Setting the GW stage: The low frequency realm (LISA & PTA)

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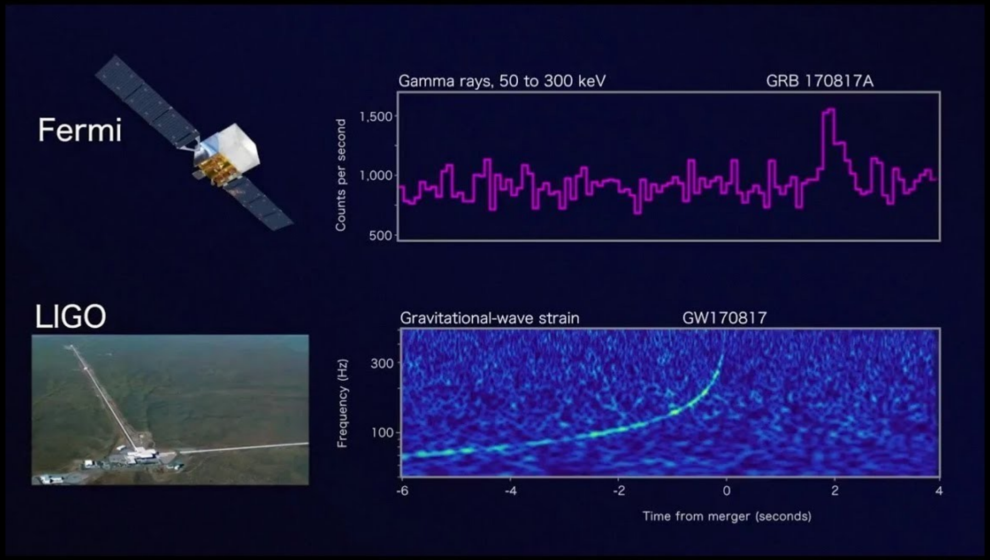
(Universita` di Milano Bicocca)

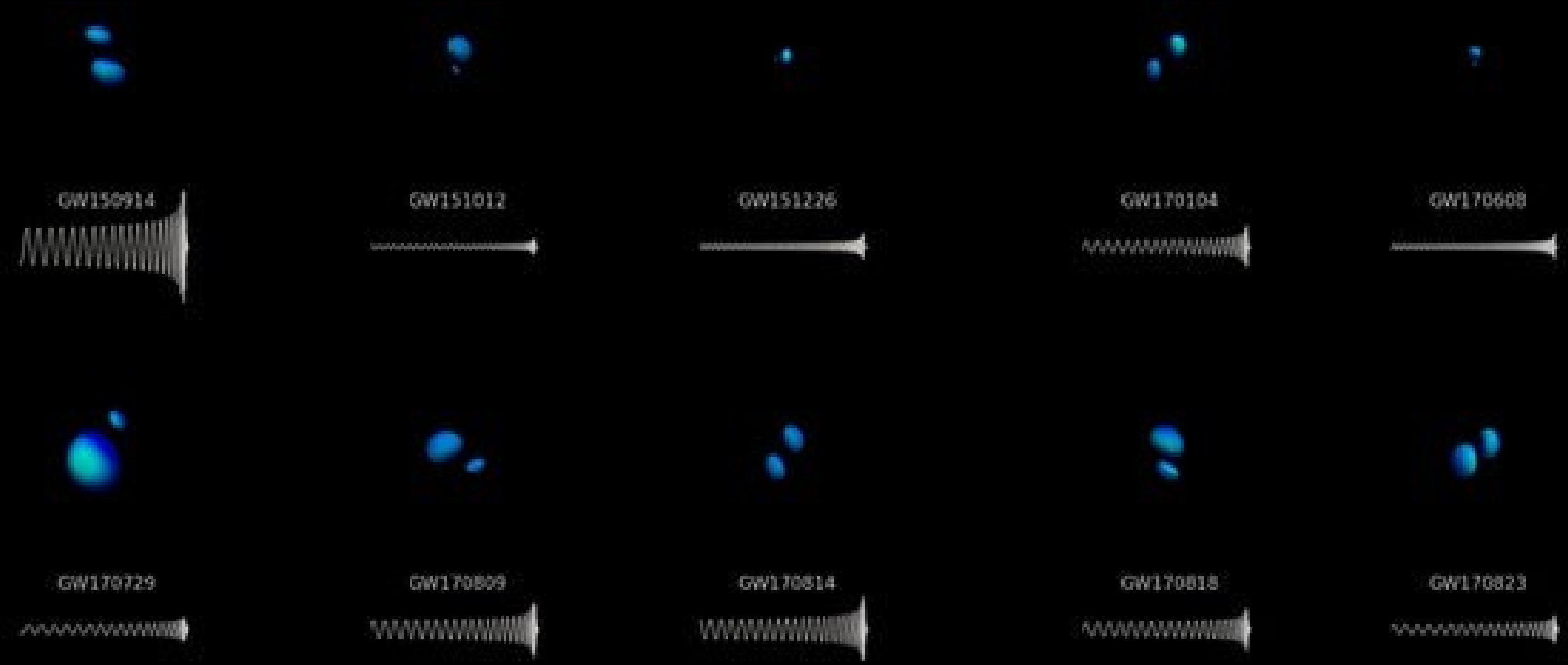
Habemus GWs!

We see black hole binaries (BHB) and neutron star (NS) binaries coalescing for the first time (several Abbott+ 2016 2017)

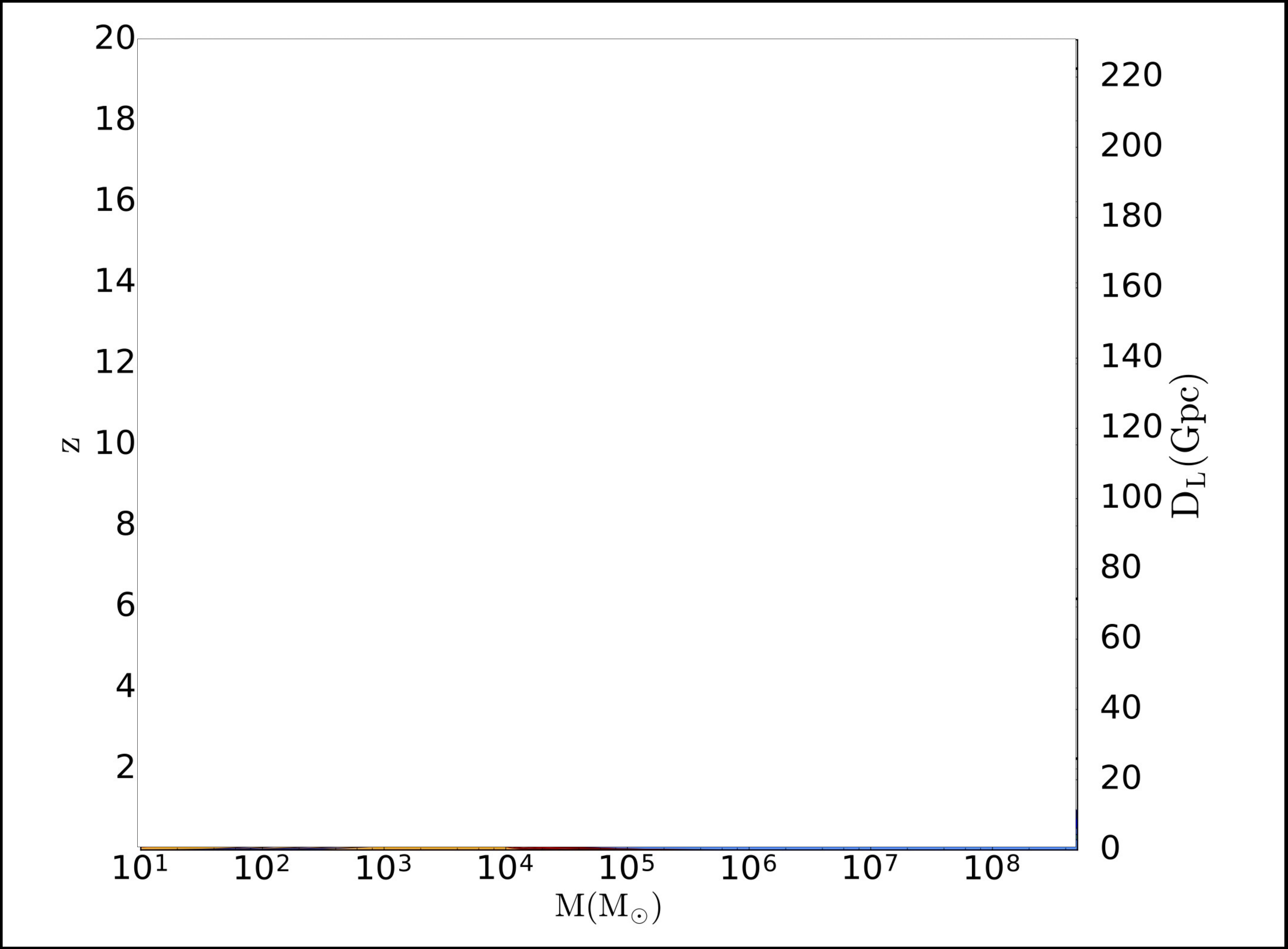


- -GRB-NS merger connection
- -Heavy element production
- -NS EoS
- -First tests of GR in the strong field regime
- -Interesting astrophysical information (masses, spins)

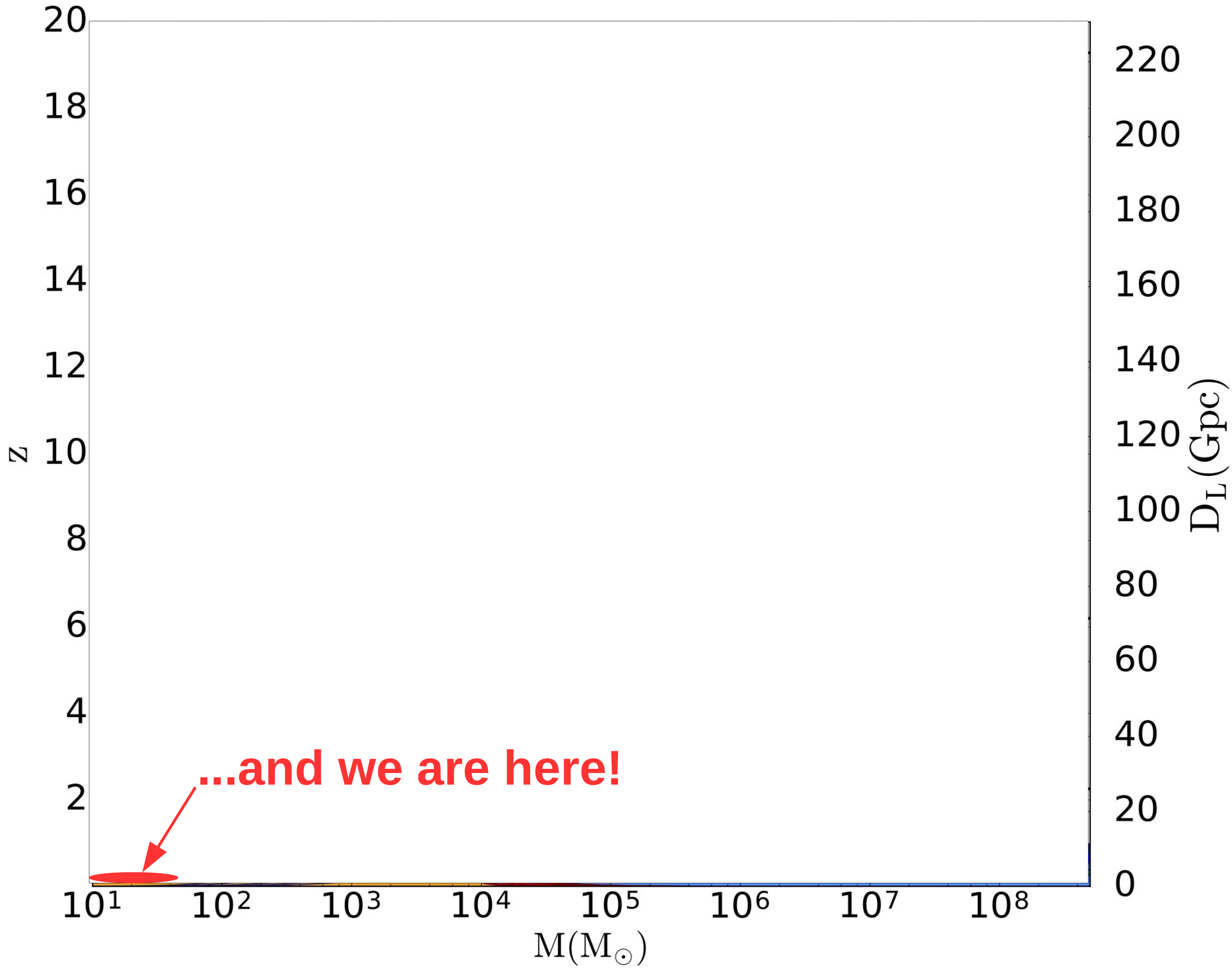
→ Formation scenario?

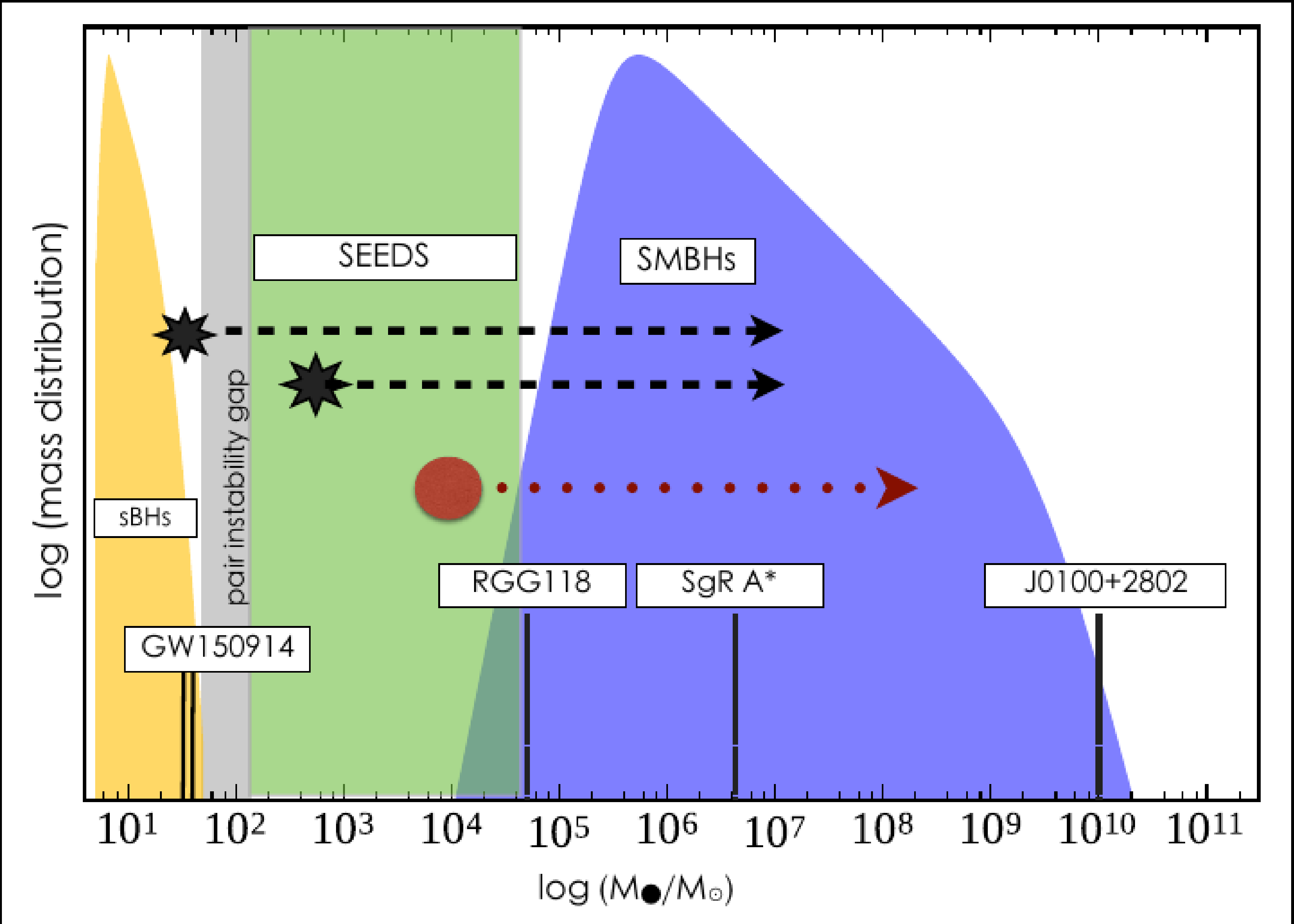


The parameter space of black holes

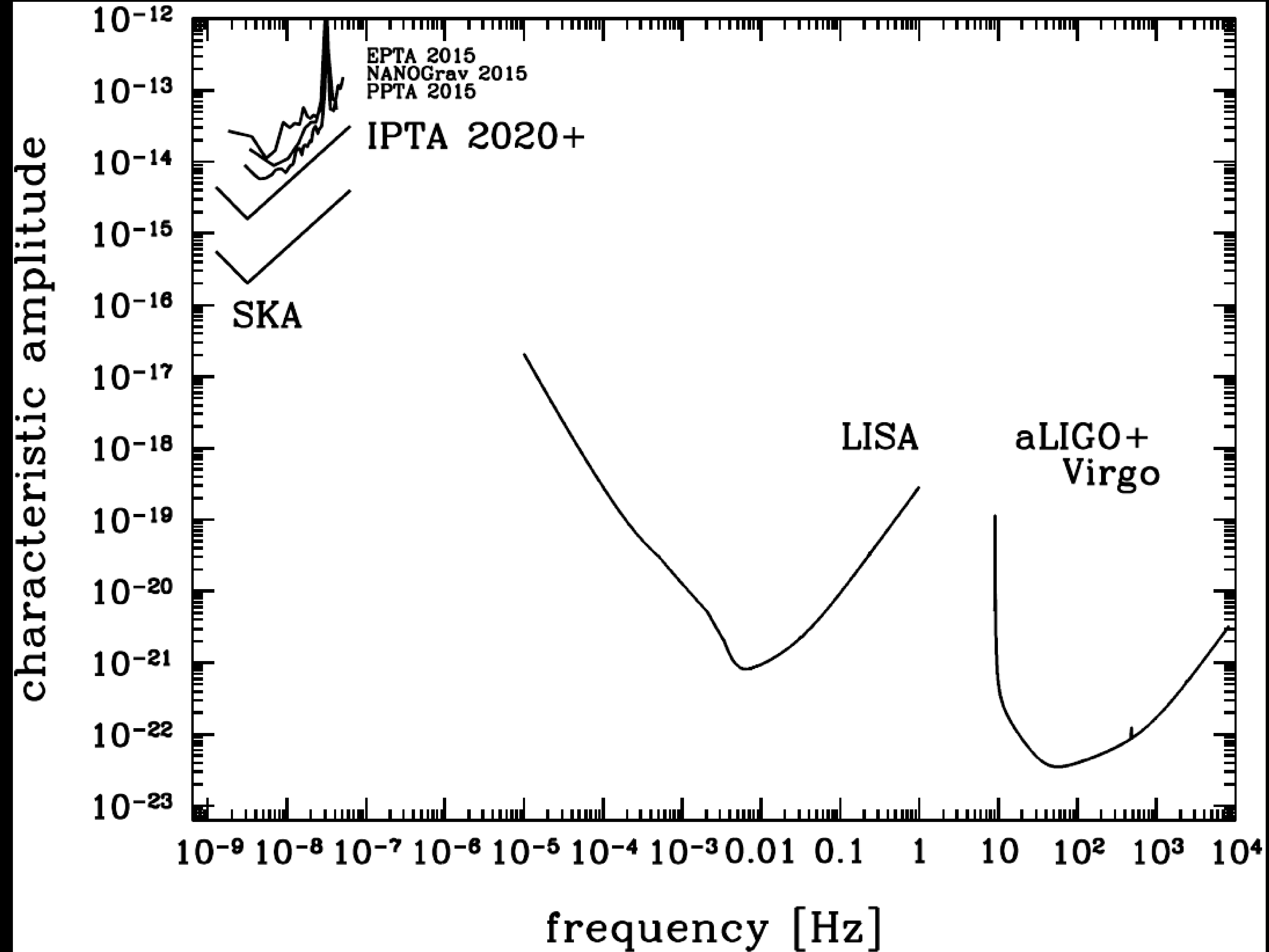


The parameter space of black holes

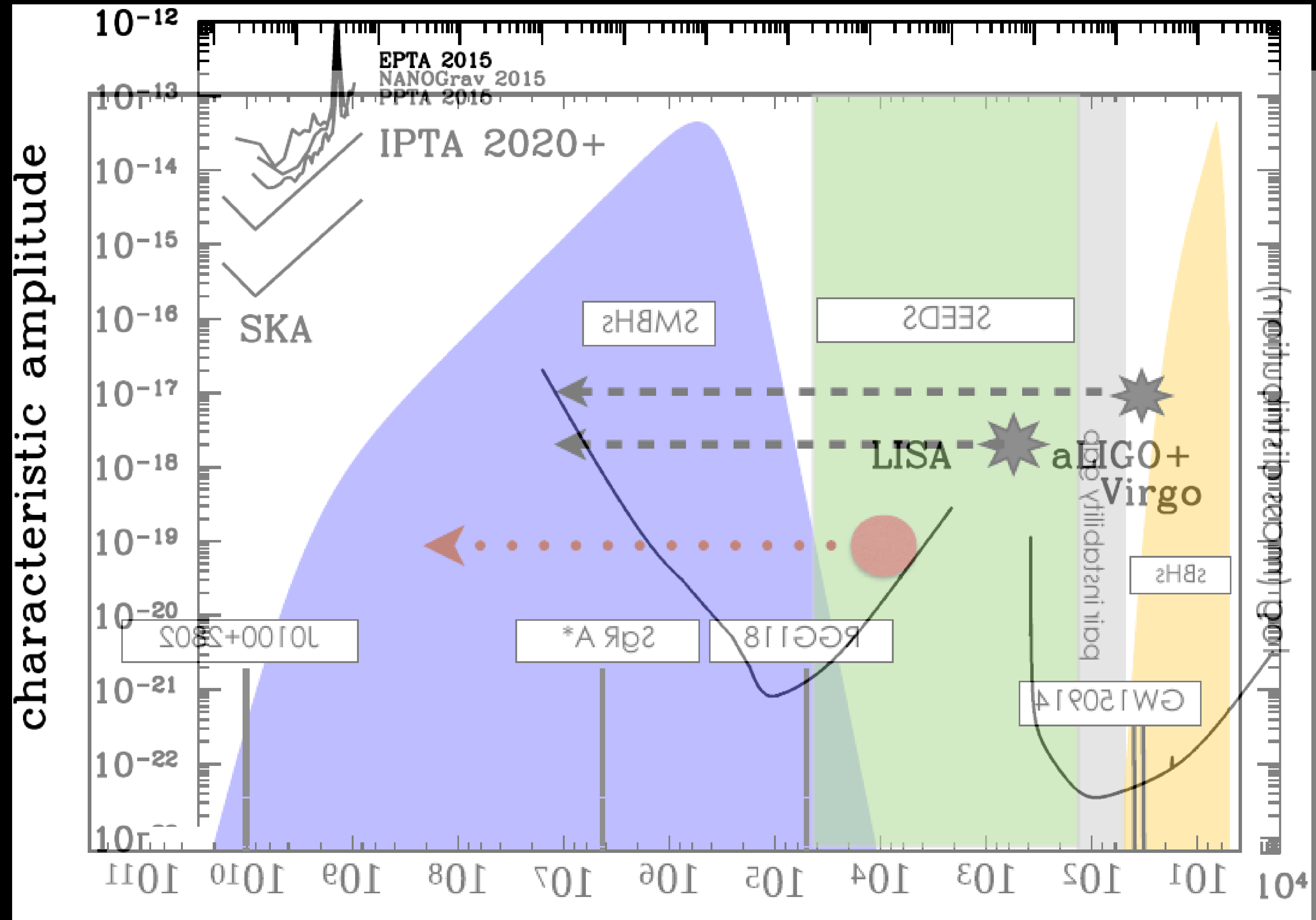




log (mass distribution)
log (M●/M☉)
SEEDS
SMBHs
sBHs
pair instability gap
GW150914
RGG118
SgR A*
J0100+2802
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11



EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
LISA
aLIGO+
Virgo
characteristic amplitude
frequency [Hz]
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^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 0.01 0.1 1 10 10^{2} 10^{3} 10^{4}



characteristic amplitude
EPTA 2015
NANOGrav 2015
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SKA
SMBHs
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LISA
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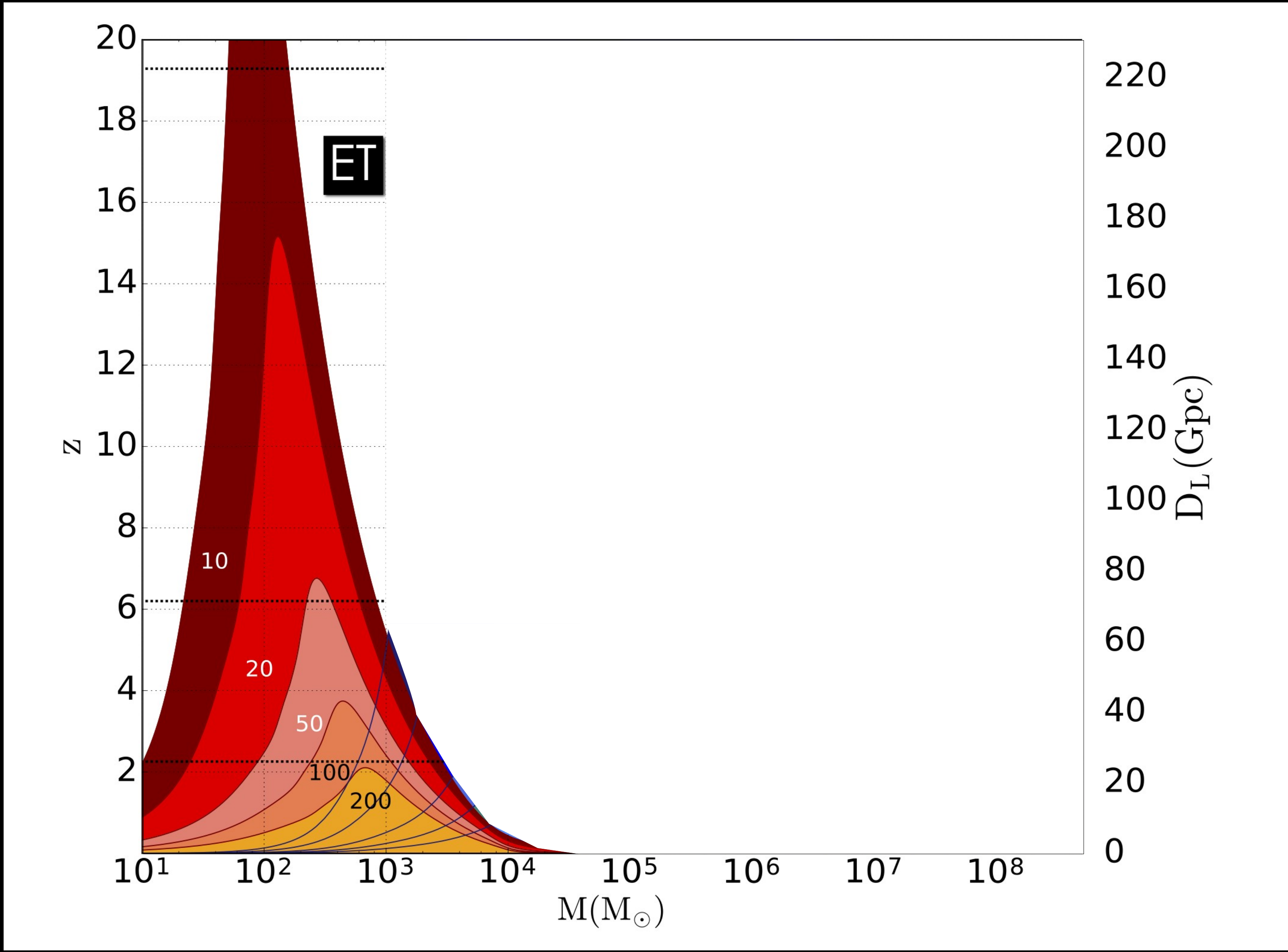
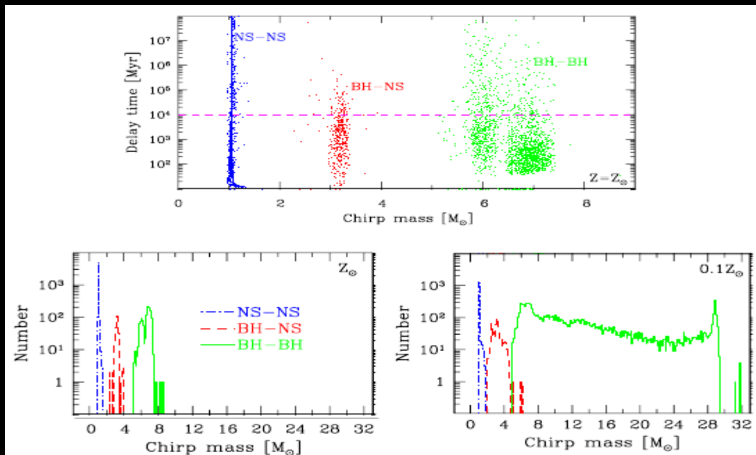
Virgo
sBHs
J0100+2802
Sgr A*
RGG118
GW150914
pair instability gap

3G detectors: example reach of ET



- All LIGO-like BHBs in the Universe up to z~20 (~10^5/yr)
- All neutron star binaries (NSBs) to z~2-3 (~10^4/yr)
- intermediate mass Bhs (IMBHs) up to z~2 (???)
- SNe? Rotating NSs?



A glimpse of astrophysics:

Cosmic NSB BHB NS-BH merger rate

-NS-BH mass gap?

-Second mass gap?

-IMBH mass gap/desert?

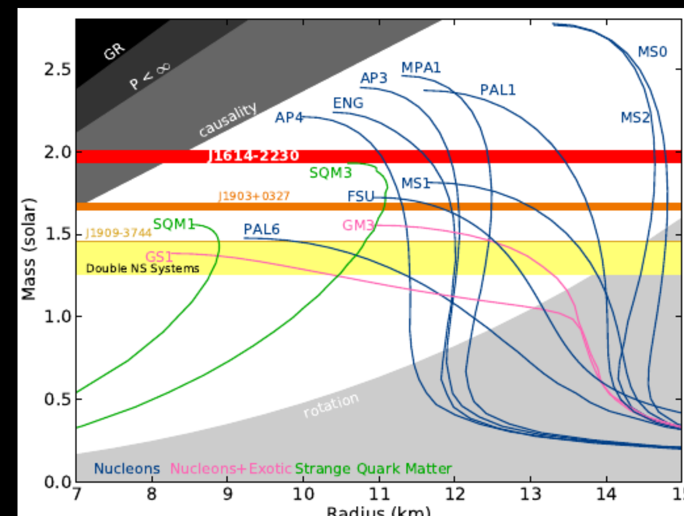
-Astrophysical origin (eg field vs clusters)?

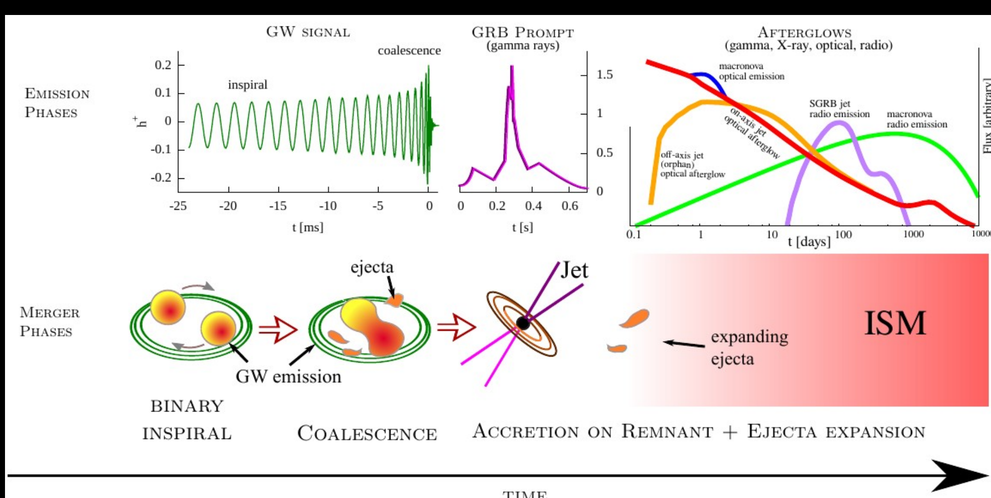
(DeMink+ Belczinsky+ Mandel+ Rasio+ Antonini+ Rodriguez+ Kocsis+ Naoz+ ....)

Nuclear physics with NS mergers

Constrain the equation of state of ultradense NS matter **(Read+ Hinderer+ Del Pozzo+ ...)**

Gravitational wave spectroscopy of merger remnants? **(Rezzolla+, Bernuzzi+ Shibata+ ...)**





Multim@#$%&!% astronomy

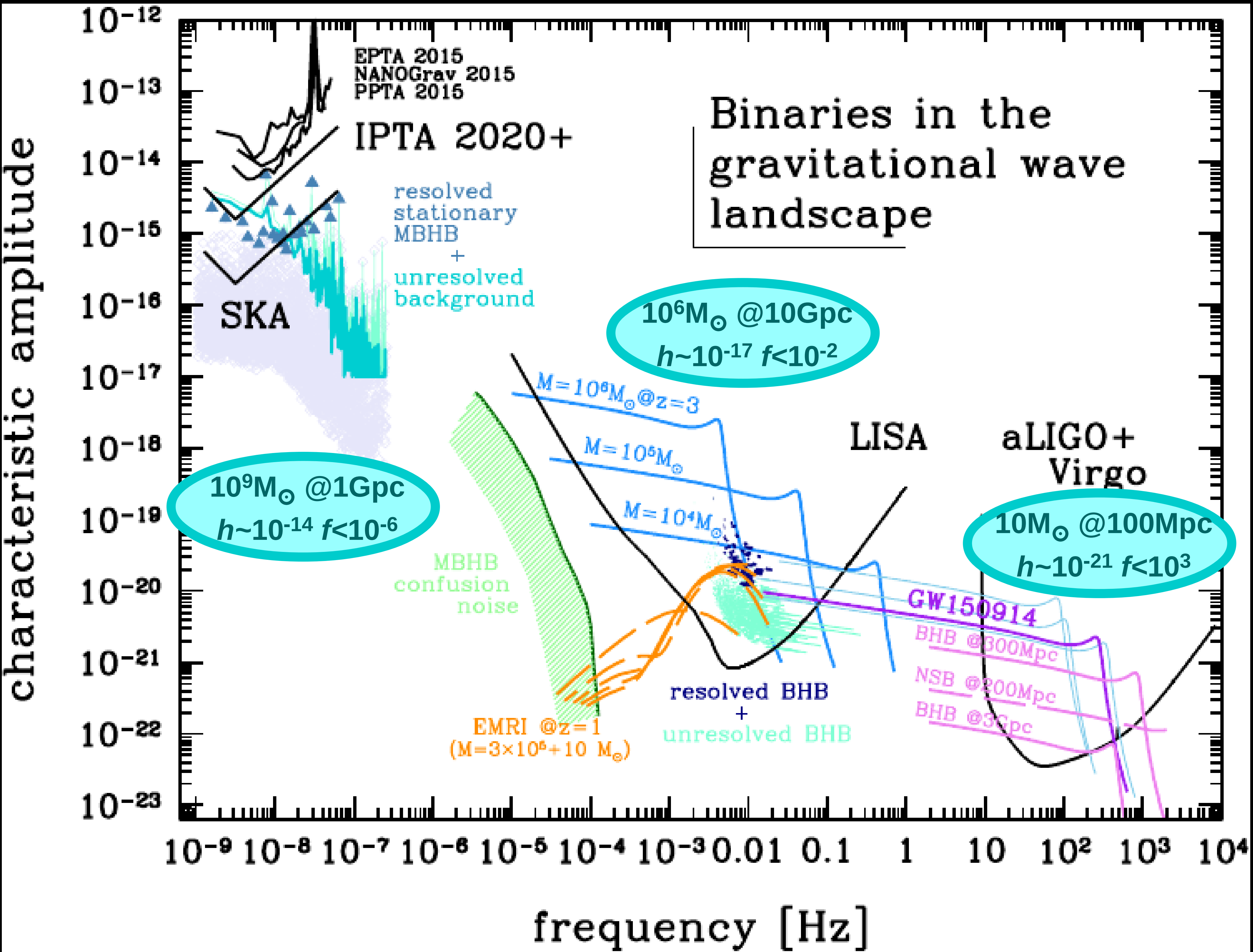
-short GRBs?

-X-ray isotropic?

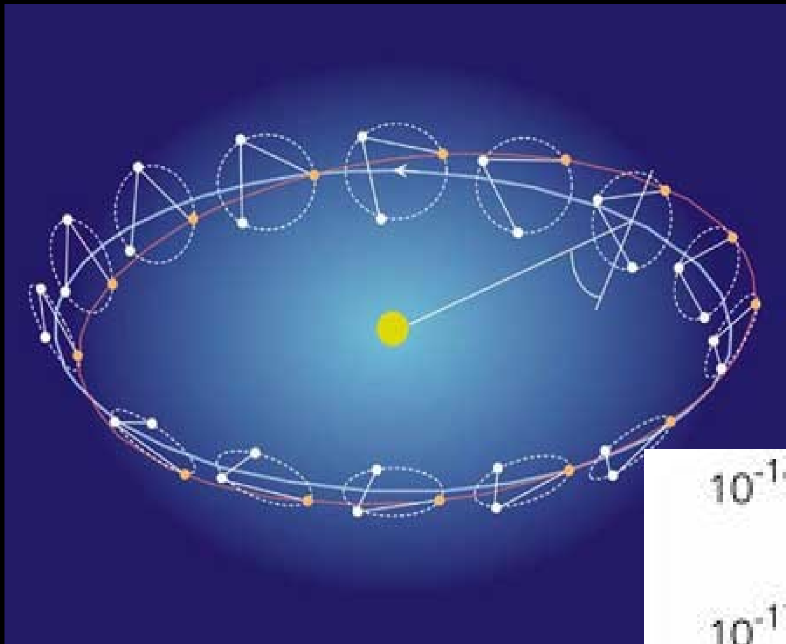
-IR Kilonova?

-long term radio followup?

(Metzger & Berger 2012, Abbott+ 2017 see all the rest of the conference)

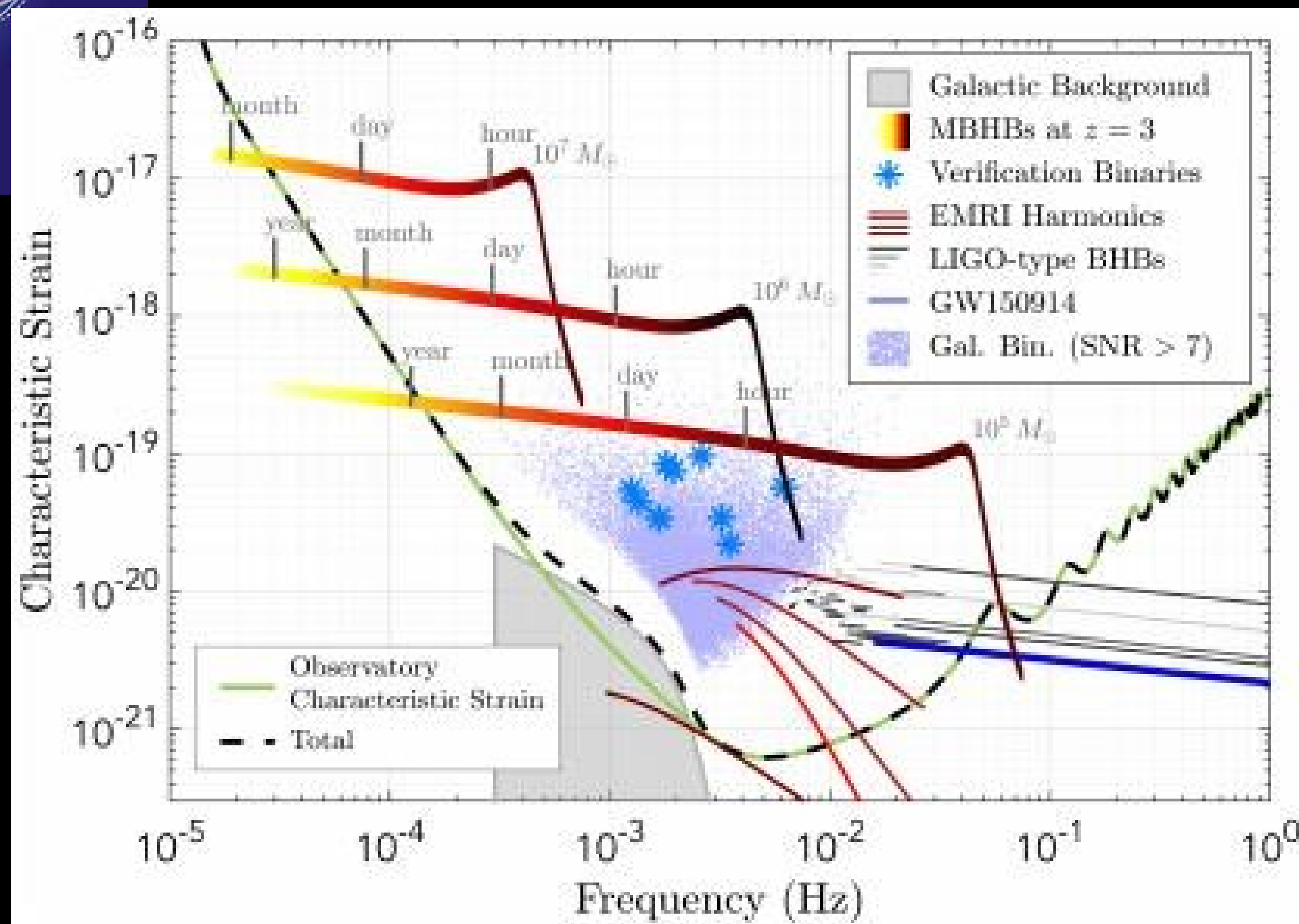

Binaries in the gravitational wave landscape
characteristic amplitude
frequency [Hz]
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB
+
unresolved background
$10^6 M_\odot$ @10Gpc
h~10^{-17} f<10^{-2}
$10^9 M_\odot$ @1Gpc
h~10^{-14} f<10^{-6}
$10 M_\odot$ @100Mpc
h~10^{-21} f<10^3
$M=10^6 M_\odot$@z=3
$M=10^5 M_\odot$
$M=10^4 M_\odot$
LISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
resolved BHB
+
unresolved BHB
EMRI @z=1
($M=3\times10^5+10\ M_\odot$)
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^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 0.01 0.1 1 10 10^2 10^3 10^4

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



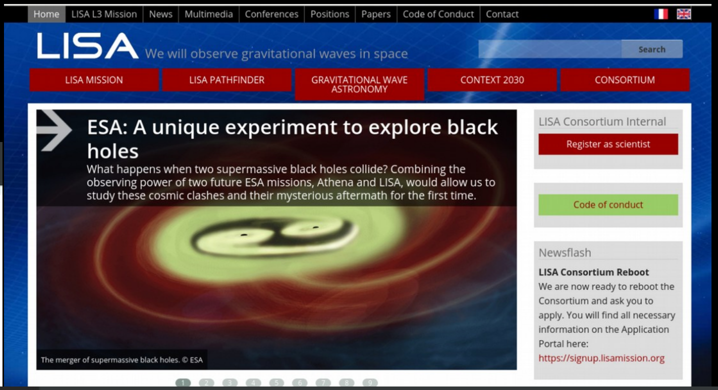
3 satellites trailing the Earth connected through laser links

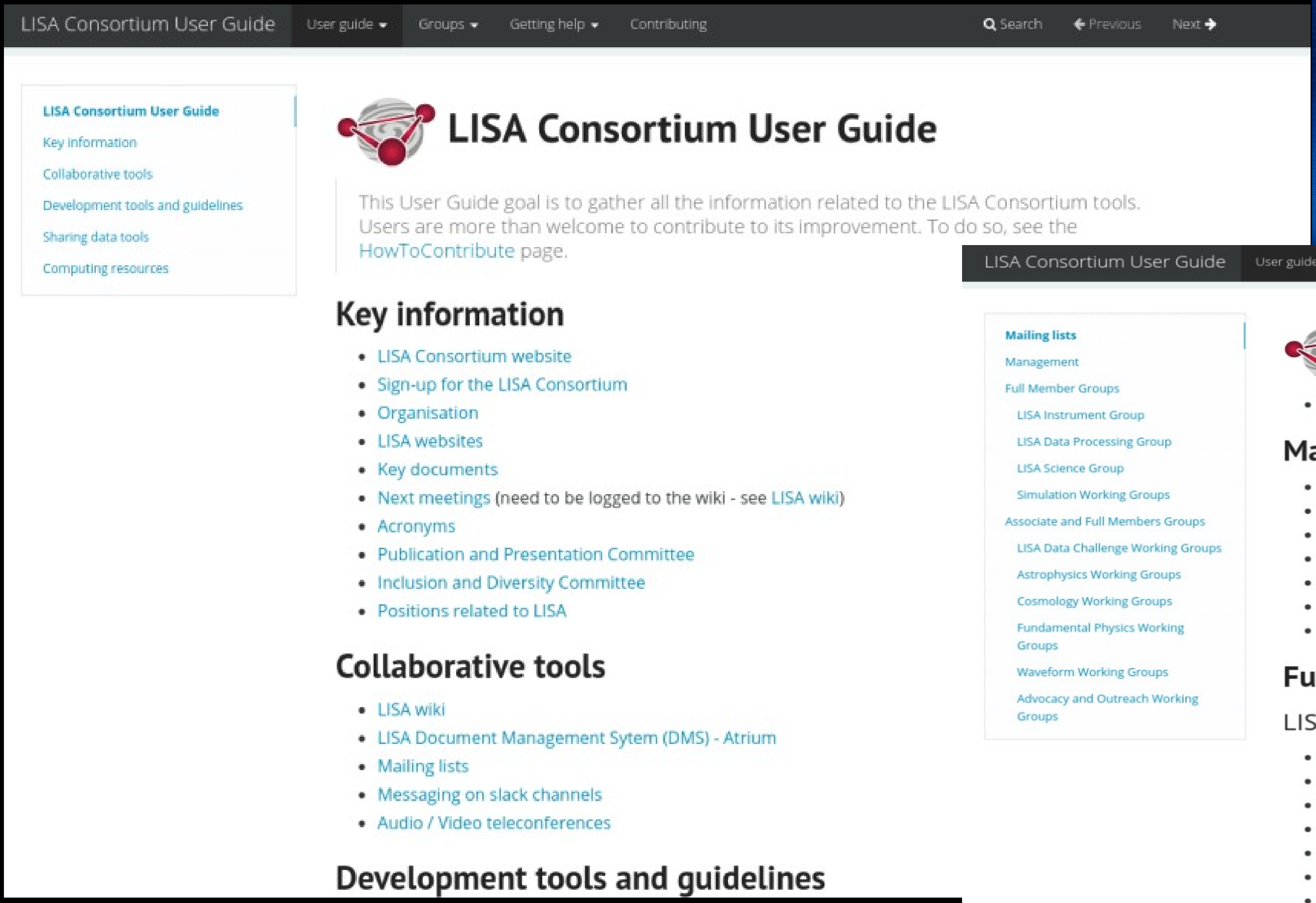
Proposed baseline:
2.5M km armlength
6 laser links
4 yr lifetime (10 yr goal)

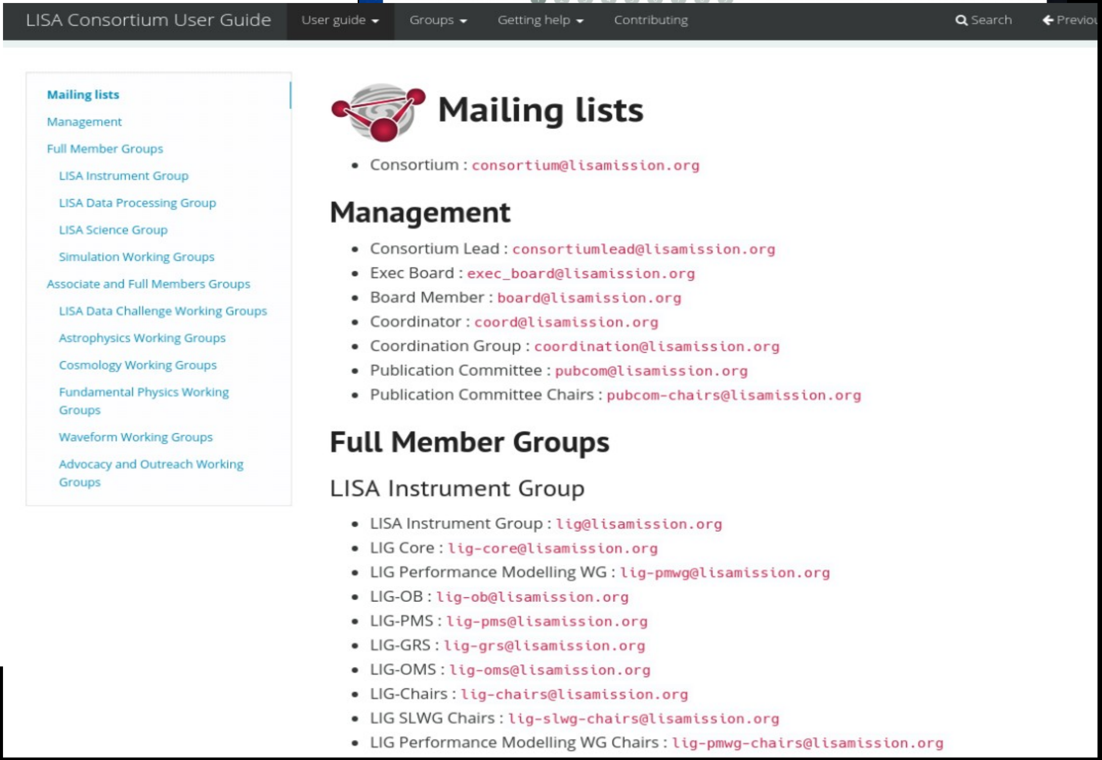
The LISA Consortium

- Now a thriving community: 800+ among full and associate members
- Several **working groups** connecting to the community: astrophysics, fundamental physics, cosmology, waveforms
- Several **working packages** defining deliverables
- 2 consortium meetings/yr, LISA symposium every 2 years, dedicated WG meetings every year

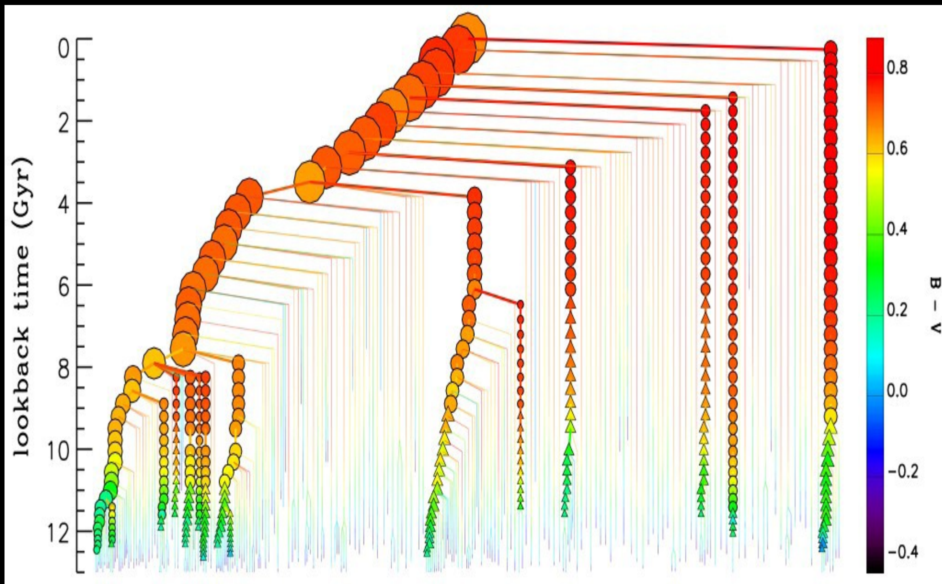
https://www.lisamission.org/







MBH evolution in a nutshell



(From de Lucia et al. 2006)

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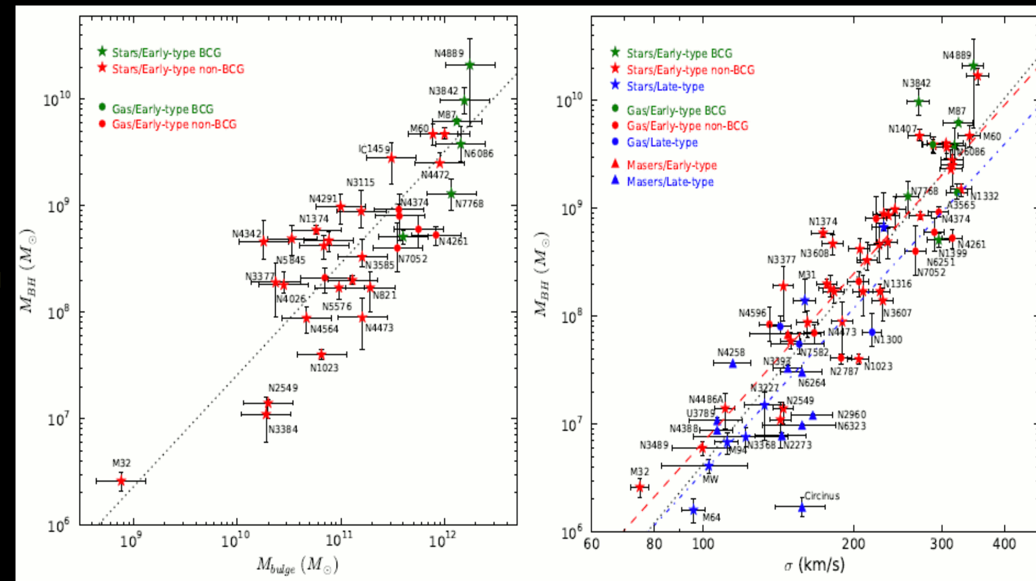

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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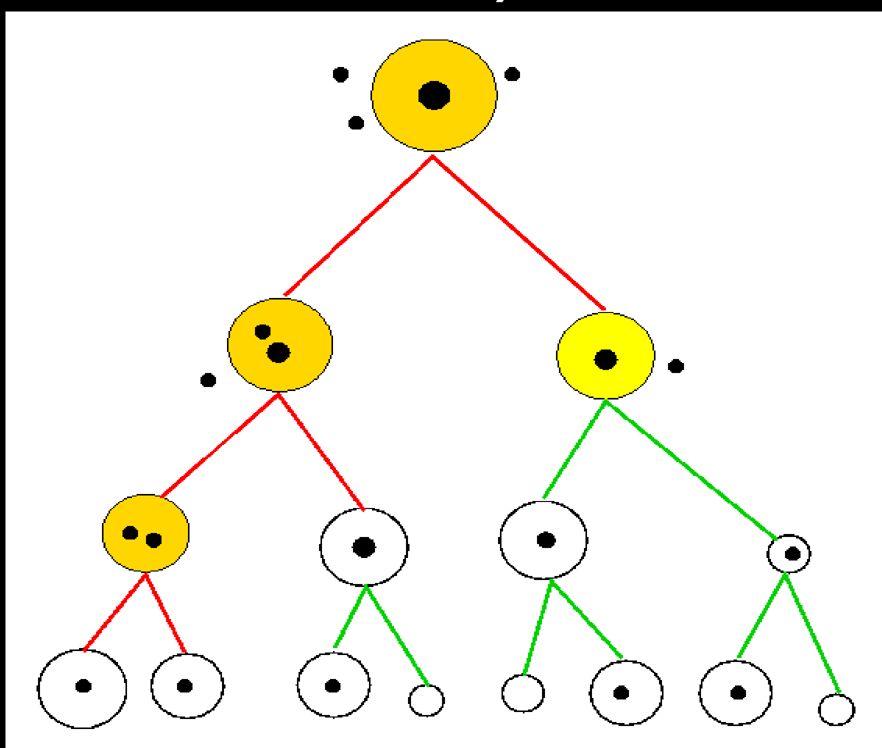
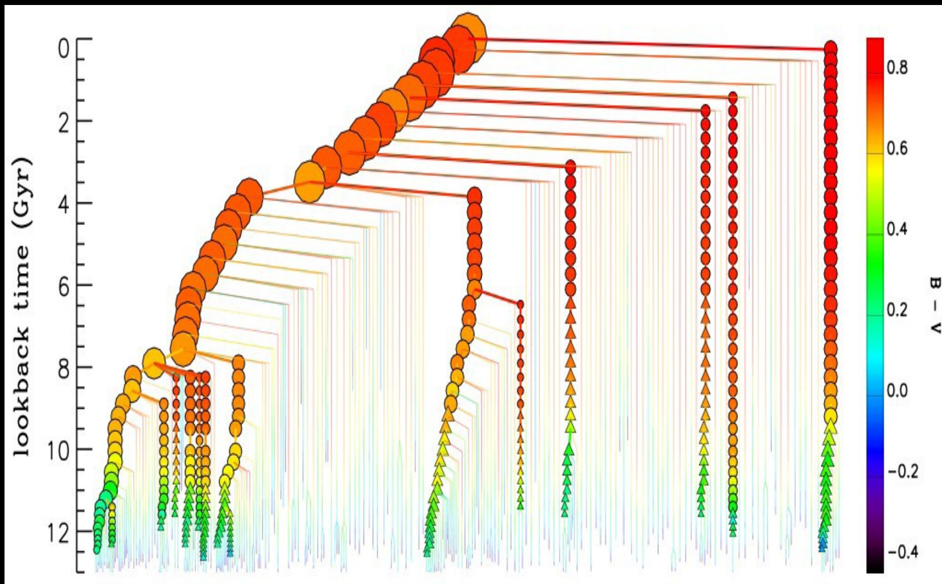


(Menou et al 2001, Volonteri et al. 2003)

MBH evolution in a nutshell



(From de Lucia et al. 2006)

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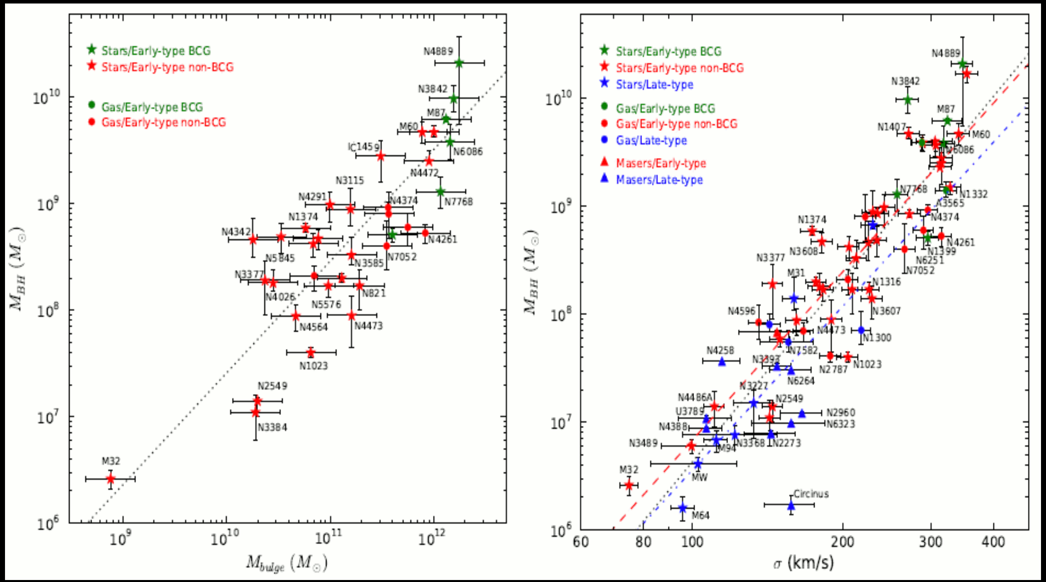

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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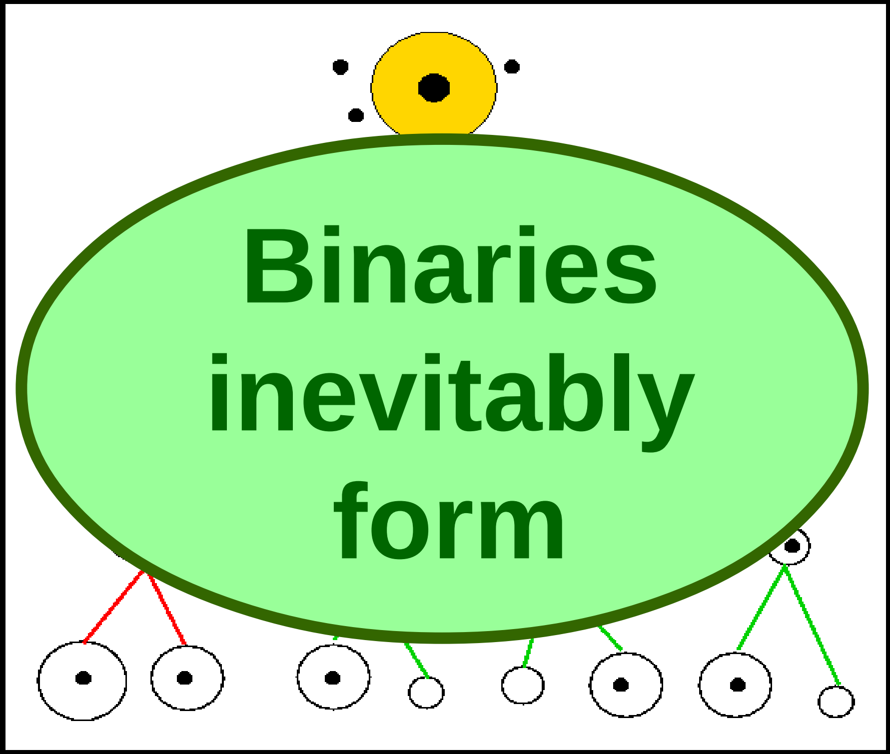
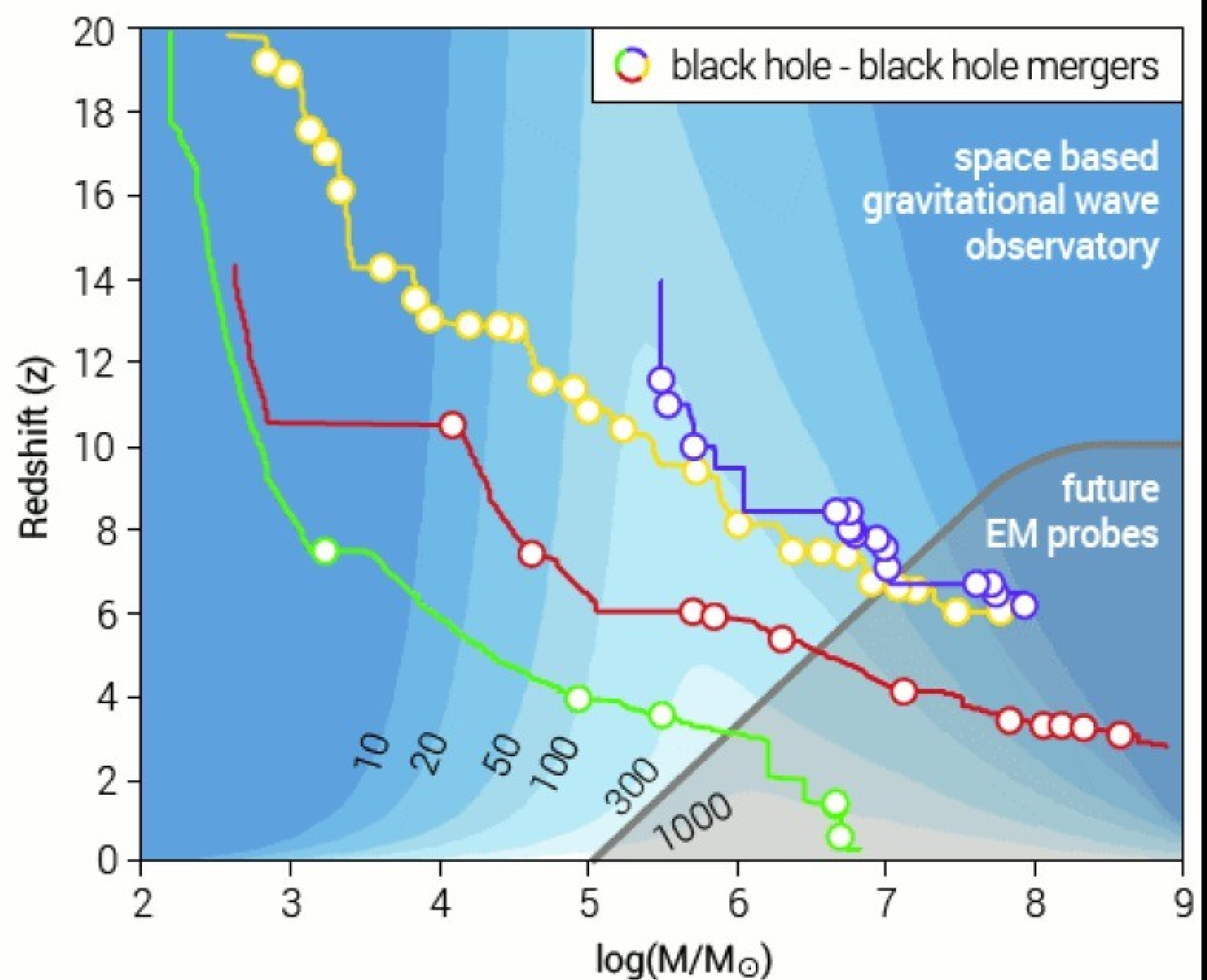


(Menou et al 2001, Volonteri et al. 2003)

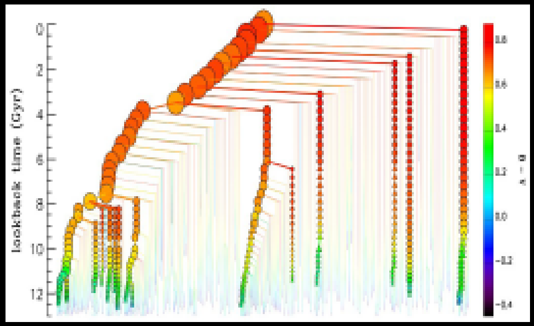
*Where and when do the first MBH seeds form?
*How do they grow along the cosmic history?
*What is their role in galaxy evolution?
*What is their merger rate?
*How do they pair together and dynamically evolve?


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

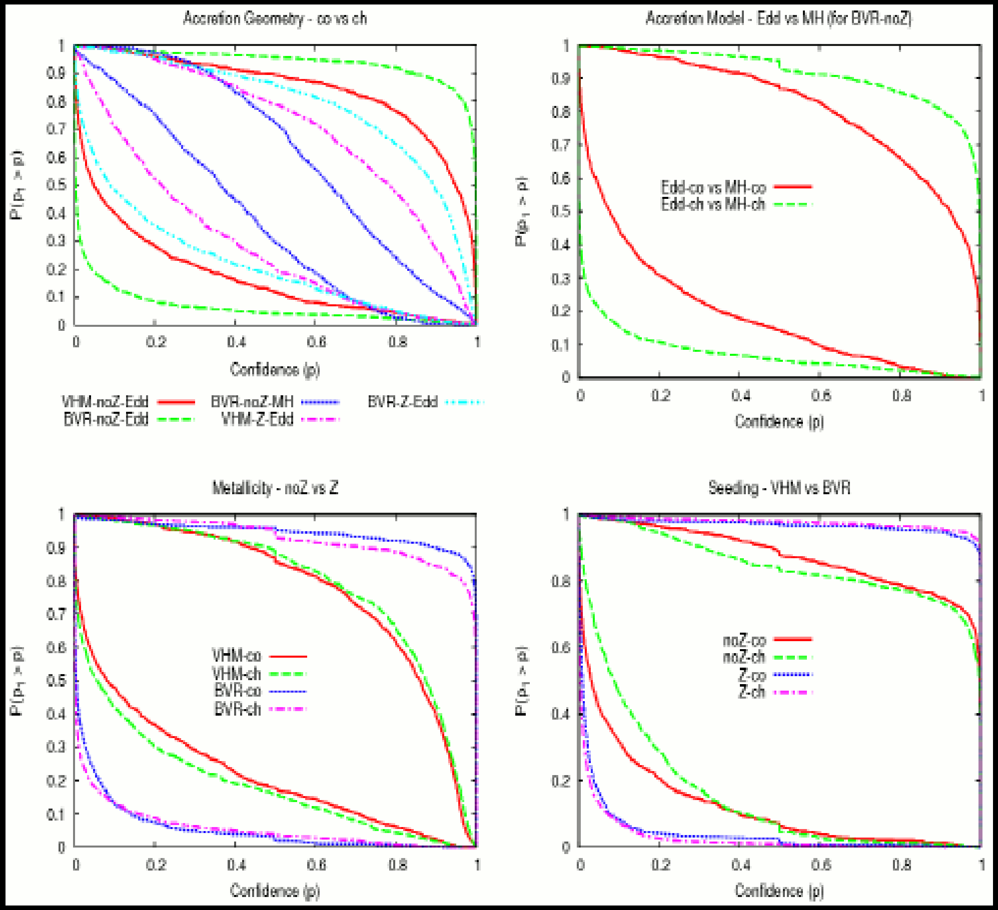
MBH astrophysics with GW observations

Astrophysical unknowns in MBH formation scenarios

1- MBH seeding mechanism (heavy vs light seeds)
2- Metallicity feedback (metal free vs all metallicities)
3- Accretion efficiency (Eddington?)
4- Accretion geometry (coherent vs. chaotic)



CRUCIAL QUESTION:
Given a set of LISA observation of coalescing MBH binaries, what astrophysical information about the underlying population can we recover?

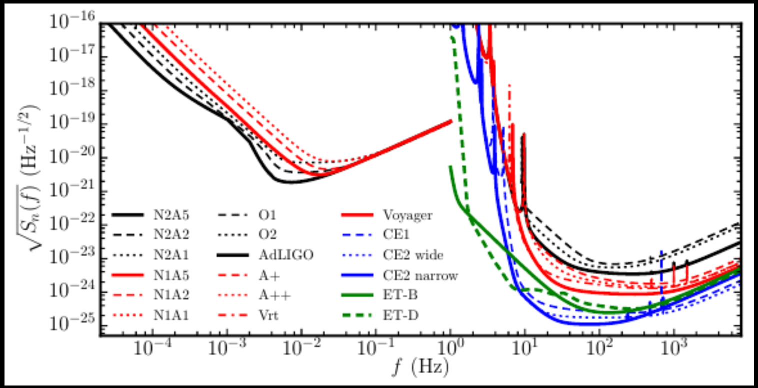


Create catalogues of observed binaries including errors from eLISA observations and compare observations with theoretical models

AS et al. 2011, see also Plowman et al 2011

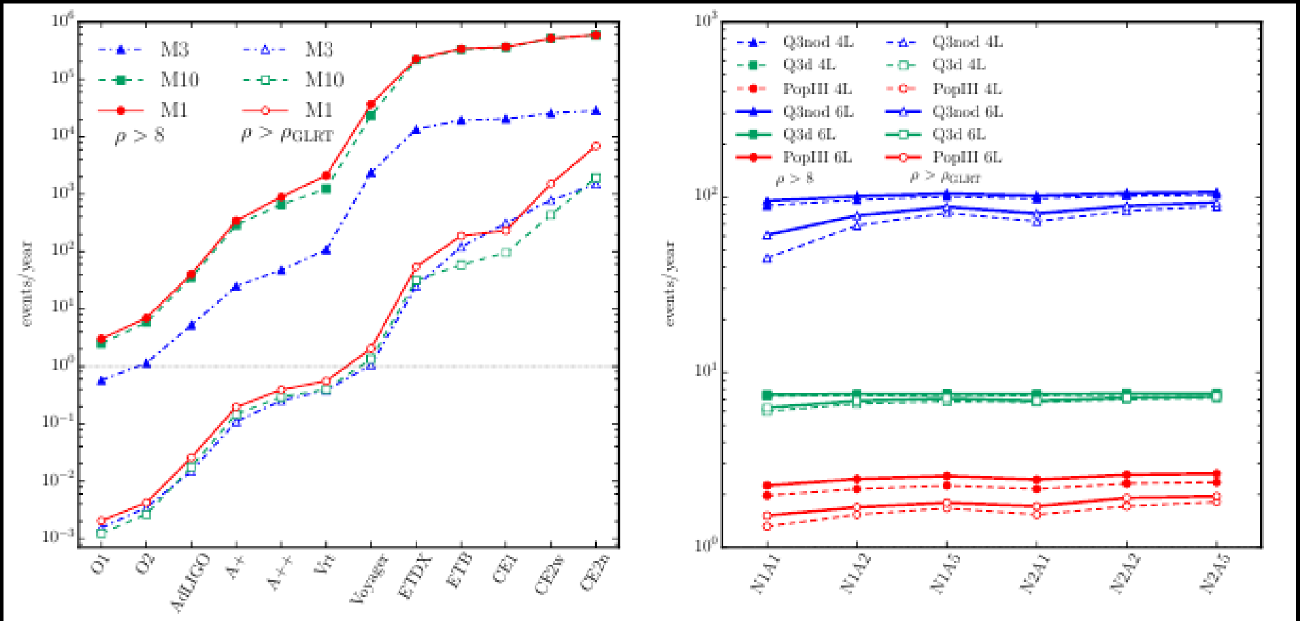
Resolving ringdown modes: BH spectroscopy

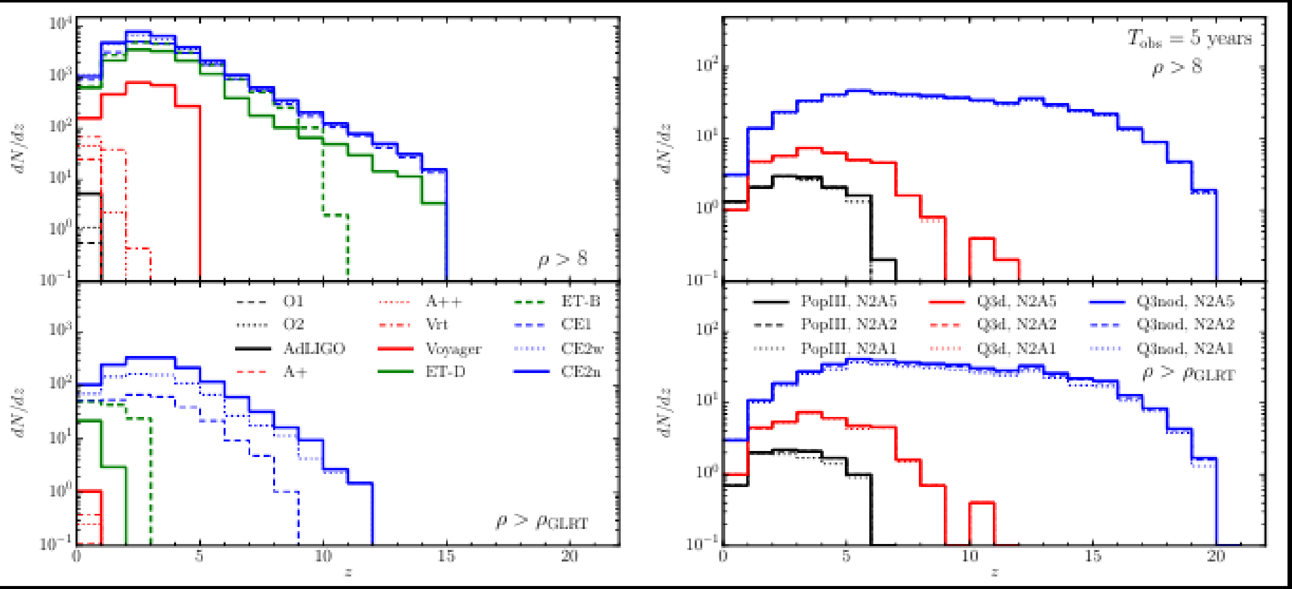
(Berti et al. 2016)



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

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





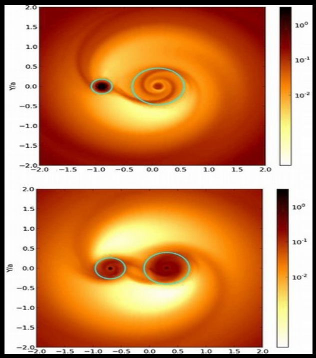
LIGO will not enable BH spectroscopy on individual BHB mergers

Voyager/ET type detectors are needed

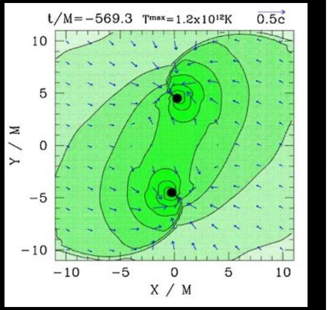
eLISA will enable precise BH spectroscopy on few to 100 events/yr also at very high redshifts

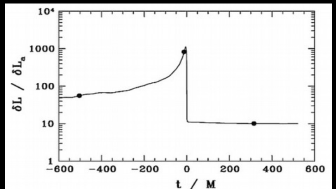
Associated electromagnetic signatures?

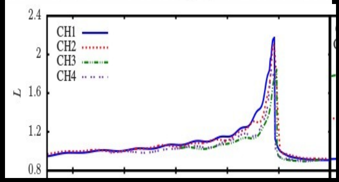
In the standard circumbinary disk scenario, the binary carves a cavity: no EM signal (Phinney & Milosavljevic 2005).
However, all simulations (hydro, MHD) showed significant mass inflow (Cuadra et al. 2009, Shi et al 2011, Farris et al 2014...)

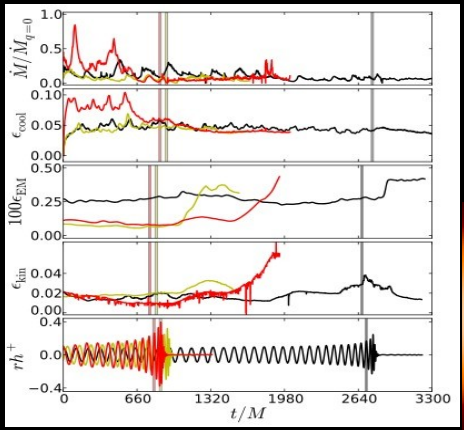


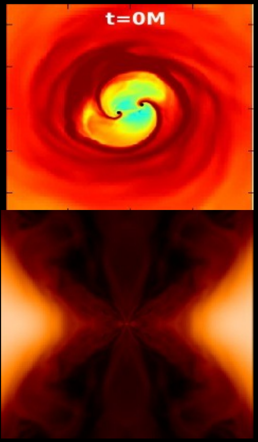
Simulations in hot gaseous clouds. Significant flare associated to merger (Bode et al. 2010, 2012, Farris et al 2012)





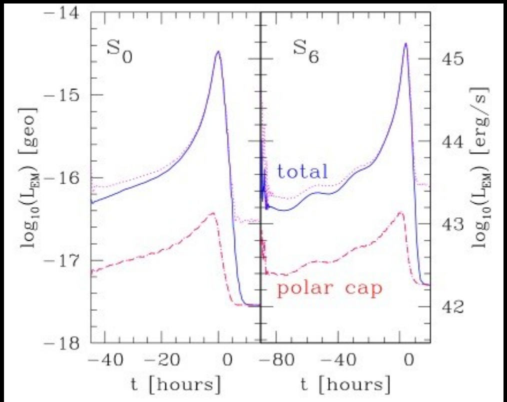


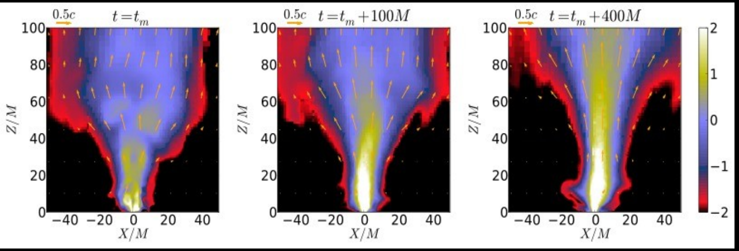




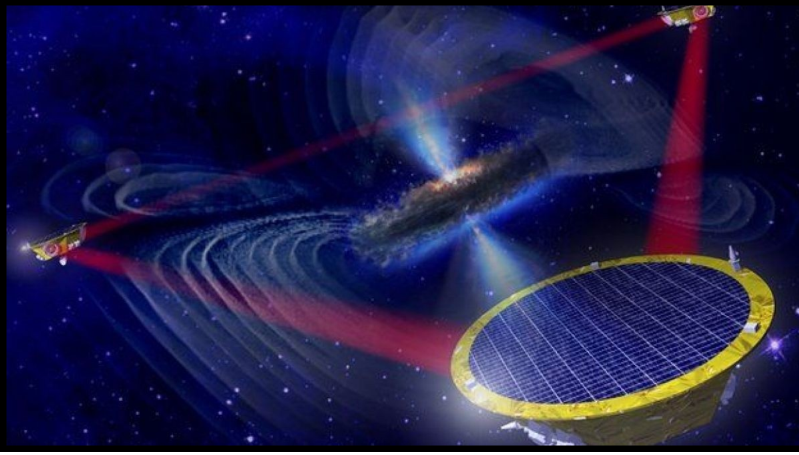
Simulations in disk-like geometry. Variability, but much weaker and unclear signatures (Bode et al. 2012, Gold et al. 2014)

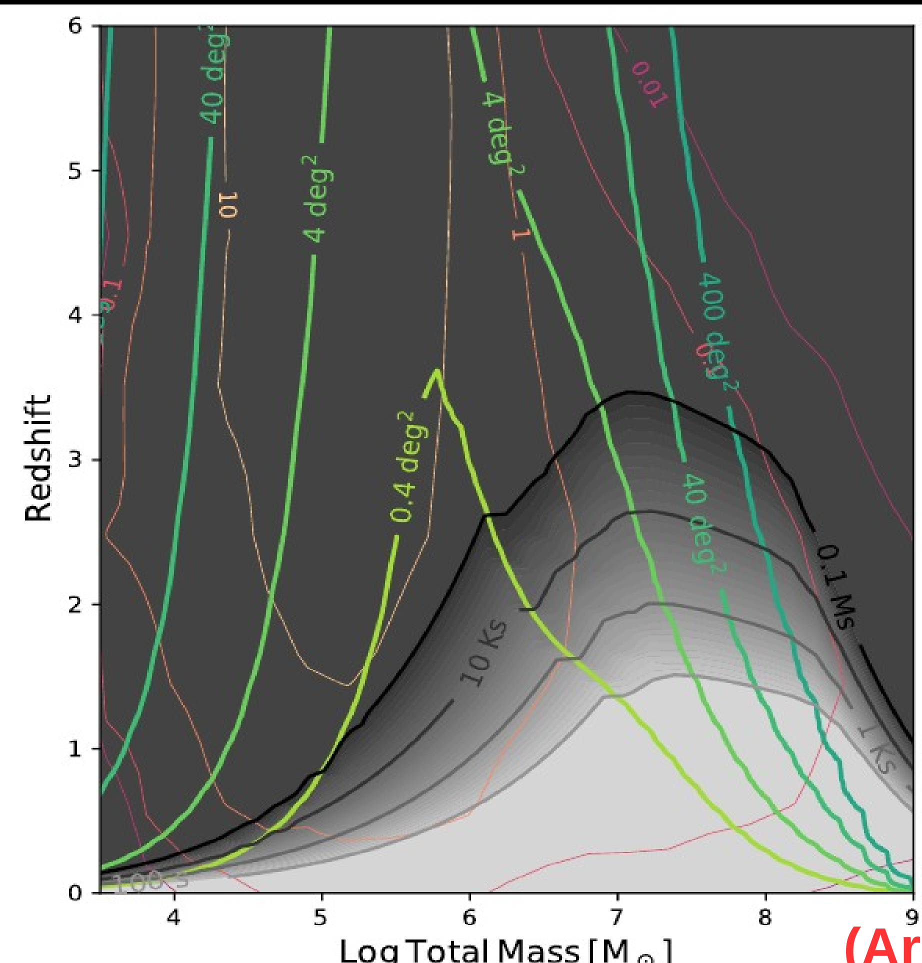
Full GR force free electrodynamics (Palenzuela et al. 2010, 2012)

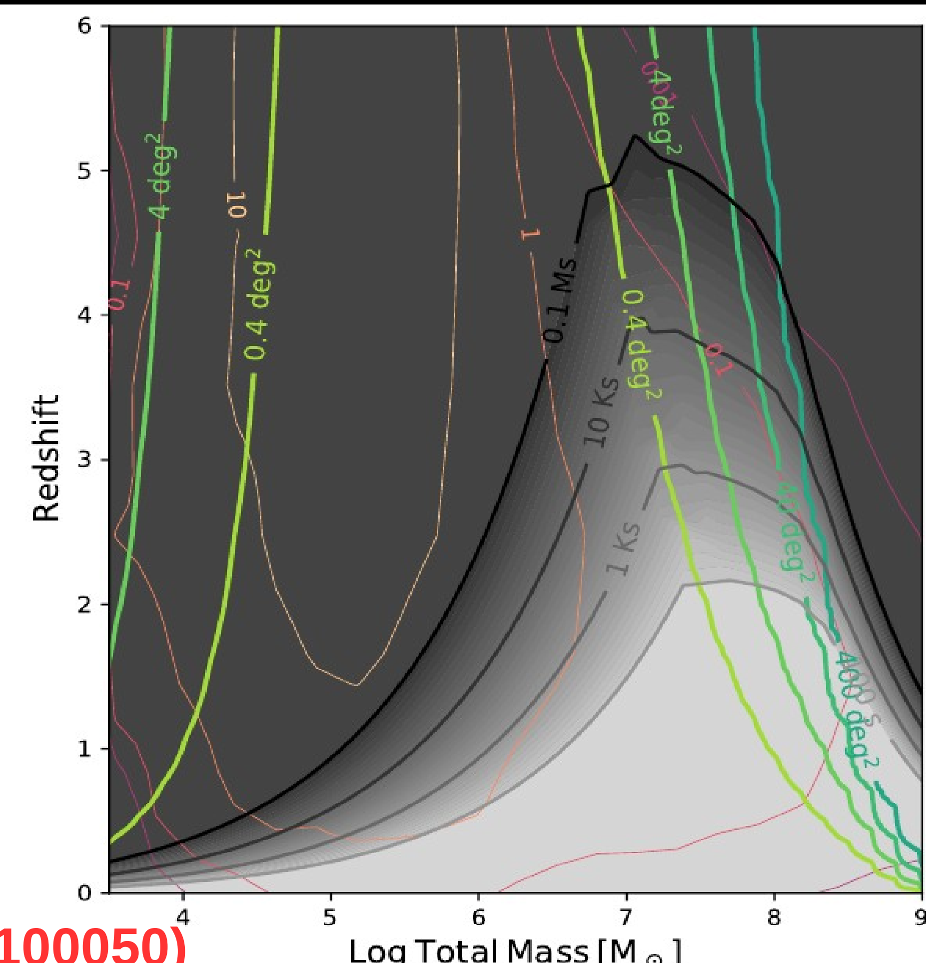




Athena & LISA in space together?

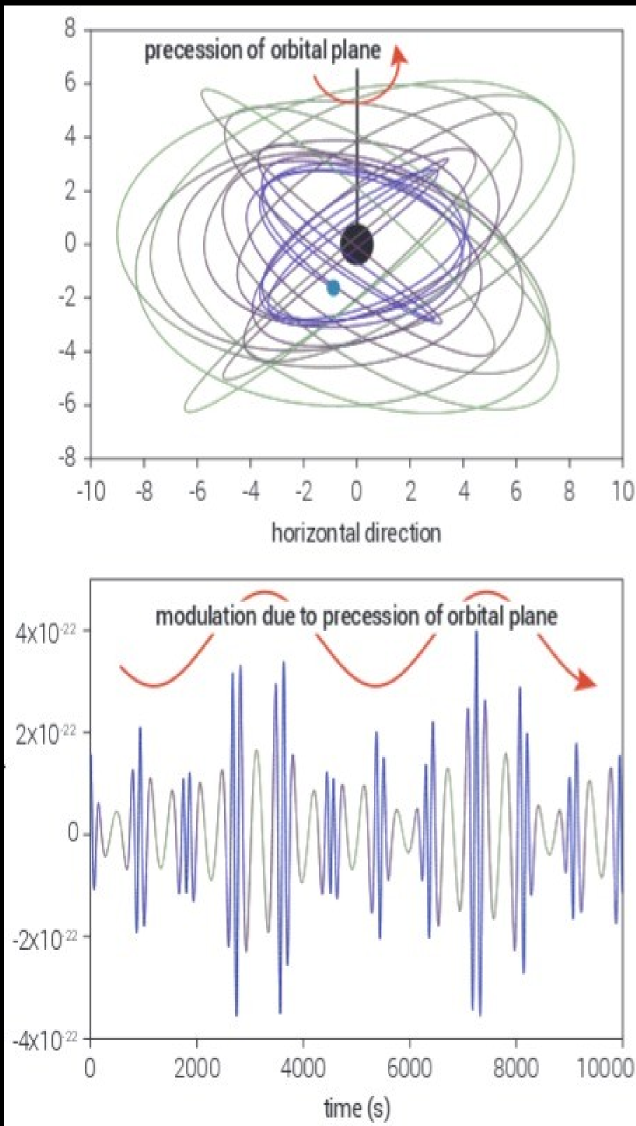




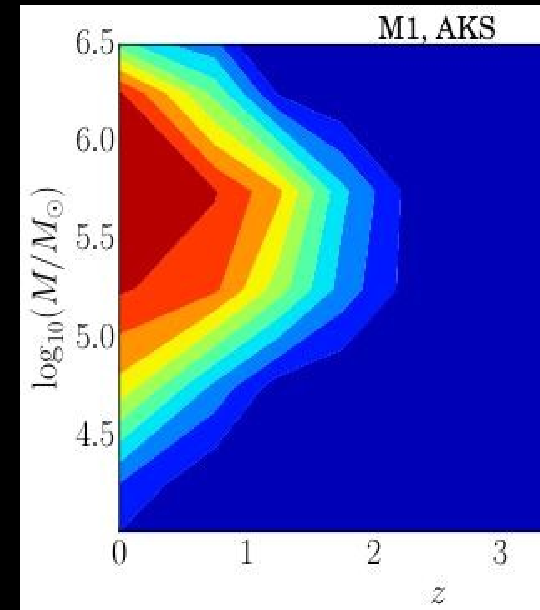


(ArXiv181100050)

Extreme mass ratio inspirals (EMRIs)

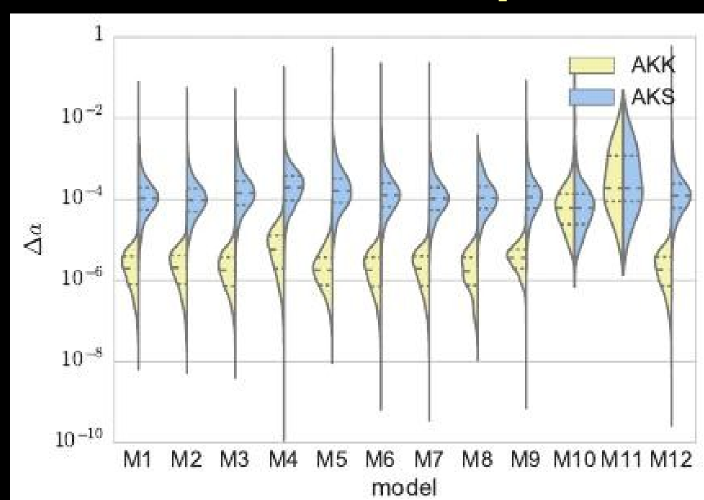


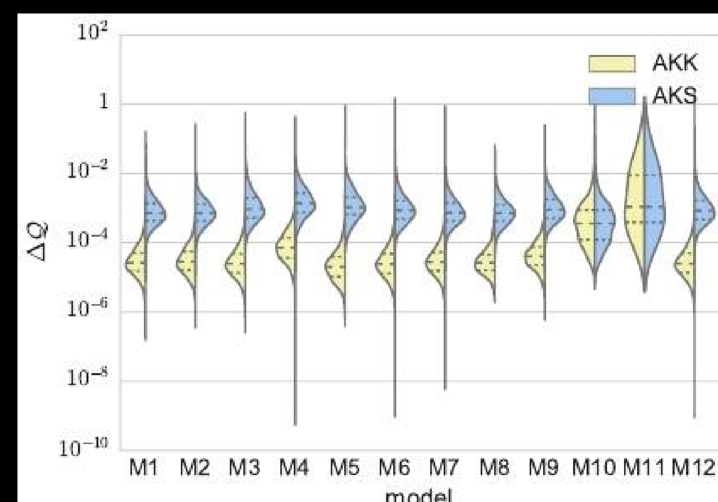
- 1-1000 detections/yr
- sky localization <10 deg2
- distance to better than 10%
- MBH mass to better than 0.01%
- CO mass to better than 0.01%
- MBH spin to better than 0.001
- plunge eccentricity <0.0001
- deviation from Kerr quadrupole moment to <0.001



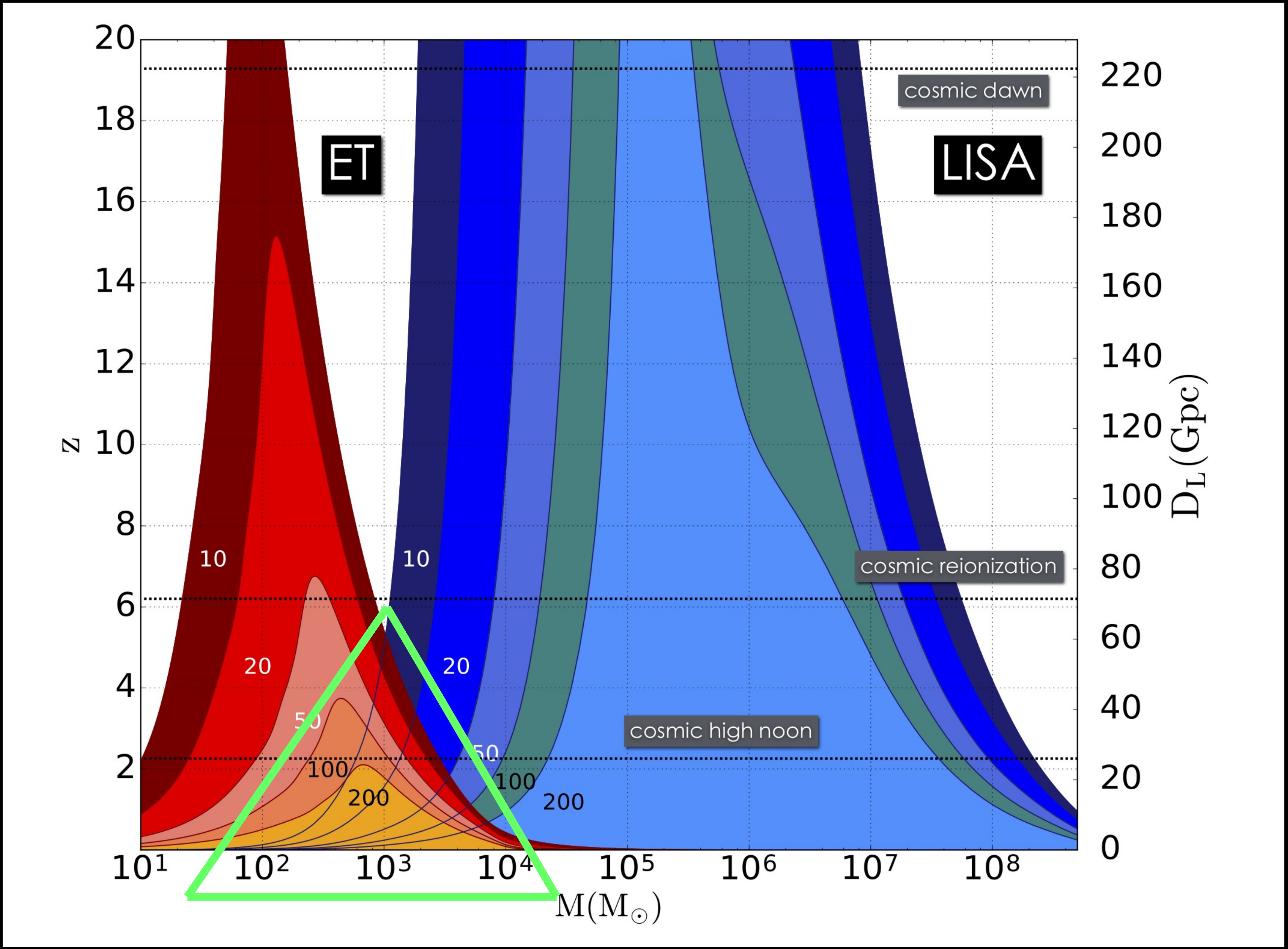
New tool for astrophysics (Gair et al 2010) cosmology (McLeod & Hogan 2008), and fundamental physics (Gair et al 2013) …
to be further explored

(Babak et al, 2017)



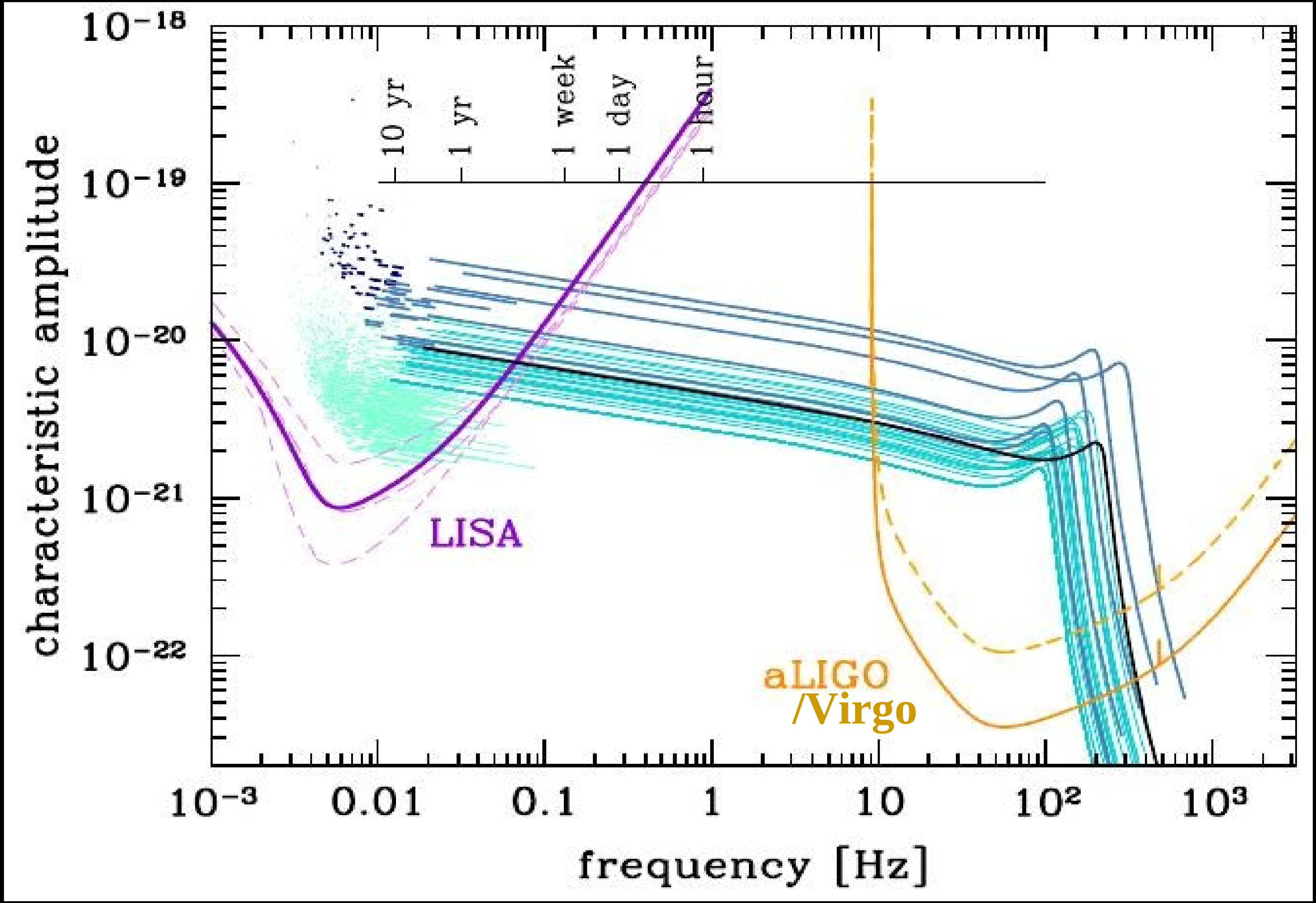


The parameter space of black holes



Implications of GW150914: multi-band GW astronomy

(AS 2016, PRL 116, 1102)



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

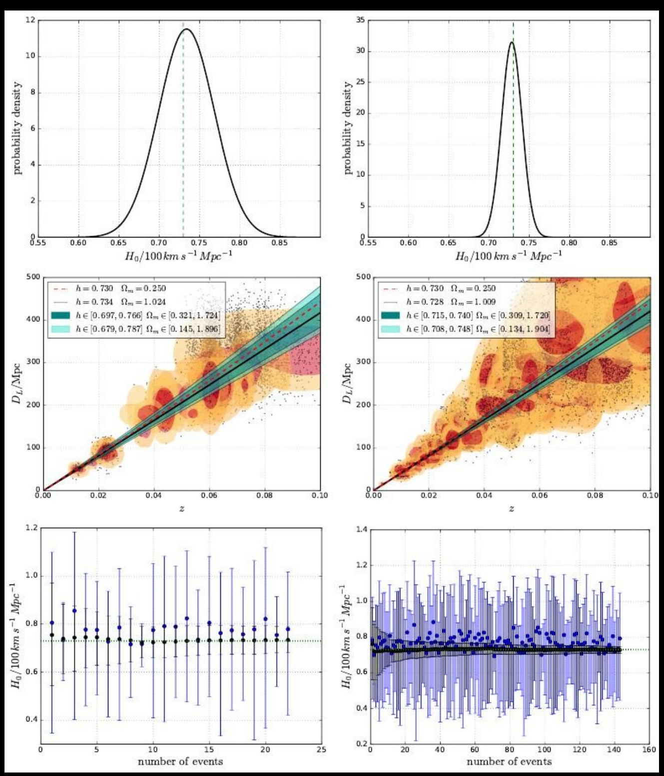
What do we do with them?

>Detector cross-band calibration and validation (LISA aLIGO)

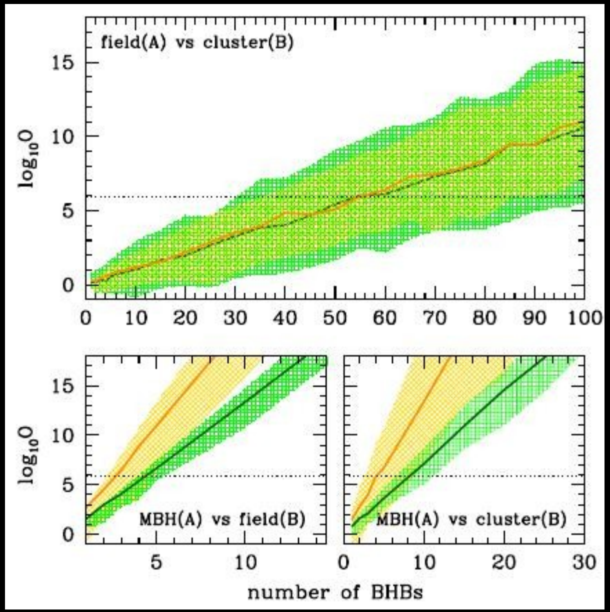
>Multiband GW astronomy: (e.g. Wong et al 2018)
-alert aLIGO to ensure multiple GW detectors are on
-inform aLIGO with source parameters: makes detection easier

>Multimessenger astronomy:
-point EM probes at the right location before the merger

>Enhanced tests of GR: e.g. strongest limits on deviations from GR
(Barausse et al 2016, Carson & Yagi 2019)

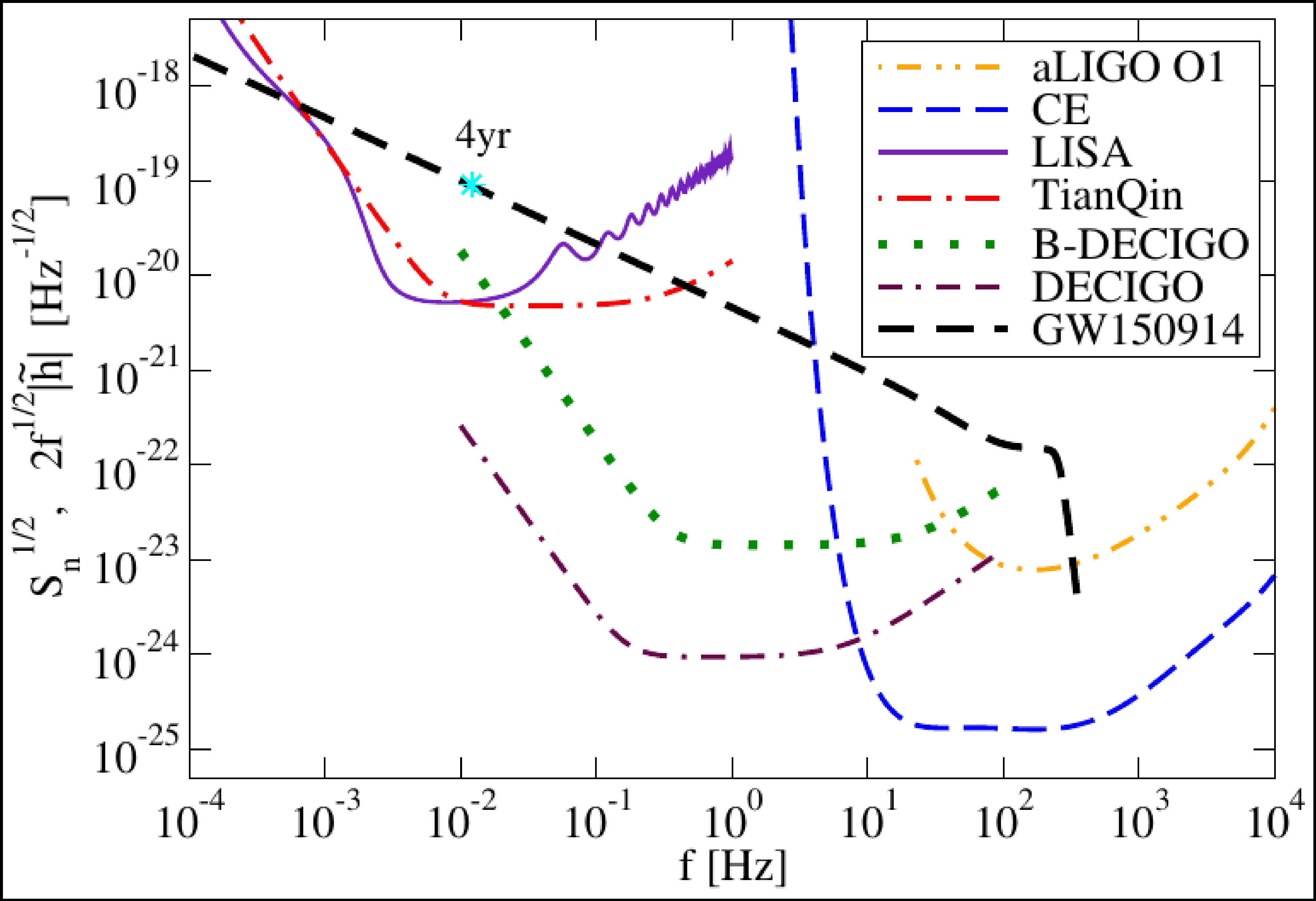


>Astrophysics:
-independent measure of spins
-measure of eccentricity
(Nishizawa, AS, Berti, Klein 2017, Breivik et al 2017, Gerosa et al. 2019, Samsing & D'orazio 2018)



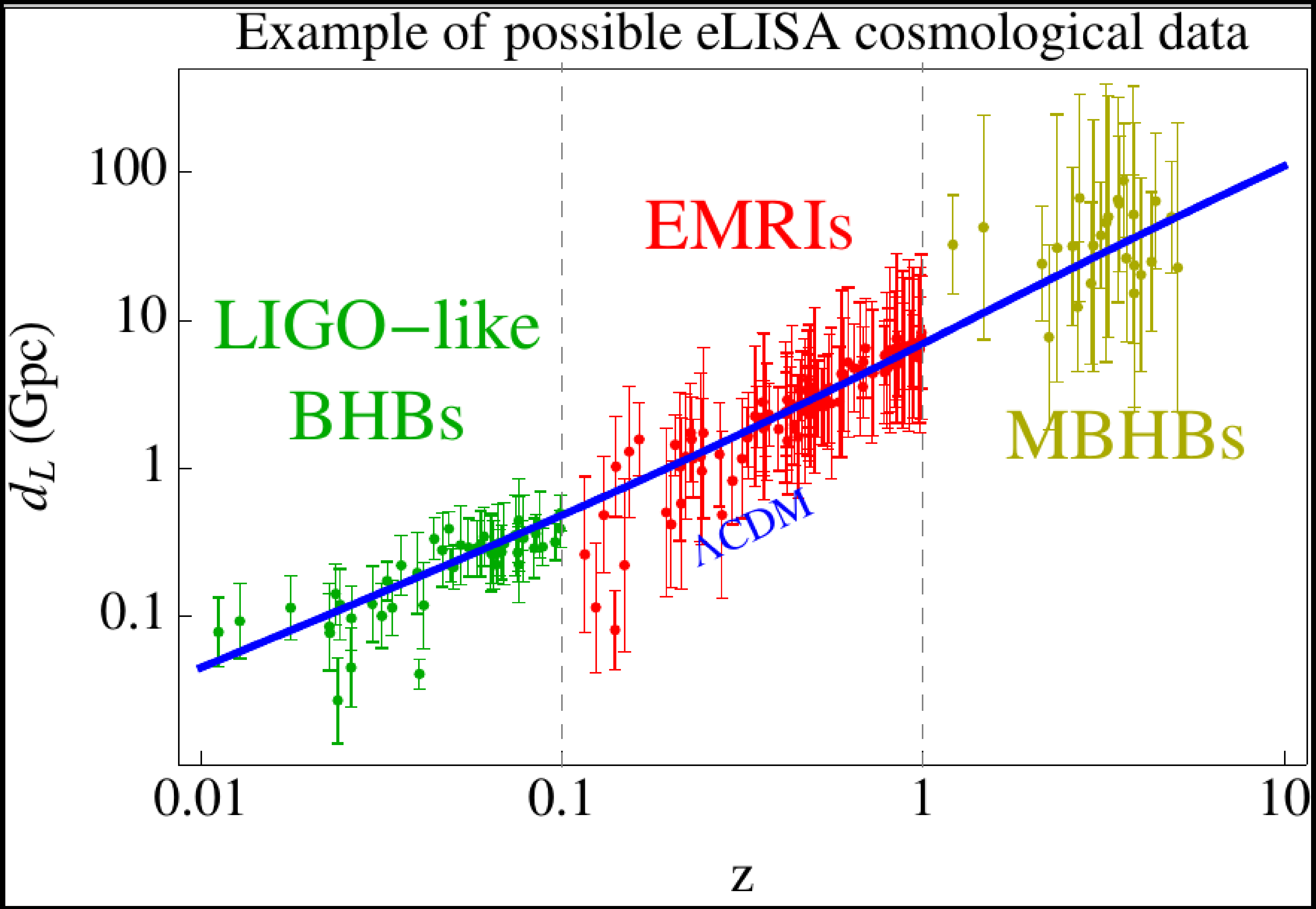
>Cosmology:
-new population of standard sirens?
(Kyutoku & Seto 2016, Del Pozzo, AS, Klein 2017)

Life would be much easier with a midband detector



Carson & Yagi 2019

Cosmology with gravitational waves



(Courtesy of N. Tamanini)

Different GW sources will allow an independent assessment of the geometry of the Universe at all redshifts.

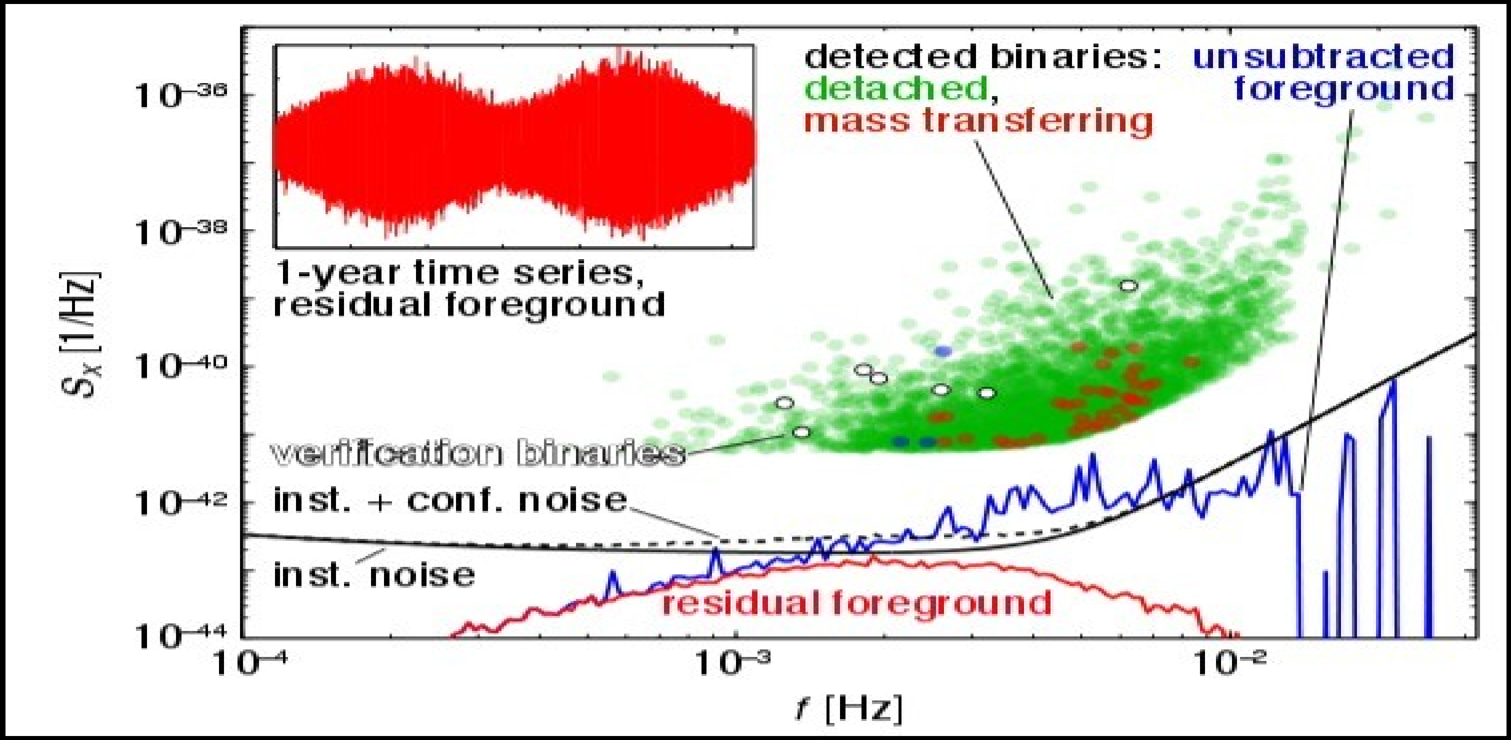
Galactic binaries

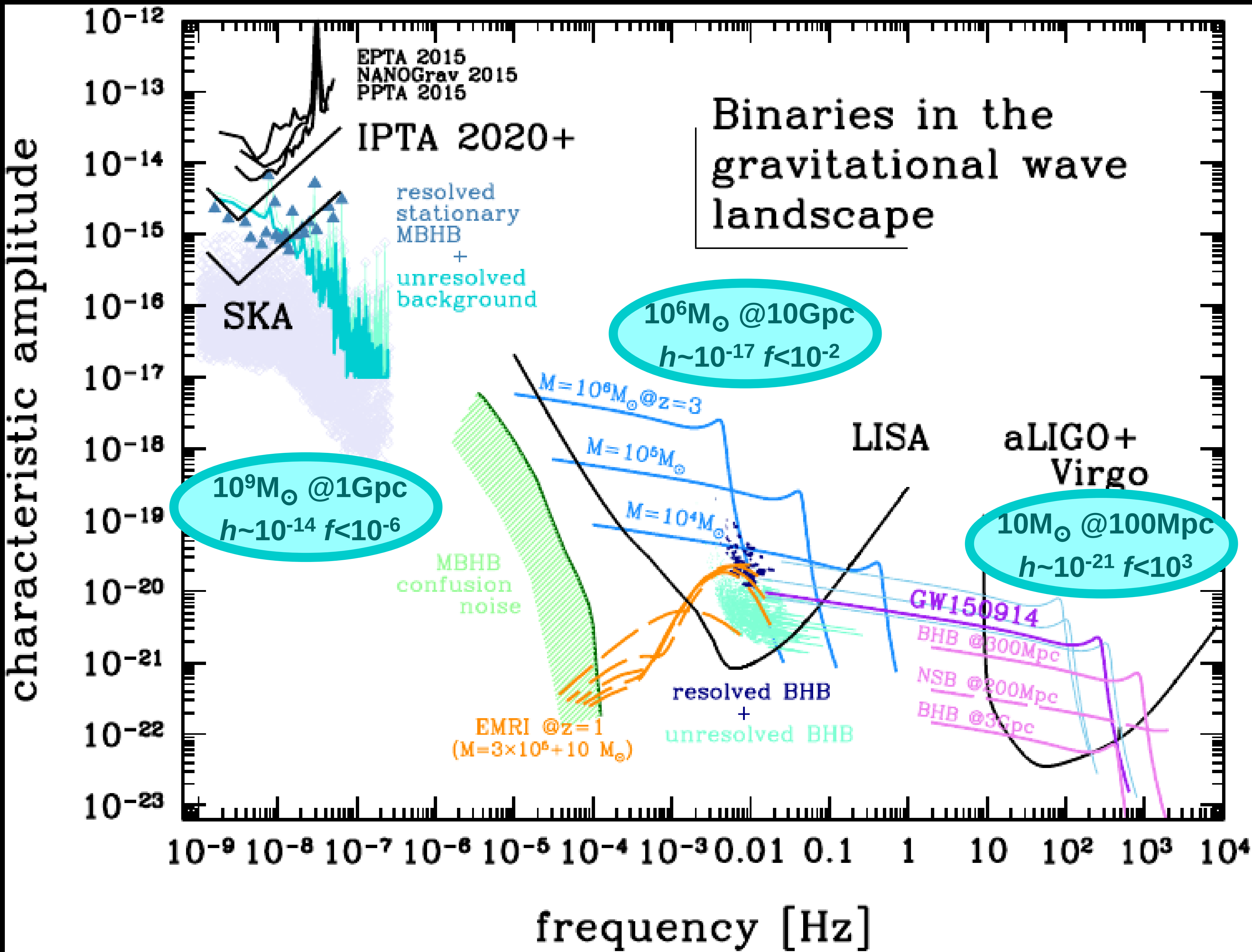
- *How many ultra-compact binaries exist in the Milky Way?*
- *What is the merger rate of white dwarfs, neutron stars and stellar mass black holes in the Milky Way (thus better constraining the rate of the explosive events associated with these sources)?*
- *What does that imply for, or how does that compare to, their merger rates in the Universe?*
- *What happens at the moment a white dwarf starts mass exchange with another white dwarf or neutron star, and what does it tell us about the explosion mechanism of type Ia supernovae?*
- *What is the spatial distribution of ultra-compact binaries, and what can we learn about the structure of the Milky Way as a whole?*

And do not forget
NS-NS and NS-BH binaries!

***Provide complementary information to ground based detectors**

***Sinergy with SKA?**



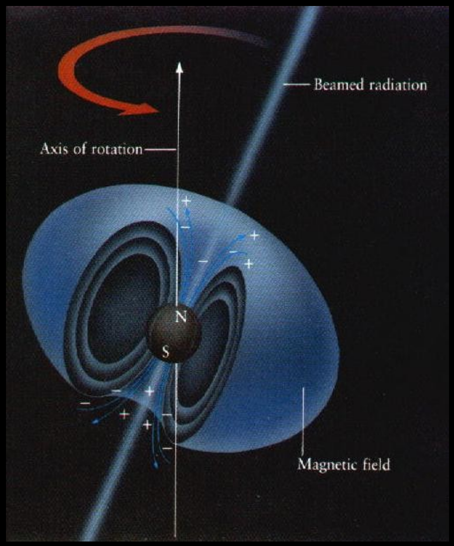


Binaries in the gravitational wave landscape
characteristic amplitude
frequency [Hz]
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB
+
unresolved background
$10^6 M_\odot$ @10Gpc
h~10^{-17} f<10^{-2}
$10^9 M_\odot$ @1Gpc
h~10^{-14} f<10^{-6}
$10 M_\odot$ @100Mpc
h~10^{-21} f<10^{3}
$M=10^6 M_\odot$@z=3
$M=10^5 M_\odot$
$M=10^4 M_\odot$
LISA
aLIGO+ Virgo
MBHB confusion noise
EMRI @z=1
($M=3\times10^5+10\ M_\odot$)
resolved BHB
+
unresolved BHB
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc

What is pulsar timing

Pulsars are neutron seen through their regular radio pulses

Pulsar timing is the art of measuring the time of arrival (ToA) of each pulse and then subtracting off the expected time of arrival given by a theoretical model for the system

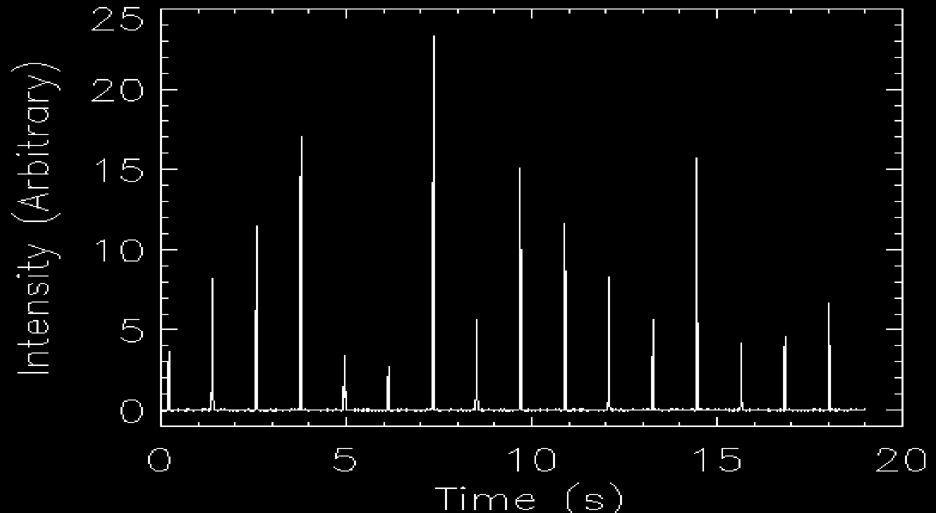


1-Observe a pulsar and measure the ToAs

2-Find the model which best fits the ToAs

3-Compute the timing residual R

$$R = \mathrm{ToA} - \mathrm{ToA}_m$$



If the timing solution is perfect (and observations noiseless), then $R=0$. R contains all uncertainties related to the signal propagation and detection, plus the effect of unmodelled physics, like (possibly) ***gravitational waves***

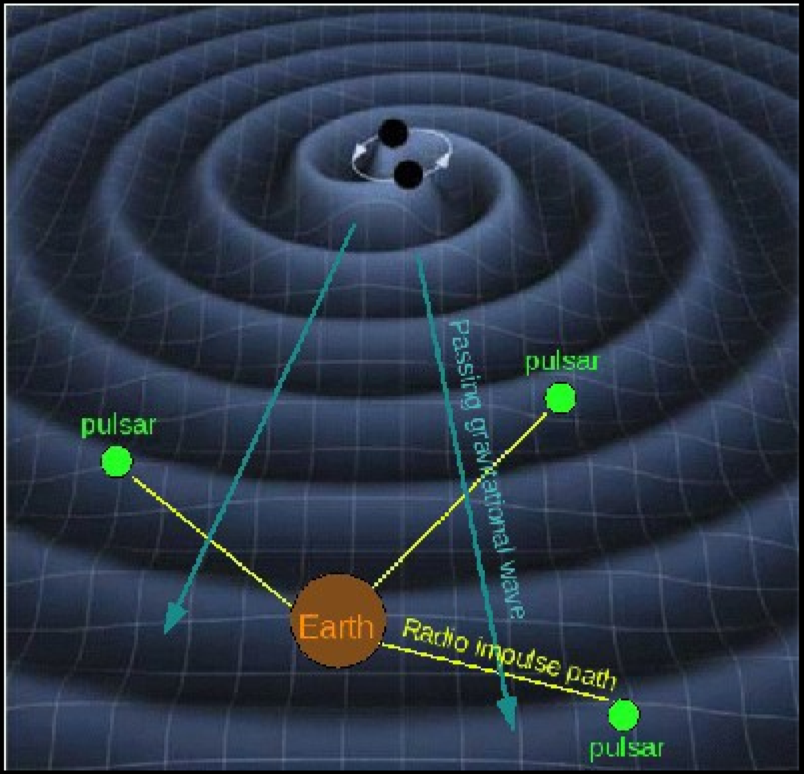
Effect of gravitational waves

The GW passage causes a modulation of the observed pulse frequency

$$\frac{\nu(t)-\nu_0}{\nu_0} = \Delta h_{ab}(t) \equiv h_{ab}(t_{\rm p},\hat{\Omega}) - h_{ab}(t_{\rm ssb},\hat{\Omega})$$

The residual is the integral of this frequency modulation over the observation time (i.e. is a de-phasing)

$$R(t) = \int_0^T \frac{\nu(t)-\nu_0}{\nu_0}\,dt$$



(Sazhin 1979, Hellings & Downs 1983, Jenet et al. 2005, AS et al. 2008, 2009)

$10^9\ M_\odot$ binary at 1Gpc: $h \sim 10^{-15}$, $f \sim 10^{-8}$

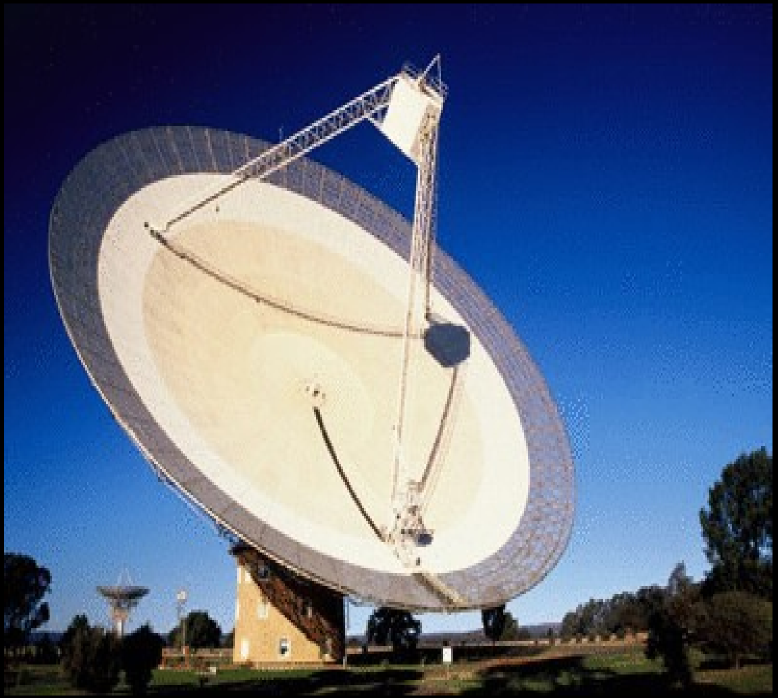
Implies a residual ~100ns

100ns is the accuracy at which we can time the most stable millisecond pulsars today!

A worldwide observational effort

EPTA/LEAP (Large European Array for Pulsars)

NANOGrav (North American nHz Observatory for Gravitational Waves)



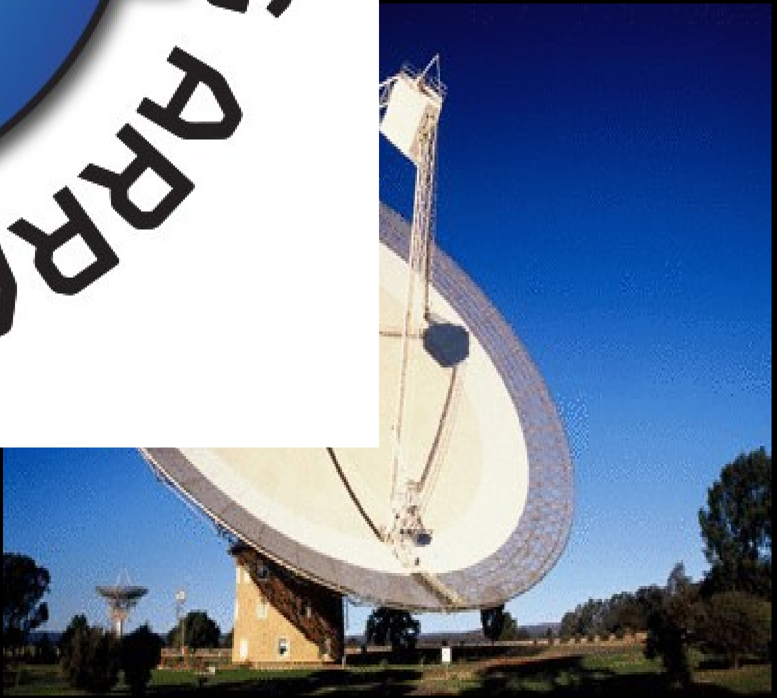
PPTA (Parkes Pulsar Timing Array)

A worldwide observational effort

E

nHz

aves)

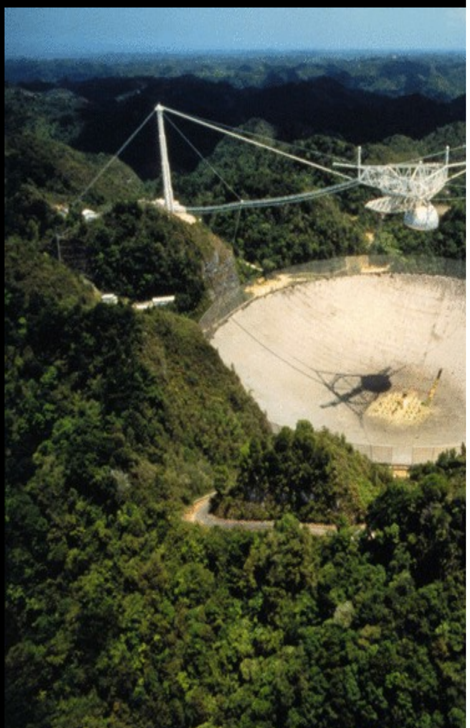


PPTA

A worldwide observational effort

INTERNATIONAL PULSAR TIMING ARRAY

IPTA

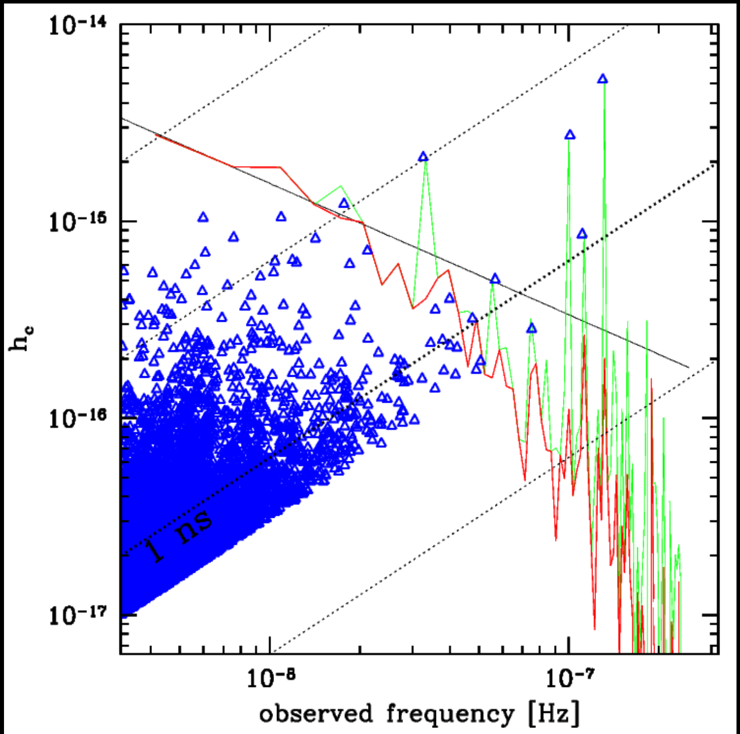


nHz
aves)

PPTA

+Indian PTA (IPTA meeting last week in PUNE)
+MeerKAT
+Chinese PTA

The expected GW signal in the PTA band



The GW characteristic amplitude coming from a population of circular MBH binaries

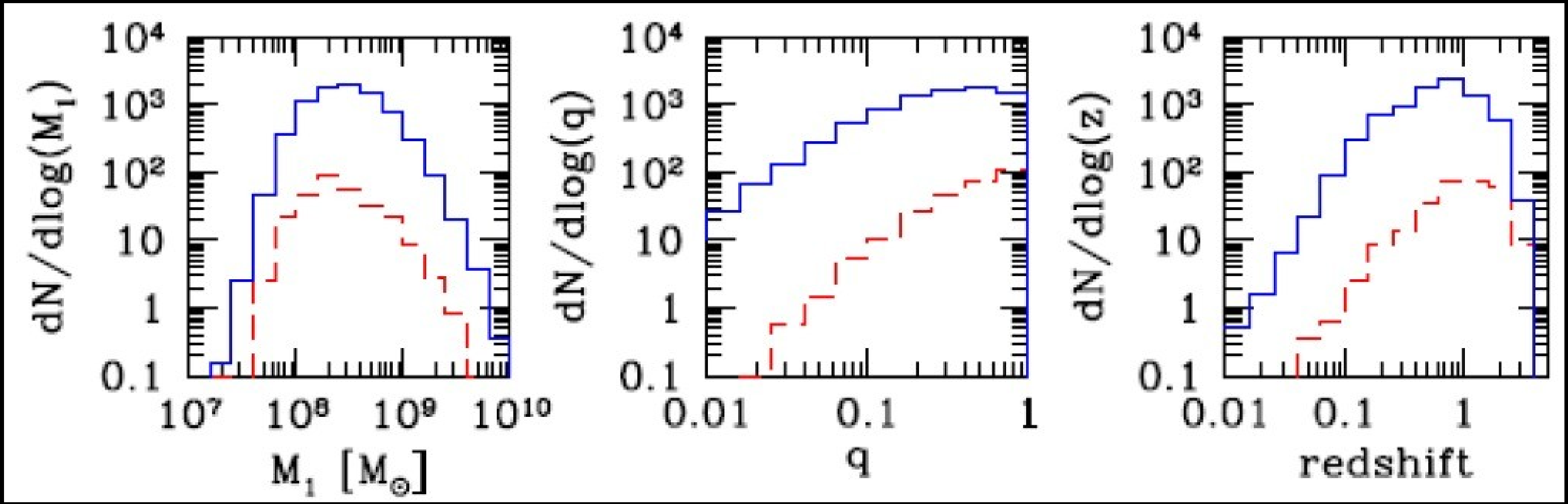
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M}\, \frac{d^3N}{dz d\mathcal{M} d\ln f_r} h^2(f_r)$$

$$\delta t_{\rm bkg}(f) \approx h_c(f)/(2\pi f)$$

Theoretical spectrum: simple power law

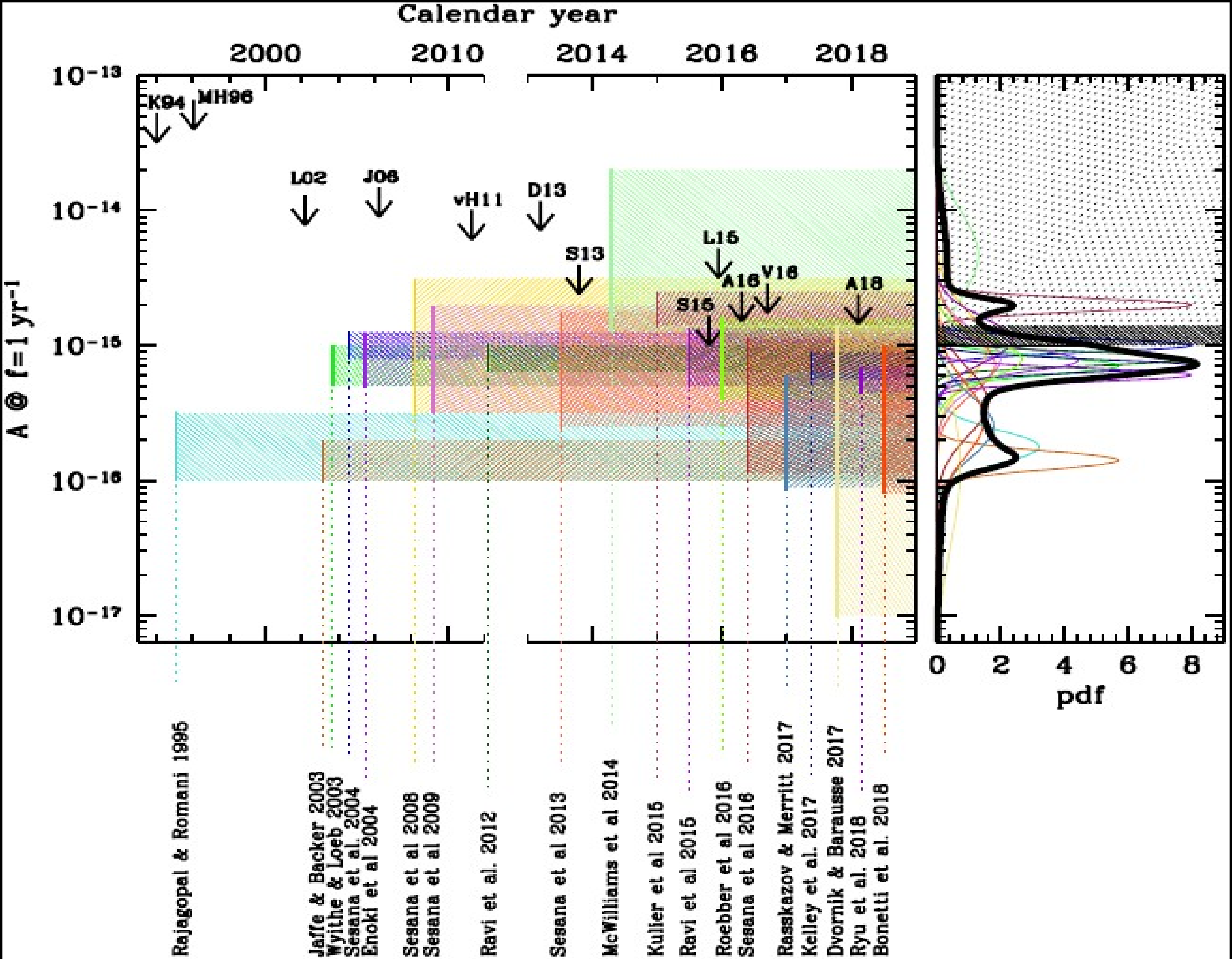
(Phinney 2001)

$$h_c(f) = A \left(\frac{f}{\rm yr^{-1}} \right)^{-2/3}$$



The signal is contributed by extremely massive ($>10^8 M_\odot$) relatively low redshift ($z<1$) MBH binaries (AS et al. 2008, 2012)

Predictions and limits



Limits are not stringent yet (Chen et al 2017, Middleton et al. 2018)

The future

MeerKAT, South Africa (2017)

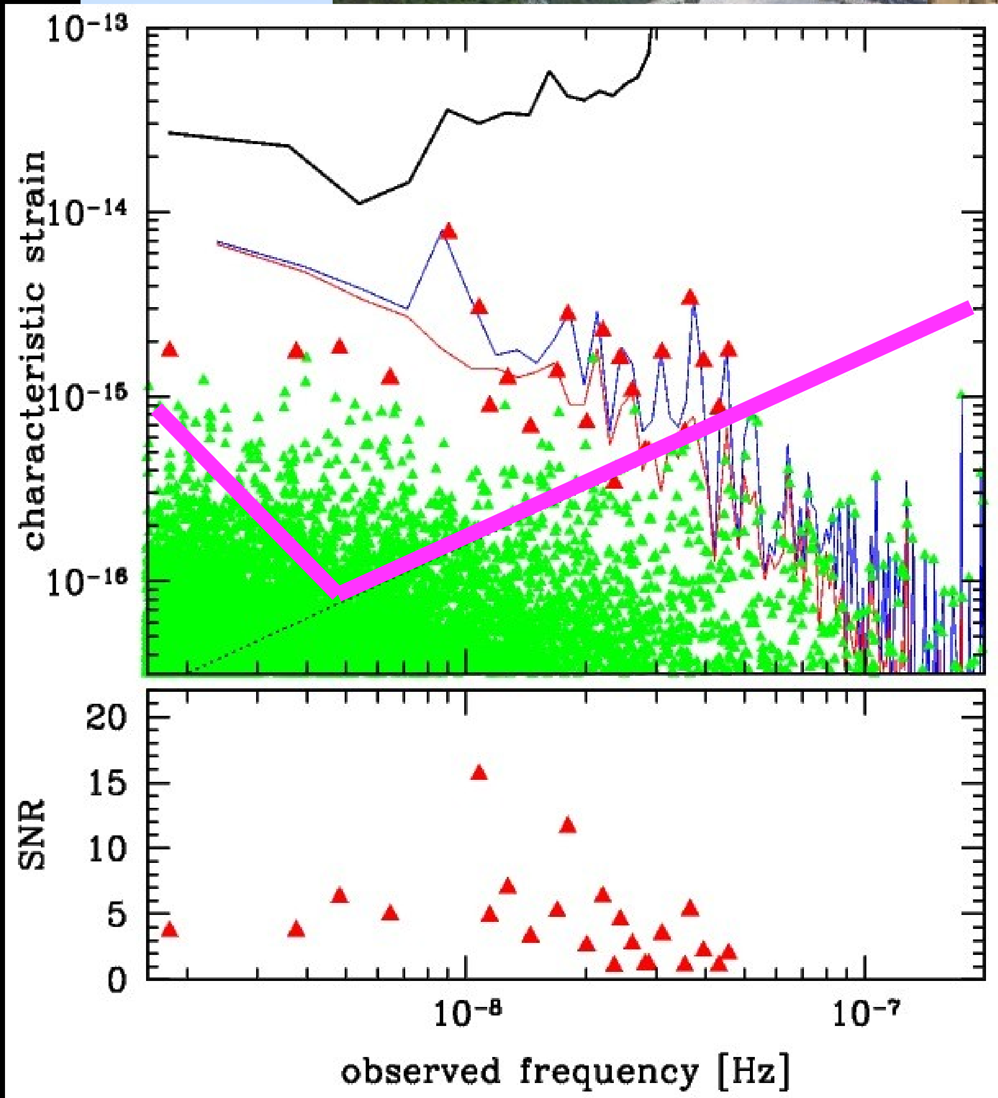
The future

FAST, China (2017)

The future

Square Kilometre Array (SKA, 2021+)

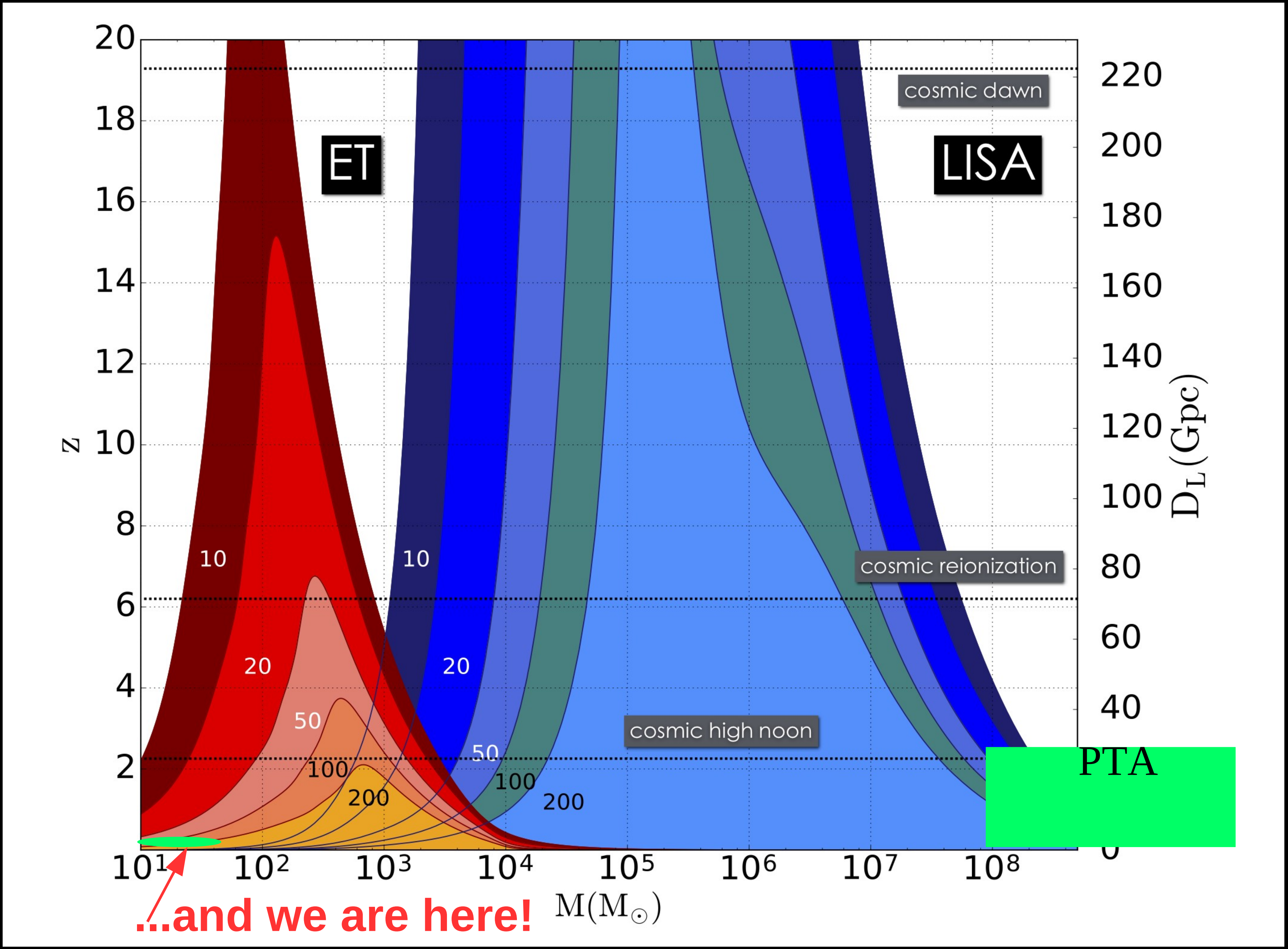
The future



Science with nHz GW detection:

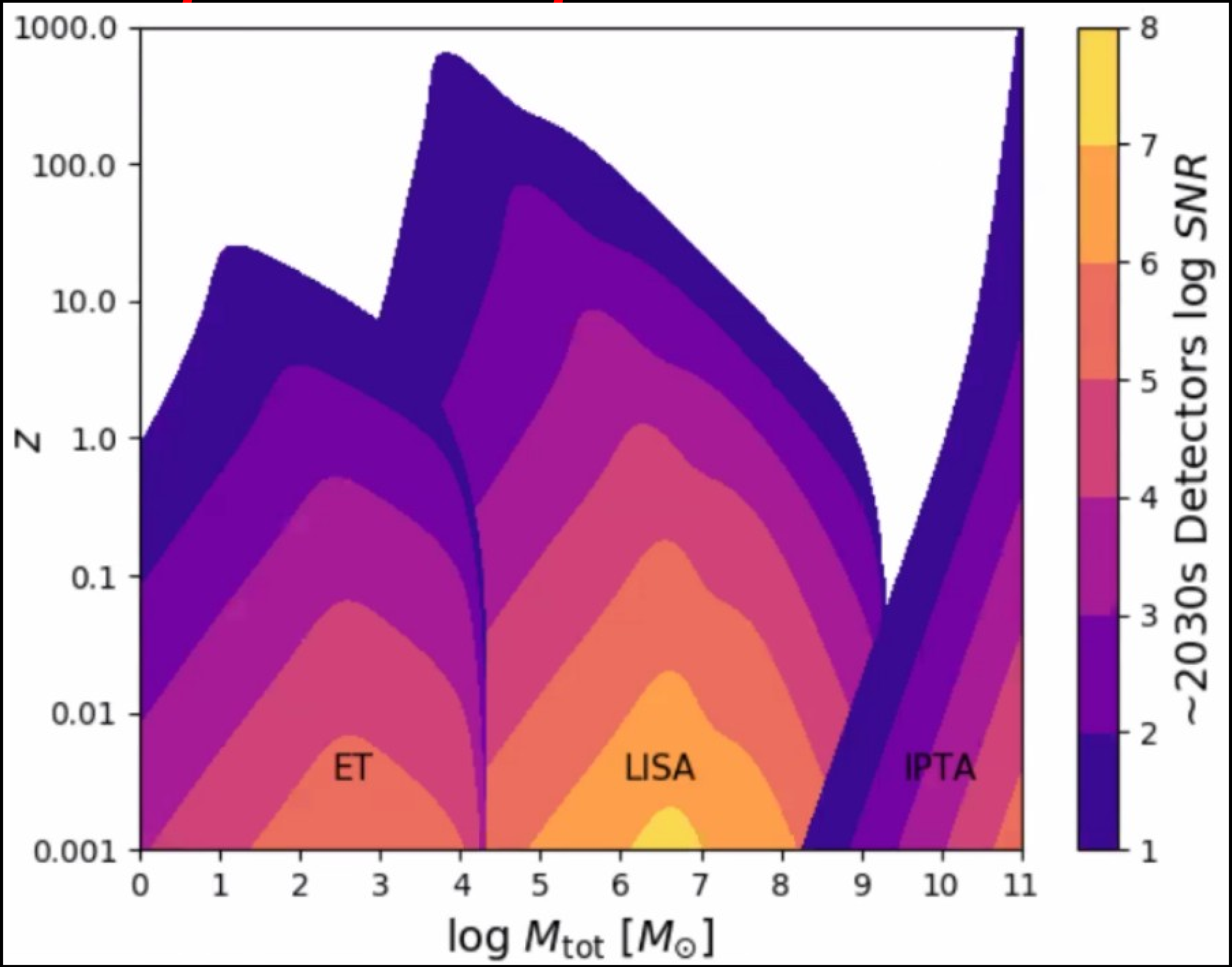
- Prove the existence of SMBHBs
- Characterize the GWB spectrum: coupling with the environment
- Insights into the dynamics of SMBHBs
- Detection and localization of tens of individual sources
- Multimessenger astronomy in the nHz regime
- Understand EM signatures of SMBHBs

The parameter space of black holes



...and we are here!

The parameter space of black holes



Doggybag

3G detectors will probe:

- -NSs to z~3-5
- -BHs to z~10-20
- -possibly seeds of SMBHs

LISA will probe a number of GW sources at low frequency.

- -galactic binaries
- -extreme mass ratio inspirals
- -LIGO sources
- -SMBHB cosmic history

LISA sources will be invaluable tools for astrophysics, cosmology and fundamental physics

PTAs can provide unique information about the dynamics and merger history of MBHBs (e.g. merger rate density, environmental coupling, eccentricity, etc.)

Current PTA limits are getting extremely interesting, showing some tension with vanilla models for the cosmic SMBHB population, but nothing can be ruled out yet