic signal in time domain

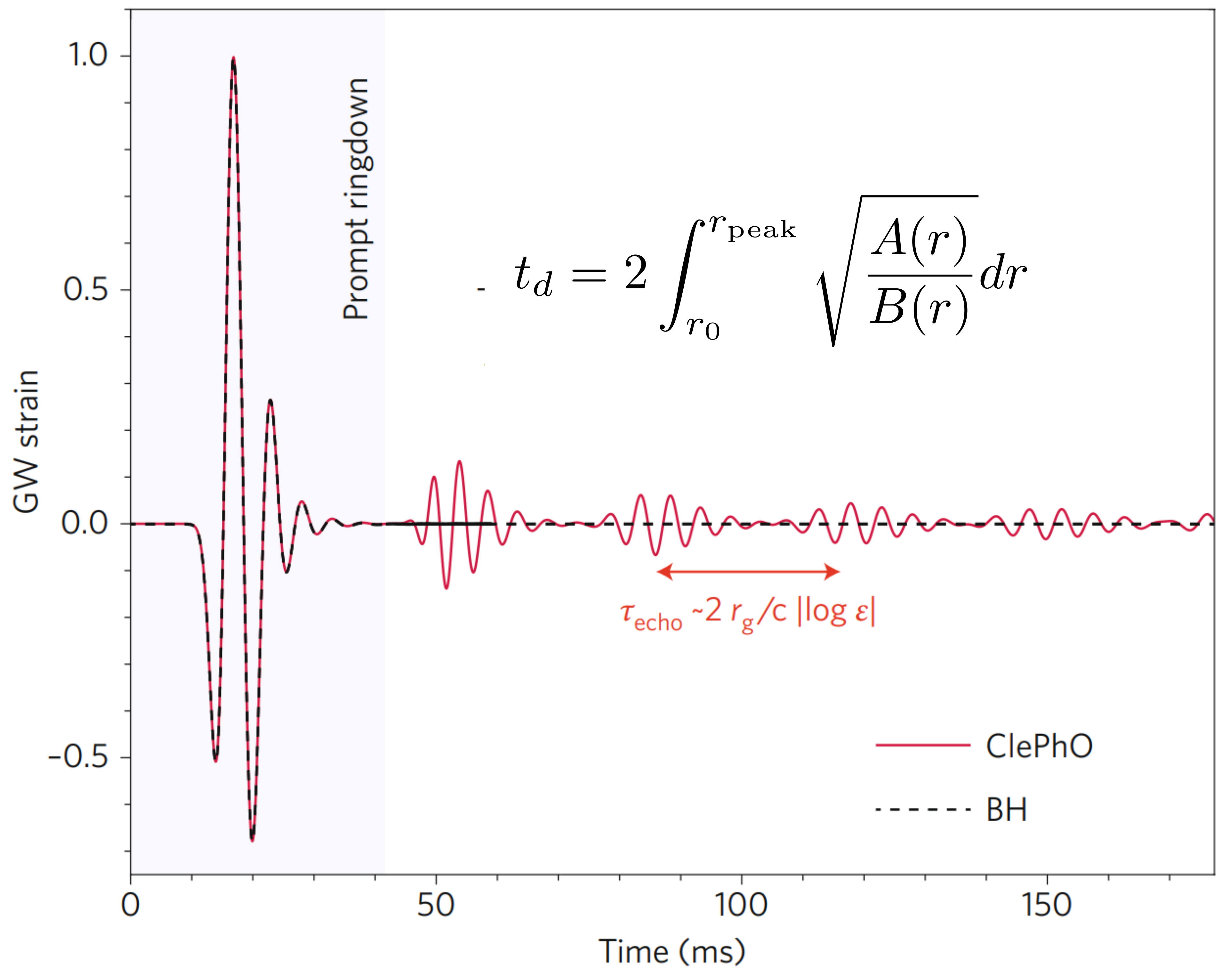
- Characterized by a nearly constant **time delay t_d** between two consecutive pulses

- Time delay **logarithmically sensitive to the tiny scale** at which deviation from black hole occurs

$$t_d \propto -r_H \ln \epsilon, \quad \epsilon \approx (r_0 - r_H)/r_H$$

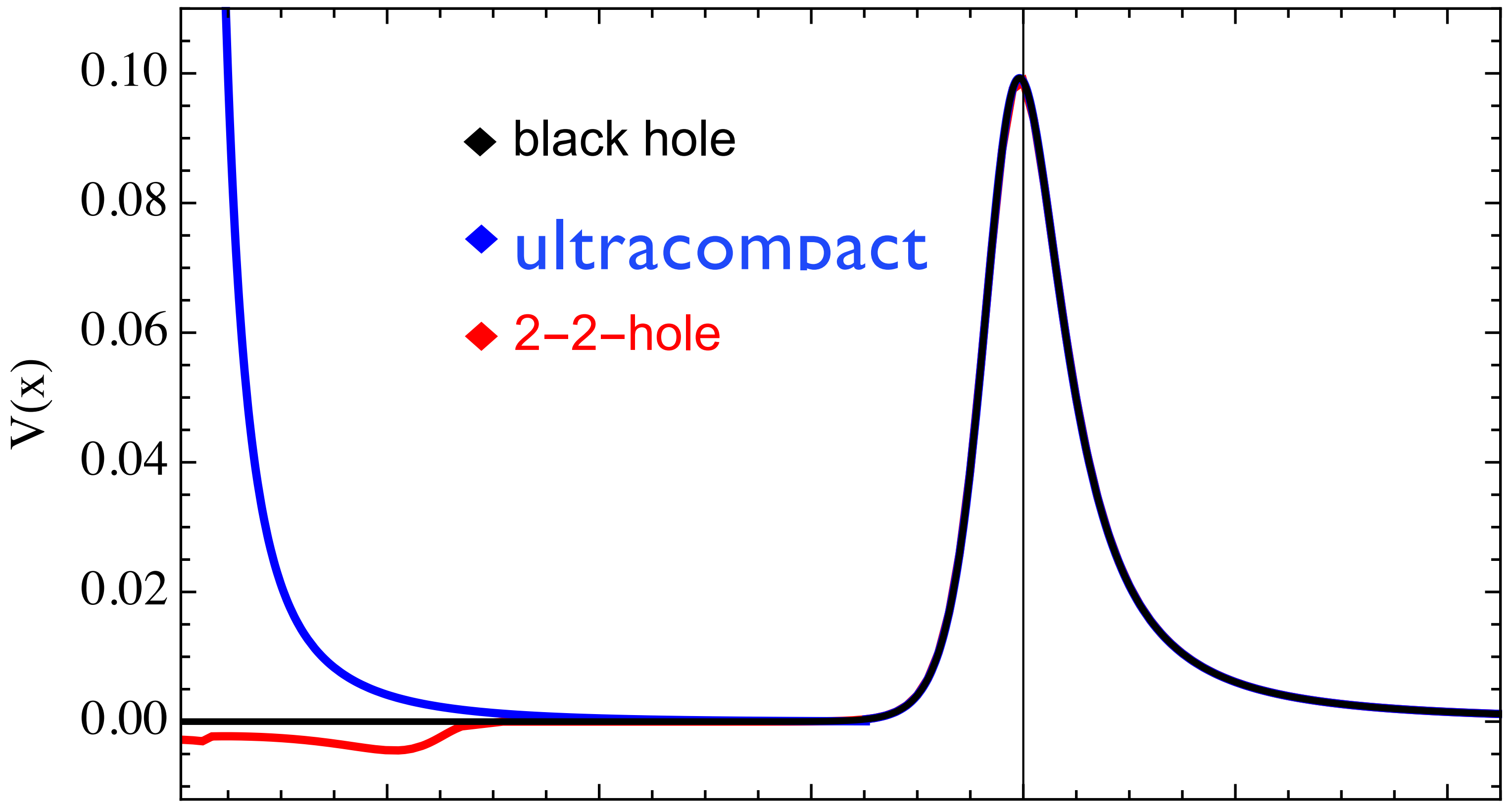
Accessible with current observations even for a Planck scale deviation, i.e. t_d~0.1s for M~$30M_\odot$

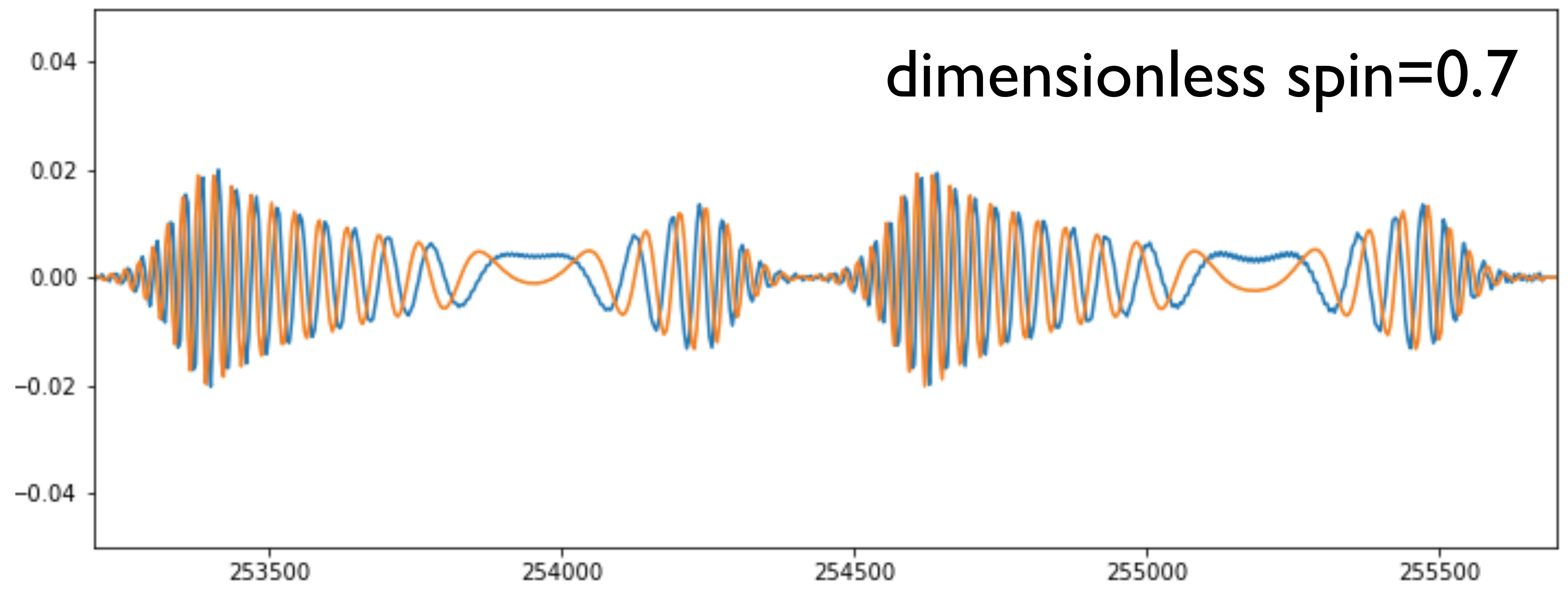
- **GW echoes serve as a perfect target to look for high scale new physics (quantum gravity!)**



HOWEVER, the echo waveform has large theoretical uncertainties, and the phase suffers in particular more

- Near-horizon corrections vary strongly with UCOs
- Source term/initial condition dependence quite uncertain
- Final object spin adds complicated structure on the waveform



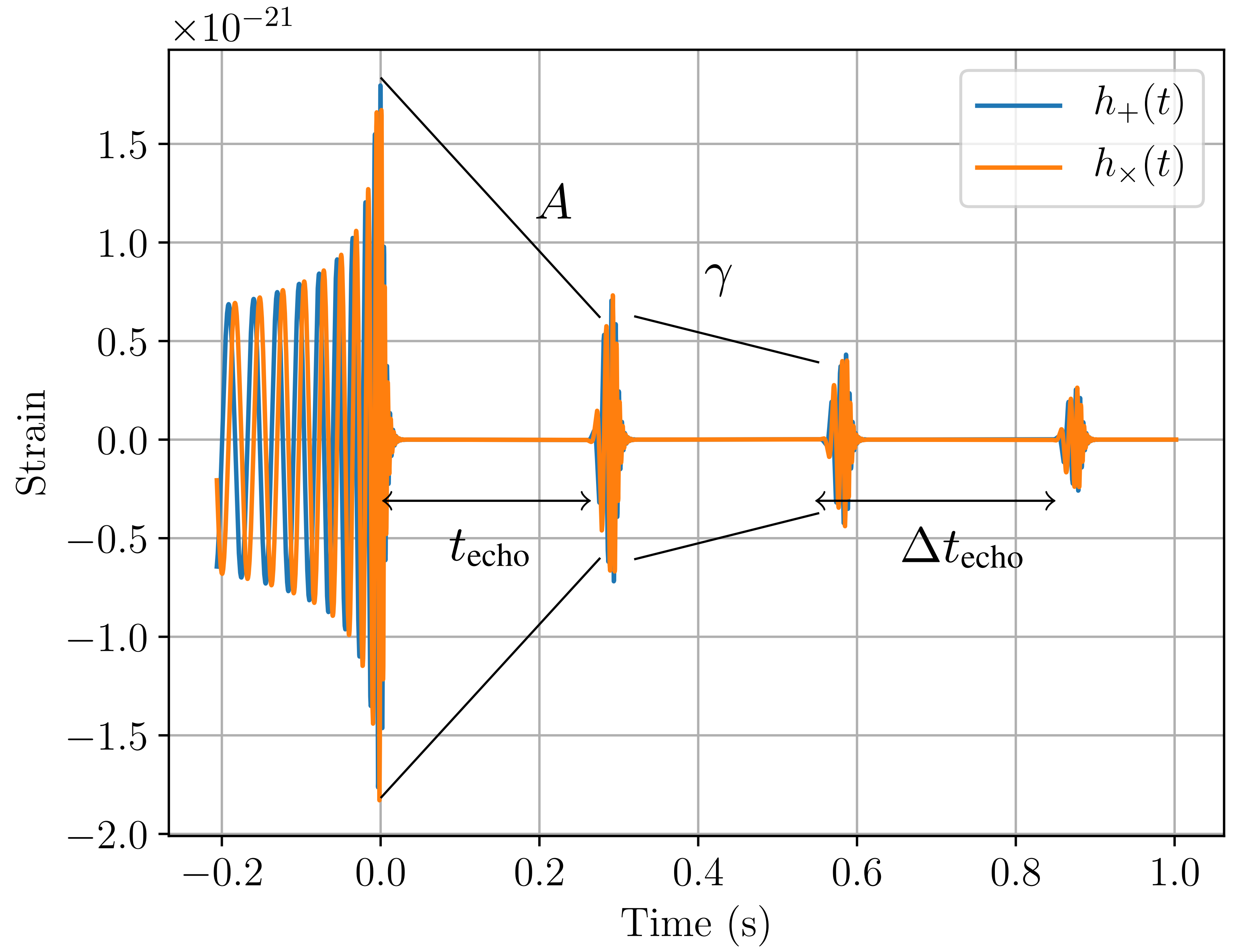


Current GW echoes search: strategies

Template-based search methods

Simple model + a small number of parameters

e.g. repeated ringdown with constant time delay and damping

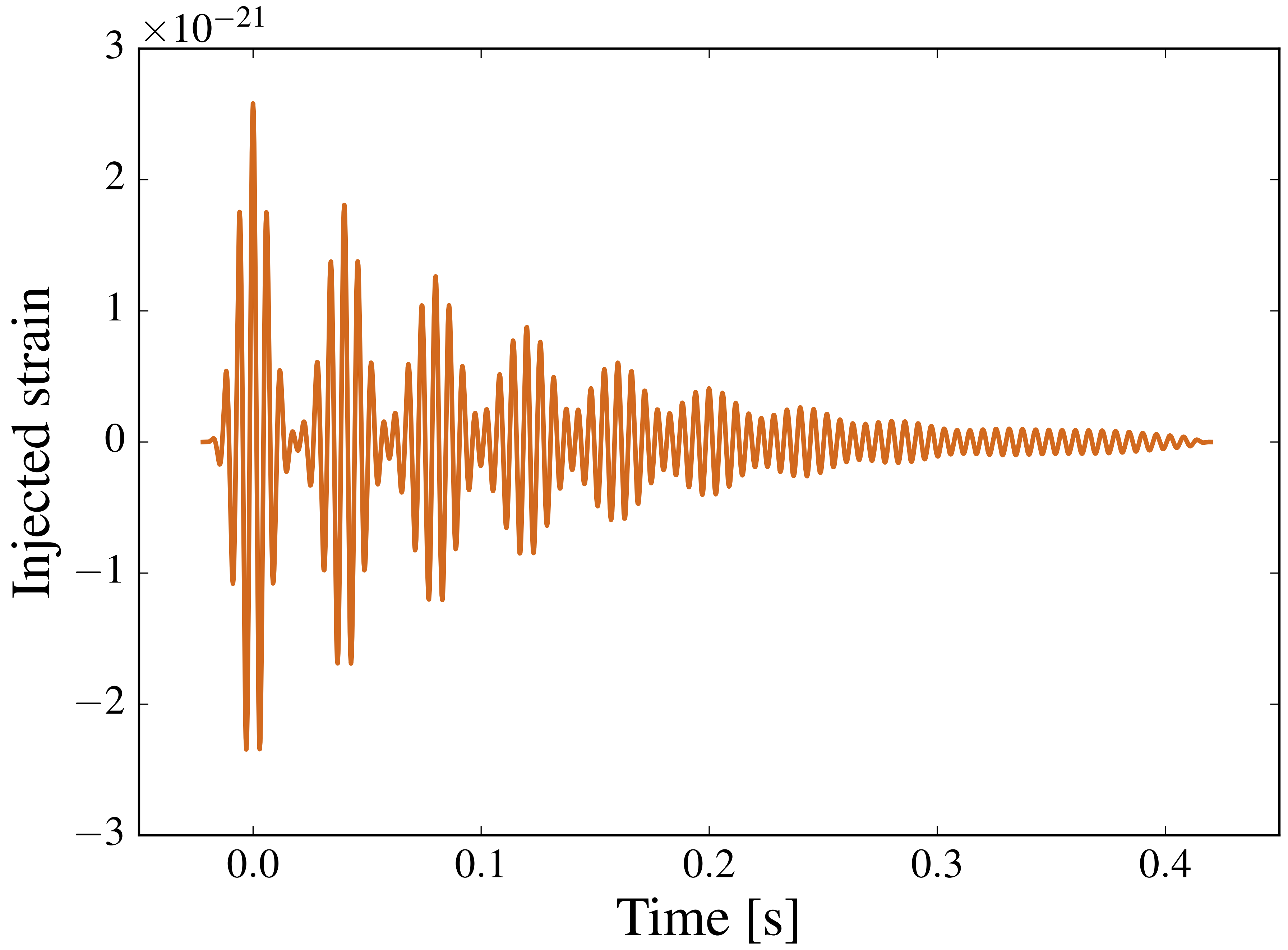


Abedi,et al., Phys. Rev. D 96, 082004 (2017); Lo et al., Phys. Rev. D 99, no.8, 084052 (2019)

Morphology-independent search

Generic model + a large number of parameters

e.g. trains of independent sin-Gaussians/wavelets



Tsang, Phys. Rev. D 98, no.2, 024023 (2018)

Current GW echoes search: results

Template-based search methods

IMR(E): inspiral–merger–ringdown(–echoes)

Event	$\log_{10} \mathcal{B}^{\mathrm{IMRE}}_{\mathrm{IMR}}$	Event	$\log_{10} \mathcal{B}^{\mathrm{IMRE}}_{\mathrm{IMR}}$
GW150914	−0.57	GW170809	−0.22
GW151226	−0.08	GW170814	−0.49
GW170104	−0.53	GW170818	−0.62
GW170608	−0.44	GW170823	−0.34
GW190408_181802	−0.93	GW190706_222641	−0.10
GW190412	−1.30	GW190707_093326	0.08
GW190421_213856	−0.11	GW190708_232457	−0.87
GW190503_185404	−0.36	GW190720_000836	−0.45
GW190512_180714	−0.56	GW190727_060333	0.01
GW190513_205428	−0.03	GW190728_064510	0.01
GW190517_055101	0.16	GW190828_063405	0.10
GW190519_153544	−0.10	GW190828_065509	−0.01
GW190521	−1.82	GW190910_112807	−0.22
GW190521_074359	−0.72	GW190915_235702	0.17
GW190602_175927	0.13	GW190924_021846	−0.03
GW190630_185205	0.08		

Abbott [LIGO Scientific and Virgo], Phys. Rev. D 103, no.12, 122002 (2021)

Morphology-independent search

N: noise; S: coherent signal; G: glitch

Event	$\log B_{S/N}$	$p_{S/N}$	$\log B_{S/G}$	$p_{S/G}$
GW150914	2.32	0.26	2.95	0.43
GW151012	-0.59	0.70	0.35	0.88
GW151226	-0.67	0.72	2.48	0.53
GW170104	1.09	0.44	3.80	0.28
GW170608	-0.90	0.75	0.90	0.82
GW170823	6.11	0.03	5.29	0.11
Combined		0.34		0.57

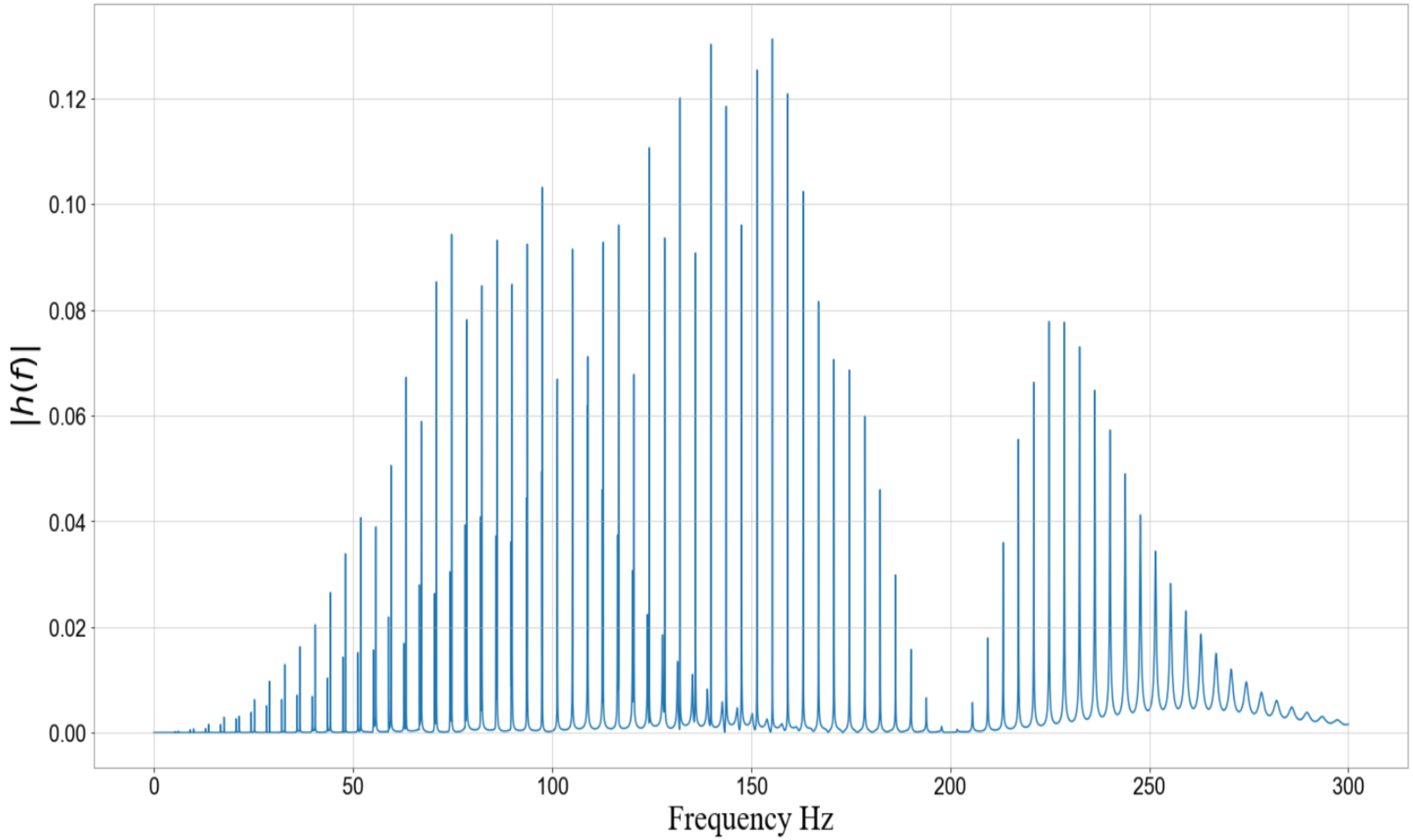
Event	$\log B_{S/N}$	$p_{S/N}$	$\log B_{S/G}$	$p_{S/G}$
GW170729	4.24	0.67	5.64	0.62
GW170809	9.05	0.31	12.69	0.09
GW170814	8.75	0.33	8.54	0.34
GW170817	11.05	0.19	10.30	0.20
GW170817+1s	6.19	0.52	9.39	0.27
GW170818	10.39	0.23	9.36	0.27
Combined		0.47		0.22

Tsang et al., Phys. Rev. D 101, no.6, 064012 (2020)

NO clear evidence of post-merger echoes

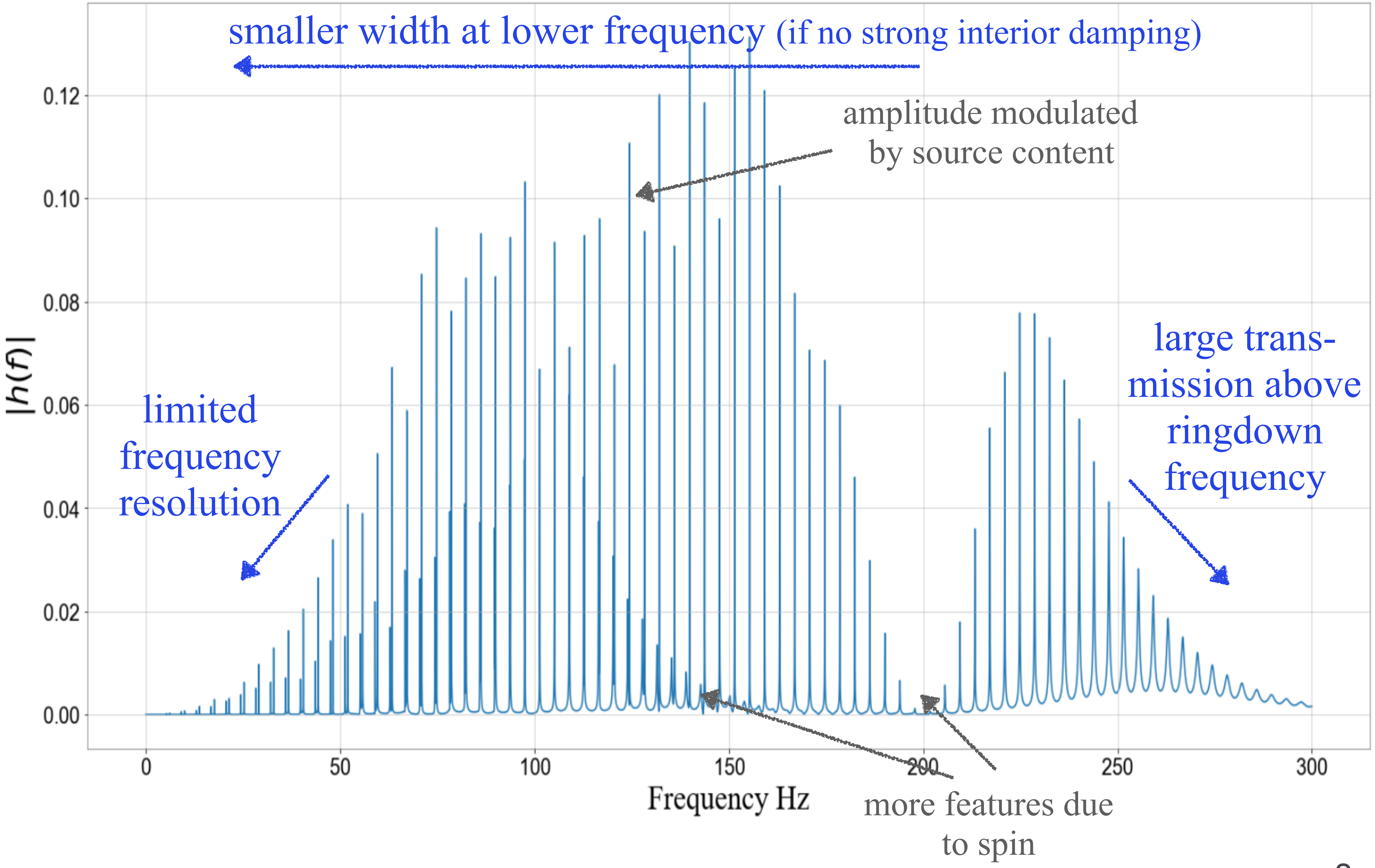
Complementary search target for echoes

- Coherent combine of many pulses leads to **a narrow resonances structure for echo amplitude in frequency** (slowly decaying QNMs of the cavity)



Complementary search target for echoes

- Coherent combine of many pulses leads to **a narrow resonances structure for echo amplitude in frequency** (slowly decaying QNMs of the cavity)
- **Ignoring phases, the resonance structure has generic features**: nearly evenly spaced resonances up to ringdown frequency



GW echoes search with combs

- Use **a uniform comb** to capture the resonance structure in noise in a rather model-independent way. Inferred comb parameters measure essential properties of echoes.

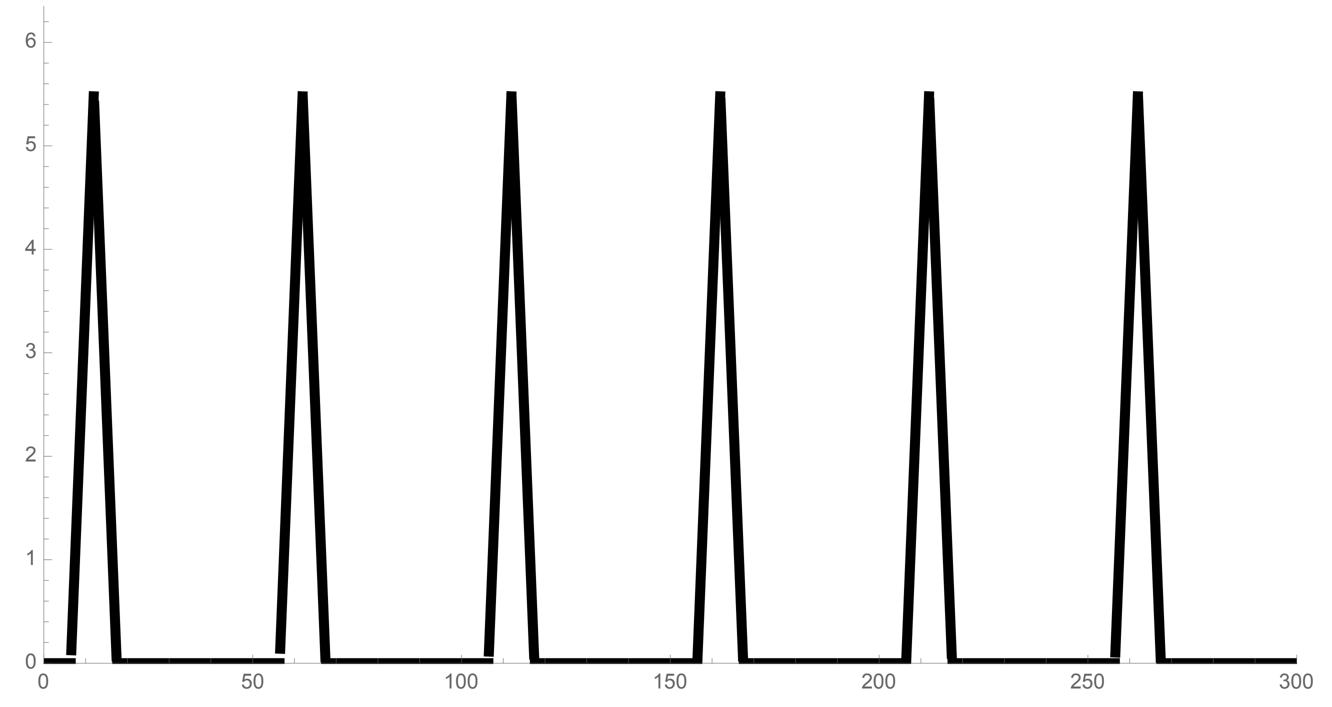
  Conklin, Holdom, **JR**, Phys. Rev. D 98, no.4, 044021 (2018)

- **Tentative evidences for echoes reported for events in GWTC-1**, with interesting correlation of derivations. **But** the search method not fully automized, and results not reproduced by others. Further optimization needed…

  Holdom, Phys. Rev. D 101, no.6, 064063 (2020)

- **We develop a Bayesian search algorithm of the resonance structure based on combs**

  JR, Di Wu, arXiv: 2107.*****



Tooth position: $f_0, \Delta f \approx 1/t_d$

Tooth amplitude: $A_{\rm comb}$

Tooth width: f_w

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

Bayesian search algorithm based on combs

For given strain data (d) and signal model (H): $p(\theta|d,H) = \dfrac{L(d|\theta,H)\pi(\theta|H)}{Z(d|H)}$

Input

- Priors (π): uniform
- **Likelihood (L): Gaussian likelihood marginalized over phase**

log-likelihood ratio:

$$\ln \frac{L(d|\theta)}{L(d|0)} = \sum_j \ln I_0 \left(4\,\delta f\,|h_j| \frac{|d_j|}{P_j} \right) - 2\,df\,\frac{|h_j|^2}{P_j}$$

overlapping term — comb SNR

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

Bayesian search algorithm based on combs

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$$\ln I_0 \left(4\,\delta f\, |h_j| \left| \frac{d_{I,j}}{P_{I,j}} + \frac{d_{J,j}}{P_{J,j}} \right| \right)$$

Two detectors: coherent combine

Bayesian search algorithm based on combs

For given strain data (d) and signal model (H): $p(\theta|d,H) = \dfrac{L(d|\theta,H)\pi(\theta|H)}{Z(d|H)}$

Input

- Priors (π): uniform
- **Likelihood (L): Gaussian likelihood marginalized over phase**

Output

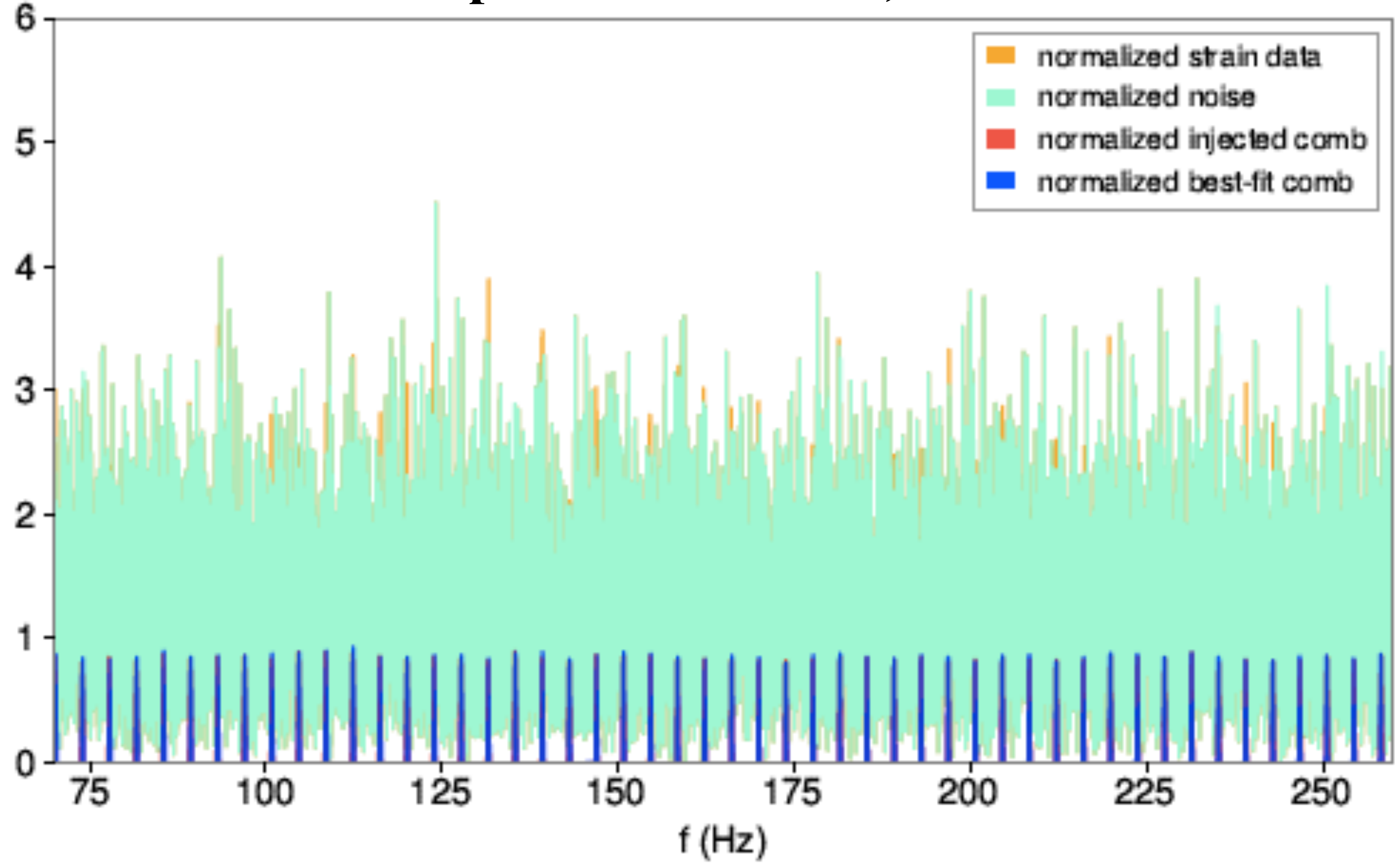
- **Bayes factor** ($B=Z_1/Z_0$, evidence ratio): detection statistics for model selection
  (Occam penalty for more complicated model)
- Posterior (p): **parameter estimation**
  (inferred comb features allow characterization of echoes)

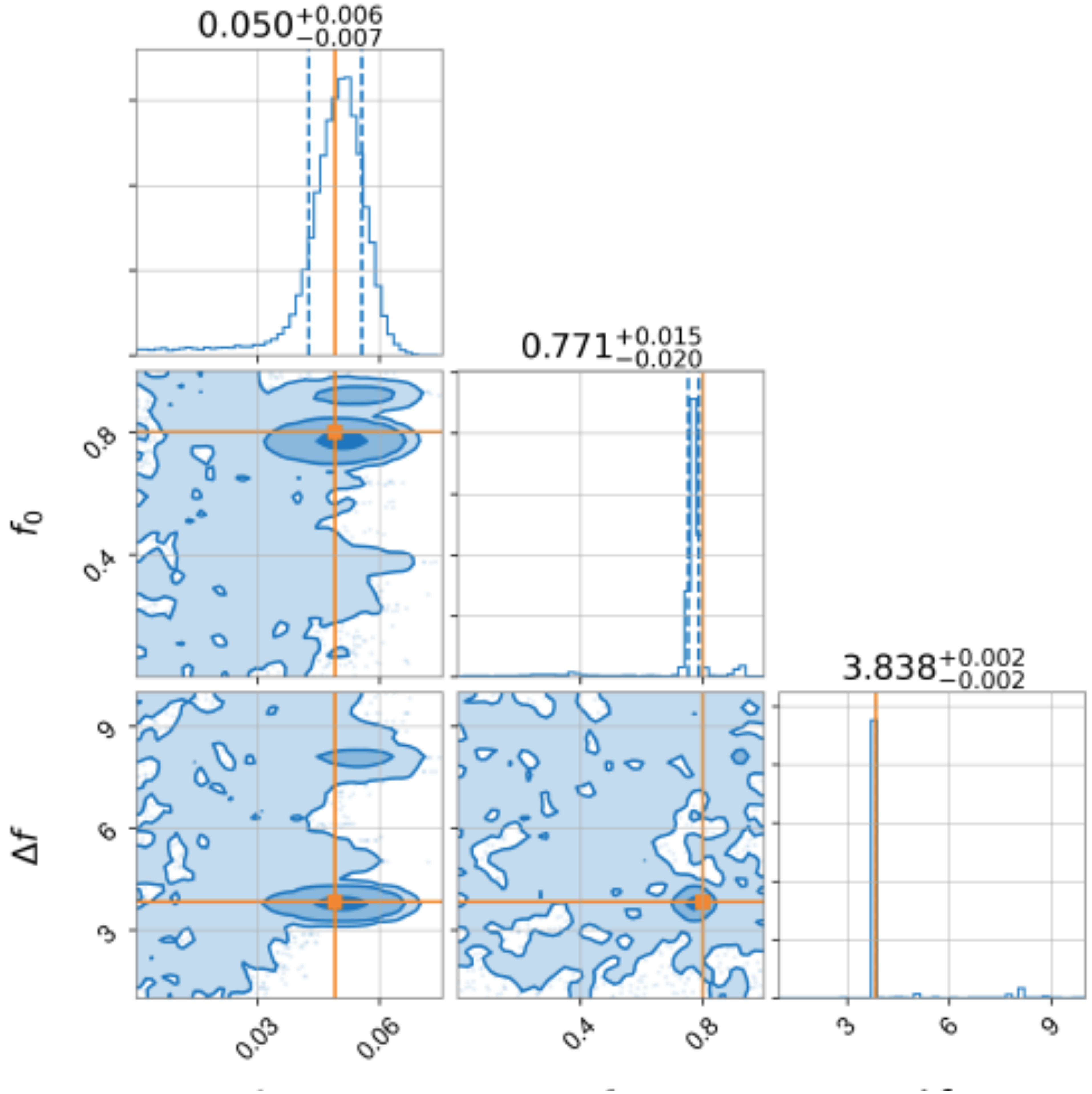
Ashton et al., 1811.02042

Comb model injections in Gaussian noise

Three search parameters: **spacing (Δf), shift (f_0), amplitude (A_{comb})**

network optimal SNR=16.5, ln*B*=0.24





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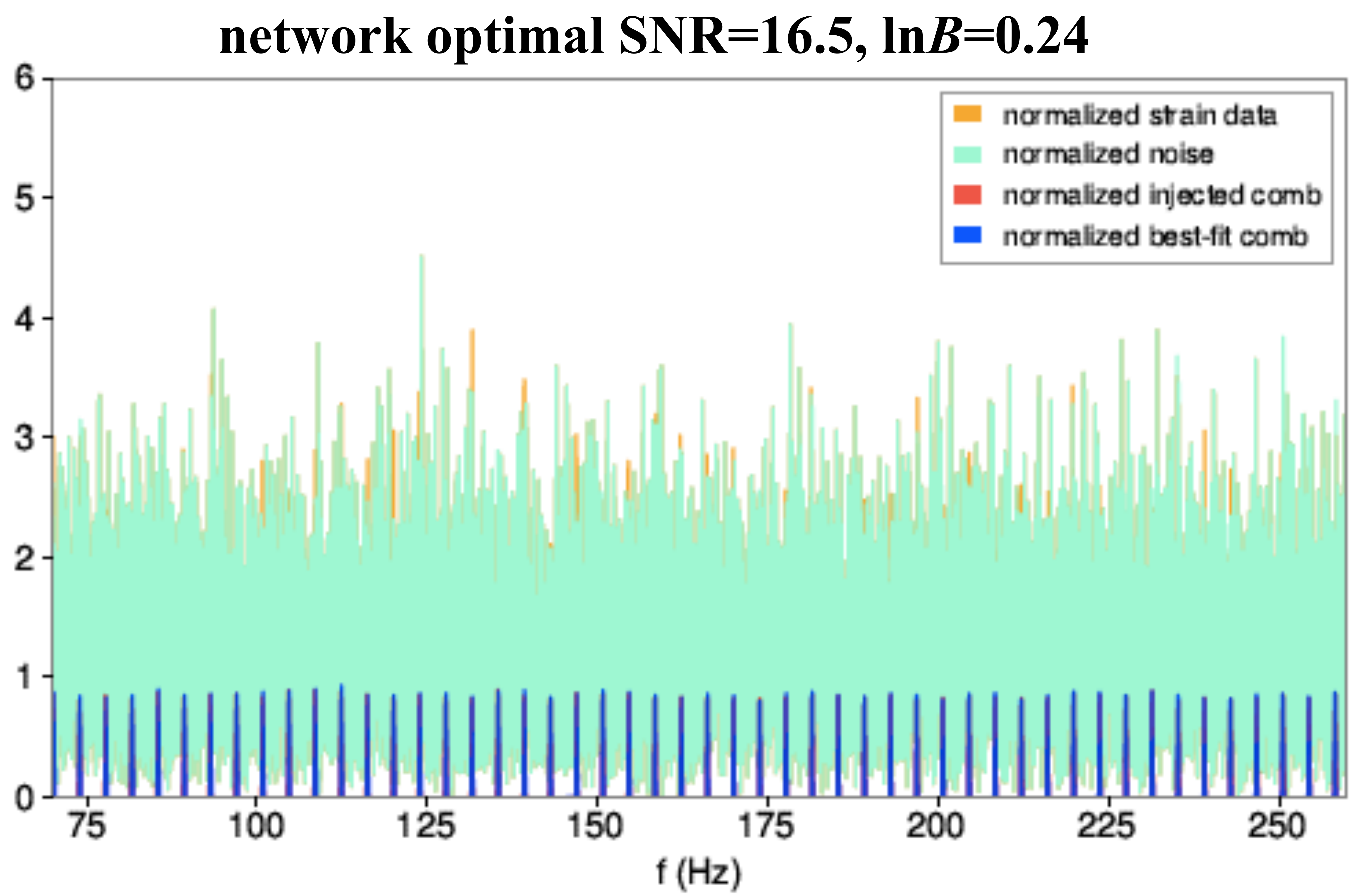
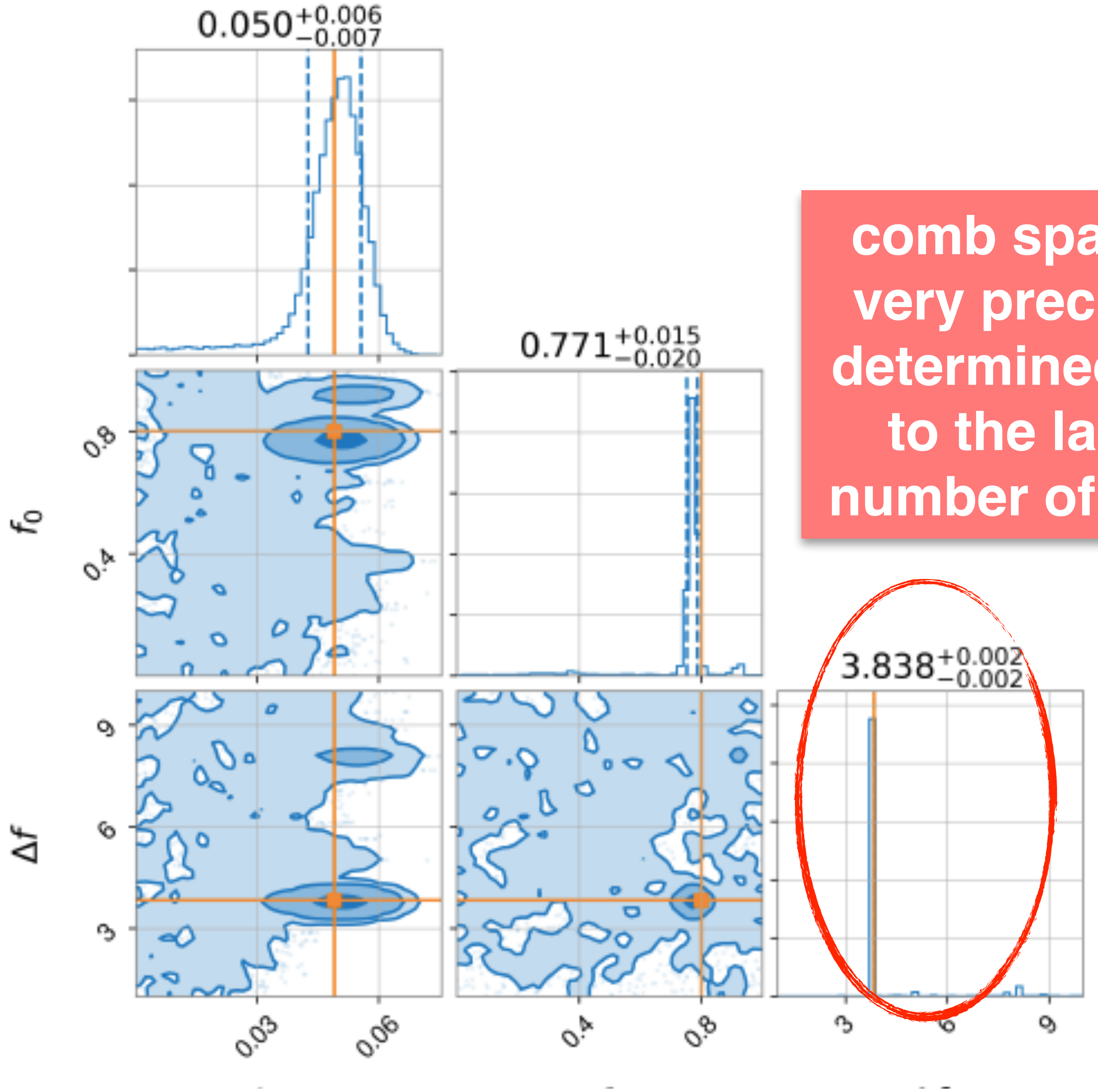
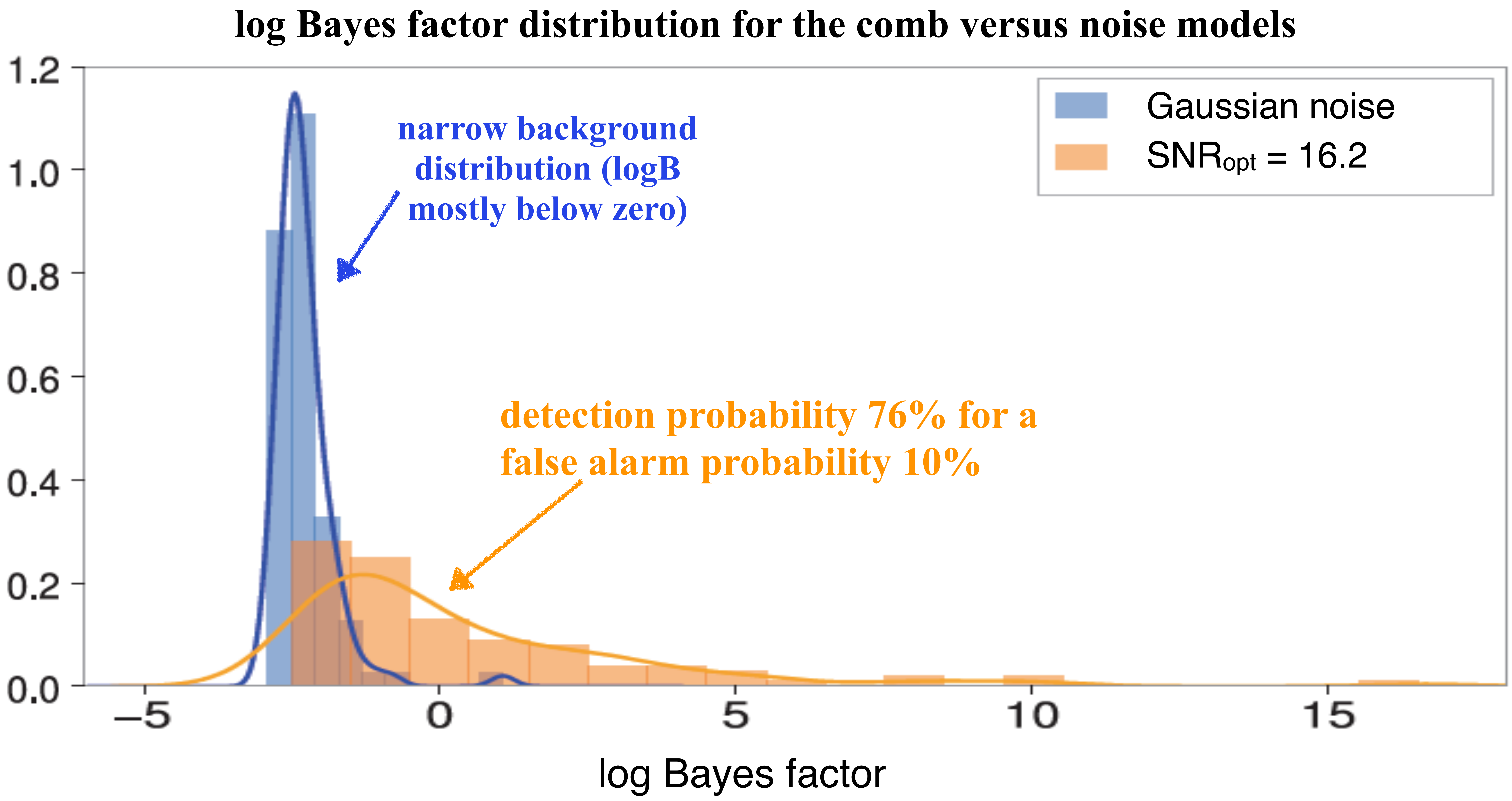




comb spacing very precisely determined due to the large number of teeth

Comb model injections in Gaussian noise

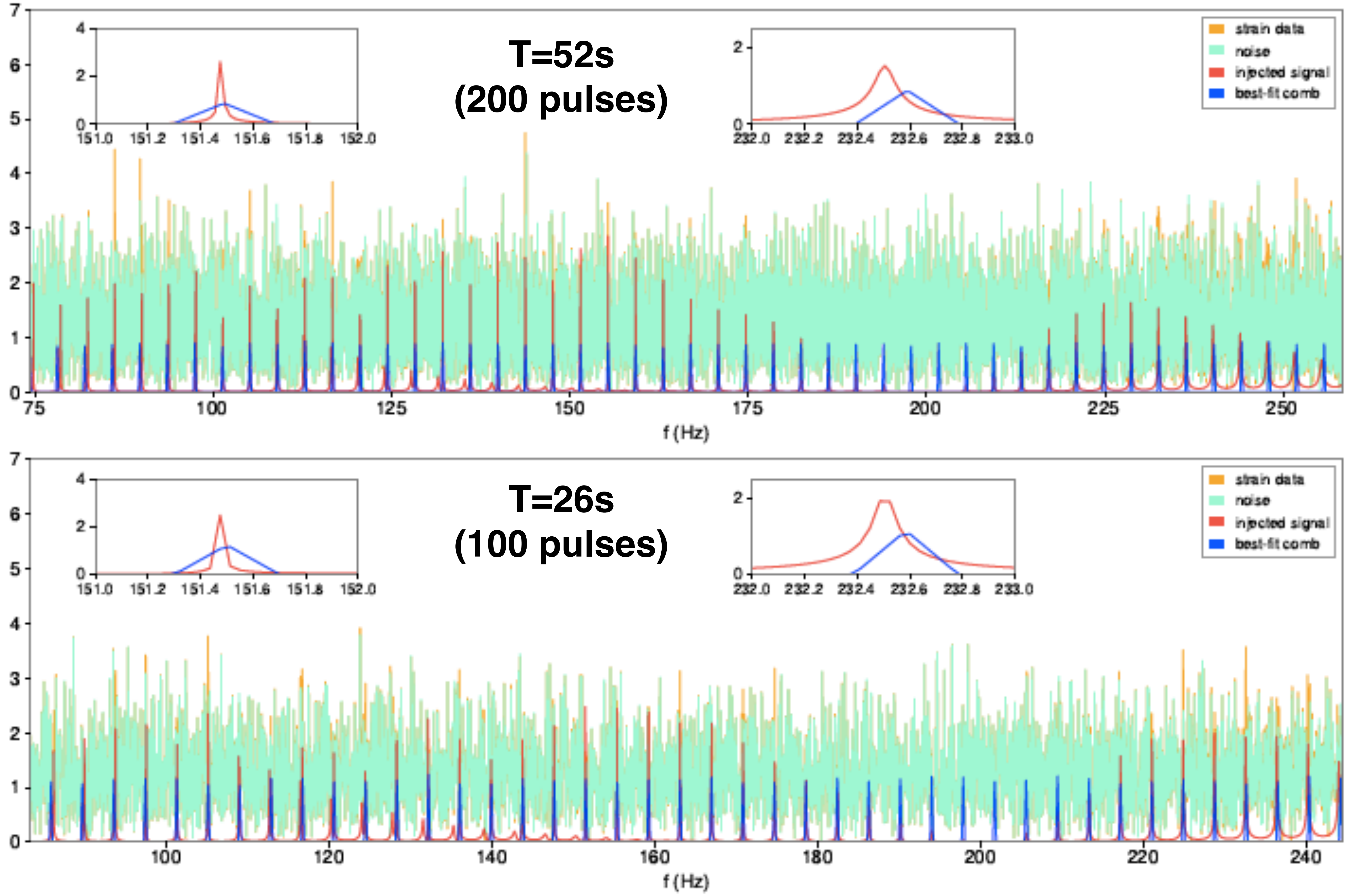


Echoes signal injections in Gaussian noise

- Vary **time duration *T*** to obtain the optimal SNR and a more evenly distributed resonance structure

- Apply **a frequency band** to select the frequency region of interest

- Δf measures the average spacing of resonances, and **time delay** $\boldsymbol{t_d = 1/\Delta f}$; A_{comb} measures the average heights of resonances



LIGO data search (O1)

- **Parameter setting:** three more parameters included to describe detector response

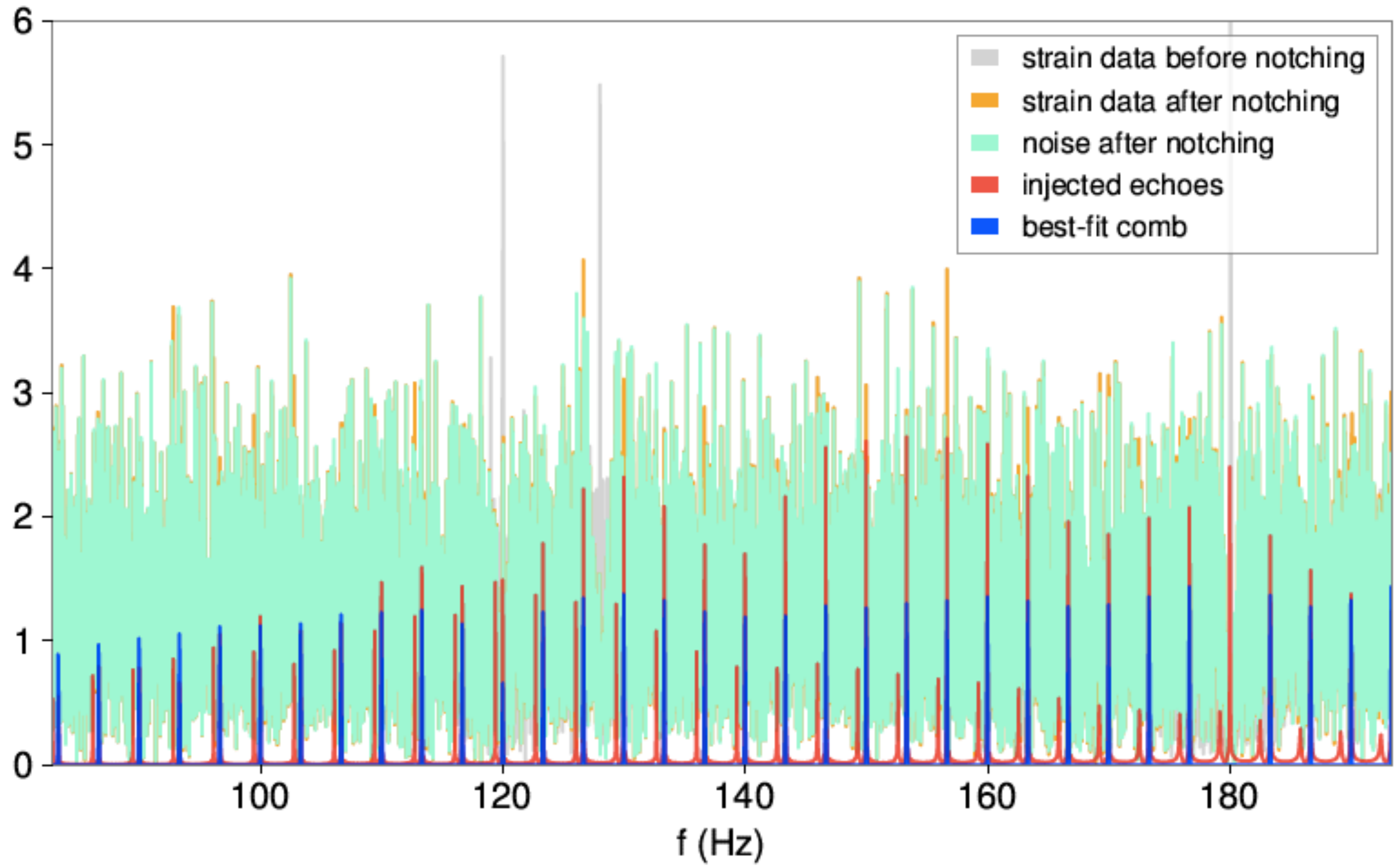
$$\ln I_0\left(4\,\delta f\,|h_j|\left|\frac{d_{H,j}}{P_{H,j}}+A_{HL}e^{i\,\phi_{HL,j}}\frac{d_{L,j}}{P_{L,j}}\right|\right),\qquad \phi_{HL,j}=\phi_{HL,0}-2\pi f_j\Delta t_{HL}\quad \text{(arrival time lag)}$$

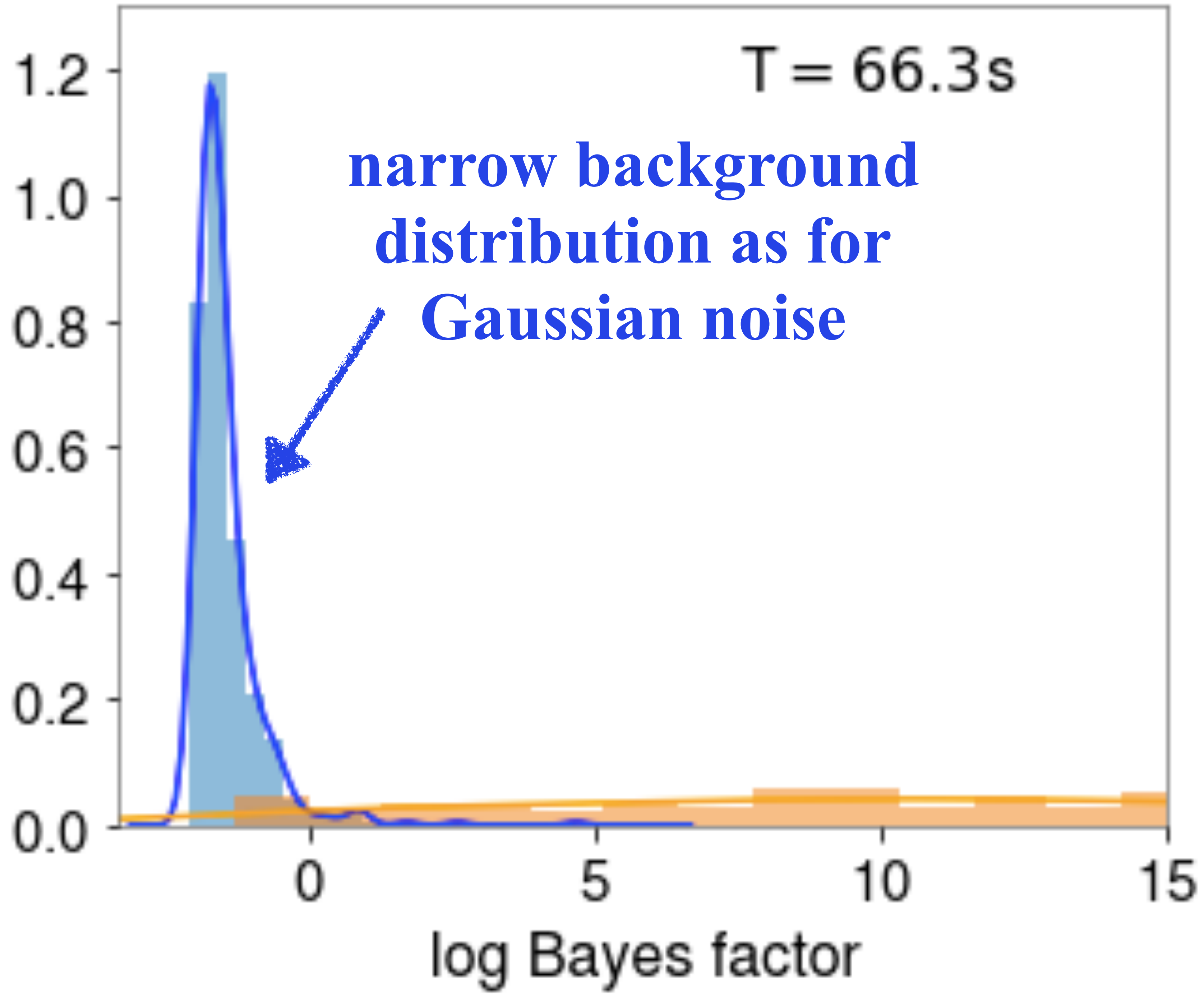
- **Non-Gaussian artifacts:** notch-out large spectral lines due to instrumental disturbances. O1 strain data polluted by a large number lines, a good place to test the algorithm. It turns out that the distribution is well behaved after notching-out a few large lines

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

Echo signal injections in LIGO noise

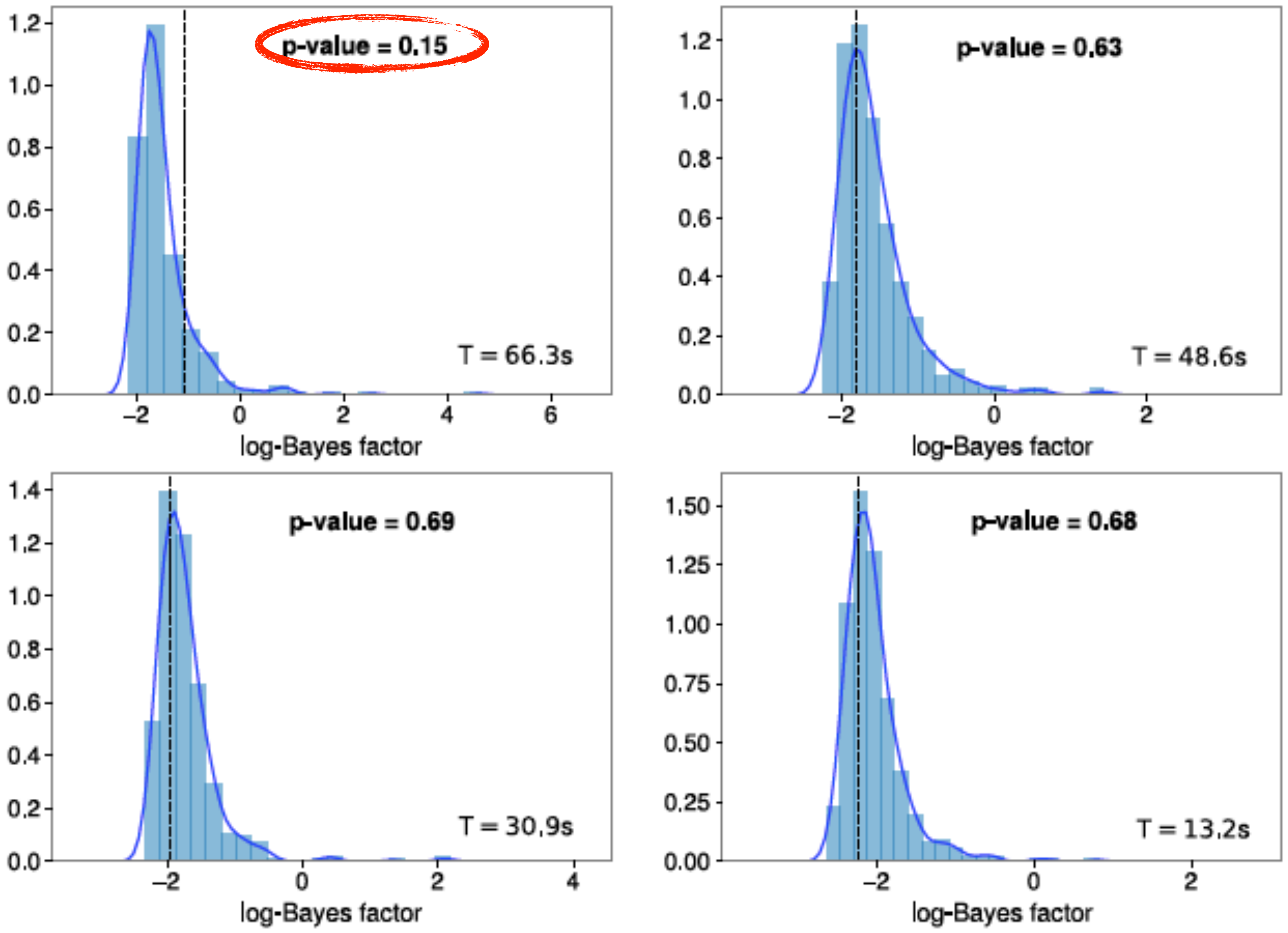
- Large instrumental lines properly mitigated (light-gray); background distribution of log Bayes factor similar to that for Gaussian noise
- Signal detection probability not much influenced even when some resonances coincide with the large lines



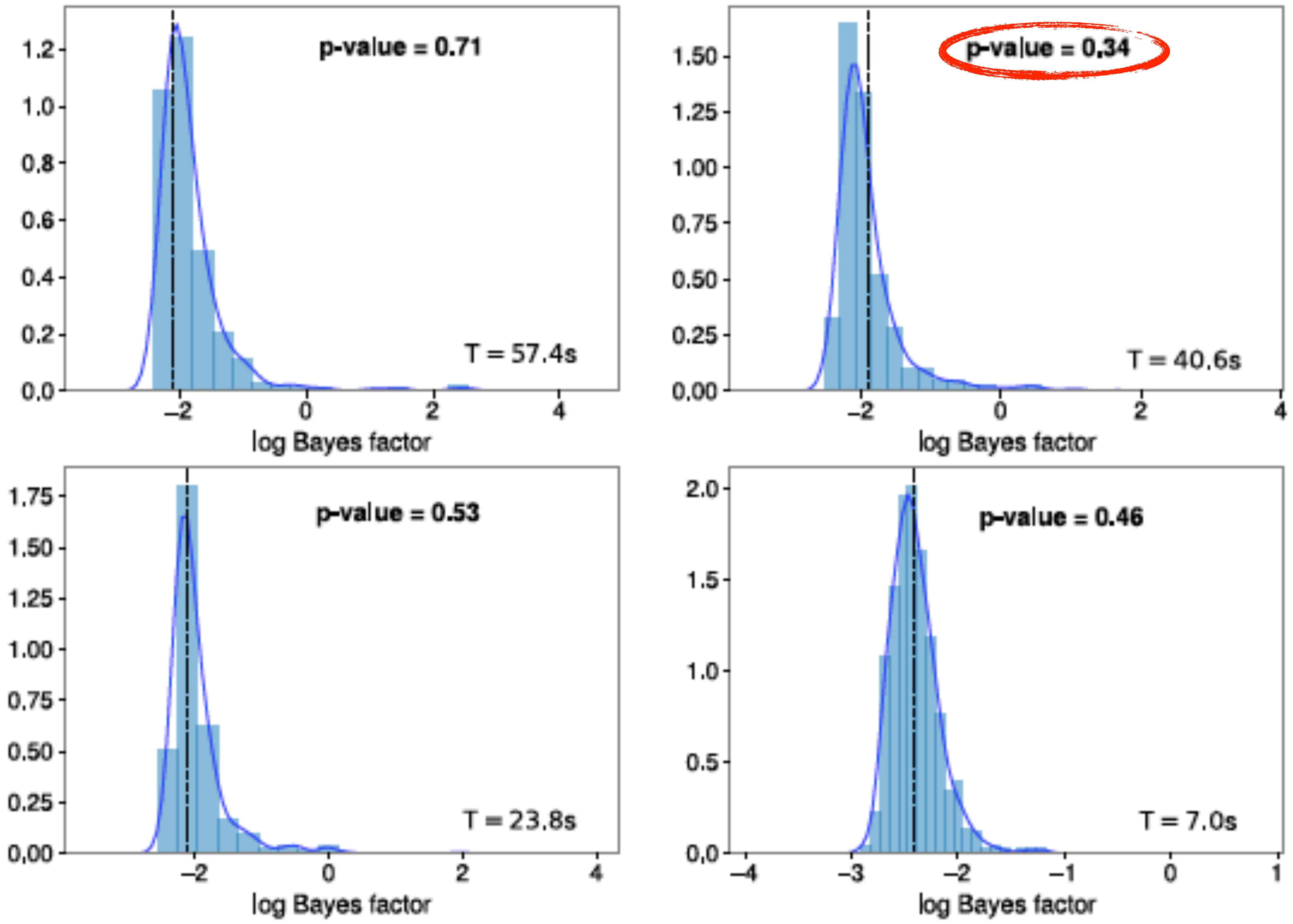


LIGO real data search

GW150914

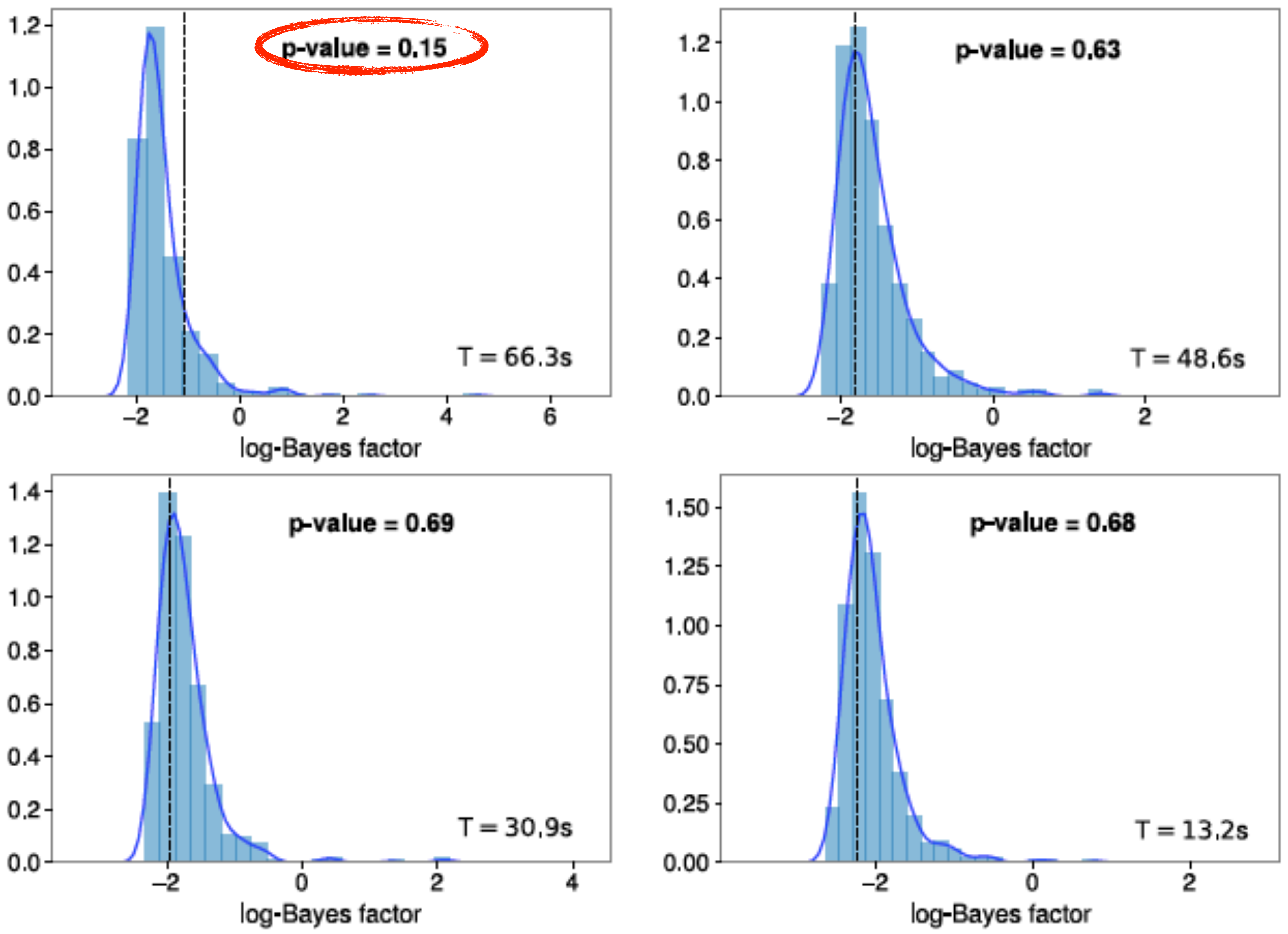


GW151012

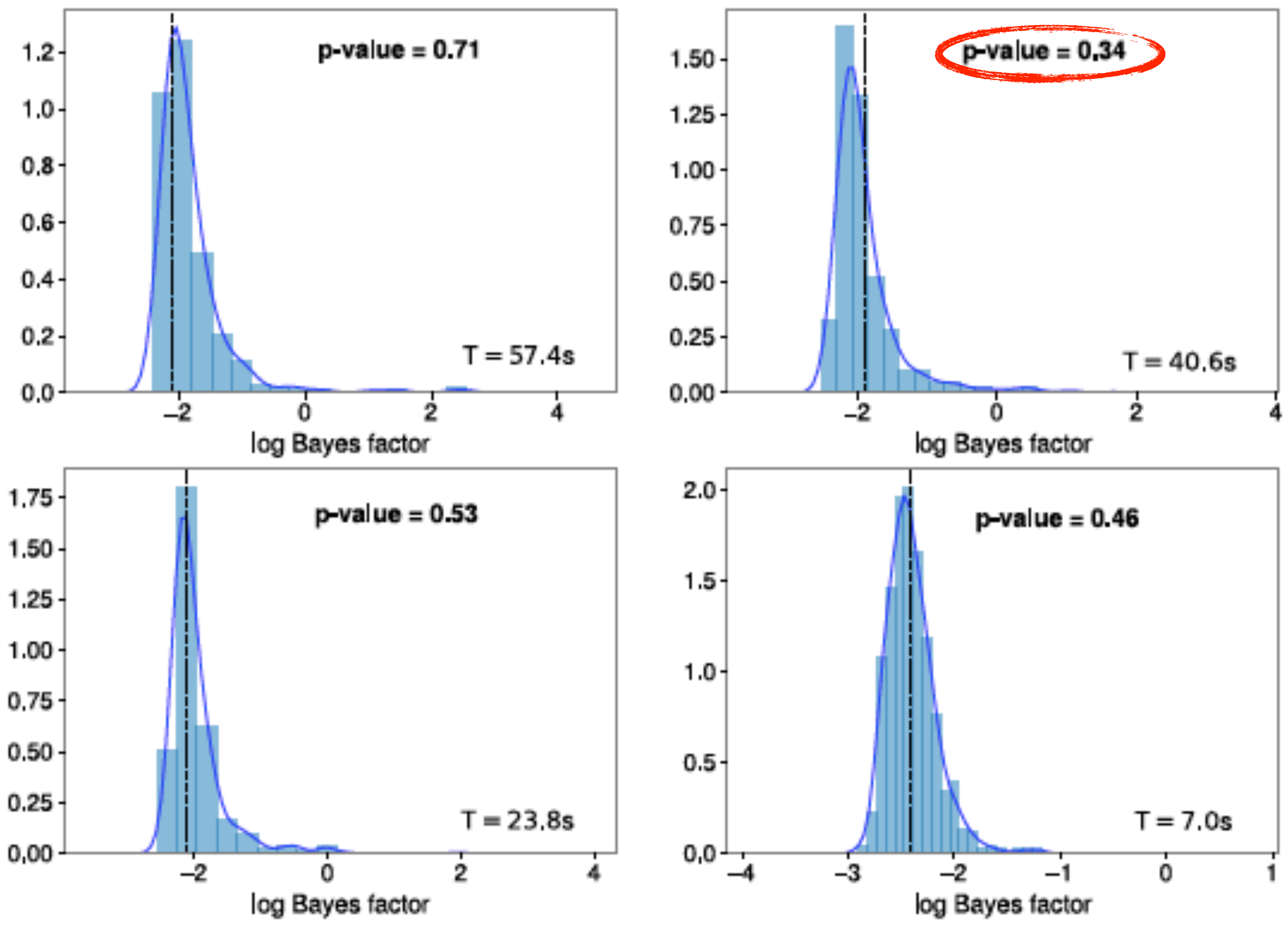


LIGO real data search

GW150914



GW151012



Search results consistent with background distributions; no clear evidence of a comb-like structure …

Summary and outlook

- GW echoes serve as a perfect target to look for near-horizon corrections at even a Planck distance around astrophysical black holes. More attention payed to quasi-periodic signal in time, while the resonance structure in frequency provides a complementary target
- We develop **a Bayesian algorithm to search for the resonance structure with combs**, where phase-marginalized likelihood play a crucial role. Algorithm validated by signal injections in both Gaussian and LIGO noise (O1). No clear evidence for echoes for GW150914 and GW151012
- Further optimization of the algorithm: comb width optimization, refined scan over time duration T, search for both negative and positive frequency components…
- **Searches on LIGO/Virgo O2 and O3 data with better data quality. Stay tuned!**

Thank You!

More on parameter setting

Comb parameters

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

Response parameters

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

Time duration T

$$\frac{t_d}{M} \approx 4\eta \ln\left(\frac{M}{\ell_{Pl}}\right) \frac{1}{2}\left[1 + (1-\chi^2)^{-1/2}\right](1+z)$$

Parameters	Priors and fixed (scan) values
Δf	uniform in $[\bar{R}_{min}/2,\ \bar{R}_{max}/1]$
f_0	uniform in $[0, 1]$
A_{comb}	uniform in $[10^{-25}\,\mathrm{Hz}^{-1}, 5\langle\tilde{P}\rangle^{1/2}]$
f_{min}	uniform in $[f_{cut}, f_H - \frac{1}{4}(f_H - f_{cut})]$
f_{max}	uniform in $[f_H, 1.1 f_{RD}]$
$\phi_{HL,0}$	uniform in $[\pi/2, 3\pi/2]$
f_w	$11/T$
A_{HL}	1
Δt_{HL}	$\Delta t_{HL,0}$
T	$T_{min} + \frac{1}{3}n(T_{max} - T_{min})$, $n = 0...3$