Background image by Soheb Mandhai

Short Gamma-ray Bursts and their afterglows in the Gravitational Wave era

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The Stargate and ENGRAVE collaborations

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School of Physics and Astronomy, University of Edinburgh, PPE Seminar – 23 October 2020

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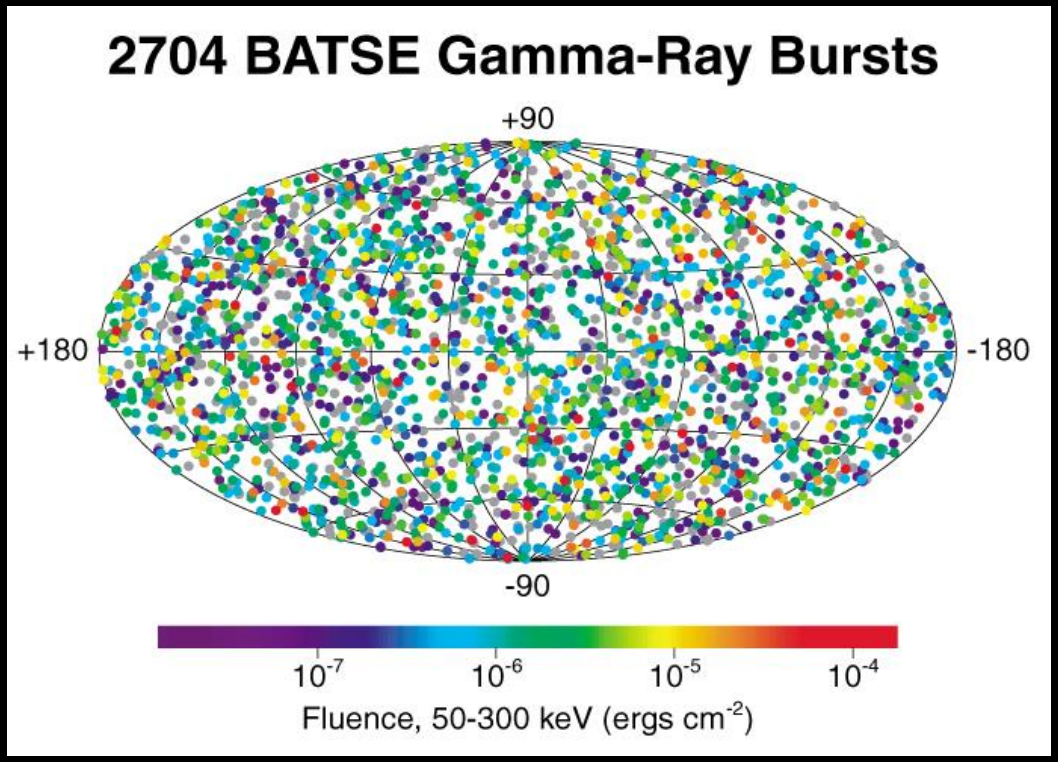
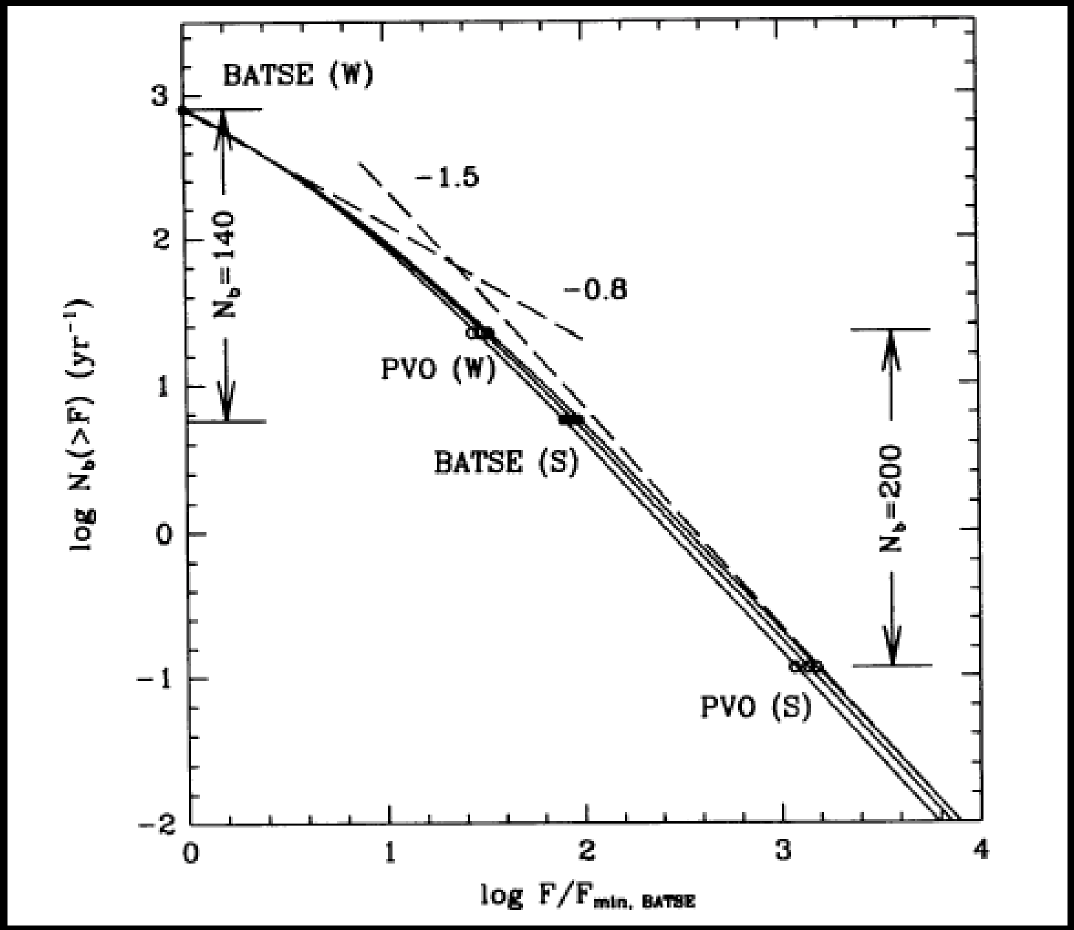
Talk Overview

- GRBs – what, where, how
- SGRBs from compact binary mergers!?
- Nearby SGRBs?
- GW associated GRB – GRB 170817A
- The afterglow – an off-axis 'regular' GRB?
- Jet structure and off-axis observations
- Alternative jet phenomenon – refreshed shocks, GRB 160821B as a GRB 170817A-like proxy

GRBS – WHAT, WHERE, AND HOW?





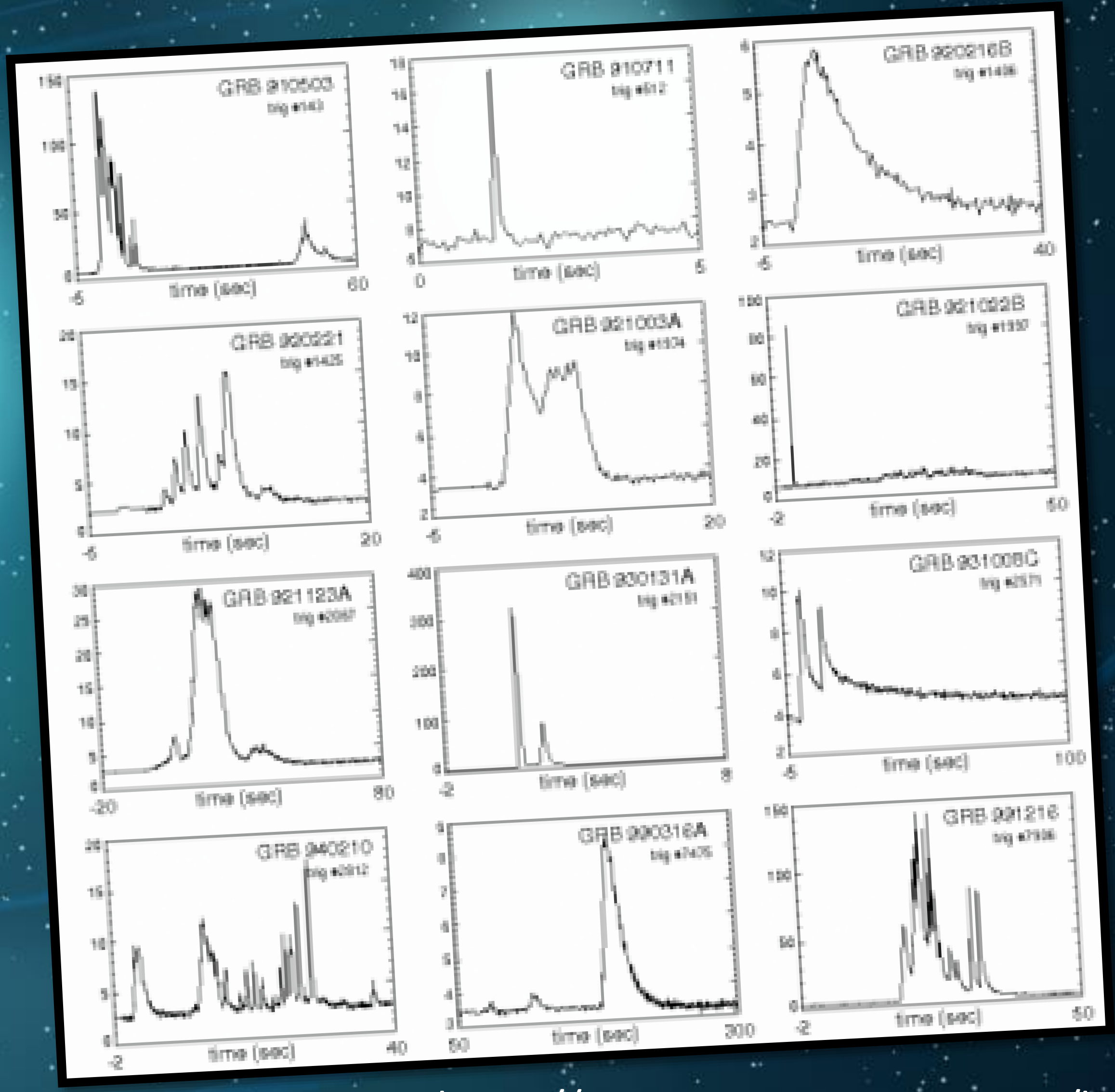
- Isotropic – *extragalactic,*
  〈*V/V*$_{max}$〉 < ½ at low *P* (ph. flux)
- Variable – *compact, relativistic*
- Two populations – *long and short*

https://gammaray.nsstc.nasa.gov/batse/grb

Mao & Paczynski 1992

The Compactness Problem for cosmological GRBs

- Sub-second variability, dt
- Compact sources, size is R < c dt
- High energy and non-thermal implies optically thin source
- Gamma-ray photon pairs with > twice the electron rest energy ($2m_e c^2$) will annihilate to produce e^+e^- pairs
- **Ultra-relativistic motion towards the observer fixes the problem!!!**
- Observed photons are blue shifted
- The size appears larger by a factor of the Lorentz factor squared
- Lorentz factor towards the observer, >100



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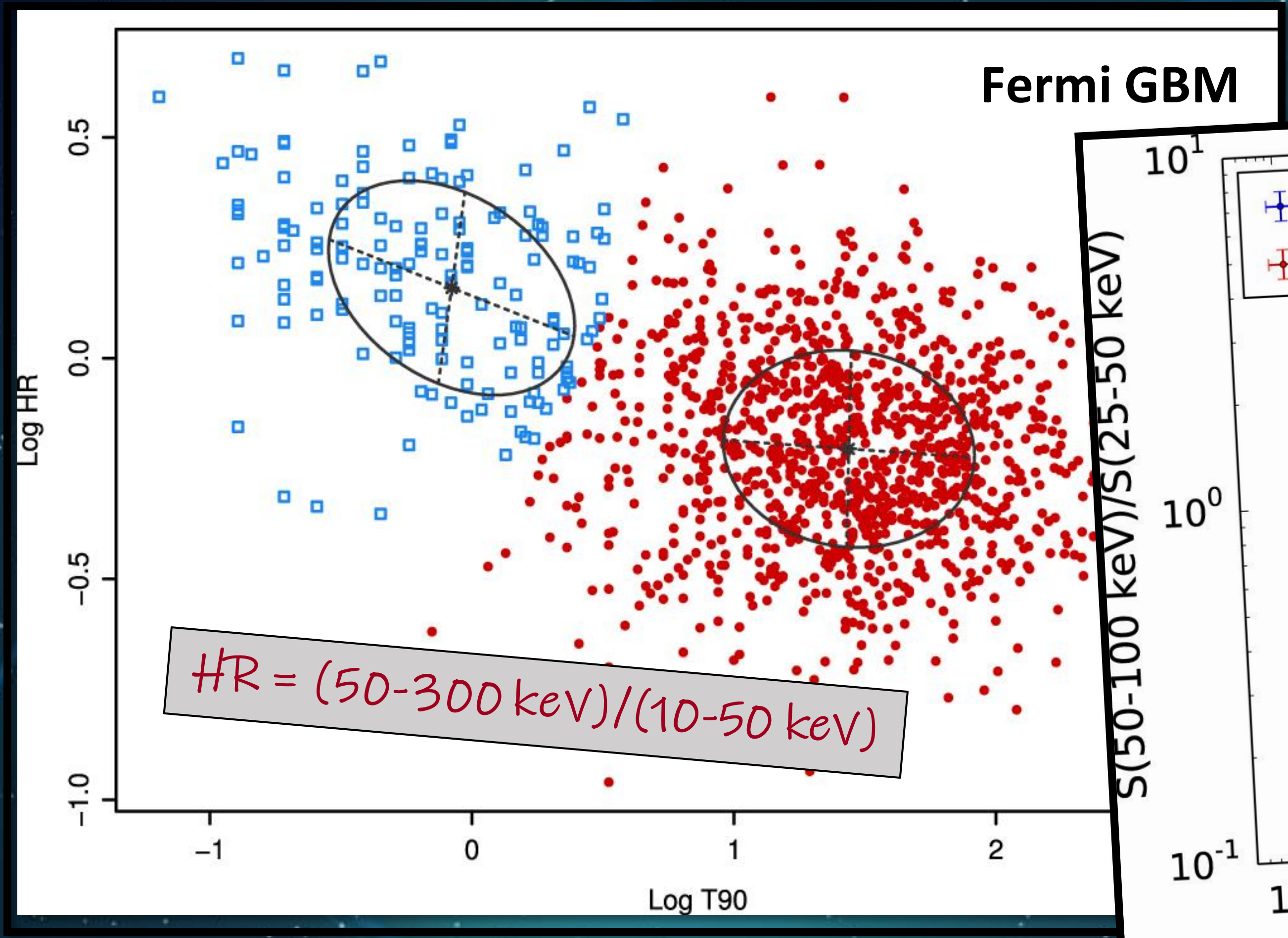
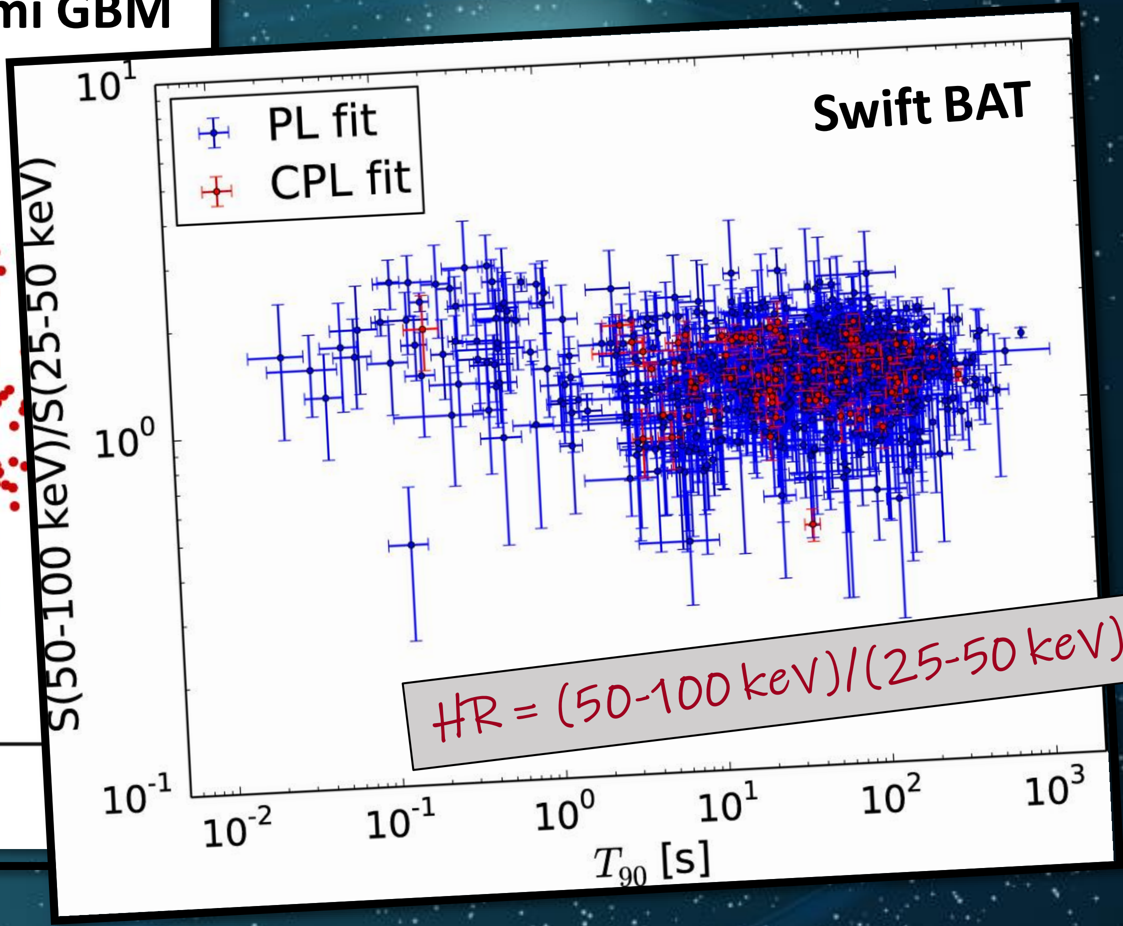
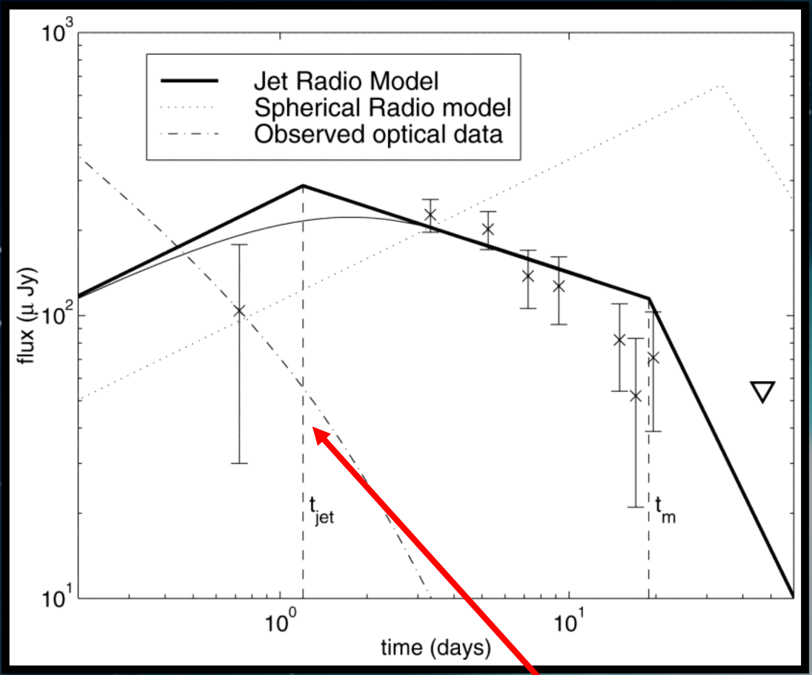


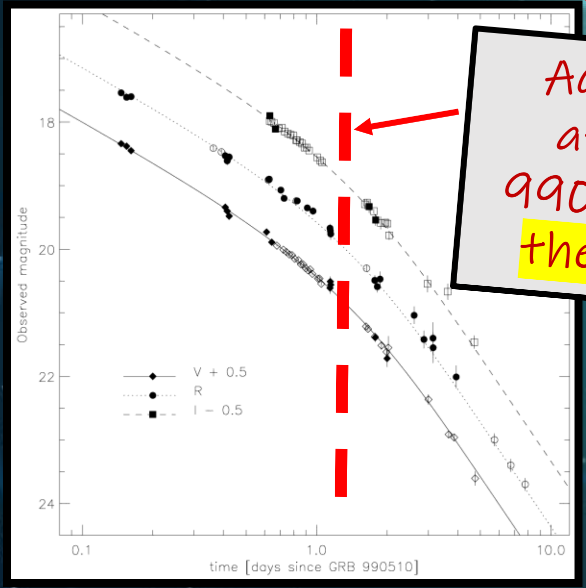


Narayan Bhat et al. 2016, Lien et al. 2016

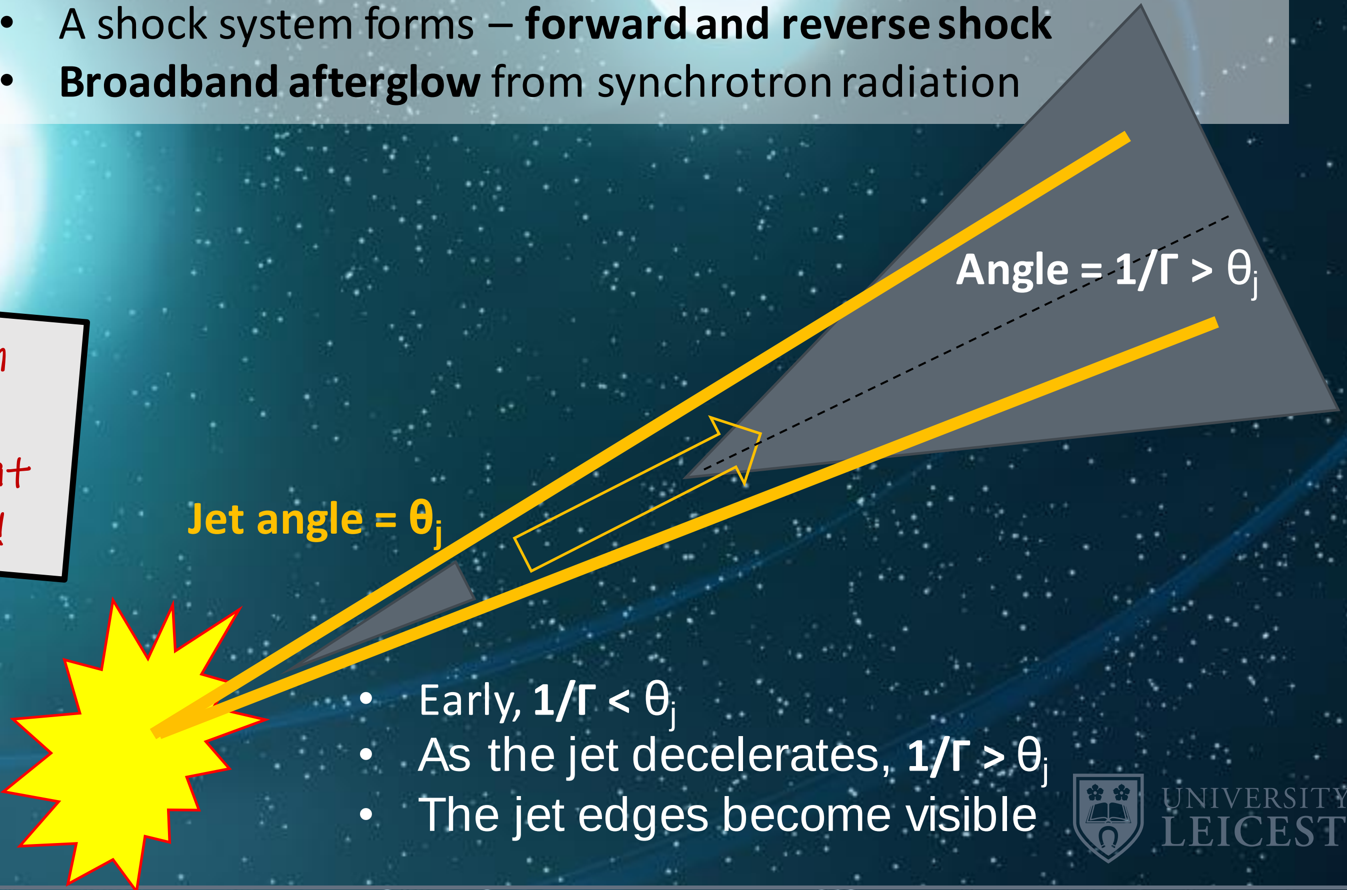
Highly energetic, relativistic explosion!!!

- The fireball will expand
- Sweeping up matter, like a snow plough
- When the mass of the swept-up matter is comparable to the explosion rest mass as $M \sim E/\Gamma^2c^2$, the **outflow will decelerate**
- A shock system forms – **forward and reverse shock**
- **Broadband afterglow** from synchrotron radiation





Achromatic break in afterglow to GRB 990510 indicates that the outflow is a jet!!!



- Early, **1/Γ < θ_j**
- As the jet decelerates, **1/Γ > θ_j**
- The jet edges become visible

Harrison et al. 1999

LONG GRBs

Associated with Type Ic broadlined **supernovae**

Redshift, <z> = 1

Max. z < 9

Isotropic equivalent energies 10^53-54 erg

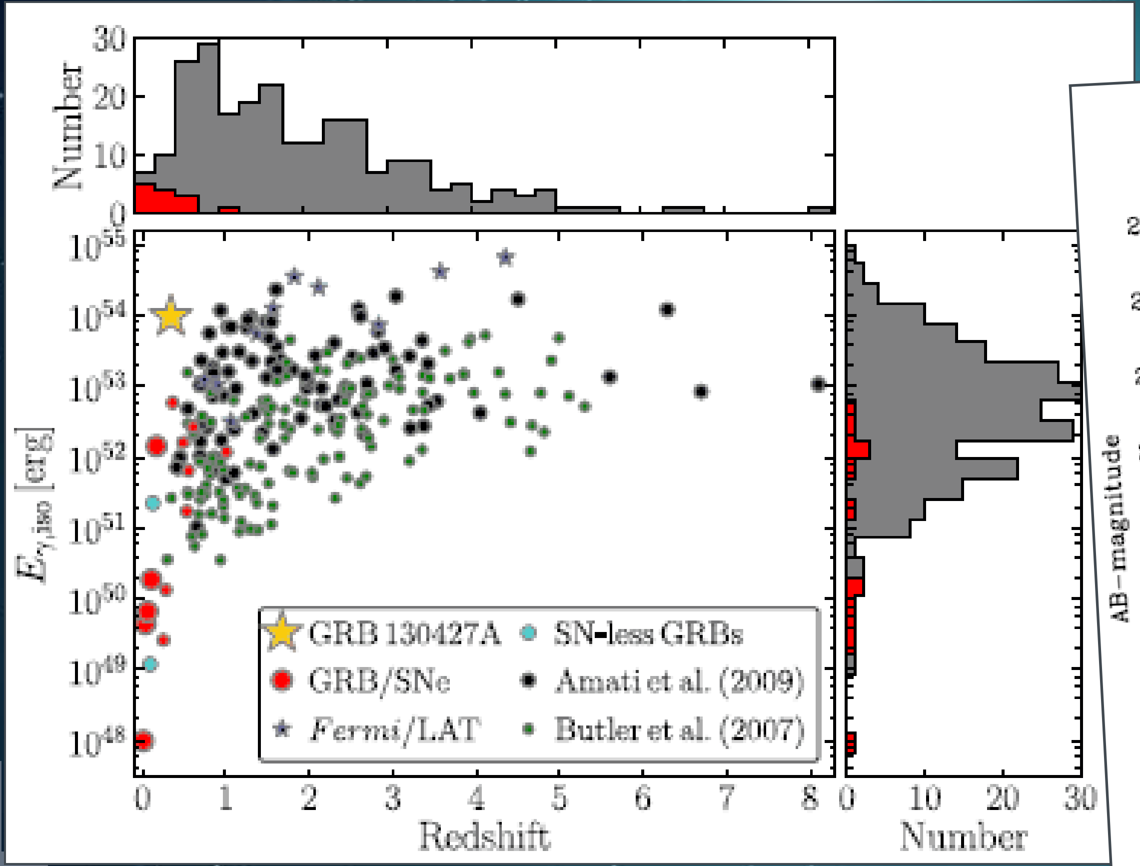
SHORT GRBs

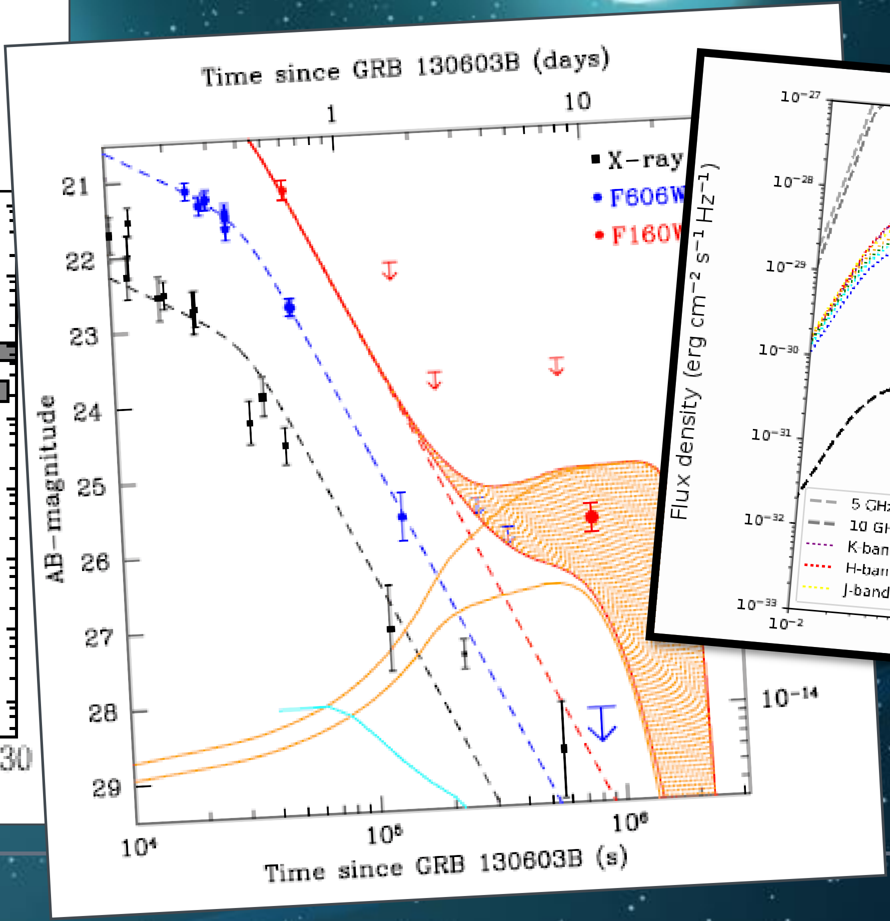
Associated with **macro/kilonovae** (from compact binary mergers)

Redshift, <z> = 0.5

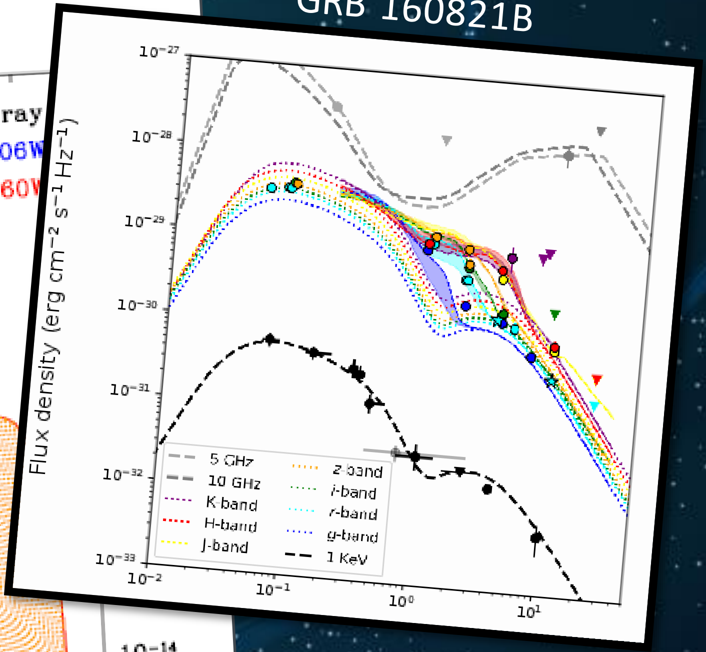
Max. z < 2.2

Isotropic equivalent energies 10^50-52 erg





GRB 160821B



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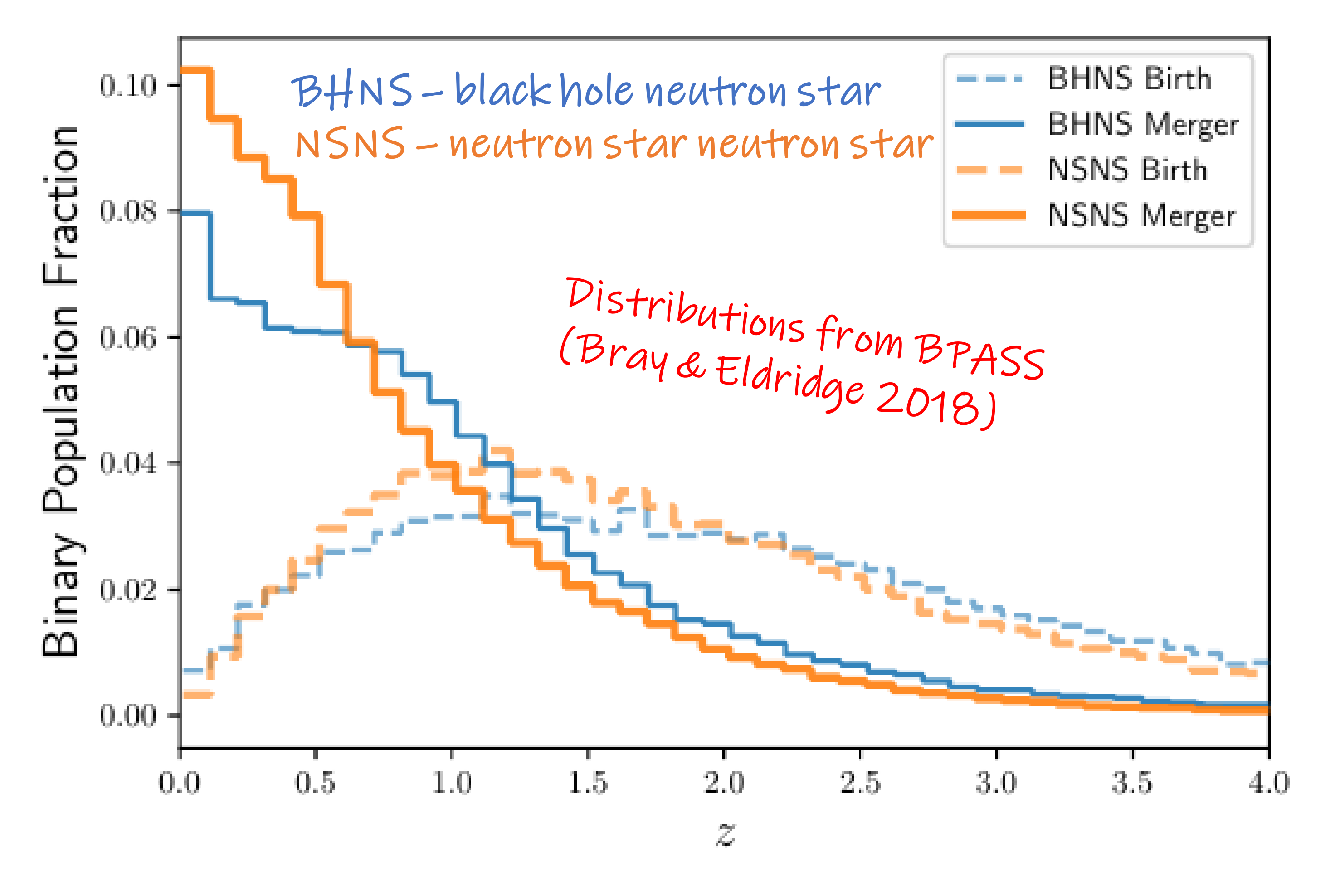
Levan+ 2016, Tanvir+ 2013, **Lamb**+ 2019b

- What fraction of the compact binary merger population do SGRBs trace?
  - The beaming fraction, $f_b = 1-\cos(\theta_j)$
  - Do all mergers result in jets?
  - Do all jets produce GRBs?
- How will the afterglow look?

Compact binary system redshift distribution

- The distribution of supernovae with redshift will follow the star-formation rate
- For compact binary mergers – there is a delay time distribution
- Population synthesis and evolution models can predict this

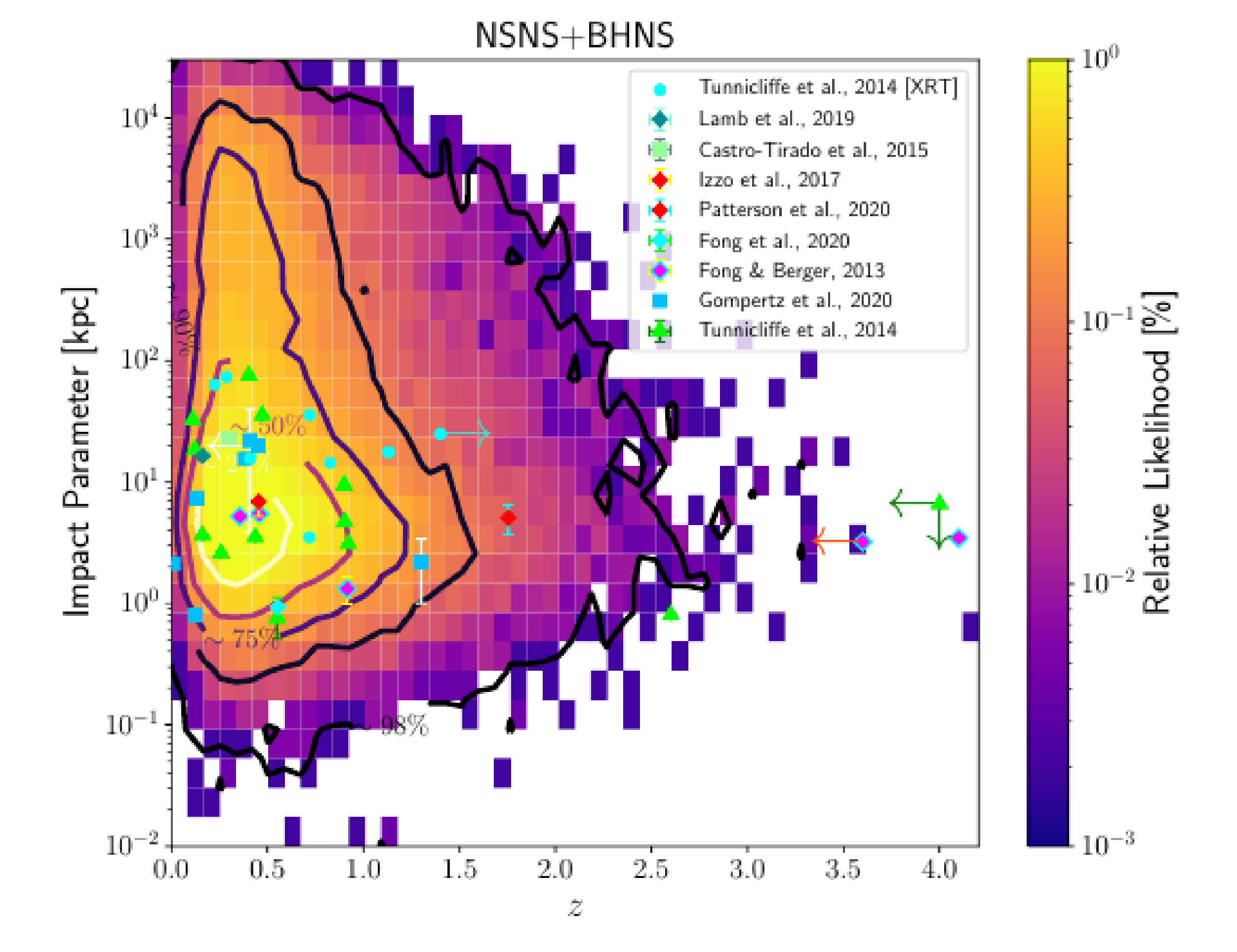


Mandhai, **Lamb**, Tanvir, Bray & Nixon (in prep)

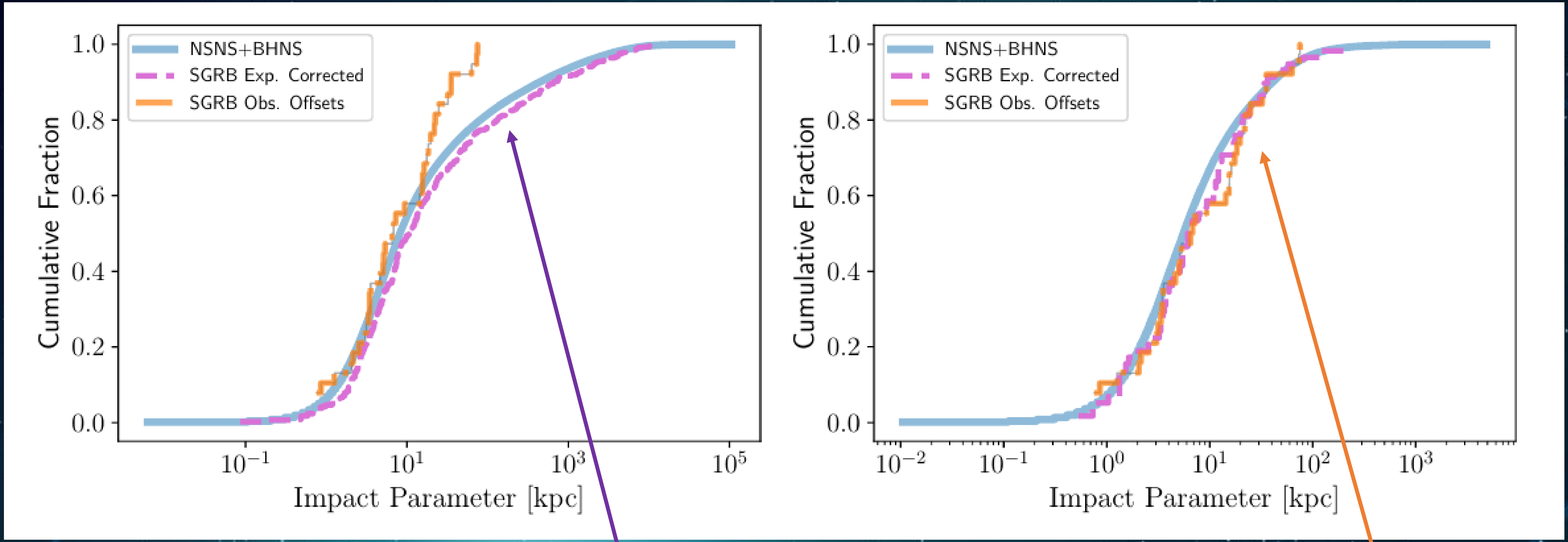
Compact binary evolution – natal kicks

NOTE – 'Impact Parameter' is the observed apparent seperation on-the-sky for the burst location to the host galaxy

- A compact binary system will have received two natal kicks in its evolution
  1. The supernova of the primary star
  2. The supernova of the secondary star
- The system can travel a long way from its birth site and even 'leave' the host galaxy
- Localised short GRBs can have a significant host offset



Mandhai, **Lamb**, Tanvir, Bray & Nixon (in prep)



BHNSs here have a mass ratio Q < 3

If all the simulation mergers result in a short GRB with the observed luminosity function – we would expect to see this distribution of observed offsets

Consider only mergers with a merger delay time of < 1 Gyr

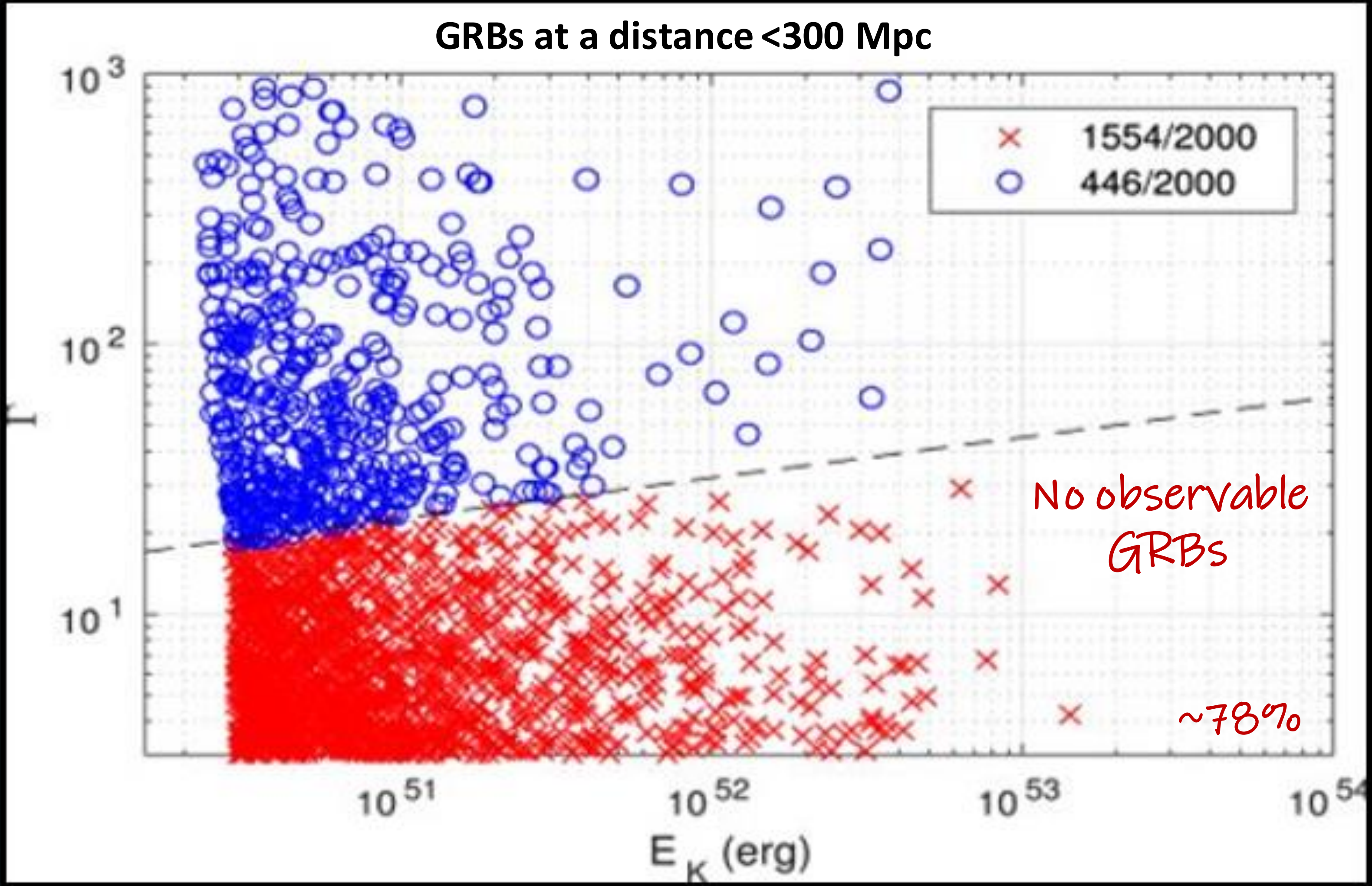
- Do mergers involving an 'old' neutron star fail to produce a GRB?
- The merger rate inferred from SGRBs is < the rate inferred from GW detections

Mandhai, **Lamb**, Tanvir, Bray & Nixon (in prep)

Failed GRBs

- To successfully produce a GRB, the jet should have a very high bulk Lorentz factor, Γ>>1
- Efficient baryon loading, or inefficient acceleration, may result in a jets with Γ<20
- The **photospheric radius** ∝ (E/Γ)^(½)
- Whereas, the **dissipation radius** ∝ Γ^2
- The GRB producing dissipation radius falls below the photospheric radius and gamma-rays are suppressed

Lamb & Kobayashi 2016



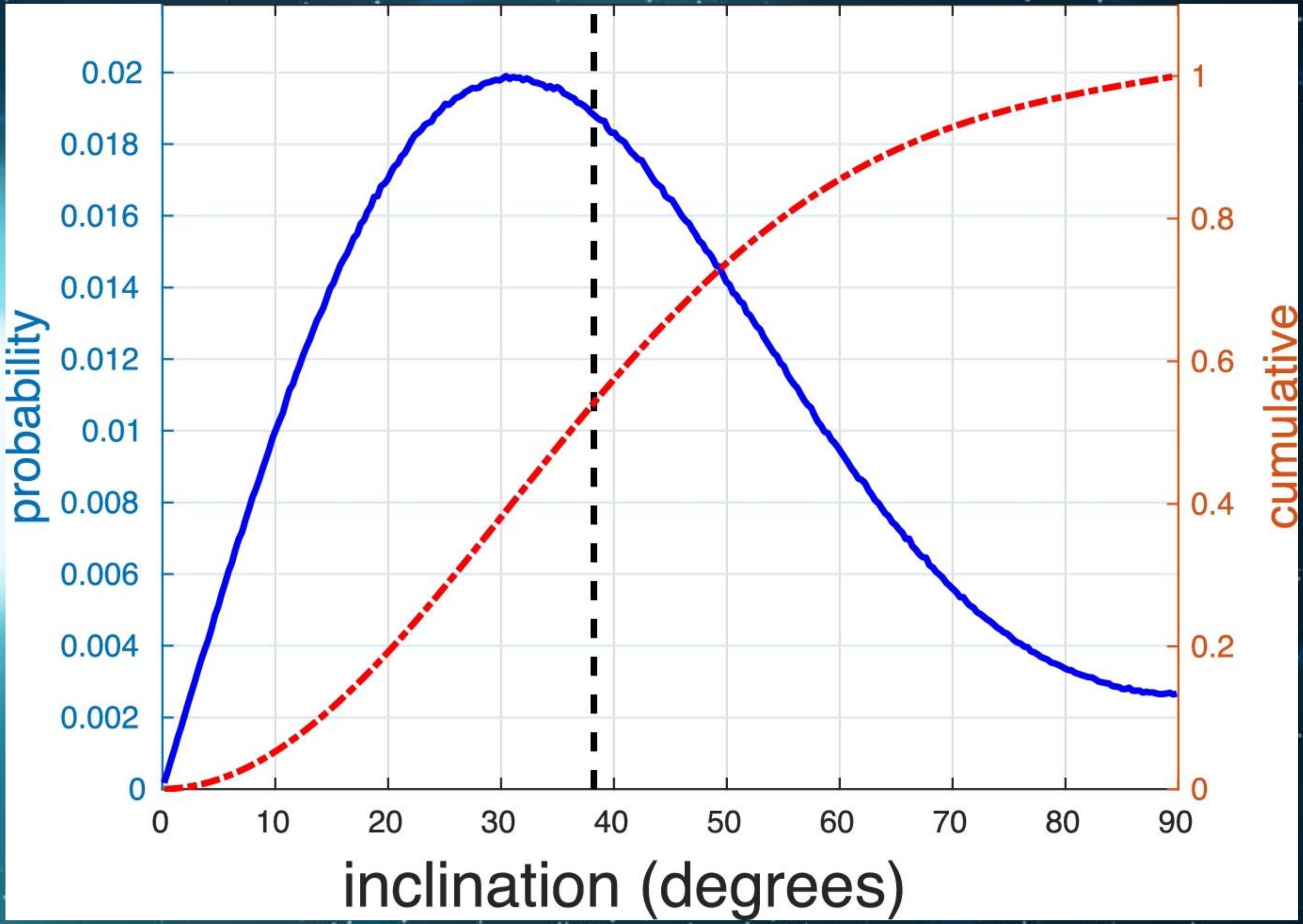
For a population of GRBs that have jet Lorentz factors that follow:
N(Γ) ∝ Γ^-1.75
and a Wanderman & Piran (2015) SGRB luminosity distribution.
The afterglow to a low-Γ jet will be brighter than 21st magnitude in 85% of cases (on-axis)
Low-Γ jets may have wider opening angles

INCLINATION OF A GW DETECTED MERGER

GW polarisation sums so that there is a larger strain for a face-on merger

$$h_+ \propto 1 + \cos^2 \iota$$
$$h_\times \propto 2 \cos \iota$$

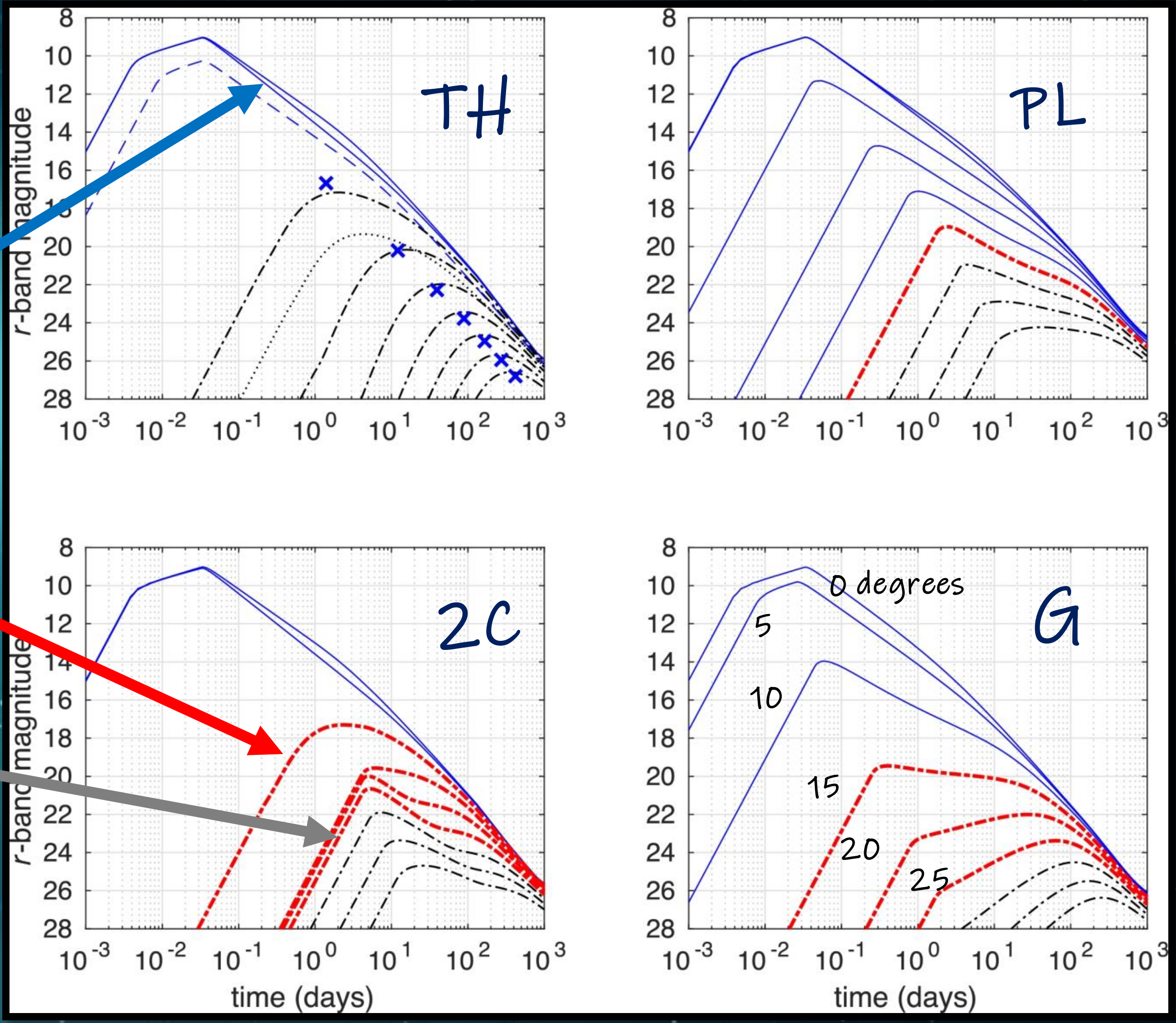
$$h \propto \sqrt{(h_+^2 + h_\times^2)}/D$$



Lamb & Kobayashi 2017

What about structured jets?

- GRBs are highly beamed, so we only see a fraction, 1-cos(θ_j) of the events.
- **Off-axis, the structure of the outflow matters!**
- **The GRB seen at 200 Mpc**
- **No observed "off-axis" GRB, but still within the outflow opening angle**
- **Off-axis, outside of outflow opening angle**
- 4 structures: 'Top-hat' (TH), 'Power-law' (PL), '2-component' (2C), and 'Gaussian' (G)



Given one well sampled GW-EM counterpart, the presence of extended jet structure could be revealed if the system is favourably inclined.

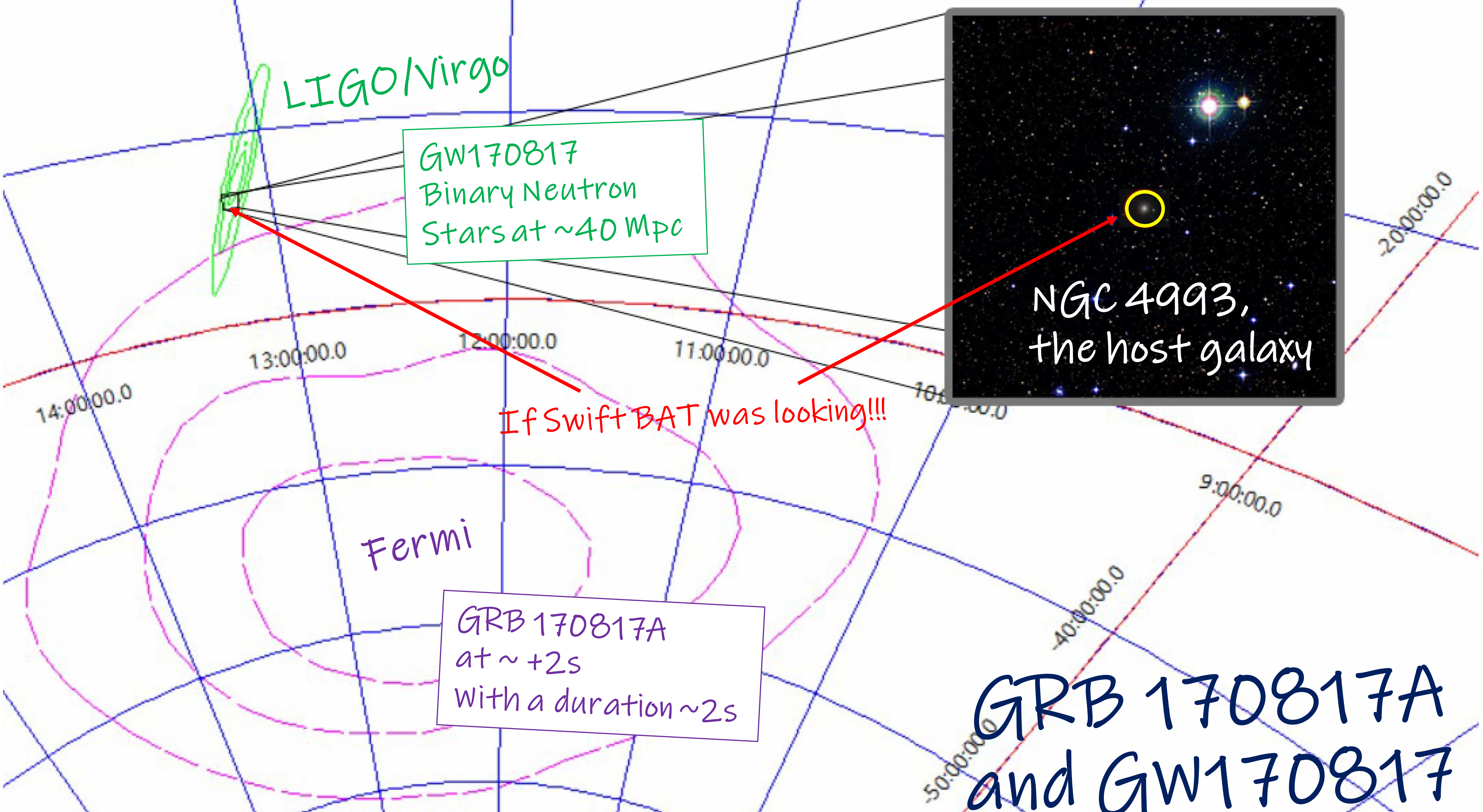
...

However, afterglows at higher inclinations, or orphan afterglows, could reveal the presence of jet structure; an achromatic re-brightening would indicate a two-component, or a power-law structured-jet. A shallow decline or **slowly brightening afterglow with a soft peak would indicate a Gaussian type jet structure observed at relatively high inclination (within the jet opening angle)...**

Gaussian structured jets as electromagnetic counterparts to gravitational wave detected neutron star mergers were not unprecedented prior to GW170817

Lamb & Kobayashi 2017

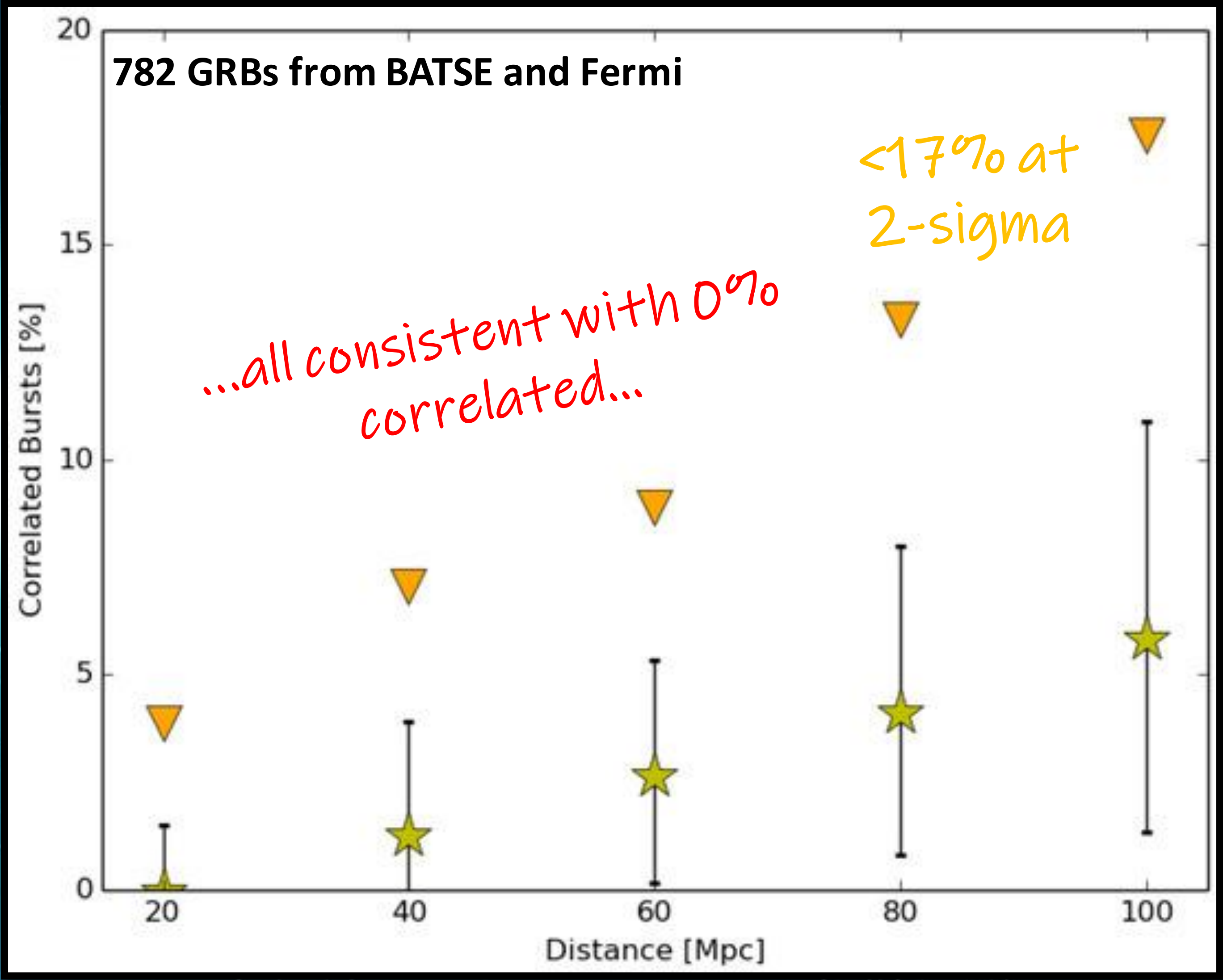
GRB 170817A and GW170817



Mandhai, Tanvir, **Lamb**, Levan & Tsang 2018

A LOCAL POPULATION OF SHORT GRBS?

- LIGO/Virgo O3 will have a NSNS horizon ~200 (300) Mpc
- We've been looking for GRBs for many years – what is the local rate?
- Observational constraints from BATSE, Fermi, and Swift
- BATSE and Fermi, < 100 Mpc, <12 per year
- Swift BAT, **< 200 Mpc, <4 per year**
- All consistent with 0 per year
- Mergers associated with a gamma-ray transient are likely very rare!



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Mandhai, Tanvir, **Lamb**, Levan & Tsang 2018

Swift GRBs <200Mpc!?

NO Swift short GRBs, unambiguosly, <200Mpc

...but 4, from literature that are possibly <400Mpc

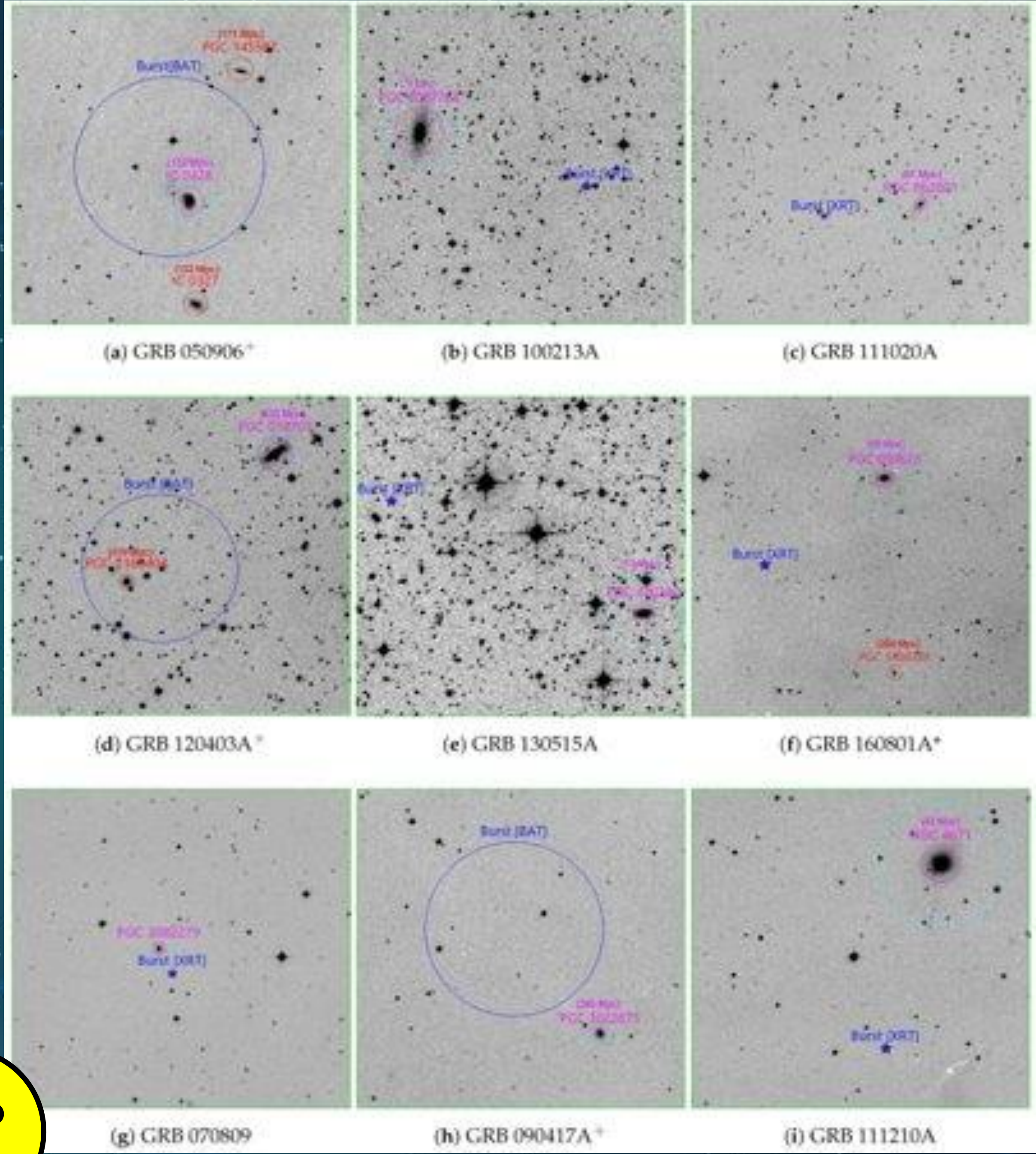
GRBs 050906, 070809, 090417A & 111020A

GRB	T_{90} (s)	Angular Separation (arcmin)	Closest Galaxy	Galaxy Type	Optical Bands (B/R) (mag)	J-Band (mag)	d (Mpc)	Impact Parameter (kpc)	E_{iso} (10^{46} ergs)
050906	0.26	2.0	IC 0328	Sc	14.0 (B)	12.2	132 [55]	77 ± 109	1.9
100213A	2.40	5.4	PGC 3087784	S0-a	14.7 (B)	11.3	78 [55]	123	39.9
111210A	2.52	6.0	NGC 4671	E	13.4 (B)	10.1	43 [55]	76	7.5
120403A	1.25	4.9	PGC 010703	Sc	14.4 (B)	12.1	133 [55]	192 ± 90	38.2
130515A	0.29	8.5	PGC 420380	S0-a	16.0 (B)	12.3	73 [57]	180	28.4
160801A	2.85	6.7	PGC 050620	Sa	15.2 (B)	12.4	59 [55]	115	10.7
070809	1.30	2.0	PGC 3082279 [52]	Sa	16.3 (B)	13.5	180 [56]	105	64.4
090417A	0.07	4.4	PGC 1022875 [53]	S0-a	15.9 (B)	13.4	360 [56]	461 ± 292	24.5
111020A	0.40	2.3	FAIRALL 1160	Sa	~14 (R)	11.7	81 [12]	54	9.4

Using 2MASS galaxy catalogue (~91% of the sky, and 97.6% redshift complete to K=11.75) estimate the minimum separation (Impact Parameter, <200kpc) for Swift bursts with T90<4s

9 candidates (5 new) – bursts below the line have host candidates that do not appear in 2MASS (111020A host was misclassified as a star!?)

Plus a visual inspection of 157 bursts!!! Thanks Soheb



(a) GRB 050906* (b) GRB 100213A (c) GRB 111020A

(d) GRB 120403A* (e) GRB 130515A (f) GRB 160801A*

(g) GRB 070809 (h) GRB 090417A* (i) GRB 111210A

Mandhai, Tanvir, **Lamb**, Levan & Tsang 2018

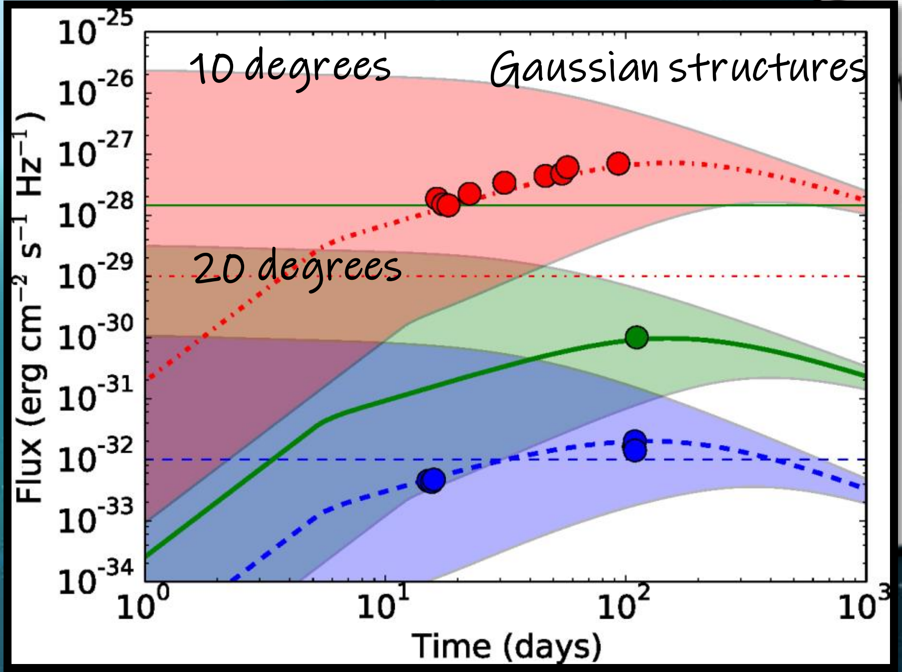
THE AFTERGLOW TO GRB 170817A – AN OFF-AXIS AND STRUCTURED JET!

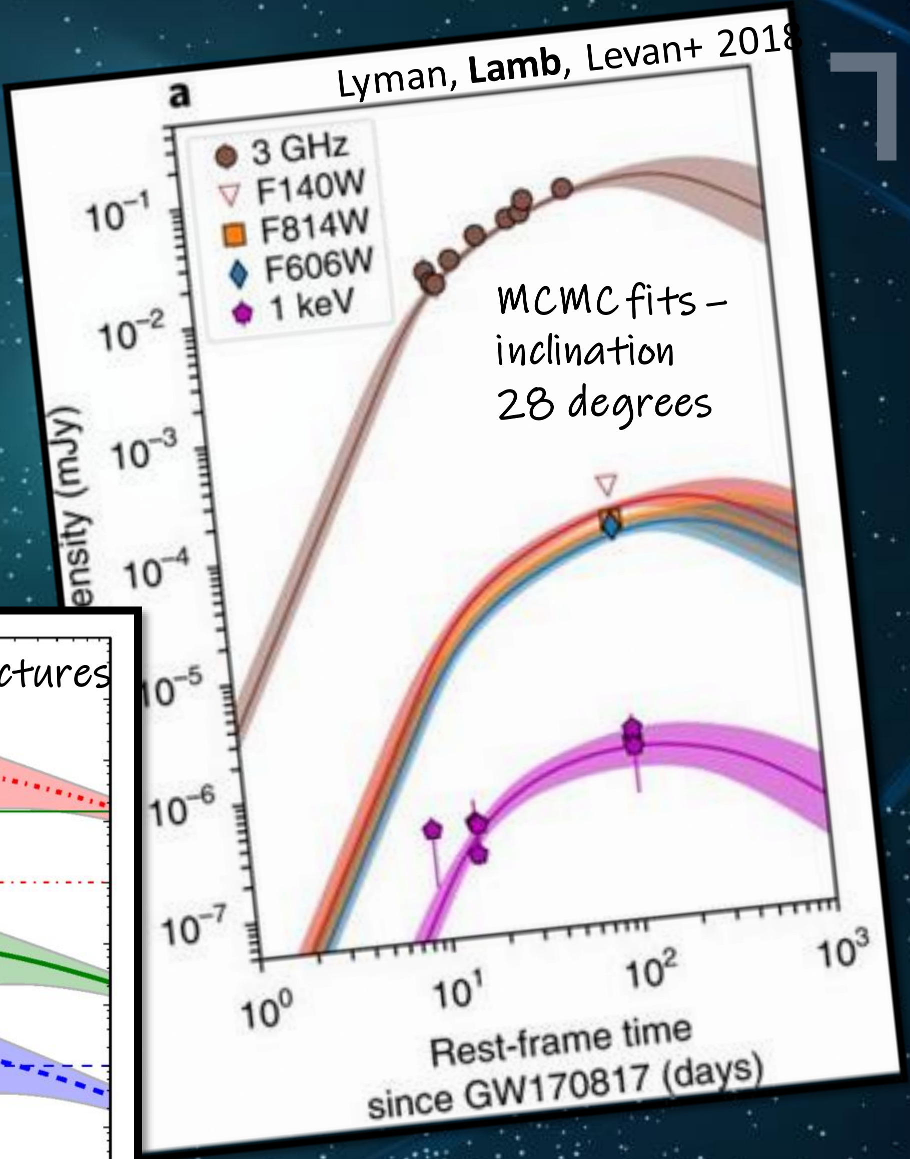
100 days post-merger – the afterglow is consistent with a structured jet

Also a choked jet cocoon! But it wasn't*, so we won't discuss this here

(see Kasliwal+ 2017, Mooley+ 2018 etc.)

*see the next few slides





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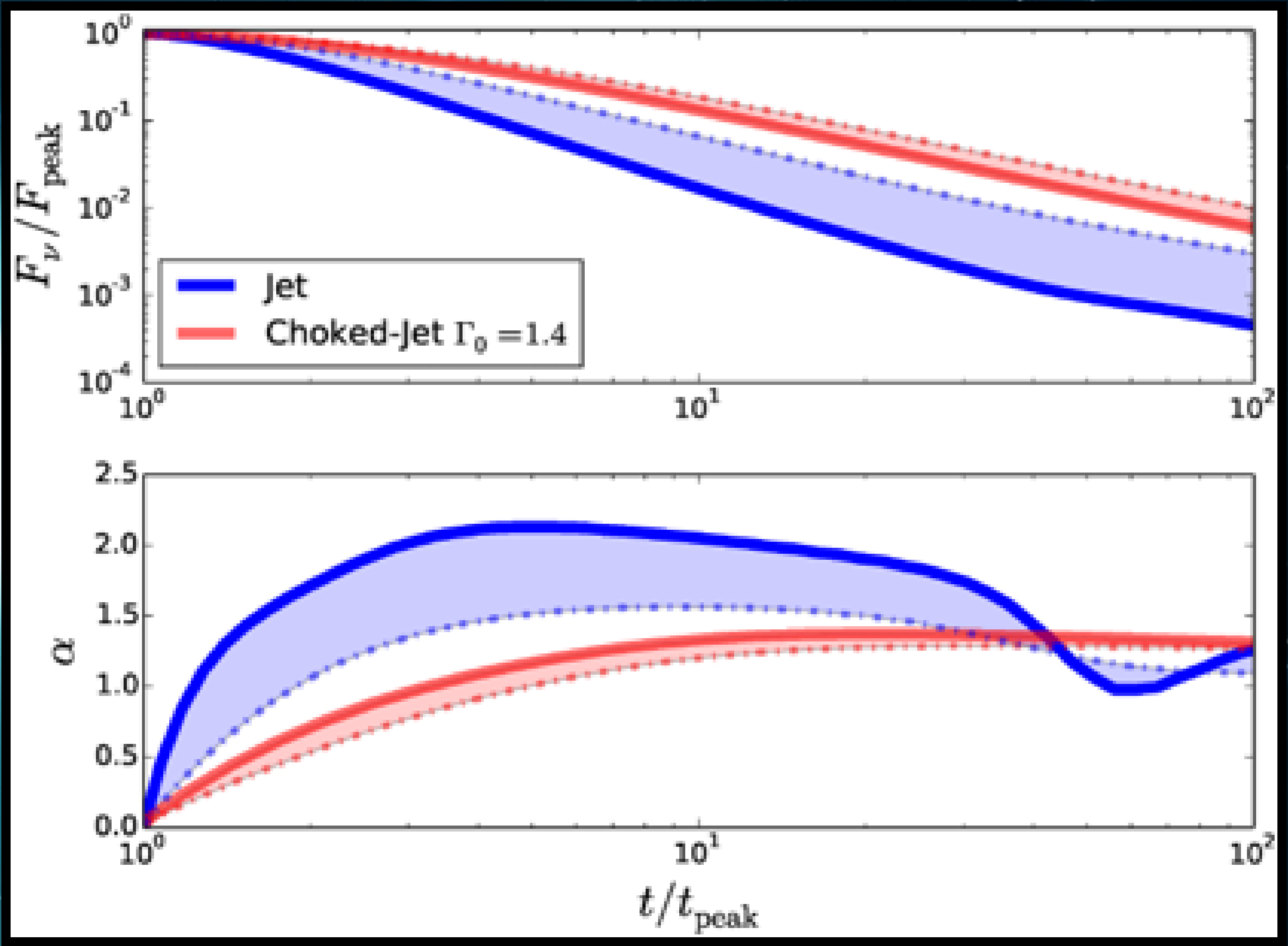
Lamb & Kobayashi 2018; Lyman, **Lamb**, Levan+ 2018

See also a heap of other papers – including but not limited to Dobie+ 2018, Ghirlanda+ 2019, Margutti+ 2018, Mooley+ 2018, Nynka+ 2018, Piro+ 2018, Resmi+ 2018, Troja+ 2018,

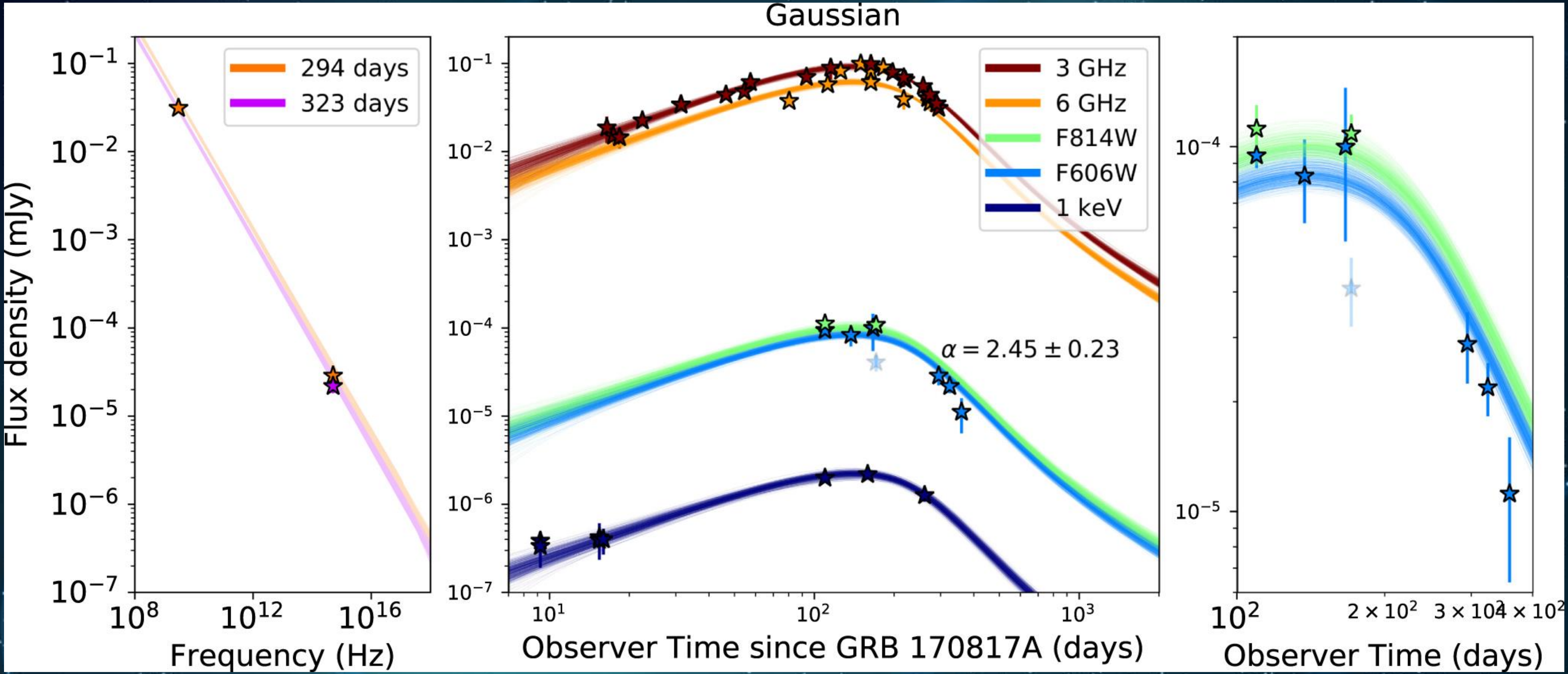
THE POST-PEAK AFTERGLOW DECLINE

For the afterglow to GRB 170817A – post-peak decline would distinguish between a wide-angled cocoon (choked jet) or a successful jet

- Outflow is core dominated and initially ultra-relativistic [jet]
- Dynamics are dominated by relativistic components until very late [jet]
- Leads to steeper decline [jet]



Lamb, Mandel & Resmi 2018



A **two-component** jet structure also works **(Lamb+** 2019a), and a **power-law** jet structure (see e.g. Margutti+ 2018, Ghirlanda+ 2019)

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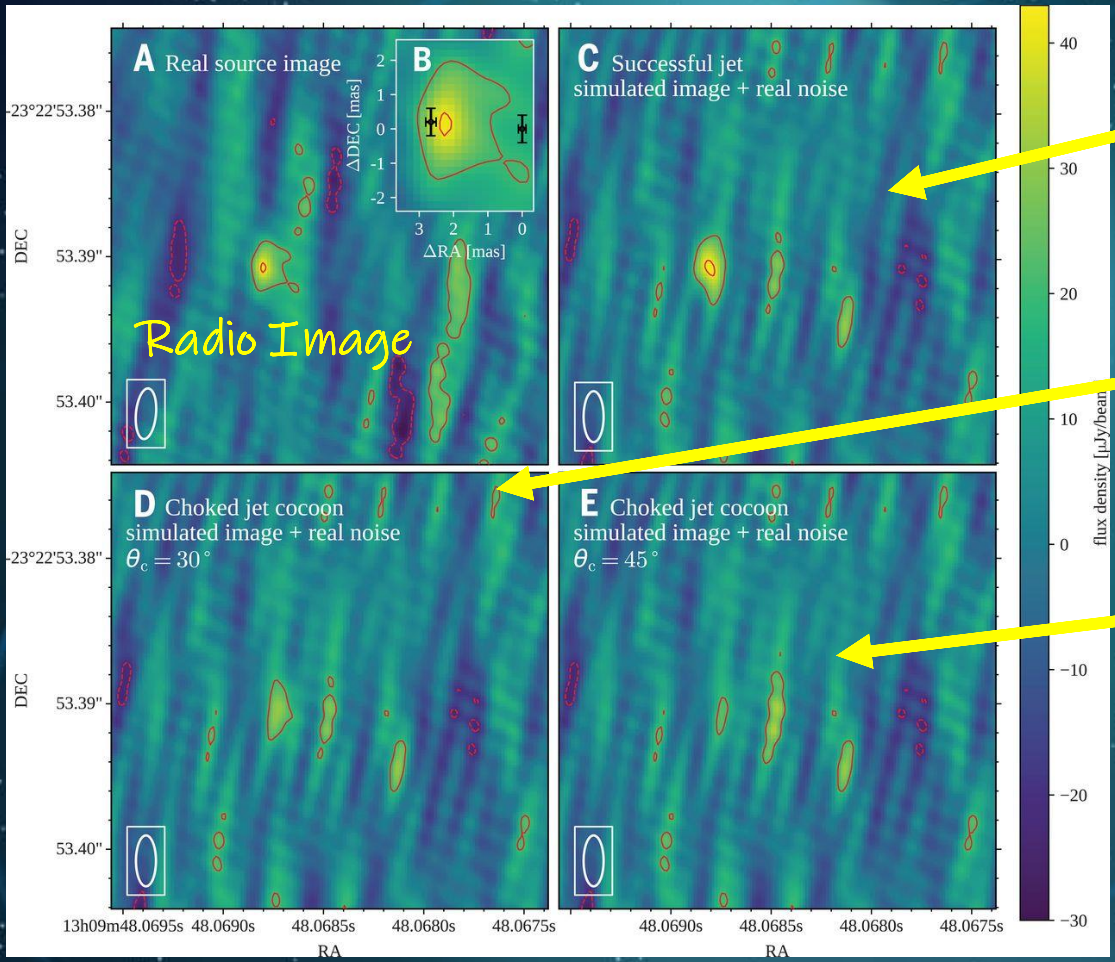
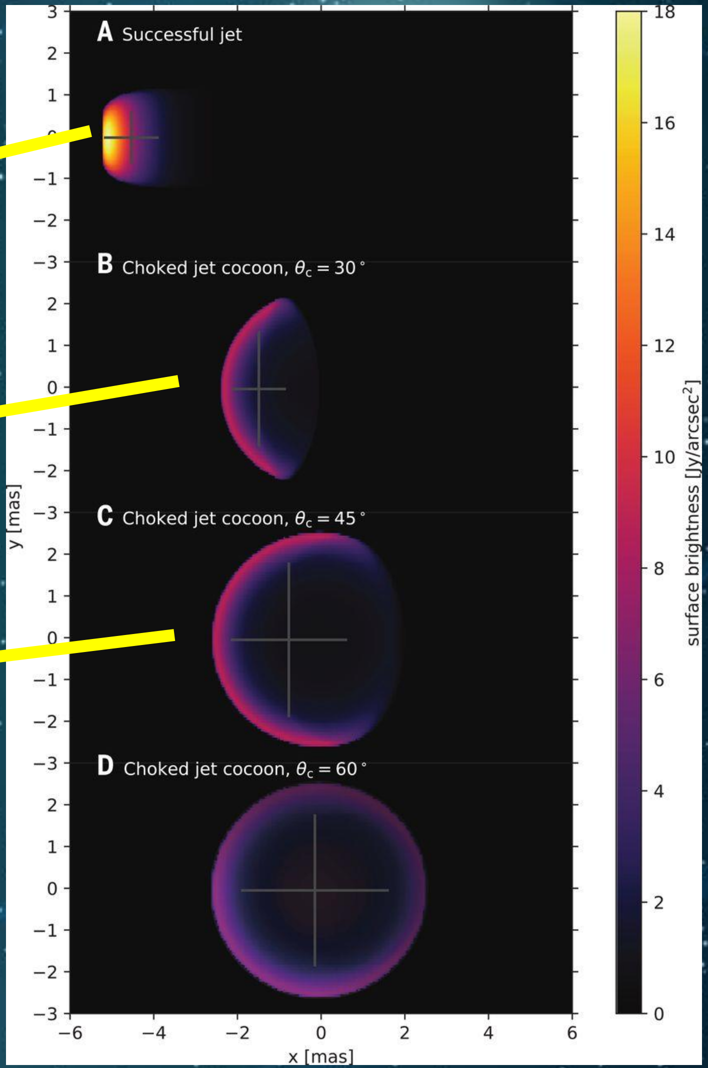
Lamb+ 2019a

RADIO IMAGING OF GW170817 CONFIRMS A JET!

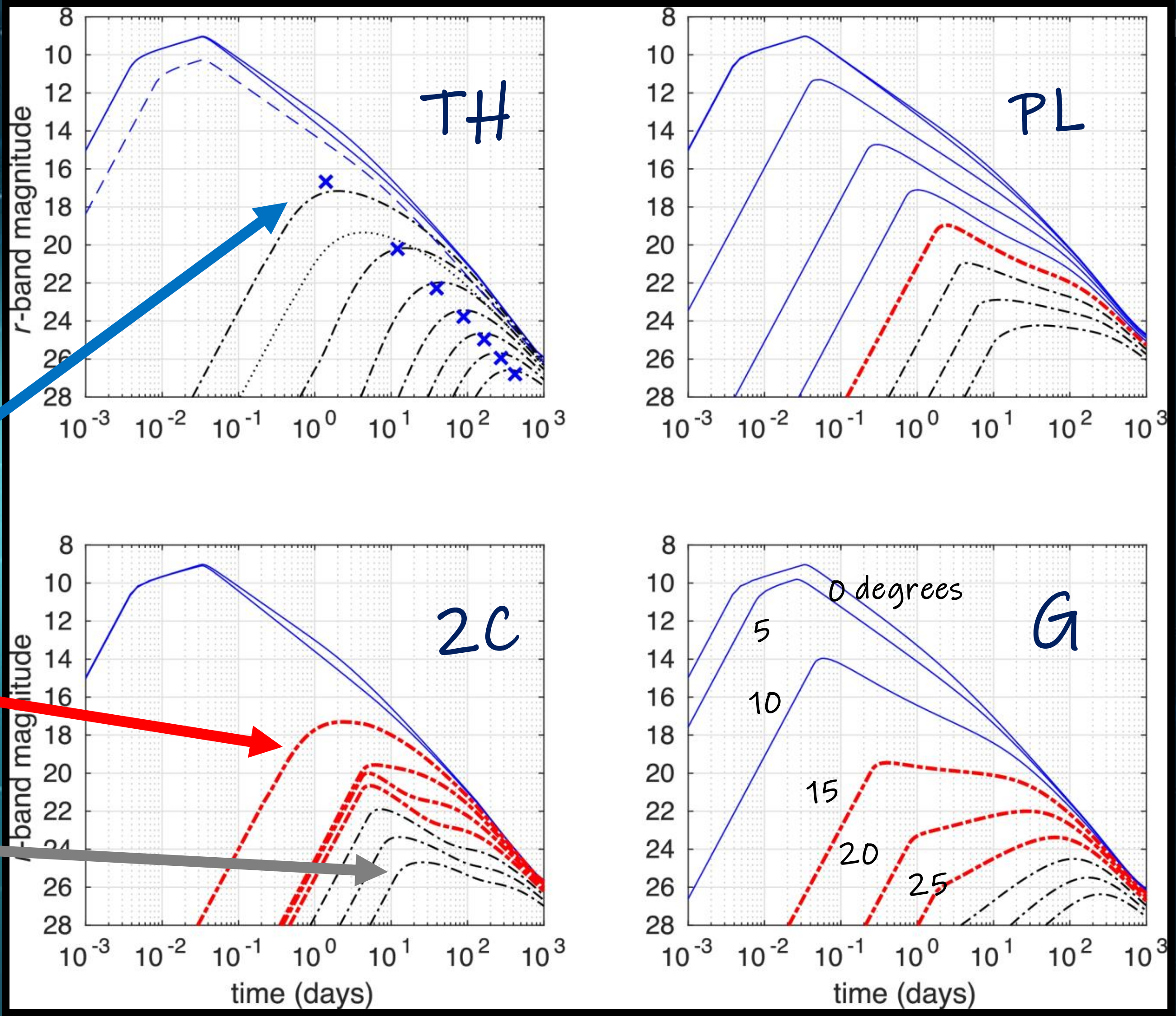




Ghirlanda+ 2019, see also Mooley+ 2019

So, it's a structured jet*!

- If jet structure profile is fixed we can use the off-axis afterglow shape to tell the inclination e.g. Wang & Giannios 2020
- **Off-axis, the structure of the outflow matters!**
- **The GRB seen at 200 Mpc**
- **No observed "off-axis" GRB, but still within the outflow opening angle**
- **Off-axis, outside of outflow opening angle**
- 4 structures: 'Top-hat' (TH), 'Power-law' (PL), '2-component' (2C), and 'Gaussian' (G)

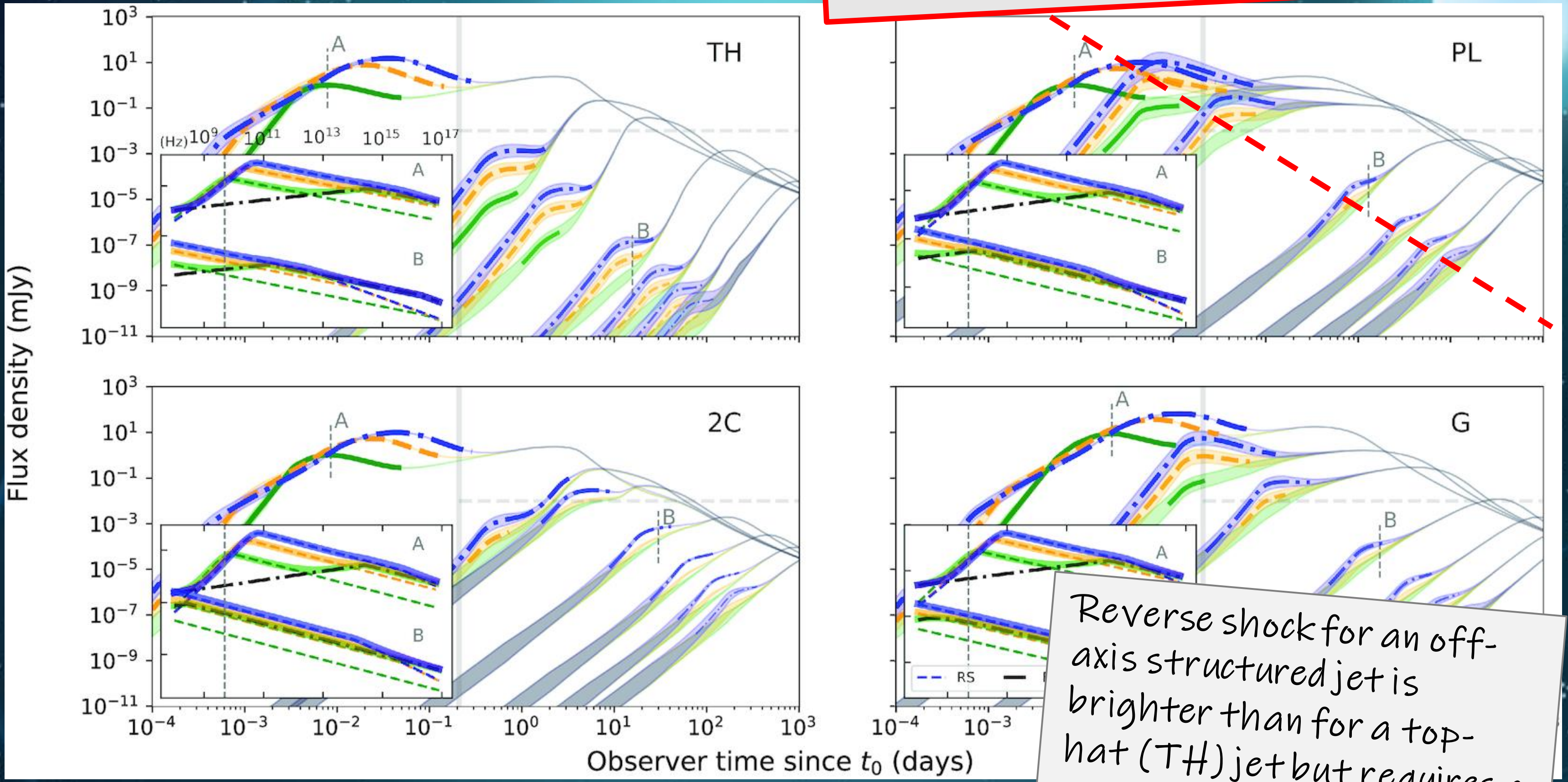


Lamb & Kobayashi 2017

*it might not be... wait until a couple more slides!!!

AFTERGLOWS TO STRUCTURED JETS – REVERSE SHOCKS

The reverse shock



Reverse shock for an off-axis structured jet is brighter than for a top-hat (TH) jet but requires a magnetised outflow

- When the outflow decelerates two shocks are established
- Forward shock has only been considered so far
- The reverse shock probes material back towards the central engine
- There can be a significant magnetic field
- The reverse shock can probe this!!!

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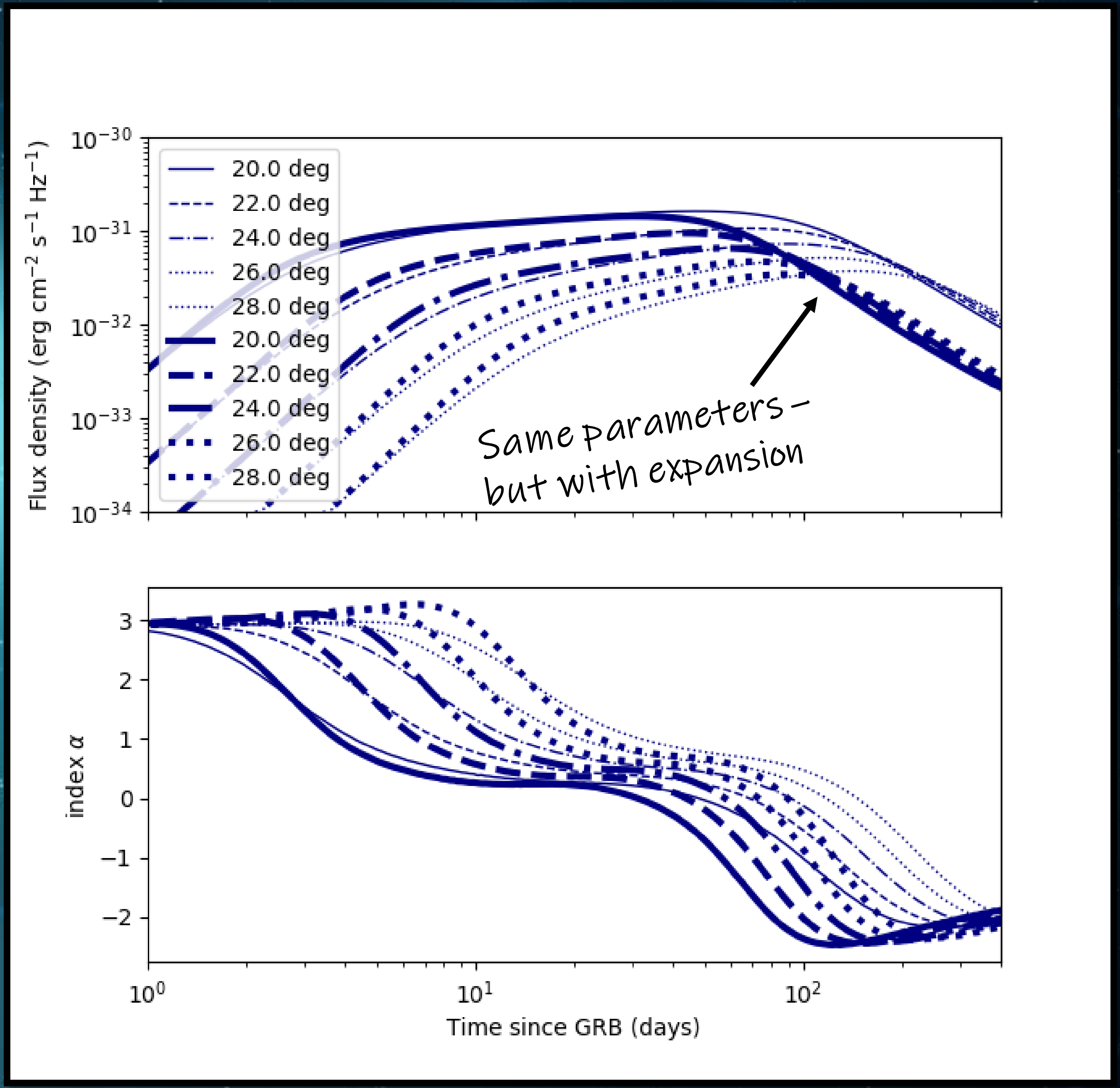
Lamb & Kobayashi 2019b

Sideways Expansion

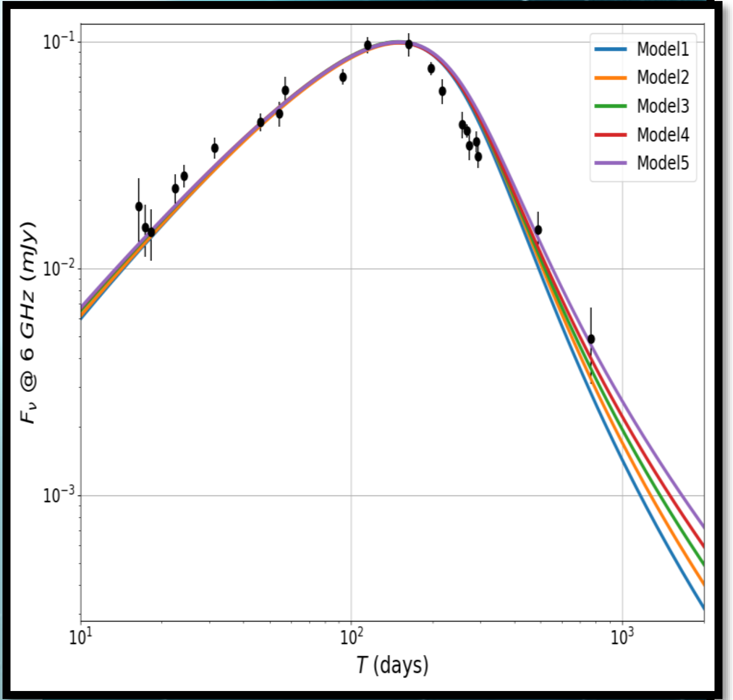
- Often overlooked as not important (as it only effects the post peak decline)
- Expansion shortens the jet break timescale
- Using the Wang & Giannios 2020 jet structure – thin line, no expansion; thick line, expansion

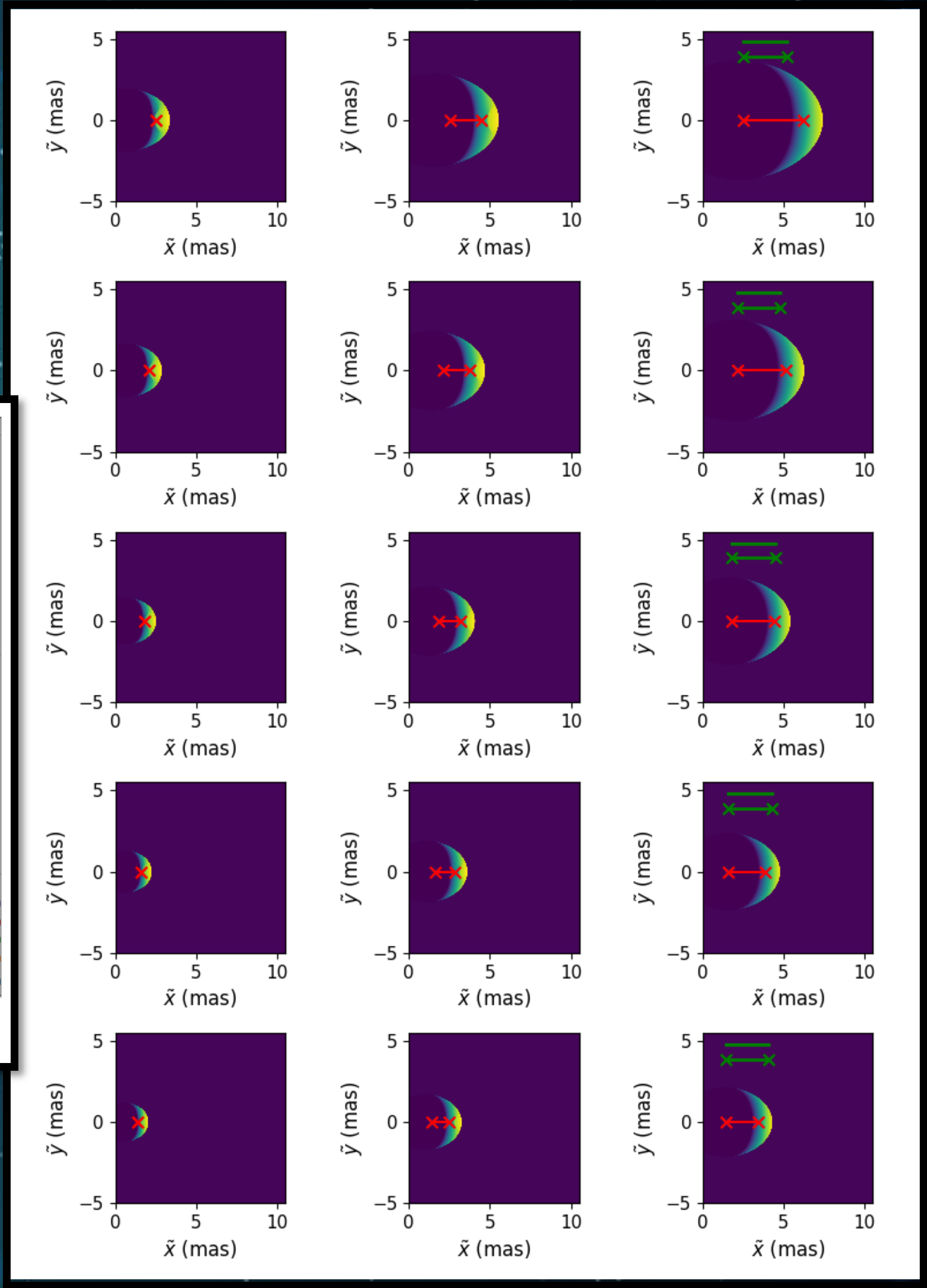


Lamb et al. (in prep)

Using the radio imaged centroid motion

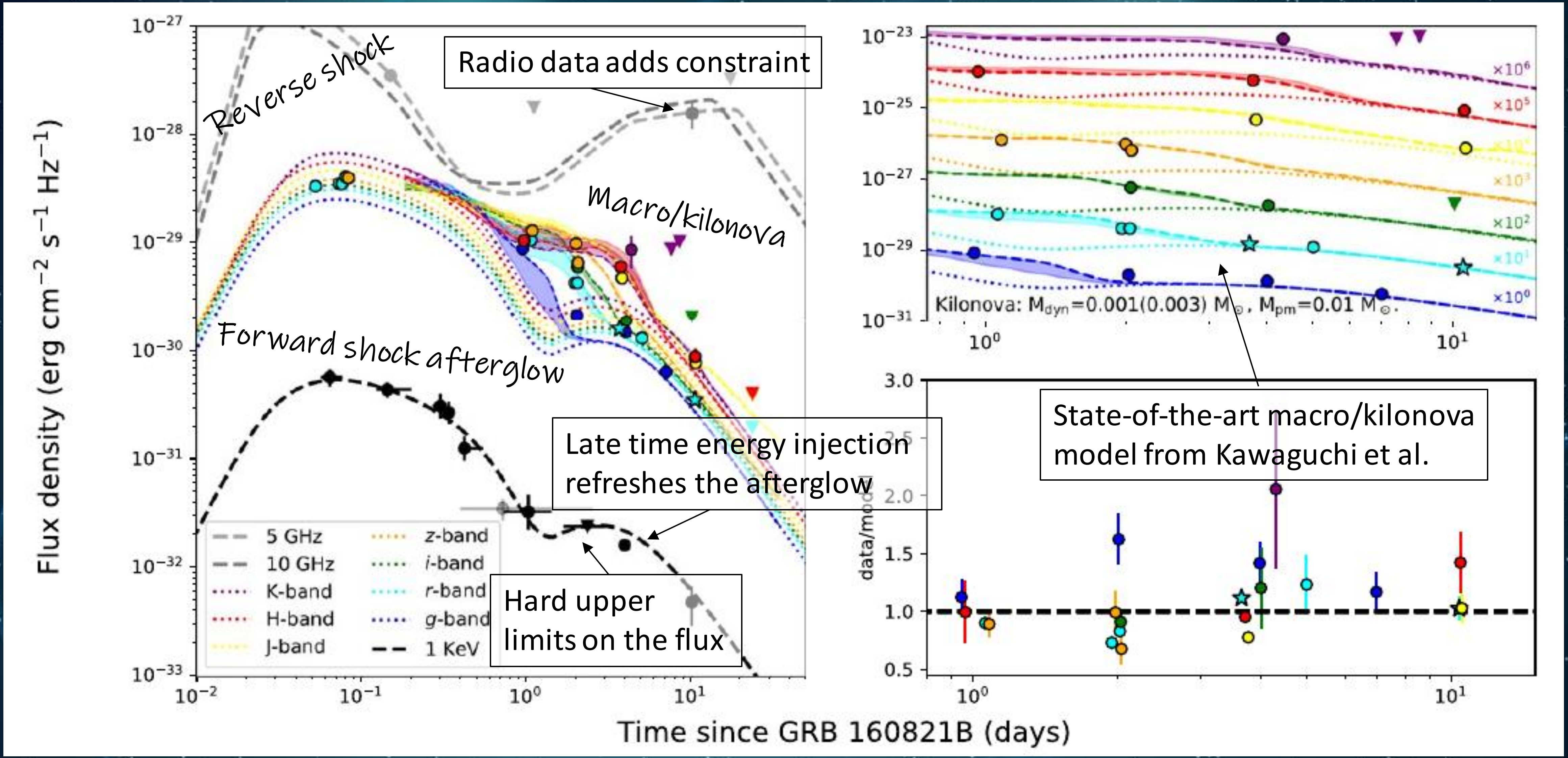
- Using a fixed jet structure (Gaussian here), the observed superluminial centroid motion can be used to better fit an afterglow model
- Independent afterglow script developed by Joe Fernandez
- Uses expansion description in Granot & Piran (2013)





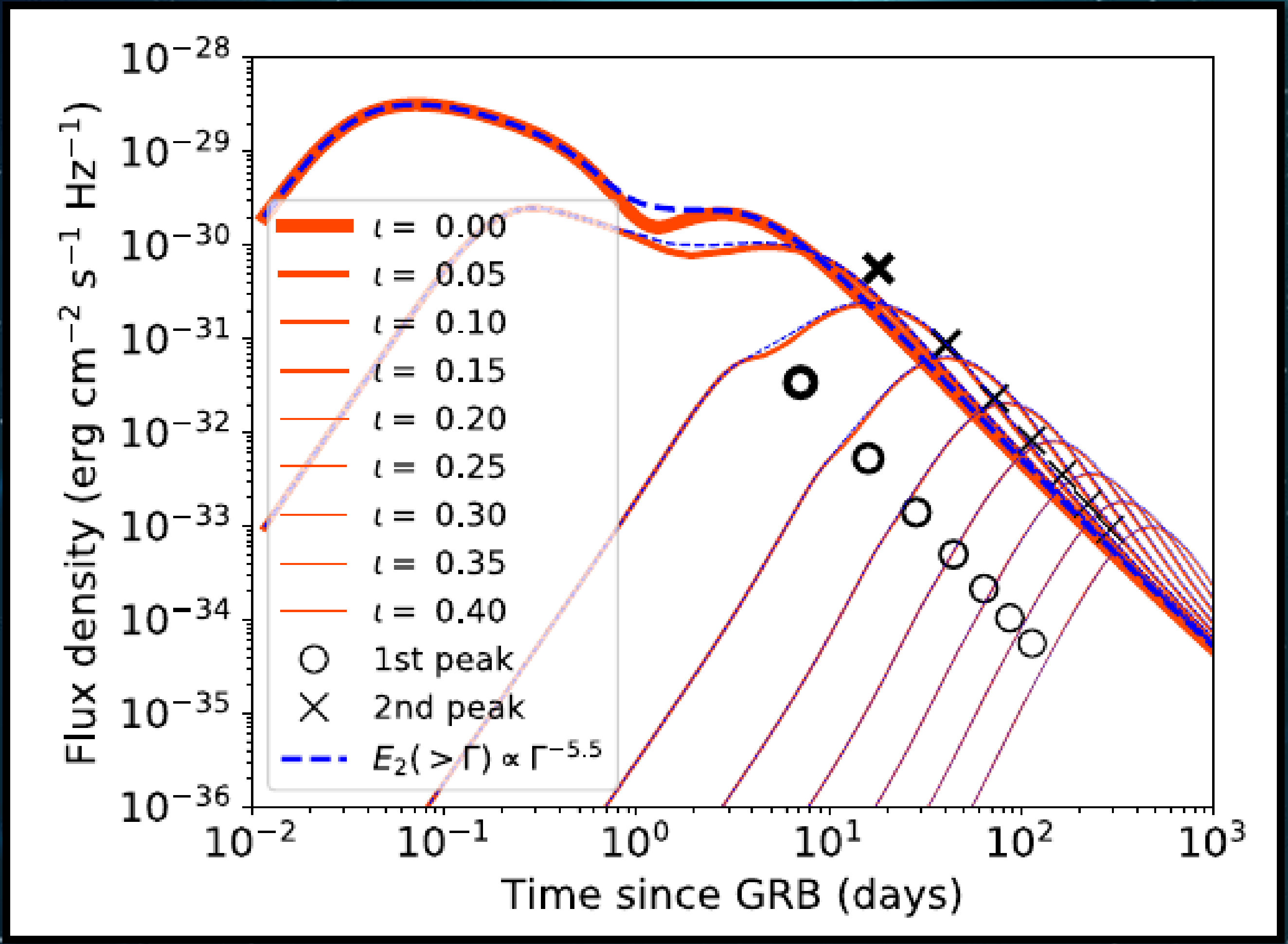
Fernandez, **Lamb** & Kobayashi (in prep)

On-axis analogues – GRB 160821B



Lamb et al. 2019b

This isn't a structured jet!? But how would it look off-axis?

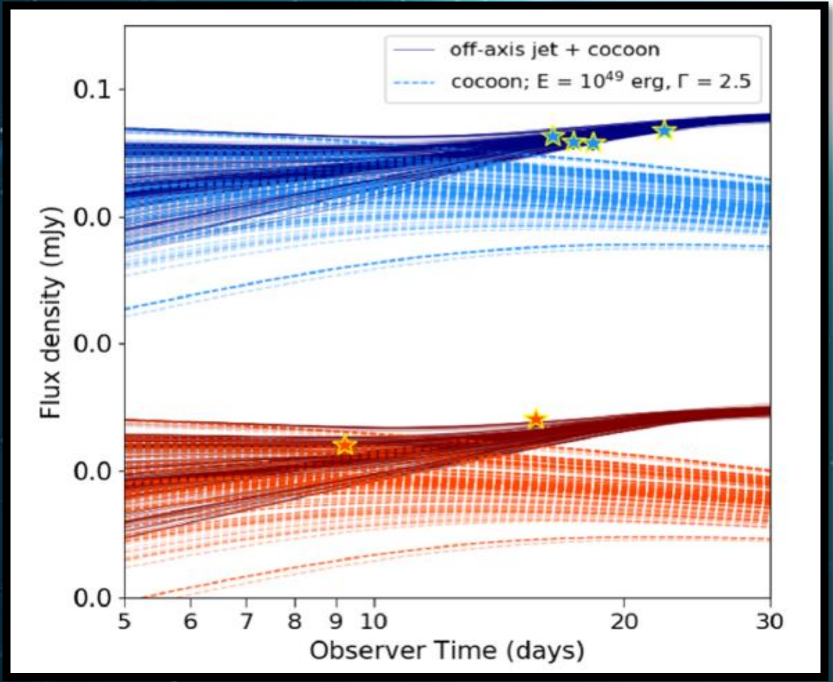


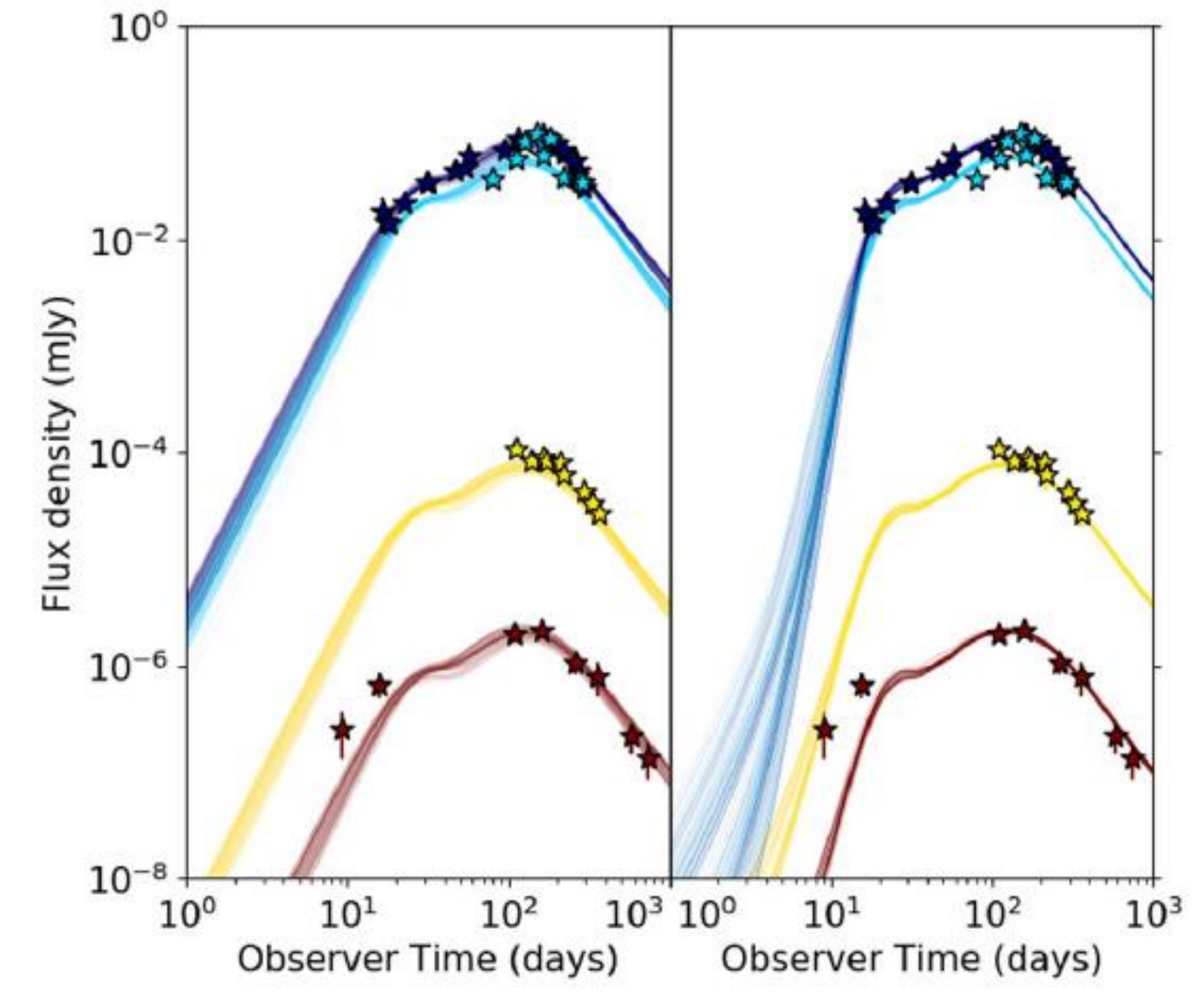
- Using the GRB 160821B parameters
- Two refreshed shock models
- We produce lightcurves for increasing inclinations
- Note that the more energetic, but fainter on-axis refreshed episode, begins to dominate the emission for off-axis observers
- At approximately 3 times the jet opening angle, the afterglow has a shallow incline to peak (analogous to GRB 170817A)

Lamb, Levan & Tanvir 2020

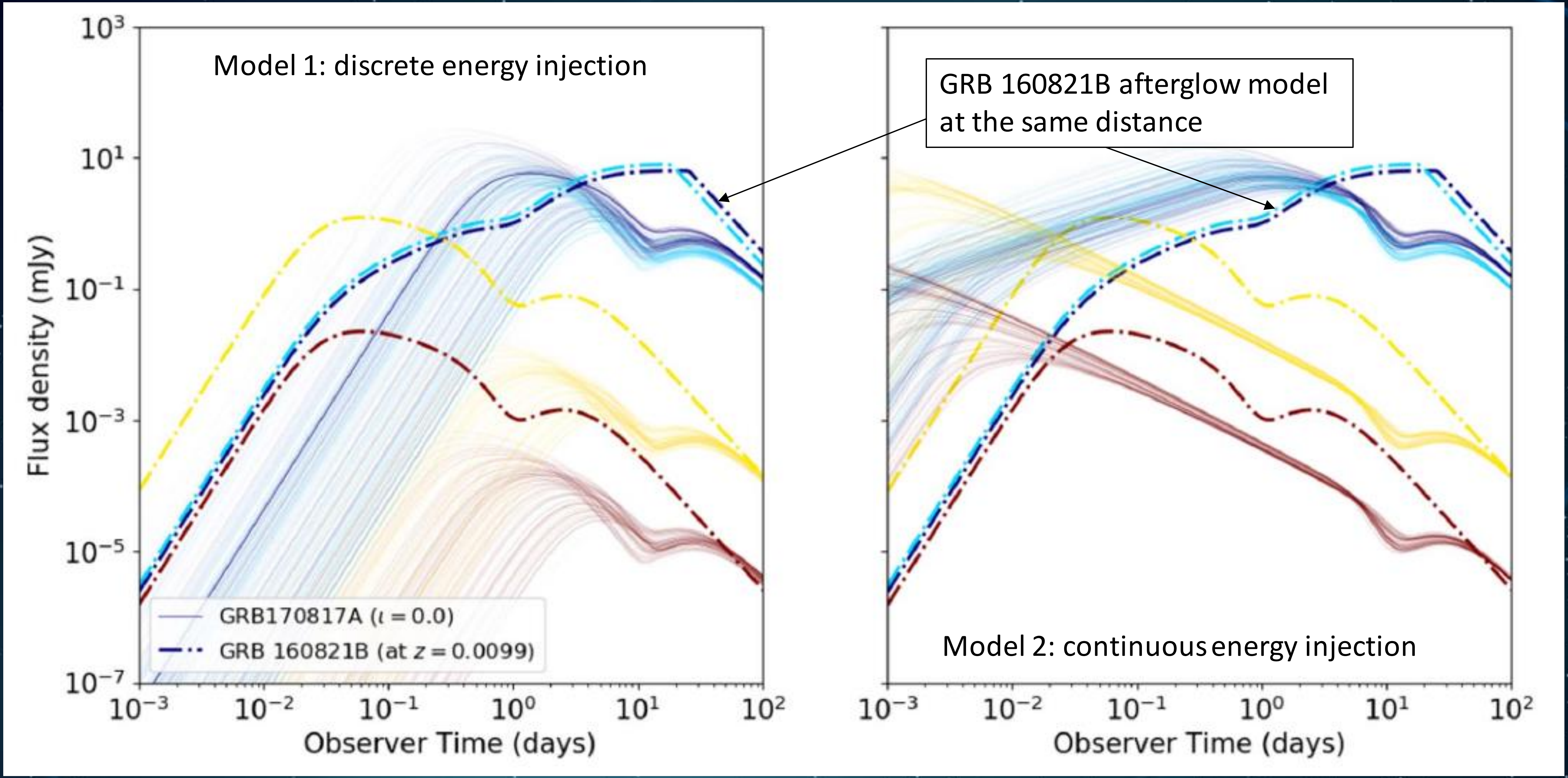
A refreshed shock model fit to GRB 170817A data

- The two refreshd shock models fit to the data
- Early X-ray data is missed but these can be explained by inclusion of a cocoon associated with the jet's passage through the ejecta (see below)
- On-axis, these afterglows appear similar





Lamb, Levan & Tanvir 2020

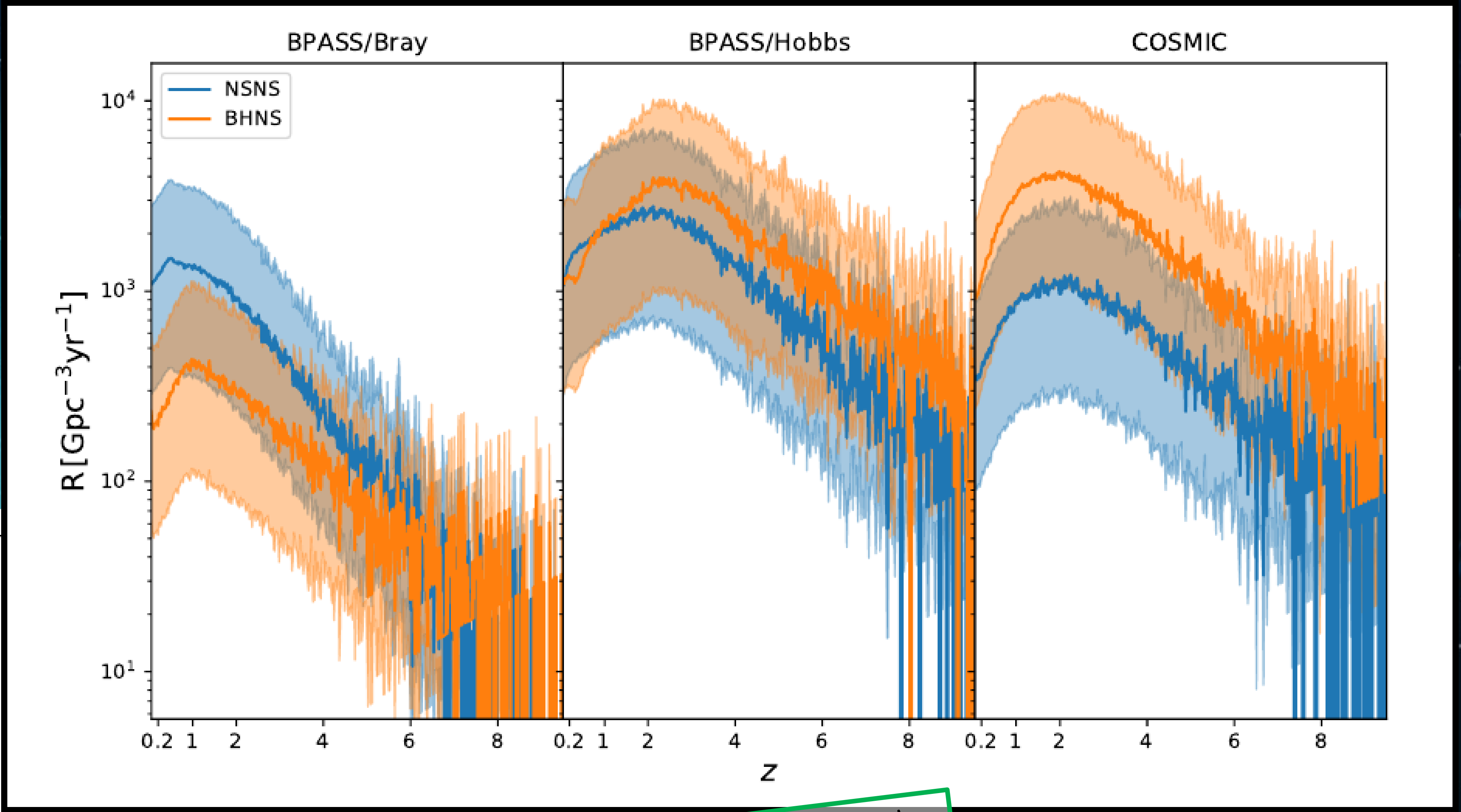


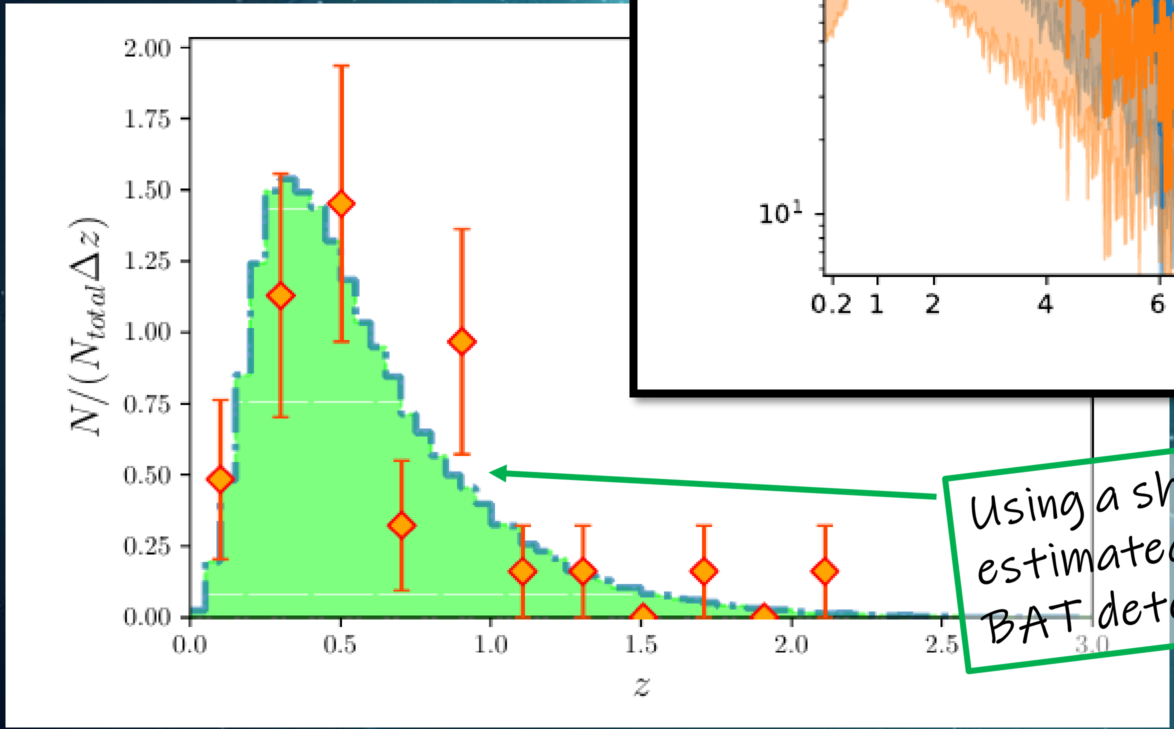
Lamb, Levan & Tanvir 2020

Summary

- Gravitational wave detected neutron star mergers give an opportunity to observe short GRB afterglows 'off-axis'
- This can reveal the jet structure
- Caution that refreshed shocks can produce the same effect, and are observed for 'on-axis' events
- Understanding the structure/dynamics of short GRB afterglows will enable their better use with GWs as cosmology probes, H_0
- No evidence for 'nearby' short GRBs in the GRB data archive – BATSE rate for <100 Mpc is consistent with zero

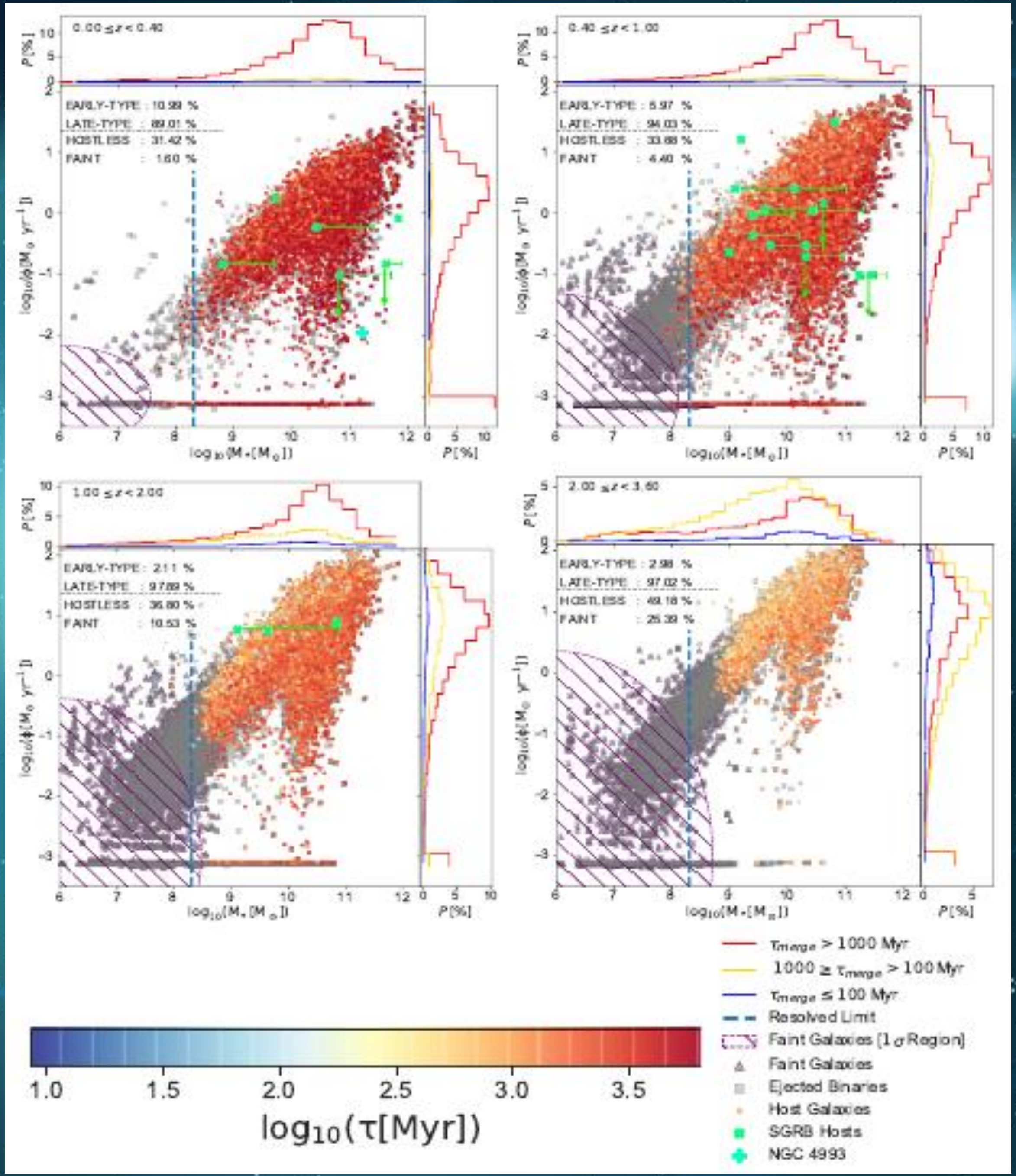
Compact binary merger rates



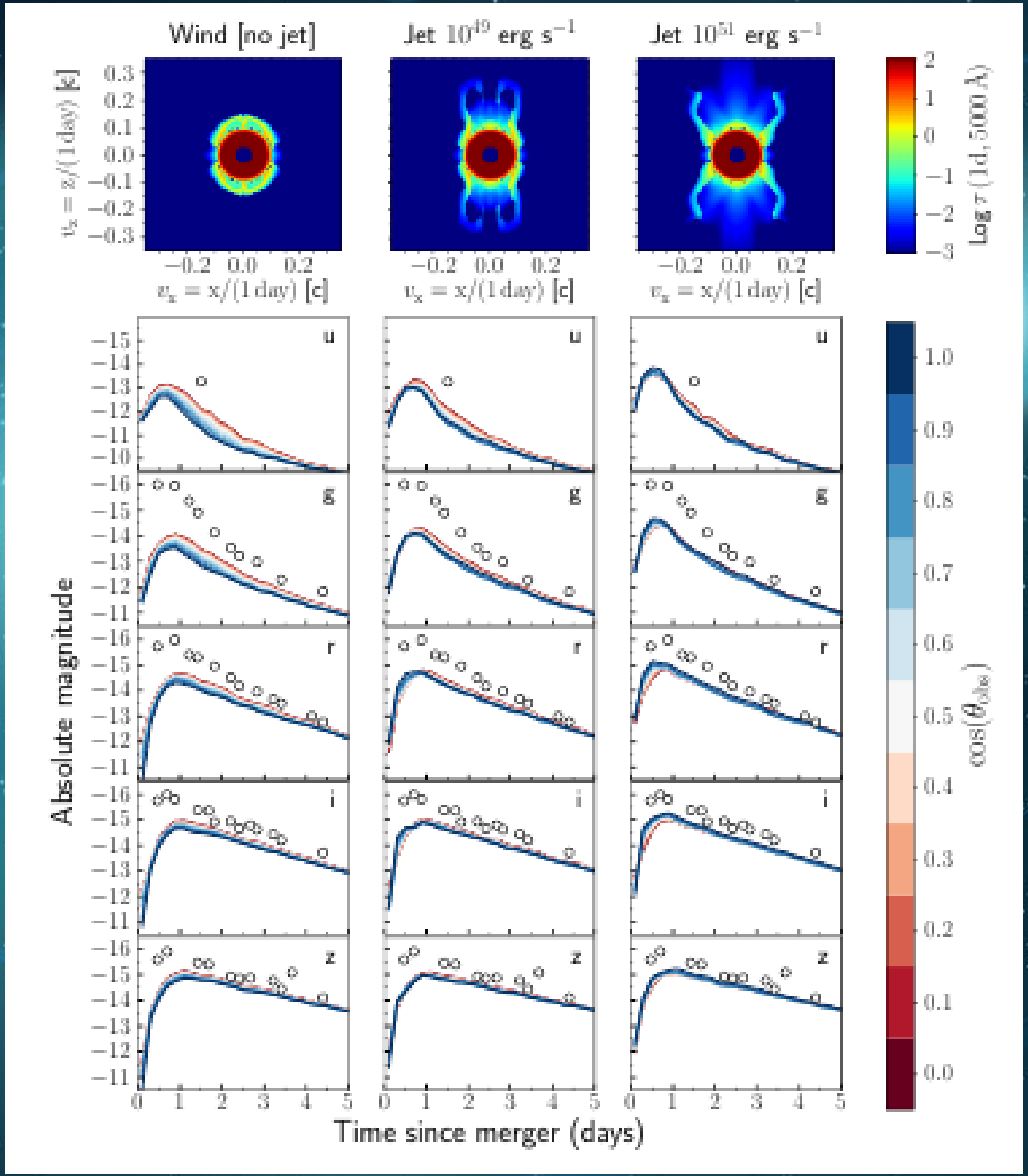


Using a short GRB luminosity function, the estimated redshift distribution for Swift BAT detectable SGRBs

Mandhai, **Lamb**, Tanvir, Bray & Nixon (in prep)



Mandhai, **Lamb**, Tanvir, Bray & Nixon (in prep)



Lorenzo et al. 2020

Two populations of GRBs

Two populations of GRBs

Short GRBs: T90 < 2s
Long GRBs: T90 > 2s

These two populations are distinct – not only in duration, but also in spectra

T90 is the timescale in which 5-95% of the gamma-ray energy arrived at the detector!