28/01/2021
GdR GWs, Cosmology

Constraining modified GW propagation with LIGO/Virgo dark sirens

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OUTLINE

- Modified GW propagation: why, how, where
- Statistical method for dark sirens
- Dealing with the catalogue: completeness and completion
- Selection bias
- Results
- Role of counterparts

with A. Finke, S. Foffa, F. Iacovelli, M. Maggiore

MODIFIED GW PROPAGATION

- General strategy to constrain the dark sector: parametrize deviations from GR

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	$G_{\rm eff}(t,k)$	LSS
	Effective anisotropic stress	$\eta(t,k)$	WL
TENSOR	**Modified GW propagation**		GWs

GR $$h''_A + 2\mathcal{H}h'_A + c^2k^2h_A = 0 \qquad h_A \propto \frac{1}{d_L^{\rm em}}$$

MG $$h''_A + 2\mathcal{H}[1-\delta(\eta)]h'_A + c^2k^2h_A = 0 \qquad h_A \propto \frac{1}{d_L^{\rm GW}}$$

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

Horndeski/DHOST
Higher dim
Non-local
Bigravity

Belgacem et al. (LISA cosmoWG), 1906.01593

HOW: (Ξ_0, n) PARAMETRIZATION

- General strategy to constrain the dark sector: parametrize deviations from GR

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BACKGROUND	Weird pressure	(w_0, w_a)	CMB+BAO+SNe
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$$d_L^{\rm GW}(z) = d_L^{\rm em}(z)\exp\left\{-\int_0^z \frac{dz'}{1+z'}\,\delta(z')\right\}$$

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

Belgacem, Dirian, Foffa, Maggiore 1712.08108
Belgacem et al. (LISA cosmoWG), 1906.01593

GW-analogue of (w_0, w_a)

WHERE: WHY (AND HOW) LOOKING IN THE LVC DATA?

- General strategy to constrain the dark sector: parametrize deviations from GR

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TENSOR	**Modified GW propagation**	(Ξ_0, n)	GWs

- Relevant parameters?

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

- Base parameters can be different
- DE EoS can evolve → ${d_L}^{\rm em}$: well constrained by CMB+BAO+SNe
- Modified GW propagation → dominant effect, constrained only by GWs, no a priori constraints

Belgacem, Dirian, Foffa, Maggiore
1805.08731

WHERE: WHY (AND HOW) LOOKING IN THE LVC DATA?

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⟶ Can start looking into current GW data

⟶ Fix other parameters, focus on Ξ_0

⟶ Exercise: constrain H_0 assuming GR

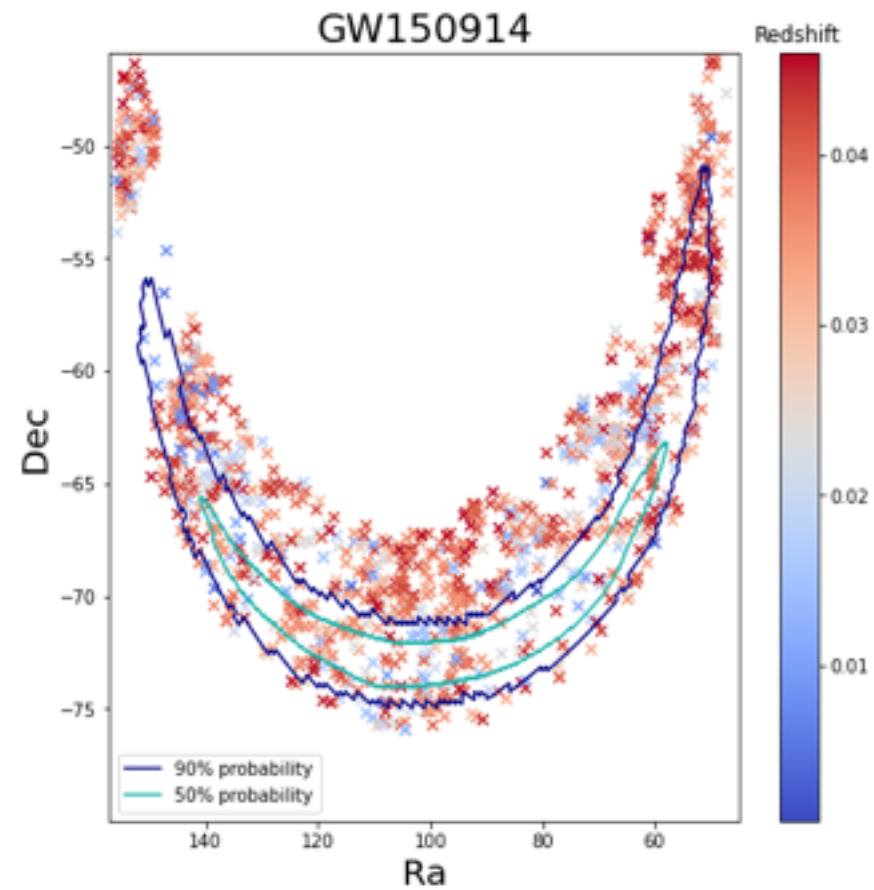
- 1 confirmed counterpart at z~0.01 , ~50 BBHs: use dark sirens and statistical method

STATISTICAL METHODS FOR DARK SIRENS

- **Basic idea:** *Schutz 1986*

$$h_A \propto 1/d_L^{\rm GW}(z; H_0, \Xi_0)$$

- GWs from compact binaries are standard sirens
- In absence of counterpart, take redshifts from all galaxies within localization region
- Compute Ξ_0 for all of them
- Doing so for many events you get a distribution peaked at the true value.



- **Full bayesian formulation:** *Del Pozzo '11, Chen et al '18, Gray et al. `19, ...*

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

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

PRIOR

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

GALAXY CATALOGUE PRIOR

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

- GLADE galaxy catalogue http://glade.elte.hu *Dália et al. '18*
- Ideally: $p_{\rm cat}(z,\hat{\Omega}) \propto \sum_\alpha w_\alpha \, \delta(z-z_\alpha)\delta^{(2)}(\hat{\Omega}-\hat{\Omega}_\alpha)$ (actually gaussian on z + uniform-in-volume prior)
  - w_α: B/K-band luminosity
- In practice we miss galaxies: $p_0(z,\hat{\Omega}) = f \, p_{\rm cat}(z,\hat{\Omega}) + (1-f) \, p_{\rm miss}(z,\hat{\Omega})$ *Chen, Fishbach, Holz '18*
  - "**COMPLETENESS**": Compute probability of missing galaxies in a region *S* around (z, Ω)

$$P_{\rm compl}(\mathcal{S};L_{\rm cut}) \equiv \frac{L_{\rm cat}(\mathcal{S};L_{\rm cut})}{\bar{l}_{\rm gal}(L_{\rm cut})V_c(\mathcal{S})}$$

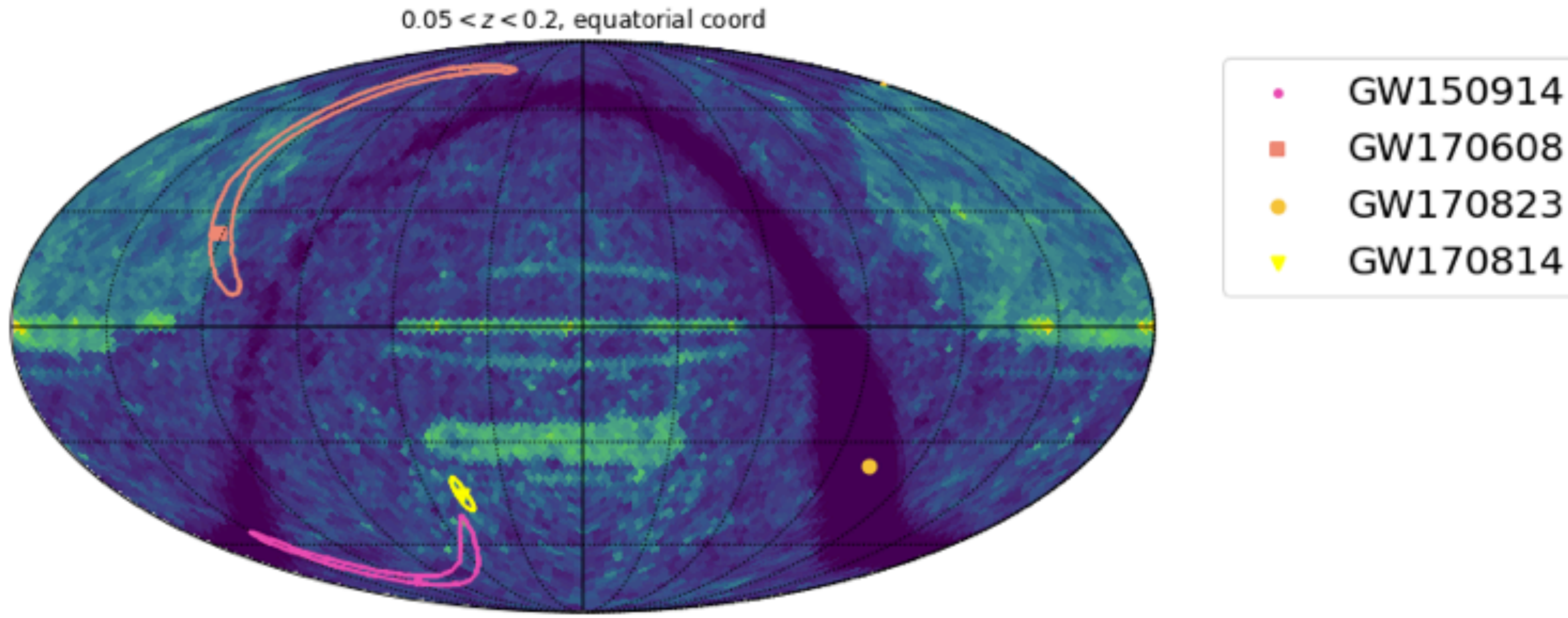
→ Numerator: Luminosity in the catalogue above some threshold $L_{\rm cut}$

→ Denominator: Expected luminosity in *S* assuming Schechter function

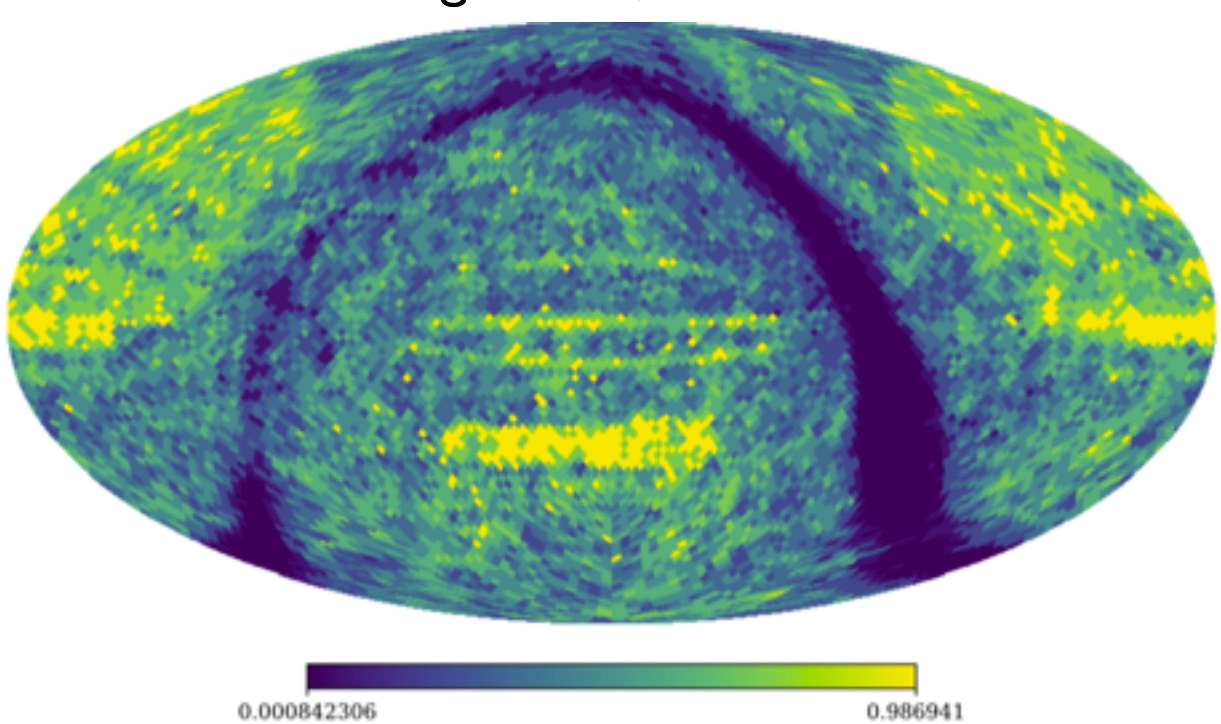
* Include angular dependence

COMPLETENESS

Observed angular dependence →



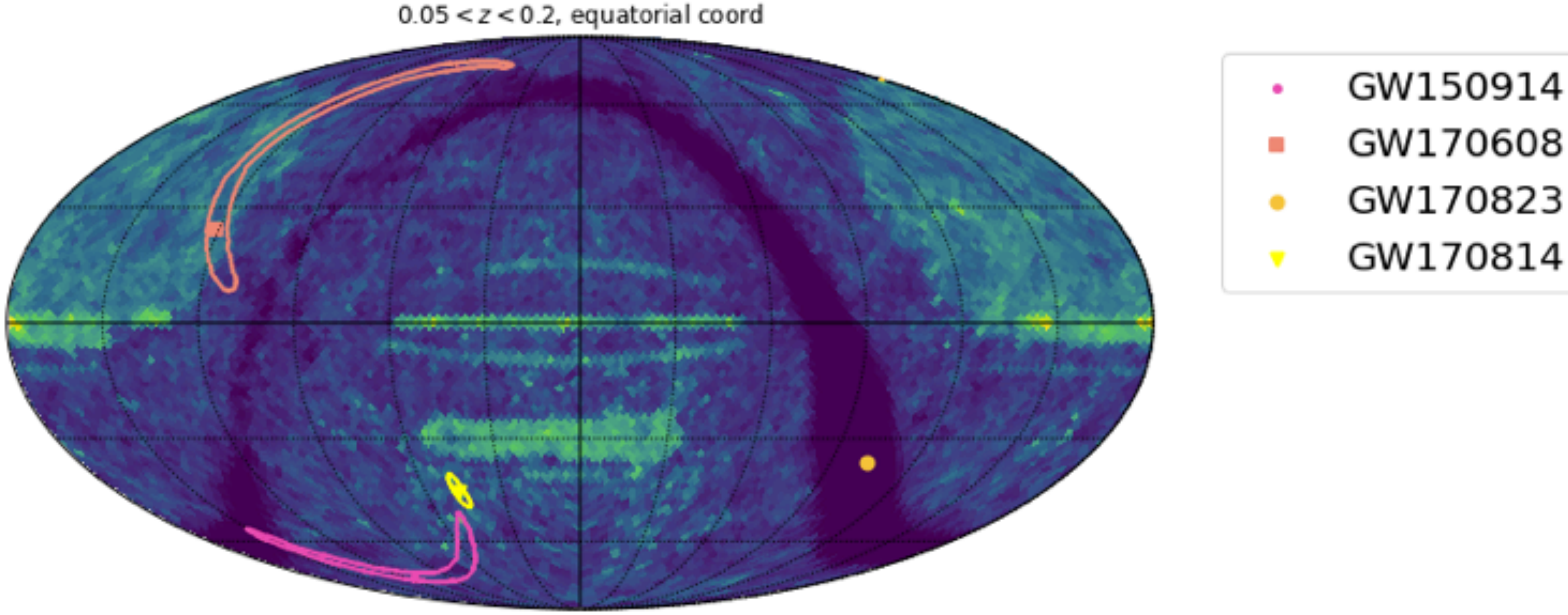
Our computation with a ML clustering algorithm, z~0.11



Previous approximations

COMPLETENESS

Observed angular dependence →



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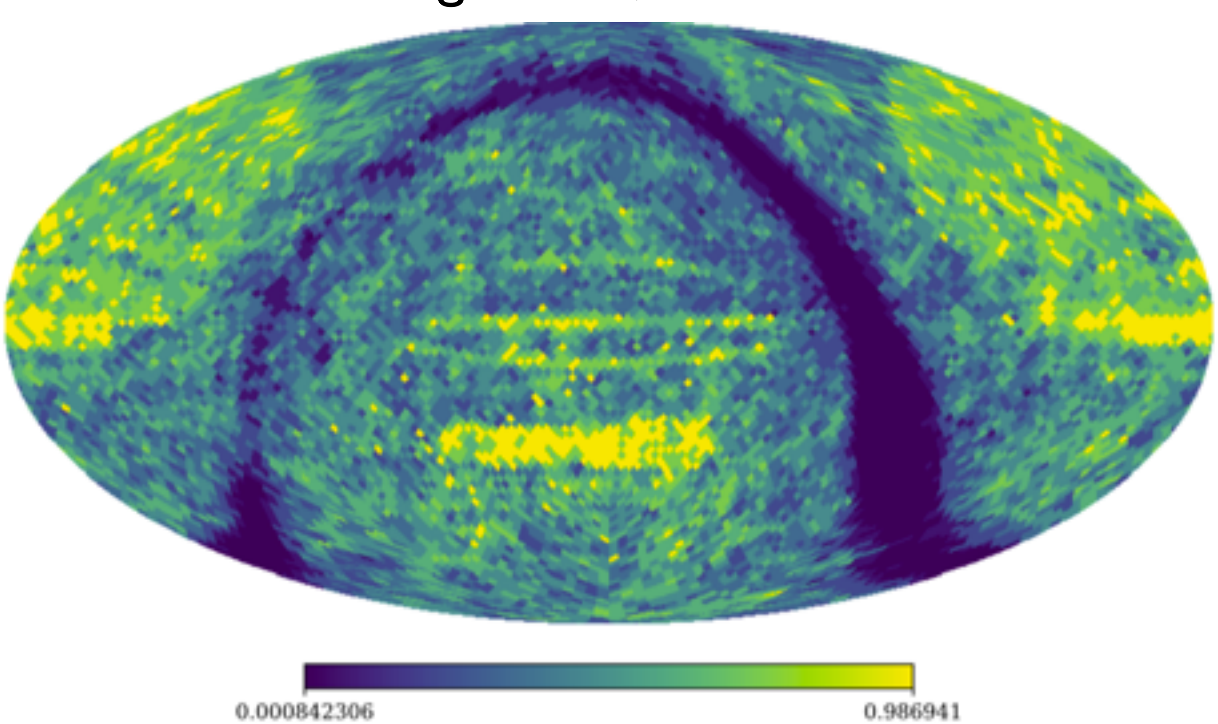

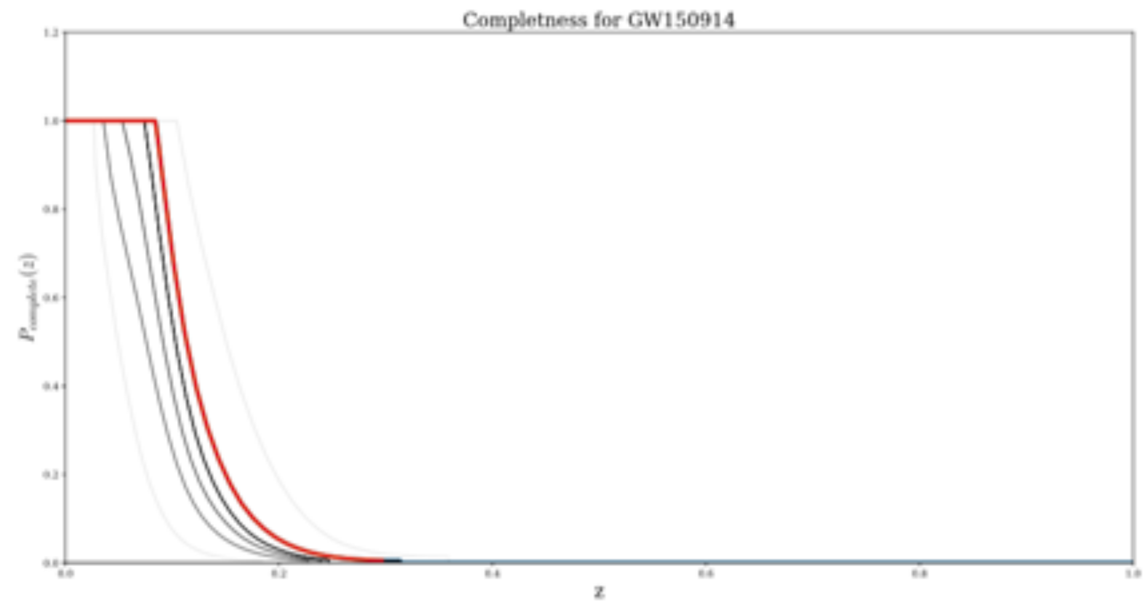

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- Ideally: $p_{\rm cat}(z,\hat{\Omega}) \propto \sum_\alpha w_\alpha \, \delta(z-z_\alpha)\delta^{(2)}(\hat{\Omega}-\hat{\Omega}_\alpha)$ (actually gaussian on z + uniform-in-volume prior)
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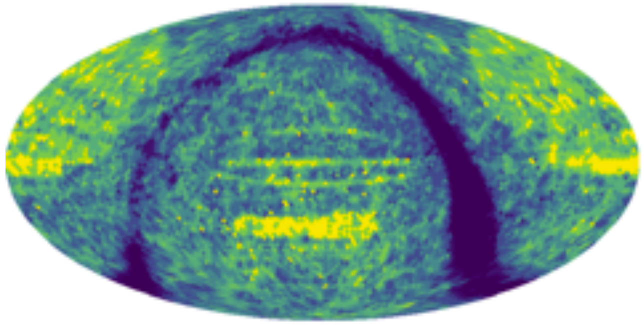
→ Luminosity in the catalogue (numerator)

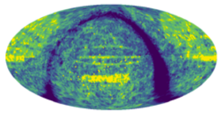
→ Expected luminosity in *S* assuming Schechter function (denominator)



  - ✱ Include angular dependence

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

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



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

BIAS

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SELECTION BIAS

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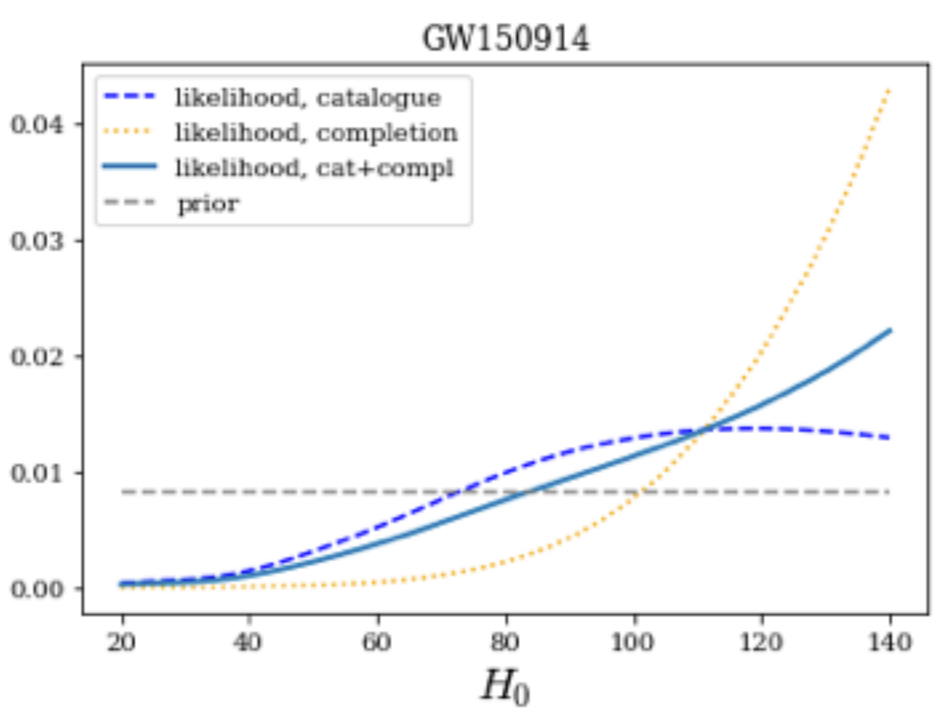
- Physical meaning: $\beta(H_0)$ = fraction of events that would be detected at given H_0

Mandel, Farr, Gair '19

$$\beta(H_0) = \int dz\, d\Omega\, dm_1\, dm_2\, d...\, p_{\rm det}(d_L(z,H_0),\hat{\Omega},m_1,m_2,...)\, p_0(z,\hat{\Omega})\, p_0(m_1,m_2)...$$

detection model : SNR(d_L , m_1, m_2, ...)>8



$z \sim H_0\, d_L$ — @given d_L, increasing H_0 moves the GW event towards higher z

$p_0(z) \sim z^2$ — correlation increases! (even for events that are totally uncorrelated with galaxy position...)

... but eventually the event would not be detected anymore! for given detector horizon, I have a max redshift

SELECTION BIAS

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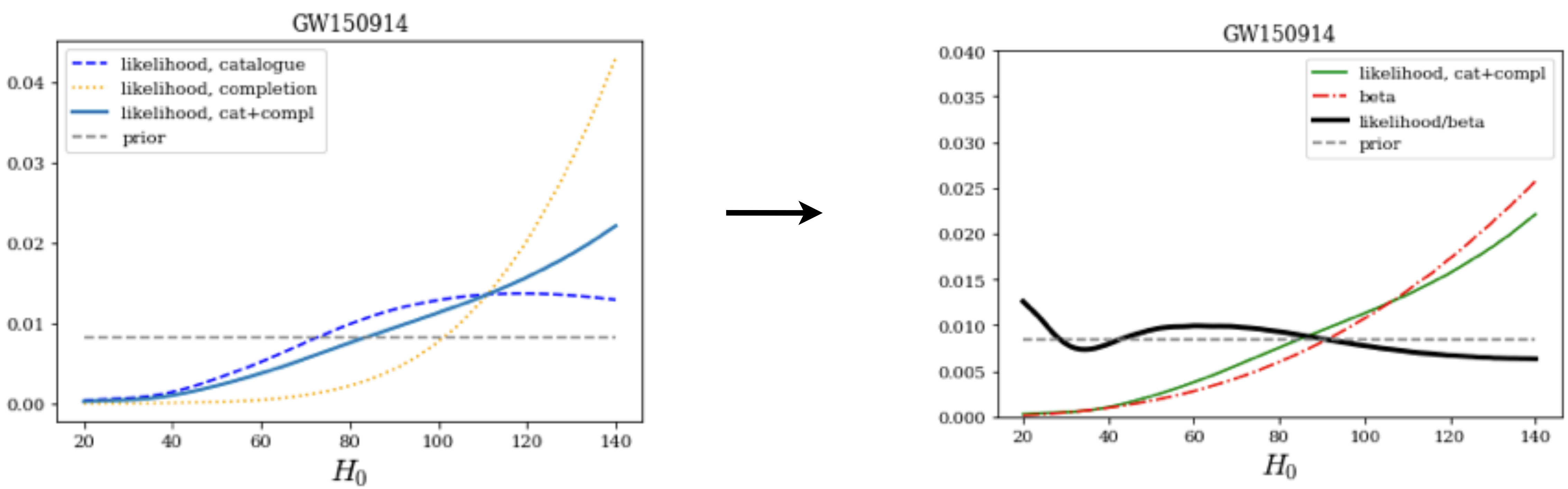

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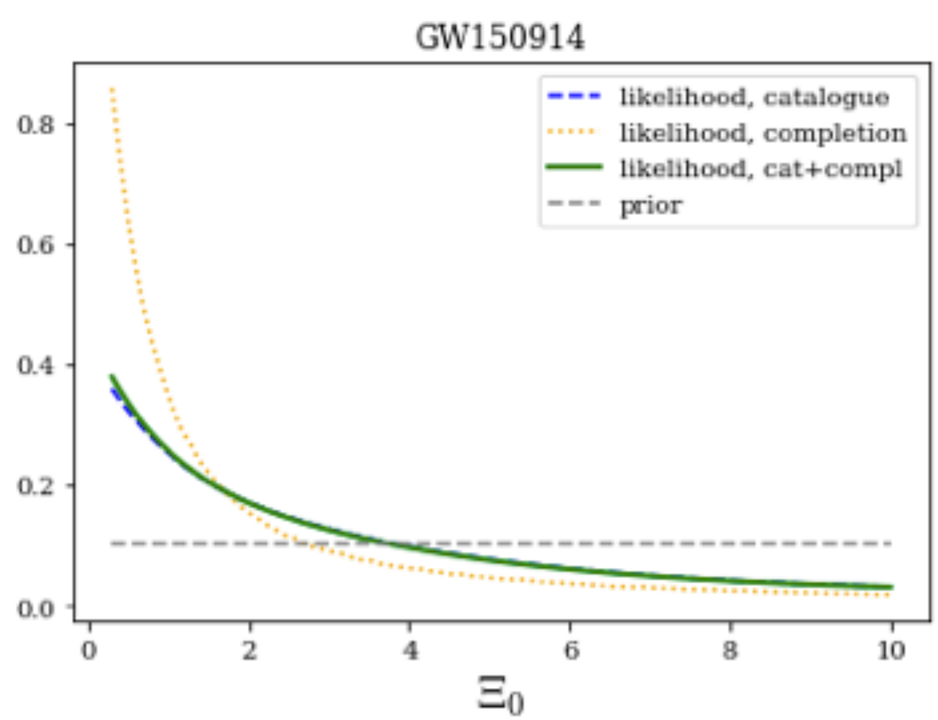
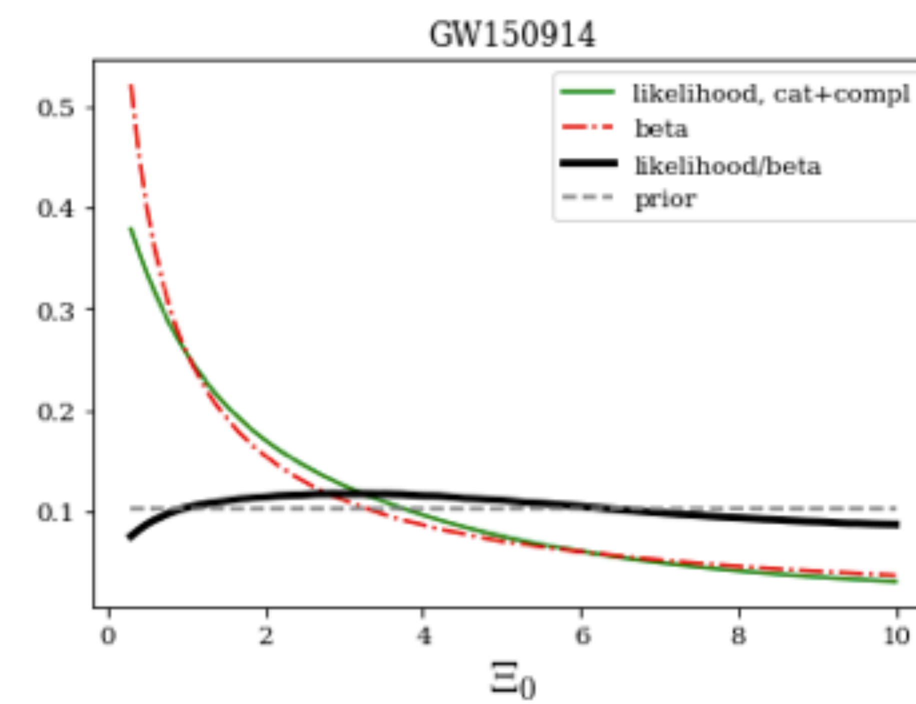
- Lesson: the correct posterior comes from a delicate compensation between likelihood and selection effects. Need to compute β accurately, especially for ***large localization regions/low completeness/Ξ_0***





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- Full MC evaluation including:
    - best-fit BBH mass function from O3a data
    - O3 strain sensitivity
    - inclusion of galaxy catalogue in the prior

- ¡ Even with this, 100% exact expression can never be computed ! Need to exclude events in regions of very low completeness
    - inclusion of extra selection effects arising from exclusion of events in low-completeness regions

RESULTS

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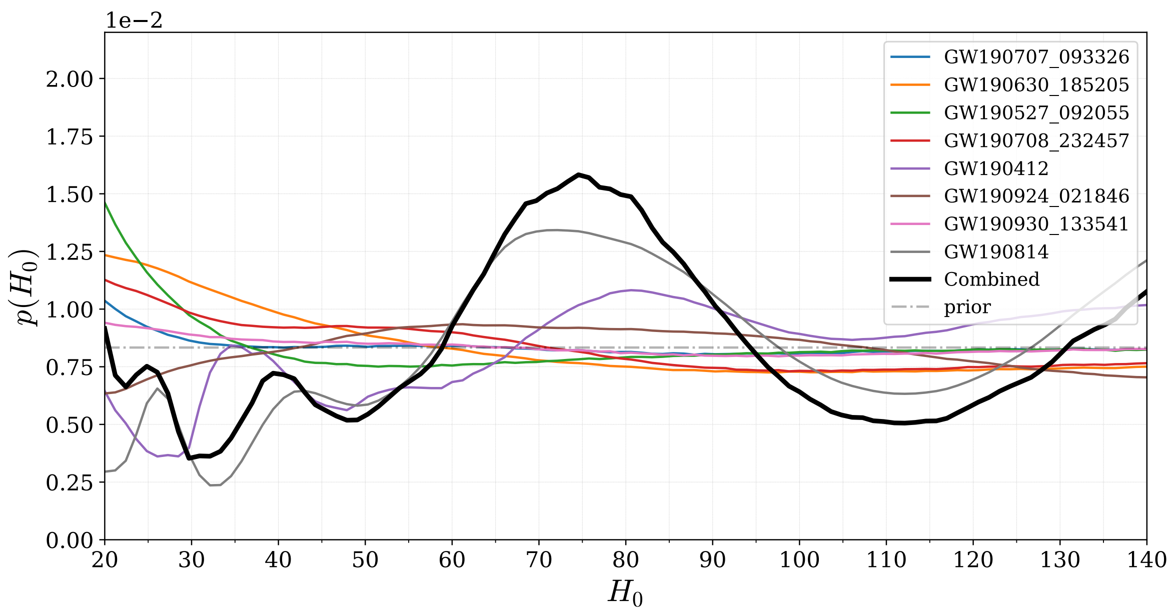
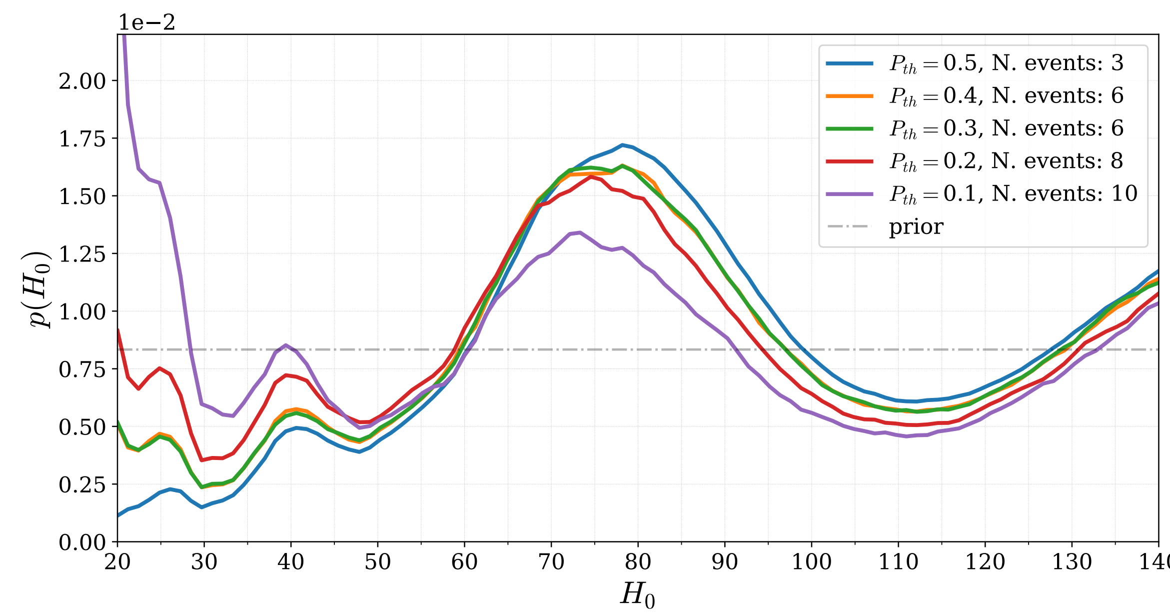
WARM UP

Individual contributions in O3a, completeness>0.2

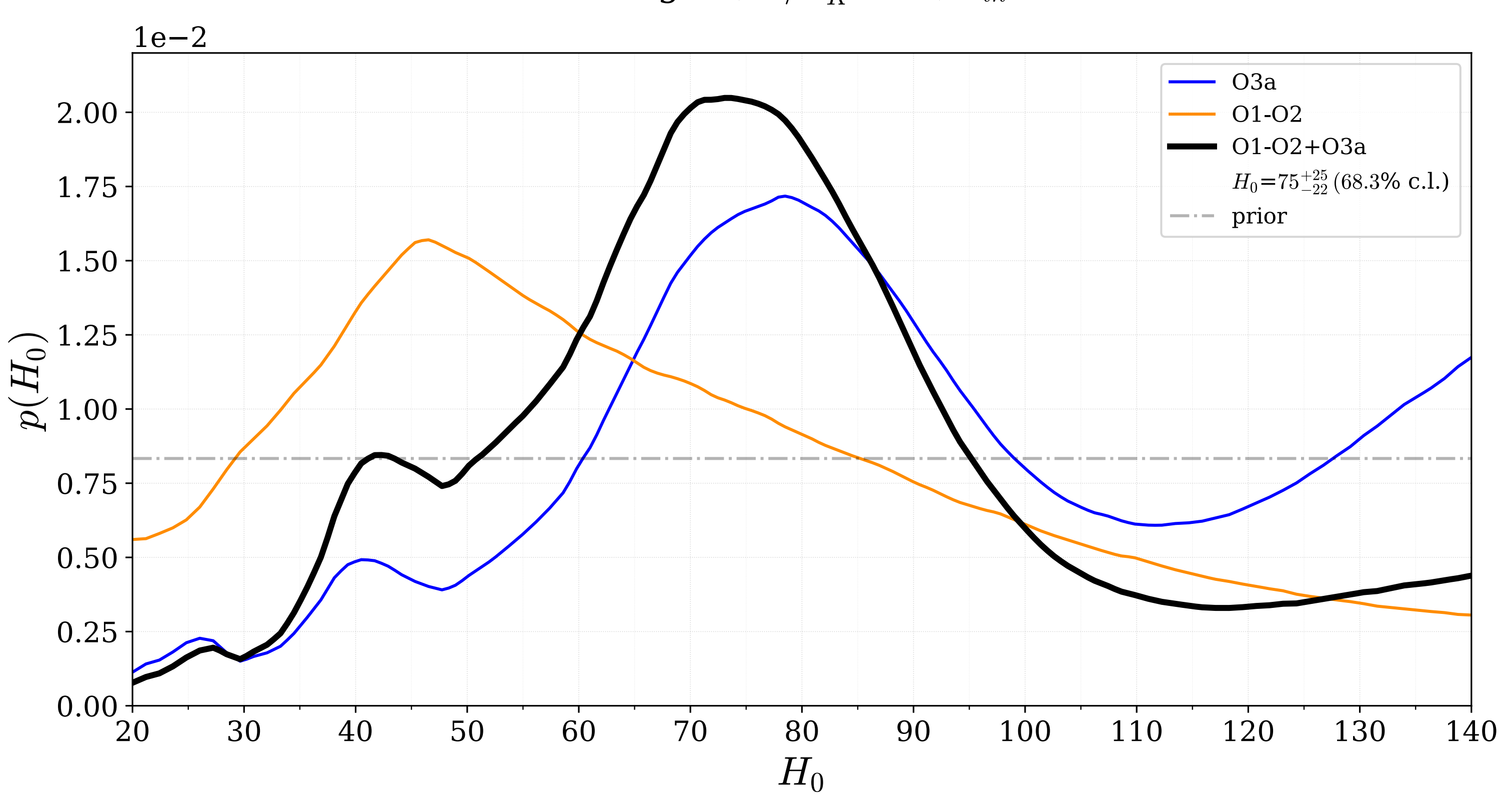


Combined results in O3a with different completeness thresholds

Mask completeness, 9 masks, mult. completion



K-band weights, $L/L_K^{\star} > 0.6$, $P_{th} = 0.5$



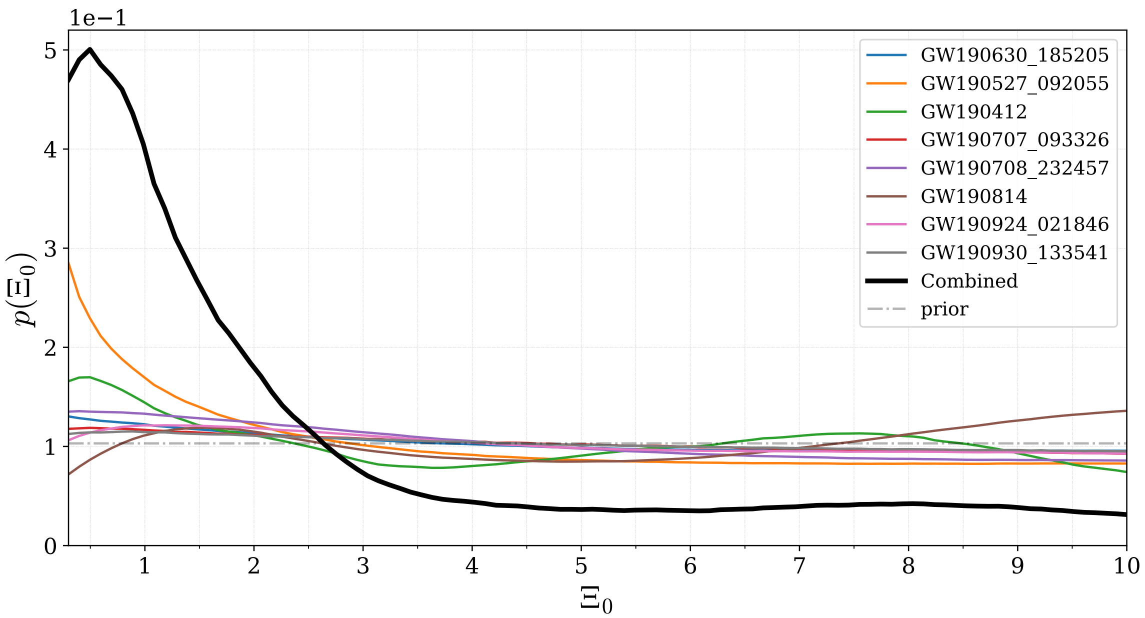
$$H_0 = 75^{+25}_{-22}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

(median & symm. 68% C.I.)

tightest bound from dark sirens only

RESULTS

Individual contributions in O3a, completeness>0.2



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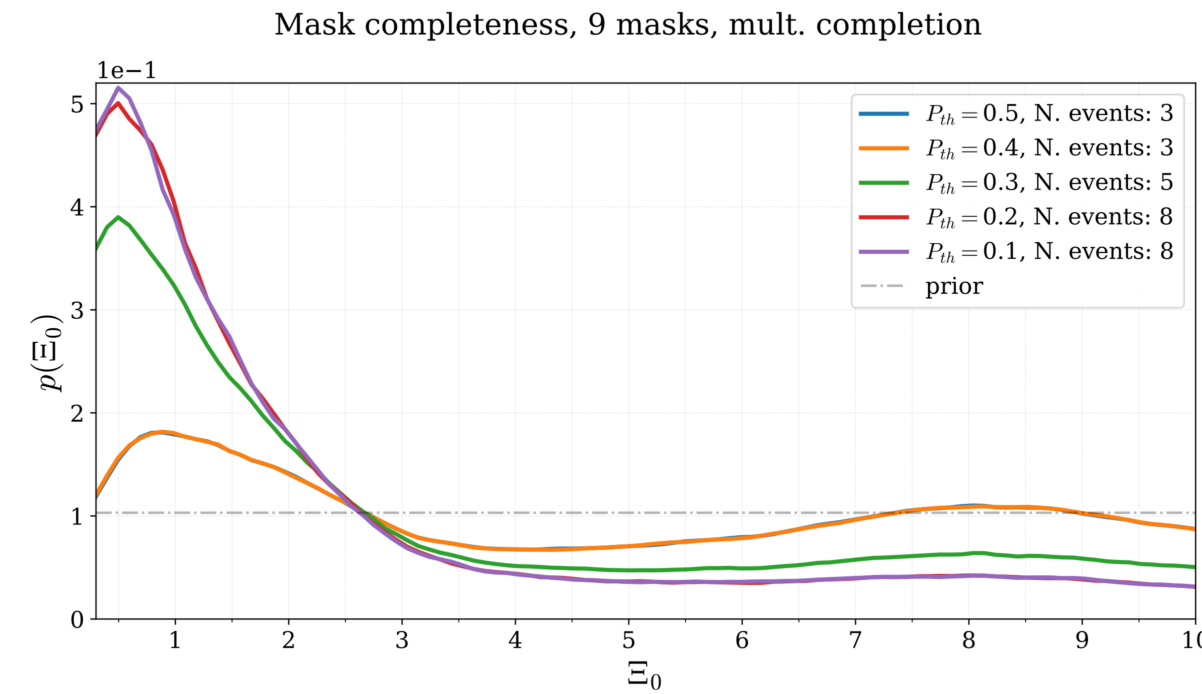
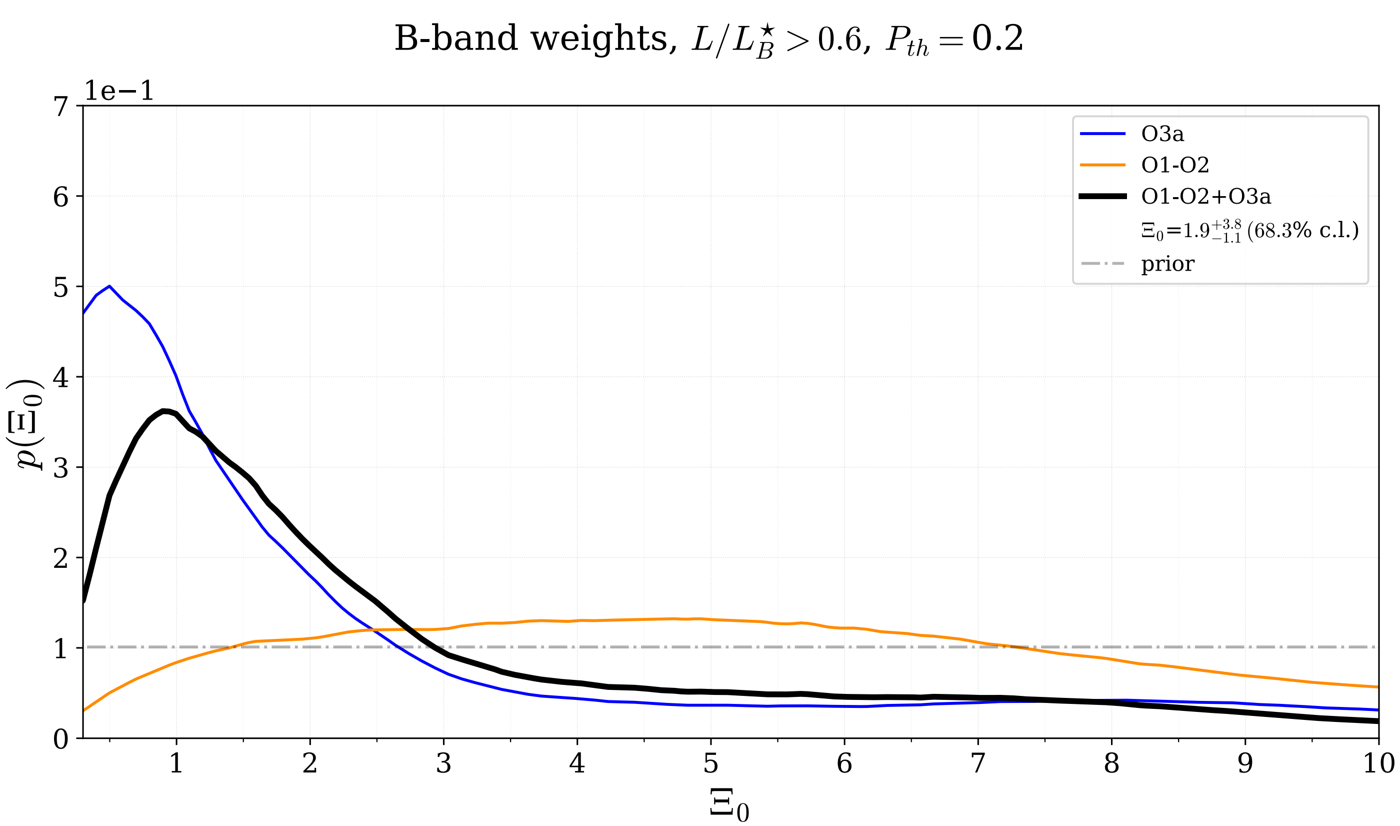




$$\Xi_0 = 1.88^{+3.83}_{-1.10}$$

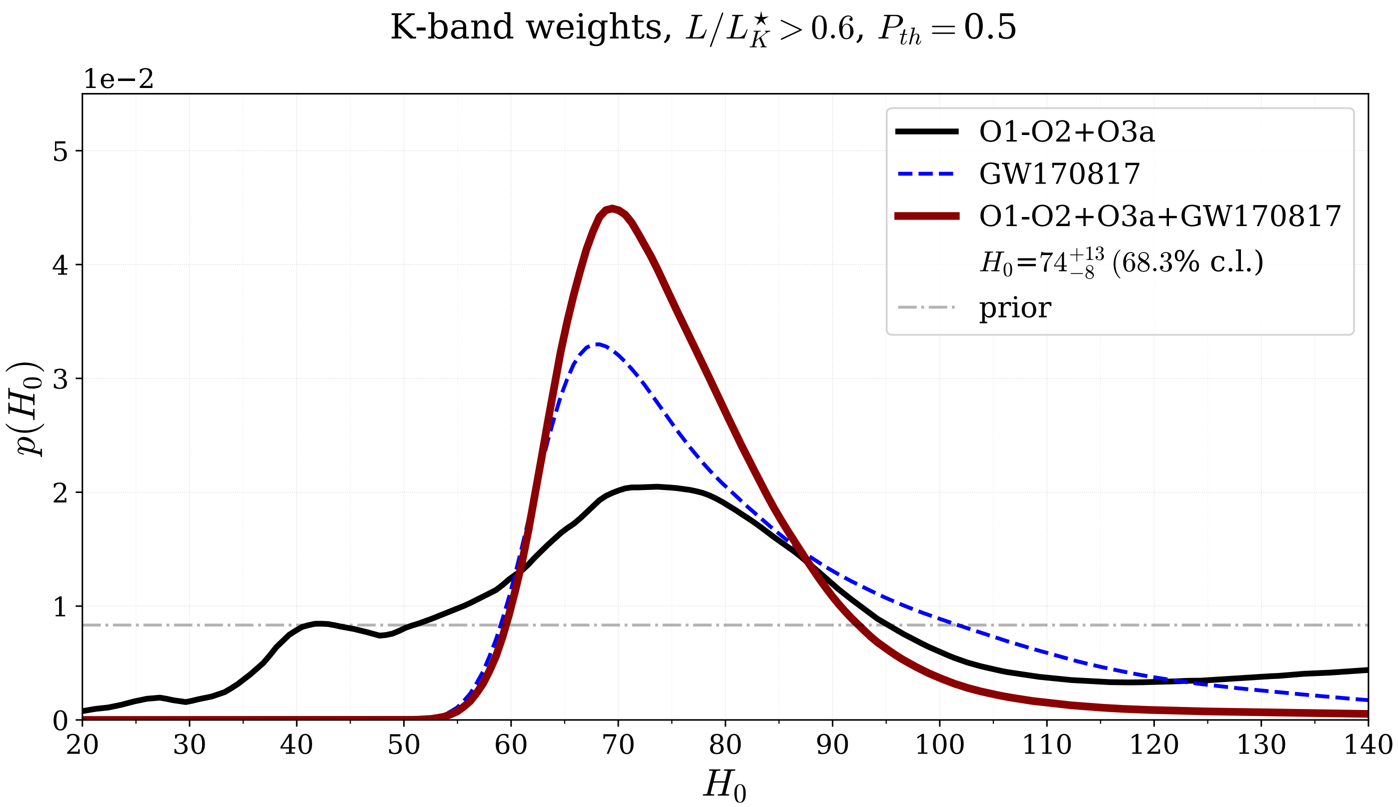
(median & symm. 68% C.I.)

first bound from dark sirens

BONUS: COUNTERPARTS

GW170817

GW170817+DARK SIRENS



GW170817 ONLY:

$$H_0 = 79^{+24}_{-12}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

GW170817 + DARK SIRENS:

$$H_0 = 74^{+13}_{-8}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

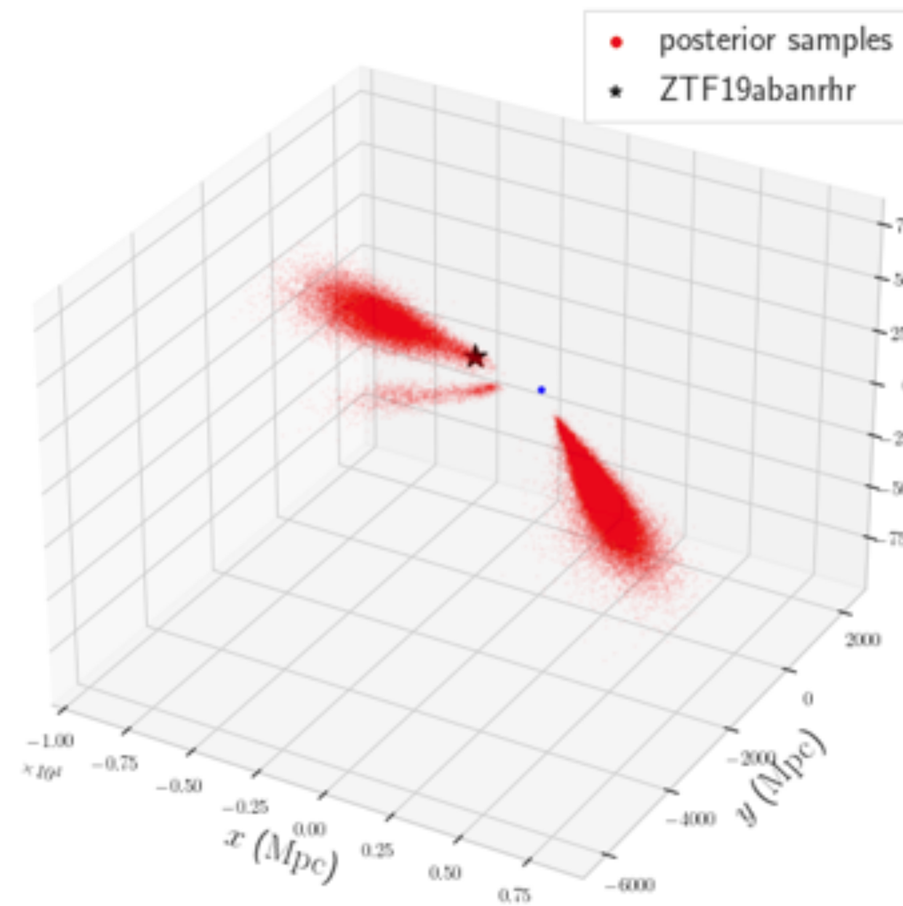
LVC 1908.06060:

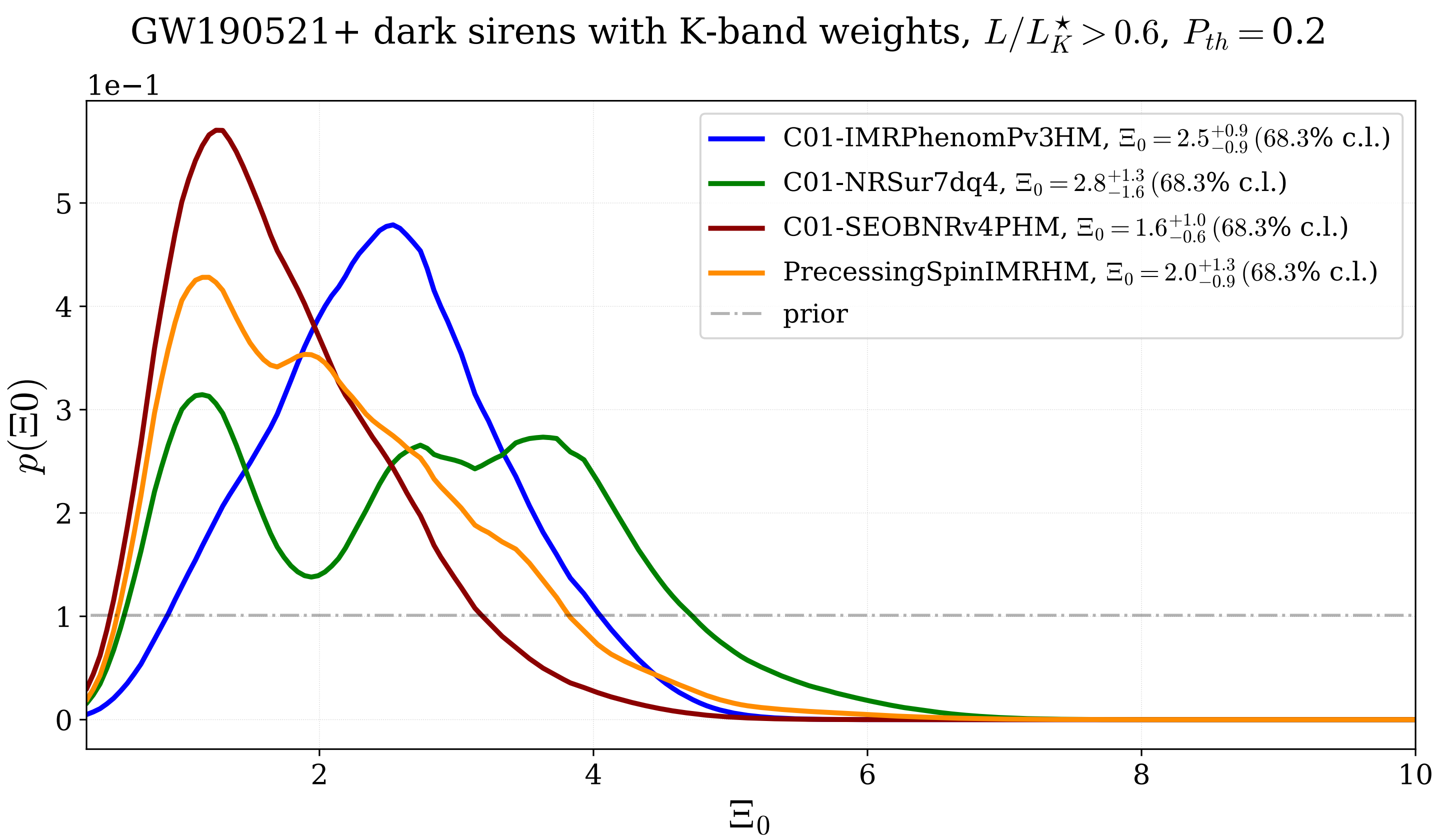
$$H_0 = 78^{+16}_{-8}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

PLAYING WITH GW190521

Parameter	
Primary mass	$85^{+21}_{-14}\ M_\odot$
Secondary mass	$66^{+17}_{-18}\ M_\odot$
Luminosity Distance	$5.3^{+2.4}_{-2.6}$ Gpc
Redshift	$0.82^{+0.28}_{-0.34}$

+ ZTF19abanrhr @ **z=0.438** ?





$$\Xi_0 = 1.6^{+1.0}_{-0.6}$$

(median & symm. 68% C.I.)

- Association is debated, population not clear, lies in the PISN mass gap, including eccentricity and informative mass prior can change the result....
- BUT this shows the potential of standard sirens to constrain modified GW propagation

SUMMARY/OUTLOOK

- In modified gravity there is a GW luminosity distance. Modified GW propagation can only be probed by GW observations, and in a more stringent way than w_0
- This method is also interesting for Hubble tension (and population models...)
- Dark sirens>>bright sirens, but statistics is still low (and localization large...): start setting up a methodology that can be applied to larger datasets
- Catalogue incompleteness is a limiting factor:
  - Completeness: include angular dependence
  - Completion: homogeneous+multiplicative
- Accurate computation of selection bias needed.
  - Use best-fit mass function, galaxy catalogue, additional selection effects
  - (Semi-analytical fast approximations available)
- First bounds on Ξ_0 from dark sirens alone, improved bounds on H_0
- Publicly available code+paper tomorrow (+-few days @90%C.L.)
- Inclusion of DES Y3 ready when the data will be released (+GWENS)
  - The method of angular dependent completion allows to include also events with partial overlap with surveys with limited footprint