GdR Marseille 15/10/24

Debiasing H_0 measurements from GW and γ-ray burst observations

arXiv:2405.02286

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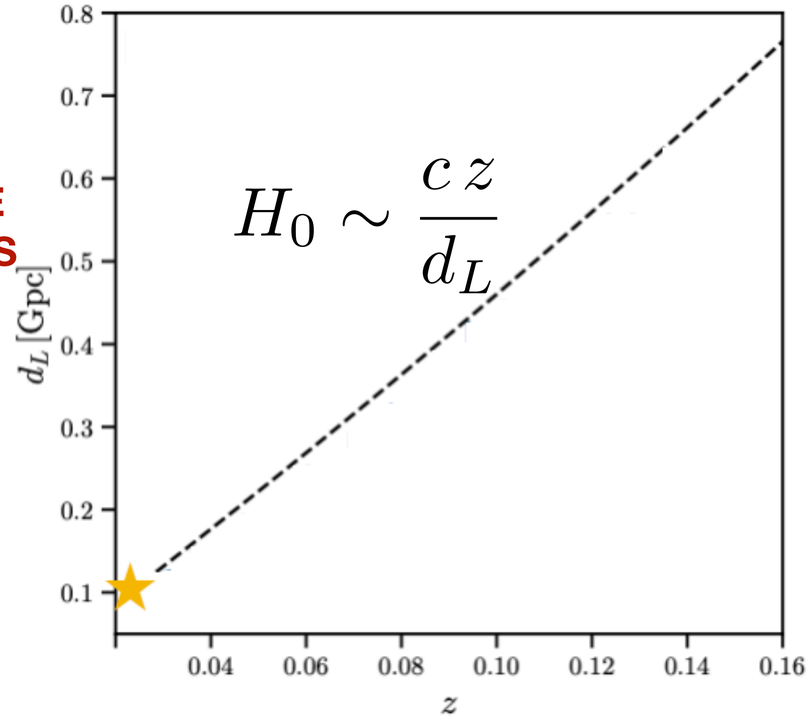
“Bright sirens” and GW170817

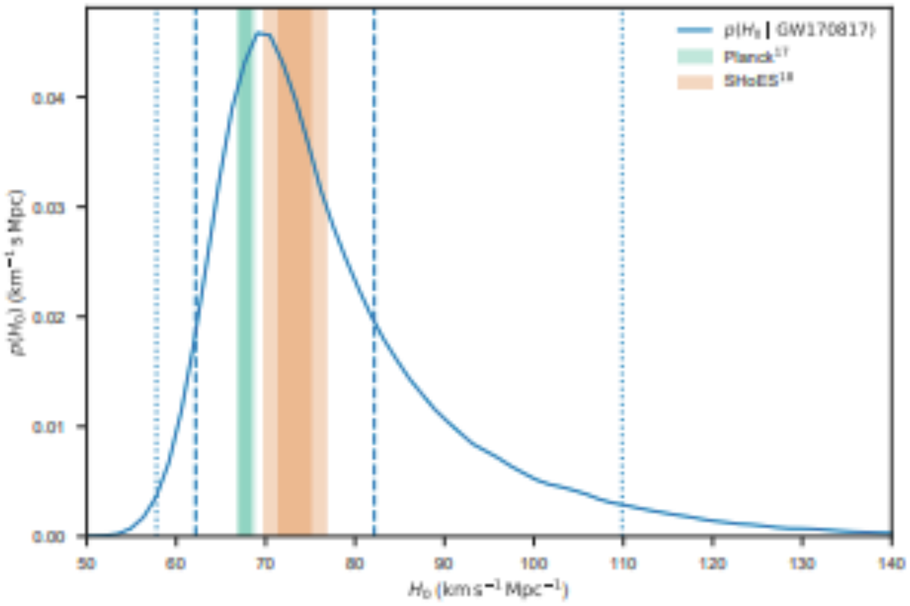
- GW distance + EM redshift = bright siren cosmology **Schutz 1986**
- 1 data point so far. Short GRB, small (but non zero) viewing angle

DISTANCE FROM GWS



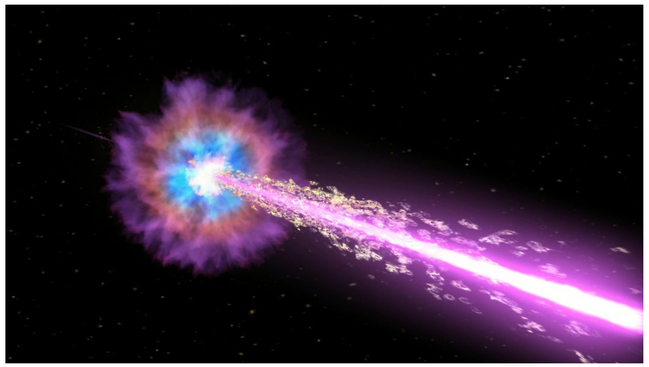
REDSHIFT FROM HOST GALAXY IDENTIFICATION

MEASURE H_0



LVC 2017

GW170817 - distance/inclination



GRB emission is **beamed**

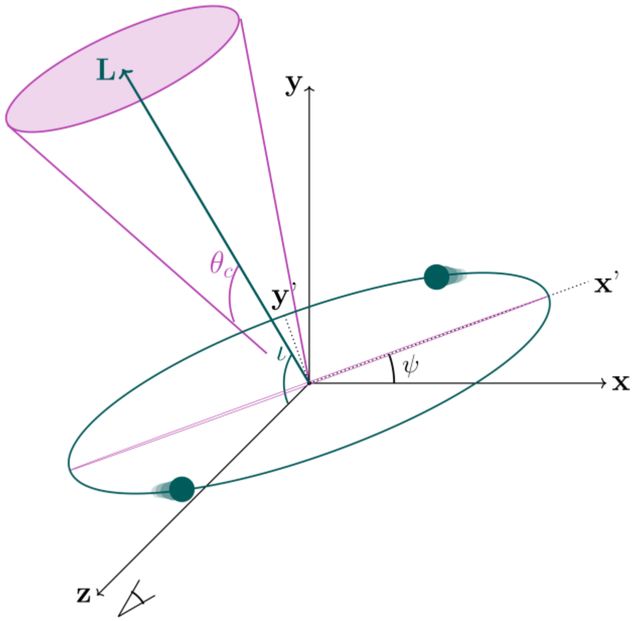
—> strong selection effect

—> strong distance-inclination correlation

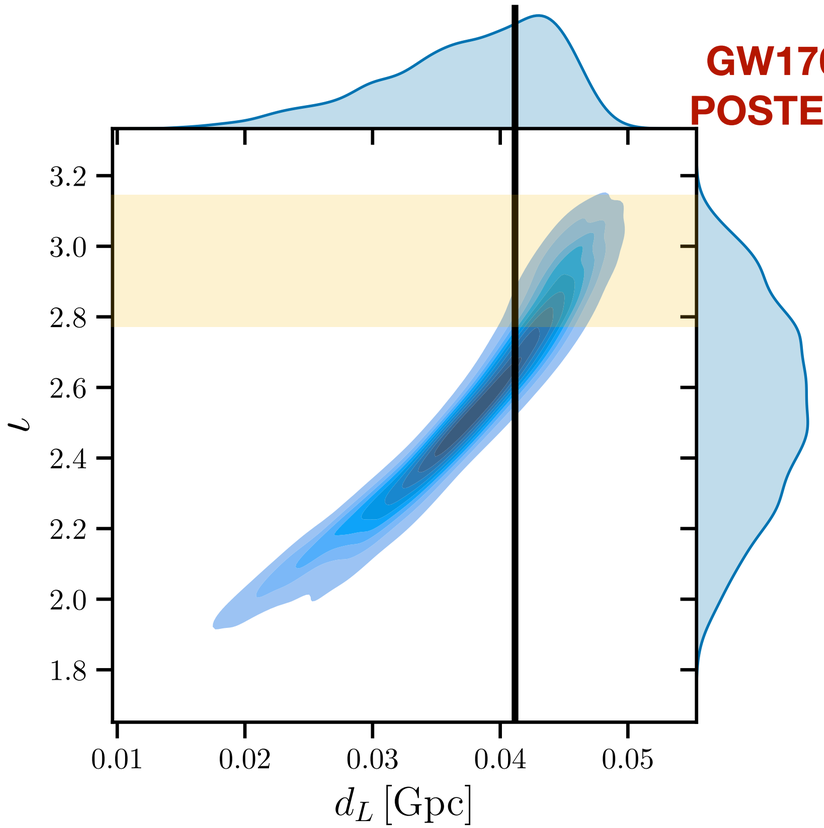
—> not accounted for at the moment

$\iota \sim 0$ E.g. $E(\iota) \sim e^{-\left(\iota^2/\iota_{\rm c}^2\right)/2}$

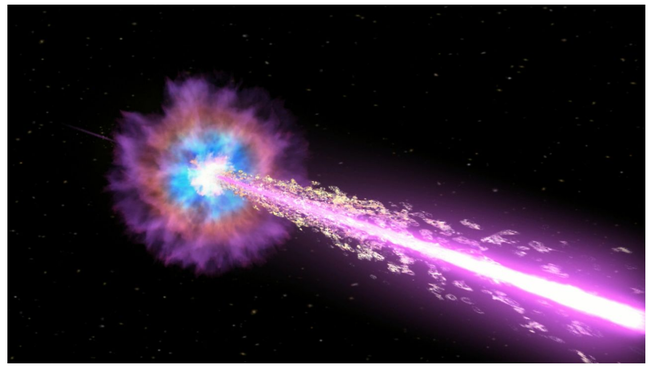
fits GW170817



$$h_{+,\times} \sim \frac{(1 \pm \cos\iota)^2}{d_L}$$



What happens next?



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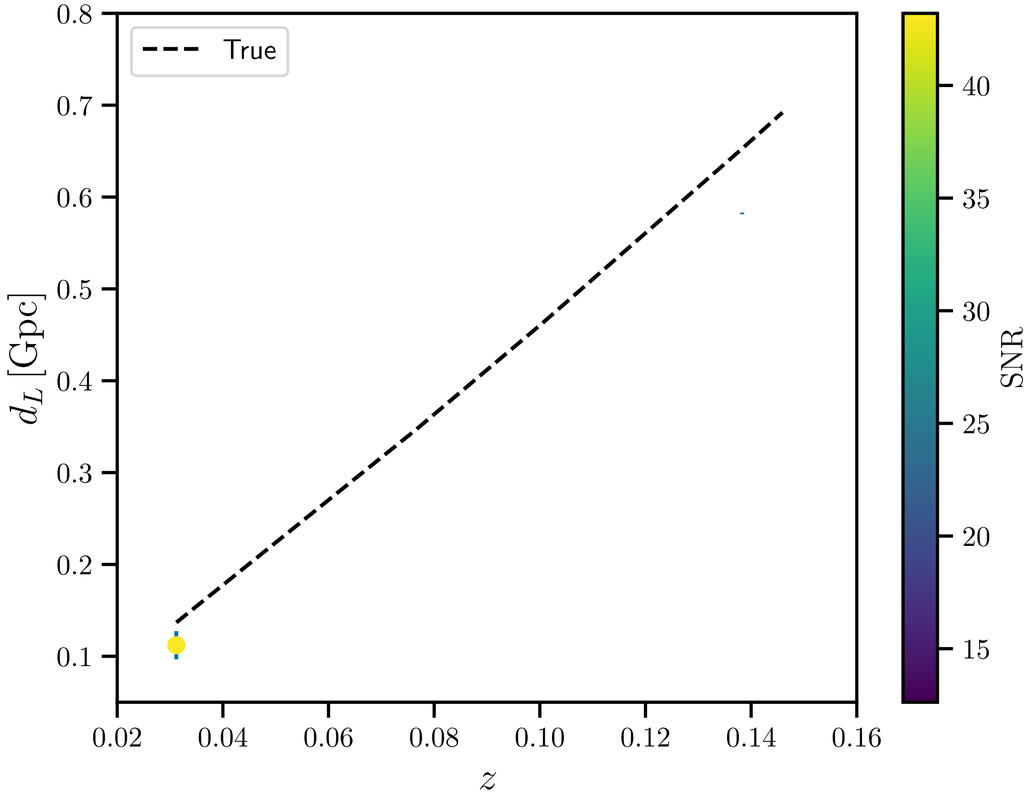
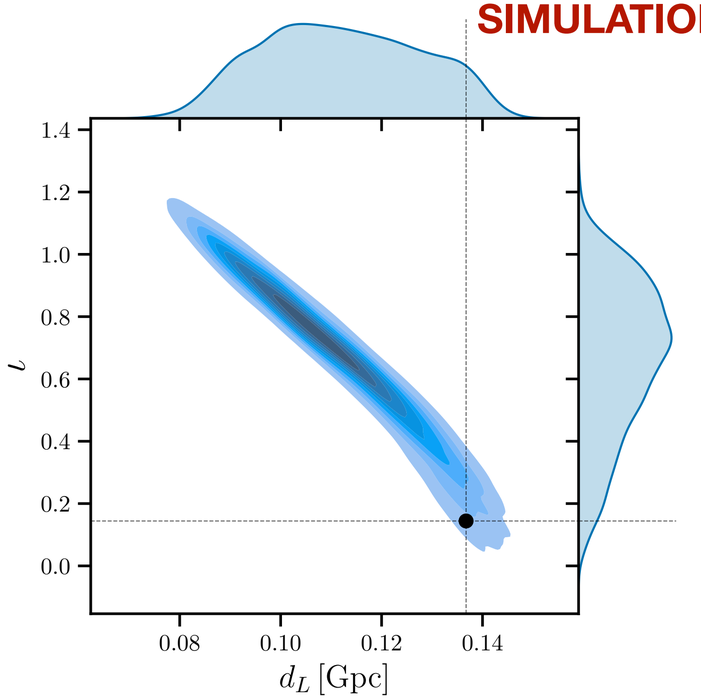
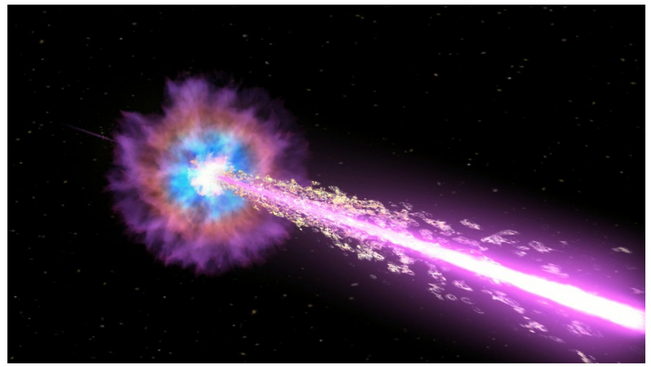


SIMULATION



What happens next?



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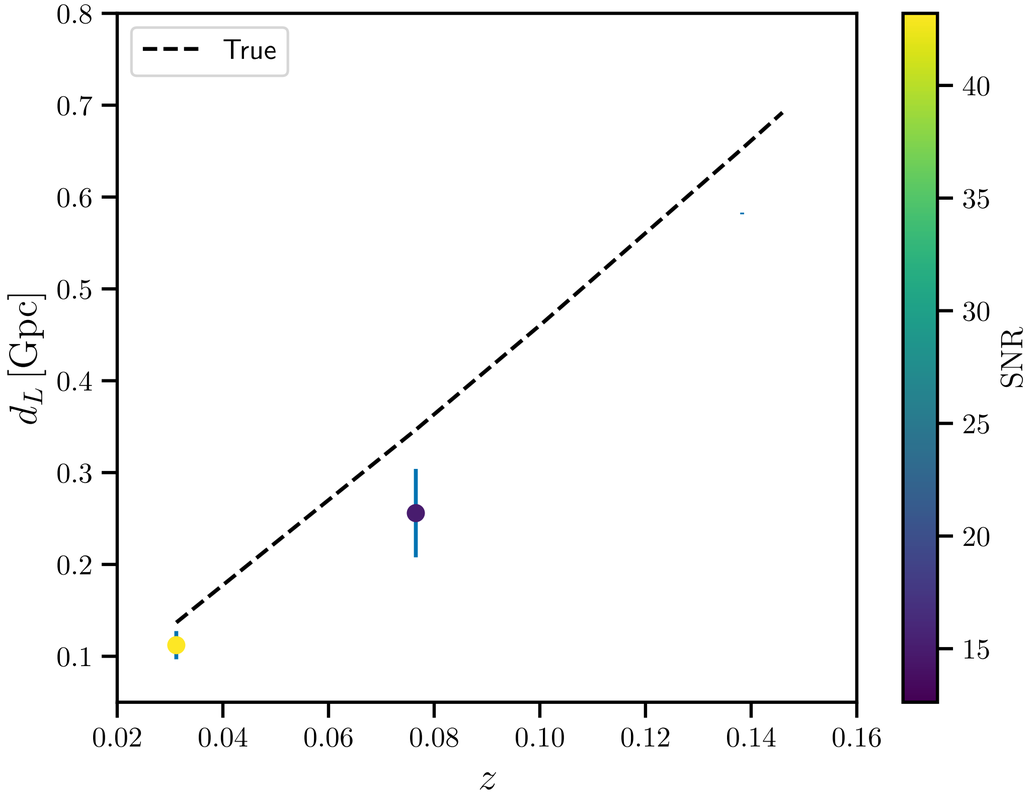
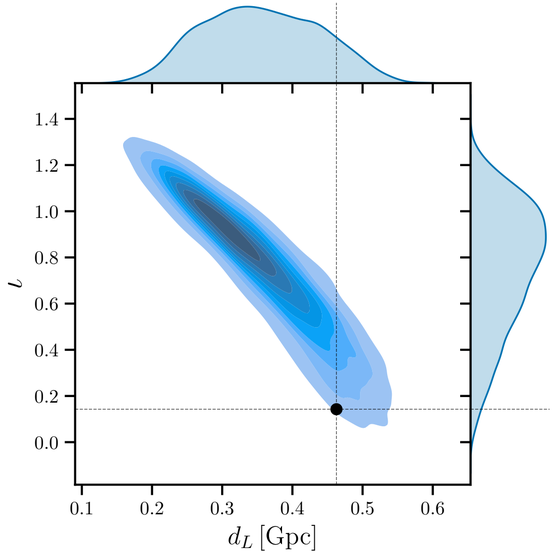
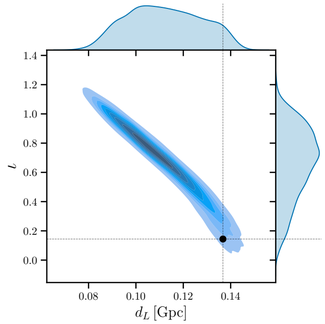




SIMULATION



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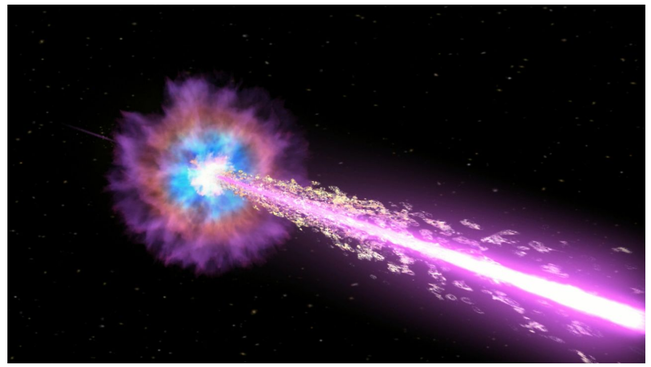

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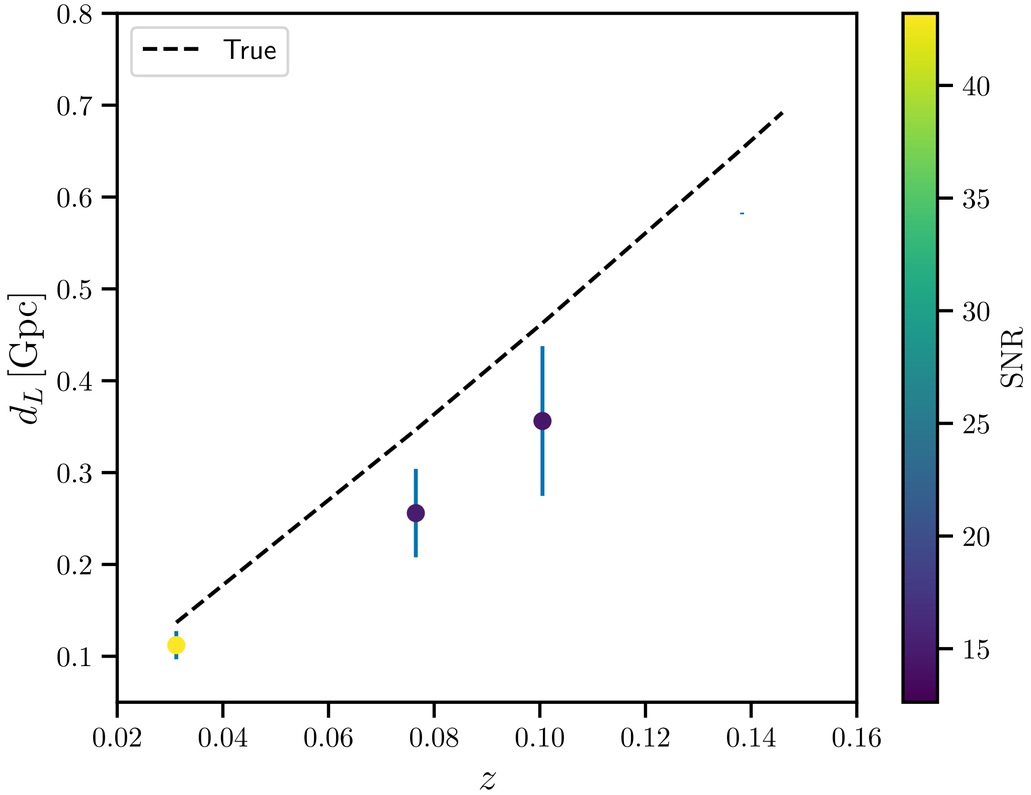
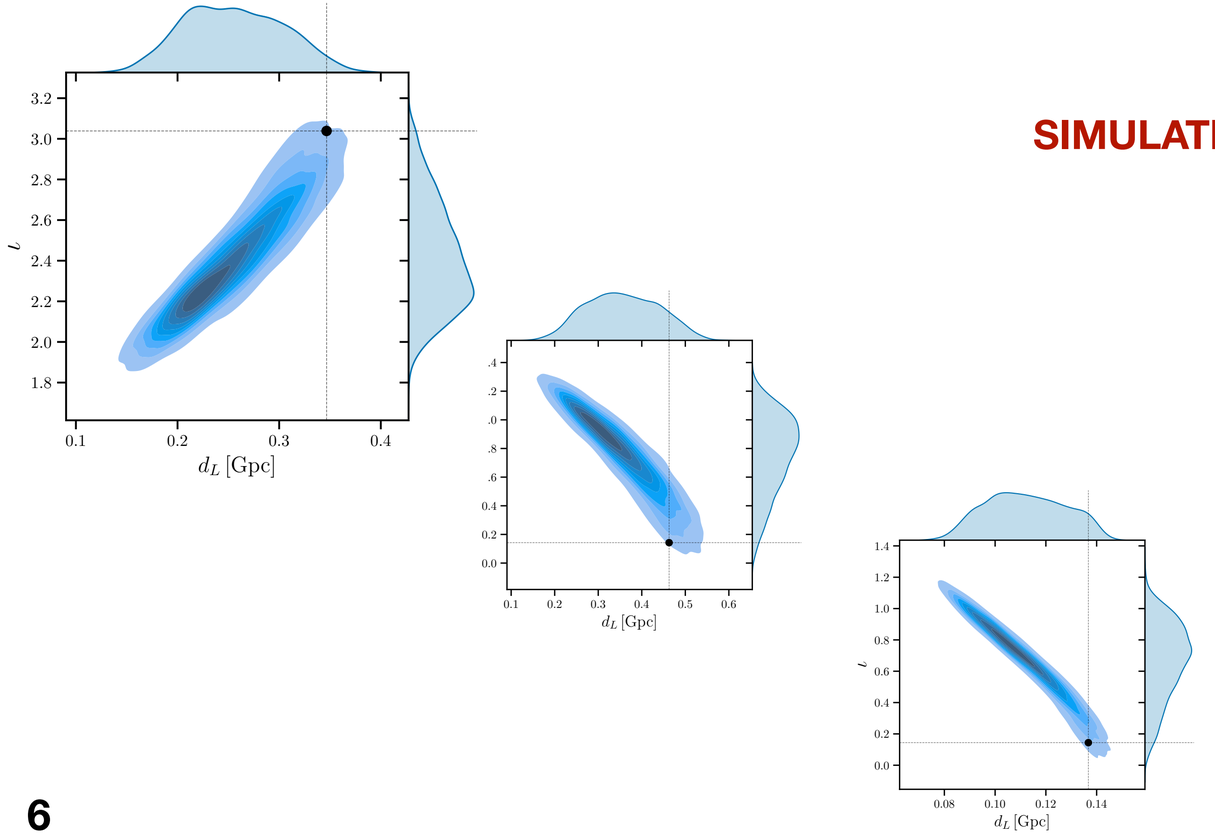
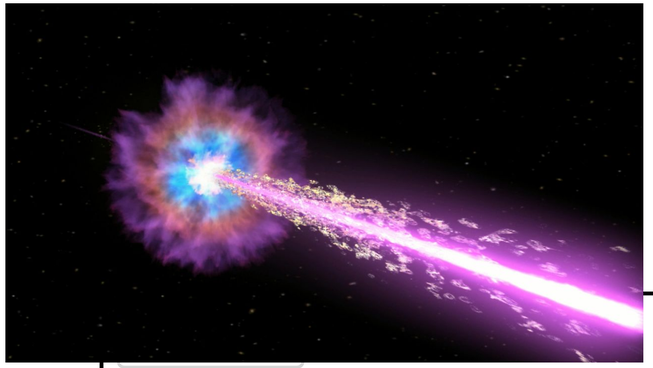




SIMULATION

Eventually...



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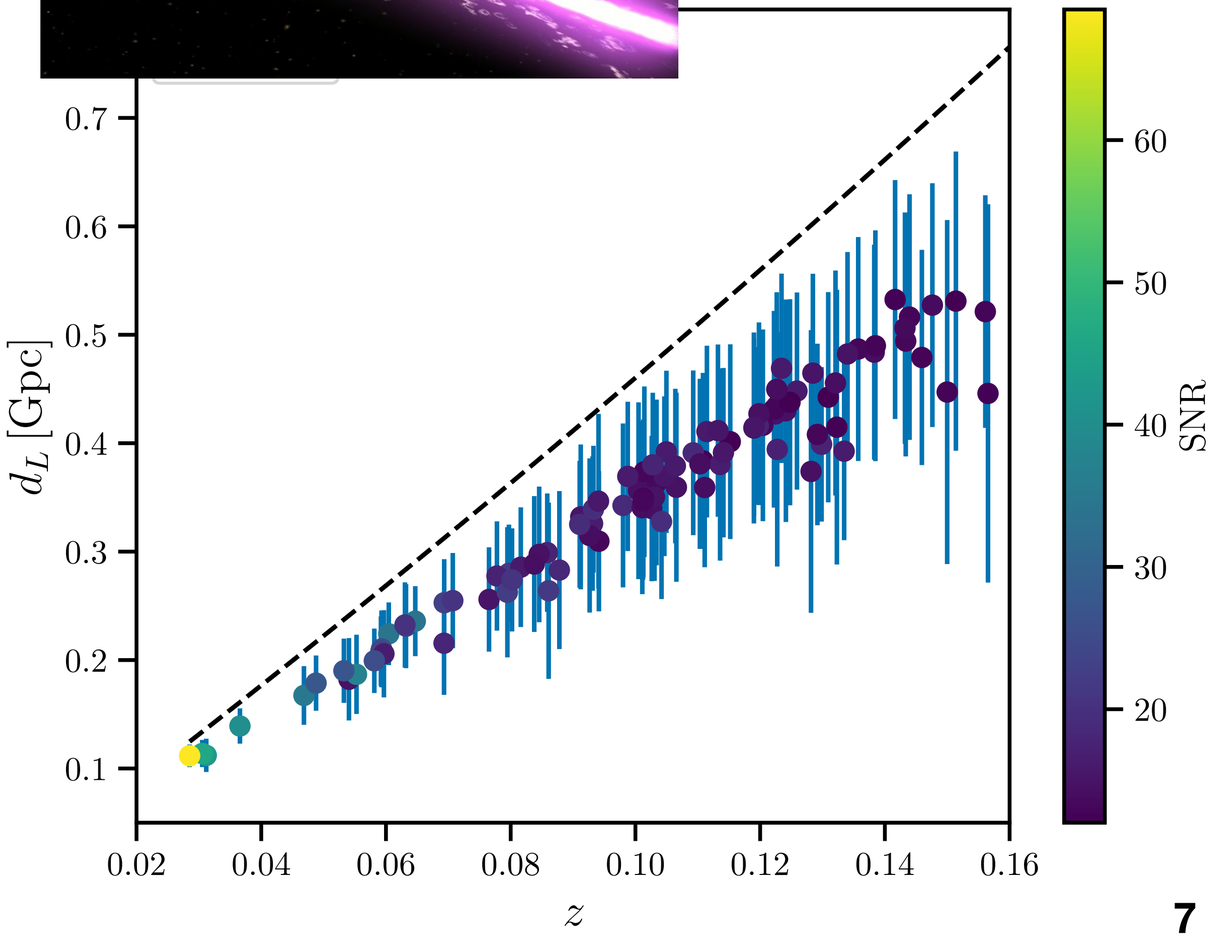


We cannot “naively” stack multi messenger events from GRBs

- Recent literature points to the need of understanding and correcting this (Chen 2020 PRL)
- Proposals put forward using sample of bright+dark (Chen + 2022 PRL)

De-biasing with just multimessenger events

- Intuitive argument: imposing prior on inclination angle would mitigate the bias.
- We do not know the max inclination angle, but we can infer it from data!
- The fact that we detected a counterpart tells us that the inclination should be small.

COSMOLOGICAL + EM + POP. PARAMETERS

SINGLE - EVENT PARAMETERS

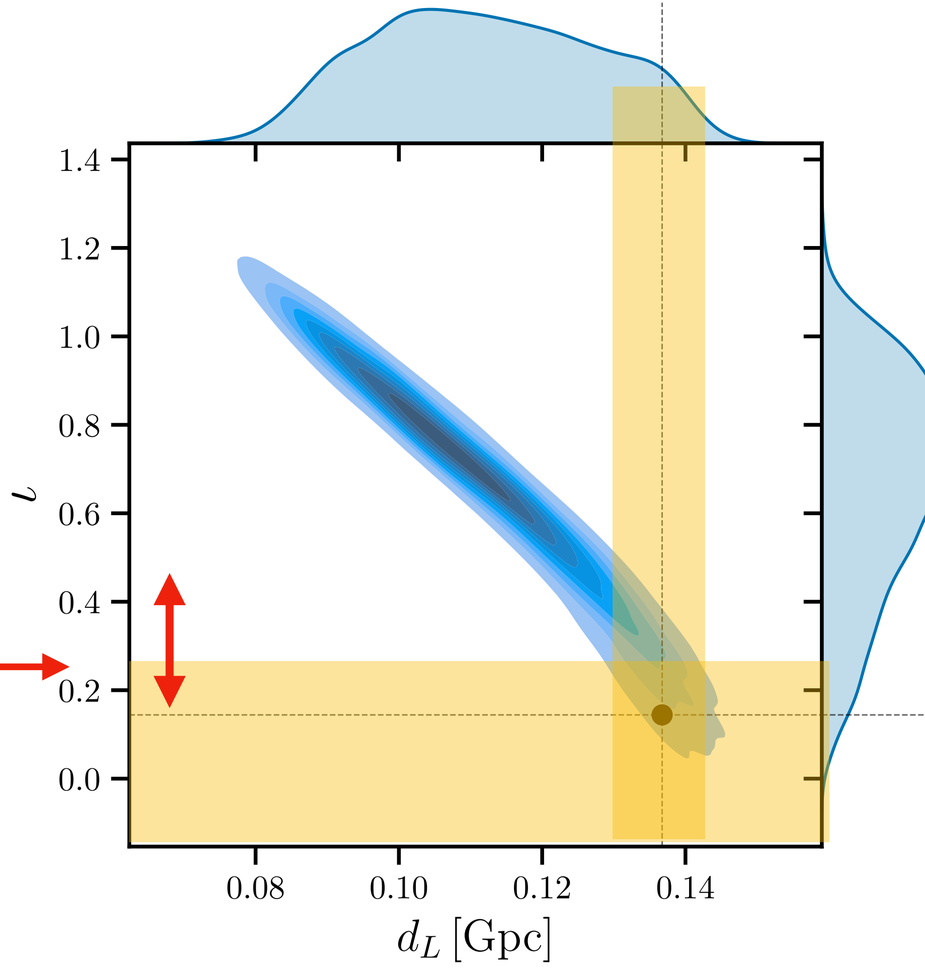
SELECTION BIAS

$$p(\boldsymbol{\lambda}, \{\boldsymbol{\theta}_i\}|d_{\rm GW}, d_{\rm EM}) \propto \frac{\pi(\boldsymbol{\lambda})}{\left[\int d\boldsymbol{\theta} P_{\rm det}(\boldsymbol{\theta}, \lambda) p_{\rm pop}(\boldsymbol{\theta}|\boldsymbol{\lambda})\right]^{N_{\rm obs}}}$$

$$\times \prod_{i=1}^{N_{\rm obs}} \mathcal{L}\left(d^i_{\rm GW}|\boldsymbol{\theta}_i\right) \mathcal{L}\left(d^i_{\rm EM}|z(d_L, \boldsymbol{\lambda}_c)\right) p_{\rm pop}(\boldsymbol{\theta}_i|\boldsymbol{\lambda}) P_{\rm det,EM}(\boldsymbol{\theta}_i, \lambda)$$

GW DATA | **REDSHIFT DATA** | **POPULATION DISTRIBUTION** | **DETECTION PROBABILITY**

AGNOSTIC TO DETAILS OF EM EMISSION

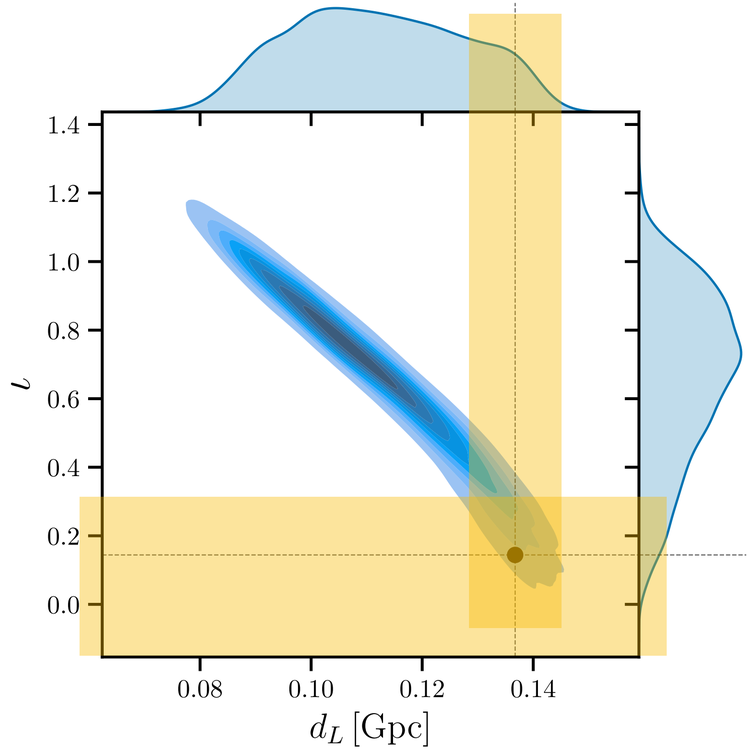


Technical problem I: hierarchical inference

- Need to accurately model the likelihood in a corner of the parameter space. High-dimensional Hamiltonian Monte Carlo

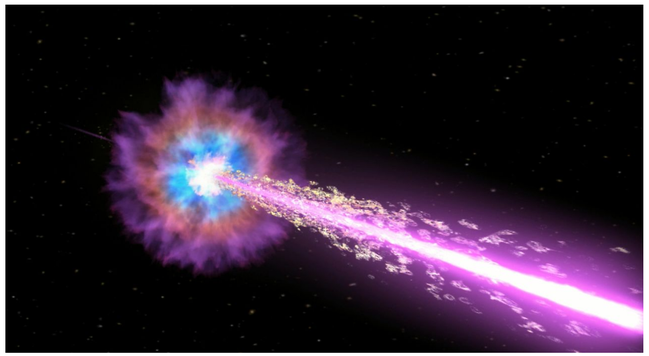
$$p(\boldsymbol{\lambda}, \{\boldsymbol{\theta}_i\} | d_{\rm GW}, d_{\rm EM}) \propto \frac{\pi(\boldsymbol{\lambda})}{\left[\int d\boldsymbol{\theta} P_{\rm det}(\boldsymbol{\theta}, \lambda) p_{\rm pop}(\boldsymbol{\theta}|\boldsymbol{\lambda})\right]^{N_{\rm obs}}}$$

$$\times \prod_{i=1}^{N_{\rm obs}} \mathcal{L}\left(d^i_{\rm GW}|\boldsymbol{\theta}_i\right) \mathcal{L}\left(d^i_{\rm EM}|z(d_L, \boldsymbol{\lambda}_c)\right) p_{\rm pop}(\boldsymbol{\theta}_i|\boldsymbol{\lambda}) P_{\rm det,EM}(\boldsymbol{\theta}_i, \lambda)$$



4 x N_{events} + $N_{paramters}$ = up to > 200 dimensions for 50 events

Technical problem II : be careful with simulations



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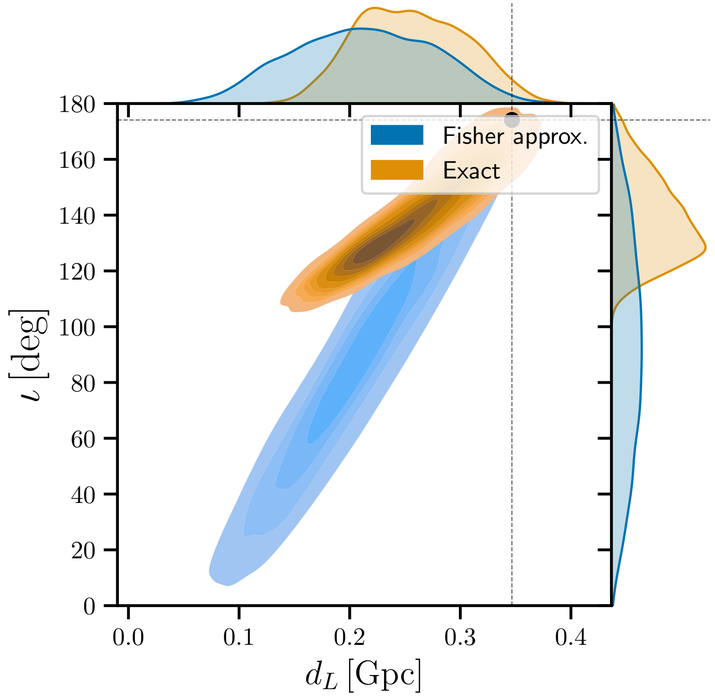
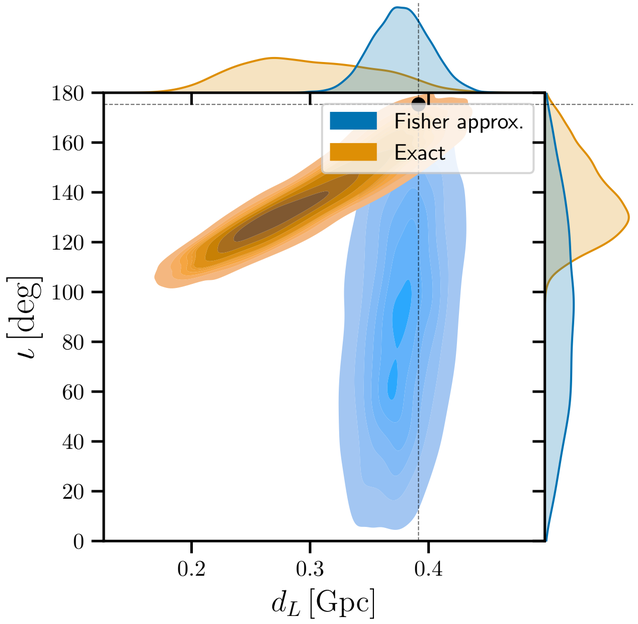




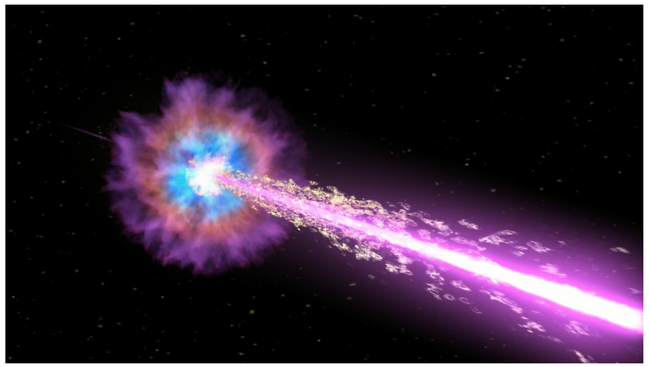
We cannot use simplified models of the distance-inclination correlation

NO FISHER MATRIX APPROX.

NO $\Delta d_L \sim 1/SNR$

- New likelihood approximant beyond Fisher - exact in the space (d_L - ι)

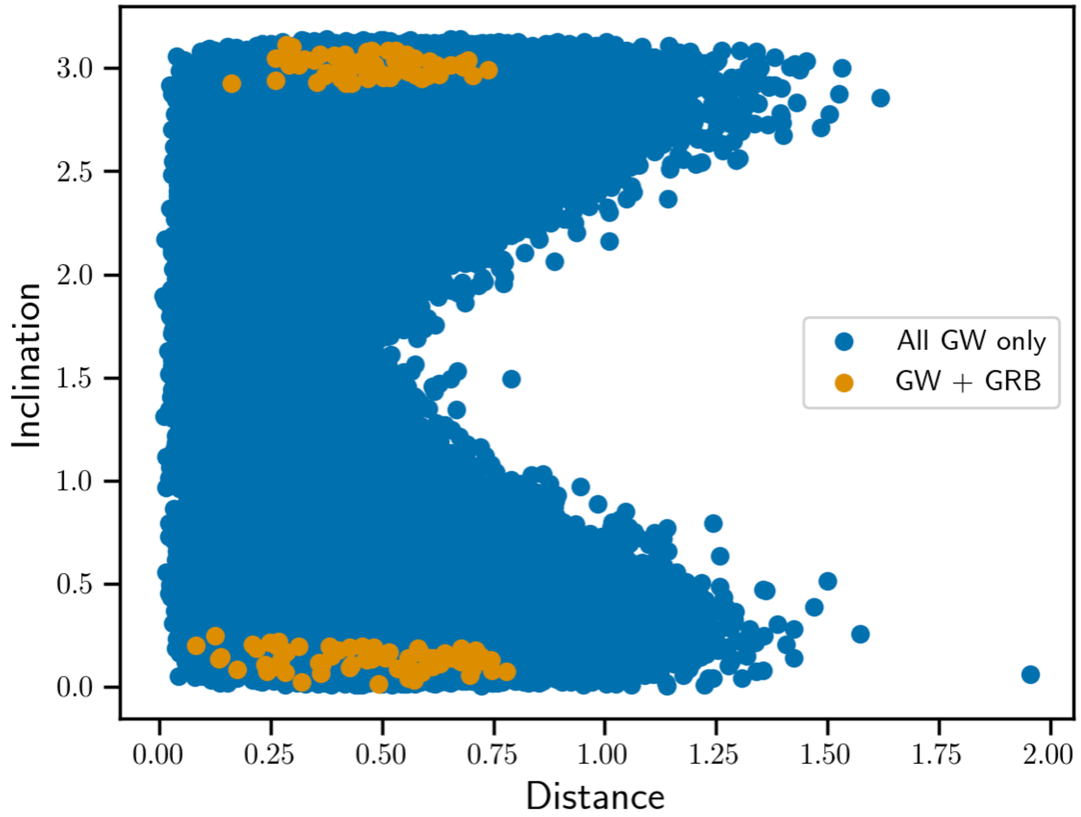
Simulations



Fiducial values from fit to GW170817 + EM data

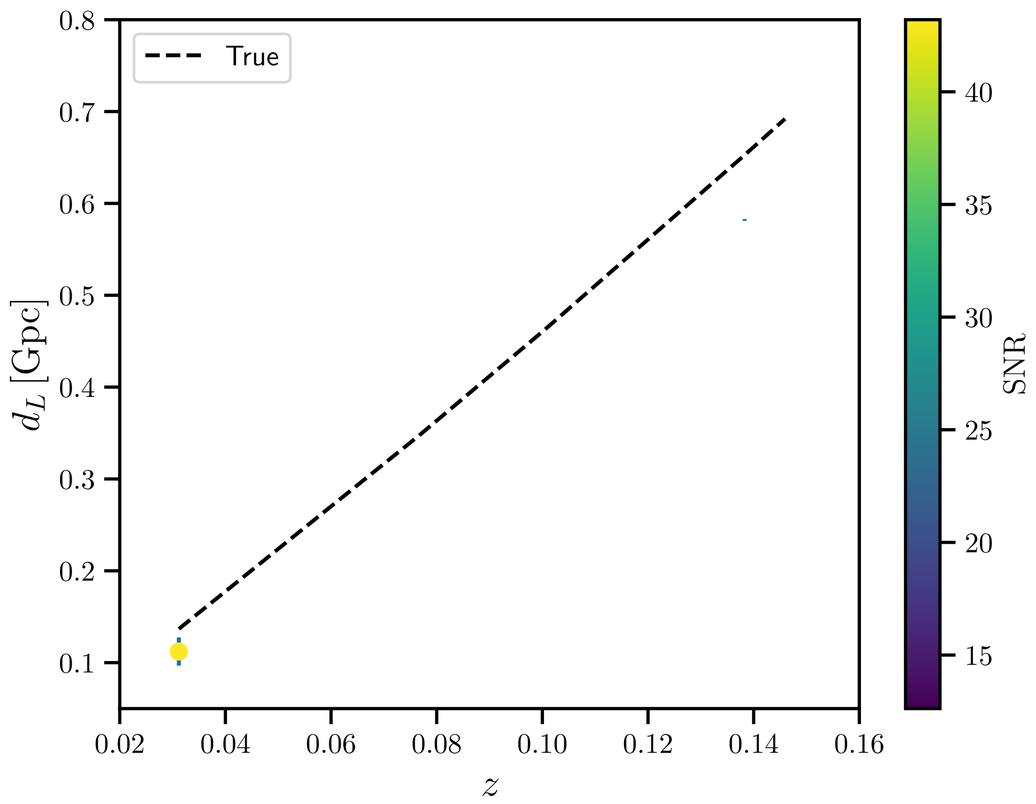
$$P_{\rm det,EM} = 1 \text{ if } \quad F_{\rm GRB} \propto \frac{E_0}{(4\pi d_L^2)} e^{-(\iota^2/\iota_{\rm c}^2)/2} \quad > F_{\rm th}$$

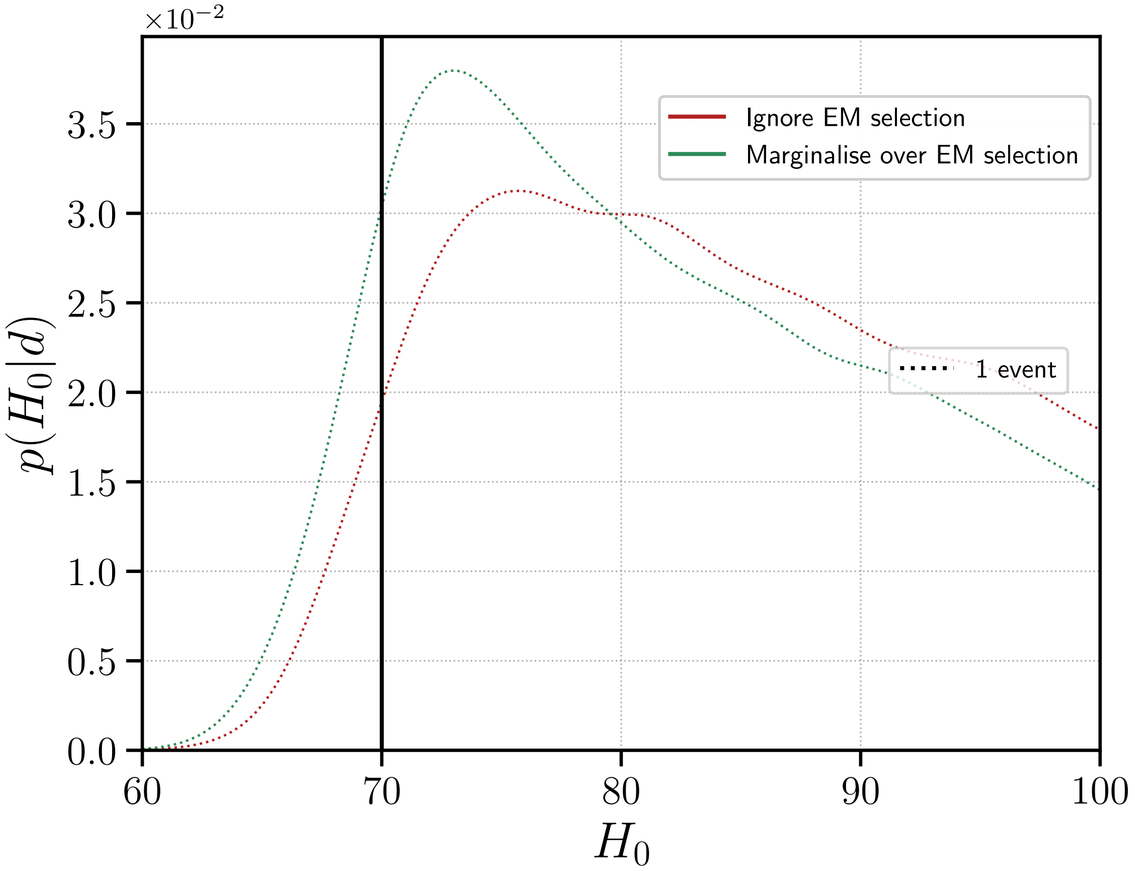
$$\iota_{\rm c} = 0.057 \text{ (Troja + 2017)}$$



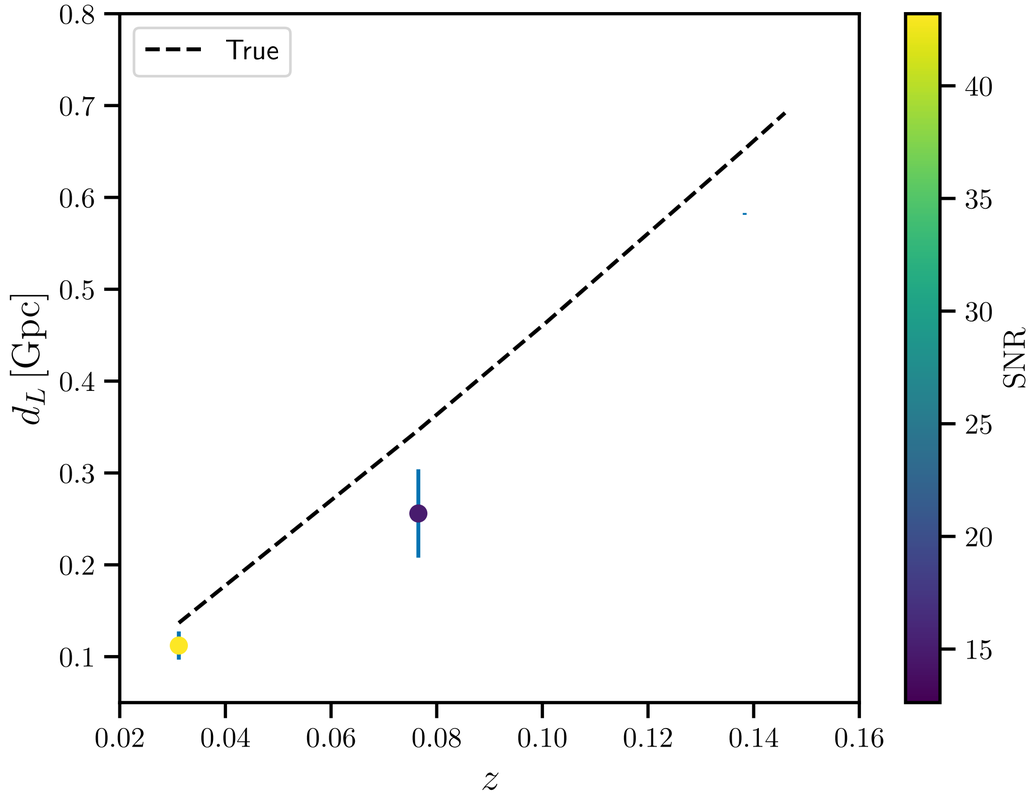
—> GRB detected only if **inclination <~ 10 deg (0.2 rad)**

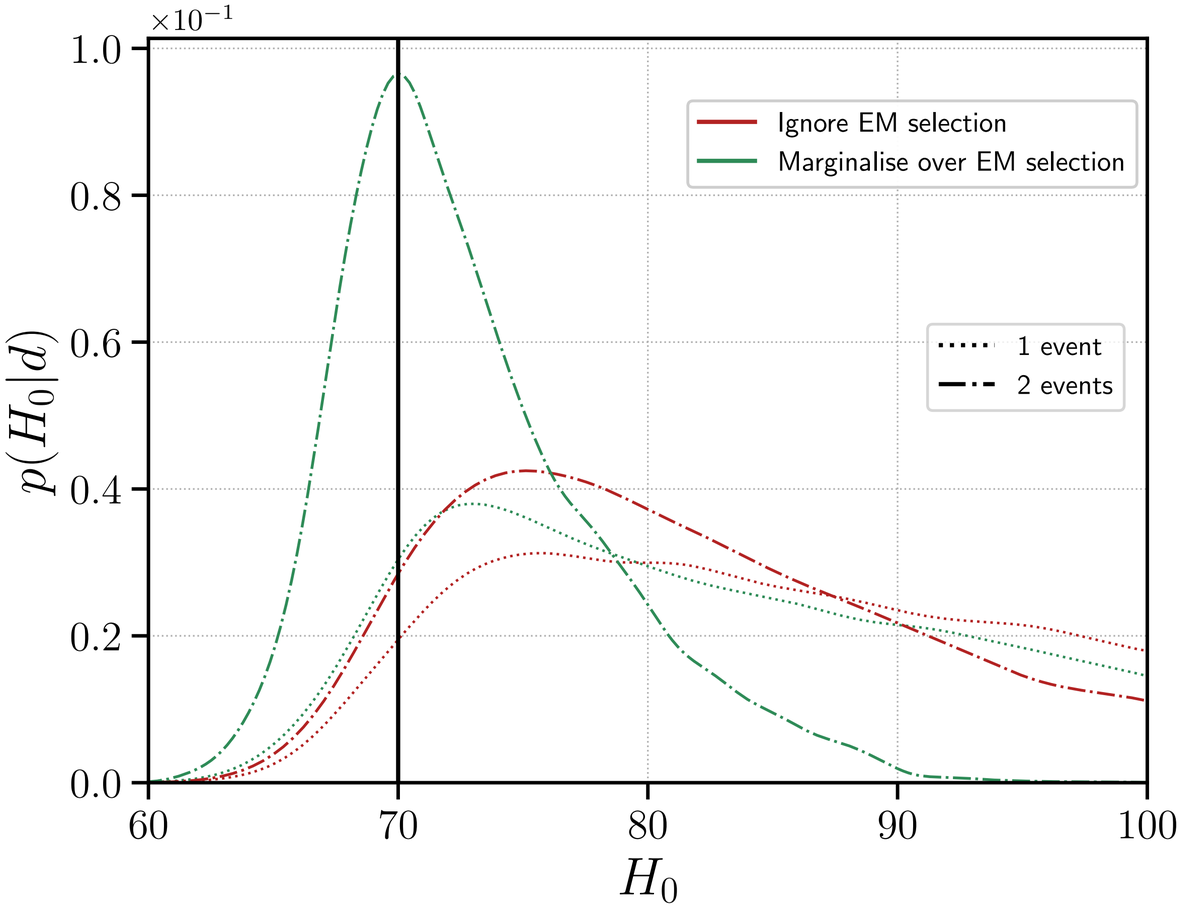
Results


True
d_L [Gpc]
z
SNR

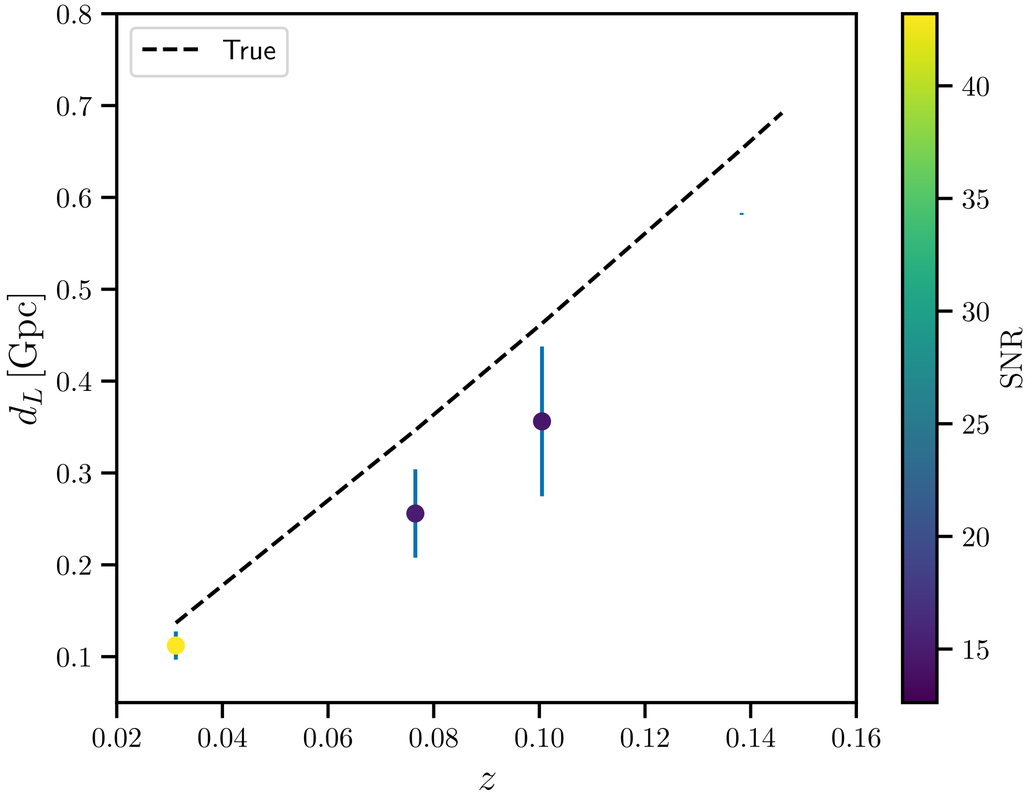

$\times 10^{-2}$
Ignore EM selection
Marginalise over EM selection
1 event
$p(H_0|d)$
H_0

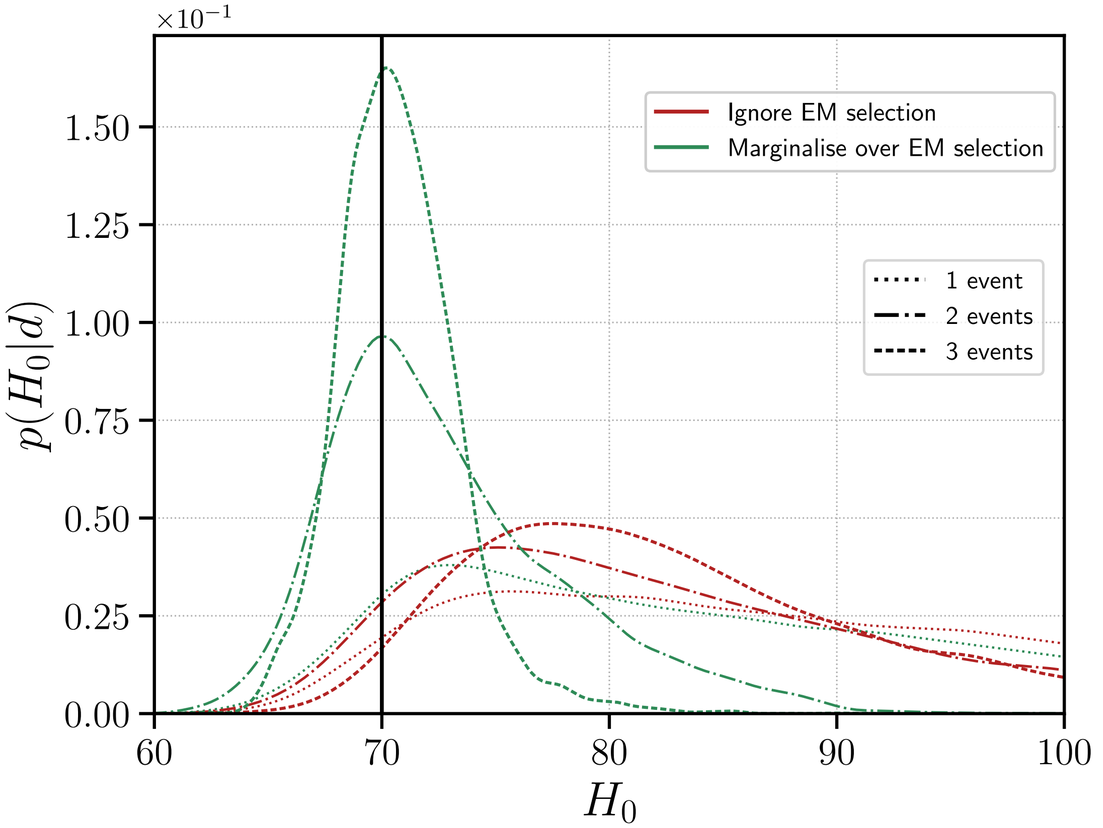
Results


True
d_L [Gpc]
z
SNR

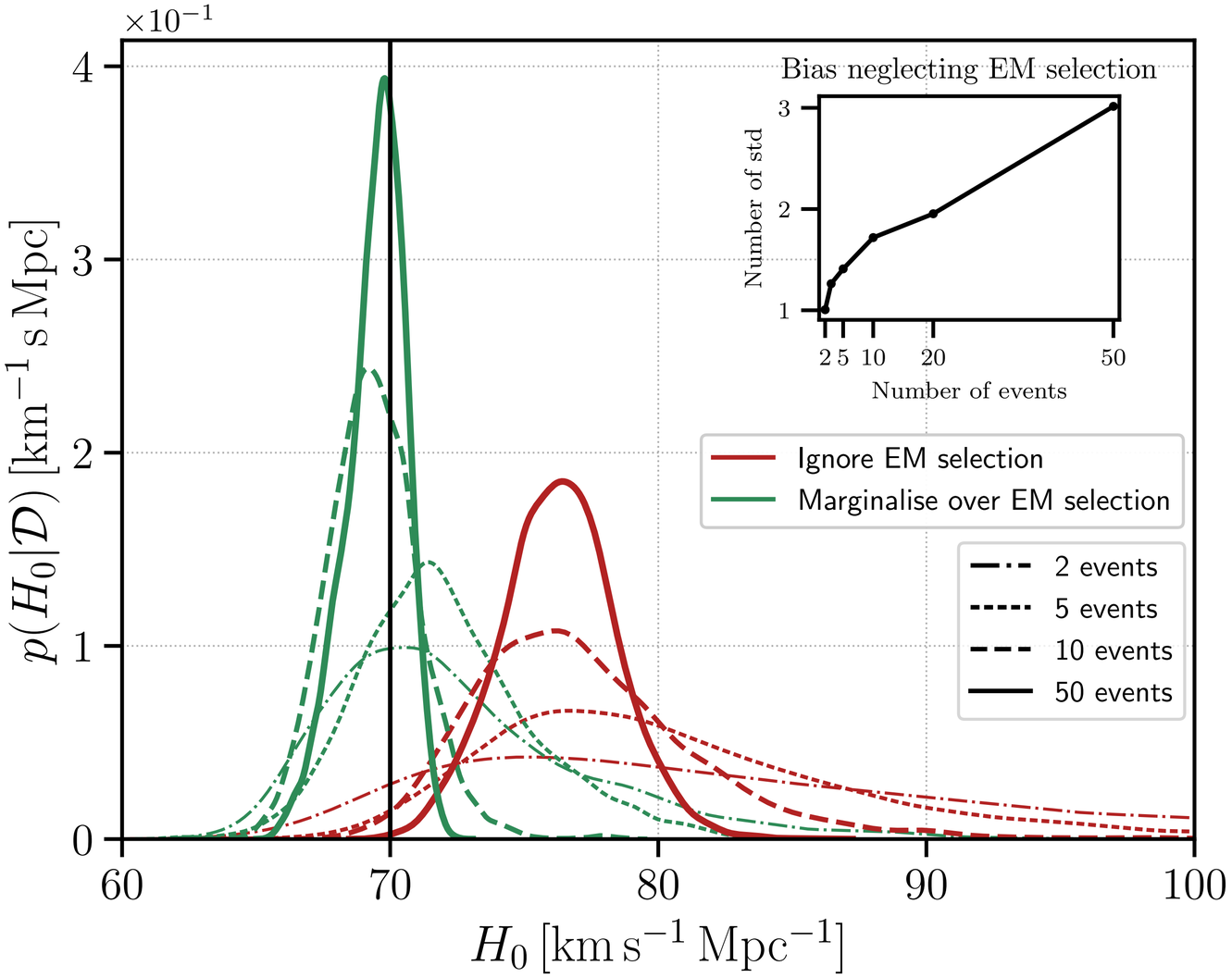

$\times 10^{-1}$
Ignore EM selection
Marginalise over EM selection
1 event
2 events
$p(H_0|d)$
H_0

Results


True
d_L [Gpc]
z
SNR


$\times 10^{-1}$
Ignore EM selection
Marginalise over EM selection
1 event
2 events
3 events
$p(H_0|d)$
H_0

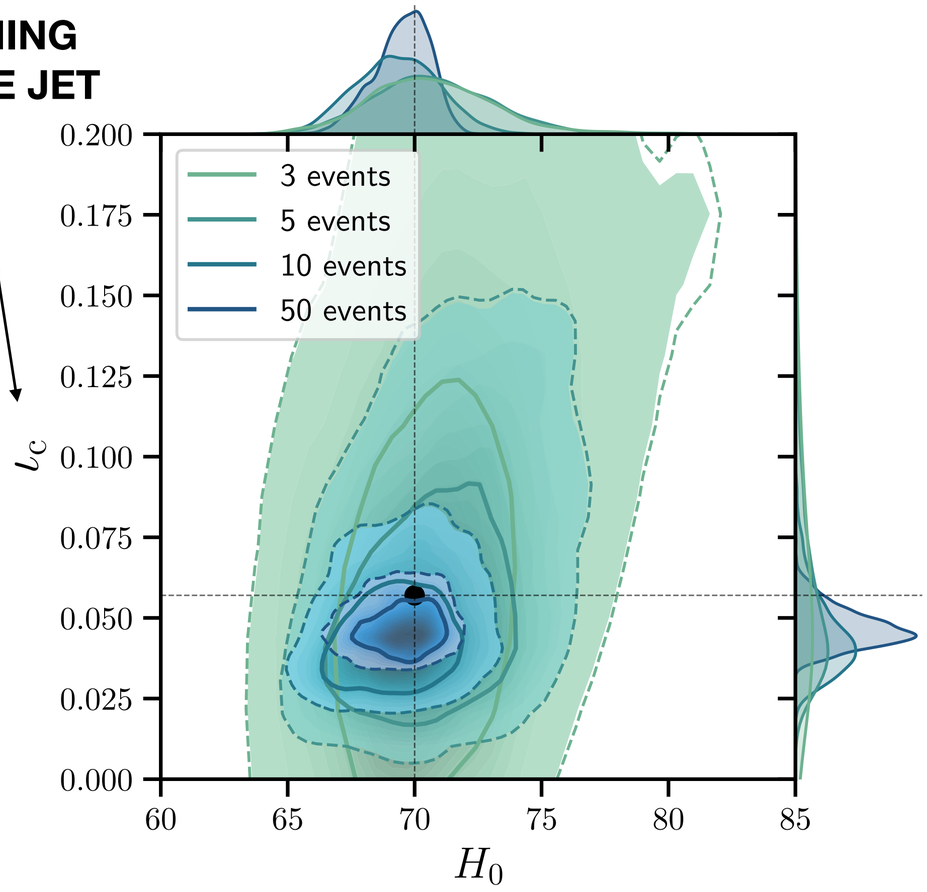
Results - unbiased Hubble constant



WORRY ABOUT THIS STARTING FROM 2 EVENTS. DO THIS FOR O5/3G.

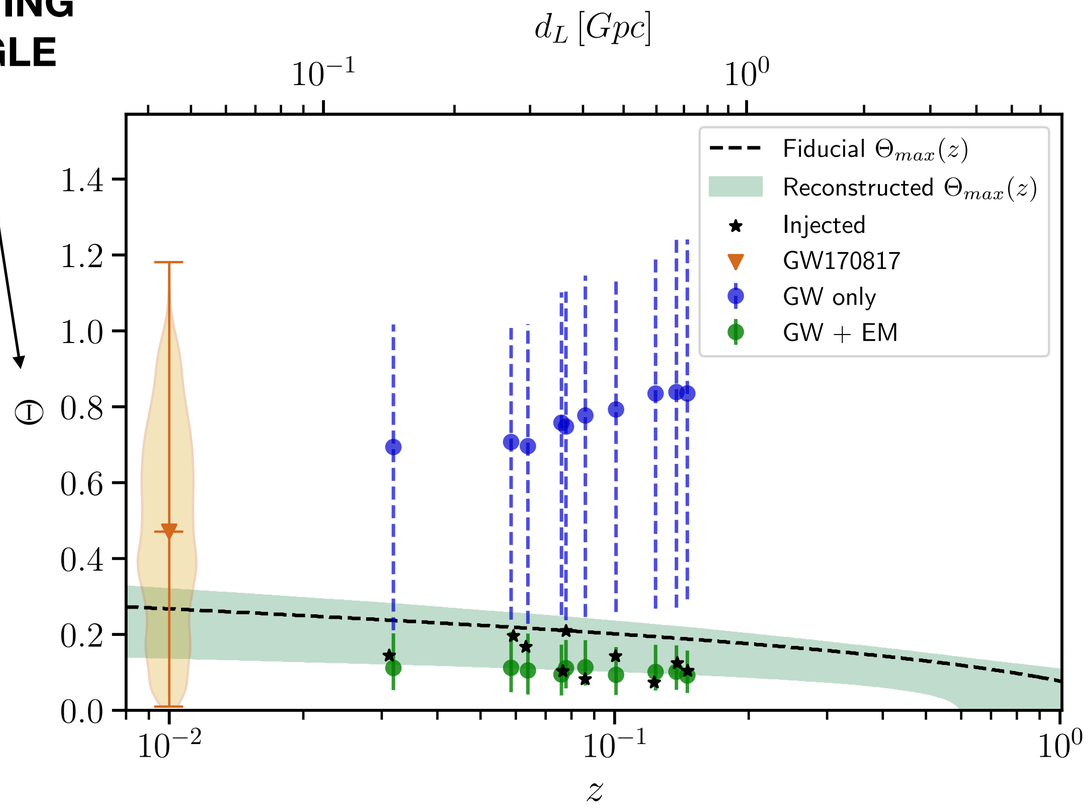
Results - GRB inclination

OPENING OF THE JET



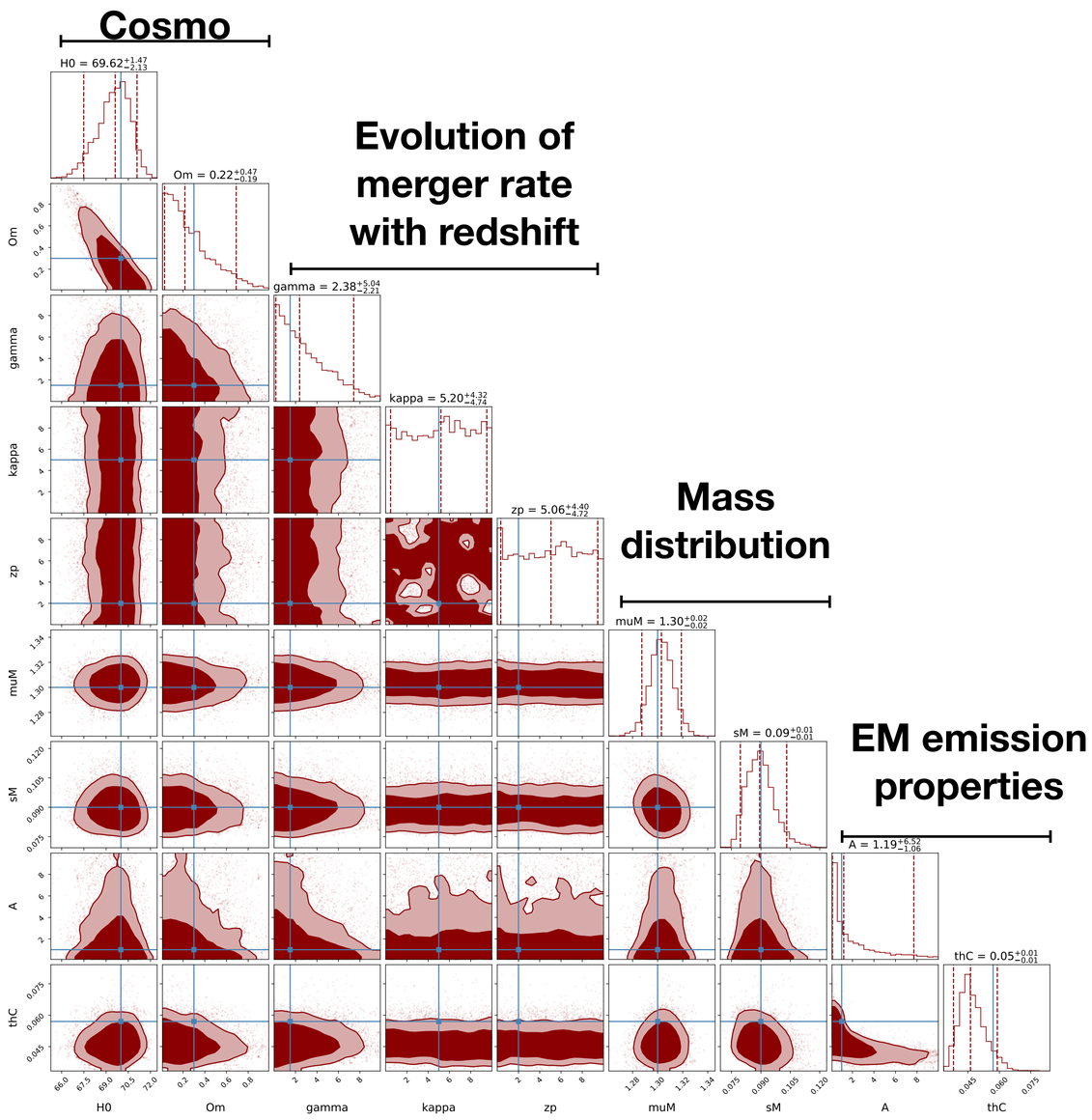
- Reconstruction of max inclination angle
- Reconstruction of individual inclinations

VIEWING ANGLE



- Could also fix Hubble and reconstruct GRB emission model without inclination measurement

Results - population properties

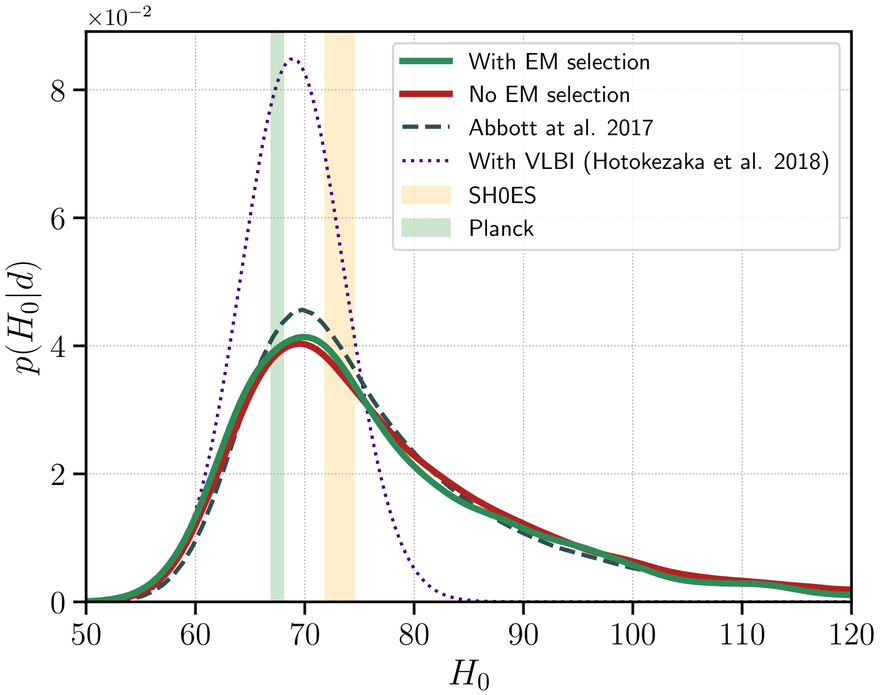


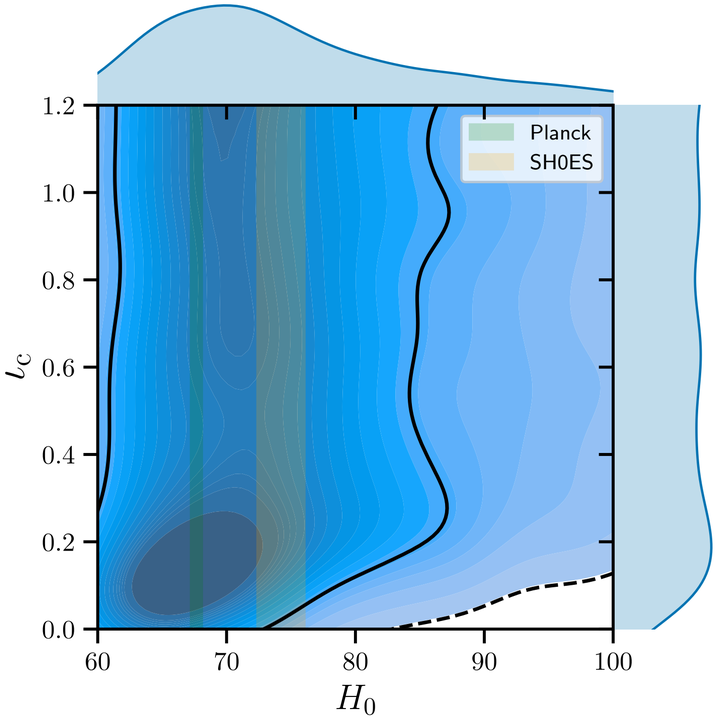
- Infer all population + EM selection parameters
- … + all individual sources' masses, redshift, inclinations
- **with 3G, can determine mass and redshift distributions**

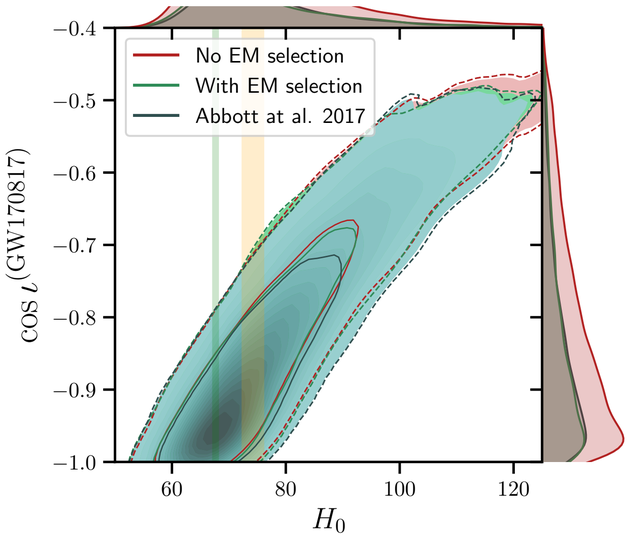
Conclusion

- If GRB emission is beamed, expect bias on the Hubble constant unless the EM selection effect is accounted for.
- We don't know the max inclination angle. But we can marginalise over it - reconstruction of GRB detection probability without inclination measurements
- Relevant even for 2 events (O4?). Crucial for O5/ET with tens of bright sirens
- When simulating these bright sirens, correct modelling of the GW likelihood in distance-inclination plane is mandatory.

Check: GW170817







- Consistent with expectation - 1 event does not make a population…

Likelihood approximant

- Fisher-like expansion for intrinsic variables
- No expansion for distance, inclination (possibly sky loc)

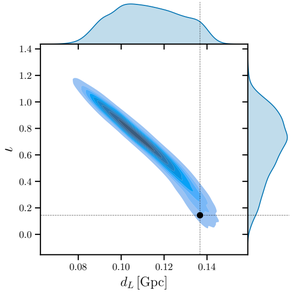
$$\mathcal{L}(s \mid \boldsymbol{\theta}) \propto \exp\{-(s - h(\boldsymbol{\theta}) \mid s - h(\boldsymbol{\theta}))/2\} \, .$$

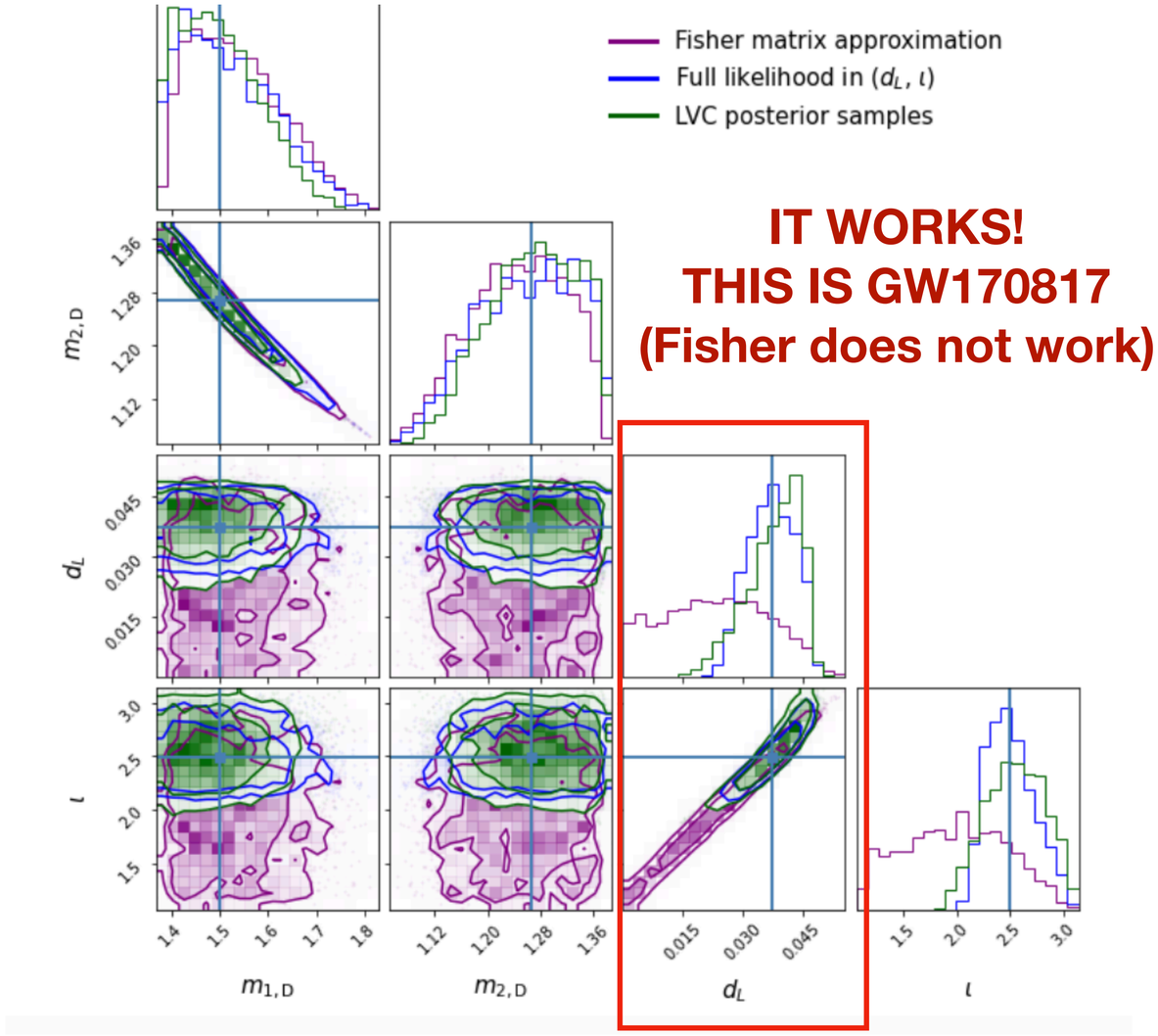
$$h(\boldsymbol{\theta}) = h_0 + h_i \, \delta\theta^i + \ldots$$

$$\{\mathcal{M}_c, \eta, d_L, \theta, \phi, \iota, \psi, t_c, \Phi_c, \chi_{1,c}, \chi_{2,c}\}$$

Exact

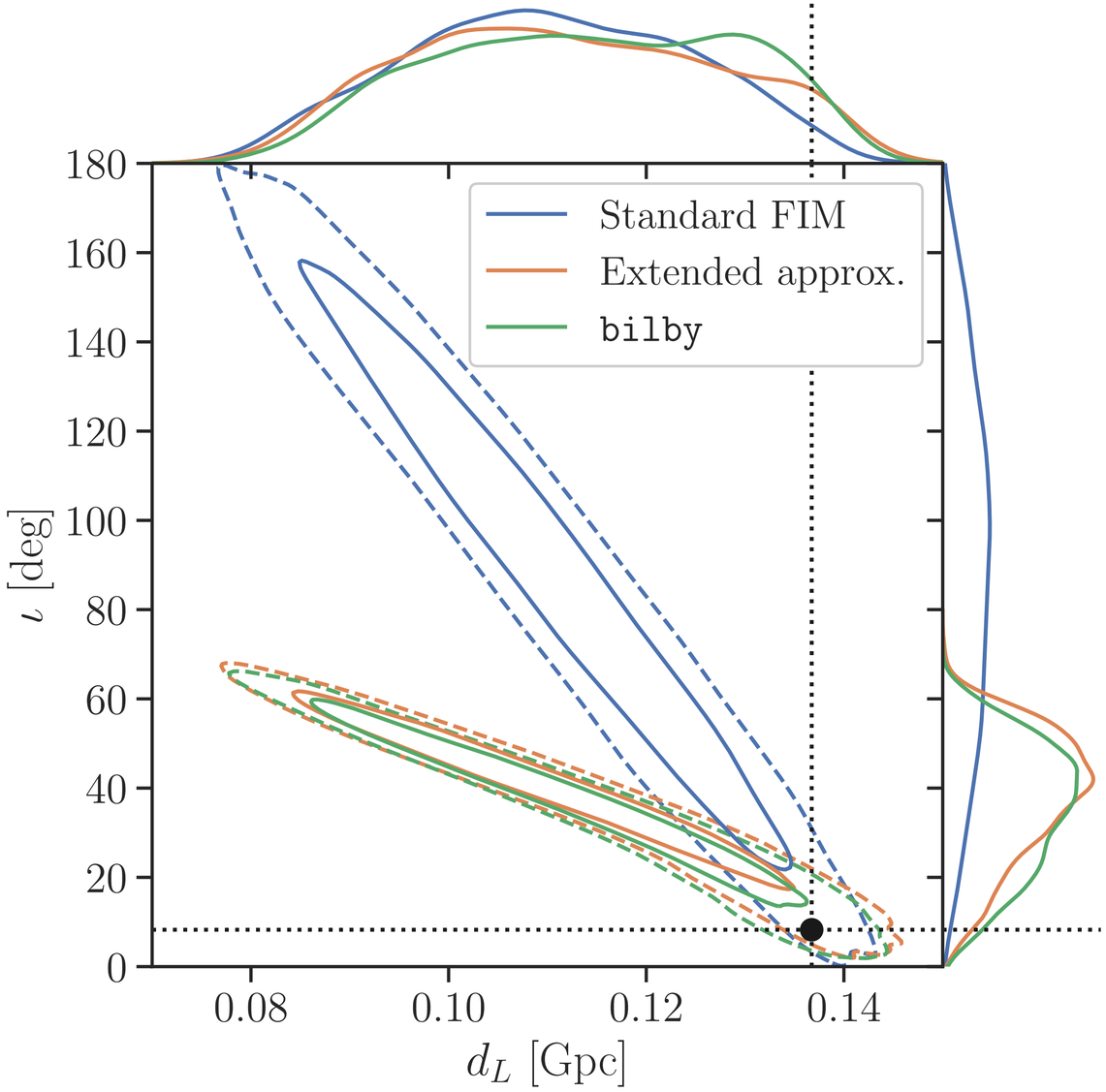
$$h_{+,\times} \sim \frac{(1 \pm \cos\iota)^2}{d_L}$$





IT WORKS!
THIS IS GW170817
(Fisher does not work)

Likelihood approximant VS bilby



- No approximation in (d_L - ι)