Black hole astrophysics with the next generation of ground-based gravitational-wave detectors

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July 10 2017

Where are we?

- Advanced detectors (second generation, 2G) have detected 4 binary black holes (BBH)
  - Component masses measured at few x 10% level
  - Spins very hard to measure
  - Oriented face-on/off
  - Up to reshift of ~0.2
  - See LVC, PRL **118** 221101, PRX **6** 041015

Where are we?

- We have estimated the merger rate of BBH to be in the range

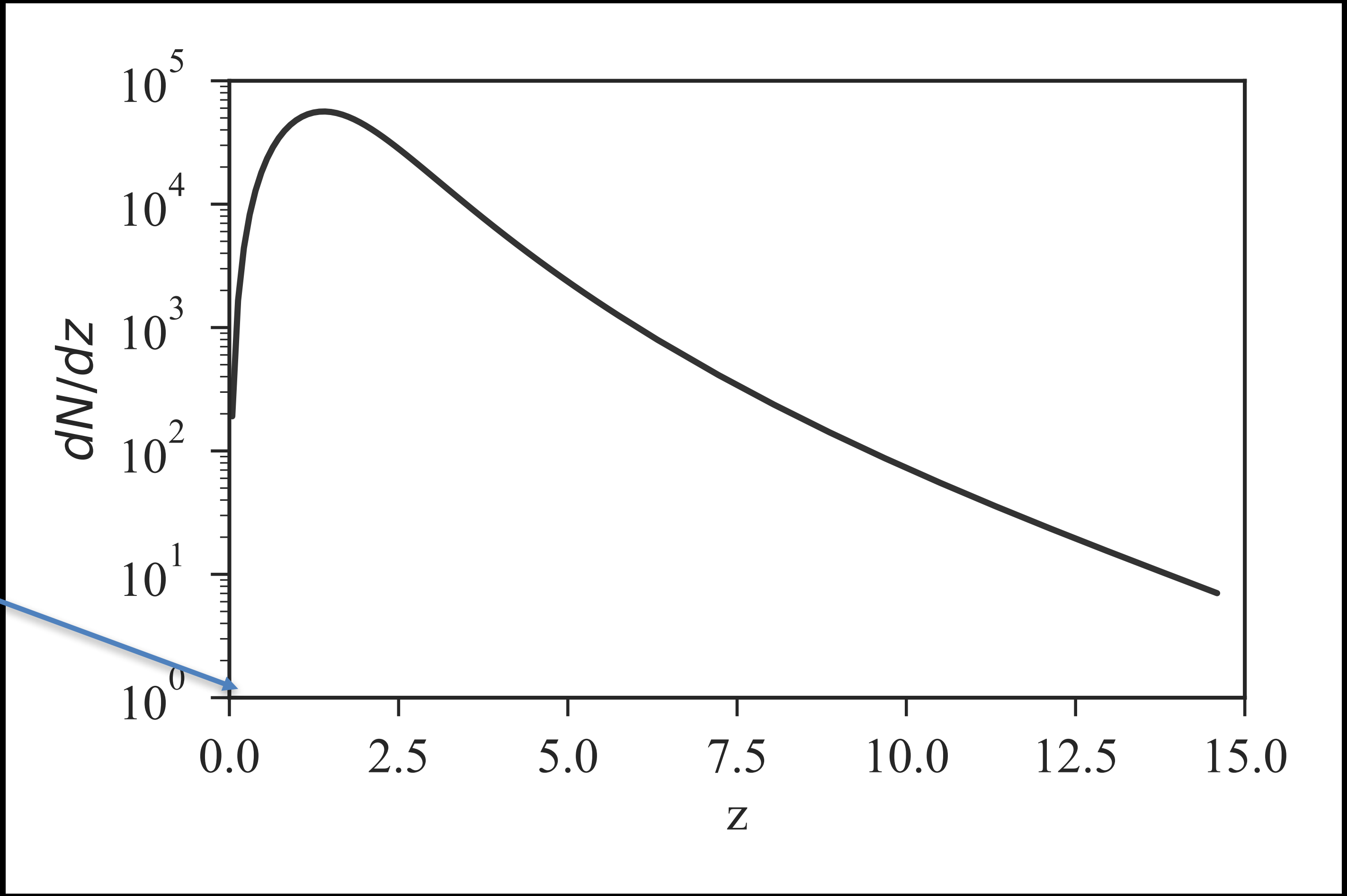
$$12\text{–}213\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

LVC, PRL **118** 221101

- Will eventually be able to answer many questions:
  - Formation channels
  - Mass function
  - Bounds on deviation from GR
  - More!

Where are we?

You are here!



Where do we go from here?

- With 2G at design, we'll go up to z ~ 1
- If we want to detect BBH at high redshift, we need something else

- Proposed third—generation (3G) ground based detectors will
  - Be a factor of ~>10 more sensitive that 2G-design
  - Detect BBH from redshifts >10
  - Detect a lot of BBH, with very large signal-to-noise ratio (SNR)

Where do we go from here?

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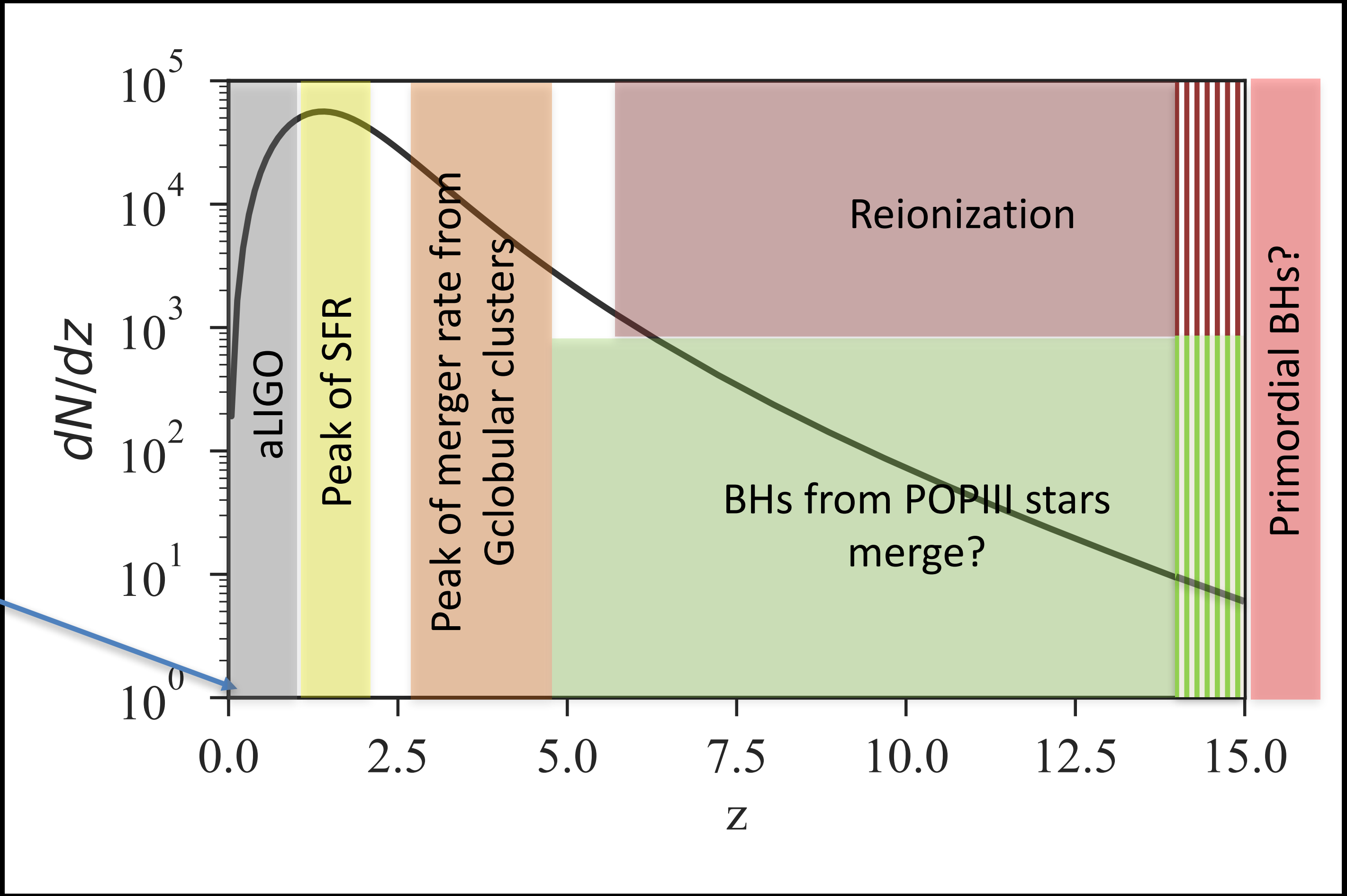
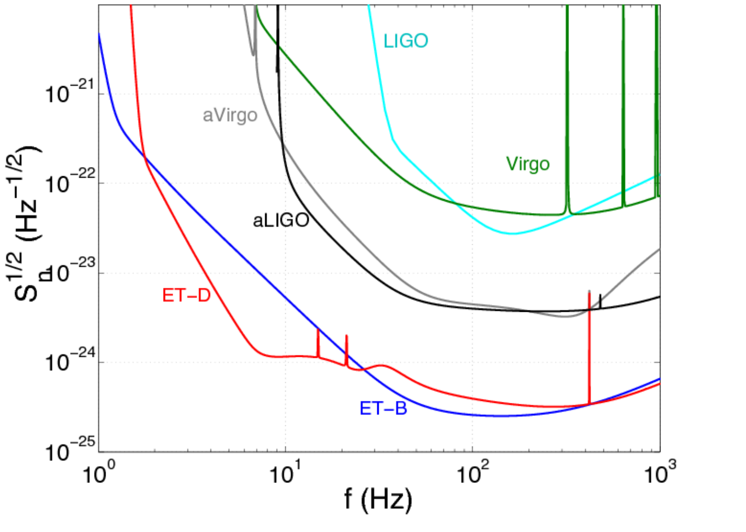


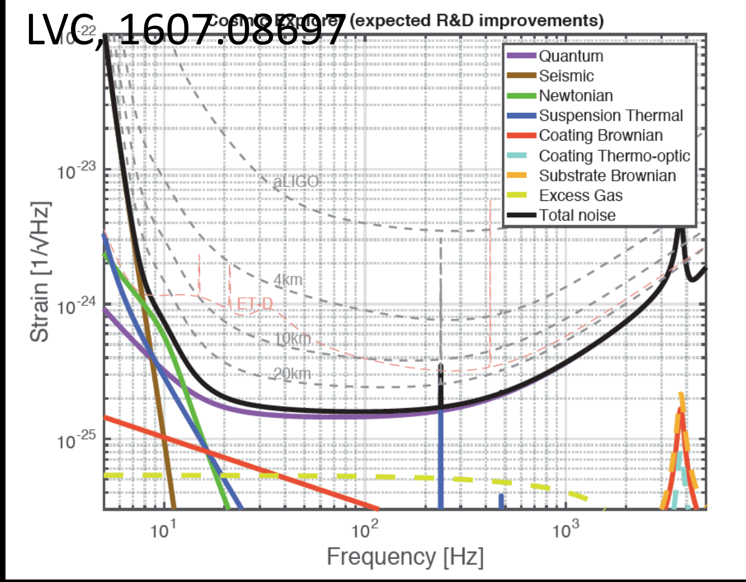
Proposed 3G detectors

- Einstein Telescope
  - 10 Km long arms
  - Triangular shape
  - Underground
  - Sensitivity down to few Hz
- Cosmic Explorer
  - 40 Km long arms
  - L shaped
  - Over ground
  - Sensitivity down to ~8Hz

Regimbau+, PRD 86 122001



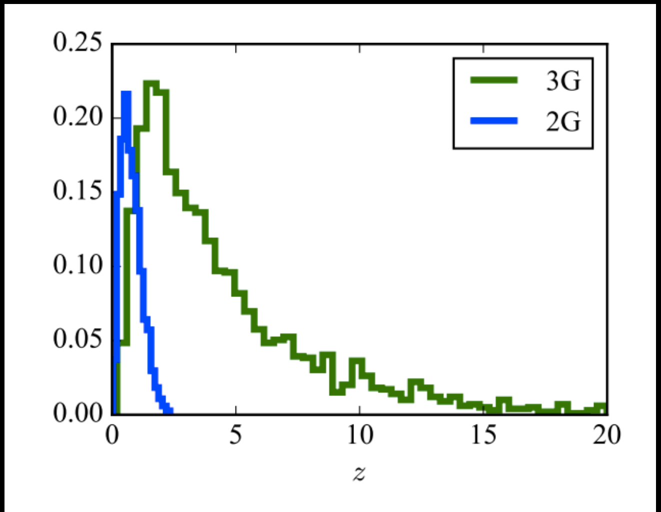
LVC, 1607.08697



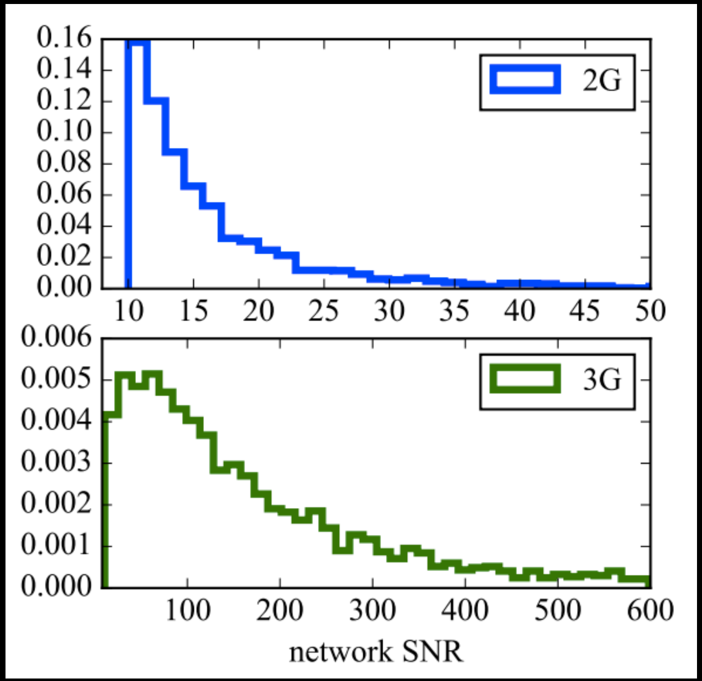
LIGO

Loud and clear

- BBH detected by 3G detectors will typically be *loud*
- Most events from redshift of a few
- For stellar mass BBH, remove selection bias toward higher mass



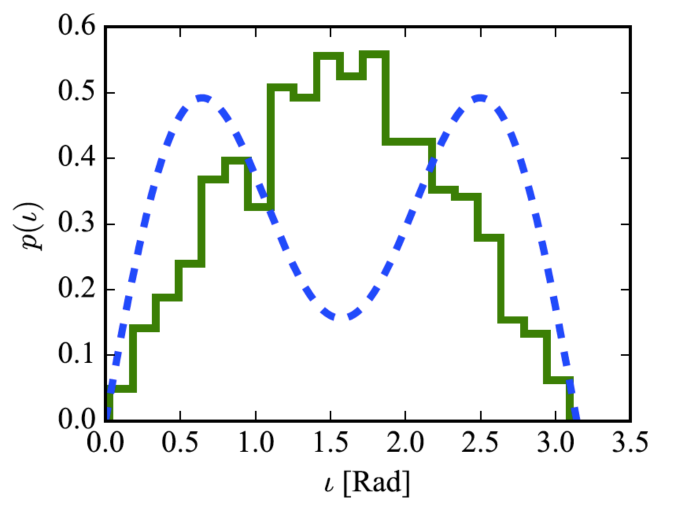
Vitale, PRD(R) 94 121501



BBH with component masses in range [6,100]M

… and well oriented

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



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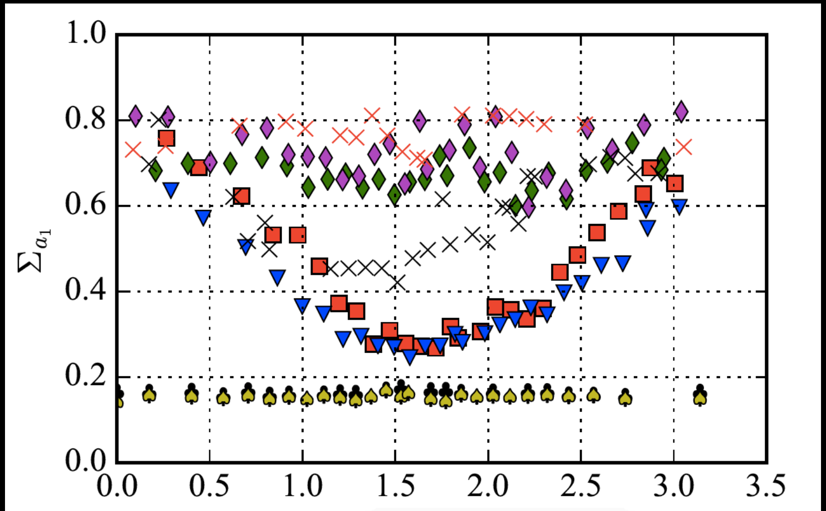


Vitale+, PRL **112** 251101, PRD 95 064053

Formation channels

- Many methods have been proposed to study the formation channels of BBH (and compact binaries in general)
  – Shown to work for 2G – local universe
- 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

Why a network?

- For advanced detectors
  - Sky localization
  - Recognize glitches
  - Increase network duty cycle
- For A+, Voyager, ET, CE
  - All of the abovementioned
  - Mass estimation!! (Through luminosity distance and cosmology)

$$m^s = \frac{m^{det}}{1+z}$$

Locations

	Longitude	Latitude	Orientation	Type
L	-1.58	0.533	2.83	CE
C	1.82	0.67	1.57	CE
I	1.34	0.34	0.57	CE
E	0.182	0.76	0.34	ET
A	2.02	-0.55	0	CE

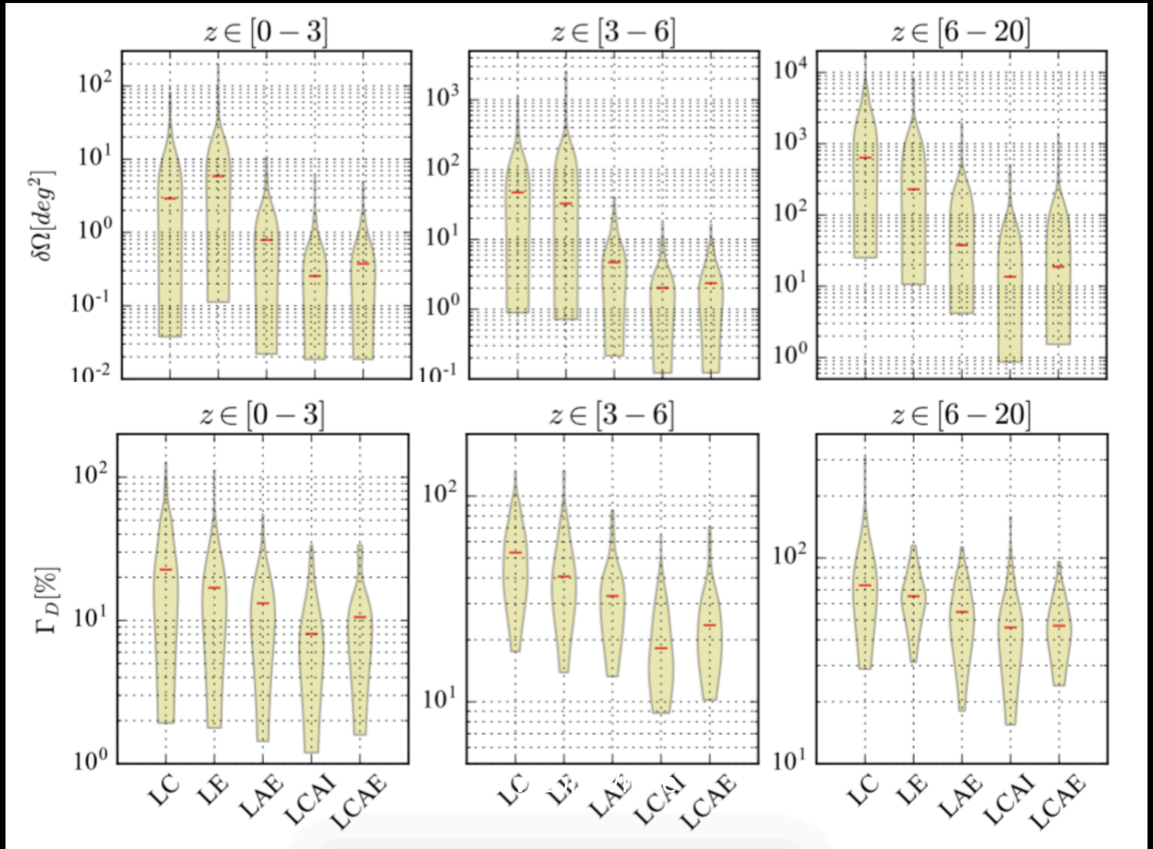
Vitale & Evans, PRD 95 064052

Extrinsic parameters (3G)

- Precise distance and sky position:
  - EM (if luminous), isotropy, cosmology (ongoing work with Hsin-Yu Chen)

Sky location

Luminosity Distance



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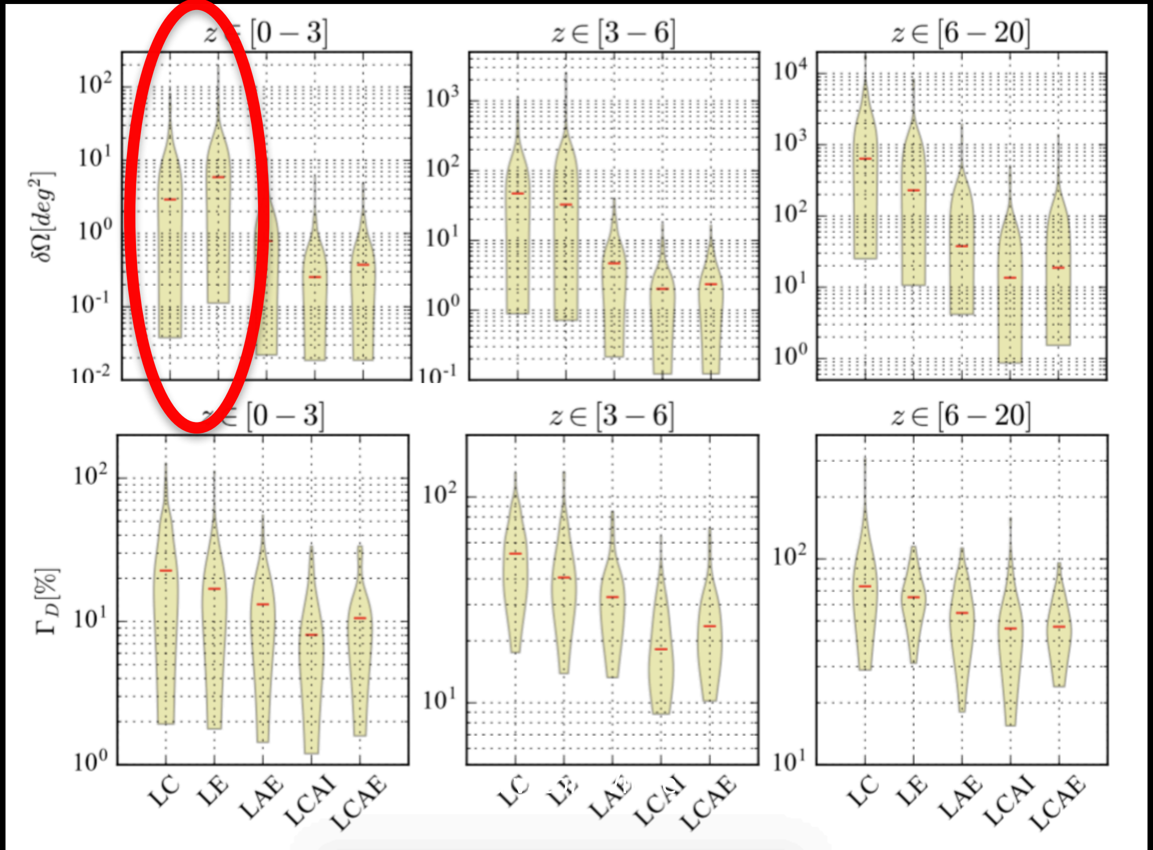

Even with 2 detectors, many sources localized better than 1deg2

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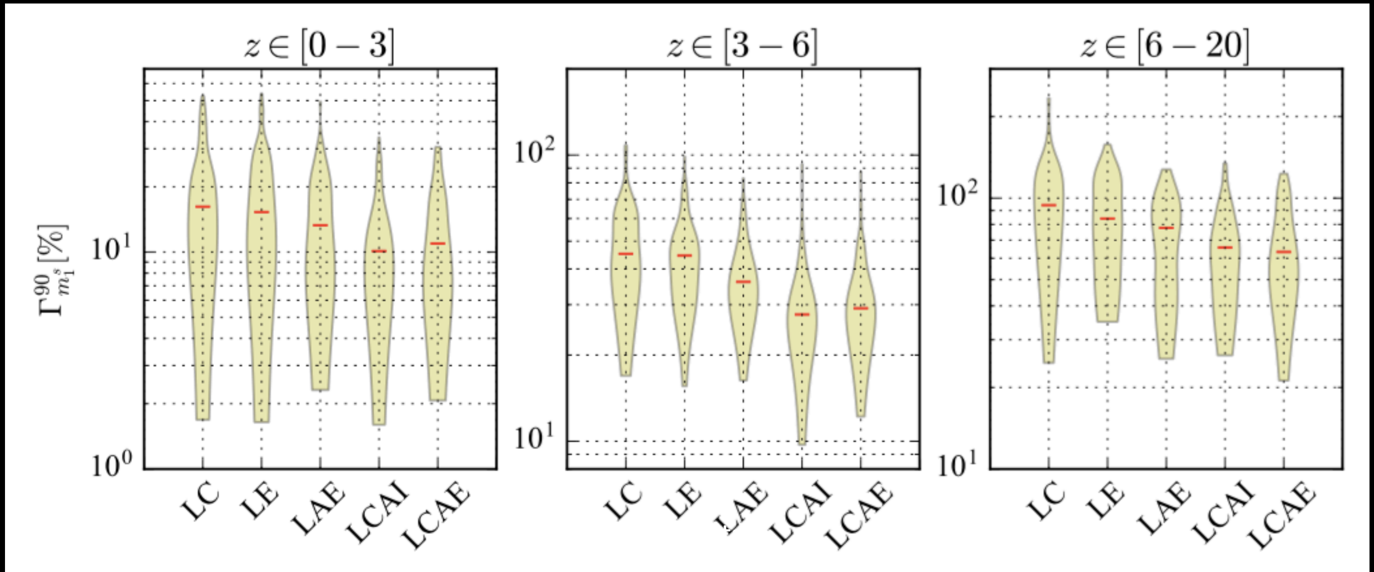
Source frame masses (3G)

- Especially at large redshifts, having more than 2 sites is important to measure component masses
- Uncertainties of [few-10]% for z<3
- Factor 1.5-2 better with 4 IFOs w.r.t. 2 IFOs



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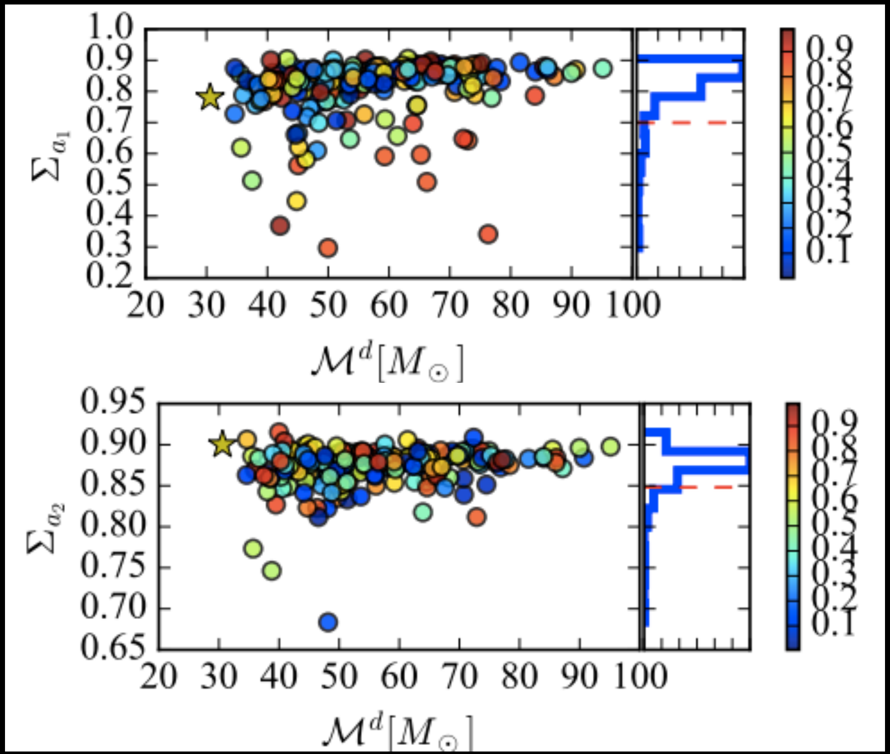
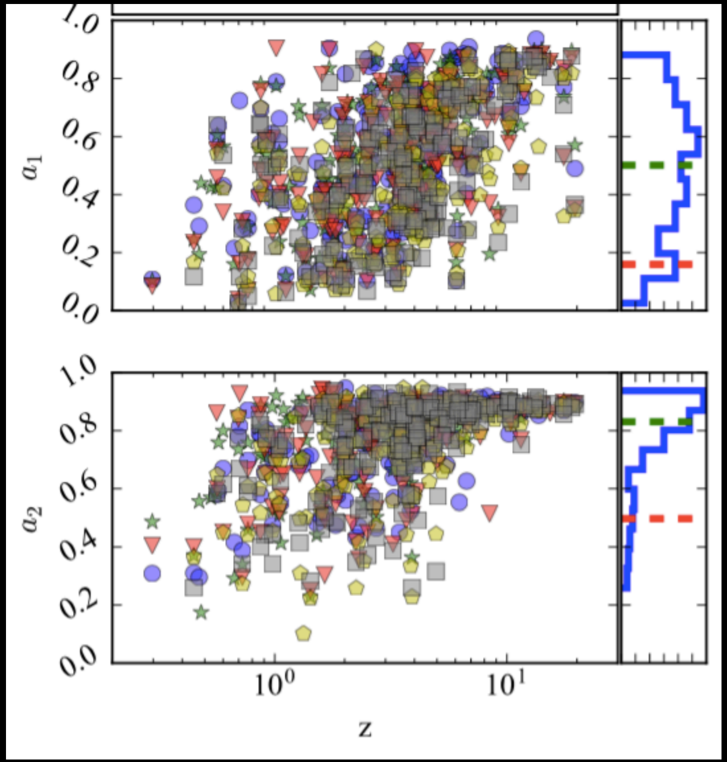
Spins

- Due to larger SNR and isotropic orbital orientation, 3G will get much better spin estimation than 2G

2G





3G

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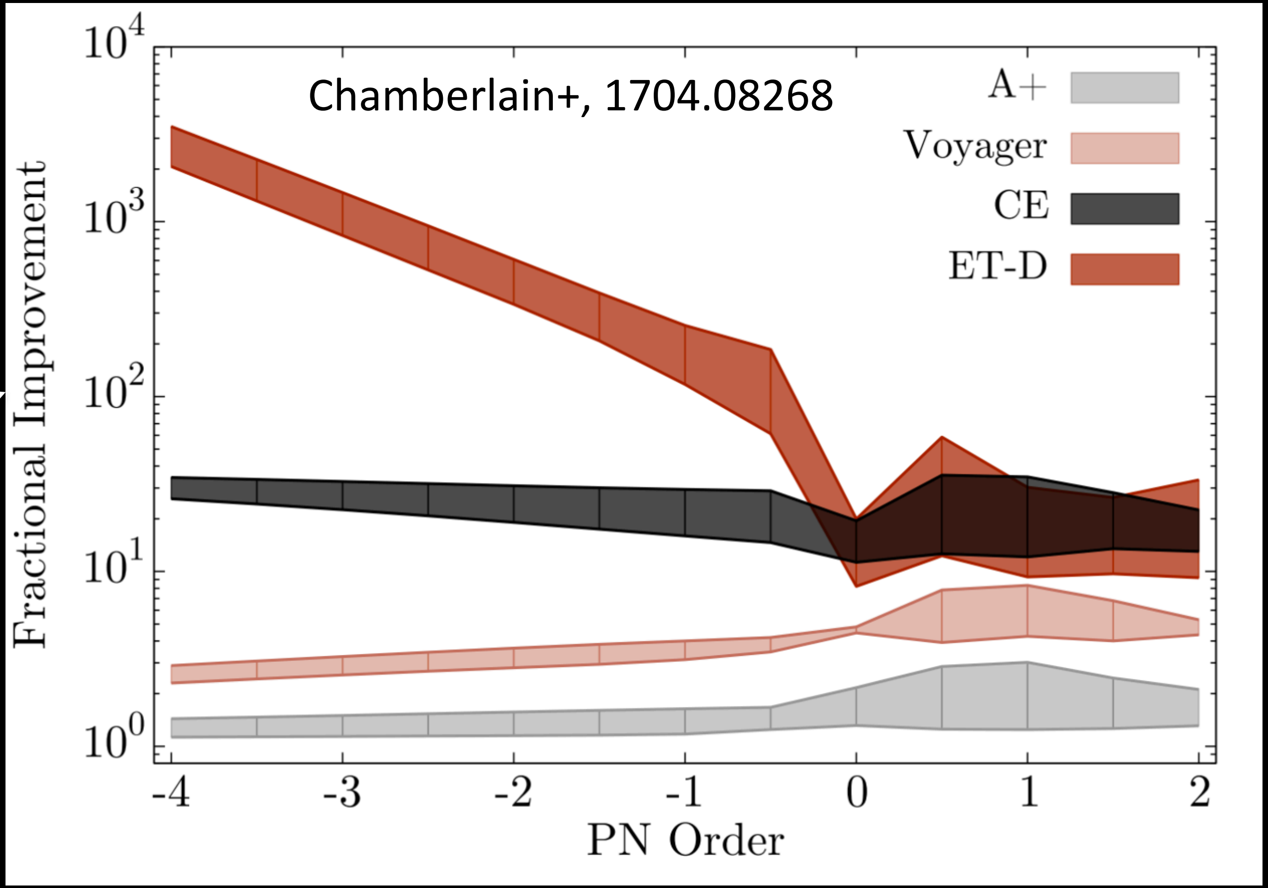
Tests of general relativity

- Larger SNR and better low frequency will yield dramatic improvements

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



How many events?

- Using the rates calculated after GW170104
  - ~ 10^5 BBH coalesce in the universe per year

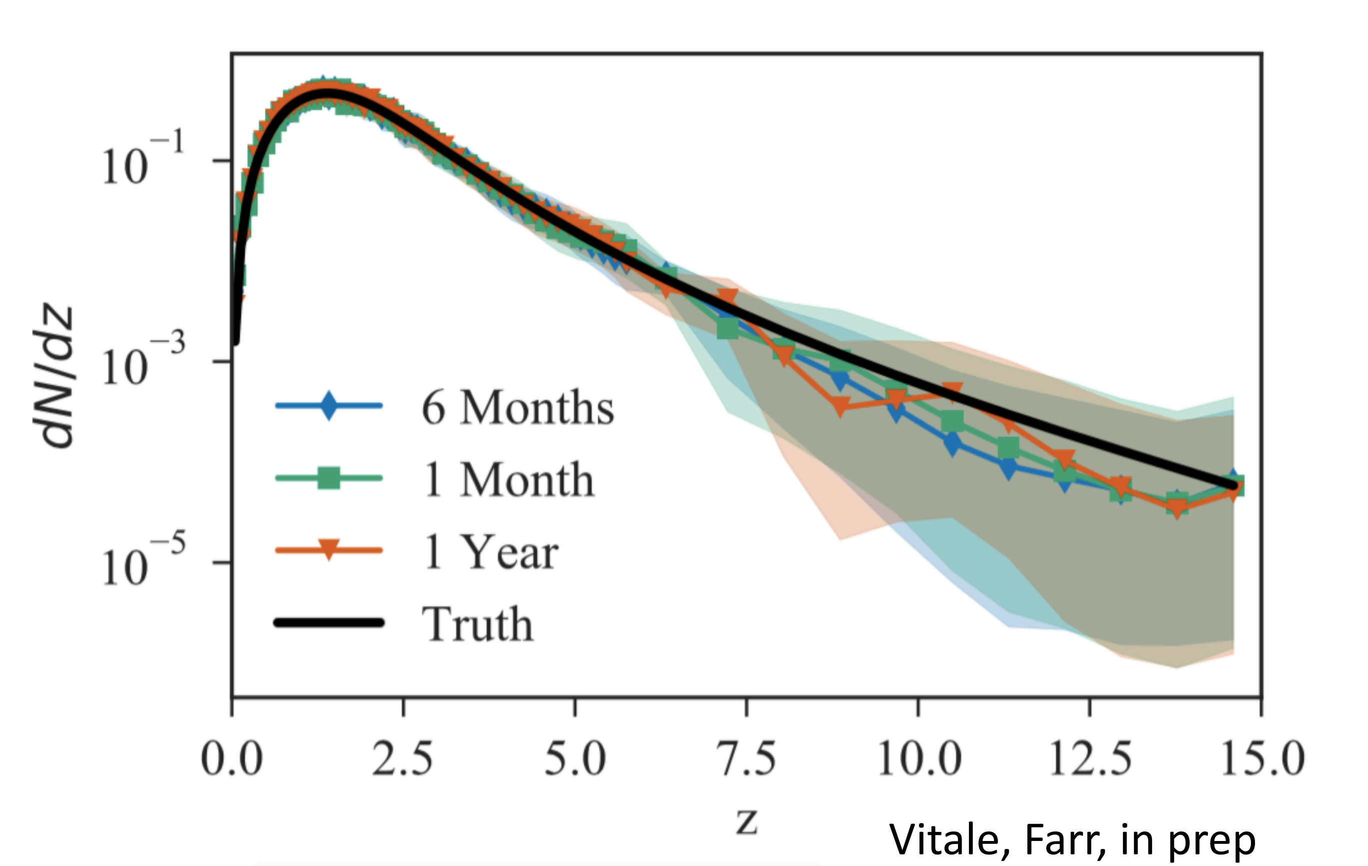
- With 3G detectors, we will detect 99.9% of them (Regimbau+, PRL 118, 151105)

Merger rate density

- We can calculate the merger rate as a function of redshift
- Generate 1, 6, 12 months worth of BBH detections by 3G detectors
  - Assume Madau-Dickinson star formation rate (SFR)
  - Assume time delay between merger and formation goes as 1/t
  - Formation rate proportional to SFR

Merger rate density

- Merger rate density can be reconstructed after only 1 month of detections



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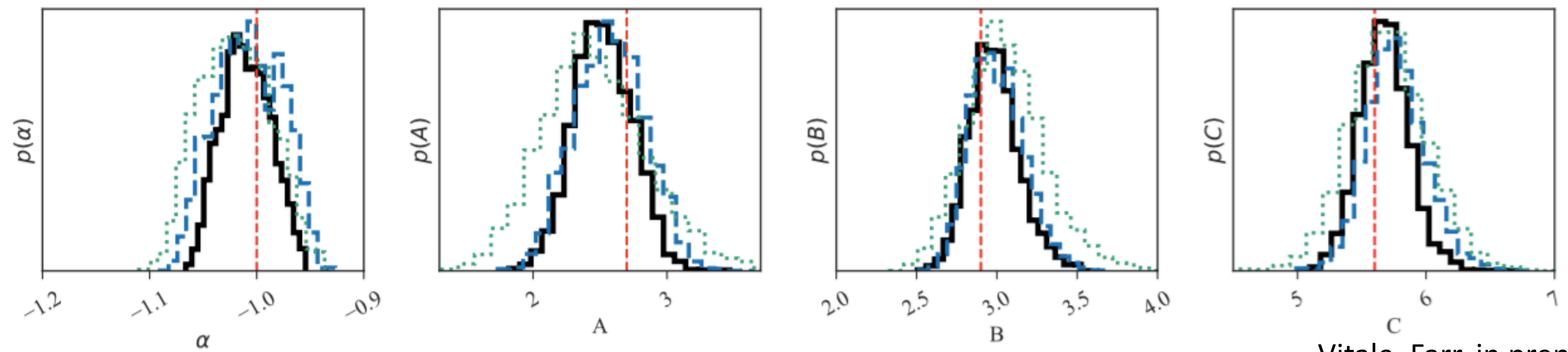
SFR

- Can measure the time delay power law coefficient and well as the parameters of the SFR



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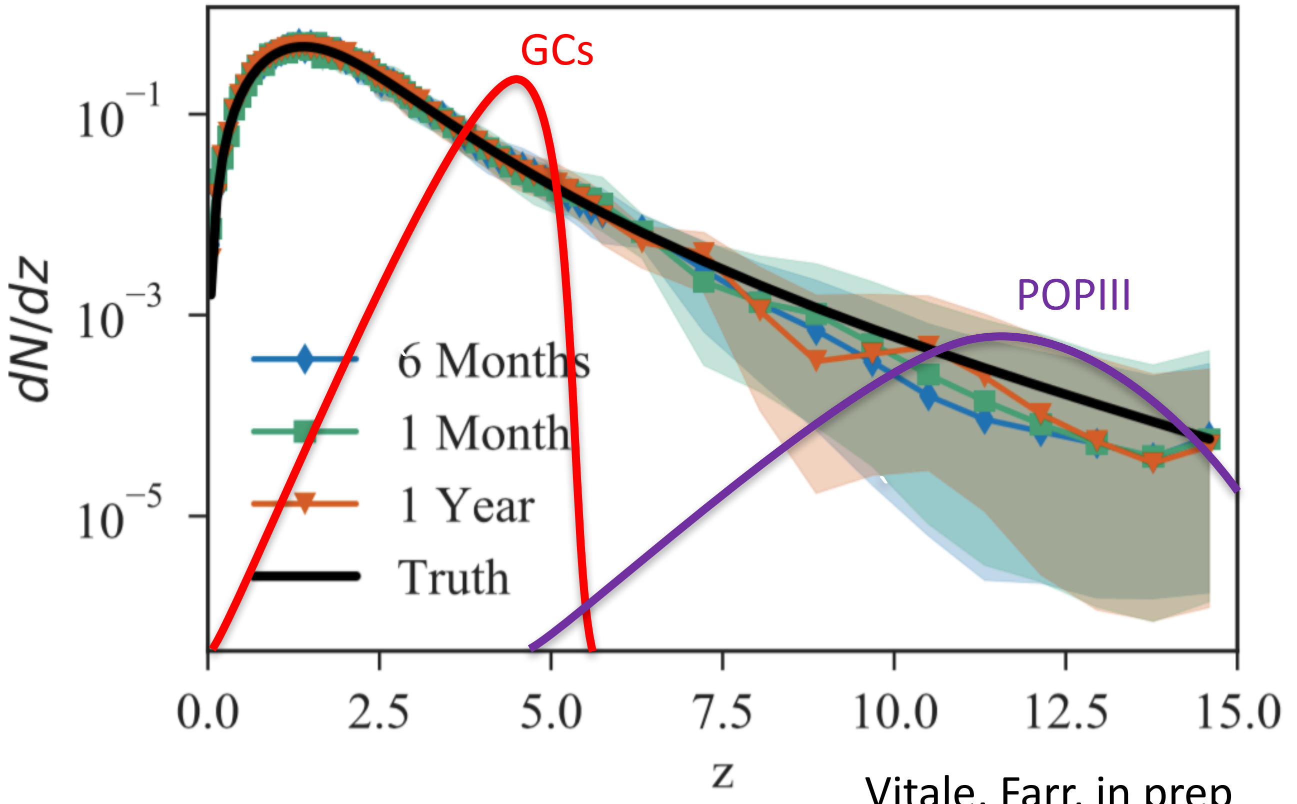
SFR template: $$\psi_{MD}(z) = \nu \frac{(1+z)^A}{(1+\frac{1+z}{B})^C}$$

Formation channels

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



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Heterogeneous networks

Motivation

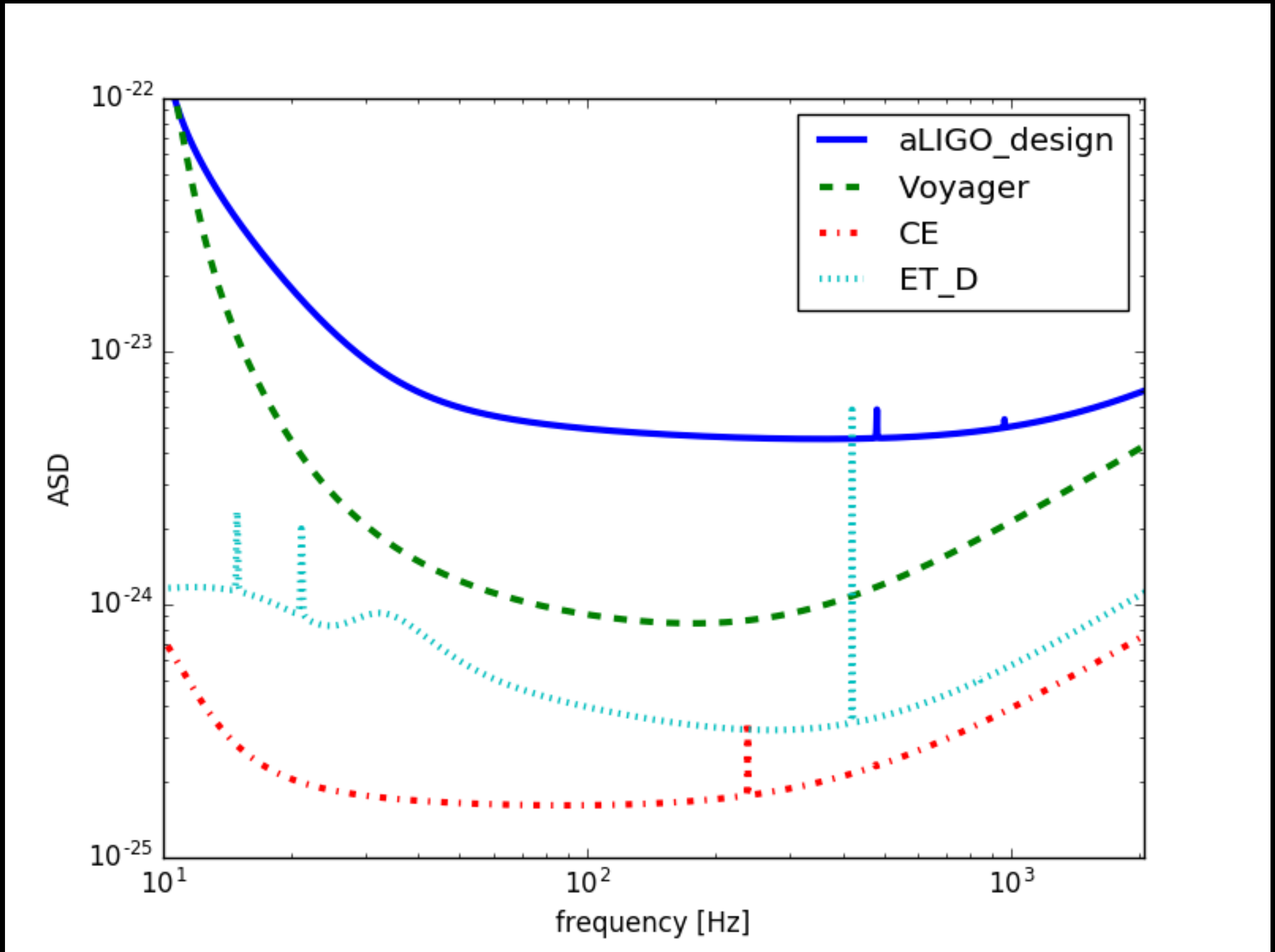
- Would like to have two (or more!) 3G detectors
- Funding or timelines might in fact result in only 1 3G detector to be online, at least for a while

- We might have
  - 1 3G
  - 1 or more detectors from previous generations

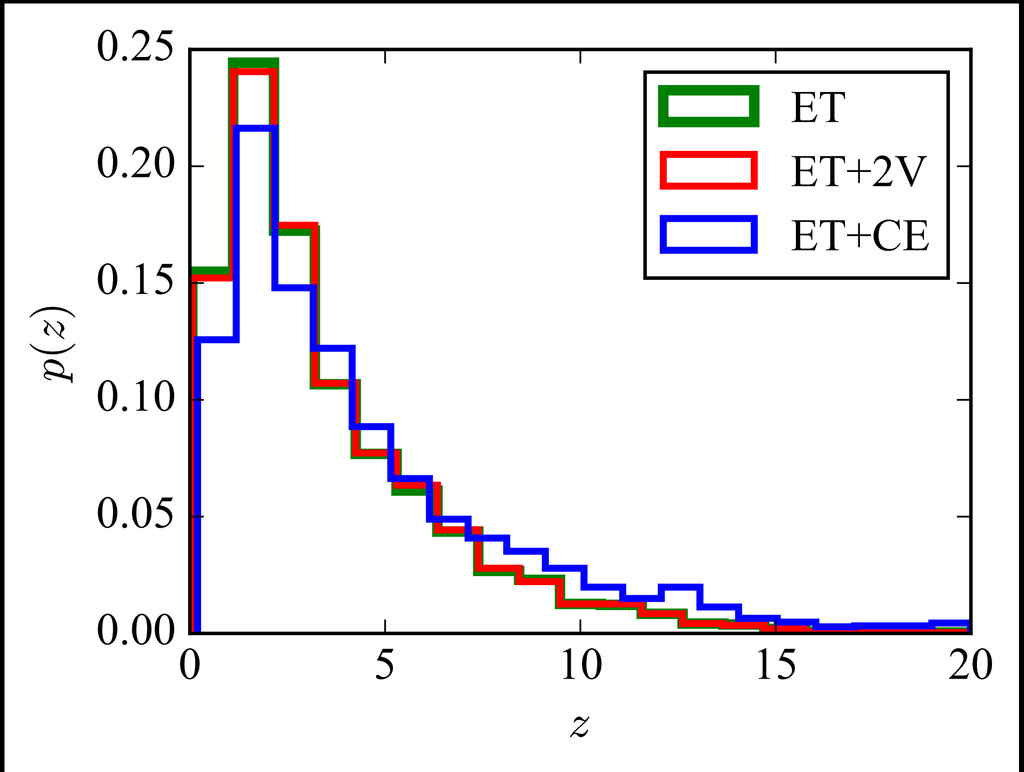
Heterogeneous networks

- Does it make sense to keep old detectors running if a 3G is online?
- Guesstimates:
  - 3G-2G. Factor >10 difference. 2G are of no help
  - 3G-A+. Factor ~>5 difference. A+ probably of no help
  - 3G-Voyager: Voyager might help for sky localization (not detection/range)

Possible sensitivities



Observing most of the BBH in the universe



- Considered population of BBH with component masses in the range [6,100] M
- Uniform in com. vol.
- As long as at least 1 ET detector is included, BBH are detected up to redshift of ~15
- Adding Voyager won't change much
- Adding a CE pushes the typical detection farther away

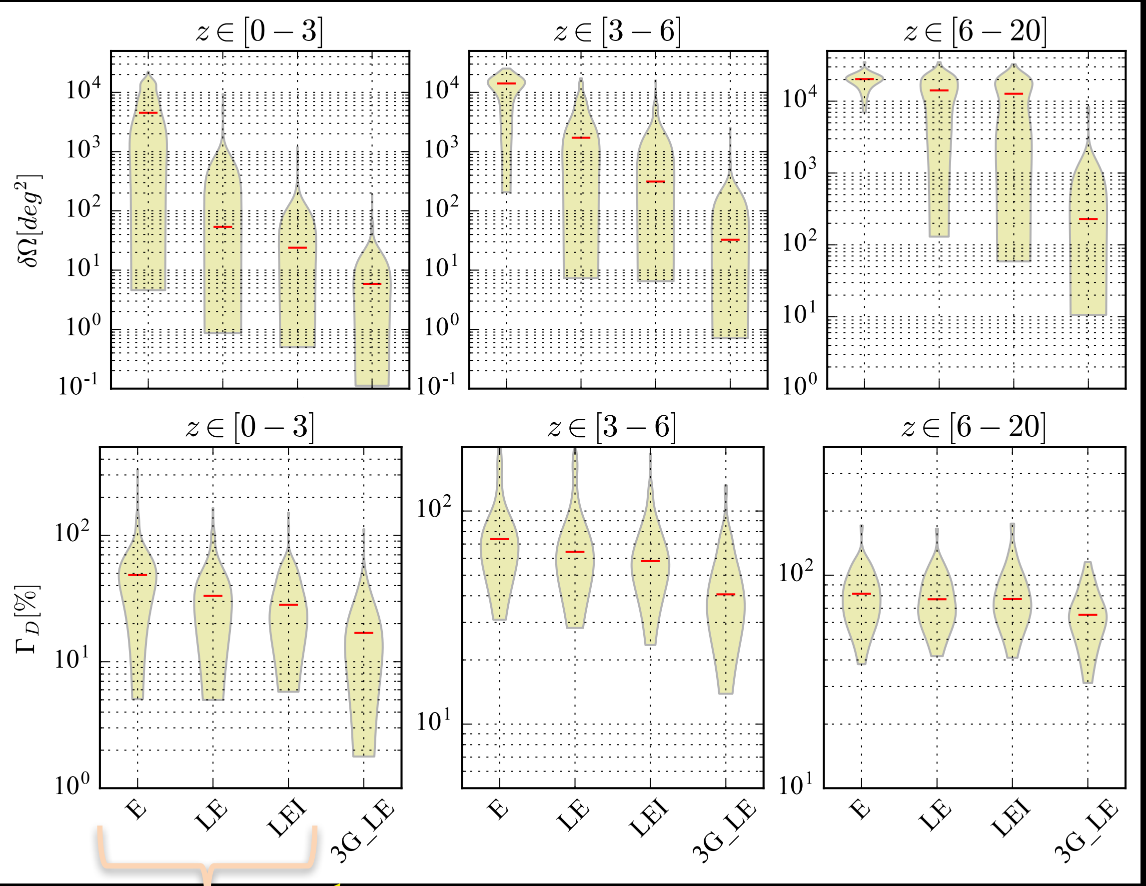
Extrinsic parameters (2.5G+3G)

- Adding a Voyager significantly improves sky localization - factor ~100
- Will check, but probably similar conclusion will hold for BNS
- However with only 1 3G will rarely have localizations better than 1deg2

- Marginal improvement in distance estimation

Sky location

Luminosity Distance



1 ET (+ Voyager(s))

3G only

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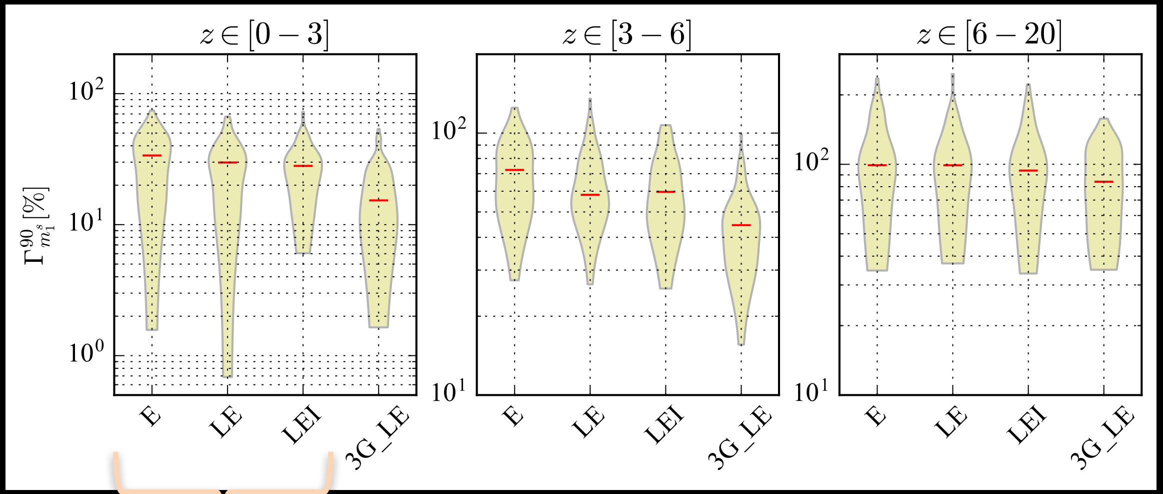
Source frame masses (2.5G+3G)

- Adding a Voyager does **not** improve estimation of component masses
- A factor of ~2 to be gained by adding a second 3G detector

Component mass



1 ET (+ Voyager(s))

3G only

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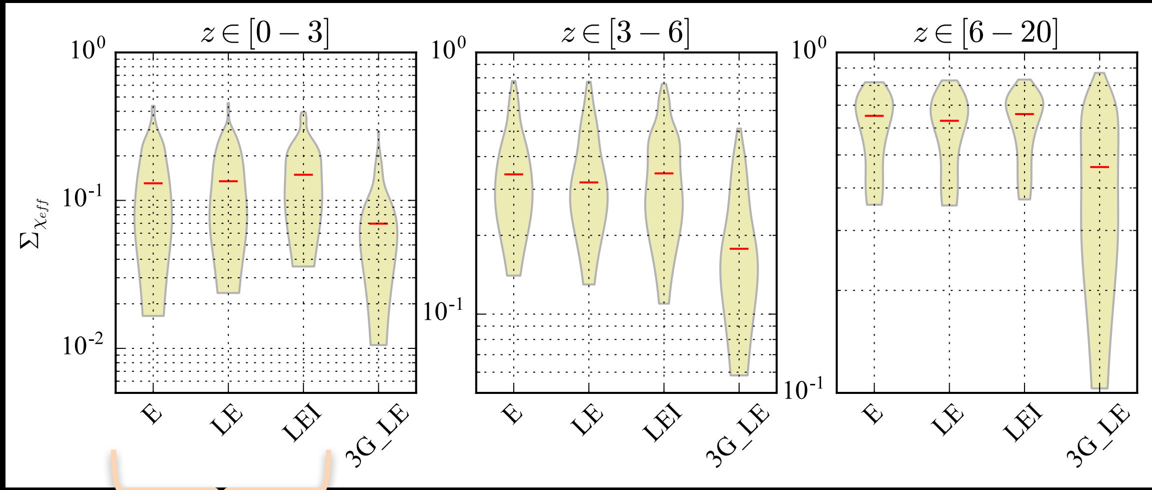
Spins (2.5G+3G)

- Adding a Voyager does **not** improve estimation of component spins
- Two (or more) 3G detectors would do better at measuring spins (more SNR, more visible precession)

Component spins



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1 ET (+ Voyager(s))

3G only

Conclusions

- Advanced detectors will explore the local universe (z ~ 1) and characterize black holes
- A new generation is required to detect BH everywhere in the universe
  - Characterization of BH masses and spins
  - Precise tests of general relativity
  - Access to BH throughout cosmic history