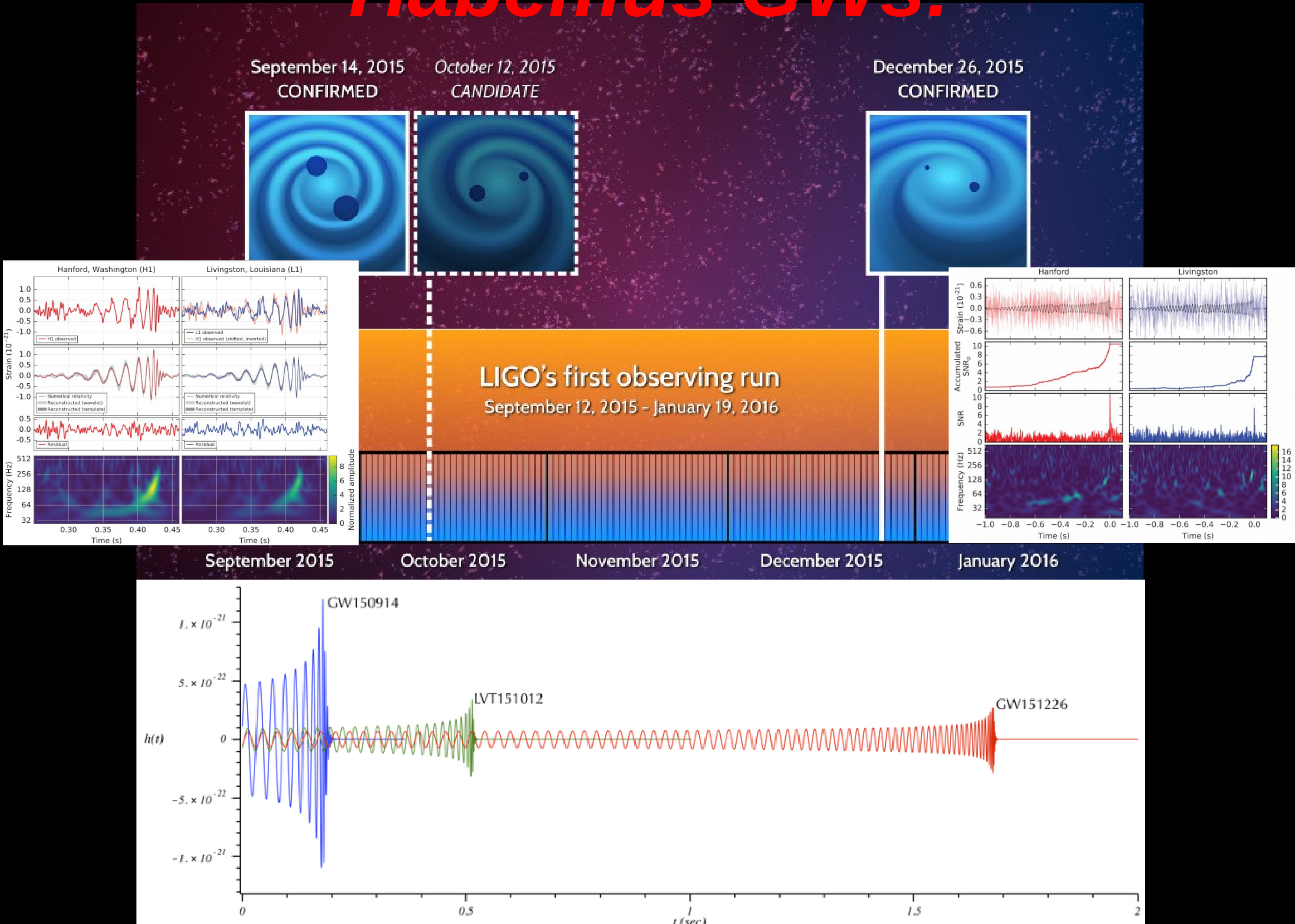
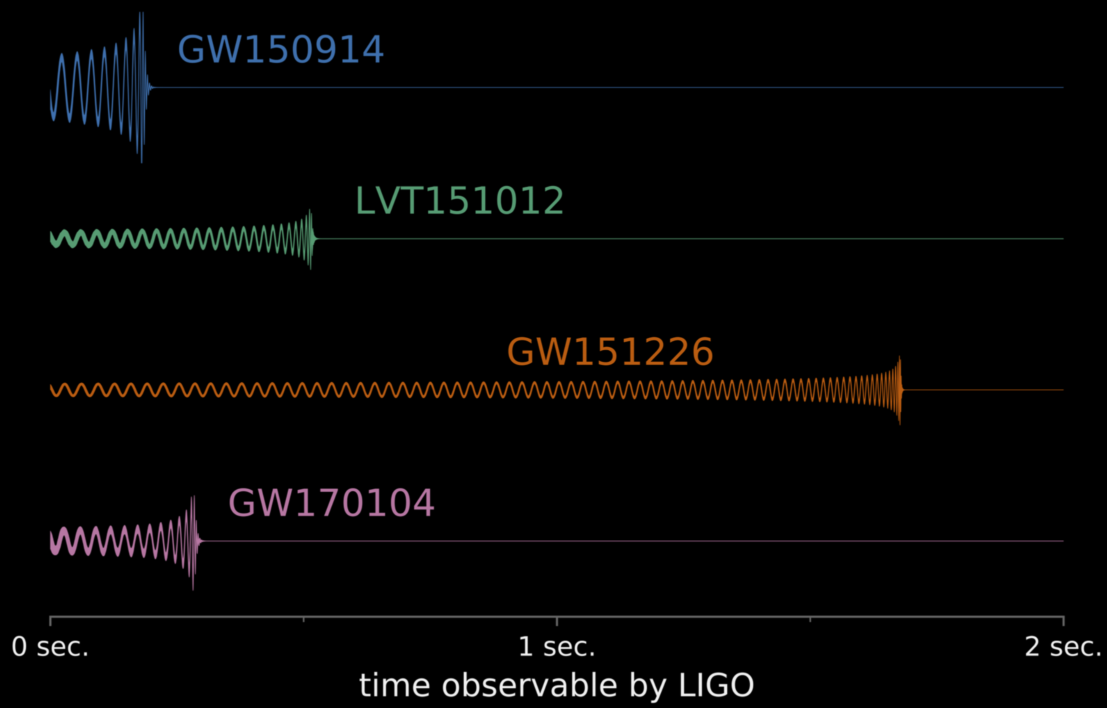
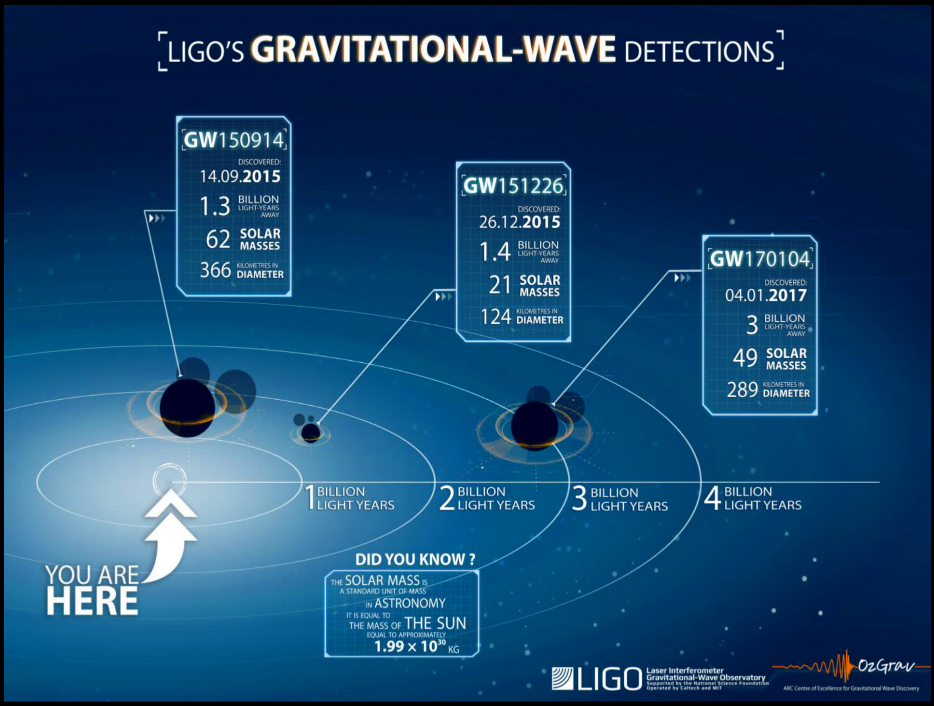
The long vision of gravitational wave astrophysics: all wavelegths in our scope

Alberto Sesana
(University of Birmingham)

Habemus GWs!


September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
Frequency (Hz)
Normalized amplitude
Time (s)
Hanford
Livingston
Accumulated SNR
SNR
Normalized Energy
GW150914
LVT151012
GW151226
$h(t)$
t (sec)





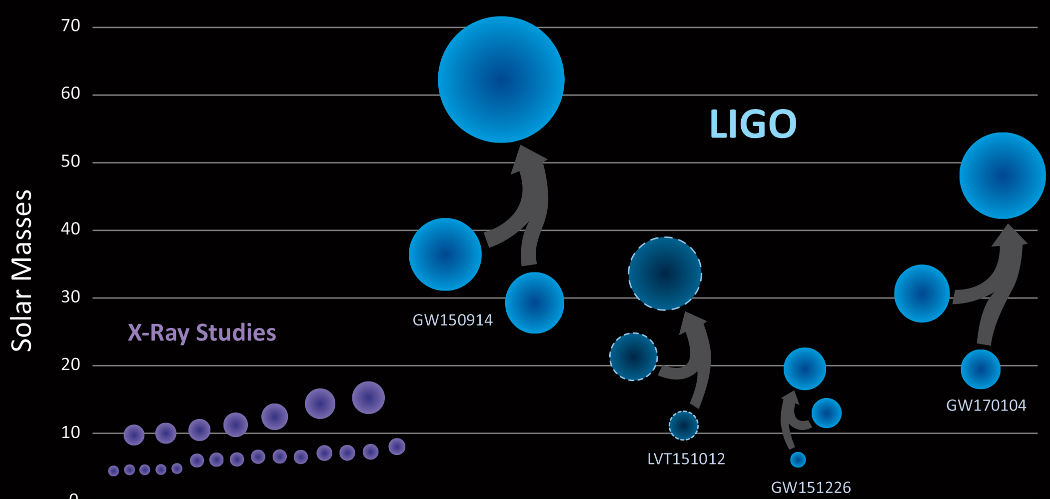
We see BHB coalescing for the first time (several Abbott+ 2016 2017)

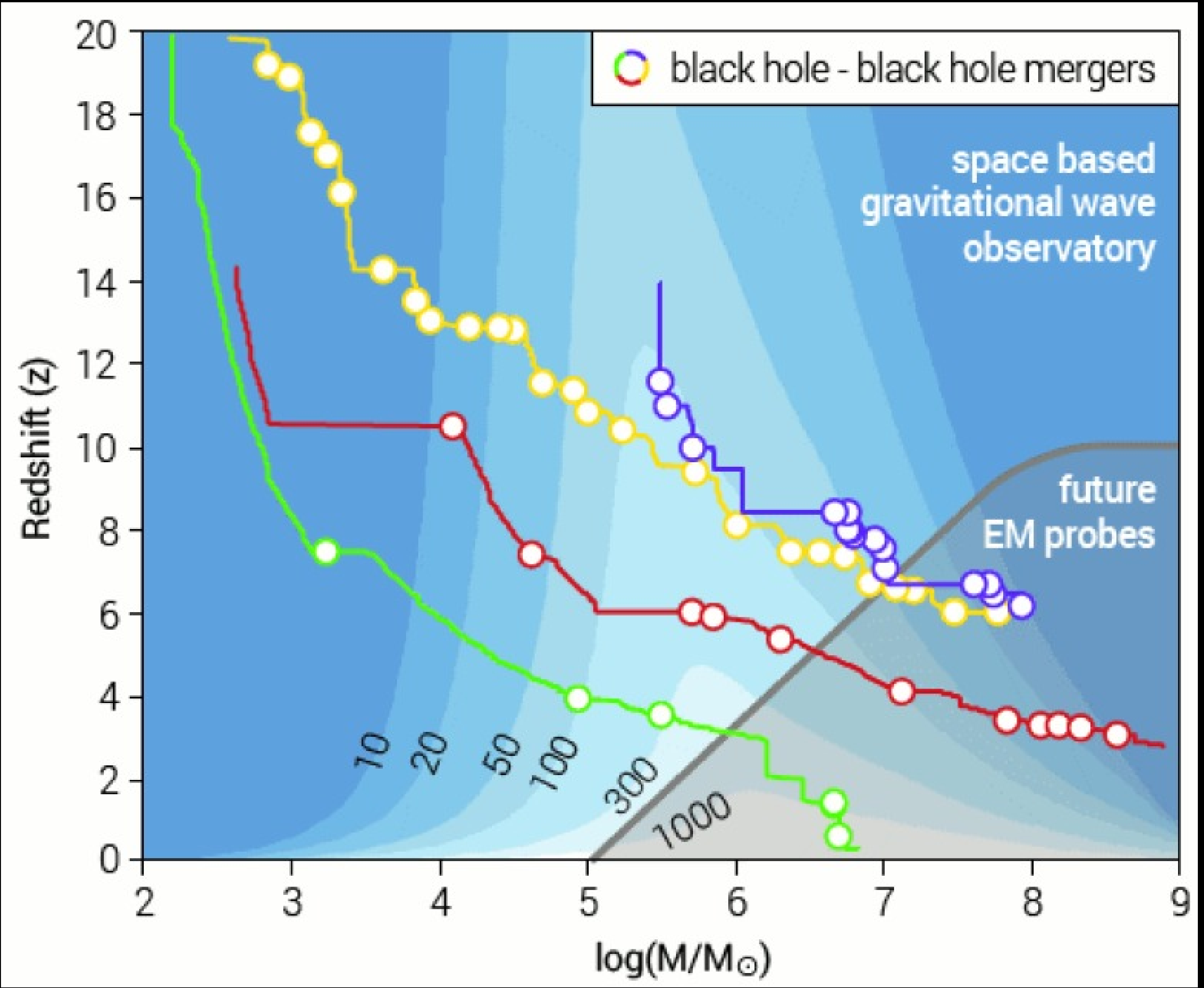
First tests of GR in the strong field regime

Interesting astrophysical information (masses, spins)

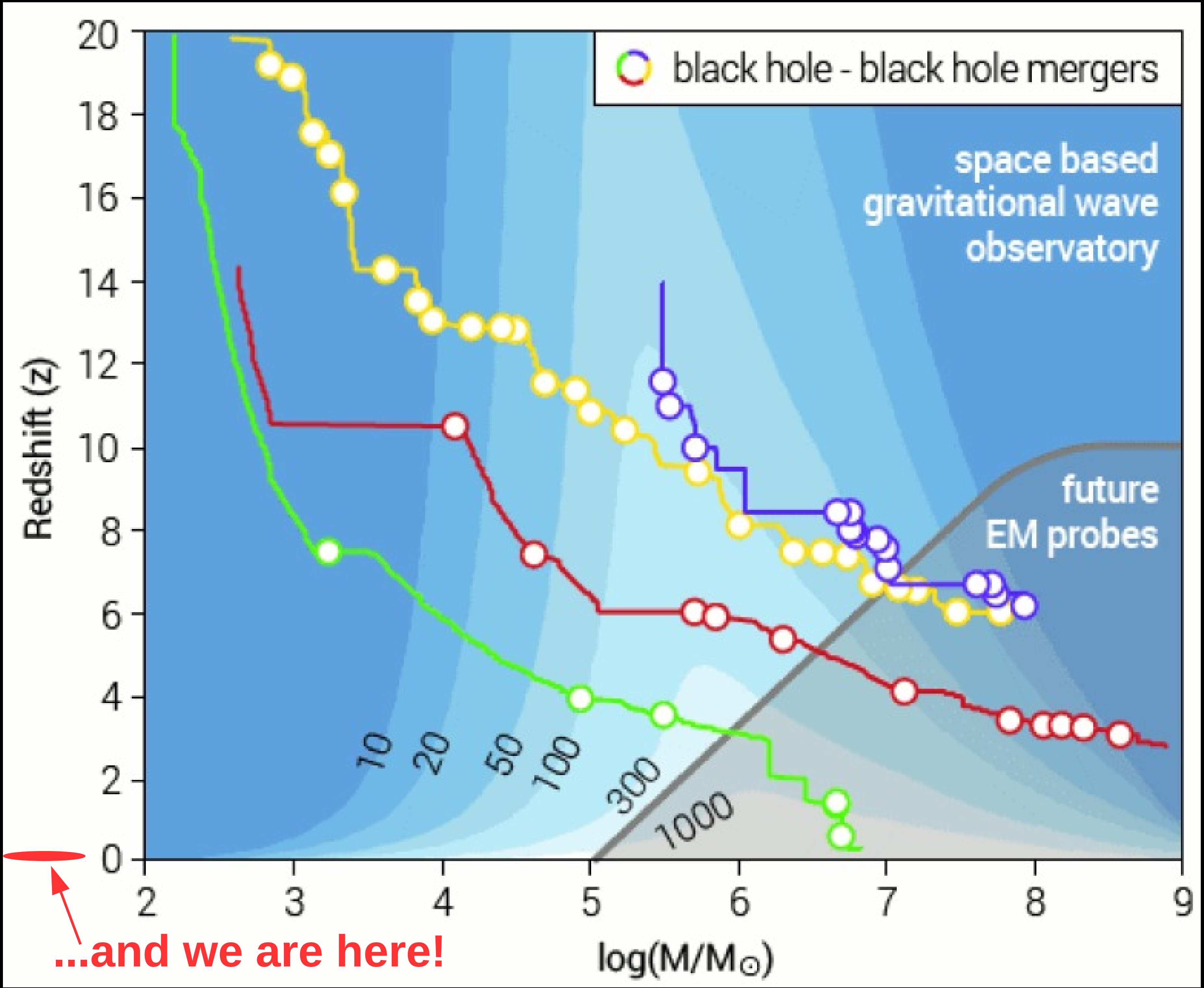
Formation scenario?

Black Holes of Known Mass





black hole - black hole mergers
space based
gravitational wave
observatory
future
EM probes
10
20
50
100
300
1000
Redshift (z)
log(M/M⊙)


black hole - black hole mergers
space based gravitational wave observatory
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Redshift (z)
log(M/M⊙)
0
2
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14
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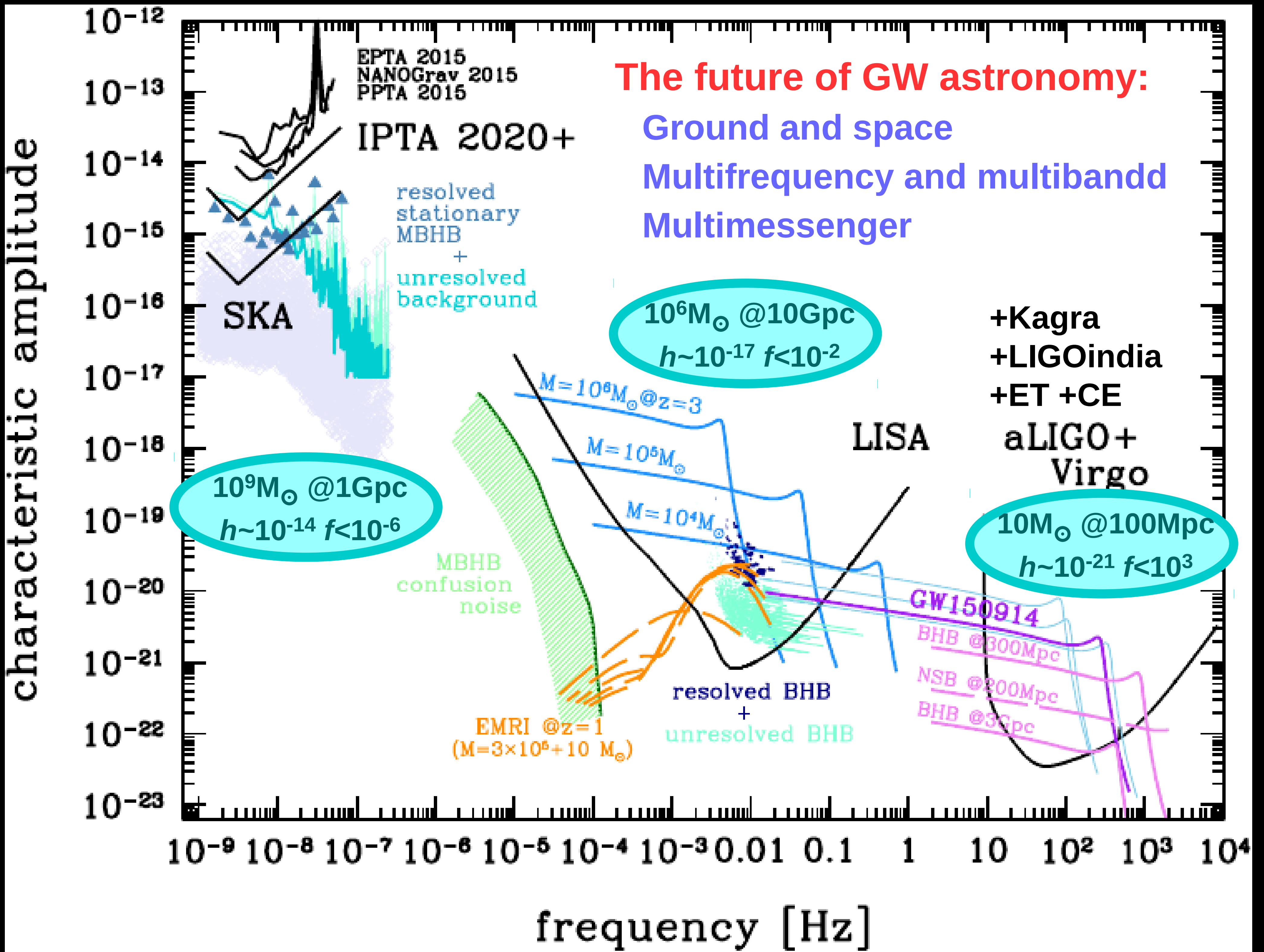
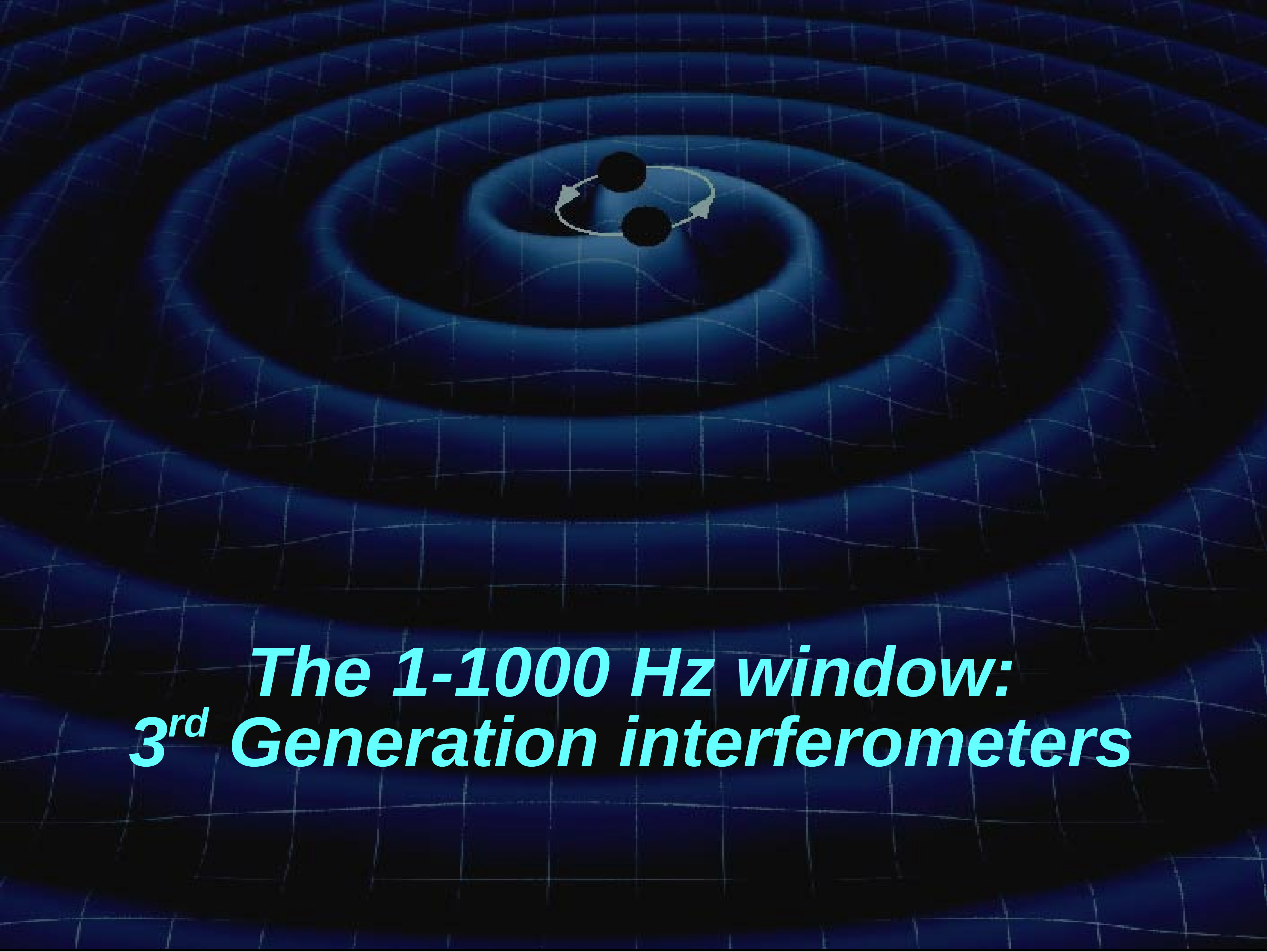
10
20
50
100
300
1000
...and we are here!

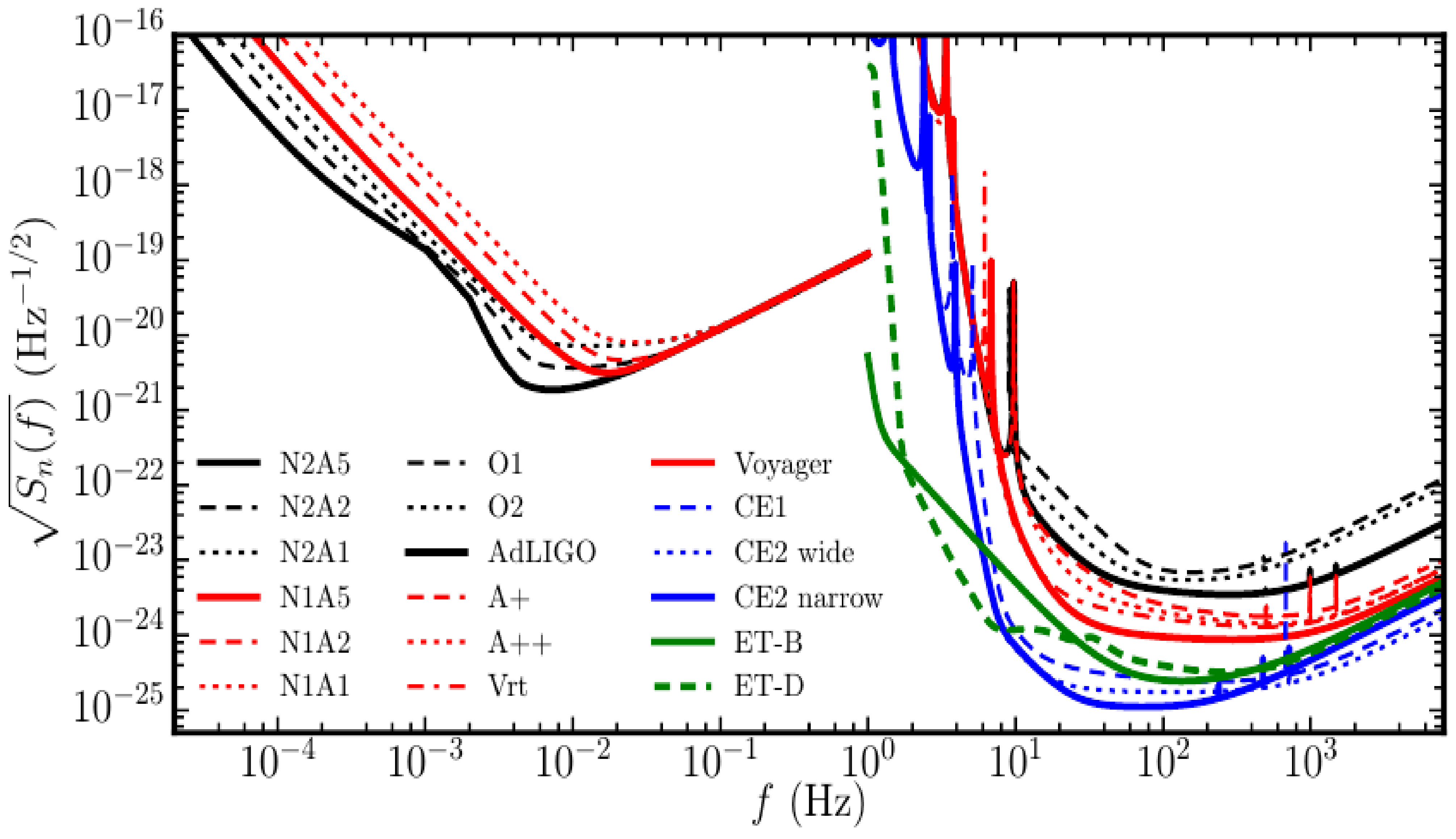


The future of GW astronomy:
Ground and space
Multifrequency and multibandd
Multimessenger
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB + unresolved background
$10^6 M_\odot$ @10Gpc
$h \sim 10^{-17}$ $f < 10^{-2}$
$10^9 M_\odot$ @1Gpc
$h \sim 10^{-14}$ $f < 10^{-6}$
$10 M_\odot$ @100Mpc
$h \sim 10^{-21}$ $f < 10^3$
+Kagra
+LIGOindia
+ET +CE
LISA
aLIGO+ Virgo
$M=10^6 M_\odot$@z=3
$M=10^5 M_\odot$
$M=10^4 M_\odot$
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
resolved BHB + unresolved BHB
EMRI @z=1 ($M=3\times10^5+10\ M_\odot$)
characteristic amplitude
frequency [Hz]



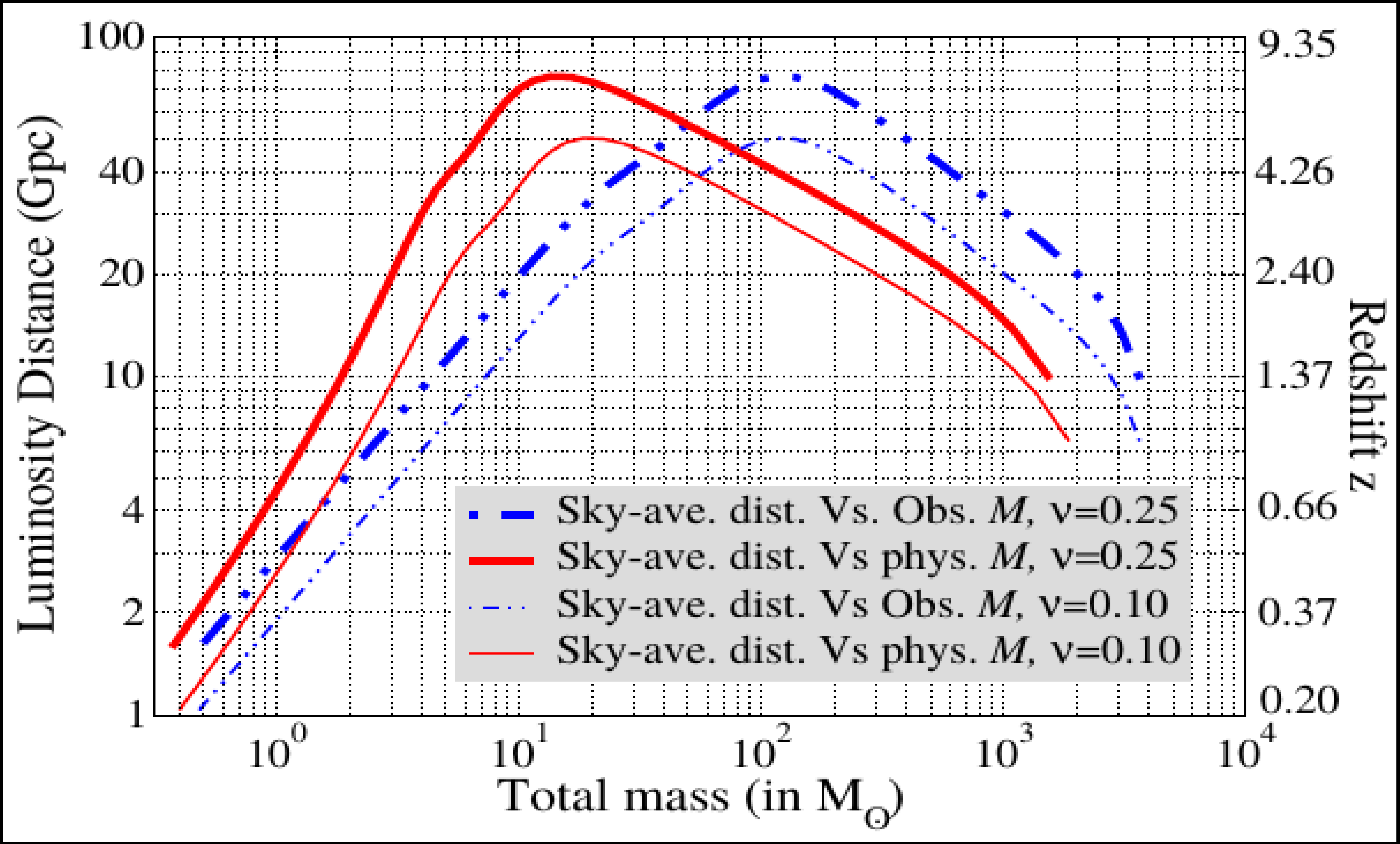
The 1-1000 Hz window: 3rd Generation interferometers

A number of 3G detectors on the table



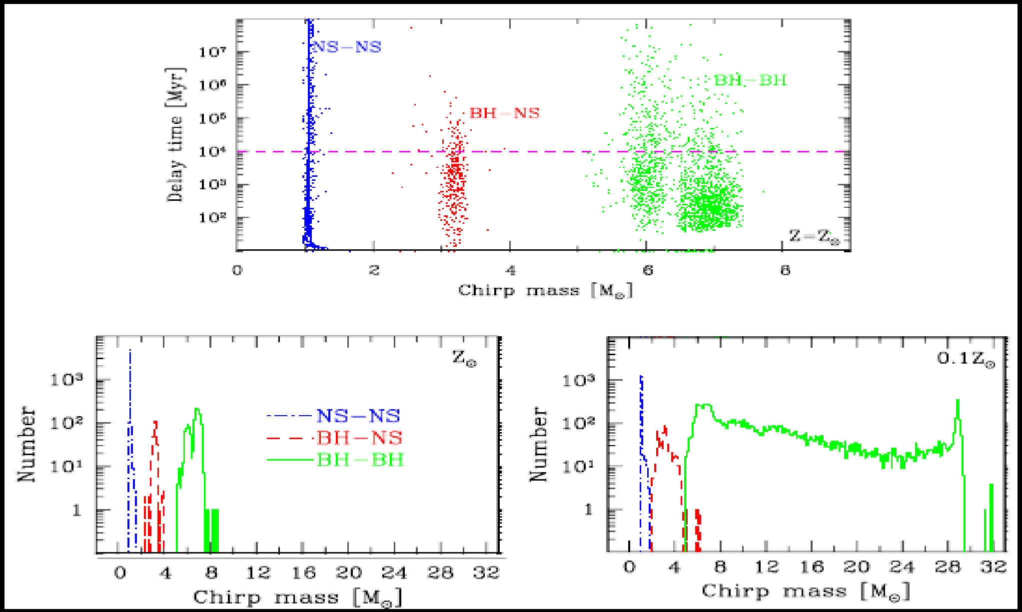
(Berti et al. 2016)

Example: reach of ET

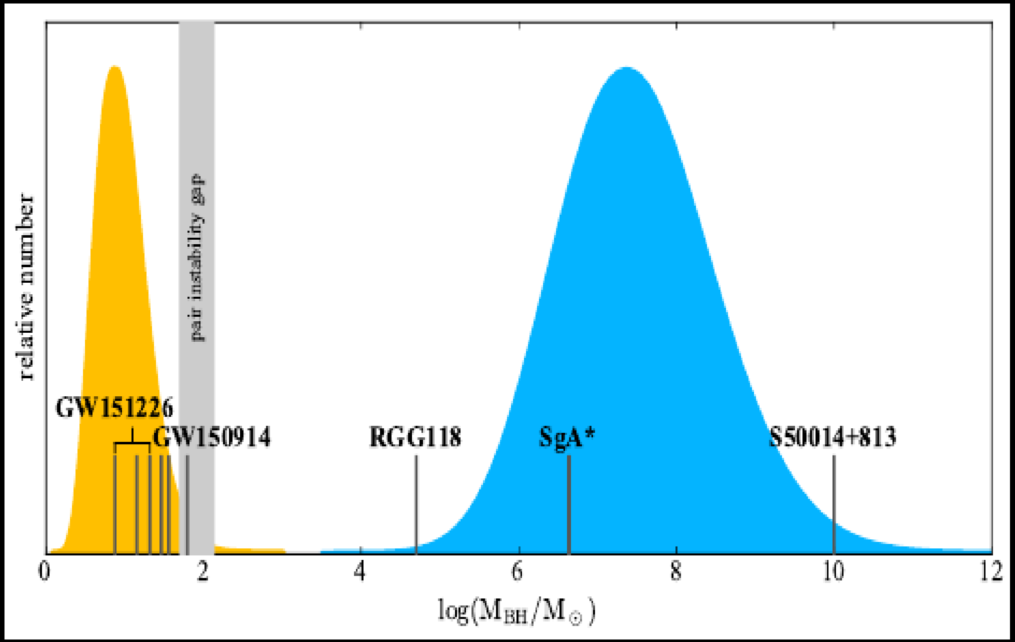


- All LIGO-like BHBs in the Universe up to *z*~5 (~10^5/yr)
- All NS-NS binaries to *z*~1 (~10^4/yr)
- IMBHs up to *z*~2 (???)
- SNe? Rotating NSs?

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

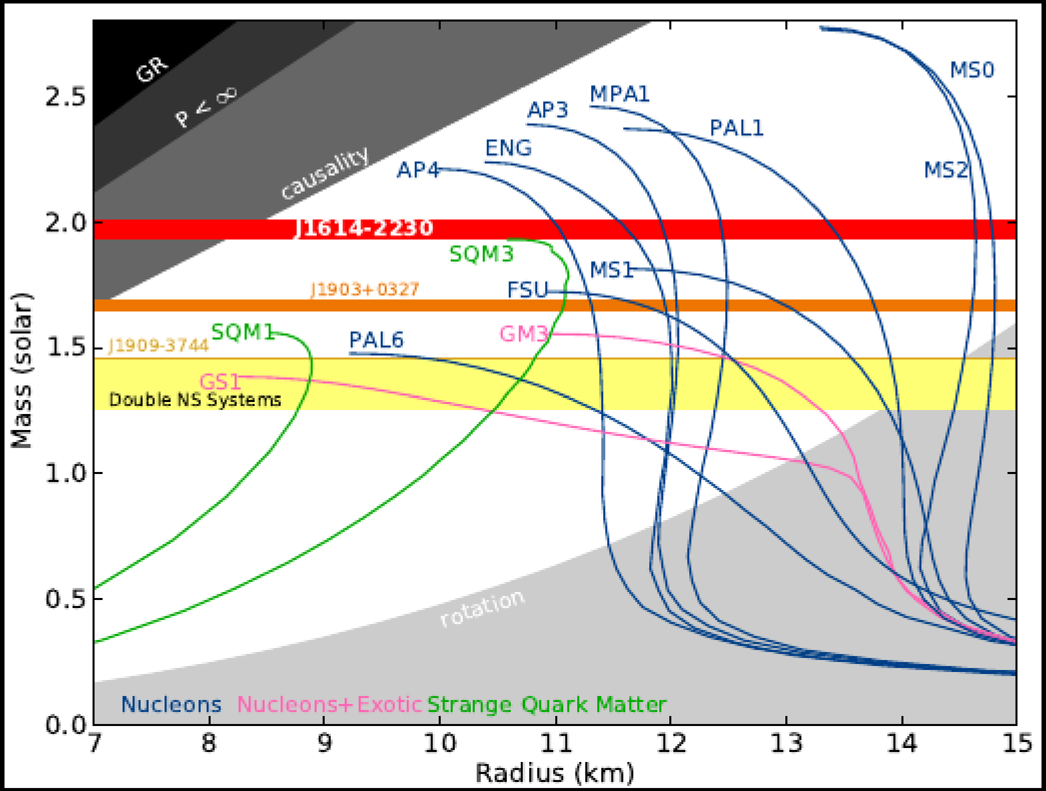
Redshift dependent mass functions (like QSO!)

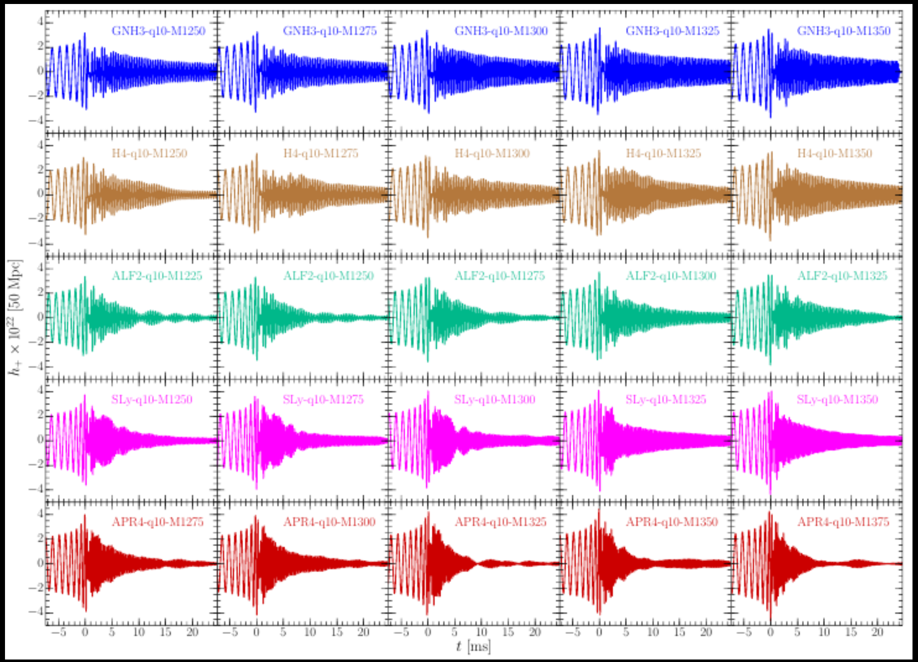
NS-BH mass gap?
Second mass gap?
IMBH mass gap/desert?

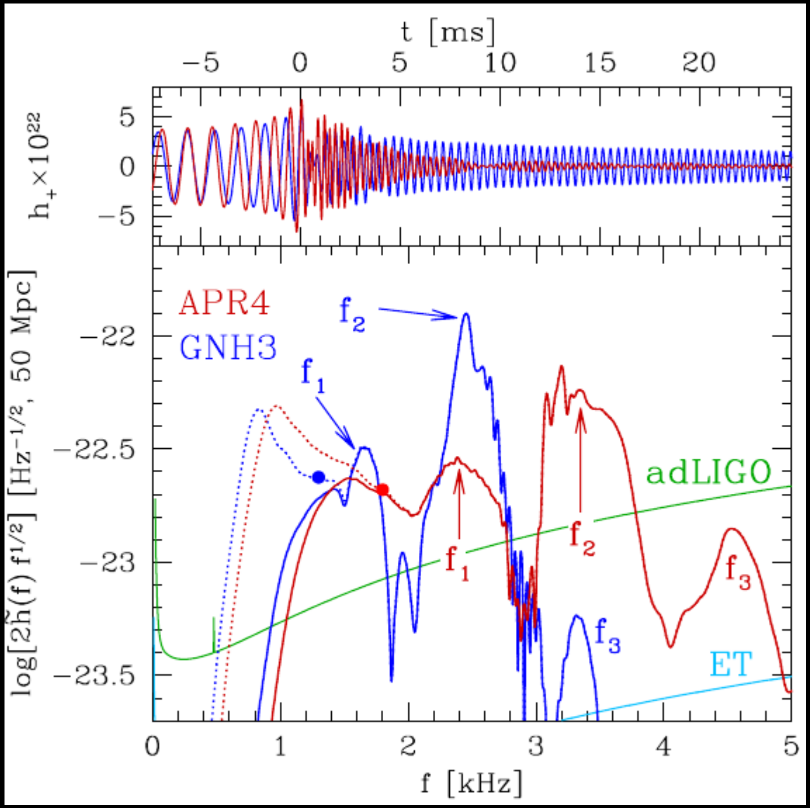
Astrophysical origin?

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

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



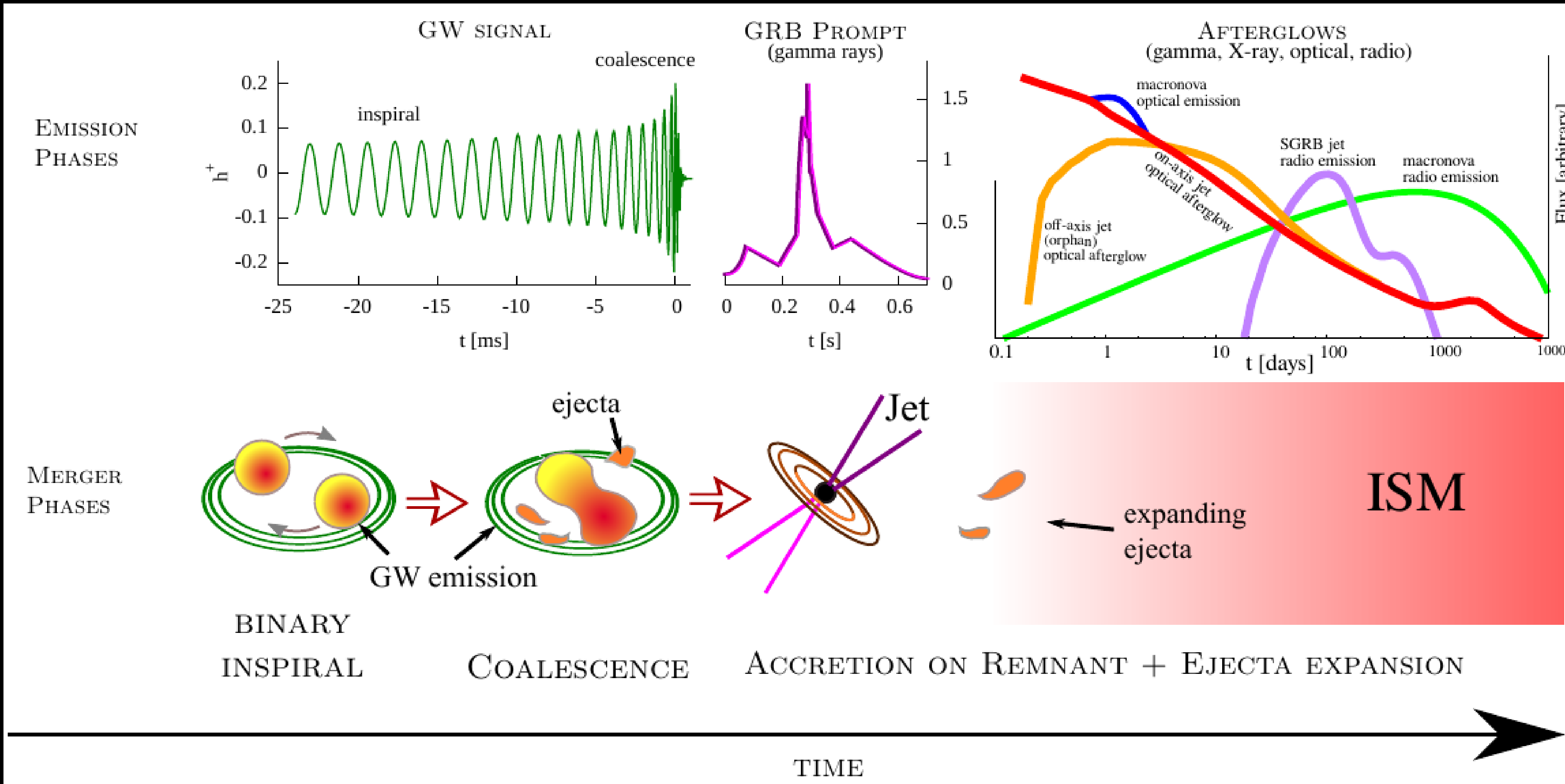




Nuclear physics with NS mergers

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?

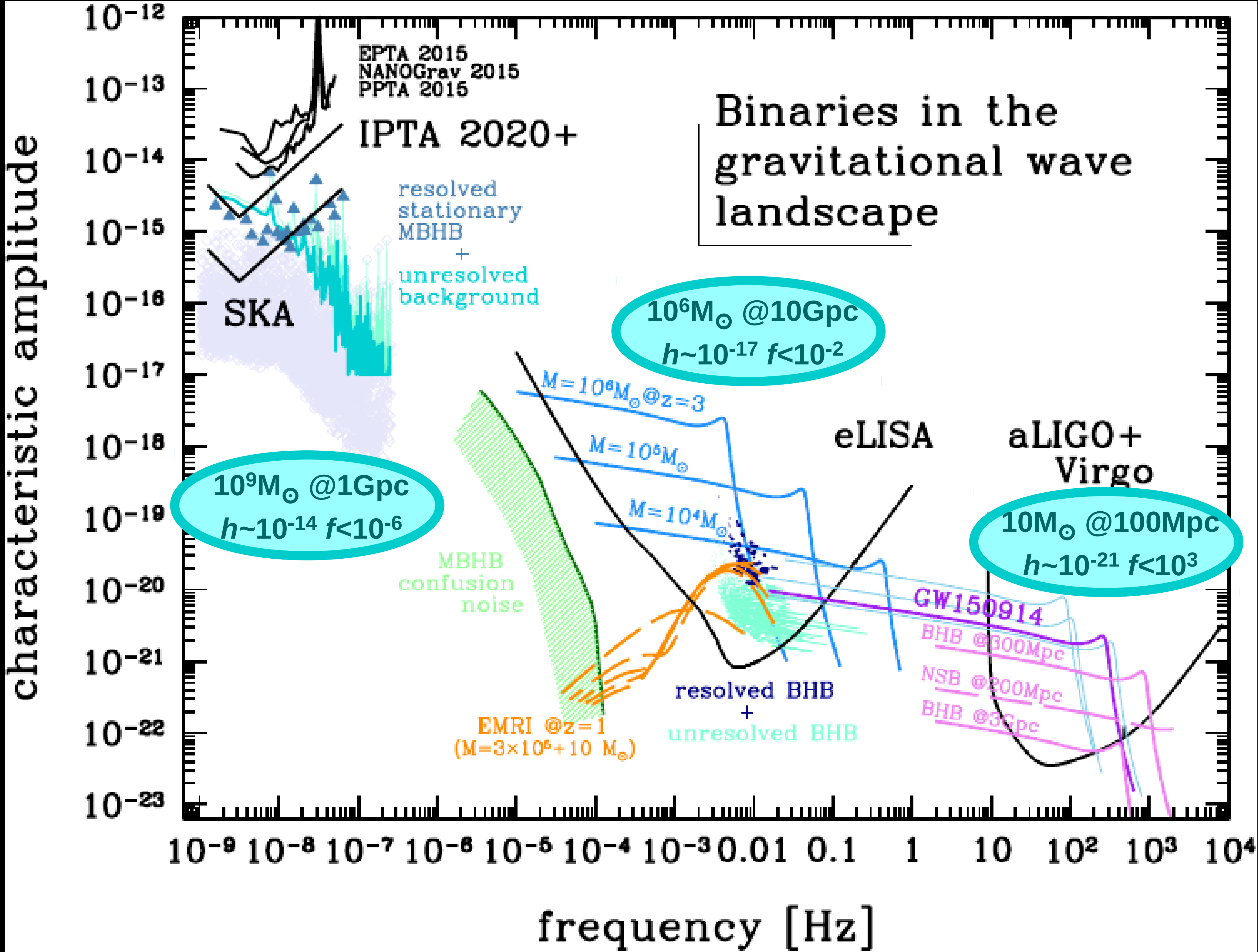
(Metzger & Berger 2012)

SKA SQUARE KILOMETRE ARRAY

eROSITA

LSST Large Synoptic Survey Telescope

The millihertz window: LISA



Binaries in the gravitational wave landscape
characteristic amplitude
frequency [Hz]
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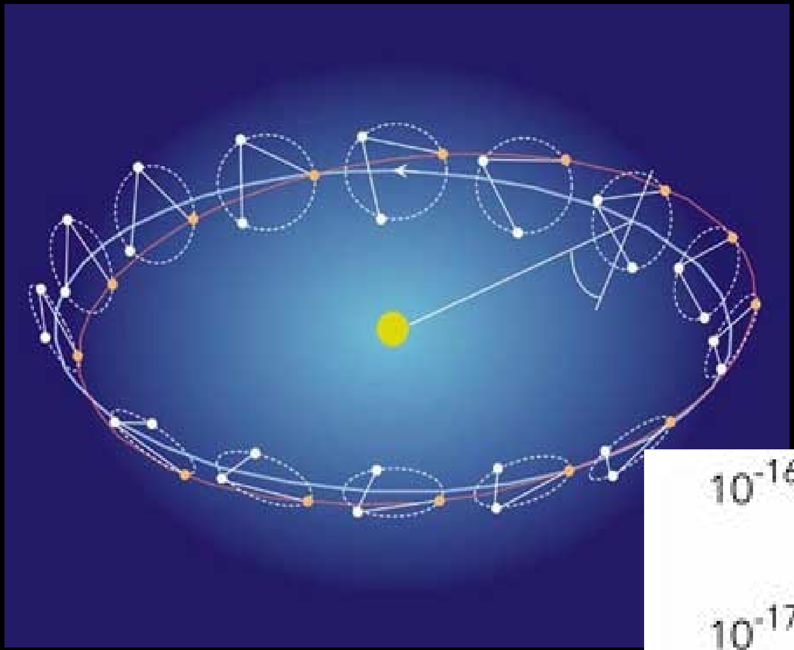
EMRI @z=1
($M=3\times10^5+10\ M_\odot$)

The Laser Interferometer Space Antenna

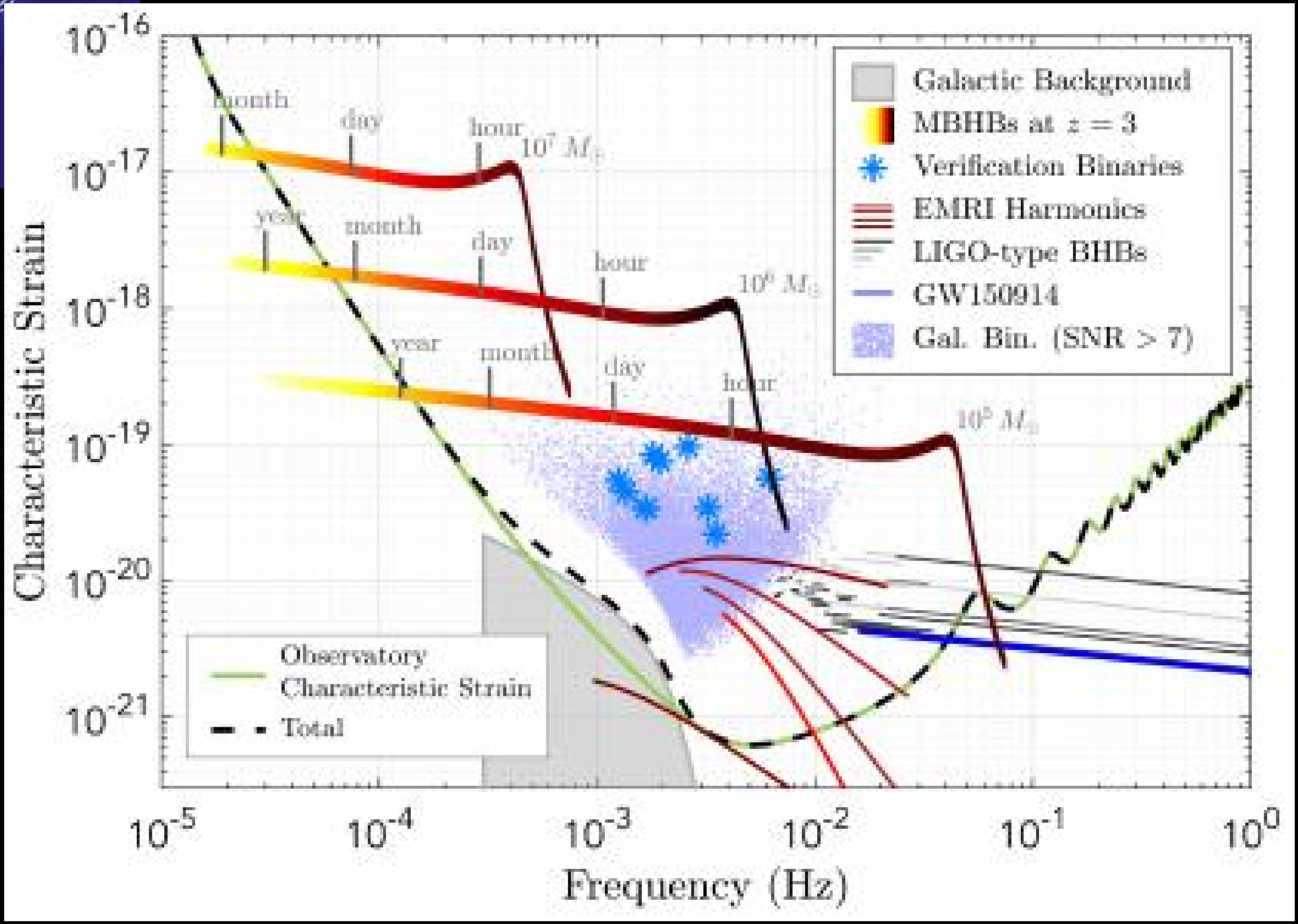


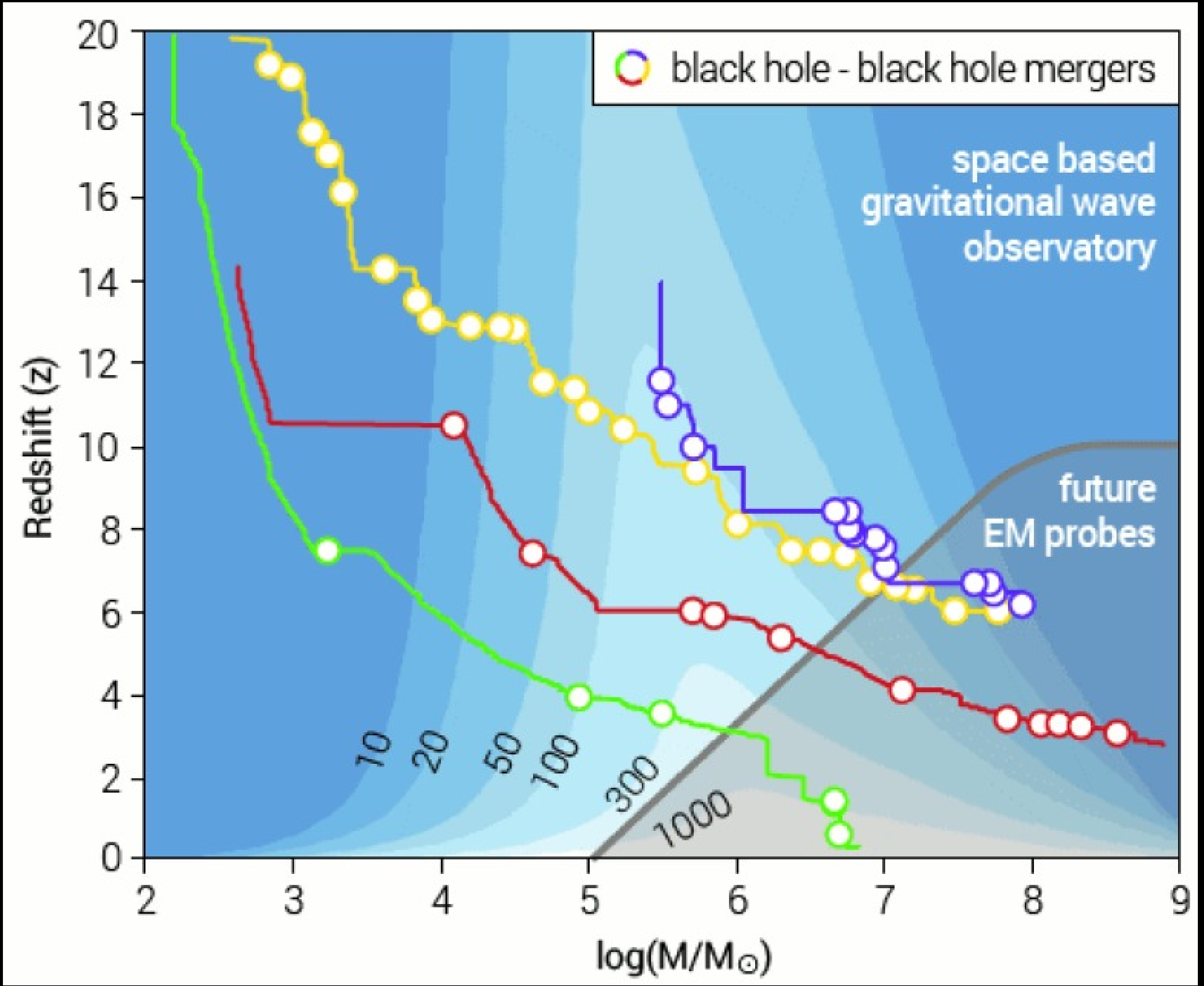
Sensitive in the mHz frequency range where MBH binary evolution is fast (chirp)

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)

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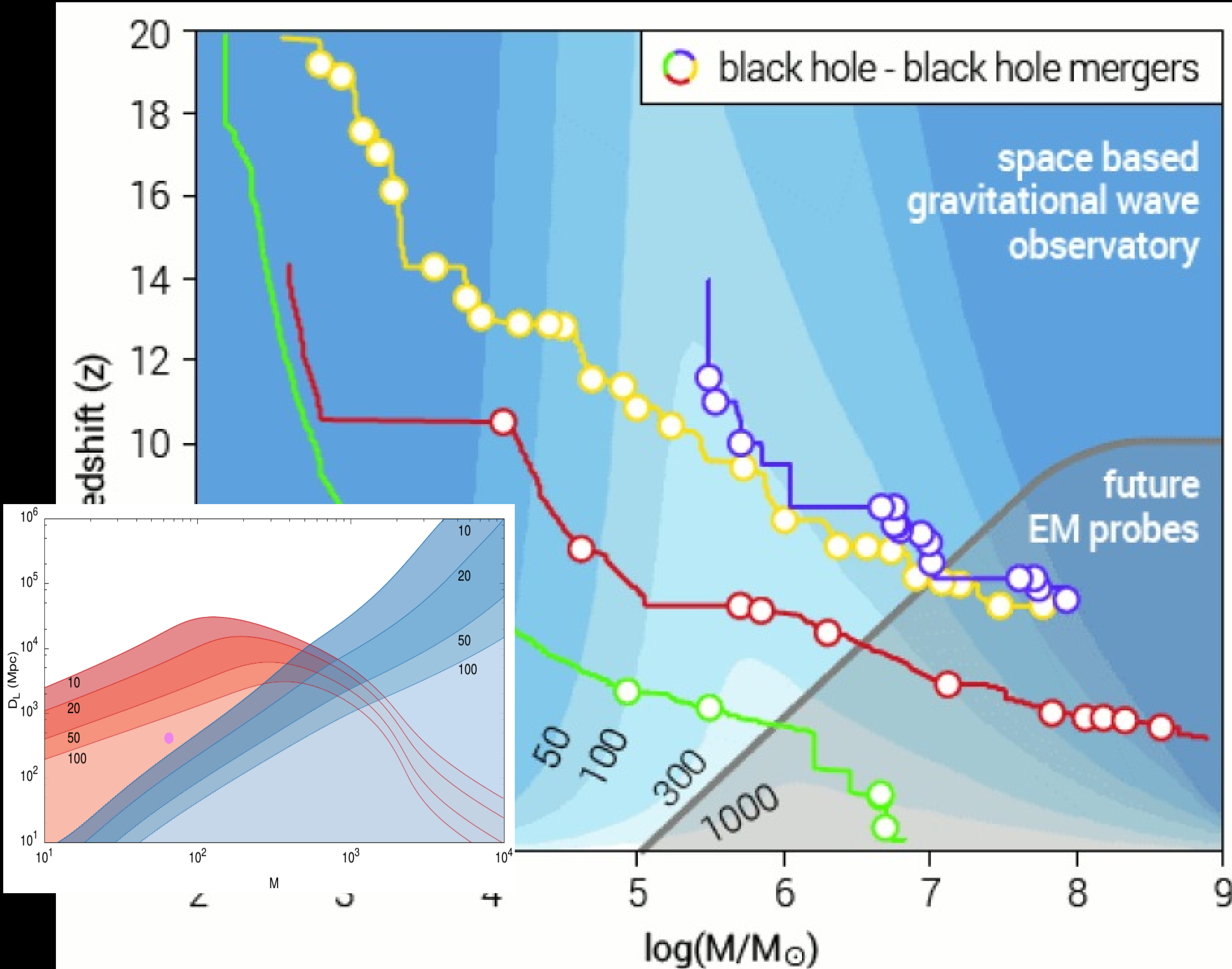

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log(M/M⊙)
D_L (Mpc)
M
10^1
10^2
10^3
10^4
10^5
10^6
10
20
50
100

MBHB: detections and parameter estimation

(Klein, Barausse, AS et al. 2016)

~100+ detections

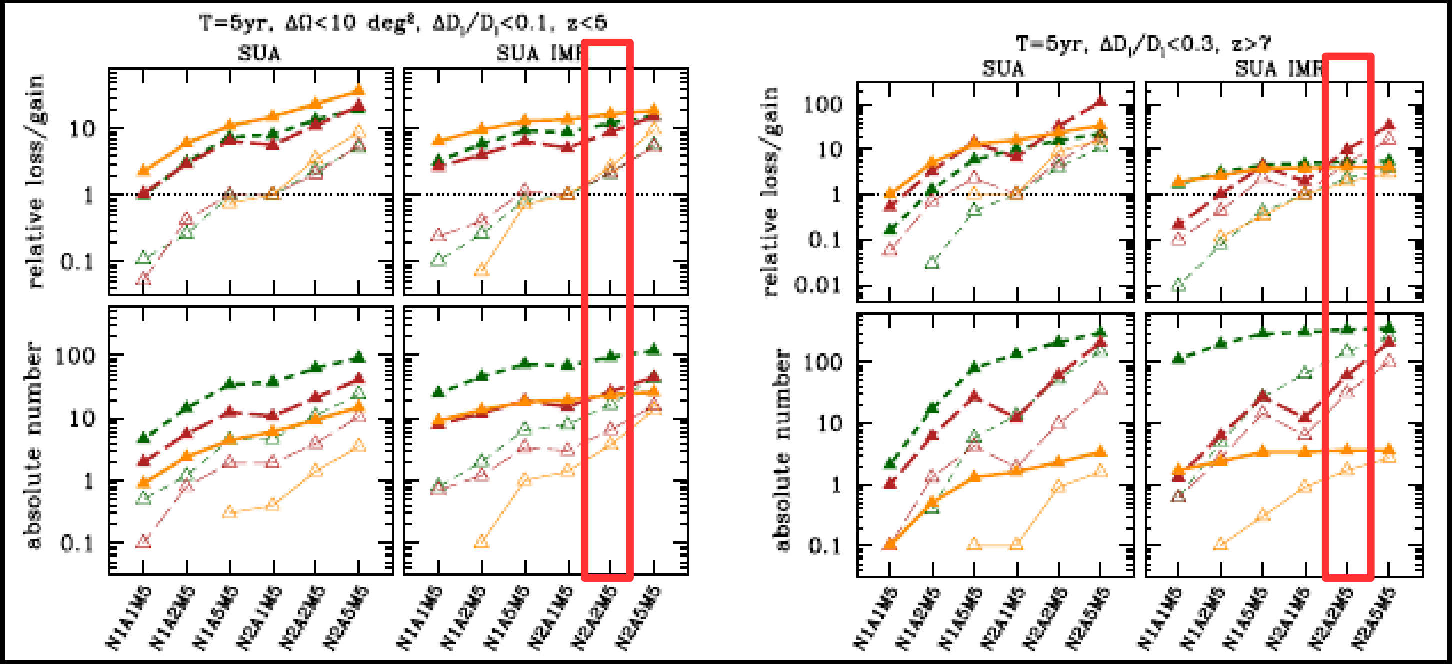
~100+ systems with sky localization to 10 deg2

~100+ systems with individual masses determined to 1%

~50 systems with primary spin determined to 0.01

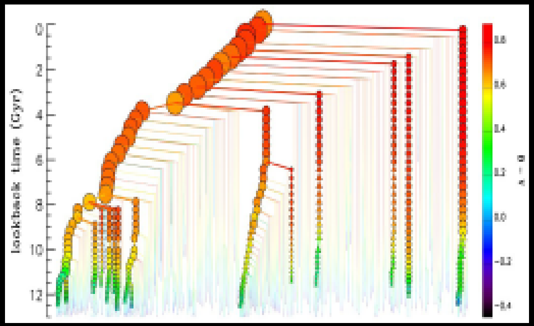
~50 systems with secondary spin determined to 0.1

~50 systems with spin direction determined within 10deg



MBH astrophysics with GW observations

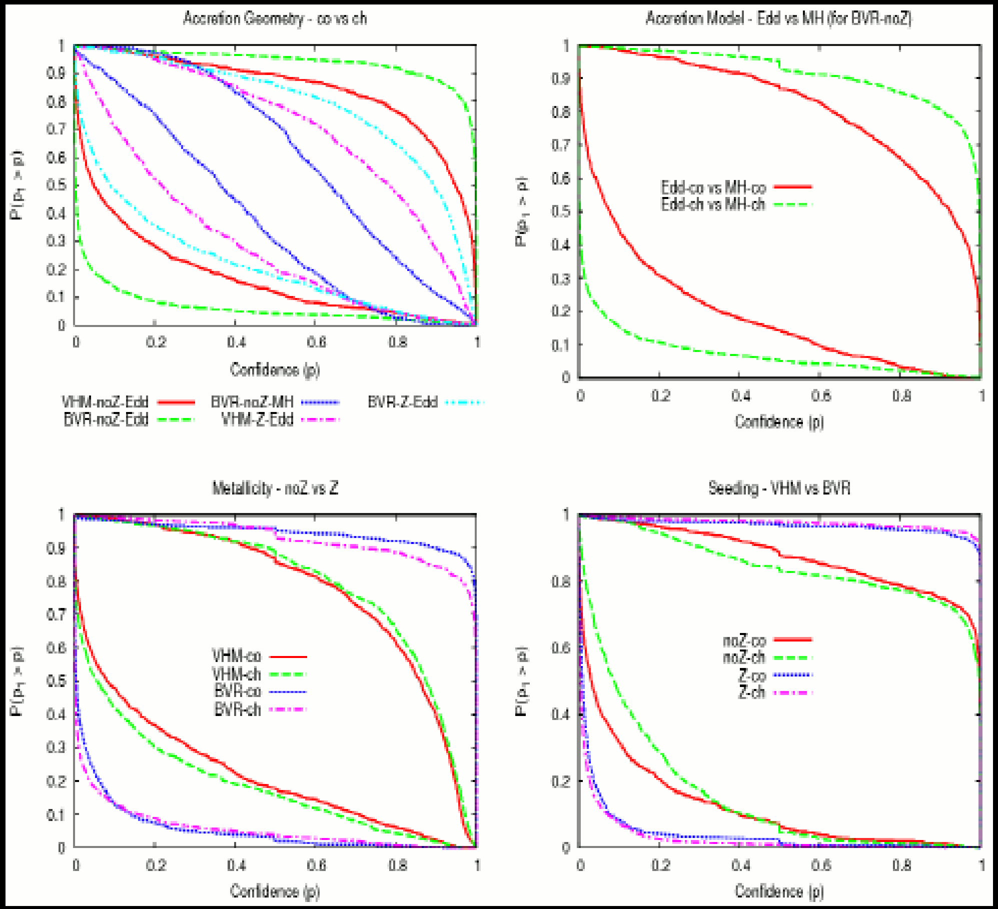
Astrophysical unknowns in MBH formation scenarios



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?

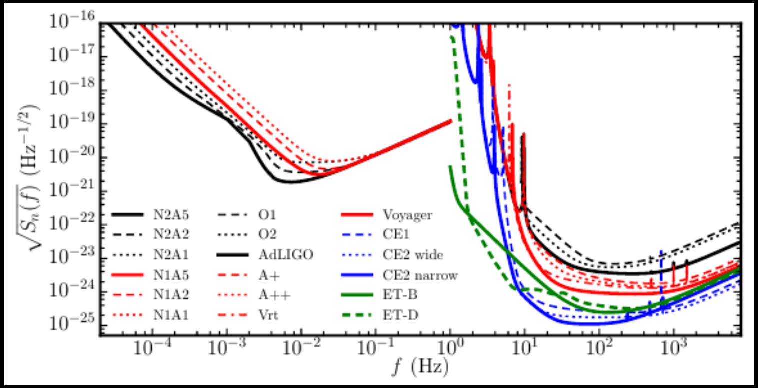
Create catalogues of observed binaries including errors from eLISA observations and compare observations with theoretical models



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

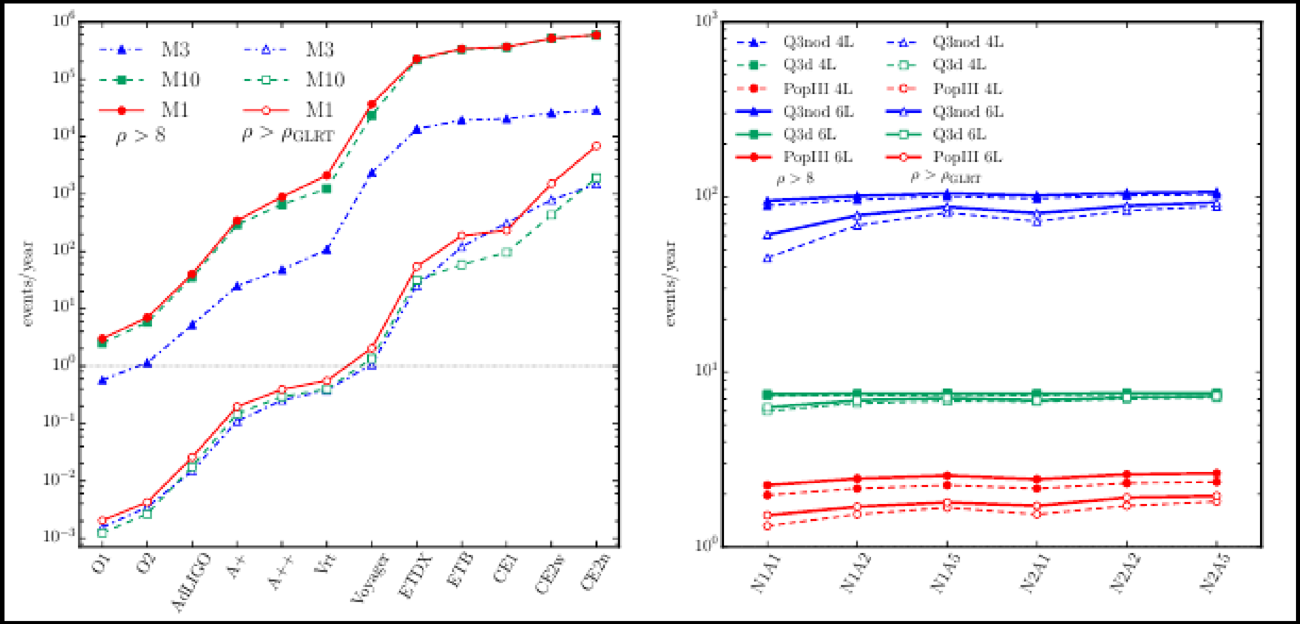
Resolving ringdown modes: BH spectroscopy

(Berti et al. 2016)



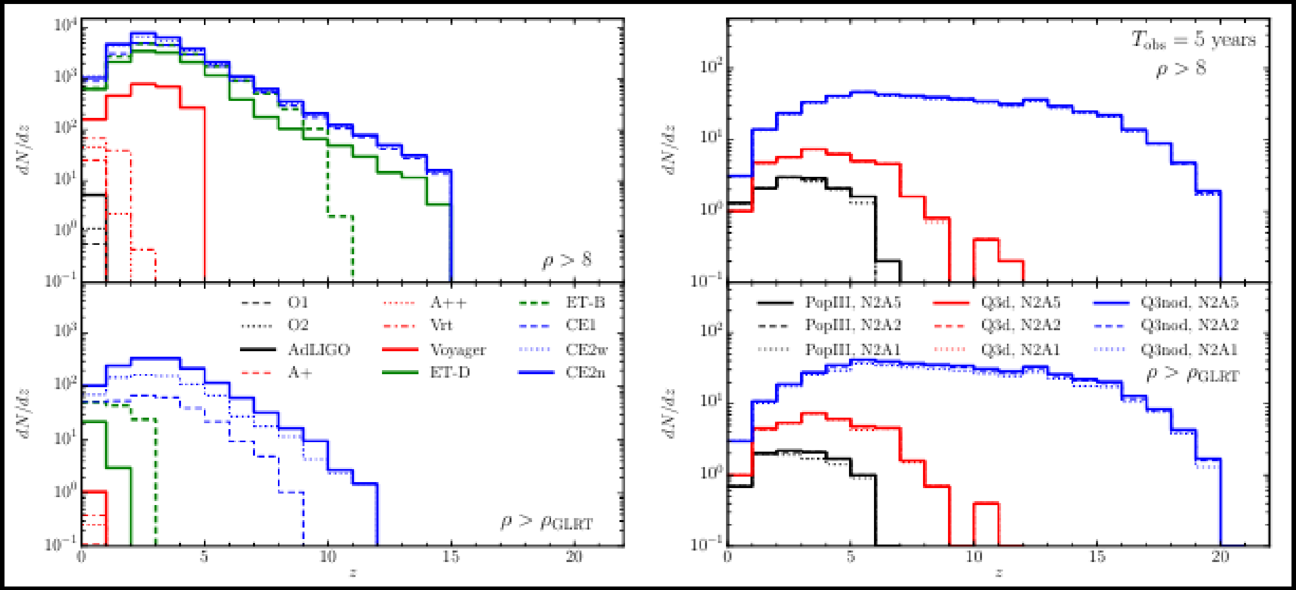
$$\rho^{2,3}_{\rm GLRT} = 17.687 + \frac{15.4597}{q-1} - \frac{1.65242}{q}\,,$$

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



LIGO will not enable BH spectroscopy on individual BHB mergers

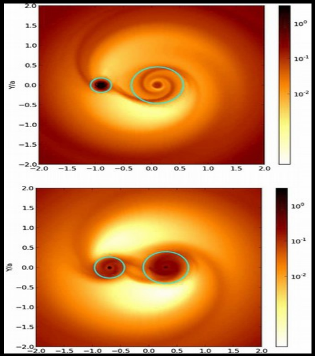
Voyager/ET type detectors are needed



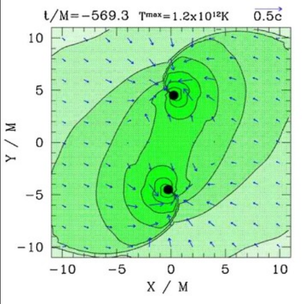
eLISA will enable precise BH spectroscopy on few to 100 events/yr also at very high redshifts

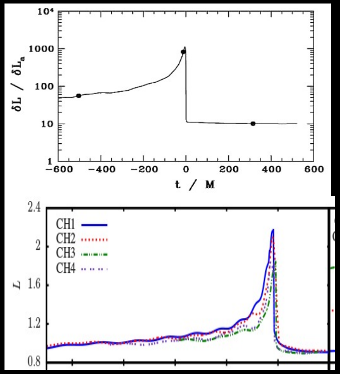
Associated electromagnetic signatures?

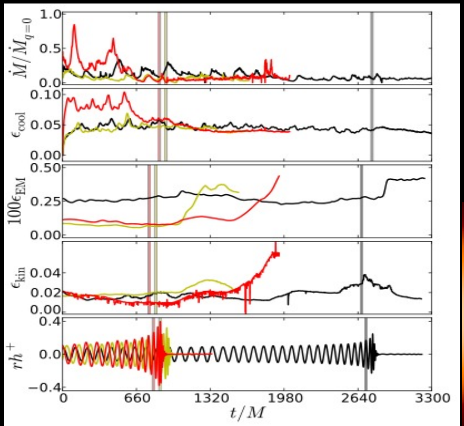
In the standard circumbinary disk scenario, the binary carves a cavity: no EM signal (Phinney & Milosavljevic 2005).
However, all simulations (hydro, MHD) showed significant mass inflow (Cuadra et al. 2009, Shi et al 2011, Farris et al 2014...)

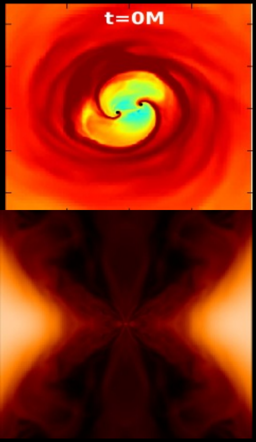


Simulations in hot gaseous clouds. Significan flare associated to merger (Bode et al. 2010, 2012, Farris et al 2012)



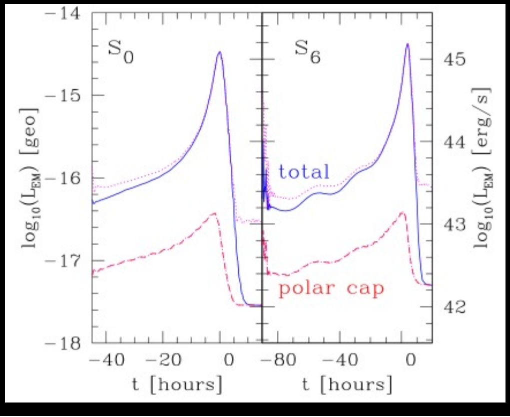


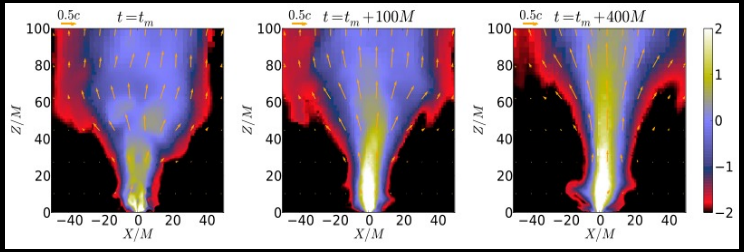




Simulations in disk-like geometry. Variability, but much weaker and unclear signatures (Bode et al. 2012, Gold et al. 2014)

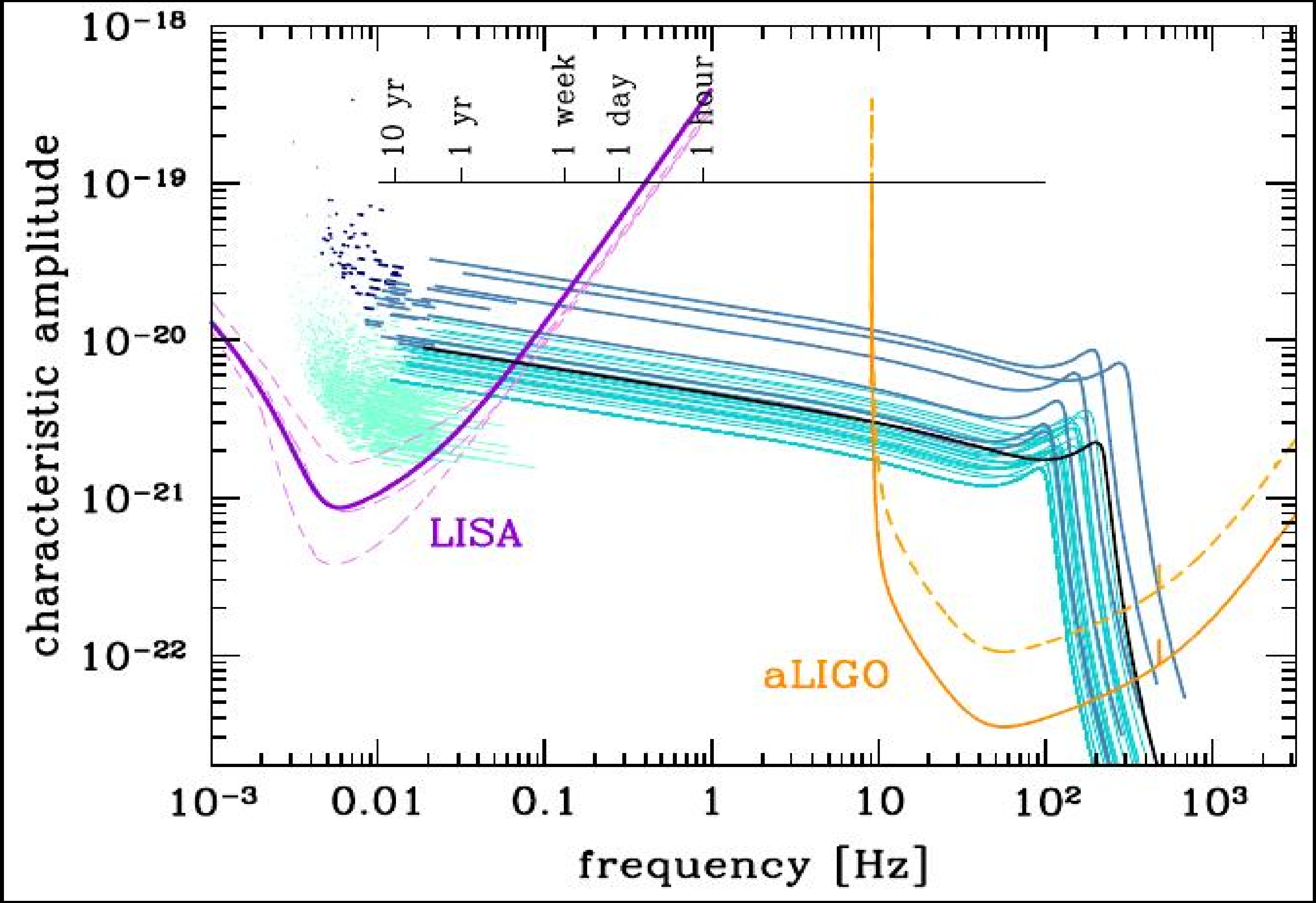
Full GR force free electrodynamics (Palenzuela et al. 2010, 2012)





Implications of GW150914: multi-band GW astronomy

(AS 2016, PRL 116, 1102)



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

What do we do with them?

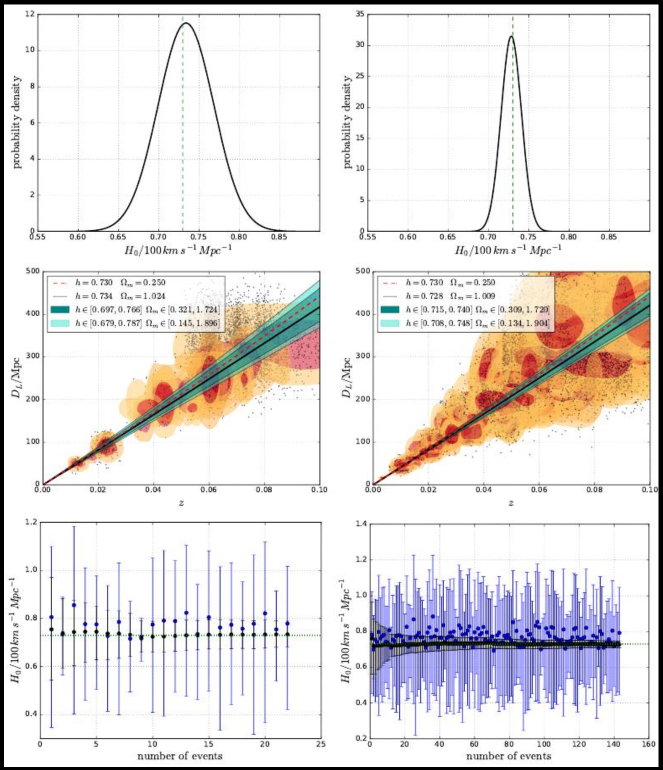
>Detector cross-band calibration and validation (LISA aLIGO)

>Multiband GW astronomy:
- -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

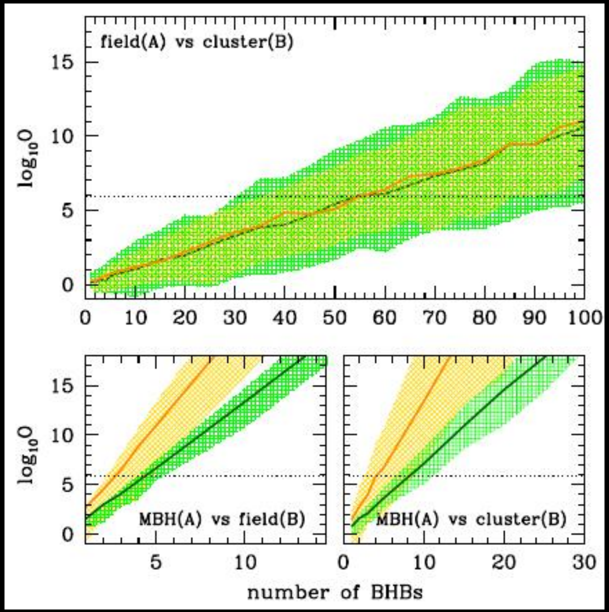
>Enhanced tests of GR: e.g. strongest limits on deviations from GR

(Barausse et al 2016)



>Astrophysics:
- -independent measure of spins
- -measure of eccentricity

(Nishizawa, AS, Berti, Klein 2017, Breivik et al 2017)

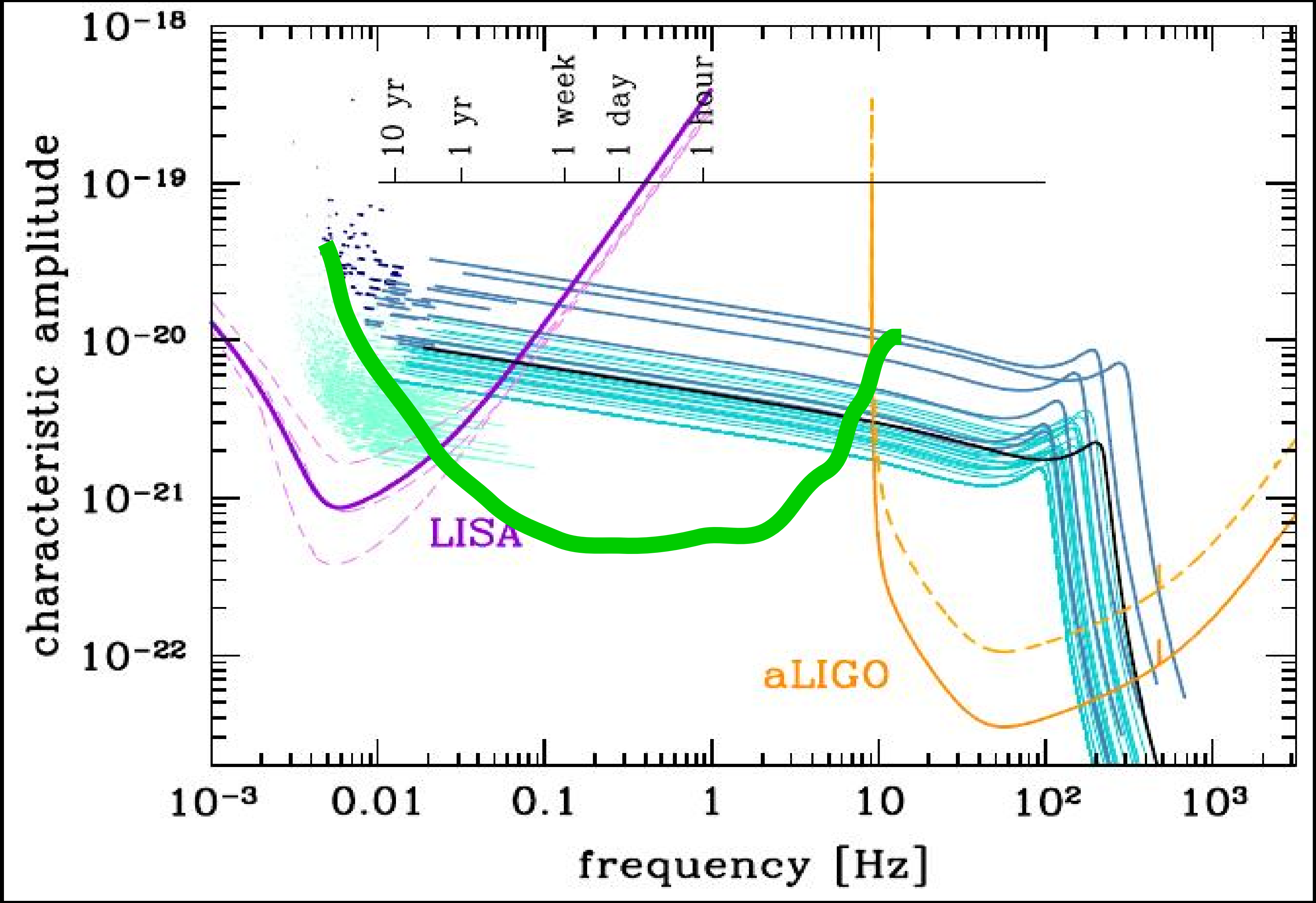


>Cosmology:
- -new population of standard sirens?

(Kyutoku & Seto 2016, Del Pozzo, AS, Klein 2017)

Implications of GW150914: multi-band GW astronomy

(AS 2016, PRL 116, 1102)

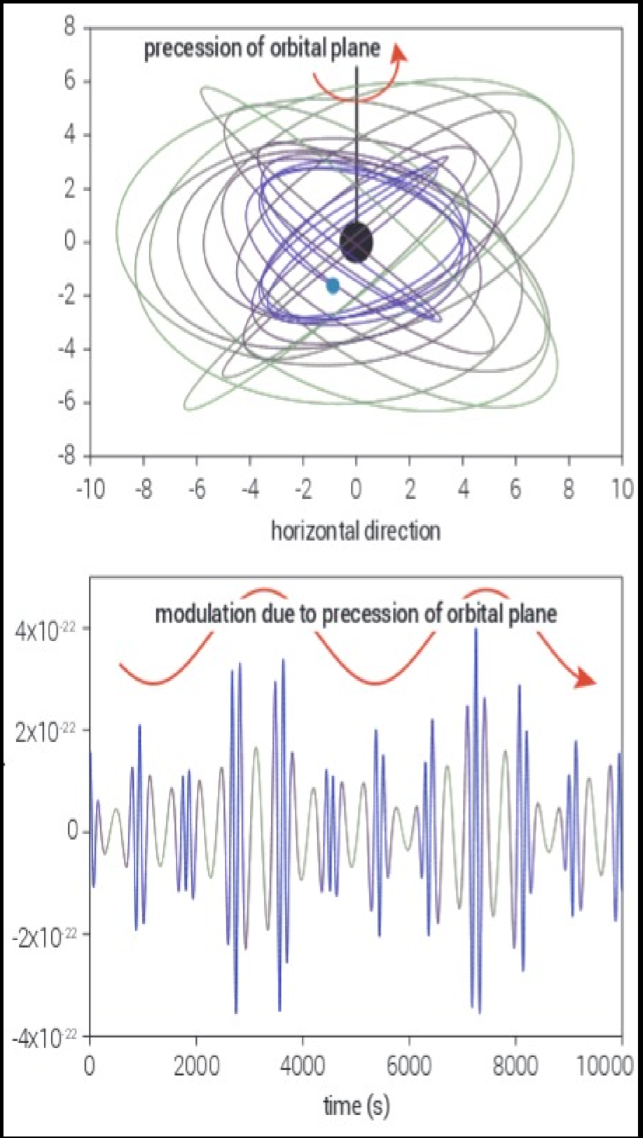


BHB will be detected by LISA and cross to the LIGO band, assuming a 5 year operation of LISA.

Extreme mass ratio inspirals (EMRIs)

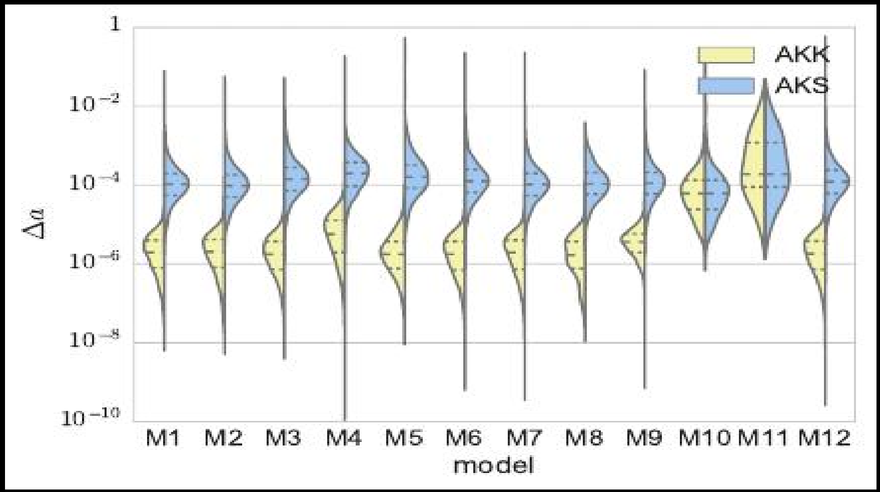
- *What is the mass distribution of stellar remnants at the galactic centres and what is the role of mass segregation and relaxation in determining the nature of the stellar populations around the nuclear black holes in galaxies?*
- *Are massive black holes as light as $\sim 10^5 M_\odot$ inhabiting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

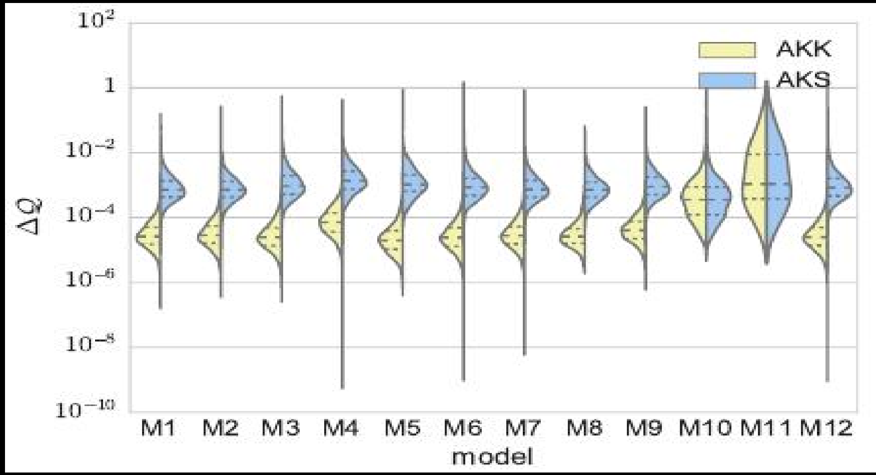
- *Does gravity travel at the speed of light ?*
- *Does the graviton have mass?*
- *How does gravitational information propagate: Are there more than two transverse modes of propagation?*
- *Does gravity couple to other dynamical fields, such as, massless or massive scalars?*
- *What is the structure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



EMRI: detection, parameter estimation, science

(Babak, Gair, AS 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%

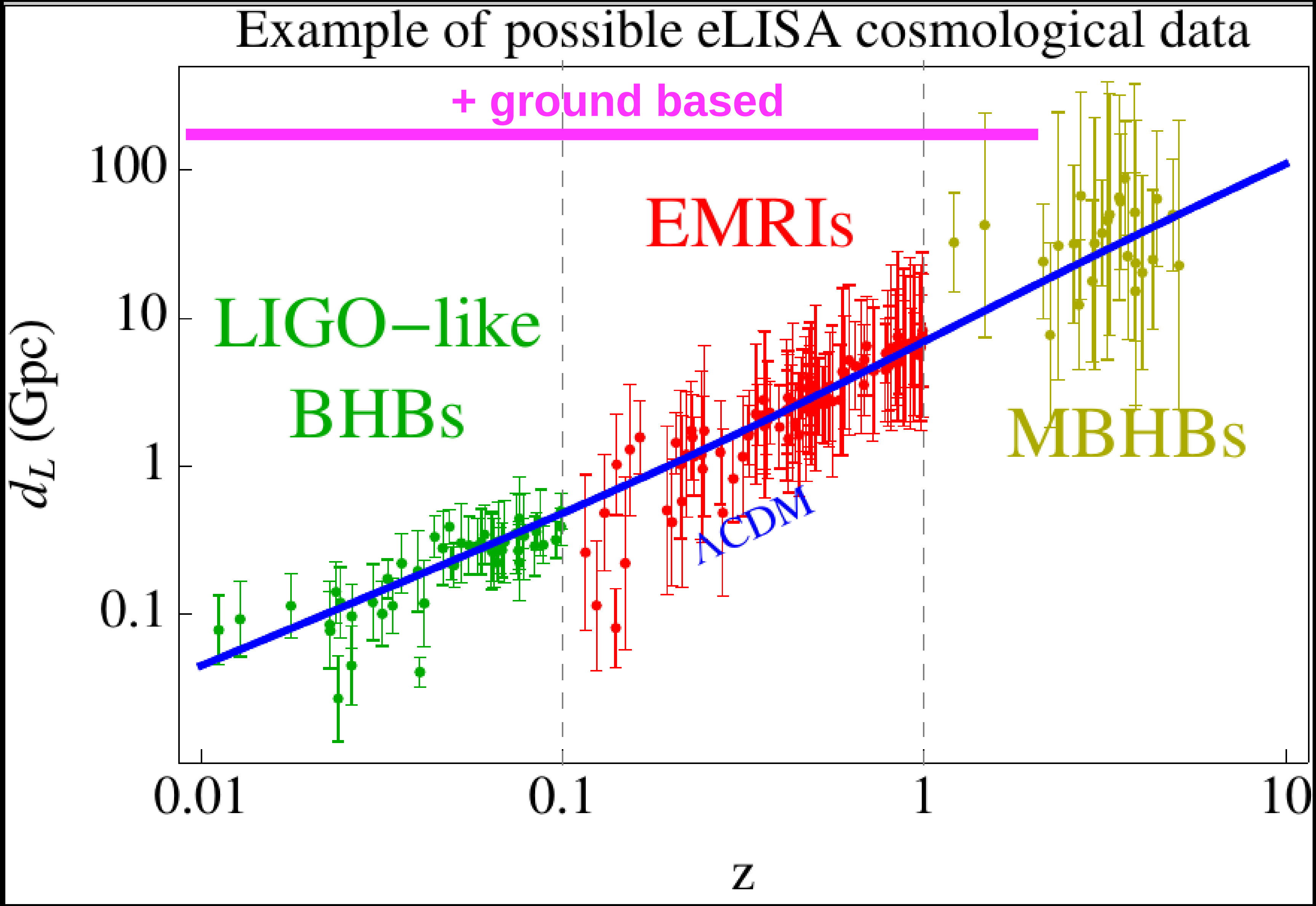
~MBH spin to better than 0.001

~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

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?*

Galactic binaries

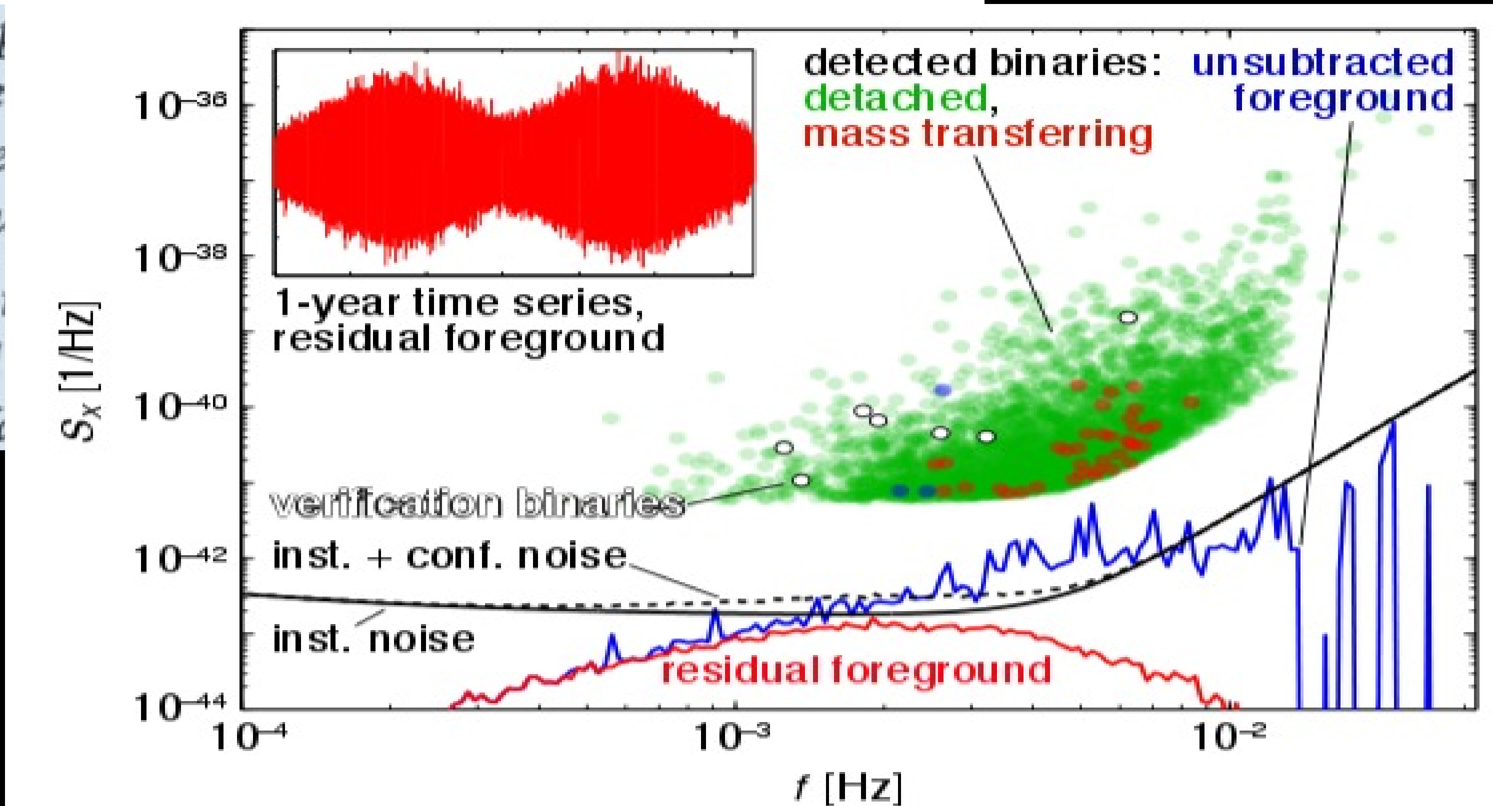
- How... Wa...
- Wh... and... ter... atea...
- Wh... thei...
- What ha... exchange... what doe... type Ia su...
- What is ... ries, and... Milky Wa...

Arm	Noise	Links	Full ID	S/N> 7	2-D	3-D	$\dot{f} < 20\%$	$\dot{f} < 20\%$
A1	N1	L4	L4A1M2N1	569	241	82	464	1
		L6	L6A1M2N1	952	418	103	672	3
	N2	L4	L4A1M2N2	5248	1366	452	1496	1
		L6	L6A1M2N2	8805	2390	600	1936	3
A2	N1	L4	L4A2M2N1	1298	498	205	809	3
		L6	L6A2M2N1	2043	800	246	1056	3
	N2	L4	L4A2M2N2	9189	2754	1001	2255	3
		L6	L6A2M2N2	14757	4562	1257	2804	3
A5	N1	L4	L4A5M2N1	3073	987	410	1275	3
		L6	L6A5M2N1	4987	1674	548	1604	3
	N2	L4	L4A5M2N2	13634	5558	1816	3287	3
		L6	L6A5M2N2	21744	8815	2127	3989	3

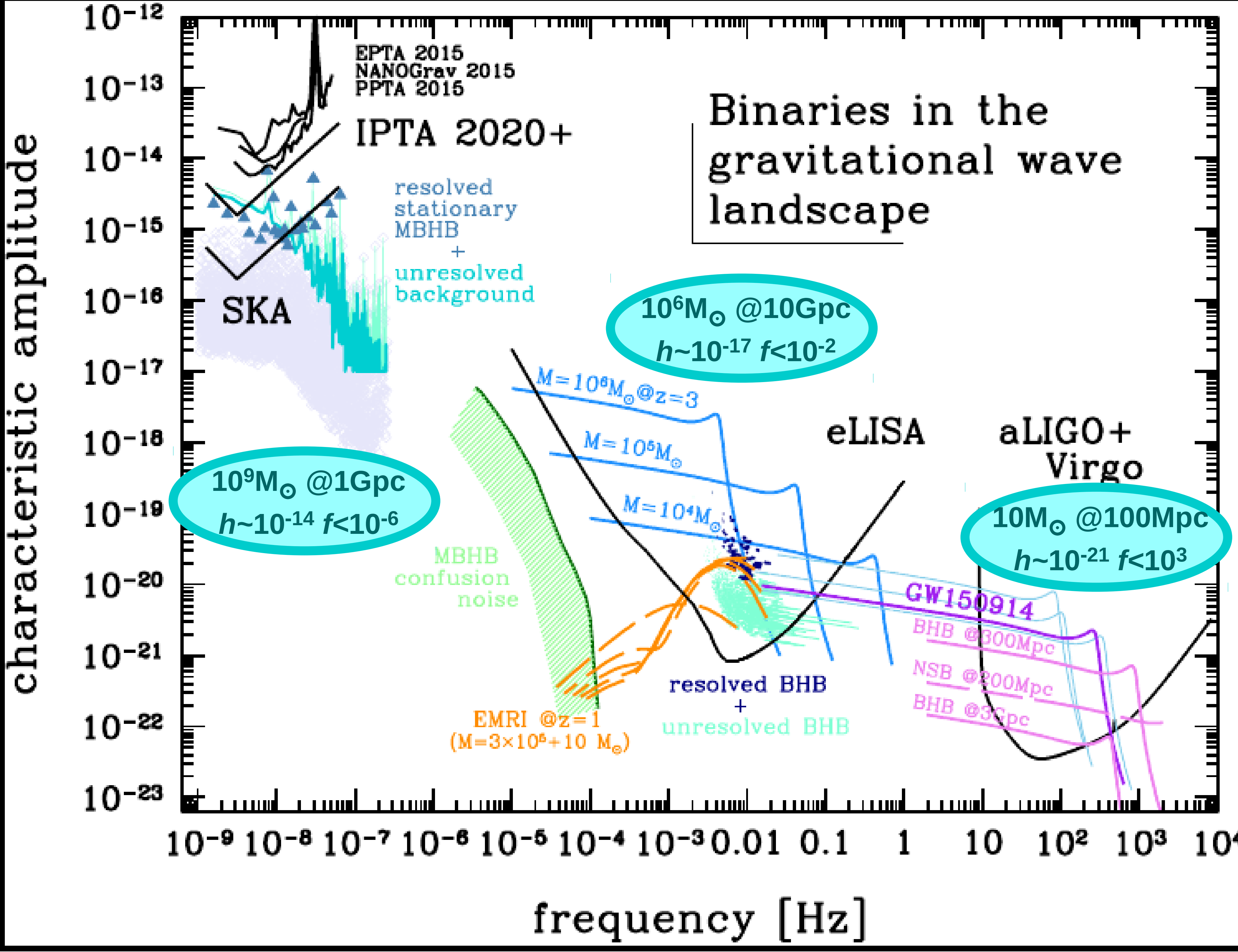
And do not forget
NS-NS and NS-BH binaries!

*Provide complementary information to ground based detectors

*Sinergy with SKA?



The nanohertz window: moving into the SKA era

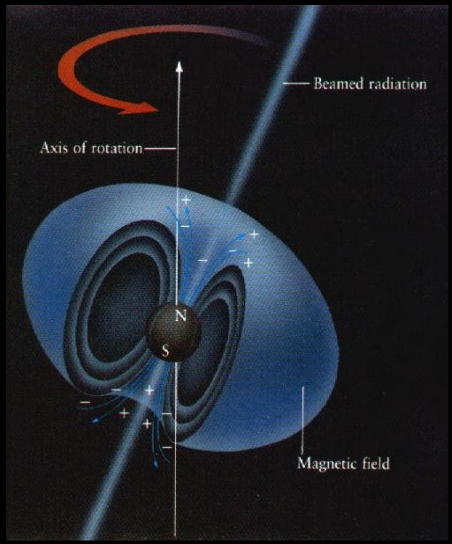


Binaries in the gravitational wave landscape
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB + unresolved background
10^6M⊙ @10Gpc
h~10^-17 f<10^-2
10^9M⊙ @1Gpc
h~10^-14 f<10^-6
10M⊙ @100Mpc
h~10^-21 f<10^3
M=10^6M⊙@z=3
M=10^5M⊙
M=10^4M⊙
eLISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
resolved BHB + unresolved BHB
EMRI @z=1
(M=3×10^5+10 M⊙)
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

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



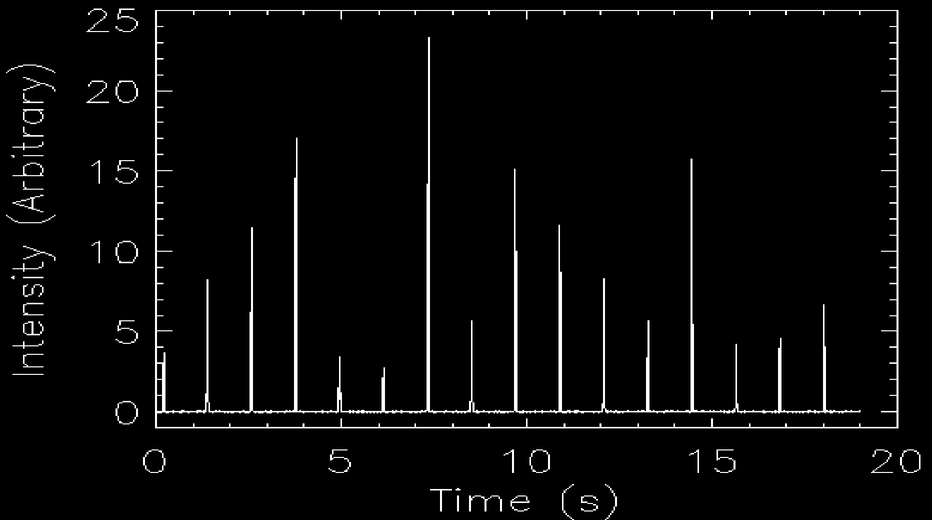
1-Observe a pulsar and measure the ToAs

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*



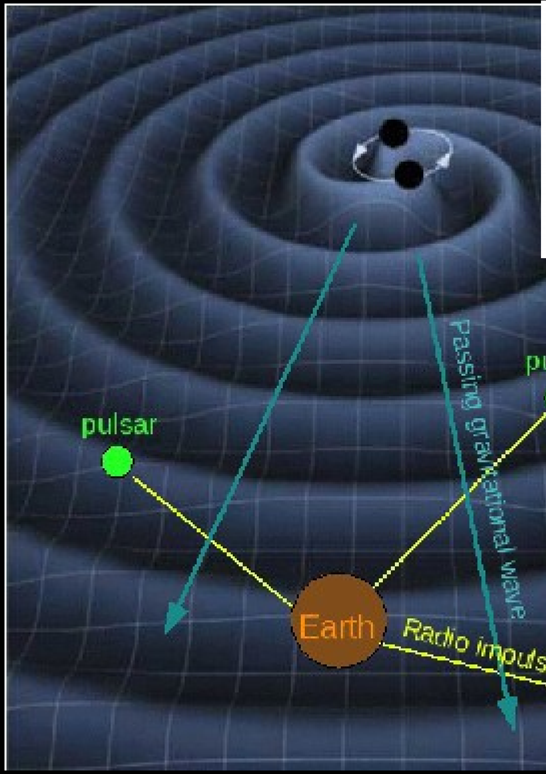
Effect of gravitational waves

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)

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



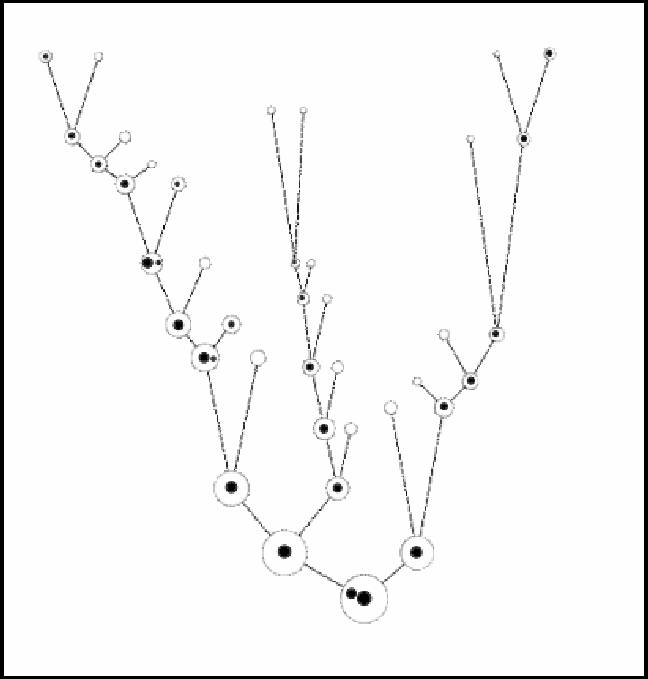
(Sazhin 1979, Hellings & Downs 1983, Jenet et al. 2005, AS et al. 2008, 2009)

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

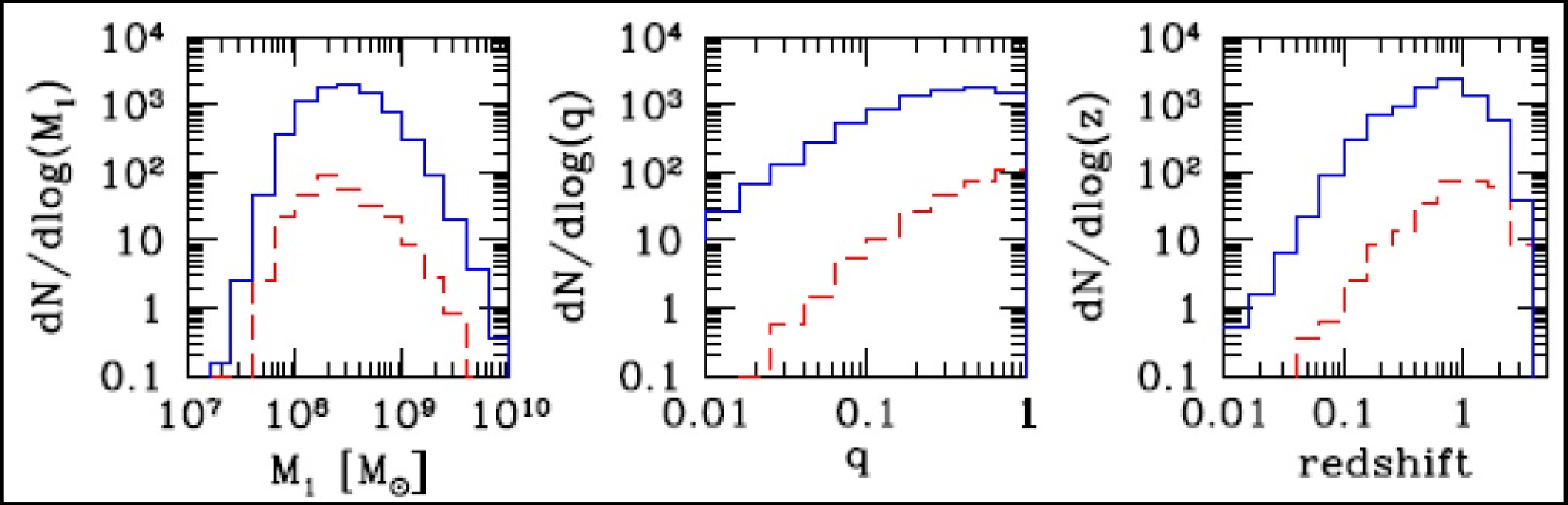
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^3N}{dz d\mathcal{M} d\ln f_r} h^2(f_r)$$

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

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)

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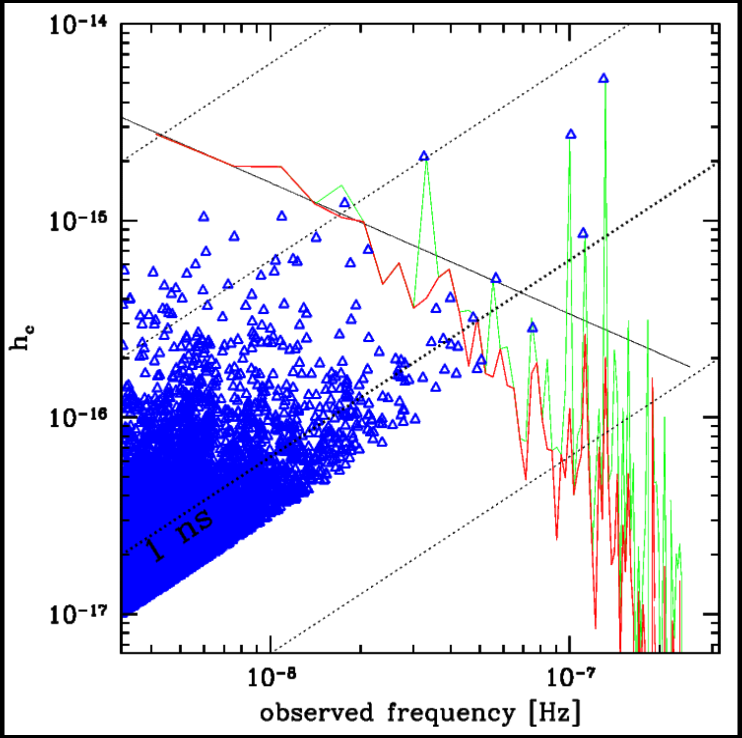

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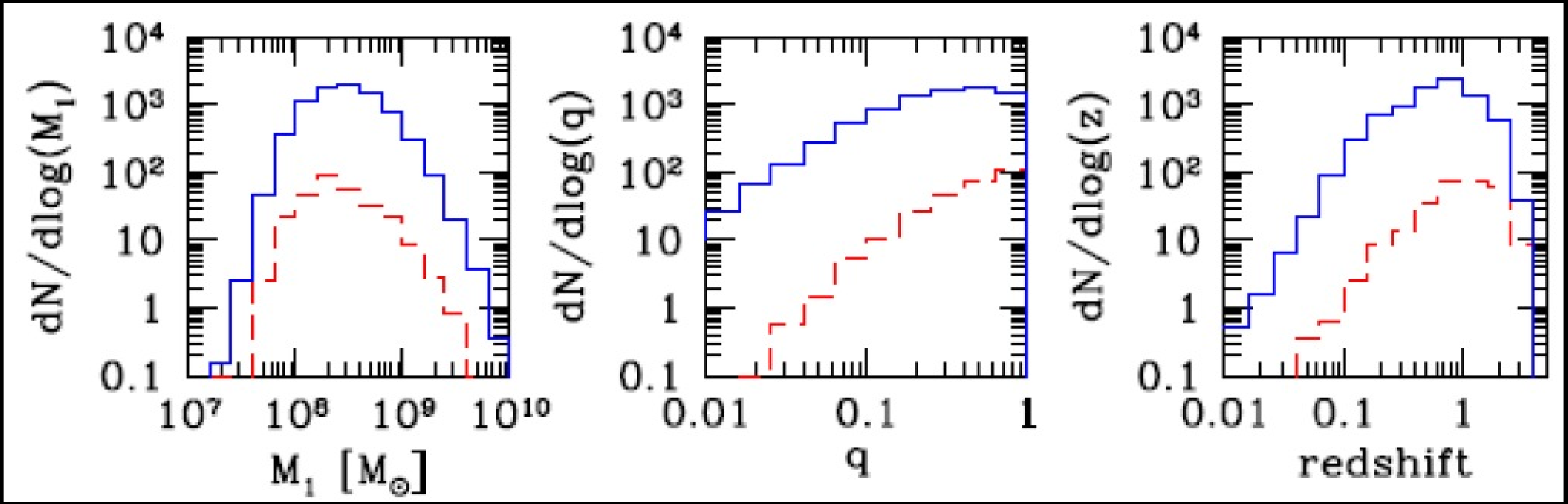

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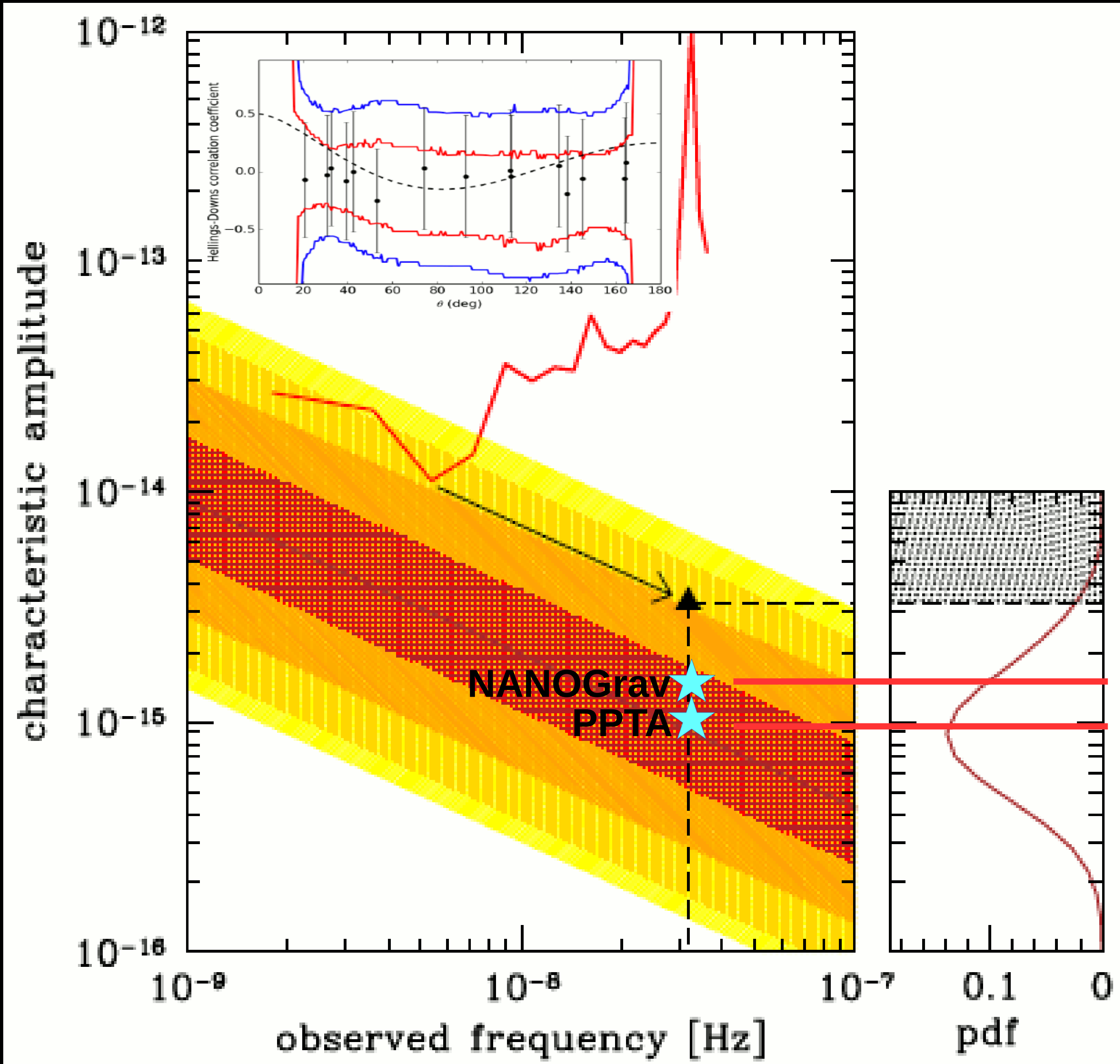
No detection: constraining SMBHBs?



(Lentati et al. 2015, Arzoumanian et. 2016, Shannon et al. 2015)

Predictions shown here (AS 2013):

>Assume circular GW driven binaries

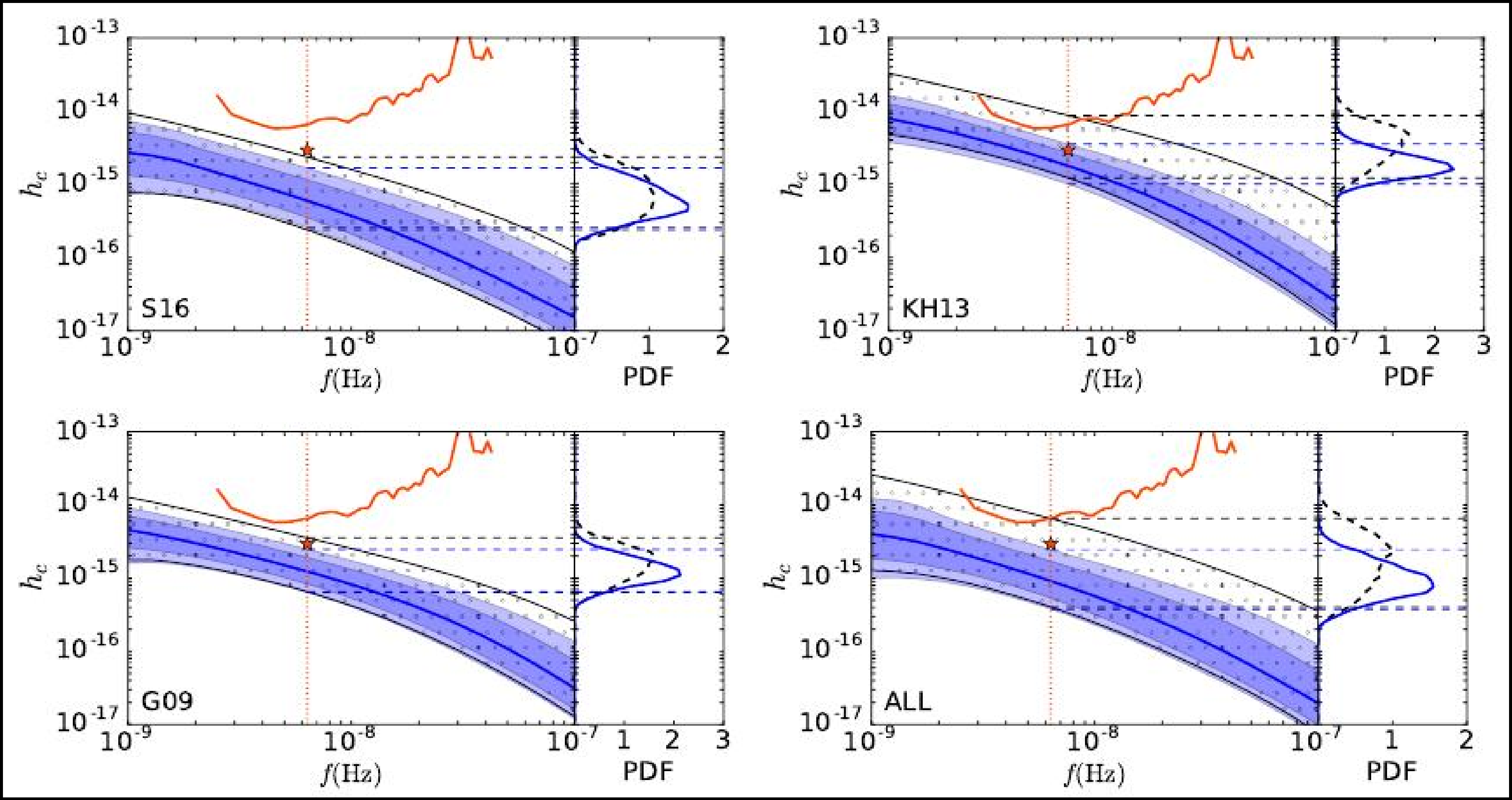
>Efficient MBH binary merger following galaxy mergers

>Uncertainty range takes into account:
- -merger rate
- -MBH-galaxy relation
- -accretion timing

(AS 2008, 2013; Ravi et al. 2012, 2015; Roebber er al. 2015; Kulier et al. 2014; McWilliams et al. 2014)

...not quite 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)

The future

MeerKAT, South Africa (2017)

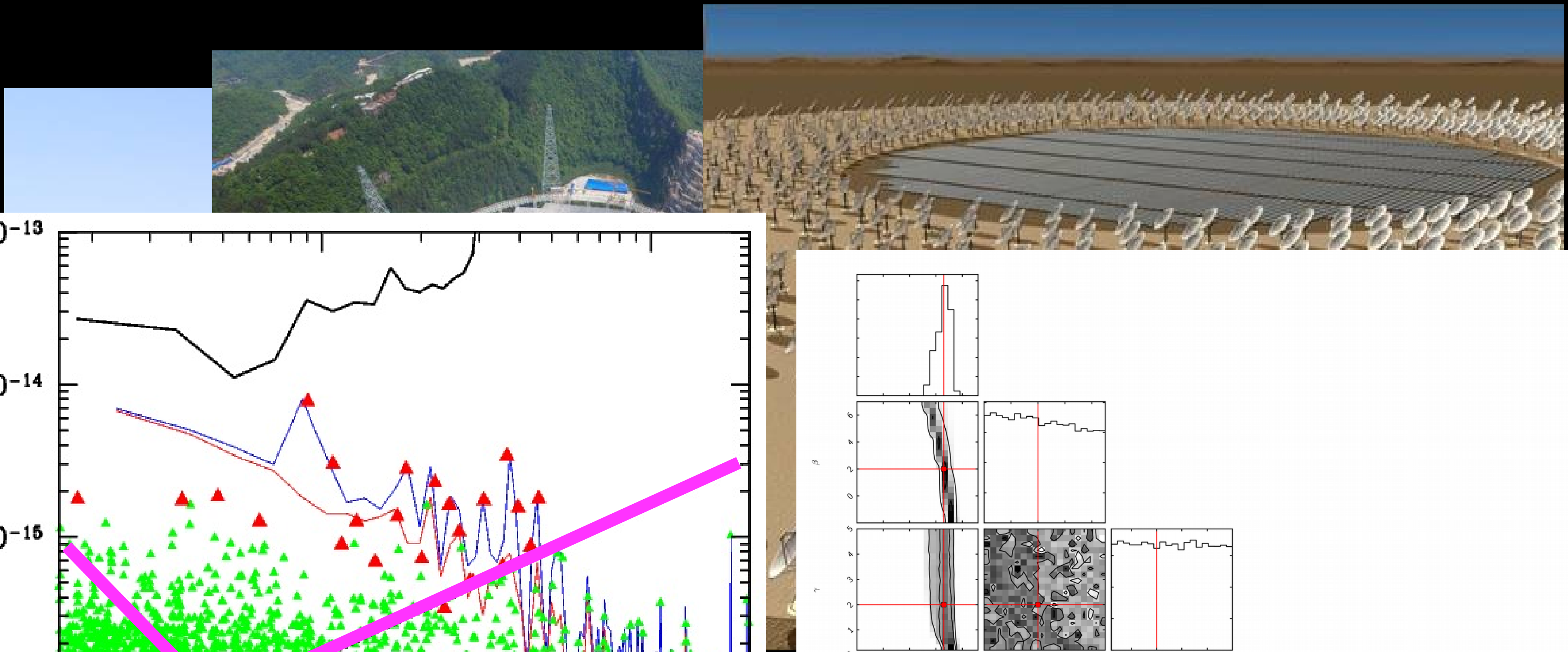
The future

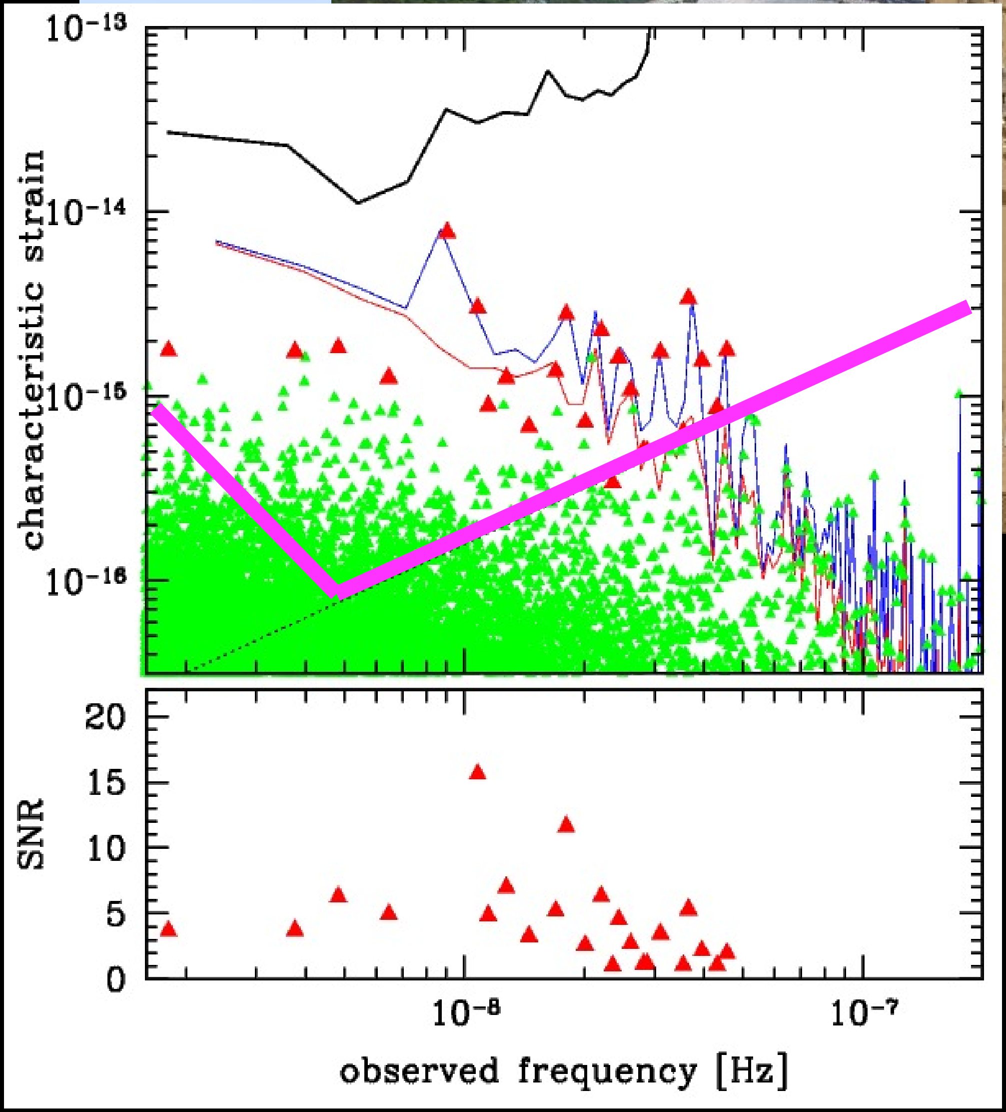
FAST, China (2017)

The future

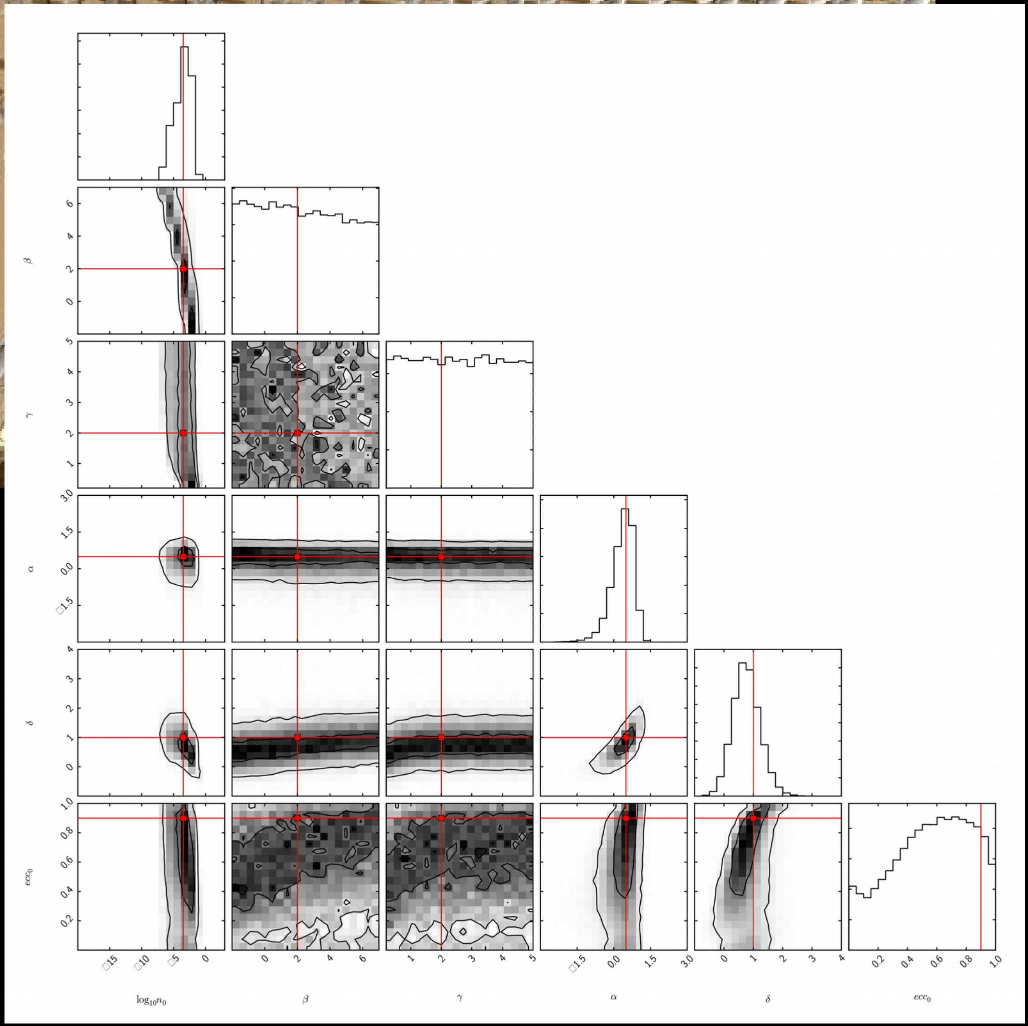
Square Kilometre Array (SKA, 2021+)

The future

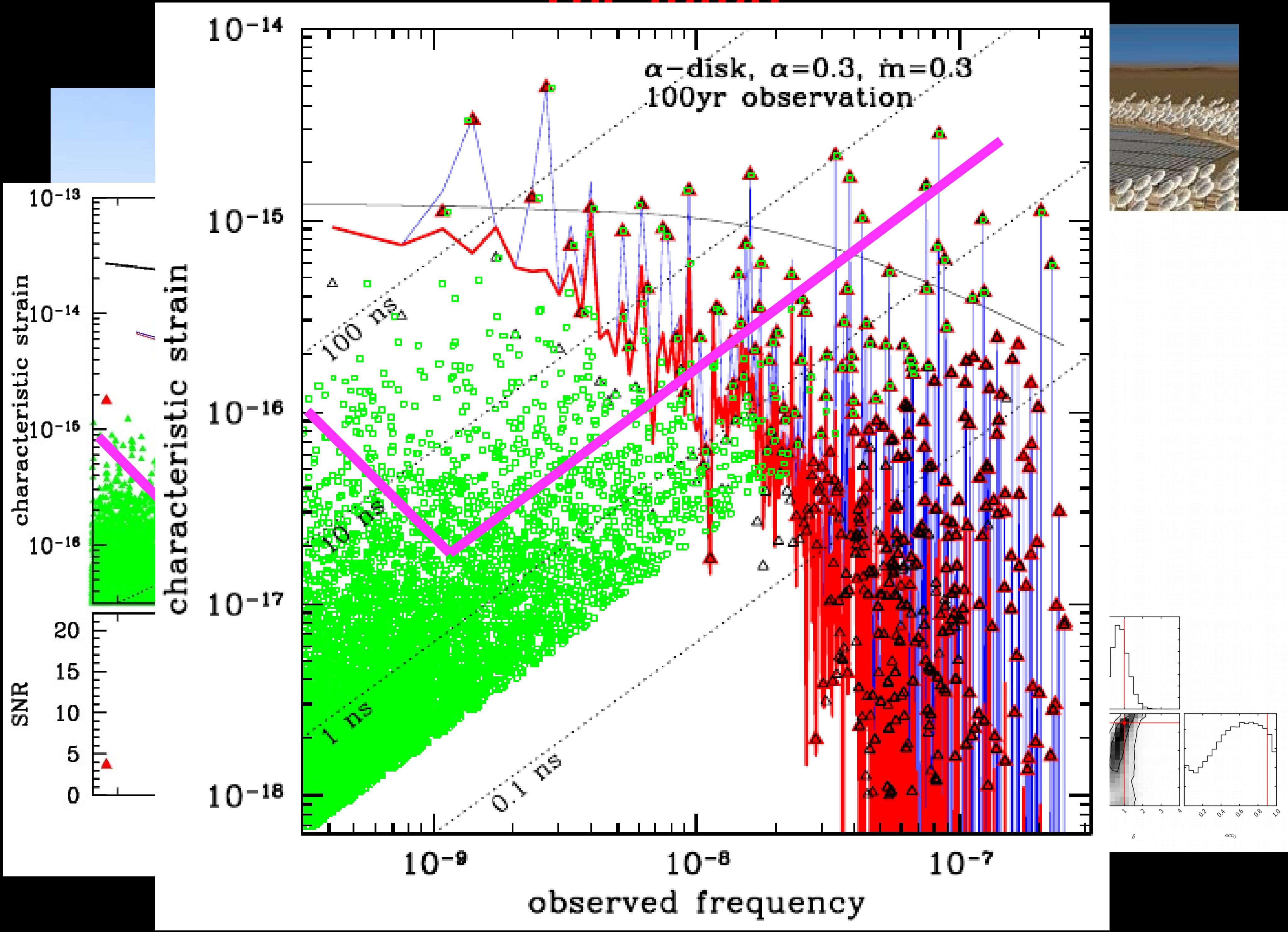




characteristic strain
SNR
observed frequency [Hz]
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-8}
10^{-7}
20
15
10
5
0

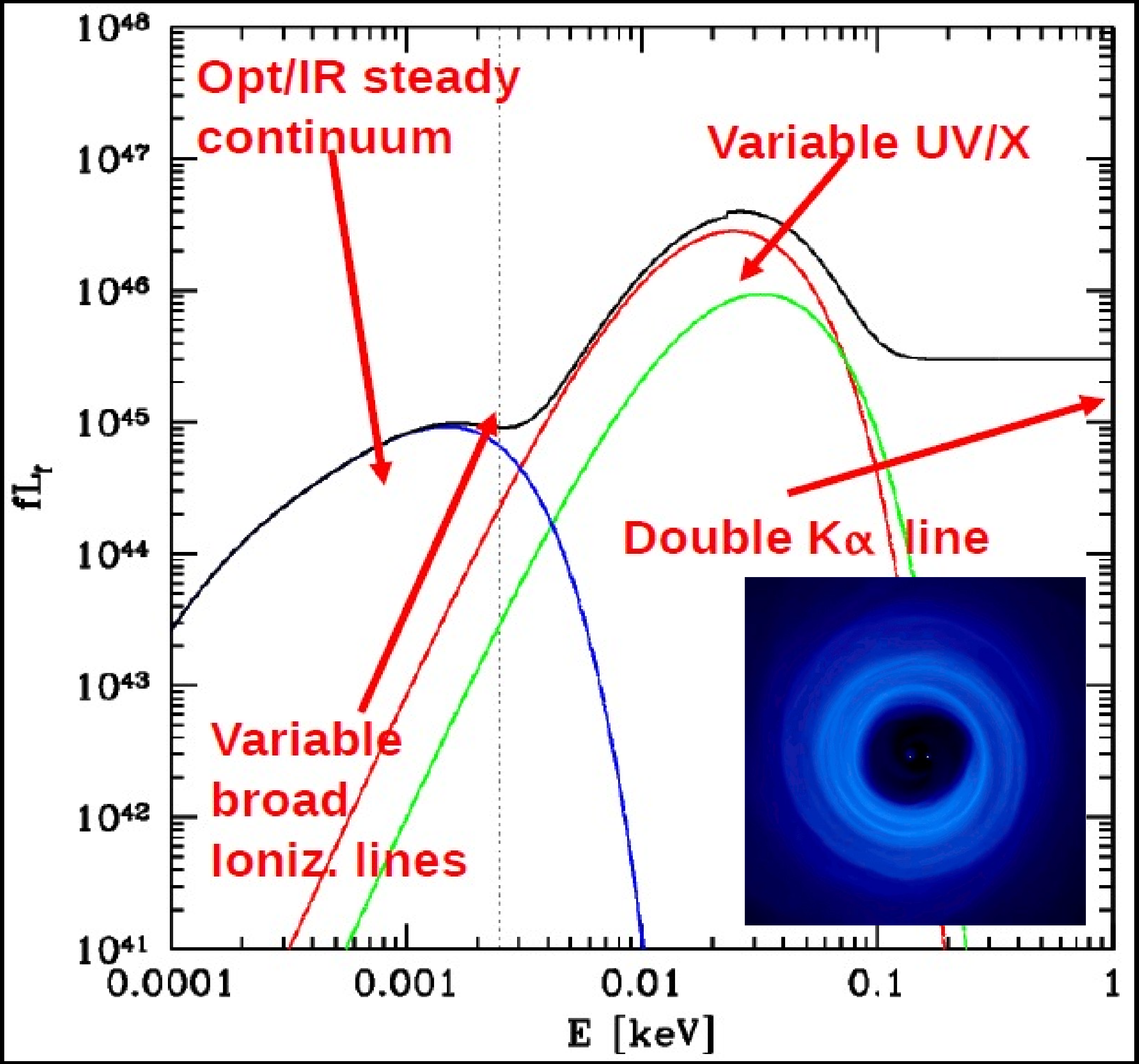


The future


α−disk, α=0.3, ṁ=0.3
100yr observation
characteristic strain
observed frequency
100 ns
10 ns
1 ns
0.1 ns
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻⁹
10⁻⁸
10⁻⁷
10⁻¹³
SNR
20
15
10
5
0

Associated electromagnetic signatures PTA

MBH binary + circumbinary disk



(Roedig et al. 2011, AS et al. 2012,
Tanaka et al. 2012, Burke-Spolaor 2013)

A variety of possibilities:

Optical/IR dominated by the outer disk: Steady/modulated?

UV generated by inner streams/minidisk: periodic variability?

X rays variable from periodic shocks or intermittent corona?

Variable broad emission line in response to the varying ionizing continuum?

Double fluorescence lines?

Science beyond the first nHz GW detection:

Prove the existence of SMBHBs

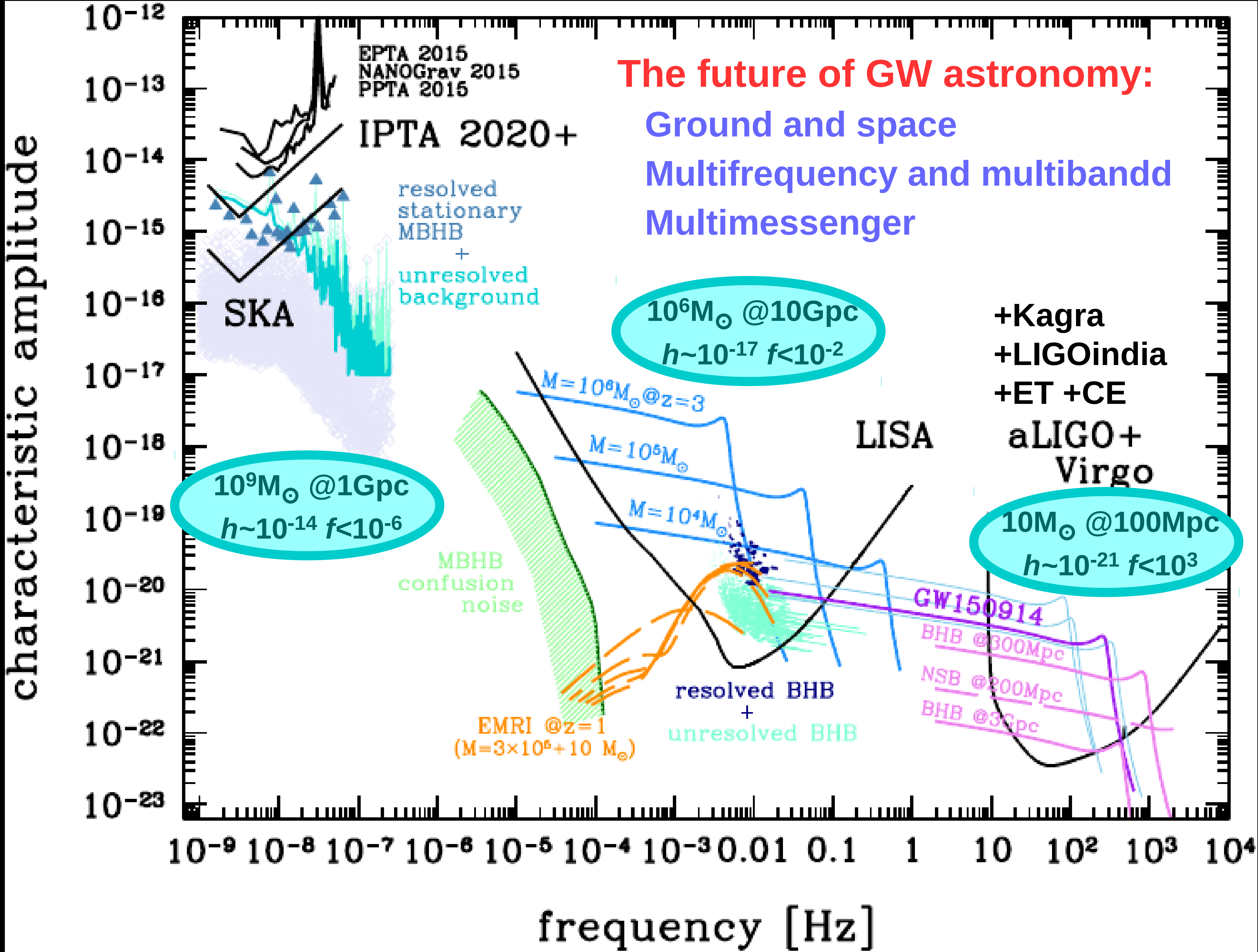
Characterize the GWB spectrum: coupling with the environment

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 of GW astronomy:
Ground and space
Multifrequency and multibandd
Multimessenger
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}
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h~10^{-14} f<10^{-6}
$10 M_\odot$ @100Mpc
h~10^{-21} f<10^3
+Kagra
+LIGOindia
+ET +CE
LISA
aLIGO+ Virgo
$M=10^6 M_\odot$ @z=3
$M=10^5 M_\odot$
$M=10^4 M_\odot$
MBHB confusion noise
EMRI @z=1
($M=3\times10^5+10\ M_\odot$)
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