On multiband GW astronomy

What are we learning from GW observations of merging binaries, and what do we need to learn more?

Emanuele Berti, Johns Hopkins University

KITP GravAst19, June 18 2019

Credits:

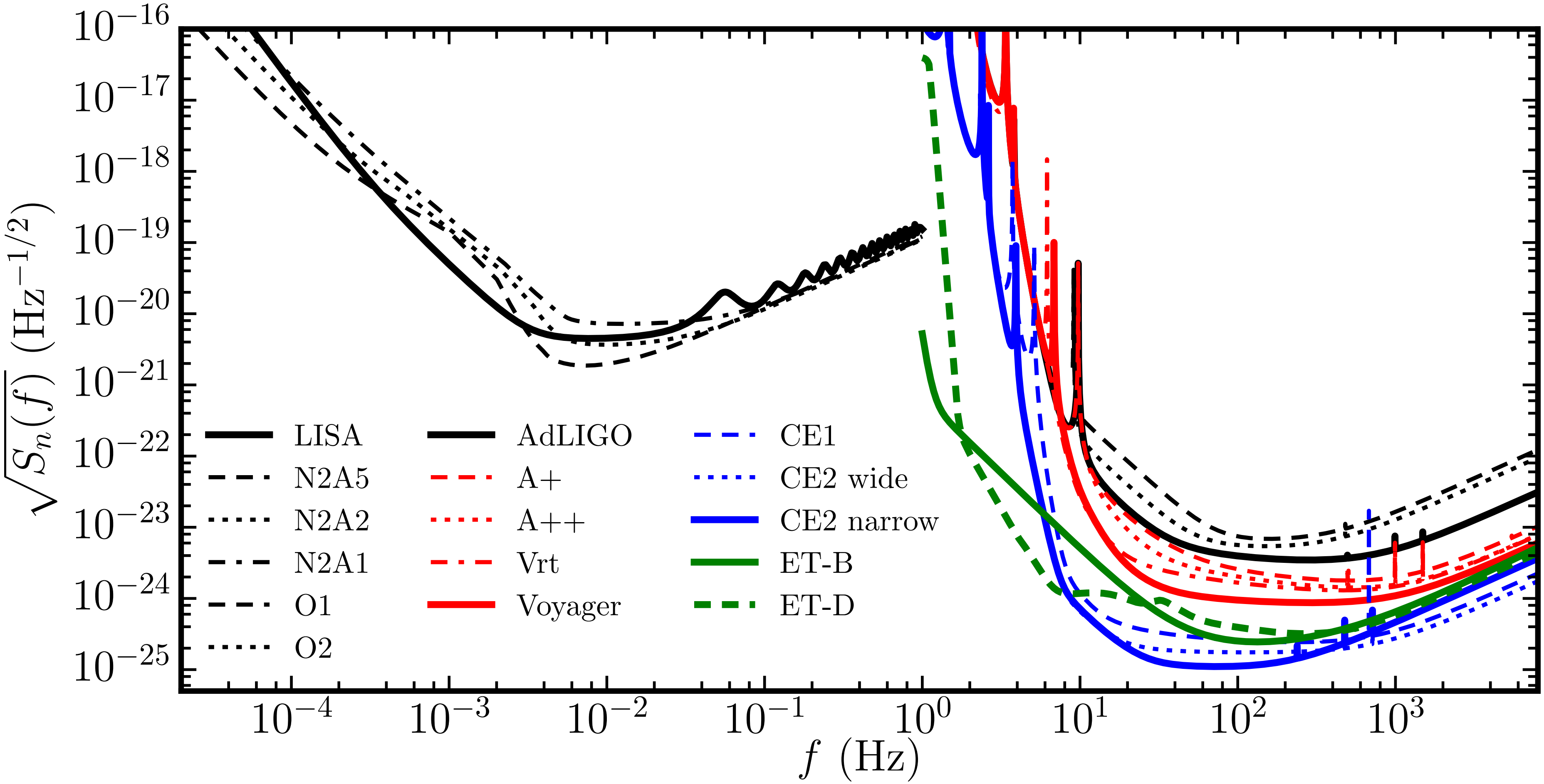
Davide Gerosa, Kaze Wong

+Baibhav, Belczynski, Bouffanais, Chen, Cutler, Di Carlo, Dominik, Fryer, Giacobbo, Holz, Kesden, Klein, Kovetz, Littenberg, Ma, Mapelli, Nishizawa, O'Shaughnessy, Sesana, Sperhake, Tanay, Trifirò, Vitale, Volonteri, Wysocki…
(and apologies to people who did not fit on this slide!)

JOHNS HOPKINS UNIVERSITY

O1/O2 catalog recap
Spins
Multiband GW astronomy
Midband detectors
Multiple mergers and v_{esc}

Gravitational wave detectors



$$f = 170.2\left(\frac{100 M_\odot}{M}\right)\ \text{Hz}$$

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

[EB+, 1605.09286]

Home
Call for Membership of Topical Teams
Call for White Papers
Workshop: first announcement
Senior Committee
Q&A

VOYAGE 2050
LONG-TERM PLANNING OF THE ESA SCIENCE PROGRAMME

***** Workshop dates announced: 29 to 31 October, Madrid, Spain *****
***** See first announcement *****

4 March 2019

The Science Programme of the European Space Agency (ESA) relies on long-term planning of its scientific priorities. The first long-term plan, Horizon 2000, was the result of an exercise started in 1983, and it was followed by an extension, Horizon 2000 Plus, that resulted in the initiation of the Gaia and BepiColombo missions. The successive planning exercise, Cosmic Vision, was started in 2004 and is the current basis against which the content of the Science Programme is set.

Cosmic Vision is the result of a bottom-up process that began with a consultation of the broad scientific community. The plan, which comprises a variety of missions and extends up to 2035, defines the wide-ranging and ambitious scientific questions to be addressed by missions in the ESA Science Programme.

The next planning cycle of the ESA Science Programme, Voyage 2050, is now underway. In keeping with the bottom-up, peer-reviewed nature of the Science Programme, the definition of the next plan relies on open community input and on broad peer review. The community input will be gathered through the Call for White Papers, while the peer review of this input will take place through a two-tiered committee structure, with a Senior Committee of 13 European scientists supported by a number of Topical Teams. Scientists interested in participating in peer review process are invited to respond to the Call for Membership of the Topical Teams.

MEMBERSHIP OF TOPICAL TEAMS

Scientists working in ESA Member States and with an interest in any topic in space science and in the relevant technologies are welcome to apply for membership of the Topical Teams. Space science is defined here in a broad sense, including the observation of the Universe, planetary

DOCUMENTATION

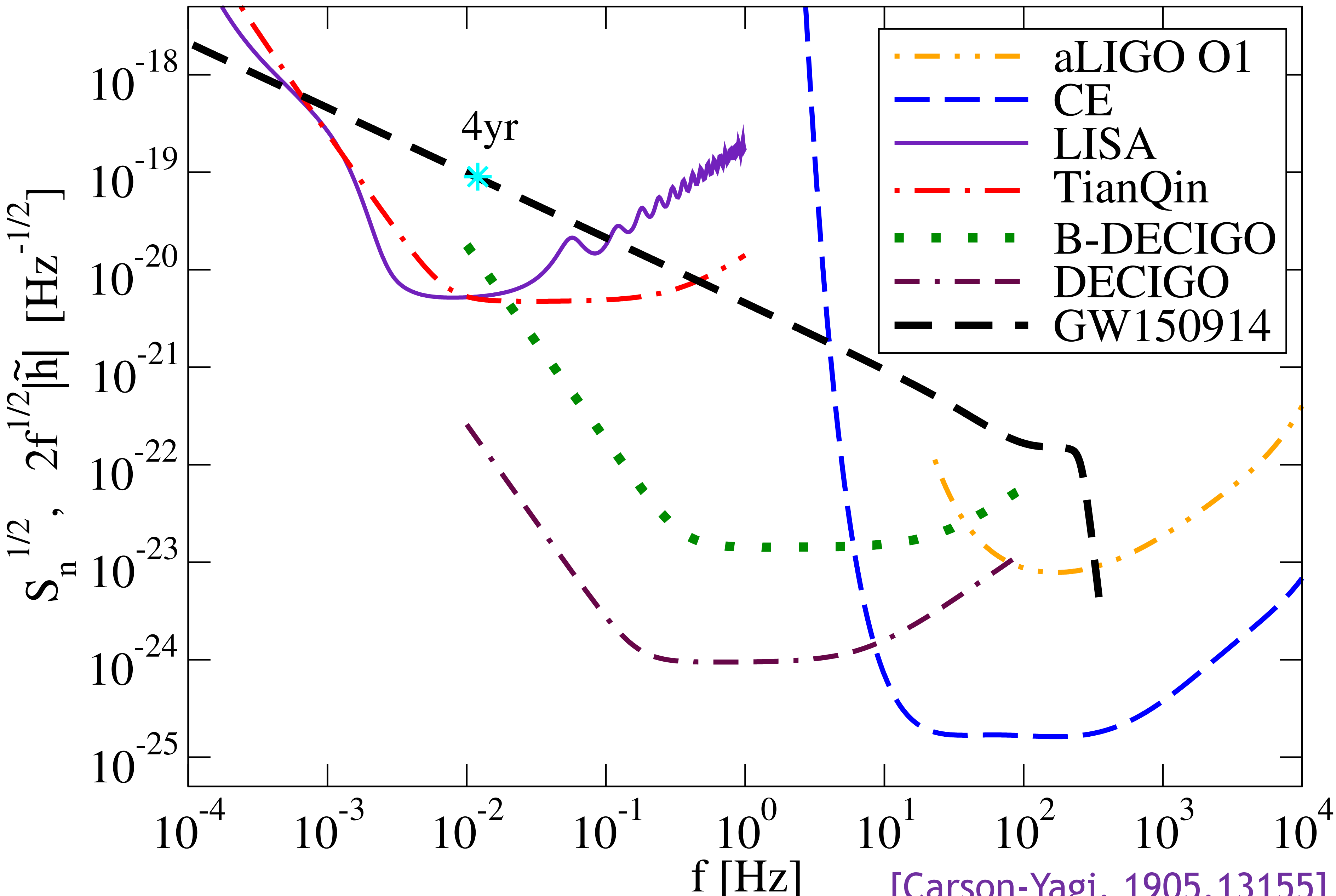
Letter of Invitation - White Papers (pdf)

Letter of Invitation - Topical Team membership (pdf)

Call for White Papers (pdf)

Call for Membership of Topical Teams (pdf)

Mid-band detectors etcetera…



[Carson-Yagi, 1905.13155]

01/02 recap

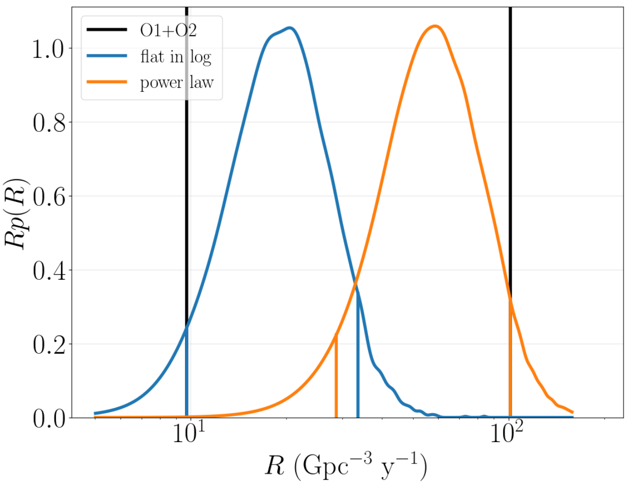
The O1/O2 catalog

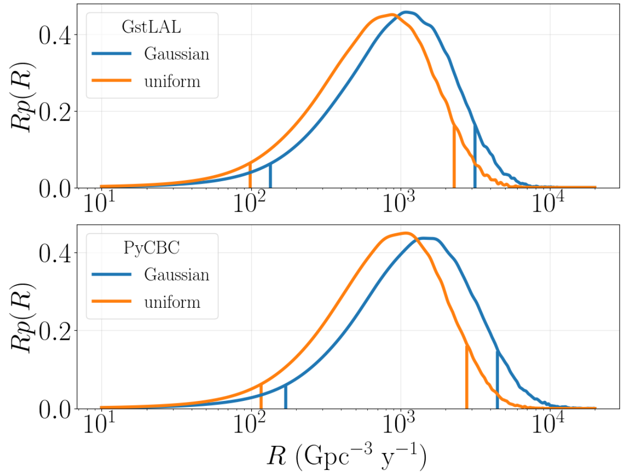
Event	UTC Time	FAR $[\mathrm{y}^{-1}]$ PyCBC	FAR $[\mathrm{y}^{-1}]$ GstLAL	FAR $[\mathrm{y}^{-1}]$ cWB	Network SNR PyCBC	Network SNR GstLAL	Network SNR cWB
GW150914	09:50:45.4	$< 1.53 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 1.63 \times 10^{-4}$	23.6	24.4	25.2
GW151012	09:54:43.4	0.17	7.92×10^{-3}	–	9.5	10.0	–
GW151226	03:38:53.6	$< 1.69 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	0.02	13.1	13.1	11.9
GW170104	10:11:58.6	$< 1.37 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.91×10^{-4}	13.0	13.0	13.0
GW170608	02:01:16.5	$< 3.09 \times 10^{-4}$	$< 1.00 \times 10^{-7}$	1.44×10^{-4}	15.4	14.9	14.1
GW170729	18:56:29.3	1.36	0.18	0.02	9.8	10.8	10.2
GW170809	08:28:21.8	1.45×10^{-4}	$< 1.00 \times 10^{-7}$	–	12.2	12.4	–
GW170814	10:30:43.5	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 2.08 \times 10^{-4}$	16.3	15.9	17.2
GW170817	12:41:04.4	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	–	30.9	33.0	–
GW170818	02:25:09.1	–	4.20×10^{-5}	–	–	11.3	–
GW170823	13:13:58.5	$< 3.29 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.14×10^{-3}	11.1	11.5	10.8

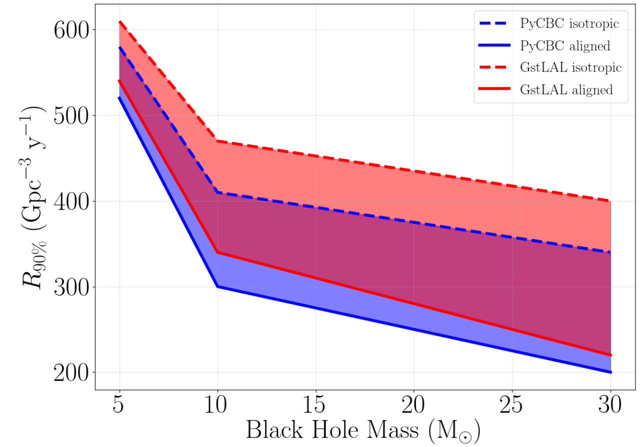
Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	χ_{eff}	$M_{\mathrm{f}}/\mathrm{M}_\odot$	a_{f}	$E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	179
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

Rates: better constraints, evidence of growth with z

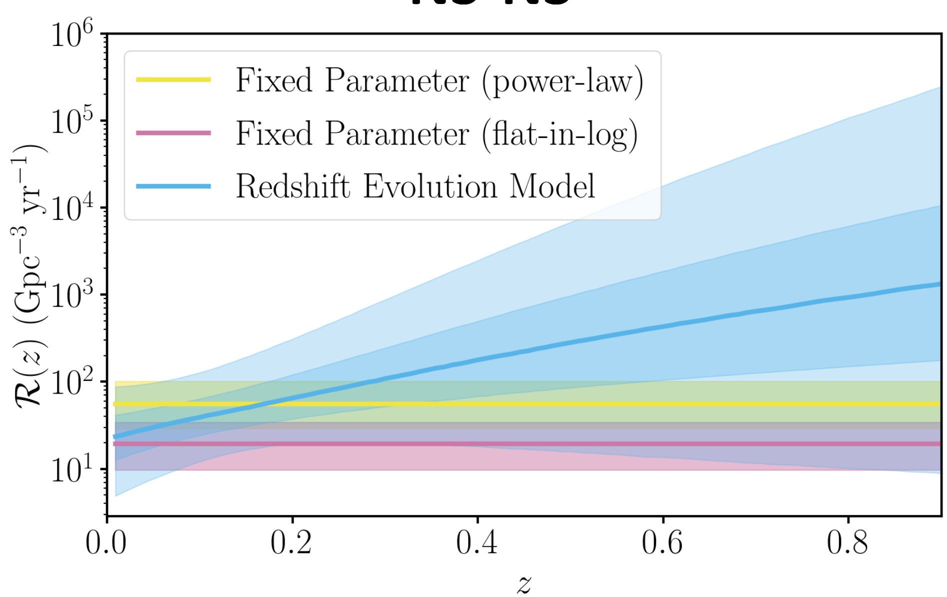
20 **60**



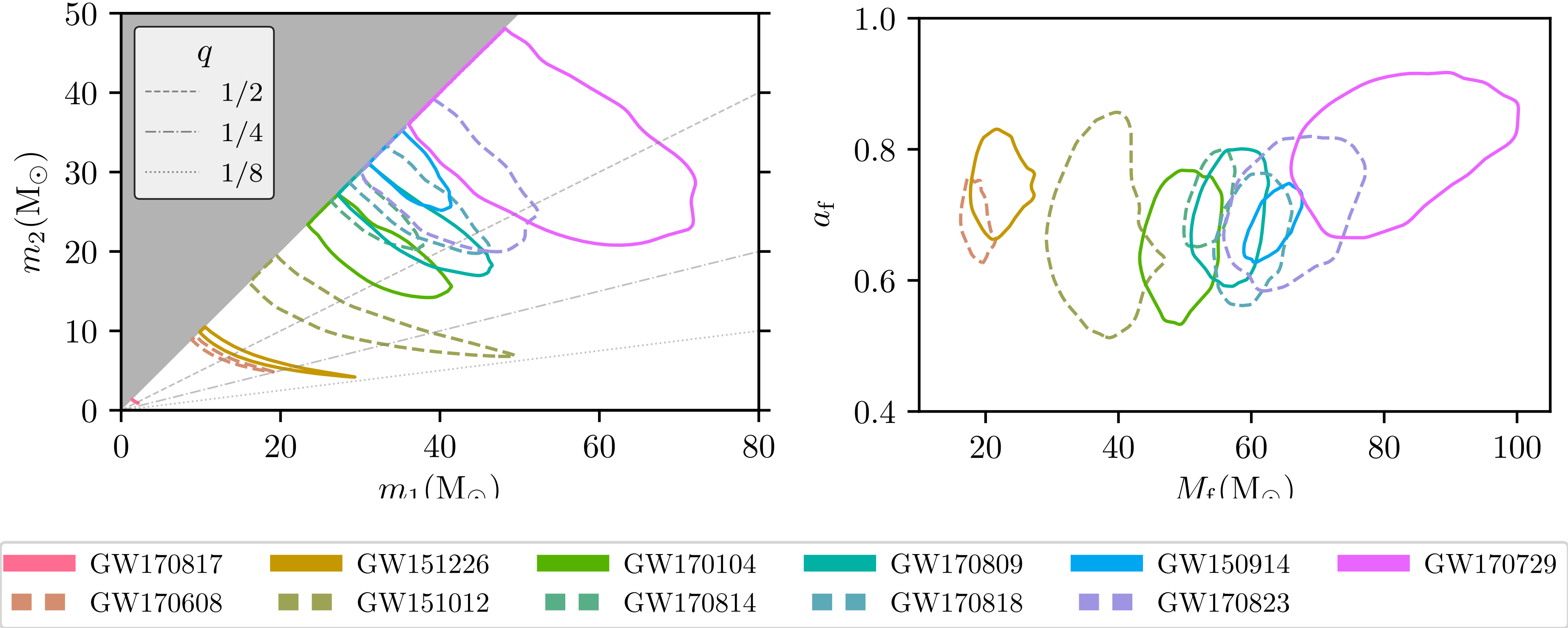




BH-BH **NS-NS** **NS-BH**



Masses, remnant mass/spin



GW170729 is special in many ways!

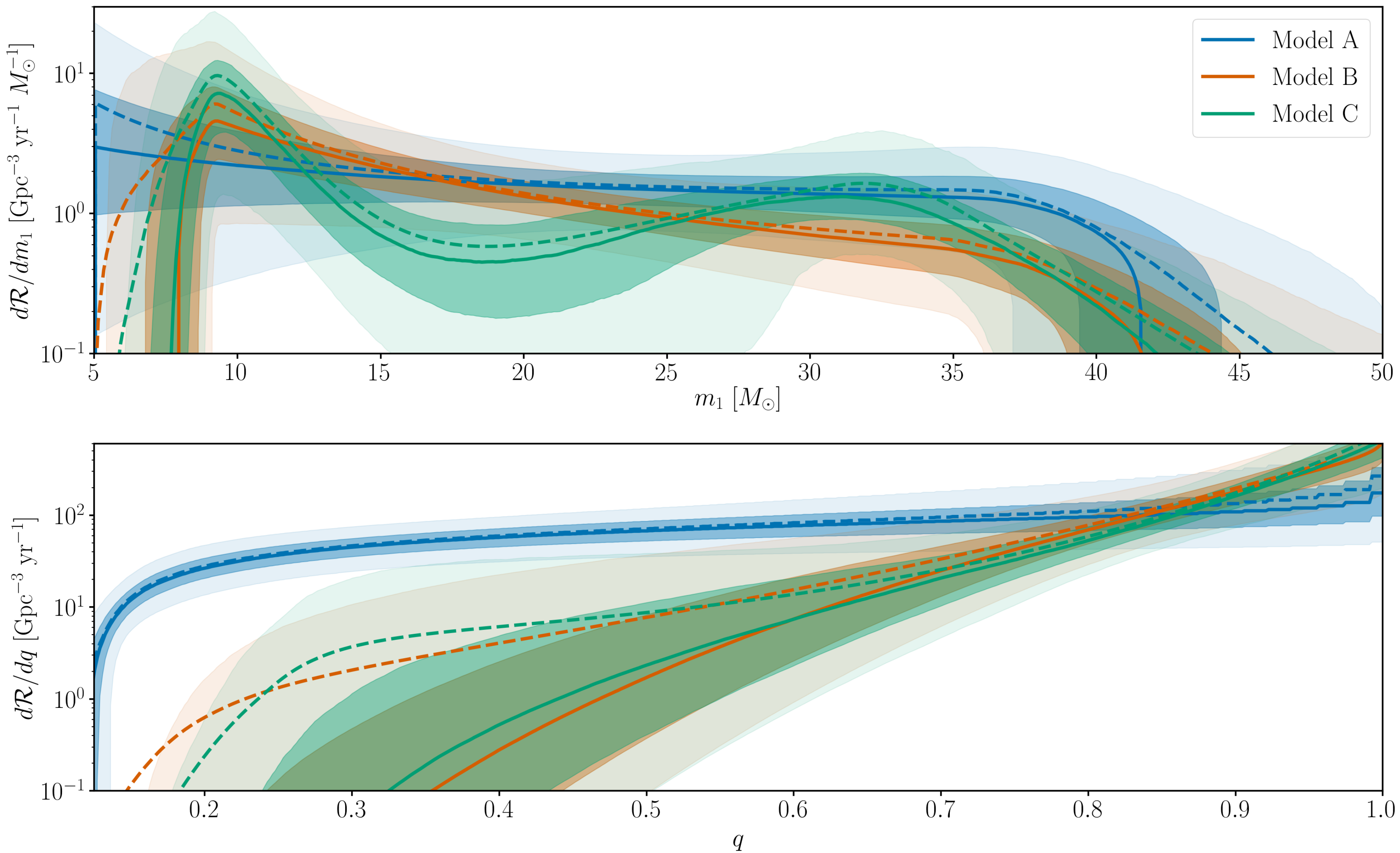
(50.6 + 34.3) M_{sun}, at edge of PISN/PPISN gap; 80.3 M_{sun} remnant

Farthest: D_L~3Gpc

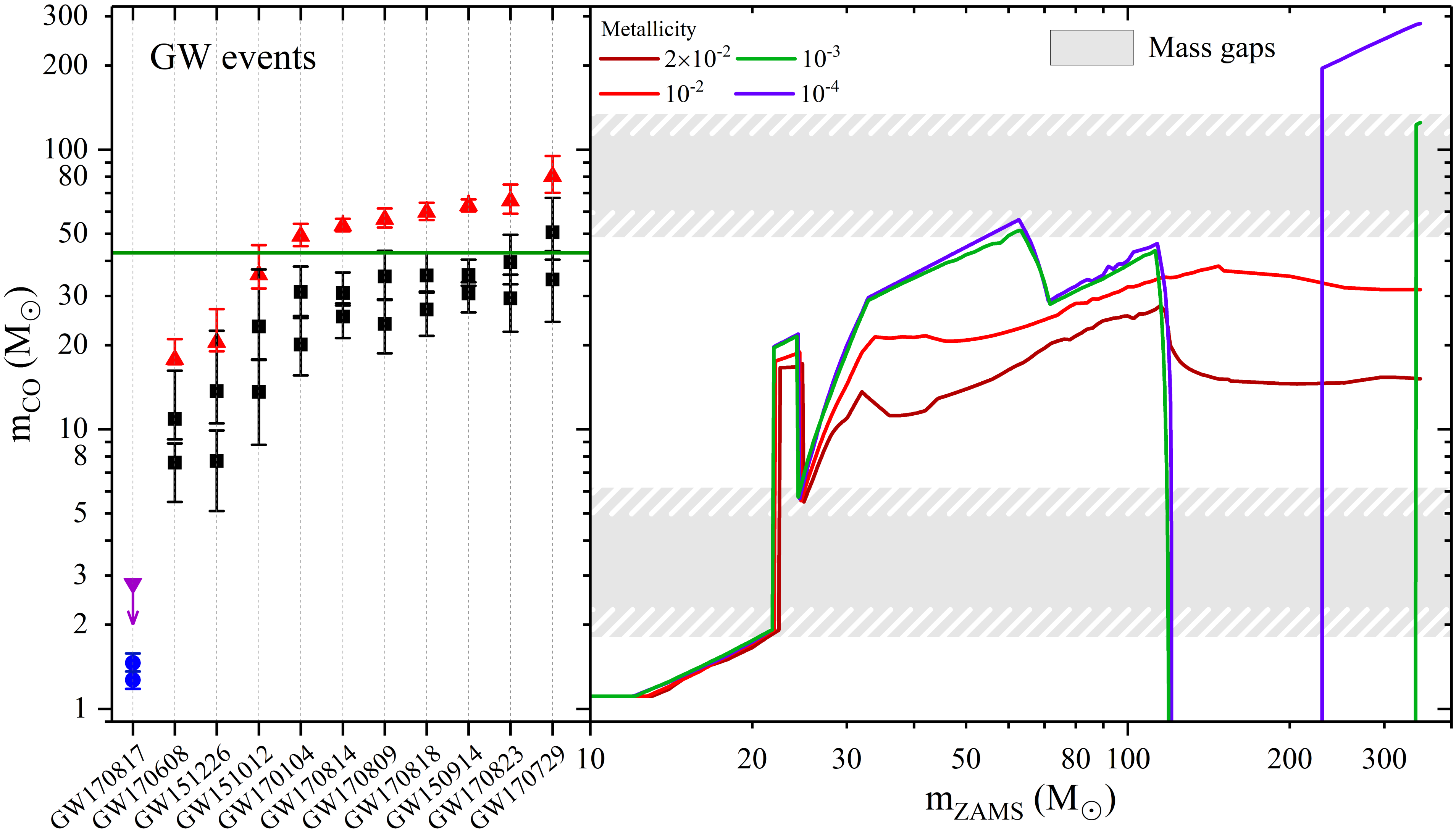
Largest spin

Low SNR (Virgo was in commissioning phase)

Where are the heavy BHs?



Evidence for the second mass gap?



Spins

with Gerosa, Kesden, O’Shaughnessy, Sperhake, Wong…

The sound of black holes (Ryan Lang & Scott Hughes)

1) Two neutron stars (1.5+1.5), LIGO

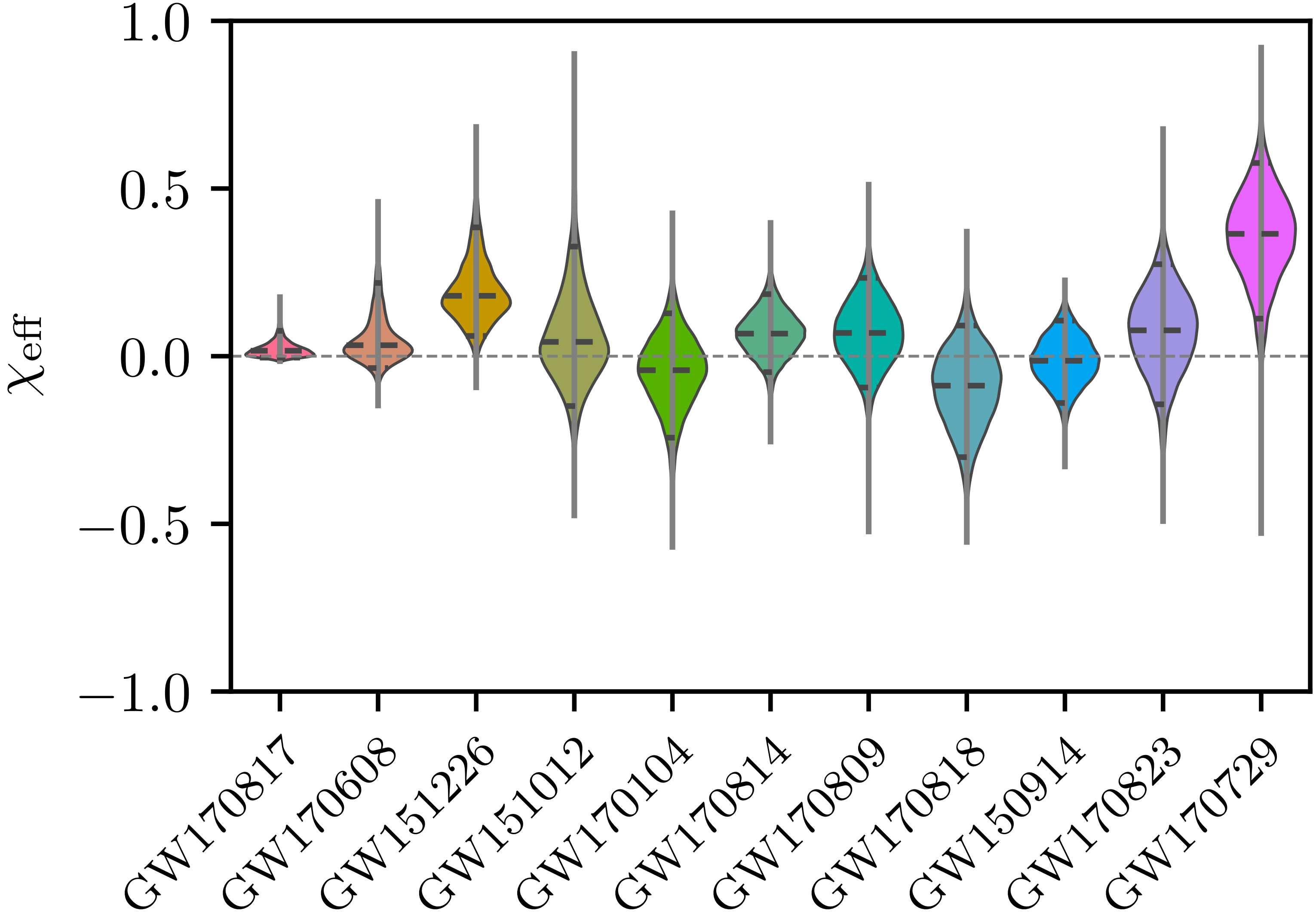
2) Two black holes (2.5+2.5), LIGO

3) Two black holes (50+50), LIGO

4) Two black holes, q=1/3, LISA, no spin

5) Two black holes, q=1/3, LISA, spinning

Effective spins

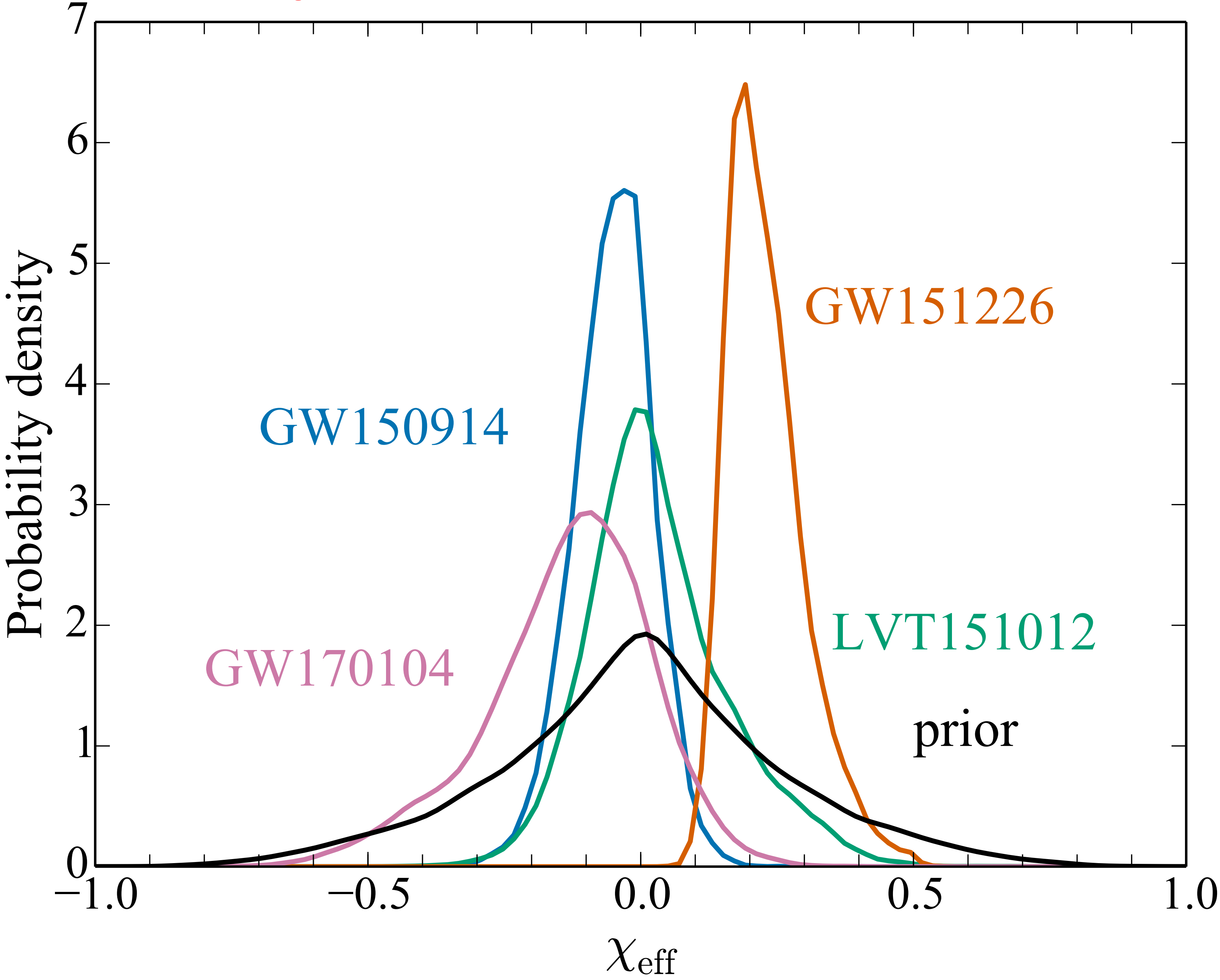


GW151226: χ_{eff}=0.18

GW170729: χ_{eff}=0.36

GW170104: evidence for χ_{eff}<0 mostly gone

Low effective spin disfavors field – but are data informative?



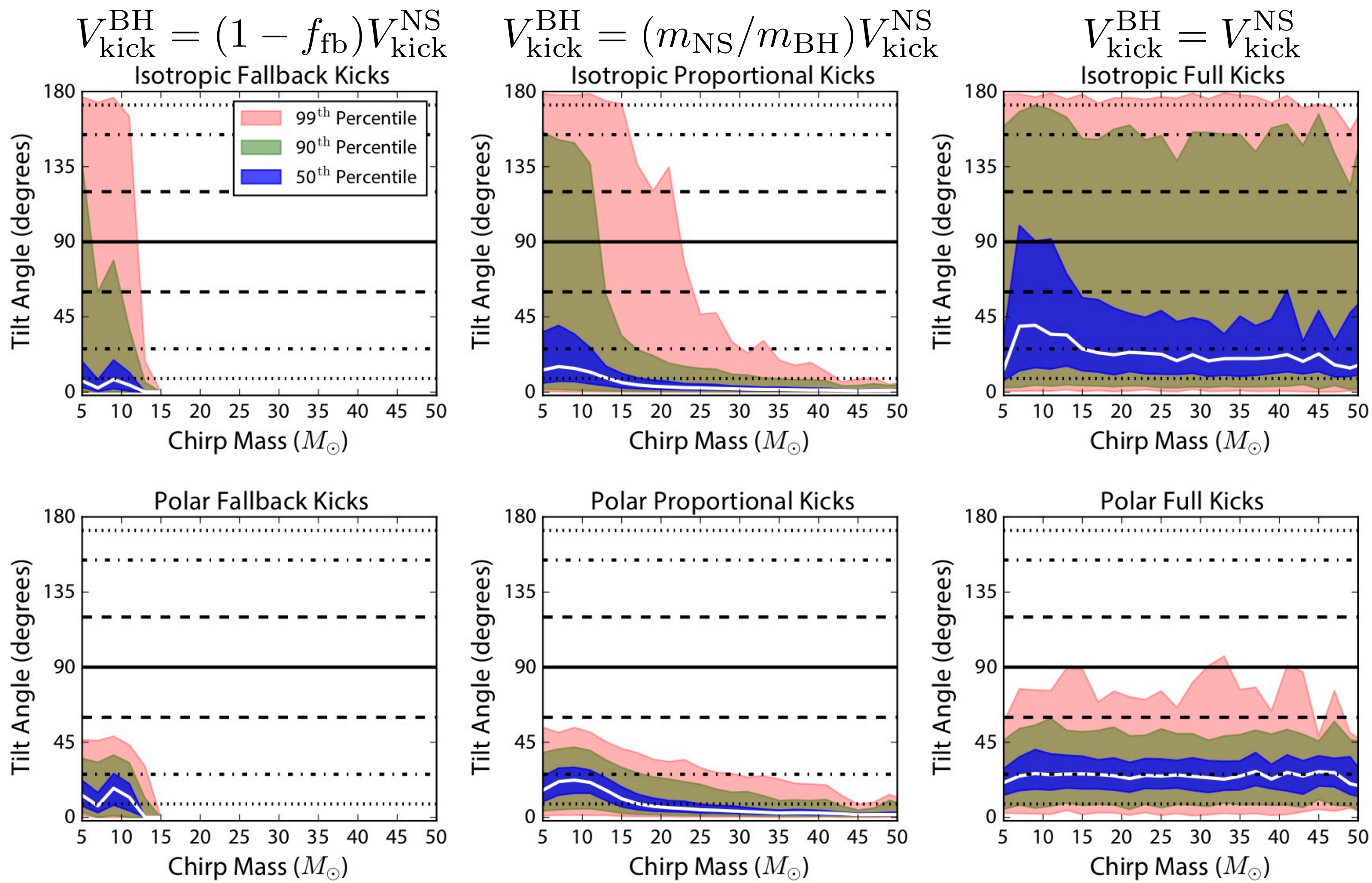
Misalignment and cluster formation

Does a single measurement of $\chi_{eff}<0$ rule out field formation?

Neutron stars: Maxwellian with σ=265 km/s [Hobbs+ 2005]

Colors: misalignment of <u>total</u> spin θ_{LS} in field; solid lines: cluster, $p(\theta_{\rm LS}) = \sin(\theta_{\rm LS})/2$

GW150914: M_{chirp}=28 M_{sun}, full kicks unlikely



[Rodriguez+, 1609.05916]

Does field formation *really* predict alignment?

PHYSICAL REVIEW D **70**, 124020 (2004)

Spin-orbit resonance and the evolution of compact binary systems

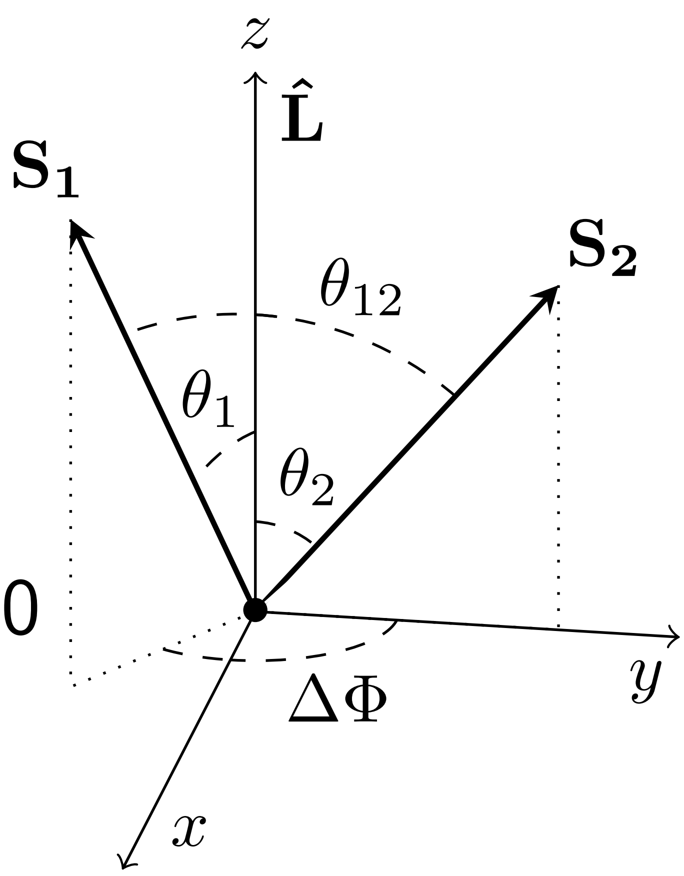
Jeremy D. Schnittman
Department of Physics, MIT, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA
(Received 14 September 2004; published 16 December 2004)

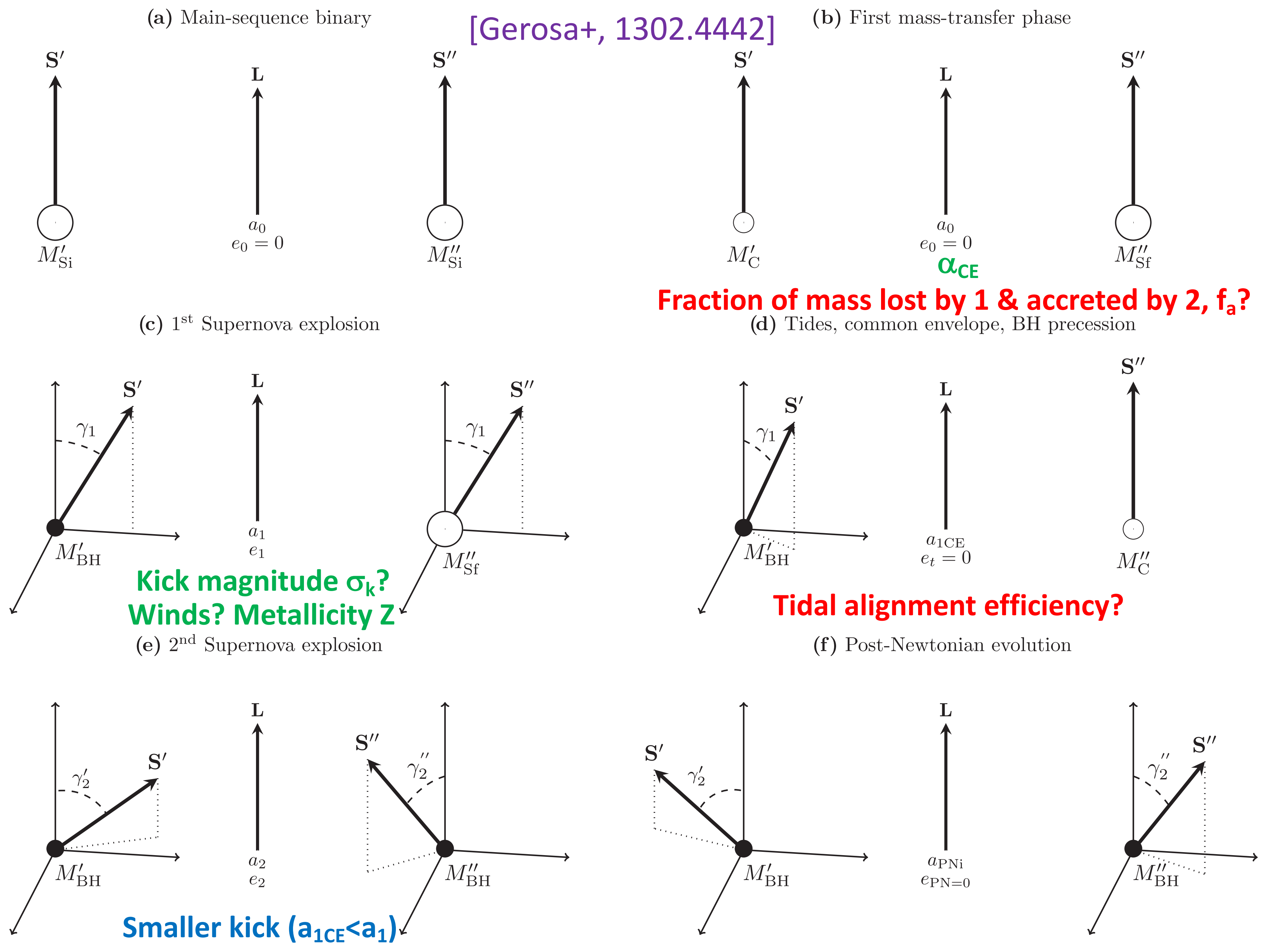
$$\mathbf{S_2} \cdot (\mathbf{L} \times \mathbf{S_1}) = 0$$

$$\frac{d}{dt}\mathbf{S_2} \cdot (\mathbf{L} \times \mathbf{S_1}) = 0$$

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

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

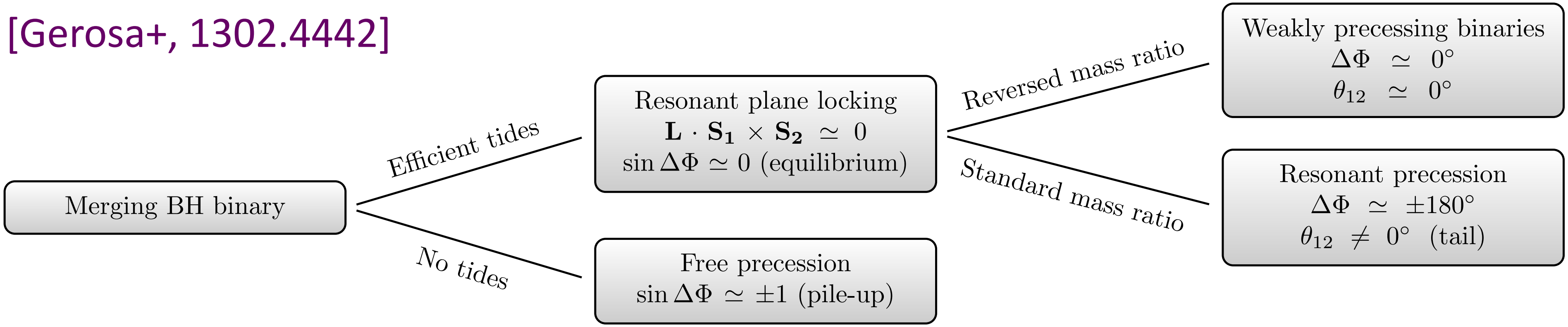


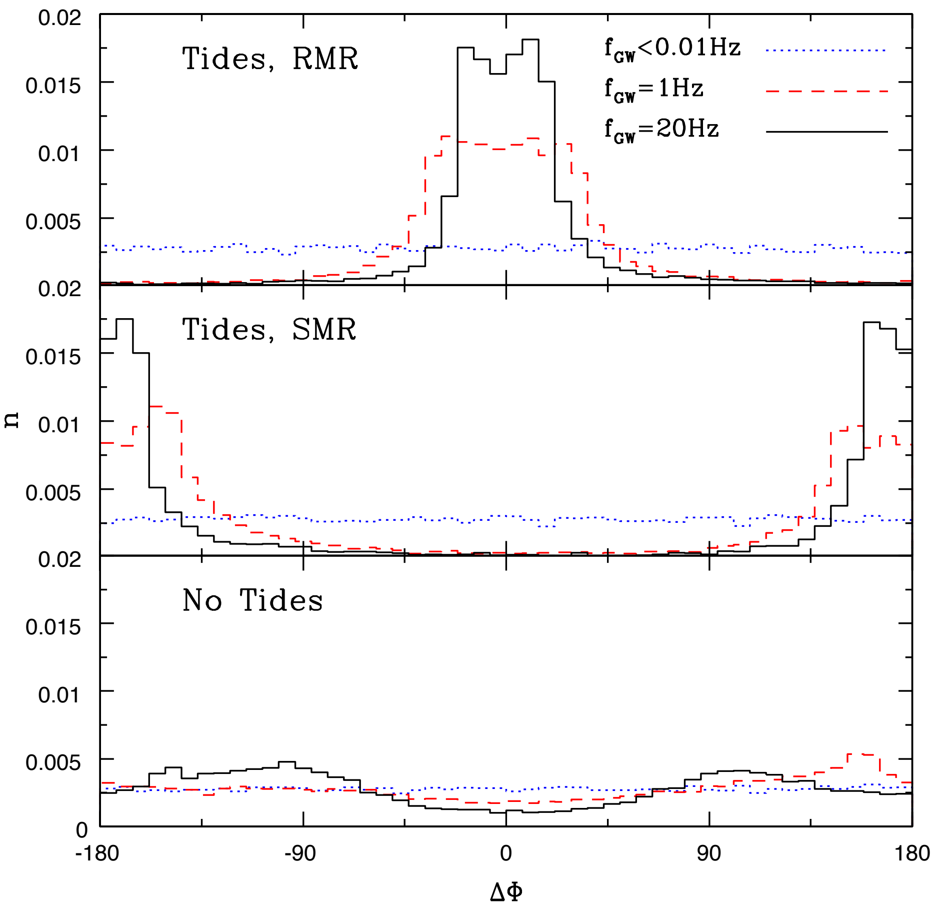


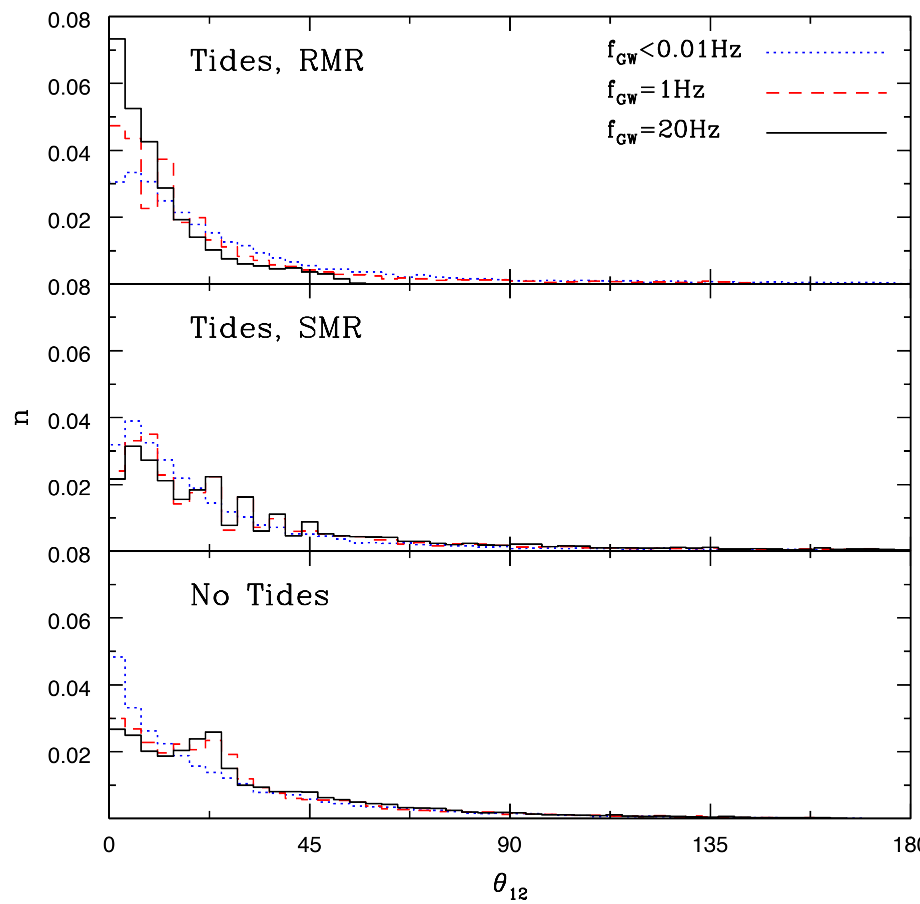
(a) Main-sequence binary
[Gerosa+, 1302.4442]
(b) First mass-transfer phase
S′
L
S″
a_0
$e_0 = 0$
M'_{Si}
M''_{Si}
S′
L
S″
a_0
$e_0 = 0$
M'_C
M''_{Sf}
α_{CE}
Fraction of mass lost by 1 & accreted by 2, f_a?
(c) 1st Supernova explosion
(d) Tides, common envelope, BH precession
S′
γ_1
L
S″
γ_1
a_1
e_1
M'_{BH}
M''_{Sf}
Kick magnitude σ_k?
Winds? Metallicity Z
S′
γ_1
L
S″
a_{1CE}
$e_t = 0$
M'_{BH}
M''_C
Tidal alignment efficiency?
(e) 2nd Supernova explosion
(f) Post-Newtonian evolution
S′
γ'_2
L
S″
γ''_2
a_2
e_2
M'_{BH}
M''_{BH}
Smaller kick ($a_{1CE}<a_1$)
S′
γ'_2
L
S″
γ''_2
a_{PNi}
$e_{PN=0}$
M'_{BH}
M''_{BH}

Inverse problem: binary evolution from GW observations

[Gerosa+, 1302.4442]

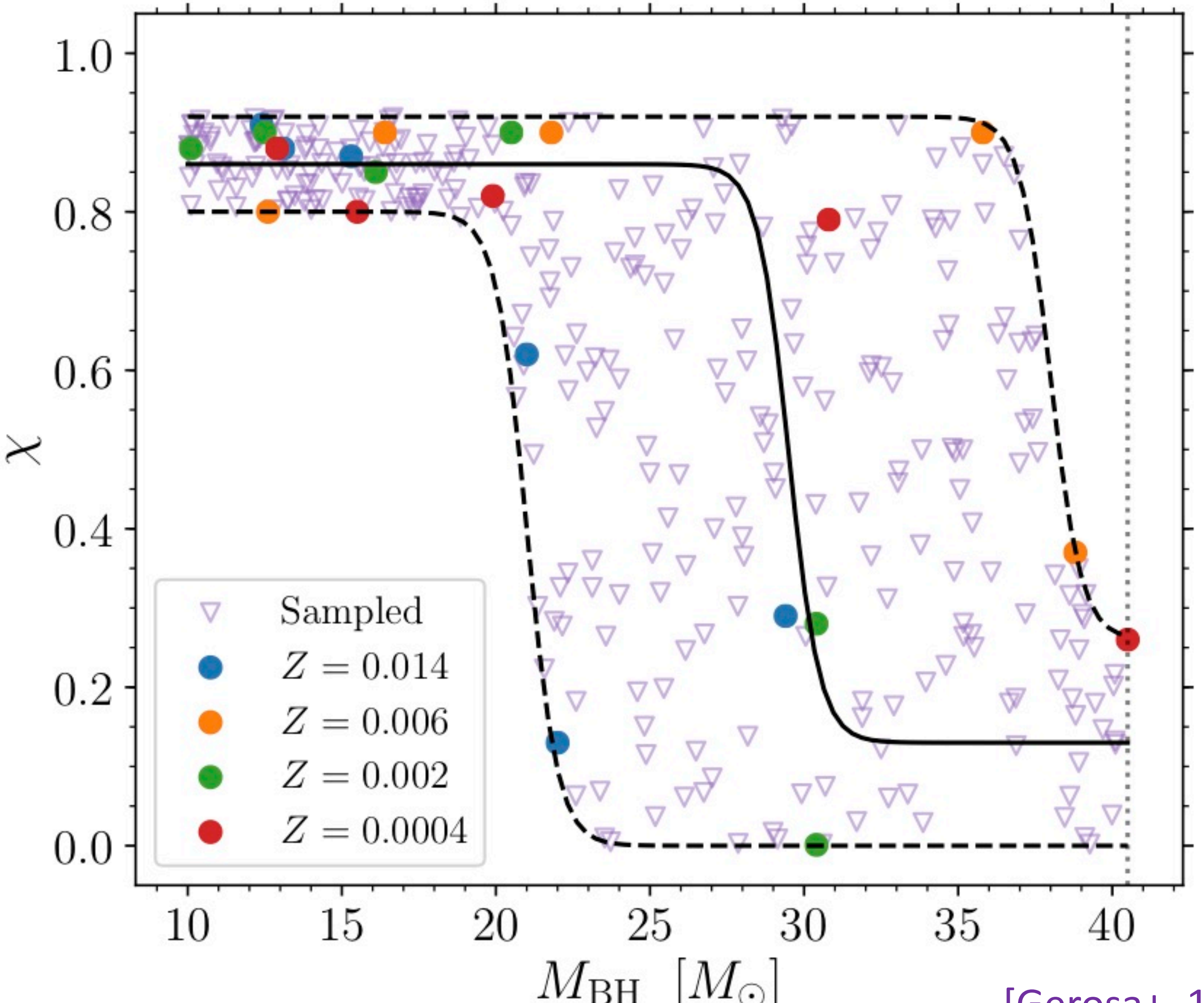






Full population synthesis study

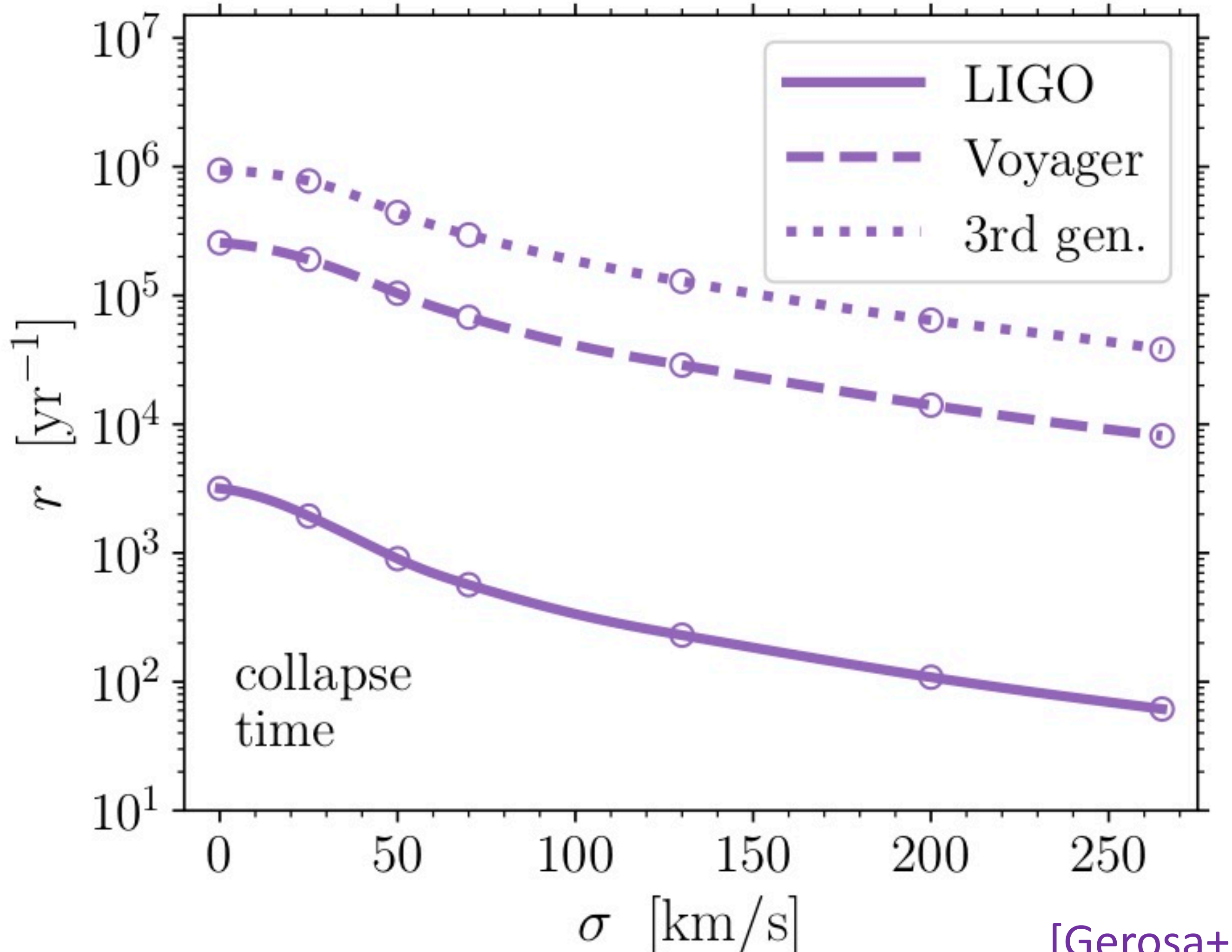
Spin magnitude: "uniform", "max", "collapse" (spin decreases with mass)



[Gerosa+, 1808.02491]

Full population synthesis study

Spin magnitude: ”uniform”, “max”, “collapse” (spin decreases with mass)
Spin directions: “all tides”, “no tides”, “time”: tidal alignment time from [Kushnir+]
Detectability: LAL waveforms
Stellar evolution: Startrack. Key elements: metallicity, CE evolution, kick magnitude σ



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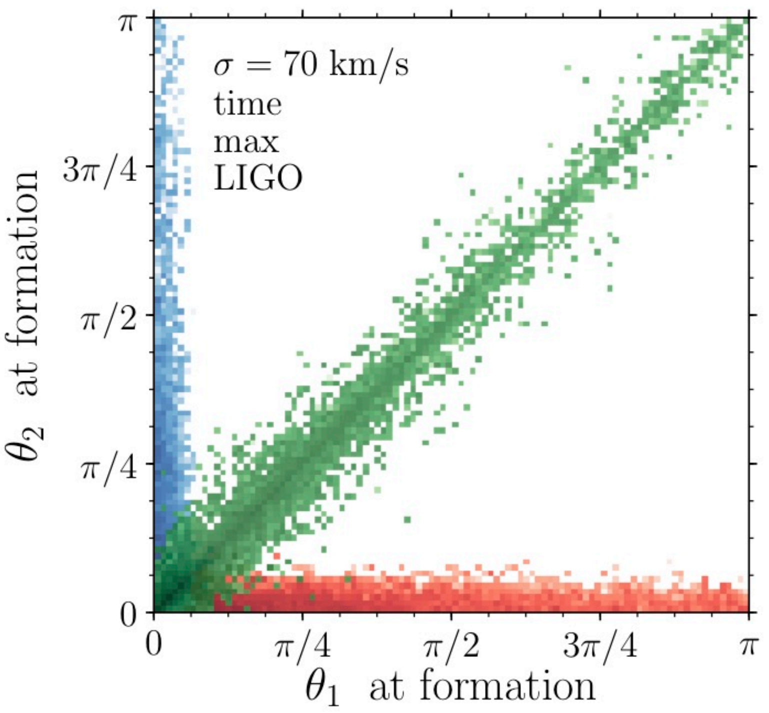

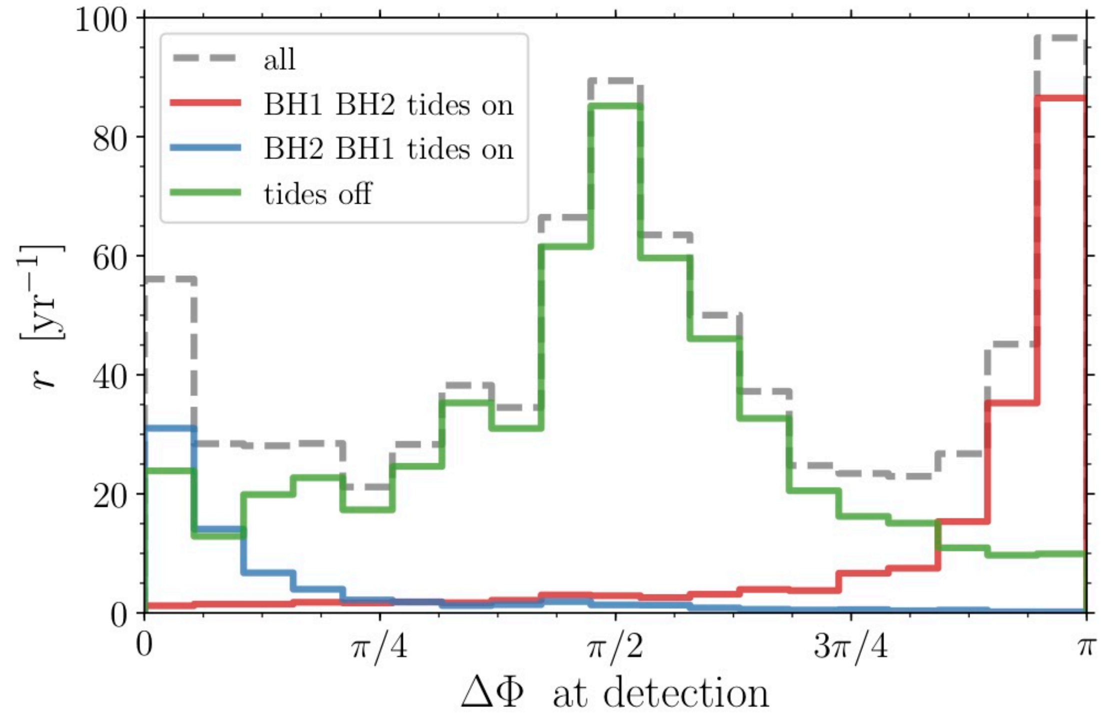

[Gerosa+, 1808.02491]

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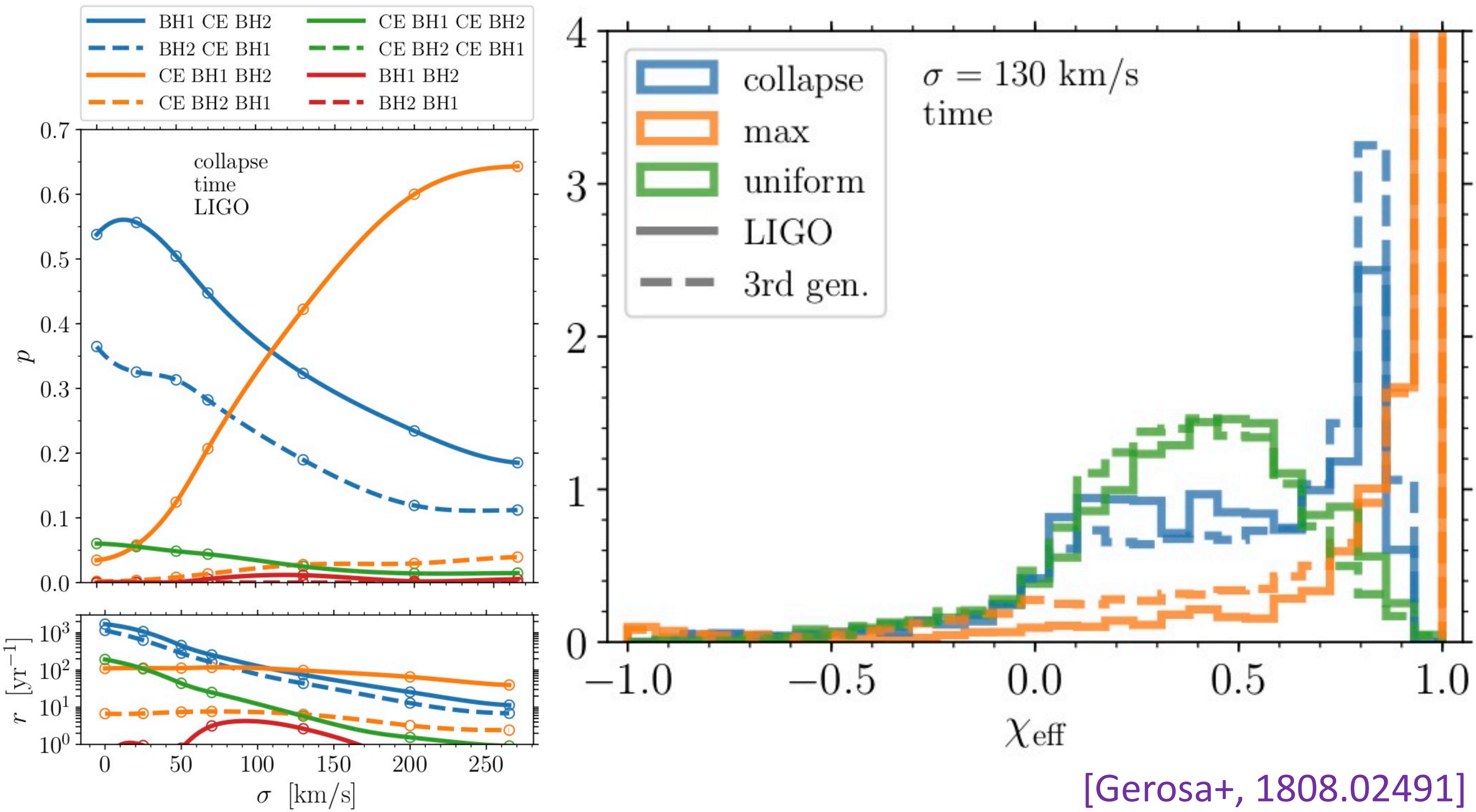
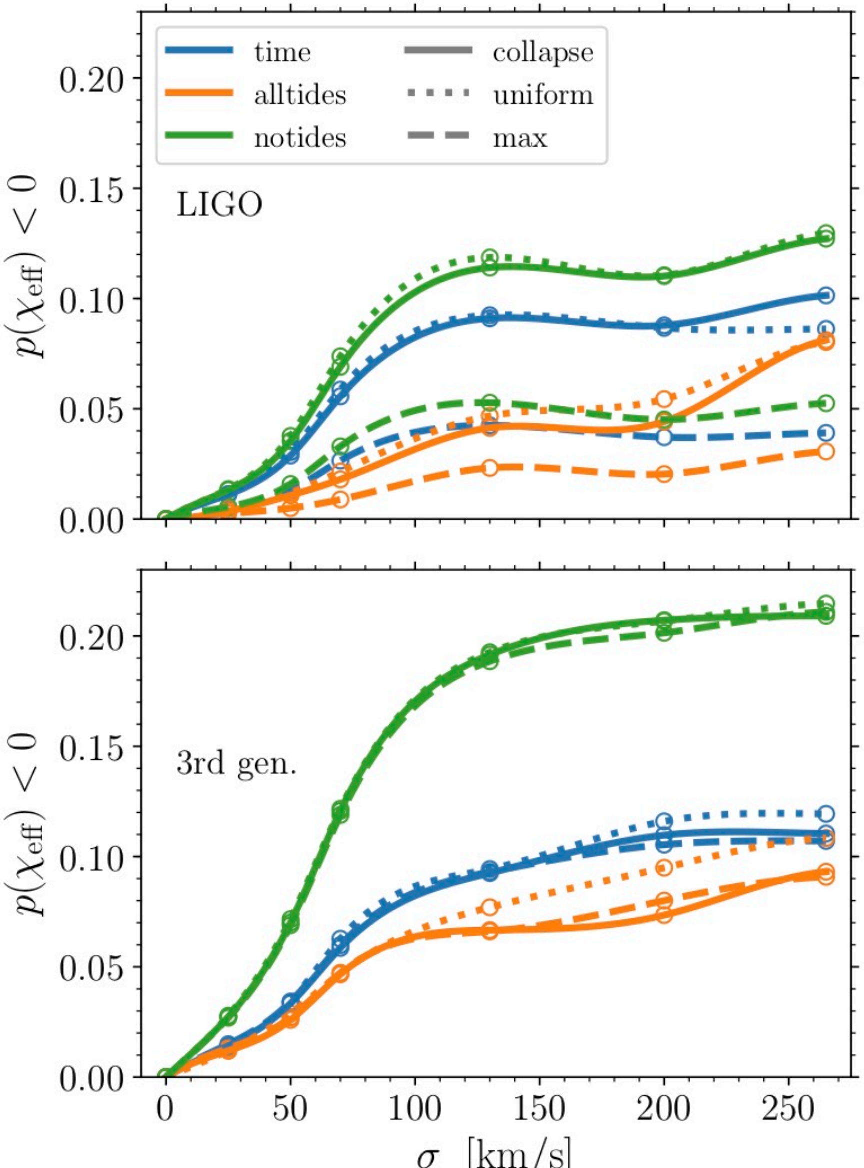


[Gerosa+, 1808.02491]

Full population synthesis study

Does a single measurement of χ_{eff}<0 rule out field formation?

No!



Trends:

Larger kicks give larger misalignments (fiducial Rodriguez model: small BH kicks)

Typically 3%-10% of binaries have χ_{eff}<0

In this model no kick gives no misalignment by construction, but "BANANA"

Conservative statement: single detections with χ_{eff}<0 suggest dynamical formation if

- **Spins are initially aligned**
- **Black hole kicks are small**

Tides matter, spin magnitude doesn't: break magnitude/misalignment degeneracy

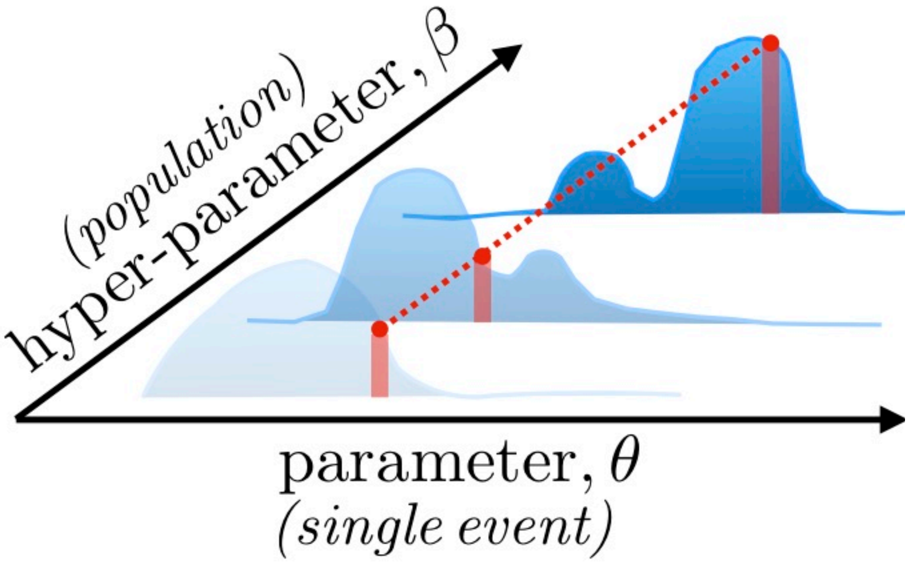
[Gerosa+, 1808.02491]

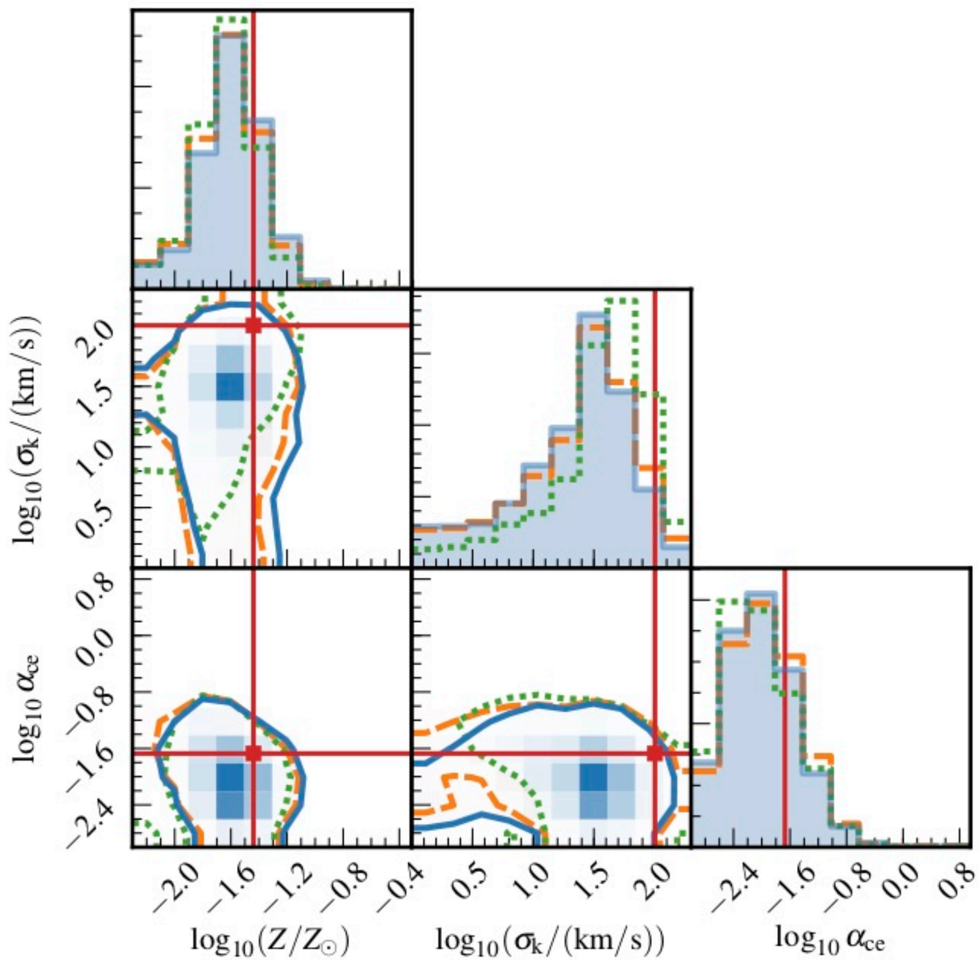
Ultimate goal: constrain hyperparameters

https://davidegerosa.com/spops/

Main uncertainties in population synthesis models:

metallicity (Z), common envelope (α_{ce}), kick magnitude (σ_k)





[Taylor+Gerosa, 1808.02491]

Why does spin precession matter?

Precessional dynamics in vacuum is

- **Understood!**
  Schnittman's spin-orbit resonances
  An integral of motion (ξ or χ_{eff}) allows effective potential approach
  Phase transitions between different "morphologies"

- **Important**
  Connects astrophysics of spin alignment at formation (initial conditions)
  to precessional dynamics in the band of GW detectors (LIGO/LISA)

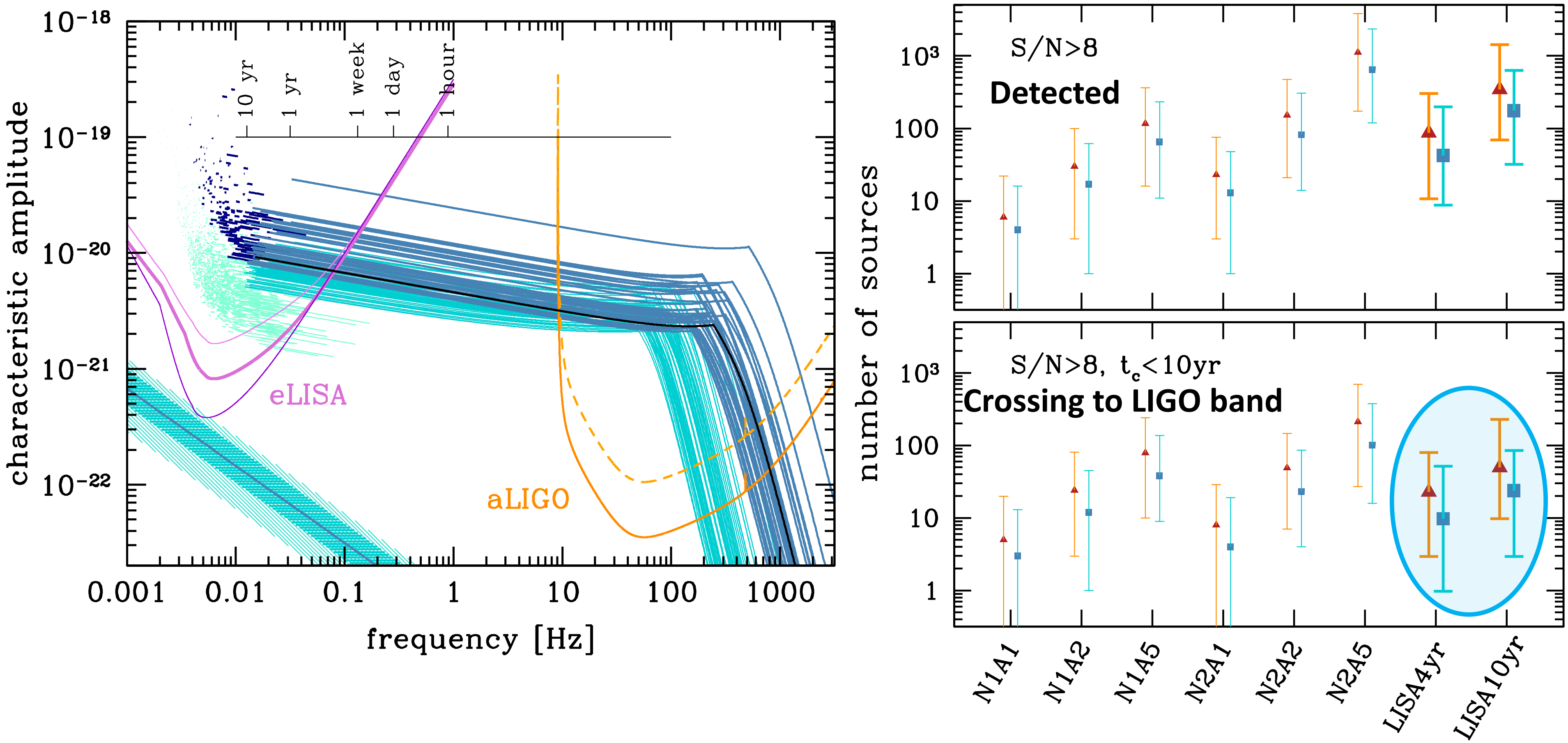
- **Allows us to address the inverse problem:**
  Given precessional dynamics, infer astrophysical formation

  LIGO: mass transfer, tidal alignment, supernova kicks
  LISA: complementary information
  targets different population
  eccentricity

LISA and multiband gravitational-wave astronomy

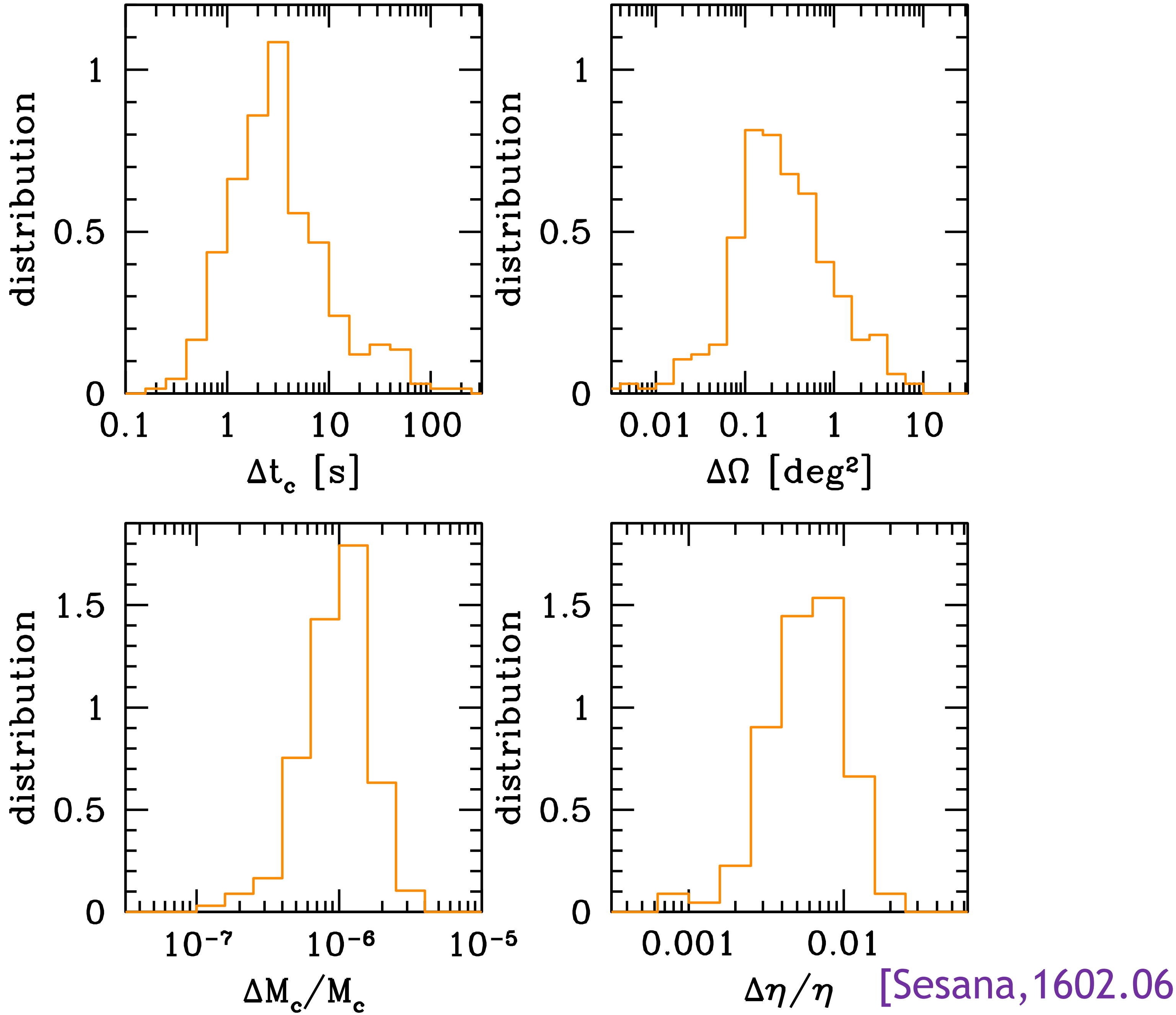
with Nishizawa, Sesana, Klein, Tanay, Wong, Cutler, Kovetz, Vitale, Jani…

Multiband rates: few to ~100 events



[Sesana,1602.06951; 1702.04356]

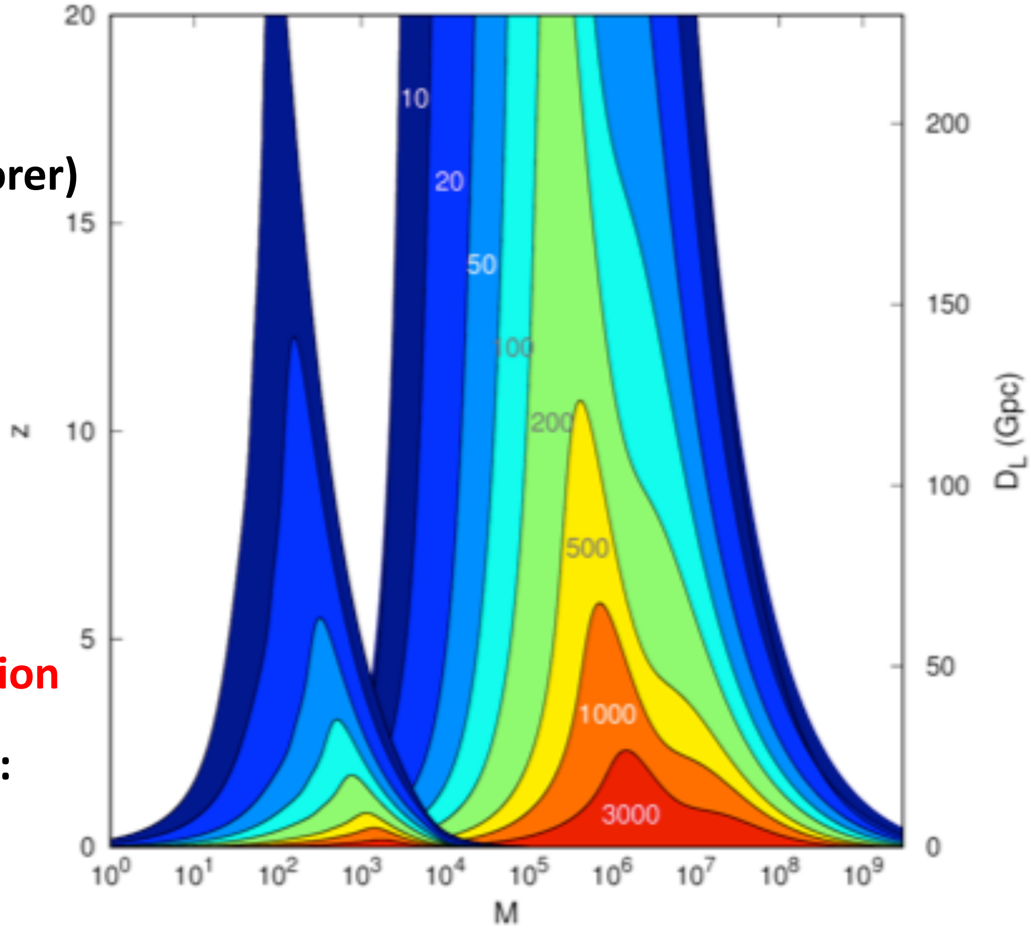
Time of arrival: seconds, localization: <1 deg²



[Sesana,1602.06951]

Multiband observations in the 3G era

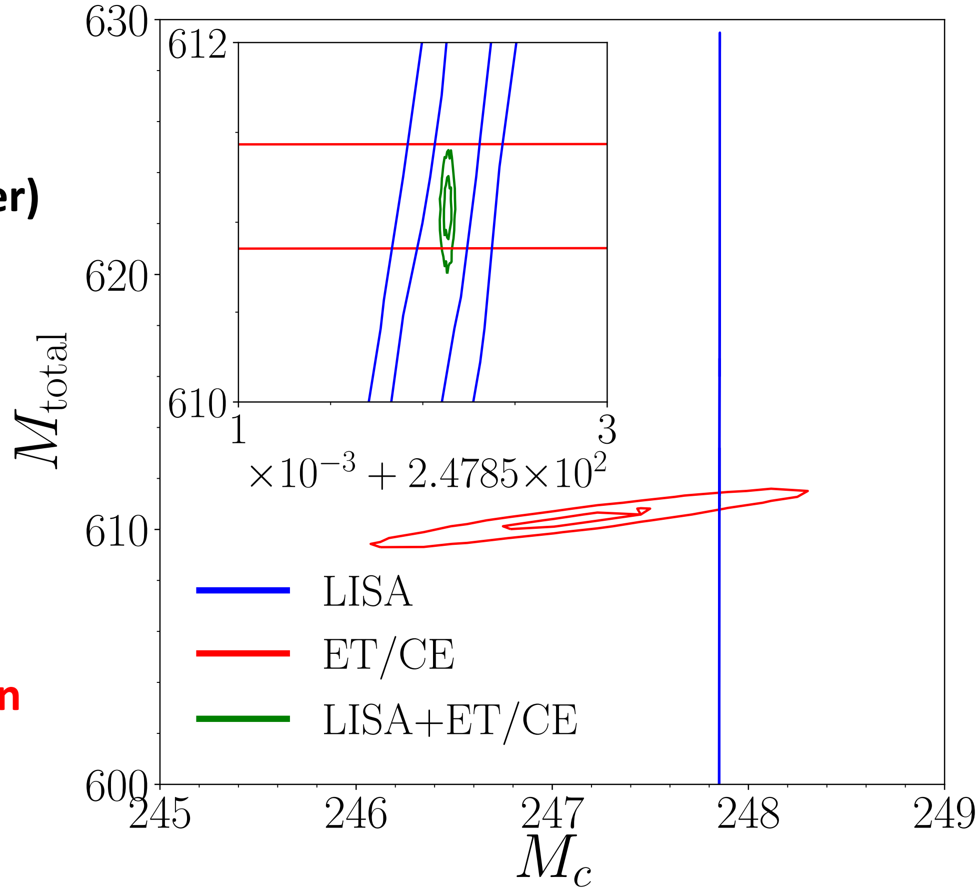
- Limited improvements on 3G PE
  GW150914:
  SNR~700 (2000) in Voyager (Cosmic Explorer)
  [cf. Vitale 1605.01037]
- However LISA will break degeneracies:
  (χ_1, χ_2) from LISA, χ_{eff} and χ_f from LIGO
  M_{chirp} from LISA, M from LIGO
- Use 3G detections to remove foreground and go after stochastic backgrounds
- Use LISA for 3G phase/amplitude calibration
- Post-process LISA data after 3G detection: boost LISA multiband event rates



[Figure courtesy of Neil Cornish]

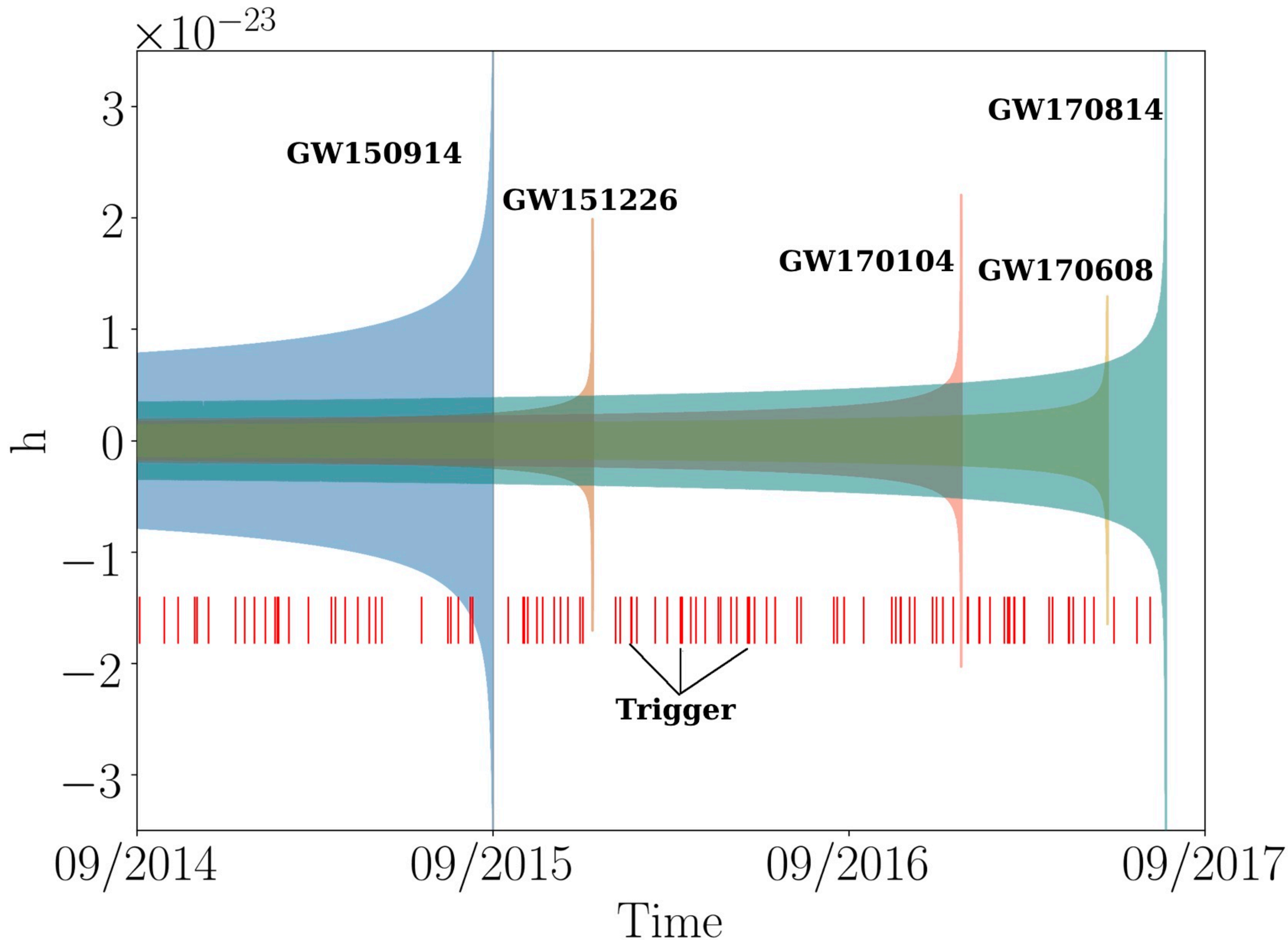
Multiband observations in the 3G era

- **Limited improvements on 3G PE**
  GW150914:
  SNR~700 (2000) in Voyager (Cosmic Explorer)
  [cf. Vitale 1605.01037]
- **However LISA will break degeneracies:**
  (χ_1, χ_2) from LISA, χ_{eff} and χ_f from LIGO
  M_{chirp} from LISA, M from LIGO
- **Use 3G detections to remove foreground and go after stochastic backgrounds**
- **Use LISA for 3G phase/amplitude calibration**
- **Post-process LISA data after 3G detection: boost LISA multiband event rates**

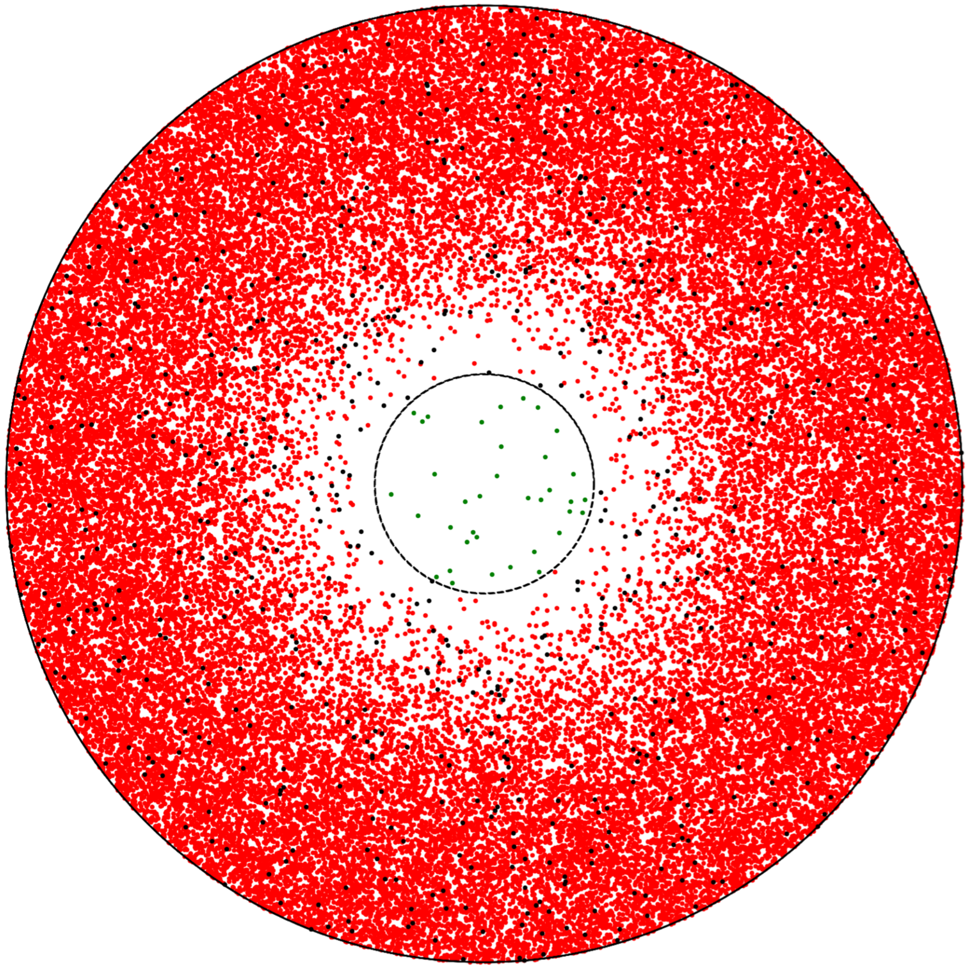


[Cutler+, 1903.04069]

Expanding the LISA horizon from the ground



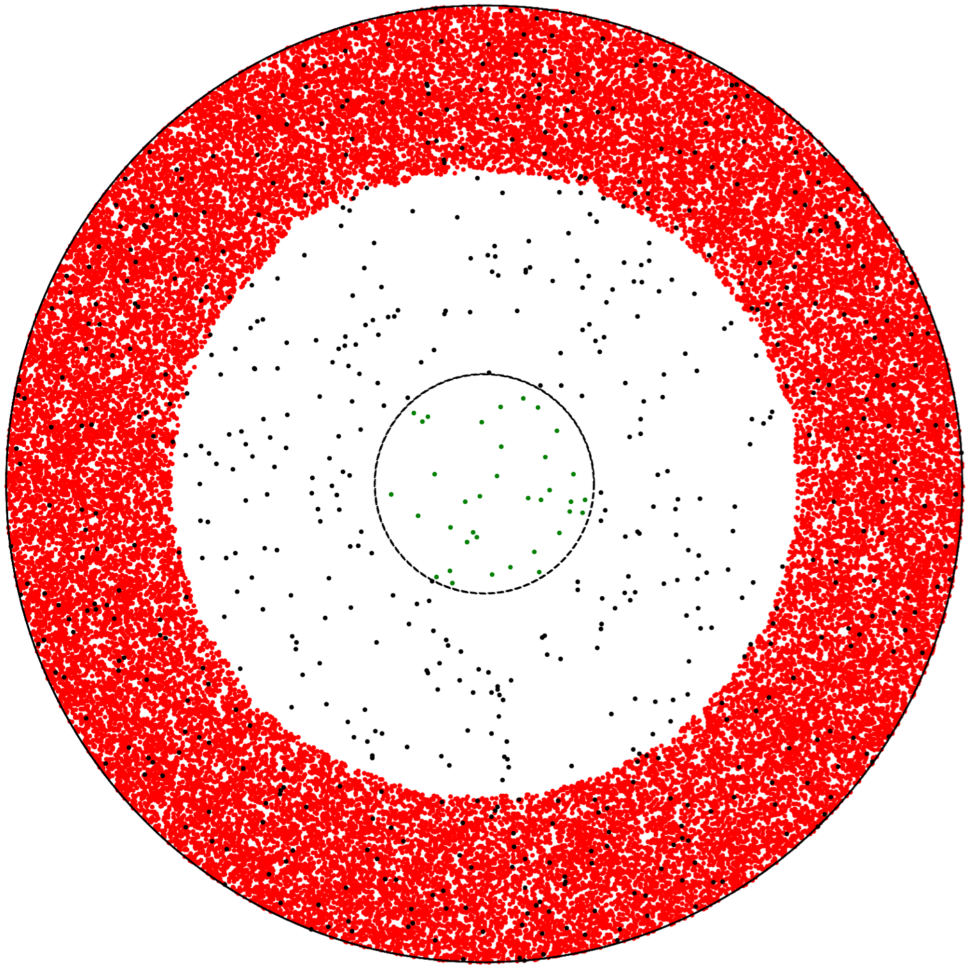
Expanding the LISA horizon from the ground



- Outer circle: ρ=2 LISA threshold
- Black dots:
  astrophysical events
  (all of them detected by LIGO)
- Red dots: noise
- Detected with
  no extra information from LIGO

[Wong, Kovetz, Cutler, EB, 1808.08247]

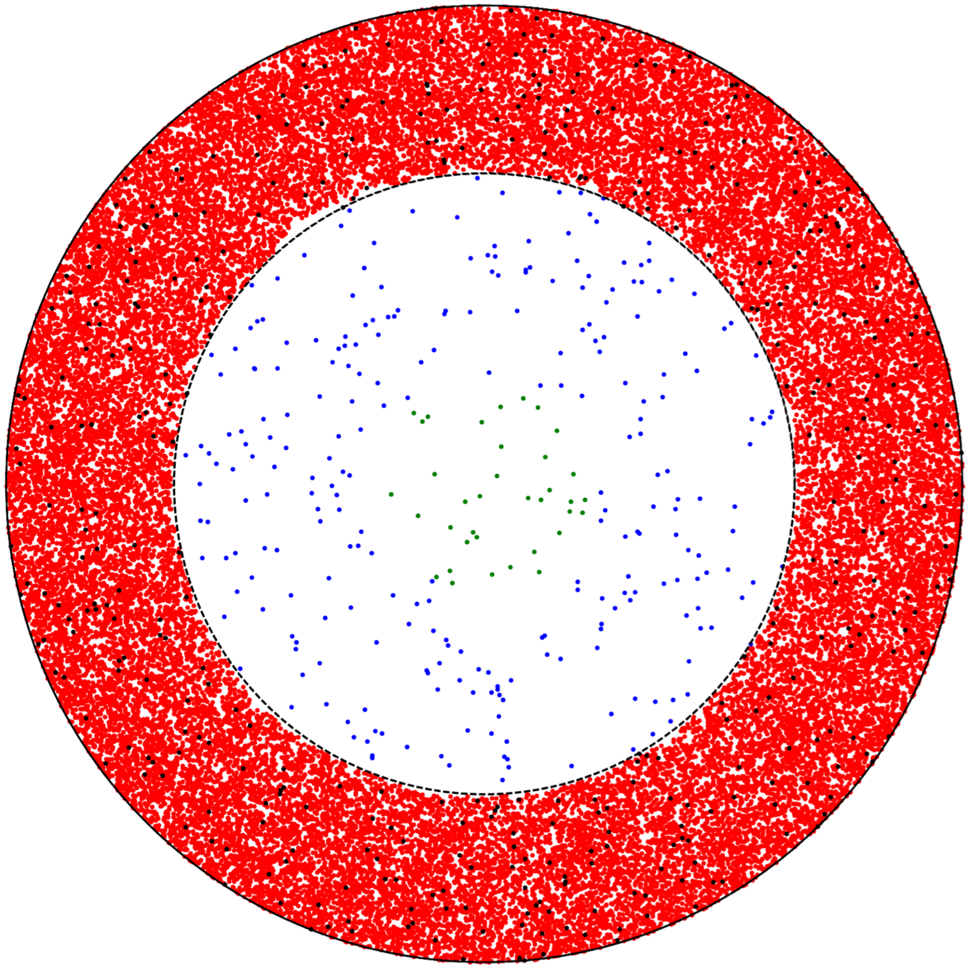
Expanding the LISA horizon from the ground



- Outer circle: ρ=2 LISA threshold
- Black dots:
  astrophysical events
  (all of them detected by LIGO)
- Red dots: noise
- Detected with
  no extra information from LIGO
- Remove noise if event properties
  do not agree with LIGO detections

[Wong, Kovetz, Cutler, EB, 1808.08247]

Expanding the LISA horizon from the ground

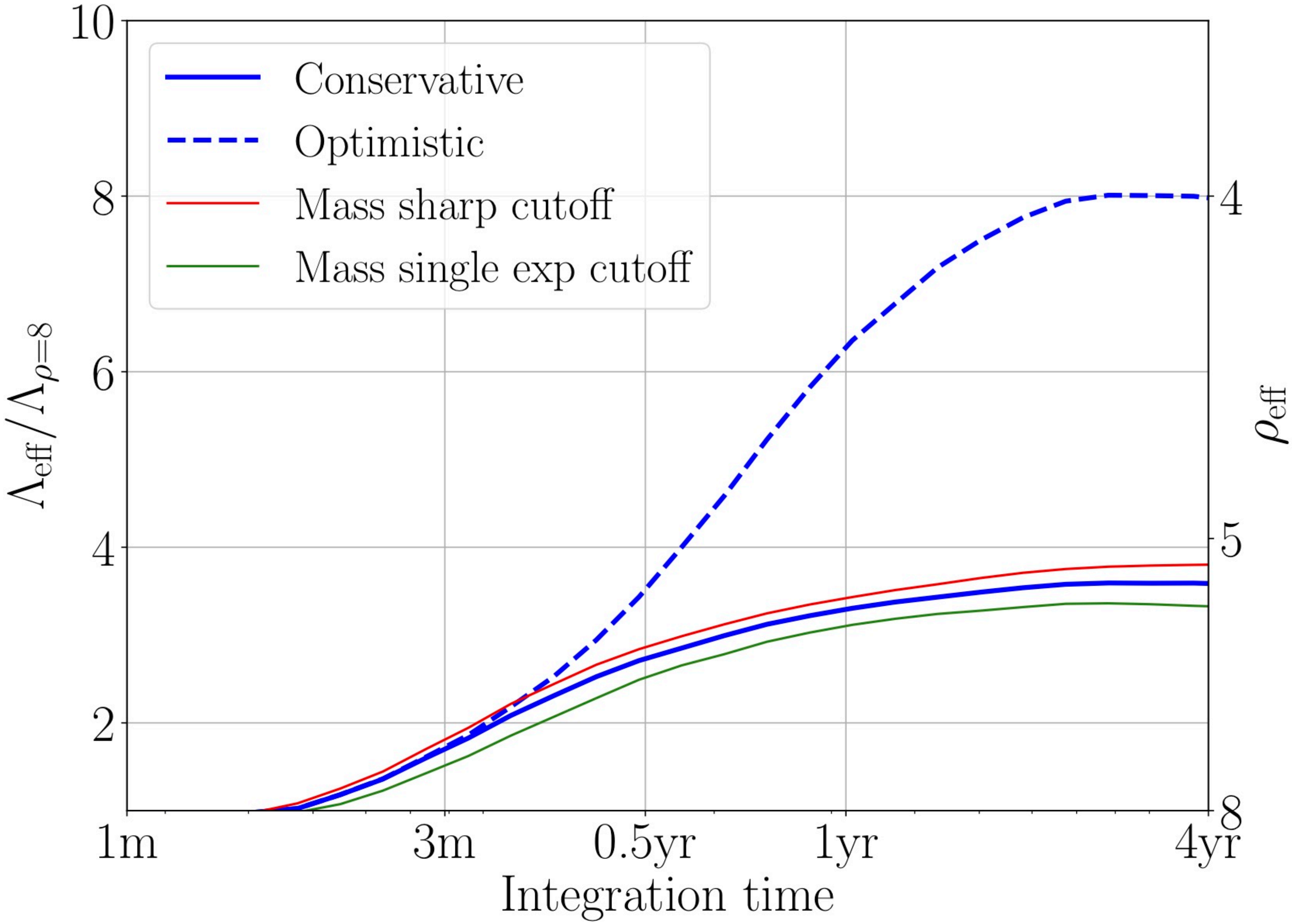


- Outer circle: ρ=2 LISA threshold
- Black dots:
  astrophysical events
  (all of them detected by LIGO)
- Red dots: noise
- Detected with
  no extra information from LIGO
- Blue dots:
  recovered by LIGO coincidence

Rates increase by a factor $(8/4)^3=8$

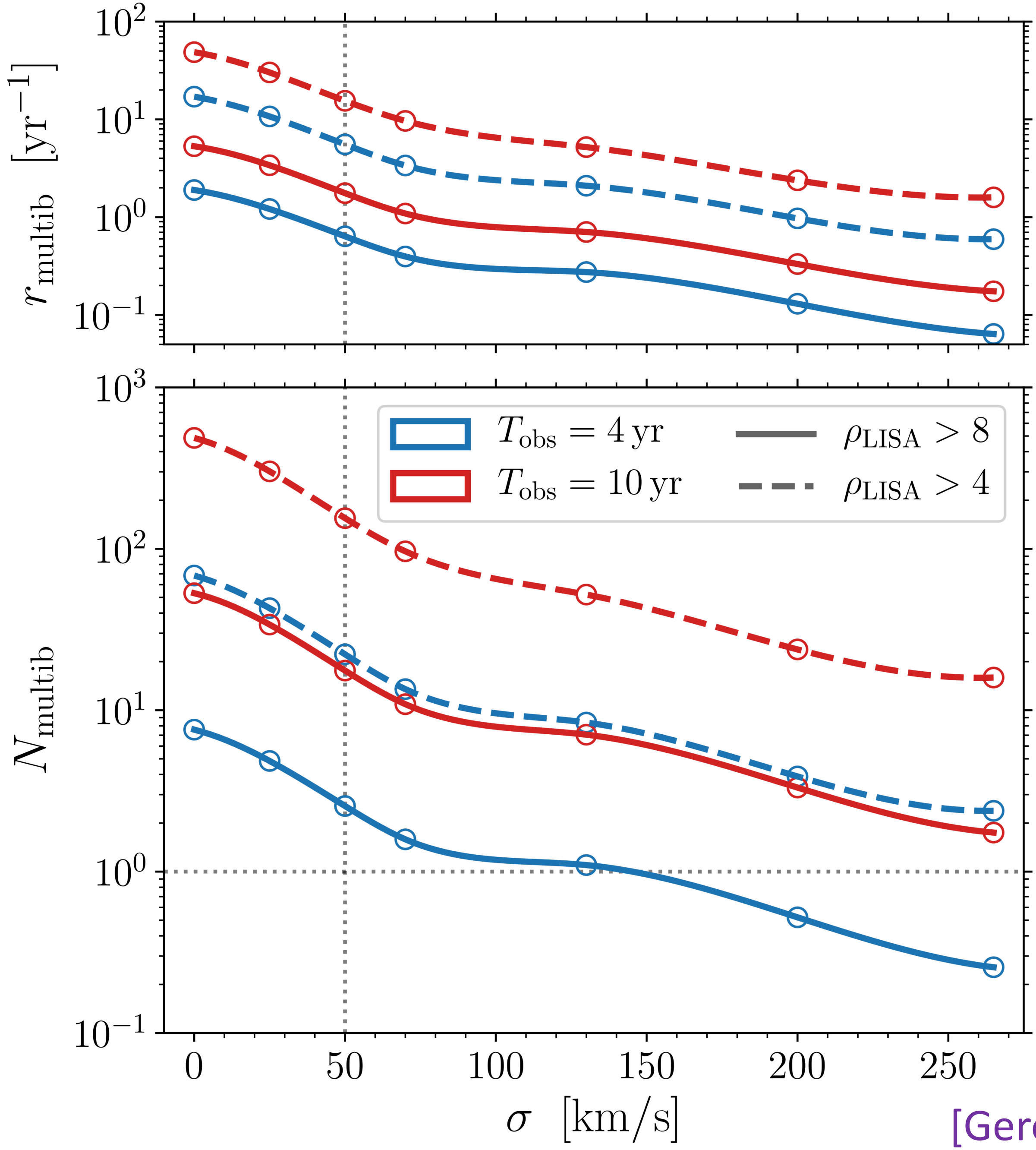
[Wong, Kovetz, Cutler, EB, 1808.08247]

Expanding the LISA horizon from the ground



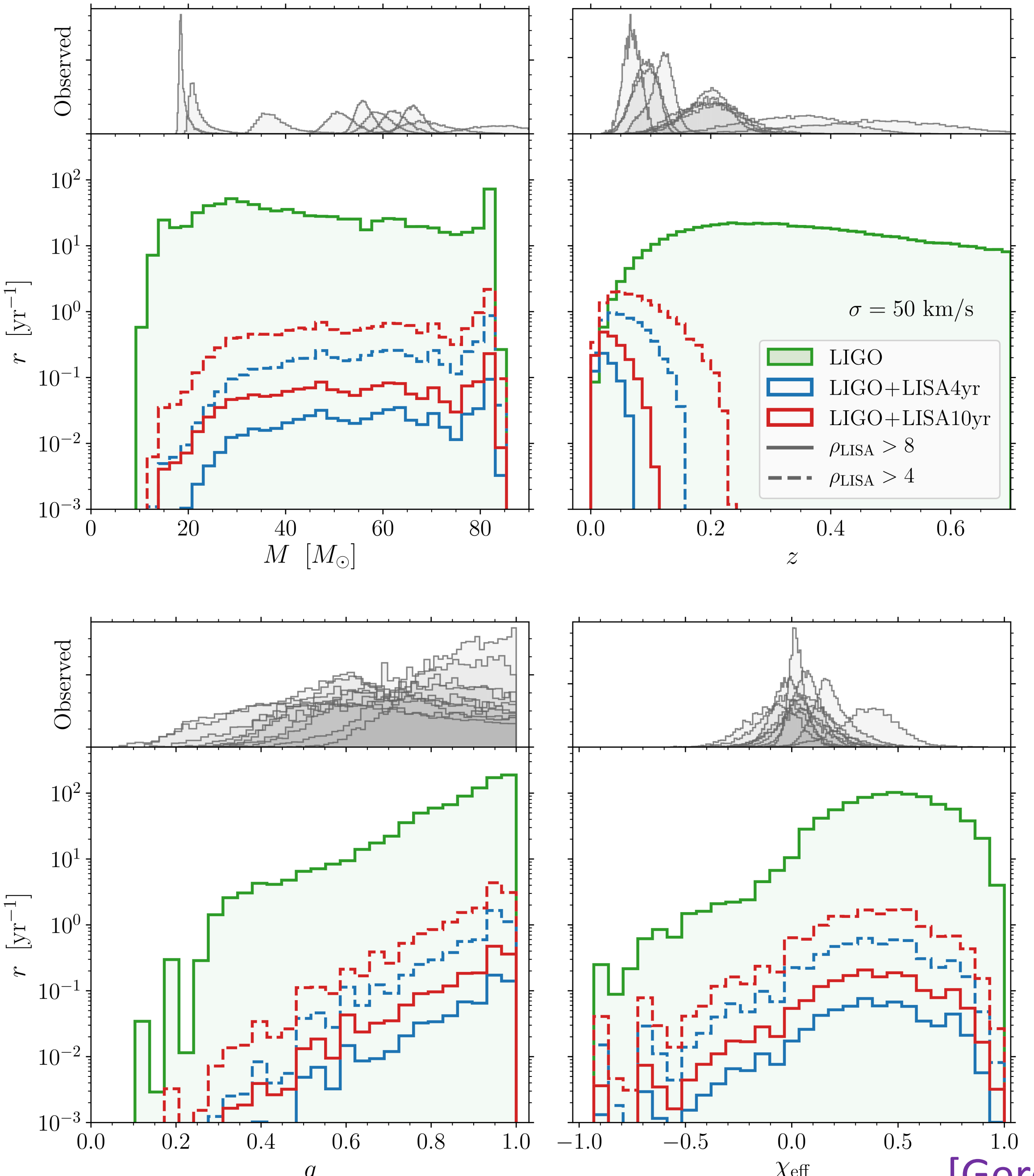
[Wong, Kovetz, Cutler, EB, 1808.08247]

Multiband rates for field binaries



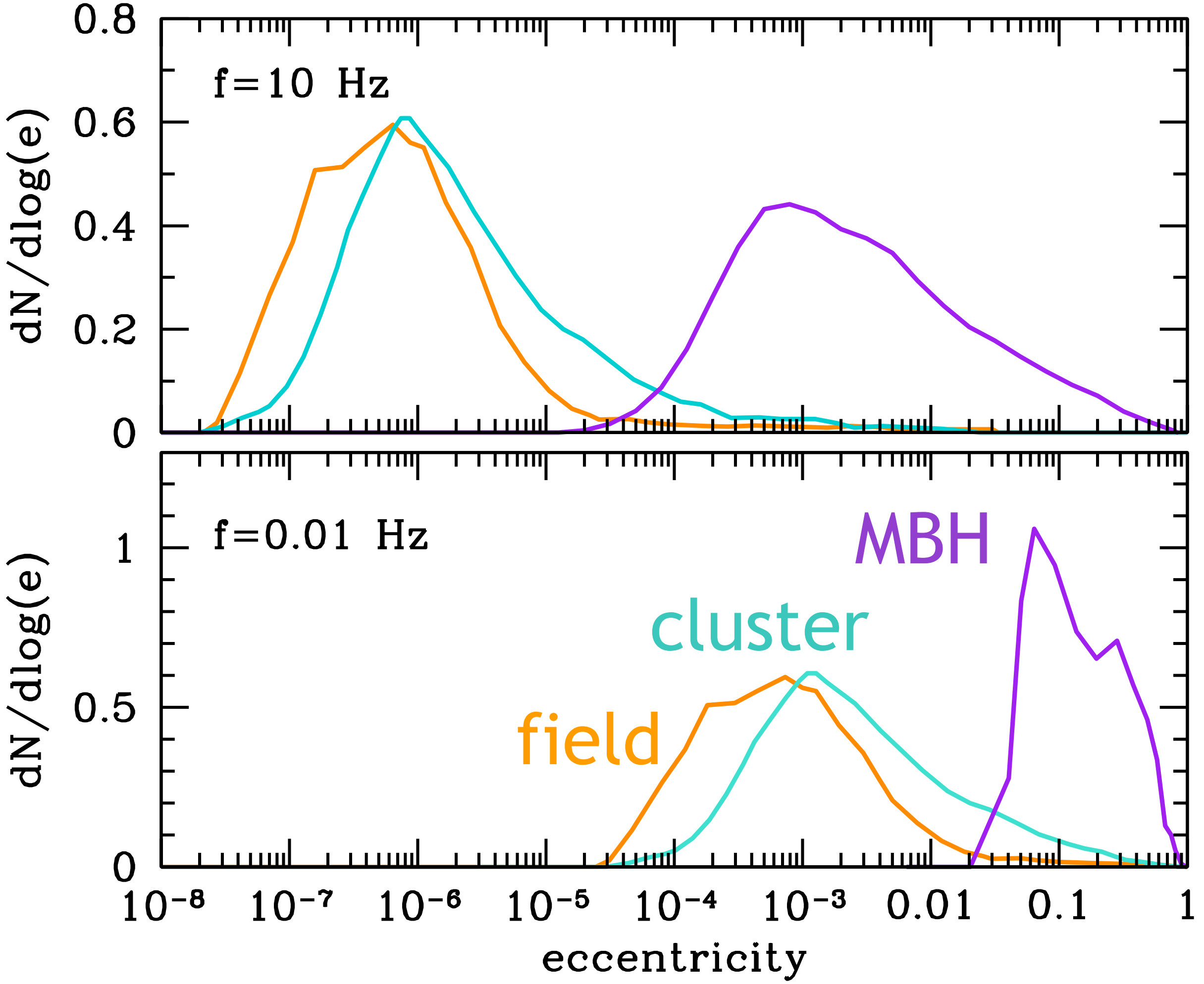
[Gerosa+, 1902.00021]

Which sub-population gives multiband events?



[Gerosa+, 1902.00021]

Field, clusters or triples?



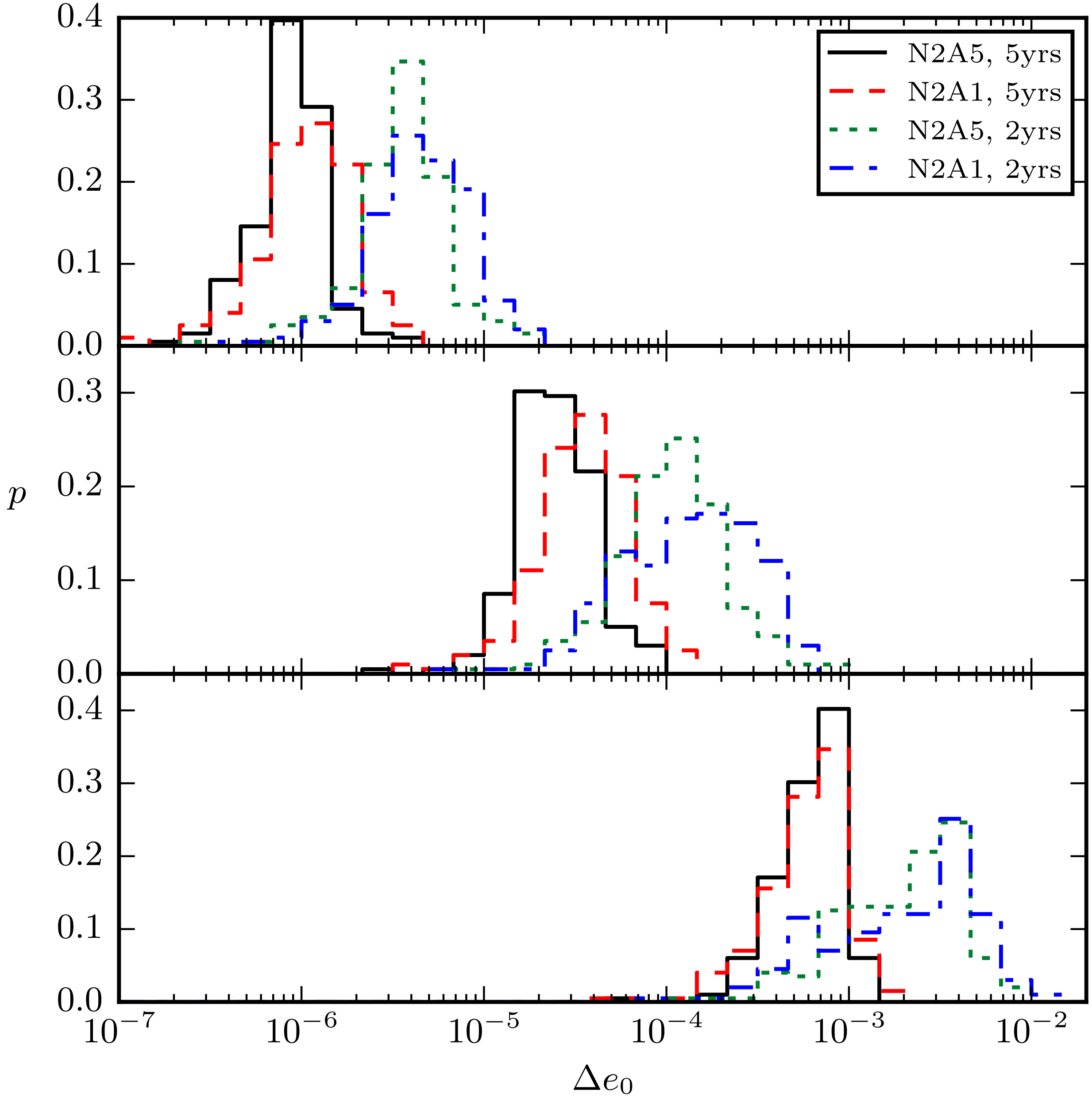
$$e \sim f^{-19/18} \sim f^{-1}$$

Kozai around MBHs
[Antonini+, 1509.05080]
or primordial black holes
[Cholis+, 1606.07437]
can generate
large eccentricity
in LISA band

Is e measurable?
Yes, if large enough

[Nishizawa+,1605.01341; 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; Tanay+, 1905.08811]

Triples easy to tell apart – what about field vs. cluster?

		3σ		5σ	
eLISA base	$N_{\rm obs}$	N_{50}	N_{90}	N_{50}	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 will help

Can we distinguish eccentricity distributions for (say) **MBH vs. primordial** scenarios?

[Nishizawa+,1606.09295]

GR effects and 2-body/3-body mergers inside clusters

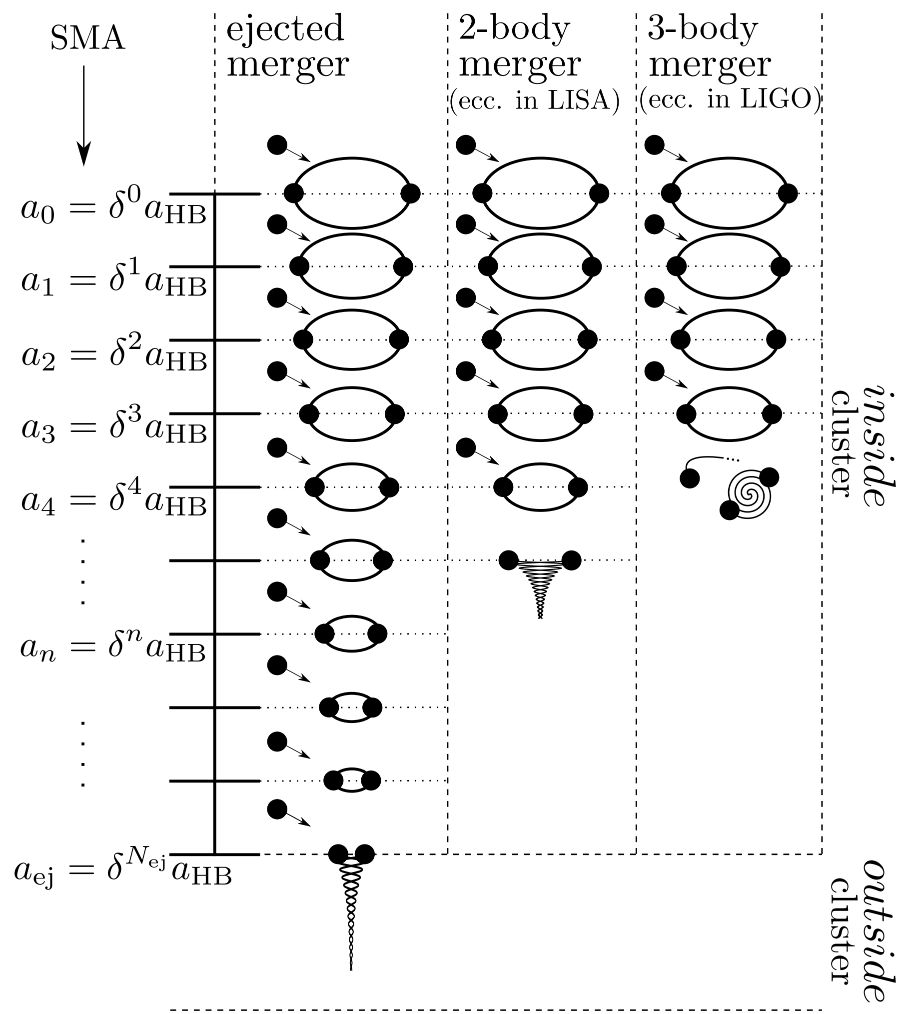
Multiple mergers? Eccentric binaries in LIGO?
More (4x as many) eccentric mergers?

Rodriguez+: in-cluster eccentric LIGO mergers

*"We present models of realistic globular clusters with **post-Newtonian dynamics** [...] we find that nearly half of all binary black hole mergers occur inside the cluster, with **about 10% of those mergers entering the LIGO/Virgo band with eccentricities greater than 0.1.** In-cluster mergers lead to the birth of a **second generation** of black holes with larger masses and high spins, which, depending on the black hole natal spins, can sometimes be retained in the cluster and merge again."*

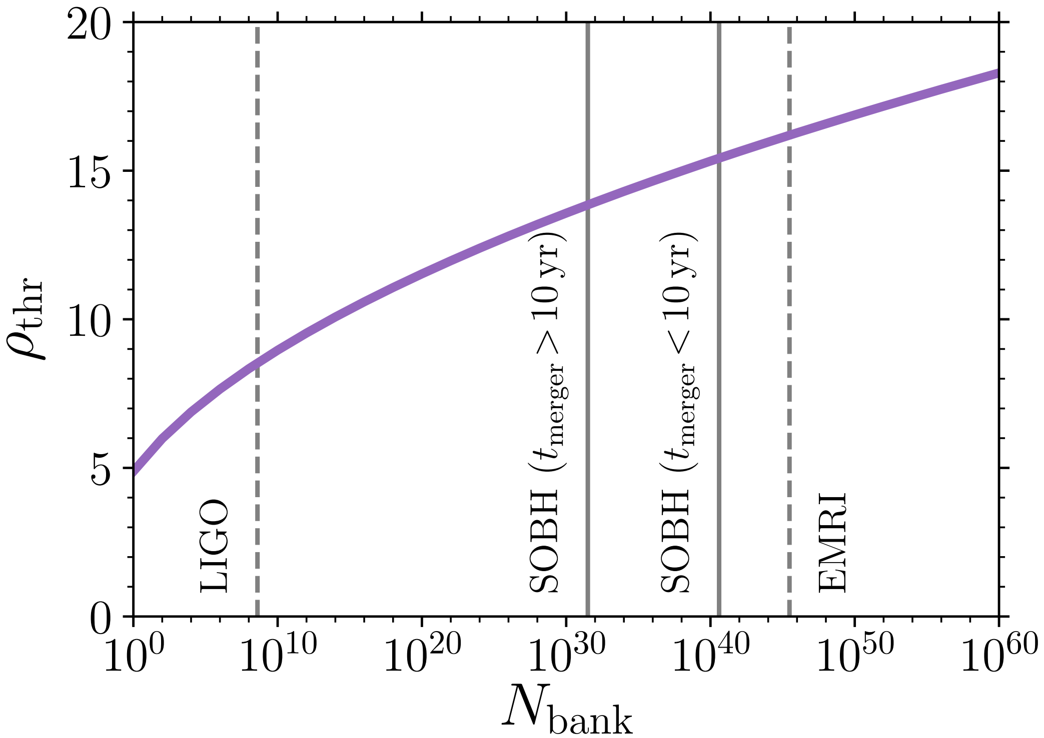
Samsing+: measurable e in LISA for 40% of in-cluster mergers

*"We show that **nearly half of all binary black hole (BBH) mergers dynamically assembled in globular clusters have measurable eccentricities (e > 0.01) in the LISA band** when General Relativistic corrections are properly included in the N-body evolution [...] the relatively large population of eccentric LISA sources reported here originates from **BBHs that merge between hardening binary-single interactions** inside their globular cluster".*



[Gerosa+EB, 1703.06223; Rodriguez+, 1712.04937; Samsing+, 1804.06519]

…but, are multiband binaries still too quiet for LISA?



m_1, m_2 $[M_\odot]$	$N_{\rm bank}^{(\rm fast)}$	$N_{\rm bank}^{(\rm slow)}$	$\rho_{\rm thr}^{(\rm fast)}$	$\rho_{\rm thr}^{(\rm slow)}$
5 − 50	$10^{40.6}$	$10^{31.5}$	15.4	13.9
10 − 50	$10^{38.4}$	$10^{30.5}$	15.1	13.7
20 − 50	$10^{37.5}$	$10^{29.8}$	14.9	13.5
archival	$10^{11.7}$	–	9.4	–

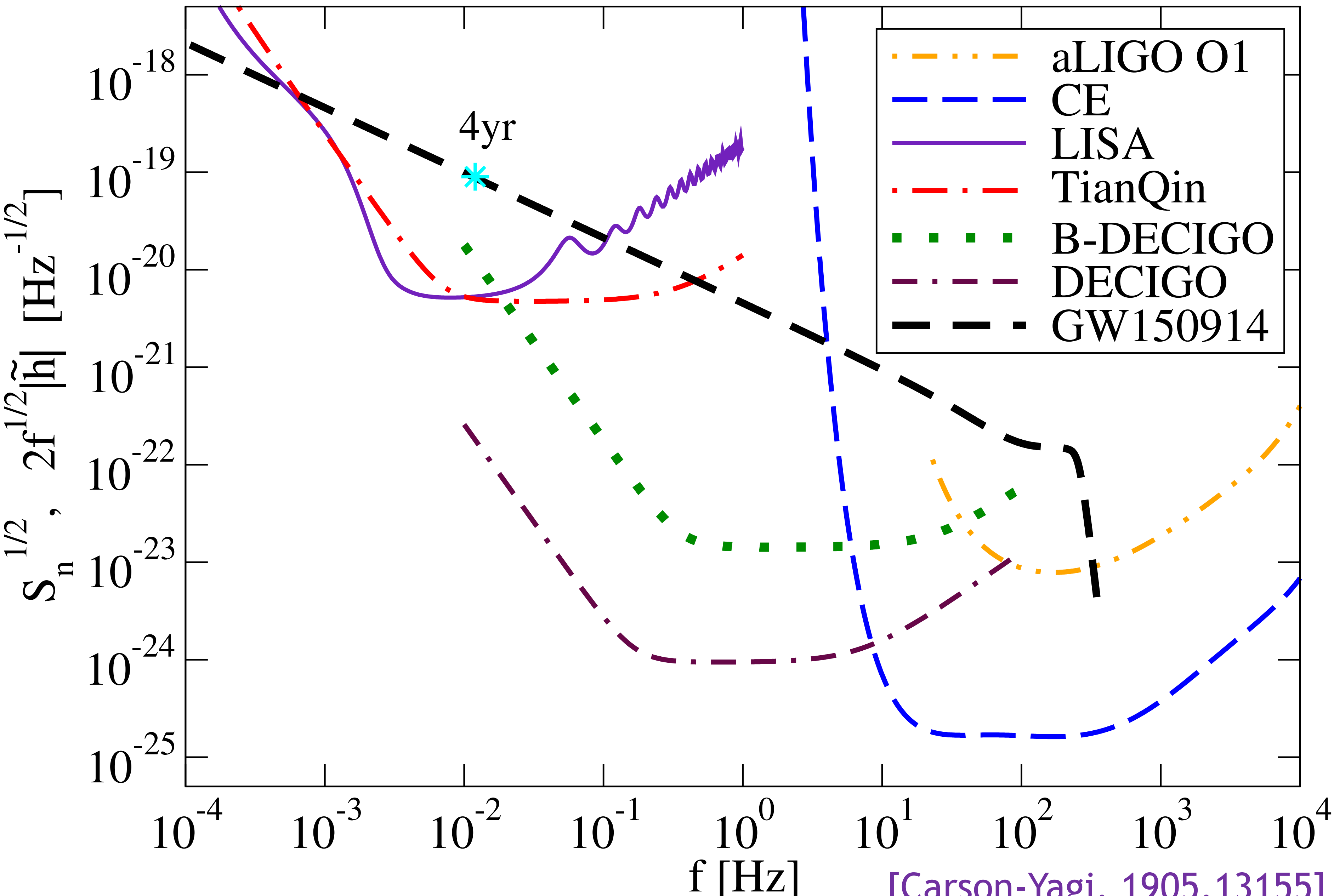
Table 1. Total effective number of templates in the bank and corresponding threshold SNR. We consider different lower-mass limits, as well as a representative archival search for a GW150914-like event. Superscripts $^{(\rm fast)}$ and $^{(\rm slow)}$ correspond to fast- ($0 < t_{\rm merger} < 10$ yr) and slow-chirping (10 yr $< t_{\rm merger} < 100$ yr) binaries, respectively. The results for the row highlighted in gray are shown in Fig. 1.

[Moore-Gerosa-Klein, 1905.11998]

Midband detectors?

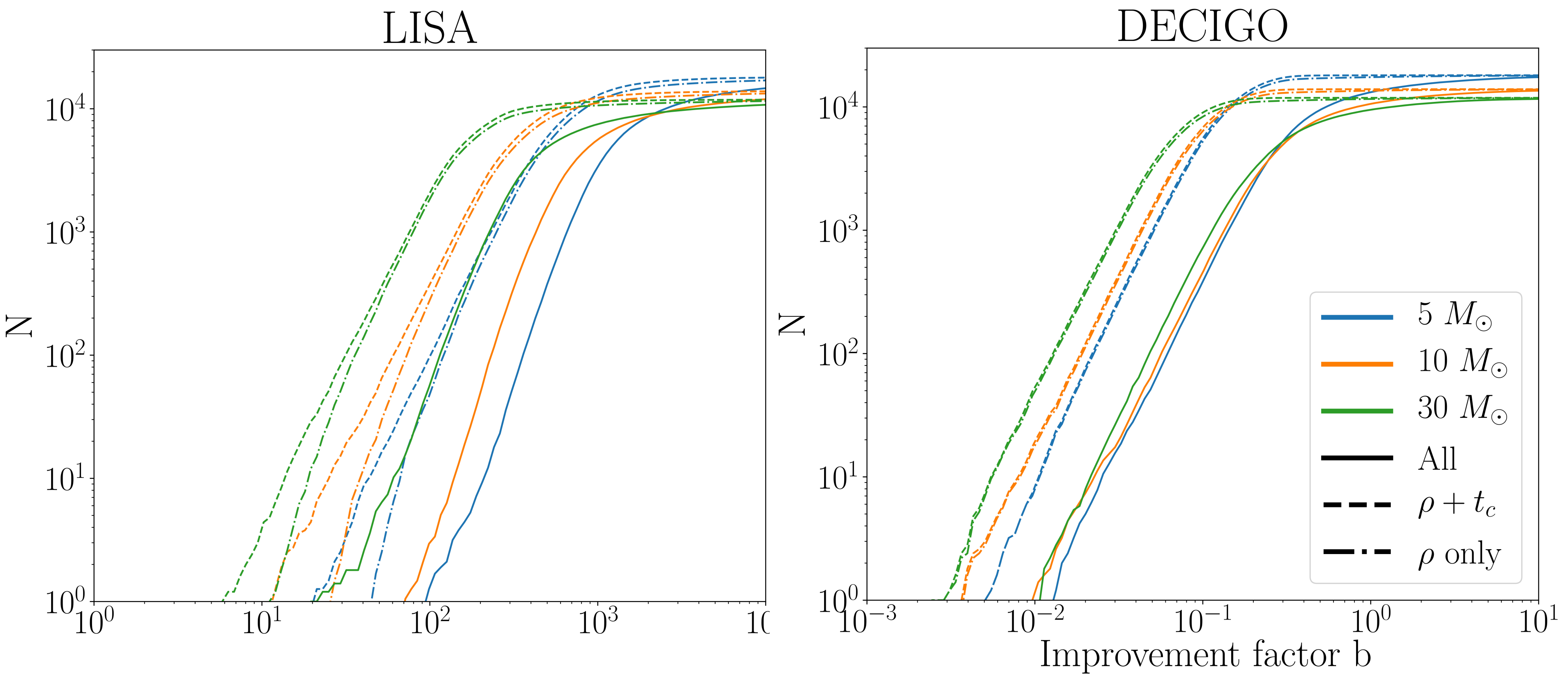
with Wong

Mid-band detectors etcetera…



[Carson-Yagi, 1905.13155]

Neutron star-black hole forewarning? (preliminary!)

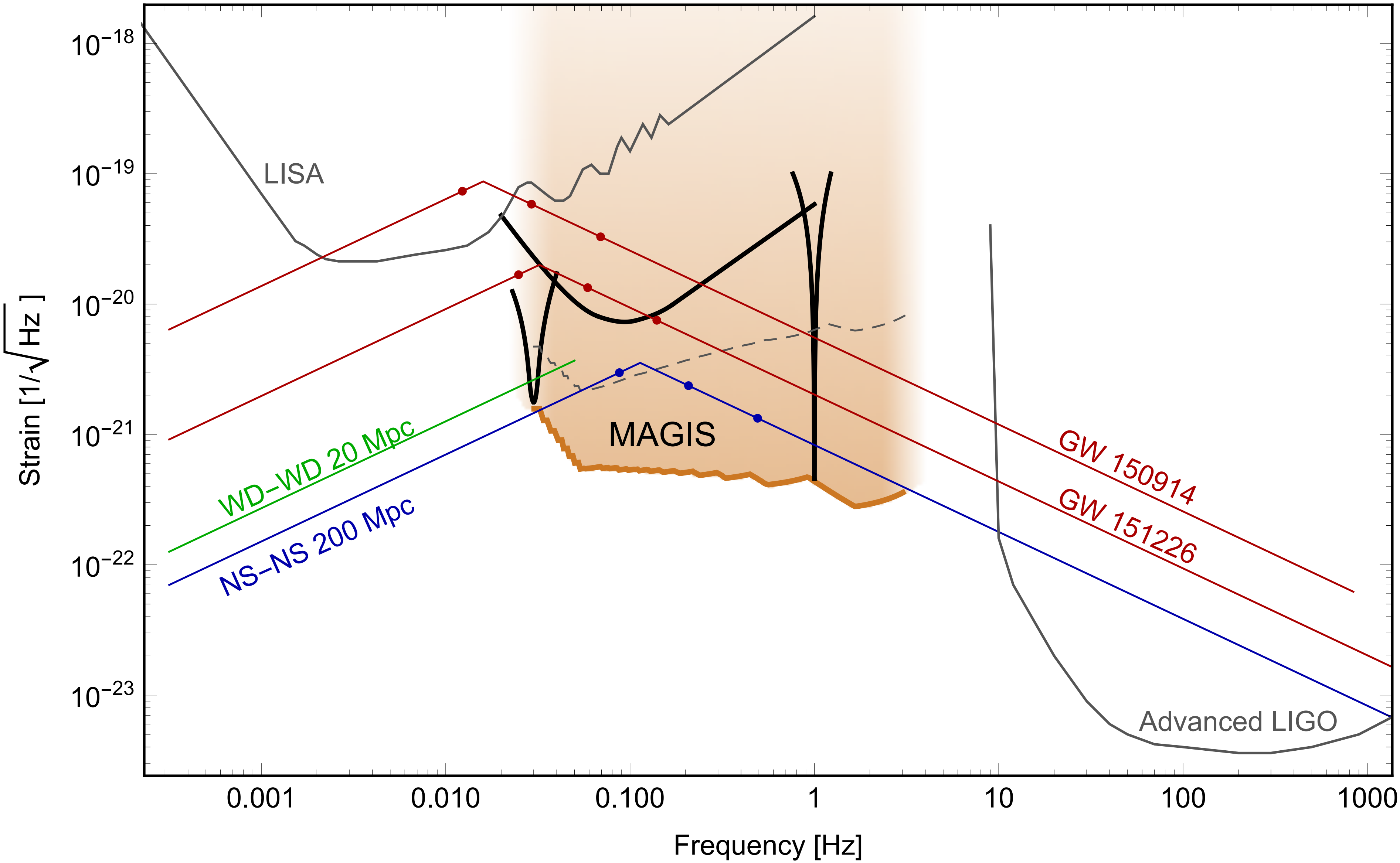


1.4 M_{sun} NS + variable-mass BH

"All": $\rho>8$, $\Delta t_c<10$ s, $\Delta\Omega < 1$ deg^2
"$\rho+t_c$": $\rho>8$, $\Delta t_c<10$ s
"ρ only": $\rho>8$

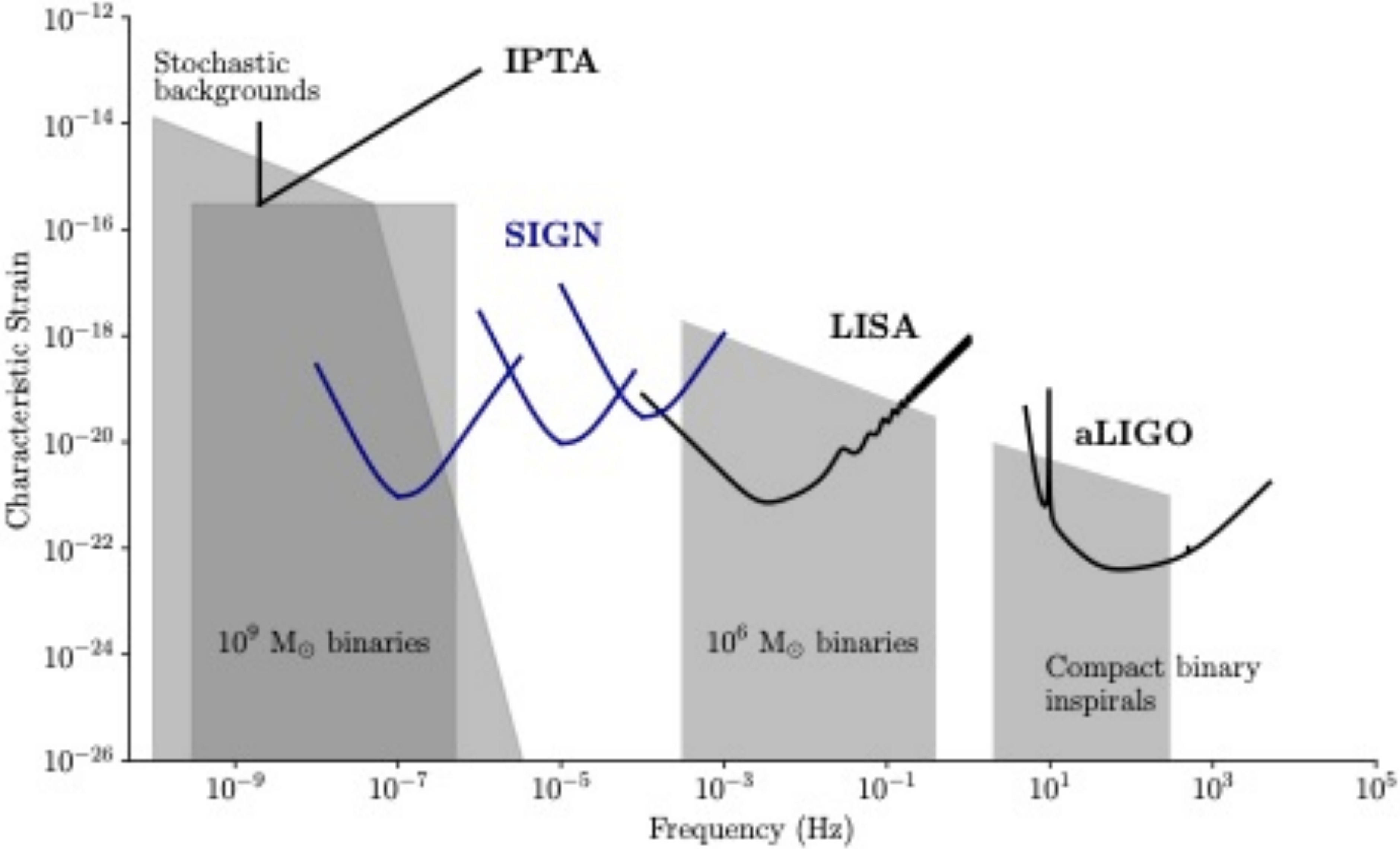
[Kaze Wong, unpublished]

Midband: atom interferometry



[Graham, Hogan, Kasevich, Rajendran, Romani, 1711.02225]

Low-midband: stellar interferometry?

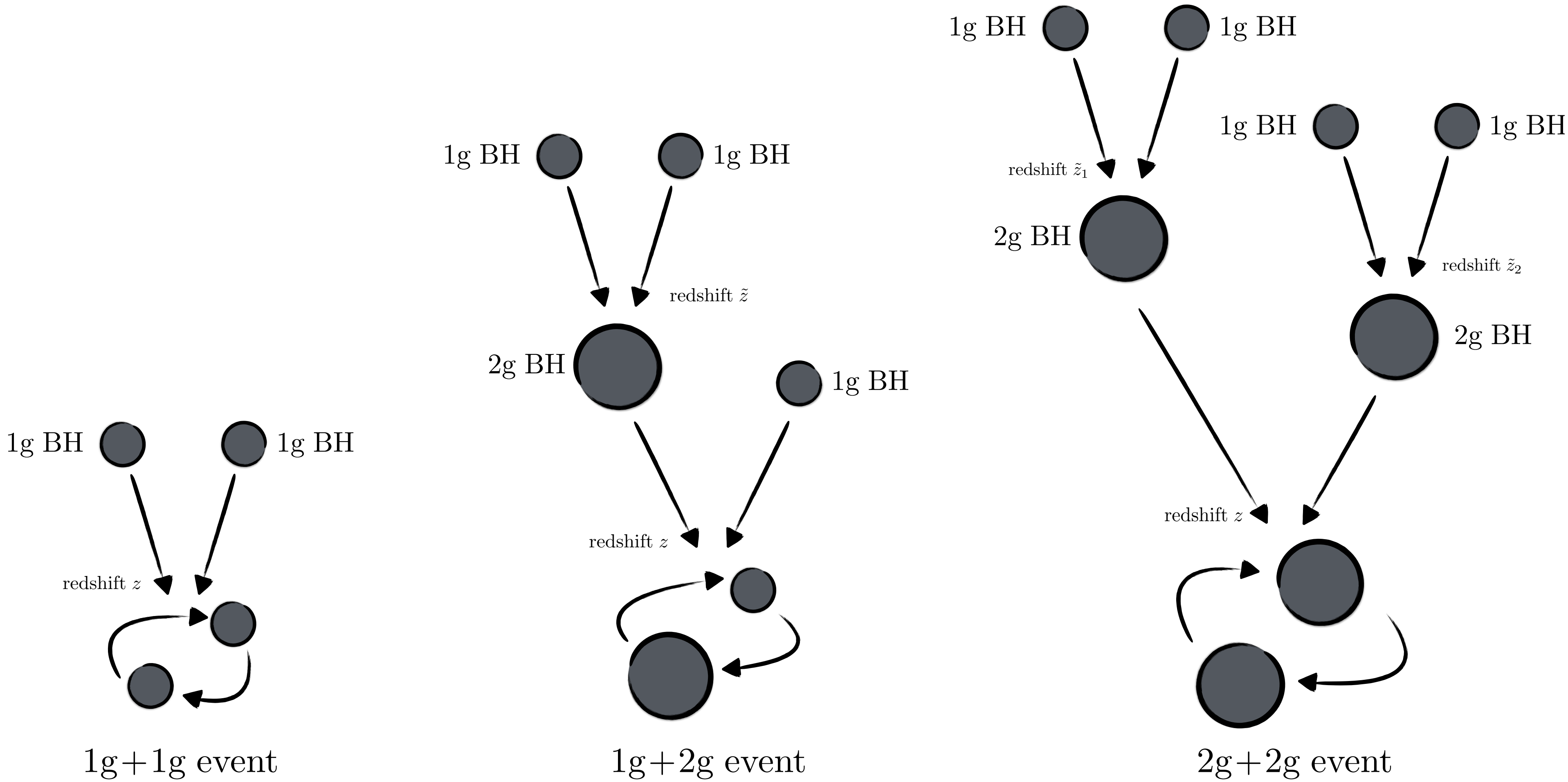


[Park+, 1906.06018]

Multiple mergers and escape velocities

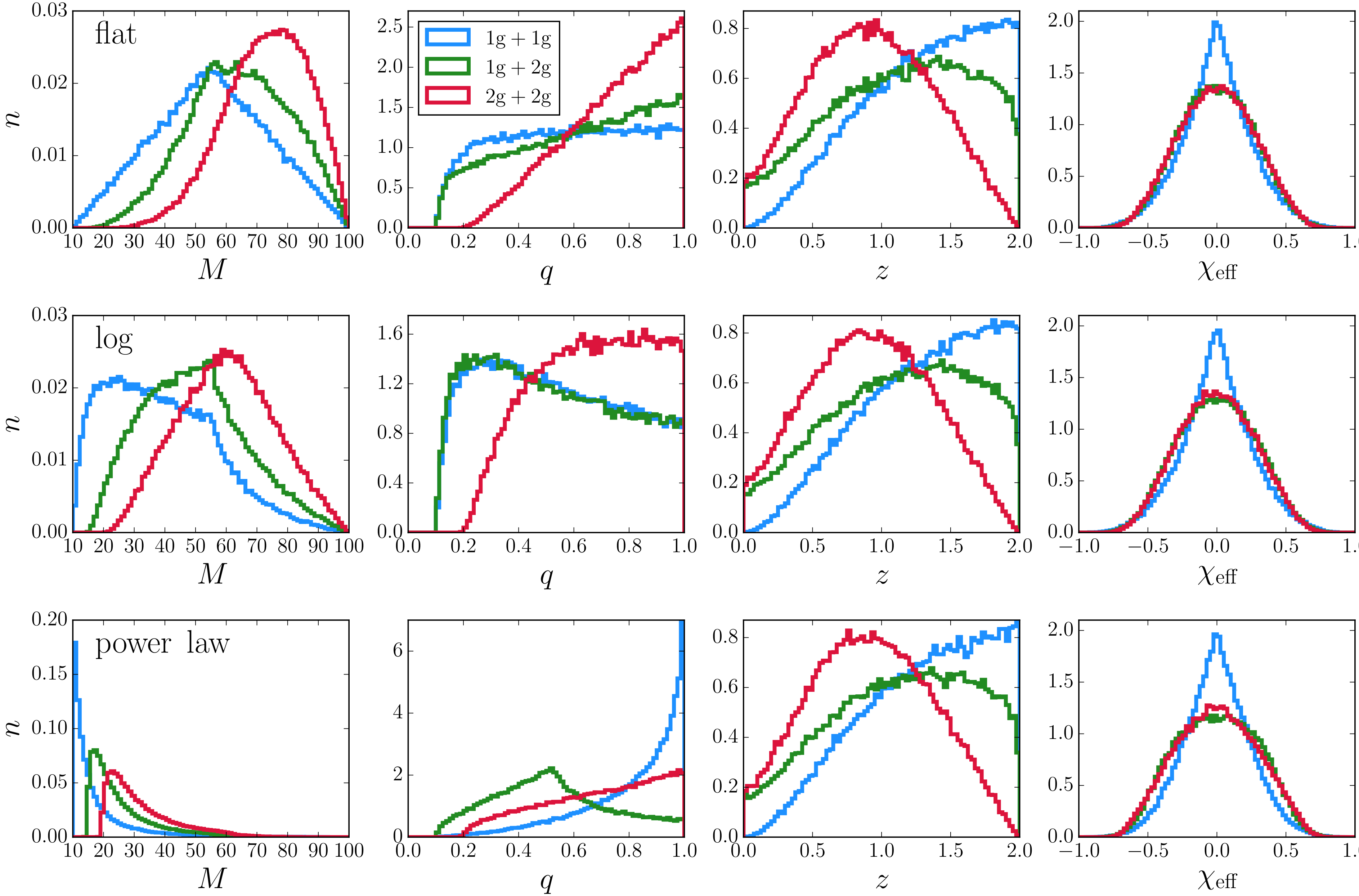
with Gerosa

Collapse or previous mergers?

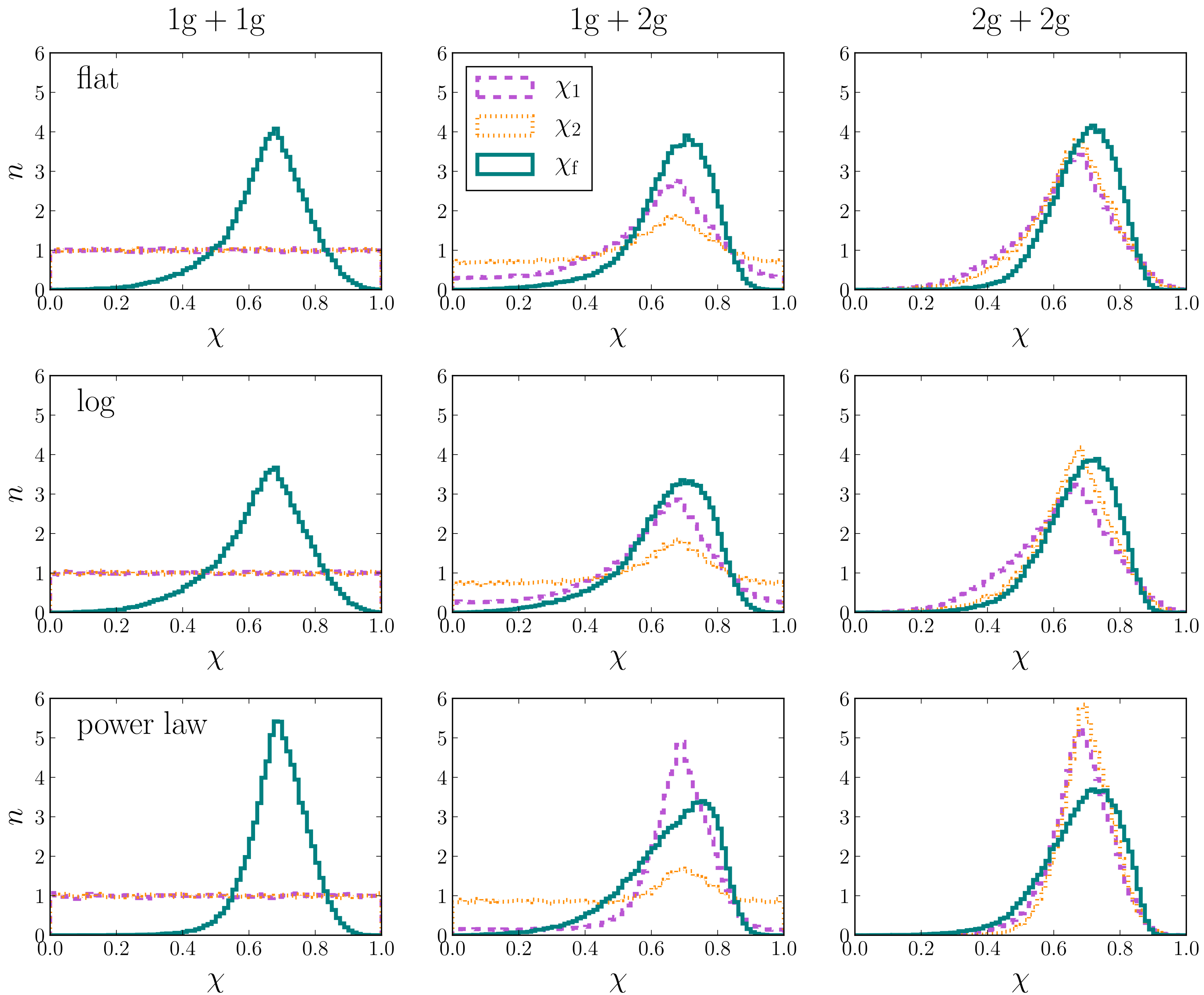


[Gültekin-Miller-Hamilton, astro-ph/0402532, astro-ph/0509885]
[Gerosa+EB,1703.06223; Fishbach+, 1703.06869]

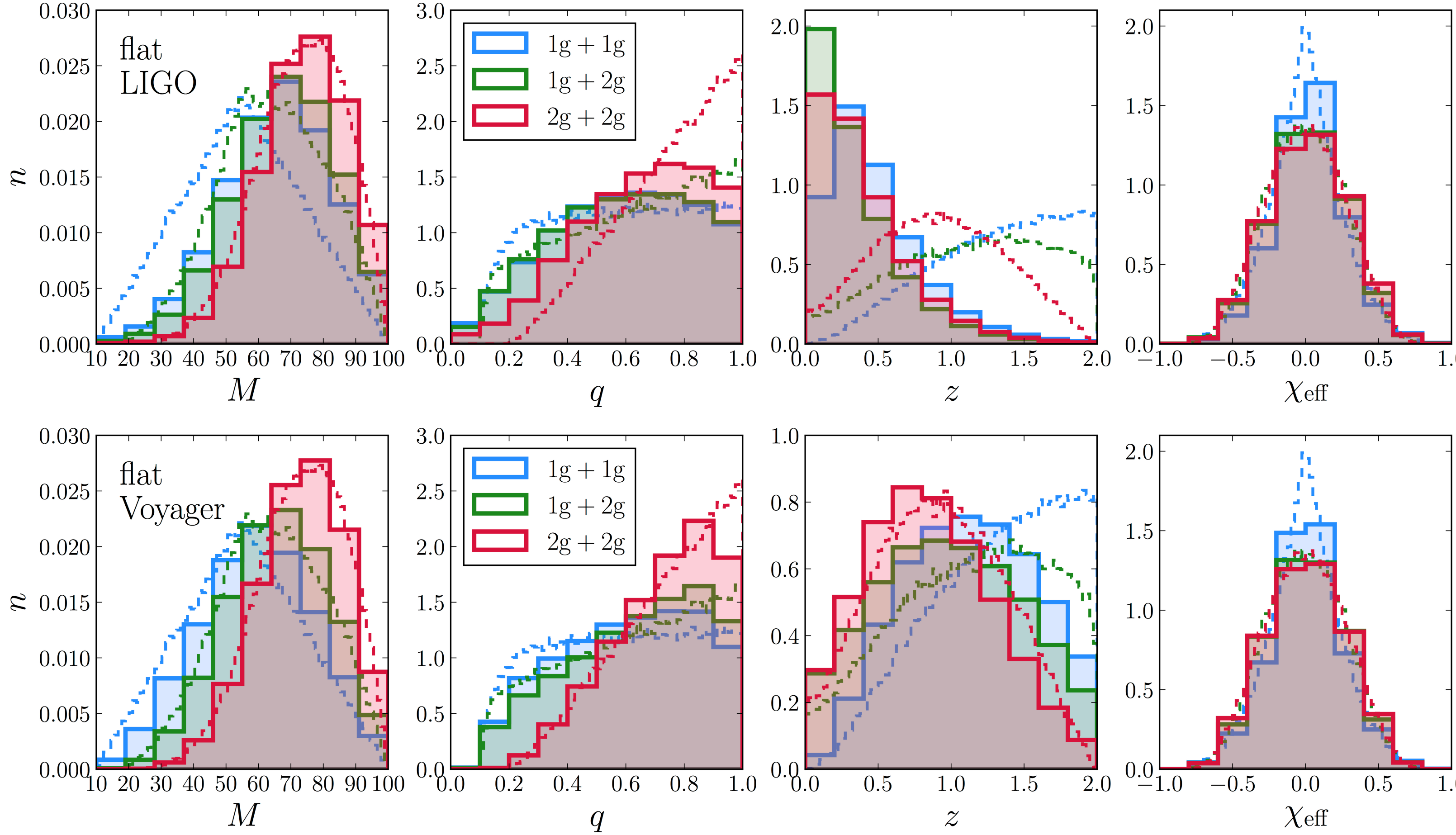
Collapse or previous mergers? LIGO observables



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)

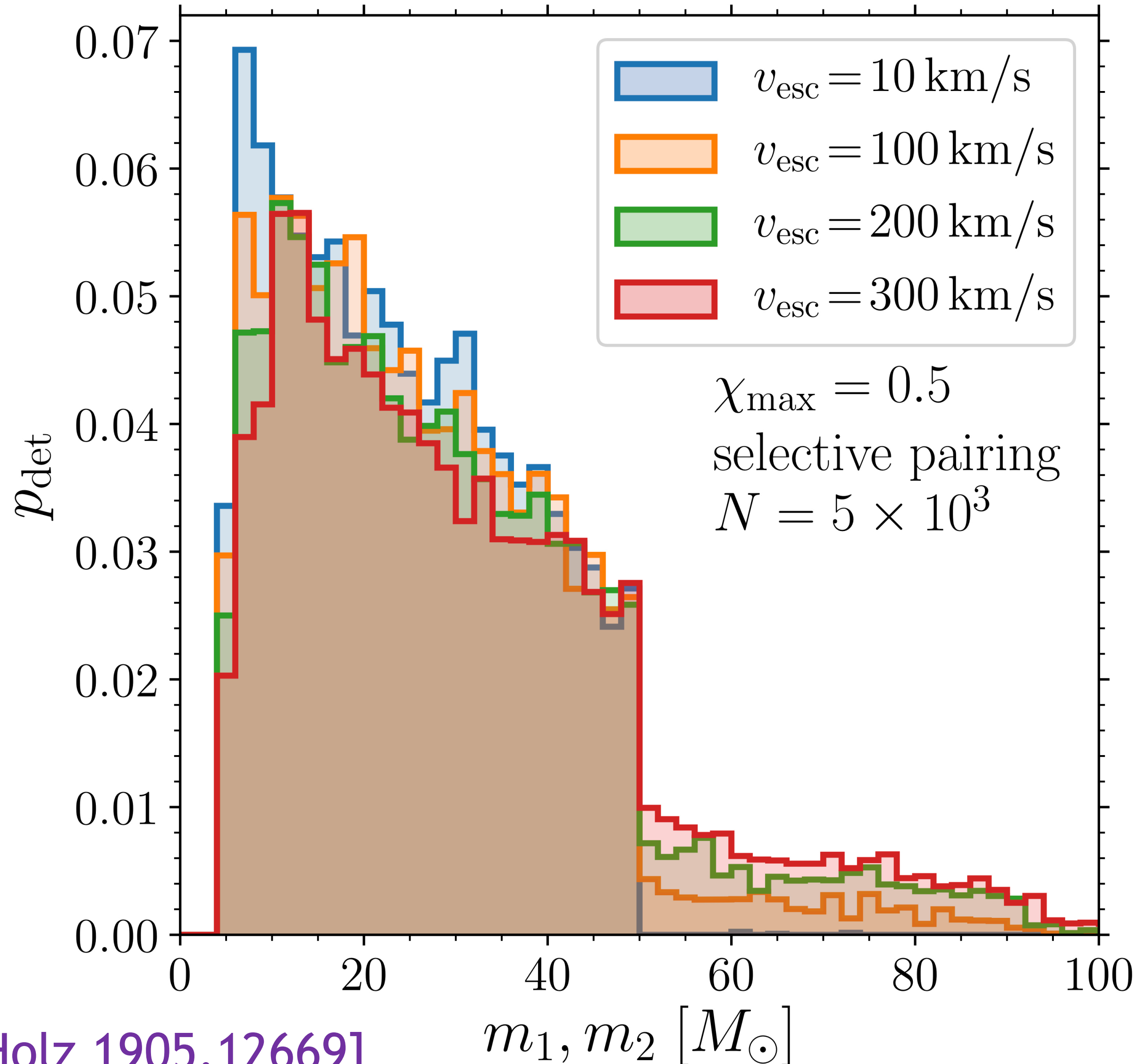
Multiple generation mergers and escape speeds

- **First generation:**
  Masses $p(m) \propto m^{\gamma}$ **in** $m \in [5, 50] M_{\odot}$ **with gap,** $\gamma = -2.3$

  Spins uniform in $[0, \chi_{\max}]$

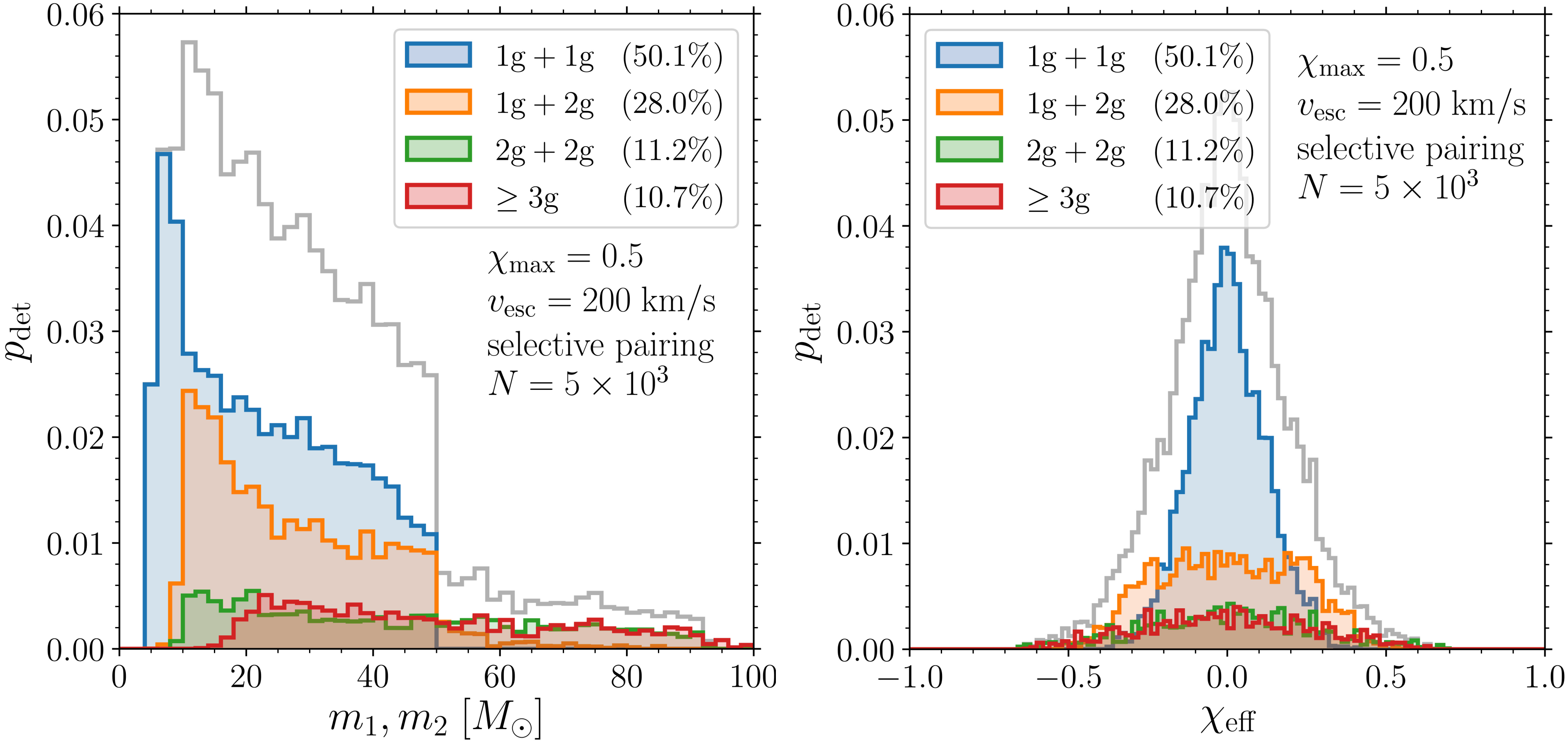
- **Random pairing:**
  $p_{\text{pair}}(m_1, m_2) = \text{const}$

- **Selective pairing:**
  $p_{\text{pair}}(m_1, m_2) \propto m_1^{\alpha} m_2^{\beta}$

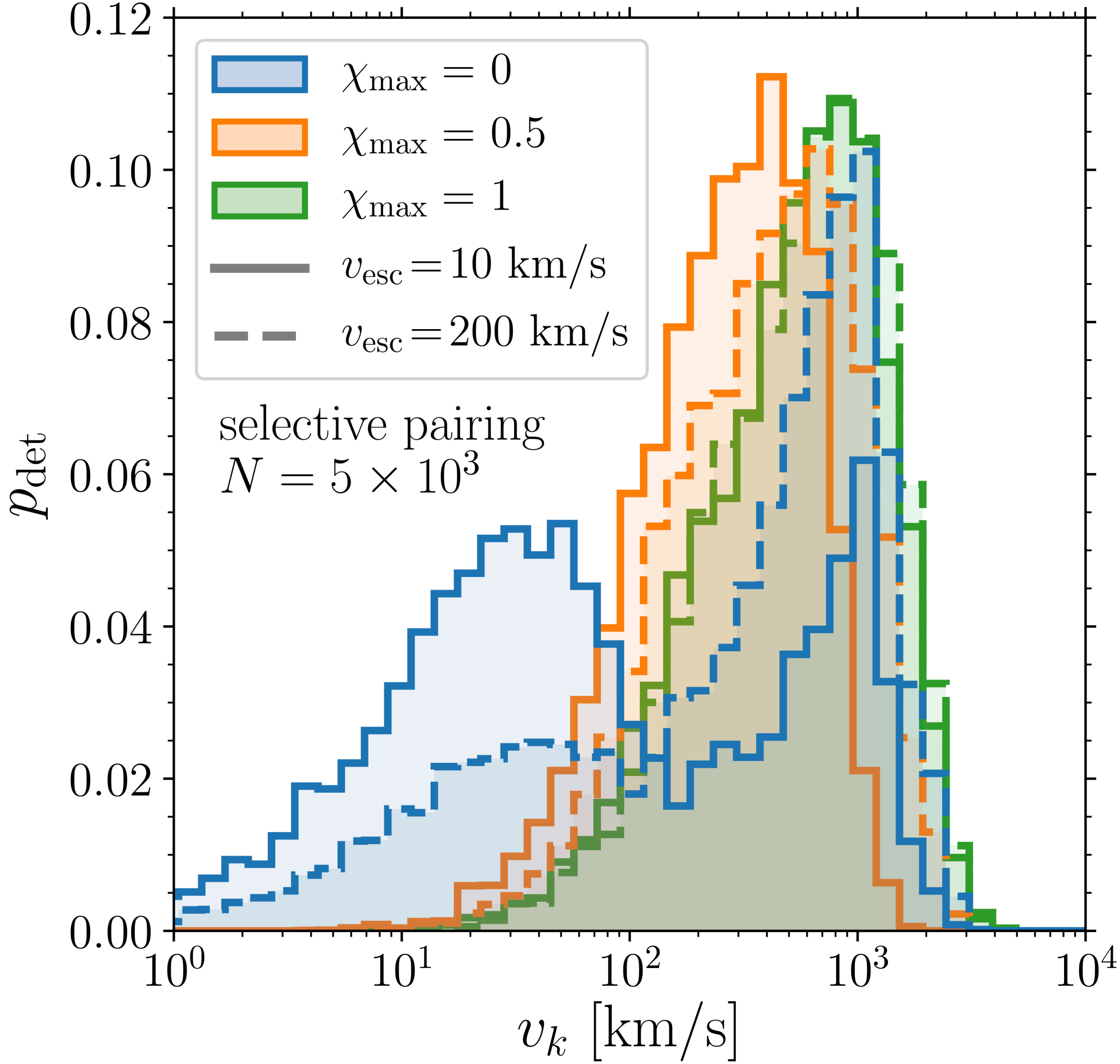


[LVC 1811.12940, Fishbach-Holz 1905.12669]

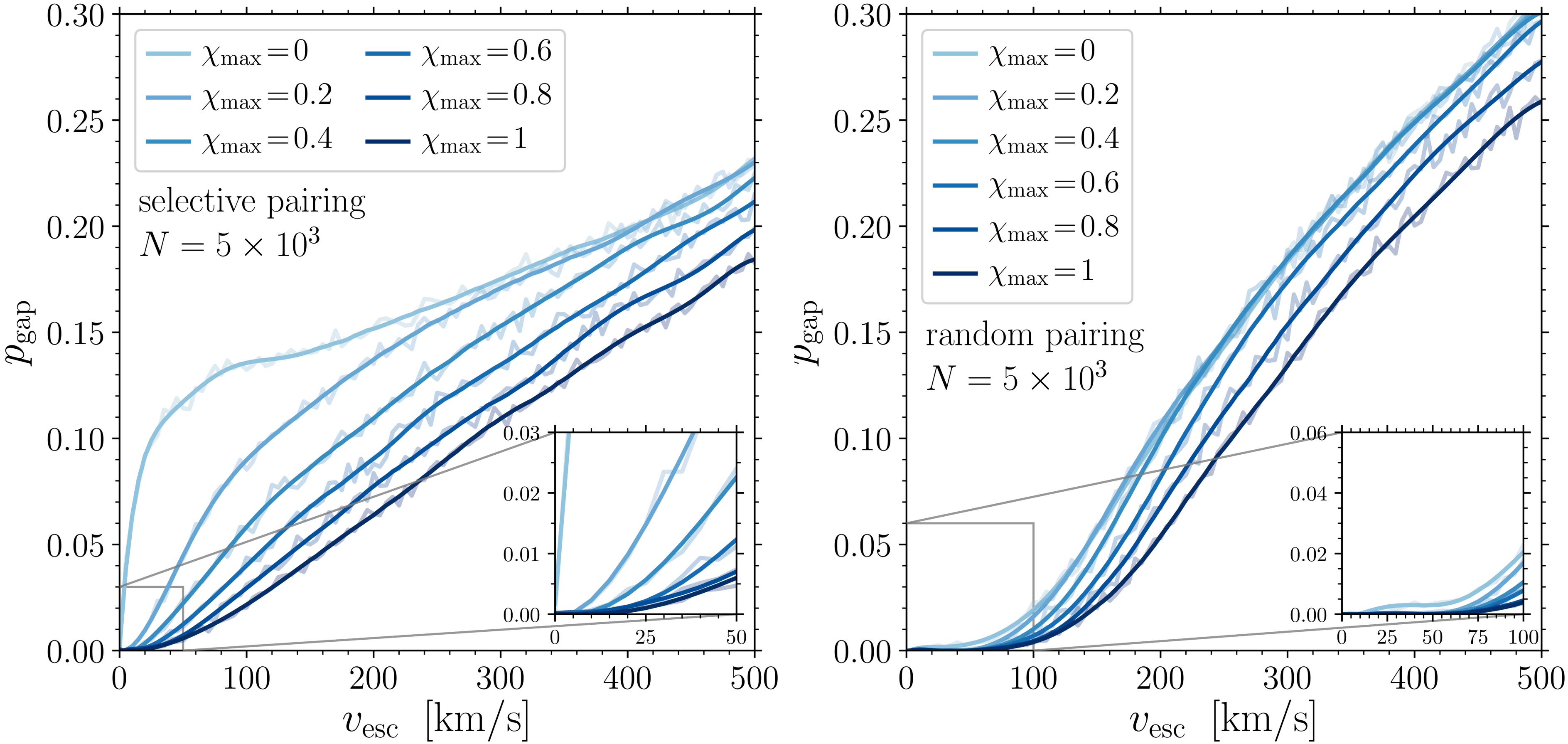
What generations contribute?



Effect of maximum spin



Probability (BH in the gap) vs. escape velocity



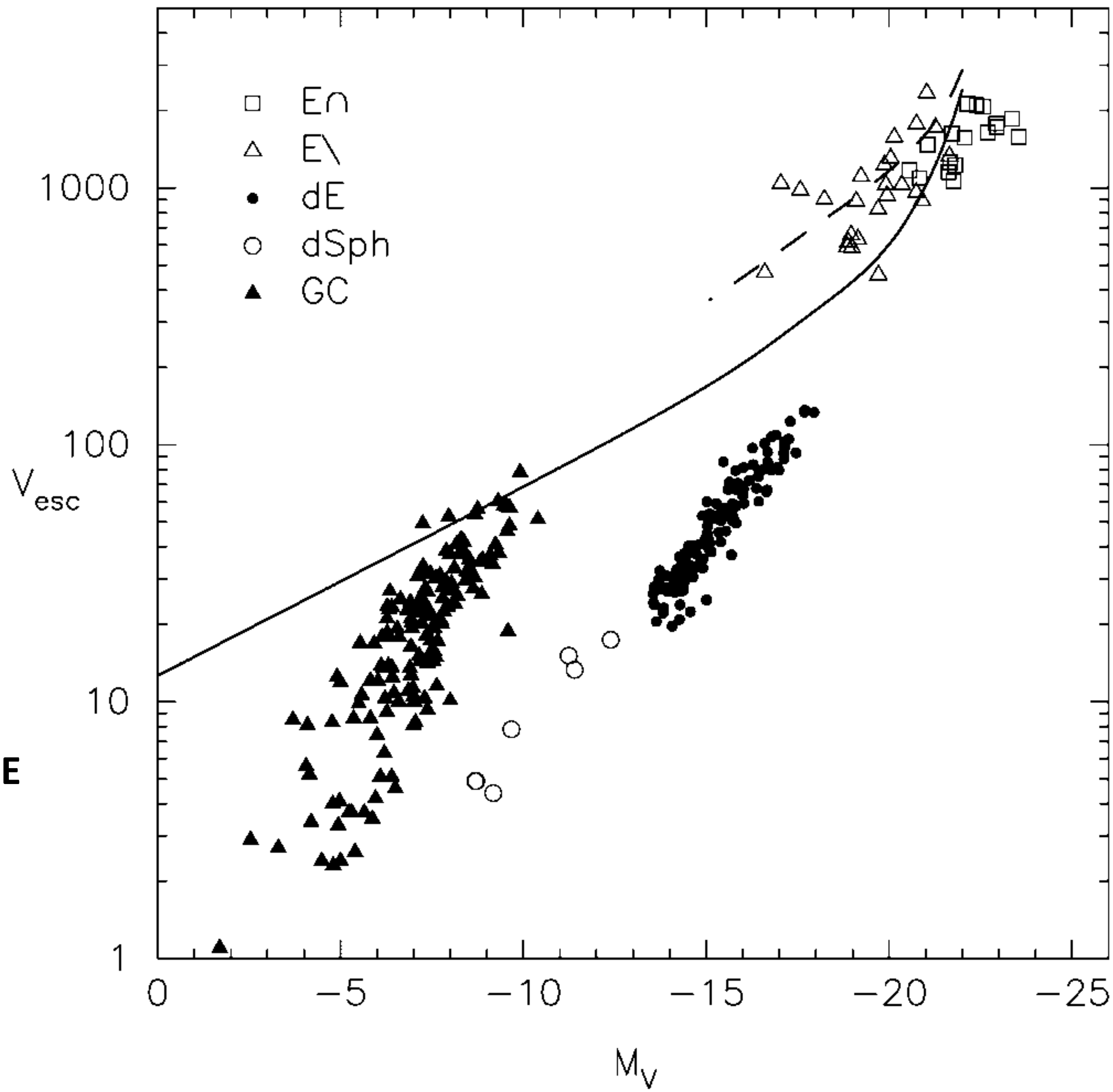
Typical escape velocities

Legend:

- **E:** giant elliptical
- **dE:** dwarf elliptical
- **dSph:** dwarf spheroidal
- **GC:** globular cluster

Solid line:
mean v_{esc} from DM halos

Dashed line:
v_{esc} from luminous+DM for E



[Merritt+, astro-ph/0402057]