3G – low-frequency & populations

Salvatore Vitale
MIT

GWADW, Elba
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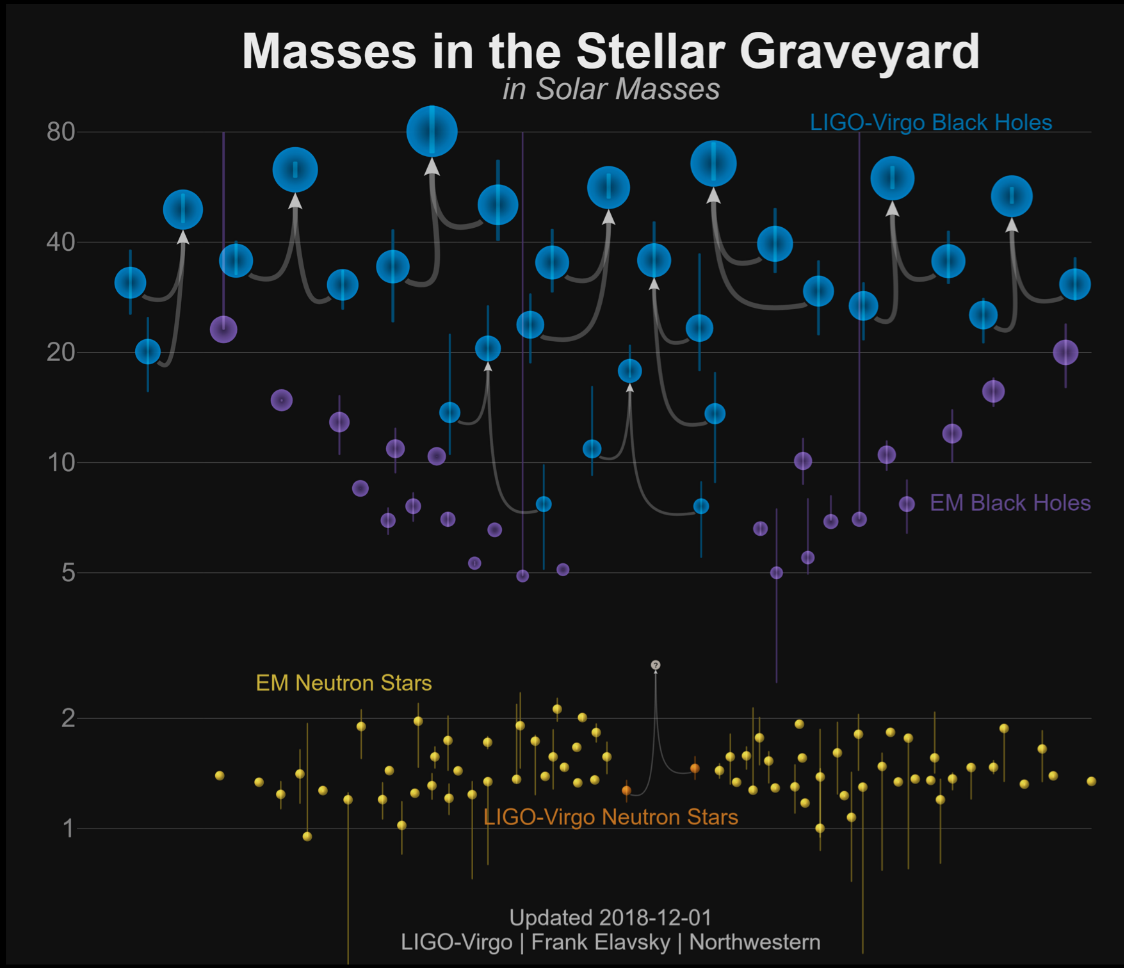
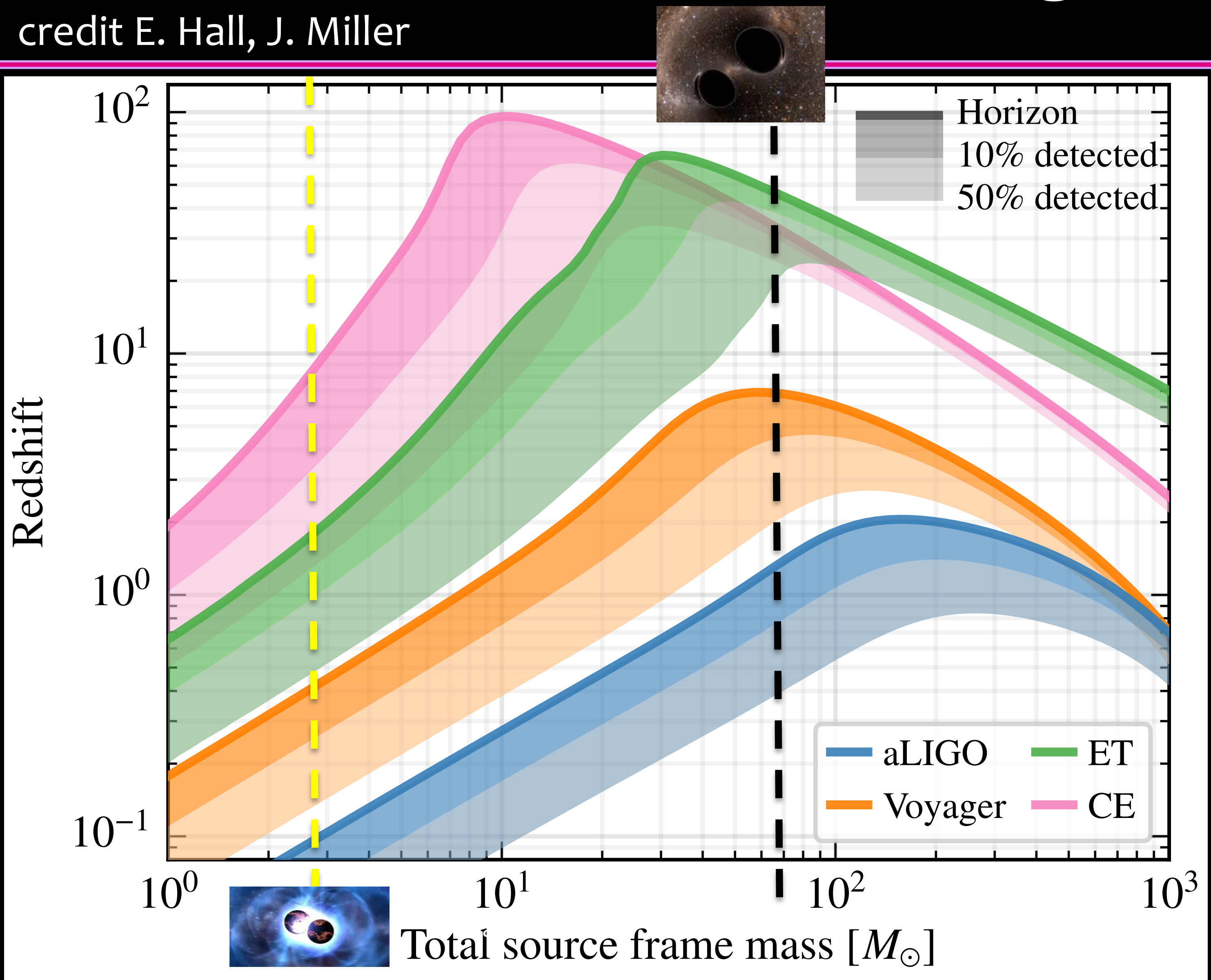
Where are we?

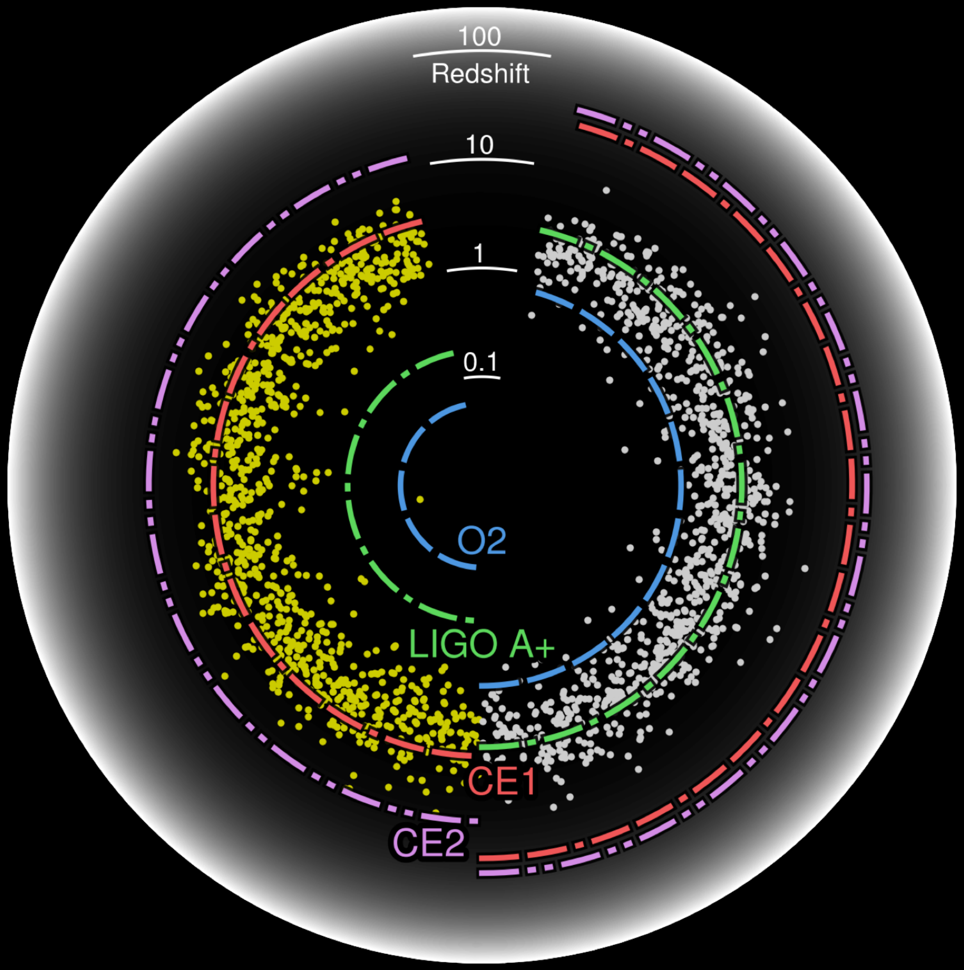
- In the first two science runs advanced detectors have detected
  - – 10 binary black holes (BBH) LVC, Arxiv:1811.12907
  - – And 1 binary neutron star (BNS), LVC PRL **119**, 161101, PRX 9 011001
    - Electromagnetic emission also detected!
- First 50 days of O3:
  - – ~10 BBH, 1 BNS, 1 NSBH (?) candidates shared with the public



Where do we go from here?

credit E. Hall, J. Miller





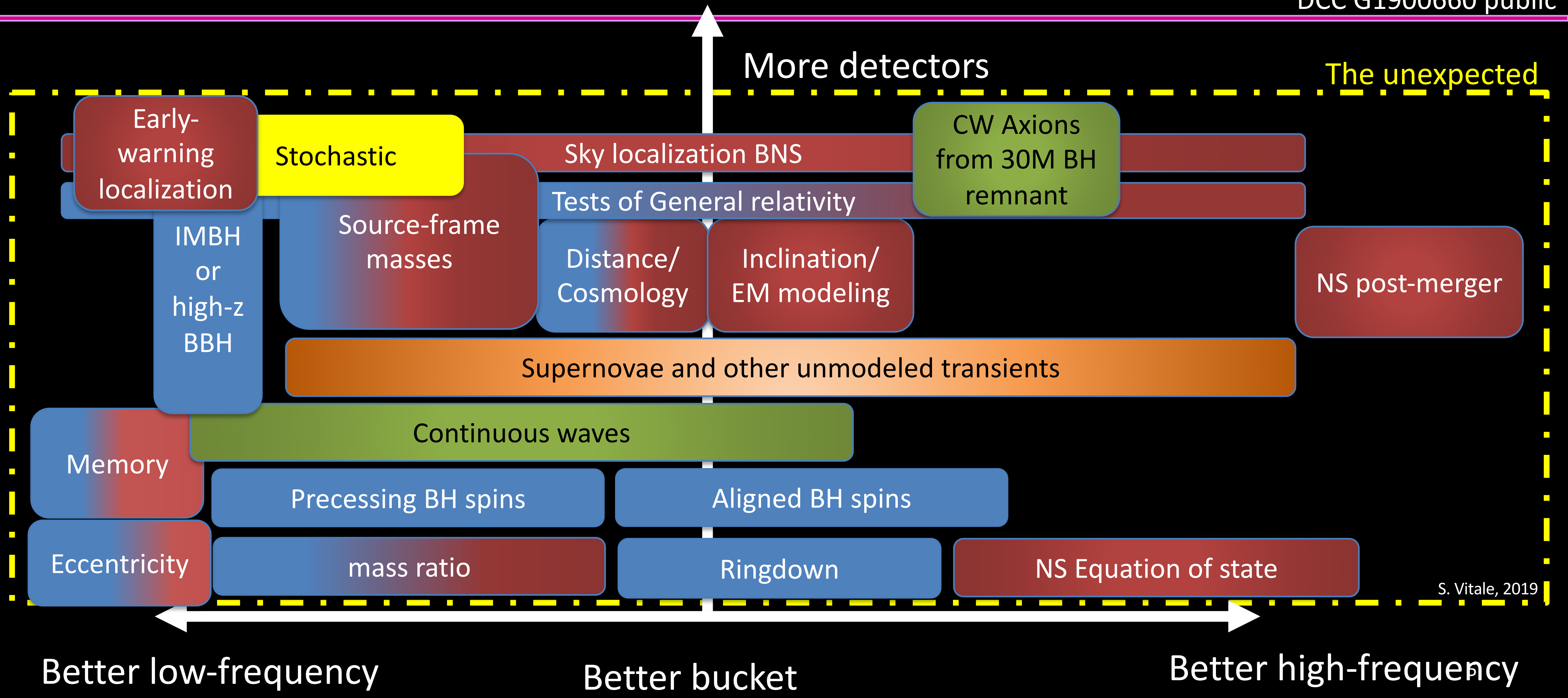
Hall/Vitale

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)
- They will overlap in time, which leads to interesting challenges (Regimbau+, Arxiv: 1201.3563; Meacher+ Arxiv:1511.01592)

Low/High frequency - Network size trade off

DCC G1900660 public



Low/High frequency - Network size trade off

Me Michael C

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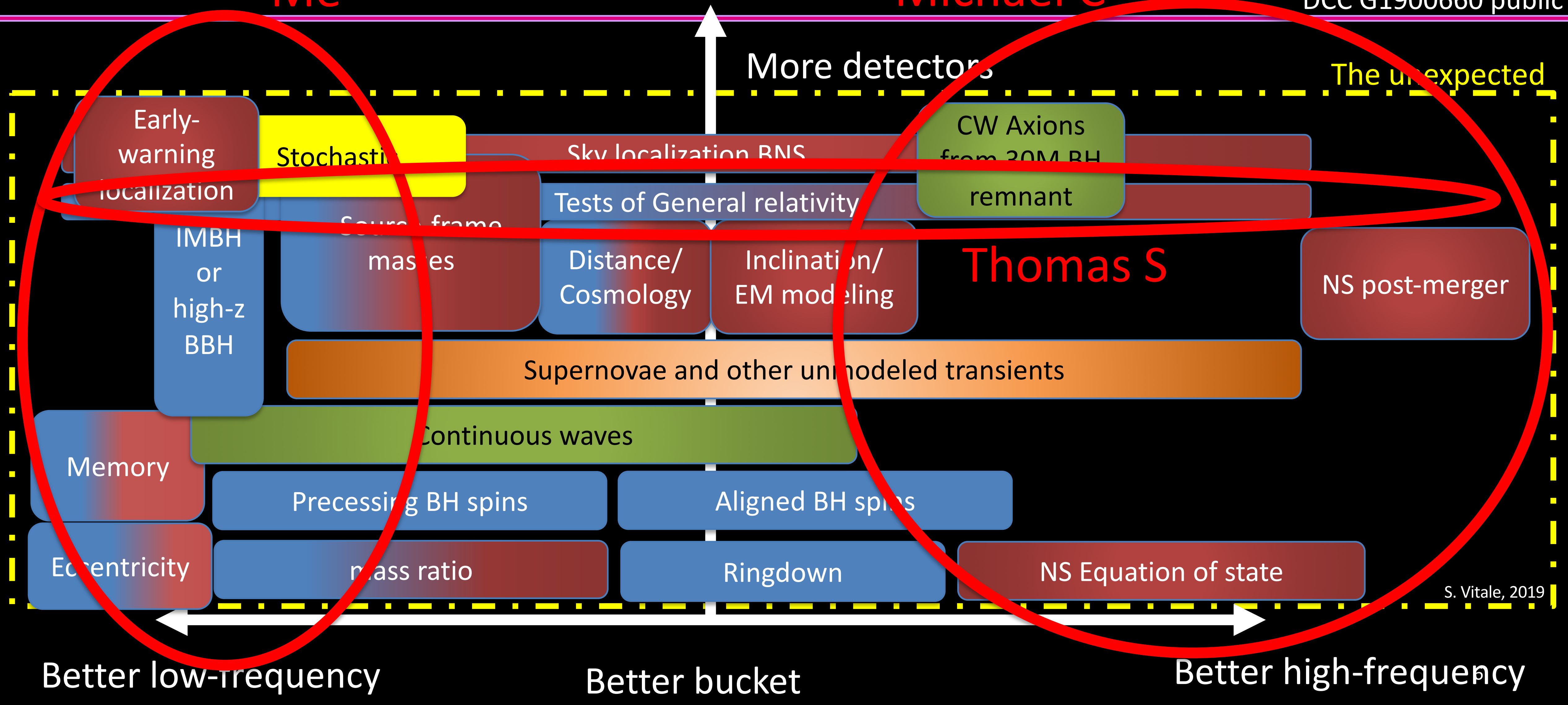
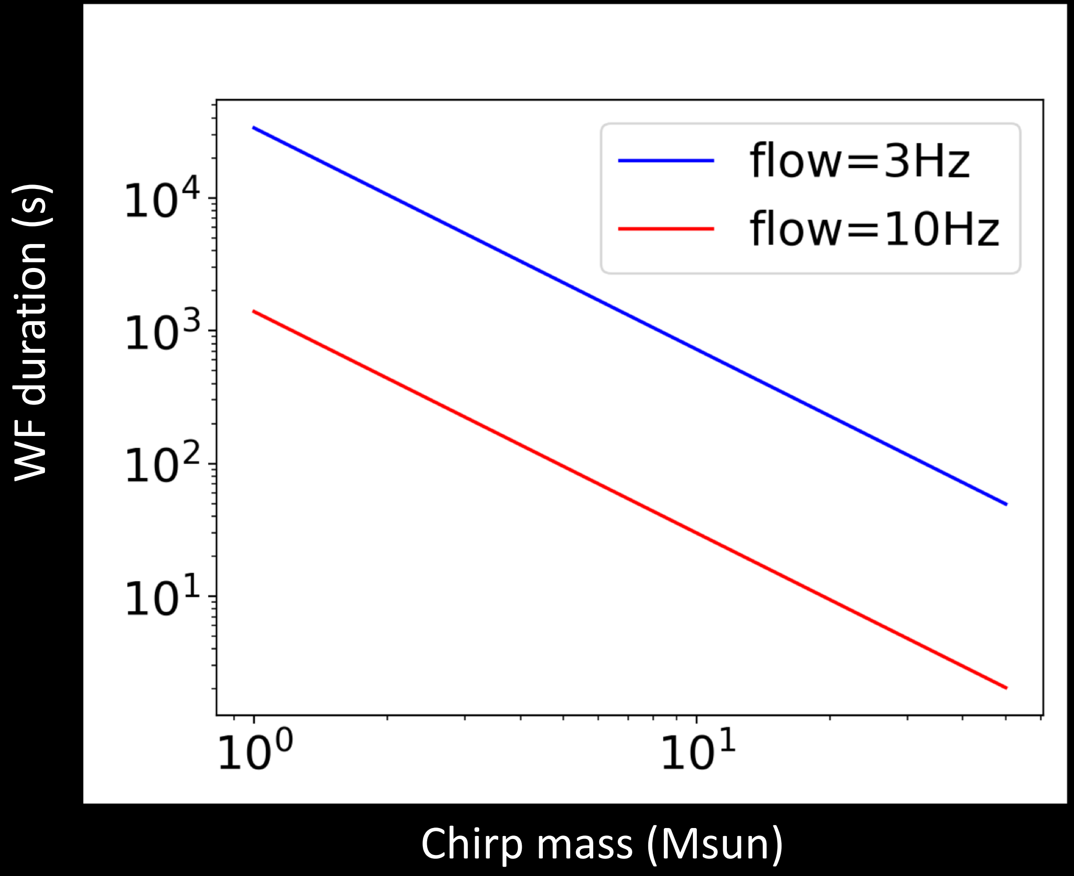


Low frequency – computational challenges

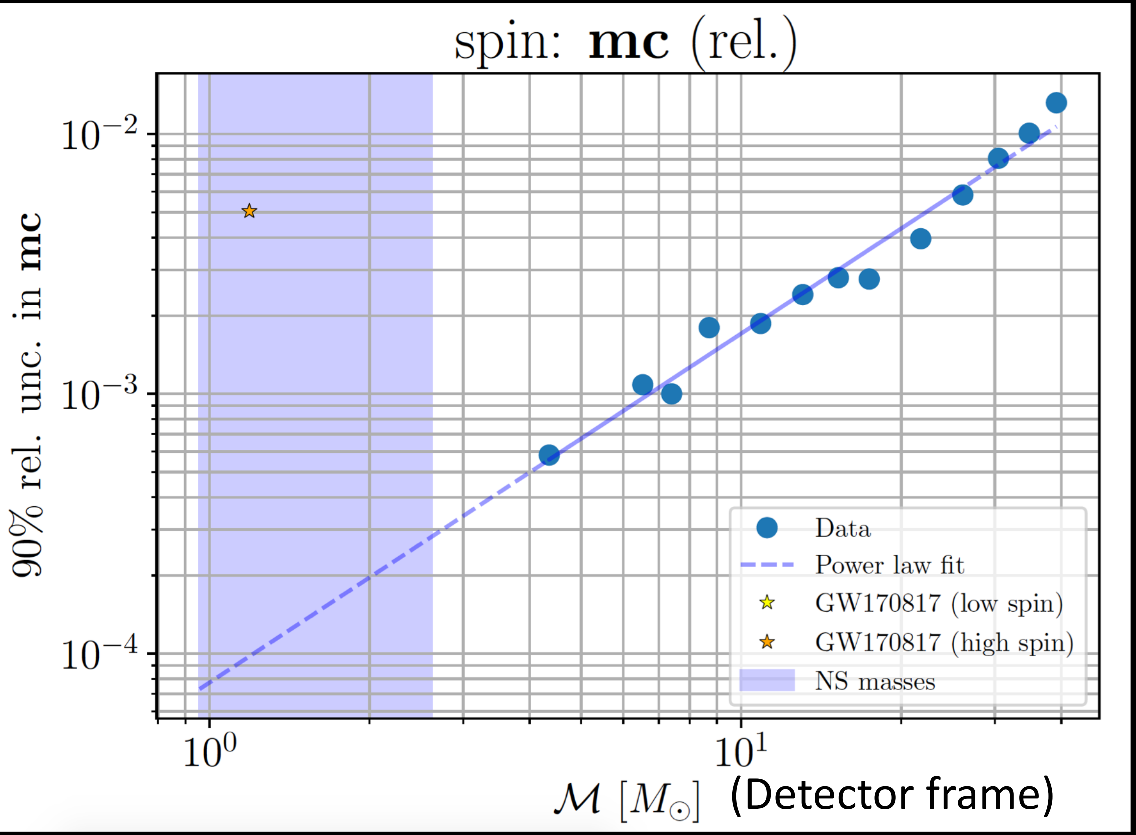


- We would love to know how well CBC parameters can be measured in 3G. However…
- The duration of waveforms (and hence the computational time required) blows up
  - As flow decreases
  - As the chirp mass decreases
- With current methods, we **cannot** run parameter estimation codes on binary neutron stars for 3G

Chirp mass extrapolation

SNR=32, CE

flow=10

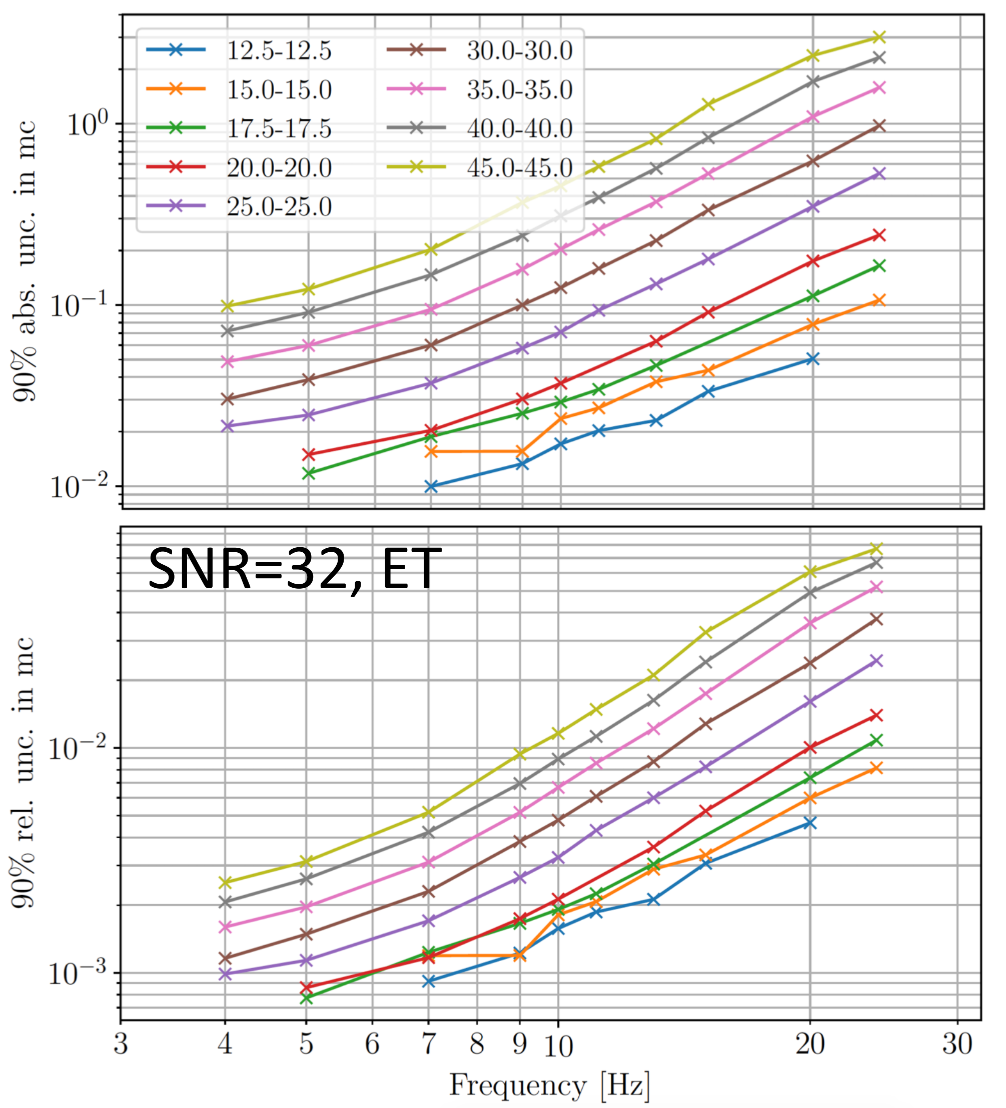


Whittle+, preliminary

- Run actual PE (meaning MCMC, not Fisher matrix) for decreasing true chirp mass
- See if the results can be extrapolated to the BNS mass region

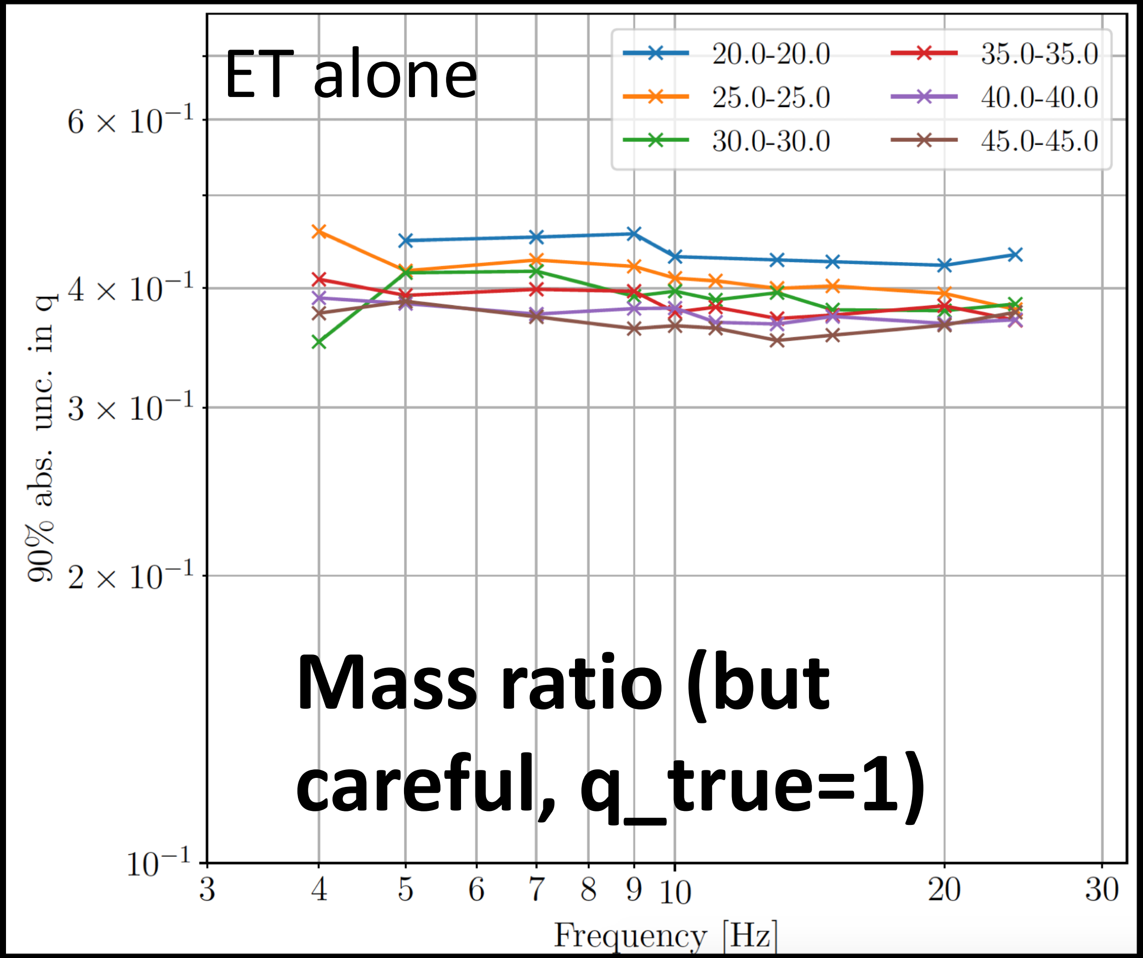
Lower-frequency extrapolation

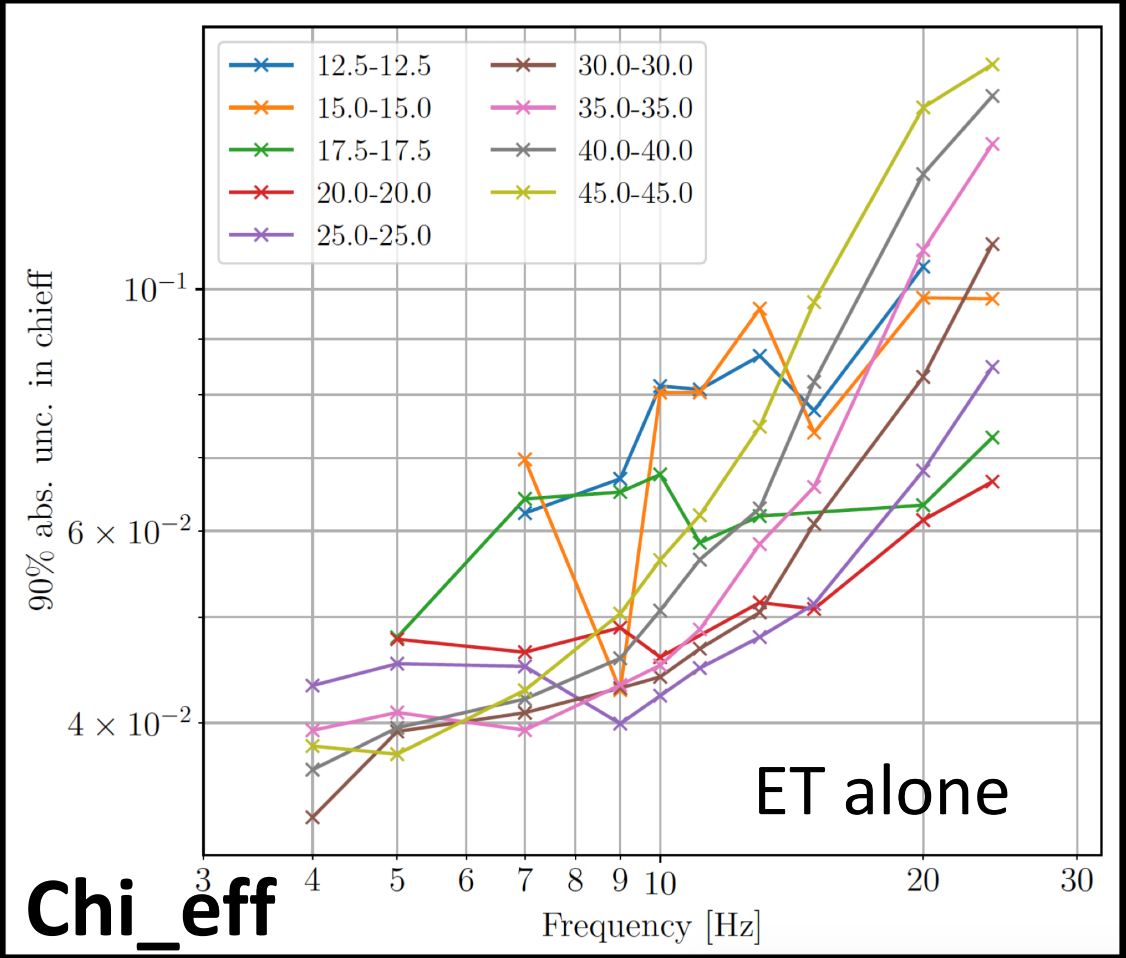
Whittle+, preliminary



- Run actual PE (meaning MCMC, not Fisher matrix) for decreasing lower frequency
- See if the results can be extrapolated to the BNS mass region
- Ongoing: 2D mass/flow extrapolation
- Caveat: don't have time dependent antenna patterns
  - Does anybody?

What gets better and what doesn't



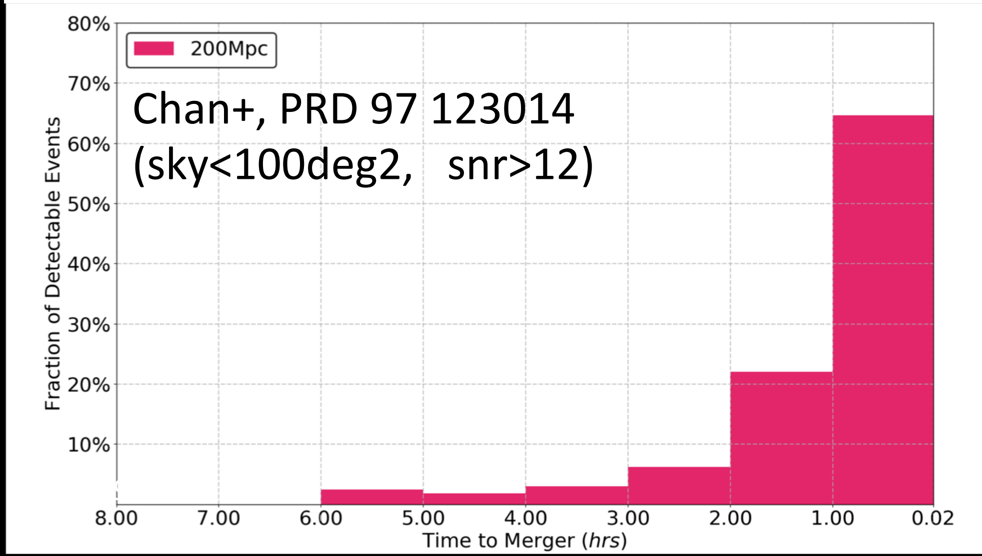


Whittle+, preliminary

Early warning for BNS

Network	d (Mpc)	n	100 sec	0.5 hrs	2 hrs	5 hrs	10 hrs
ET & CE	40	500	100%	100%	99%	66%	18%
	200		100%	74%	13.4%	2%	0%
	400		98%	27%	4%	0%	0%
	800		51%	4%	0%	0%	0%
	1600		5%	1%	0%	0%	0%
	Uniform [1]	5000	4%	1%	0%	0%	0%

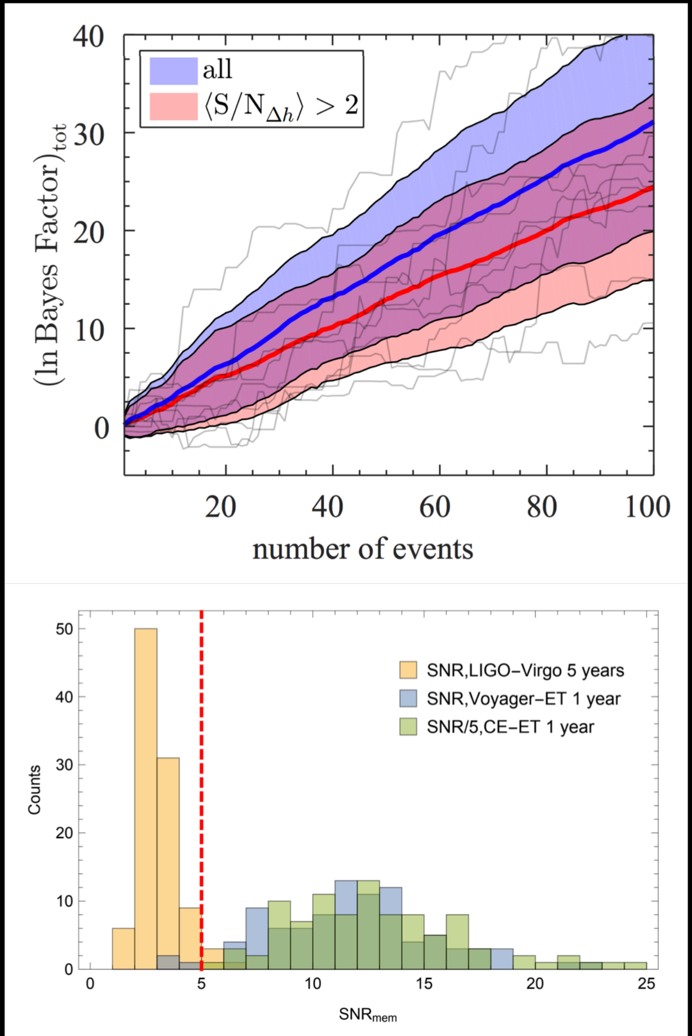
[1] Uniformly distributed in the comoving volume.



- Early warning that a BNS is about to merge -> better chances to understand the energetics of EM emission, pre-merger emission
- Lots of work my many people (UWA, PSU, Glasgow)
- Especially for network with >=ET+CE, can get significant fractions of nearby events with early warning
  - Question: can EM successfully follow-up 100deg2 at >200Mpc?

Memory effect

Lasky+, PRL 117, 061102



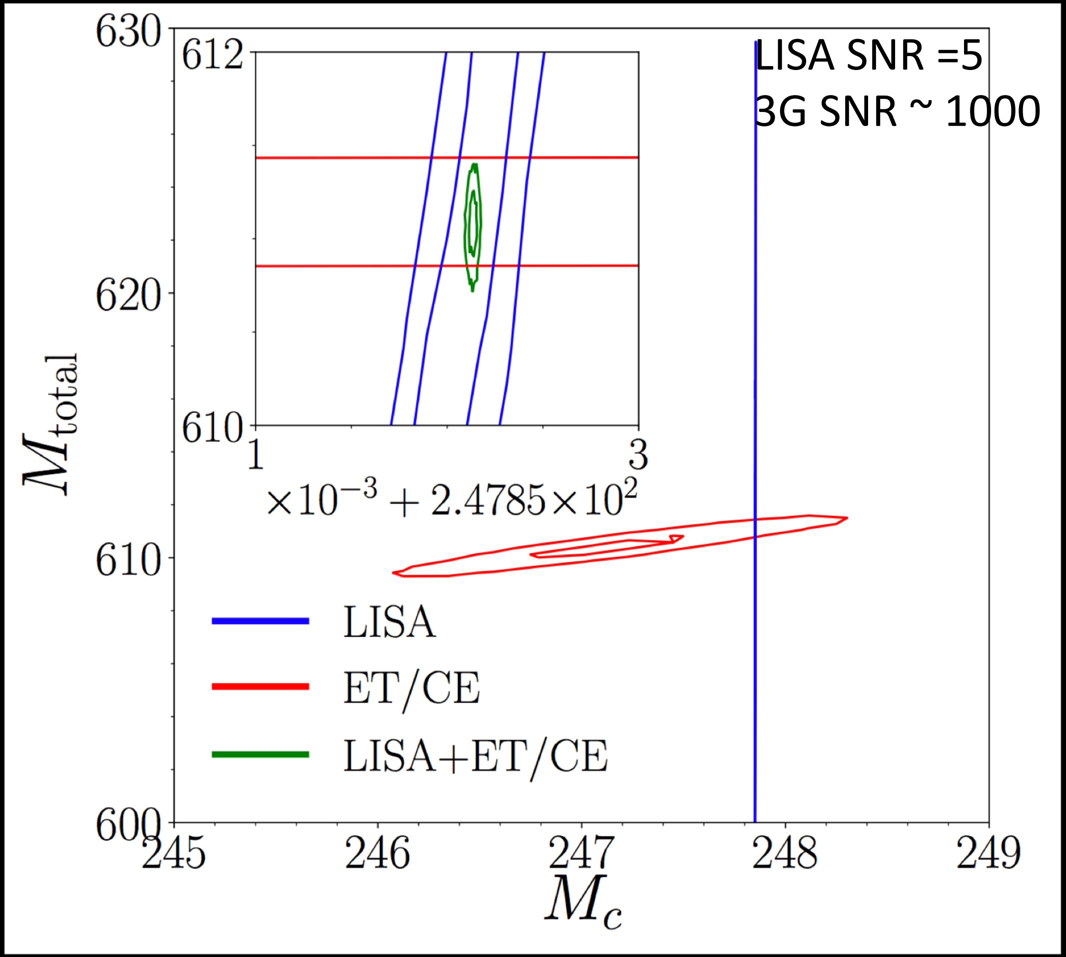
Yang+, PRL 121, 071102

- 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

IMBH, multibanding

- 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)
- For nearby IMBH, LISA might provide Mchirp info, but not for z>~0.3
  - Still need decent f-low
  - But do IMBH exist…?

Cutler+, 1903.04069

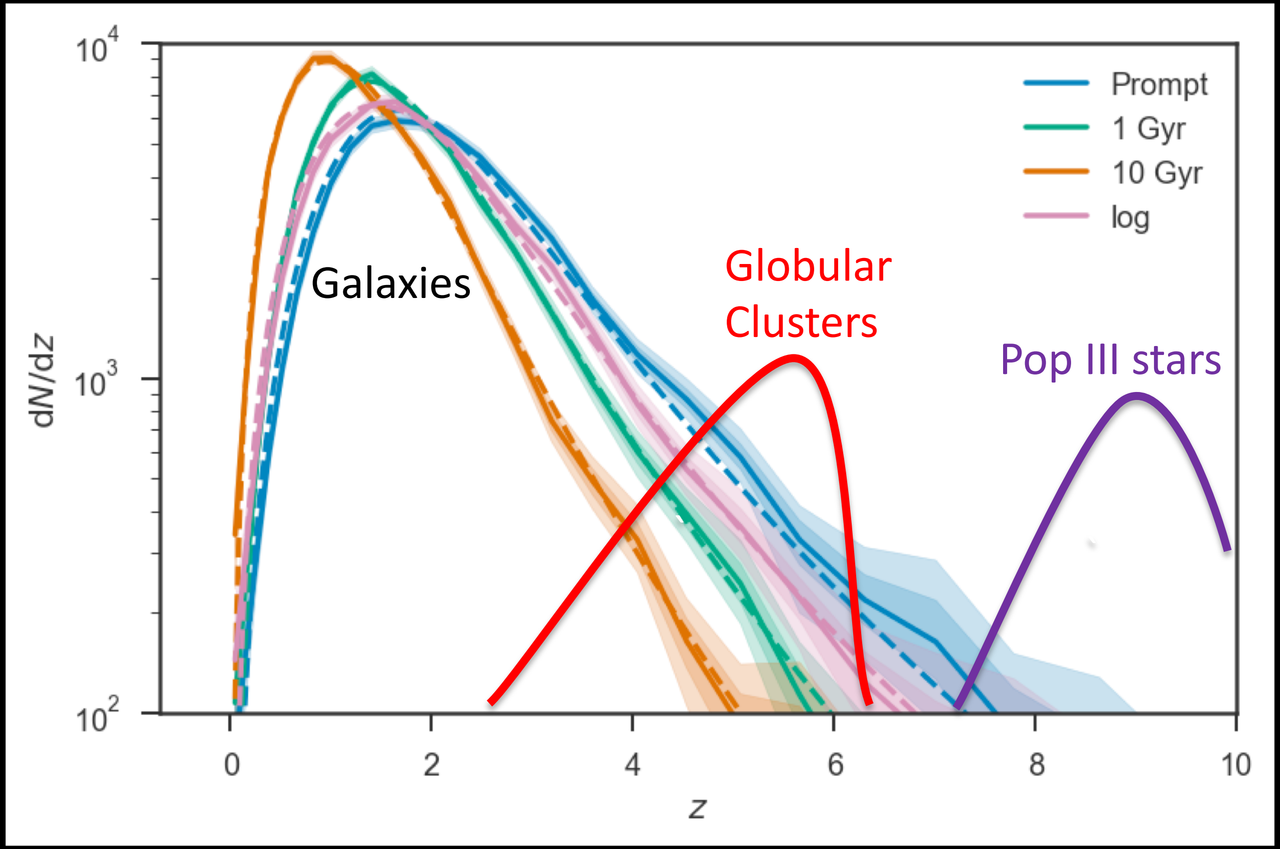


BBH Formation channels

- 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)

BBH formation channels

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

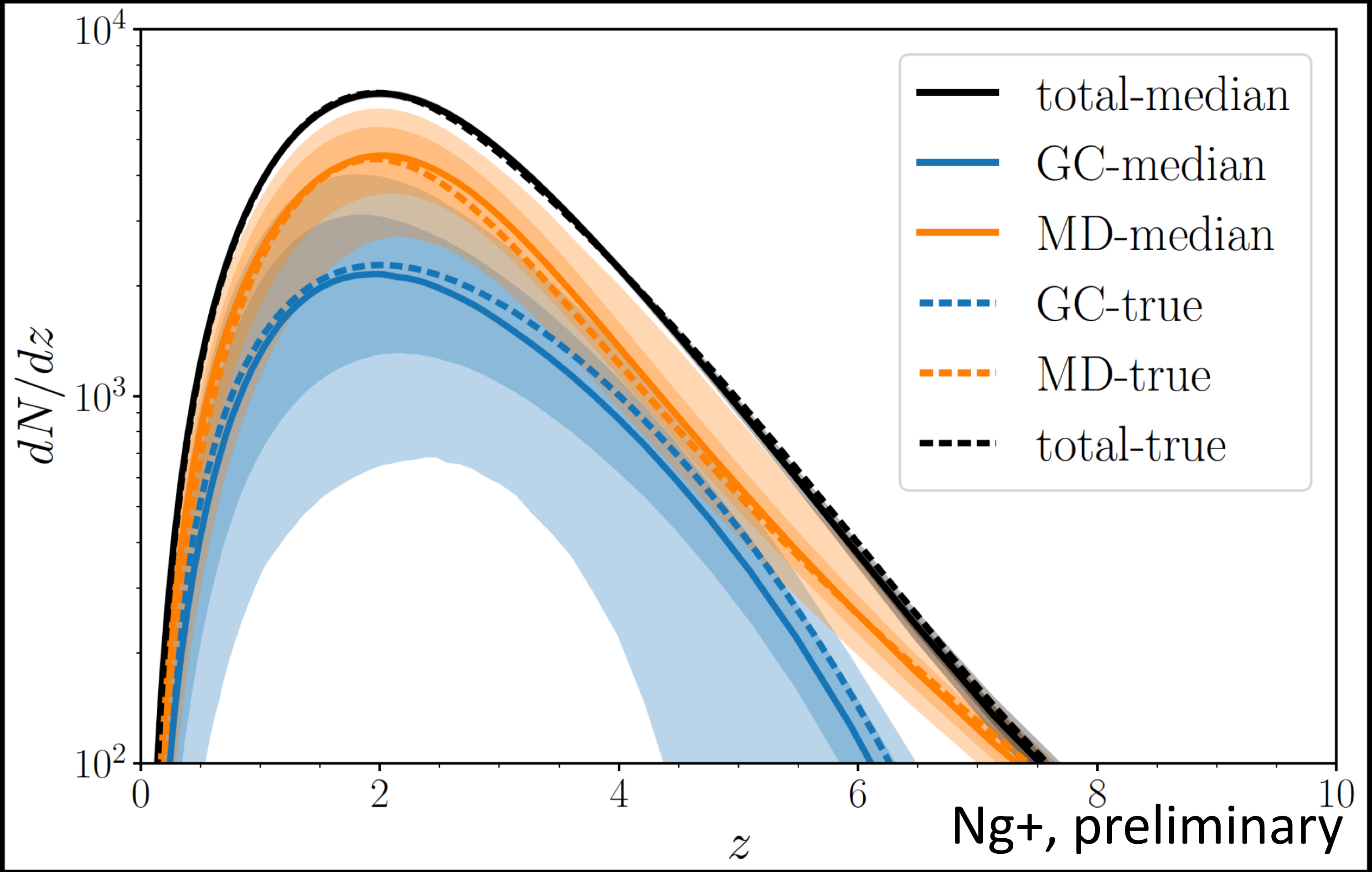


There might be more sub-populations
(e.g. AGN disks,
Bartos+ Nature Com, 8 831)

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.



But still…

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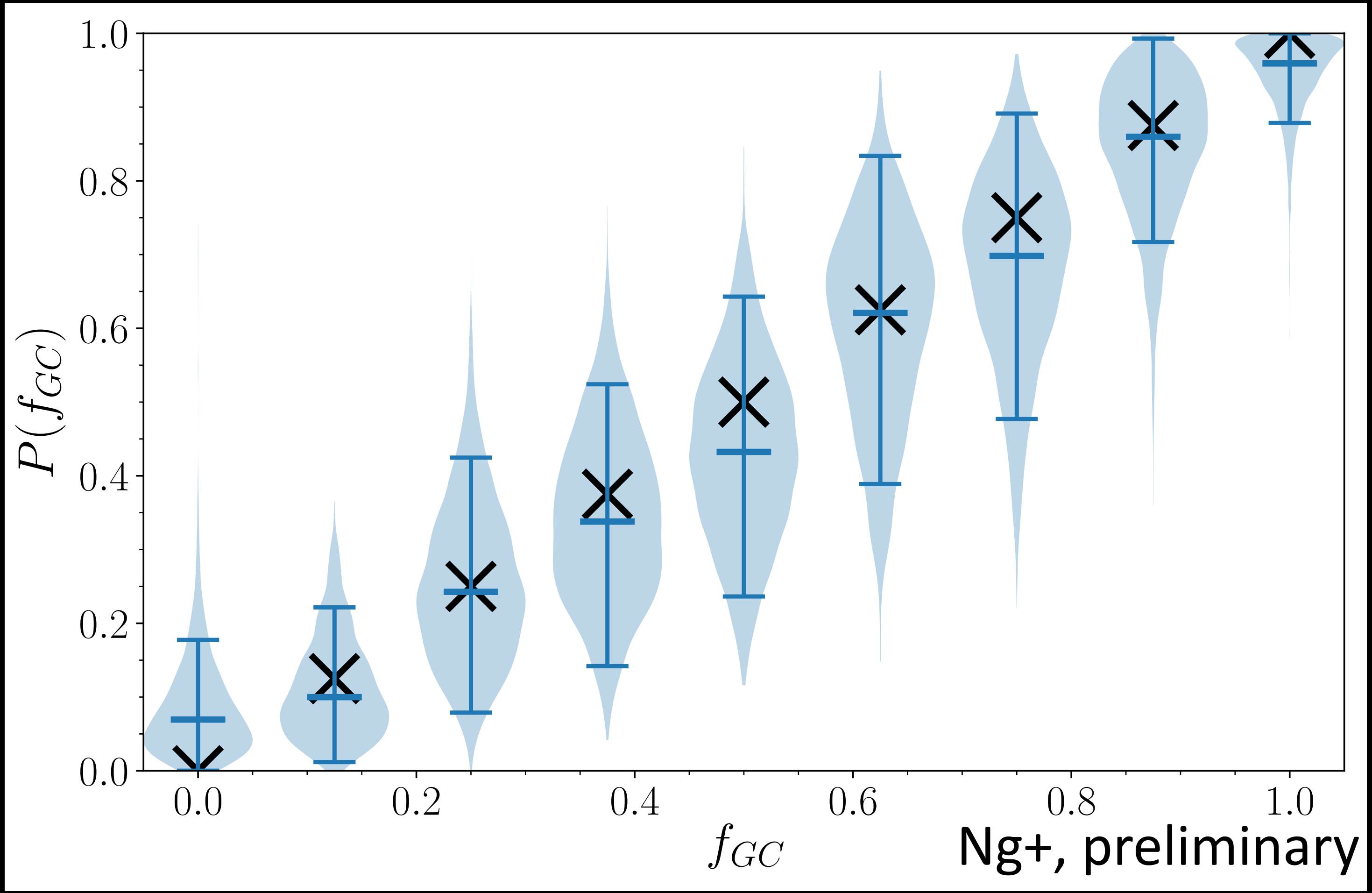
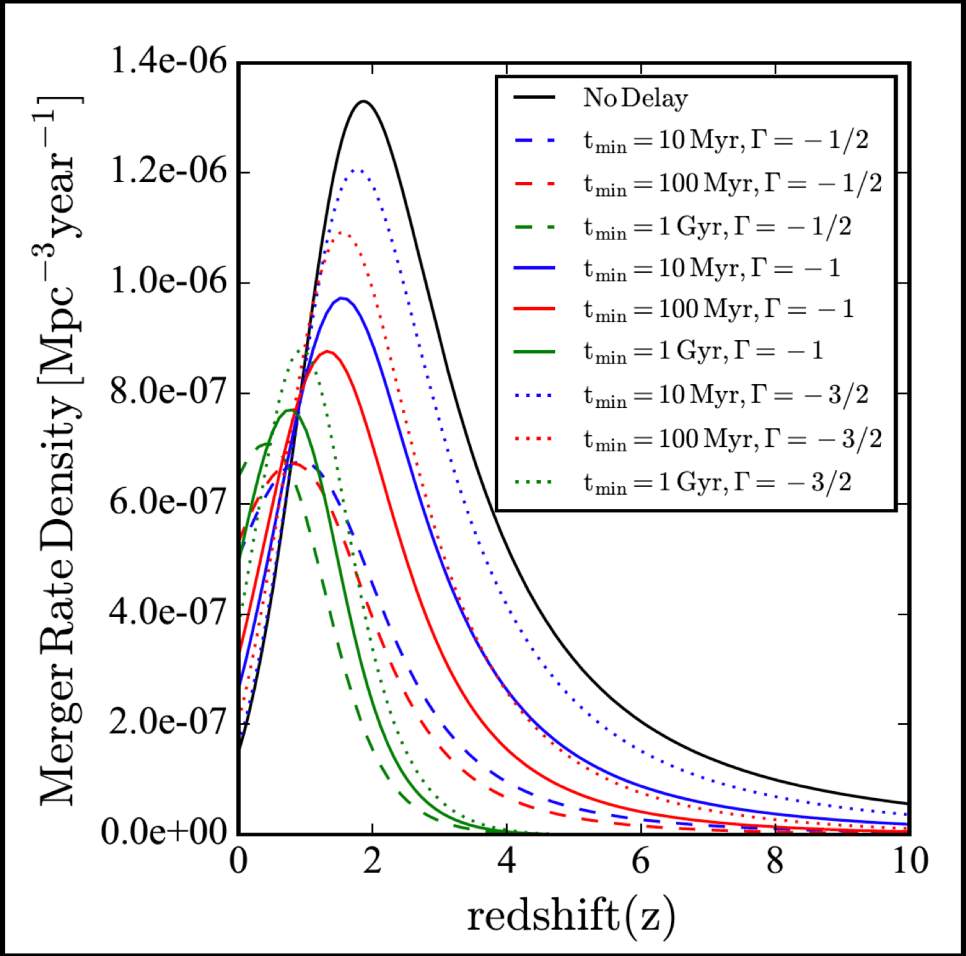


Time-delay distribution for BNS

Safarzadeh+, 1904.10976



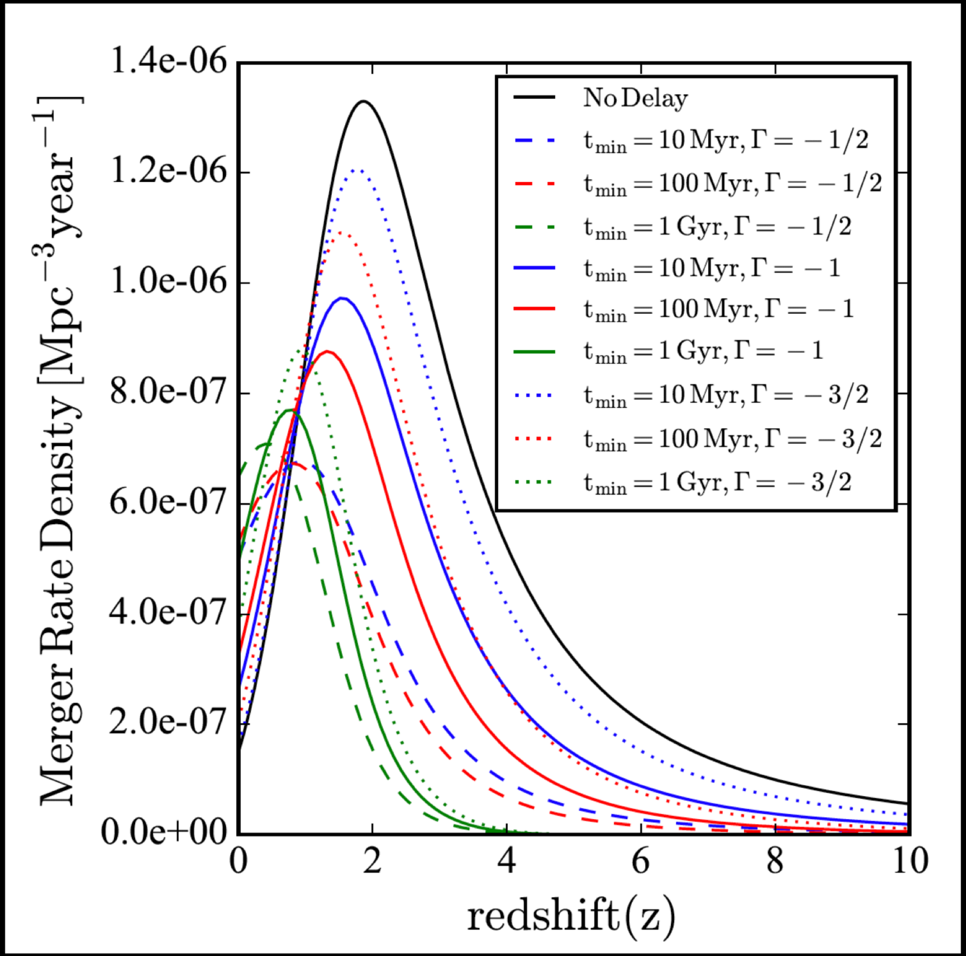
All BNS

$$\dot{n}(z) = \int_{z_b=10}^{z_b=z} \lambda \frac{dP_m}{dt}(t - t_b - t_{\min})\psi(z_b)\frac{dt}{dz}(z_b)dz_b$$

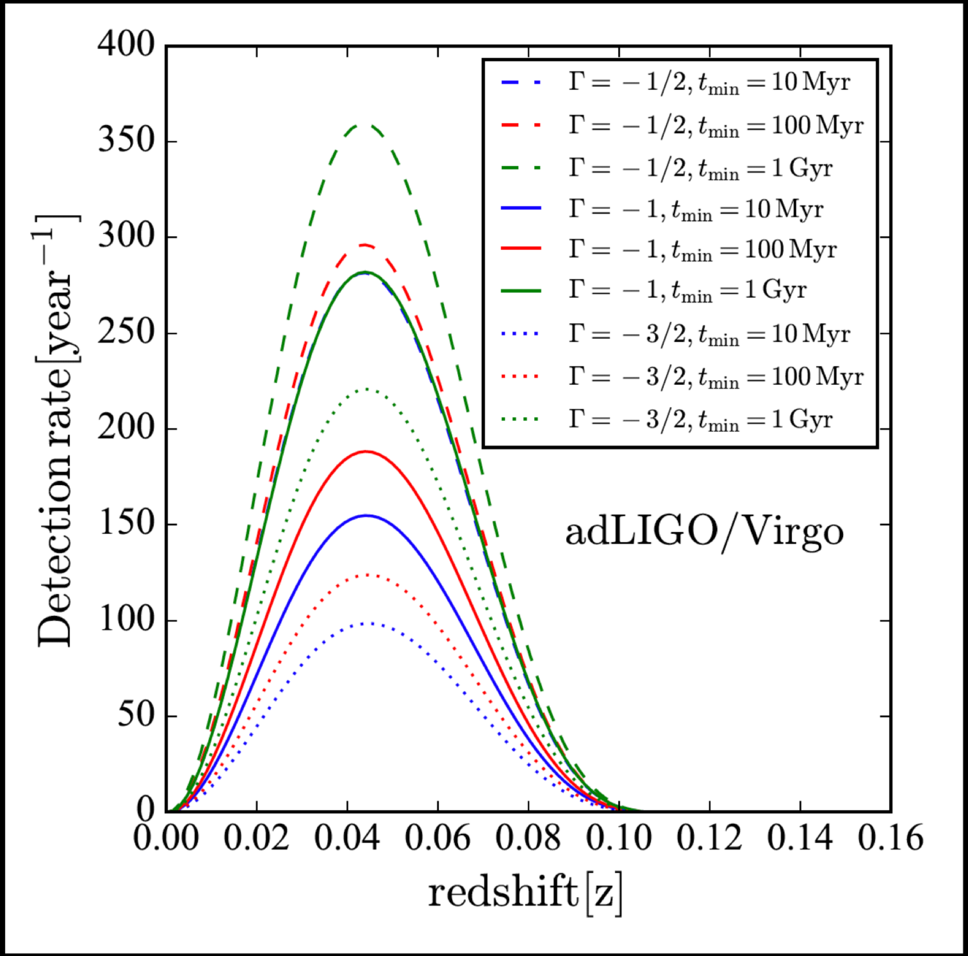
$$dP_m/dt \propto t^{\Gamma}$$

Time-delay distribution for BNS

Safarzadeh+, 1904.10976



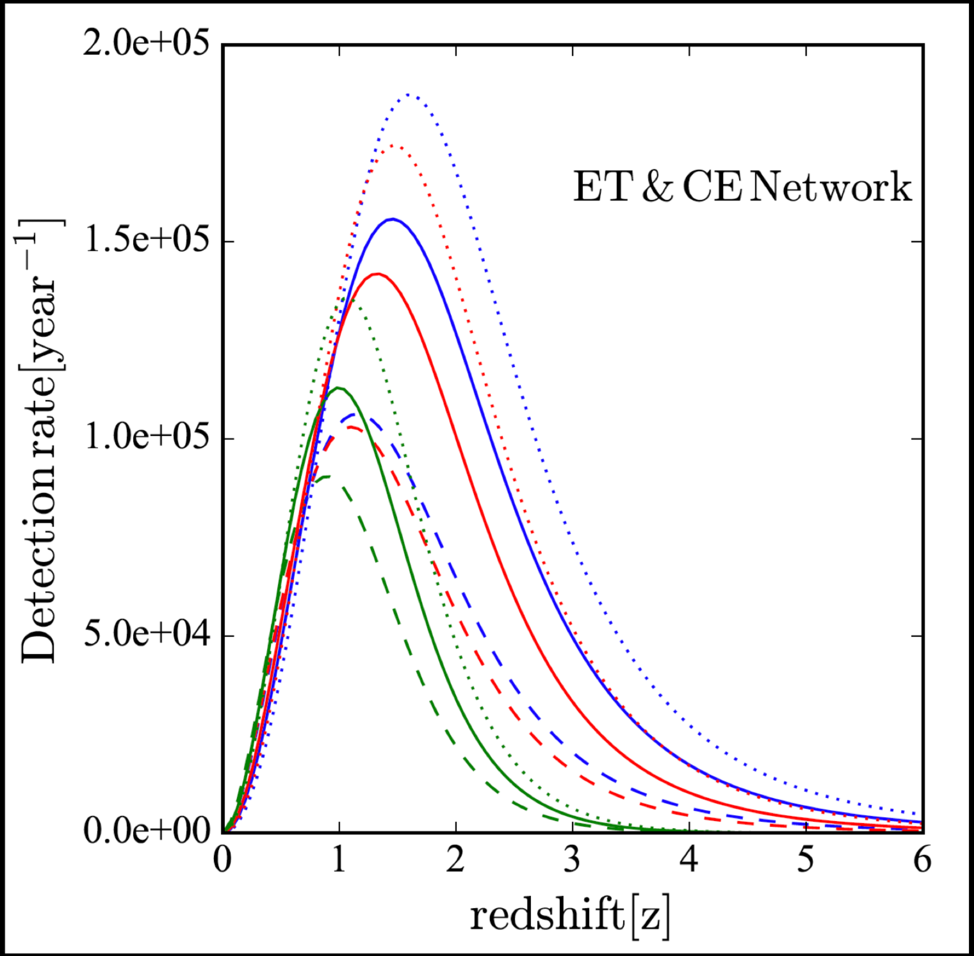
All BNS



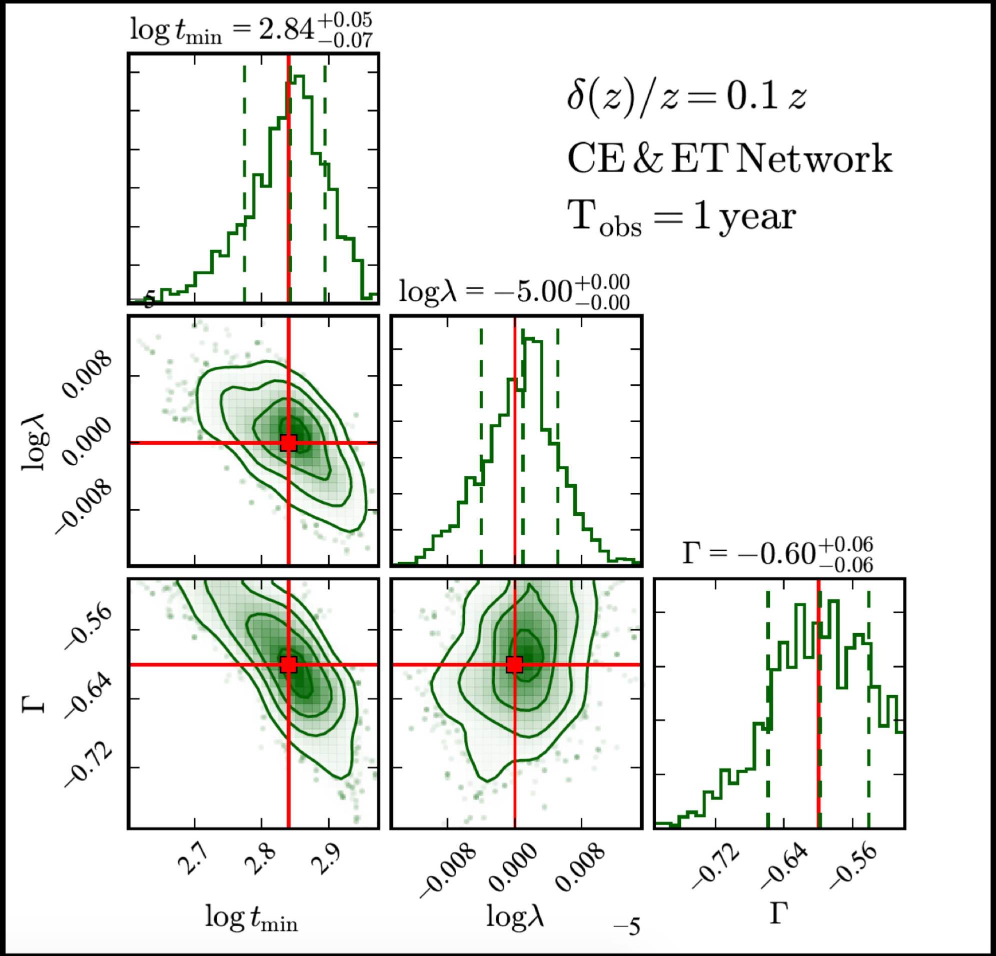
2G detectable

Time-delay distribution for BNS

Safarzadeh+, 1904.10976



3G detectable

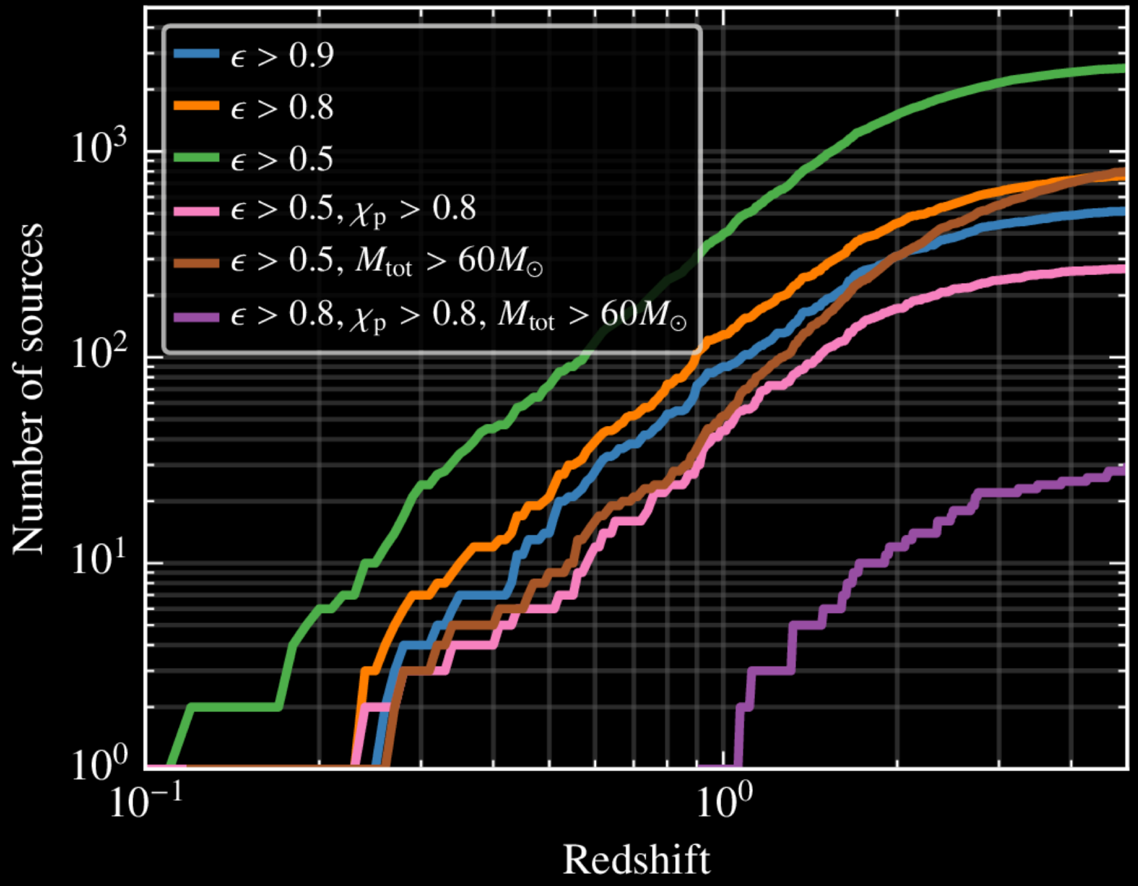


More from populations

- These are just examples of what can be done with large numbers of CBCs
- Others examples include
  - Cosmology
  - Measurement of mass and spin distributions
    - Do these vary with z? How?
  - Features in the mass function
  - Higher probability of getting rare events/outliers

Rare events

w/ E. Hall and C. Rodriguez; (slowly) in prep



- Together with populations, one gets rare events, showing peculiar properties
- However, those might not be super loud
  - Don't expect SNR of 1000s with eccentricity with spin precession with XYZ (replace with your secret dream)

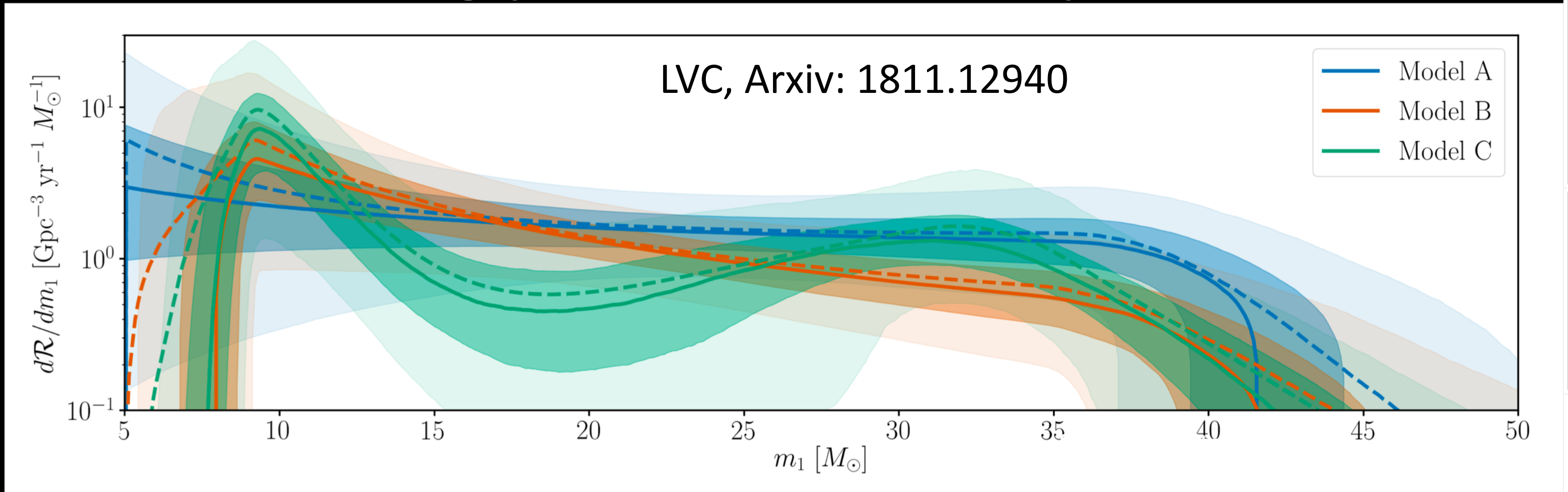
Thanks!

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;

Inferring the BH mass distribution

- Can use hierarchical methods to infer the underlying properties of the BH mass function
- Used 3 models, increasing complexity (and number of parameters!) [Refs5]
- No strong preference for any one model



Model	α	$m_{\max}$
A	[-4, 12]	[30, 100]
B	[-4, 12]	[30, 100]
C	[-4, 12]	[30, 100]

	Mass Parameters					
Model	$m_{\min}$	β_q	λ_m	μ_m	σ_m	δm
A	**5**	**0**	**0**	N/A	N/A	N/A
B	[5, 10]	[-4, 12]	**0**	N/A	N/A	N/A
C	[5, 10]	[-4, 12]	[0, 1]	[20, 50]	(0, 10]	[0, 10]

Model	A	B	C, $\lambda_m = 0$	C, $\delta_m = 0$
$\ln \mathrm{BF}^i_C$	-2.37	-1.40	-2.12	0.14