Gravitational wave astronomy, strong gravity and new physics

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YKIS 2018, Kyoto, Feb 23 2018

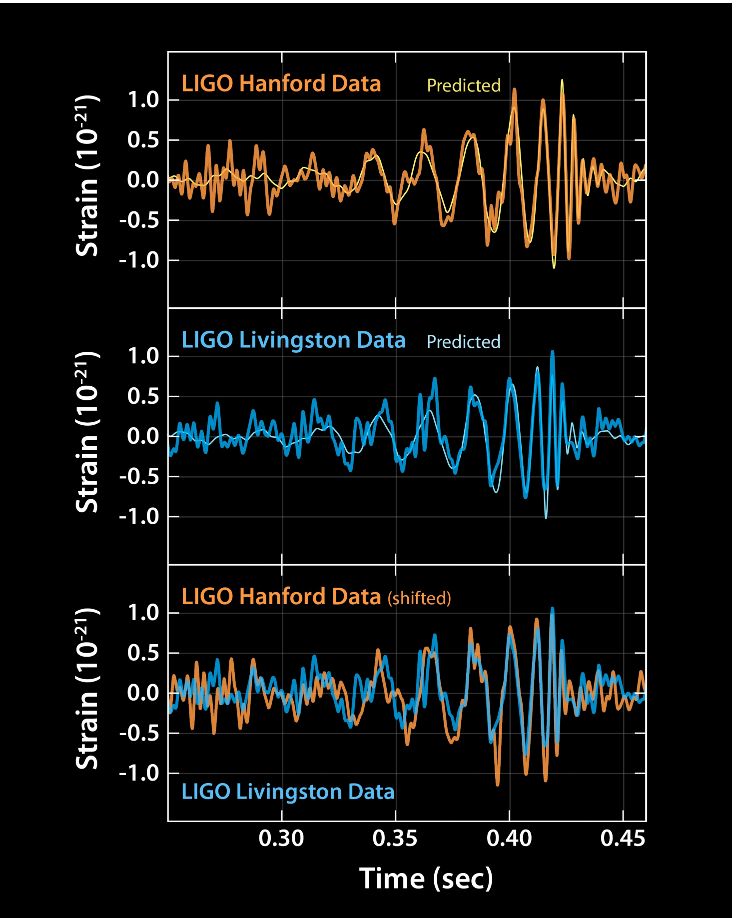
Two years ago…

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)



Physics

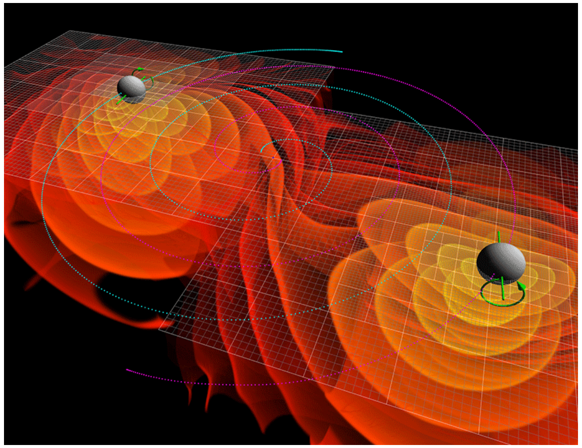
VIEWPOINT

The First Sounds of Merging Black Holes

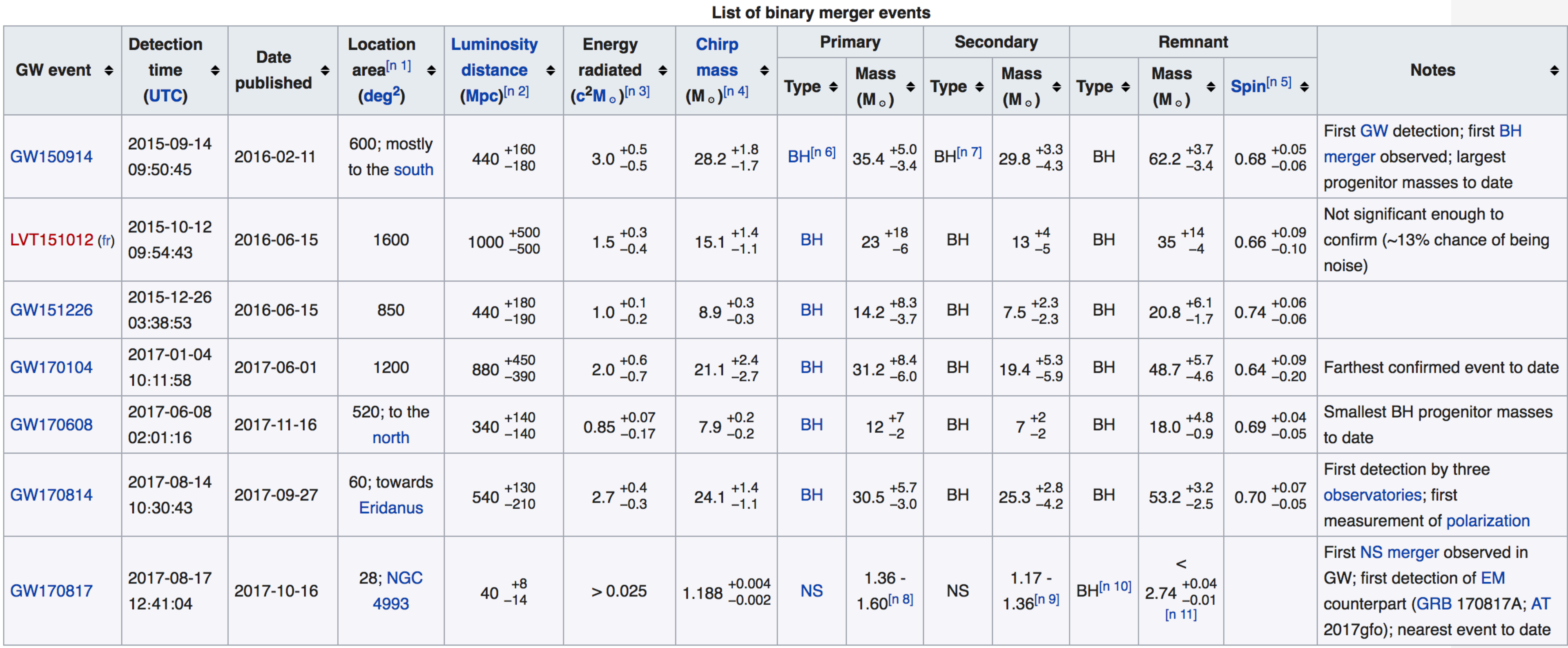
Gravitational waves emitted by the merger of two black holes have been detected, setting the course for a new era of observational astrophysics.

by Emanuele Berti*,†

For decades, scientists have hoped they could "listen in" on violent astrophysical events by detecting their emission of gravitational waves. The waves, which can be described as oscillating distortions in the geometry of spacetime, were first predicted to exist by Einstein in 1916, but they have never been observed directly. Now, in an extraordinary paper, scientists report that they have detected the waves at the Laser Interferometer Gravitational-wave Observatory (LIGO) [1]. From an analysis of the signal, researchers from LIGO in the US, and their collaborators from the Virgo interferometer in Italy, infer that the gravitational waves were produced by the inspiral and merger of two black holes (Fig. 1), each with a mass that is more than 25 times greater than that of our Sun. Their finding provides the first observational evidence that black hole binary systems can form and merge in the Universe.



O1/O2 catalog: so far 5.87 confirmed BH-BH, one NS-NS



List of binary merger events

GW event	Detection time (UTC)	Date published	Location area[n 1] (deg^2)	Luminosity distance (Mpc)[n 2]	Energy radiated ($c^2 M_\odot$)[n 3]	Chirp mass ($M_\odot$)[n 4]	Primary		Secondary		Remnant			Notes
							Type	Mass ($M_\odot$)	Type	Mass ($M_\odot$)	Type	Mass ($M_\odot$)	Spin[n 5]	
GW150914	2015-09-14 09:50:45	2016-02-11	600; mostly to the south	440^{+160}_{-180}	$3.0^{+0.5}_{-0.5}$	$28.2^{+1.8}_{-1.7}$	BH[n 6]	$35.4^{+5.0}_{-3.4}$	BH[n 7]	$29.8^{+3.3}_{-4.3}$	BH	$62.2^{+3.7}_{-3.4}$	$0.68^{+0.05}_{-0.06}$	First GW detection; first BH merger observed; largest progenitor masses to date
LVT151012 (fr)	2015-10-12 09:54:43	2016-06-15	1600	1000^{+500}_{-500}	$1.5^{+0.3}_{-0.4}$	$15.1^{+1.4}_{-1.1}$	BH	23^{+18}_{-6}	BH	13^{+4}_{-5}	BH	35^{+14}_{-4}	$0.66^{+0.09}_{-0.10}$	Not significant enough to confirm (~13% chance of being noise)
GW151226	2015-12-26 03:38:53	2016-06-15	850	440^{+180}_{-190}	$1.0^{+0.1}_{-0.2}$	$8.9^{+0.3}_{-0.3}$	BH	$14.2^{+8.3}_{-3.7}$	BH	$7.5^{+2.3}_{-2.3}$	BH	$20.8^{+6.1}_{-1.7}$	$0.74^{+0.06}_{-0.06}$	
GW170104	2017-01-04 10:11:58	2017-06-01	1200	880^{+450}_{-390}	$2.0^{+0.6}_{-0.7}$	$21.1^{+2.4}_{-2.7}$	BH	$31.2^{+8.4}_{-6.0}$	BH	$19.4^{+5.3}_{-5.9}$	BH	$48.7^{+5.7}_{-4.6}$	$0.64^{+0.09}_{-0.20}$	Farthest confirmed event to date
GW170608	2017-06-08 02:01:16	2017-11-16	520; to the north	340^{+140}_{-140}	$0.85^{+0.07}_{-0.17}$	$7.9^{+0.2}_{-0.2}$	BH	12^{+7}_{-2}	BH	7^{+2}_{-2}	BH	$18.0^{+4.8}_{-0.9}$	$0.69^{+0.04}_{-0.05}$	Smallest BH progenitor masses to date
GW170814	2017-08-14 10:30:43	2017-09-27	60; towards Eridanus	540^{+130}_{-210}	$2.7^{+0.4}_{-0.3}$	$24.1^{+1.4}_{-1.1}$	BH	$30.5^{+5.7}_{-3.0}$	BH	$25.3^{+2.8}_{-4.2}$	BH	$53.2^{+3.2}_{-2.5}$	$0.70^{+0.07}_{-0.05}$	First detection by three observatories; first measurement of polarization
GW170817	2017-08-17 12:41:04	2017-10-16	28; NGC 4993	40^{+8}_{-14}	> 0.025	$1.188^{+0.004}_{-0.002}$	NS	1.36 - 1.60[n 8]	NS	1.17 - 1.36[n 9]	BH[n 10]	$< 2.74^{+0.04}_{-0.01}$ [n 11]		First NS merger observed in GW; first detection of EM counterpart (GRB 170817A; AT 2017gfo); nearest event to date

What can we learn from GW observations?

Astrophysics

- What can we learn from LIGO observables?
- Rates, masses, spins, eccentricity
- Merger vs. collapse

Strong gravity

- Black hole spectroscopy and systematic errors
- Tests of modified gravity:
    - parametrized tests
    - scalar-Gauss-Bonnet

Beyond Standard Model physics

- Detect/constrain dark matter with LIGO/LISA?
- Exotic compact objects and echoes

Astrophysics: LIGO/Virgo/LISA

What do we learn from:

Rates
Masses
Spins
Distance
(Eccentricity)?

How do we expect that information to change on a time scale of months/years?

Can we use statistics to answer simple astrophysical questions?

Are BHs born from collapse or previous mergers? (1703.06223, 1703.06869)

Are BH spins aligned with the orbital plane or very small? (1706.01385)

The million dollar question:

What formation scenario(s) - field, cluster, triples, Pop III, primordial BHs… - are favored?

Is there only one mechanism at work?

Are the first observations dominated by a single channel?

What evidence/how many observations does it take to favor any scenario over the others?

What does it take to convincingly rule out a scenario for one event / overall?

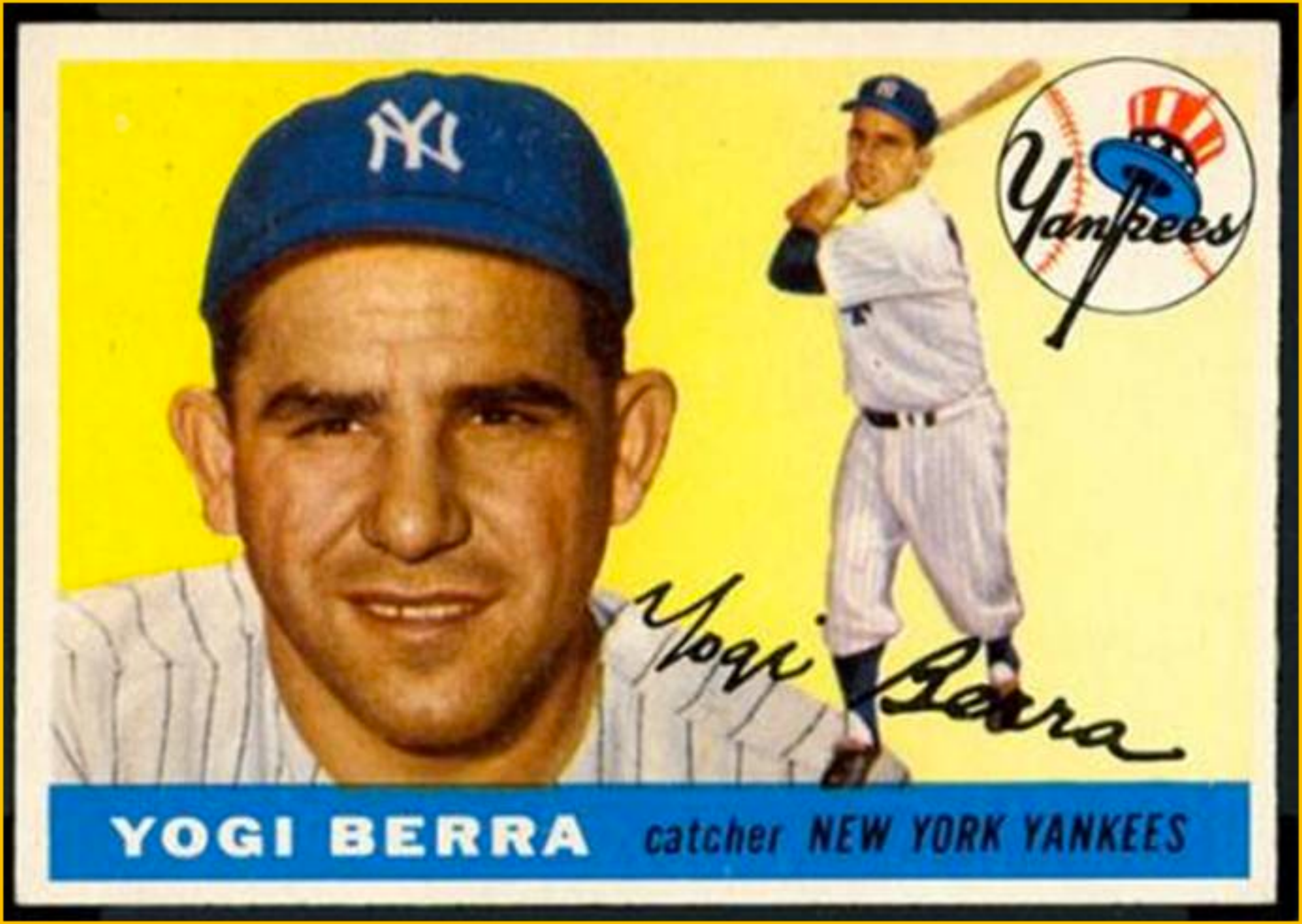
[$M>130M_{sun}$: no collapse, $M<1M_{sun}$: primordial origin, spin antialignment: clusters]

Can we do better with multiband (LISA/LIGO) observations or third-generation detectors?

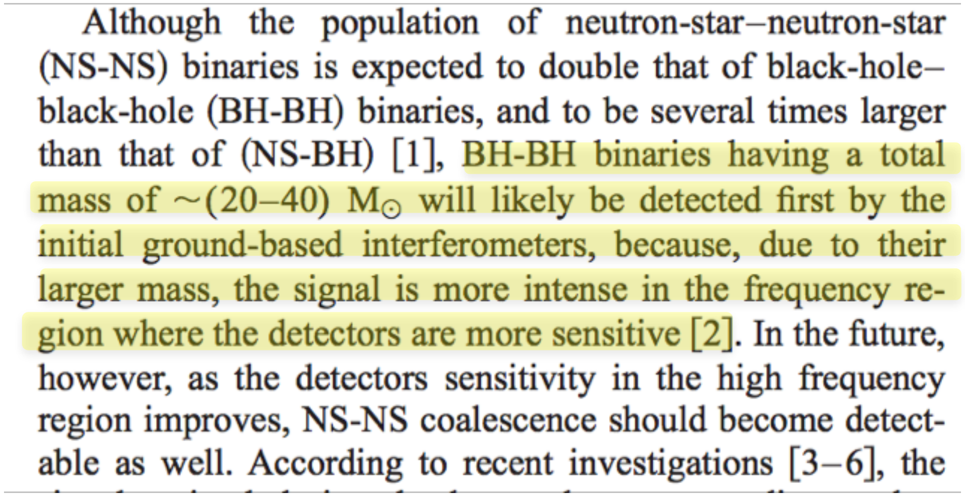
Rates

with Dominik, Belczynski, O’Shaughnessy, Holz, Fryer…

"It's tough to make predictions, especially about the future."



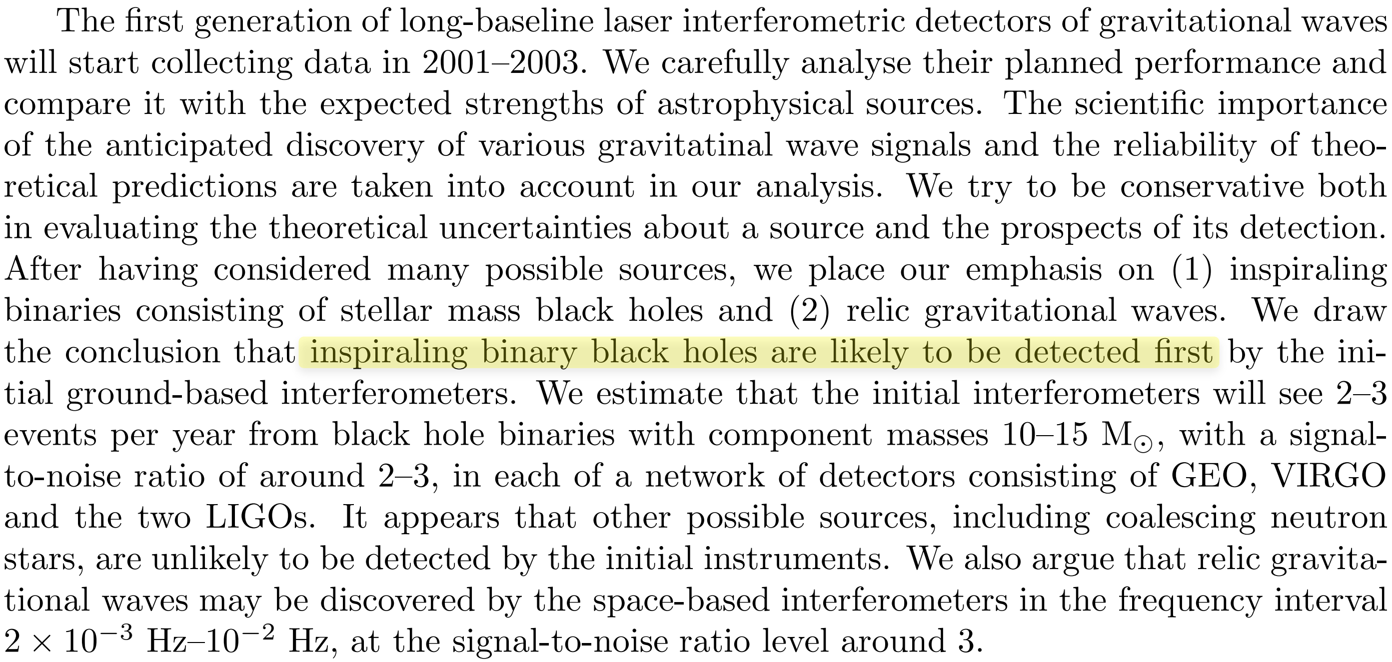
Were binary black hole detections unexpected?



Although the population of neutron-star–neutron-star (NS-NS) binaries is expected to double that of black-hole–black-hole (BH-BH) binaries, and to be several times larger than that of (NS-BH) [1], BH-BH binaries having a total mass of $\sim$(20–40) $M_\odot$ will likely be detected first by the initial ground-based interferometers, because, due to their larger mass, the signal is more intense in the frequency region where the detectors are more sensitive [2]. In the future, however, as the detectors sensitivity in the high frequency region improves, NS-NS coalescence should become detectable as well. According to recent investigations [3–6], the

[EB+, gr-qc/0208011]

[Grishchuk+, astro-ph/0008481]



The first generation of long-baseline laser interferometric detectors of gravitational waves will start collecting data in 2001–2003. We carefully analyse their planned performance and compare it with the expected strengths of astrophysical sources. The scientific importance of the anticipated discovery of various gravitatinal wave signals and the reliability of theoretical predictions are taken into account in our analysis. We try to be conservative both in evaluating the theoretical uncertainties about a source and the prospects of its detection. After having considered many possible sources, we place our emphasis on (1) inspiraling binaries consisting of stellar mass black holes and (2) relic gravitational waves. We draw the conclusion that inspiraling binary black holes are likely to be detected first by the initial ground-based interferometers. We estimate that the initial interferometers will see 2–3 events per year from black hole binaries with component masses 10–15 $M_\odot$, with a signal-to-noise ratio of around 2–3, in each of a network of detectors consisting of GEO, VIRGO and the two LIGOs. It appears that other possible sources, including coalescing neutron stars, are unlikely to be detected by the initial instruments. We also argue that relic gravitational waves may be discovered by the space-based interferometers in the frequency interval 2×10^{-3} Hz–10^{-2} Hz, at the signal-to-noise ratio level around 3.

Official LIGO rate paper

> “The **most confident** among these estimates are the rate predictions for coalescing binary neutron stars which are based on extrapolations from observed binary pulsars in our Galaxy”

[Abbott+, 1003.2480]

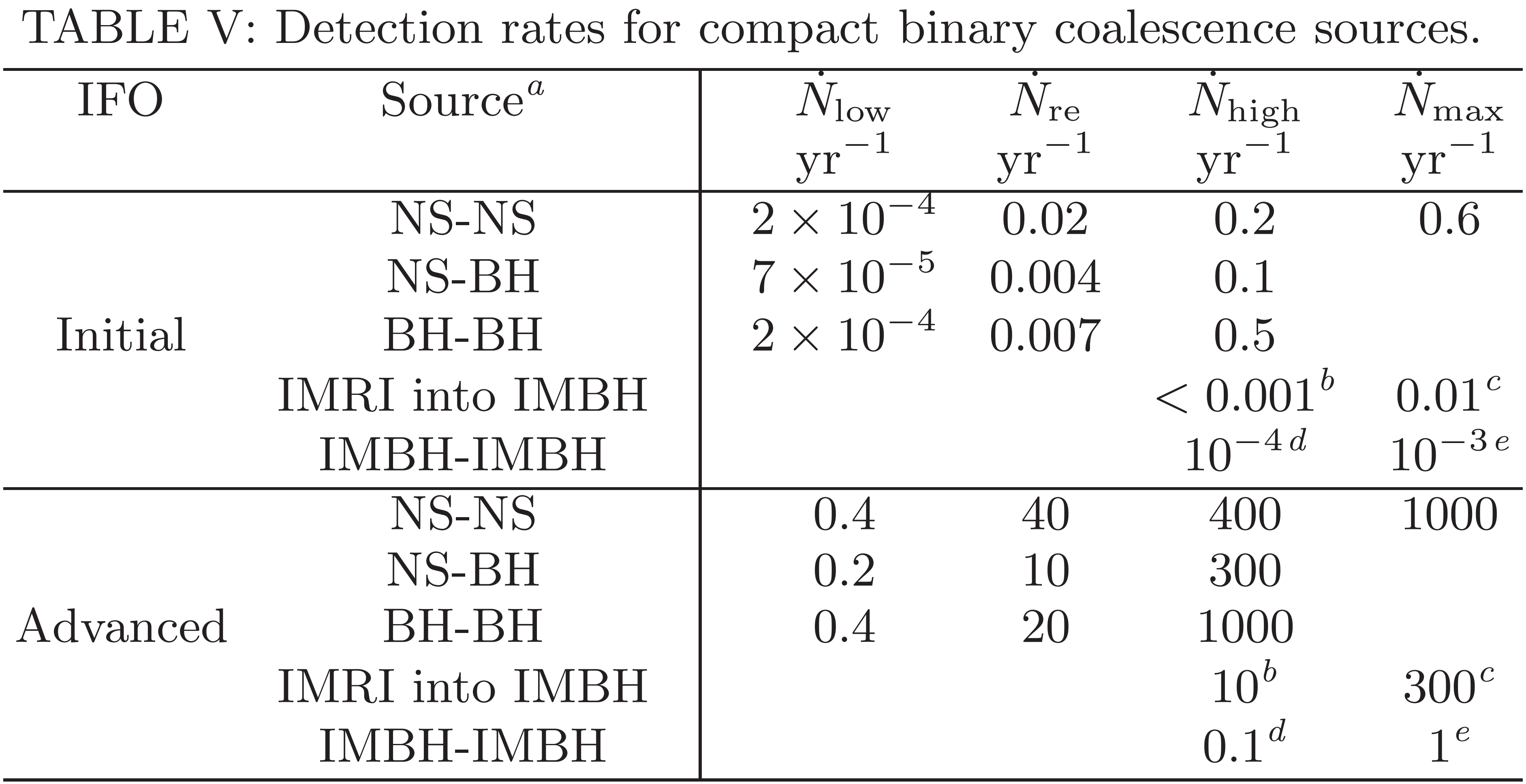
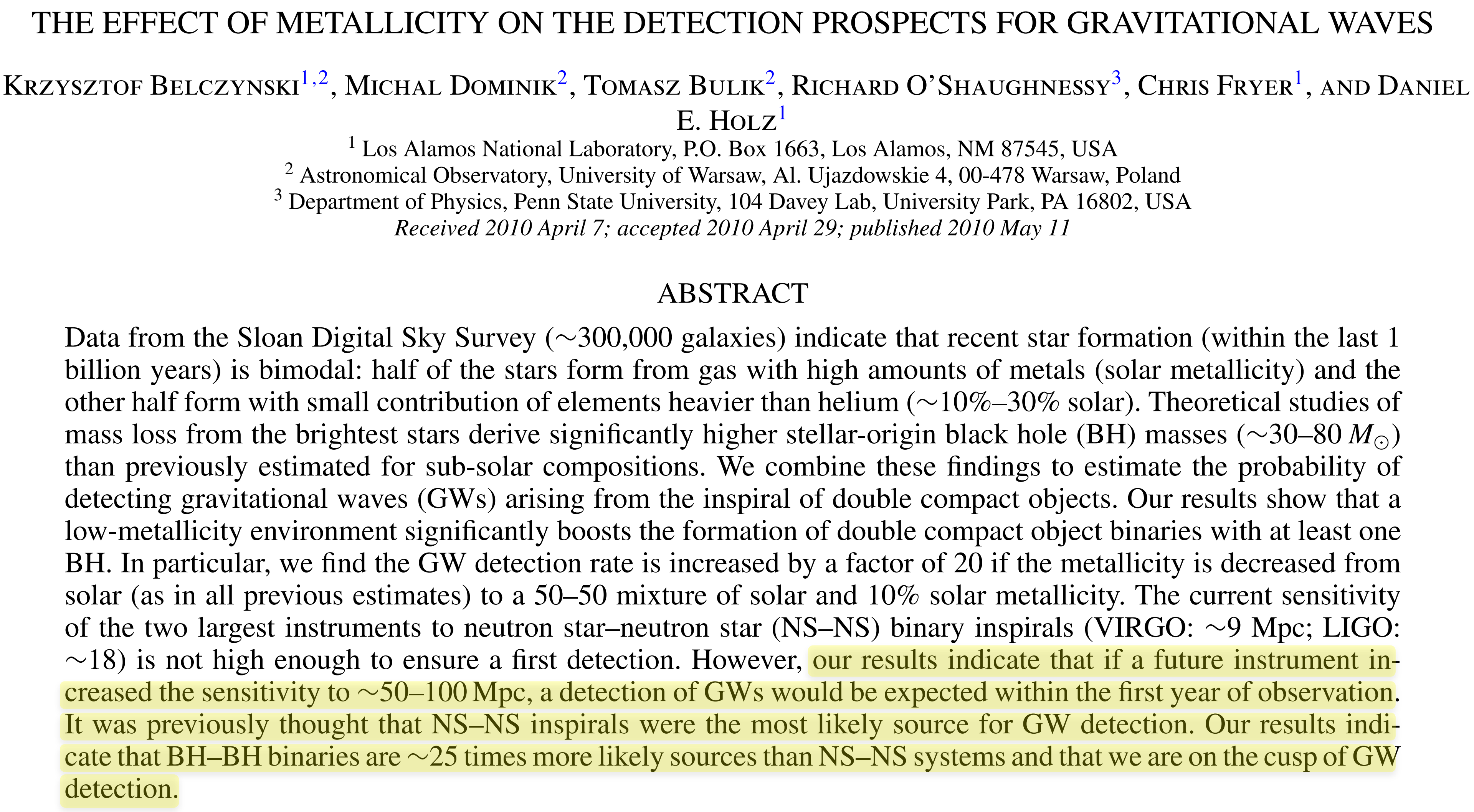


TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\mathrm{low}}$ yr^{-1}	$\dot{N}_{\mathrm{re}}$ yr^{-1}	$\dot{N}_{\mathrm{high}}$ yr^{-1}	$\dot{N}_{\mathrm{max}}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^{b}$	0.01^{c}
	IMBH-IMBH			$10^{-4\,d}$	$10^{-3\,e}$
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^{b}	300^{c}
	IMBH-IMBH			0.1^{d}	1^{e}

Population synthesis: low Z boosts black hole rates (2010)



THE EFFECT OF METALLICITY ON THE DETECTION PROSPECTS FOR GRAVITATIONAL WAVES

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ABSTRACT

Data from the Sloan Digital Sky Survey (~300,000 galaxies) indicate that recent star formation (within the last 1 billion years) is bimodal: half of the stars form from gas with high amounts of metals (solar metallicity) and the other half form with small contribution of elements heavier than helium (~10%–30% solar). Theoretical studies of mass loss from the brightest stars derive significantly higher stellar-origin black hole (BH) masses (~30–80 $M_{\odot}$) than previously estimated for sub-solar compositions. We combine these findings to estimate the probability of detecting gravitational waves (GWs) arising from the inspiral of double compact objects. Our results show that a low-metallicity environment significantly boosts the formation of double compact object binaries with at least one BH. In particular, we find the GW detection rate is increased by a factor of 20 if the metallicity is decreased from solar (as in all previous estimates) to a 50–50 mixture of solar and 10% solar metallicity. The current sensitivity of the two largest instruments to neutron star–neutron star (NS–NS) binary inspirals (VIRGO: ~9 Mpc; LIGO: ~18) is not high enough to ensure a first detection. However, our results indicate that if a future instrument increased the sensitivity to ~50–100 Mpc, a detection of GWs would be expected within the first year of observation. It was previously thought that NS–NS inspirals were the most likely source for GW detection. Our results indicate that BH–BH binaries are ~25 times more likely sources than NS–NS systems and that we are on the cusp of GW detection.

Population synthesis rates using Z evolution, IMR waveforms

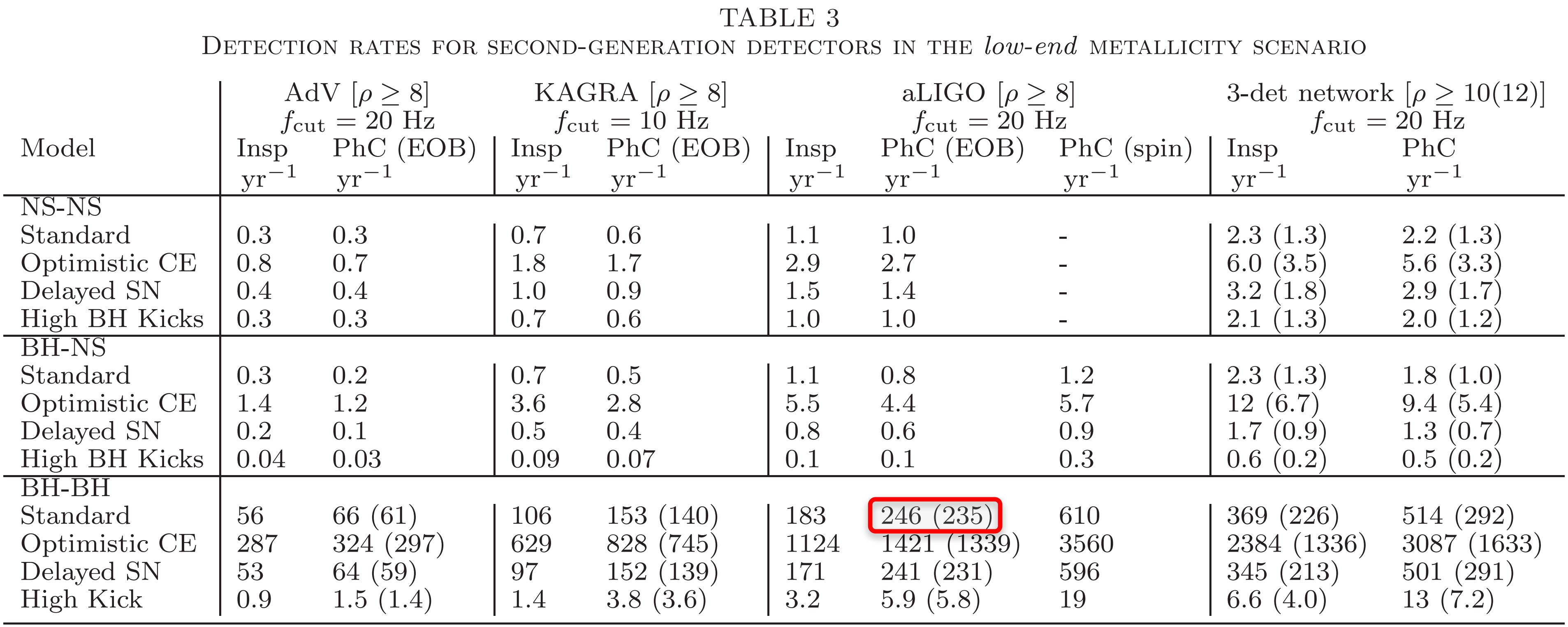


TABLE 3

Detection rates for second-generation detectors in the *low-end* metallicity scenario

Model	AdV $[\rho \geq 8]$ $f_{\rm cut} = 20$ Hz		KAGRA $[\rho \geq 8]$ $f_{\rm cut} = 10$ Hz		aLIGO $[\rho \geq 8]$ $f_{\rm cut} = 20$ Hz			3-det network $[\rho \geq 10(12)]$ $f_{\rm cut} = 20$ Hz	
	Insp yr^{-1}	PhC (EOB) yr^{-1}	Insp yr^{-1}	PhC (EOB) yr^{-1}	Insp yr^{-1}	PhC (EOB) yr^{-1}	PhC (spin) yr^{-1}	Insp yr^{-1}	PhC yr^{-1}
NS-NS									
Standard	0.3	0.3	0.7	0.6	1.1	1.0	-	2.3 (1.3)	2.2 (1.3)
Optimistic CE	0.8	0.7	1.8	1.7	2.9	2.7	-	6.0 (3.5)	5.6 (3.3)
Delayed SN	0.4	0.4	1.0	0.9	1.5	1.4	-	3.2 (1.8)	2.9 (1.7)
High BH Kicks	0.3	0.3	0.7	0.6	1.0	1.0	-	2.1 (1.3)	2.0 (1.2)
BH-NS									
Standard	0.3	0.2	0.7	0.5	1.1	0.8	1.2	2.3 (1.3)	1.8 (1.0)
Optimistic CE	1.4	1.2	3.6	2.8	5.5	4.4	5.7	12 (6.7)	9.4 (5.4)
Delayed SN	0.2	0.1	0.5	0.4	0.8	0.6	0.9	1.7 (0.9)	1.3 (0.7)
High BH Kicks	0.04	0.03	0.09	0.07	0.1	0.1	0.3	0.6 (0.2)	0.5 (0.2)
BH-BH									
Standard	56	66 (61)	106	153 (140)	183	246 (235)	610	369 (226)	514 (292)
Optimistic CE	287	324 (297)	629	828 (745)	1124	1421 (1339)	3560	2384 (1336)	3087 (1633)
Delayed SN	53	64 (59)	97	152 (139)	171	241 (231)	596	345 (213)	501 (291)
High Kick	0.9	1.5 (1.4)	1.4	3.8 (3.6)	3.2	5.9 (5.8)	19	6.6 (4.0)	13 (7.2)

[Dominik+, 1202.4901; 1308.1546; 1405.7016]

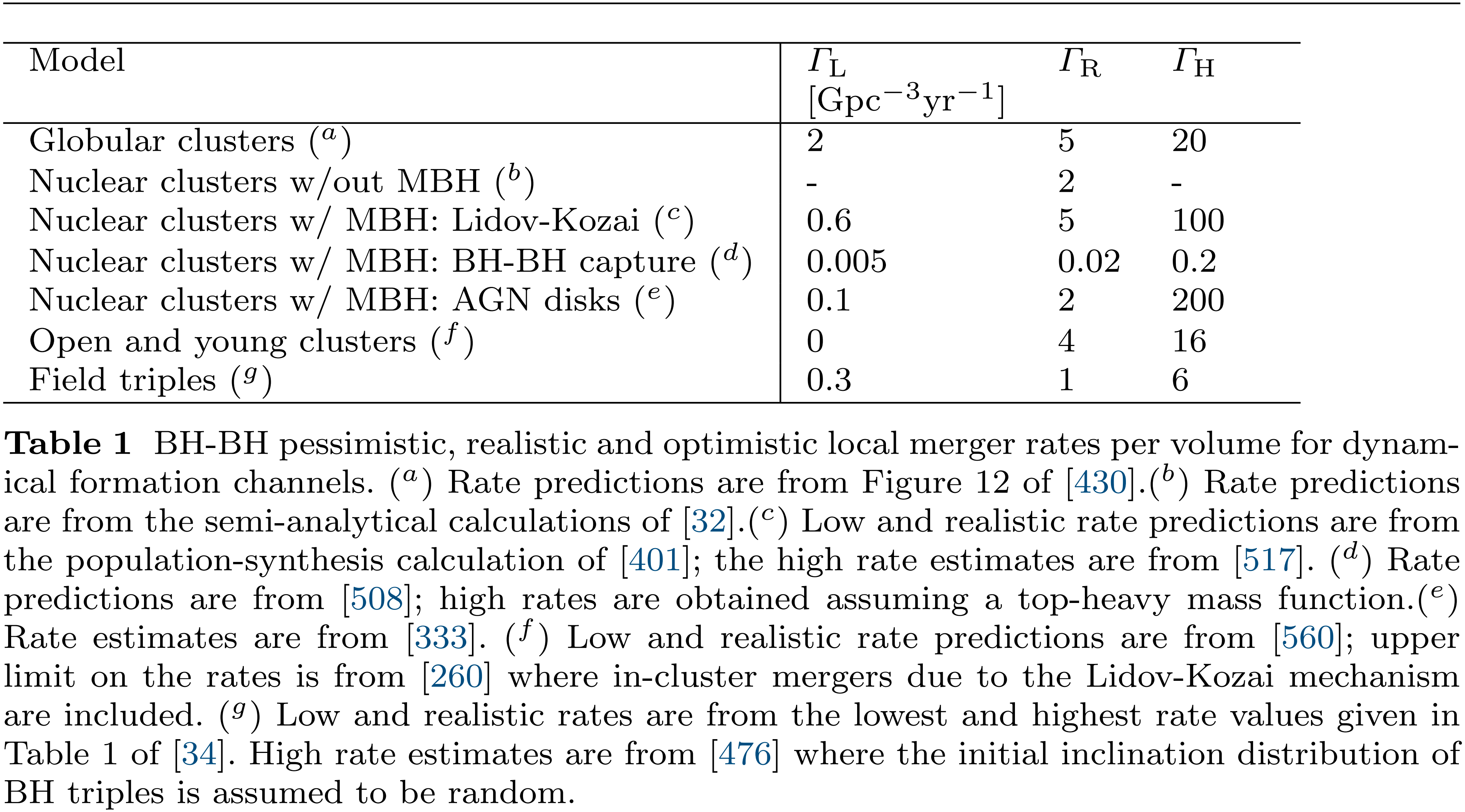
Shown: rates per year for Advanced LIGO at design sensitivity

Rescaled to actual O1 duration (46-48 days): about 30 events

O1 sensitivity: roughly factor 8 below design, 4 events (LIGO: three candidates!)

Dynamical formation channels

Inferred local merger rate from LIGO data: [9-220] Gpc^{-3} yr^{-1}

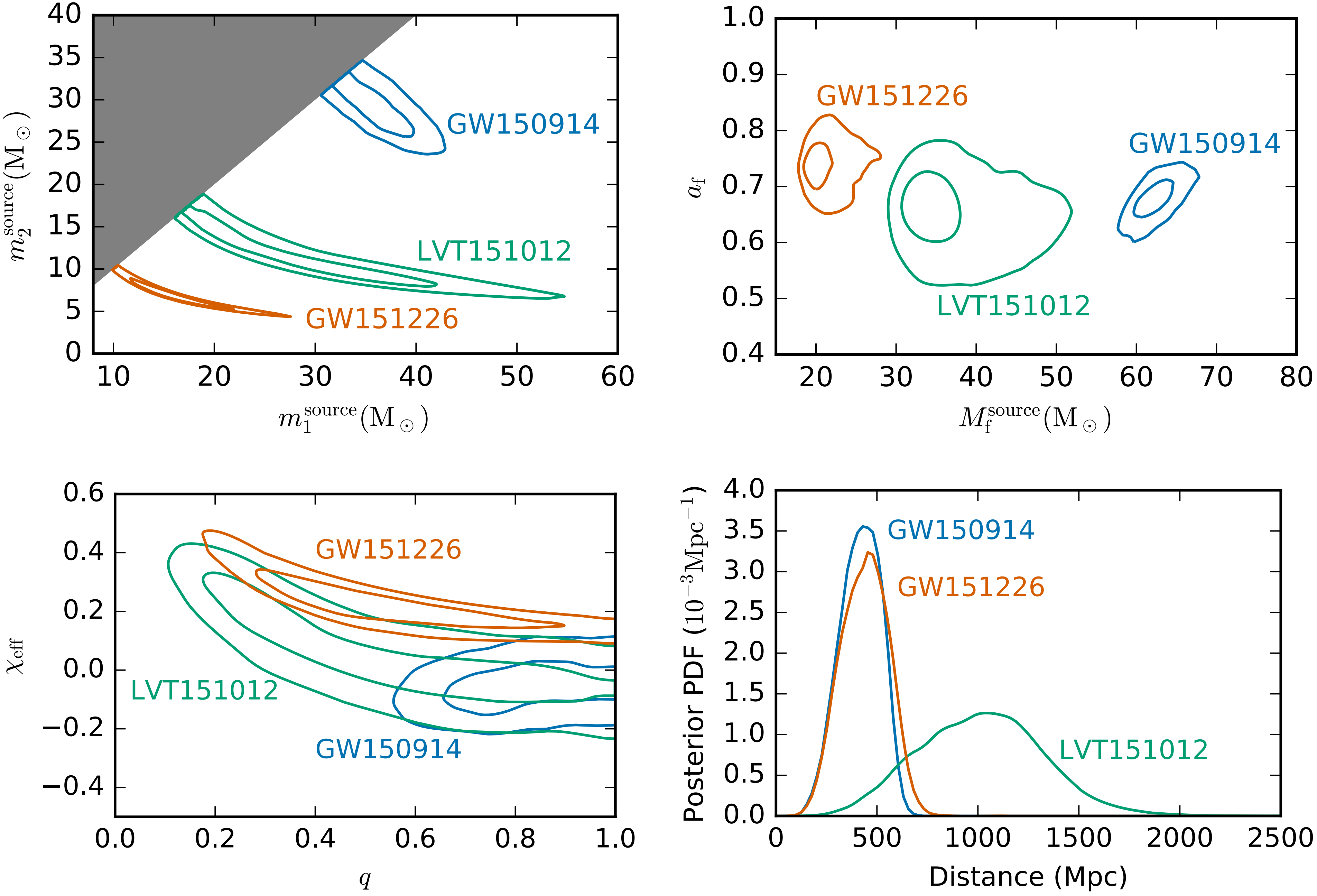


Model	$\Gamma_{\rm L}$ [Gpc^{-3}yr^{-1}]	$\Gamma_{\rm R}$	$\Gamma_{\rm H}$
Globular clusters (^{a})	2	5	20
Nuclear clusters w/out MBH (^{b})	-	2	-
Nuclear clusters w/ MBH: Lidov-Kozai (^{c})	0.6	5	100
Nuclear clusters w/ MBH: BH-BH capture (^{d})	0.005	0.02	0.2
Nuclear clusters w/ MBH: AGN disks (^{e})	0.1	2	200
Open and young clusters (^{f})	0	4	16
Field triples (^{g})	0.3	1	6

Table 1 BH-BH pessimistic, realistic and optimistic local merger rates per volume for dynamical formation channels. (^{a}) Rate predictions are from Figure 12 of [430].(^{b}) Rate predictions are from the semi-analytical calculations of [32].(^{c}) Low and realistic rate predictions are from the population-synthesis calculation of [401]; the high rate estimates are from [517]. (^{d}) Rate predictions are from [508]; high rates are obtained assuming a top-heavy mass function.(^{e}) Rate estimates are from [333]. (^{f}) Low and realistic rate predictions are from [560]; upper limit on the rates is from [260] where in-cluster mergers due to the Lidov-Kozai mechanism are included. (^{g}) Low and realistic rates are from the lowest and highest rate values given in Table 1 of [34]. High rate estimates are from [476] where the initial inclination distribution of BH triples is assumed to be random.

[Antonini…EB…+, Living Reviews in Relativity, upcoming]

LIGO O1 - observables: masses, final/effective spin, distance

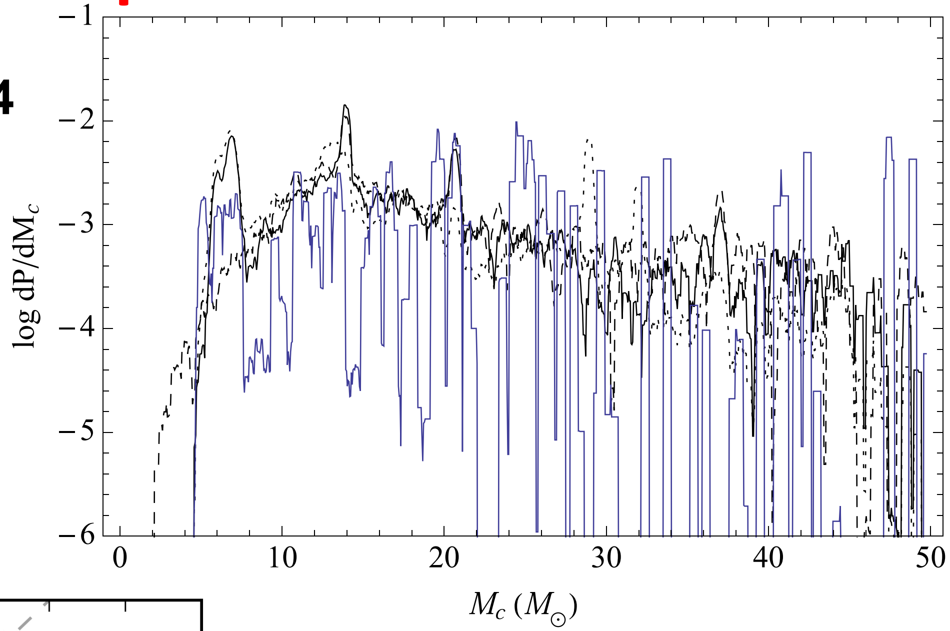


Masses

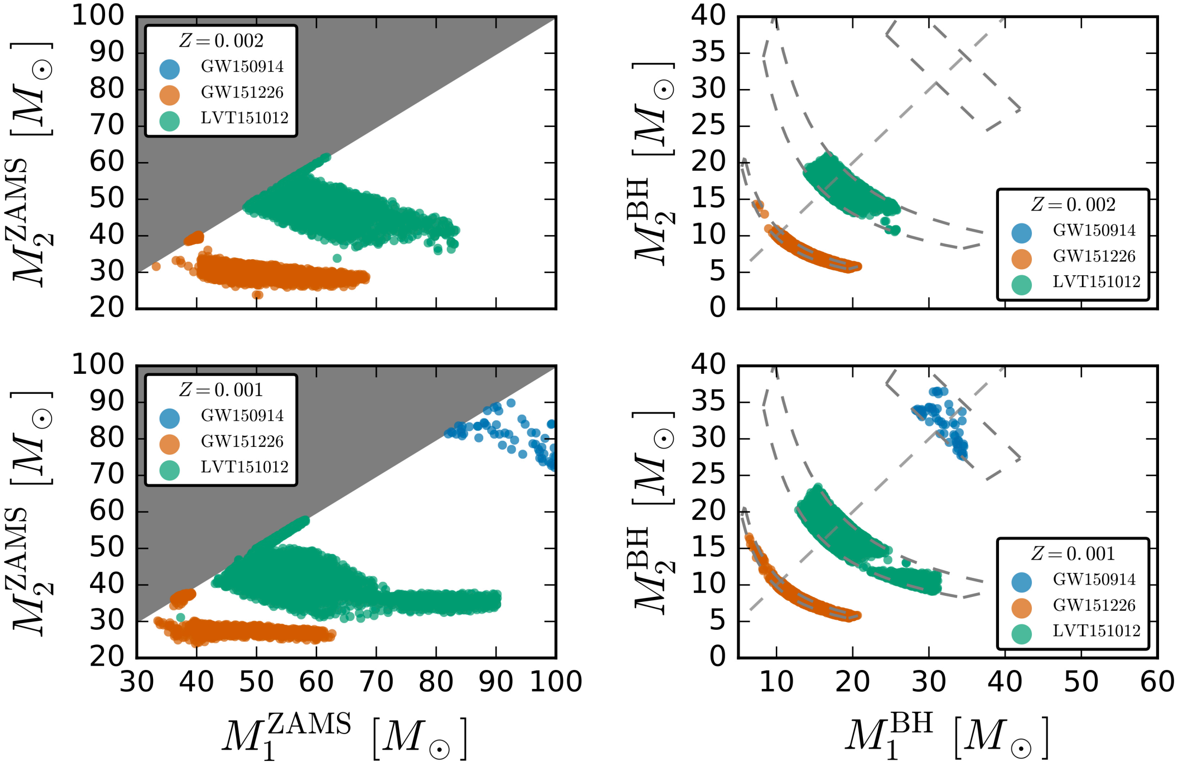
“Ordinary” field formation can reproduce observed masses

Highest measured chirp mass: GW150914

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \simeq 28 M_\odot$$

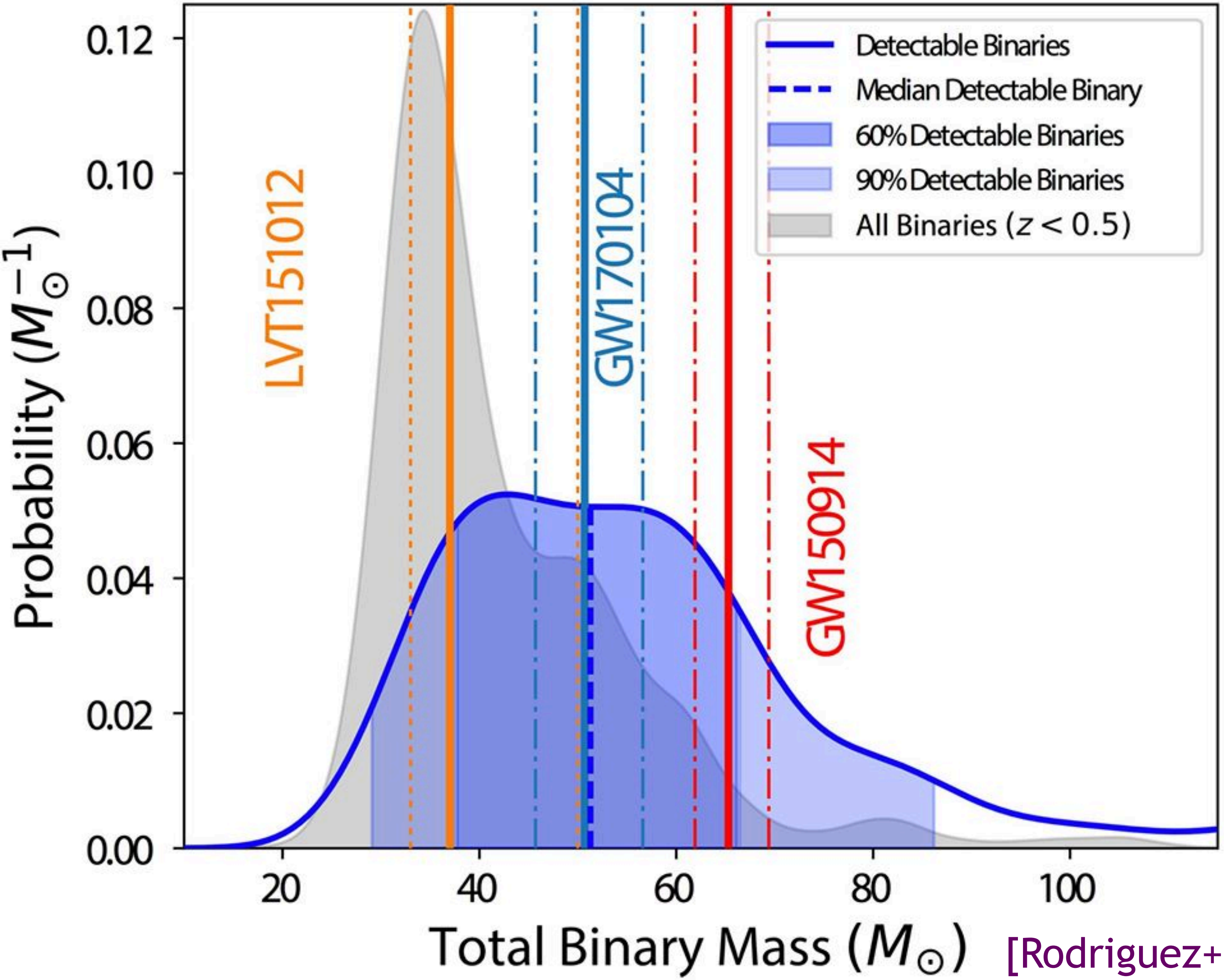


[Dominik+, 1405.7016]



[Stevenson+, 1704.01352]

Clusters: GW151226/GW170608 (22/19M_{sun}) unlikely

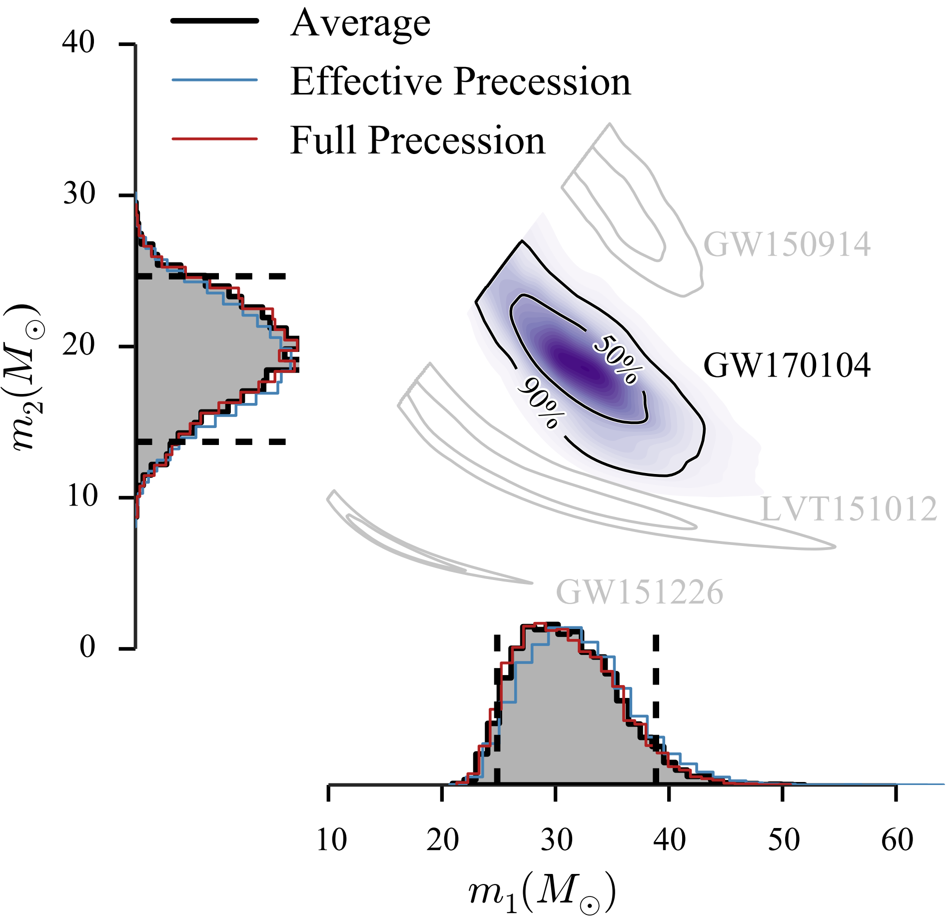


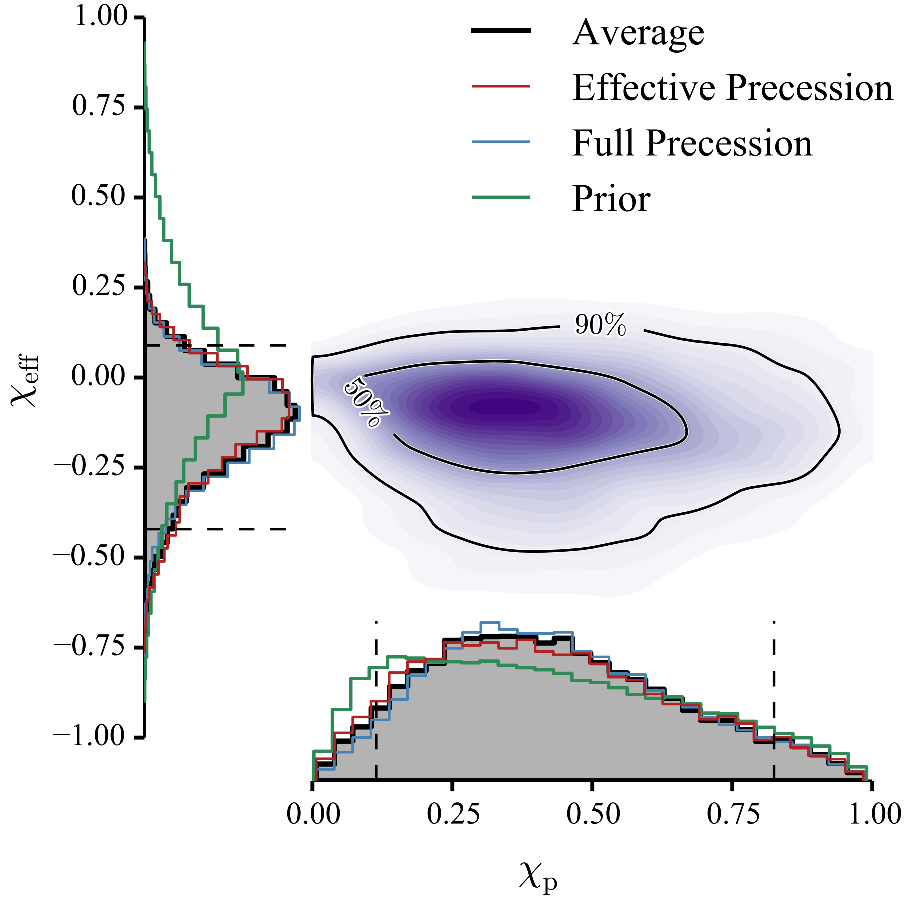
[Rodriguez+, 1604.04254]

Spins

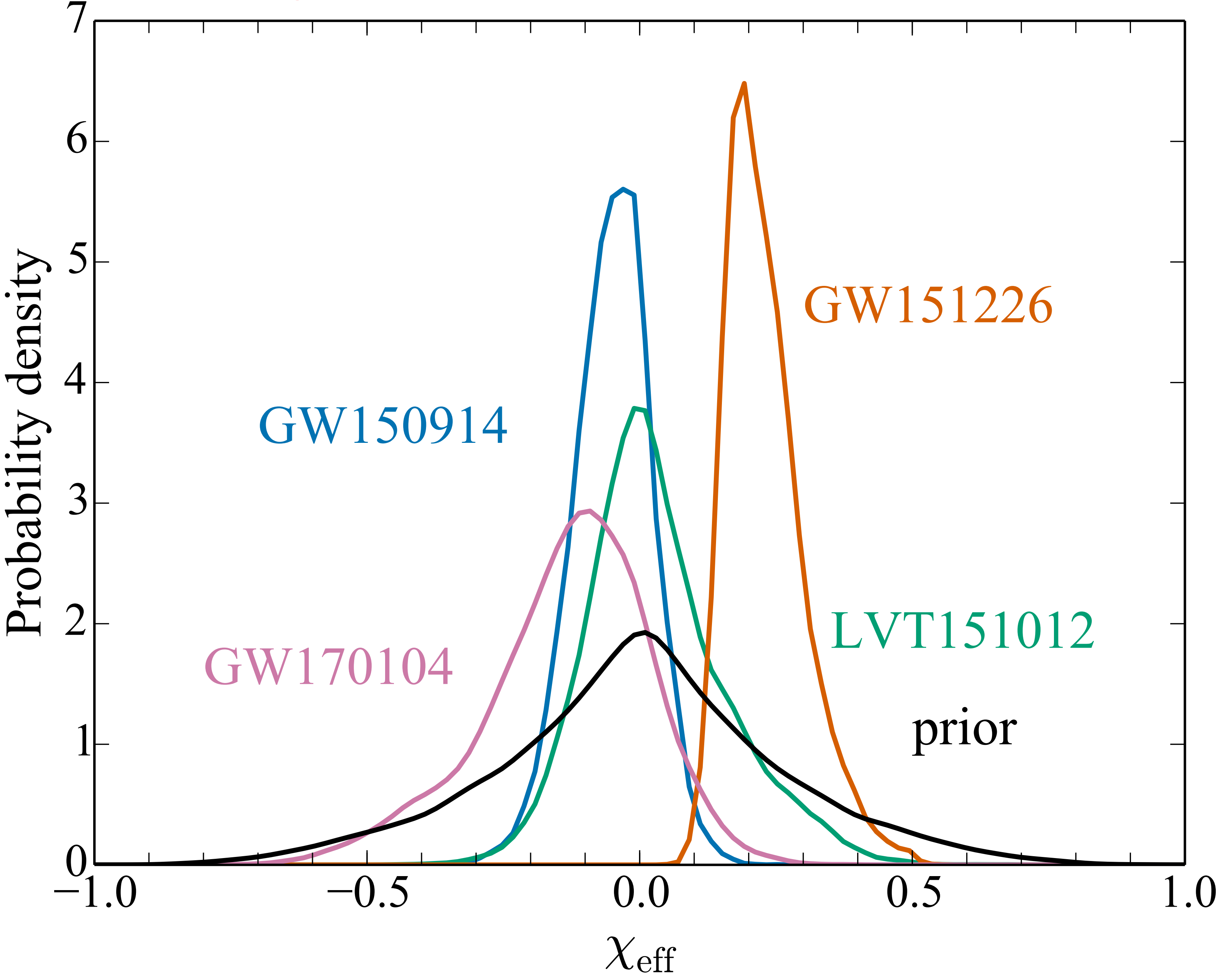
with Gerosa, Kesden, O’Shaughnessy, Sperhake…

GW170104: marginal evidence for misalignment

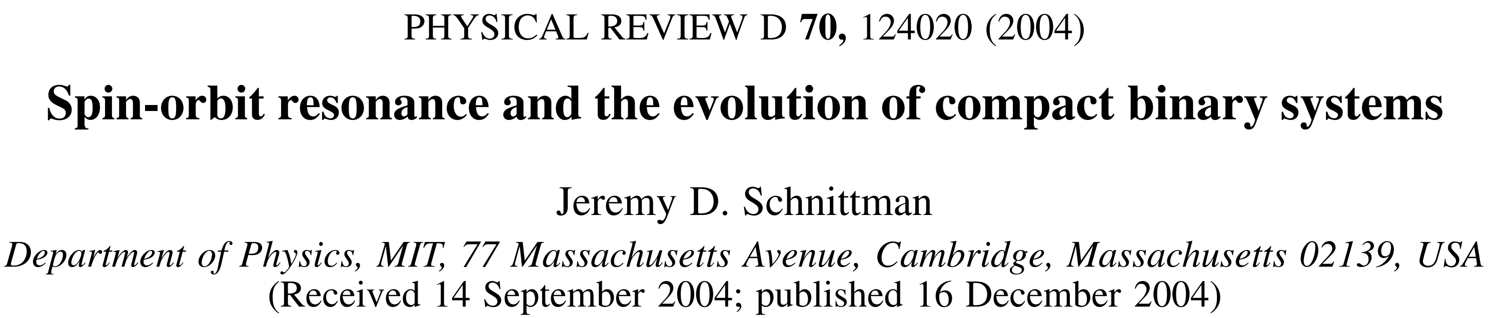




Low effective spin disfavors field – but are data informative?



Does field formation *really* predict alignment?



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Spin-orbit resonance and the evolution of compact binary systems

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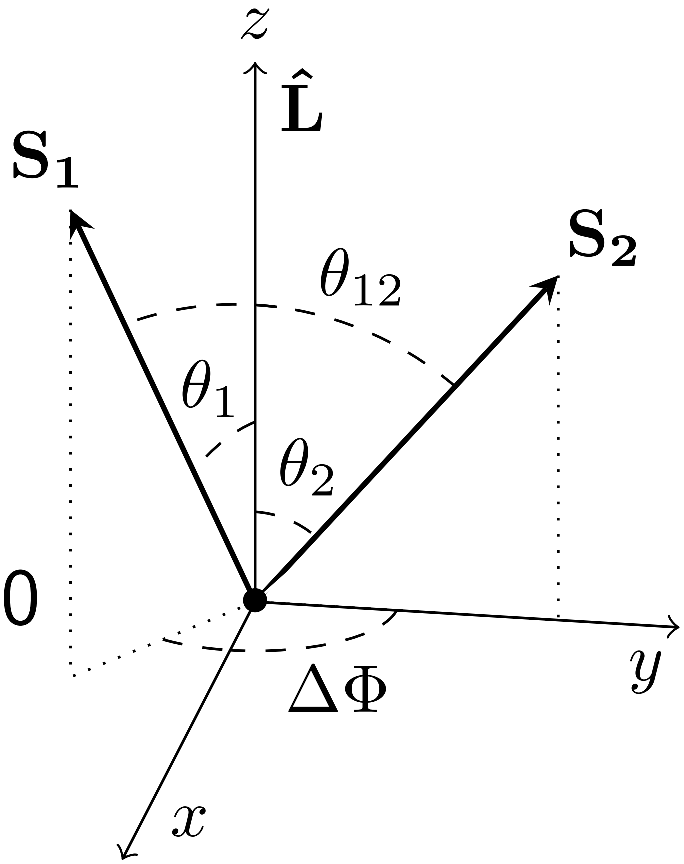
(Received 14 September 2004; published 16 December 2004)

$$\mathbf{S}_2 \cdot (\mathbf{L} \times \mathbf{S}_1) = 0$$

$$\frac{d}{dt}\mathbf{S}_2 \cdot (\mathbf{L} \times \mathbf{S}_1) = 0$$

$$\theta_1 < \theta_2 \;:\quad \Delta\Phi \to 0 \quad \text{and} \quad \theta_{12} \to 0$$

$$\theta_1 > \theta_2 \;:\quad \Delta\Phi \to \pm\pi$$



Spin-orbit resonance locking

Efficient locking needs:

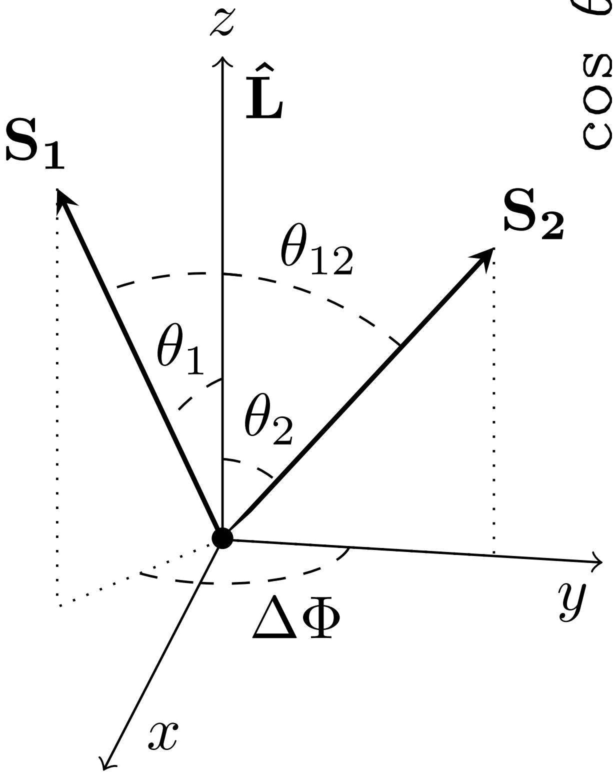
$$\theta_1 \neq \theta_2$$

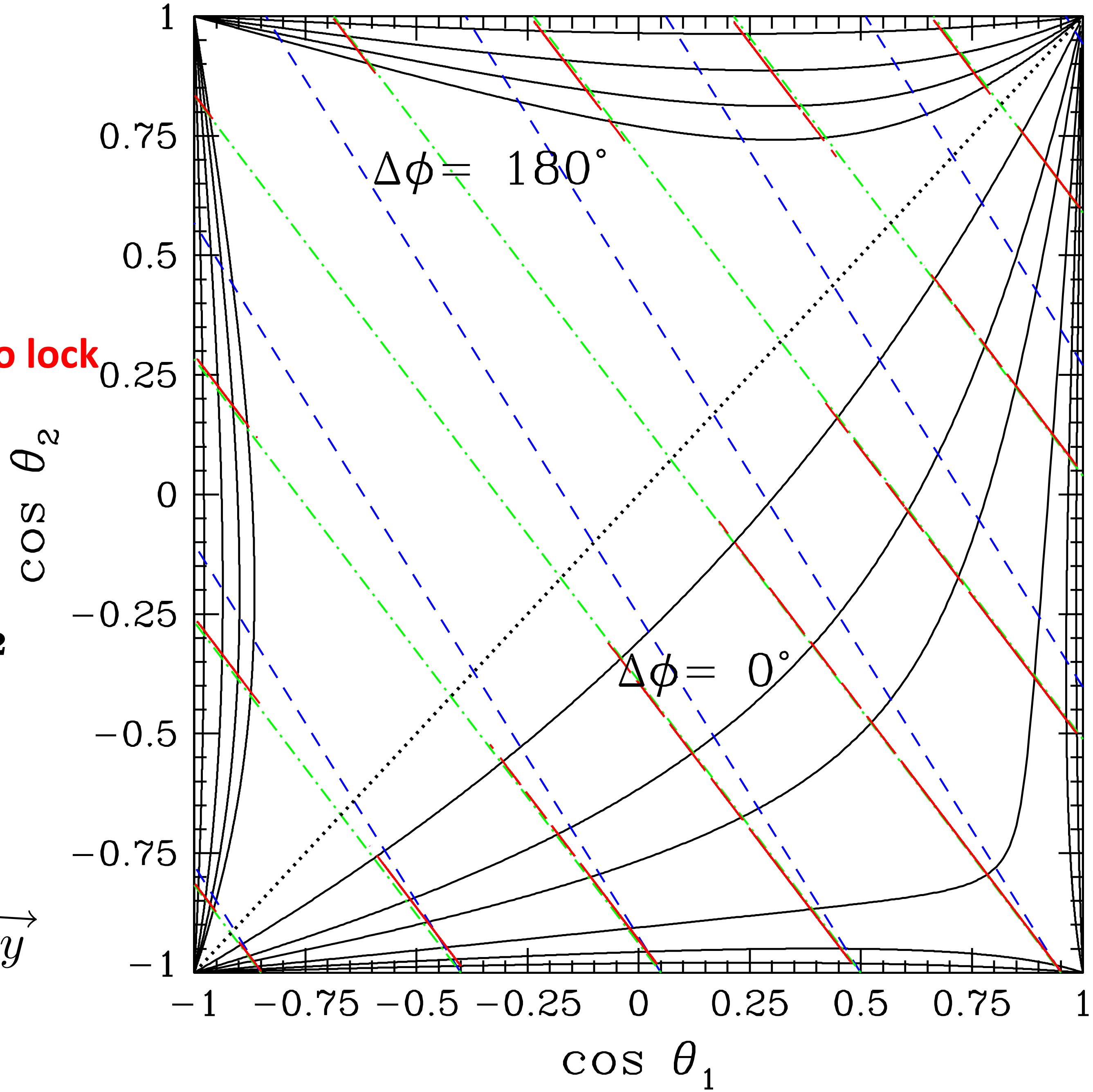
$$0.4 \lesssim q \lesssim 1$$

$$\chi_i \gtrsim 0.5$$

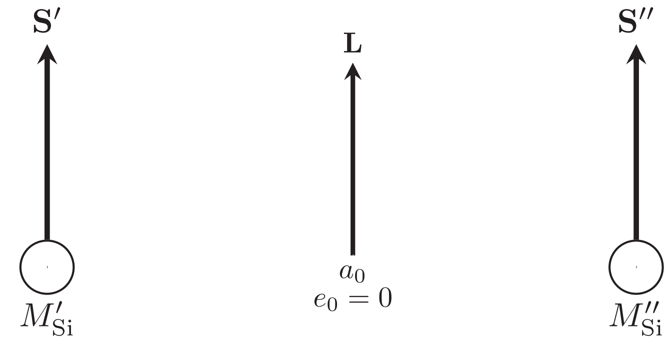
Neutron stars unlikely to lock

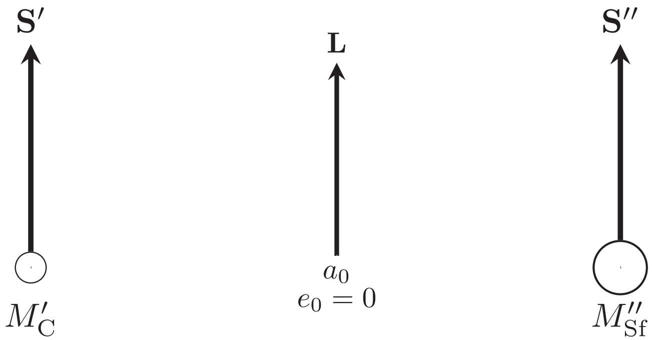
[Kesden+, 1002.2643]



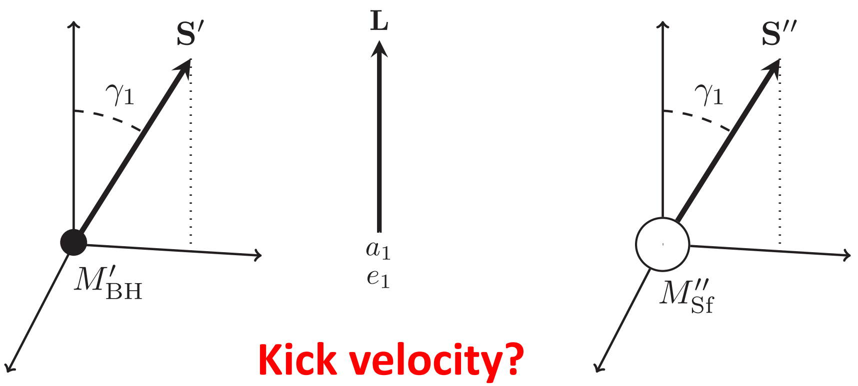


[Gerosa+, 1302.4442]

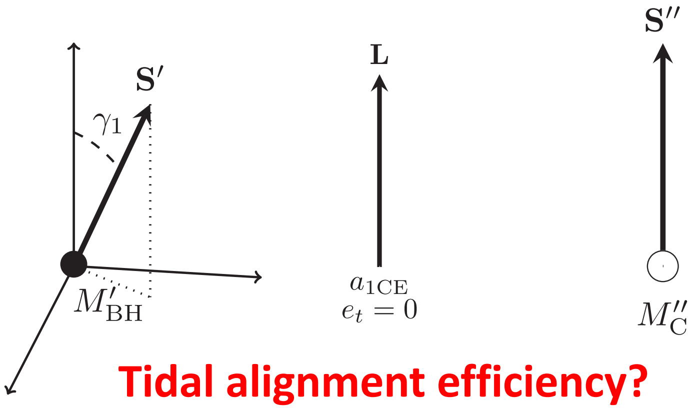

(a) Main-sequence binary


(b) First mass-transfer phase

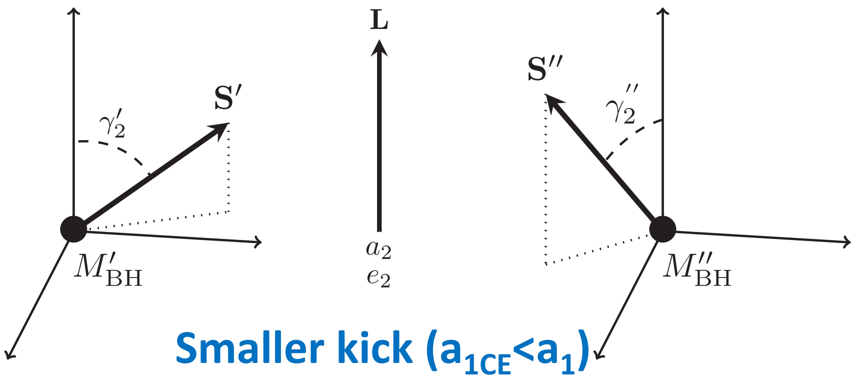
Fraction of mass lost by 1 & accreted by 2, f_a?


(c) 1st Supernova explosion

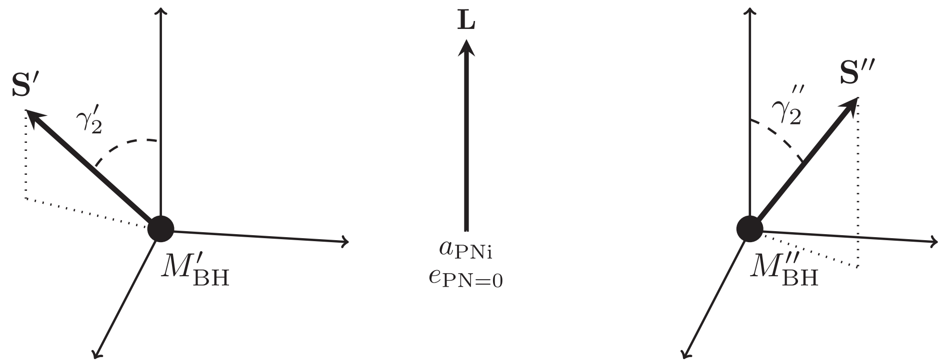
Kick velocity?


(d) Tides, common envelope, BH precession

Tidal alignment efficiency?

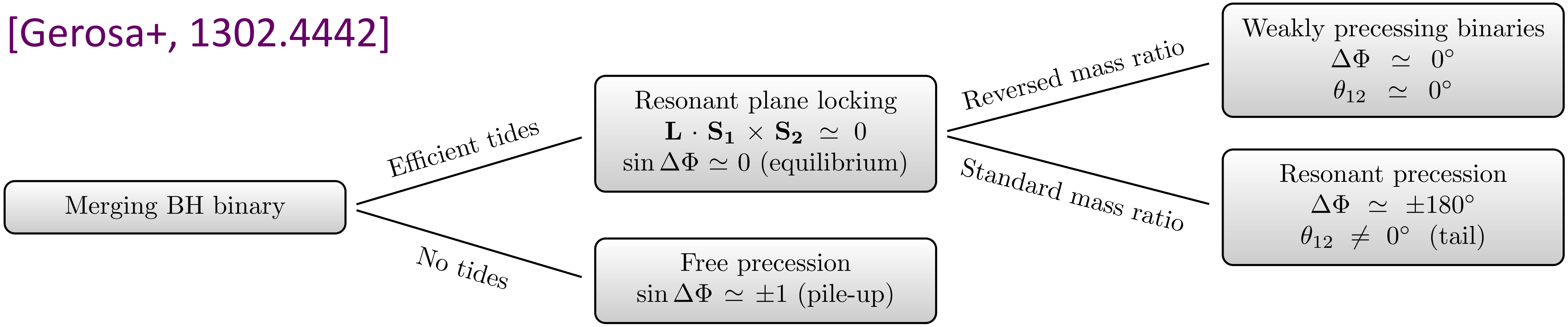

(e) 2nd Supernova explosion

Smaller kick ($a_{\rm 1CE} < a_1$)


(f) Post-Newtonian evolution

Inverse problem: binary evolution from GW observations

[Gerosa+, 1302.4442]



Merging BH binary

Efficient tides

Resonant plane locking
$\mathbf{L} \cdot \mathbf{S_1} \times \mathbf{S_2} \simeq 0$
$\sin \Delta\Phi \simeq 0$ (equilibrium)

No tides

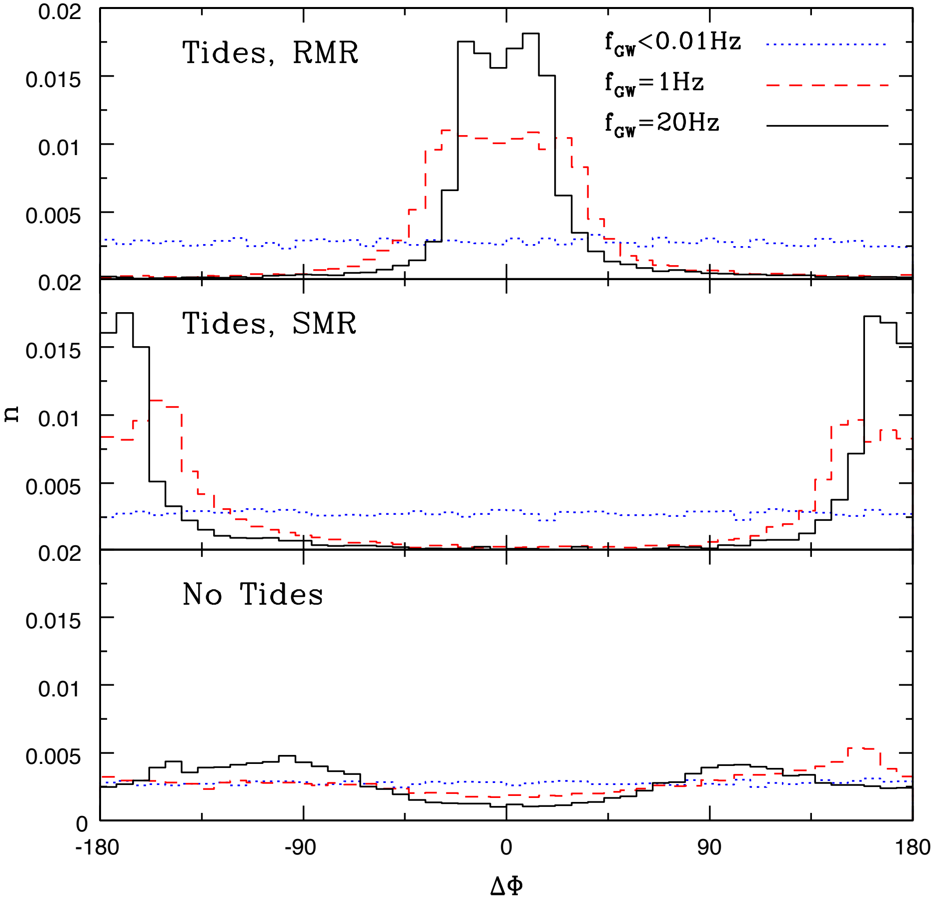
Free precession
$\sin \Delta\Phi \simeq \pm 1$ (pile-up)

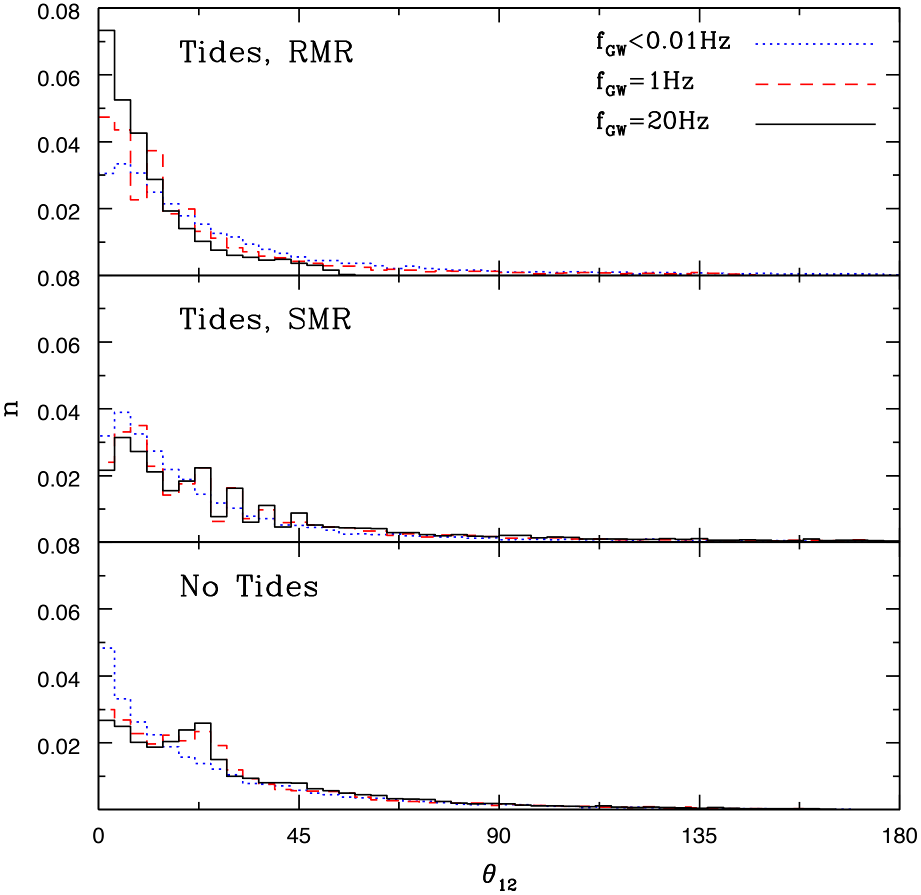
Reversed mass ratio

Weakly precessing binaries
$\Delta\Phi \simeq 0°$
$\theta_{12} \simeq 0°$

Standard mass ratio

Resonant precession
$\Delta\Phi \simeq \pm 180°$
$\theta_{12} \neq 0°$ (tail)





Separation of time scales

$$r_\mathrm{g} = \frac{GM}{c^2}$$

$$q = \frac{m_2}{m_1} \leq 1$$

$$E = -\frac{G\eta M^2}{2r}$$

$$\eta = \frac{m_1 m_2}{M^2} = \frac{q}{(1+q)^2}$$

$$L = \eta(rGM^3)^{1/2}$$

$$t_\mathrm{orb} \sim \frac{1}{\omega_\mathrm{orb}} \sim \left(\frac{r^3}{GM}\right)^{1/2}$$

$$t_\mathrm{pre} \sim \frac{1}{\omega_\mathrm{pre}} \sim \frac{1}{\eta}\frac{c^2 r^{5/2}}{(GM)^{3/2}} \sim \frac{t_\mathrm{orb}}{\eta}\frac{r}{r_\mathrm{g}}$$

$$t_\mathrm{GW} \sim \frac{E}{\dot{E}_\mathrm{GW}} \sim \frac{1}{\eta}\frac{c^5 r^4}{(GM)^3} \sim \frac{t_\mathrm{orb}}{\eta}\left(\frac{r}{r_\mathrm{g}}\right)^{5/2}$$

$$t_\mathrm{orb} \ll t_\mathrm{pre} \ll t_\mathrm{GW}$$

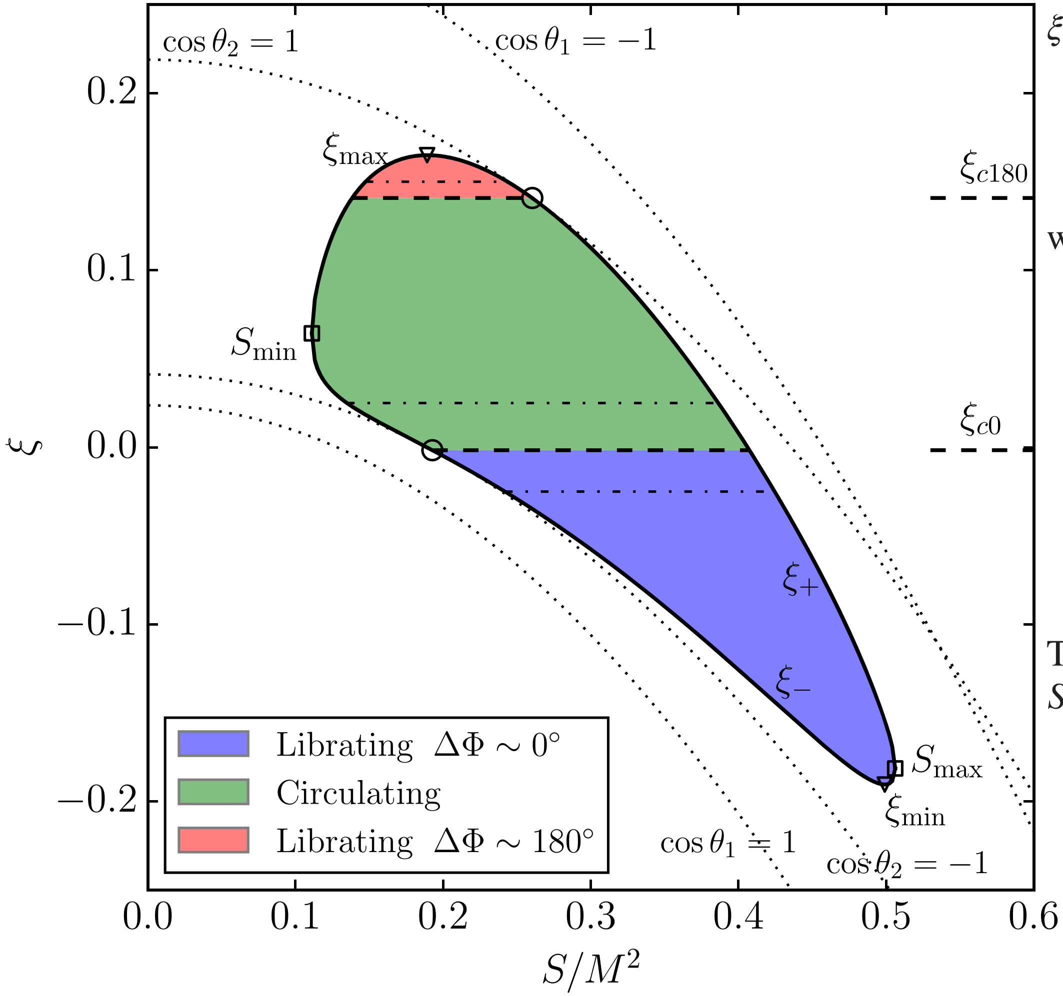
[Kesden+, 1411.0674]

Effective spin conservation and effective potential

Only S varies on precessional time scale

$$E = V(r, L) \Longrightarrow r_\pm(E, L) \qquad \xi = \xi_\pm(S) \Longrightarrow S_\pm(L, J, \xi)$$

$$\boxed{\xi \equiv M^{-2}[(1+q)\mathbf{S}_1 + (1+q^{-1})\mathbf{S}_2] \cdot \hat{\mathbf{L}}}$$



$$\xi(S,\varphi') = \{(J^2 - L^2 - S^2)[S^2(1+q)^2 - (S_1^2 - S_2^2)(1-q^2)] - (1-q^2)A_1A_2A_3A_4\cos\varphi'\}/(4qM^2S^2L), \quad (4)$$

where

$$A_1 \equiv [J^2 - (L-S)^2]^{1/2}, \quad (5a)$$

$$A_2 \equiv [(L+S)^2 - J^2]^{1/2}, \quad (5b)$$

$$A_3 \equiv [S^2 - (S_1 - S_2)^2]^{1/2}, \quad (5c)$$

$$A_4 \equiv [(S_1 + S_2)^2 - S^2]^{1/2}. \quad (5d)$$

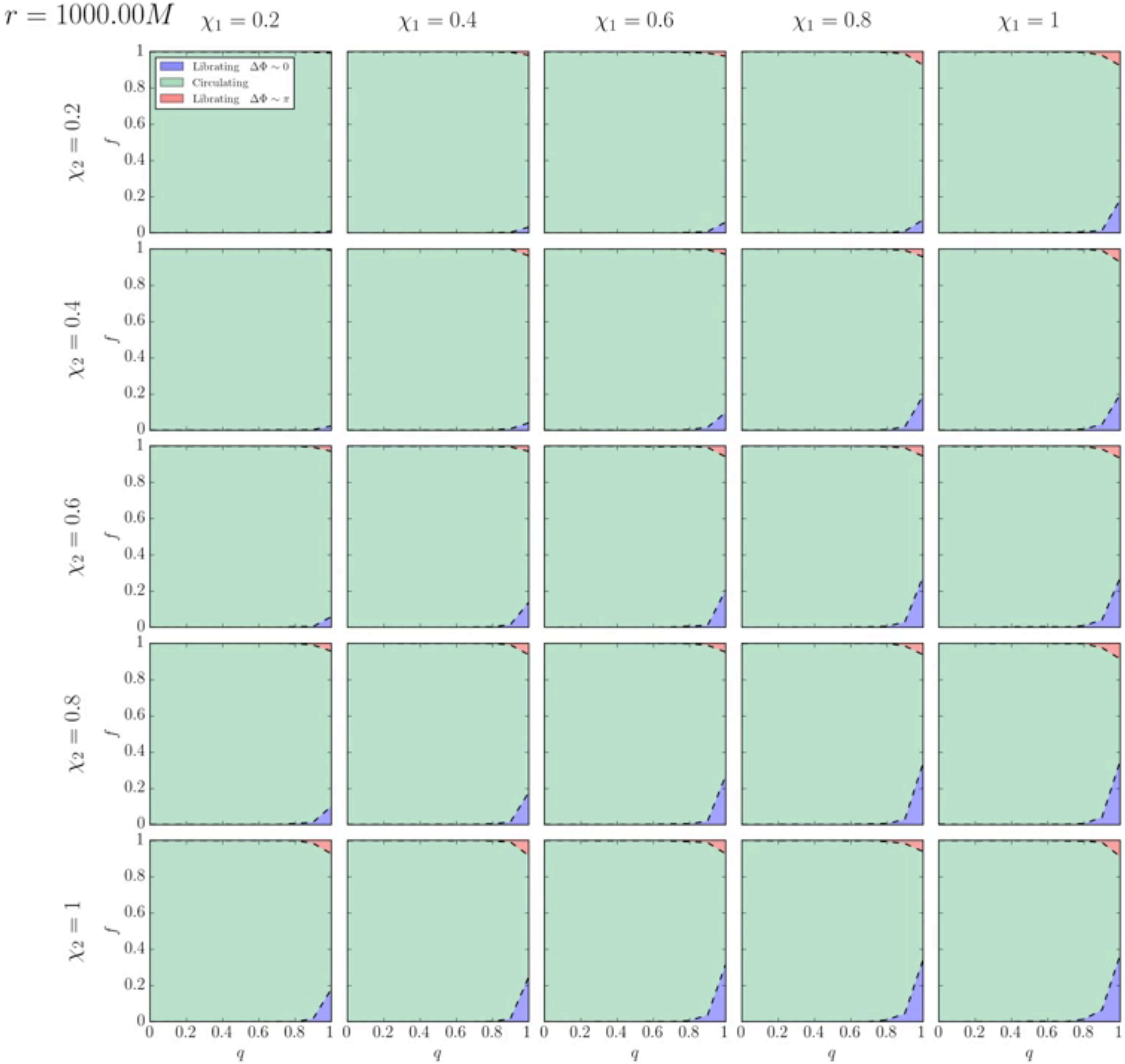
The A_i's are real in the allowed range $J_{\rm min} \le J \le J_{\rm max}$, $S_{\rm min} \le S \le S_{\rm max}$, where

$$J_{\rm min} = L - S_1 - S_2, \quad (6a)$$

$$J_{\rm max} = L + S_1 + S_2, \quad (6b)$$

$$S_{\rm min} = \max\{|J-L|, |S_1 - S_2|\}, \quad (6c)$$

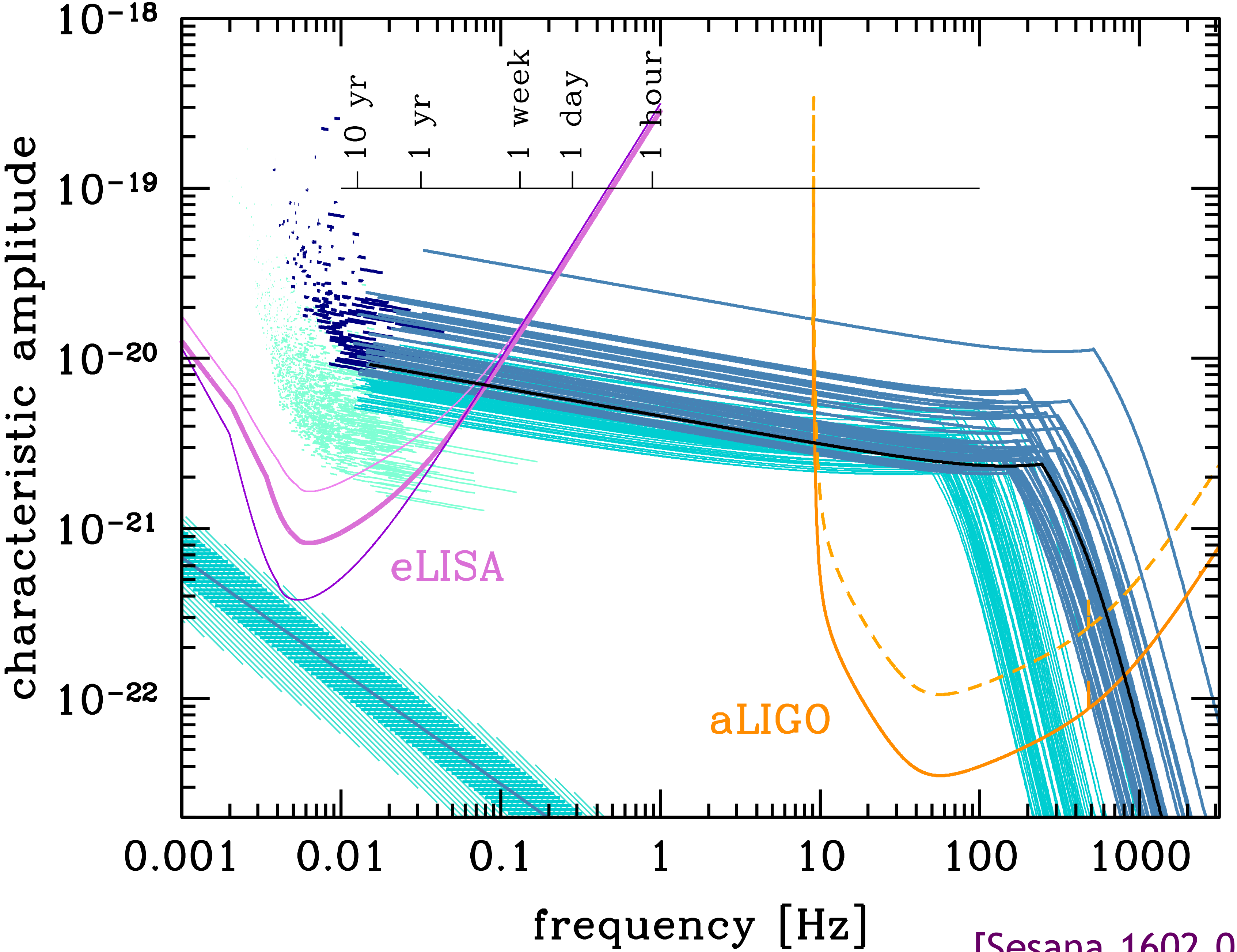
$$S_{\rm max} = \min\{J + L, S_1 + S_2\}. \quad (6d)$$


$r = 1000.00M$
$\chi_1 = 0.2$
$\chi_1 = 0.4$
$\chi_1 = 0.6$
$\chi_1 = 0.8$
$\chi_1 = 1$
$\chi_2 = 0.2$
$\chi_2 = 0.4$
$\chi_2 = 0.6$
$\chi_2 = 0.8$
$\chi_2 = 1$
Librating $\Delta\Phi \sim 0$
Circulating
Librating $\Delta\Phi \sim \pi$
f
q
0
0.2
0.4
0.6
0.8
1

Eccentricity

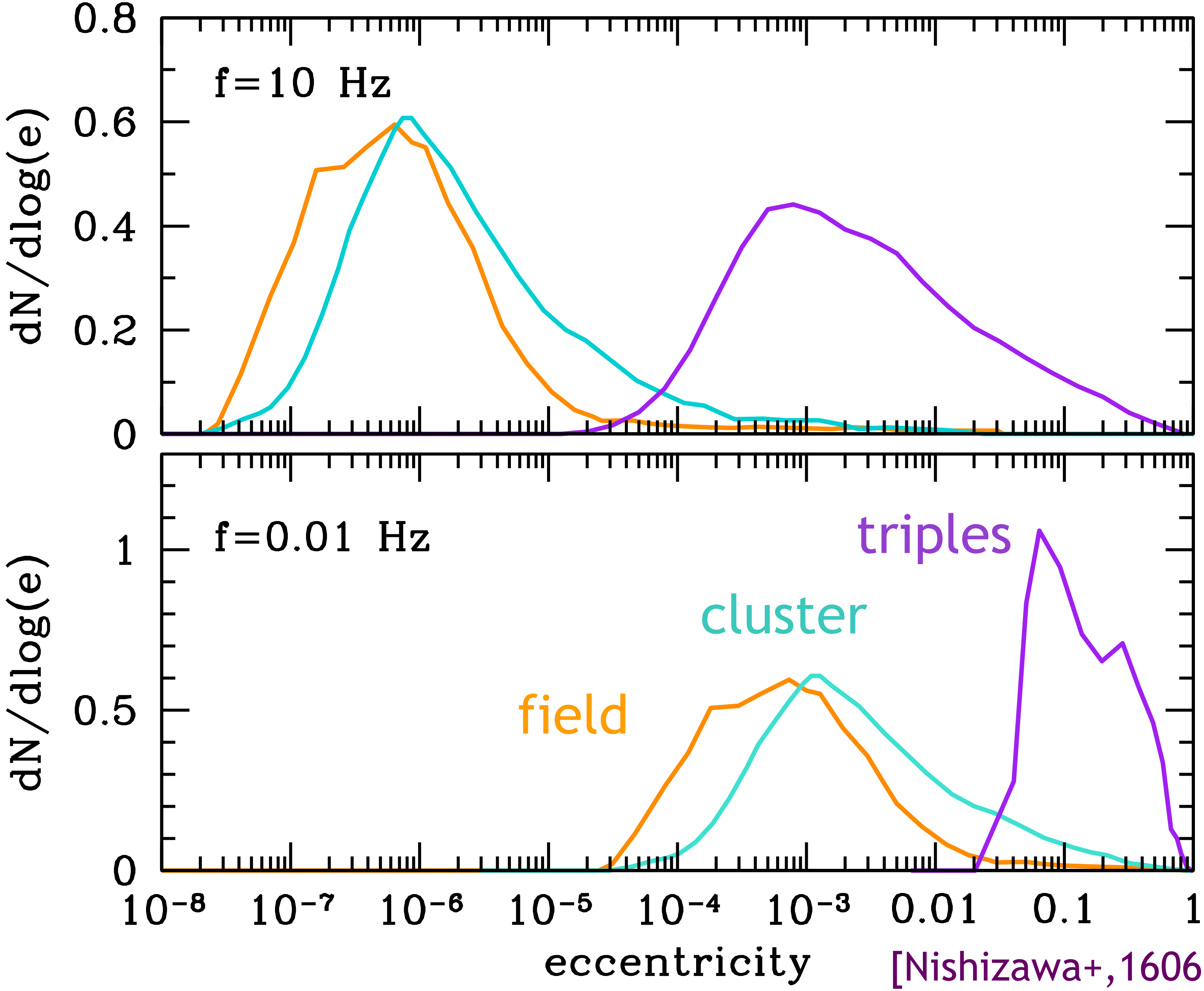
with Nishizawa, Klein, Sesana

Multi-band gravitational wave astronomy



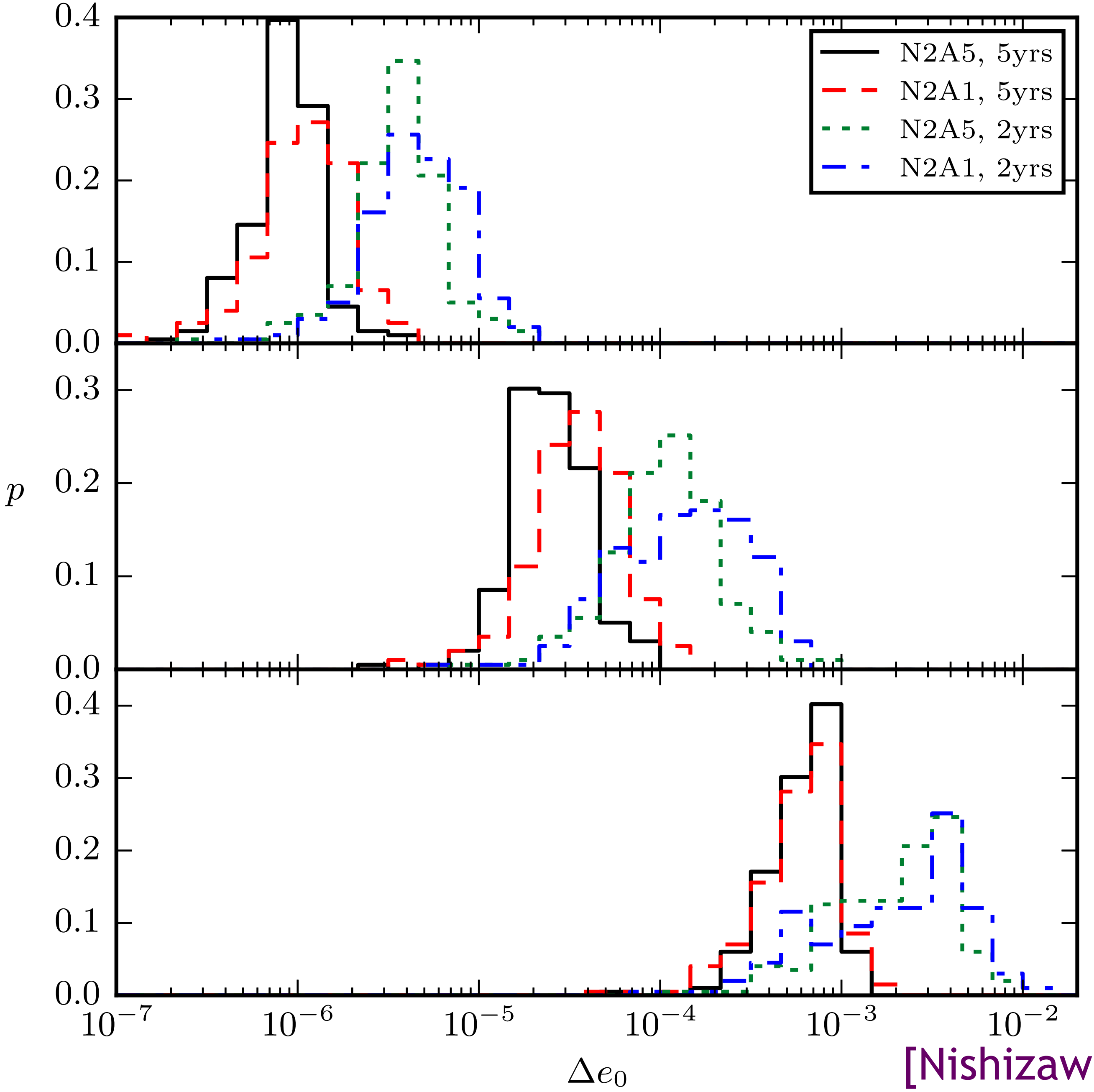
[Sesana,1602.06951]

Field, clusters or triples? $e \sim f^{-18/19} \sim f^{-1}$



[Nishizawa+,1606.09295]

Eccentricity: measurable if $e_0>10^{-3}$ at $f=10^{-2}$Hz



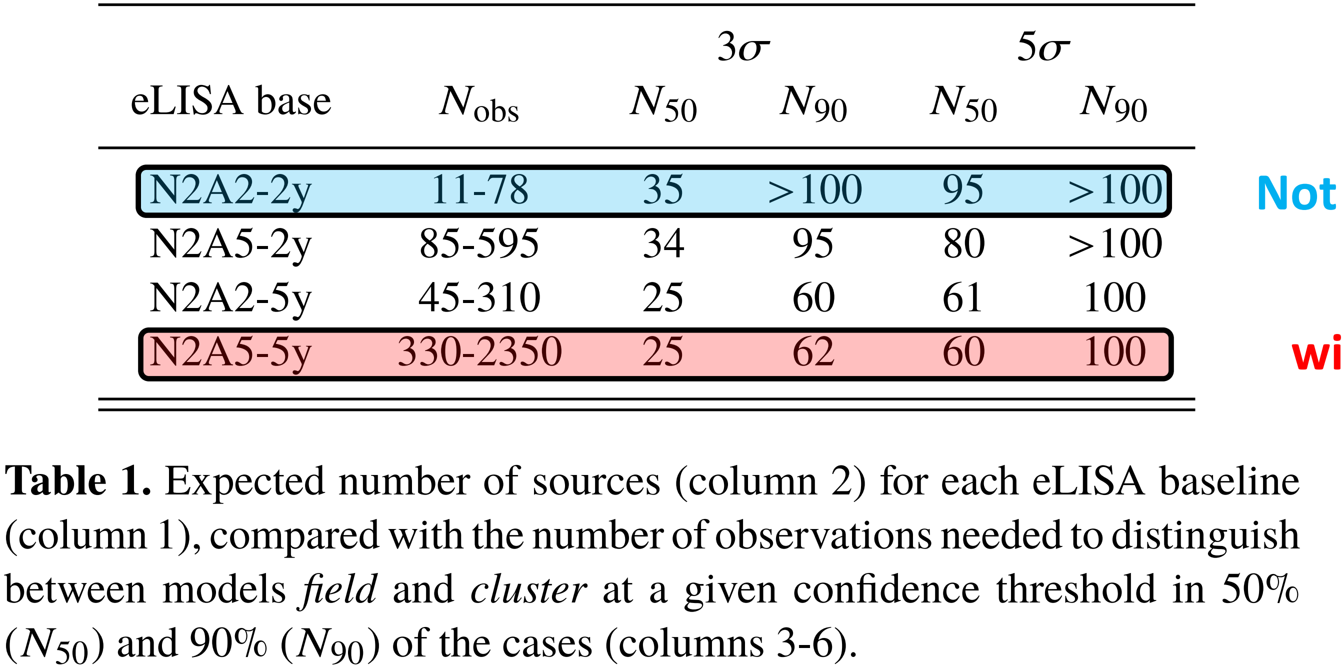
$e_0=0.1$

$e_0=0.01$

$e_0=0.001$

[Nishizawa+,1603.04075]

Field or cluster formation?



eLISA base	$N_{\rm obs}$	3σ N_{50}	3σ N_{90}	5σ N_{50}	5σ N_{90}
N2A2-2y	11-78	35	>100	95	>100
N2A5-2y	85-595	34	95	80	>100
N2A2-5y	45-310	25	60	61	100
N2A5-5y	330-2350	25	62	60	100

Table 1. Expected number of sources (column 2) for each eLISA baseline (column 1), compared with the number of observations needed to distinguish between models *field* and *cluster* at a given confidence threshold in 50% (N_{50}) and 90% (N_{90}) of the cases (columns 3-6).

Not enough detections?

5σ confidence
with 90% probability

Predictions may be **pessimistic!**

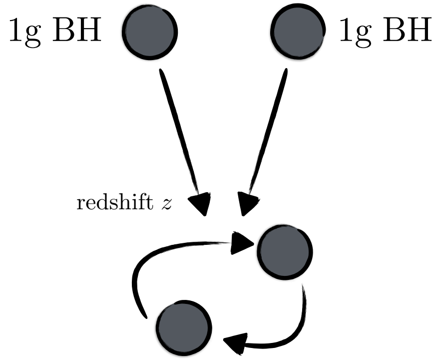
Correlations between e and masses/spins/kicks will help

[Nishizawa+,1606.09295]
[Breivik+, 1606.09558]

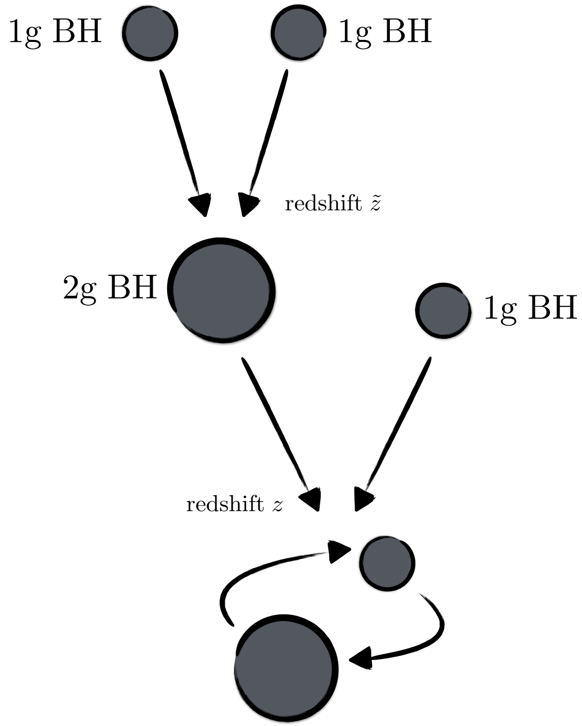
Collapse or previous mergers?

with Gerosa

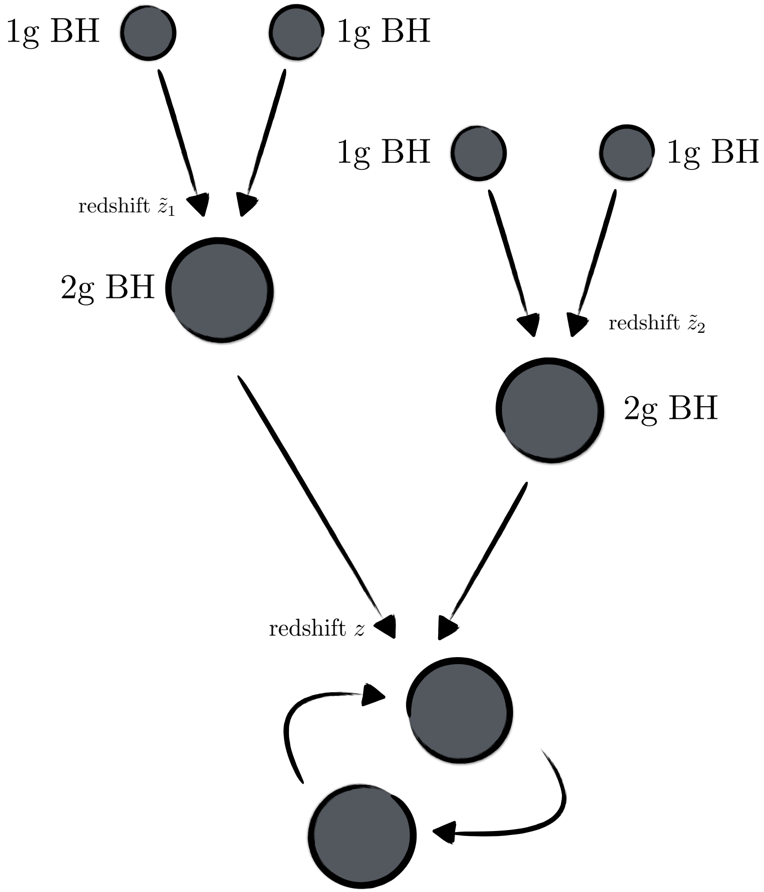
Collapse or previous mergers?



1g+1g event



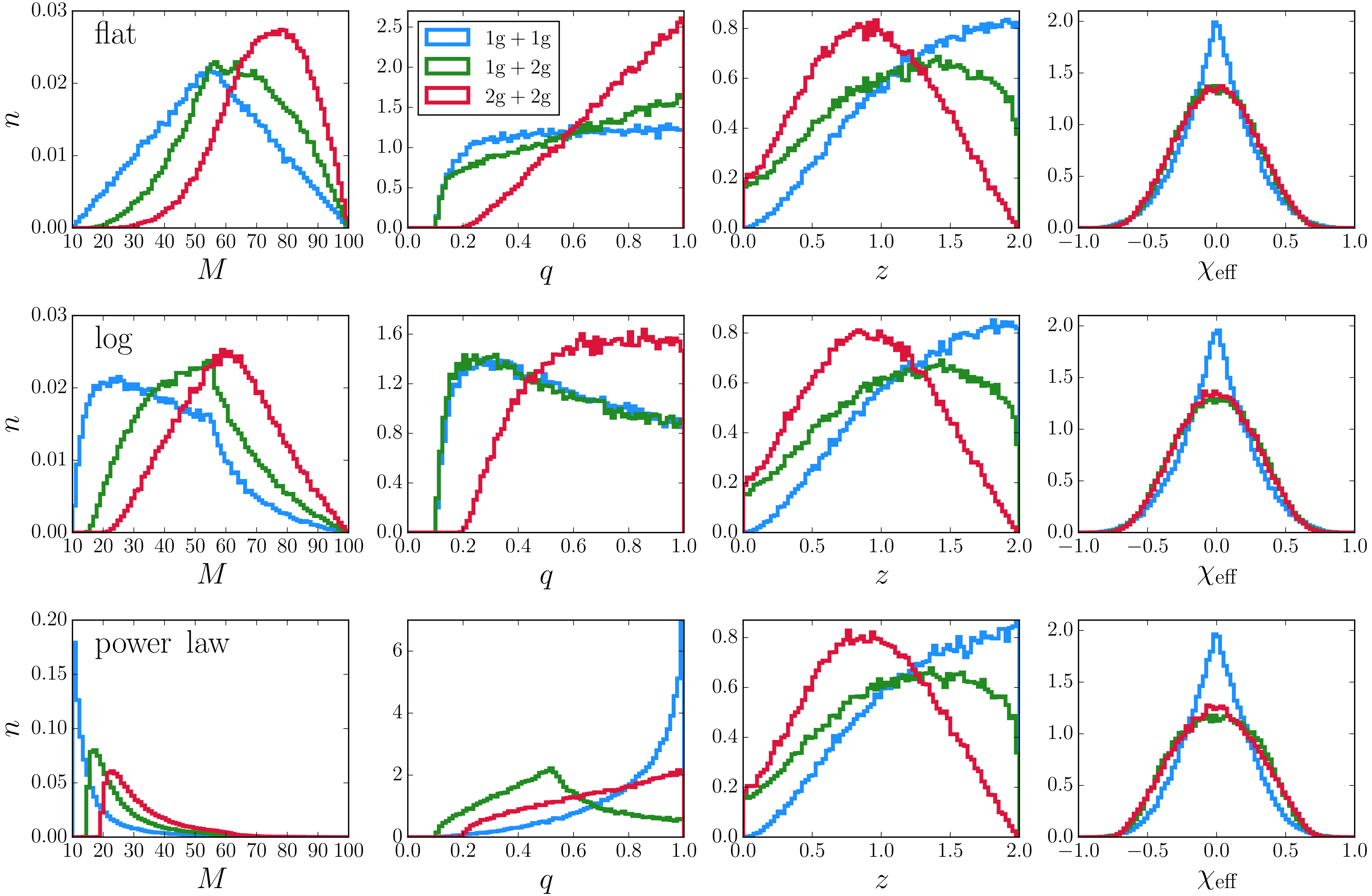
1g+2g event



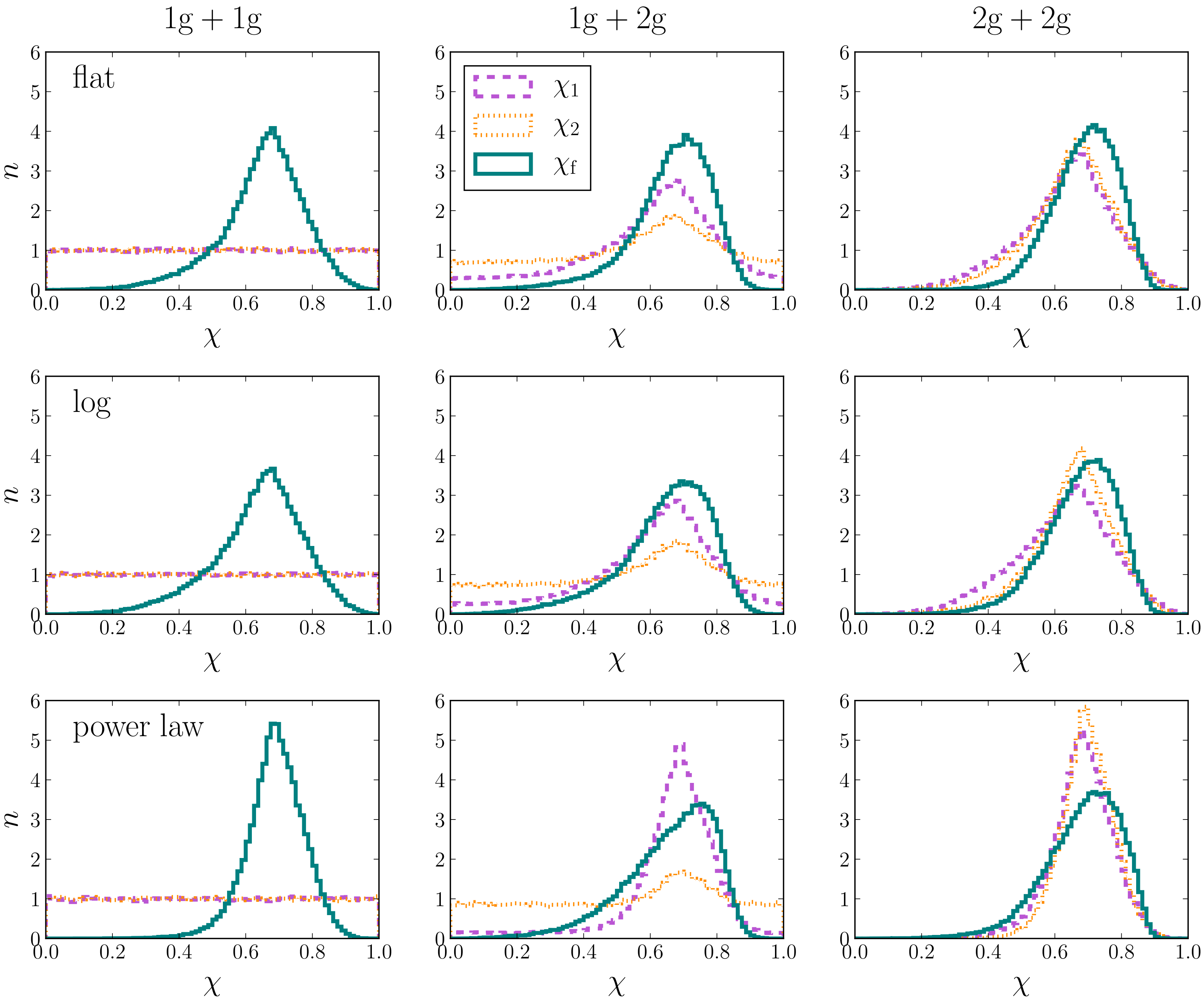
2g+2g event

[Gerosa+EB,1703.06223; Fishbach+, 1703.06869]

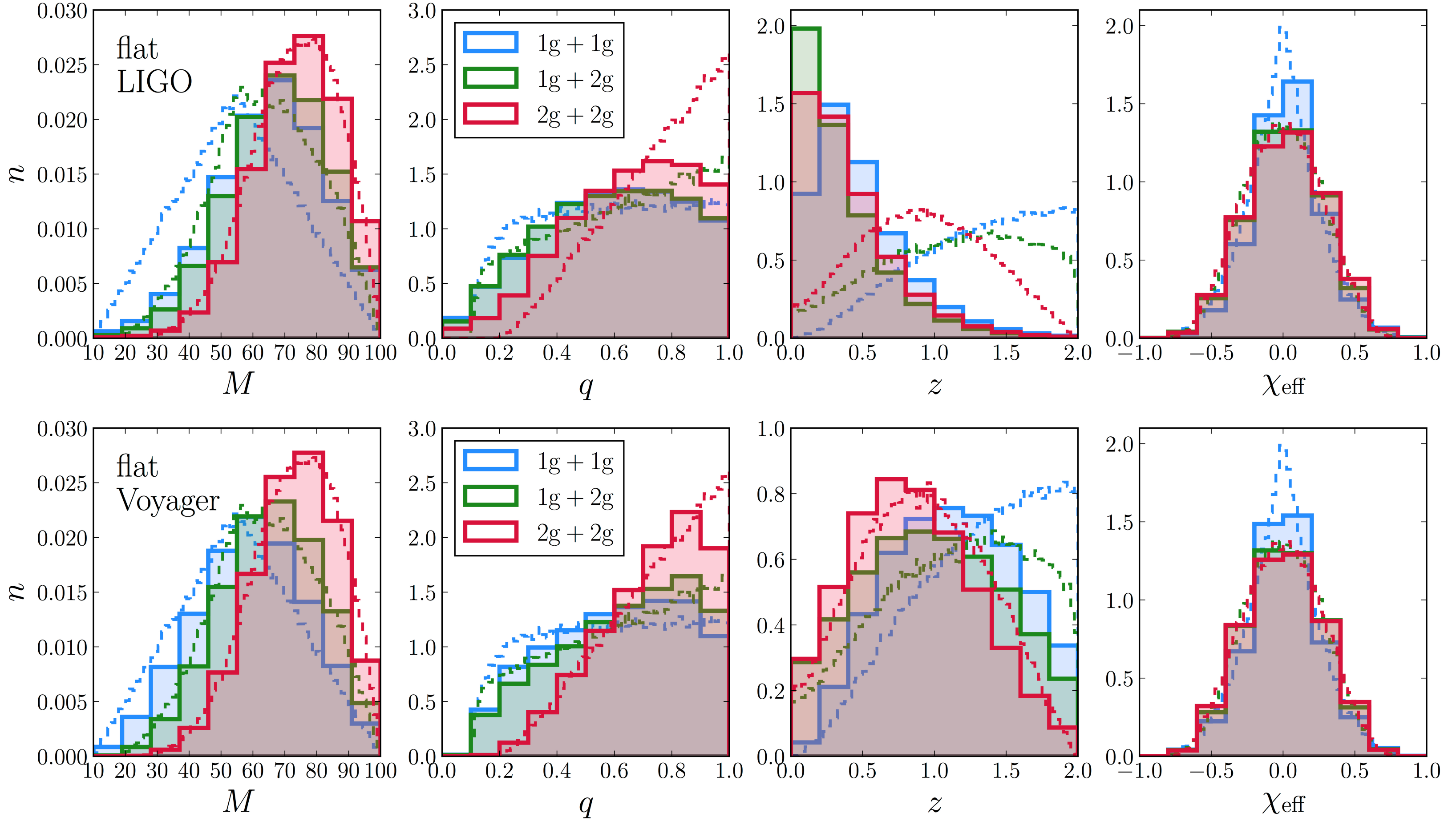
Collapse or previous mergers? LIGO observables



Collapse or previous mergers?

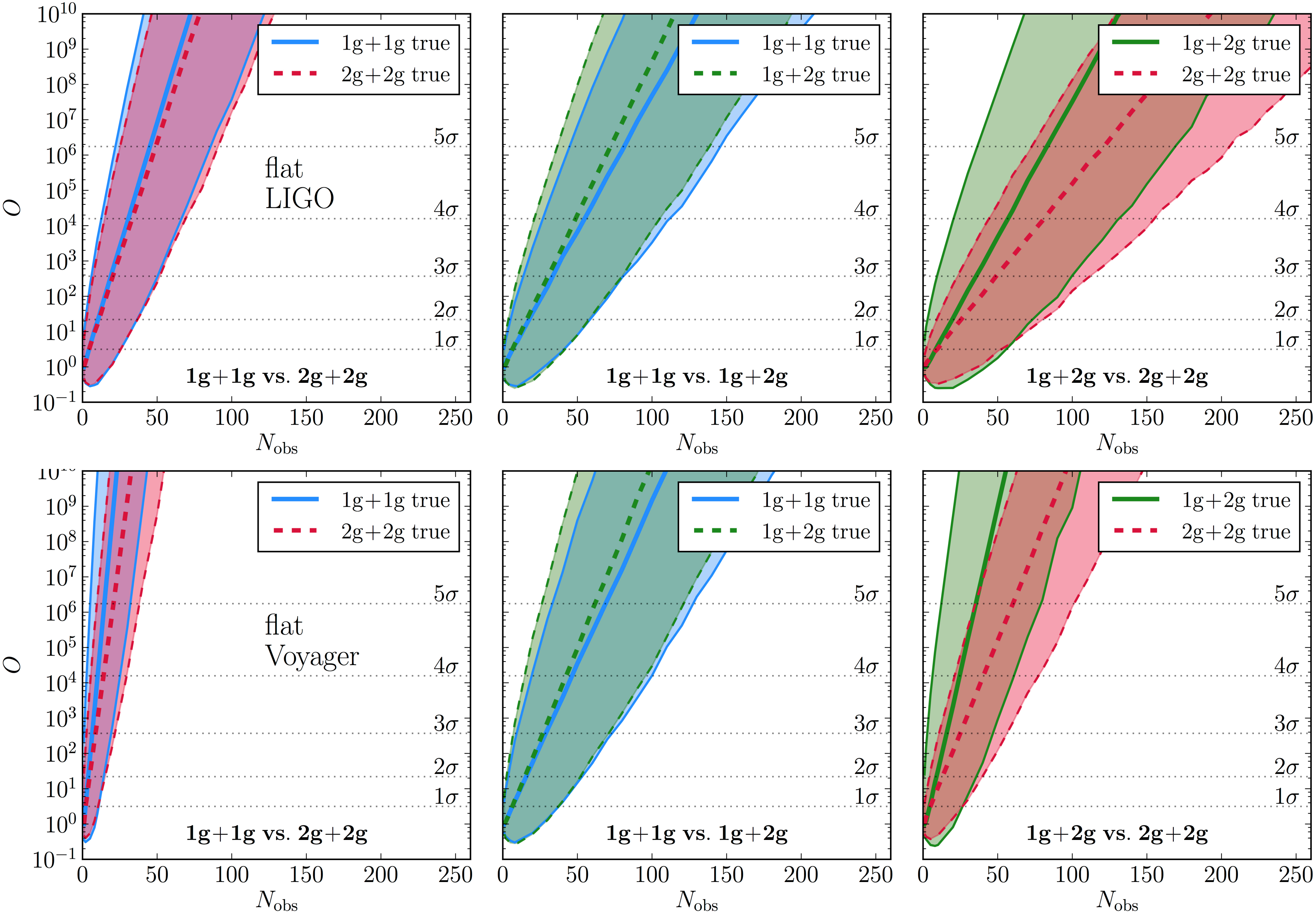


Collapse or previous mergers?



		1g+1g vs. 2g+2g	1g+1g vs. 1g+2g	1g+2g vs. 2g+2g
O1 LIGO	flat	12.7 (15.8)	2.0 (2.0)	6.4 (7.6)
	log	3.3 (3.5)	0.9 (0.9)	3.5 (3.8)
	power law	0.7 (1.0)	1.3 (1.6)	0.6 (0.6)
Ad. LIGO (design)	flat	30.2 (37.8)	1.4 (3.7)	21.9 (10.11)
	log	4.3 (7.0)	0.6 (1.4)	6.9 (5.1)
	power law	0.6 (1.7)	1.0 (3.8)	0.6 (0.5)

Collapse or previous mergers?



Fundamental physics: strong gravity, beyond Standard Model

Modified gravity and new physics with gravitational waves

New physics

- **Modified GR**
  - Most theories: same BHs as GR
  - Dynamics can be different

$$G_{\mu\nu}$$

- **Beyond Standard Model physics**

$$T_{\mu\nu}$$

Can we test…

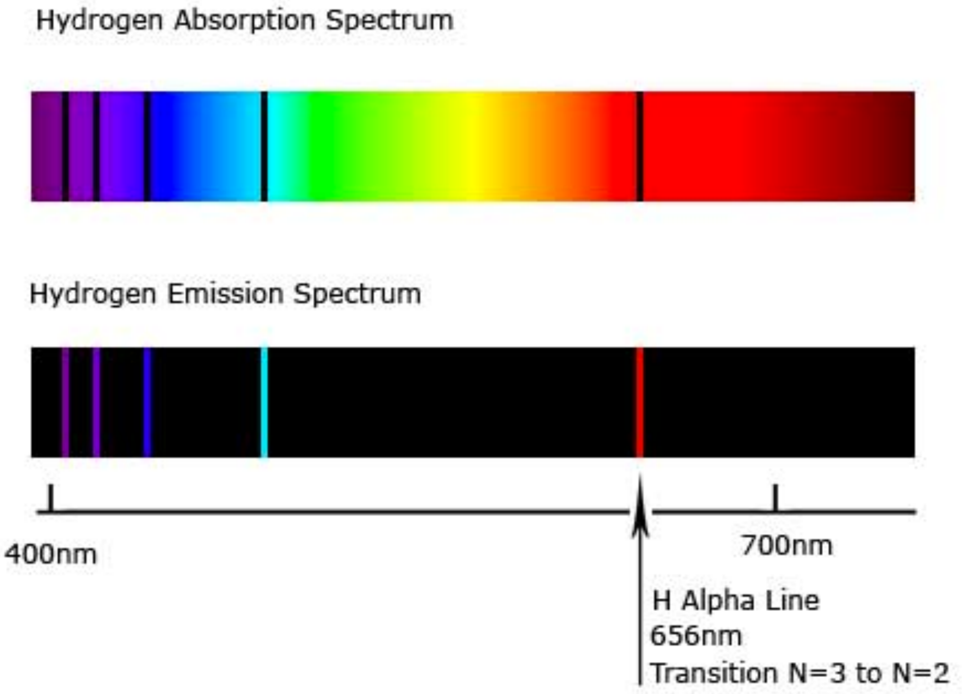
- **The Kerr paradigm?**
  - Metric (no-hair theorem)
  - Dynamics (GWs)
- **Theories beyond GR**
  - Current constraints
  - Parametrized tests vs specific theories
  - An example: scalar-Gauss-Bonnet gravity
- **Exotic compact objects & beyond SM?**
  - Formation
  - Generic instability
  - Observational signatures?
- **Ultralight fields/dark matter candidates?**
  - Astrophysics and rates
  - Formation/nonlinearities/spin 1, spin 2

Black hole spectroscopy

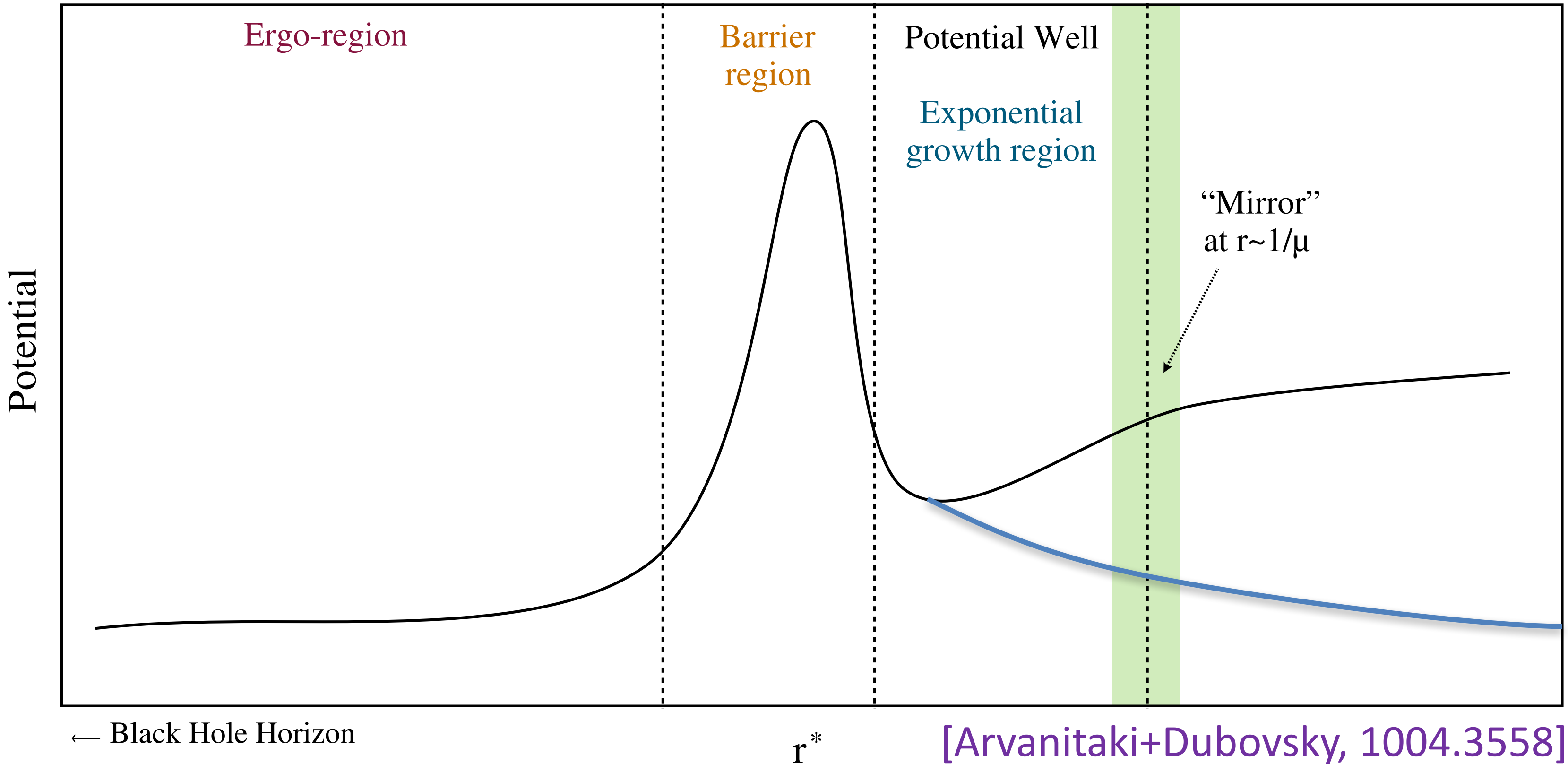
with Cardoso, Barausse, Baibhav, Belczynski, Sesana…

Black hole spectroscopy

"After the advent of gravitational wave astronomy, the observation of [the black hole's] resonant frequencies might finally provide direct evidence of black holes with the same certainty as, say, the 21 cm line identifies interstellar hydrogen."
Steve Detweiler, ApJ 239, 292 (1980)



Black hole dynamics: wave scattering



[Arvanitaki+Dubovsky, 1004.3558]

Quasinormal modes:

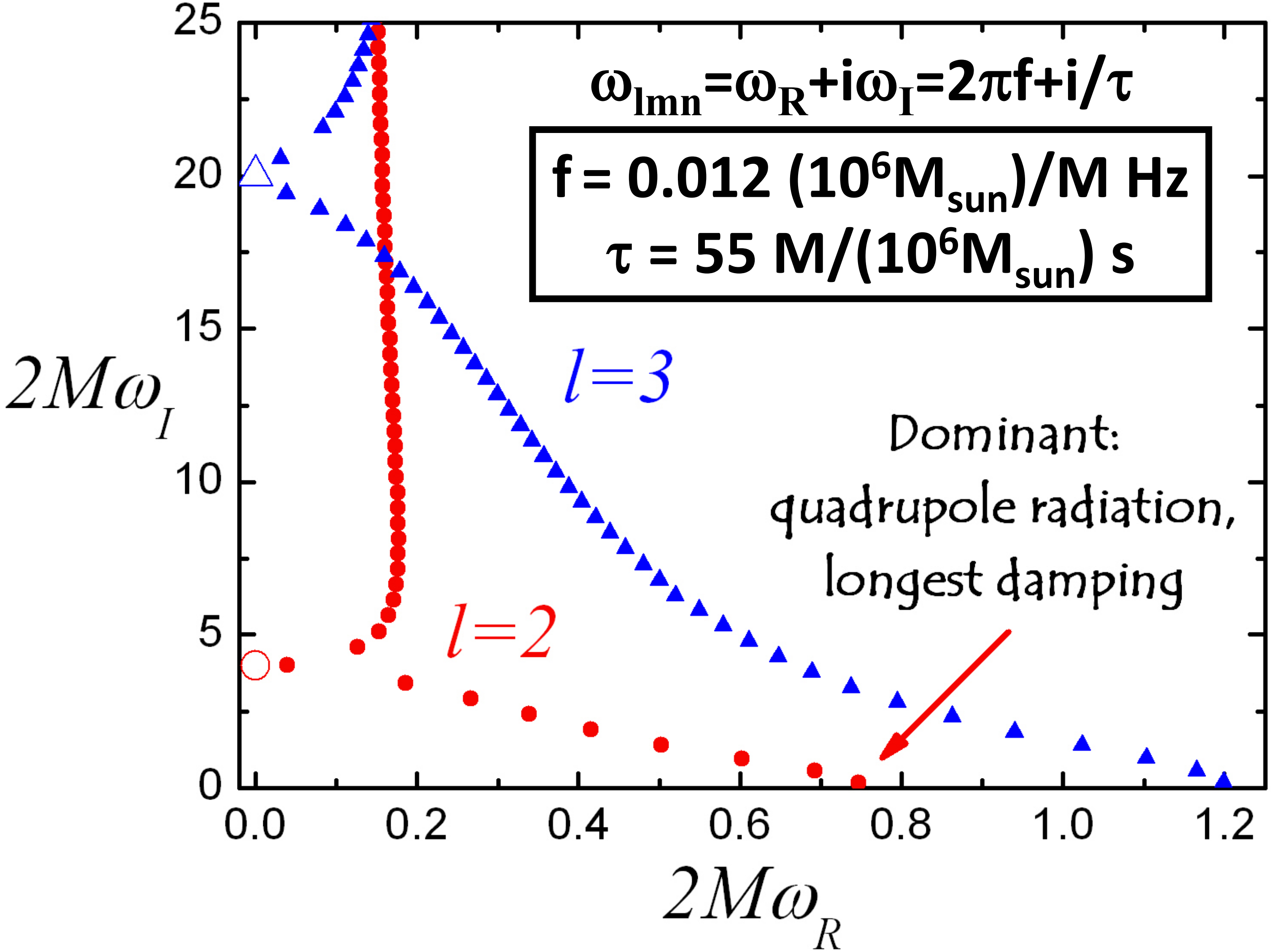
- ☐ Ingoing waves at the horizon, outgoing waves at infinity
- ☐ Discrete spectrum of damped exponentials ("ringdown") [EB++, 0905.2975]

Massive scalar field:

- ☐ Superradiance: black hole bomb when $0 < \omega < m\Omega_H$
- ☐ Hydrogen-like, unstable bound states [Detweiler, Zouros+Eardley…]

Ringdown: black hole spectroscopy

$$r\left(h_{+}+ih_{\times}\right)=\sum_{lmn}A_{lmn}\exp(i\omega_{lmn}t)S_{lmn}(\theta,\varphi)$$

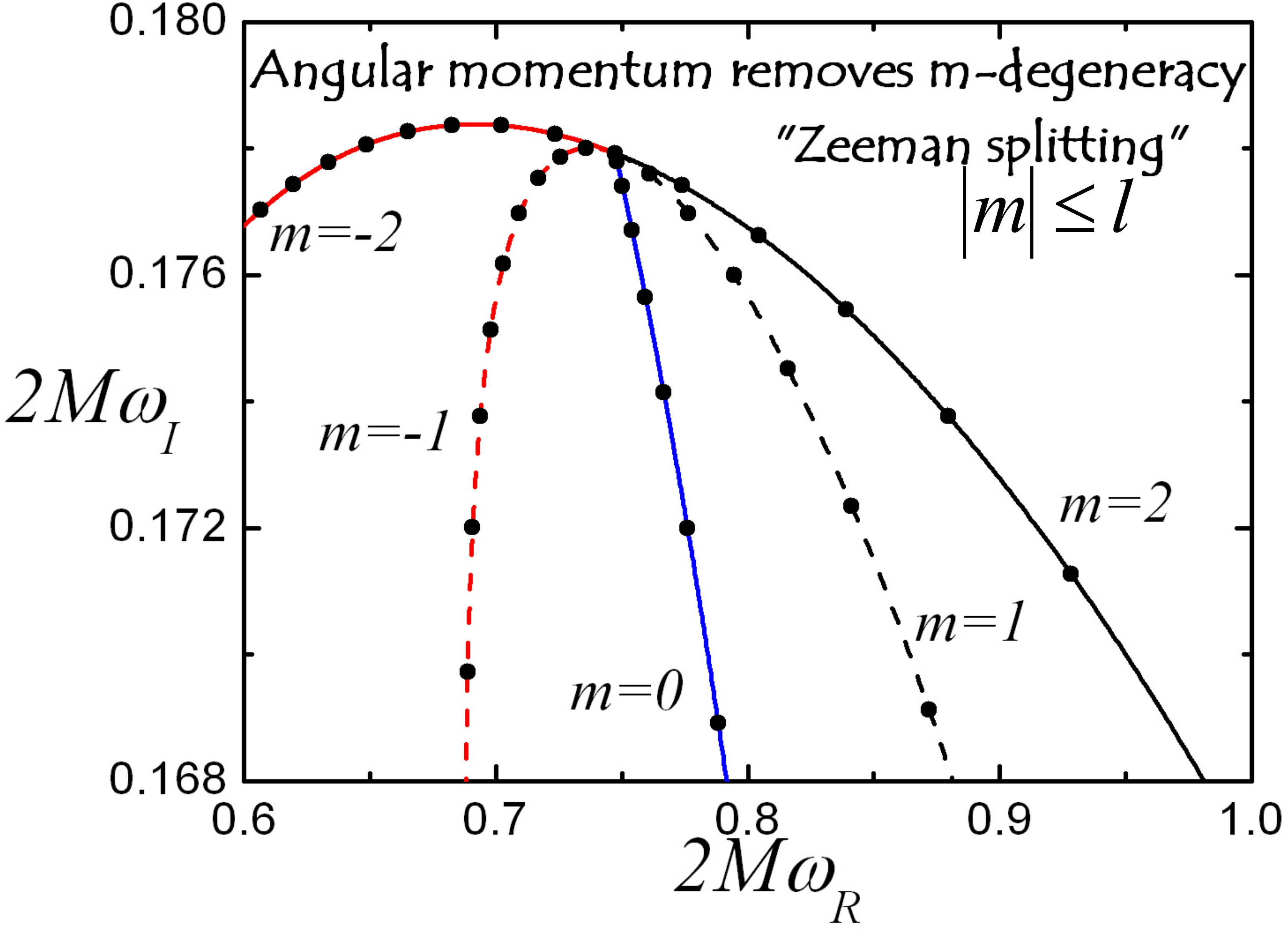


$\omega_{lmn}=\omega_R+i\omega_I=2\pi f+i/\tau$

$f = 0.012\ (10^6 M_{sun})/M$ Hz
$\tau = 55\ M/(10^6 M_{sun})$ s

Dominant:
quadrupole radiation,
longest damping

Spectroscopy of rotating (Kerr) black holes



Angular momentum removes m-degeneracy

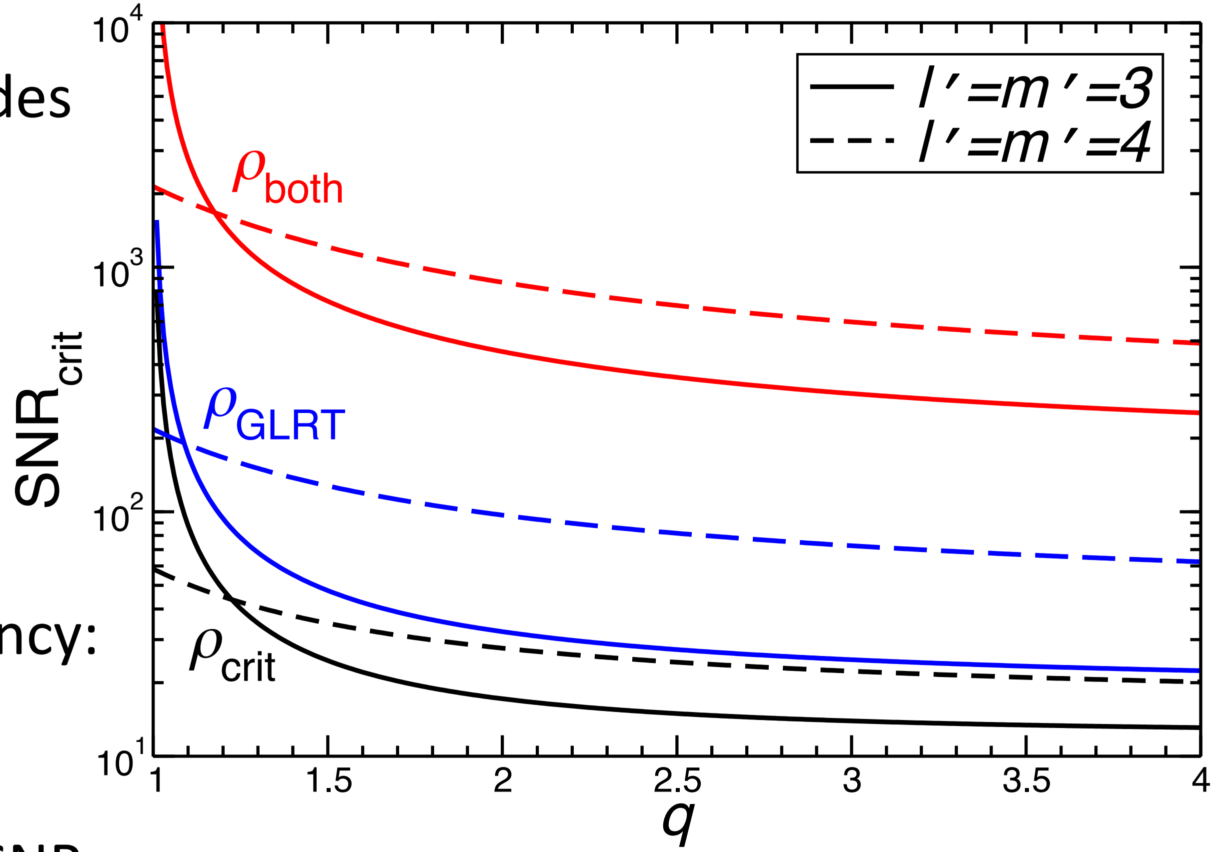
"Zeeman splitting"

$|m| \leq l$

Critical SNR for black hole spectroscopy

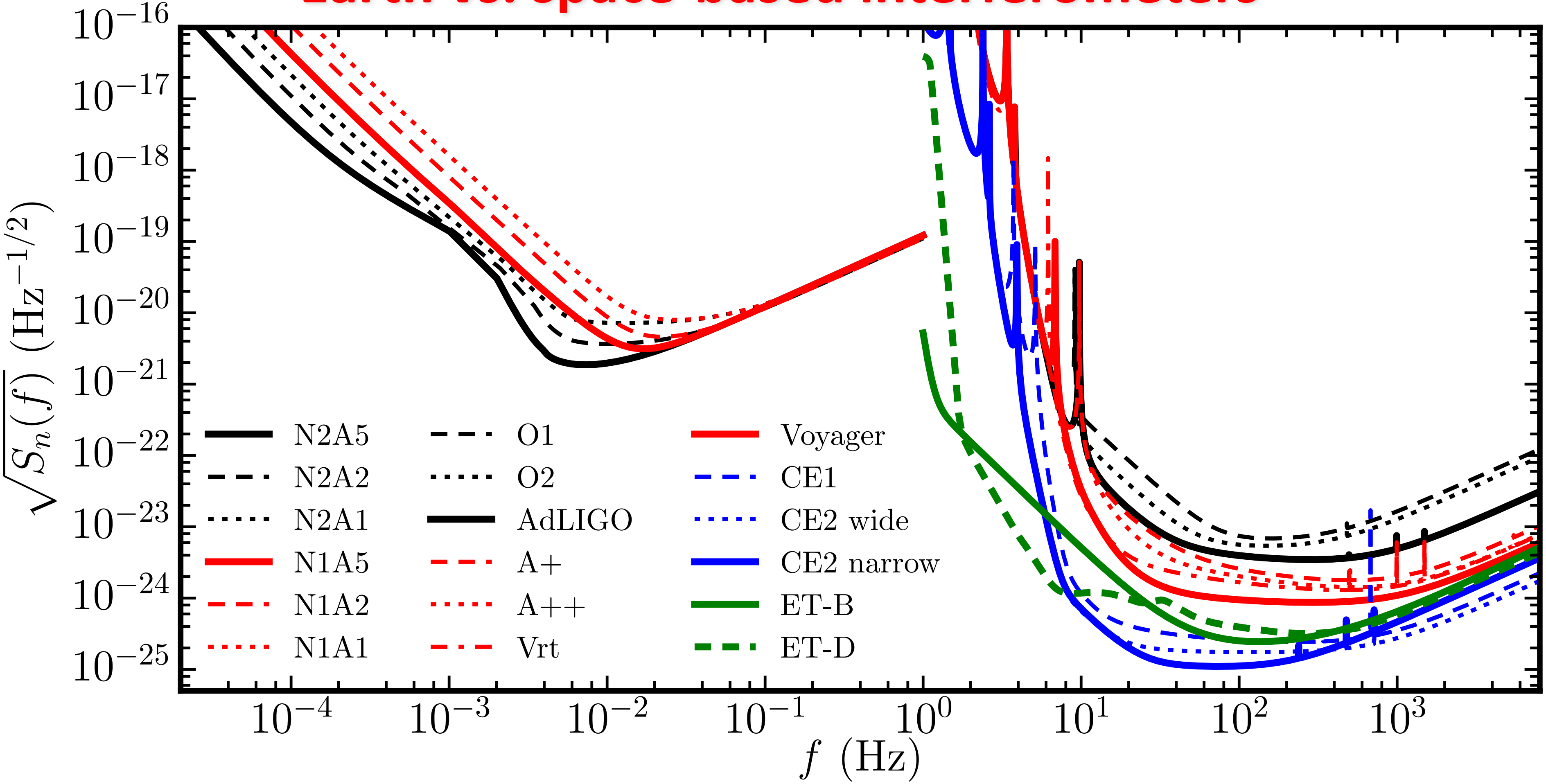
- ☐ In GR, black holes oscillate in a set of discrete complex-frequency modes (quasinormal modes) determined only by mass **M** and spin **a**
- ☐ One mode: **(M,a)**
- ☐ Any other mode frequency: **No-hair theorem test**

[EB+, gr-qc/0707.1202]



- ☐ Feasibility depends on SNR: **for nearly equal-mass binaries (q~1), need SNR>50 or so**
  GW150914: ringdown SNR of ~7

Earth vs. space-based interferometers

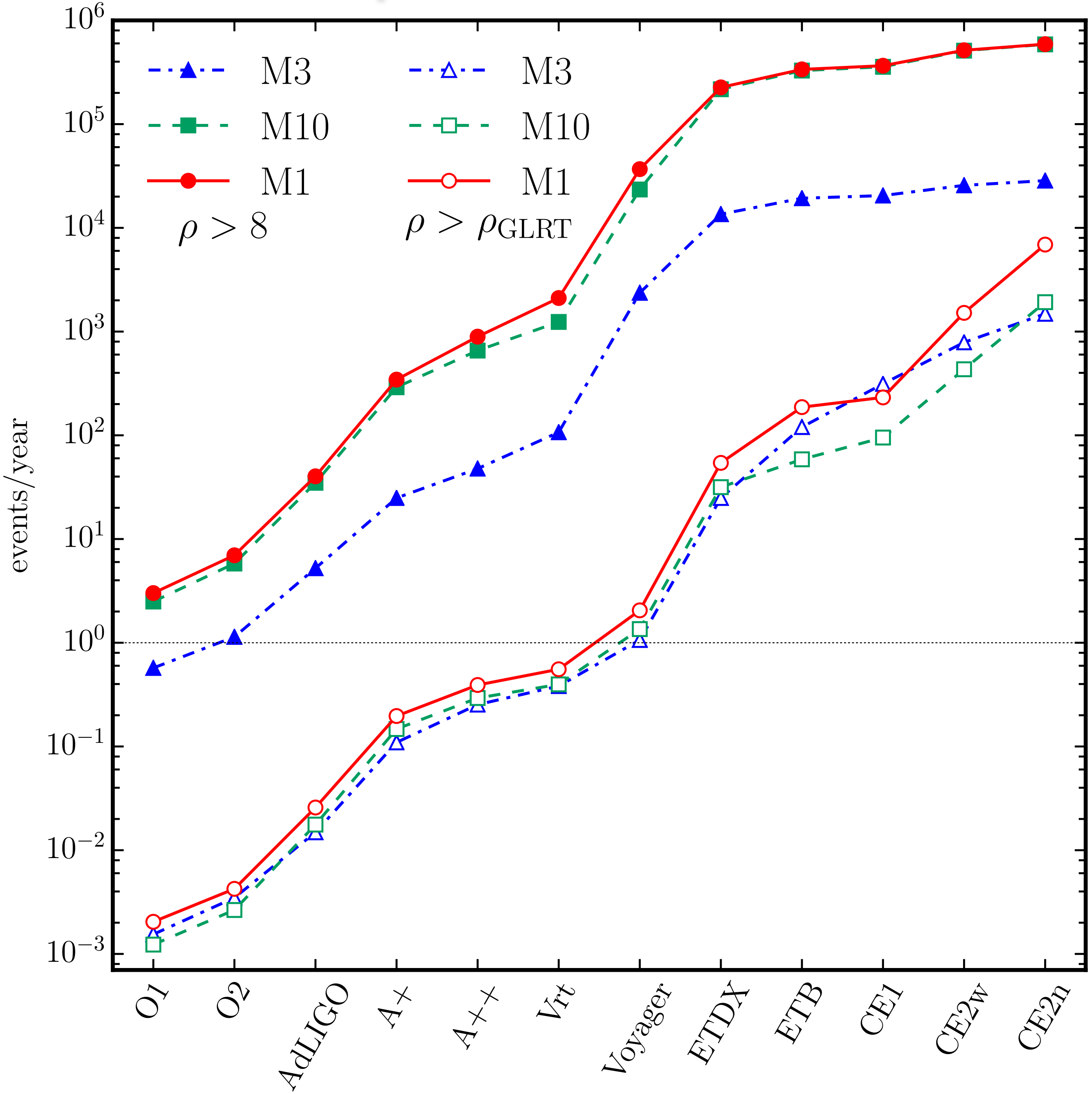


f = 170.2 ($10^2 M_{\mathrm{sun}}$)/M Hz

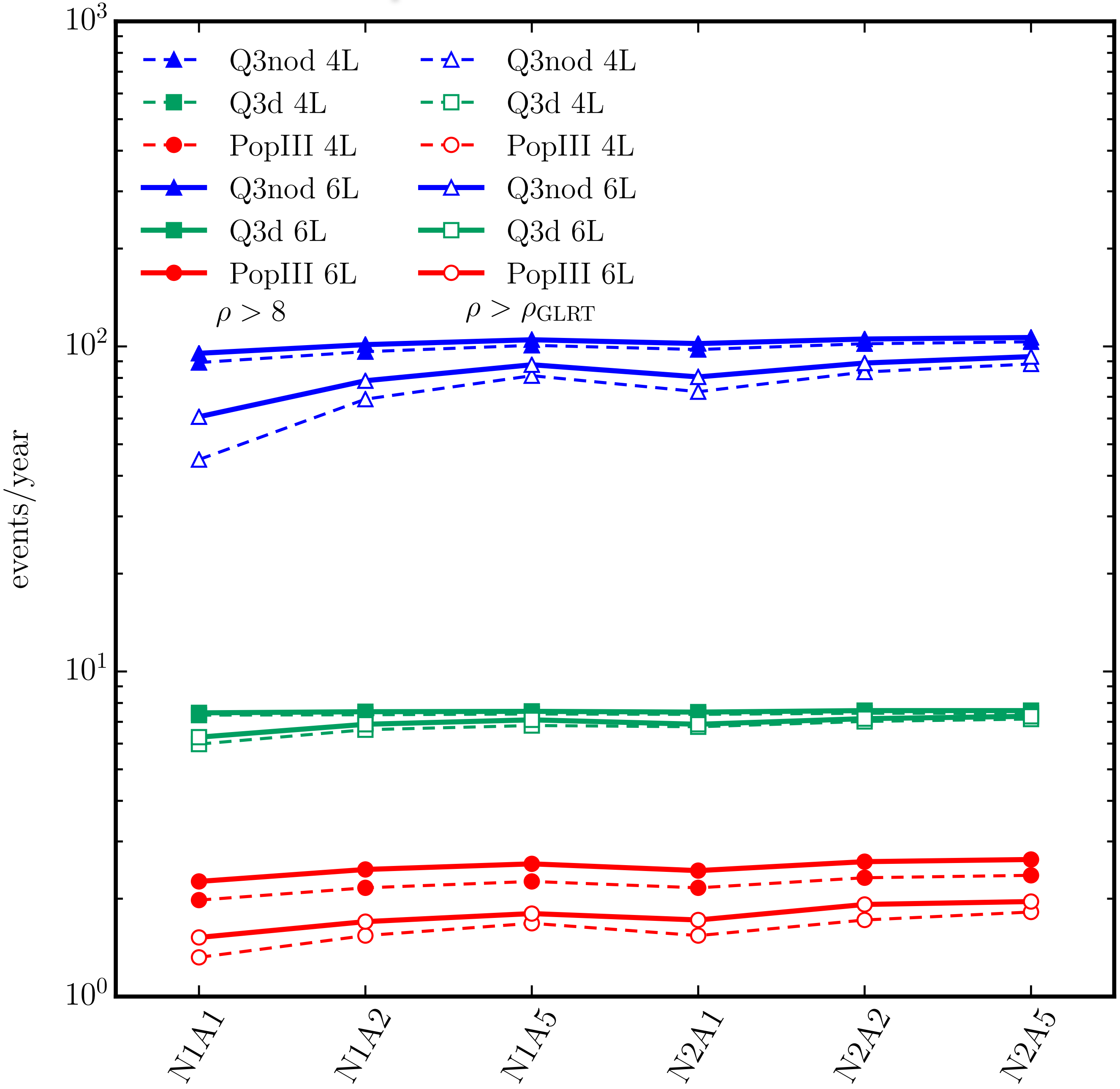
$$\rho = \frac{\delta_{\mathrm{eq}}}{D_{\mathrm{L}}\mathcal{F}_{lmn}}\left[\frac{8}{5}\frac{M_z^3\epsilon_{\mathrm{rd}}}{S_n(f_{lmn})}\right]^{1/2}$$

[EB+, 1605.09286]

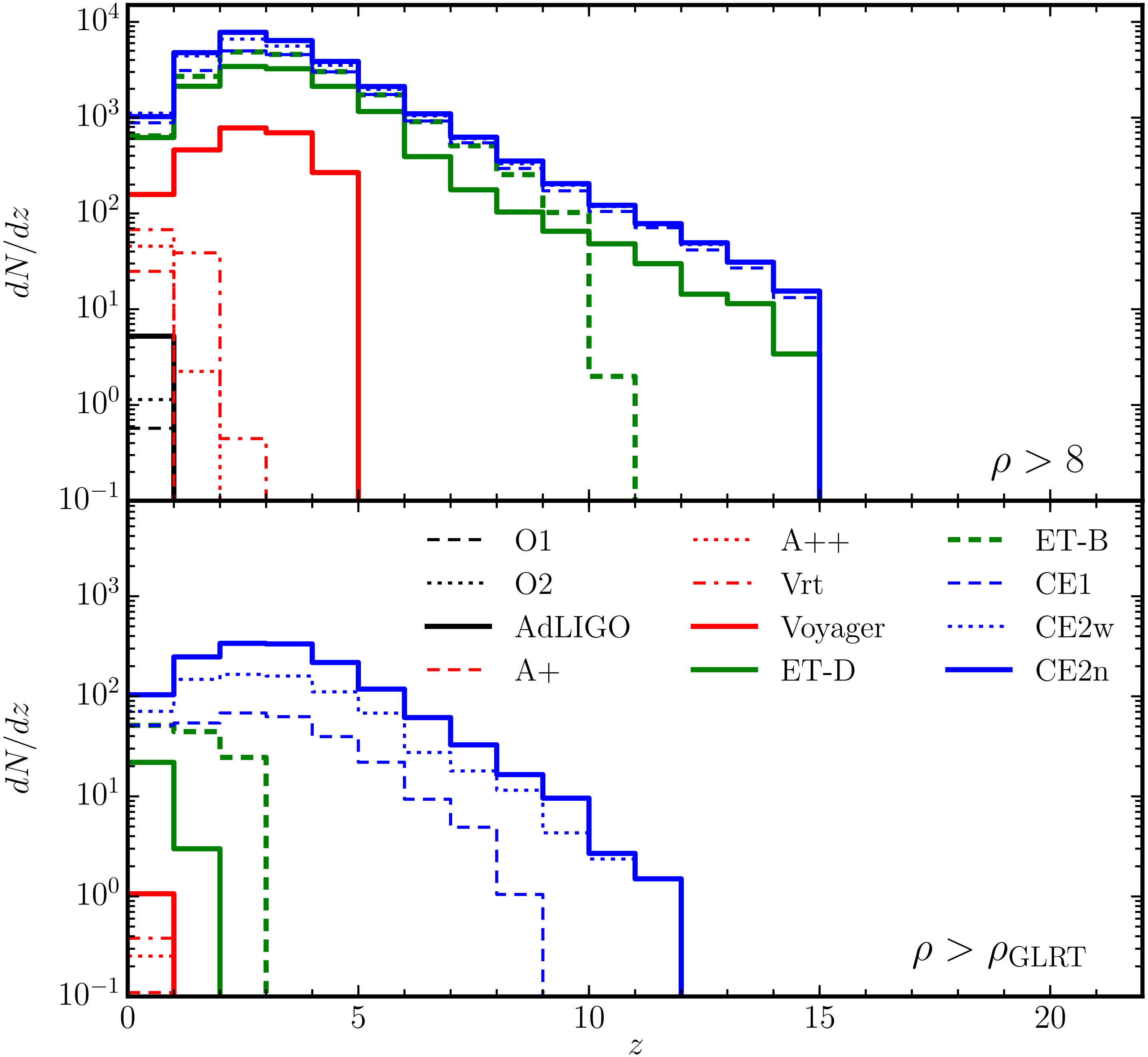
Earth vs. space-based: detection rates



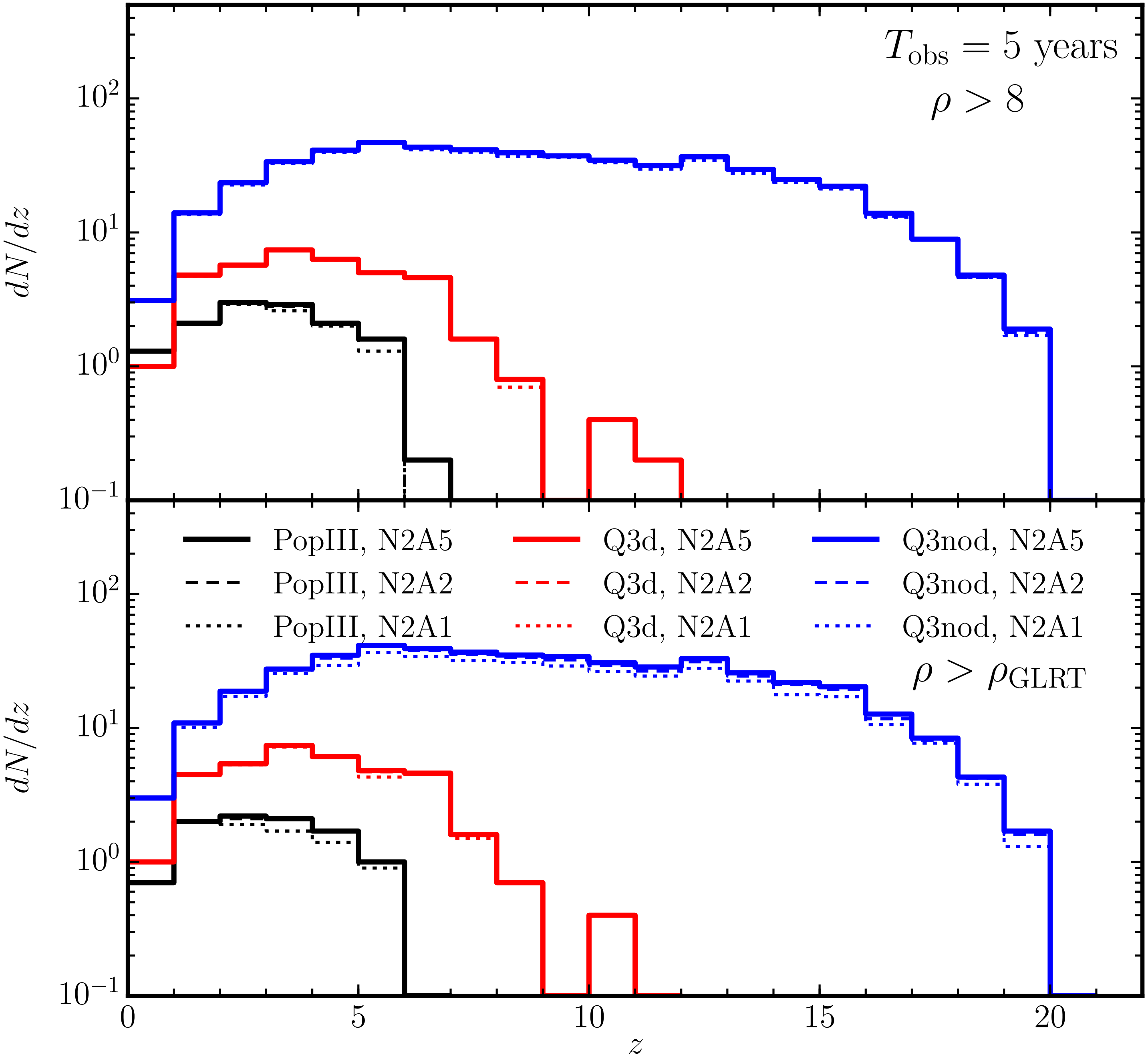
Earth vs. space-based: detection rates



Earth vs. space-based: redshift distribution



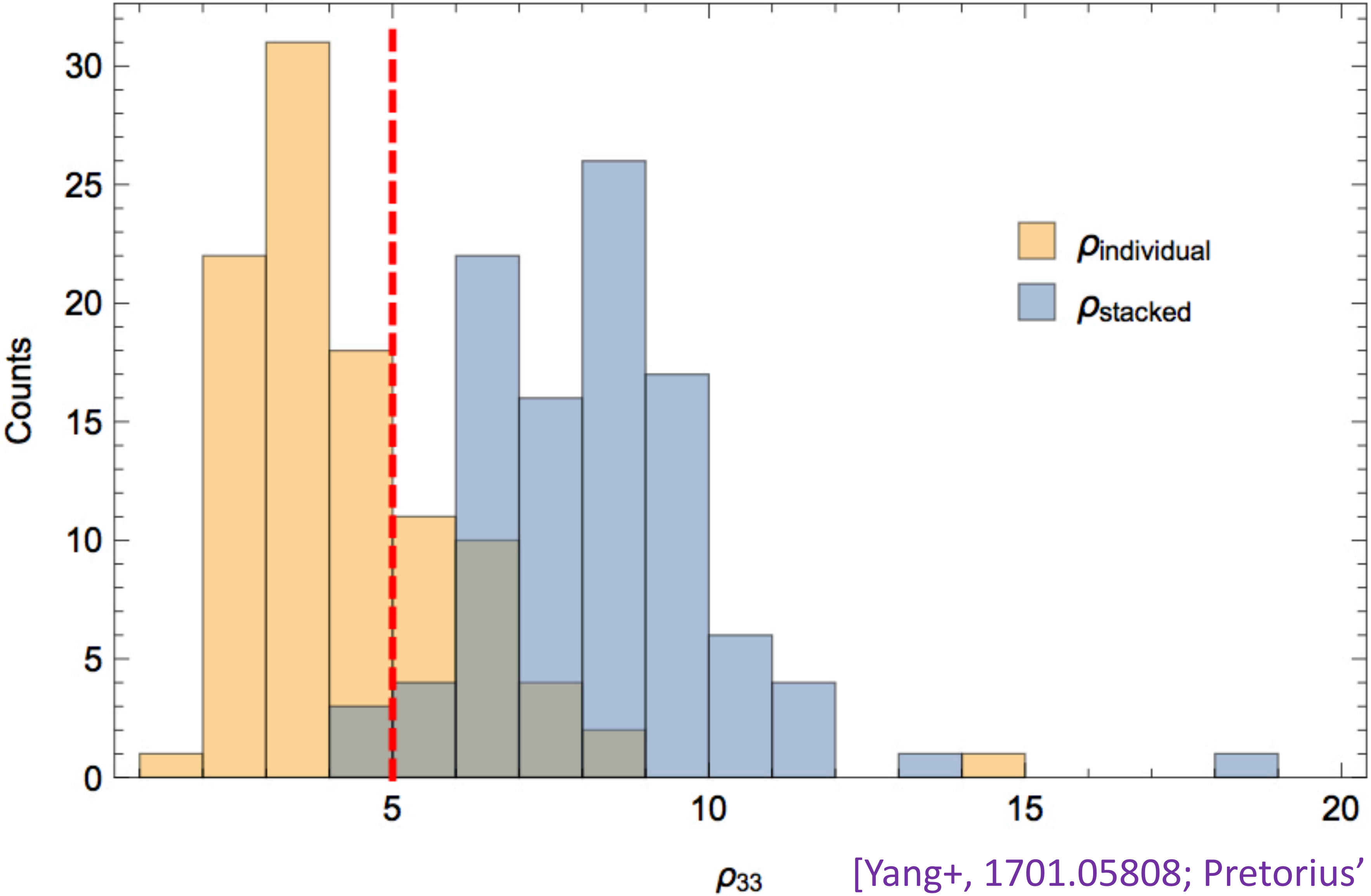
Earth vs. space-based: redshift distribution



Do not rule out tests with Advanced LIGO!

"Coherent mode stacking"

increases SNR ρ_{33} of the subdominant mode



[Yang+, 1701.05808; Pretorius' talk]

Are we limited by systematics?

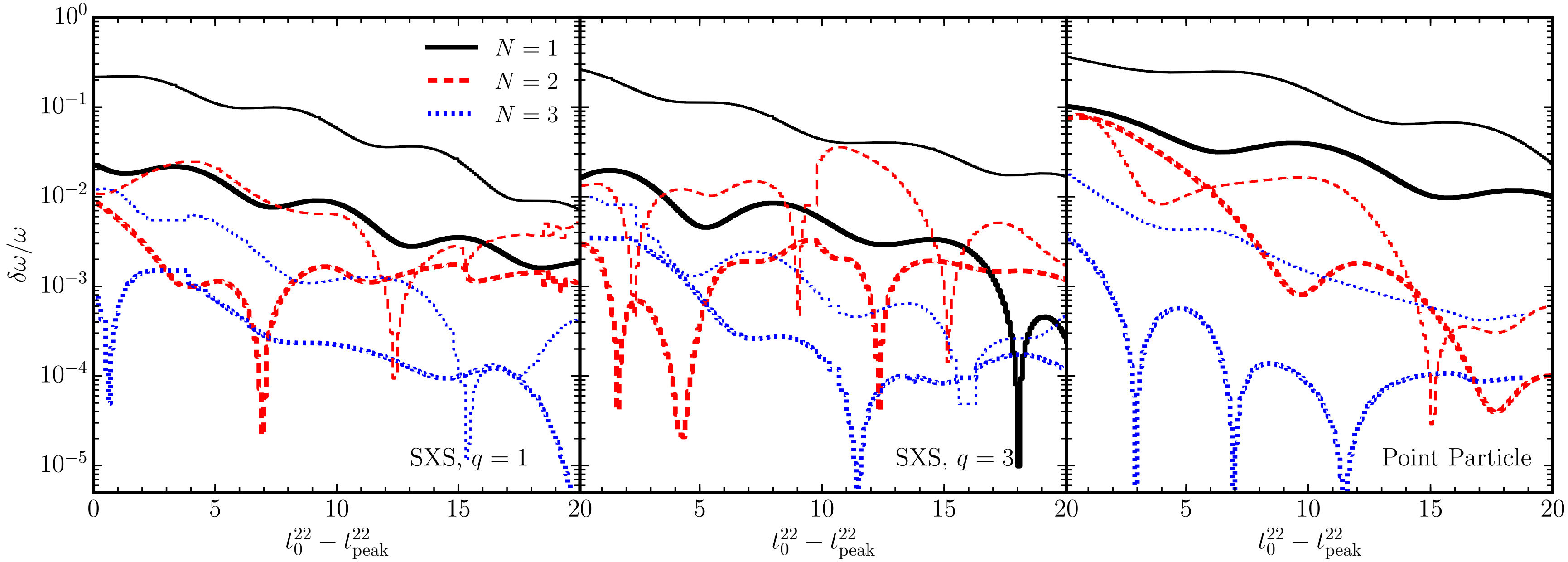


FIG. 1. Fractional errors $\delta\omega_{\rm r}/\omega_{\rm r}$ (thick lines) and $\delta\omega_{\rm i}/\omega_{\rm i}$ (thin lines) between the fundamental $\ell = m = 2$ QNM frequencies computed from BH perturbation theory and those obtained by fitting N overtones to numerical waveforms according to method (i) (see text). Left: SXS waveforms, $q = 1$; middle: SXS waveforms, $q = 3$; right: point-particle waveforms. Here $t_{\rm peak}^{22}$ is the time at which the amplitude of the $l = m = 2$ mode is maximum, and time is measured in units of $c^3/(GM)$.

[Baibhav+, 1710.02156]

Post-Kerr black hole spectroscopy parametrization?

Eikonal limit: QNM frequency ~ (photon ring frequency)+(1/Lyapunov exponent) i

$$\omega_{\rm K} = \sigma_{\rm K} + \beta_{\rm K},$$
$$\omega_{\rm obs} = \sigma + \beta_{\rm K}.$$

$$\boxed{\omega_{\rm obs} - \omega_{\rm K} = \sigma - \sigma_{\rm K} \neq 0.}$$

$$g_{\mu\nu} = g^{\rm K}_{\mu\nu}(r) + \epsilon h_{\mu\nu}(r) + \mathcal{O}(\epsilon^2),$$

$$\Omega_0 = \Omega_{\rm ph} + \epsilon\delta\Omega_0 + \mathcal{O}(\epsilon^2),$$
$$\gamma_0 = \gamma_{\rm ph} + \epsilon\delta\gamma_0 + \mathcal{O}(\epsilon^2).$$

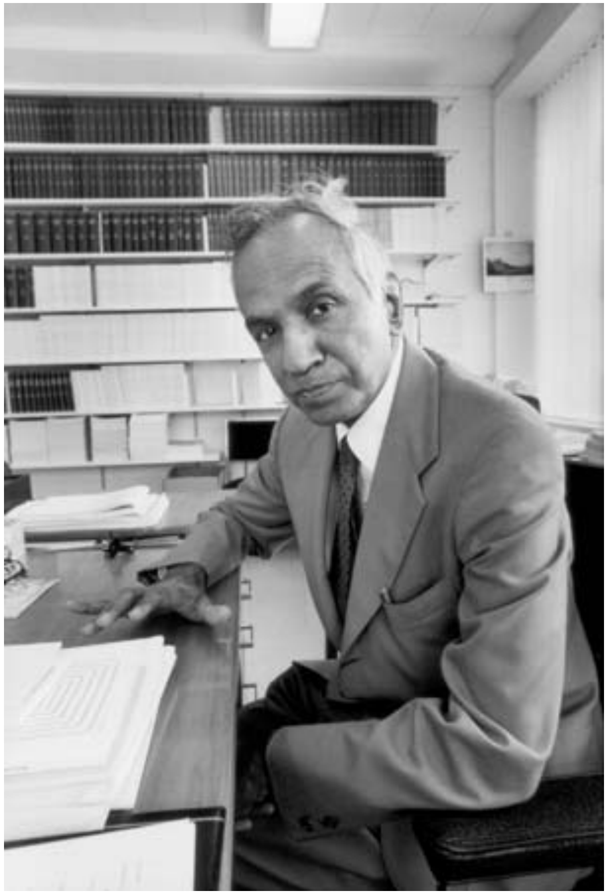
$$\sigma_{\rm R} = m\left(\Omega_{\rm ph} + \epsilon\delta\Omega_0\right),$$
$$\sigma_{\rm I} = -\frac{1}{2}|\gamma_{\rm ph} + \epsilon\delta\gamma_0|.$$

[Glampedakis+, 1706.05152; Tattersall+, 1711.01992]

Binary black hole tests of modified gravity

with Silva, Sakstein, Gualtieri, Sotiriou…

No-hair theorems



Black holes in GR are uniquely described by only two parameters – mass and spin

[Carter, Israel, Hawking, Robinson, 1970s]

*"**In my entire scientific life**, extending over forty-five years, **the most shattering experience** has been the realization that an exact solution of Einstein's equations of general relativity, discovered by the New Zealand mathematician, Roy Kerr, provides the absolutely exact representation of untold numbers of massive black holes that populate the universe."*
(S. Chandrasekhar)

Similar "no hair" theorems apply to modified gravity

- ✓ Brans-Dicke [Hawking, Thorne & Dykla, Chase, Bekenstein]
- ✓ Multiple scalars [Heusler, gr-qc/9503053]
- ✓ Bergmann-Wagoner, f(R) [Sotiriou & Faraoni, 1109.6324]
- ✓ Horndeski [Hui-Nicolis, 1202.1296; Sotiriou-Zhou; Maselli+]
- ✓ Higher-order curvature [Psaltis+, 0710.4564]

…but beware:
same metric does not mean same dynamics!

"Dynamical" no-hair in scalar-tensor theories

$$S = \frac{1}{16\pi}\int\left[\phi R - \frac{\omega(\phi)}{\phi} g^{\mu\nu}\phi_{,\mu}\phi_{,\nu} + M(\phi)\right](-g)^{1/2} d^4x$$
$$+ \int \mathcal{L}_{\mathrm{M}}(g^{\mu\nu}, \Psi) d^4x,$$

Orbital period derivative:

$$\boxed{\frac{\dot{P}}{P} = -\frac{8}{5}\frac{\mu m^2}{r^4}\kappa_1 - \frac{\mu m}{r^3}\kappa_D \boxed{S^2}}$$

$$\kappa_1 = \mathcal{G}^2\left[12 - 6\xi + \xi\boxed{\Gamma^2}\left(\frac{4\omega^2 - m_s^2}{4\omega^2}\right)^{\frac{5}{2}}\Theta(2\omega - m_s)\right]$$

$$\kappa_D = 2\mathcal{G}\xi\left(\frac{\omega^2 - m_s^2}{\omega^2}\right)^{\frac{3}{2}}\Theta(\omega - m_s)\,.$$

$$\xi = \frac{1}{2 + \omega_{\mathrm{BD}}},$$

$$\mathcal{G} = 1 - \xi(s_1 + s_2 - 2s_1s_2),$$

$$\Gamma = 1 - 2\frac{s_1m_2 + m_1s_2}{m}.$$

1) No dipole if **$S=s_1-s_2=0$** **(need NS-BH!)**

2) For binary black holes **$\Gamma=0$**: same as GR!

[Alsing+, 1112.4903]

Ways around no-hair theorems for LIGO's black holes?

Scalar-tensor theory:

- ✓ To leading post-Newtonian order
  [Will & Zaglauer 1989]
- ✓ Equations of motion up to 2.5PN
  [Mirshekari & Will, 1301.4680]
- ✓ To all post-Newtonian orders in the extreme mass ratio limit
  [Yunes+, 1112.3351]

Ways around:

1) **Matter**
   [Barausse+, 1212.5053]
2) **Nonzero potential (e.g. mass term) or nontrivial boundary conditions**
   [Healy+, 1112.3928; Horbatsch-Burgess, 1111.4009; Berti+, 1304.2836]
3) **Curvature sources RHS**: EdGB, dCS, Lorentz-violating theories

$$\square^{(0)}\vartheta^{(1)} = -\frac{m_{\rm pl}}{8}\ell^2\ {}^*RR^{(0)}$$

Scalar Gauss-Bonnet gravity

$$S = \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\left[R - \frac{1}{2}\nabla_\alpha\varphi\nabla^\alpha\varphi + f(\varphi)\mathscr{G}\right] + S_\mathrm{m}[g_{\mu\nu},\psi]$$

Field equations:

$$\Box\varphi = -f_{,\varphi}\mathscr{G}\,,$$

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = T_{\mu\nu}\,.$$

Kerr is a solution if: $f_{,\varphi}(\varphi_0) = 0$

No hair theorem: $f_{,\varphi\varphi}\,\mathscr{G} < 0$

Why? In the linearized regime, $\left[\Box + f_{,\varphi\varphi}(\varphi_0)\,\mathscr{G}\right]\delta\varphi = 0$

Construct black hole solutions that have a GR limit but can scalarize: $\boxed{f = \eta\varphi^2/8}$

[Silva+, 1711.02080]

Black hole solutions in scalar-Gauss-Bonnet gravity

Einstein-dilaton-Gauss-Bonnet: $f = e^{\alpha\varphi}$ **Kerr not a solution!**

[Mignemi-Stewart 93, Kanti+ 96, Pani-Cardoso 09, Yunes-Stein 11…]

Shift-symmetric Gauss-Bonnet: $f = a\varphi$ **Kerr not a solution!**

[Sotiriou-Zhou 14, Barausse-Yagi 15, Benkel+ 16…]

Silva+ 1711.02080 **(our model)** $\boxed{f = \eta\varphi^2/8}$

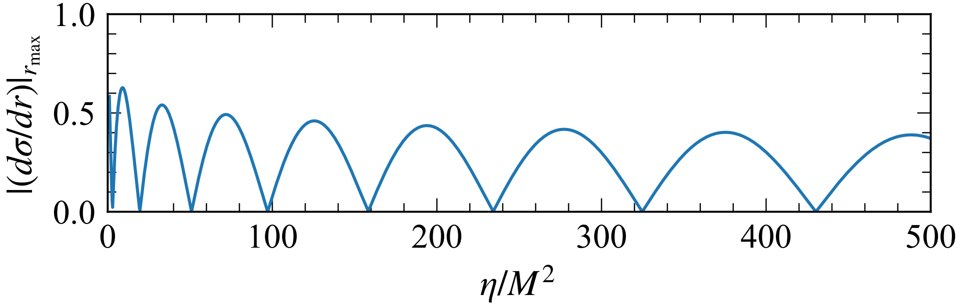
Doneva+ 1711.01187

$$f = \frac{1 - \exp(-6\varphi^2)}{12}$$

Antoniou+ 1711.03390, 1711.07431 **polynomial, inverse polynomial, logarithmic…**

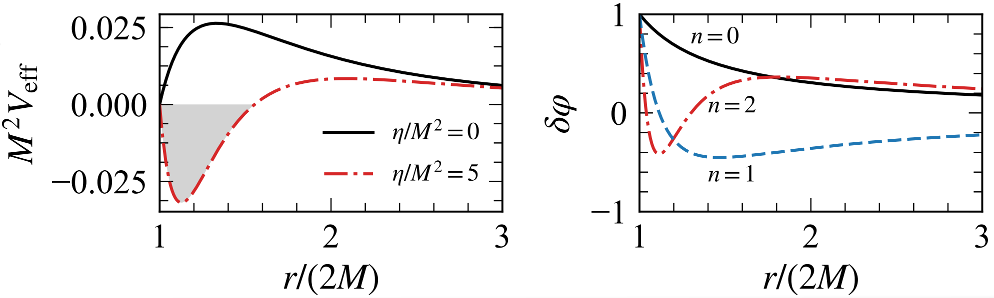
Scalarized solution

$$\boxed{\begin{aligned} &R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = T^{\varphi}_{\mu\nu} \\ &\Box\varphi = -\frac{\eta}{4}\varphi\mathcal{G} \end{aligned}}$$



Linearized case: discrete solutions (scalarization threshold) with n nodes

$$\eta/M^2 = 2.90, 19.50, 50.93\ldots$$

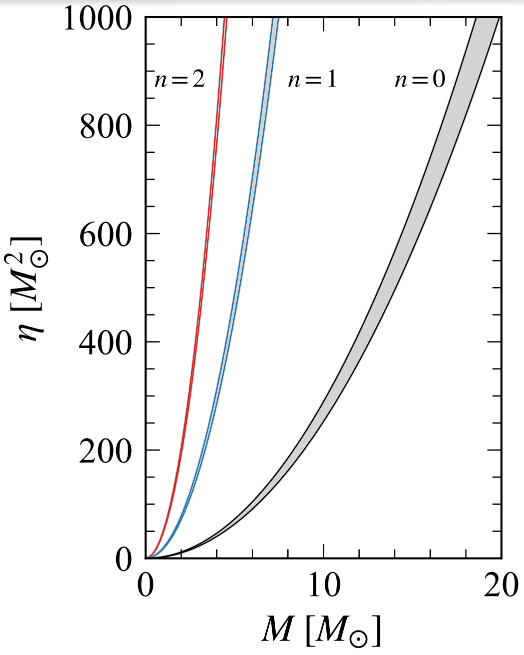


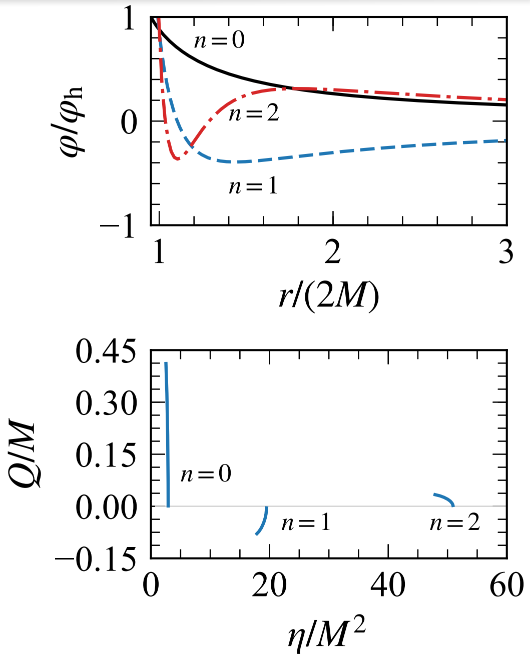
Full solution: bands

Left edge: threshold

Right edge: singularity at horizon

For given η, solutions differ from GR in finite mass ranges





Beyond the Standard Model: dark matter searches with GWs?

Ultralight fields / dark matter candidates

Superradiance when $\omega < m\Omega_H$ - strongest instability: **l=m=1**, $\mu M \sim 1$

[Dolan, 0705.2880]

For **μ=1eV, M=M_{sun} : $\mu M \sim 10^{10}$**

Need light scalars (or primordial black holes!)

Evolution of instability

Nonlinear effects?

Perturbation theory is ok

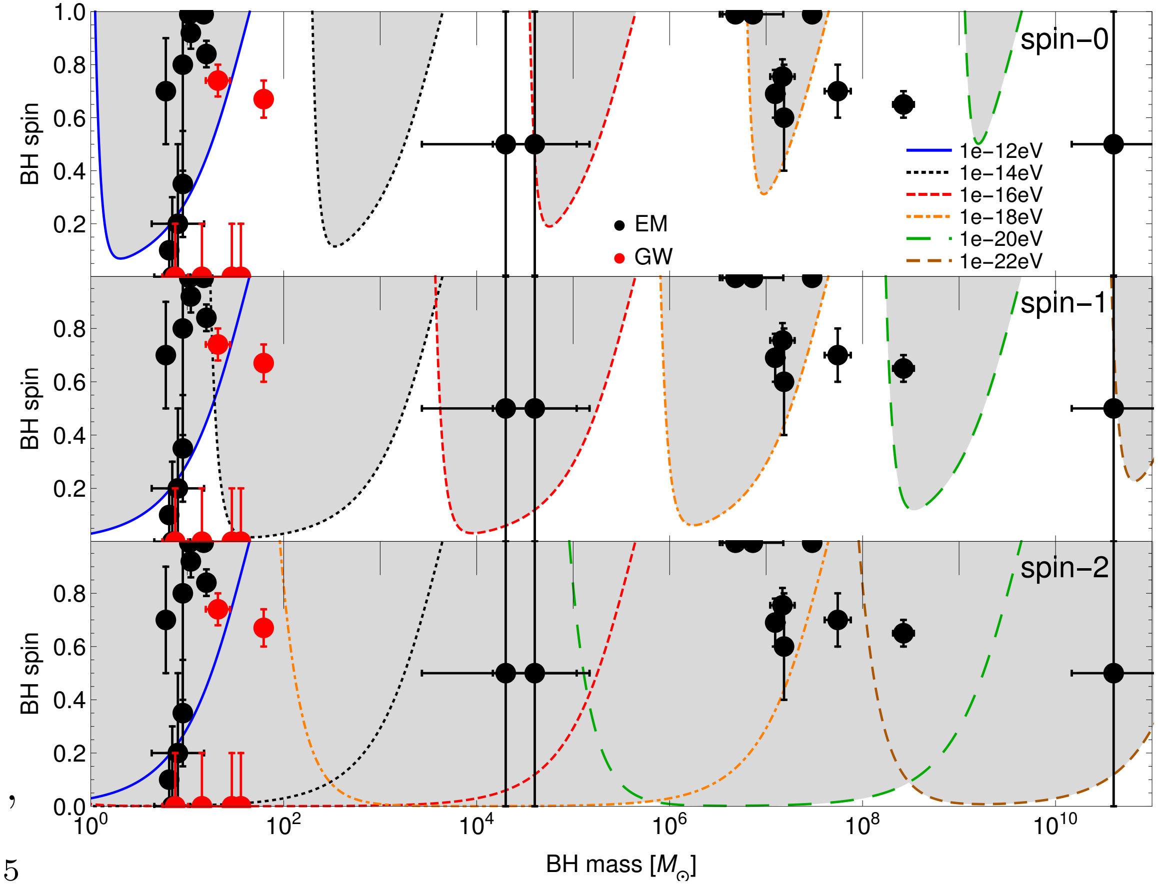
[East-Pretorius, 1704.04791]

GW signatures

Periodic sources

Stochastic background

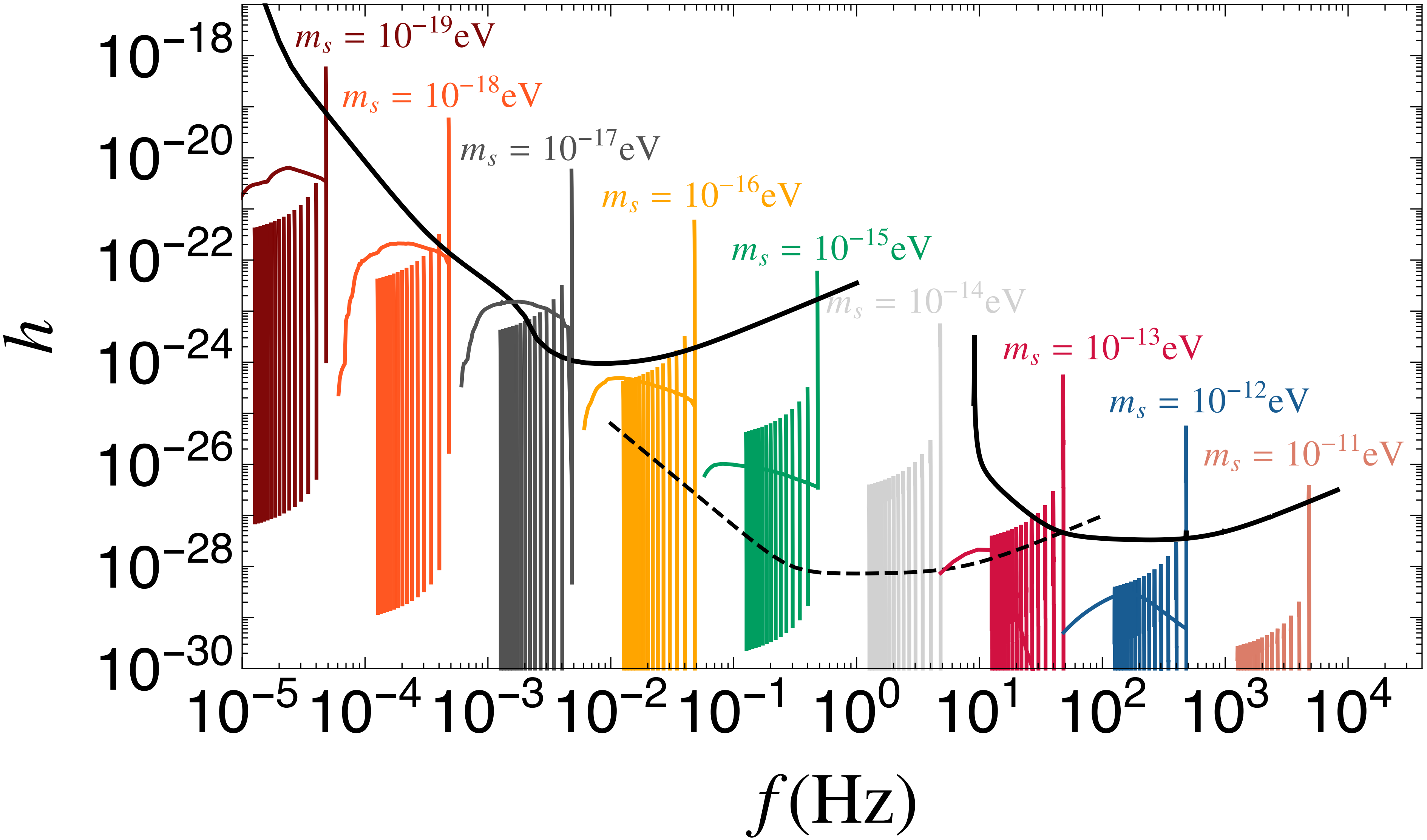
Regge holes



$$\tau_{\rm inst} \sim 0.07\,\chi^{-1}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^9 \,{\rm yr}\,,$$

$$\tau_{\rm GW} \sim 6\times10^4\,\chi^{-1}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{15} \,{\rm yr}\,.$$

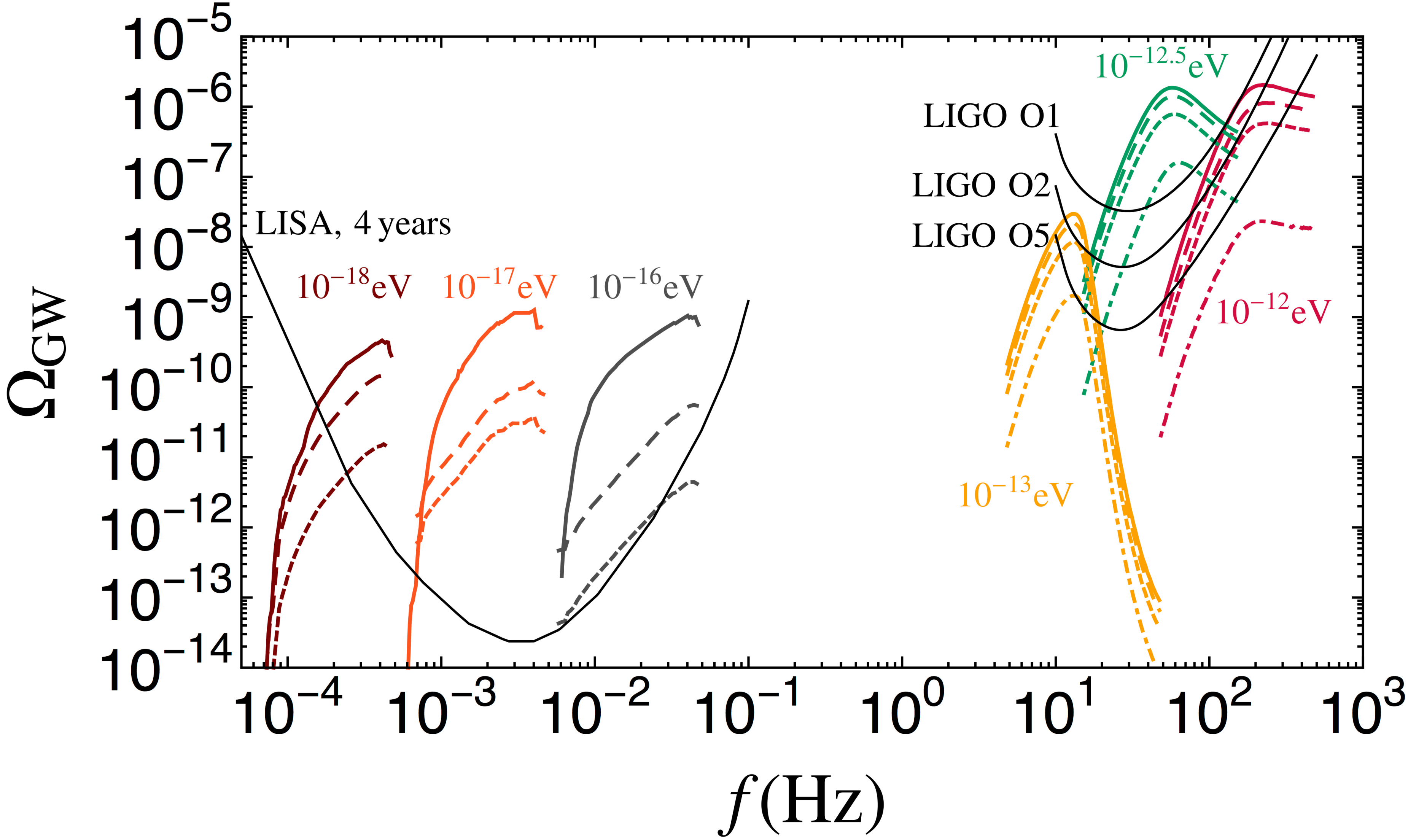
Resolved signals and stochastic background



Vertical lines: **a/M=0.9**, **z=0.01-3.01** (right to left), **μM** grows along vertical lines

[Brito+, 1706.05097]

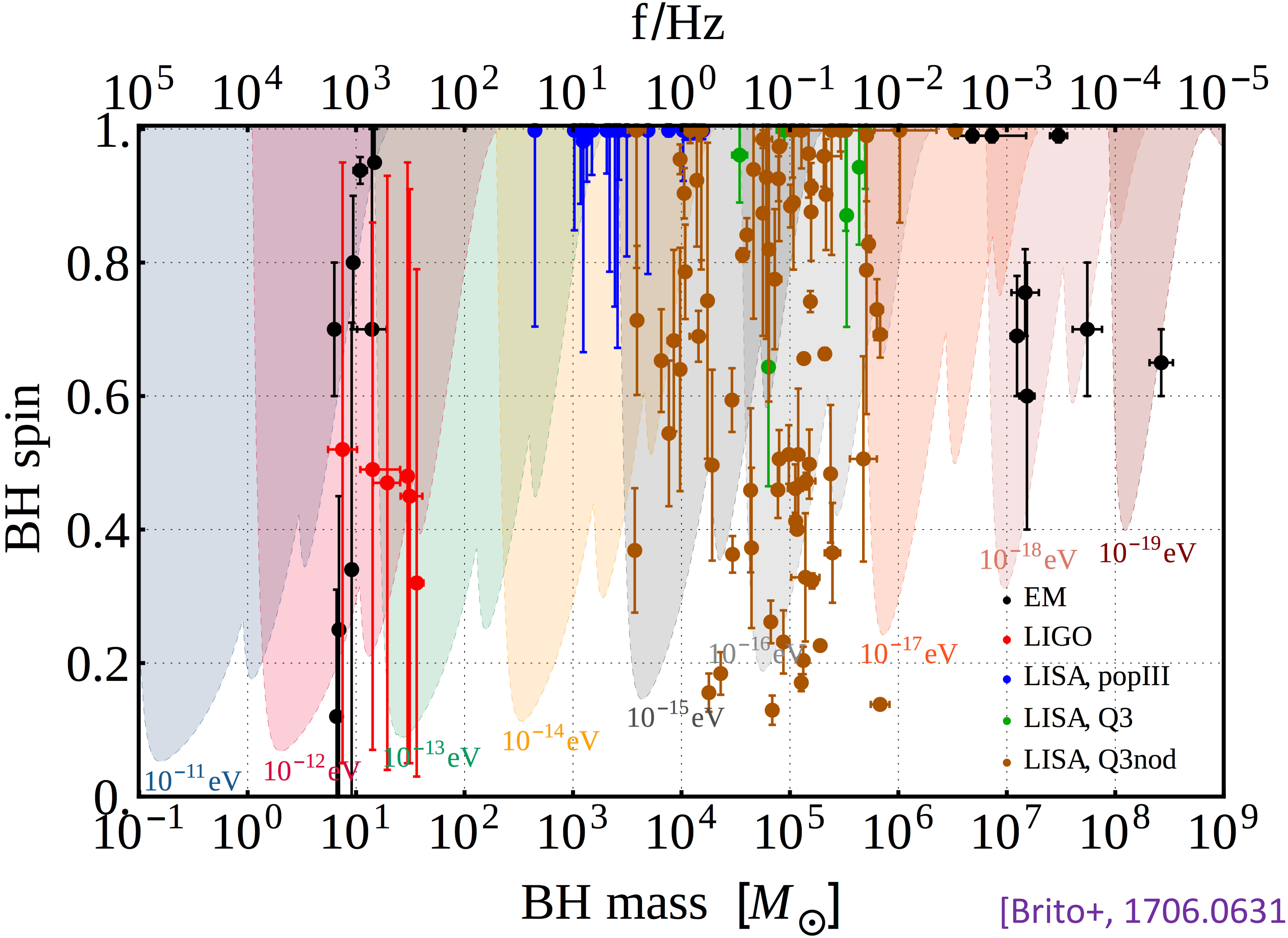
Stochastic background: energy density



Frequency-integrated sensitivity curves [Thrane-Romano, 1310.5300]

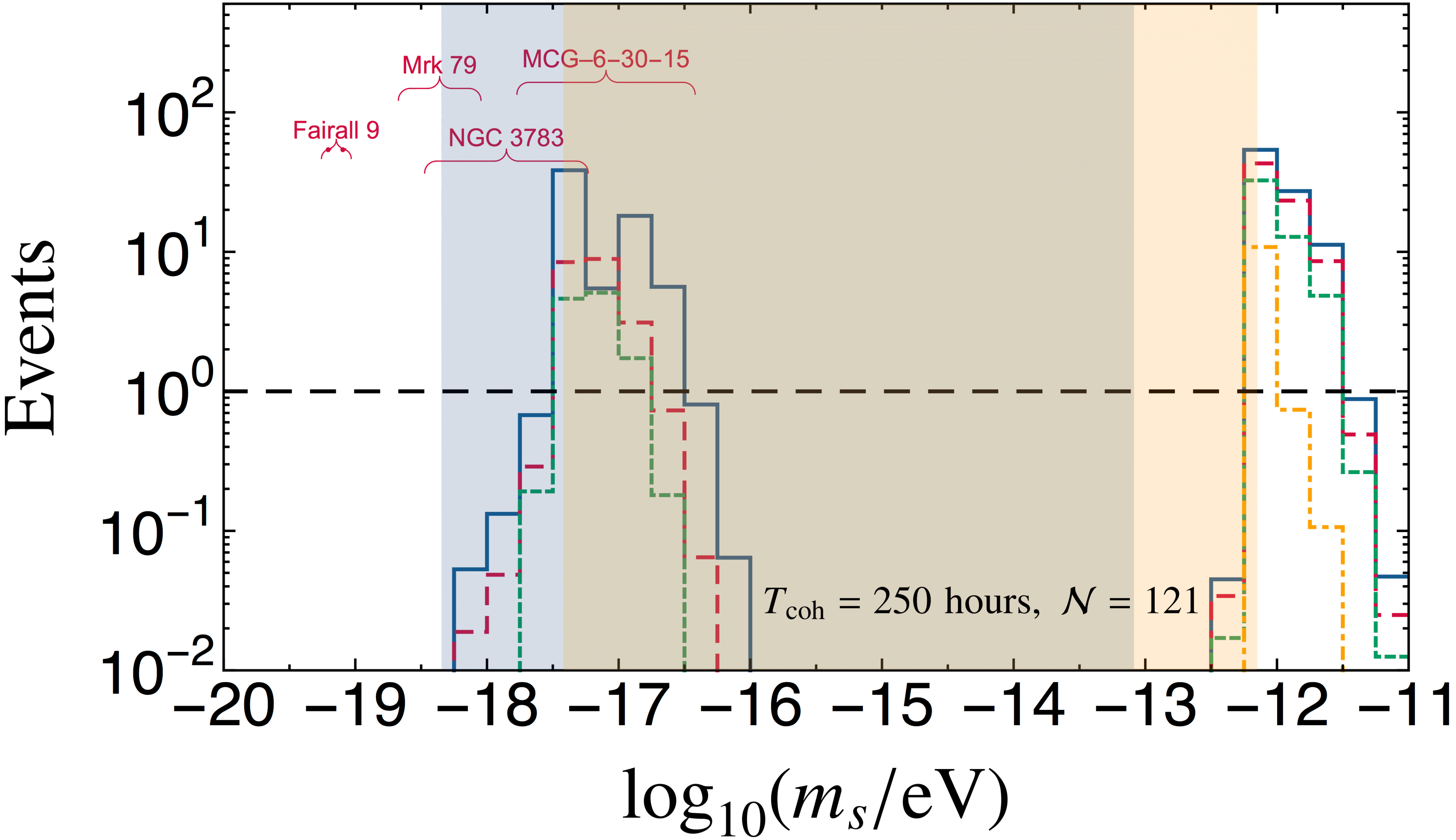
[Brito+, 1706.05097]

Mass bounds from holes in the Regge plane: LISA



[Brito+, 1706.06311]

Resolvable events + bounds from holes in Regge plane



AdLIGO: very conservative estimate, maximum BH mass around 10 M_{sun}

Hundreds of events at $\mu \sim 10^{-13}$ eV possible

[Brito+, 1706.05097]

Beyond the Standard Model: exotica

Exotic ultracompact objects (UCOs) and beyond-SM physics

Models?

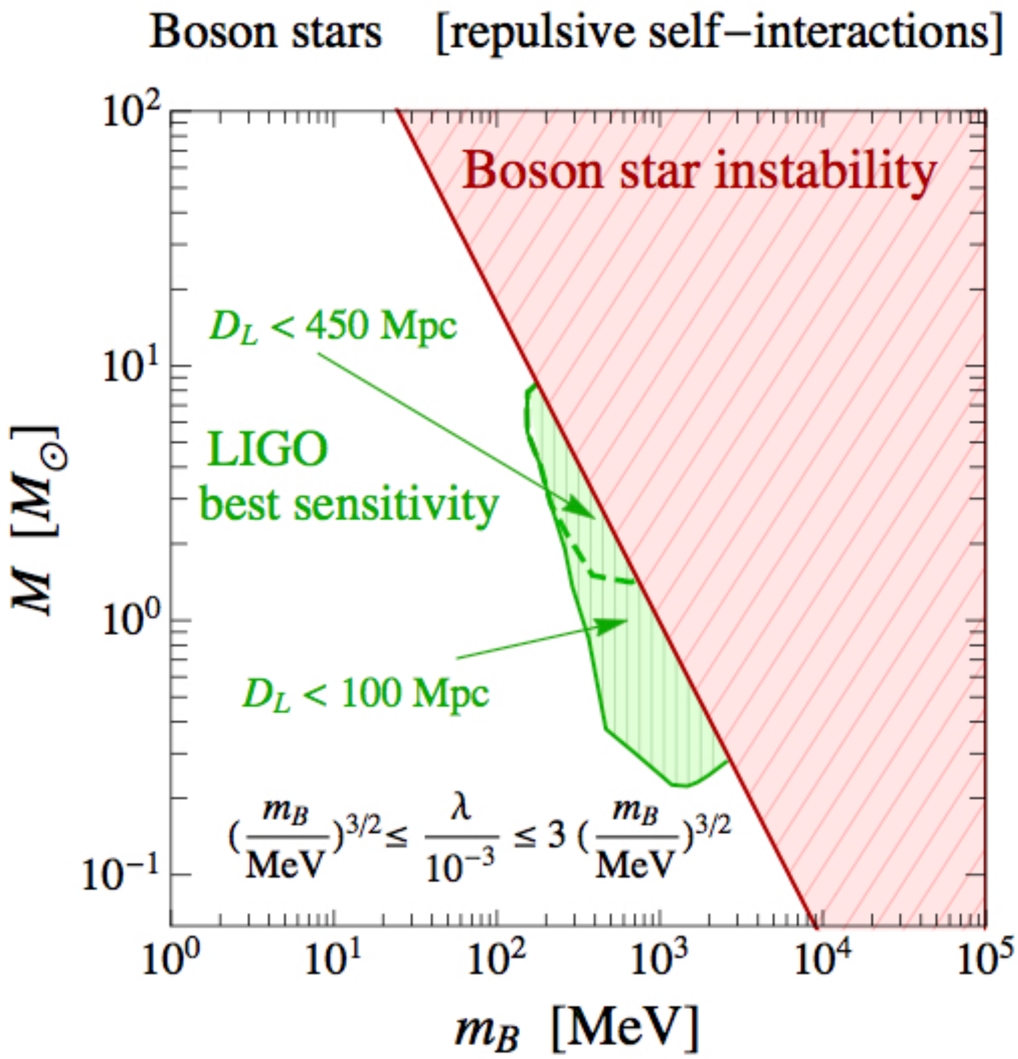
- Boson stars
- Fermion stars
- Dark stars
- Gravastars

Do we see horizon or photon sphere?

Formation/stability
of UCOs with a photon sphere

GW signatures:
mass/spin distribution?

Rates must match what we see

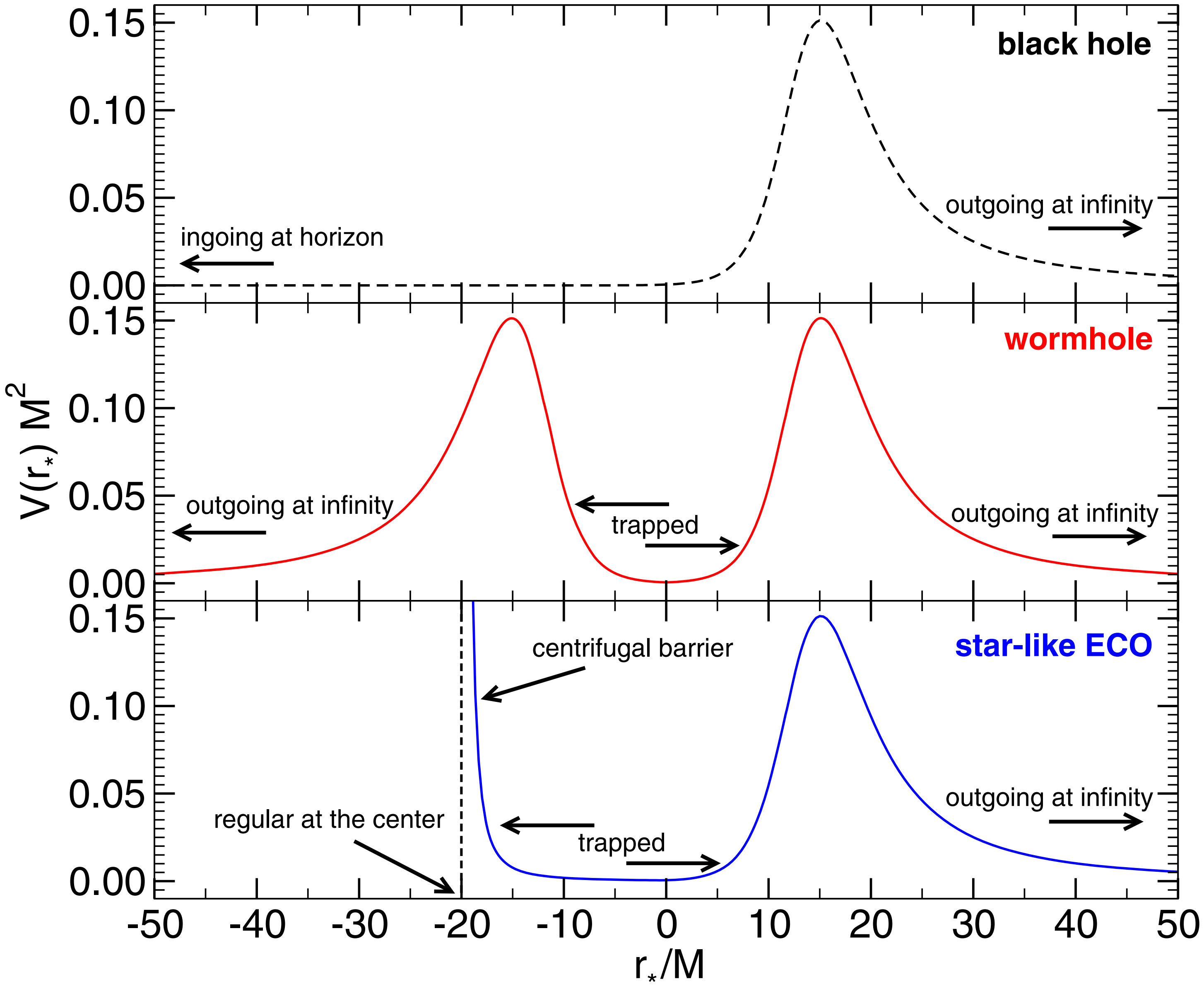


Other signatures?

- "Matter" modes (inspiral resonances, merger/ringdown)?
- Accretion onto a surface (Broderick/Narayan)

[Giudice+, 1605.01209]

Planck scale structures near the horizon and echoes



[Cardoso+, 1602.07309 and 1608.08637; Abedi/Dykaar/Afshordi, 1612.00266]

Signatures of quantum corrections near the horizon?

Delay time between echoes:

$$\Delta t_{\text{echoes}} \sim 2M \log\left(\frac{r_0}{2M} - 1\right)$$

Beyond toy models?

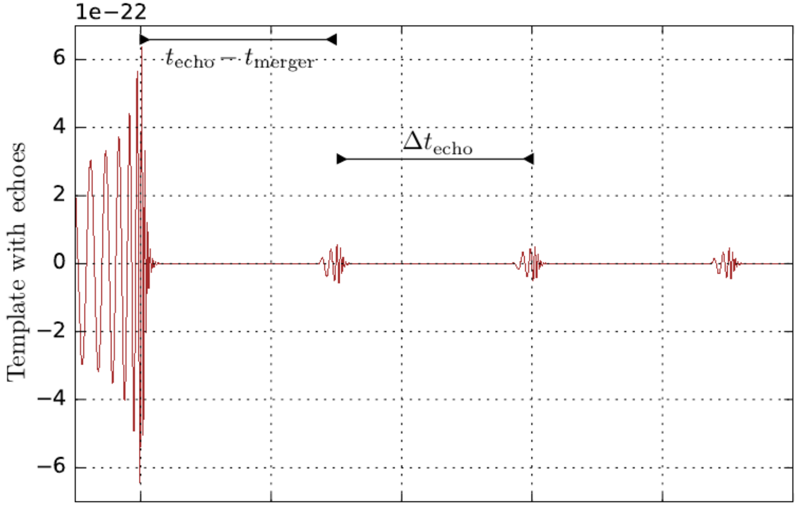
Formation

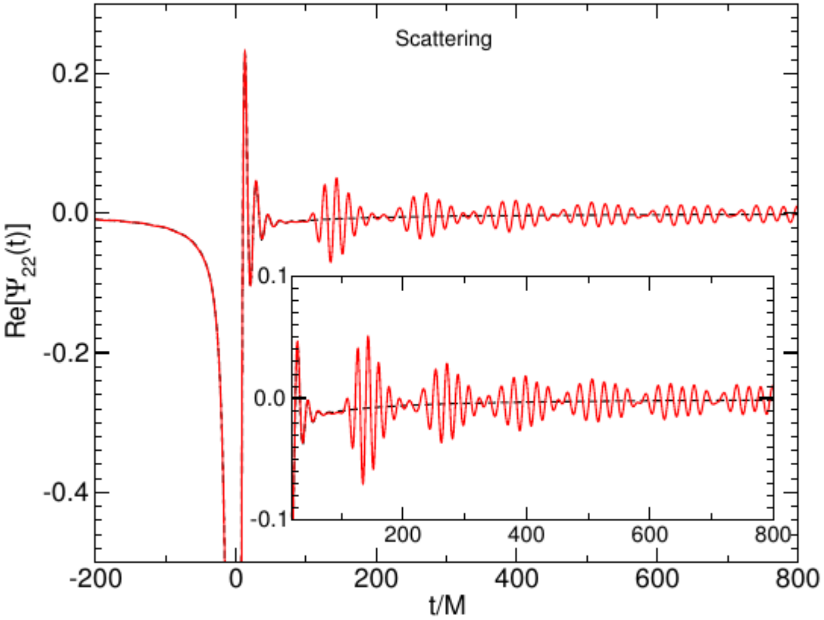
Stability
(ergoregion instability stronger as $r_0 \to 2M$)

Model independent constraints?

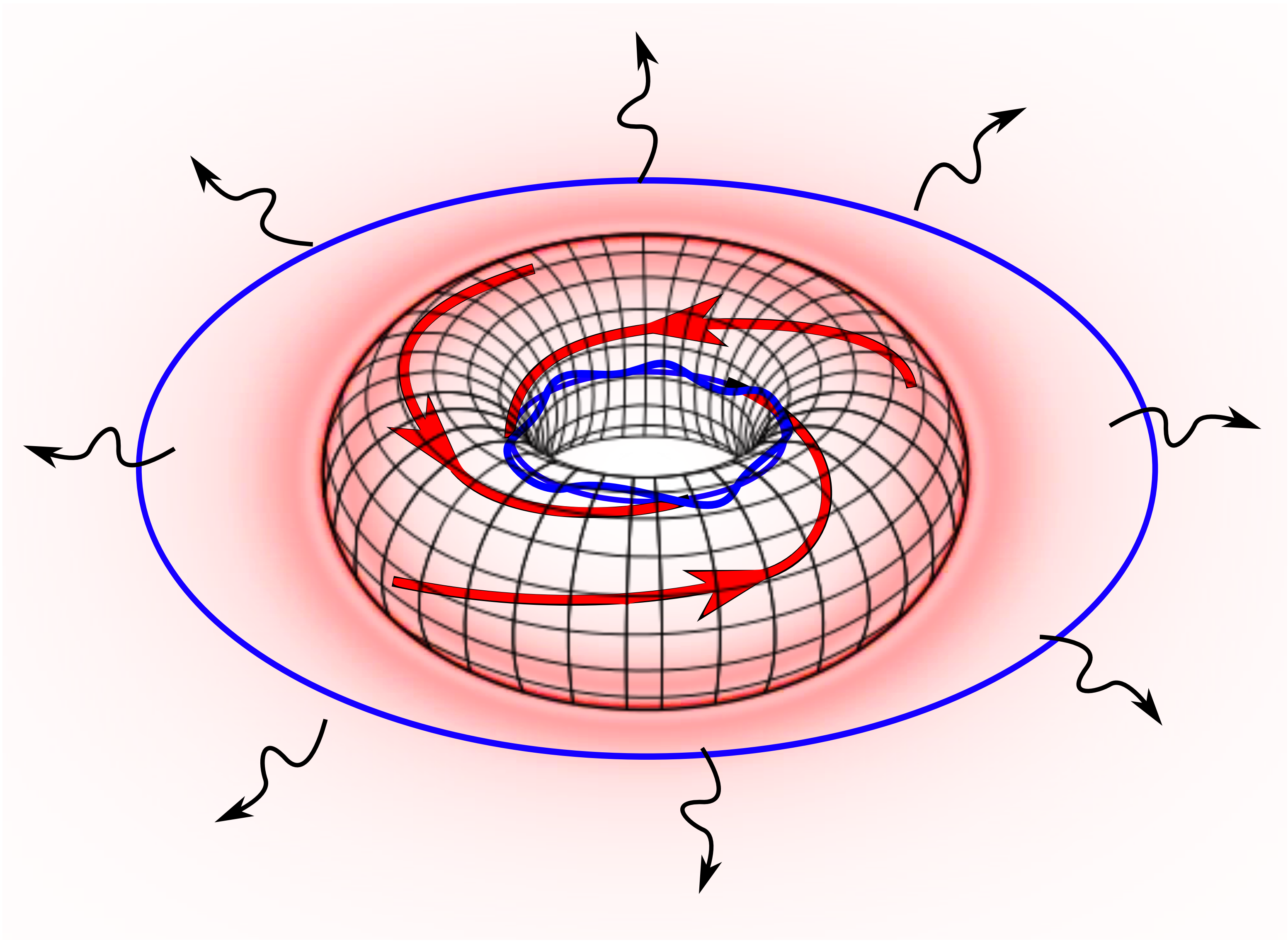
Planck-scale corrections within reach?

Which SNR? Data analysis?





Light-ring instability of ultracompact objects is generic



[Cunha+, 1708.04211; Keir, 1404.7036]

Summary

- ✓ **Astrophysics**

  Rates: probably multiple channels
  (field, clusters, triples, Pop III, primordial BHs…)
  Masses: clusters cannot explain low-mass events
  Spins: small effective spin compatible with different explanations
  morphology and "black hole binary archaeology"
  Eccentricity: LISA could distinguish between channels
  Statistics in LIGO/Virgo: collapse or multiple mergers?

- ✓ **Strong gravity**

  Black hole spectroscopy: AdLIGO needs coherent stacking
  Third generation detectors, eLISA: high-SNR tests at larger redshift
  Modified gravity constraints via black hole binary mergers?
  Maybe… (case study: scalar-Gauss-Bonnet gravity)

- ✓ **Beyond Standard Model physics**

  Light bosons (10^{-12}eV/10^{-17}eV in LIGO/LISA) via superradiant instabilities
  Exotica and "echoes": Planck structure at the horizon?