Complementarity of Earth-based and space-based detectors: binary populations and tests of strong gravity

Emanuele Berti, Mississippi/IST Lisbon/Caltech

In collaboration with

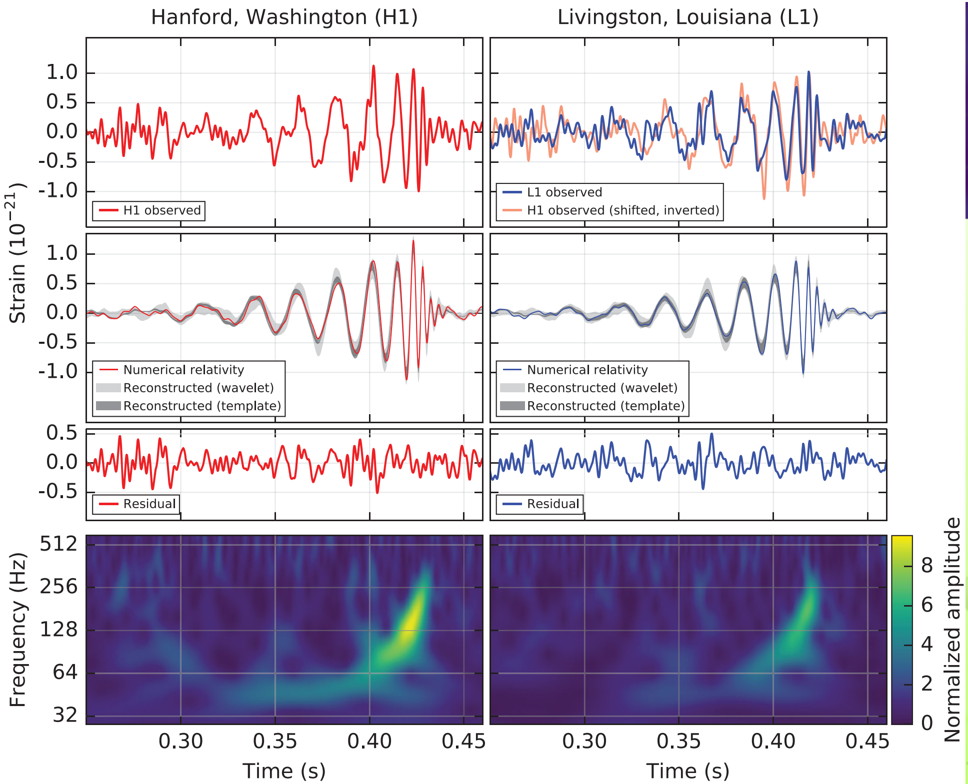
A.Sesana, A.Nishizawa, A.Klein,
E.Barausse, K.Belczynski, V.Cardoso

GR21, New York, July 12 2016

INVESTIGADOR FCT

QUALIFICAR É CRESCER.

Direct detection of gravitational waves: GW150914



Combined (Hanford/Livingston)
SNR: 24

GW150914:FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	less than 1 in 5 million
false alarm rate	1 in 200,000 yr
Source Masses	M⊙
total mass	65
chirpmass	28
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	62
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.7
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

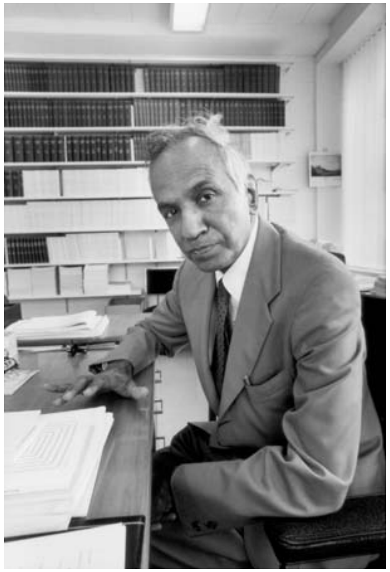
duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	< 1.2×10^{-22} eV
coalescence rate	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameters with a range (e.g. distance) are 90% credible bounds; fractional error on parameters without a range is less than 10%. **Acronyms:** L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

Pathfinder launch (Dec 3 2015)
PRL 116, 231101

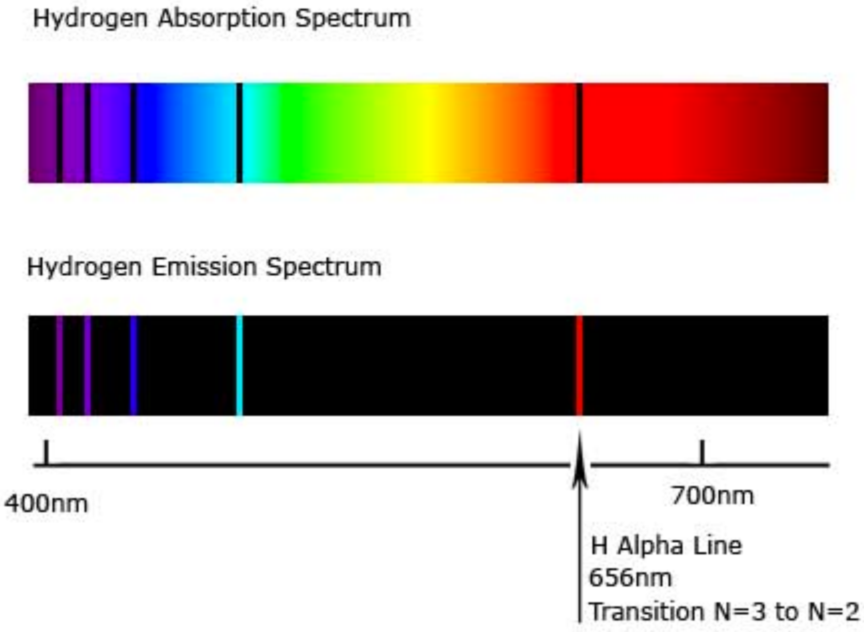
Black hole spectroscopy

No-hair theorems and black hole spectroscopy



"**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, *The Mathematical Theory of Black Holes*

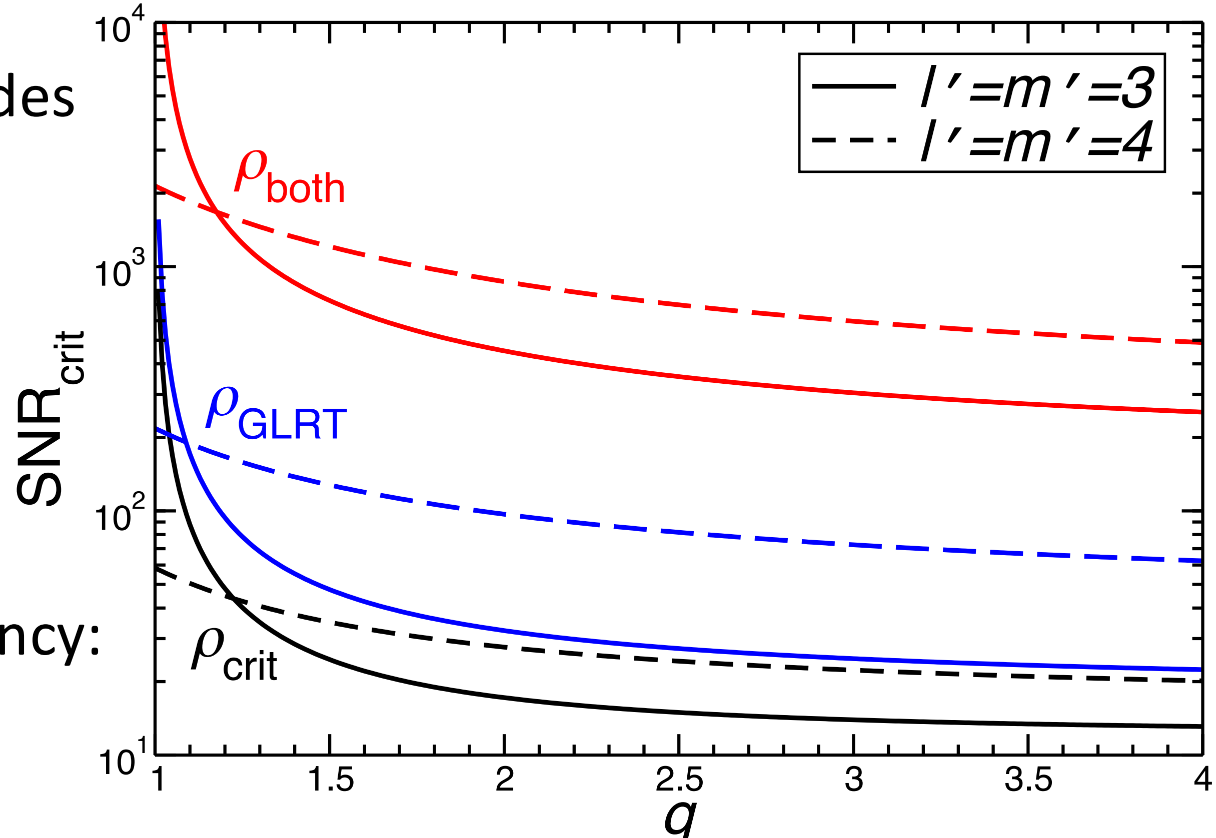
"After the advent of gravitational wave astronomy, the observation of [the black hole's] resonant frequencies might finally provide direct evidence of black holes with the same certainty as, say, the 21 cm line identifies interstellar hydrogen."
Steve Detweiler, ApJ 239, 292 (1980)



Critical SNR for black hole spectroscopy

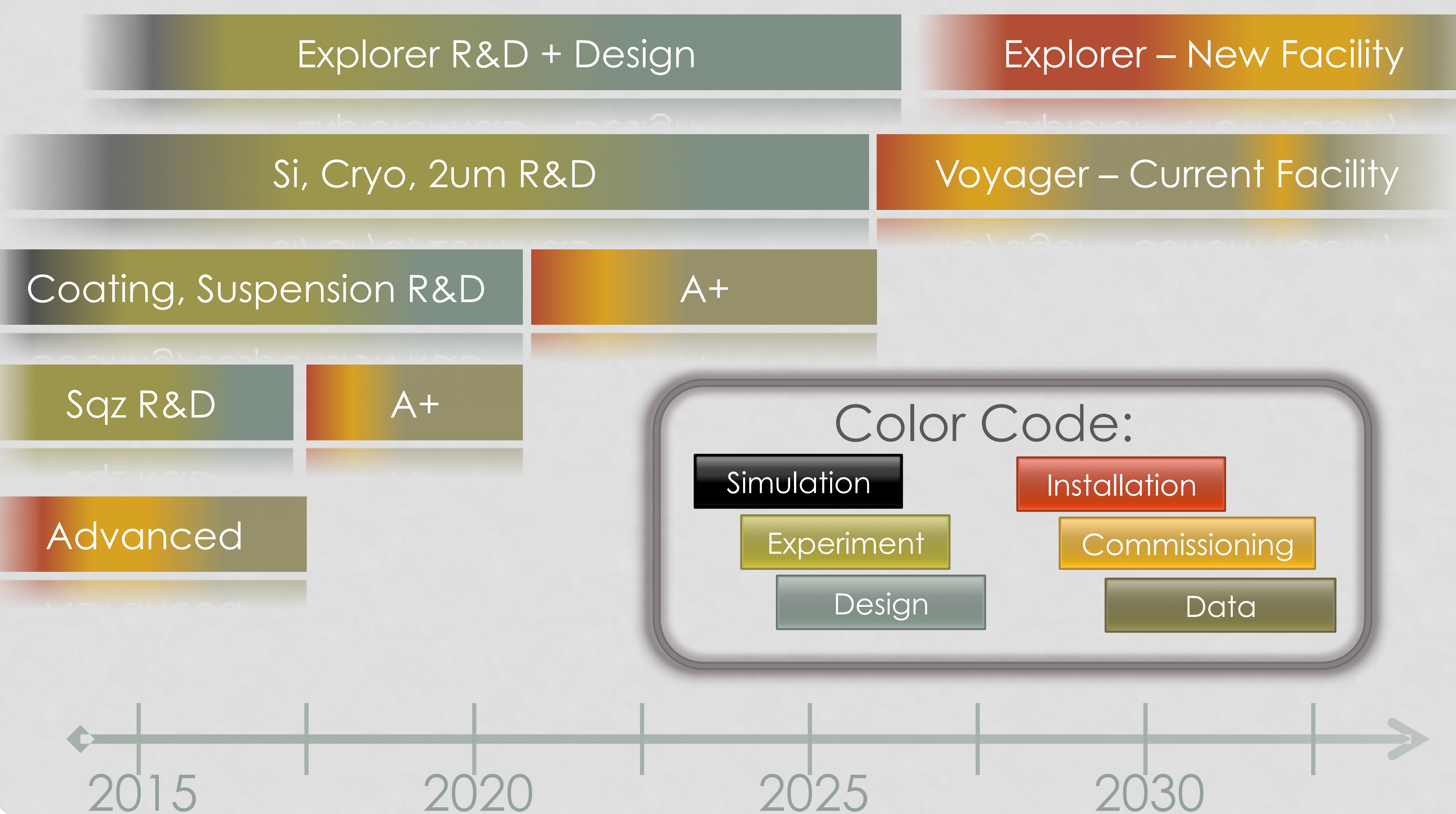
[EB+, gr-qc/0707.1202]

- In GR, black holes oscillate in a set of discrete complex-frequency modes (quasinormal modes) determined only by mass **M** and spin **a**



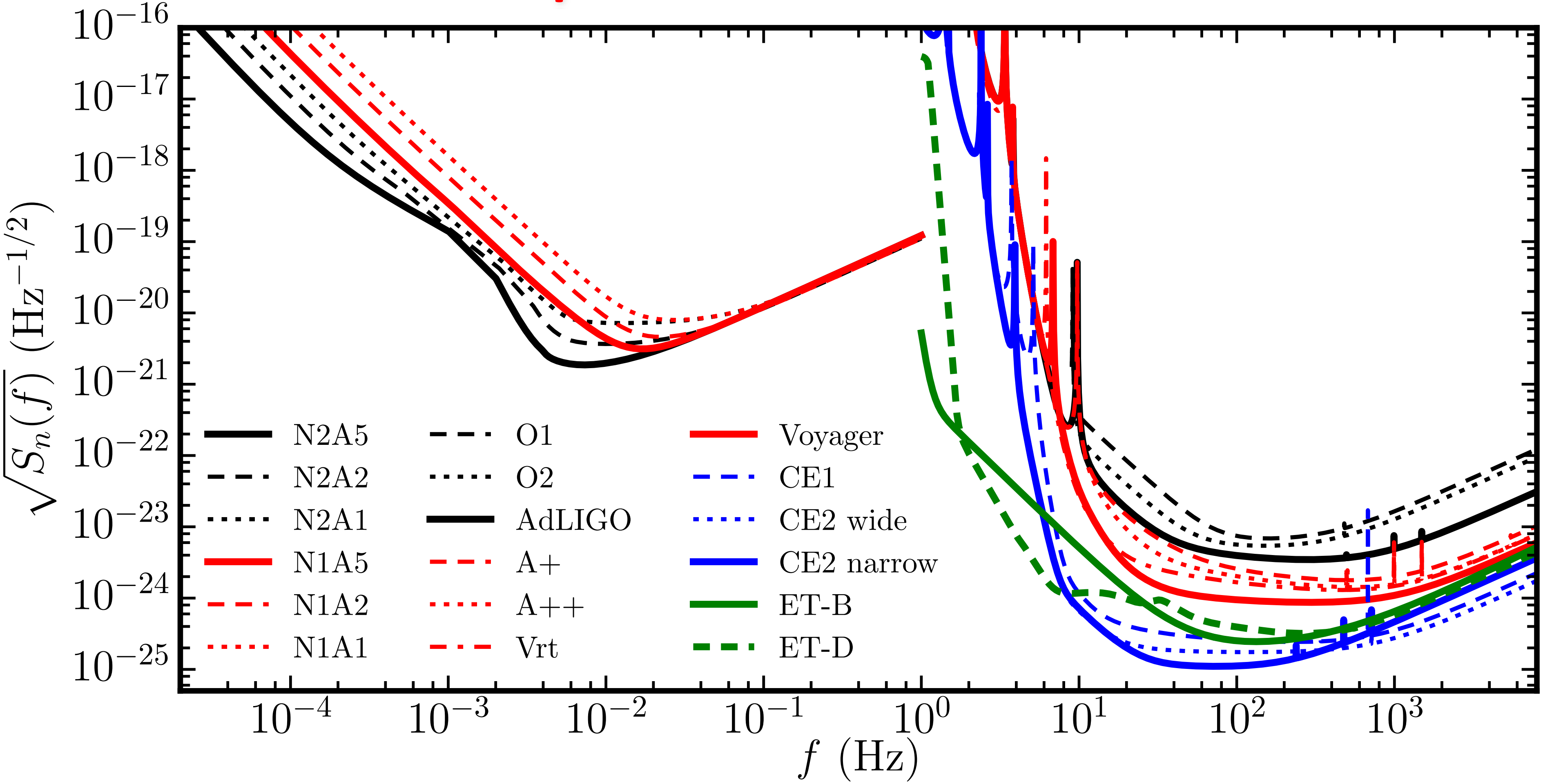
- One mode: **(M,a)**
- Any other mode frequency: **No-hair theorem test**
- Feasibility depends on SNR: **for nearly equal-mass binaries (q~1), need SNR>50 or so** GW150914: ringdown SNR of ~7

Timeline for commissioning of advanced detectors



LIGO Instrument Science White Paper:
https://dcc.ligo.org/public/0120/T1500290/002/T1500290.pdf

Earth vs. space-based interferometers



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

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

[EB+, 1605.09286]

Astrophysical population models

Stellar mass black hole binaries:
Startrack (Belczynski+)

- **M1**
  Standard, $M<100M_{sun}$

- **M10**
  Pair-instability mass loss
  $M<50M_{sun}$

- **Model M3**
  Pessimistic
  High kicks, lower limit on rates

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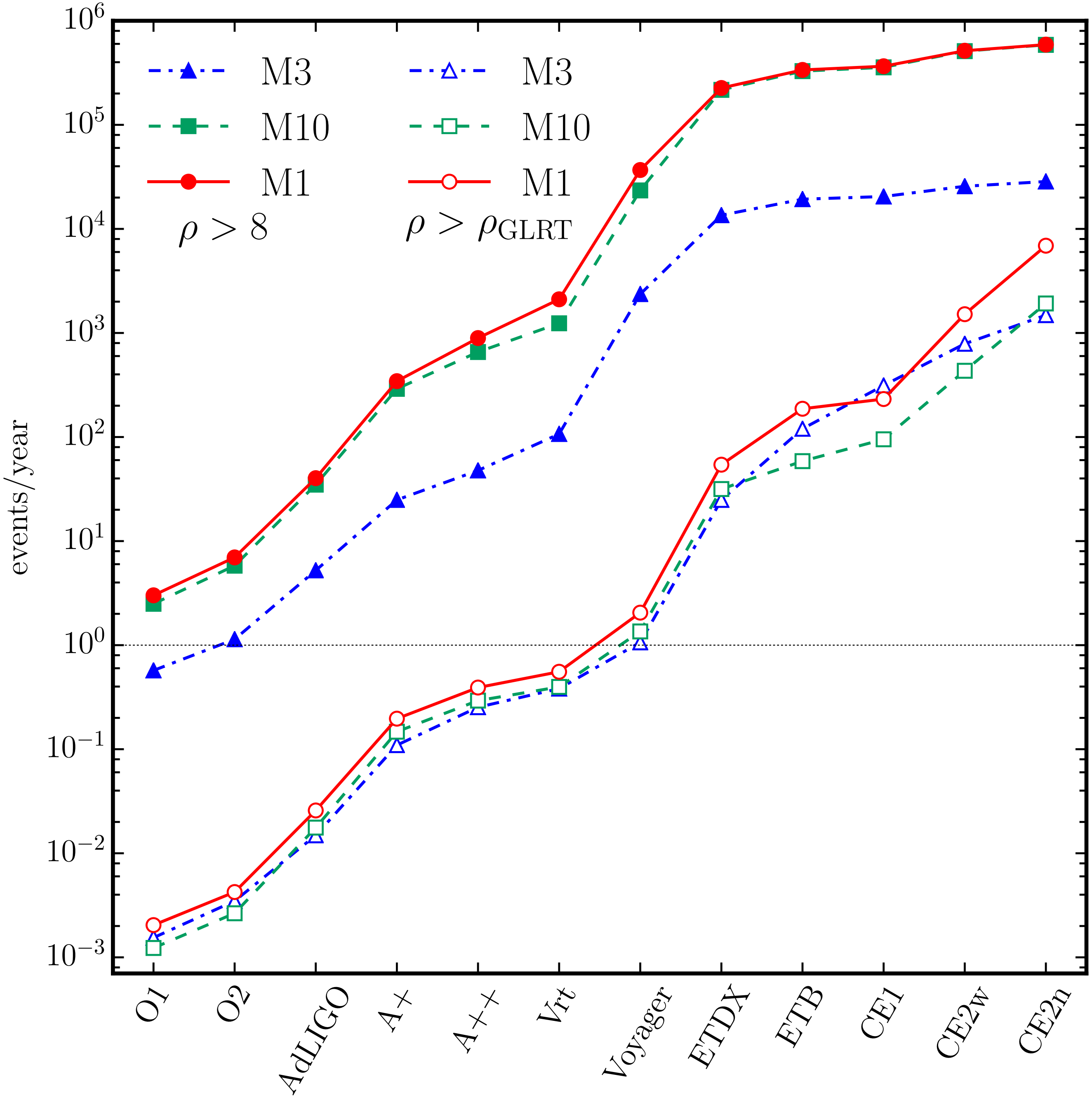
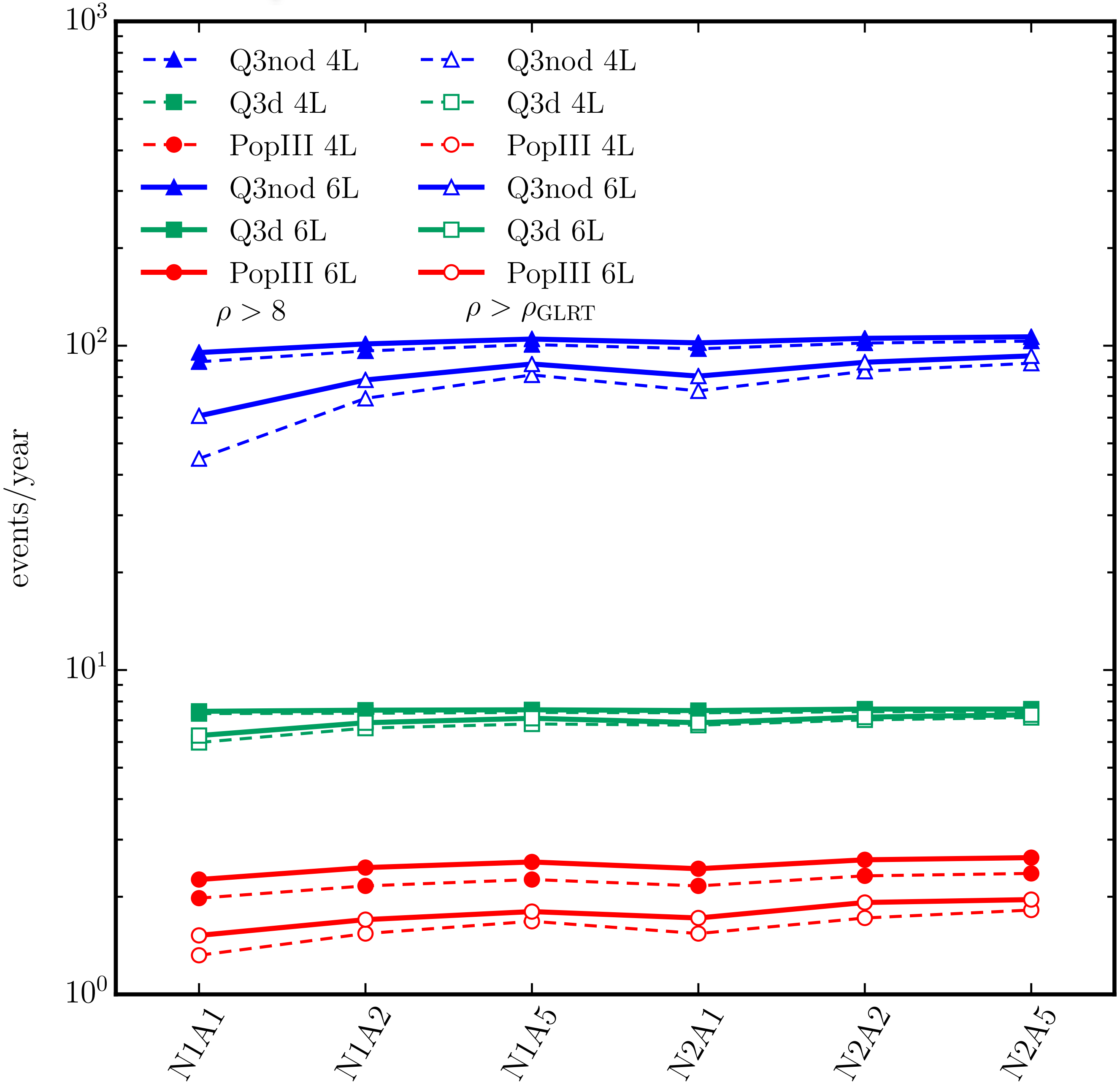
Massive black hole binaries: Barausse+

- **PopIII**
  Light seeds
- **Q3nod**
  Heavy seeds
  No delays
- **Q3d**
  Heavy seeds
  Final parsec problem

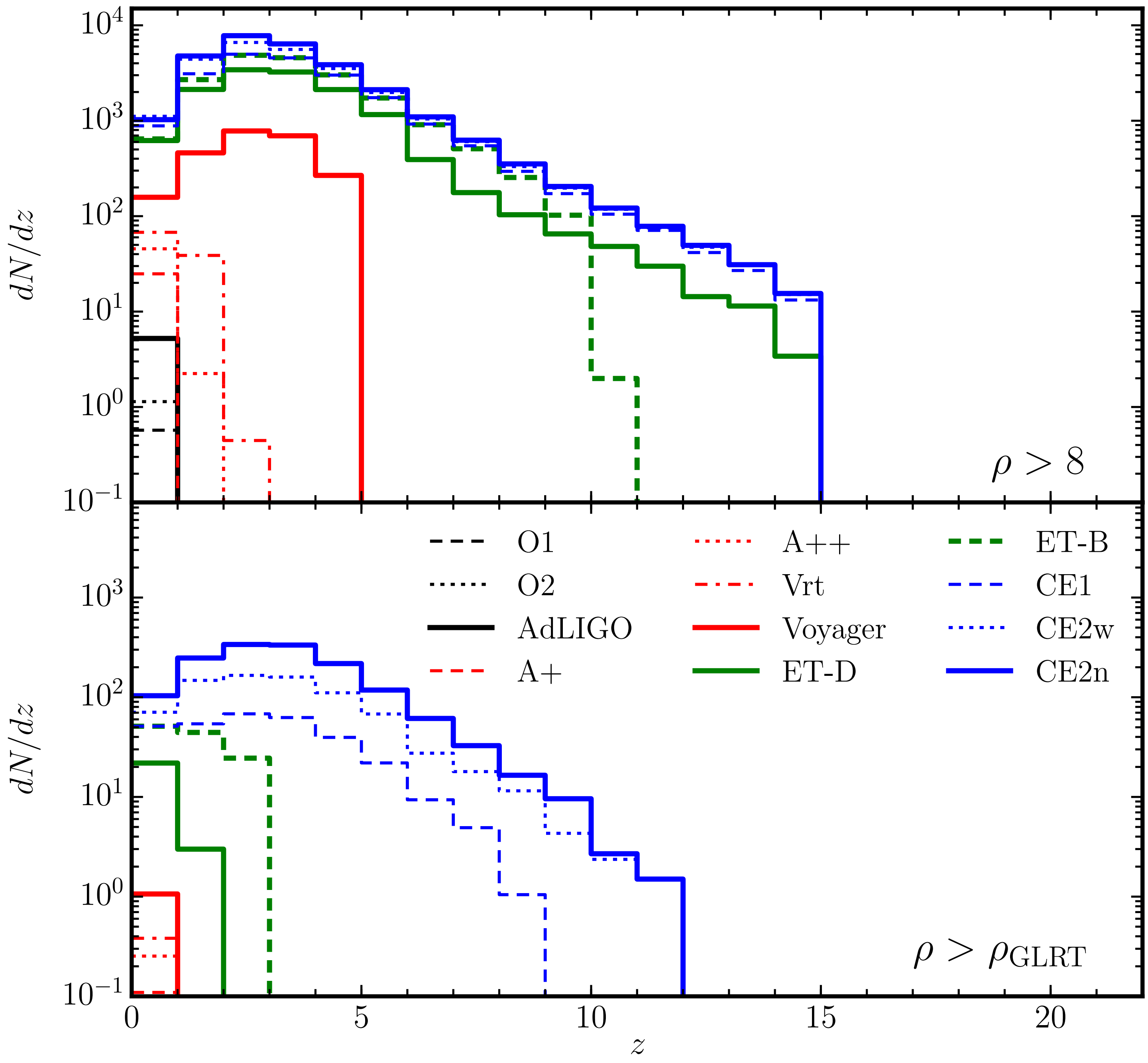
Earth-based: detection rates



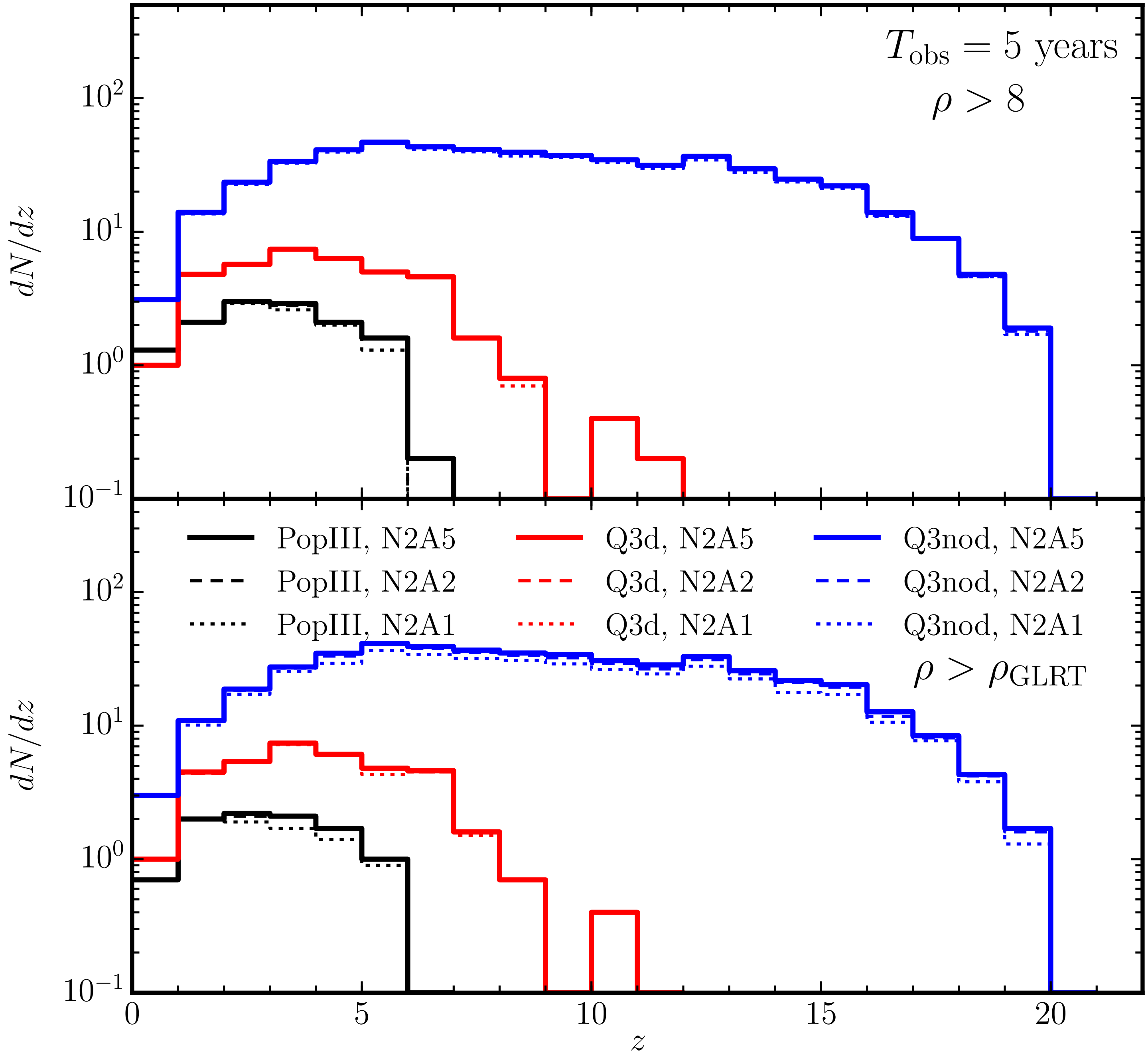
Space-based: detection rates



Earth-based: redshift distribution

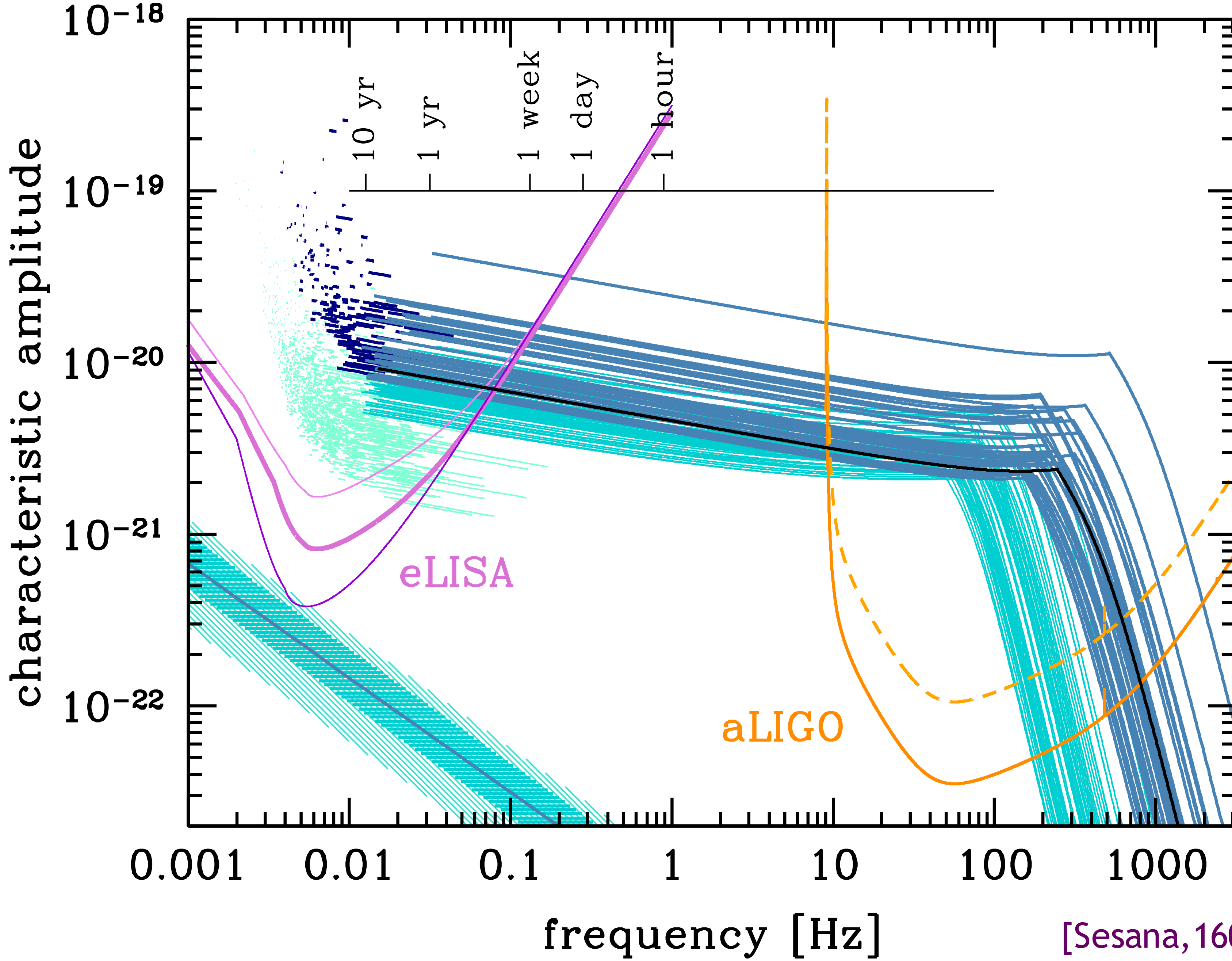


Space-based: redshift distribution



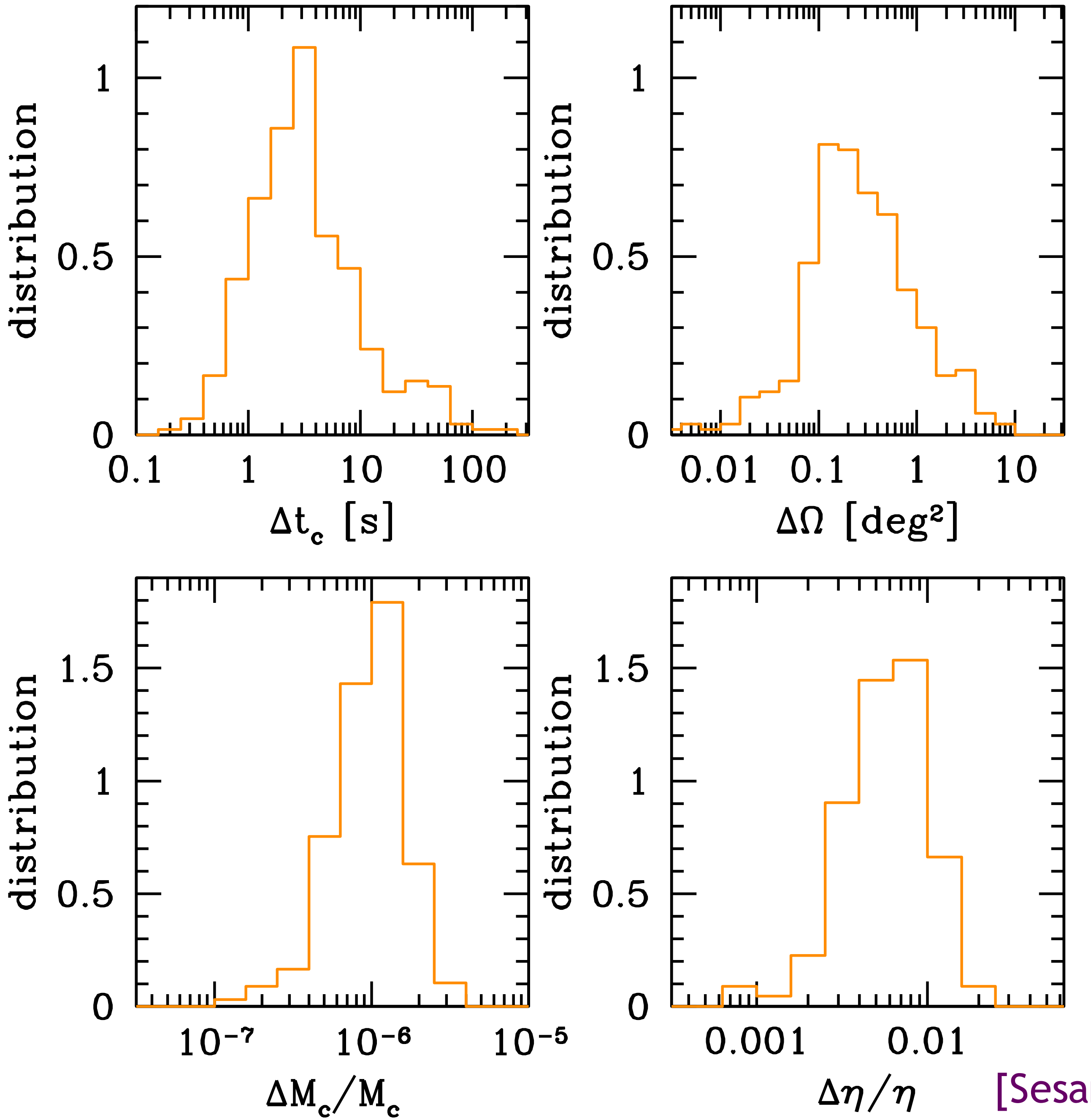
Multiband astronomy and binary formation

Multi-band gravitational wave astronomy



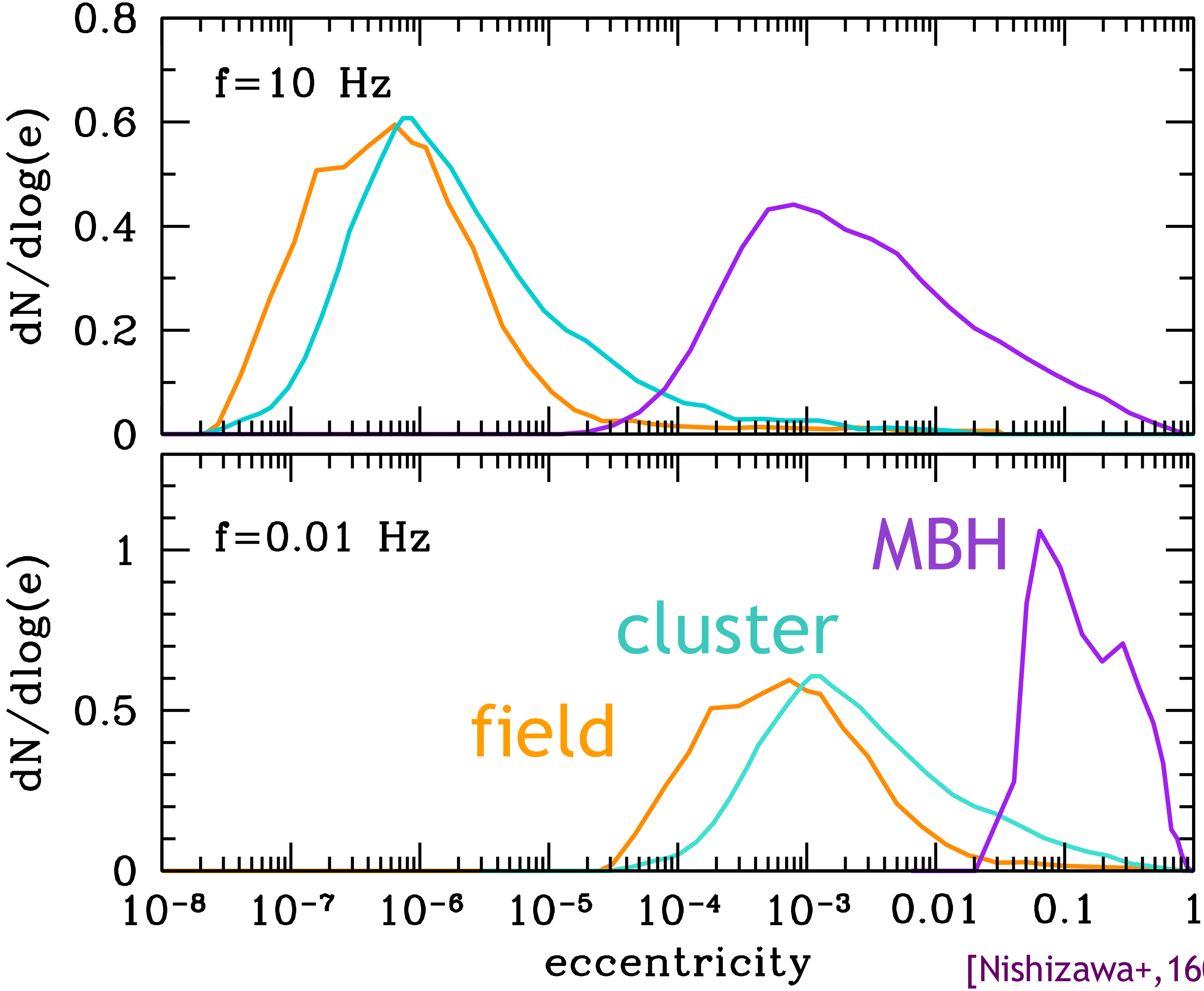
[Sesana, 1602.06951]

Time of arrival: seconds, localization: <1 deg^2



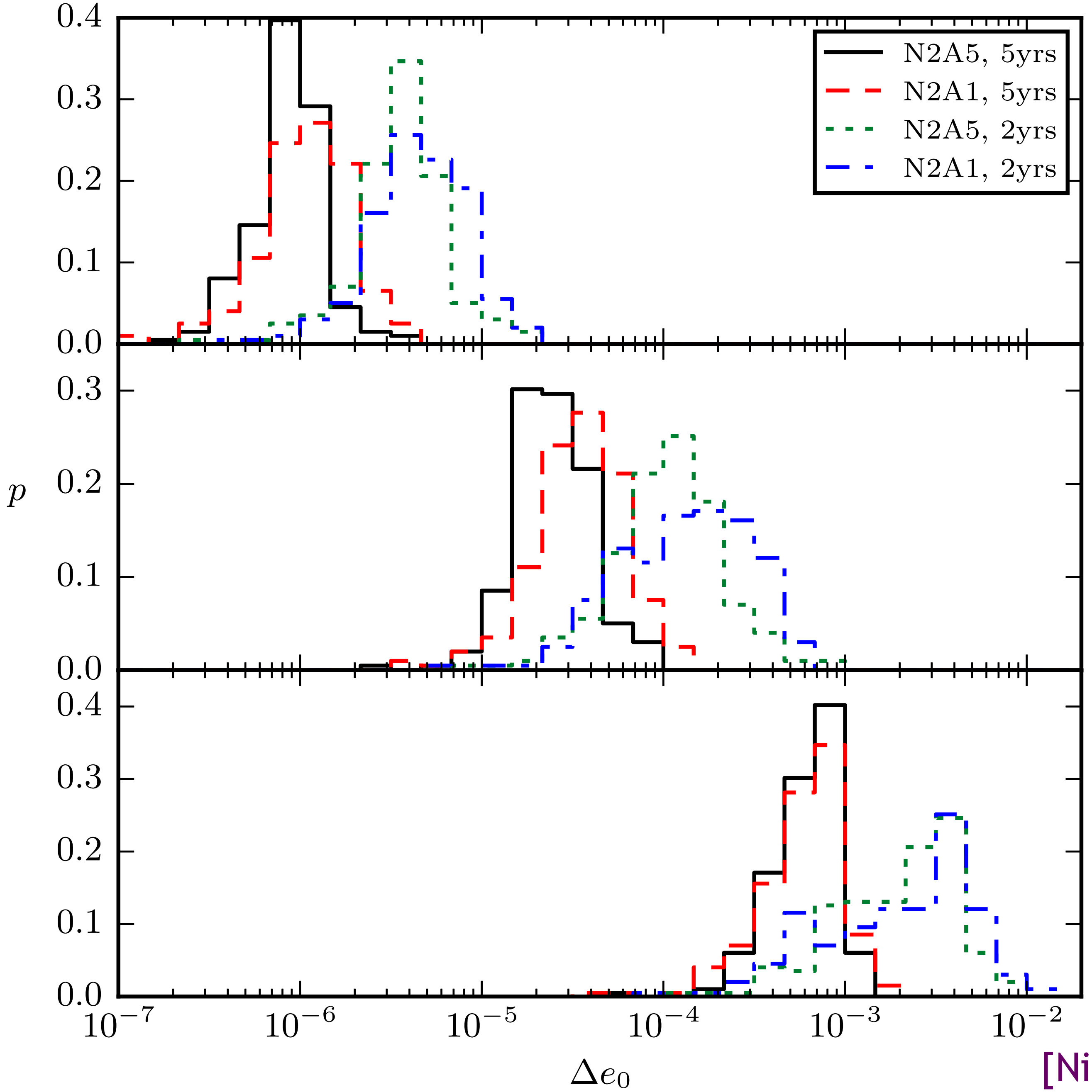
[Sesana, 1602.06951]

Field or cluster formation?



[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_{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

Not enough detections?

5σ confidence with 90% probability

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).

Predictions may be **pessimistic!**

Correlations between e and masses/spins/kicks will help

Breivik et al.: field/cluster e distributions more separated

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

Summary

✓ **Black hole spectroscopy:**

On Earth, despite the high SNR of GW150914, we need:

Voyager-class detectors for significant rates
Einstein Telescope for z~3
Cosmic Explorer for large z

…or better data analysis!

null tests? [Ghosh+, 1602.02453]
stacking? [Lasky+, 1605.01415]

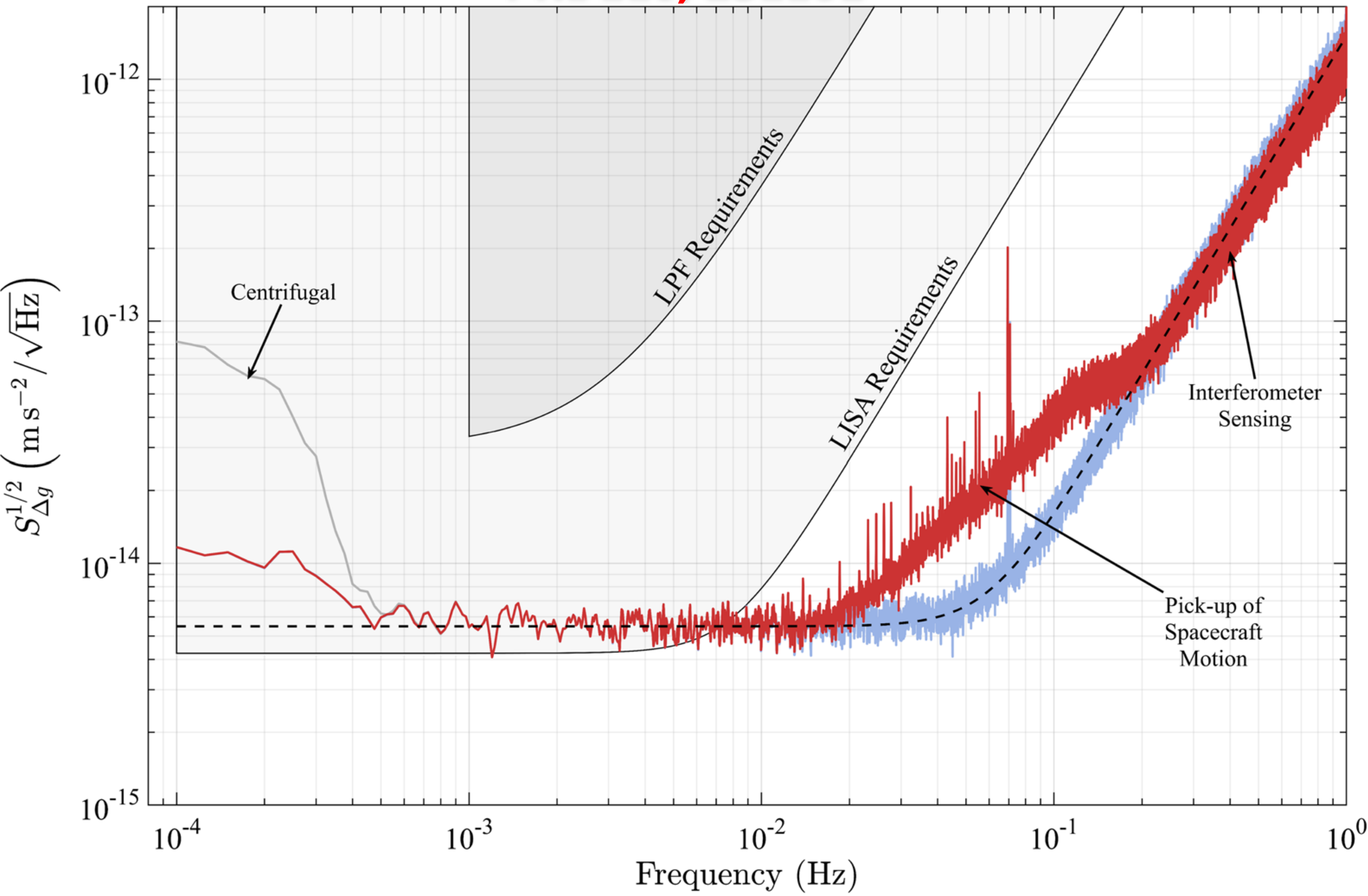
LISA can do this with almost all detected systems (few-hundreds)

✓ **Promise of multiband astronomy:**

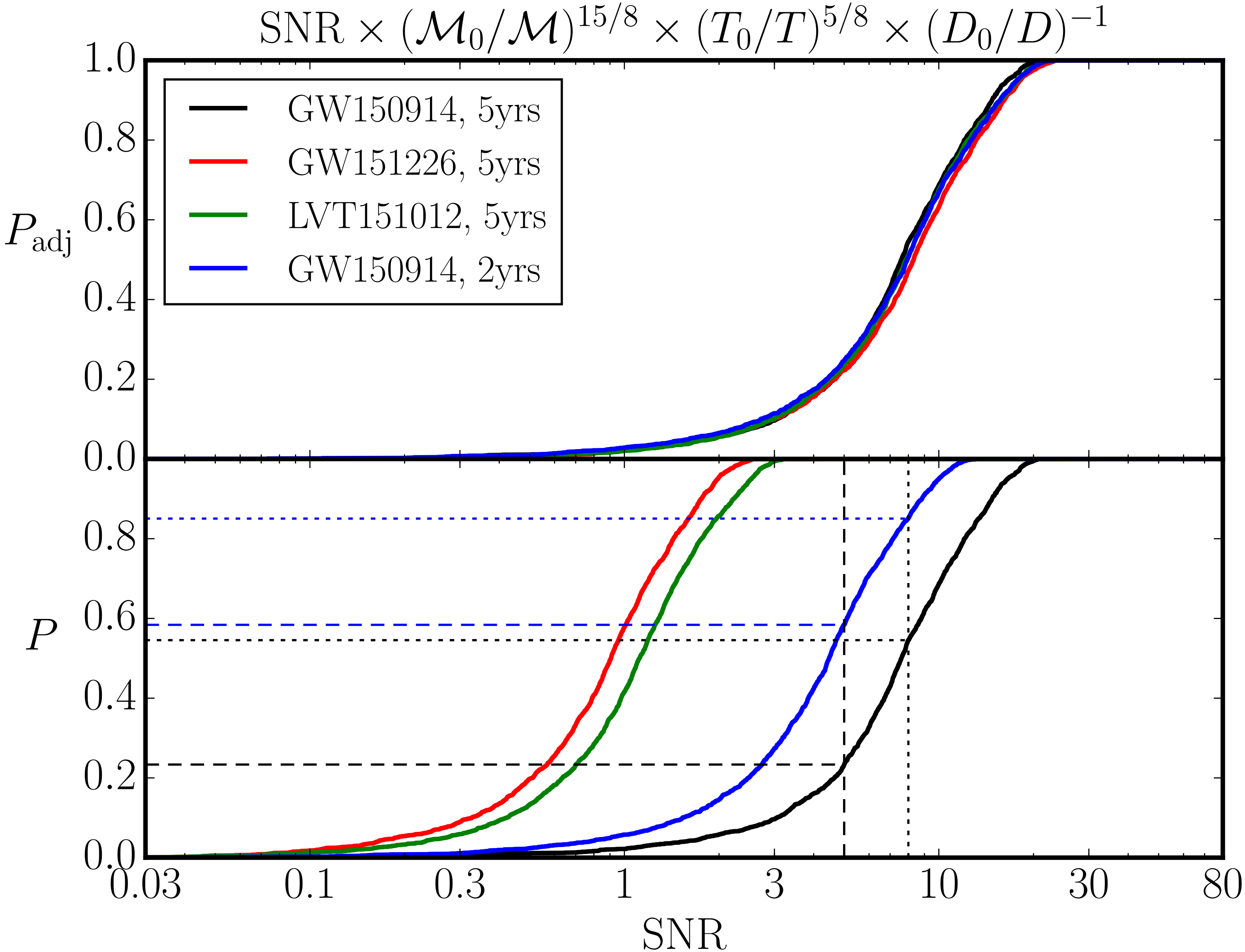
Early warning [Sesana]
Improved parameter estimation [Vitale]
Improved GR tests [Barausse+]
BH formation via eccentricity in LISA band [Nishizawa+, Breivik+, Seto+]

Extra slides

Pathfinder launch (Dec 3 2015)
PRL 116, 231101



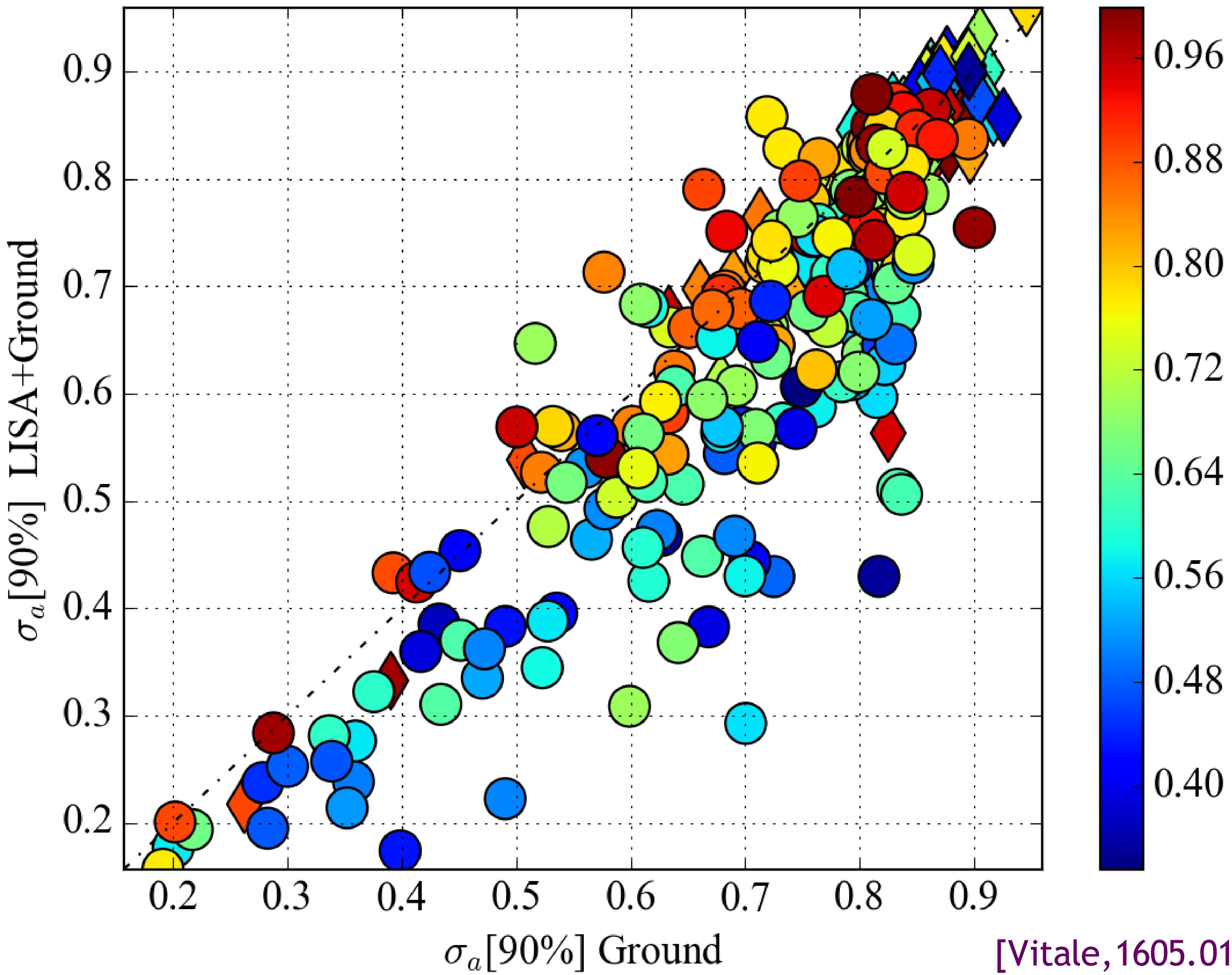
Astrophysics: dense stellar clusters or field formation?



$$\rho \propto \mathcal{M}^{15/8} T_{\rm obs}^{5/8}$$

[Klein+,in preparation]

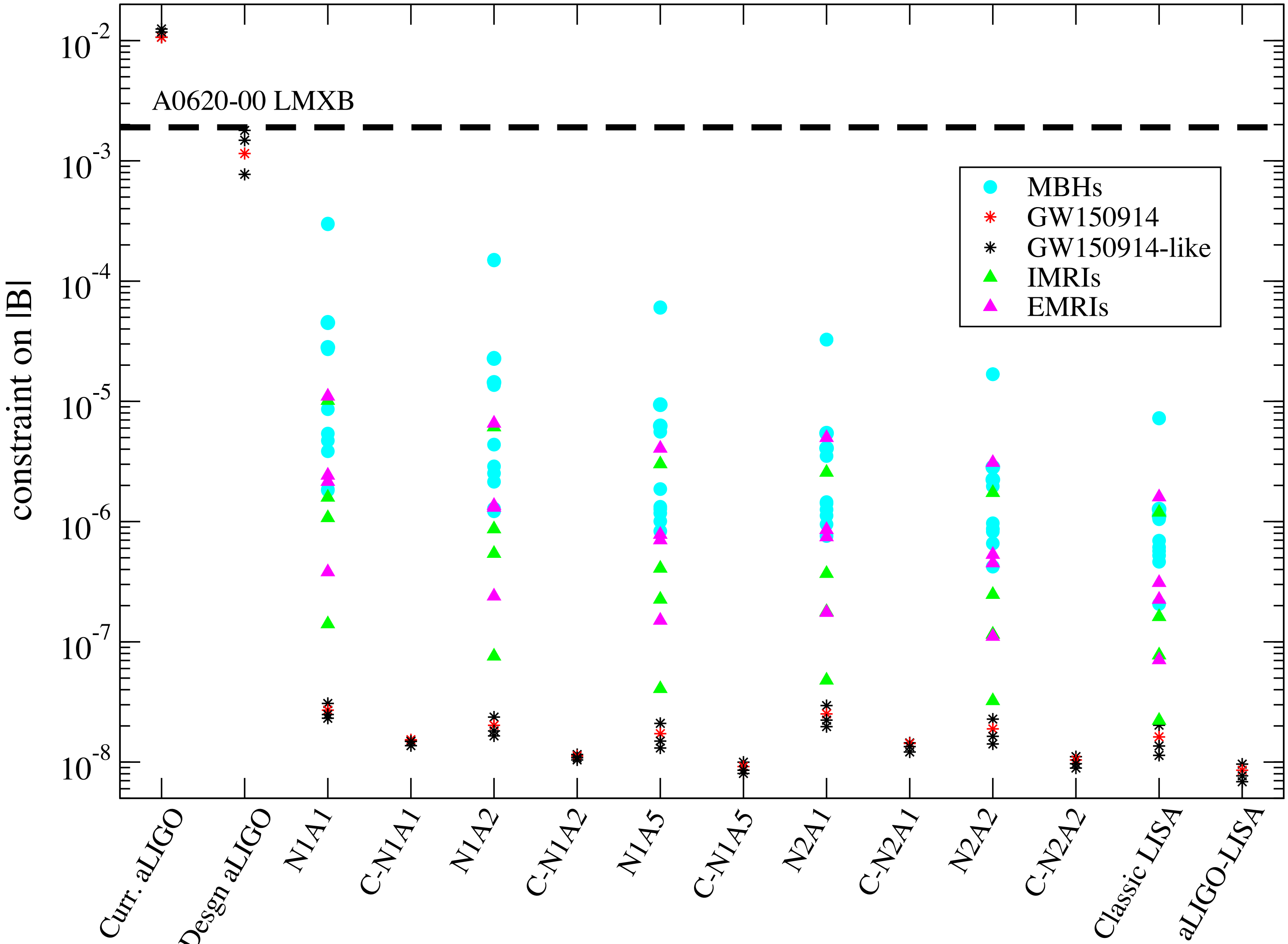
Errors on primary (circles) and secondary (diamonds) spins



[Vitale,1605.01037]

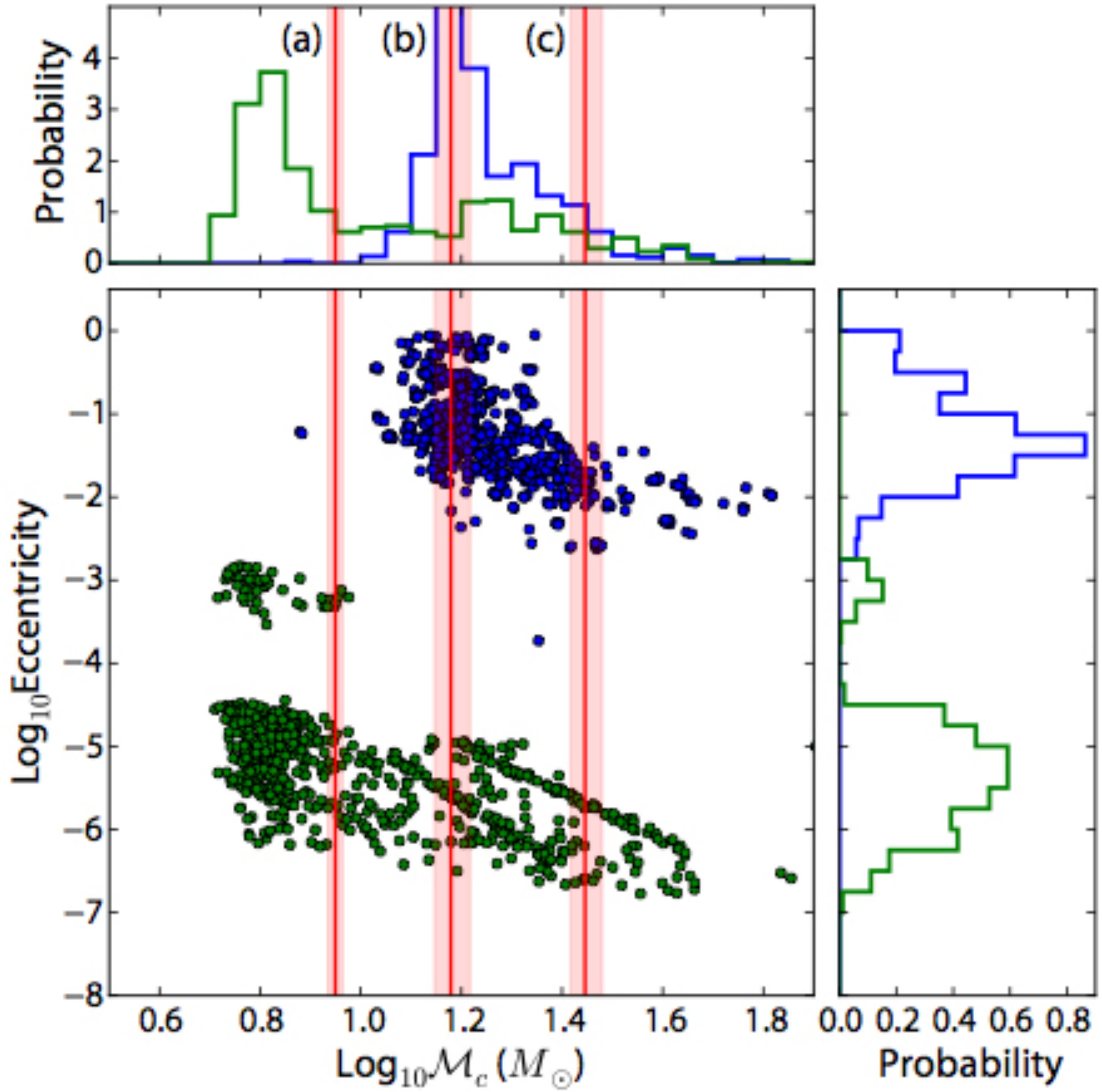
Improved tests of GR

$$\dot{E}_{\rm GW} = \dot{E}_{\rm GR}\left[1 + B\left(\frac{Gm}{r_{12}c^2}\right)^{-1}\right]$$



[Barausse+,1603.04075]

Field or cluster formation?

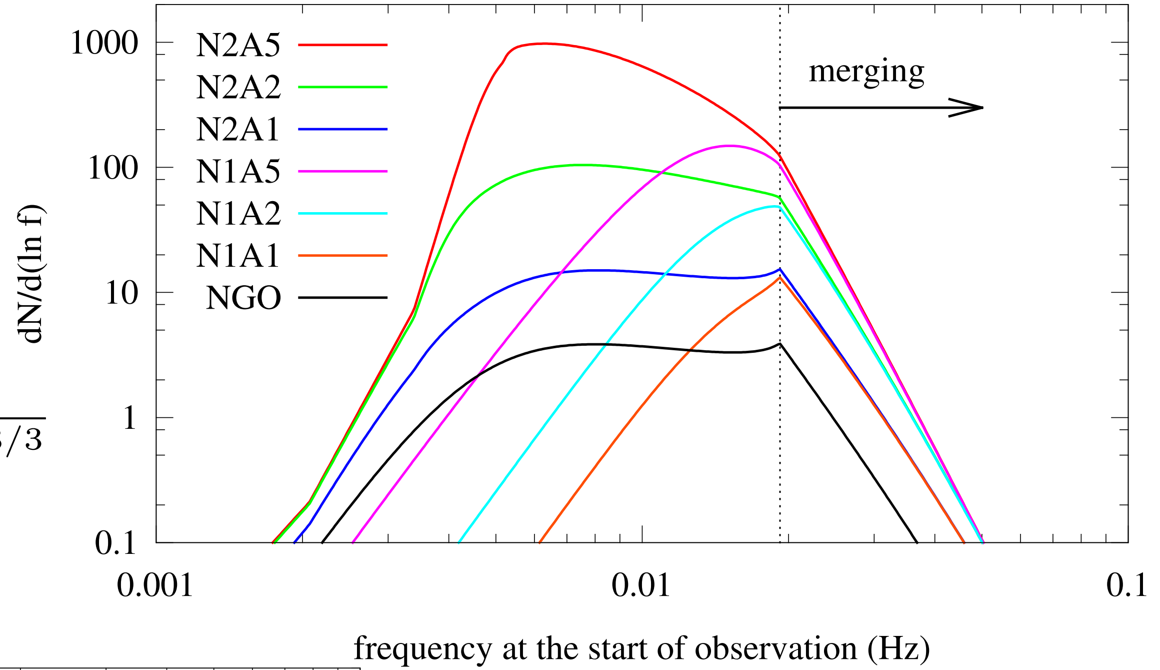


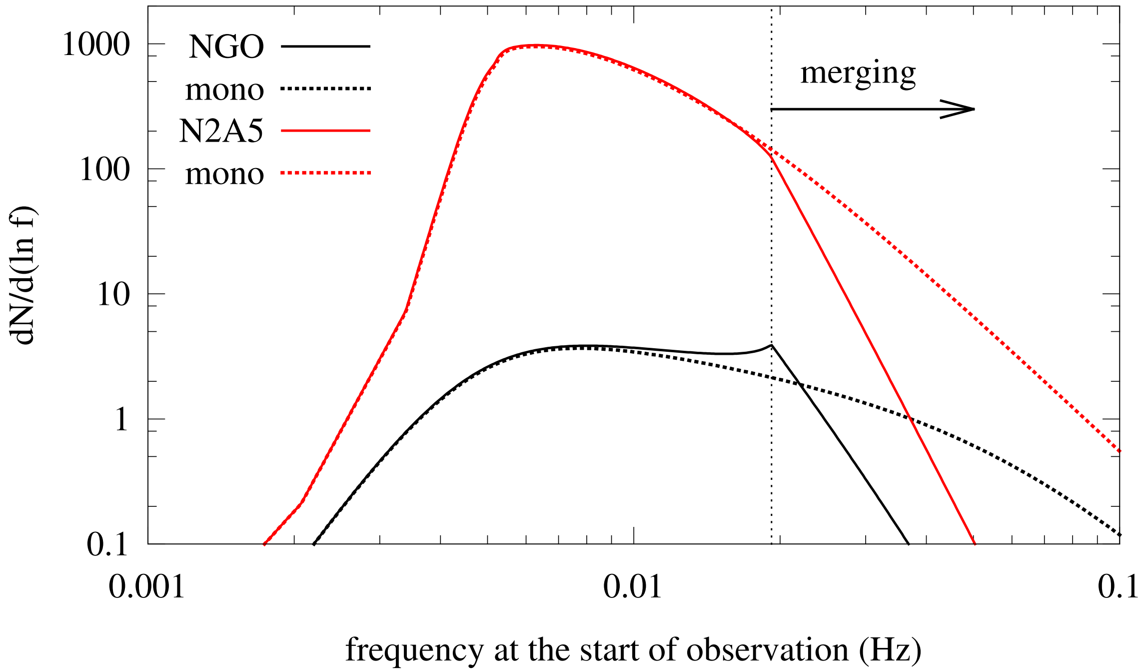
[Breivik+, 1606.09558]

Astrophysics: dense stellar clusters or field formation?

$$\rho \propto \mathcal{M}^{5/3} T_{\rm obs}^{1/2} f_{\rm f}^{-1/3}$$

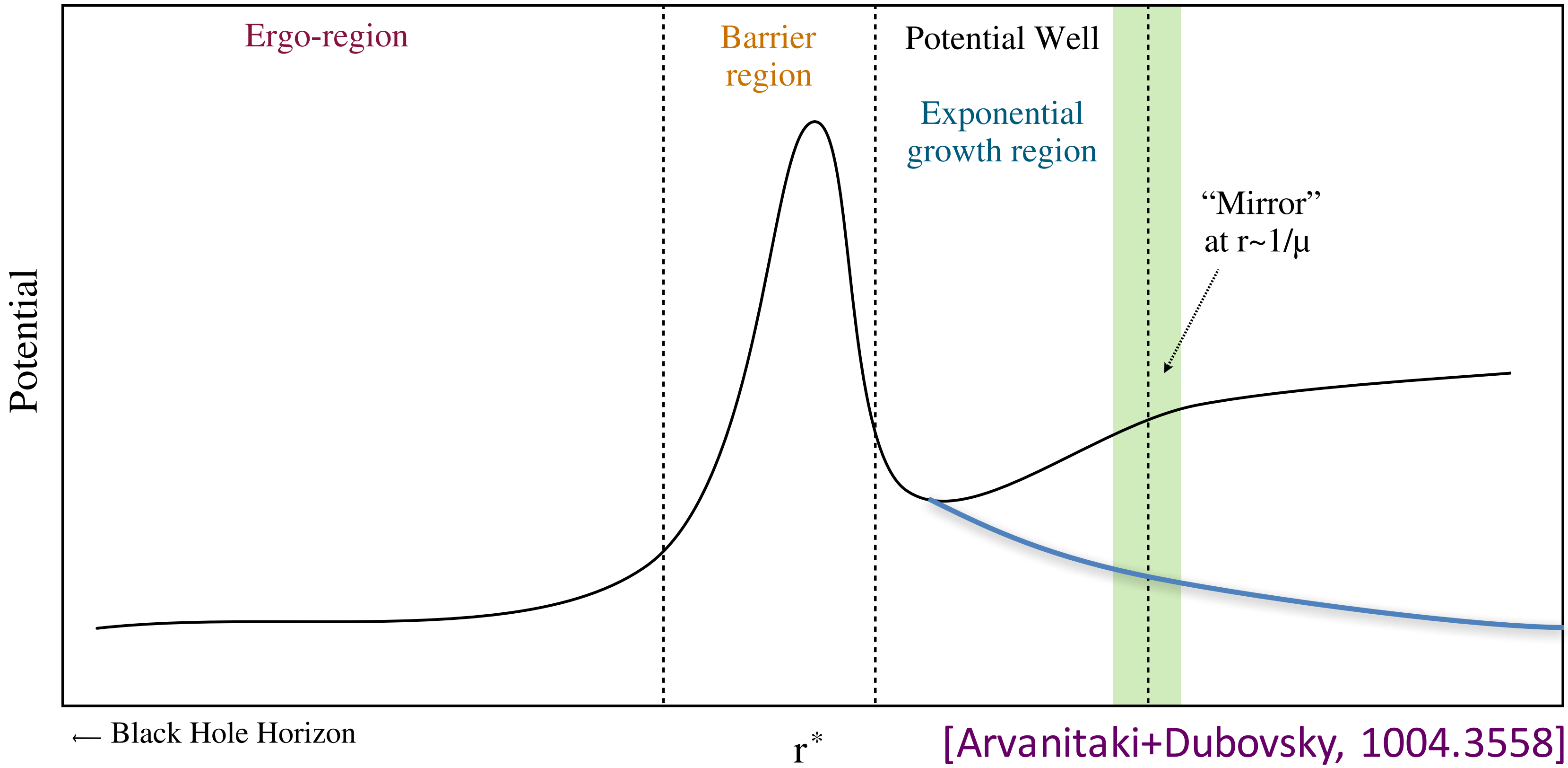
$$\frac{dn}{d\ln f} = \frac{f}{\dot{f}} R = \frac{5c^5 R}{96\pi^{8/3} G^{5/3} \mathcal{M}^{5/3} f^{8/3}}$$





[Seto+,1606.02298]

Black hole dynamics: wave scattering



[Arvanitaki+Dubovsky, 1004.3558]

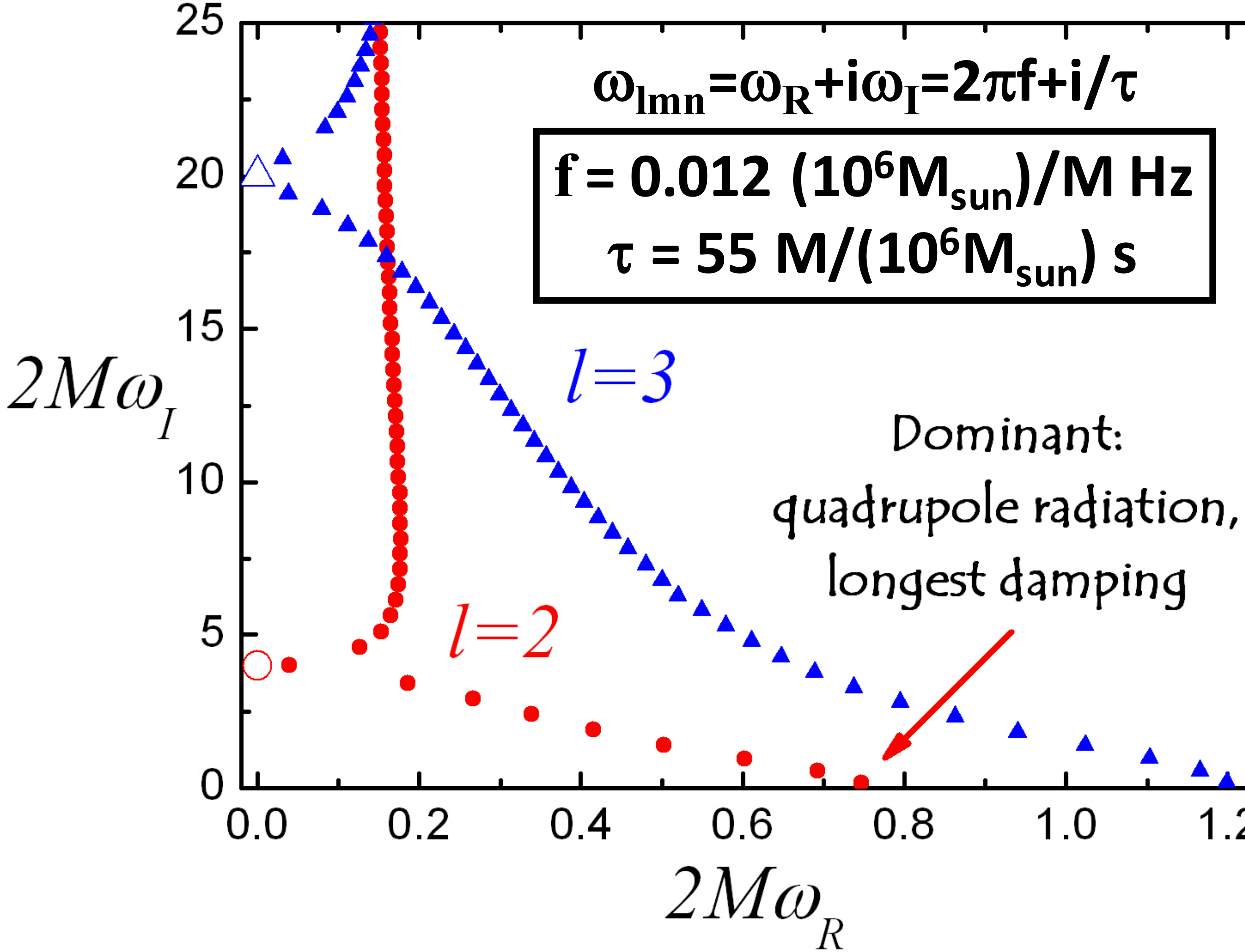
Quasinormal modes:

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

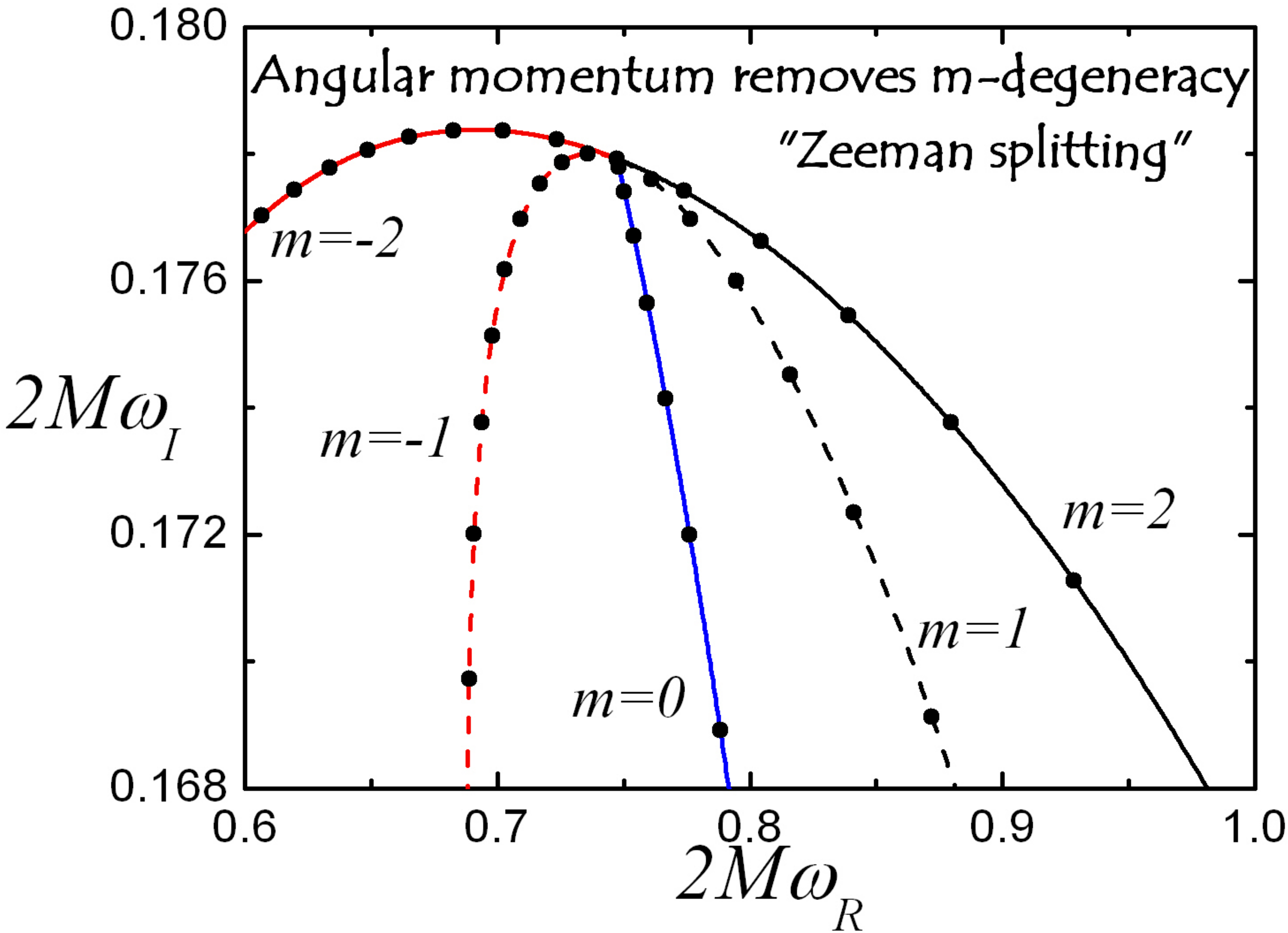
Massive scalar field:

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

Ringdown: black hole spectroscopy



Spectroscopy of rotating (Kerr) black holes



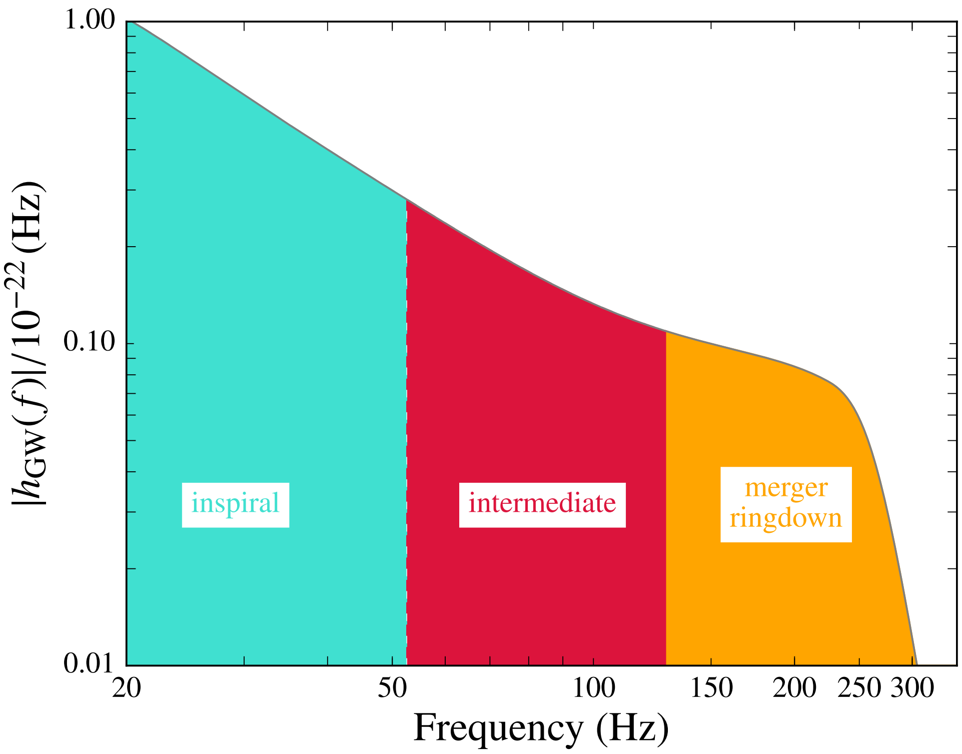
The LIGO GR test paper: signal consistent with GR merger

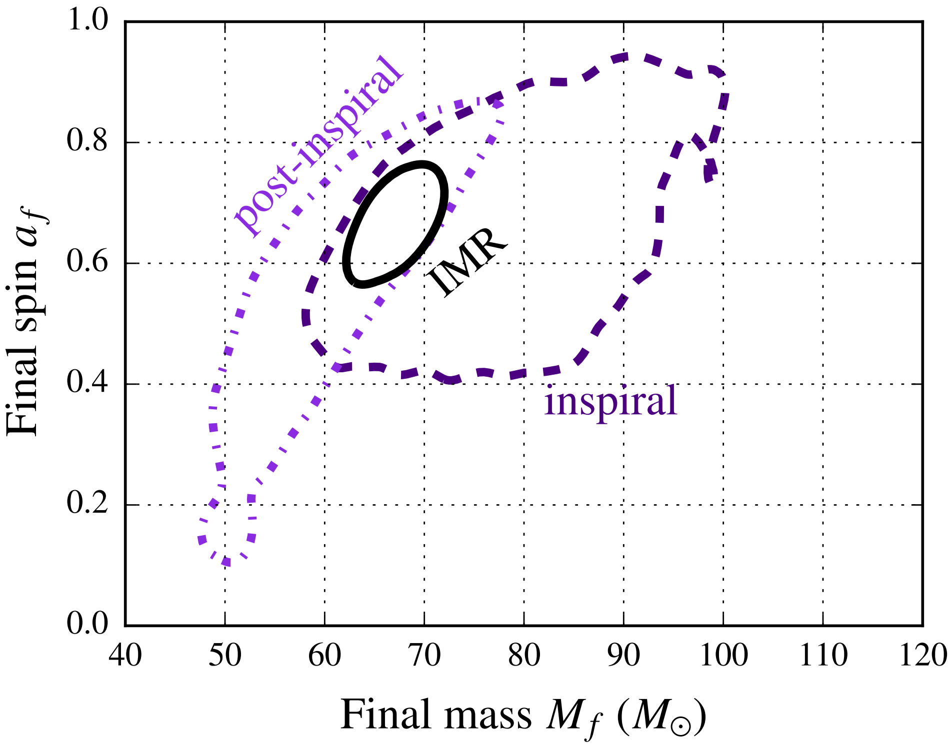
1) **LALInference: "maximum a posteriori" waveform**
   BayesWave: residual after subtraction is consistent with noise

2) **Inspiral and post-inspiral predict the same (M_f, a_f)**

3) **Data post-peak consistent with fundamental QNM for the given (M_f, a_f): f=251Hz, τ=4ms**

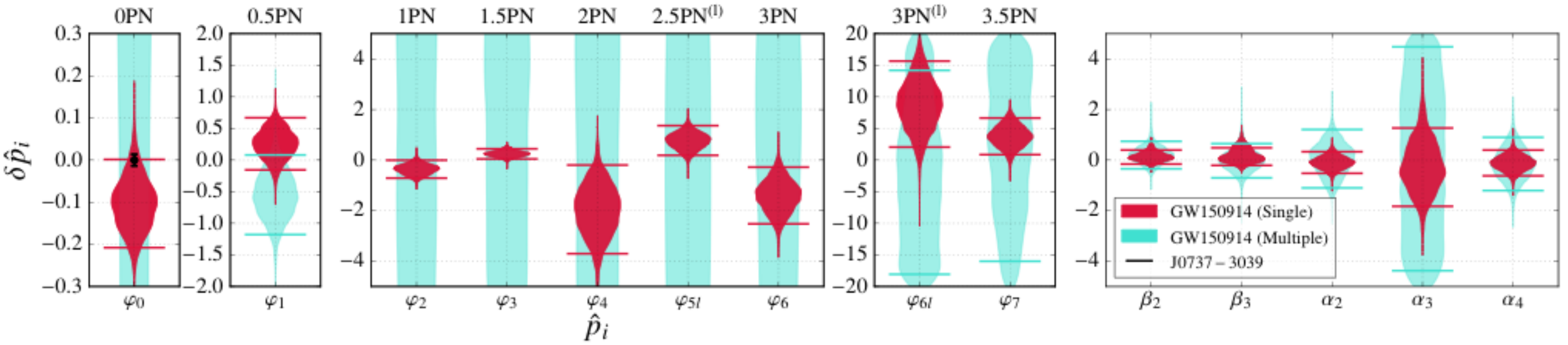
[LVC, 1602.03841]





The LIGO GR test paper: gIMR and propagation

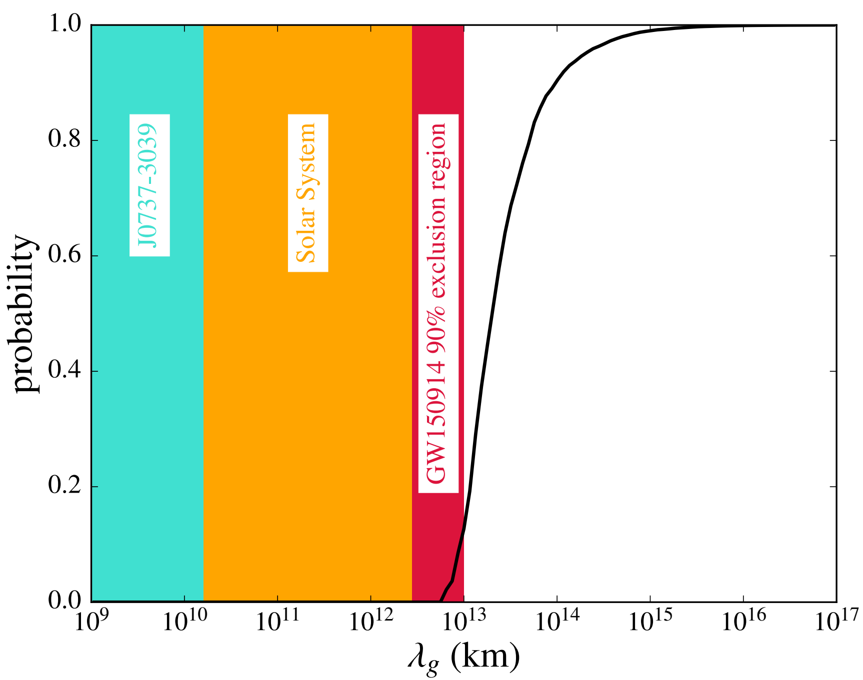
4) gIMR ("generalized" IMR): measure PN and parametrized waveform coefficient (related to ppE)



5) Graviton Compton wavelength $\lambda_g > 10^{13}$ km ($m_g < 1.2 \times 10^{-22}$)

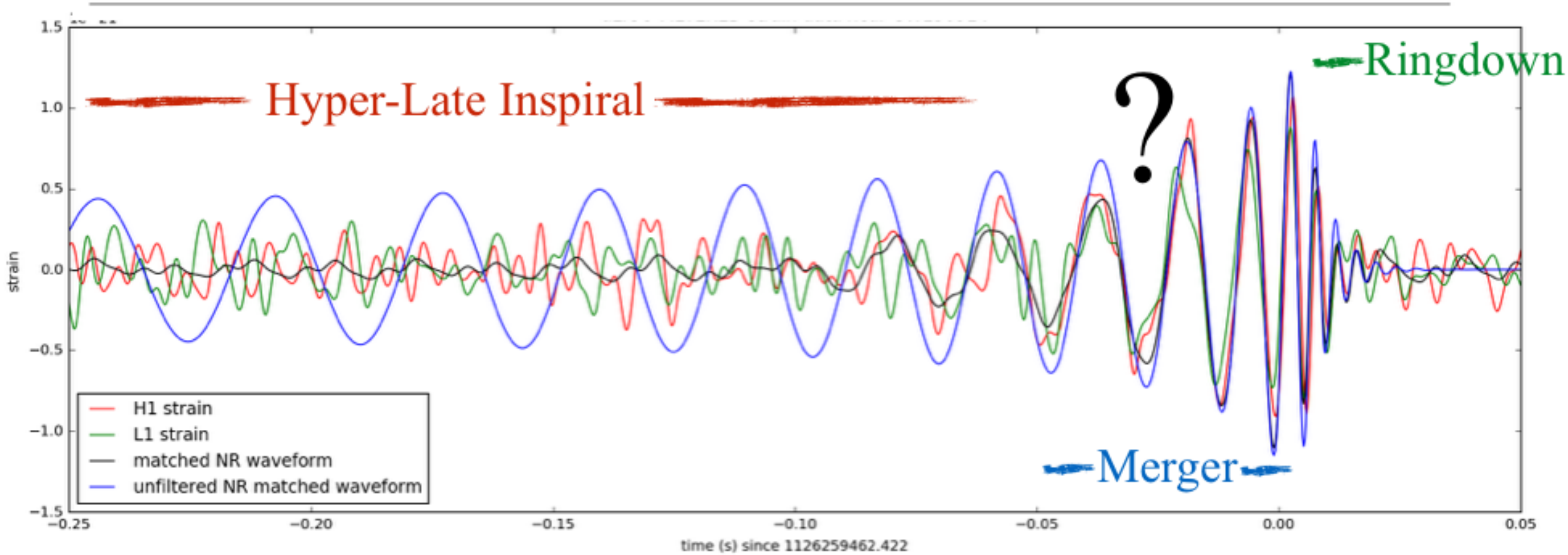
[Will 1998]

6) No polarization information

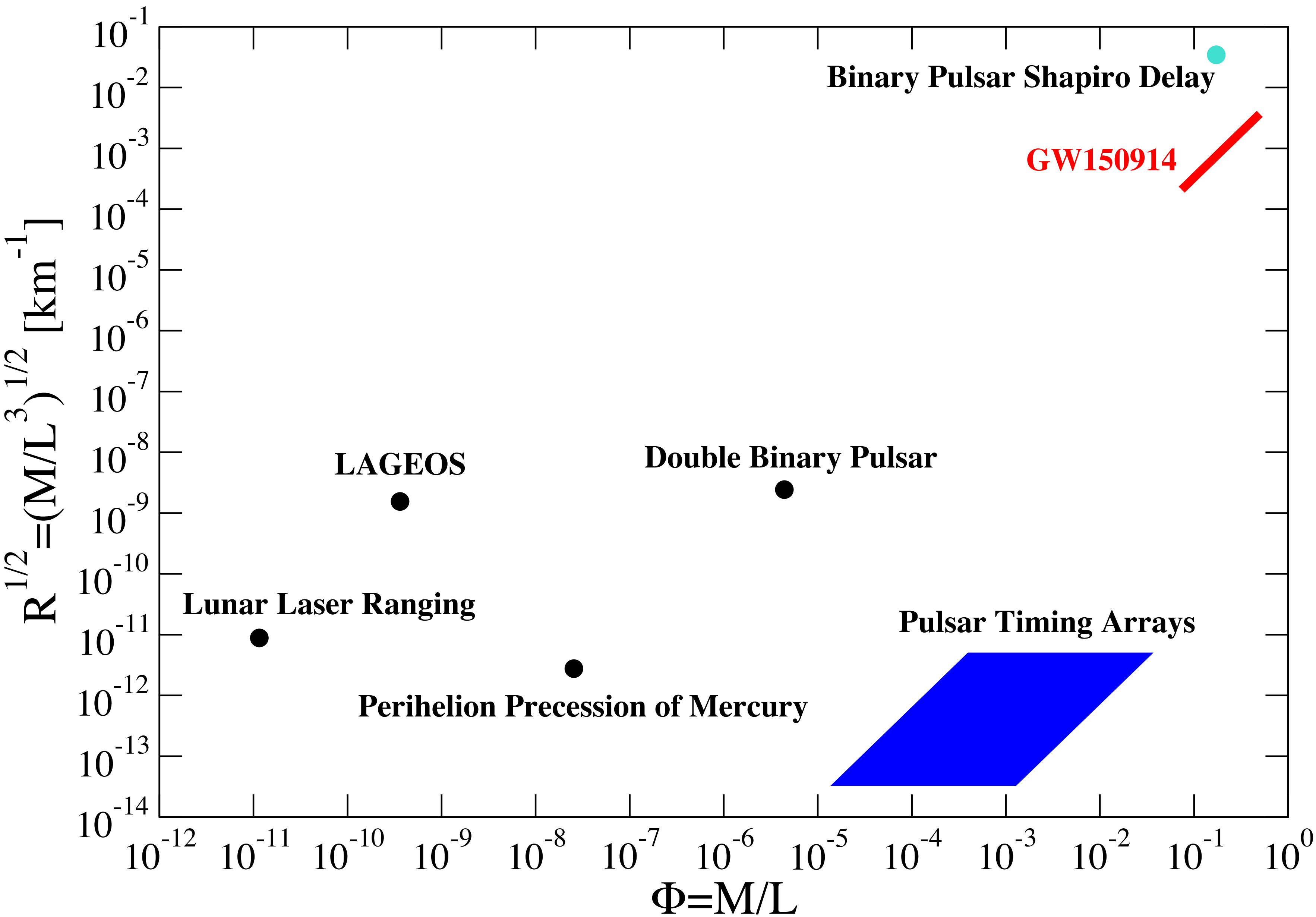


Theoretical Physics Implications of GW150914

	Theoretical Mechanism	GR Pillar	PN	$\lvert\beta\rvert$ GW150914	Example Theory Constraints: Repr. Parameters	GW150914	Current Bounds
Generation	Scalar Field Activation	SEP	-1	$\mathbf{1.6 \times 10^{-4}}$	$\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km]	—	10^7 [39], 2 [40–42]
		SEP, No BH Hair	-1	$\mathbf{1.6 \times 10^{-4}}$	$\lvert\dot{\phi}\rvert$ [1/sec]	—	10^{-6} [43]
		SEP, Parity Invariance	$+2$	$\mathbf{1.3 \times 10^{1}}$	$\sqrt{\lvert\alpha_{\rm CS}\rvert}$ [km]	—	10^8 [44, 45]
	Vector Field Activation	SEP, Lorentz Invariance	0	$\mathbf{7.2 \times 10^{-3}}$	(c_+, c_-)	$\mathbf{(0.9, 2.1)}$	$(0.03, 0.003)$ [46, 47]
	Extra Dimension Mass Leakage	4D spacetime	-4	$\mathbf{9.1 \times 10^{-9}}$	ℓ [μm]	$\mathbf{5.4 \times 10^{10}}$	10–10^3 [48–52]
	Time-Varying G	SEP	-4	$\mathbf{9.1 \times 10^{-9}}$	$\lvert\dot{G}\rvert$ [10^{-12}/yr]	$\mathbf{5.4 \times 10^{18}}$	0.1–1 [53–57]
Propagation	Massive graviton	massless graviton	$+1$	$\mathbf{1.3 \times 10^{-1}}$	m_g [eV]	$\mathbf{1.2 \times 10^{-22}}$ [12]	10^{-29}–10^{-18} [58–62]
	Modified Dispersion Relation	$v_g = c$	$+4.75$	$\mathbf{1.8 \times 10^{2}}$	$\mathbb{A} > 0$ [$1/\sqrt{\rm eV}$]	$\mathbf{3.1 \times 10^{-13}}$	—
	(*Multifractional Spacetime*)		$+4.75$	$\mathbf{1.8 \times 10^{2}}$	$\mathbb{A} < 0$ [$1/\sqrt{\rm eV}$]	$\mathbf{3.1 \times 10^{-13}}$	1.9×10^{-26} [63]
	Modified Dispersion Relation	$v_g = c$	$+5.5$	$\mathbf{2.3 \times 10^{2}}$	$\mathbb{A} > 0$ [1/eV]	$\mathbf{1.6 \times 10^{-7}}$	—
	(*Modified Special Relativity*)		$+5.5$	$\mathbf{2.3 \times 10^{2}}$	$\mathbb{A} < 0$ [1/eV]	$\mathbf{1.6 \times 10^{-7}}$	2.7×10^{-36} [63]
	Modified Dispersion Relation	$v_g = c$	$+7$	$\mathbf{8.7 \times 10^{2}}$	$\mathbb{A} > 0$ [$1/{\rm eV}^2$]	$\mathbf{9.3 \times 10^{4}}$	—
	(*Extra Dimensions*)		$+7$	$\mathbf{8.7 \times 10^{2}}$	$\mathbb{A} < 0$ [$1/{\rm eV}^2$]	$\mathbf{9.3 \times 10^{4}}$	4.6×10^{-56} [63]
	Modified Dispersion Relation (*Lorentz Violation*)	SEP, Lorentz Invariance	—	—	c_+	$\mathbf{0.7}$ [64]	$(0.03, 0.003)$ [46, 47]

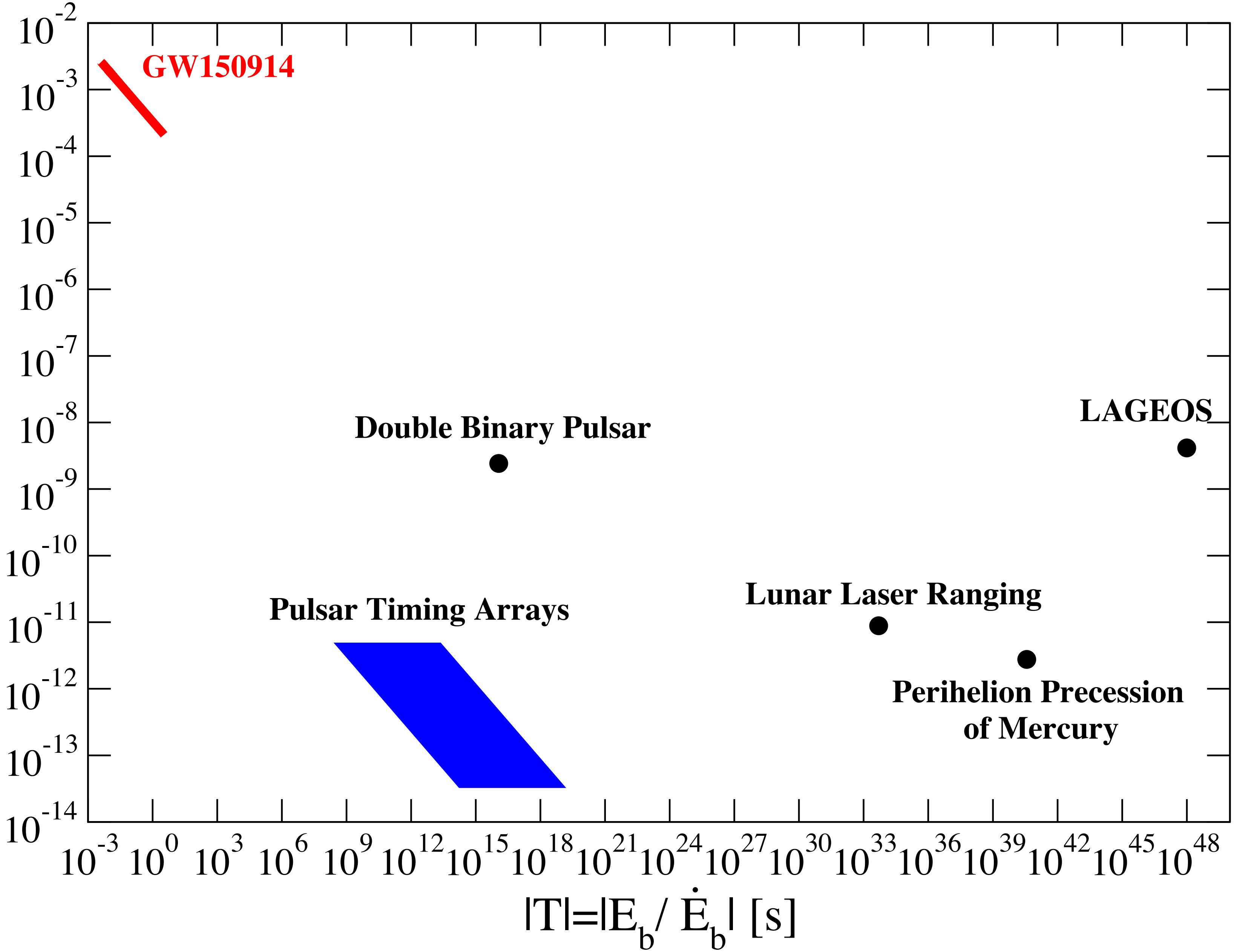


Strong field probes: black hole mergers



[Yunes-Yagi-Pretorius, 1603.09955]

Dynamics: radiation reaction timescales



[Yunes-Yagi-Pretorius, 1603.09955]

Pathfinder launch (Dec 3 2015)
(L)Isabella