What is “Non GR” in Extreme Gravity?

“Within-GR” Extreme Gravity: interesting GR effects, esp. beyond-leading order.

“Non-GR” Extreme Gravity: *(everything NOT included in standard GR waveform templates, esp. strong-field tests)*

- **Modified Gravity - The nature of gravity (EXG 2, Tuesday)**
  But also widely interpreted as…

- **Beyond Standard Model particles, e.g Dark Matter (EXG 1, Wednesday)**
  - Ultralight bosons (e.g. axions, fuzzy DM, dark photons…)
  - Primordial BHs
- **Exotic Compact objects (in GR and beyond) (EXG 1, Wednesday)**
  - Boson stars
  - Horizonless ultracompact objects
- **Environmental effects? (EXG X?)**
  - Accretion, disks, gravitational pull, dynamical friction, planetary migration

EXG 1:
The nature of compact objects

Compact objects

- "Black hole mimickers"
  - Black hole-like objects from alternative theories of gravity
  - Exotic objects not requiring deviations from GR (e.g. boson stars)

- Ordinary black holes interacting with dark matter particles

Black hole mimickers

How certain are we that the massive compact objects we are observing are the "standard" black holes of general relativity?

Alternatives ("black hole mimickers"):

- Boson stars
- Dark matter stars
- Gravastars
- Wormholes
- Firewalls, fuzzballs
- *The unknown*

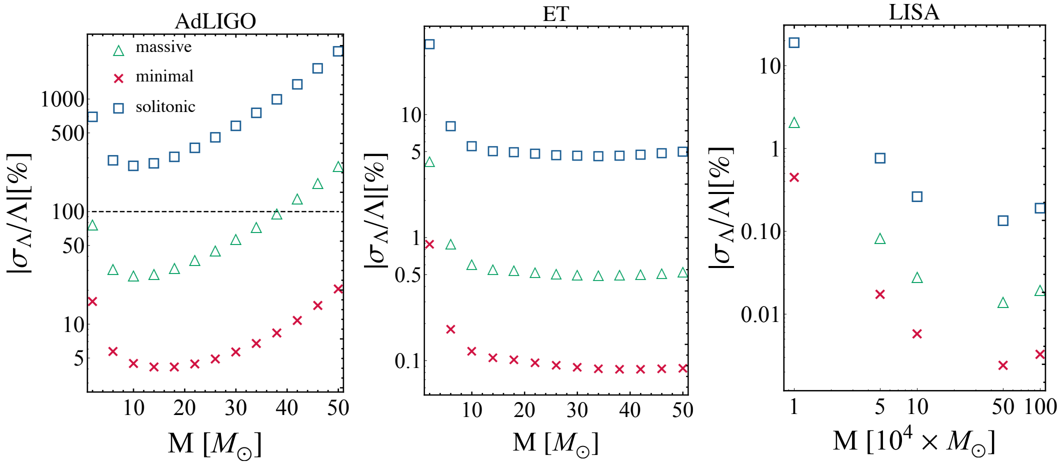
Gravitational wave signatures of black hole mimickers

1. Anomalous effects during inspiral
   - Tidal deformability
   - Tidal heating
   - Anomalous spin-induced quadrupole moments

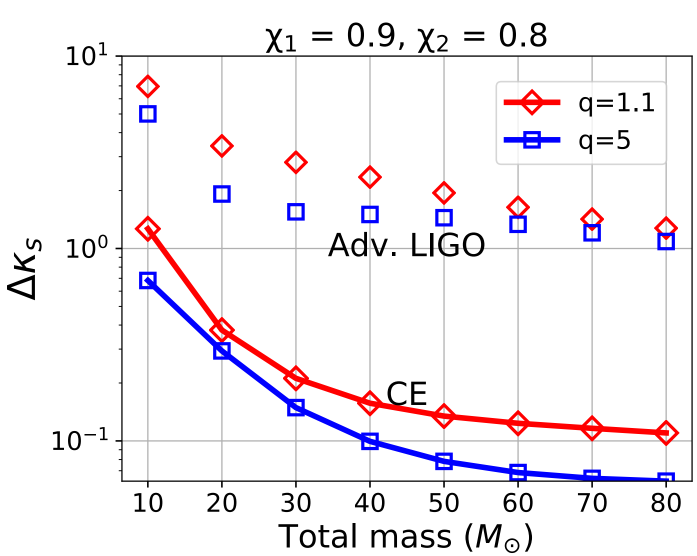
2. Anomalous effects during ringdown
   - Indirect tests of no-hair theorem

3. Post-ringdown
   - Echoes

1. Anomalous effects during inspiral



Cardoso et al., PRD **95**, 084014 (2017)



Krishnendu et al., PRL **119**, 091101 (2017)
Krishnendu et al., PRD **99**, 064008

- Tidal deformability during inspiral
  - Finite size effects cause tidal deformations in the phase starting at 5PN
  - $(R/m)^5$; can be large for boson stars
- Spin-induced quadrupole moment during inspiral
  - 2PN effect, quadratic in spins
  - κ_s = 1 for ordinary black holes, but not for black hole mimickers
  - Hard to access with 2G, while 3G measurements to few percent
- Tidal heating
  - Absorption of radiation
  - $2.5^{(l)}$PN but linear in spin

2. Testing the no hair conjecture

- Black hole "no hair" conjecture:
  Stationary, vacuum black hole completely determined by mass and spin

- Black hole ringdown: QNM frequencies and damping times all determined by mass and spin

$$h(t) = \sum_{nlm} \mathcal{A}_{nlm} e^{-t/\tau_{nlm}} \cos(\omega_{nlm} t + \phi_{nlm})$$

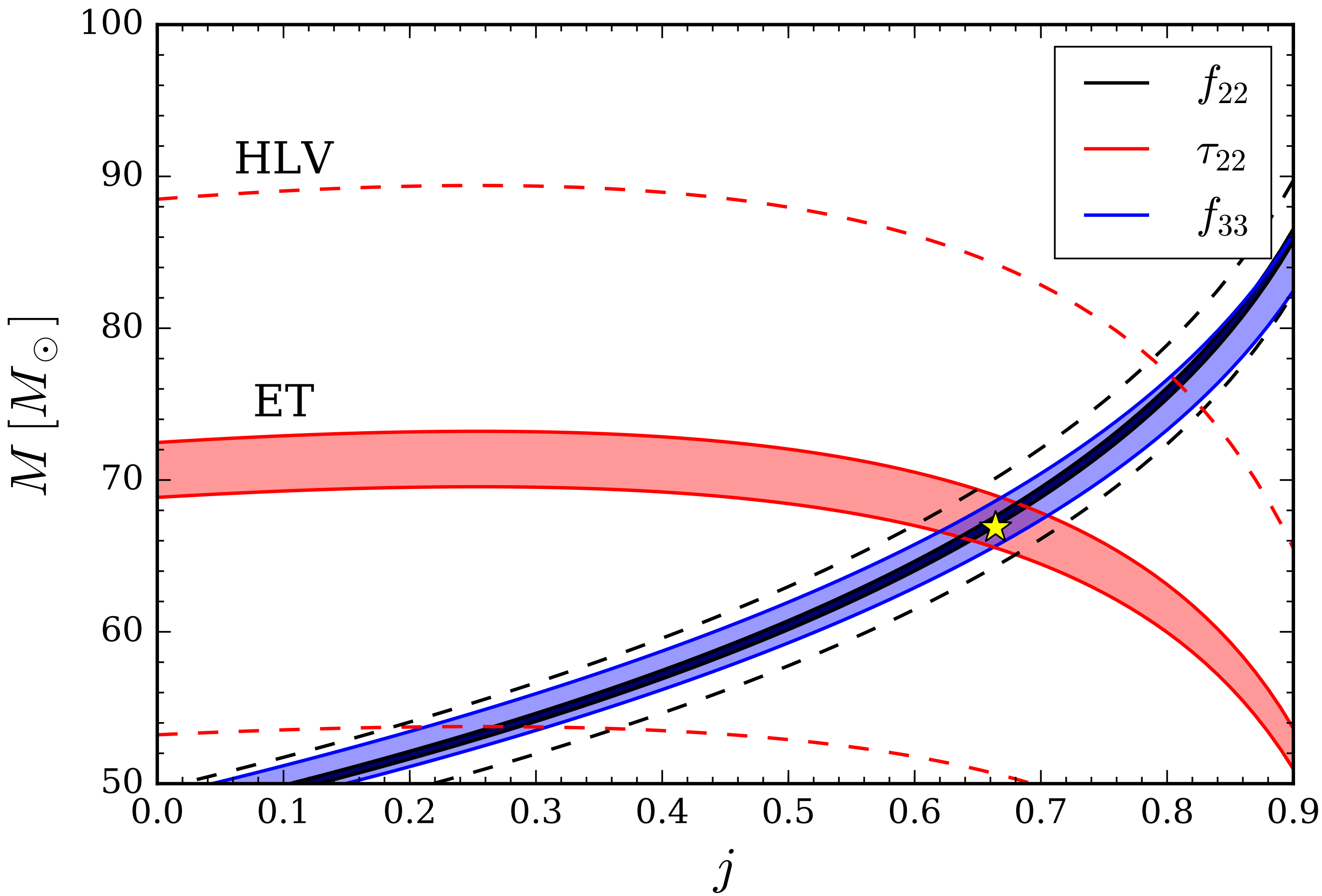
  - Linearized Einstein equations around Kerr background force specific dependences:

$$\omega_{nlm} = \omega_{nlm}(M_f, a_f)$$
$$\tau_{nlm} = \tau_{nlm}(M_f, a_f)$$

  - However, amplitudes $\mathcal{A}_{nlm}$ depend on how the black hole came into being (masses and spins of the progenitor binary)
    - Modeling with input from NR simulations

2. Testing the no hair conjecture

- Only two of the ω_{lmn} , τ_{lmn} are independent; check for consistency between any three of them



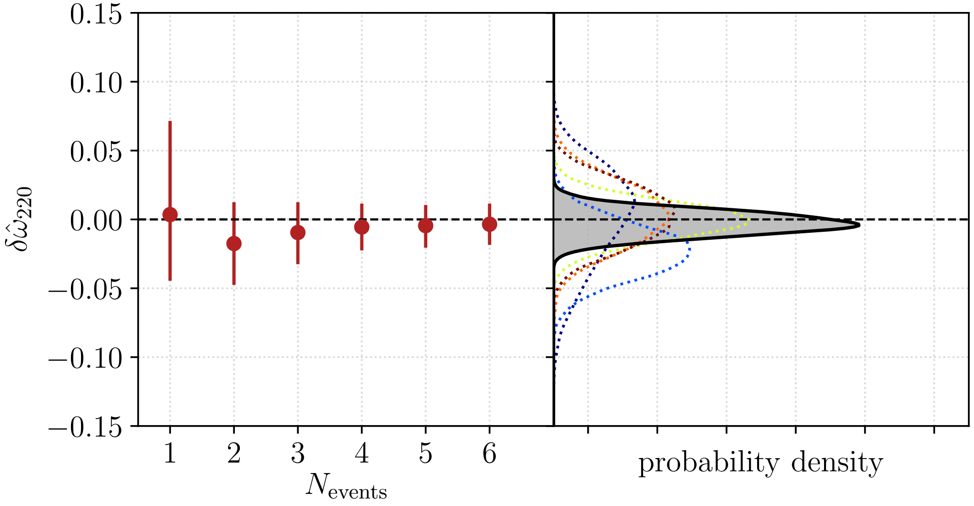
Adapted from Brito et al., PRD **98**, 084038 (2018)

2. Testing the no hair conjecture

- To test no-hair conjecture, no need to separately "see" the different ringdown modes
  - Can begin by allowing for deviations in dependences of frequencies, damping times on mass, spin:

$$\omega_{lmn}(M_f, a_f) \;\rightarrow\; (1 + \delta\hat{\omega}_{lmn})\,\omega_{lmn}(M_f, a_f)$$
$$\tau_{lmn}(M_f, a_f) \;\rightarrow\; (1 + \delta\hat{\tau}_{lmn})\,\tau_{lmn}(M_f, a_f)$$

  - Let the $\delta\hat{\omega}_{lmn}$ and $\delta\hat{\tau}_{lmn}$ vary in turn, and measure them together with all the other parameters in the problem
  - Advanced LIGO/Virgo at design sensitivity, and 6 sources similar to GW150914
    - $\delta\hat{\omega}_{220}$ measurable to O(2%)
    - $\delta\hat{\tau}_{220}$ measurable to O(10%)



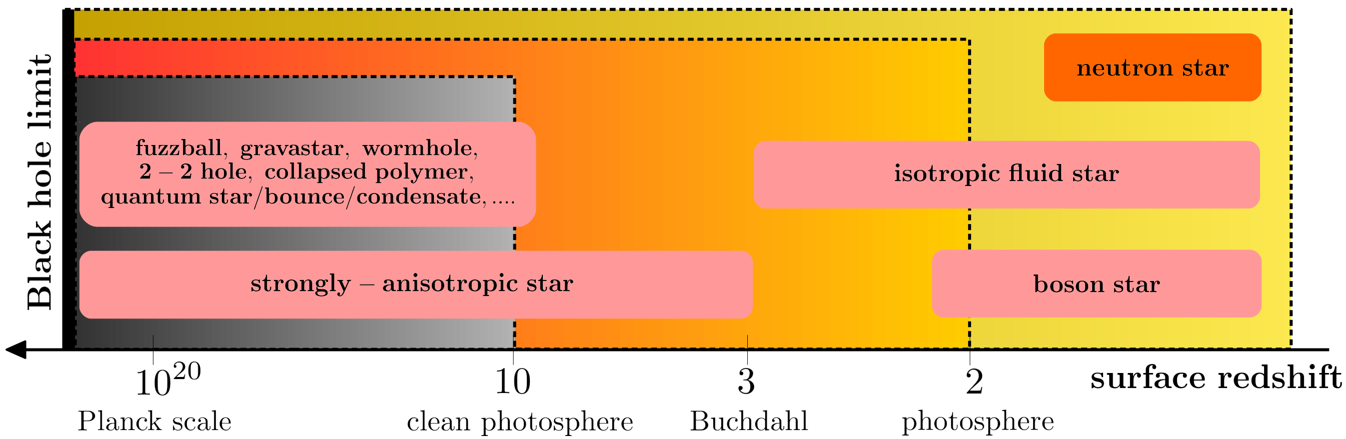
- Going beyond the linearized regime

E.g. Del Pozzo & Nagar, PRD **95**, 12034 (2017)

Carulllo et al., PRD **98**, 104020 (2018)
Brito et al., PRD **98**, 084038 (2018)

3. Echoes

Adapted from Cardoso et al., Nat. Astron. **1**, 586 (2017)



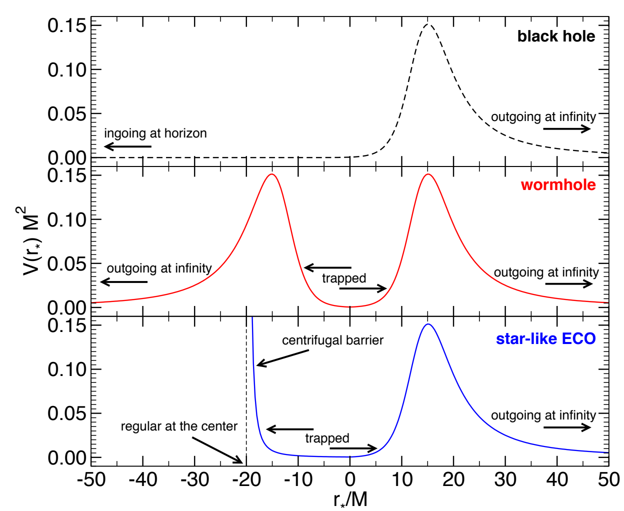
- If surface redshift z >> 1, prompt ringdown signal identical to that of BH
  - Also, any electromagnetic signal may be highly redshifted
- However, for z > 1.7 there is a photon sphere
  - Quasi-trapped modes
  - Train of *echoes* emerging with time delay

    $\tau \sim M \log(z)$

    and at time intervals

    $\Delta t \simeq nM \log(M/\ell)$
  - n = 8 for wormholes, n = 6 for gravastars, …
  - For GW150914 (M = 65 M_{sun}) and $\ell = \ell_{Planck}$:

    Δt = 117 ms



Cardoso et al., PRD **94**, 084031 (2016)

The nature of dark matter

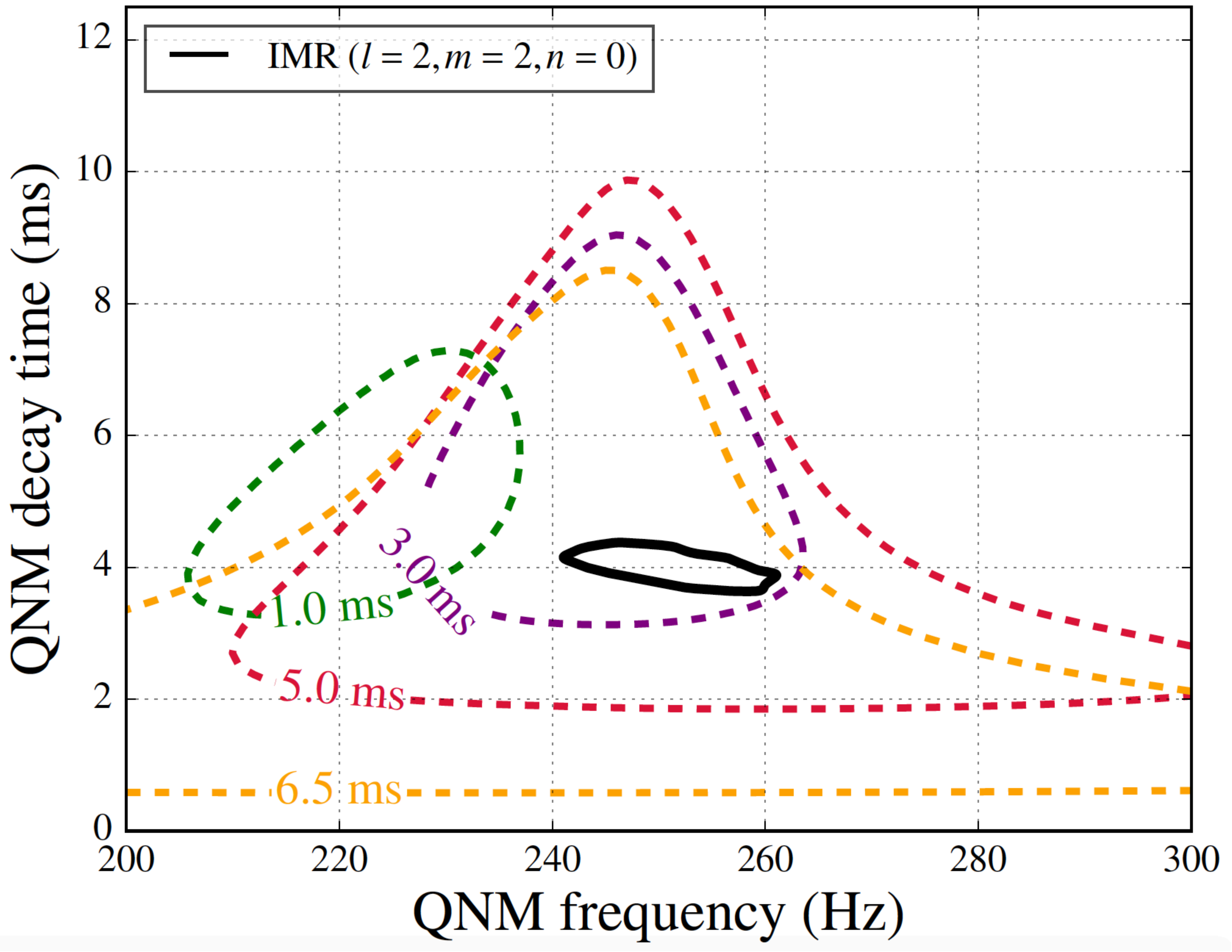
- Can black holes themselves contribute to dark matter?
  - Primordial black holes with masses 0.1 – 100 M_{sun}
  - Excess in the mass distribution in certain ranges?
  - Black holes at very high redshift would almost have to be primordial (ET and Cosmic Explorer reach out to z ~ 20, well before star formation)

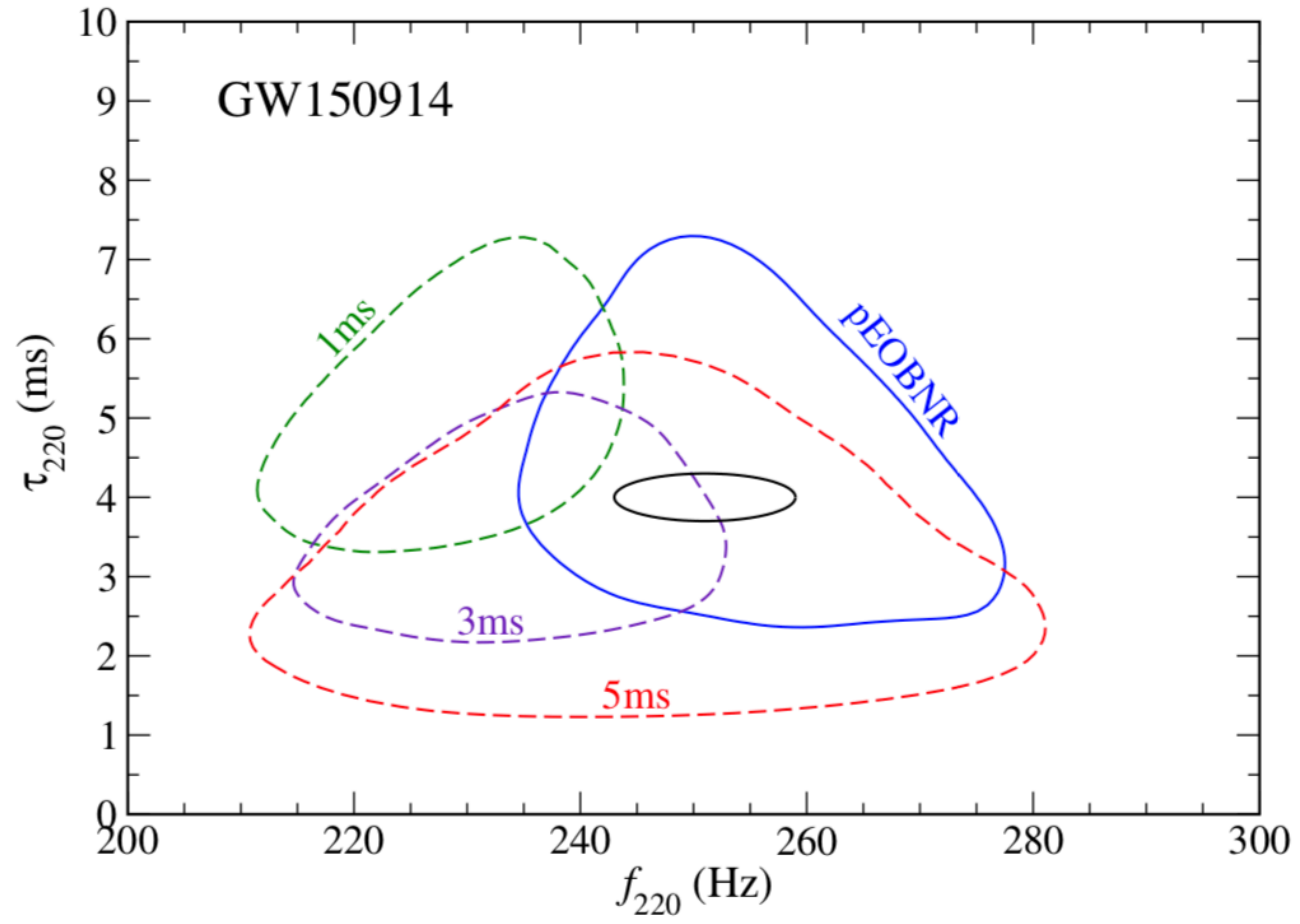
- Can dark matter particles be detected with binary compact objects?
  - Accumulation of dark matter particles around compact objects: gravitational drag having cumulative effect over many orbits
    - *Joint LISA-ET/CE observations of the same sources*
  - Accumulation of dark matter particles in the centers of neutron stars
    - Collapse to a black hole: abundance of light black holes could be indicative of the process

- New light particles
  - Bosons with mass 10^{-21} – 10^{-10} eV may extract rotational energy from BH to form condensates: impact on binary dynamics, continuous waves from annihilation, stochastic background

GW150914: THE DAY WE SAW A BLACK HOLE RINGING

- Nowadays benchmark:

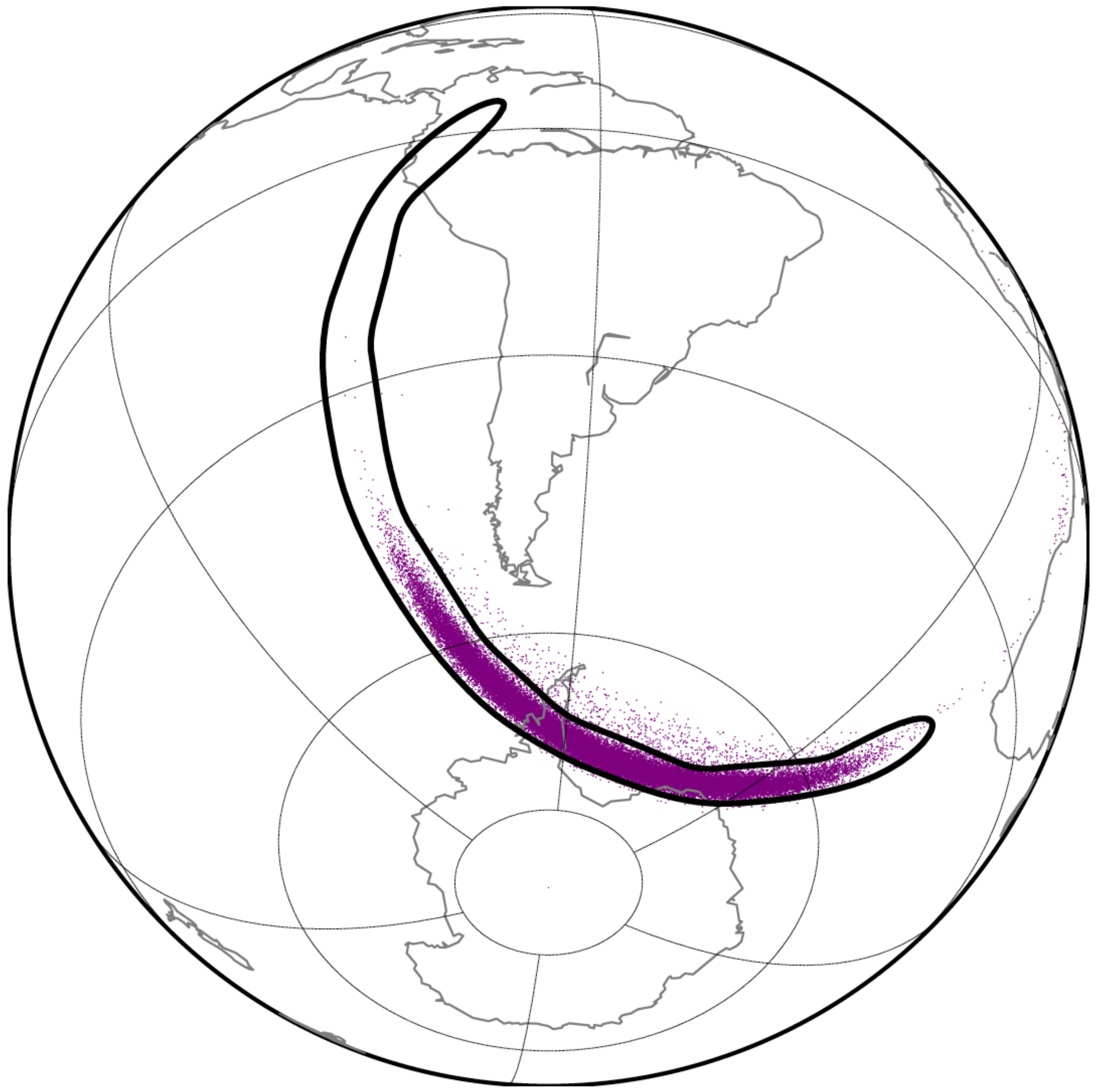


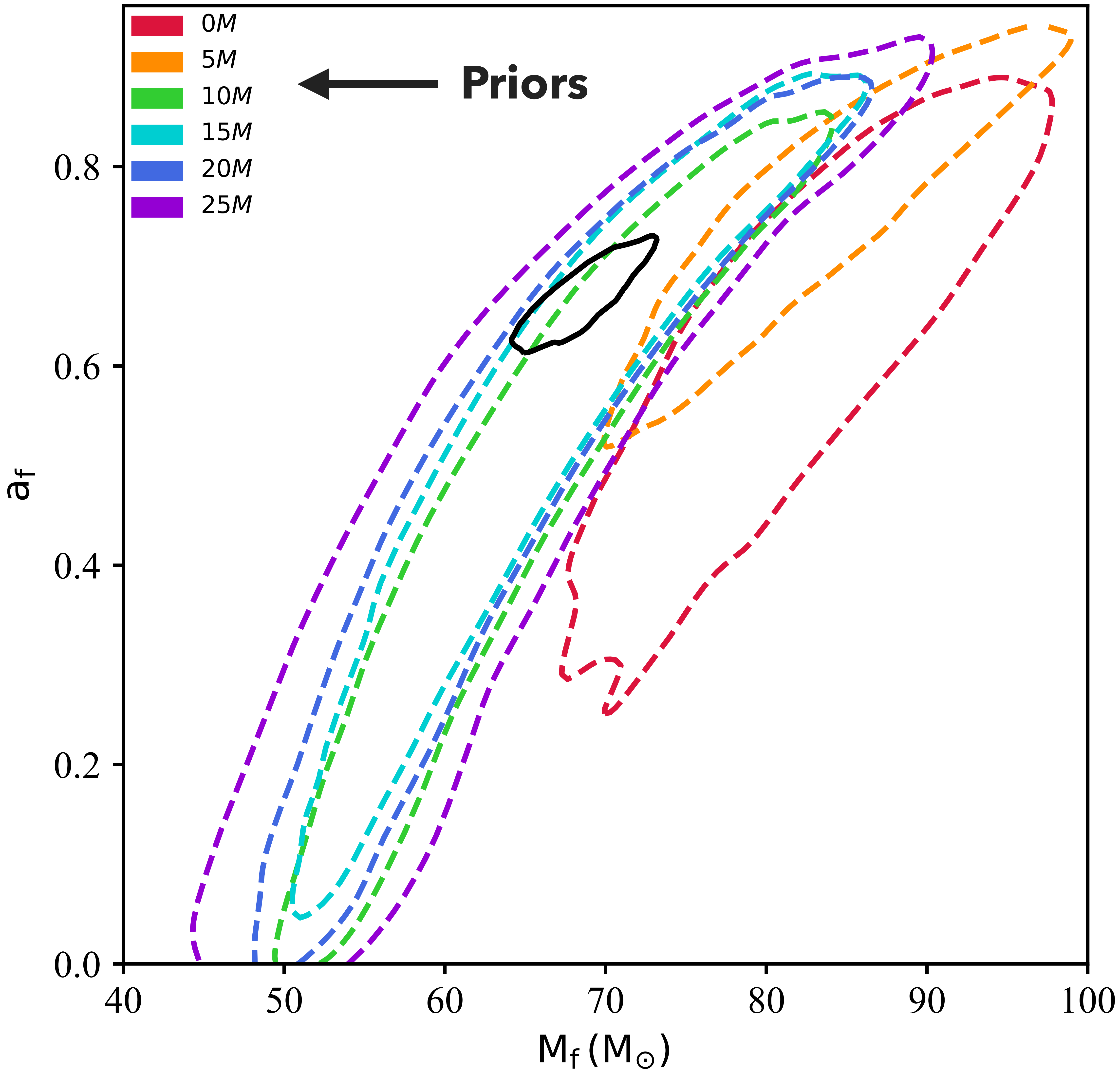


Brito, Buonanno, Raymond PRD 98, 084038 (2018)

RINGDOWN PE: WHERE ARE WE?

- Recent improvements:





Carullo, Del Pozzo, Veitch arXiv:1902.07527 (2019)

RINGDOWN MODELING: WHERE ARE WE?

- Where are we with ringdown waveforms?
  - **Higher modes** amplitudes (EOB, London+)
  - Do we need **overtones**? (Recent Giesler+ claims we do)
  - Doppler **redshift** from kicks:
    - (Should be) Not relevant for LIGO
    - Relevant for LISA: Gerosa, Moore (2016)
  - **Precession** (?)
  - Estimates for **2nd order** perturbations (?)

TESTING GR

- What can we (hope to) accomplish with LIGO?
  - **Agnostic** tests:
    - Parametrized null tests
    - Direct measurement of multiple frequencies
  - Test **specific** alternative proposals
  - **Combine** events

AREA QUANTIZATION: INTRODUCTION

- Long ago ***Bekenstein*** and ***Mukhanov*** proposed that the ***area*** of a BH may be quantized in terms of the ***Planck length***:

$$A = \alpha l_P^2 N = \alpha \hbar G N$$

- In a recent study [1] it was argued that ***area quantization*** together with ***coherent single graviton emission*** would lead to:

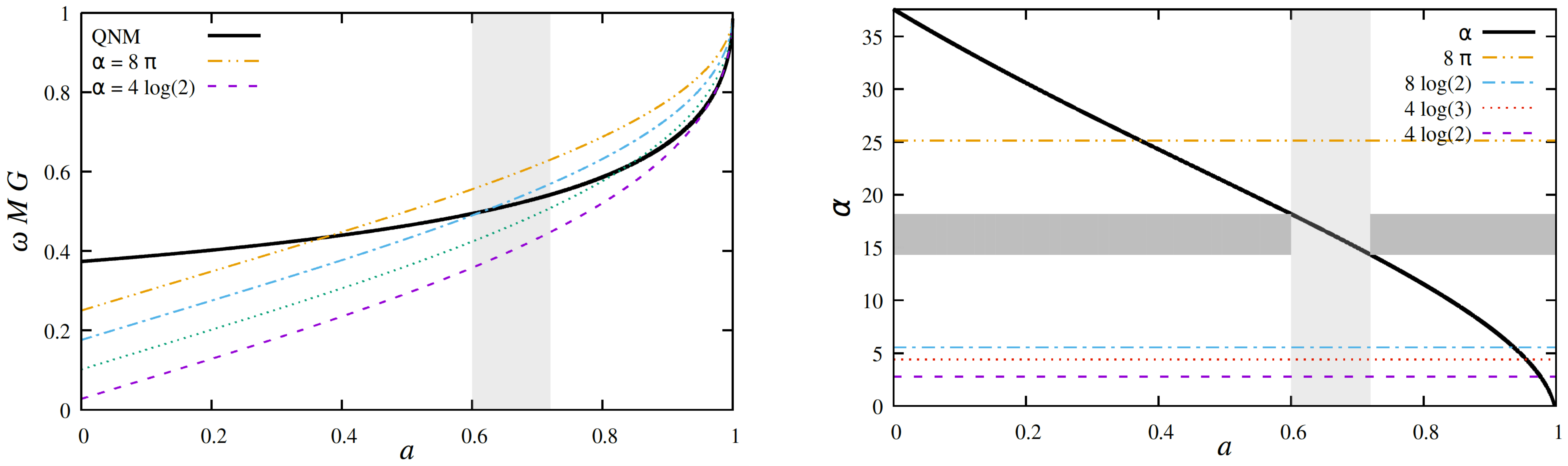
$$\Delta A = 16\pi G^2 M \left(1 + \frac{1}{\sqrt{1-a^2}}\right) \Delta M - \frac{8\pi G a}{\sqrt{1-a^2}} \Delta J.$$

$$\omega_n = -\frac{\Delta M}{\hbar}$$

$$\Delta J = -\hbar m$$

[1] Foit, Kleban CQG 36 (2019) 035006

CONSTRAINTS ON AREA QUANTIZATION

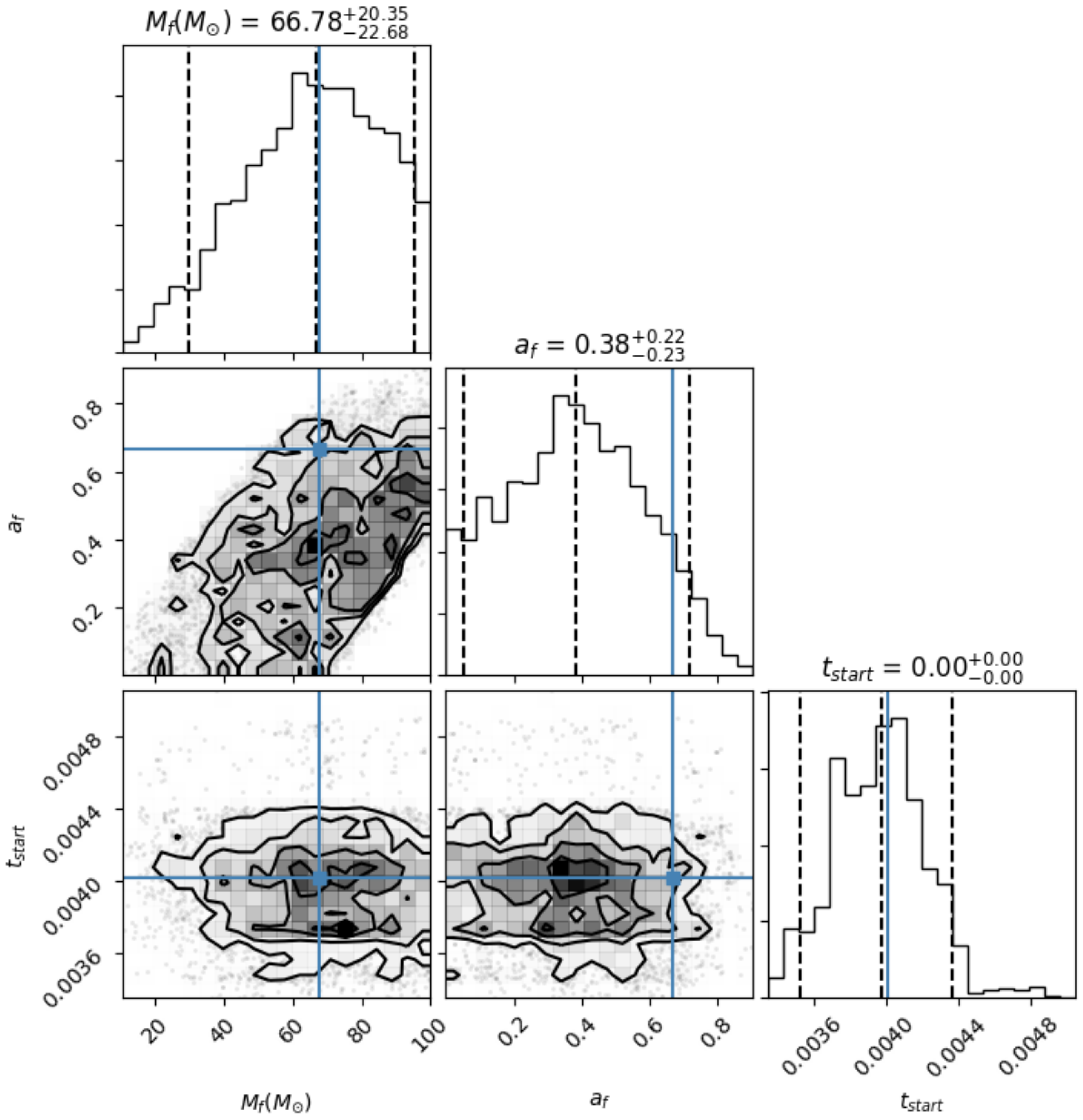


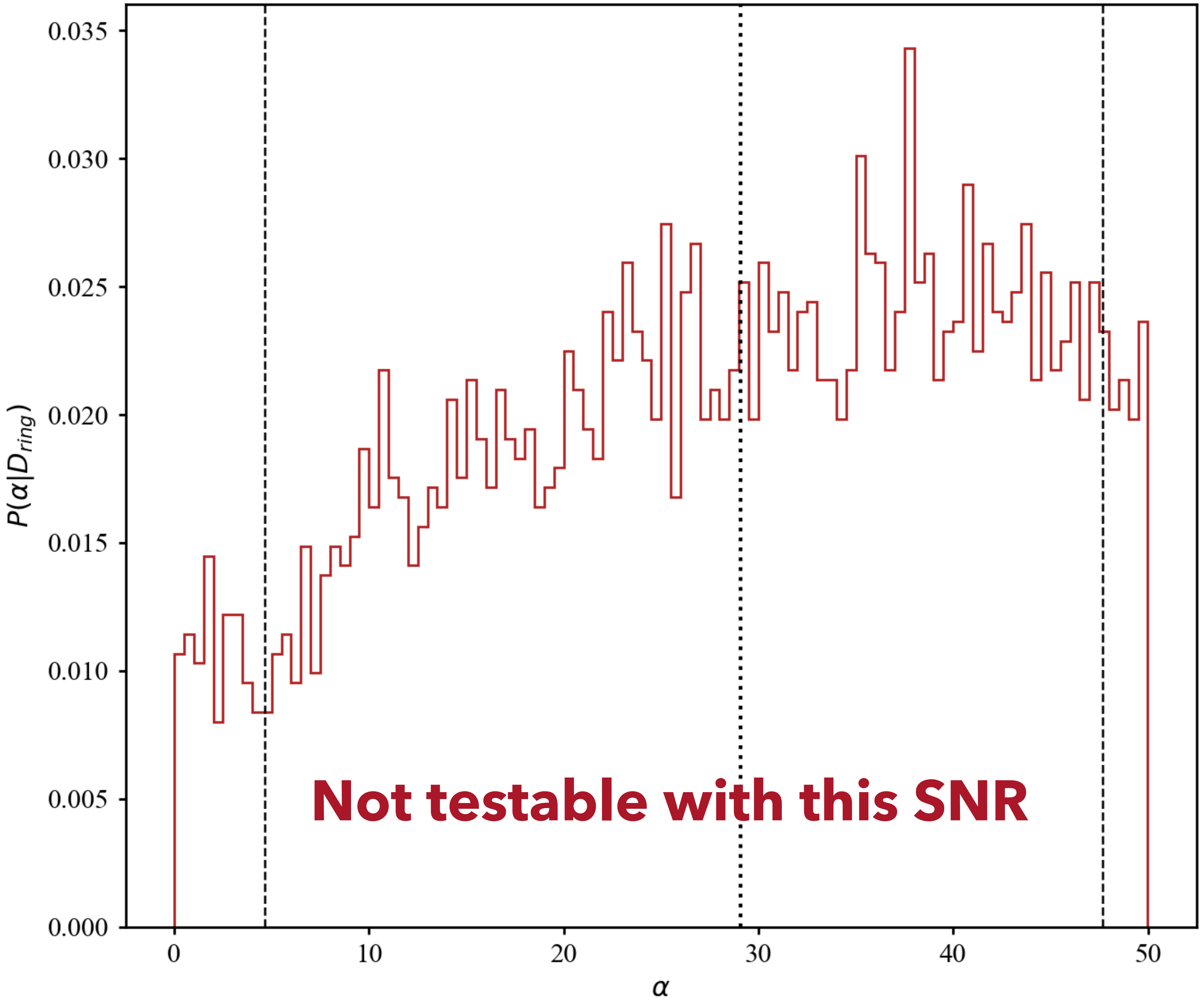
- Assume ***GR emission*** valid during the ***merger*** (questionable if we accept area quantization)

- ***Exclude*** a large portion of the ***proposals in the literature*** for α (including Bekenstein, Maggiore, Hod, Mukhanov)

AREA QUANTIZATION: CONSISTENT ANALYSIS ON GW150914

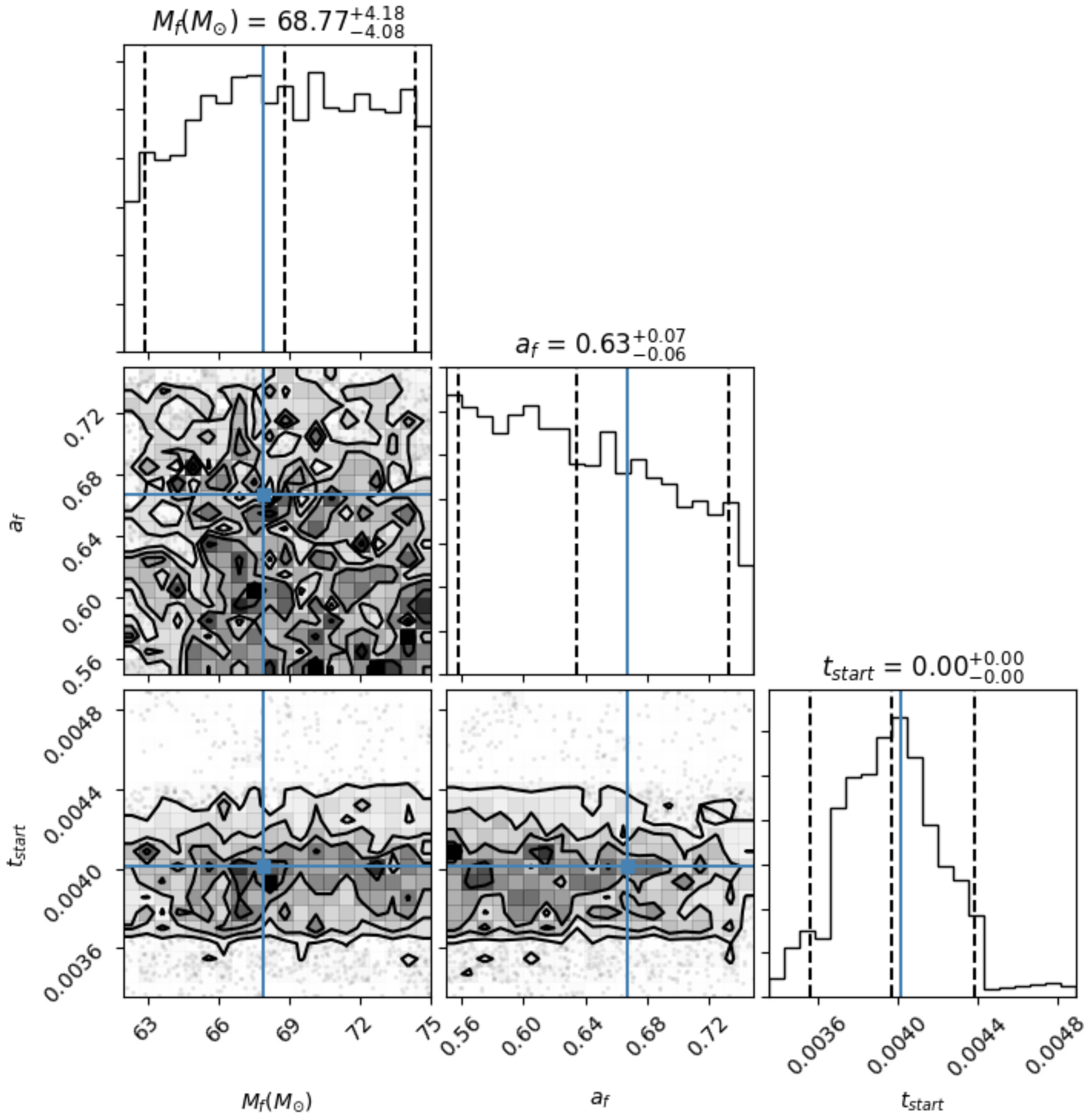
- A ***consistent analysis*** uses the ***quantized spectrum*** proposal to fit the ringdown signal and estimates (M_f, a_f, α) according to this spectrum:

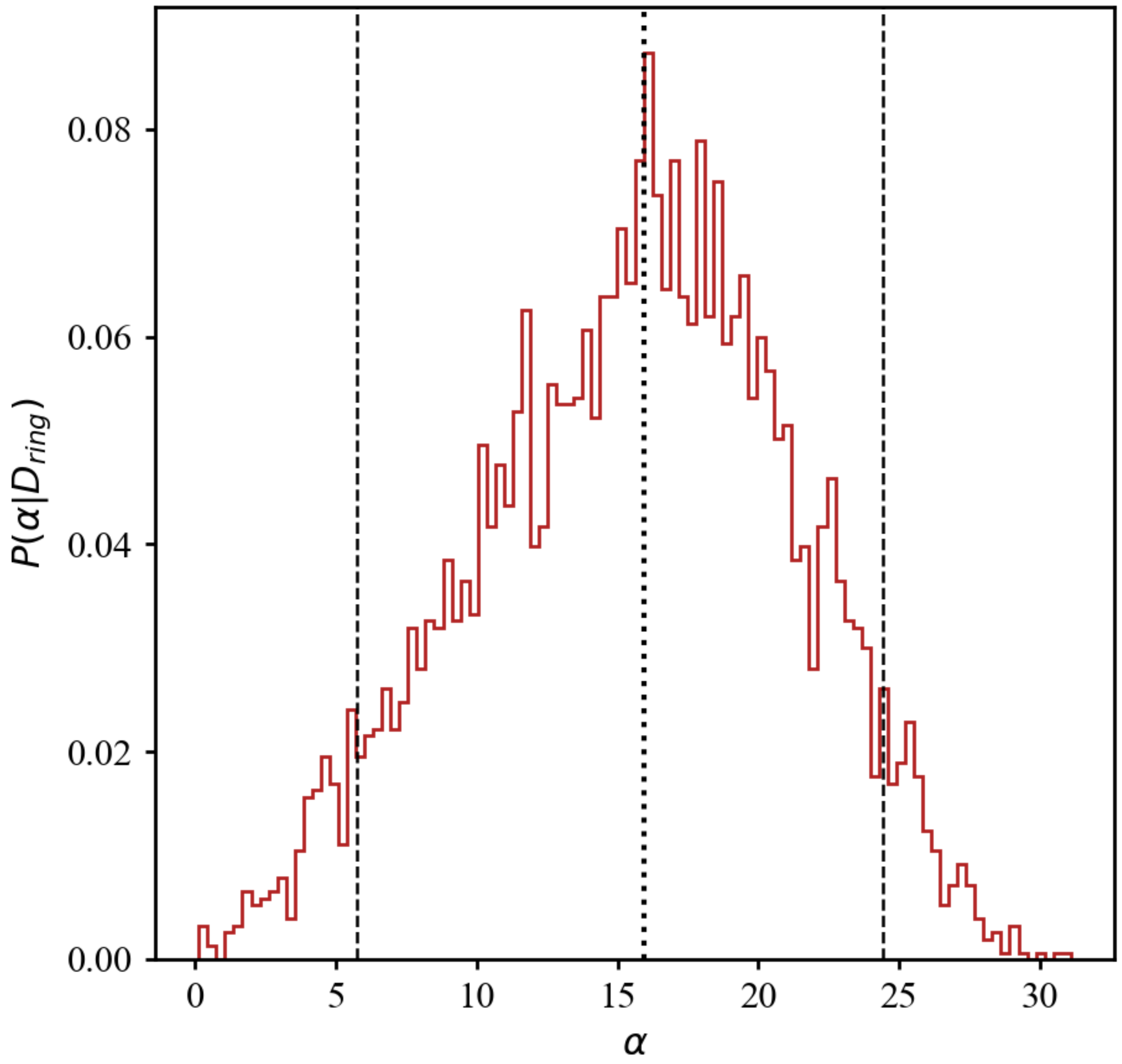




AREA QUANTIZATION: CONSISTENT ANALYSIS ON GW150914

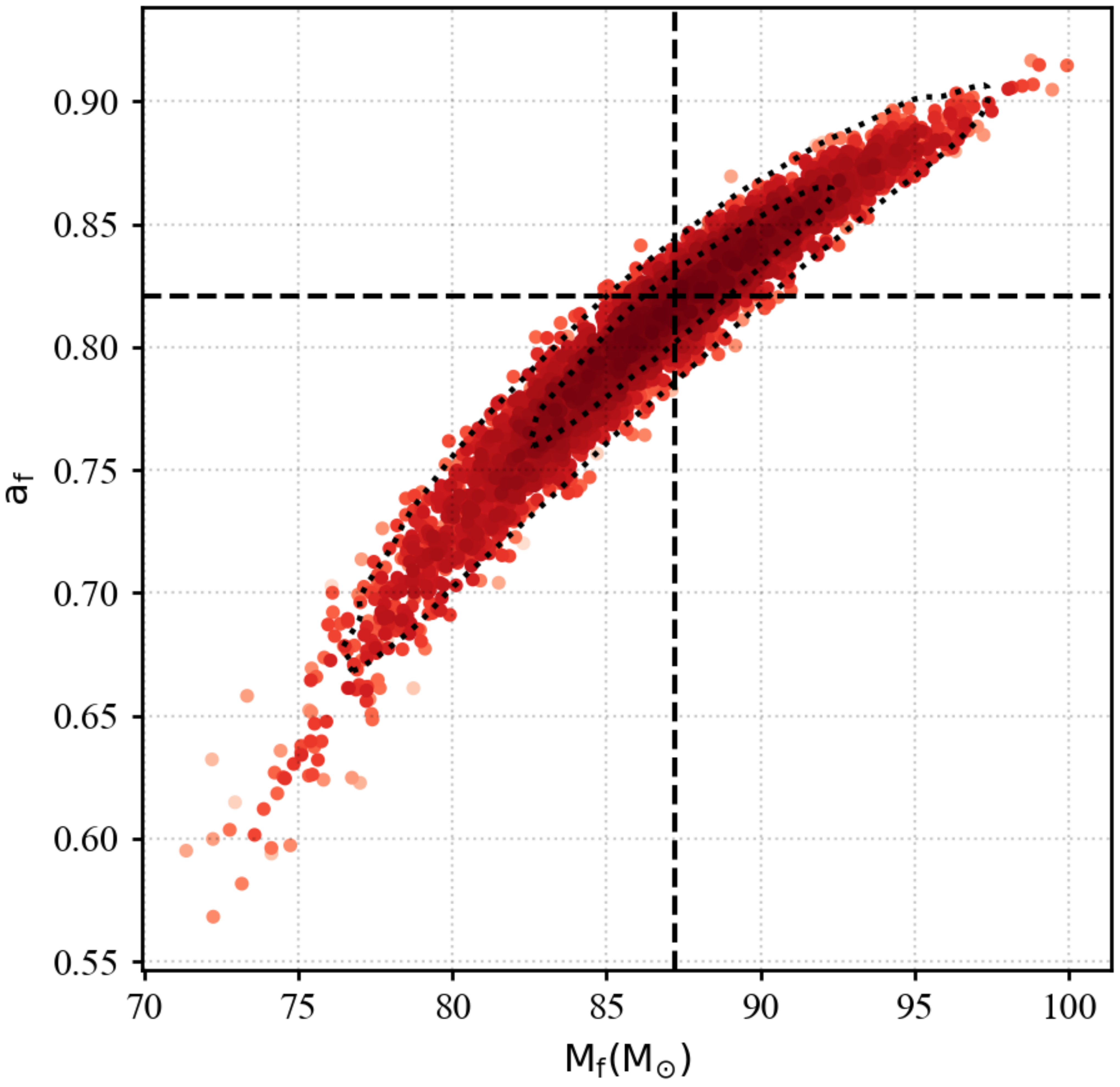
- What if we ***restrict the prior*** on (M_f, a_f) to the ***GR predicted*** values from ***inspiral***?





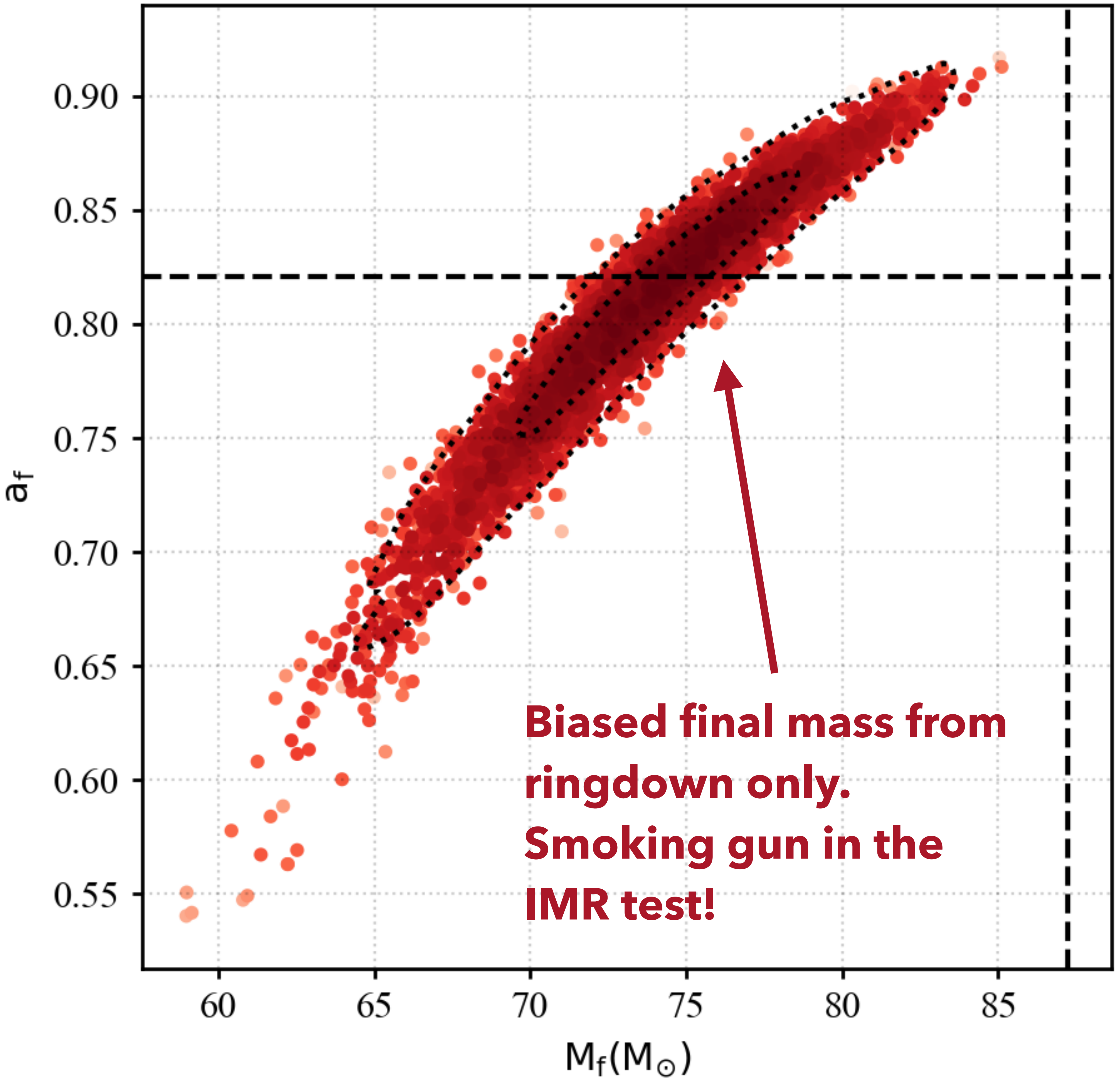
AREA QUANTIZATION: SMOKING GUN SIGNATURE

- ***Inject GR*** and recovery with GR:



- ***Inject quantized-area*** and recovery with GR:

Laghi+ (in prep)



BEYOND GR PHENOMENOLOGY

- What kind of phenomenology should we search for?
  - Echoes
  - Breaking of isospectrality?
  - Specific set of “hairs”?
  - …

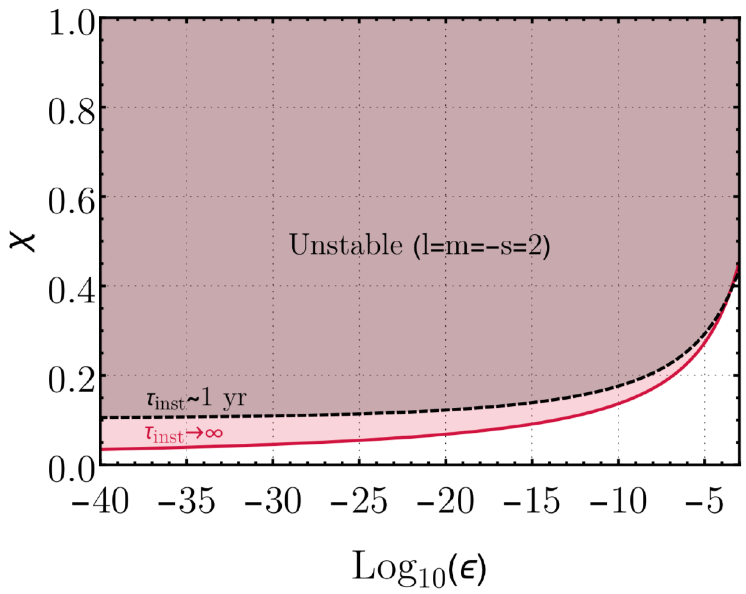
Ergoregion instability

Spinning horizonless compact objects are unstable above a critical value of the spin, in the absence of dissipation mechanisms.

Friedman, Commun. Math. Phys. 63, 243 (1978)
Cardoso et al., PRD **77**, 124044 (2008)
Chirenti et al., PRD **78**, 084011 (2008)
Pani et al., PRD **82**, 044009 (2008)

- **Kerr-like** black hole mimicker
  - Surface at $r_0 = r_+(1+\epsilon), \epsilon \ll 1$
  - Reflectivity coefficient $\mathcal{R}$

- **Perfectly reflecting surface** $|\mathcal{R}|^2 = 1$ ⟶ **Ergoregion instability**



EM et al., PRD **96**, 104047 (2017)

* For $\epsilon \to 0$, even slowly spinning black hole mimickers are unstable

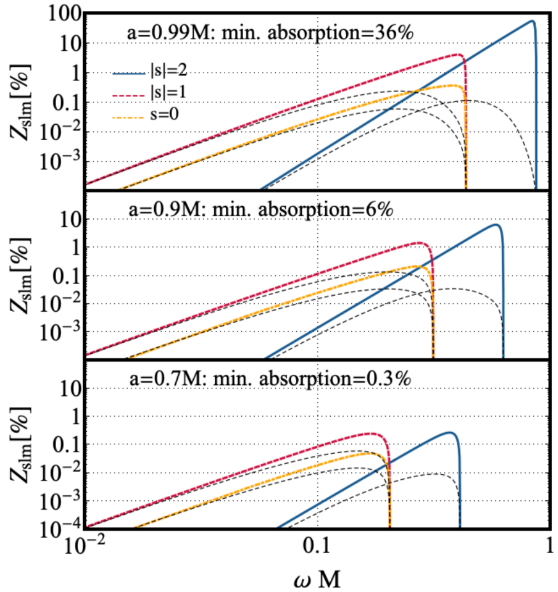
* The timescale of instability is short compared to astrophysical timescales

$$\tau_{\rm inst} \sim 30 \left(\frac{M}{10 M_\odot}\right) \mathrm{s}$$

Ergoregion instability

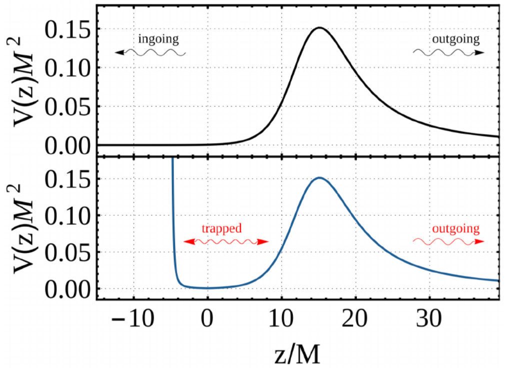
- **Partially absorbing surface** $|\mathcal{R}|^2 < 1$ ⟶ **The instability is quenched**

The minimum absorption rate to quench the instability is the maximum amplification factor of superradiance.



EM et al., PRD **99**, 064007 (2019)

Spin	Absorption
0.7	0.3%
0.9	6%
any	~60%



Cardoso et al., arXiV:1707.03021 (2017)

✱ How to model matter for a stable black hole mimicker?

✱ Frequency-dependent absorption? Wang et al., arXiv:1905.00446 (2019)

Echo template modelling

- **Templates for matched filters**

  * Time-domain template based on standard GR template $\mathcal{M}(t)$

$$h(t) \equiv A \sum_{n=0}^{\infty} (-1)^{n+1} \gamma^n \mathcal{M}(t + t_{\rm merger} - t_{\rm echo} - n\Delta t_{\rm echo}, t_0)$$

Abedi et al., PRD **96**, 082004 (2017)

- 5 parameters
- Phenomenological
- No frequency modulation

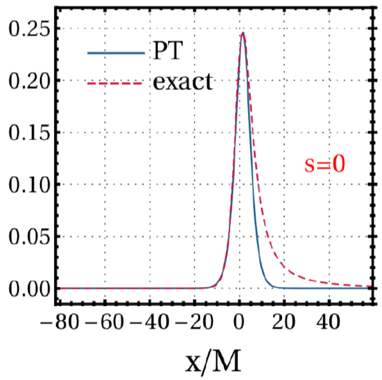
  * Time-domain sine Gaussians Maselli et al., PRD **96**, 064045 (2017)

$$h(t) \equiv \sum_{n=0}^{N-1} (-1)^{n+1} \mathcal{A}_{n+1} e^{-y_n^2/2\beta_1^2} \cos(2\pi f_1 y_n)$$

- Interference of trapped modes
- Many parameters
- Phenomenological

  * Frequency-domain template by approximating the BH potential

Testa et al., PRD **98**, 044018 (2018)



$$\tilde{Z}^+(\omega) = \tilde{Z}^+_{BH}(\omega) + \mathcal{K}(\omega)\tilde{Z}^-_{BH}(\omega)$$

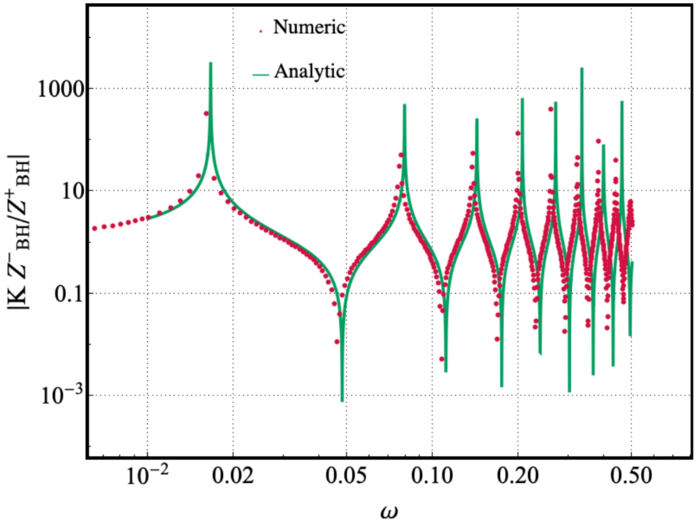
$$\mathcal{K}(\omega) = \frac{\mathcal{T}_{BH}\mathcal{R}e^{-2ikx_0}}{1 - \mathcal{R}_{BH}\mathcal{R}e^{-2ikx_0}}$$

Mark et al., PRD **96**, 084002 (2017)

- 2 parameters
- Physical interpretation
- Extension to spinning, gravitational cases difficult

Echo template modelling

- **Analytical template in low-frequency** EM, Testa, Bhagwat, Pani, work in progress



- Spinning and gravitational cases
- It captures low-frequency echoes which contributes more to the SNR
  $$\omega_R - m\Omega \sim |\log \epsilon|^{-1}$$
- It breaks down at $\omega \sim \omega^{BH}_{QNM}$

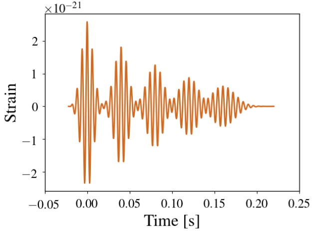
Unmodelled searches

- Searches with Fourier windows Conklin et al., PRD **98**, 044021 (2018)
- Wavelets for burst searches Tsang et al., PRD **98**, 024023 (2018)

Morphology-independent search for echoes

- BayesWave is an algorithm to search for unmodelled coherent signals.
  Cornish et al., Class. Quantum Grav. 32, 135012 (2015)
- Wavelets of a comb of sine-gaussians (rather than Morlet-Gabor) are used for reconstruction.

1. A, Amplitude
2. f_0, Central frequency
3. τ, Decay time
4. t_0, Central time
5. ϕ_0, Phase offset
6. dt, Time separation
7. $d\phi$, Fixed phase shift
8. γ, Damping (in A)
9. w, Widening (in τ)



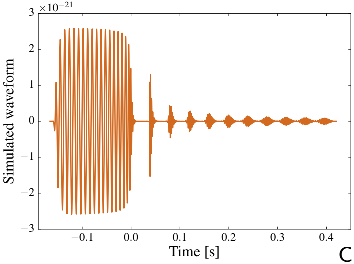
Detector Output = Signal + Glitch + Gaussian Noise

- Signal model: $F^{+}_{\mathrm{detector}}(\theta,\phi,\psi)h_{+}(t-t_{arr}) + F^{\times}_{\mathrm{detector}}(\theta,\phi,\psi)h_{\times}(t-t_{arr})$
  - $d.o.f. = 9N_{wavelet} + 4$
- Glitch model: independent sum of wavelets in each detector
  - $d.o.f. = 9N_{wavelet}N_{detector}$
- Noise model: estimated by BayesLine algorithm

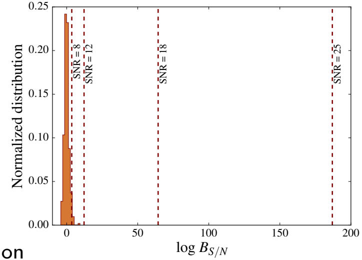
If a coherent signal is present in the data, then typically a smaller number of basis functions will be needed to reconstruct it than to reconstruct incoherent glitches, leading to an Occam penalty for the glitch model.

Studies on simulated signal

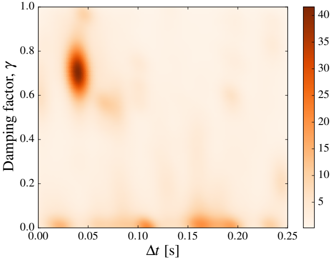
Signal

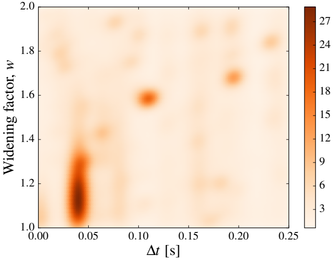


Background and foreground

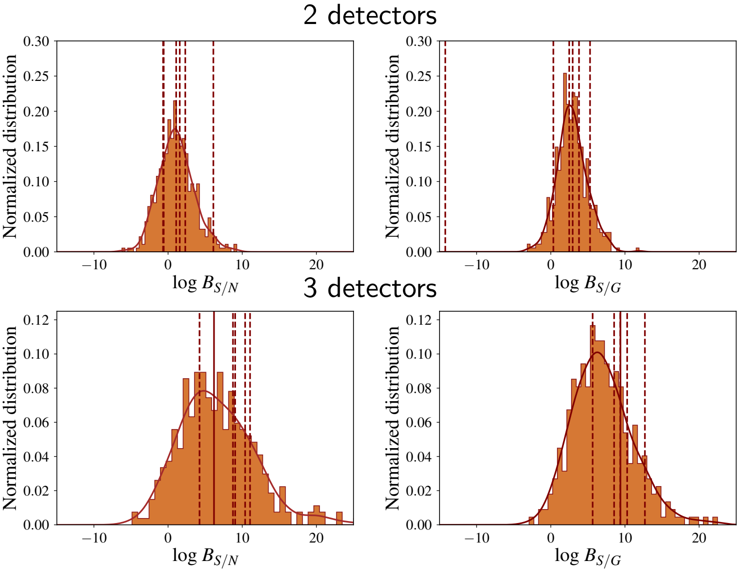


Characterisation

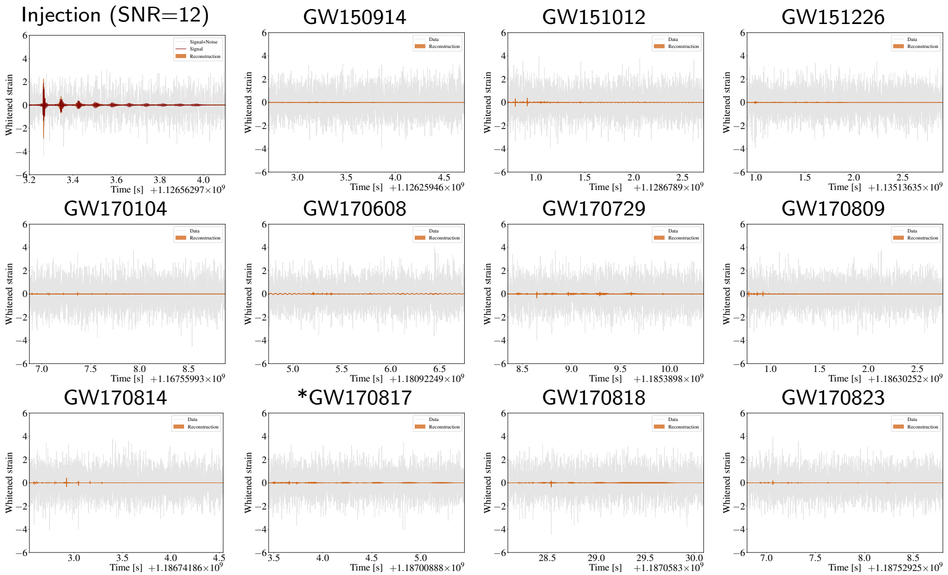




GWTC-1 result



Reconstructions from injection and all GWTC-1 detections

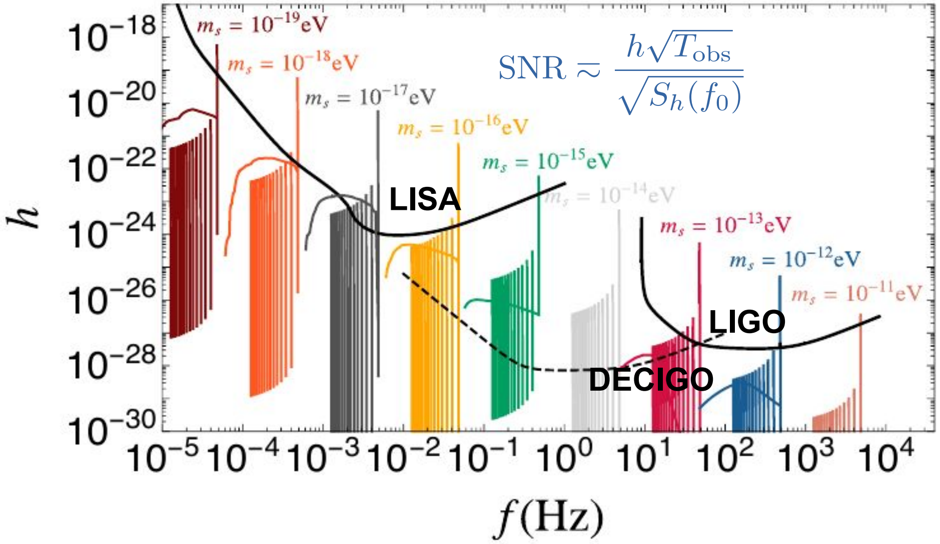


EXG 1: the nature of compact objects

- **ECO coalescences: [short blanket problem]**
    - **IMR waveforms:** for boson stars? Anisotropic stars? Other ECOs?
    - **Echoes:** improve current templates; other approaches? [bursts, resonances]
- **Axion-like particles & superradiance:** vectors? Tensors?
- **Tidal effects:** should we model them better? (see WFM session)
- **EMRIs?** (different multipoles, no horizon, Love numbers, resonances)
    - Current projected bounds too optimistic? [simplistic waveforms, enchilada problem]
    - 1 radian requirement: enough for PE? And for tests of GR? Prescription?
    - Quadrupolar and tidal corrections beyond PN modelling? Or is enough?
    - Compare bounds on ECOs with those coming from 3G
- **Ringdown**: general framework, role of overtones, extra modes (~new polarization)
- **DM environment:** waveforms?
- **PBHs: ?**

GW periodic signal from axions

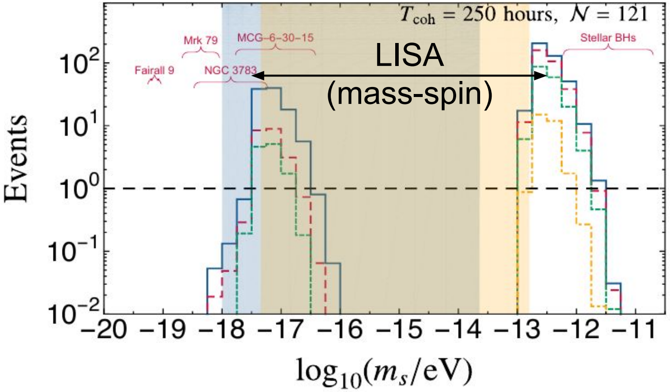
Brito+, PRL 2017, PRD 2017



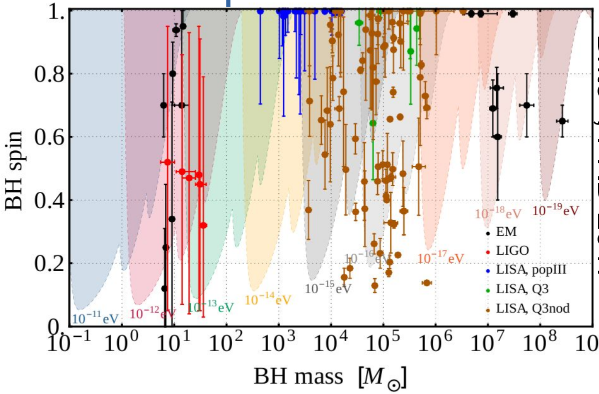
Multiband GW constraints on ultralight fields

GW signatures of axions

- Direct detection

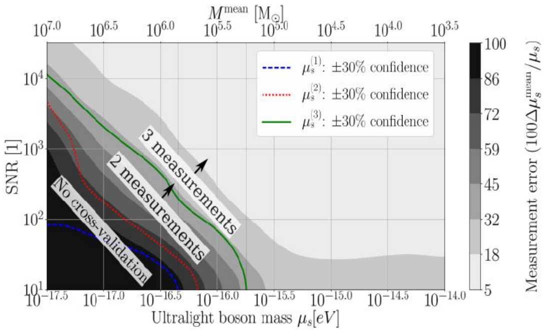


- Mass-spin measurements

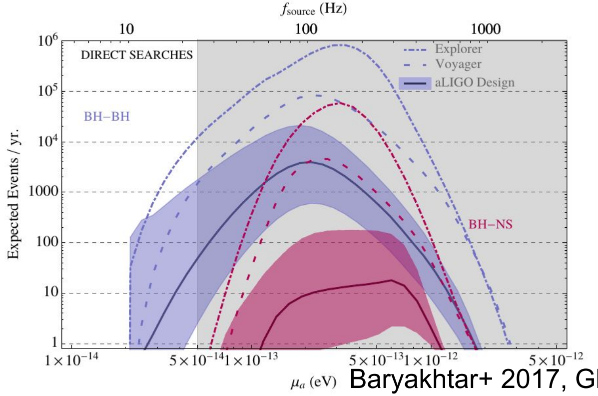


Brito+, PRD 2017

EMRIs & resonances

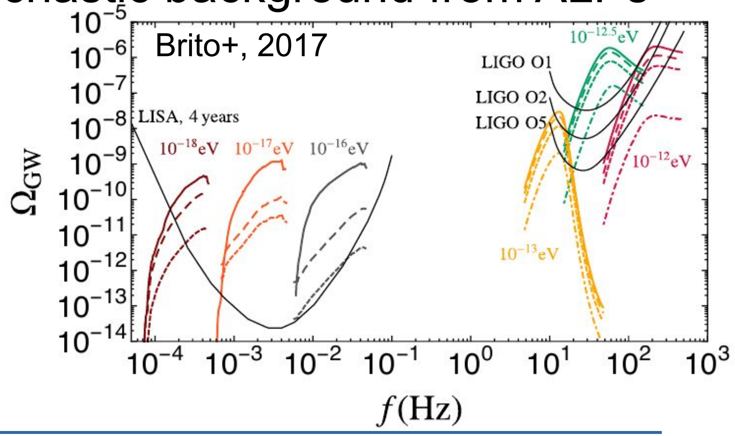


- Follow-up searches



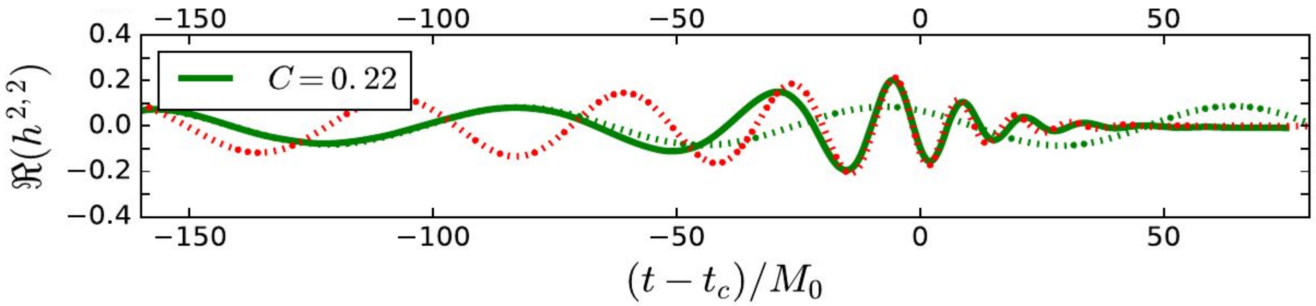
Baryakhtar+ 2017, Ghosh+, 2018

- Stochastic background from ALPs



BBSs or BBHs?

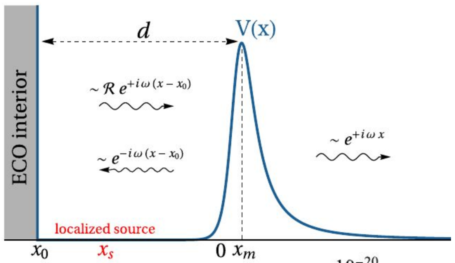
- Can binary boson stars mimic the **full** signal from BBH coalescence?

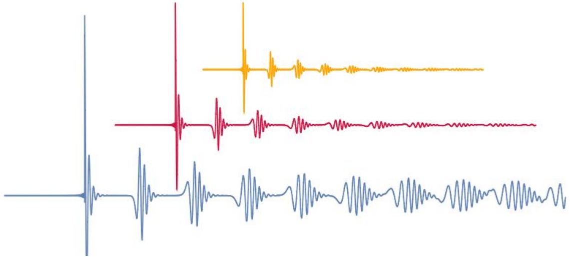


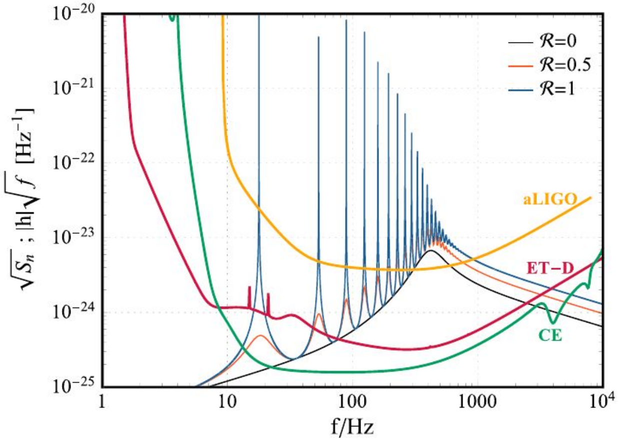
[Palenzula, PP+, PRD96, 104058 (2017)]

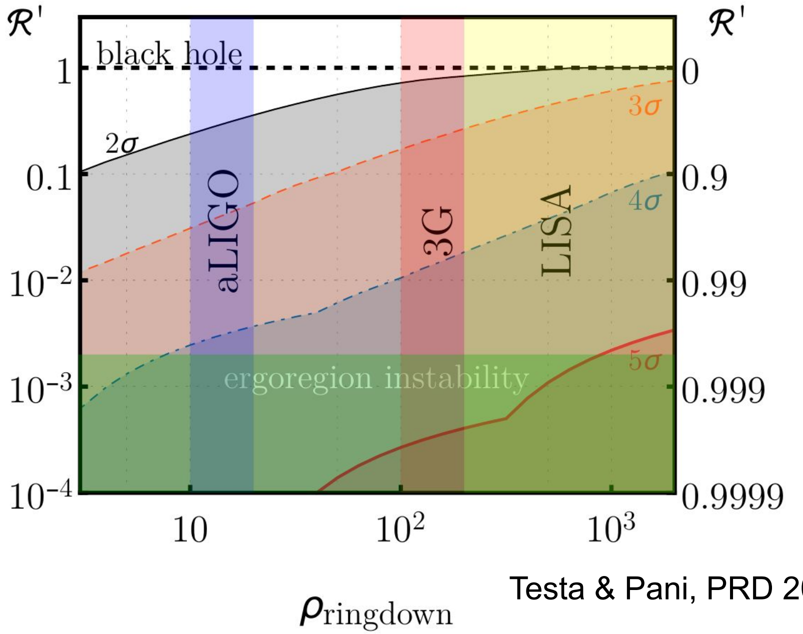
- “Short-blancket” problem: mimicking IMR signal of BBHs is hard

GW echoes: detectability









Testa & Pani, PRD 2018

- Echoes might be louder than ringdown, signal strongly depends on reflectivity
- Several developments, but better modeling of echoes waveforms needed