Cosmology with Einstein Telescope

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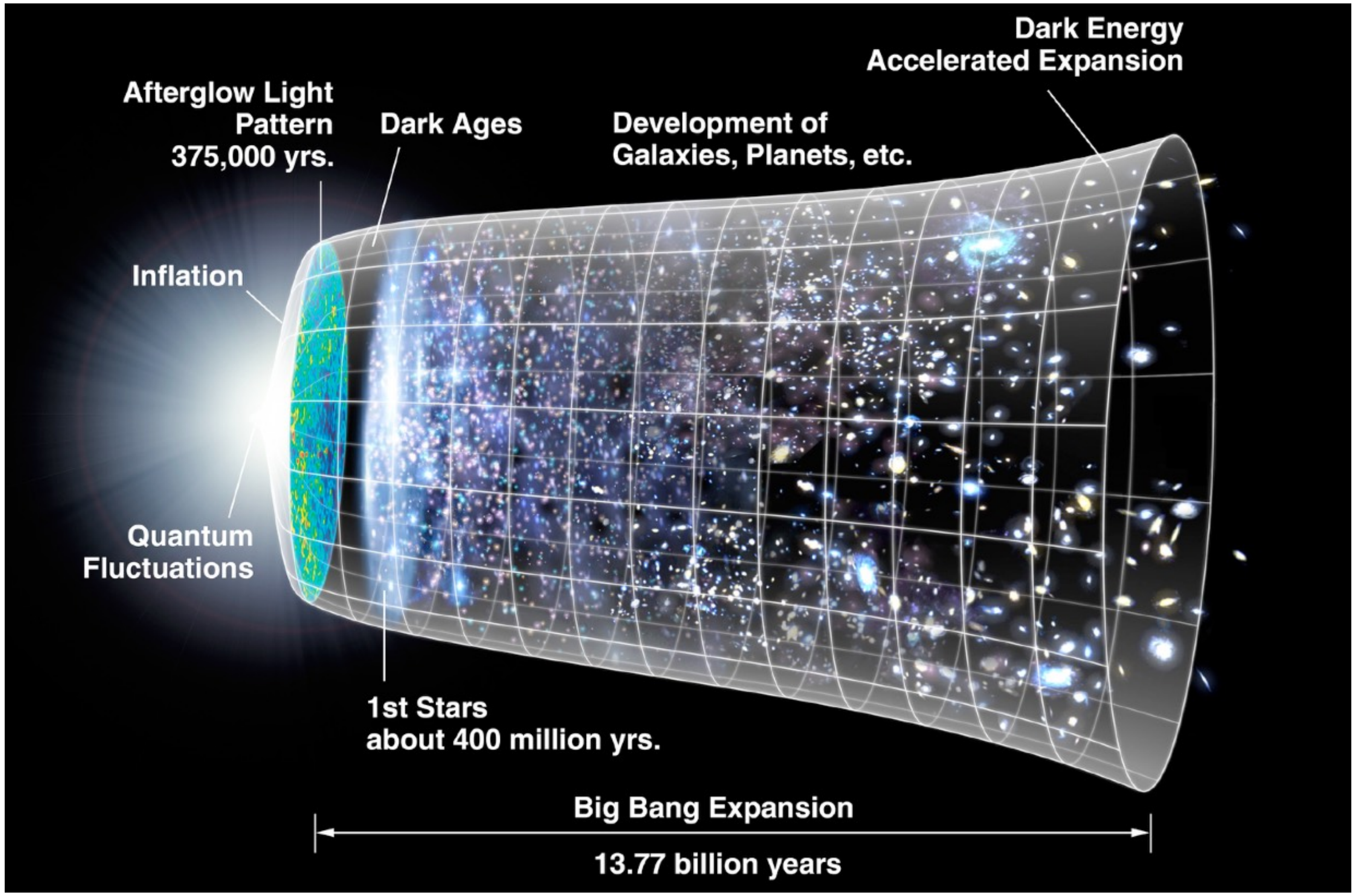

Gravitational waves and cosmology

late-time universe

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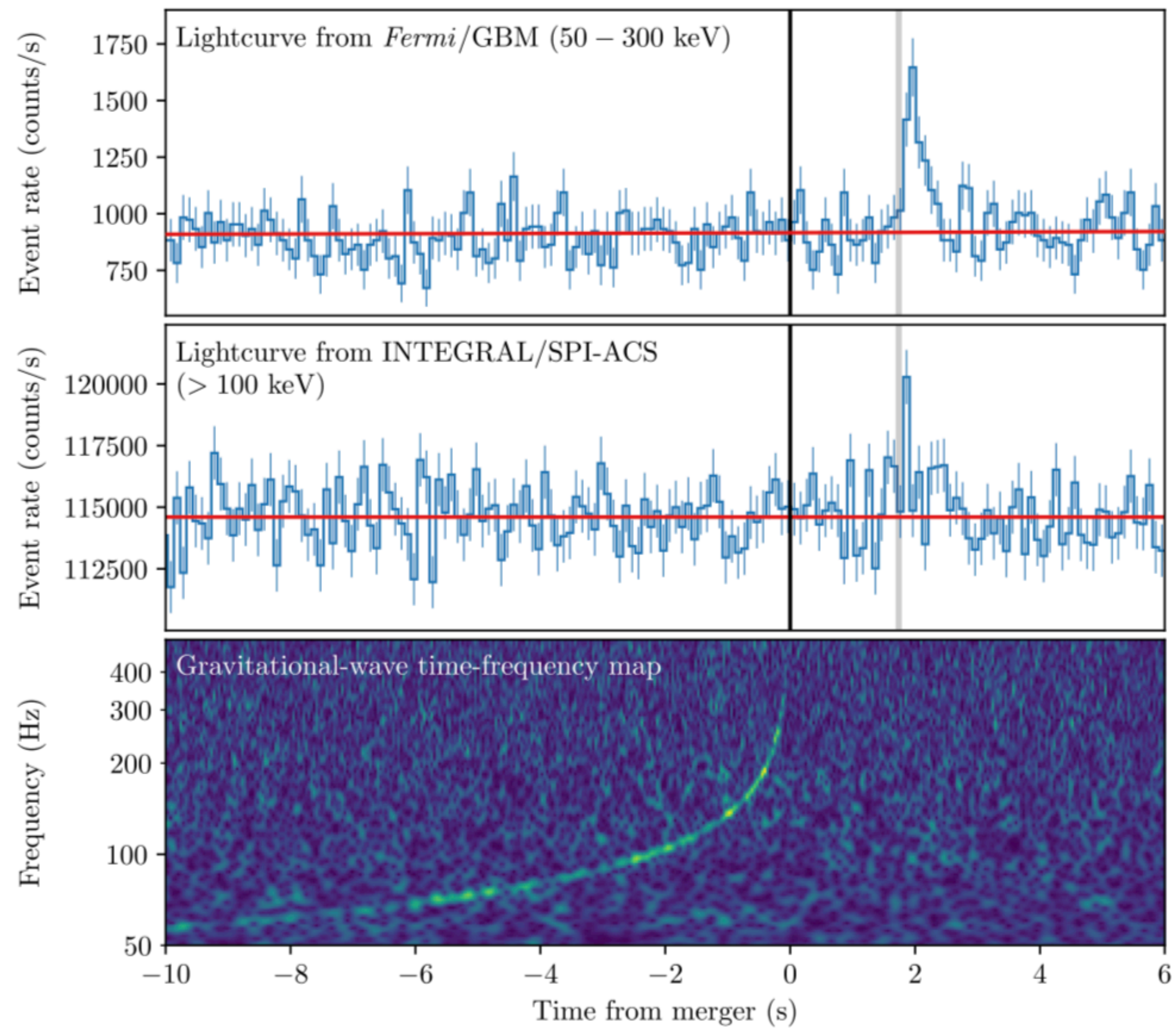
Individual sources
and populations of sources
at cosmological distances
e.g. binary neutron stars (BNS),
binary black holes (BBH),
neutron star- black-hole binary (NS-BH)…

↓

– Expansion rate $H(z)$
– H_0, Hubble constant
– Ω_m
– beyond $\Lambda\mathrm{CDM}$
dark energy $w(z)$ and dark matter
– modified gravity (modified GW propagation)
– astrophysics; eg BH populations, PISN mass gap?

$z \sim 0.01$

1.74 s



B. P. Abbott +, APJL, 848:L13 (2017)

$$-3 \times 10^{-15} \leq \frac{c_{GW} - c}{c} \leq +7 \times 10^{-16}$$

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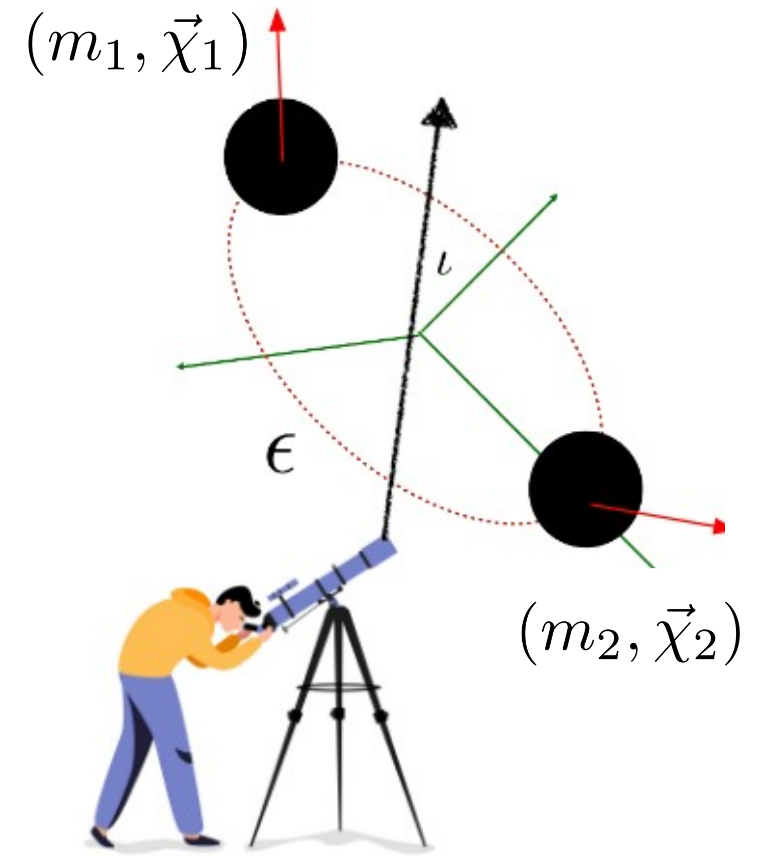
Very early universe
$t \gtrsim t_{Pl}$

Stochastic background
of GWs of cosmological origin

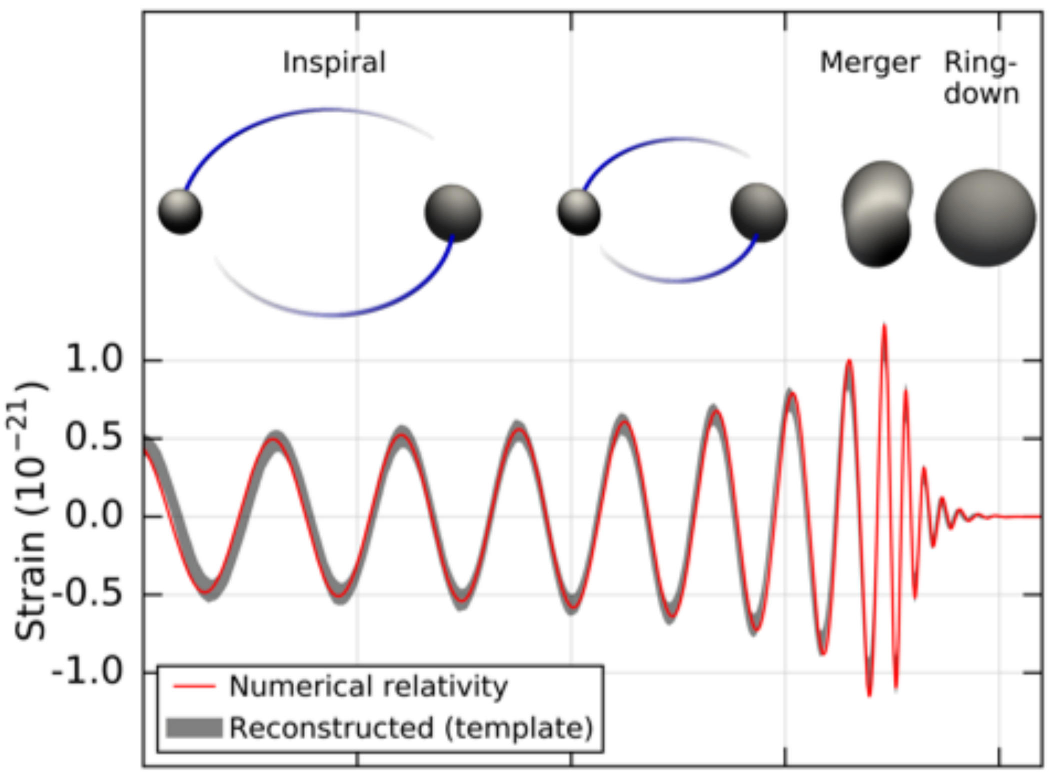
– quantum processes during inflation
– primordial black holes
– Phase transitions in Early universe
– topological defects, eg cosmic strings
– …..

Binary basics



- GW signal from binary mergers depends on intrinsic parameters (determining the phase evolution: spins, masses etc) and extrinsic parameters (sky position, luminosity distance, inclination etc)

- Crucial parameters for cosmology: *redshifted* / detector frame masses; luminosity distance



$\mathrm{fn}(d_L; \mathcal{M}_z)$

$\mathrm{fn}(t; \mathcal{M}_z)$

$$m_{1,2}^{\mathrm{det}}(z) = (1+z) m_{1,2}$$

$$\mathcal{M}_z = (1+z)\mathcal{M}$$

chirp mass $\mathscr{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$

In general relativity, allowing for possible dark energy:

$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{\mathrm{d}z'}{\left[\Omega_m (1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w(z'))}\right]^{1/2}}$$

Binary basics

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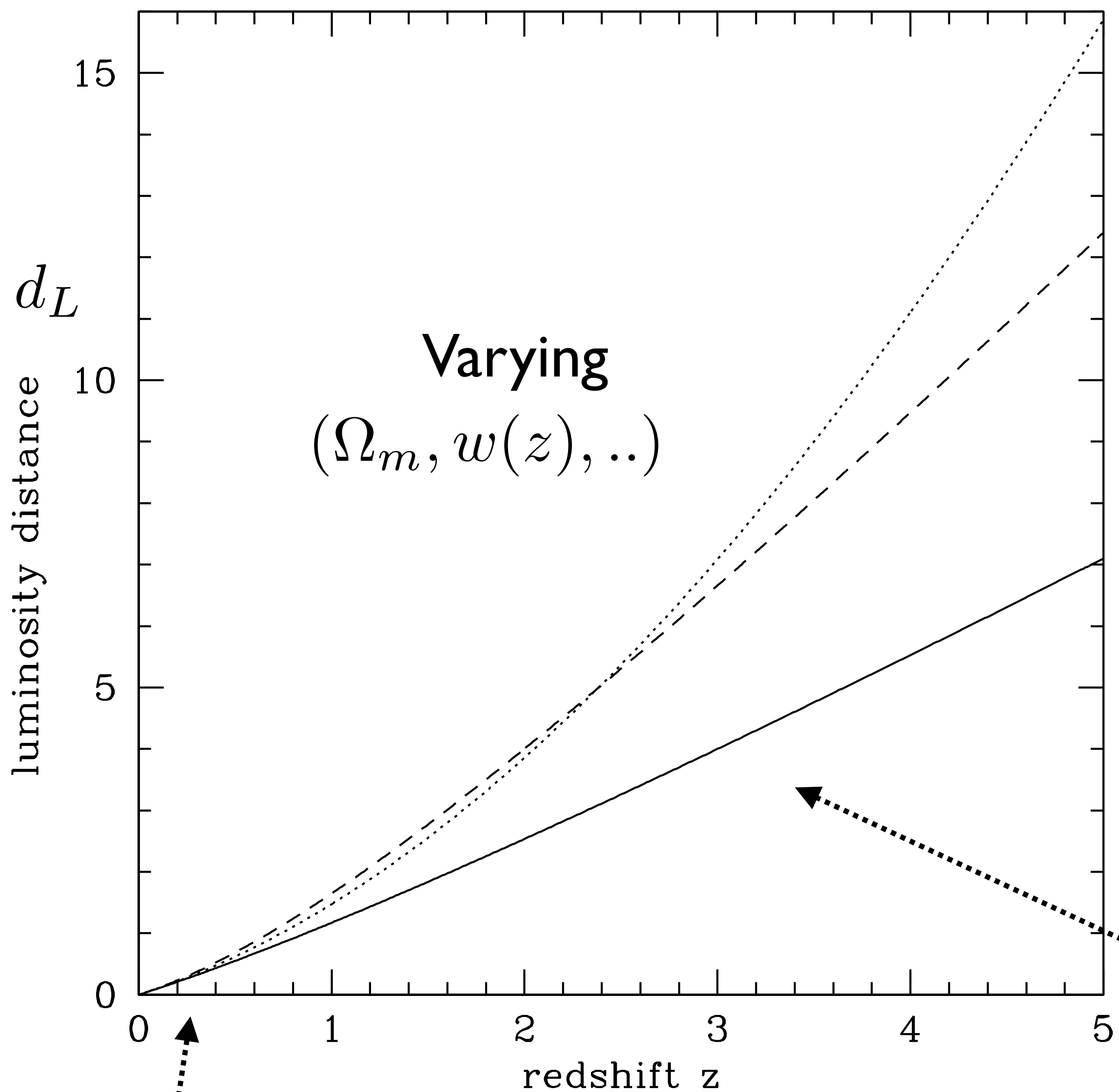


- From GW observations, determine d_L

$$\sigma_{d_L}^{\text{inst}} \sim \frac{2d_L}{\rho}$$

- *But* gravity is scale-free: perfect degeneracy between source masses, redshift, spins.. Some extra non-gravitational information is necessary to determine z.

For larger z (ET) , sensitive to other cosmological parameters, and can potentially access

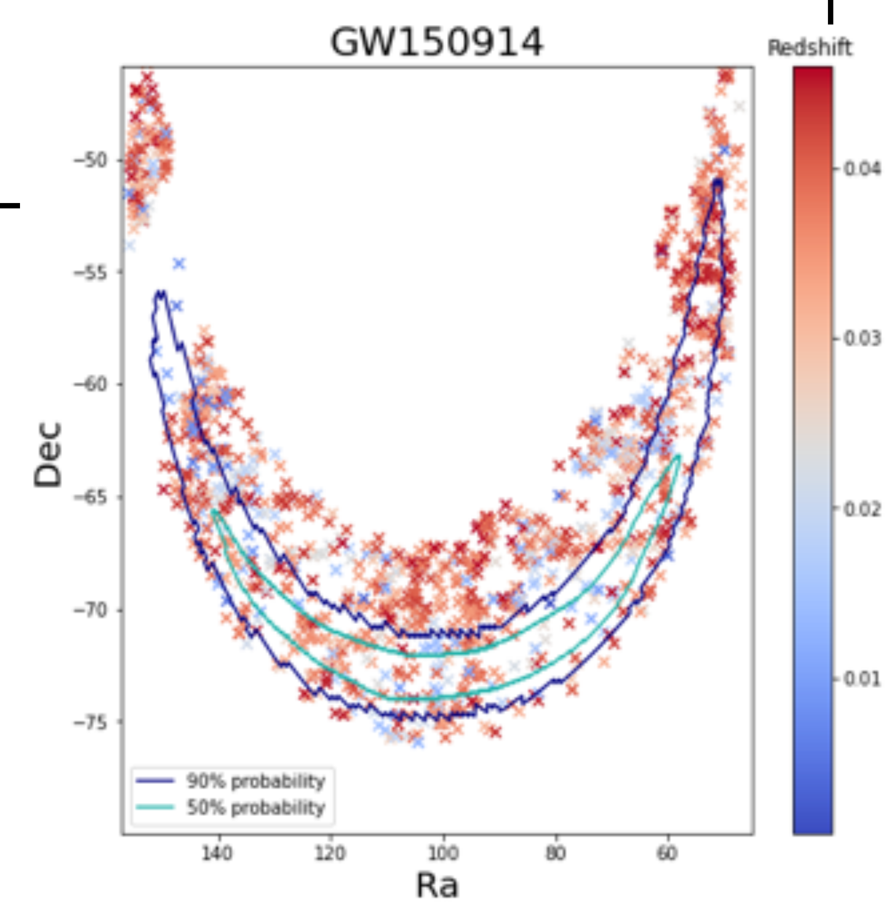
$$H(z) = H_0\left[\Omega_m(1+z')^3 + \Omega_\Lambda(1+z')^{3(1+w(z'))}\right]^{1/2}$$

For $z \ll 1$ (LIGO-Virgo): $d_L = \frac{cz}{H_0}$

Determining the redshift

- Crux of doing cosmology with ET is to determine *redshift* of the sources.

1. A direct EM counterpart with an associated redshift measurement *[B.Schutz, '86]* (such as the BNS GW170817 together with optical identification of host galaxy NGC4993)
2. A collection of galaxies localized in the GW localization volume (i.e. using galaxy catalogues) *[B.Schutz, '86]*
3. Knowledge of the *source frame mass distribution*
4. *for NS, a* measure of the tidal deformability + equation of state
5. ….



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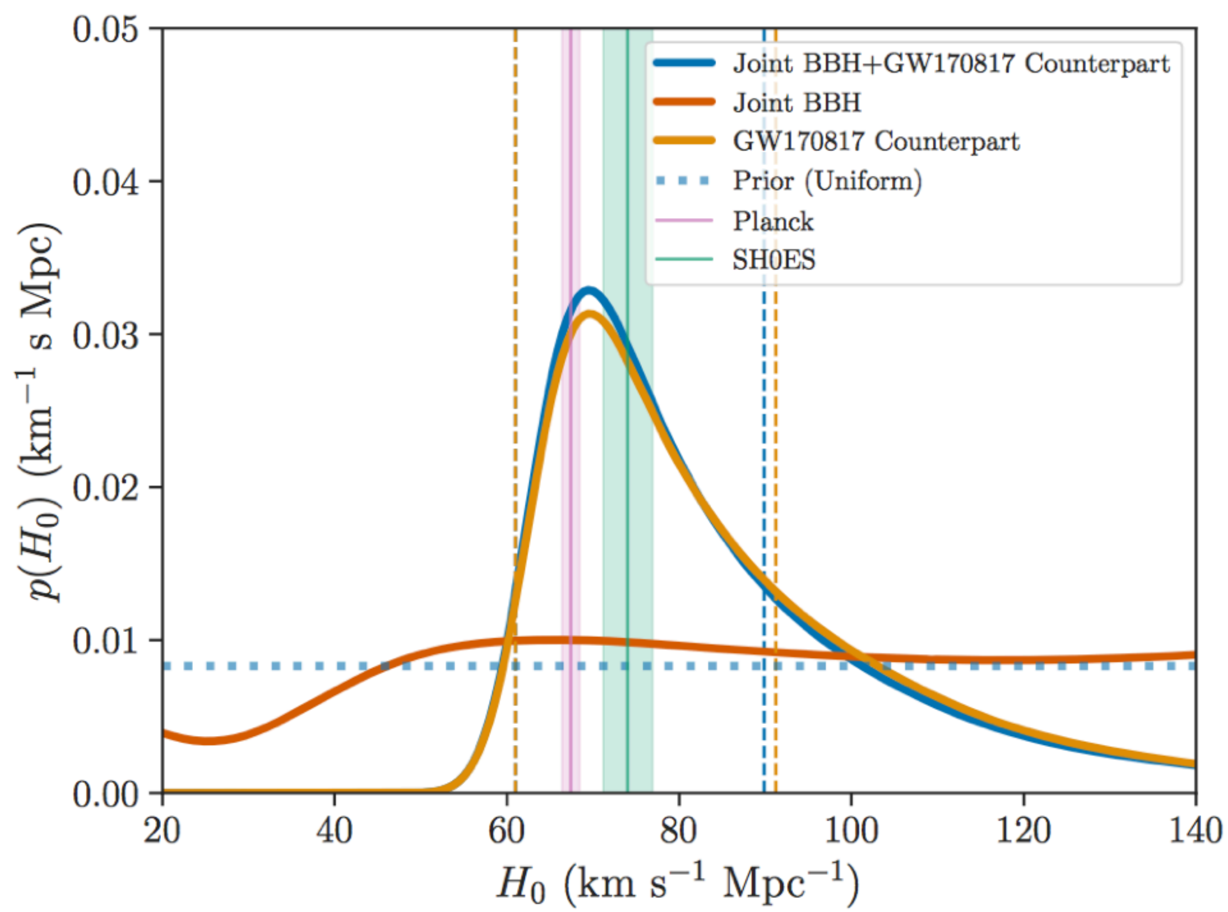
1. and 2. used for O1 and O2 events from LIGO-Virgo

Only GW170817, with z from NGC4993

$$H_0 = 69^{+17}_{-8}\ \mathrm{km/Mpc/s}$$

including 6 BBHs leads to ~4% improvement

$$H_0 = 69^{+16}_{-8}\ \mathrm{km/Mpc/s}$$



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- **For ET,** galaxy catalogues will probably will be incomplete up to redshifts observed

- Approaches 3. and 4. **use no EM data**, and hence work also for BBH (more numerous, heavier and observable to larger z). Basic idea:

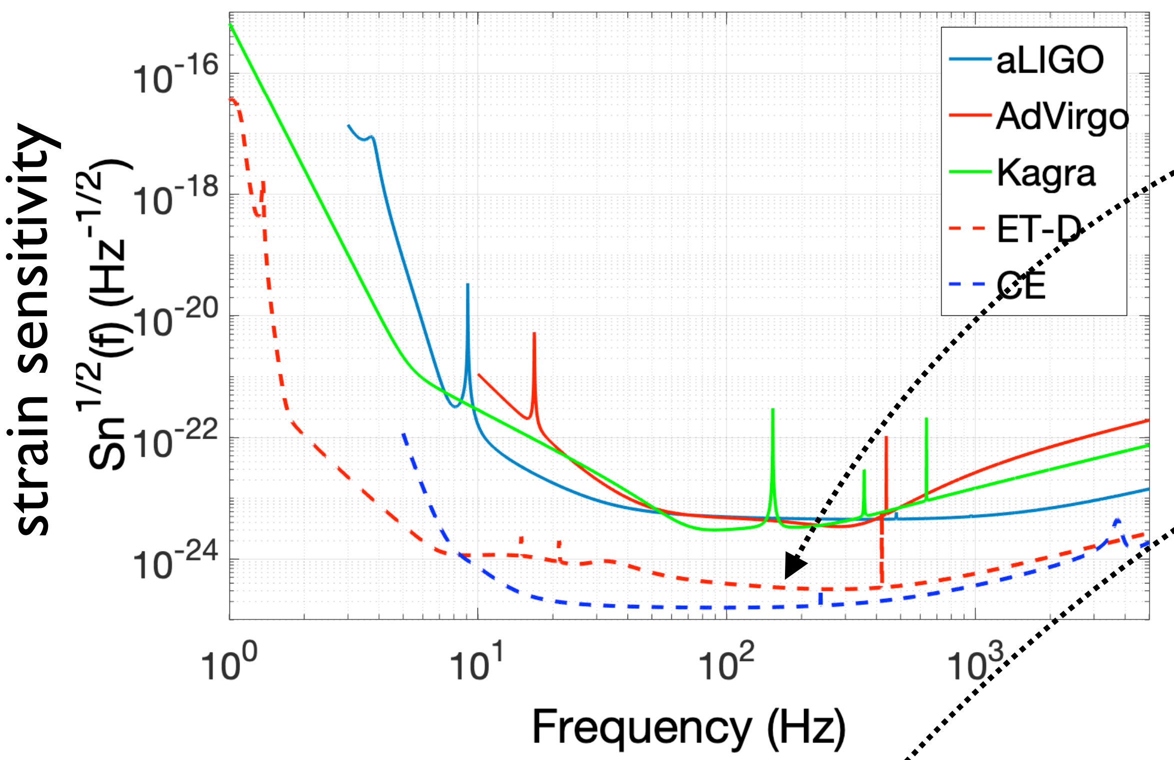
$$m_{1,2}^{\rm det} = [1 + z(d_L, H_0, \ldots)] m_{1,2}^{\rm source}$$

from knowledge of source mass (for a population or individual source), together with given observed mass can infer z-distribution.

Very roughly expect errors to scale as $\sim 1/\sqrt{N}$

ET basics

[figure from 1907.01487]



- order of magnitude more sensitive wrt 2G detectors
- wider frequency band

→ larger detection horizon

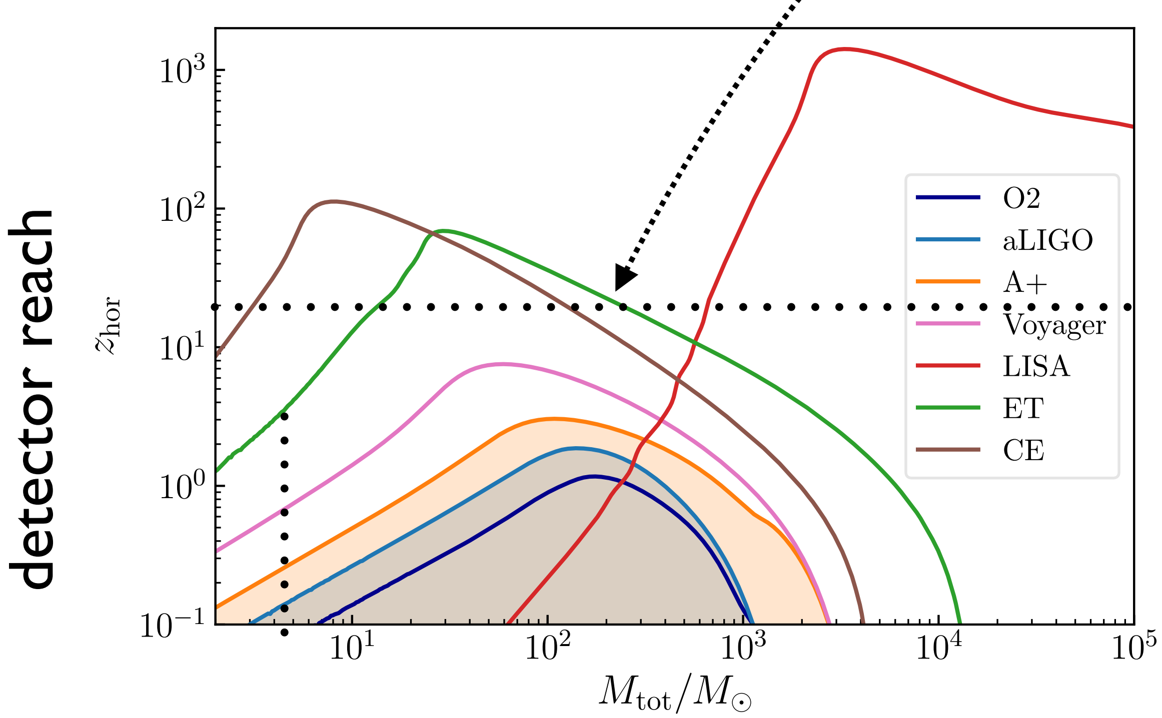
→ larger detection rates:

BBH $10^5 - 10^6/\mathrm{year}$

BNS $\sim 10^4/\mathrm{year}$ of which $\sim \mathcal{O}(10^2 - 10^3)/\mathrm{year}$ with counterparts,
depending on EM facilities operating at the time

and also NS-BH

[figure from 2006.02211]



Horizon redshift as a function of total *source frame* mass for an SNR detection threshold of rho=8. For LISA assumes 4 yrs obsv.

→ Must consider weak lensing of signals

$$\sigma_{d_L}^{\mathrm{lens}} \sim 0.05 d_L z$$

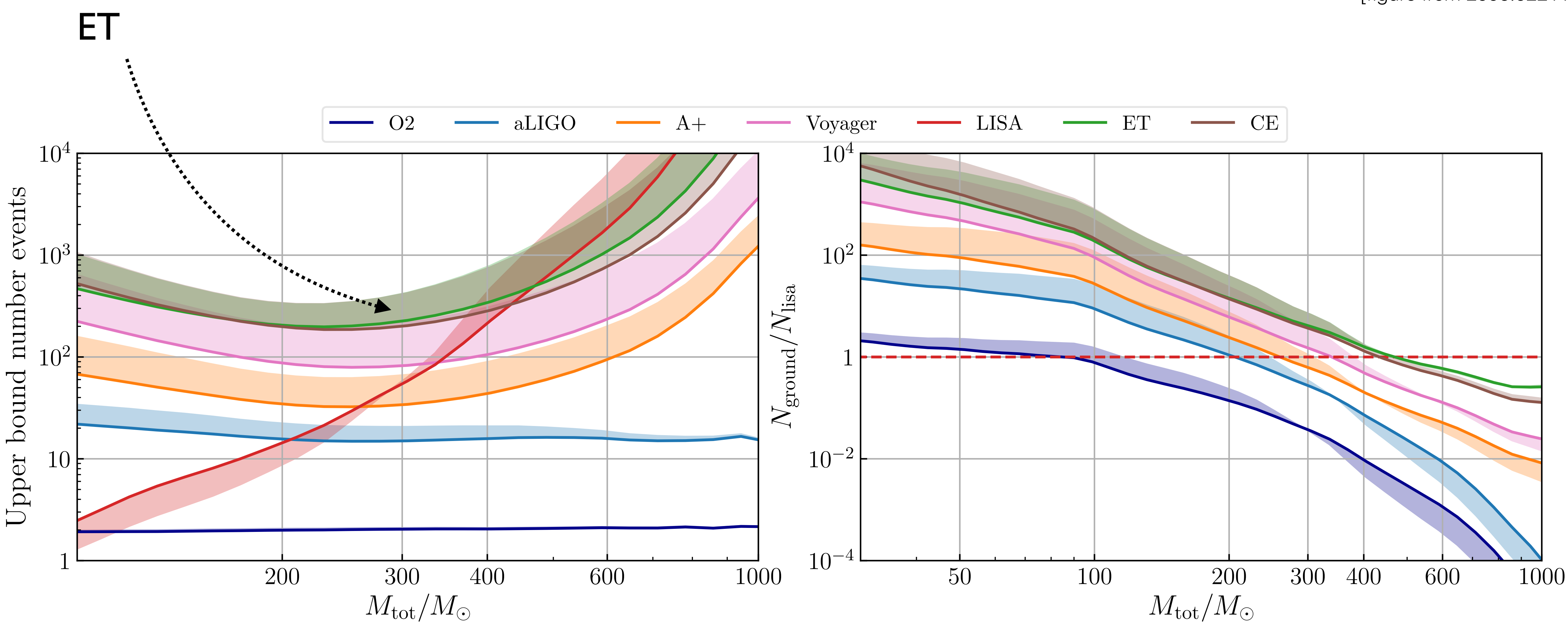
$$\sigma_{d_L}^{\mathrm{inst}} \sim \frac{2d_L}{\rho}$$

similar order of magnitude for z ~ few

ET basics

Distribution of events as a function of their total source frame mass, for an observing time of 1year (except LISA=4years)

[figure from 2006.02211]



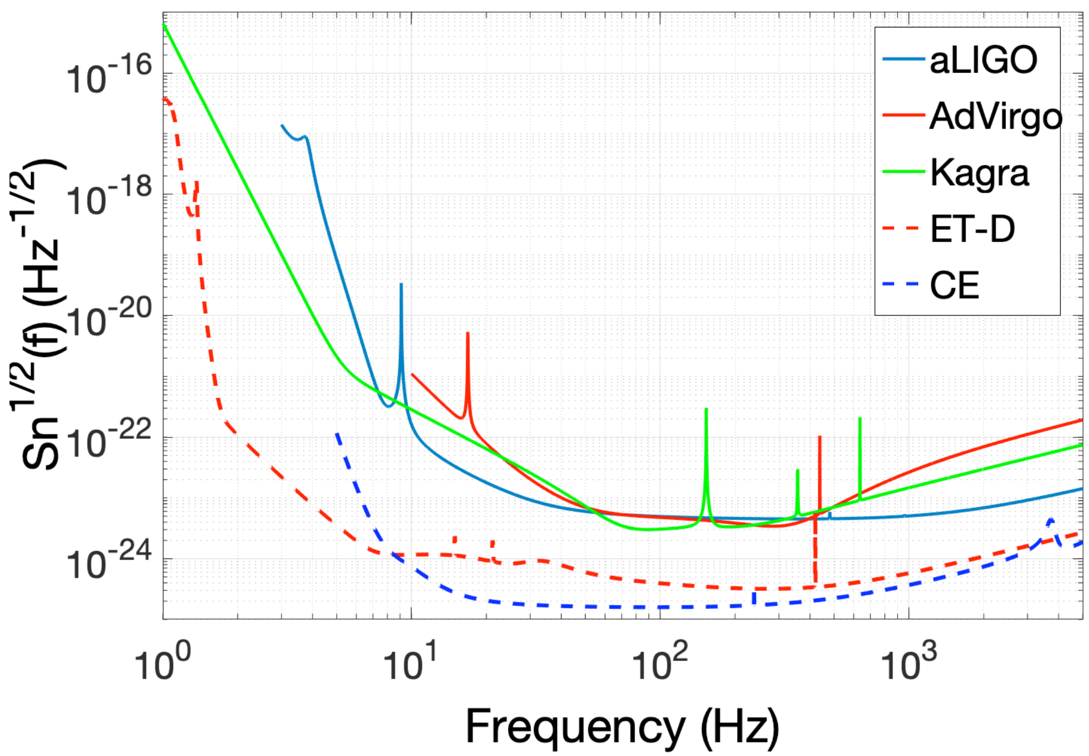
maximum number of events detected given the upper bounds from the O1 and O2 runs [bands indicate difference resulting from a redshift evolution tracking the star formation rate]

Ratio between the number of non-spinning, equal mass binaries detected by different ground-based detectors, with respect to LISA

In range Mtot < 400 Msun, ET will detect more BBH in 1 year than LISA in 4 years, and several hundred events.

ET basics

[figure from 1907.01487]



– wider frequency band

→ for a binary entering frequency band of ET at $f_{\rm low}$, time to merger

$$T \sim 10^{-3} f_{\rm low}^{-8/3} \left(\frac{c^3}{G\mathcal{M}} \right)^{5/3}$$

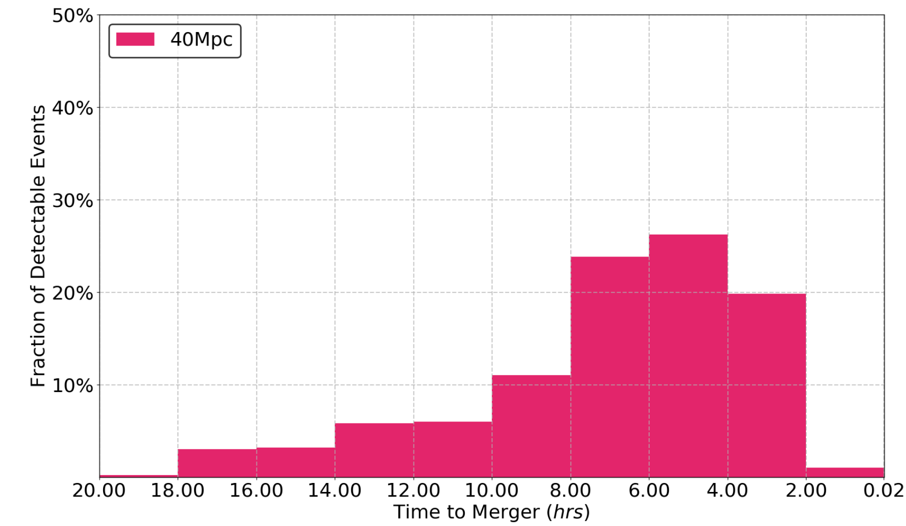
→ BNS in-band for up to ~ 5 days

- Given the merger rates for BNS, BBH and BH-NS, expect that a typical BNS signal will be overlapped by a number of BBH signals, which may merge at similar times => effect on parameter estimation? Possible biases?

- cannot neglect the rotation of the earth (need to take into account time dependence of detector response functions)

- helps in the localization of BNS. For BNS at 40Mpc with ET, 50% are localized with 90% confidence to < 2 deg squared. *[Chan et al, 2018]*

- Can help early warnings: possible that signals accumulate SNR such that a trigger is considered significant before the merger occurs -> early warning before coalescence? *[Chan et al, 2018]*



fraction of BNS events with SNR for GW detection and localization < 100 deg^2 at 90% confidence

ET: forecasts for cosmology

[Cai et al, 1608.08008]
[Belgacem et al,1907.01487]
[Ganz et al, in preparation]
[Ezquiaga et al, 2006.02211]
[You et al 2004.00036]
…

Generally proceed through **construction of a mock GW source catalogues**

– distribution of events in redshift

draw redshifts from a probability distribution $p(z) \propto \frac{dV_c}{dz}\frac{R(z)}{(1+z)}$
merger rate typically from O2 rates and populations estimates, or other models

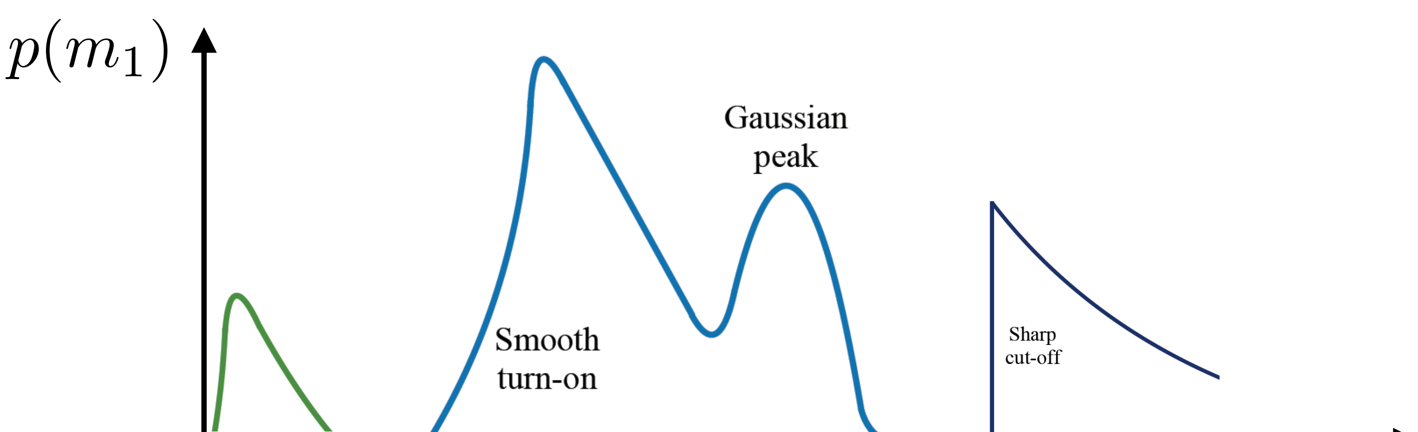
– Given fiducial values of $(H_0, \Omega_m, \ldots)$ determine $d_L(z)$

– Different assumptions made on error $\sigma_{d_L(z)}$

[assumed gaussian Fisher-Matrix approach, or analytic beyond gaussian, or using likelihoods from Bilby, or…
Include lensing error

– calculate SNR for each GW in the catalogue, if > threshold then event observable.

+ mass model, with masses drawn from a probability distribution $p(m_1, m_2)$



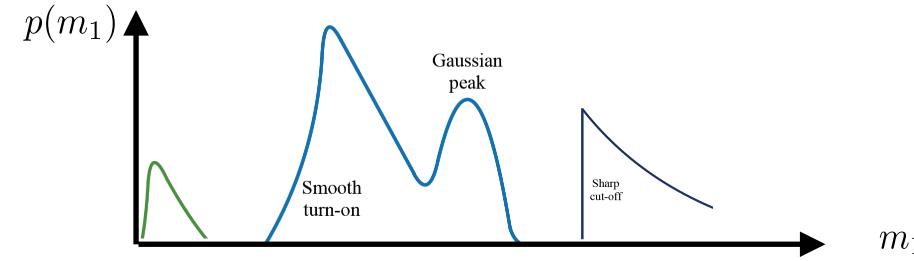
BNS-BH mass-gap

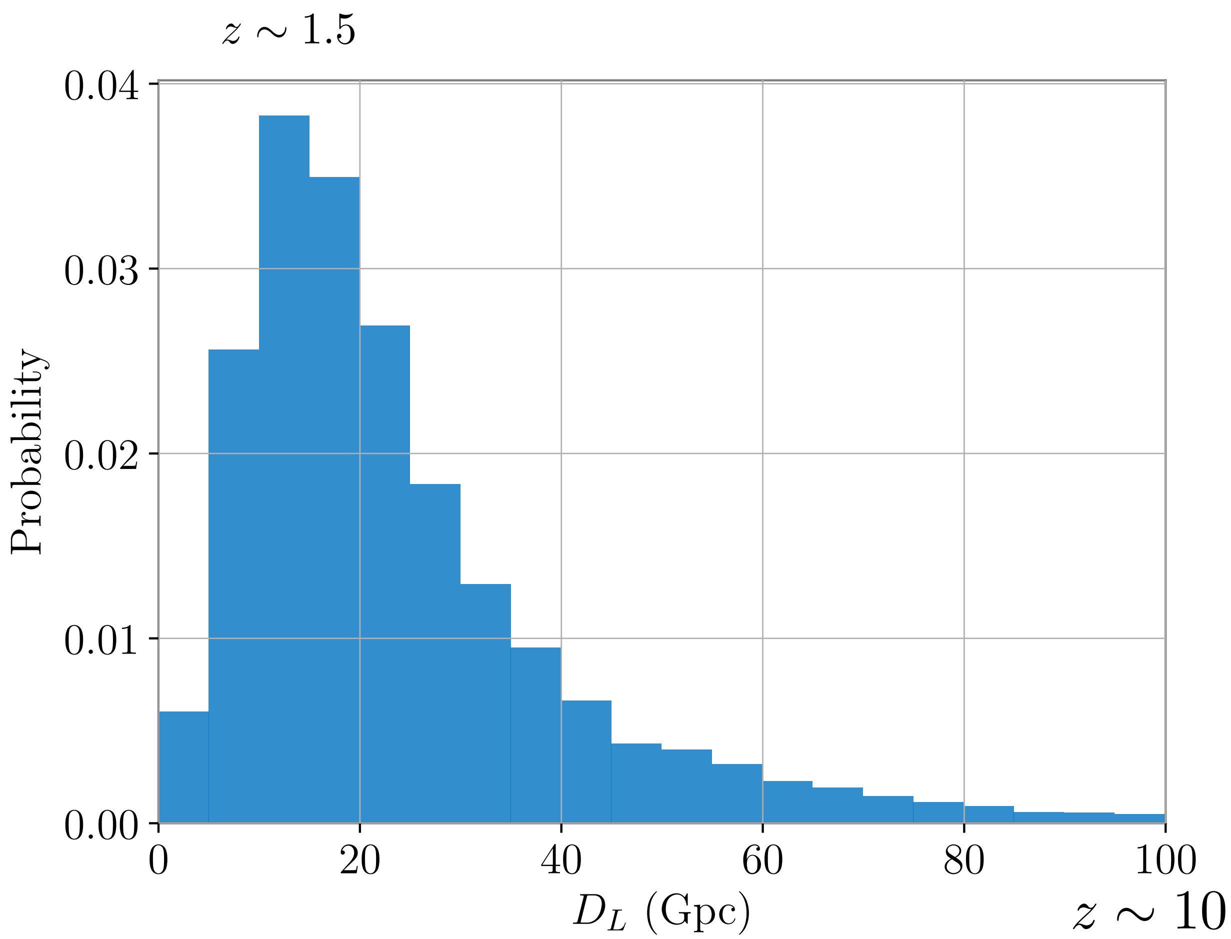
PISN-mass-gap?

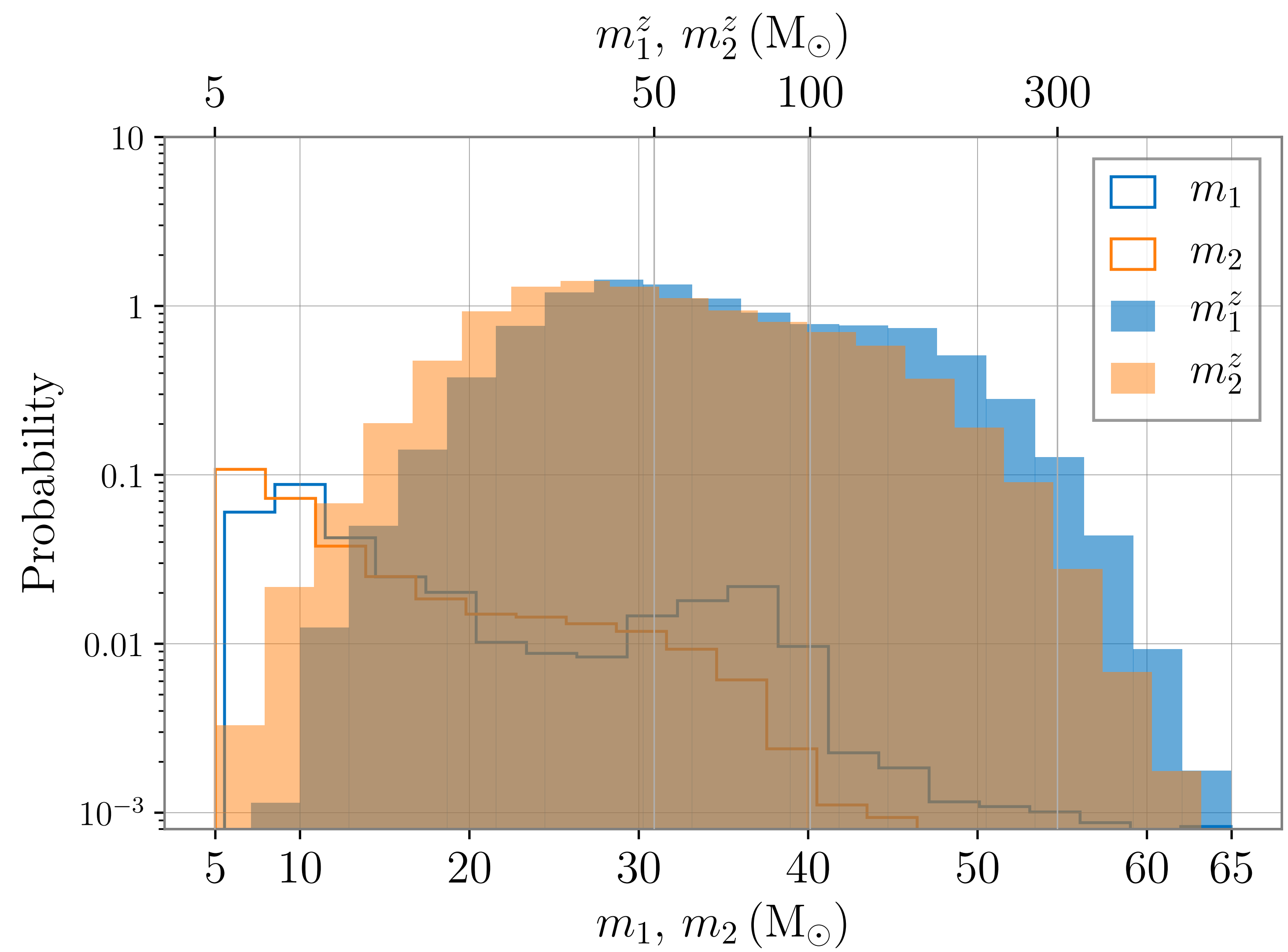
m_1

+ for BNS and/or NS-BH need criterion to determine those GW events which also observable in EM

simulated population of BBHs in ET:
calibrated on *a power-law + gaussian peak model* from GWTC-2, and BBH merger rate from LVC 2020, *Mmax=65 and Mmin=5 fixed*







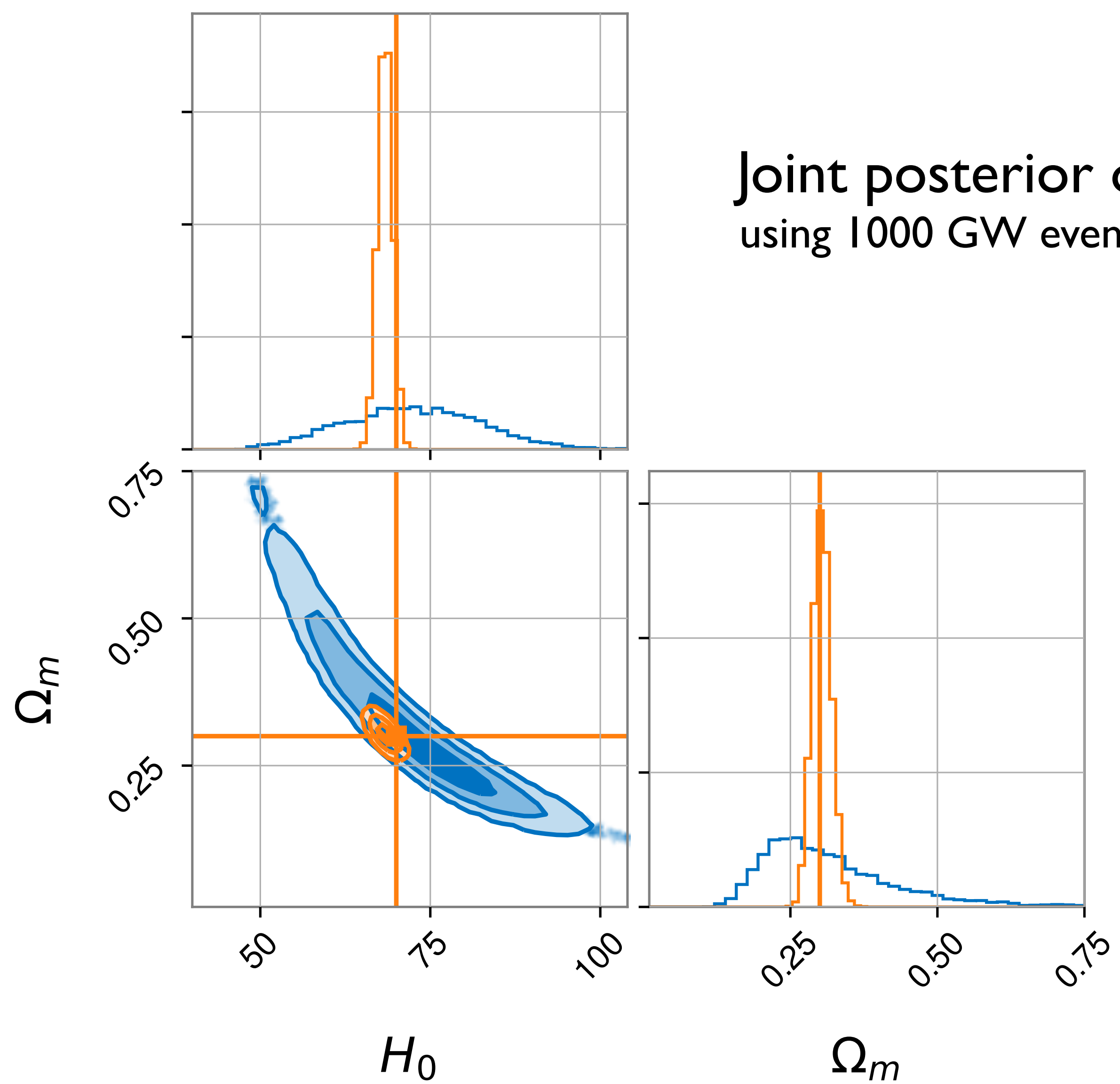
$$m^z_{1,2} = m_{1,2}\left[1 + z_{1,2}(D_L)\right] .$$

Figure 1. The distribution of luminosity distance (D_L) and black hole masses (m_1, m_2) for a simulated BBH population detectable by third-generation detectors, where the probability is normalized with the logarithm of mass.

CONSTRAINTS: simulated population of BBH in ET

[2004.00036]

- Carry out a full hierarchical Bayesian inference to compute posterior distributions on parameters describing the population, including (H_0, Ω_m)



Joint posterior on (H_0, Ω_m)
using 1000 GW events detected by ET

orange: assuming all population parameters known a priori

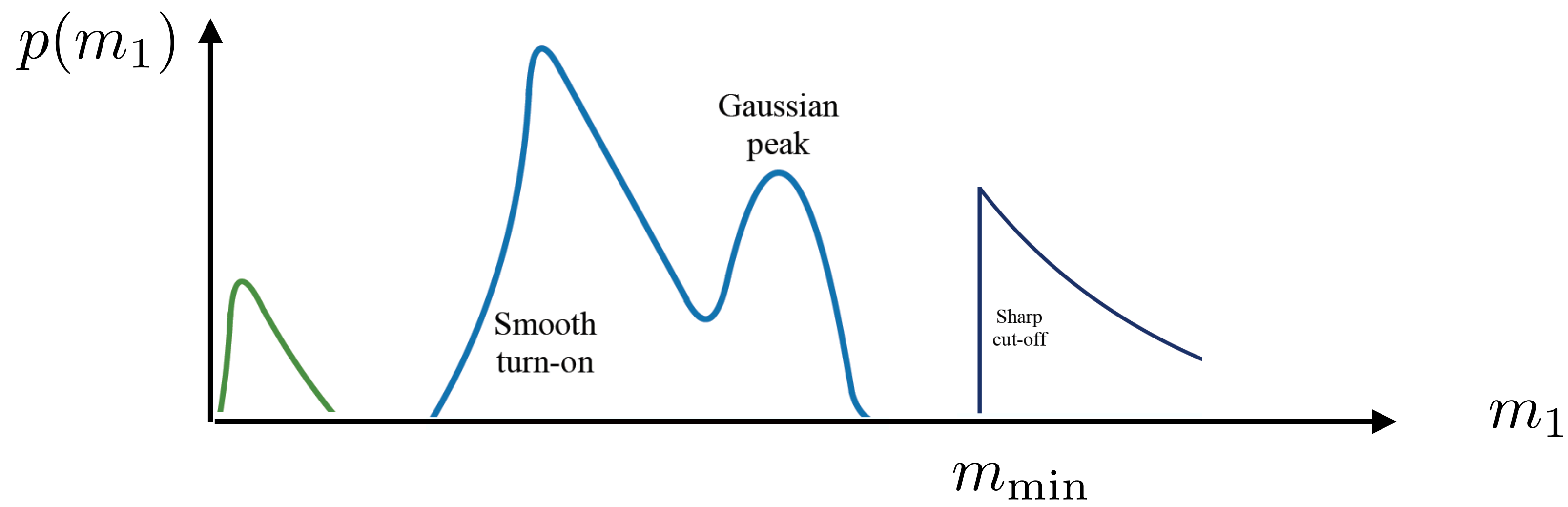
blue: marginalizing over population parameters

"1 year observation of ET will constrain the Hubble constant to a few % given our current knowledge of the black hole mass distribution, the cosmic star formation rate, and the binary merger delay time distribution. If/when our understanding of the above quantities is improved, which is plausible in the ET era, a sub-percent measurement precision is likely."

[2006.02211]:

simulated population of intermediate mass BBHs in ET:

– assume a uniform distribution of BH masses above $m_{\min}$



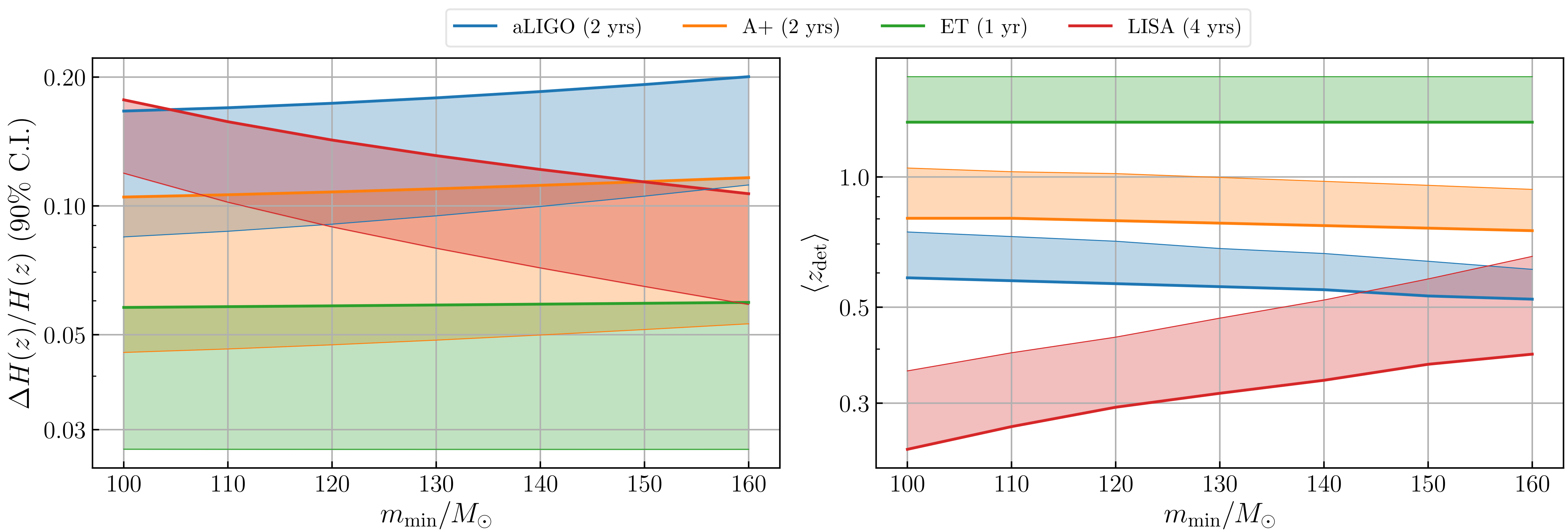


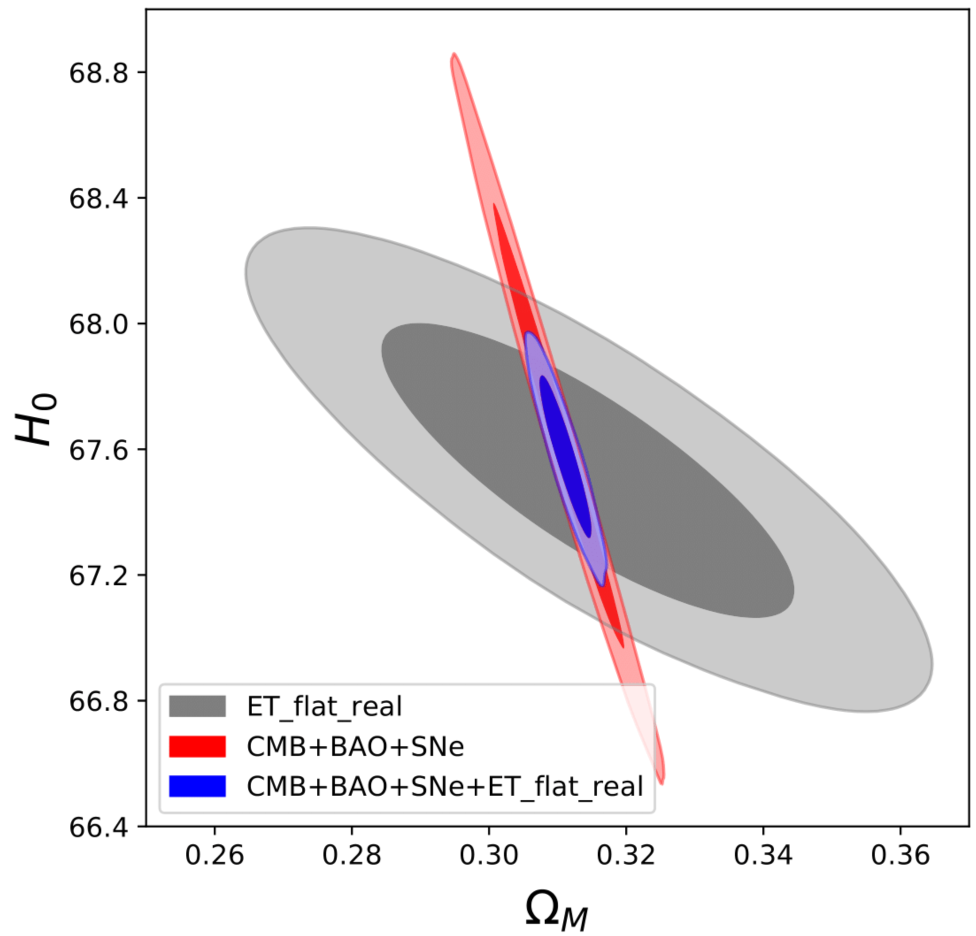
FIG. 5. (Left panel) Estimated fractional error on the Hubble parameter $\Delta H(z)/H(z)$ at 90% confidence interval (C.I.) obtained from standardizable GW sirens above the PISN gap, and (right panel) their most probable detected redshift. For both plots we assumed a uniform distribution of BBHs masses from $m_{\min}$ to $m_{\min} + 60 M_\odot$ with comoving merger rate $\mathcal{R}_c = 0.1\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$. The shaded regions represent the uncertainty in the redshift evolution of the merger rate between a constant rate (thick line) and a rate following the star formation rate (thin line)

CONSTRAINTS: simulated population of BNS with EM counterparts in ET:

[Belgacem et al, 1907.01487]

For LambdaCDM

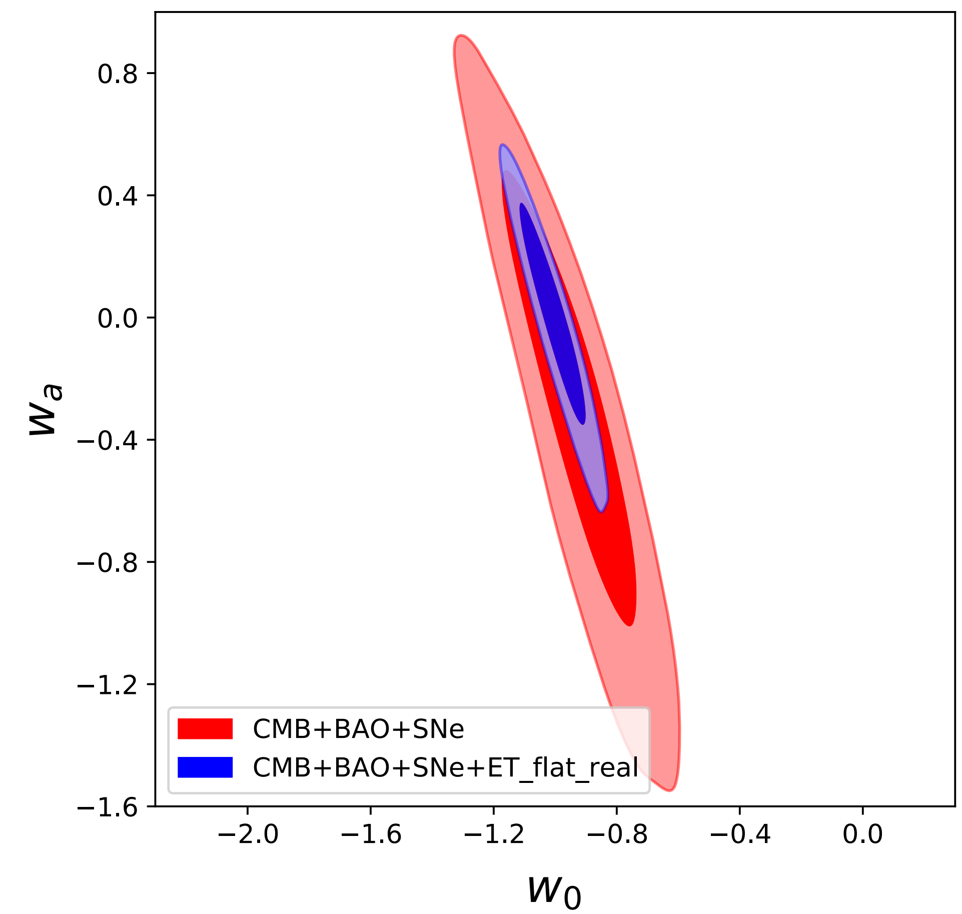
	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
ET_flat_real	0.42 %	6.17 %
CMB+BAO+SNe	0.72 %	2.11 %
CMB+BAO+SNe+ET_flat_real	0.26 %	0.82 %



Allowing evolving Dark Energy

$$w = w_0 + w_a \frac{z}{1+z}$$

(w_0, w_a)extension	Δw_0	Δw_a
CMB+BAO+SNe	0.140	0.483
CMB+BAO+SNe+ET	0.058	0.224



Assuming all population parameters are known a priori

[Cai et al, 1608.08008]

simulated population of BNS and BH-NS with EM counterparts in ET:

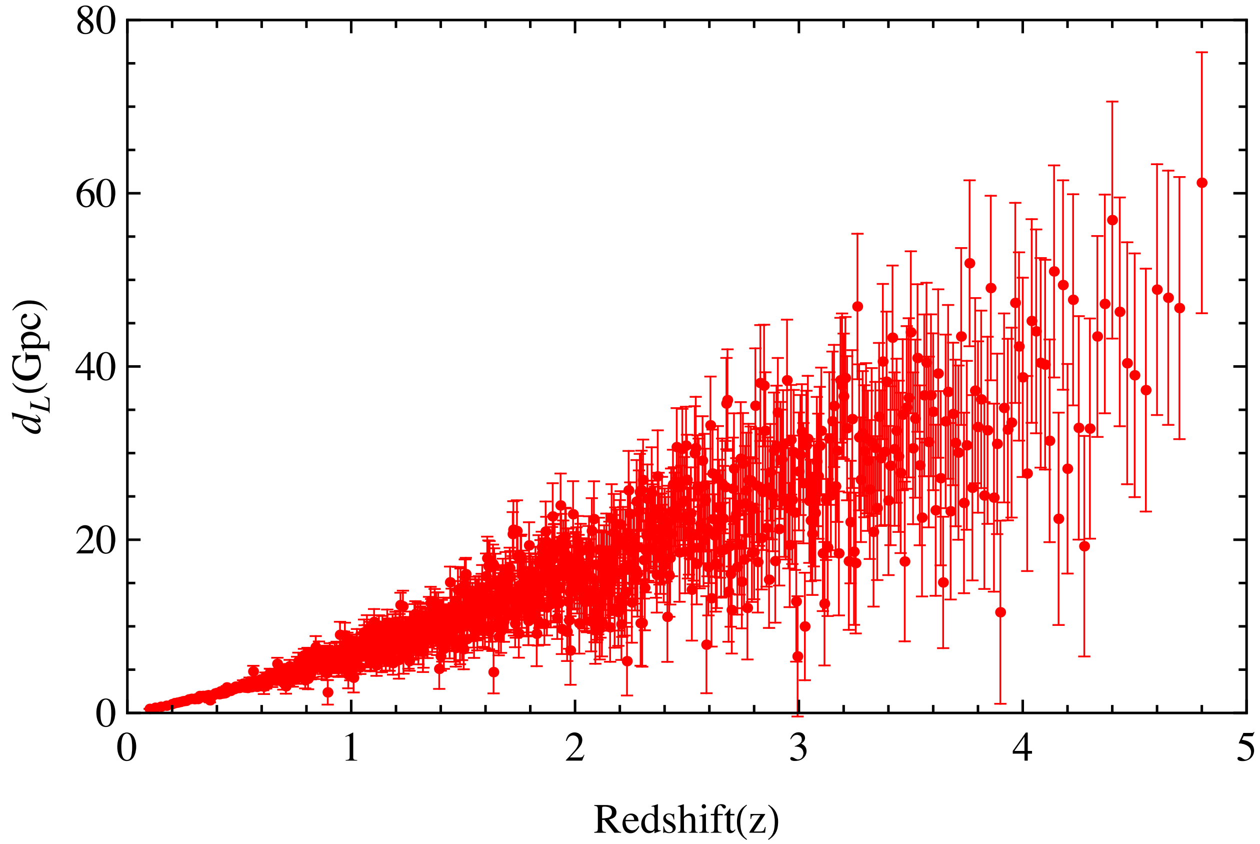


FIG. 1: An example catalogue with 1000 observed events of redshift, luminosity distance, and the error of the luminosity distances from the fiducial model.

- NS mass distribution uniform in interval $[1,2]\ M_\odot$
- BH mass distribution uniform in interval $[3,10]\ M_\odot$

Predictions more optimistic, as include also NS-BH population
(i) these can also emit a counterpart => more events
(ii) louder signals

CONSTRAINTS: simulated population of BNS and BH-NS with EM counterparts in ET:

[Cai et al, 1608.08008]

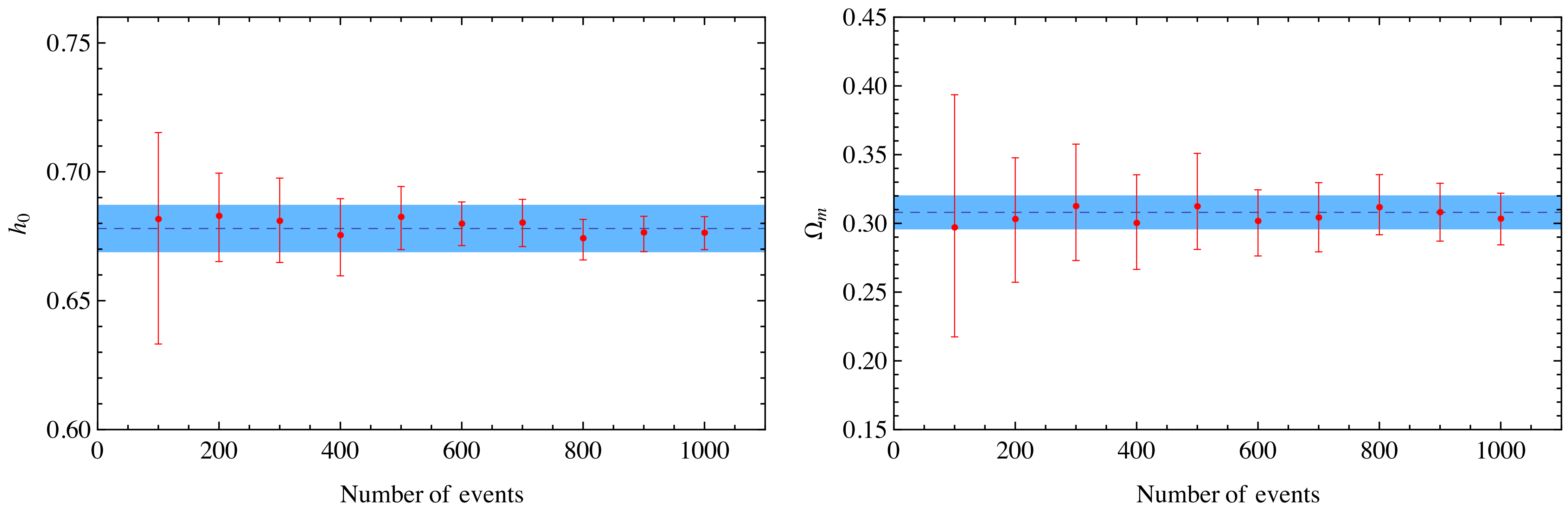


FIG. 2: Sixty-eight percent confidence level (C.L.) (red line) and the best fit (red dot) for H_0 (left) and Ω_m (right) for a variable number of GW events with EM counterpart. The fiducial model is shown as the dashed line. For a comparison, the blue shaded area is the 68% C.L. constrained by the *Planck* temperature data combined with *Planck* lensing in the current *Planck* 2015 results.

with ~600 events get an accuracy on H0 comparable to Planck

Conclusion and outlook

• With ET, different ways to extract information on H0 and dark energy through BBH, BNS populations. **Cosmology hand in hand with astrophysics**

• Expect important impact on measurements of cosmological parameters, certainly resolving the Hubble tension

• Number of effects to consider: overlapping sources and parameter estimation; higher order modes; precessing spins; waveform accuracy ? etc

• Other methods: redshift from tidal deformation and post-merger signal *[Messenger et al]*

– if a NS mergers with a compact object and is tidally deformed, extra phase in waveform which depends on the source mass through the tidal deformation parameter. Provided an equation of state is know, and if the tidal deformation parameters are accurately measured -> source mass and hence z. (Prediction, in Lambda CDM of inference on H0 of ~7% with O(10000) events)

• ET can also constrain *modified gravity theories*, particularly those in which the *propagation* of GWs is affected.

$$h_A \propto \frac{1}{d_L^{\mathrm{GW}}}$$

$$d^{\mathrm{GW}}(z) = d_{\mathrm{EM}}(z) \exp\left[\int_0^z \frac{\alpha_M(z)}{1+z} dz\right]$$