

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

Calum de Saint Croix

Chris Messenger*

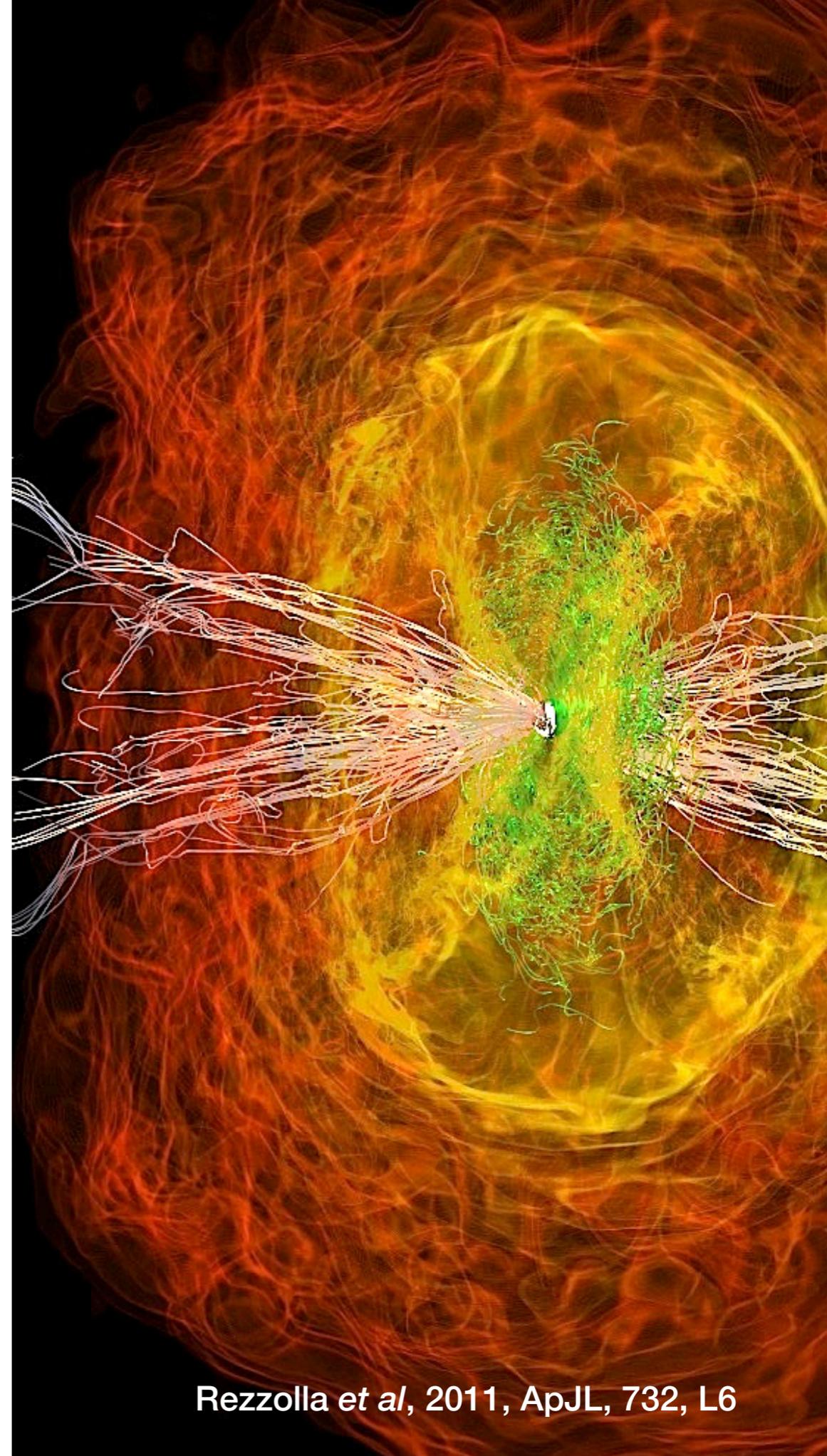
Siong Heng

Martin Hendry

Xilong Fan

Outline

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



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 ($z \sim 0.1$).
- 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

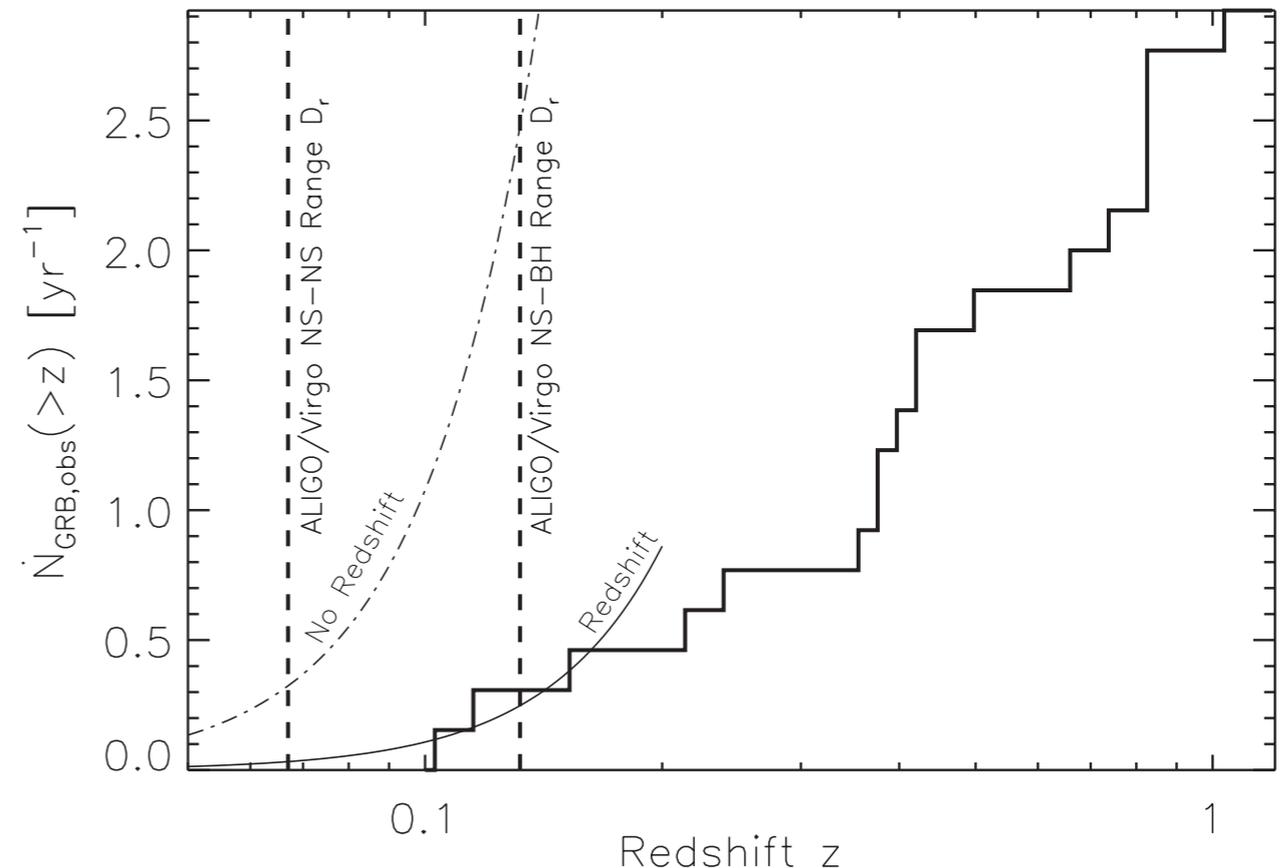
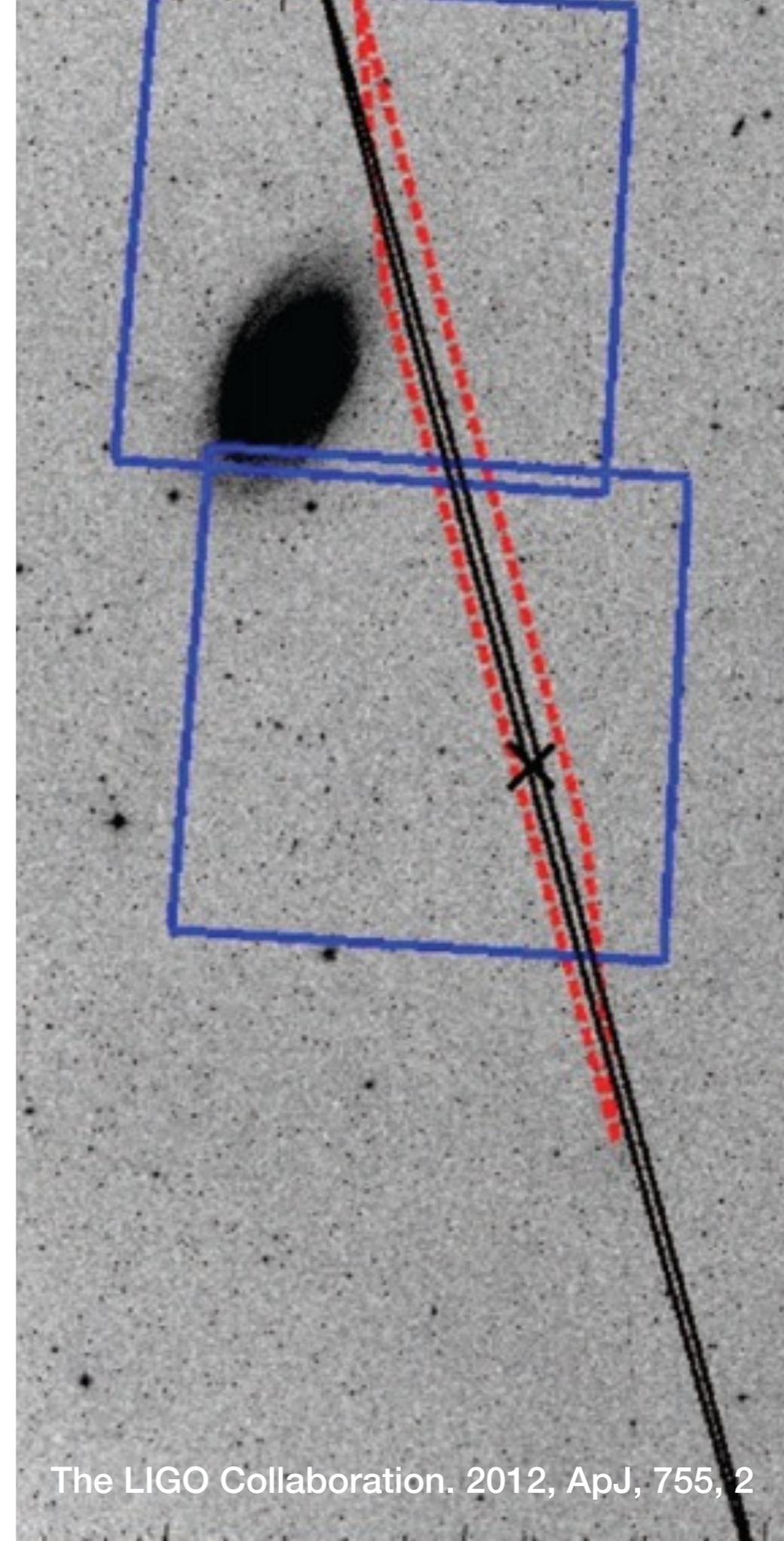


Figure 2. Cumulative detection rate of SGRBs with measured redshifts $< z$ (thick solid line), calculated using 19 (mostly *Swift*) SGRBs (e.g., Berger 2011). Dashed vertical lines mark the estimated sensitivity range of ALIGO/Virgo to NS–NS and NS–BH mergers, respectively, including a boost due to the face-on binary orientation. The thin solid line shows an approximate fit to $\dot{N}_{\text{GRB,obs}}(< z)$ 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.

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]



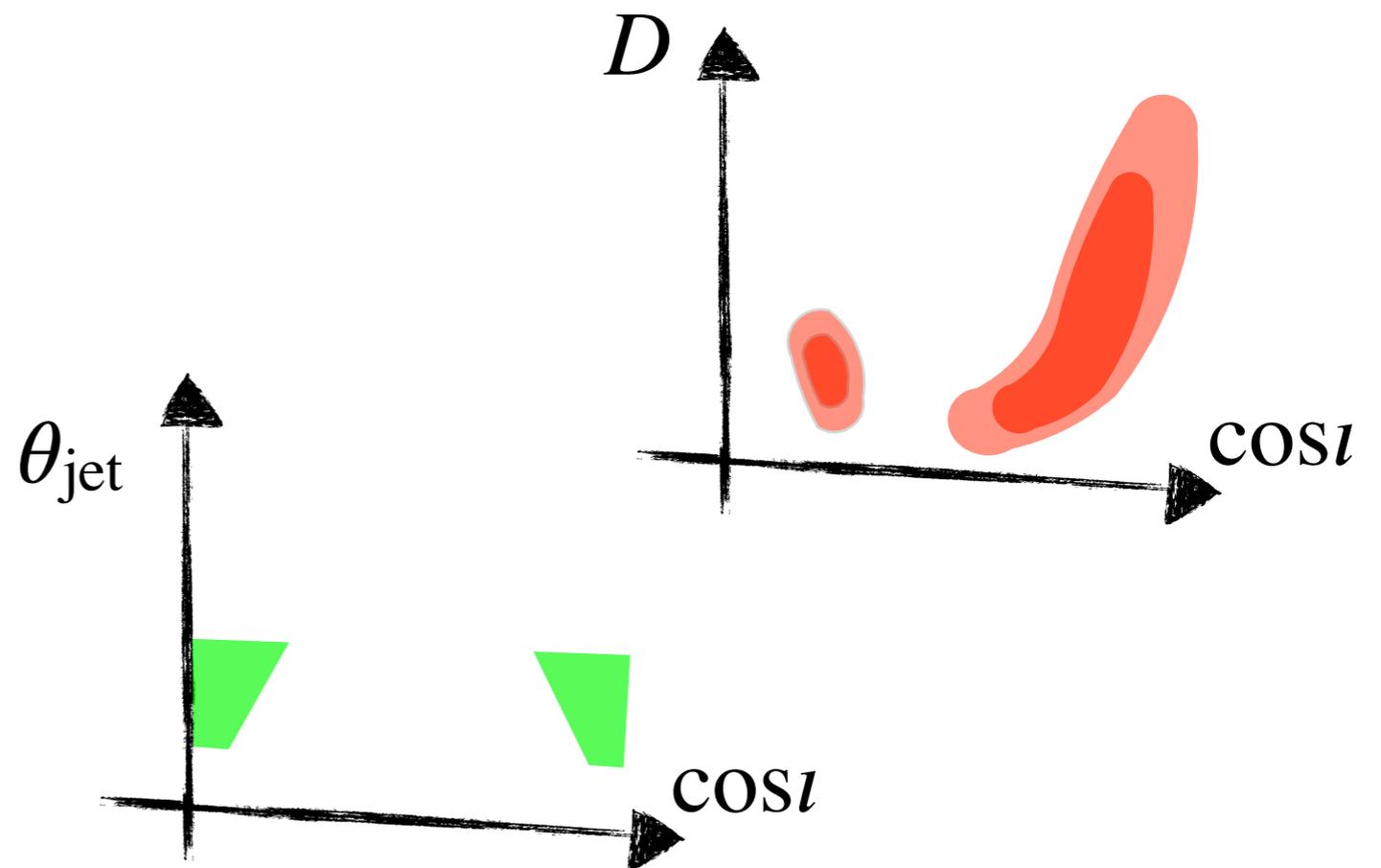
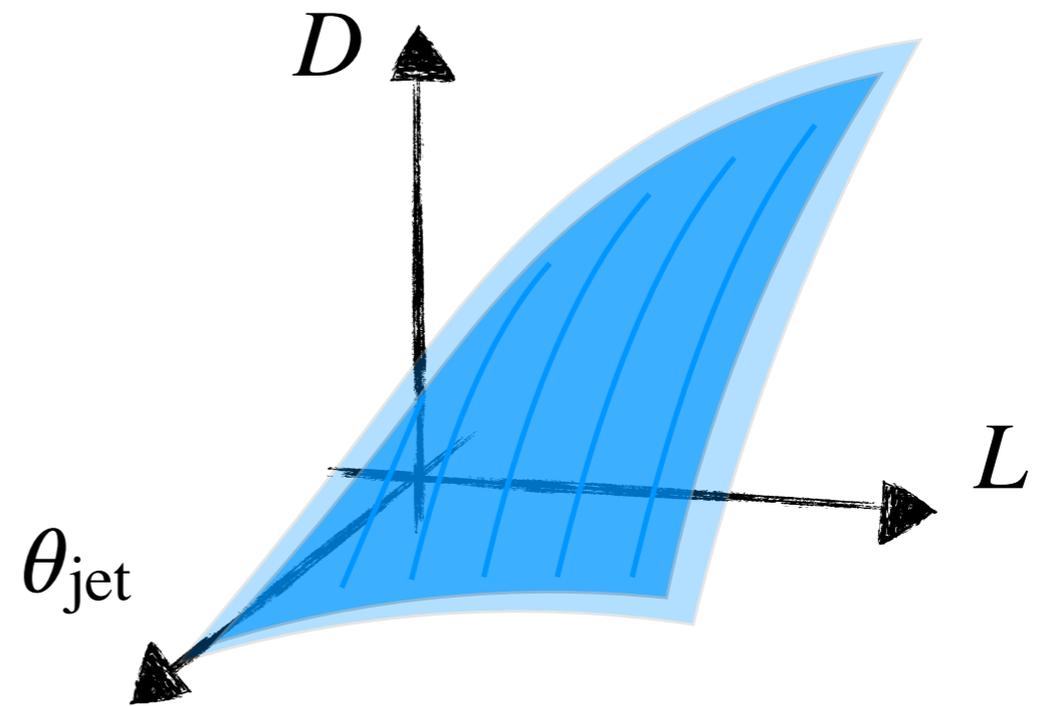
The model

- We have assumed that every BNS merger generates a sGRB, but only see the sGRB if the inclination angle (i) is $<$ the jet opening angle (θ_{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 (θ_{jet}) is drawn from a uniform distribution ($5^\circ, 30^\circ$) degs.
- We have access to the full Bayesian posterior on the GW parameters but the relevant GW parameters are distance (D) and inclination (i).
- 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

likelihood of flux

samples - drawn from
GW posterior

conditional
prior on θ

L prior

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

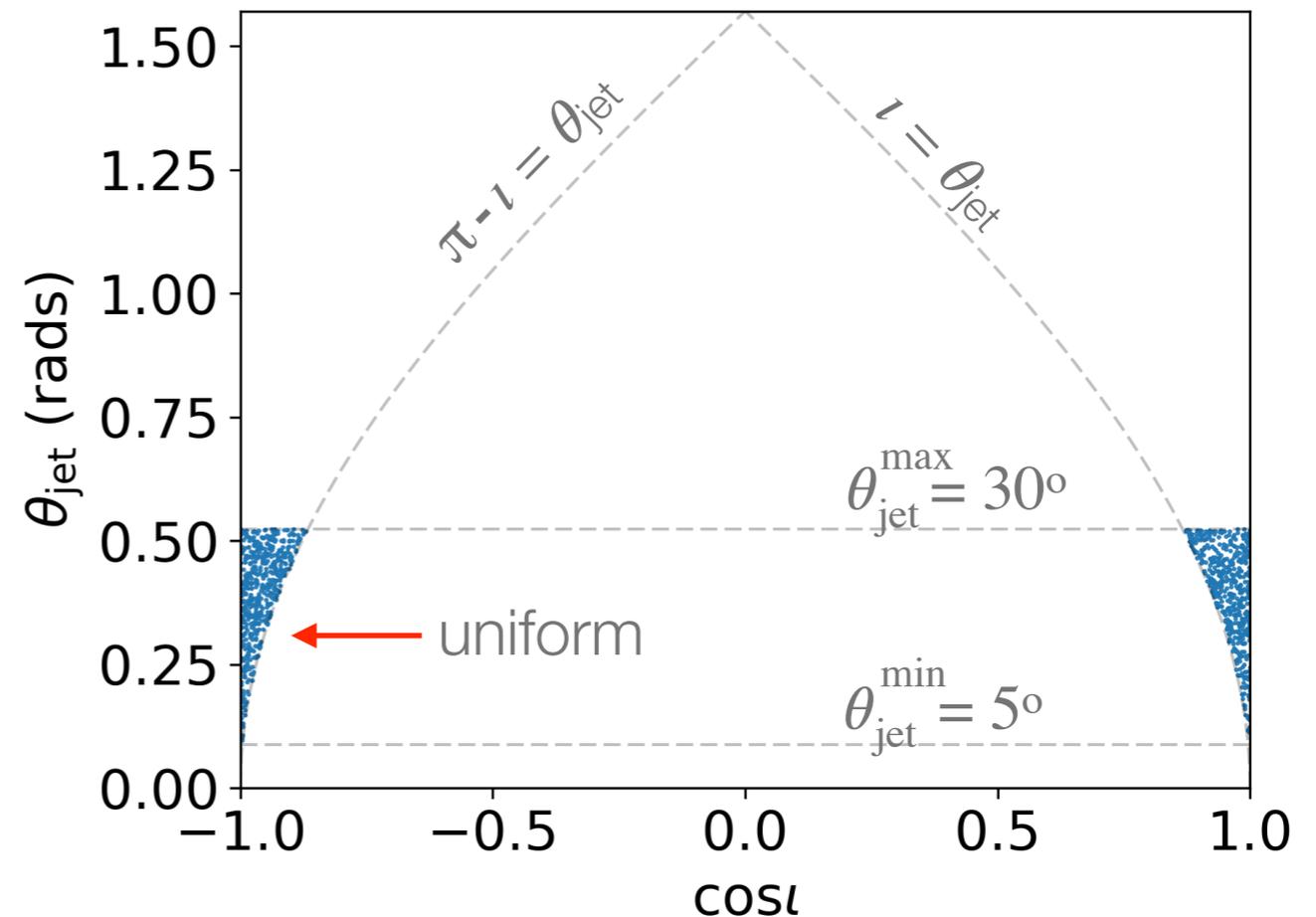
$$\propto p(\gamma|I) \prod_{i=1}^N \sum_{j=1}^n \iint p(f_i|D_{i,j}, L_i, \theta_i) p(\theta_i|\iota_{i,j}, I) p(L_i|\gamma, I) dL_i d\theta_i$$

- 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 $\gamma = -1.4$.
- 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



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

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 .

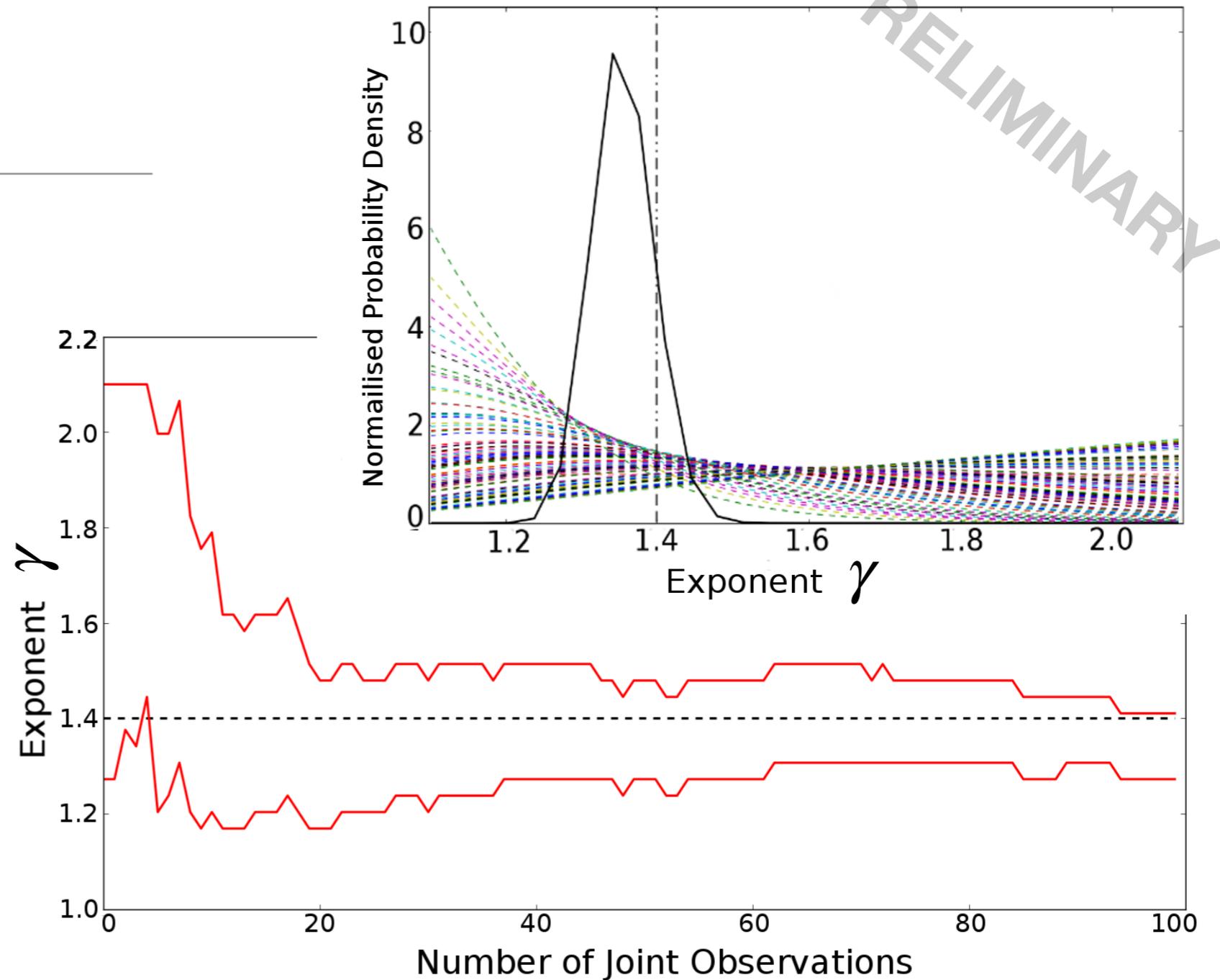
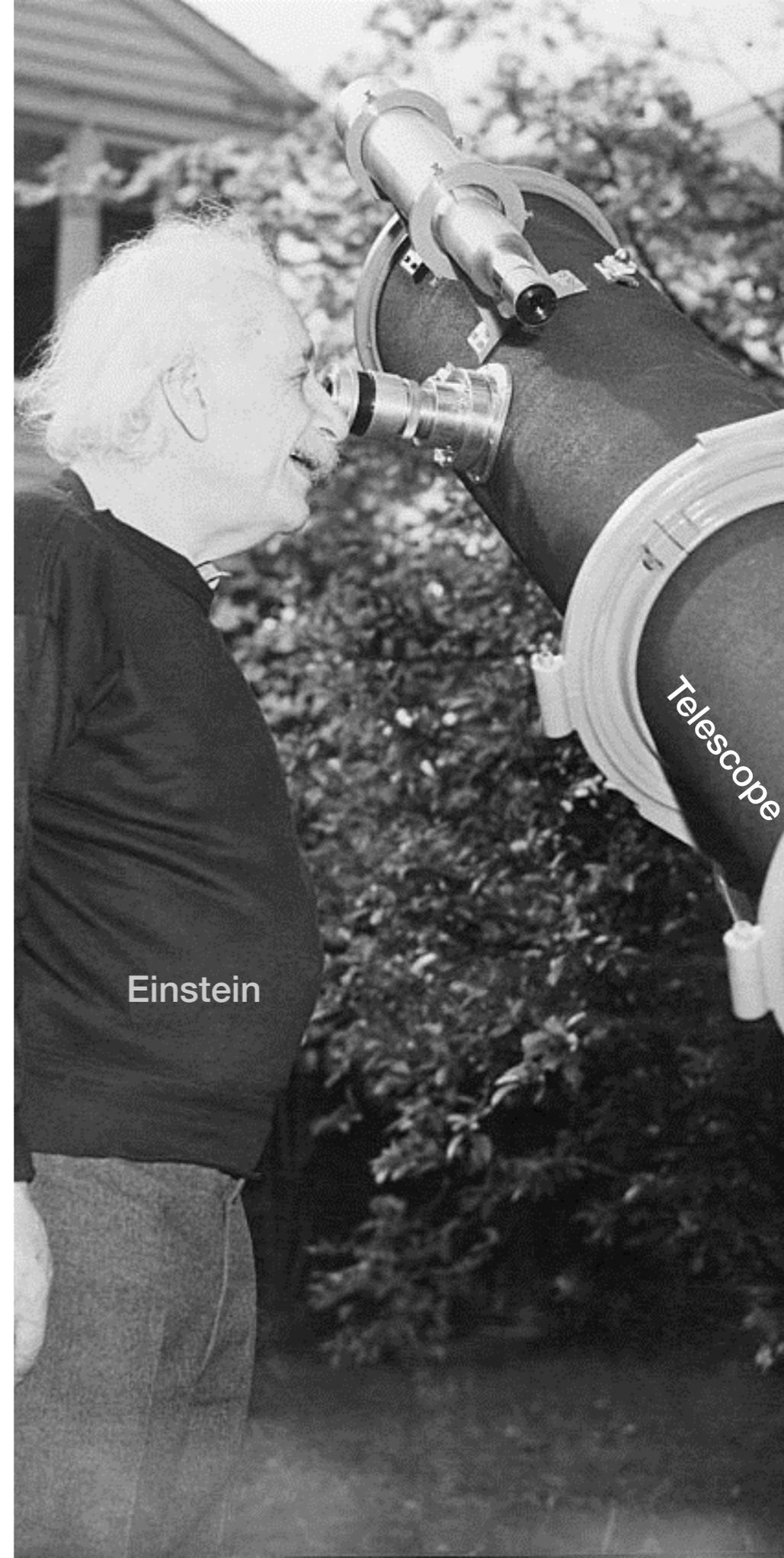


Fig: Preliminary results from **Calum de Sainte Croix's** Masters project showing the evolution of the 95% credible region as the number of joint detections is increased. Inset: the individual posterior probability distributions on the power-law index/exponent (coloured dashed lines) from 100 joint sGRB-GW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

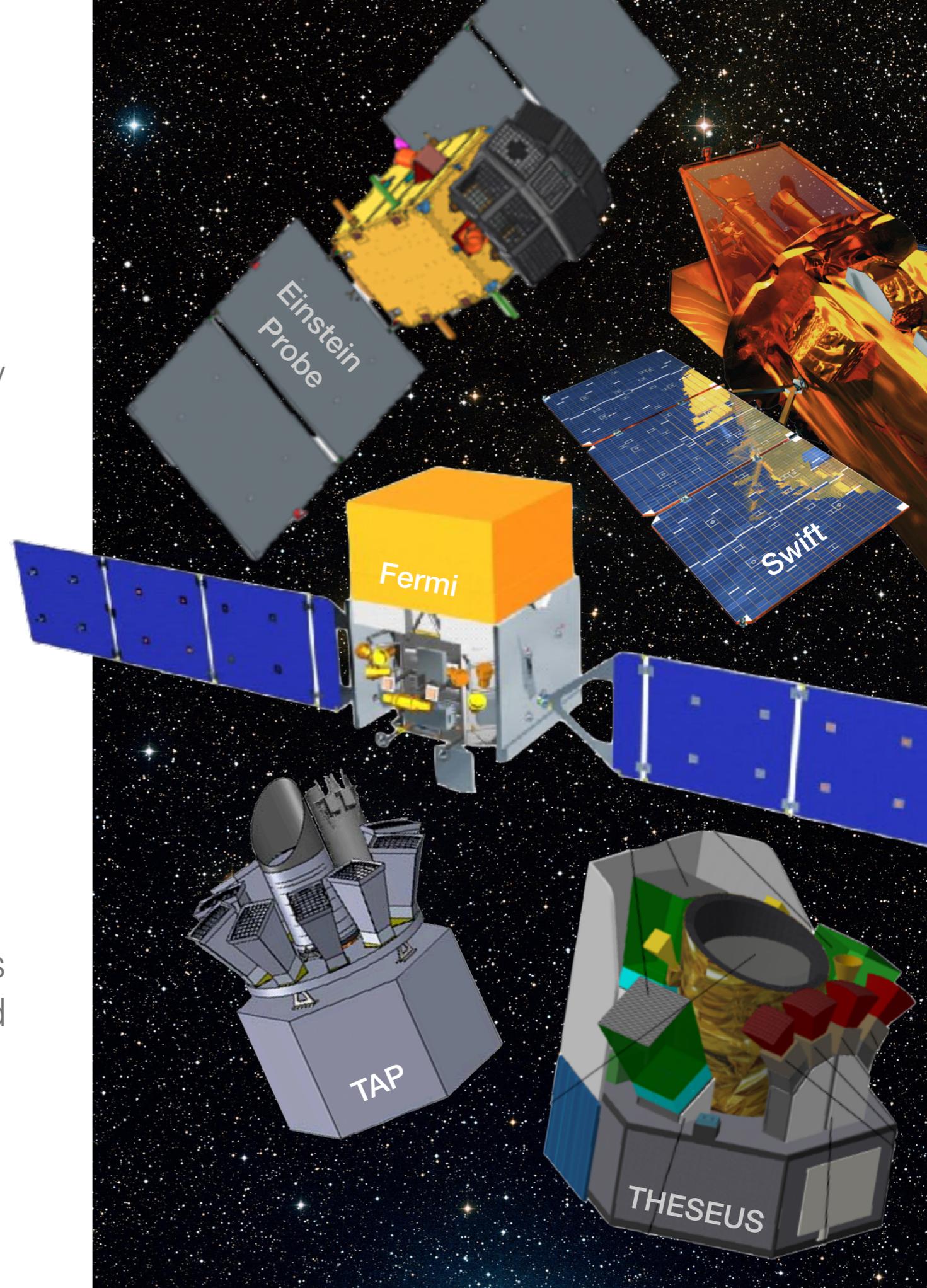
Conclusions

- 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 $\sim 30\%$ 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**.



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