26/04/2021

GReCO, IAP

Cosmology with dark sirens from GWTC-2

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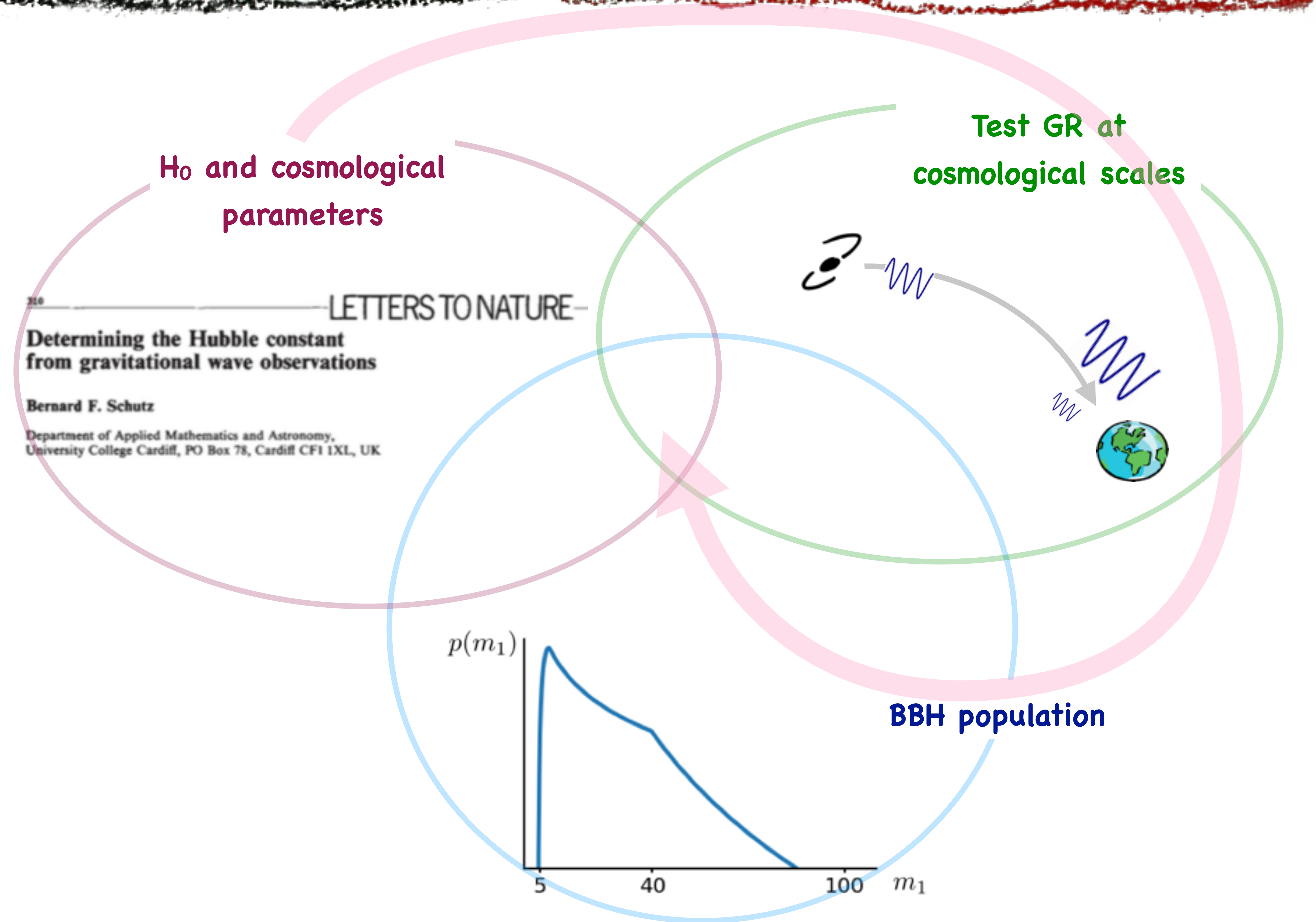
OVERVIEW



H_0 and cosmological parameters

Test GR at cosmological scales

BBH population

310 LETTERS TO NATURE

Determining the Hubble constant from gravitational wave observations

Bernard F. Schutz

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OUTLINE

(1) GWs at cosmological distances

(2) The distance. Modified GW propagation - why, how, where

(3) The redshift & how to get it

(4) GWs + galaxy catalogs.

- Completeness, completion, selection bias, “systematics”
- Application to GWTC-2

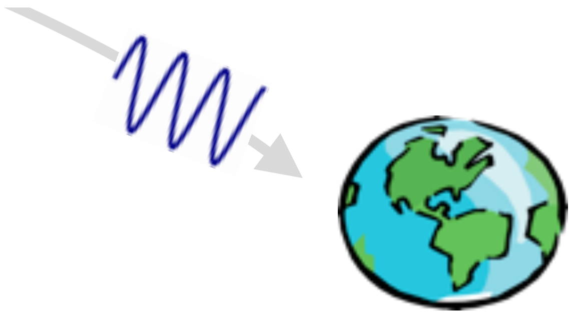
(5) GWs alone: cosmology meets population models

GWs AT COSMOLOGICAL DISTANCES - GR

$\{m_1, m_2, z\}$

- Time and frequency redshifted
- Amplitude scales as ~1/a

$$h \propto \frac{1}{R}\left(\frac{G\mathcal{M}_c}{c^2}\right)^{5/3}\left(\frac{\pi f_S(\tau_S)}{c}\right)^{2/3}$$ (x time-dep. phase x inclination)



$$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

$\{m_1^D, m_2^D, d_L\}$

$$h \propto \frac{1}{R\,a(t_O)(1+z)}\left(\frac{G\mathcal{M}_c(1+z)}{c^2}\right)^{5/3}\left(\frac{\pi f_O(\tau_O)}{c}\right)^{2/3}$$

LUMINOSITY DISTANCE $d_L^{\rm em}(z; H_0, \ldots)$ **“standard siren”**

DETECTOR-FRAME MASSES

$$\mathcal{M}_c^D = \mathcal{M}_c \times (1+z)$$
$$m_i^D = m_i \times (1+z)$$

redshift is not determined

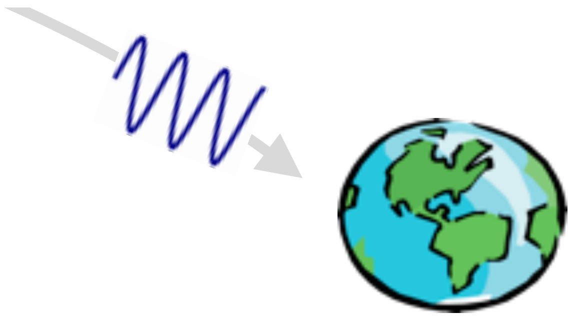
GWs AT COSMOLOGICAL DISTANCES - GR

$\{m_1, m_2, z\}$

$h \propto 1/d_L$

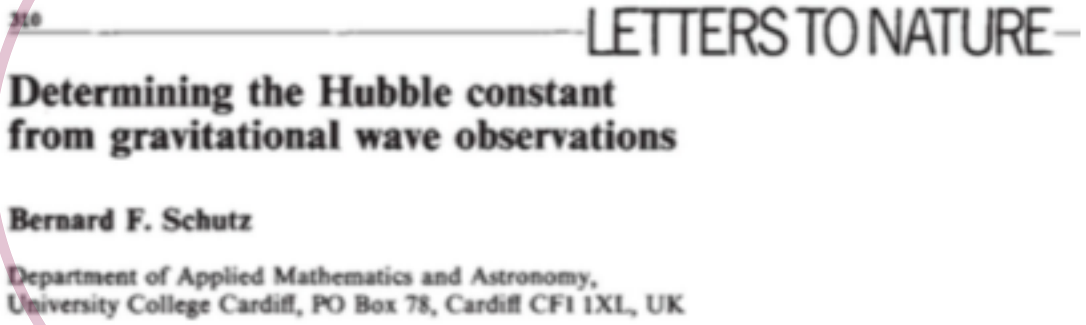
“standard siren”

- Time and frequency redshifted
- Amplitude scales as ~1/a



$\{m_1^D, m_2^D, d_L\}$

H₀ and cosmological parameters



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$d_L^{\rm em}(z; H_0, ...)$

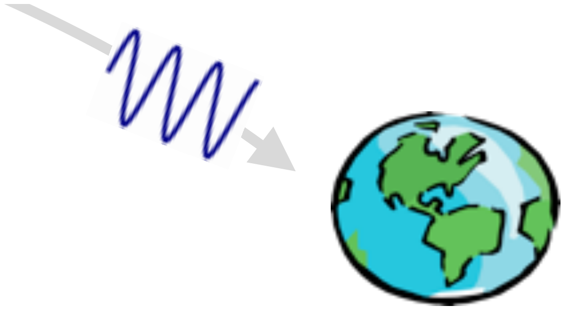
GWs AT COSMOLOGICAL DISTANCES -MG

$\{m_1, m_2, z\}$

$h \propto 1/d_L$

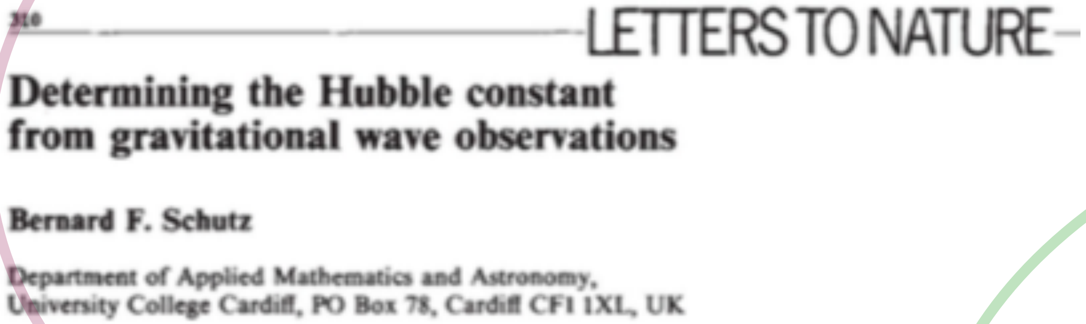
“standard siren”

- Time and frequency redshifted
- **Amplitude scales as ~1/a**



$\{m_1^D, m_2^D, d_L\}$

H₀ and cosmological parameters



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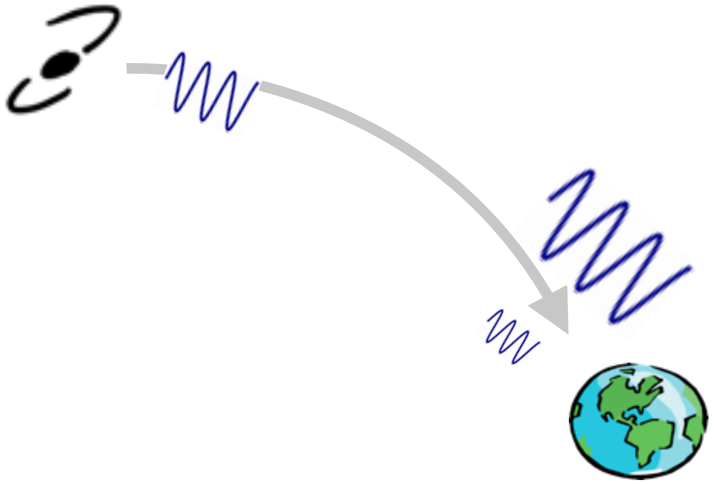
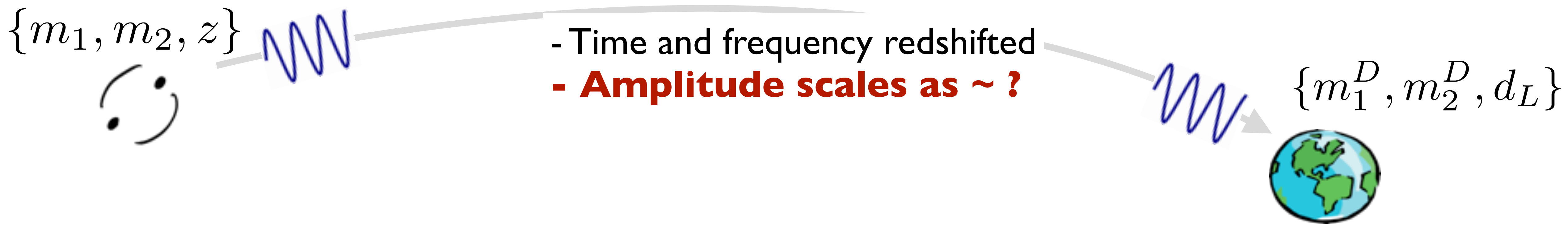
$d_L^{\rm em}(z; H_0, ...)$

Test GR at cosmological scales



MODIFIED GW PROPAGATION: WHY



$\{m_1, m_2, z\}$

- Time and frequency redshifted
- **Amplitude scales as ~ ?**

$\{m_1^D, m_2^D, d_L\}$

GR

$$h_A'' + 2\mathcal{H}h_A' + c^2k^2h_A = 0$$

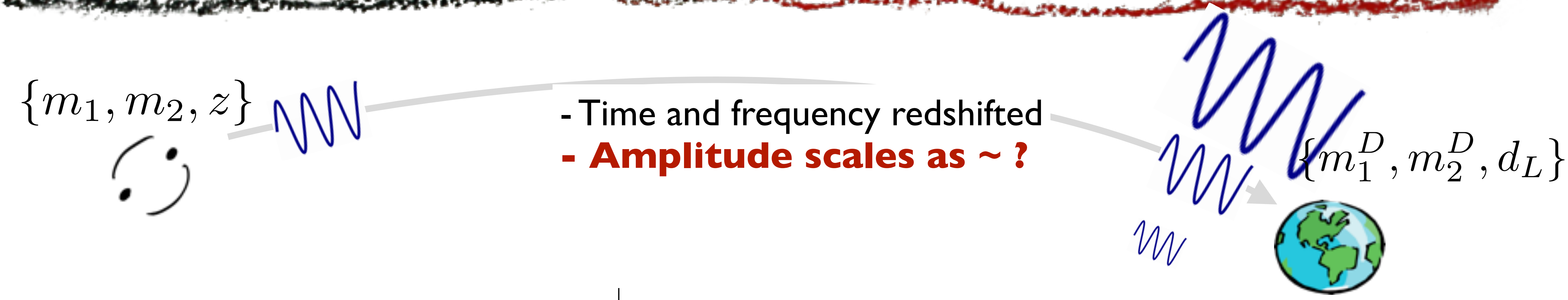
$$\chi_A(\eta,\vec{k}) = a(\eta)\,h_A(\eta,\vec{k})$$

$$\chi_A'' + (k^2 - \cancel{a''/a})\chi_A = 0$$

SUB-HORIZON

$$h_A = \frac{\chi_A}{a} \propto 1/d_L^{\rm em}$$

MODIFIED GW PROPAGATION: WHY



$\{m_1, m_2, z\}$

- Time and frequency redshifted

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$\{m_1^D, m_2^D, d_L\}$

GR

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SUB-HORIZON

$$h_A = \frac{\chi_A}{a} \propto 1/d_L^{\rm em}$$

MG

$$h_A'' + [2 + \alpha_M(\eta)]\mathcal{H}h_A' + c^2k^2h_A = 0$$

$$\chi_A(\eta,\vec{k}) = a_{GW}(\eta)\,h_A(\eta,\vec{k})$$

$$a_{GW}'/a_{GW} = \mathcal{H}\,[1 + \alpha_M(\eta)/2]$$

GWs FEEL “EFFECTIVE SCALE FACTOR”

$$h_A = \frac{\chi_A}{a_{GW}} \propto 1/d_L^{\rm GW}$$

Amendola, Sawicki, Kunz, Saltas
1712.08623
Belgacem, Dirian, Foffa, Maggiore
1712.08108
Lagos, Fishbach, Landry, Holz
1901.03321

Horndeski/DHOST
Higher dim
Non-local
Bigravity
.....

$$d_L^{\rm GW}(z) = d_L^{\rm em}(z)\exp\left\{\frac{1}{2}\int_0^z \frac{dz'}{1+z'}\,\alpha_M(z')\right\}$$

THIS IS MEASURED FROM GWs !

MODIFIED GW PROPAGATION: HOW (Ξ_0, n)

- General strategy to constrain deviations from GR: parametrize their physical effects

BASE PARAMETERS		$(H_0, \Omega_{\rm M}, ...)$	CMB+BAO+SNe
BACKGROUND	Weird pressure	(w_0, w_a)	CMB+BAO+SNe
(SCALAR	▷ Effective Newton`s constant ▷ Effective anisotropic stress	$G_{\rm eff}(t,k)$ $\eta(t,k)$	LSS WL)
TENSOR	**Modified GW propagation**	(Ξ_0, n)	GWs

MG $$d_L^{\rm GW}(z) = d_L^{\rm em}(z) \exp\left\{\frac{1}{2}\int_0^z \frac{dz'}{1+z'}\,\alpha_M(z')\right\}$$

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

Belgacem, Dirian, Foffa, Maggiore 1805.08731
Belgacem et al. (LISA cosmoWG), 1906.01593

$$\boxed{\frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}}$$

GW-analogue of (w_0, w_a)

(Or : parametrise directly $\alpha_{\rm M}$ *Lagos, Fishbach, Landry, Holz 1901.03321*)

MODIFIED GW PROPAGATION: WHERE

- General strategy to constrain deviations from GR: parametrize their physical effects

BASE PARAMETERS		$(H_0, \Omega_{\rm M}, ...)$	CMB+BAO+SNe
BACKGROUND	Weird pressure	(w_0, w_a)	CMB+BAO+SNe
TENSOR	**Modified GW propagation**	(Ξ_0, n)	GWs

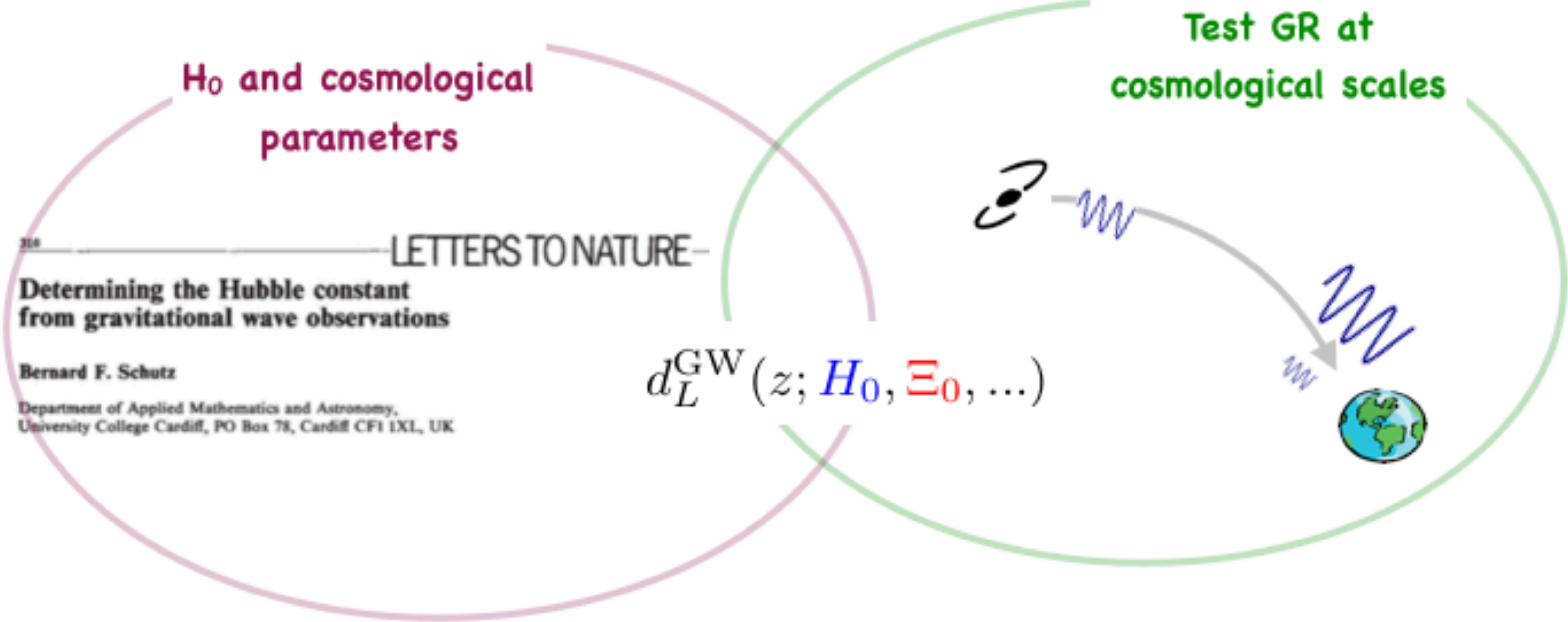
$$d_L^{\rm gw}(z) = \left[\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right] \times \frac{c}{H_0}(1+z)\int_0^z \frac{dz'}{\sqrt{\Omega_{\rm M}(1+z')^3 + \rho_{\rm DE}(z'; w_0, w_a)/\rho_0}}$$

- Effects of modified gravity:
  - Base parameters can be different
  - DE EoS can evolve → Deviations constrained to % level
  - Modified GW propagation → dominant effect, largely unconstrained.

GW-based **test of GR (where Ξ_0=1)**

Belgacem, Dirian, Foffa, Maggiore
1805.08731

$$d_L^{\rm gw}(z) = \left[\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right] \times \frac{c}{H_0}\,(1+z)\int_0^z \frac{dz'}{\sqrt{\Omega_{\rm M}(1+z')^3 + \rho_{\rm DE}(z';w_0,w_a)/\rho_0}}$$



H₀ and cosmological parameters

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$$d_L^{\rm GW}(z; H_0, \Xi_0, \ldots)$$

Test GR at cosmological scales

GETTING THE REDSHIFT

$$d_L^{\rm gw}(z) = \left[\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right] \times \frac{c}{H_0}(1+z)\int_0^z \frac{dz'}{\sqrt{\Omega_{\rm M}(1+z')^3 + \rho_{\rm DE}(z';w_0,w_a)/\rho_0}}$$

- Measure redshift directly from a **direct EM counterpart** - so far only 1 (+1 ?)

  Schutz 1986

- Use information from galaxies in some **catalog** that fall in the GW localization region
- Use information on the **source frame mass**

  Taylor, Gair, Mandel 1108.5161
  Taylor, Gair 1204.6739
  Farr, Fishbach, Ye, Holz 1908.09084

- (Other methods: EOS for NS, correlation with LSS , ...)

  Messenger, Read 1107.5725

  Mukherjee, Wandelt, Silk 2012.15316

GALAXY CATALOGS

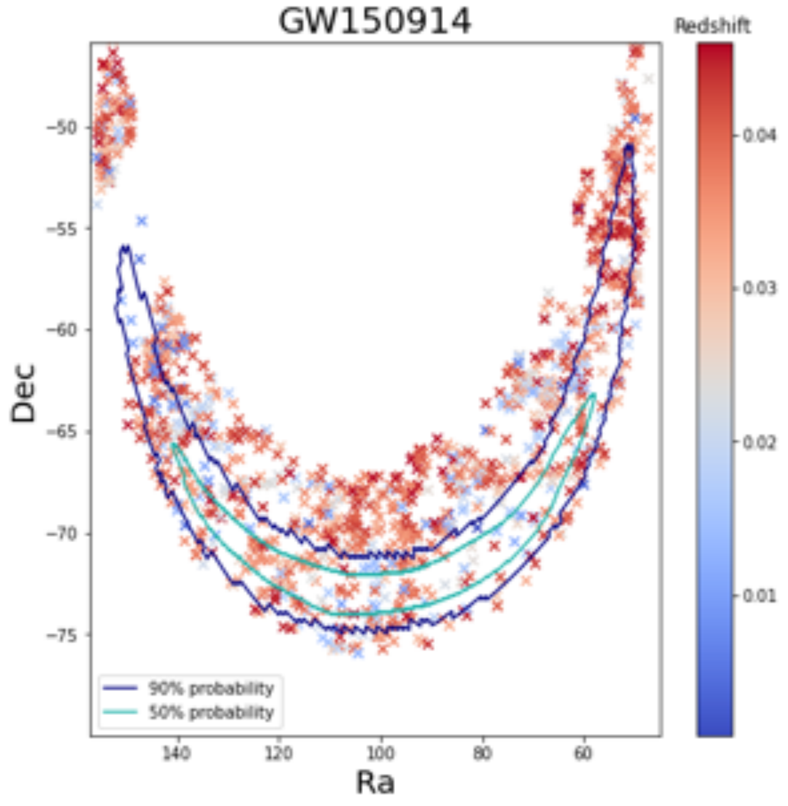
2101.12660 Finke, Foffa, Iacovelli, Maggiore, MM

GETTING THE REDSHIFT

- Use information from galaxies in some **catalog** that fall in the GW localization region

Schutz 1986

  - In absence of counterpart, take redshifts from all galaxies within localization region
  - Compute H_0/Ξ_0 for all of them
  - Doing so for many events you get a distribution peaked at the true value - spurious associations averaged out



- In bayesian language:

Del Pozzo '11, Chen et al '18, Gray et al. `19, ...

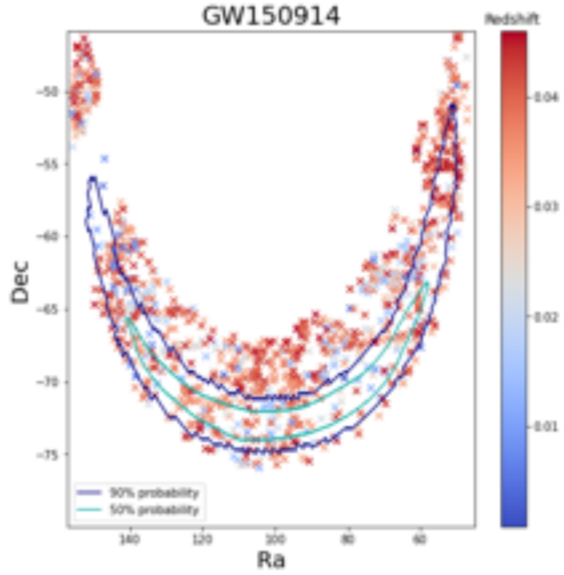
$$p(\lambda|\mathcal{D}_{\rm GW}) \propto \frac{\pi(\lambda)}{\beta(\lambda)^{N_{\rm obs}}} \prod_{i=1}^{N_{\rm obs}} \int dz\, d\Omega\, p(\mathcal{D}^i_{\rm GW}|d_L(z;\lambda),\hat{\Omega})\, p_0(z,\hat{\Omega}) \qquad \lambda = H_0, \Xi_0$$

  - GW likelihood : LVC skymaps (direction-dependent gaussian approx.)
  - Use a galaxy catalogue prior on redshift and position; marginalize
  - Correct for selection bias

GALAXY CATALOGUE PRIOR

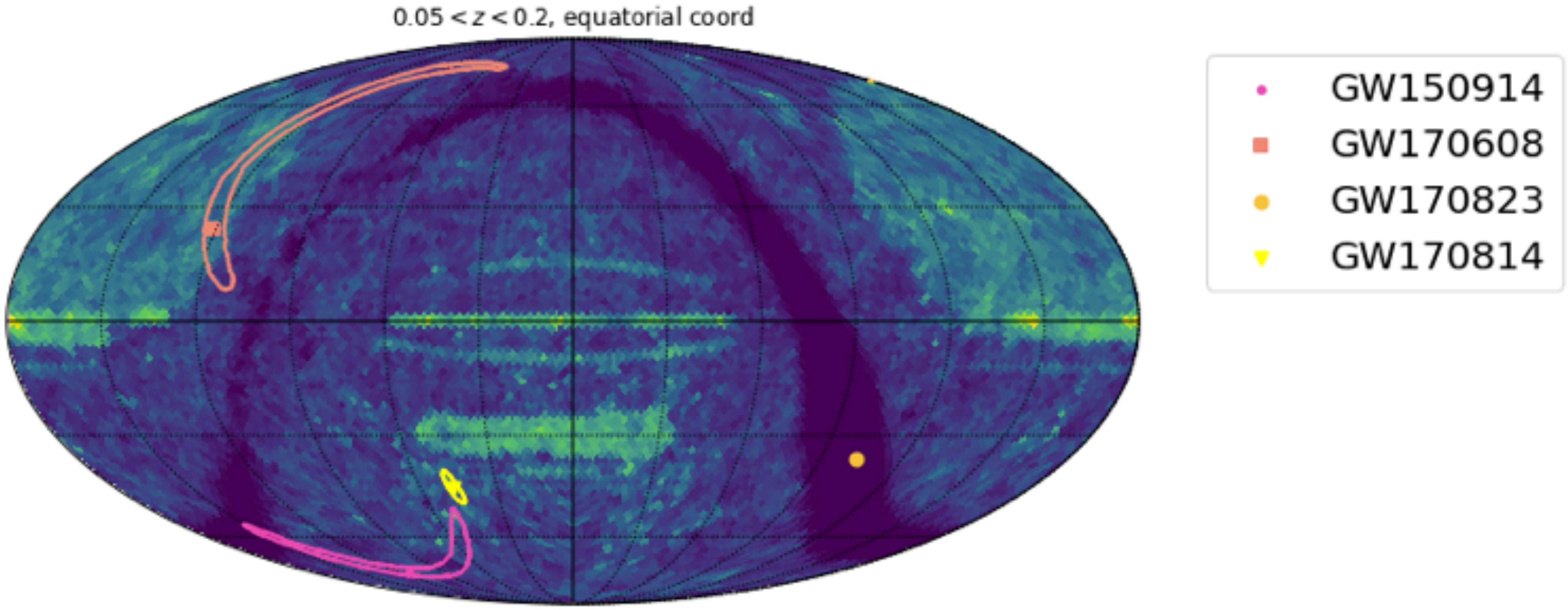
$$p(\lambda|\mathcal{D}_{\rm GW}) \propto \frac{\pi(\lambda)}{\beta(\lambda)^{N_{\rm obs}}} \prod_{i=1}^{N_{\rm obs}} \int dz d\Omega \, p(\mathcal{D}^i_{\rm GW}|d_L(z;\lambda),\hat{\Omega}) \, p_0(z,\hat{\Omega}) \qquad \lambda = H_0, \Xi_0$$

- GLADE galaxy catalogue — *http://glade.elte.hu* — *Dália et al.'18*
- Ideally: prior=smoothed delta functions on galaxy redshift and position
- In practice we miss galaxies: — *Chen, Fishbach, Holz '18*
  - "**COMPLETENESS**": Compute probability of missing galaxies around (z, Ω)

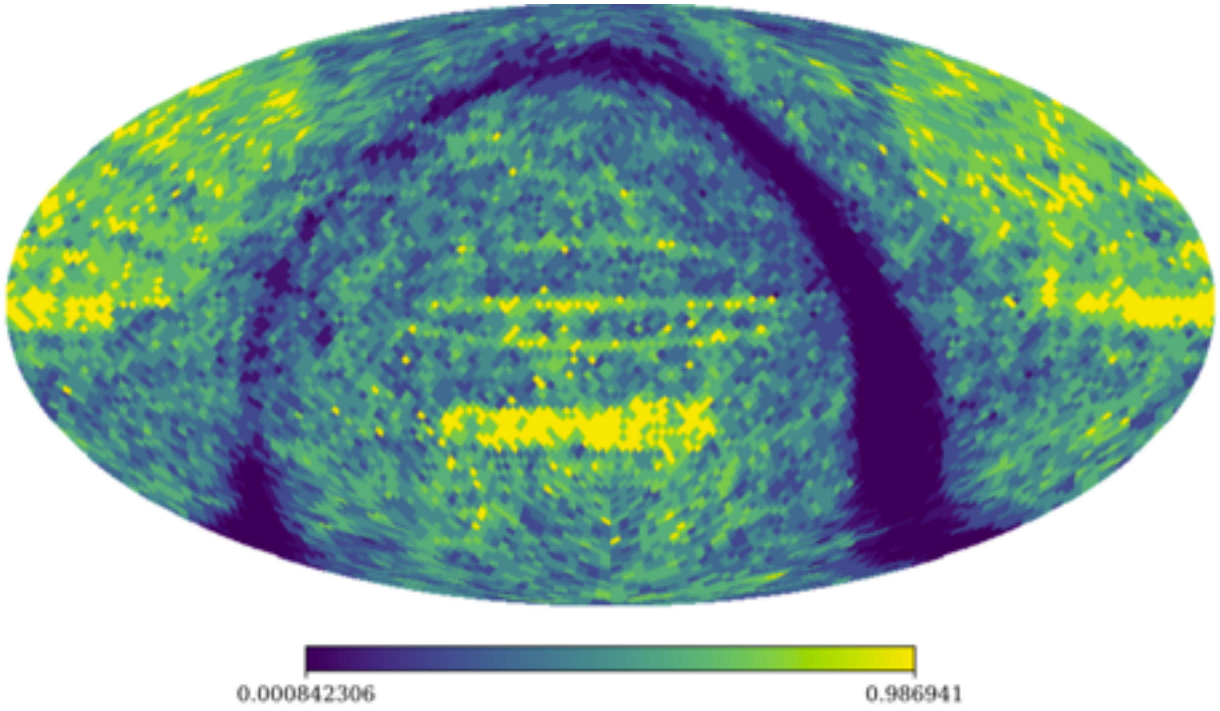


COMPLETENESS

Observed
density
projected on
the sky →



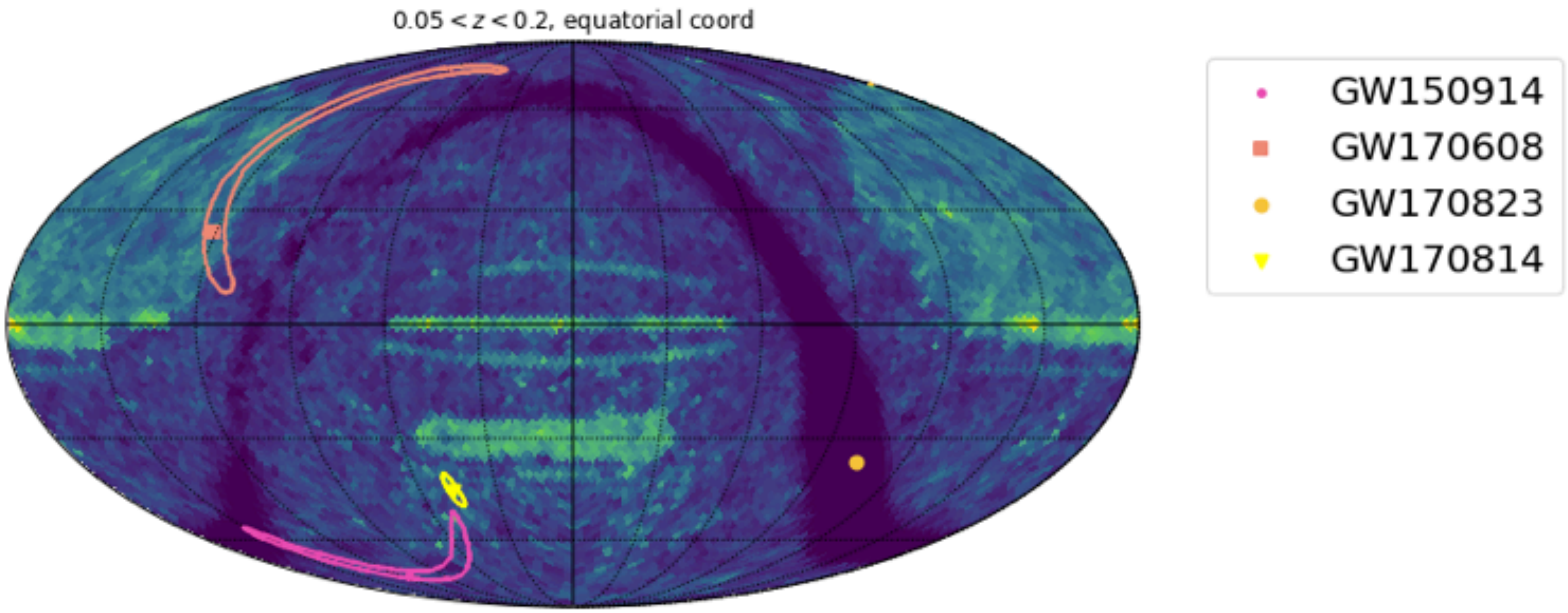
Our computation with a ML clustering algorithm, z~0.11



Neglecting angular dependence

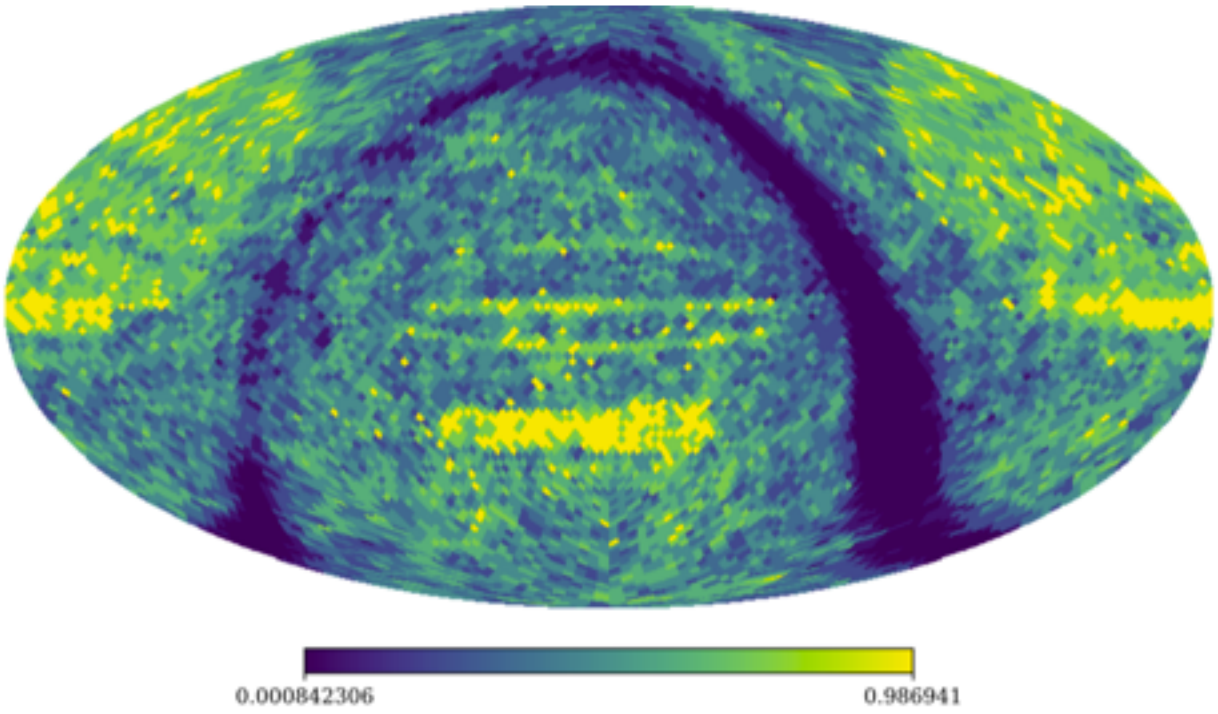
COMPLETENESS

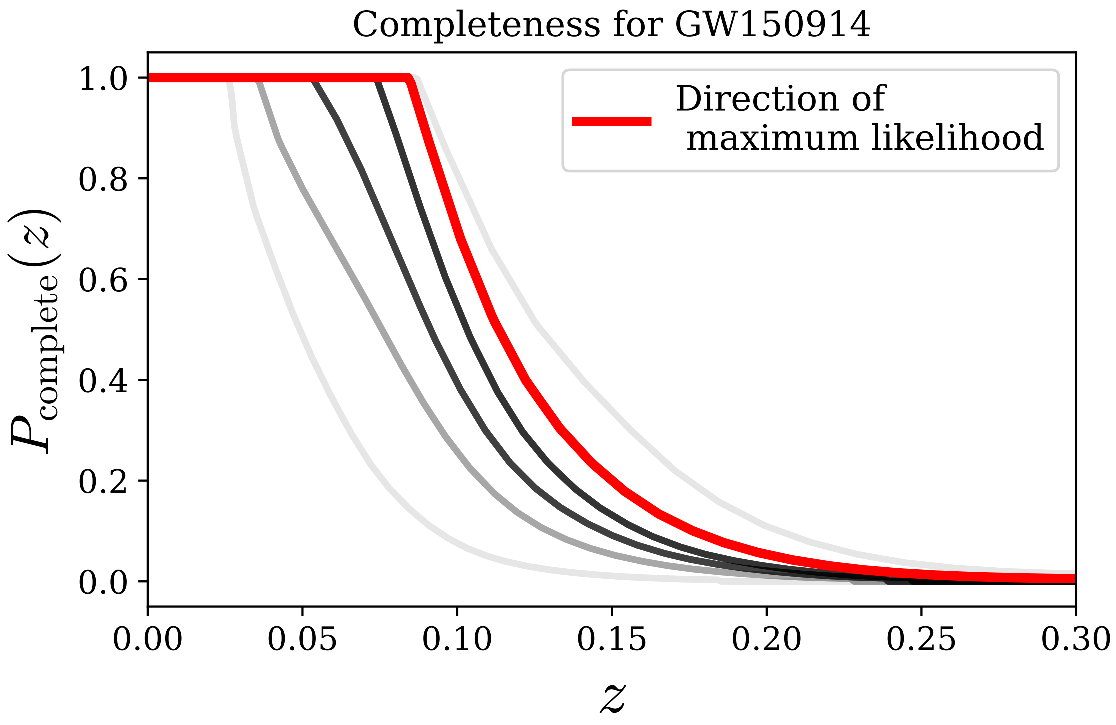
Observed density
projected on
the sky →



0.05 < z < 0.2, equatorial coord

Our computation with a ML clustering algorithm, z~0.11



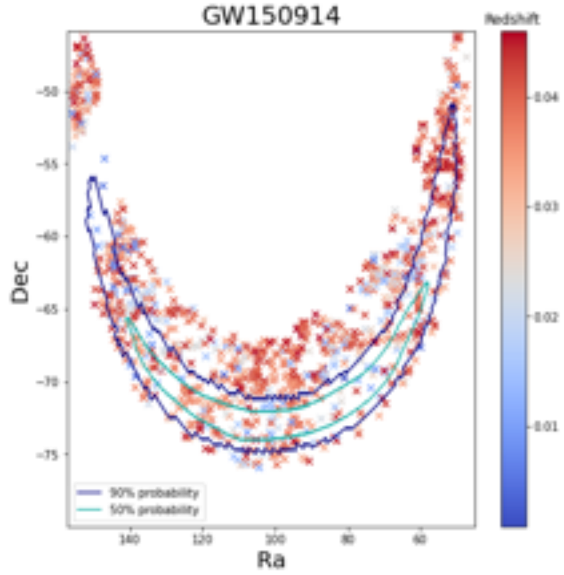


Completeness for GW150914

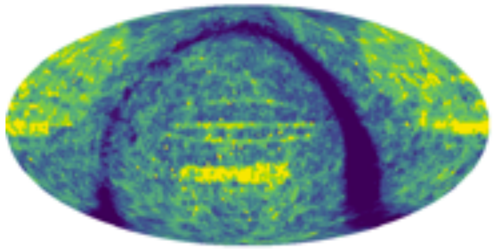
GALAXY CATALOGUE PRIOR

$$p(\lambda|\mathcal{D}_{\rm GW}) \propto \frac{\pi(\lambda)}{\beta(\lambda)^{N_{\rm obs}}} \prod_{i=1}^{N_{\rm obs}} \int dz d\Omega\, p(\mathcal{D}^i_{\rm GW}|d_L(z;\lambda),\hat{\Omega})\, p_0(z,\hat{\Omega}) \qquad \lambda = H_0, \Xi_0$$

- GLADE galaxy catalogue   http://glade.elte.hu   *Dália et al. '18*

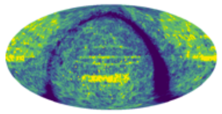


- Ideally: prior=smoothed delta functions on galaxy redshift and position
- In practice we miss galaxies: *Chen, Fishbach, Holz '18*
  - "**COMPLETENESS**": Compute probability of missing galaxies around (z, Ω)
    - ✱ Include angular dependence



  - "**COMPLETION**": Specify how missing galaxies are distributed
    - "*Homogeneous*": spread galaxies uniformly →

    - ✱ "*Multiplicative*": add galaxies near those you have →



    - ✱ Interpolate between hom. and mult. completion: use mult. in fairly complete regions, hom. otherwise

SELECTION BIAS

$$p(\lambda|\mathcal{D}_{\rm GW}) \propto \frac{\pi(\lambda)}{\beta(\lambda)^{N_{\rm obs}}} \prod_{i=1}^{N_{\rm obs}} \int dz d\Omega \, p(\mathcal{D}^i_{\rm GW}|d_L(z;\lambda),\hat{\Omega})\, p_0(z,\hat{\Omega}) \qquad \lambda = H_0, \Xi_0$$

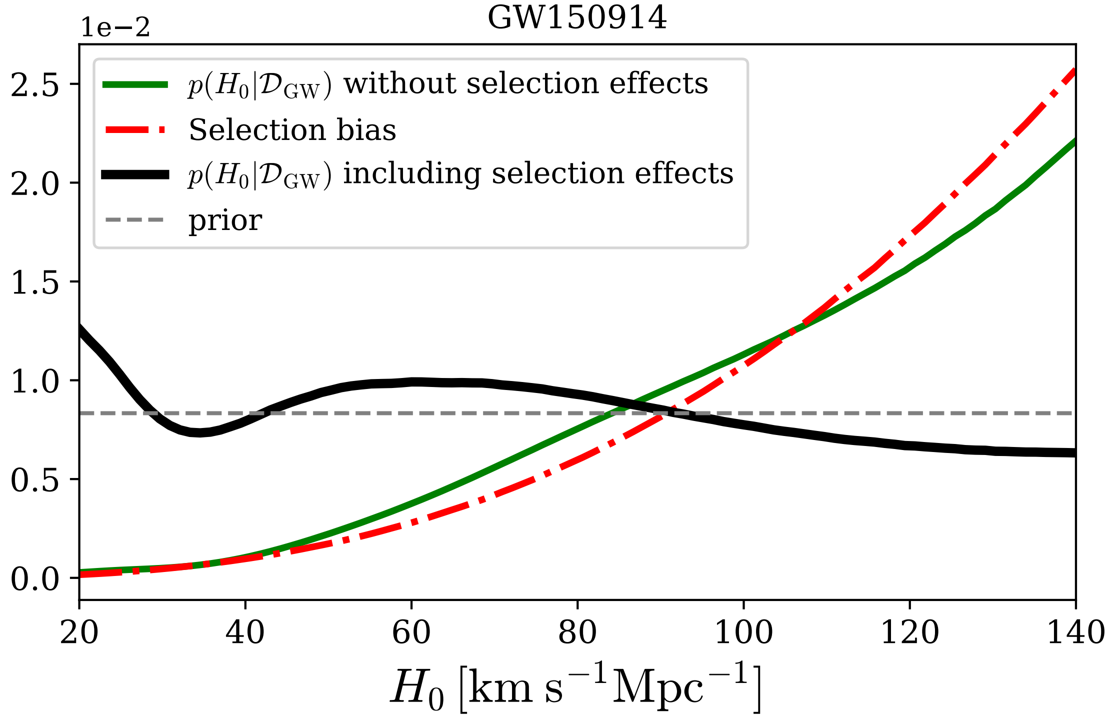
- Physical meaning: β(λ) = fraction of expected events detected at given λ

Mandel, Farr, Gair '19

$$d_L \sim \frac{z}{H_0}$$

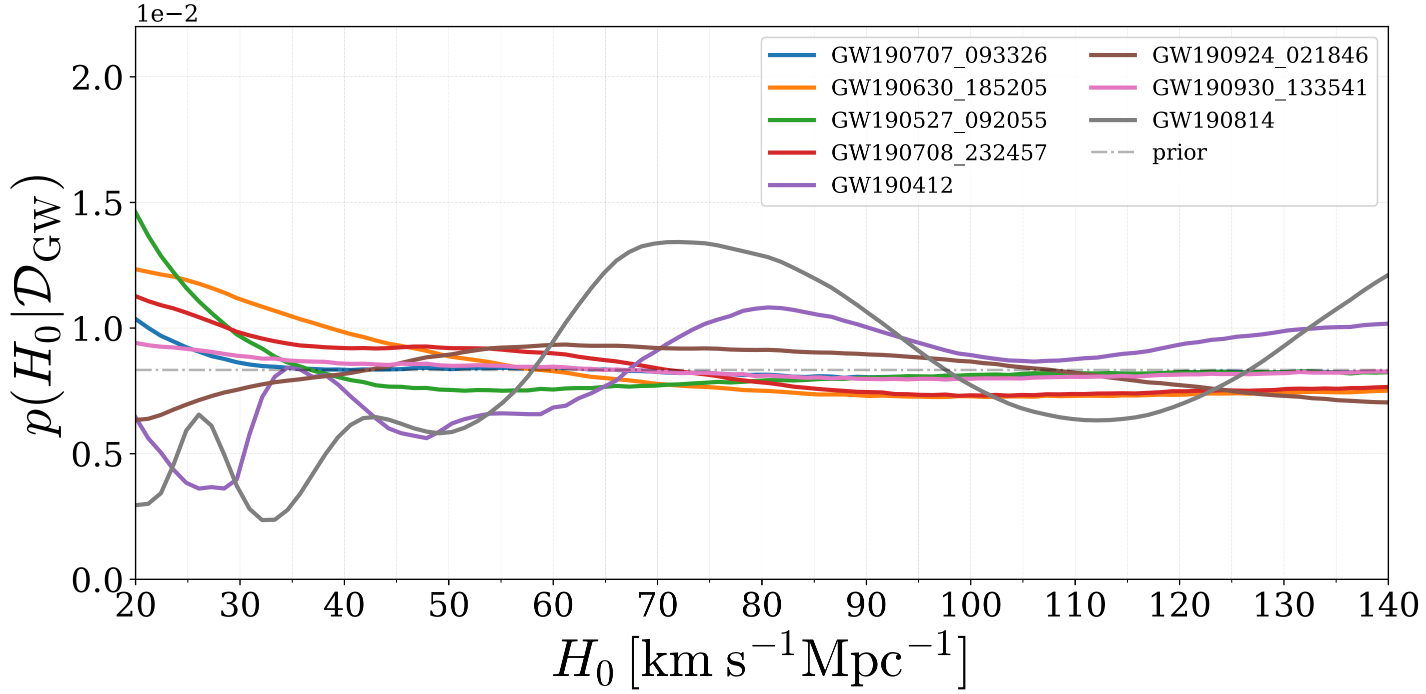
for event @ true redshift z, increasing H_0 moves it *closer* to us, making it easier to observe !

Detecting higher correlation at high H_0 is just a consequence of selection bias: nearby events are easier to observe
Biased result if this is not accounted for.



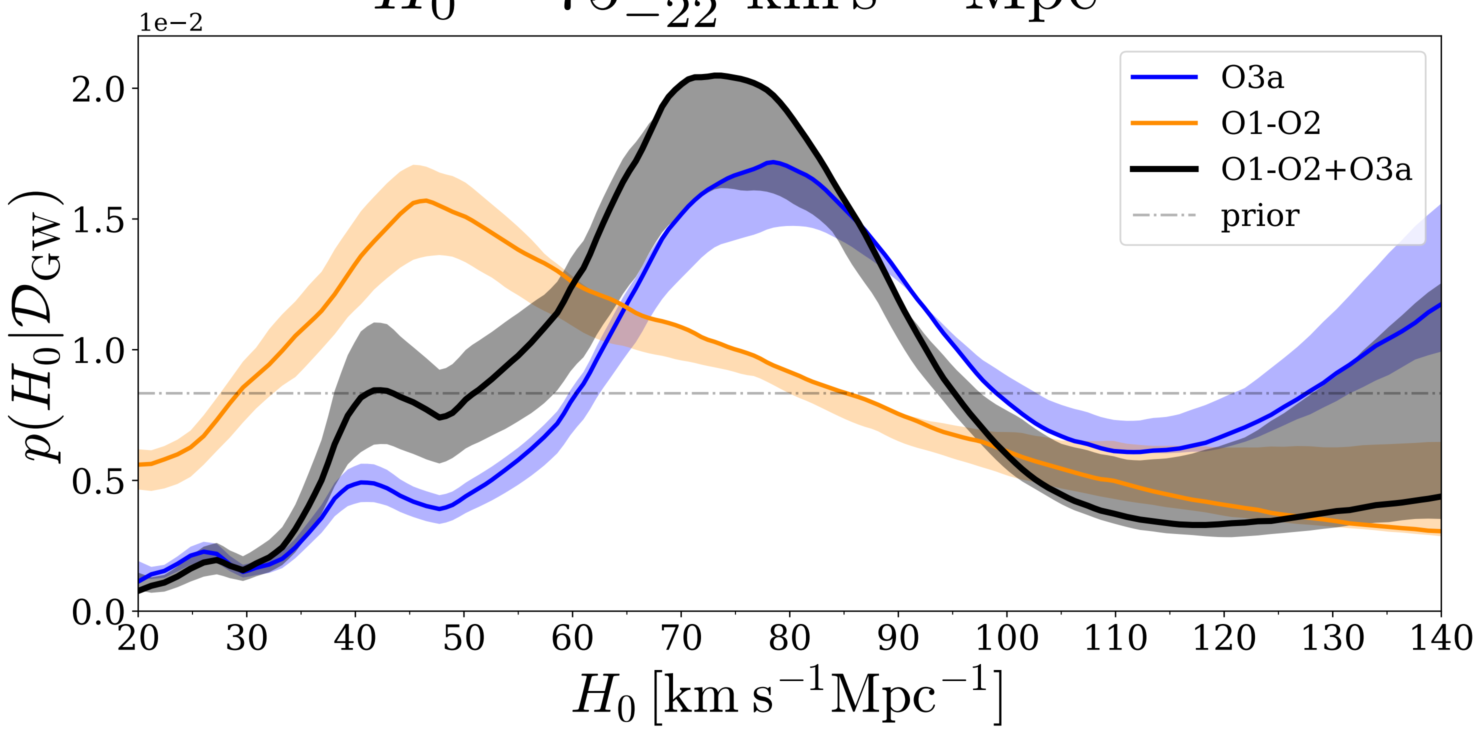
- Evaluation:
  - generate mock events from *reference population* (*source* mass+redshift distribution)
  - include galaxy catalogue in sampling redshift
  - check how many events are detected by the experiment (SNR>8)
  - + throw away those that fall in regions where catalog is incomplete

RESULTS



Individual contributions in O3a

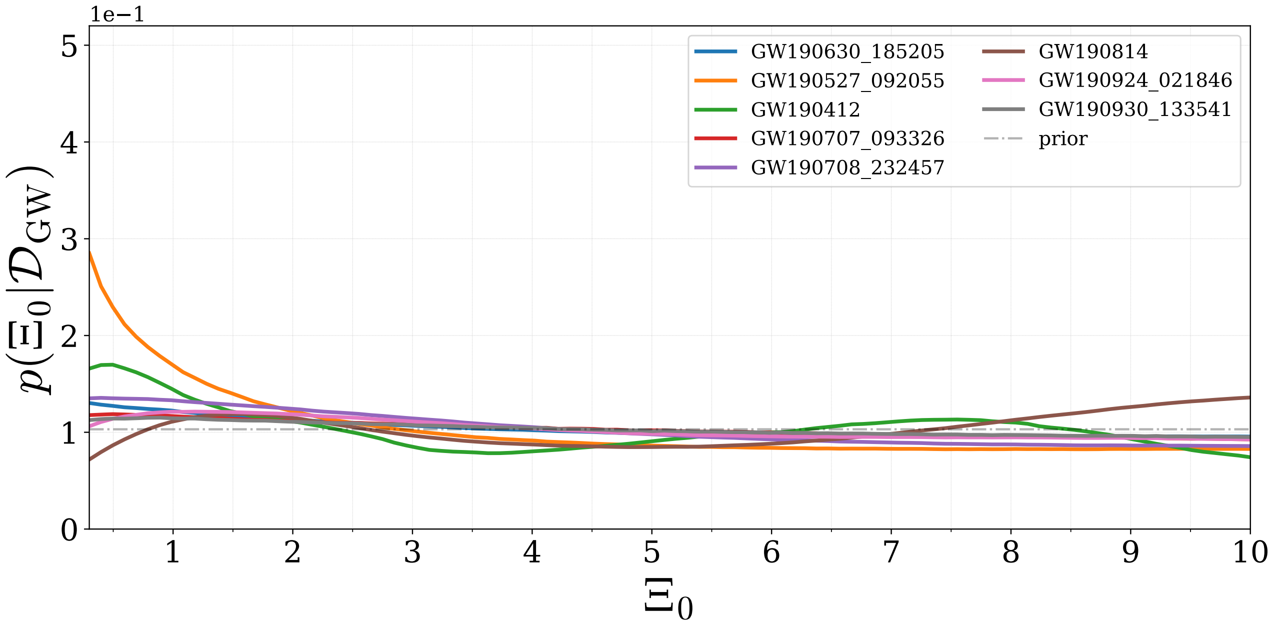
$$H_0 = 75^{+25}_{-22}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$



- O1-O2 + O3a, completeness>50%
- The shaded band shows variation with different assumptions for BBH rate evolution: astrophysics matters!
- This effect increases with larger detector reach

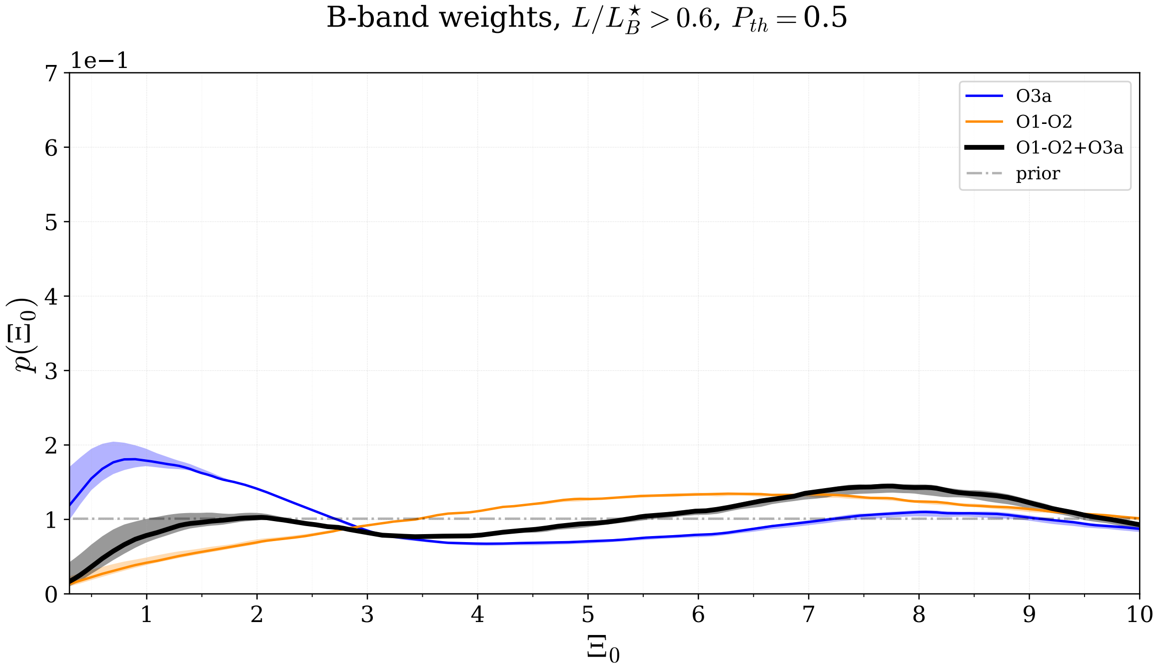
RESULTS

Individual contributions in O3a



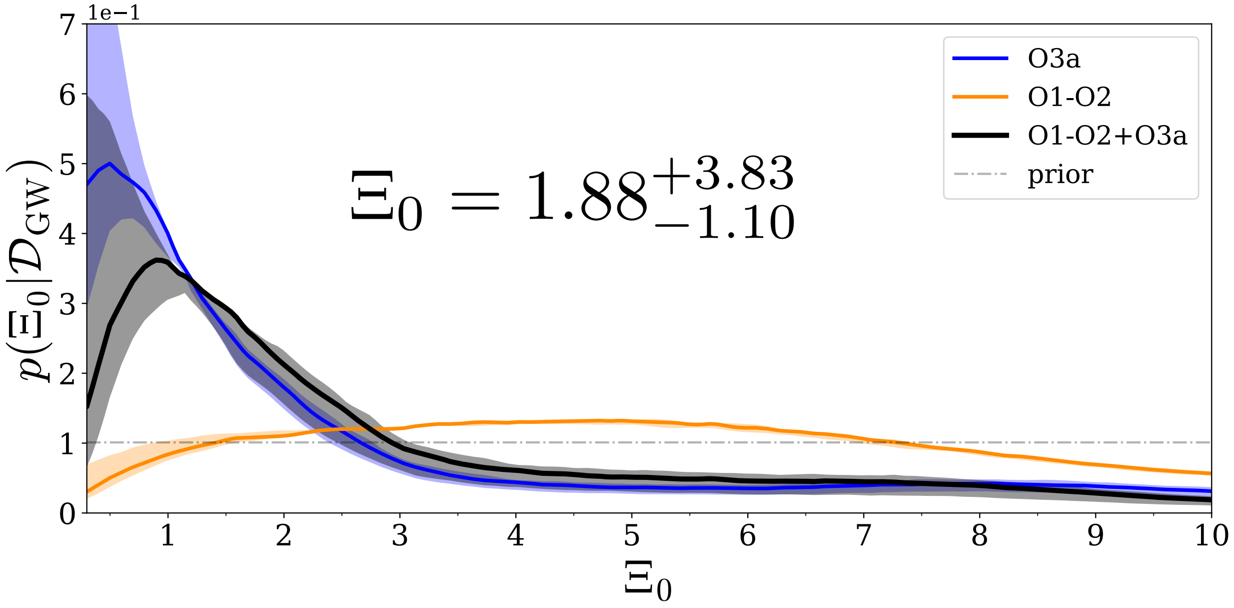
- 1st proof of principle of application to modified GW propagation
- Need more events in complete regions to get robust bound

Result with completeness>0.5



Result with completeness>0.2

(take with care!)



SYSTEMATICS AND BEYOND

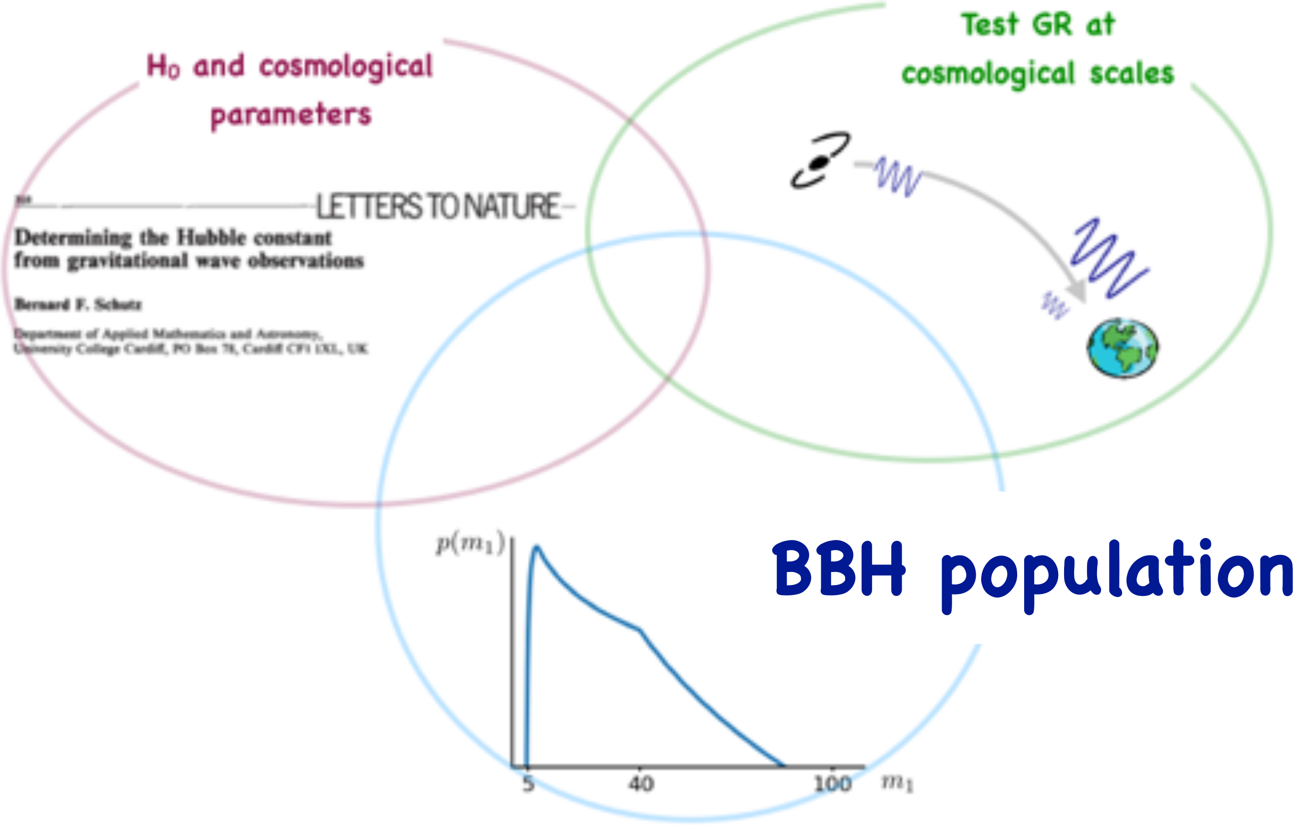
- GW side: good localization needed
- Catalogue **incompleteness** is the main limiting factor
  - Completeness: include angular dependence (allows to include also events with partial overlap with surveys with limited footprint , e.g. DES)
  - Completion: homogeneous+multiplicative

→ Can we obtain redshift from GW "only" ?

- Knowledge of **astrophysics** - BBH population used in evaluating selection effects

→ Is the inverse true, i.e. does cosmology affect population analyses?

see *Mastrogiovanni et al 2103.14663*

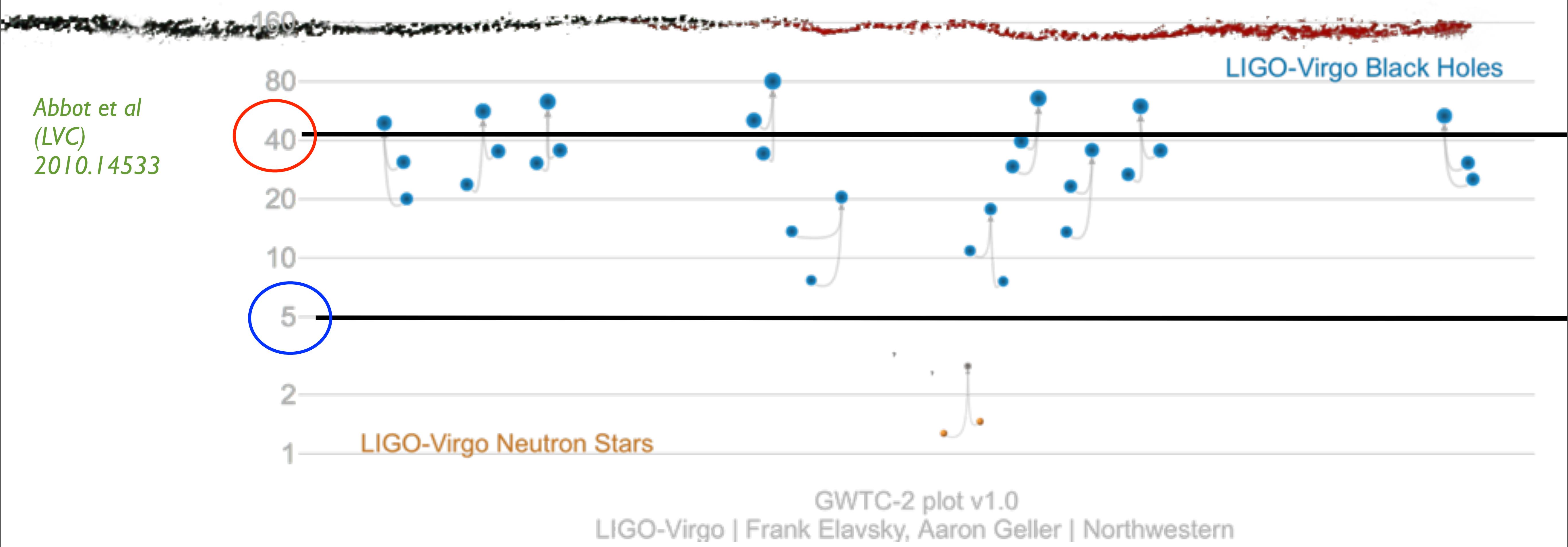


POPULATION MODELS

in progress...

see:
Mastrogiovanni et al 2103.14663
Ezquiaga, 2104.05139

FROM POPULATION MODELS...

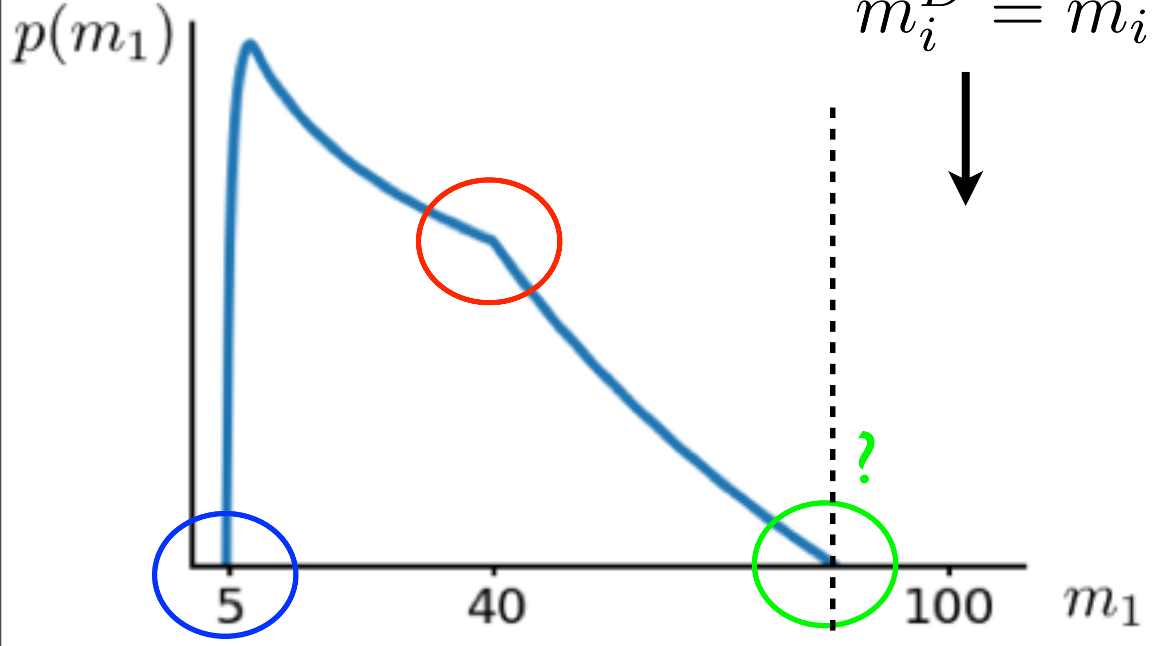


Abbot et al (LVC) 2010.14533

GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

$$m_i^D = m_i \times (1+z)$$

↓



- **Features** in the source frame mass distribution provides the extra information on the mass !
- Astrophysics predicts a “gap” in the mass distribution
- Can reconstruct population properties with hierarchical inference (usually done *fixing cosmology)*

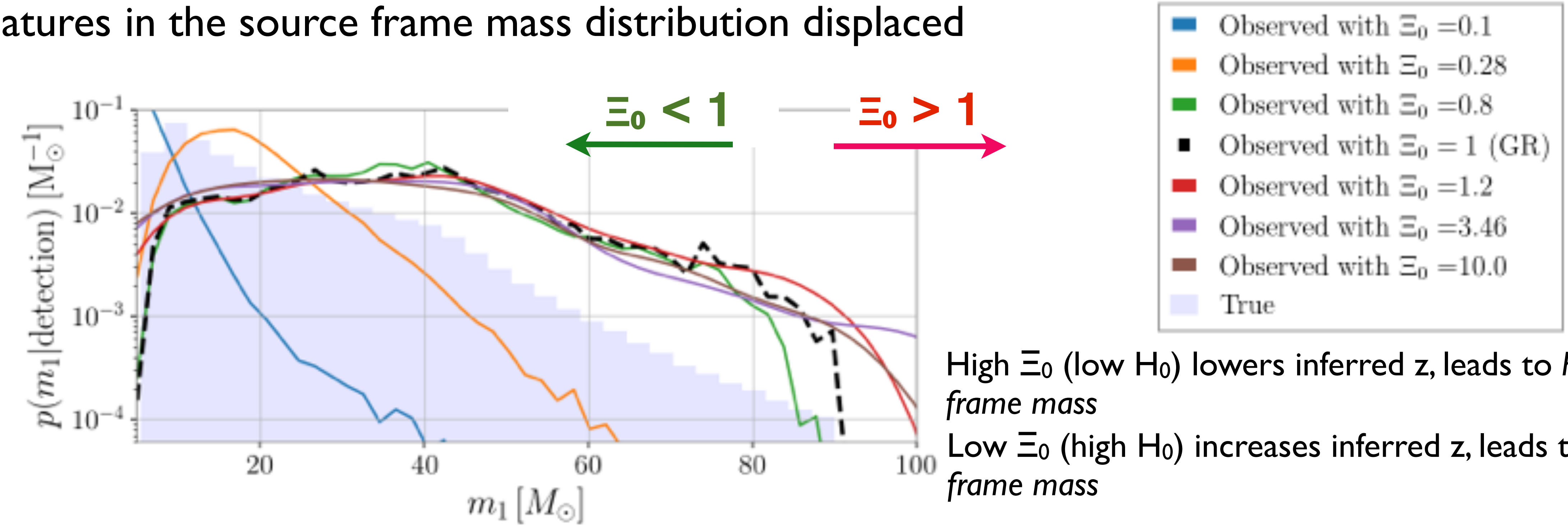
...TO COSMOLOGY

Farr, Fishbach, Ye, Holz 1908.09084
You, Zhu, Ashton, Thrane, Zhu 2004.00036
Ezquiaga, Holz 2006.02211

see Ezquiaga, 2104.05139

$$z\left(d_L; H_0, \Xi_0, \ldots\right) \qquad m_i = \frac{m_i^D}{1 + z\left(d_L; H_0, \Xi_0, \ldots\right)}$$

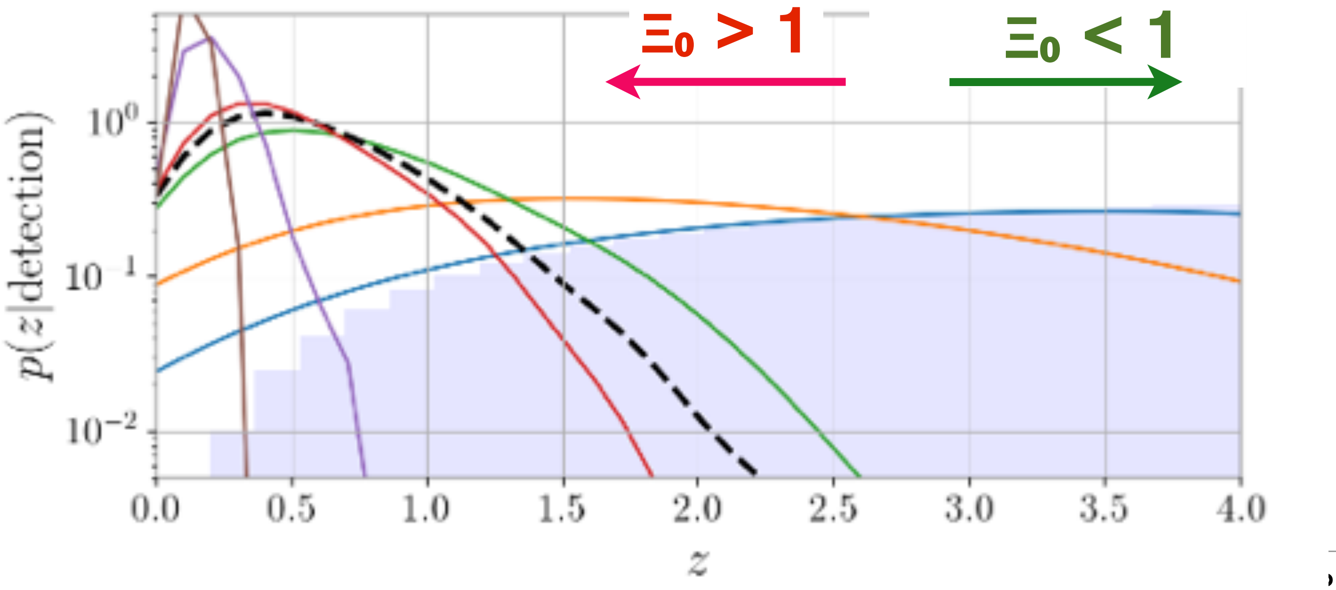
- Detectability of events: large mass/low distance are easier to observe
- Features in the source frame mass distribution displaced



High Ξ_0 (low H_0) lowers inferred z, leads to *higher source frame mass*

Low Ξ_0 (high H_0) increases inferred z, leads to *lower source frame mass*

- Evolution of BBH merger rate with redshift can look different

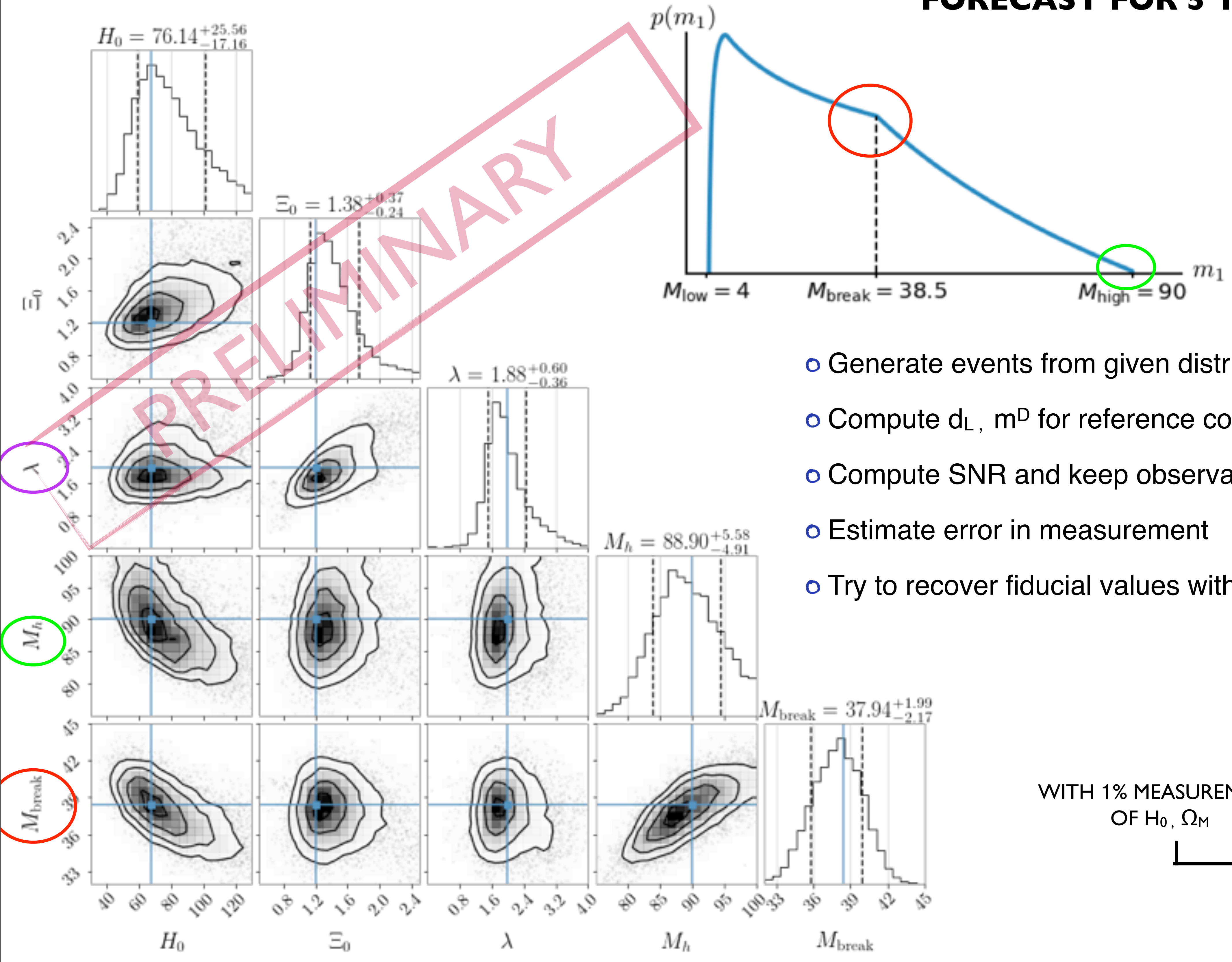


Low Ξ_0 places the events at given z *closer* to us

(Eventually could observe everything...)

PUTTING IT ALL TOGETHER

FORECAST FOR 5 YRS OF aLIGO



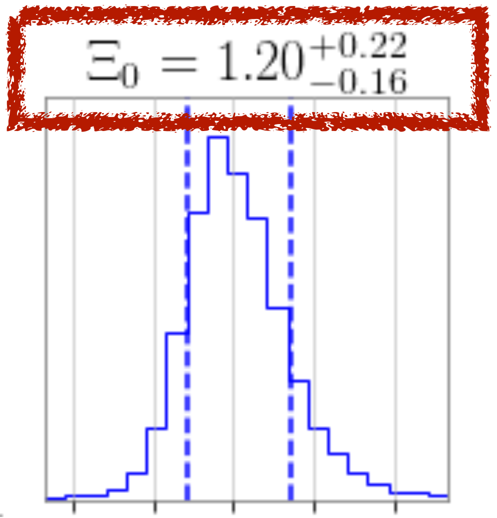
$$\frac{dN}{dV\,dt} \propto (1+z)^{\lambda}$$

- Generate events from given distribution in mass and redshift
- Compute d_L, m^D for reference cosmology ⟶ $h_0 = 0.6774$, $\Xi_0 = 1.2$
- Compute SNR and keep observable events
- Estimate error in measurement
- Try to recover fiducial values with MCMC

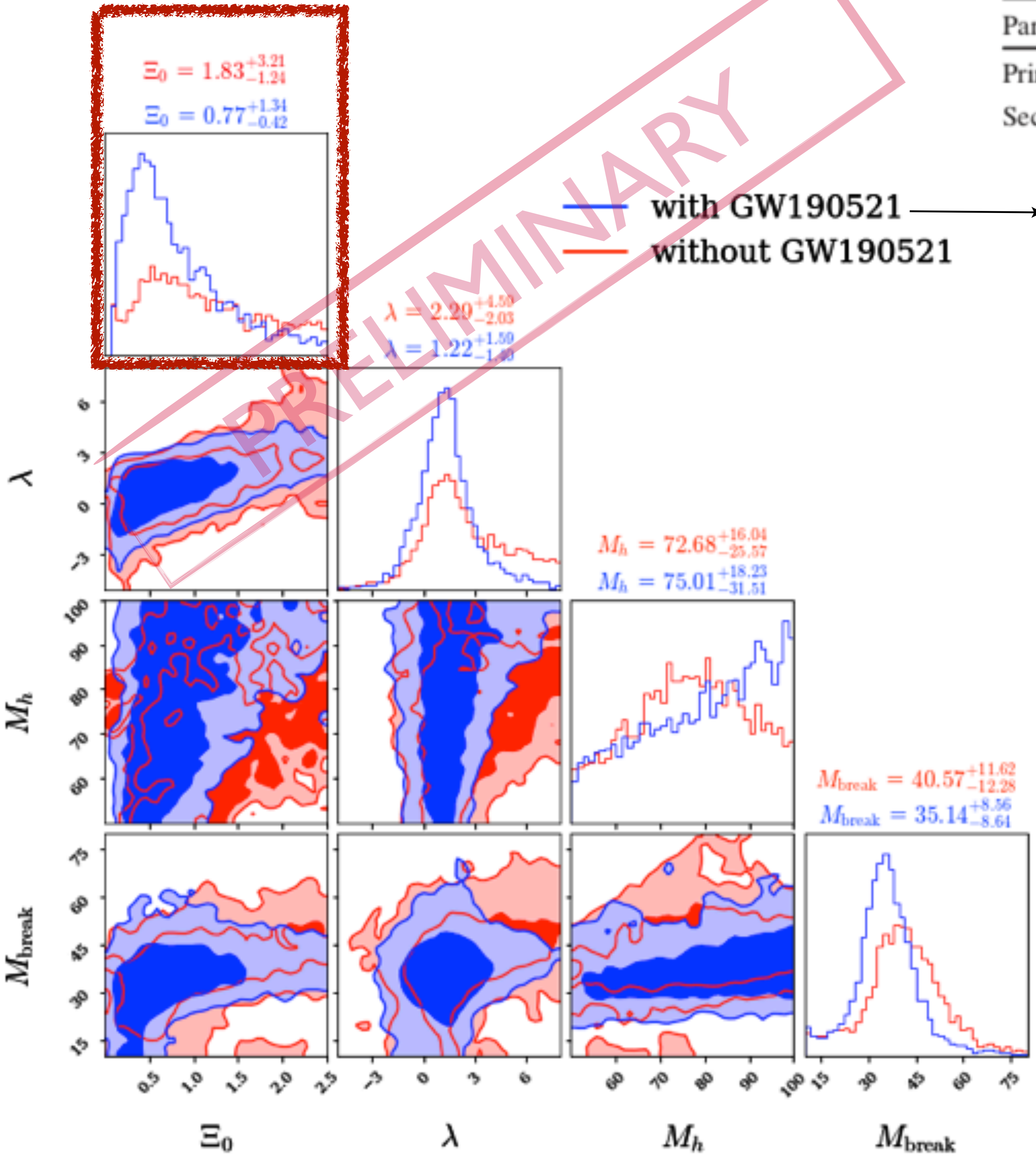
WITH 1% MEASUREMENT
OF H_0, Ω_M

$\longrightarrow$

$\Xi_0 = 1.20^{+0.22}_{-0.16}$

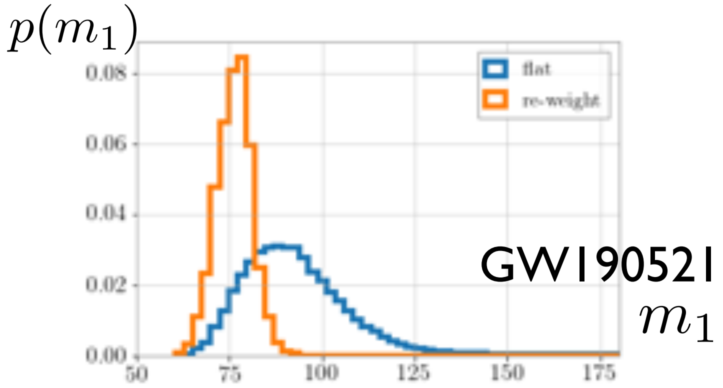


REALITY IS MORE COMPLEX: GWTC-2



Parameter	GW190521
Primary mass	$85^{+21}_{-14}\ M_\odot$
Secondary mass	$66^{+17}_{-18}\ M_\odot$

with GW190521 → pushes Ξ_0<1 to bring heaviest event to lower mass

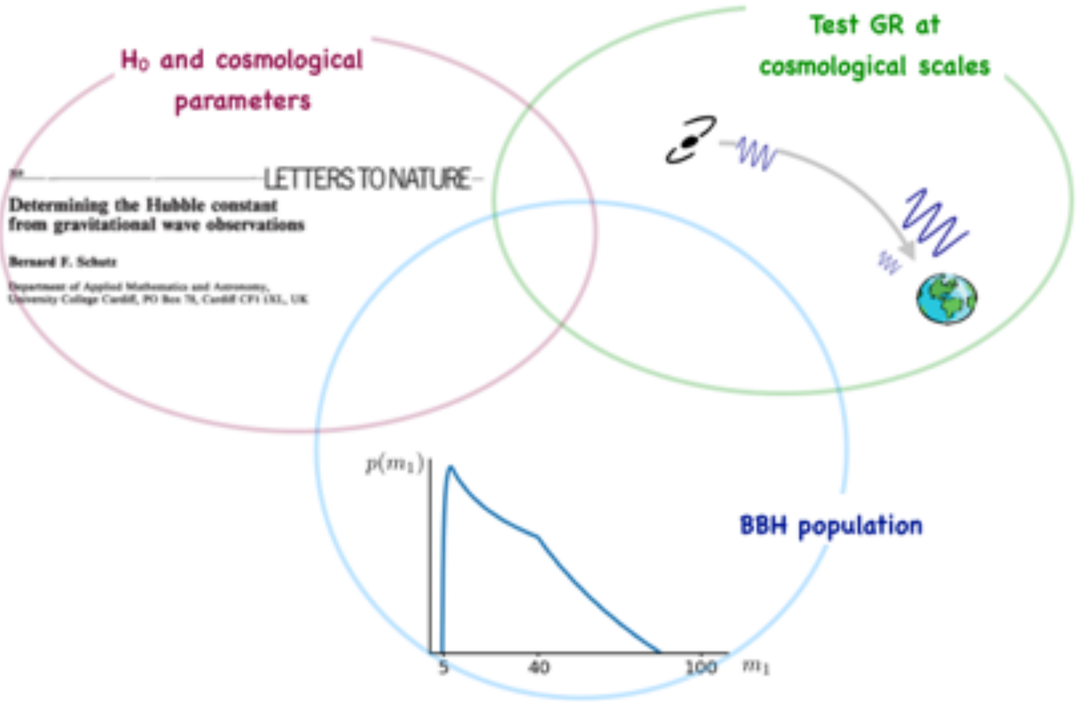


- **Population model conditioned on the astrophysical assumption**: other populations could be there
- Example: GW190521 could be a “heavy” outlier
- Excluding it seem to have a *large* impact on Ξ_0 .

OUTLOOK

Main idea:

- Look for modified GW propagation (+Hubble) in GWTC-2 dark sirens + prepare the ground for upcoming observations. Interplay cosmo/MG/population



Summary:

- 1 - obtain redshift from galaxy catalogs.
  - Proof of principle: bound on Ξ_0 from dark sirens
  - Incompleteness is main limiting factor
  - Knowledge about population=systematic to quantify
- 2 - population + cosmological analysis.
  - Can lead to GW-based ~20% constraint on modified GW propagation in few yrs
  - GWs-”only” , but relies on pop.models (more on the astro side? PBHs?)
- 1+2(+...) = ? Computational challenge! Fast evaluation of likelihood? Likelihood-free? ML ?
- 2 (or 1+2) is fascinating for both astrophysics AND cosmology/modified gravity
- For cosmology alone, explore other methods that do not rely on population modeling

Mukherjee, Wandelt, Silk 2012.15316

Bonus:

- Code: https://github.com/CosmoStatGW/