What will LISA reveal about black hole astrophysics?

Emanuele Berti, University of Mississippi

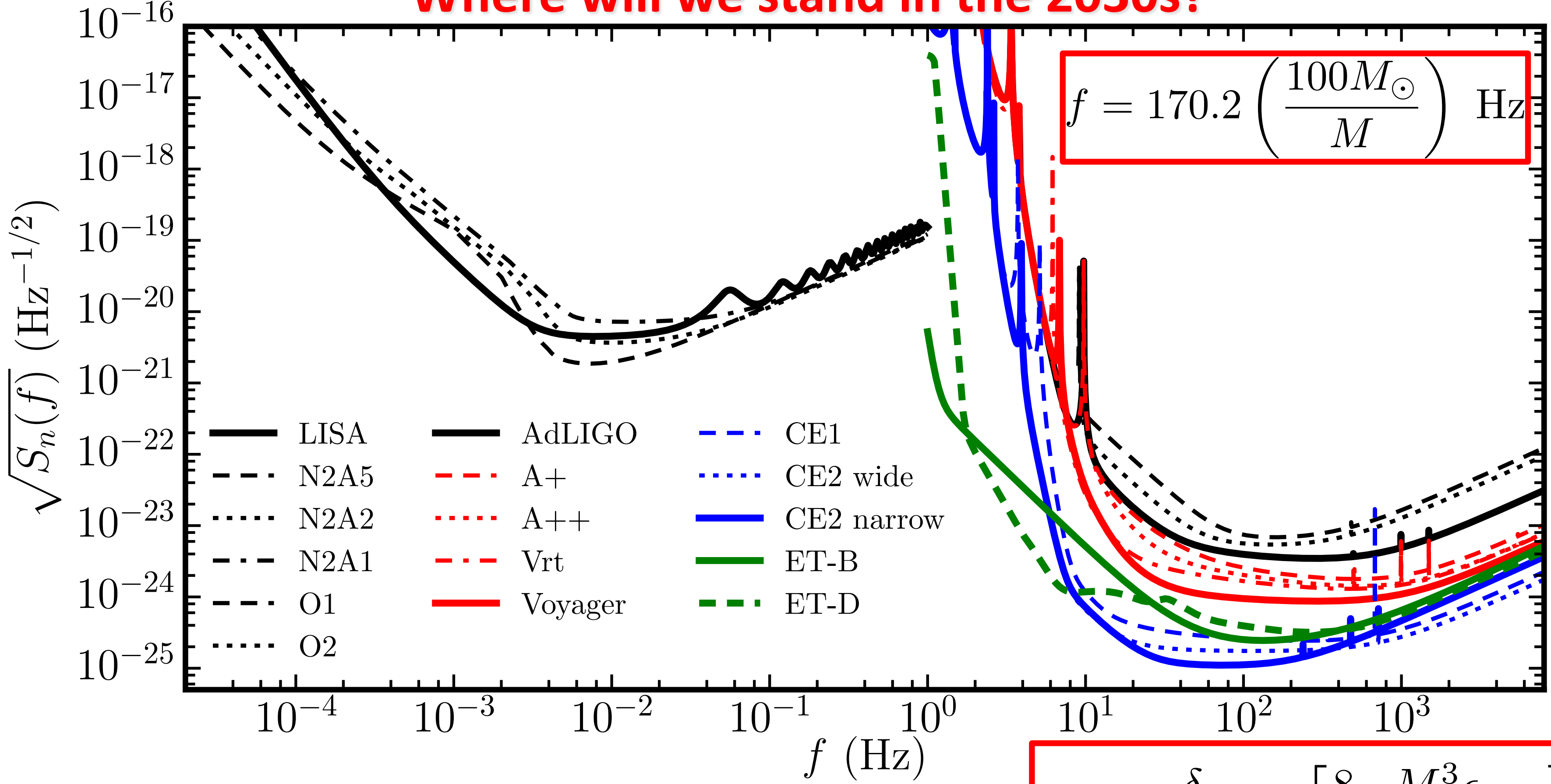
GW SIG Minisymposium, Apr 14 2018

LIGO/Virgo: 5.87 confirmed stellar mass black hole mergers + GW170817

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

Where will we stand in the 2030s?



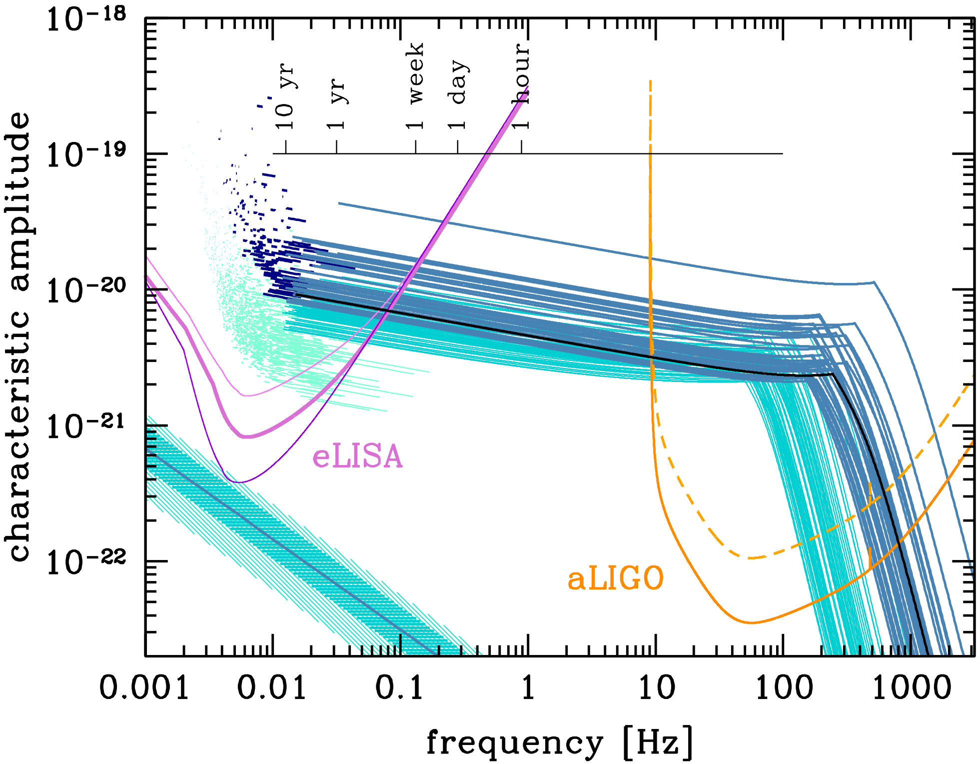
$$f = 170.2 \left(\frac{100 M_\odot}{M}\right) \mathrm{Hz}$$

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

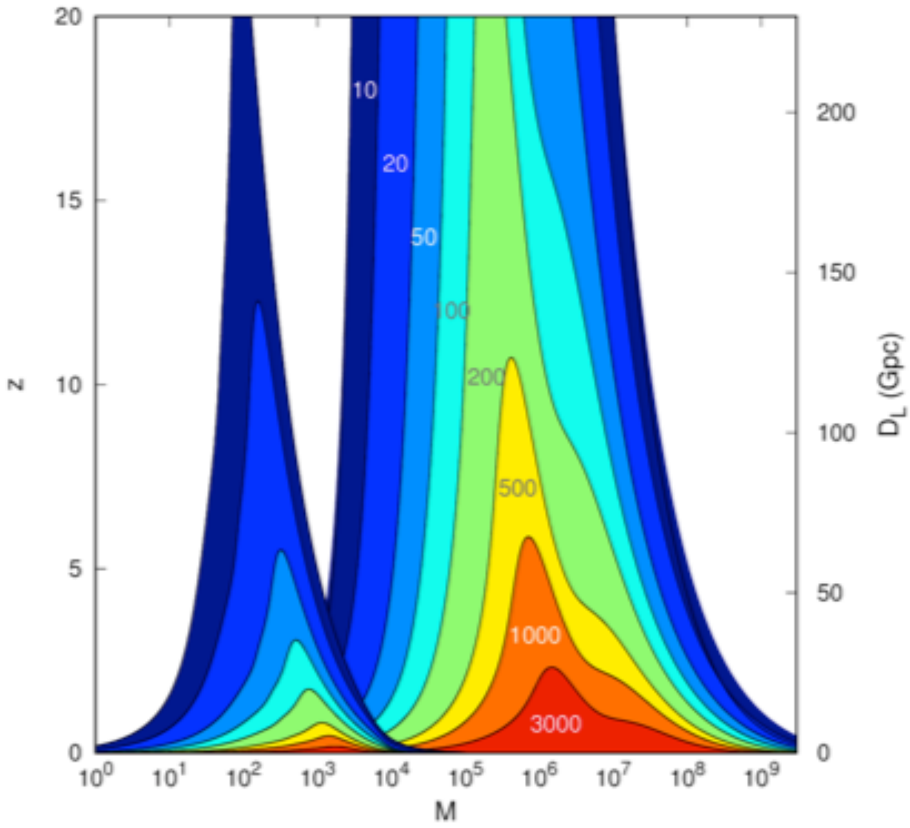
[EB+, 1605.09286]

Complementarity! Multi-band

2030s: Einstein Telescope vs. LISA

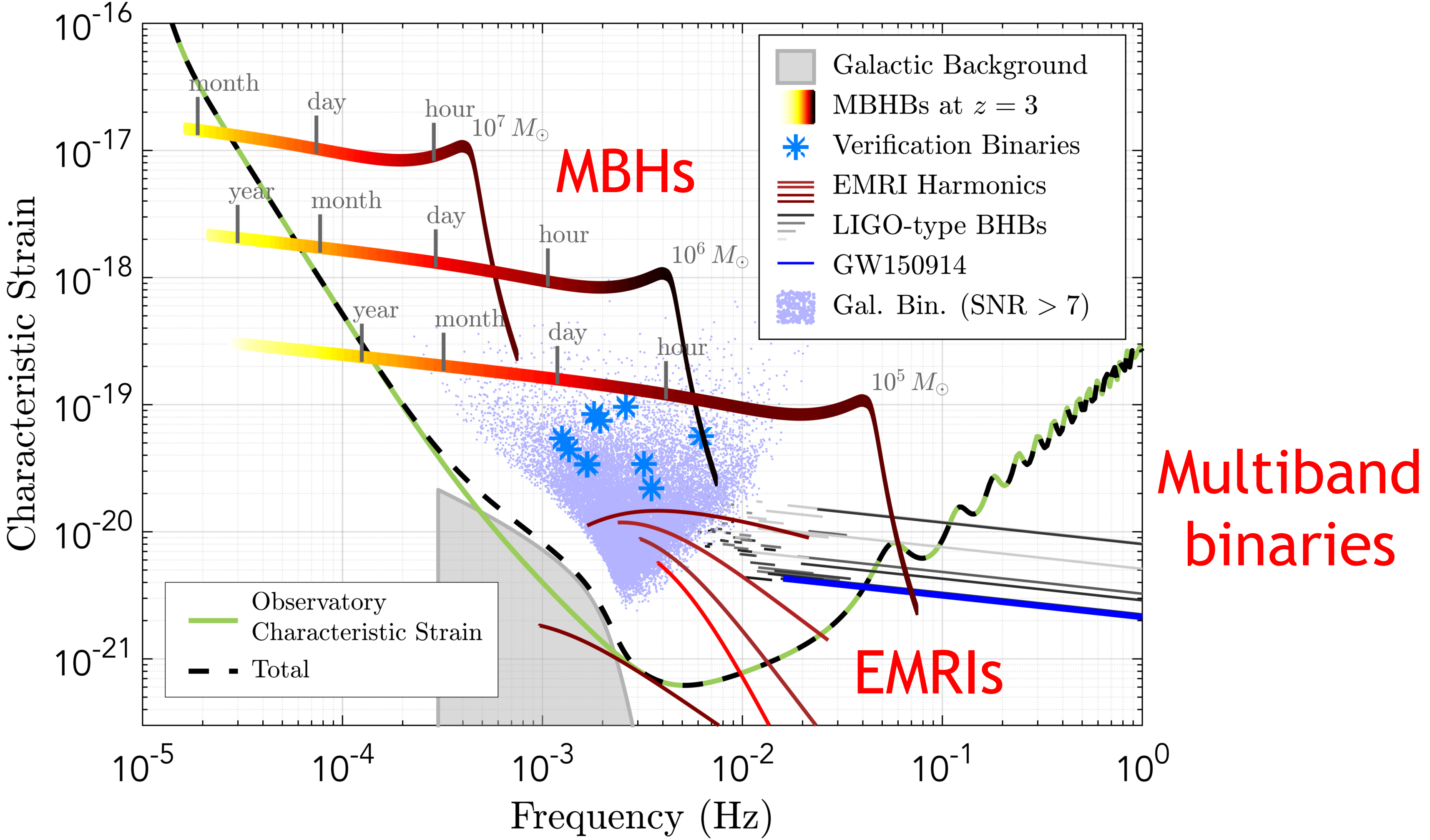


[Sesana,1602.06951]



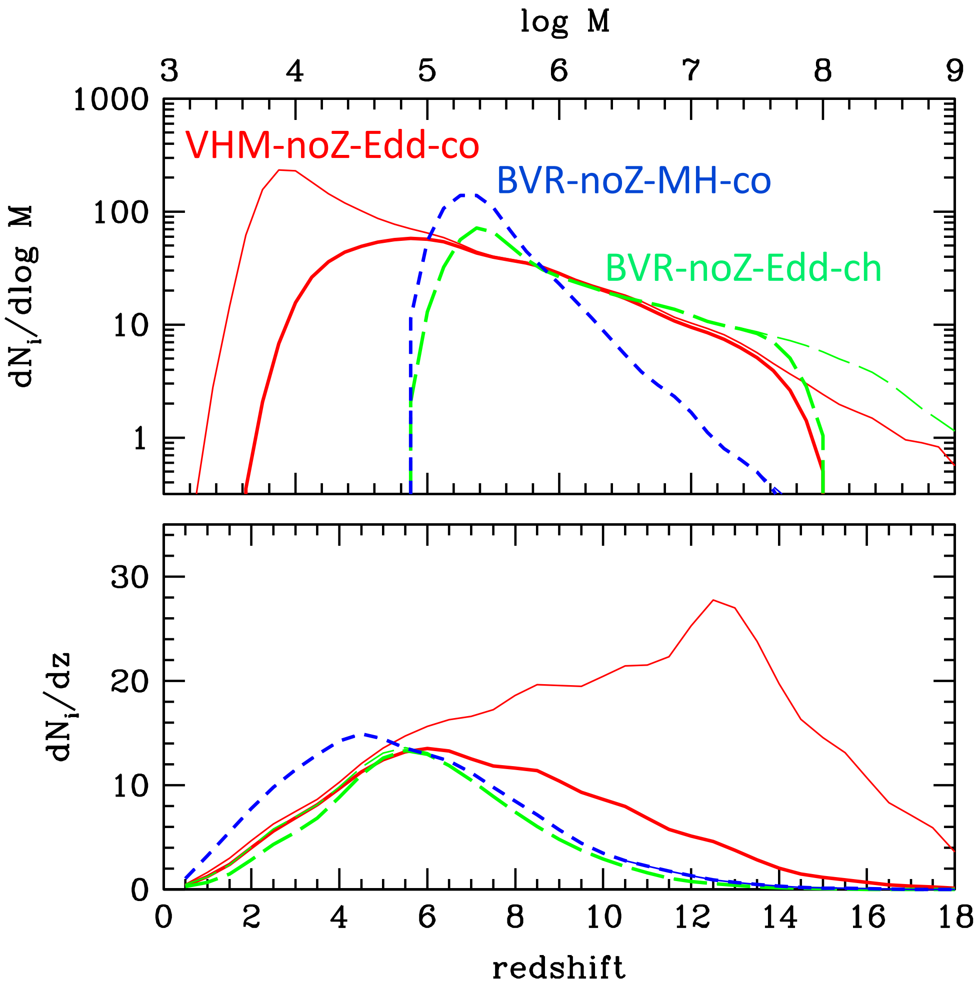
[Figure courtesy of Neil Cornish]

LISA sources: “the whole enchilada”



Massive black holes

Can we tell apart models with different growth/merger physics?



Models chosen to have different

- **Seeds:**
  light or heavy?
- **Metallicity Z:**
  efficiency of gas inflow
- **Accretion efficiency:**
  Eddington vs. Merloni-Heinz
- **Accretion geometry:**
  coherent vs. chaotic

[Sesana+, 1011.5893]

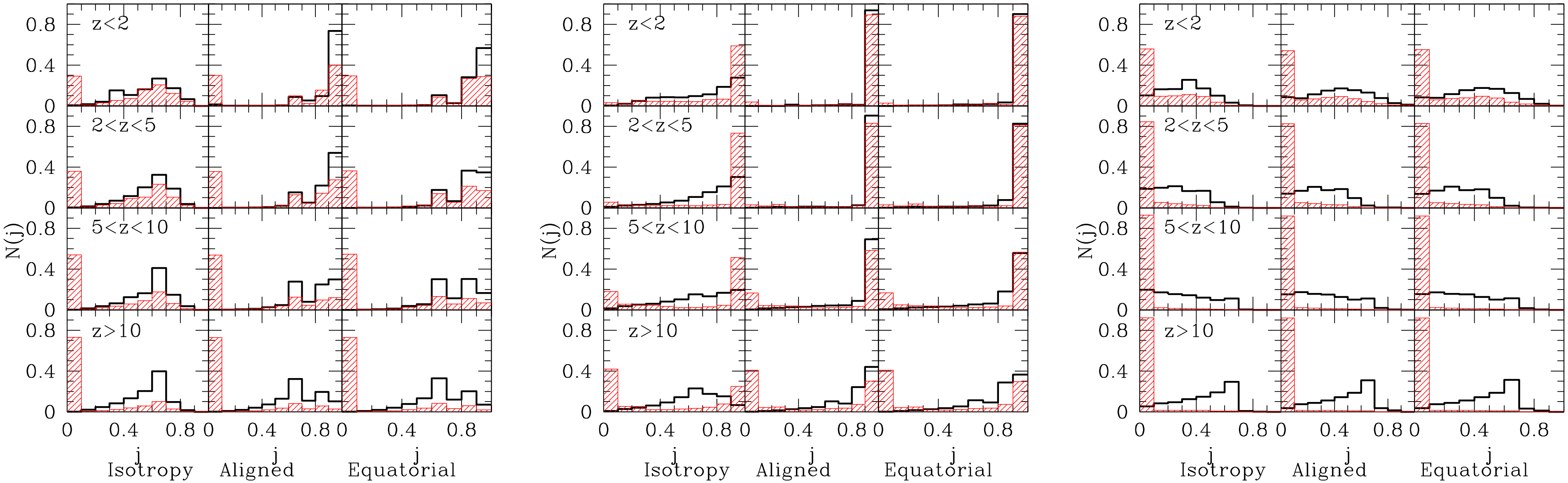
Black hole spins encode growth history

Growth by:

Mergers only: spin ~0.7

Mergers+coherent accretion: spin close to one

Mergers+chaotic accretion: spin close to zero

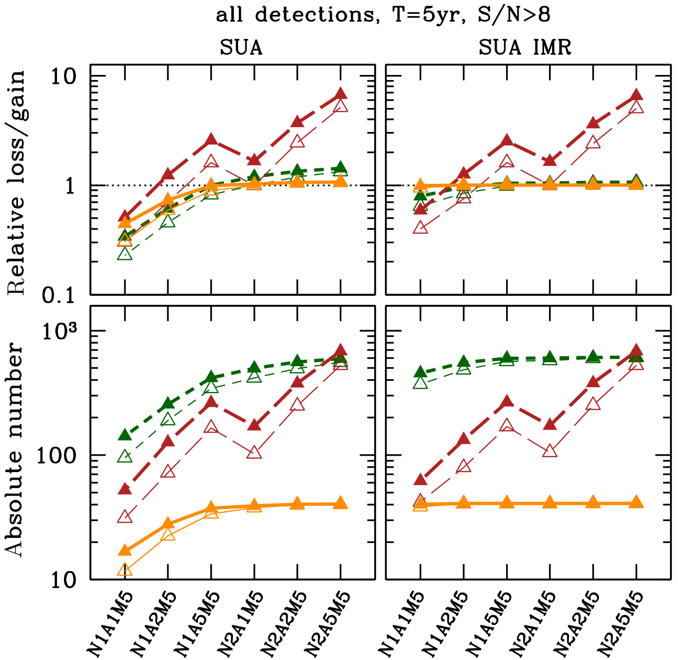


[EB+Volonteri, 0802.0025; Sesana+, 1402.7088]

How many binaries can we detect? Can we measure parameters/localize?

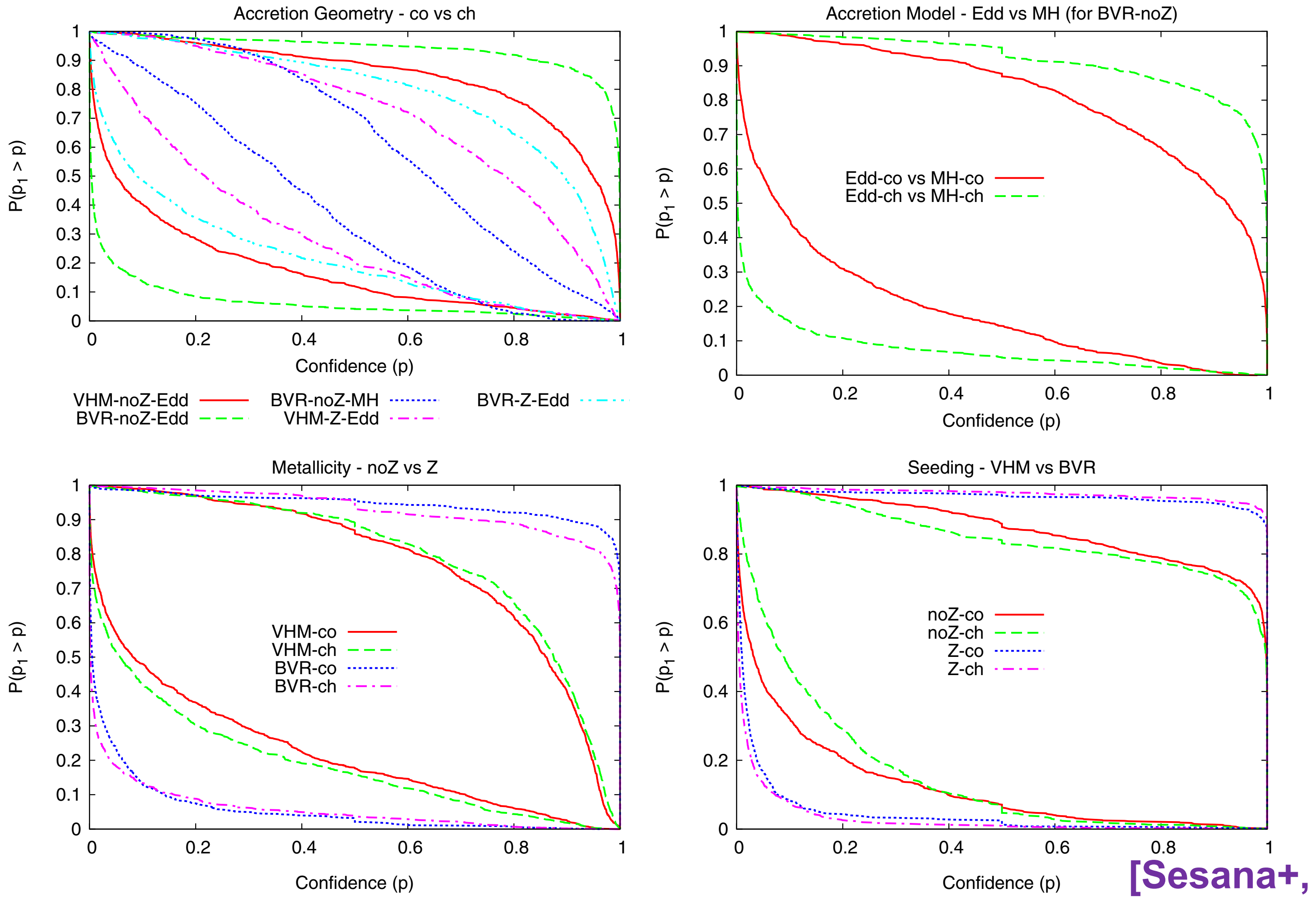
Configuration ID	$\Delta m_{1z,2z}/m_{1z,2z}<0.01$ popIII	Q3-nod	Q3-d	$\Delta\chi_1 < 0.01$ popIII	Q3-nod	Q3-d	$\Delta\chi_2 < 0.1$ popIII	Q3-nod	Q3-d	$\Delta\theta_{\chi_{1,2}} < 10$ deg popIII	Q3-nod	Q3-d	$\Delta\chi_r < 0.1$ popIII	Q3-nod	Q3-d
N2A5M2L6	146.6	141.8	13.3	45.3	76.8	2.6	41.8	44.7	3.9	21.0	40.9	9.4	3.5	31.4	10.9
N2A5M2L4	94.6	108.5	11.3	32.4	60.5	2.1	21.2	27.2	2.5	11.5	19.1	4.8	3.0	18.5	10.7
N2A2M2L6	71.4	99.6	10.9	28.3	54.4	2.0	17.1	22.2	2.1	11.7	18.9	5.1	3.3	27.0	10.5
N2A2M2L4	40.7	69.1	8.4	19.6	40.8	1.5	8.2	11.1	1.1	6.0	7.7	2.3	2.9	17.0	10.2
N2A1M2L6	30.4	66.4	8.5	18.7	39.3	1.5	7.4	10.8	1.0	6.1	9.2	2.9	3.1	21.3	9.5
N2A1M2L4	15.3	41.2	6.3	13.4	27.6	1.0	3.8	4.9	0.6	3.1	3.0	1.0	2.9	12.3	9.3
N1A5M2L6	40.7	49.3	7.0	20.5	29.8	0.9	7.3	8.0	0.6	5.7	6.8	1.9	3.0	22.1	10.5
N1A5M2L4	18.7	29.8	4.7	14.6	20.3	0.6	3.6	3.7	0.4	2.5	2.2	0.6	2.7	16.5	10.3
N1A2M2L6	11.6	20.4	3.2	12.6	12.6	0.2	2.2	2.4	0.2	1.8	2.2	0.6	2.7	15.0	9.2
N1A2M2L4	4.4	10.1	2.3	7.5	8.2	0.1	1.1	1.0	0.1	0.8	0.6	0.2	2.6	12.1	9.2
N1A1M2L6	3.3	8.7	2.4	4.8	5.7	0.1	0.6	0.6	0.1	0.7	0.6	0.2	2.2	9.1	6.6
N1A1M2L4	1.6	3.8	1.0	2.4	3.3	0.0	0.3	0.4	0.1	0.3	0.2	0.1	2.1	7.8	6.4

Configuration ID	$\Delta\Omega < 10\,\mathrm{deg}^2$ & $\Delta D_l/D_l < 0.1$ & $z < 5$ SUA popIII	SUA Q3-nod	SUA Q3-d	SUA IMR popIII	SUA IMR Q3-nod	SUA IMR Q3-d	$z > 7$ & $\Delta D_l/D_l < 0.3$ SUA popIII	SUA Q3-nod	SUA Q3-d	SUA IMR popIII	SUA IMR Q3-nod	SUA IMR Q3-d
N2A5M2L6	14.5	34.8	6.0	16.1	47.4	10.1	71.6	117.2	1.2	71.6	141.1	1.4
N2A5M2L4	3.2	8.7	1.1	4.8	16.0	4.9	10.2	54.4	0.6	30.4	96.8	1.0
N2A2M2L6	6.8	23.2	3.8	9.2	35.2	9.5	20.8	82.6	0.9	20.8	134.4	1.4
N2A2M2L4	1.6	4.2	0.4	2.6	5.8	1.6	2.8	18.0	0.2	10.1	54.0	0.7
N2A1M2L6	3.4	14.9	2.5	5.7	26.4	7.8	3.9	50.9	0.6	3.9	120.1	1.3
N2A1M2L4	0.6	1.7	0.1	1.0	2.6	0.5	0.5	0.8	0.0	2.6	41.8	0.2
N1A5M2L6	4.0	13.7	1.9	7.0	27.3	7.5	9.8	30.5	0.4	9.9	111.9	1.2
N1A5M2L4	0.7	1.6	0.0	1.2	2.6	0.2	1.3	2.2	0.0	5.2	9.0	0.2
N1A2M2L6	1.9	5.1	0.8	4.4	18.0	5.5	2.3	6.6	0.2	2.4	77.7	1.0
N1A2M2L4	0.4	0.5	0.0	0.6	1.0	0.1	0.2	0.4	0.0	1.0	2.0	0.0
N1A1M2L6	0.7	1.5	0.2	2.7	9.8	3.9	0.2	0.1	0.0	0.5	0.4	0.6
N1A1M2L4	0.2	0.2	0.0	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0



[Klein+, 1511.05581]

Can we tell models apart?



[Sesana+, 1011.5893]

Extreme mass ratio binaries

EMRIs: rates, GR tests, new physics?

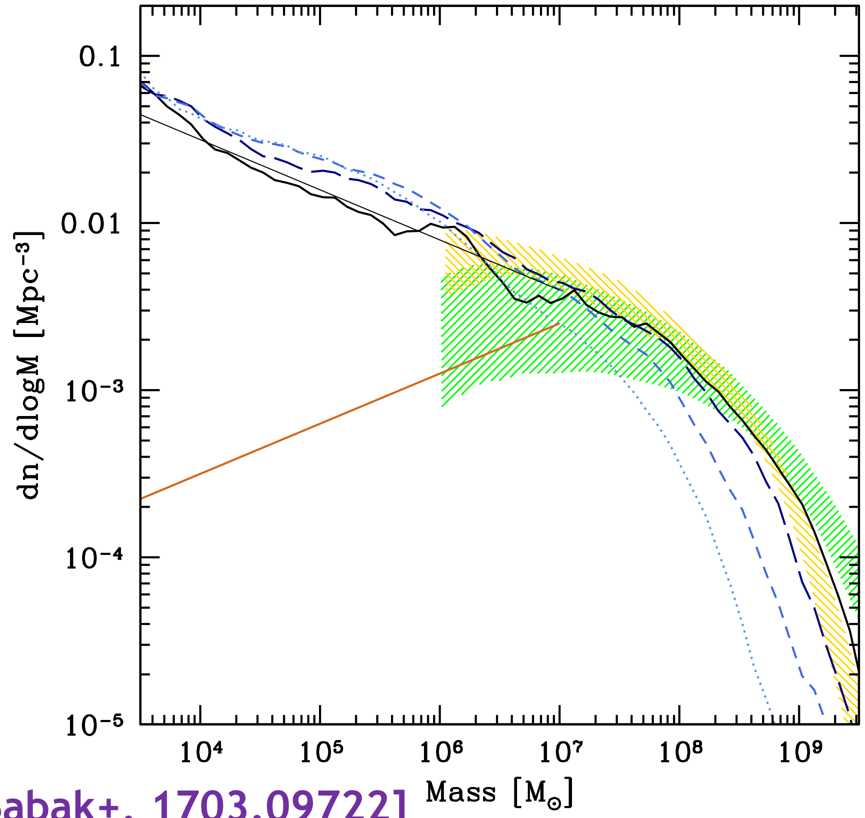
Model	Mass function	MBH spin	Cusp erosion	M–σ relation	N_p	CO mass $[M_\odot]$	EMRI rate $[\mathrm{yr}^{-1}]$ Total	Detected (AKK)	Detected (AKS)
M1	Barausse12	a98	yes	Gultekin09	10	10	1600	294	189
M2	Barausse12	a98	yes	KormendyHo13	10	10	1400	220	146
M3	Barausse12	a98	yes	GrahamScott13	10	10	2770	809	440
M4	Barausse12	a98	yes	Gultekin09	10	30	520 (620)	260	221
M5	Gair10	a98	no	Gultekin09	10	10	140	47	15
M6	Barausse12	a98	no	Gultekin09	10	10	2080	479	261
M7	Barausse12	a98	yes	Gultekin09	0	10	15800	2712	1765
M8	Barausse12	a98	yes	Gultekin09	100	10	180	35	24
M9	Barausse12	aflat	yes	Gultekin09	10	10	1530	217	177
M10	Barausse12	a0	yes	Gultekin09	10	10	1520	188	188
M11	Gair10	a0	no	Gultekin09	100	10	13	1	1
M12	Barausse12	a98	no	Gultekin09	0	10	20000	4219	2279

- **Rates very uncertain (1-10^4/yr): depend on Low-mass MBH mass function, spin, cusp erosion post-merger, M-σ, ratio of direct plunges to EMRIs, waveform model**
- **Tests of GR: Kerr BH quadrupole within $\Delta Q \sim 10^{-4}$**
- **New physics: Dark matter, scalar clouds (e.g. axions) modify dynamics**
- **New astrophysics: Multiband EMRIs, standard candles**

[Babak+, 1703.09722]

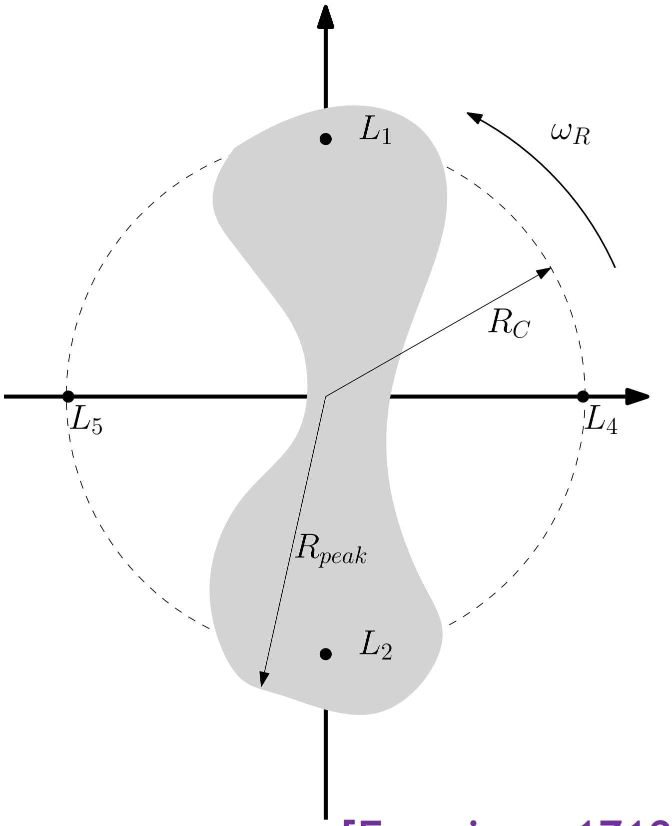
Astrophysics / physics payoff

Reveal MBH mass function at low masses?



[Babak+, 1703.09722]

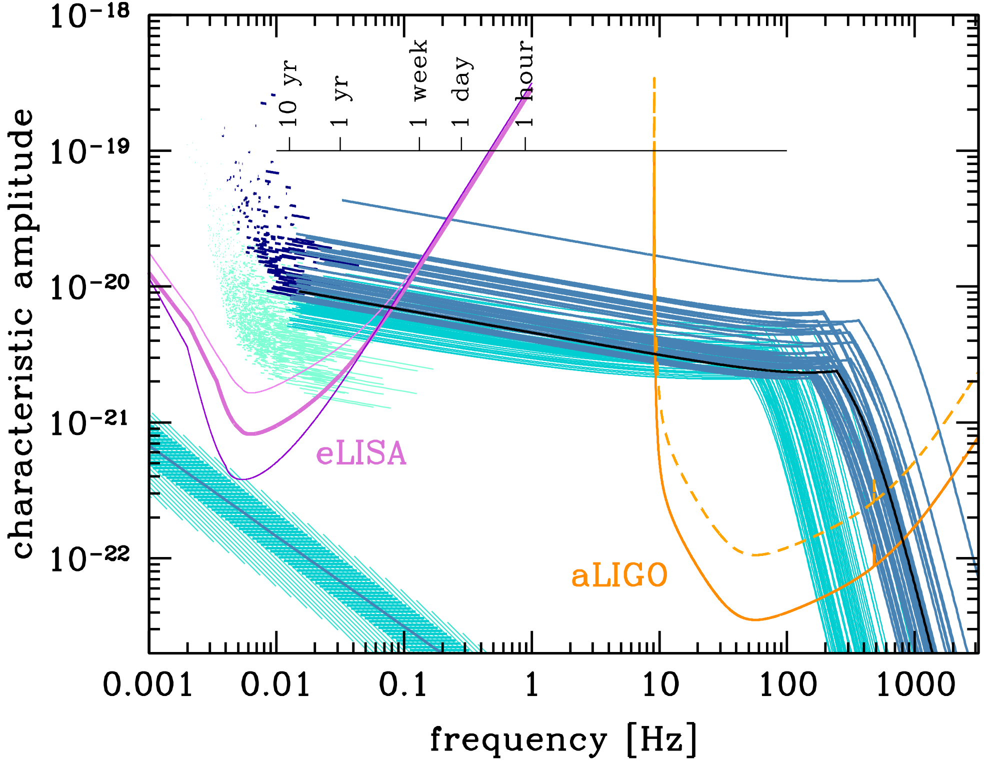
Detect boson clouds / dark matter?

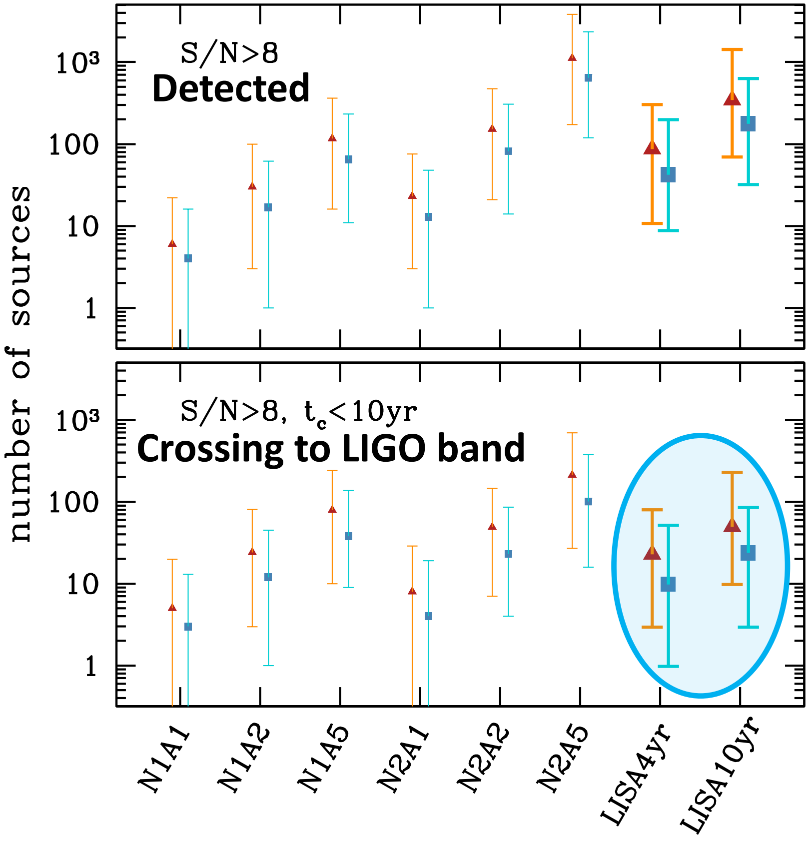


[Ferreira+, 1710.00830]

Multiband black hole binaries

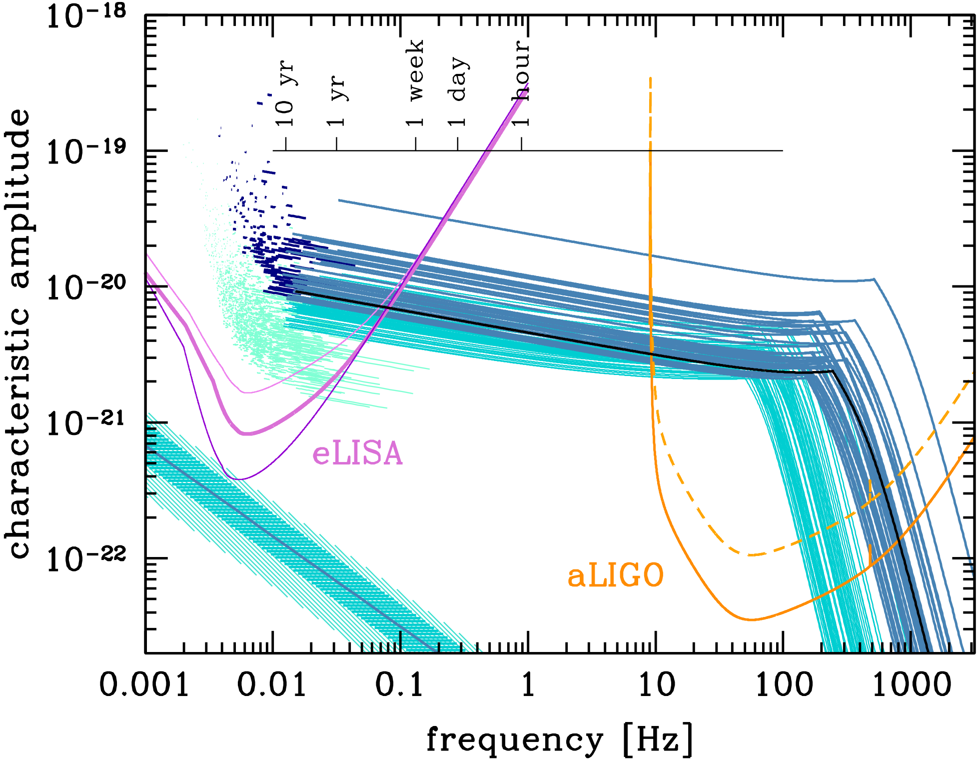
Complementarity! Multi-band





[Sesana,1602.06951; 1702.04356]

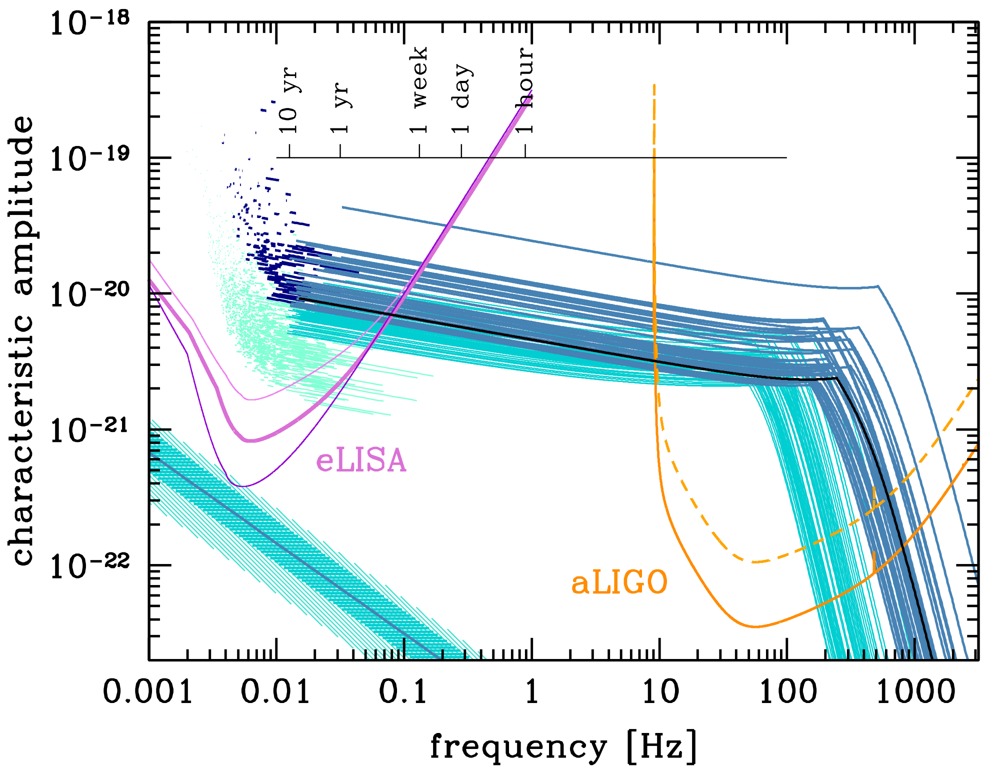
Complementarity! Multi-band



[Sesana,1602.06951]

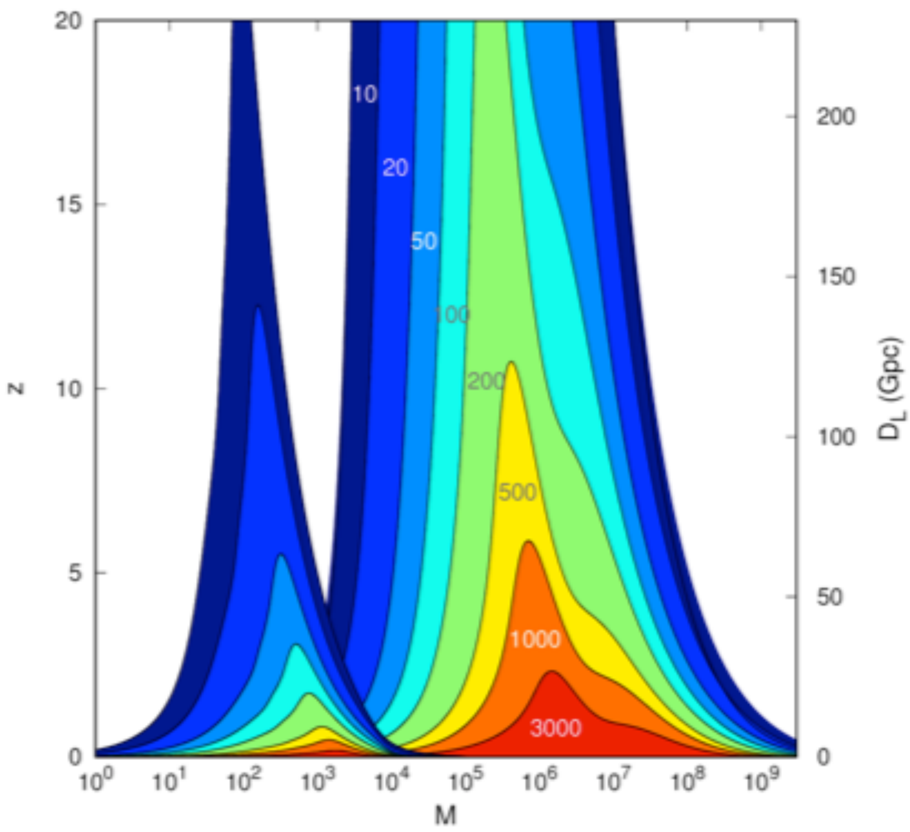
- **LISA early warning (Δt_{merger}~1s) and localization ($\Delta\Omega$~0.1-1deg^2) for LIGO/EM observations**
- **LISA can measure eccentricity: Clusters? [Rodriguez+] Triples? [Antonini+] Primordial BHs? [Cholis, Kovetz+]**
- **LISA improvements on LIGO PE [Vitale 1605.01037]**
- **New population of standard sirens [Del Pozzo+ 1703.01300]**
- **Better tests of GR [Yunes' talk]**

Complementarity! Multi-band



[Sesana,1602.06951]

2030s: 3G (e.g., ET) vs. LISA



[Figure courtesy of Neil Cornish]

Complementarity! Multi-band 2030s: 3G (e.g., ET) vs. LISA

- **Limited improvements on 3G PE**
  GW150914:
  SNR~700 (2000) in Voyager (Cosmic Explorer)

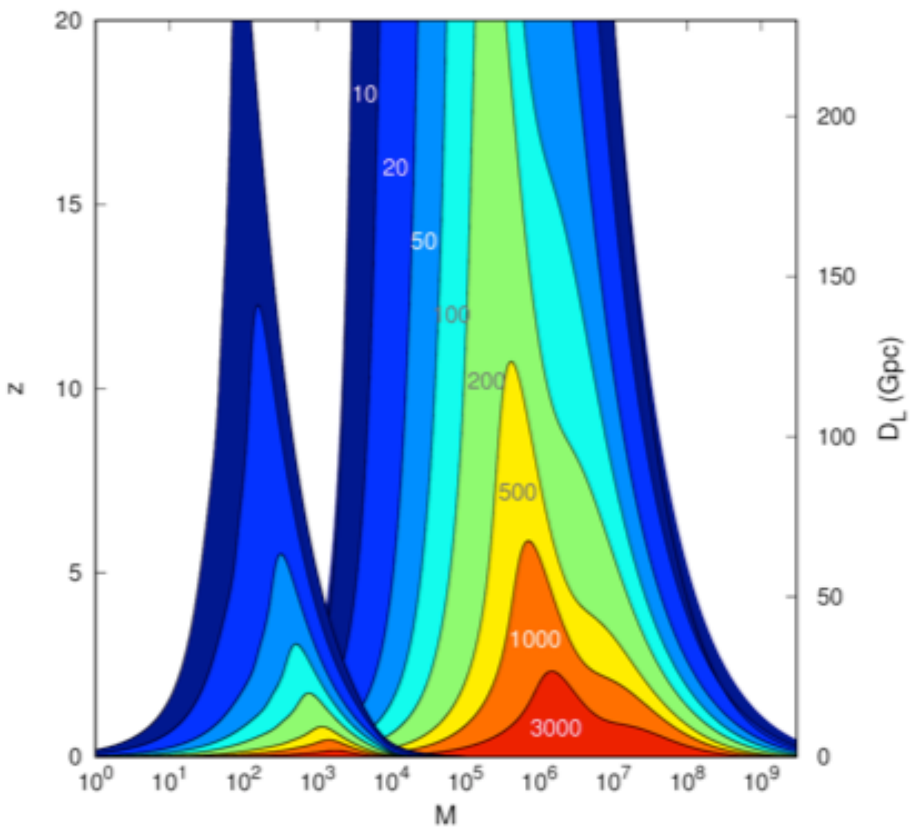
- **LISA breaks degeneracies:**
  (χ_1, χ_2) from LISA, χ_{eff} and χ_f from LIGO
  M_{chirp} from LISA, M from LIGO

- **IMBHs?**

- **Post-process LISA data after 3G detection: boost LISA multiband event rates**

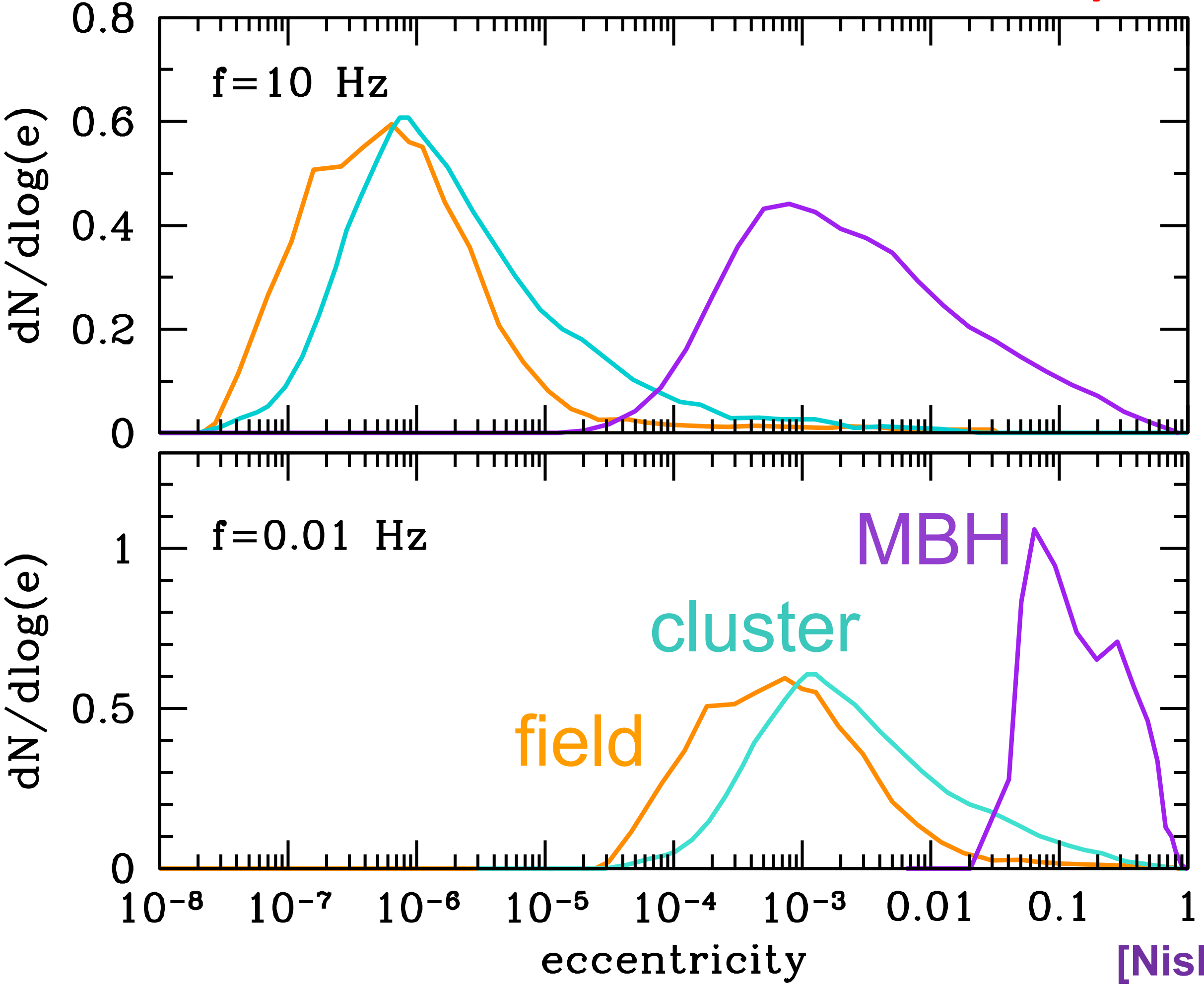
- **Use 3G detections to remove foreground and go after stochastic backgrounds**

- **Use LISA for 3G phase/amplitude calibration**



[Figure courtesy of Neil Cornish]

Field or cluster formation? Kozai or primordial black holes?



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

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

Measurable
if $e_0 > 10^{-3}$ at $f = 10^{-2}$Hz

[Nishizawa+, 1605.01341; 1606.09295]

Field or cluster formation? Kozai or primordial black holes?

eLISA base	N_{obs}	3σ		5σ	
		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).

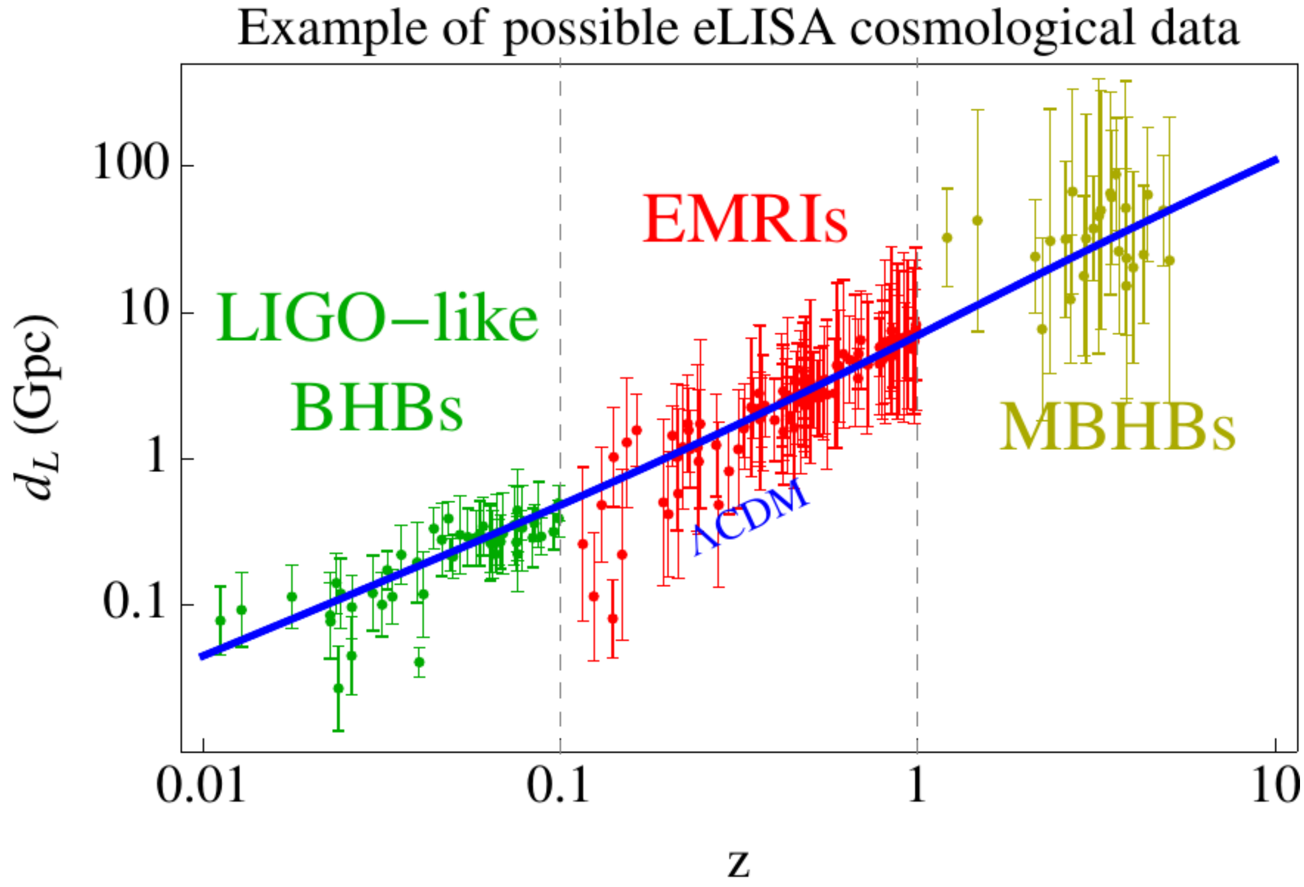
Predictions may be **pessimistic!**

Correlations between e and masses/spins/kicks will help

Can ask the same question for **MBH vs. primordial** scenarios

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

Independent assessment of geometry of the Universe at all z



[Tamanini+, in preparation]

PHYSICAL REVIEW D **83,** 044036 (2011)

Reconstructing the massive black hole cosmic history through gravitational waves

Alberto Sesana,[1,*] Jonathan Gair,[2,†] Emanuele Berti,[3,4,‡] and Marta Volonteri[5,§]

PHYSICAL REVIEW D **93,** 024003 (2016)

Science with the space-based interferometer eLISA: Supermassive black hole binaries

Antoine Klein,[1] Enrico Barausse,[2,3] Alberto Sesana,[4] Antoine Petiteau,[5] Emanuele Berti,[1,6] Stanislav Babak,[7] Jonathan Gair,[8,9] Sofiane Aoudia,[10] Ian Hinder,[7] Frank Ohme,[11] and Barry Wardell[12,13]

PHYSICAL REVIEW D **94,** 064020 (2016)

eLISA eccentricity measurements as tracers of binary black hole formation

Atsushi Nishizawa,[1,*] Emanuele Berti,[1,2,†] Antoine Klein,[1,2,‡] and Alberto Sesana[3,§]

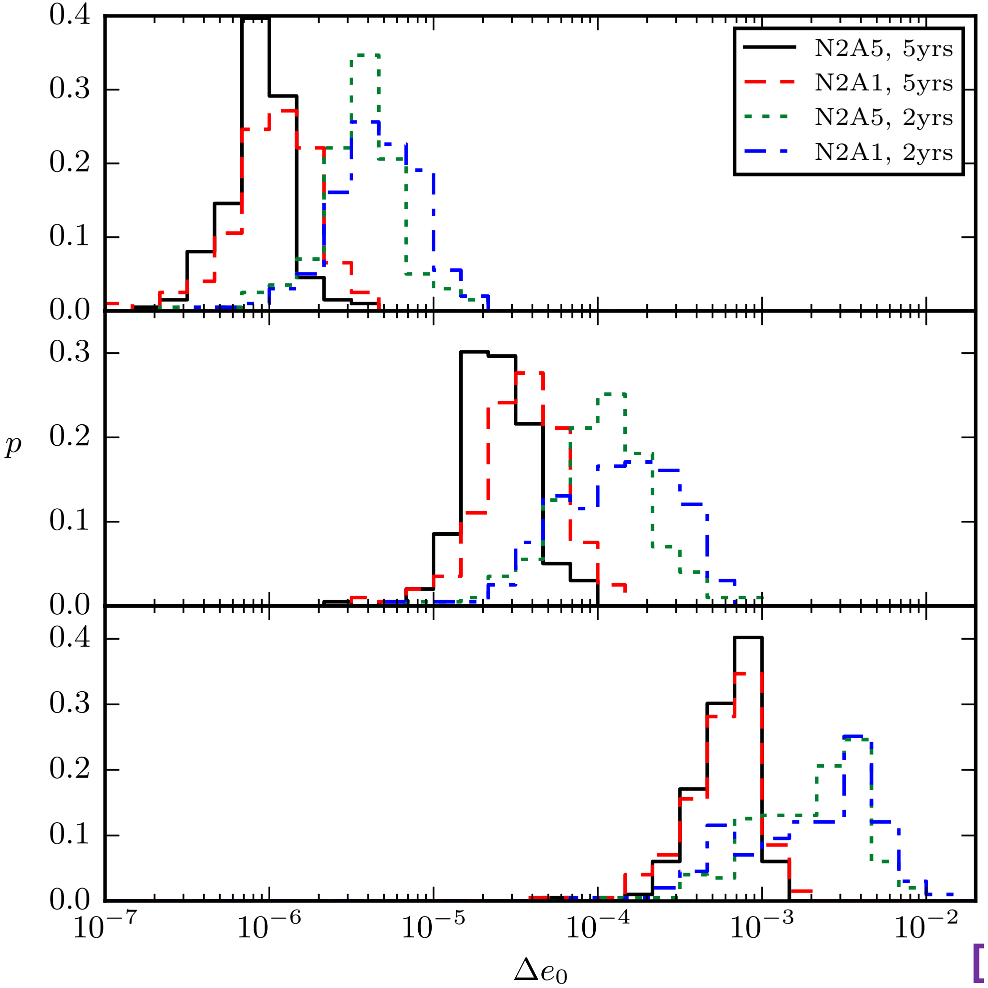
PHYSICAL REVIEW D **95,** 103012 (2017)

Science with the space-based interferometer LISA. V. Extreme mass-ratio inspirals

Stanislav Babak,[1] Jonathan Gair,[2] Alberto Sesana,[3] Enrico Barausse,[4] Carlos F. Sopuerta,[5] Christopher P. L. Berry,[3] Emanuele Berti,[6,7] Pau Amaro-Seoane,[5,8] Antoine Petiteau,[9] and Antoine Klein[4]

Extra slides

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



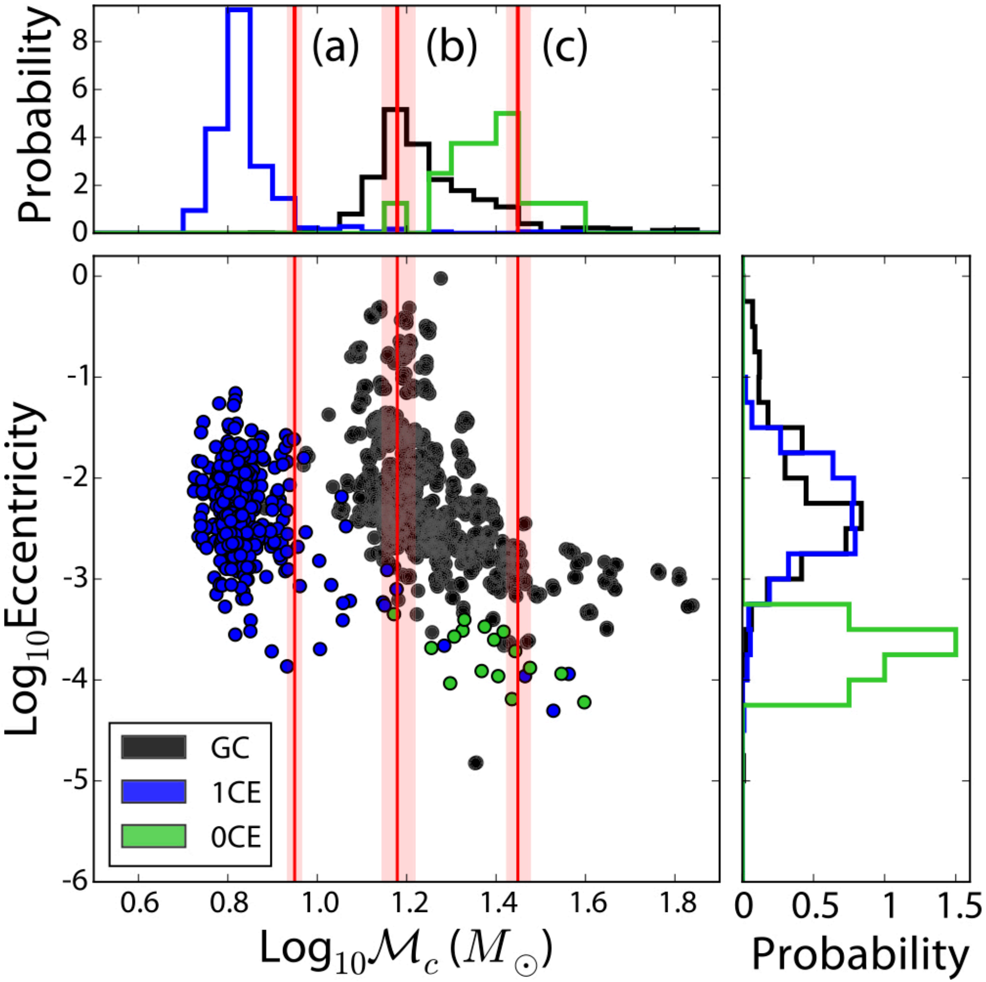
e_0=0.1

e_0=0.01

e_0=0.001

[Nishizawa+,1606.09295]

Correlations

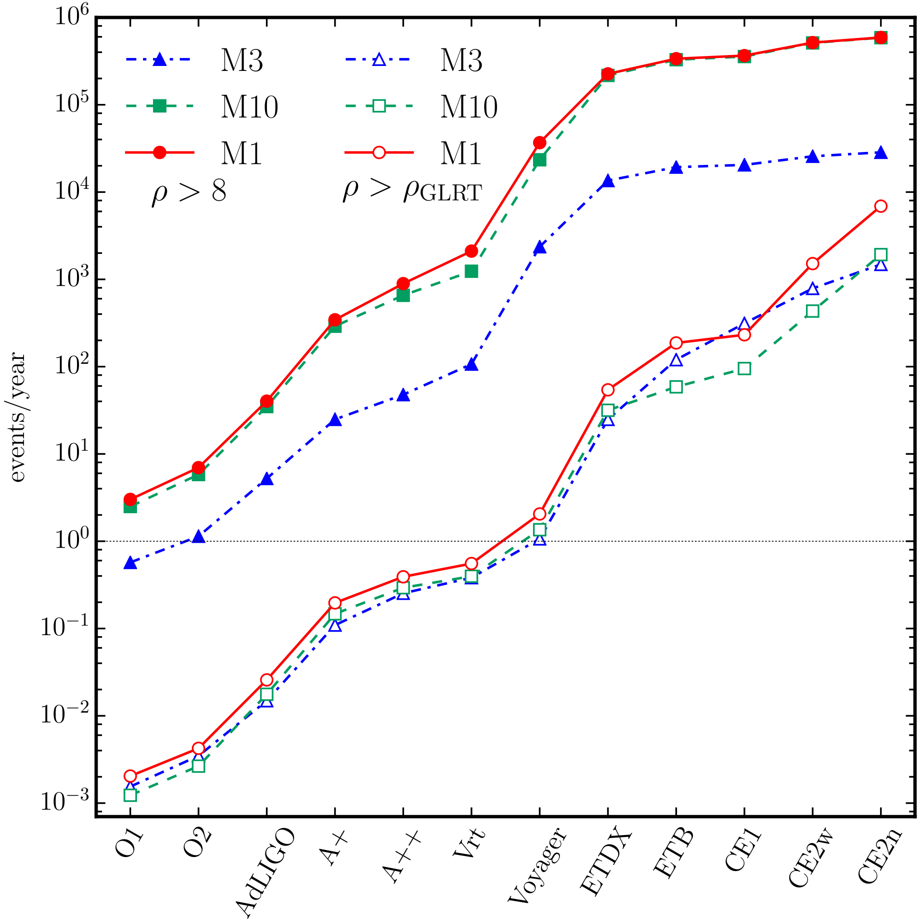


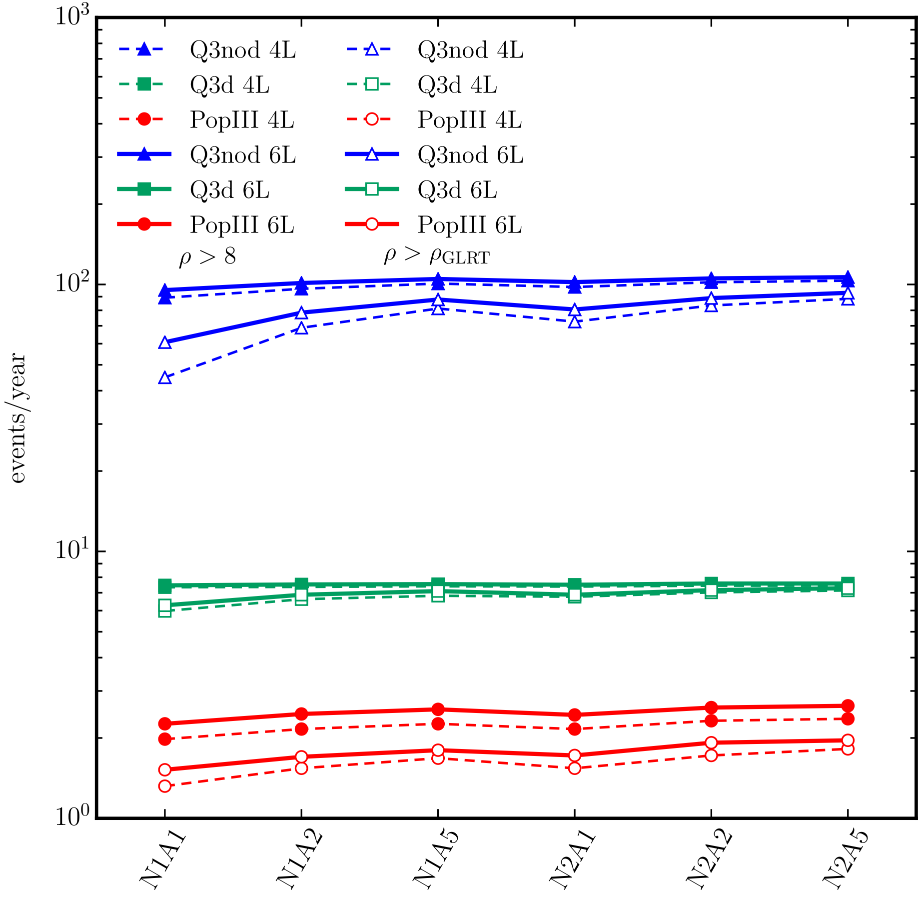
Green/Blue:
In isolation

Black:
Dense stellar environments

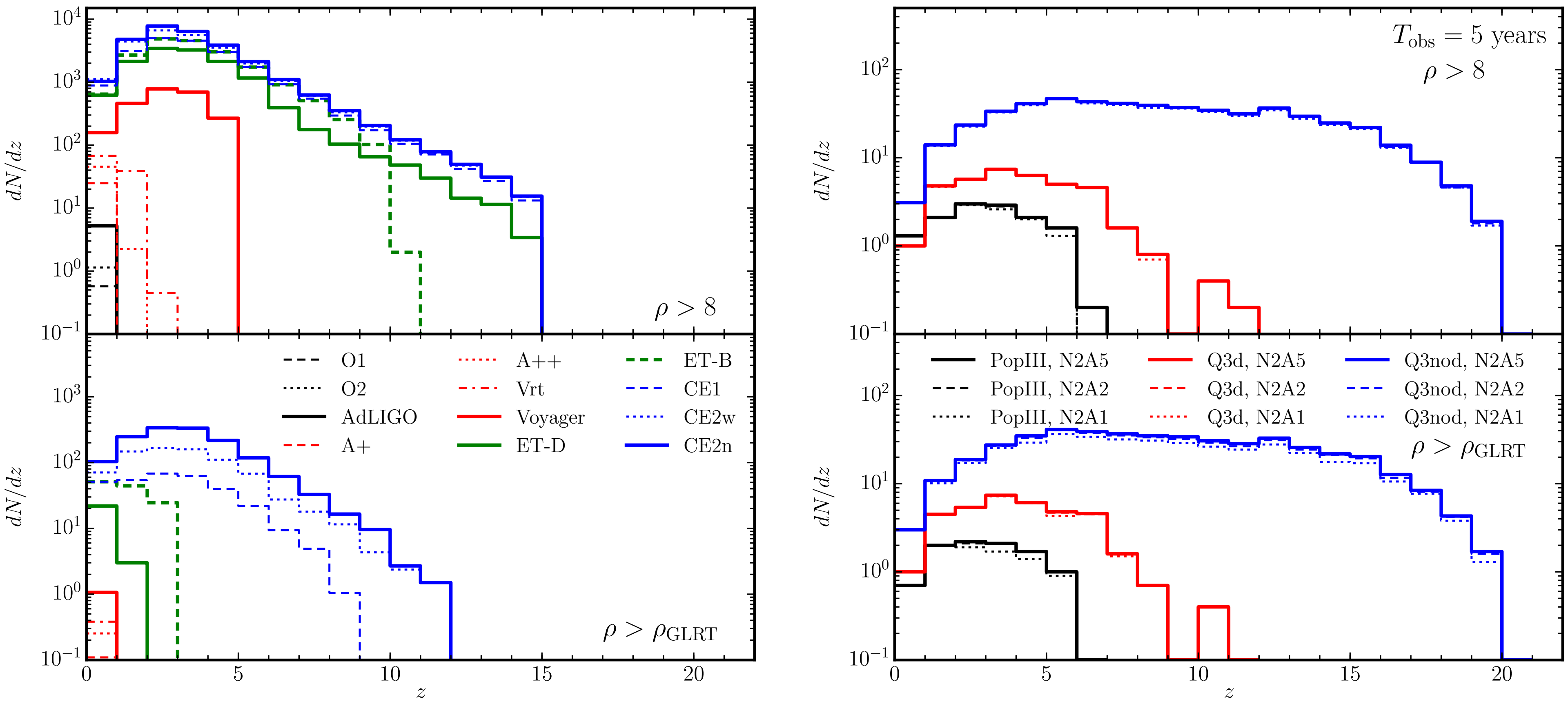
[Breivik+, 1606.09558]

Earth vs. space-based: ringdown detections and black hole spectroscopy

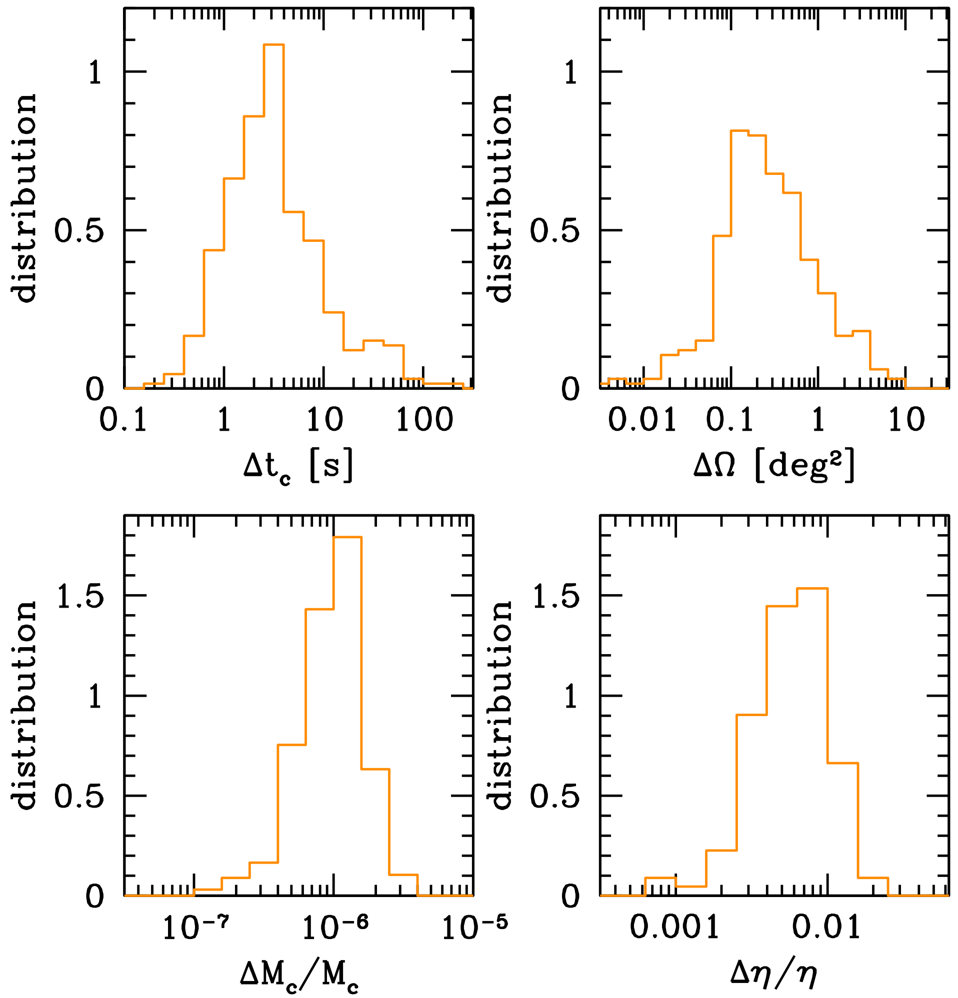




Earth vs. space-based: redshift distribution

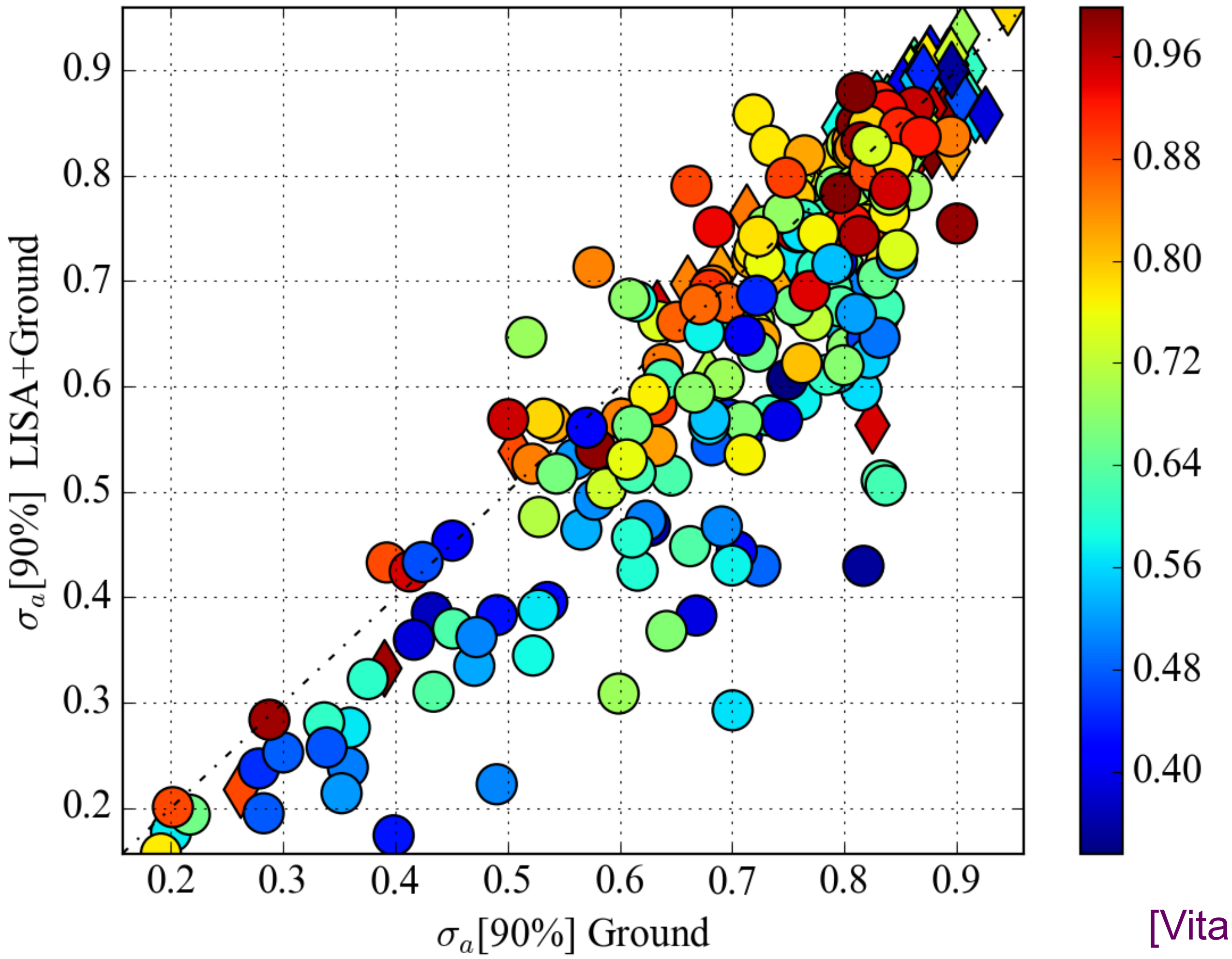


Time of arrival: seconds, localization: <1 deg^2



[Sesana,1602.06951]

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



[Vitale,1605.01037]