Probing the Intrinsic Properties of Short Gamma-Ray Bursts using Gravitational Wave Detections

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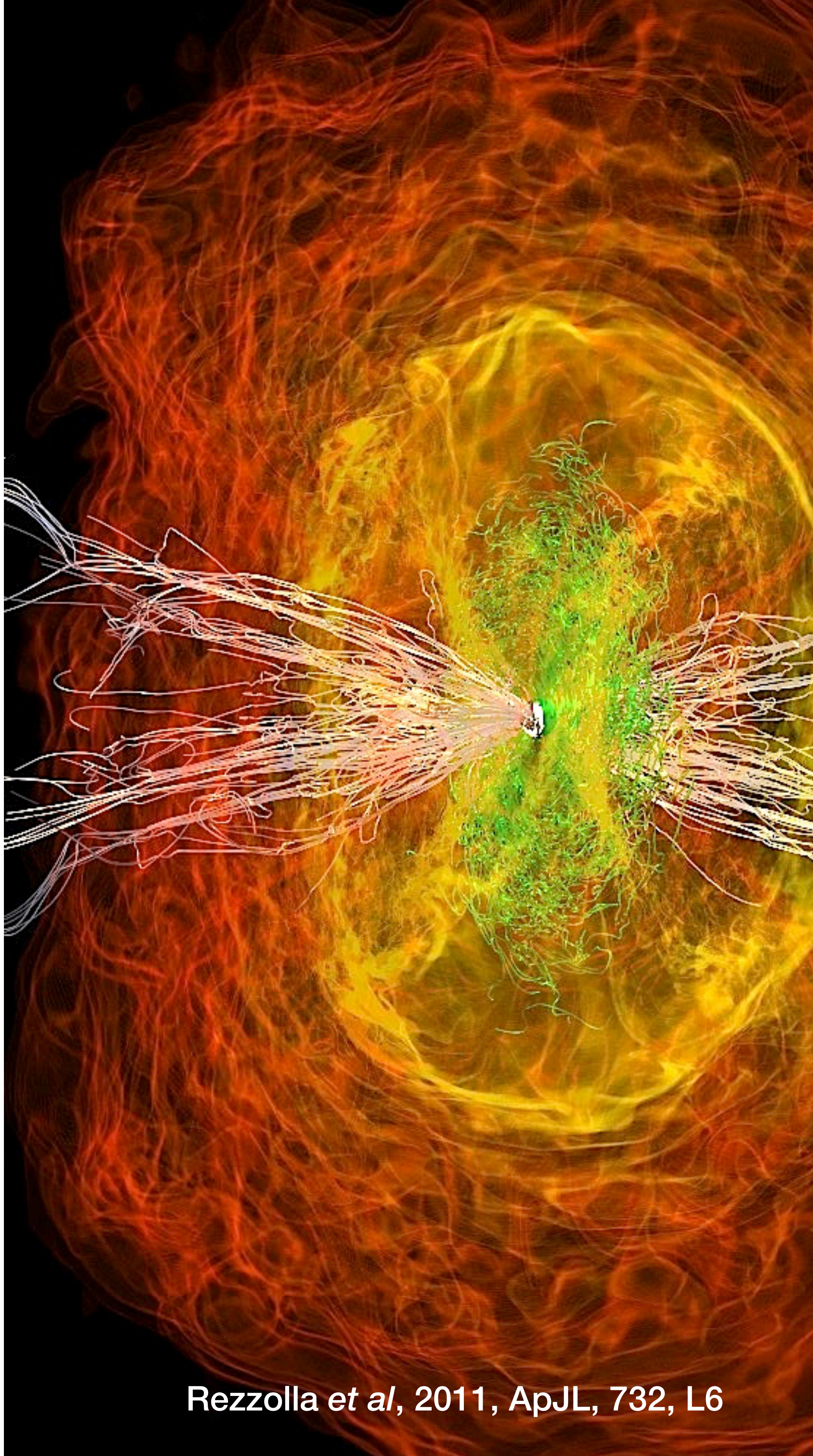
Outline

- Joint GRB-GW detections
- The aim
- The model
- Single event
- Combining information
- The simulation
- Results
- Conclusions



Rezzolla *et al*, 2011, ApJL, 732, L6

Joint GRB-GW observations

- sGRBs are likely due to the merger of BNS systems [Eichler et al, 1989, Nature 340, 126, Narayan et al, 1992, ApJ. 395, L83]
- Advanced detectors expect to see BNS systems at design up to 450Mpc (z ~ 0.1).
- sGRBs are seen to far higher distances.
- Rates of events are consistent (beaming is an important factor).
- Advanced detectors expect to see ~1 joint event per year. [Clark et al, 2015, ApJ, 809, 53]
- 3rd gen is a different story

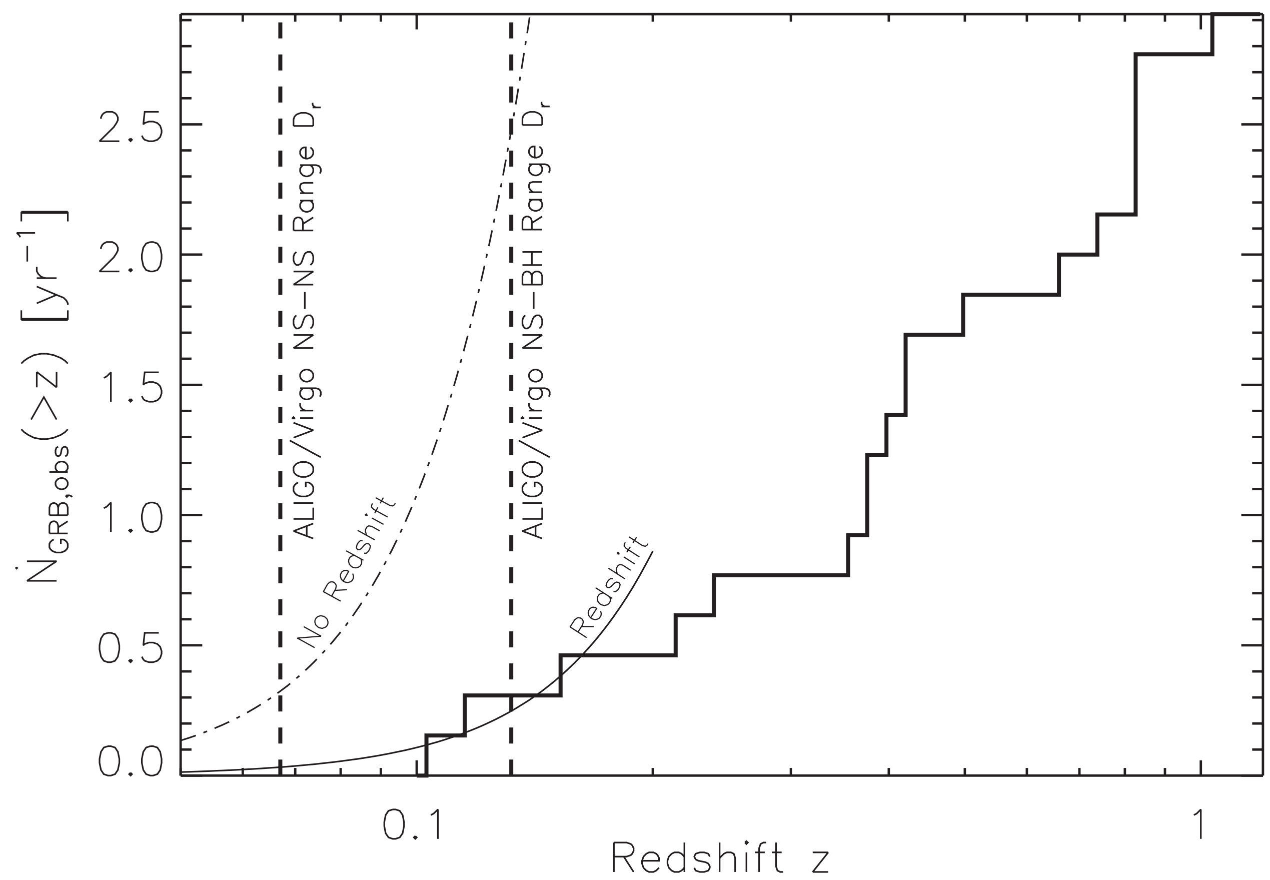
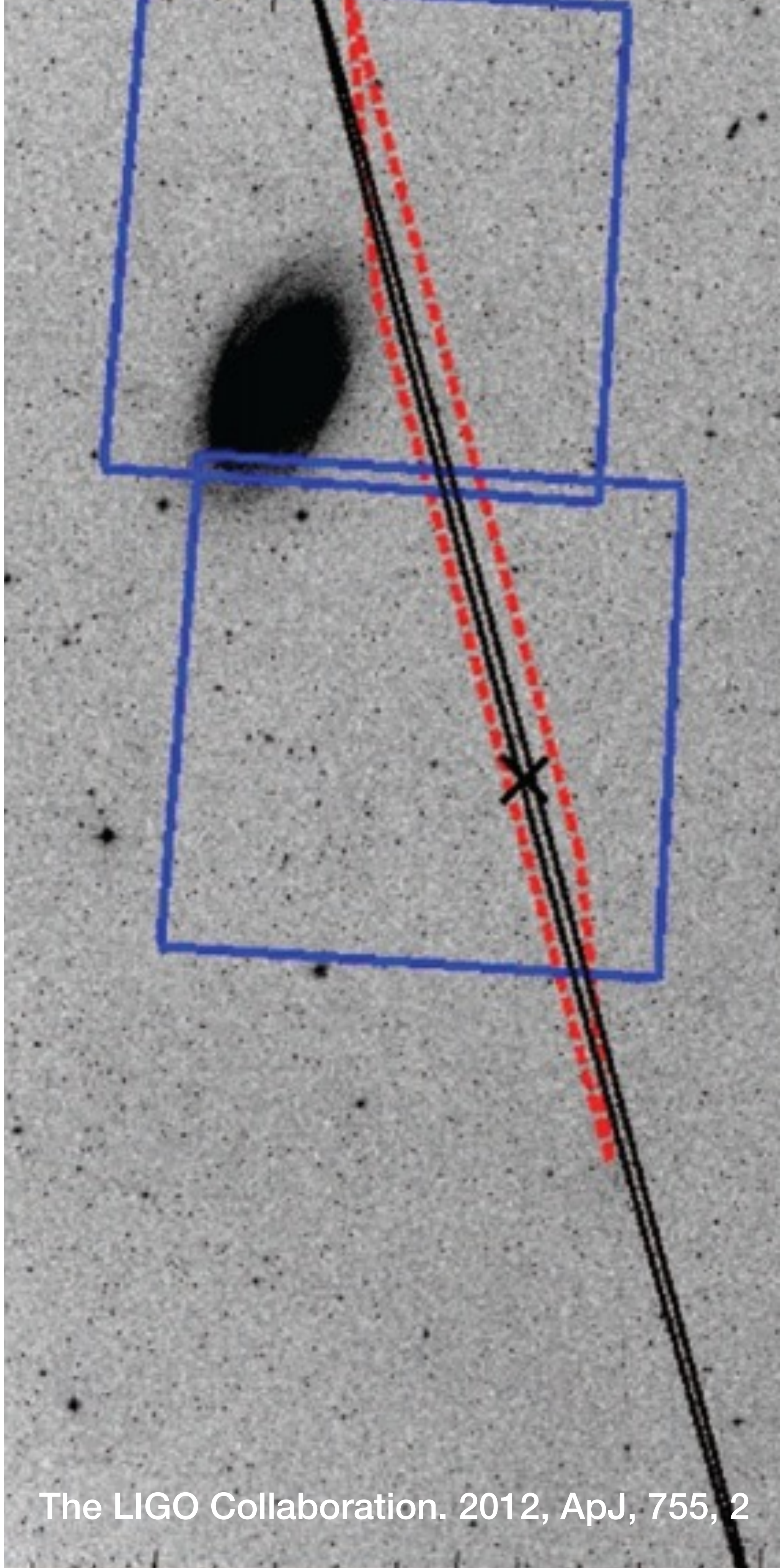


Figure 2. Cumulative detection rate of SGRBs with measured redshifts $< z$ (thick solid line), calculated using 19 (mostly *Swift*) SGRBs (e.g., Berger 2011). Dashed vertical lines mark the estimated sensitivity range of ALIGO/Virgo to NS–NS and NS–BH mergers, respectively, including a boost due to the face-on binary orientation. The thin solid line shows an approximate fit to $\dot{N}_{GRB,obs}(< z)$ at low redshift. The dot-dashed line shows an estimate of the *total* SGRB detection rate (with or without redshift information) by an all-sky γ-ray telescope with a sensitivity similar to *Fermi*/GBM.

Metzger, B. D., & Berger, E. 2012, ApJ, 746, 48

The aim

- This talk will address the issue of what we can learn from combining information.
- The example we choose is the **intrinsic luminosity distribution** of sGRBs.
- Specifically those without an identified host galaxy.
- The additional information extracted from the GW detection can help us determine L.
- A collection of such detections can determine the distribution of L.
- Existing results for GRBs [Wanderman & Piran, 2015, MNRAS, 448, 3026, Pescalli *et al*, 2015, MNRAS, 447, 1911, Howell *et al*, 2014, MNRAS, 444, 15]

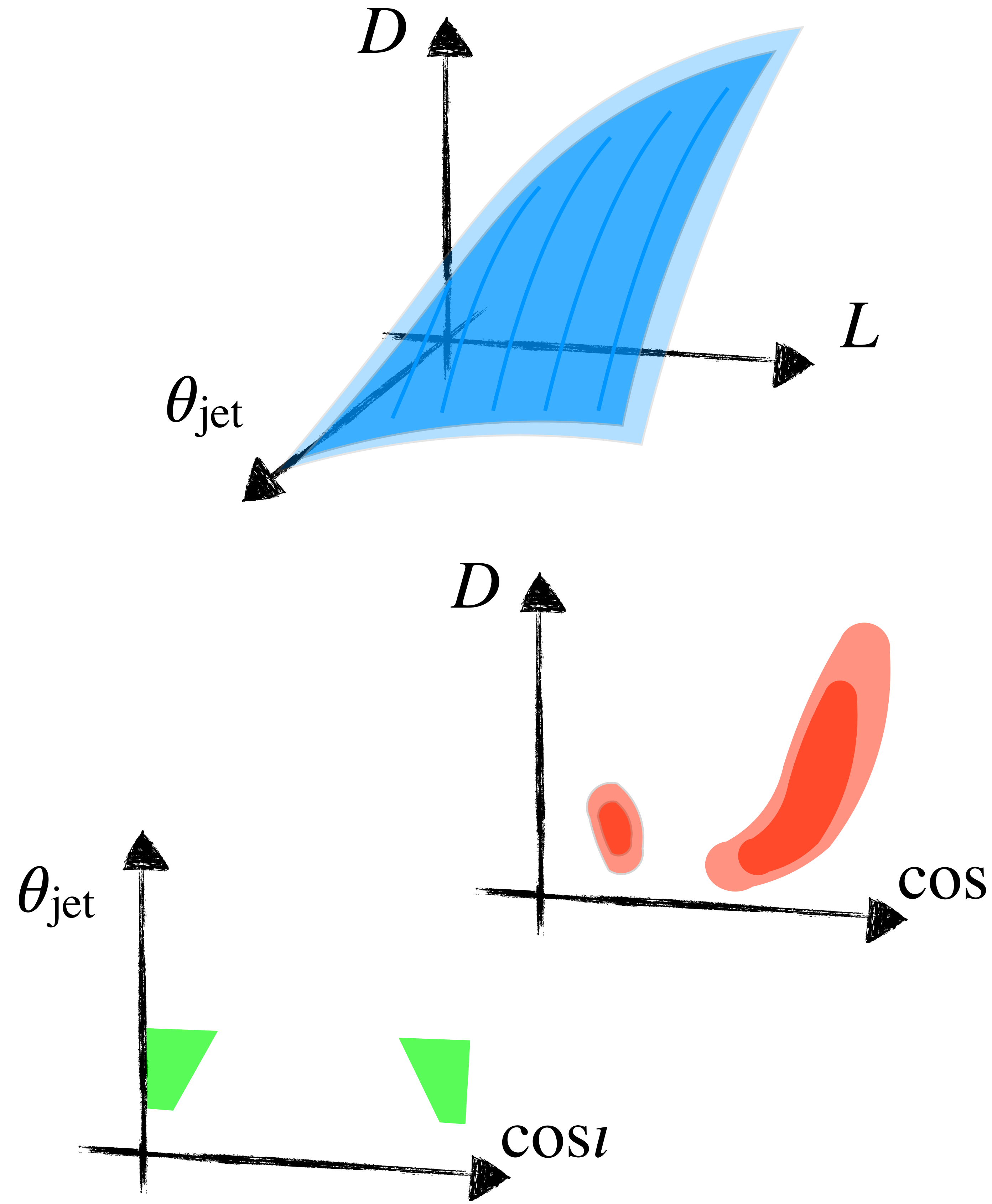


The model

- We have assumed that every BNS merger generates a sGRB, but only see the sGRB if the inclination angle (ι) is < the jet opening angle ($\theta_{\rm jet}$).
- We assume that we have a very well localised sGRB without a host galaxy.
- The only EM information we have about the event is the peak flux (f) with a 30% Gaussian uncertainty.
- The jet half-opening angle ($\theta_{\rm jet}$) is drawn from a uniform distribution (5^{o},30^{o}) degs.
- We have access to the full Bayesian posterior on the GW parameters but he relevant GW parameters are distance (D) and inclination (ι).
- The peak luminosity (L) of the sGRB is drawn from a power-law distribution and has a fixed lower and upper cut-off.
- We aim to determine the spectral index (γ).

Combining information - single event

- The flux measurement provides massive degeneracy between distance and luminosity (and jet angle).
- The GW measurement gives some (poor) distance constraints, but …
- The constraint on the inclination angle from the jet improves the distance and reduces the luminosity uncertainty.
- **See Siong Heng's talk**.



Combining information - multiple events

- We use a Hierarchical Bayesian approach.
- The global spectral index parameter γ governs the luminosity prior on all events.

posterior on L distribution parameters

samples - drawn from GW posterior

conditional prior on θ

likelihood of flux

L prior

$$p(\gamma|\{f,G\},I)$$

$$\propto p(\gamma|I)\prod_{i=1}^{N}\iiiint p(f_i|D_i,L_i,\theta_i)p(G_i|D_i,\iota_i)p(D_i,\iota_i|I)p(\theta_i|\iota_i,I)p(L_i|\gamma,I)dD_i dL_i d\theta_i d\iota_i$$

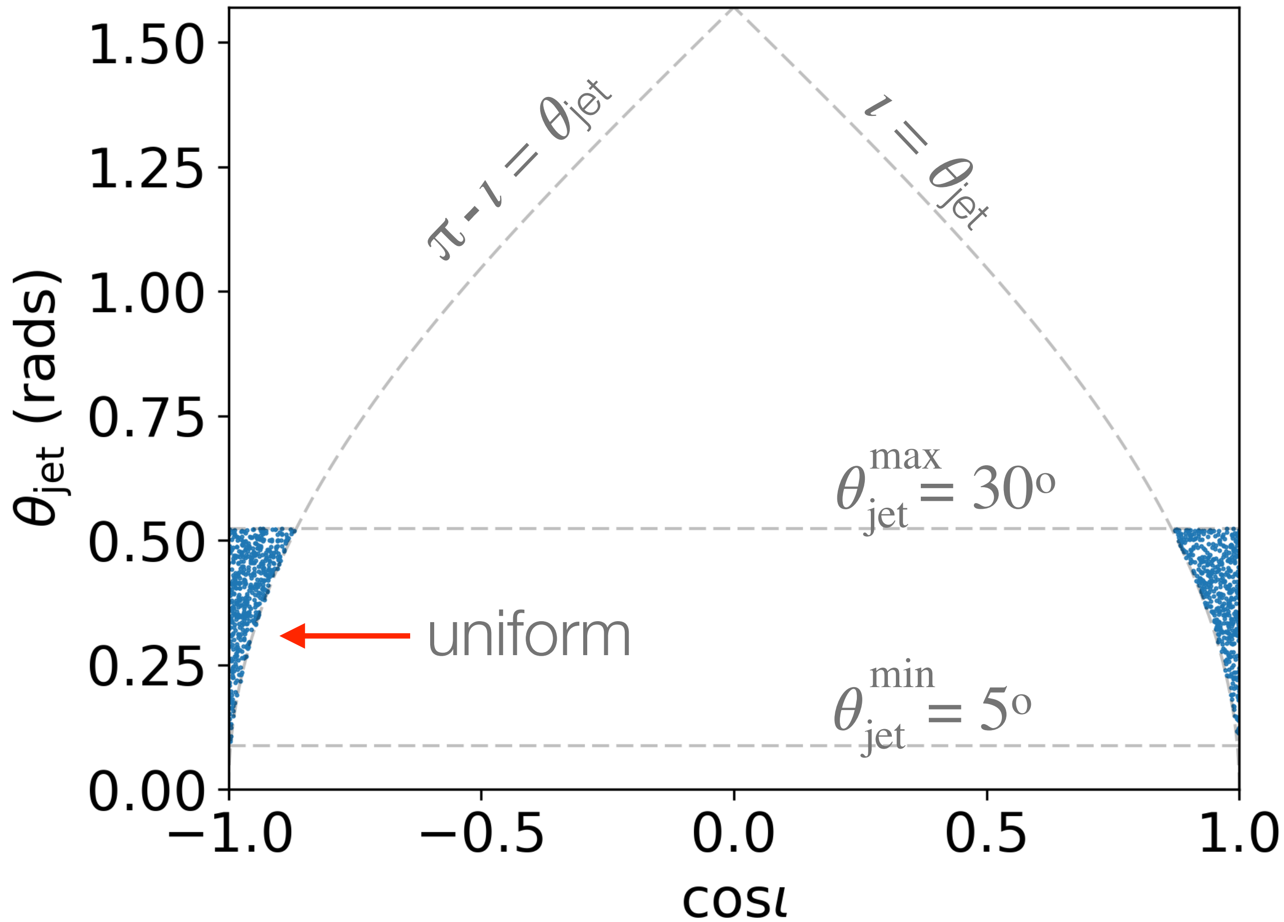
$$\propto p(\gamma|I)\prod_{i=1}^{N}\sum_{j=1}^{n}\iint p(f_i|D_{i,j},L_i,\theta_i)p(\theta_i|\iota_{i,j},I)p(L_i|\gamma,I)dL_i d\theta_i$$

- We use a simple trick to perform marginalisation over D,ι - involves simple summing over GW samples.

Simulation

- We simulated 1000 joint sGRB-GW events.
- We assumed an H-L-V Advanced network at design sensitivity.
- All sGRB luminosities were sampled from a power-law distribution with index γ = -1.4.
- Distances were uniform in volume up to the advanced network horizon distance (450 Mpc).
- Posterior GW samples were obtained using *lalinference*.
- No SNR cuts were applied.

Fig: The joint distribution of simulated inclination and jet opening angles must be uniform on cos and theta but restricted by the beaming selection effects



$$p(\theta_{\rm jet}|\cos\iota, I) = \begin{cases} \left(2\left(\iota - \theta_{\rm jet}^{\rm max}\right)\right)^{-1}, & \text{if } |\cos\iota| > \cos\theta_{\rm jet}^{\rm max} \\ 0, & \text{otherwise} \end{cases}$$

Results

- The individual sources (dashed curves) do not particularly constrain the power-law index.
- Multiple observations are far more powerful.
- The spectral index is constrained to ±0.2 after $O(10)$ joint detections.
- After $O(100)$ this is ±0.1.

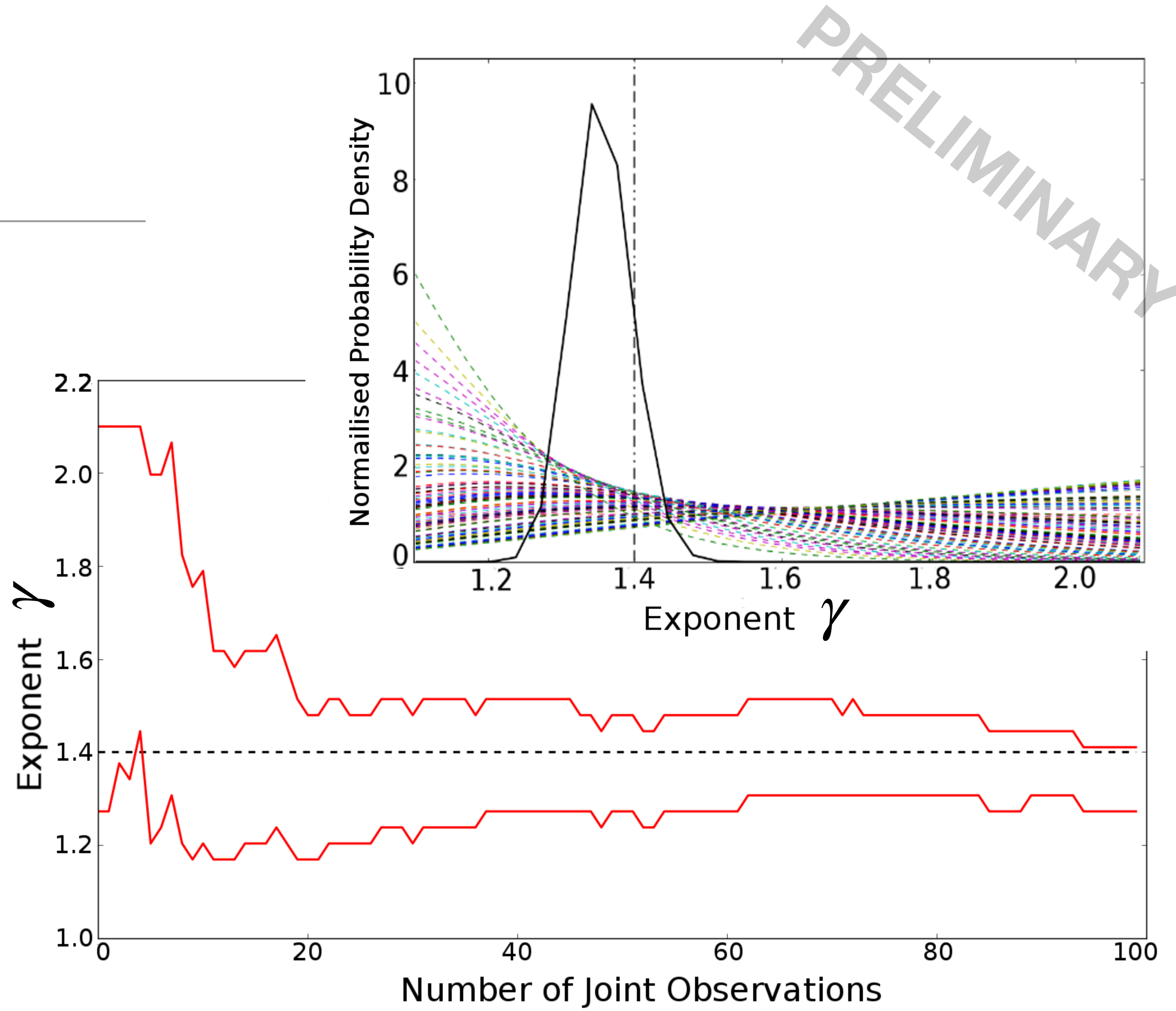
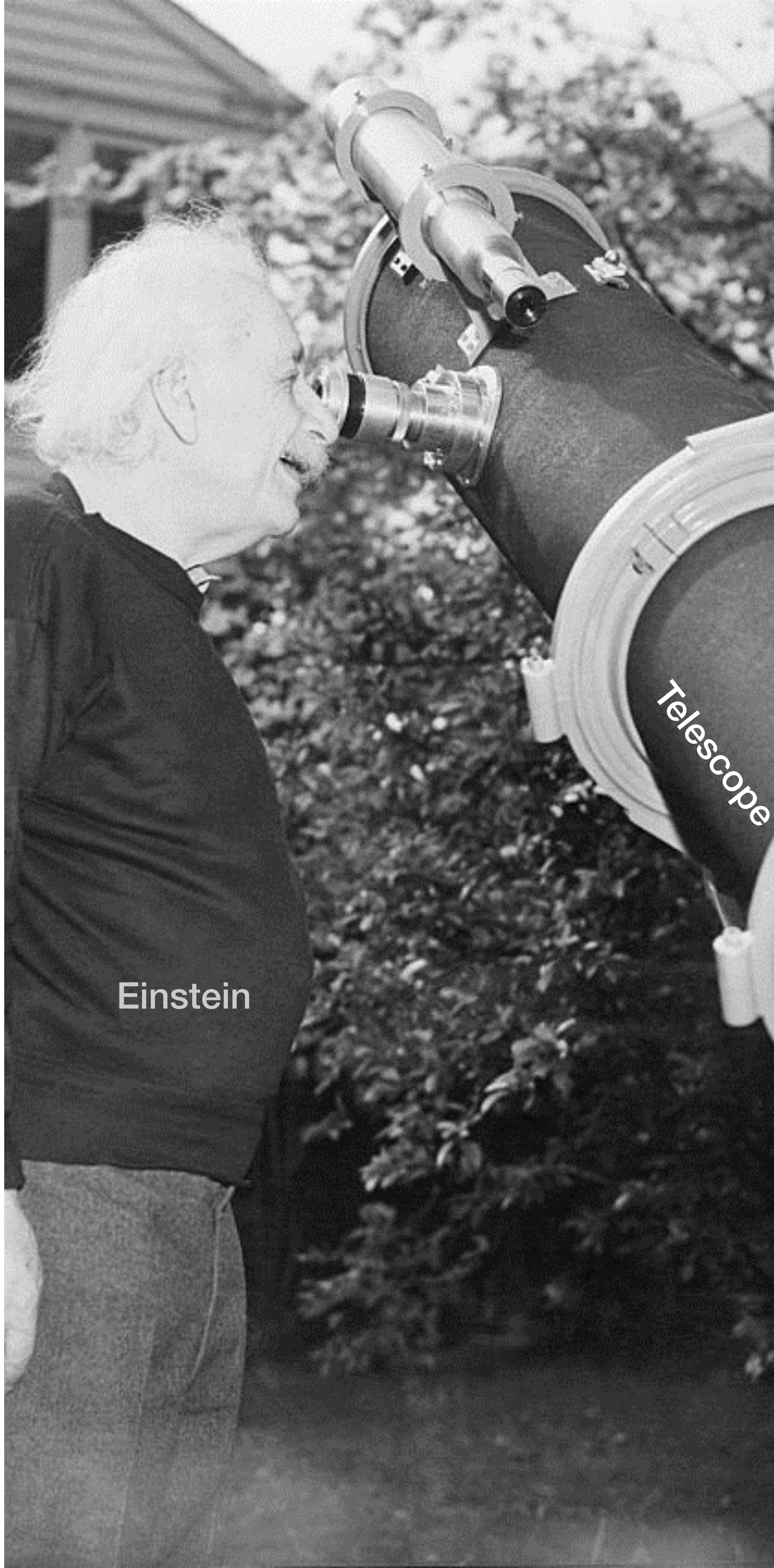


Fig: Preliminary results from **Calum de Sainte Croix's** Masters project showing the evolution of the 95% credible region as the number of joint detections is increased. Inset: the individual posterior probability distributions on the power-law index/exponent (coloured dashed lines) from 100 joint sGRB-GW detections. The solid black line is the combined posterior and the vertical black dashed-dotted line is the true simulated value.

Conclusions

- So using the relationships between the EM and GW parameters we can infer parameter(s) describing the signal population.
- We only need *O*(10) sources to make a constraining measurement (error scale consistent with existing EM methods. [Wanderman & Piran, 2015, MNRAS, 448, 3026]
- This is not unfeasible for Advanced Detectors but not likely given the expected rates.
- 3rd generation detectors will see the majority of BNS mergers with an sGRB counterpart.
- So powerful inference will be possible.



More conclusions

- Hold on, what about the ~30% of all sGRBs that have a redshift/host-galaxy and therefore a distance?
  - Can't we do this right now **without** GWs?
  - Ultimately, with GWs luminosities for nearly all sGRBs can be used.
- There are lots of additional selection effects that should be included.
- We can also add additional parameters (broken power-law?, more complicated parameter dependence?, …) and perform **model selection**.

Thank you for your attention.