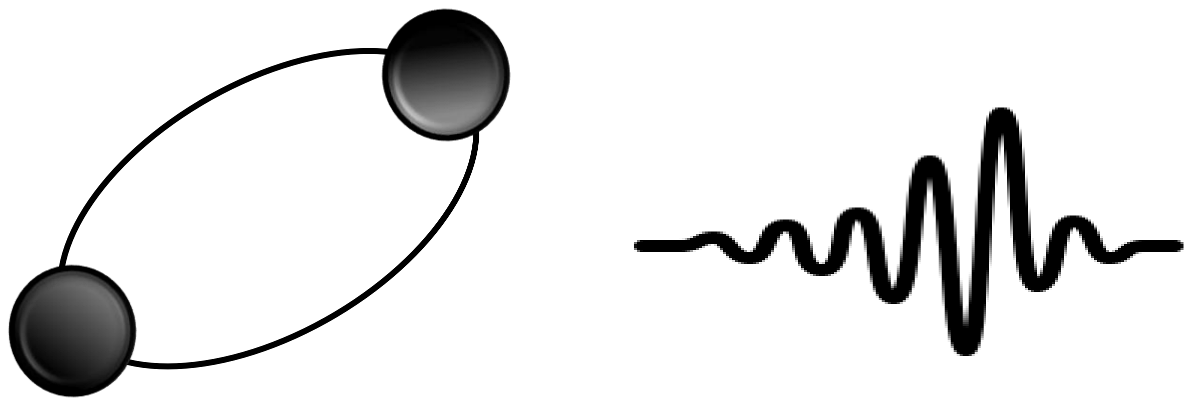
Exploring fundamental physics with Einstein Telescope



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Based on:
F. Crescimbeni, G. Franciolini, P. Pani, A. Riotto, 2402.18656, F. Crescimbeni, G. Franciolini, P. Pani, M. Vaglio, 2408.14287, R. F. Rosato, F. Crescimbeni, S. Yi, E. Berti, P. Pani, 2604.11895, A. Valletta, F. Crescimbeni, T. Takagiri, F. Pannarale, P. Pani, *in preparation*.

Contents

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- Tidal deformability: the importance of subsolar objects
- Tests of General Relativity with ET
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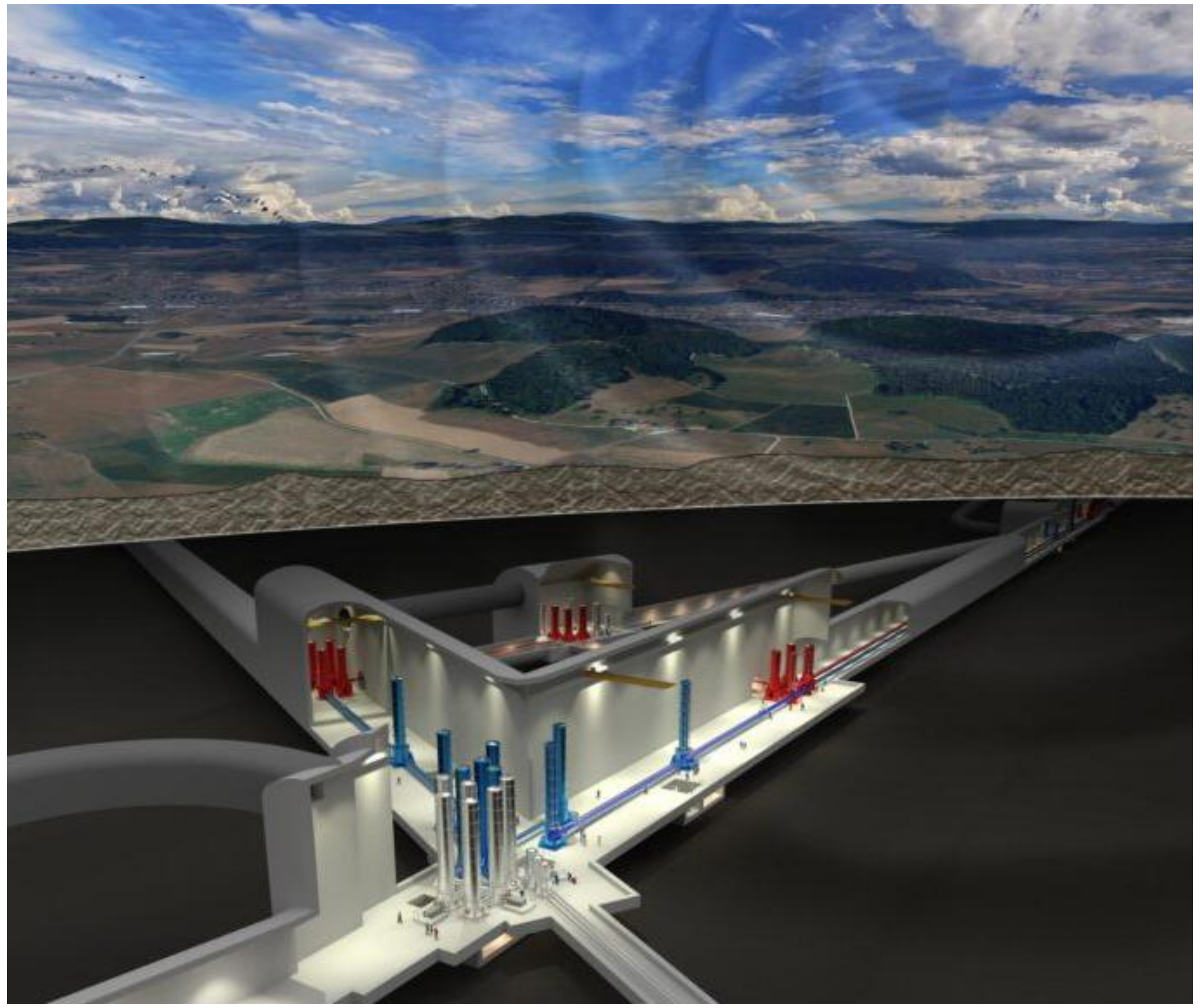
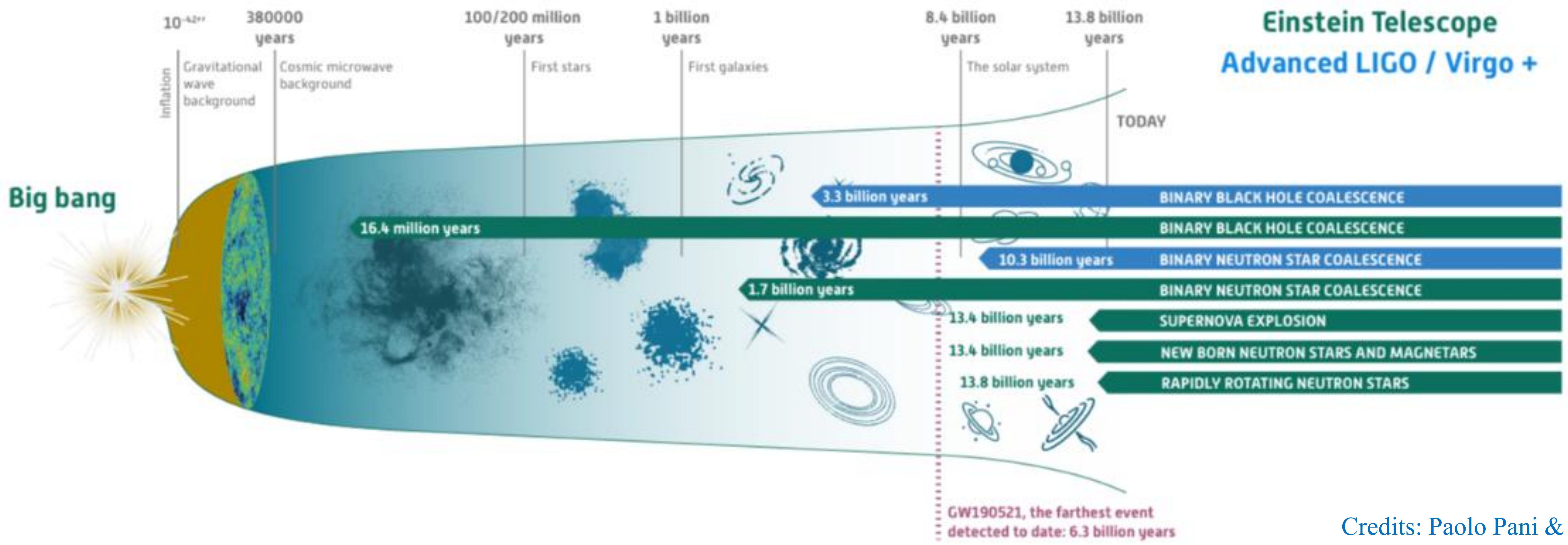


An introduction to Einstein Telescope

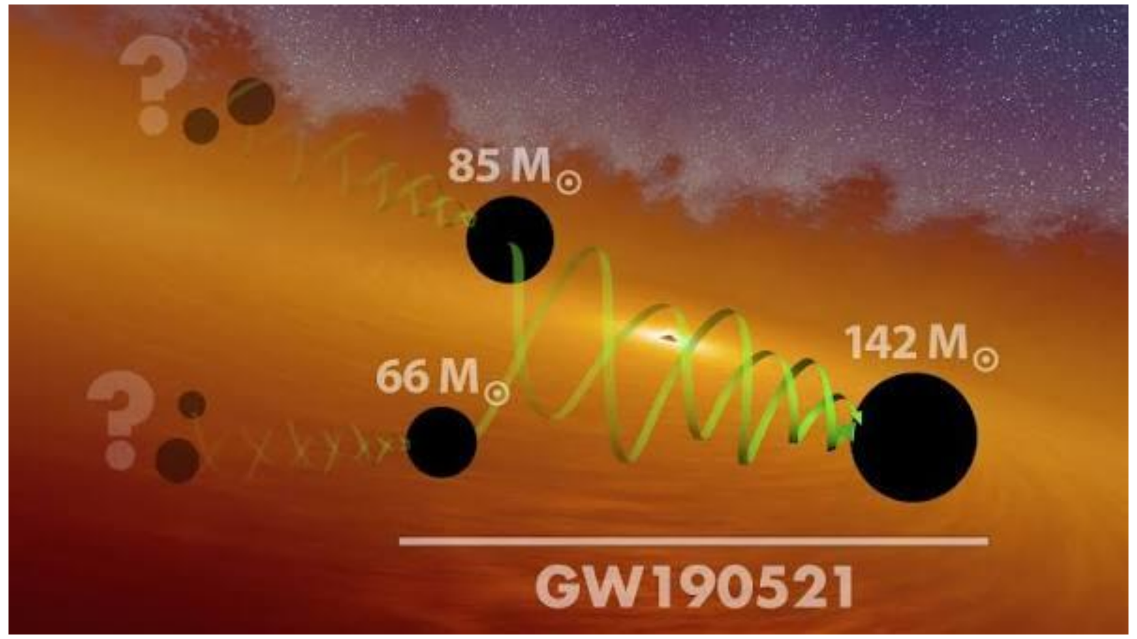


Credits: Paolo Pani & INFN

- ET will provide precision measurements of GW sources in the nearby Universe.
- A discovery machine investigating the first moments of the Universe.

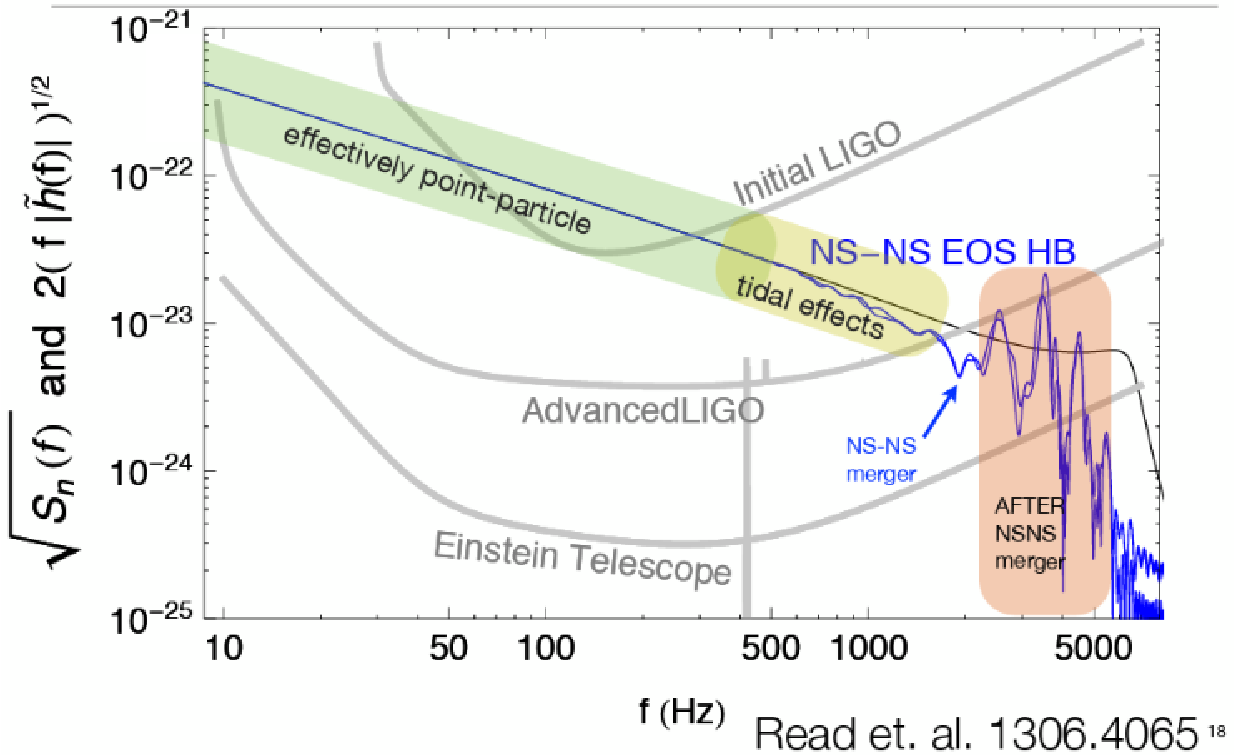
Fundamental physics with the Einstein Telescope: some examples

Case 1: special events



- Subsolar events, intermediate mass black holes.
- Primordial (PBH) origin? Pop III?

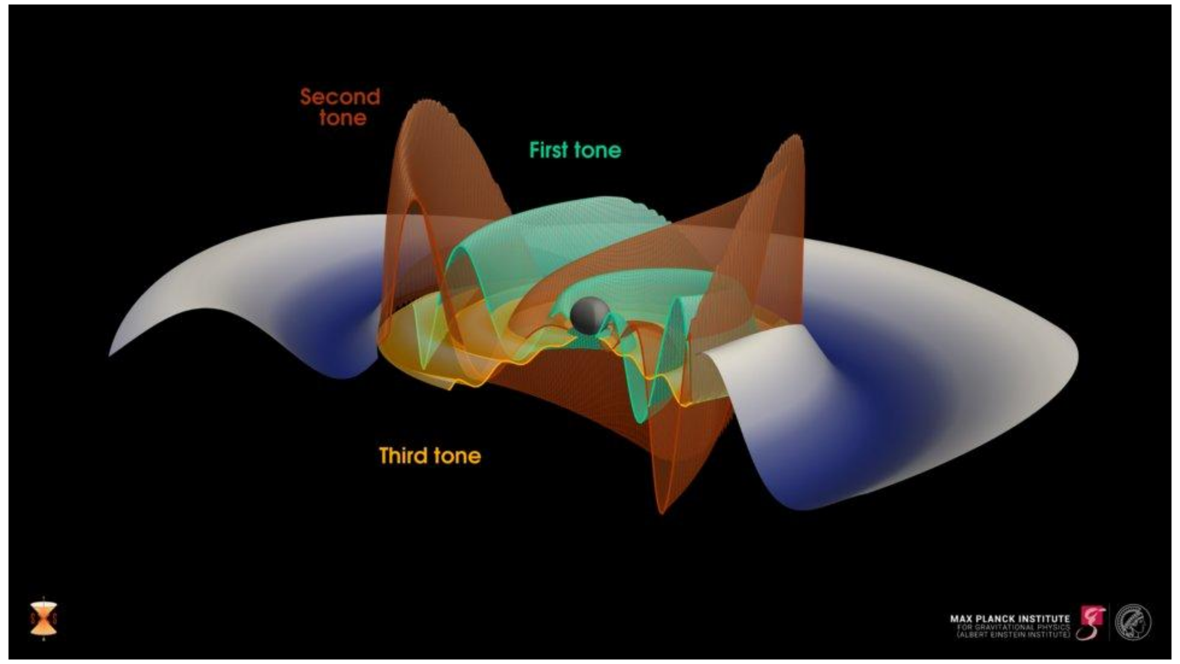
Case 2: Nuclear physics



Read et. al. 1306.4065 [18]

- Infer on the tidal deformability
- Constraints on the EoS
- Electromagnetic counterpart

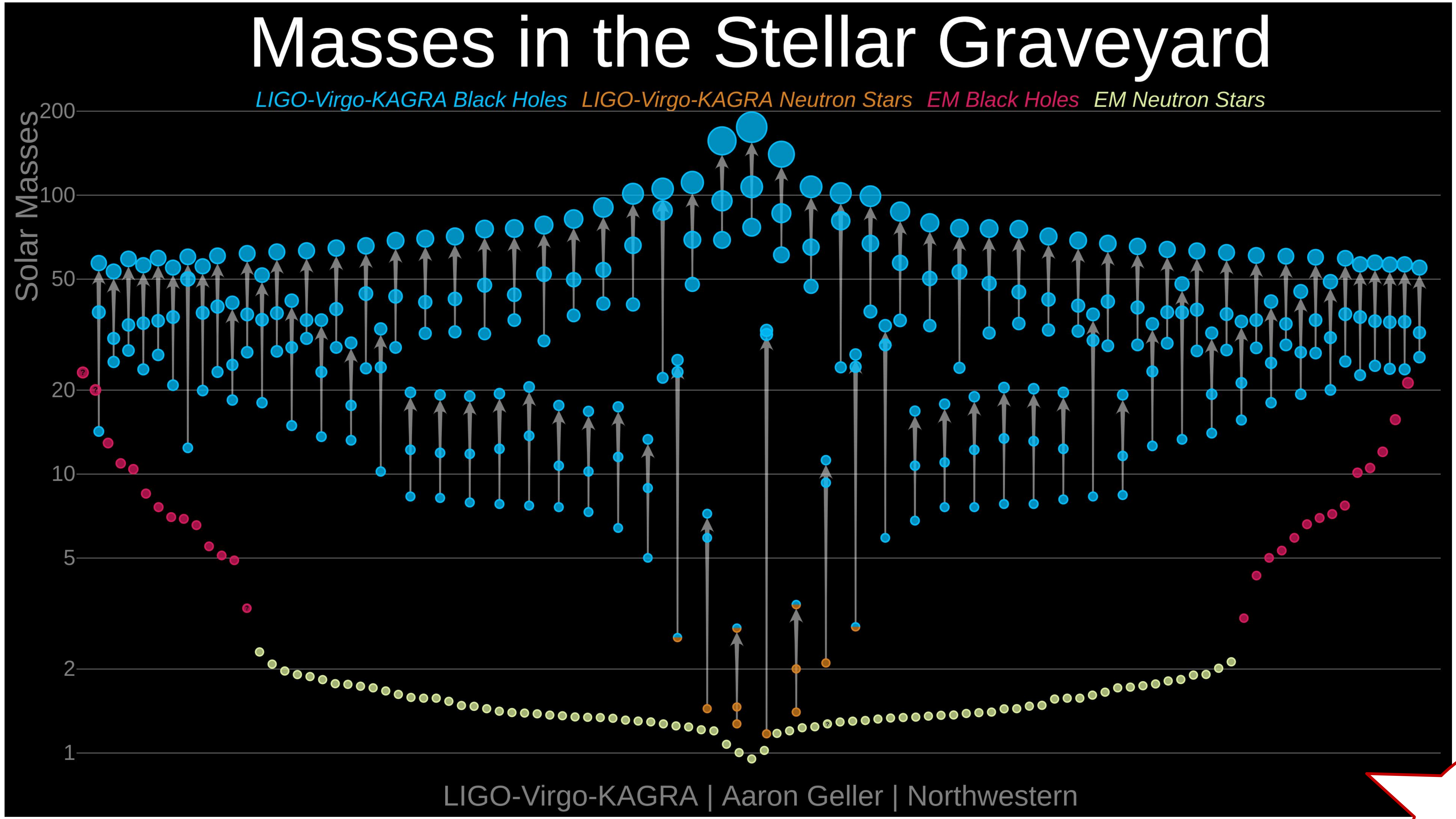
Case 3: BH Spectroscopy



- Measuring more that one mode is used as a GR consistenceny check.
- Fundamental mode and first overtone: 6% and 30% accuracy.

Tidal love numbers: the importance of subsolar objects

Subsolar compact objects still missing



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

Subsolar compact objects from GW observations still not comfidently detected!

SSM candidates and how they are deformed

- Astrophysics objects: Light neutron stars (Metzger-Hui-Cantiello, 2024; De Luca+, 2026).

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

Non-zero tidal deformabilities

- Exotic compact objects: boson stars, fermionic stars (Cardoso-Pani, 2019; Del Grosso+, 2023);

New physics

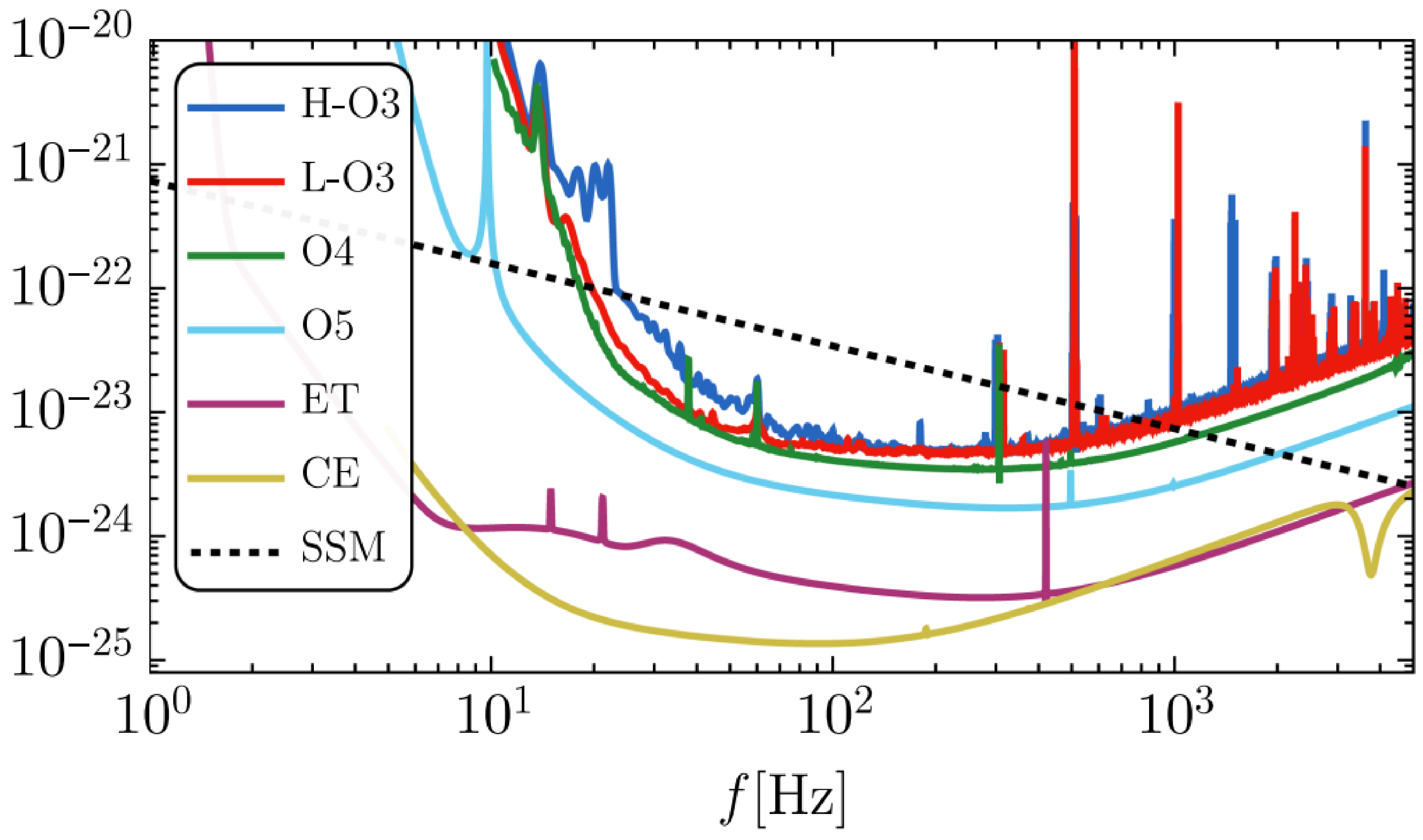
- Primordial black holes (S. Hawking, 1971).

$$\Lambda = 0$$

Non-deformable (symmetry properties)

Waveform modeling of SSM binaries

➢ Subsolar objects will be mostly observed in the inspiral part of the signal.



Point particle phase: contains mass and spin effects

Tidal phase

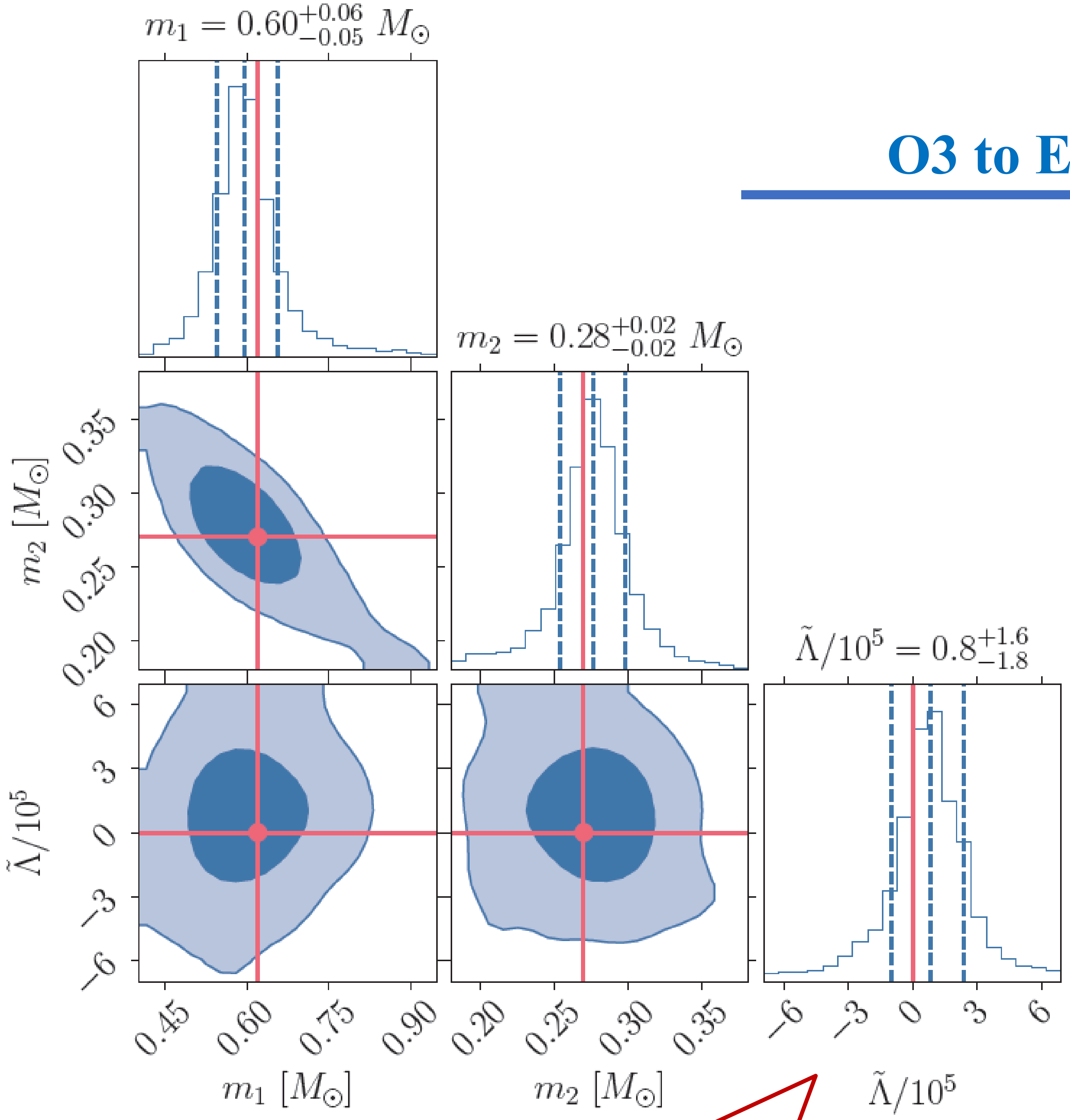
$$\begin{cases} \psi(x) = \underbrace{\psi_{\mathrm{pp}}(x)}_{\text{Up to 4PN}} + \underbrace{\delta\psi_{\mathrm{tidal}}(x)}_{\text{5PN + 6PN}} \\ x = (\pi f M)^{2/3} \end{cases}$$

Combinations of Λ_1 and Λ_2

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

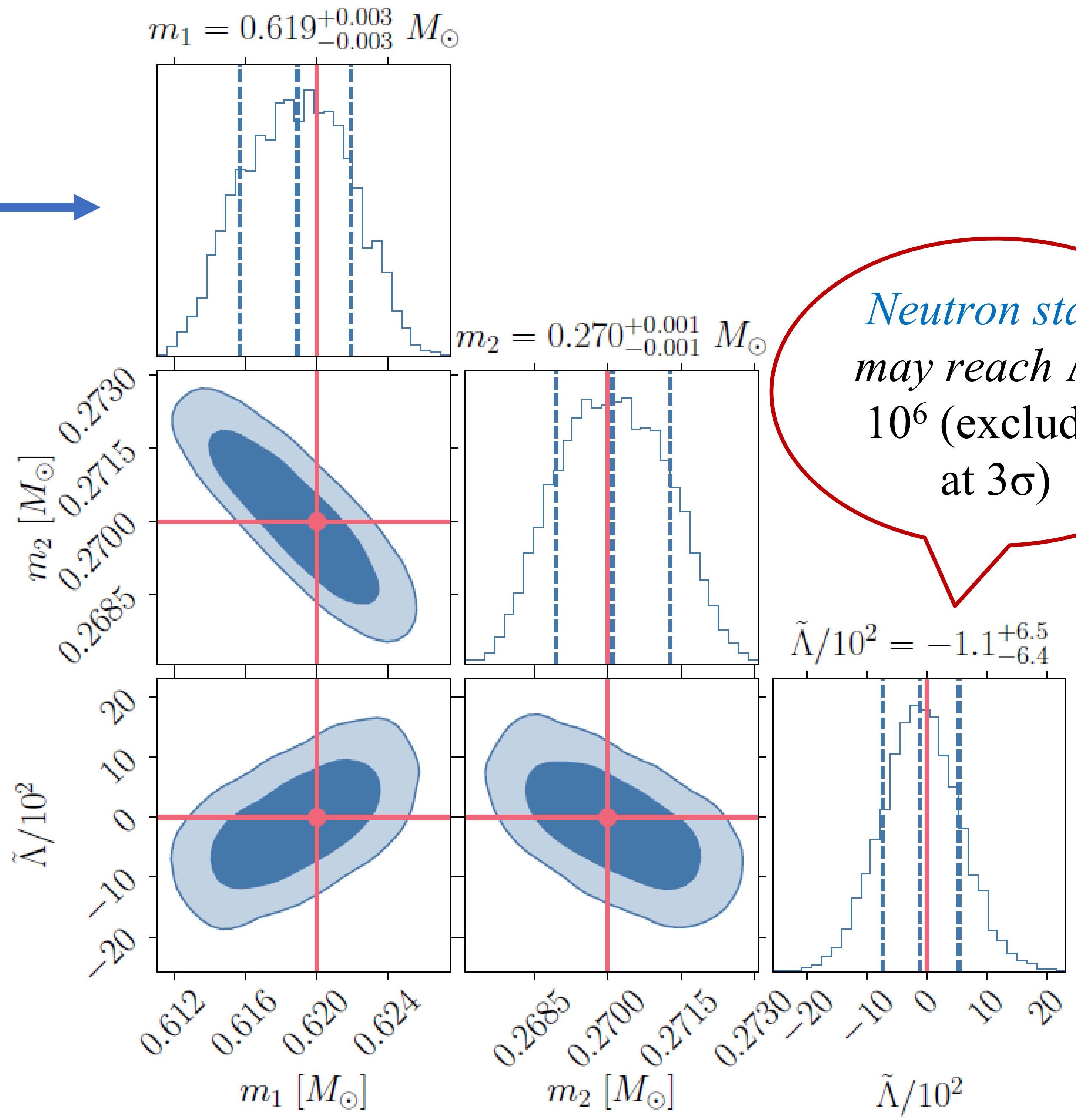
PBH binary injections

- Bayesian inference analysis performed with Bilby (Ashton+, 2018)
- PBH binary injections + recovery
- Inject SSM200308 parameters (Prunier+, 2023) + zero tides
- O3 sensitivity



Effective tidal: undistinguishable SSM candidates

O3 to ET

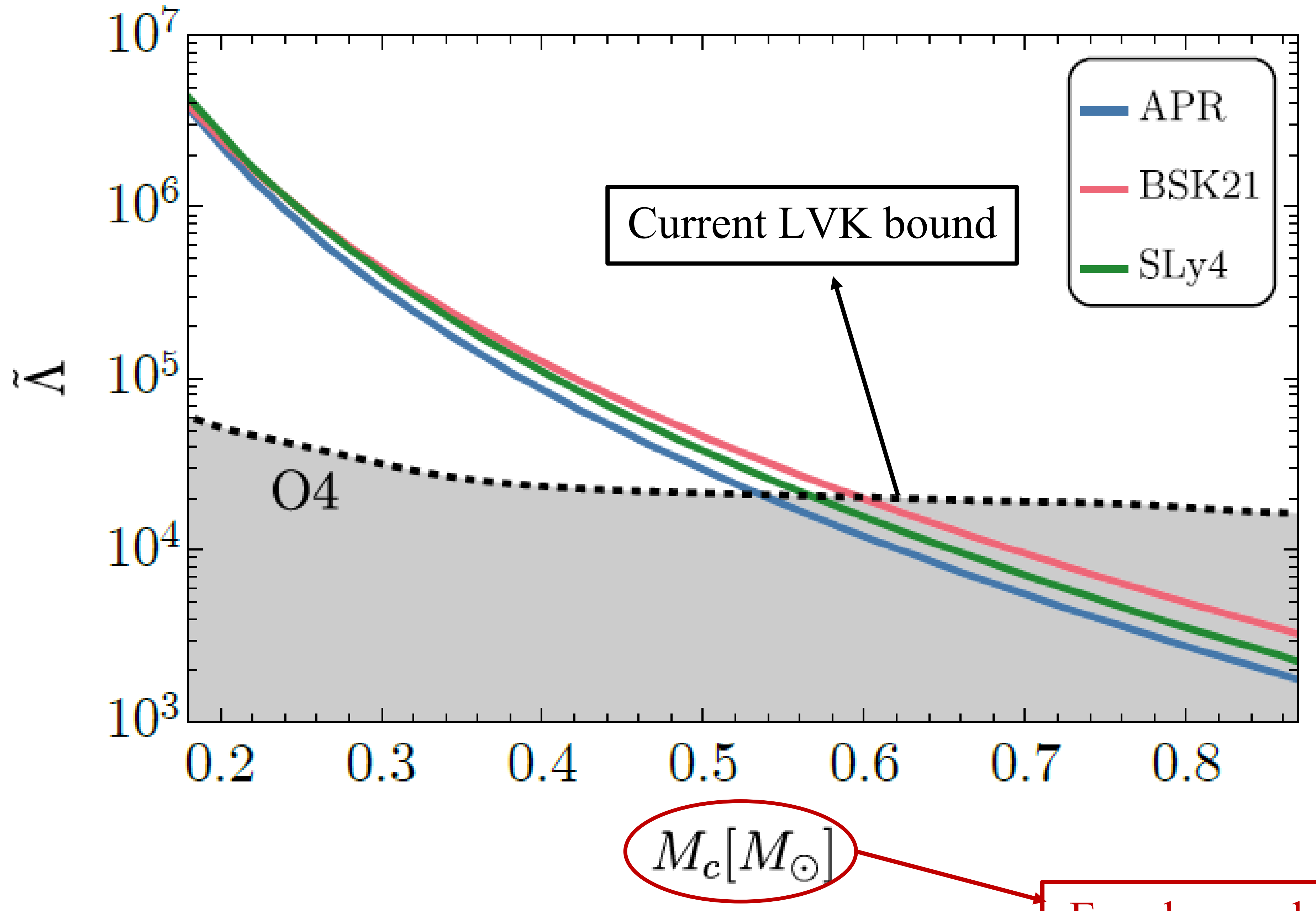


Neutron stars may reach $\Lambda \approx 10^6$ (excluded at 3σ)

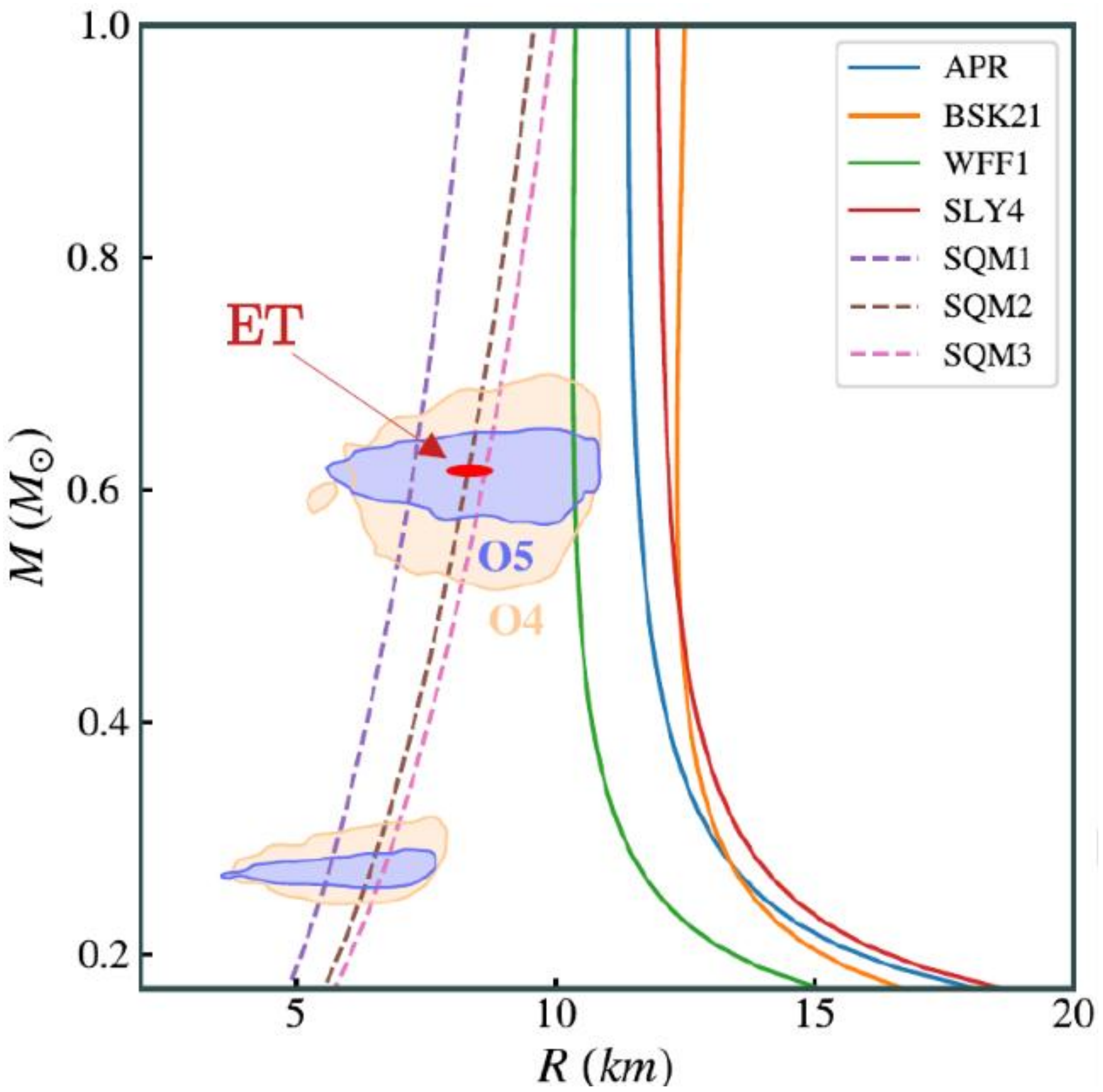
FC-Franciolini-Pani-Riotto, 2024

Nuclear physics implications of a SSM detection

➢ Large tidals can be exploited to constrain the NS EoS.



Equal-mass binaries



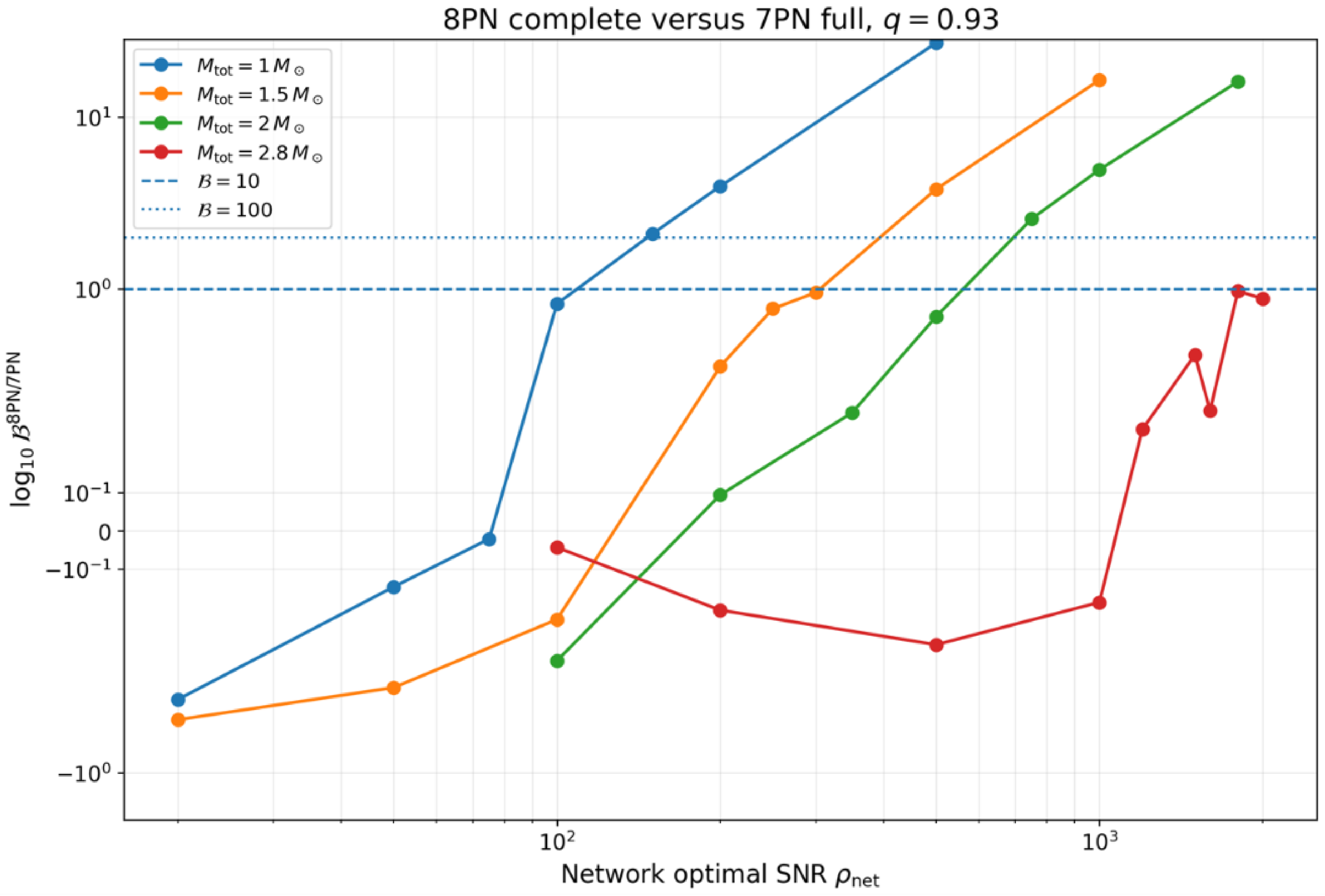
FC-Franciolini-Pani-Vaglio, 2024

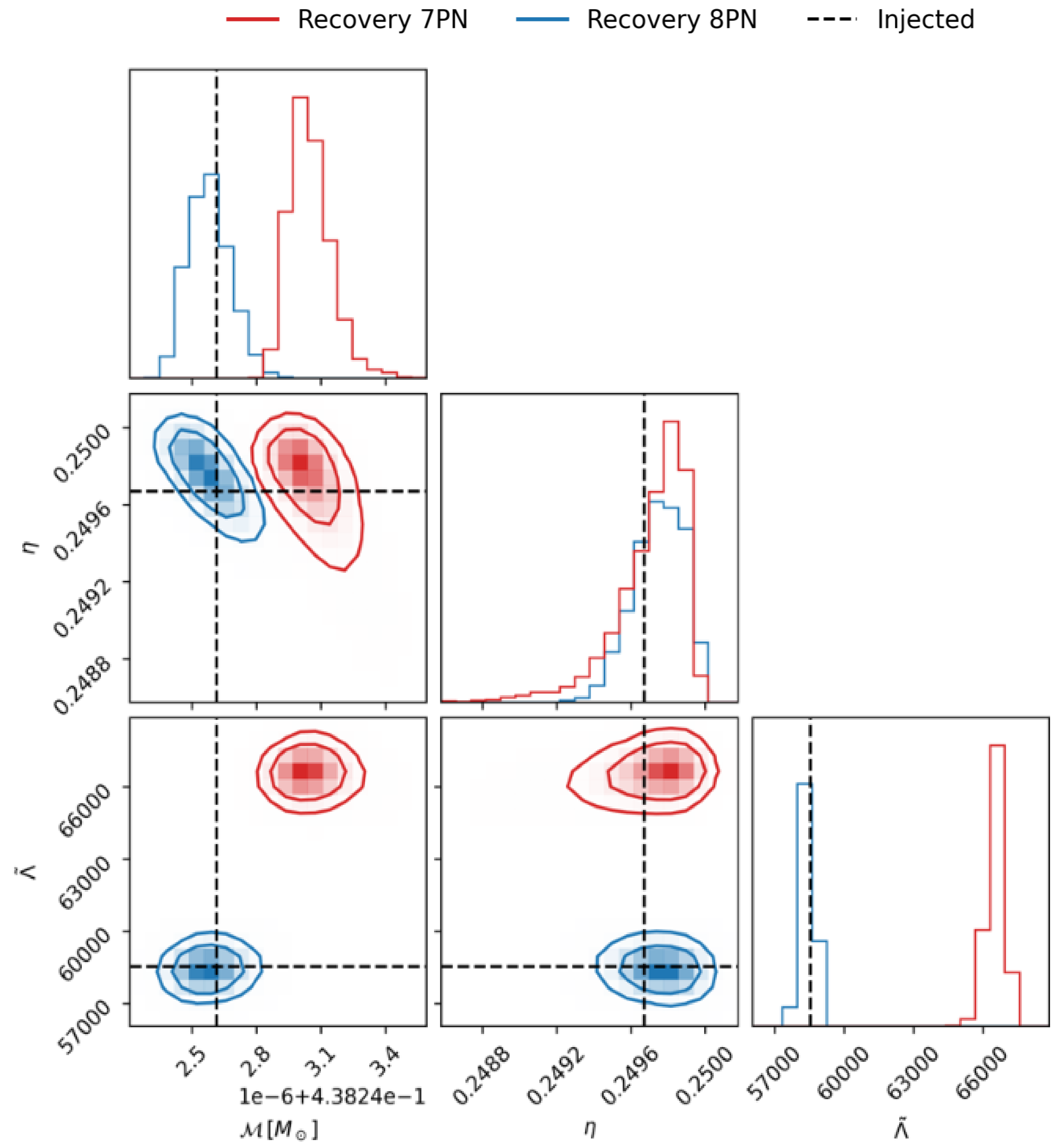
Including higher tidal terms

- Higher tidal corrections are computed up to 8PN (Chakraborty, Pani, 2026).

$$\delta\psi_{\rm tidal} = \frac{3}{128\eta x^{5/2}}\left[\mathcal{A}_5 x^5 + \mathcal{A}_6 x^6 + \mathcal{A}_{13/2} x^{13/2} + \mathcal{A}_7 x^7 + \mathcal{A}_8 x^8\right]$$

- Compare the hypotheses A=up to 8PN and B=up to 7PN with Bayes factors.





Valletta, FC+, in preparation

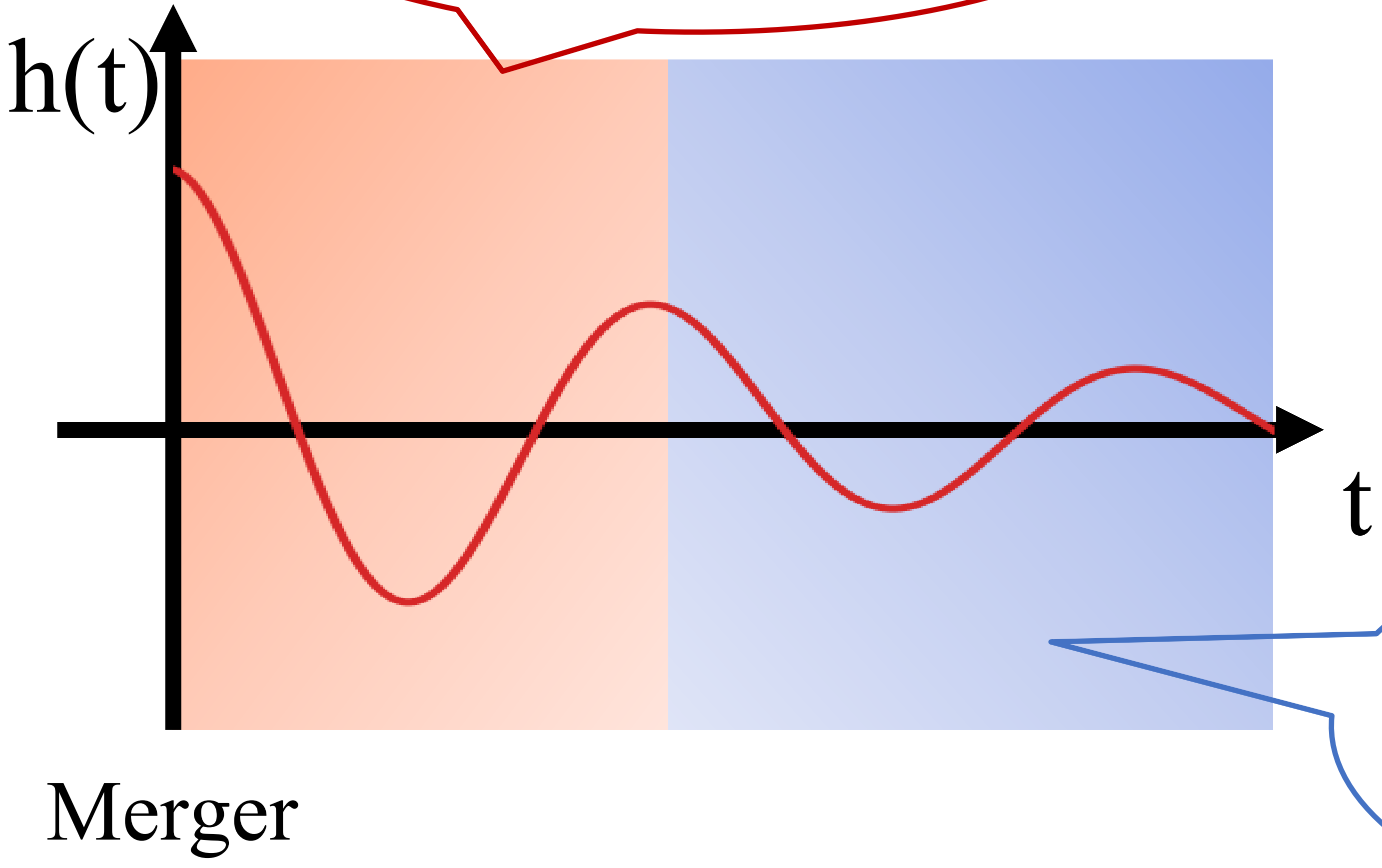
Tests of General Relativity with ET

Tests of GR: black hole spectroscopy

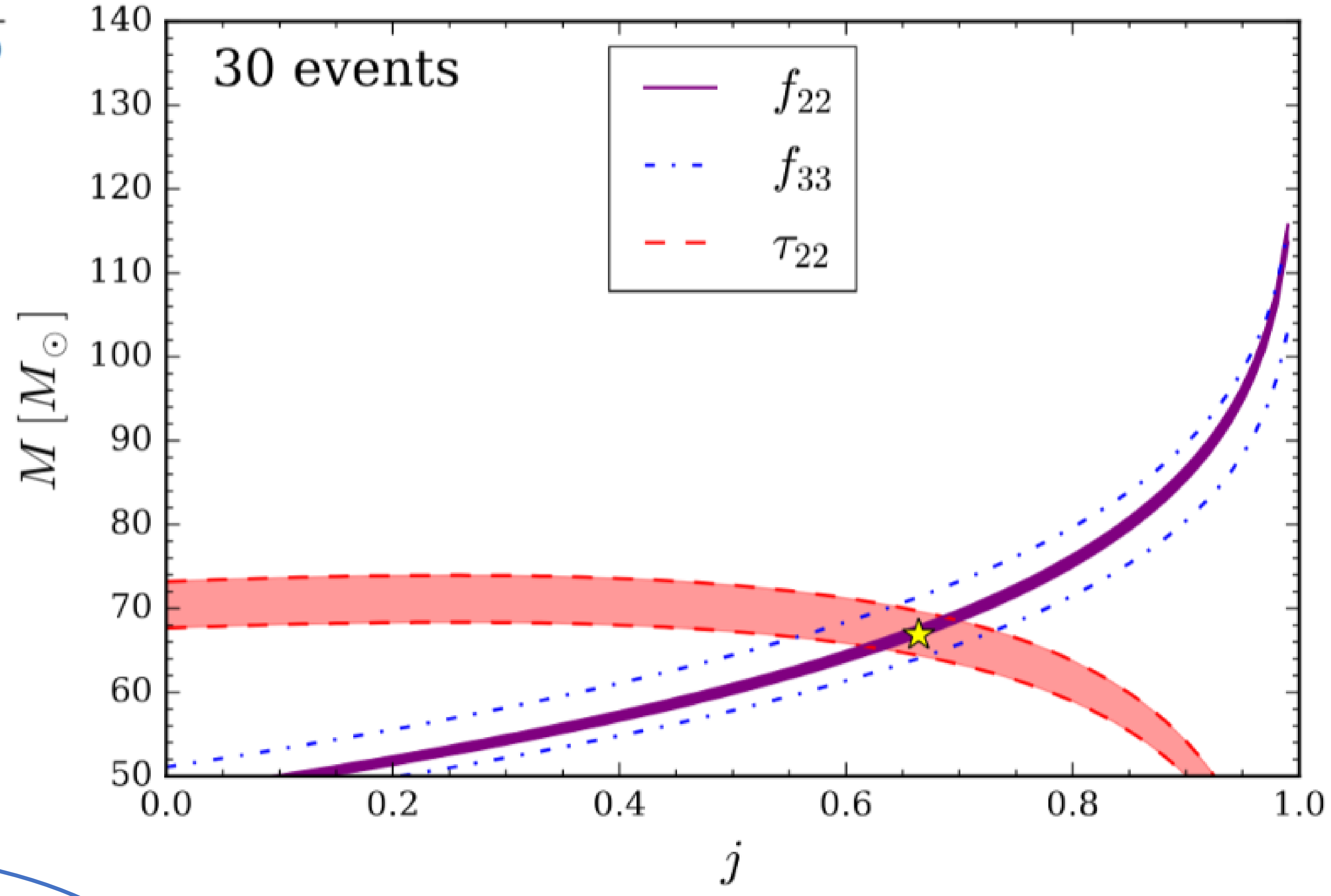
➢ Time domain analyses: measure quasi-normal modes and perform consistency checks.

$$h(t) = \sum_{\ell,m,n} A_{\ell mn} e^{i\left[2\pi f^{\mathrm{Kerr}}_{\ell mn}(1+\delta f_{\ell mn})t+\phi_{\ell mn}\right]} e^{-\frac{t}{\tau^{\mathrm{Kerr}}_{\ell mn}(1+\delta \tau_{\ell mn})}}$$

Early times:
non-linearities and
transient effects



Late times:
Quasi-Normal-Mode
superposition



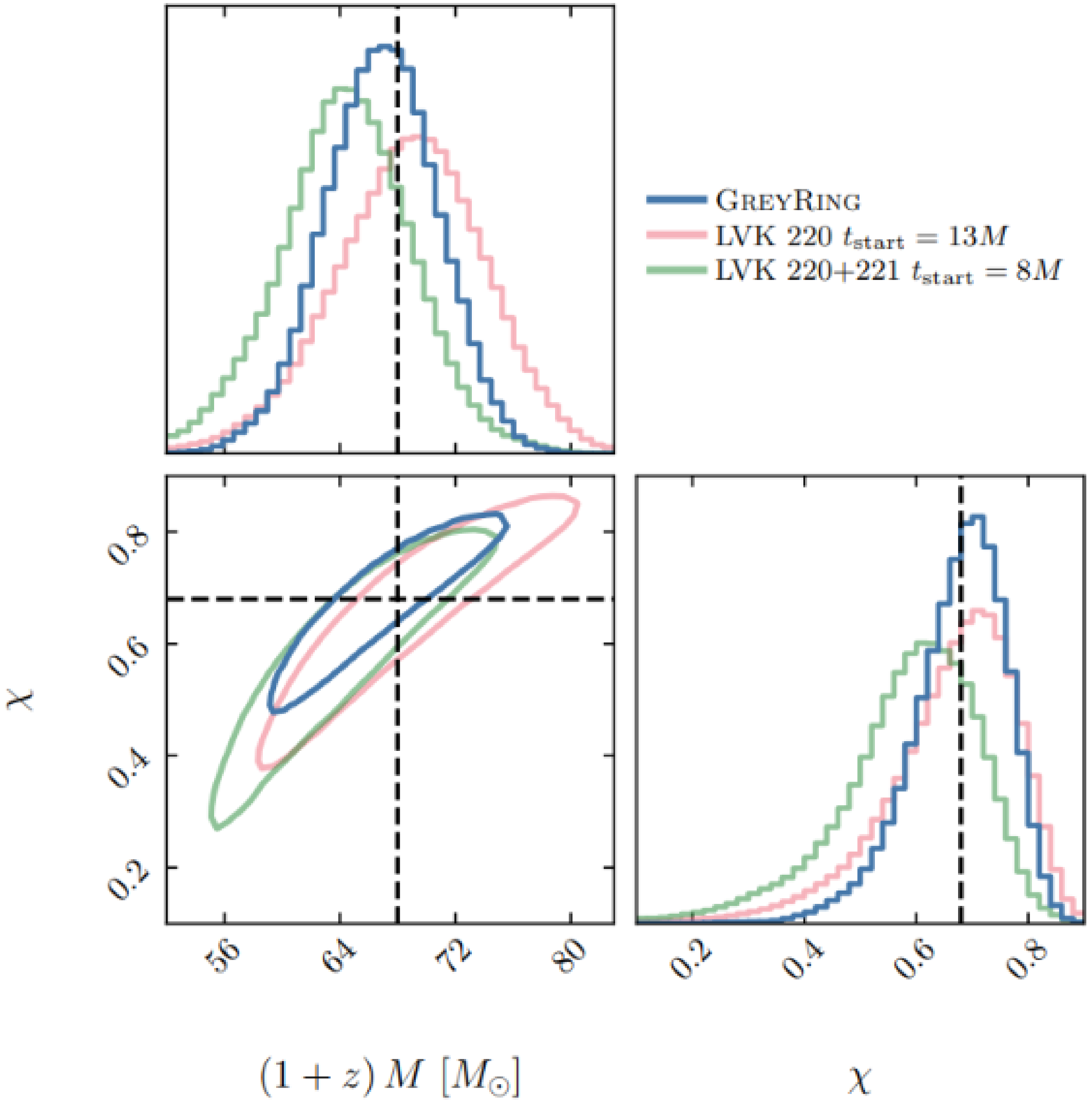
Brito+, 2015

Tests of GR: greybody factors

- Model the postmerger in the frequency domain with the reflectivity of the black hole:

$$\tilde{h}_{\ell m}(\omega) = \frac{M A_{\ell m}}{(M\omega)^{p_{\ell m}}} R_{\ell m}(M\omega, \chi)\, e^{i\frac{c_{\ell m}}{M\omega}}\, e^{i(\phi_c + \omega t_c)}$$

- Novel test of GR along with standard BH spectroscopy (Rosato-FC+, 2026).



Rosato, FC+, 2026

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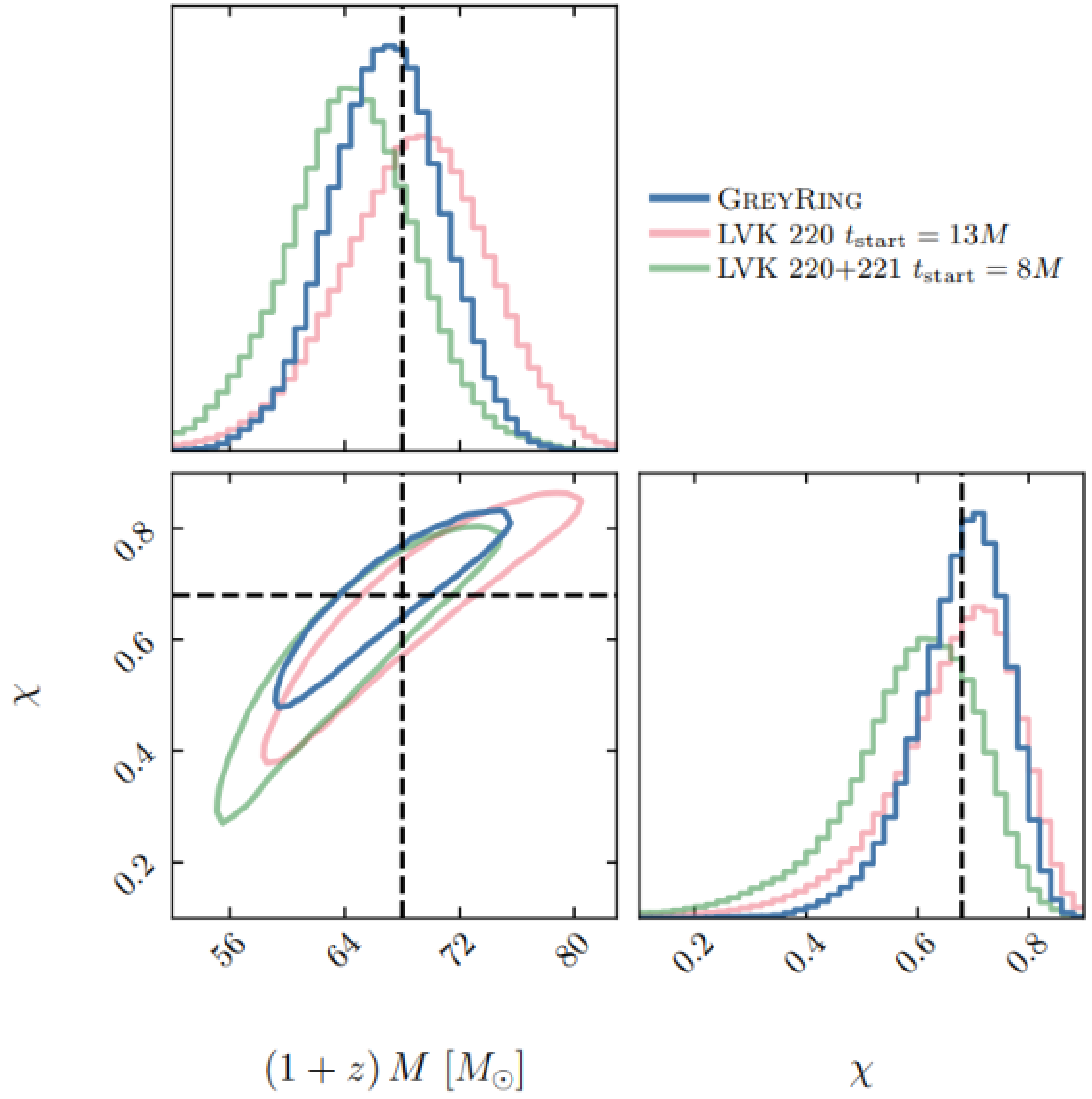

Rosato, FC+, 2026

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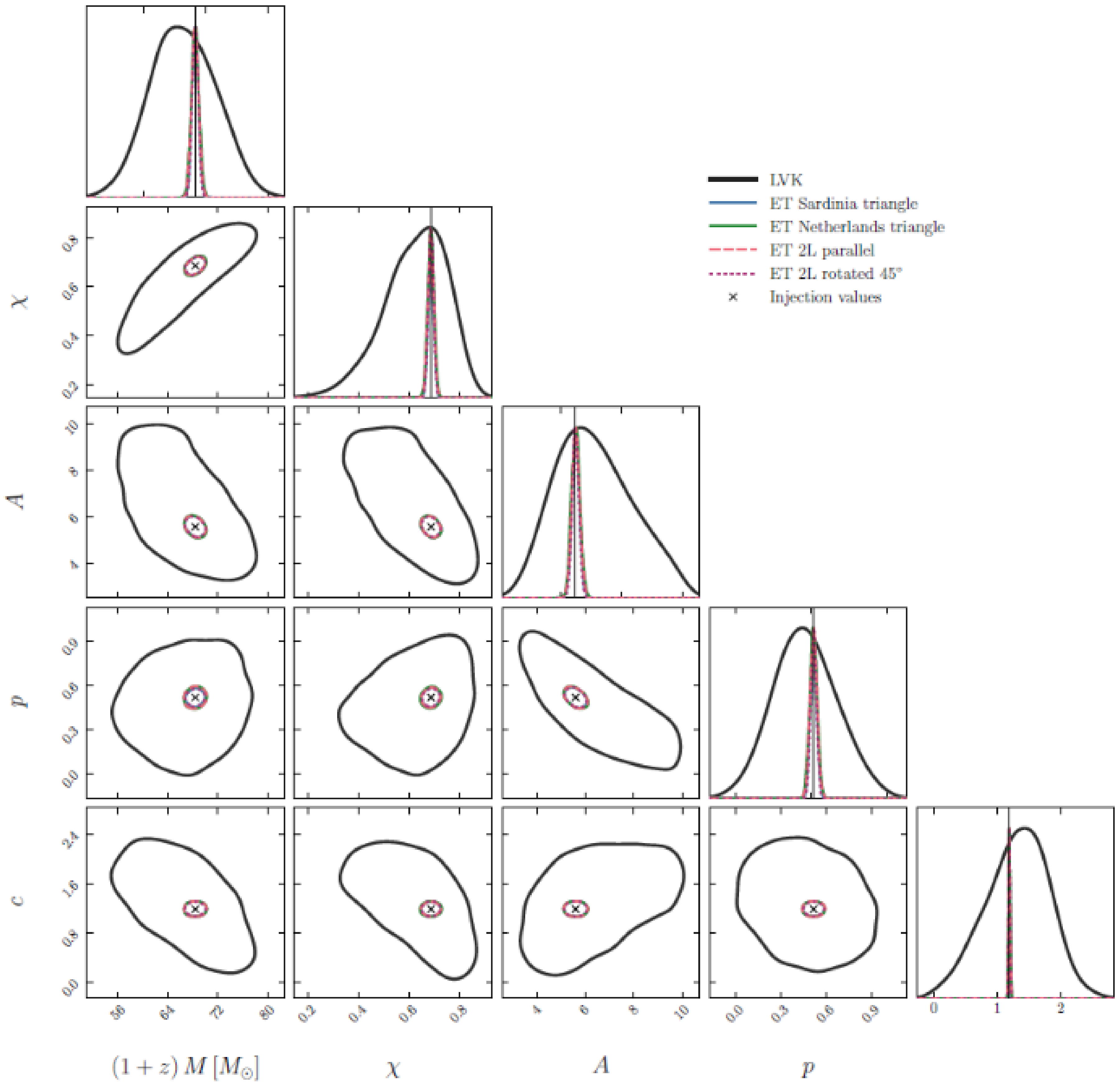


Rosato, FC+, in preparation

Conclusions and future developments

Take-home messages:

- Tidal parameters can help us understanding the nature of compact objects.
- Tests of GR in the inspiral and in the ringdown will be much improved with ET.

Future directions of the fundamental physics division in ET:

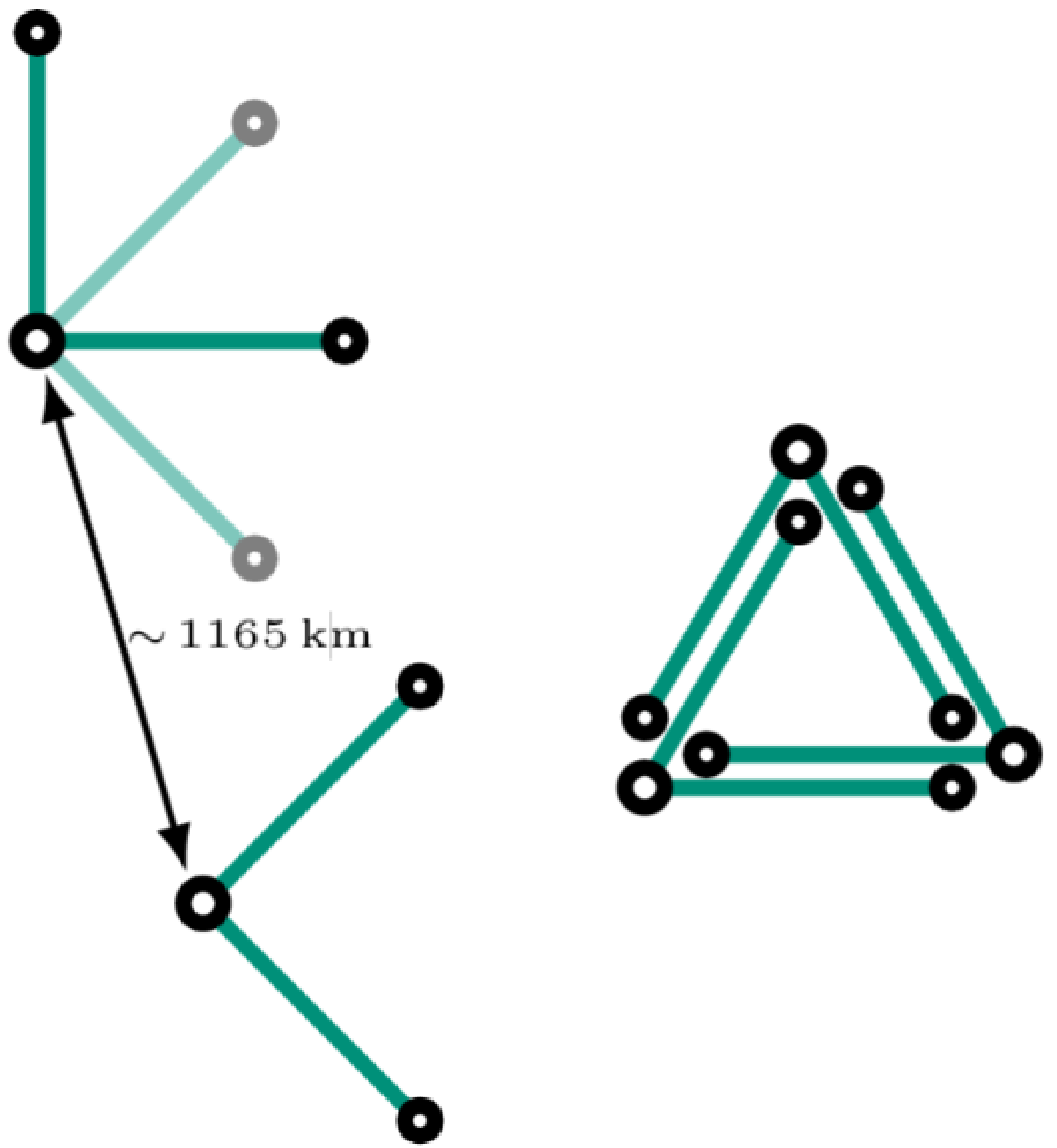
- Developing framework and performing inspiral-merger-ringdown consistency test
- Investigating the impact of overlapping signals on tests of gravity
- Designing methods for stacking multiple GW events

Thank you for your attention!

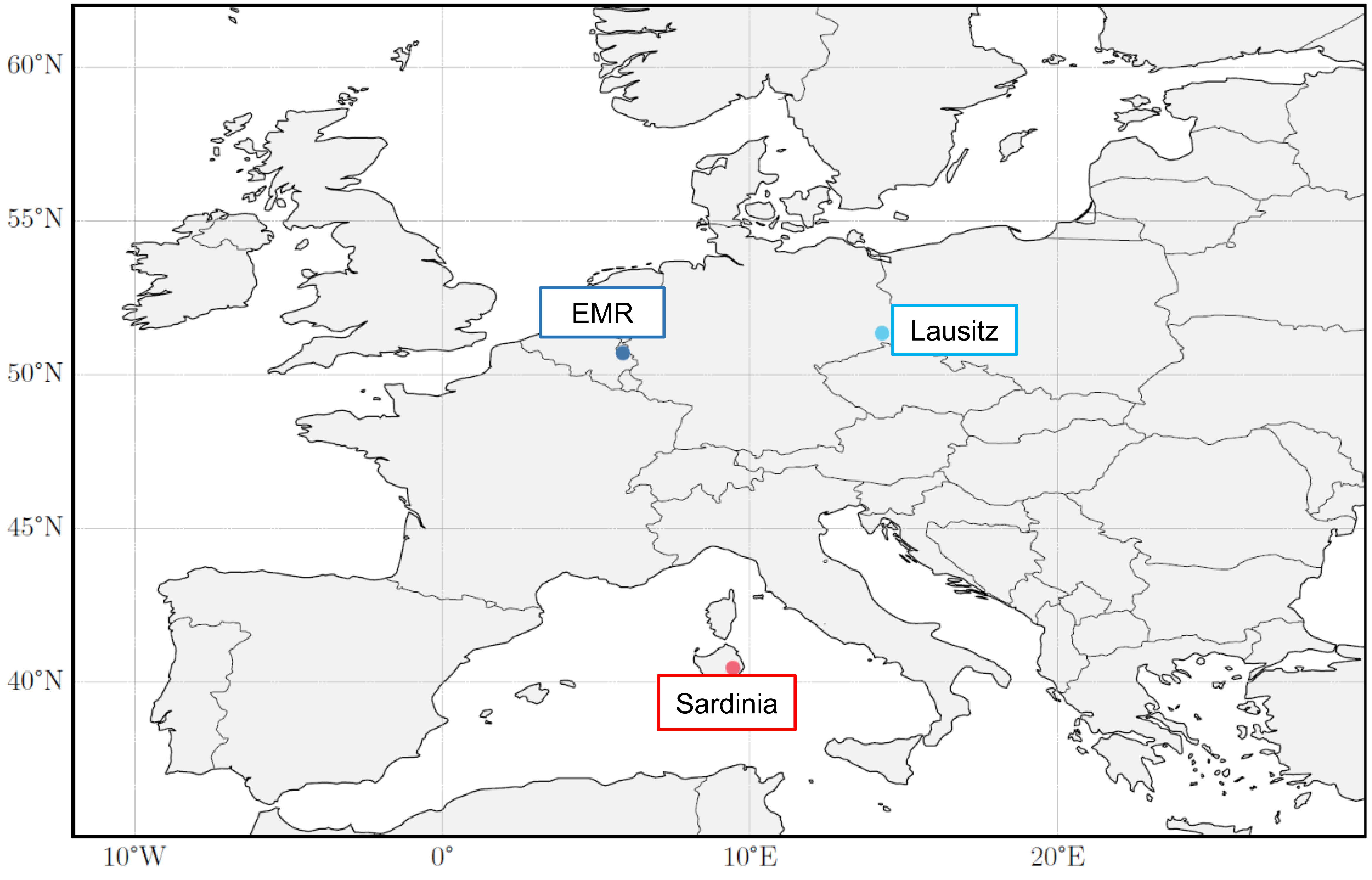
Back-up slides

Einstein Telescope: geometry and site(s)

- Currently 3 candidate sites.
- Triangle vs L-shaped instruments.



Branchesi+ (CoBA paper), 2023



Crescimbeni+, to appear

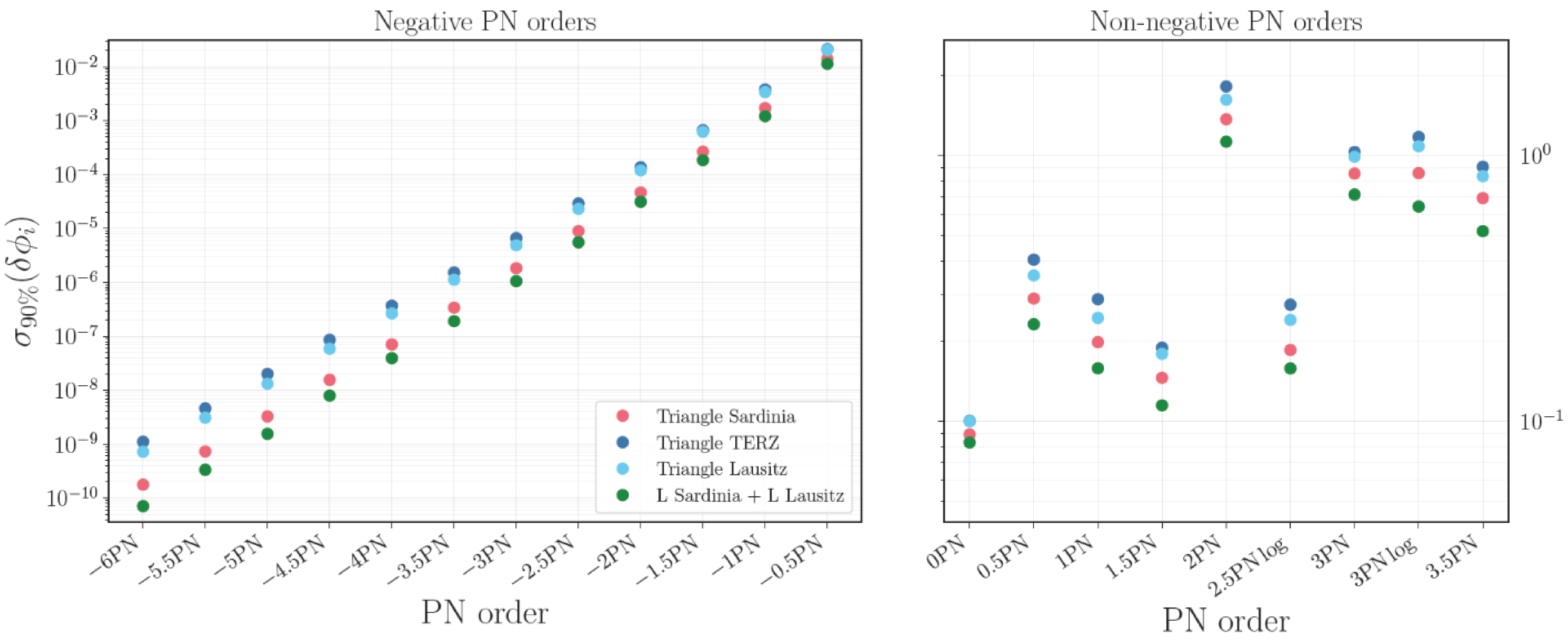
Tests of GR: inspiral

- Consider a binary with M_{src}=40M_0, q=0.74, and z=4.

- Apply PN deviations on the GW phase.

$$\Psi_{\rm insp}(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\eta} v^{-5} \left[\sum_i \phi_i v^i + \sum_i \phi_i^\ell v^i \log v \right]$$

$$\phi_i \to \phi_i^{\rm GR}\left(1+\delta\hat{\phi}_i\right), \qquad \phi_i^\ell \to \phi_i^{\ell,{\rm GR}}\left(1+\delta\hat{\phi}_i^\ell\right)$$

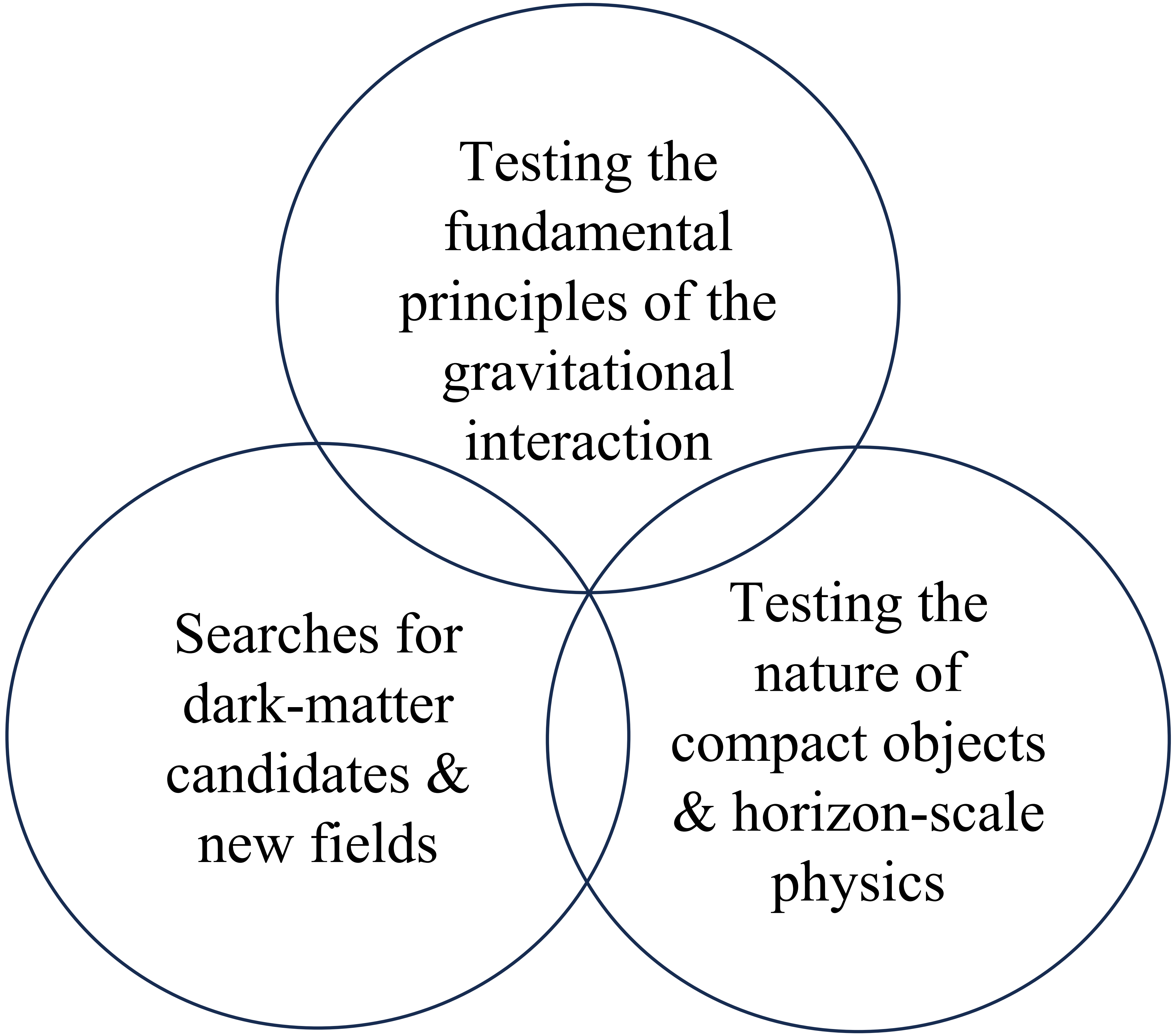


Crescimbeni+, to appear

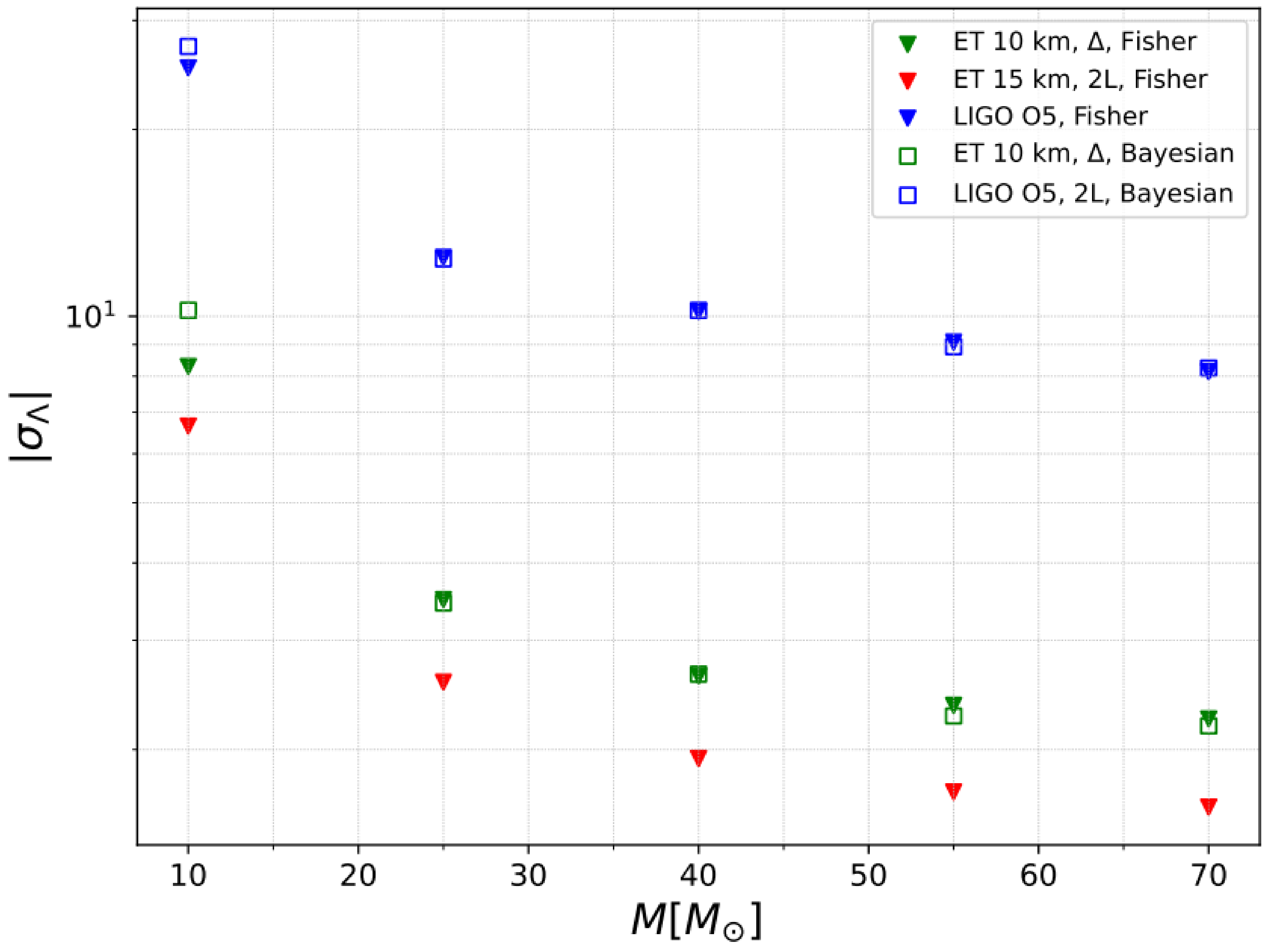
- Negative PN constraints can be further analyzed with low-frequency GW detectors.

Possible sinergies with LISA and LGWA!

Division 1 activities in the Einstein Telescope collaboration



Constraining tidal deformability at higher masses



ET Bluebook, chapter 1 (Fundamental Physics division).

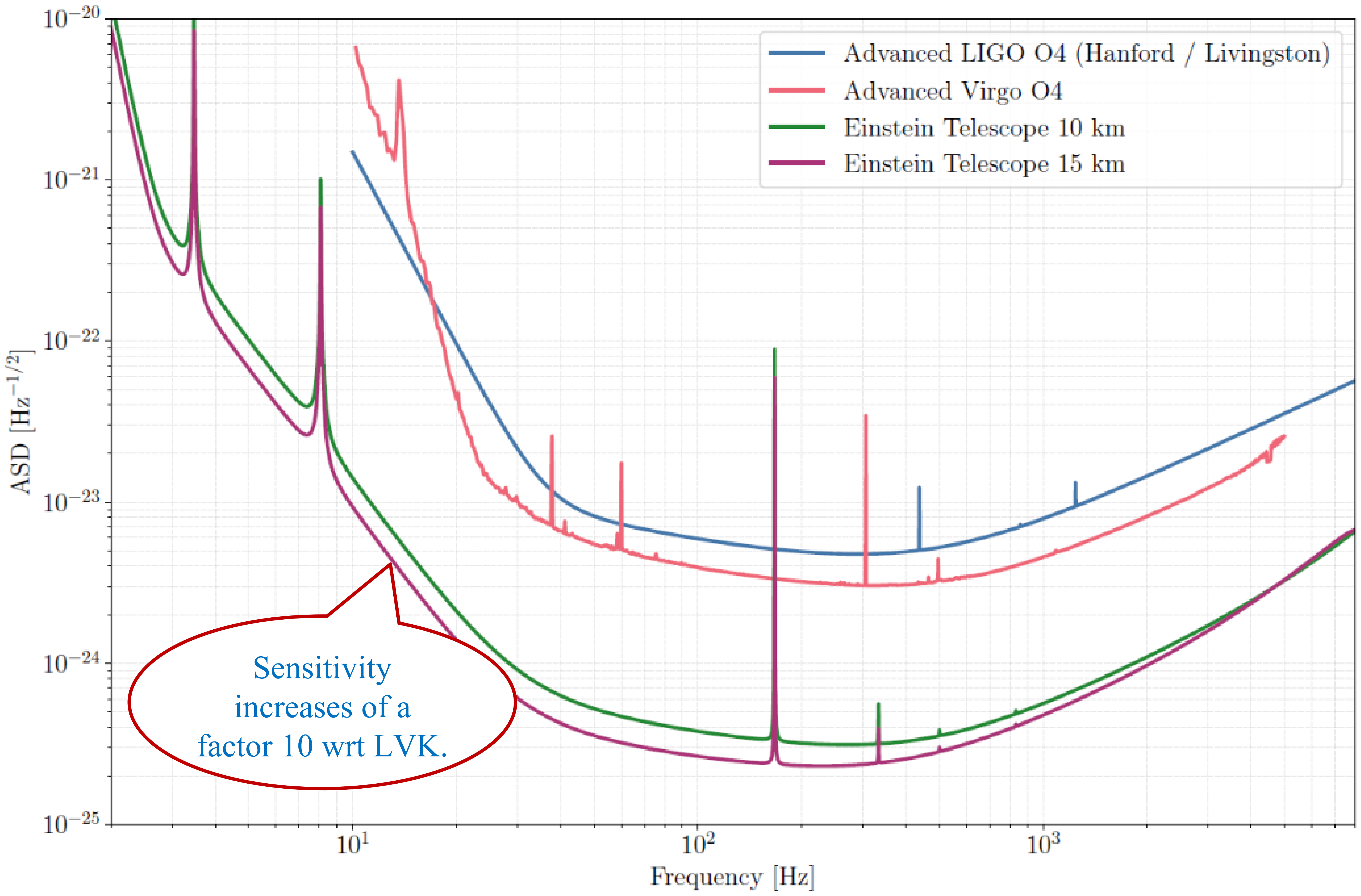
- Inject zero tidal deformability.
- Increasing the mass further constraints the uncertainty on Λ.
- Constrain environments (De Luca+, 2025).

Dupletsa+, 2022

Scientific goals of Einstein Telescope

Dramatic improvement in sensitivity at low frequency (few Hz – 10Hz):

- Cosmology (high-z sources),
- Intermediate-mass BHs,
- Multimessenger (early warnings),
- Tests of gravity & early universe
- … and much more!

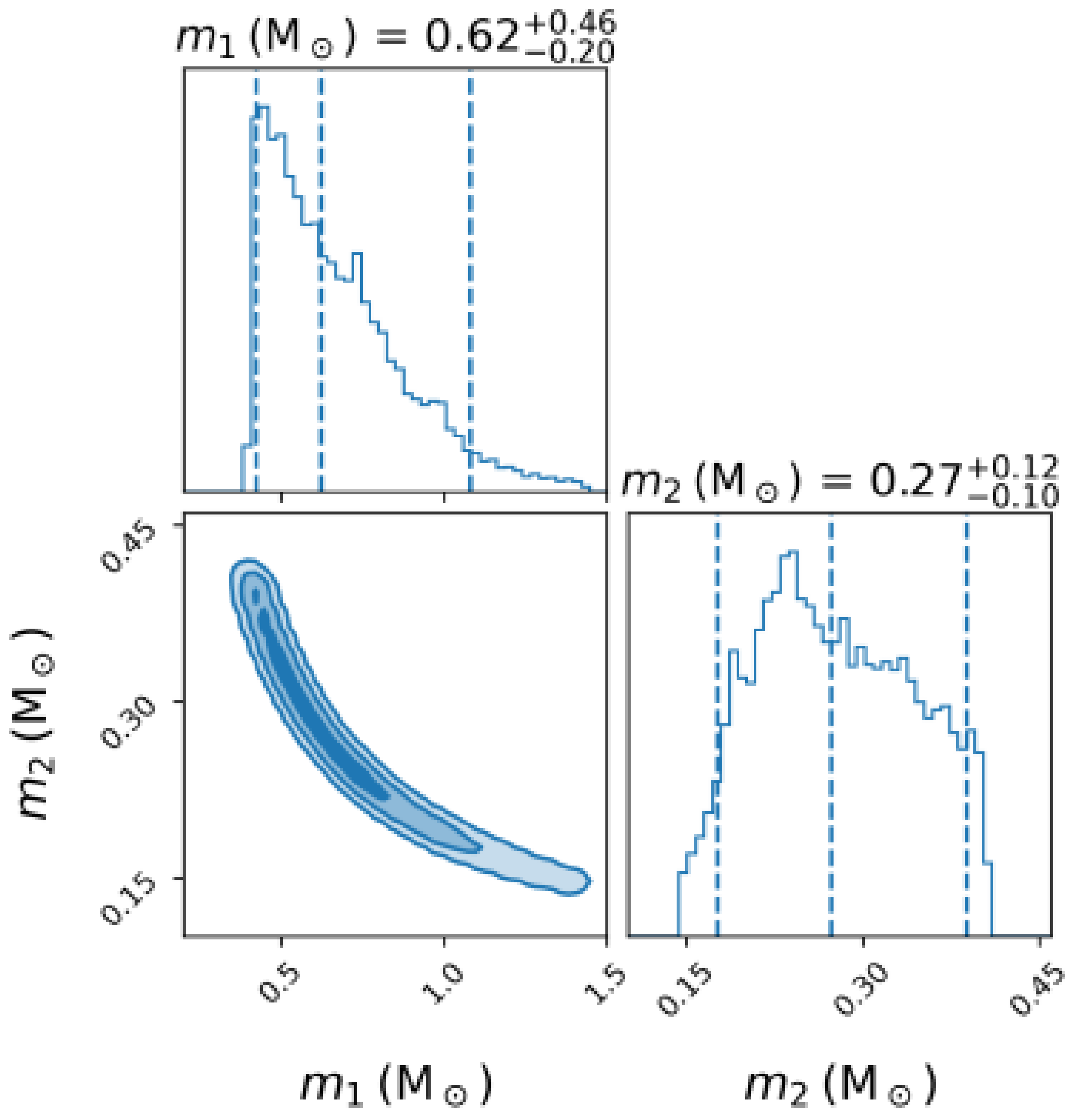


Putative detections of subsolar objects

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

- Subsolar mergers (SSM) searches have been performed thought the years, finding no conclusive evidences, yet ;) [LVK, 2018; LVK, 2019; LVK, 2022; Nitz-Wang, 2021; LVK, 2026].

- SSM-like trigger (denoted as SSM200308) detected during O3 was recently reanalyzed [Prunier+, 2023] under the assumption that it was a binary of PBHs.



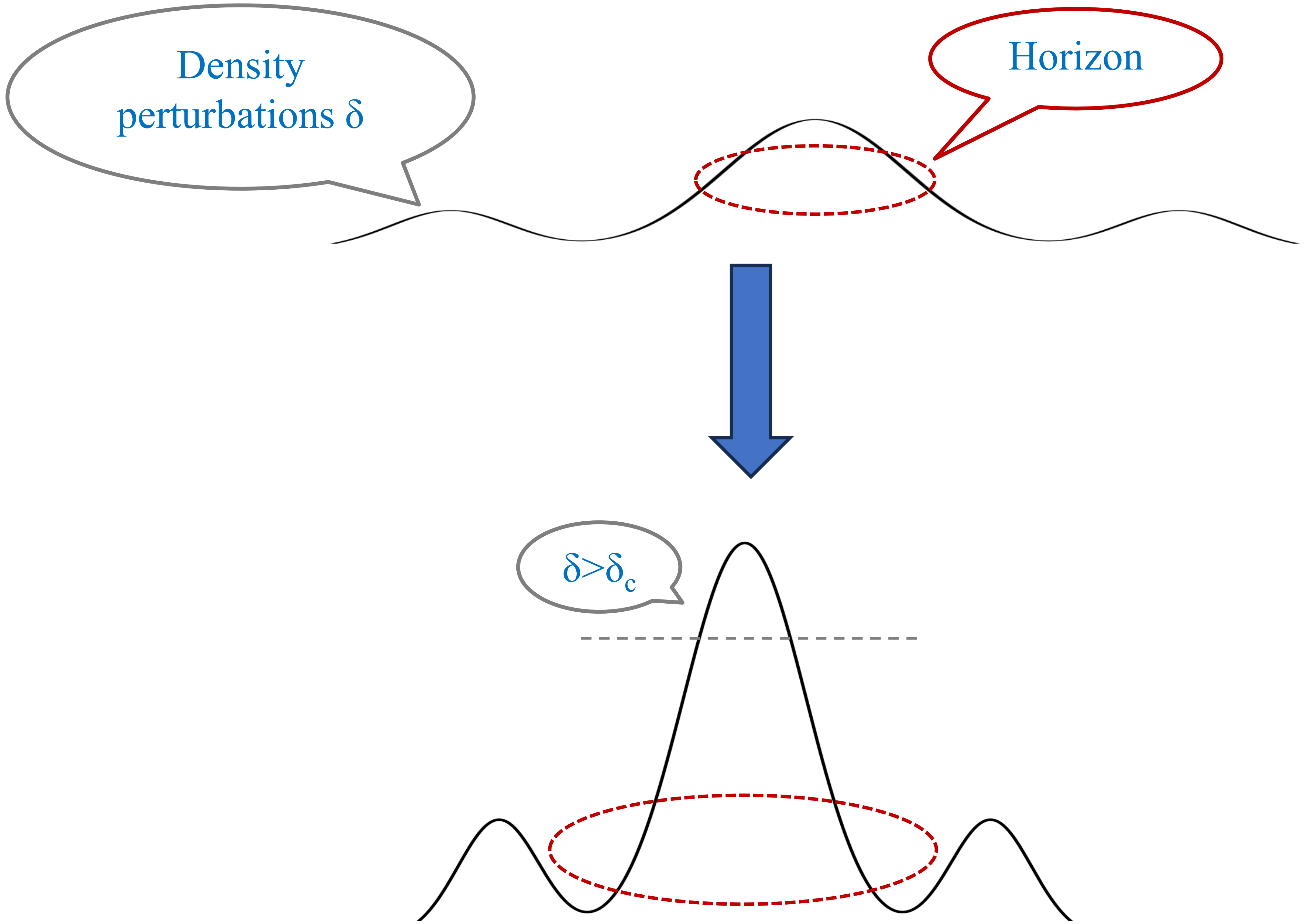
Prunier+, 2023

Introduction on Primordial Black Holes

- Primordial Black Holes (PBHs) are black holes formed in the early Universe, after the inflation era.

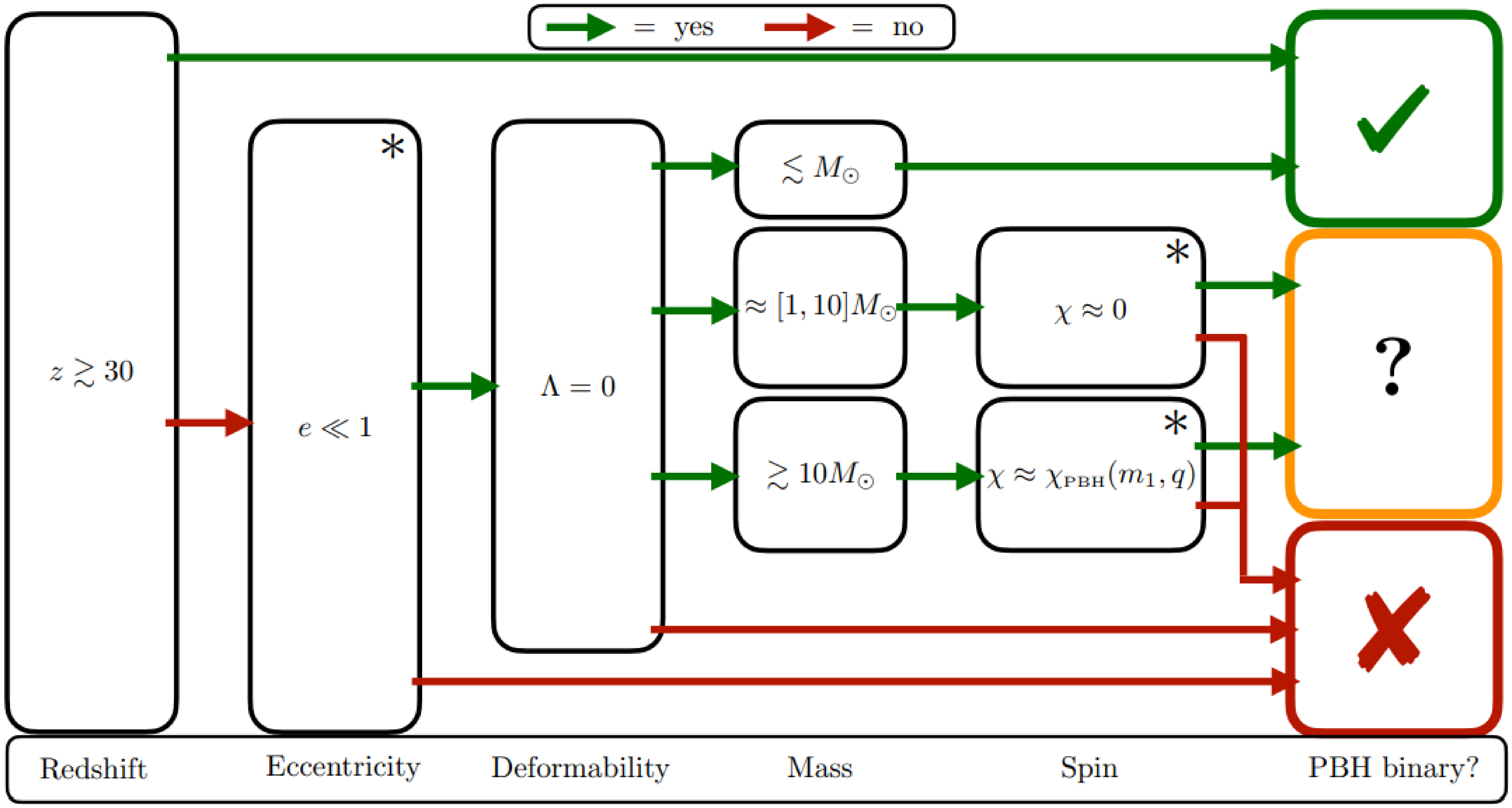
- They behave like cold and collisionless fluids, thus optimal candidates for Dark Matter.

- Depending on the mass, we can use a different experiment to search them.



Collapse of sizable Gaussian overdensities in the radiation-dominated early Universe (Carr+ 2021).

Flowchart for PBH identification



Franciolini-Cotesta+, 2021

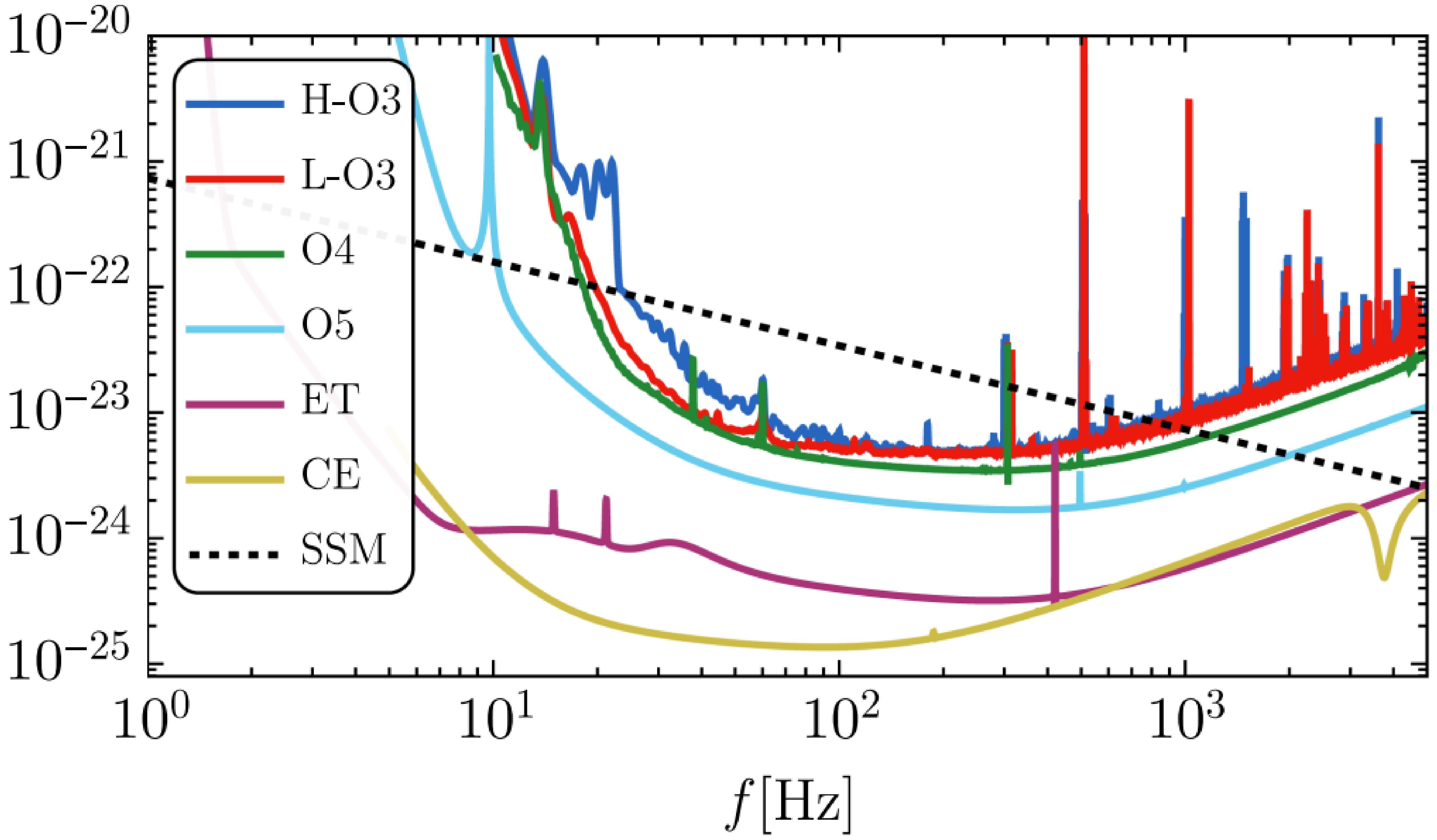
Waveform modelling of SSM binaries

- We will observe only the inspiral part of the signal, described by the TaylorF2 waveform [Damour+, 2000].

Tapering smoothing: keeps into account possible tidal disruption

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

Amplitude: scales as the inverse of distance



Tidal deformabilities for boson stars

- Assume for instance boson stars (BSs) with quartic potential [Pacilio+, 2020]:

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

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

- Invert relation to find:

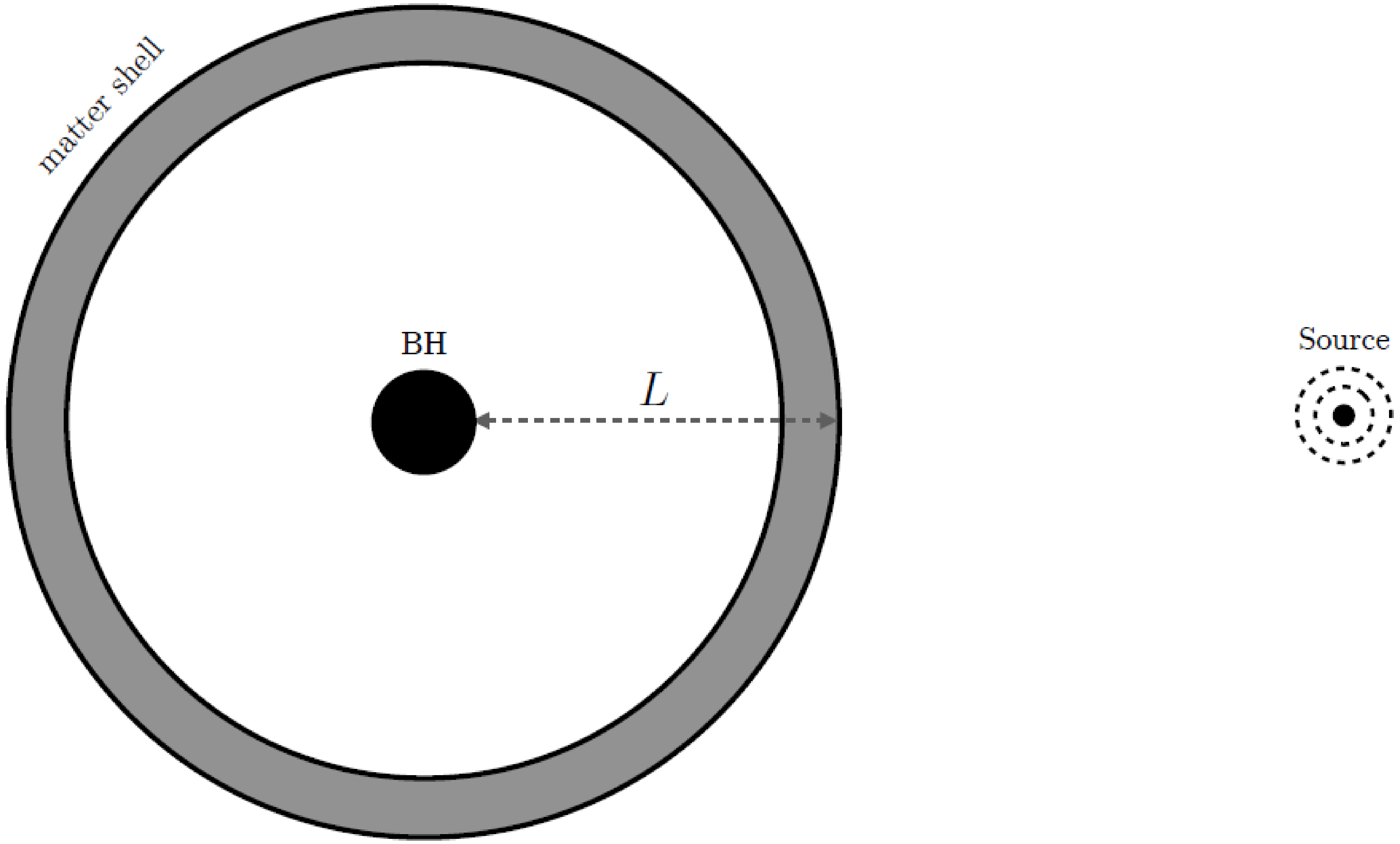
$$\Lambda = \Lambda(m/m_B)$$

- 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!

Do we really exclude PBHs if $\Lambda \neq 0$?



- Having $\Lambda \neq 0$ 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, 2024].

Nuclear physics implications of a SSM detection

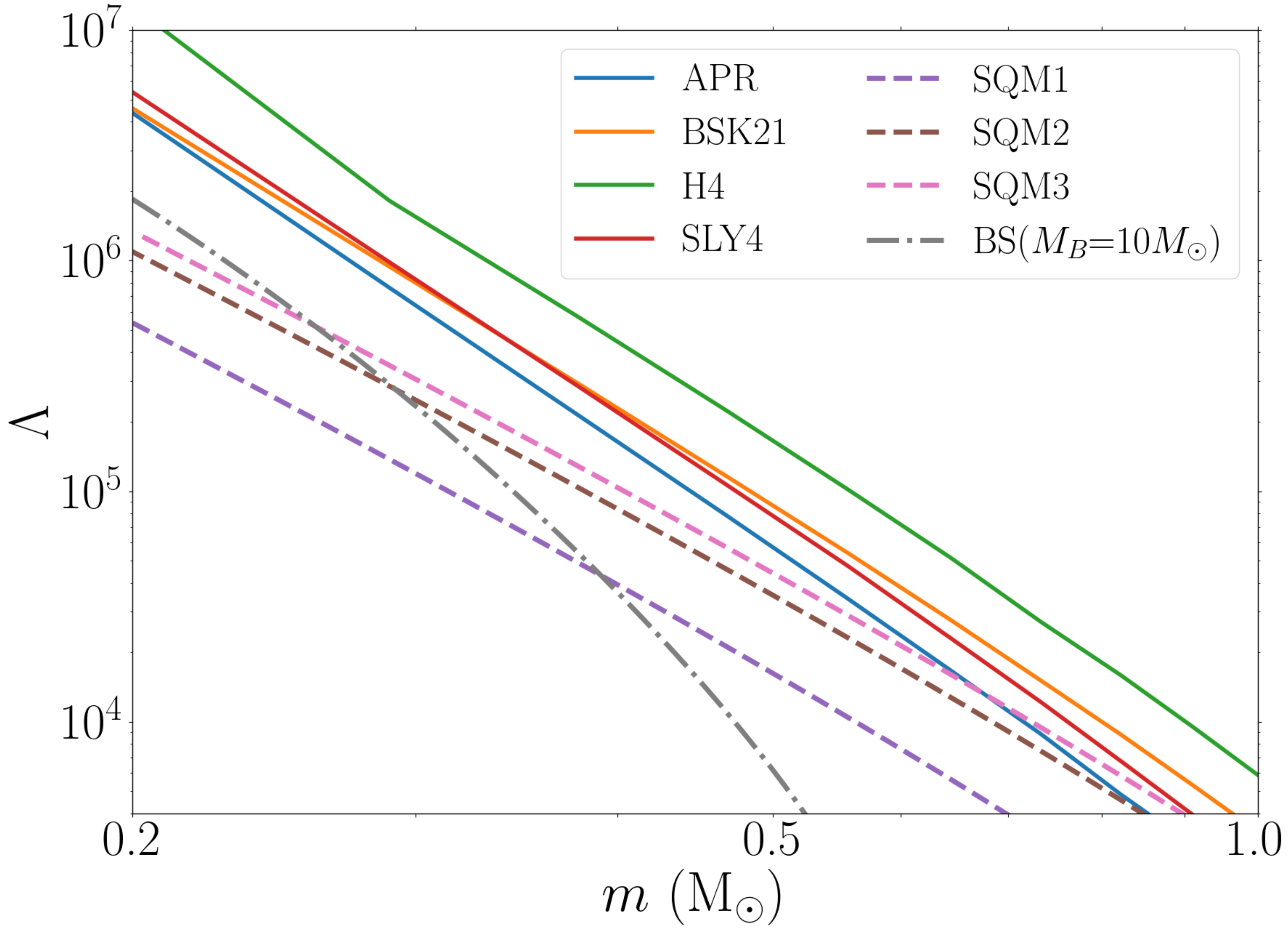
If the SSM objects are identified as light NSs/SQM stars:

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

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

- 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

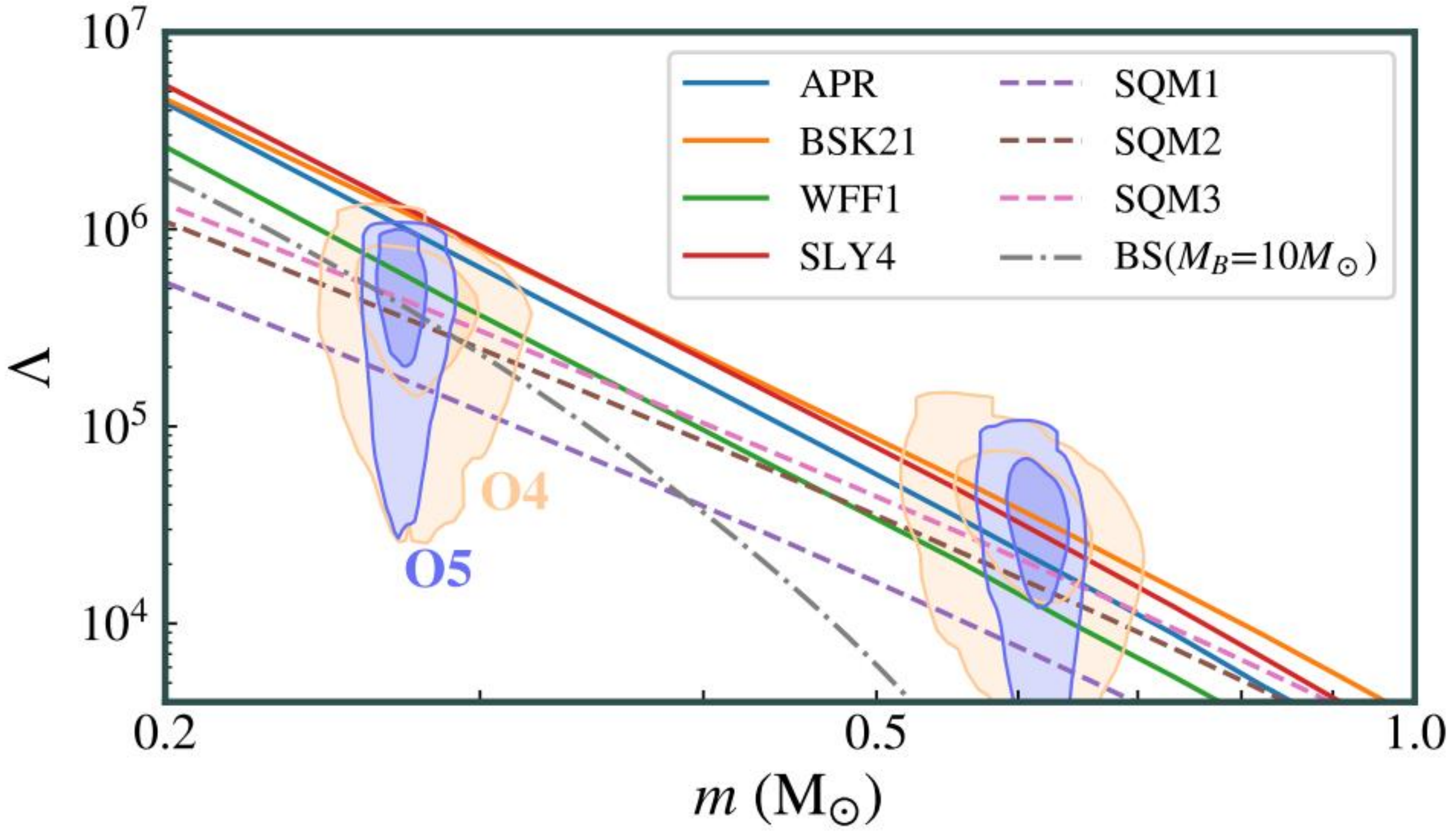
FC-Franciolini-Pani-Vaglio, 2024

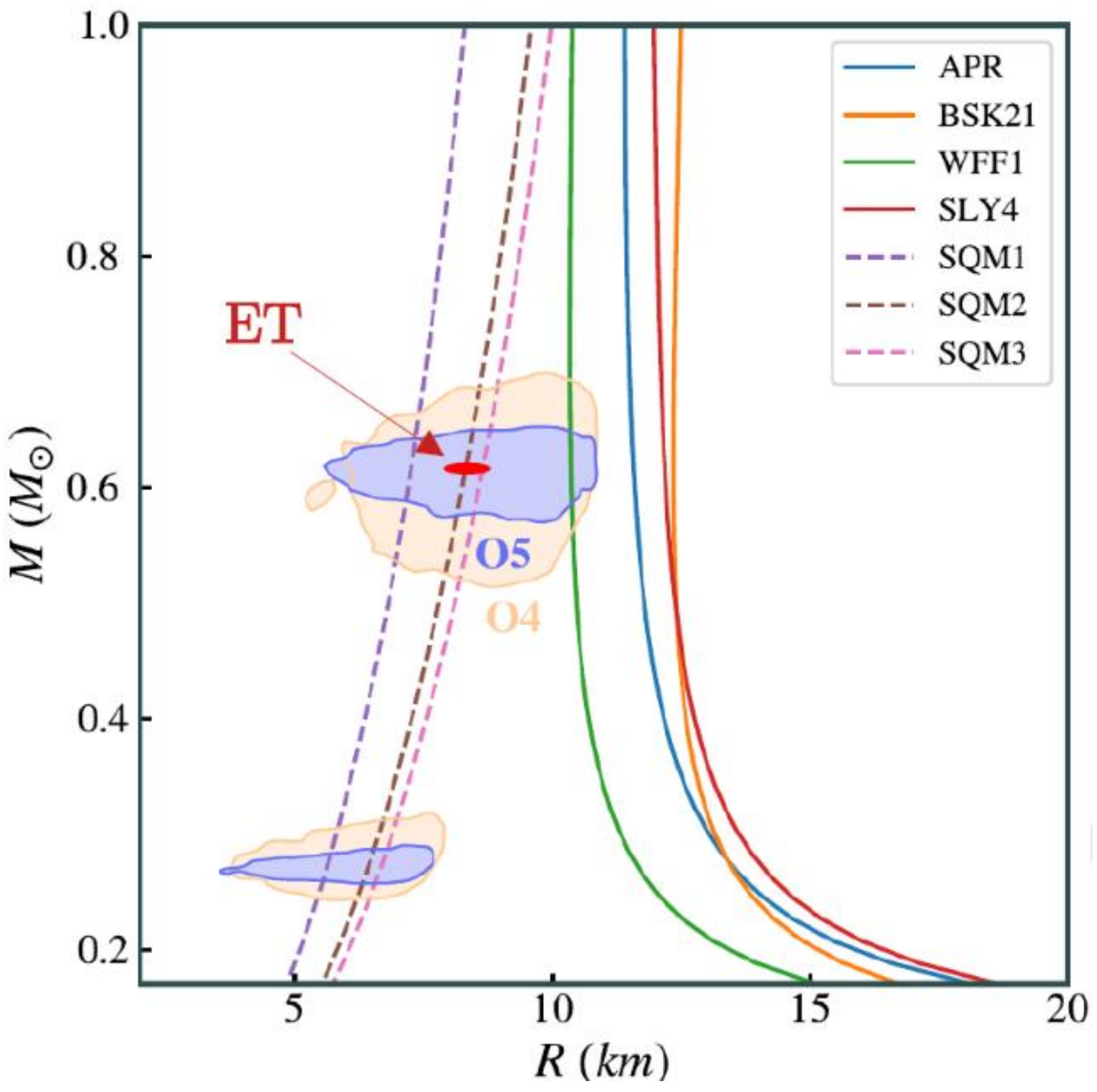
Nuclear physics implications of a SSM detection

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.





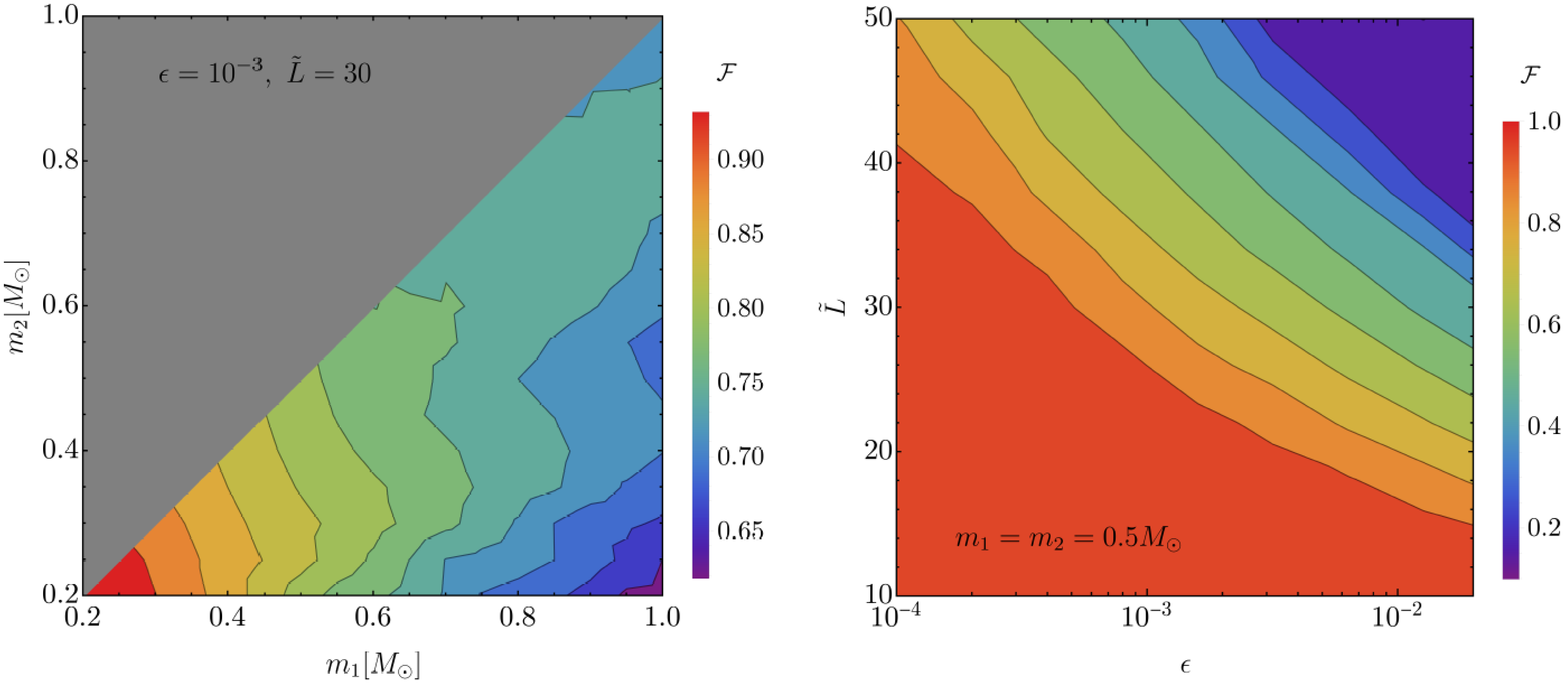
FC-Franciolini-Pani-Vaglio, 2408.14287

Number of detected events in ET – impact of different designs

	$N^{\rm tot}$	$N^{\rm SS}$	$N^{z>10}$	$N^{z>30}$	$N^{\rm LMG}$	$N^{\rm UMG}$
Intrinsic population	1 920 000	708 487	1 400 384	795 904	300 220	7774
Configuration	$N^{\rm tot}_{\rm det}$	$N^{\rm SS}_{\rm det}$	$N^{z>10}_{\rm det}$	$N^{z>30}_{\rm det}$	$N^{\rm LMG}_{\rm det}$	$N^{\rm UMG}_{\rm det}$
△-10km-HFLF-Cryo	13 347	1650	336	17	2638	235
△-15km-HFLF-Cryo	30 912	4281	1099	91	6443	376
2L-15km-45°-HFLF-Cryo	24 900	3345	824	66	5132	332
2L-15km-0°-HFLF-Cryo	26 585	3580	940	65	5517	356
2L-20km-45°-HFLF-Cryo	35 524	5206	1434	140	7550	374
2L-20km-0°-HFLF-Cryo	45 650	6745	1962	187	9809	465
1L-20km-HFLF-Cryo	22 852	3019	698	37	4656	310
△-10km-HF	4804	553	4	0	1023	74
△-15km-HF	12 739	1660	106	0	2747	130
2L-15km-45°-HF	10 714	1379	76	0	2239	113
2L-15km-0°-HF	10 762	1374	79	0	2297	114
2L-20km-45°-HF	20 704	2900	286	0	4574	175
2L-20km-0°-HF	15 951	2211	210	0	3515	146
1L-20km-HF	7610	987	51	0	1633	84
CE-40km	41 650	6250	2050	142	8732	378
(CE-40km)-(CE-20km)	55 832	8702	2995	223	11 897	469
(CE-40km)-(△-10km-HFLF-Cryo)	56 964	8668	2876	226	12 108	510
(CE-40km)-(2L-15km-45°-HFLF-Cryo)	68 524	10 669	3604	331	14 713	590
(CE-40km)-(2L-15km-0°-HFLF-Cryo)	65 245	10 127	3366	294	13 990	563
(CE-40km)-(CE-20km)-(△-10km-HFLF-Cryo)	71 414	11 300	3945	332	15 430	589
(CE-40km)-(CE-20km)-(2L-15km-45°-HFLF-Cryo)	82 812	13 297	4757	443	17 975	663
(CE-40km)-(CE-20km)-(2L-15km-0°-HFLF-Cryo)	77 974	12 444	4379	396	16 827	621
LVKI-O5	49	7	0	0	10	1

Franciolini+, 2023

Do we really exclude BPBHs if Λ=0?



De Luca+. 2024

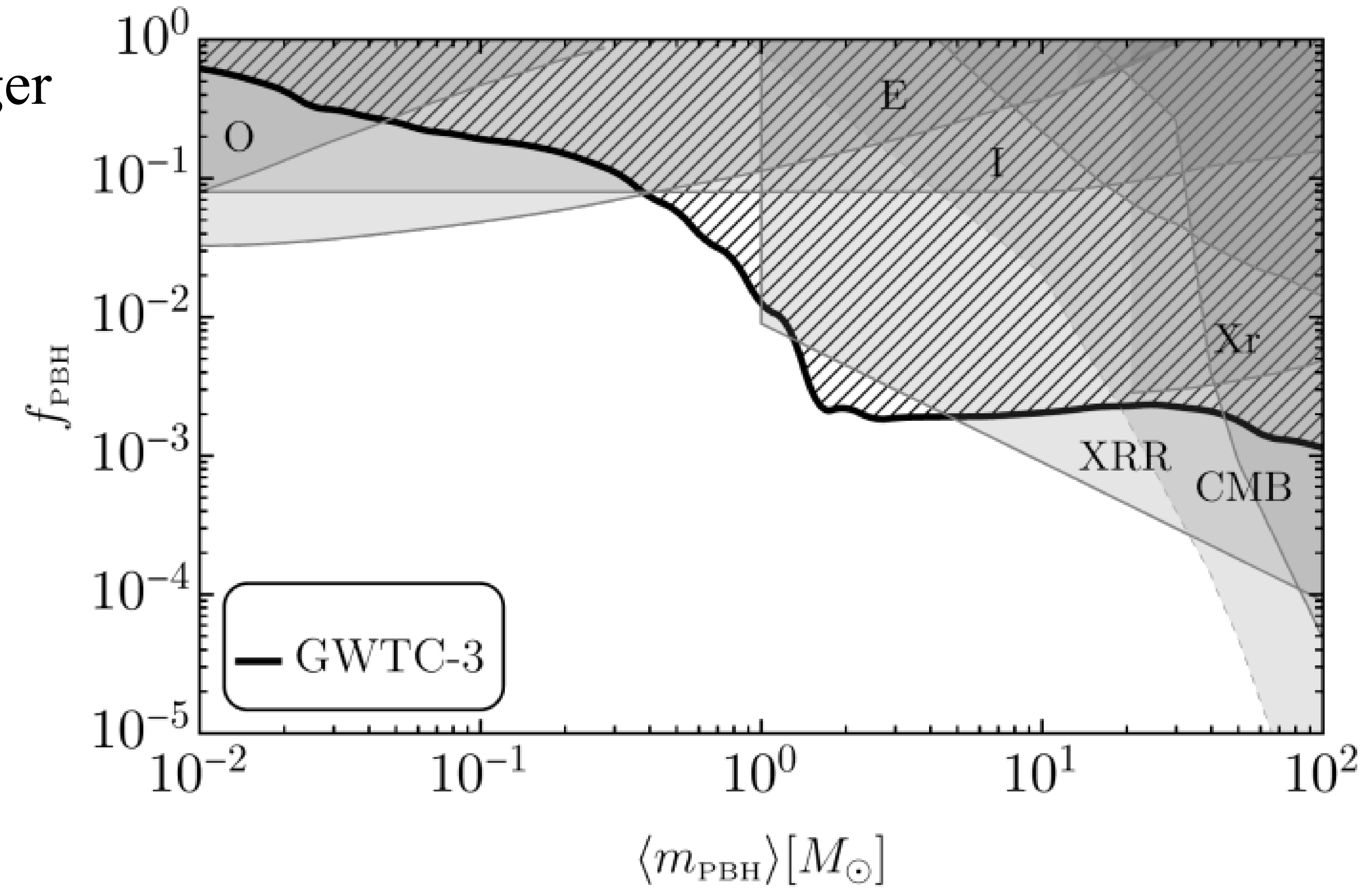
Cosmology implications of a SSM detection

If an SSM PBH binary is detected:

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

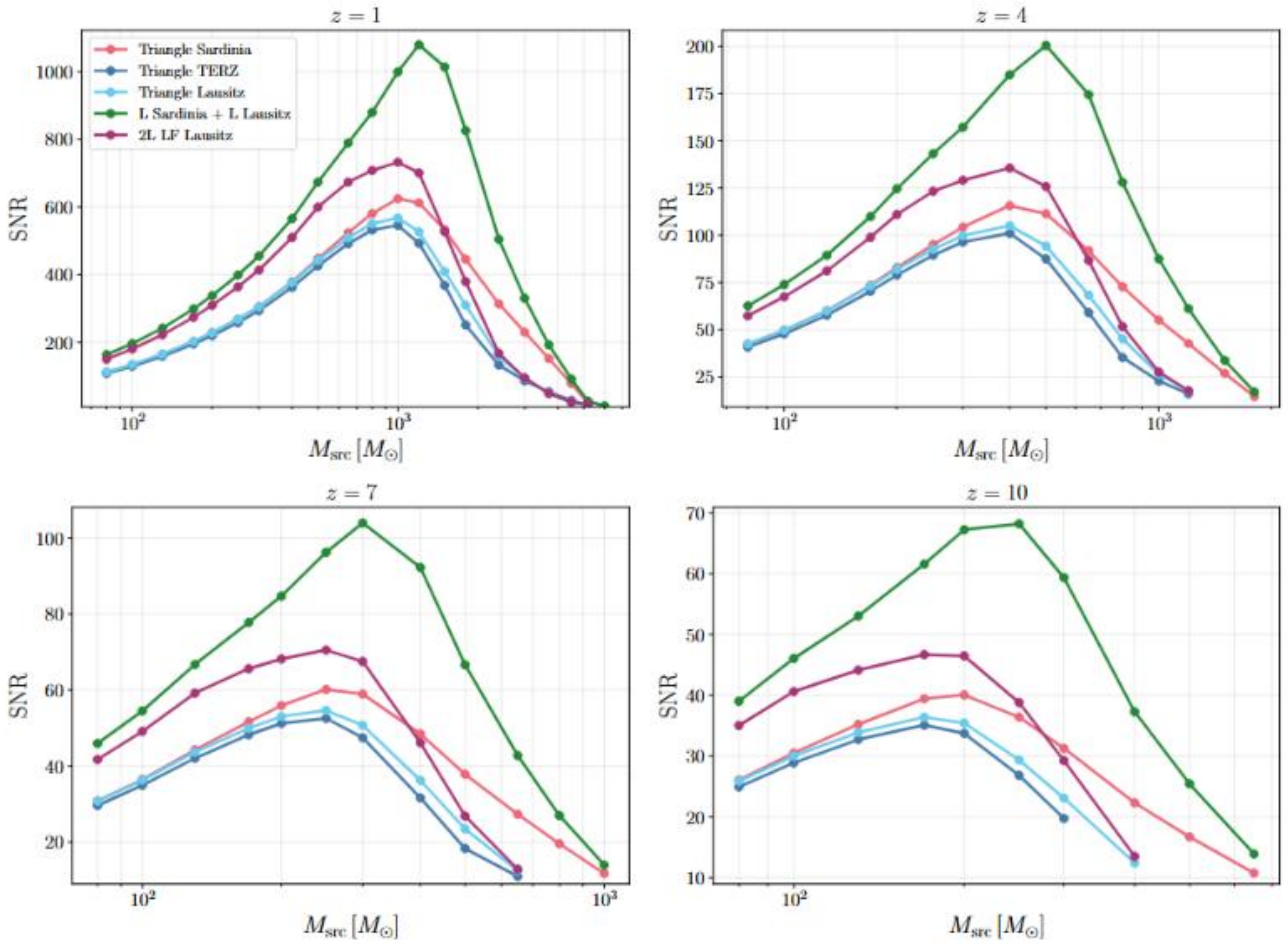
$$f_{\rm PBH} \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$$

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



Franciolini-Pani-Musco-Urbano, 2022

SNR trends with different designs



Crescimbeni+, in preparation