Title: TBA

Speakers: Tessa Baker

Series: Strong Gravity

Date: May 18, 2023 - 1:00 PM

URL: https://pirsa.org/23050149

Abstract: Abstract and Zoom Link: https://pitp.zoom.us/j/97541386696?pwd=S0trZmpOQlZMb2ZUb29RUGxNSElYUT09

THE ROYAL SOCIETY

Queen Mary University of London

European Research Council

Beyond Standard Sirens:

Gravitational Wave Cosmology without EM Counterparts

Tessa Baker, Queen Mary University of London

Perimeter Institute, 18/05/23

Outline

- The promises & challenges of Standard Sirens.
- The alternative: Dark Sirens.
- Tests of gravity with GWs.
  (and without counterparts)

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LSC

LISA CONSORTIUM

Bartolomeo Fiorini

Ashim sen Gupta

Konstantin Leyde (joining soon)

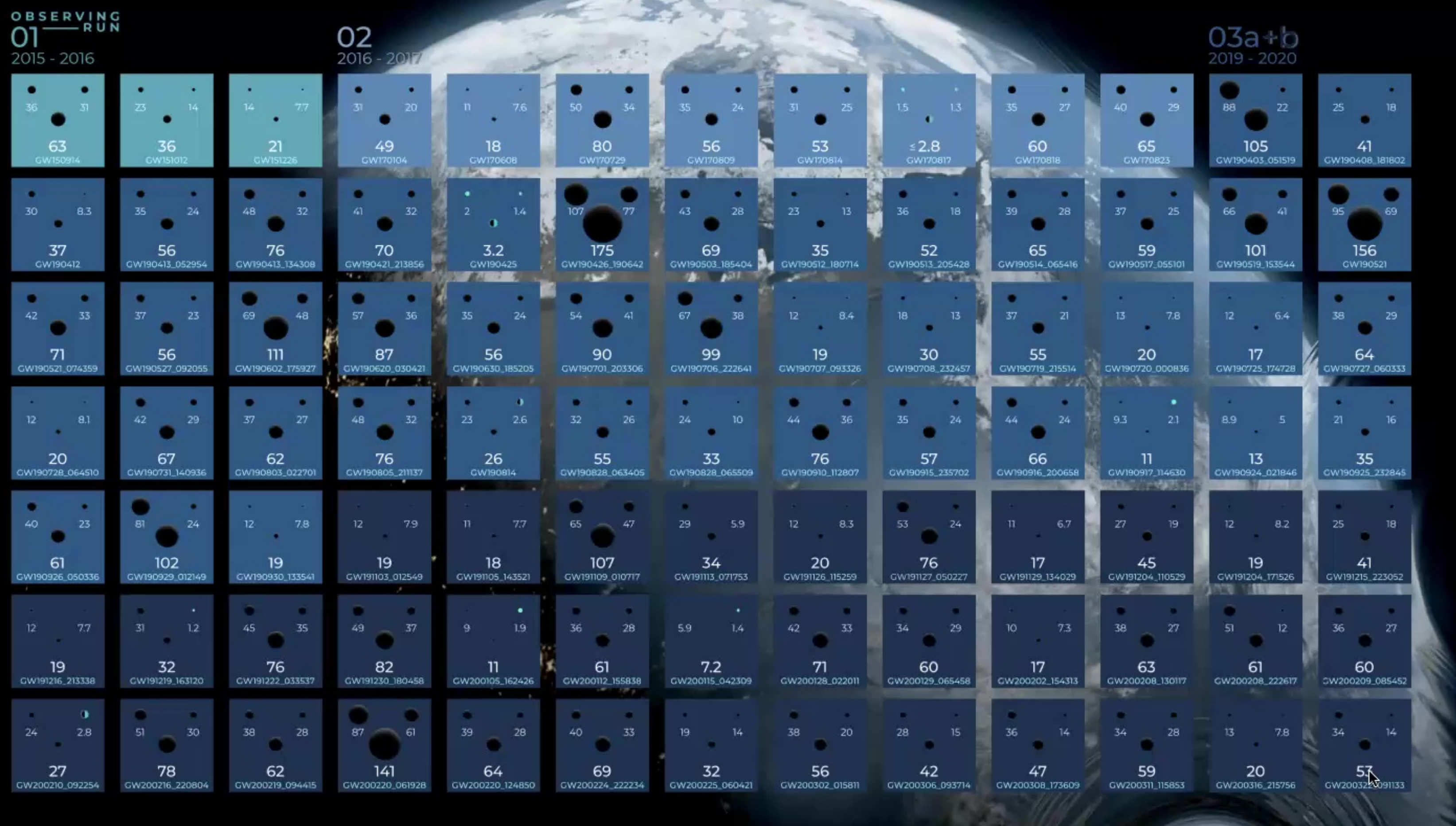
Charlie Dalang

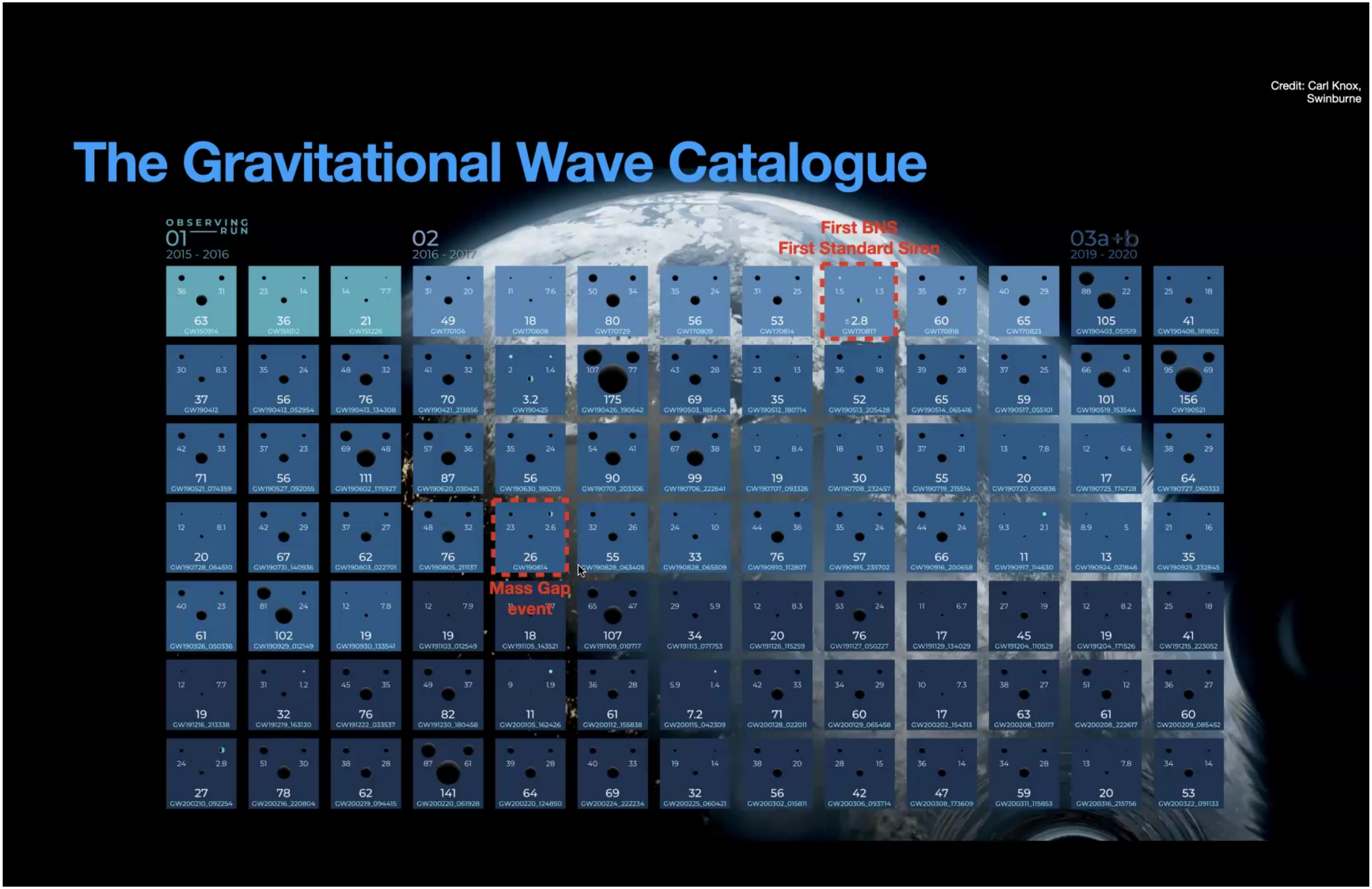
Anson Chen

Stefano Zazzera

Credit: Carl Knox, Swinburne

The Gravitational Wave Catalogue




Credit: Carl Knox, Swinburne
The Gravitational Wave Catalogue
OBSERVING RUN
O1
2015 - 2016
O2
2016 - 2017
O3a+b
2019 - 2020
First BNS
First Standard Siren
Mass Gap event

The Promise of Standard Sirens

Standard Siren = GW event with EM counterpart of any kind

Luminosity Distance - Redshift Relation

- Why all the excitement?

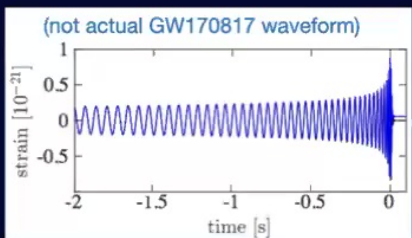
$$\tilde{h}_{+,\times}(f) \propto \frac{\mathcal{M}_z^2}{\boxed{d_L}} (\pi \mathcal{M}_z f)^{-\frac{7}{6}} \times \text{(polarisation angles)} \times \text{(inclination factor)}$$

Luminosity distance $\quad d_L(z) = (1+z)\int_0^z \frac{d\tilde{z}}{H(\tilde{z})}$

➡ The Hubble function contains the most important parameters in cosmology, e.g.

$$H(z)^2 = H_0^2 \left(\Omega_M (1+z)^3 + \Omega_{\rm DE} (1+z)^{3(1+w_0)}\right)$$

Big Results with Standard Sirens

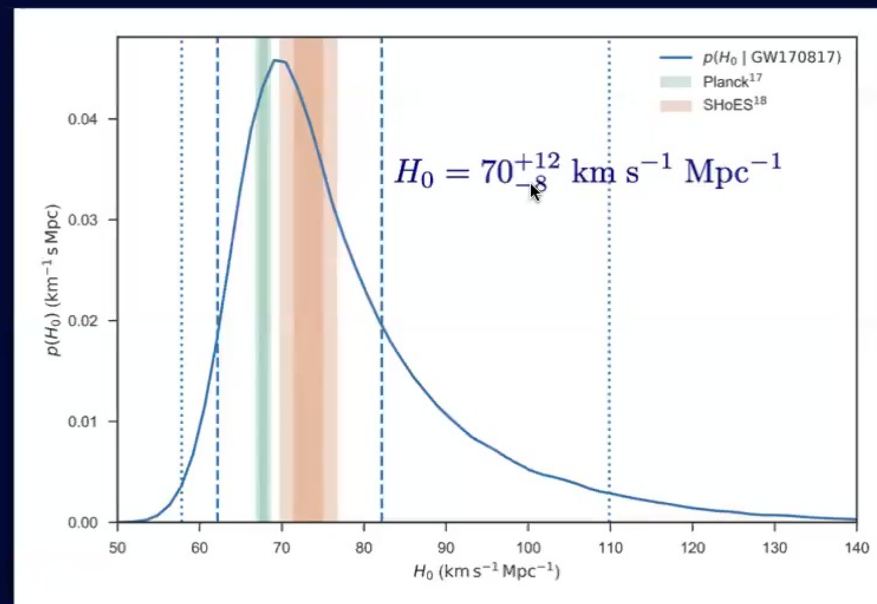


d_L

- → Constrain d_L-z relation
- → Independent H_0 measurement
- → Solve Hubble tension

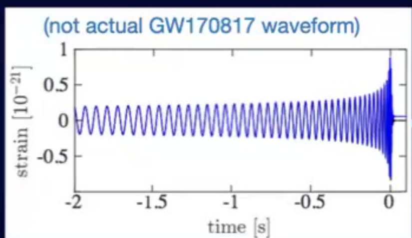
NASA/ESA Hubble

z



LIGO-Virgo-KAGRA, 2017.

Big Results with Standard Sirens



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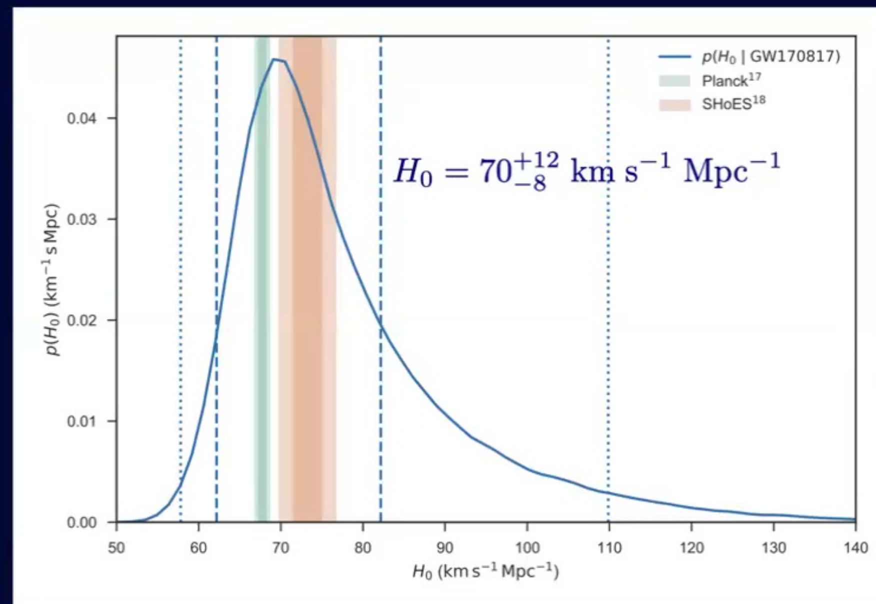


LIGO-Virgo-KAGRA, 2017.

But also! Cosmological extended gravity theories change the d_L-z relation (more later)

→ Detect / constrain deviations from GR

Not as easy as it seems…

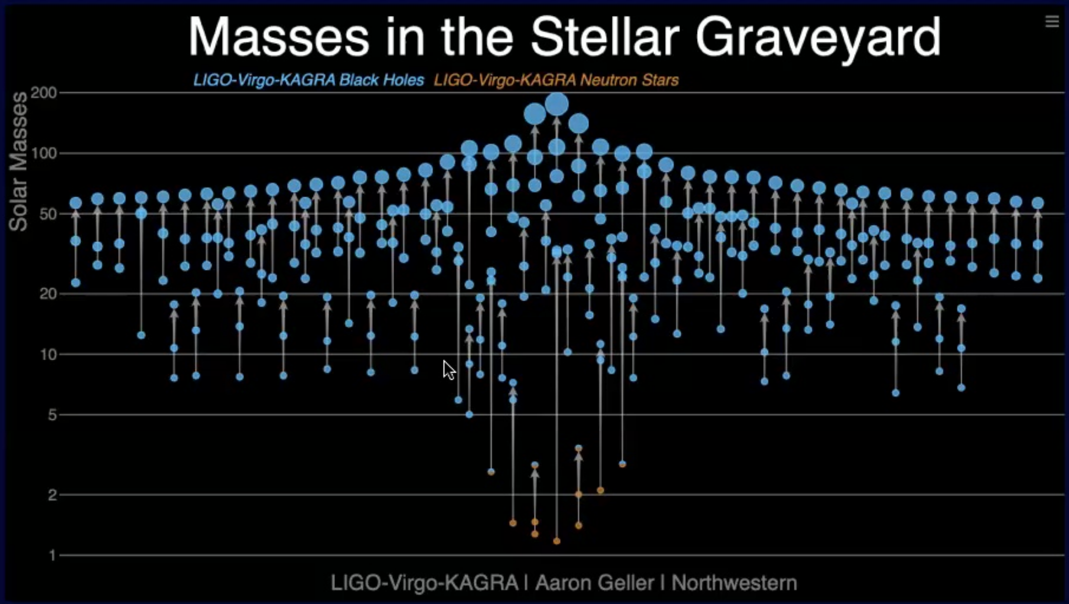
- %-level constraints on H_0 will need ~50-100 Standard Sirens *(H.Y. Chen et al. 2015)*

  The rate of Standard Sirens is unknown.

- …should we just wait?

  - You'd be ignoring all black hole data.

  - EM counterparts only at low z. Great for H_0, not so good for, e.g. GR tests.



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- …should we just wait?

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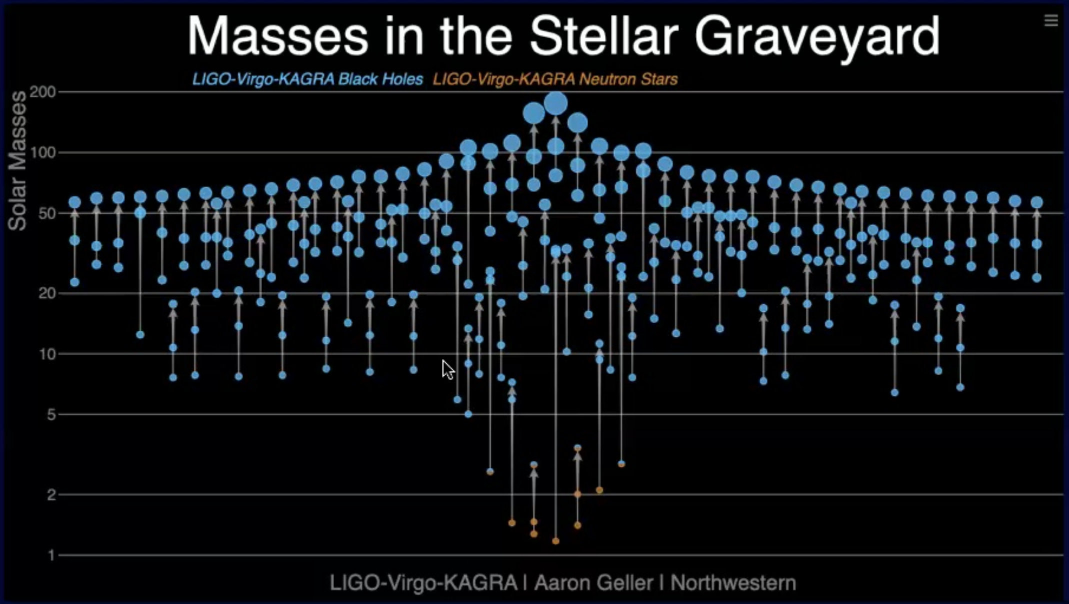
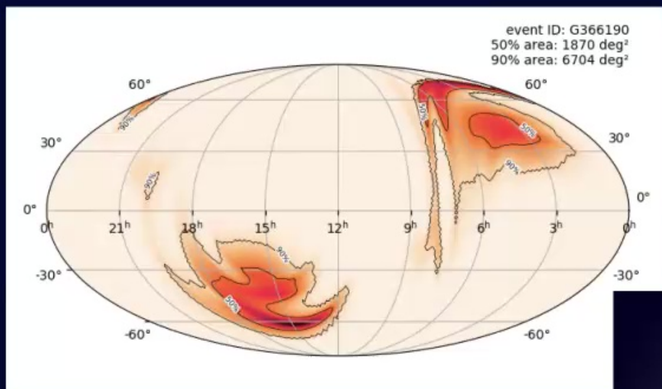
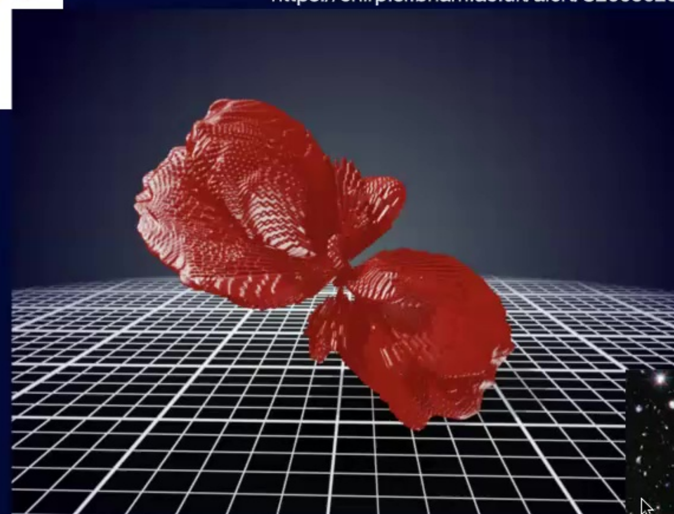
  - Almost no idea how long this could take 🤷‍♀️





https://chirp.sr.bham.ac.uk/alert/S200302c



Dark Sirens

a.k.a. ‘statistical sirens’
or ‘the galaxy catalogue method’

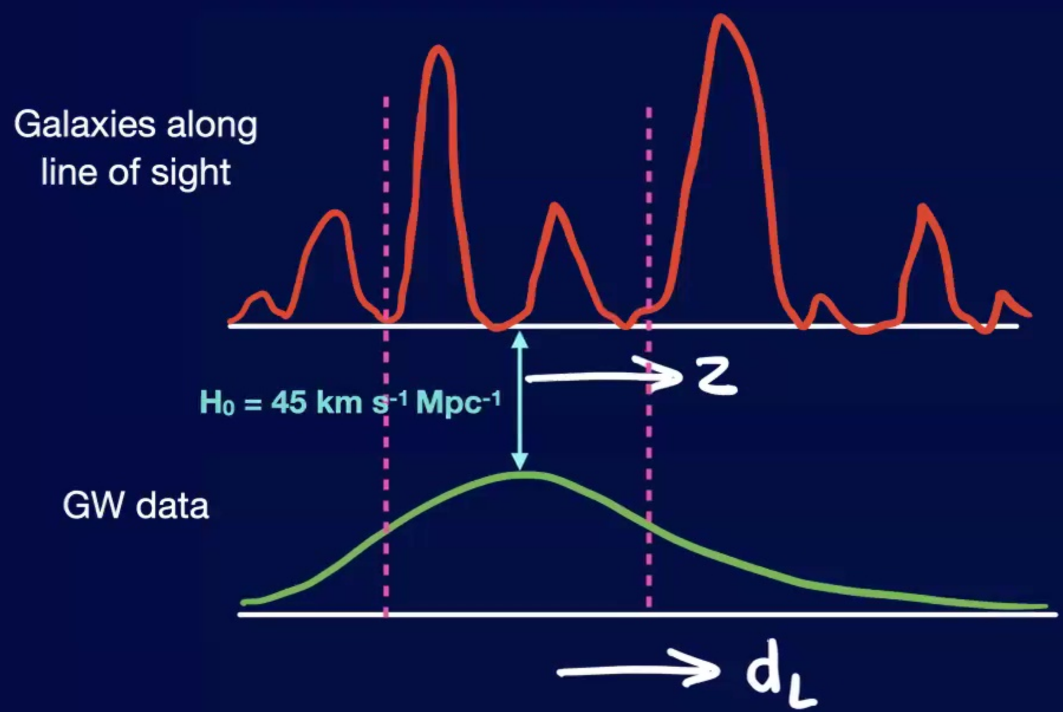
NASA Hubble

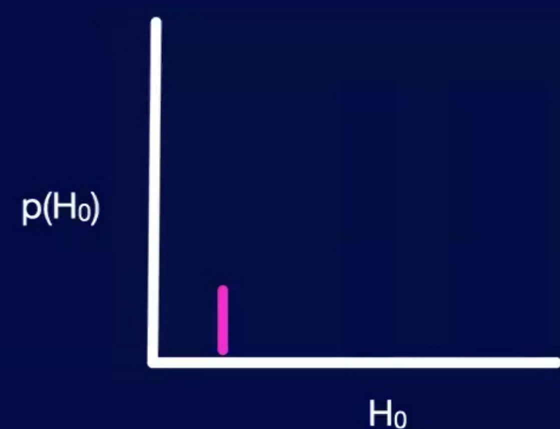
Mandel et al. (2019)
Gray et al. (2019)
Finke et al. (2021)

Dark Sirens — the Idea

At low redshift, the d_L-z relation is dominated by H_0 (recall Hubble's law: $v \sim H_0 d$)

$\rightarrow c z \sim H_0 d$





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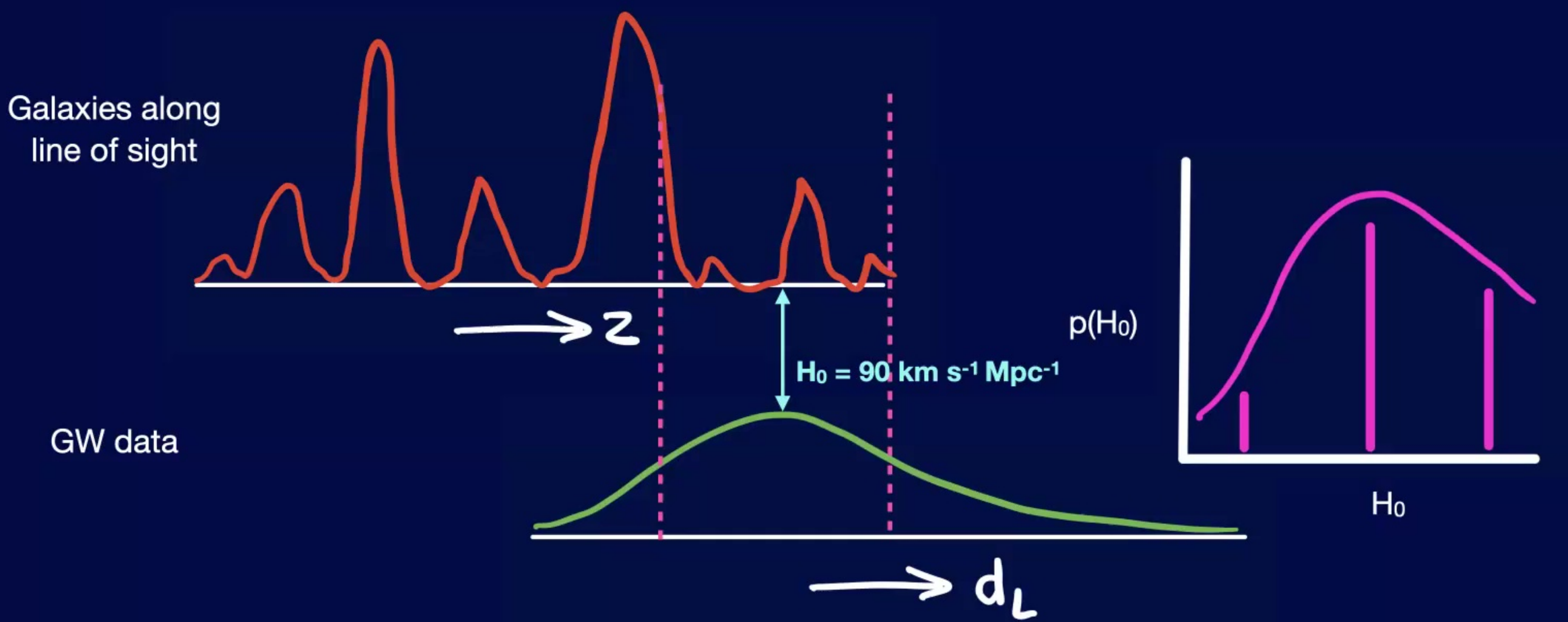

c z ~ H_0 d

Hierarchical Bayesian Formalism

NB: toy version only!

Full calculation: Mandel et al. (2019)
Gray et al. (2019)
Finke et al. (2021)

GW data set

Bayes' theorem:

$$p\left(H_0|\mathcal{D}_{\rm GW}\right) = p\left(H_0\right)\frac{p\left(\mathcal{D}_{\rm GW}|H_0\right)}{p\left(\mathcal{D}_{\rm GW}\right)} \longrightarrow \prod_i^{\rm events} p\left(\mathcal{D}^i_{\rm GW}|H_0\right)$$

GW events are independent

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Sky position (pixel)

Galaxy magnitude

$c\,z \sim H_0\,d$

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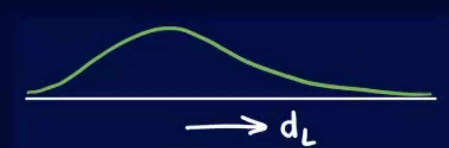
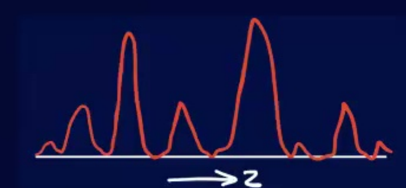
GW parameter estimation pipeline

galaxy catalogue

Galaxy magnitude

Sky position (pixel)





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GW parameter estimation pipeline

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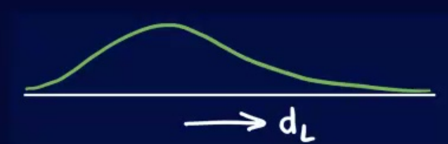
Galaxy magnitude

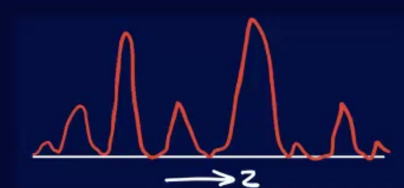
Sky position (pixel)

Cancels out 'geometric effect':

Higher H_0 → more volume → more galaxies

Crucial to avoid biasing H_0 posterior.





Mandel et al. (2019)
Gray et al. (2019)
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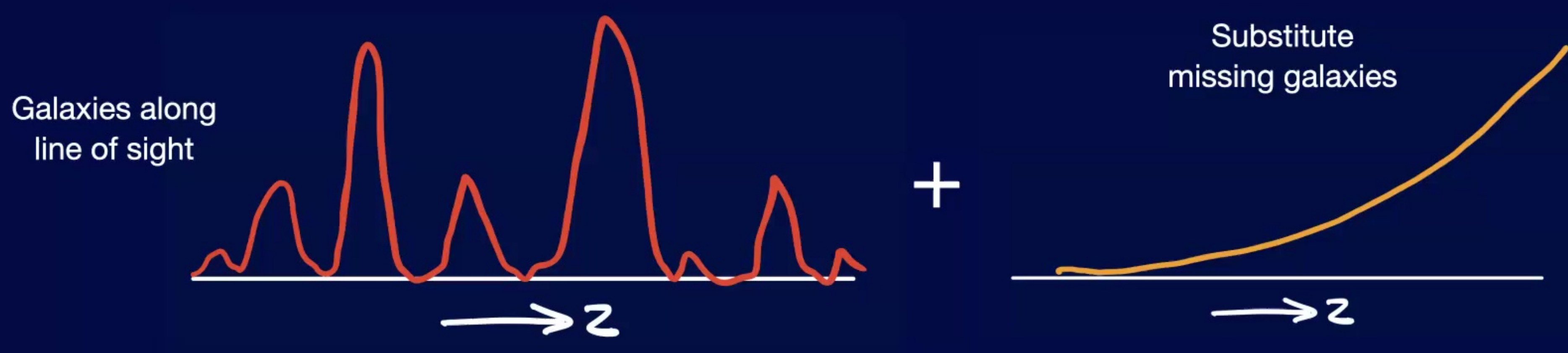
Galaxy Catalogue Incompleteness



$$p(z) = p(\text{in cat.}) \times \{\text{catalogue distrib.}\} + [1 - p(\text{in cat.})] \times \{\text{uniform distrib.}\}$$

Mandel et al. (2019)
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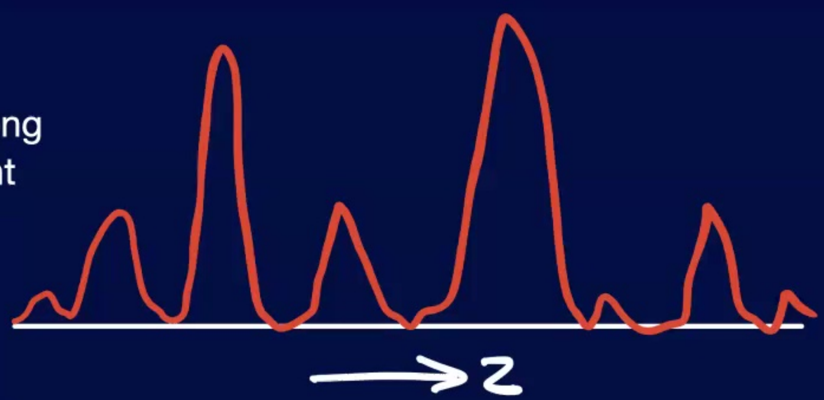
Galaxy Catalogue Incompleteness

Galaxies along line of sight



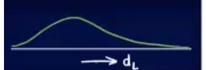
+

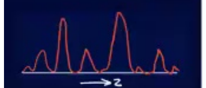
Substitute missing galaxies

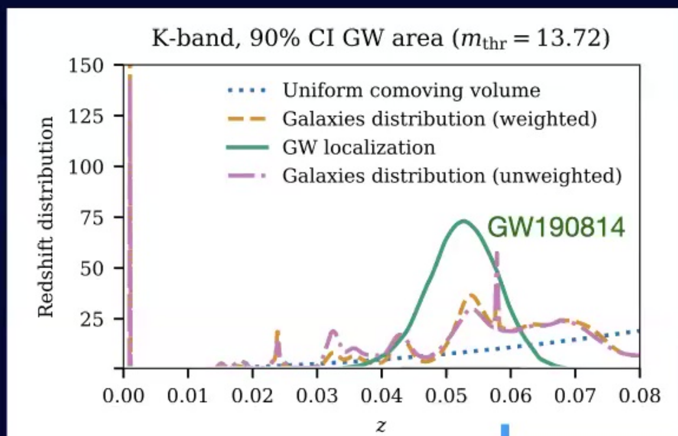
$$p(z) = p(\text{in cat.}) \times \{\text{catalogue distrib.}\} + [1 - p(\text{in cat.})] \times \{\text{uniform distrib.}\}$$

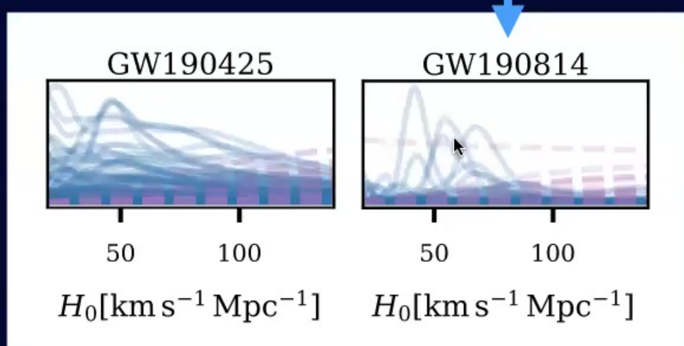
Can include weights based on galaxy magnitude.
(Proxy for star formation, stellar mass, etc.)

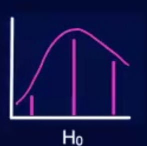
Dark Sirens — Current Results



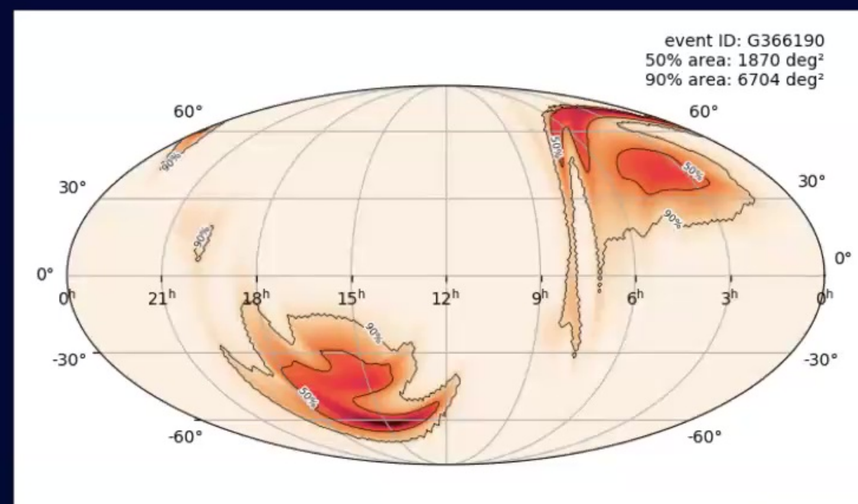






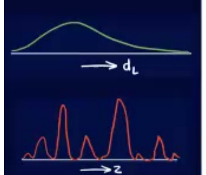


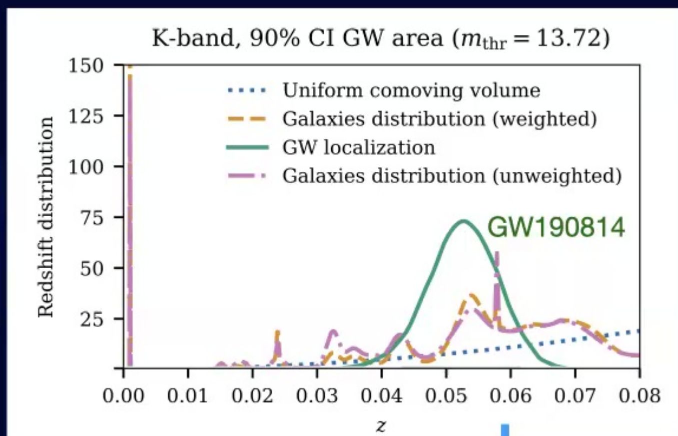
LIGO-Virgo-KAGRA (2022):
'Constraints on the cosmic expansion history from GWTC-3'

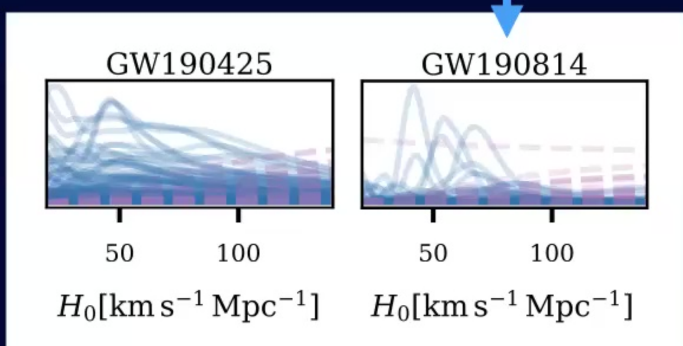


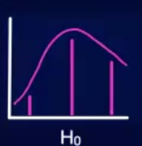
(Demo purposes only — neither event on the left!)

Dark Sirens — Current Results









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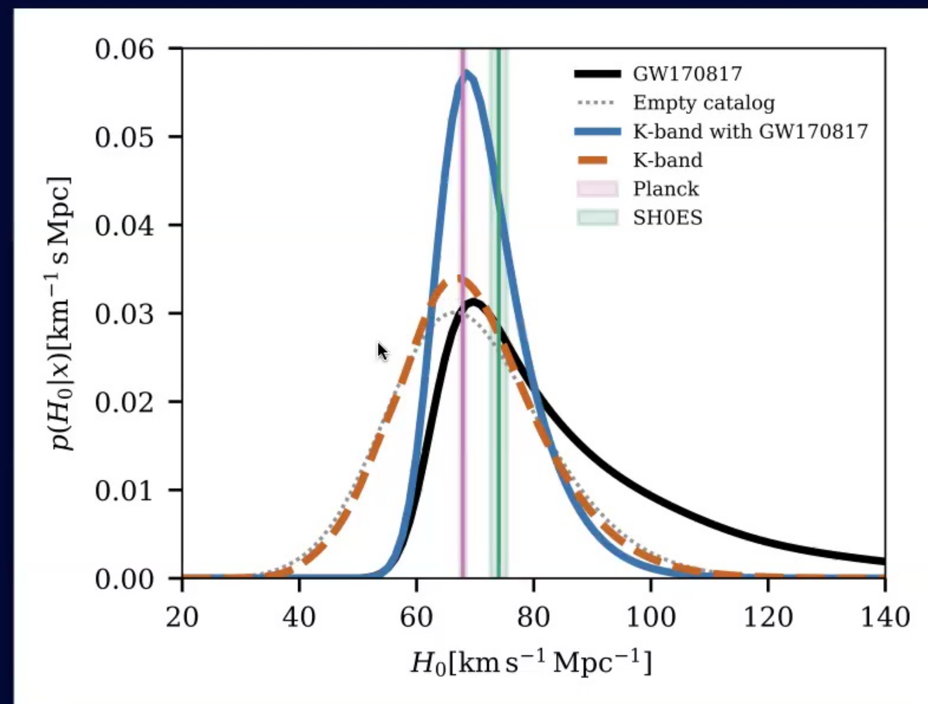

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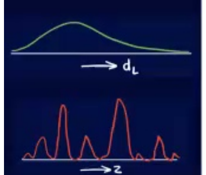

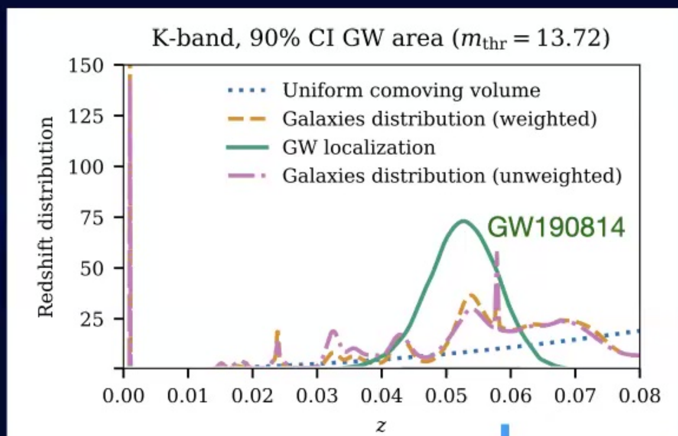

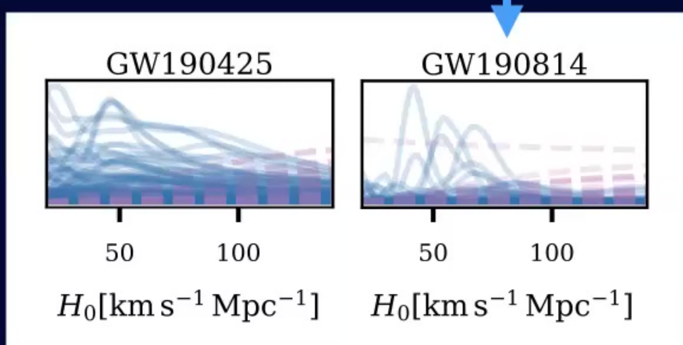

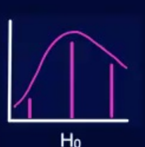

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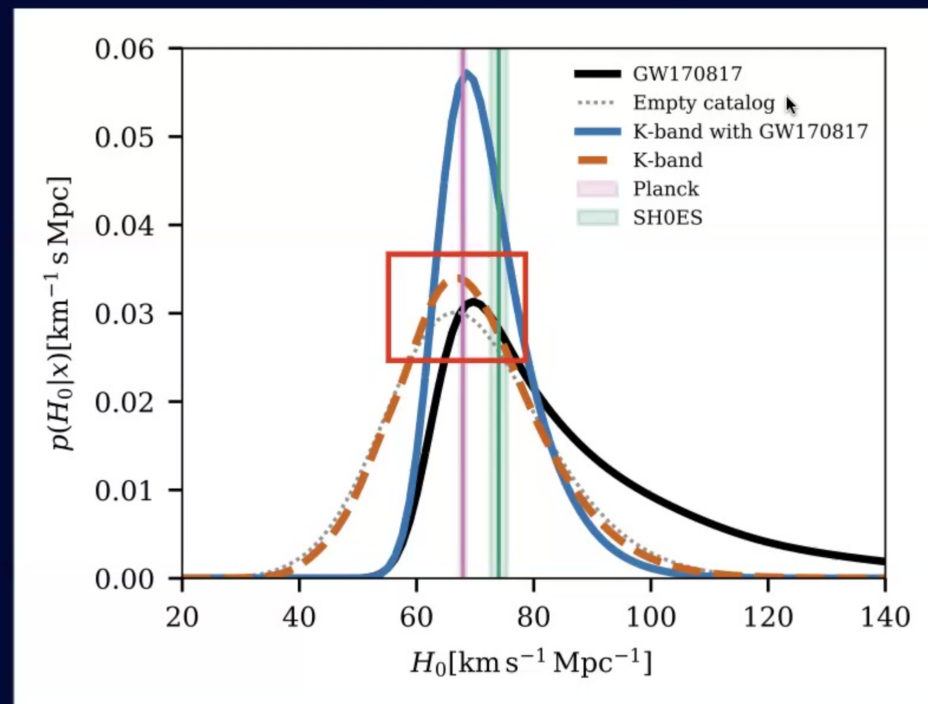
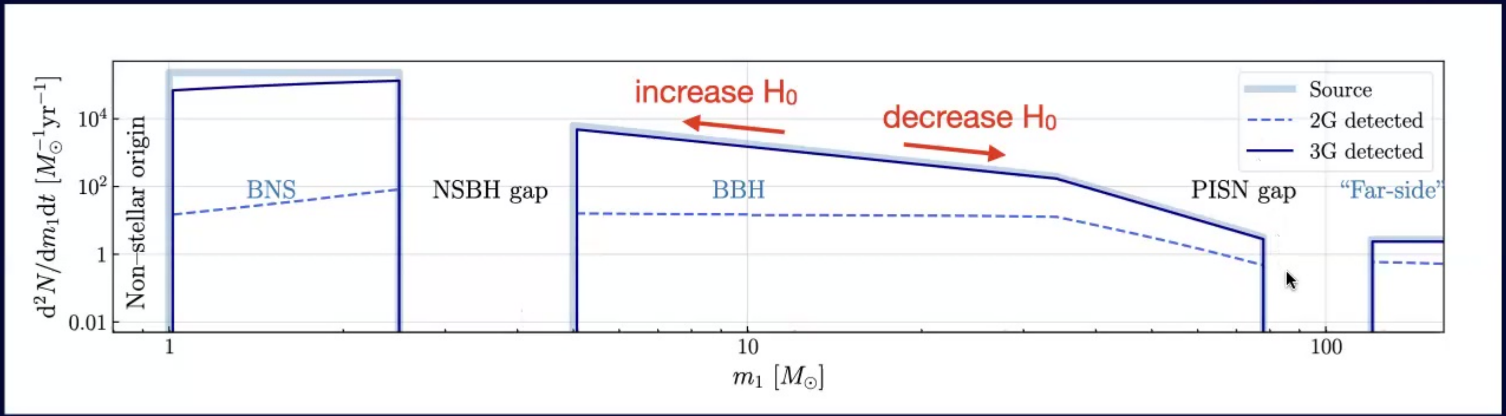


Mass Distribution — Friend or Foe?

Ezquiaga & Holz (2022)



$$m_1^{\rm det} = (1+z)\,m_1$$

GW data constrain (m_1^{det}, d_L)

Determined by d_L-z relation, for a given H_0.

$c\,z \sim H_0\,d$

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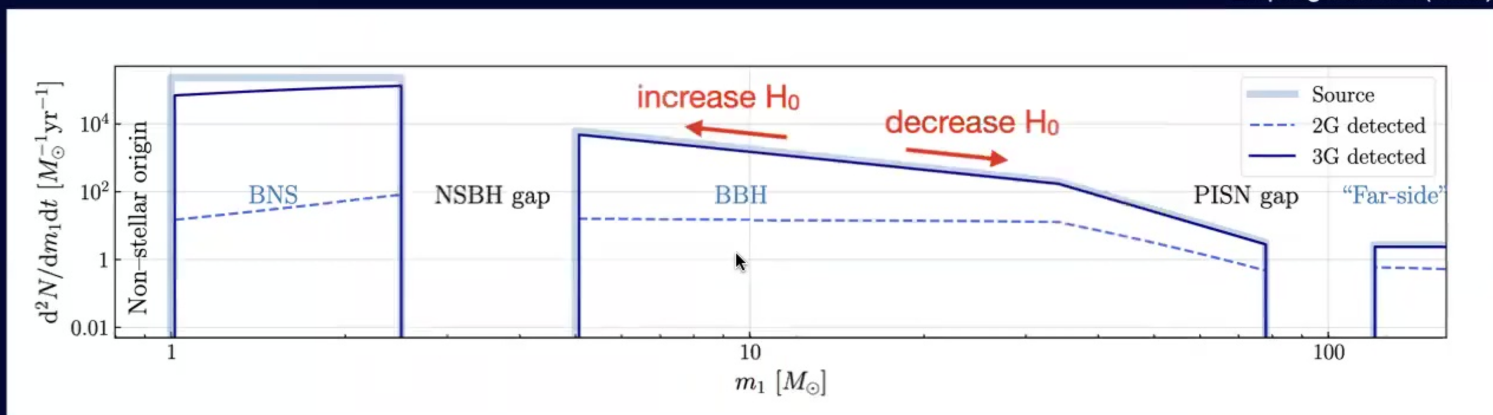

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➡ The source-frame mass distribution of compact objects gives some constraints on H_0. 🙂

➡ We really should vary all the mass distribution parameters along with cosmology. 😩

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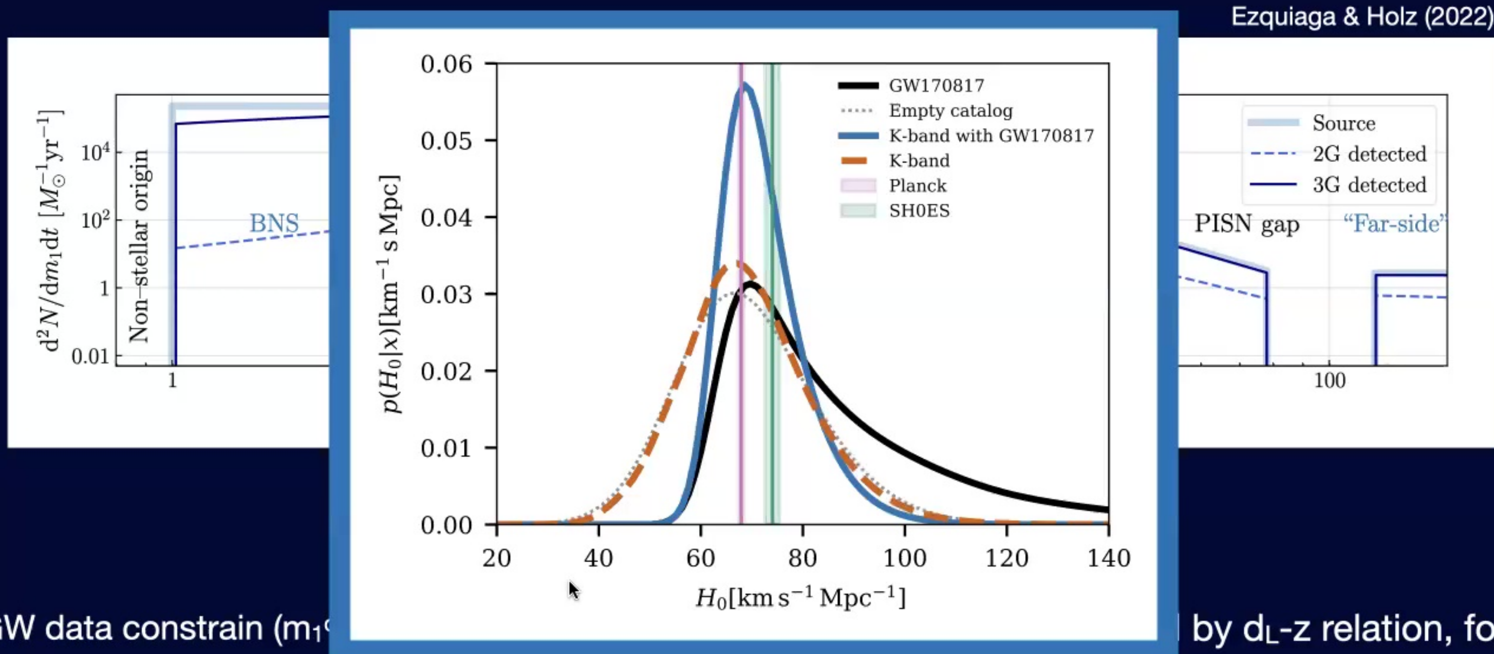

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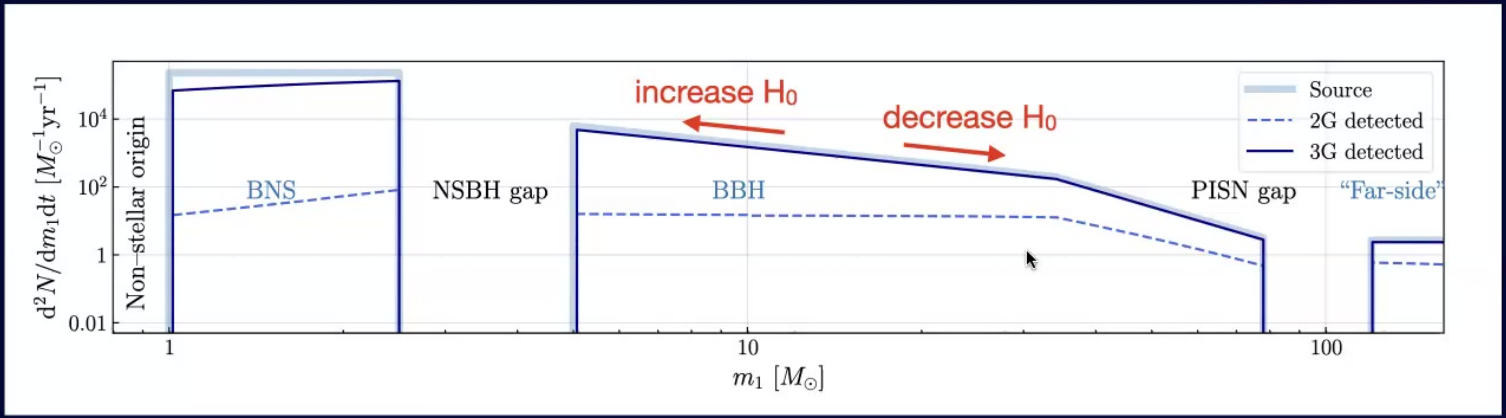

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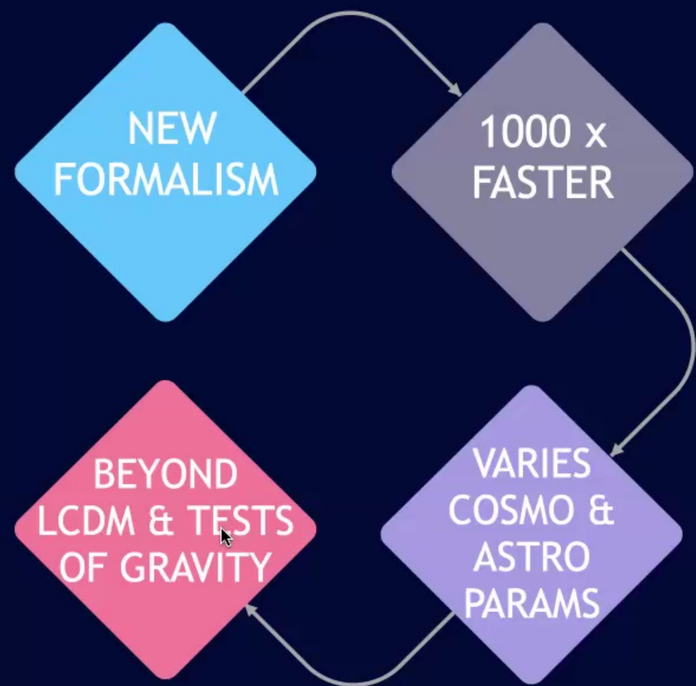
Dark Sirens — the holy grail

Sample a combined likelihood for all astrophysical and cosmological parameters.

Stop press!



Two codes can now do this:

gwcosmo (Gray et al.)

and

IcaroGW (Mastrogiovanni et al.)

Look out for our results in O4....

Hierarchical Bayesian Formalism

NB: toy version only!

Full calculation: Mandel e
Gray et a
Finke et

GW data set

Bayes' theorem: $p\left(H_0|\mathcal{D}_{\rm GW}\right) = p\left(H_0\right) \frac{p\left(\mathcal{D}_{\rm GW}|H_0\right)}{p\left(\mathcal{D}_{\rm GW}\right)} \longrightarrow \prod_i^{\rm events} p\left(\mathcal{D}^i_{\rm GW}|H_0\right)$

GW events are indepen

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GW parameter estimation pipeline

galaxy catalogue

Sky p

Galaxy ma

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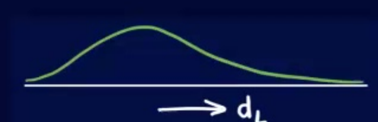
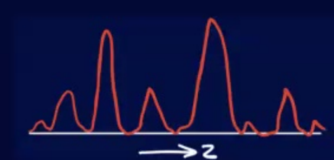
Higher H_0 → more volume → more galaxies

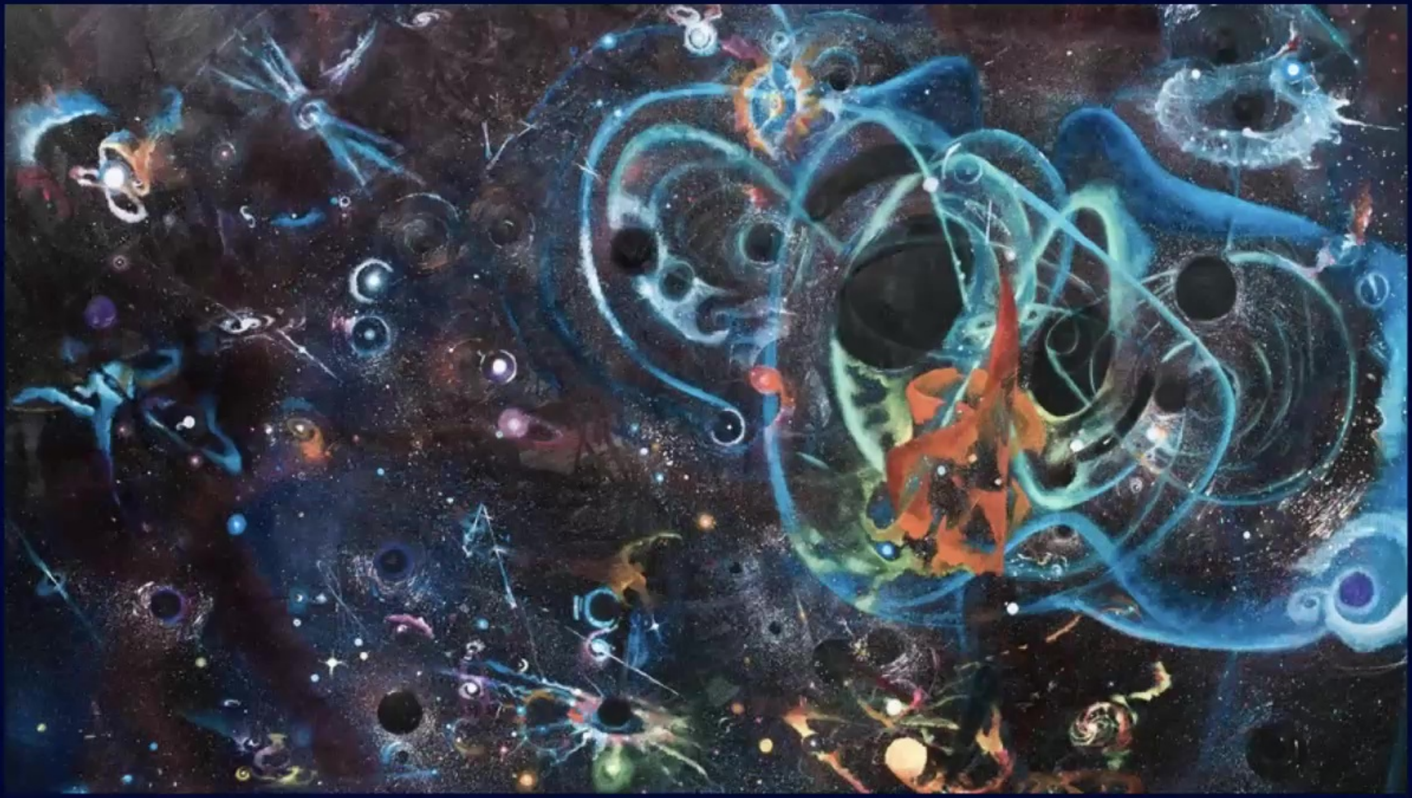
Crucial to avoid biasing H_0 posterior.





T. Baker 13 Perime

Tests of Gravity with GWs



`Infinite LIGO Dreams'

Penelope Cowley

Dark Siren Tests of Gravity

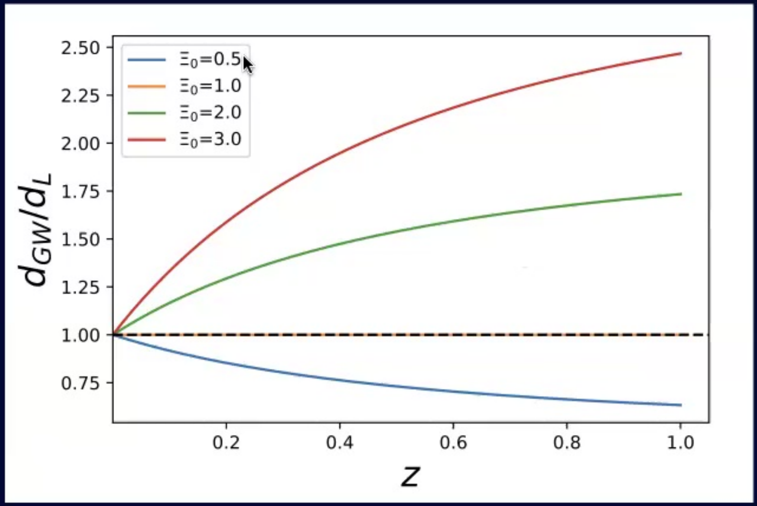
Deviations from GR affect GW luminosity distances:

$$\tilde{h}_{+,\times}(f) \propto \frac{\mathcal{M}_z^2}{\boxed{d_{\rm GW}}} (\pi \mathcal{M}_z f)^{-\frac{7}{6}} \times \text{(polarisation angles)} \times \text{(inclination factor)}$$

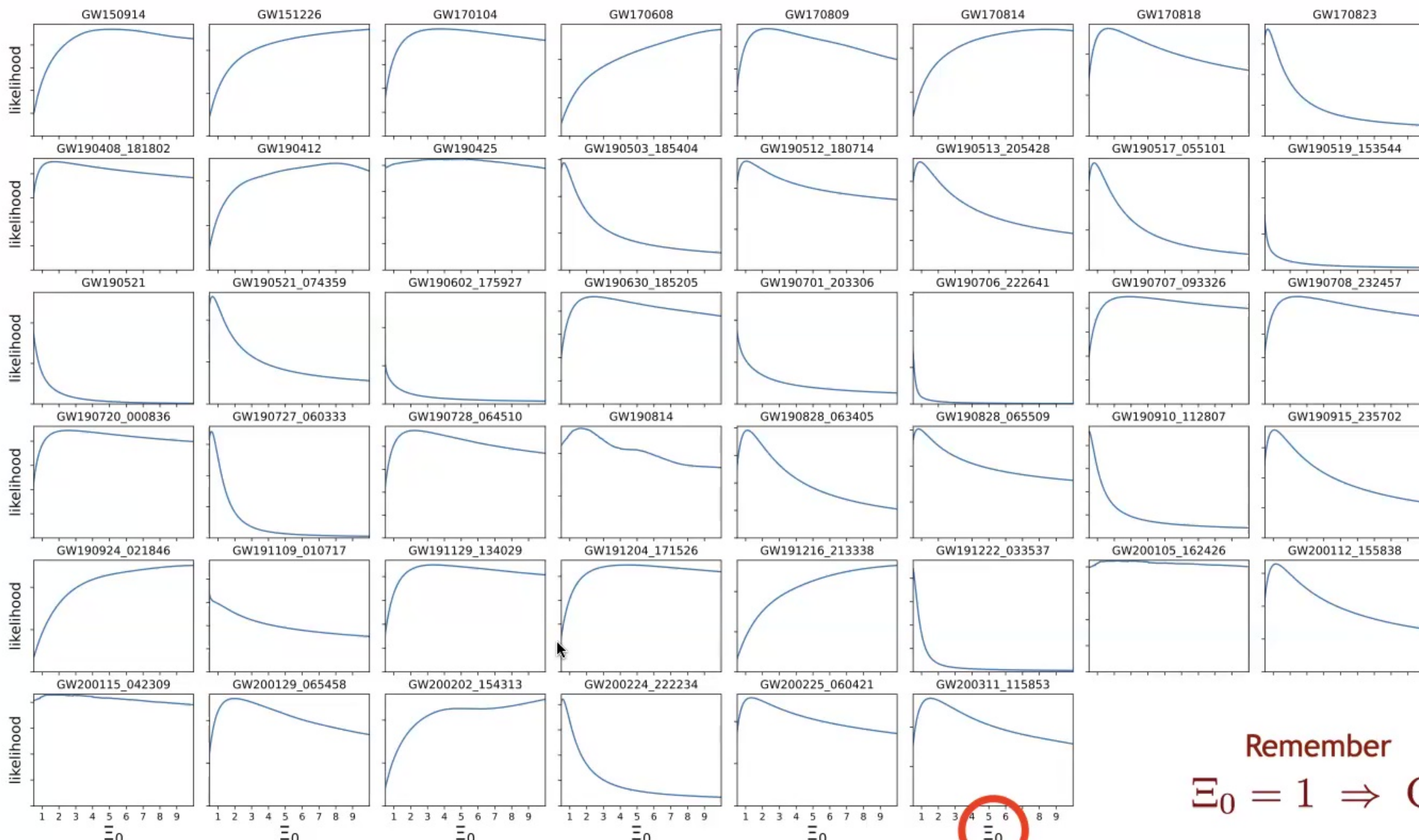
GW Luminosity distance parameterisation

$$\frac{d_{\rm GW}}{d_L} = \Xi_0 + \frac{(1-\Xi_0)}{(1+z)^n}$$

Belgacem et al. (2018)



Results from O3 data (preliminary)

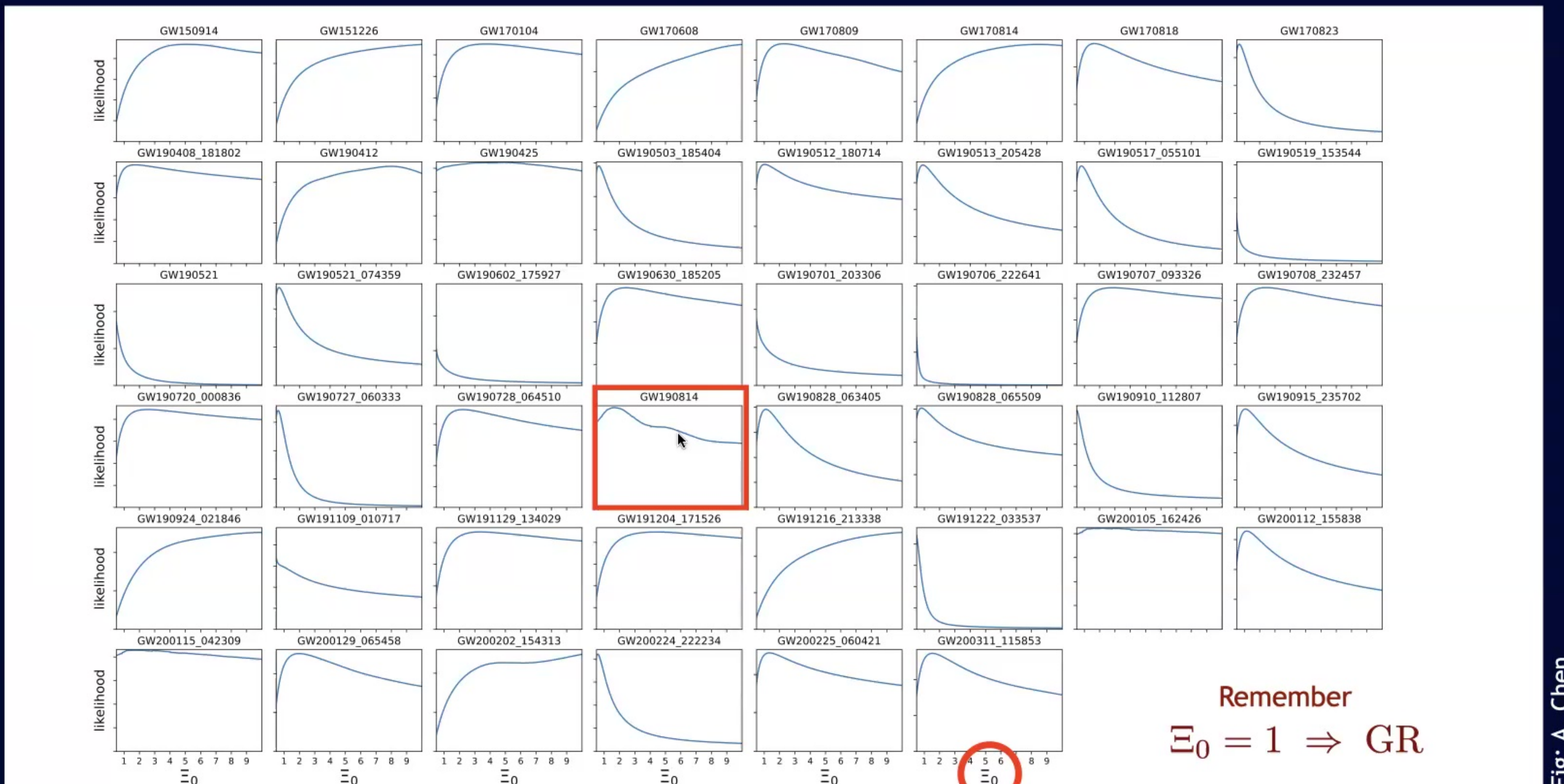


Remember

$\Xi_0 = 1 \Rightarrow \text{GR}$

Fig: A. Chen

Results from O3 data (preliminary)



Results from O3 data (preliminary)

Parameters describing black hole mass distribution

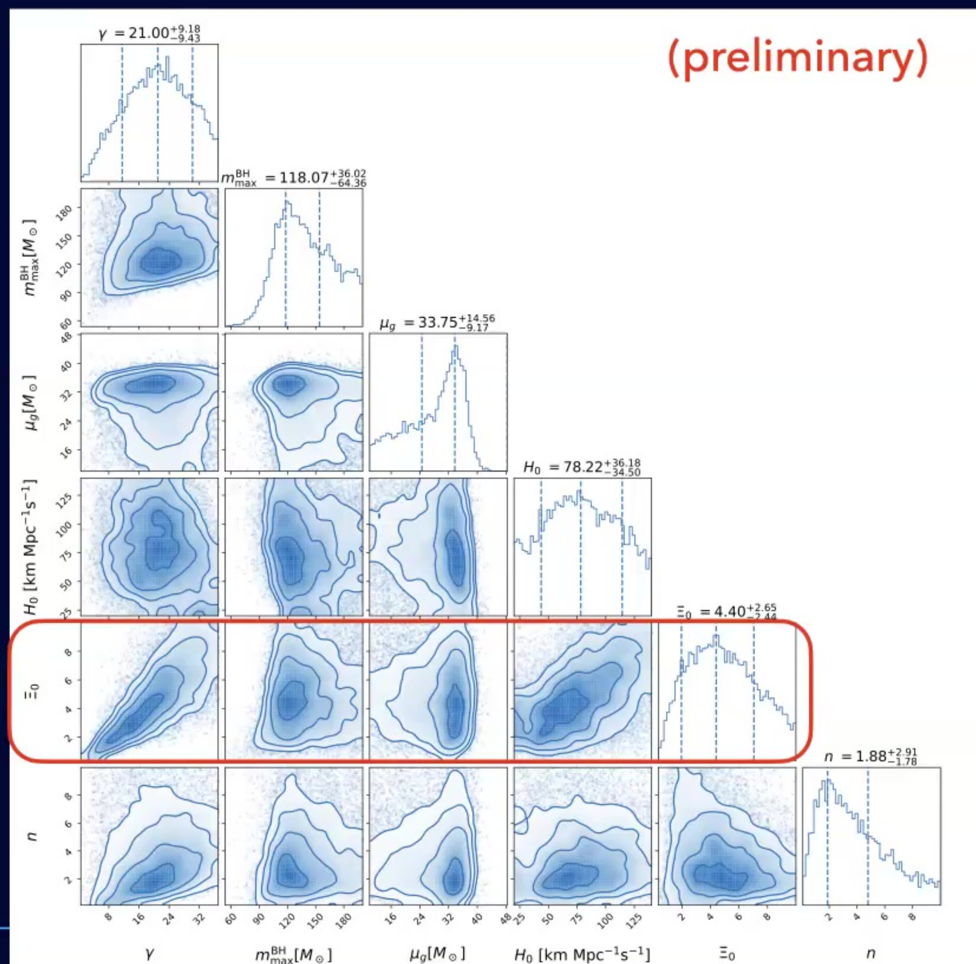
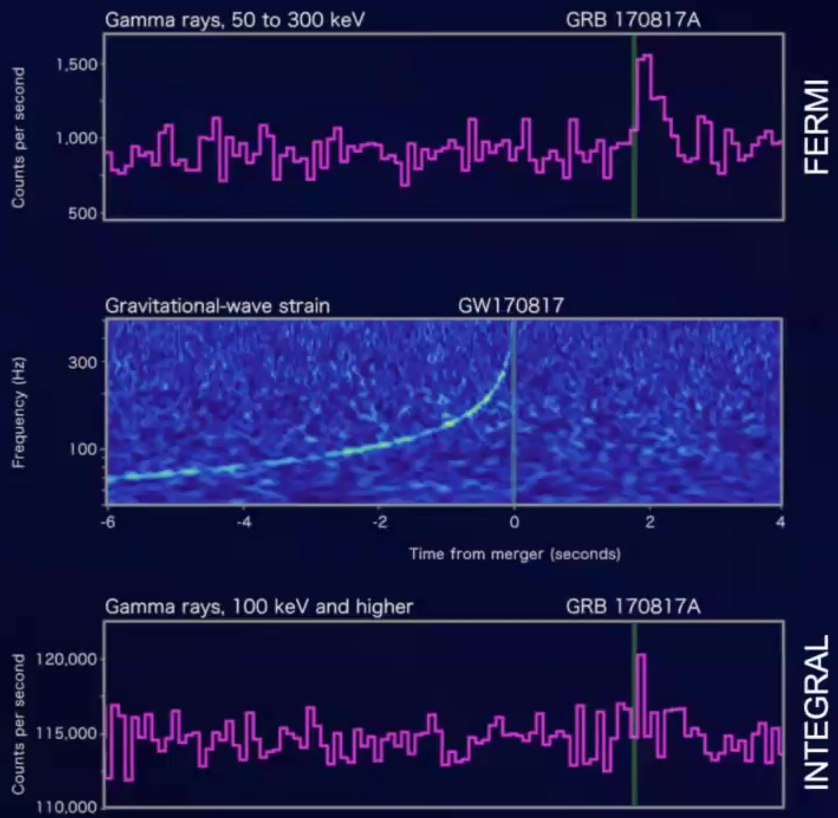


Figure: Anson Chen

We use the code **gwcosmo** (Gray et al.), extended for MG by Anson Chen.

1710.06394
1710.05832
1710.05834

Propagation Speed with GW170817

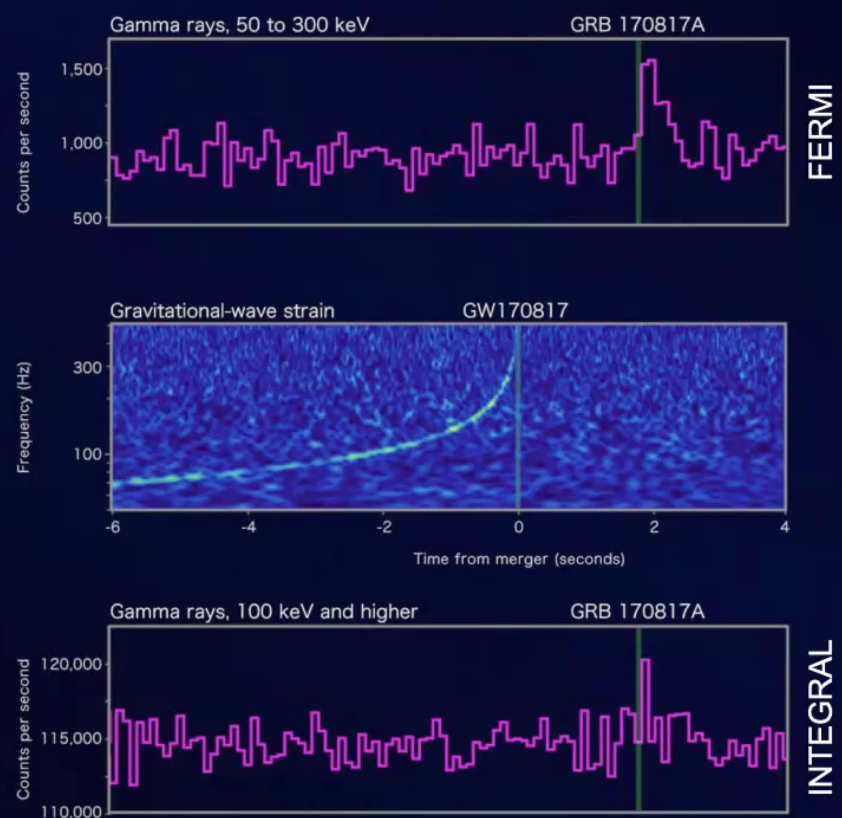


- Propagation speed of GWs was constrained by GW170817 & GRB170817a.
- $\Delta t = t_{GW} - t_{GRB} = 1.7s$

$$\Rightarrow \frac{\delta c_T}{c} = \left|1 - \frac{c_T}{c}\right| \lesssim 10^{-15}$$

1710.06394
1710.05832
1710.05834

Propagation Speed with GW170817



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$$\Rightarrow \frac{\delta c_T}{c} = \left|1 - \frac{c_T}{c}\right| \lesssim 10^{-15}$$

- Claim — this ruled out a lot of **Horndeski** theories.

Horndeski = general 'parent theory' of all* gravity models with scalar fields

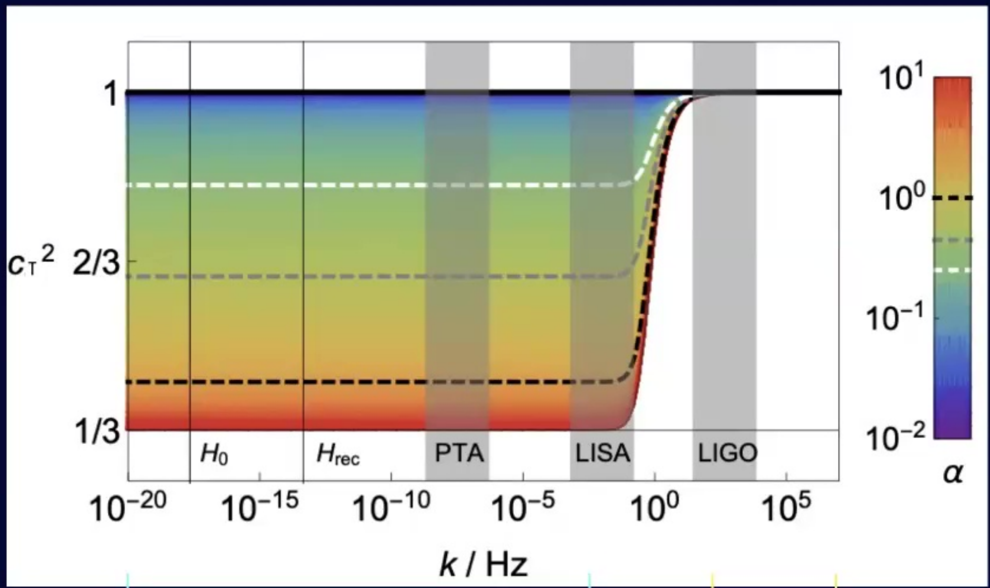
*slight oversimplification

Running propagation speed

- But when viewed as an EFT, the Horndeski family has an energy cut-off scale (where the theory breaks down)

Cut-off scale:

$$\Lambda_{EFT} \sim 260\,\mathrm{Hz}$$



de Rham & Melville (2018)

Horndeski/EFT valid here, $c_T \neq c$

$c_T \rightarrow c$ here (Lorentz invariance required at high energies)

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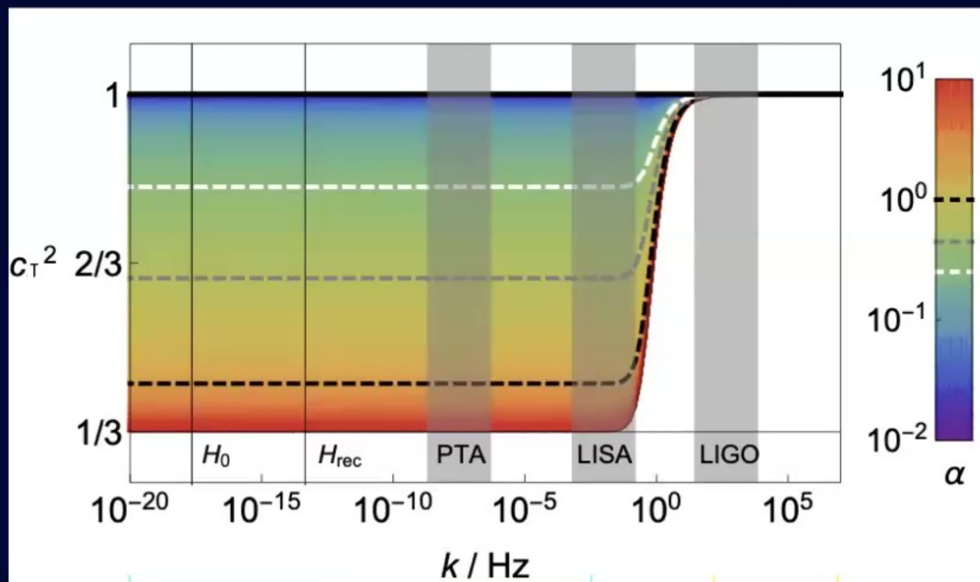


de Rham & Melville (2018)

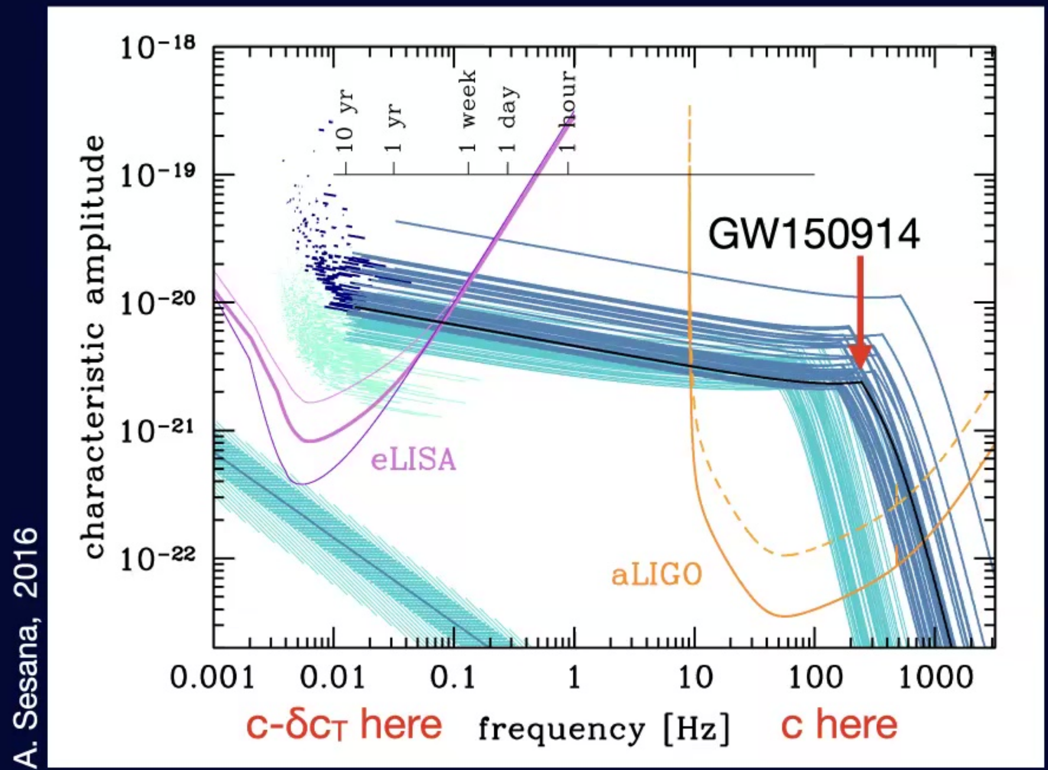
Horndeski/EFT valid here, $c_T \neq c$

$c_T \rightarrow c$ here (Lorentz invariance required at high energies)

- So the question of GW propagation speed *at low frequencies* is back on the table…

arXiv 2209.14398

Constraints from Multiband Sources



A change in the speed of propagation causes a a shift in coalescence time of the binary:

$$t - t_c = \tau_{\rm GR} + \frac{D}{c}\frac{\delta c_T}{c} + \text{subleading corrections}$$

Large (~ billion years)

Tiny, e.g. 10^{-15}

→ **Overall shift of 2 mins in coalescence time**

→ **Constraint on $\delta c_T/c \sim 10^{-15}$**

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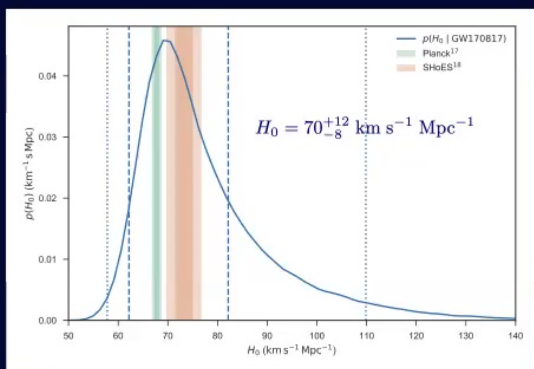
Conclusions

1.



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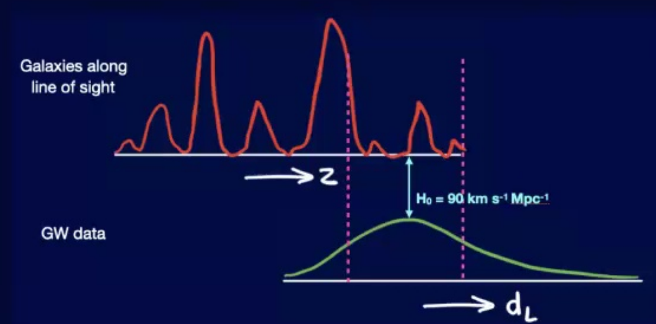

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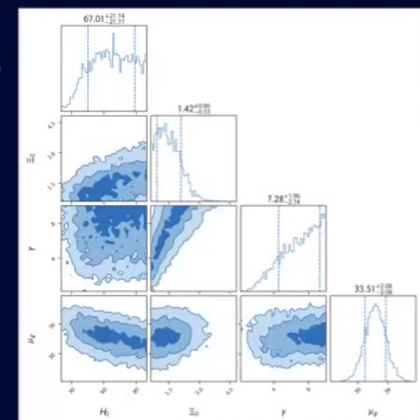
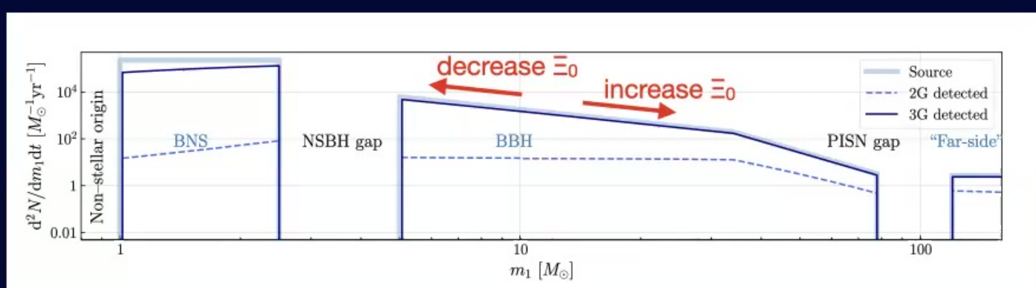


4.



5.