Cosmology and Astrophysics with 3G detectors

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ET Workshop
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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 redshift 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

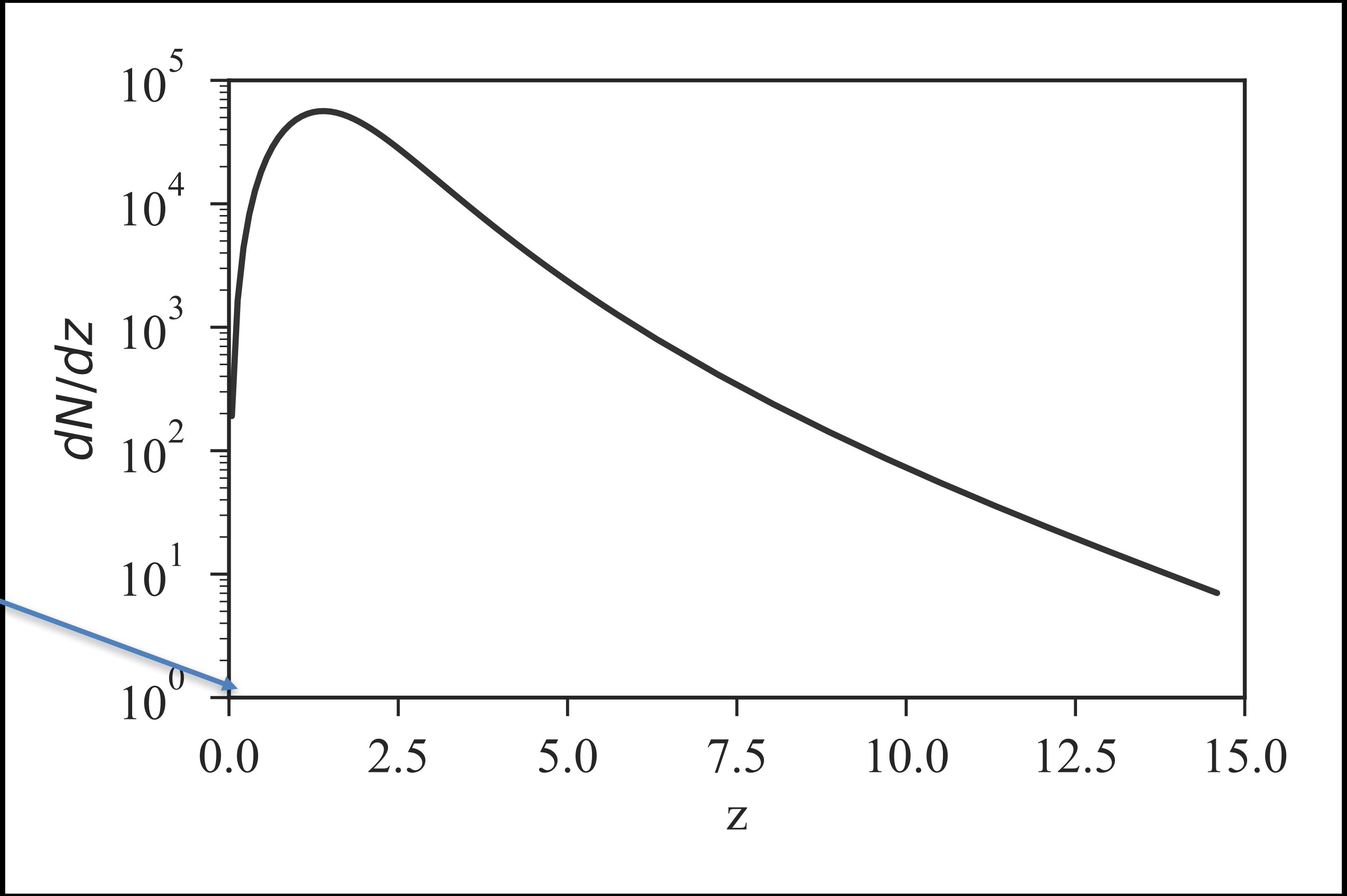
$12\text{–}213\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

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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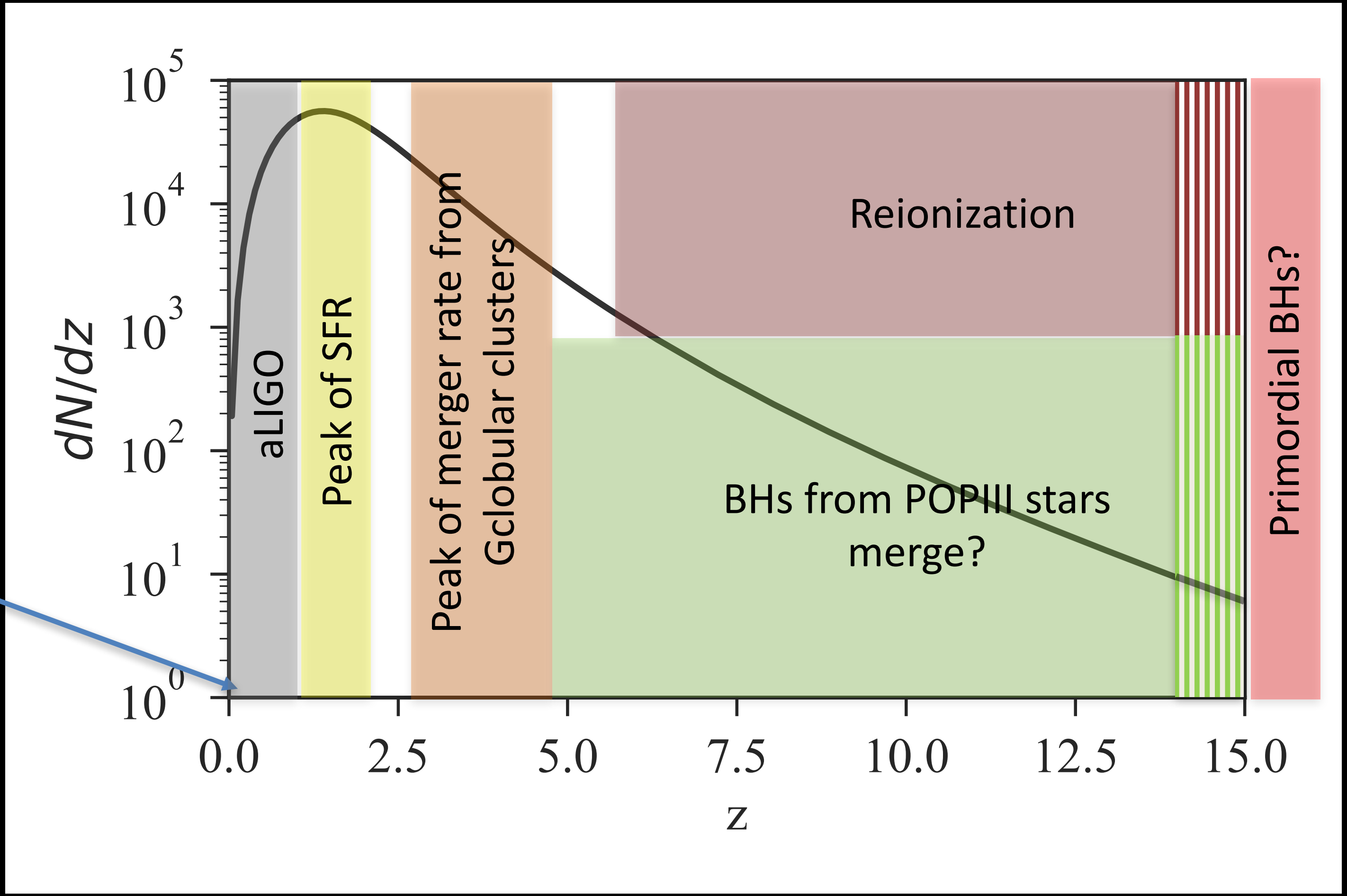

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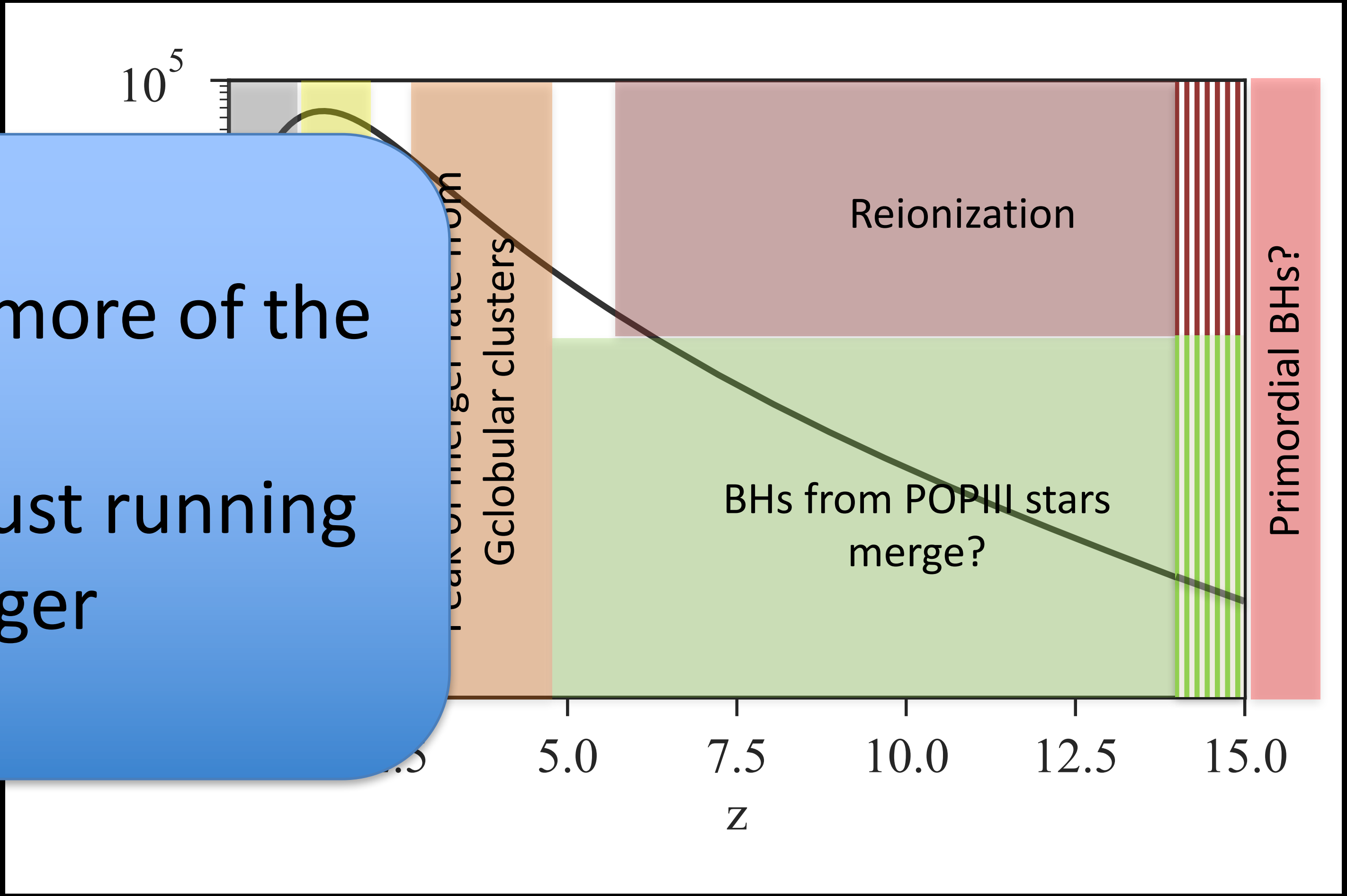
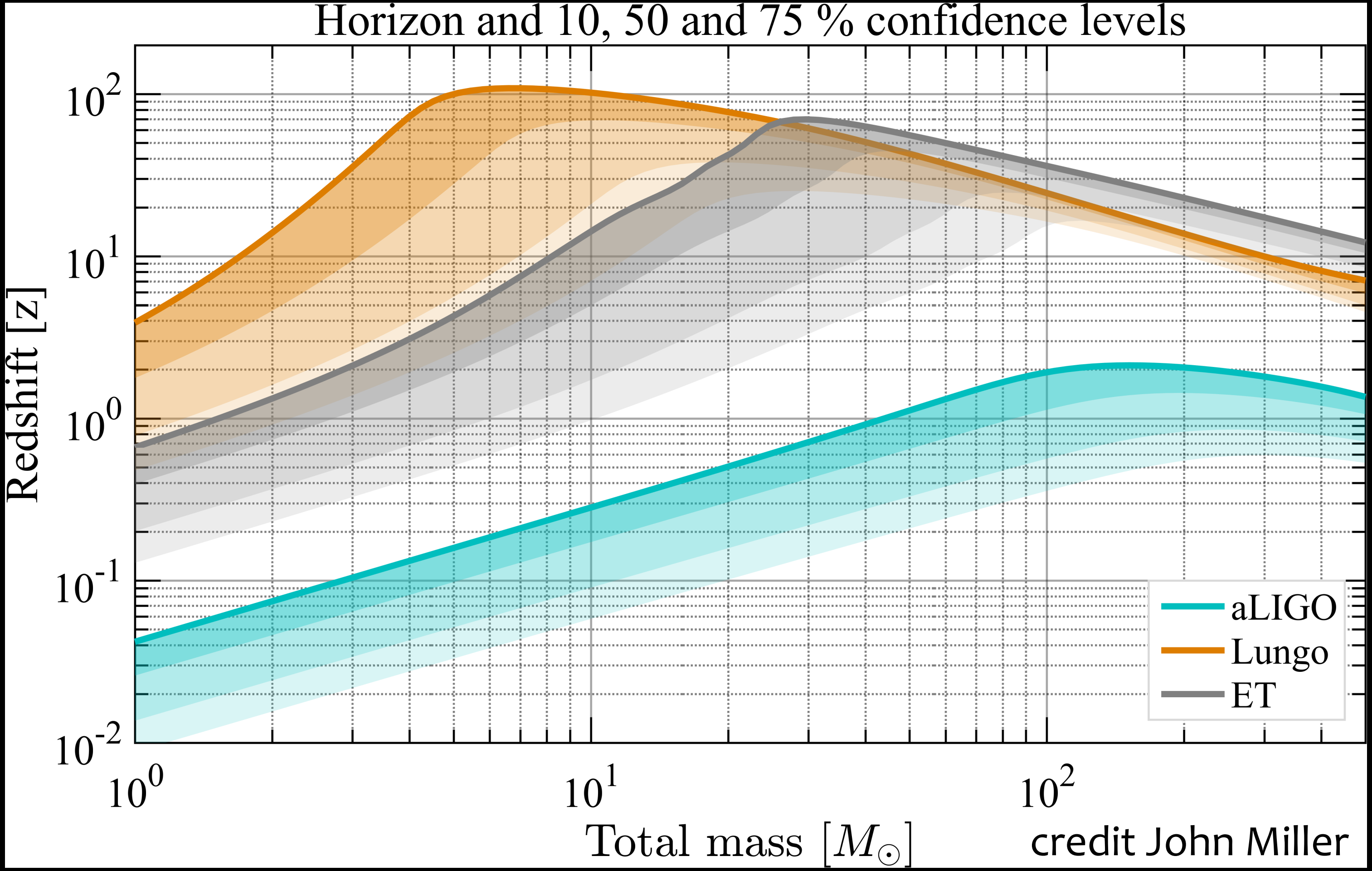


Going 3G does NOT mean more of the same.

Cannot access 3G events just running 2G 10^3 times longer

Where do we go from here?



credit John Miller

Going 3G

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

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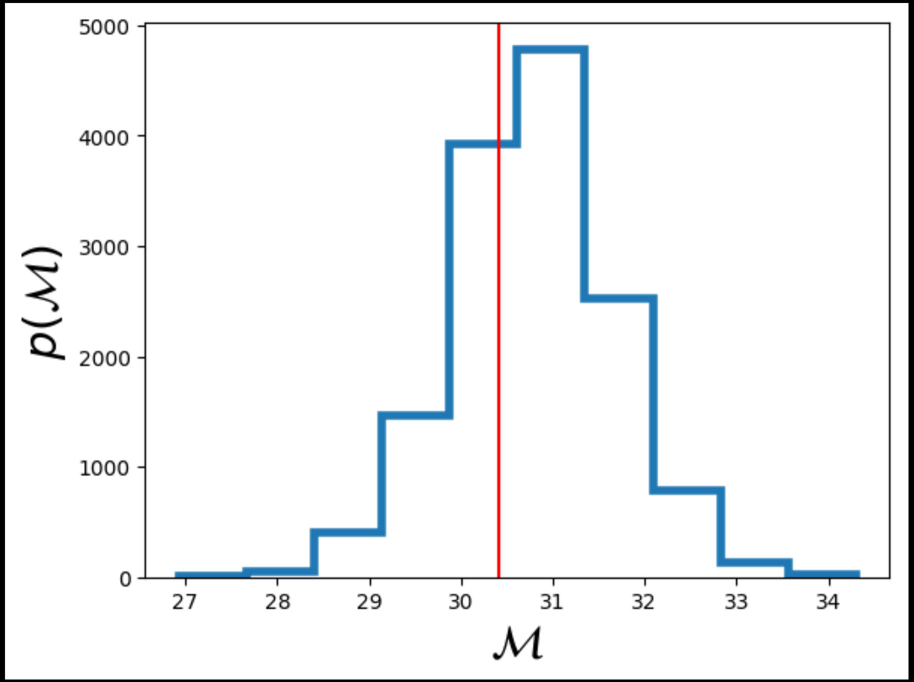

Vitale, preliminary

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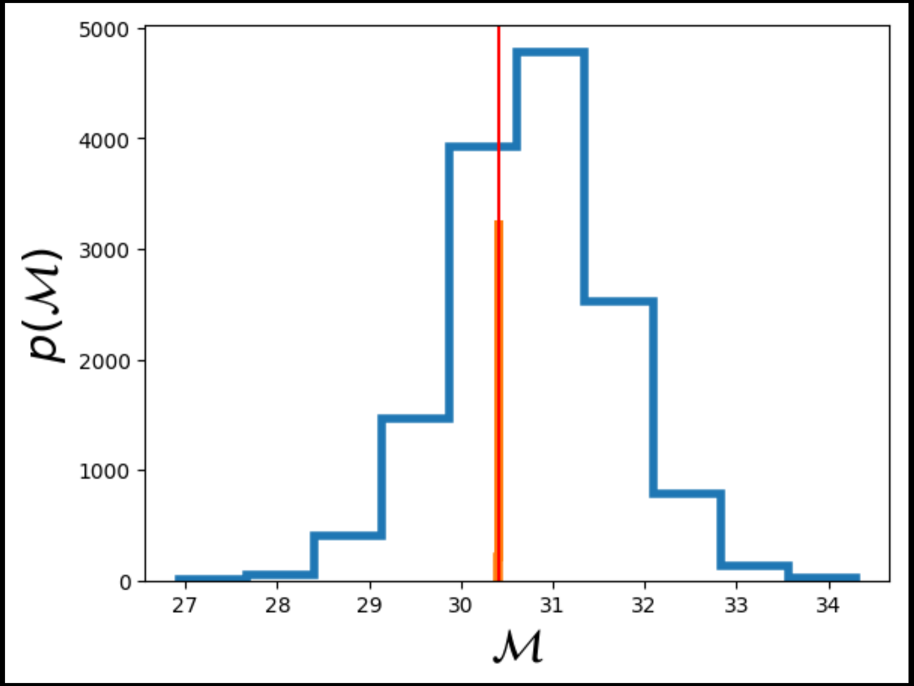

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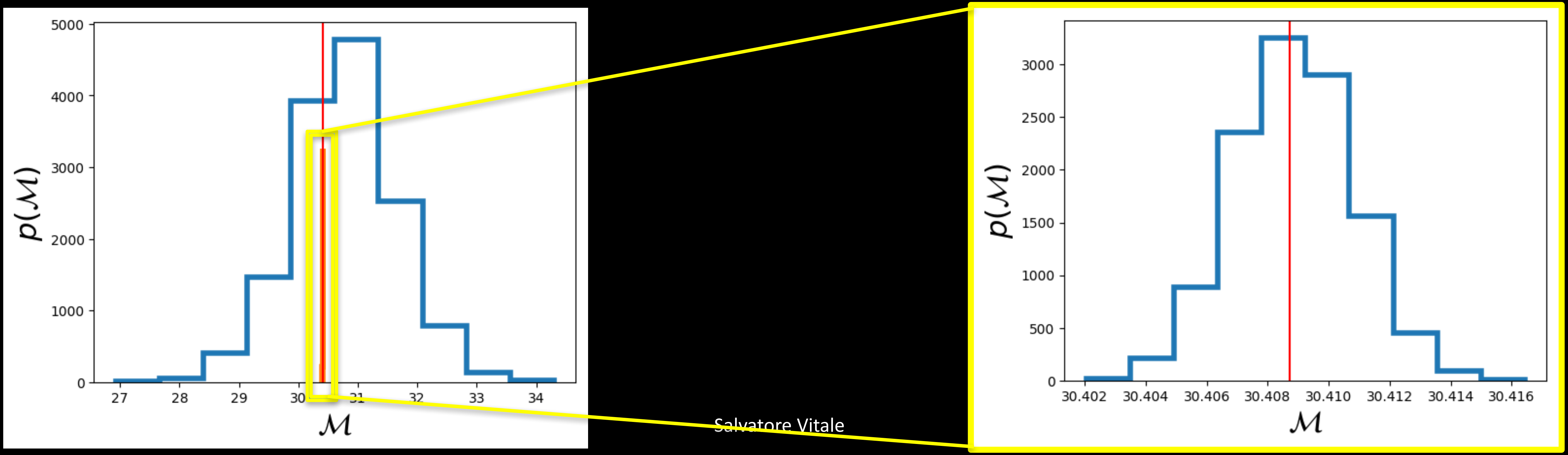

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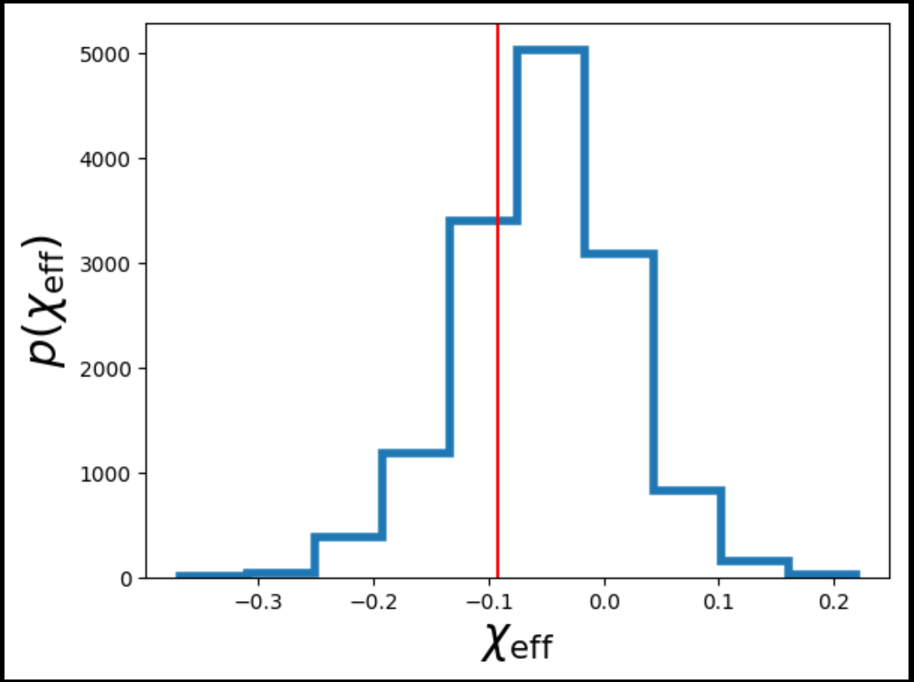

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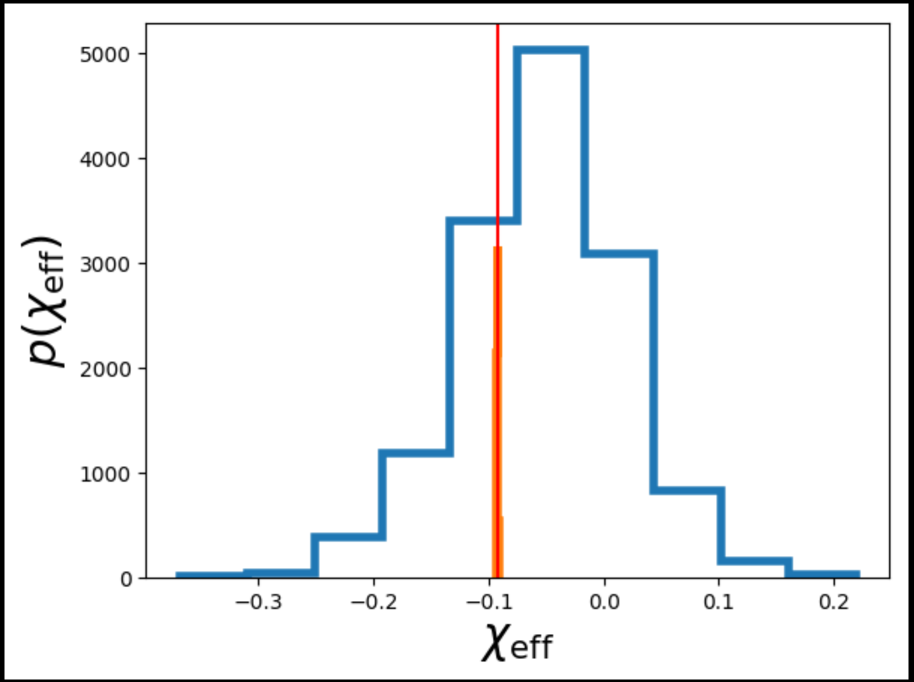

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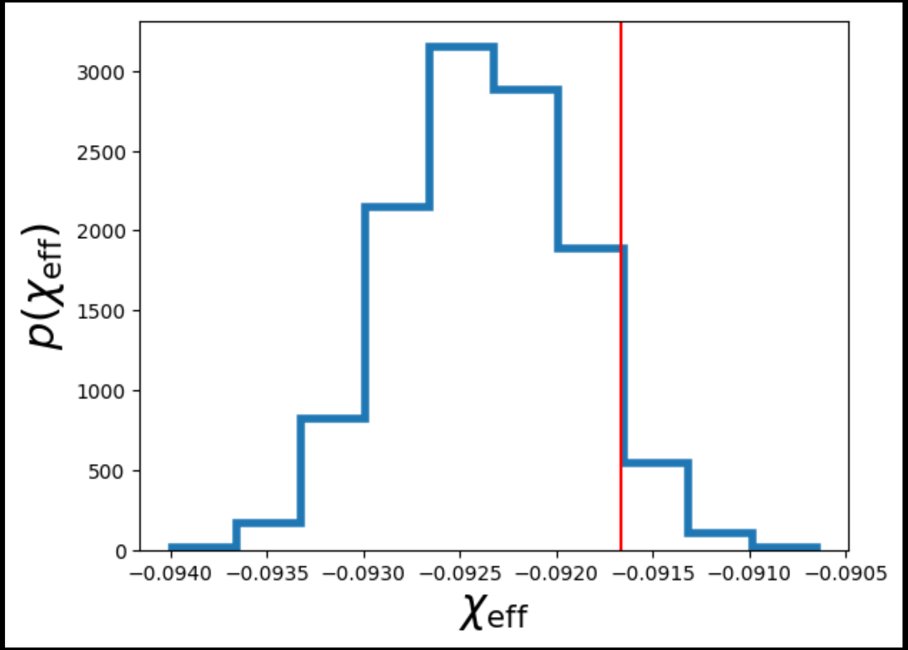

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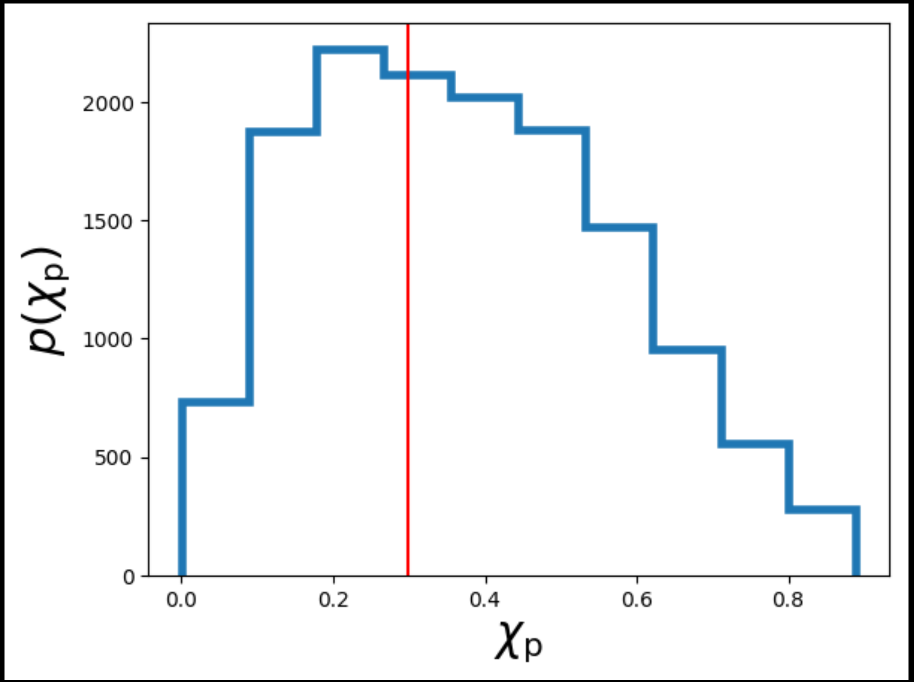

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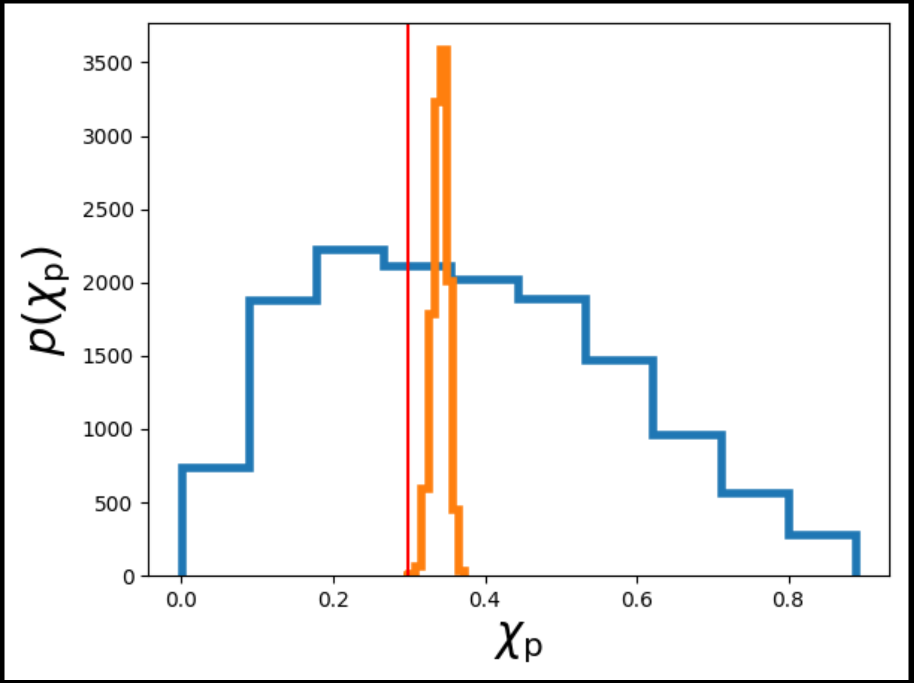


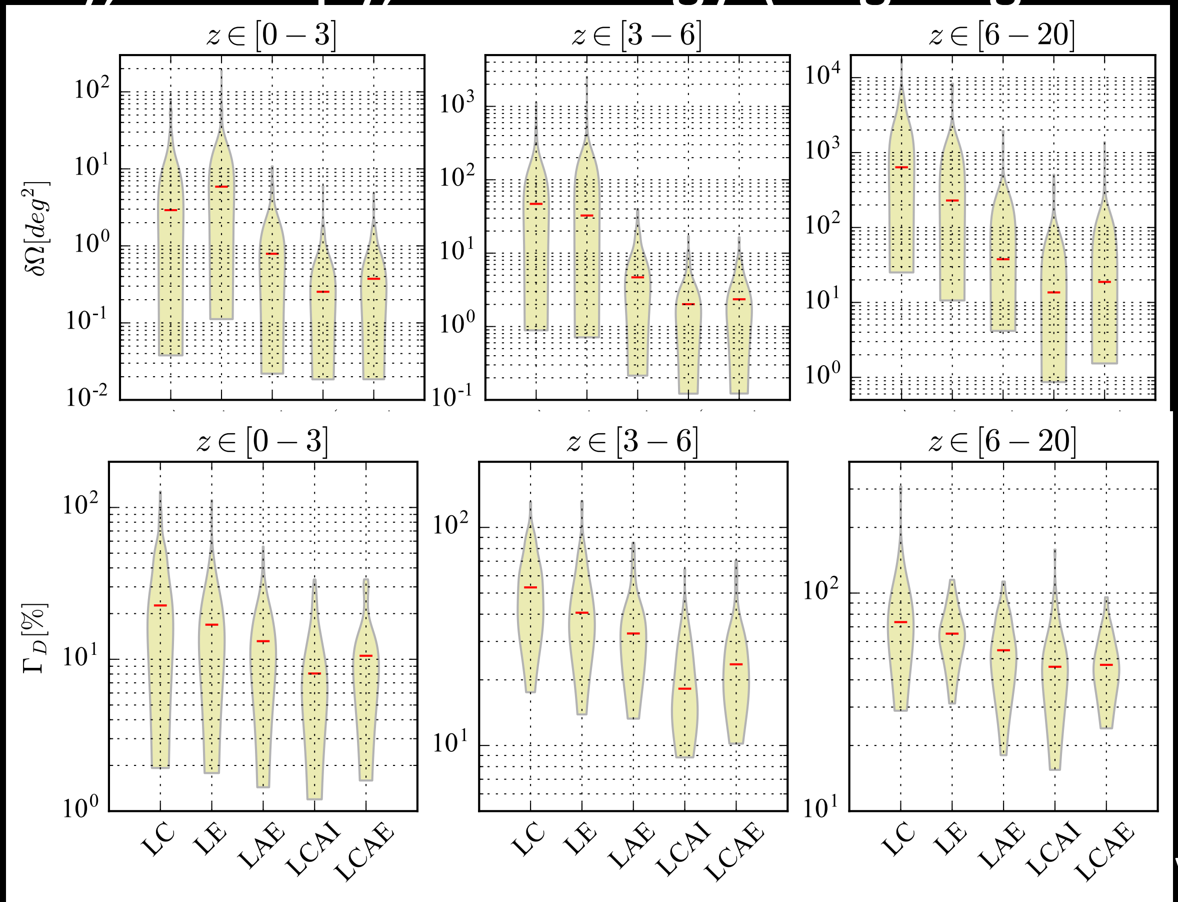
Vitale, preliminary

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+)
- 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

Extrinsic parameters (3G)

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



Sky location

Luminosity Distance

Vitale & Evans, PRD 95 064052

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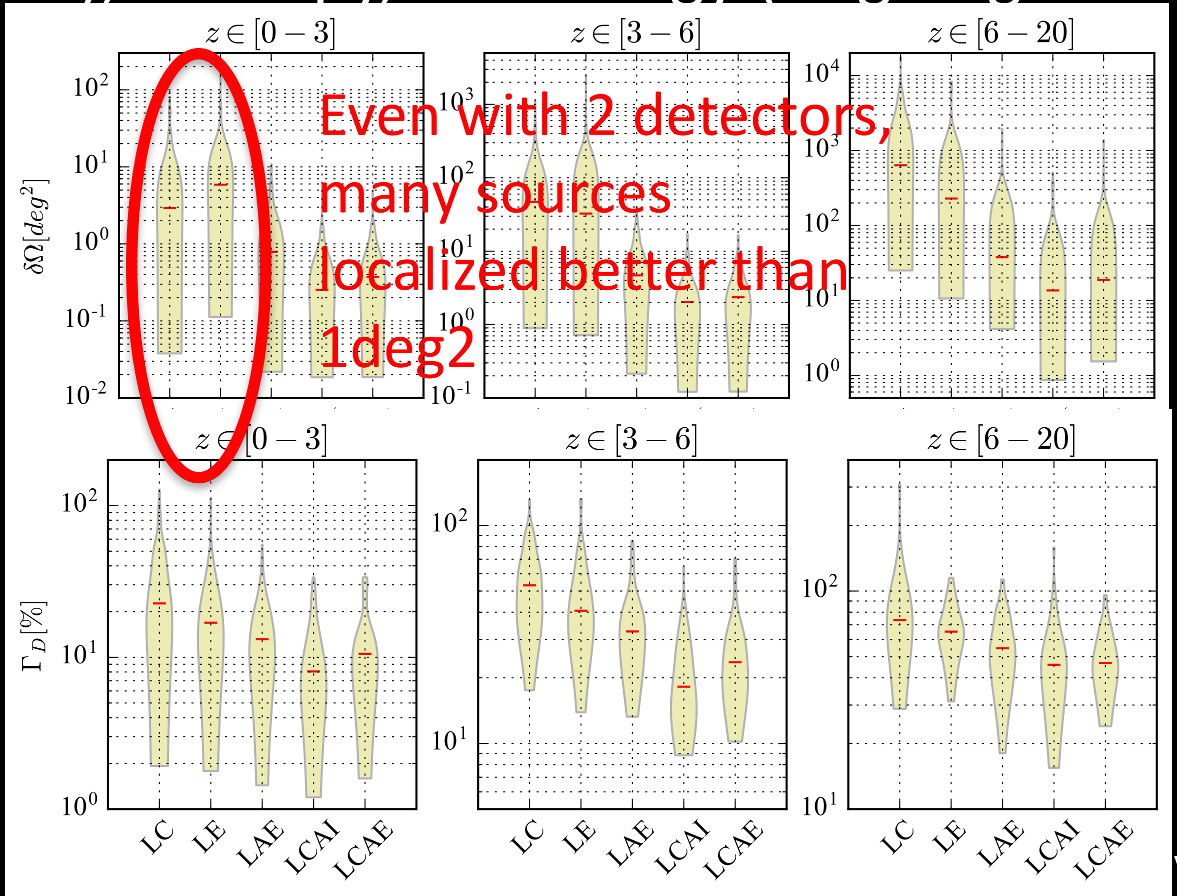
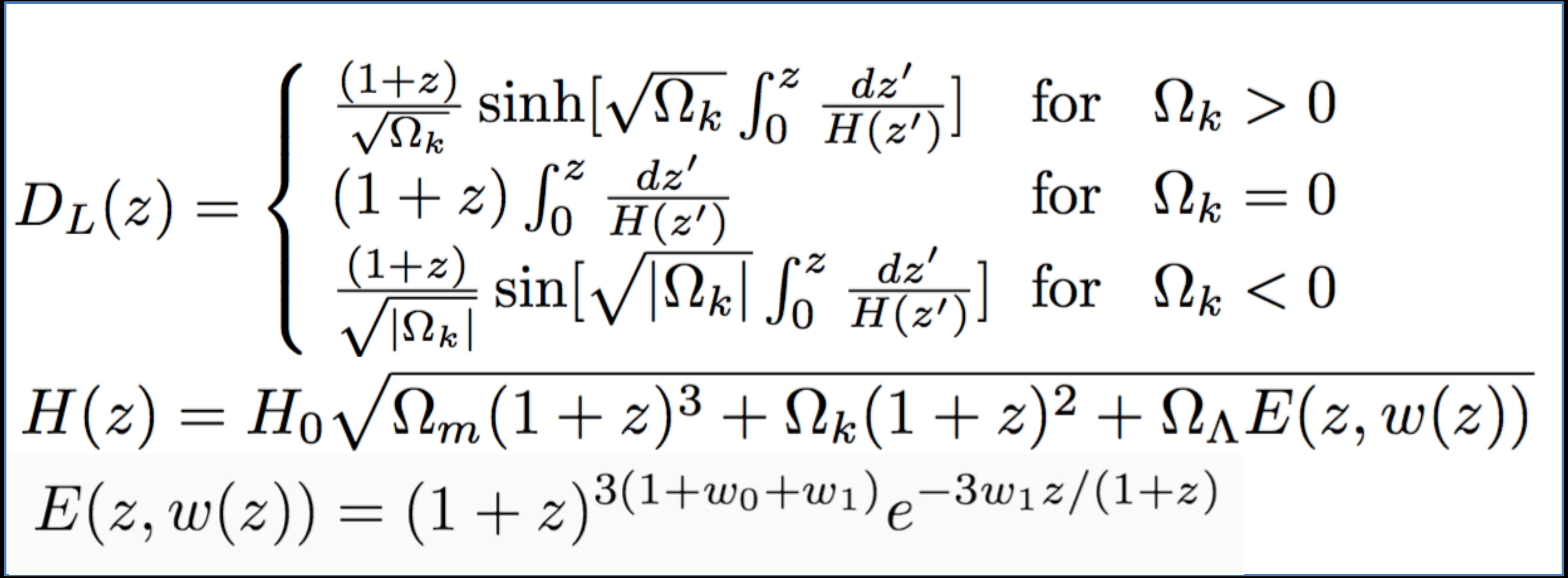


Even with 2 detectors, many sources localized better than 1deg2

Vitale & Evans, PRD 95 064052

Cosmology

- To measure the cosmology one needs luminosity distance *and* redshift of the source



$$D_L(z) = \begin{cases} \frac{(1+z)}{\sqrt{\Omega_k}} \sinh[\sqrt{\Omega_k} \int_0^z \frac{dz'}{H(z')}] & \text{for} \quad \Omega_k > 0 \\ (1+z) \int_0^z \frac{dz'}{H(z')} & \text{for} \quad \Omega_k = 0 \\ \frac{(1+z)}{\sqrt{|\Omega_k|}} \sin[\sqrt{|\Omega_k|} \int_0^z \frac{dz'}{H(z')}] & \text{for} \quad \Omega_k < 0 \end{cases}$$

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda E(z, w(z))}$$

$$E(z, w(z)) = (1+z)^{3(1+w_0+w_1)} e^{-3w_1 z/(1+z)}$$

- The GW data analysis will provide the distance
- How do we get the redshift?

How to measure the redshift?

- If the CBC produces an EM counterpart (e.g. GRB) (Sathyaprakash+ CQG 27 215006, Nissanke+ 1307.2638)
- If one knows the neutron star (NS) equation of state (Read & Messenger PRL 108 091101; Del Pozzo+ 1506.06590)
- If the post-merger signal is observed (Messenger+ PRX 4, 041004)
- If the shape of NS mass distribution is known (Taylor+ PRD 85 023535; Taylor & Gair PRD 86, 023502)
- Even if no EM is found, but there is a reliable galaxy catalog (Schutz, Nature 1986, Del Pozzo PRD 86 043011)

Short GRBs

- Nissanke+ 1307.2638 looks at the prospects for 2G detectors
  - – Assumes N joint GW+EM detections and look at measurement of H_0
    - Statistical of few % with O(10) joint detections
    - Uncertainty in the rate and beaming angle -> could take months of decades
- Sathyaprakash+, CQG 27 215006, considers 3G (Einstein telescope)
  - – Assumes 10^{-3} of BNS will be detected with EM counterparts→ 1000 joint detections over 3 years
  - – H_0 assumed known
  - – 1-sigma $\Omega_M$at 18%, Ω_Λ at 4%, w 18%
  - – Errors are smaller if weak lensing systematics can be corrected

NS equation of state

- Proof of principle in Read and Messenger (PRL 108 091101)
- Full Bayesian analysis in Del Pozzo+ (1506.06590)
  - Einstein Telescope, 1000 BNS sources, no EM required
  - Considers different equation of state and estimate *all* cosmological parameters
    - H_0 with 90% confidence interval of ~10%
    - Ω_M: ~65%
    - Ω_Λ: ~40%
    - w_0 and w_1: 0.8 and 0.9 (factor of 3 better if the rest is known)

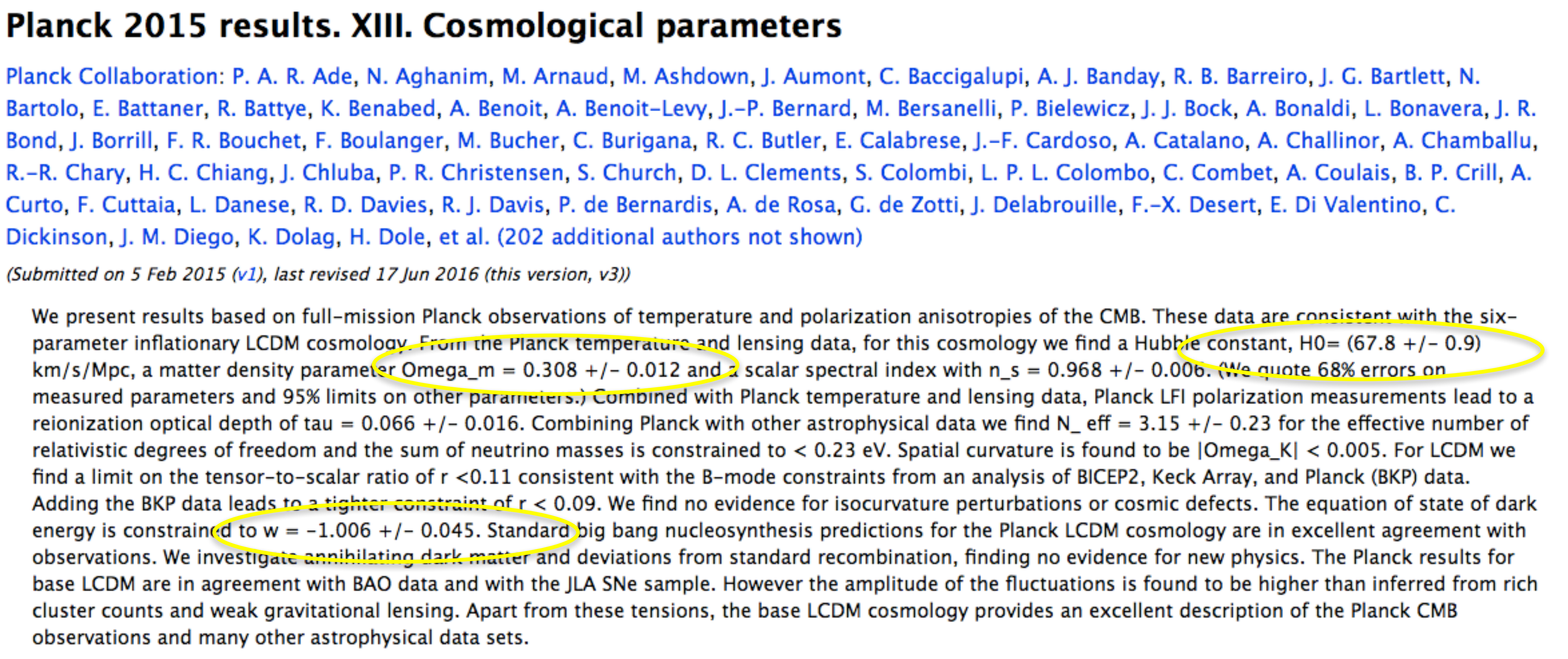
Mass distribution

- Taylor+ (PRD 85 023535 and 86 023502) assume mass distribution for NS in BNS it is Gaussian with unknown mean and sigma

- Measure mass distribution parameters together with cosmology
  - 2G : H_0 at 10% with ~100 BNS if true mass distribution sigma $<0.04 M_\odot$
  - 3G: All known except DE. Precision comparable with EM with 10^5 BNS

Statistical approach

- For each GW detection, just use all galaxies in 3D sky error
- Del Pozzo (1108.1317) finds for 2G:
  - H_0 at 15% (95% CI) with 10 sources. Better if more than 3 interferometers online or more detections.
  - Omega's unmeasurable with 50 sources
  - Did not consider DE
- 3G: Ongoing…



Planck 2015 results. XIII. Cosmological parameters

Planck Collaboration: P. A. R. Ade, N. Aghanim, M. Arnaud, M. Ashdown, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, N. Bartolo, E. Battaner, R. Battye, K. Benabed, A. Benoit, A. Benoit-Levy, J.-P. Bernard, M. Bersanelli, P. Bielewicz, J. J. Bock, A. Bonaldi, L. Bonavera, J. R. Bond, J. Borrill, F. R. Bouchet, F. Boulanger, M. Bucher, C. Burigana, R. C. Butler, E. Calabrese, J.-F. Cardoso, A. Catalano, A. Challinor, A. Chamballu, R.-R. Chary, H. C. Chiang, J. Chluba, P. R. Christensen, S. Church, D. L. Clements, S. Colombi, L. P. L. Colombo, C. Combet, A. Coulais, B. P. Crill, A. Curto, F. Cuttaia, L. Danese, R. D. Davies, R. J. Davis, P. de Bernardis, A. de Rosa, G. de Zotti, J. Delabrouille, F.-X. Desert, E. Di Valentino, C. Dickinson, J. M. Diego, K. Dolag, H. Dole, et al. (202 additional authors not shown)

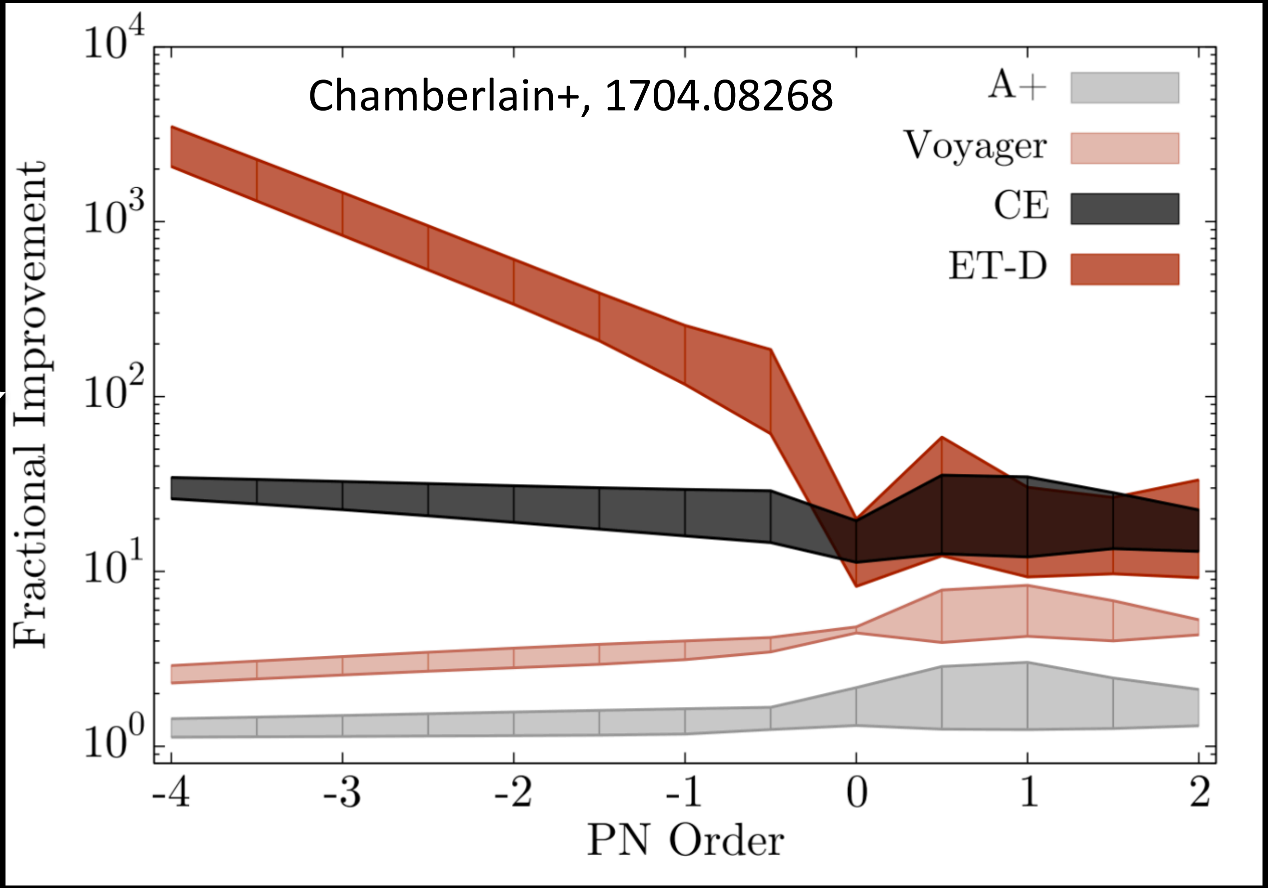
(Submitted on 5 Feb 2015 (v1), last revised 17 Jun 2016 (this version, v3))

We present results based on full-mission Planck observations of temperature and polarization anisotropies of the CMB. These data are consistent with the six-parameter inflationary LCDM cosmology. From the Planck temperature and lensing data, for this cosmology we find a Hubble constant, H0= (67.8 +/- 0.9) km/s/Mpc, a matter density parameter Omega_m = 0.308 +/- 0.012 and a scalar spectral index with n_s = 0.968 +/- 0.006. (We quote 68% errors on measured parameters and 95% limits on other parameters.) Combined with Planck temperature and lensing data, Planck LFI polarization measurements lead to a reionization optical depth of tau = 0.066 +/- 0.016. Combining Planck with other astrophysical data we find N_ eff = 3.15 +/- 0.23 for the effective number of relativistic degrees of freedom and the sum of neutrino masses is constrained to < 0.23 eV. Spatial curvature is found to be |Omega_K| < 0.005. For LCDM we find a limit on the tensor-to-scalar ratio of r <0.11 consistent with the B-mode constraints from an analysis of BICEP2, Keck Array, and Planck (BKP) data. Adding the BKP data leads to a tighter constraint of r < 0.09. We find no evidence for isocurvature perturbations or cosmic defects. The equation of state of dark energy is constrained to w = -1.006 +/- 0.045. Standard big bang nucleosynthesis predictions for the Planck LCDM cosmology are in excellent agreement with observations. We investigate annihilating dark matter and deviations from standard recombination, finding no evidence for new physics. The Planck results for base LCDM are in agreement with BAO data and with the JLA SNe sample. However the amplitude of the fluctuations is found to be higher than inferred from rich cluster counts and weak gravitational lensing. Apart from these tensions, the base LCDM cosmology provides an excellent description of the Planck CMB observations and many other astrophysical data sets.

Tests of general relativity

- Larger SNR and better low frequency will yield dramatic improvements

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



Chamberlain+, 1704.08268

How many events?

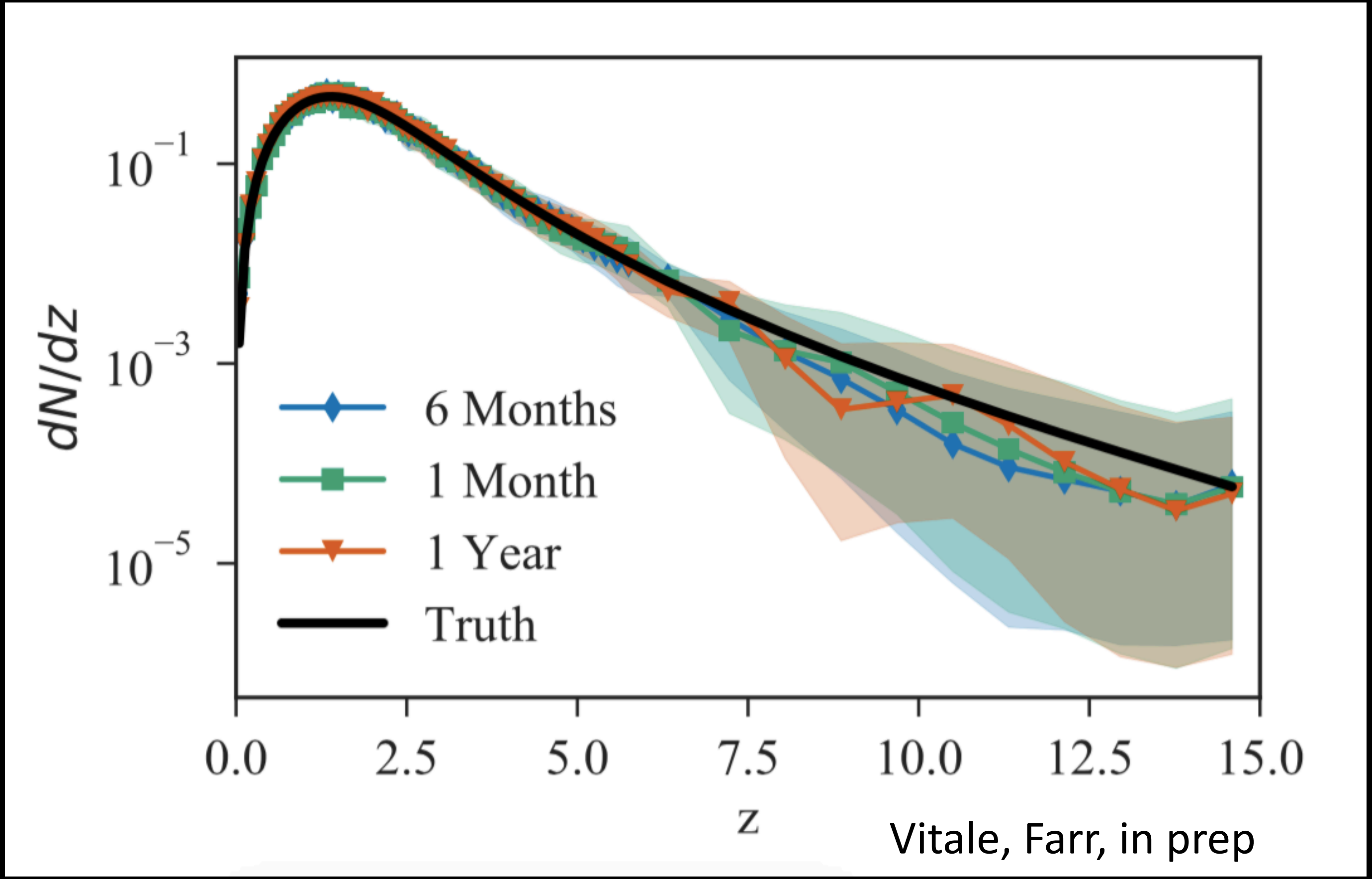
- Using the rates calculated after GW170104
  - ~ 10^5 BBH coalesce in the universe per year
- With 3G detectors, we will detect 99.9% of them (Regimbau+, PRL 118, 151105)

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

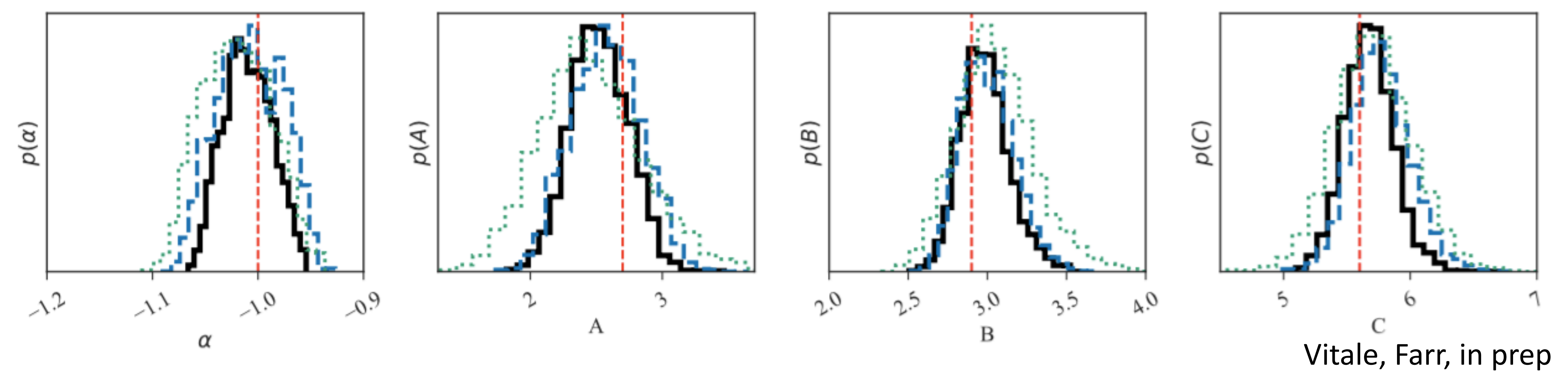
- Merger rate density can be reconstructed after only 1 month of detections



Vitale, Farr, in prep

SFR

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

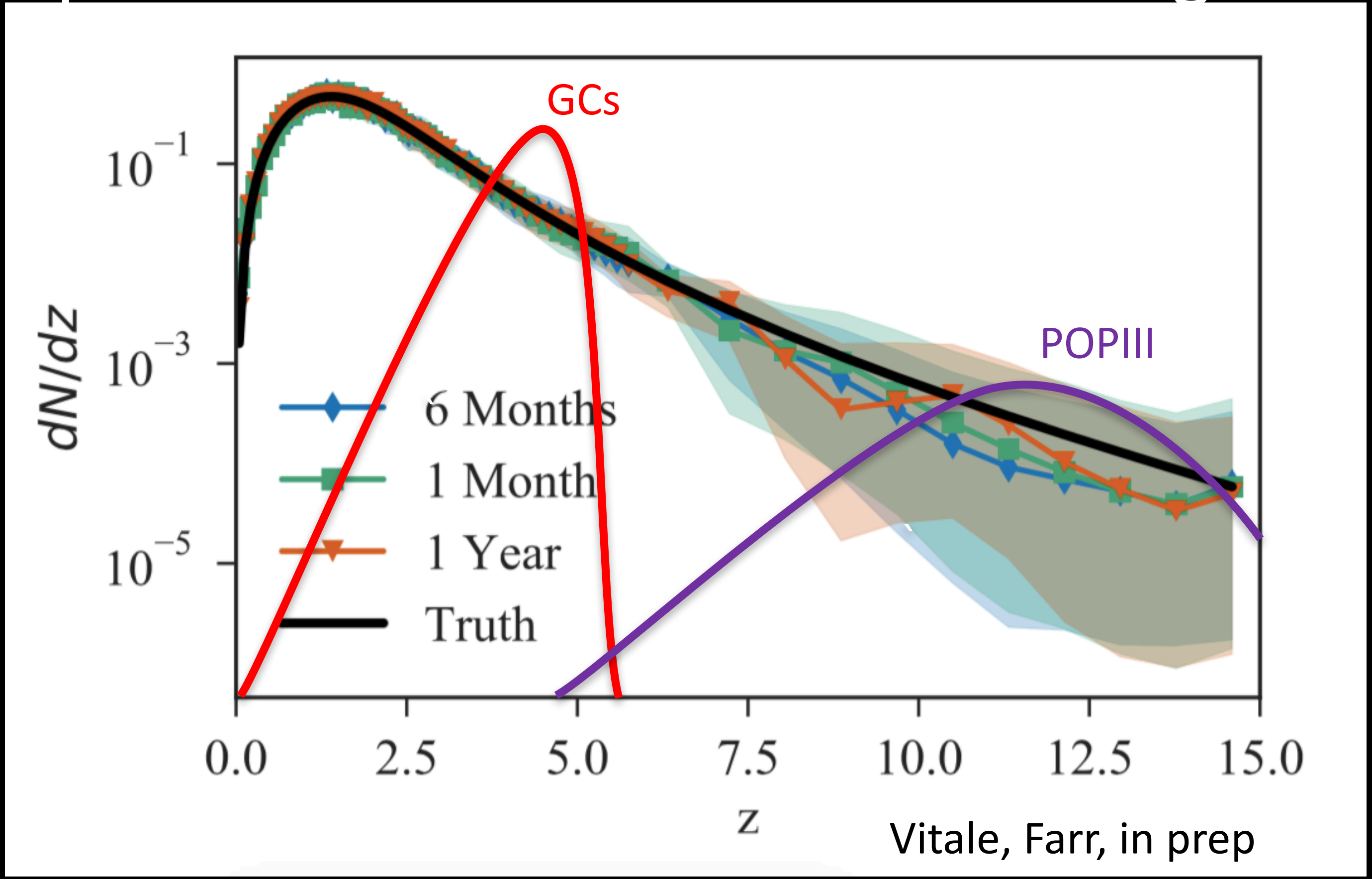


Vitale, Farr, in prep

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



Vitale, Farr, in prep

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
  - Cosmology