

The background of the slide is a dark blue, textured surface representing a gravitational well. It features concentric, wavy rings that create a sense of depth and curvature. In the center of the well, two small black spheres are shown in a circular orbit, connected by a thin white line with arrows indicating the direction of motion.

The promise of multi-band gravitational wave astronomy

Alberto Sesana
(University of Birmingham)

OUTLINE

>Gravitational waves across the frequency spectrum

>GW150914: a gift from LIGO

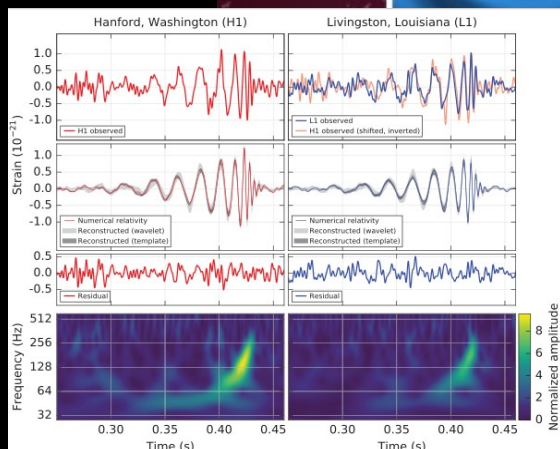
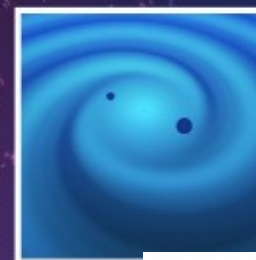
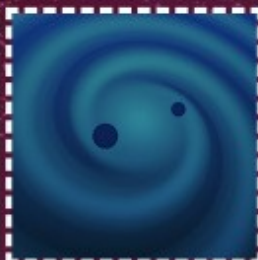
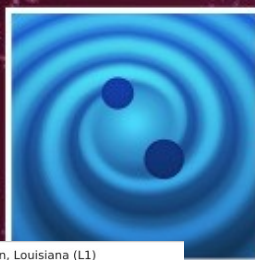
- **>Stellar BHs in the eLISA band: multi-band GW astronomy with eLISA and ground based interferometers**

Habemus GWs!

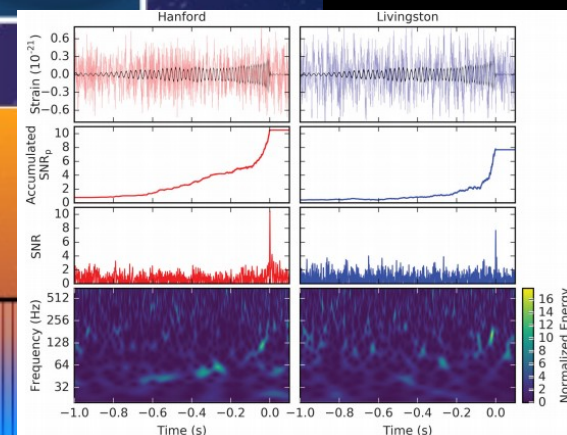
September 14, 2015
CONFIRMED

October 12, 2015
CANDIDATE

December 26, 2015
CONFIRMED



LIGO's first observing run
September 12, 2015 - January 19, 2016



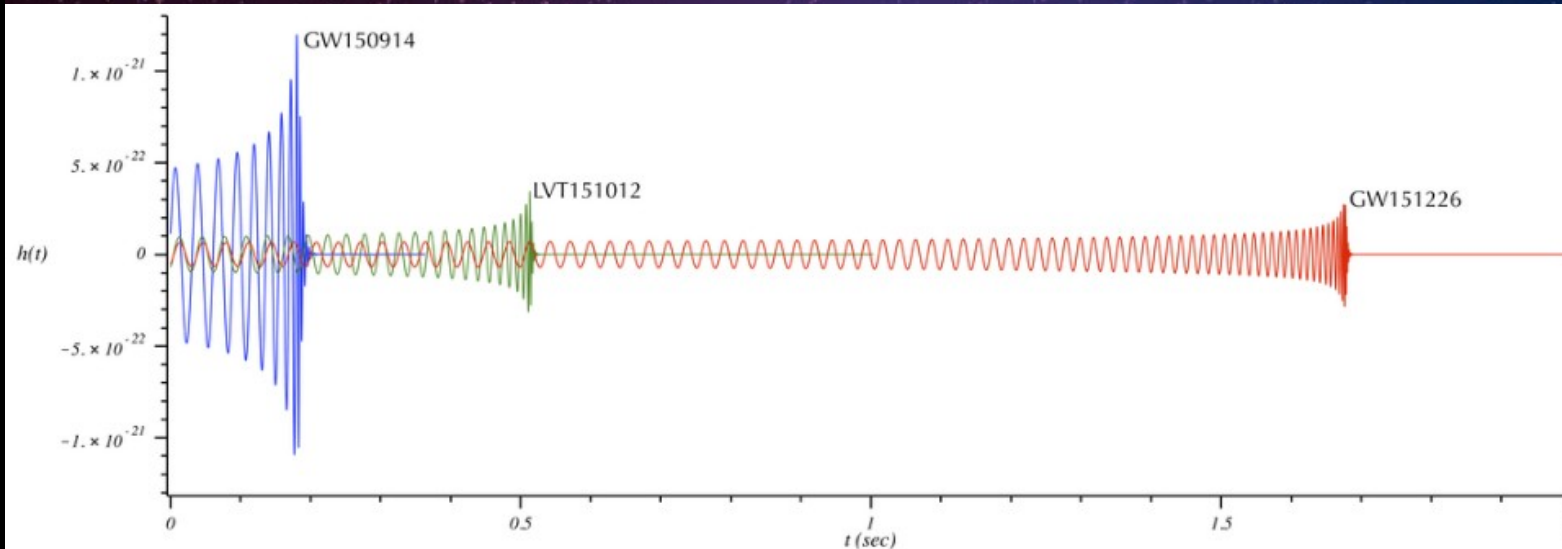
September 2015

October 2015

November 2015

December 2015

January 2016



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

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

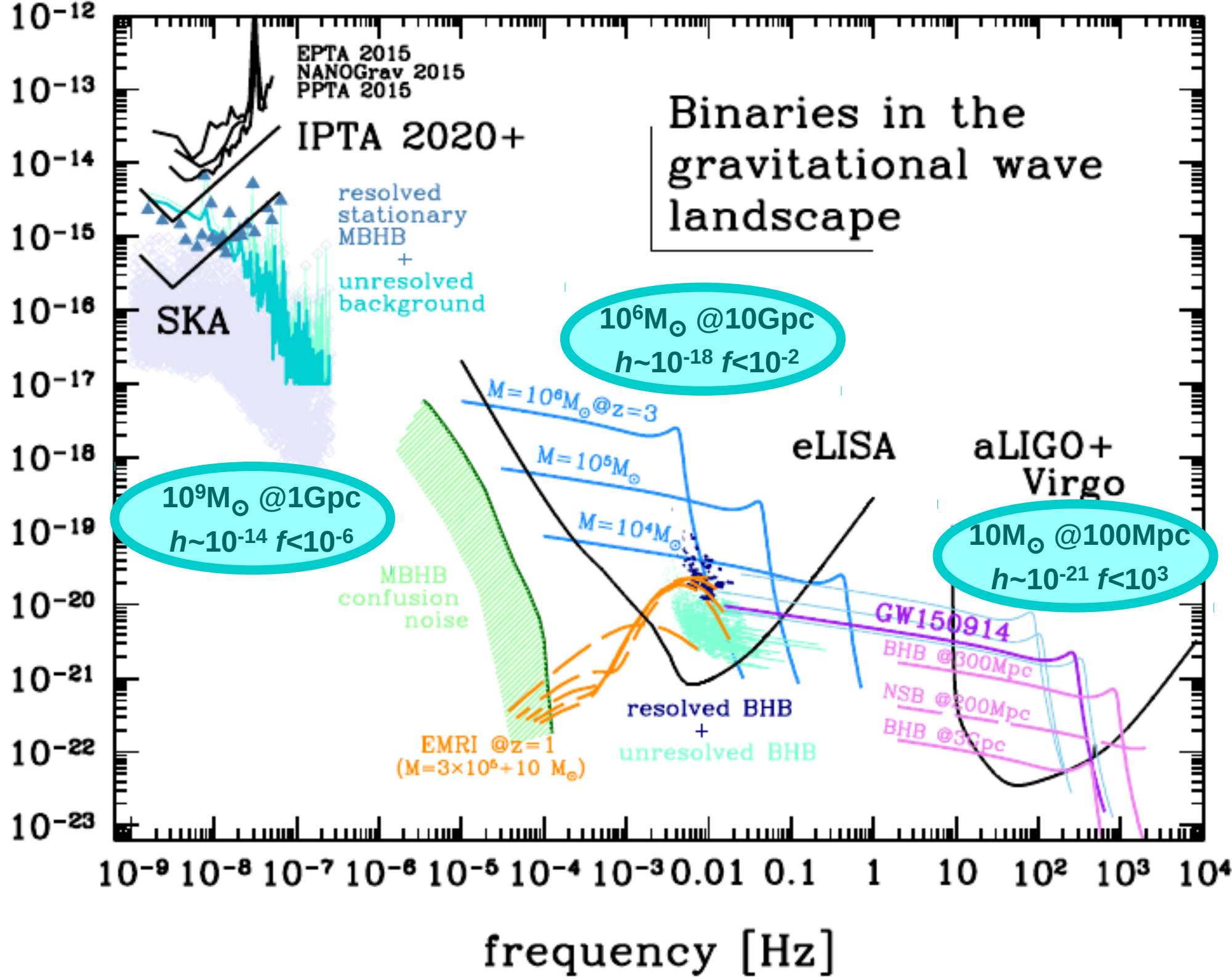
$$f \sim \frac{c}{2\pi R_s} \sim 10^4 \text{Hz} \frac{M_\odot}{M}$$

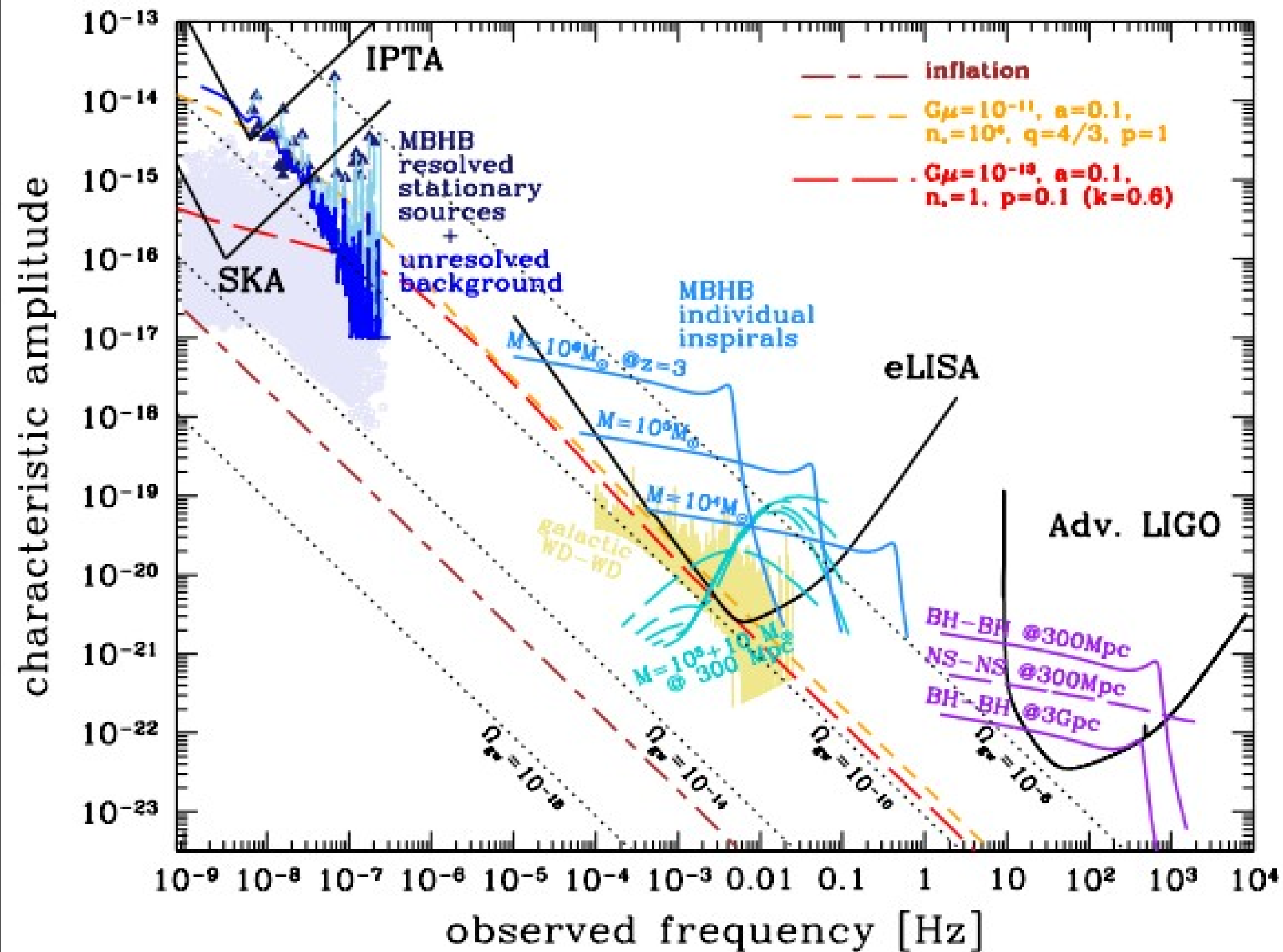
$10 M_\odot$ binary at 100 Mpc: $h \sim 10^{-21}$, $f < 10^3$

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

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

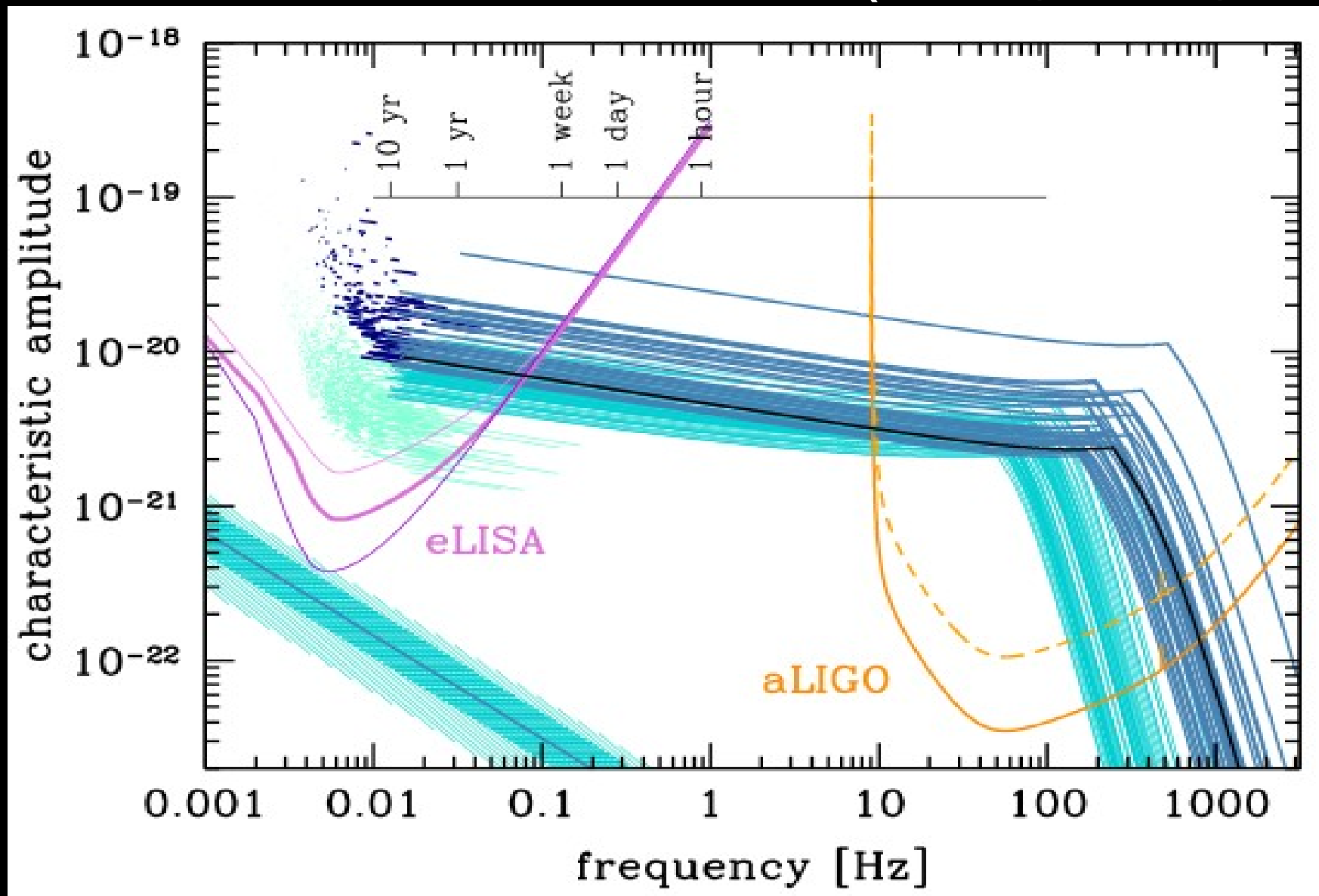
characteristic amplitude





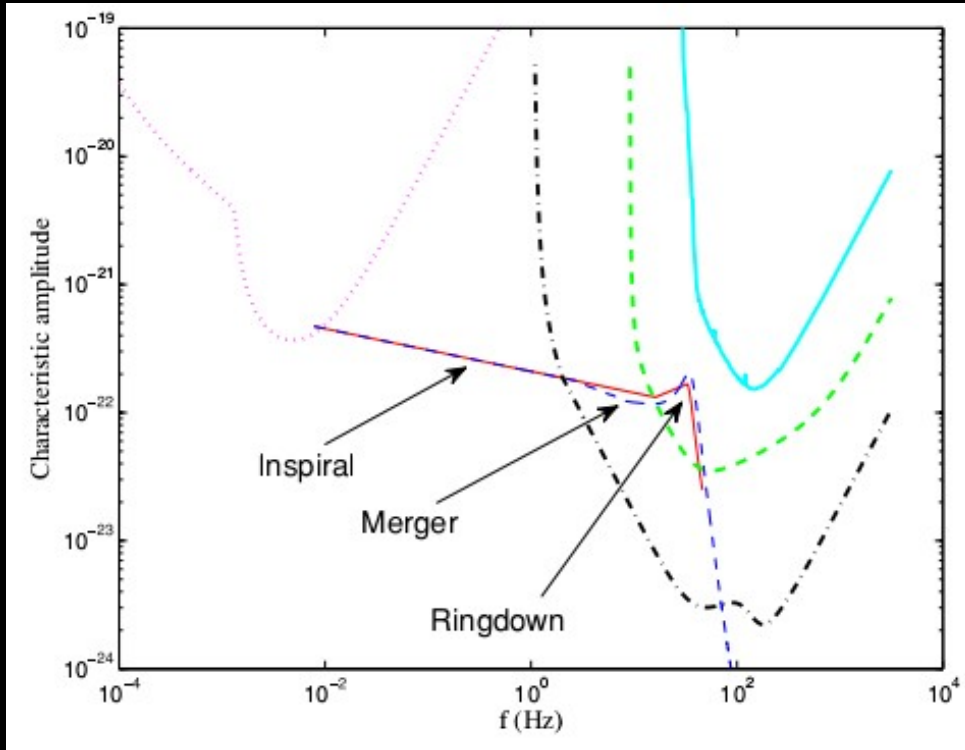
An unexpected scenario: multi-band GW astronomy

(AS 2016, PRL 116, 1102)



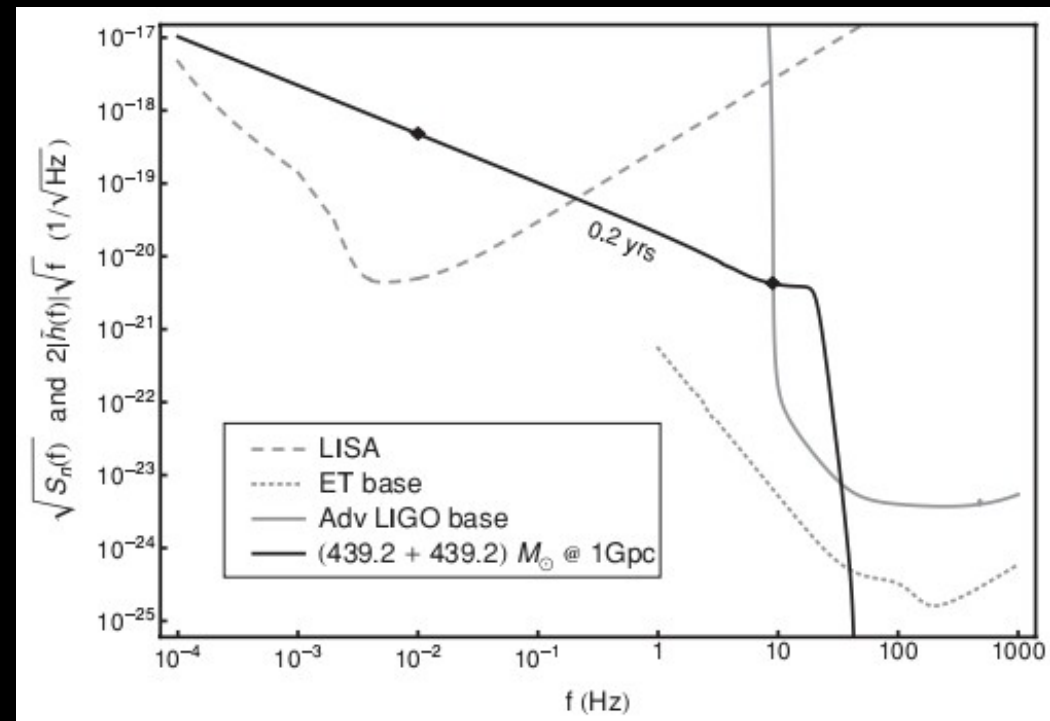
**BHB will be detected by eLISA and cross to the LIGO band,
assuming a 5 year operation of eLISA.**

The idea was already around in the literature



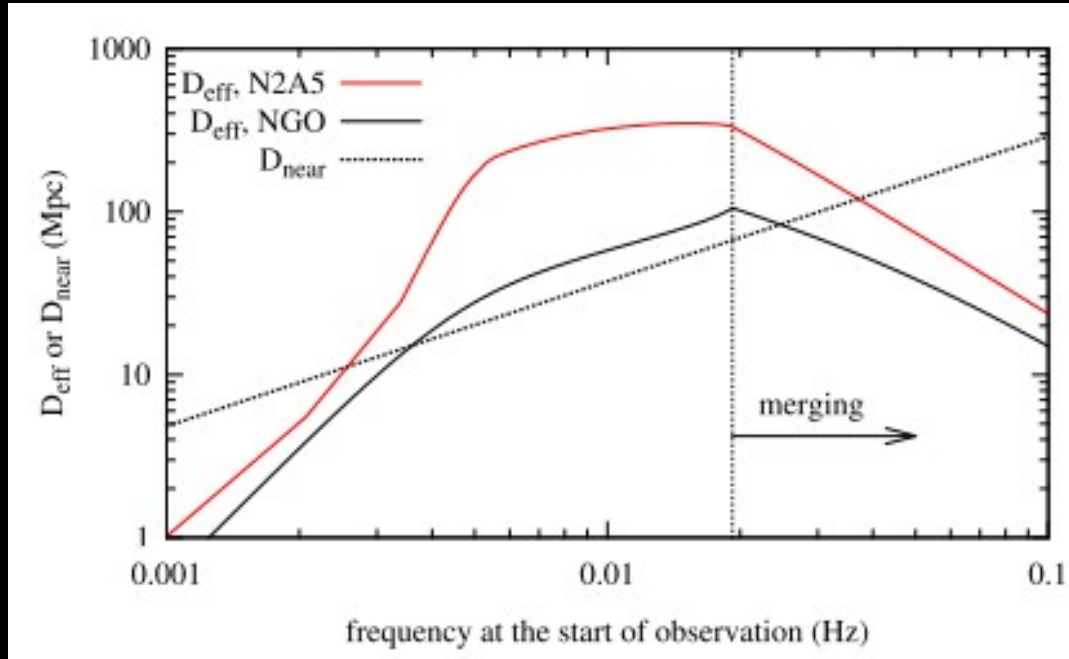
PopIII seeds merging at late times ($z \sim 2$) could be seen both in LISA and aLIGO/ET (AS et al. 2009)

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



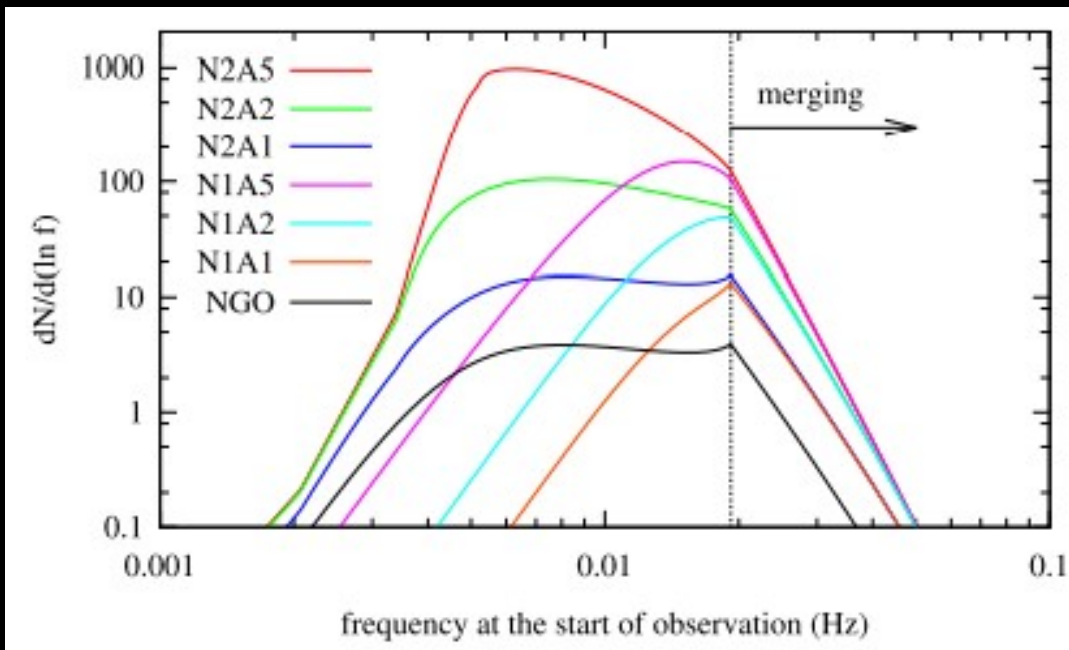
Distribution of sources across the band

(Kyutoku & Seto 2016)



Reach of eLISA for GW150915.
Up to $z \sim 0.1$ at $f \sim 0.01$ Hz

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

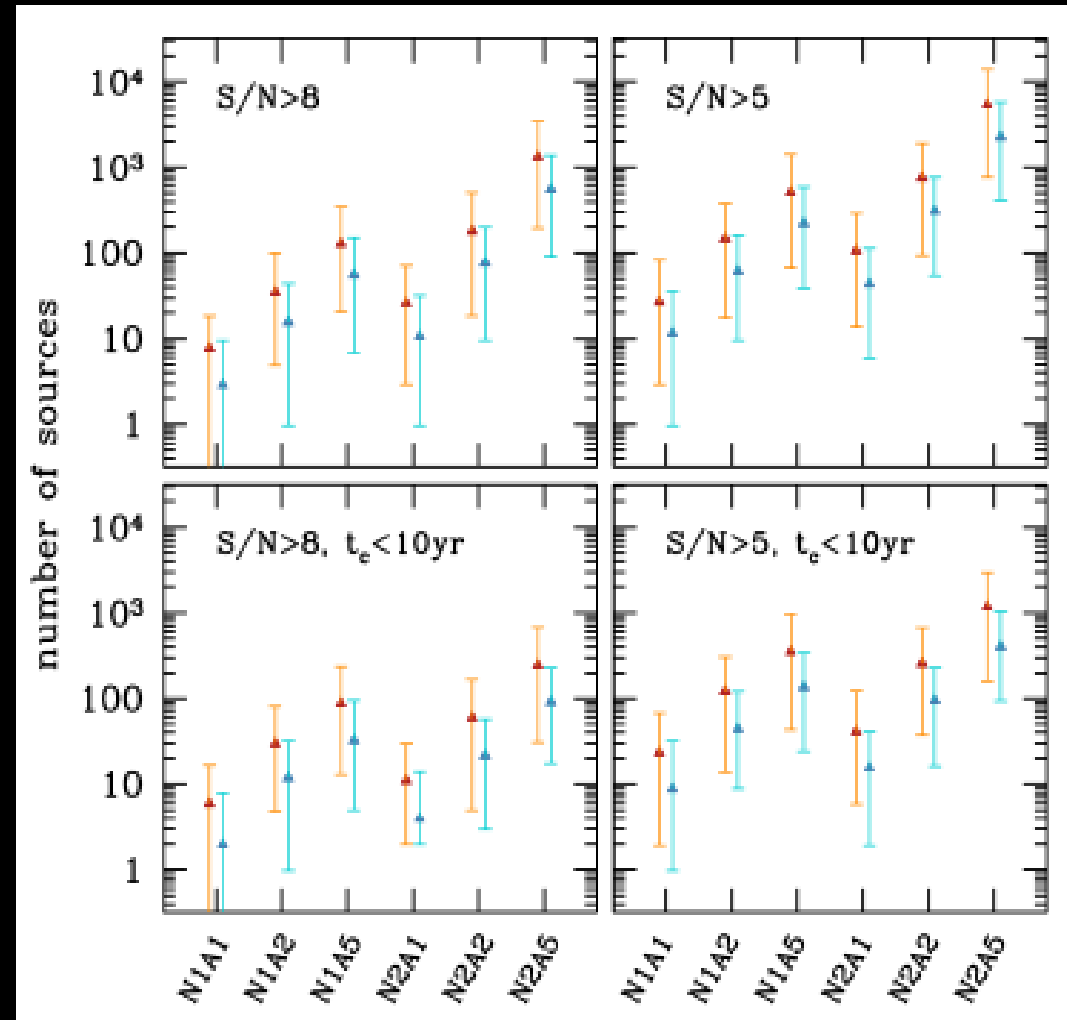
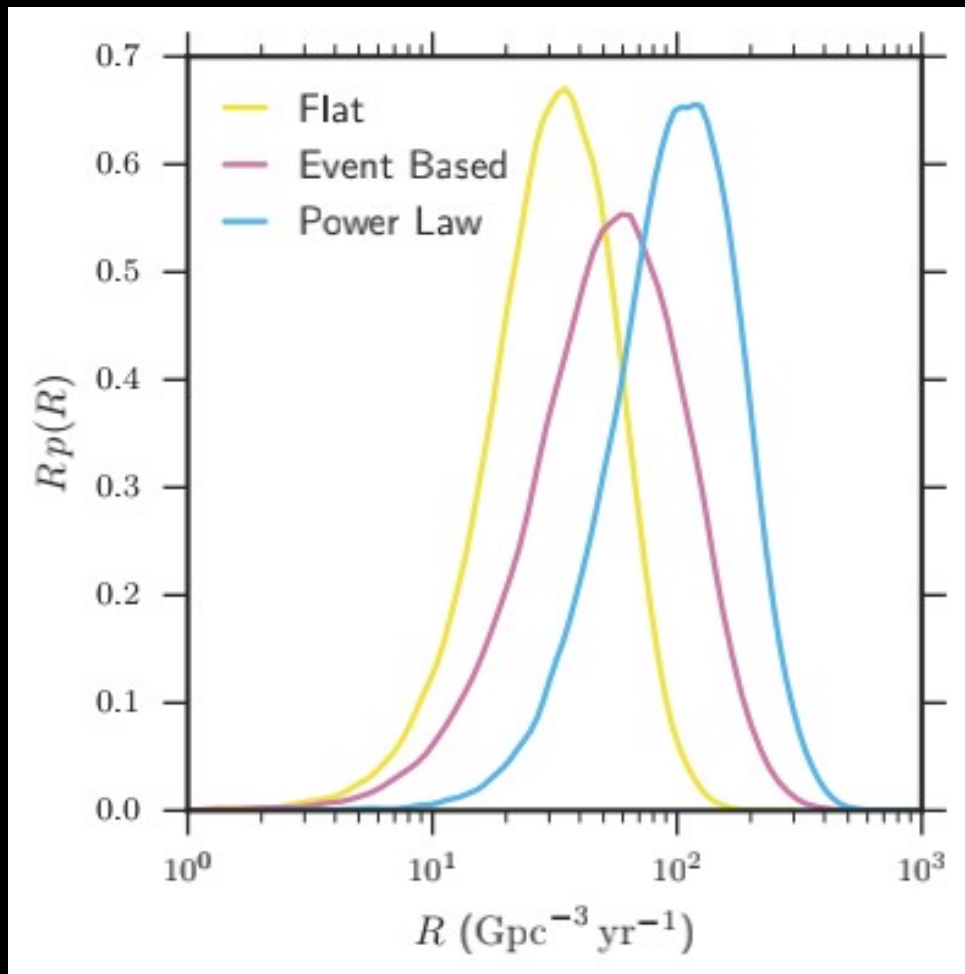


Number of observable sources ($S/N > 8$) is a strong function of frequency*.

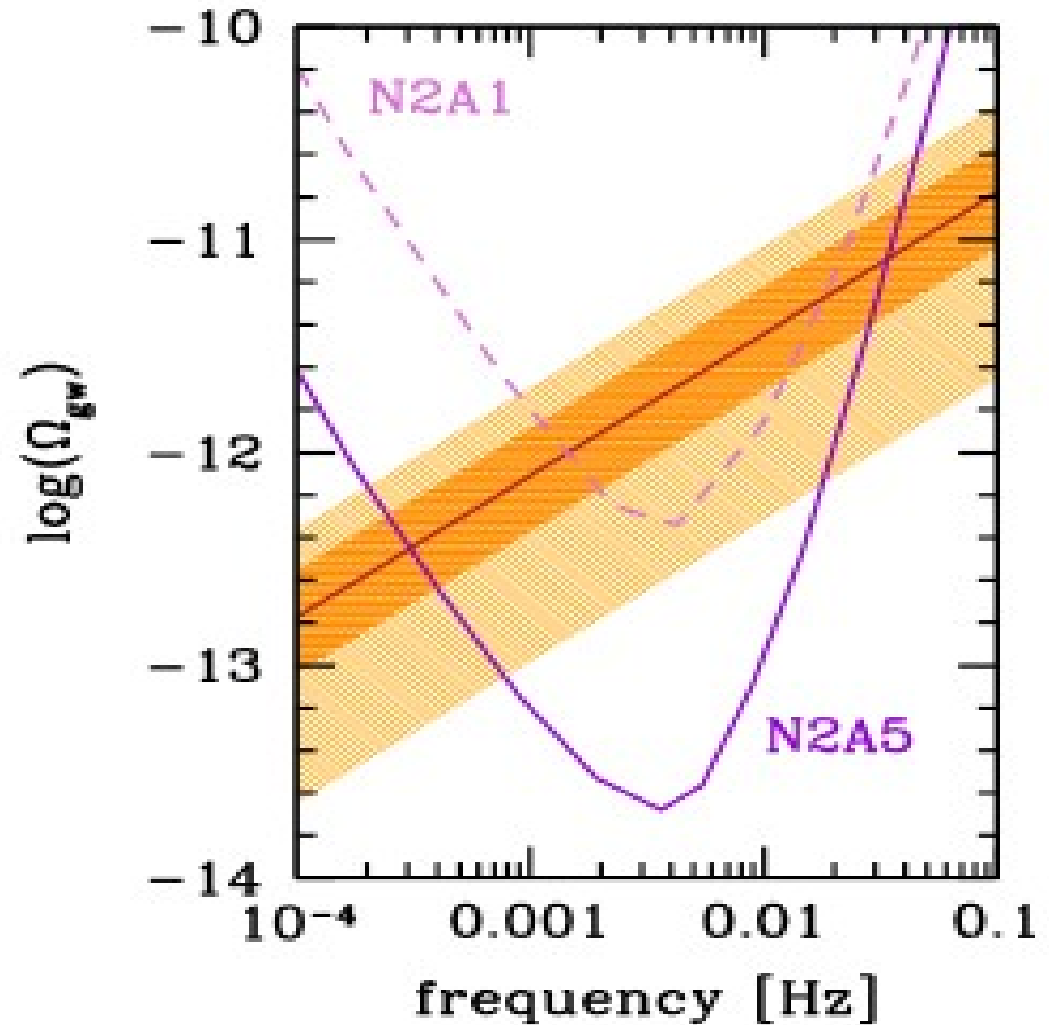
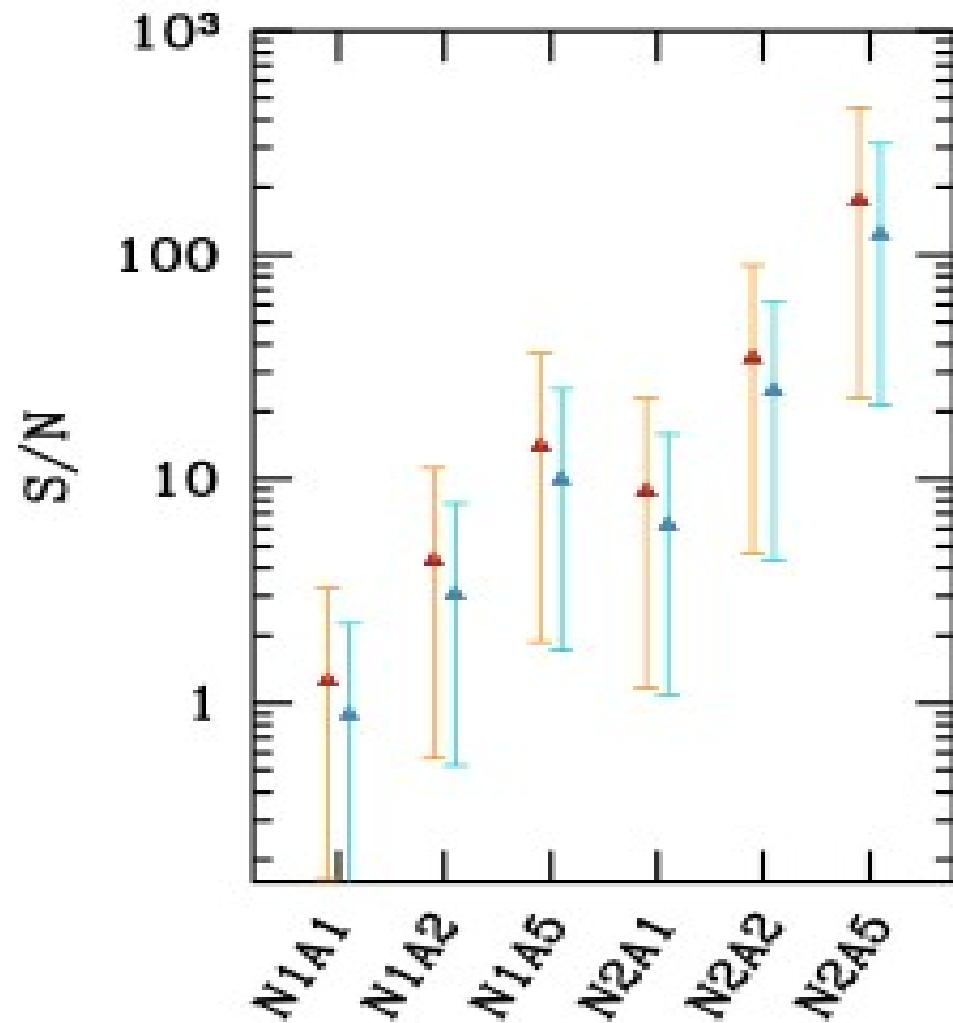
*that is the main reason of rather pessimistic initial estimates about the observability of these sources by eLISA

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

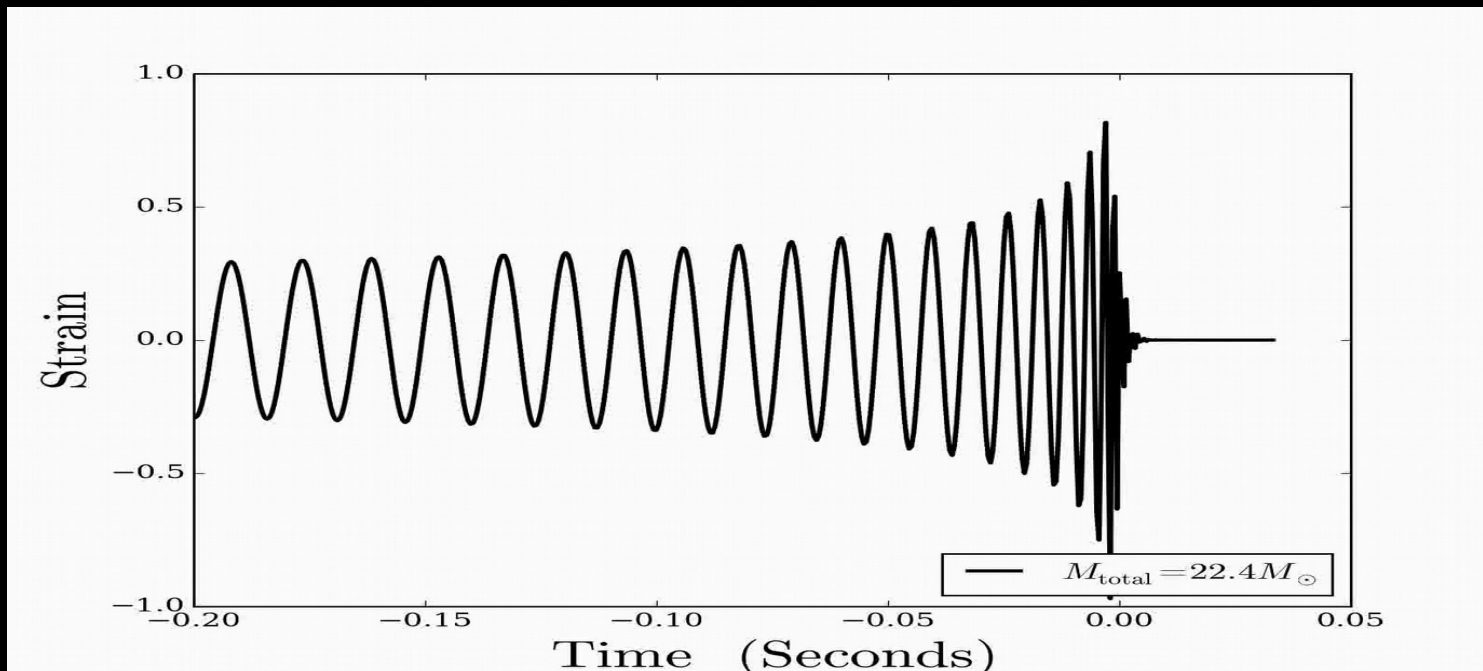
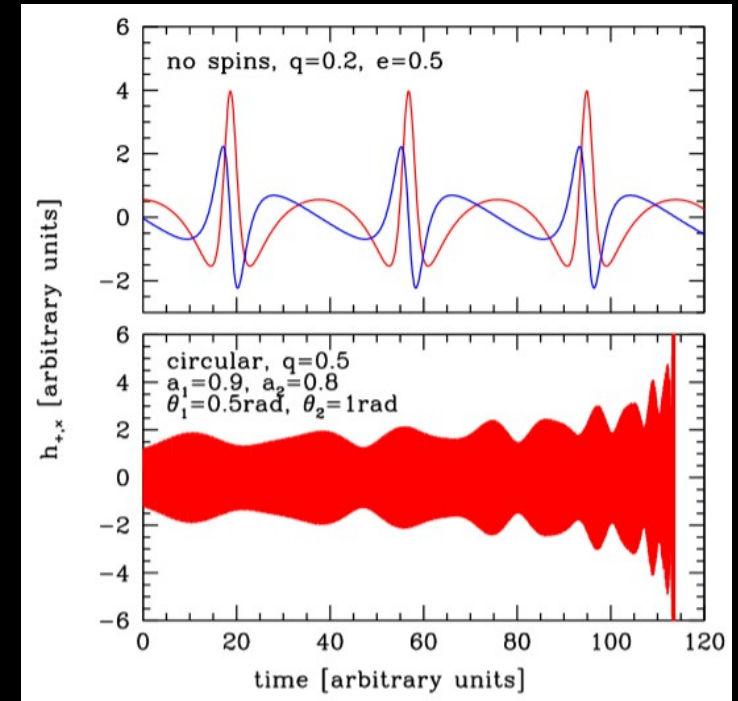
What do we do with them?

- >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

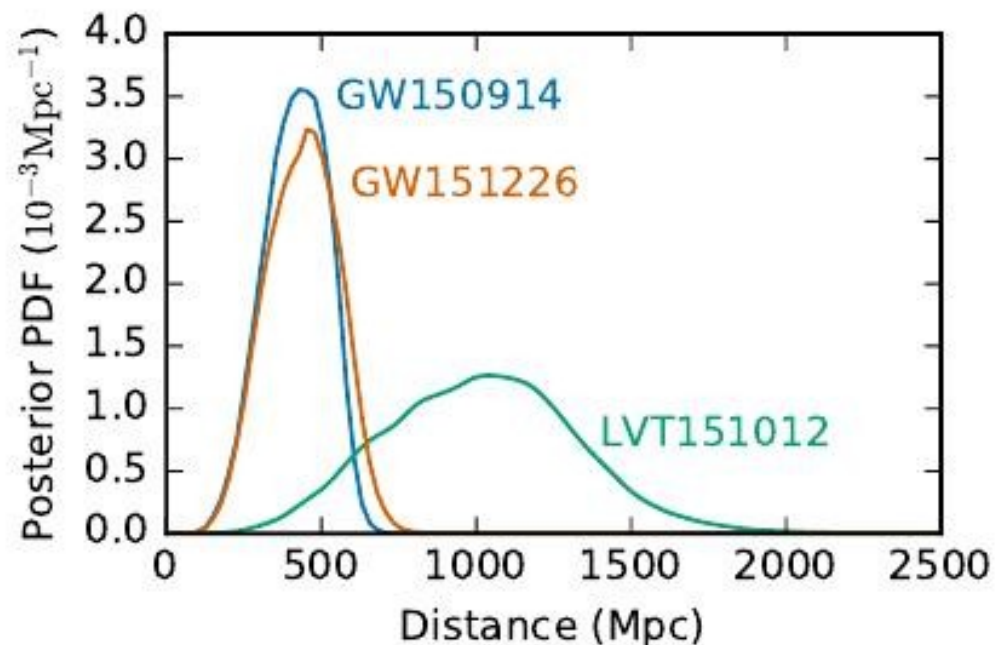
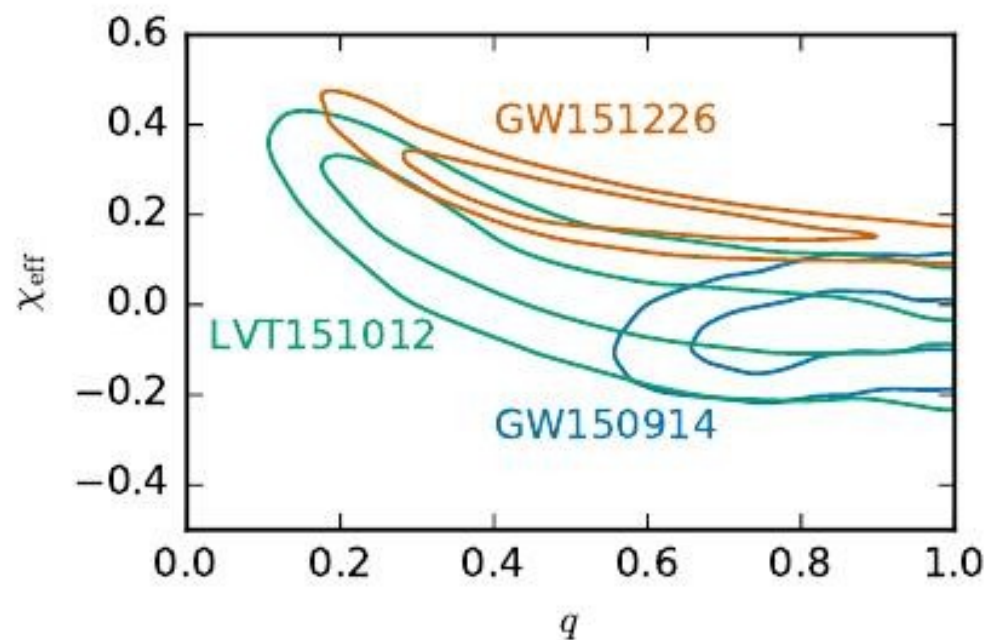
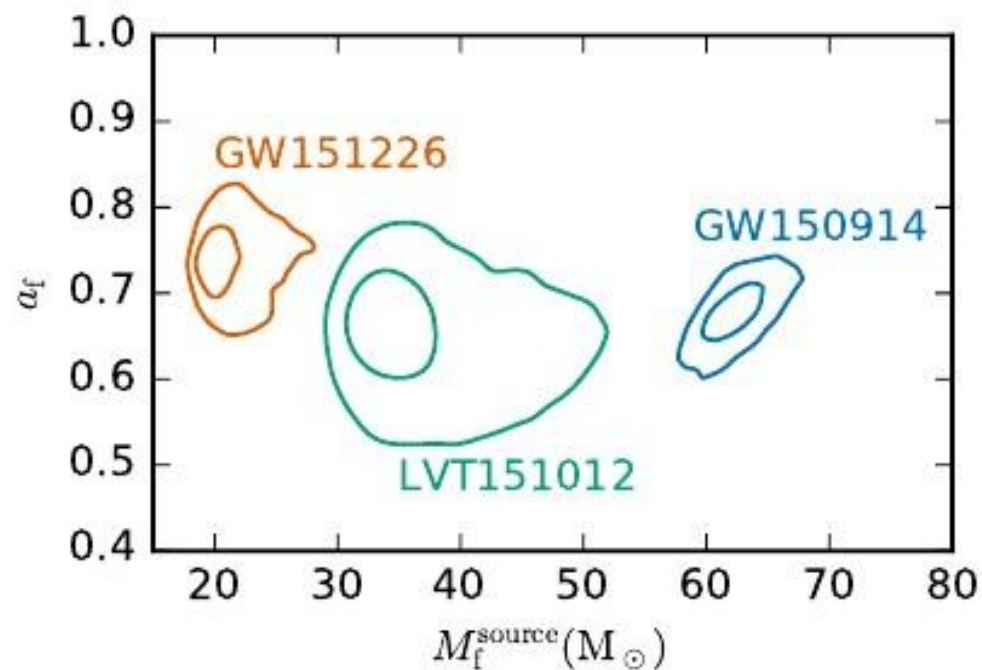
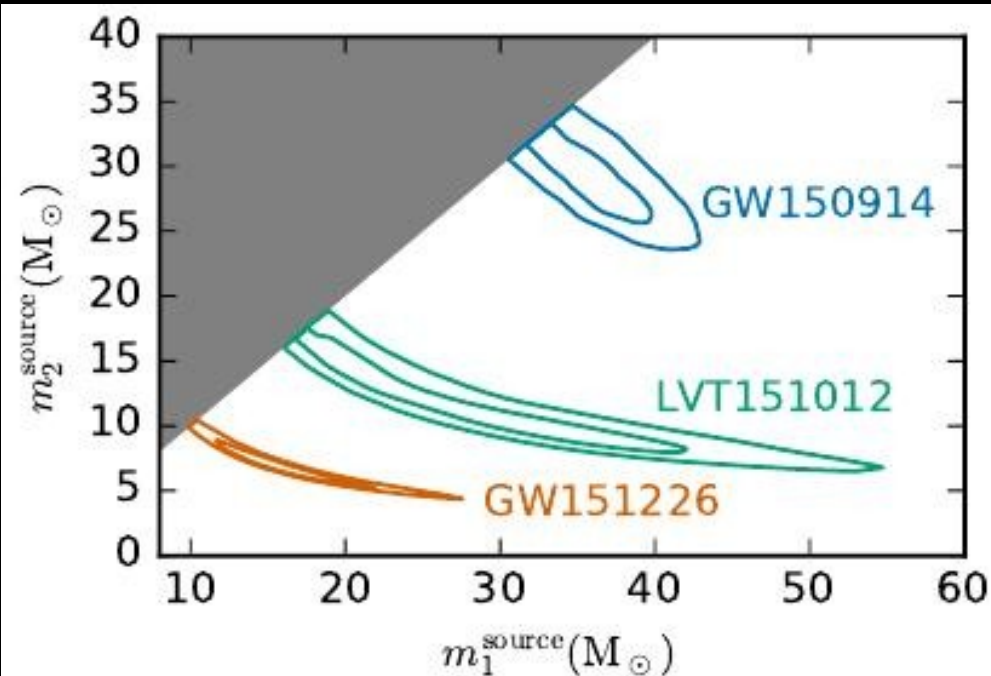
- >Masses have the largest impact on the phase modulation
- >Eccentricity impacts the waveform and the phase modulation
- >Spins impact the waveform and the phase modulation (but weaker effect)

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



(Courtesy W. del Pozzo)

(astro)physical properties

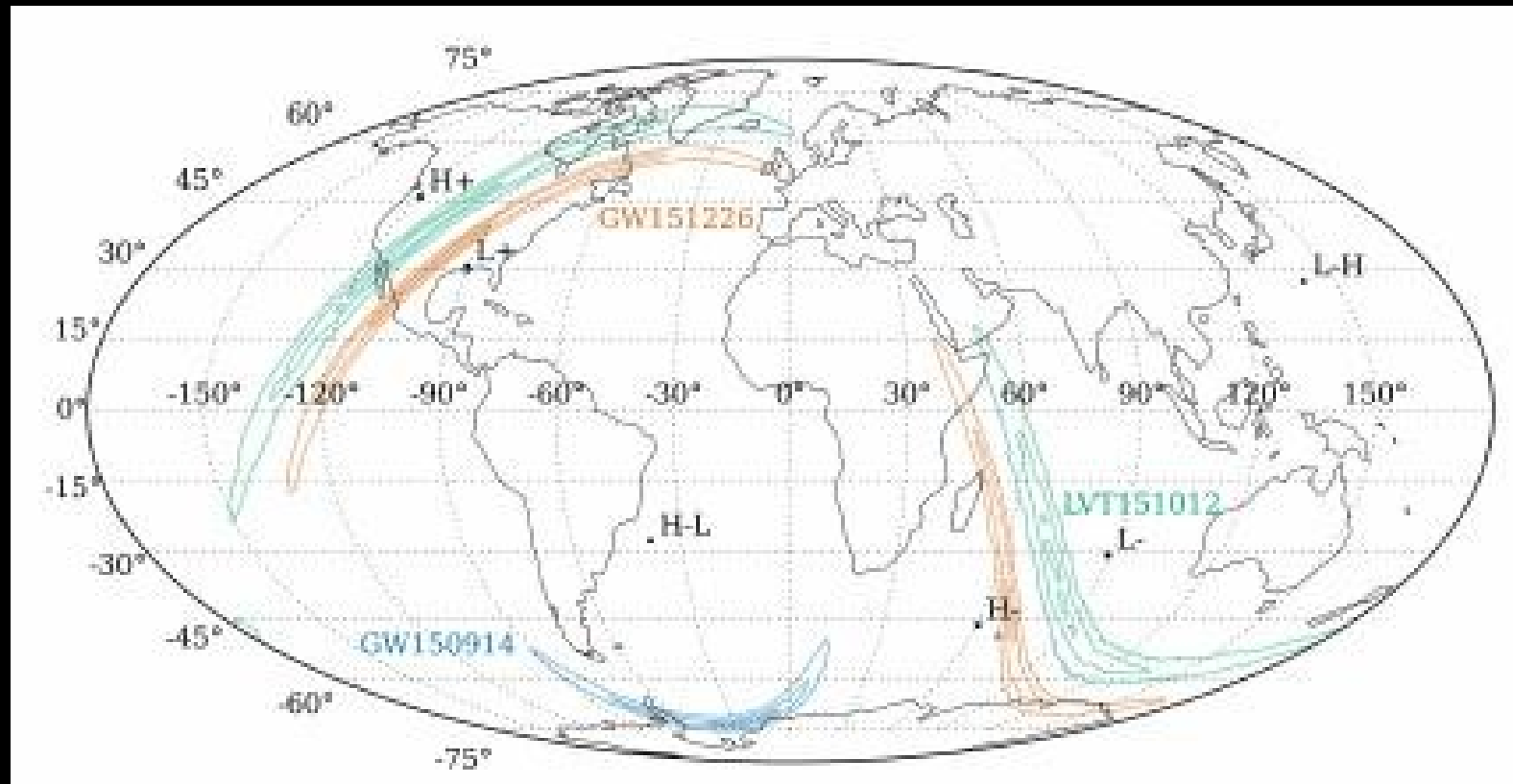


Extraction of information from the waveform

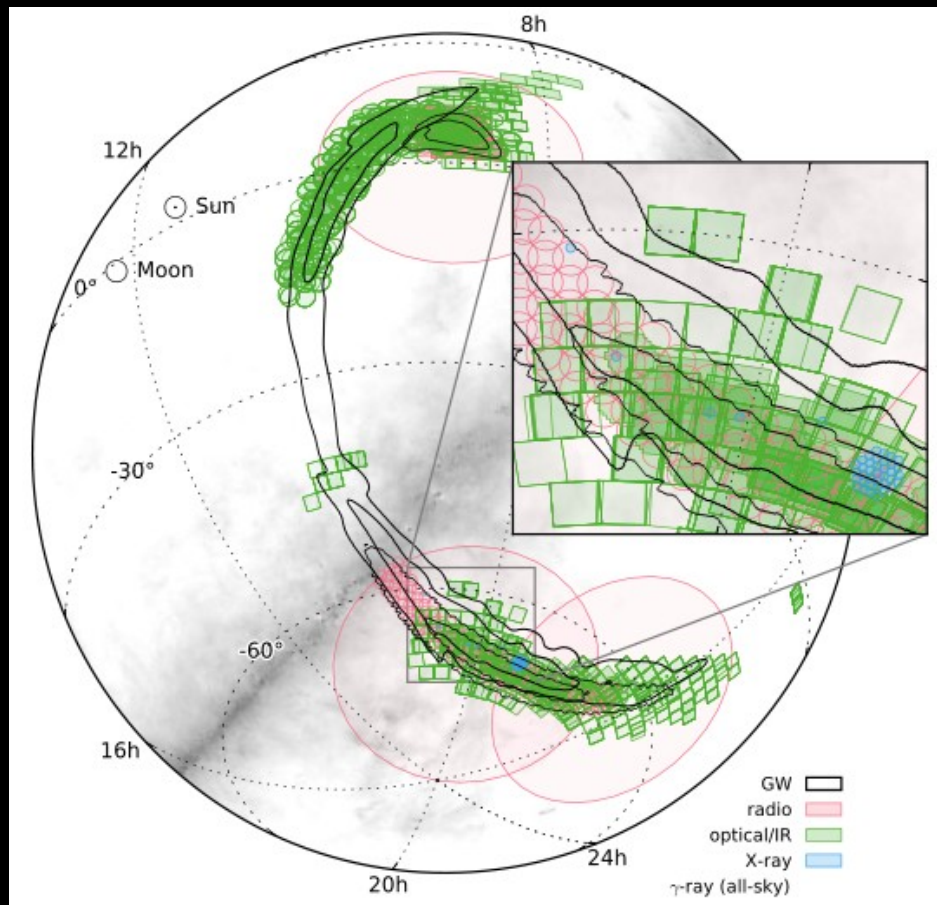
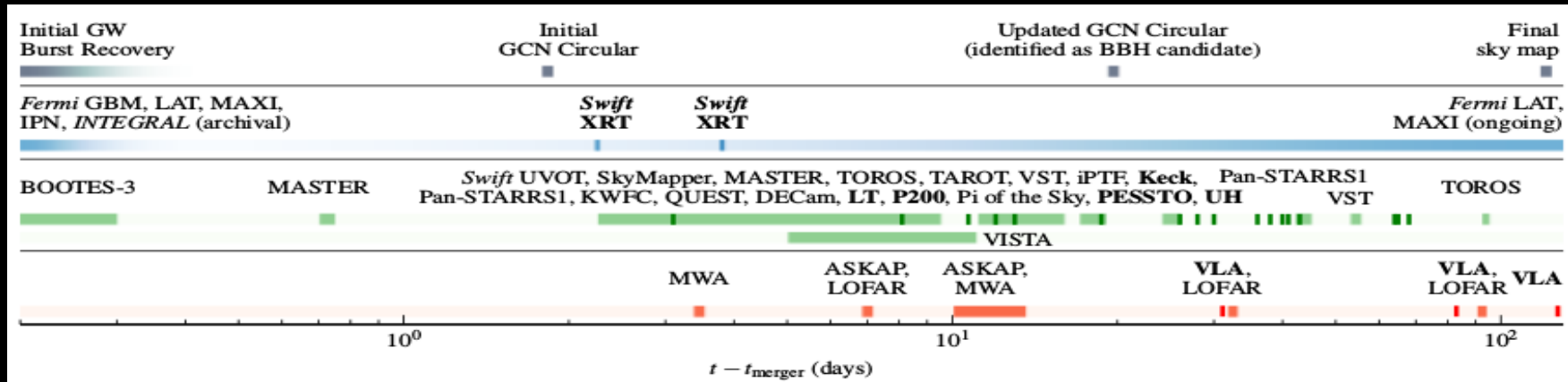
>Sky location essentially measured through triangulation:
two detectors \longrightarrow poor information

>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!

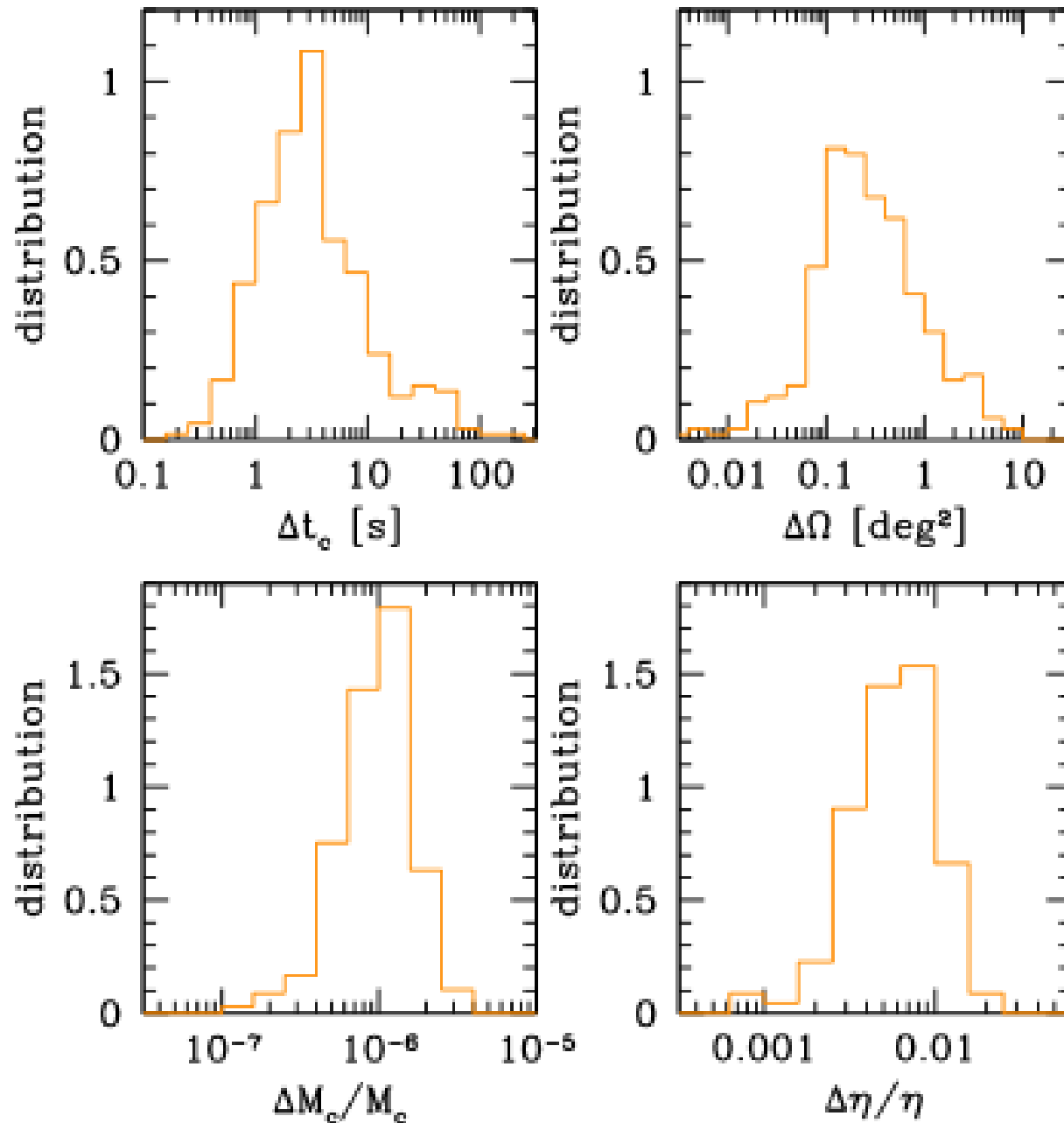
Nevertheless everybody jumped on the event for follow-ups

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

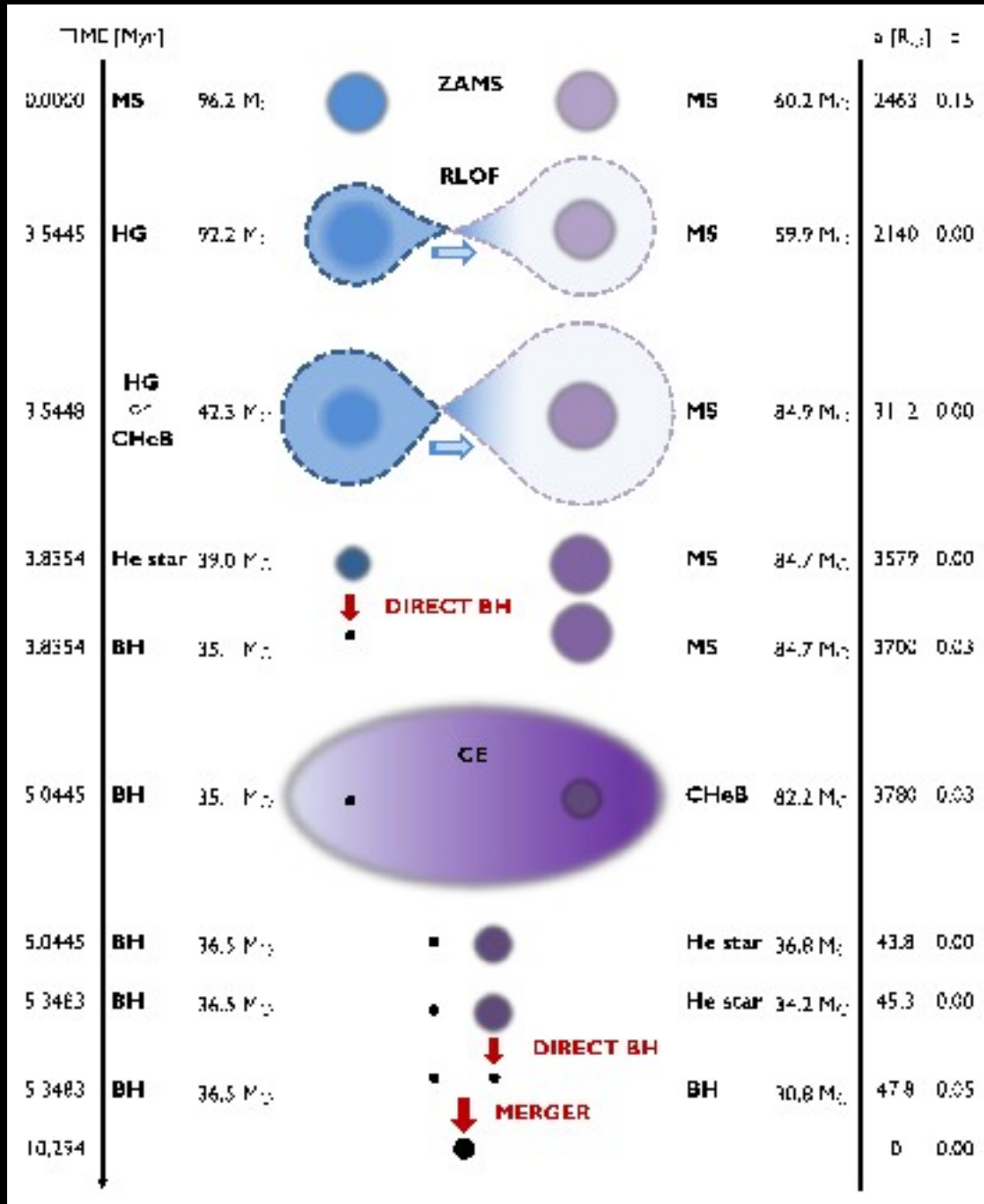


System crossing to the aLIGO band can be located with sub deg² precision (Klein et al. In prep.)

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



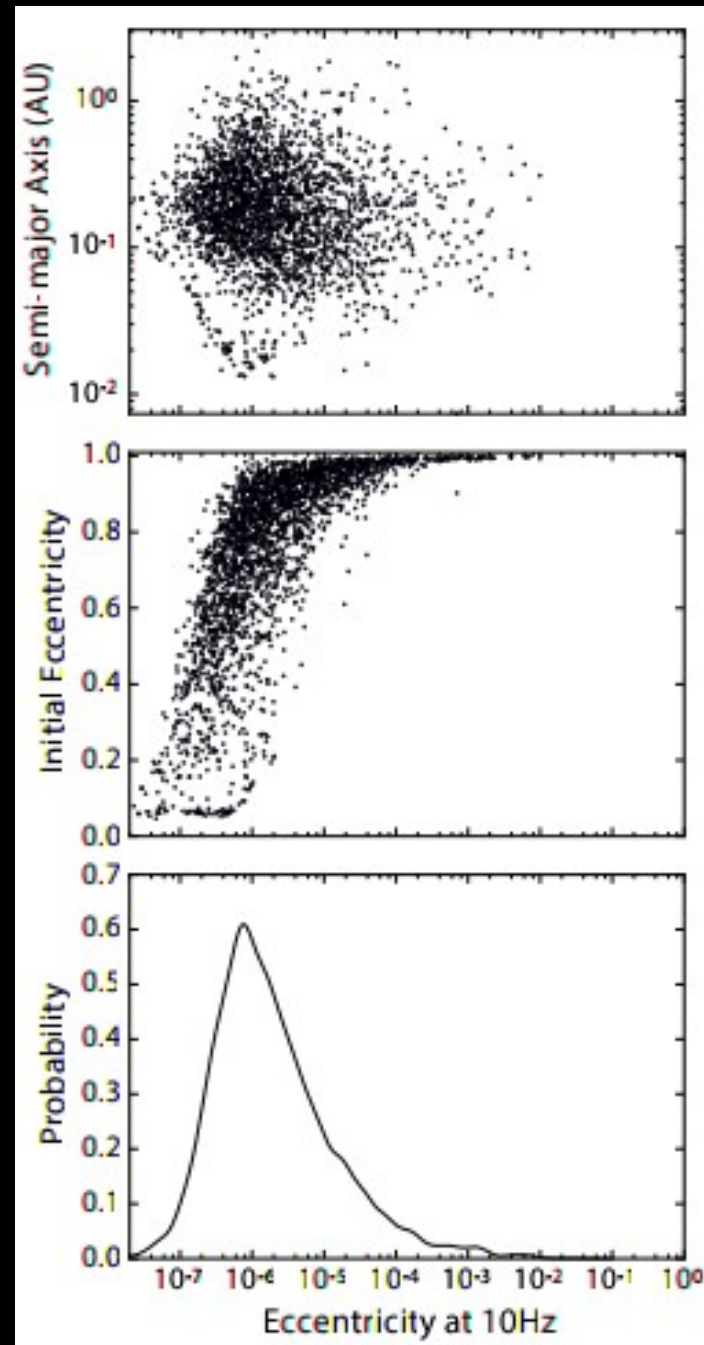
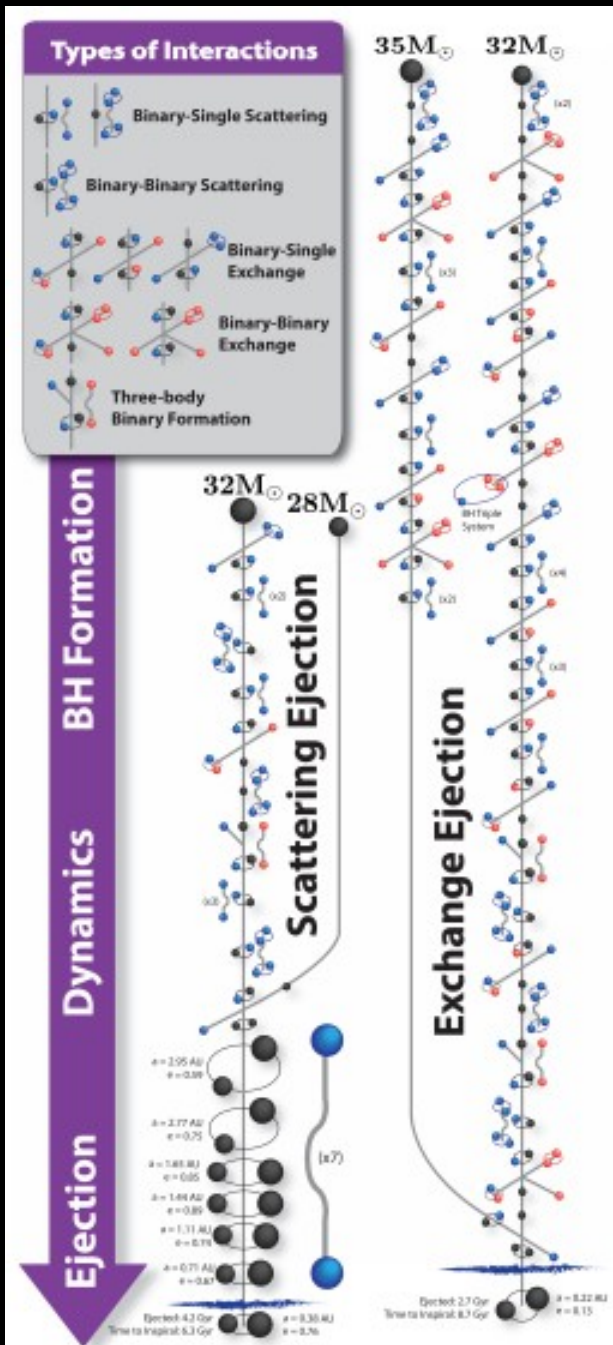
Dynamical capture

Complications

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

Features:

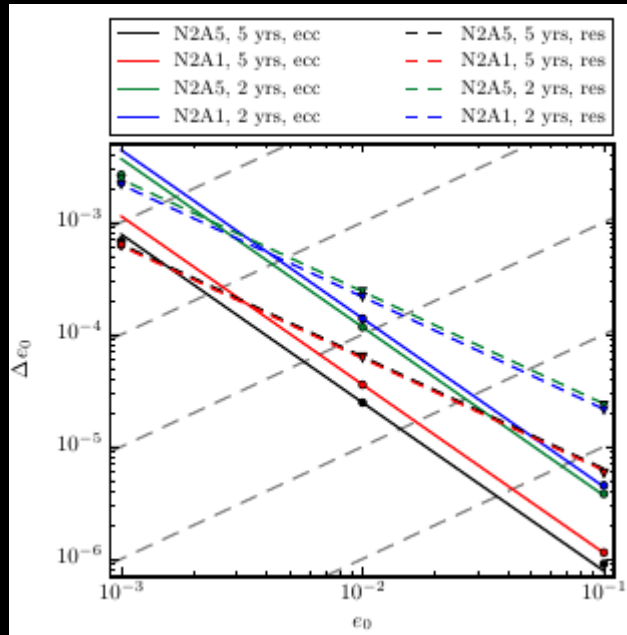
- randomly oriented spins?
- high formation eccentricities



(Rodriguez et al. 2016)

Measuring eccentricity with eLISA

(Nishizawa et al. 2016)



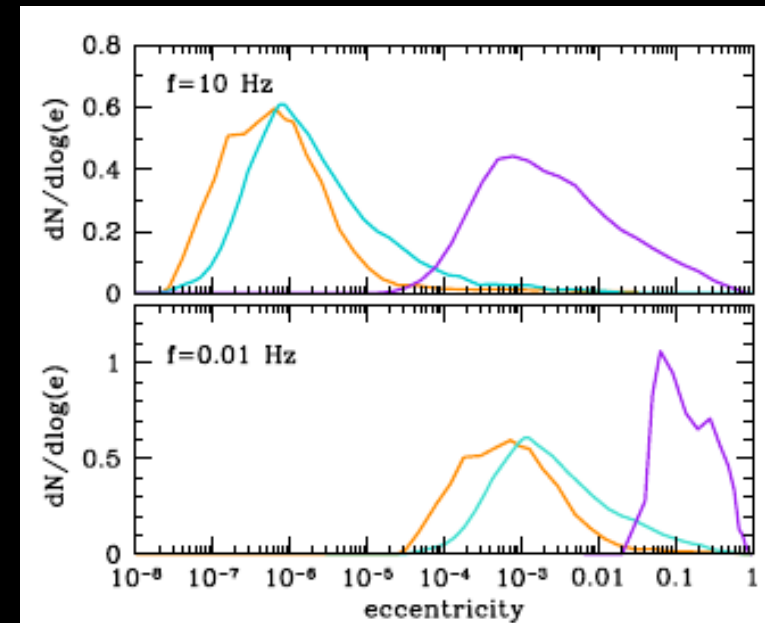
>aLIGO can only place upper bounds on e , but eLISA can measure e if $>10^{-3}$

>GW circularization implies much higher eccentricities in the eLISA band

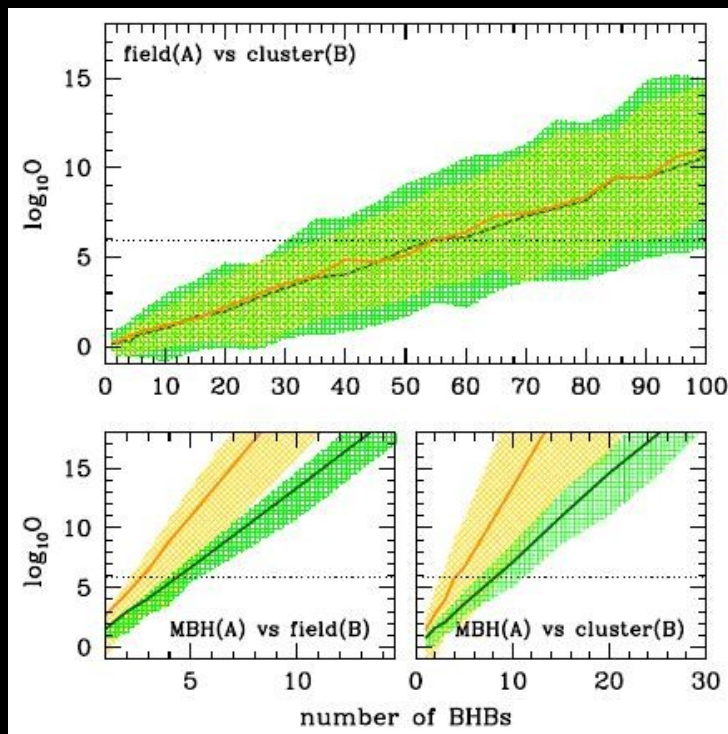
Different formation channel imply different e distributions.
Too small to be measured by LIGO but accessible to LISA

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)



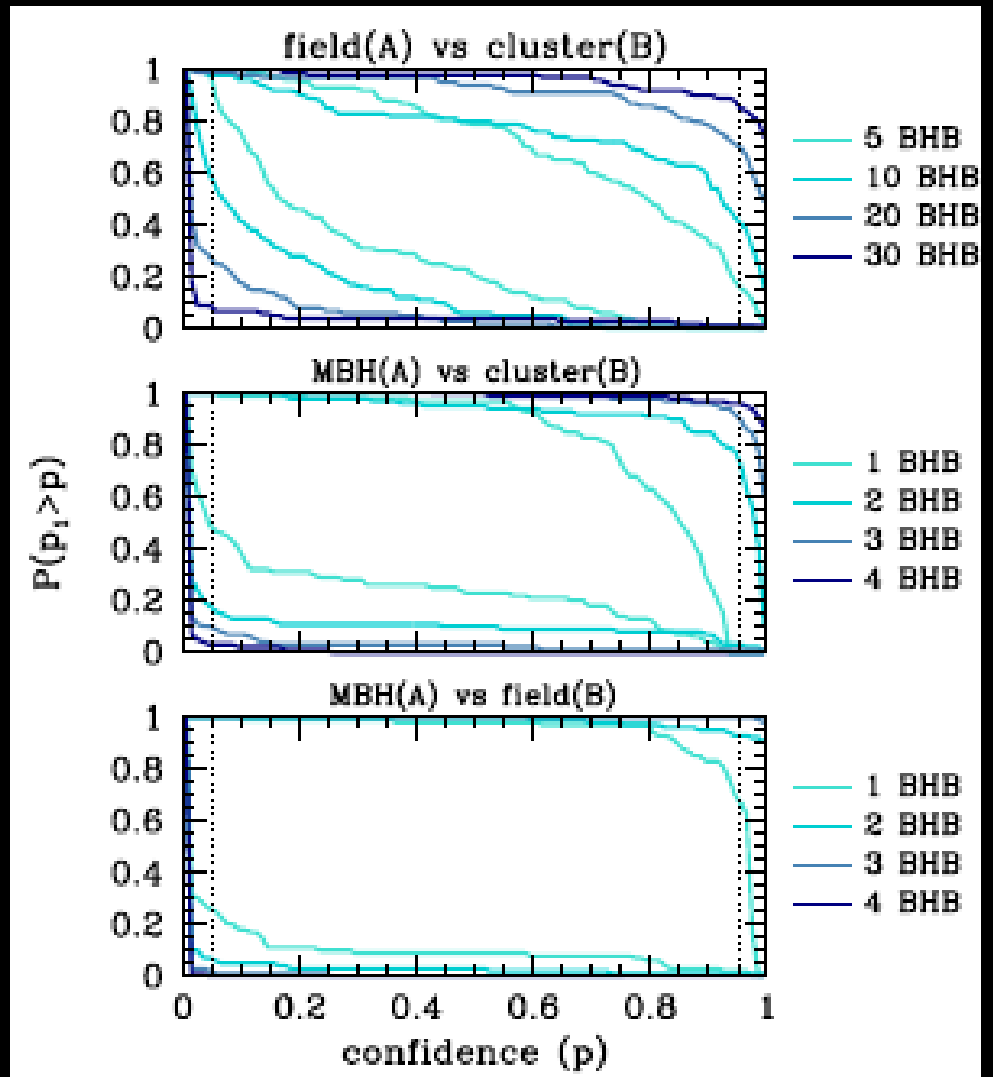
Assessing BHB origin using eccentricity



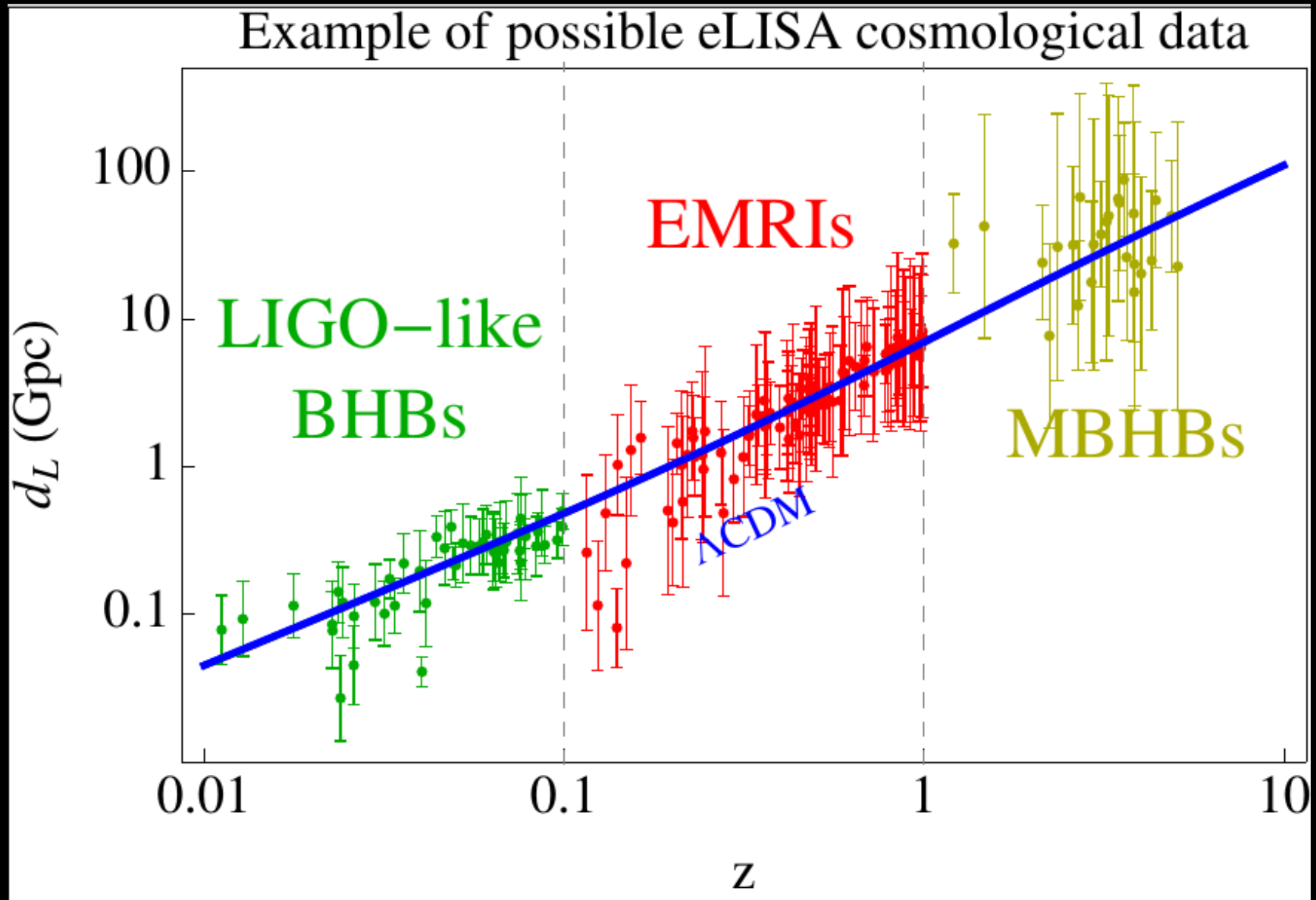
Different formation channels result in different e distributions in the eLISA band, (see also Breivik et al. 2016)

eLISA can tell formation scenarios apart with few tens of observations (Nishizawa et al. 2016)

Can be complemented to aLIGO spin measurements.



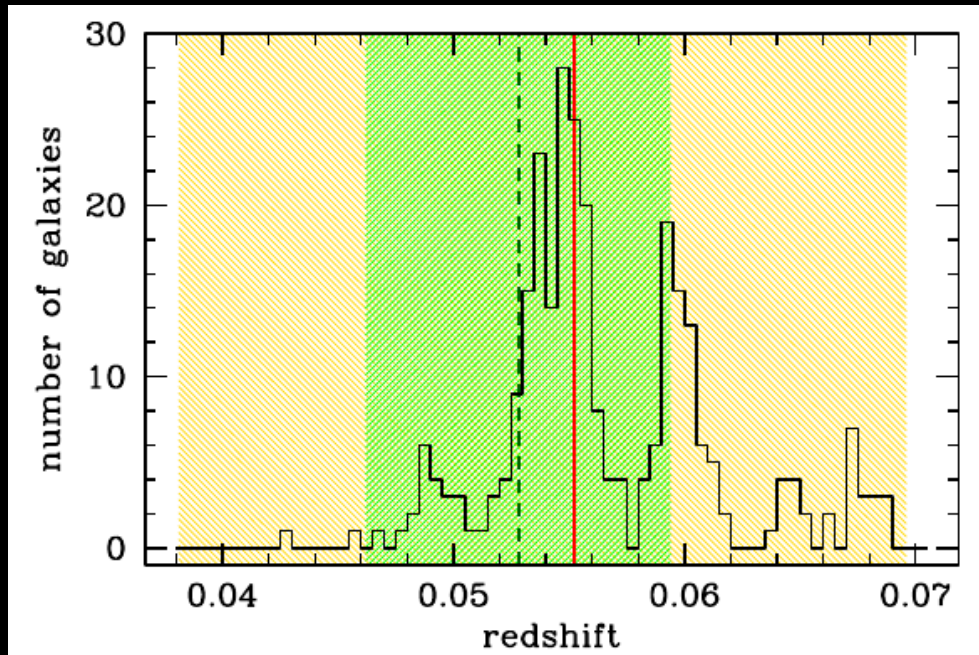
Cosmology with gravitational waves



(Courtesy of N. Tamanini)

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

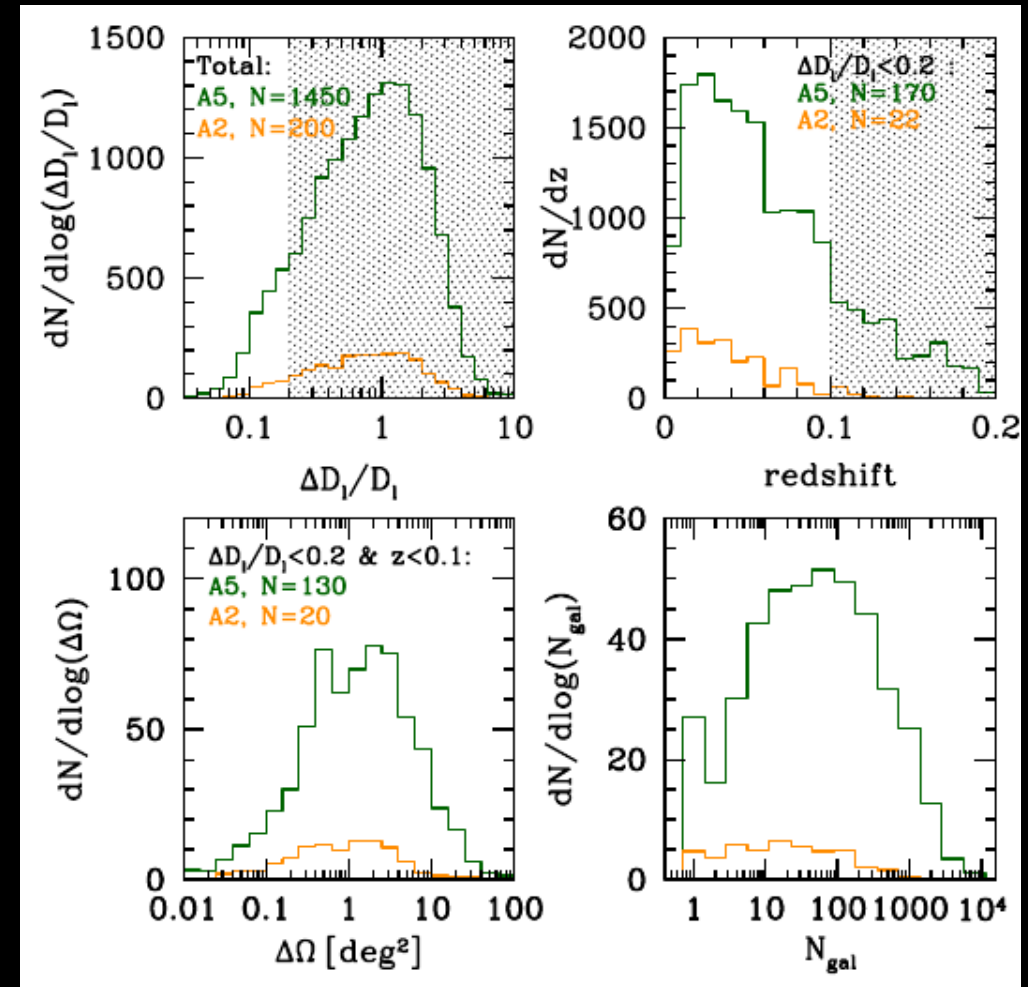
BHBs as standard sirens: measuring H_0



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

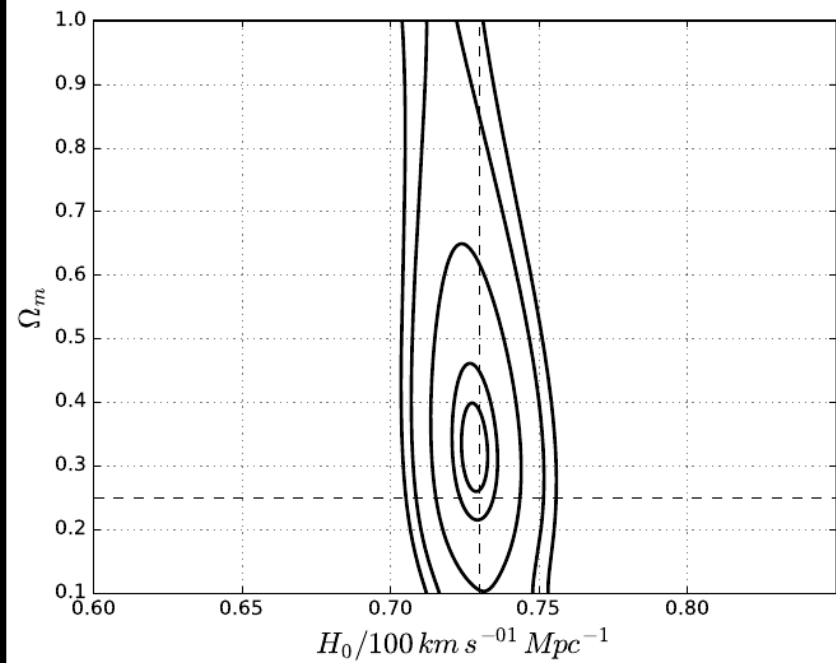
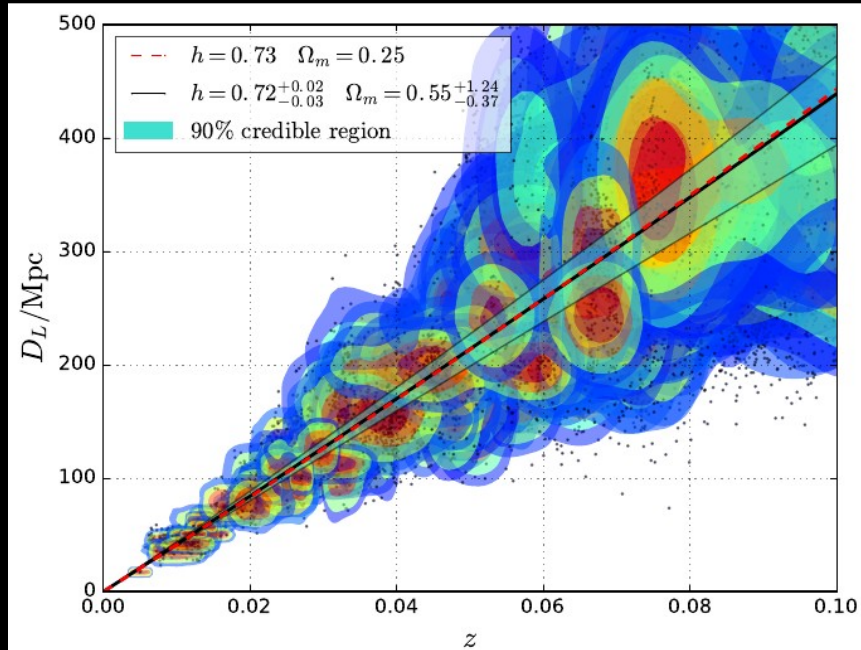


Work in progress, h determined to up to...

AstroBonus: few local events have 1 galaxy in the errorbox

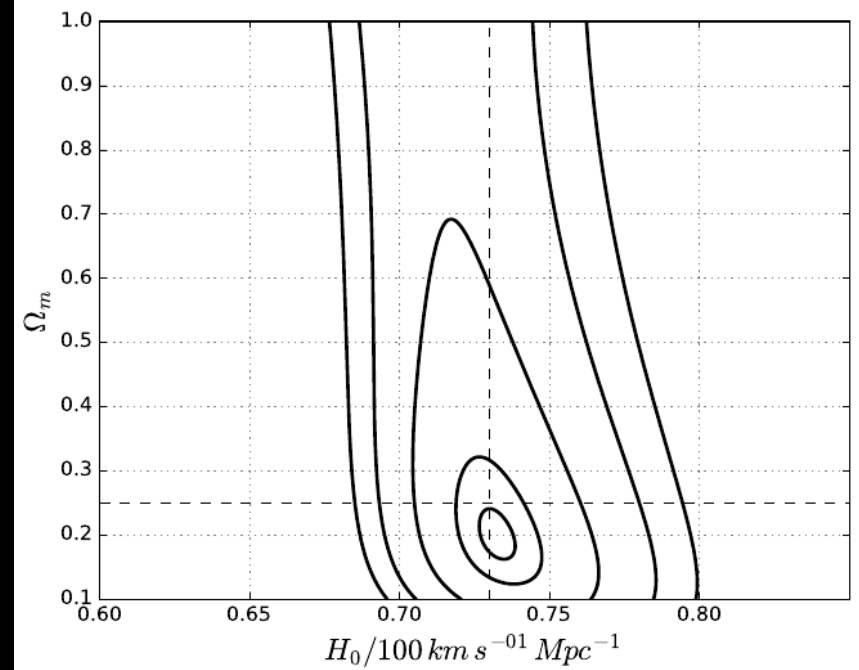
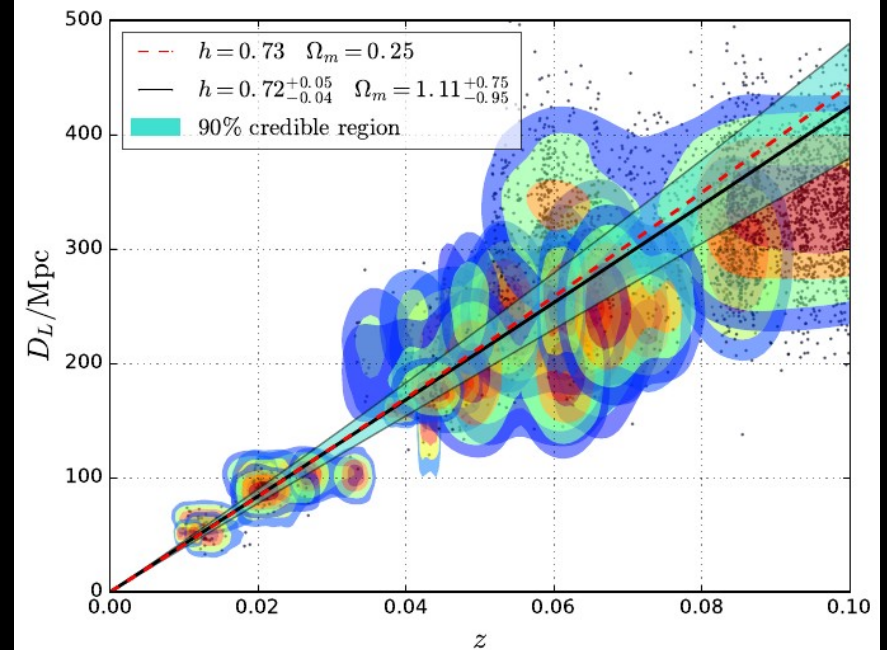
5Gm

h determined at $\sim 2\%$



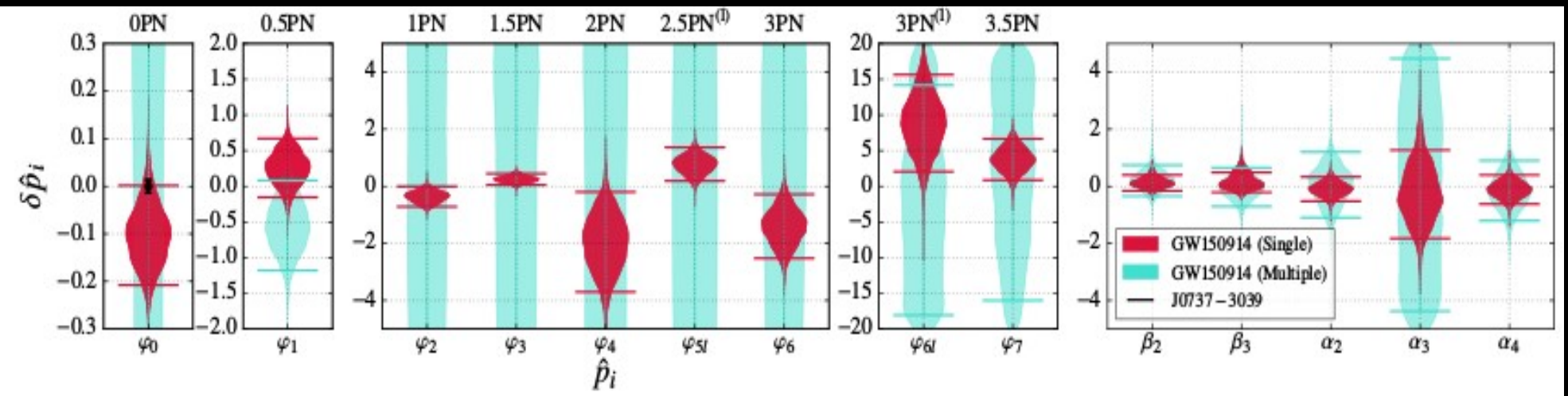
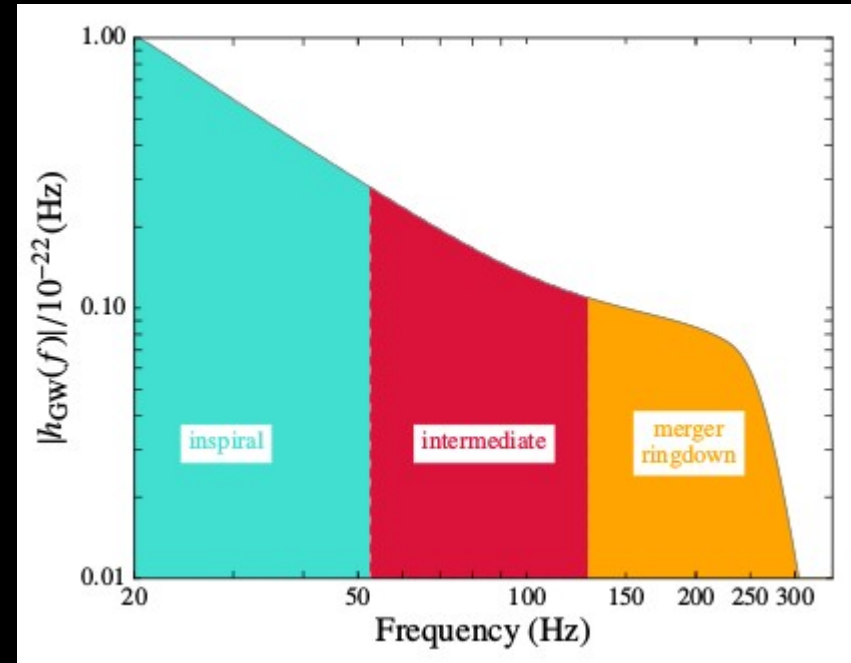
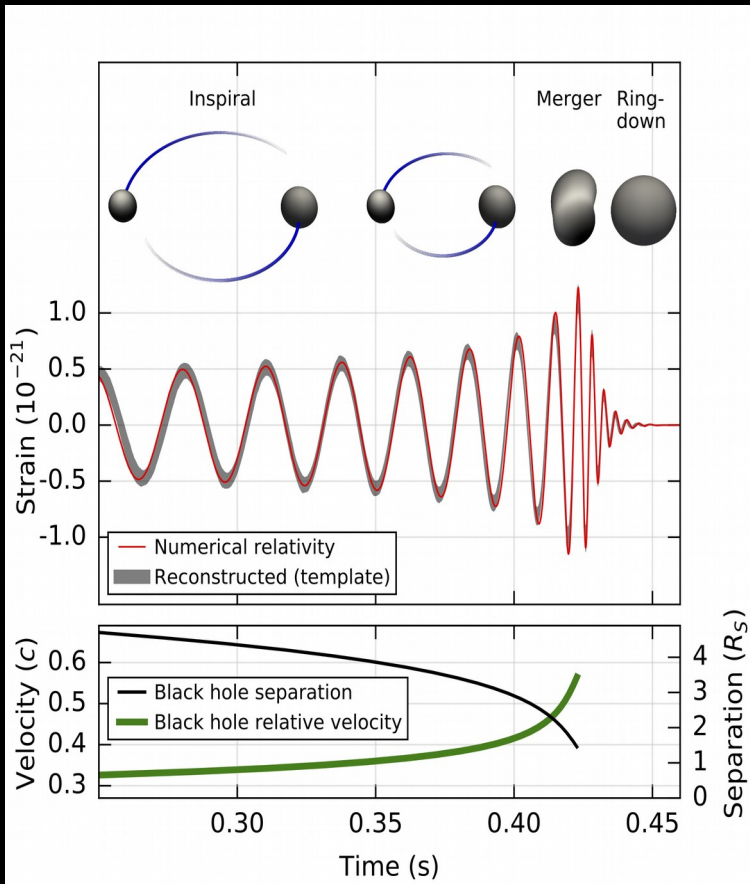
2Gm

h determined at $\sim 5\%$



Tests of GR

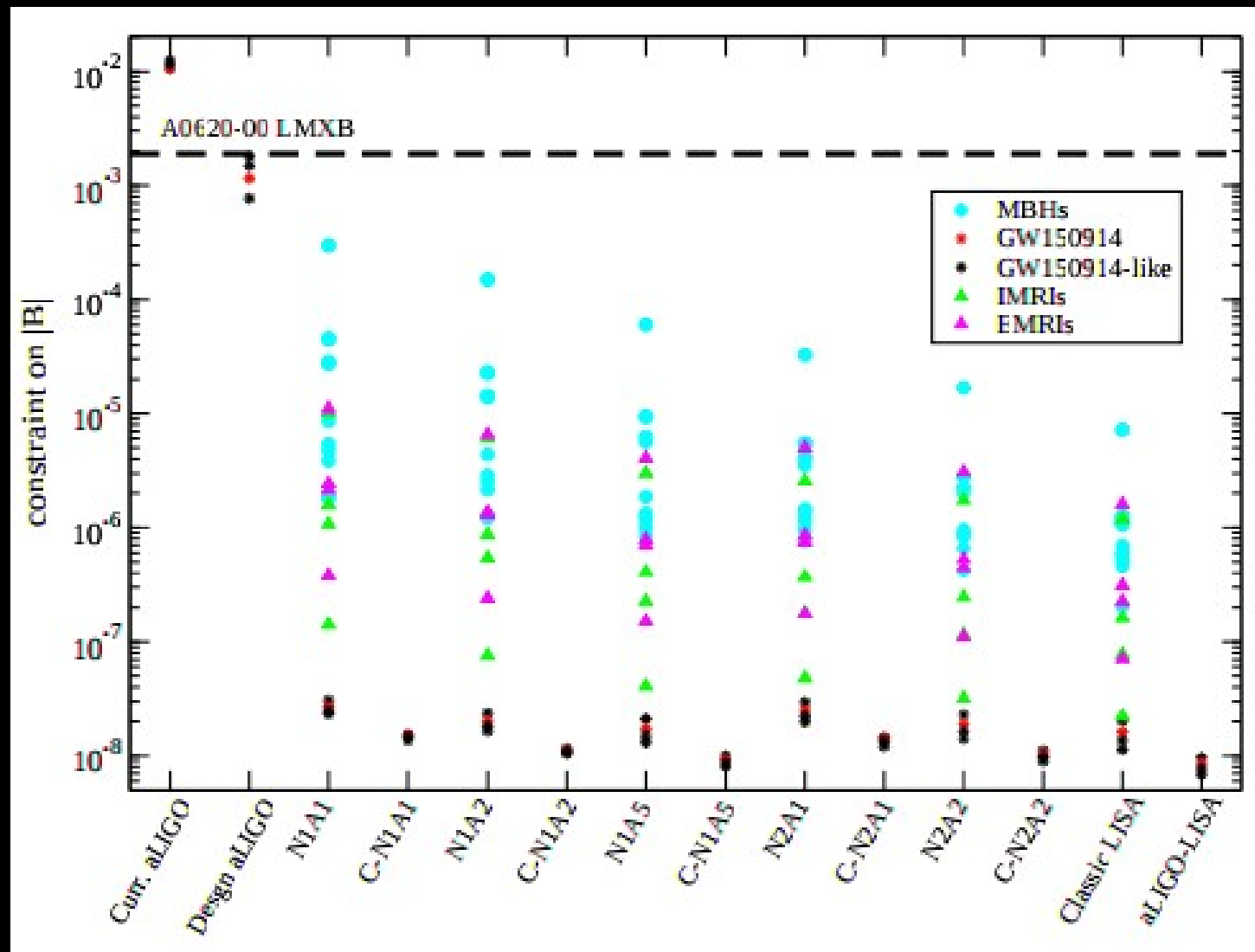
GW150914 provides the most stringent tests of gravity in the strong field regime:
NO EVIDENCE FOR DEVIATIONS FROM GR



Tests of Gravity combining eLISA and aLIGO

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

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



(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 explore)

