Primordial Black Holes or else?
Tidal tests on subsolar gravitational-wave observations

Speaker:

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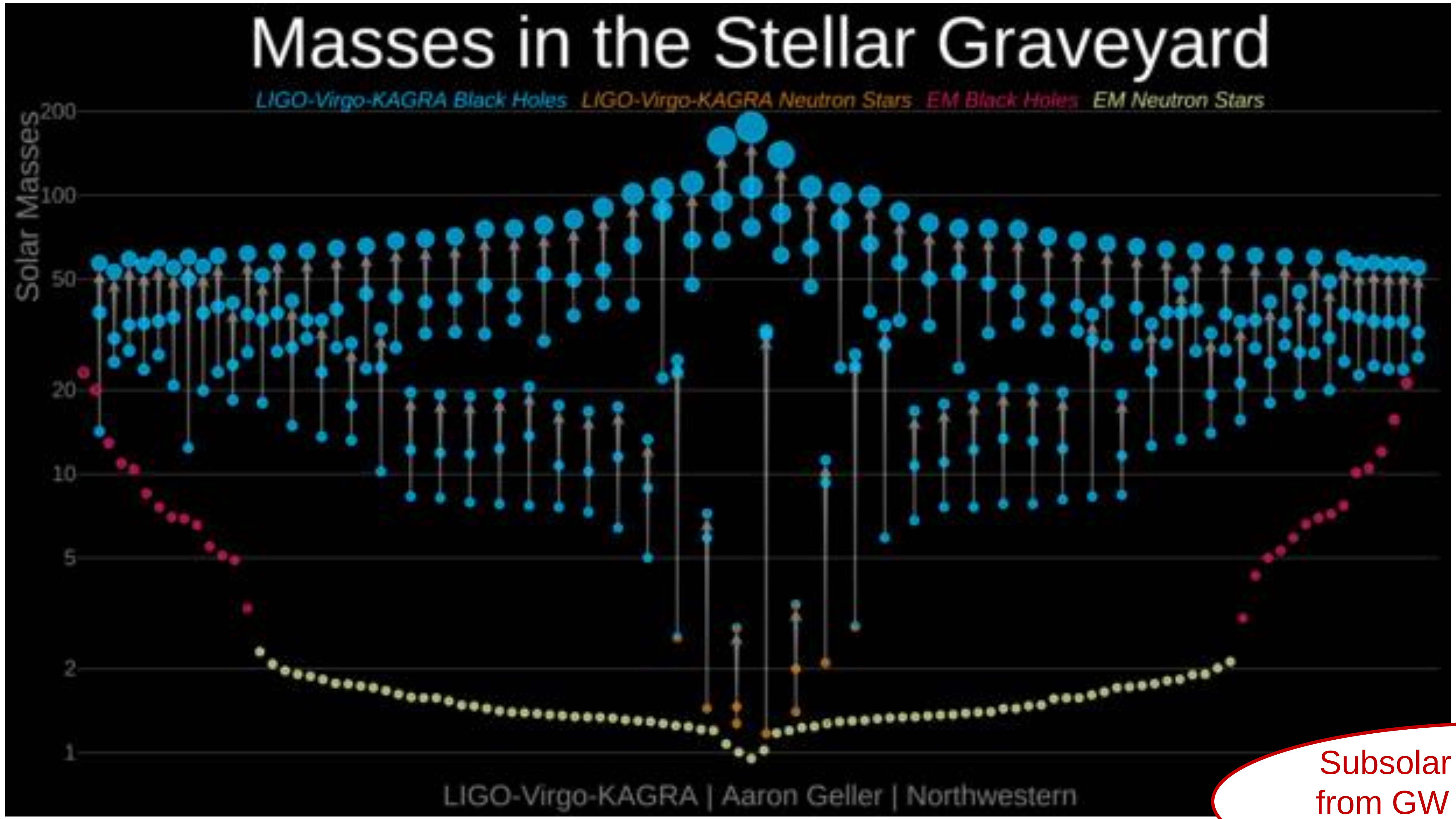
Based on:
F. Crescimbeni, G. Franciolini, P. Pani, and A. Riotto, *Phys.Rev.D* 109 (2024) 12, 124063.

Introduction

- During the first 3 observing runs, LVK collaboration detected nearly 90 events → nearly 100 hundred for the fourth observing runs, and many more are expected in the future with 3G detectors.



Source ref. www.ligo.caltech.edu/MIT/image/ligo20211107a

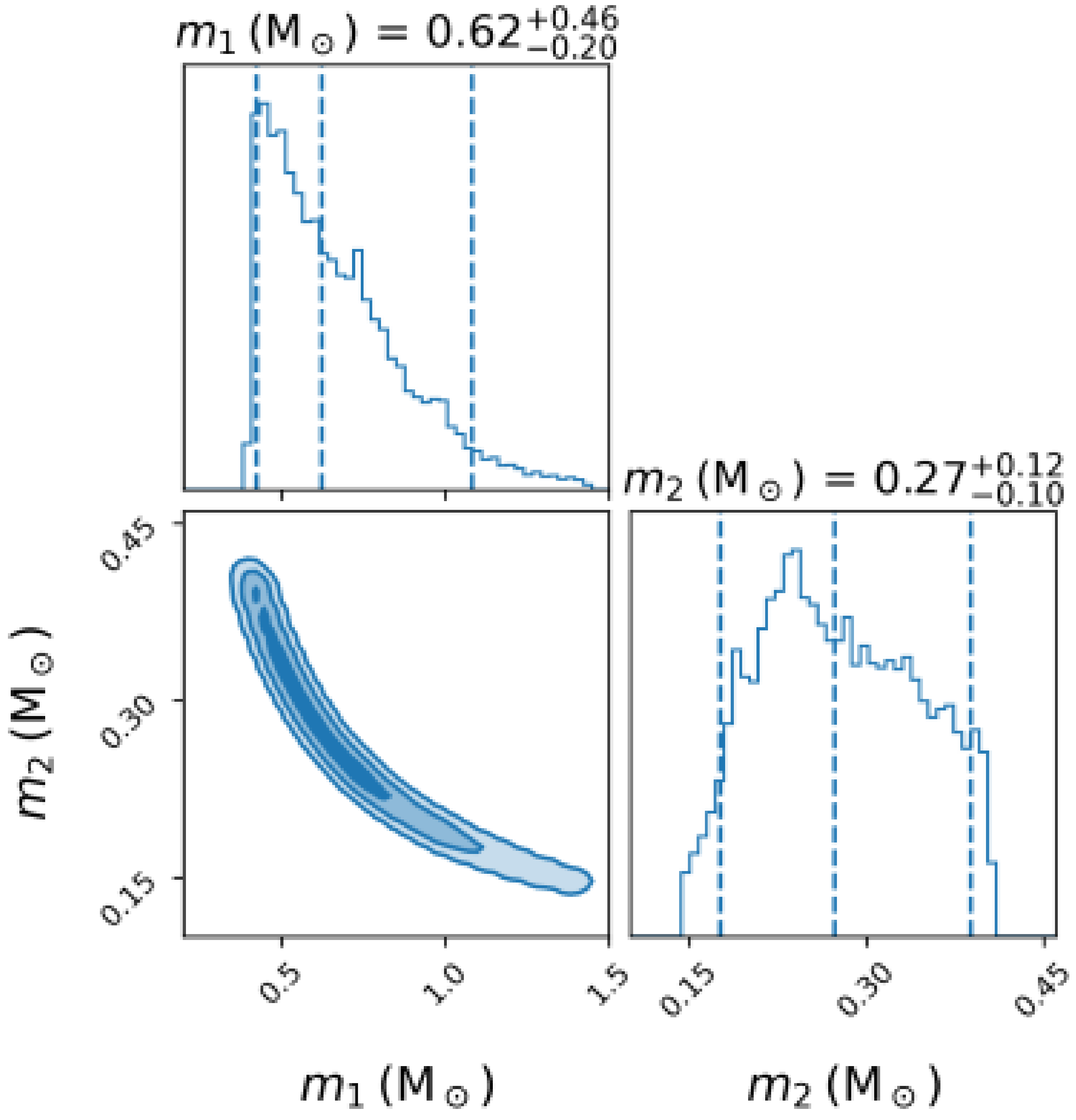
Subsolar compact objects from GW observations still missing!

Putative detections of subsolar binaries

- The observation of at least a subsolar mass (SSM) object in a binary black hole merger could be a signature of primordial black holes (PBHs) detection.

- Subsolar mergers searches have been performed thought the years, finding no conclusive evidences [LVK,'18; LVK '19; LVK '22; Nitz-Wang, 2102.00868].

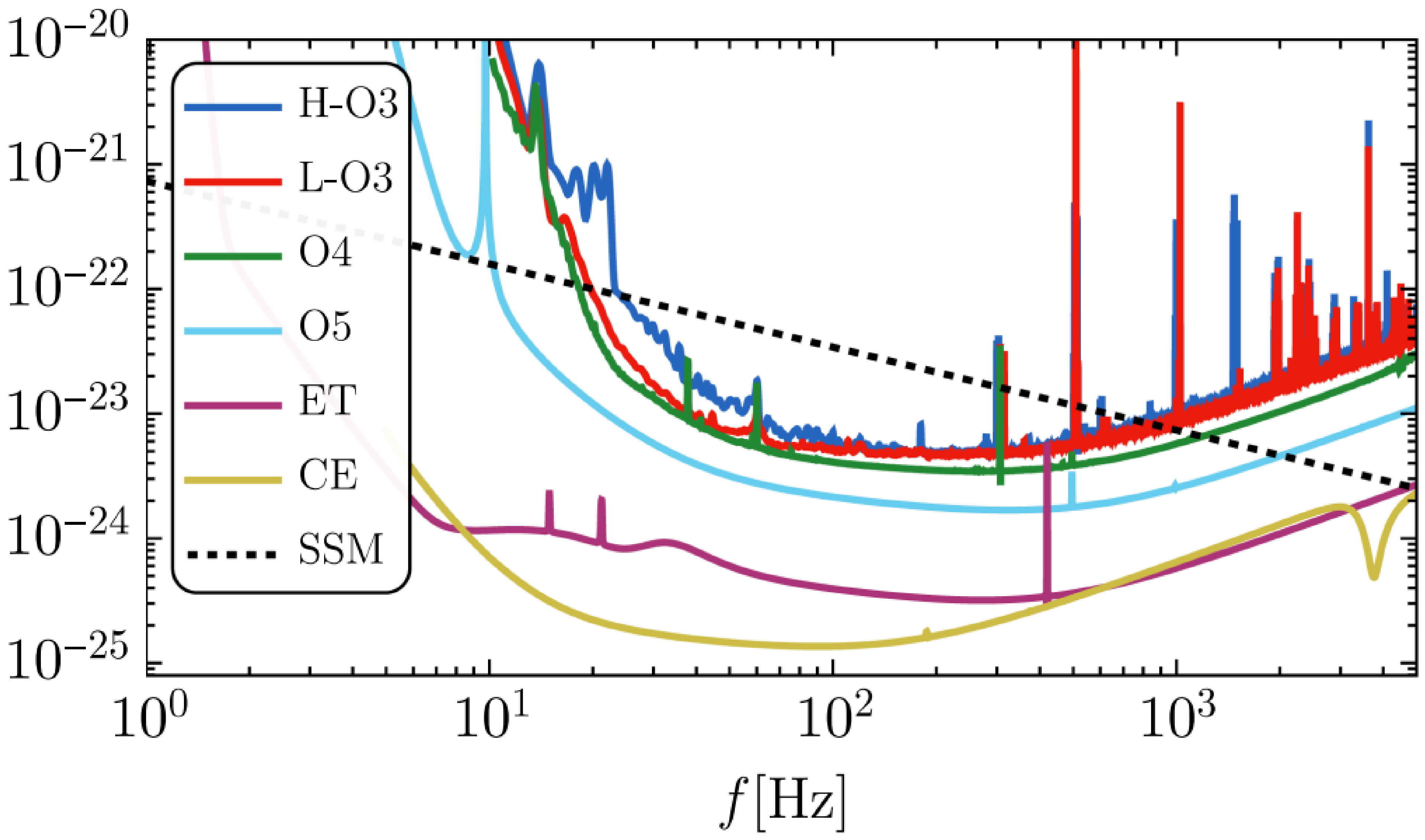
- SSM-like trigger (denoted as SSM200308) detected during O3 was recently reanalyzed [Prunier+, 2311.16085] under the assumption that it was a binary of primordial black holes (PBHs).



Source ref. Prunier+, 2311.16085

Objectives of this work

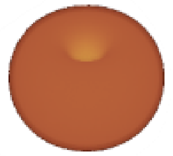
- A signal compatible with a subsolar merger could be observed already during the ongoing O4 run of the LIGO/Virgo/Kagra (LVK) Collaboration.
- We investigate whether current and future experiments would have sufficient sensitivity required to detect SSM200308-like events.
- Distinguish PBHs from other astrophysical systems or more exotic competitors in the SSM range.



SSM candidates

- Astrophysics objects: Light neutron stars, white dwarfs;

- Exotic compact objects: Q-balls, boson stars, fermionic stars;

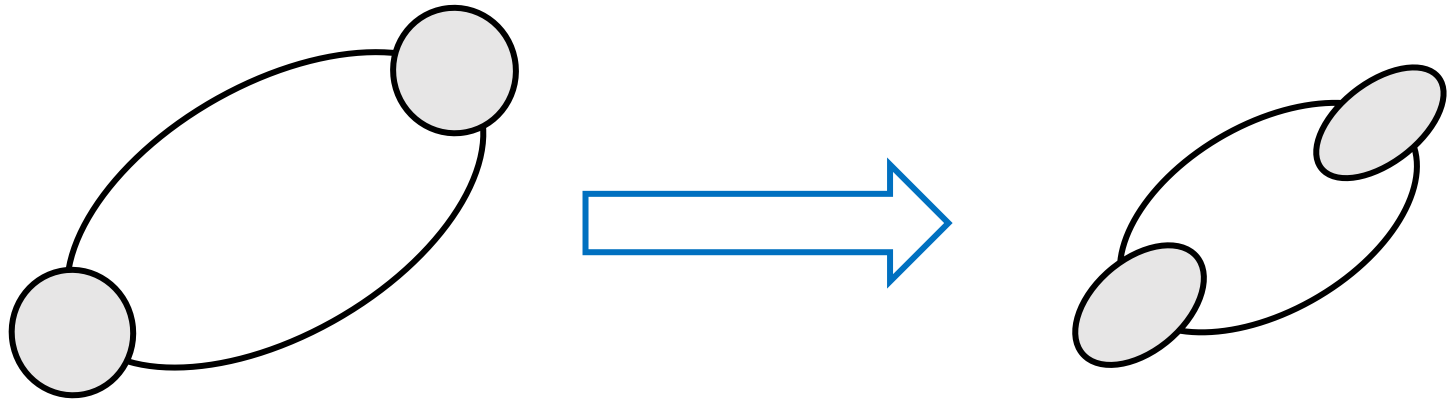


- Primordial black holes.

New physics

$$\Lambda = \frac{2}{3} k_2 \left(\frac{Gm}{R} \right)^{-5}$$

Non-zero tidal deformabilities

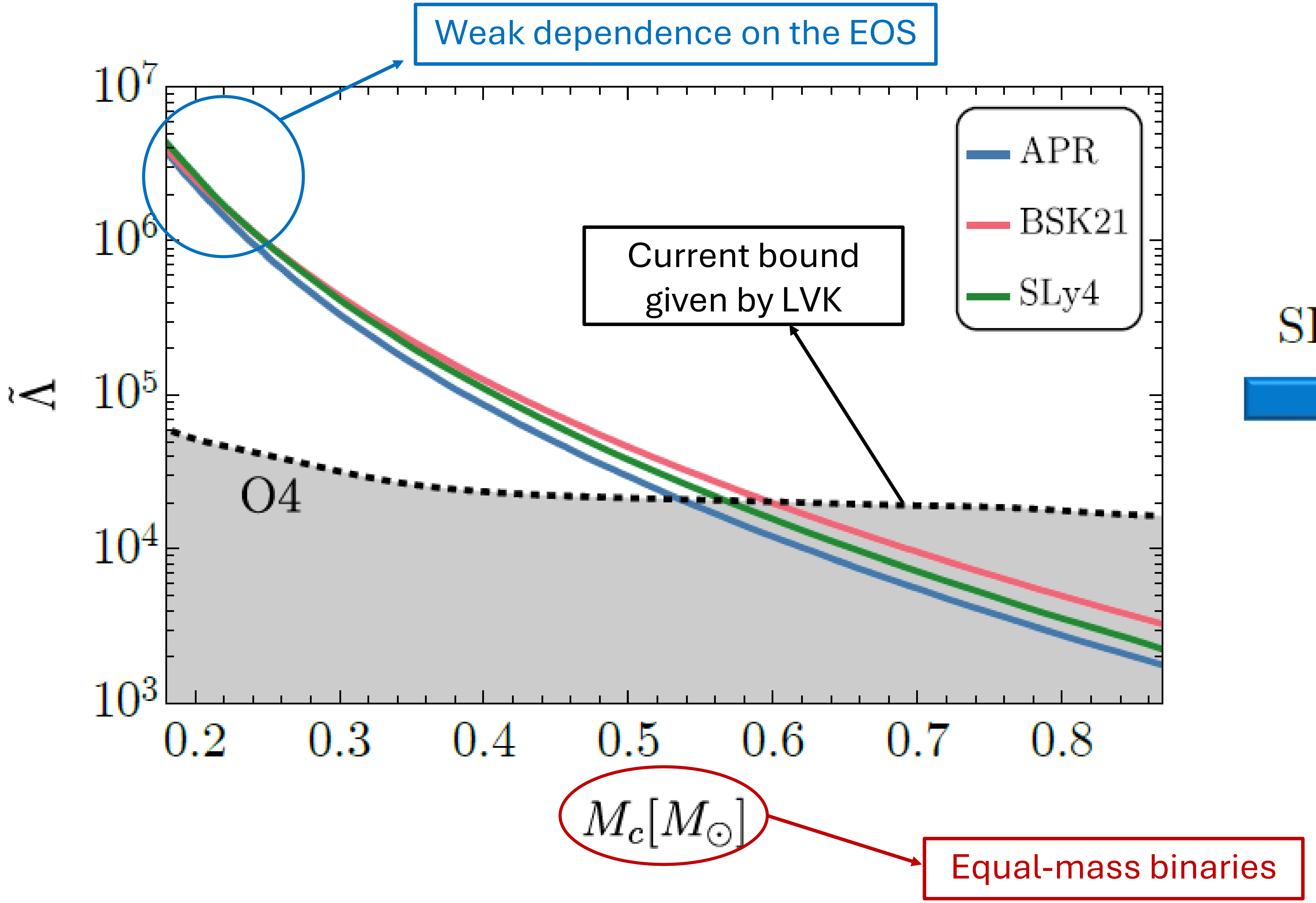


$$\Lambda = 0$$

Non-deformable (symmetry properties)

Tidal deformabilities for neutron stars

- Subsolar objects are less sensitive for EOS effects!



SLy4 →

$$\Lambda = 7.3 \cdot 10^4 \left(\frac{m}{0.5 M_\odot}\right)^{-4.7}$$

Tidal deformabilities for boson stars

- Assume for instance boson stars (BSs) with quartic potential [Pacilio+, 2007.05264]:

$$V(|\phi|) = \frac{\mu^2}{2}|\phi|^2 + \frac{\lambda}{4}|\phi|^4$$

$$\frac{m}{m_B} = \frac{\sqrt{2}}{8\sqrt{\pi}}\left[-0.828 + \frac{20.99}{\log\Lambda} - \frac{99.1}{(\log\Lambda)^2} + \frac{149.7}{(\log\Lambda)^3}\right] \quad \Longleftrightarrow \quad \begin{aligned} &\lambda \gg \mu^2 \\ &m_B = \sqrt{\lambda}/\mu^2 \end{aligned}$$

- Invert relation to find:

$$\Lambda = \Lambda(m/m_B)$$

- In this model, BSs exist for $m/m_B < 0.06$, which gives $\Lambda > 289$.

- Λ can span many orders of magnitude as the mass deviates from its maximum value (e.g., $\Lambda \approx 1.7\times10^6$ for $m/m_B = 0.02$).

- An upper bound on Λ can rule out some models!

Waveform modeling of SSM binaries

- We adopt a TaylorF2 waveform [Damour+, 0010009] which includes also possible tidal disruption effects modeling:

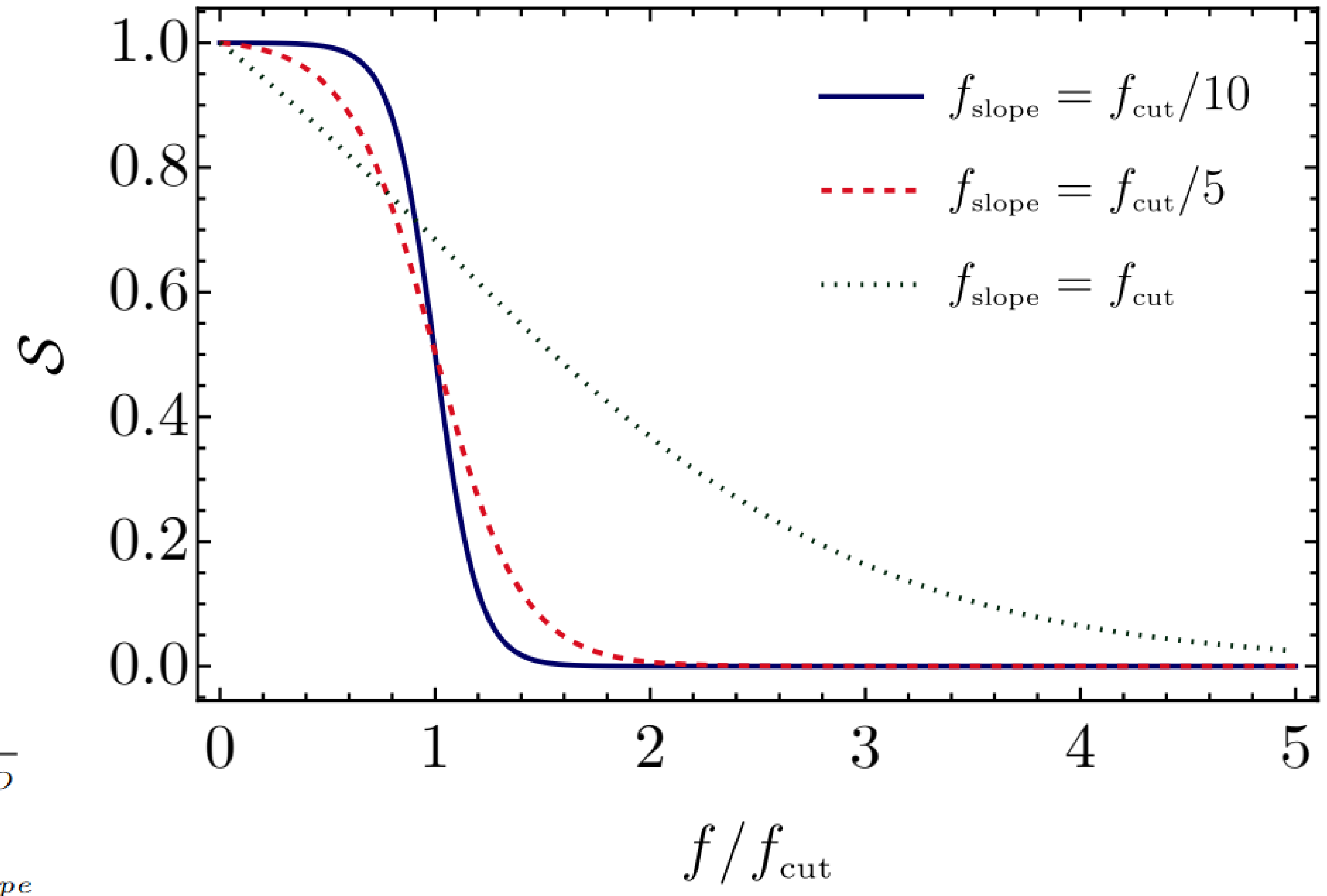
Amplitude: scales as the inverse of distance

Phase: contains tidal deformability

$$\tilde{h}(f) = \mathcal{A} f^{-\frac{7}{6}} \mathcal{S}(f) e^{i\psi(f)}$$

Tapering smoothing: keeps into account possible tidal disruption

$$\mathcal{S}(f) = \left[\frac{1 + e^{-\tilde{\lambda}_f/\delta\tilde{\lambda}_f}}{1 + e^{(f/f_{\rm ISCO} - \tilde{\lambda}_f)/\delta\tilde{\lambda}_f}} \right] \Longleftrightarrow \begin{cases} \tilde{\lambda}_f = \frac{f_{cut}}{f_{ISCO}} \\ \delta\tilde{\lambda}_f = \frac{f_{slope}}{f_{ISCO}} \end{cases}$$



Source ref. De Luca+, 2212.03343

Waveform modeling of SSM objects

- GW phase (augmented at 5PN and 6PN) [Kidder-Will, 9211025; Wade+, 1402.5156] :

$$\underbrace{\psi(x) = \psi_{\rm pp}(x)}_{\text{Point-particle phase}} + \underbrace{\delta\psi_{\rm tidal}(x)}_{\text{Tidal phase}} \quad \Longleftrightarrow \quad \delta\psi_{\rm tidal} = \frac{3}{128\eta x^{5/2}}\left[\left(-\frac{39}{2}\tilde{\Lambda}\right)x^5 + \left(-\frac{3115}{64}\tilde{\Lambda} + \frac{6595}{364}\sqrt{1-4\eta}\,\delta\tilde{\Lambda}\right)x^6\right]$$

- Some definitions...

$$\tilde{\Lambda} = \frac{8}{13}\left[\left(1+7\eta-31\eta^2\right)(\Lambda_1+\Lambda_2) + \sqrt{1-4\eta}\left(1+9\eta-11\eta^2\right)(\Lambda_1-\Lambda_2)\right]$$

$$\delta\tilde{\Lambda} = \frac{1}{2}\left[\sqrt{1-4\eta}\left(1-\frac{13272}{1319}\eta+\frac{8944}{1319}\eta^2\right)(\Lambda_1+\Lambda_2) + \left(1-\frac{15910}{1319}\eta+\frac{32850}{1319}\eta^2+\frac{3380}{1319}\eta^3\right)(\Lambda_1-\Lambda_2)\right]$$

Injection simulations of SSM200308-like systems

PBH binary injections + recovery (Bayesian inference + Fisher analysis):

- Inject SSM200308 parameters + zero tides and neglect tapering → $\tilde{\Lambda} = \delta\tilde{\Lambda} = 0$ and $\tilde{\lambda}_f = 1$

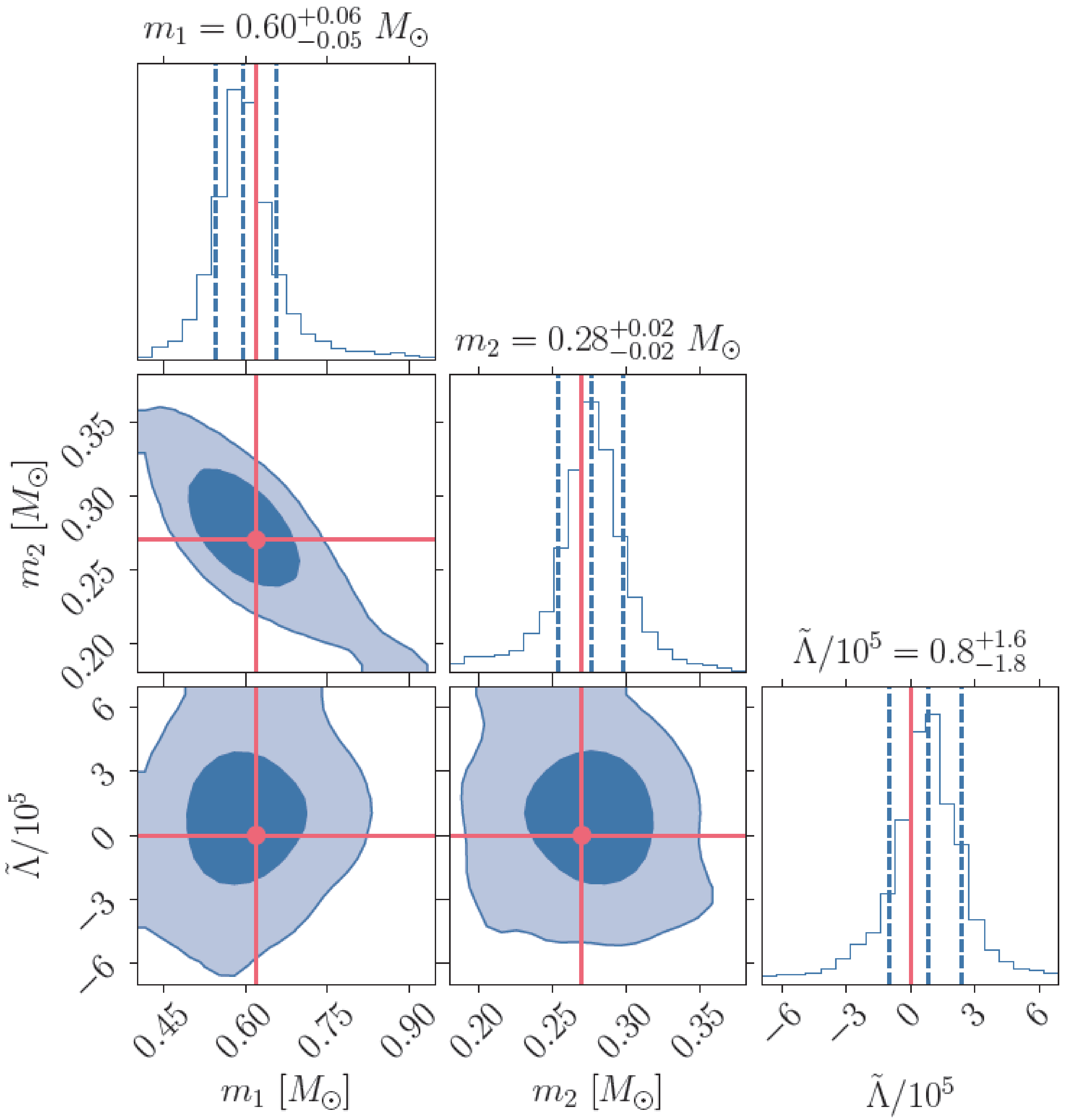
NS binary injections + recovery (Fisher):

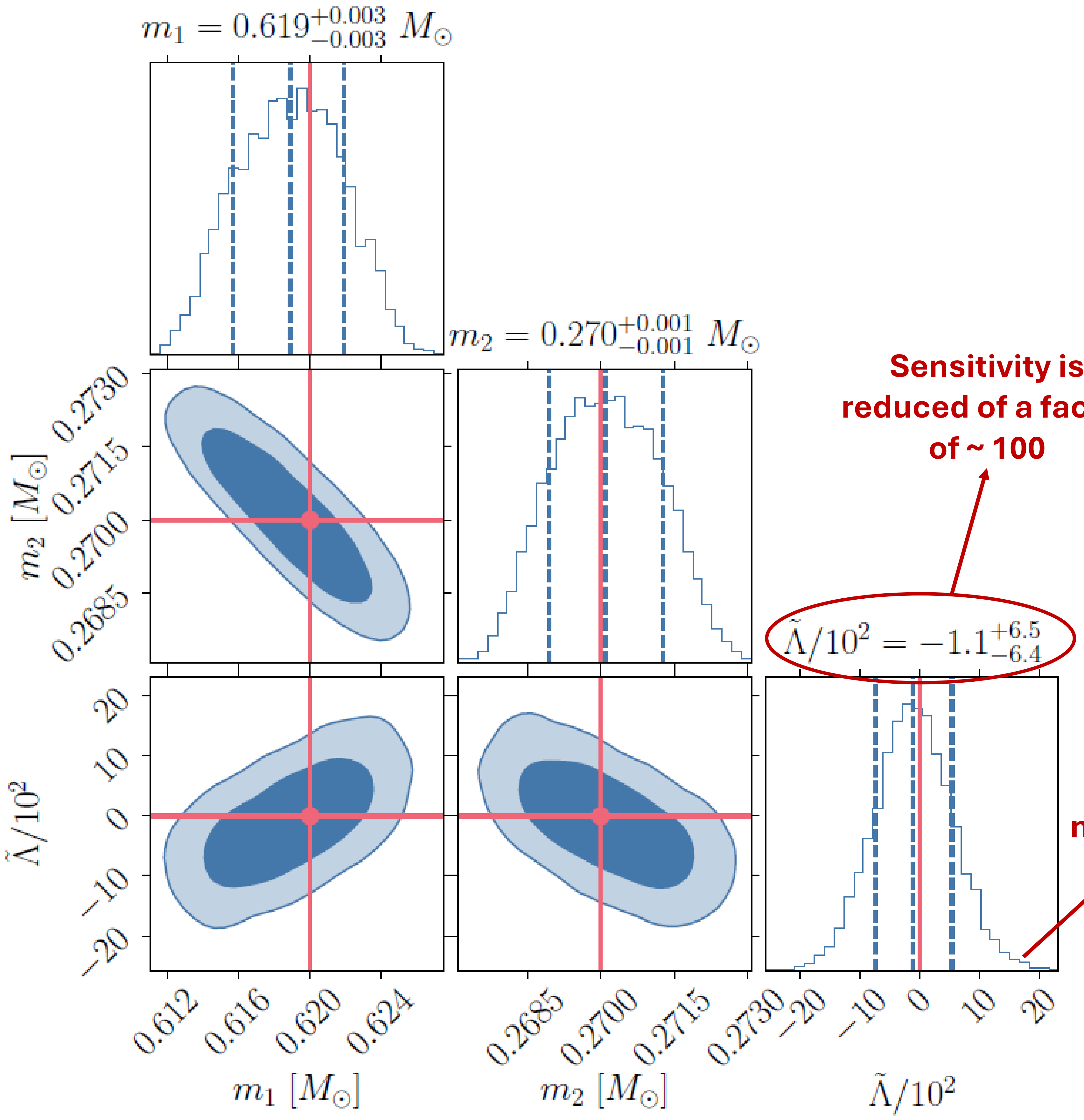
- Inject non-zero tides assuming SLy4 EOS → $\tilde{\Lambda} = 1.5 \cdot 10^5 \quad \delta\tilde{\Lambda} = 4.9 \cdot 10^4 \quad \tilde{\lambda}_f = 0.075$

General requirements:

- SSM constraint [Franciolini+, 2112.10660] ↔ $m_i + 3\Delta m_i < M_\odot$
- Exclude PBH nature ↔ $\tilde{\Lambda} - 3\Delta\tilde{\Lambda} > 0\,, \quad \text{and/or}$ $\tilde{\lambda}_f + 3\Delta\tilde{\lambda}_f < 1$

Bayesian inference result of PBH binary injections: O3 vs ET+2CE





Sensitivity is reduced of a factor of ~ 100

***m/m_B* = 0.02 BS models ruled out.**

Fisher results of NS binary injections

Network	LVK O3	LVK O4	LVK O5	ET+2CE
BNS SSM200308 ($\tilde{\Lambda} = 1.5 \cdot 10^5, \delta\tilde{\Lambda} = 4.9 \cdot 10^4, \tilde{\lambda}_f = 0.075$)				
SNR	7.90	12.8	22.4	398
$\Delta m_1/m_1$	0.47	0.22	0.082	0.0017
$\Delta m_2/m_2$	0.39	0.19	0.070	0.0015
$\Delta\tilde{\Lambda}/\tilde{\Lambda}$	0.86	0.66	0.55	0.047
$\Delta\tilde{\lambda}_f/\tilde{\lambda}_f$	0.38	0.24	0.13	0.015

$m_i + 3\Delta m_i < M_\odot$

$\tilde{\Lambda} - 3\Delta\tilde{\Lambda} > 0$

$\tilde{\lambda}_f + 3\Delta\tilde{\lambda}_f < 1$

Results:

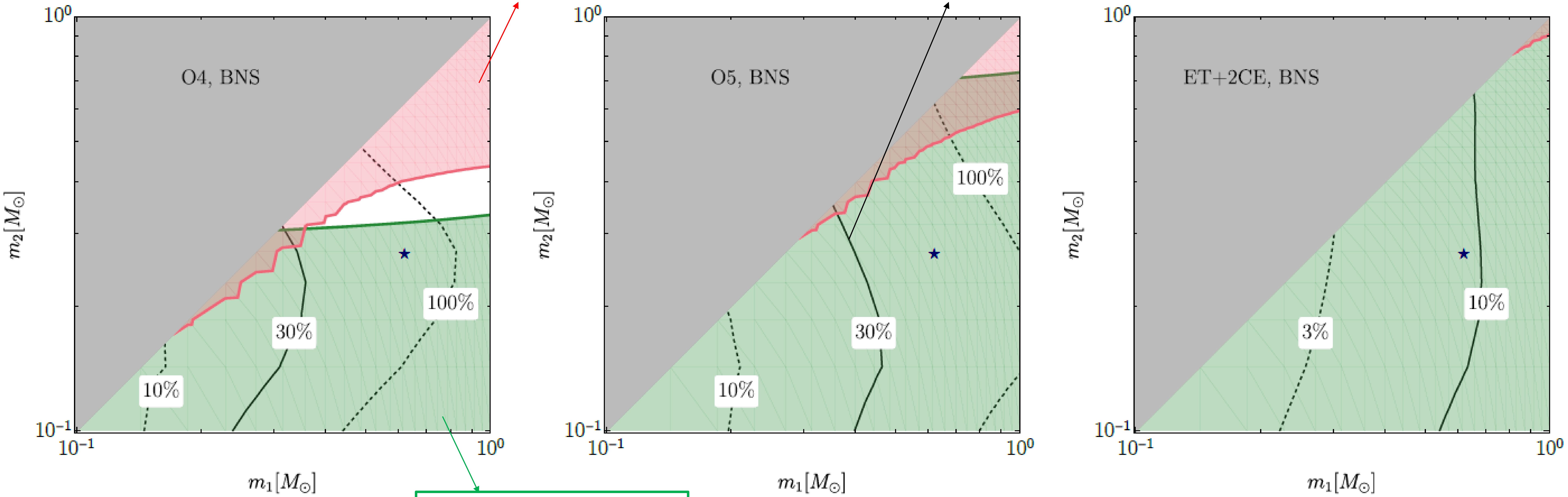
- we can be certain that the binary is subsolar from O5 on;
- tidal deformability distiguishes PBHs from BNSs only with 3G detectors;
- tidal disruption is well constrained from O3 on.

Exploring the Fisher parameter space: the NS binary case

- We scan the parameter space where both masses are in the range $m_1, m_2 \in [0.1; 1]$.
- We assume optimally oriented binaries at a distance corresponding to the threshold for detection with O4 sensitivity.

$$m_i + 3\Delta m_i \not< M_\odot$$

Relative precision on effective tidal

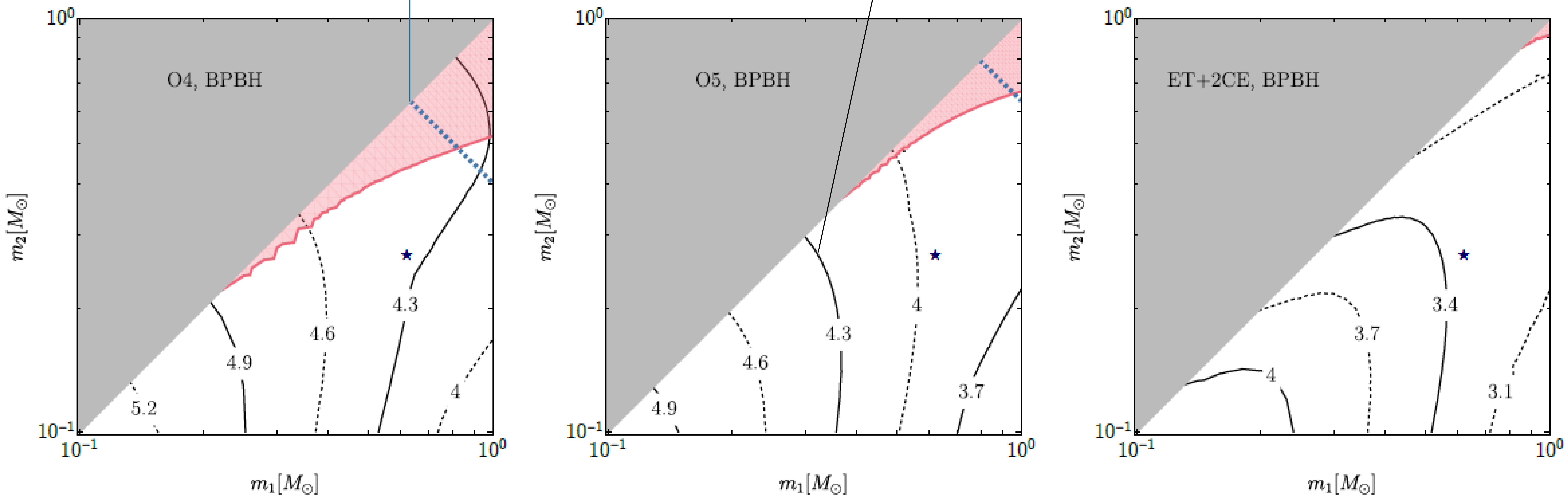


$$\tilde{\lambda}_f + 3\Delta\tilde{\lambda}_f < 1$$

Exploring the Fisher parameter space: the PBH binary case

BNS tidal bound assuming SLy4 EOS

$\log_{10}$ upper bounds of the effective tidal at 3σ C.L.



Take-home messages and future works

Take-home messages:

- SSM binary events could be detectable starting from O4 → very high precision with ET!
- Effective tidal parameter will be well-constrained, at least to compare the PBH hypothesis against the subsolar NS one, or even against more exotic hypotheses.

Future works on this topic:

- Build a more accurate waveform (demanding, important effects due to the tidal disruptions);
- Studying implications of cosmology and nuclear physics for SSM objects [Crescimbeni+, 2408.14287] see M. Vaglio's talk!

Thank you for your attention!

Back-up slides

Binary maximum frequency of material compact objects

- A GW signal has a maximum frequency of the order of ISCO:

$$f_{\rm ISCO} = \frac{c^3}{(6^{3/2}\pi G M)} = 4.4\,\mathrm{kHz}\left(\frac{M_\odot}{M}\right)$$

- binaries of stellar objects are typically characterized by smaller maximal frequencies (hard surface, tidal disruption,...)

$$r_{T,i} = \left(\frac{2m_j}{m_i}\right)^{1/3} r_i \quad \Longrightarrow \quad f_T = \frac{1}{\pi}\sqrt{\frac{GM}{(\max[r_{T,1}, r_{T,2}])^3}}$$

Binary maximum frequency of material compact objects

- White dwafts:

$$r_{\rm WD} = 0.013\, r_\odot \left(\frac{m_{\rm WD}}{M_\odot}\right)^{-1/3} \quad \Rightarrow \quad f_{\rm max}^{\rm WD} = 0.13\,{\rm Hz}\left(\frac{m_{\rm WD}}{M_\odot}\right) \quad \Rightarrow$$

Detectable by deci-Hz detectors

- Neutron stars:

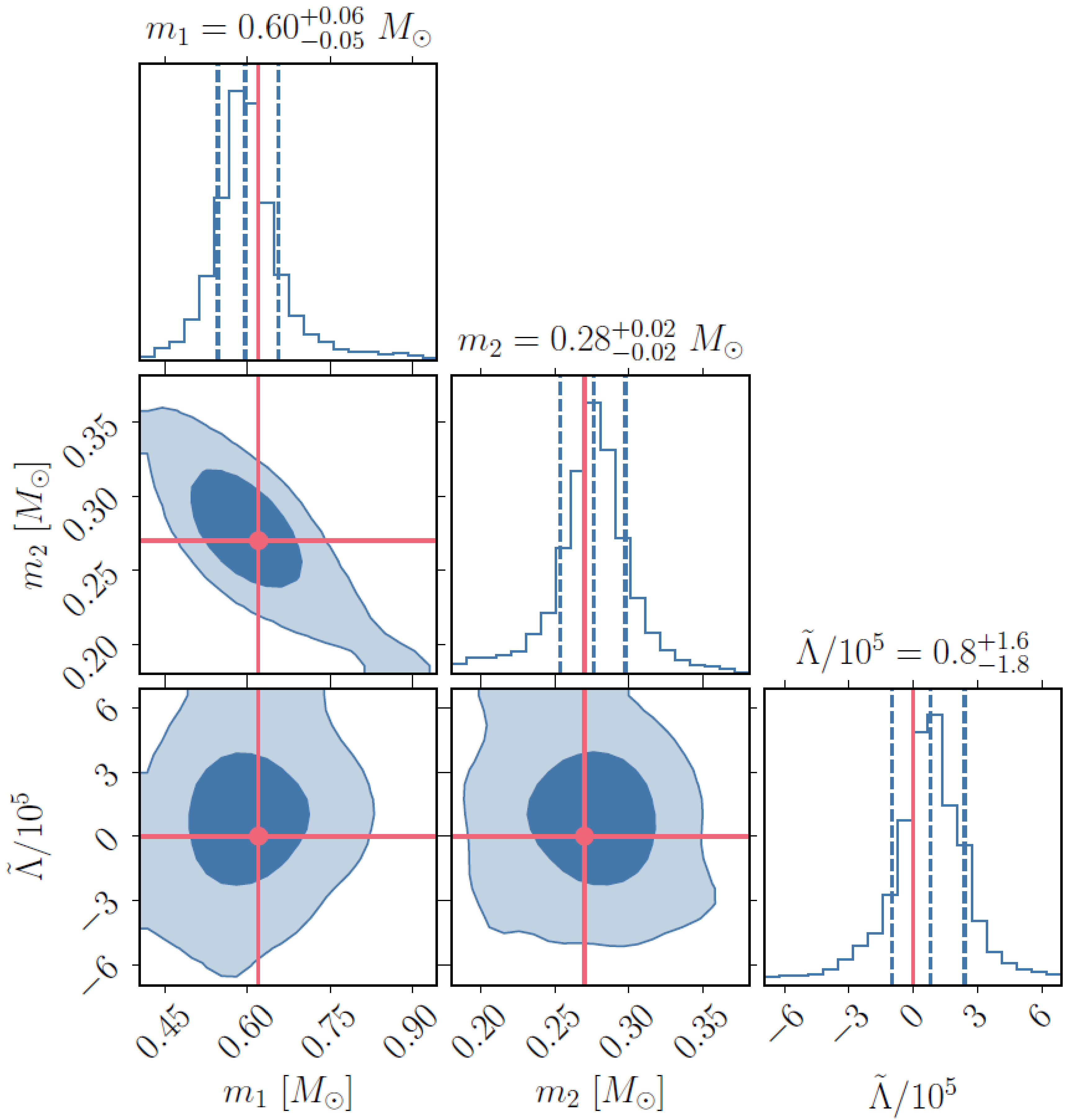
$$f_{\rm max}^{\rm NS} \approx 1.4\,{\rm kHz}\left(\frac{m_{\rm NS}}{0.5 M_\odot}\right)^{1/2}\left(\frac{15\,{\rm km}}{r_{\rm NS}}\right)^{3/2}$$

More accurate expression $\Rightarrow$

$$f_{\rm RO}/{\rm Hz} = -26.9 - 35.5\left(\frac{m_1}{M_\odot}\right) - 3.02\left(\frac{m_1}{M_\odot}\right)^2 + 1690\left(\frac{m_2}{M_\odot}\right) - 575\left(\frac{m_2}{M_\odot}\right)^2$$

[Bandopadhyay+, 2212.03855]

Bayesian inference vs Fisher for BPBHs: O3

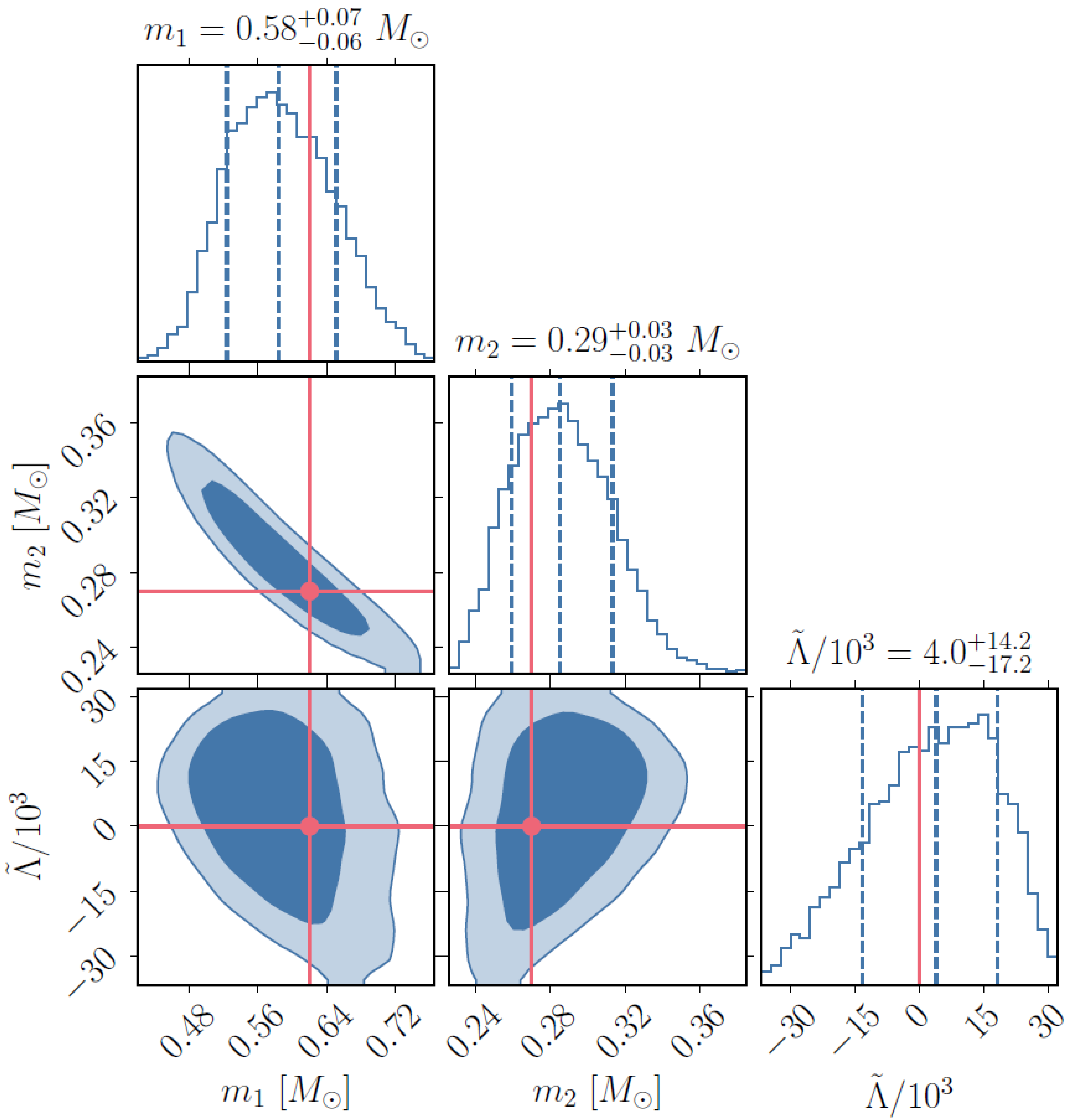


Network	LVK O3	LVK O4	LVK O5	ET+2CE
BPBH SSM200308 ($\tilde{\Lambda} = \delta\tilde{\Lambda} = 0, \tilde{\lambda}_f = 1$)				
SNR	8.76	14.6	24.8	430
$\Delta m_1/m_1$	0.21	0.14	0.053	$6.4 \cdot 10^{-3}$
$\Delta m_2/m_2$	0.18	0.12	0.046	$5.5 \cdot 10^{-3}$
$\Delta\tilde{\Lambda}$	$1.9 \cdot 10^4$	$1.3 \cdot 10^4$	$7.8 \cdot 10^3$	$7.7 \cdot 10^2$

Example of exclusion of BS model

$$m_1 = m_2 = 0.62 M_\odot \quad \tilde{\Lambda} > 3 \cdot 10^4 \quad m_B \gtrsim 15 M_\odot$$

Bayesian inference vs Fisher for BPBHs : O4



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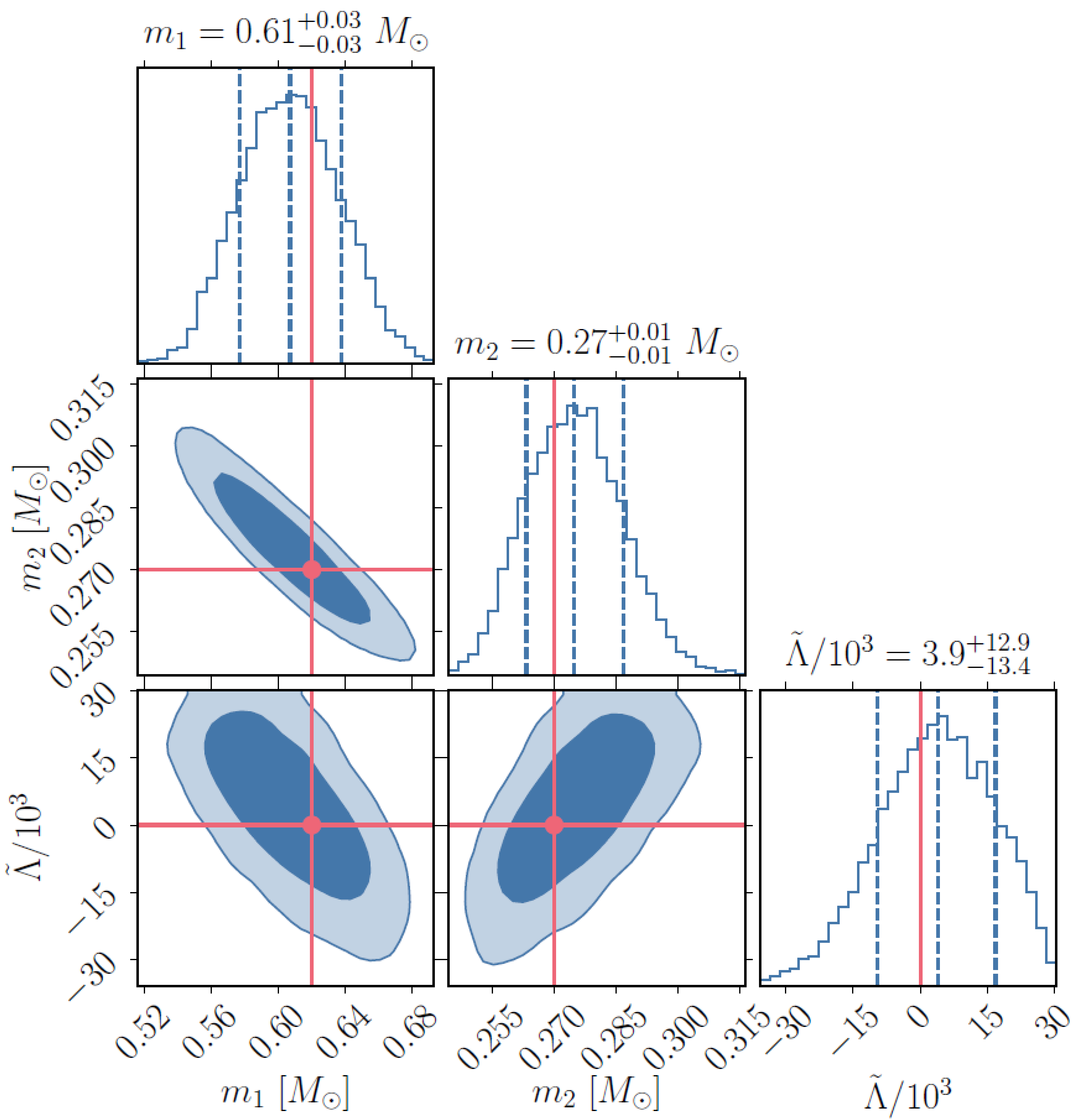
Bayesian inference vs Fisher for BPBHs: O5



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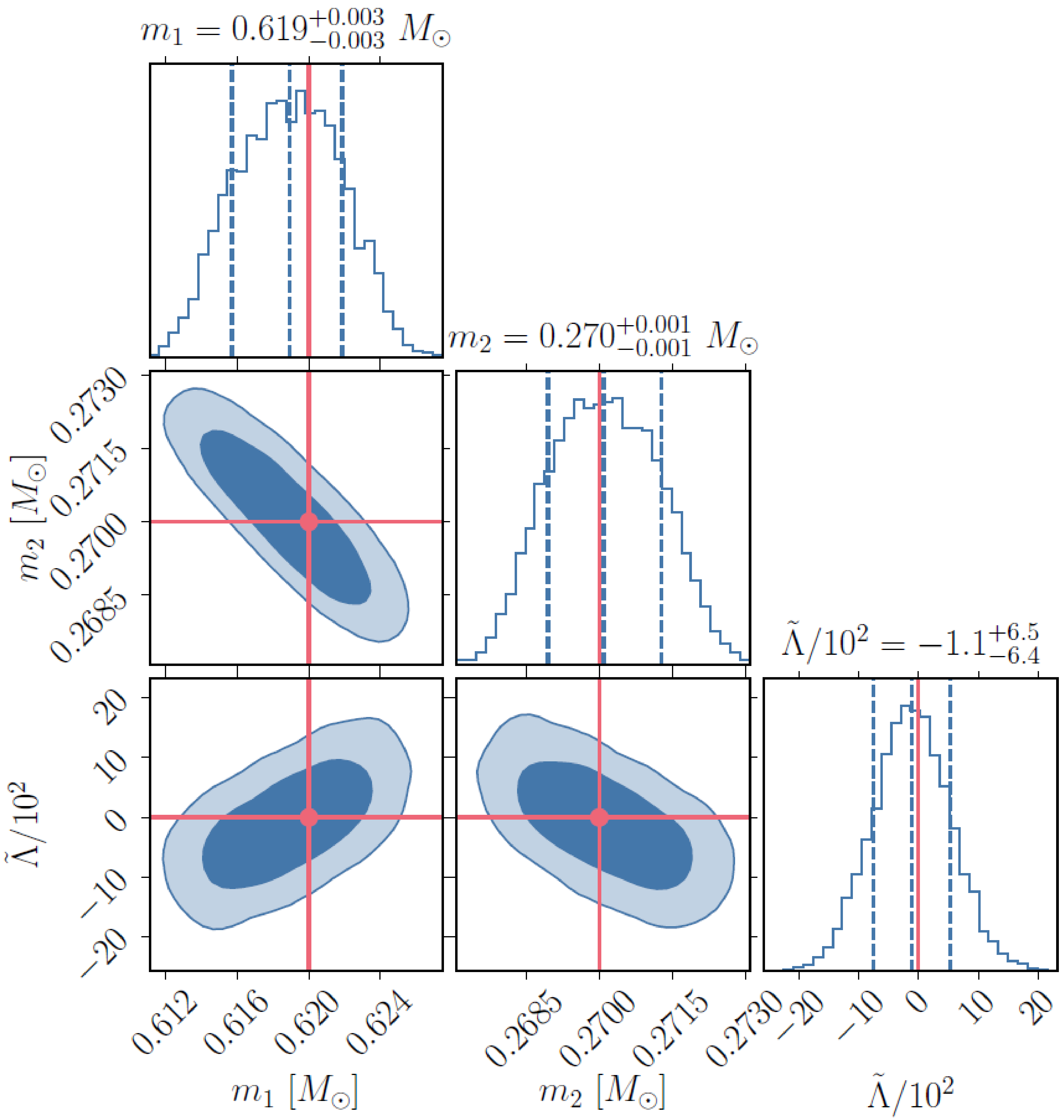
Bayesian inference vs Fisher for BPBHs: ET+2CE



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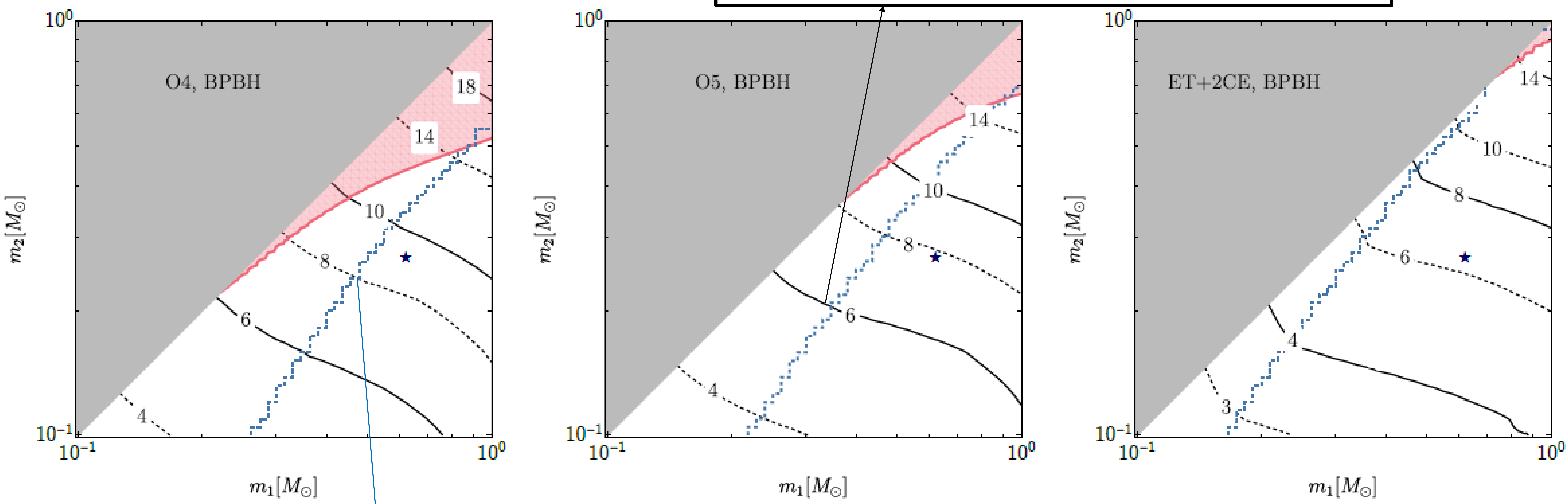
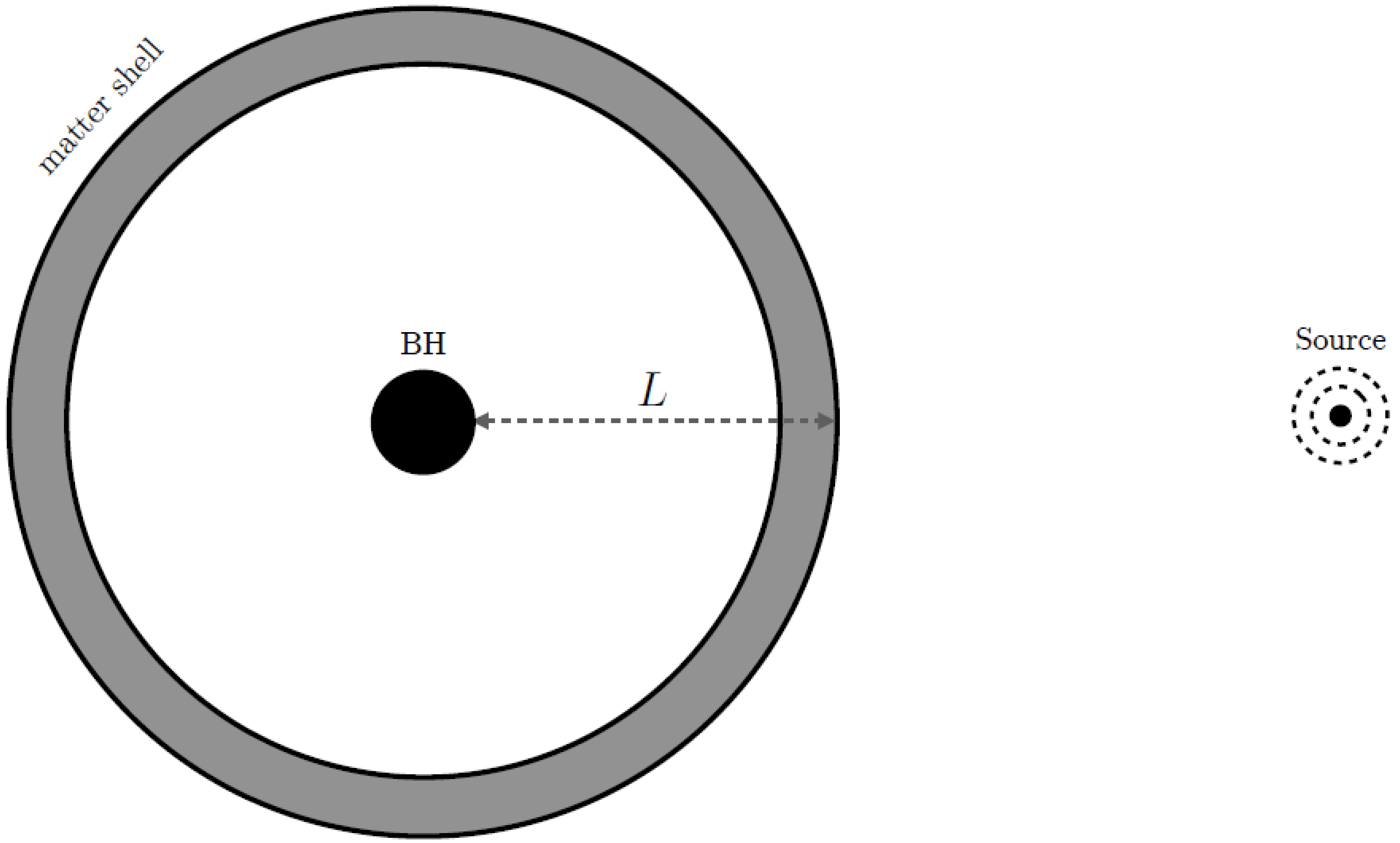
Exploring the Fisher parameter space: constraints on BSs with large quartic interaction

values of $m_B/M_\odot$ above which the tidal deformability would be incompatible with future upper bounds (at 3σ C.L.)



BS existence bound: $m_i < 0.06\, m_B$

Do we exclude BPBHs if Λ=0?

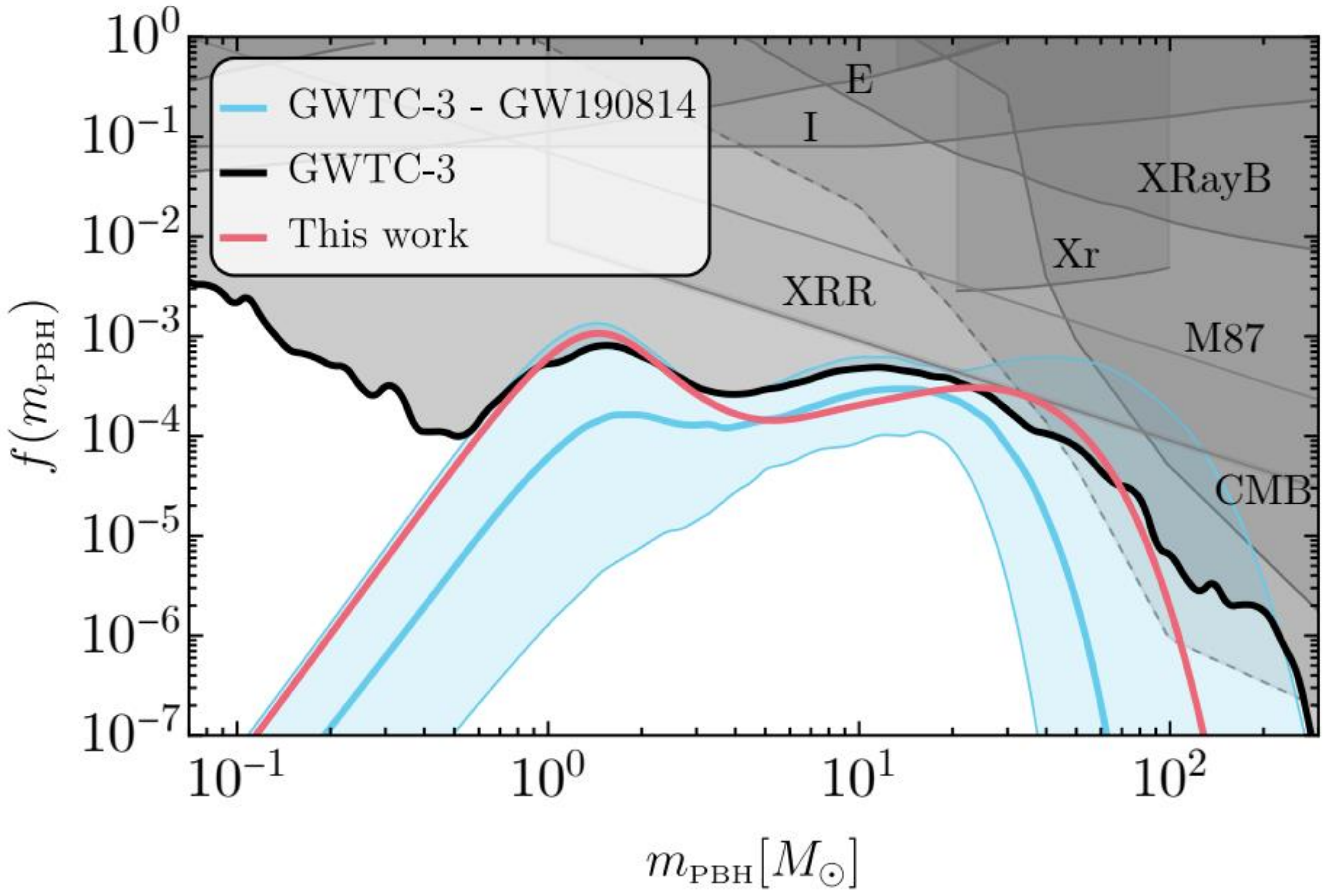


- Having Λ=0 may not exclude PBHs at all.
- If a PBH presents an astrophysical environment, tidal deformabilities will be different from zero.

$$k_2 = -\frac{\epsilon}{5}\left(\frac{L}{r_s}\right)^6$$

- Distinguish between BPBHs with environment and 'naked' PBHs [De Luca, Franciolini, Riotto, 2408.14207].

Subsolar event rates vs PBH abundance



Source ref. Iacovelli+, 2304.03160

$$f(m_{\rm PBH}) \equiv \frac{1}{\Omega_{\rm DM}} \frac{d\Omega_{\rm PBH}}{d\ln m_{\rm PBH}} = m_{\rm PBH} f_{\rm PBH} \psi(m_{\rm PBH})$$

PBH abundance

Mass function distribution

Dark matter fraction