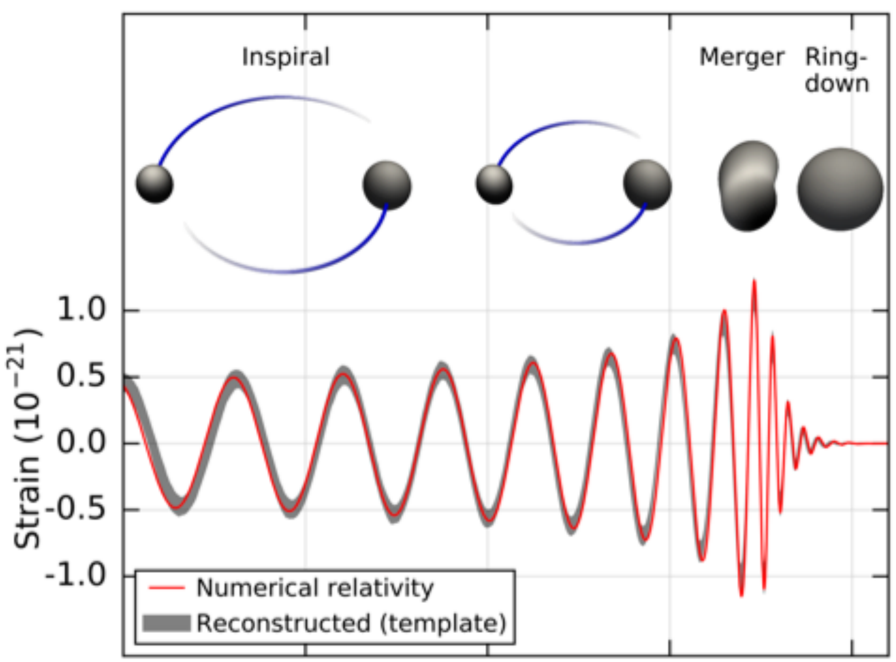
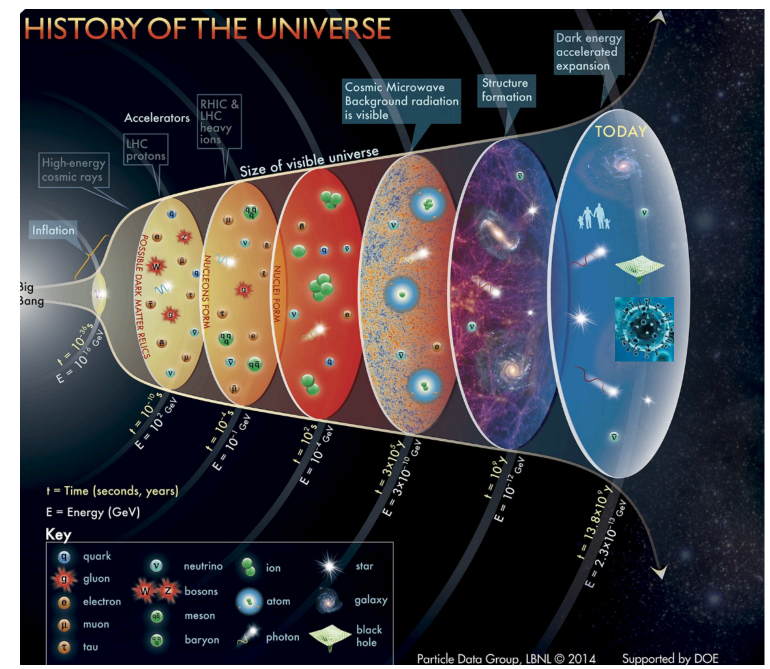
Constraints on cosmology & modified gravity from binary black holes

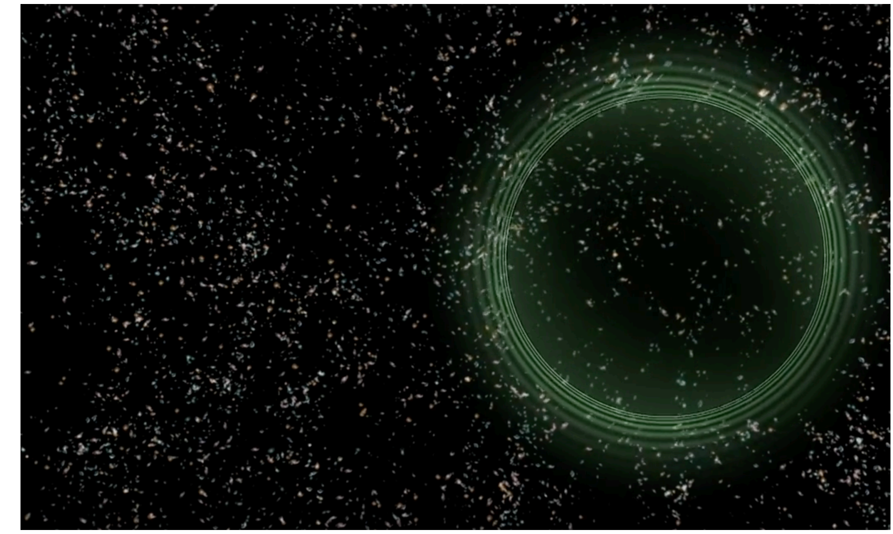




Danièle Steer, K.Leyde, S.Mastrogiovanni, E.Chassande-Mottin, K.Karathanasis

[arXiv: 2202.00025, arXiv: 2103.14663]

Gravitational waves and cosmology



late-time universe

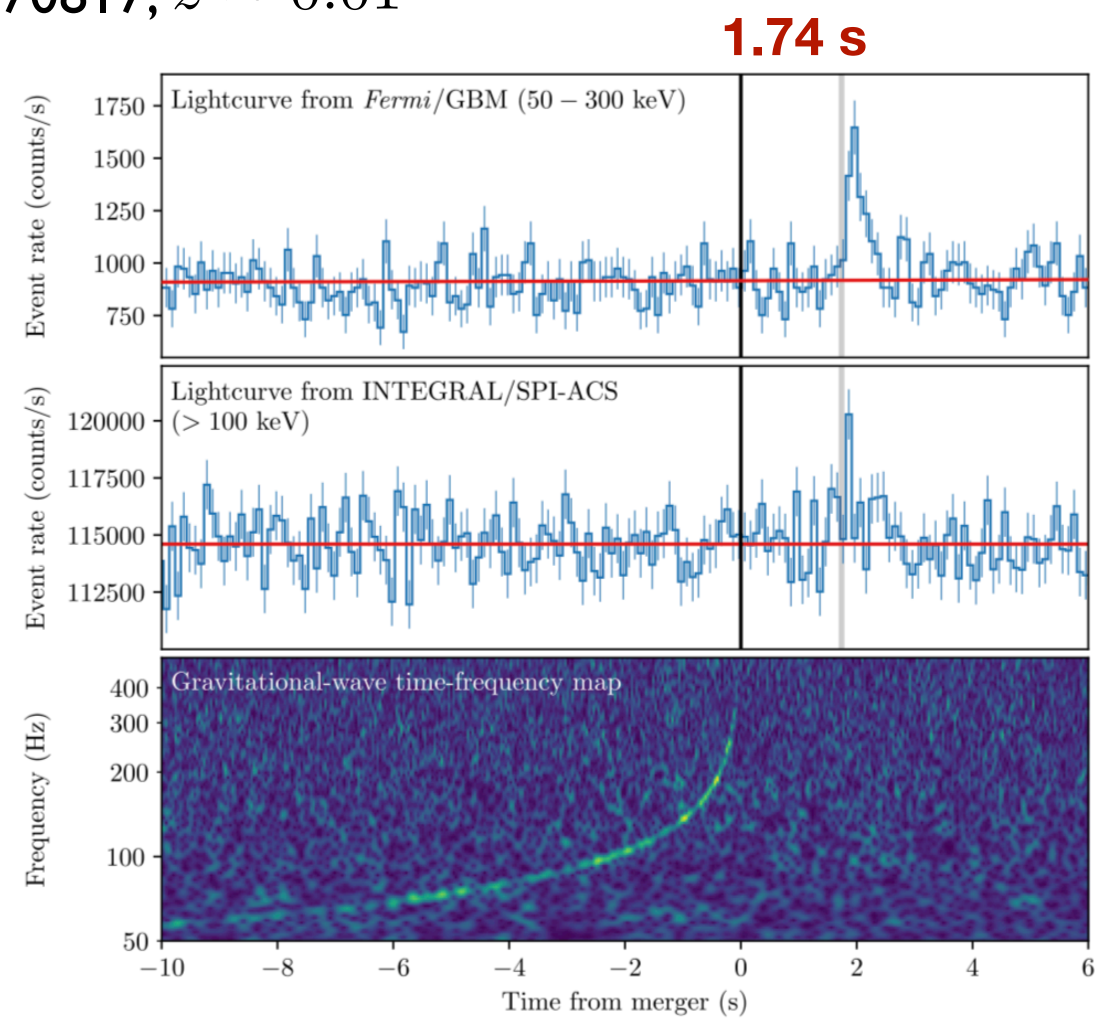
↕

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 (eg. through modified GW propagation)
– astrophysics; eg BH populations, PISN mass gap?

BNS-GW170817, $z \sim 0.01$

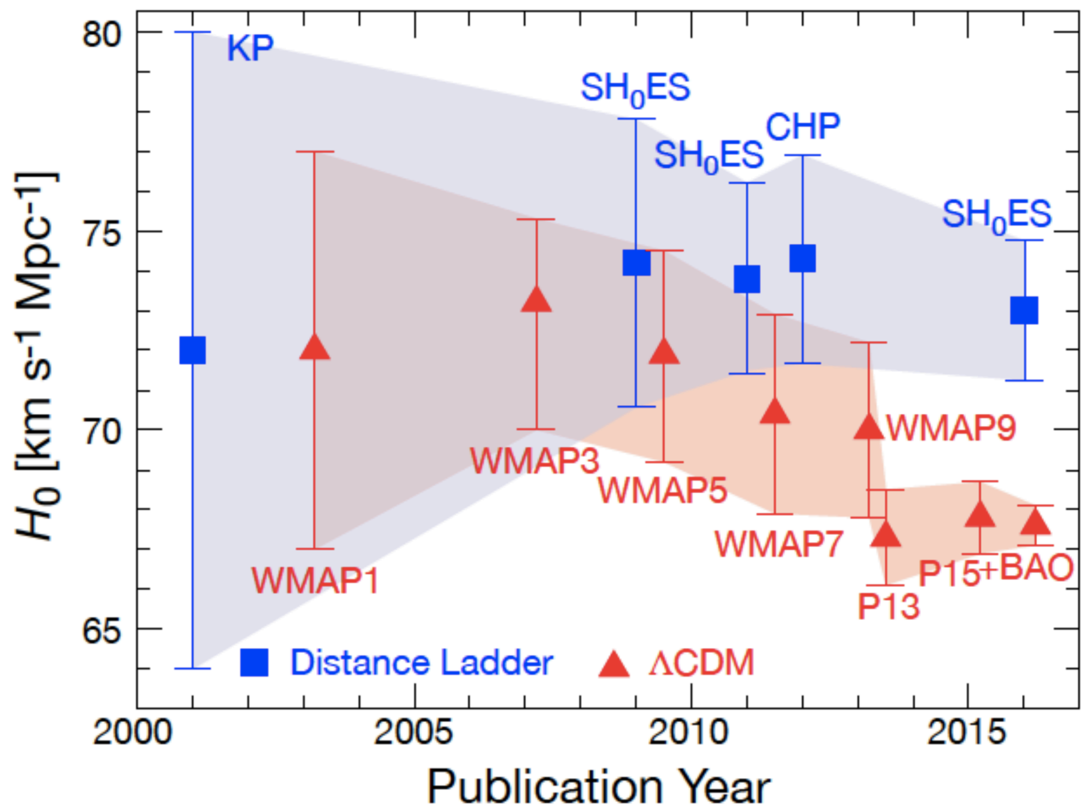


B. P. Abbott +, APJL, 848:L13 (2017)

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

Hubble constant?

[W.Freedman, 1706.02739]



• Blue: SNIa nearby universe + calibration based on Cepheid distance scale: distance ladder.

$$H_0 = 73.04 \pm 1.04\ \mathrm{km/s/Mpc}$$

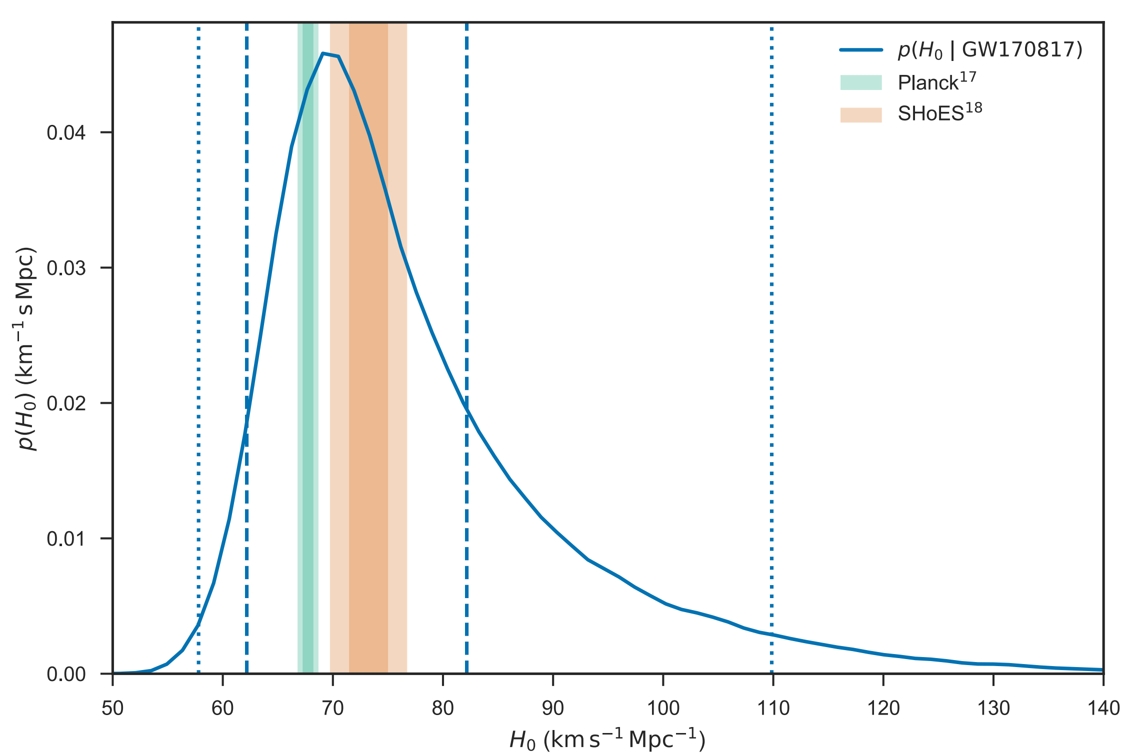
[2112.04510, SH0ES and Pantheon+ collaborations, Reiss et al]

• Red: from early universe CMB physics, assumes ΛCDM

$$H_0 = 67.36 \pm 0.54\ \mathrm{km/s/Mpc}$$

[2018 Planck collaboration]

• 4-sigma tension between measurements that calculate the sound horizon at decoupling (+assumption.ΛCDM) and those that do not.



First measurement of H0
using GW170817+counterpart:

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

[1710.05835]

$$v_H = H_0 \times d$$

Gravitational waves and cosmology

late-time universe

Observations to date (by LVK): 90 events
*2 BNS, **83 BBH**, 5 NSBH or BBH*

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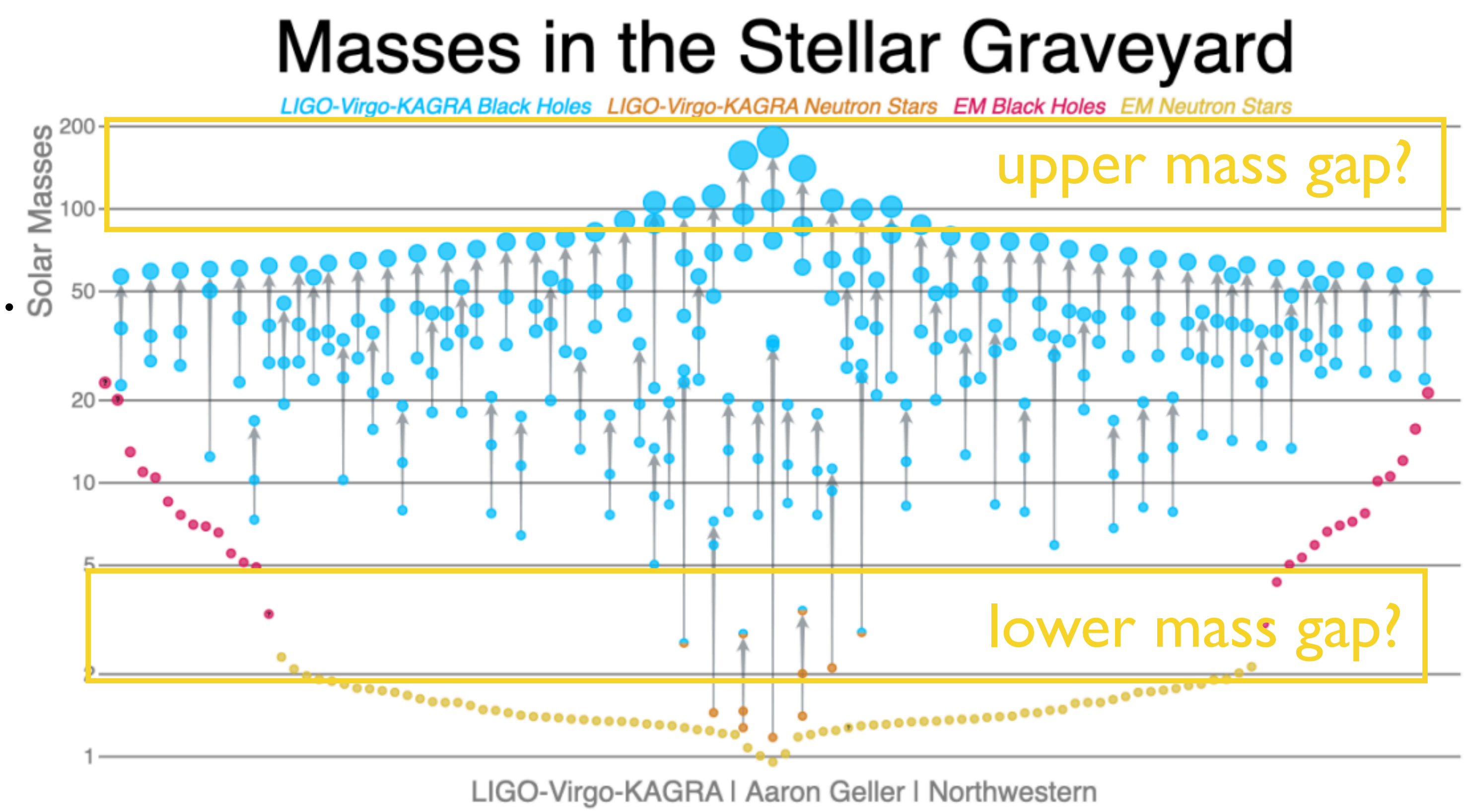
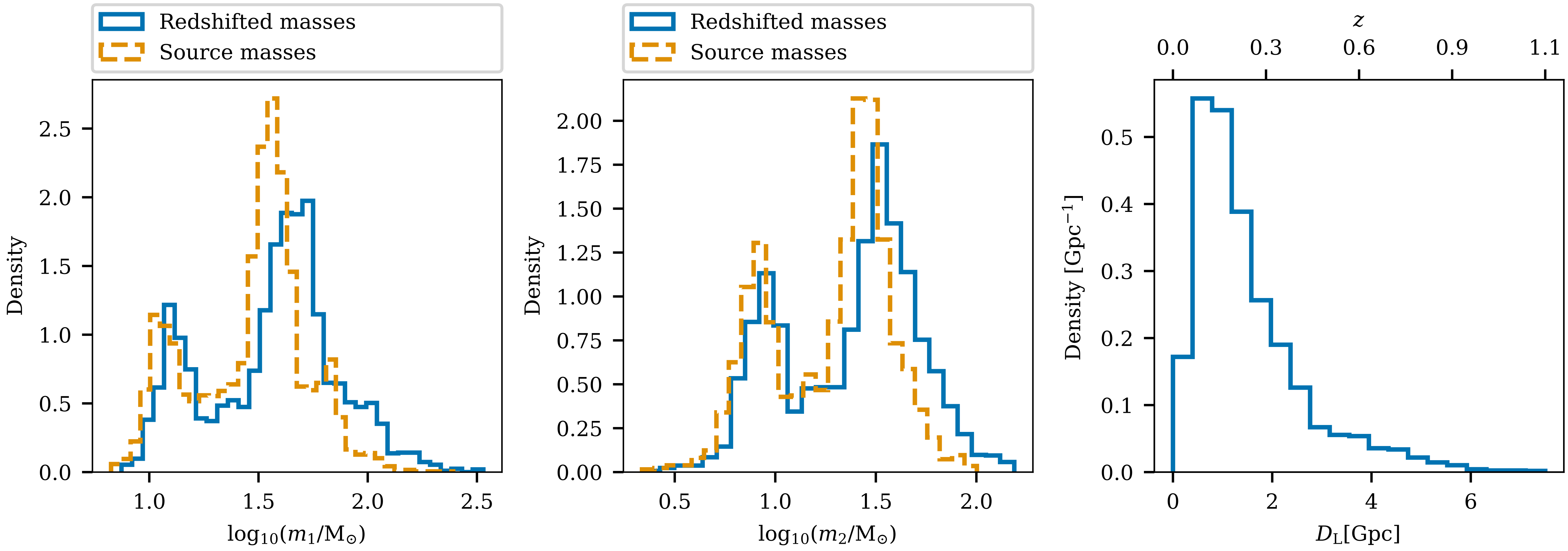


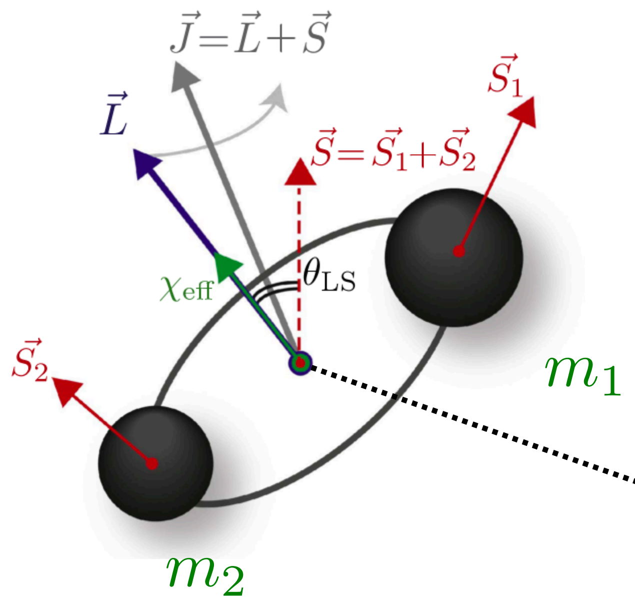
– Expansion rate $H(z)$
– H_0, Hubble constant
– Ω_m
– beyond ΛCDM
dark energy $w(z)$ and dark matter
– modified gravity (e.g. modified GW propagation)
– astrophysics + cosmo: BH populations, mass gaps?
– primordial BH populations ?

– Fixing Planck cosmology: mass and distance distribution of the 42 loudest BBH events (SNR>11)



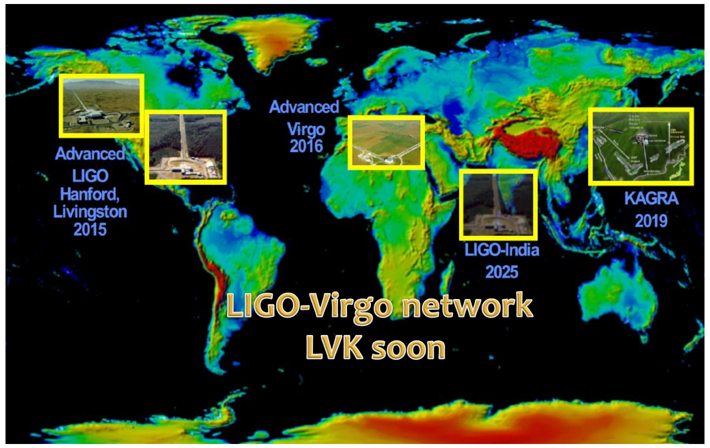
[2111.03604]

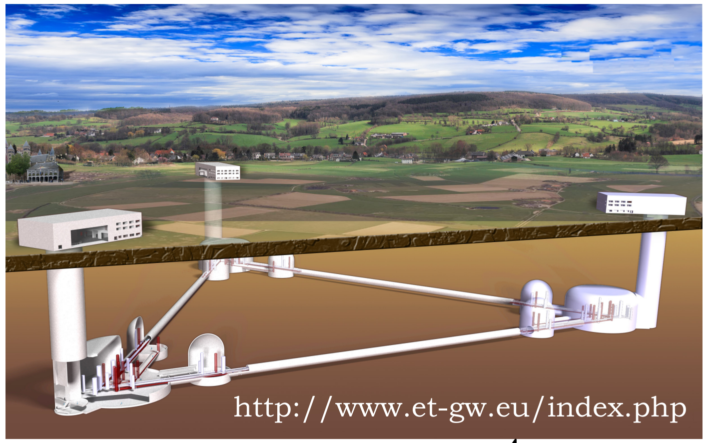
Late time universe with BBHs



$$d \sim \frac{c\,z}{H_0}$$

$10\,\mathrm{Hz} < f < 5\,\mathrm{kHz}$





$1\,\mathrm{Hz} < f < 10^4\,\mathrm{Hz}$

- ***Merger frequency*** (Assuming merger at ISCO, point particles, quadrupole..)

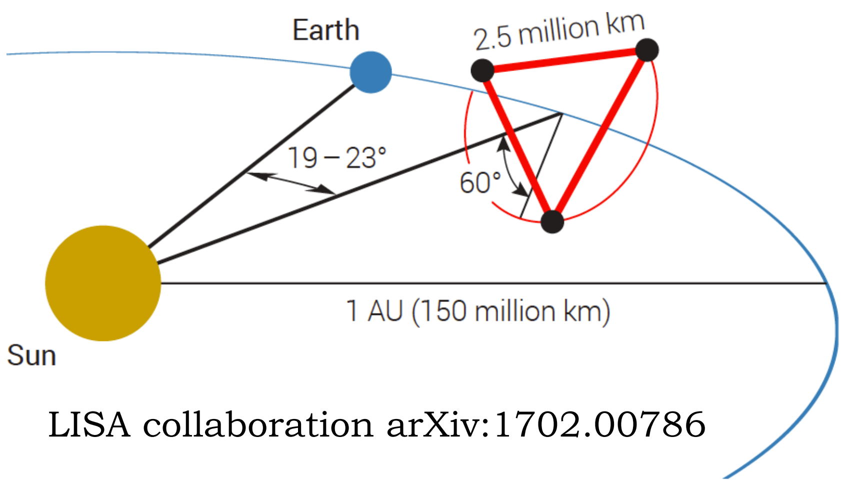
$$\boxed{f_{\rm merger} = \frac{1}{6^{3/2}\pi}\left(\frac{c^3}{GM}\right)}$$

M=total mass

- ***Amplitude/distance***

$$\boxed{h \sim \frac{4c}{d_L}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3}(\pi f)^{2/3}}$$

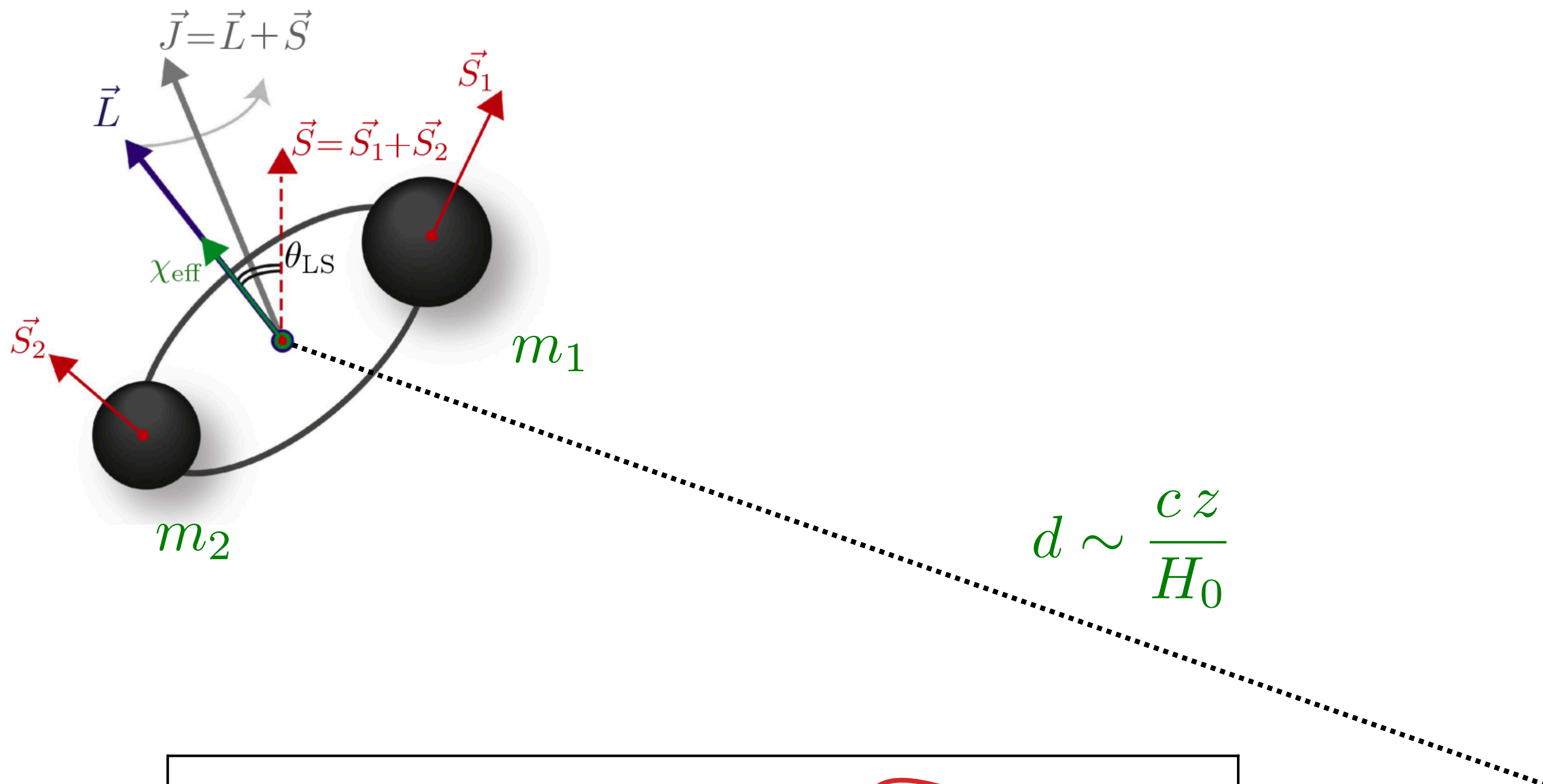
Chirp mass

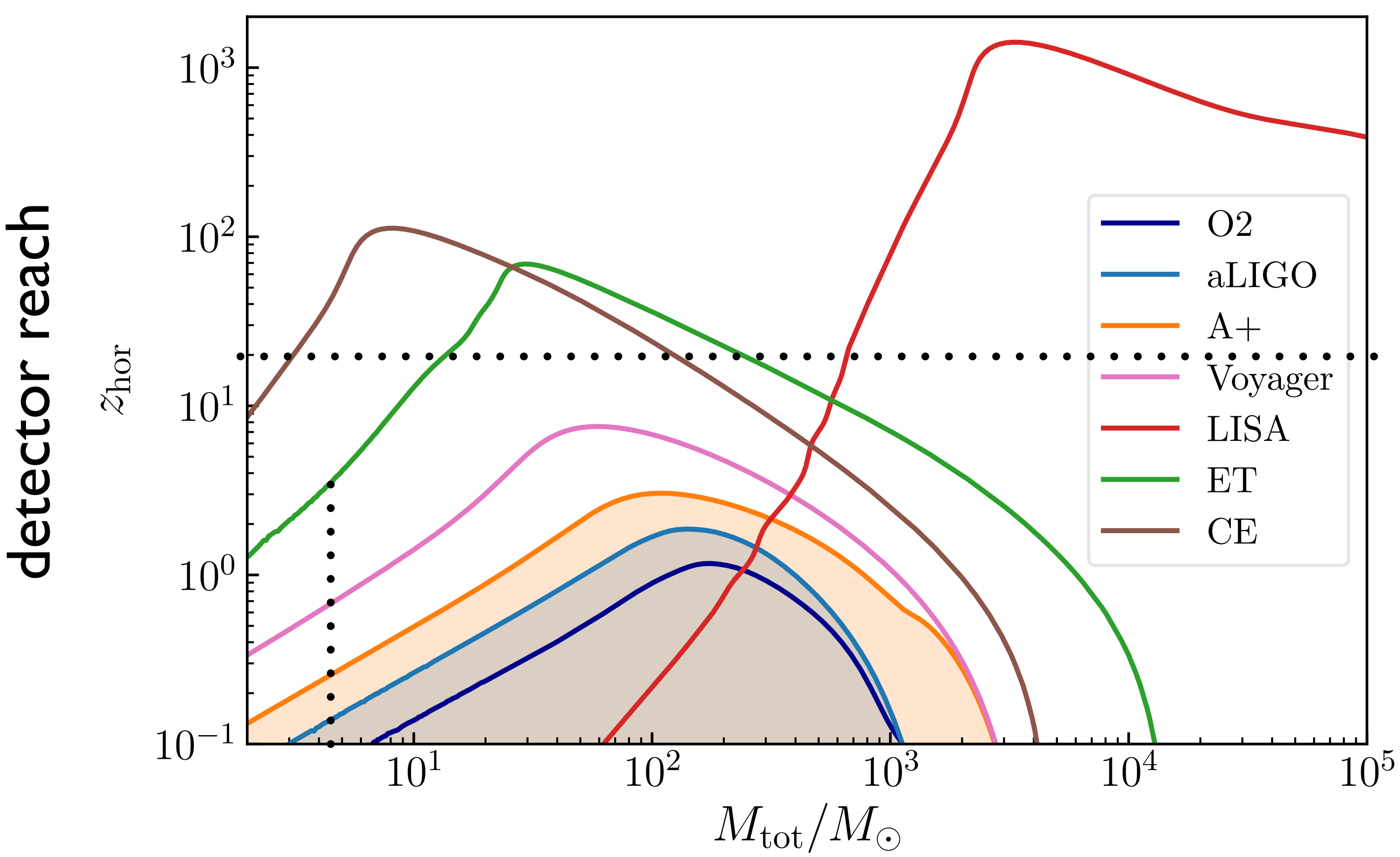


LISA collaboration arXiv:1702.00786

$10^{-4}\,\mathrm{Hz} < f < 1\,\mathrm{Hz}$

Late time universe with BBHs

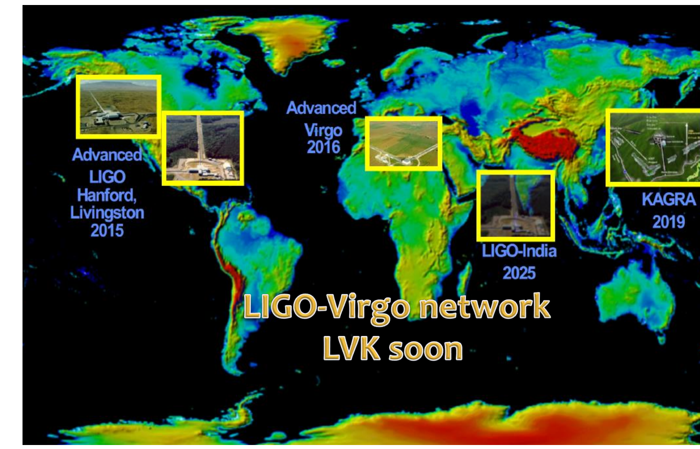


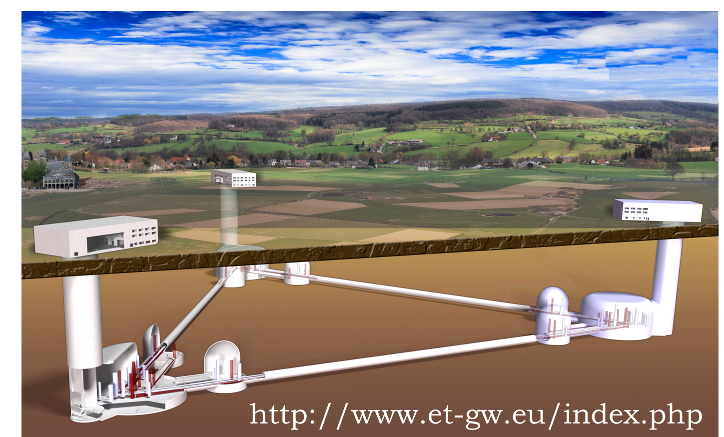


Horizon redshift as a function of total *source frame* mass for an SNR detection threshold of rho=8. For LISA assumes 4 yrs obs.

[figure from 2006.02211]

$10\,\mathrm{Hz} < f < 5\,\mathrm{kHz}$





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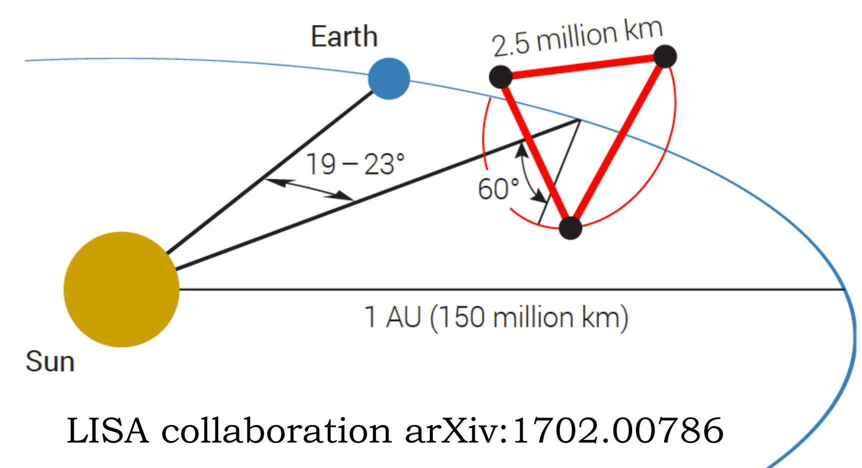

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Very early universe
$t \gtrsim t_{Pl}$

Stochastic background
of GWs of cosmological origin

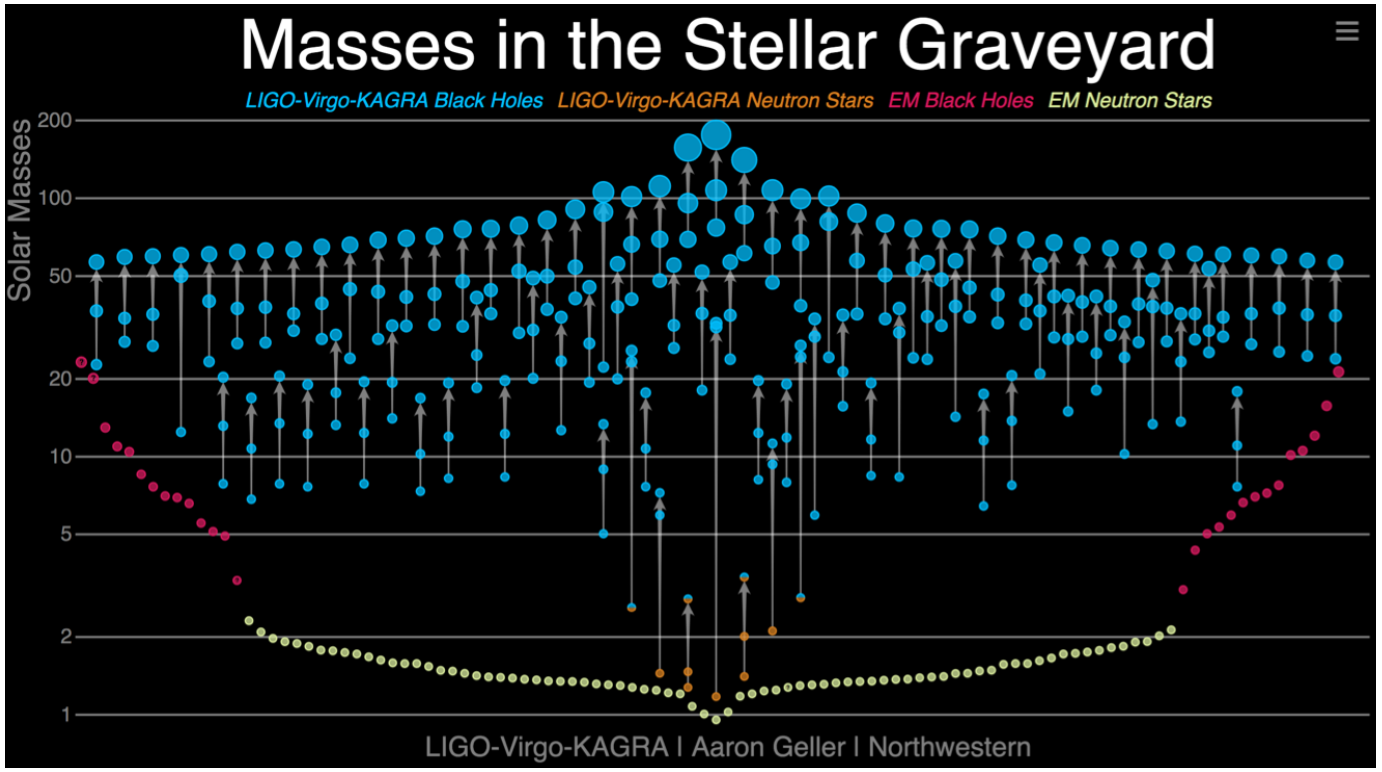
– quantum processes during inflation
– primordial black holes
– Phase transitions in Early universe
– topological defects, eg cosmic strings
– …..

More speculative. Early universe sources beyond standard model of particle physics!

[LIGO-Virgo 2101.12130] $\Omega_{\mathrm{GW}} \leq 5.8 \times 10^{-9}$
at $f \sim 25\mathrm{Hz}$

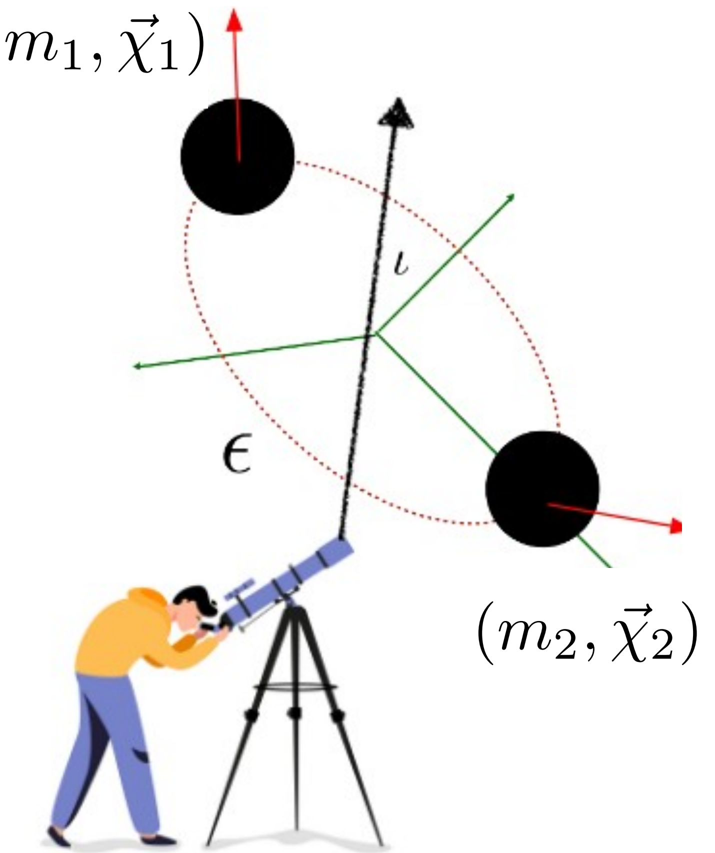
1) Assume General Relativity: constraints on **cosmology with BBH**

2) Turn on modifications to GR: constraints on **cosmology & modified gravity with BBHs**



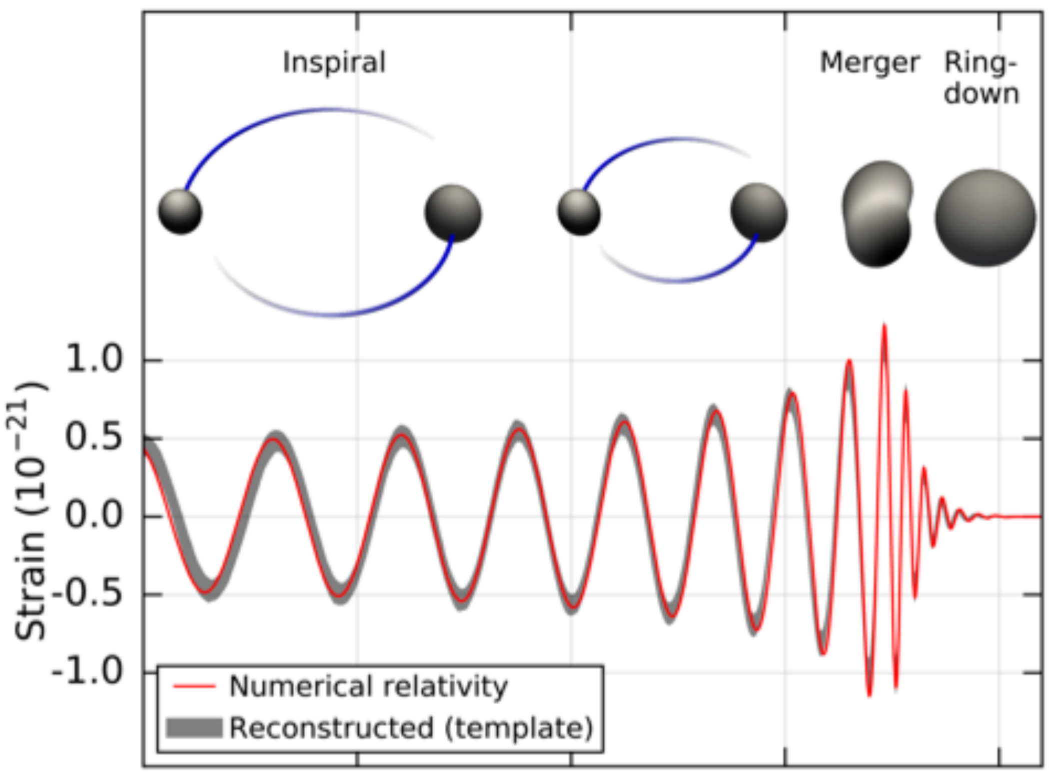
[2111.03606]

Cosmological parameters with binaries



- 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



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

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

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

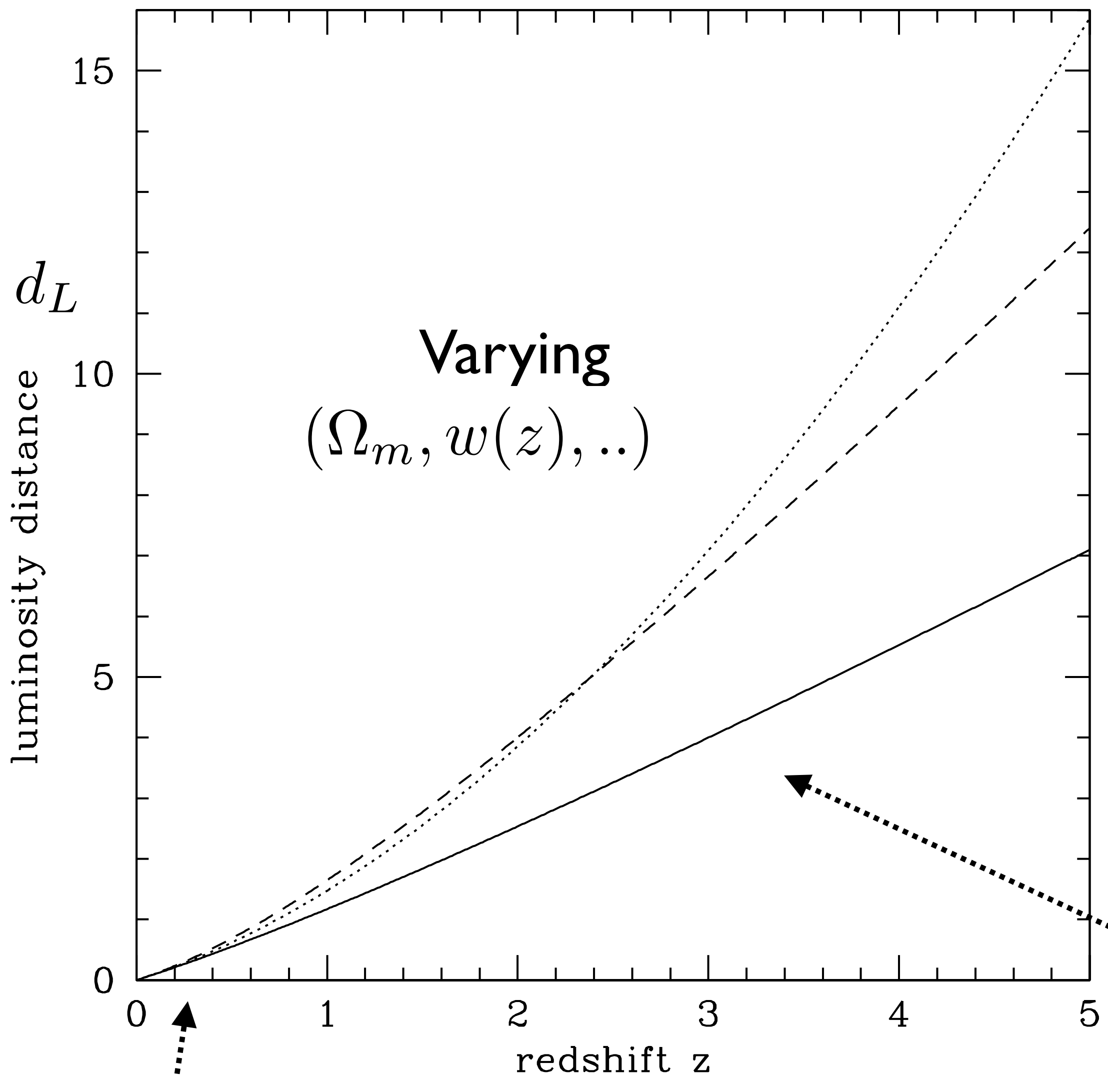
$$\mathcal{M}_z = (1+z)\mathcal{M}$$

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

In general relativity, allowing for possible dark energy:

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

Cosmological parameters with binaries



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

- GW observations determine d_L $\qquad \sigma_{d_L}^{\rm inst} \sim \frac{2d_L}{\rho}$

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

For larger z (ET, LISA, CE..), 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): $d_L = \frac{cz}{H_0}$

$$cz = H_0\, D_L$$

$$\frac{\Delta H_0}{H_0} \sim \frac{\Delta z}{z} + \frac{\Delta D_L}{D_L}$$

dominant quadrupole mode: degeneracy between distance and inclination gives *large*, ~20%-40% errors on luminosity distance.

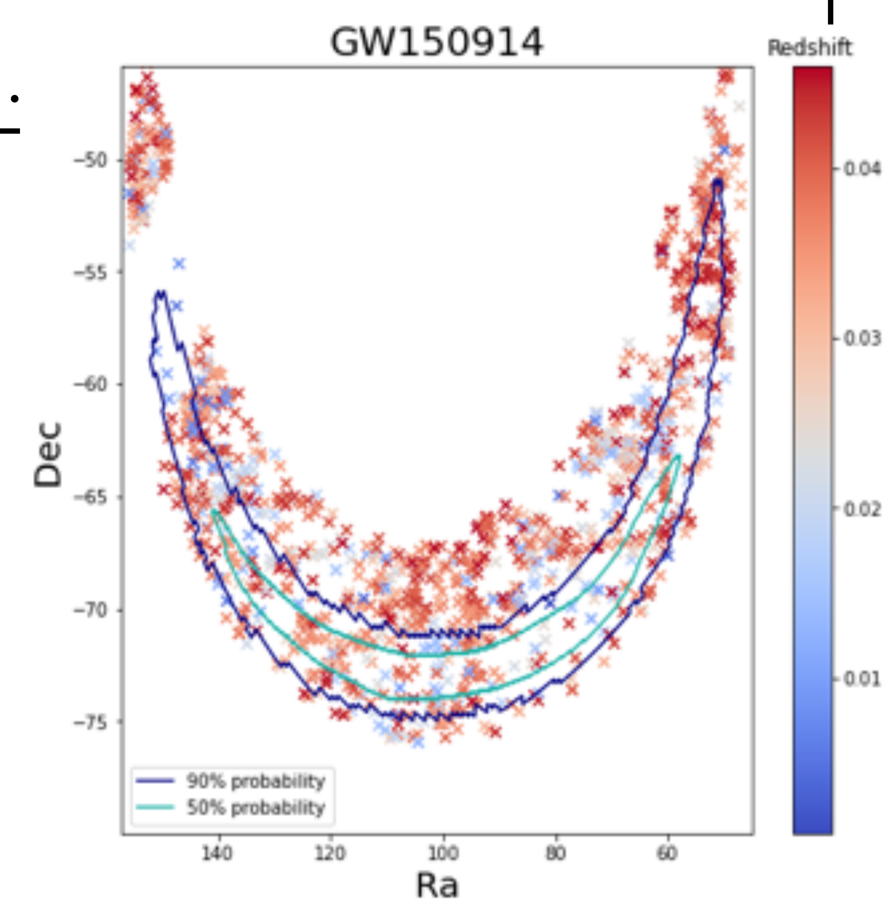
Higher order modes: more important as difference in masses increases (e.g. GW-190412). Help break (distance/inclination) degeneracy.
So can spin precession effects.

Determining the redshift

$$d_L = \frac{cz}{H_0}$$

- Crux of doing late-time cosmology with GWs: determining *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…



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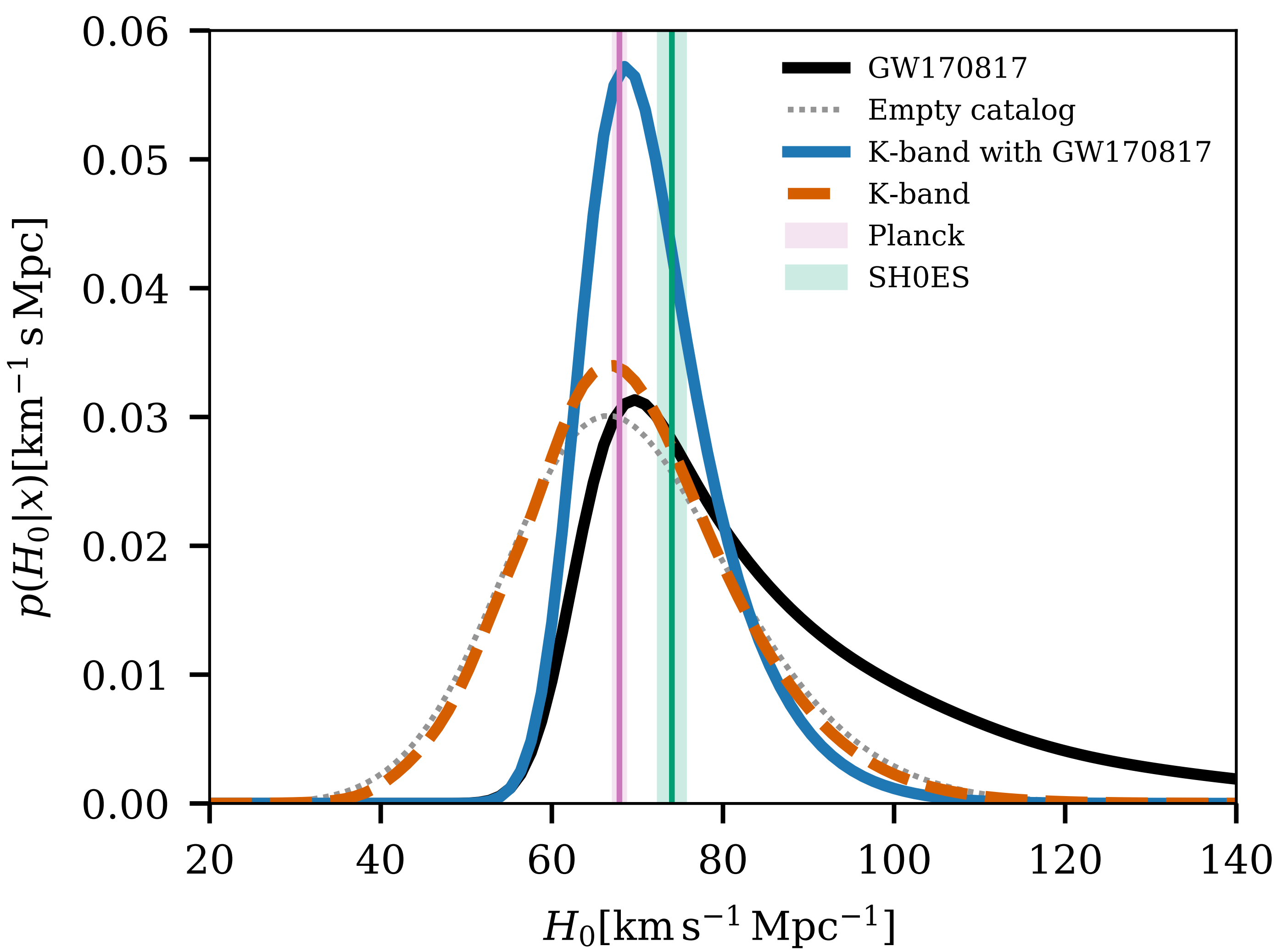
1. and 2. used for all BBH events from LIGO-Virgo O3 run, with SNR>11, assuming GR:

Only GW170817, with z from NGC4993

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

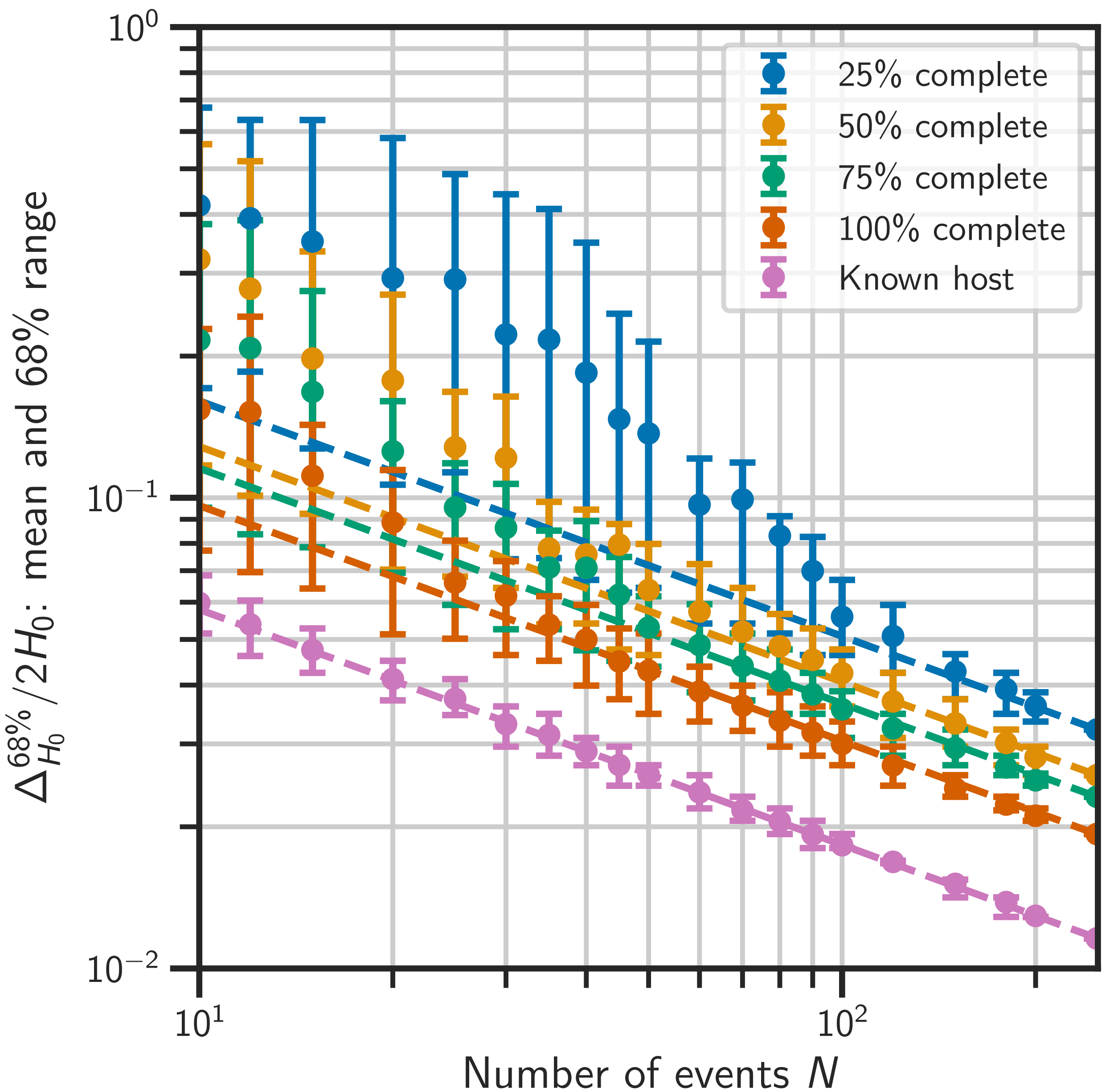
including BBHs leads to improvement

$$H_0 = 68^{+8}_{-6} \text{ km/s/Mpc}$$



[B.P.Abbot et al. arXiv:2111.03604]

What are the prospects for solving H0 tension with LIGO-Virgo with methods 1 and 2 ?



catalogue of simulated signals in 2015-2016 observing run.

H0 accurate to ~3% with:

~30 events with identified host galaxy,
~100 events with a galaxy catalogue that is 100% complete

dashed lines: $1/\sqrt{N}$

Phys.Rev.D 101 (2020) 12, 122001

Determining the redshift

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   (such as the BNS GW170817 together with optical identification of host galaxy NGC4993)

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• **Higher z,** galaxy catalogues will probably will be incomplete

• Approaches 3 **uses no EM data**, and hence work also for BBH (more numerous, heavier and observable to larger z).

ET: BBH $10^5 - 10^6/\mathrm{year}$
BNS $\sim 10^4/\mathrm{year}$

• Basic idea:

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

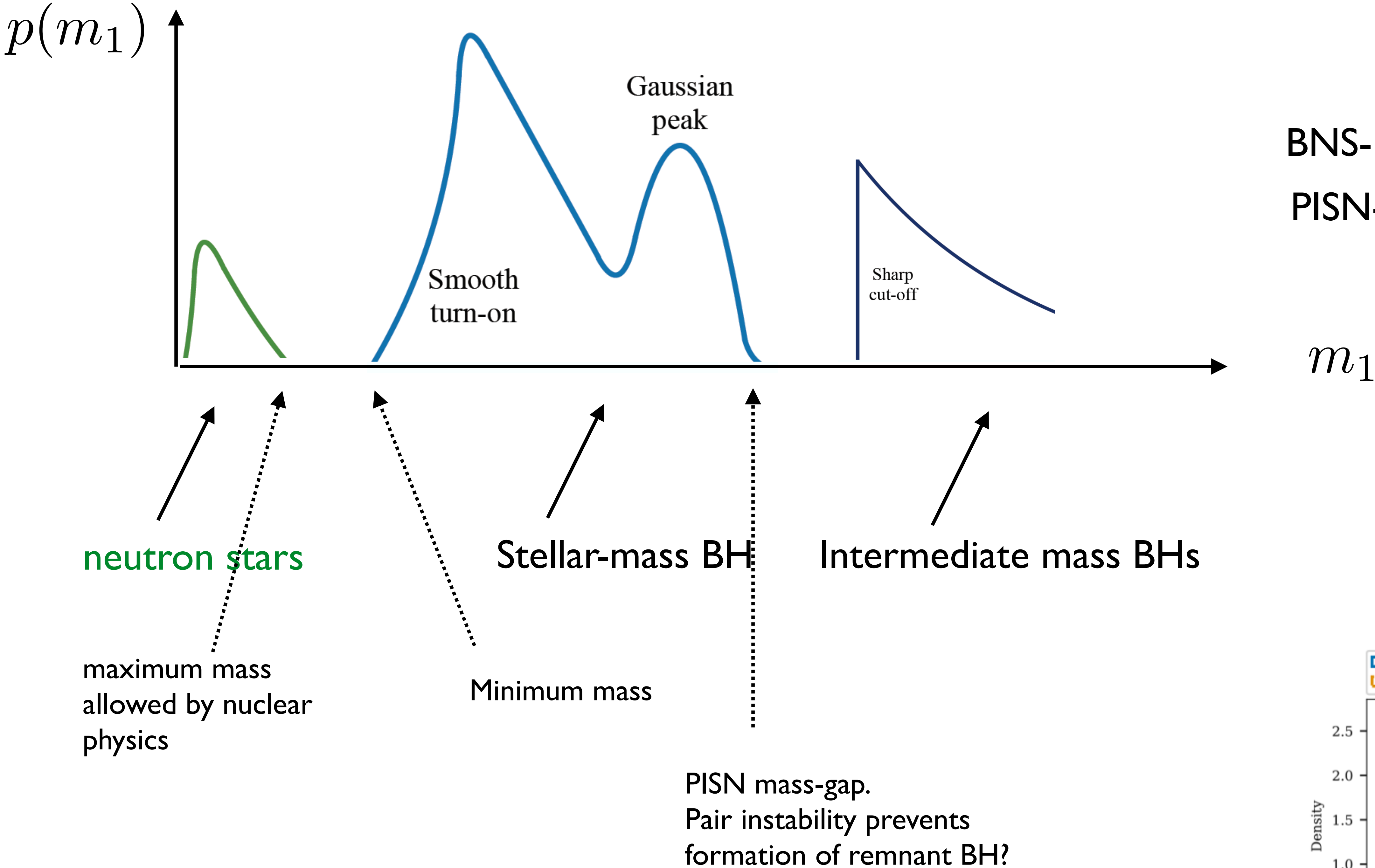
$$\frac{\delta z}{z} \sim \frac{\delta m_{1,2}^{\mathrm{source}}}{m_{1,2}^{\mathrm{source}}} \frac{1}{z}$$

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 $\sim 1/\sqrt{N}$

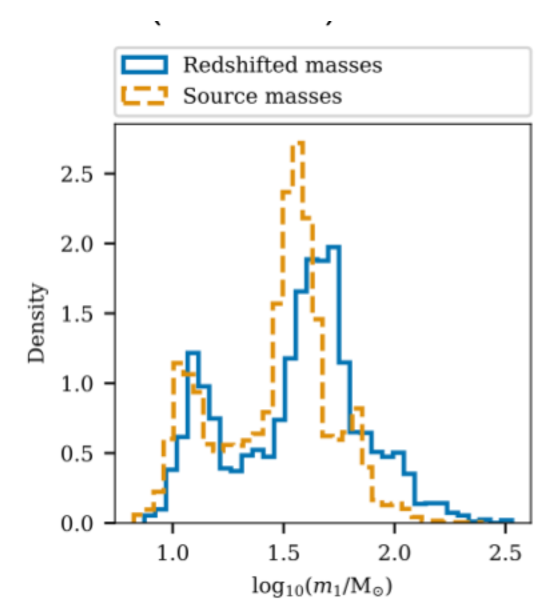
Knowledge of source frame mass distribution

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



BNS-BH mass-gap

PISN-mass-gap?



[Taylor, Gair et al, 2012]
100 obs -> H0 to 20%
+ mean and variance of mass distribution

LIGO/Virgo: forecasts for cosmology with Stellar-mass BH

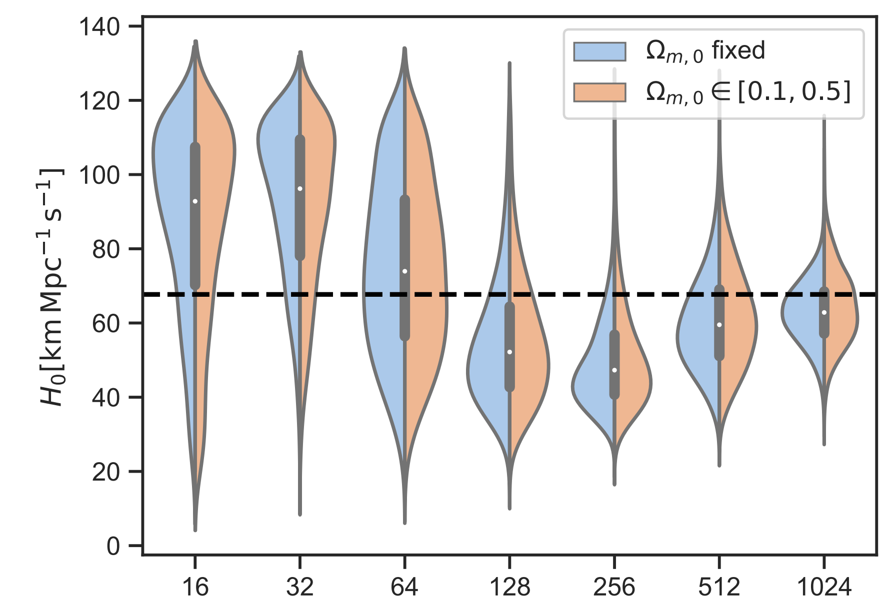
[Mastrogiovanni et al 2103.14663]

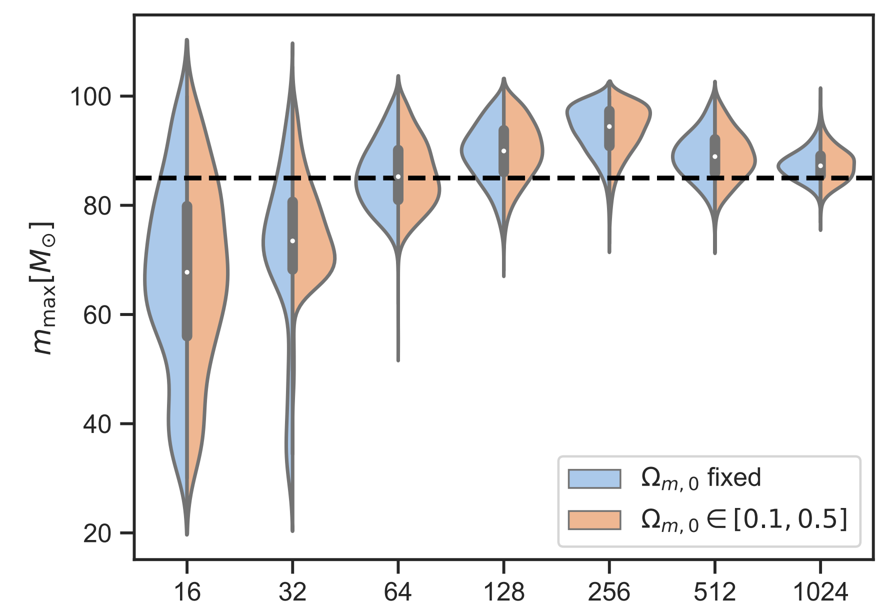
- Simulate a set of BBH GW events (*power-law + gaussian peak model, described by 8 parameters*) detected in LIGO and Virgo data assuming sensitivities comparable to the recent O2 and O3 observing runs

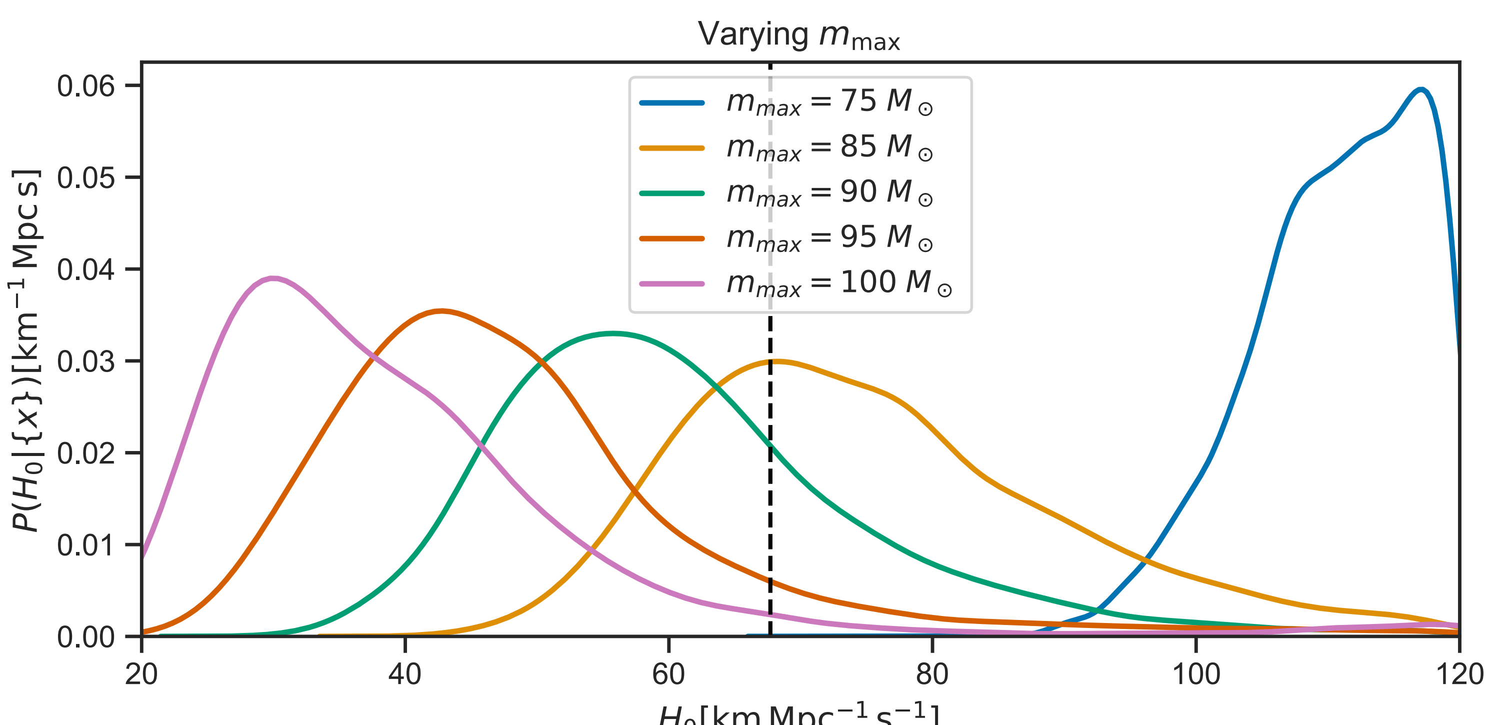
- Use hierarchical Bayesian inference scheme to **estimate jointly** **the source-frame mass model parameters, H0, Ωm, merger rate.**

  – **tight correlation** between estimation of source frame mass spectrum + cosmo parameters.

  – Effect of fixing the underlying mass model with incorrect parameters => incorrect results
  e.g. m_{max} in a range around its true value







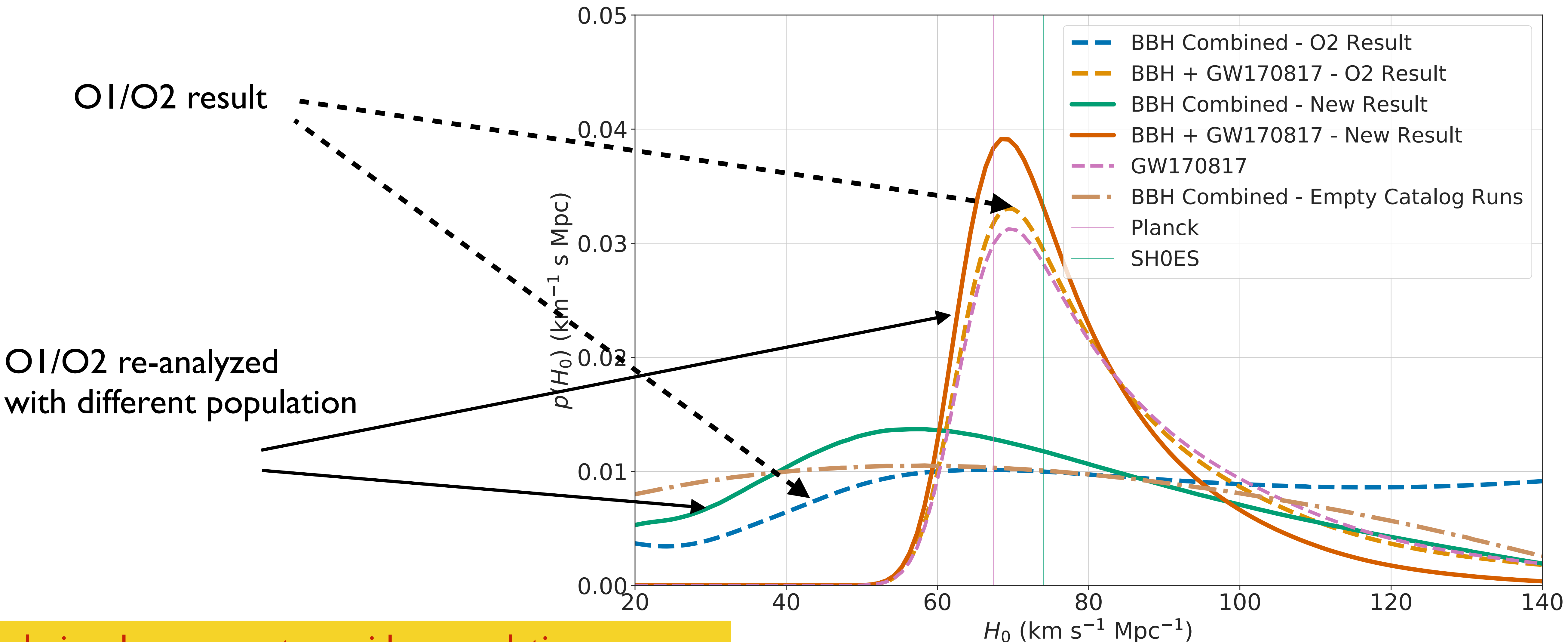
$$m^{\rm det} \sim (1 + d_L H_0) m^{\rm max}$$

• Population assumptions on source-frame mass spectrum in fact are *also important for "method 2" (with galaxy catalogues)*! They come in when dealing with the *incompleteness* of galaxy catalogues (these are flux limited and galaxies with magnitudes fainter than some threshold won't be in there)

• Source-frame mass spectrum implicitly provides information

• (in O1/O2 GWTC-1 analysis, an *a priori* source population model was taken (a power-law).)

• Impact of the assumption?



Analysis schemes must consider population
+ cosmological parameters jointly and not separately

Applying method 3 to Modified gravity

[K.Leyde et al 2202.00025]

$$\boxed{h'' + 2[1 + \alpha_M(\eta)]\frac{a'}{a}h' + k^2 c_T^2(\eta, k/a)h = 0,}$$

GWs in modified gravity can differ from those of GR in broadly 3 different ways

– **extra degrees of freedom**: over and above the + and x polarisations of GR

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GWs in modified gravity can differ from those of GR in broadly 3 different ways

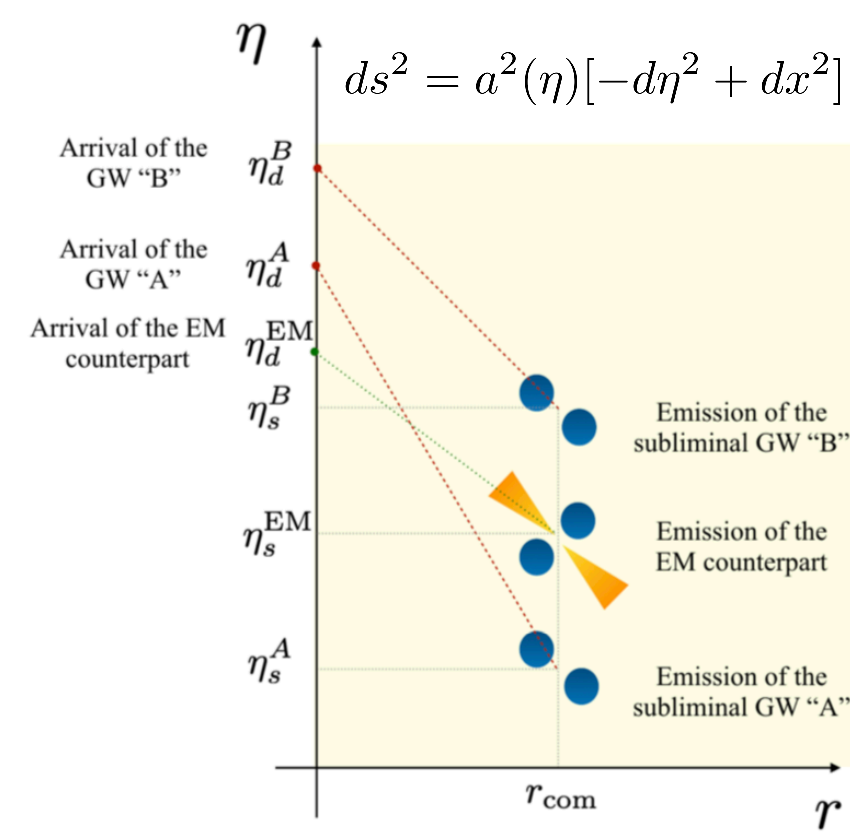
– **extra degrees of freedom**: over and above the + and x polarisations of GR

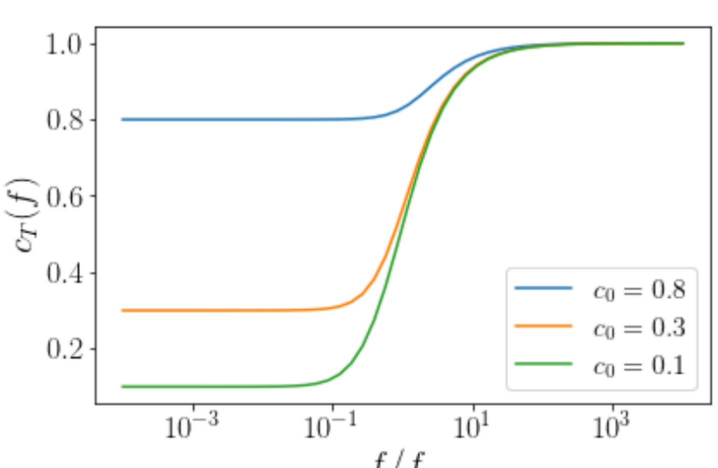
– **propagation effects**: waves can travel differently from the source to the detector

e.g. whereas in GR $c_T = c = 1$
- dispersion effects
- modified friction terms:
  GW energy dissipates differently with the expansion of the universe => modified amplitude.
- and can modify background evolution of univ.

$m_g \leq 1.27^{-23} \mathrm{eV}/c^2$

[2112.06861]





[2203.00566]

EFT ansatz for GW phase velocity,
see also *[de Rham and Melville, 1806.09417]*

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GWs in modified gravity can differ from those of GR in broadly 3 different ways

– **extra degrees of freedom**: over and above the + and x polarisations of GR

– **propagation effects**: waves can travel differently from the source to the detector

– **generation**: outgoing radiation and its relation to the properties of the source

Sources themselves may have different properties.

e.g. Horizons or not?

structure and evolution of stars may be modified e.g. screening 5th forces

=> populations of BH may have different properties

• Calculation of highly accurate waveforms in alternate theories is difficult

[L.Bernard et al, 2201.10924; 1.5PN order in masses scalar tensor theory; Julié et al, 2202.01329; in Einstein-scalar Gauss Bonnet Langlois et al 2103.14750; in DHOST …]

Applying method 3 to Modified gravity

[K.Leyde et al 2202.00025]

$$h'' + 2[1 + \alpha_M(\eta)]\frac{a'}{a}h' + k^2 c_T^2(\eta, k/a)h = 0,$$

- Simplest assumption: **only a modified friction term**

– Only 2 d of f (+,x); wave function at source identical;

– no modified dispersion relation, so gravitons are massless and propage with $c_T = c = 1$ at all frequencies (e.g. certain Horndeski, DHOST..) theories

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

M. Lagos et al Phys. Rev. D 99, 083504 (2019),

Consider 3 parametrisations:

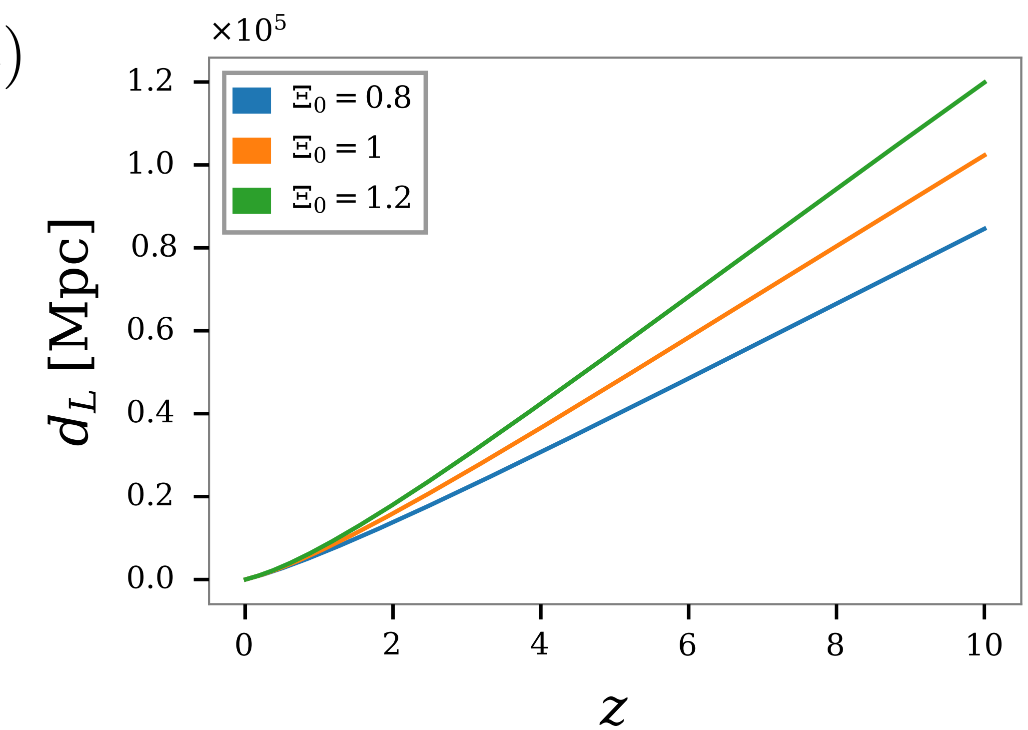
a) Phenomenological model of *[1906.01593], two parameters* (Ξ_0, n)

$$d_L^{\mathrm{GW}} = d_L^{\mathrm{EM}}\left(\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right)$$

$\Xi_0 = 1$ => GR for all z

$\Xi_0 \neq 1$ => for $z \ll 1$ reduces to GR

for $z \gg 1$, different luminosity distances $d_L^{\mathrm{GW}} \to \Xi_0 d_L^{\mathrm{EM}}$



b) Assume friction term is linked to dark energy content of the universe *[1404.3713…]*

$$\alpha_M(z) = c_M \frac{\Omega_\Lambda(z)}{\Omega_\Lambda(0)},$$

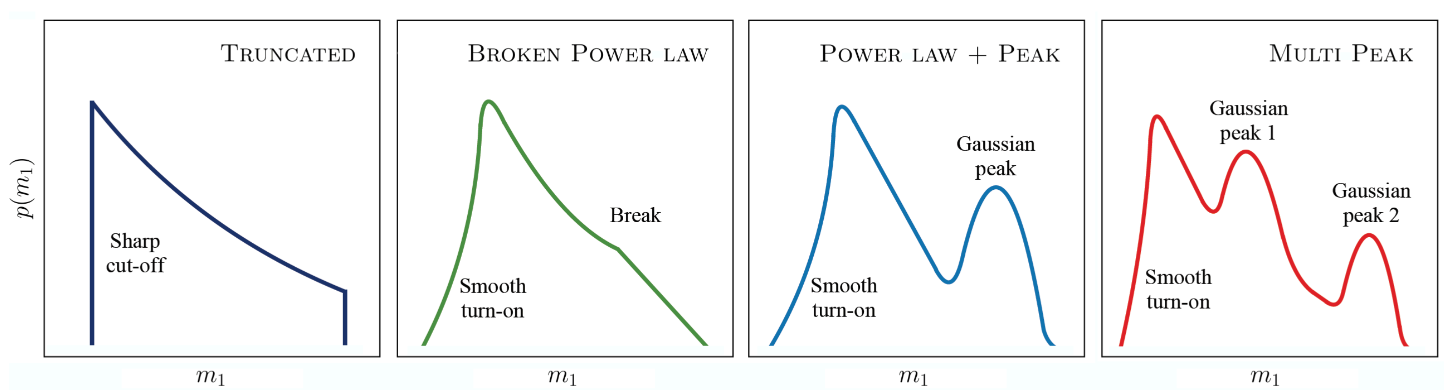
$$d_L^{\rm GW} = d_L^{\rm EM} \exp\left[\frac{c_M}{2\Omega_\Lambda} \ln \frac{1+z}{\left[\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda\right]^{1/3}}\right]$$

c) Model an extra dimensional universe with screening scale (comoving scale R_c), motivated from e.g. DGP *[0709.0003, 2109.08748]*

$$d_L^{\rm GW} = d_L^{\rm EM}\left[1 + \left(\frac{d_L^{\rm EM}}{(1+z)R_c}\right)^n\right]^{\frac{D-4}{2n}}$$

$d_L^{\rm EM} \ll R_c$ reduces to GR

- Consider 4 different source mass population models, motivated from *[2010.14533]*,



$(m_{\rm min}^{(s)}, m_{\rm max}^{(s)}, \ldots)$

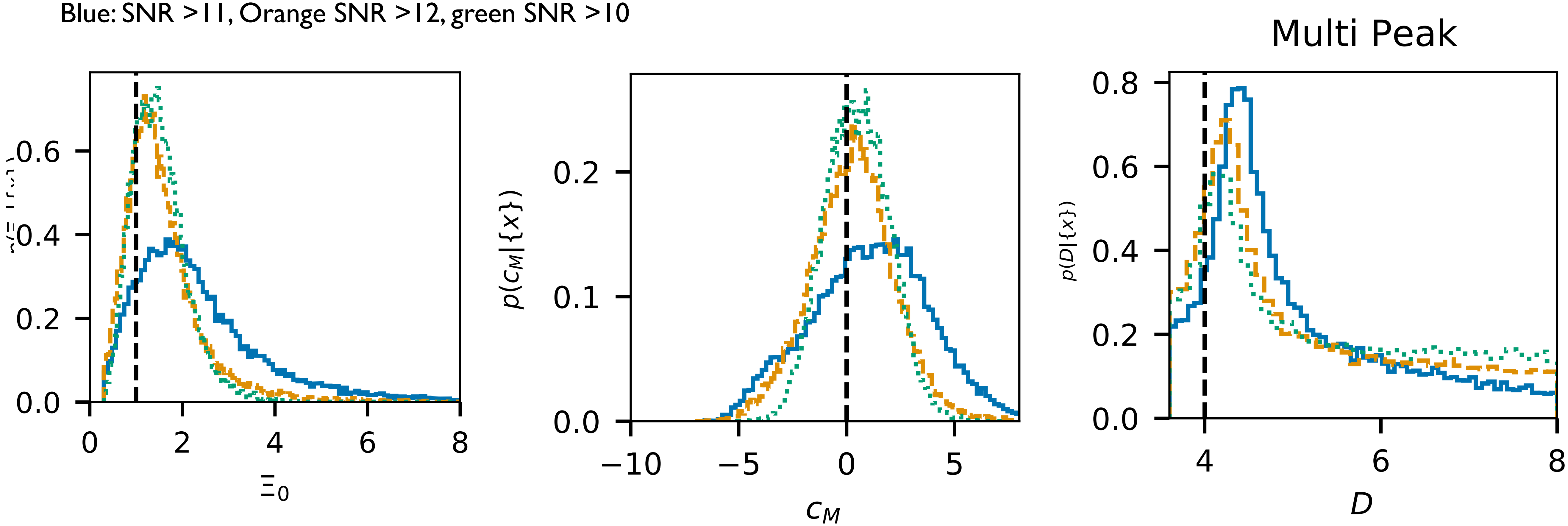
(note: *[2111.03634], GWTC3 shows inconclusive evidence for upper mass-gap)*

AIM: estimate jointly, using O3 data – the cosmological parameters (H_0, Ω_m)
– source mass parameters $(m^{(s)}_{\min}, m^{(s)}_{\max}, \ldots)$
– modified gravity parameters

Results using O3 data :

- Comparing Bayes factors: GR with multi-peak model is preferred!
- For this mass model, posteriors on modified gravity parameters:

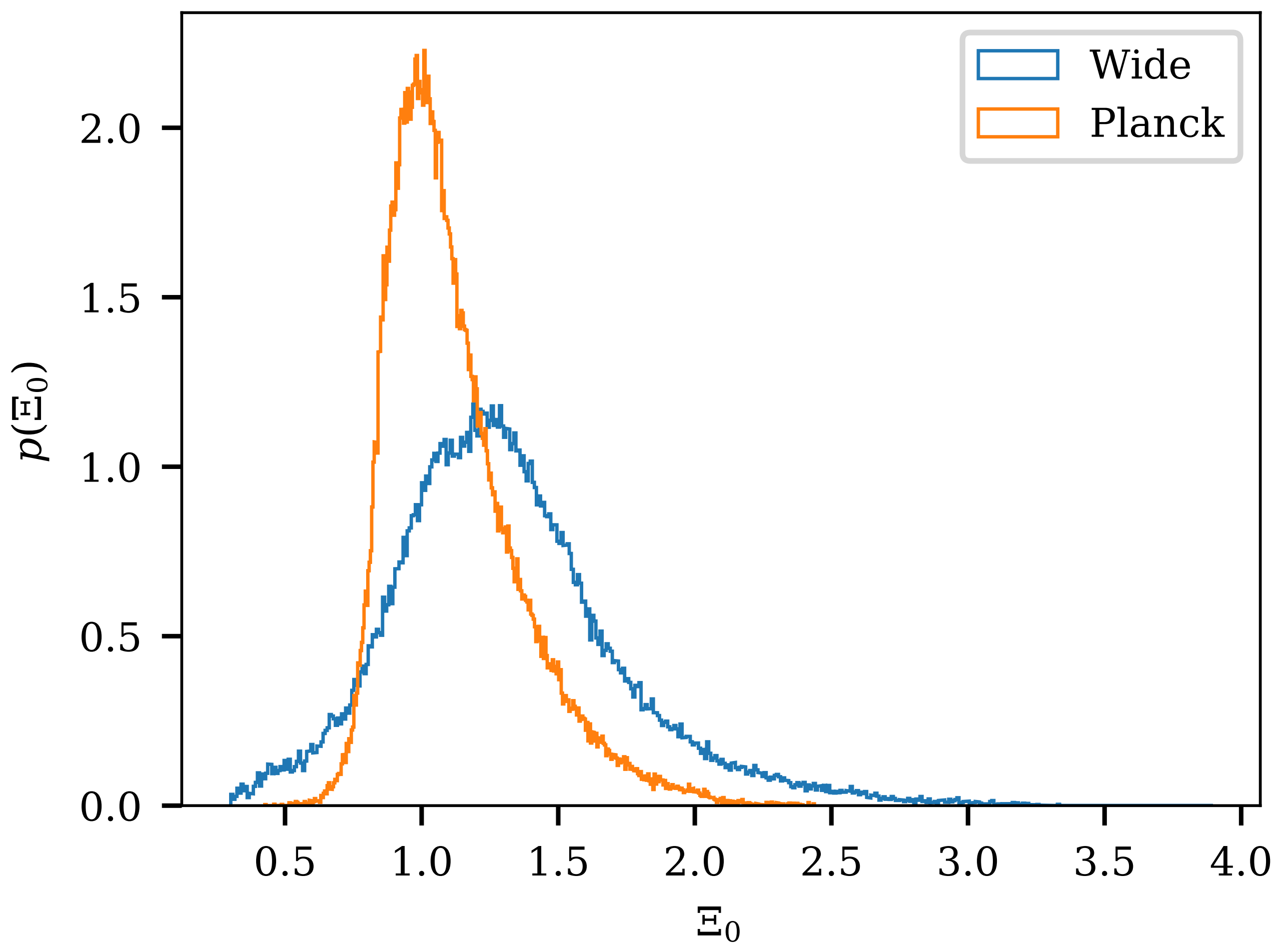
Blue: SNR >11, Orange SNR >12, green SNR >10



- For all modified gravity models, values of parameters are compatible with their GR values at 90% confidence level!

Forecasts for O4 and O5 :

- Simulate expected data, assuming GR, with 87 events for O4, and 423 for O5 (1 year of data).



Blue = agnostic priors on the cosmological parameters $\Xi_0 = 1.27^{+0.41}_{-0.33}$ O4+O5 (n unconstrained)
Orange = narrow priors. $\Xi_0 = 1.08^{+0.27}_{-0.16}$ for O4+O5

	Agnostic	*From Planck*
H_0	$\mathcal{U}(30, 130)$	$\mathcal{U}(66.07, 68.47)$
Ω_M	$\mathcal{U}(0.05, 0.4)$	$\mathcal{U}(0.3082, 0.3250)$

Conclusion and outlook

• Different ways to extract information on H0 and modified gravity using GWs.

• Bright/dark siren (galaxy catalogue) methods will become less viable for sources at high z

• BBH, BNS populations. **Cosmology hand in hand with astrophysics**

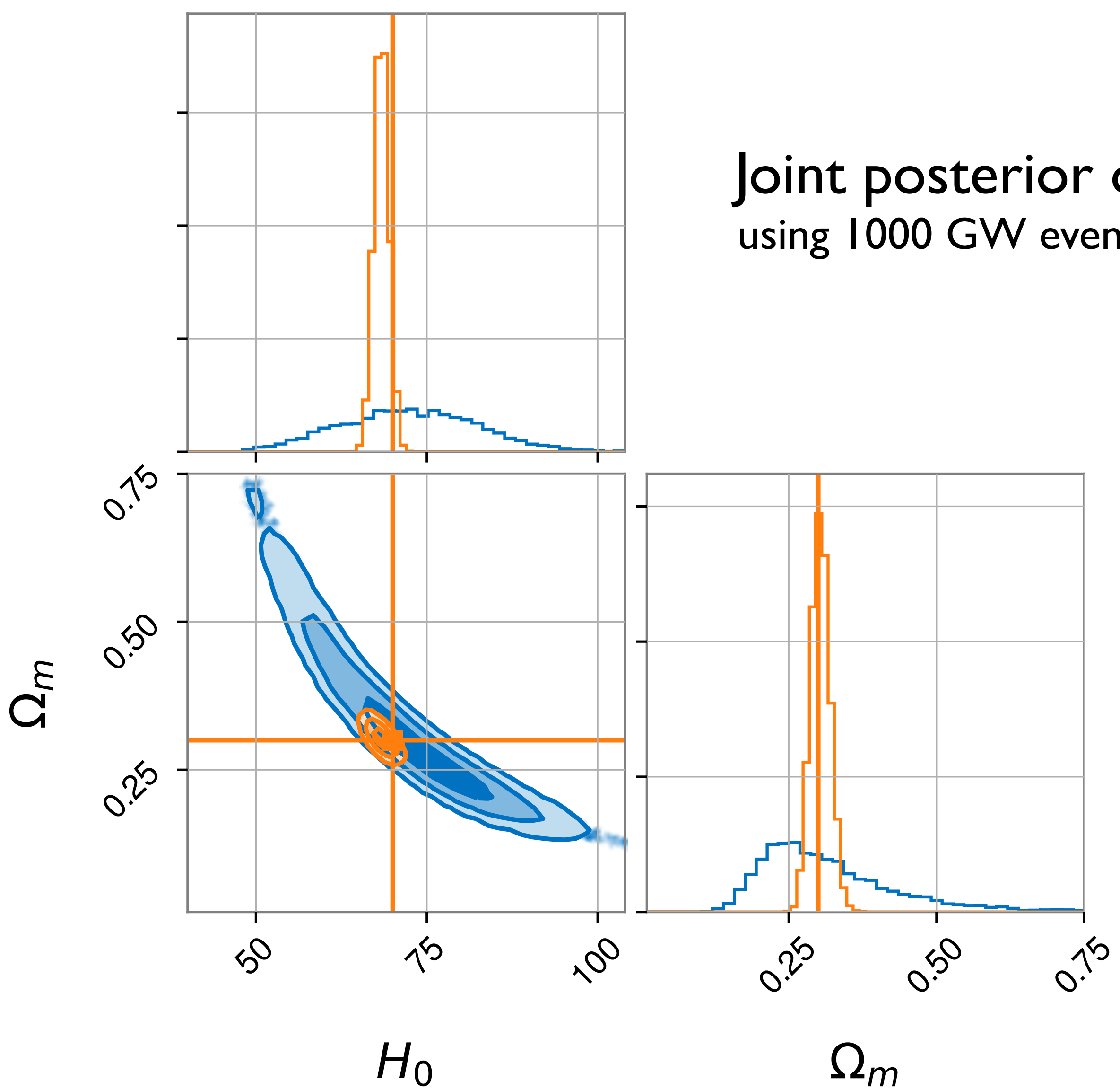
• Expect important impact on measurements of cosmological parameters, certainly addressing H0 tension, and constraining propagation effects in modified gravity

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

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)



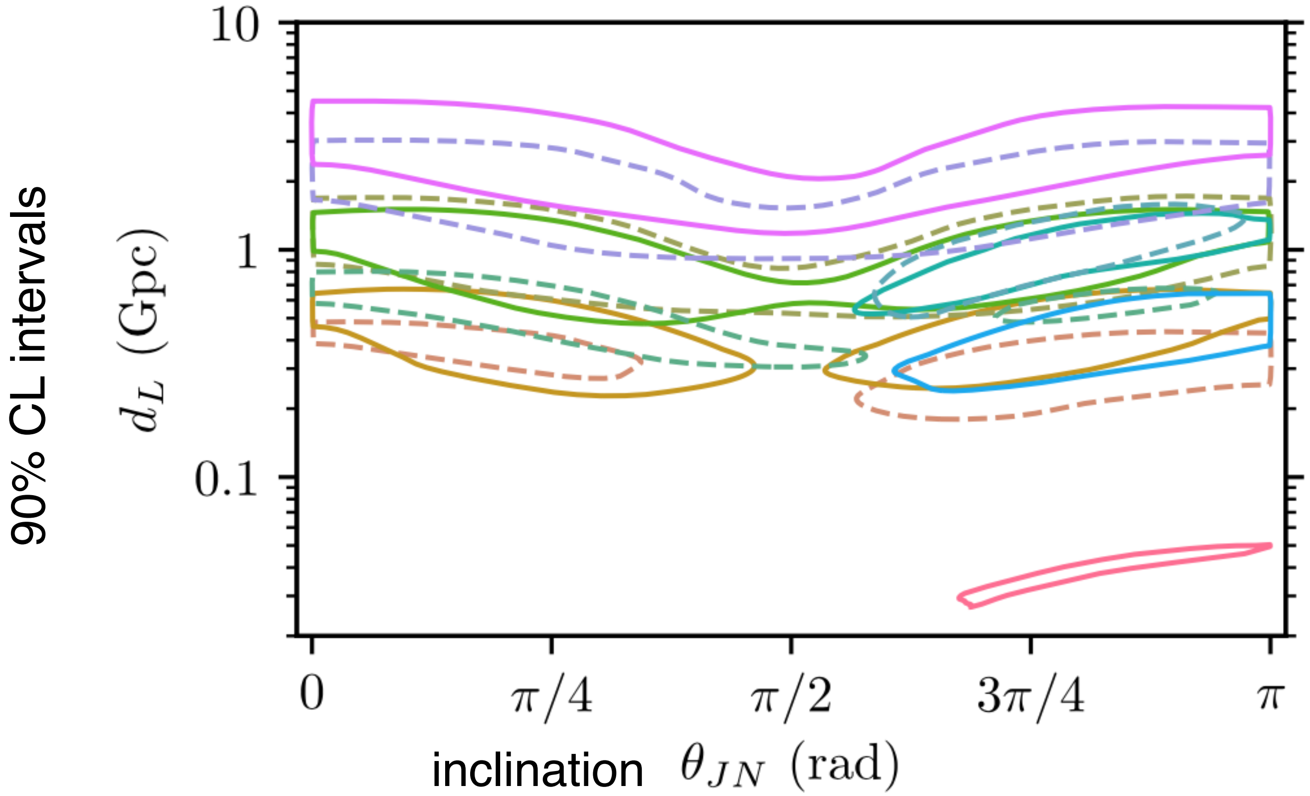
Joint posterior on (H_0, Ω_m)
using 1000 GW events detected by ET

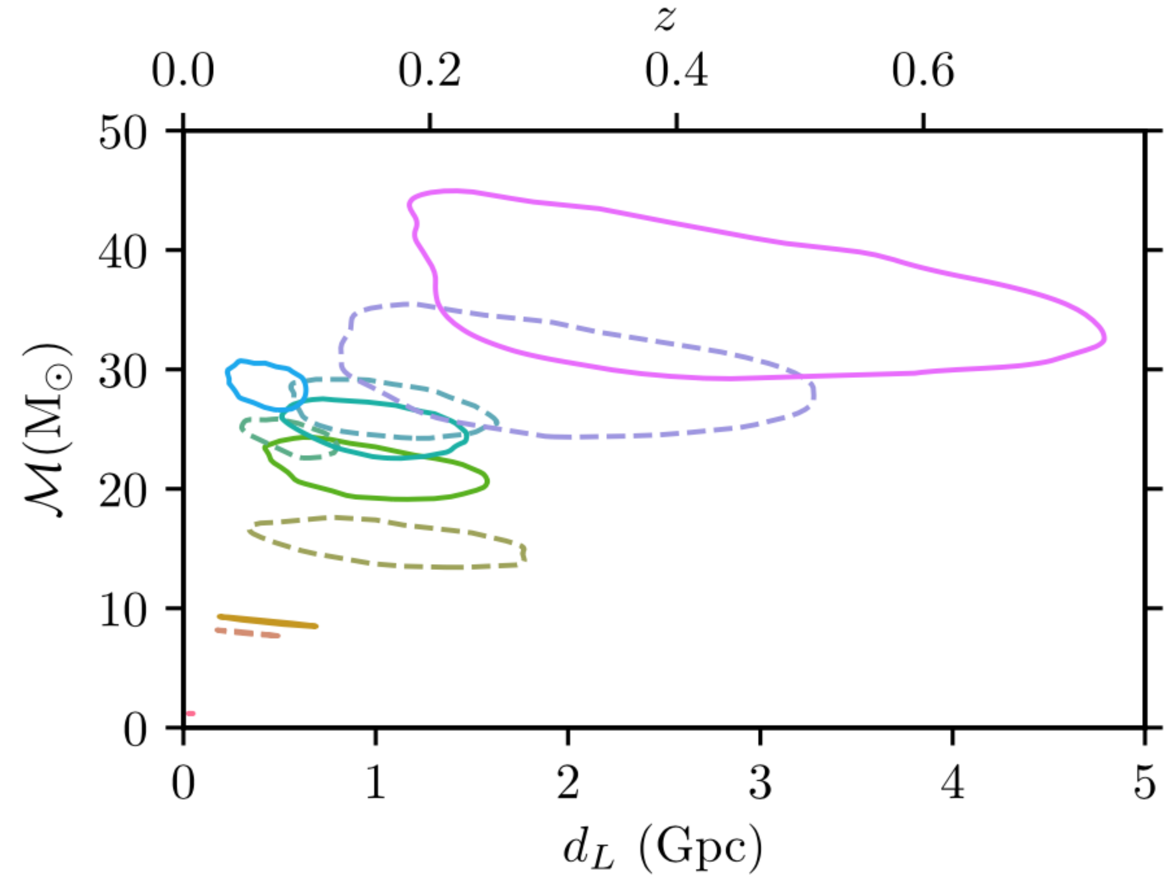
orange: assuming
all population parameters
known a priori

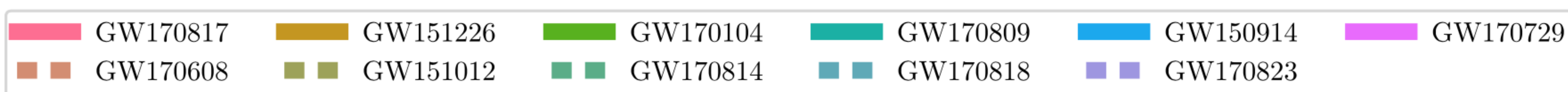
blue: marginalizing
over population parameters

"1 year observation of ET will constrain the Hubble constant to a few % given our current knowledge of the black hole mass distribution [.]… If/when our understanding of the above quantities is improved, which is plausible **in the ET era, a sub-percent measurement precision is likely**."

O1+O2 catalogue

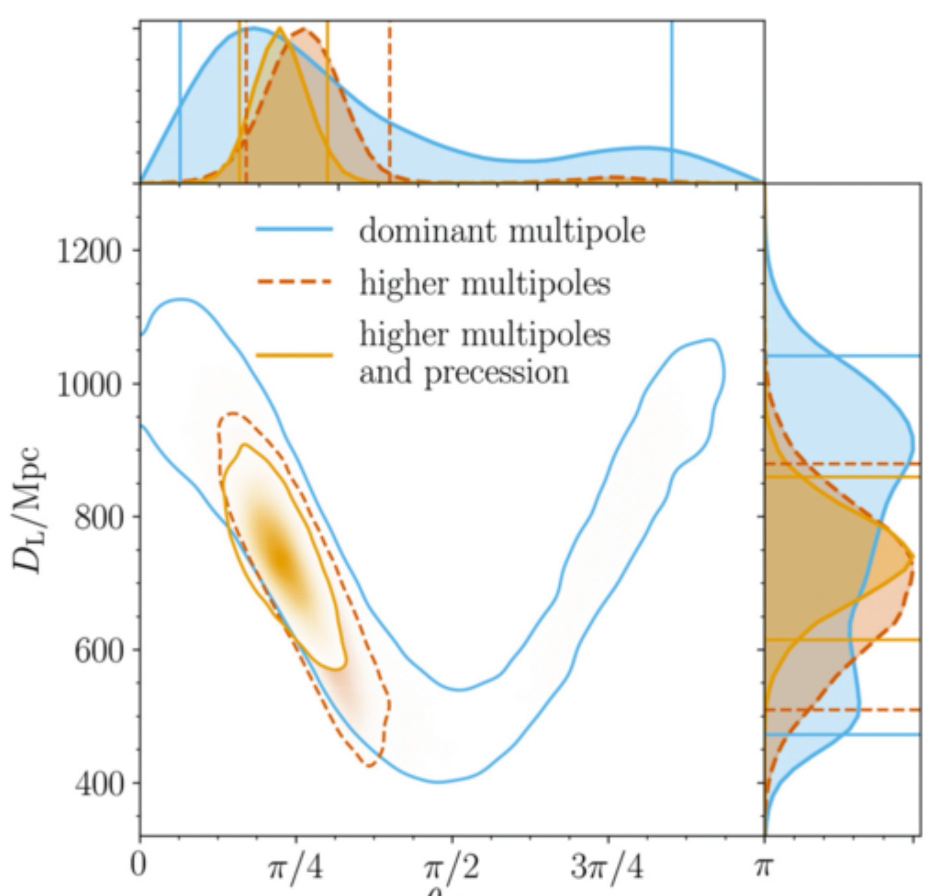






190412 event:
effect of higher order multipoles

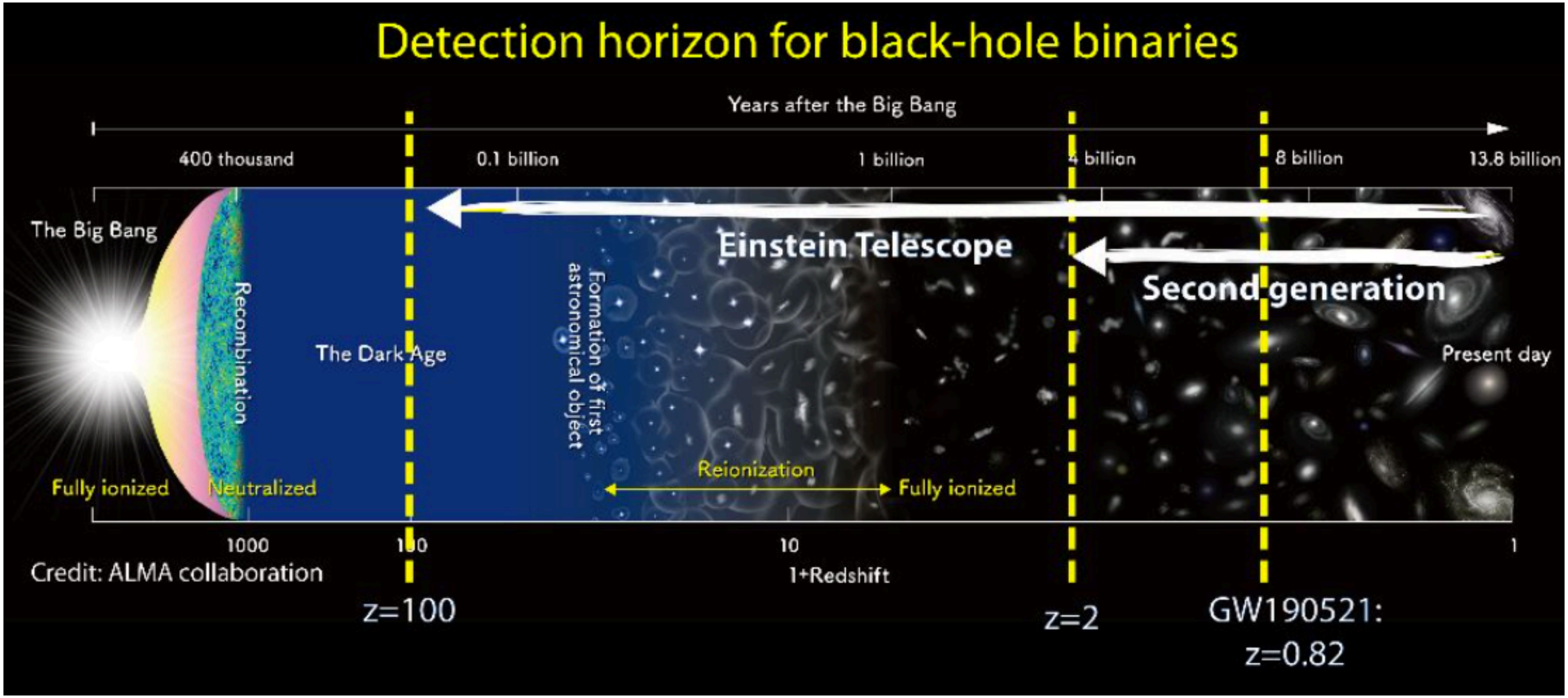
$m_1 \sim 30 M_\odot$
$m_2 \sim 8 M_\odot$



Higher order modes: more important as difference in masses increases.
Help break (distance/inclination) degeneracy.

So can spin precession effects.

And the redshift?



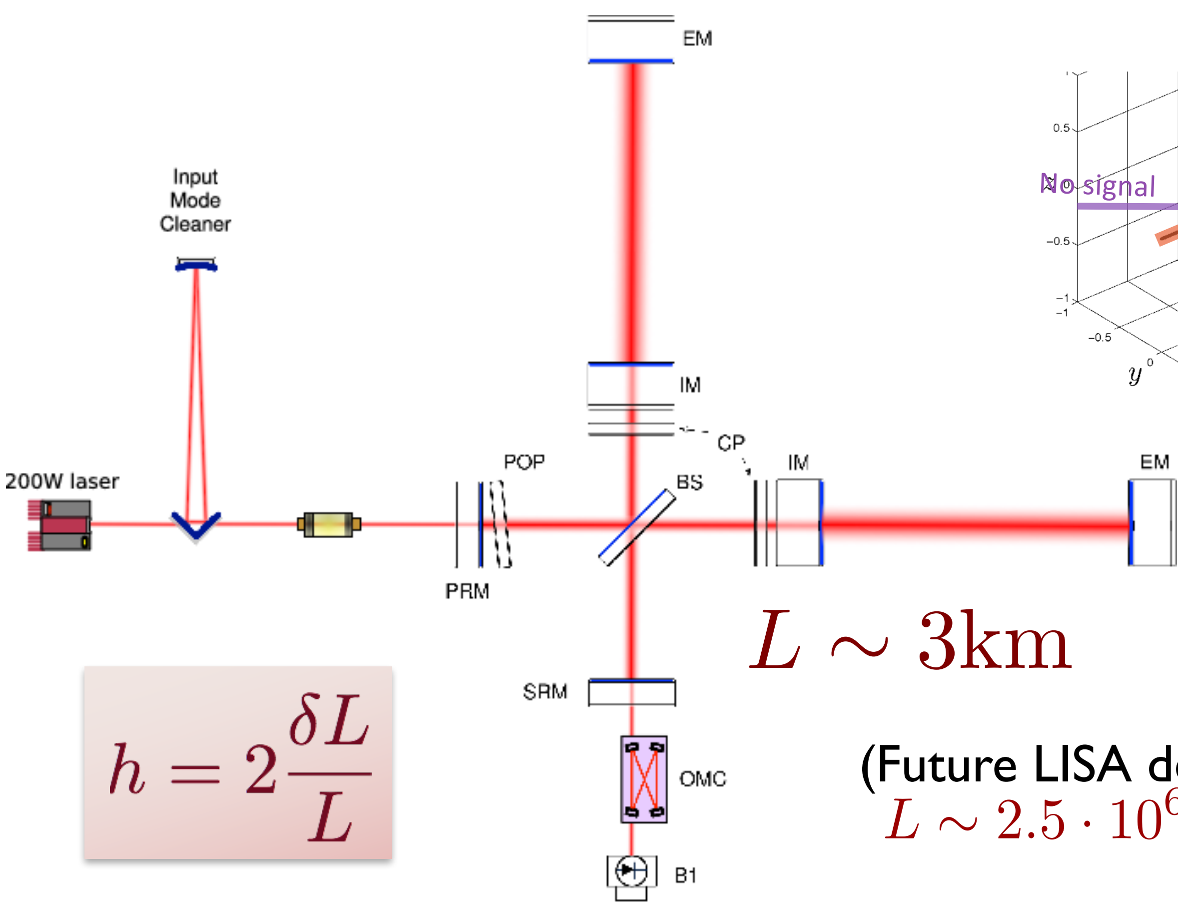
can the distance measurement of a single BBH source be precise enough to establish its primordial origin?

[K.Ng et al, 2108.07276]. In the future, with a network of one Einstein Telescope, and 2 Cosmic Explorers (US+Australia), maybe.

– single BBH event with masses between 20-40 Msun, merging at z>40, can infer z>30 at up to 97% credibility with a network of one ET, one CE in the US and one CE in Australia. (some caveats: depends on redshift prior, mass ratios, inclinations…)

I) Introduction

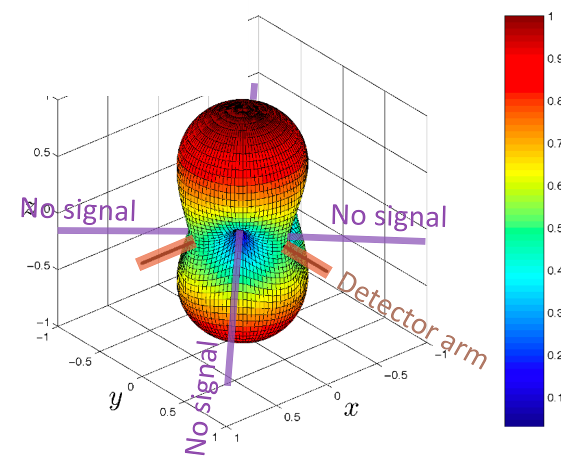
Network of LIGO-Virgo-Kagra detectors: Michelson interferometers, measure **one** dimensionless quantity, the gravitational wave strain h

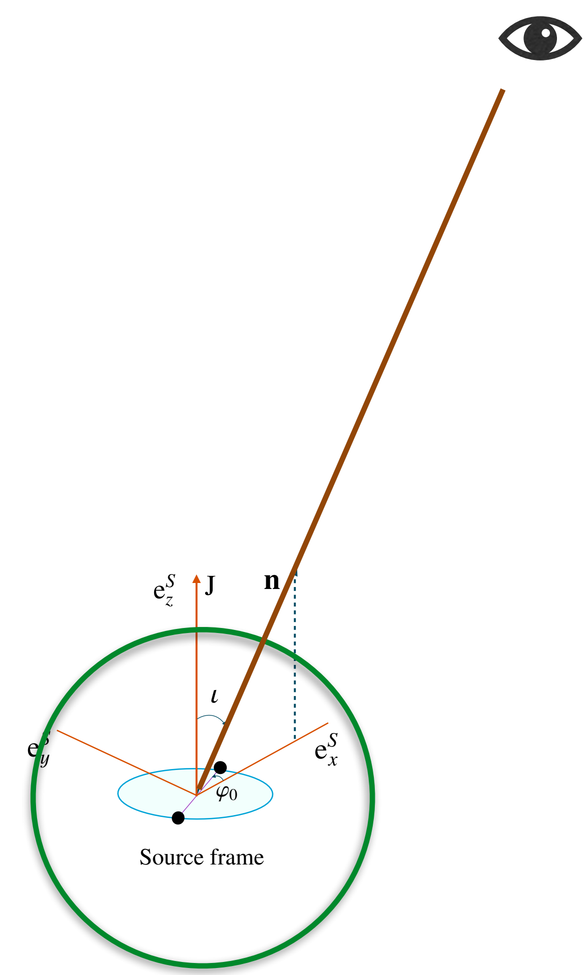


$$h = 2\frac{\delta L}{L}$$

$$L \sim 3\mathrm{km}$$

(Future LISA detector $L \sim 2.5 \cdot 10^6 \mathrm{km}$)





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In GR:

$$h(t,\theta,\phi,\psi) = F_+(t,\theta,\phi,\psi)h_+(t) + F_\times(t,\theta,\phi,\psi)h_\times(t)$$

waveforms of 2 physical polarisations of the GW at the detector, depend on:
– all parameters describing the source, mass(es), spin(s), equation of state…
– propagation of waves from source to detector