Globular Clusters as Sources of Gravitational Waves

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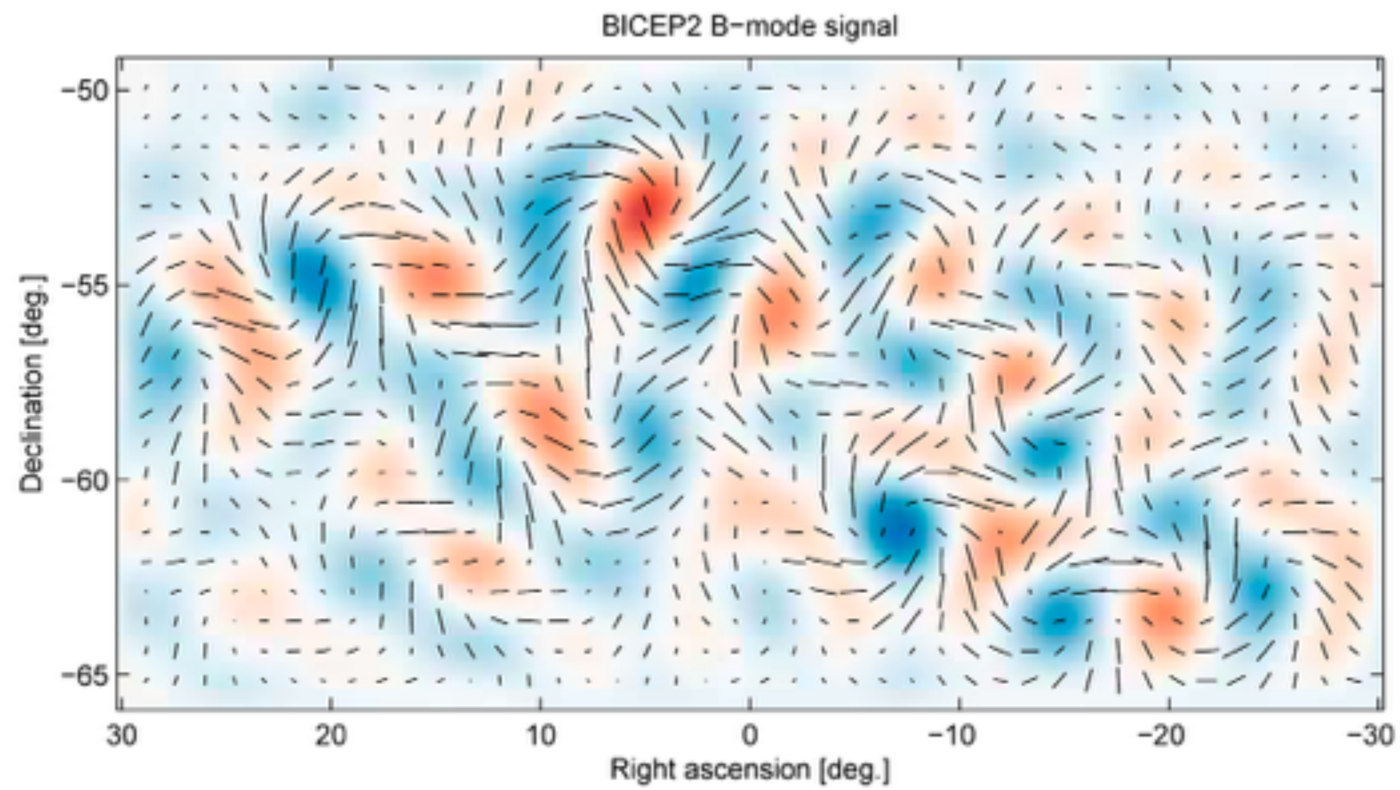
There are many talks on potential sources of gravitational radiation in globular clusters:

- Rasio
- Strader
- Giersz
- van den Berg
- Aarseth
- Knigge
- Ivanova
- Lanzoni
- Mapelli
- Tauris

… so I will give a tutorial on gravitational wave observations and provide some examples of their use in understanding clusters.

We are entering the age of gravitational wave astronomy



BICEP2 Collaboration: arXiv:1403.3985v2

2014: BICEP2 results indicate primordial gravitational wave background from inflation.

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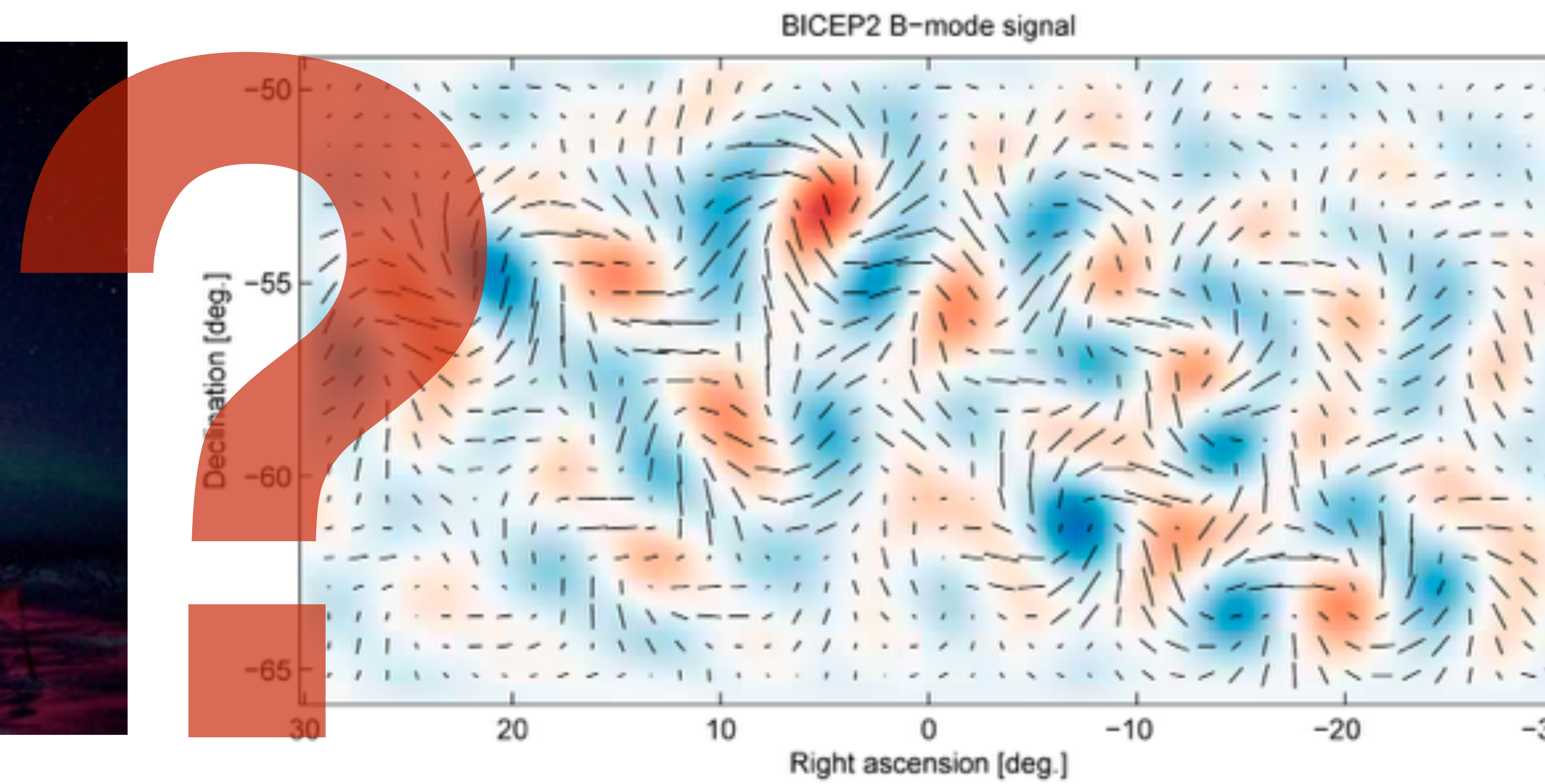

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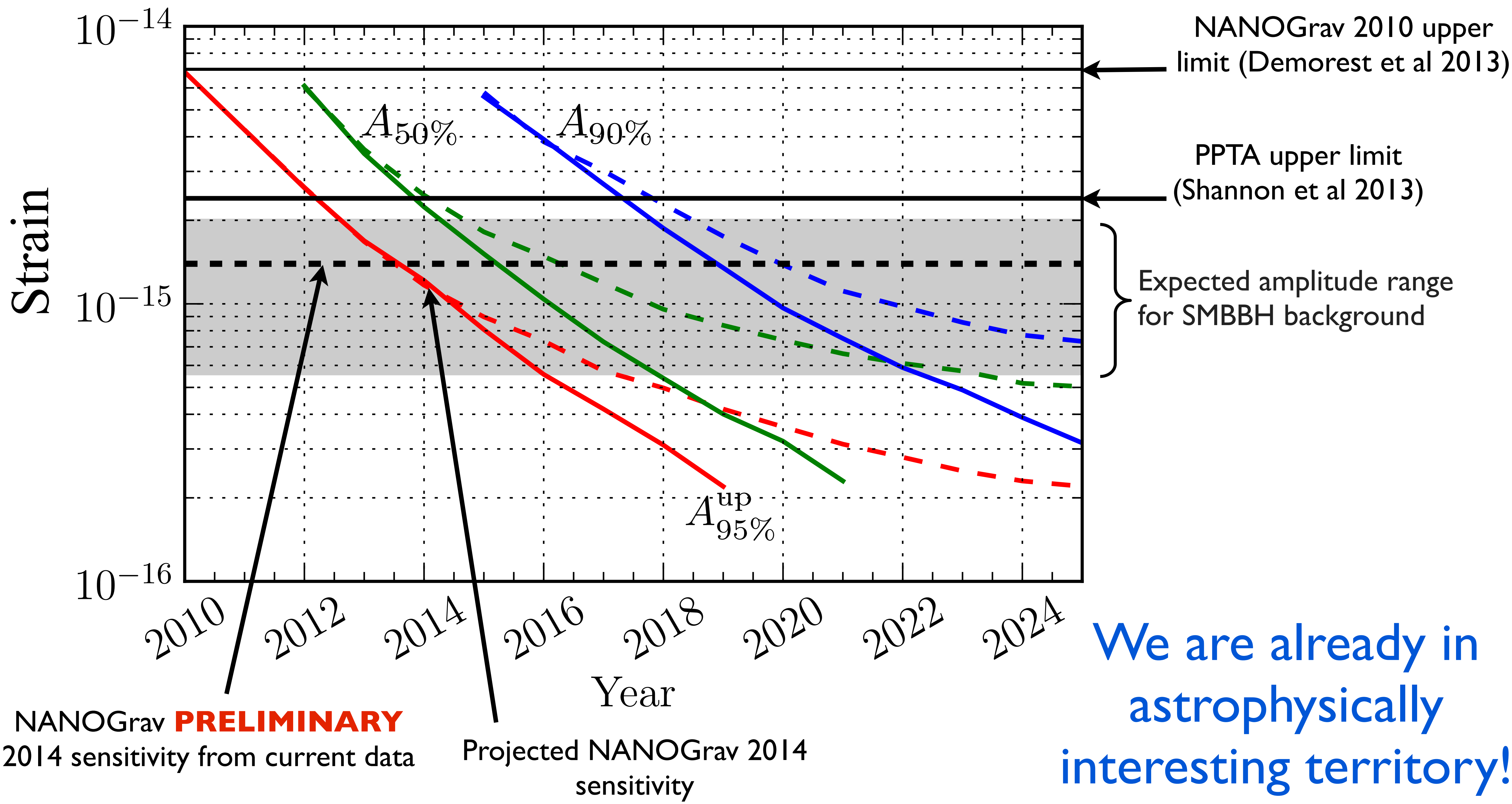
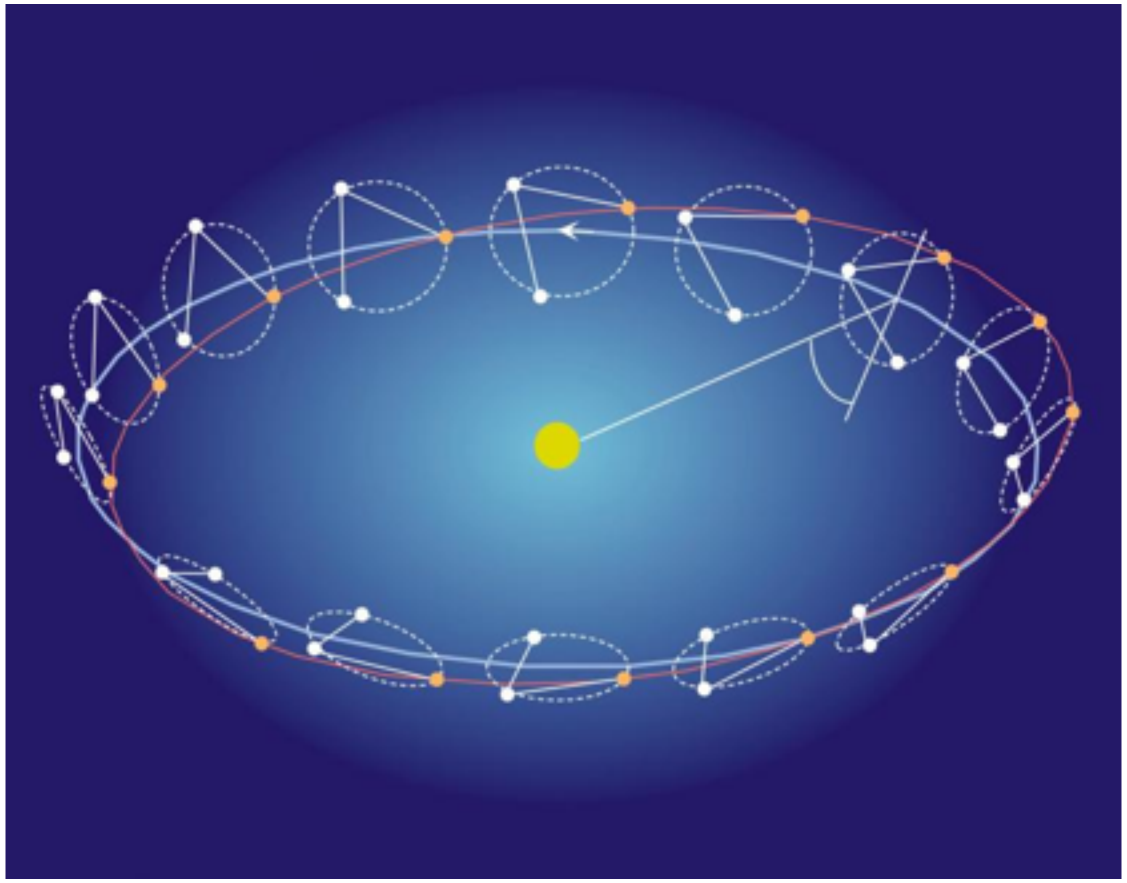
The transformational advance

The NANOGrav PFC will open a new observational window onto the nano-Hz band of the GW spectrum.



We are already in astrophysically interesting territory!

"It is important to remember that this is a decisive time in the gravitational wave detection effort..."

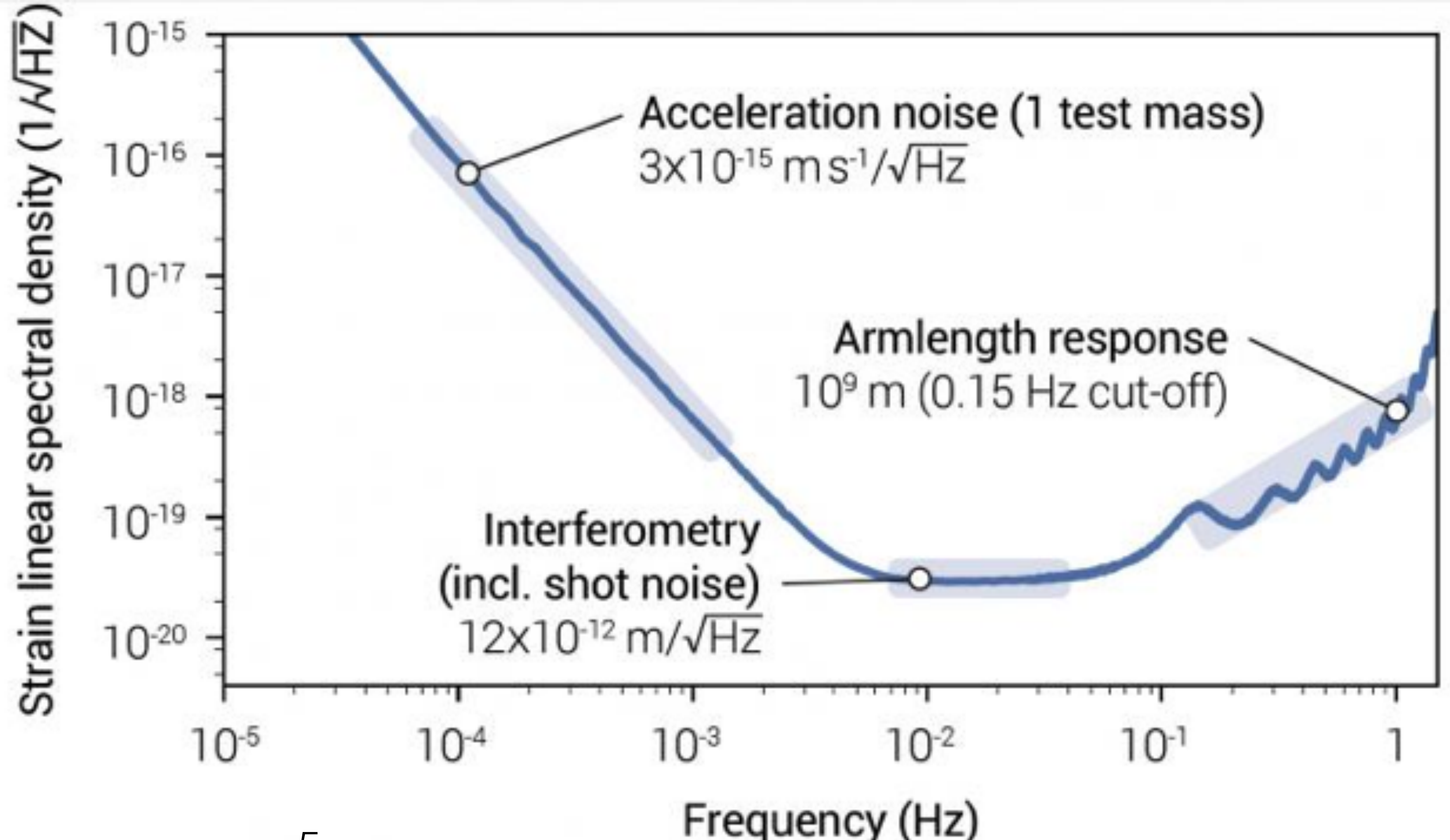


eLISA: Sensitive to mHz

- SMBH mergers
- Extreme Mass Ratio Inspirals
- Compact Object Binaries

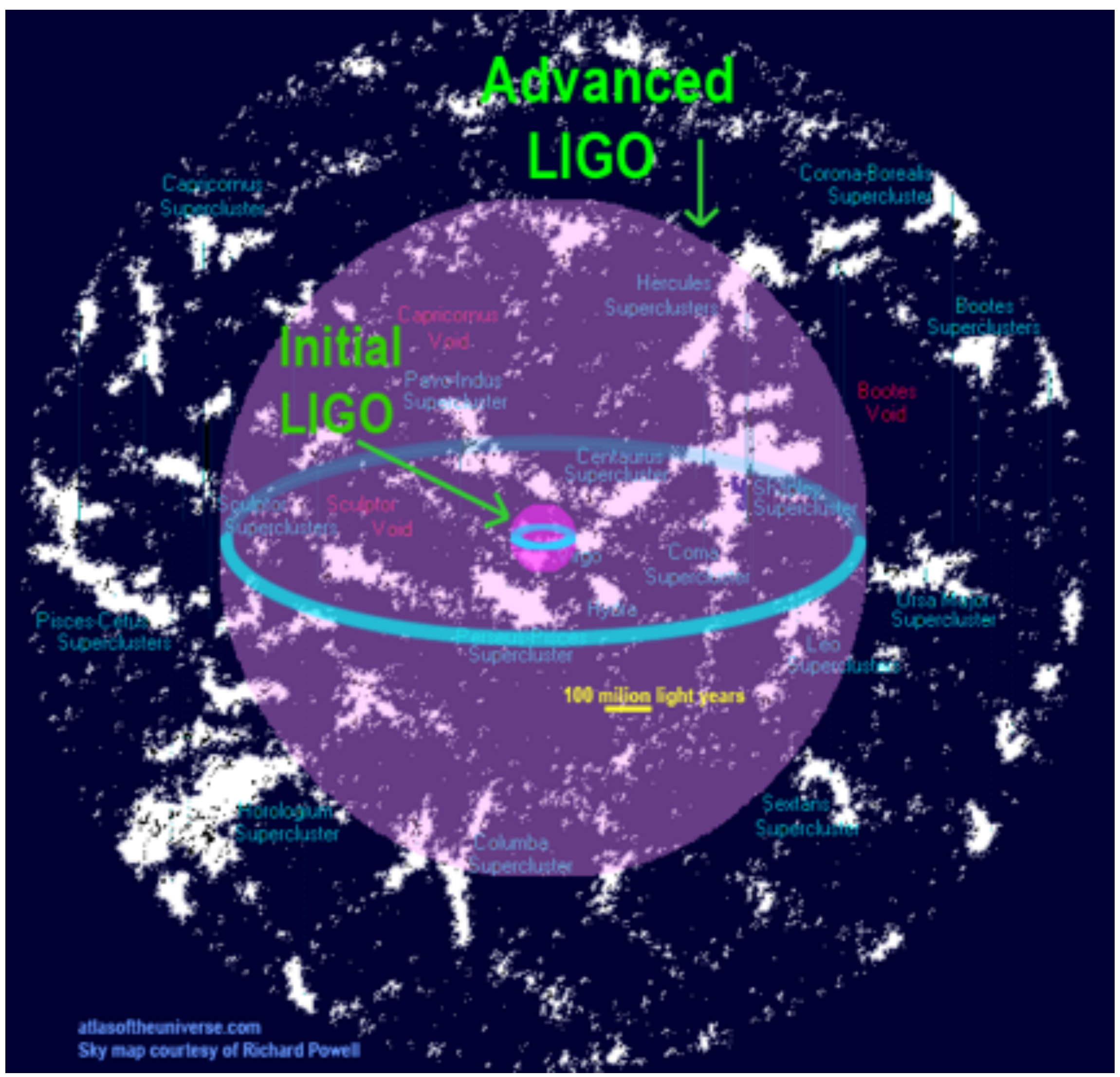
ESA L3 Mission

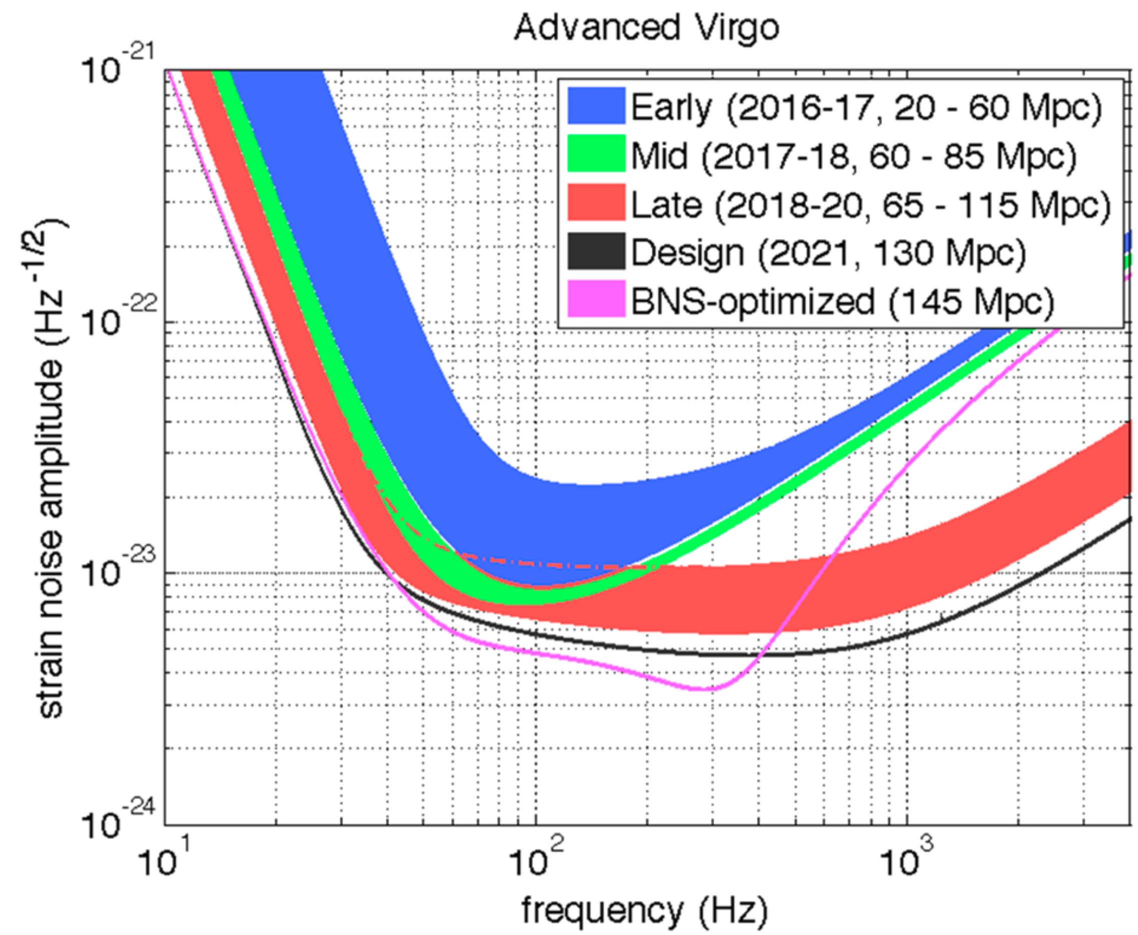
Scheduled launch: 2034

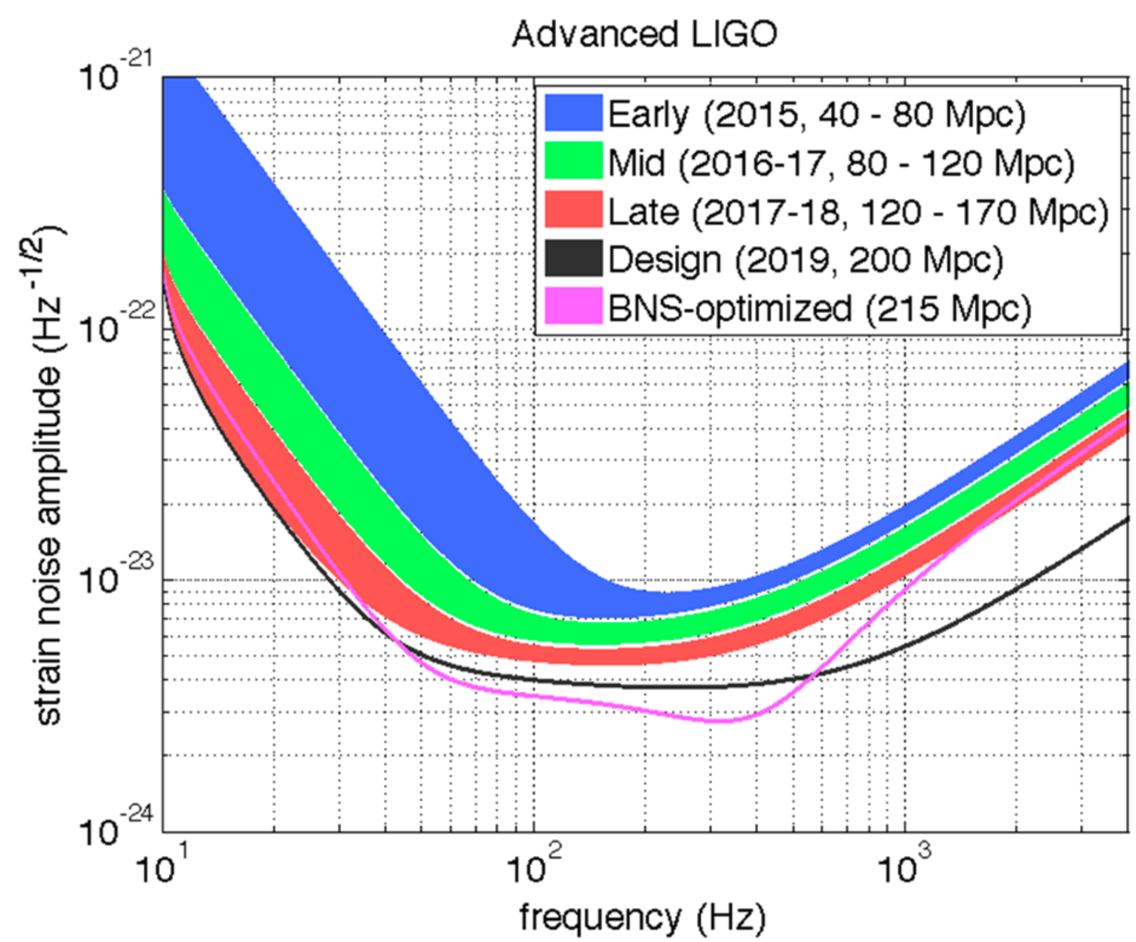


Advanced LIGO/Virgo

First Science Runs 2015
Design Sensitivity 2019







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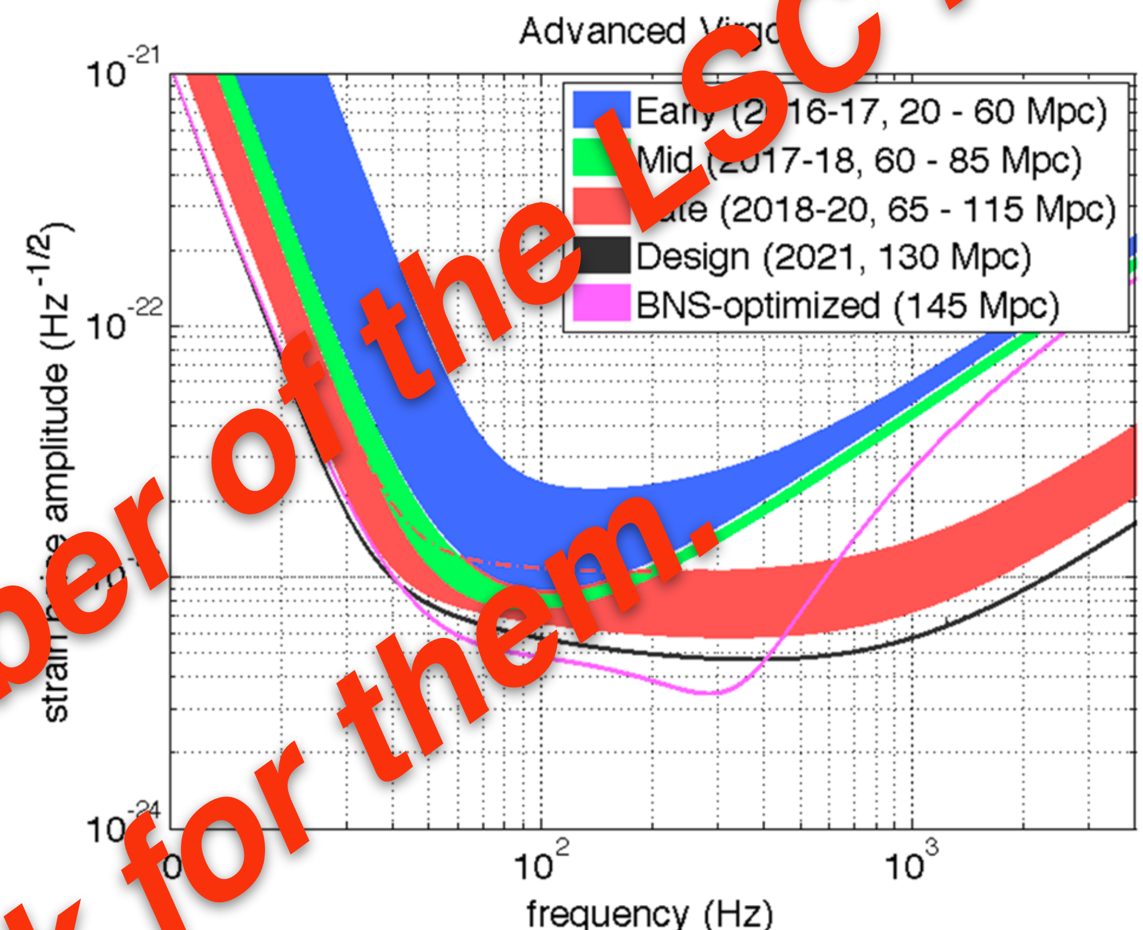
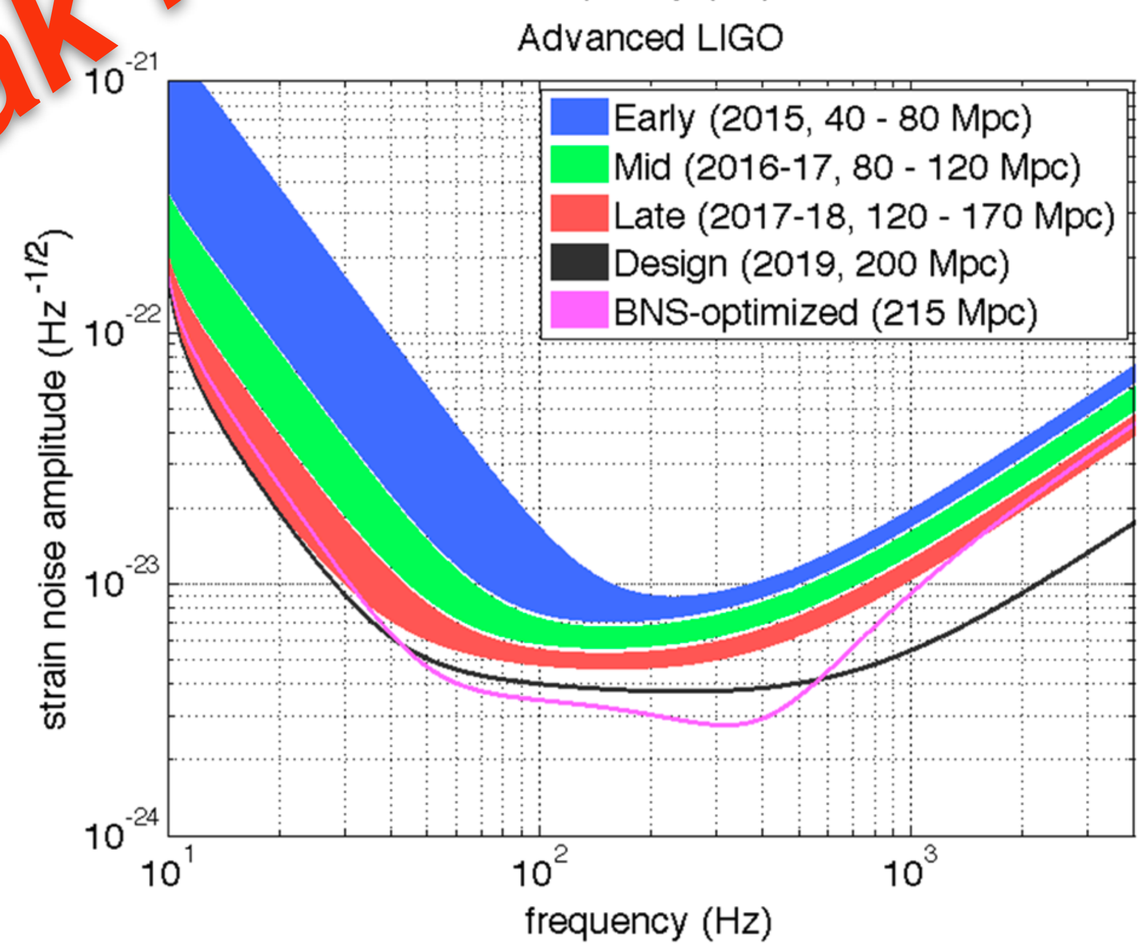
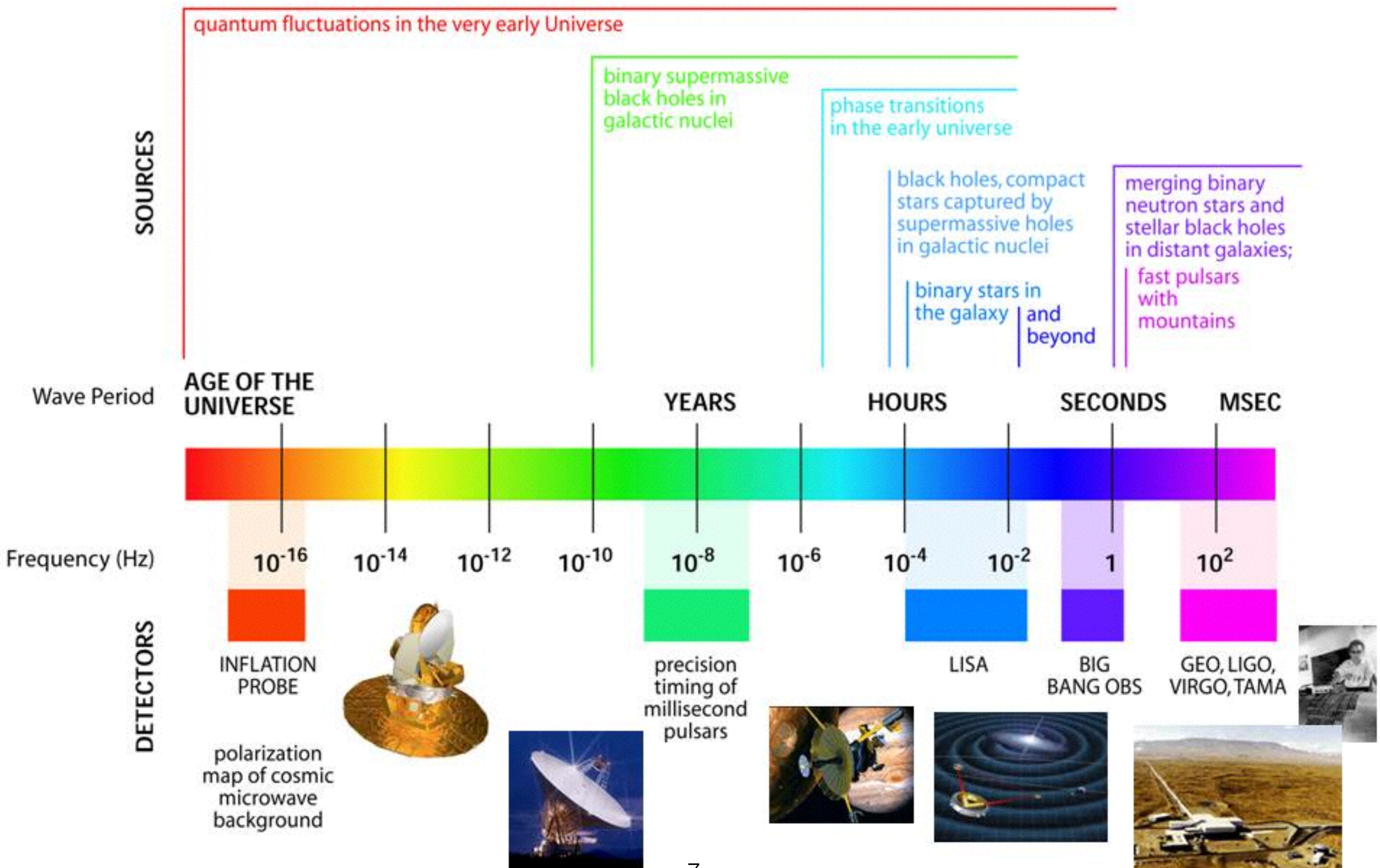
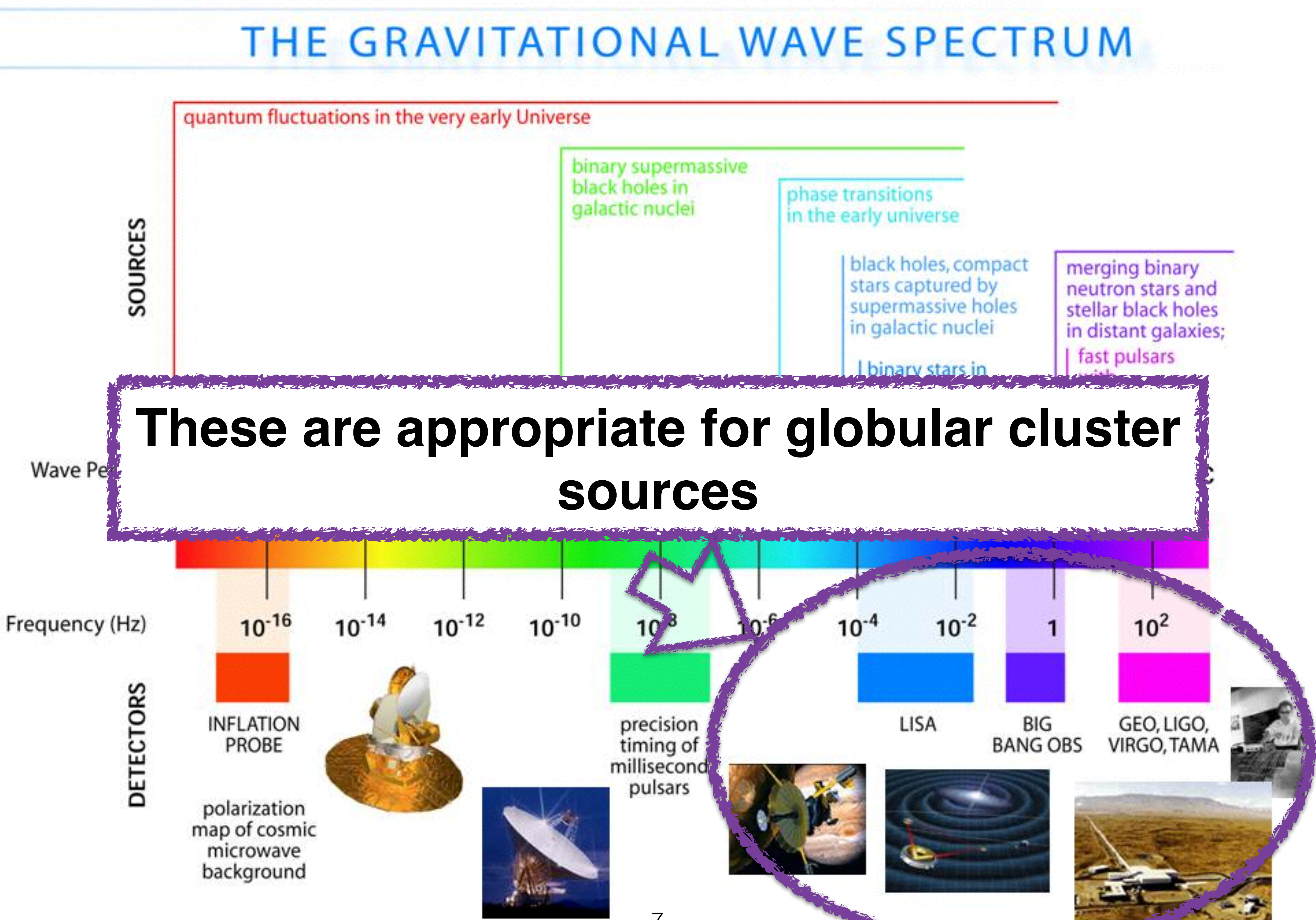




I am no longer a member of the LSC …
I don't speak for them.

THE GRAVITATIONAL WAVE SPECTRUM



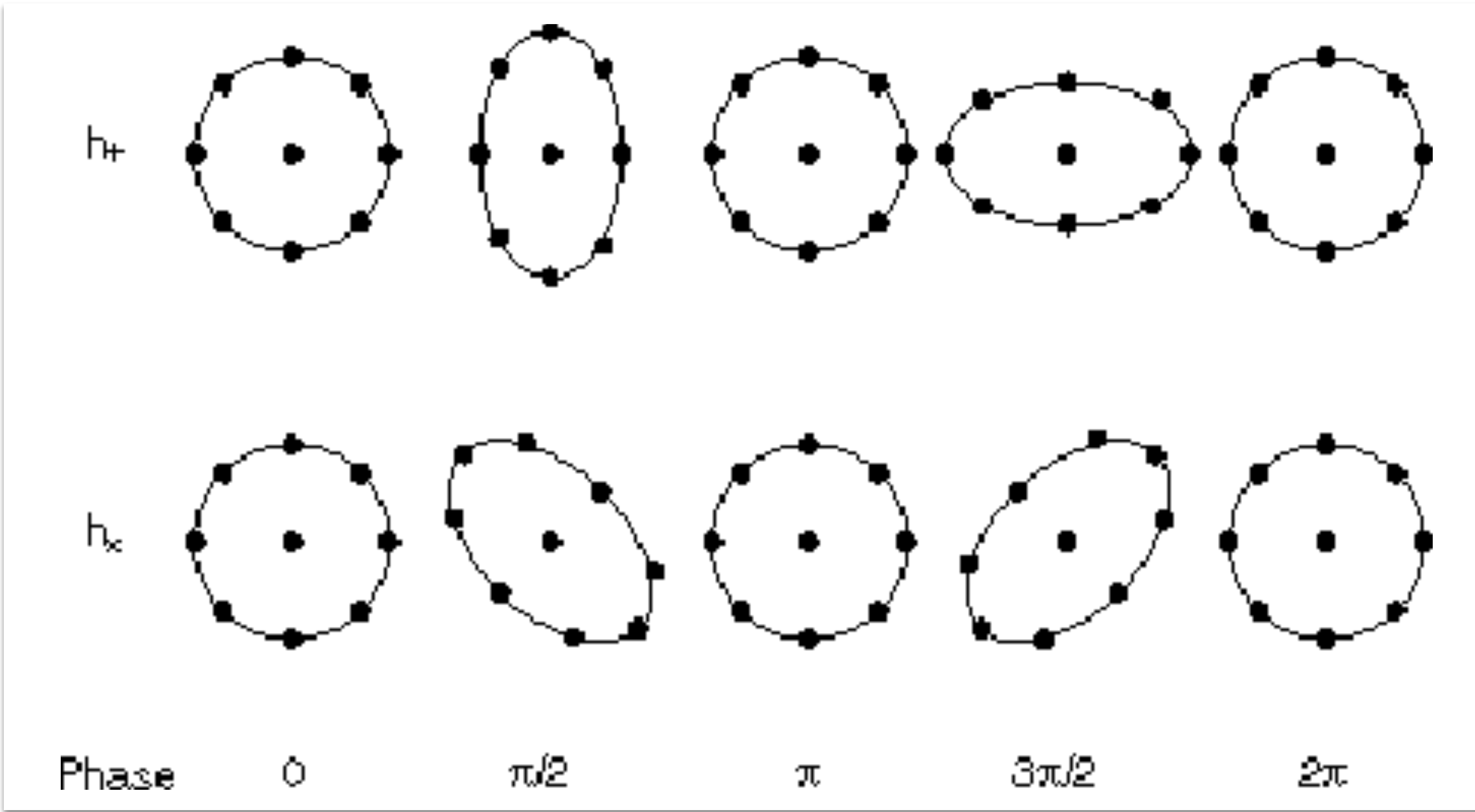


These are appropriate for globular cluster sources

What is a gravitational wave?

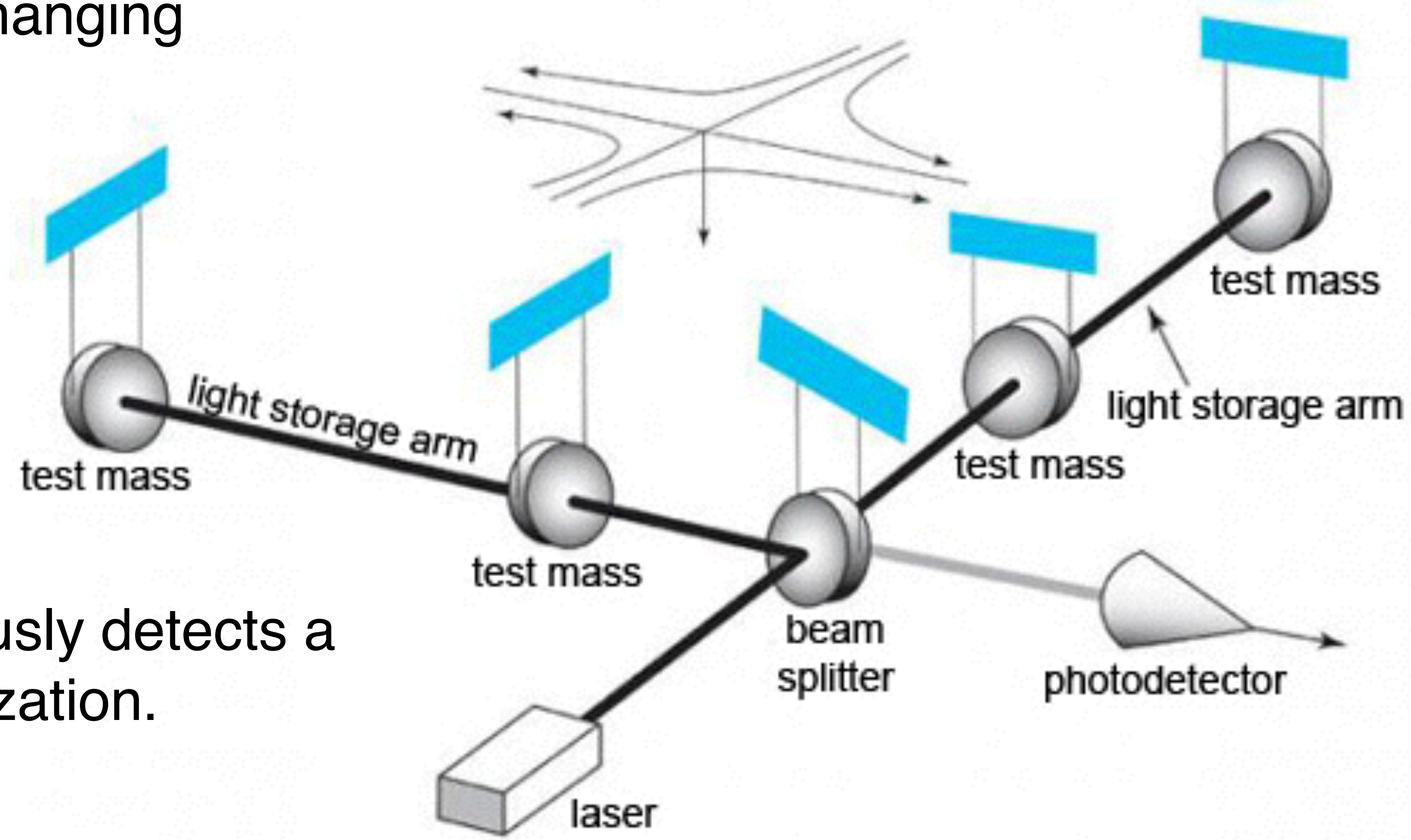
- Perturbation in the metric of space-time.
- Quadrupolar
- Affects measured distances between objects.
- Two polarizations

What is a gravitational wave?



Interferometry

- These detectors all rely on a form of interferometry to detect the changing distance.



- Instantaneously detects a single polarization.

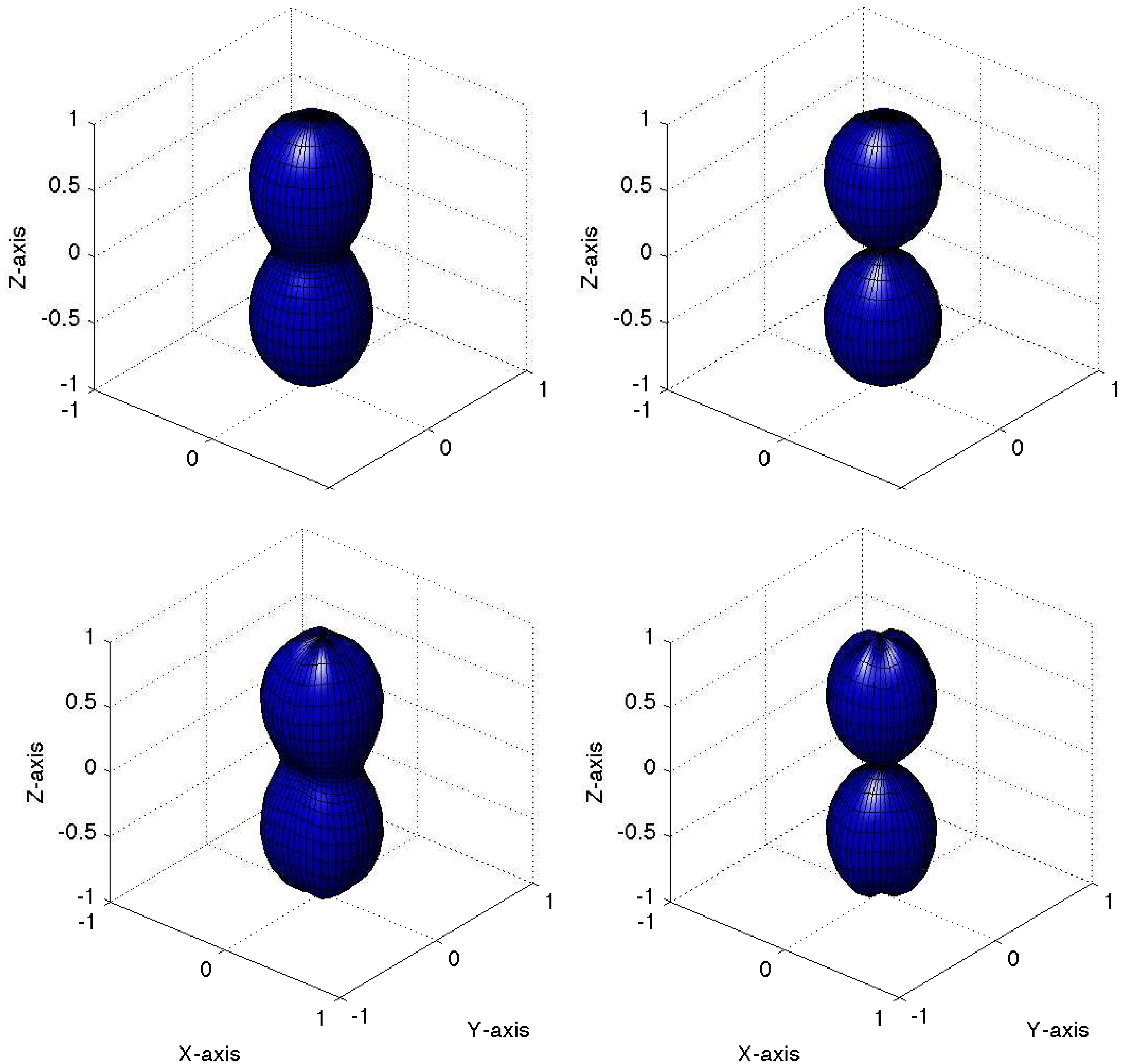
Binary Waveforms

- Power and polarization depend on orientation of orbital plane.
- Low frequency sources (eLISA) have very small power radiated, can approximate by monochromatic waves.

$$h_0 \propto \frac{M_1 M_2}{(M_1 + M_2)^{1/3}} \frac{(2f_{\mathrm{orb}})^{2/3}}{r} g(e)$$

$$h_0 \propto M_{\mathrm{chirp}}^{5/3} \frac{(f_{\mathrm{gw}})^{2/3}}{r} g(e)$$

h_+ $\qquad$ $h_\times$



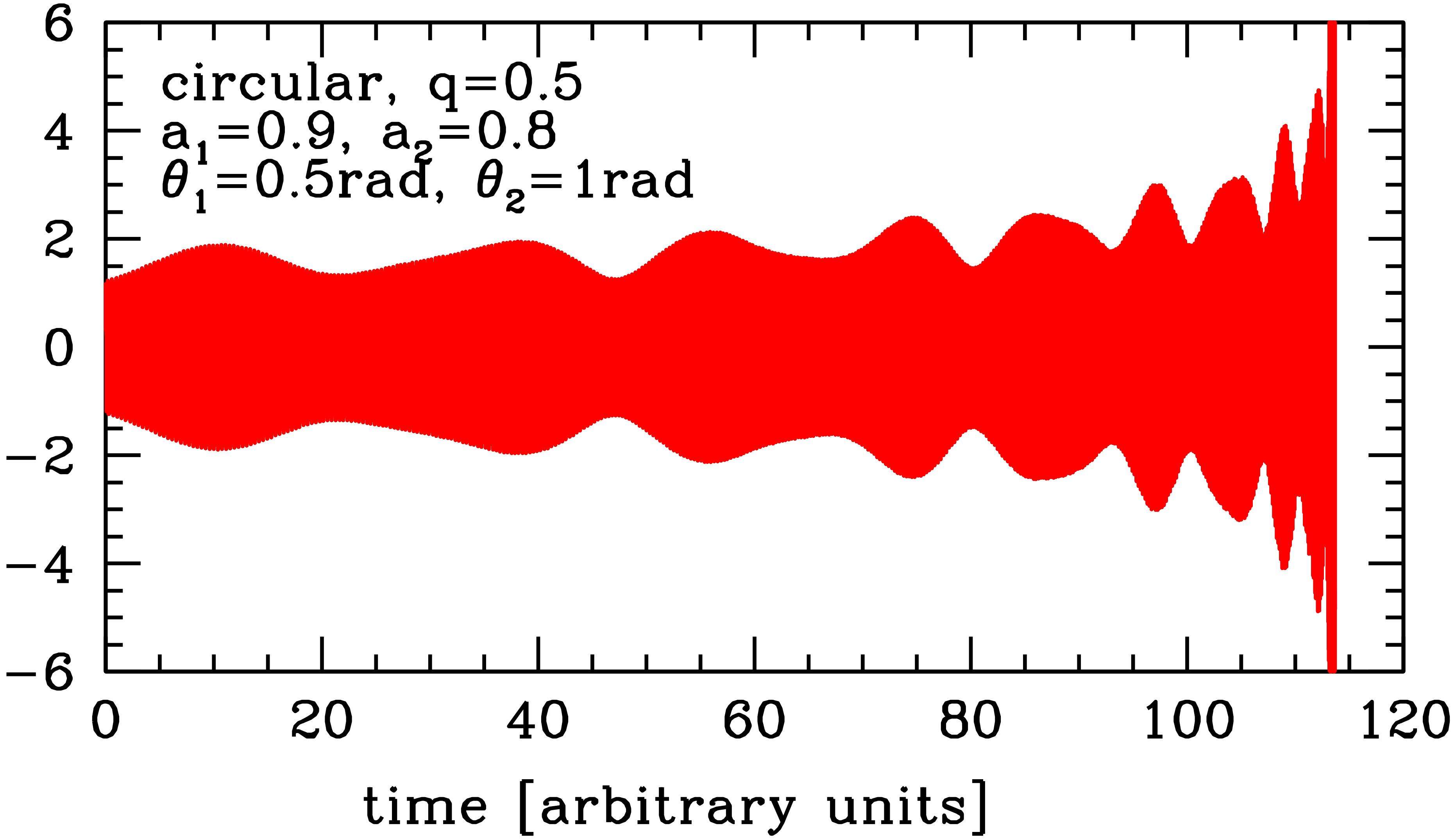
e = 0

e = 0.999

- High frequency sources will include inspiral and merger (and ringdown if final object is a black hole).

- Need NR or PN expansion

- Spins and frame dragging will precess the orbital plane.



- Detection through ‘Matched Filtering’

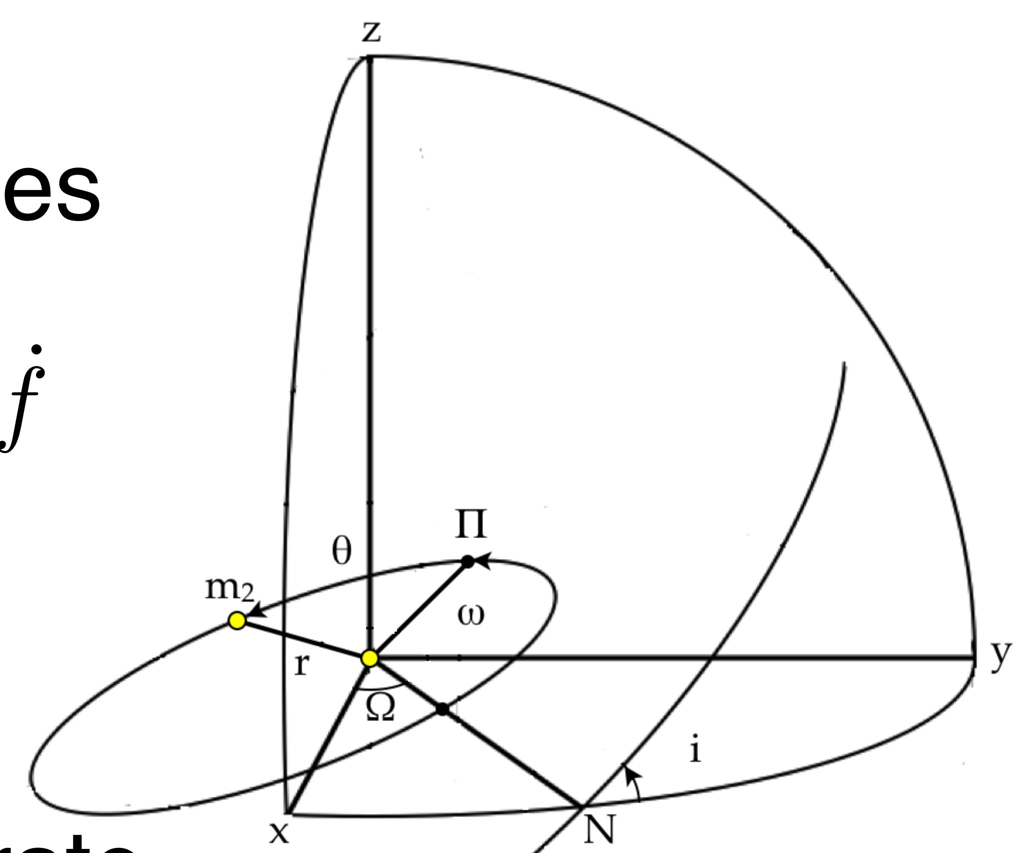
- Model the waveform with parameters for relevant physical properties

- All the usual orientation angles

$$M_{\rm chirp},\ \eta = M_1 M_2/M^2,\ f,\ \dot{f}$$

- Spins, sky location, distance

- Parameters may be degenerate



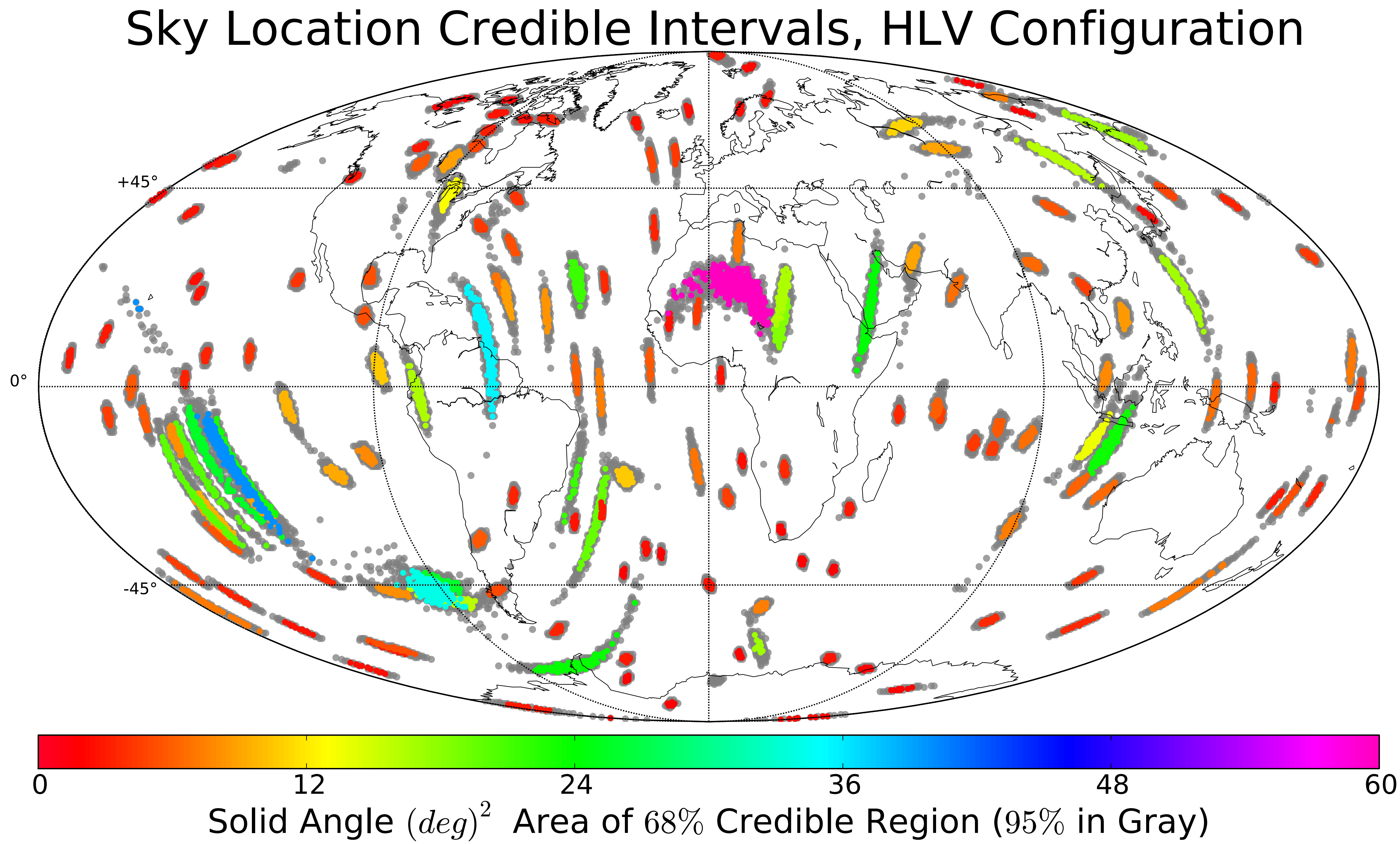


FIG. 6.— The uncertainties on the sky of 160 BNS systems in the HLV detector configuration. Each region represents a single injection, with the colored central region representing the 68% uncertainty region on the sphere, and the gray shade representing the 95% uncertainty region. The color scheme indicates the total solid angle size of the 68% region. Note the similar shape of the uncertainty regions at particular points; this is due to the specific pattern of sensitivity over the sky for the three-detector network.

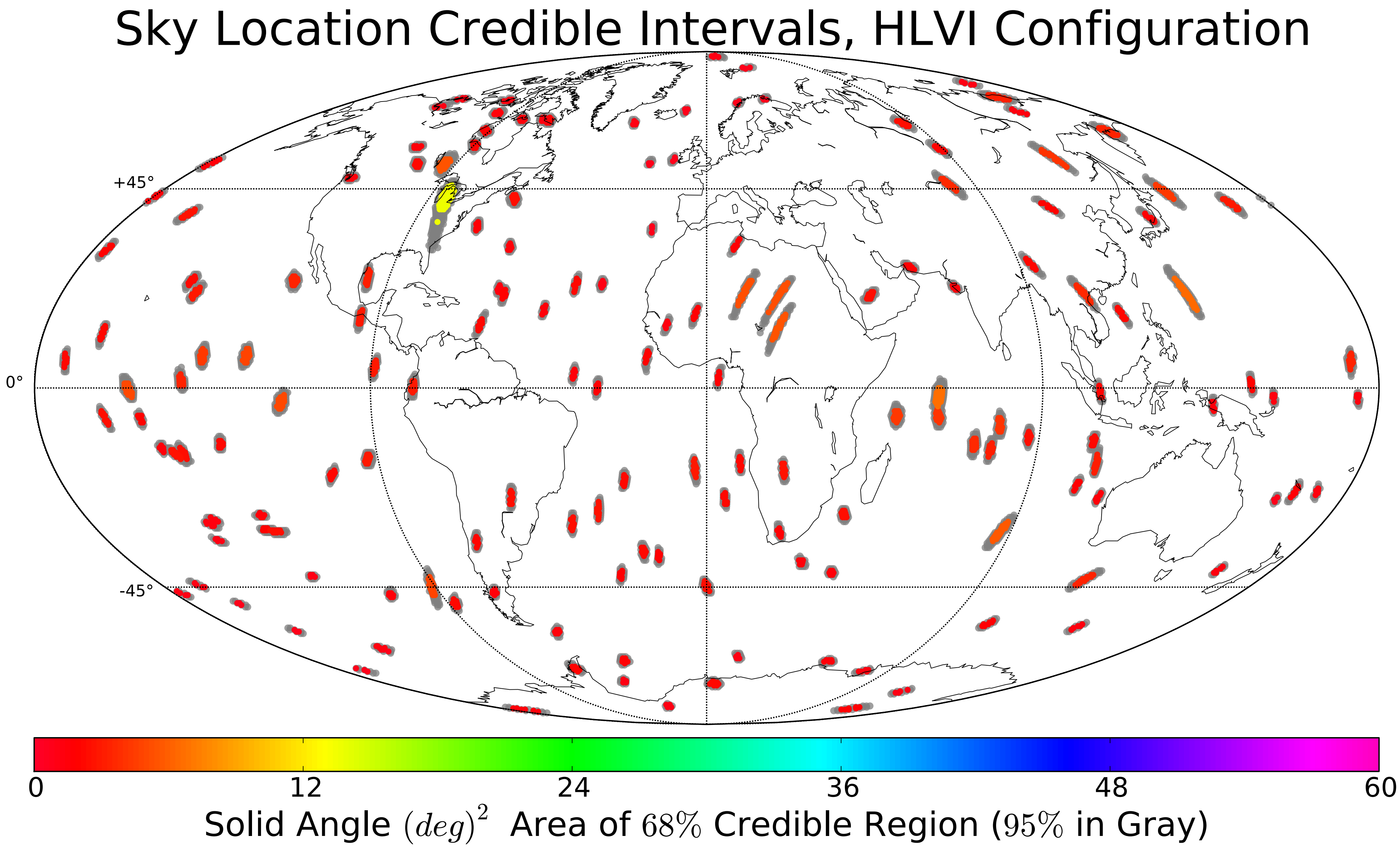
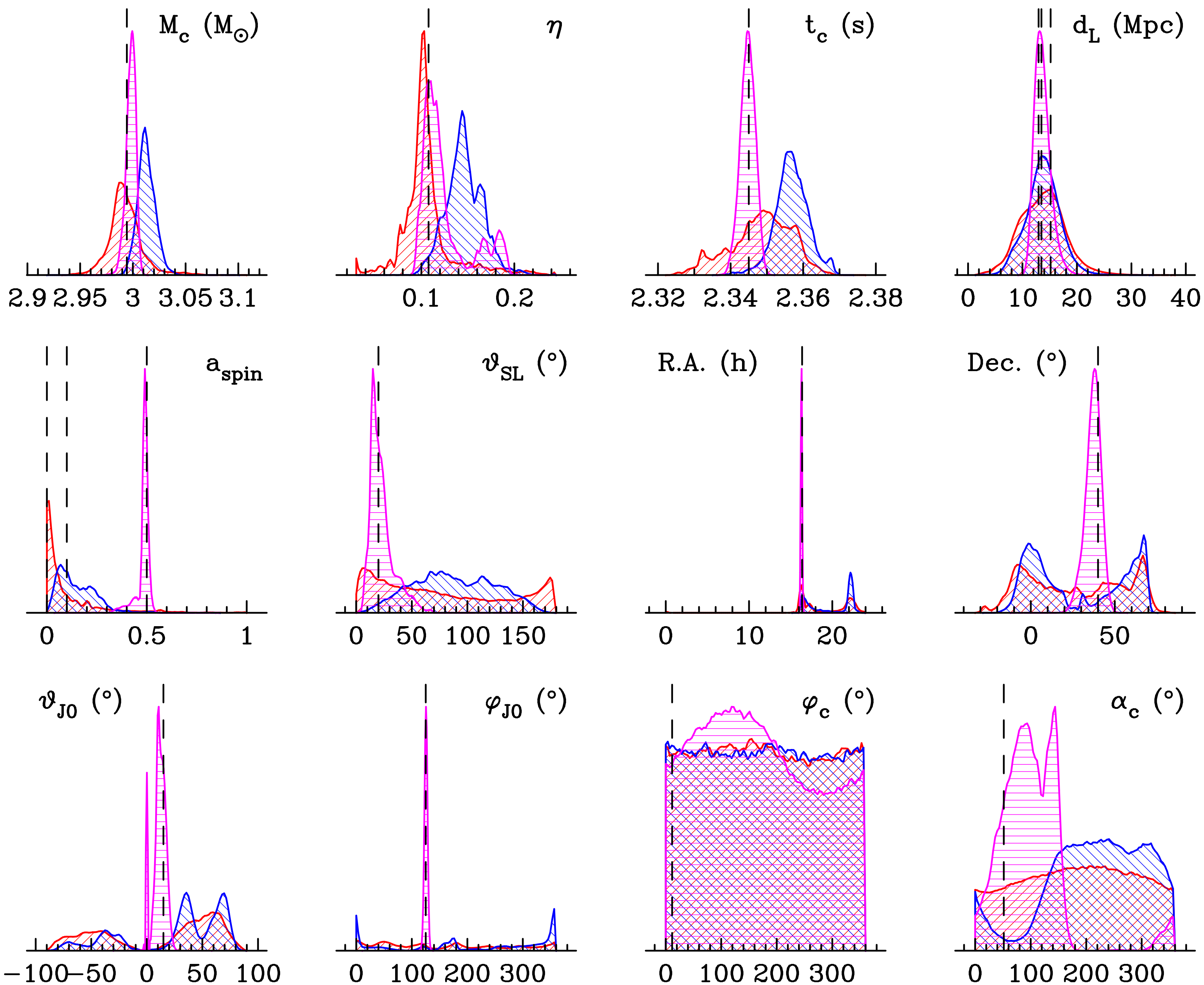


FIG. 7.— The same as Fig 6, except for the HLVI detector configuration. Note the substaintally lower average uncertainties on the skies for the majority of the injections. Also note the lack of large, “banana-shaped” uncertainties that were recovered by the HLV configuration. The two improvements are due to the breaking of the plane degeneracy that is facilitated by the transition to a four-detector network.

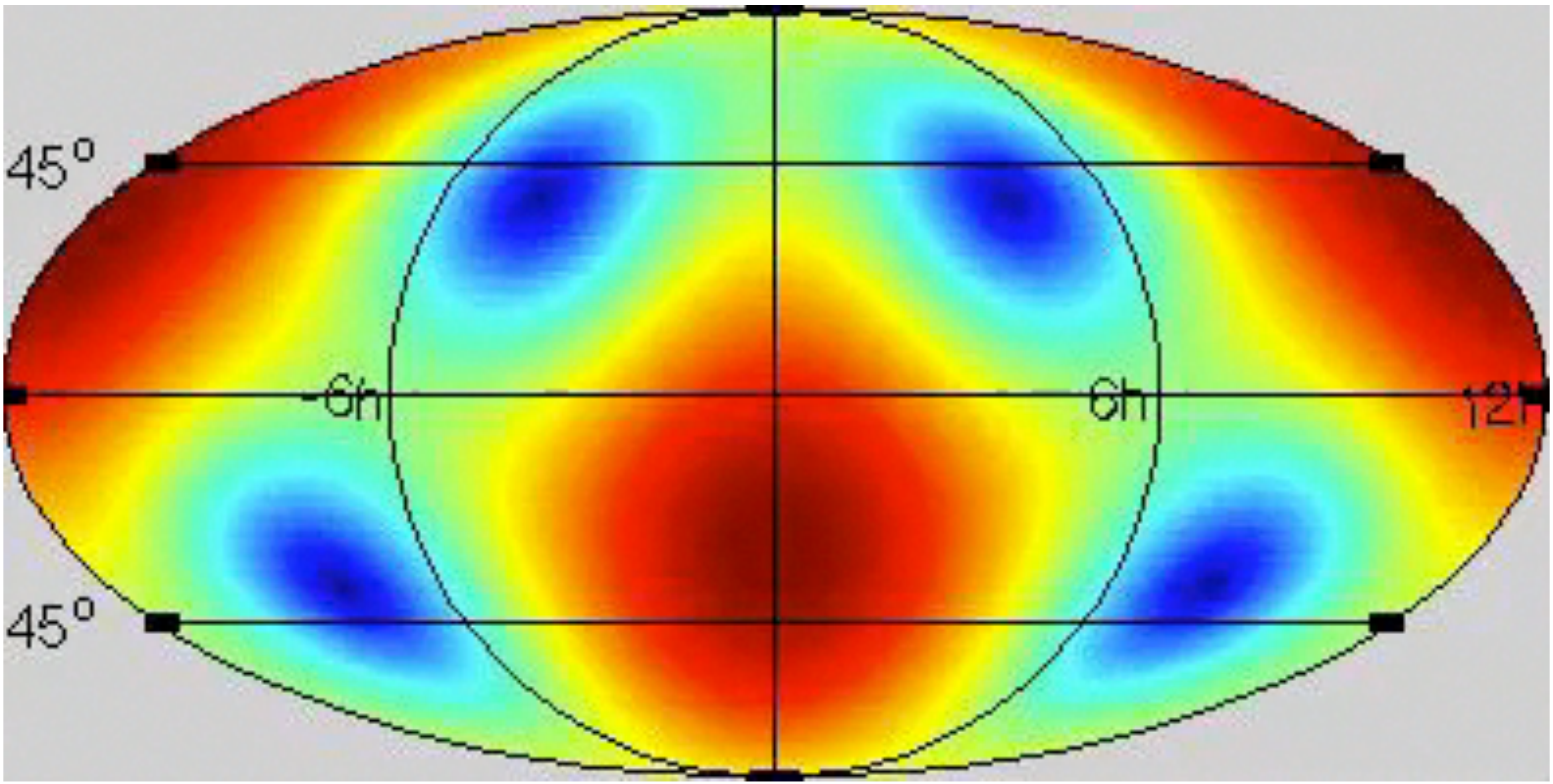


Parameters:

- H1 & L1
- $M = 10, 1.4\, M_\odot$
- $d_L \approx 16 - 21$ Mpc
- $a_{\rm spin} = 0.0, 0.1, 0.5$
- $\theta_{\rm SL} = 20^\circ$
- ΣSNR ≈ 17.0
- Dashed lines show true values
- PDFs scaled to surface area

M. van der Sluys et al. APS presentation 2008 (LIGO-G080185-00-Z)

Localization (PSF)



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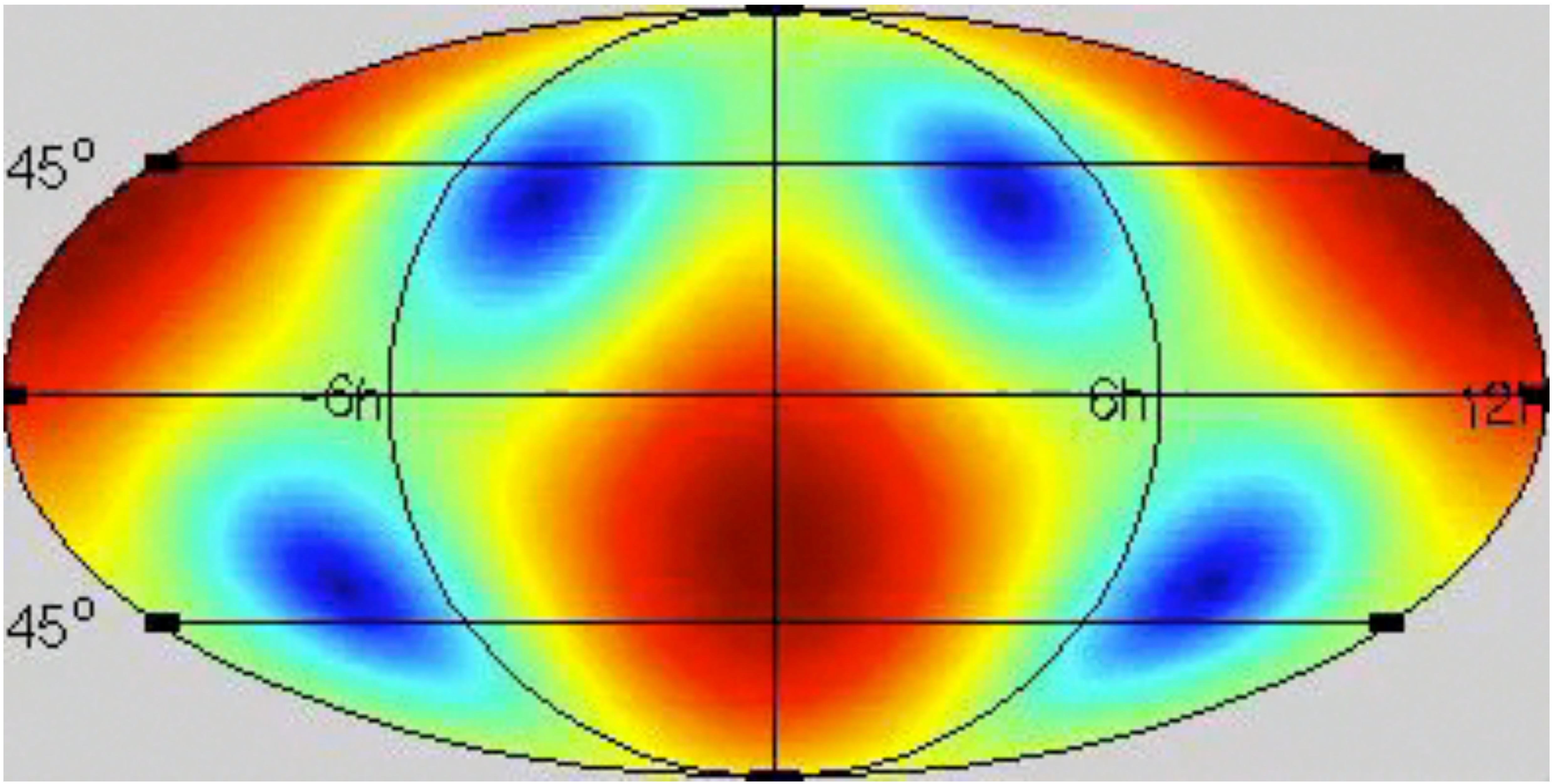
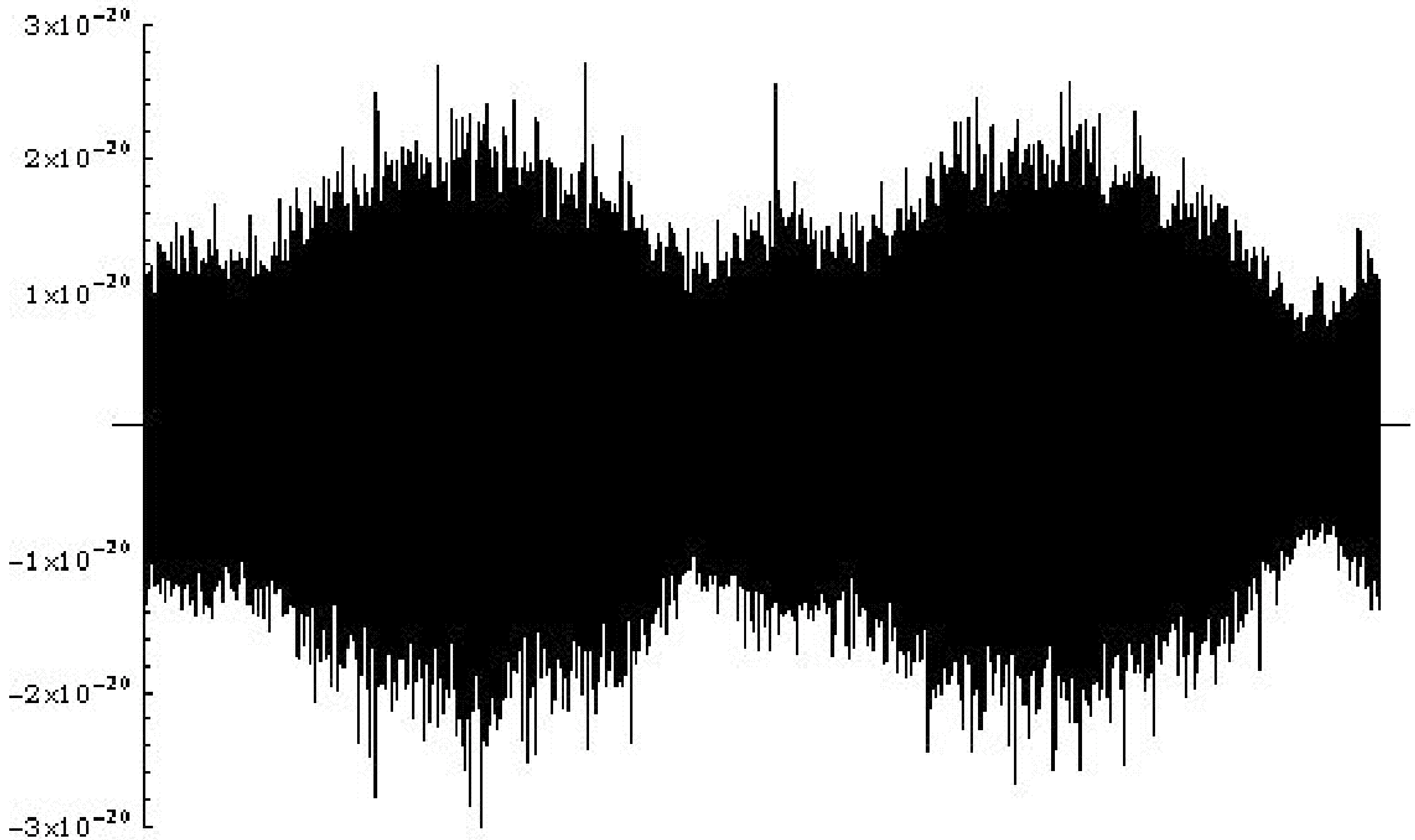
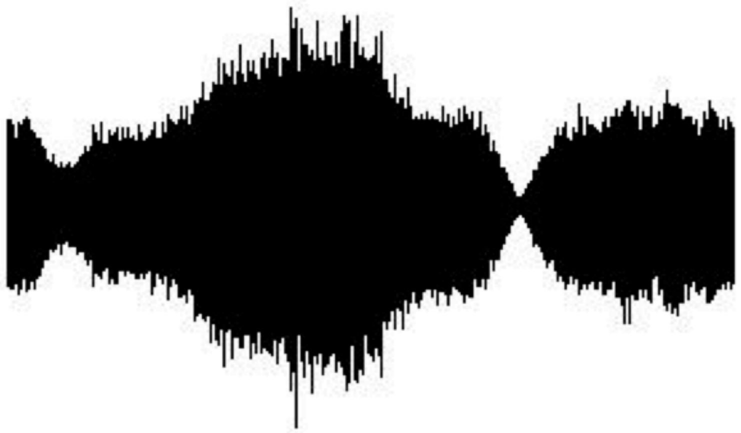


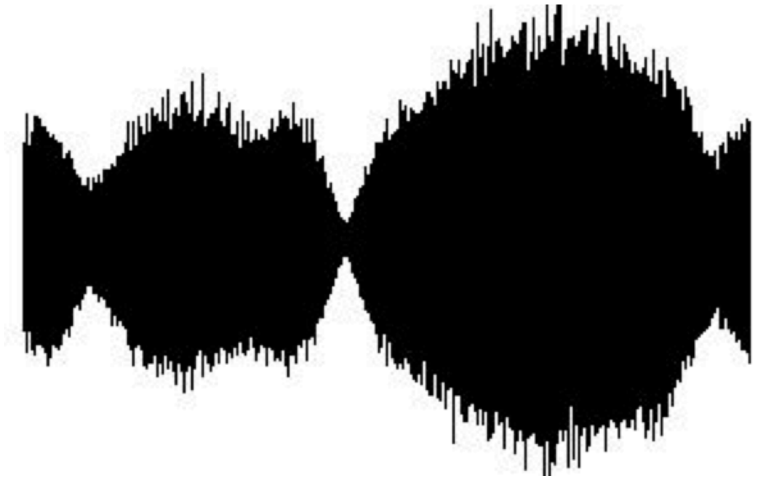
Amplitude Modulation



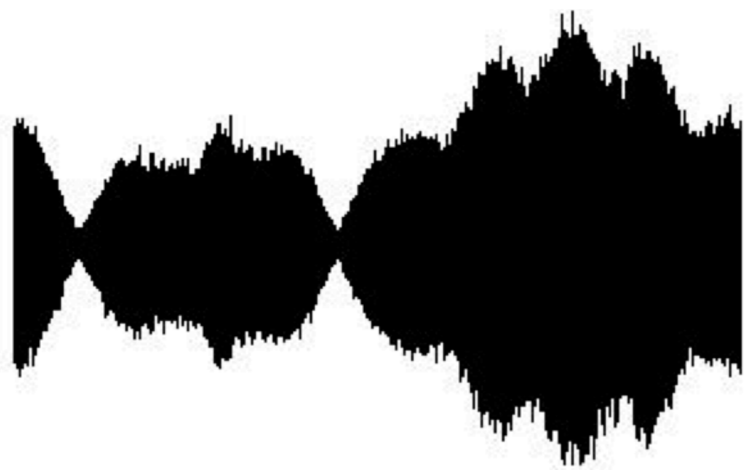
MJB, De Goes, Lunder 2004



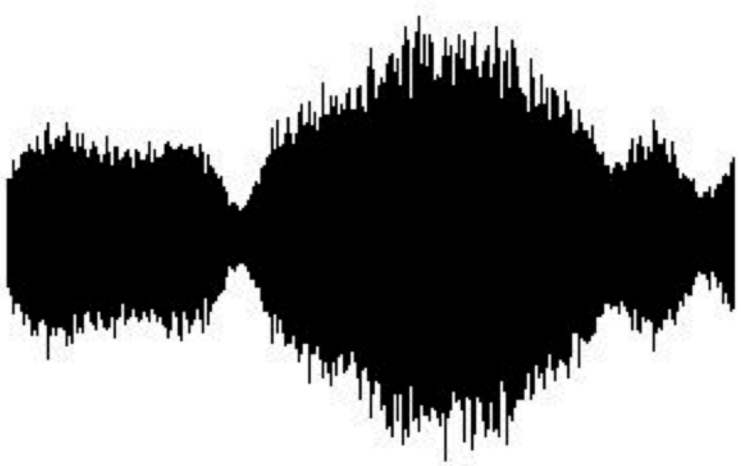
NGC 7808



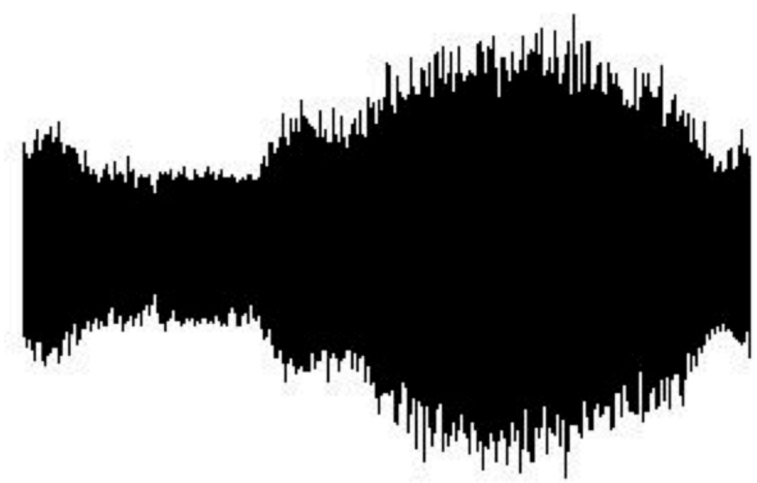
NGC 6397



NGC 6752



NGC 5139



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Detections with LIGO/Virgo are expected in ~2016-2018.

After the first detection …

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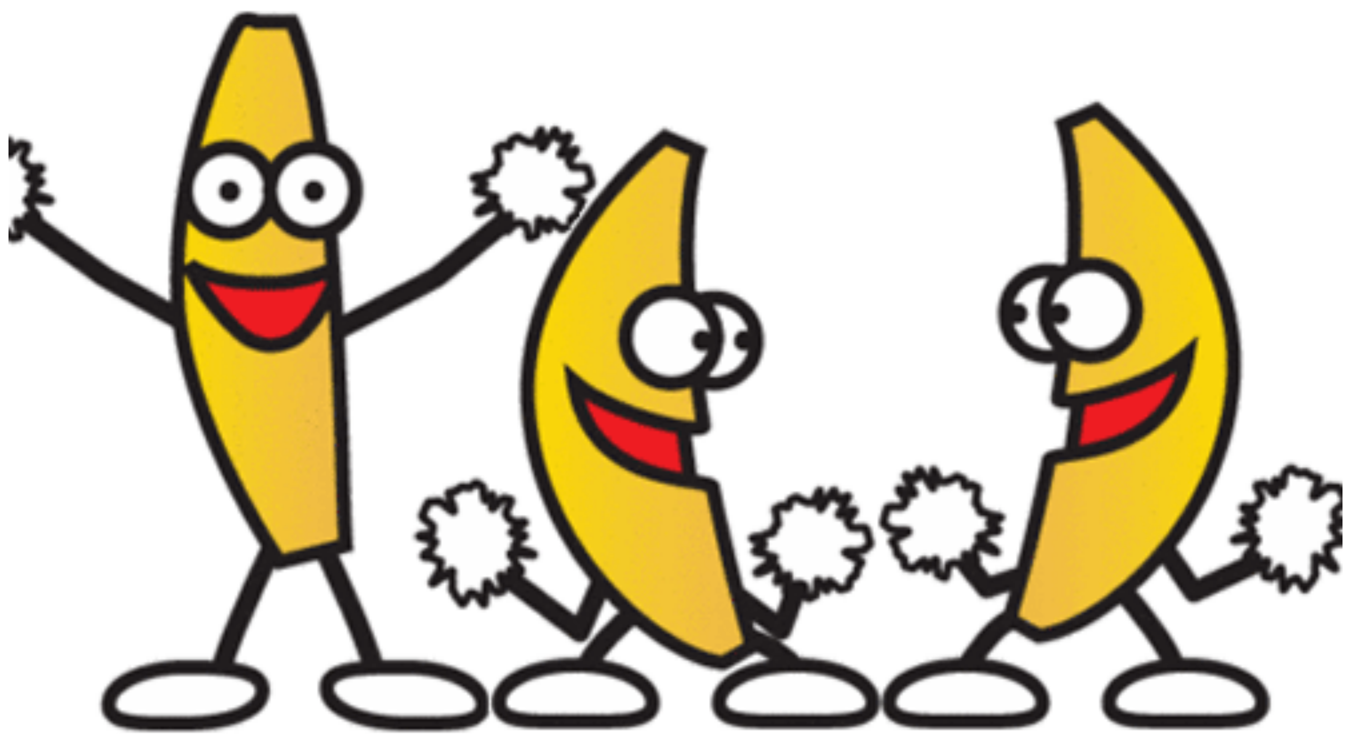

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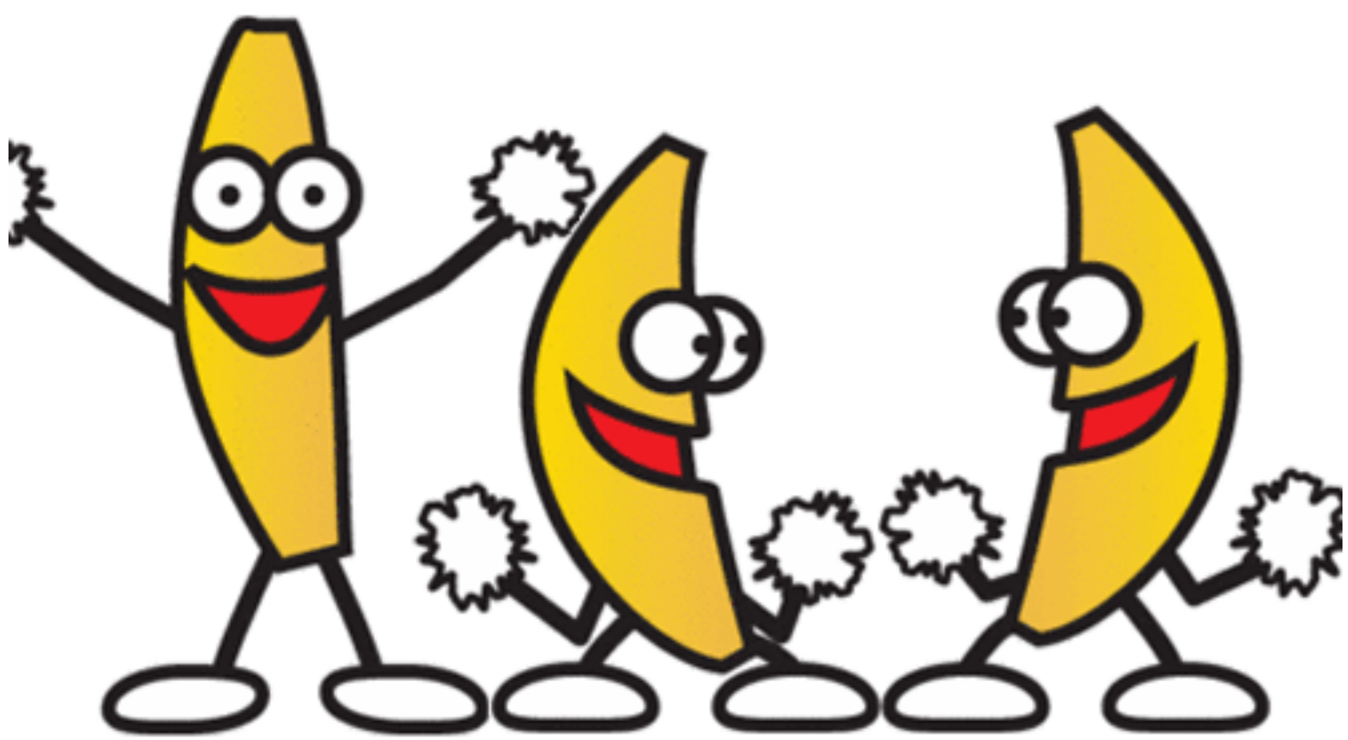

… but then what?

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After the first detection …

SCIENCE !

… but then what?

Galactic Globulars

- Most likely to be LISA sources.
- Angular resolution ~ 1 square degree.
- Can use targeted searches.
- Will identify all sources within a given globular.
- More detail on sources in today's talks.

Some comments …

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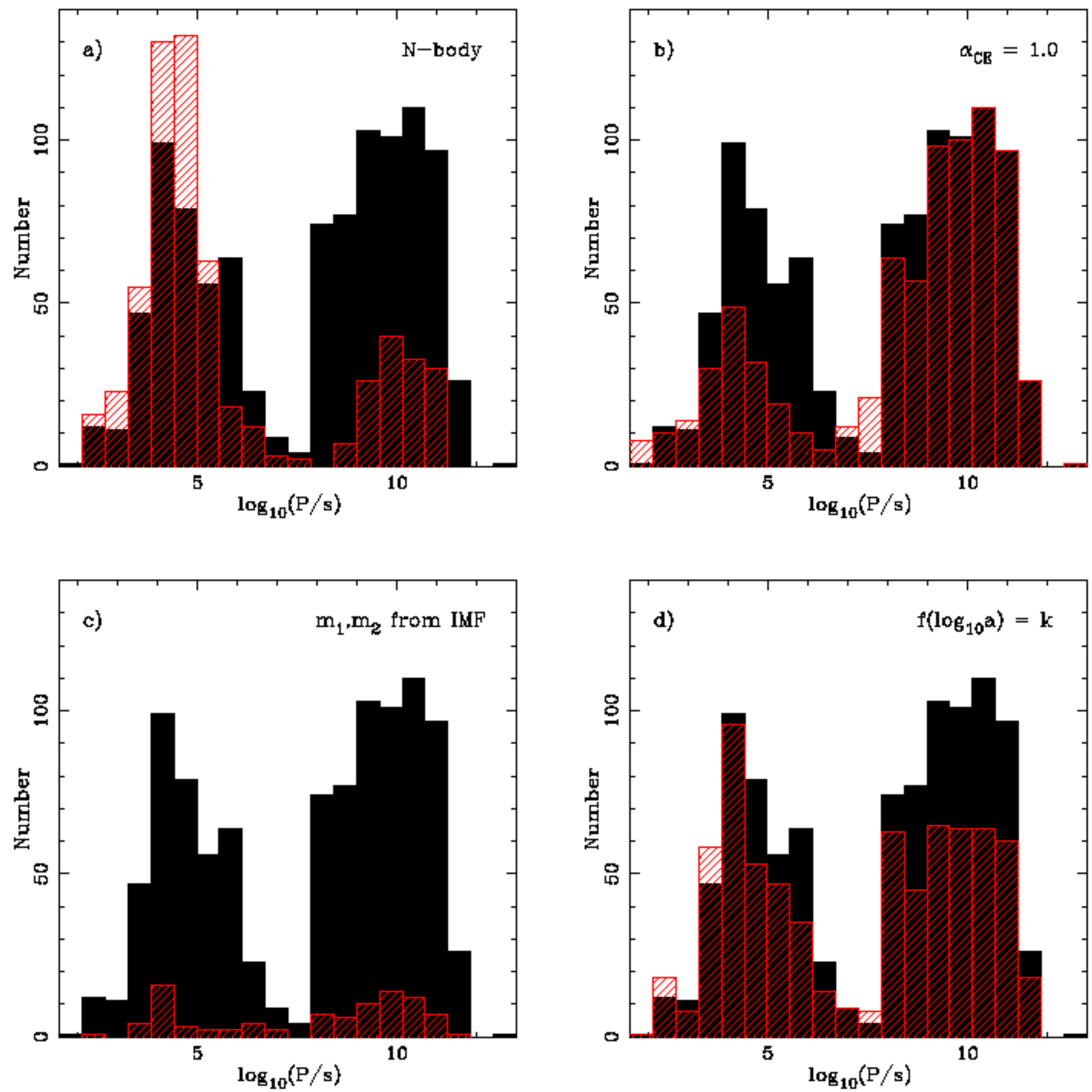
Some examples of questions that may be answered by eLISA observations:

Close white dwarf binaries in globular clusters

Modeling the population with standard assumptions shows an enhancement of short period systems over the field population

Varying these assumptions produces significant variations in the population.

eLISA would provide a census of the shortest period systems.



Hurley & Shara, 2003

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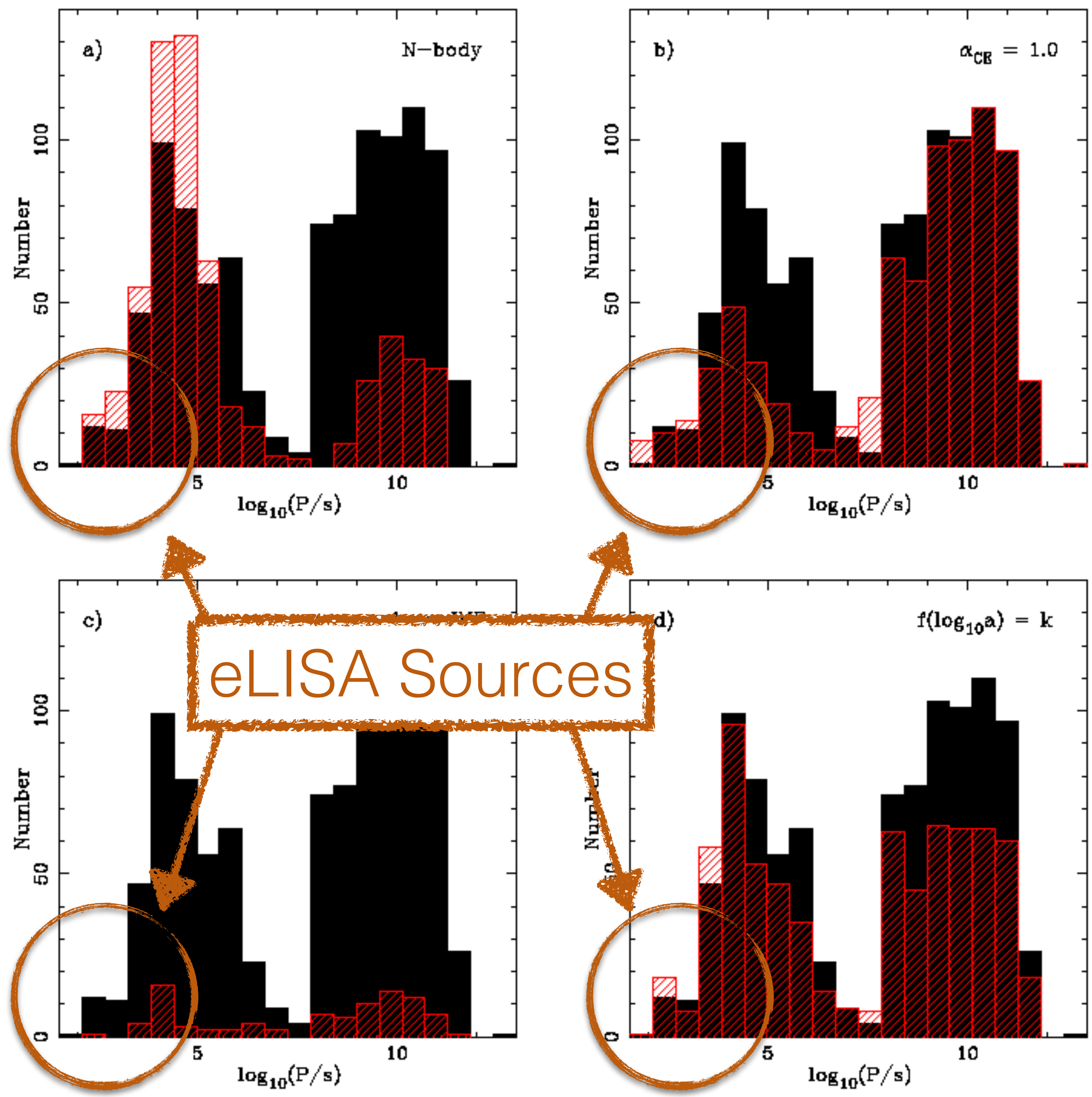
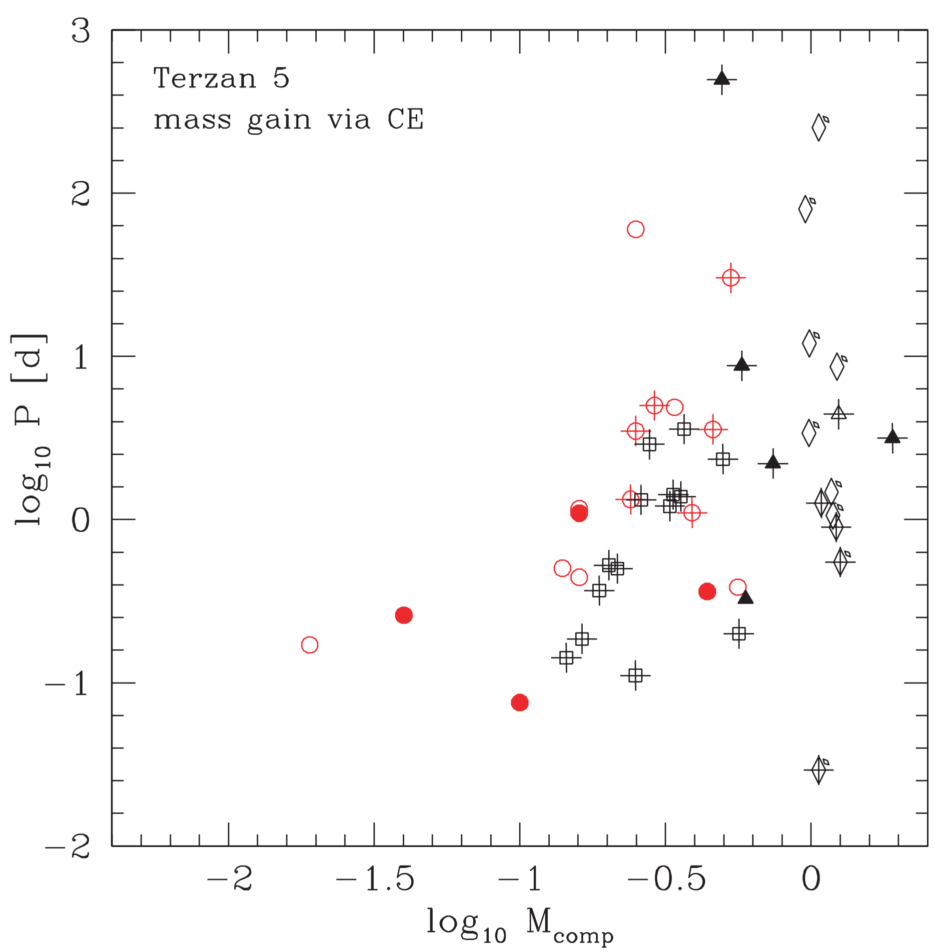


Hurley & Shara, 2003

Neutron star binaries (progenitors of LMXBs, MSPs)

- Observable objects are current and post MT.
- Pre-MT inspiral phase are best GW sources.



Ivanova +, 2008

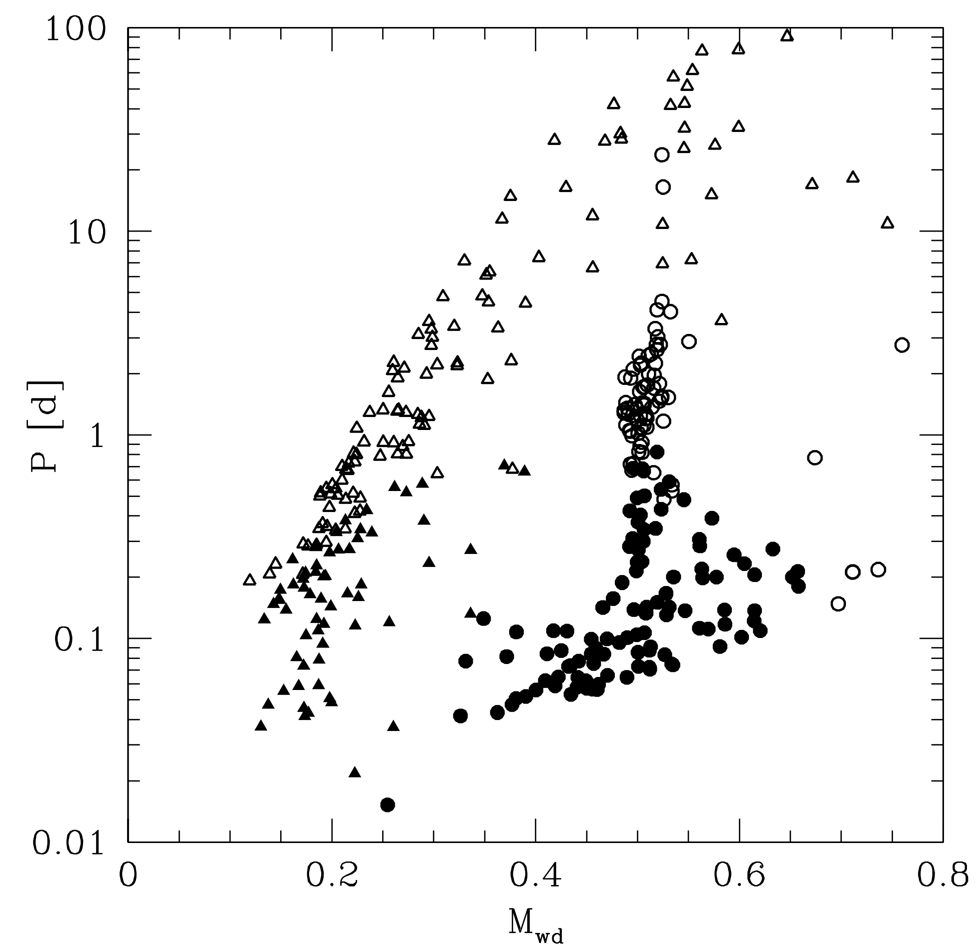


Figure 3. Companions in binary systems formed via physical collision with a RG during the scattering experiment ($Z = 0.001$). The triangles are WDs, the circles are He stars; the solid symbols denote the systems that started the MT before 11 Gyr.

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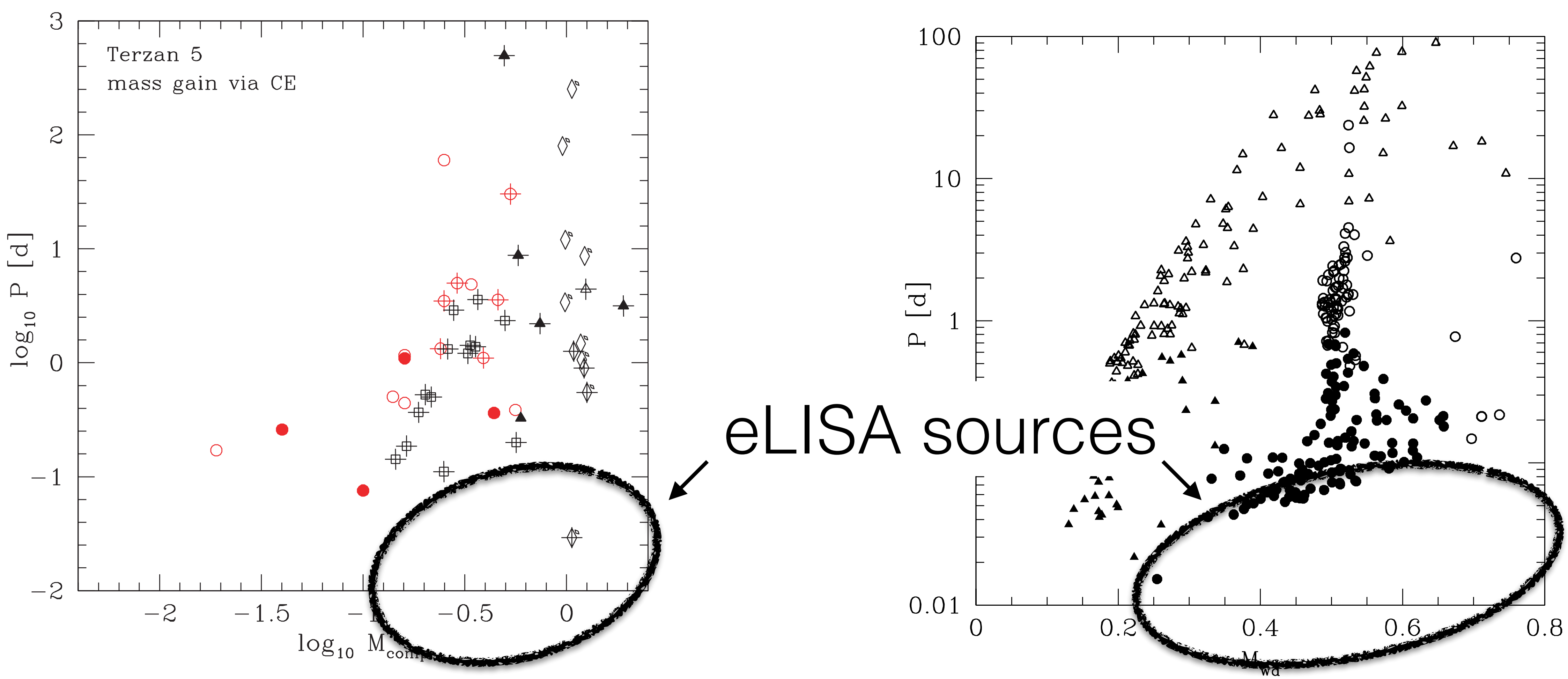

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Binary Black Holes

- Binary black holes retained by globular clusters will have a spread in eccentricity due to continued interactions.
- BBH ejected by clusters will have lower eccentricities due to circularization through emission of GW.
- Unlikely to be seen in Galactic Globulars

Downing +, 2010, 2011

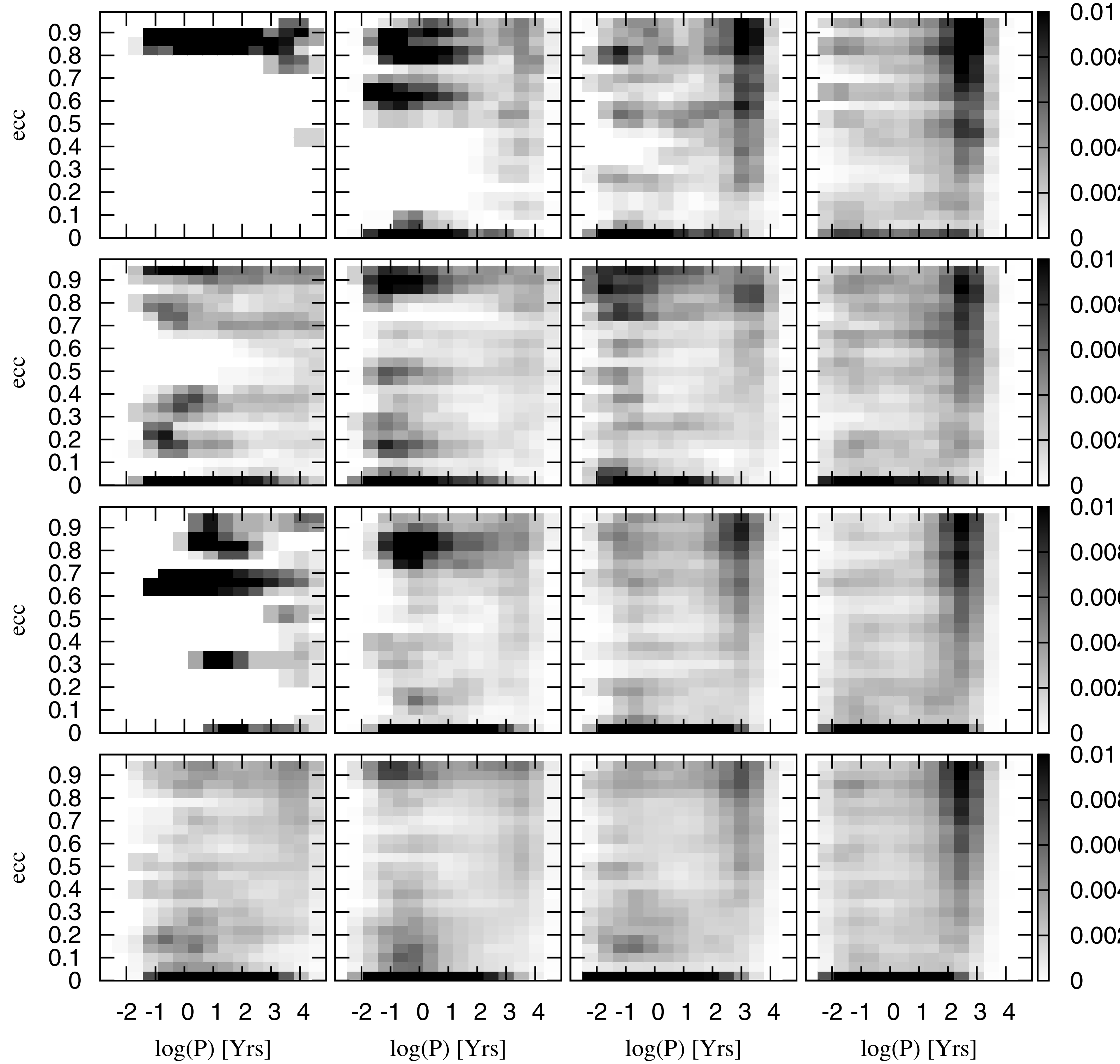
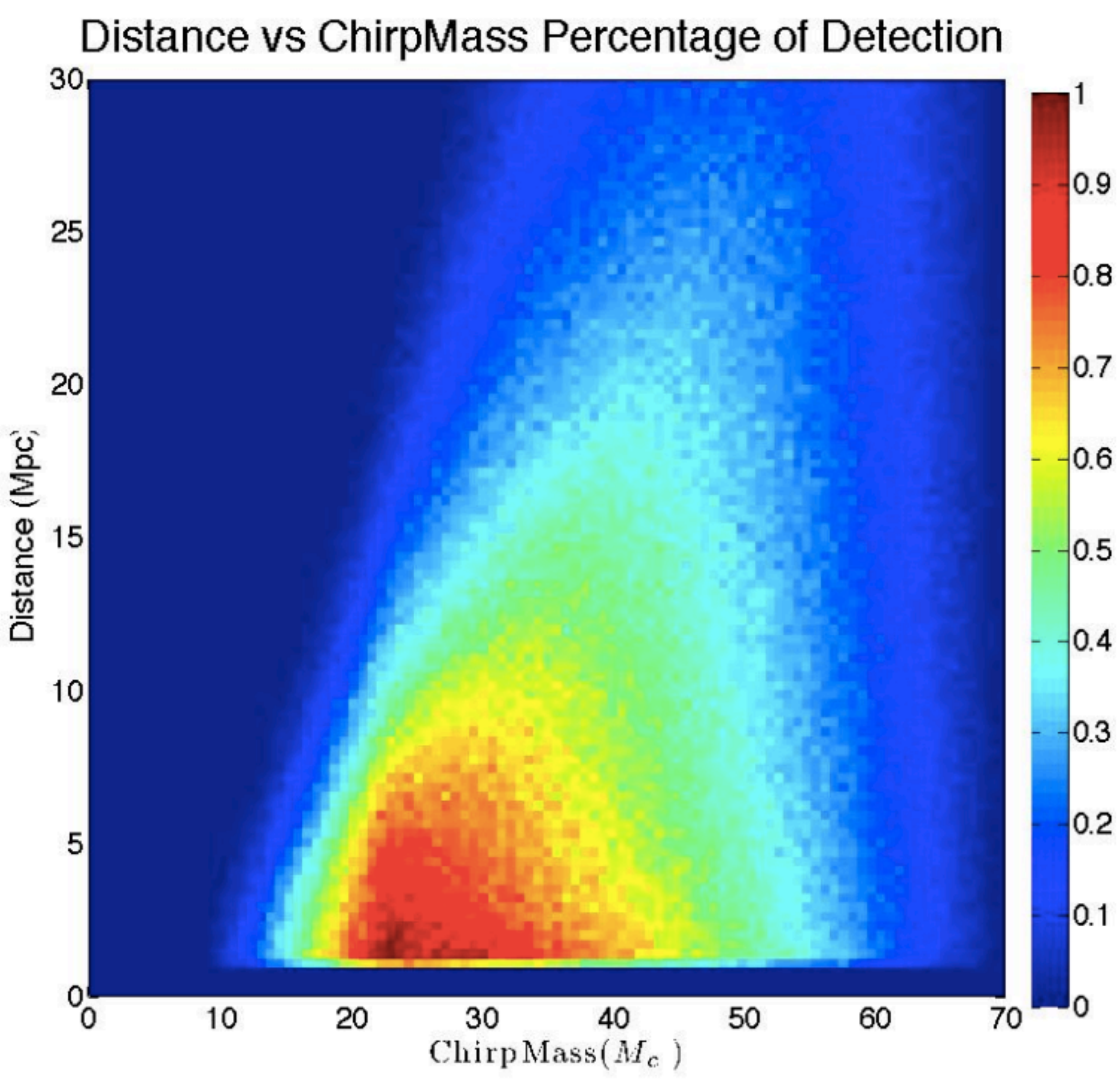


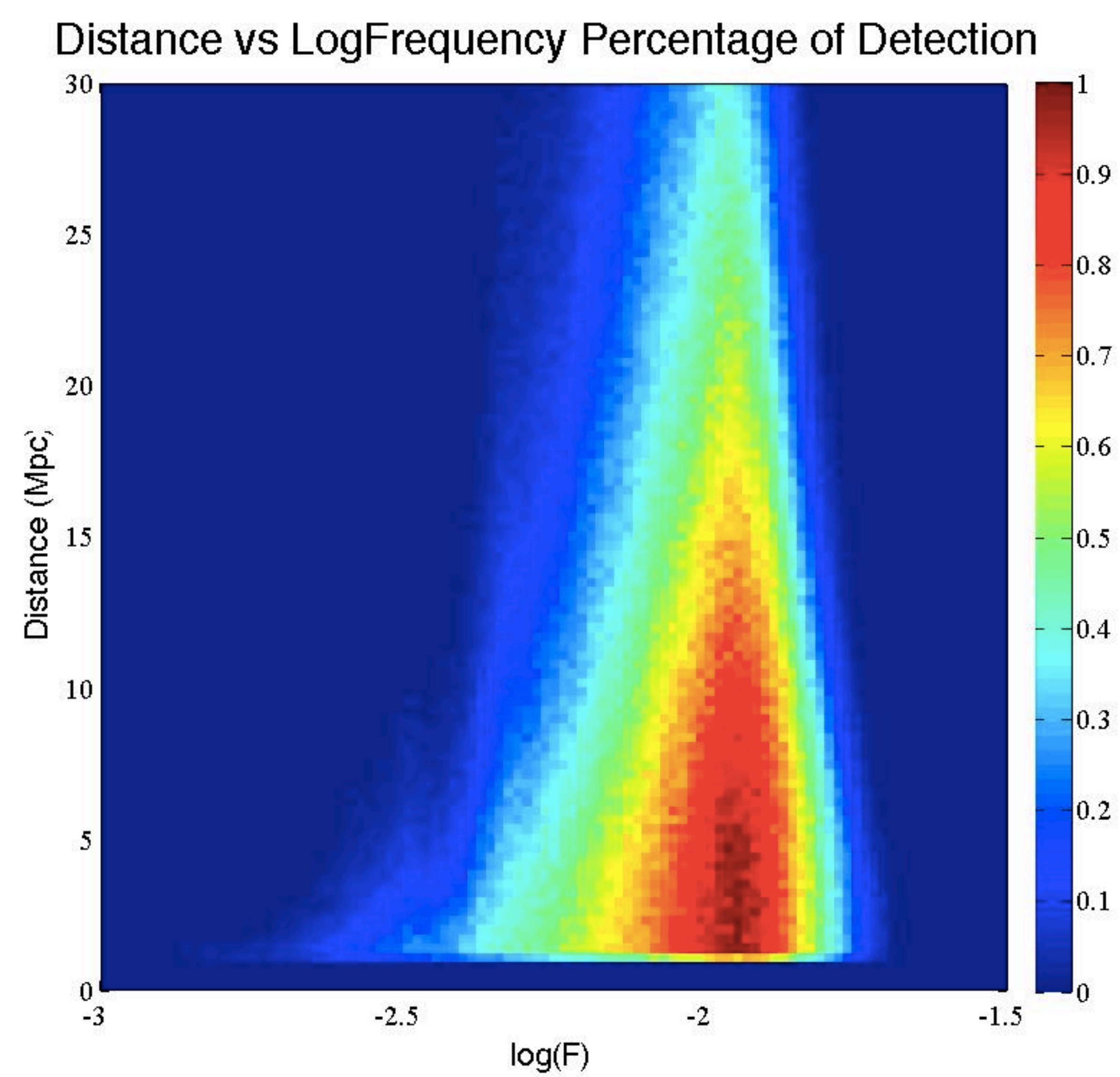
Figure 8. The eccentricity as a function of period for all BH–BH binaries at all times in all simulations. From top to bottom: $f_b = 0.1$ and $Z = 0.02$, $f_b = 0.5$ and $Z = 0.02$, $f_b = 0.1$ and $Z = 0.001$ and $f_b = 0.5$ and $Z = 0.001$. Form left to right: $r_t/r_h = 21,\ 37,\ 75$ and 180.

Extragalactic BBH may be detectable to ~20 Mpc

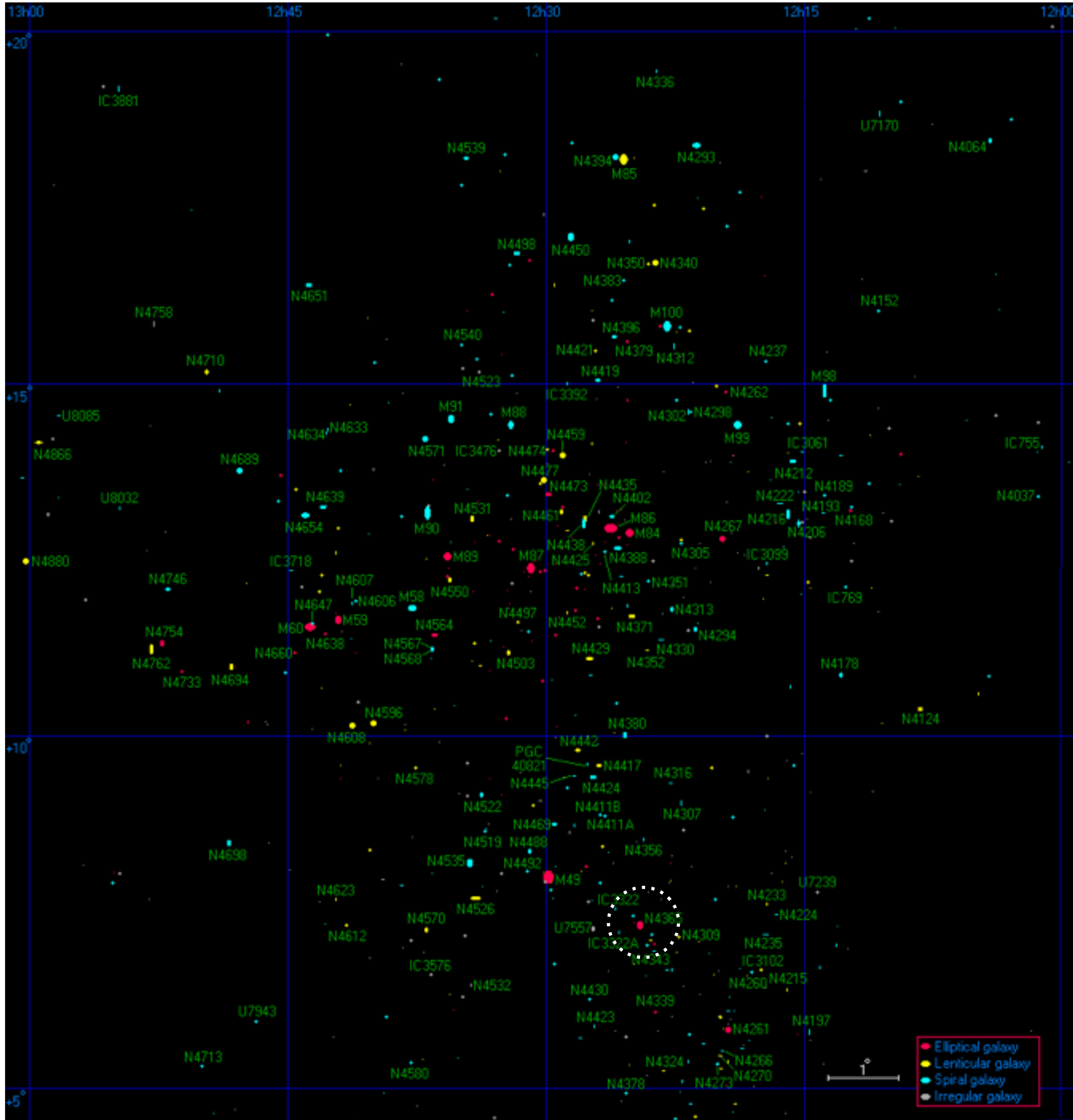
Hinojosa, MB, in prep

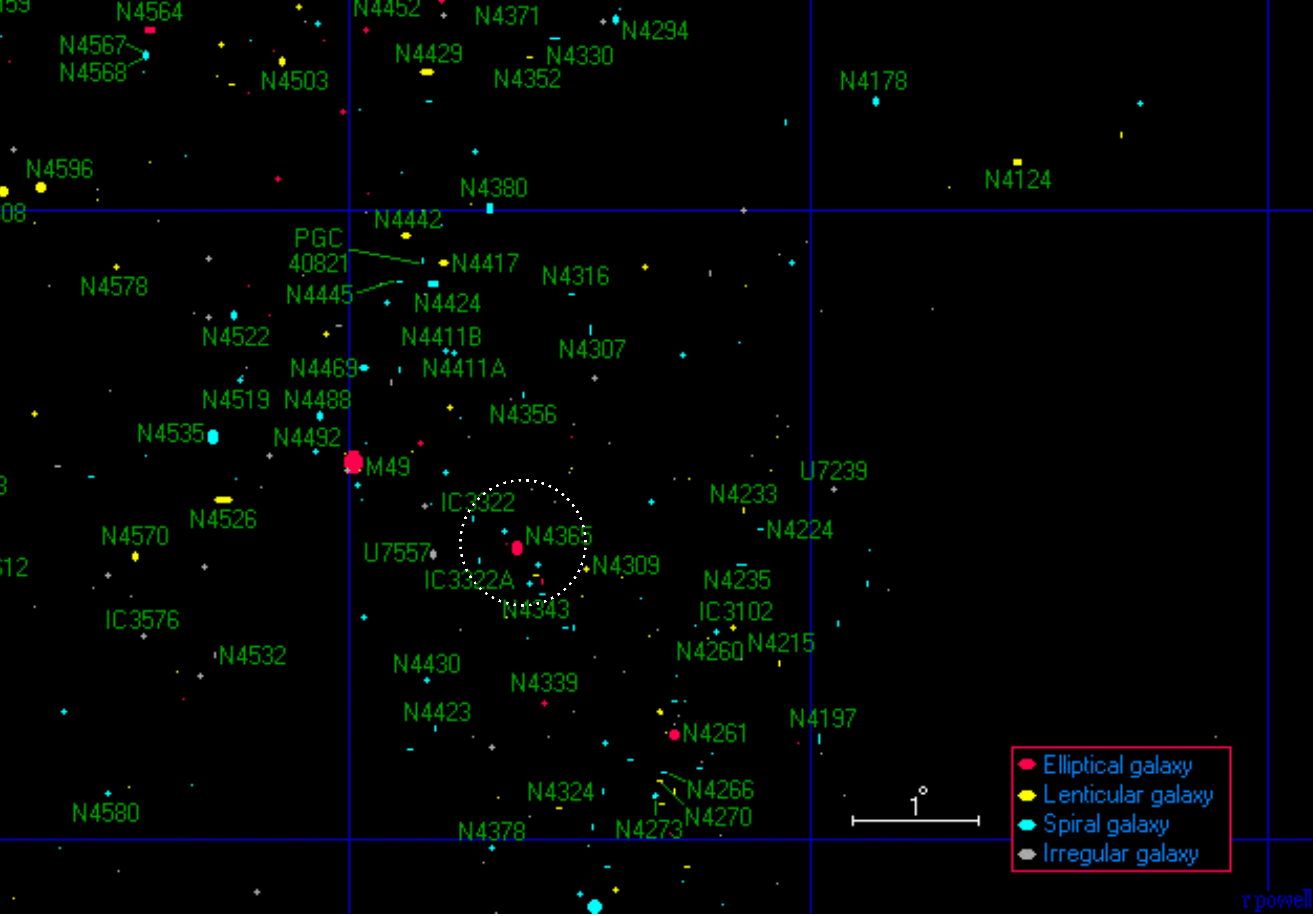
BBH from globulars will be more massive due to low metallicity and dynamical interactions.





eLISA error box superimposed on a chart of the Virgo cluster, centered on NGC 4365 for a typical BBH signal.

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M49
U7239
IC3322
N4233
N4526
N4365
N4224
N4570
U7557
N4309
IC3322A
N4235
N4343
IC3102
IC3576
N4215
N4260
N4532
N4430
N4339
N4197
N4423
N4261
N4266
N4324
N4580
N4270
N4378
N4273
1°
Elliptical galaxy
Lenticular galaxy
Spiral galaxy
Irregular galaxy
r.powell

FIG. 7.— A three color (gri) Suprime-Cam image of NGC 4365, with its globular cluster (GC) candidates marked by small circles. This image is a zoom-in at $\sim 18' \times 17'$ ($\sim 120 \times 110$ kpc) of the original, which is three times the area. An *HST*/Advanced Camera for Surveys image mosaic was also used to select GCs out to $\sim 4'$ from the galactic center. Blom et al. (2012a) determined that NGC 4365 has 6450±110 GCs and that its GC system extends beyond 9.5 galaxy effective radii.

LIGO/Virgo Sources

LIGO/Virgo frequency range of 10 Hz - 2 kHz

Coalescences of NS, BH binaries are in this range.

Rare events — extragalactic clusters.

Binary Type	NS-NS	NS-BH	BH-BH
Range (Mpc)	300	650	1000
Rates (yr	40	10	20

Advanced LIGO website
N.B. rates paper [CQG, **27**, 173001 (2010)] gives horizon distances, which are ~2.26 times larger than the average distance (which we call the range).
Rates paper ignores dynamically formed binaries.

How to distinguish cluster binaries?

- Field binaries may have aligned spins
  - Evidence from mass transferring systems. (XTE J1550-564) Steiner & McClintock, ApJ, 745:136, 2012.
  - Kicks may disrupt the alignment
  - Resonant alignments Gerosa + 2013, 2014
- Star formation rate/delay times
- Cluster binaries should have unaligned spins
- Early epoch of cluster formation plus rapid mass segregation

Conclusion/Summary

- Gravitational waves provide a complementary view of compact binaries compared with e+m waves.

- eLISA will explore ultra-compact binaries throughout the Galactic globular cluster system.

- eLISA may observe high-mass black hole binaries within ~15 Mpc. These are most likely globular cluster sources.

- LIGO/Virgo will observe NS/BH binary coalescences within 300 Mpc → 1 Gpc. Many of these will be dynamically formed.

Commentary

- If dynamical evolution models produce detached compact object binaries with mHz orbital frequencies, consider gravitational waves as additional discriminators.

- Much of LIGO/Virgo event rates do not include dynamically formed systems.

- Additional eLISA sources (e.g.: compact object + smbh/mbhb) are present in galactic nuclei, but are not part of this talk.