Astrophysics with the next generation of ground-based gravitational-wave detectors

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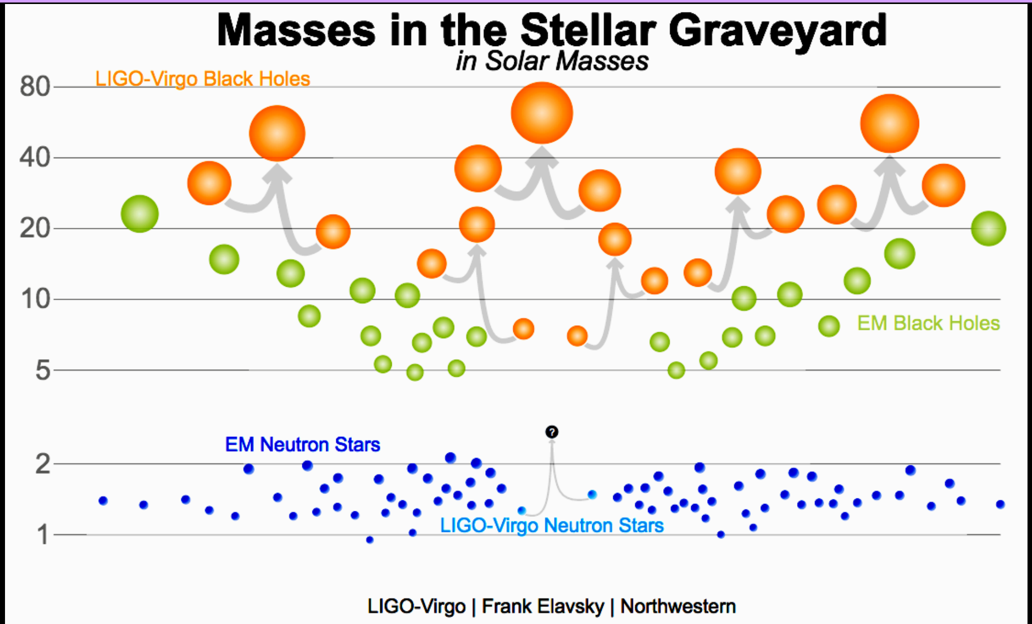
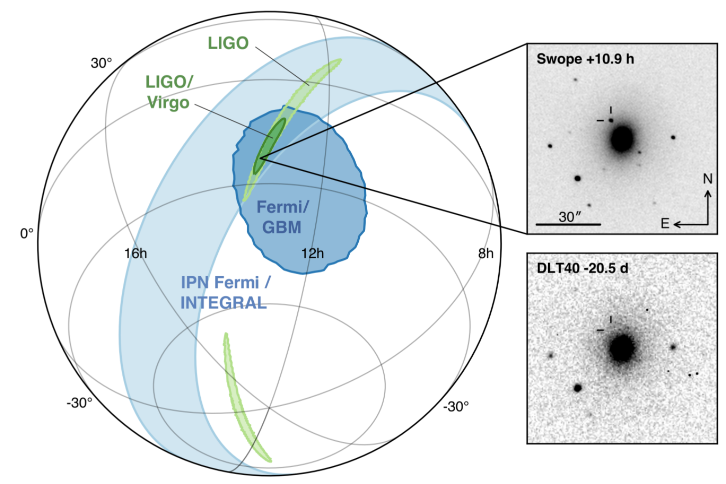
April APS 2018

Where are we?

- Advanced detectors (second generation, 2G) have detected 6 binary black holes (BBH)
  - Component masses measured at few x 10% level
  - Spins very hard to measure
  - Oriented face-on/off
  - Up to redshift of ~0.2
  - See LVC, PRL **118** 221101, PRX **6** 041015, https://www.ligo.org/detections.php
- And one binary neutron star (BNS), LVC PRL **119**, 161101
  - First GW bounds on the equation of state (EOS) of nuclear matter
  - Joint EM-GW detection





LVC and friends, ApJL, 848:L12, 2017

Where are we?

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

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

LVC, PRL **118** 221101

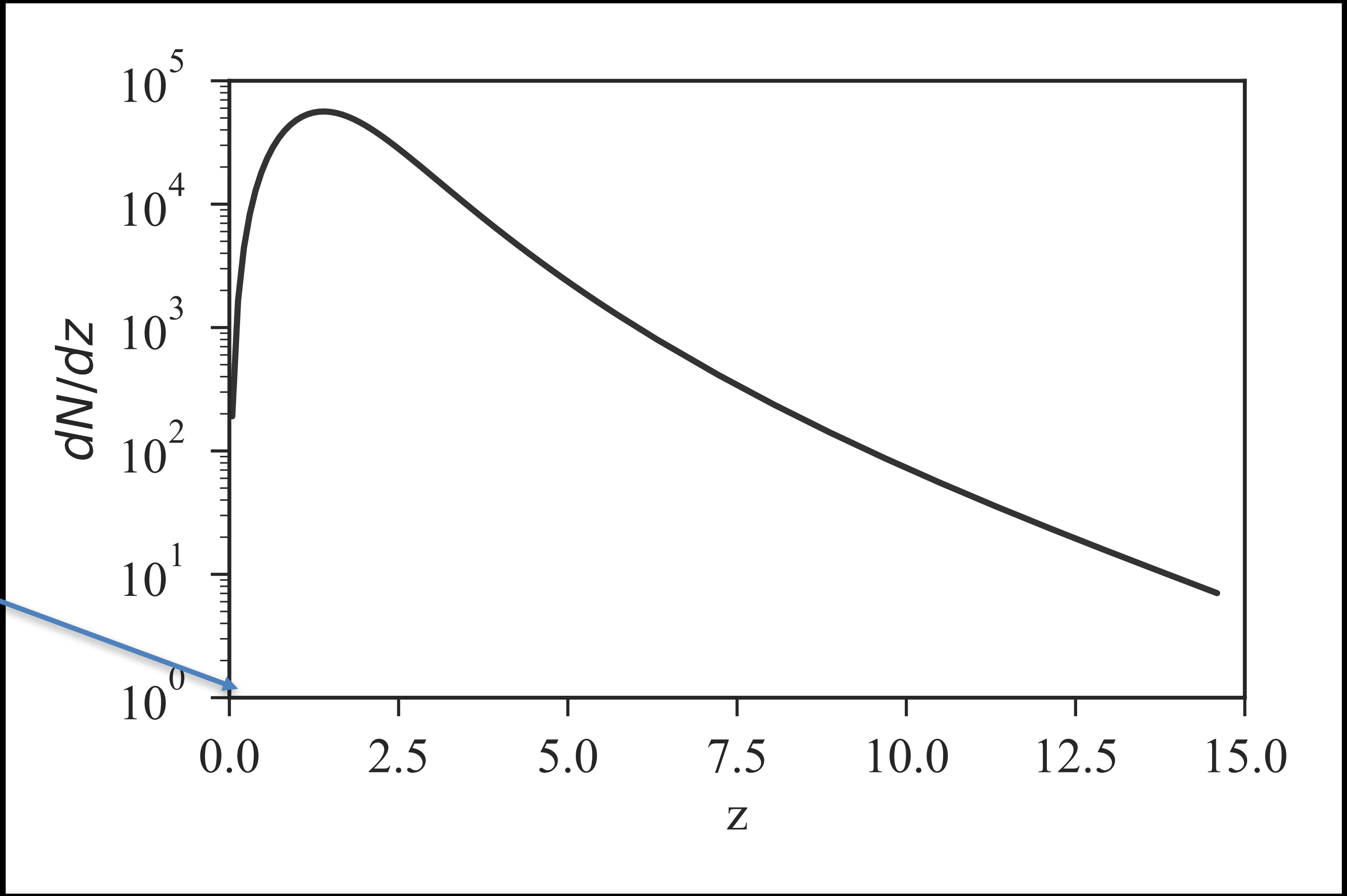
$$1540^{+3200}_{-1220}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

LVC, PRL **119** 161101

- Will advance the exploration of extremes of astrophysics and gravity
- solve open questions in fundamental physics and astronomy
- provide insights into most powerful events in the Universe
- boost the impact of multi-messenger astronomy
- likely to reveal new objects and phenomena

Where are we?

You are here!



Where do we go from here?

- With 2G at design, we'll go up to z ~ 1 for BBH and ~0.1 for BNS
- If we want to detect sources at high redshift, we need something else

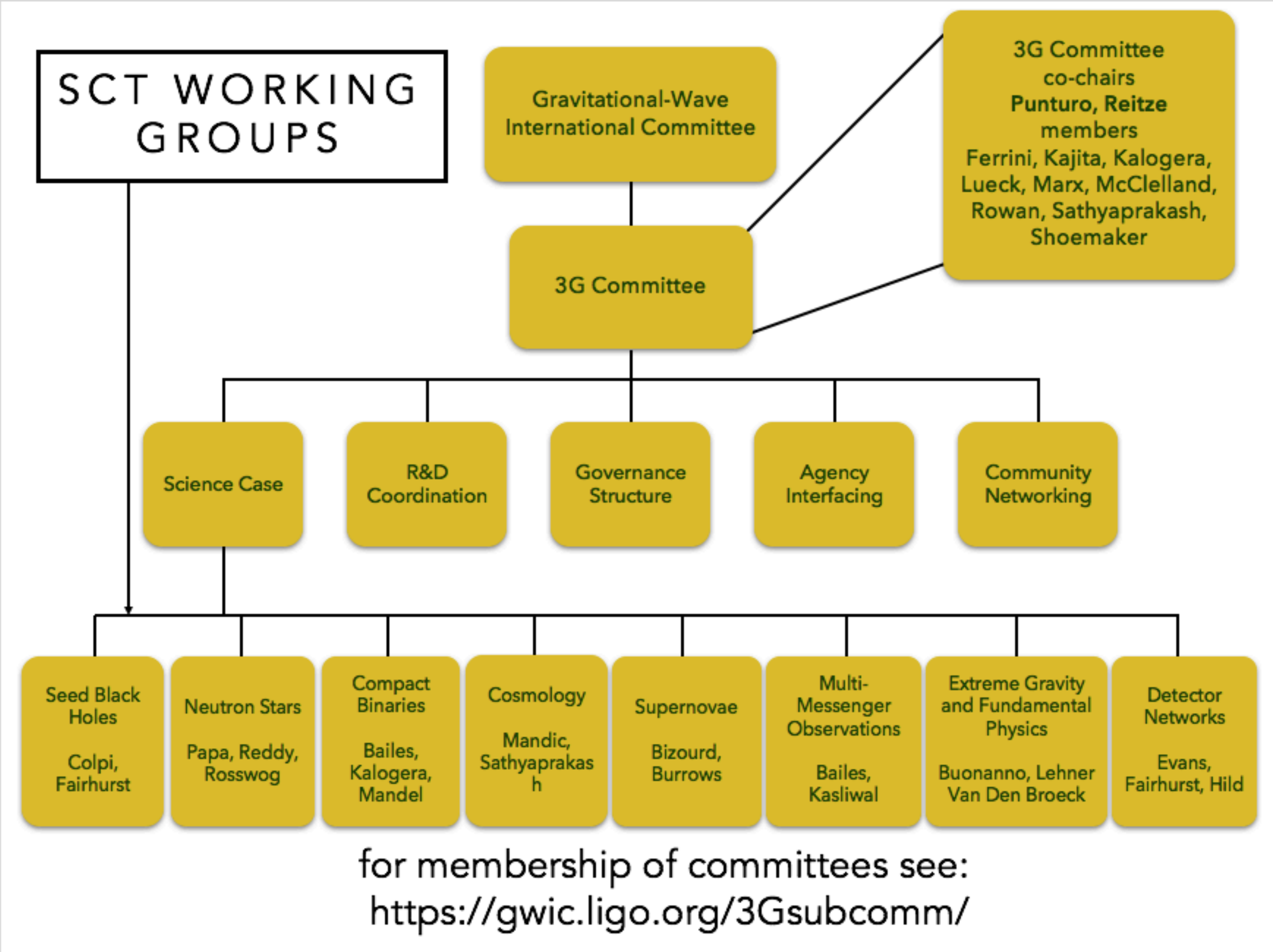
- Proposed third—generation (3G) ground based detectors will
  - Be a factor of ~>10 more sensitive that 2G-design
  - Detect BBH from redshifts >10
  - Detect a lot of sources, with very large signal-to-noise ratio (SNR)

A science case for next-generation detectors

- LIGO and Virgo both have facility-imposed limits on sensitivity
  - a compelling case to build detectors that can observe deeper into cosmos
- to fully exploit the GW window we will require new facilities
- Gravitational Wave International Committee (GWIC) formed a subcommittee to develop a vision for the next generation of ground-based detectors
- one of the charges to the GWIC subcommittee is:
  - *"commission a study of ground-based gravitational wave science from the global scientific community, investigating potential science vs. architecture vs. network configuration vs. cost trade-offs, …"*
  - GWIC subcommittee has constituted five 3G subcommittees:
- (1) Science Case Team (3G-SCT), (2) R&D Coordination, (3) Governance, (4) Agency Interfacing, (5) Community Networking
- Science Case will be developed by an international consortium of scientists under the leadership of the 3G-SCT (18 members)

Science Case: Goals, Timeline

- develop a robust science case unique to GW observations for the next generation of ground-based detectors
  - help with position papers for national and international studies and surveys
    - APPEC and ESFRI roadmaps in Europe, US decadal survey, …
- science case document to be delivered by Dec. 2018
  - study supported by **eight** working groups
  - ~ 150 researchers from around the world have joined the 3G-SCT consortium

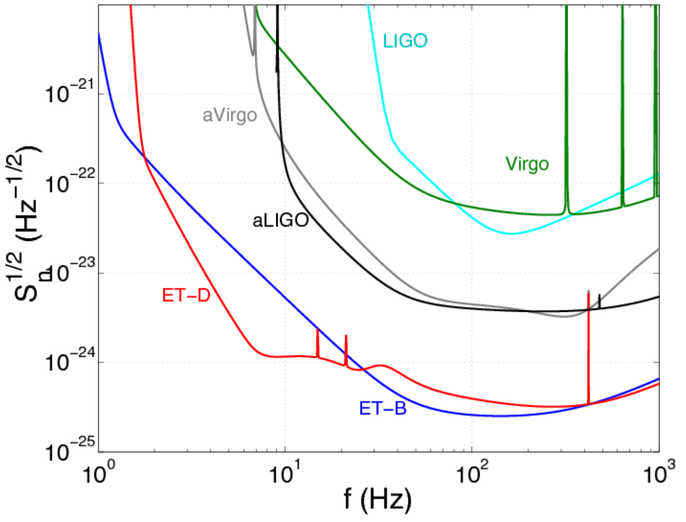


Interested in contributing? Email Vicky Kalogera and Bangalore Sathyaprakash!

Proposed 3G detectors

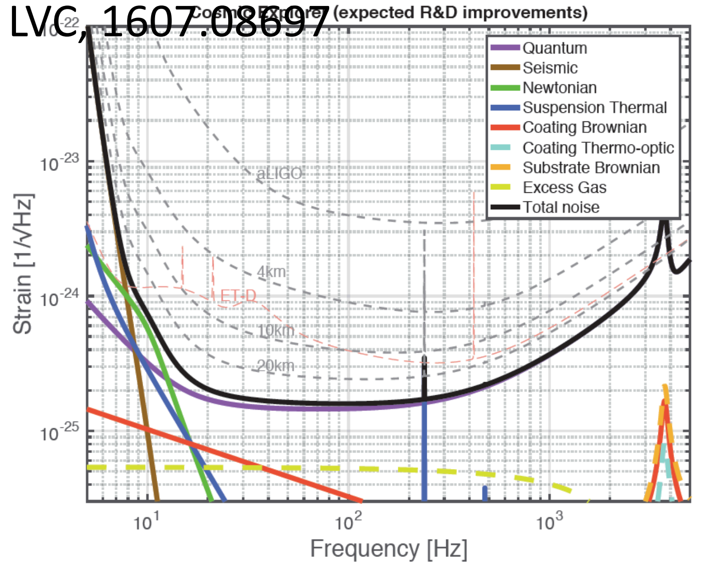
- Einstein Telescope
  - 10 Km long arms
  - Triangular shape
  - Underground
  - Sensitivity down to few Hz

Regimbau+, PRD 86 122001



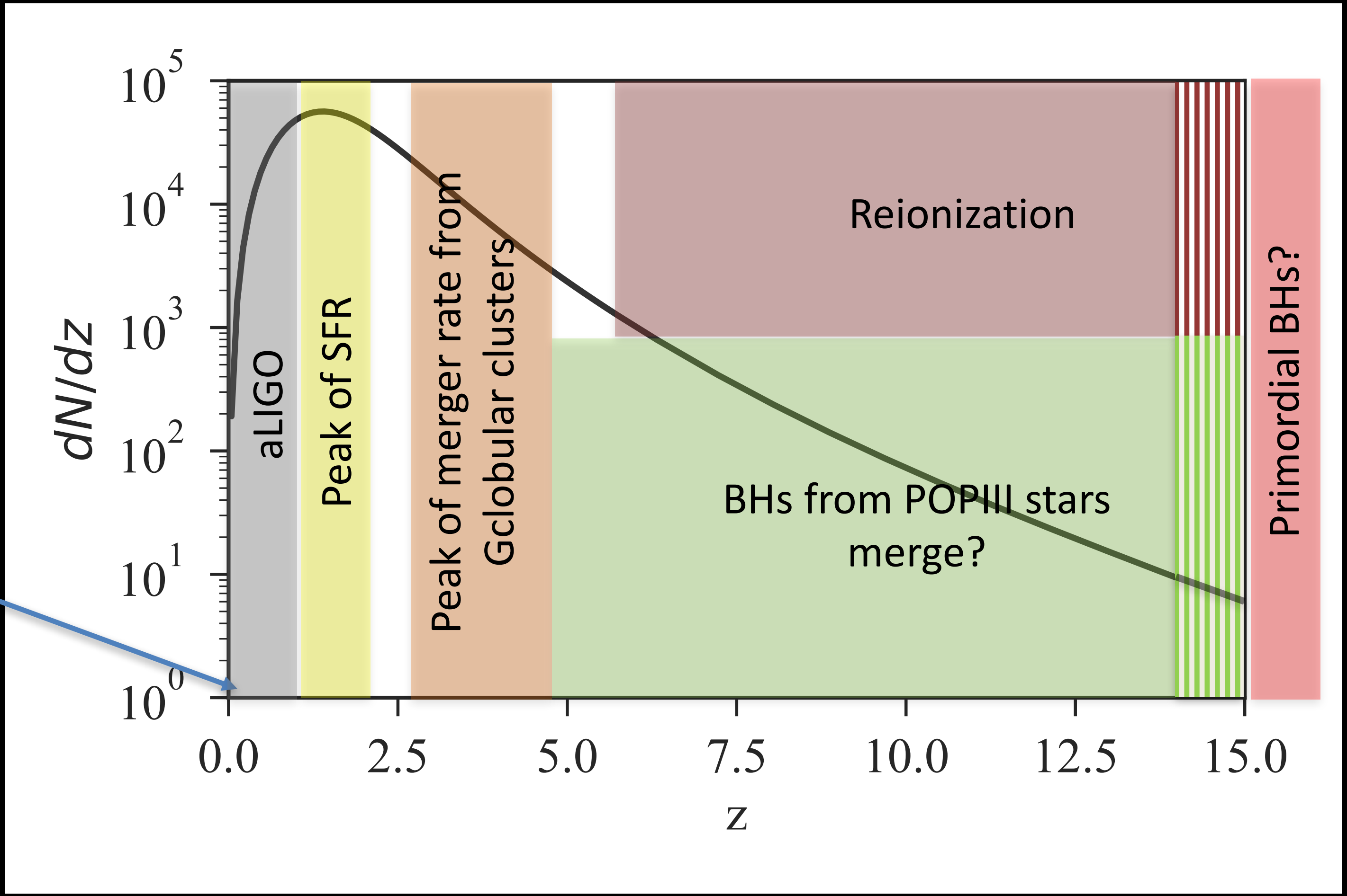
- Cosmic Explorer
  - 40 Km long arms
  - L shaped
  - Over ground
  - Sensitivity down to ~8Hz

LVC, 1607.08697



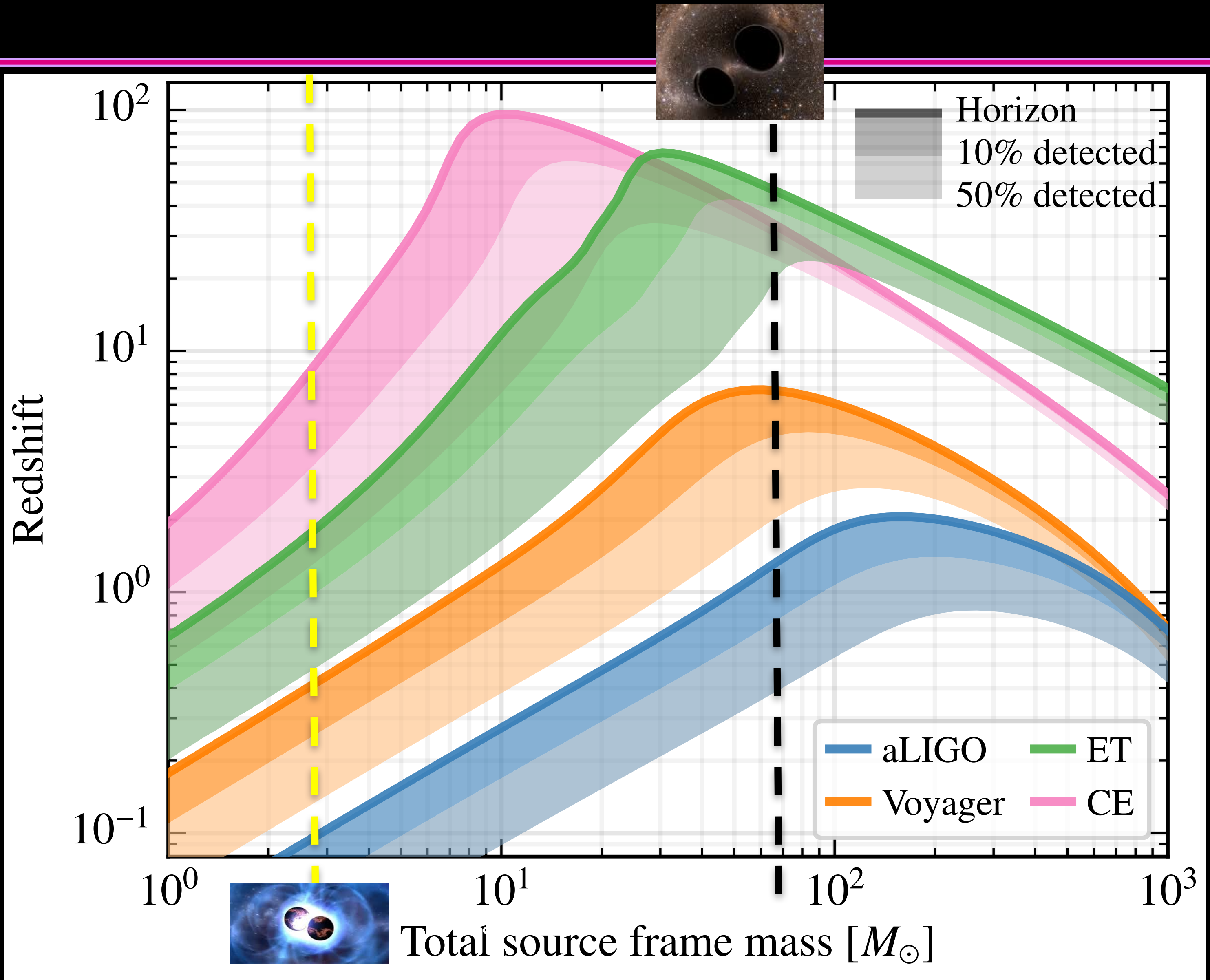
Where do we go from here?

You are here!



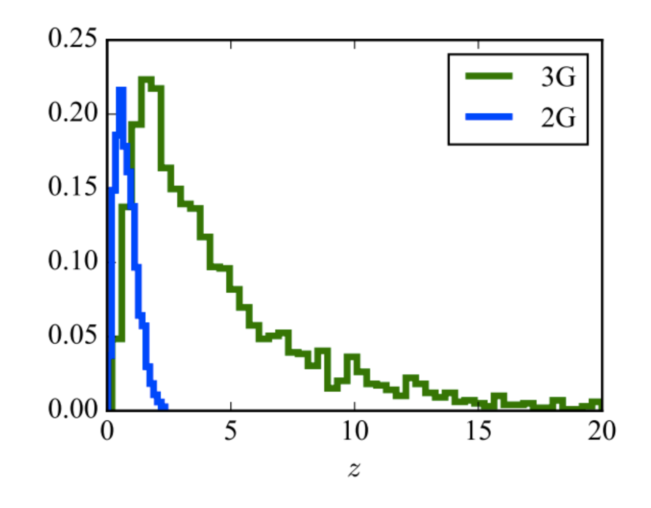
Where do we go from here?

credit E. Hall, J. Miller

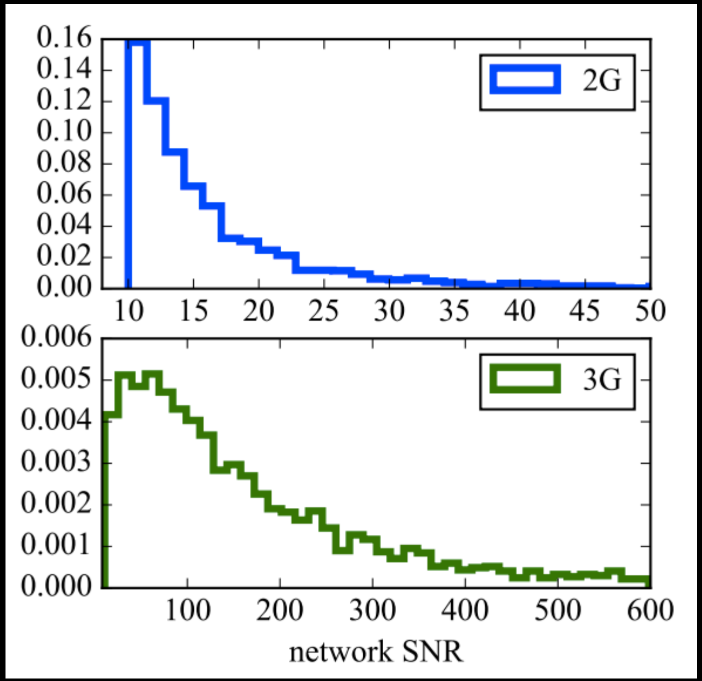


Loud and clear

- BBH detected by 3G detectors will typically be *loud*
- Most events from redshift of a few



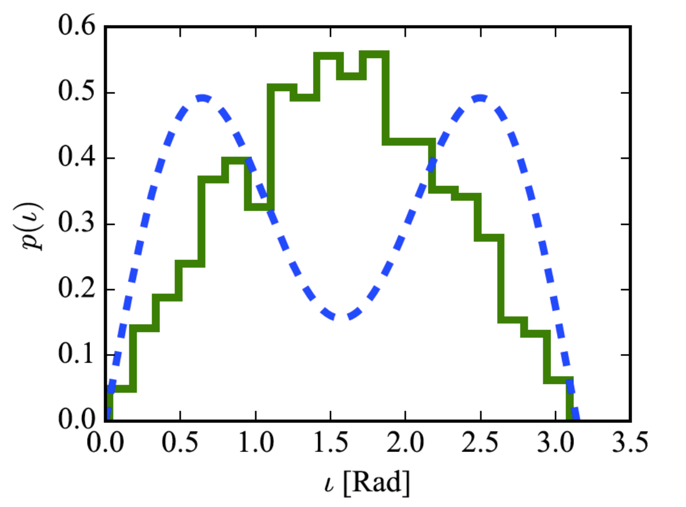
Vitale, PRD(R) 94 121501



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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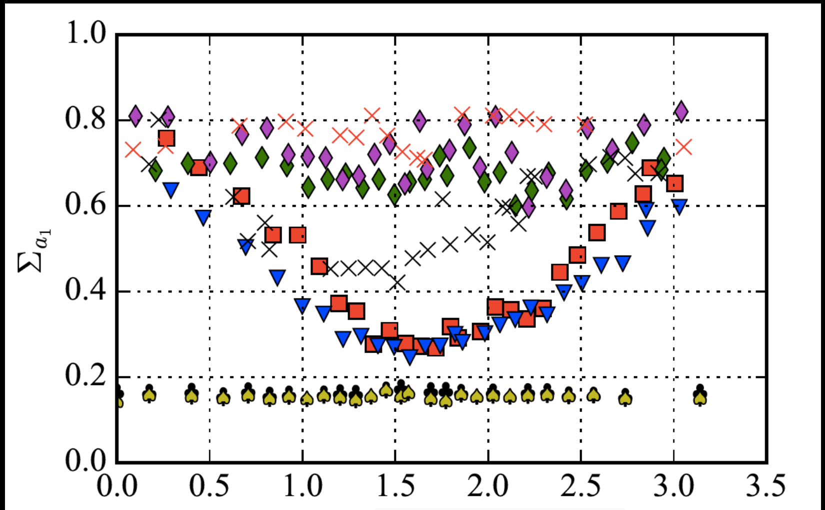


Vitale+, PRL **112** 251101, PRD 95 064053

Why a network?

- For advanced detectors
  - Sky localization, distance estimation
  - Glitch rejection
  - Increase network duty cycle
- For more sensitive detectors
  - 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

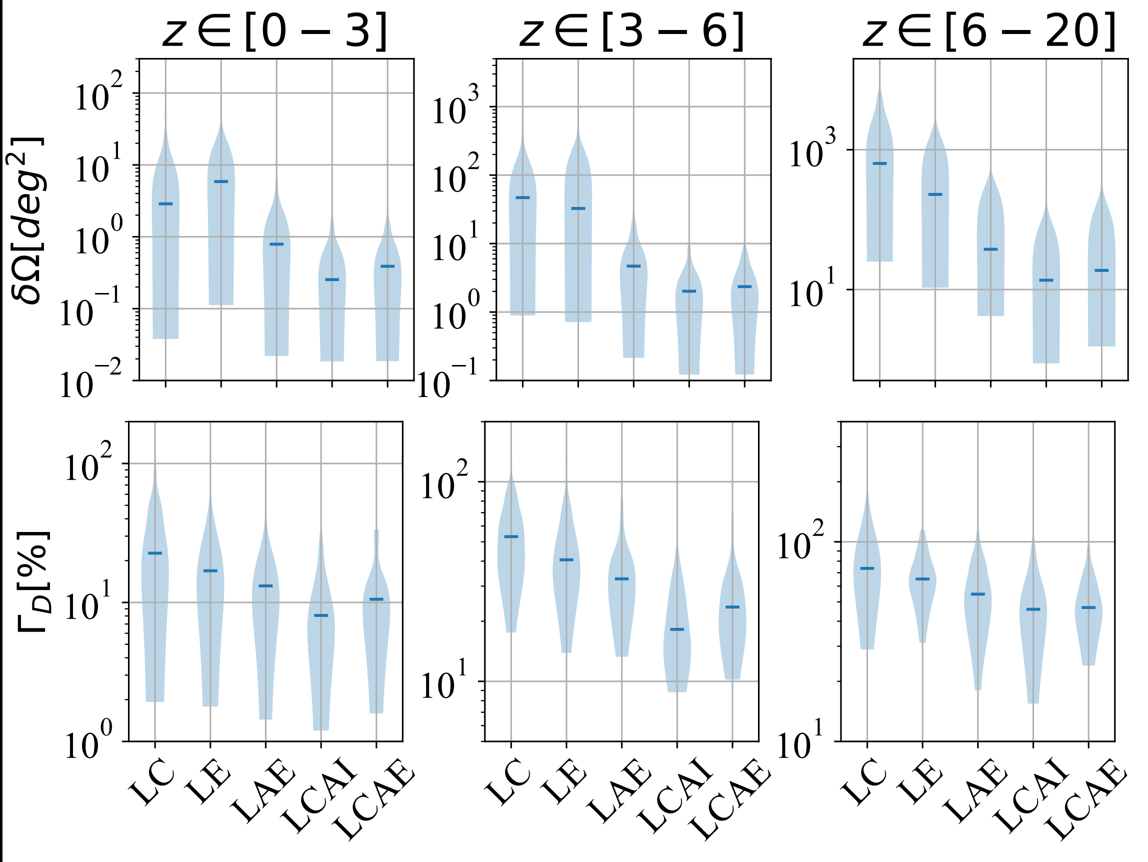
Vitale & Evans, PRD 95 064052

BBH Extrinsic parameters

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

Sky location

Luminosity Distance



Vitale & Evans, PRD 95 064052

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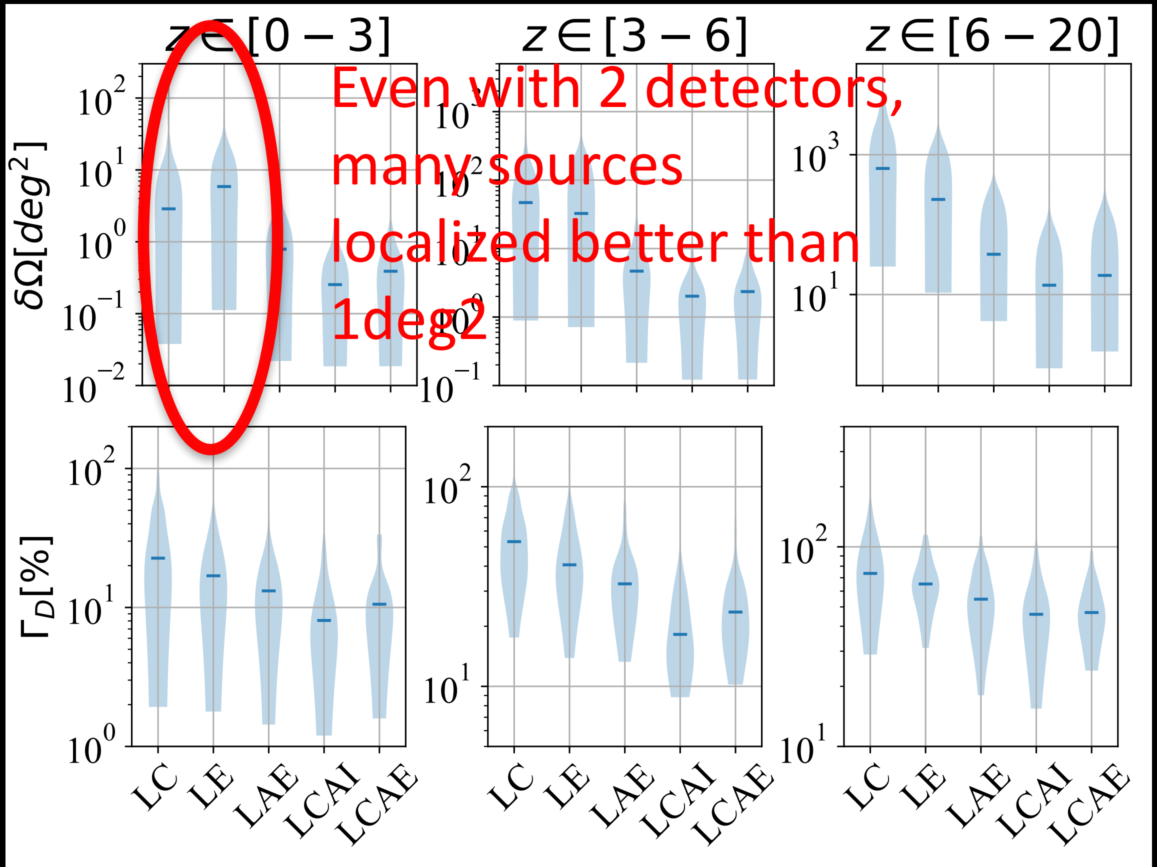

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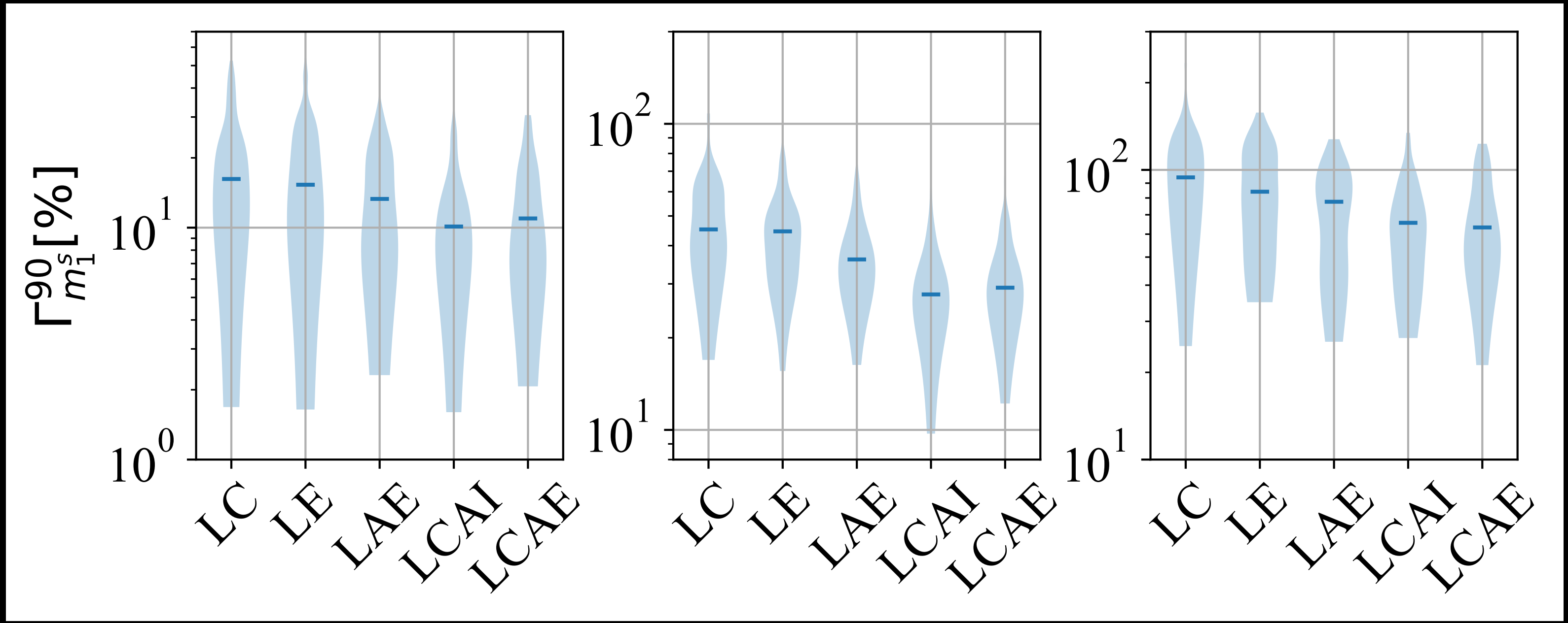
BBH Source frame masses

- 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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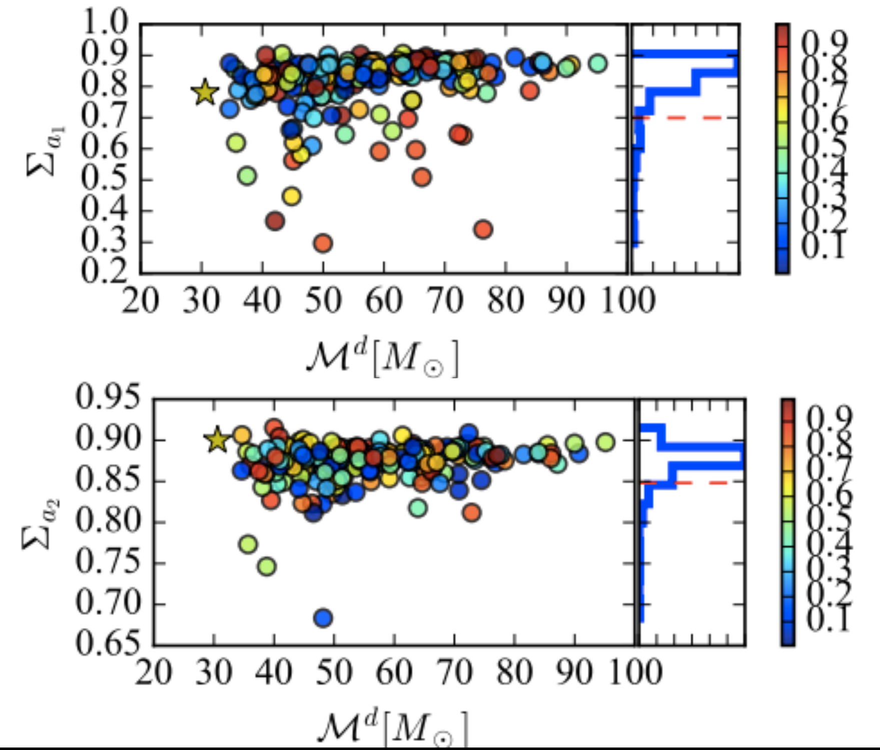
BBH Spins

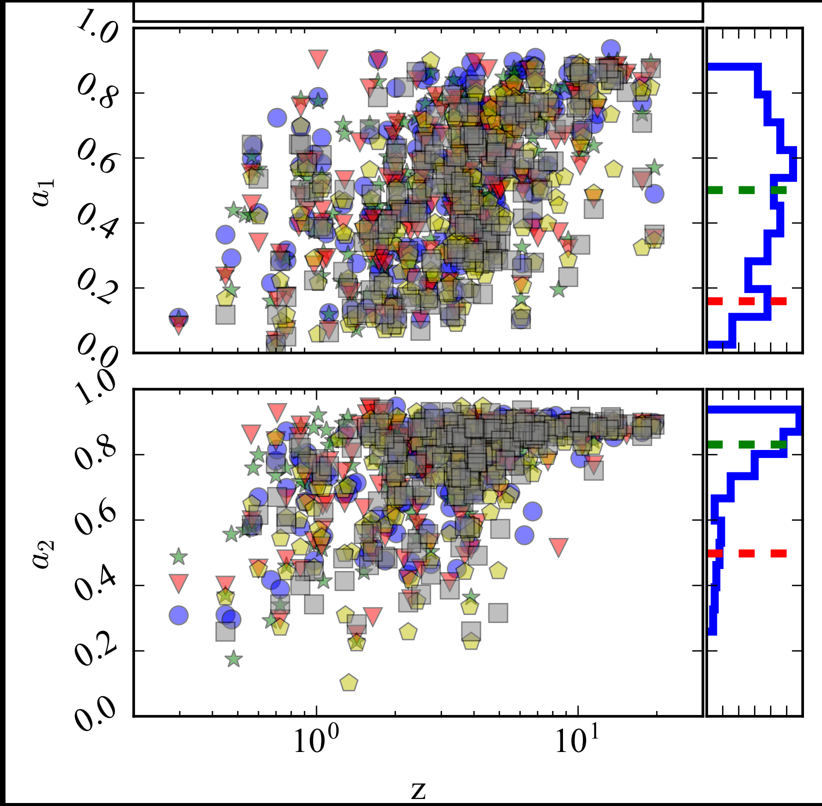
- Due to larger SNR and isotropic orbital orientation, 3G will get much better spin estimation than 2G

2G



Vitale+, PRD 95 064053

3G



Vitale & Evans PRD 95 064052

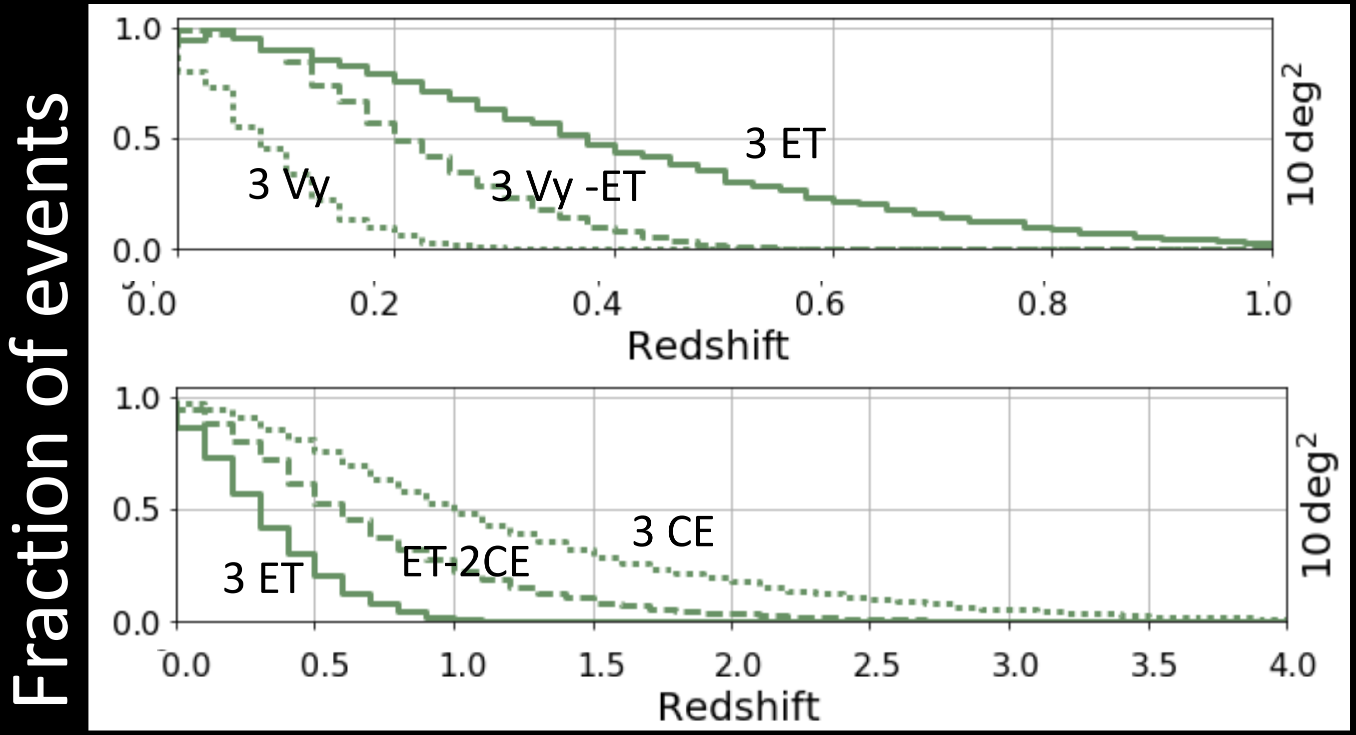
BBH Formation channels

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

BNS Localization

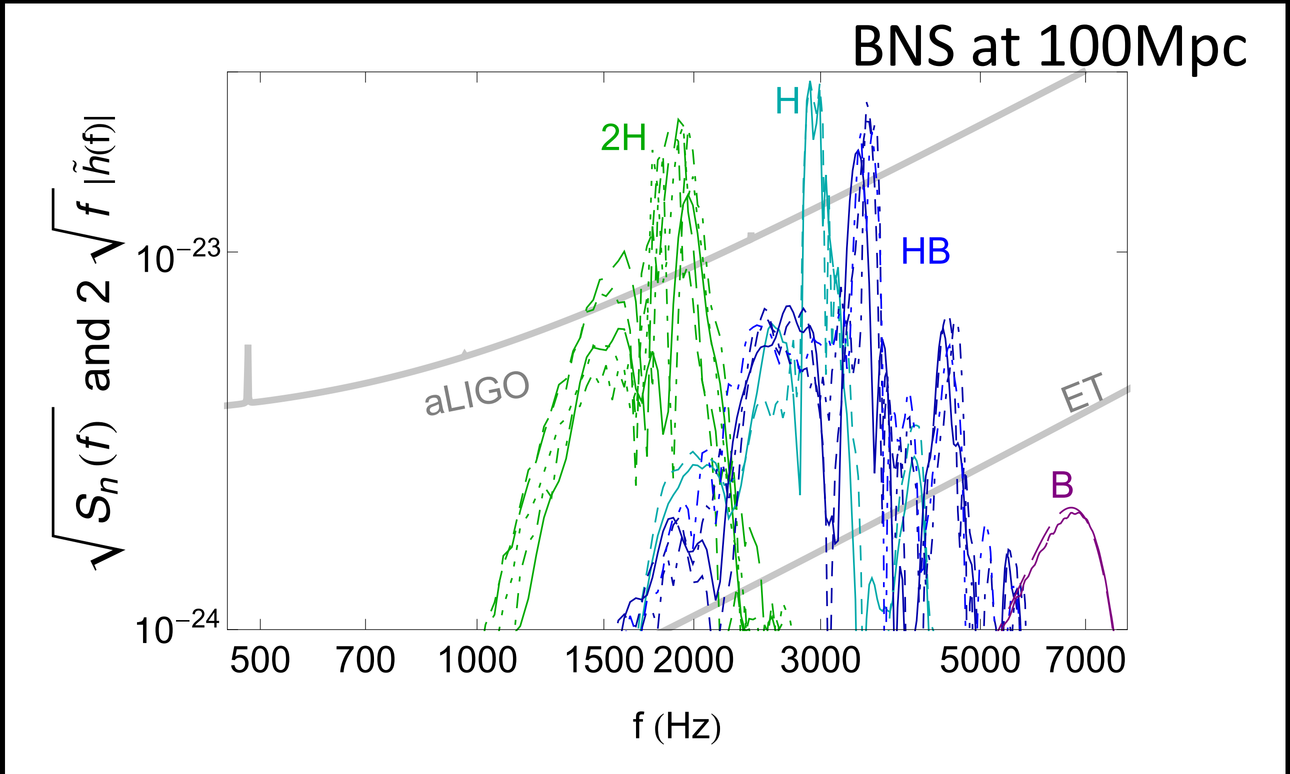
- Will detect BNS at large redshifts
- A significant fraction of which can be localized to a few deg2
  - H0, dark energy EOS (Sathyaprakash+ 0906.4151; Del Pozzo+ 1506.06590; many more)

Mills+ 1708.00806



Equation of state and postmerger

- 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

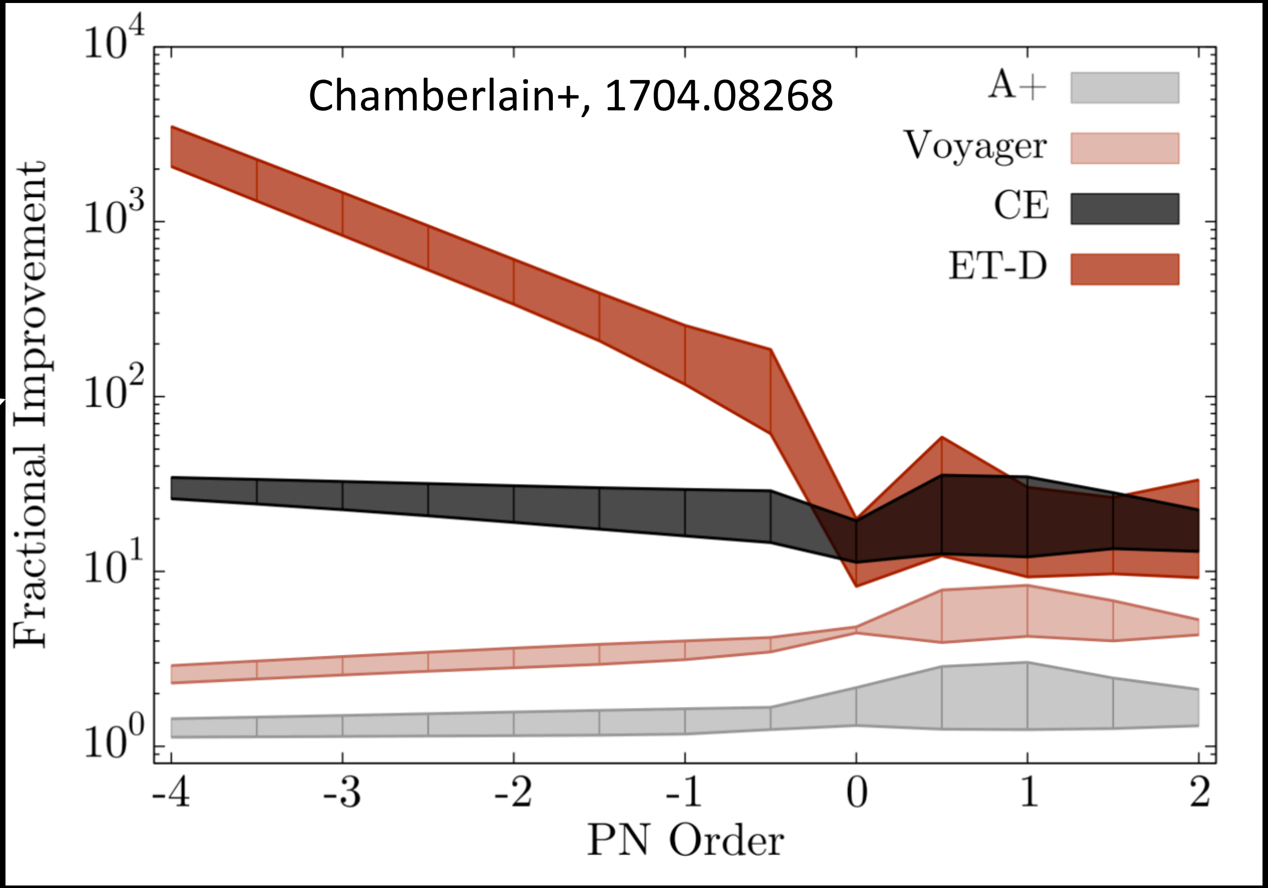


Adapted from Read+ PRD 88, 044042

Tests of general relativity

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

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



How many events?

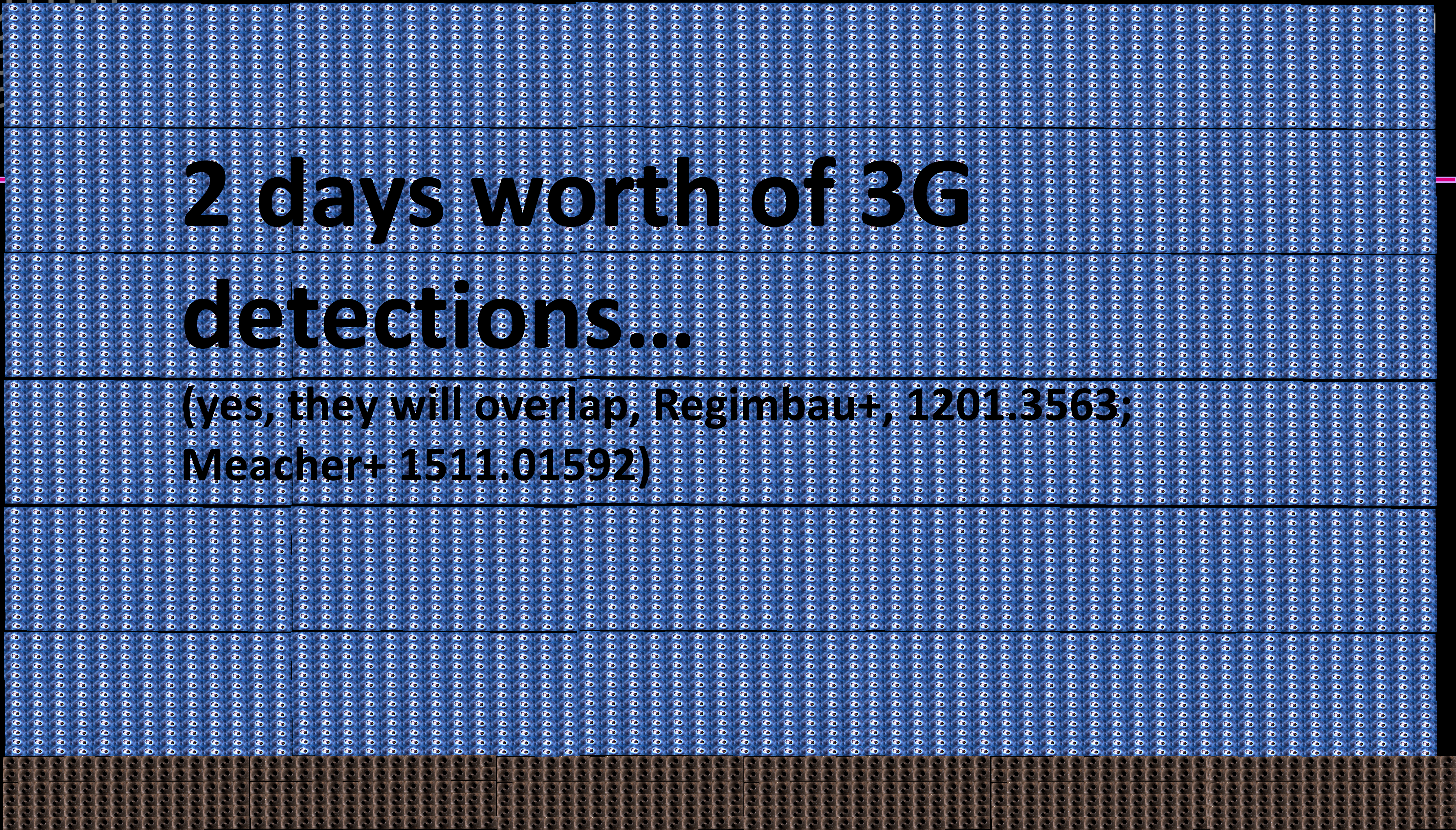
- Using the rates calculated with O2 events and projecting…
- 3G detectors will detect
  - ~ 10^5 BBH per year (Regimbau+, PRL 118, 151105)
  - ~ 10^6 BNS per year (LVC, 1710.05837)

A few months worth of advanced detector time


1.5 hrs worth of
3G detections…

2 days worth of 3G detections…

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

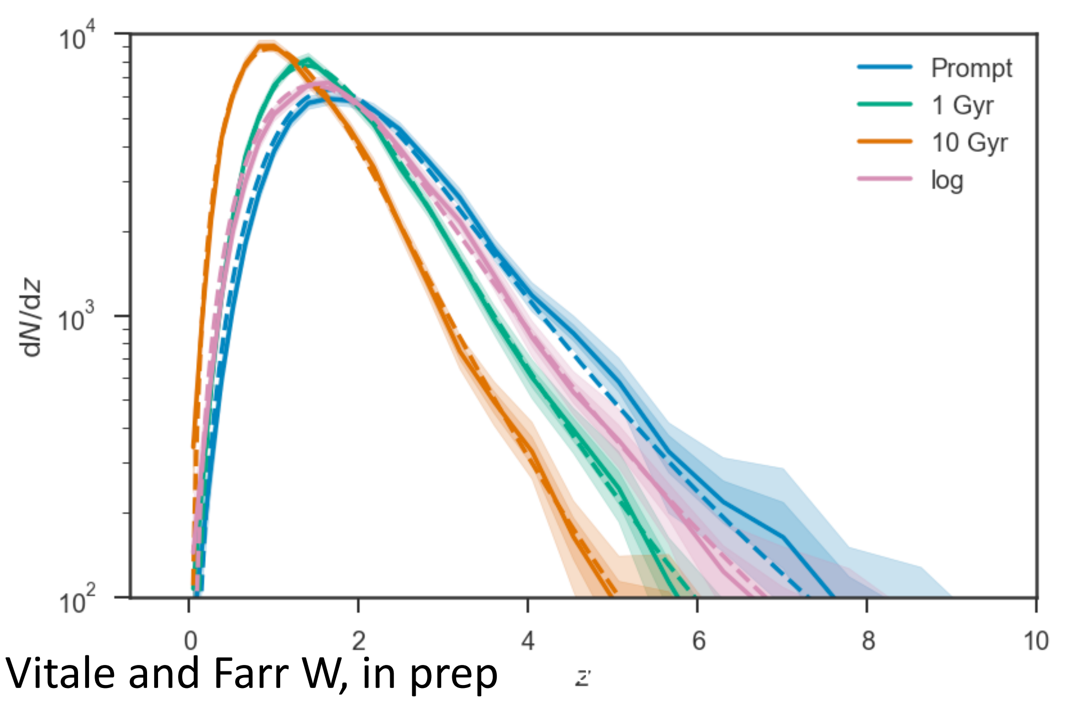


Merger rate density

- We can calculate the BBH merger rate as a function of redshift
- Generated 1, 6, 12 months worth of BBH detections by 3 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

Merger rate density

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



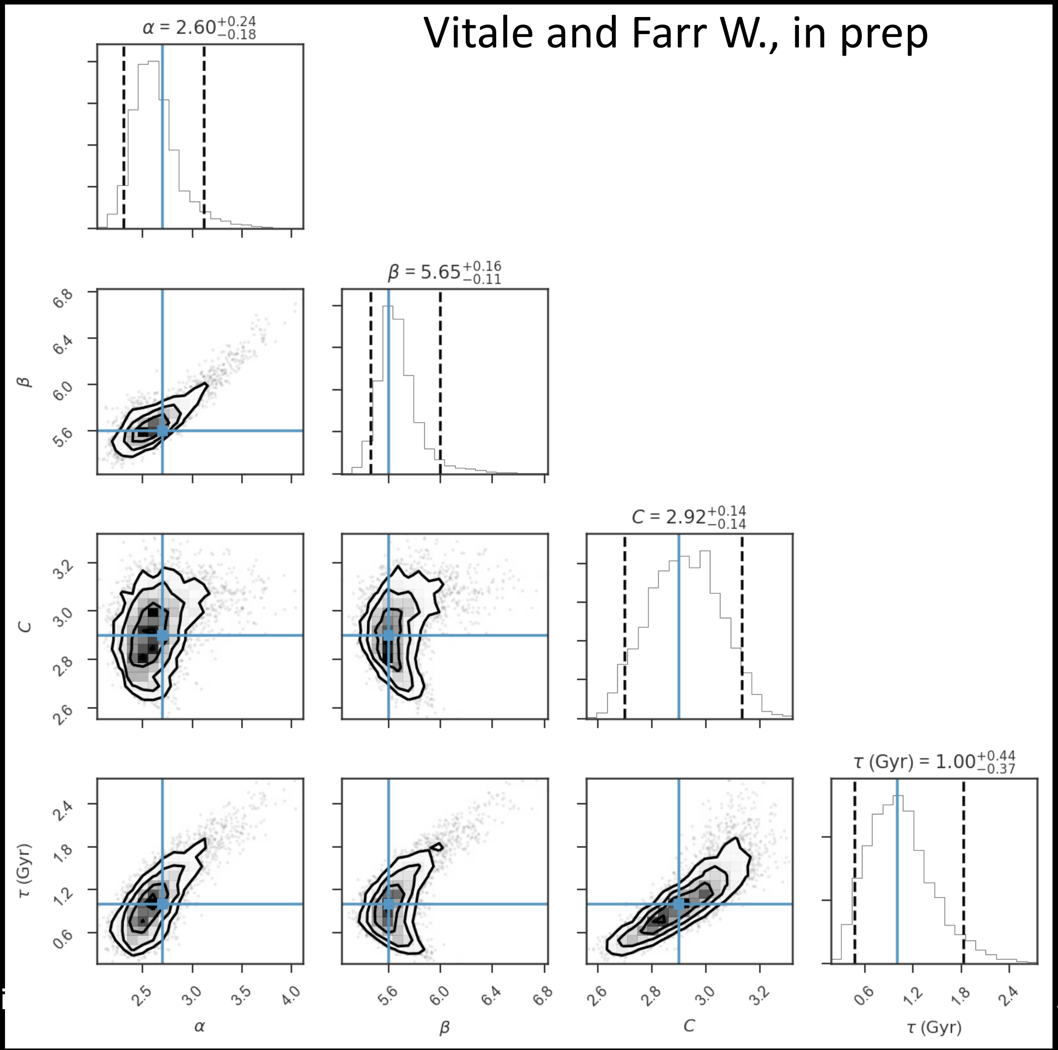
Vitale and Farr W, in prep

Star formation rate

- **If** a model for SFR and time delay is assumed, can measure the time delay coefficient and well as the parameters of the SFR

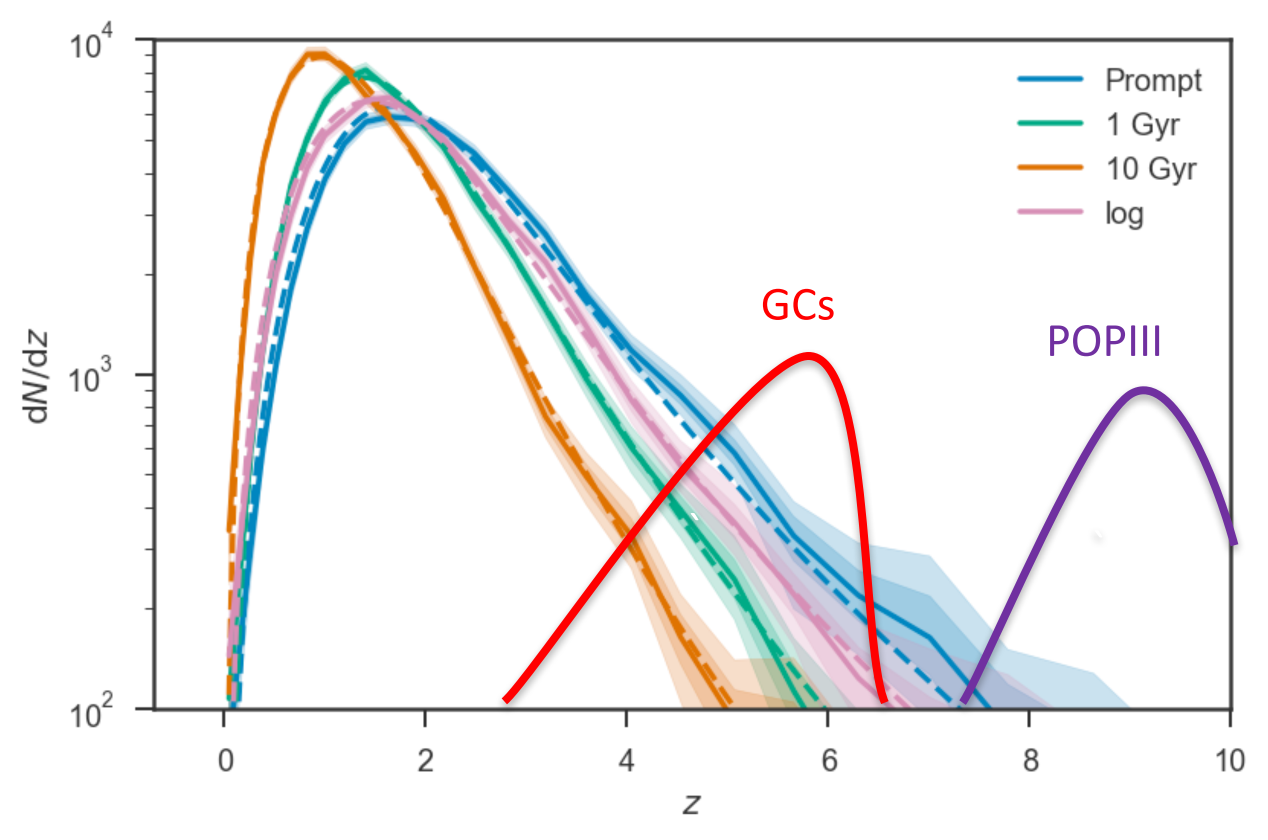
SFR template:

$$\psi_{MD}(z) = \psi_0 \frac{(1+z)^\alpha}{(1+\frac{1+z}{C})^\beta}$$



Formation channels

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



Going 3G

- 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 $D_{\rm L}/\mathrm{Mpc}$	440^{+140}_{-180}

LVC 1602.03840

Going 3G

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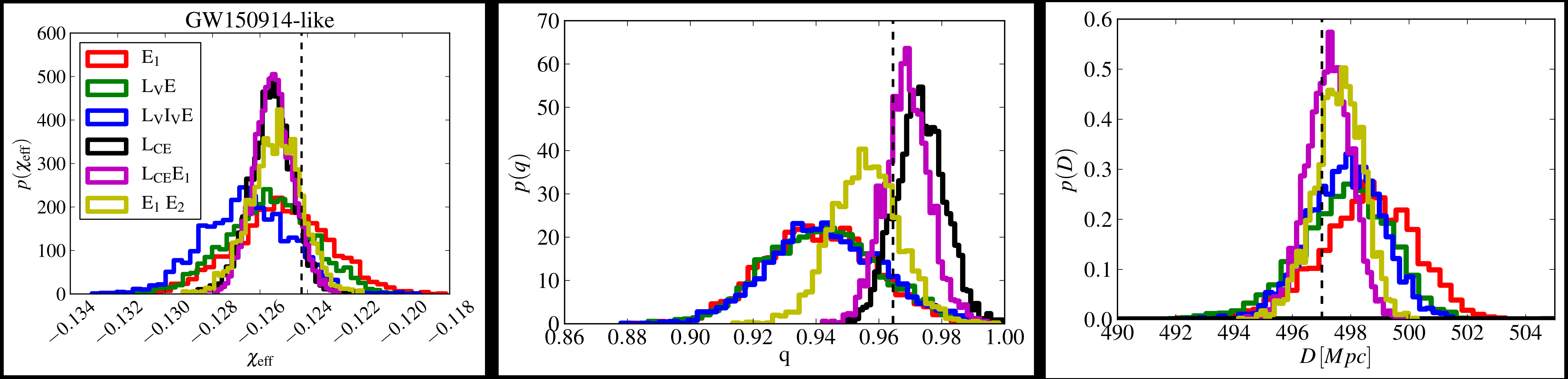


Vitale, Whittle, *imminent*

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, formation channels, evolution,…
  - Thousands of neutron stars, EOS, cosmology,...
  - Precise tests of general relativity
  - Access to sources throughout cosmic history

Thanks

Challenges

- 3G detectors also come with important challenges
  - Low frequency -> long waveforms -> need to keep runtime manageable
  - Hundreds of events per day
  - Computational challenges
  - High SNR -> require extremely high WF faithfulness
  - High SNR -> require extremely good instrument calibration

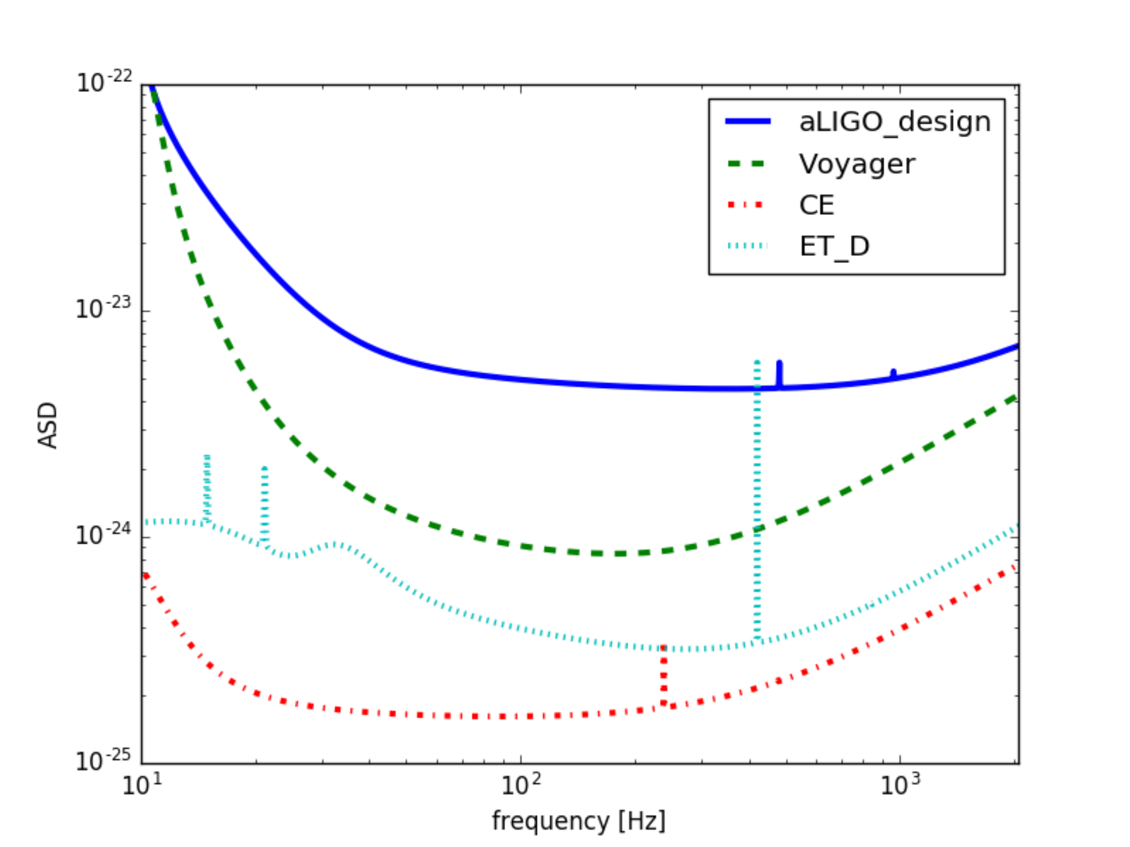
Backup

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

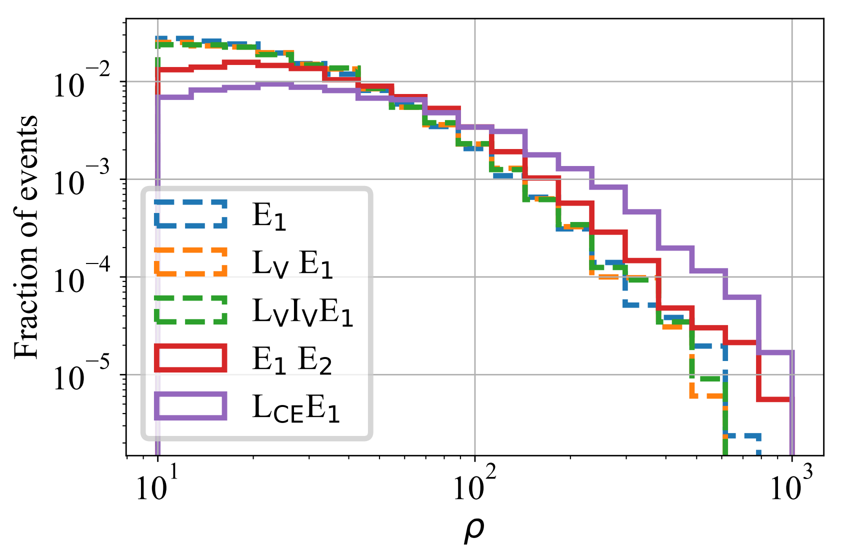
- We might have
  - 1 3G
  - 1 or more detectors from previous generations

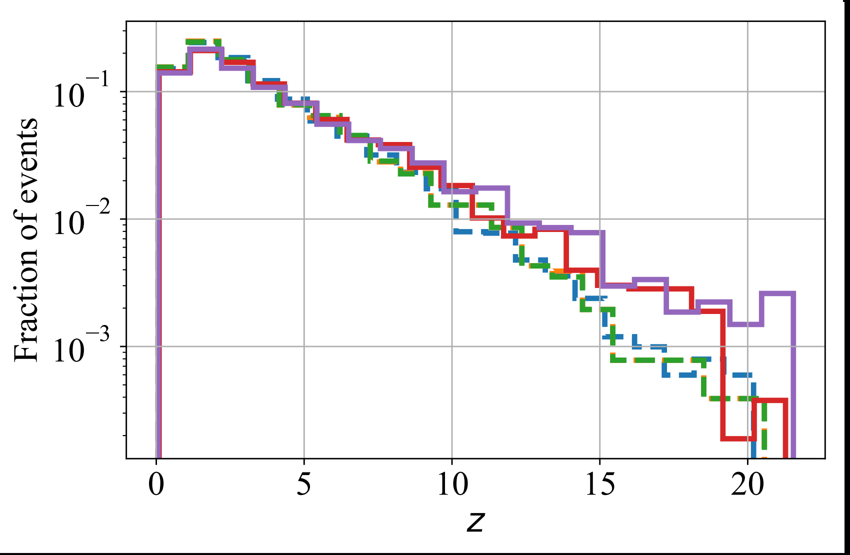


Heterogeneous networks

- 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)

Observing most of the BBH in the universe



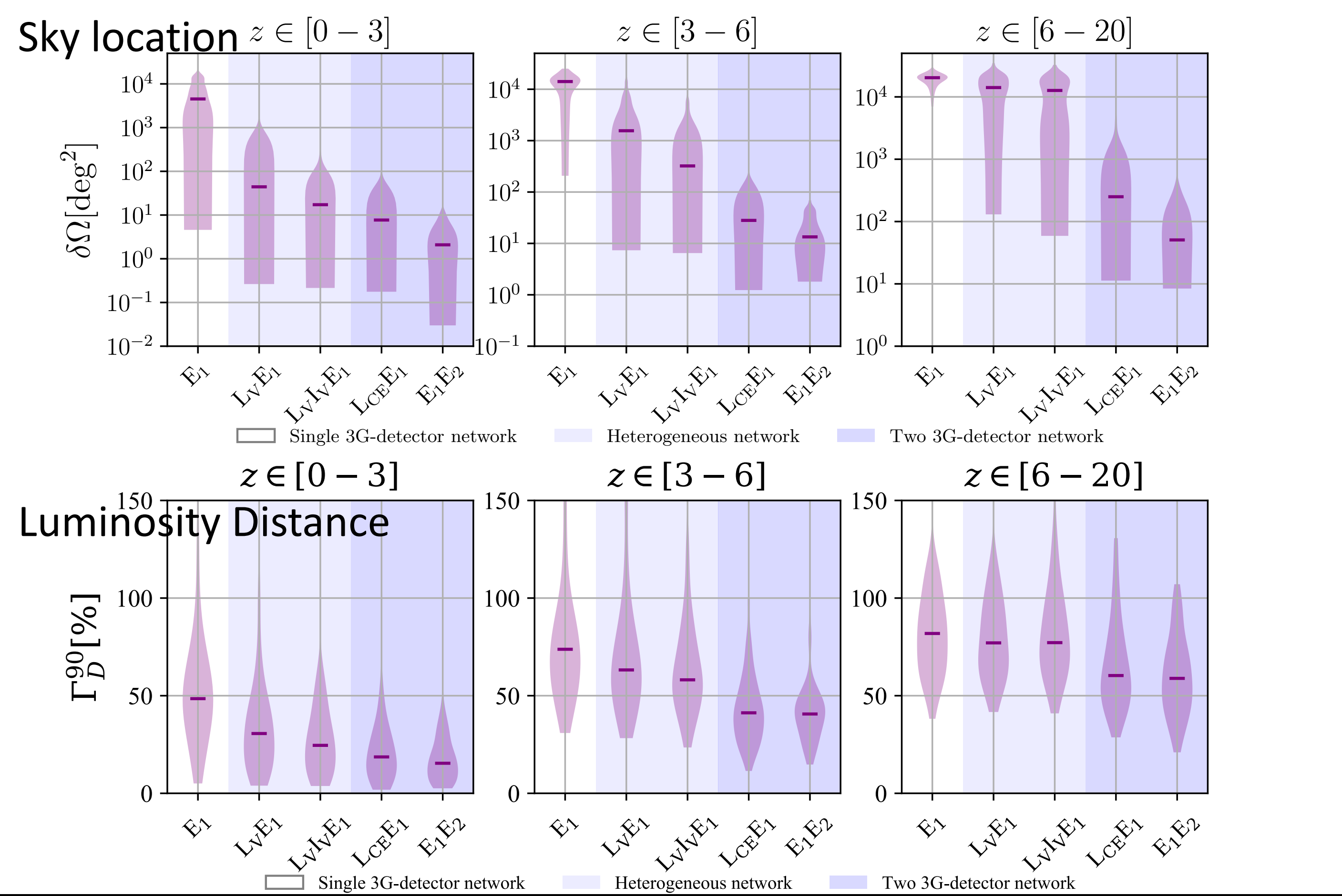


- Considered population of BBH with component masses in the range [6,100] M
- Uniform in com. vol.
- As long as at least 1 ET detector is included, BBH are detected up to redshift of ~15
- Adding Voyager won't change much
- Adding a CE pushes the typical detection farther away

Extrinsic parameters (2.5G+3G)

- Adding a Voyager significantly improves sky localization - factor ~100
- See Mills+ for BNS sky localization precision
- However with only 1 3G will rarely have localizations better than 1deg2

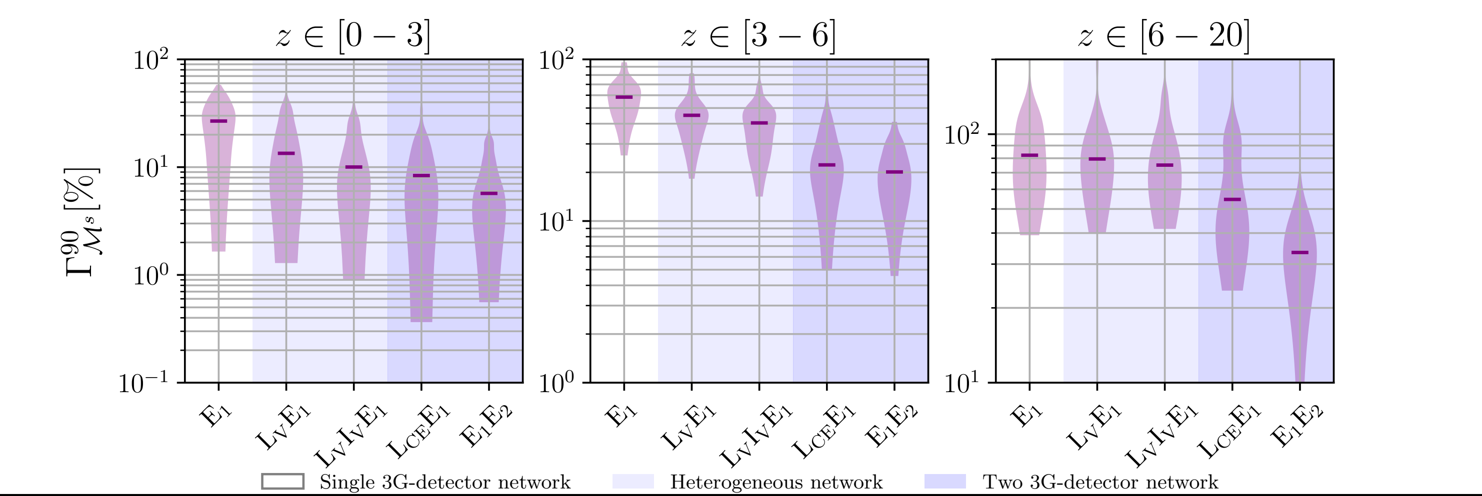
- Smaller improvement in distance estimation



Vitale, Whittle, *imminent*

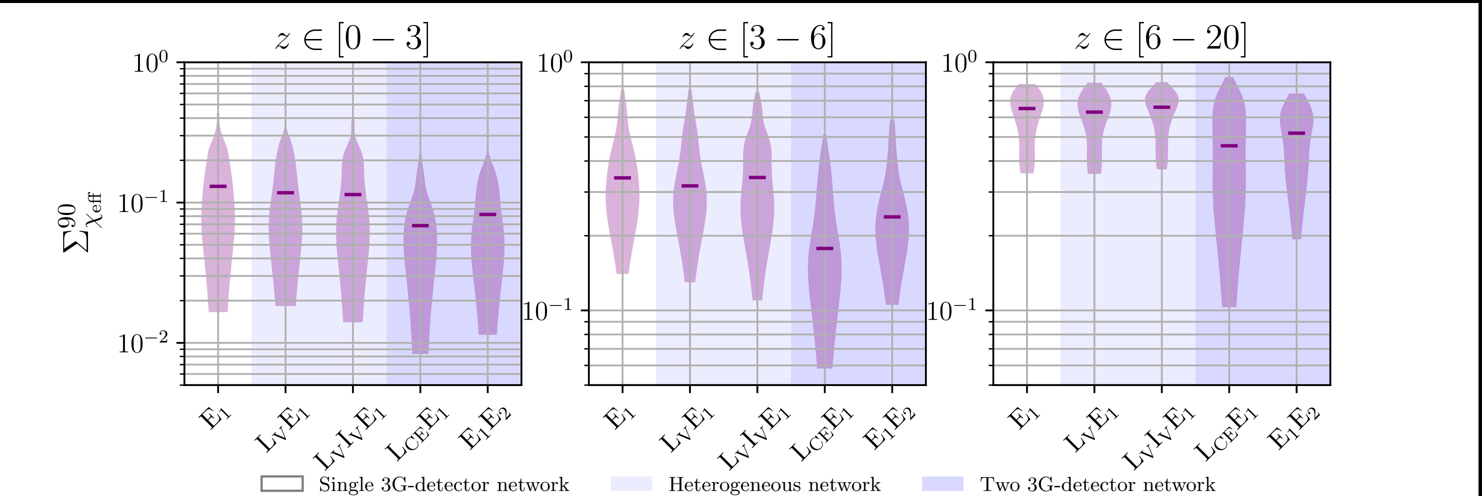
Intrinsic parameters (2.5G+3G)

- Adding a Voyager can improve the **source frame** mass estimation (since distance is needed to convert from detector frame)



Source frame chirp mass

Effective spin



- No improvement for spin parameters

Vitale, Whittle, *imminent*