The promise of multi-band gravitational wave astronomy

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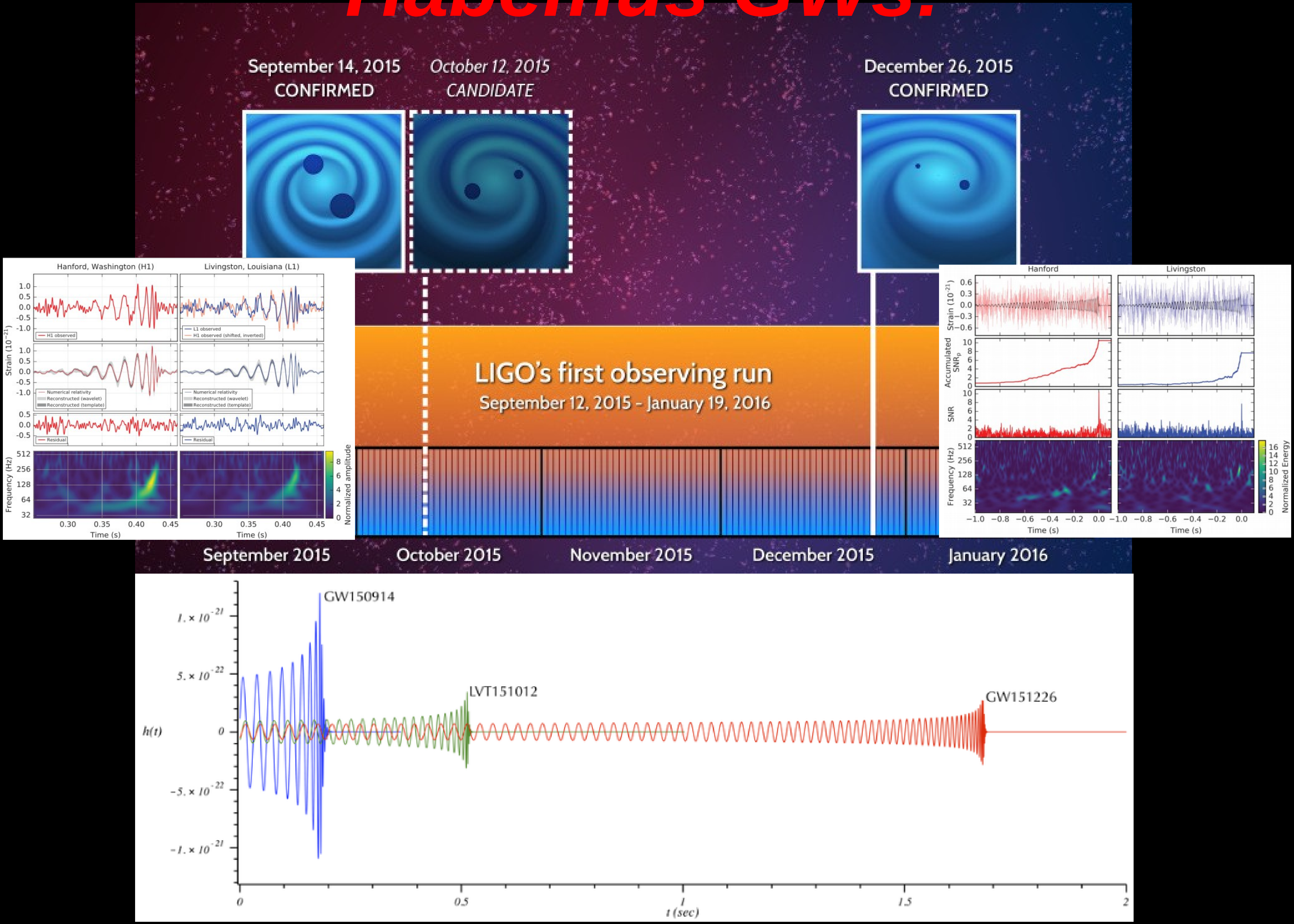
OUTLINE

>Gravitational waves across the frequency spectrum

>GW150914: a gift from LIGO

>Stellar BHs in the eLISA band: multi-band GW astronomy with eLISA and ground based interferometers

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)
Hanford
Livingston
GW150914
LVT151012
GW151226
h(t)
t (sec)

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

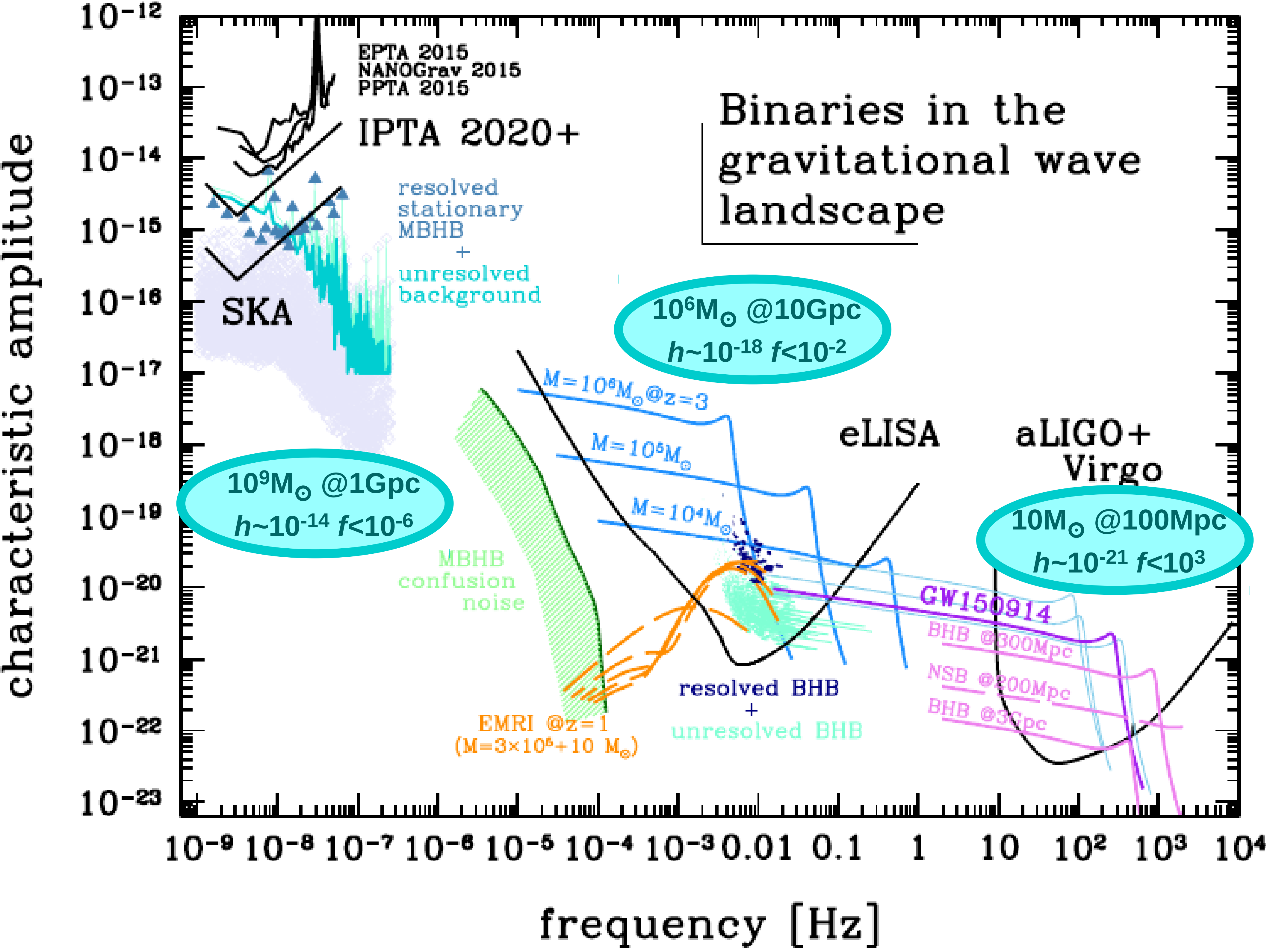
$$h \sim 10^{-20}\frac{M}{M_\odot}\frac{\mathrm{Mpc}}{D}$$

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

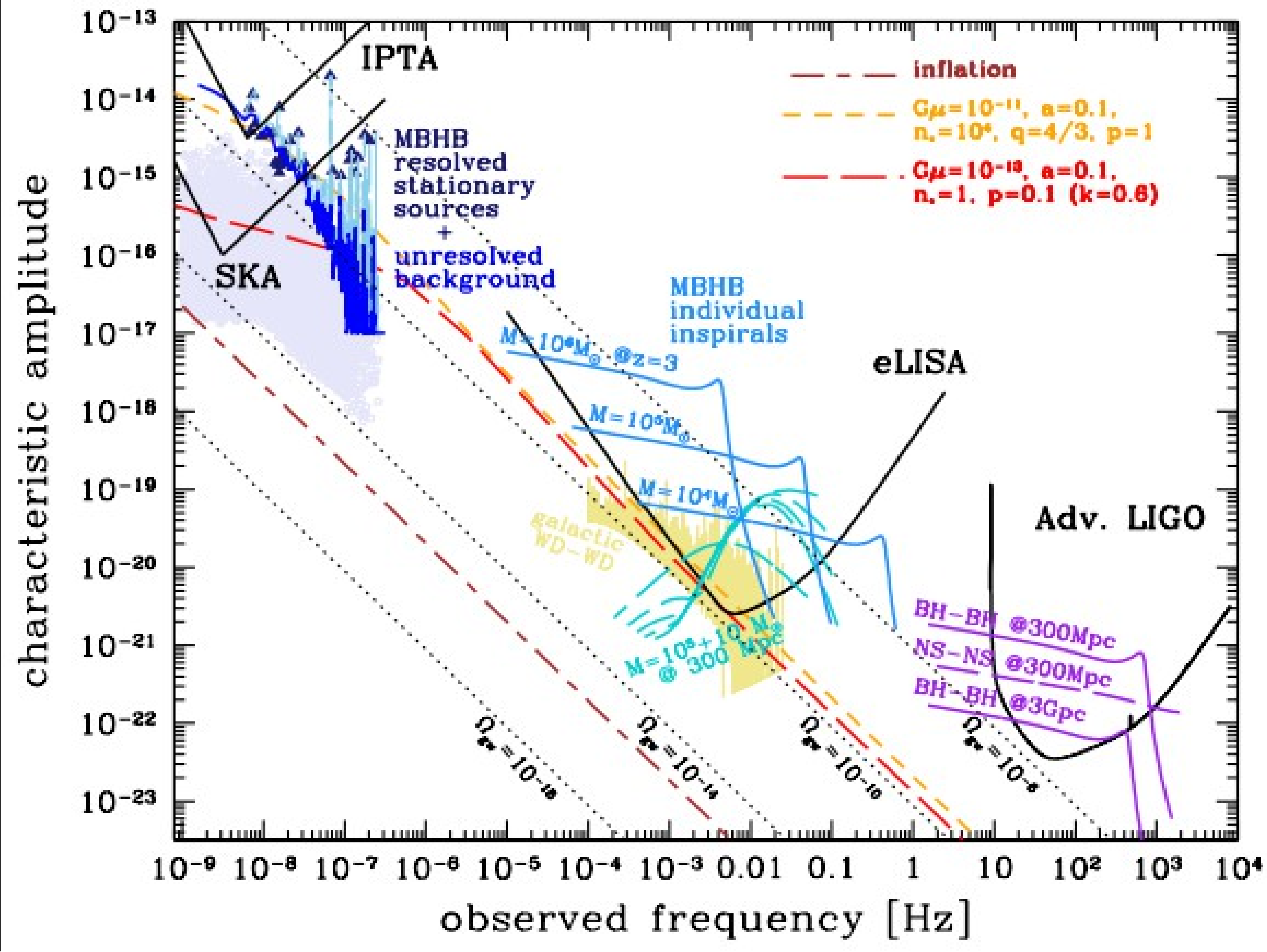
10 $M_\odot$ binary at 100 Mpc: $h \sim 10^{-21}$, $f < 10^{3}$

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

10^9 $M_\odot$ binary at 1Gpc: $h \sim 10^{-14}$, $f < 10^{-6}$

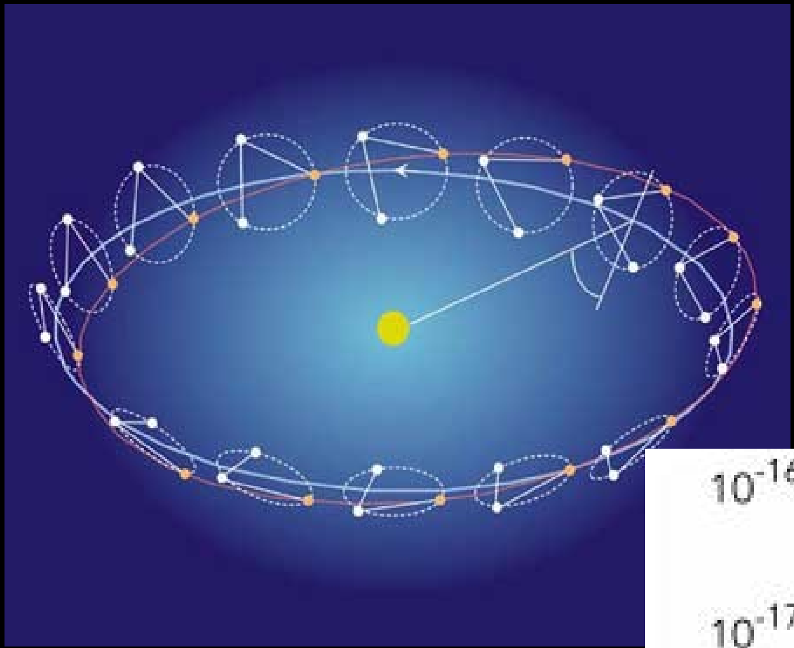


characteristic amplitude
frequency [Hz]
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB + unresolved background
Binaries in the gravitational wave landscape
$10^6 M_\odot$ @10Gpc
$h \sim 10^{-18}$ $f < 10^{-2}$
$10^9 M_\odot$ @1Gpc
$h \sim 10^{-14}$ $f < 10^{-6}$
$10 M_\odot$ @100Mpc
$h \sim 10^{-21}$ $f < 10^{3}$
$M=10^6 M_\odot$ @z=3
$M=10^5 M_\odot$
$M=10^4 M_\odot$
eLISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
EMRI @z=1
($M=3\times10^5+10$ $M_\odot$)
resolved BHB + unresolved BHB



IPTA
SKA
inflation
Gμ=10^-11, a=0.1,
n_s=10^4, q=4/3, p=1
Gμ=10^-13, a=0.1,
n_s=1, p=0.1 (k=0.6)
MBHB
resolved
stationary
sources
+
unresolved
background
MBHB
individual
inspirals
M=10^6 M⊙ @z=3
M=10^5 M⊙
M=10^4 M⊙
eLISA
Adv. LIGO
galactic
WD-WD
BH-BH @300Mpc
NS-NS @300Mpc
BH-BH @3Gpc
characteristic amplitude
observed frequency [Hz]

The Laser Interferometer Space Antenna

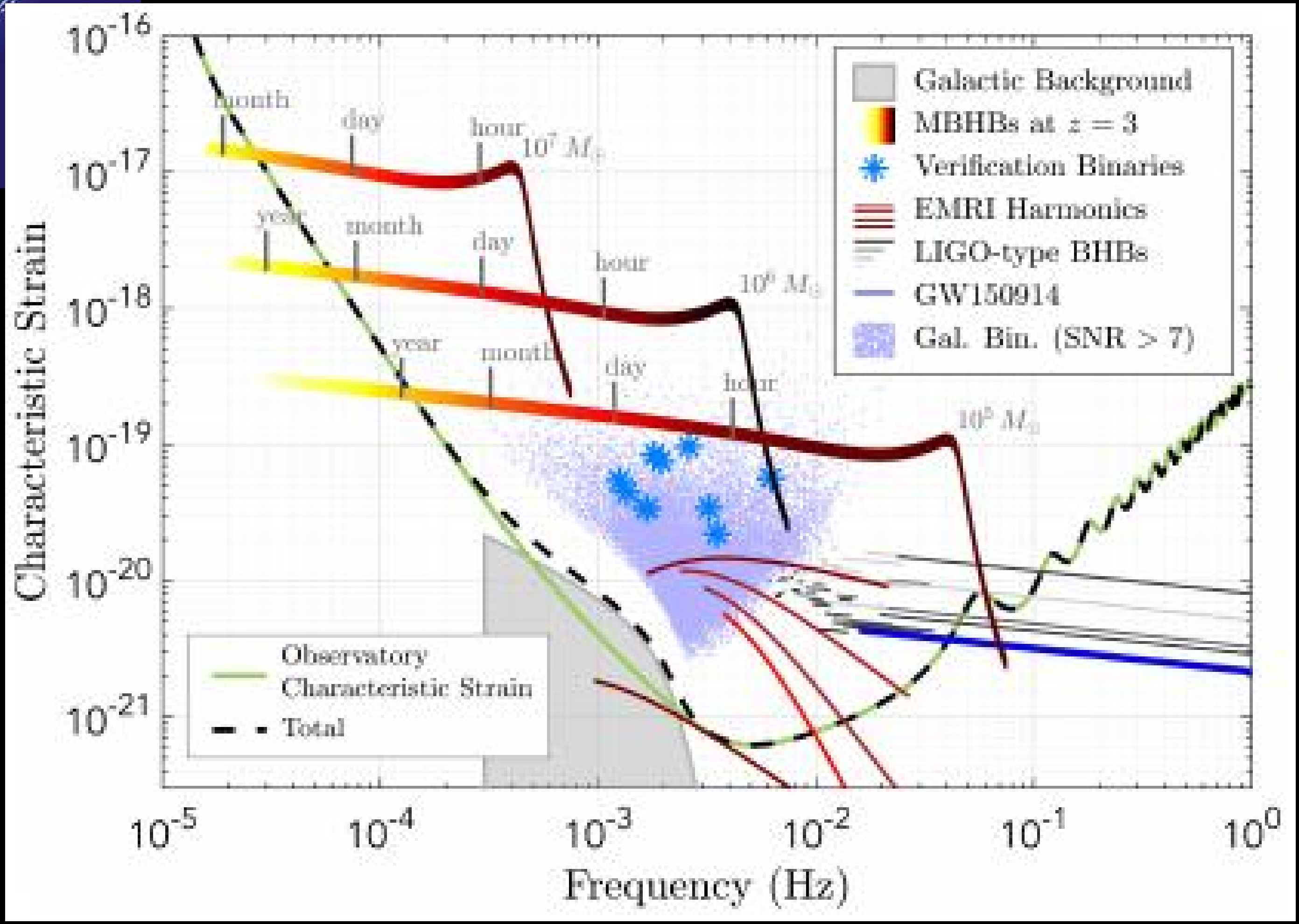


Sensitive in the mHz frequency range where MBH binary evolution is fast (chirp)

Observes the full inspiral/merger/ringdown

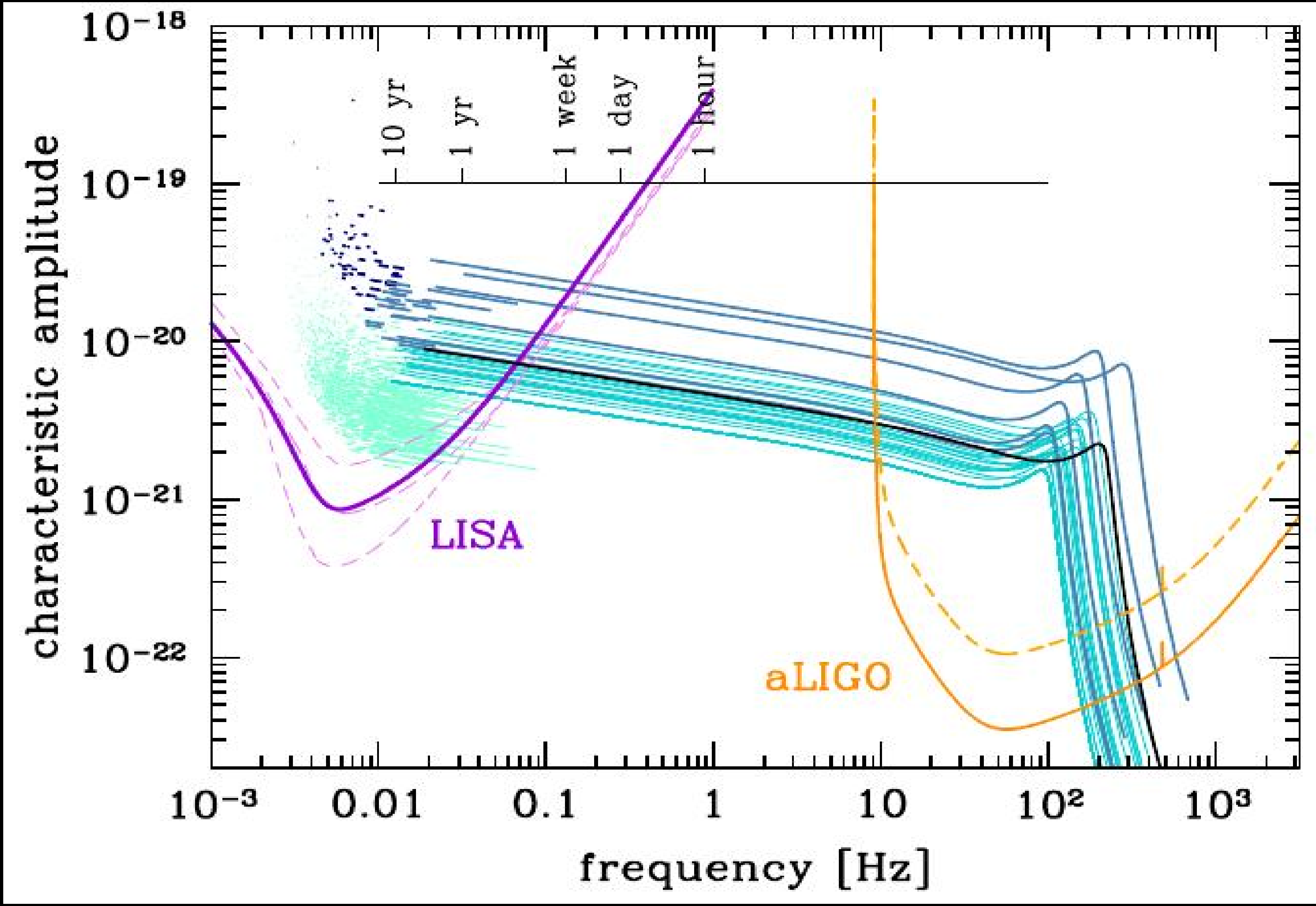
3 satellites trailing the Earth connected through laser links

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



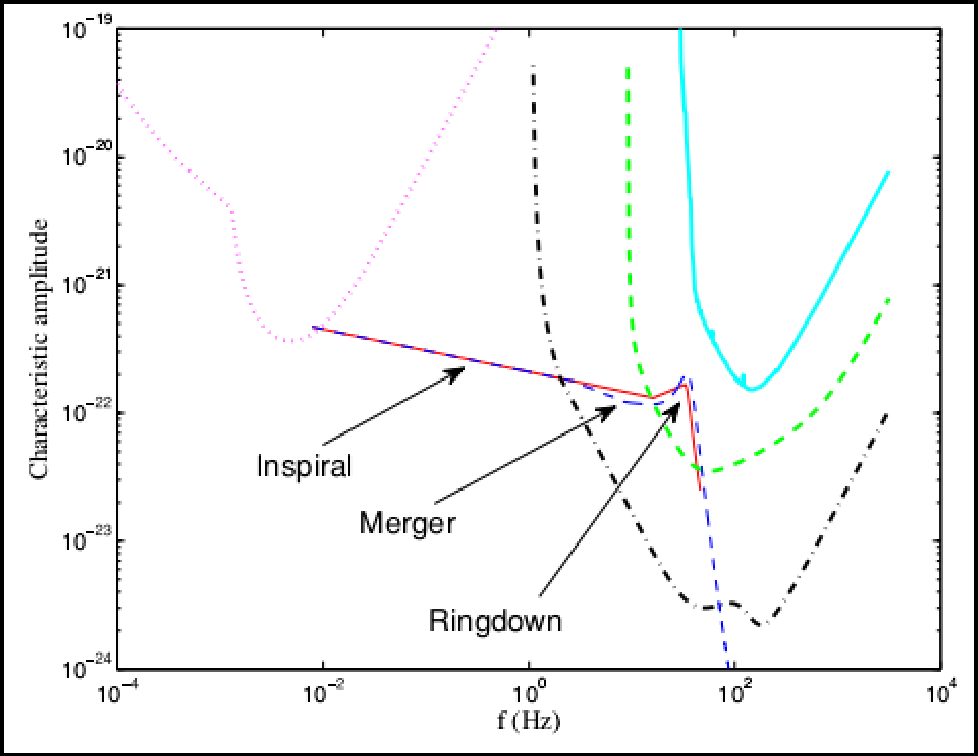
An unexpected scenario: multi-band GW astronomy

(AS 2016, PRL 116, 1102)



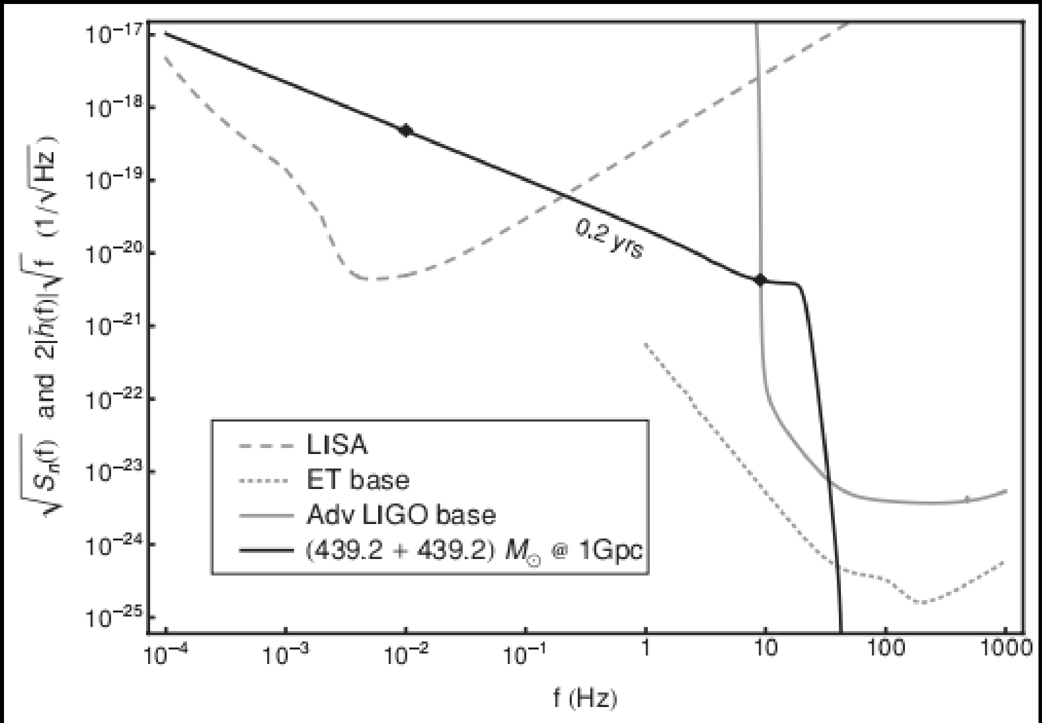
BHB will be detected by eLISA and cross to the LIGO band,
assuming a 5 year operation of eLISA.

The idea was already around in the literature



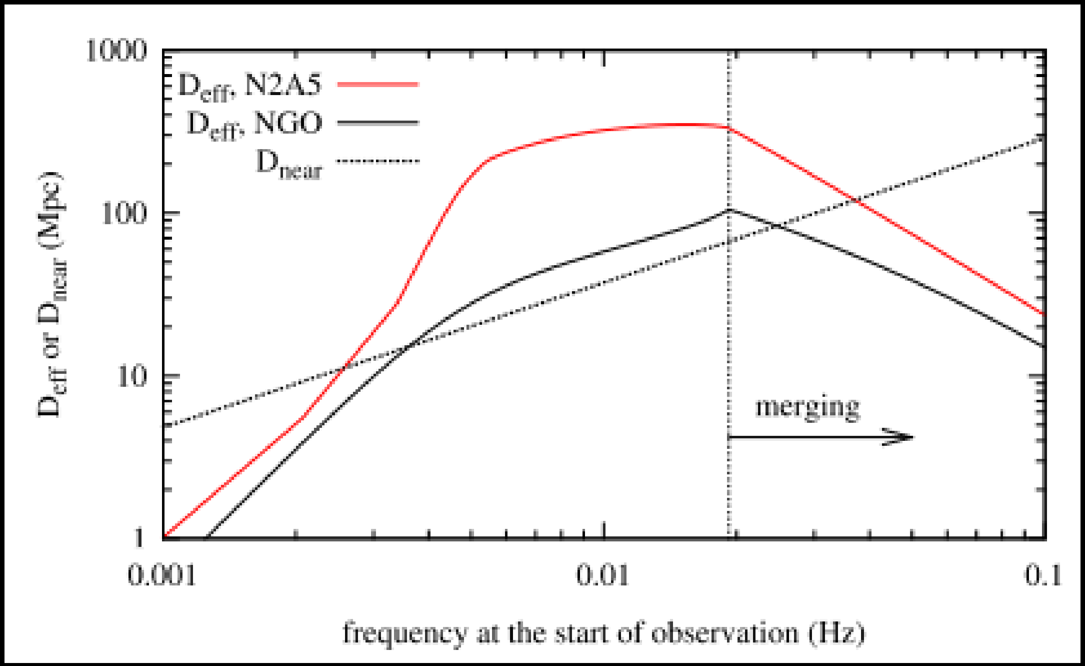
PopIII seeds merging at late times (z~2) could be seen both in LISA and aLIGO/ET (AS et al. 2009)

IMBH binaries formed in star cluster can also cross from LISA to LIGO/ET in a short timescale (Amaro-Seoane & Santamaria 2010)



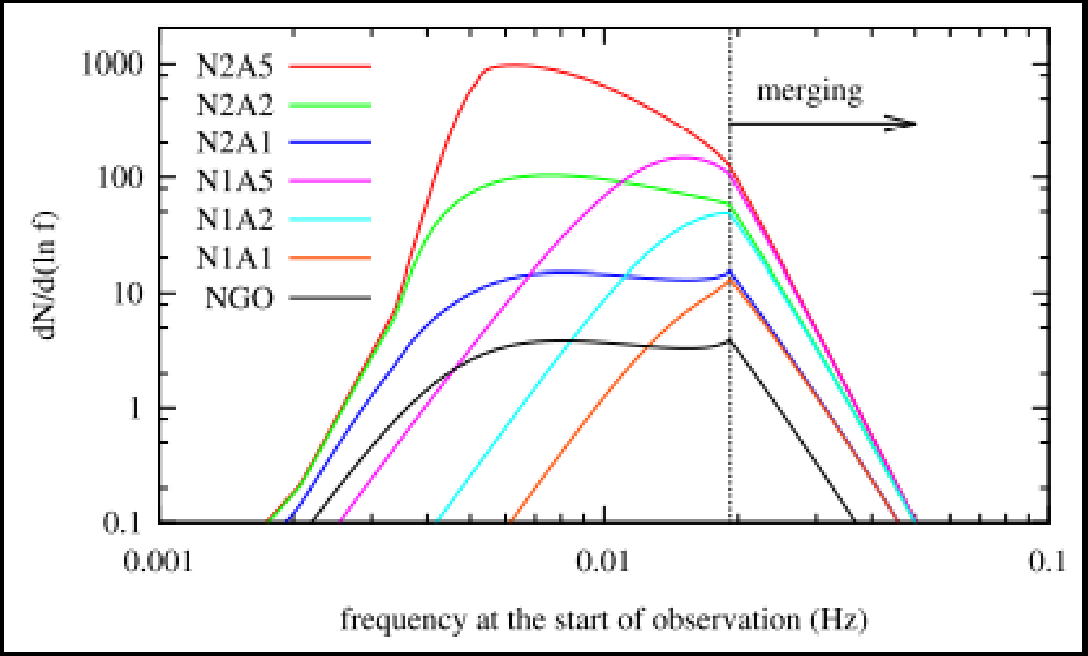
Distribution of sources across the band

(Kyutoku & Seto 2016)



Reach of eLISA for GW150915. Up to z~0.1 at f~0.01Hz

-Almost stationary at f<0.02 Hz
-Evolving to the LIGO band for f>0.02 Hz

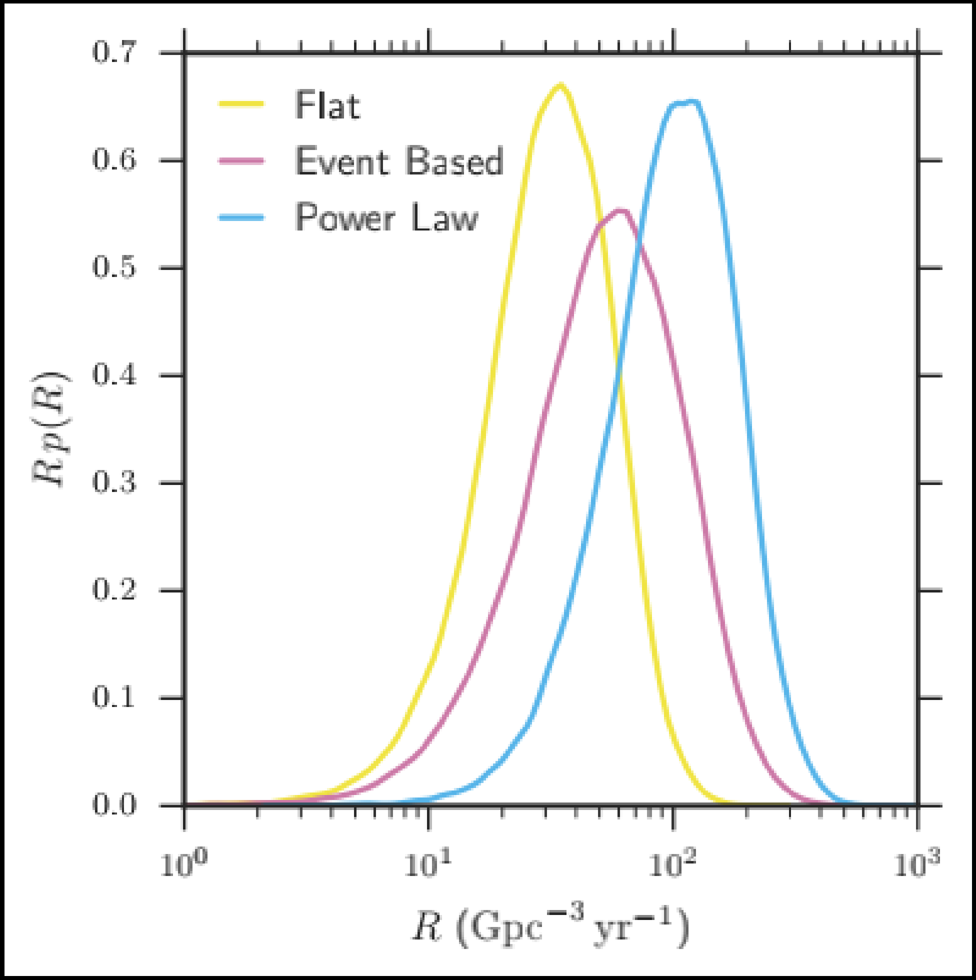


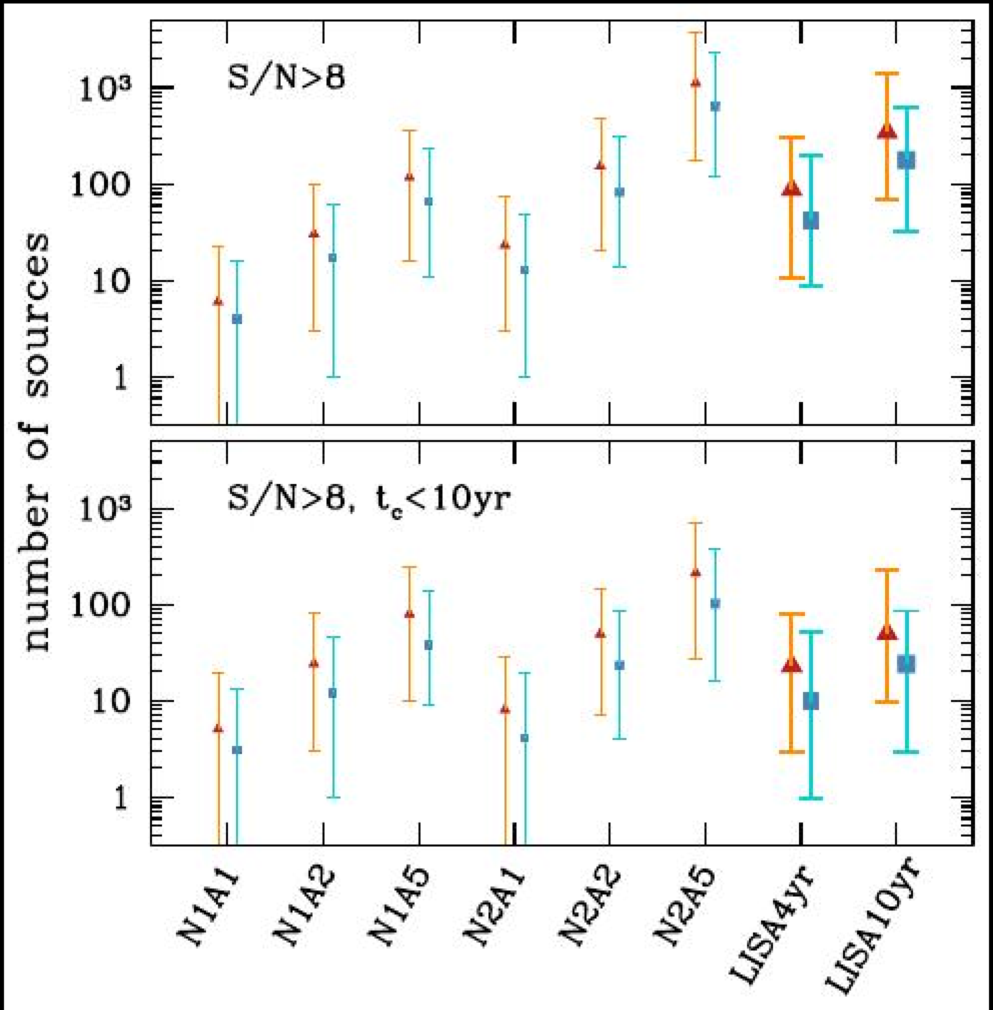
Number of observable sources (S/N>8) is a strong function of frequency*.

*that is the main reason of rather pessimistic initial estimates about the observability of these sources by eLISA

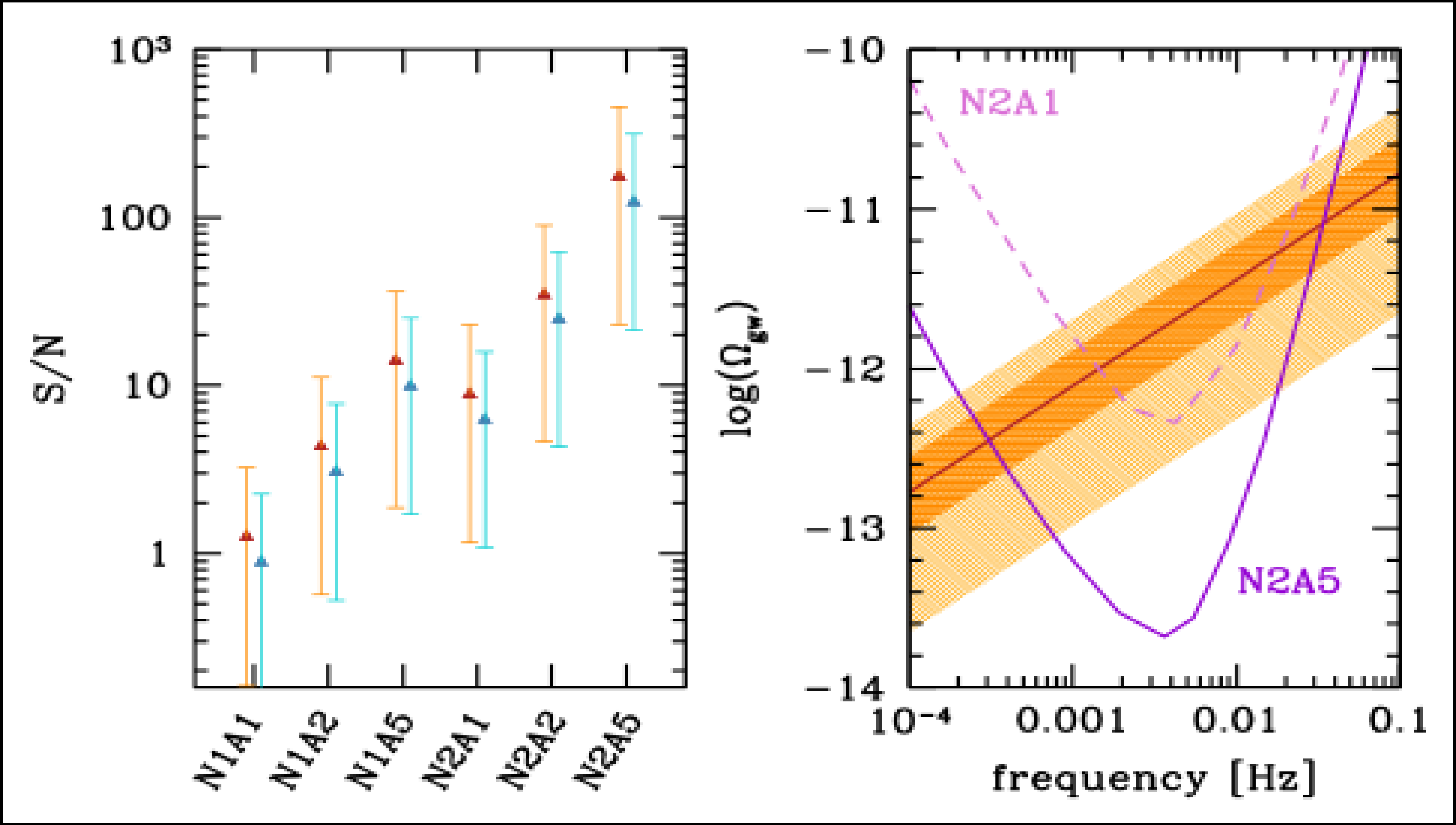
How many BHBs in the eLISA band?

Implied BHB mass distributions and merger rates higher than previously thought and BHs are more massive





eLISA will detect up to thousands of BHBs with S/N>8 up to few hundreds crossing to the aLIGO band in 5yr



Unresolved sources will form a confusion noise detectable with high S/N

What do we do with them?

>Detector cross-band calibration and validation (eLISA 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

>Astrophysics:

-independent measure of spins
-measure of eccentricity

>Cosmology:

-new population of standard sirens?

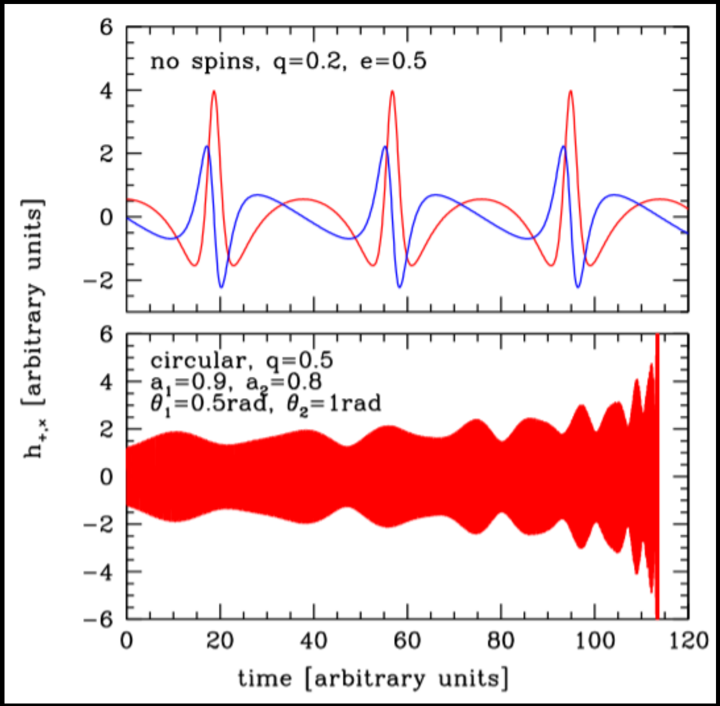
Extraction of information from the waveform

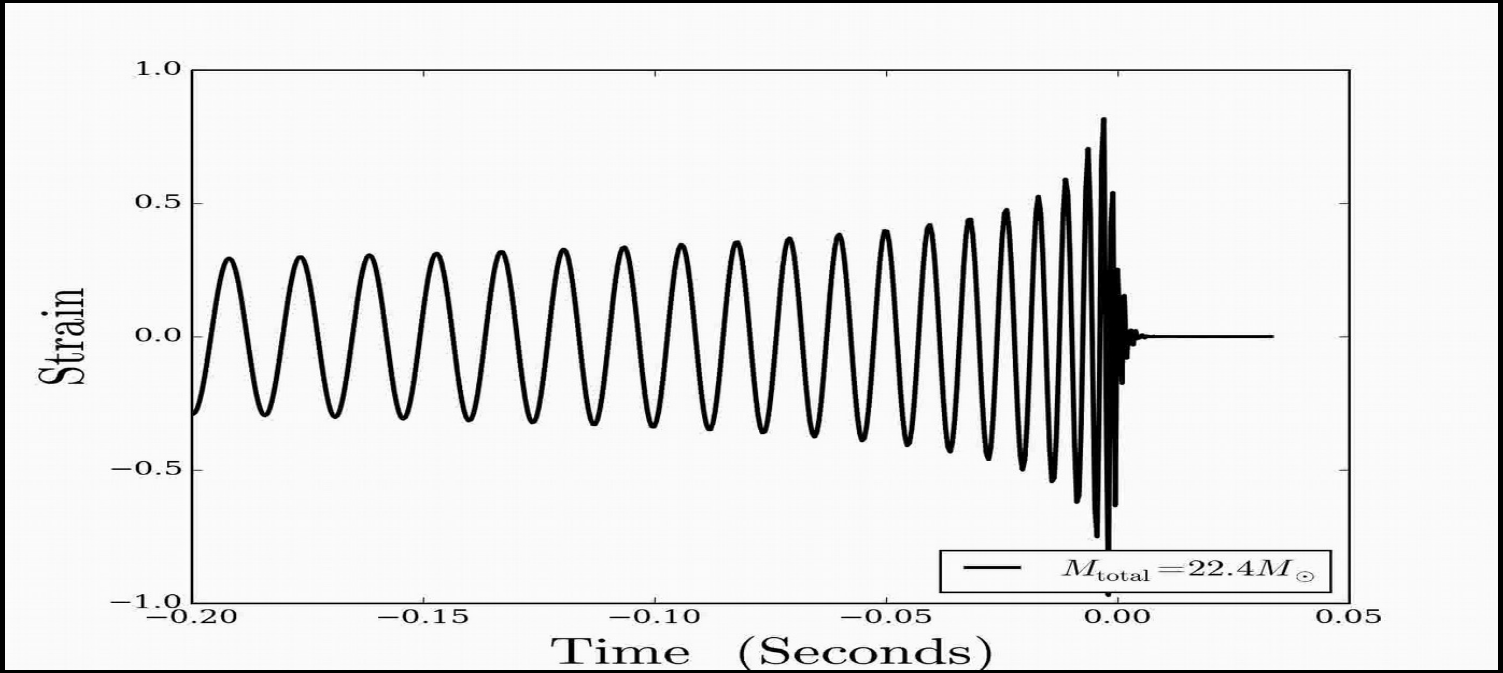
>Masses have the largest impact on the phase modulation

>Eccentricity impacts the waveform and the phase modulation

>Spins impact the waveform and the phase modulation (but weaker effect)

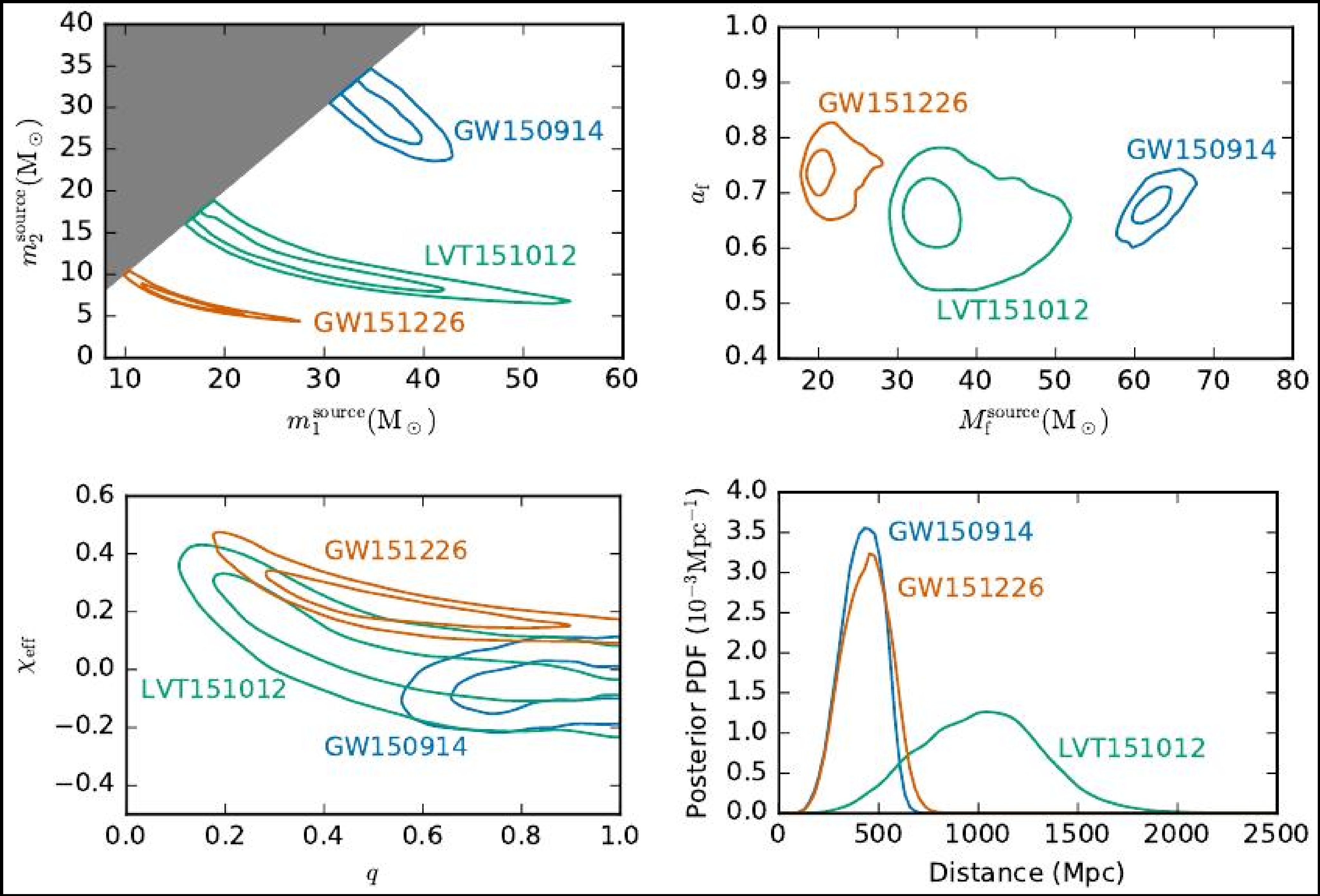
Depend on the number of cycles and SNR, can be easily measured with high precision





(Courtesy W. del Pozzo)

(astro)physical properties

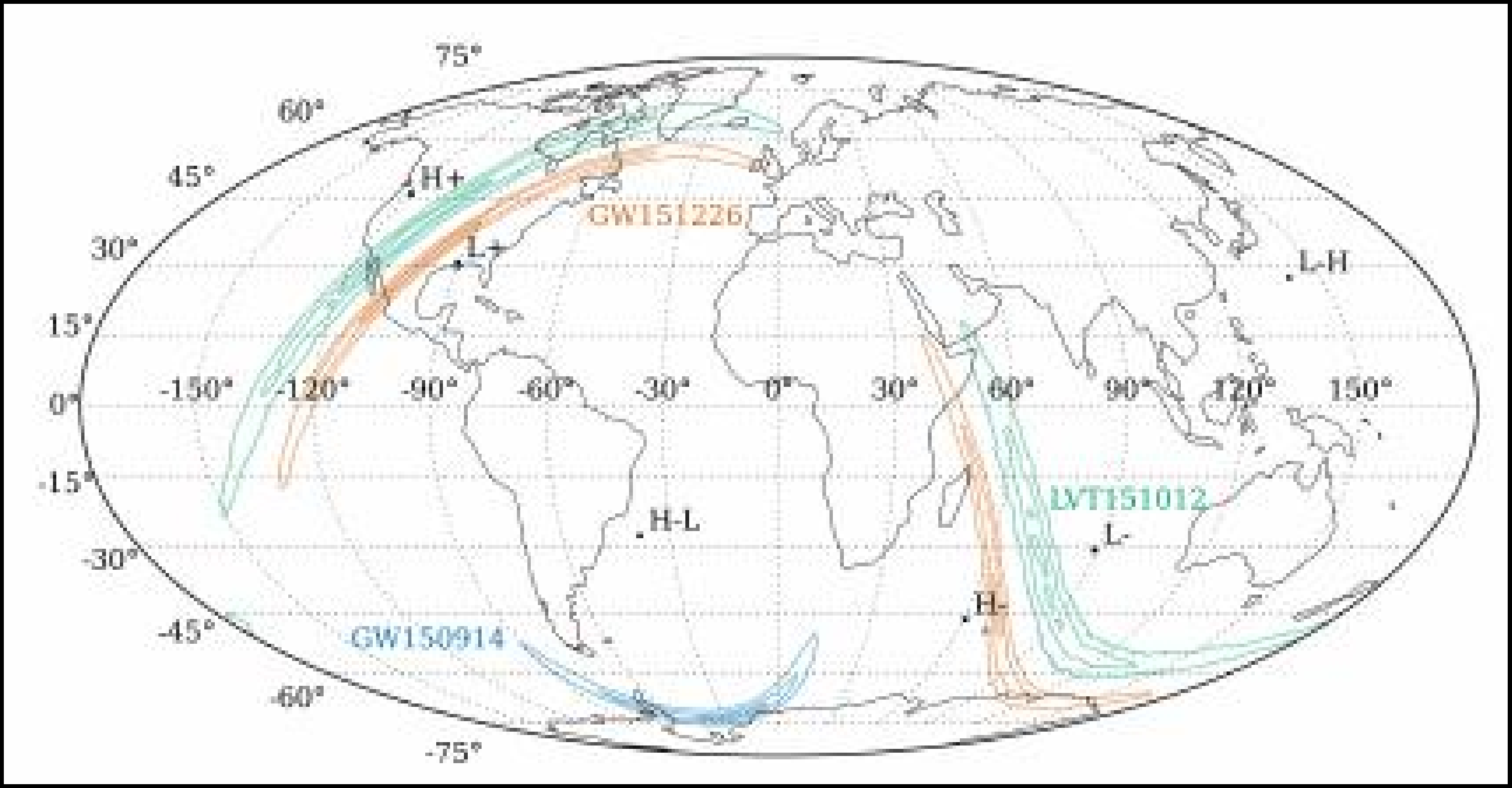


Extraction of information from the waveform

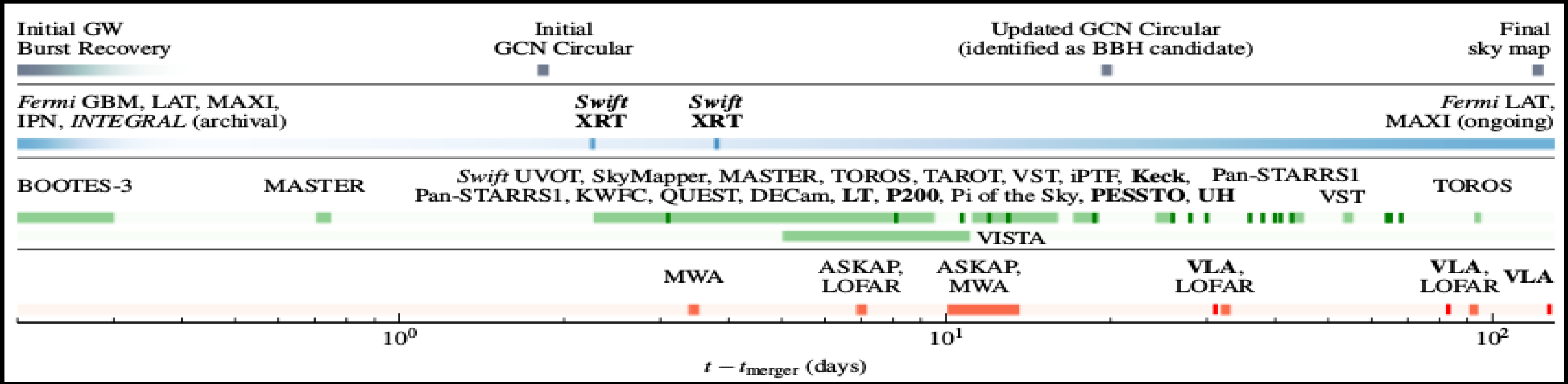
>Sky location essentially measured through triangulation:
two detectors ⟶ poor information

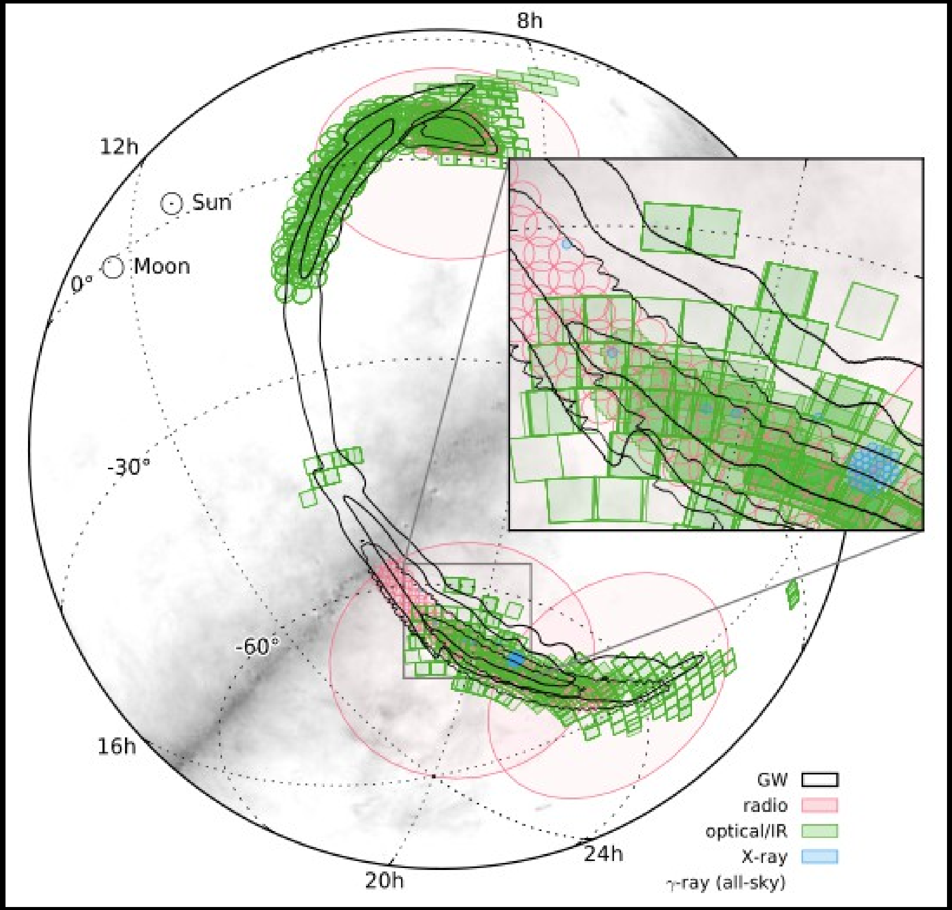
>Distance impacts the waveform amplitude (degenerate with masses, and sky location, inclination)

Depend on number of detection, polarization disentanglement, SNR.
Measurement is more difficult.



Sky localization and follow-up EM campaigns





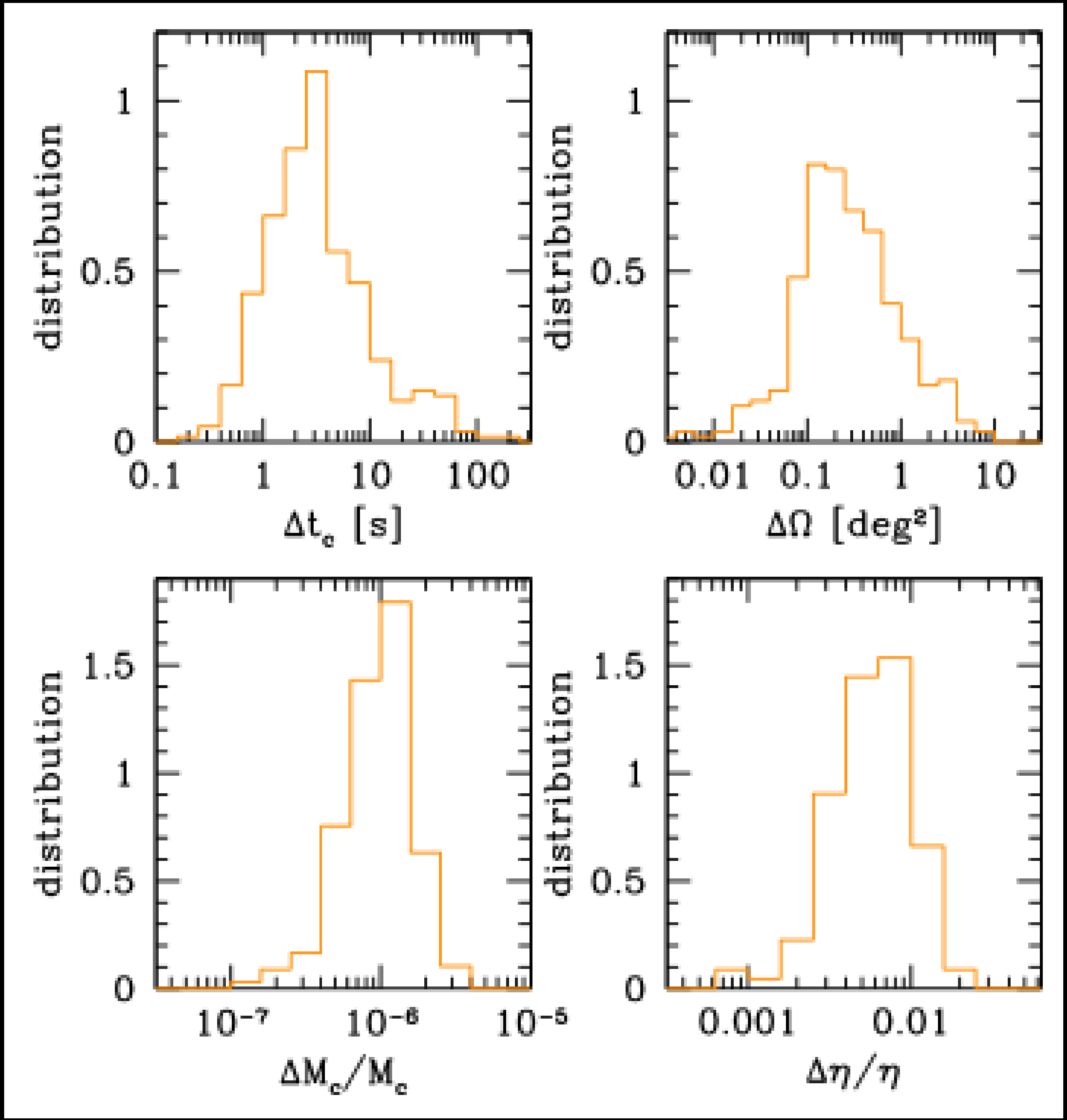
GW150914: huge error box!

Nevertheless everybody jumped on the event for follow-ups

Those campaigns are however very unlikely to succeed because of:
1-wide error box
2-delay wrt the coalescence

1 will improve with more detectors, 2 is bound to remain a limitation (extension to lower *f* will help though)

Sky pre-localization and coincident EM campaigns

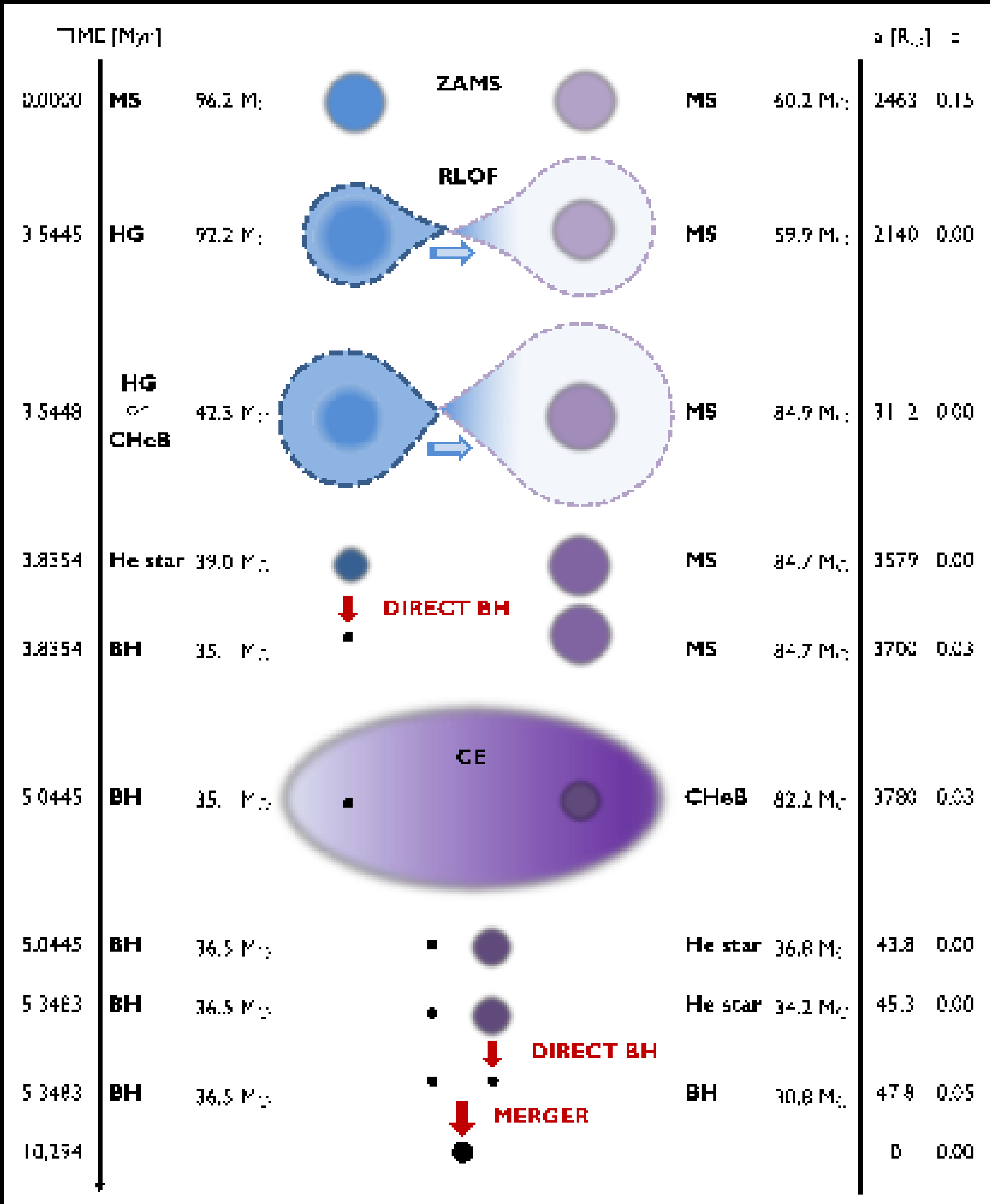


System crossing to the aLIGO band can be located with sub deg2 precision (Klein et al. In prep.)

Merger time can be predicted within 10 seconds (but see Bonvin et al. 2016)

Make possible to pre-point all instruments: open the era of coincident GW-EM astronomy (even though a counterpart is not expected).

Astrophysics: BHB origin



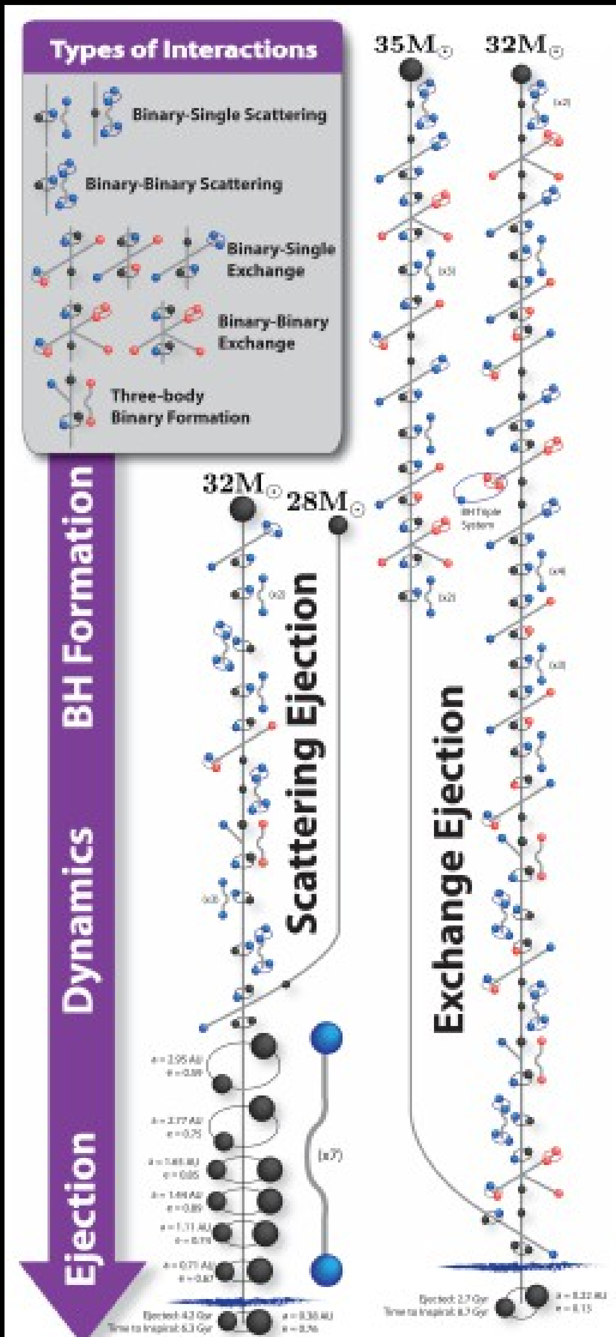
(Belczynski et al. 2016)

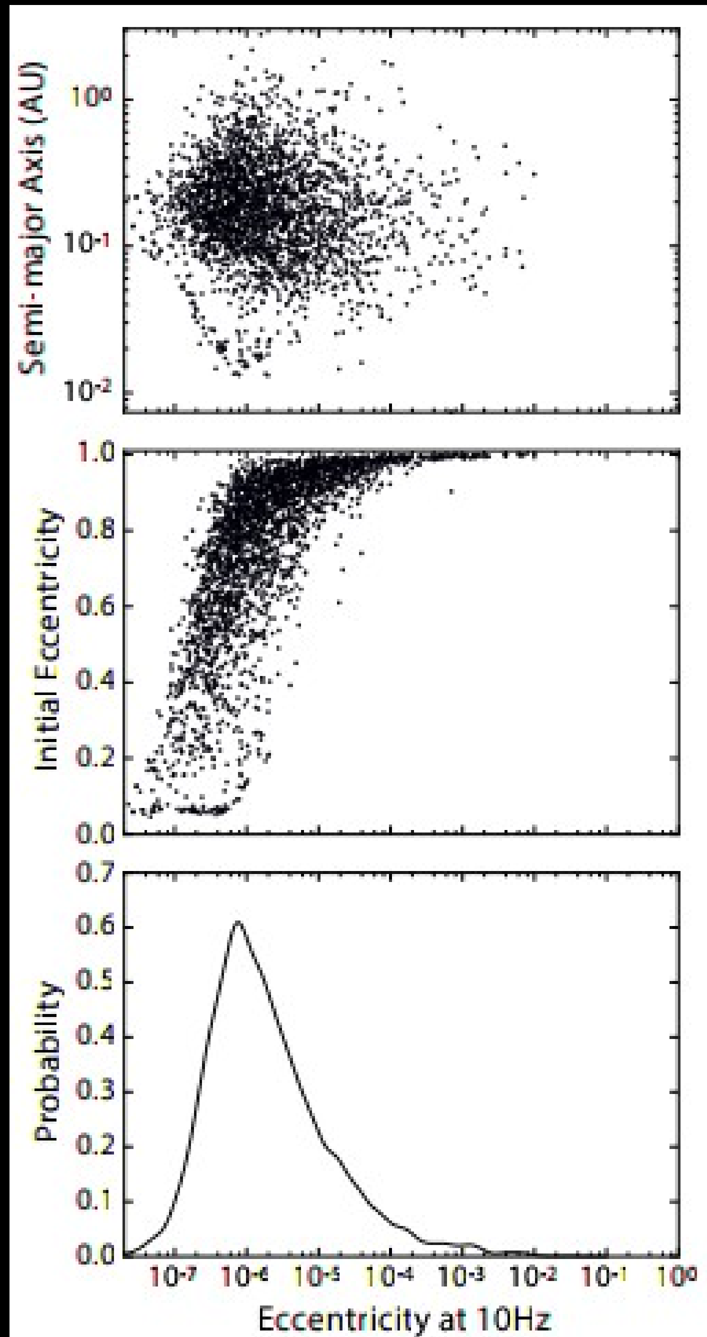
Evolution of massive Binaries

Complications
- -common envelope
- -kicks
- -metallicity
- -rotation

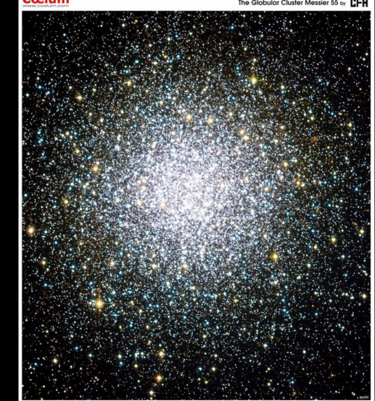
Features:
- -Preferentially high, aligned spins?
- -small formation eccentricity

Astrophysics: BHB origin





(Rodriguez et al. 2016)



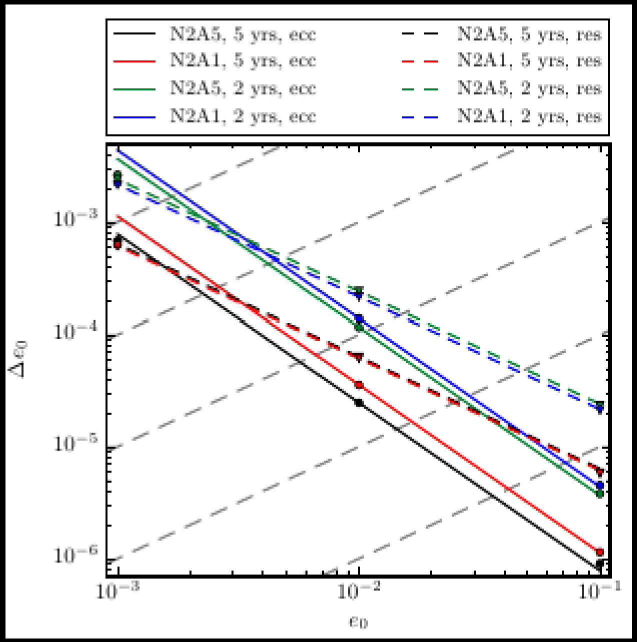
Dynamical capture

Complications
-mass segregation
-winds
-ejections
-multiple interactions
-resonant dynamics (Kozai-Lidov)

Features:
-randomly oriented spins?
-high formation eccentricities

Measuring eccentricity with eLISA

(Nishizawa et al. 2016)

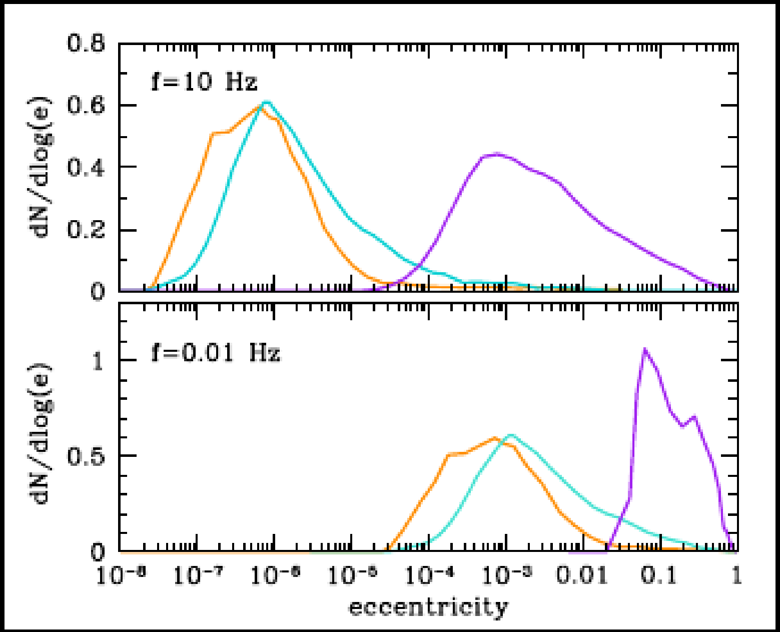


>aLIGO can only place upper bounds on *e*, but eLISA can measure *e* if >10^{-3}

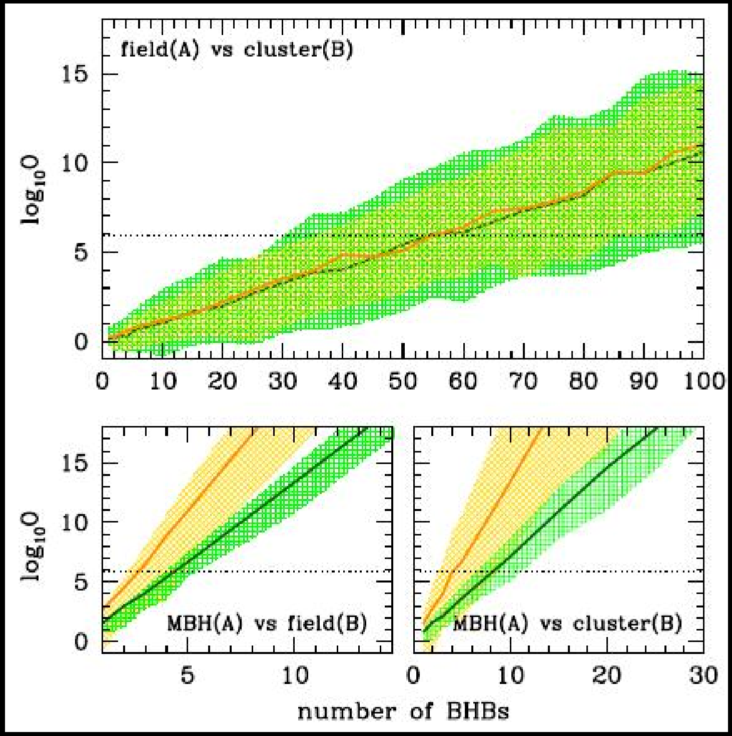
>GW circularization implies much higher eccentricities in the eLISA band

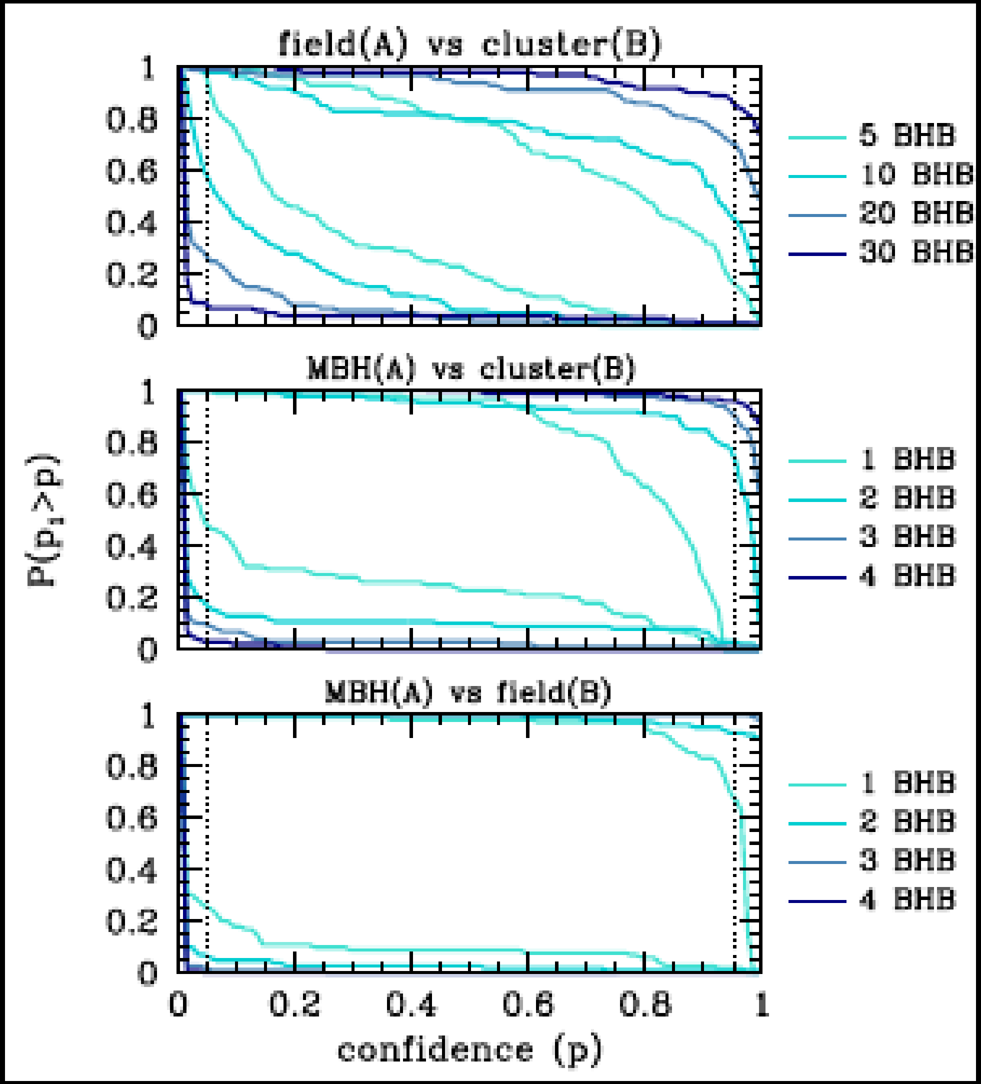
Different formation channel imply different e distributions.
Too small to be measured by LIGO but accessible to LISA

Proof of concept: three BHB formation scenarios
- -field binaries (Kowalska et al 2011)
- -dynamical formation in Gcs (Rodriguez et al. 2016)
- -Kozai resonances around a MBH (Antonini & Perets 2012)



Assessing BHB origin using eccentricity



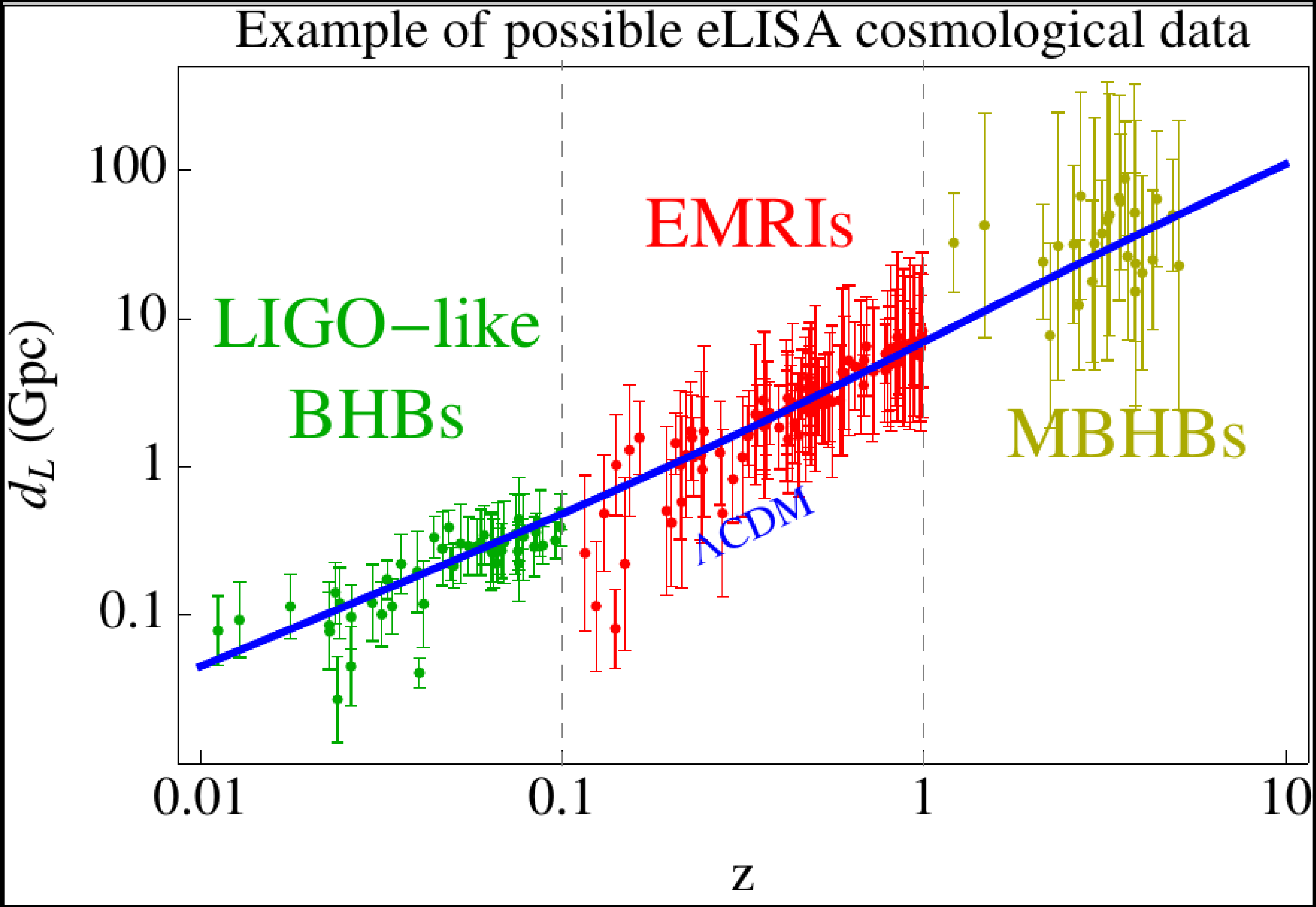


Different formation channels result in different *e* distributions in the eLISA band, (see also Breivik et al. 2016)

eLISA can tell formation scenarios apart with few tens of observations (Nishizawa et al. 2017)

Can be complemented to aLIGO spin measurements.

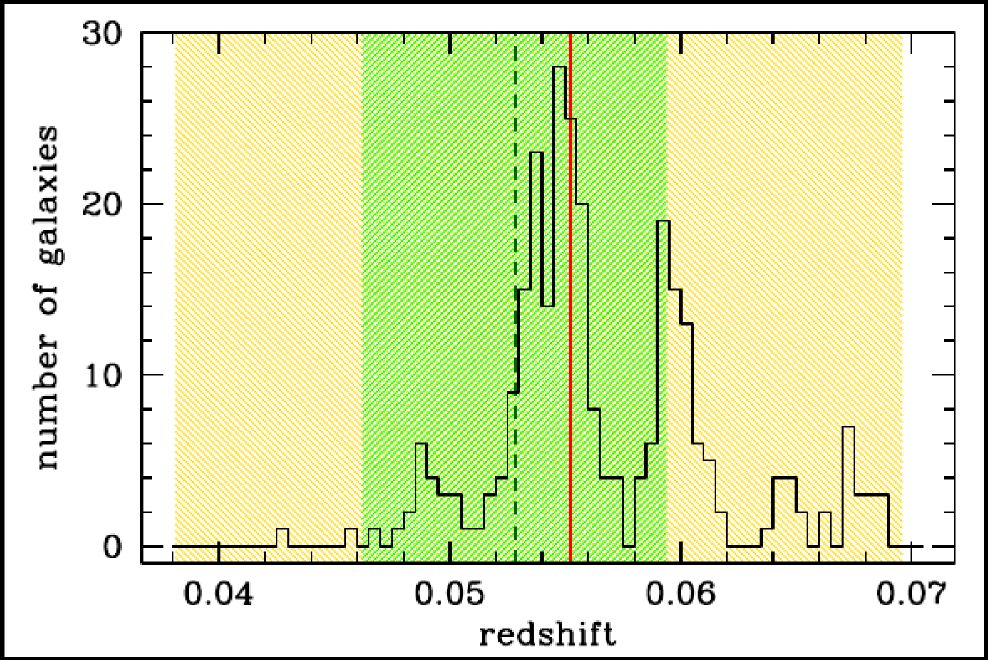
Cosmology with gravitational waves

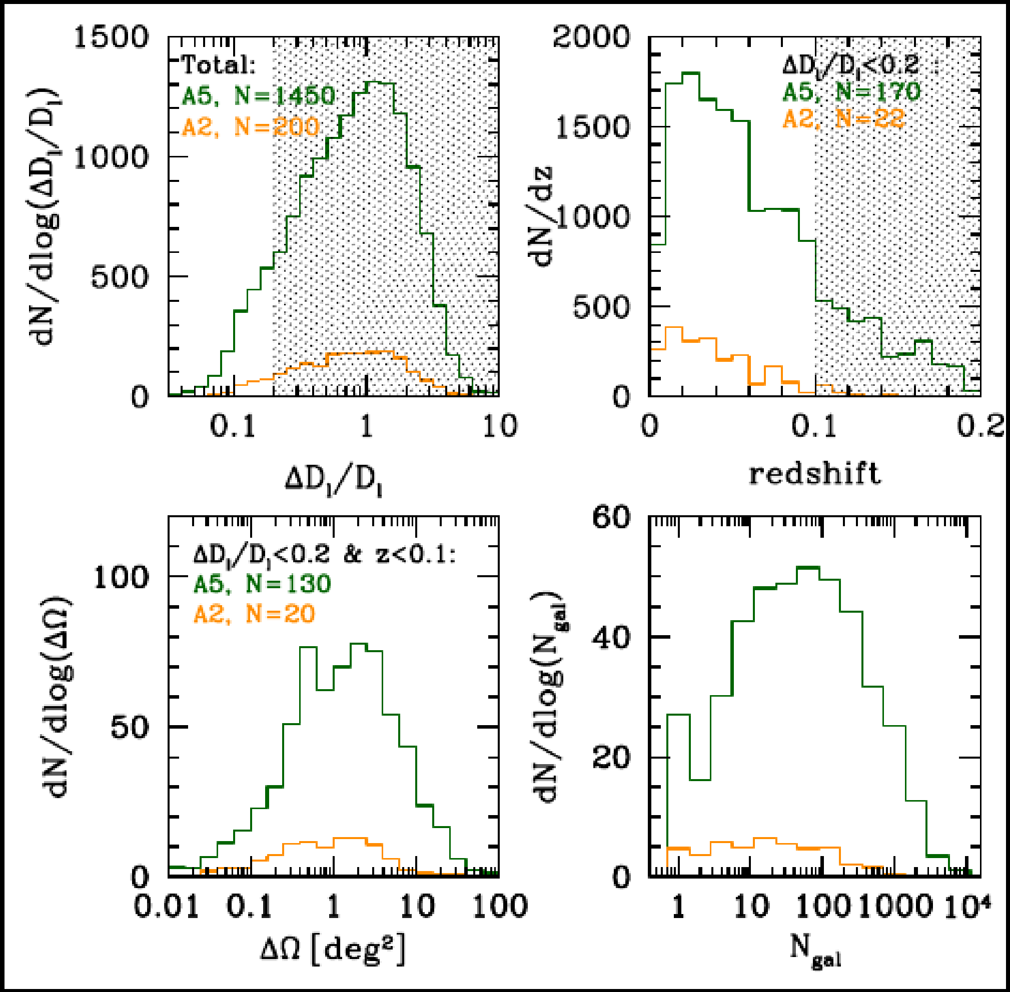


(Courtesy of N. Tamanini)

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

BHBs as standard sirens: measuring H_0



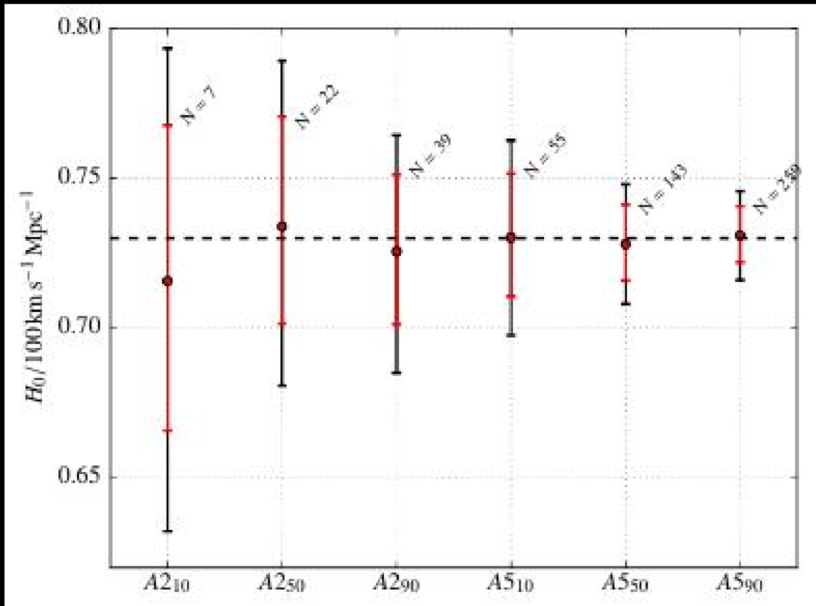


No counterpart required
(McLeod & Hogan 2008, Petiteau et. al 2011)

- **-Many sources at z<0.1**
- **-small errorbox consider all possible hosts within the errorbox assuming a broad prior on *h***
- **-combine statistically the likelihood of the hosts in each errorbox to determine *h***

Work in progress, h determined to up to...
AstroBonus: few local events have 1 galaxy in the errorbox

Results



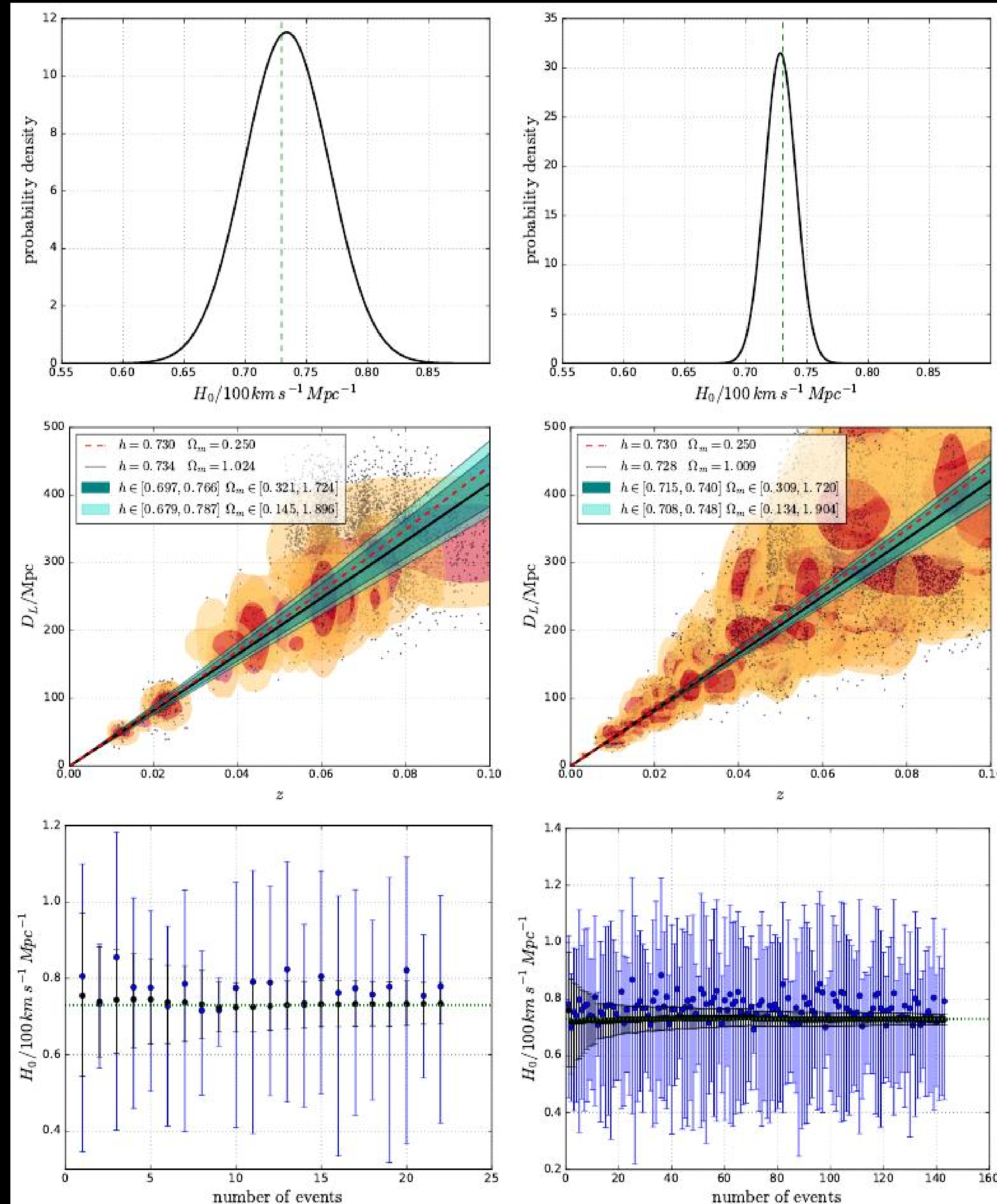
The precision of the measurement scales with √N , regardless of the detector design.

2Gm

h determined at ~5%

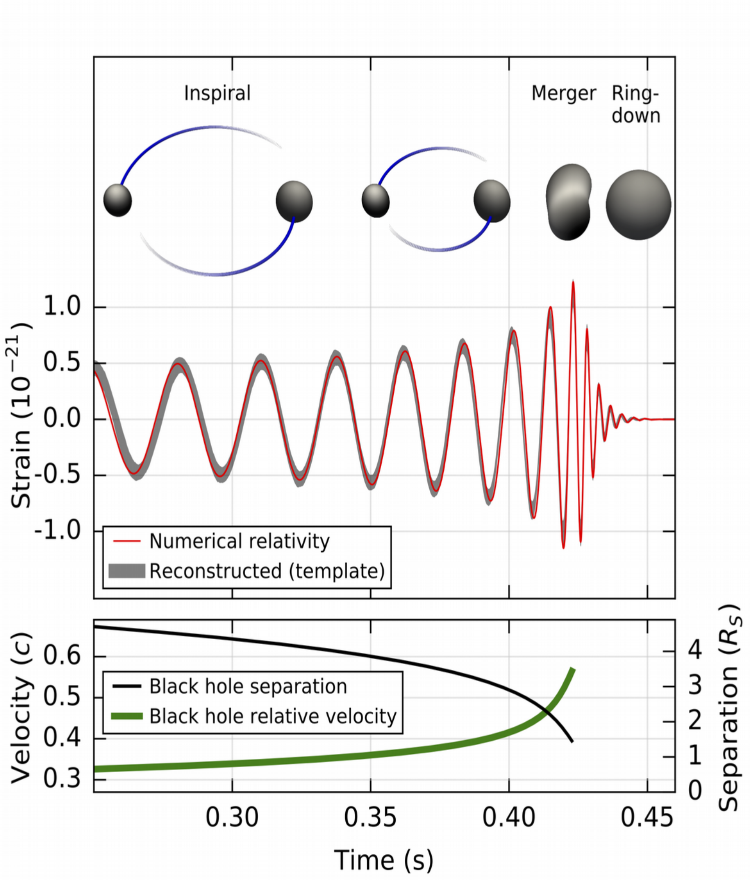
5Gm

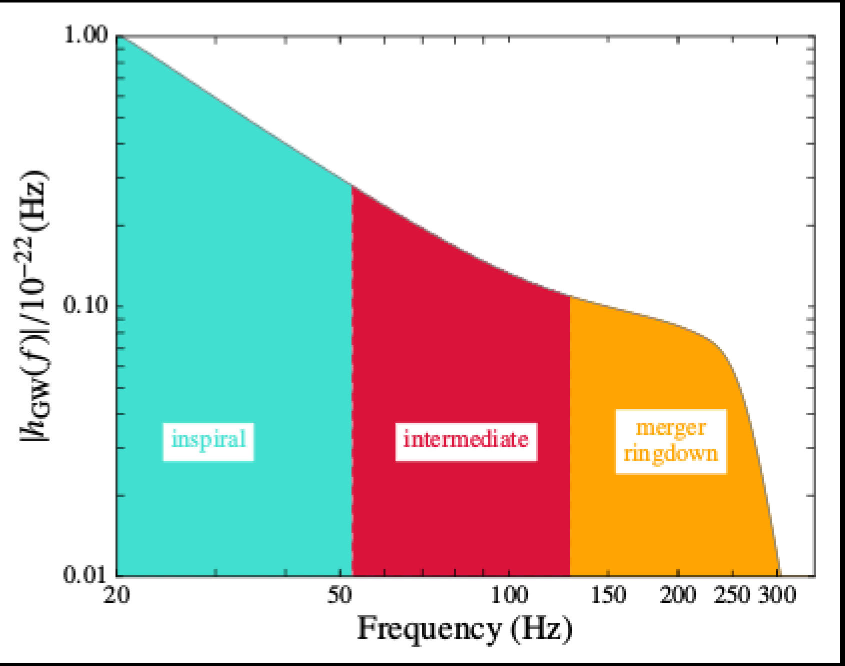
h determined at ~2%

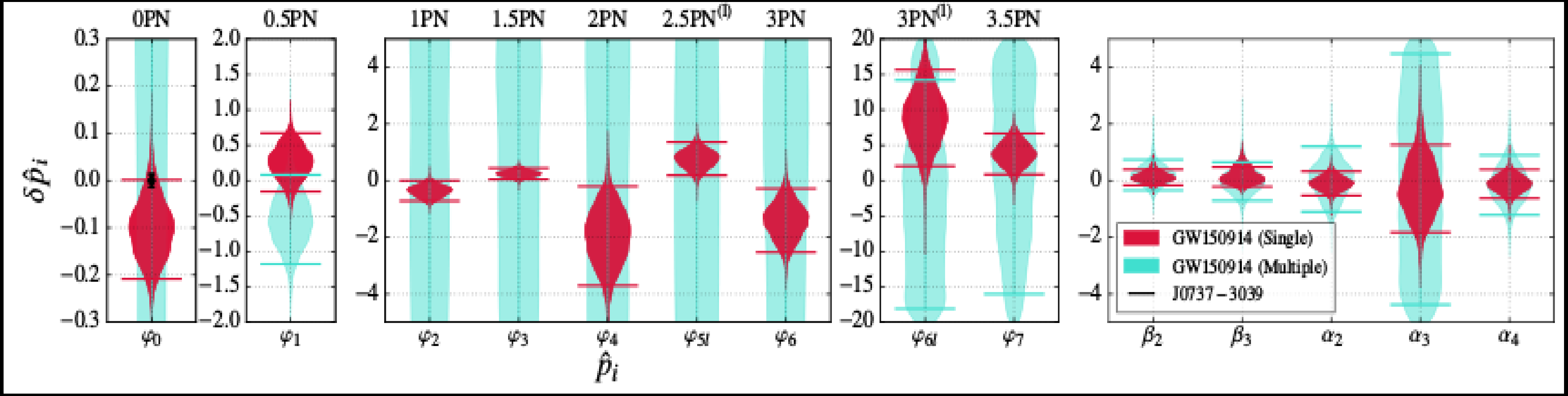


Tests of GR

GW150914 provides the most stringent tests of gravity in the strong field regime:
NO EVIDENCE FOR DEVIATIONS FROM GR



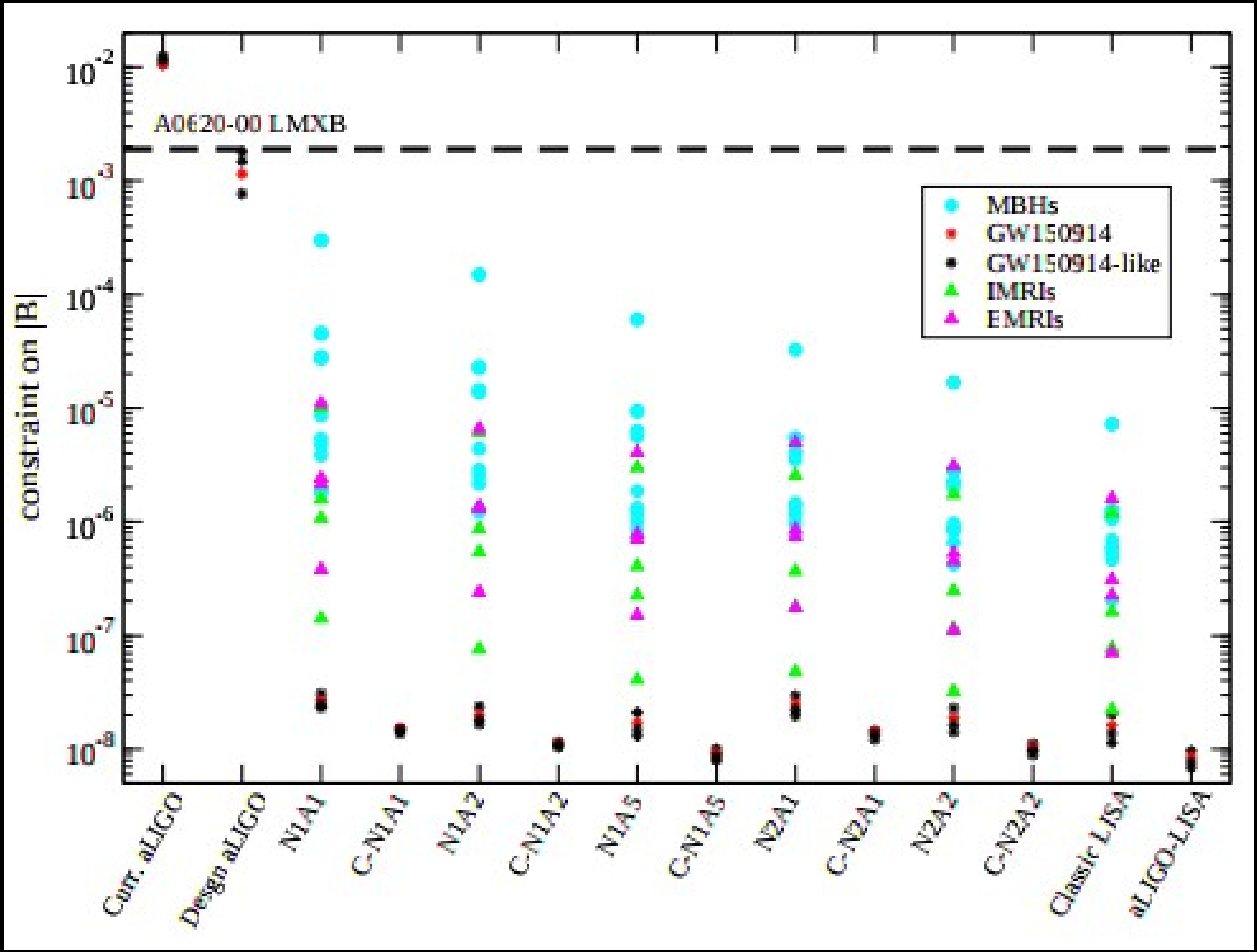




Tests of Gravity combining eLISA and aLIGO

BH dipole emission will cause a de-phase observable over several decades in frequency

$$\dot{E}_{\rm GW} = \dot{E}_{\rm GR}\left[1 + B\left(\frac{Gm}{r_{12}c^2}\right)^{-1}\right]$$



(Barausse et al. 2016)

Summary

>eLISA will enable GW physics and astrophysics at all scales

>GW150914 is the prototype of eLISA/aLIGO multi-band GW sources

>number of sources very uncertain but vast scientific potential (most of it yet to be explored)