

Estimating short gamma-ray burst luminosities in conjunction with gravitational wave observations

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Motivation & outline

- Multi-messenger observations can be combined to improve our knowledge of gravitational wave progenitors
- We present an approach to do this for joint short-GRB and gravitational wave observations from binary neutron stars
- Though the details discussed here are relevant for sGRB-GW, the general approach is applicable to any joint EM-GW observations
- Methodology
- Characterisation
 - Simulation
 - Example case study
 - Ensemble results
- Summary & discussion

The general idea

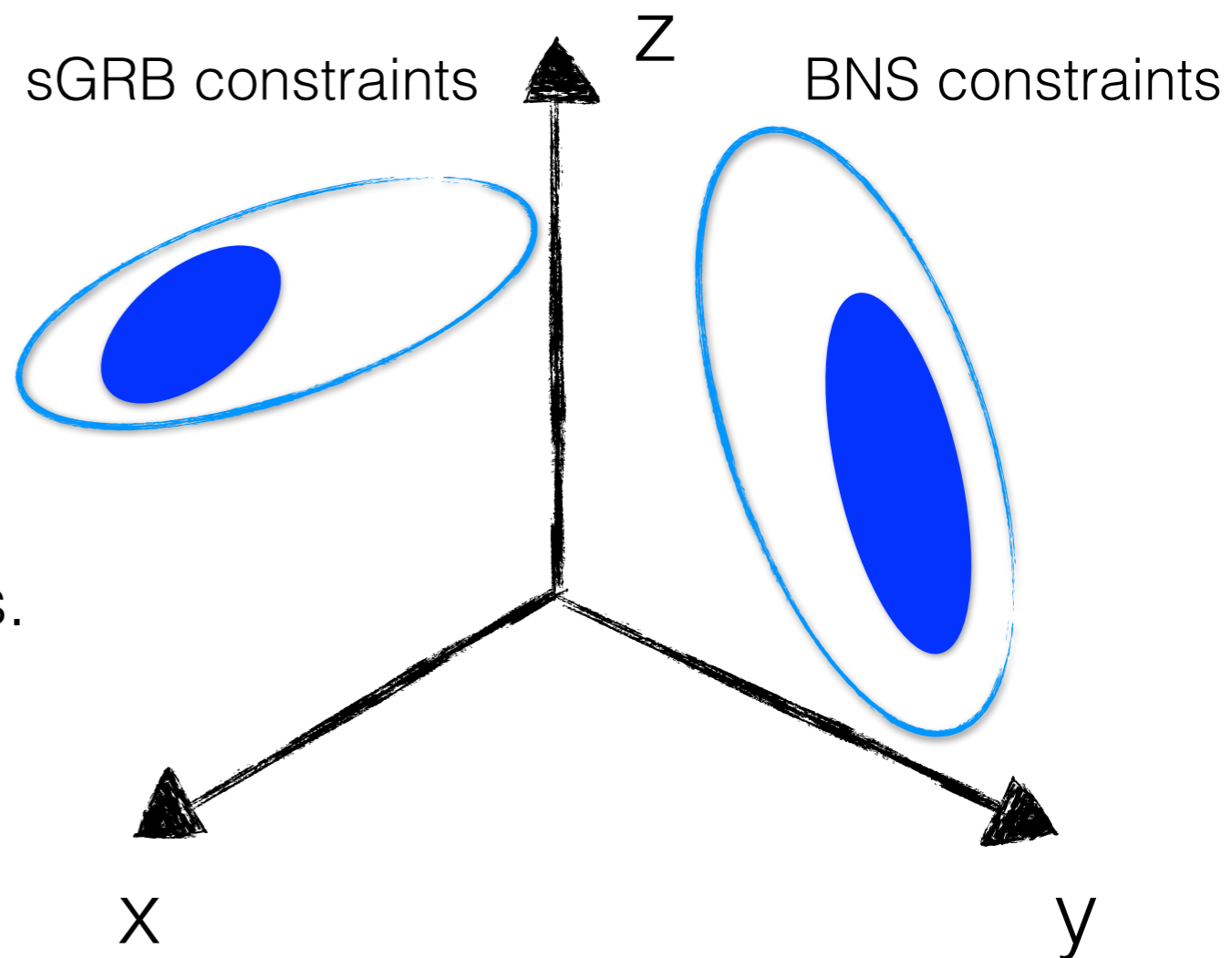
- For a joint sGRB-BNS detection, we combine the results to enhance our inference.
- A BNS detection allows us to constrain d , $\cos i$, + others.
- An sGRB detection without an identified host gives us flux, a function of θ_{jet} , d , and L , + others.
- Require $\theta_{\text{jet}} > i$

d - distance

i - inclination angle

θ_{jet} - GRB half opening angle

L - GRB luminosity



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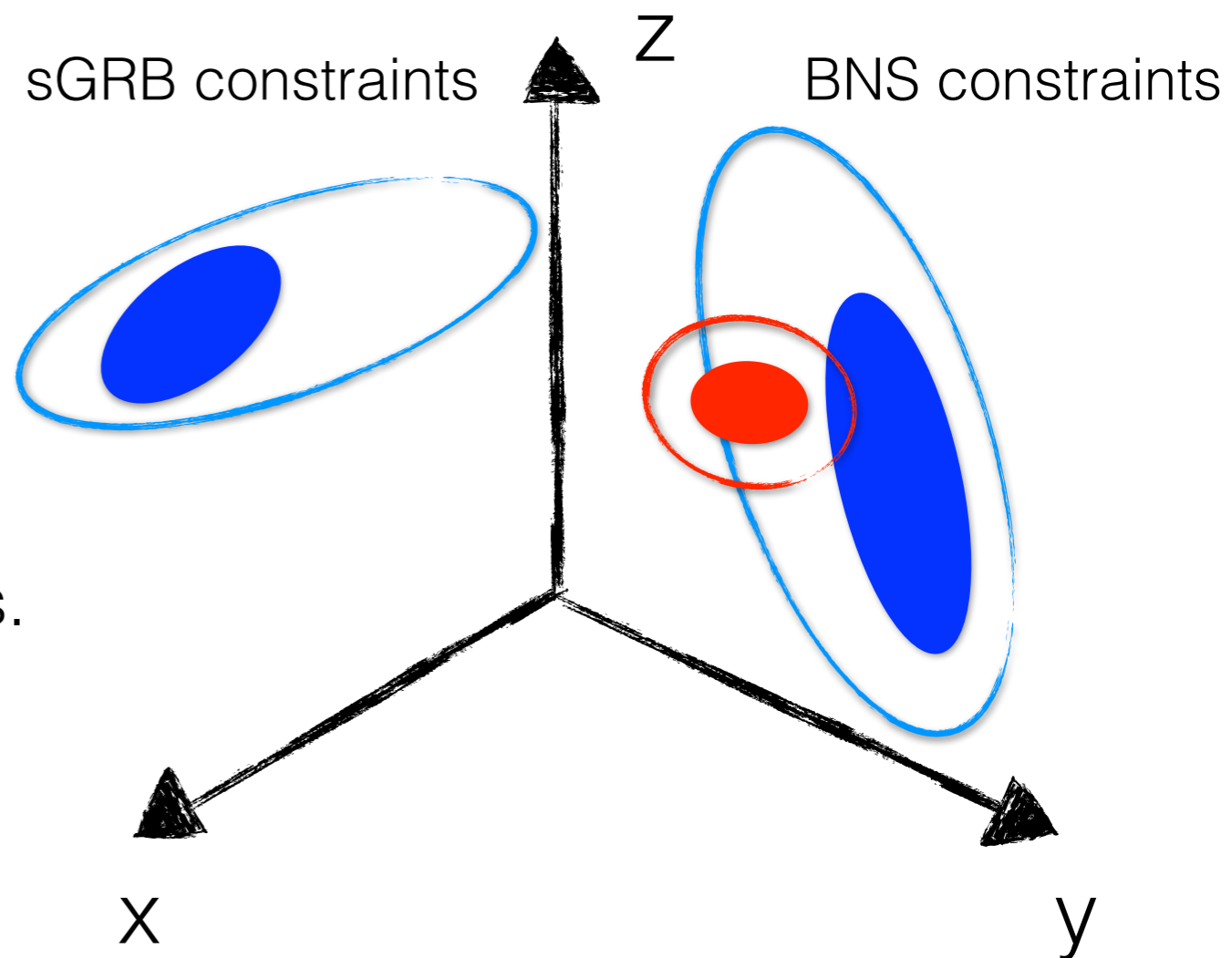
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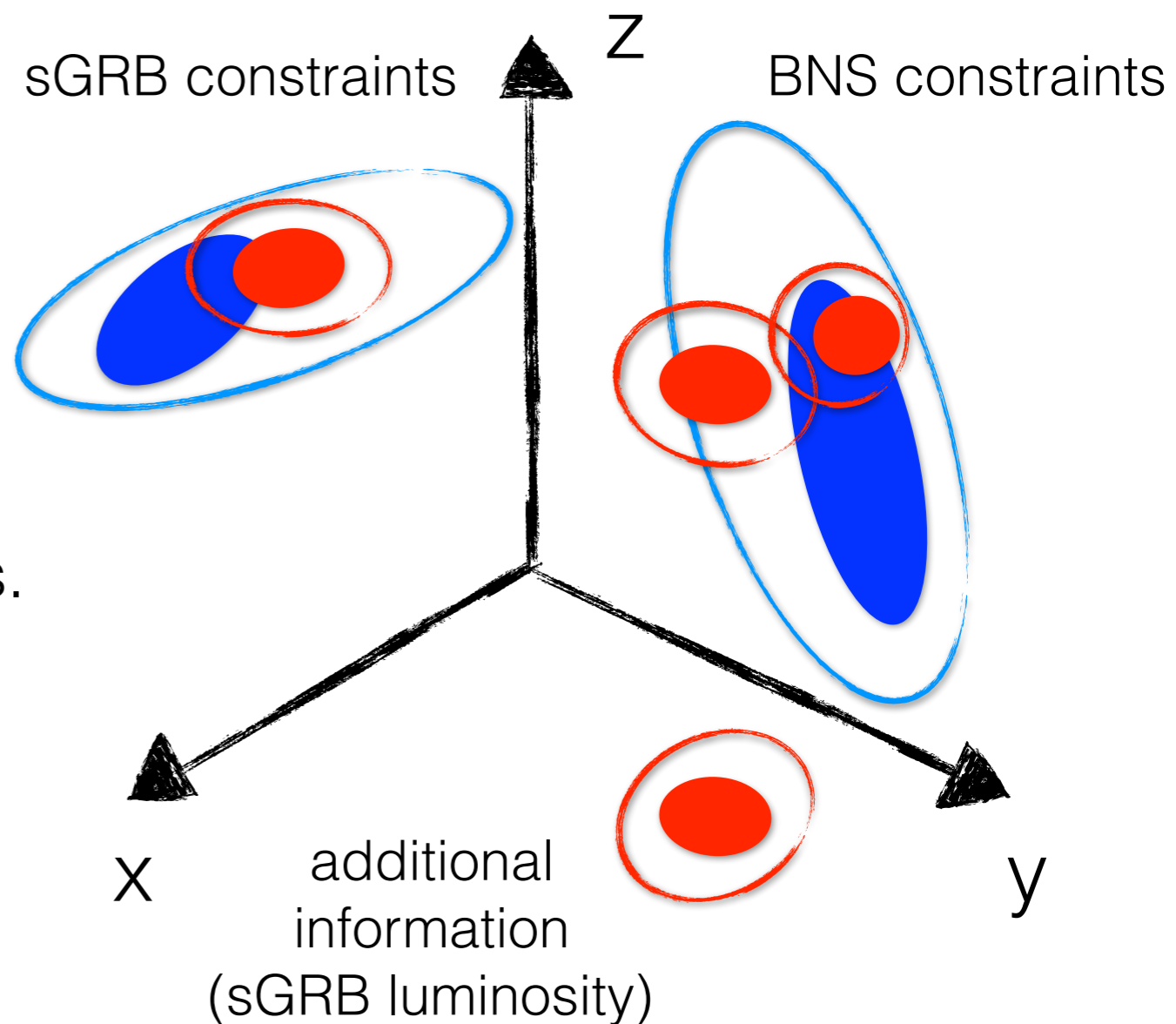
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The procedure

- From Bayes' theorem, we can write down the posterior for all parameters as

$$p(\theta|\mathbf{S}, \mathbf{D}, I) \propto p(\gamma, \omega, \phi|I)p(\mathbf{D}|\gamma, \omega, I)p(\mathbf{S}|\gamma, \phi, I)$$

- The sGRB likelihood is

$$p(\mathbf{S}|\gamma, \phi, I) = \frac{1}{\sigma_{F_\gamma} \sqrt{2\pi}} \exp \left(-\frac{(F_\gamma - F_{\text{th}})^2}{2\sigma_{F_\gamma}^2} \right)$$

- The measured flux is mapped to the sGRB luminosity, L , by

$$F_{\text{th}}(d, L, \theta_{\text{jet}}) = \frac{L}{4\pi d^2 (1 - \cos \theta_{\text{jet}})}.$$

d : source distance

θ_{jet} : sGRB half-opening angle

- Assume peak flux observed by ideal (lossless) sGRB detector

\mathbf{D} : gravitational wave data

\mathbf{S} : EM data (sGRB observations)

γ : parameters common to GW & EM

ω : parameters for GW only

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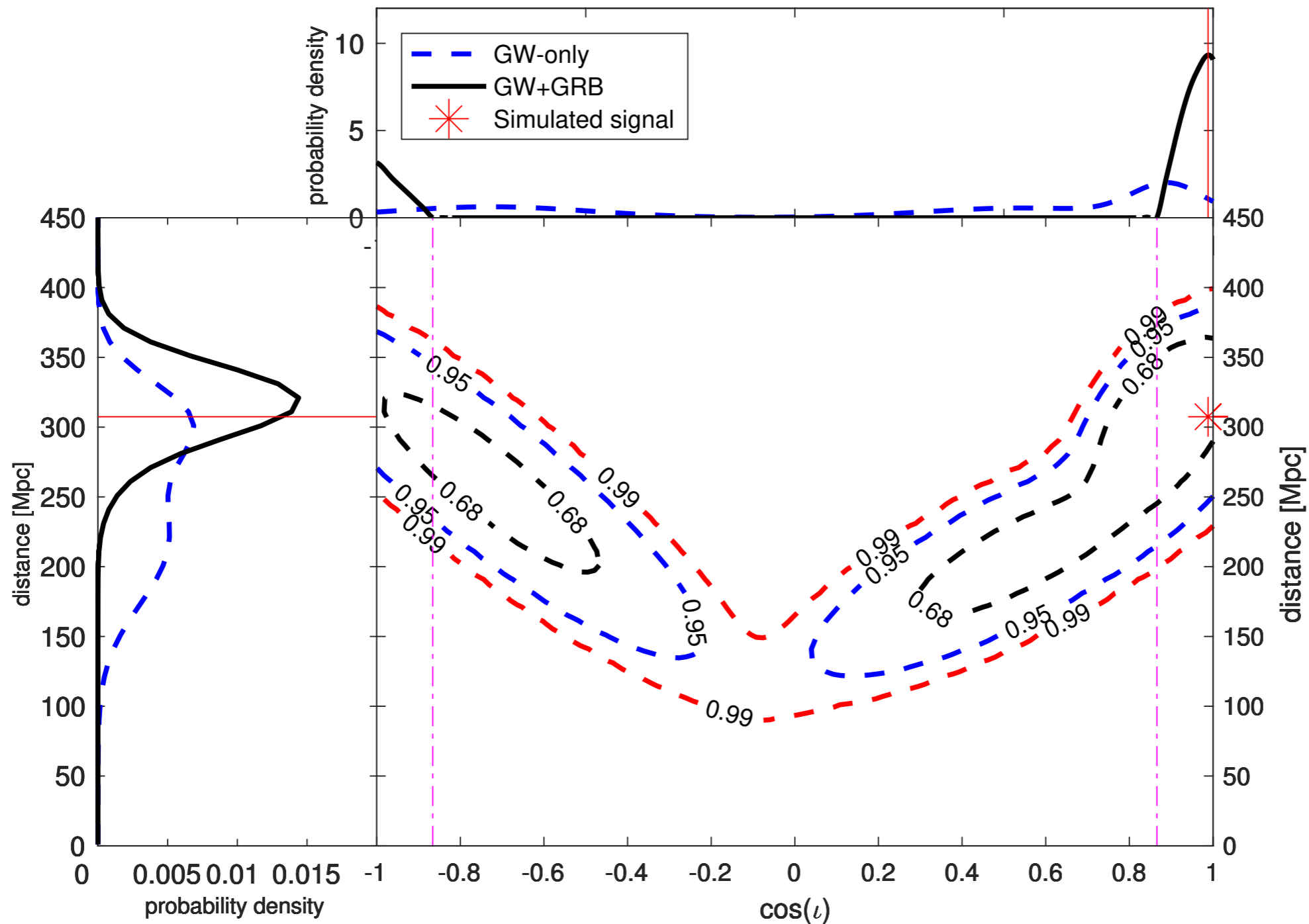
Characterising the method

- We simulated 1000 BNS signals in Advanced LIGO and Advanced Virgo noise at design sensitivity
- Extract posteriors using lalinference.
- Assume all simulated signals are jointly observed with sGRB
- Parameters are selected with priors
 - sources are located uniform in volume up to 400 Mpc.
 - jet opening angle uniform θ_{jet} between (5,30) degs.
 - $\cos i$ uniform between (-1,1) (jet angle must be consistent).
 - sGRB luminosity L drawn from a power law distribution (index -1.4 and cut-off at 10^{49} ergs/s).

$$p(L|I) = \frac{0.4}{L_{\text{min}}} \left(\frac{L}{L_{\text{min}}} \right)^{-1.4}.$$

- Peak flux is computed from L , d and θ_{jet} + noise.
- Combine posteriors using a KDE approach.

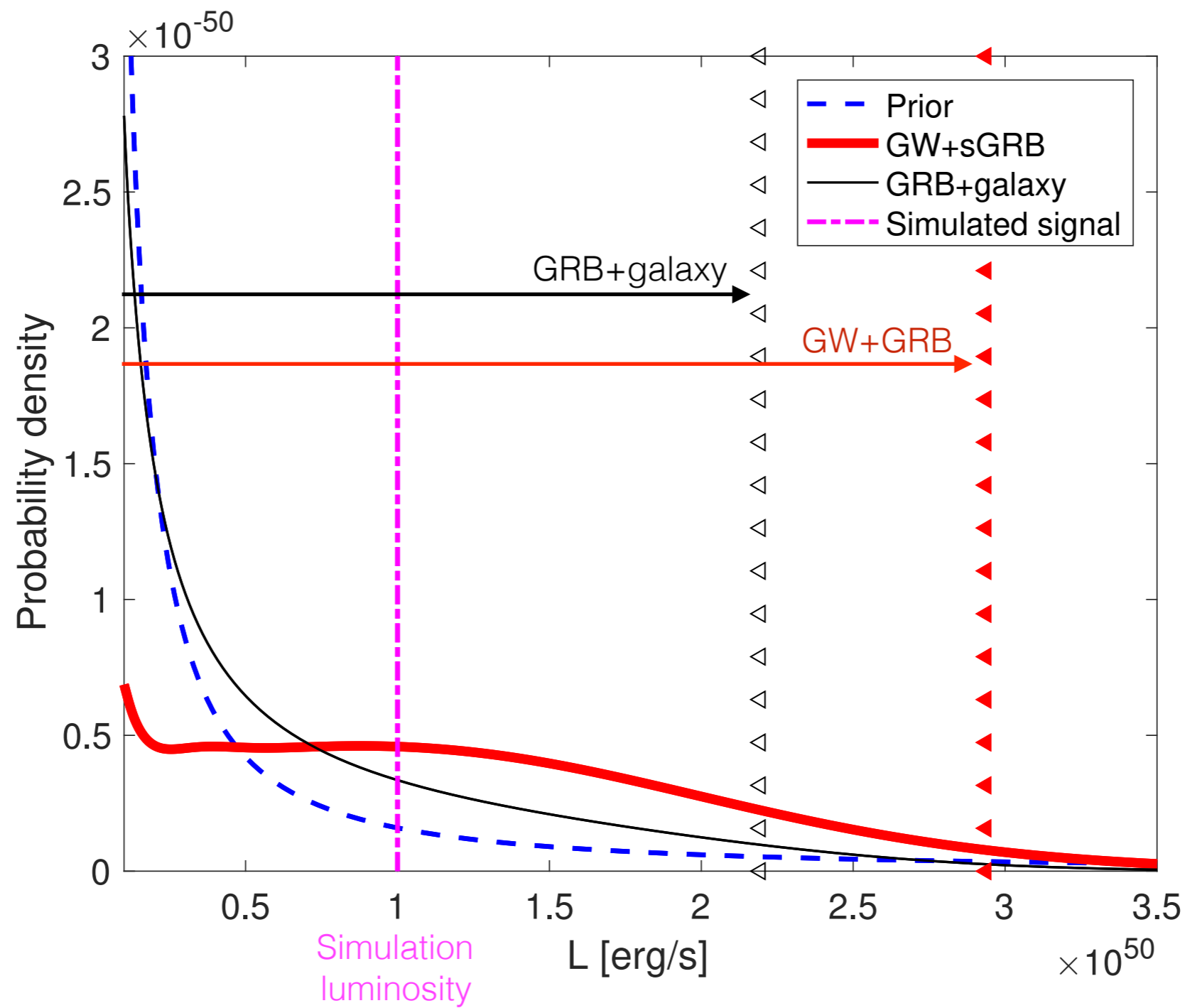
Example



SNR = 14.8

$$\begin{aligned}d &= 307 \text{ Mpc} \\ \cos i &= 0.97 \\ \theta_{\text{jet}} &= 19.95^\circ \\ L &= 10^{51} \text{ erg}\end{aligned}$$

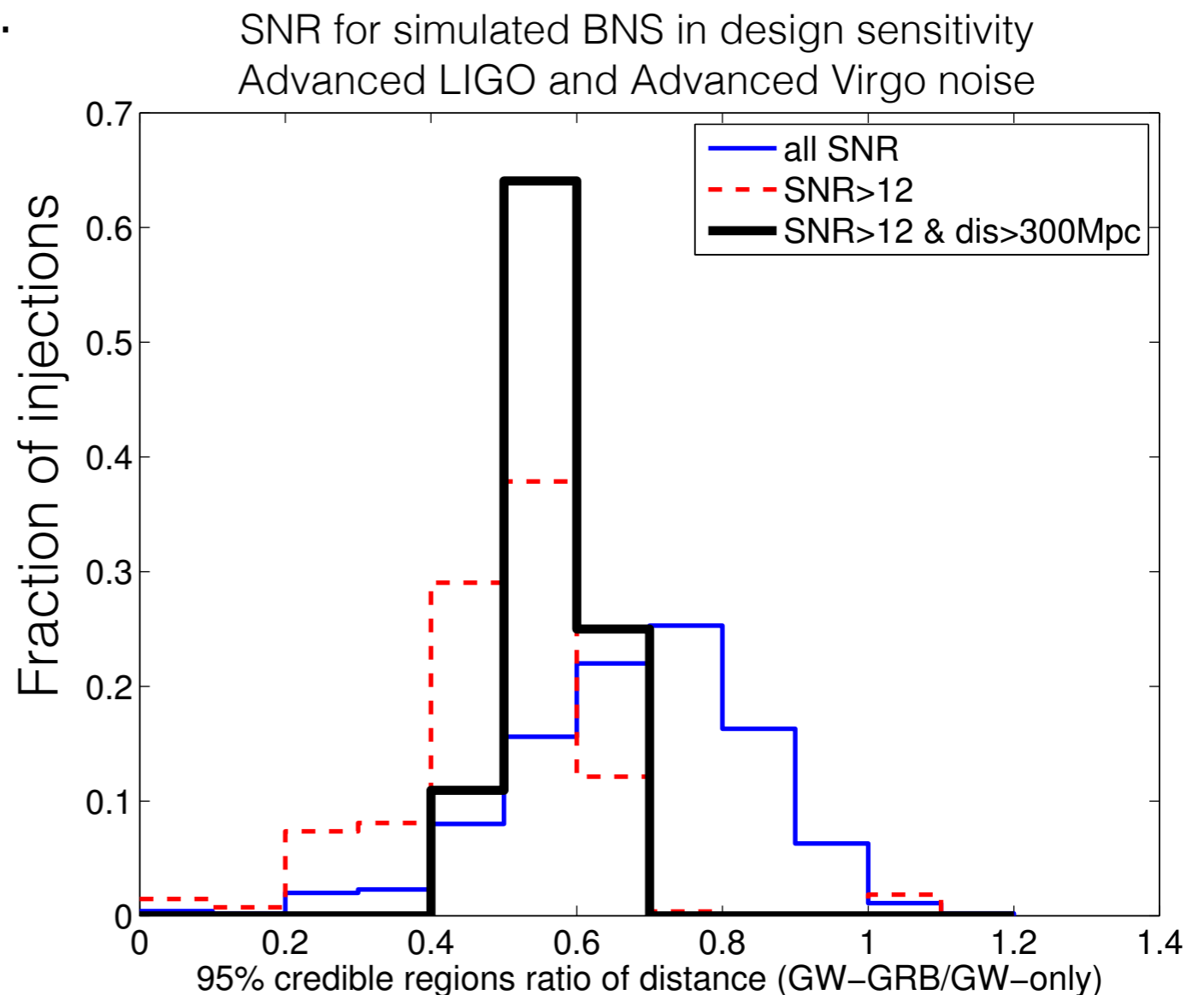
Example



The results

- We take the 95% credible intervals on distance for GW only cases and for joint sGRB-GW cases.
- Then we take the ratio and histogram.
- Smaller ratios imply a reduction in posterior width.
- With and without SNR cuts we get median improvements of factors of ~ 2 and ~ 1.25 .

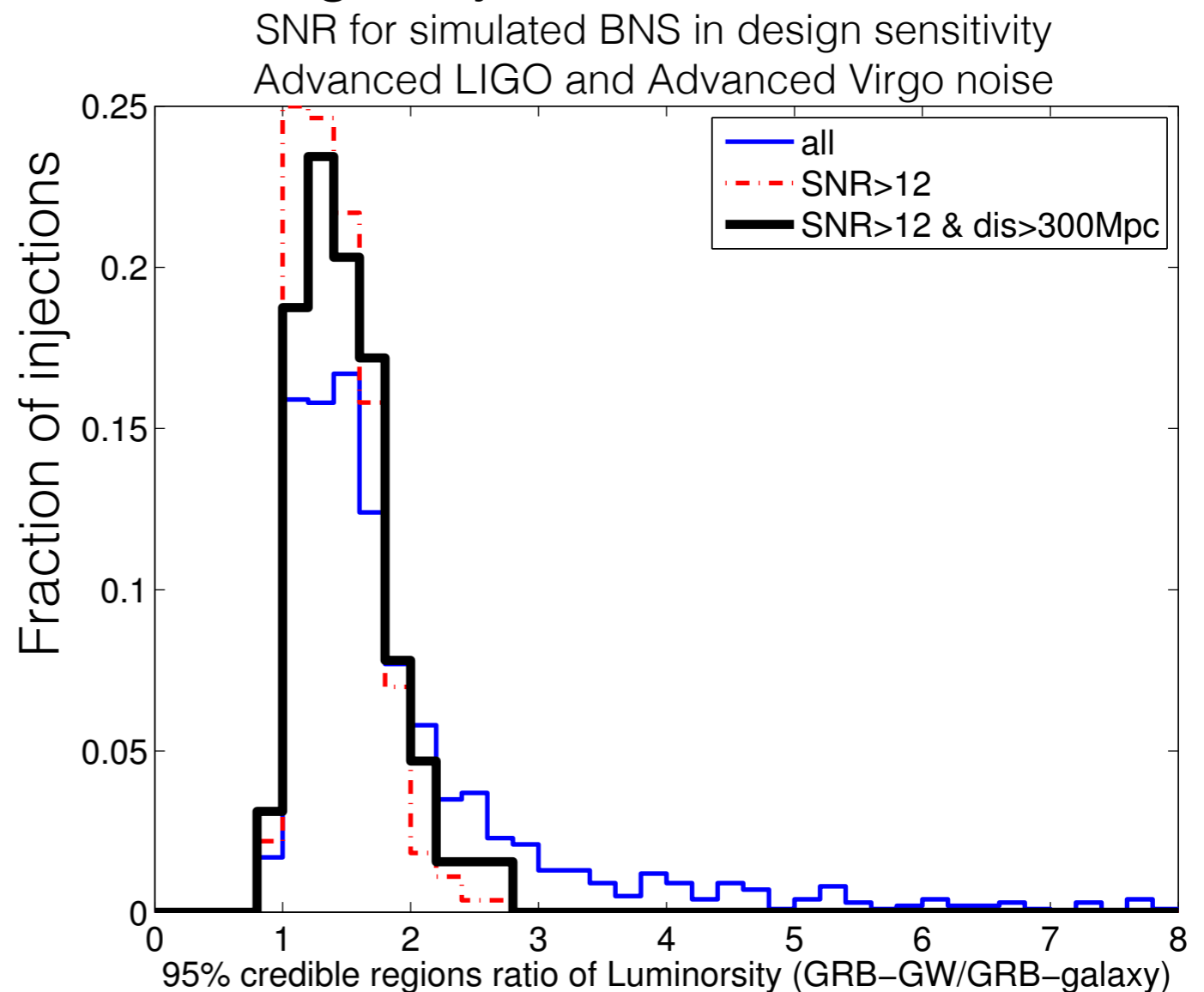
all: 1000; SNR > 12: 272;
SNR > 12 & $d > 300$ Mpc: 64



The results

- Here we do the same for luminosity except we compare with the case of an sGRB with an identified host galaxy where the distance is known exactly (no GWs).
- We find that the median of the ratio distribution is ~ 2 .
- Hence luminosity inference is comparable to the ideal non-GW case (host with exact distance).

all: 1000; SNR > 12 : 272;
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Discussion

- Using only sGRB and GW observations, we have inferred the sGRB luminosity without requiring additional information.
- The uncertainty in the sGRB luminosity inference with GWs is comparable to non-GW cases (host with exact distance).
- As expected, distance and inclination inference is improved.
- For Advanced LIGO & Advanced Virgo at design sensitivity, we may have 1 sGRB-GW joint observation
- For A+, we will likely have a few per year
- ET will detect all BNS up to $z \sim 1$
 - determine luminosity function (see talk by Chris Messenger)
- Method is applicable to all joint observations with GWs
 - eg. X-ray, IR,...