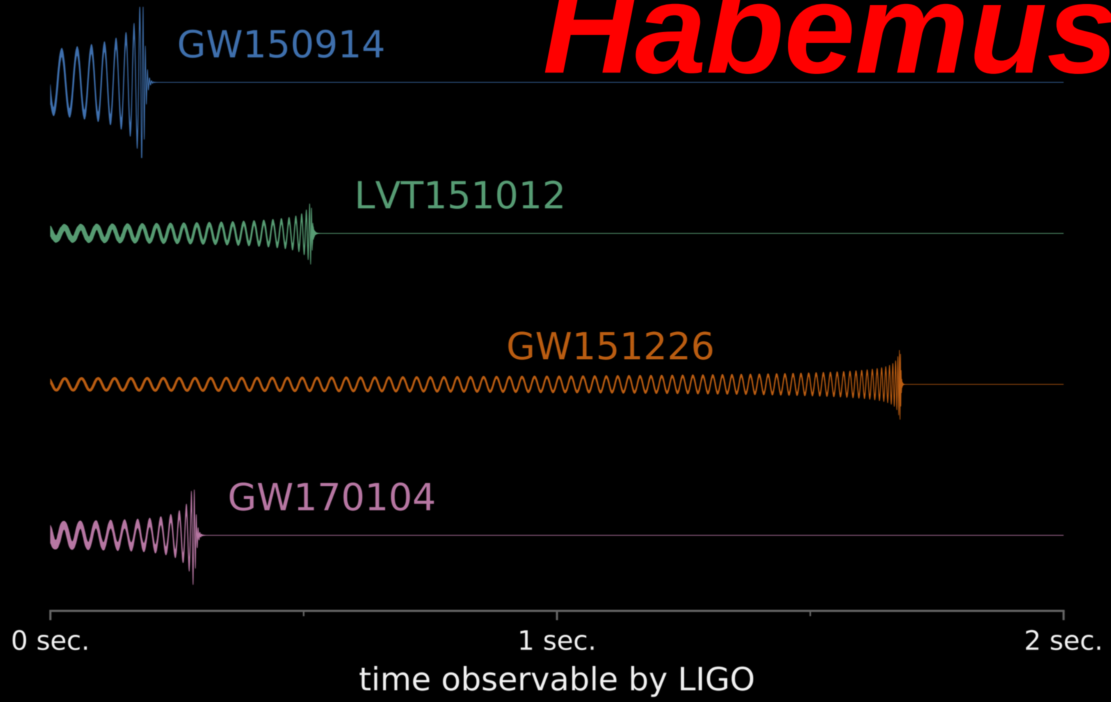
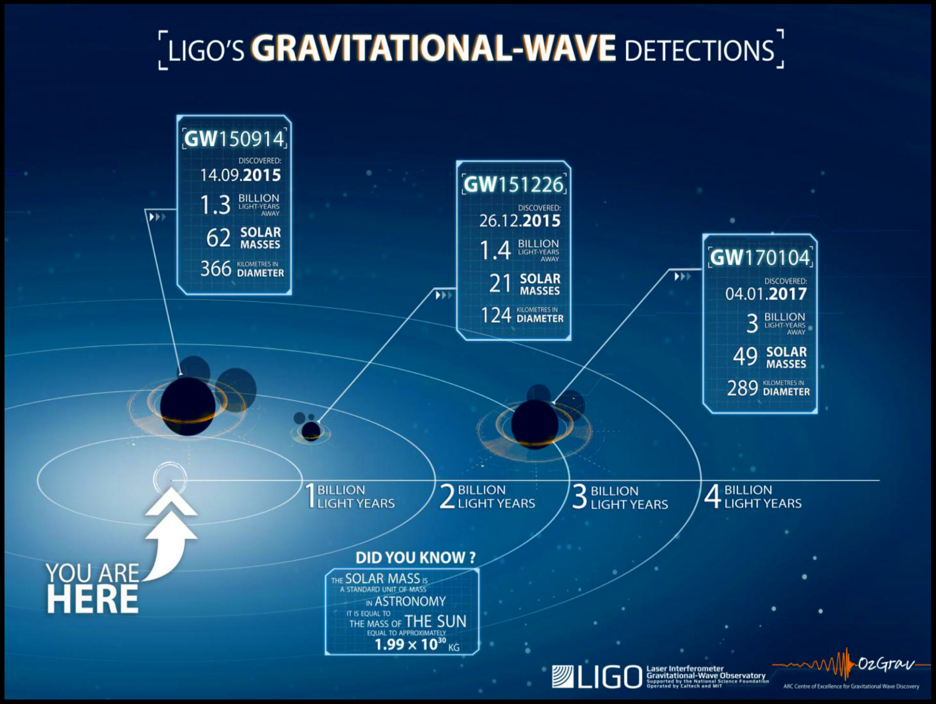
# The long vision of Gravitational wave astronomy

**Alberto Sesana**
(University of Birmingham)

# Habemus GWs!



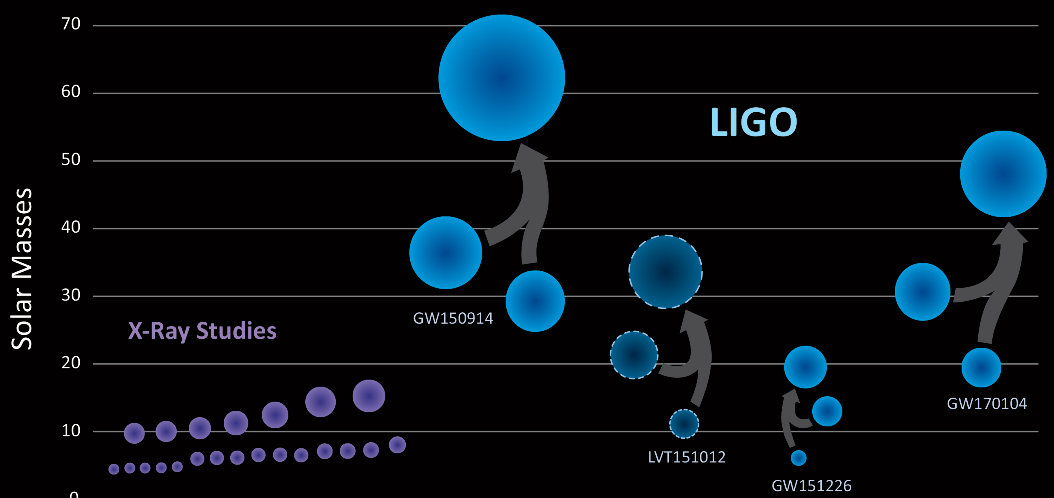

**We see BHB coalescing for the first time** (several Abbott+ 2016 2017)

Black Holes of Known Mass

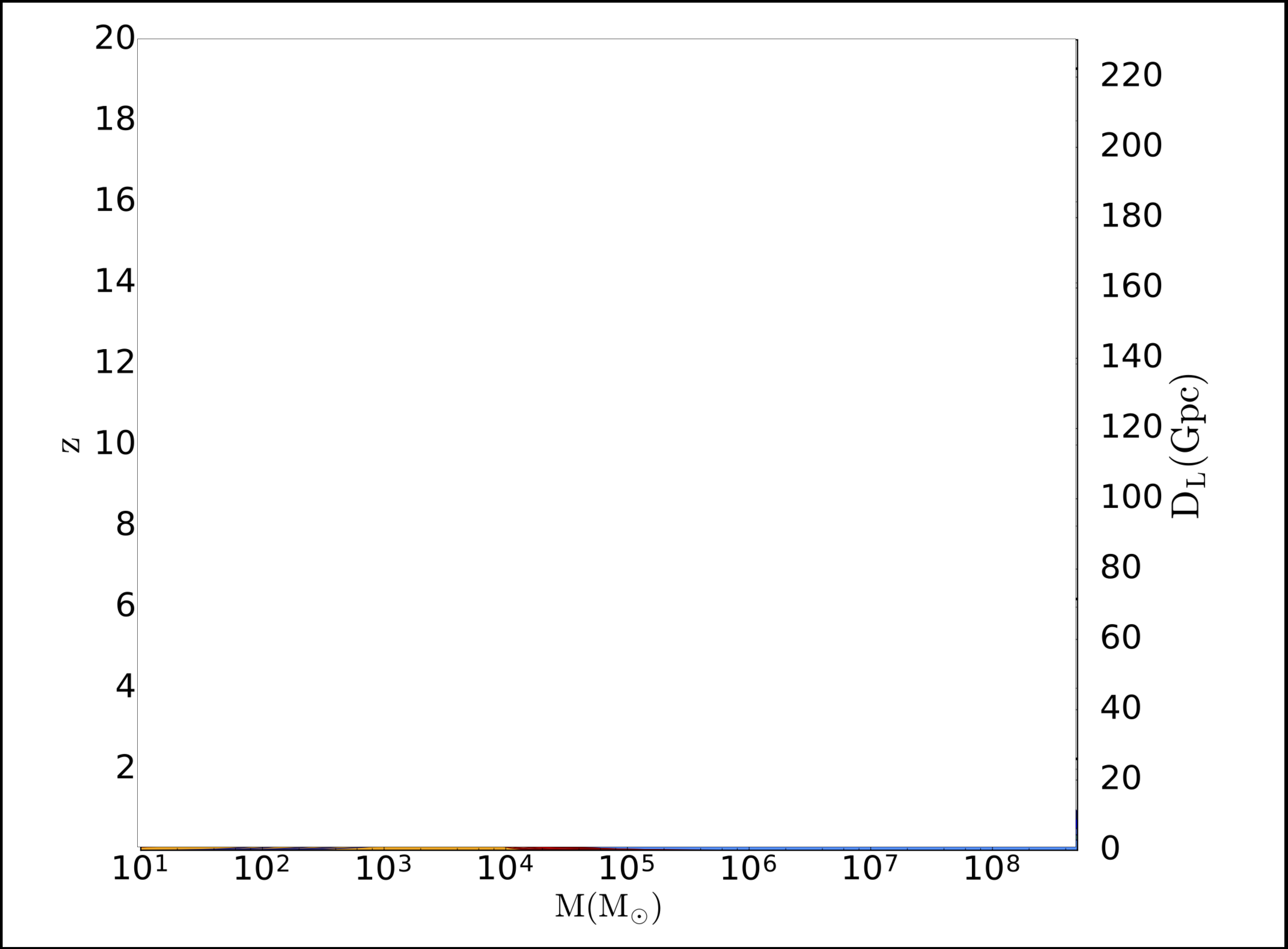
**First tests of GR in the strong field regime**

**Interesting astrophysical information (masses, spins)**

**Formation scenario?**



# The parameter space of black holes



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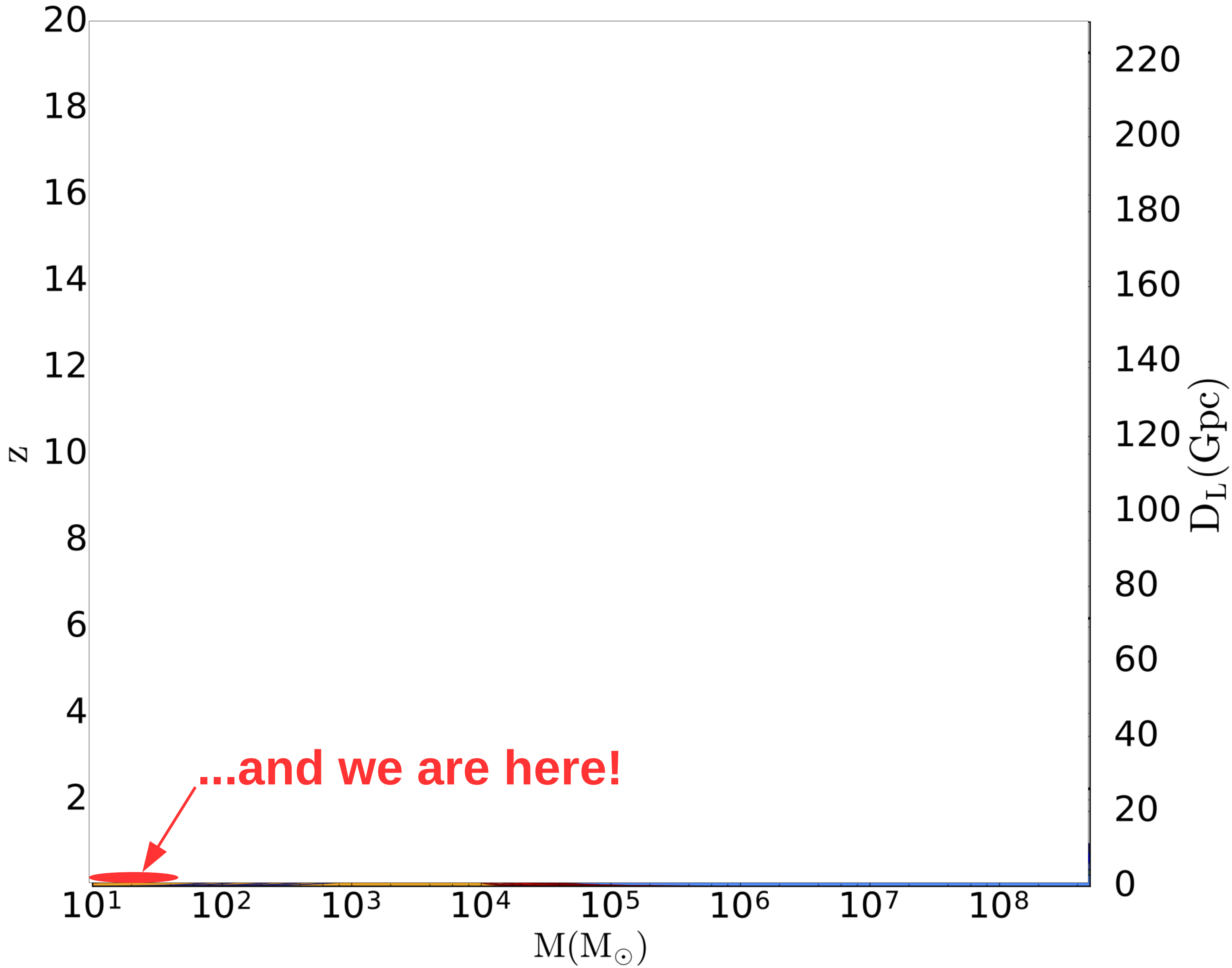
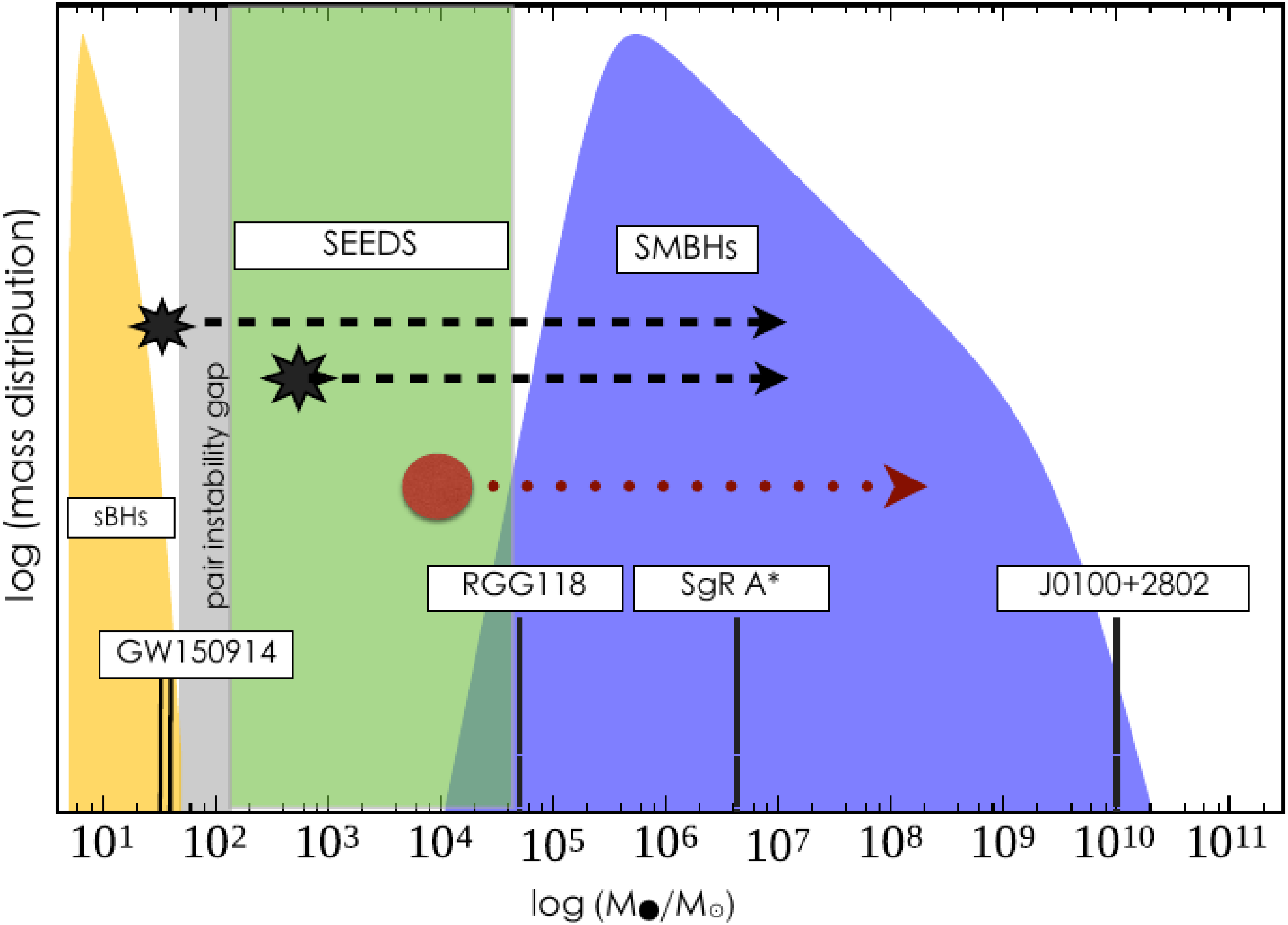




SEEDS
SMBHs
sBHs
pair instability gap
RGG118
SgR A*
J0100+2802
GW150914
$10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$ $10^{11}$
log (mass distribution)
log $(M_\bullet/M_\odot)$

# *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**

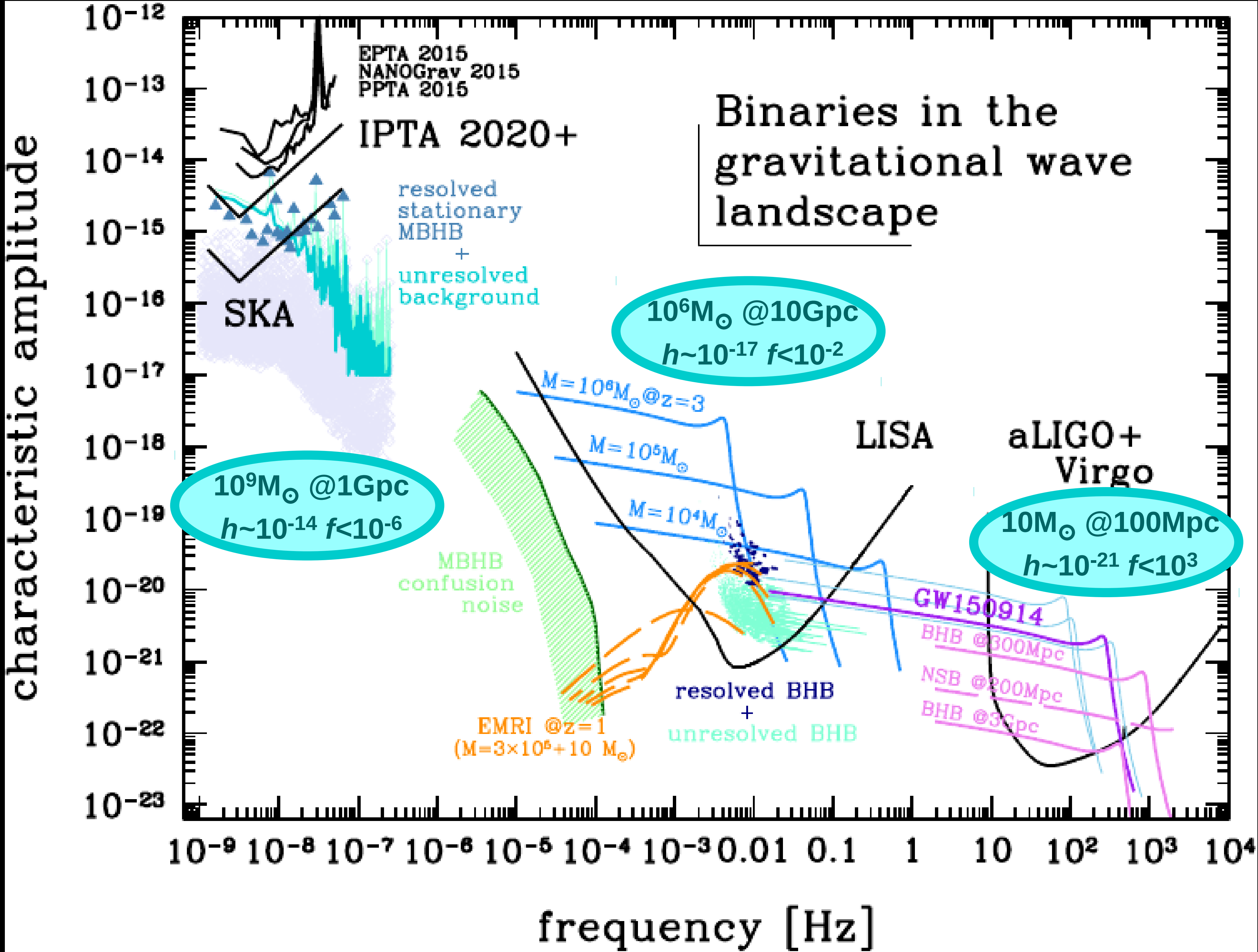
$$h \sim 10^{-20}\,\frac{M}{M_\odot}\,\frac{\mathrm{Mpc}}{D}$$

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

**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: $h \sim 10^{-14}$, $f < 10^{-5}$**



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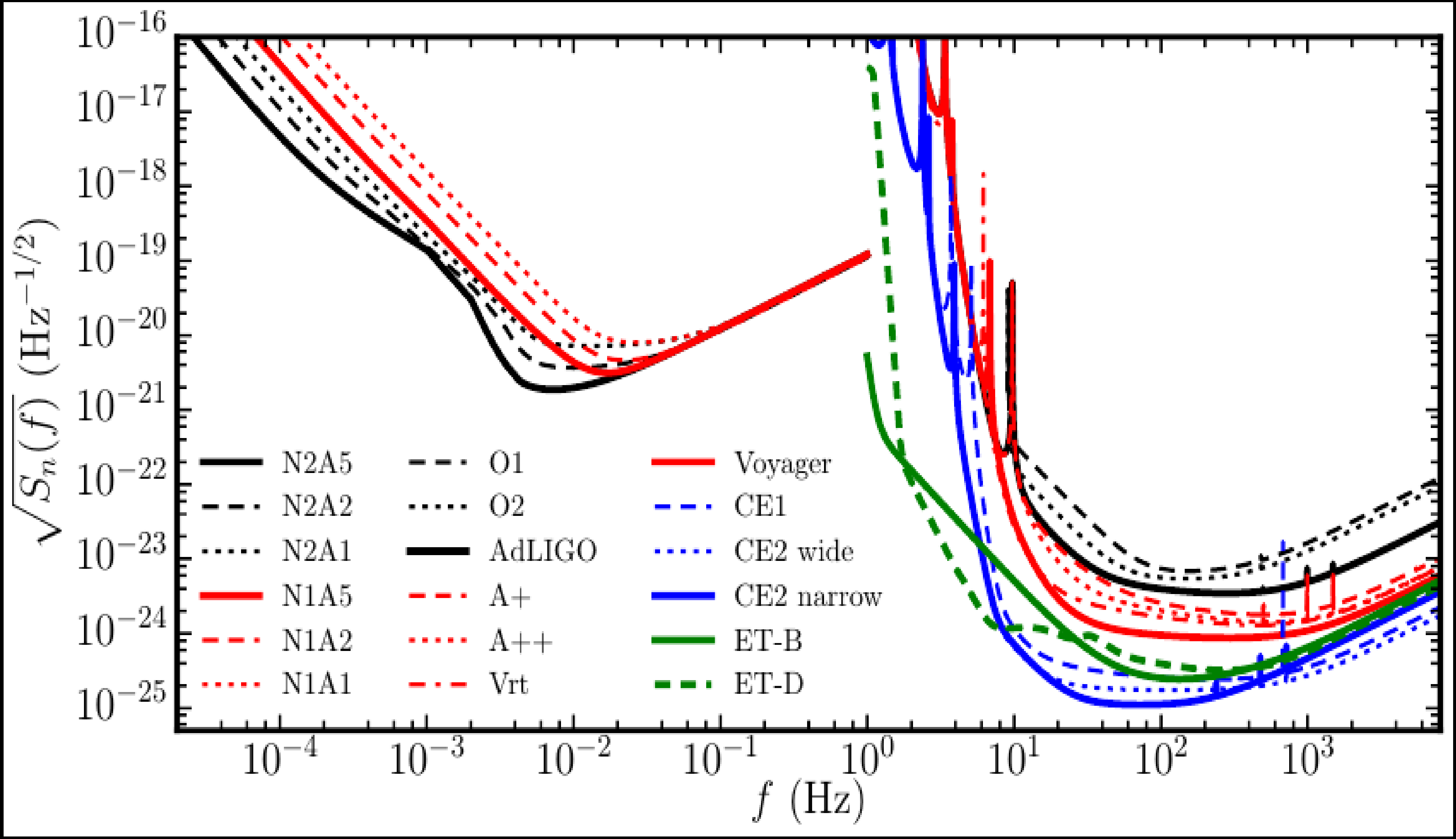
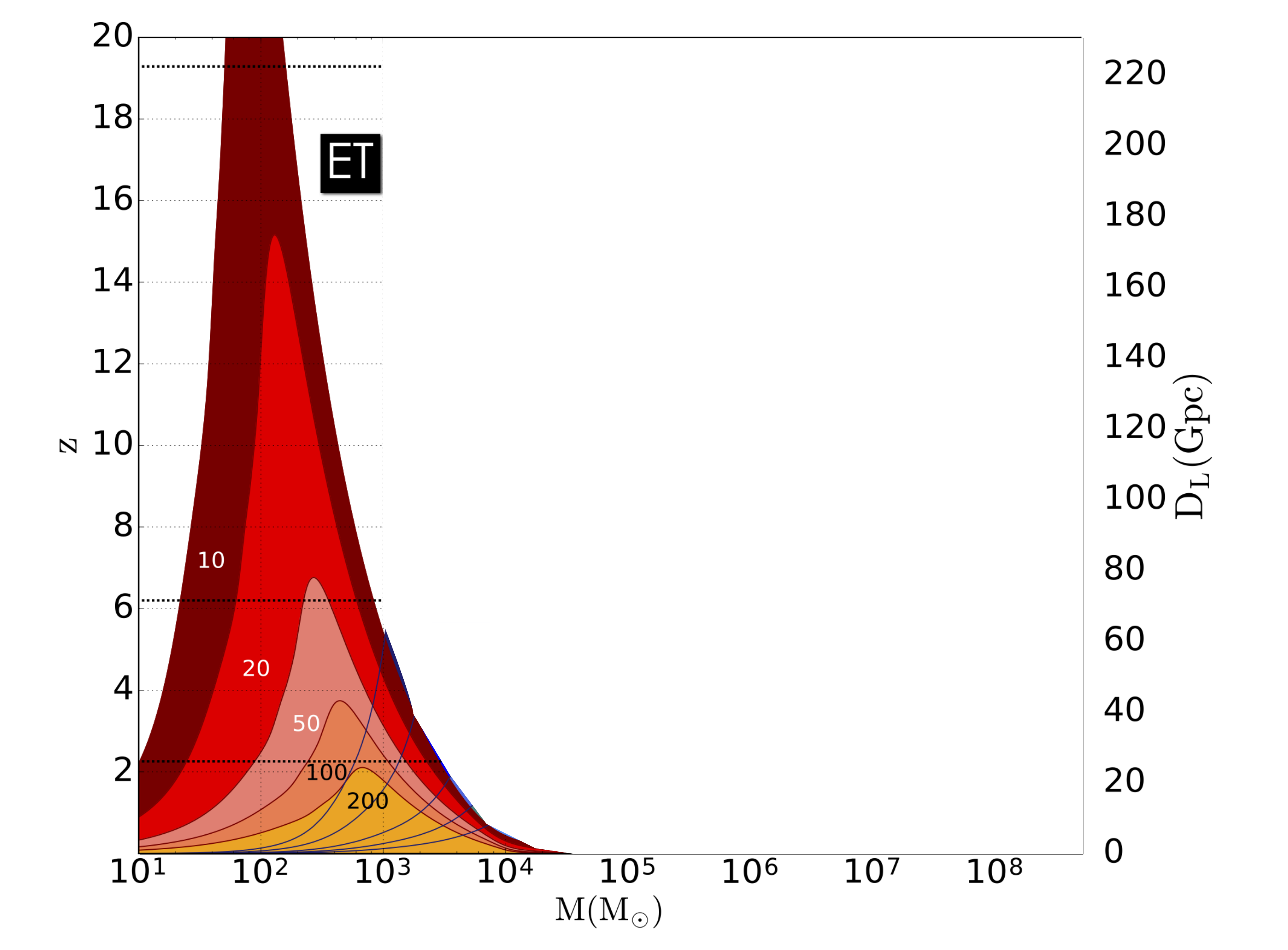
$10^9 M_\odot$ @1Gpc
$h \sim 10^{-14}$ $f < 10^{-6}$
$10 M_\odot$ @100Mpc
$h \sim 10^{-21}$ $f < 10^3$
$M = 10^6 M_\odot$ @z=3
$M = 10^5 M_\odot$
$M = 10^4 M_\odot$
LISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
resolved BHB
+
unresolved BHB
EMRI @z=1
($M = 3\times10^5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

# *A number of 3G detectors on the table*



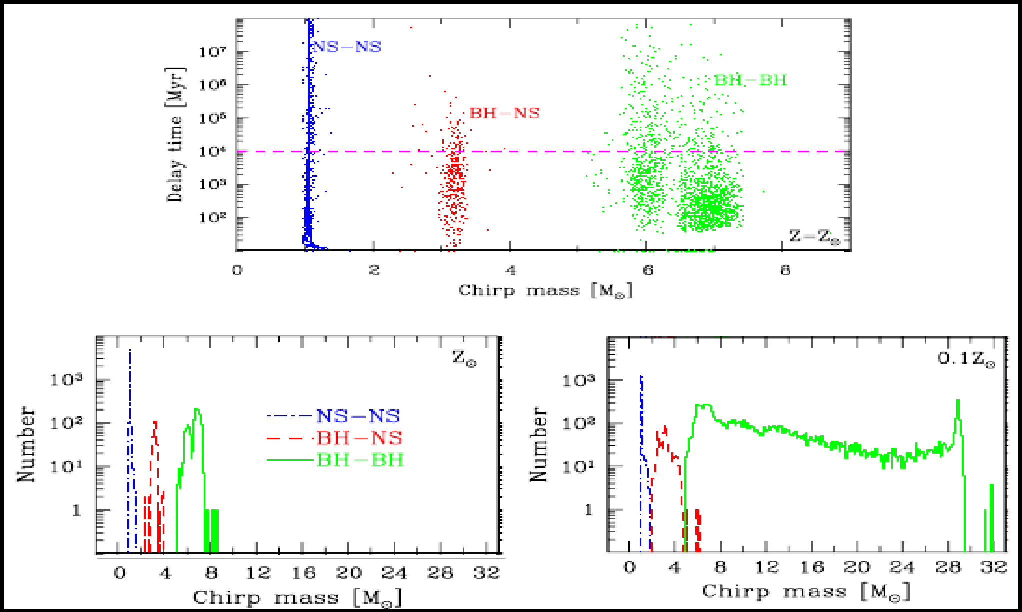

**(Berti et al. 2016)**

# Example: reach of ET

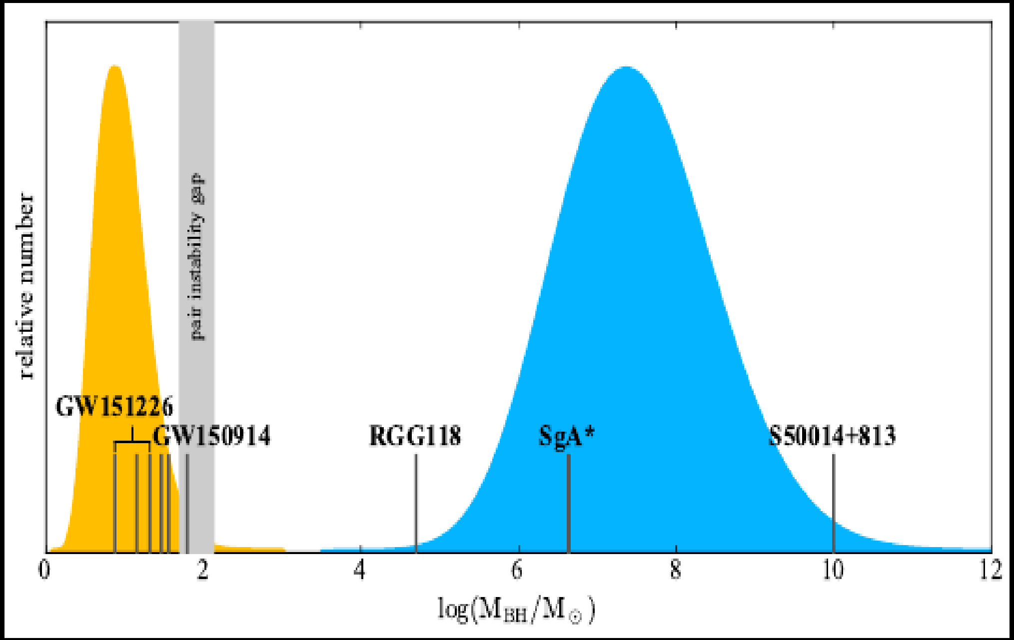



- -All LIGO-like BHBs in the Universe up to $z$~20 (~$10^5$/yr)
- -All NS-NS binaries to $z$~2-3 (~$10^4$/yr)
- -IMBHs up to $z$~2 (???)
- -SNe? Rotating NSs?

# A glimpse of astrophysics:




(Courtesy of T. Bulik)




(Colpi & AS 2017)

Cosmic evolution of the NSB BHB NS-BH merger rate

Connection with the SFR and metallicity evolution

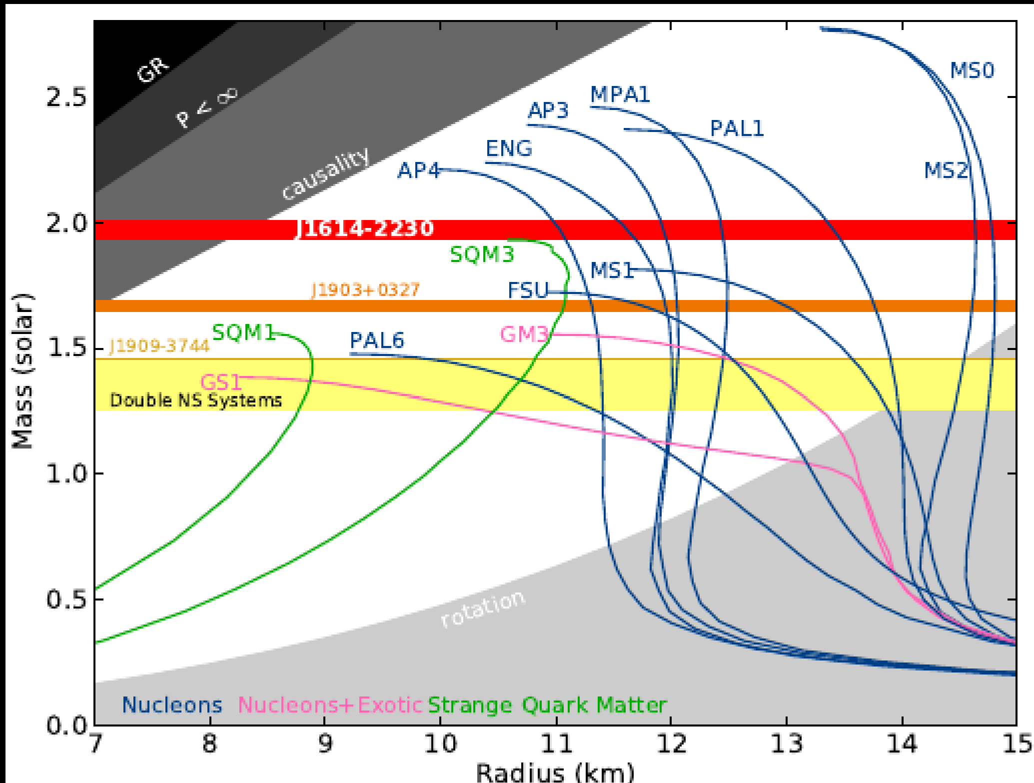
Redshift dependent mass functions (like QSO!)

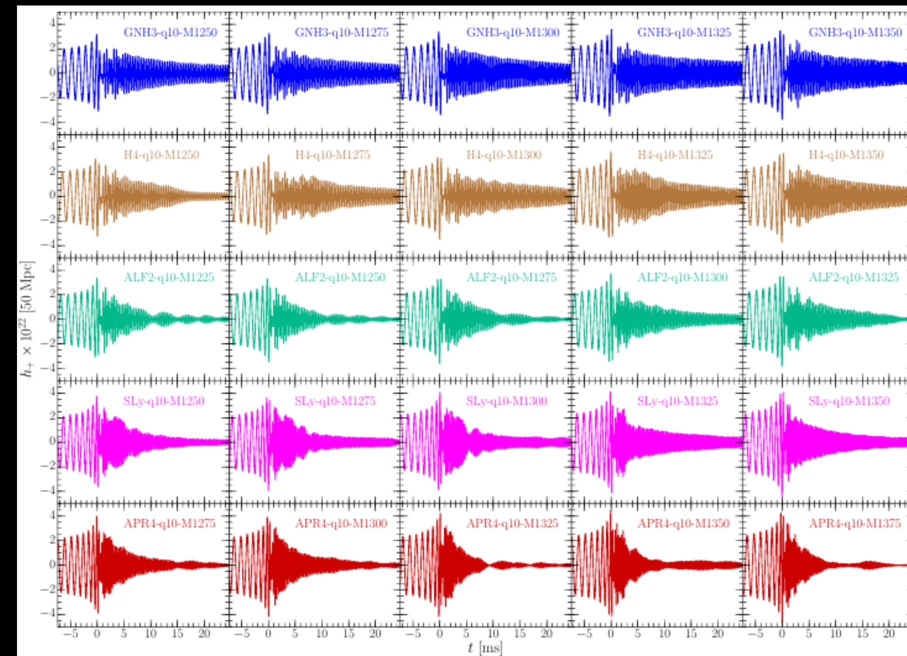
NS-BH mass gap?
Second mass gap?
IMBH mass gap/desert?

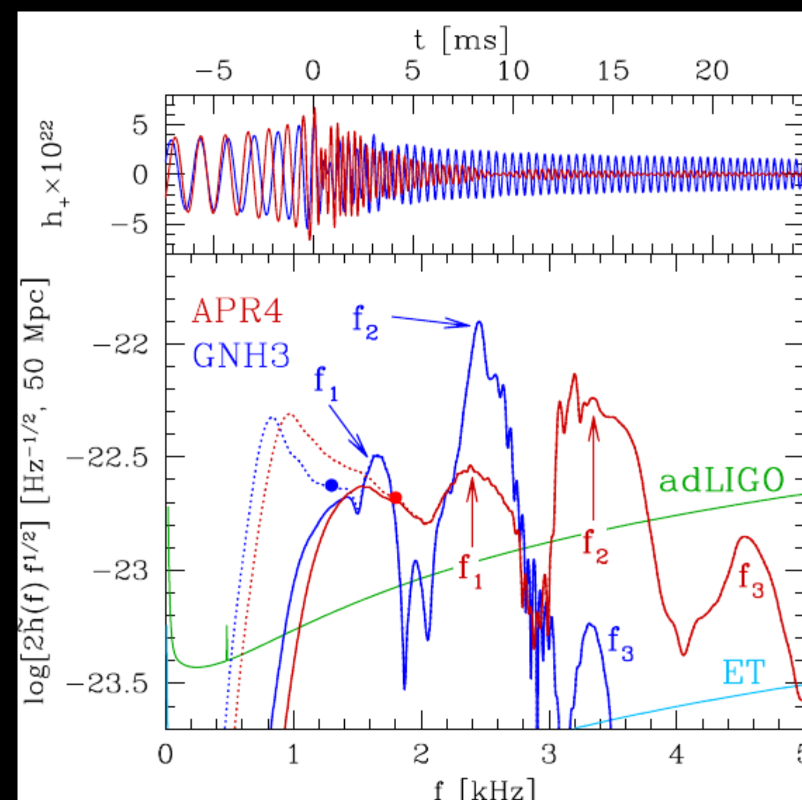
Astrophysical origin?

- -field binary evolution?
- -dynamics in clusters?
- -three body interactions?
- -nuclear star clusters?

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



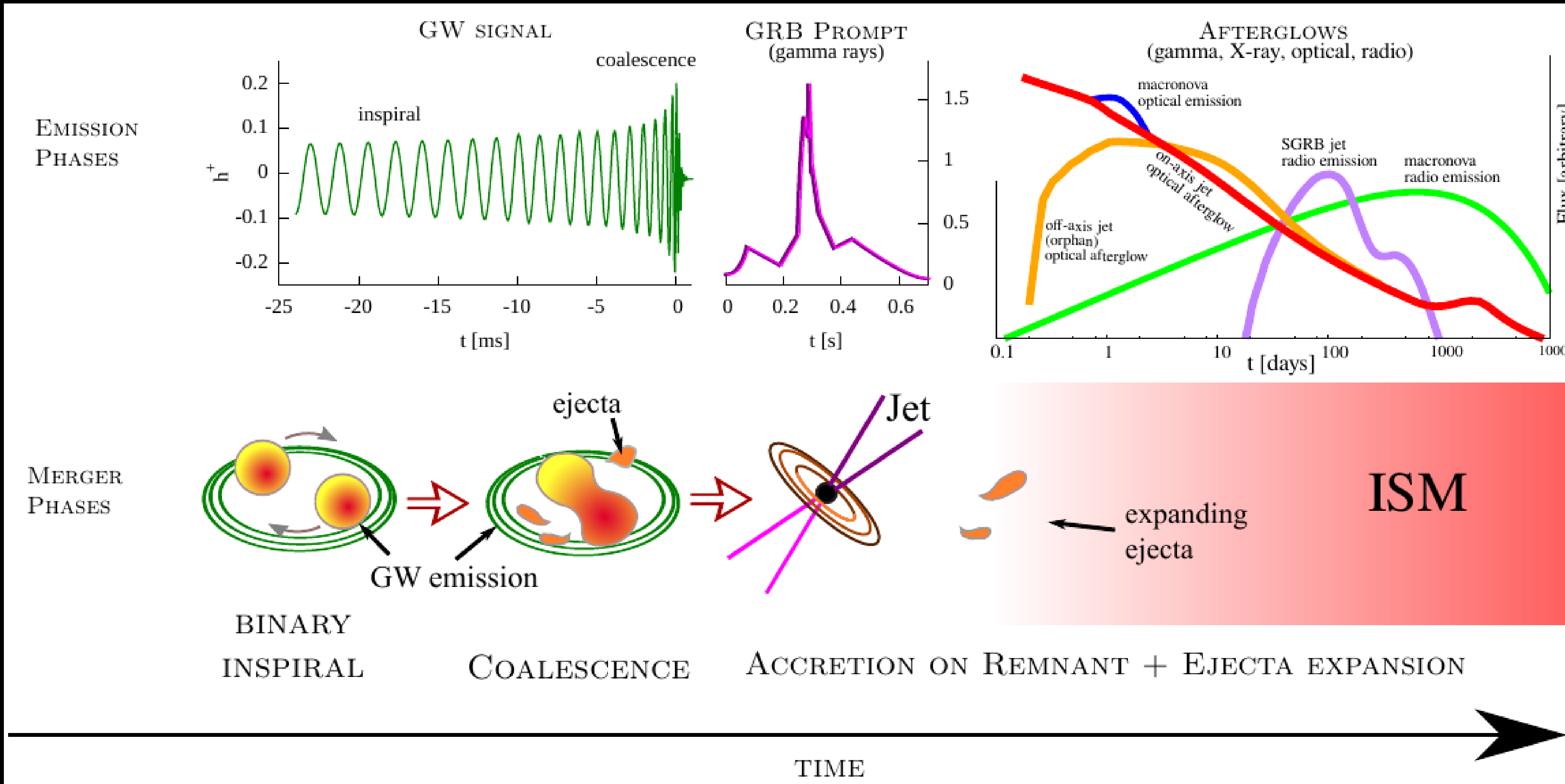






# Nuclear physics with NS mergers

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

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




**Multimessenger astronomy**

- -SGRBs?
- -X-ray isotropic?
- -IR Kilonova?
- -long term radio followup?

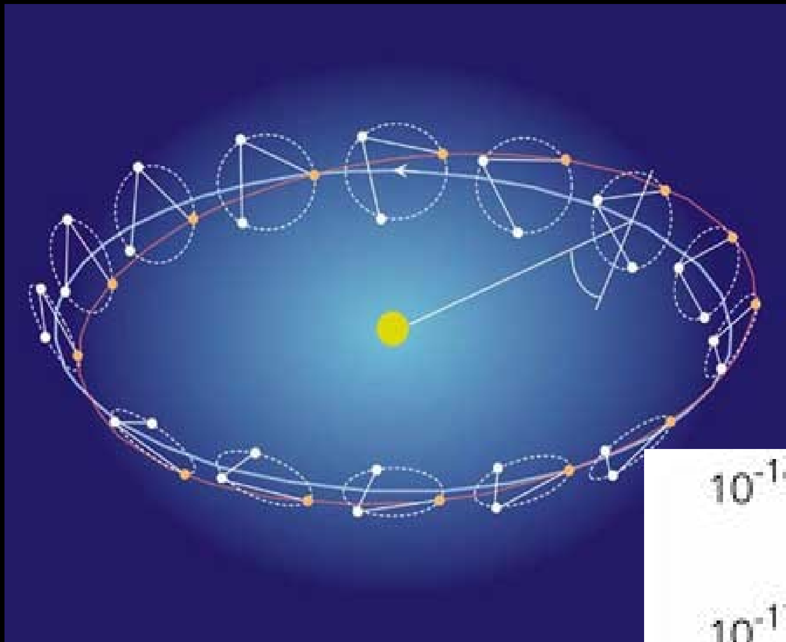
(Metzger & Berger 2012)

SKA SQUARE KILOMETRE ARRAY

eROSITA

LSST Large Synoptic Survey Telescope

# *The Laser Interferometer Space Antenna*

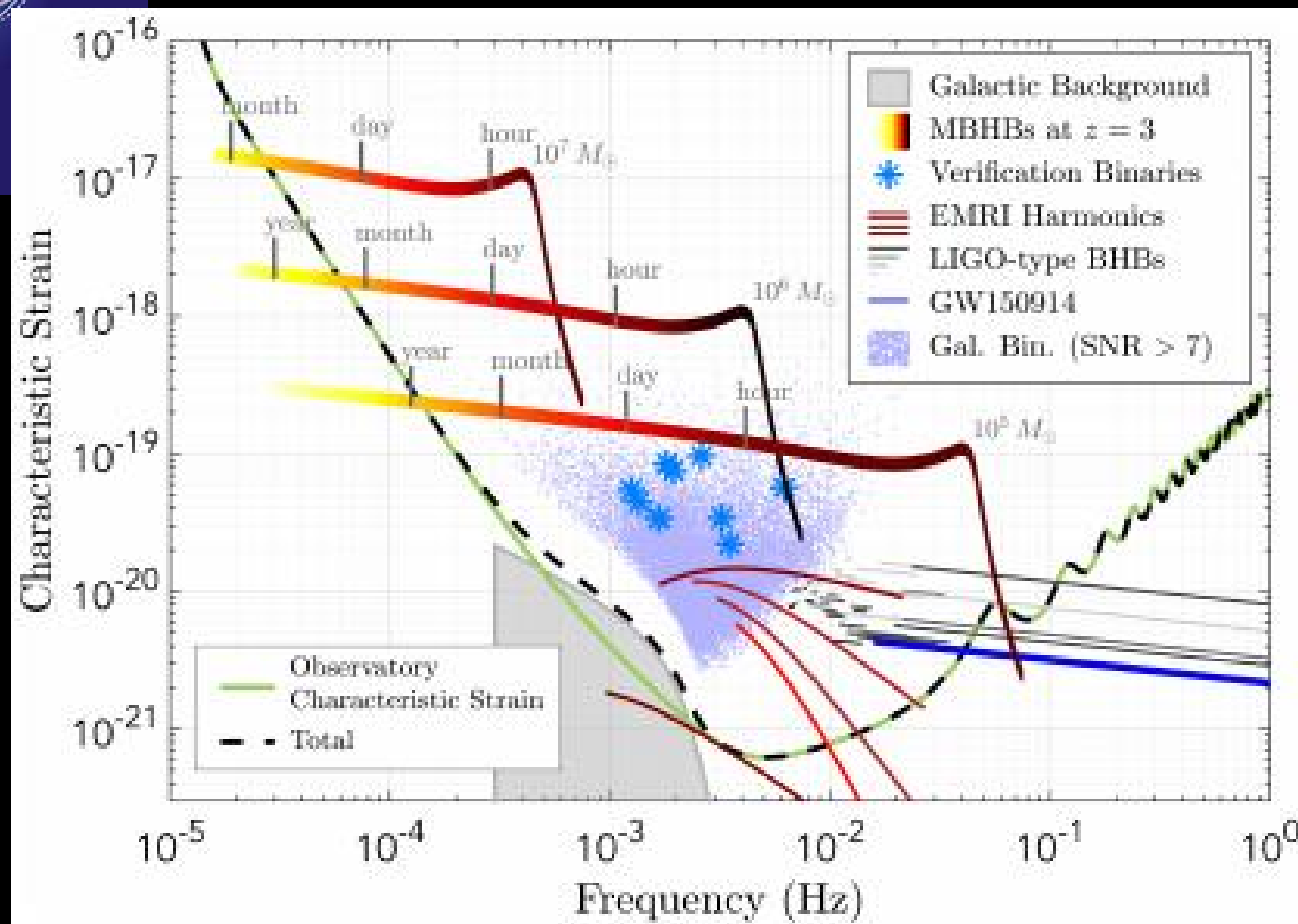


Sensitive in the mHz frequency range where MBH binary evolution is fast (chirp)

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)



# *Observational facts*

**1- In all the cases where the inner core of a galaxy has been resolved (i.e. In nearby galaxies), a massive compact object (which I'll call Massive Black Hole, MBH  for convenience) has been found in the centre.**

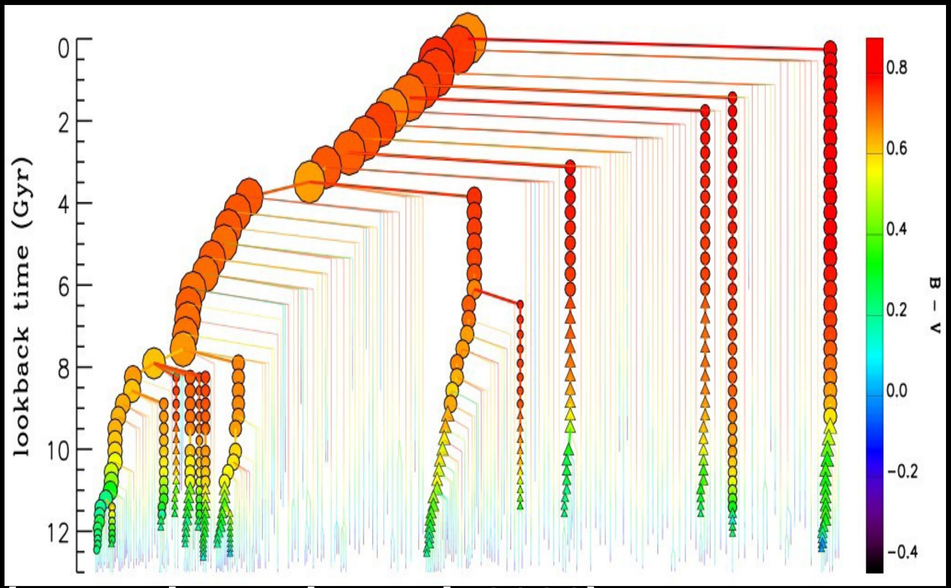
**2- MBHs must be the central engines of Quasars: the only viable model to explain this cosmological objects is by means of gas accretion onto a MBH.**

**3- Quasars have been discovered at z~7, their inferred masses are ~$10^9$ solar masses!**

**THERE WERE $10^9$ SOLAR MASS BHs WHEN THE UNIVERSE WAS <1Gyr OLD!!!**

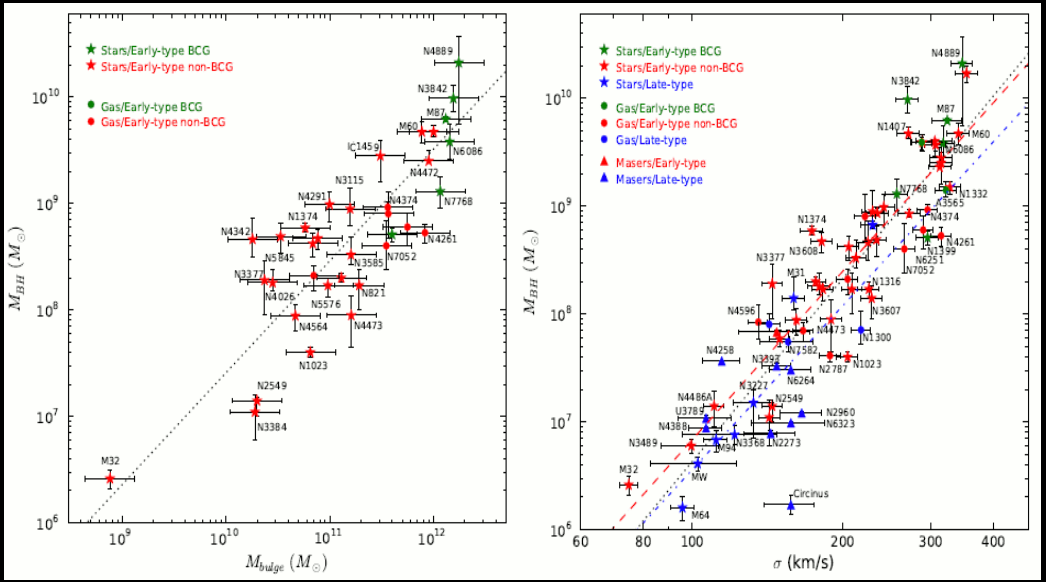
***MBH formation and evolution have profound consequences for GW astronomy***

# MBH evolution in a nutshell




(From de Lucia et al. 2006)

+




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

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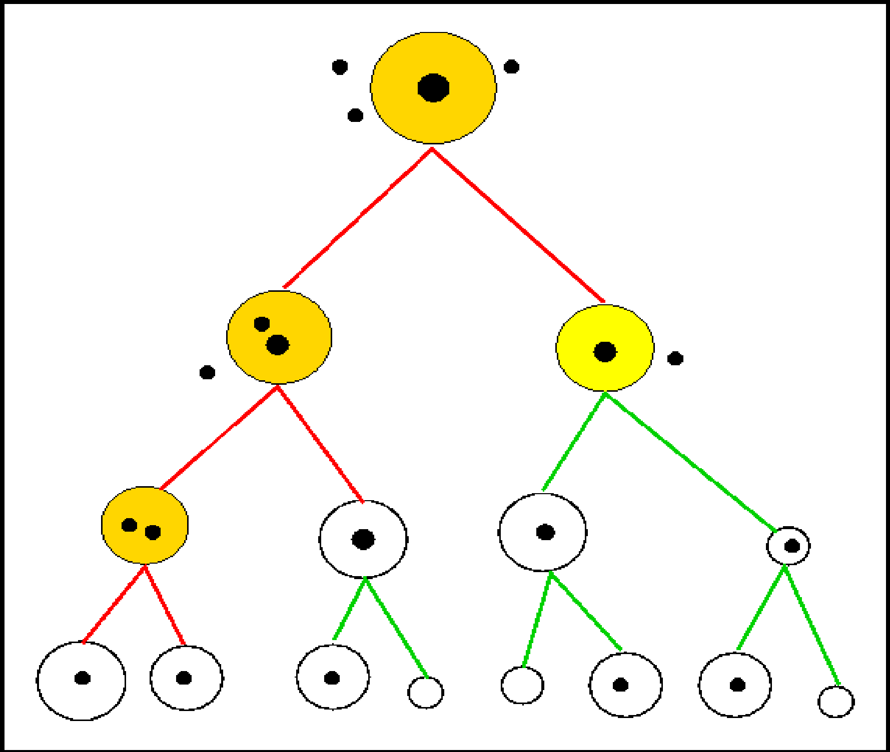

(Menou et al 2001, Volonteri et al. 2003)

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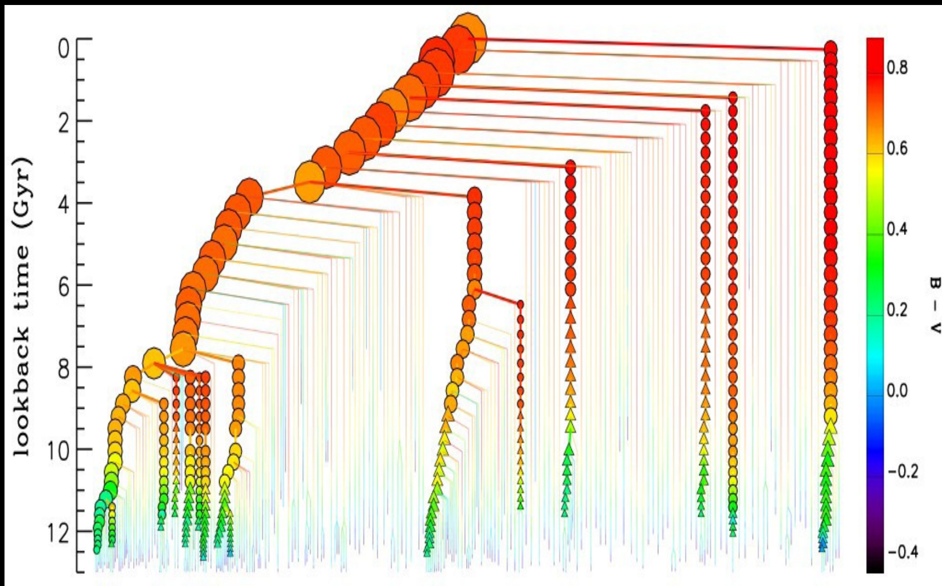


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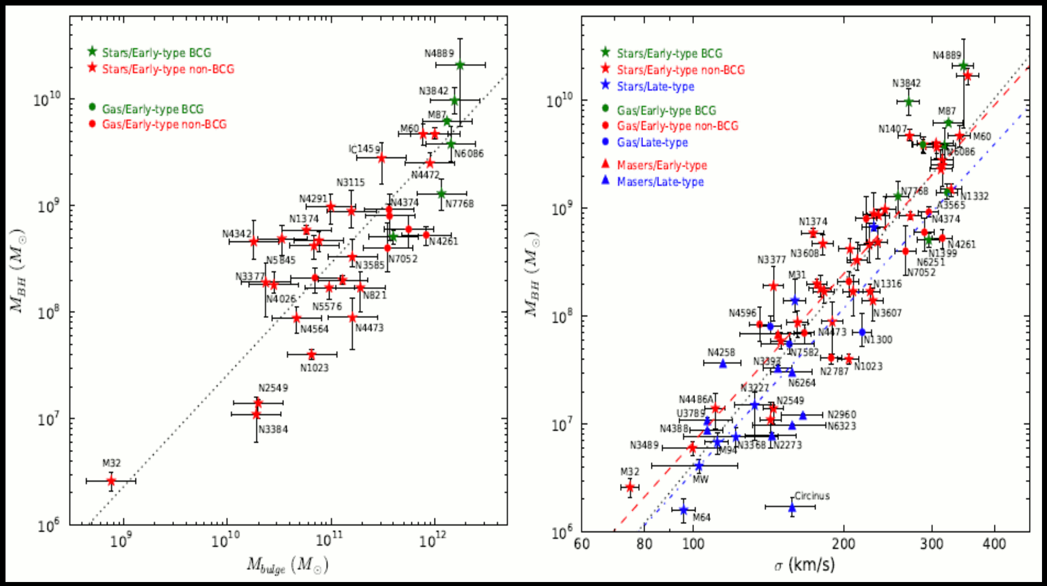


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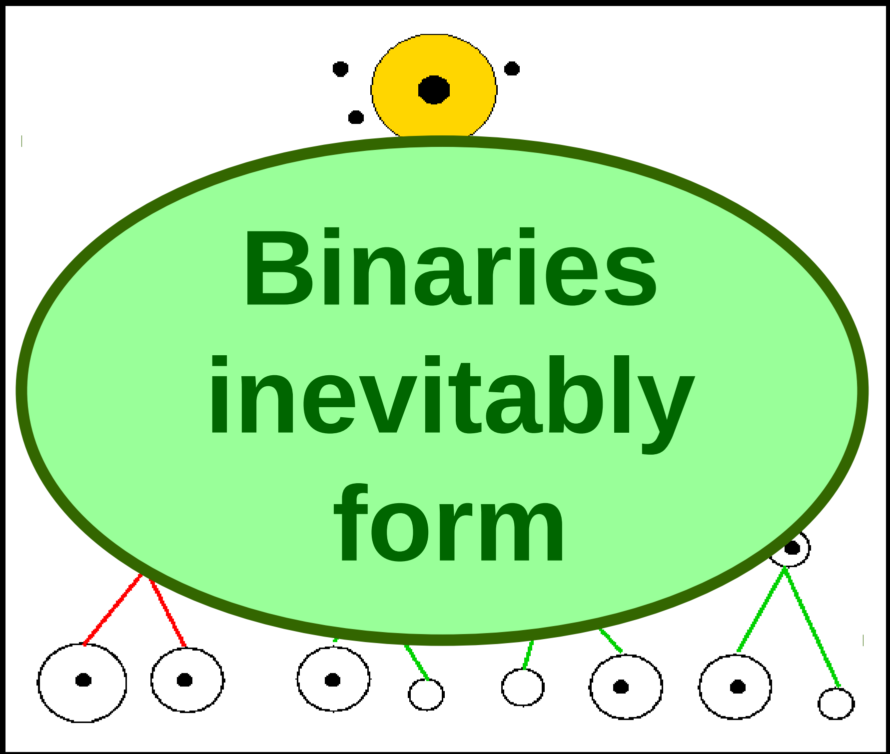
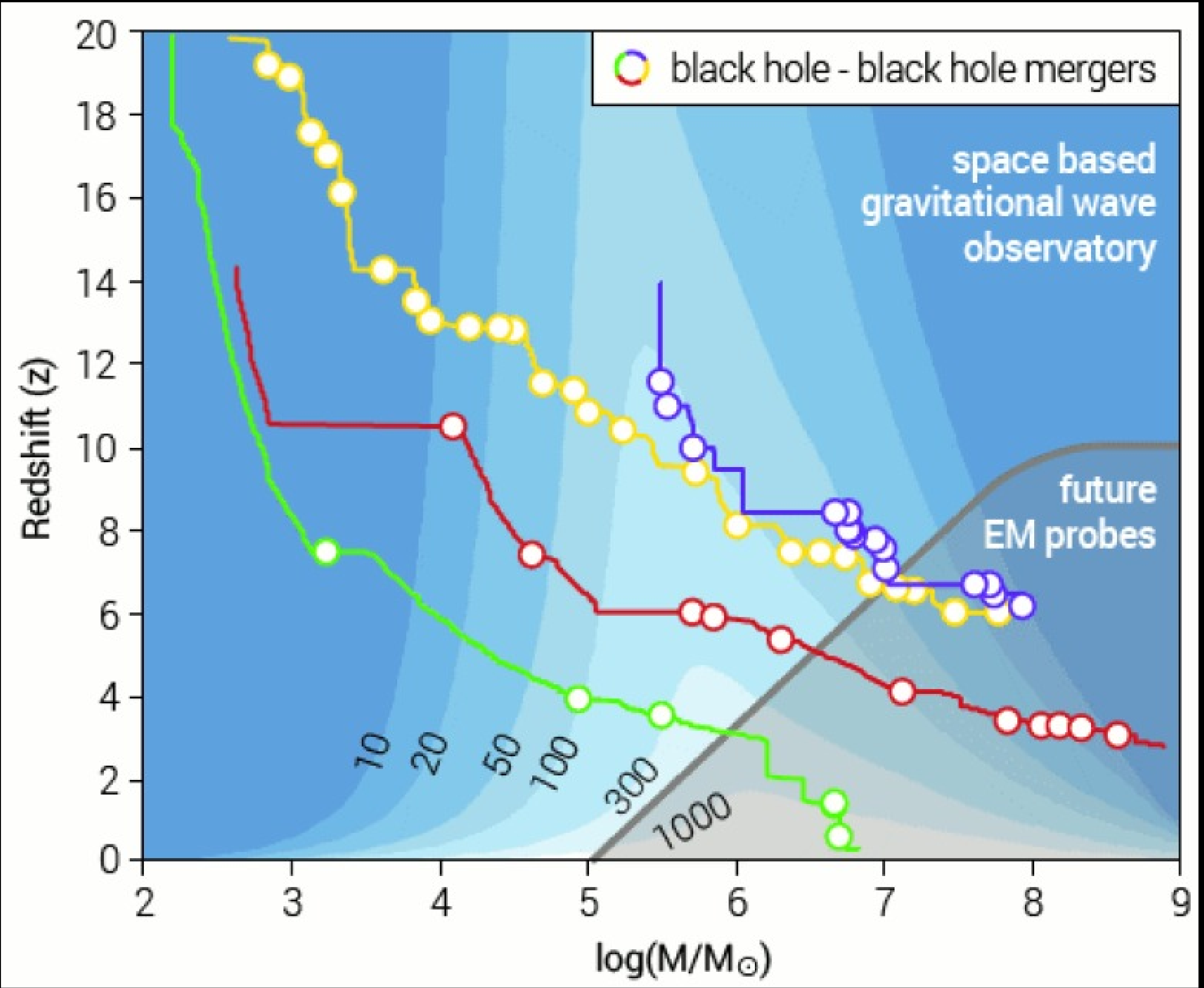


**Binaries inevitably form**

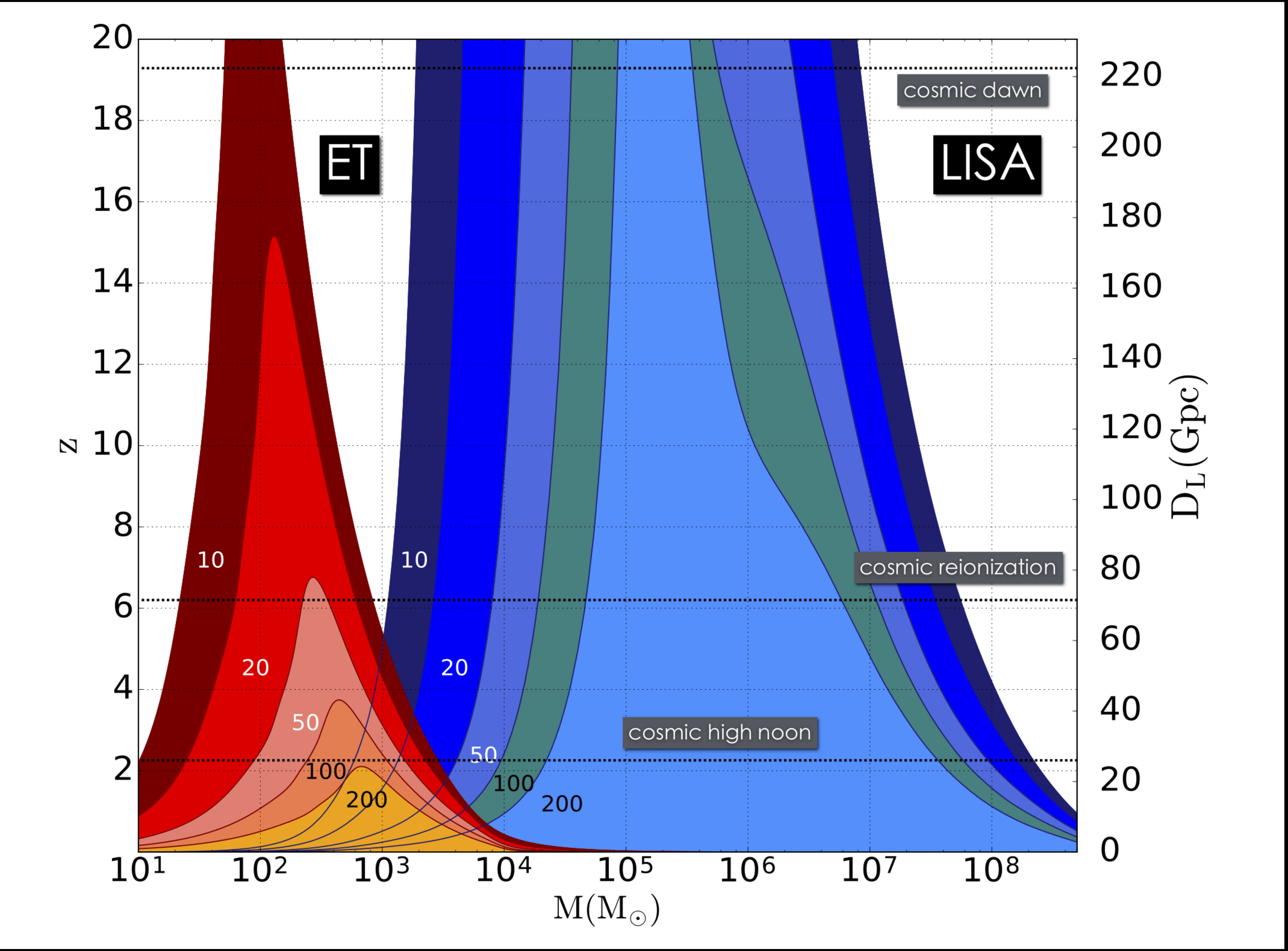
(Menou et al 2001, Volonteri et al. 2003)

***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
Redshift (z)
log(M/M⊙)
10
20
50
100
300
1000
0
2
4
6
8
10
12
14
16
18
20
2
3
4
5
6
7
8
9

# The parameter space of black holes



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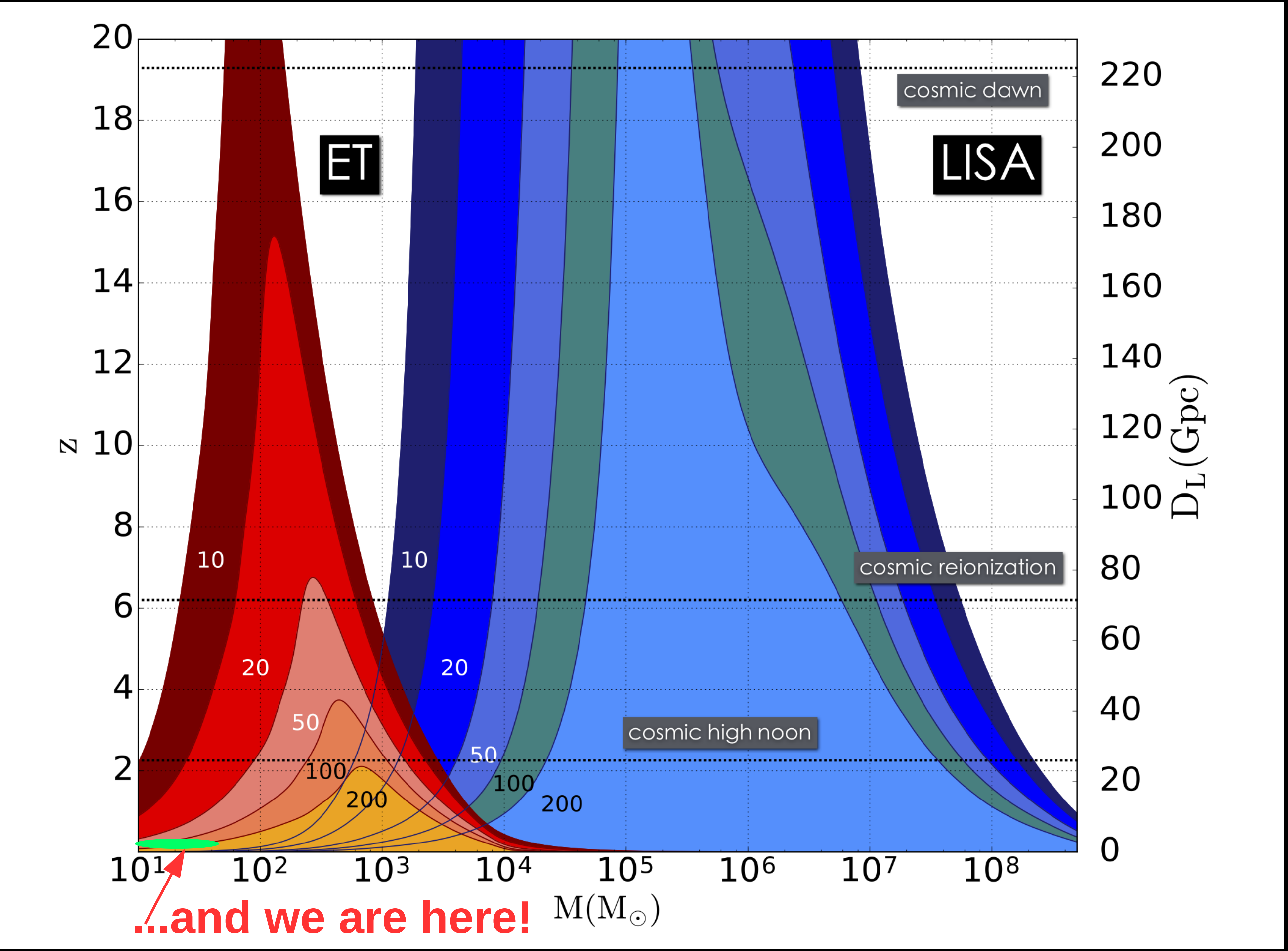
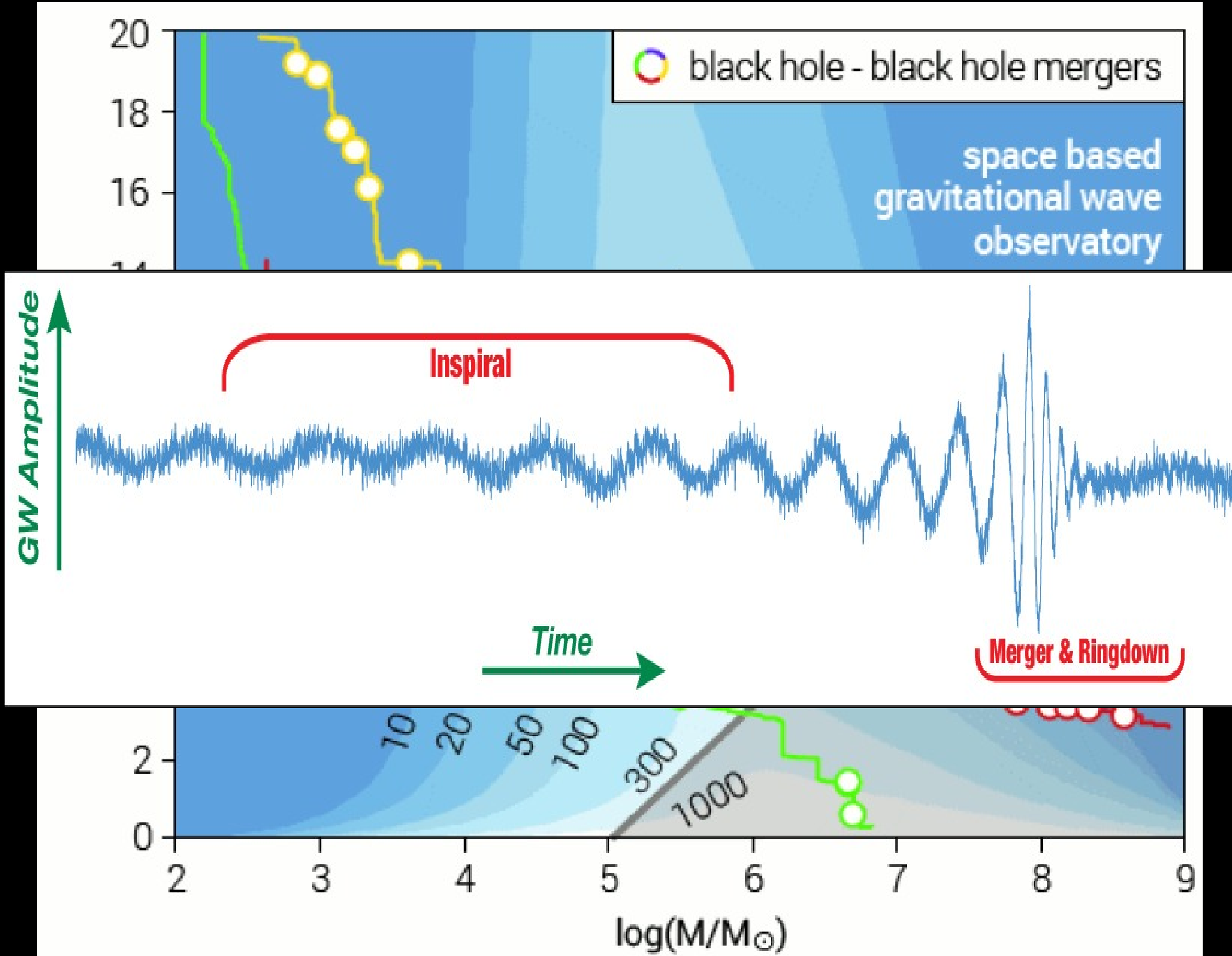




black hole - black hole mergers
space based gravitational wave observatory
GW Amplitude
Inspiral
Time
Merger & Ringdown
10
20
50
100
300
1000
20
18
16
2
0
2
3
4
5
6
7
8
9
log(M/M⊙)

# *Summary of LISA parameter estimation*

**Assuming 4 years of operation and 6 links:**

**~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**

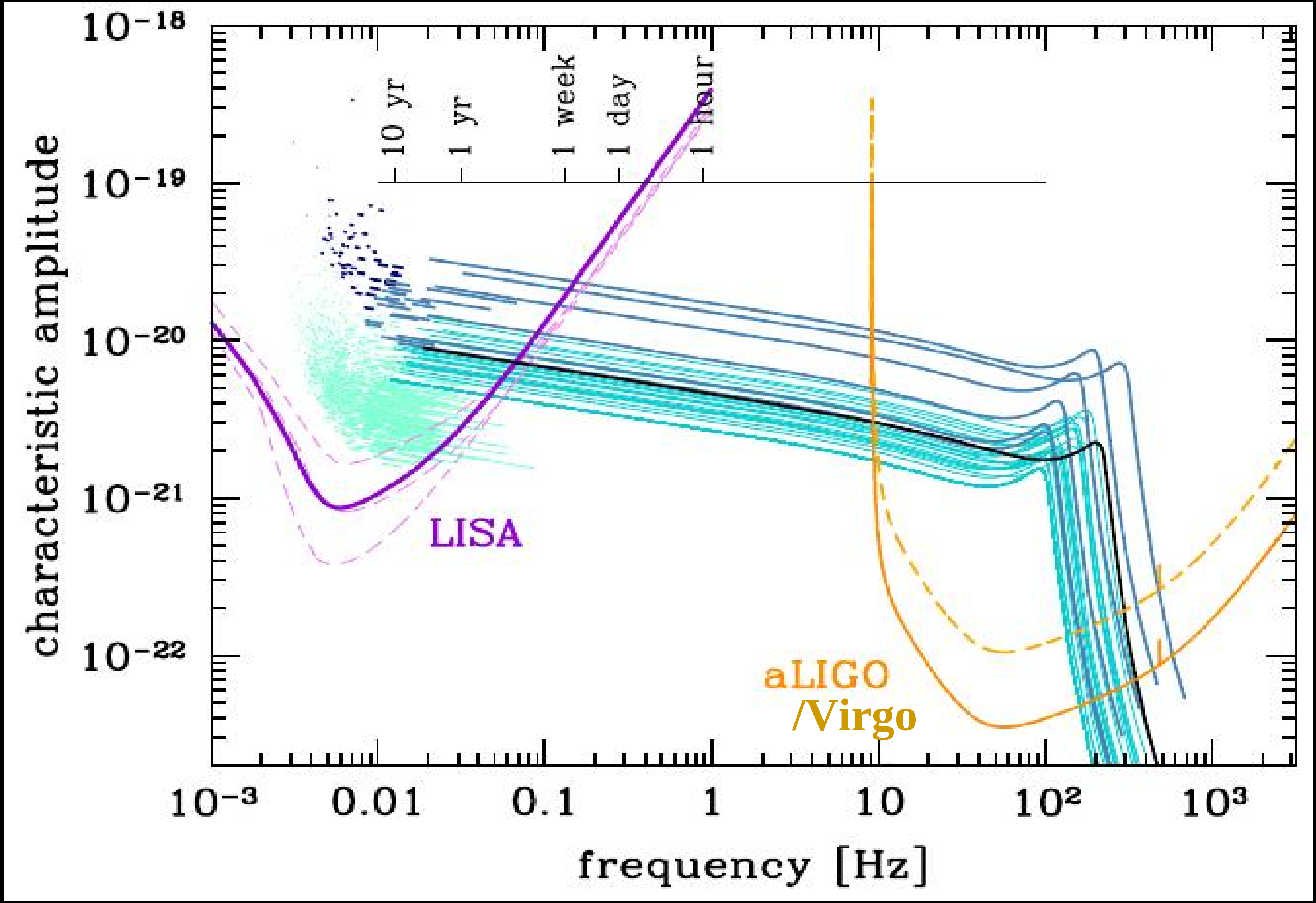
**~50 systems with secondary spin determined to 0.1**

**~50 systems with spin direction determined within 10deg**

**~30 events with final spin determined to 0.1**

# Implications of GW150914: multi-band GW astronomy

(AS 2016, PRL 116, 1102)

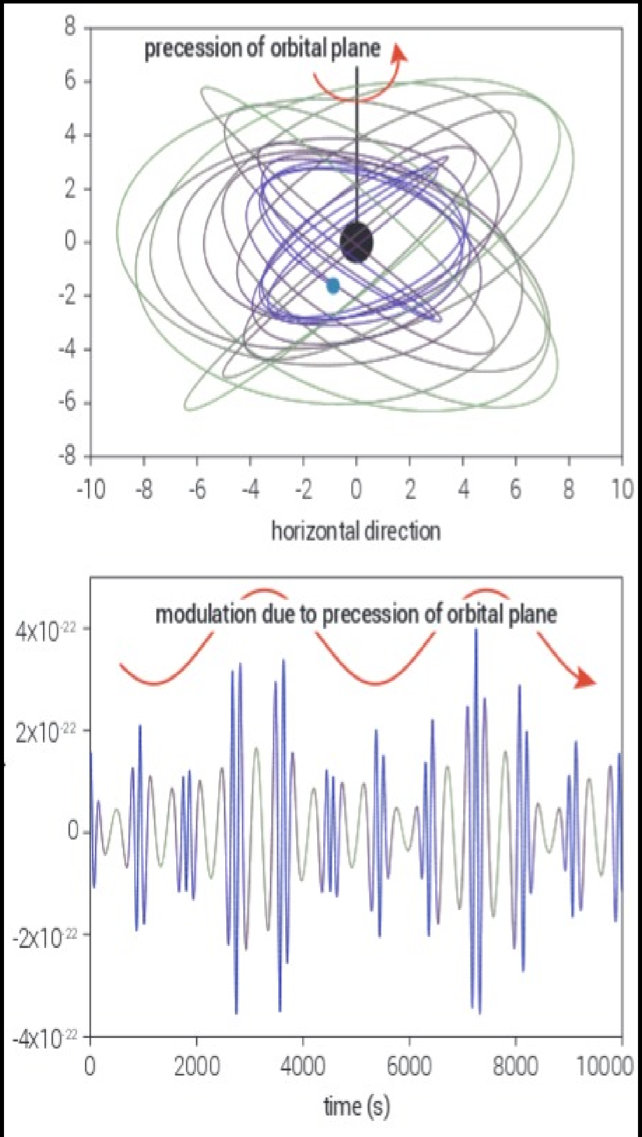



**BHB will be detected by LISA and cross to the LIGO/Virgo band, assuming a 5 year operation of LISA.**

# Extreme mass ratio inspirals (EMRIs)

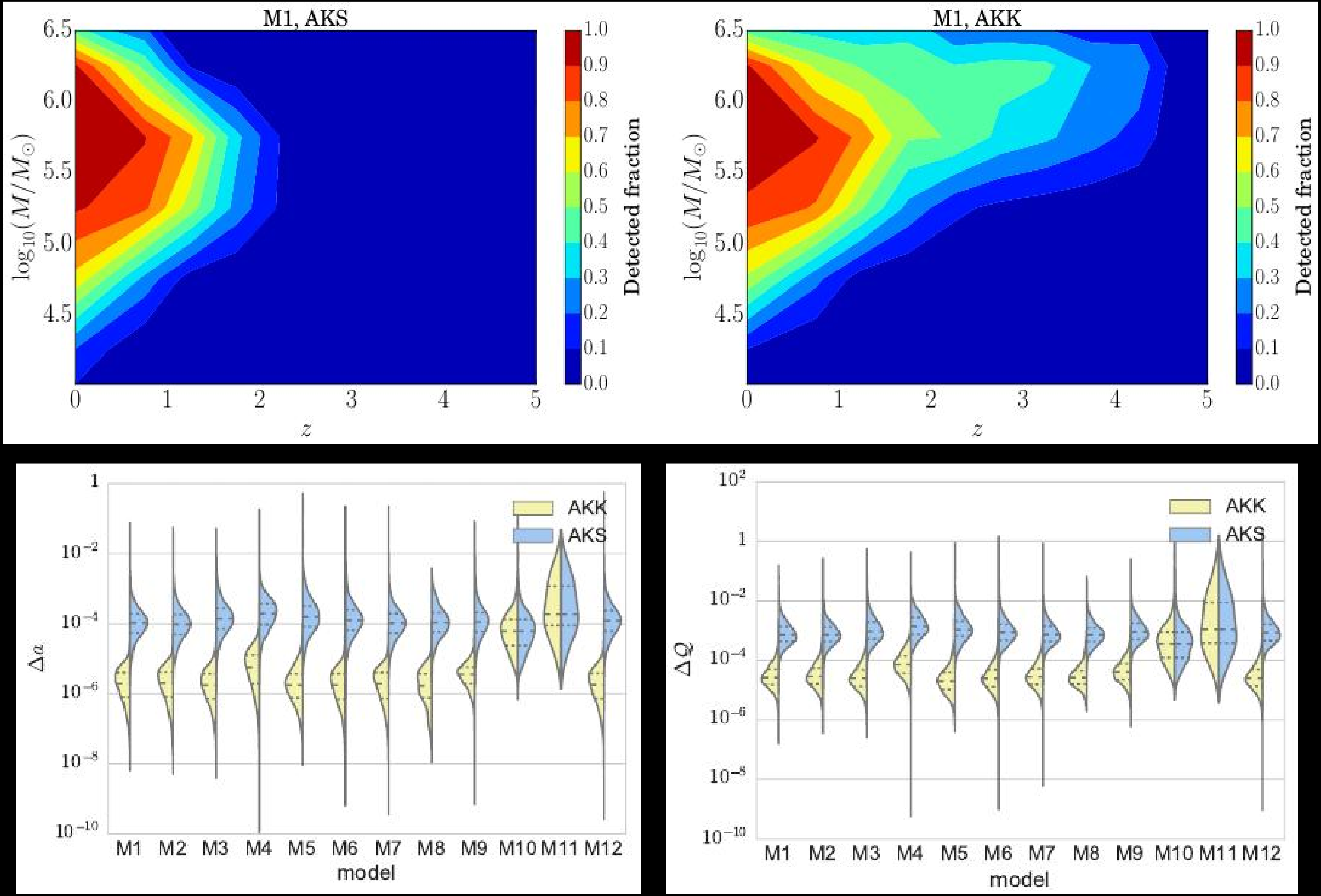
- *What is the mass distribution of stellar remnants at the galactic centres and what is the role of mass segregation and relaxation in determining the nature of the stellar populations around the nuclear black holes in galaxies?*
- *Are massive black holes as light as $\sim 10^5 M_{\odot}$ inhabiting the cores of low mass galaxies? Are they seed black hole relics? What are their properties?*

- *Does gravity travel at the speed of light ?*
- *Does the graviton have mass?*
- *How does gravitational information propagate: Are there more than two transverse modes of propagation?*
- *Does gravity couple to other dynamical fields, such as, massless or massive scalars?*
- *What is the structure of spacetime just outside astrophysical black holes? Do their spacetimes have horizons?*
- *Are astrophysical black holes fully described by the Kerr metric, as predicted by General Relativity?*

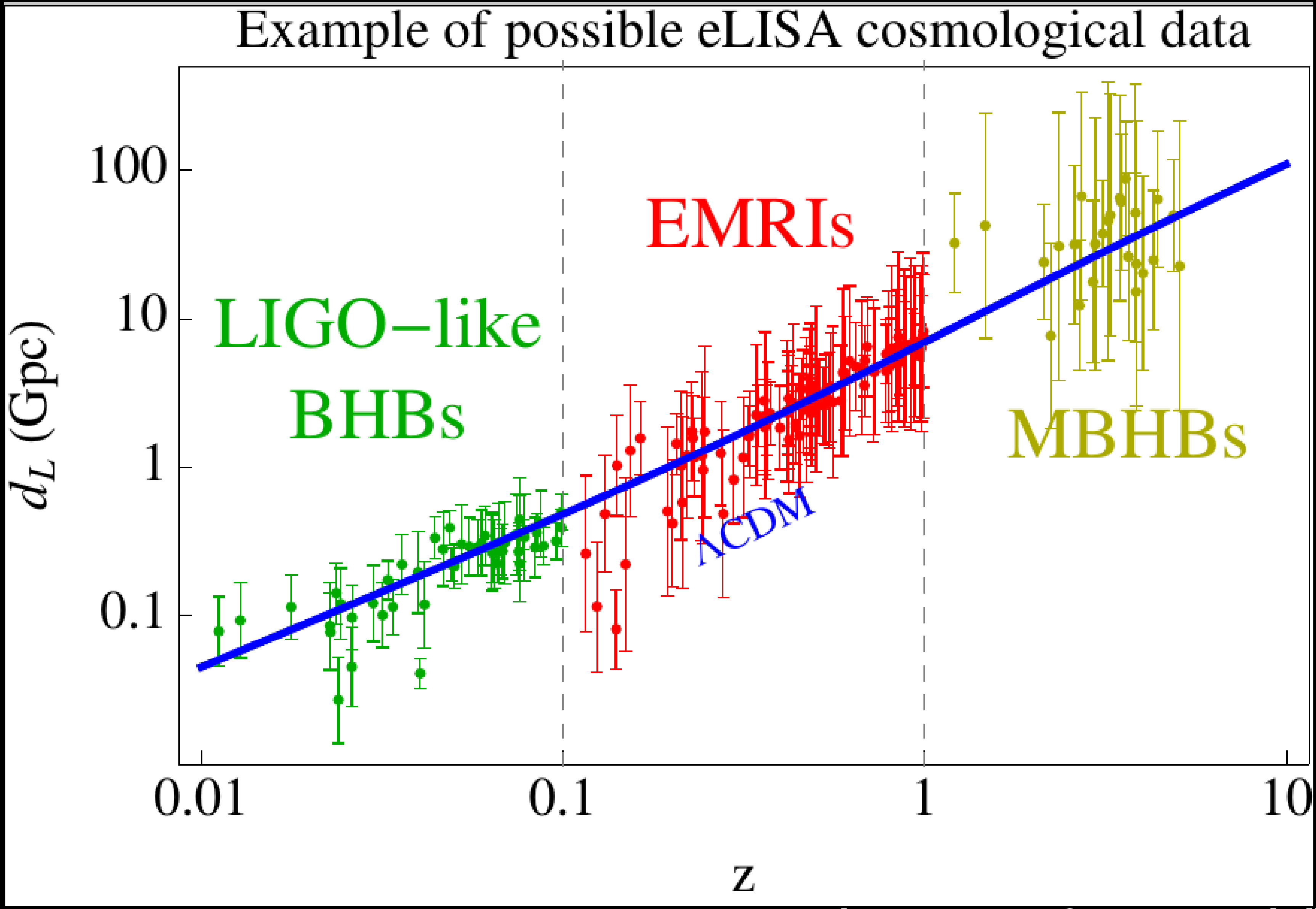


# *Selected results: LISA reach and parameter estimation*

**(Babak et al, 2017)**

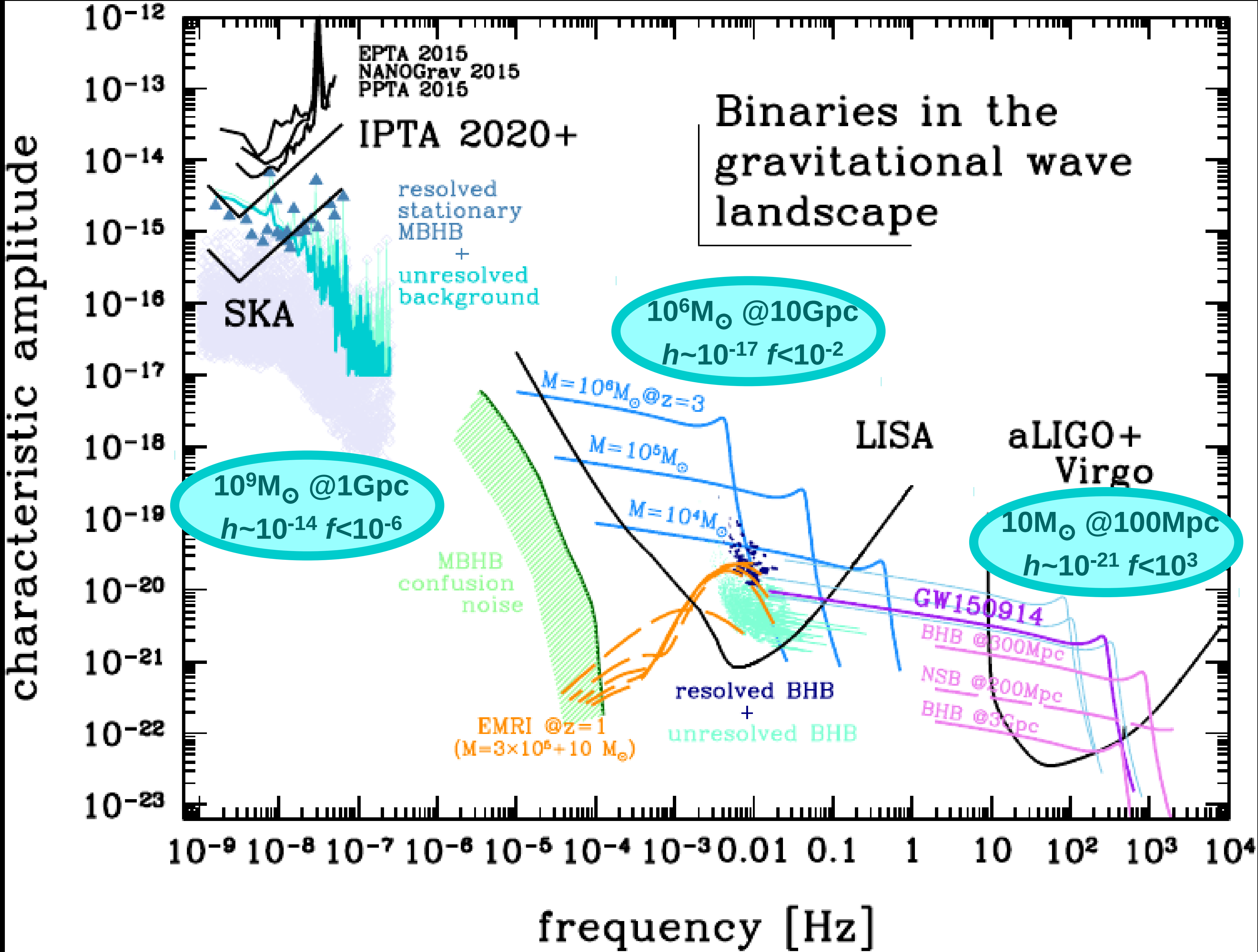


# *Cosmology with gravitational waves*




**(Courtesy of N. Tamanini)**

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



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MBHB confusion noise
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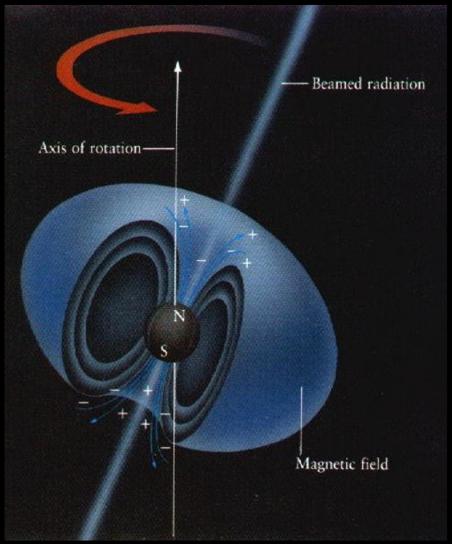
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
resolved BHB
+
unresolved BHB
EMRI @z=1
($M=3\times10^5+10$ $M_\odot$)
characteristic amplitude
frequency [Hz]

# *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

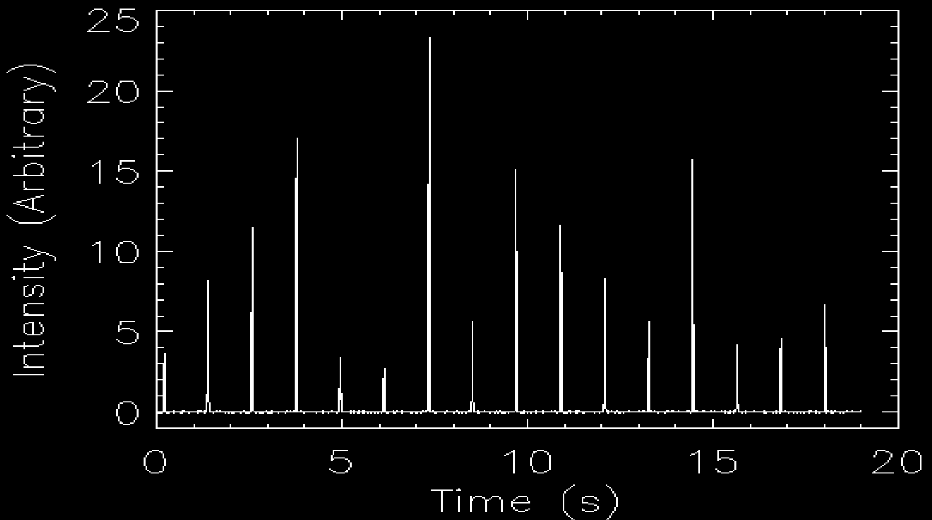



1-Observe a pulsar and measure the ToAs

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***

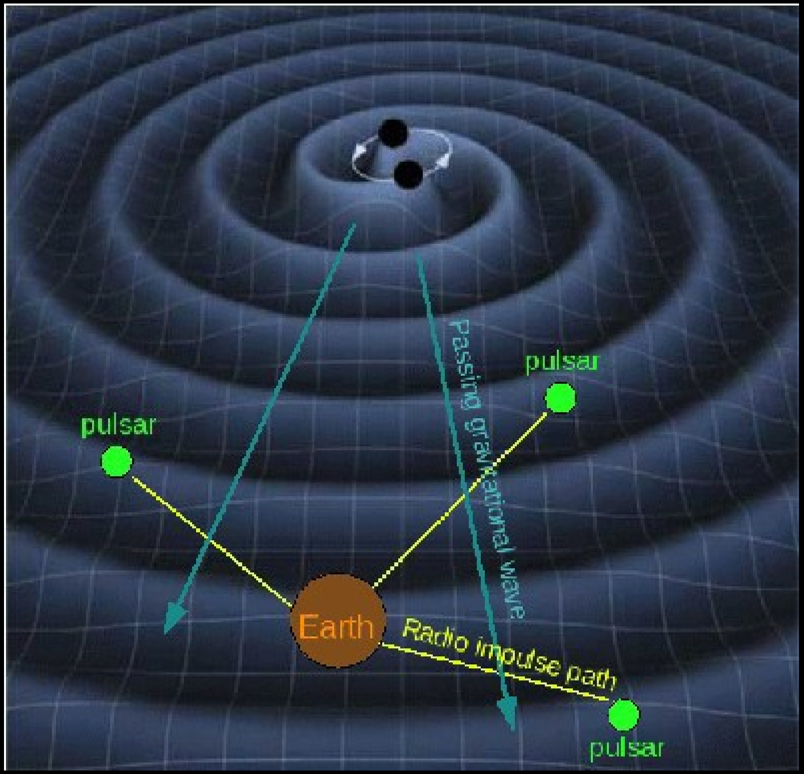
# *Effect of gravitational waves*

**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)**

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



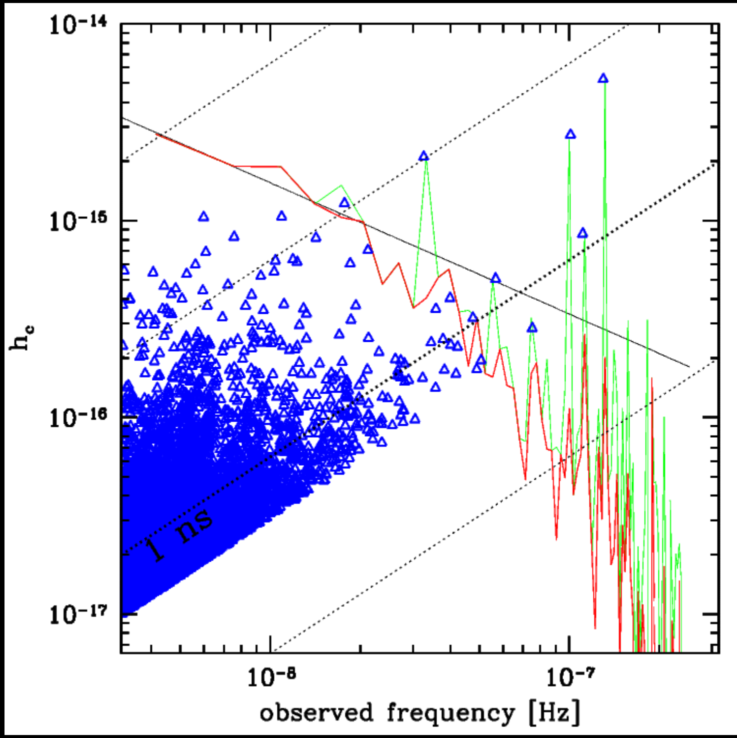

**(Sazhin 1979, Hellings & Downs 1983, Jenet et al. 2005, AS et al. 2008, 2009)**

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

**Implies a residual ~100ns**

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

# The expected GW signal in the PTA band




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

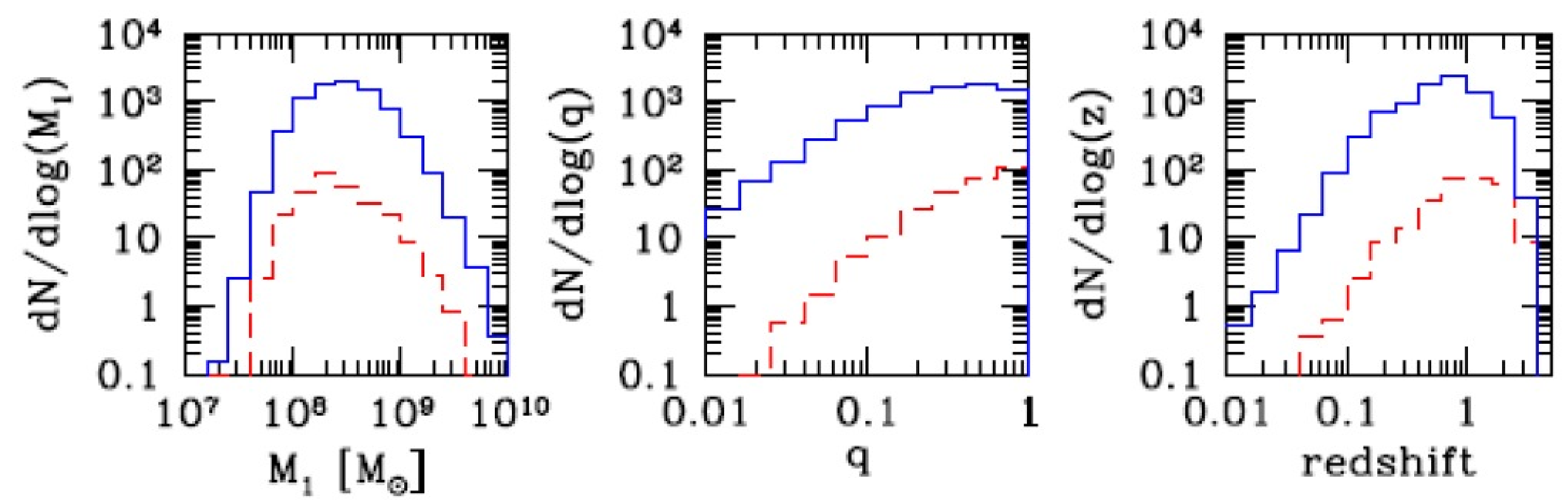
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \frac{d^3N}{dz d\mathcal{M} d\ln f_r} h^2(f_r)$$

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

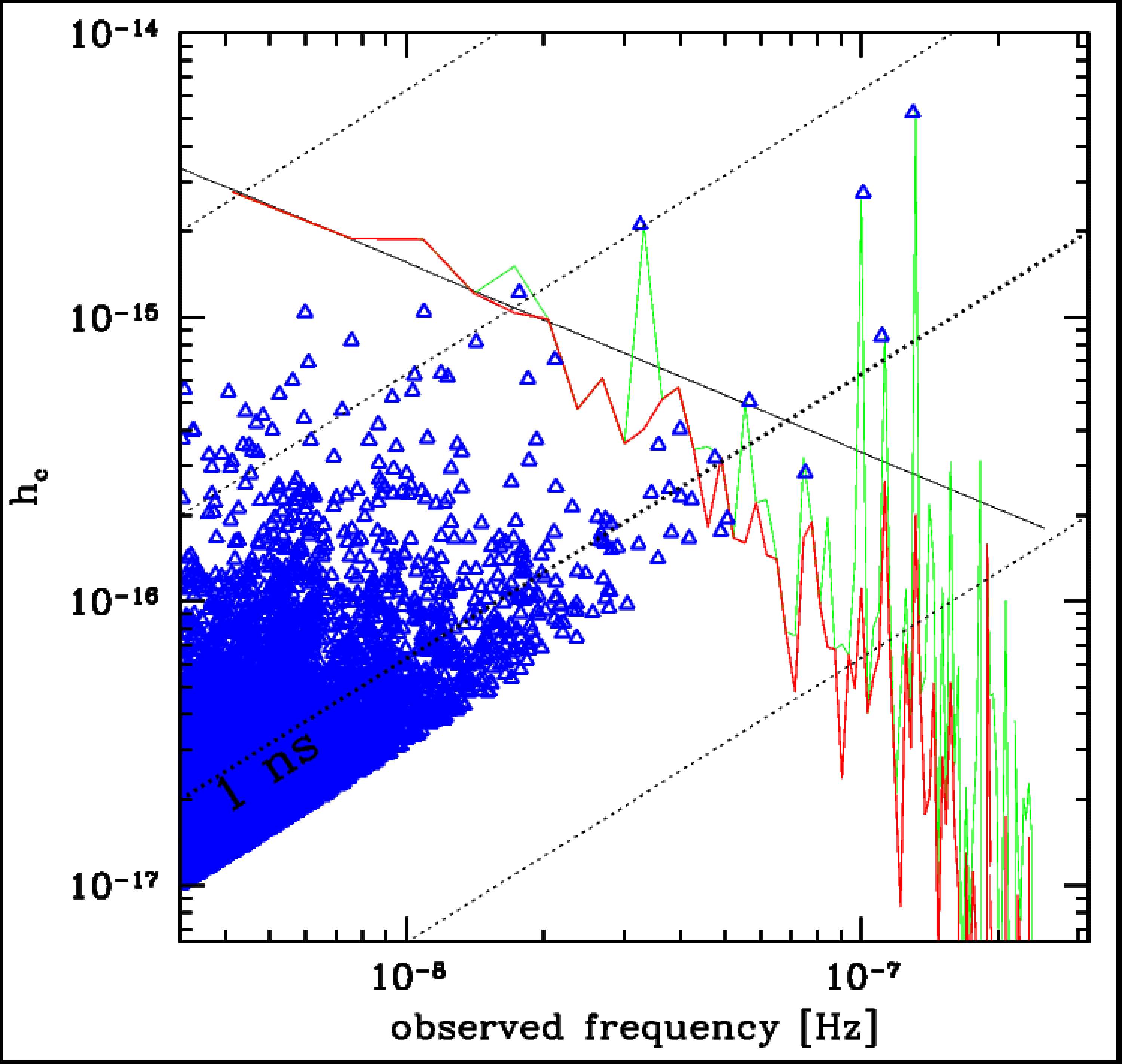
**Theoretical spectrum: simple power law**

**(Phinney 2001)**

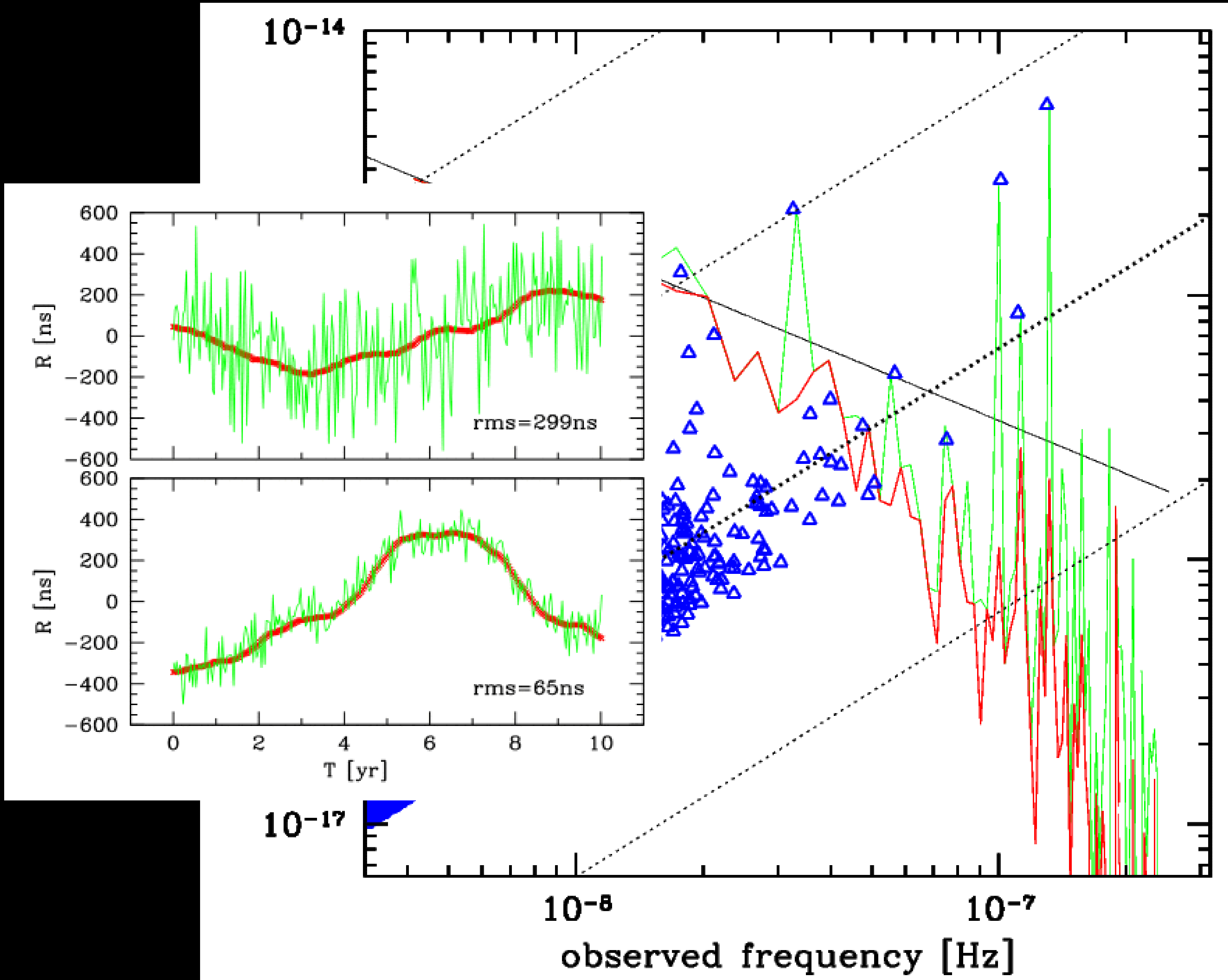
$$h_c(f) = A \left(\frac{f}{\rm yr^{-1}}\right)^{-2/3}$$



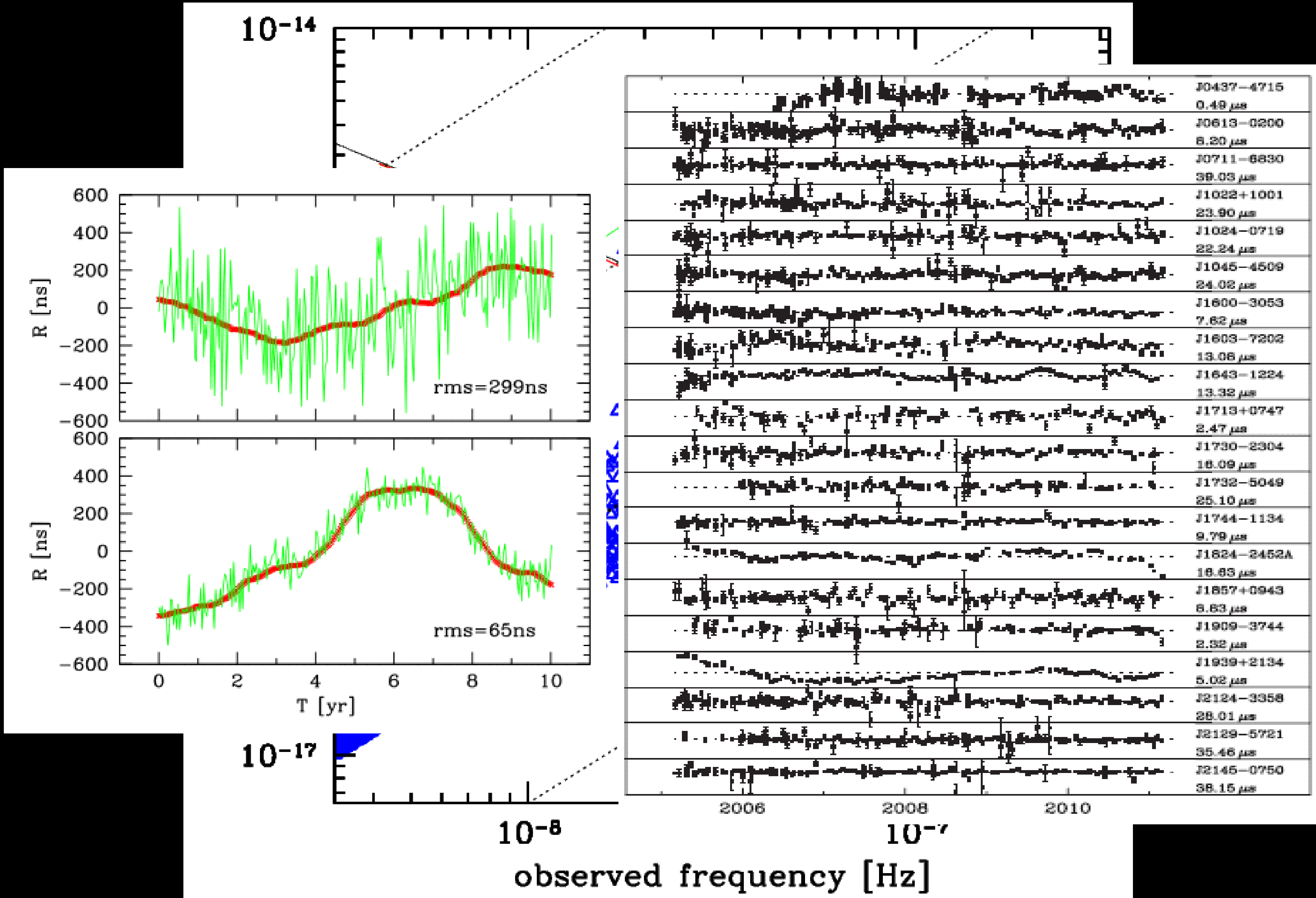

**The signal is contributed by extremely massive (>$10^8 M_\odot$) relatively low redshift ($z$<1) MBH binaries (AS et al. 2008, 2012)**



$10^{-14}$
$10^{-15}$
$10^{-16}$
$10^{-17}$
$h_c$
1 ns
$10^{-8}$
$10^{-7}$
observed frequency [Hz]

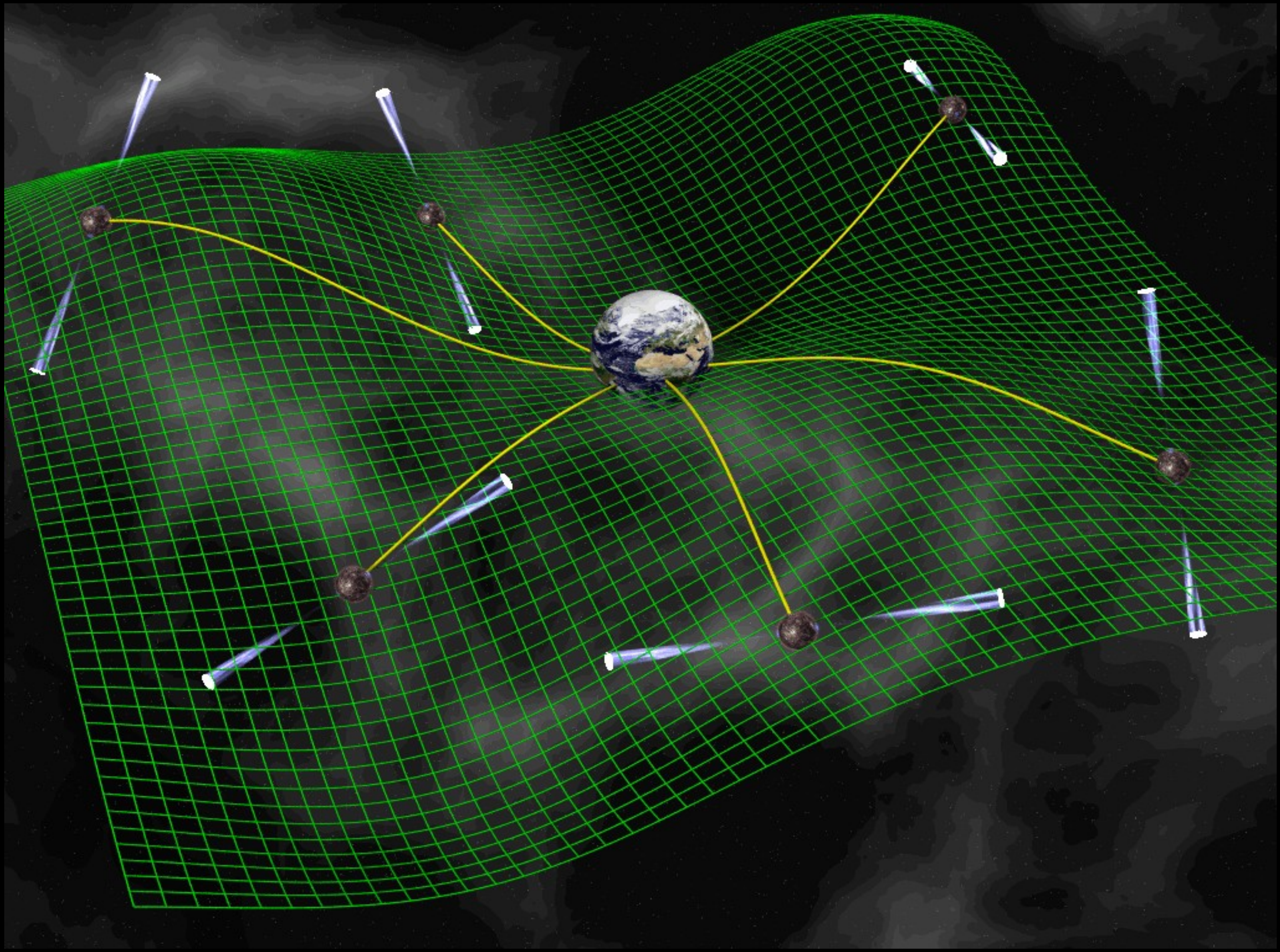


$10^{-14}$
$10^{-17}$
$10^{-8}$
$10^{-7}$
observed frequency [Hz]
600
400
200
0
−200
−400
−600
R [ns]
rms=299ns
rms=65ns
0
2
4
6
8
10
T [yr]

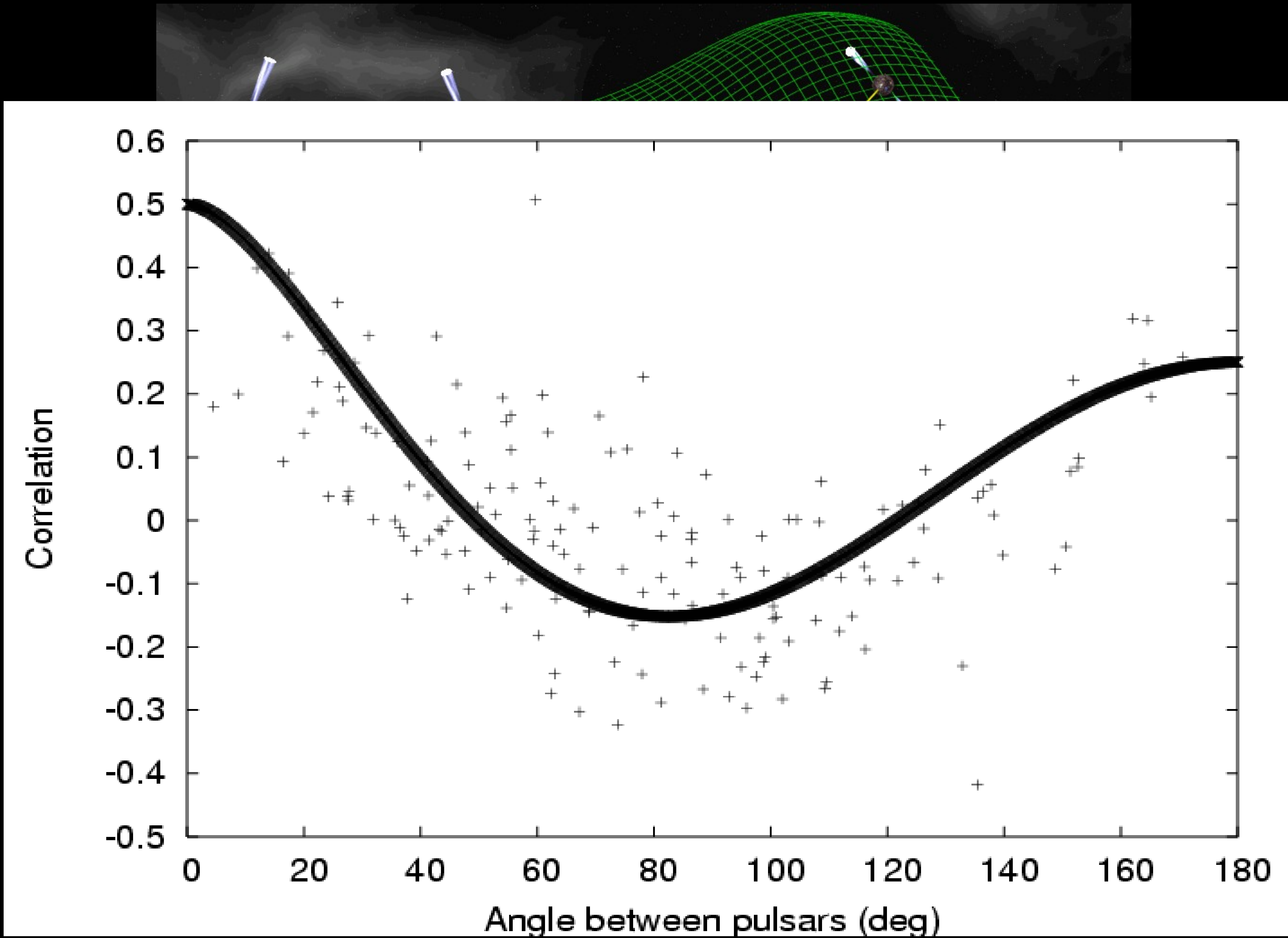


$10^{-14}$
$10^{-17}$
$10^{-8}$
$10^{-7}$
observed frequency [Hz]
R [ns]
600
400
200
0
−200
−400
−600
rms=299ns
rms=65ns
T [yr]
0
2
4
6
8
10
J0437−4715
0.49 µs
J0613−0200
6.20 µs
J0711−6830
39.03 µs
J1022+1001
23.90 µs
J1024−0719
22.24 µs
J1045−4509
24.02 µs
J1600−3053
7.62 µs
J1603−7202
13.06 µs
J1643−1224
13.32 µs
J1713+0747
2.47 µs
J1730−2304
16.09 µs
J1732−5049
25.10 µs
J1744−1134
9.79 µs
J1824−2452A
16.63 µs
J1857+0943
6.63 µs
J1909−3744
2.32 µs
J1939+2134
5.02 µs
J2124−3358
28.01 µs
J2129−5721
35.46 µs
J2145−0750
38.15 µs
2006
2008
2010

# *We are looking for a correlated signal*



# *We are looking for a correlated signal*

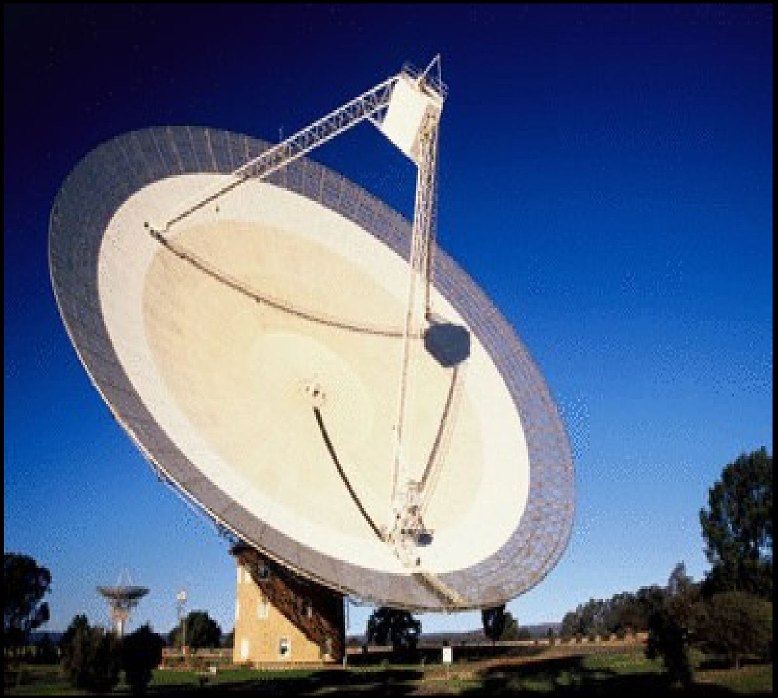



**(Hellings & Downs 1983)**

# A worldwide observational effort

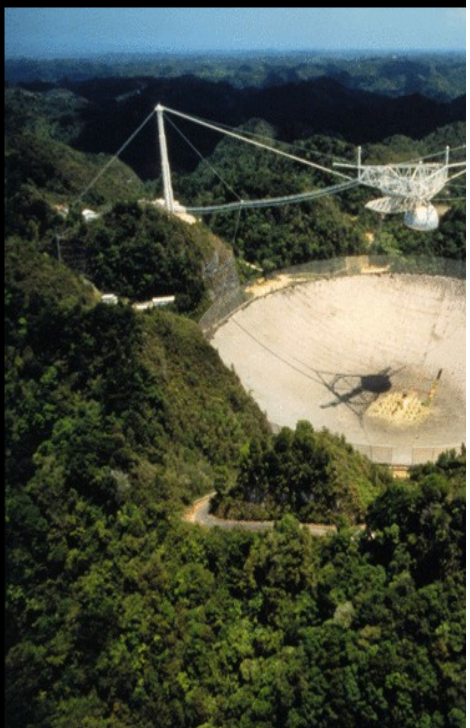
**EPTA/LEAP** **(Large European Array for Pulsars)**

**NANOGrav** **(North American nHz Observatory for Gravitational Waves)**



**PPTA** **(Parkes Pulsar Timing Array)**

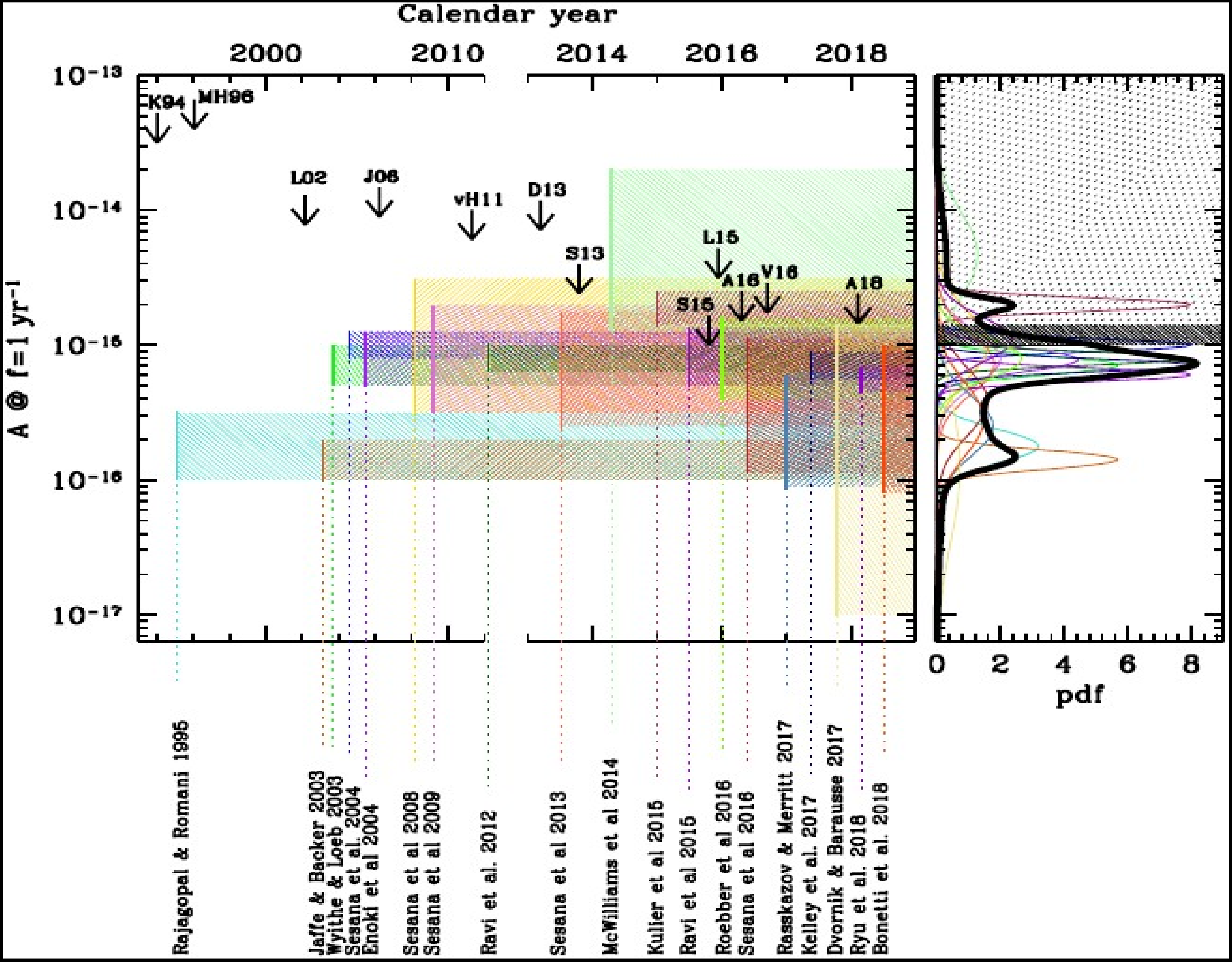
# *A worldwide observational effort*



nHz
aves)

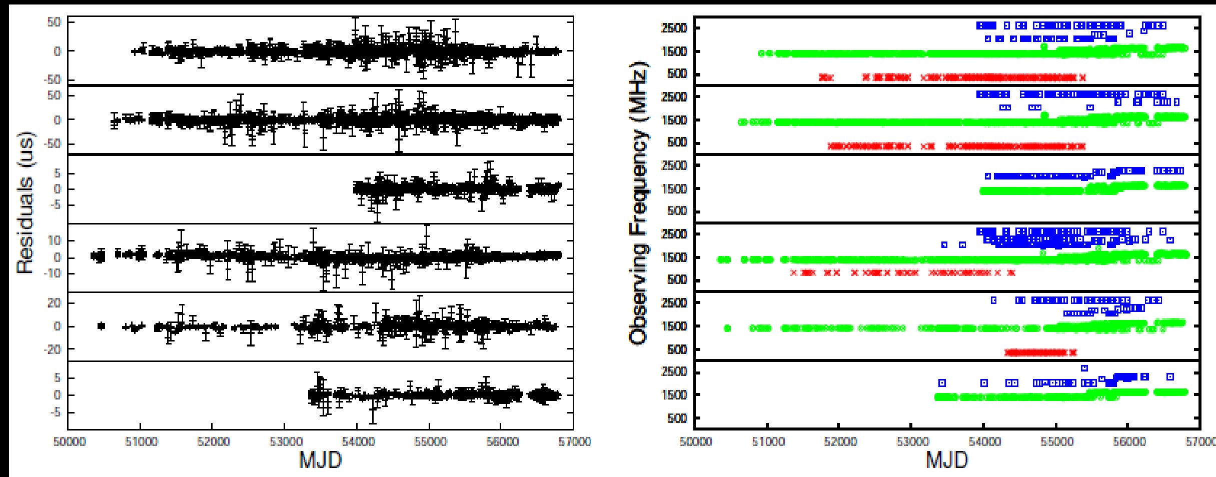
PPT

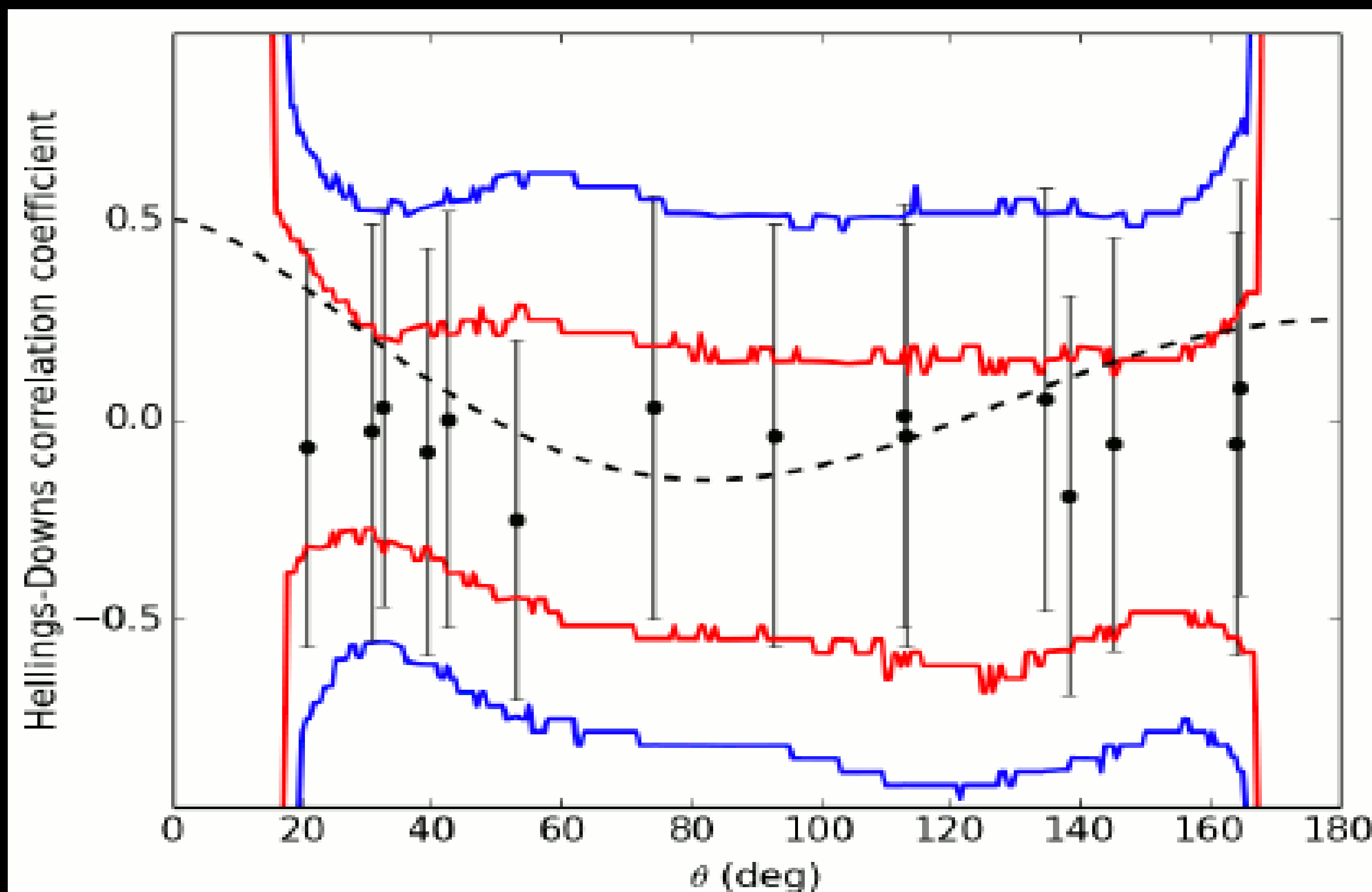
# Predictions and limits




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

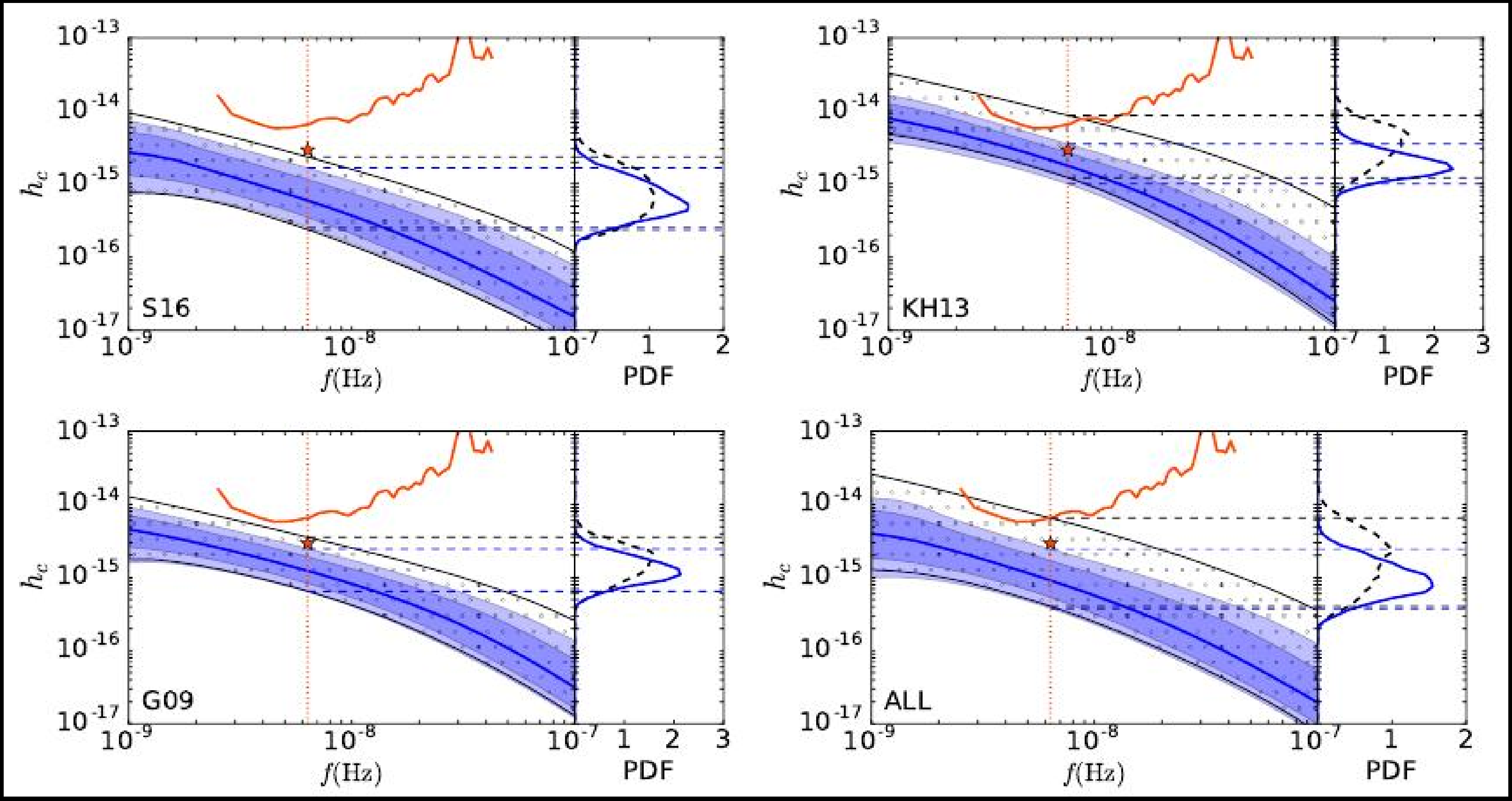
# *Pulsar correlations* (EPTA, Lentati et al. 2015)



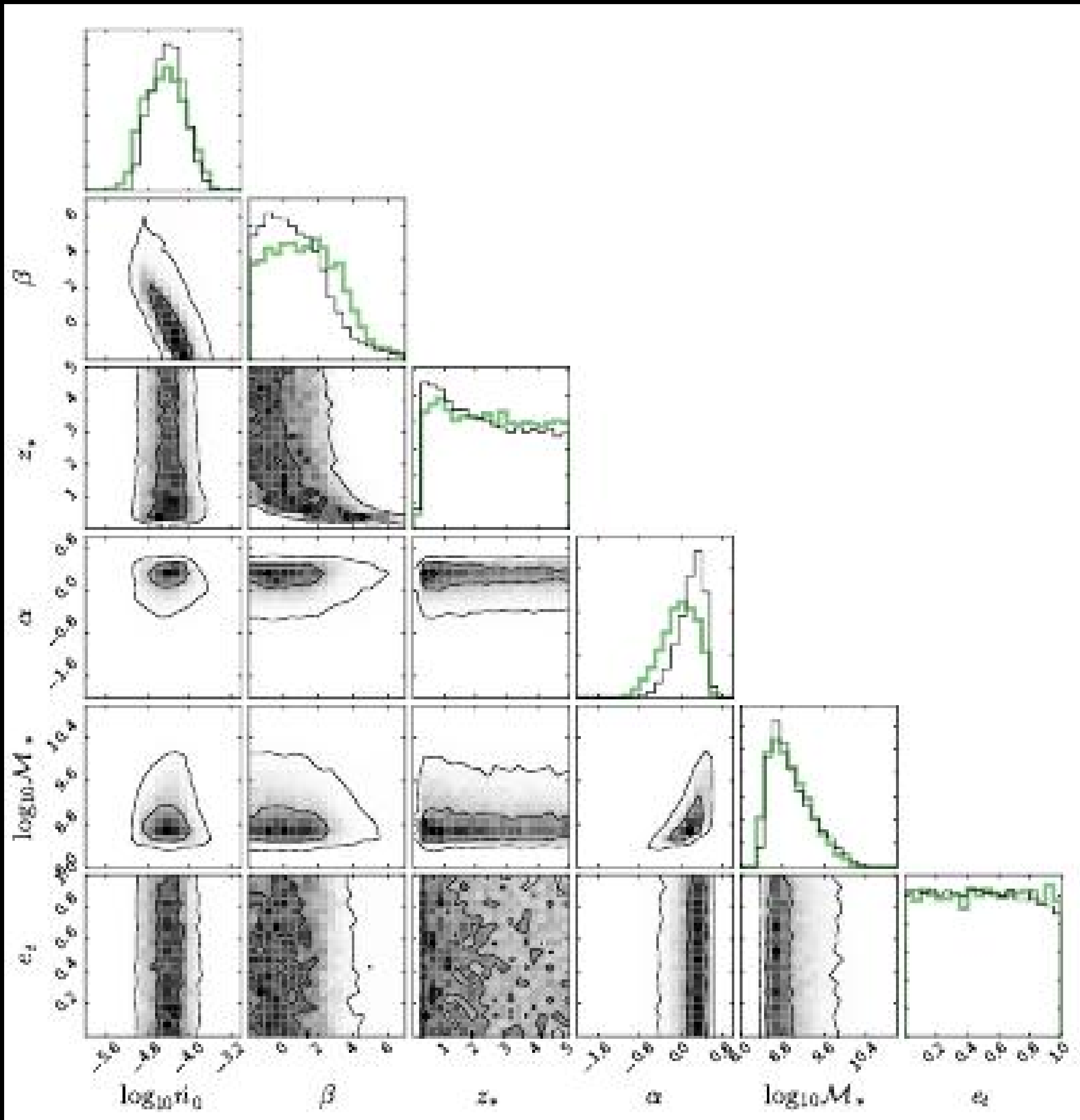
# *Limits are not stringent yet*

-Comprehensive set of semianalytic models anchored to observations of galaxy mass function and pair fractions **(AS 2013, 2016)**
-Include different BH mass-galaxy relations
-Include binary dynamics (coupling with the environment/eccentricity)




**(Middleton et al., submitted)**

# *Limits are not stringent yet*



SMBHB population described by an analytic model (Chen et al. 2016, 2017)

Can put constraints on the parameters

Prior and posterior distributions on the parameters look pretty similar

The limit is not very informative (yet)

## Science beyond the first 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 the EM signature of SMBHBs

# *The future*

**MeerKAT, South Africa (2017)**

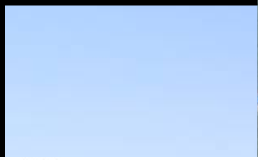
# *The future*

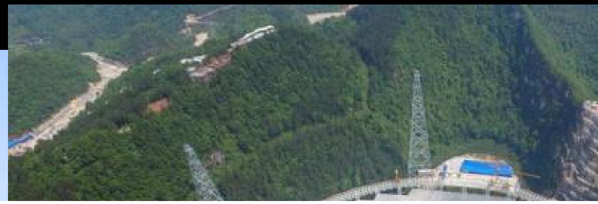
FAST, China (2017)

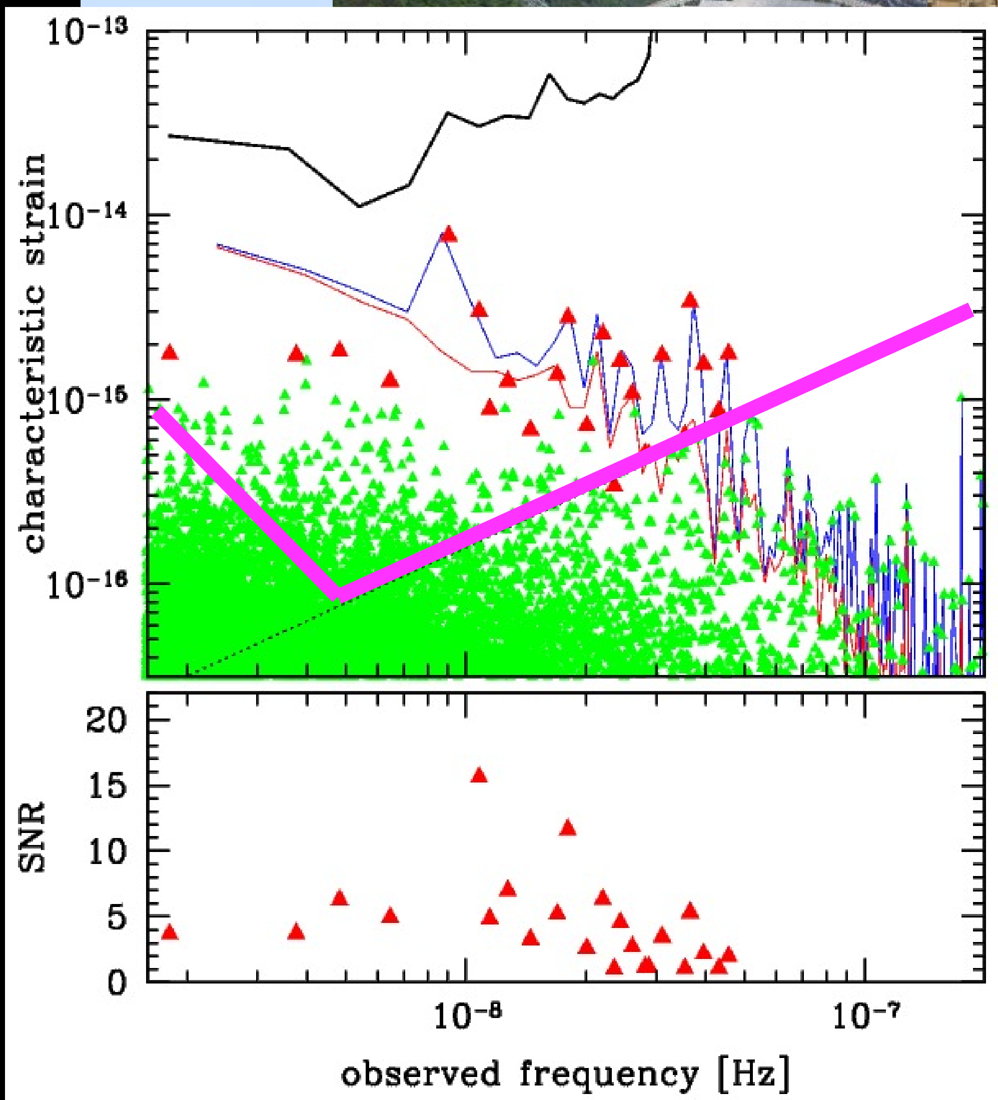
# *The future*

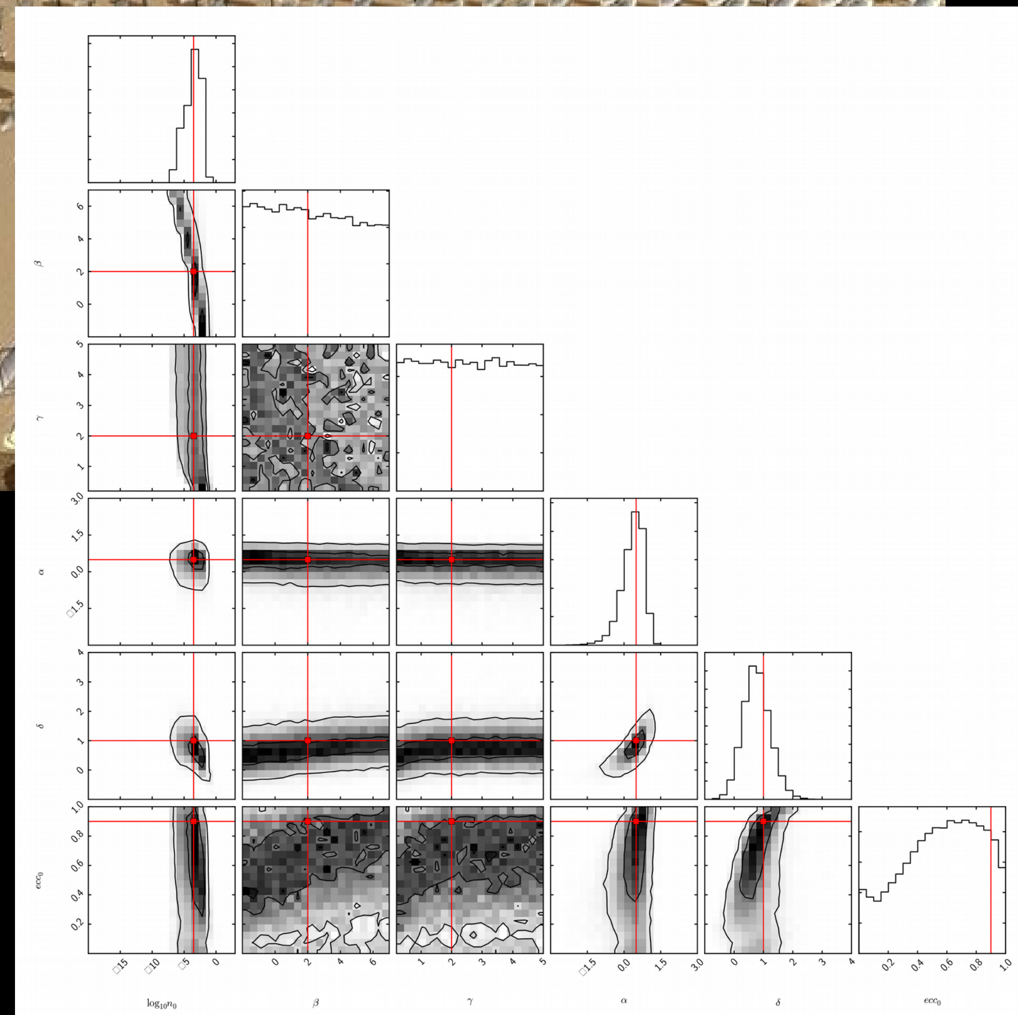
Square Kilometre Array (SKA, 2021+)

# The future

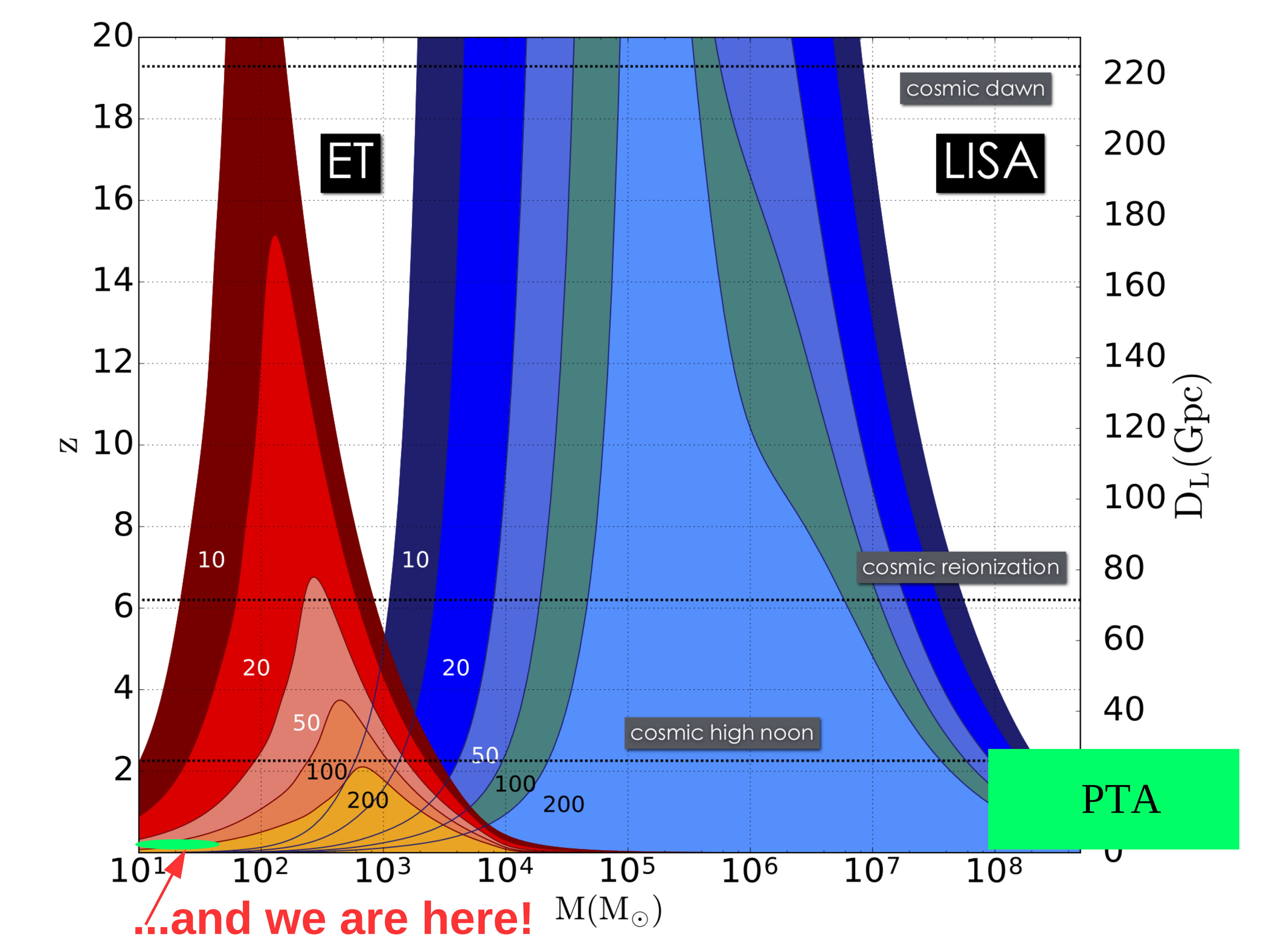





characteristic strain
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$
SNR
20
15
10
5
0
$10^{-8}$
$10^{-7}$
observed frequency [Hz]



# 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