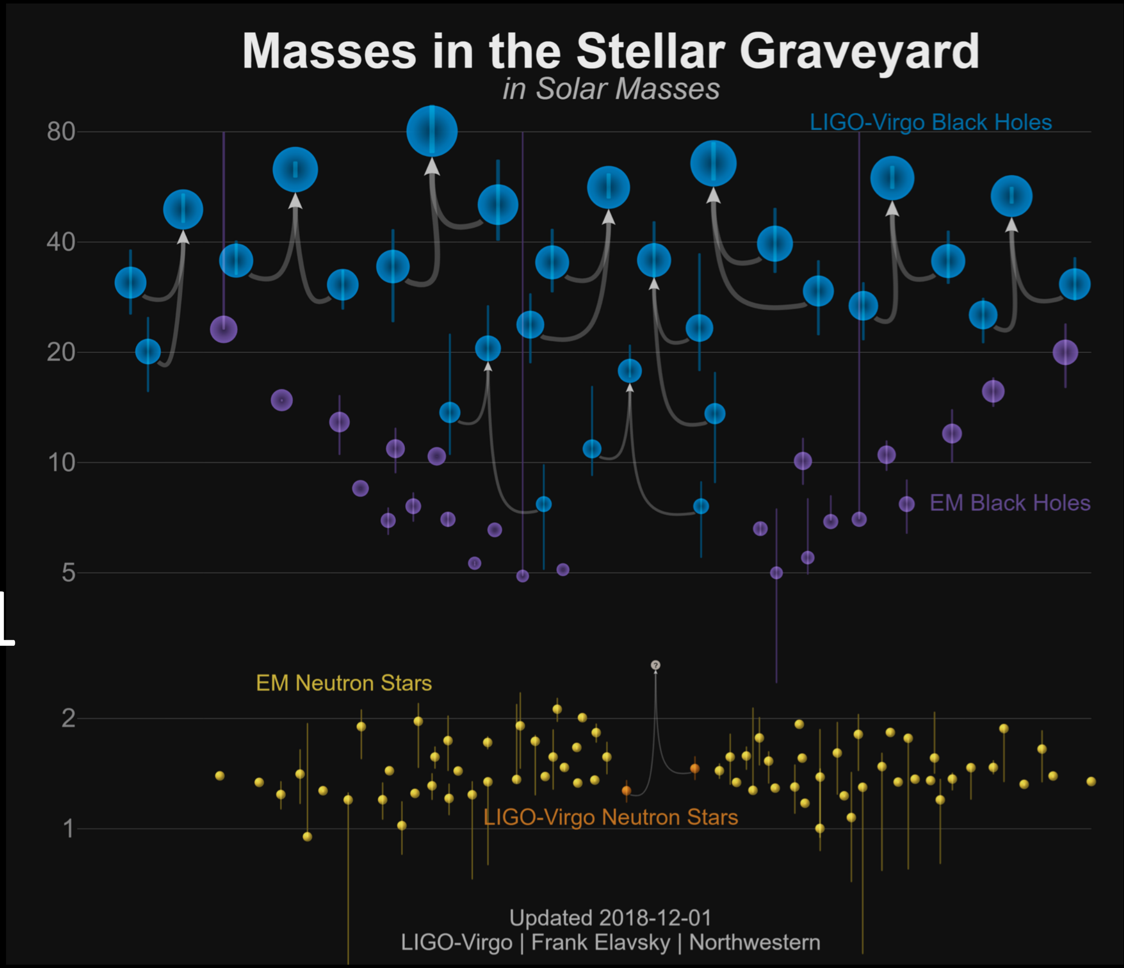
3G Science Case

Salvatore Vitale
MIT

1st Kagra-Virgo-3G workshop
Feb 16 2019

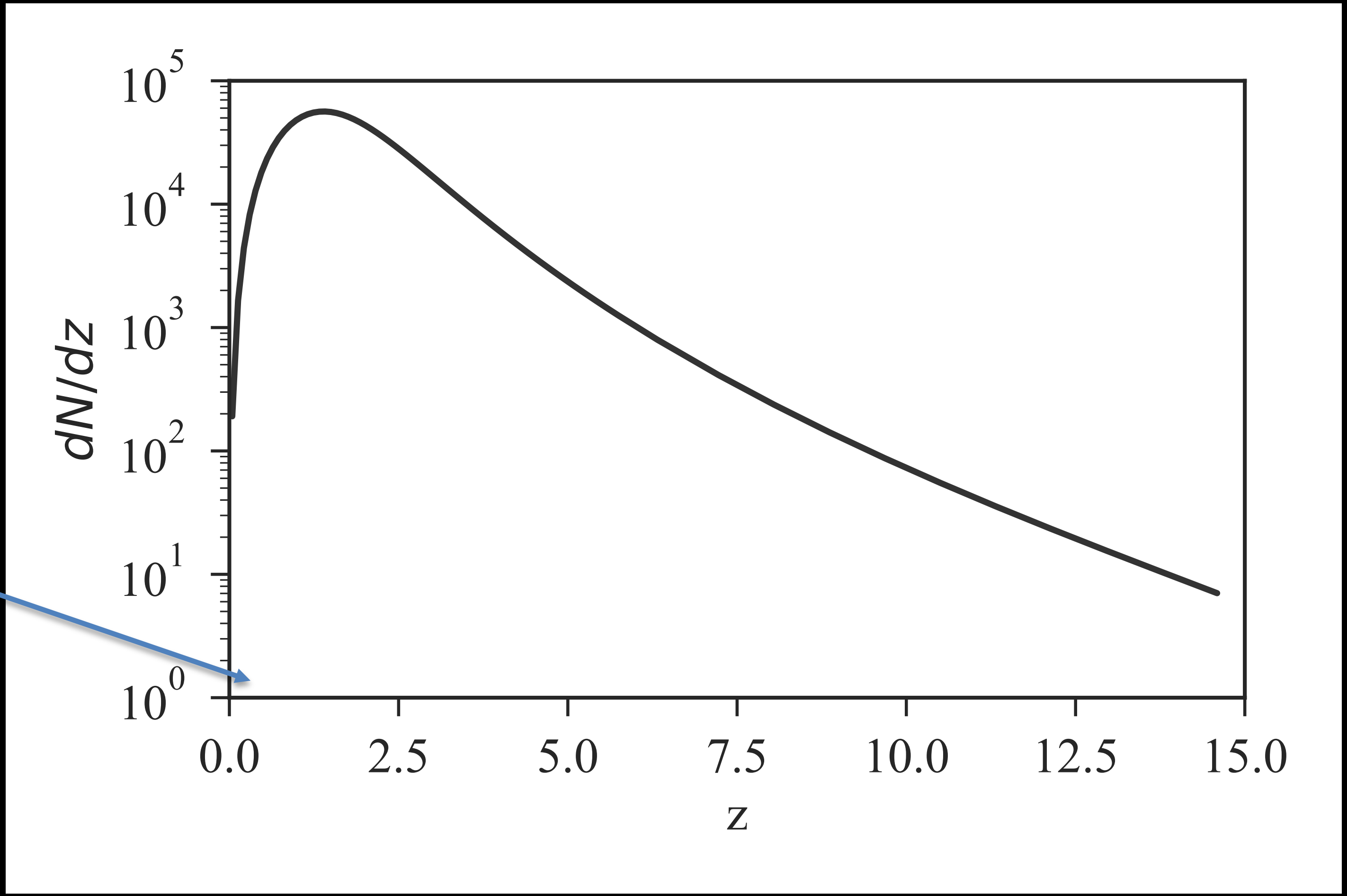
Where are we?

- In the first two science runs advanced detectors have detected
- 10 binary black holes (BBH) LVC, Arxiv:1811.12907
- And 1 binary neutron star (BNS), LVC PRL **119**, 161101, PRX 9 011001
  - Electromagnetic emission also detected!



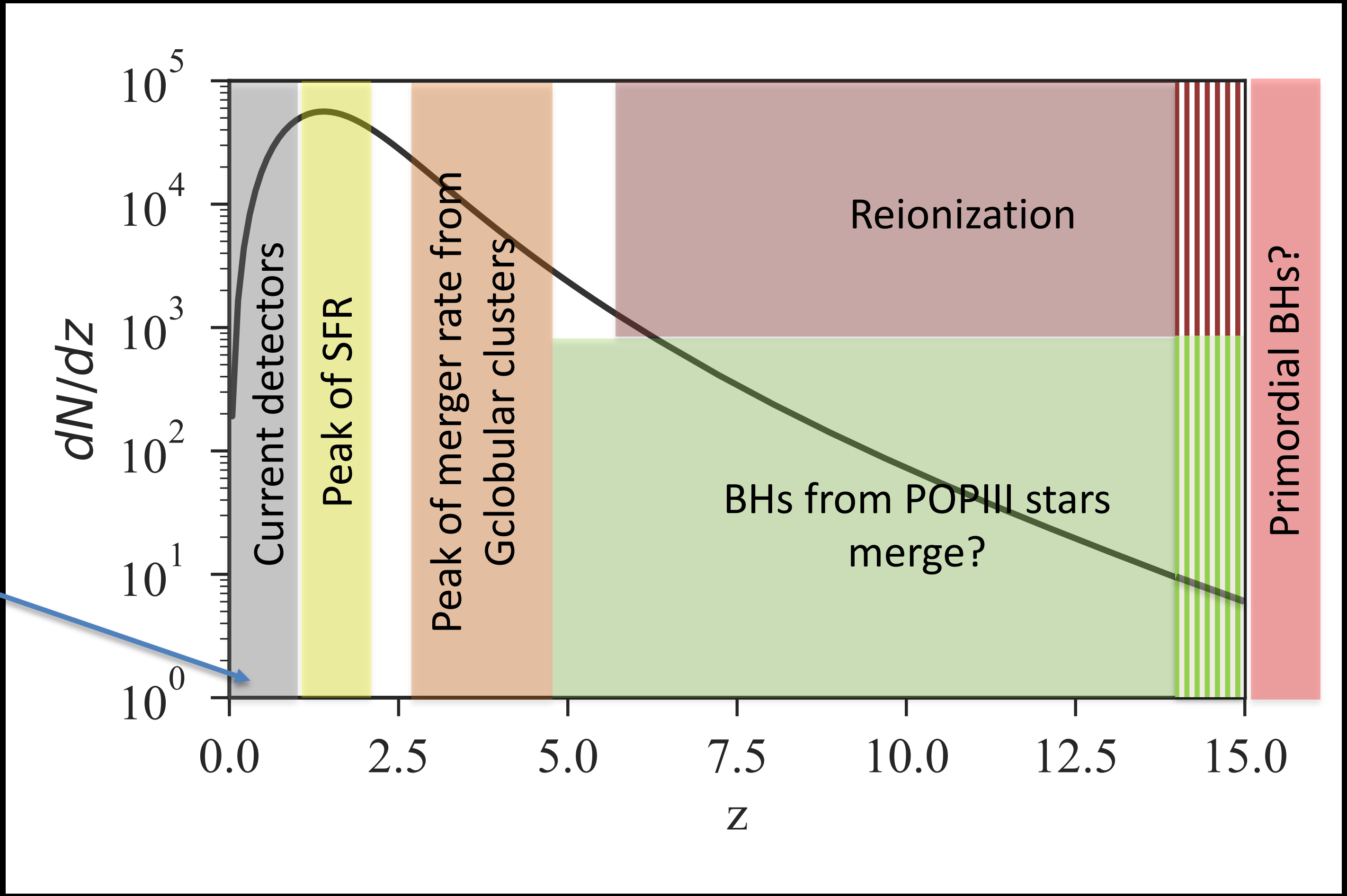
Where are we?

You are here!



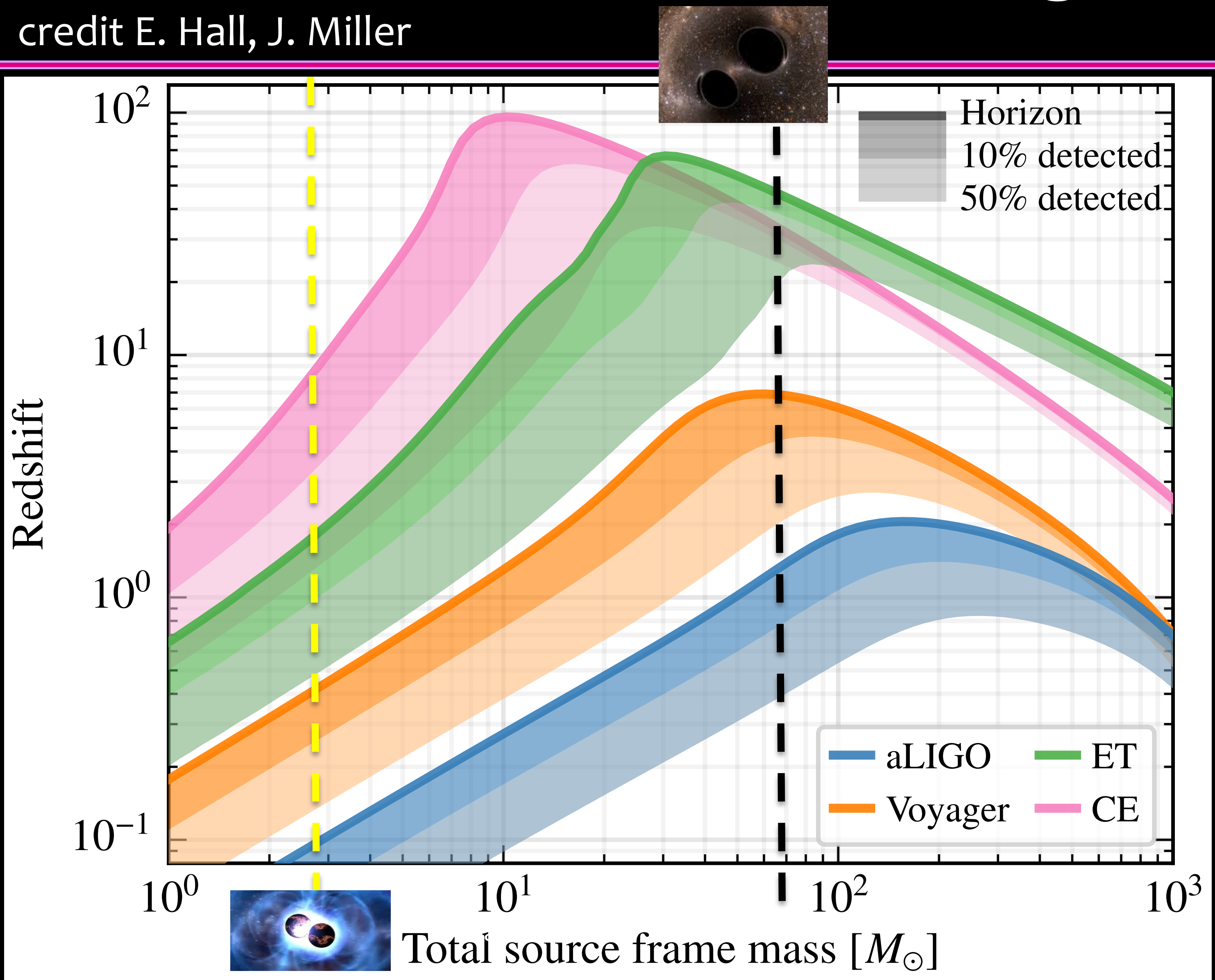
Where do we go from here?

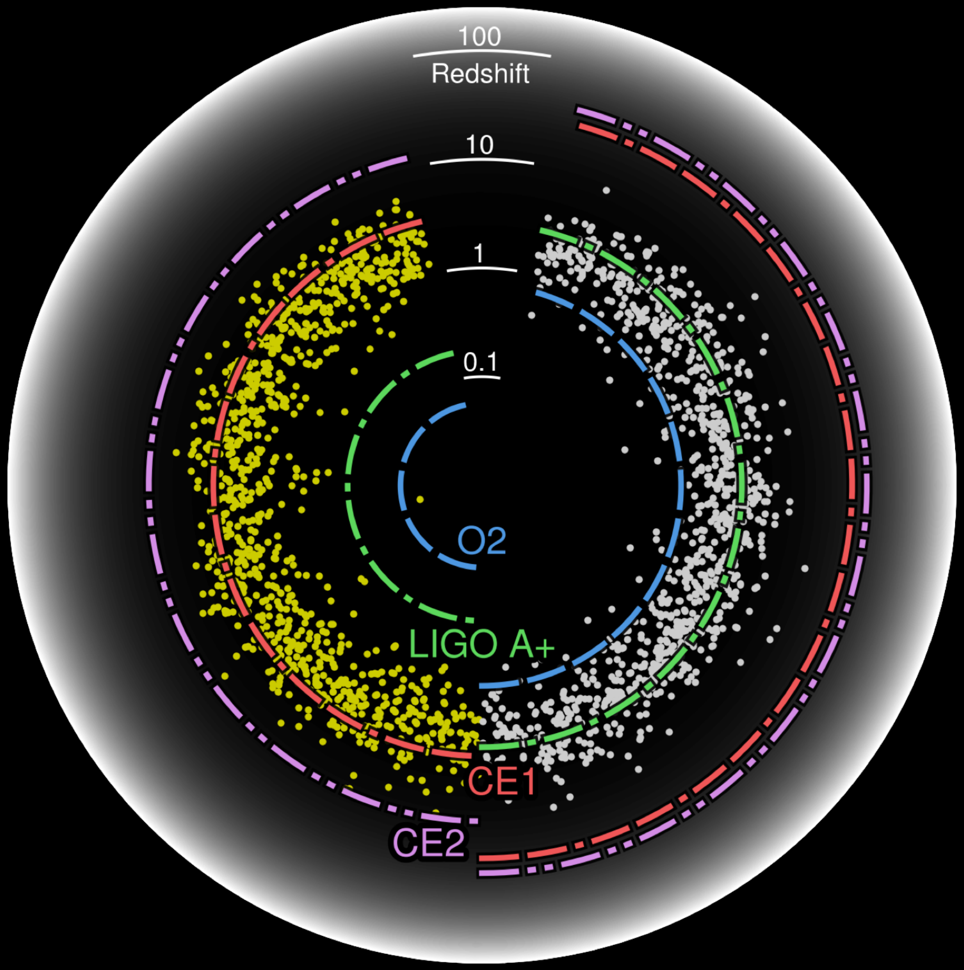
You are here!



Where do we go from here?

credit E. Hall, J. Miller

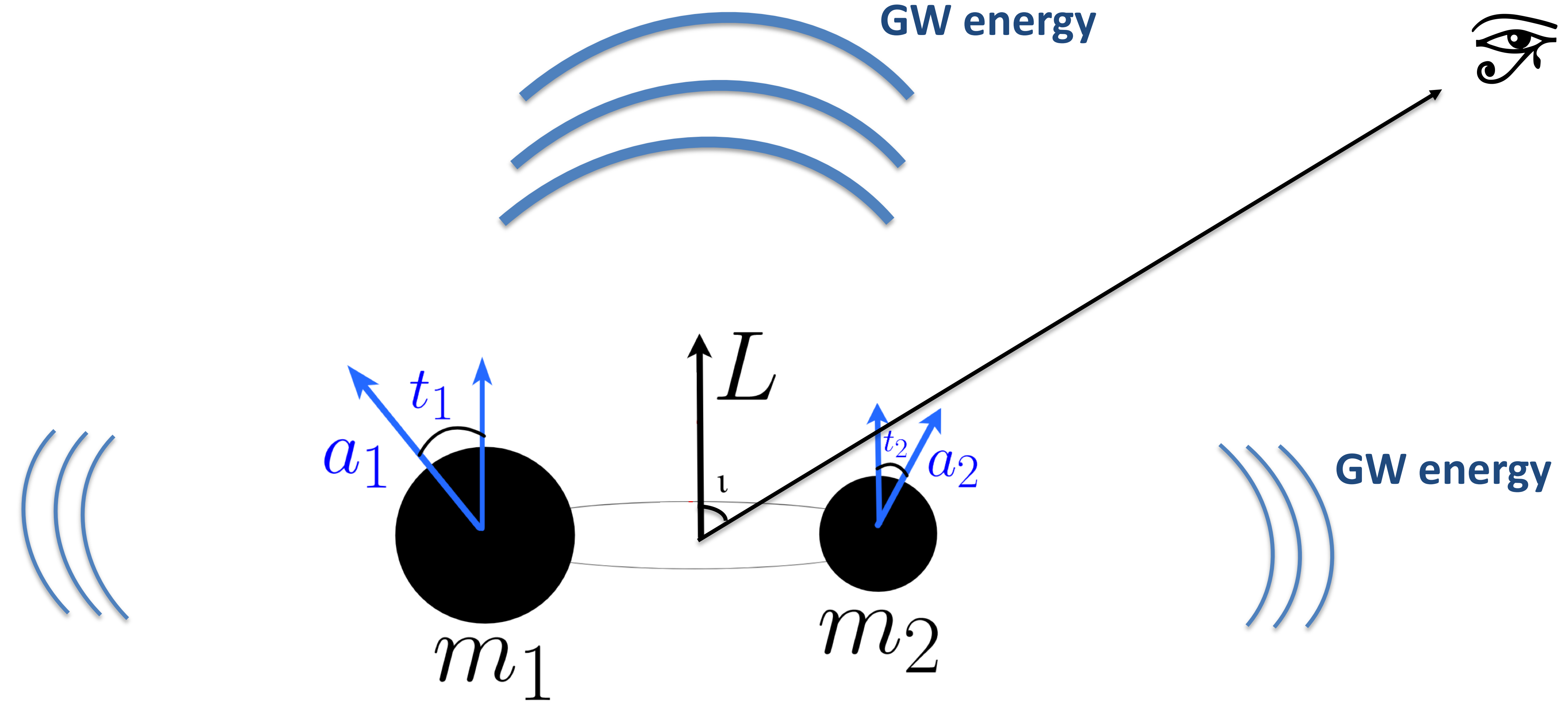




Hall/Vitale

GRAVITATIONAL-WAVE ANATOMY

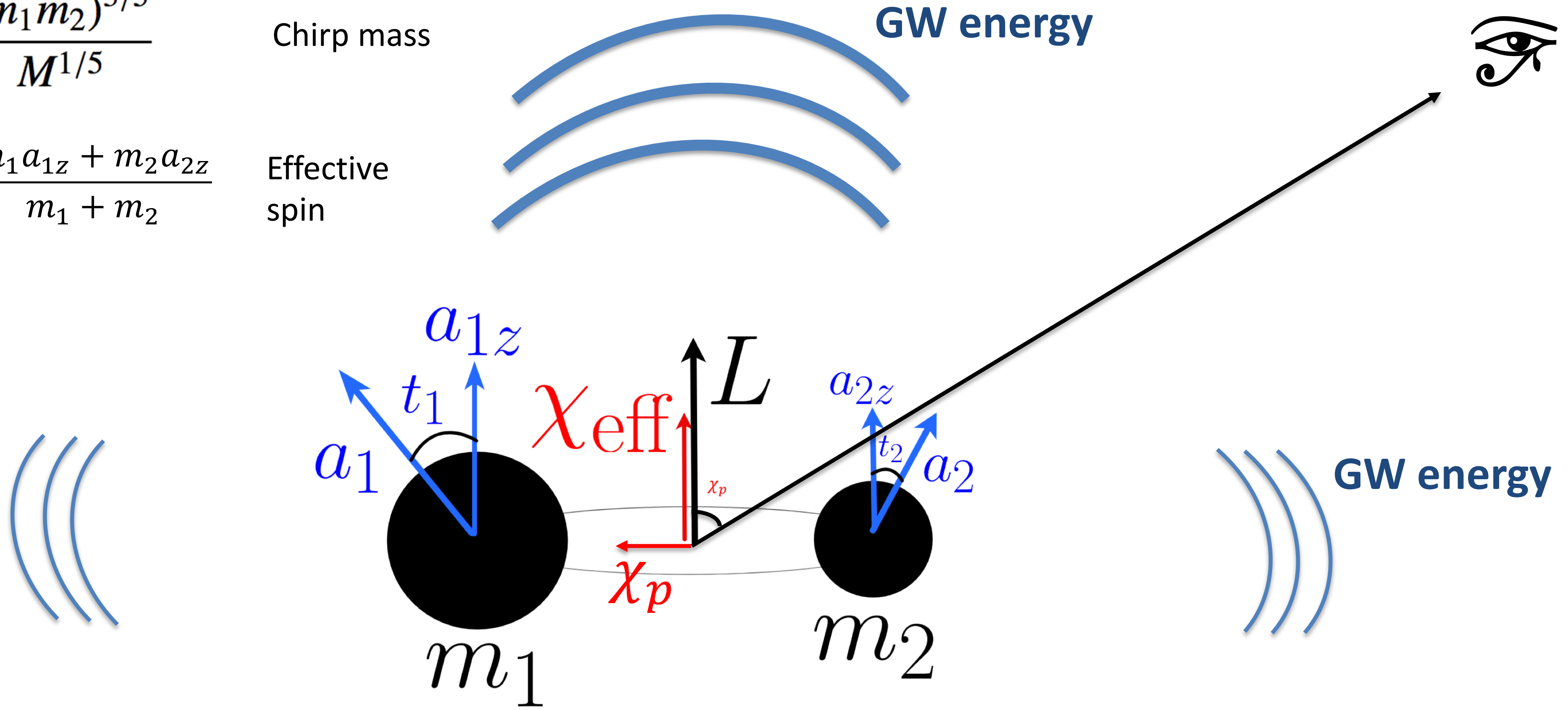
Gravitational-wave anatomy - source



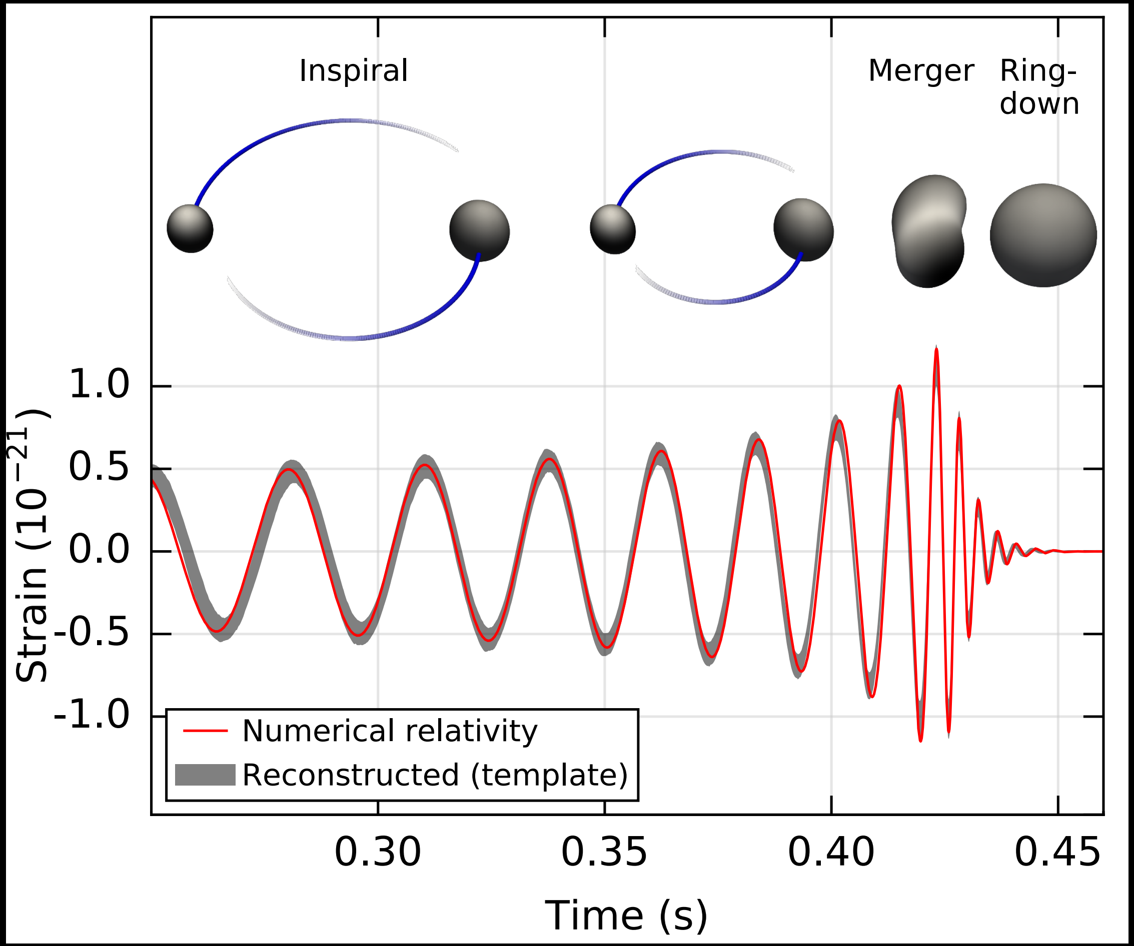
Gravitational-wave anatomy - source

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$$ Chirp mass

$$\chi_{eff} = \frac{m_1 a_{1z} + m_2 a_{2z}}{m_1 + m_2}$$ Effective spin



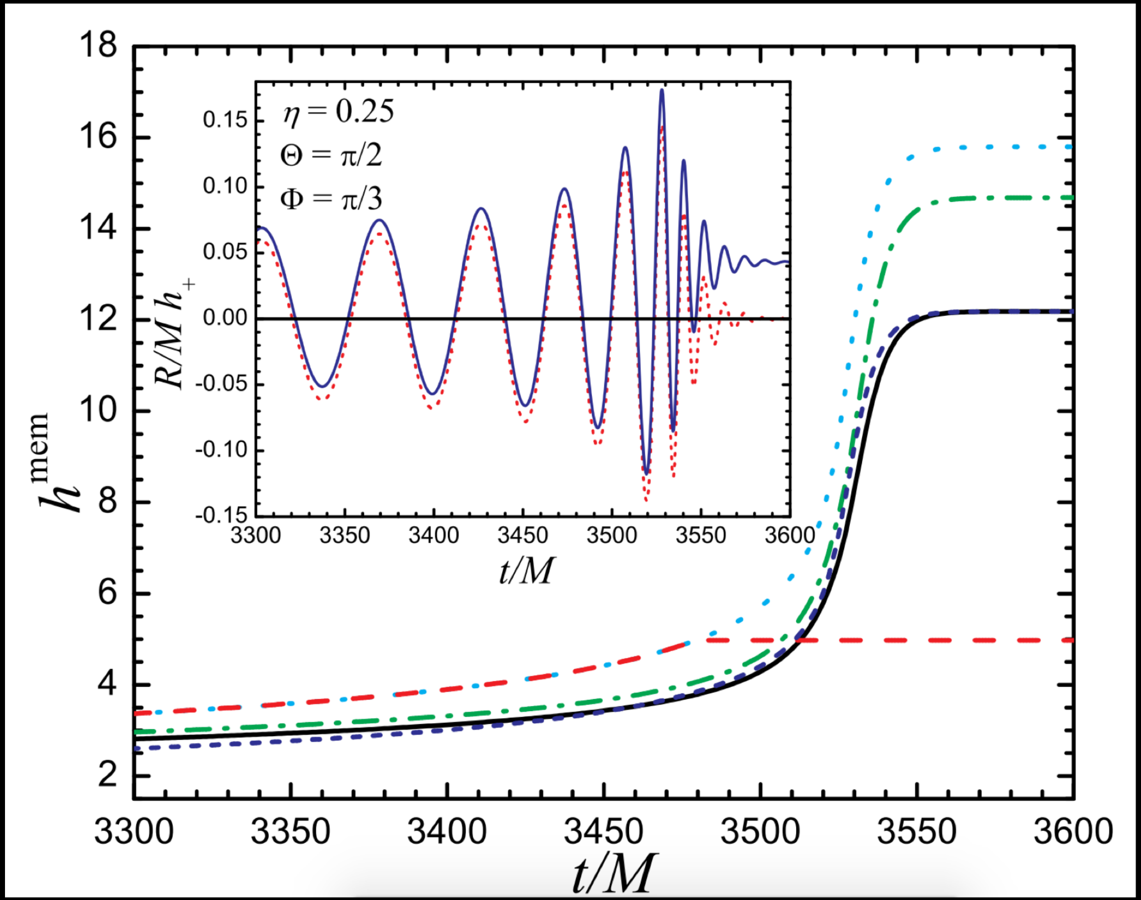
Gravitational-wave anatomy - parameters



LVC, PRL 116 061102

- Duration: total mass, spins
- Phasing: chirp mass, mass ratio, spins
- Overall amplitude: distance, orbital inclination
- Amplitude modulation: spins angles
- Merger-ringdown: nature of the compact objects

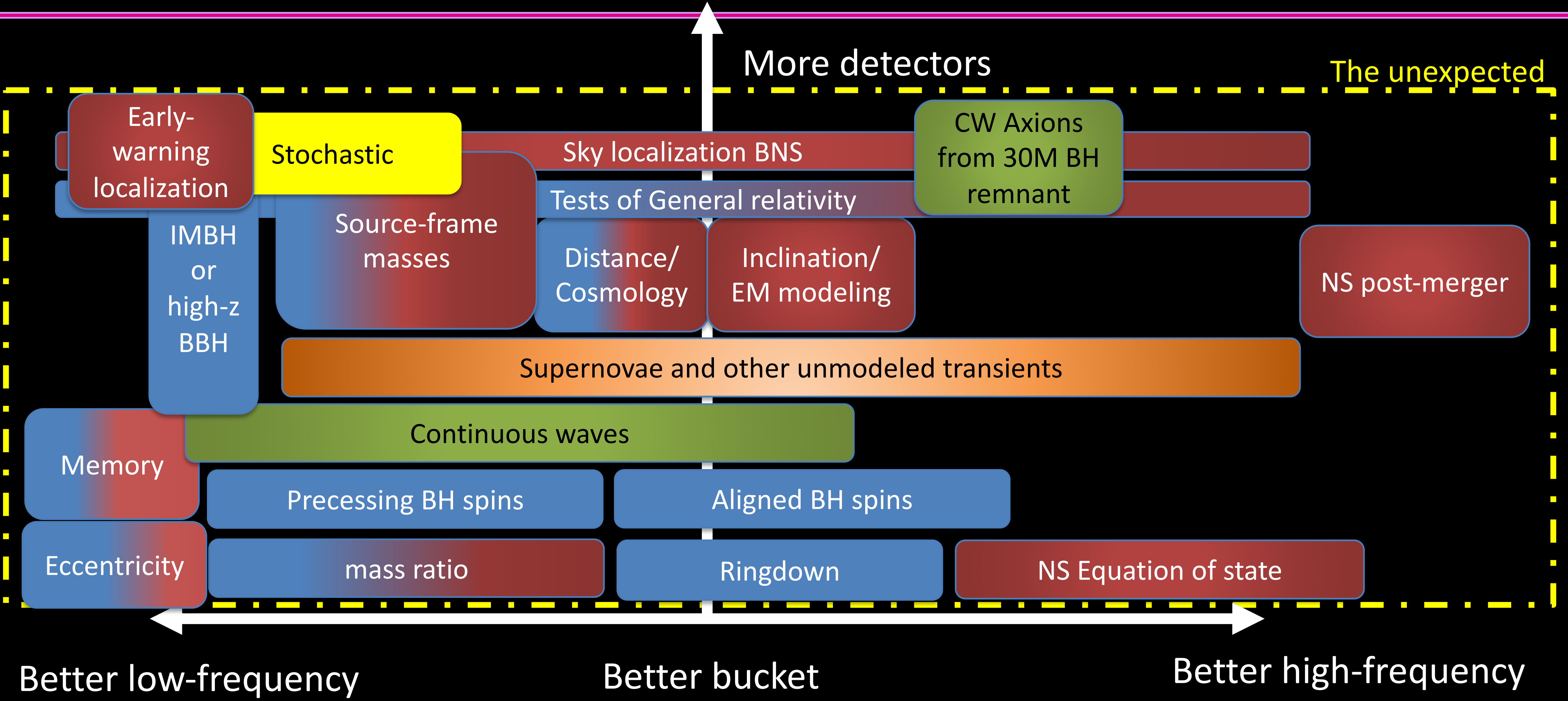
Don't forget the memory!



Favata, Arxiv 0902.3660

- A slow monotonic overall drift in the GW envelope is also expected
  - Non-linear (Christodoulou) Memory effect
- Visible at flow (<20 Hz) frequencies
- Stronger if orbital plane is edge-on

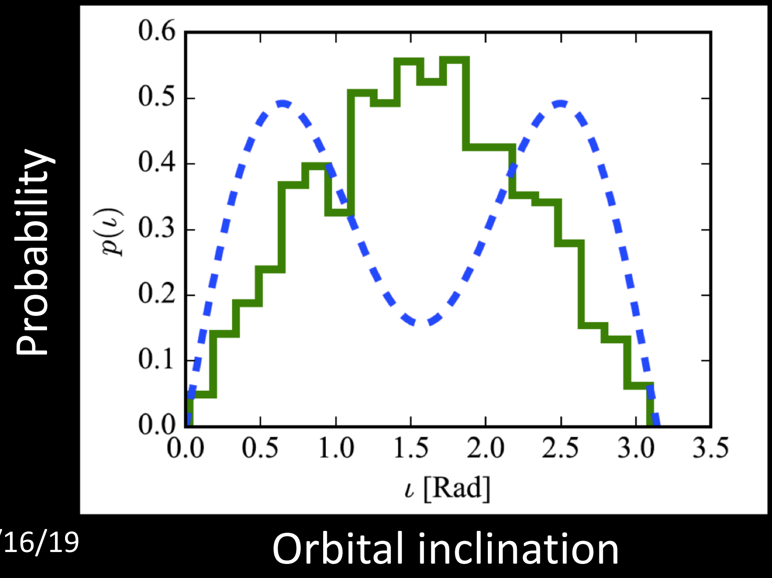
Low/High frequency - Network size trade off



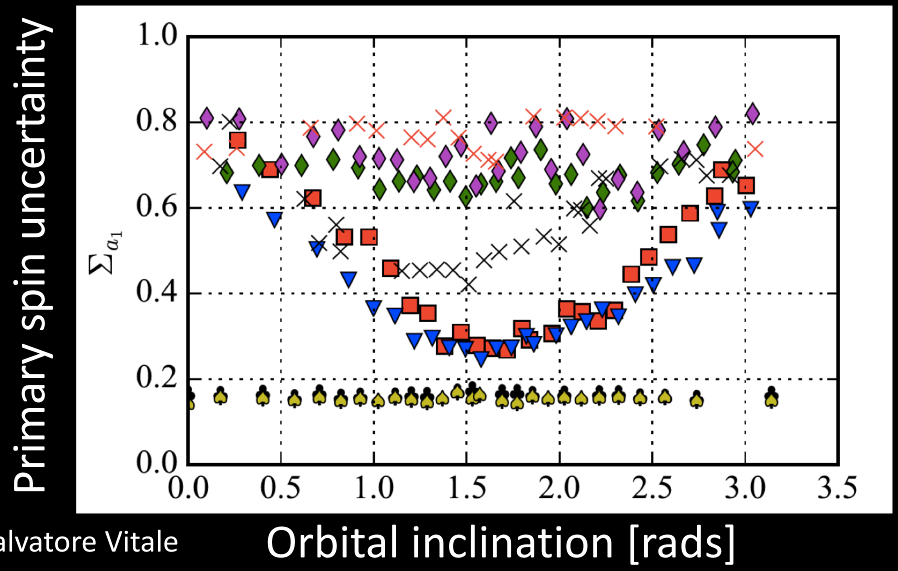
BBH orbital orientations

- Their inclination angle distribution will be isotropic
  - Better ringdown tests, memory effect, spin precession, distance estimation [Refs4]

Schutz, CQG 28, 125023 , Vitale, PRD(R) 94 121501



Vitale+, PRL **112** 251101, PRD 95 064053



Black hole masses and spins

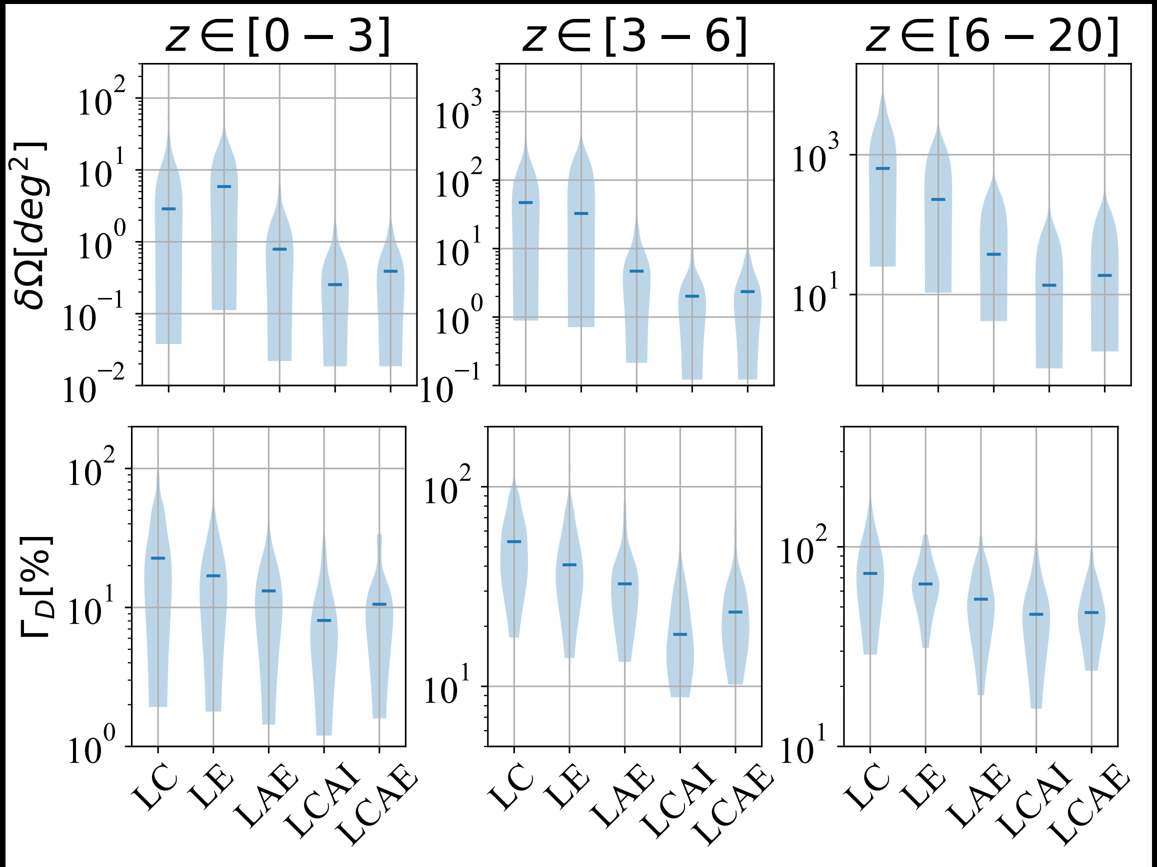
- Source-frame component masses
  - Uncertainties of [few-10]% for z<3
  - Factor 1.5-2 better with 4 detectors w.r.t. 2 detectors
- Component spins
  - Due to larger SNR and isotropic orbital orientation, 3G will get much better spin estimation than current detectors
  - Typical uncertainty on spin magnitude of primary ~0.5 (instead of ~unmeasurable)
  - See Vitale & Evans, PRD 95 064052 for details.

BBH Extrinsic parameters

- Precise distance and sky position:
  - EM (if luminous), isotropy, cosmology

Sky location

Luminosity Distance



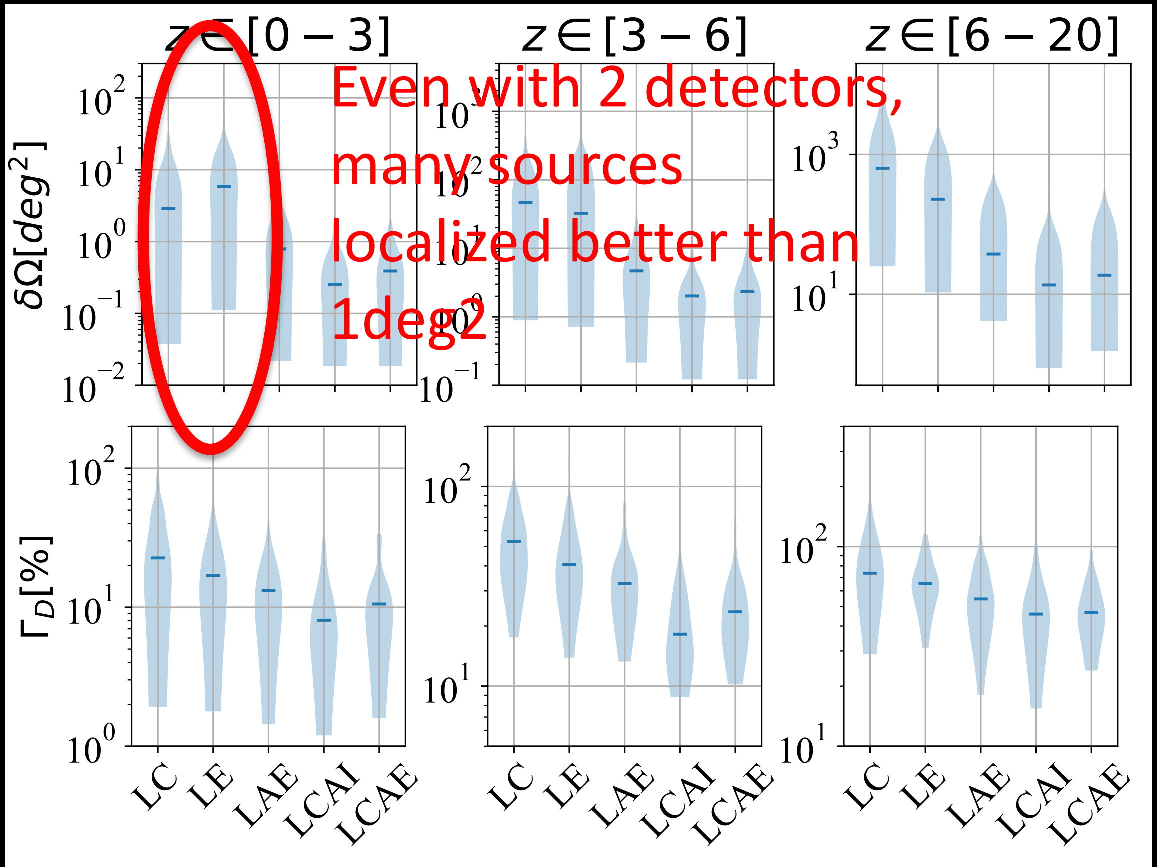
Vitale & Evans, PRD 95 064052

BBH Extrinsic parameters

- Precise distance and sky position:
  - EM (if luminous), isotropy, cosmology

Sky location

Luminosity Distance

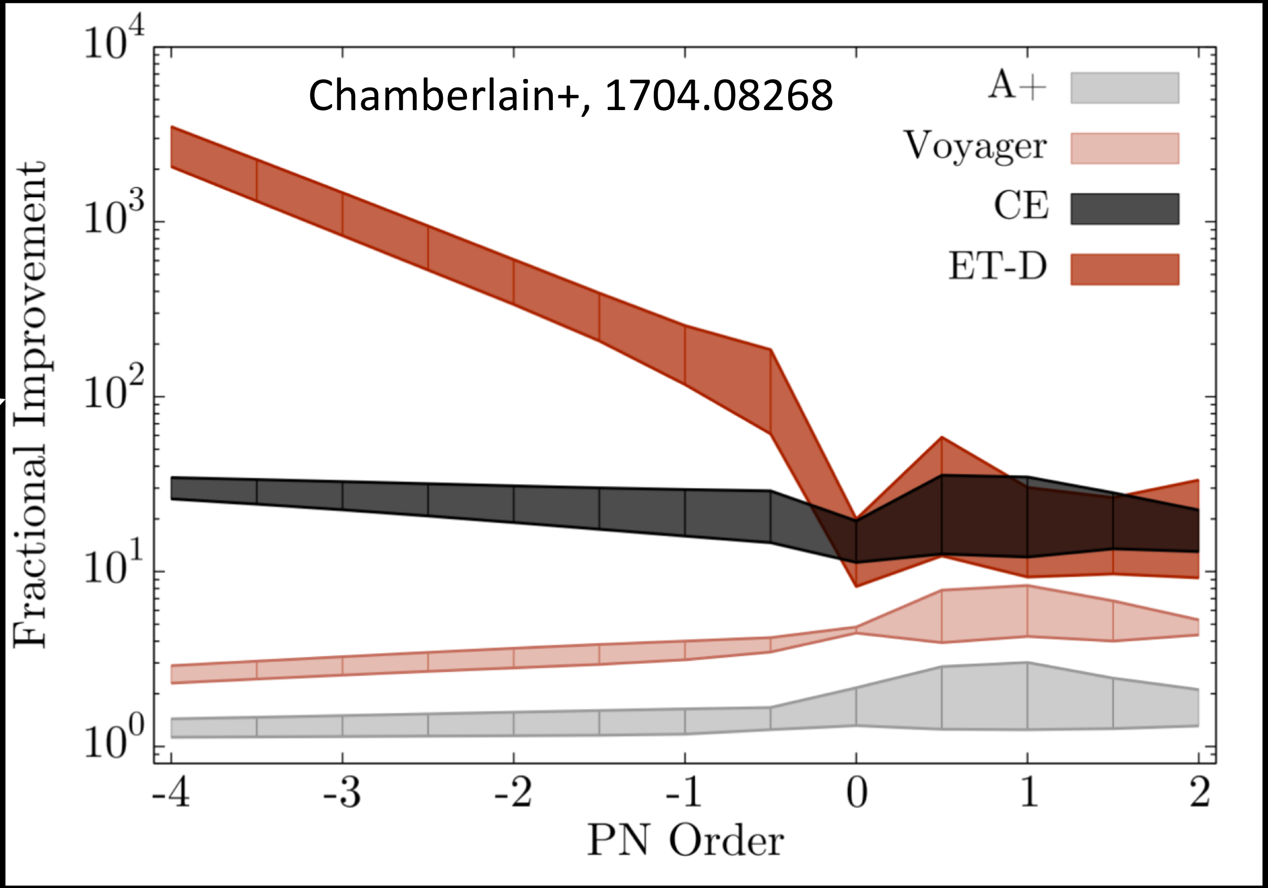


Vitale & Evans, PRD 95 064052

Tests of general relativity

- Larger SNR and better low frequency will yield dramatic improvements
- Also, precise ringdown tests, memory effect, propagation tests, more!

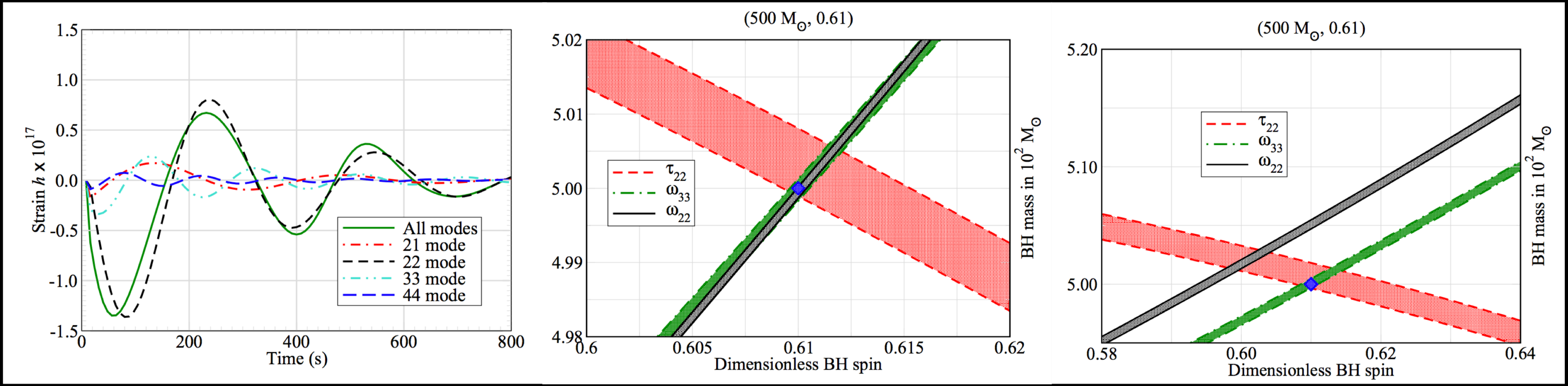
$$\frac{\text{Uncertainty w/ detector X}}{\text{Uncertainty w/ aLIGO}}$$



Ringdown tests

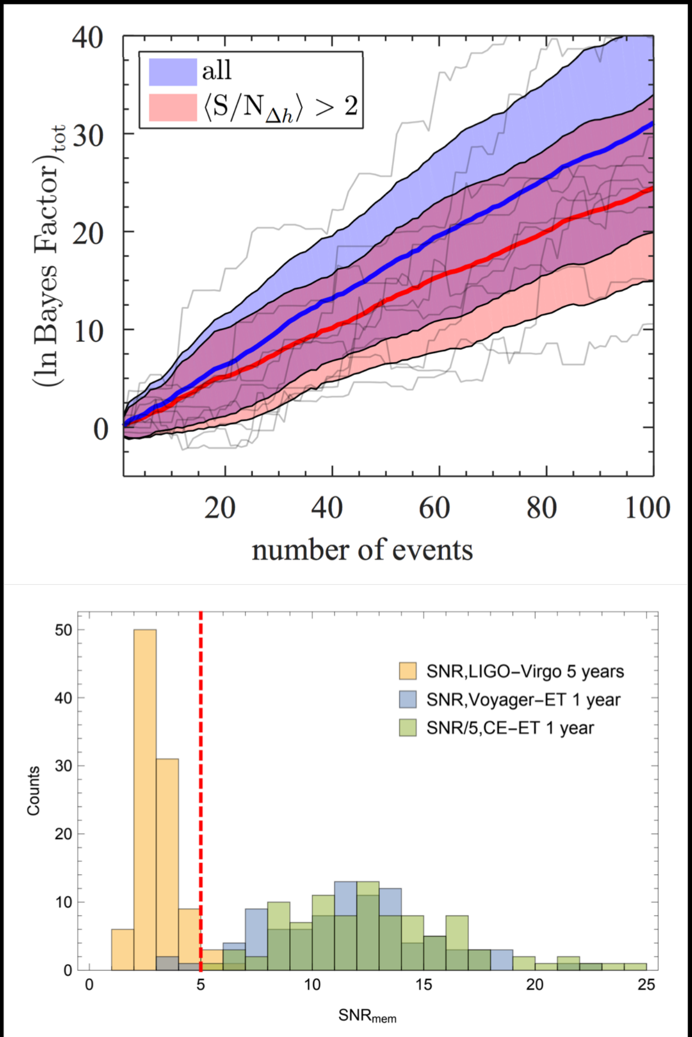
- Ringdown modes only depend on final BH mass and spins (in GR)
- If one can measure more than 2 of the ringdown parameters (dumping times, frequencies) then the others can be used for consistency checks

Gossan+, 1111.5819



Memory

Lasky+, PRL 117, 061102



Yang+, 1803.02429

- Very challenging to detect with advanced detectors
- Lasky+ showed that one might make a statistical detection given >>1 sources
  - Somewhat optimistic assumptions
- Yang+ focuses on 3G and quantifies SNR in the memory phase

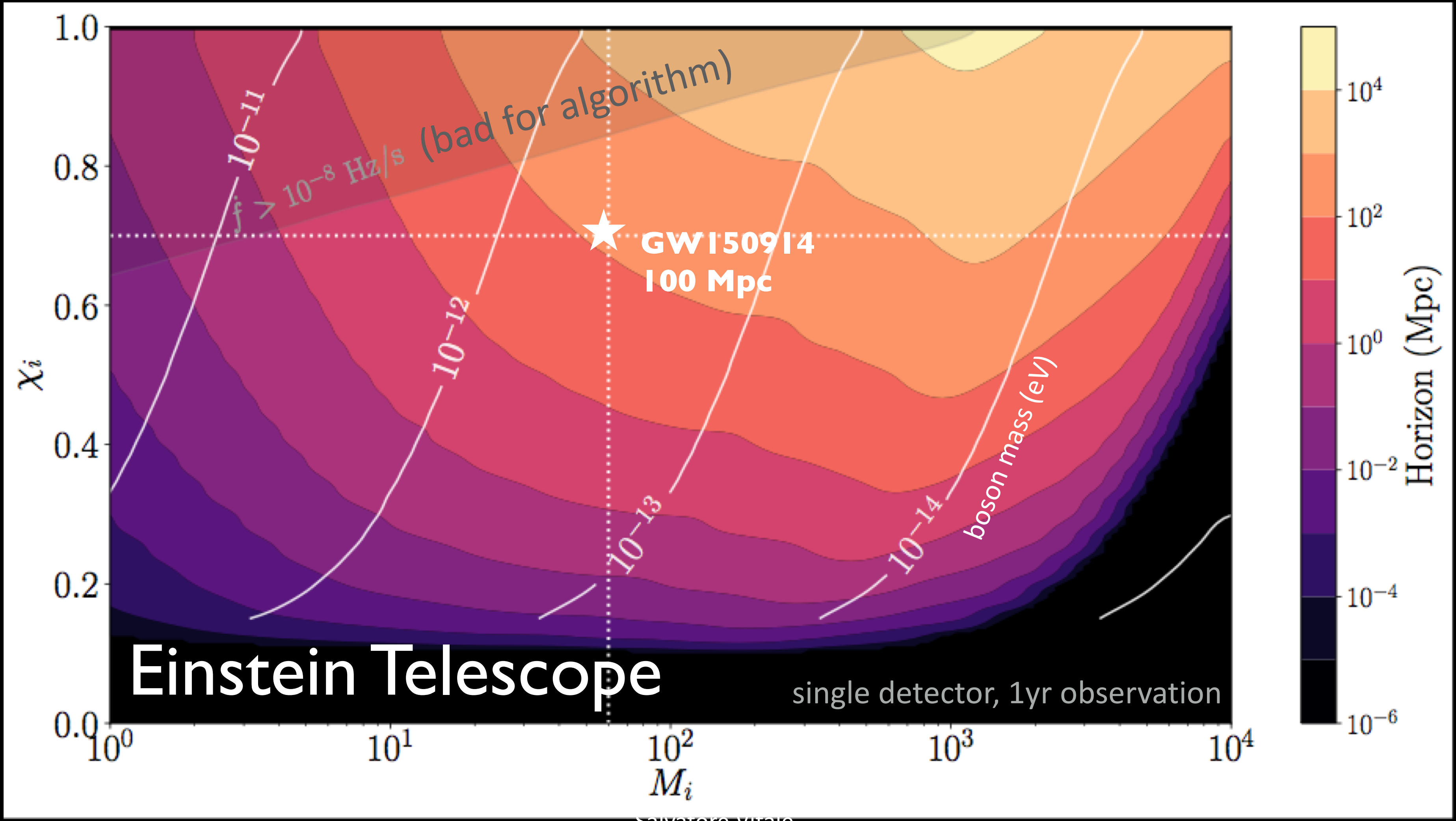
Axions and all that

- Axions are proposed ultralight bosons that can extend the standard model and could be viable dark-matter candidates

$$10^{-19} \lesssim \mu/\mathrm{eV} \lesssim 10^{-11}$$

- If an ultralight boson exists, they will spontaneously form clouds around spinning black holes
- These clouds will emit potentially detectable gravitational waves, providing evidence for a new particle
  - Nearly monocromatic GWs
- We can perform direct searches using known black holes

horizon distance

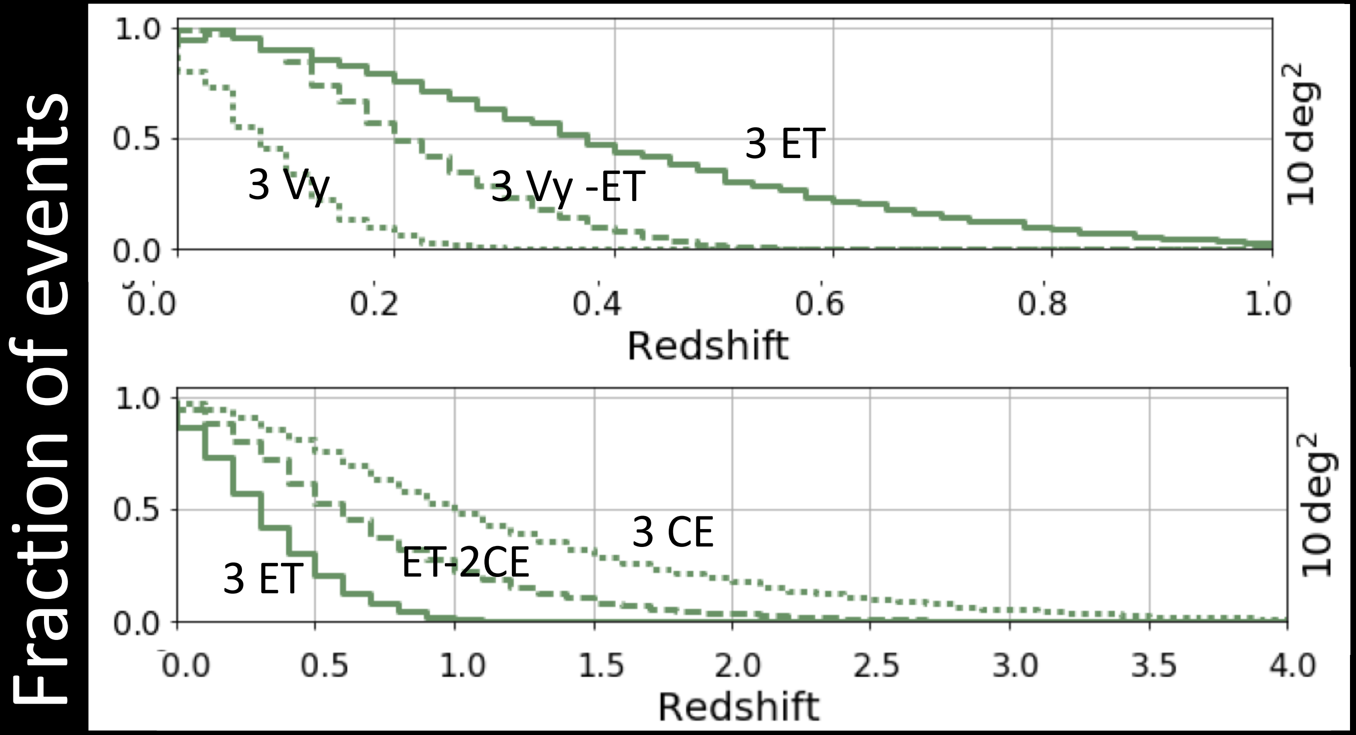


Isi+, Arxiv: 1810.03812

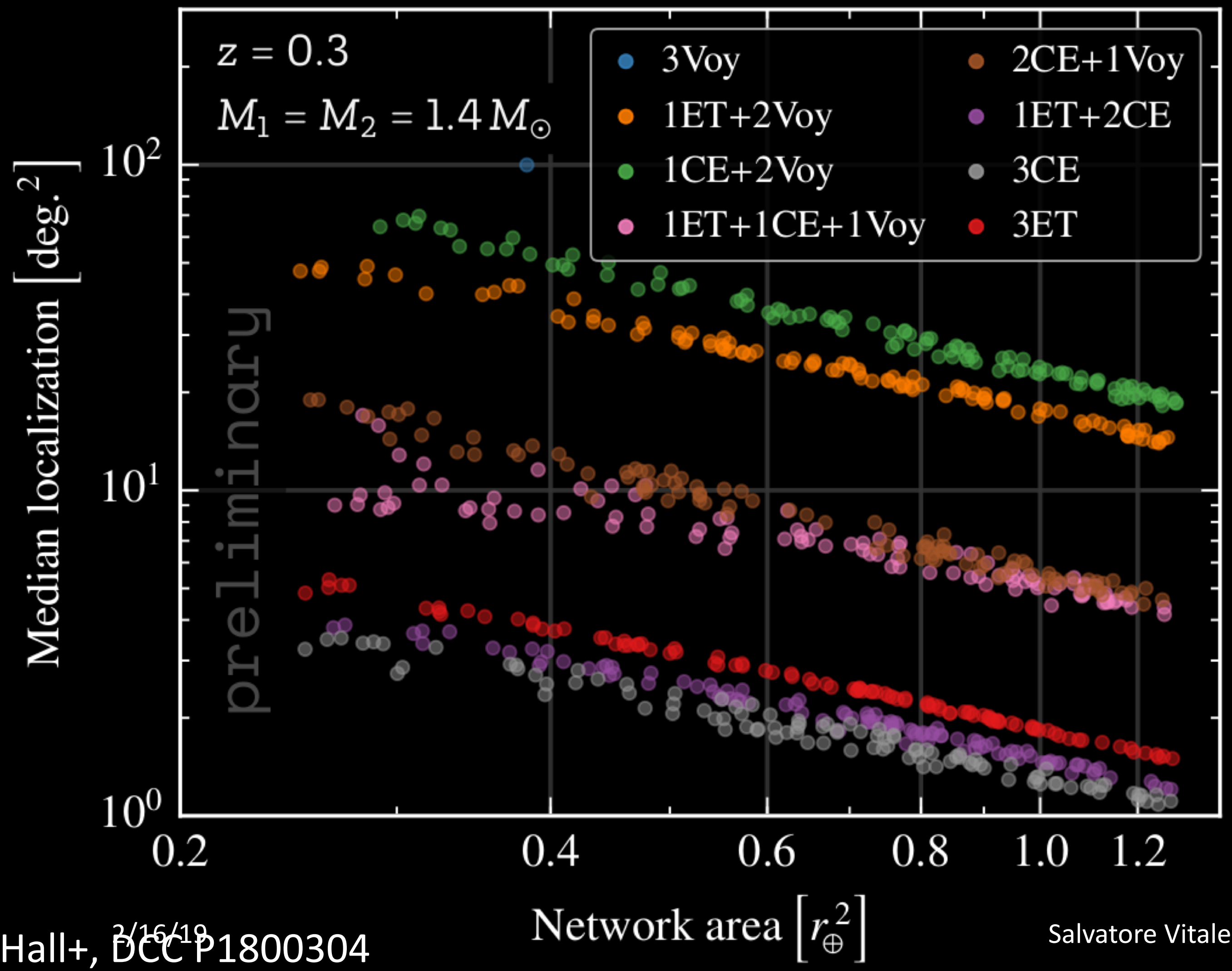
Binary neutron stars - Localization

- Will detect BNS at large redshifts
- A significant fraction of which can be localized to a few deg2
  - H0, dark energy EOS (Sathyaprakash+ Arxiv: 0906.4151; Del Pozzo+ Arxiv:1506.06590; many more)

Mills+ PRD 97 97, 104064



NS localization vs Network size

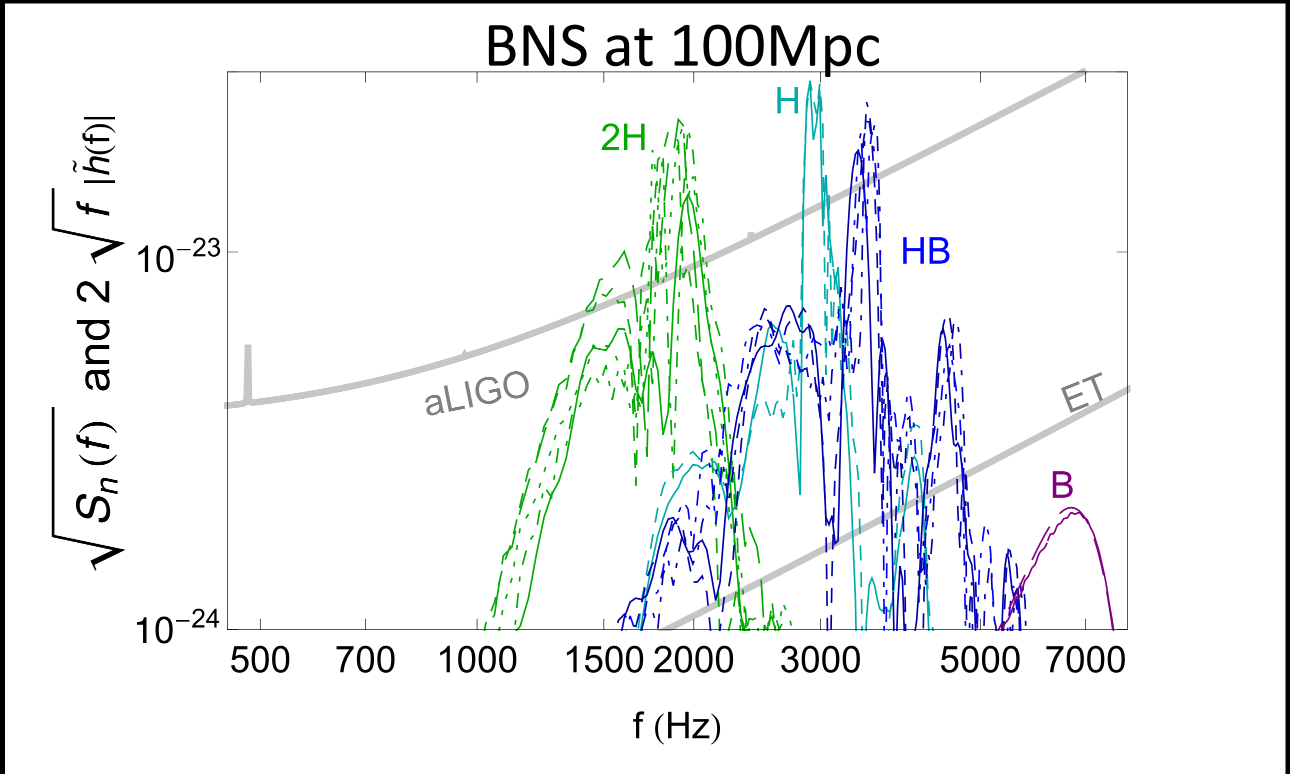


- Simulate hundreds of randomly generated networks
- Conclusion: the type of detector matters more than location or orientation (also holds true for other metrics)

Hall+, DCC P1800304

Binary neutron stars - Equation of state

- Advanced detectors will start measuring the equation of state of neutron stars
  - Most likely from the inspiral phase
  - With a bit of luck, hints of postmerger physics
- 3G detectors will easily measure the EOS from both inspiral and post-inspiral

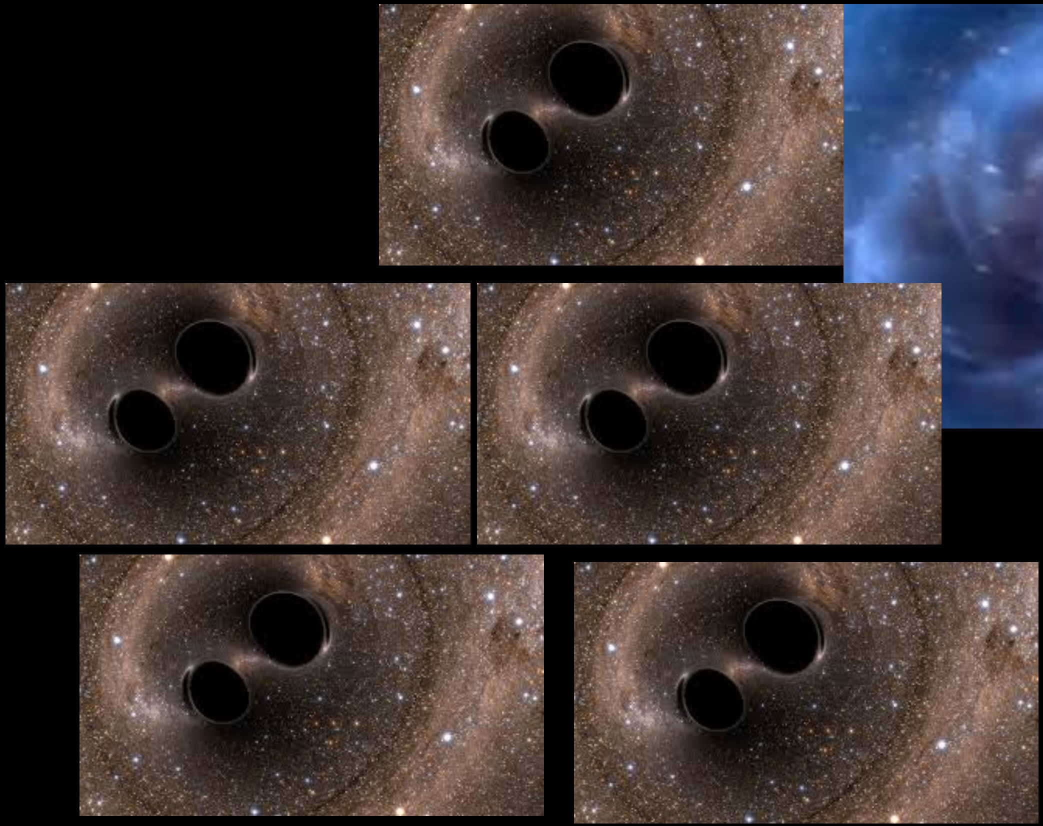


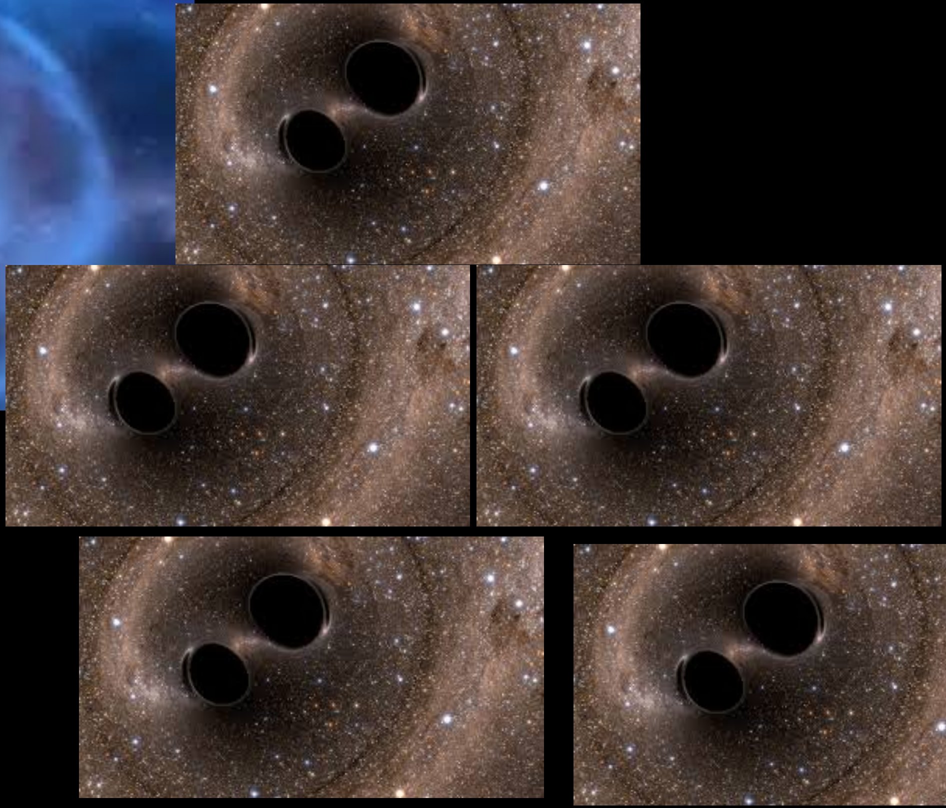
Read+ PRD 88, 044042

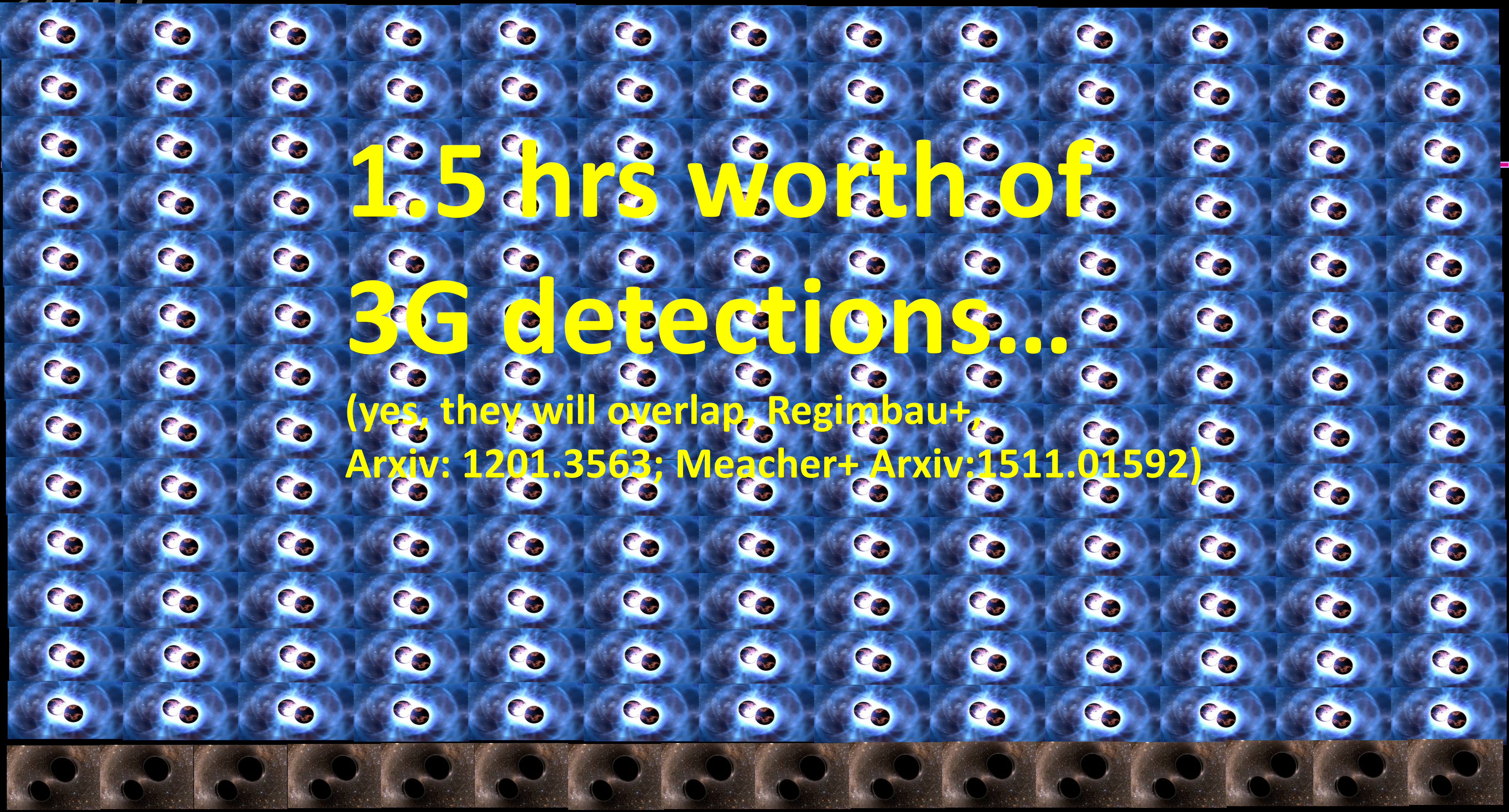
How many events?

- Using the rates calculated with O2 events and projecting…
- 3G detectors will detect
  - ~ 10^5 BBH per year (Regimbau+, PRL 118, 151105)
  - ~ 10^6 BNS per year (LVC, PRL 120, 091101)

~1 year worth of advanced detector time







1.5 hrs worth of 3G detections...

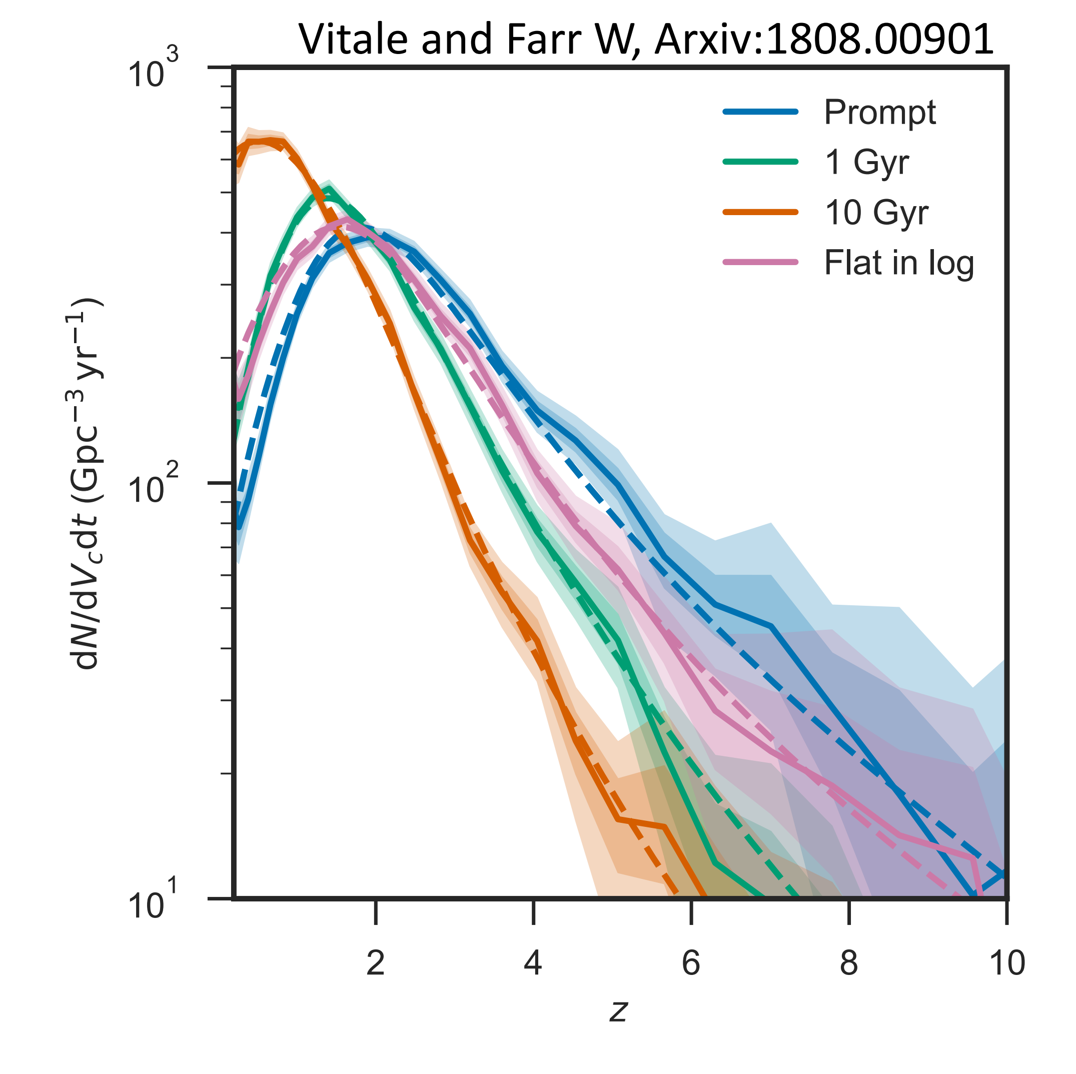
(yes, they will overlap, Regimbau+, Arxiv: 1201.3563; Meacher+ Arxiv:1511.01592)

BBH Formation channels

- Many methods have been proposed to study the formation channels of BBH (and compact binaries in general)
  - Shown to work for advanced detectors in the local universe [Refs1]
- With 3G:
  - Study how the fraction of CBC from each channels evolve with redshift
  - Accessing thousands of BBH per year we can study the explosion mechanism of SNe (O'Shaughnessy+, PRL 119 011101 shows what can be learned with GW151226 alone)

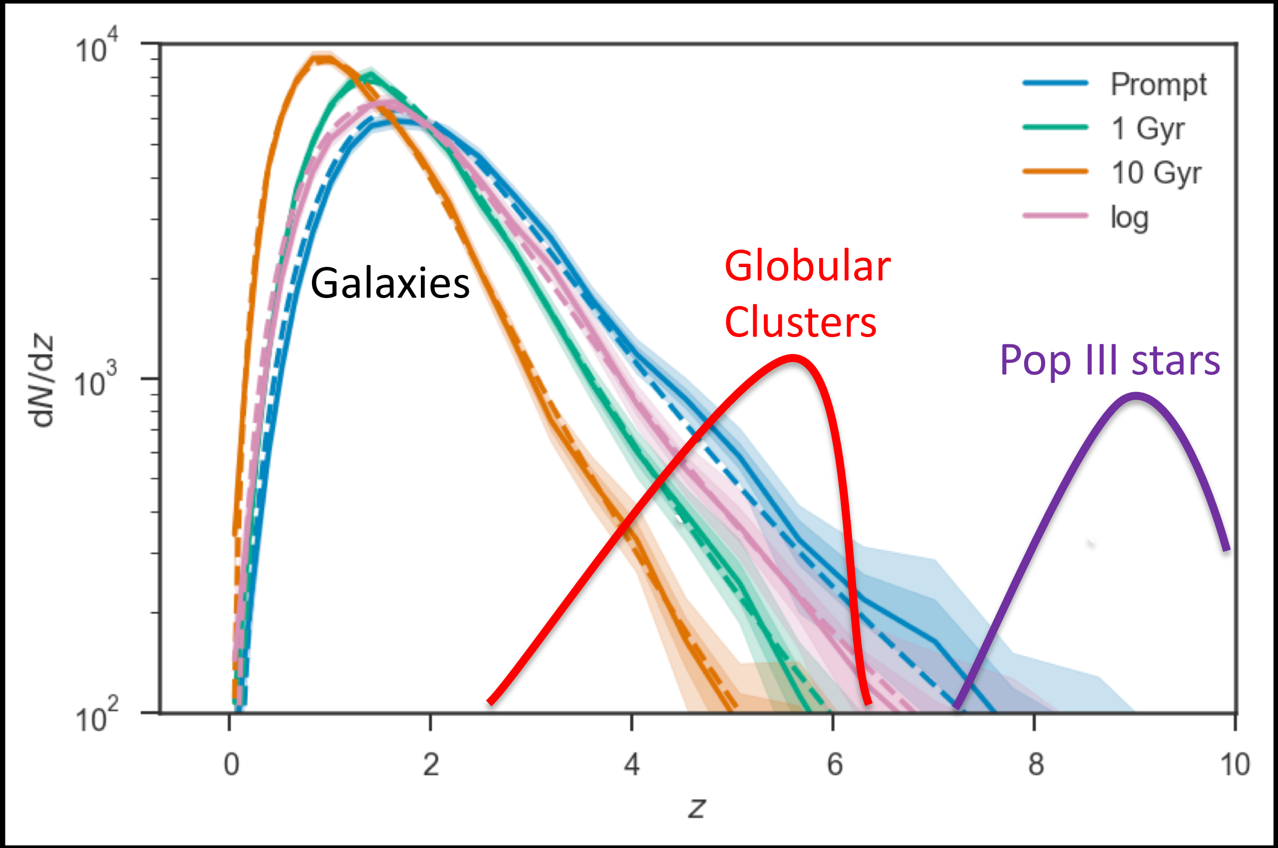
Merger rate density

- We can calculate the BBH merger rate as a function of redshift
- Generated 1 months worth of BBH detections by 3G detectors
  - Assume Madau-Dickinson star formation rate (SFR)
  - Tried several prescriptions for the time delay between merger and formation
  - BBH formation rate proportional to SFR
- For BNS see Van Den Broeck JPCS 484 012008. Also Sathyaprakash CQG 29 124013



Formation channels

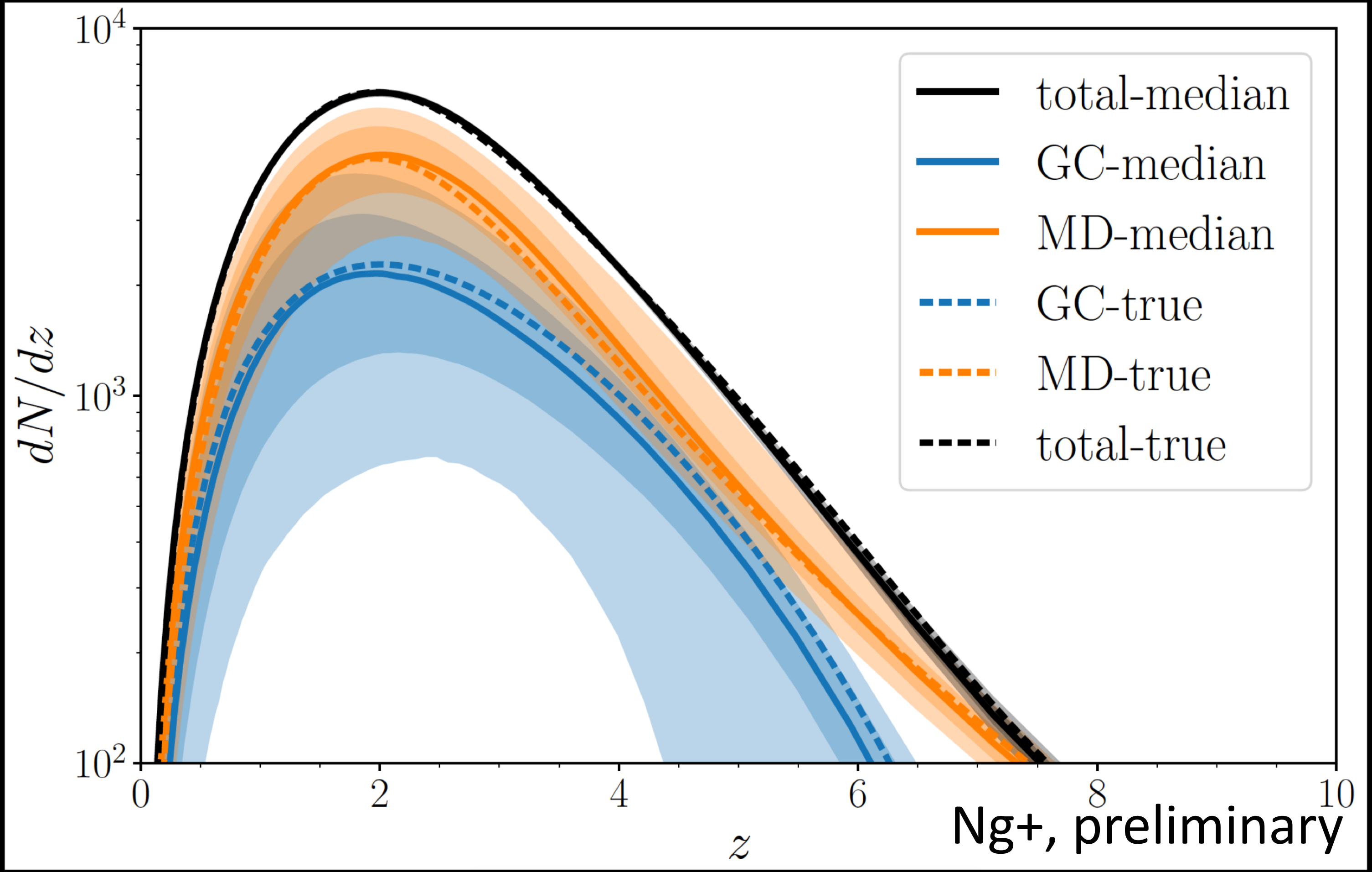
- Depending on relative abundances, might be able to distinguish populations and calculate branching ratios



Reality is always harder

- Considered a fraction of sources coming from galactic fields (as before)
- And the rest coming from globular clusters

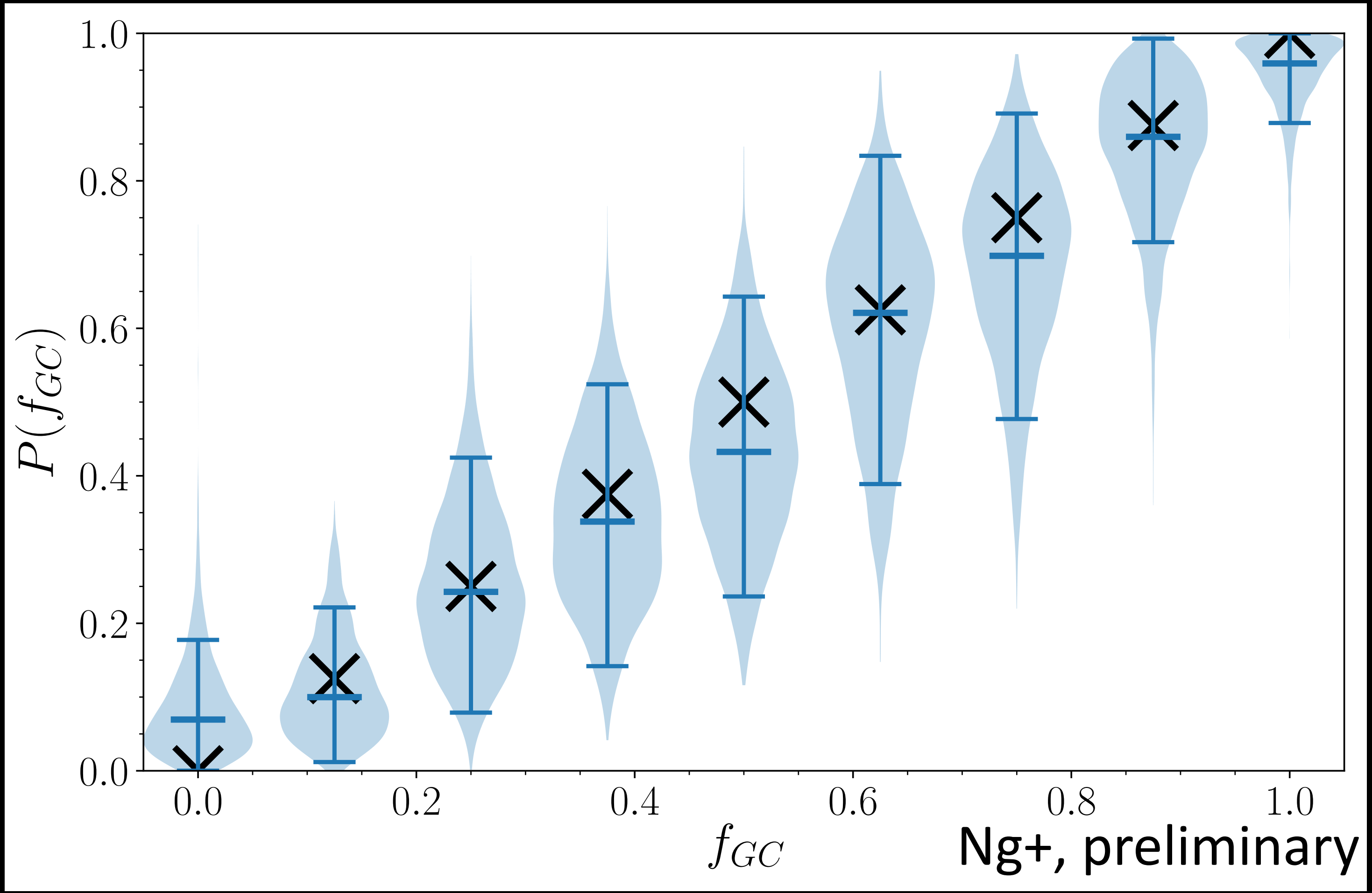
- Madau-Dickinson template for the star-formation rate in galaxies
- Log-Normal for globular clusters (based on Carl Rodriguez' simulations.
- Measure characteristic parameters of each population, plus branching ratios between populations.



Reality is always harder

- Considered a fraction of sources coming from galactic fields (as before)
- And the rest coming from globular clusters

- Madau-Dickinson template for the star-formation rate in galaxies
- Log-Normal for globular clusters (based on Carl Rodriguez' simulations.
- Measure characteristic parameters of each population, plus branching ratios between populations.



Golden BBH events

- A GW150914-like event will have SNR~2000 in a cosmic explorer facility.
- How well can we do?

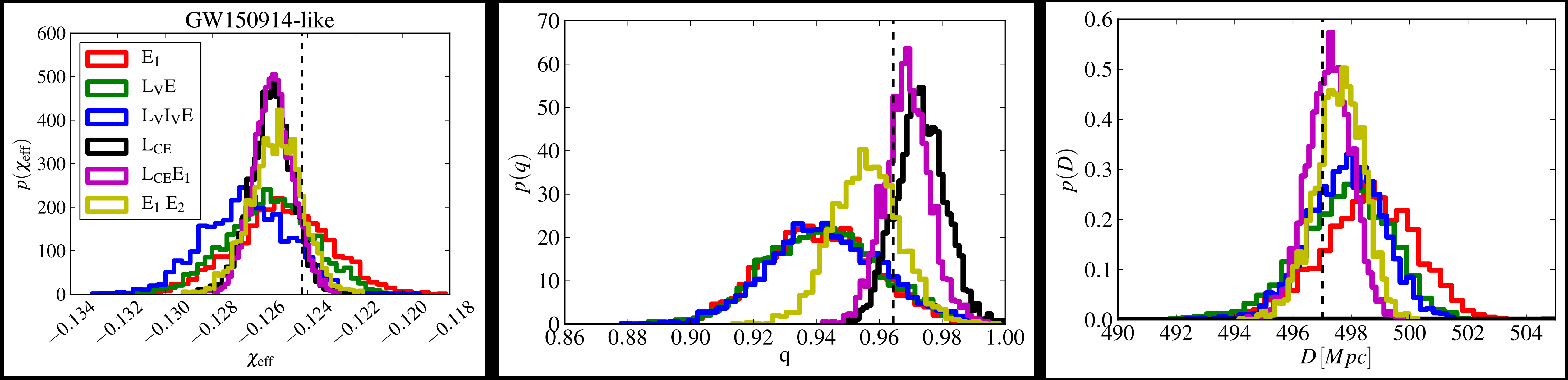
Precision for a few key parameters for GW150914

Mass ratio q	$0.84^{+0.14}_{-0.21}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.03^{+0.14}_{-0.15}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	440^{+140}_{-180}

LVC 1602.03840

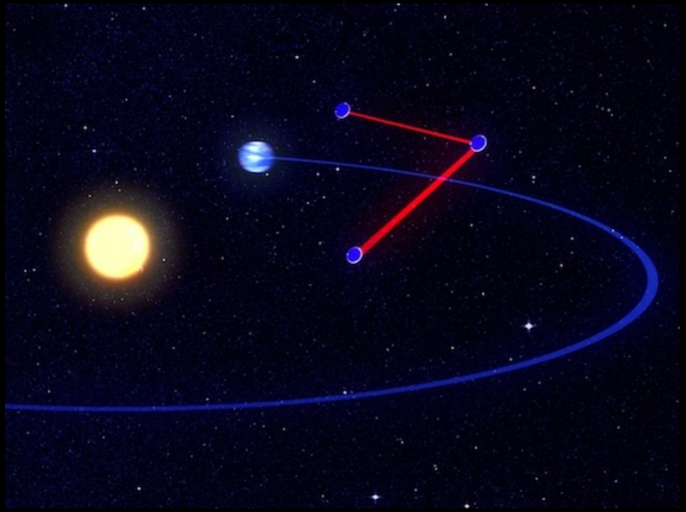
Golden BBH events

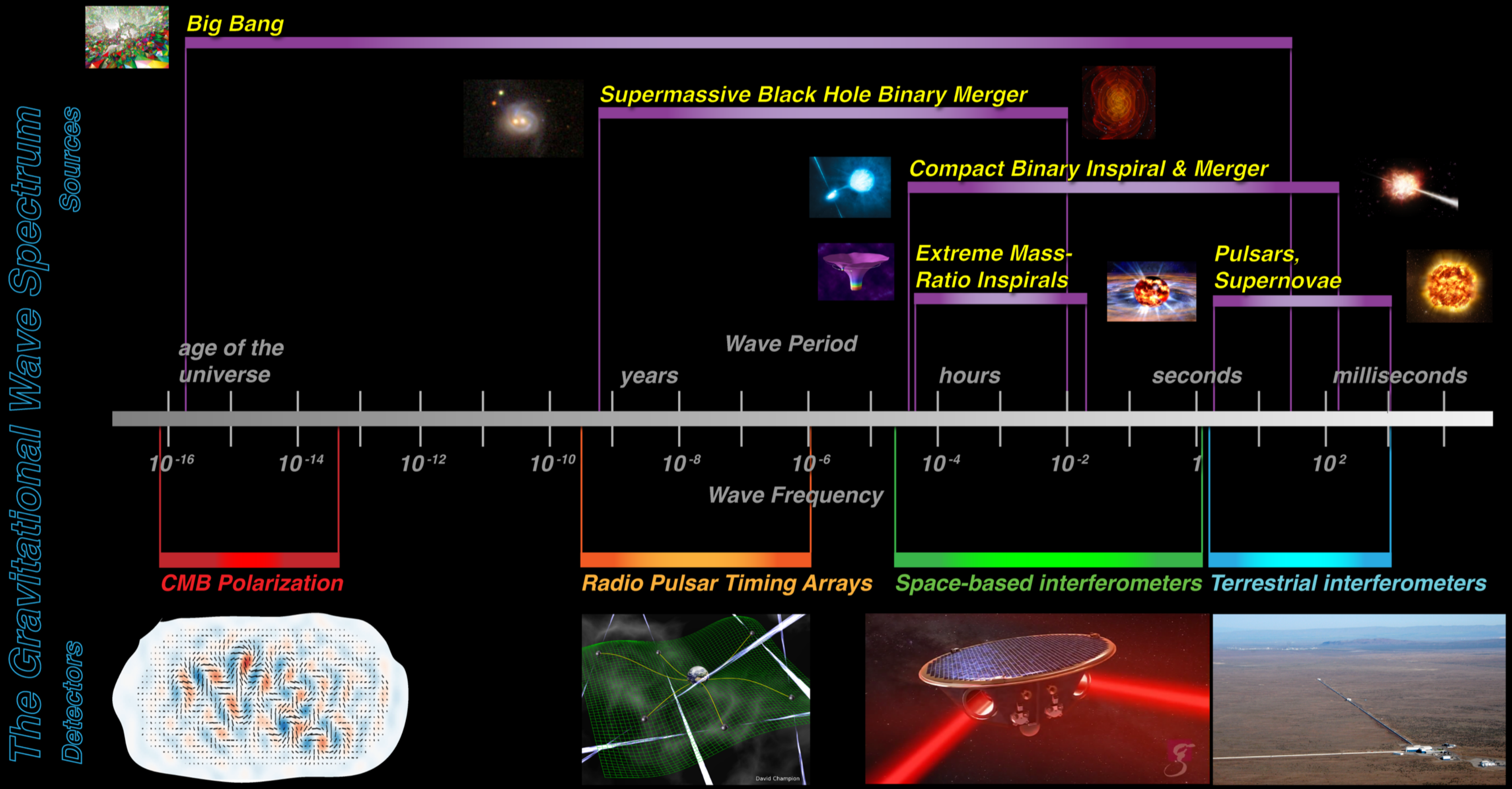
- A GW150914-like event will have SNR~2000 in a cosmic explorer facility.
- How well can we do?



Vitale, Whittle, PRD 98, 024029

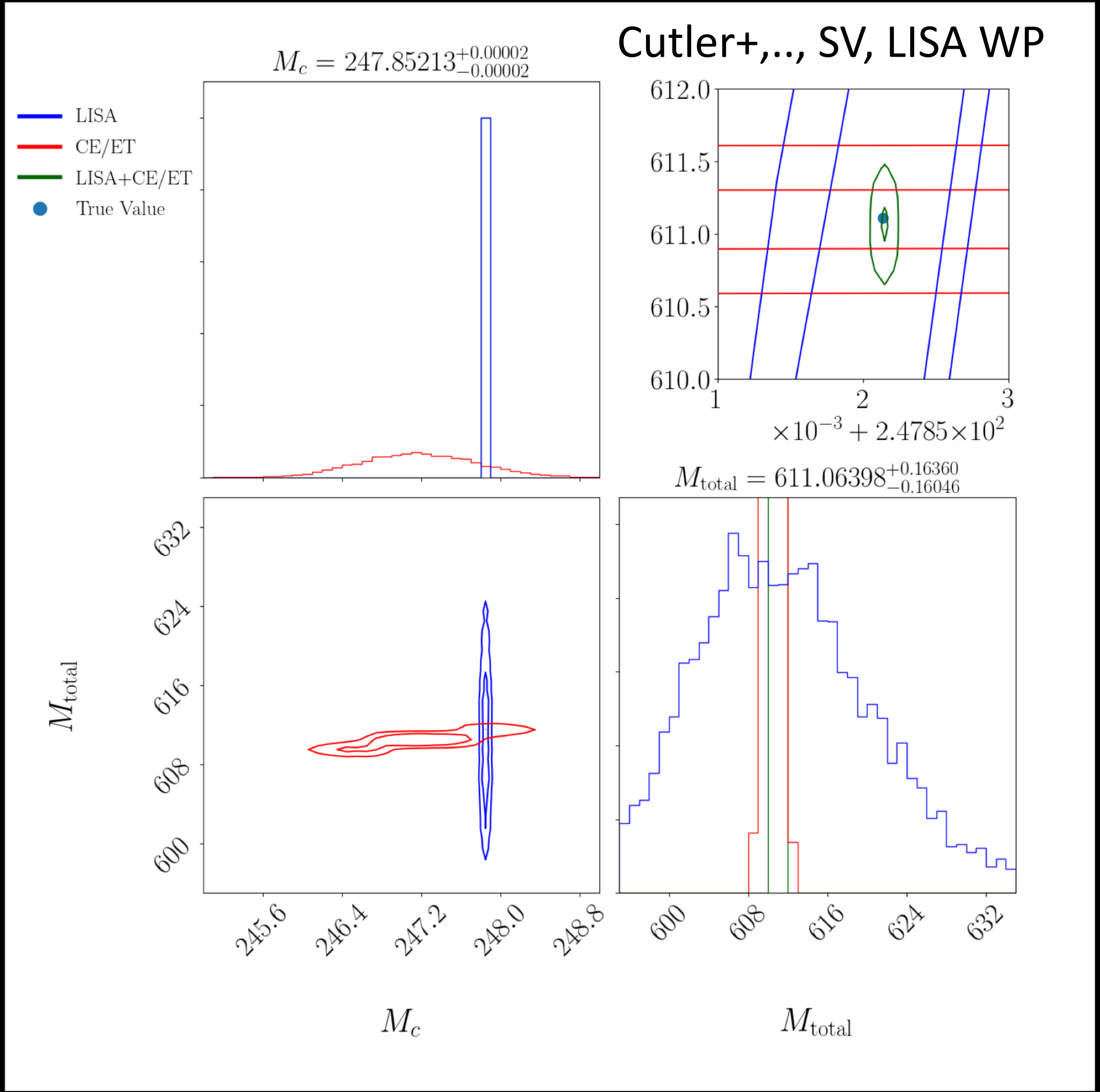
Multibanding – LISA



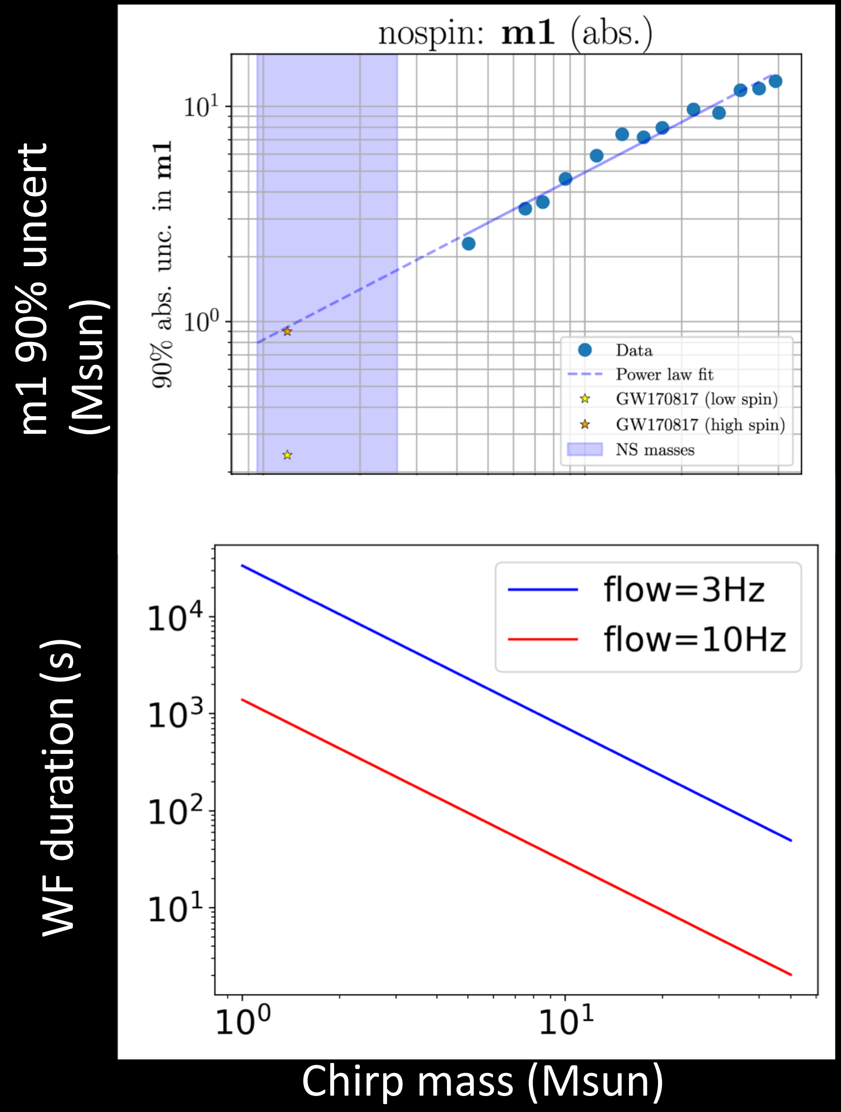


Multibanding – LISA

- The space-based LISA GWs detector can observe heavy BBH and intermediate-mass BBH
- Some of those signals will also be visible from the ground (years later)
- Complementary information! (Sesana PRL 116, 231102; Vitale PRL 117, 051102; Barausse+ PRL 116, 241104)



Computing – you cannot always get what you want



- The duration of waveforms (and hence the computational time required) blows up
  - As flow decreases
  - As the chirp mass decreases
- With current methods, we cannot run parameter estimation codes on binary neutron stars for 3G
- Work needed

Conclusions

- Advanced detectors will explore the local universe (z ~ 1)
- A new generation is required to detect sources everywhere in the universe
  - Characterization of BH masses and spins, formation channels, evolution,…
  - Thousands of neutron stars, EOS, cosmology,...
  - Precise tests of general relativity
  - Access to sources throughout cosmic history

Thanks!

References

- [Refs1]: Mandel+ CQG 27, 114007; Vitale+ CQG 34, 03LT01; Farr+ ApJ, 854, L9; Farr+ Nature, 548, 426; Stevenson+ MNRAS, 471, 280; Talbot +PRD , 96, 023012
- [Refs2]: Del Pozzo+ PRL 111 071110; Chatziionannou+ PRD 97 104036; Lackey+ PRD 91 043002; Read+ PRD 79 124032
- [Refs3]: LVC ApJL, 833, 1; Wysocki+ Arxiv: 1805.06442; Farr+ , PRD 91, 023005; Gaebel+ Arxiv:1809.03815
- [Refs4]:Gossan+, PRD 85 124056; Berti+, Arxiv:1801.03587; Yang+ PRL 121, 071102; Vitale+, PRD 95 064052
- [Refs5]: Fishbach+, ApJ, 851, L25; Wysocki+ Arxiv: 1805.06442; Kovetz+, PRD 95, 103010; Talbot +PRD , 96, 023012;