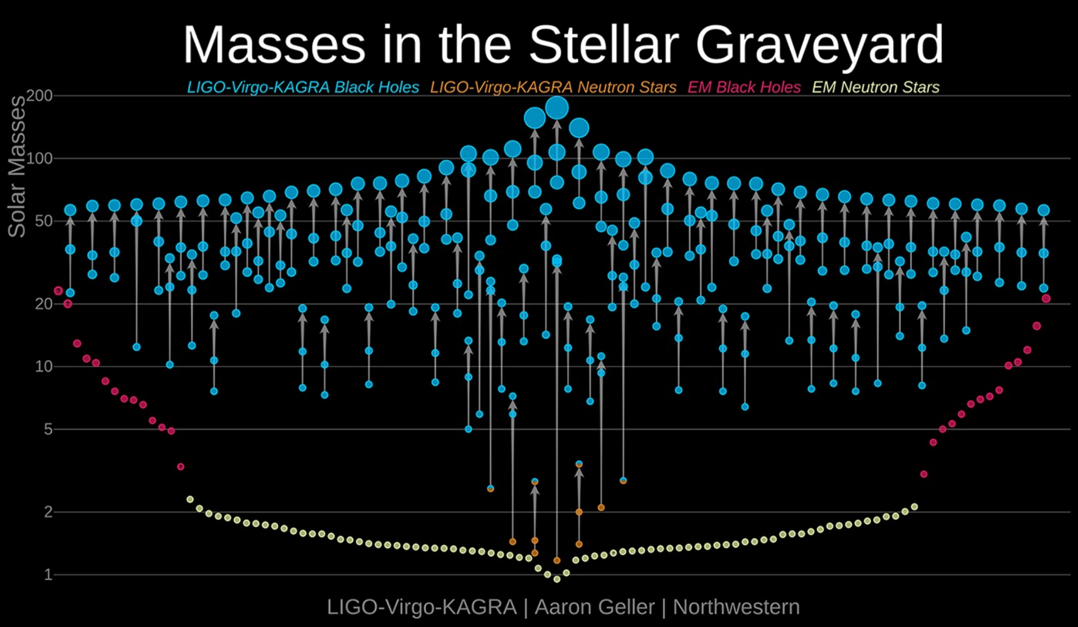
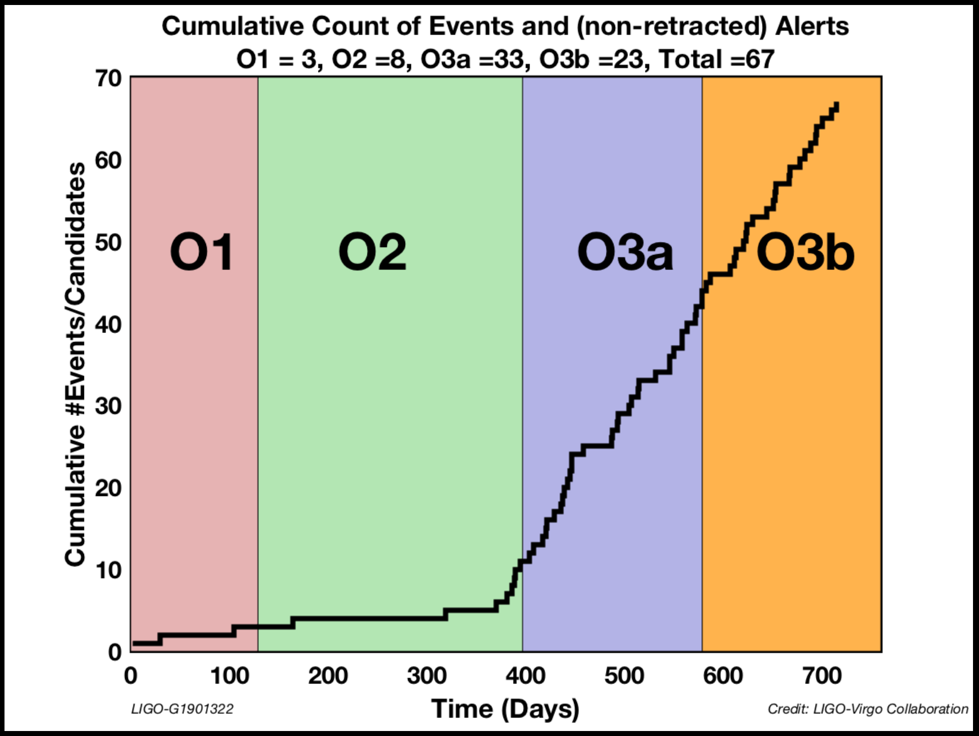
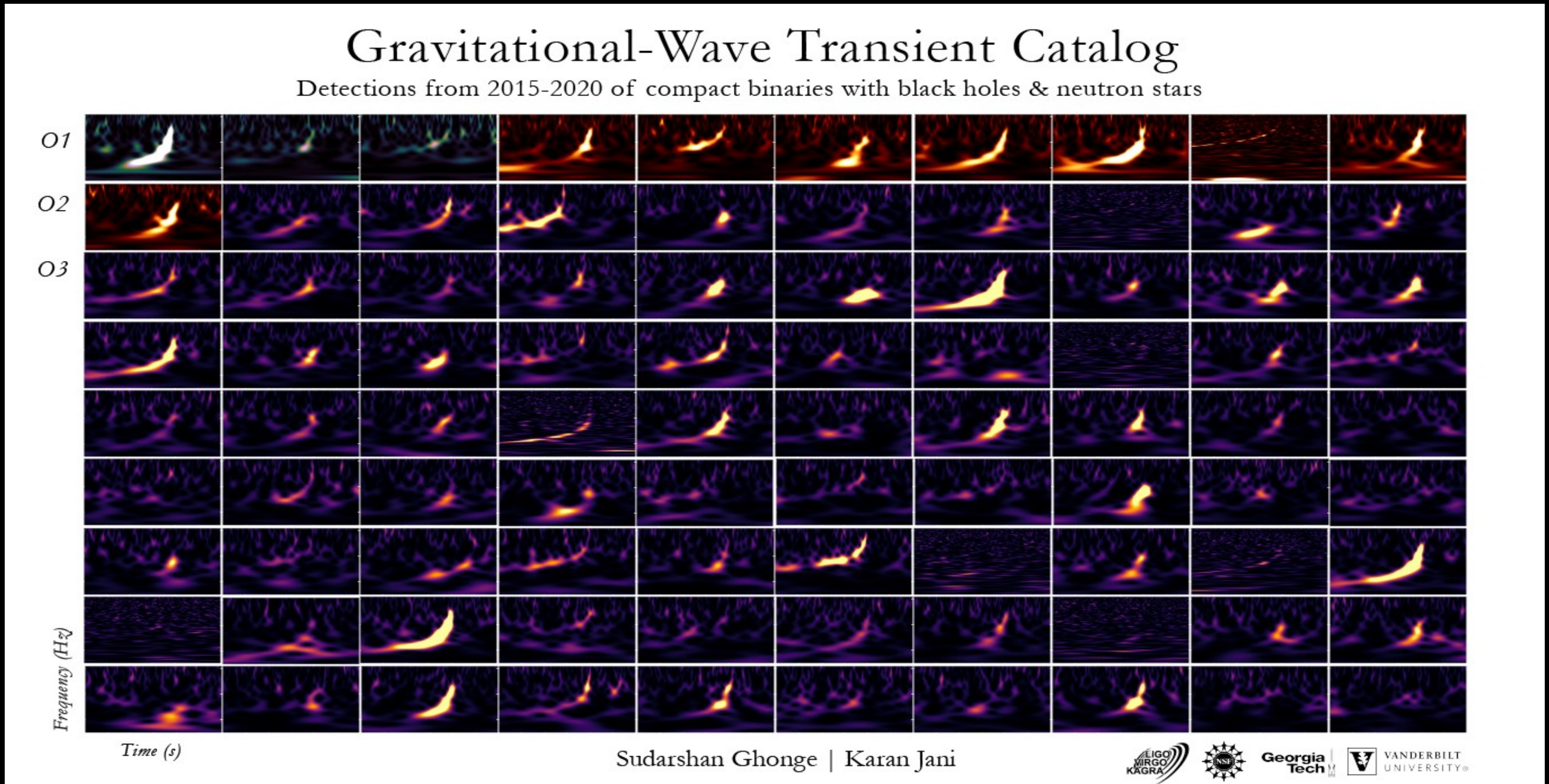
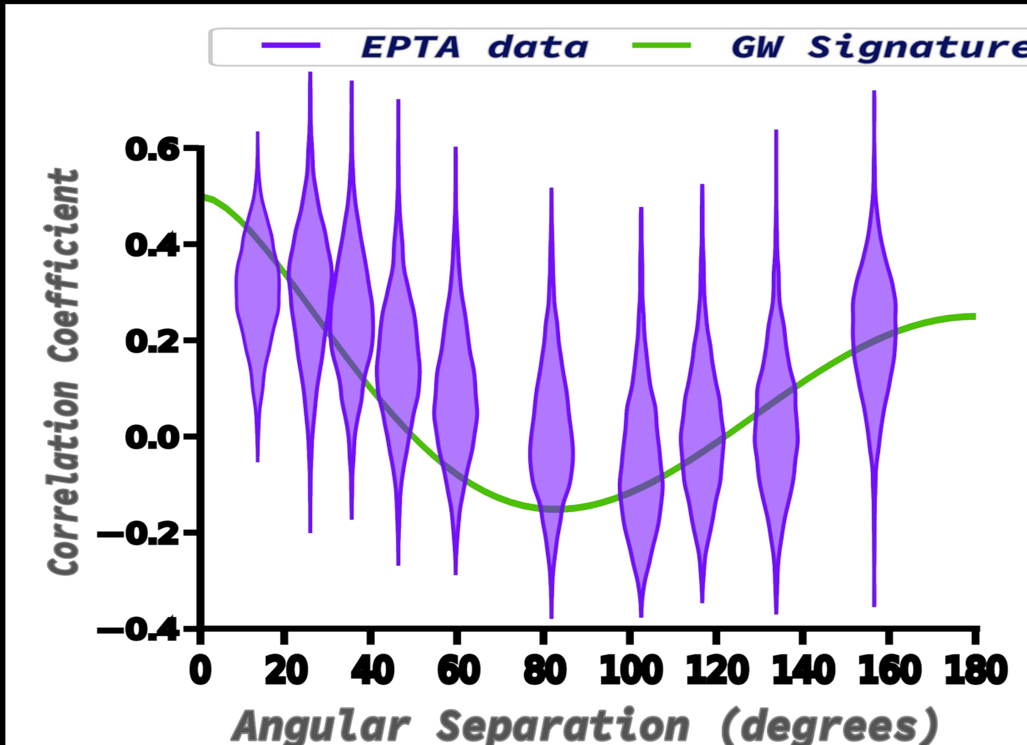
LISA and its sources in the gravitational wave landscape

Alberto Sesana
(Universita` di Milano Bicocca)


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

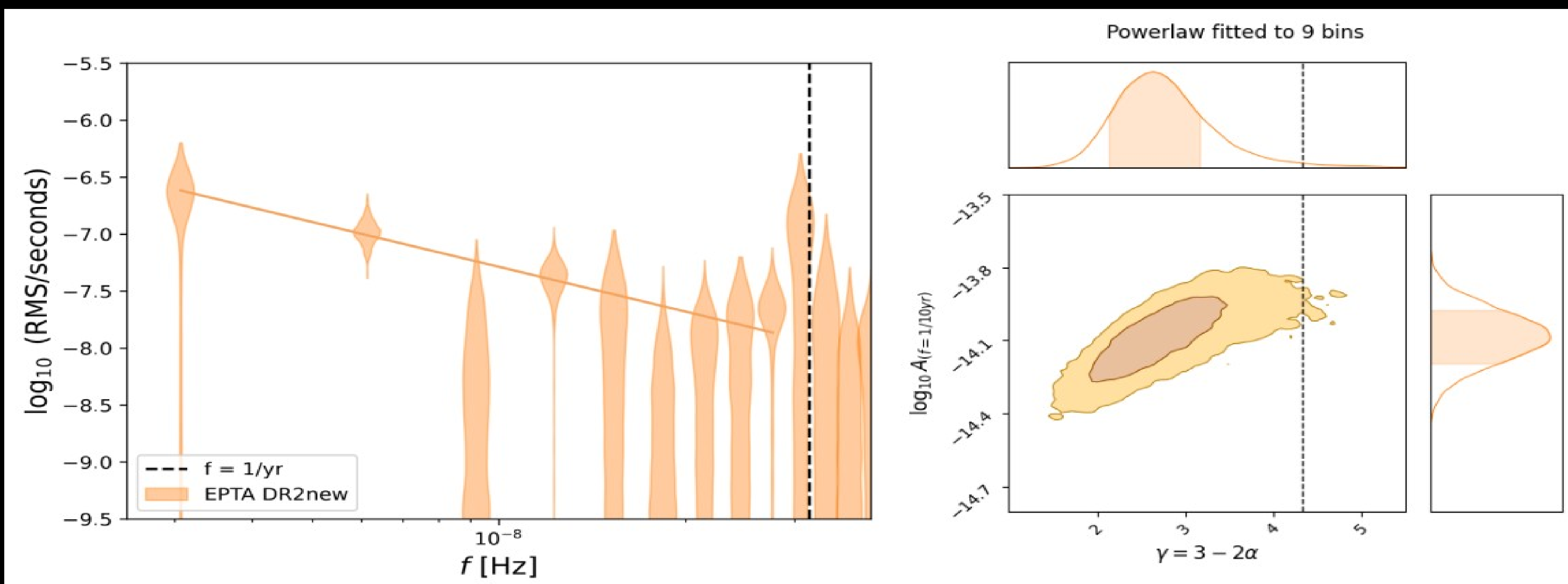

Cumulative Count of Events and (non-retracted) Alerts
O1 = 3, O2 =8, O3a =33, O3b =23, Total =67
O1
O2
O3a
O3b
Cumulative #Events/Candidates
0
10
20
30
40
50
60
70
0
100
200
300
400
500
600
700
Time (Days)
LIGO-G1901322
Credit: LIGO-Virgo Collaboration


Gravitational-Wave Transient Catalog
Detections from 2015-2020 of compact binaries with black holes & neutron stars
O1
O2
O3
Frequency (Hz)
Time (s)
Sudarshan Ghonge | Karan Jani
Georgia Tech
VANDERBILT UNIVERSITY

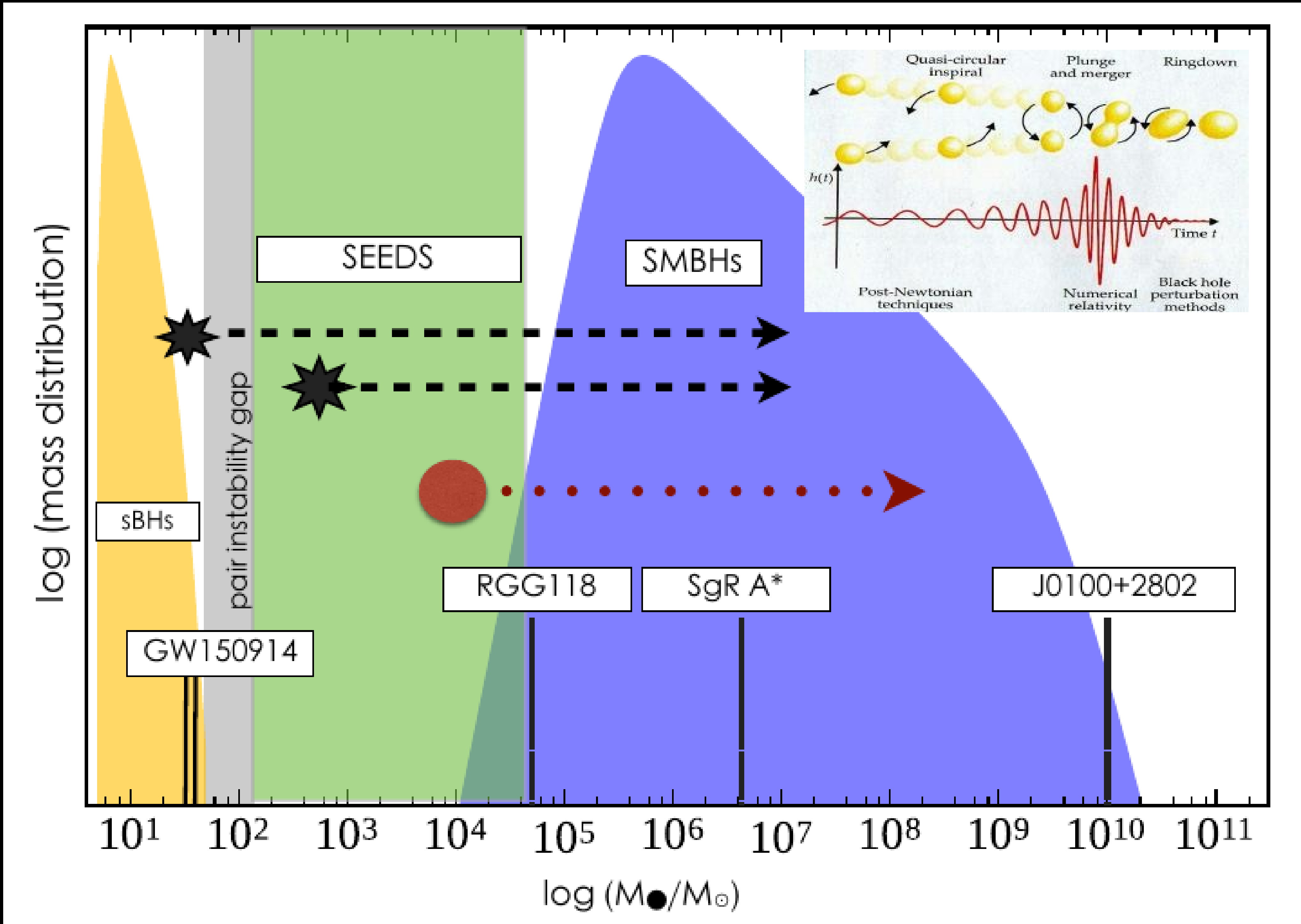


(Antoniadis+23, Agazie+23, Reardon+23, Xu+23)

ID	Model	DR2full ENTERPRISE	DR2full FORTYTWO	DR2full+ ENTERPRISE	DR2new ENTERPRISE	DR2new FORTYTWO	DR2new+ ENTERPRISE
1	PSRN + CURN	–	–	–	–	–	–
2	PSRN + GWB	4	5	4	60	62	65
3	PSRN + CLK	< 0.01	< 0.01	< 0.01	0.2	1.2	0.3
4	PSRN + EPH	< 0.01	$\sim 10^{-4}$	< 0.01	0.2	0.2	1.3
5	PSRN + CURN + CLK	2	1	2.7	0.8	2	1.6
6	PSRN + CURN + EPH	1	0.1	1	1	1	1.6
7	PSRN + GWB + CURN	3	3	4	27	13	25
8	PSRN + GWB + CLK	5	12	7	28	35	57
9	PSRN + GWB + EPH	3	3	3.6	33	29	43



Similar results as NANOgrav, PPTA, CPTA



SEEDS
SMBHs
pair instability gap
sBHs
GW150914
RGG118
SgR A*
J0100+2802
Quasi-circular inspiral
Plunge and merger
Ringdown
h(t)
Time t
Post-Newtonian techniques
Numerical relativity
Black hole perturbation methods
log (mass distribution)
10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹
log (M●/M☉)

Heuristic scalings

We want compact accelerating systems
Consider a BH binary of mass M, and semimajor axis a

$$h \sim \frac{R_S}{a}\frac{R_S}{r} \sim \frac{(GM)^{5/3}(\pi f)^{2/3}}{c^4 r}$$

In astrophysical scales

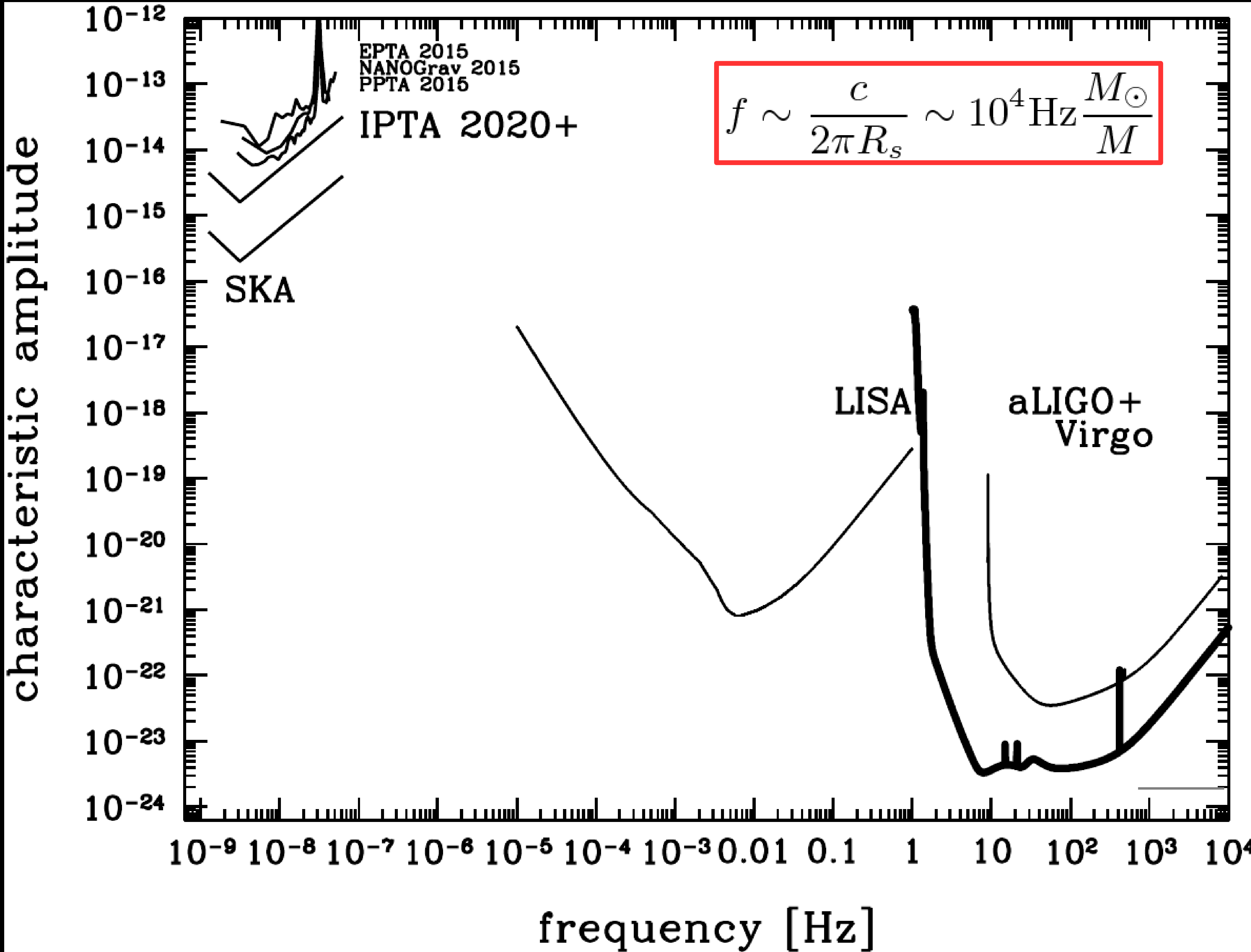
$$h \sim 10^{-20}\frac{M}{M_\odot}\frac{\mathrm{Mpc}}{D}$$

$$f \sim \frac{c}{2\pi R_s} \sim 10^4\,\mathrm{Hz}\frac{M_\odot}{M}$$

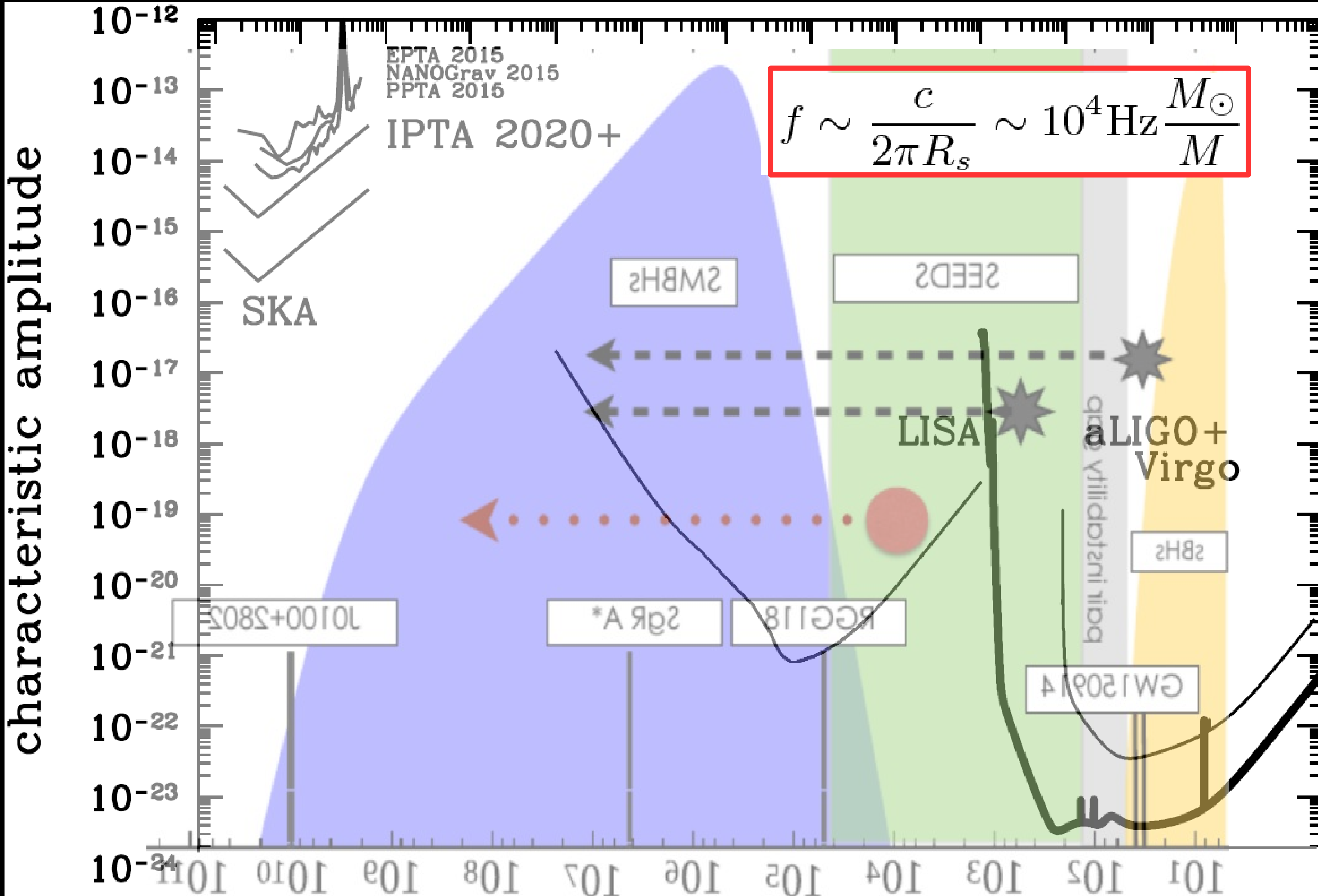
10 $M_\odot$ binary at 100 Mpc: $h \sim 10^{-21}$, $f < 10^3$

10^6 $M_\odot$ binary at 10 Gpc: $h \sim 10^{-18}$, $f < 10^{-2}$

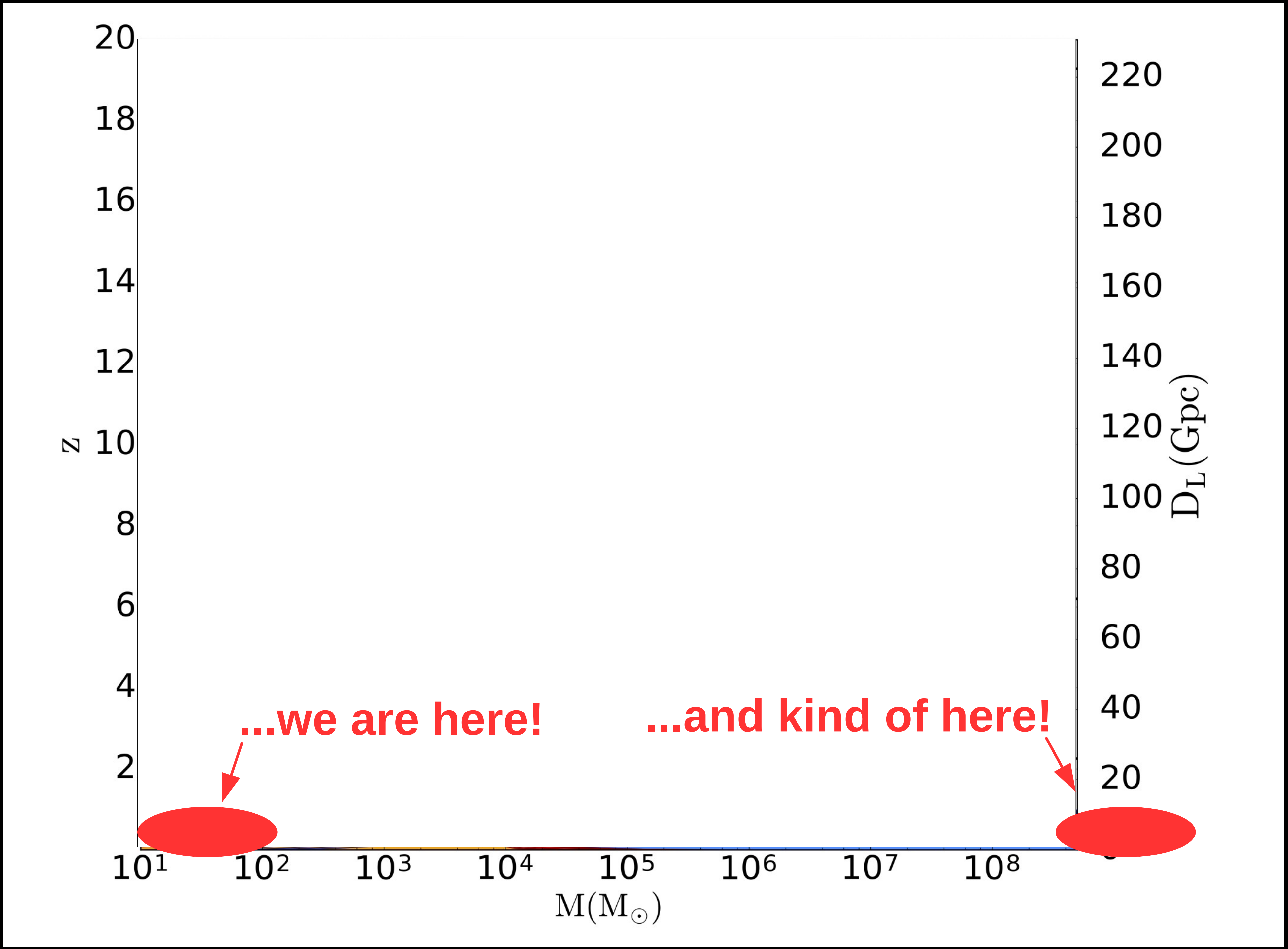
10^9 $M_\odot$ binary at 1Gpc: $h \sim 10^{-14}$, $f < 10^{-5}$



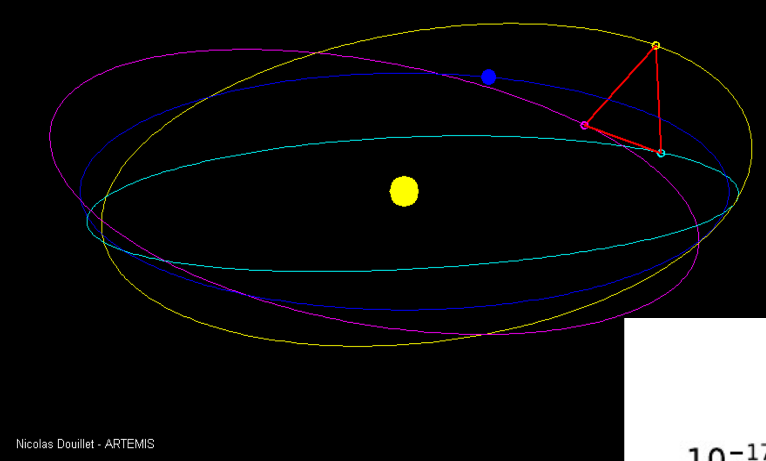
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
$f \sim \frac{c}{2\pi R_s} \sim 10^4 \mathrm{Hz} \frac{M_\odot}{M}$
LISA
aLIGO+
Virgo
characteristic amplitude
frequency [Hz]


characteristic amplitude
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
$f \sim \dfrac{c}{2\pi R_s} \sim 10^4\,\mathrm{Hz}\,\dfrac{M_\odot}{M}$
LISA
aLIGO+
Virgo

The parameter space of black holes



The Laser Interferometer Space Antenna



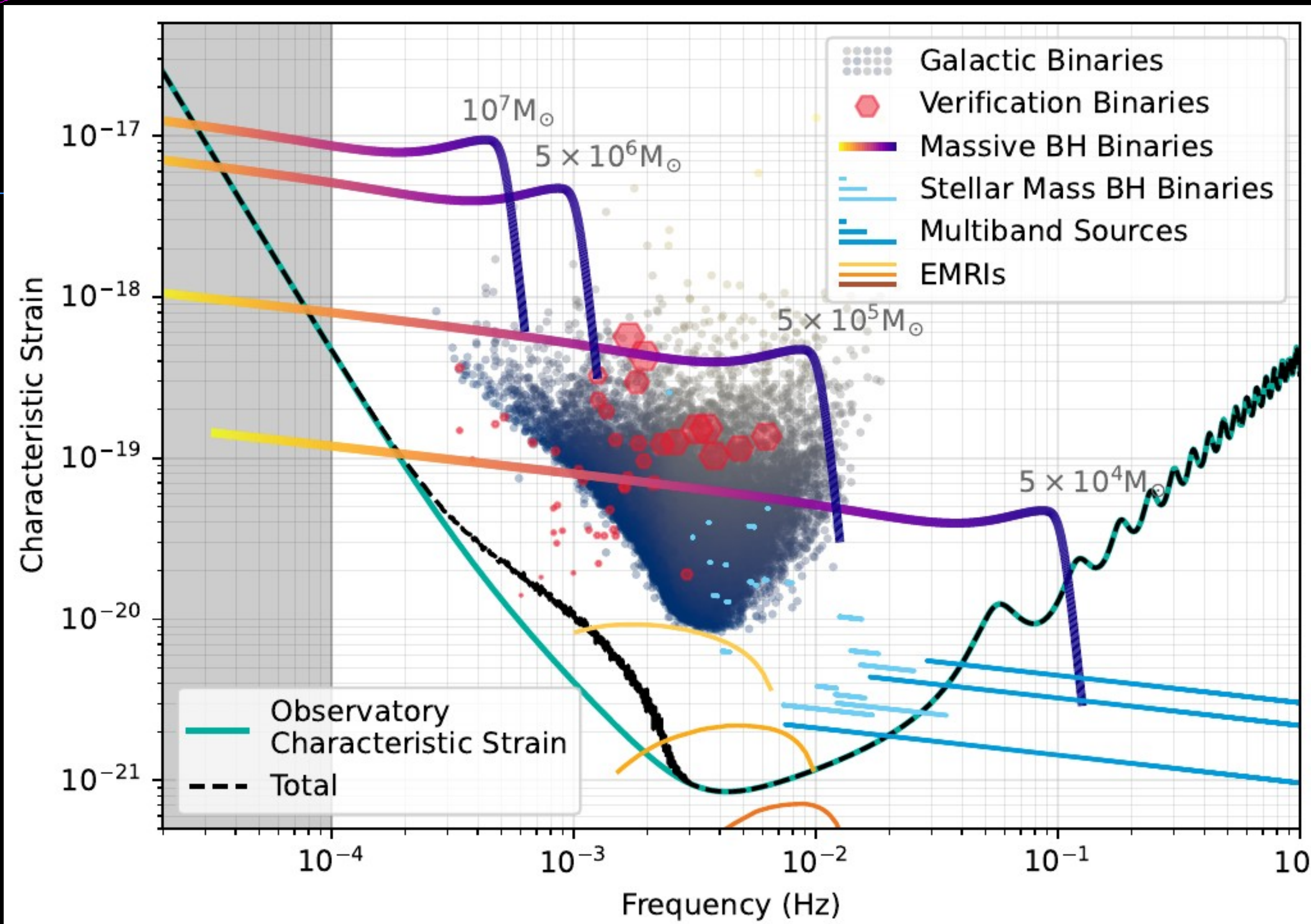
Sensitive in the mHz frequency range where massive black hole (MBH) binary (MBHB) evolution is fast (chirp)

Observes the full inspiral/merger/ringdown

(LISA Red Book: arXiv:2402.07571)

3 satellites trailing the Earth connected through laser links

Proposed baseline:
2.5M km armlength
6 laser links
4.5 yr lifetime
(10 yr goal)



The Laser Interferometer Space Antenna

ADOPTED BY ESA ON JAN 25!!!

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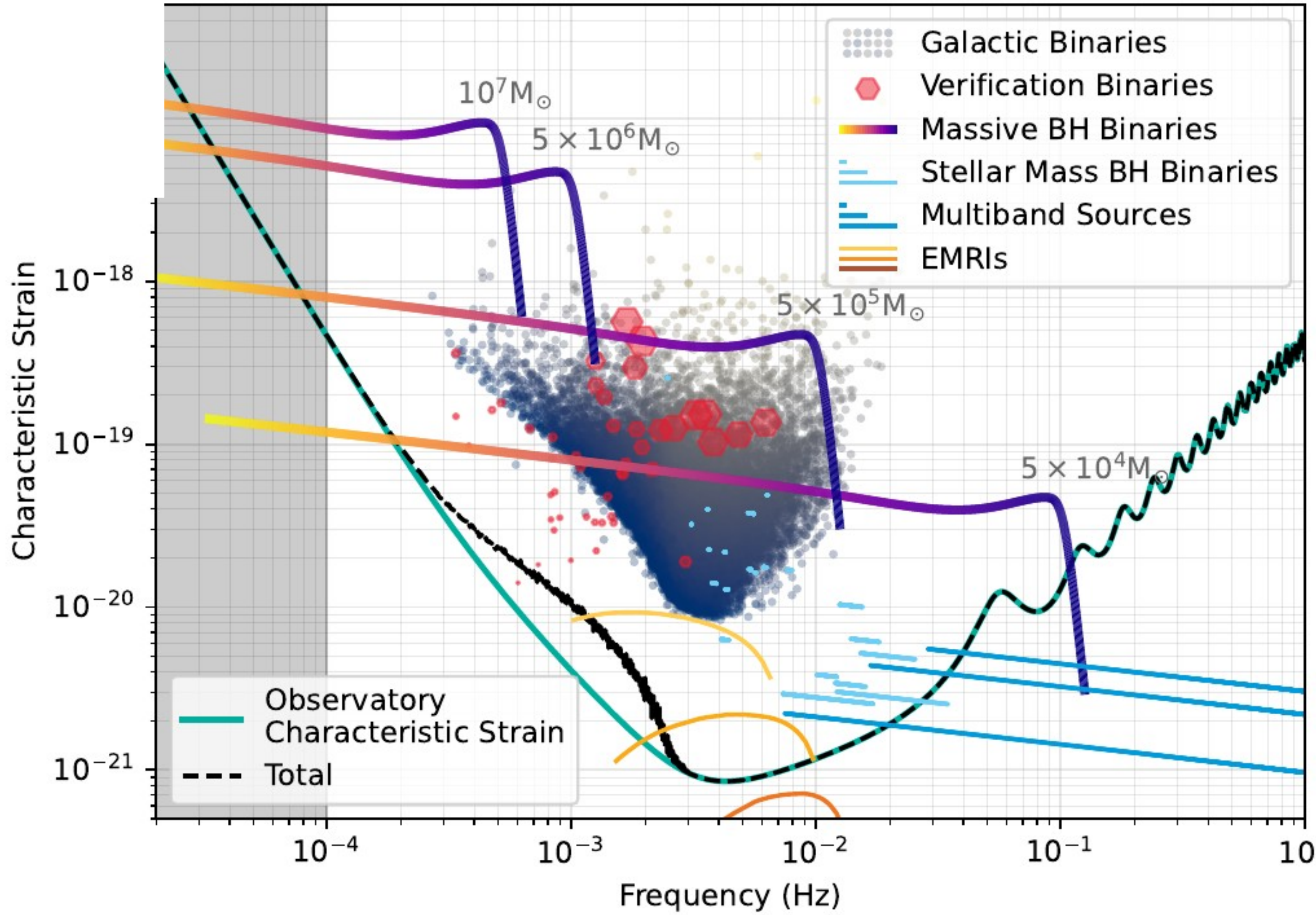
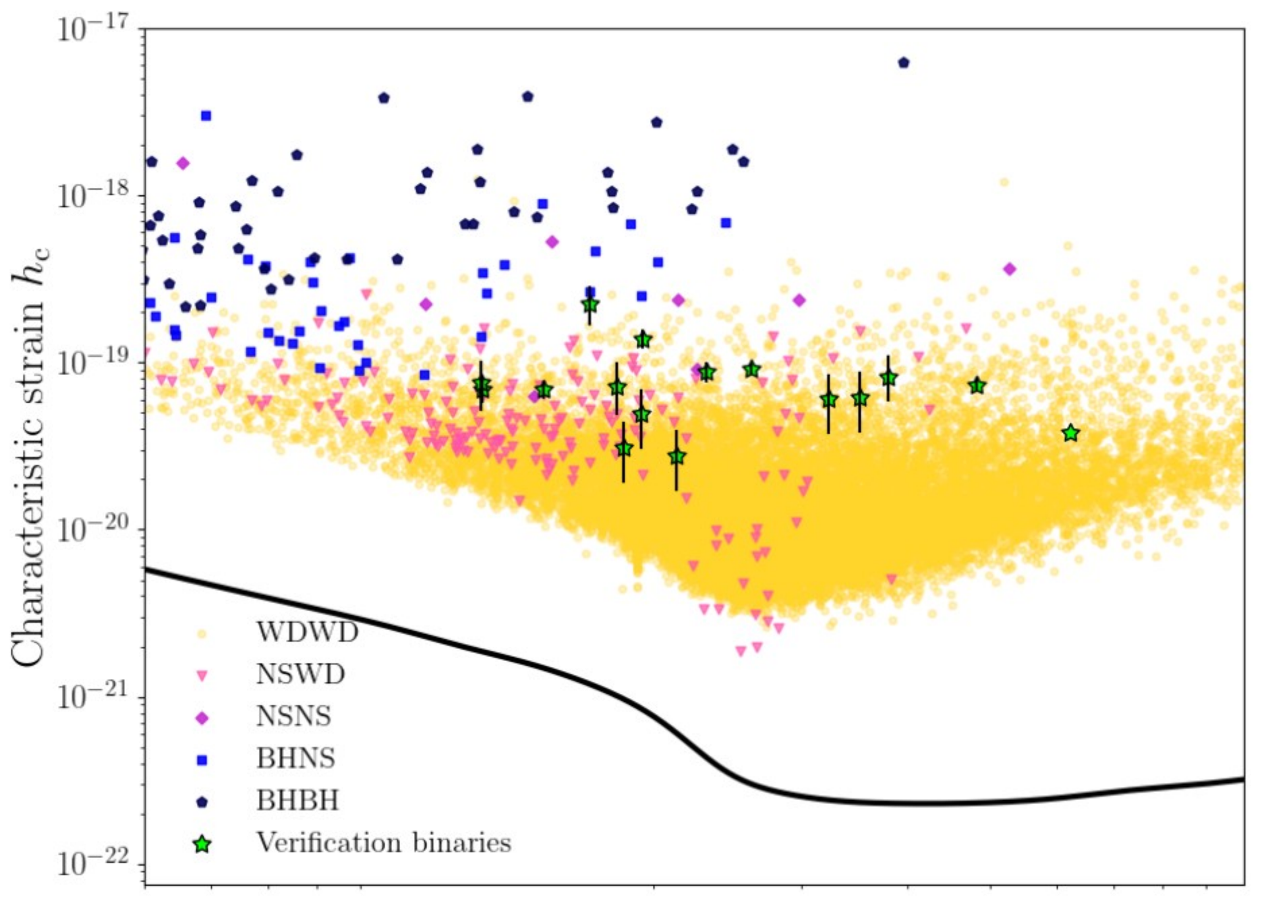
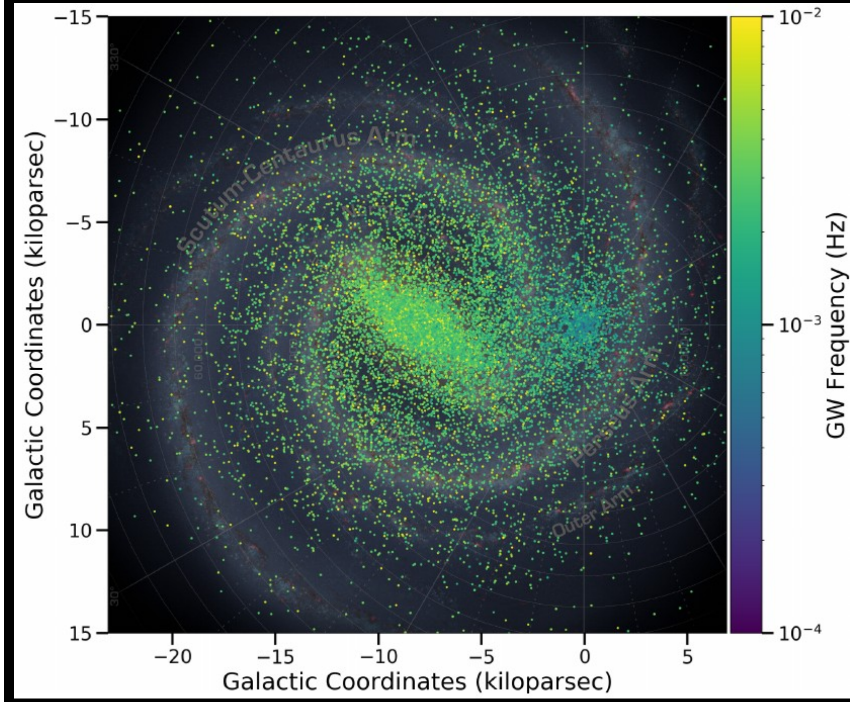


Galactic Binaries

- 100M WD binaries in the Galaxy
- 20k+ individual detection + stochastic GWB
- characterization of the structure of the galaxy
- rate of WD binary mergers in our galaxy (SN1a connection?)
- binary astrophysics
- multimessenger astrophysics
- NS/BH binaries



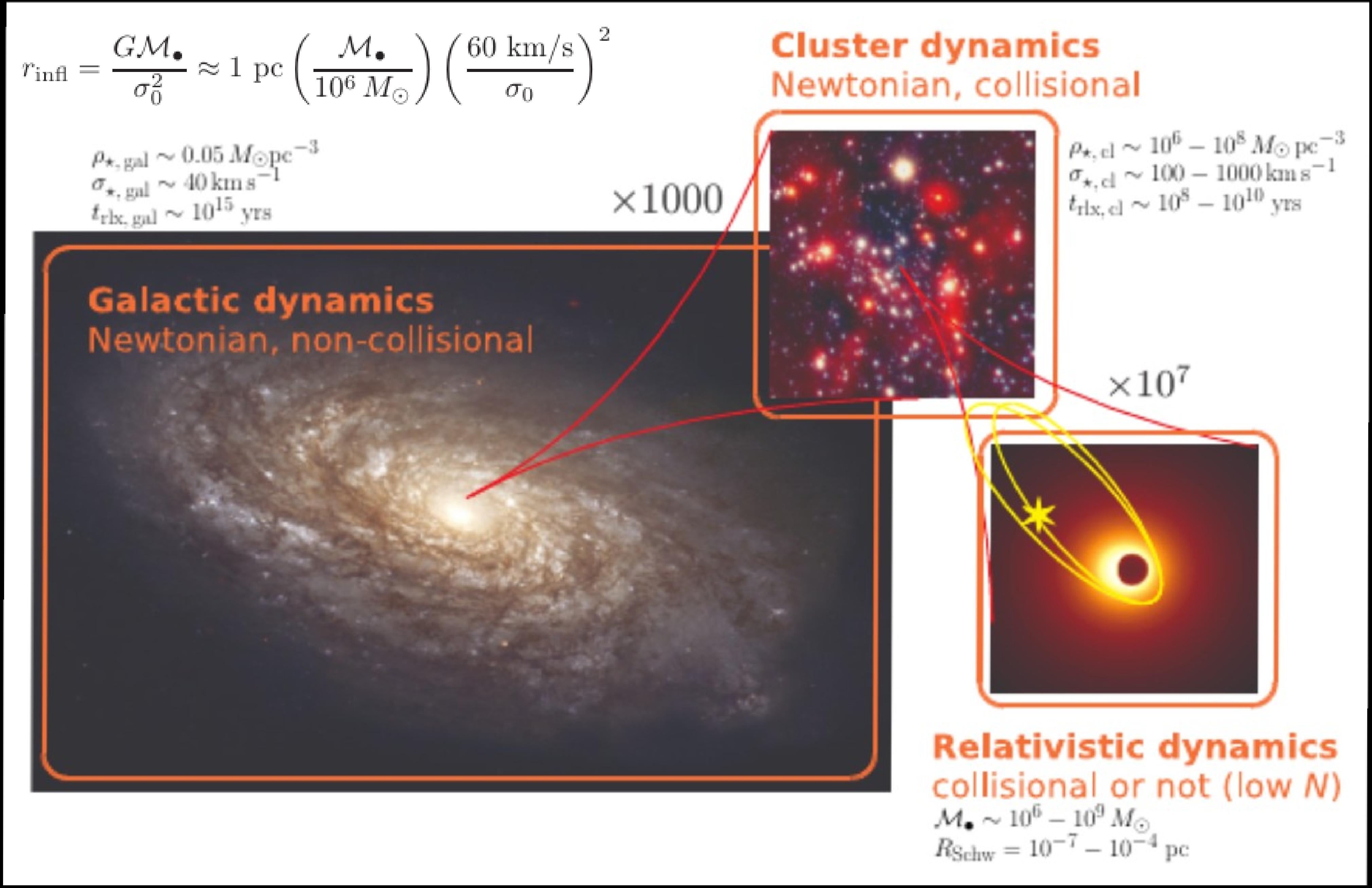


(LISA Red Book)

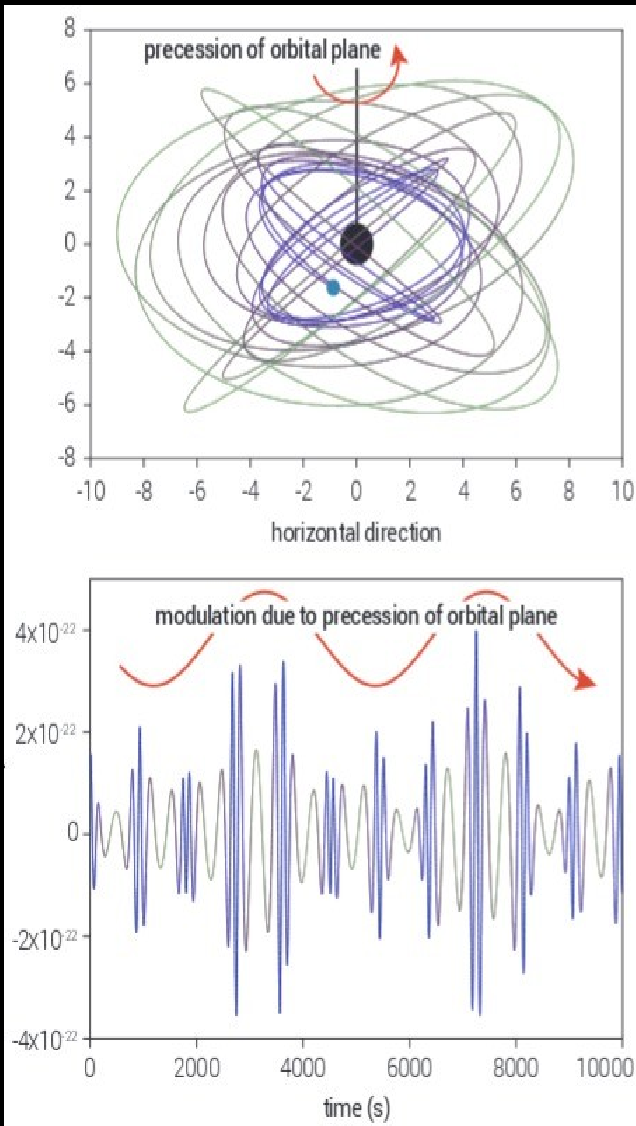
Extreme mass ratio inspirals (EMRIs)

Two body encounters can deflect compact objects in relativistic orbits around the central SMBH.

(Courtesy of P. Amaro-Seoane)

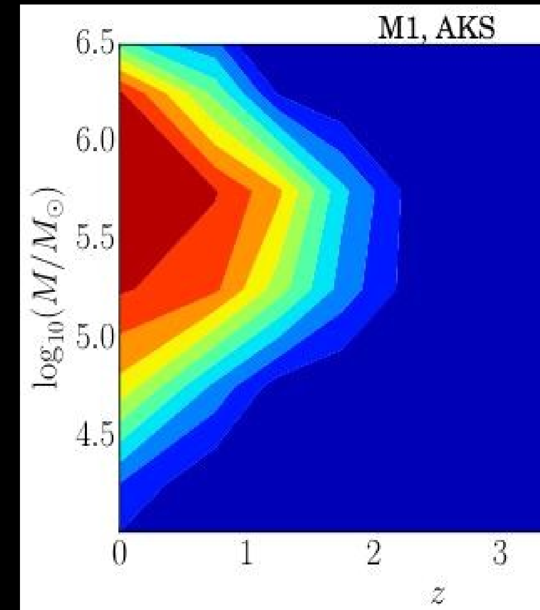


LISA potential for EMRIs

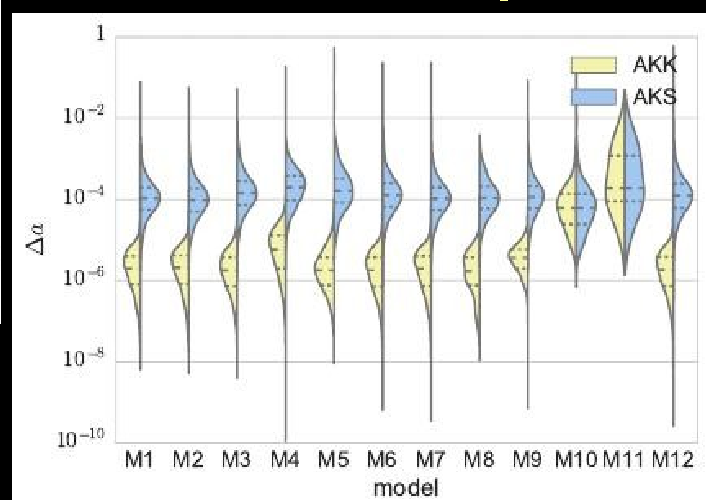


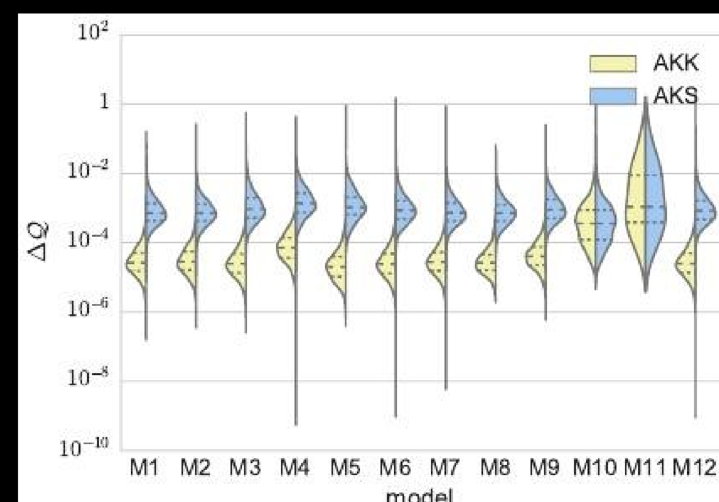
(Babak et al, 2017)

- 1-1000 detections/yr
- sky localization <10 deg2
- distance to better than 10%
- MBH mass to better than 0.01%
- CO mass to better than 0.01%
- MBH spin to better than 0.001
- plunge eccentricity <0.0001
- deviation from Kerr quadrupole moment to <0.001

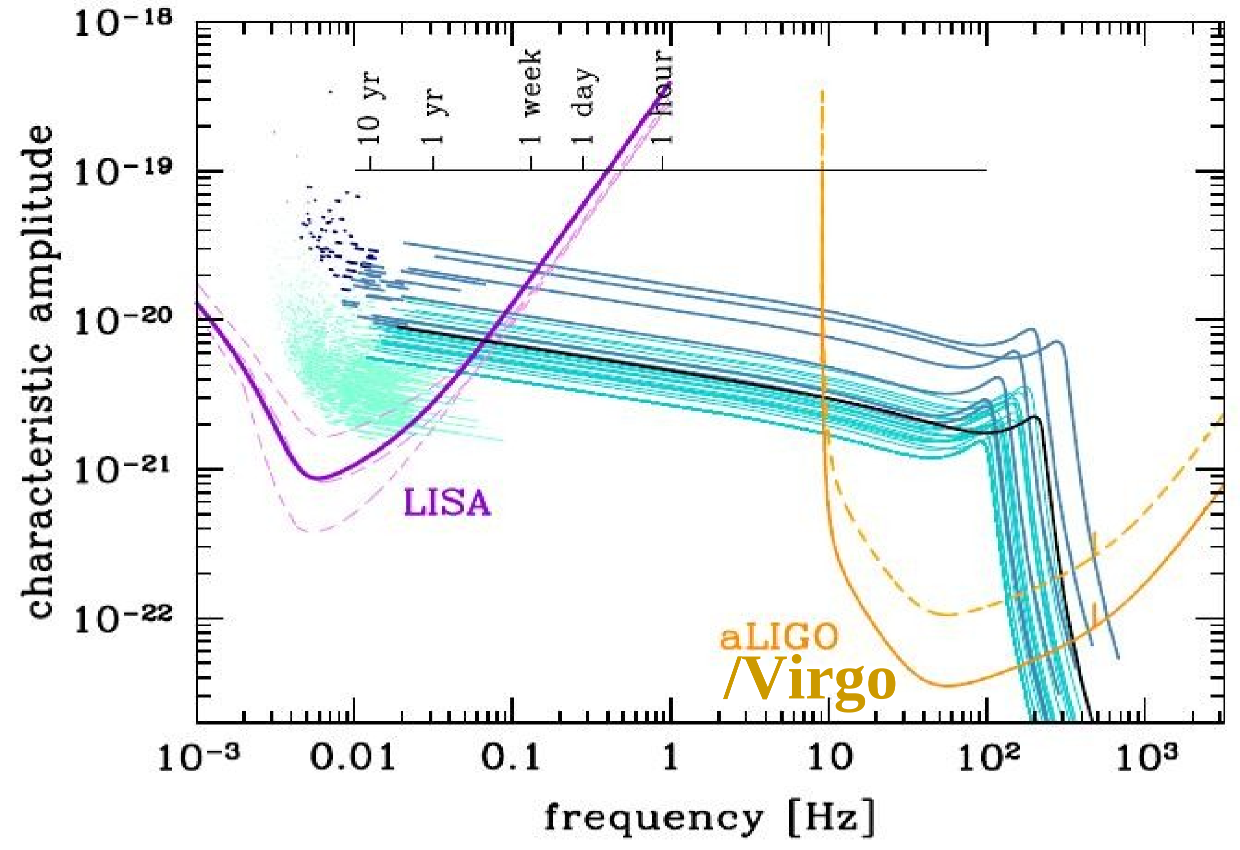


New tool for astrophysics (Gair et al 2010) **cosmology** (McLeod & Hogan 2008), **and fundamental physics** (Gair et al 2013) …
to be further explored





Extragalactic sBHBs: multi-band GW astronomy?



(AS 2016, PRL 116, 1102)

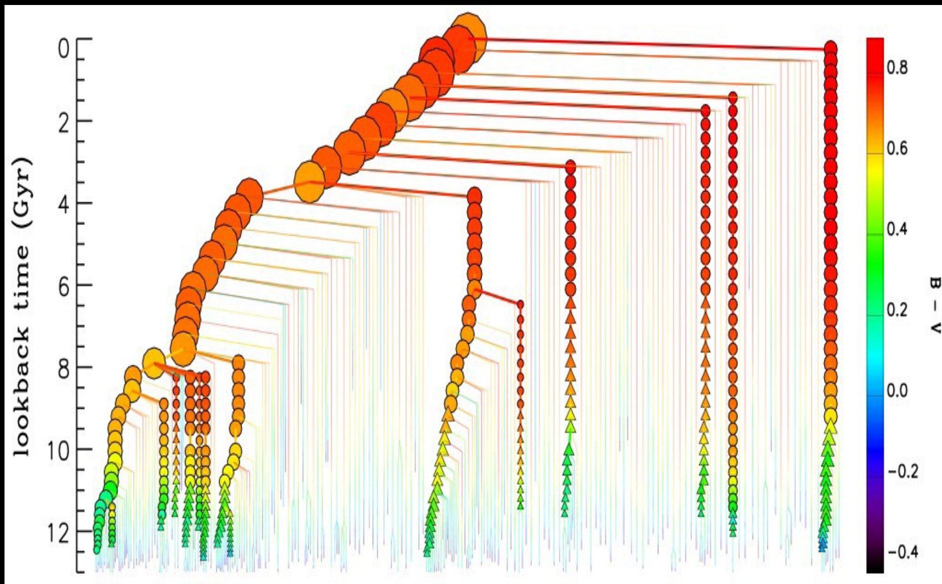
sBHB will be detected by LISA and cross to the LIGO/Virgo band, assuming a 5 year operation of LISA.

Unfortunately expected rates do not seem great.

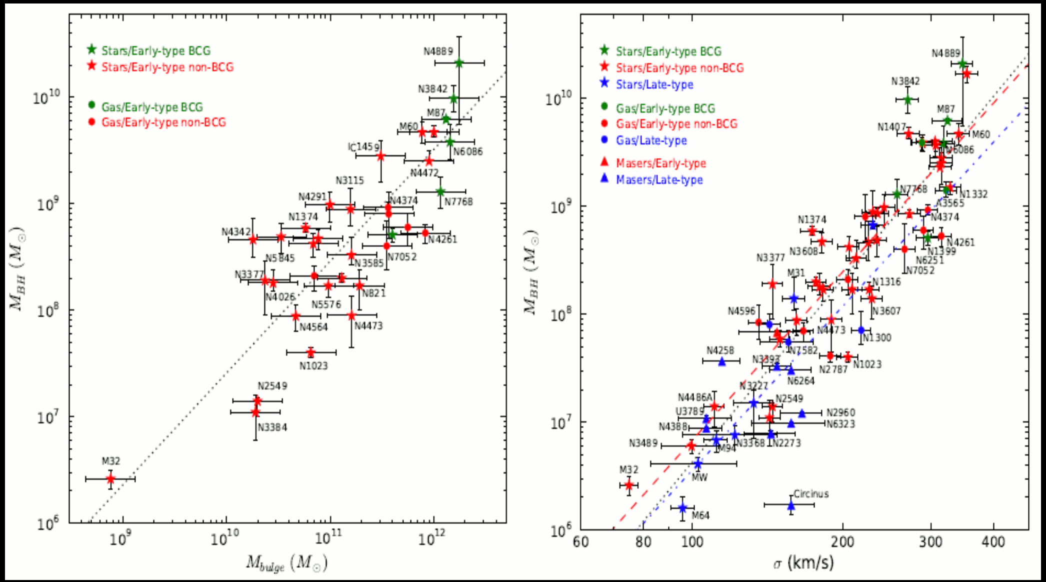
(LISA Red Book)

	sBHB type	definition	$\langle N \rangle$	90 % confidence	no sBHB (%)
SI 4.1	detected	SNR > 8	4.9	0.4 – 9.8	2.2
	archival	$5 <$ SNR < 8 & $t_c < 15$ yr	5.6	0.8 – 10.0	1.4
SI 4.2	massive	SNR > 8 & $m_1 > 50\,M_\odot$	1.3	0 – 3.6	34.1
SI 4.3	multiband	SNR > 8 & $t_c < 15$ yr	1.5	0 – 3.8	26.7
		SNR > 8 & $t_c < 4.5$ yr	0.4	0 – 1.4	67.7

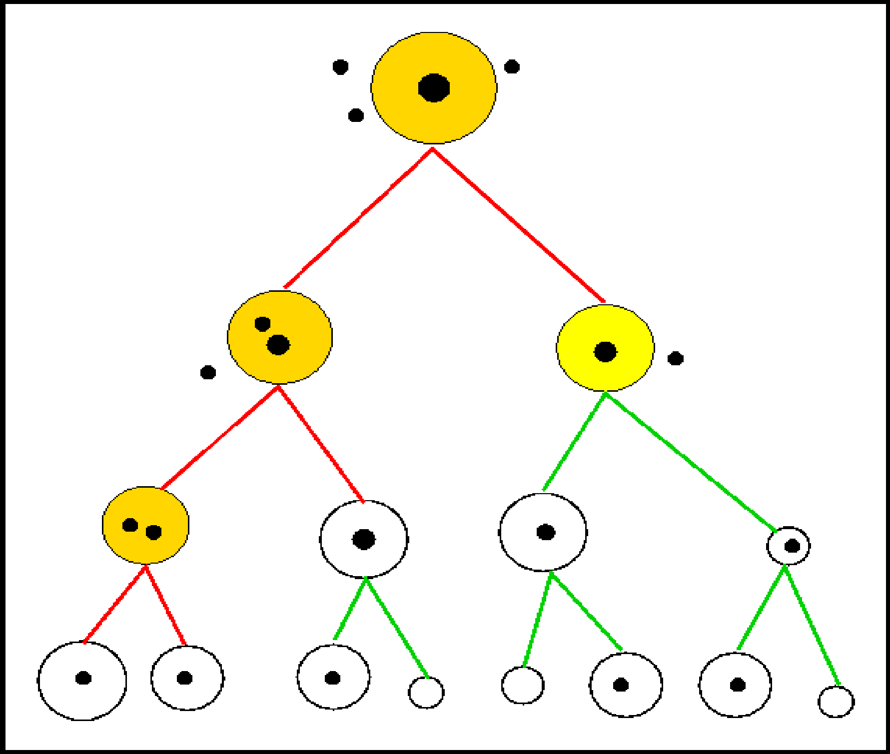
Massive black hole binaries (MBHBs)



(From de Lucia et al. 2006)

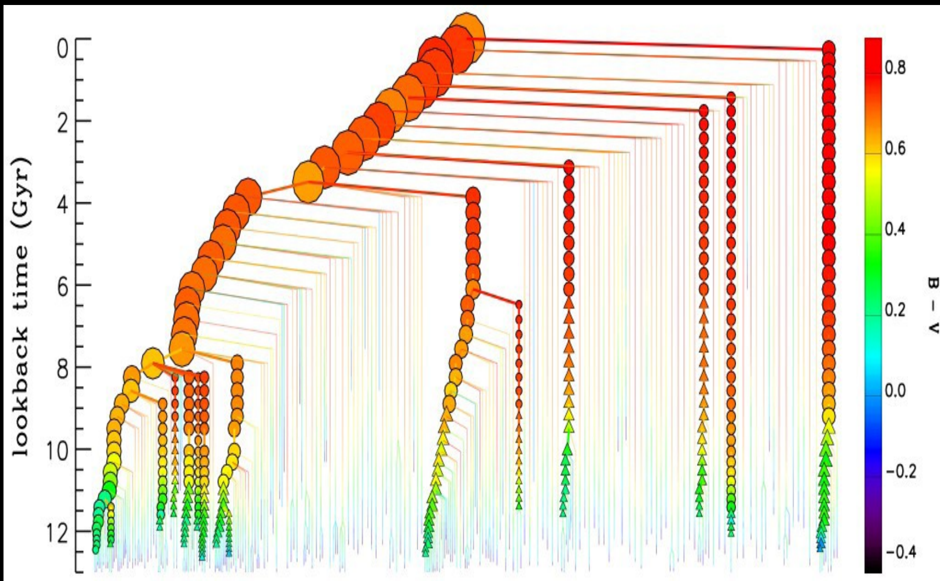


(Ferrarese & Merritt 2000, Gebhardt et al. 2000)



(Menou et al 2001, Volonteri et al. 2003)

Massive black hole binaries (MBHBs)



(From de Lucia et al. 2006)

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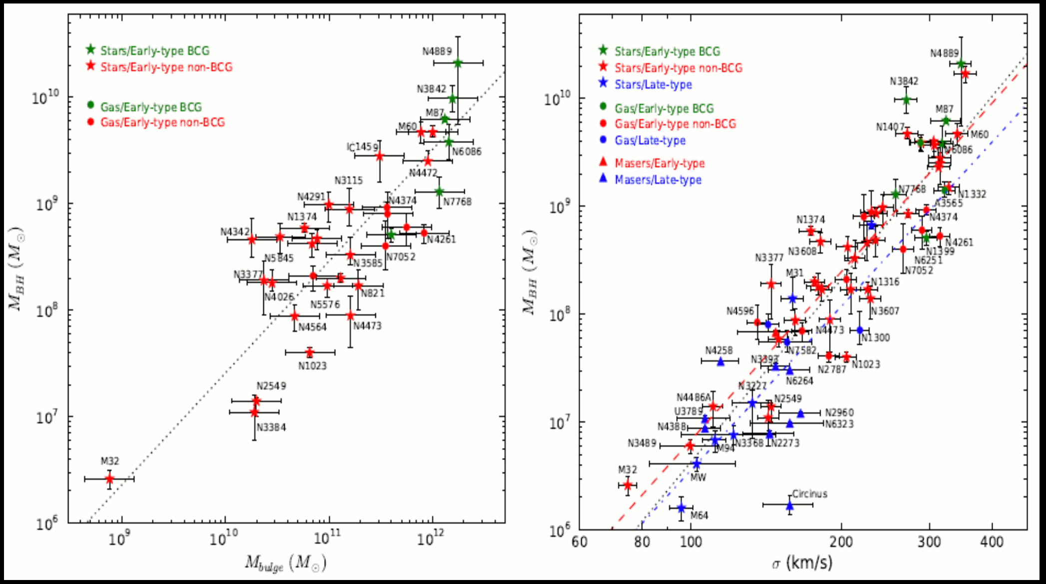

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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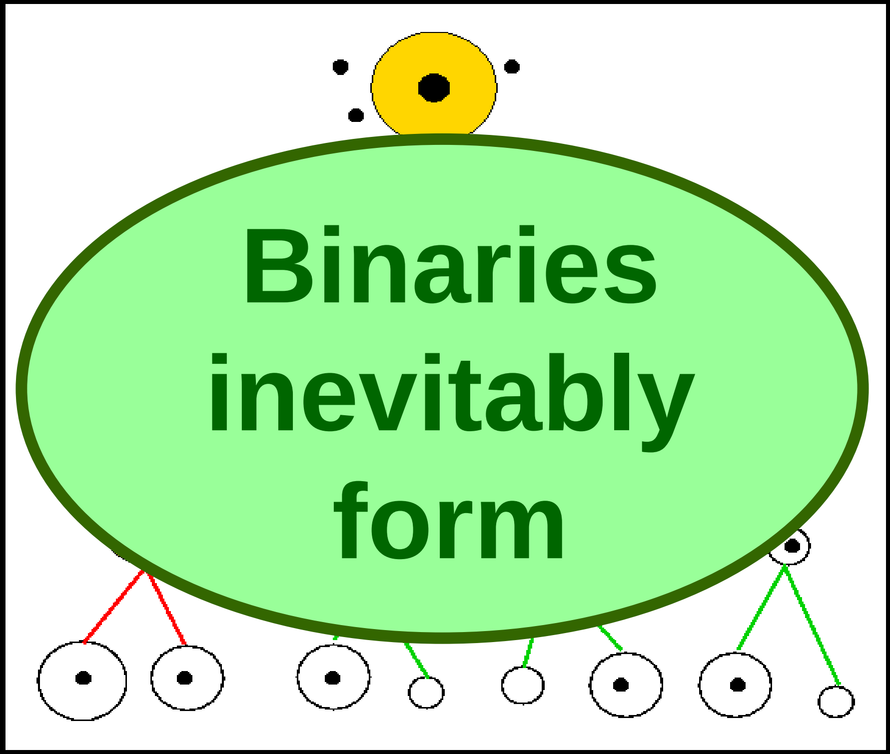
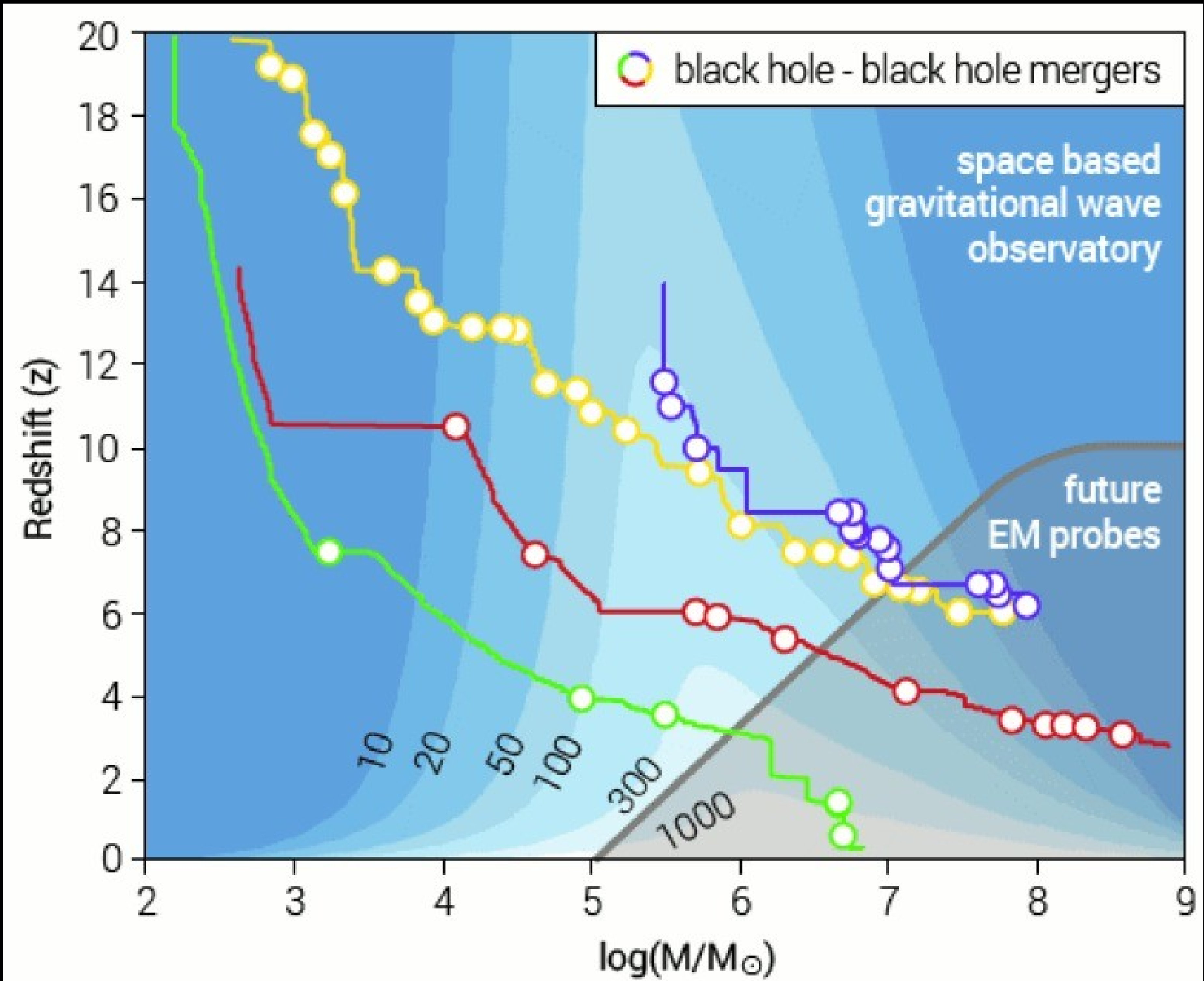


Binaries inevitably form

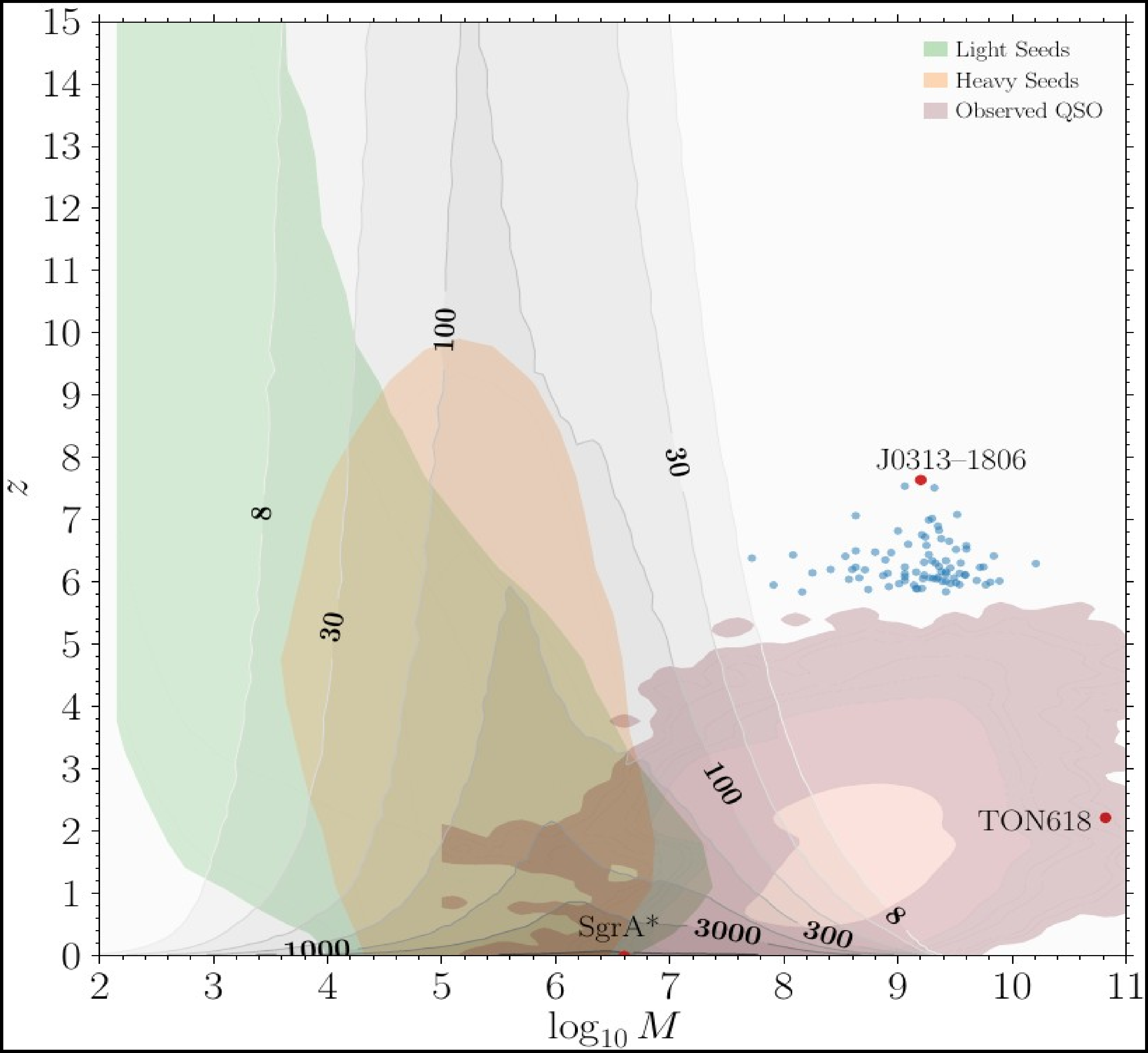
(Menou et al 2001, Volonteri et al. 2003)

***Where and when do the first MBH seeds form?**
***How do they grow along the cosmic history?**
***What is their role in galaxy evolution?**
***What is their merger rate?**
***How do they pair together and dynamically evolve?**



black hole - black hole mergers
space based gravitational wave observatory
future EM probes
10
20
50
100
300
1000
Redshift (z)
log(M/M⊙)
0
2
4
6
8
10
12
14
16
18
20
2
3
4
5
6
7
8
9

The complementarity of LISA and EM probes

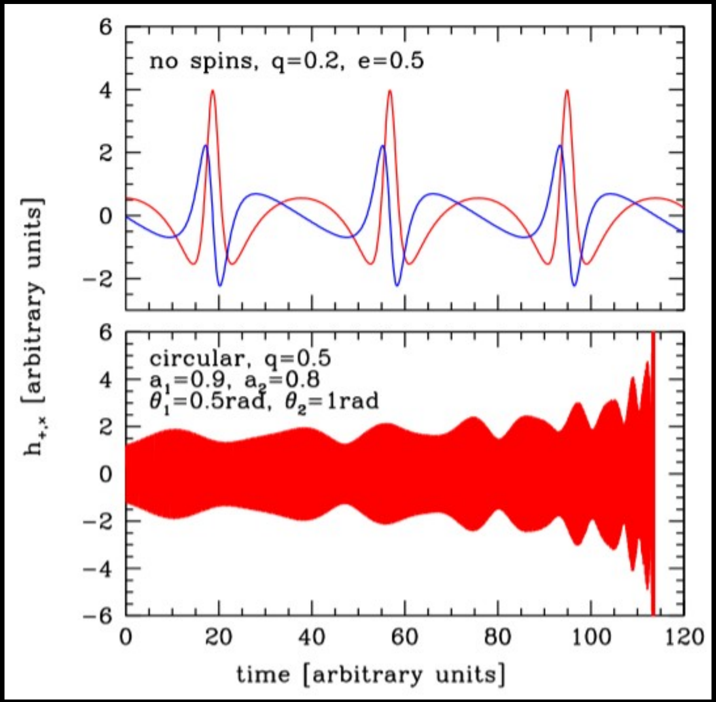


What LISA will measure

Assuming 4 years of operation:

~100+ detections

~100+ systems with sky localization to 10 deg2



~100+ systems with individual masses determined to 1%

~50 systems with primary spin determined to 0.01

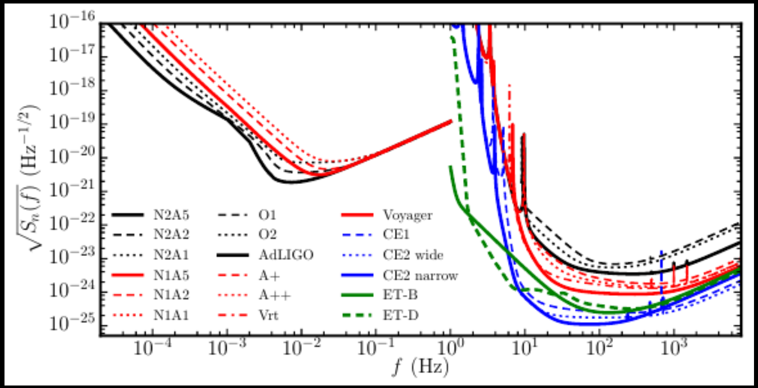
~50 systems with secondary spin determined to 0.1

~50 systems with spin direction determined within 10deg

~30 events with final spin determined to 0.1

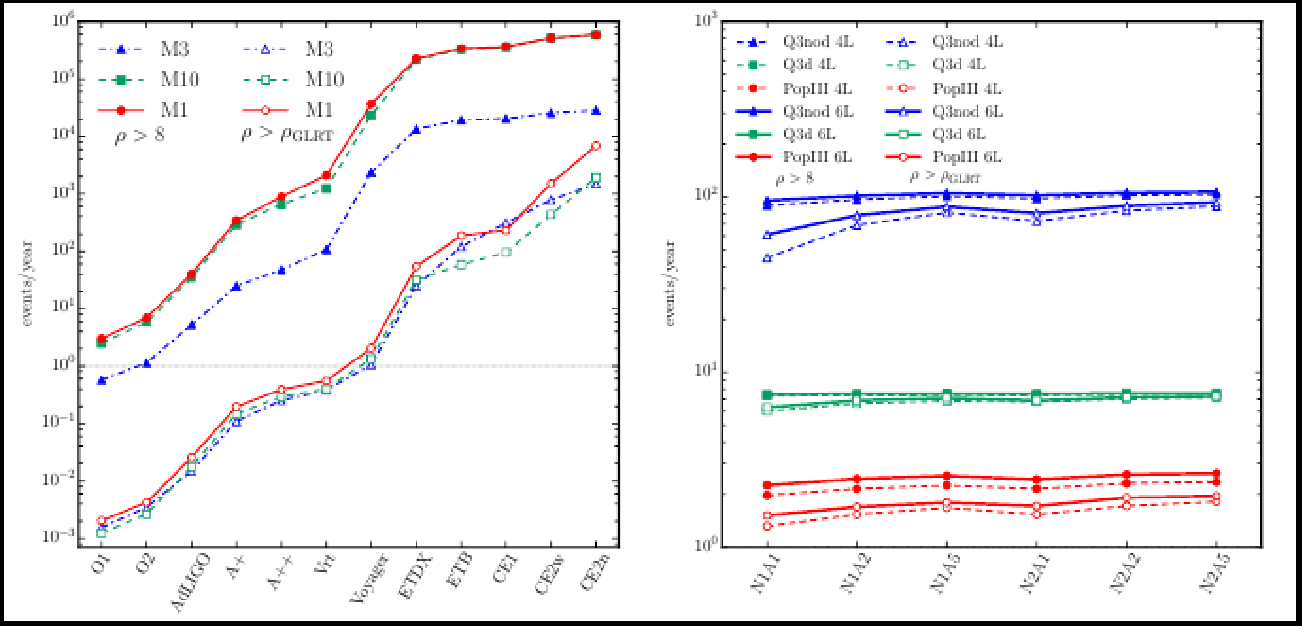
Resolving ringdown modes: BH spectroscopy

(Berti et al. 2016)



$$\rho^{2,3}_{\rm GLRT} = 17.687 + \frac{15.4597}{q-1} - \frac{1.65242}{q},$$

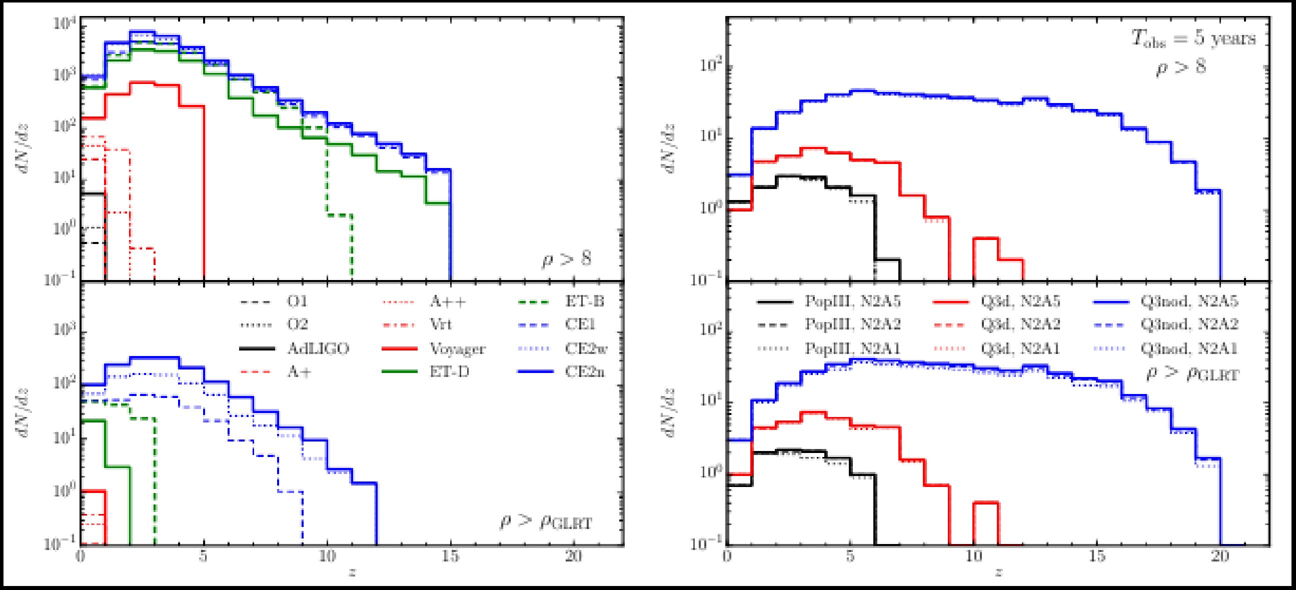
$$\rho^{2,4}_{\rm GLRT} = 37.9181 + \frac{83.5778}{q} + \frac{44.1125}{q^2} + \frac{50.1316}{q^3}$$



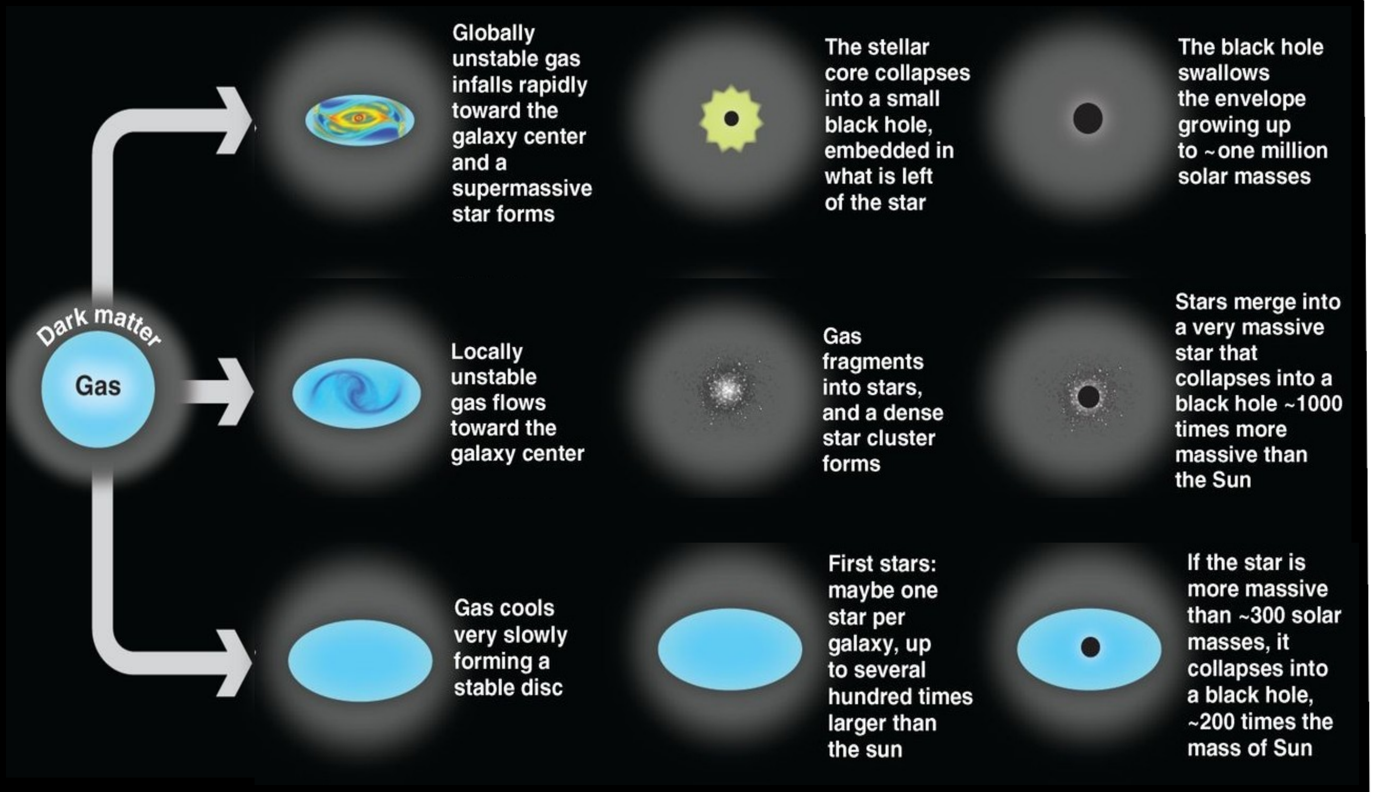
LIGO will not enable BH spectroscopy on individual BHB mergers

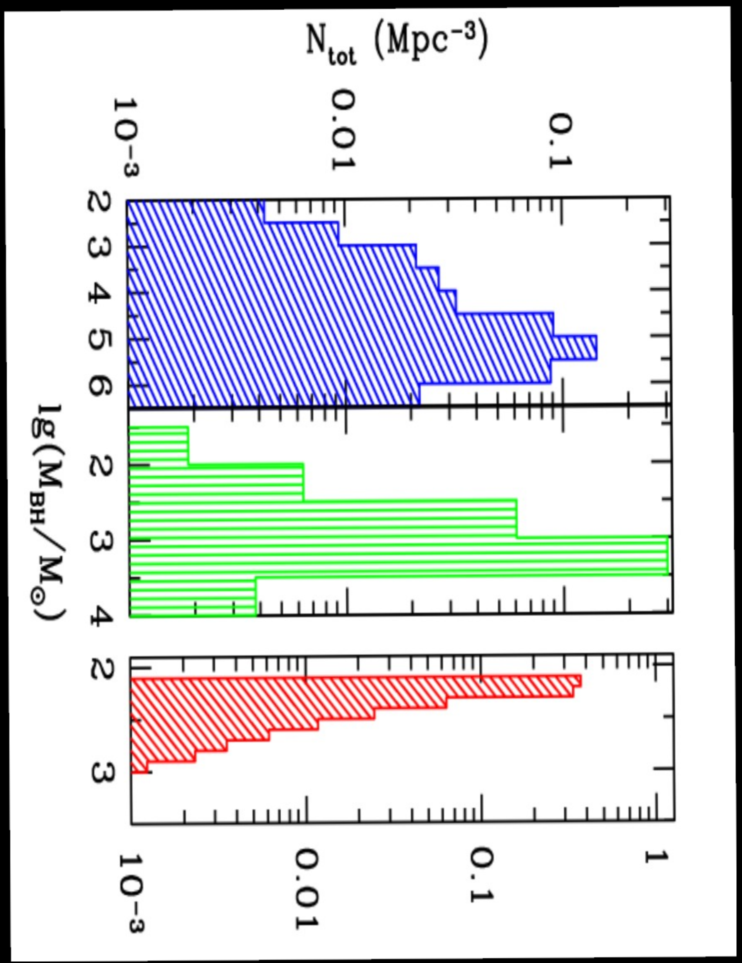
Voyager/ET type detectors are needed

eLISA will enable precise BH spectroscopy on few to 100 events/yr also at very high redshifts



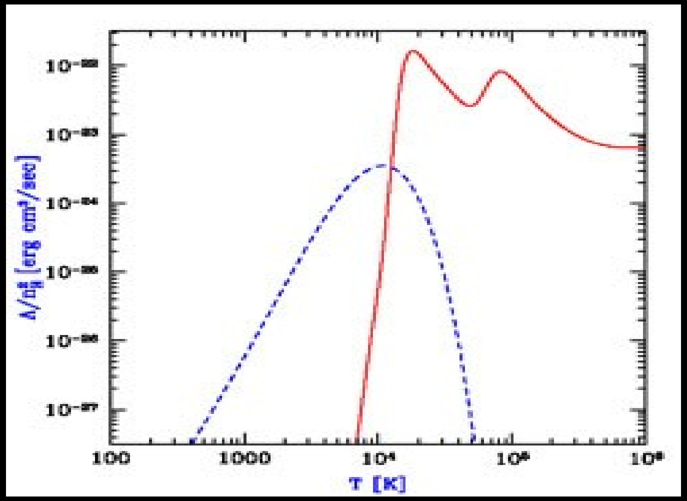
Seed BH formation



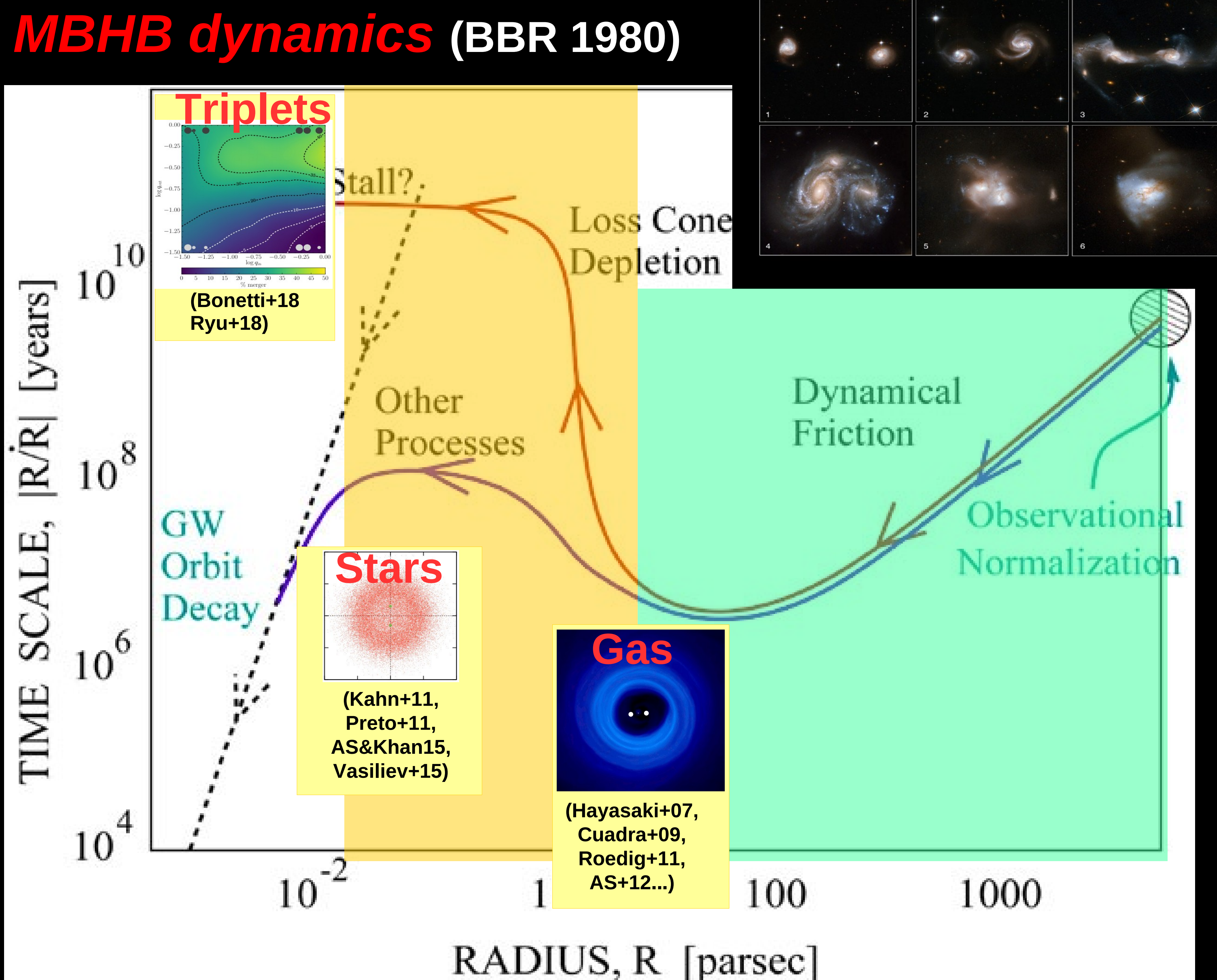


Critically depends on:

- -content of H_2
- -vicinity of an ionizing source
- -fragmentation
- -metallicity

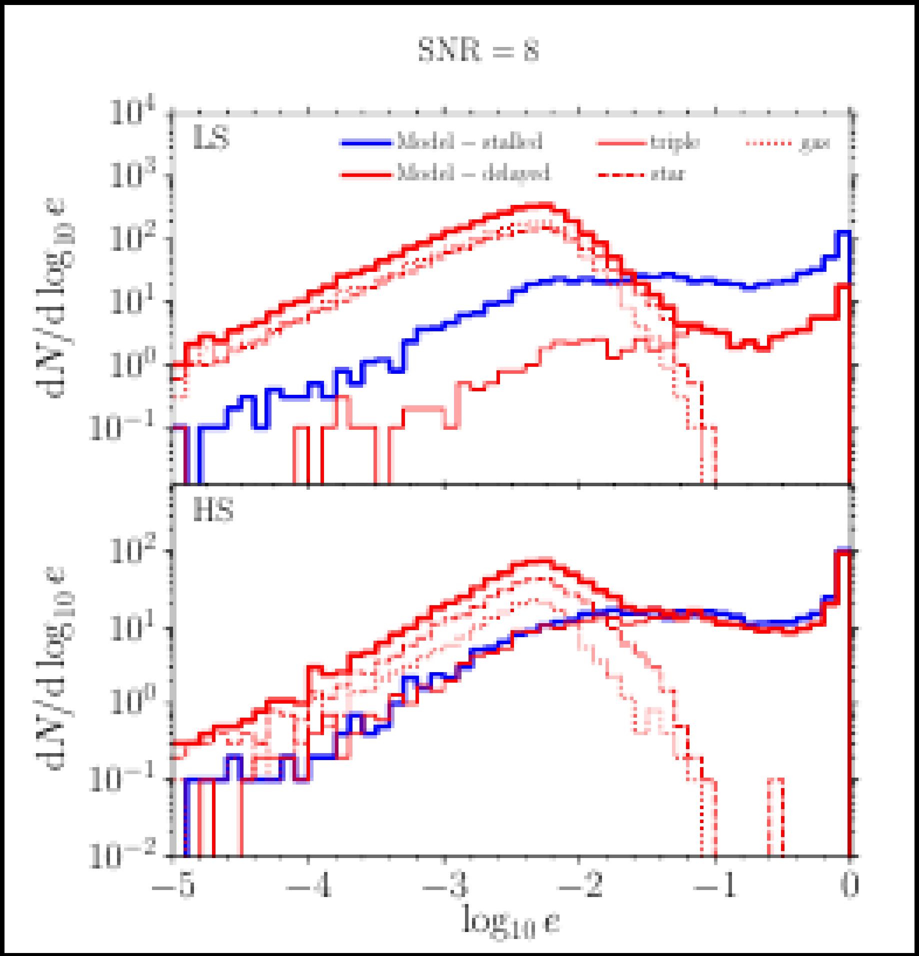


MBHB dynamics (BBR 1980)

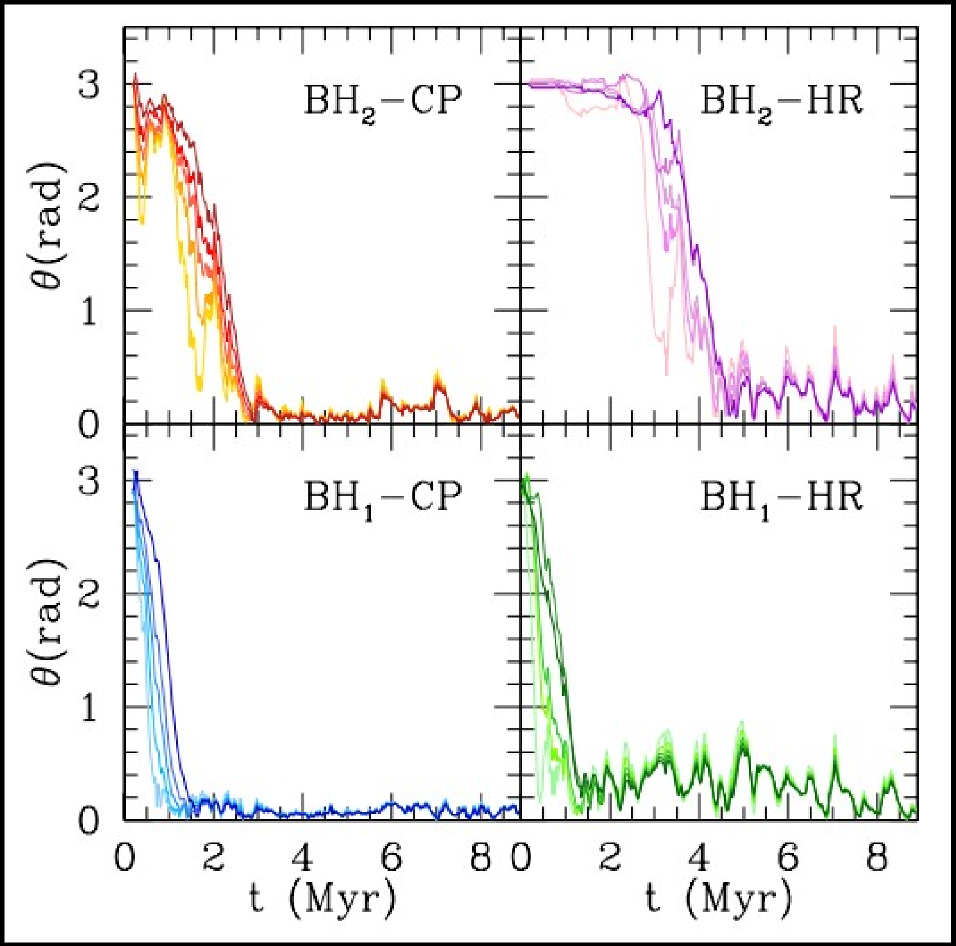


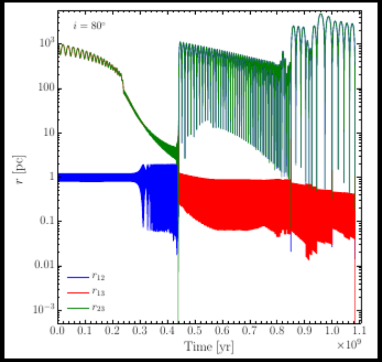
Constrains on dynamics: eccentricity & Spins

Bonetti et al 2019

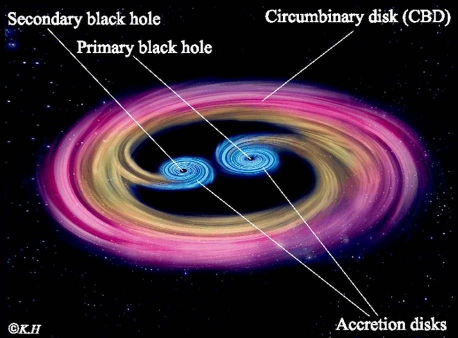


Dotti et al. 2010



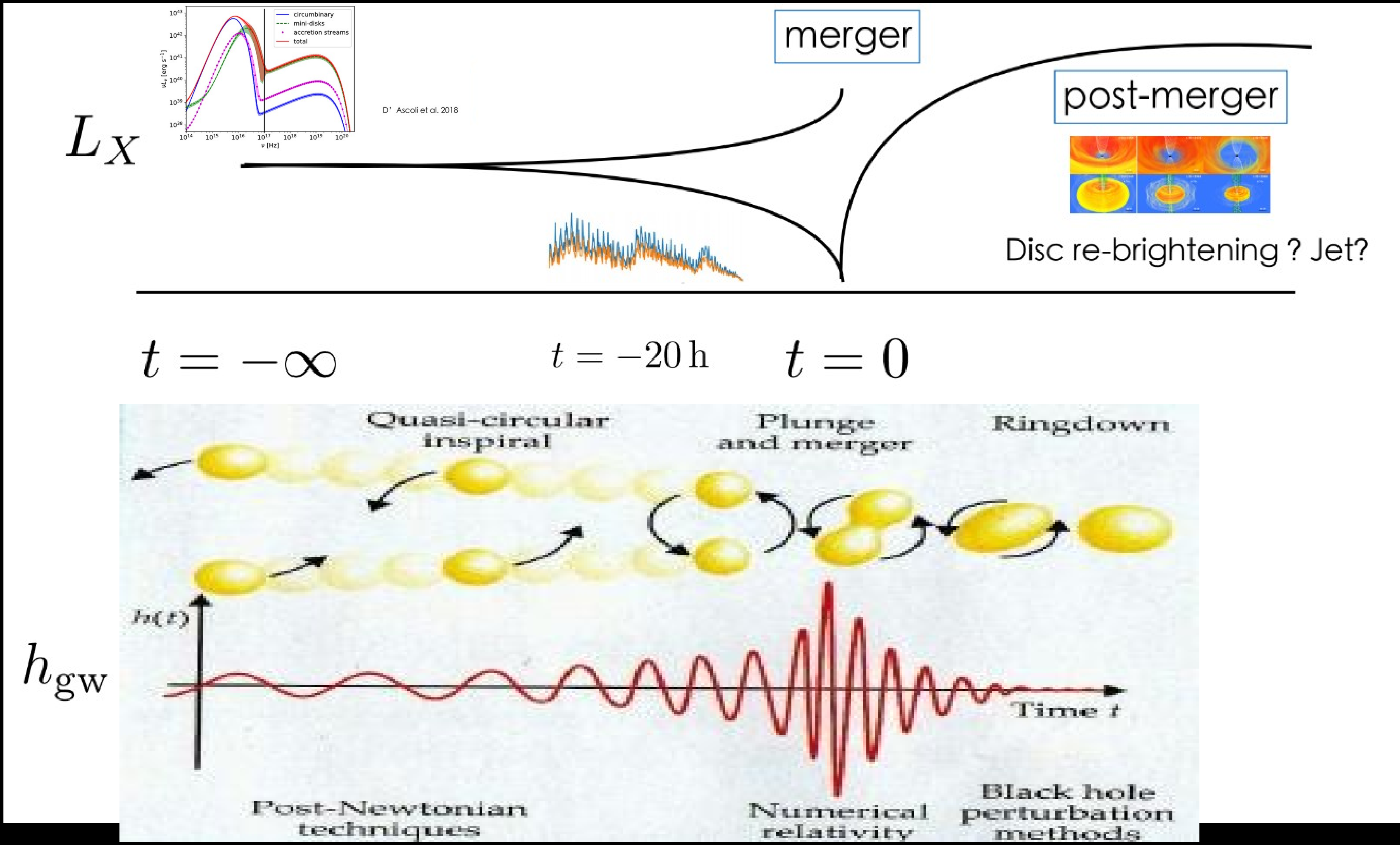


Triple interaction will give a substantial population of highly eccentric systems in the LISA band



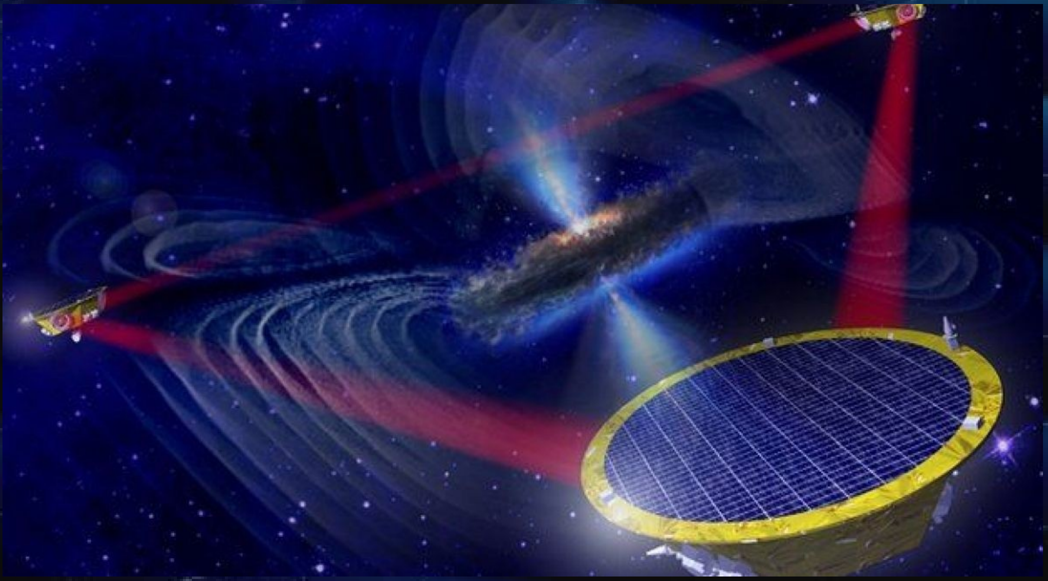
Gas driven inspiral produces spins that are aligned with the orbital angular momentum

MBHBs: multimessenger sources



(Palenzuela+ 2010, Gold+ 2014, Farris+ 2014, Tang+ 2017, 2018, D'Ascoli+ 2018, ...)

Opportunities for LISA -Athena, LSST/Rubin, …, synergies



LSST

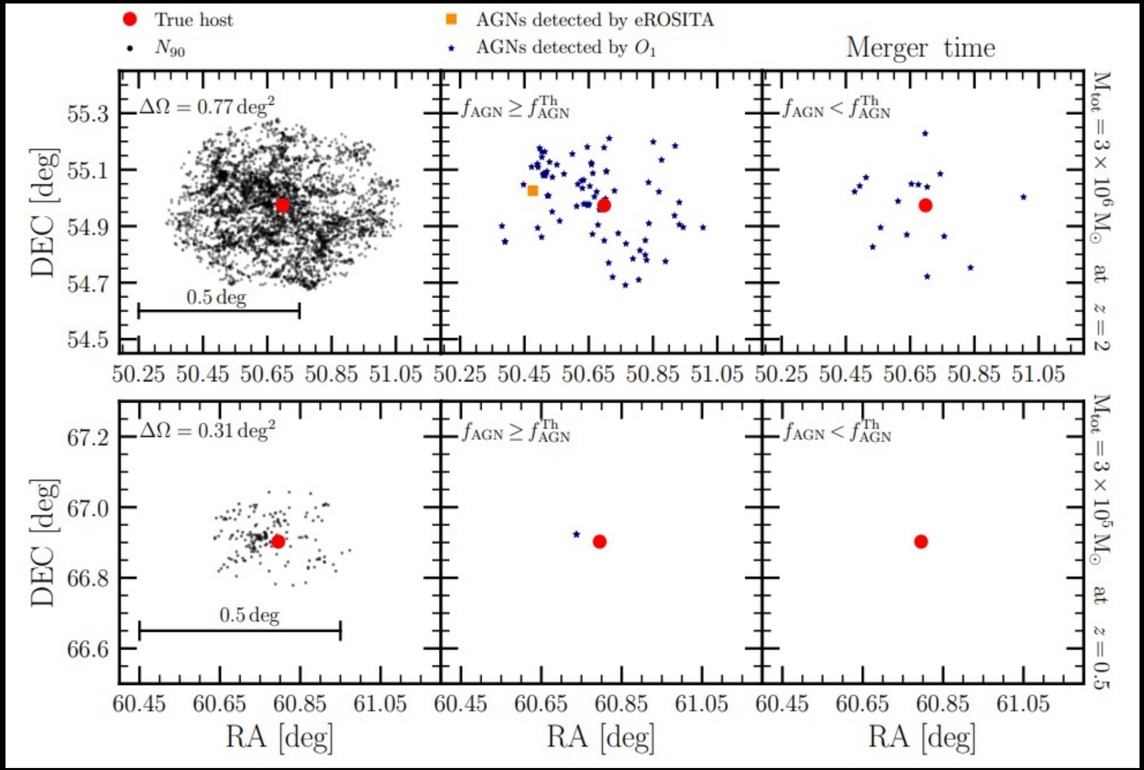
Large Synoptic Survey Telescope

-LISA will see MBHBs at all redshift

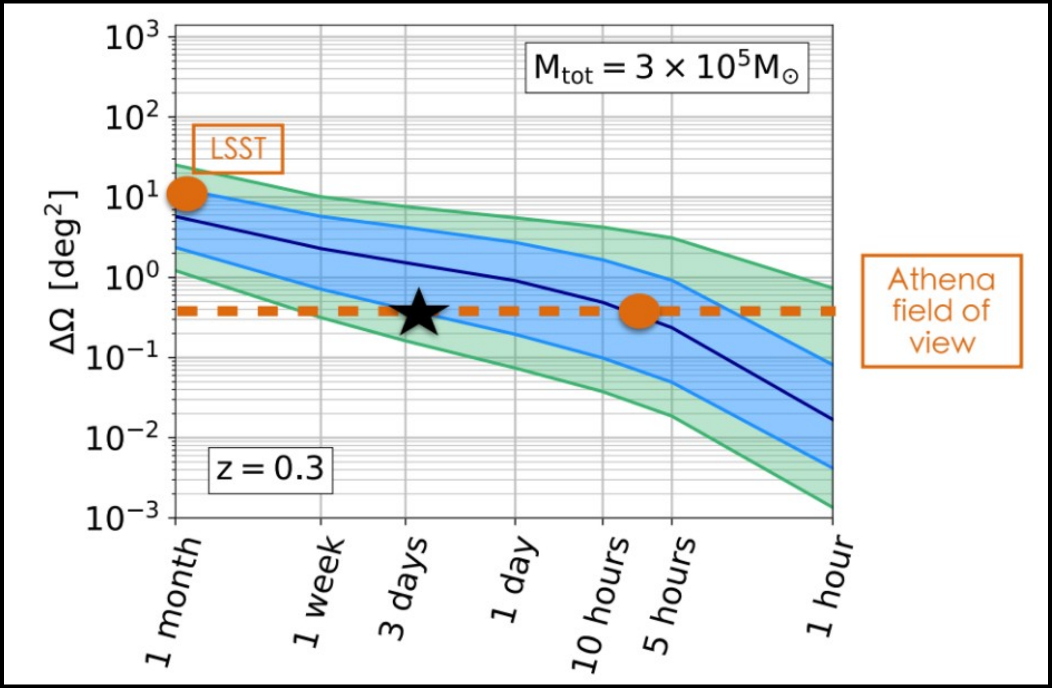
-sky localization <1deg² @z<2

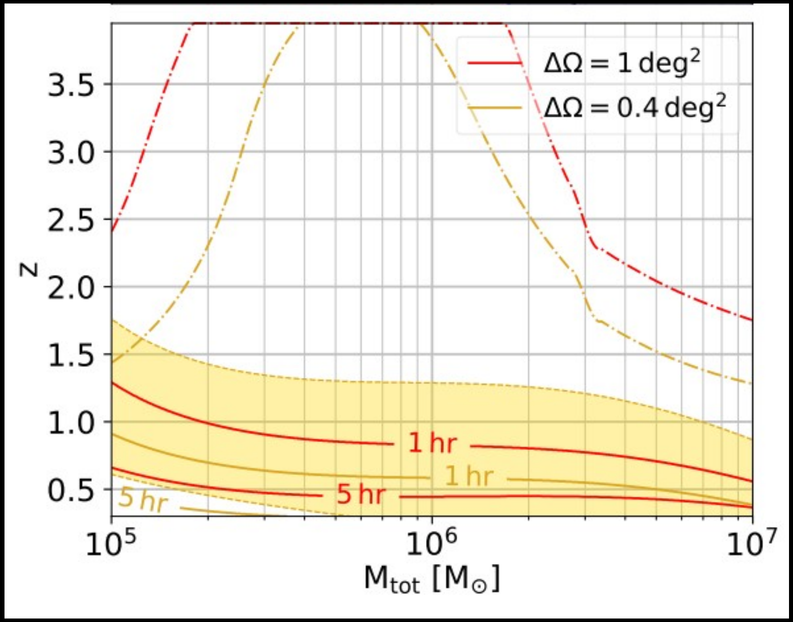
-advanced localization quite hard

-many galaxies in the error box (need distinctive features)



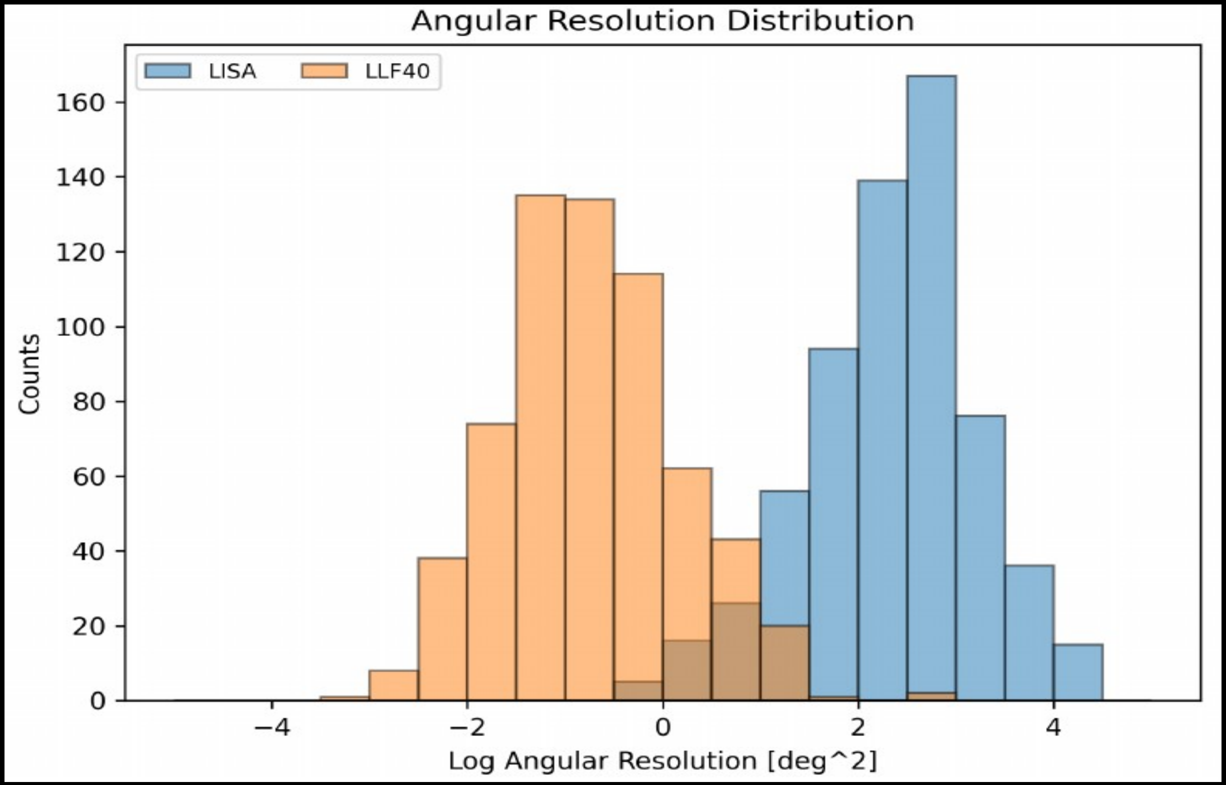
(Lops+ 22)



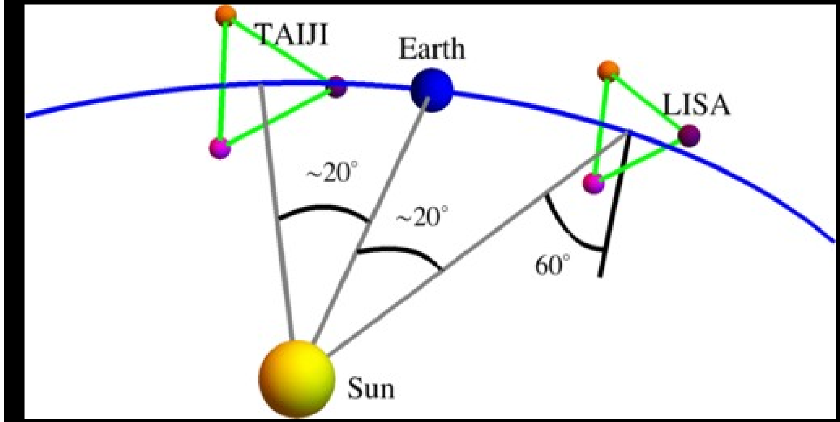


(Mangiagli+20)

The power of two space detectors



(Shuman & Cornish 2021)



Taiji
is essentialy LISA's twin
(Ruan et al 2018)

Improve sky localization by ~10^3
Improve distance estimate by ~10

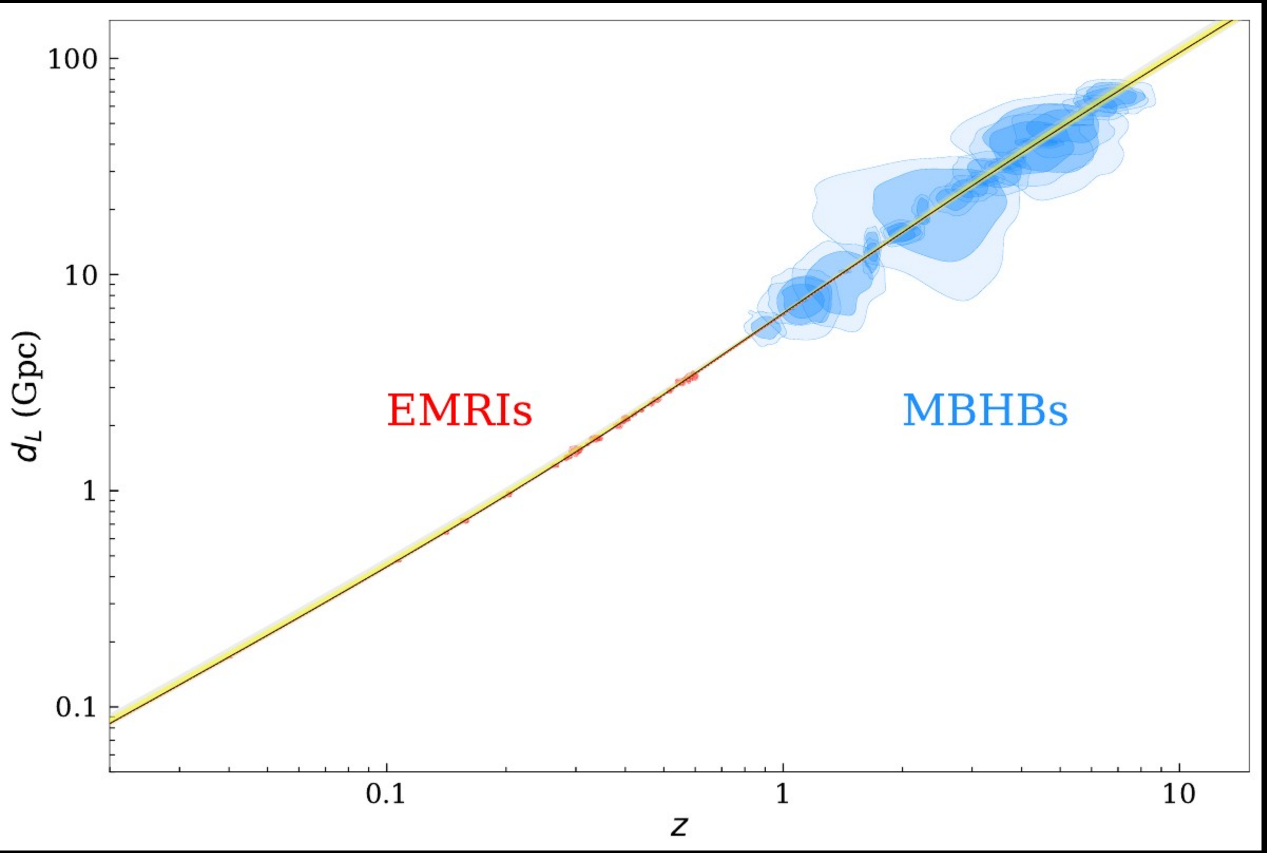
→

- **-Identify counterparts**
- **-multimessenger astronomy**
- **-cosmology and cosmography**
- **-identify high z binaries**

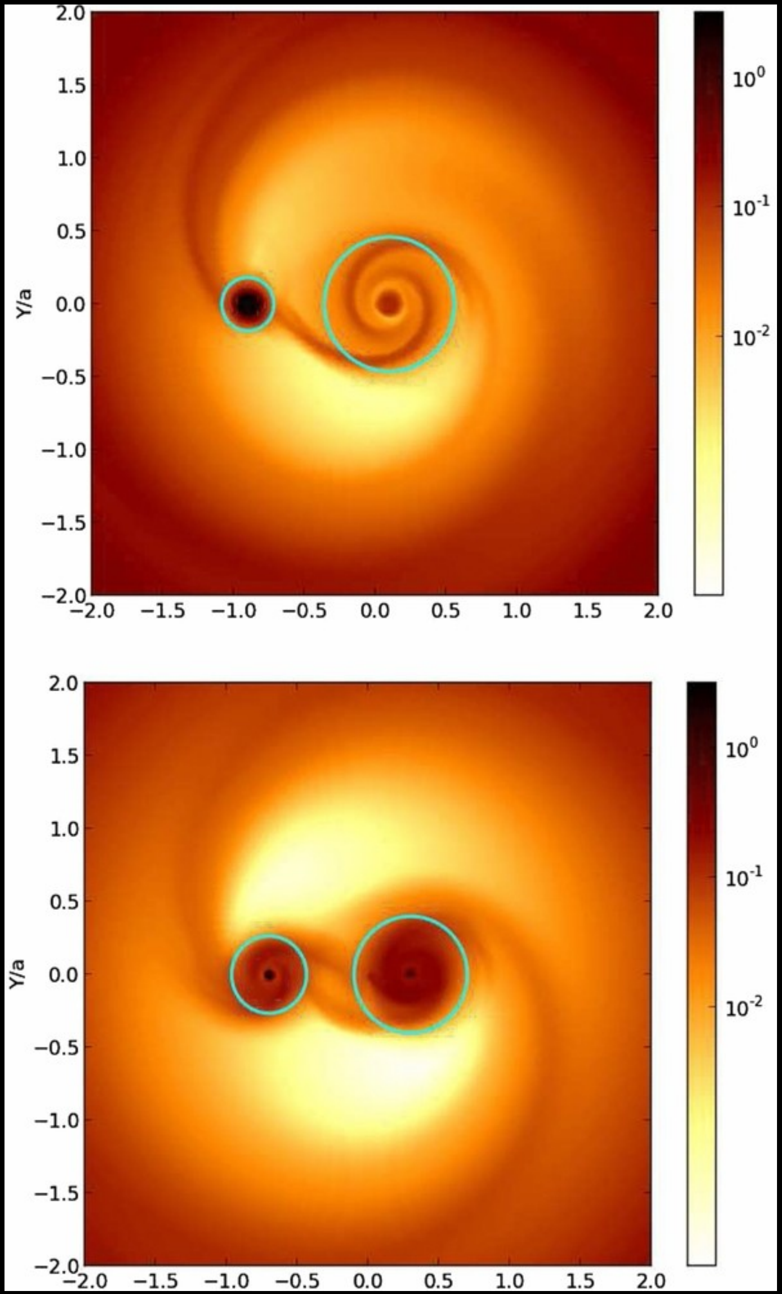
(See also Feng+ 2019; Fan+ 2020; Liu+ 2020; Wang+ 2019,2020,2022; Omiya&Seto 2020; Ruan+ 2019; Orlando+ 2021 ….)

Why multimessenger?

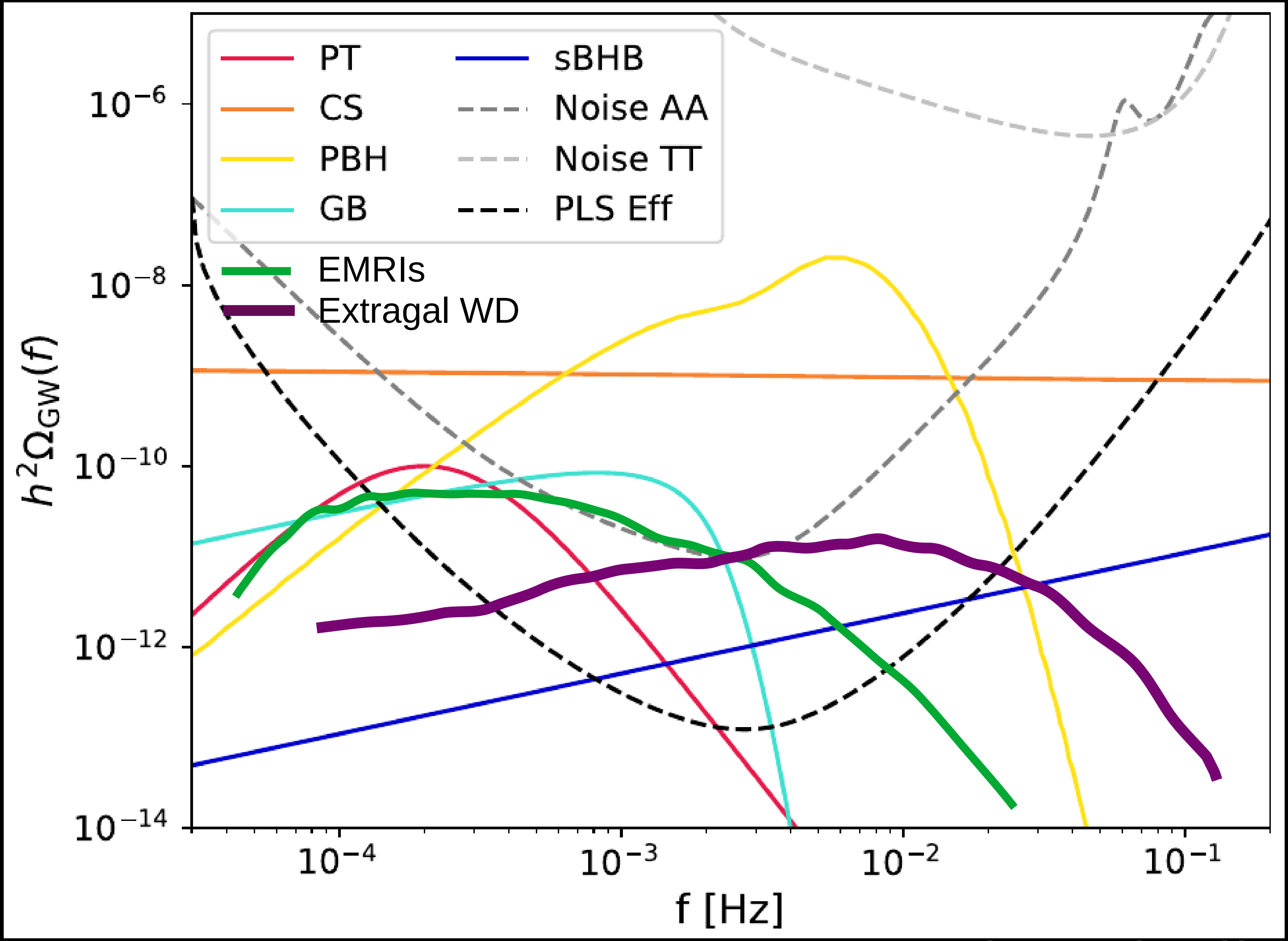
- Cosmology and cosmography at high *z*
- Study of accretion on MBHs with known mass and spins
- Test MBH-galaxy co-evolution
- Study of the interplay between MBHs and gas (torques, disk structure, disk models)
- Host galaxy, Jet launches, Quasar birth ...



LISA Red Book

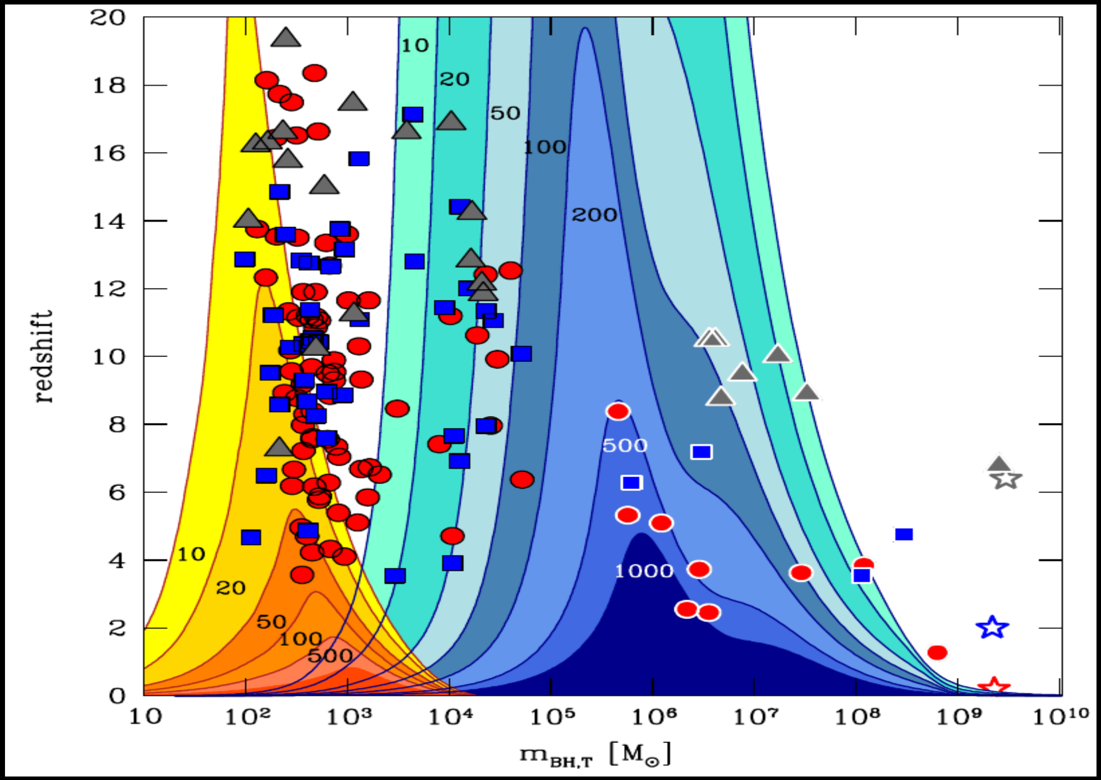


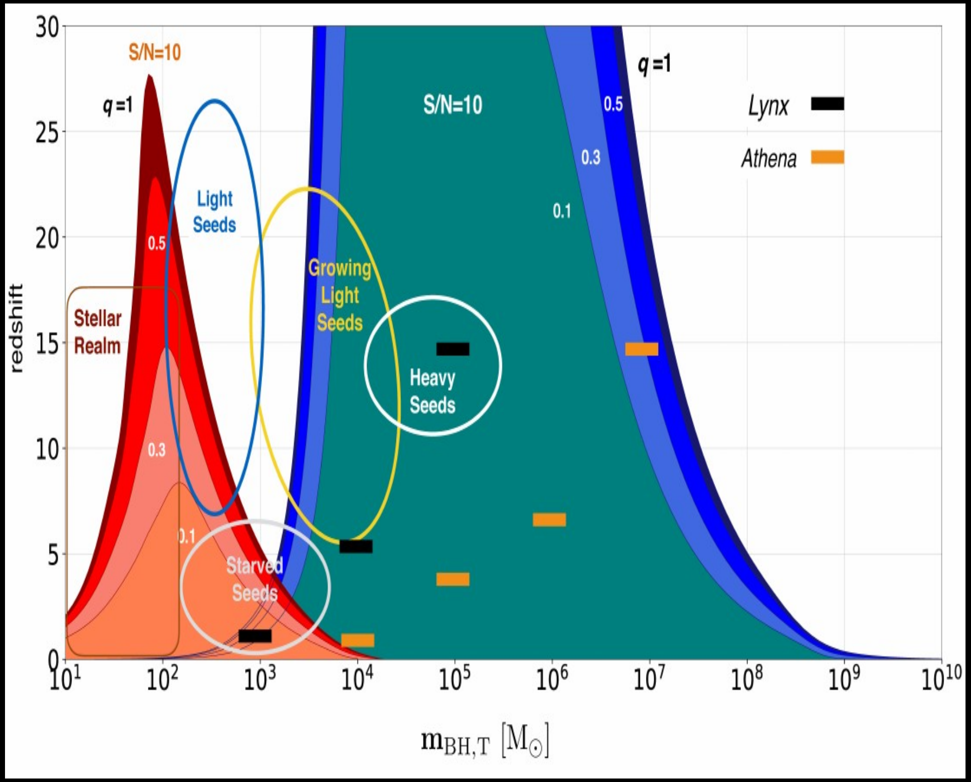
Astro and cosmo stochastic backgrounds

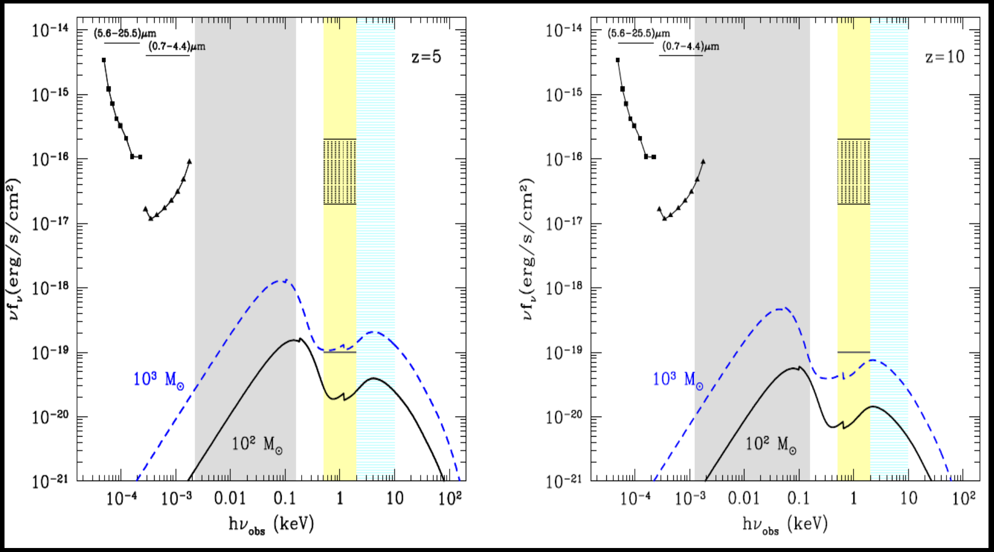


(LISA Red Book)

Complementing LISA with 3G







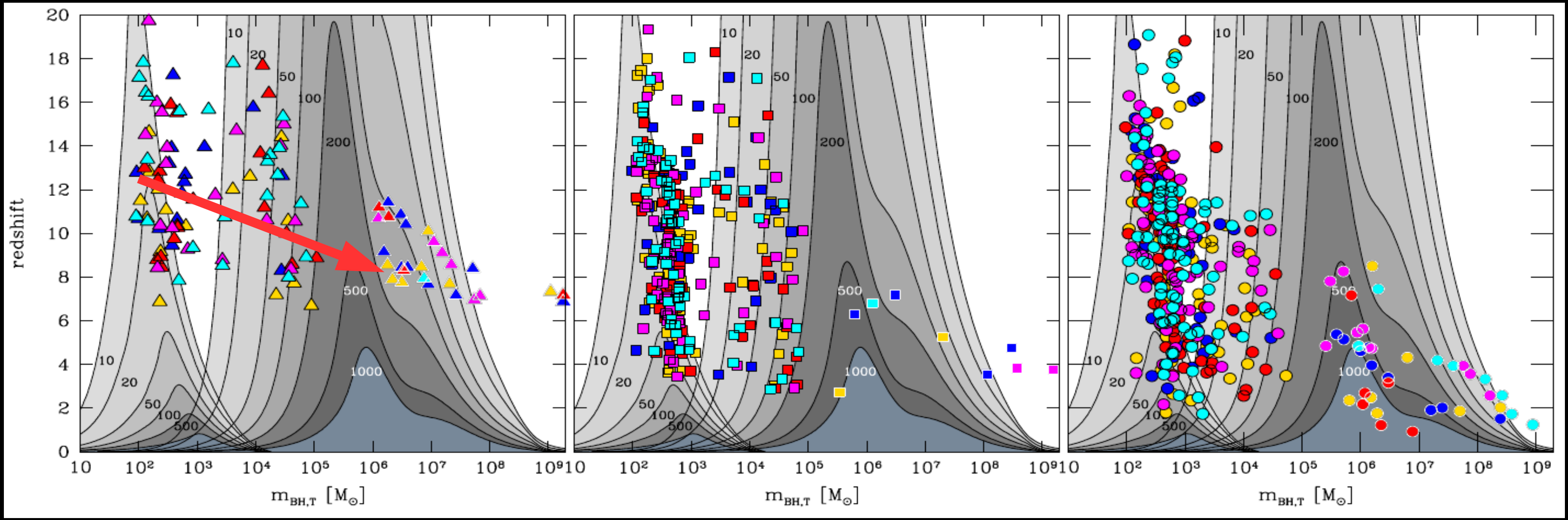
-ET is almost perfectly complementary to LISA

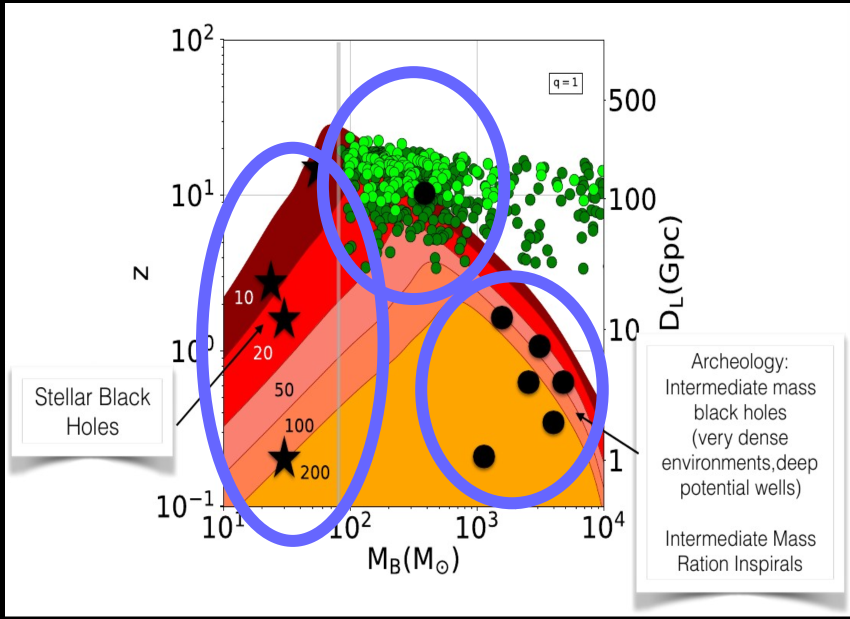
-can see the first mergers of popIII seeds up to high z

-it reaches deeper than EM probes

(Valiante+ 20)

3G as important as LISA for seeds!





-How to connect seeds to SMBHs?

-statistical consistence between LISA and ET detection?

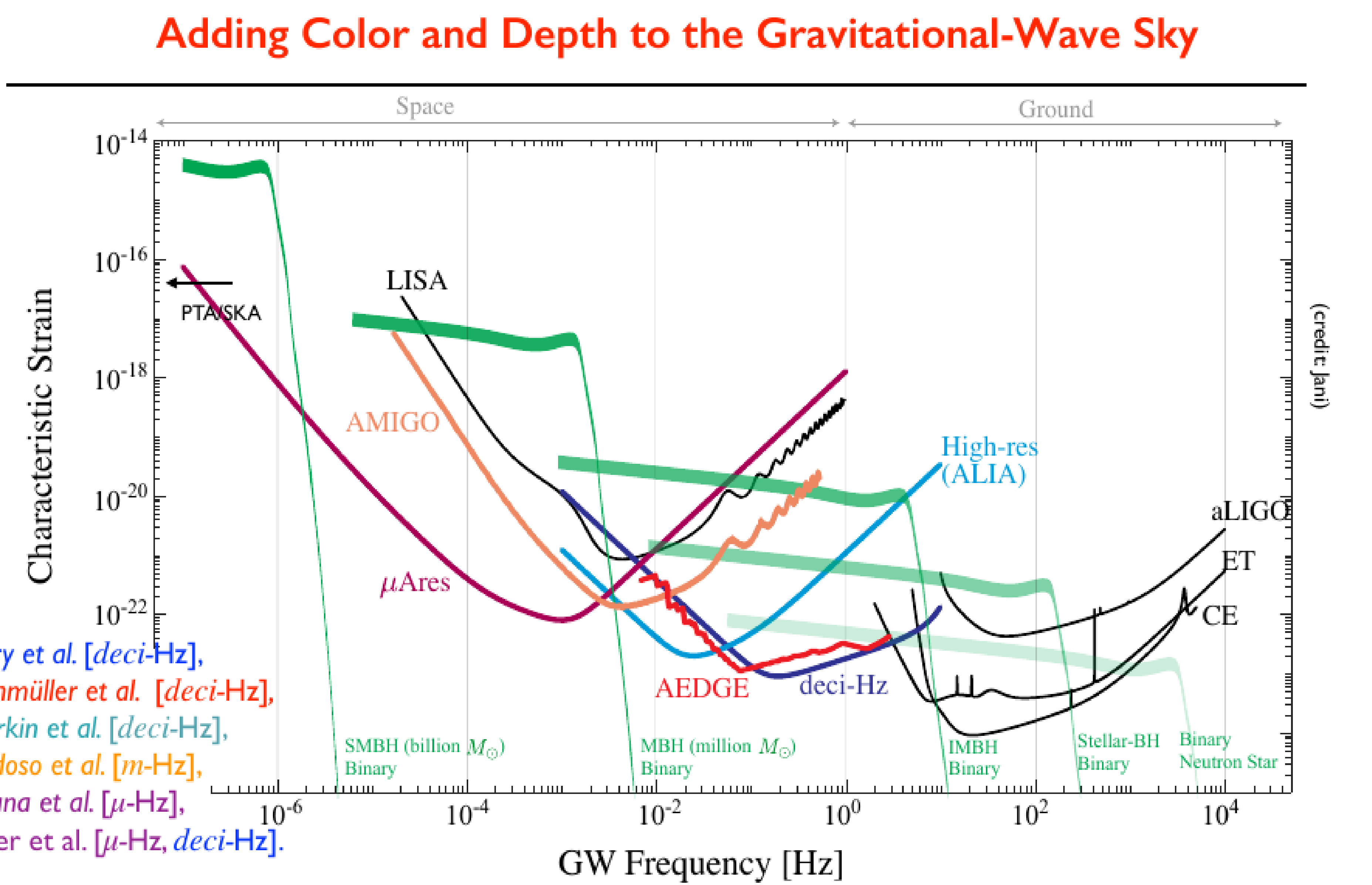
-combination with high z X-ray LF?

-identification of separate subclusters in the ET detected sources?

-Combining MBHs and SOBHs in SAMs? What's the way to go?

...and there's more to come!

GW space detector concepts submitted to the Voyage 2050 call



WPs. Berry *et al.* [*deci*-Hz],
Buchmüller *et al.* [*deci*-Hz],
Dvorkin *et al.* [*deci*-Hz],
Cardoso *et al.* [*m*-Hz],
Sesana *et al.* [μ-Hz],
Baker et al. [μ-Hz, *deci*-Hz].

(Courtesy of A. Buonanno)

Doggybag

LISA will provide an unprecedented view of the gravitational universe

- **-it will observe all MBHB mergers in the Universe**
- **-it will unveil the nature od MBH seeds and their early growth**
- **-it will shed light on the dynamics of MBHBs**
- **-it will allow unprecedented tests of GR**

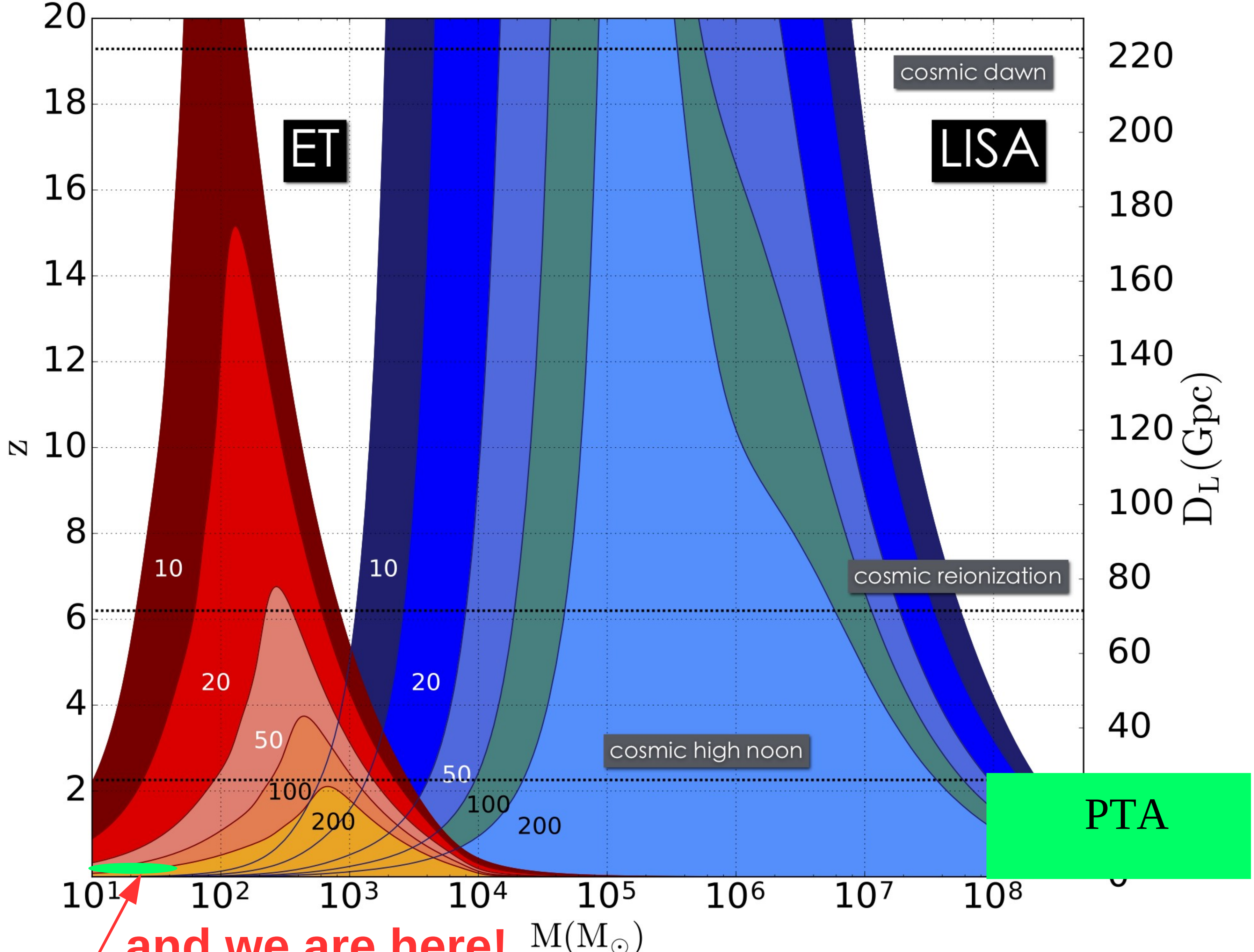
LISA+Athena/LSST/(…) will enable a multimessenger view of MBHBs

- **-cosmography at all redshifts**
- **-accretion theory**
- **-gas dynamics in dynamically evolving spacetime geometries**

LISA+Taiji/Tianqin will allow to pin down the galaxy host of many MBHBs

LISA+3G will enable the full reconstruction of the MBH cosmic history

...In about 20 years…



...and we are here!