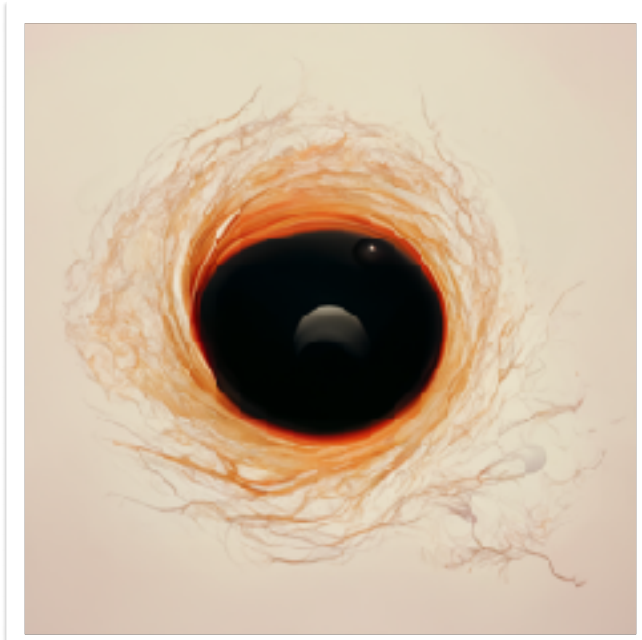
Challenging GR with future detectors: the case of ***3G*** *ground based interferometers*

@ Connecting the dots
Albert Einstein Institute, 16th June 2023



Andrea Maselli

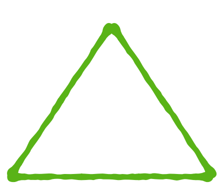
GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

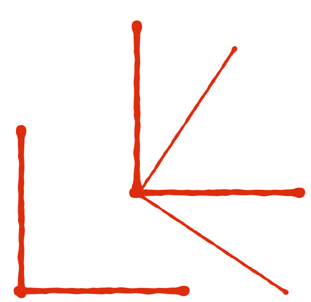
Latest on the 3G design performances

M. Branchesi + arXiv gr-qc: 2303.15923

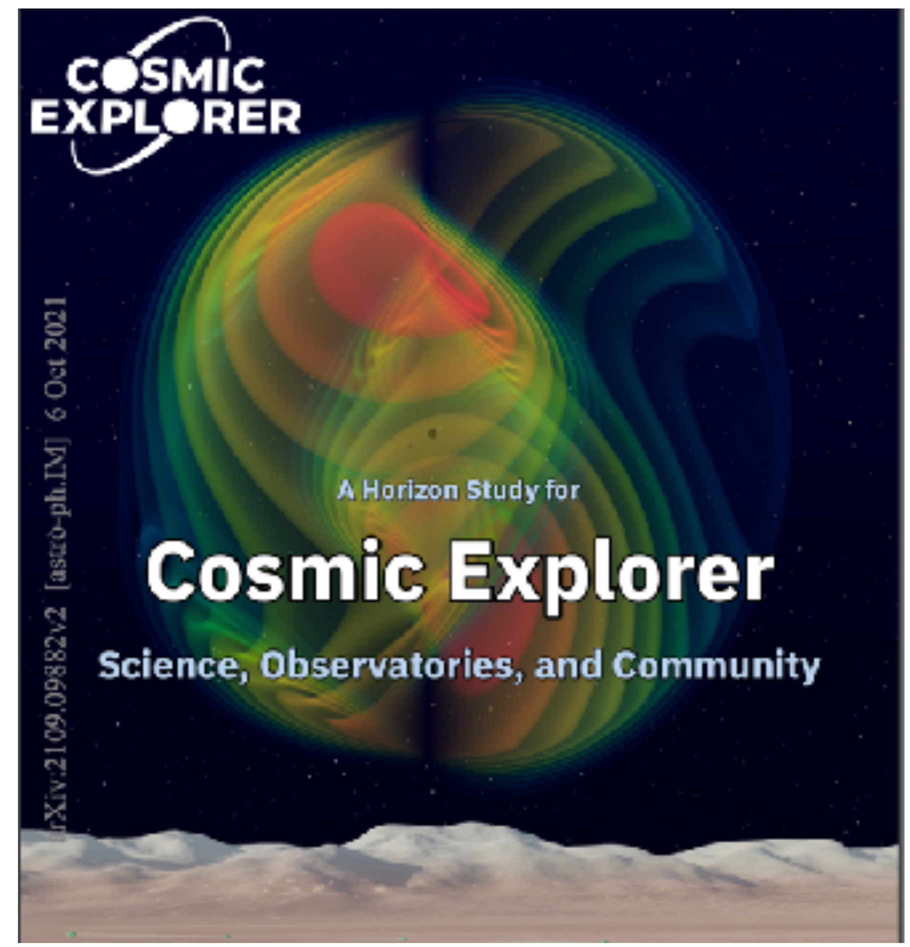
Science with the Einstein Telescope: a comparison of different designs

Marica Branchesi,[1,2] Michele Maggiore,[3,4] David Alonso,[5] Charles Badger,[6] Biswajit Banerjee,[1,2] Freija Beirnaert,[7] Swetha Bhagwat,[8,9] Guillaume Boileau,[10,11] Ssohrab Borhanian,[12] Daniel David Brown,[13] Man Leong Chan,[14] Giulia Cusin,[15,3,4] Stefan L. Danilishin,[16,17] Jerome Degallaix,[18] Valerio De Luca,[19] Arnab Dhani,[20] Tim Dietrich,[21,22] Ulyana Dupletsa,[1,2] Stefano Foffa,[3,4] Gabriele Franciolini,[8] Andreas Freise,[23,16] Gianluca Gemme,[24] Boris Goncharov,[1,2] Archisman Ghosh,[7] Francesca Gulminelli,[25] Ish Gupta,[20] Pawan Kumar Gupta,[16,26] Jan Harms,[1,2] Nandini Hazra,[1,2,27] Stefan Hild,[16,17] Tanja Hinderer,[28] Ik Siong Heng,[29] Francesco Iacovelli,[3,4] Justin Janquart,[16,28] Kamiel Janssens,[10,11] Alexander C. Jenkins,[30] Chinmay Kalaghatgi,[16,26,31] Xhesika Koroveshi,[32,33] Tjonnie G. F. Li,[34,35] Yufeng Li,[36] Eleonora Loffredo,[1,2] Elisa Maggio,[22] Michele Mancarella,[3,4,37,38] Michela Mapelli,[39,40,41] Katarina Martinovic,[6] Andrea Maselli,[1,2] Patrick Meyers,[42] Andrew L. Miller,[43,16,26] Chiranjib Mondal,[25] Niccolò Muttoni,[3,4] Harsh Narola,[16,26] Micaela Oertel,[44] Gor Oganesyan,[1,2] Costantino Pacilio,[8,37,38] Cristiano Palomba,[45] Paolo Pani,[8] Antonio Pasqualetti,[46] Albino Perego,[47,48] Carole Périgois,[39,40,41] Mauro Pieroni,[49,50] Ornella Juliana Piccinni,[51] Anna Puecher,[16,26] Paola Puppo,[45] Angelo Ricciardone,[52,39,40] Antonio Riotto,[3,4] Samuele Ronchini,[1,2] Mairi Sakellariadou,[6] Anuradha Samajdar,[21] Filippo Santoliquido,[39,40,41] B.S. Sathyaprakash,[20,53,54] Jessica Steinlechner,[16,17] Sebastian Steinlechner,[16,17] Andrei Utina,[16,17] Chris Van Den Broeck,[16,26] and Teng Zhang[9,17]





M. Evans + arXiv gr-qc: 2109.09882



The Inspiral

Inspiral tests of gravity are the most easy/common/safe tool used so far

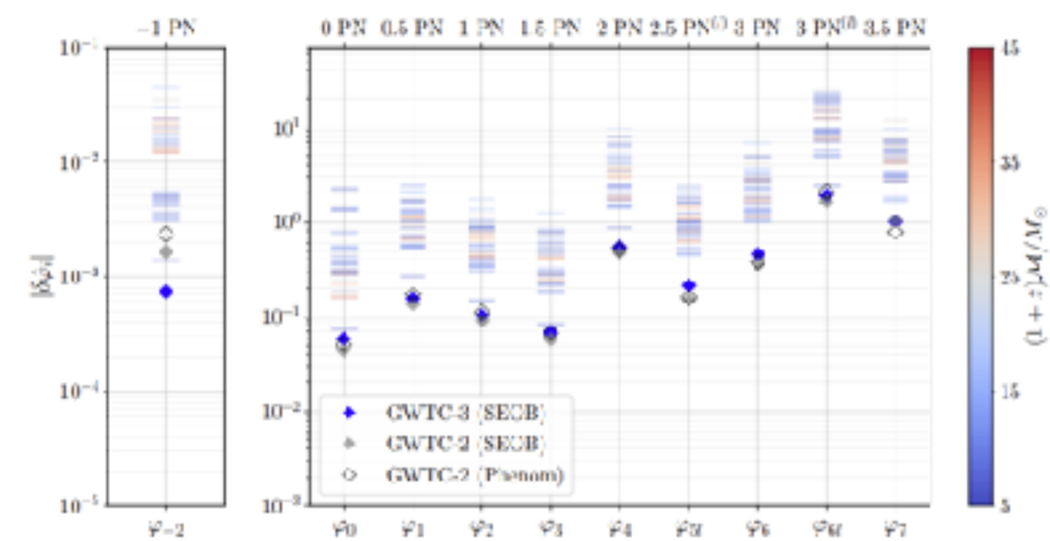
- *easiest implementation of the two flavours*

vs.

agnostic ⟷ *theory specific*

- *changes into binary's binding energy/flux*

→ *GW signal modification*



Abbott +, PRL 2112.06861 (2021)

- *accumulate with many cycles*
- *perturbatively included within pN*

$$\tilde{h}(f) = \mathcal{A}(f)\mathrm{e}^{i\phi(f)}$$

$$\phi(f) \longrightarrow \phi(f) + \beta(\mathcal{M}\pi f)^{(2\gamma-5)/3}$$

type (γ)

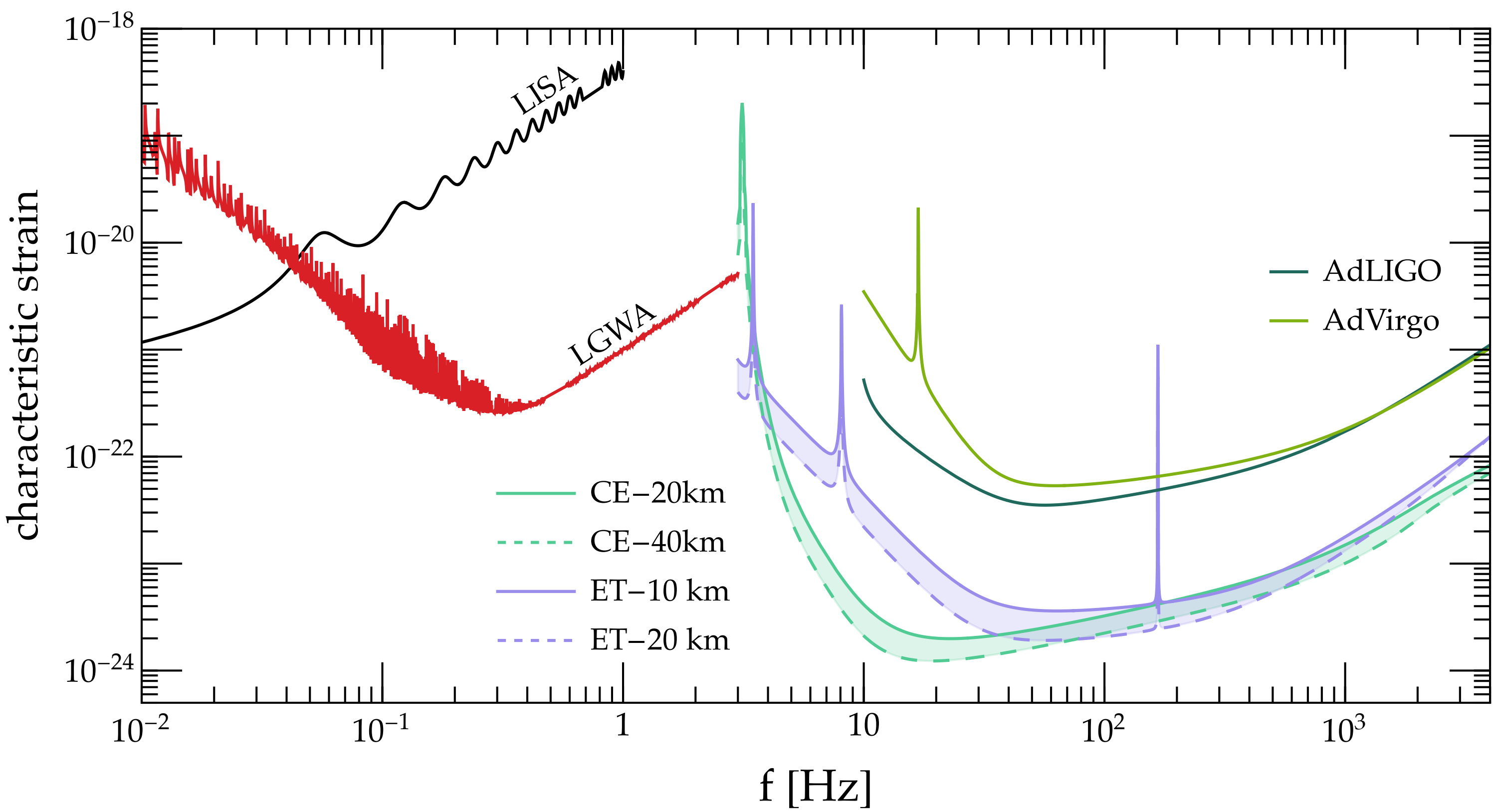
amplitude (β)

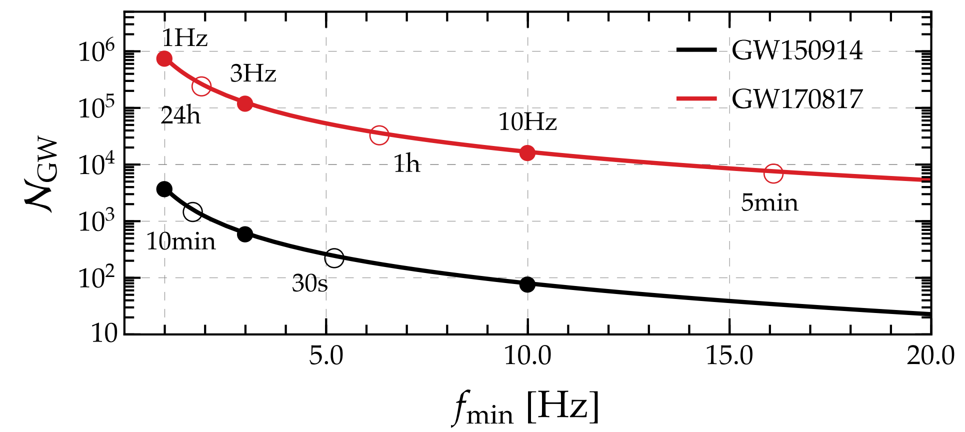
(γ, β) *can be potentially mapped to "specific" theories*

The Inspiral

Deeper and wider in frequencies

J. Harms +, Astrophys. J. 910, 1 (2021)



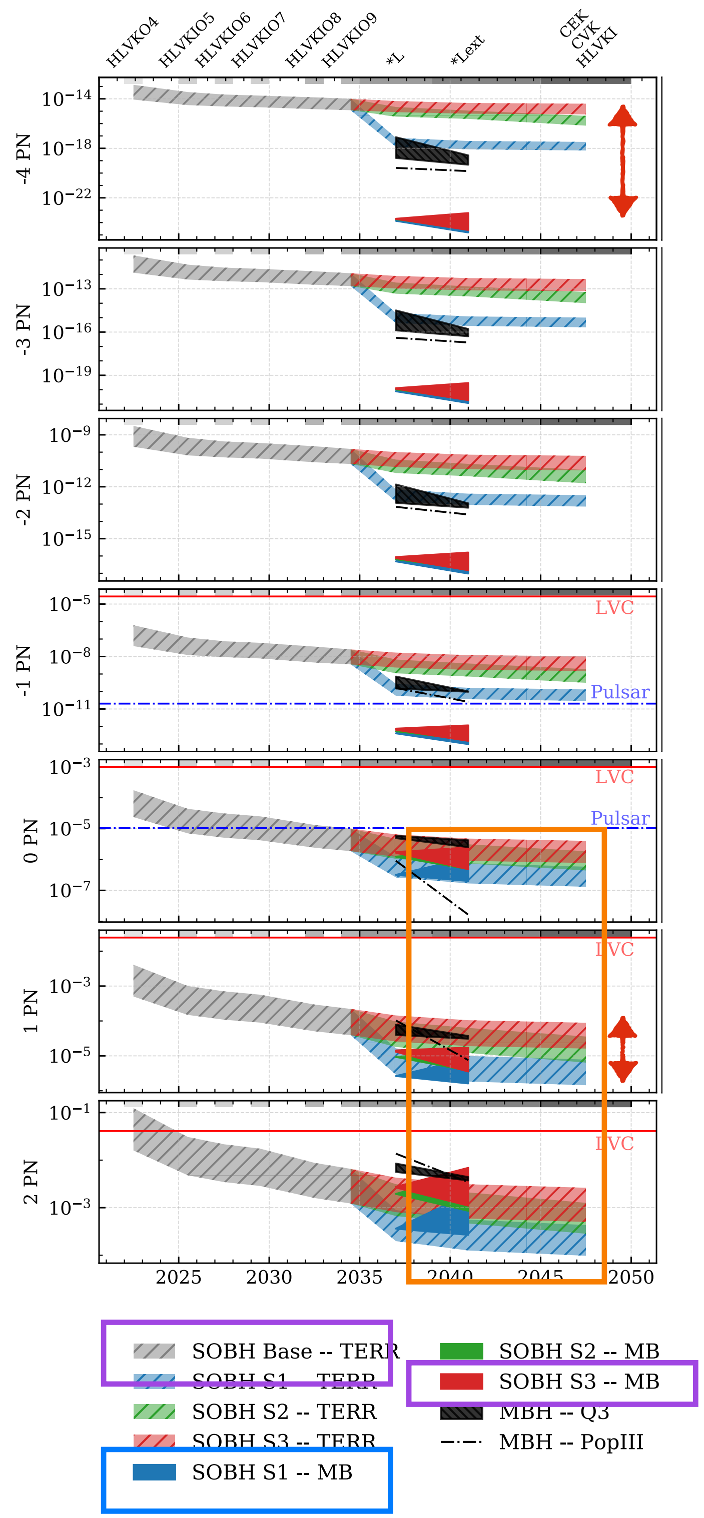


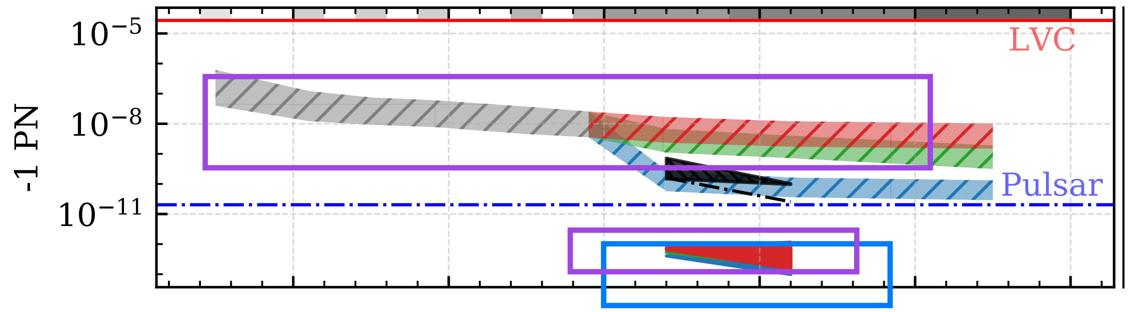
- *opportunity for <u>pre-Newtonian</u> effects, working at low frequencies (e.g. dipole, but also environmental)*
- *multi-band observations (IMRI potentially surfing all frequency bands)*
- *More asymmetric binaries*

The Inspiral

Constraints from 3G detectors

S. Perkins+, PRD 103, 044024 (2021)





- *sources in multi-band do the best at negative pN*
- *stellar mass sources for 3G worse than massive for LISA at negative pN*
- *stellar-mass sources for 3G potentially better than massive for LISA at positive pN*
- *ground based upgrades (don't) play a role for (positive) negative pN*

<u>what do we learn?</u>

The Inspiral

Map to specific theories of gravity

$$\phi(f) \longrightarrow \phi(f) + \beta(\mathcal{M}\pi f)^{(2\gamma-5)/3}$$

Theory or physical process	Physical modification	G/P	PN order	β	Theory parameter	$2\gamma-5$
Generic dipole radiation	Dipole radiation	G	-1	(B2)	$\delta\dot{E}$	-7
Einstein-dilaton Gauss-Bonnet	Dipole radiation	G	-1	(B3)	$\sqrt{\alpha_{\rm EdGB}}$	-7
Black Hole Evaporation	Extra dimensions	G	-4	(B6)	$\dot{M}$	-13
Time varying G	LPI	G	-4	(B7)	$\dot{G}$	-13
Massive Graviton	Nonzero graviton mass	P	1	(B11)	m_g	-3
dynamical Chern-Simons	Parity violation	G	2	(B8)	$\sqrt{\alpha_{\rm dCS}}$	-1
Noncommutative gravity	Lorentz violation	G	2	(B10)	$\sqrt{\Lambda}$	-1

- *same type may correspond to different physical effect when mapped to a given theory beyond GR*
    - *coupling's theory can depend on the source's properties*
        - *actual constraints can change due to scalings and/or correlations*

The Inspiral

Gauss Bonnet

$$\beta_{\rm EdGB} = -\frac{5}{7168}\frac{\zeta_{\rm EdGB}}{\eta^{18/5}}\frac{\left(m_1^2 s_2^{\rm EdGB} - m_2^2 s_1^{\rm EdGB}\right)^2}{m^4}$$

$$s_i^{\rm EdGB} = \frac{2\left[\left(1-\chi_i^2\right)^{1/2} - 1 + \chi_i^2\right]}{\chi_i^2},$$

$$\zeta_{\rm EdGB} \sim \alpha^2_{\rm EdGB}/m^4$$

Chern Simons

$$\beta_{\rm dCS} = -\frac{5}{8192}\frac{\zeta_{\rm dCS}}{\eta^{14/5}}\frac{\left(m_1 s_2^{\rm dCS} - m_2 s_1^{\rm dCS}\right)^2}{m^2} + \frac{15075}{114688}\frac{\zeta_{\rm dCS}}{\eta^{14/5}}\frac{\left(m_2^2\chi_1^2 - \frac{350}{201}m_1 m_2 \chi_1\chi_2 + m_1^2\chi_2^2\right)}{m^2}$$

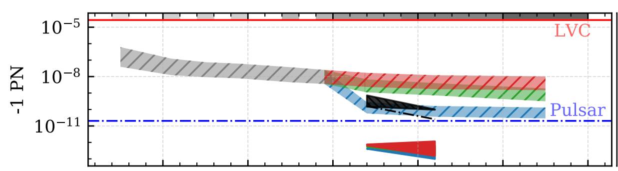
$$s_i^{\rm dCS} = \frac{2 + 2\chi_i^4 - 2\left(1-\chi_i^2\right)^{1/2} - \chi_i^2\left[3 - 2\left(1-\chi_i^2\right)^{1/2}\right]}{2\chi_i^3},$$

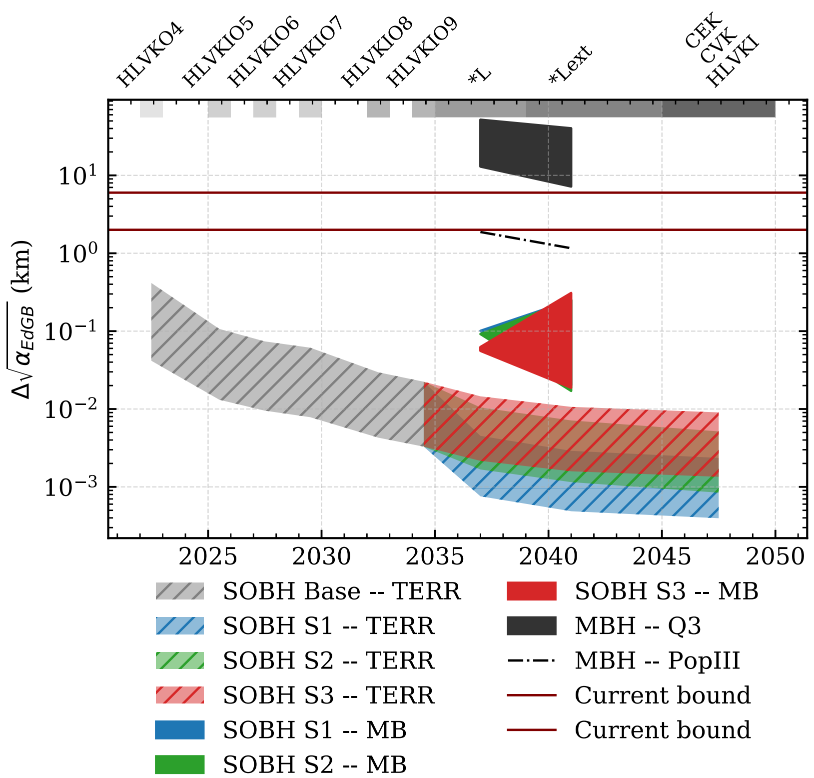
$$\zeta_{\rm dCS} \sim \alpha^2_{\rm dCS}/m^4$$

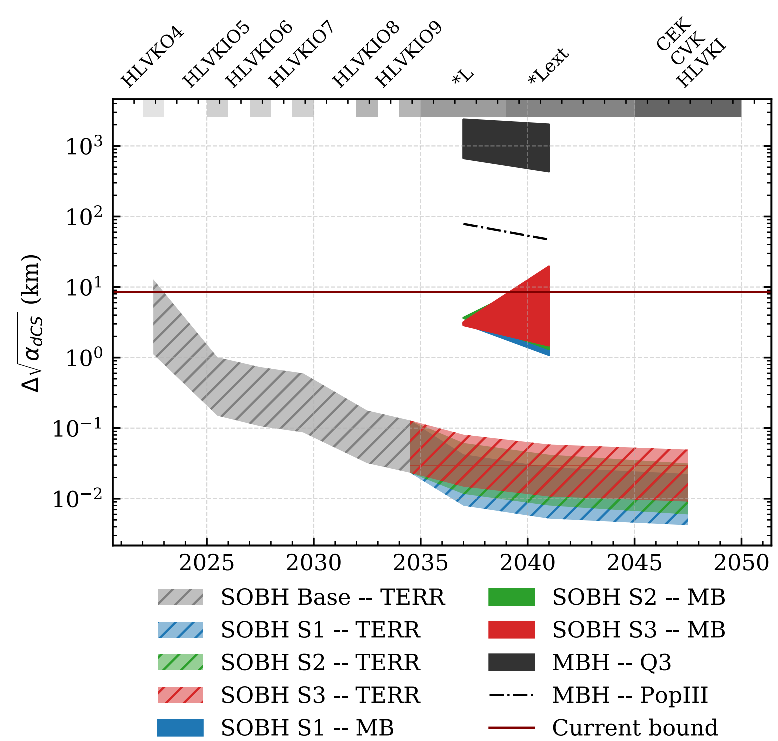
Massive graviton

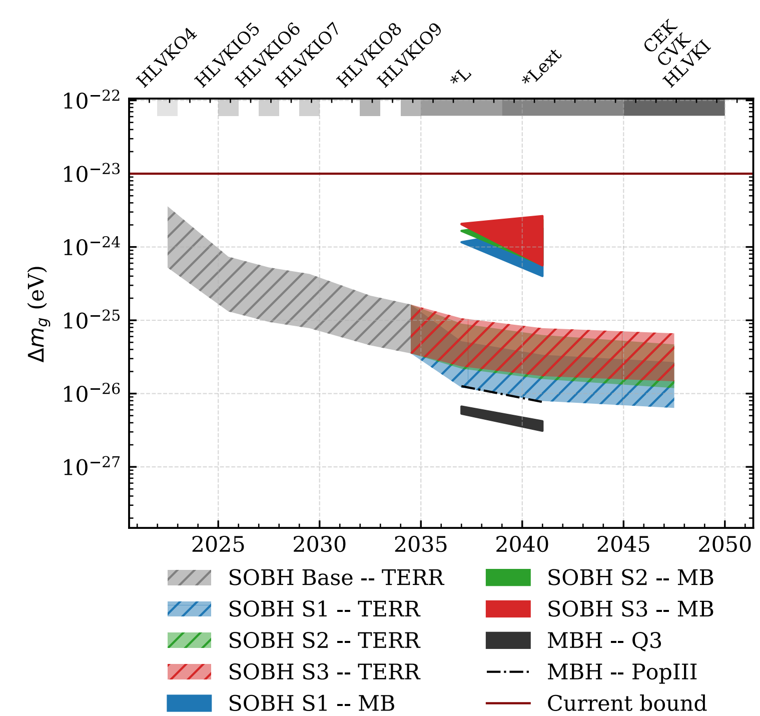
$$\beta_{\rm MG} = \pi^2 \frac{D_0}{1+z}\frac{\mathcal{M}_z}{\lambda^2_{\rm MG}}$$

$$D_0 \equiv (1+z)\int_0^z \frac{1}{H(z')}\frac{dz'}{(1+z')^2}$$









The Inspiral

More on agnostic-to-specific deviations

- *generic deviations from the Kerr multipolar structure* $M_\ell^{\rm kerr} + iS_\ell^{\rm kerr} = M^{\ell+1}(i\chi)^\ell$

$$M_{20} = -\kappa M^3 \chi^2 \longrightarrow \kappa = \kappa(couplings, M, \chi)$$

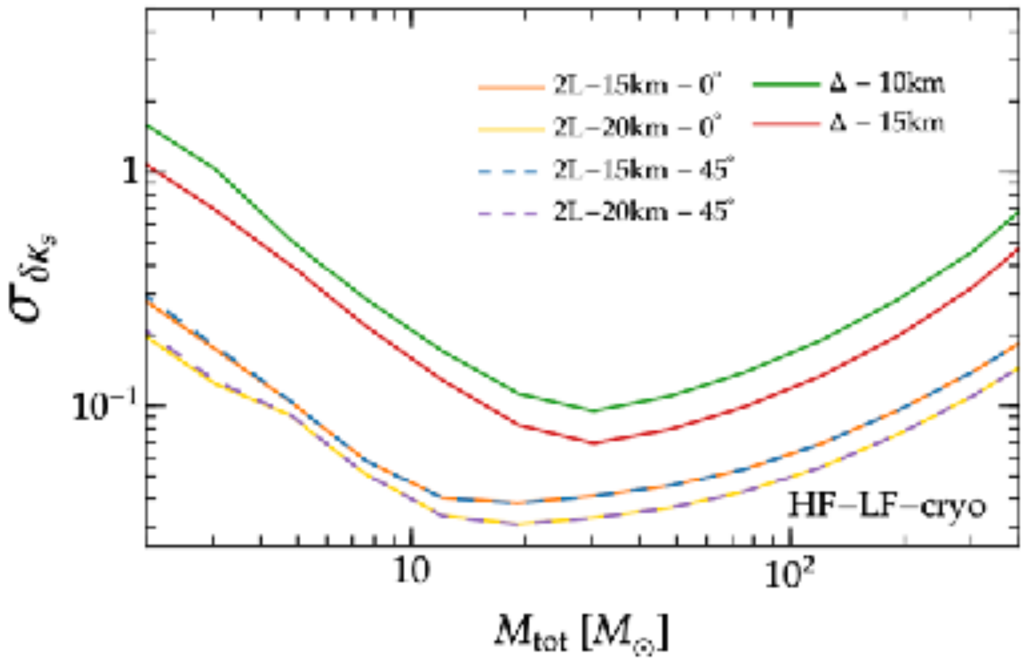
$$M_{20} = -M^3\chi^2[(1 + 0.061618\zeta_{\rm EdGB}^2 + \ldots) - \chi^2\zeta_{\rm EdGB}^2(0.0308519 + \ldots)]$$

A. M. + PRD 92, 083014 (2015)

Quadrupole entering the waveform at 2PN

$$\kappa_s = \frac{\kappa_1 + \kappa_2}{2} \qquad \kappa_a = \frac{\kappa_1 - \kappa_2}{2}$$

$$\kappa_s = 1 + \delta\kappa_s \longrightarrow$$



M. Branchesi + arXiv gr-qc: 2303.15923

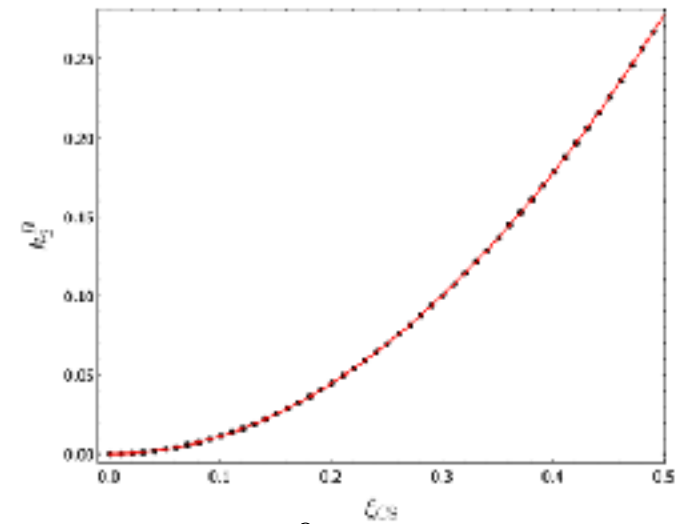
- *More sophisticate models with broken equatorial symmetry and non-axisymmetric*

N. Loutrel+, PRD 105, 124050 (2022)

The Inspiral

- *Tidal Love numbers*
  - *tidal parameters for Kerr BHs vanish*
  - *scalar tidal love numbers*

L. Bernard + PRD 101, 021501 (2020)

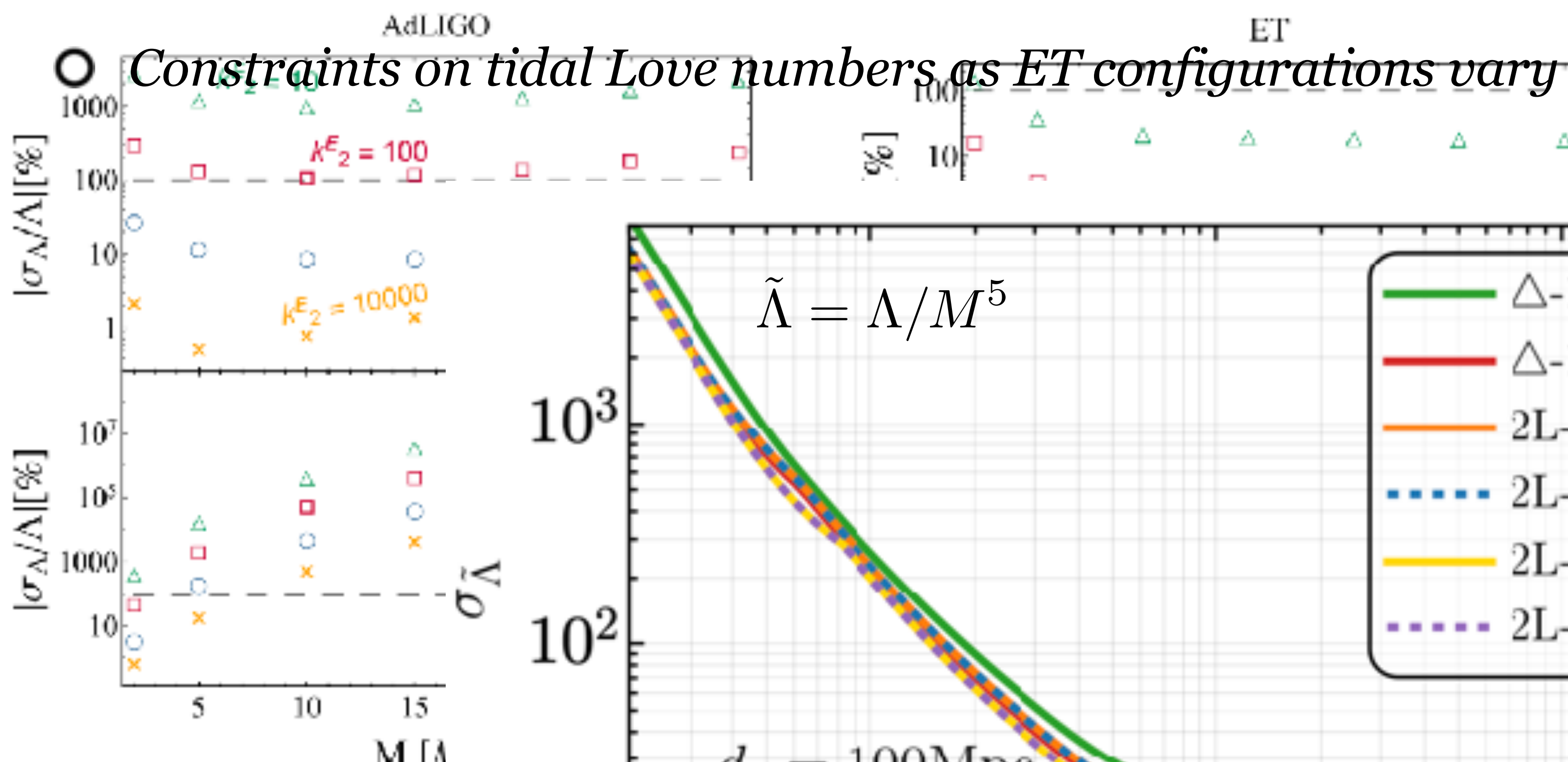


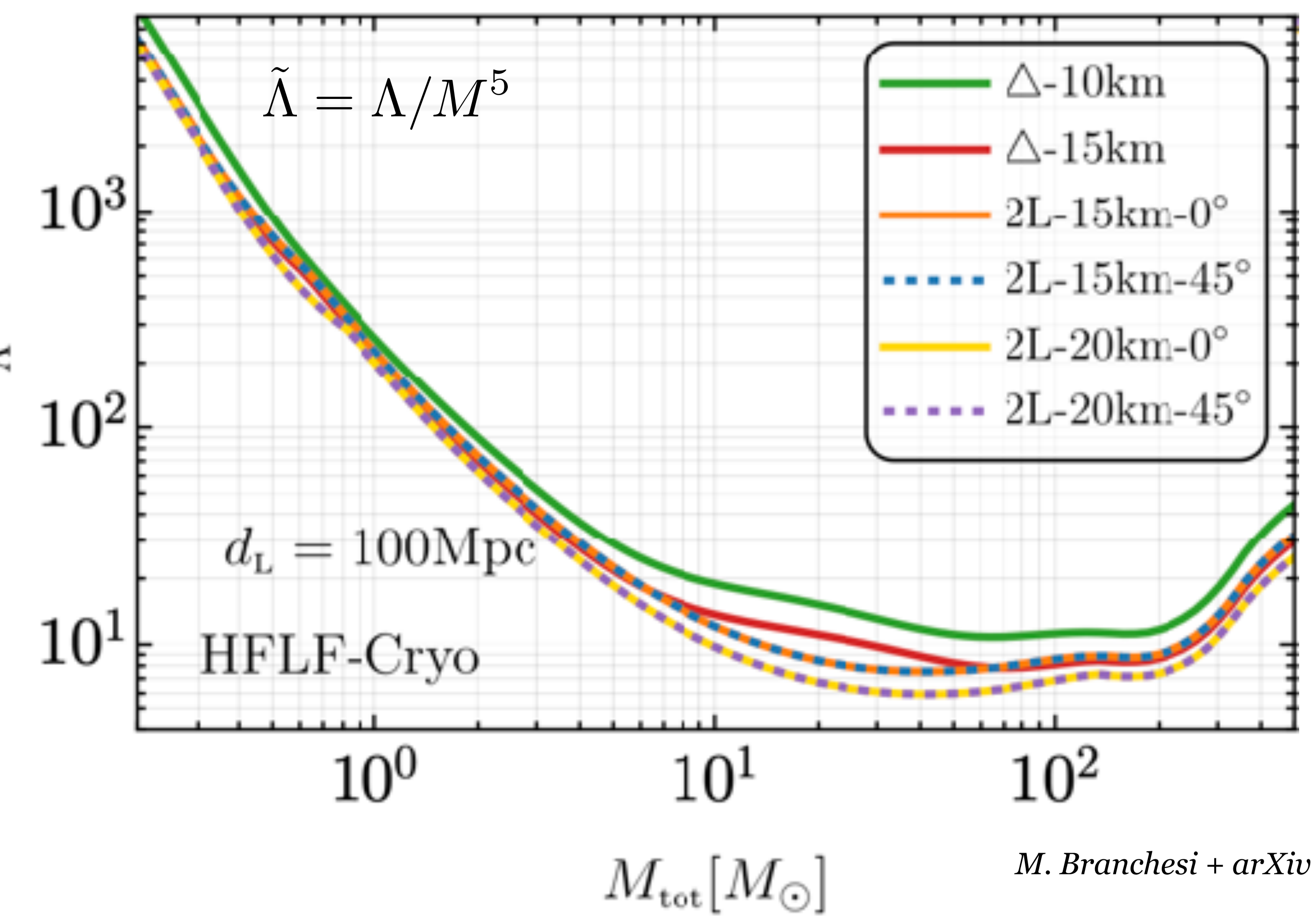
$$k_2^{\rm B} = \frac{9}{5}\left[8\zeta(3) - 9\right]\zeta_{\rm dCS}^2$$

V. Cardoso + PRD 95, 084014 (2017)

agnostic constraints on $\Lambda \sim k_2 M^5$

- *Constraints on tidal Love numbers as ET configurations vary*



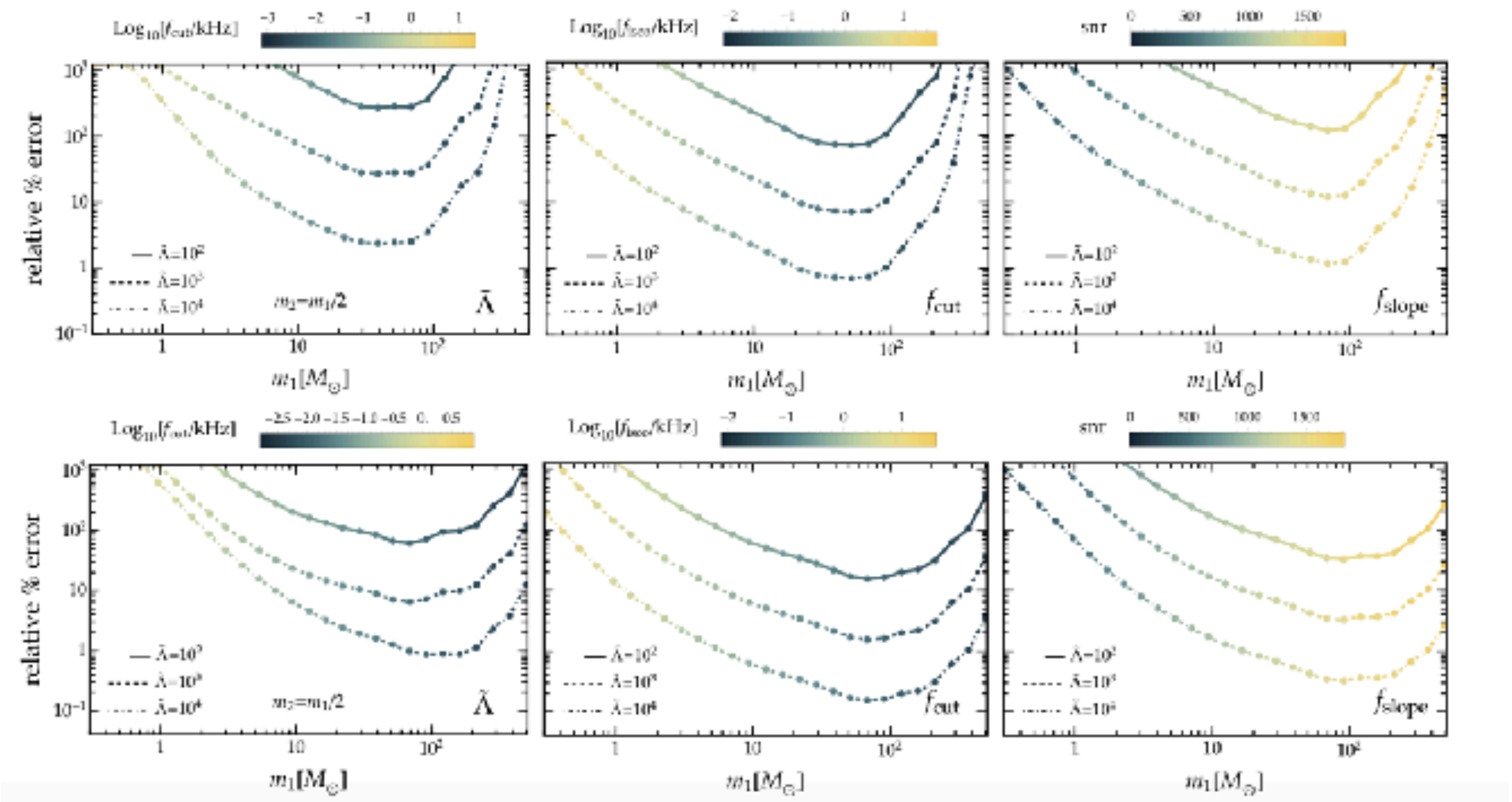


M. Branchesi + arXiv gr-qc: 2303.15923

The Inspiral

- *Frequency dependent Love numbers of dressed BHs*

$$\tilde{\Lambda} \to \mathcal{S}(f) \cdot \tilde{\Lambda} = \left[\frac{1 + e^{-f_{\rm cut}/f_{\rm slope}}}{1 + e^{(f - f_{\rm cut})/f_{\rm slope}}} \right] \cdot \tilde{\Lambda}$$



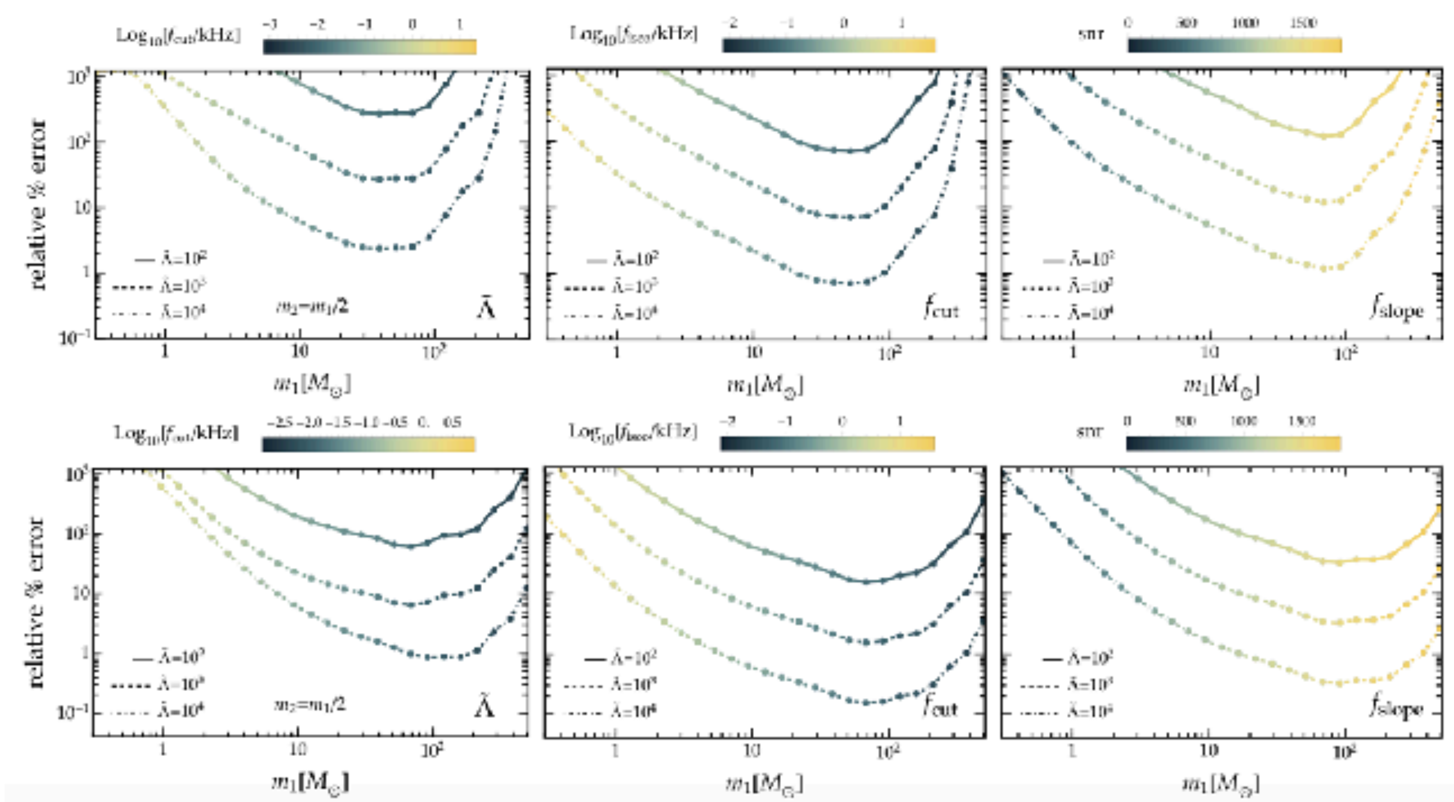
V. De Luca, A.M., P. Pani, PRD 107, 044058 (2023)

- *paved for multi-band analysis LISA-ET exploiting different frequency regimes*

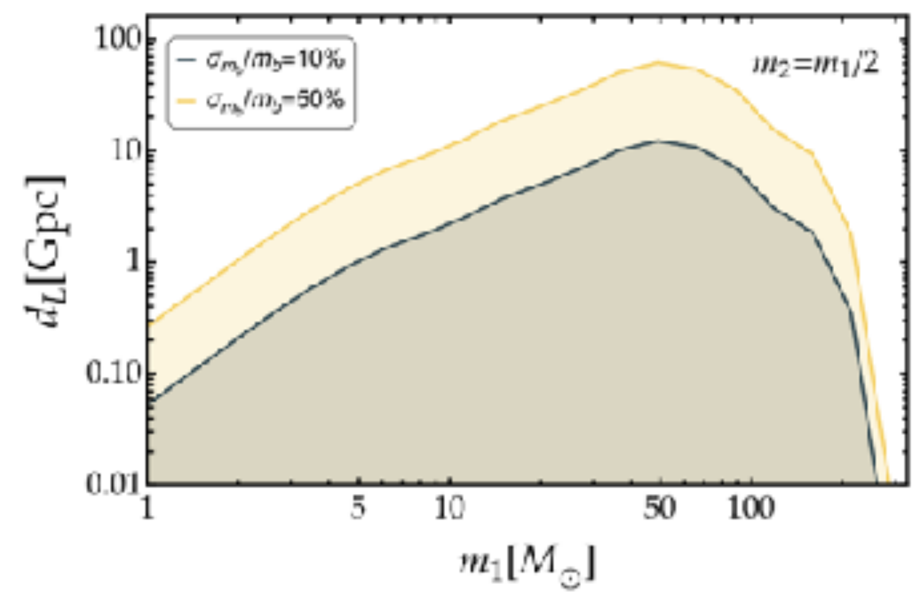
The Inspiral

- *Frequency dependent Love numbers of dressed BHs*

$$\tilde{\Lambda} \to \mathcal{S}(f) \cdot \tilde{\Lambda} = \left[\frac{1 + e^{-f_{\rm cut}/f_{\rm slope}}}{1 + e^{(f - f_{\rm cut})/f_{\rm slope}}} \right] \cdot \tilde{\Lambda}$$



maximum luminosity. distance for ultralight boson cloud



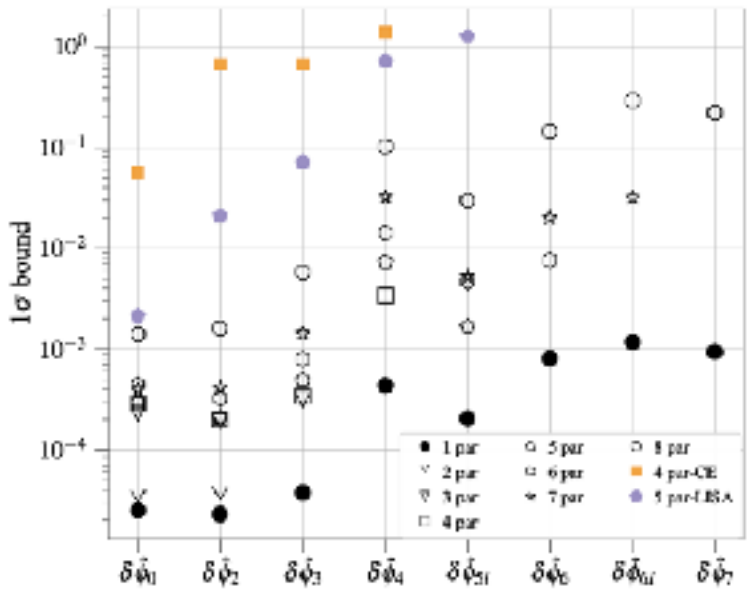
V. De Luca, A.M., P. Pani, PRD 107, 044058 (2023)

- *suited for multi-band analysis LISA-ET*

The Inspiral

- *Varying multiple parameters each time*
  - *improvement from multi-band observations*

A. Gupta +, PRL 125, 201101 (2020)
Perkins & Yunes, PRD 105, 124047 (2022)



- *Precessing ppE formalism*

N. Loutrel + PRD 107, 044046 (2023)

- *Dynamical scalarization*

M. Khalil +, PRD 100, 124013 (2019)

- *Inspiral Merger Ringdown tests*

Z. Carson & K. Yagi + PRD 101, 084050 (2020)

→ *Coherent waveform models encoding multiple effects/coefficients*

- *Less number of parameters to constrain, possibly alleviate degeneracies*
  - *lesson learnt from other sources (and phenomena)*

M. Vaglio +, gr-qc: 2302.13954 (2023)
C. Pacilio +, PRL 122, 101101 (2022)

QNMs beyond Kerr

Modelling frequencies and damping times beyond Kerr

- *Within GR extension QNMs can be written in terms of Kerr shifts*

(M, χ)

$$\omega = \omega^{\mathrm{Kerr}} + \delta\omega \qquad \tau = \tau^{\mathrm{Kerr}} + \delta\tau$$

generic deviation

$$\delta\omega \ll \omega^{\mathrm{Kerr}}$$

$$\delta\tau \ll \tau^{\mathrm{Kerr}}$$

- *In GR the full QNM spectrum is specified by the mass and the spin of Kerr BHs*
  - *Measuring one mode allows to determine mass and spin*
  - *Multiple modes provide independent null-hypothesis tests of GR*

C. Pacilio, S. Bhagwat PRD 107, 083021, (2021)

- *Deviations proportional to the fundamental coupling constants of the theory*
  - *Are QNMs competitive with other diagnostics?*

Parametrised Ringdown Spin Expansion Coefficients

A. M., P. Pani, L. Gualtieri, E. Berti, PRD 101, 024043, (2020)
G. Carullo, PRD 103, 124043, (2021)

ParSpec

Assume $i = 1 \dots N$ ringdown observations for which q modes are detected

- *Parametrise QNM in terms of a double expansion of spin χ & GR deviation*

spin order

$$M_i \omega_i^{\ell m} = \sum_{k_1=0}^{n_1} \chi_i^{k_1} \bar{\omega}_{\ell m}^{(k_1)} + \sum_{k_2=0}^{n_2} \chi_i^{k_2} \bar{\omega}_{\ell m}^{(k_2)} \gamma_i \delta\omega_{\ell m}^{(k_2)}$$

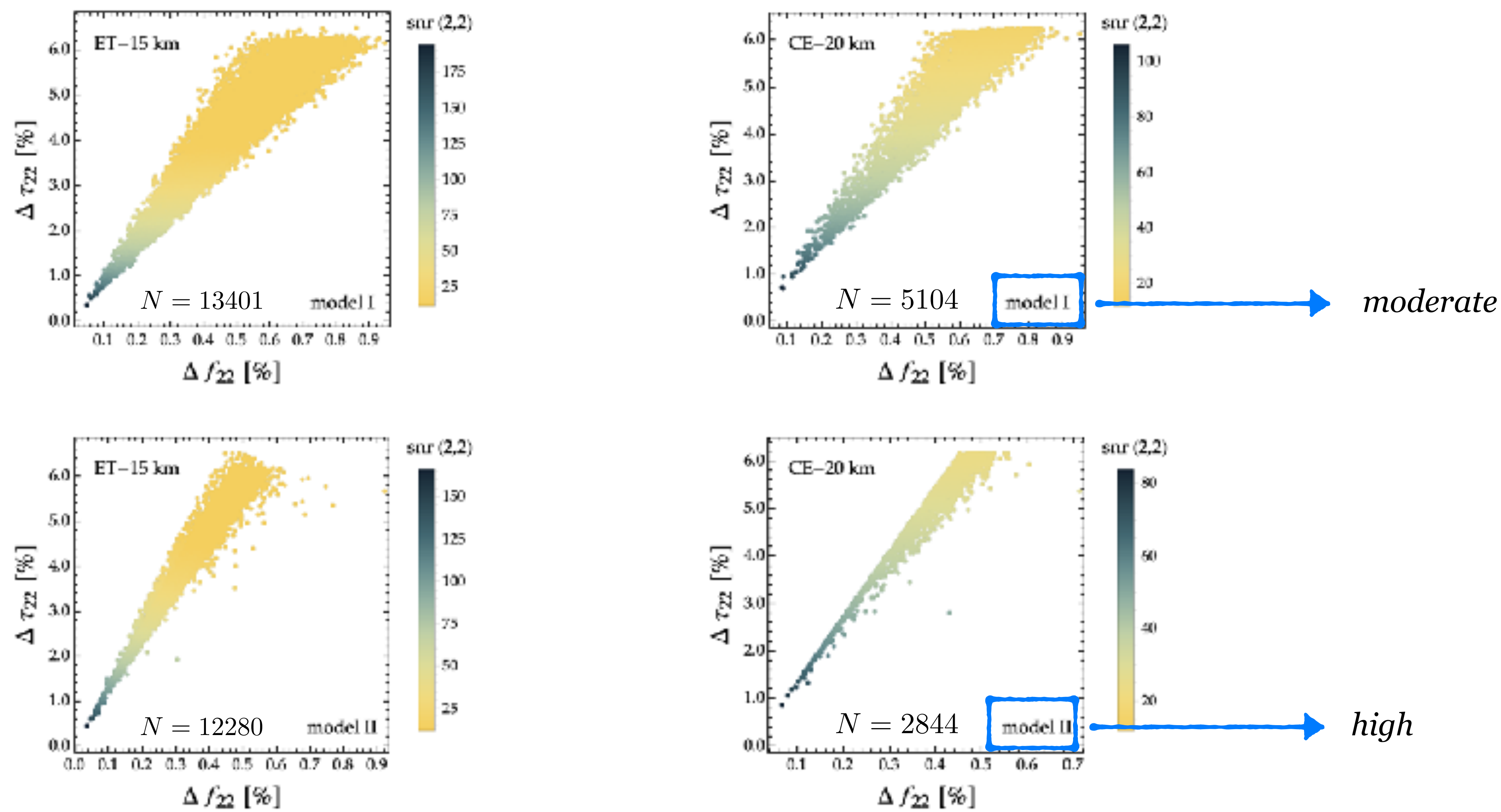
$$\tau_i^{\ell m}/M_i = \sum_{k_1=0}^{n_1} \chi_i^{k_1} \bar{\tau}_{\ell m}^{(k_1)} + \sum_{k_2=0}^{n_2} \chi_i^{k_2} \bar{\tau}_{\ell m}^{(k_2)} \gamma_i \delta\tau_{\ell m}^{(k_2)}$$

$\gamma_i \to 0$ ↓ GR

- *coefficients of the expansion for Kerr QNMs in GR*
- *beyond-Kerr corrections to the QNMs:* ***universal*** *&* $\gamma_i[\delta\tau_{\ell m}^{(k_2)}, \delta\omega_{\ell m}^{(k_2)}] < 1$
- *dimensionless coupling constants, possibly depending on the source*

QNM uncertainties

Errors on frequencies and damping times of the fundamental mode for 2 populations of BBH



- *errors on f_{22} ~ 1% for both ET and CE*
- *errors on τ_{22} ~ 1% only for $\rho \gtrsim 100$*
- *for the secondary, 33 measured in general with better accuracy than 21*

Specific models: GB gravity

Gauss Bonnet gravity with exponential coupling

L. Pierini & L. Gualtieri, PRD 106, 104009 (2023)
J. Salcedo +, PRD 94, 104024 (2016)

$$\mathcal{S}_{\rm GB} = \int d^4x\sqrt{-g}\left(R - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi + \frac{\alpha_{\rm GB}}{4}e^{\varphi}\mathcal{R}^2_{\rm GB}\right)$$

- *QNMs at the second order in the spin* $\Omega_{\ell m} = \omega_{\ell m} - i/\tau_{\ell m}$

$$\beta_{\rm sGB} = \alpha_{\rm GB}/M^2$$

$$M\Omega_{\ell m} = \left(\Omega_0^A + \beta_{\rm sGB}^2\Omega_0^B\right) + m\chi\left(\Omega_1^A + \beta_{\rm sGB}^2\Omega_1^B\right) + \chi^2\left[\left(\Omega_{2a}^A + \beta_{\rm sGB}^2\Omega_{2a}^B\right) + m^2\left(\Omega_{2b}^A + \beta_{\rm sGB}^2\Omega_{2b}^B\right)\right]$$

ParSpec map

$$\omega_{\ell m} = \frac{1}{M}\left[\bar\omega_{\ell m}^{(0)}\left(1+\beta_{\rm GB}^2\delta\omega_{\ell m}^{(0)}\right) + \chi\bar\omega_{\ell m}^{(1)}\left(1+\beta_{\rm GB}^2\delta\omega_{\ell m}^{(1)}\right) + \chi^2\bar\omega_{\ell m}^{(2)}\left(1+\beta_{\rm GB}^2\delta\omega_{\ell m}^{(2)}\right)\right] + \frac{1}{M}\sum_{k_1=3}^{6}\bar\omega_{\ell m}^{(k_1)}$$

$$\tau_{\ell m} = M\left[\bar\tau_{\ell m}^{(0)}\left(1+\beta_{\rm GB}^2\delta\tau_{\ell m}^{(0)}\right) + \chi\bar\tau_{\ell m}^{(1)}\left(1+\beta_{\rm GB}^2\delta\tau_{\ell m}^{(1)}\right) + \chi^2\bar\tau_{\ell m}^{(2)}\left(1+\beta_{\rm GB}^2\delta\tau_{\ell m}^{(2)}\right)\right] + M\sum_{k_1=3}^{6}\bar\tau_{\ell m}^{(k_1)}$$

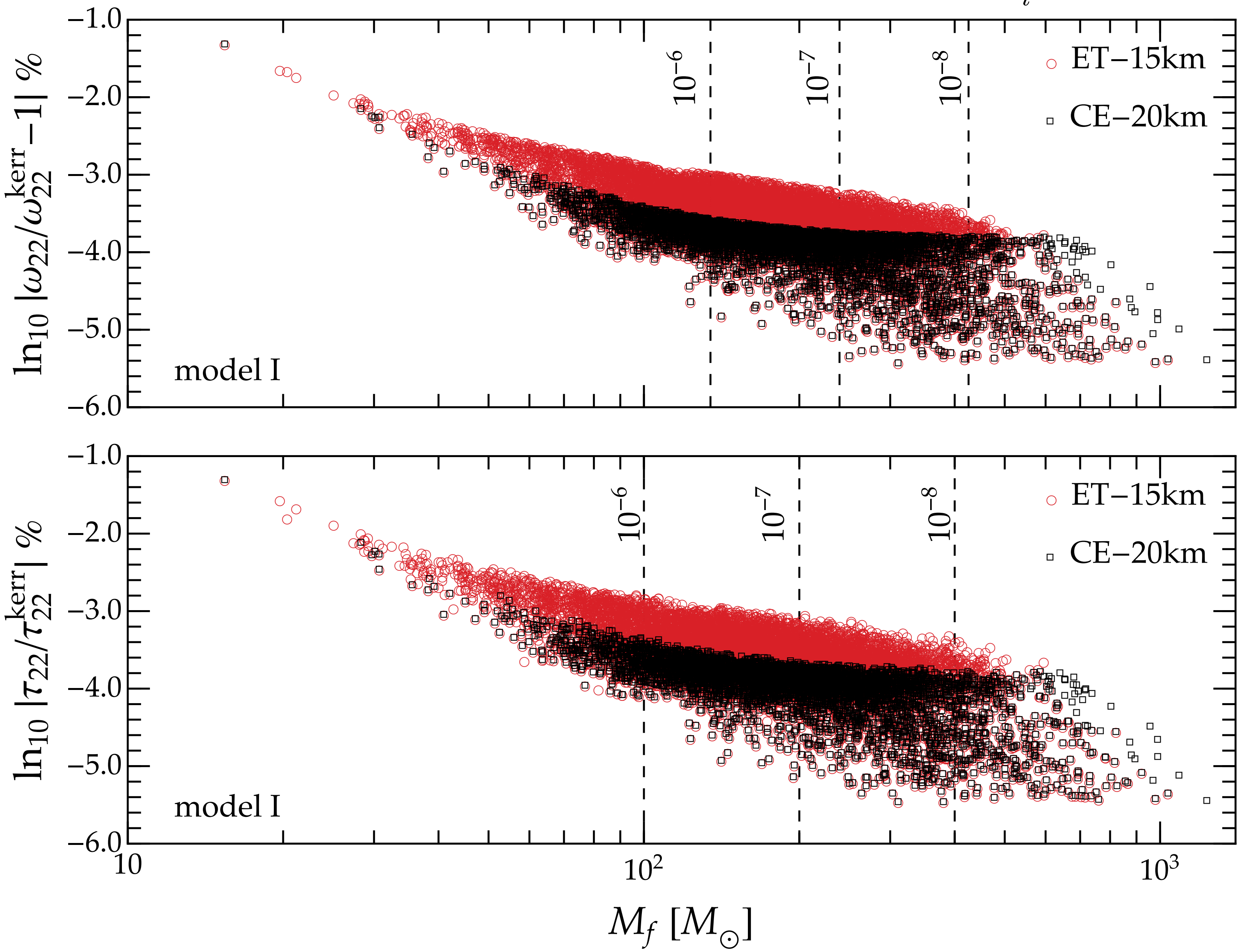
k_1	$\bar\omega_{22}^{(k_1)}$	$\bar\tau_{22}^{(k_1)}$	$\bar\omega_{33}^{(k_1)}$	$\bar\tau_{33}^{(k_1)}$	$\bar\omega_{21}^{(k_1)}$	$\bar\tau_{21}^{(k_1)}$
0	0.37367	11.2407	0.59944	10.7871	0.37367	11.2407
1	0.12578	0.2522	0.20206	0.2276	0.06288	0.1261
2	0.07178	0.6650	0.10717	0.8238	0.04487	0.7701
3	0.04800	0.5840	0.06890	0.7345	0.02183	0.4026
4	0.03601	0.6420	0.04841	0.6744	0.01642	0.3563
5	0.01389	0.0733	0.05295	0.5408	0.00590	1.2600
6	0.13021	3.9385	−0.11339	1.3153	0.05889	0

k_2	$\delta\omega_{22}^{(k_2)}$	$\delta\tau_{22}^{(k_2)}$	$\delta\omega_{33}^{(k_2)}$	$\delta\tau_{33}^{(k_2)}$	$\delta\omega_{21}^{(k_2)}$	$\delta\tau_{21}^{(k_2)}$
0	−0.03773	−0.0528	−0.09112	−0.0778	−0.03773	−0.0528
1	−0.16679	−0.0802	−0.32149	2.4495	−0.16679	−0.0176
2	−0.27788	3.9141	−0.56101	2.6150	0.11256	1.4773

How much change

Relative change in frequencies and damping times

$$\gamma_{\mathrm{GB},i} = \frac{\alpha_{\mathrm{GB}}^2}{M_i^4}$$



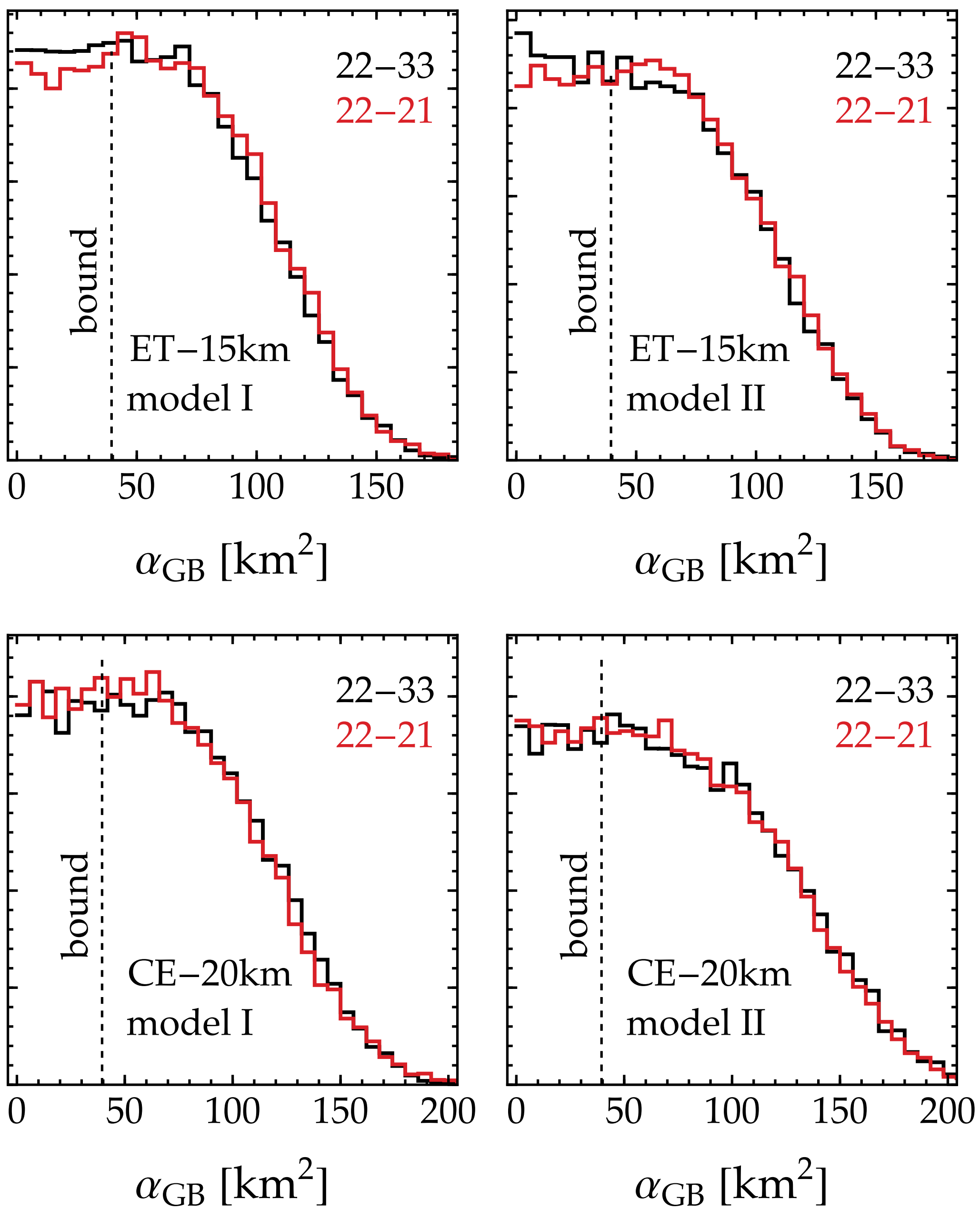
- *Current bound* $\alpha_{\mathrm{GB}}^{\mathrm{bound}} \simeq 40\ \mathrm{km}^2$

Liu +, PRD 105 06400 (2022)

sGB + ParSpec: bounds

Injected events in GB gravity with $\alpha_{\rm GB}^{\rm bound}$*, reconstructed with ParSpec*

- *sampling on* $\alpha_{\rm GB}$

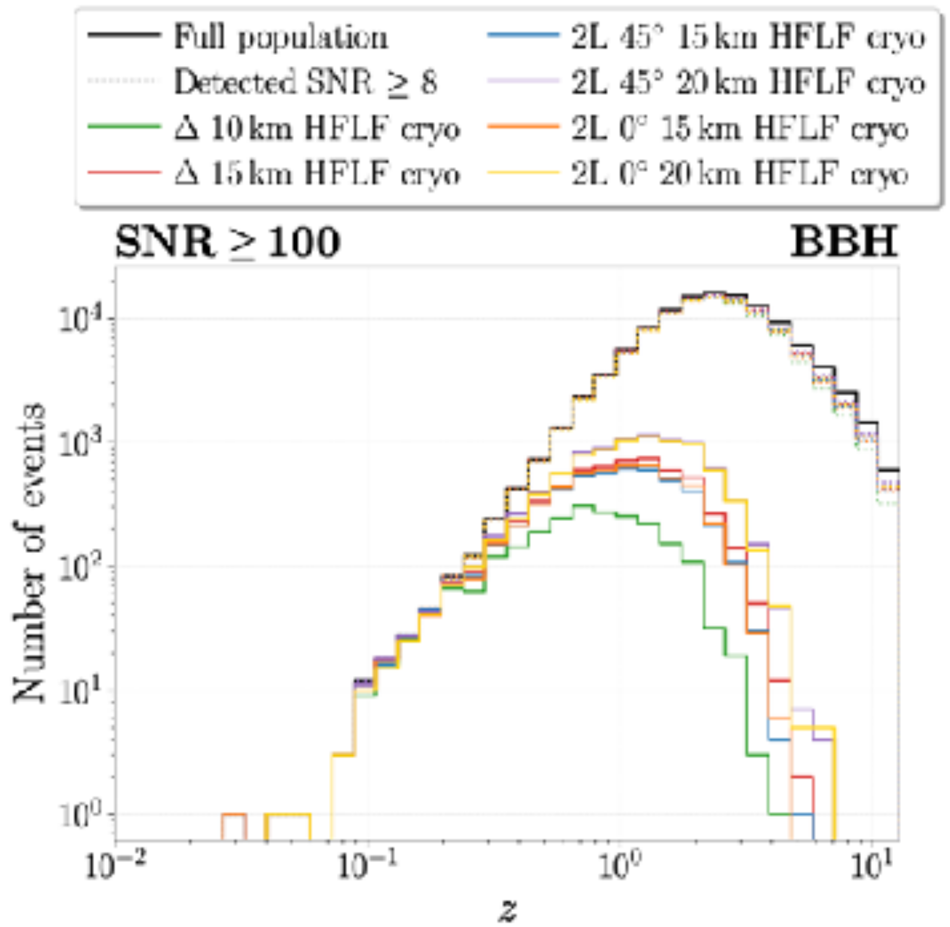


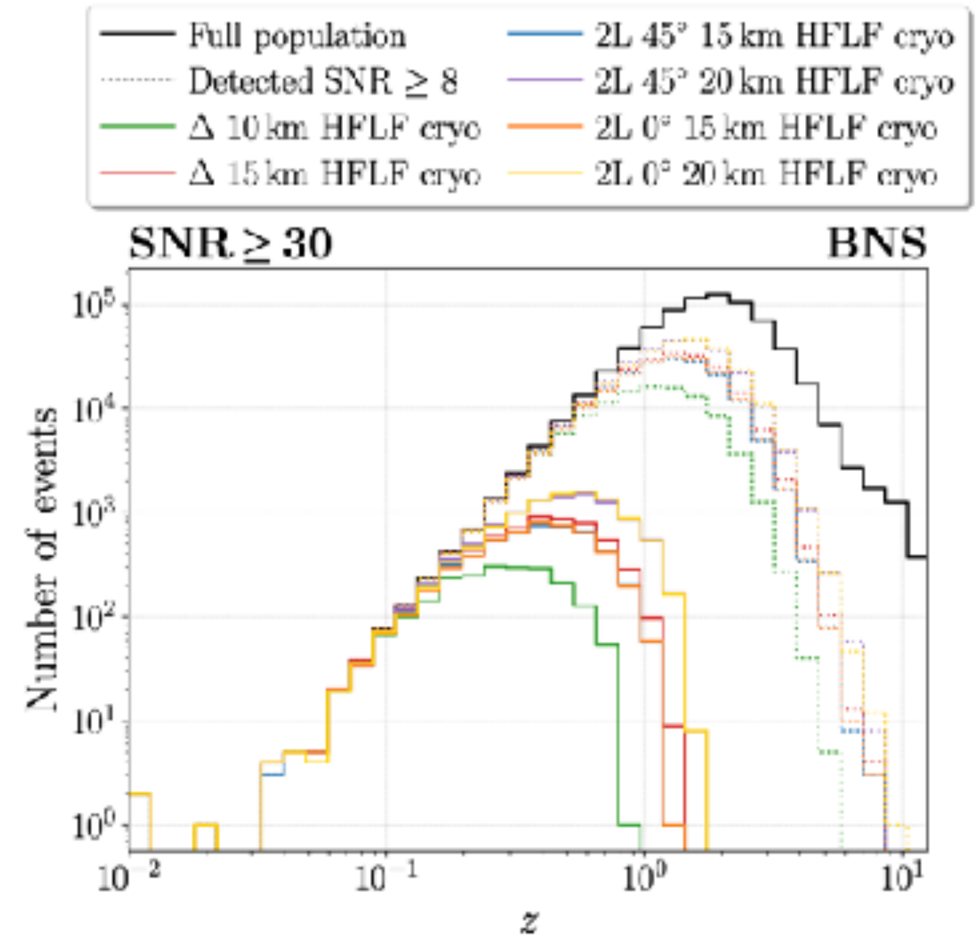
- *Spin corrections seem to play a minor role*
- *Bounds dominated by light BHs, with* $M_f \lesssim 60 M_\odot$
- *Results weaker than best constraint to date*

A. M., L. Pierini, V. Vellucci, L. Reali, E. Berti, L. Gualtieri + to appear

Summary

3G interferometers expectations



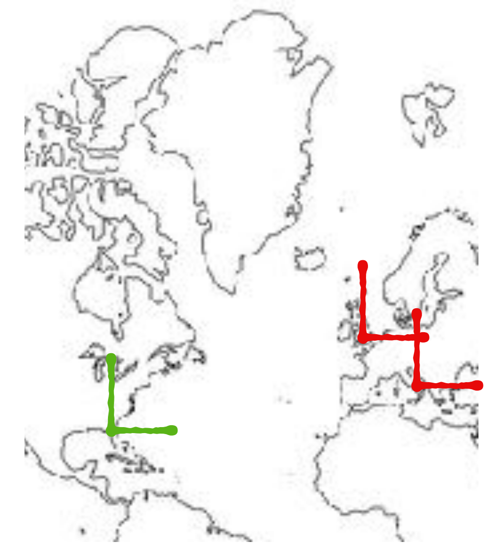


M. Branchesi + arXiv gr-qc: 2303.15923

Back up

Science Cases

Accommodate multiple scenarios



- agnostic tests the Kerr QNM spectrum
  - scale free couplings $\gamma_i = const$
    - coupling can be re-absorbed in the shifts $\gamma_i \delta\omega_{\ell m}^{(k_2)} \rightarrow \delta\omega_{\ell m}^{(k_2)}$
  - dimensional coupling constant $[\alpha] = [mass^p]$ $\gamma_i = \frac{\alpha^p}{M_i^p}$ $p = 4$
    - coupling can also be re-absorbed $\alpha\delta\omega_{\ell m}^{(k_2)} \rightarrow \delta\omega_{\ell m}^{(k_2)}$
- QNM spectrum in specific beyond GR theories
  - Gauss Bonnet and Chern Simons gravity $\gamma_i = \frac{\alpha_{\rm GB}^2}{M_i^4}$ $\gamma_i = \frac{\alpha_{\rm CS}^2}{M_i^4}$
    - map frequencies/damping times to the ParSpec shifts $\delta\omega_{\ell m}^{(k_2)}, \delta\tau_{\ell m}^{(k_2)}$
    - sampling is on the couplings $\alpha_{\rm GB,CS}$

A. M., L. Pierini, V. Vellucci, L. Reali, E. Berti, L. Gualtieri + to appear

Population models

N sources drawn from binary black hole catalogues

- *POWER LAW + PEAK phenomenological model (GWTC3 inspired)*

R. Abbott + arXiv PRX 13, 011048 (2023)

$$P(m_1) \propto [(1-\lambda)P_{\text{law}}(m_1|\gamma_1, m_{\max}) + \lambda G(m_1|\mu_m, \sigma_m)]\, S(m_1|m_{\min}, \delta_m)$$

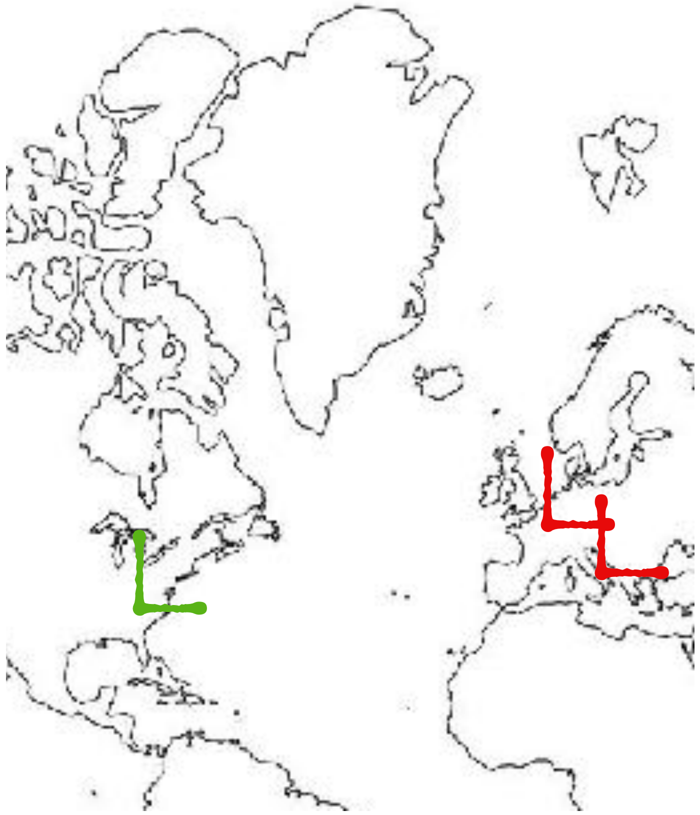
$$P(q) \propto q^{\gamma_q} S(m_1 q|m_{\min}, \delta_m)$$

- *BBH sampled up to z=10, with z-distribution following a Madau-Dickinson curve for the SFR*

- *2 spin assumptions*
  - **model I** $\chi_{1,2} \in$ *β-distribution* $(\alpha, \beta) = (2, 5)$
  - **model II** $\chi_{1,2} \in$ *uniform [-1,1]*

- *3G detectors: 2 x Einstein Telescope & Cosmic Explorer*

M. Branchesi + arXiv gr-qc: 2303.15923 (2023)

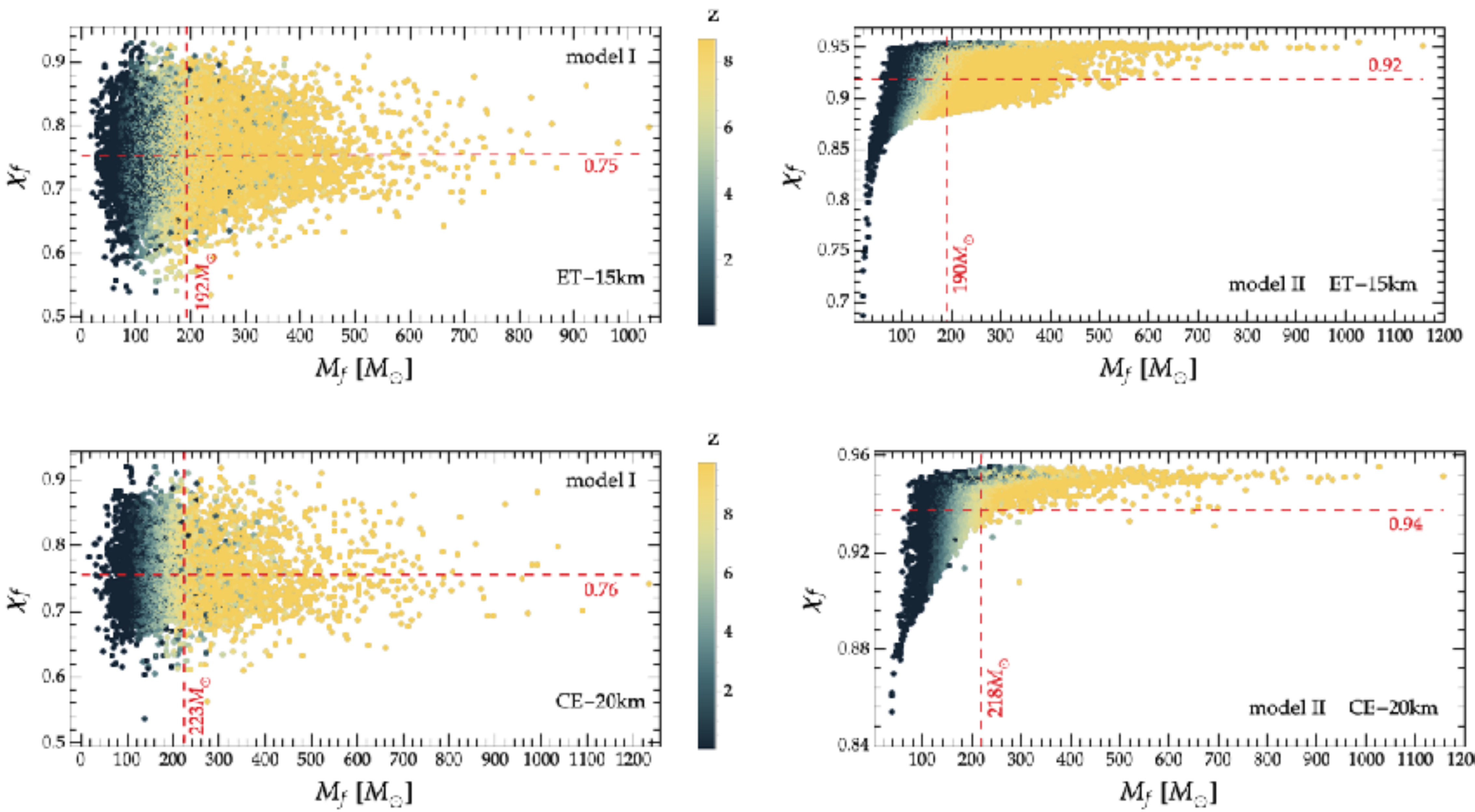


(sub)Population models

Mass-spin distributions for the selected BH remnants

β-distribution

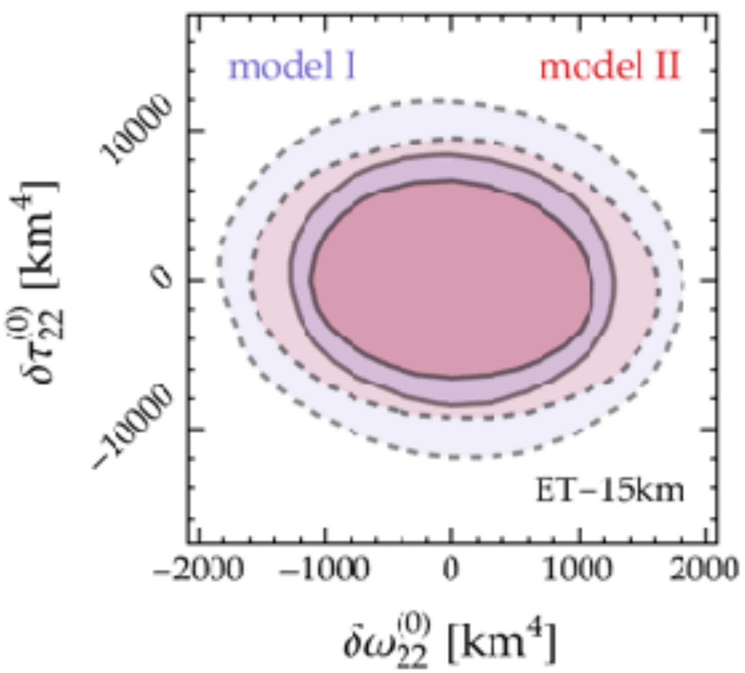
uniform [-1,1]

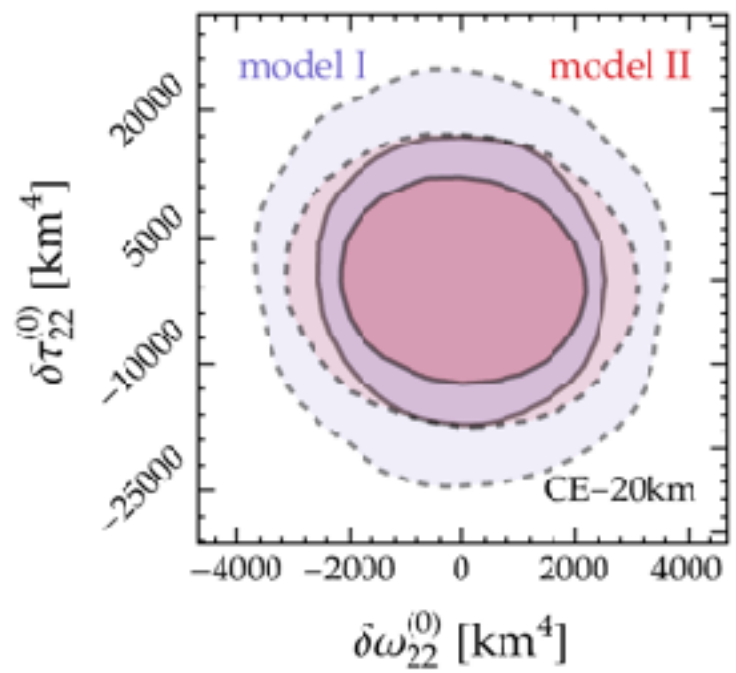


Spin-less corrections (again)

$$M_i\omega_i^{\ell m} = \sum_{k_1=0}^{6} \chi_i^{k_1}\bar{\omega}_{\ell m}^{(k_1)} + \bar{\omega}_{\ell m}^{(0)}\gamma_i\delta\omega_{\ell m}^{(0)} \qquad \tau_i^{\ell m}/M_i = \sum_{k_1=0}^{6} \chi_i^{k_1}\bar{\tau}_{\ell m}^{(k_1)} + \bar{\tau}_{\ell m}^{(0)}\gamma_i\delta\tau_{\ell m}^{(0)} \qquad \gamma_i = \frac{\alpha^4}{M_i^4}$$

2D posteriors stacking all set of events





- *bounds insensitive to spin models, strongly dependent on BH mass*
  - *posteriors dominated by* $\mathcal{O}(100)$ *events with low masses*
- *projected bound on the coupling* $\alpha \sim [\delta\omega_{22}^{(0)}]^{1/4} \sim \mathcal{O}(10\text{km})$
- *Adding spin terms does makes the posteriors uninformative*