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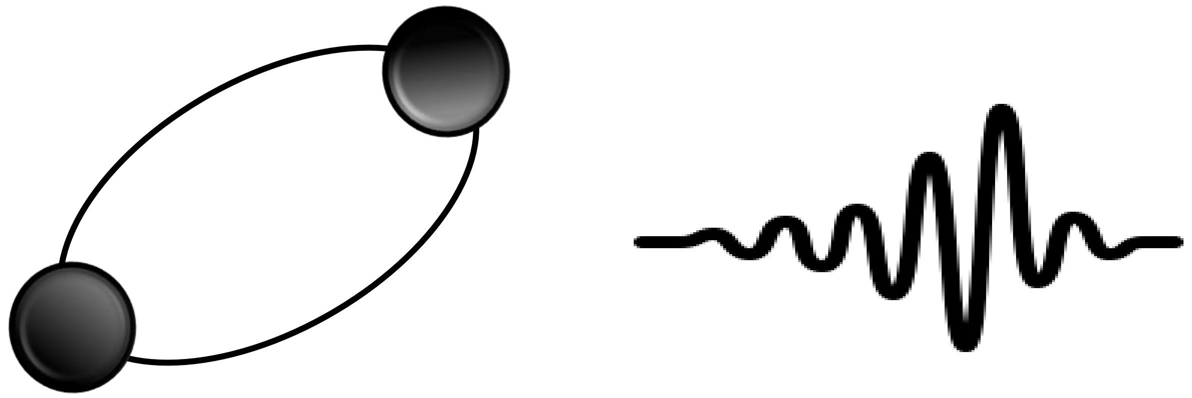
Einstein Telescope

INFN Istituto Nazionale di Fisica Nucleare
Teongrav

Can we identify primordial black holes?
Analysis and physical implications of candidate subsolar gravitational-wave events



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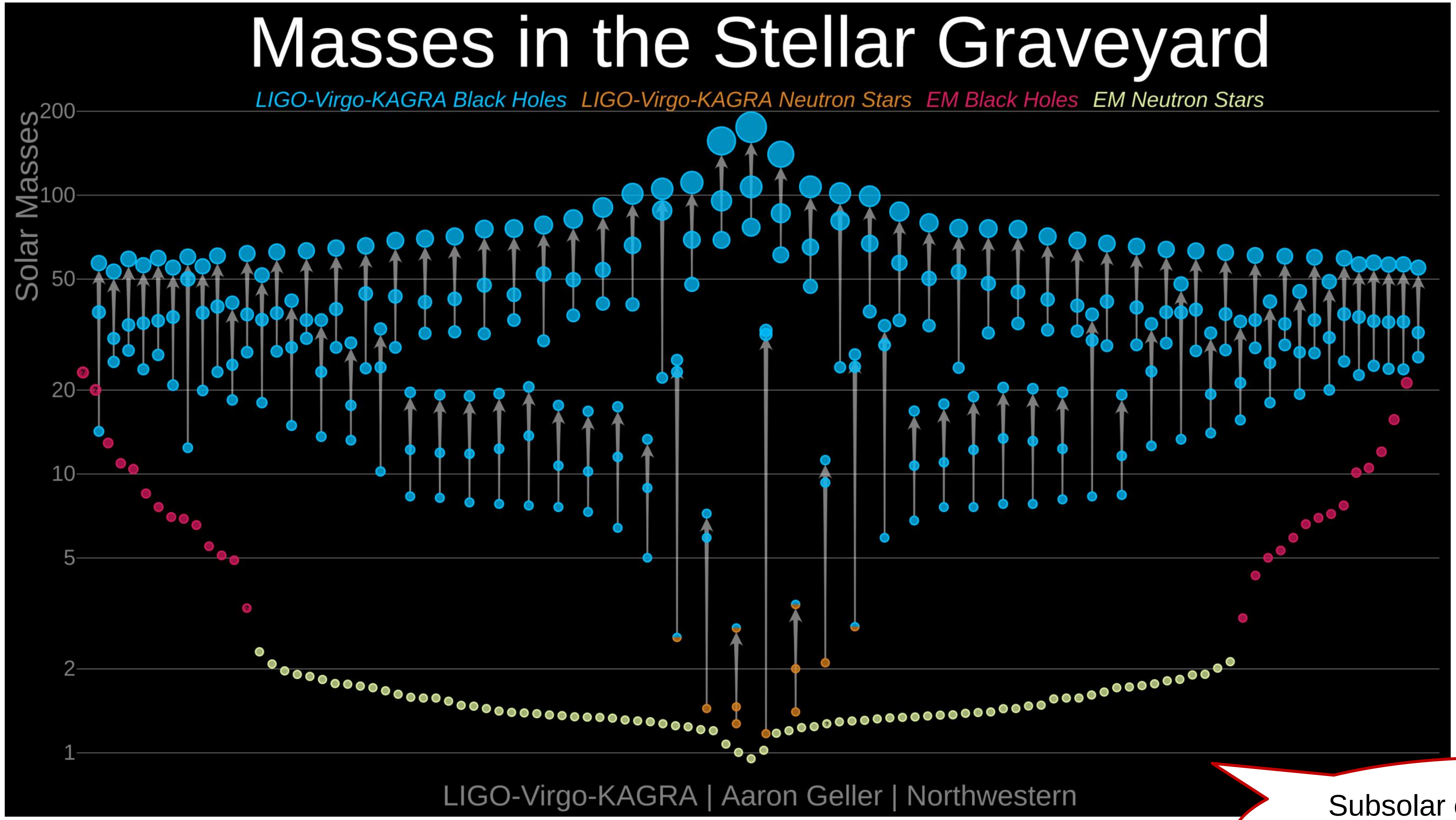
GRASP 2024, Pisa

Based on:
F. Crescimbeni, G. Franciolini, P. Pani, A. Riotto, arxiv.org/2402.18656 & F. Crescimbeni, G. Franciolini, P. Pani, M. Vaglio, arxiv.org/2408.14287

Subsolar compact objects still missing

- The detection of subsolar compact objects could imply smoking gun evidence evidence of new physics such as primordial black holes (PBHs).



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

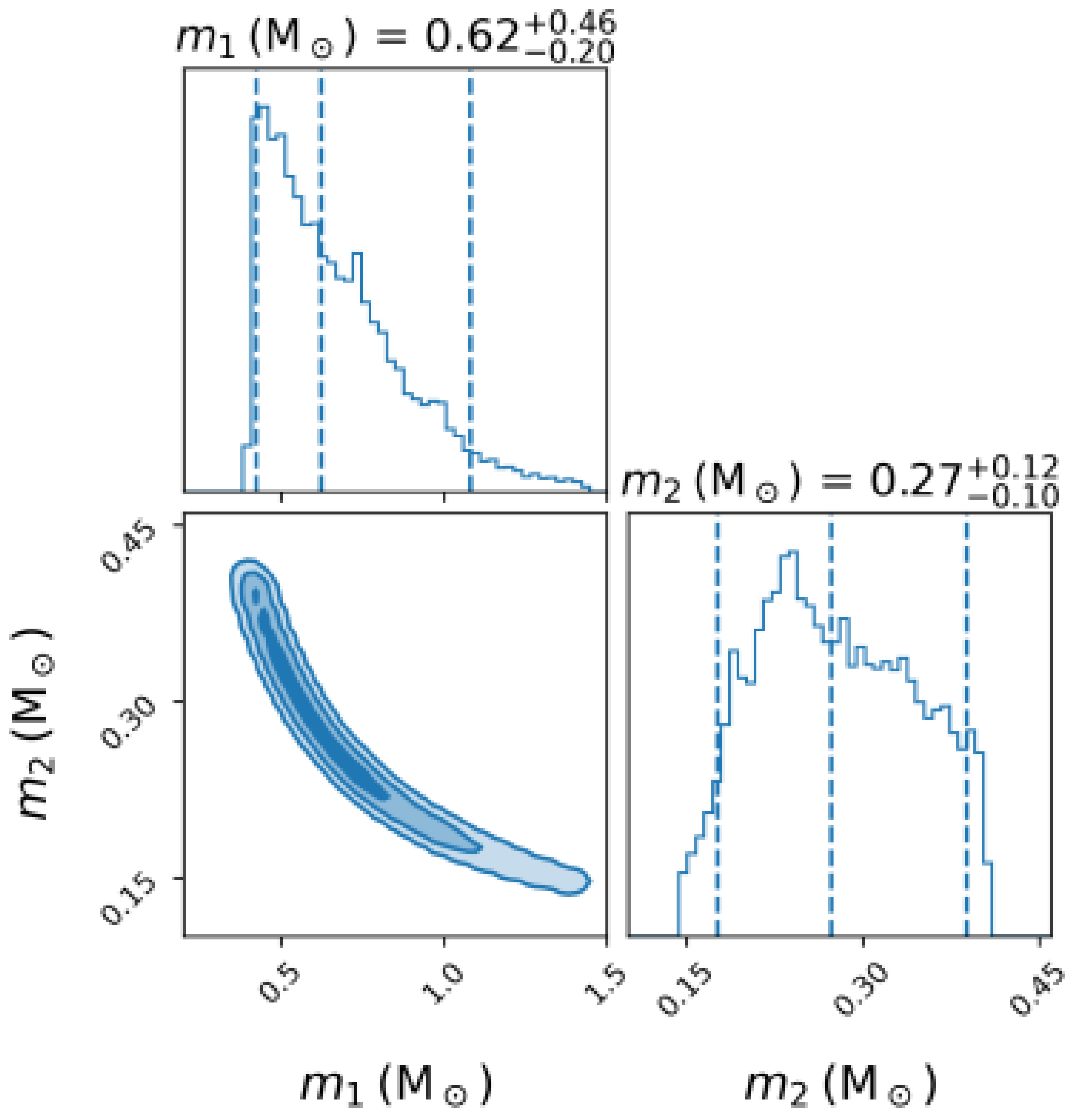
Subsolar compact objects from GW observations still not comfidently detected!

Putative detections of subsolar objects

- Candidate neutron star object identyfied as HESS J1731–347 observed with mass $0.77^{+0.20}_{-0.17} M_\odot$ [Doroshenko+, Nature Astronomy 6, 1444 (2022)].

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

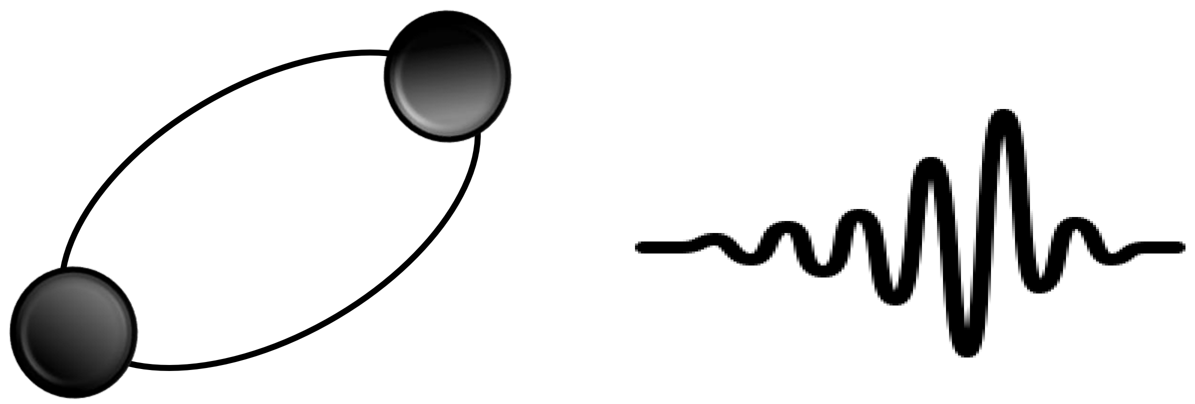
- SSM-like trigger (denoted as SSM200308) detected during O3 was recently reanalyzed [Prunier+, 2311.16085] under the assumption that it was a binary of PBHs.



Prunier+, 2311.16085

Objectives and questions

- What are possible SSM candidates?
- How can we model the GW signal of a SSM merger?



- Given an observing run, can we distinguish PBHs from other candidates in the SSM range?
- What are cosmology and nuclear physics implications of an SSM detection?

SSM phenomenology

SSM candidates and how they are deformed

- Astrophysics objects: Light neutron stars, white dwarfs, strange quark matter stars;
- Exotic compact objects: 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

$$\Lambda = 0$$

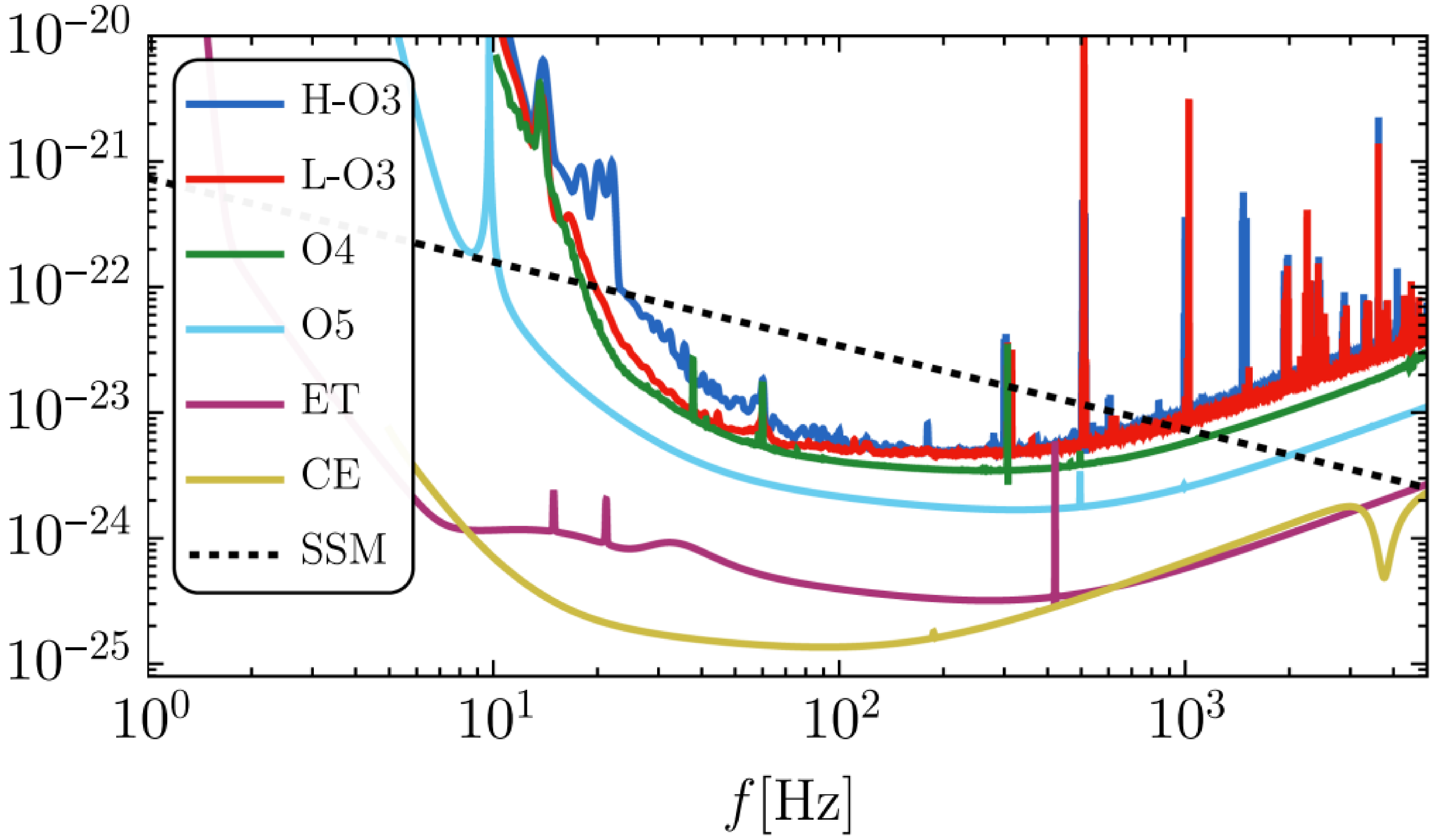
Non-deformable (symmetry properties)

Waveform modeling of SSM binaries

- We will observe only the inspiral part of the signal, described by the TaylorF2 waveform [Damour+, 0010009].

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

Amplitude:
scales as the inverse
of distance



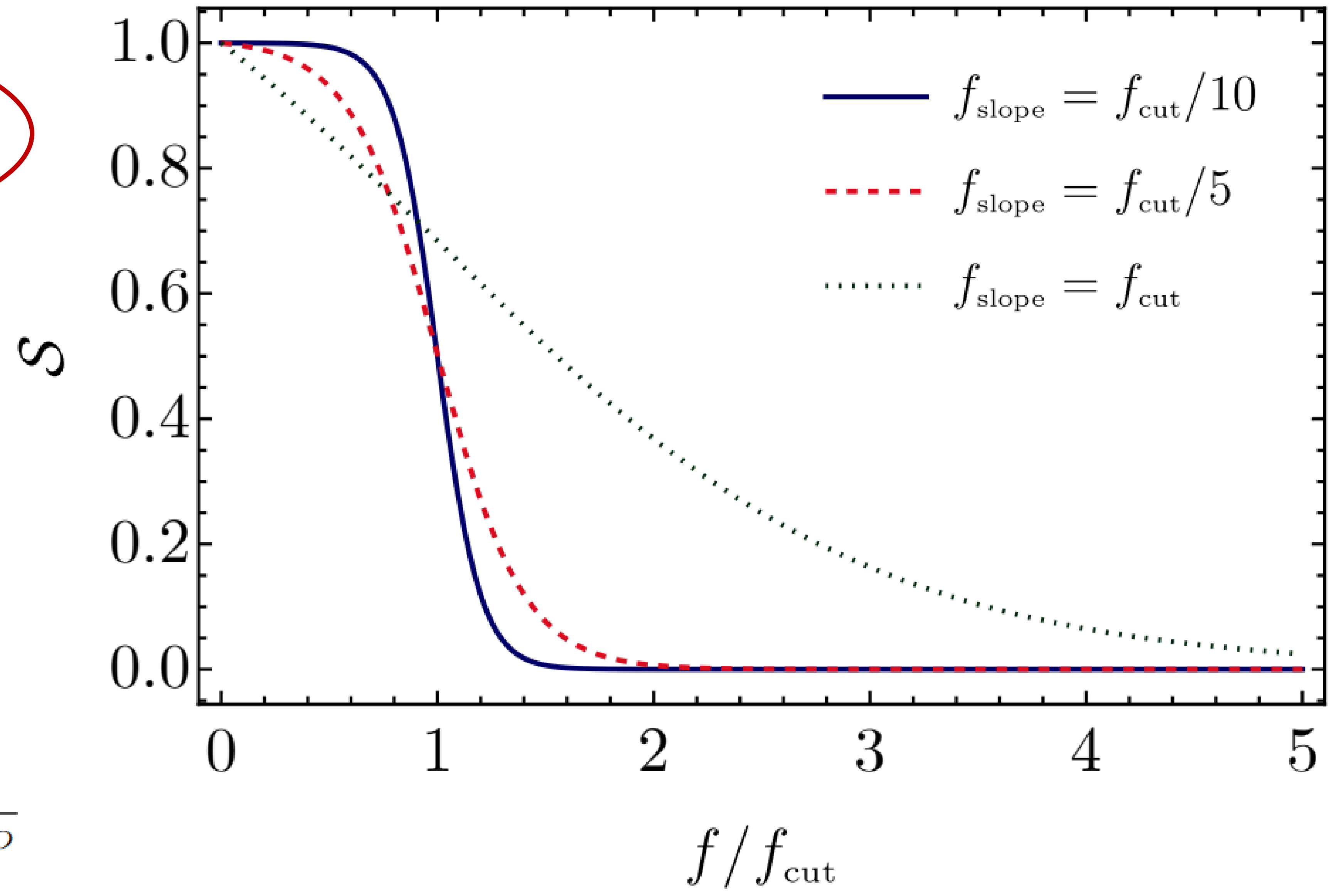
Waveform modeling of SSM binaries

- We will observe only the inspiral part of the signal, described by the TaylorF2 waveform [Damour+, 0010009].

Tapering smoothing: keeps into account possible tidal disruption

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

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



Source ref. De Luca+, 2212.03343

Waveform modeling of SSM binaries

- We will observe only the inspiral part of the signal, described by the TaylorF2 waveform [Damour+, 0010009].

Phase: contains tidal deformability

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

Point particle phase: contains mass and spin effects

Tidal phase

$$\begin{cases} \psi(x) = \underbrace{\psi_{\rm pp}(x)}_{\text{Up to 4PN}} + \underbrace{\delta\psi_{\rm tidal}(x)}_{\text{5PN + 6PN}} \\ x = (\pi f M)^{2/3} \end{cases}$$

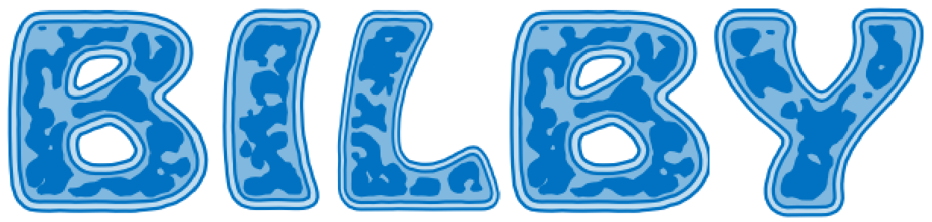
Combinations of Λ_1 and Λ_2

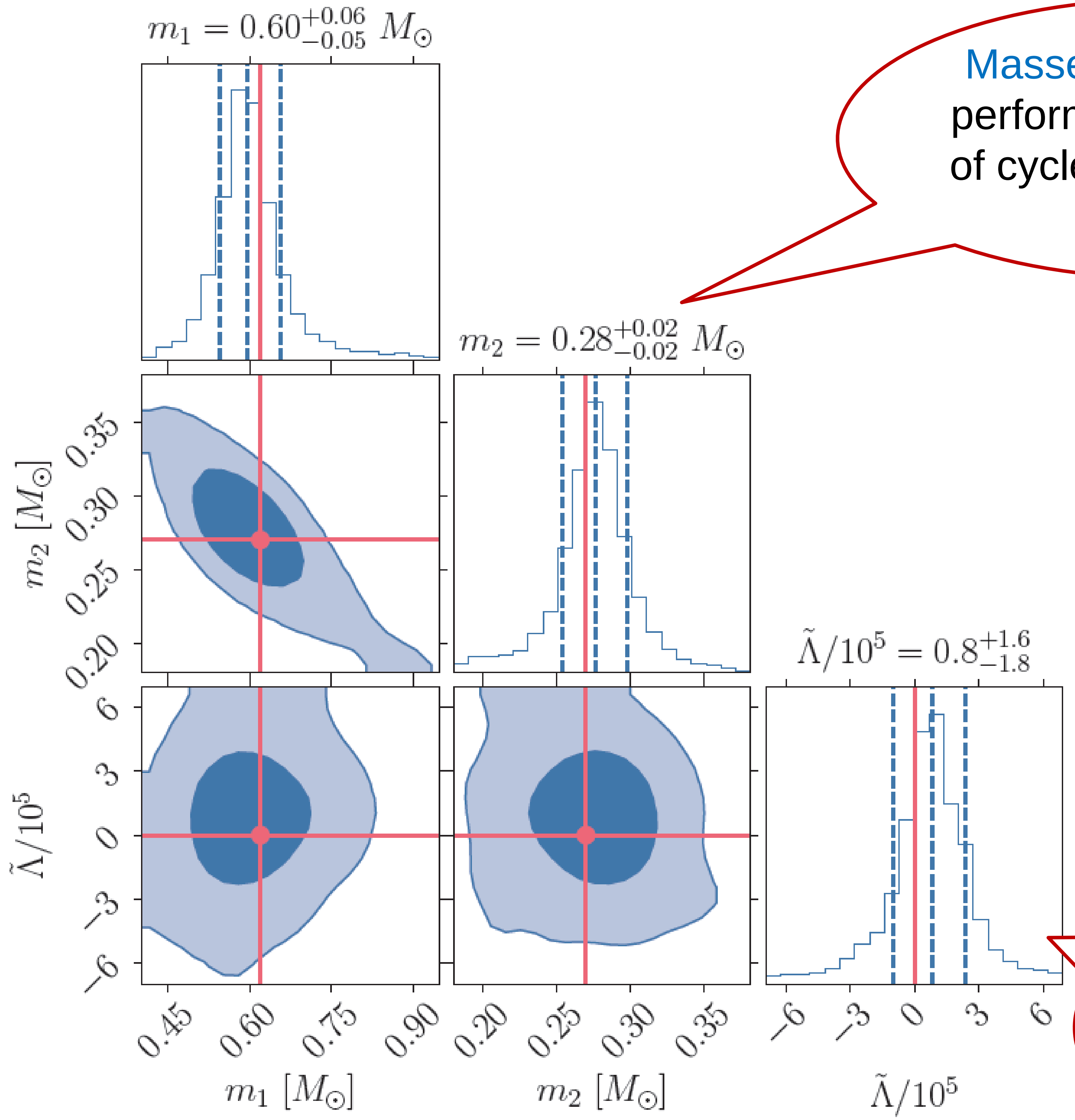
$$\delta\psi_{\rm tidal} = \frac{3}{128\eta x^{5/2}}\left[\left(-\frac{39}{2}\tilde{\Lambda}\right)x^5 + \left(-\frac{3115}{64}\tilde{\Lambda} + \frac{6595}{364}\sqrt{1-4\eta}\,\delta\tilde{\Lambda}\right)x^6\right]$$

Distinguishing between subsolar PBHs and other candidades

PBH binary injections: O3

- Bayesian inference analysis performed with Bilby [Ashton+, 1811.02042]
- PBH binary injections + recovery
- Inject SSM200308 parameters [Prunier+, 2311.16085] + zero tides and negligible tapering
- O3 sensitivity





Masses: light mergers perform a large number of cycles in the detector band.

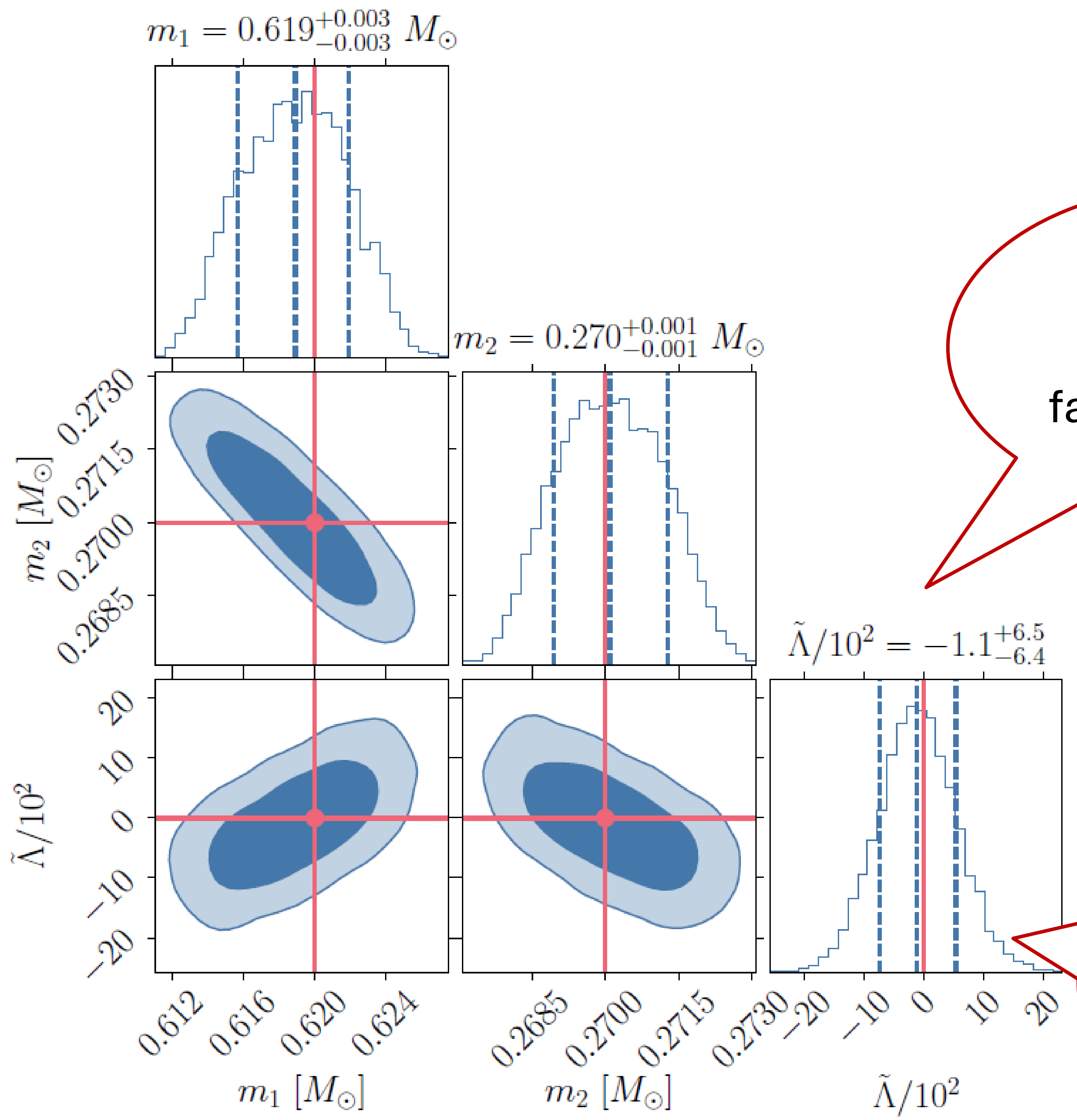
Effective tidal: undistinguishable SSM candidates

FC-Franciolini-Pani-Riotto, 2402.18656

PBH binary injections: ET+2CE

- Bayesian inference analysis performed with Bilby [Ashton+, 1811.02042]
- PBH binary injections + recovery
- Inject SSM200308 parameters [Prunier+, 2311.16085] + zero tides and negligible tapering
- ET+2CE sensitivity

BILBY



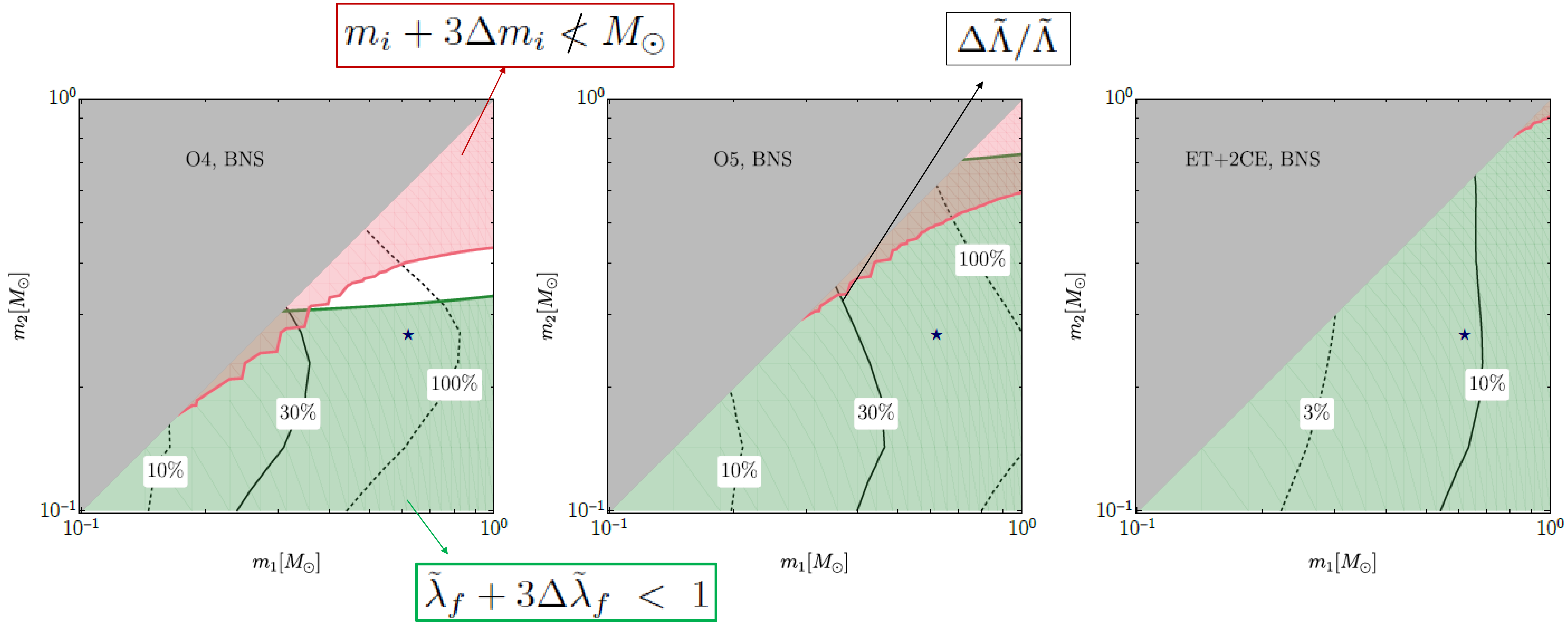
FC-Franciolini-Pani-Riotto, 2402.18656

Sensitivity is reduced of a factor of ~ 100.

Boson stars may reach $\Lambda \approx 10^6$ (excluded at 3σ)

Exploring the Fisher parameter space: the NS binary case

- Fisher analysis performed with gwfast [Iacovelli-Mancarella-Foffa-Maggiore, 2207.06910].
- Explore the masses parameter space where they vary in the range $m_1, m_2 \in [0.1; 1]$.



Cosmology and nuclear physics implications of an SSM detection

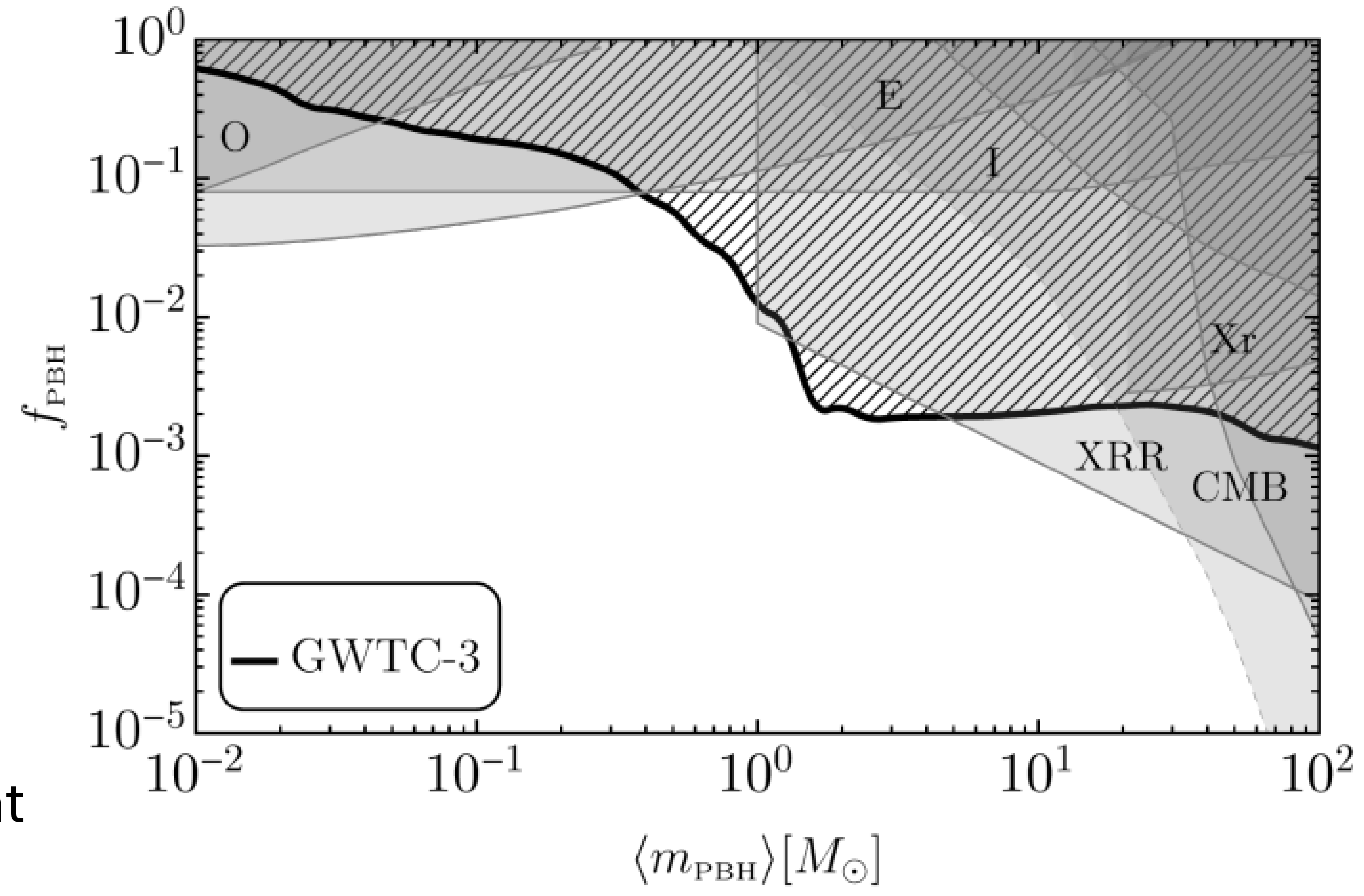
Cosmology implications of a SSM detection

If an SSM PBH binary is detected:

- infer the corresponding PBH abundance (controls the merger rate of SSM objects)

$$f_{\rm PBH} \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$$

- need at least $f_{PBH} \gtrsim O(10^{-2})$ to explain such a SSM event (upper bounds on GWTC-3).

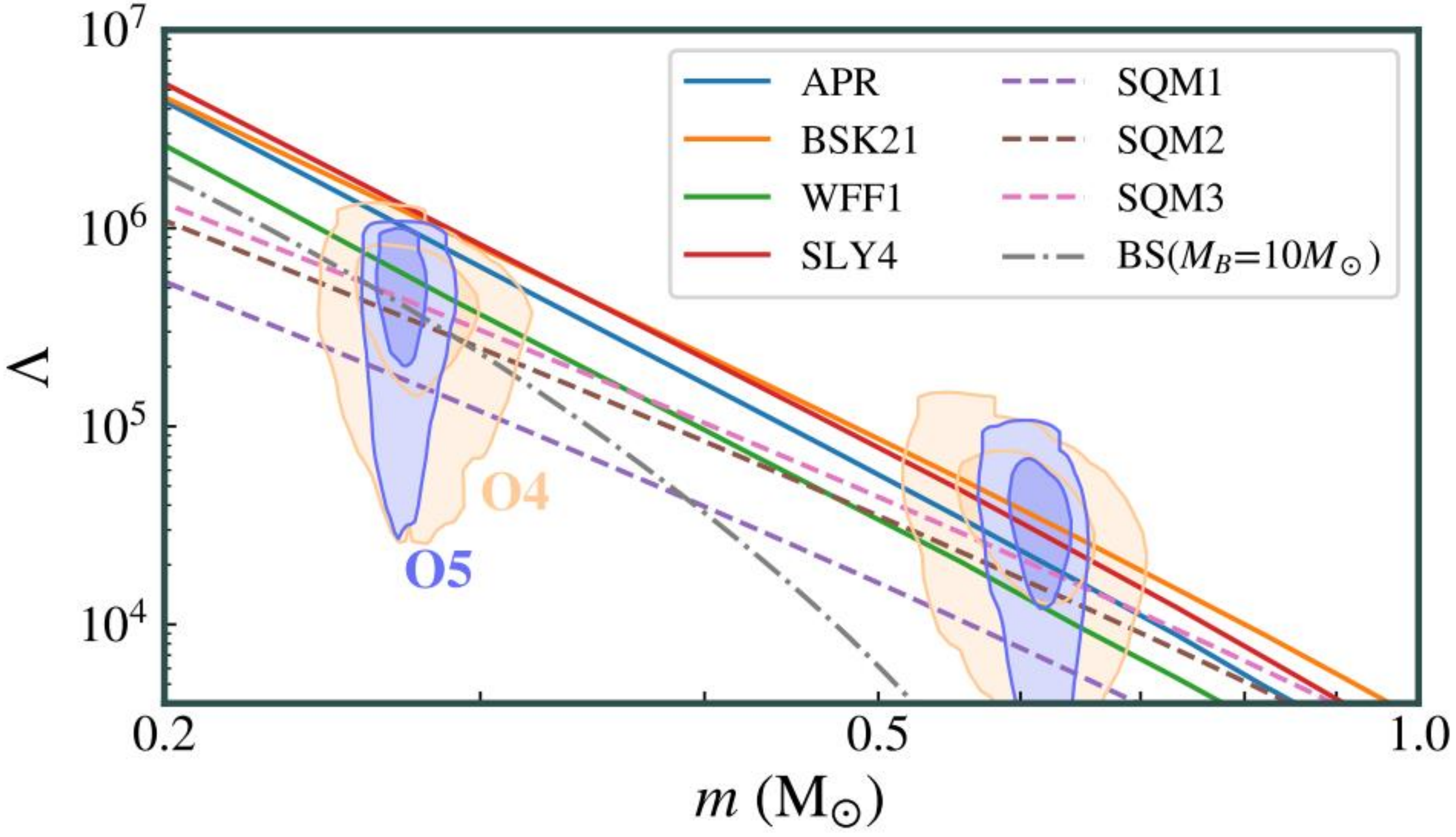


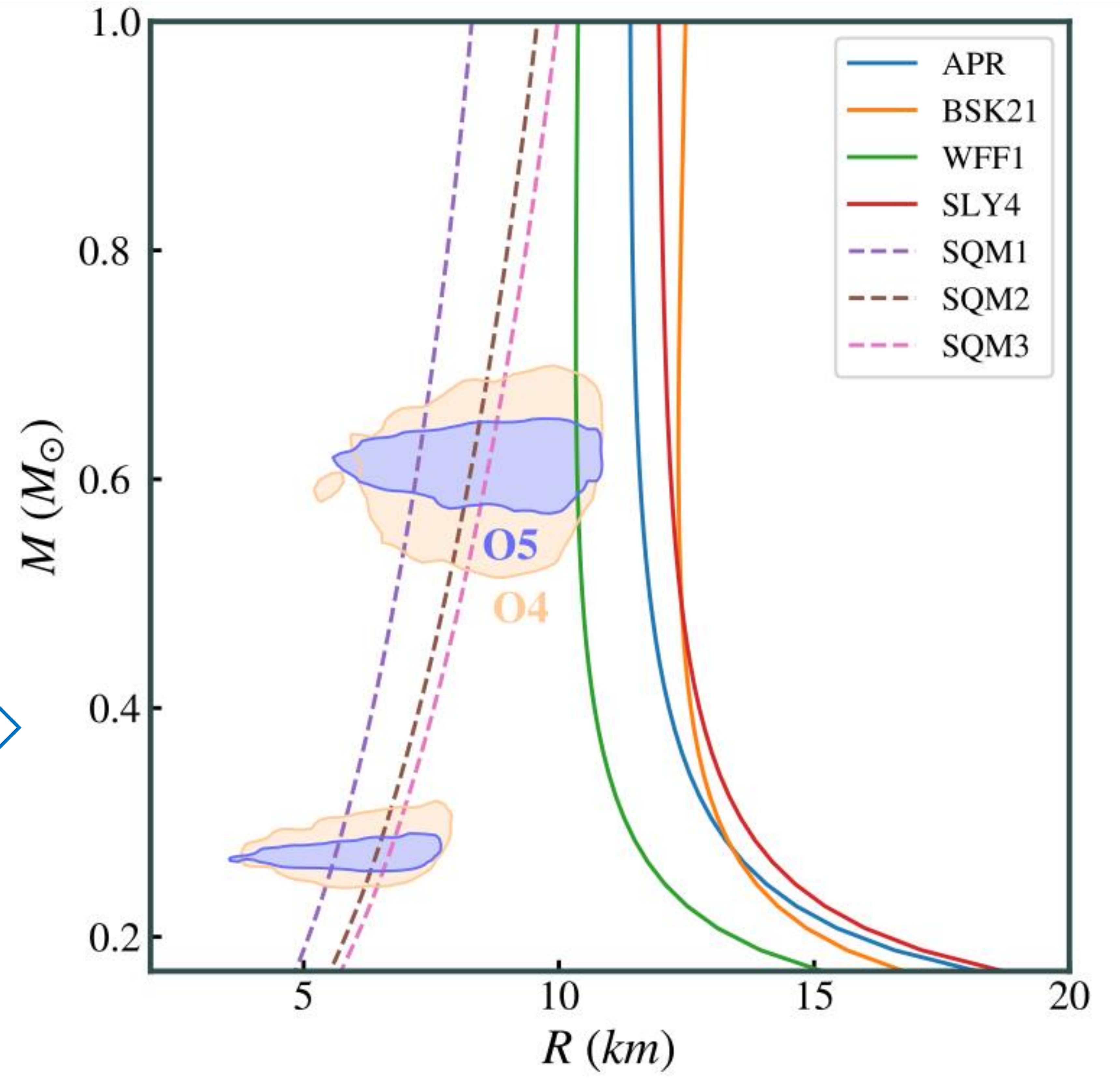
[Franciolini-Pani-Musco-Urbano, 2209.05959]

Nuclear physics implications of a SSM detection

If the SSM objects are identified as light NSs/SQM stars:

- Large tidals can be exploited to constrain the NS EoS.
- (m,Λ) can be translated in (m,R) diagram.





FC-Franciolini-Pani-Vaglio, 2408.14287

Take-home messages and future works

Take-home messages:

- Effective tidal can help distinguishing between SSM candidates.

- Important consequences in cosmology and nuclear physics implications.

Future developments:

- Merger rate of subsolar BHs: how this will affect population studies?

Thank you for your attention!

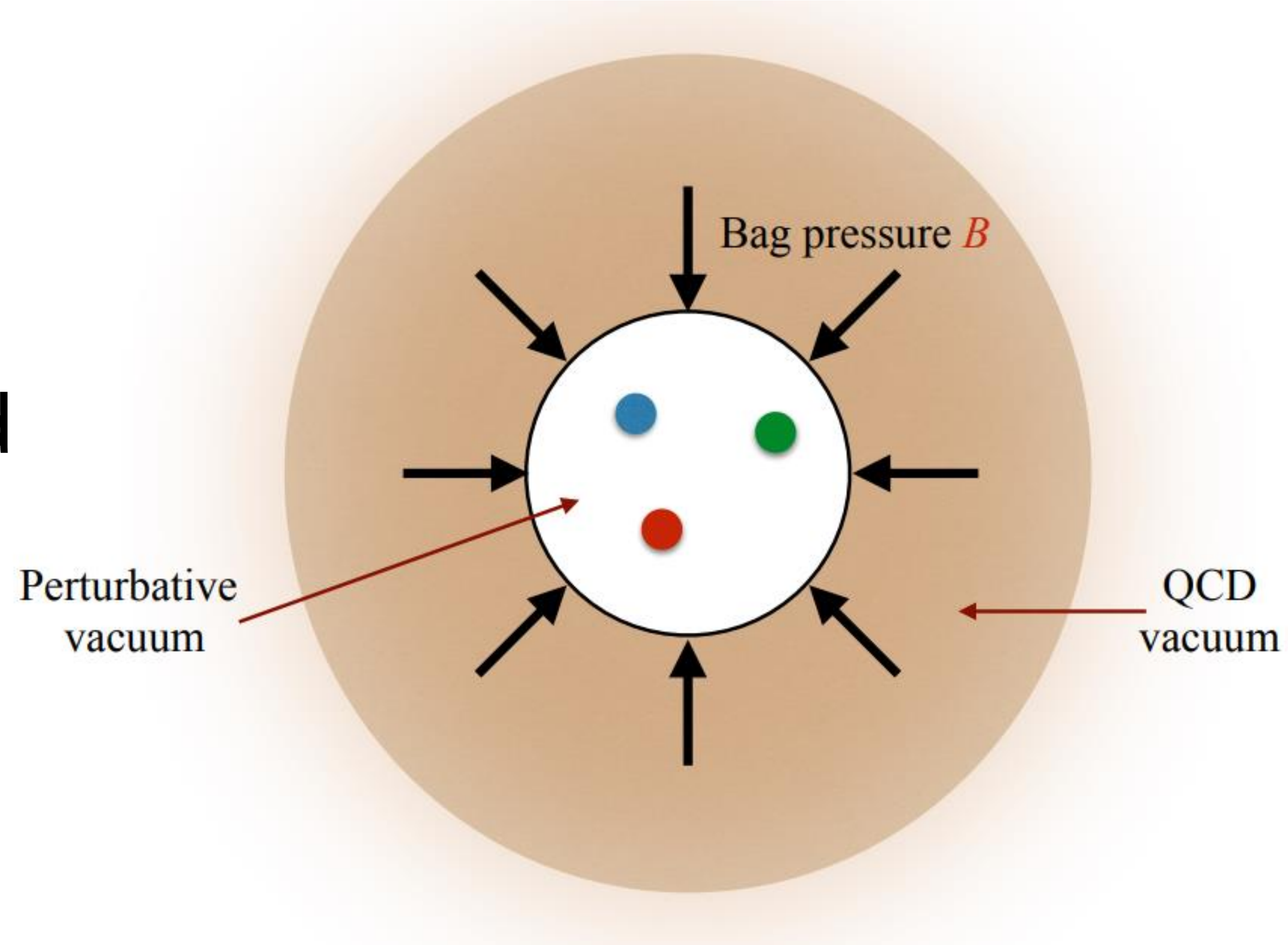
Back-up slides

Strange Quark Matter stars

- Strange quark-matter models assumes a balance of up, down, and strange quarks.

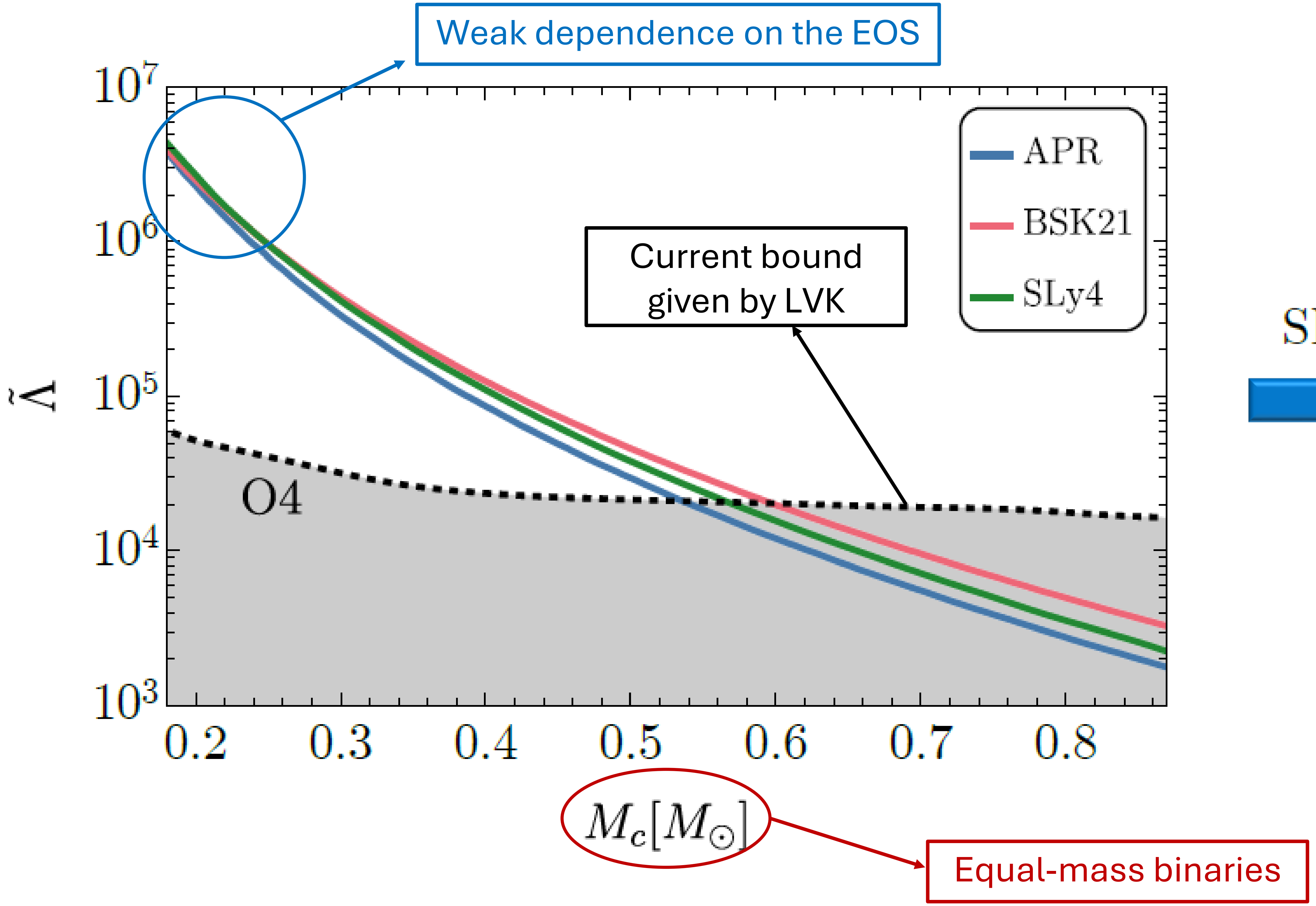
- EoS is obtained using perturbative QCD and an MIT-type bag model in which quarks are confined within a "bag" and interact via the strong force.

- This model often leads to a softer EoS compared to traditional neutron star matter because the pressure increase with density may be less steep.



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]:

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

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

- 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!

Binary maximum frequency of material compact objects

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

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

- 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:

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

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]

Waveform modeling of SSM objects

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

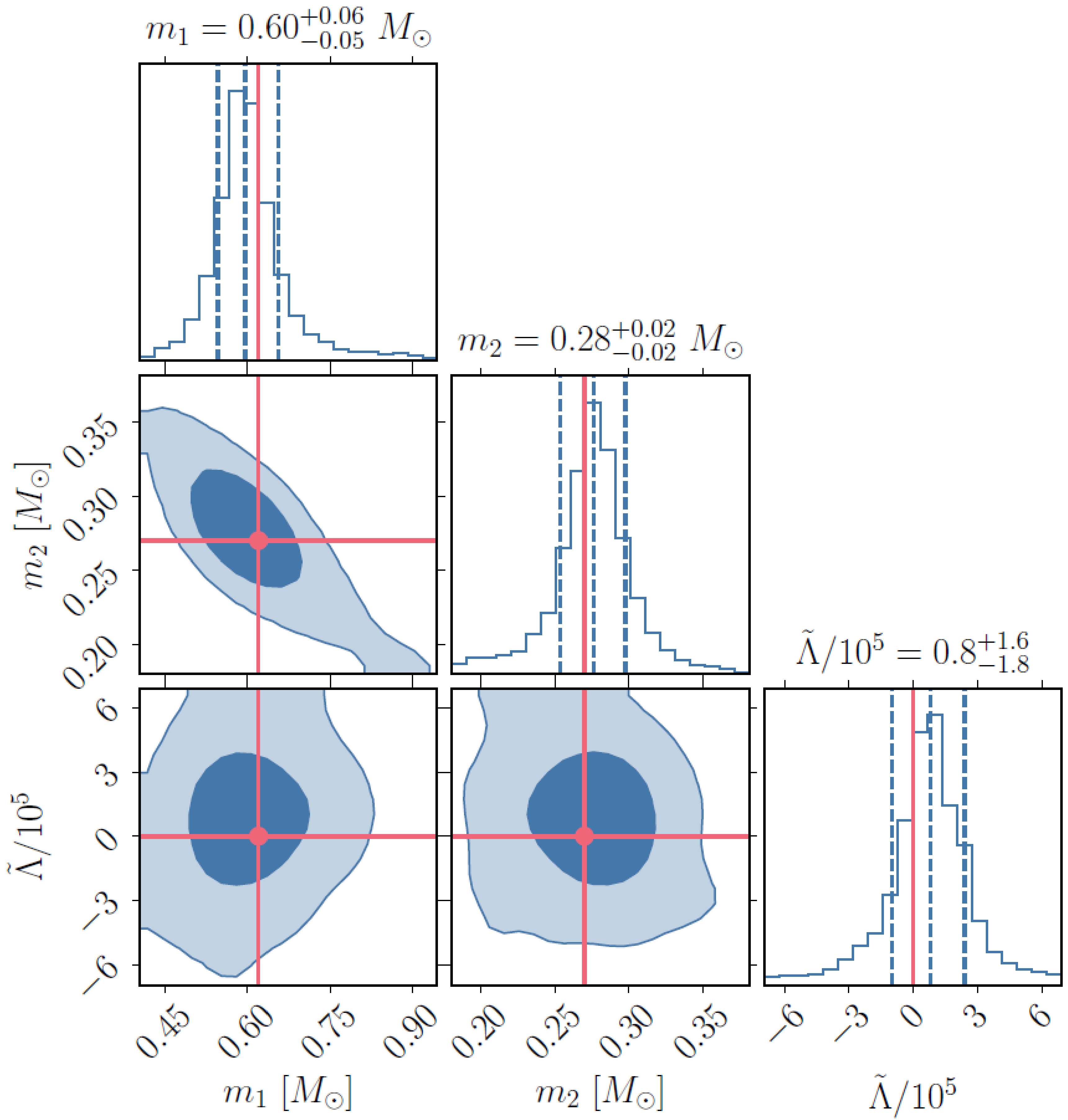
$$\psi(x) = \underbrace{\psi_{\rm pp}(x)}_{\text{Point-particle phase}} + \underbrace{\delta\psi_{\rm tidal}(x)}_{\text{Tidal phase}} \Longleftrightarrow \delta\psi_{\rm tidal} = \frac{3}{128\eta x^{5/2}}\left[\left(-\frac{39}{2}\tilde{\Lambda}\right)x^5 + \left(-\frac{3115}{64}\tilde{\Lambda} + \frac{6595}{364}\sqrt{1-4\eta}\,\delta\tilde{\Lambda}\right)x^6\rig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

- Some definitions…

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

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

Bayesian inference vs Fisher for BPBHs: O3

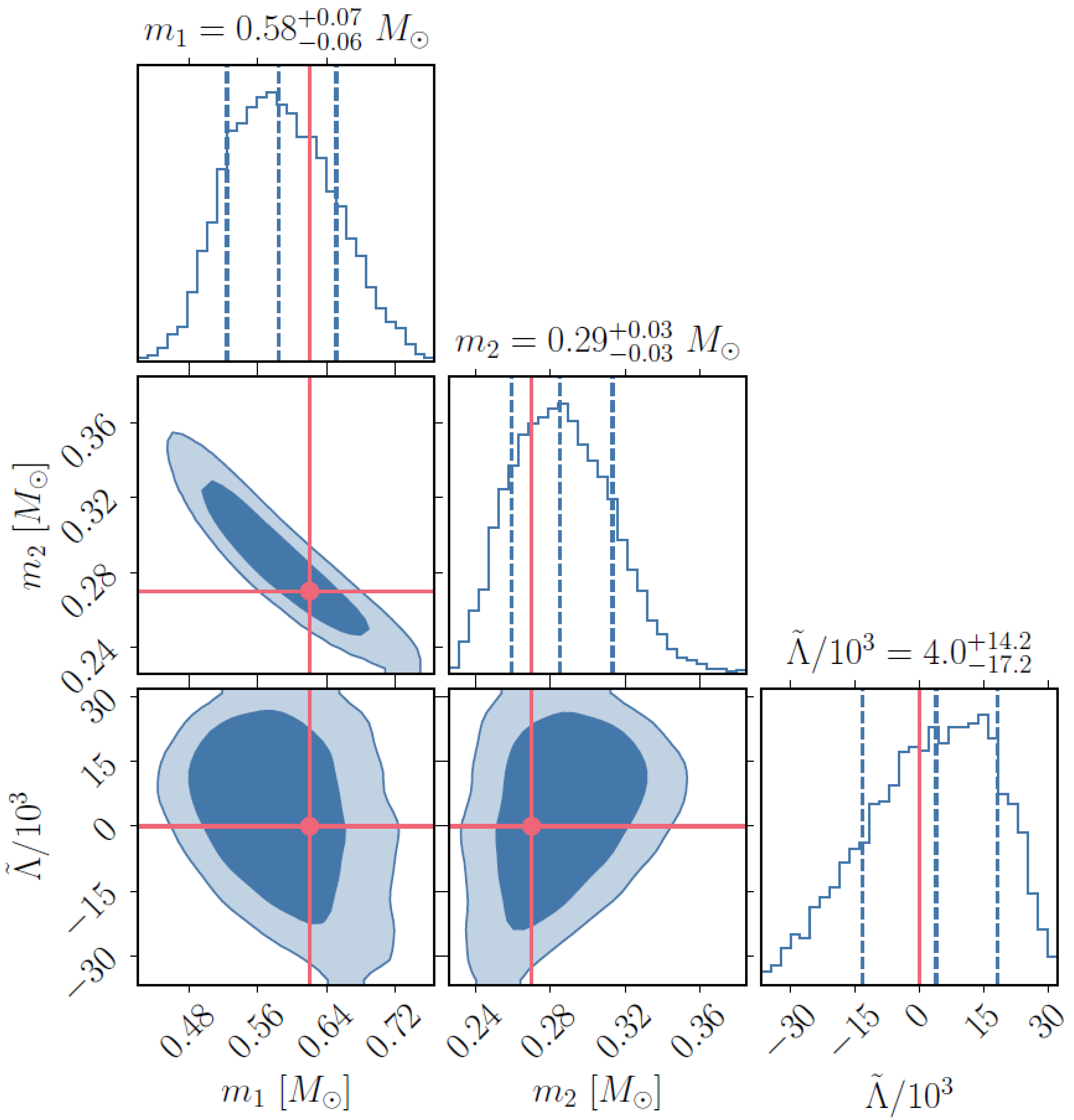


Network	LVK O3	LVK O4	LVK O5	ET+2CE
BPBH SSM200308 ($\tilde{\Lambda} = \delta\tilde{\Lambda} = 0, \tilde{\lambda}_f = 1$)				
SNR	8.76	14.6	24.8	430
$\Delta m_1/m_1$	0.21	0.14	0.053	$6.4 \cdot 10^{-3}$
$\Delta m_2/m_2$	0.18	0.12	0.046	$5.5 \cdot 10^{-3}$
$\Delta\tilde{\Lambda}$	$1.9 \cdot 10^4$	$1.3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

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



Network	LVK O3	LVK O4	LVK O5	ET+2CE
BPBH SSM200308 ($\tilde{\Lambda} = \delta\tilde{\Lambda} = 0, \tilde{\lambda}_f = 1$)				
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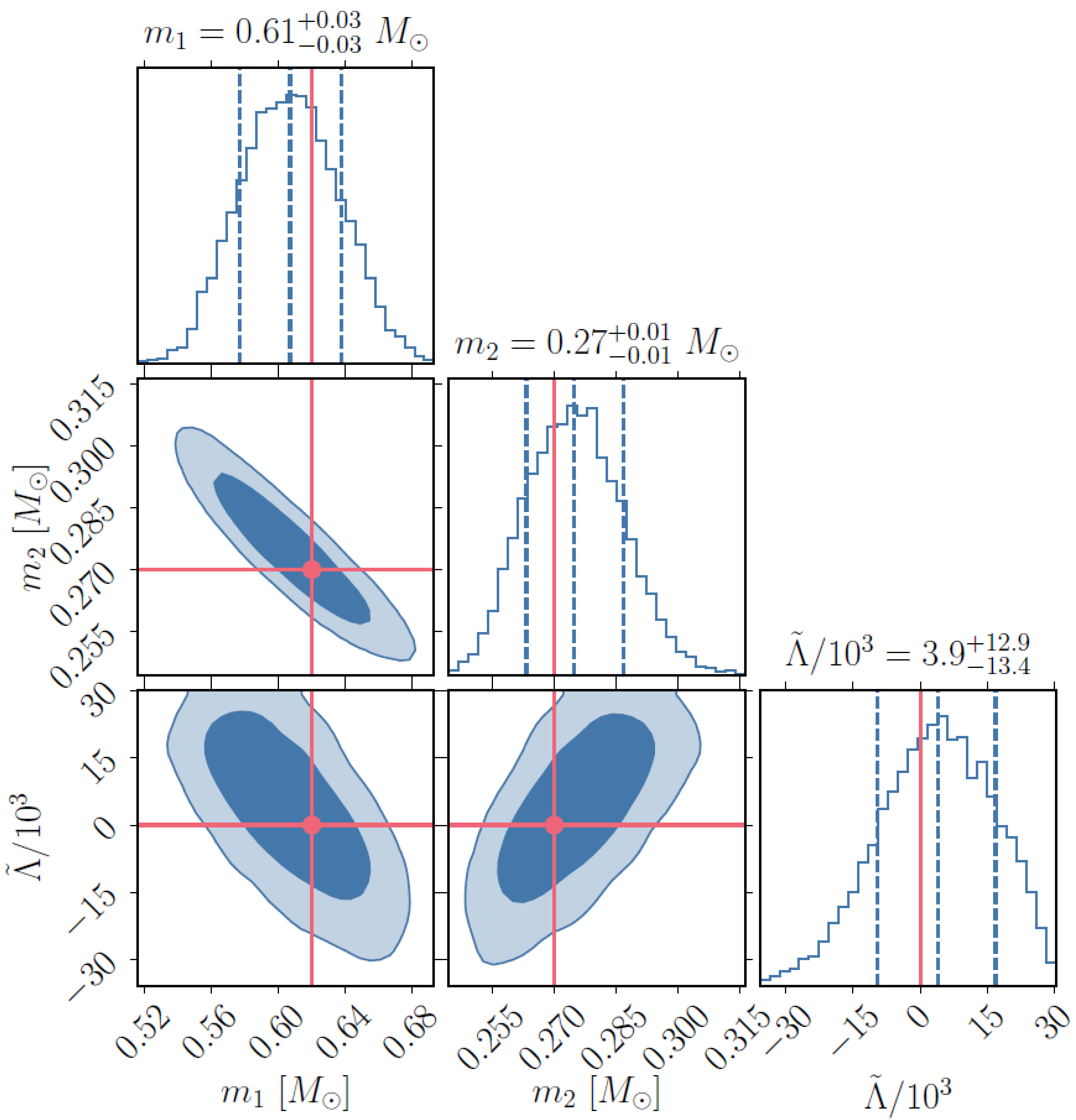
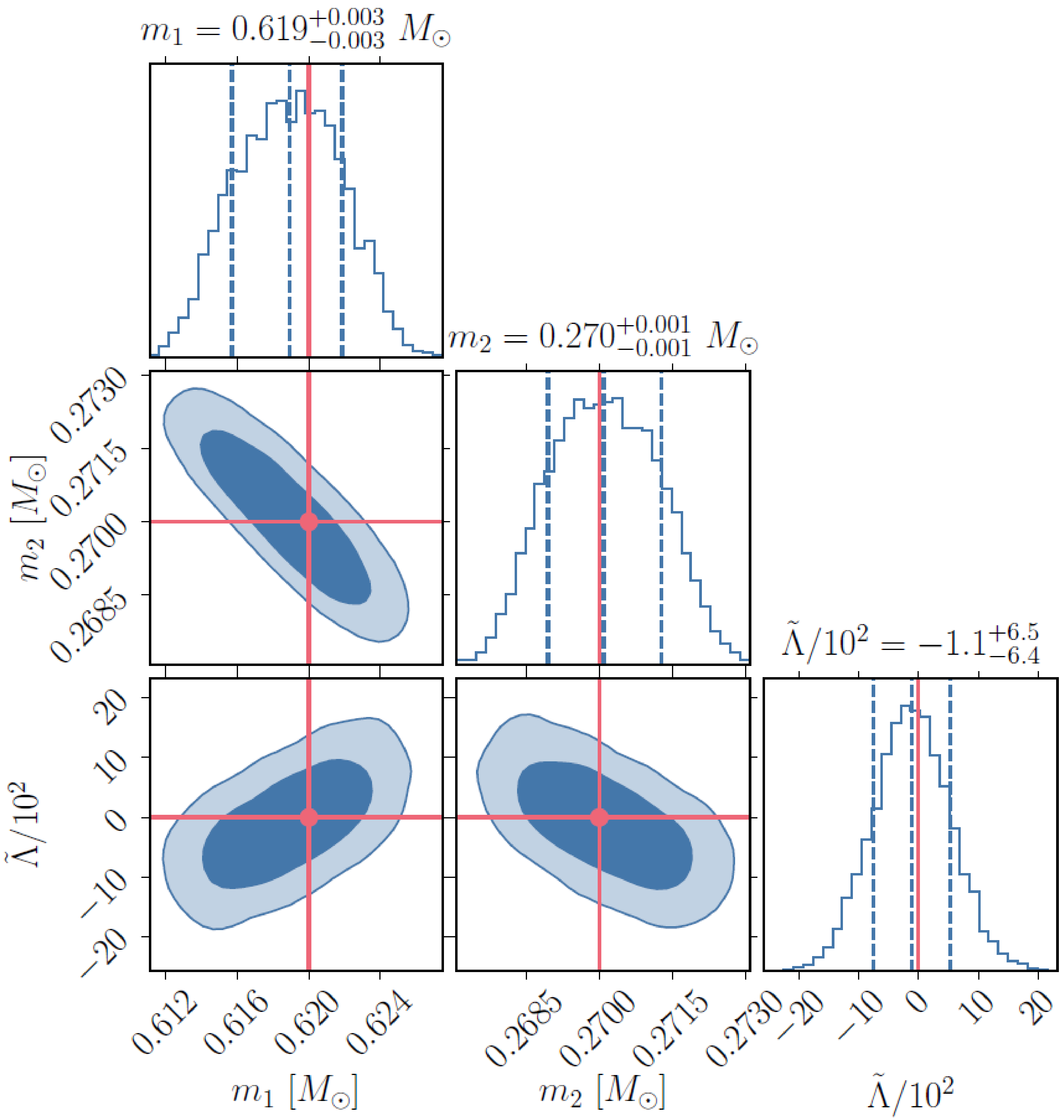
Bayesian inference vs Fisher for BPBHs: O5



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	$5.5 \cdot 10^{-3}$
$\Delta\tilde{\Lambda}$	$1.9 \cdot 10^4$	$1.3 \cdot 10^4$	$7.8 \cdot 10^3$	$7.7 \cdot 10^2$

Bayesian inference vs Fisher for BPBHs: ET+2CE



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	$5.5 \cdot 10^{-3}$
$\Delta\tilde{\Lambda}$	$1.9 \cdot 10^4$	$1.3 \cdot 10^4$	$7.8 \cdot 10^3$	$7.7 \cdot 10^2$

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

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

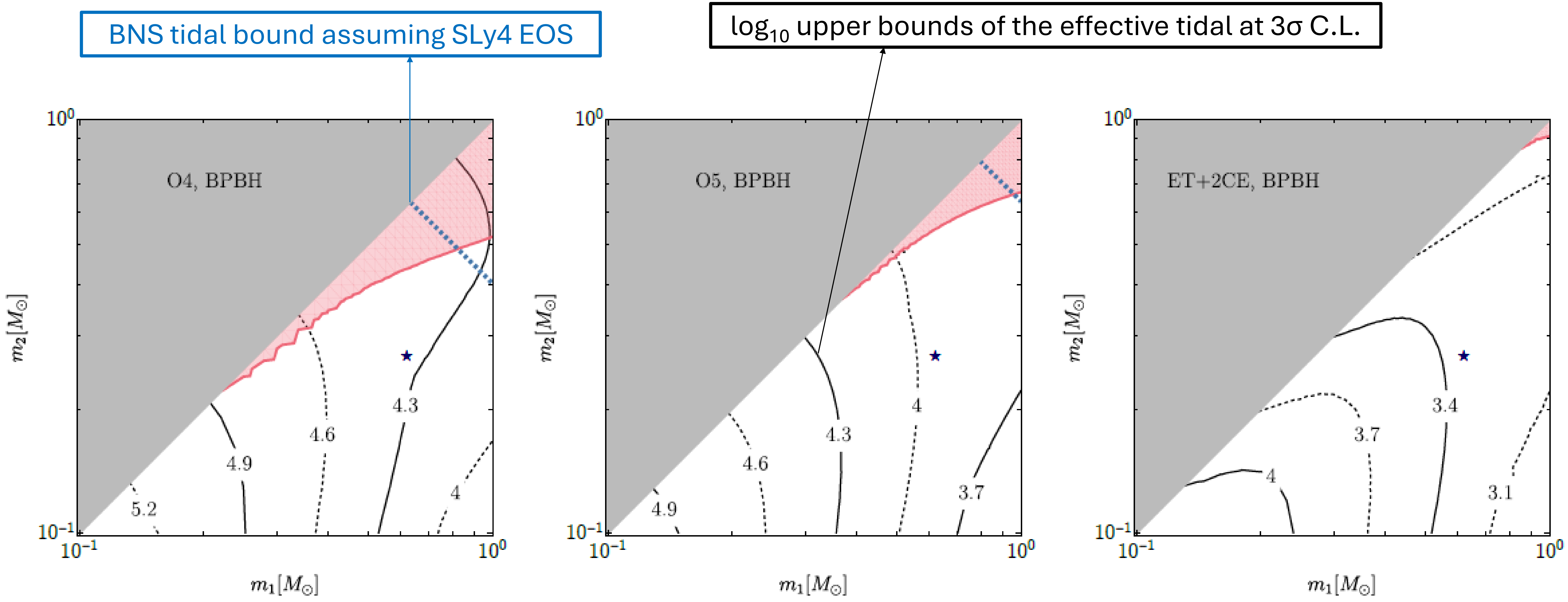
$$\tilde{\Lambda} - 3\Delta\tilde{\Lambda} > 0$$

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

Results:

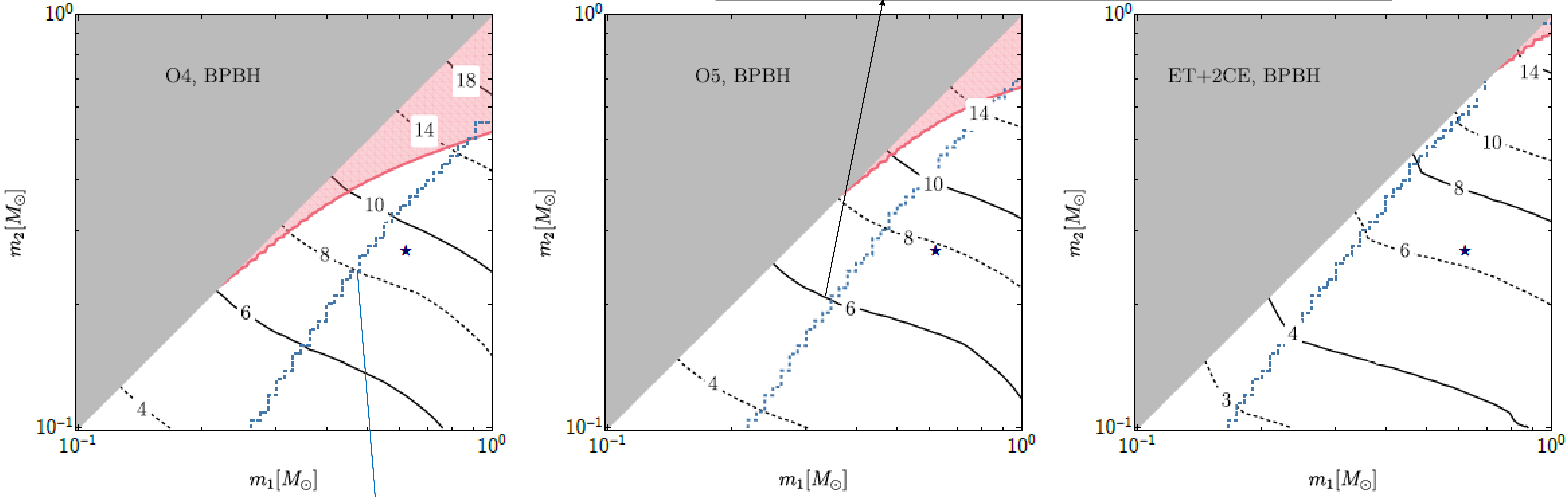
- we can be certain that the binary is subsolar from O5 on;
- tidal deformability distiguishes PBHs from BNSs only with 3G detectors;
- tidal disruption is well constrained from O3 on.

Exploring the Fisher parameter space: the PBH binary case



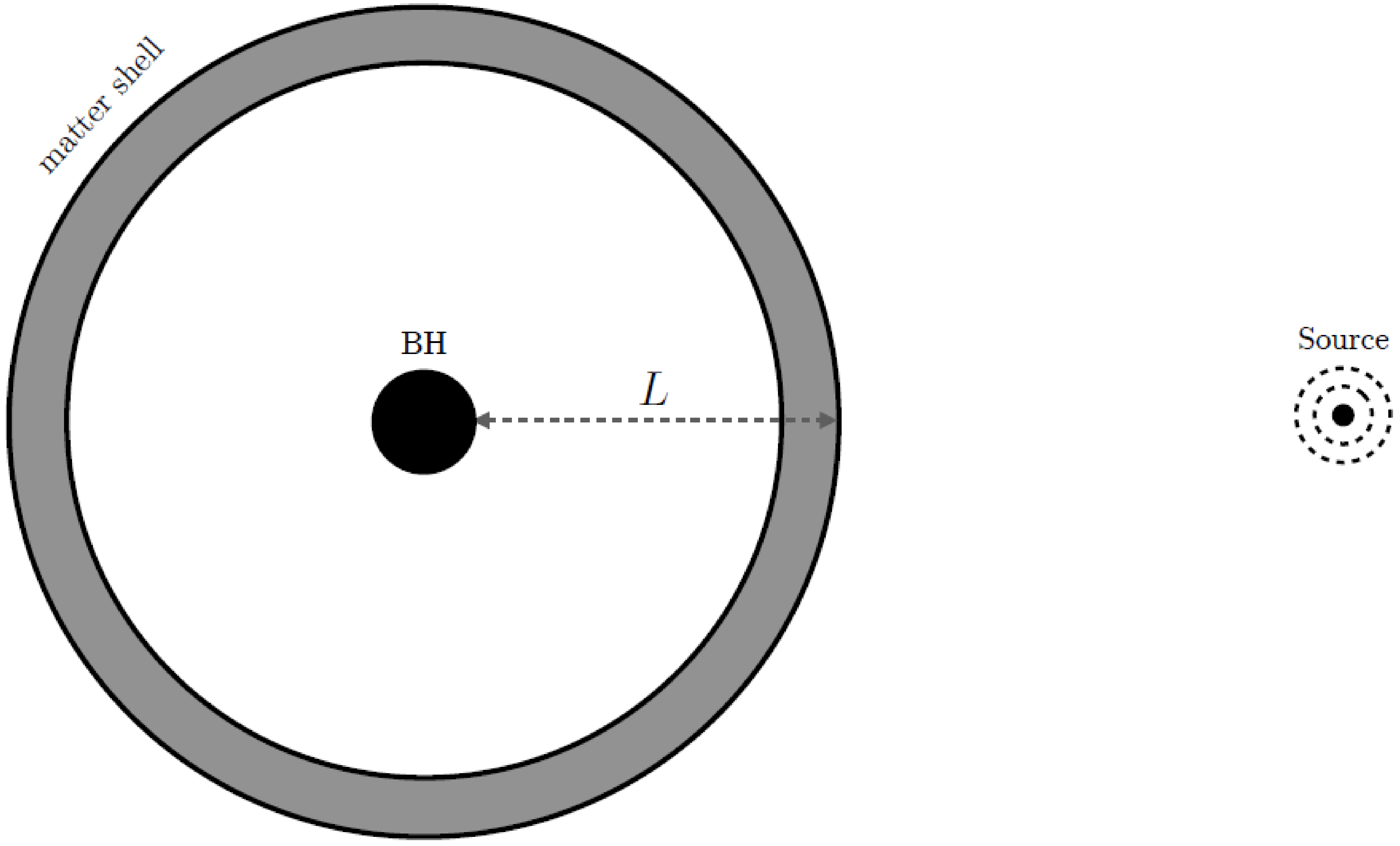
Exploring the Fisher parameter space: constraints on BSs with large quartic interaction

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?

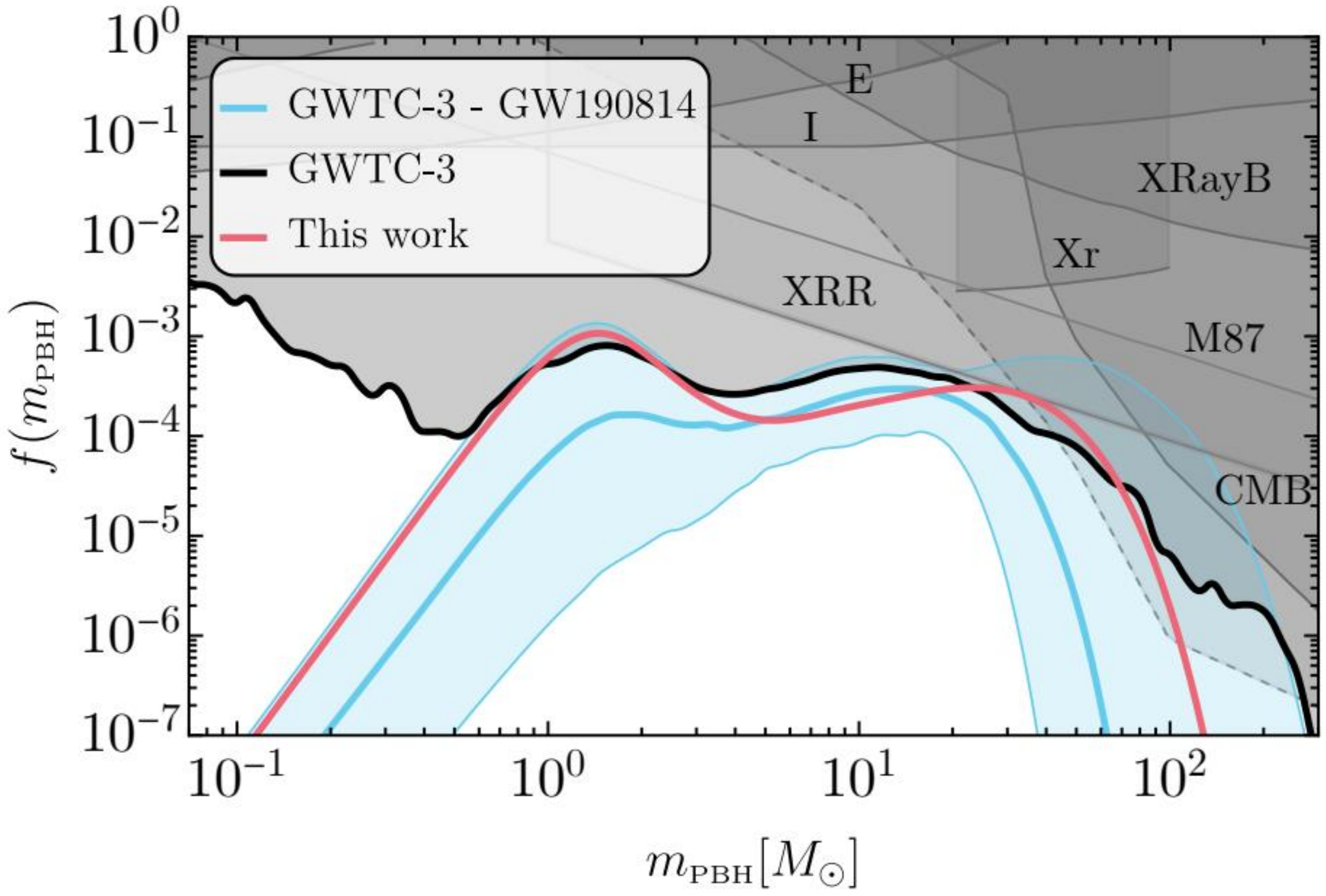


- Having Λ=0 may not exclude PBHs at all.
- If a PBH presents an astrophysical environment, tidal deformabilities will be different from zero.

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

- 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

Real data analysis of SSM200308 trigger

Model	BH1	BH2	Agnostic	NS1	NS2	BS
$m_1[M_\odot]$	$0.65^{+0.17}_{-0.15}$	$0.72^{+0.20}_{-0.17}$	$0.57^{+0.13}_{-0.10}$	$0.59^{+0.29}_{-0.08}$	$0.82^{+0.20}_{-0.14}$	$0.50^{+0.10}_{-0.07}$
$m_2[M_\odot]$	$0.26^{+0.07}_{-0.04}$	$0.23^{+0.06}_{-0.04}$	$0.29^{+0.05}_{-0.05}$	$0.27^{+0.03}_{-0.08}$	$0.21^{+0.03}_{-0.03}$	$0.32^{+0.05}_{-0.05}$
$\chi_{\rm eff}$	$0.41^{+0.05}_{-0.04}$	$0.41^{+0.22}_{-0.05}$	$-0.13^{+0.08}_{-0.09}$	$0.15^{+0.16}_{-0.43}$	$0.72^{+0.07}_{-0.26}$	$0.36^{+0.25}_{-0.21}$
$\chi_{\rm p}$	$0.45^{+0.26}_{-0.26}$	-	-	-	-	-
$d_L[\rm Mpc]$	80^{+37}_{-29}	83^{+41}_{-33}	97^{+45}_{-41}	110^{+139}_{-50}	76^{+37}_{-28}	106^{+84}_{-45}
$\Lambda_1/10^5$	-	-	-4^{+15}_{-10}	5^{+28}_{-3}	6^{+8}_{-5}	-
$\Lambda_2/10^7$	-	-	3^{+23}_{-12}	$1.3^{+0.6}_{-0.8}$	$0.3^{+0.3}_{-0.3}$	-
$\kappa_1/10^3$	-	-	15^{+347}_{-351}	-	-	-
$\kappa_2/10^3$	-	-	-287^{+114}_{-120}	-	-	-
$\log_{10}\tilde{\lambda}_f$	-	-	$-1.01^{+0.65}_{-0.42}$	-	-	-
$M_B[M_\odot]$	-	-	-	-	-	10^{+2}_{-2}
$\log_{10}\mathcal{B}$	-	0.31	-1.64	-2.68	0.22	-2.26

Nuclear physics implications of a SSM detection

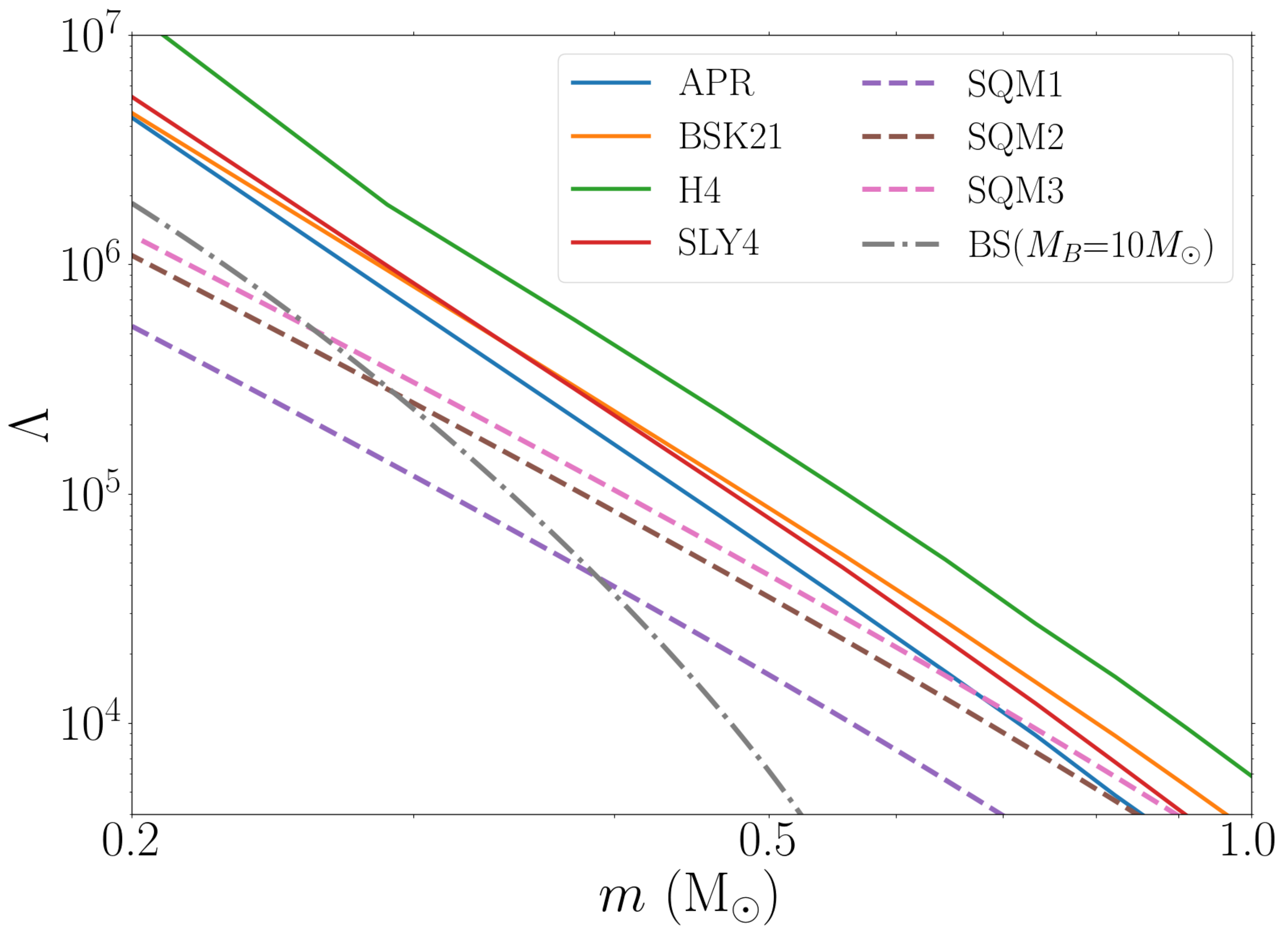
If the SSM objects are identified as light NSs/SQM stars:

- Large tidals can be exploited to constrain the NS EoS.
- Bayesian inference analysis performed by injecting/recovering models A and B, where:

$$\mathrm{A},\ \mathrm{B} \in [APR, WFF1, SQM3]$$

- Compare the hypotheses A and B with Bayes factors.

$$\mathcal{B}_A^B = \frac{Z_B}{Z_A}$$



Detectors	$m_1 [M_\odot]$	APR → SQM3	SQM3 → APR	WFF1 → SQM3	SQM3 → WFF1
O4, SNR = 25	0.63	−1.9	−3.8	0.1	−0.4
	0.27	−10.2	−19.9	−2.7	−5.0
O5, SNR = 44	0.63	−7.0	−12.3	-0.2	−1.0
	0.27	−37.5	−88.8	−11.3	−25.1

FC-Franciolini-Pani-Vaglio, 2408.14287