Tests of general relativity with gravitational waves

Sylvain Marsat (L2IT, Toulouse)

Overview

- Introduction: fundamental physics and gravitational waves
- LIGO-Virgo-Kagra observations
- GW170817 and its consequences
- Tests of GR from LVK GWTC-3 observations
- The future of GW astronomy and TGR

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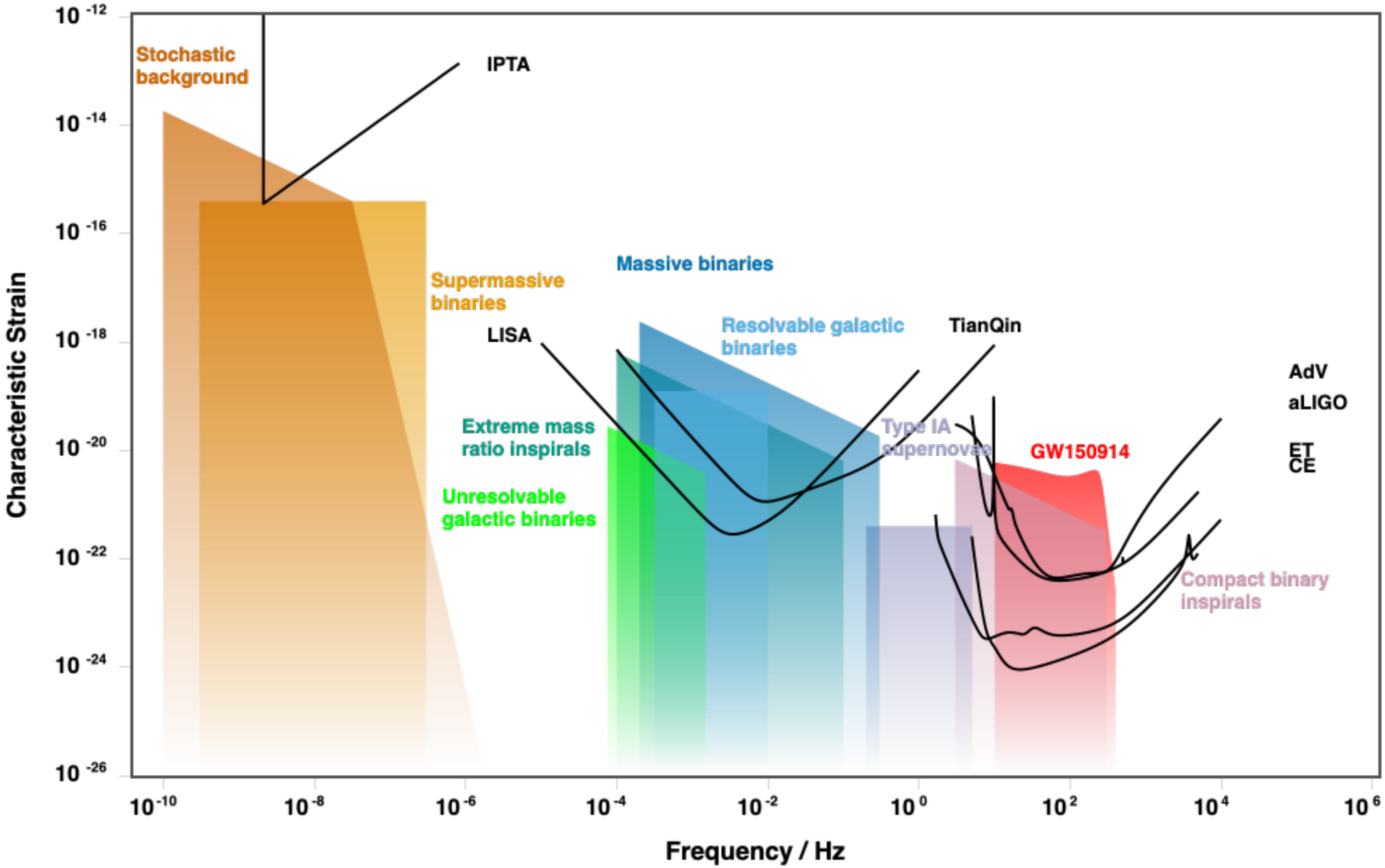
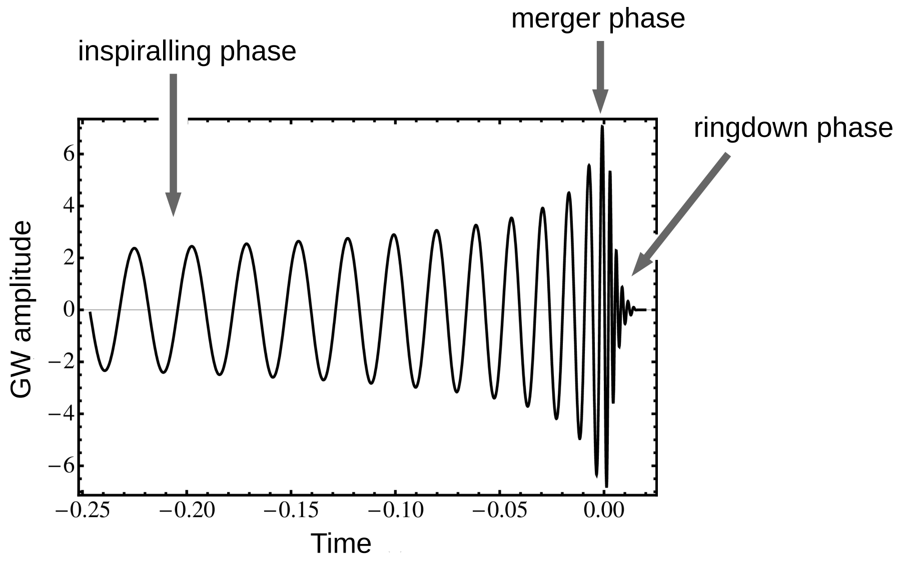
The gravitational waves landscape



[Moore&al 2014]

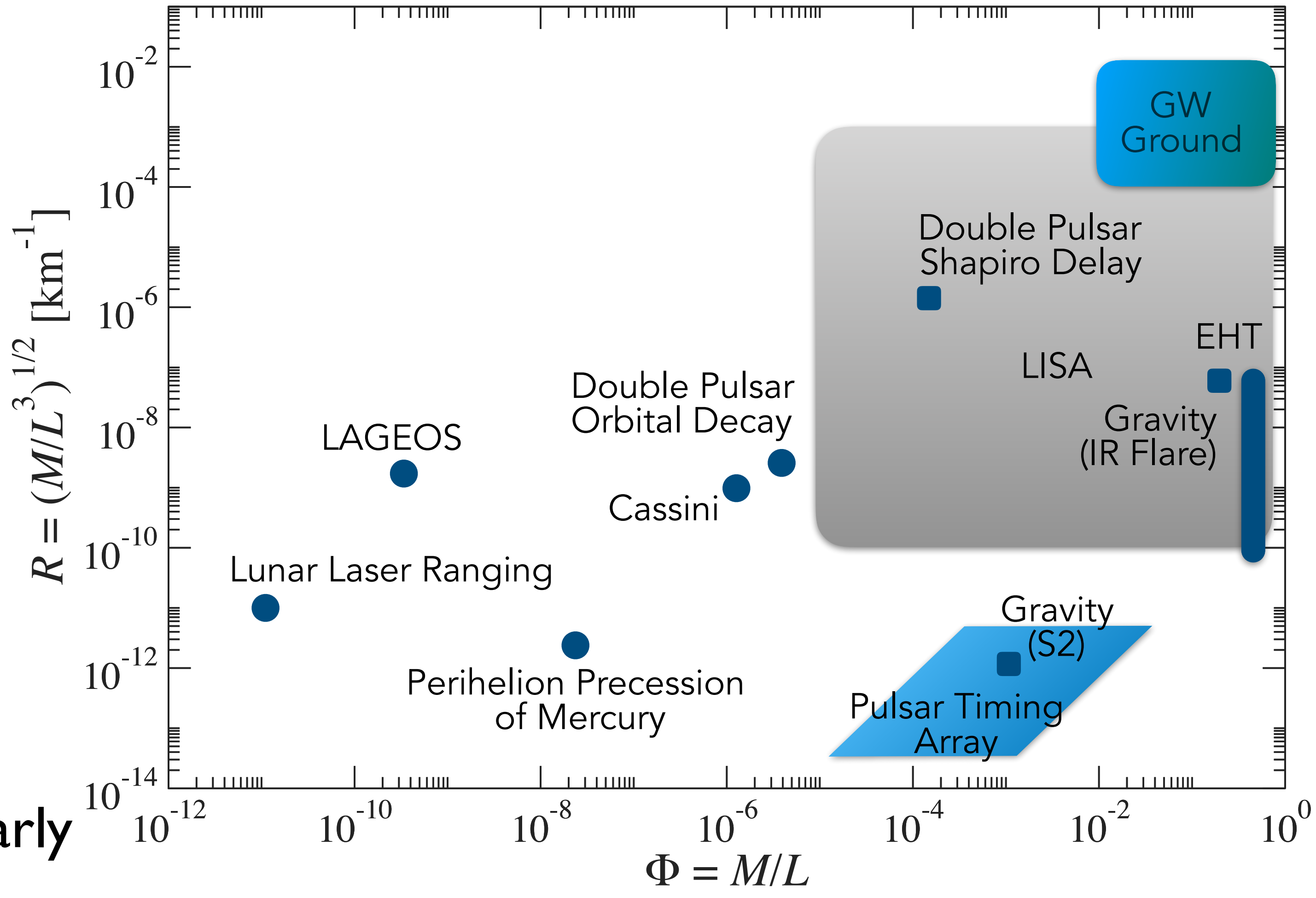
Gravitational waves and fundamental physics

Open questions in fundamental physics: dark matter/ dark energy, quantum gravity, nature of compact objects



What gravitational waves science can bring:

- Confirming the GR prediction in the first place !
- GW inspiral, merger, ringdown probe gravity and compact objects in different regimes
- Explore different scales across the GW spectrum
- Extreme phenomena in strong-field GR
- A new, independent cosmological probe
- Stochastic GW backgrounds from the early universe

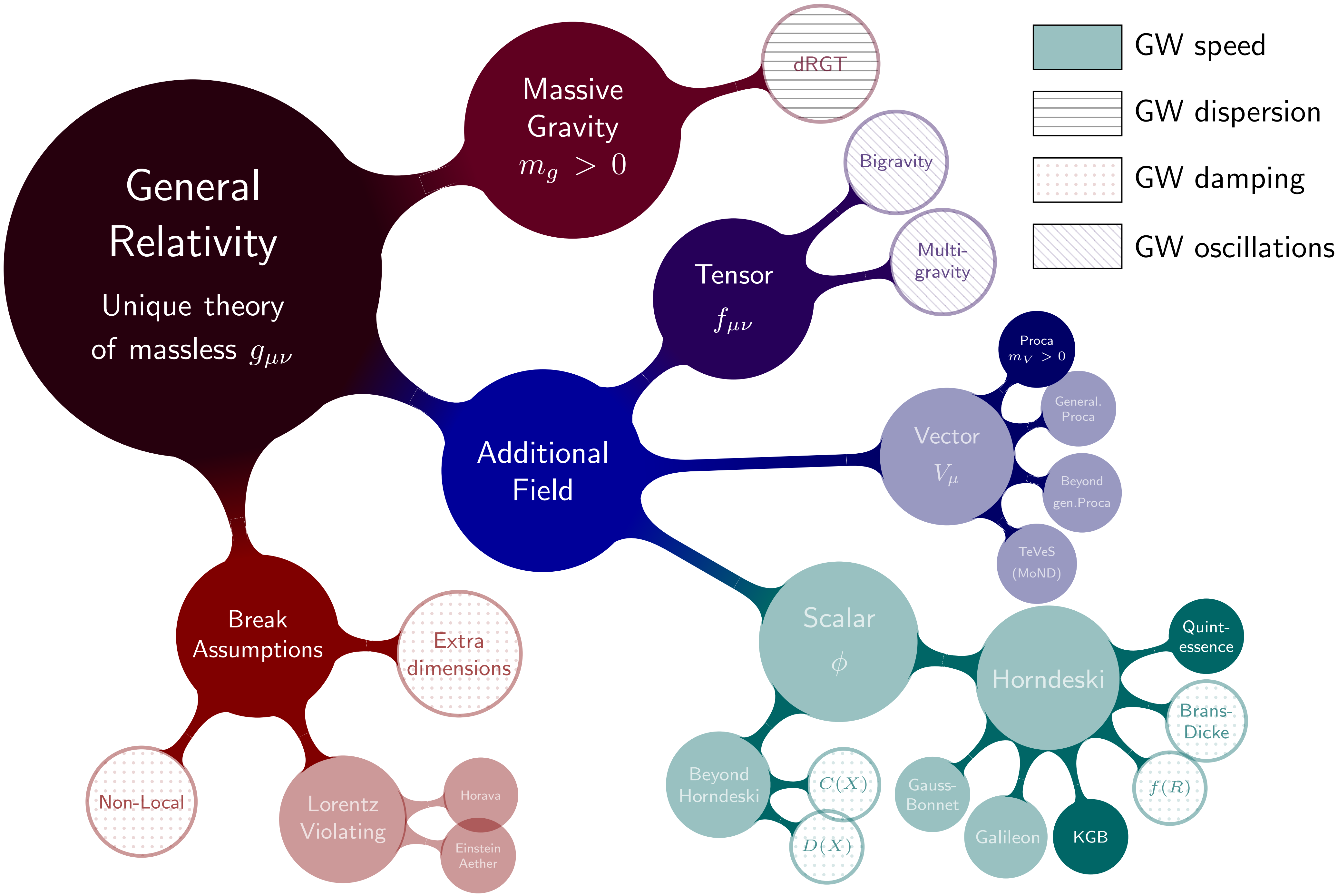


[Extreme Gravity White Paper 2020]

Gravitational waves and fundamental physics

Modified gravity roadmap

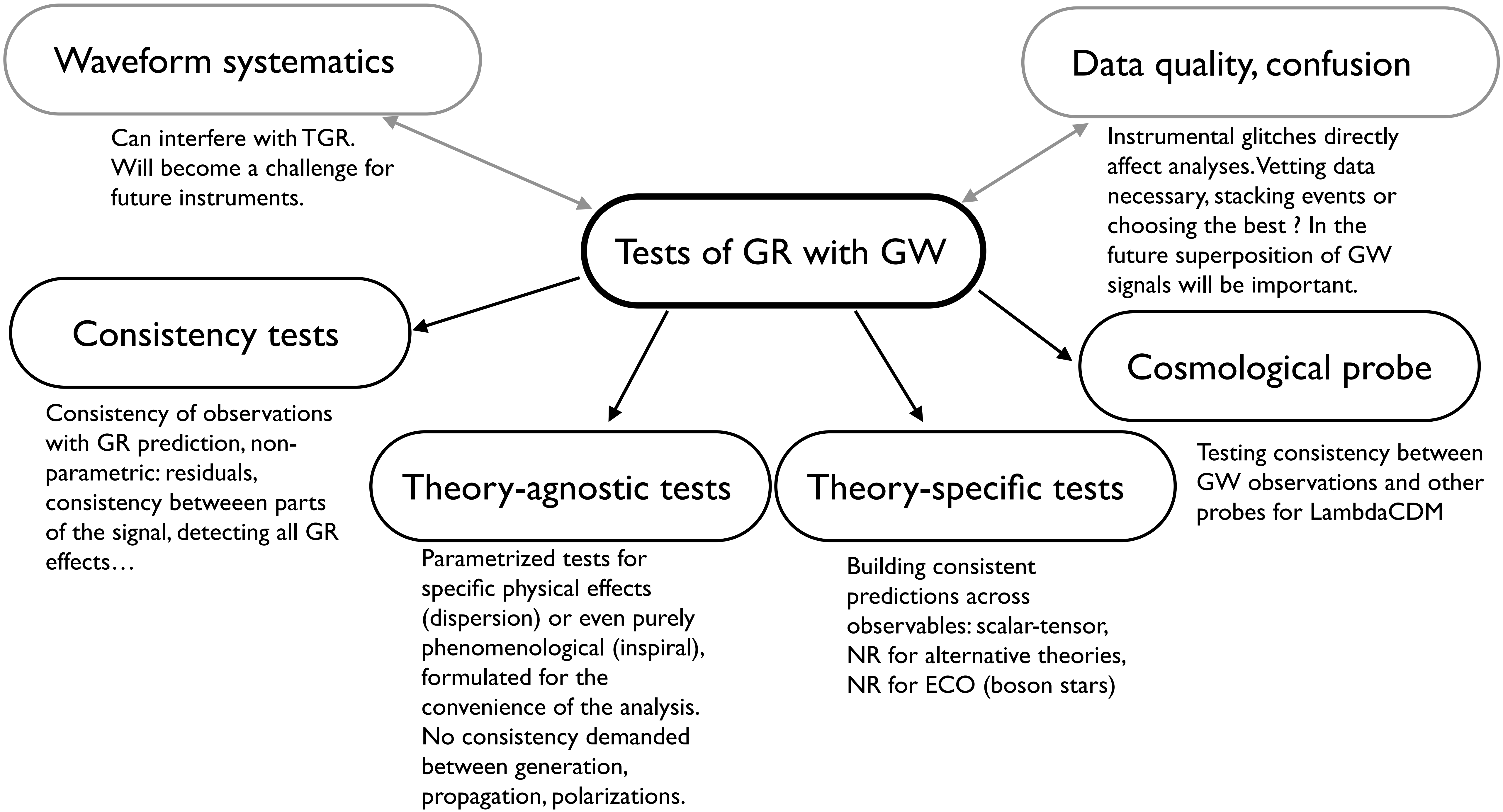
Constrained by



[Ezquiaga&al 2018]

Tests of general relativity with gravitational waves

What can we really test for from our observations ? No 1-to-1 mapping between theory space and data analysis space.



Waveform systematics

Can interfere with TGR. Will become a challenge for future instruments.

Data quality, confusion

Instrumental glitches directly affect analyses. Vetting data necessary, stacking events or choosing the best ? In the future superposition of GW signals will be important.

Tests of GR with GW

Consistency tests

Consistency of observations with GR prediction, non-parametric: residuals, consistency between parts of the signal, detecting all GR effects…

Theory-agnostic tests

Parametrized tests for specific physical effects (dispersion) or even purely phenomenological (inspiral), formulated for the convenience of the analysis. No consistency demanded between generation, propagation, polarizations.

Theory-specific tests

Building consistent predictions across observables: scalar-tensor, NR for alternative theories, NR for ECO (boson stars)

Cosmological probe

Testing consistency between GW observations and other probes for LambdaCDM

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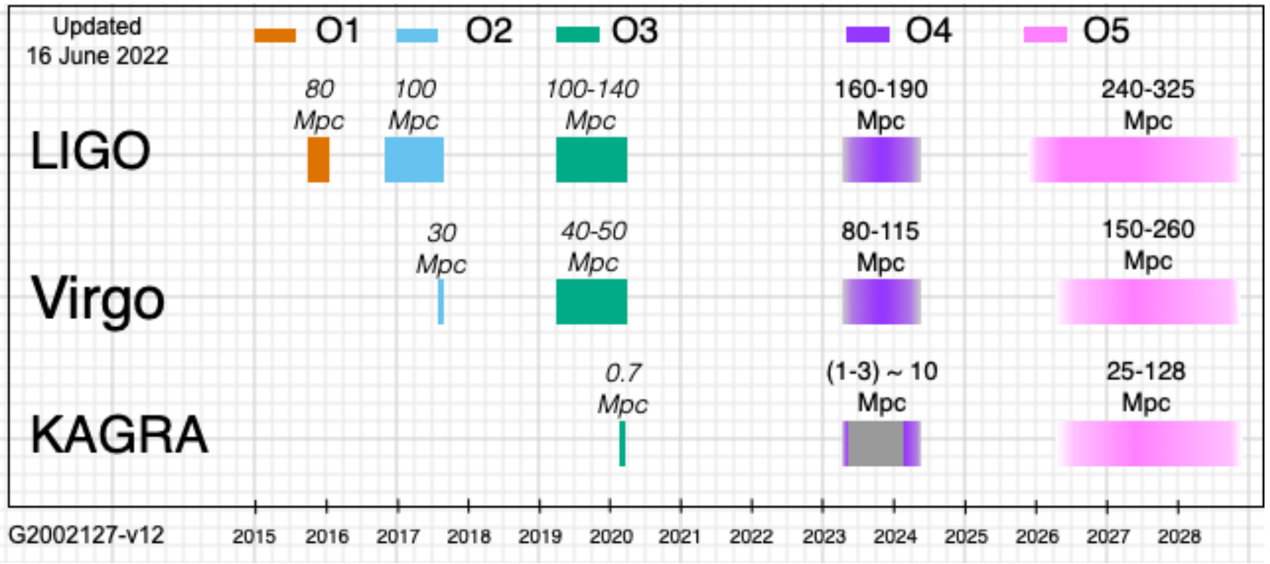
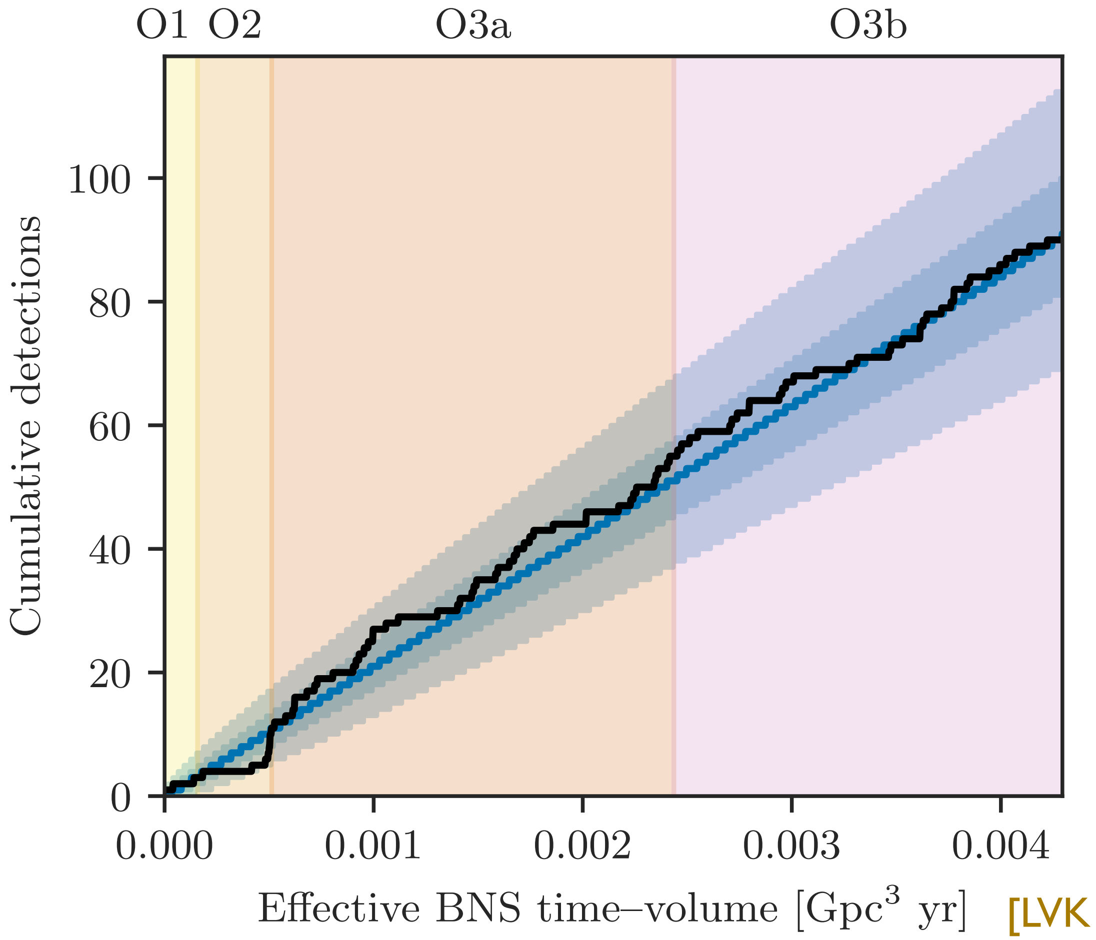
Ground based detectors: timeline

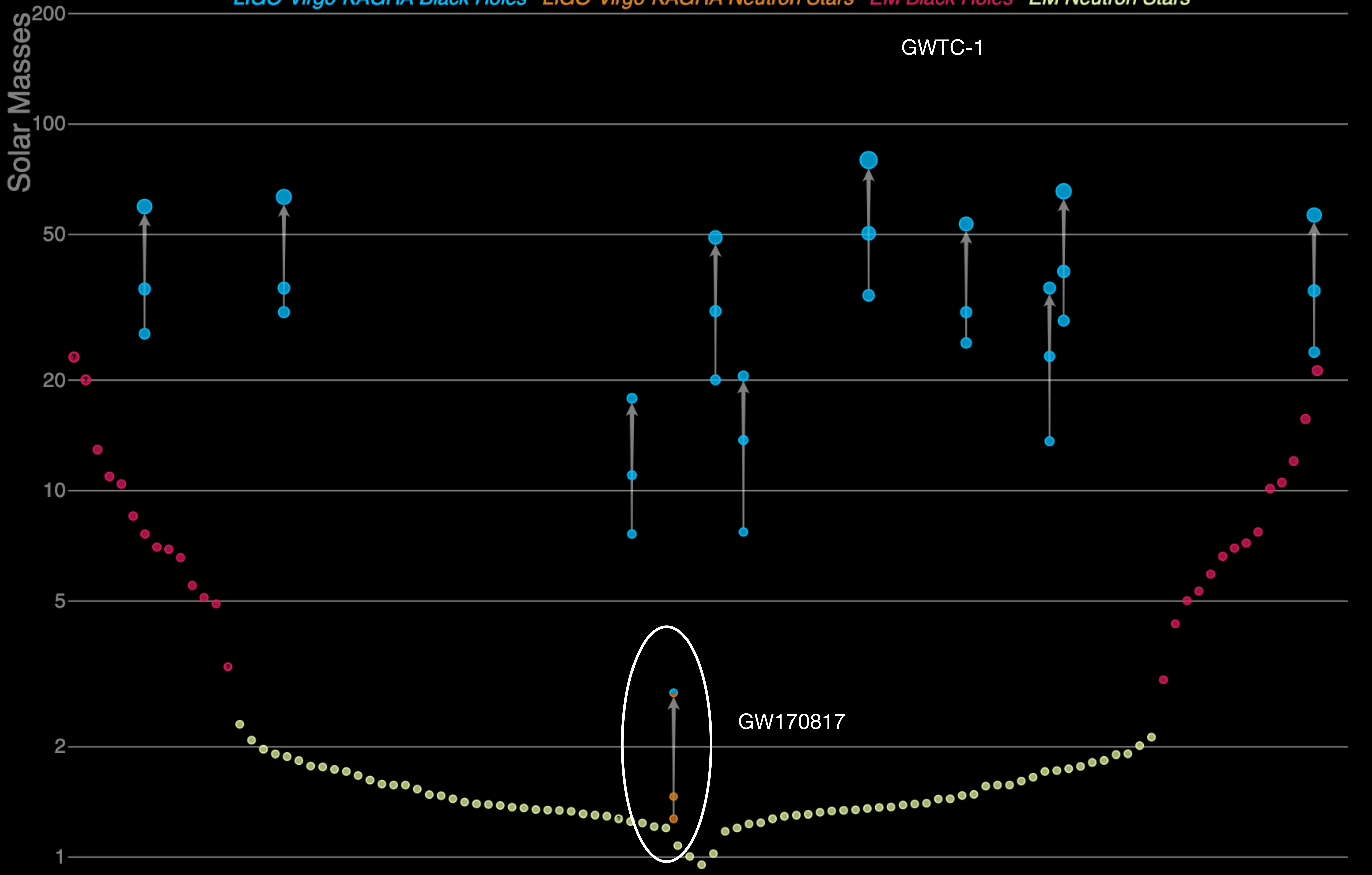


[IGWN 2022]



[LVK 2021]

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

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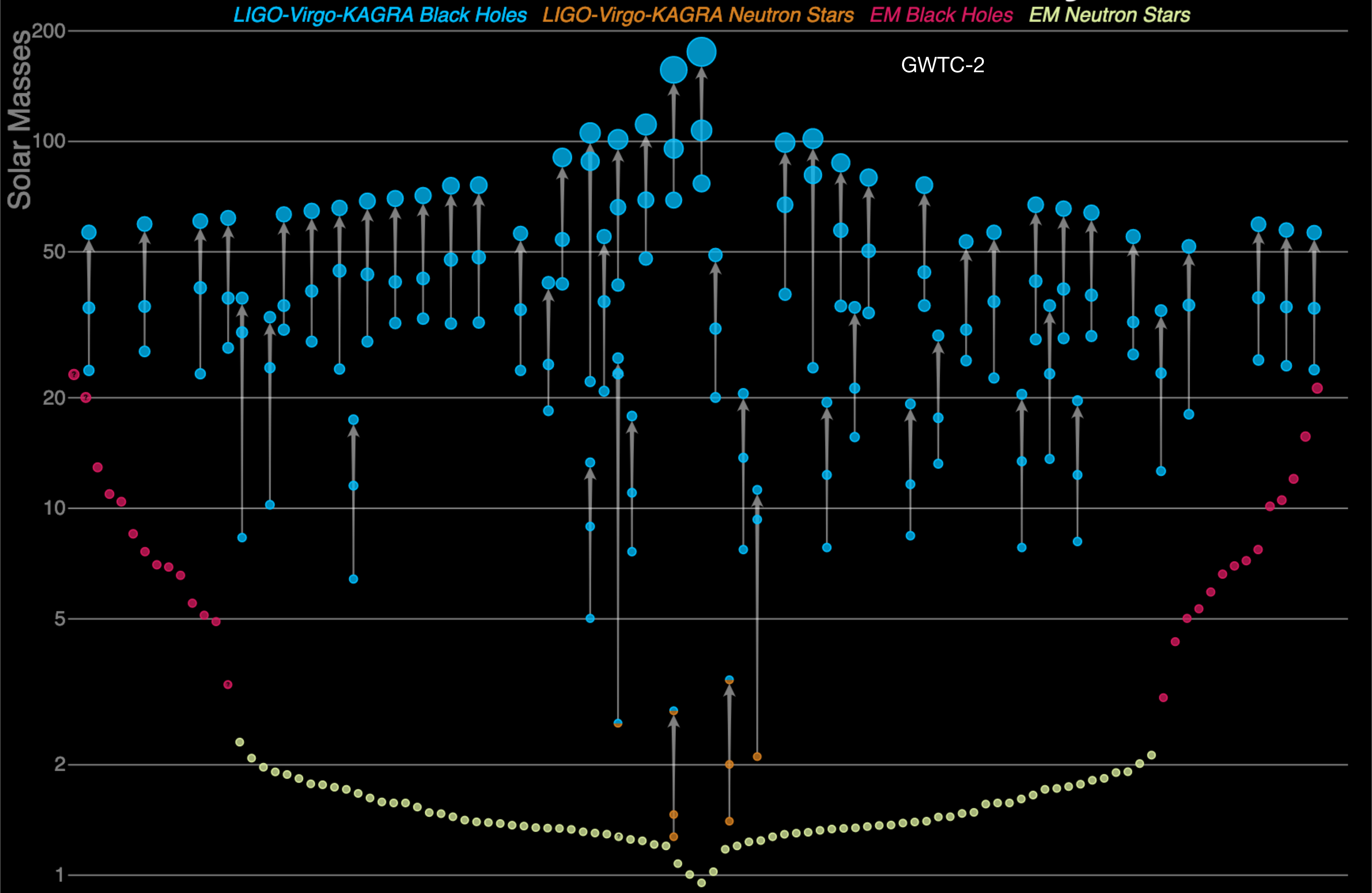

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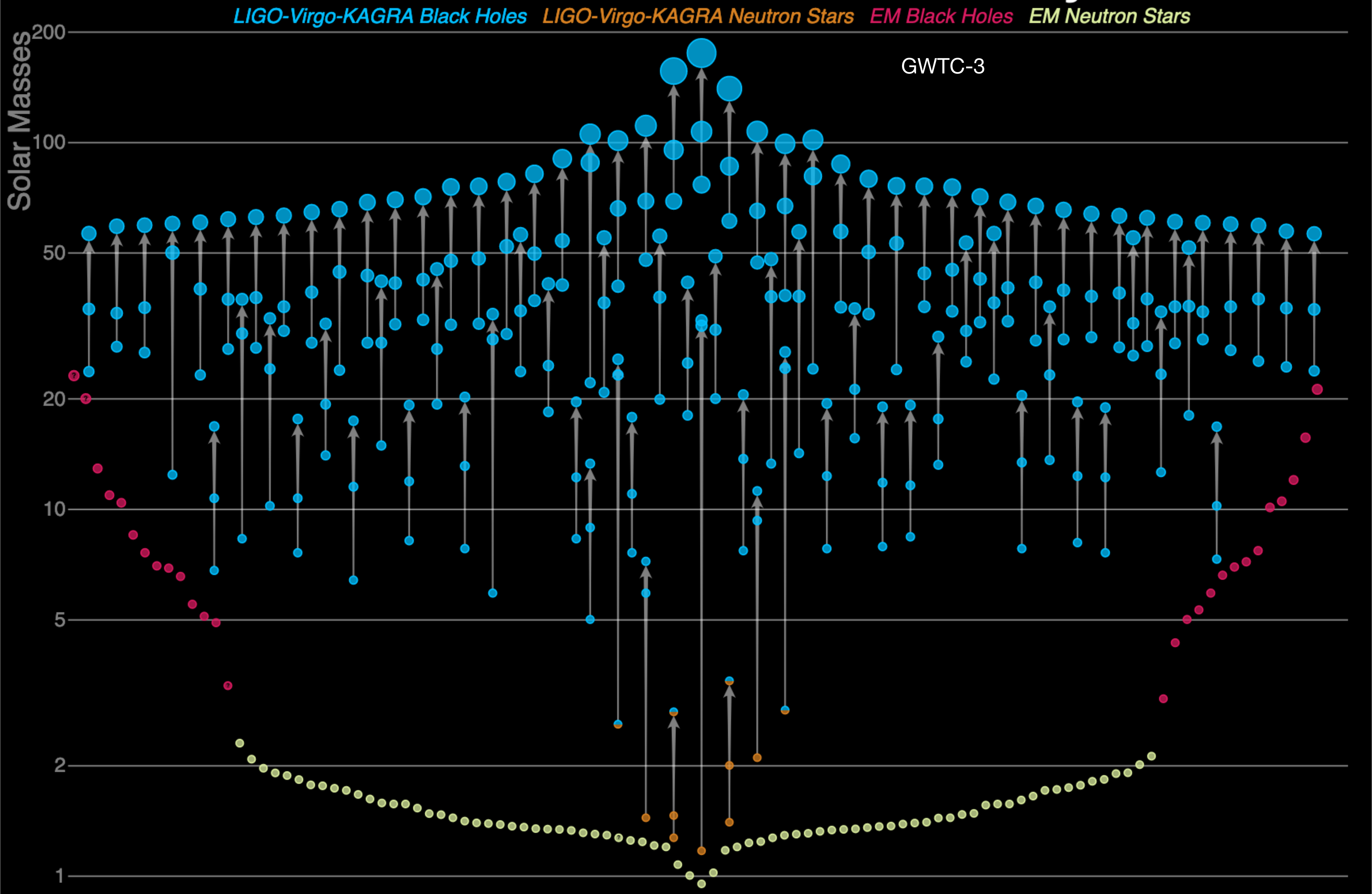

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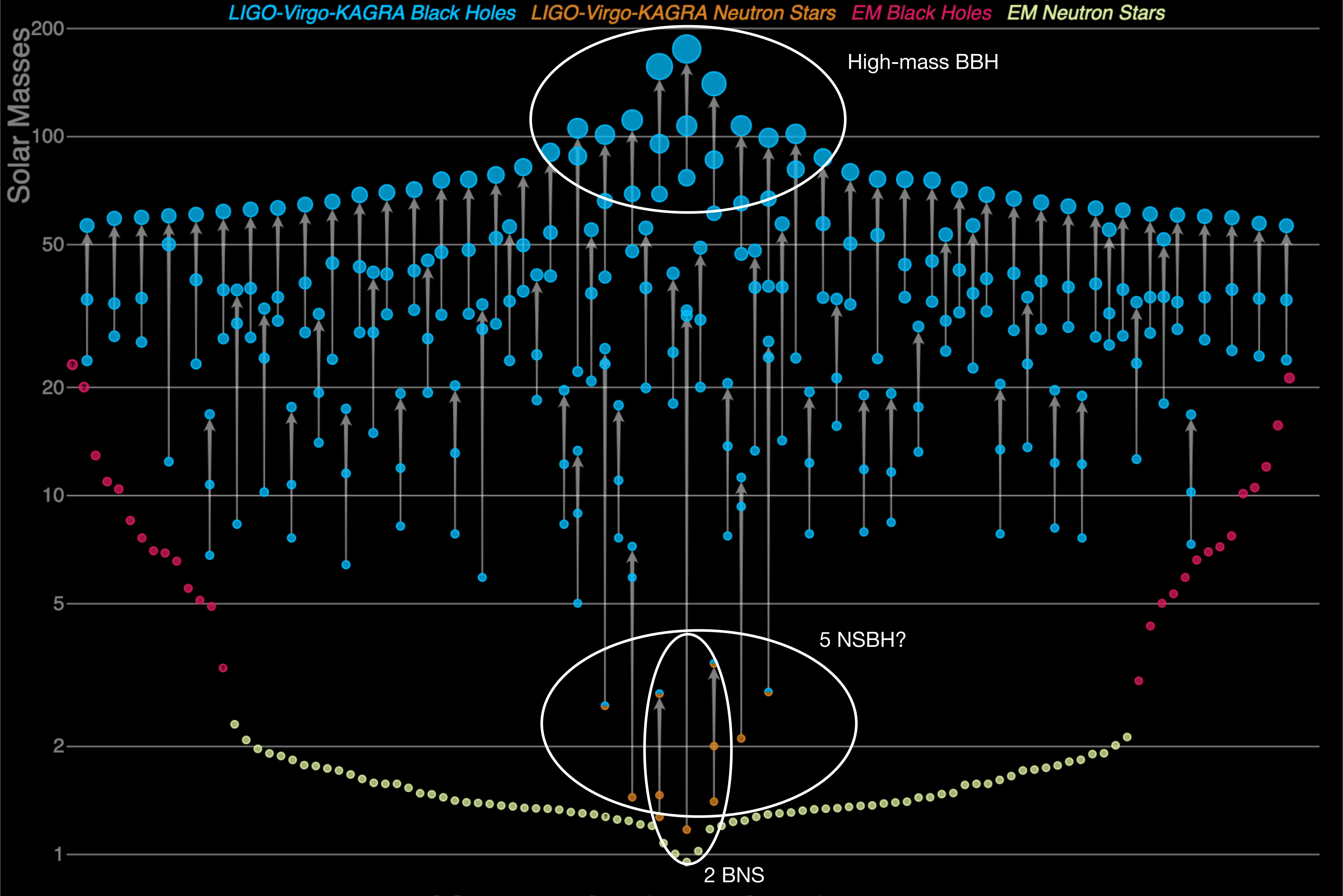
Masses in the Stellar Graveyard



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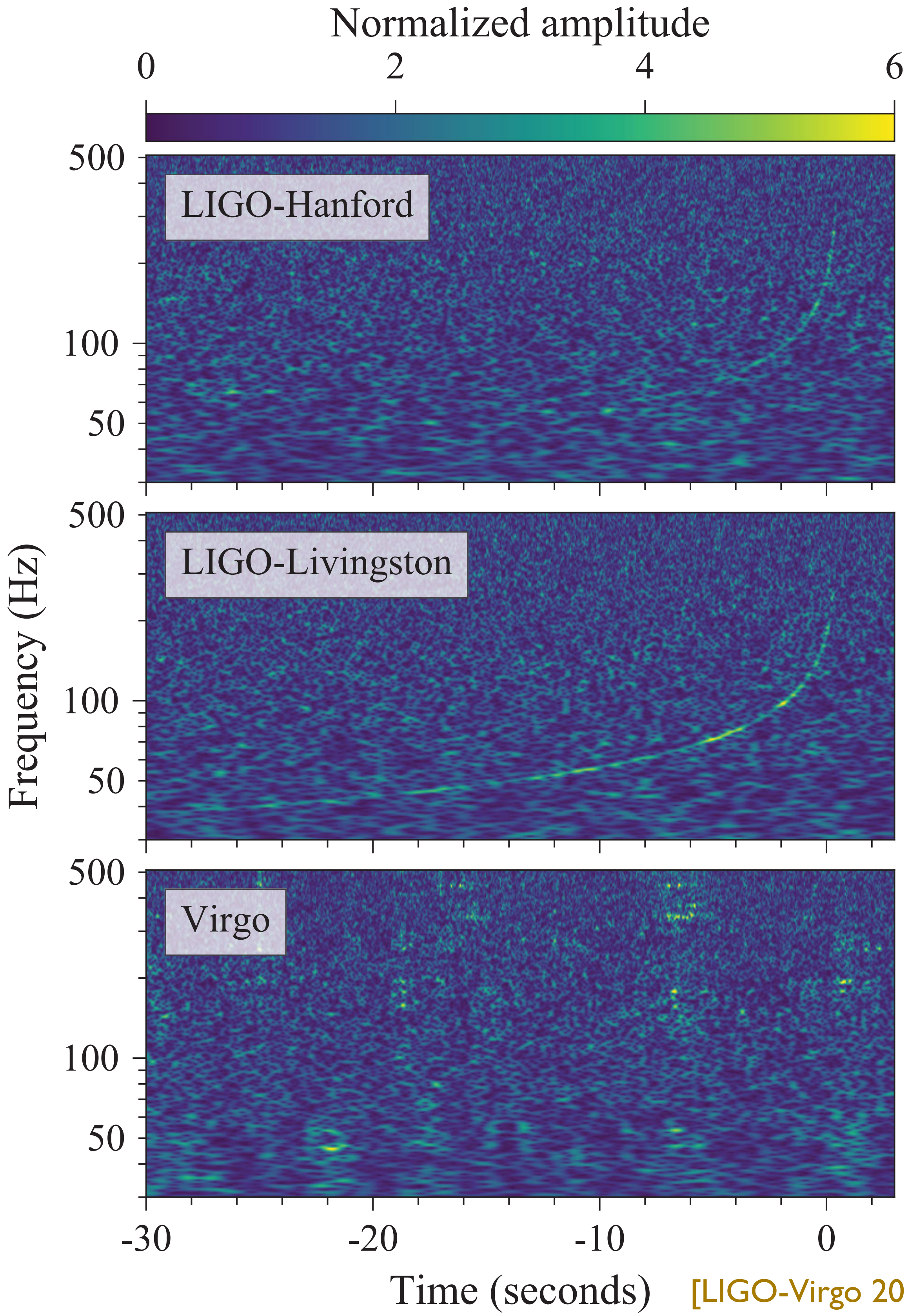
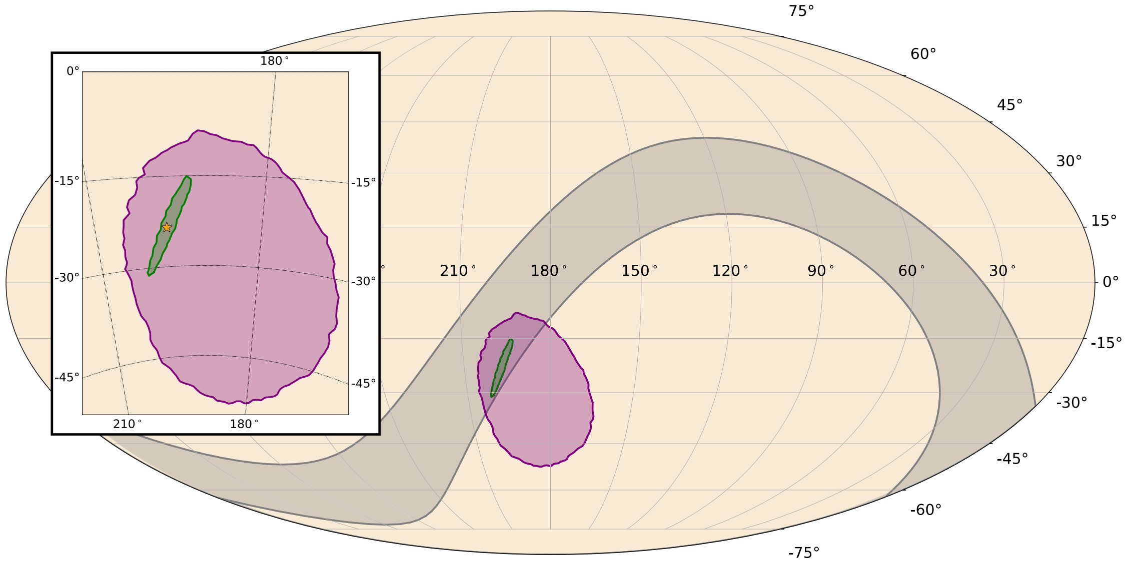
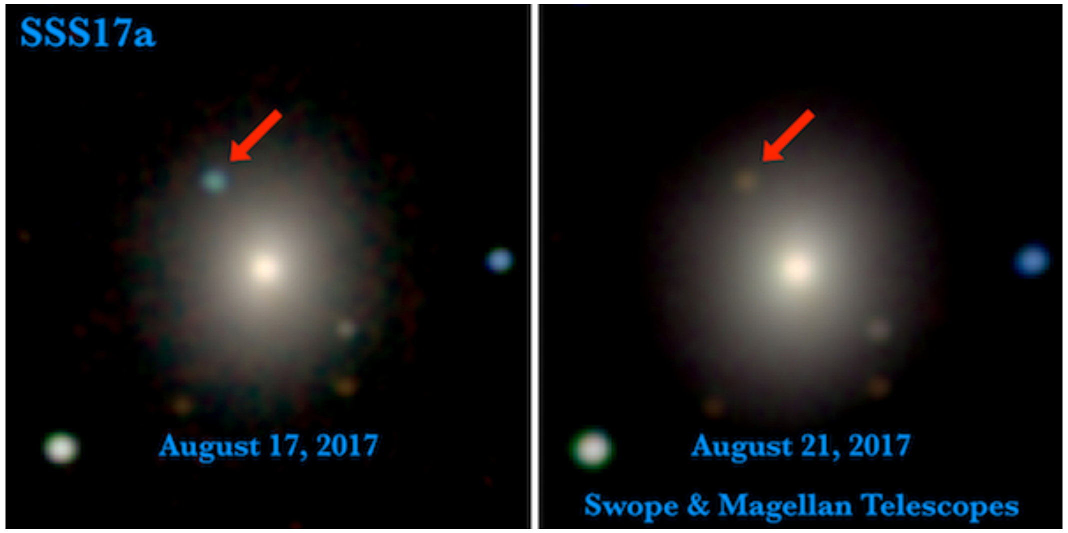
GW170817: a GW signal with EM counterpart



[LIGO-Virgo 2017]

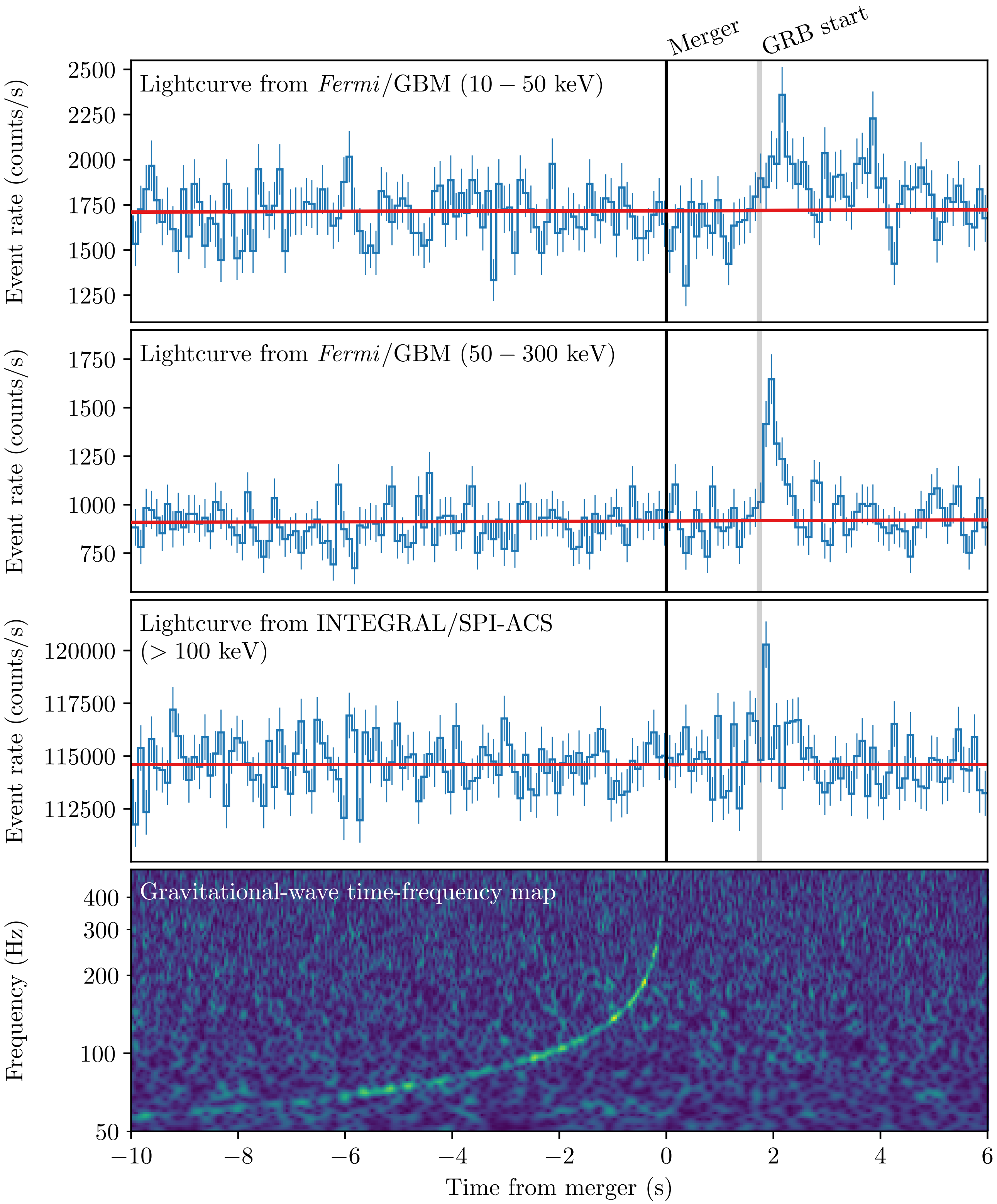


[LIGO-Virgo 2017]



[Santa Cruz and Carnegie Observatories/Ryan Foley]

GW170817: measuring the speed of gravitational waves



[LIGO-Virgo, Fermi, INTEGRAL 2017]

GRB signal received with ~1.7s delay

Assuming a ~10s delay in the original emission:

$$\boxed{-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\rm EM}} \leqslant +7 \times 10^{-16}.}$$

(Longer emissions delays are possible but not favored)

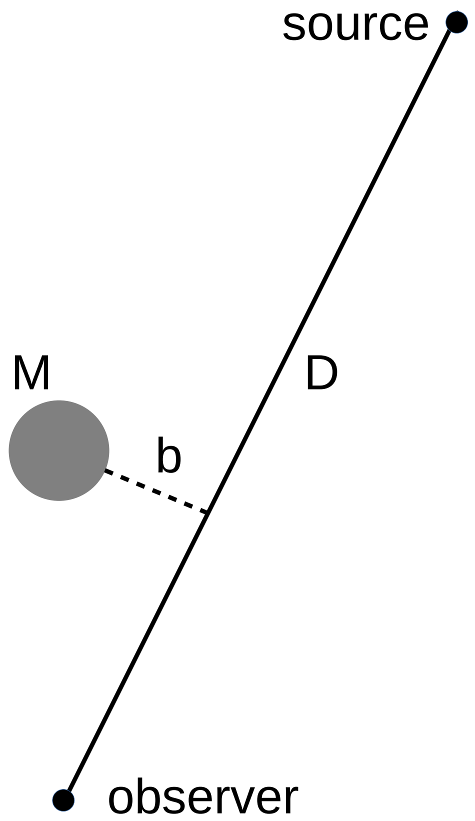
GW170817: consequences of the speed measurement

The constraint $c_g = c$ excludes wide regions of theory space

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [46] Brans-Dicke/$f(R)$ [47, 48] Kinetic Gravity Braiding [50]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [49] $G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [51], $f(\phi)\cdot$Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

[Ezquiaga&al 2017]

GW170817: Shapiro time delay test



Shapiro time delay:
propagation delay

$$\delta t_{\mathrm{S}} = -\frac{1+\gamma}{c^3} \int_{r_{\mathrm{e}}}^{r_{\mathrm{o}}} U(\boldsymbol{r}(l))\,dl$$

For a spherical mass distribution, in terms of the PPN coefficient γ :

$$\Delta t^a_{\text{Shapiro}} = (1+\gamma_a)\frac{GM}{c^3}\ln\left(\frac{D}{b}\right)$$

For GR, $\gamma_{\mathrm{GW}} = \gamma_{\mathrm{EM}} = 1$

Contribution of the mass of NGC4993 and the Milky Way: [LIGO-Virgo, Fermi, INTEGRAL 2017]

$$-2.6 \times 10^{-7} \leqslant \gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}} \leqslant 1.2 \times 10^{-6}$$

Taking into account dark matter profile: [Boran&al 2017]

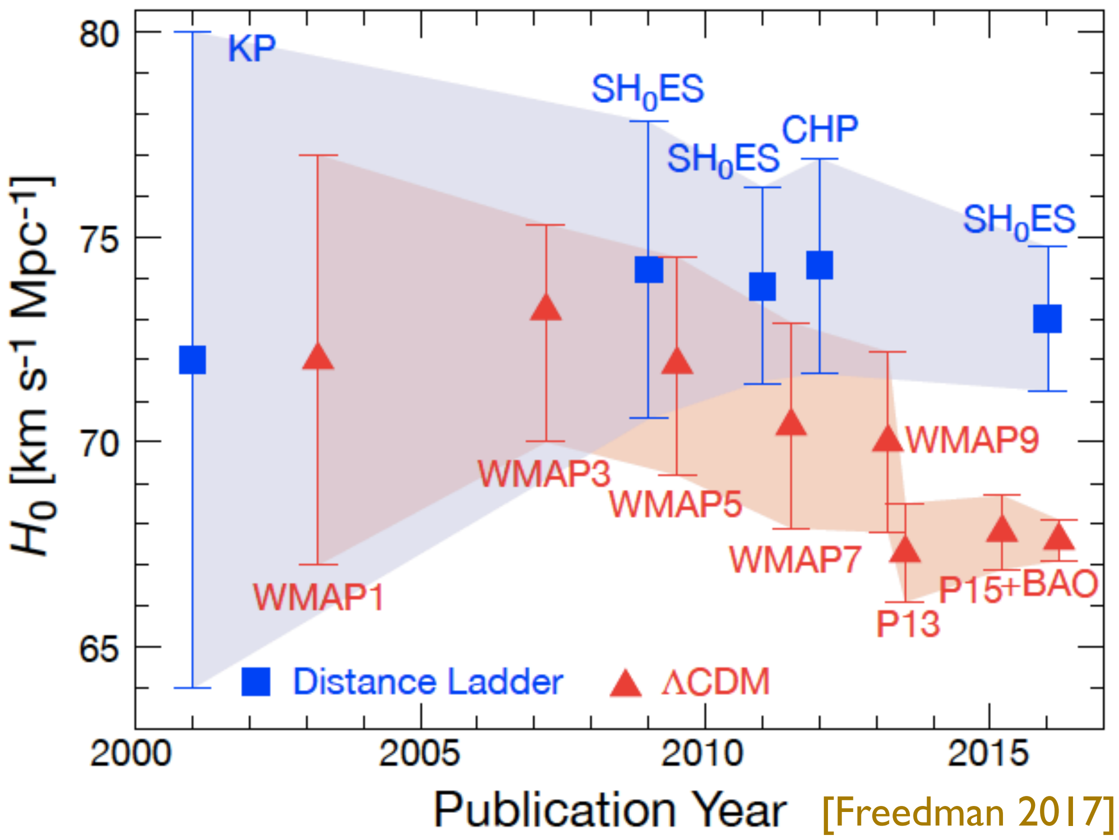
$$|\gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}}| < 9.8 \times 10^{-8}$$

Best absolute bound so far from Cassini: [Bertotti&al 2003]

$$\gamma_{\mathrm{EM}} - 1 = (2.1 \pm 2.3) \times 10^{-5}$$

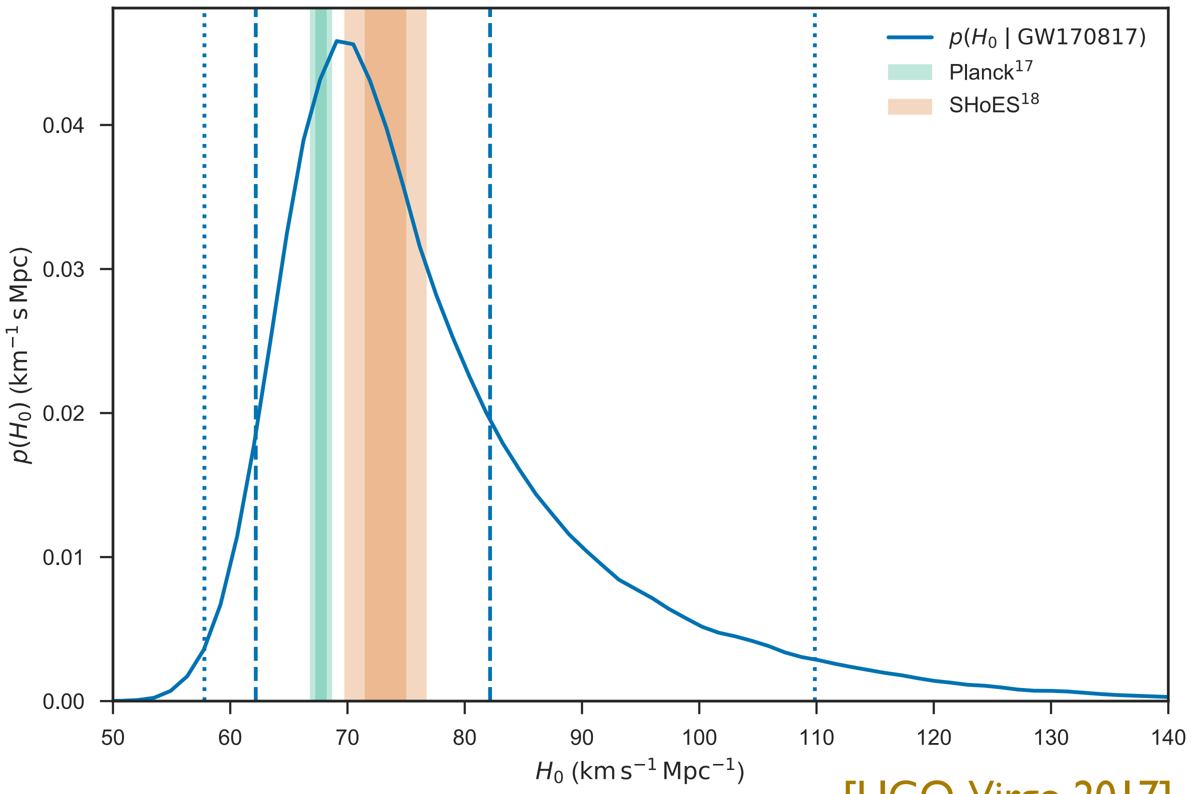
GW170817: a new measure of H0

The Hubble tension



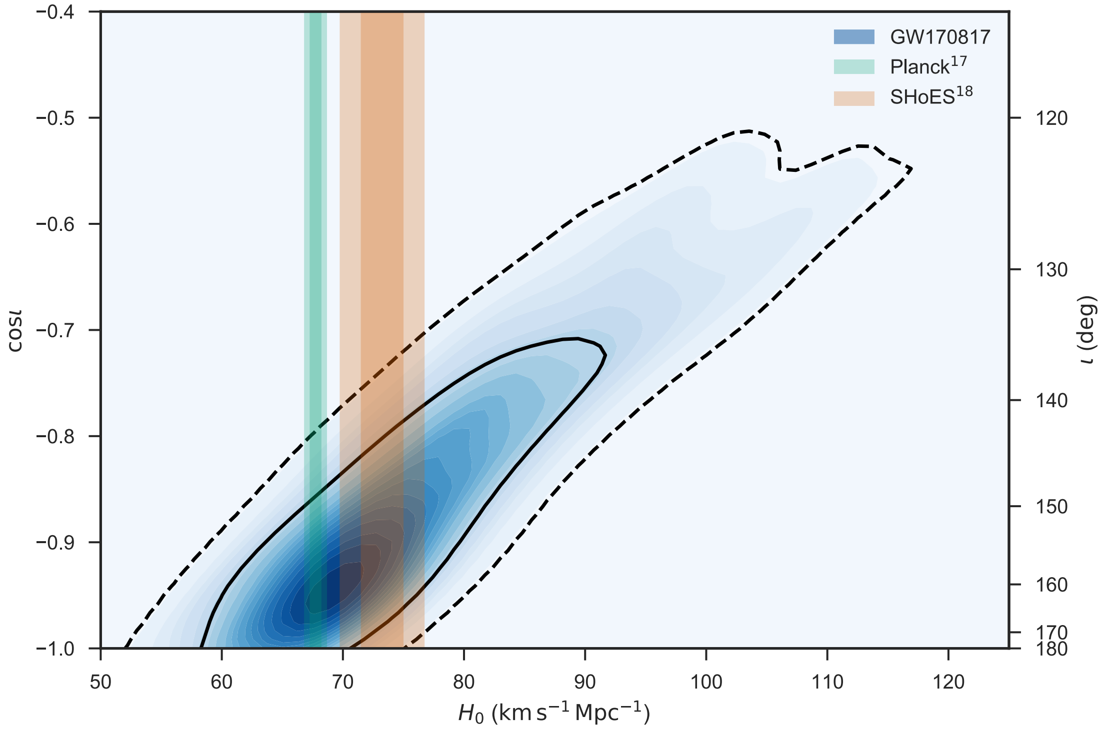
[Freedman 2017]

GW170817



[LIGO-Virgo 2017]

Distance-inclination degeneracy



Gravitational waves as standard sirens: direct access to the luminosity distance.

Different systematics !

Bright siren: presence of an EM counterpart measuring z

GW170817: constraining leakage in extra dimensions

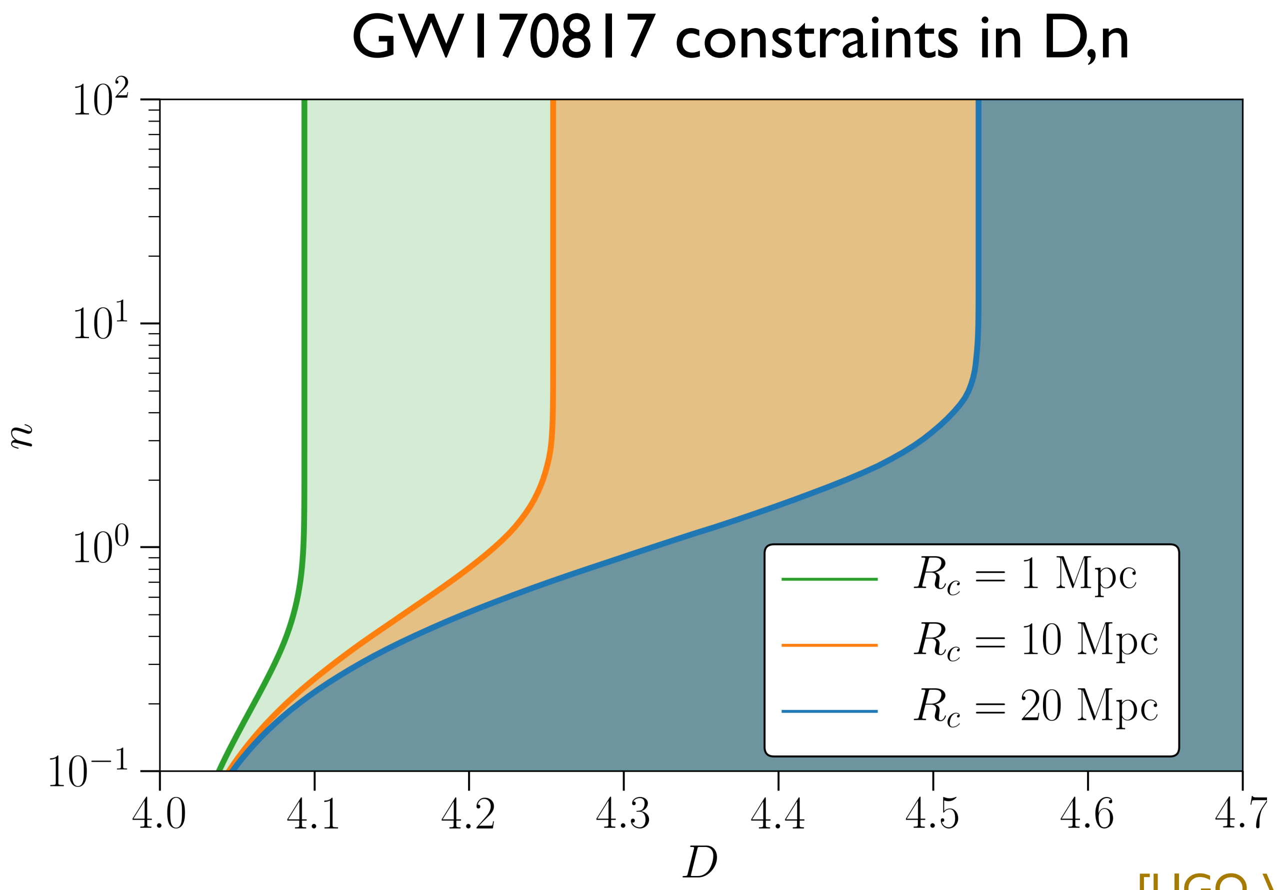
Motivation: consider the propagation of gravitational degrees of freedom in extra dimensions D>4 on large scales

Phenomenological ansatz:

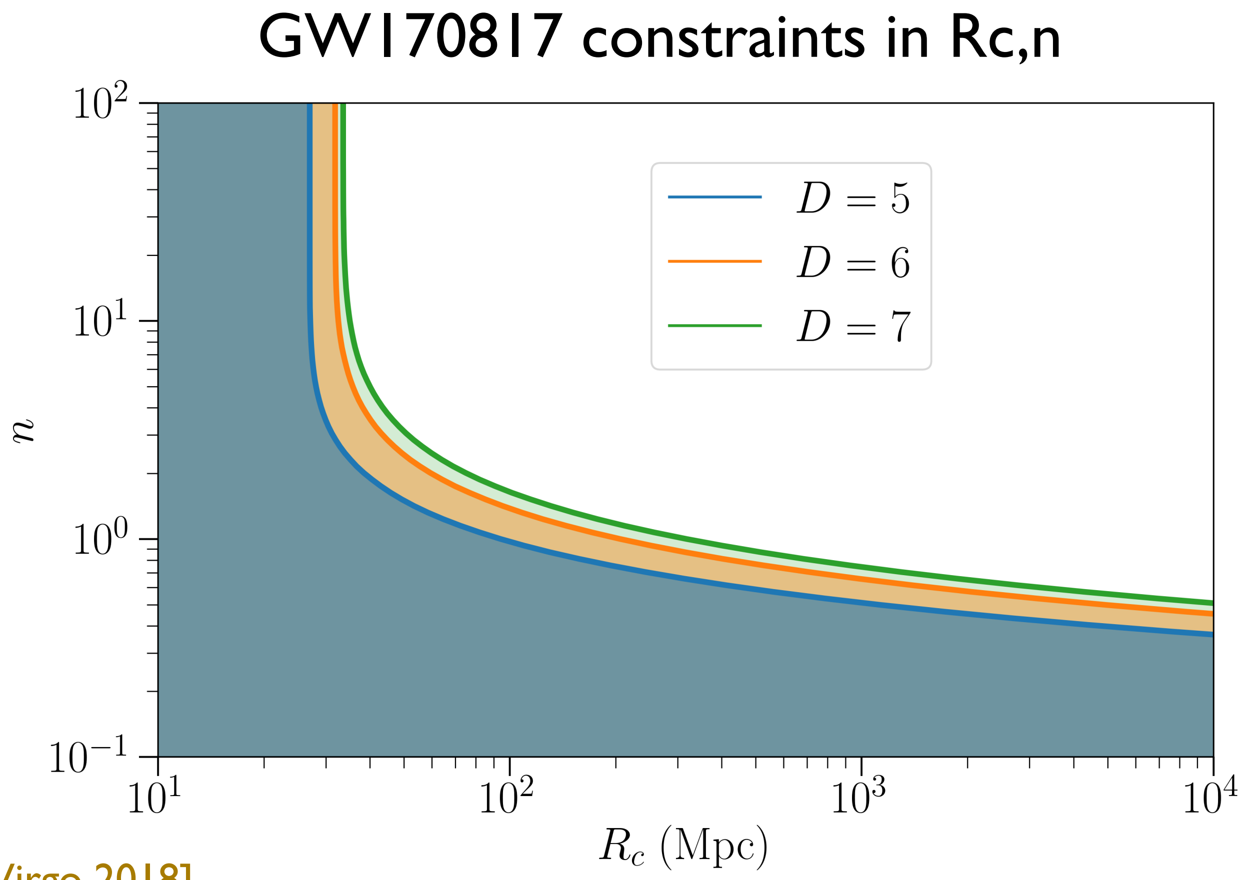
$$h \propto \frac{1}{d_L^{\mathrm{GW}}} = \frac{1}{d_L^{\mathrm{EM}}}\left[1+\left(\frac{d_L^{\mathrm{EM}}}{R_c}\right)^n\right]^{-(D-4)/(2n)}$$

R_c transition distance
n transition index

$d_L^{\mathrm{GW}},\ d_L^{\mathrm{EM}}$ both measured by GW170817 obs. (if we assume a cosmology).



GW170817 constraints in D,n



GW170817 constraints in Rc,n

[LIGO-Virgo 2018]

Testing this relation of luminosity distance also constrains scenarios with damping, oscillations.

GW170817: constraining dipolar radiation

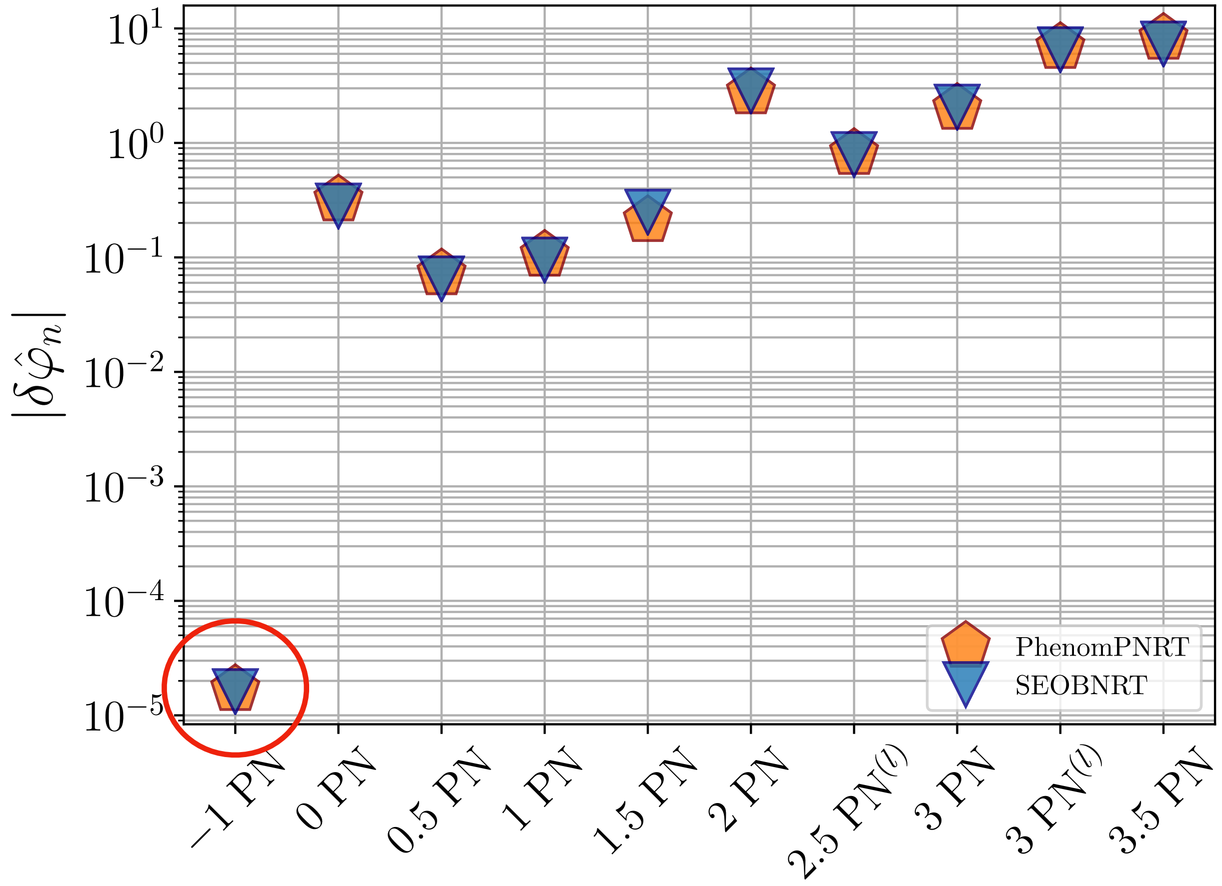
Dipolar radiation: present in particular for scalar-tensor theories

Fourier-domain phasing modified by the energy flux emitted in dipolar radiation:

$$\Psi(f) = 2\pi f t_c - \Phi_c - \pi/4 + \frac{3}{128}u^{-5/3}\left(1 - \frac{4}{7}b\eta^{2/5}u^{-2/3}\right)$$

[Will 1994]

-1PN term in the phasing



[LIGO-Virgo 2018]

Binary pulsar constraints: $|\delta\hat{\varphi}_{-2}| < 3.4 \times 10^{-8}$

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GWTC-3: tests of GR from LVK GW detections

Data analysis aspects

Bayesian analysis: $p(\theta|d) = \frac{\mathcal{L}(d|\theta)p_0(\theta)}{p(d)}$

extend waveforms to include deviations, parametrized by new params $\theta \to (\theta, \alpha)$

Bayesian hypothesis testing: Bayes ratio

$$\mathcal{B} = \frac{p(d|\mathrm{modGR})}{p(d|\mathrm{GR})}$$

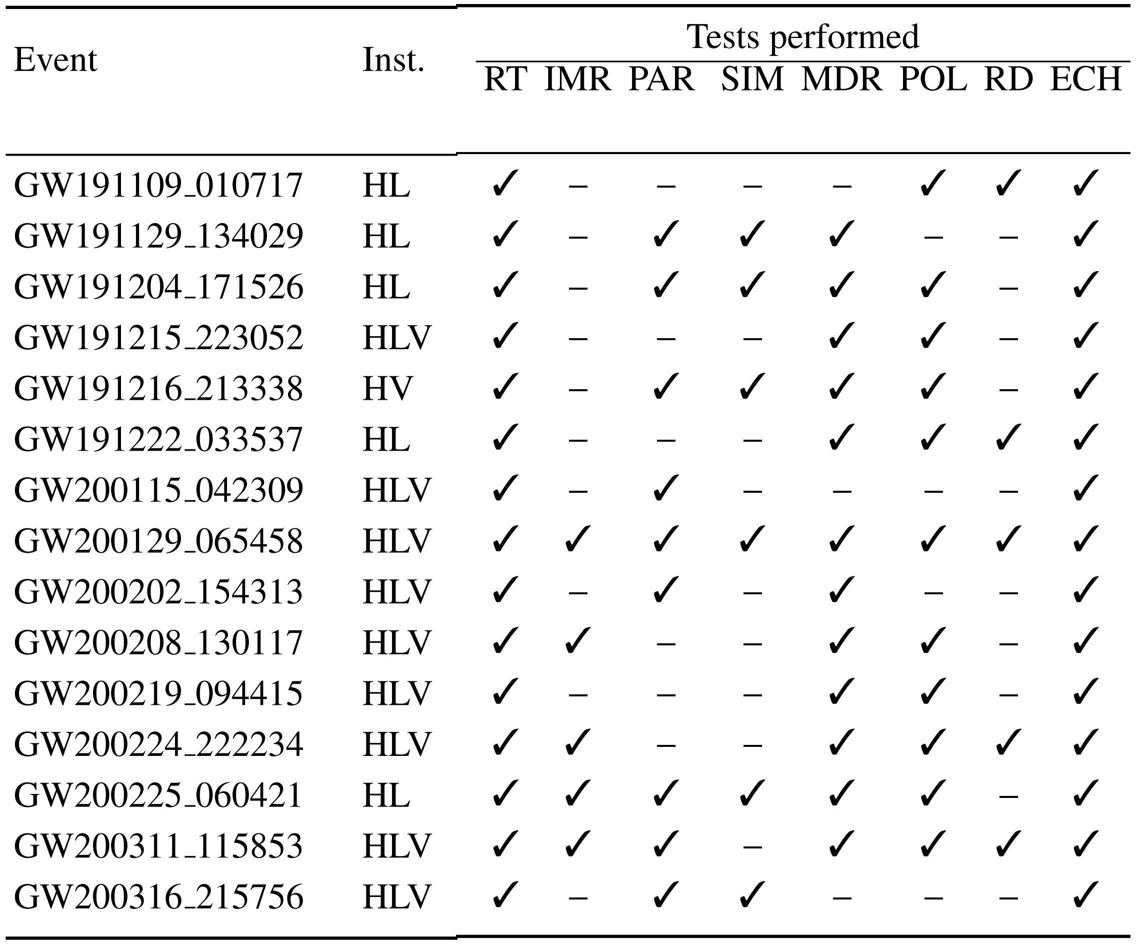
$$p(d|A) = \int d\theta p(d|\theta, A)p(\theta|A)$$ evidence

How to combine different events ?

- Fix a common value of the modGR param α for all events
- Hierarchical inference: introduce an underlying distribution, infer its hierarchical params — ex.: $\alpha \sim \mathcal{N}(\mu, \sigma)$, infer (μ, σ)

Events selection

Different tests require different selection thresholds (e.g. enough SNR in inspiral/merger)



Event	Inst.	Tests performed							
		RT	IMR	PAR	SIM	MDR	POL	RD	ECH
GW191109_010717	HL	✓	–	–	–	–	✓	✓	✓
GW191129_134029	HL	✓	–	✓	✓	✓	–	–	✓
GW191204_171526	HL	✓	–	✓	✓	✓	✓	–	✓
GW191215_223052	HLV	✓	–	–	–	✓	✓	–	✓
GW191216_213338	HV	✓	–	✓	✓	✓	✓	–	✓
GW191222_033537	HL	✓	–	–	–	✓	✓	✓	✓
GW200115_042309	HLV	✓	–	✓	–	–	–	–	✓
GW200129_065458	HLV	✓	✓	✓	✓	✓	✓	✓	✓
GW200202_154313	HLV	✓	–	✓	–	✓	–	–	✓
GW200208_130117	HLV	✓	✓	–	–	✓	✓	–	✓
GW200219_094415	HLV	✓	–	–	–	✓	✓	–	✓
GW200224_222234	HLV	✓	✓	–	–	✓	✓	✓	✓
GW200225_060421	HL	✓	✓	✓	✓	✓	✓	–	✓
GW200311_115853	HLV	✓	✓	✓	–	✓	✓	✓	✓
GW200316_215756	HLV	✓	–	✓	✓	–	–	–	✓

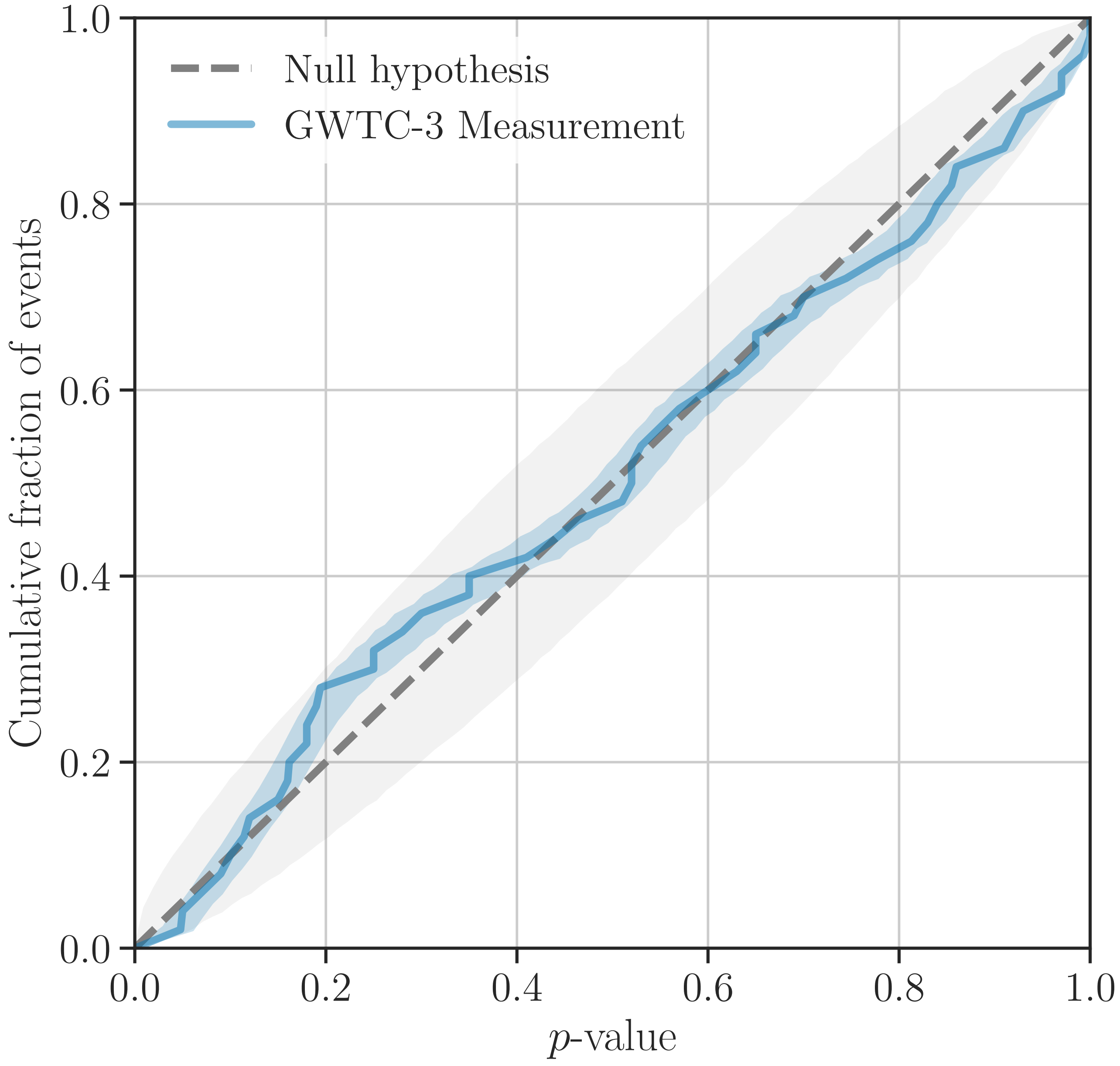
[LVK 2021]

Data quality (glitches) is crucial !

GWTC-3: residuals consistency test

Method:

- Subtract maximum-likelihood waveform (now with IMRPhenomXPHM)
- Build SNR90, measure of the SNR of the residual
- Compute the same SNR90 on noise time segments drawn from 4096s of data
- Check that the residuals p-value with respect to noise is uniform



[LVK 2021]

Likelihood:

$$\mathcal{L}(\hat{p}) = \binom{N}{n} p^n (1-p)^{N-n}$$

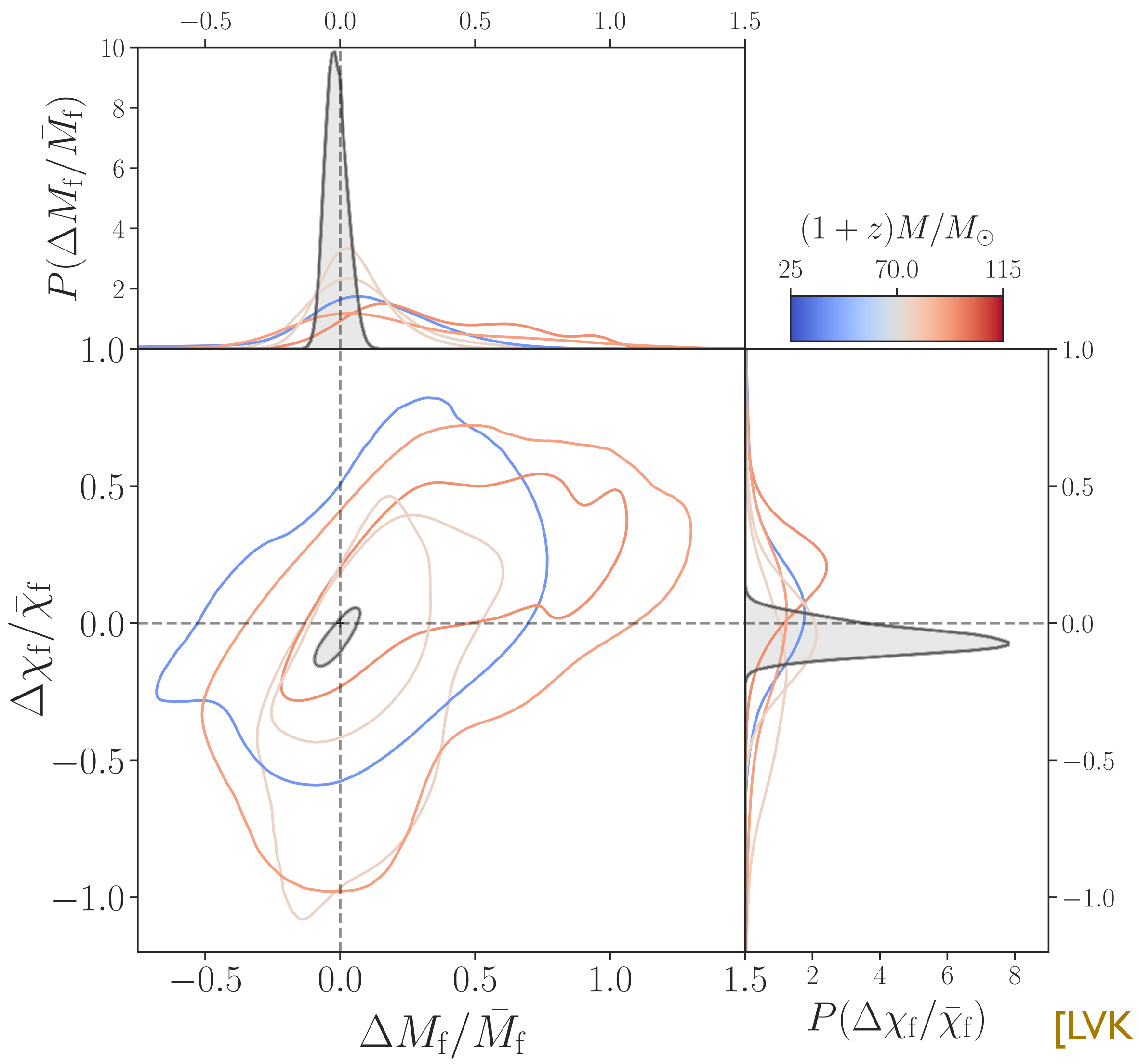
GWTC-3: IMR consistency test

Method:

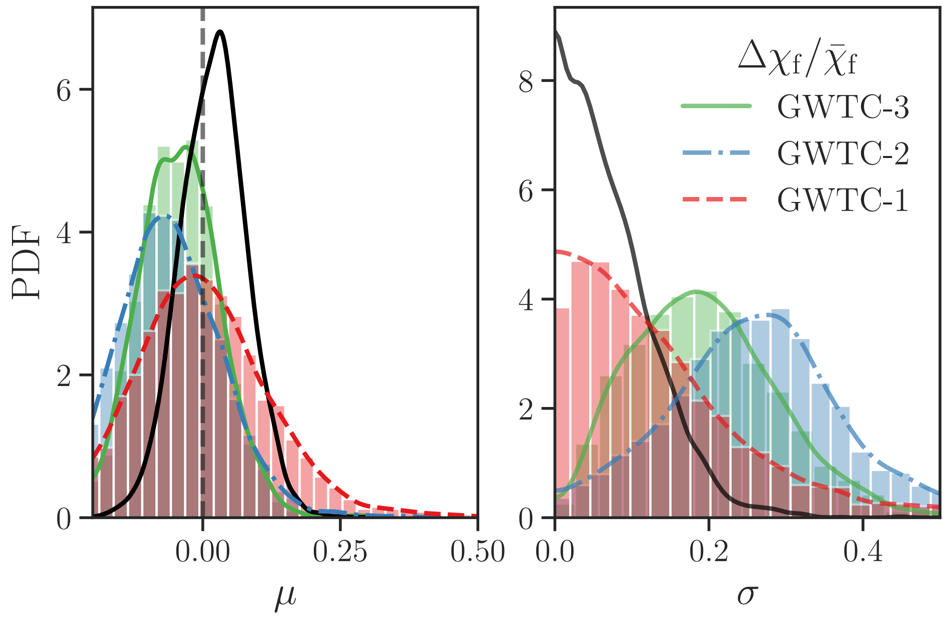
- Separate inspiral and MR signal after Kerr ISCO (must have enough SNR in both)
- Perform PE on both
- Compute final mass and spin from NR fits for both

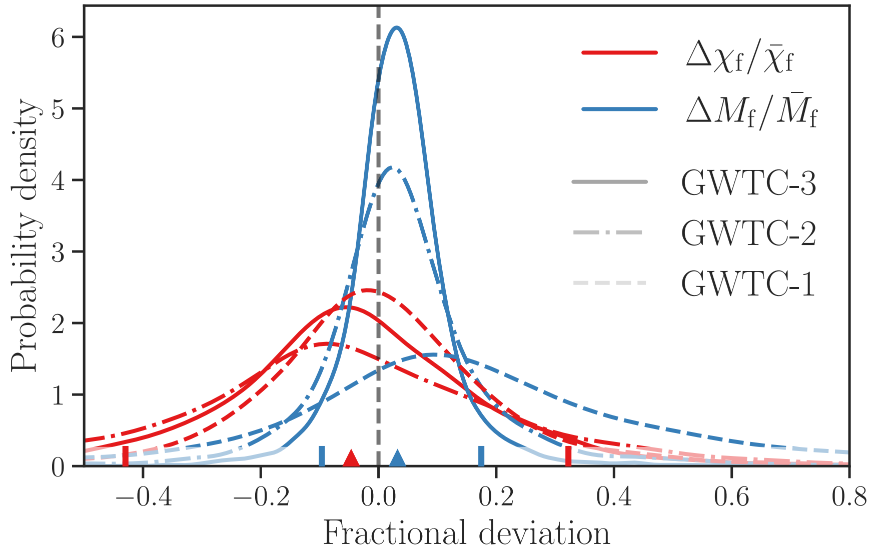
Check whether fractional deviations are compatible with 0:

$$\frac{\Delta M_{\mathrm{f}}}{\bar{M}_{\mathrm{f}}} = 2\frac{M_{\mathrm{f}}^{\mathrm{insp}} - M_{\mathrm{f}}^{\mathrm{postinsp}}}{M_{\mathrm{f}}^{\mathrm{insp}} + M_{\mathrm{f}}^{\mathrm{postinsp}}}, \quad \frac{\Delta \chi_{\mathrm{f}}}{\bar{\chi}_{\mathrm{f}}} = 2\frac{\chi_{\mathrm{f}}^{\mathrm{insp}} - \chi_{\mathrm{f}}^{\mathrm{postinsp}}}{\chi_{\mathrm{f}}^{\mathrm{insp}} + \chi_{\mathrm{f}}^{\mathrm{postinsp}}}$$



[LVK 2021]





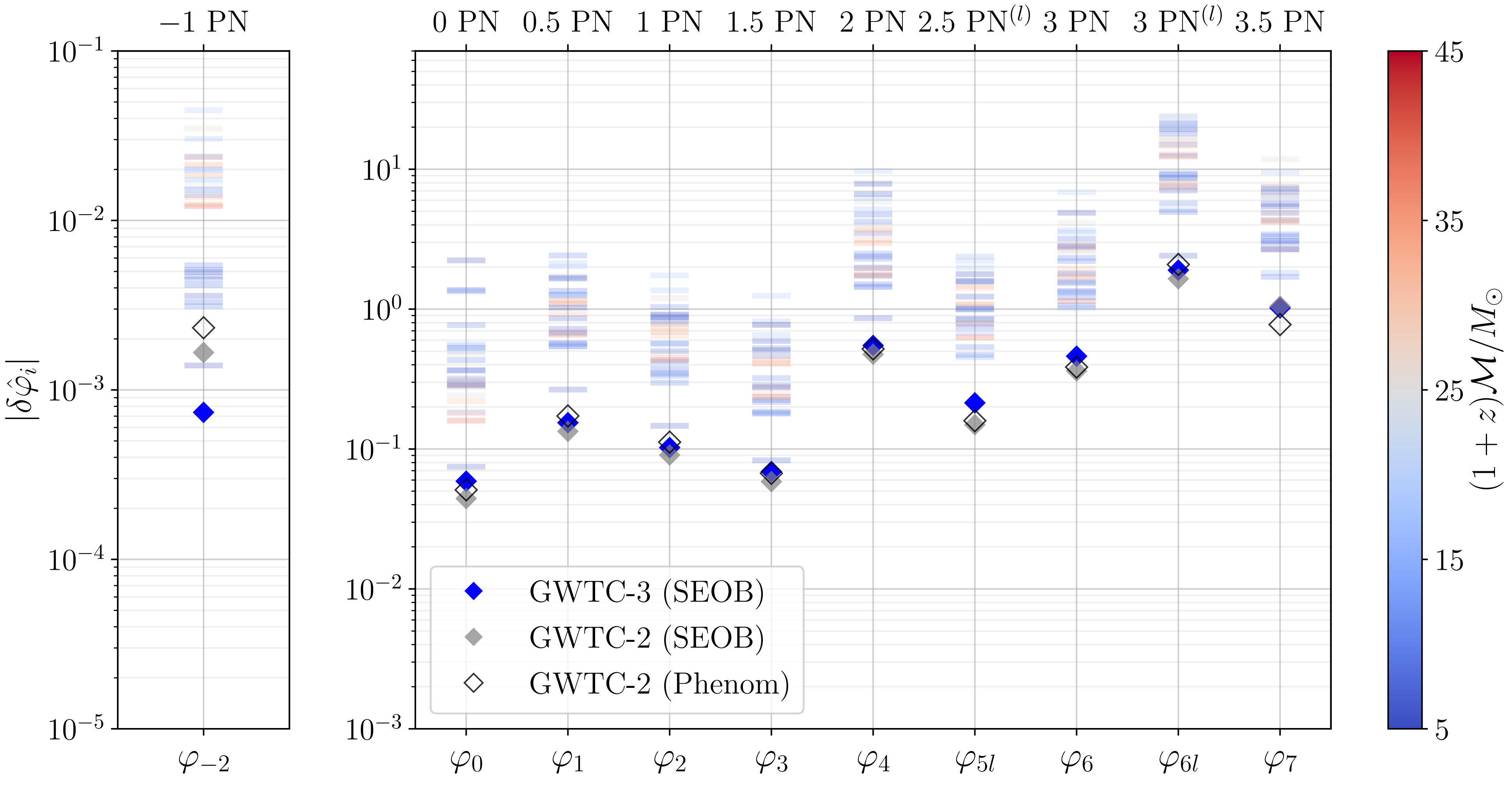
GWTC-3: generic inspiral modification

Modify PN coefficients in the inspiral part of the phasing (up to a where the effect is tapered)

$$\varphi_{\rm PN}(f) = 2\pi f t_c - \varphi_c - \frac{\pi}{4} + \frac{3}{128\eta}\left(\pi\tilde{f}\right)^{-5/3}\sum_{i=0}^{7}\left[\boxed{\varphi_i + \varphi_{i\,l}}\log(\pi\tilde{f})\right]\left(\pi\tilde{f}\right)^{i/3}$$

PN phasing coeffs (GR: functions of mass ratio, spin)

Set of coefficients: known PN coefficients + dipolar term $\{\delta\hat{\varphi}_{-2}, \delta\hat{\varphi}_0, \delta\hat{\varphi}_1, \delta\hat{\varphi}_2, \delta\hat{\varphi}_3, \delta\hat{\varphi}_4, \delta\hat{\varphi}_{5l}, \delta\hat{\varphi}_6, \delta\hat{\varphi}_{6l}, \delta\hat{\varphi}_7\}$



[LVK 2021]

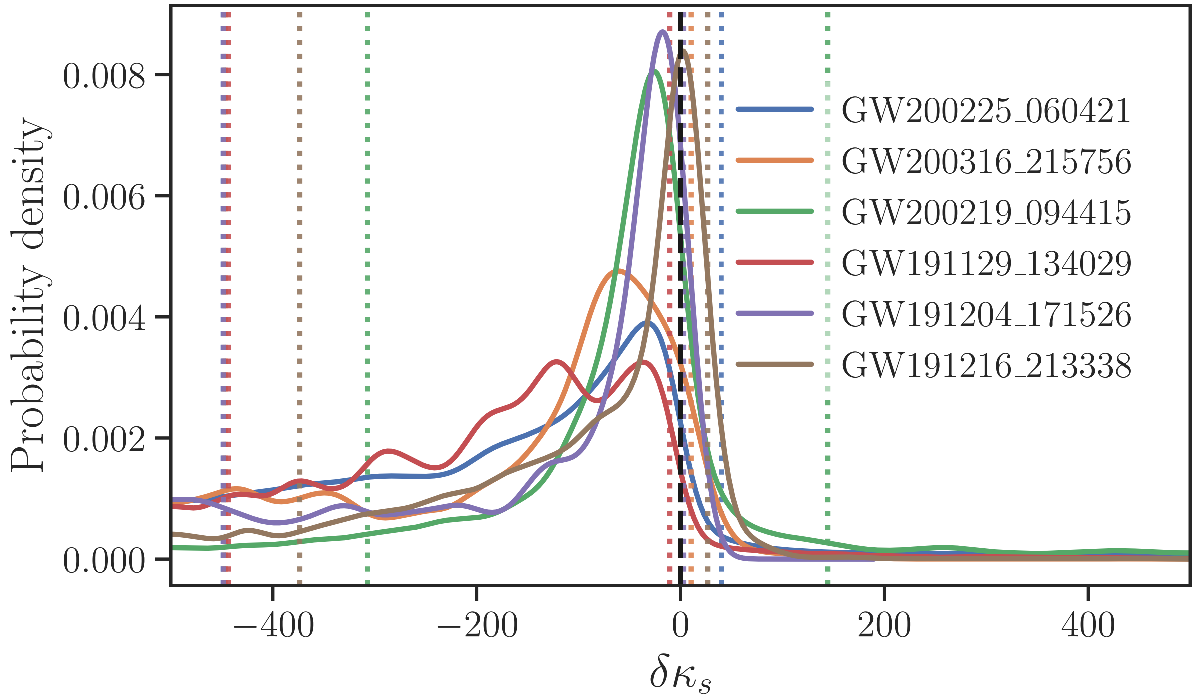
GWTC-3: spin-induced quadrupole test

Test of the multipolar structure of compact objects, as a modification of the inspiral phasing

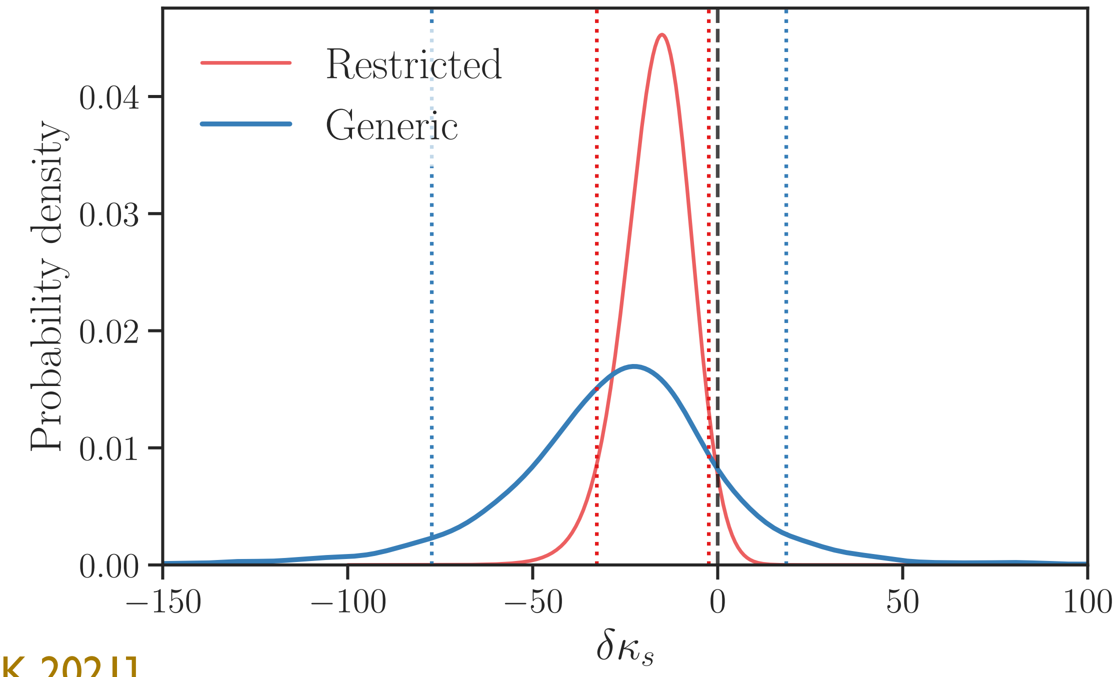
Spin-induced quadrupole: $Q = -\kappa \chi^2 m^3$

- For a Kerr black hole: $\kappa = 1$
- For a neutron star: $\kappa \simeq 2 - 14$
- Exotic compact objects (ECOs) ?

Leading order contribution at 2PN in the phasing, weak constraints for small spins.



[LVK 2021]



Here using only $\kappa_s = (\kappa_1 + \kappa_2)/2$

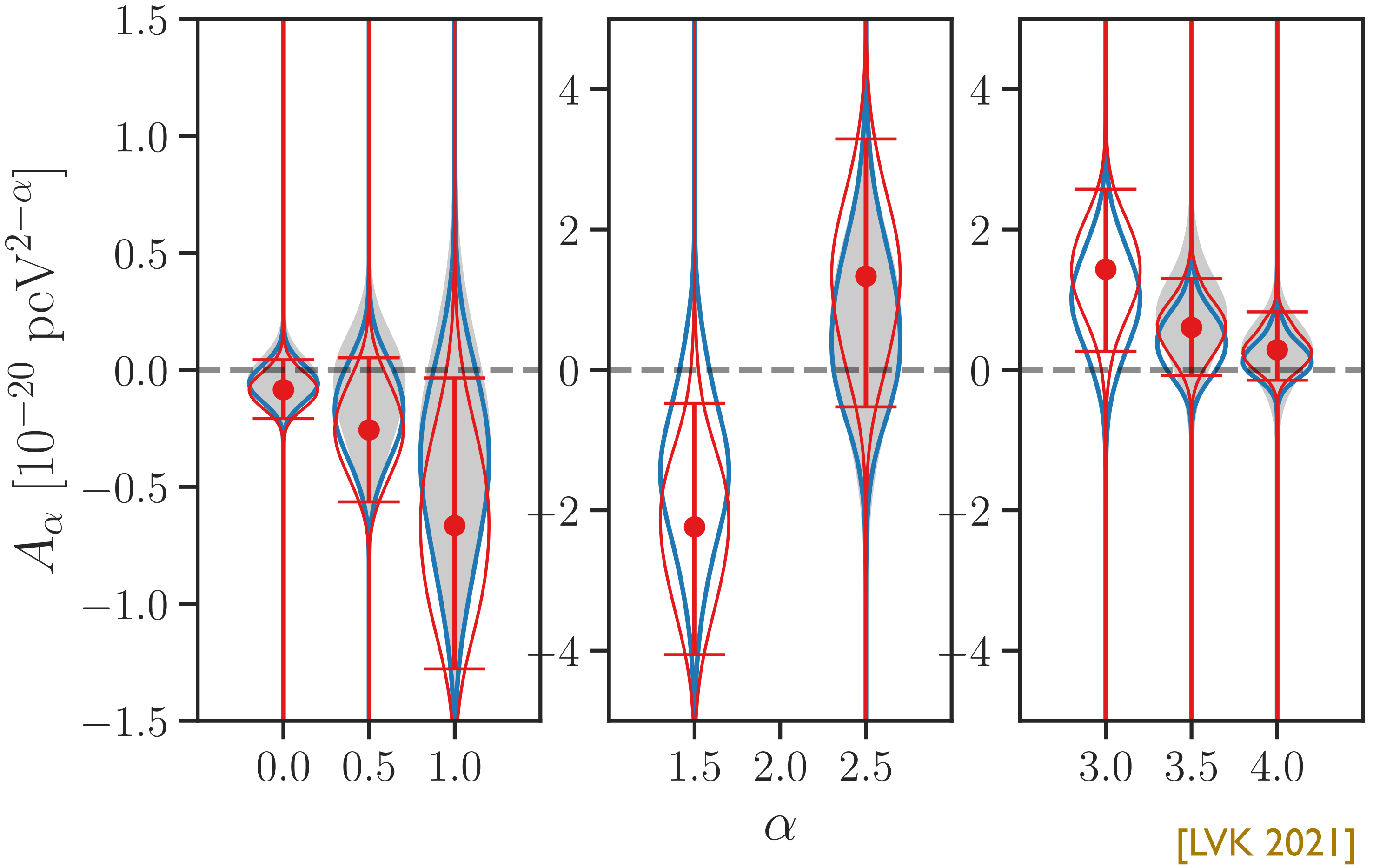
GWTC-3: dispersion relation

Test of the propagation of gravitational waves

Generalized dispersion relation considered: $E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$

- Massive gravity: $\alpha = 0$ $\sqrt{A_0} = m_g c^2$
- Change in the speed of GW: $\alpha = 2$

Low and high frequencies propagate at different speeds (except $\alpha = 2$), leaves an imprint on the phasing of the wave



[LVK 2021]

Graviton mass bound:

$$\boxed{m_g \leq 1.27 \times 10^{-23} \mathrm{eV}/c^2}$$

Graviton mass bound from solar system tests:

$$m_g \leq 3.16 \times 10^{-23} \mathrm{eV}/c^2$$

GWTC-3: ringdown tests

Test of the nature of coalescence remnants as Kerr black holes through their QNMs

Post-merger ringdown signal: spin-weighted spheroidal modes with overtones

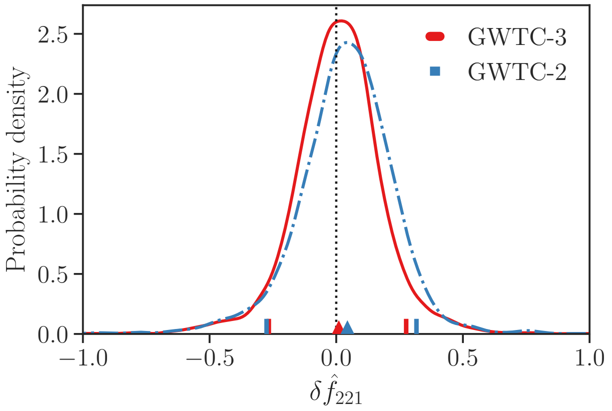
$$h_+(t) - ih_\times(t) = \sum_{\ell=2}^{+\infty} \sum_{m=-\ell}^{\ell} \sum_{n=0}^{+\infty} \mathcal{A}_{\ell mn} \exp\left[-\frac{t-t_0}{(1+z)\tau_{\ell mn}}\right] \exp\left[-\frac{2\pi i f_{\ell mn}(t-t_0)}{1+z}\right] {}_{-2}S_{\ell mn}(\theta, \phi, \chi_\mathrm{f})$$

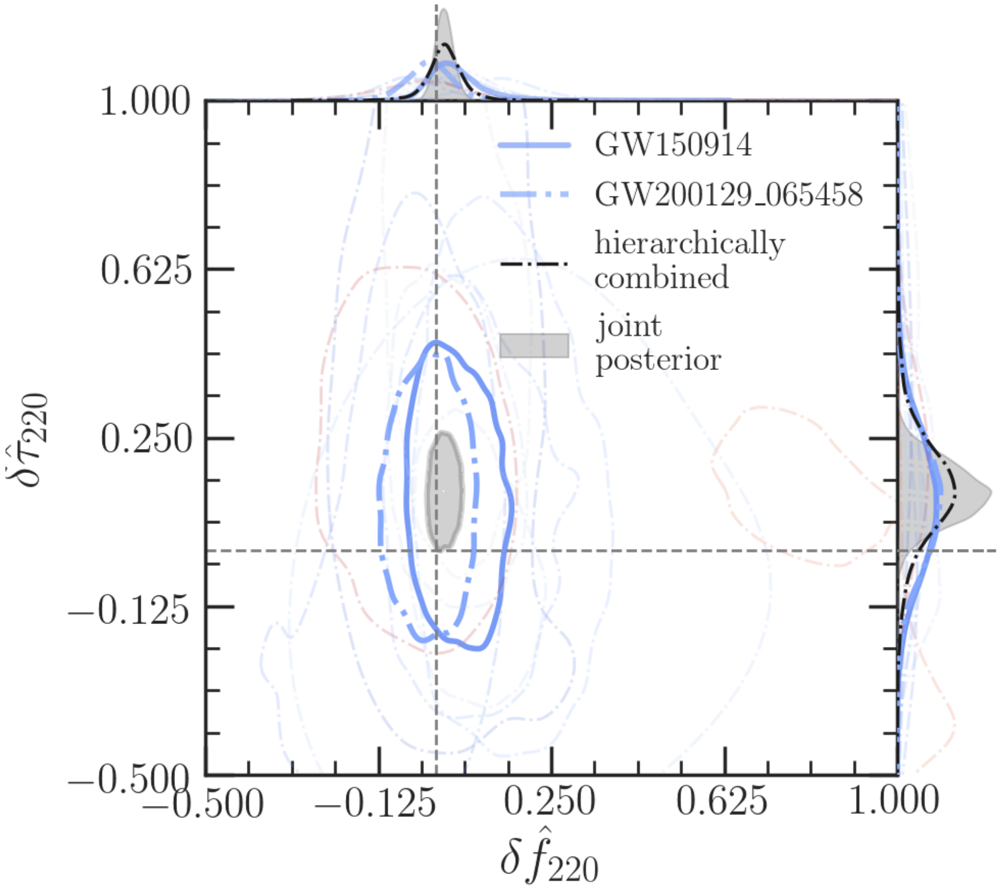
QNM frequencies and damping times functions of the remnant mass and spin in GR:

$$f_{lmn}(M_f, \chi_f), \ \tau_{lmn}(M_f, \chi_f)$$

Method:
- Analyze ringdown-only signal, consider HM, overtones, mod GR (pyRing)
- Modify QNMs inside an IMR waveform model (pSEOBNRv4HM)

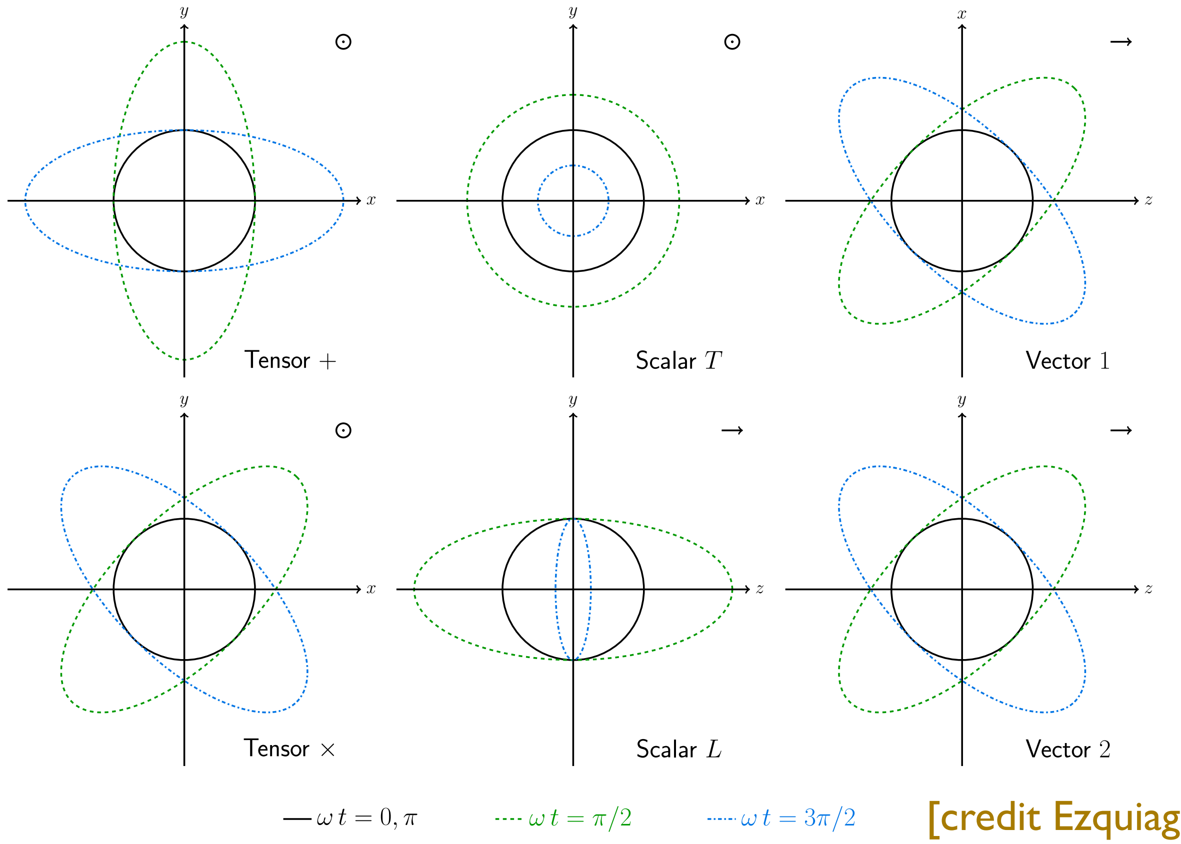
Event	Higher modes	Overtones	
	$\log_{10} \mathcal{B}^{\mathrm{HM}}_{220}$	$\log_{10} \mathcal{B}^{221}_{220}$	$\log_{10} \mathcal{O}^{\mathrm{modGR}}_{\mathrm{GR}}$
GW191109_010717	−0.11	1.03	−0.27
GW191222_033537	0.08	−0.83	−0.20
GW200129_065458	−0.00	−0.47	−0.09
GW200224_222234	0.20	0.95	−0.11
GW200311_115853	0.02	−1.16	−0.15





[LVK 2021]

GWTC-3: polarization content of GW



[credit Ezquiaga&al 2018]

Different methods:

- GR templates, Bayes ratio for full-vector and full-tensor
- GWTC-2: agnostic null-stream construction
- GWTC-3: extension of the null-stream construction for 2-detector events

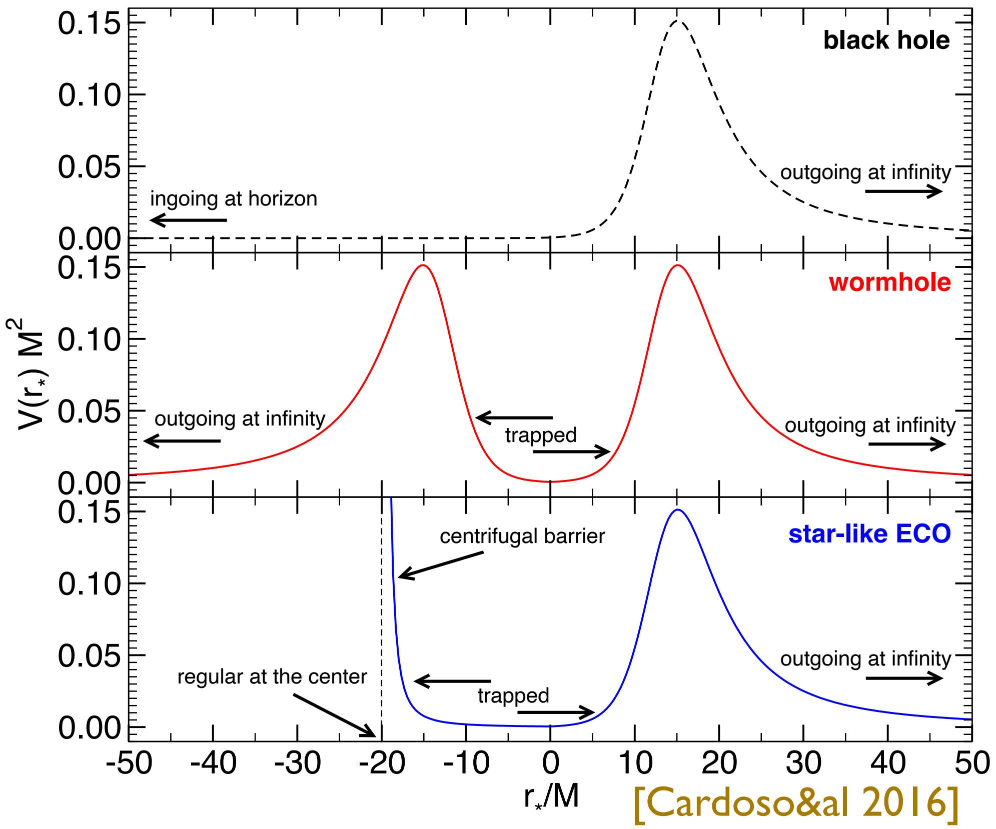
Best constraints: GW170817, known location

Full-vector and tensor disfavoured at $\mathcal{B} \sim 20$

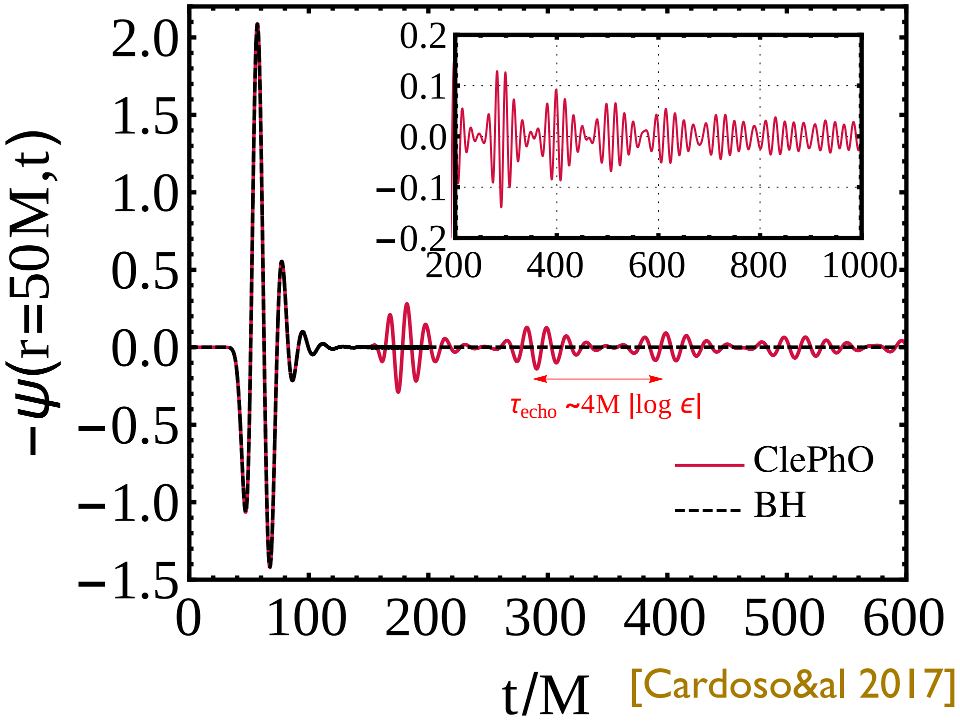
Very dependent on the number and orientation of detectors !

GWTC-3: echoes

GW echoes are generic for horizonless compact objects, have been proposed as smoking gun for Planck-scale structures at the horizon, wormholes, ECOs



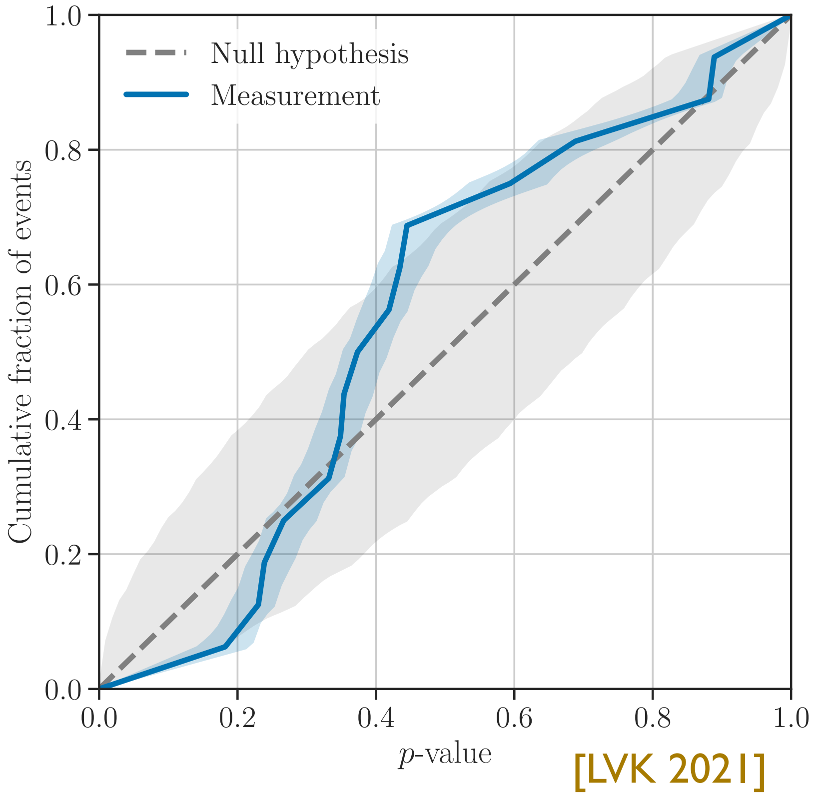
[Cardoso&al 2016]



[Cardoso&al 2017]

Method:

- GWTC-2: morphology-dependent as in [Abedi&al 2017]
- GWTC-3: morphology-independent, superposition of decaying repeating sine-Gaussians, compare the Bayes ratio of signal vs noise to the background

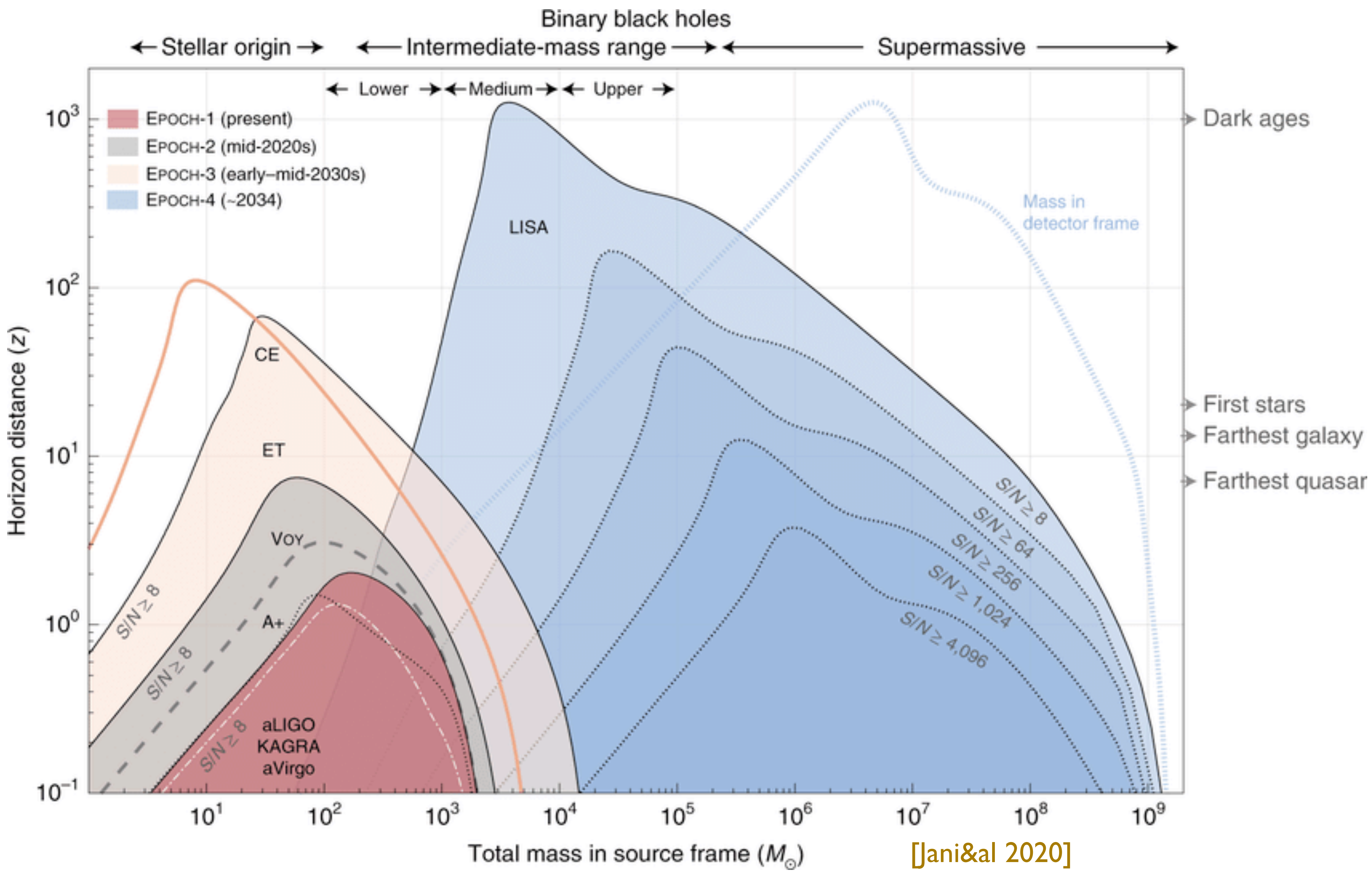


[LVK 2021]

Overview

- Introduction: fundamental physics and gravitational waves
- LIGO-Virgo-Kagra observations
- GW170817 and its consequences
- Tests of GR from LVK GWTC-3 observations
- **The future of GW astronomy and TGR**

The future of GW science

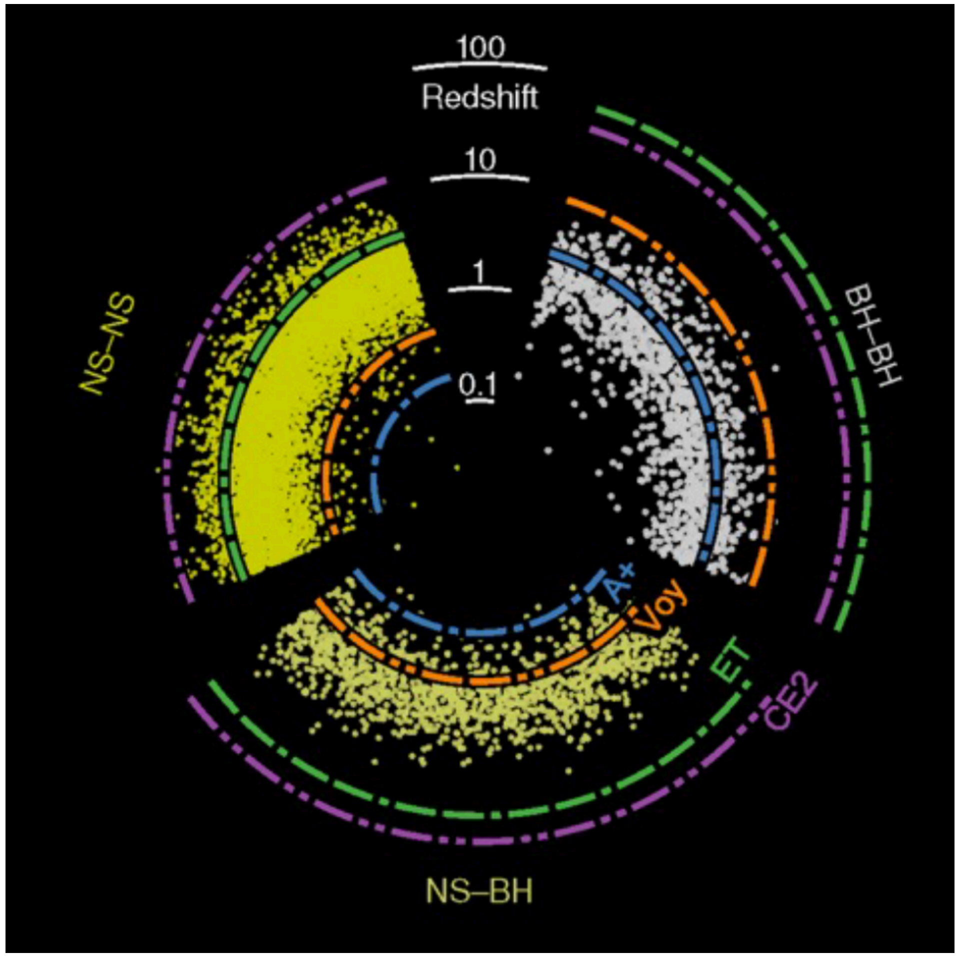


[Jani&al 2020]

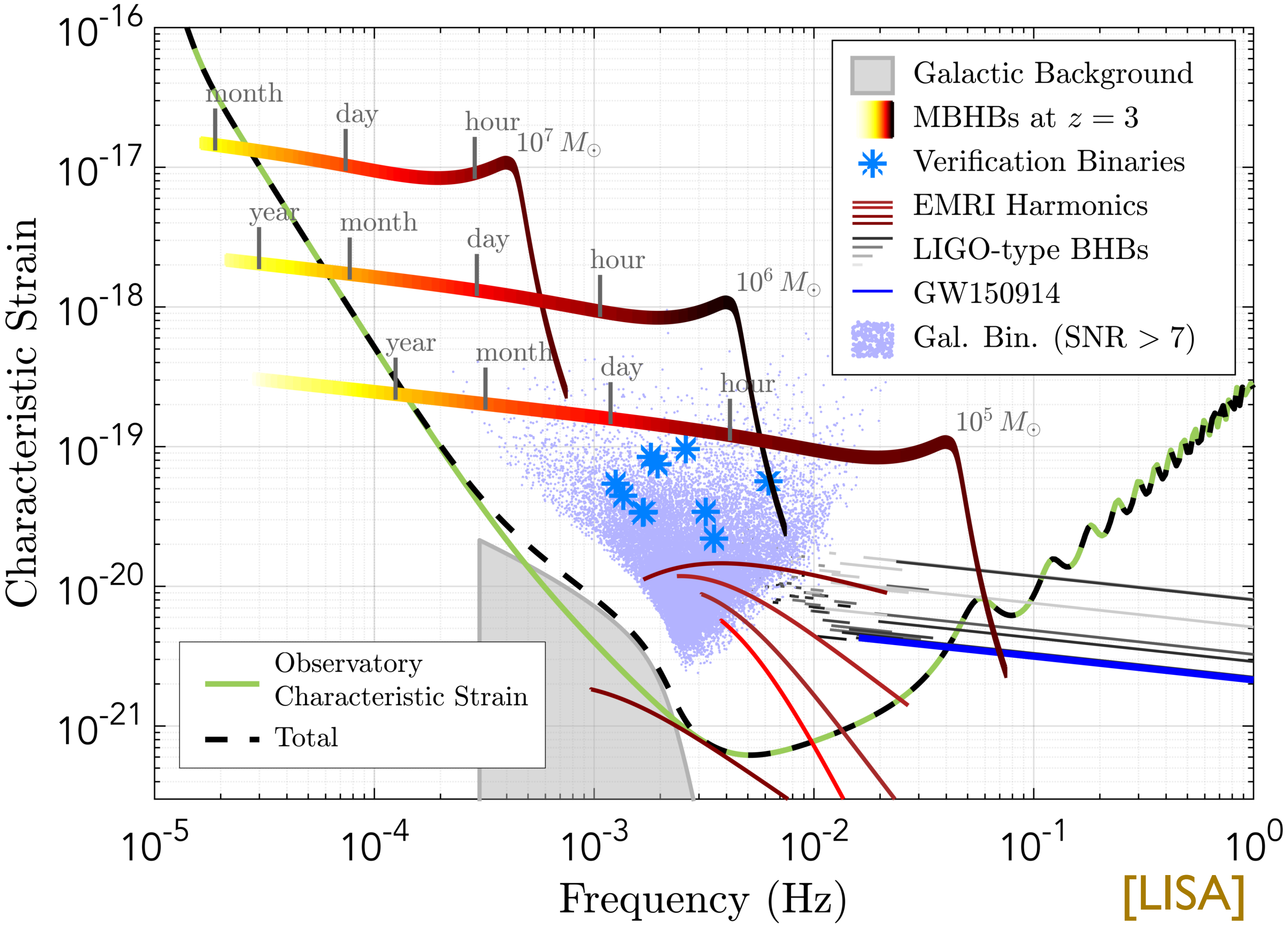
High SNRs → Great precision science !

High SNRs → Systematics become crucial…

The future of GW science



[Cosmic Explorer]



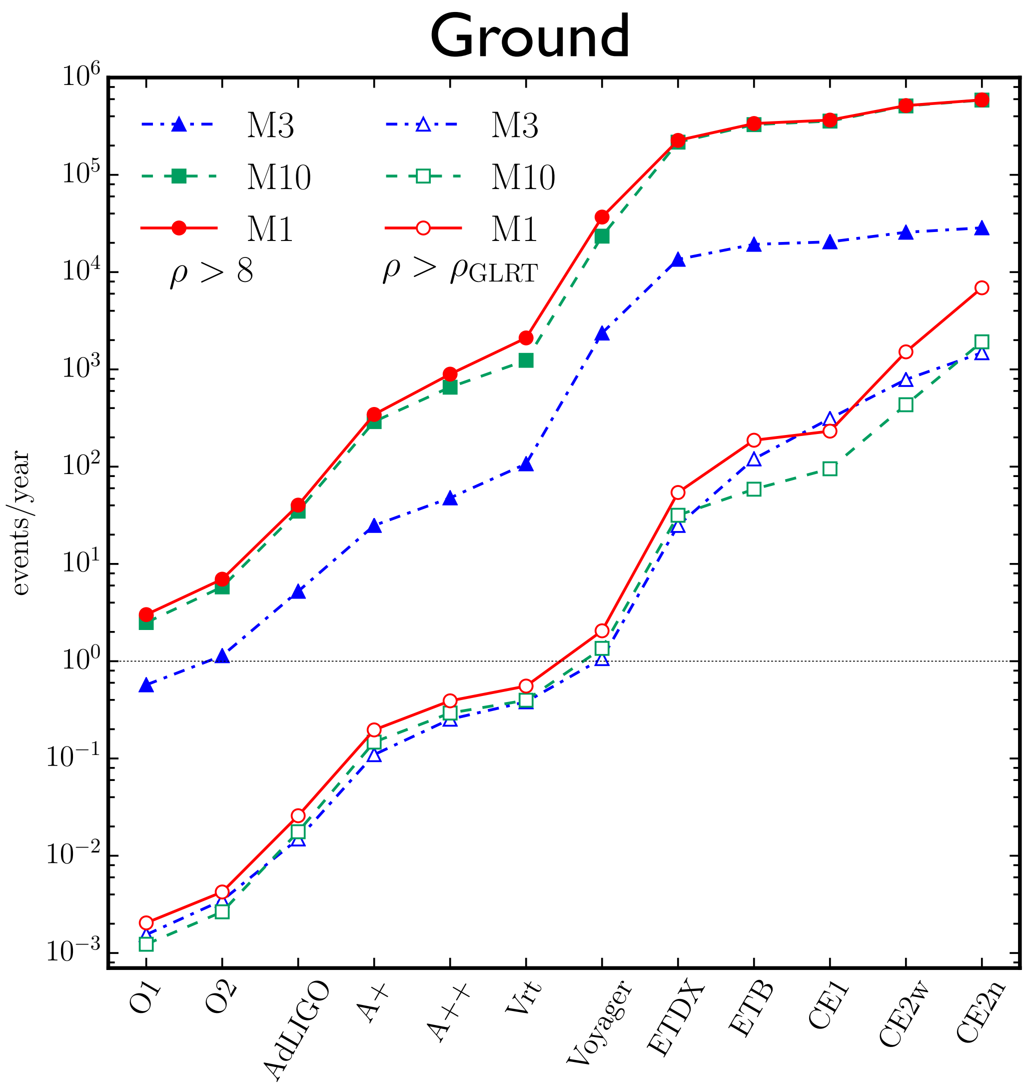
[LISA]

Large number of sources → Great statistical power !

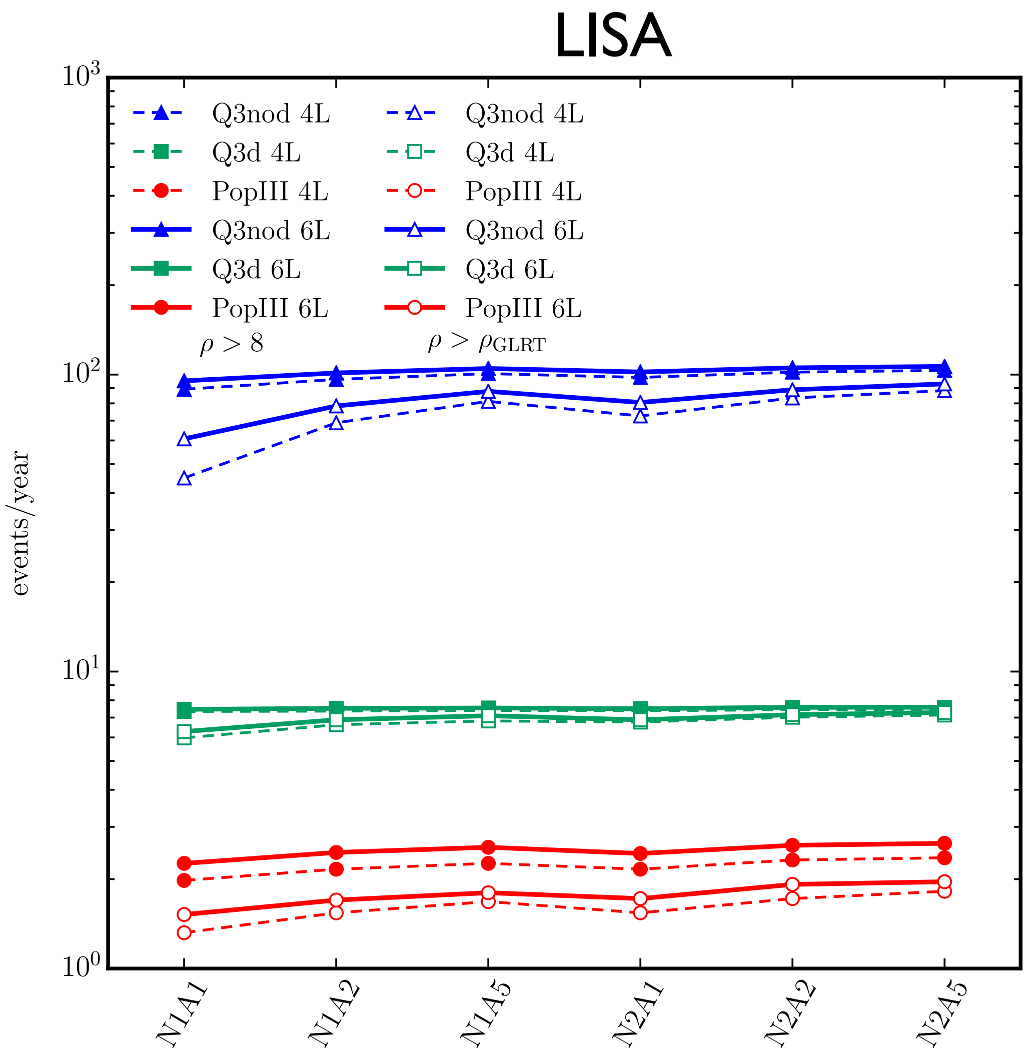
Large number of sources → Confusion/global fit become crucial…

Measuring multi-mode ringdown signals

Event rates with ringdown and multiple QNMs detectable



Ground



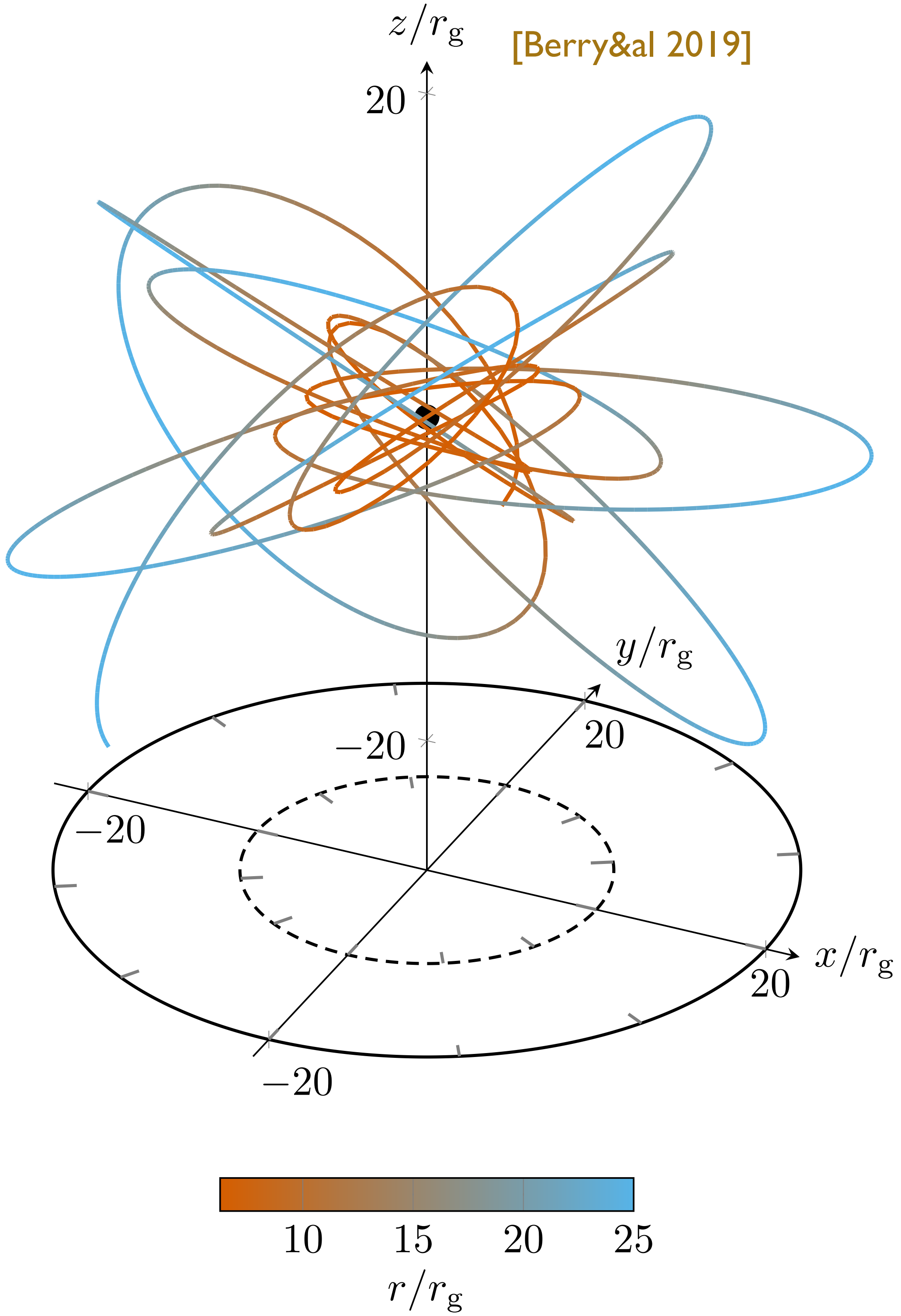
LISA

[Berti&al 2016]

Black hole spectroscopy with multiple detected QNMs

LISA: Extreme Mass Ratio Inspirals

Large number of orbital cycles in the strong-field regime:
map of the central object's spacetime

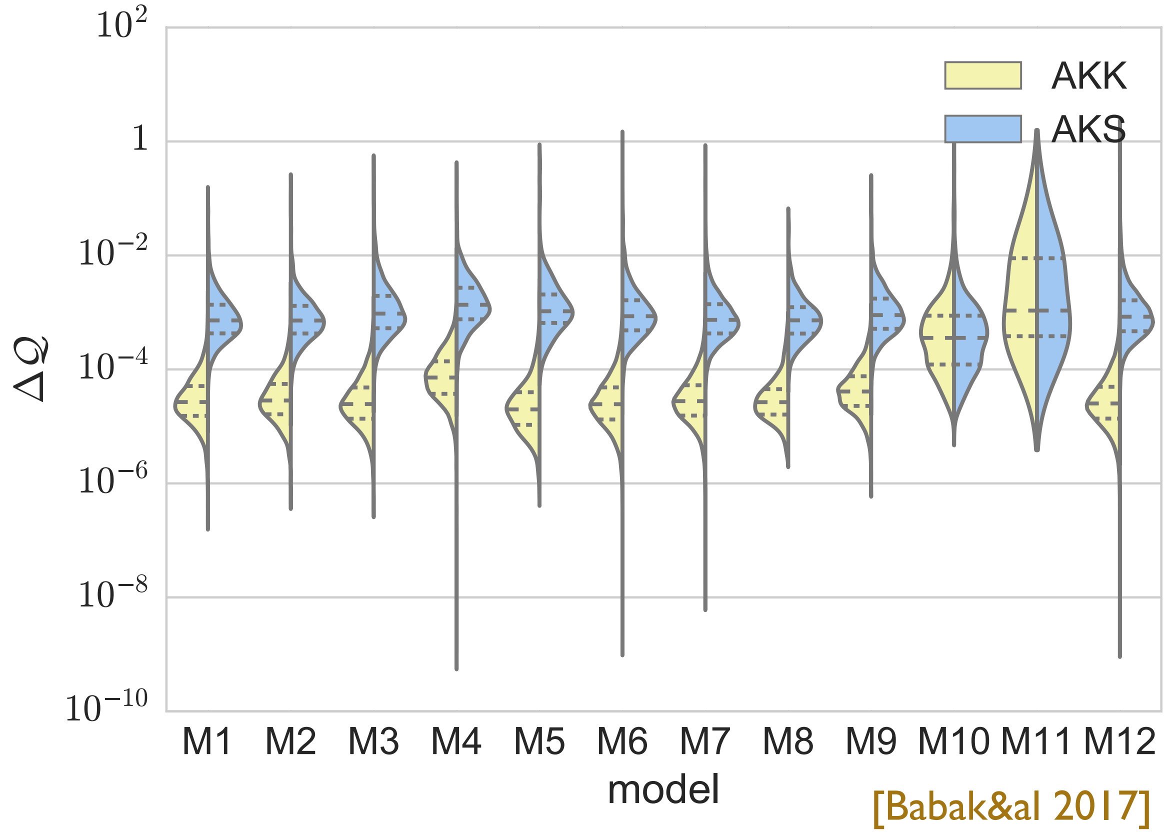


[Berry&al 2019]

Multipolar structure of Kerr: [Hansen 1974]

$$\mathcal{M}_\ell^{\rm BH} + {\rm i}\mathcal{S}_\ell^{\rm BH} = \mathcal{M}^{\ell+1}\,({\rm i}\chi)^\ell$$

Constraints on the quadrupole moment

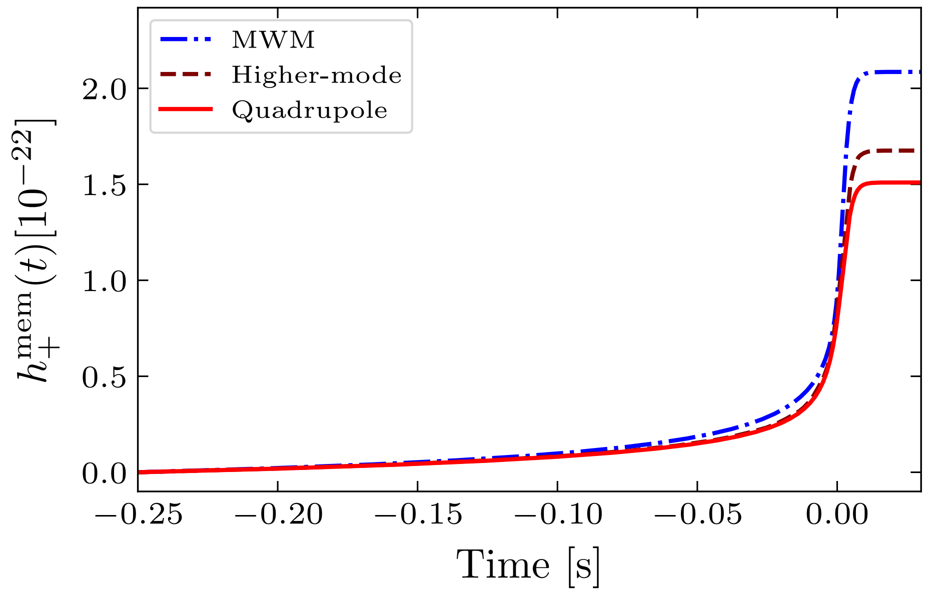


[Babak&al 2017]

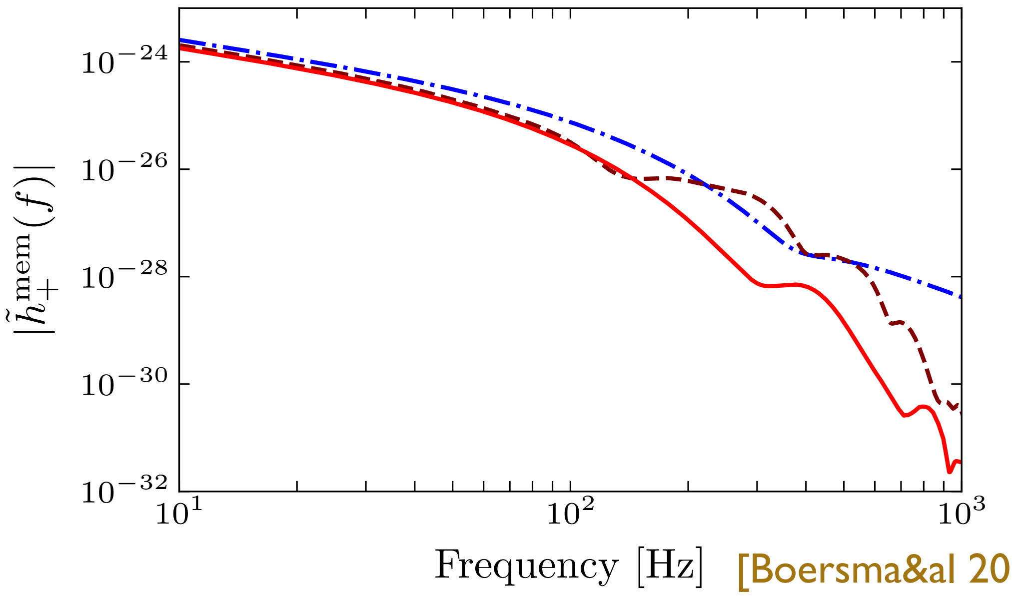
Detecting the nonlinear memory effect

Nonlinear memory: secular term in the gravitational waves [Christodoulou 1991]

$$h_{jk}^{\mathrm{TT,mem}} = \frac{4}{r}\int_{-\infty}^{u} du' \left[\int \frac{dE}{d\Omega' du}\frac{n'_j n'_k}{1-\mathbf{n}'\cdot\mathbf{n}}d\Omega'\right]^{TT}$$

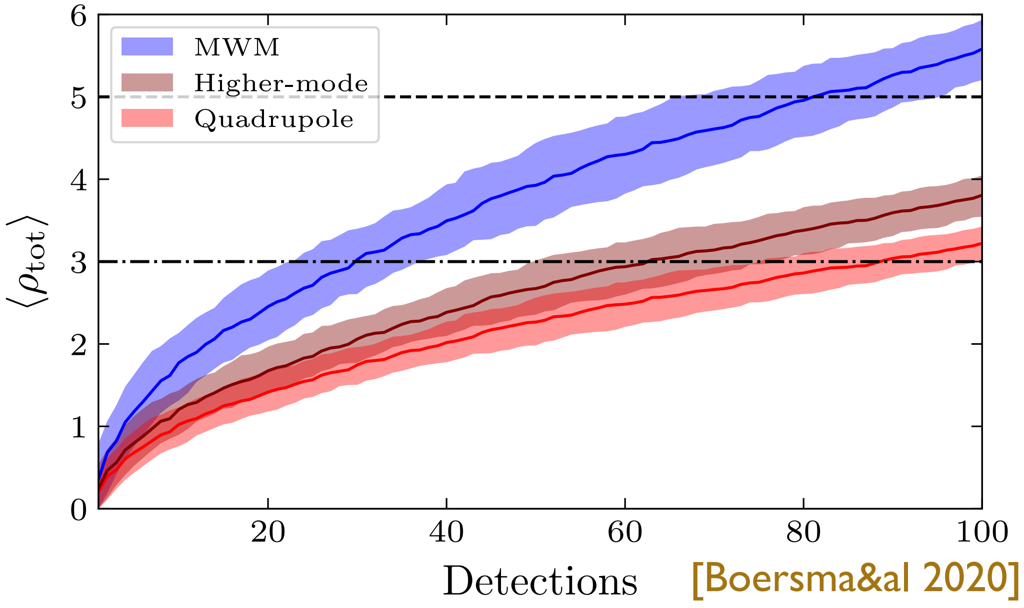


Challenging to detect, needs stacking of a large number of signals



[Boersma&al 2020]

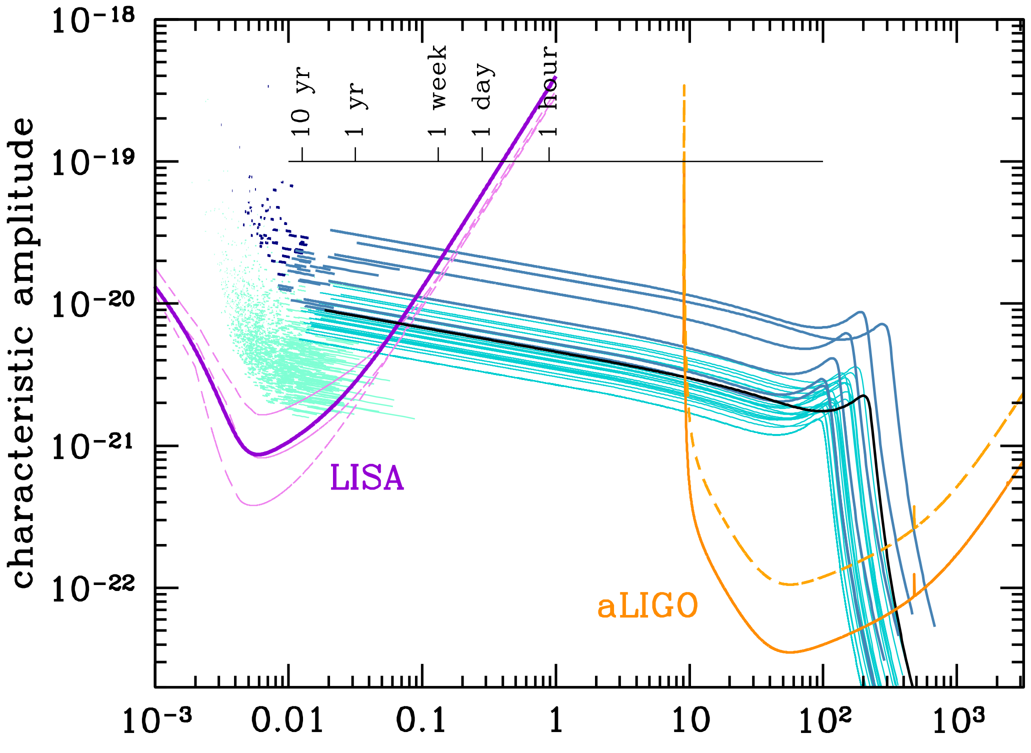
Stacking GW190514-like signals



[Boersma&al 2020]

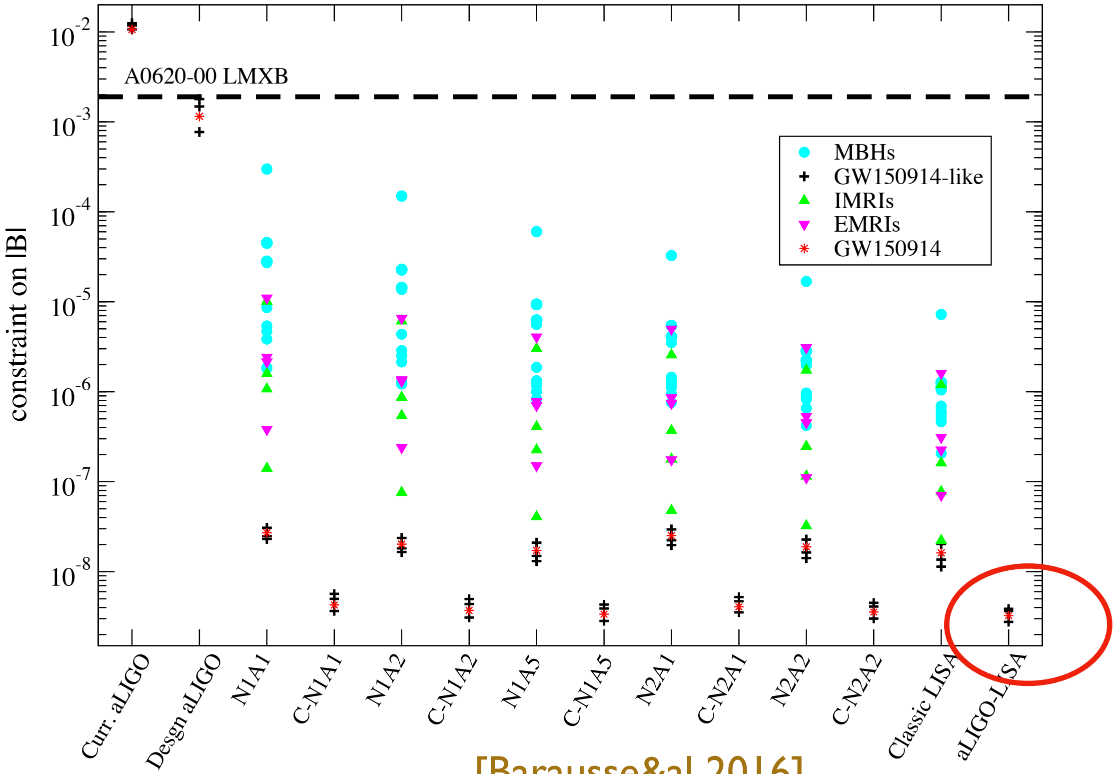
Multiband GW observations and TGR

- Challenging detections for LISA on its own
- Archival searches possible from detections on the ground



[Sesana 2017]

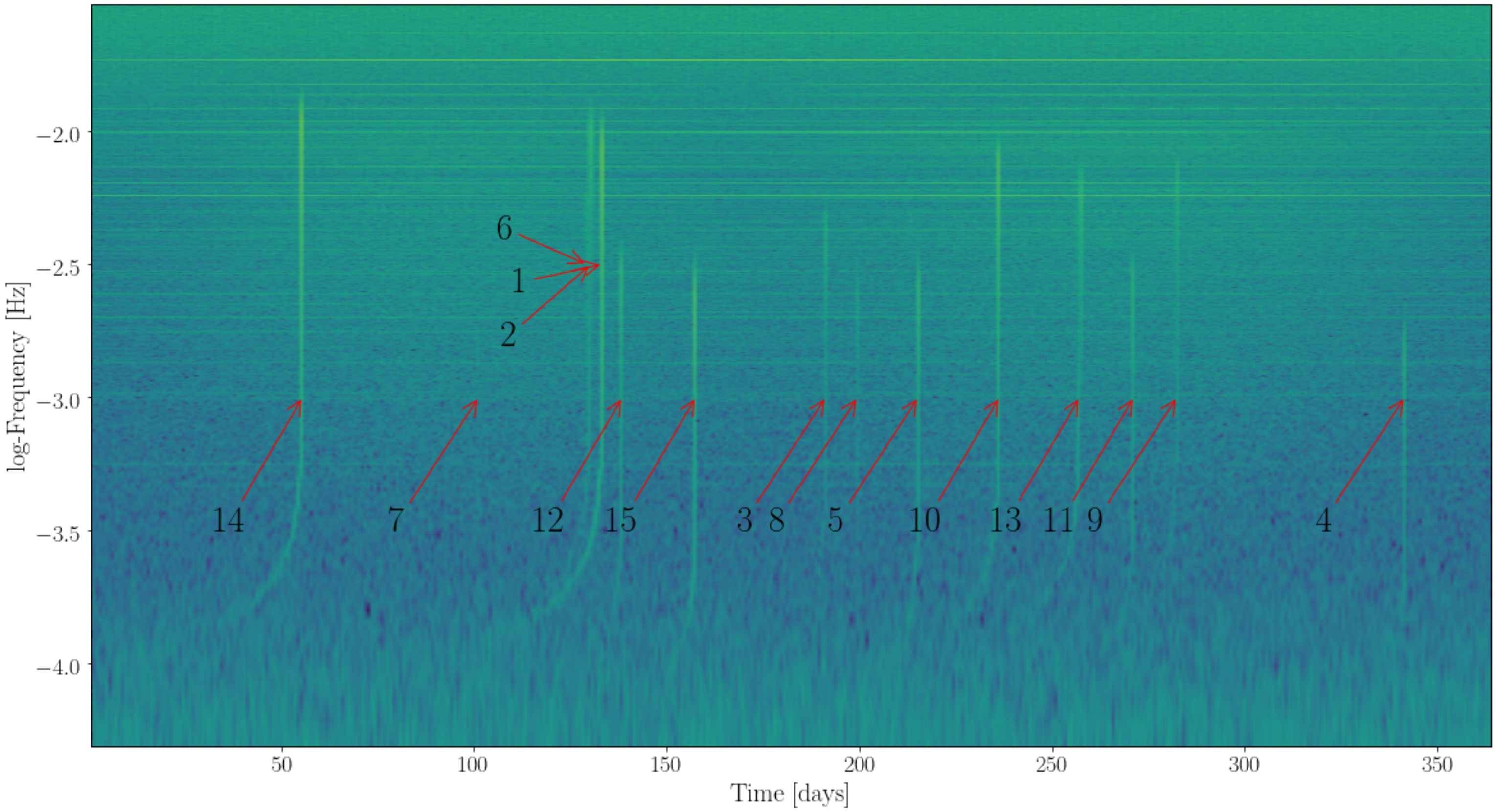
Constraints on dipolar emission from multiband observations:



[Barausse&al 2016]

Thank you !

Future instruments: source superposition and confusion



Superposition of signals for LISA

GW signals for ground, all of them