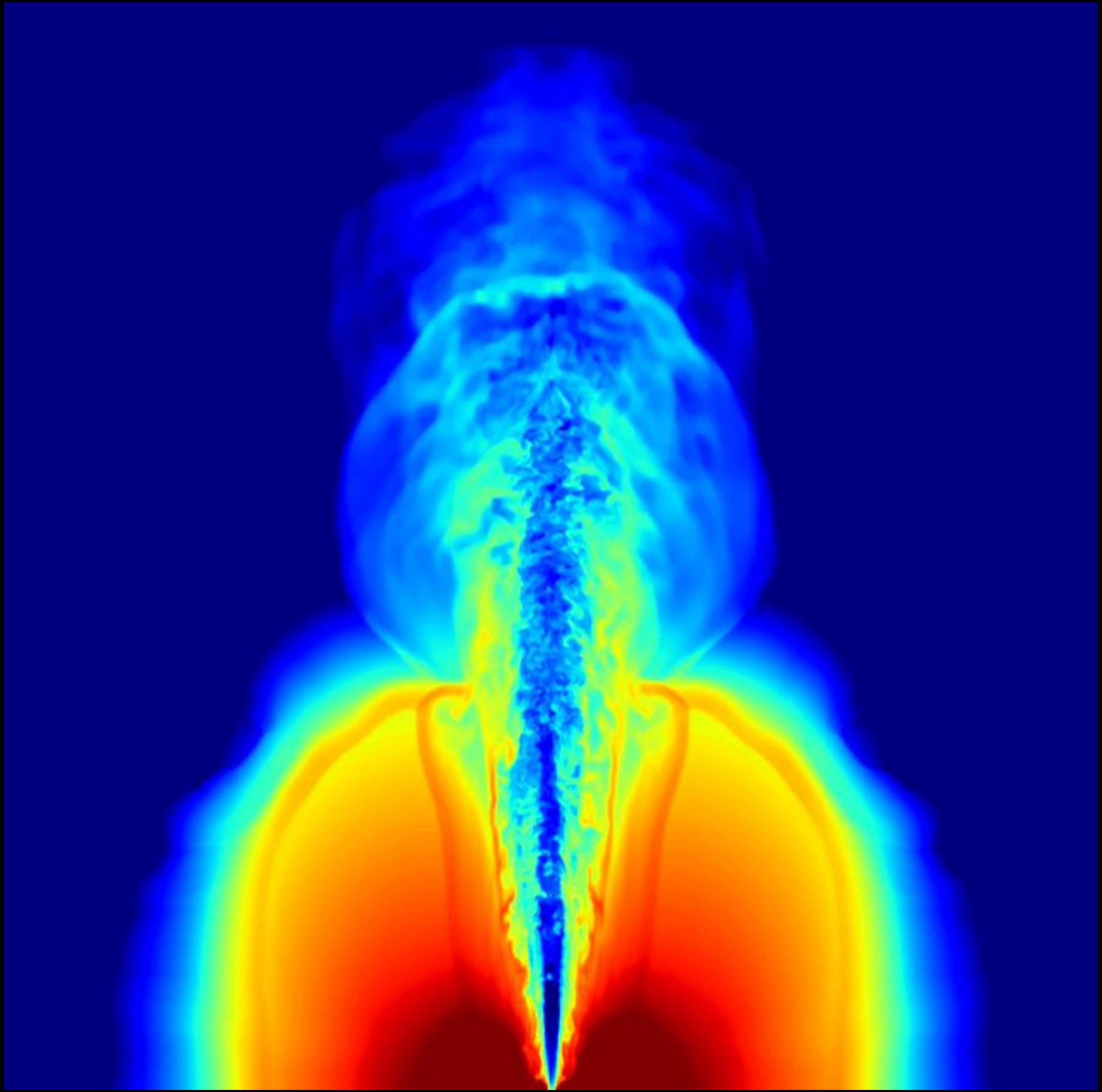


2D sliced snapshot from a 3D hydrodynamic simulation of a relativistic jet propagating through a neutrino driven wind and ejecta following a neutron star merger (credit Lorenzo Nativi)

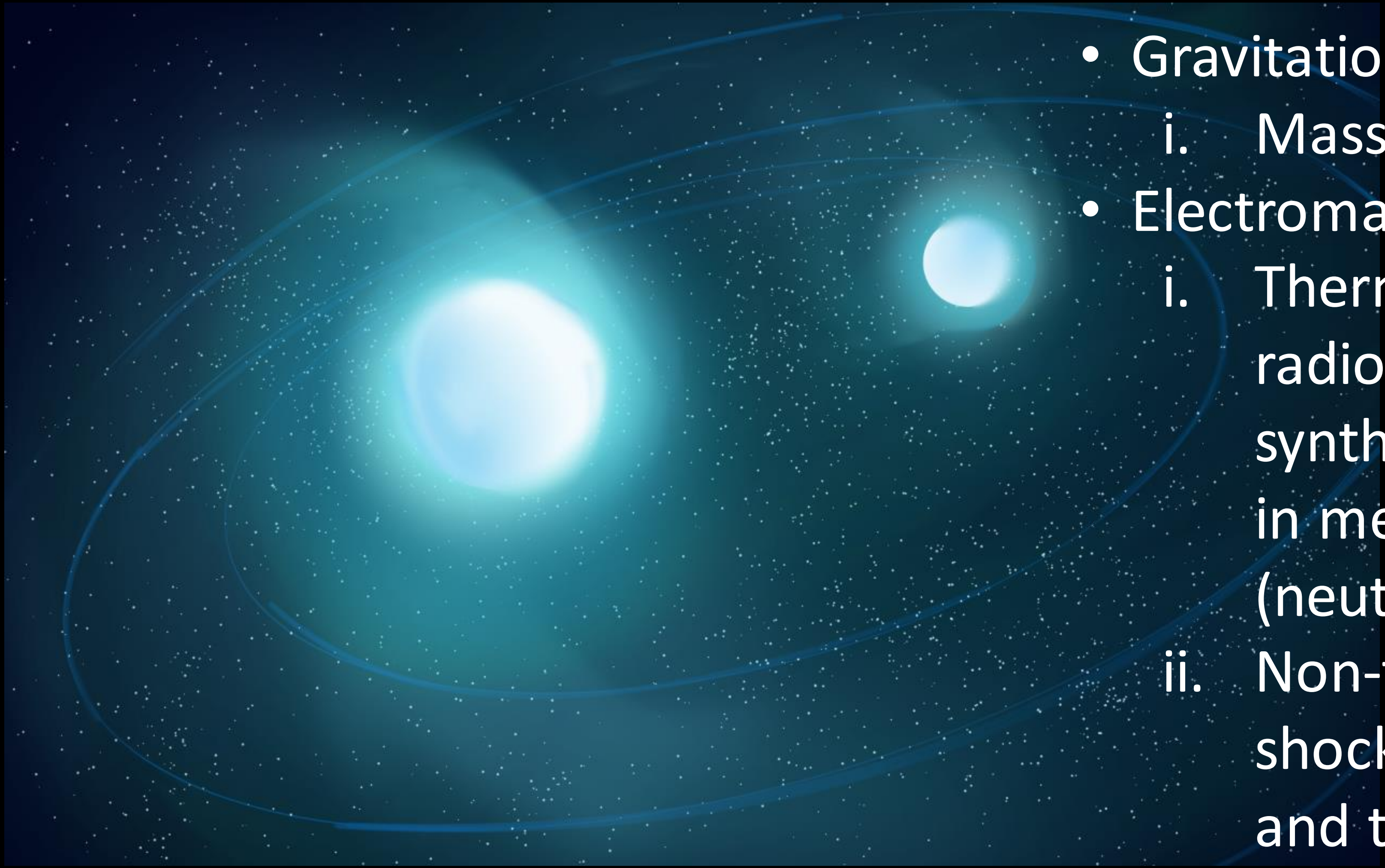
The Structure of Relativistic Jets from Neutron Star Mergers

Gavin P Lamb

UNIVERSITY OF LEICESTER

HEPP & APP Annual Conference, 5th April 2022

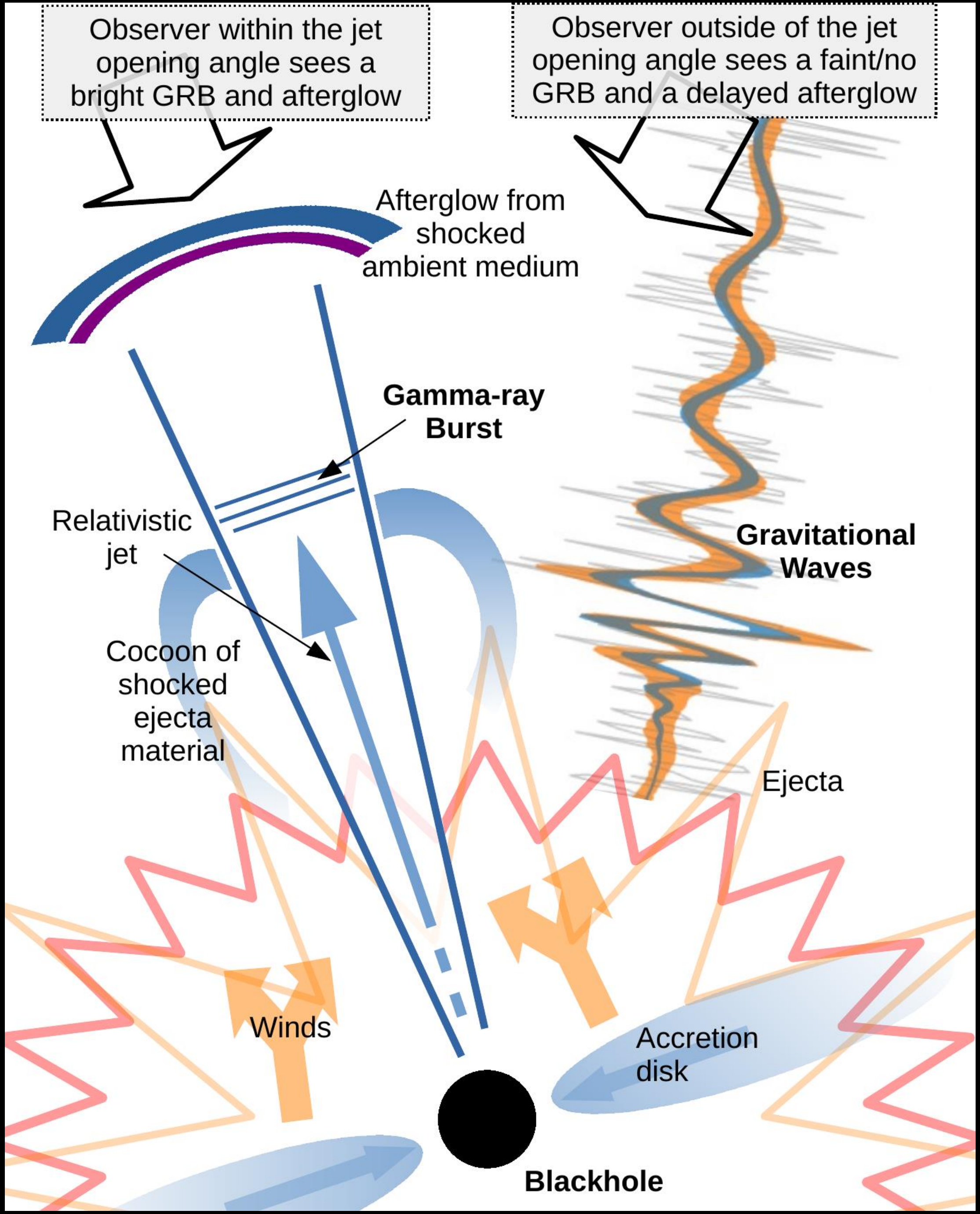
Neutron star mergers – gravitational and electromagnetic waves...



- Gravitational waves:
  i. Mass quadrupole
- Electromagnetic waves:
  i. Thermal emission from the radioactive decay of rapidly synthesised heavy elements in merger ejecta (neutrons!) – kilonova
  ii. Non-thermal emission from shocks – gamma-ray bursts and their afterglows

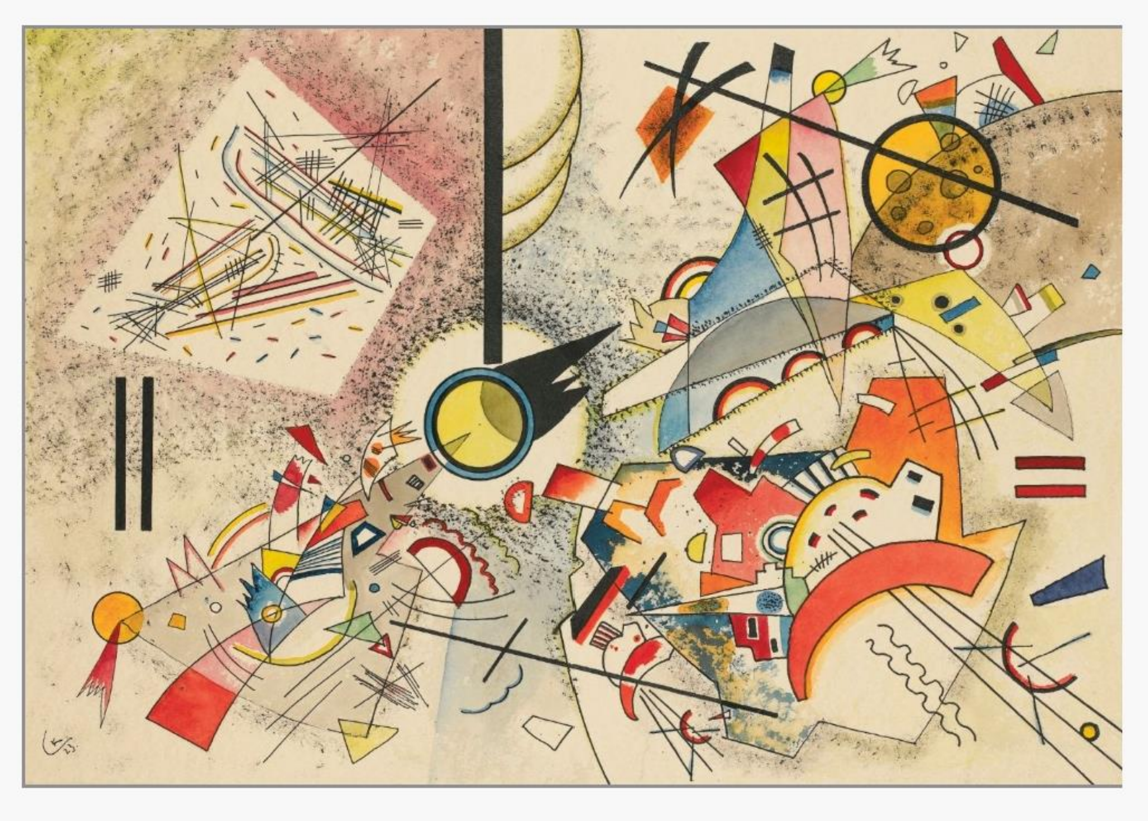
Image credit: Soheb Mandhai

A cartoon illustration...



Lamb, cartoon, 2021 – various fellowship cases and job application statements

I think this makes these systems easier to understand!? But it was recently pointed out to me* that all these cartoons look like we're making a poor man's Kandinsky!



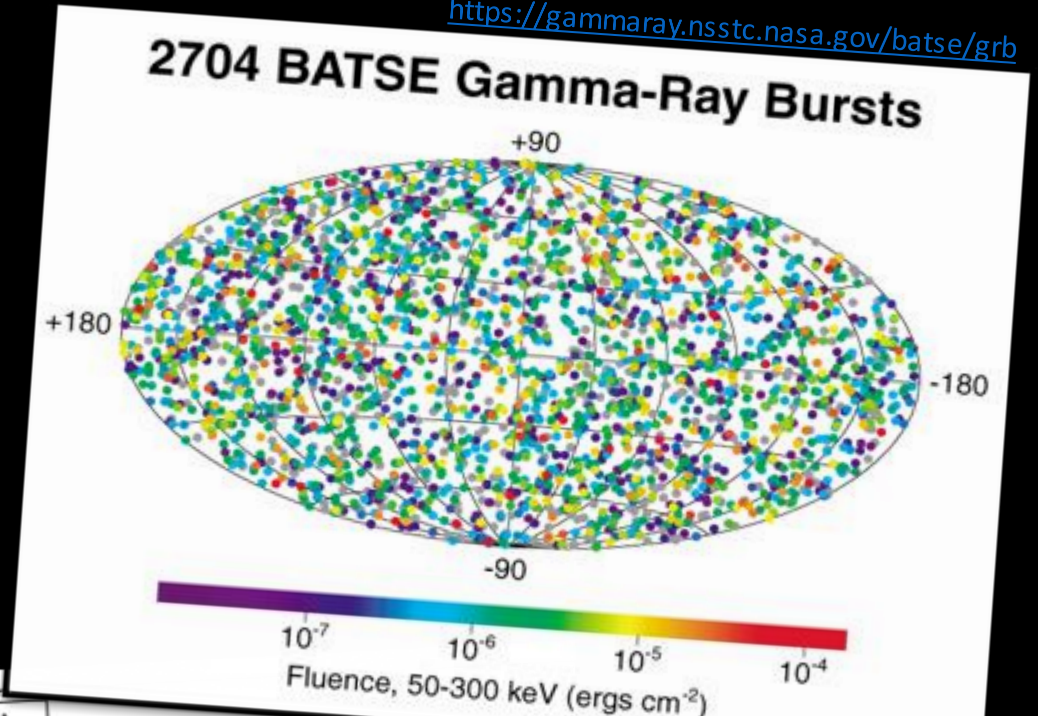
Kandinsky, No Title, 1923 – Guggenheim museum

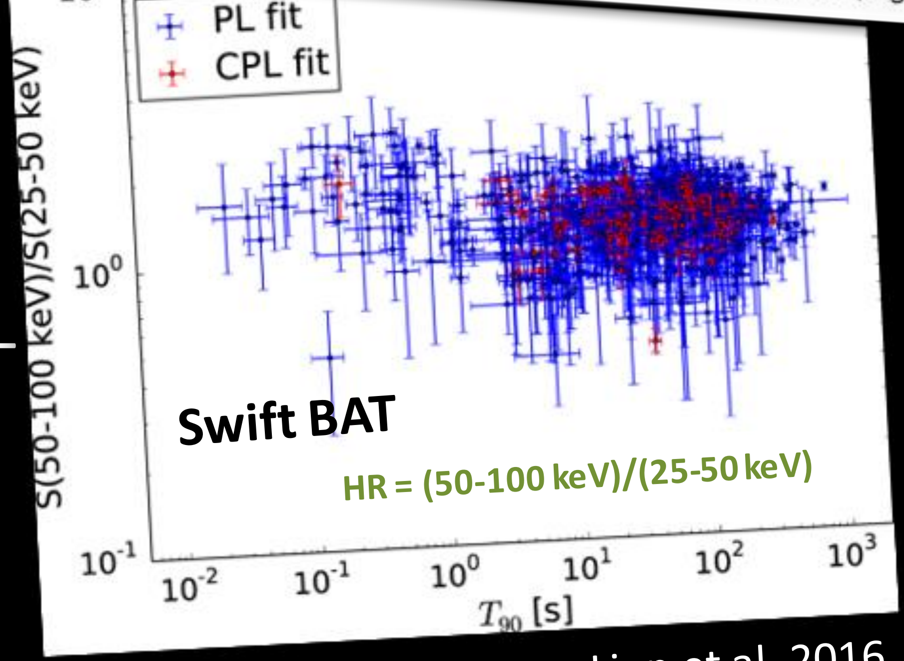
*Frederick Daigne, seminar at Leicester, 23/03/2022

Gamma Ray Bursts – what are they?

- First detected serendipitously in the 1960s
- Highly variable, transient flashes of high energy photons
- BATSE in the 1990s showed GRBs to be extragalactic and hugely energetic!
- Two distinct groupings in duration and spectral hardness - long GRBs (>2s) and **short GRBs** (<2s)

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



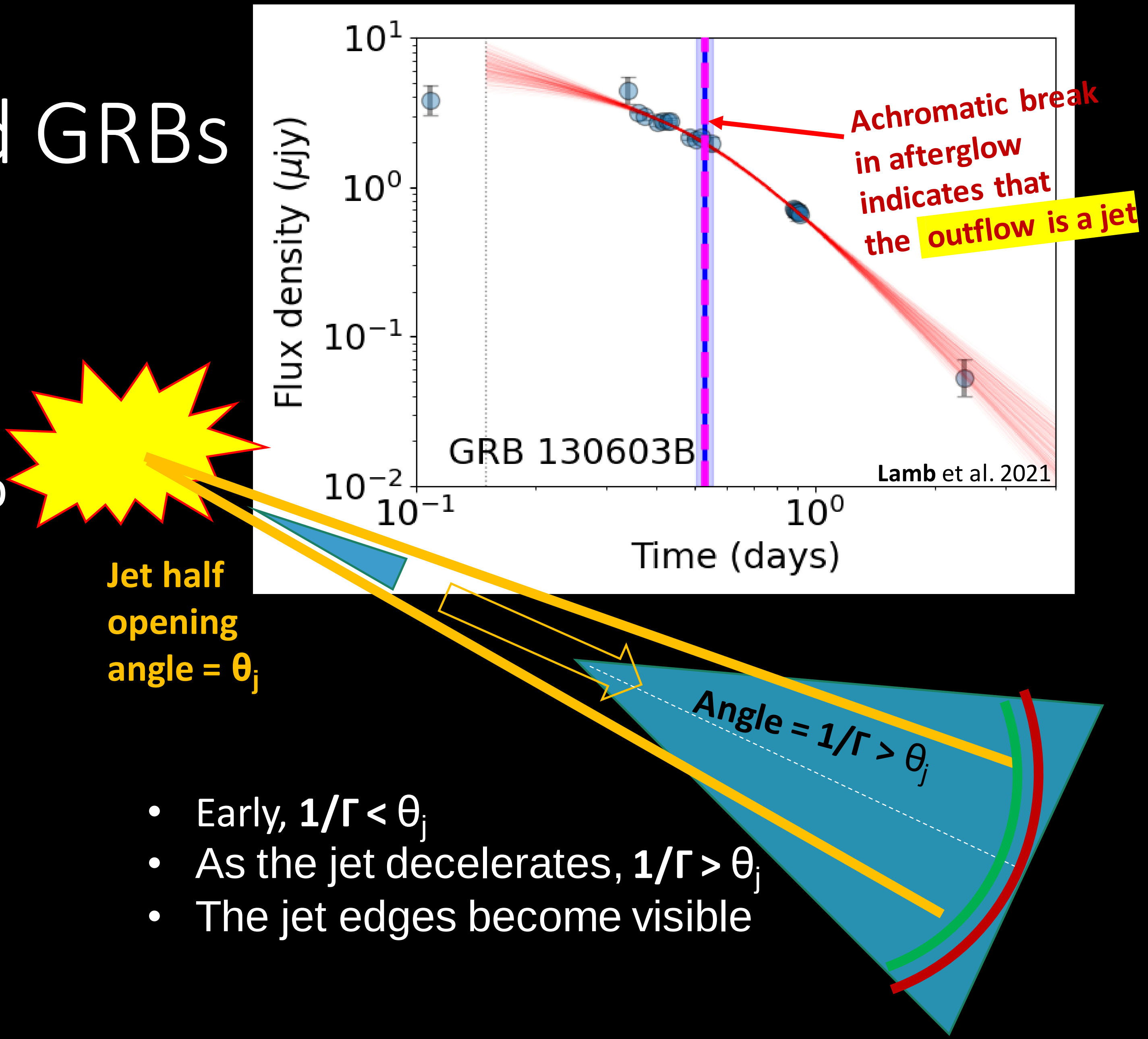


Lien et al. 2016

How we understand GRBs

Highly energetic and jetted relativistic explosions!!!

- As the jet expands it sweeps up matter, like a snow plough
- A shock system forms as the jet decelerates – leading to a forward **and** reverse **shock** system
- **Broadband afterglow** via synchrotron radiation from the decelerating shock system



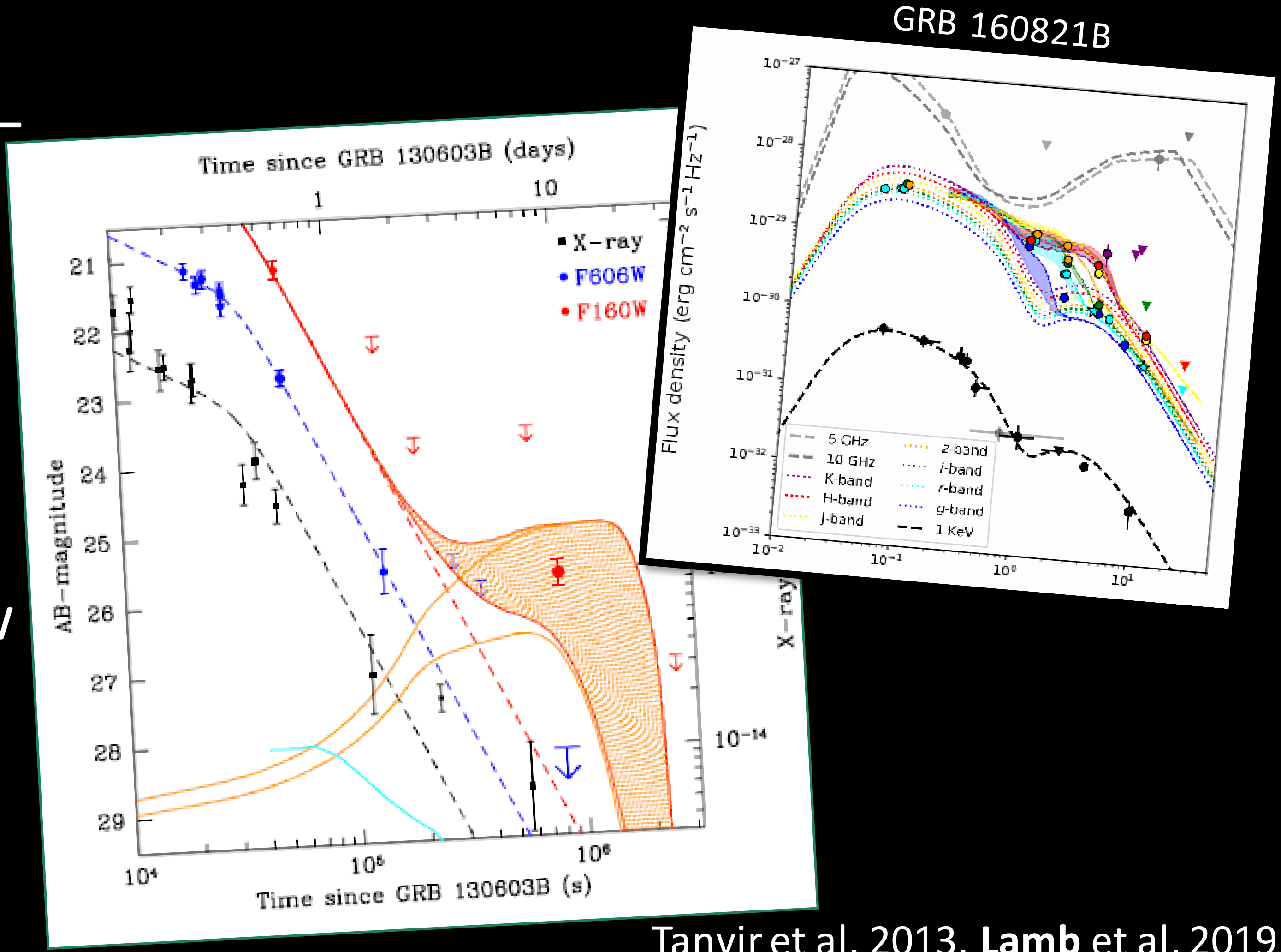
Achromatic break in afterglow indicates that the outflow is a jet

Jet half opening angle = θ_j

- Early, $\mathbf{1/\Gamma < \theta_j}$
- As the jet decelerates, $\mathbf{1/\Gamma > \theta_j}$
- The jet edges become visible

Short GRBs and Neutron Star Mergers

- The population of short GRBs has diverse host galaxy types – not just star-forming galaxies (like long GRBs)
- No supernovae in the afterglows
- Some have evidence for kilonovae within the afterglow – currently ~eleven candidate kilonovae in GRB afterglows



Tanvir et al. 2013, **Lamb** et al. 2019

Gamma-Ray vs Gravitational Wave detected Mergers

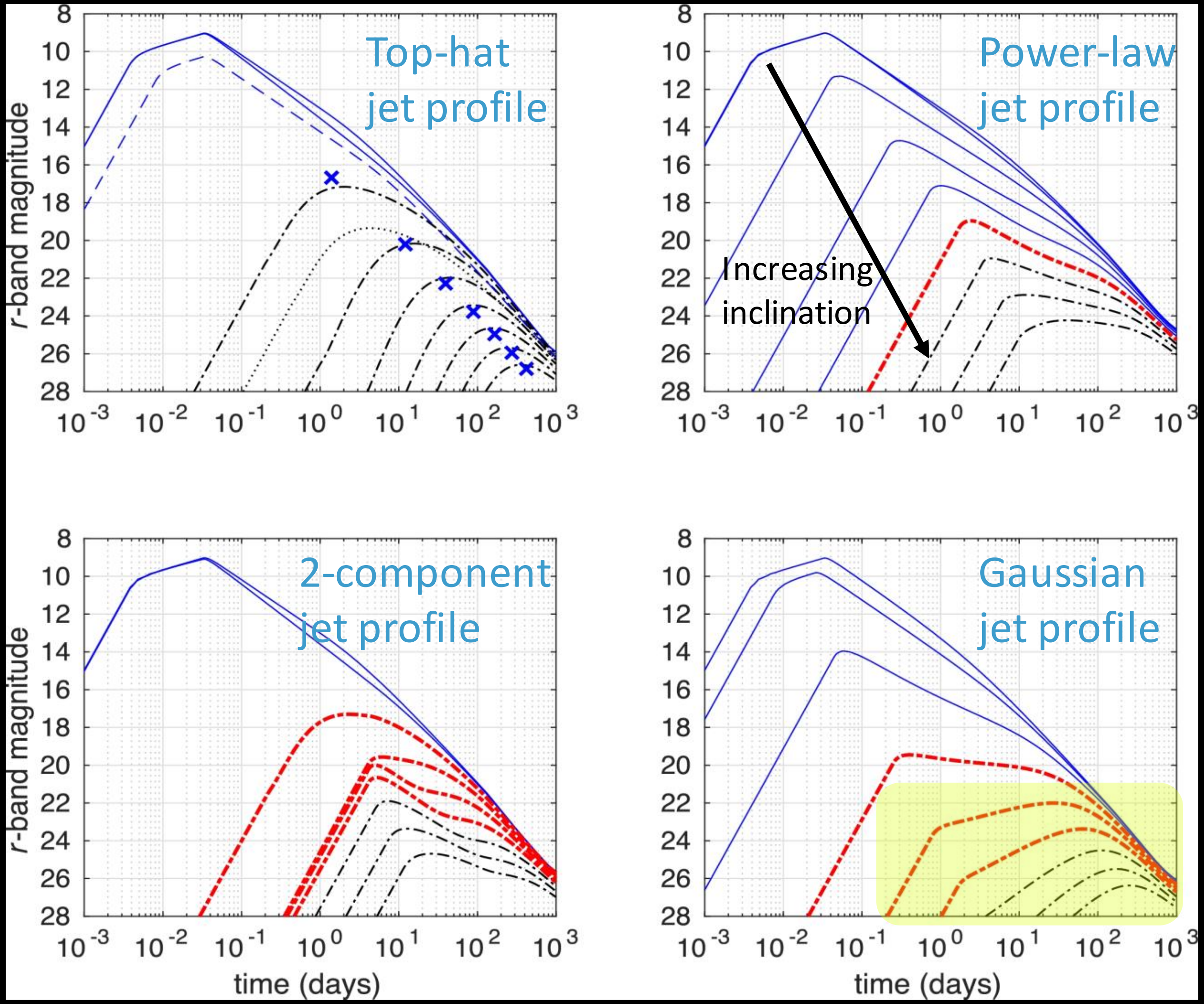
Gamma-ray selected:

- Viewed at small inclination from the jet central axis
- High energy GRB
- Large distance, >100s Mpc
- Rapid afterglow peak and decline, <10 days
- Kilonova buried within afterglow emission

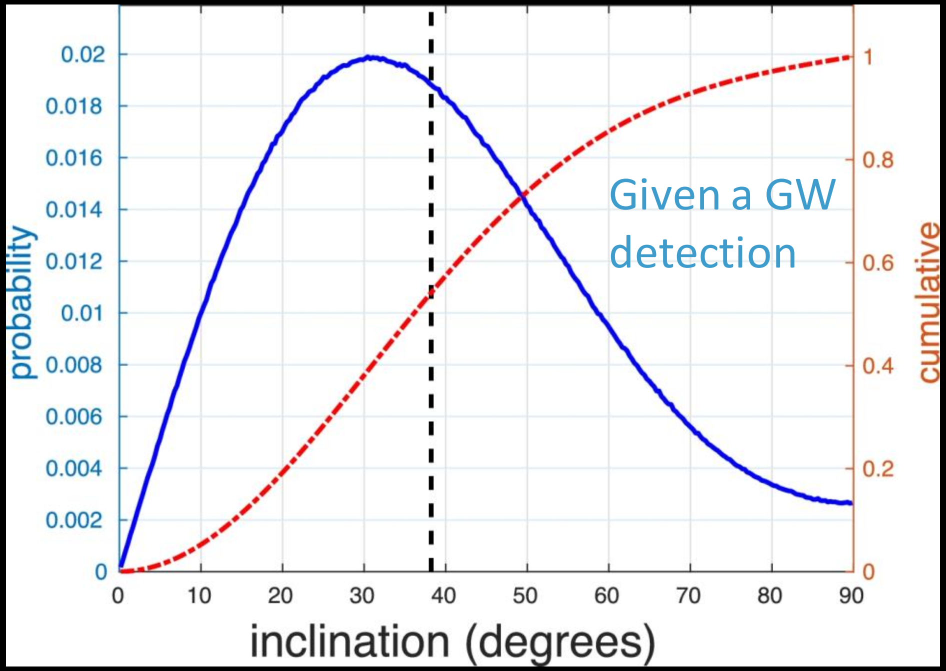
Gravitational wave selected:

- Viewed from higher inclination from the jet central axis
- No or low-luminosity GRB
- Small distance, <300 Mpc
- Delayed afterglow peak, ~100 days to peak
- Kilonova will typically precede afterglow emission

Gravitational Wave Electromagnetic Counterparts from the Jet – Geometry Matters

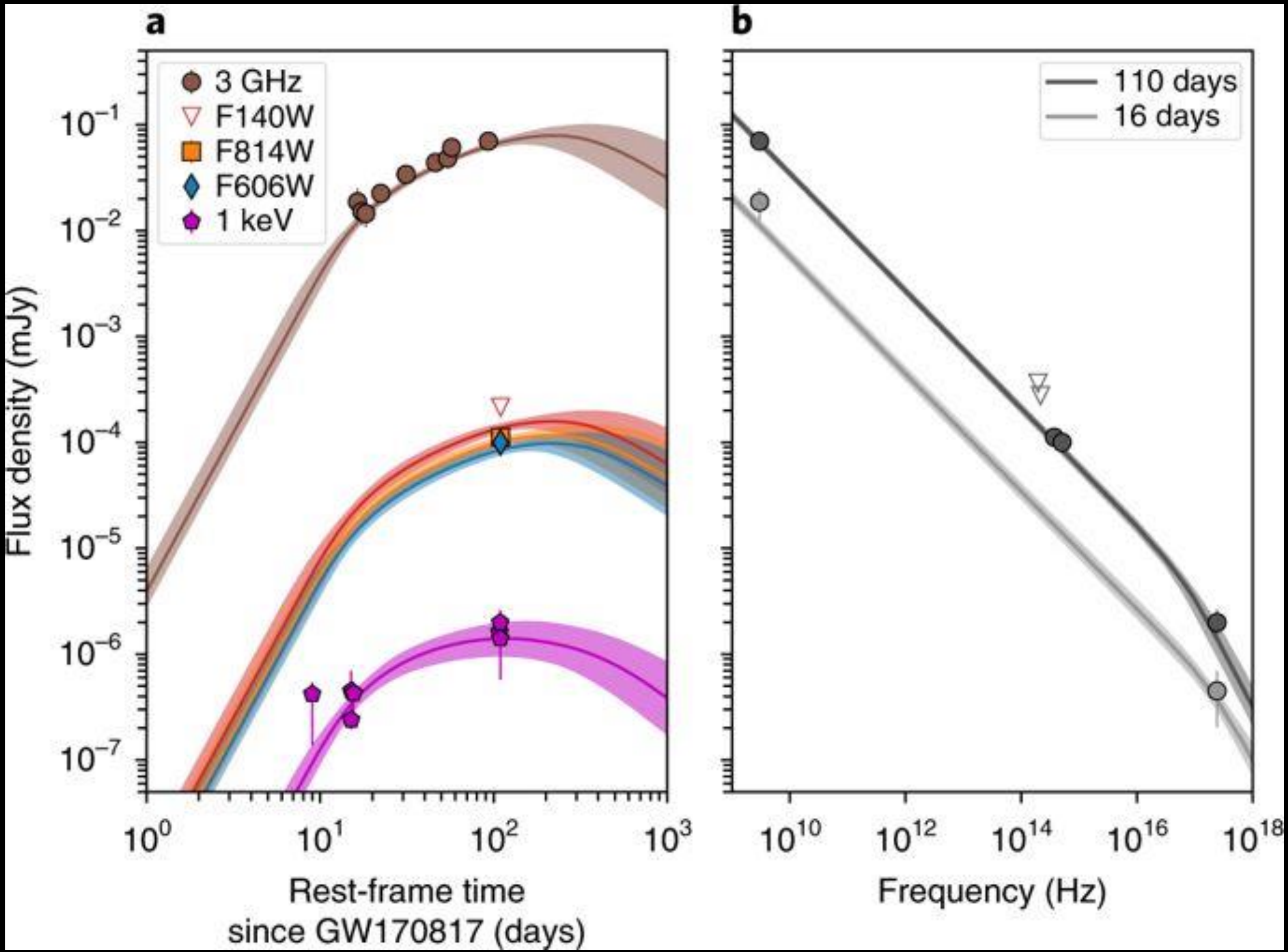


- Typically at ~30 degrees
- No bright GRB(!?)
- Lightcurve reveals jet structure

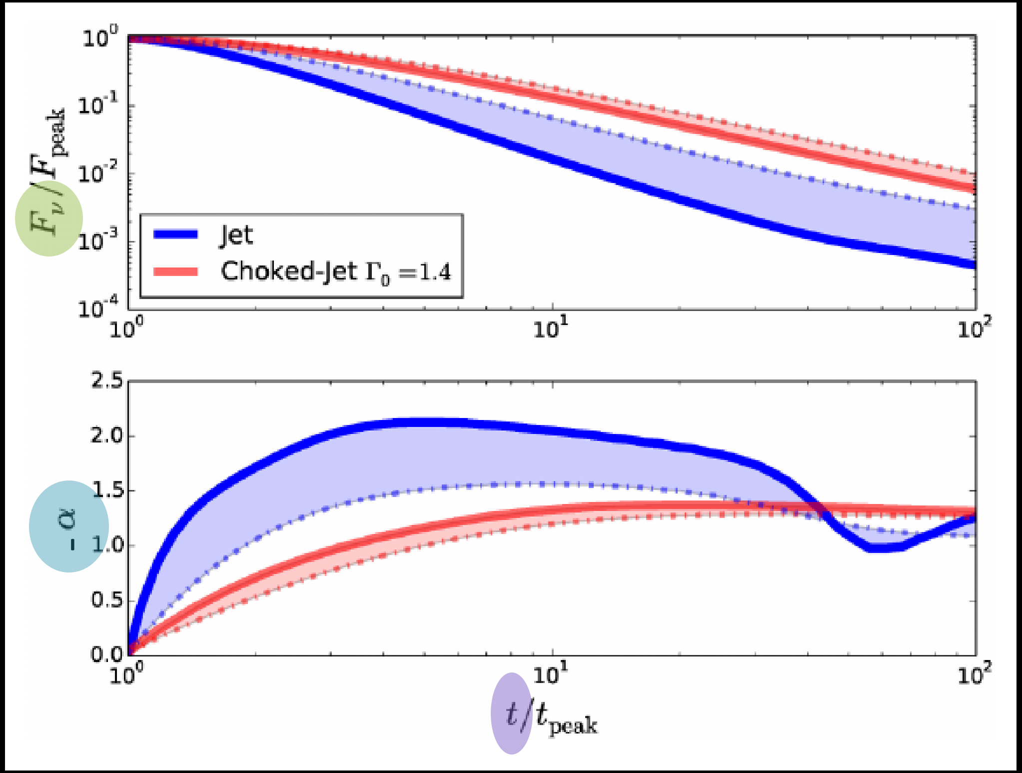


Lamb & Kobayashi 2017

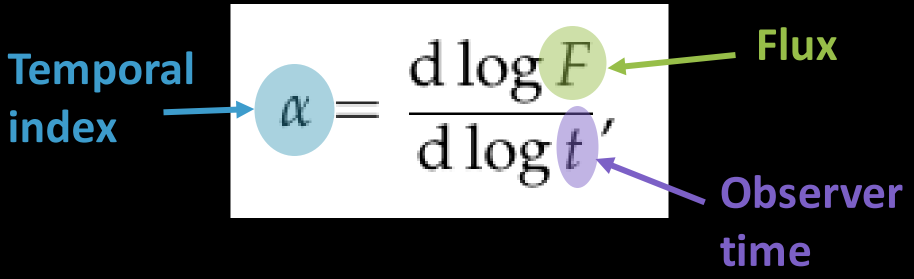
GW170817 – a binary neutron star merger



Lyman, **Lamb** et al. 2018



Lamb, Mandel & Resmi 2018



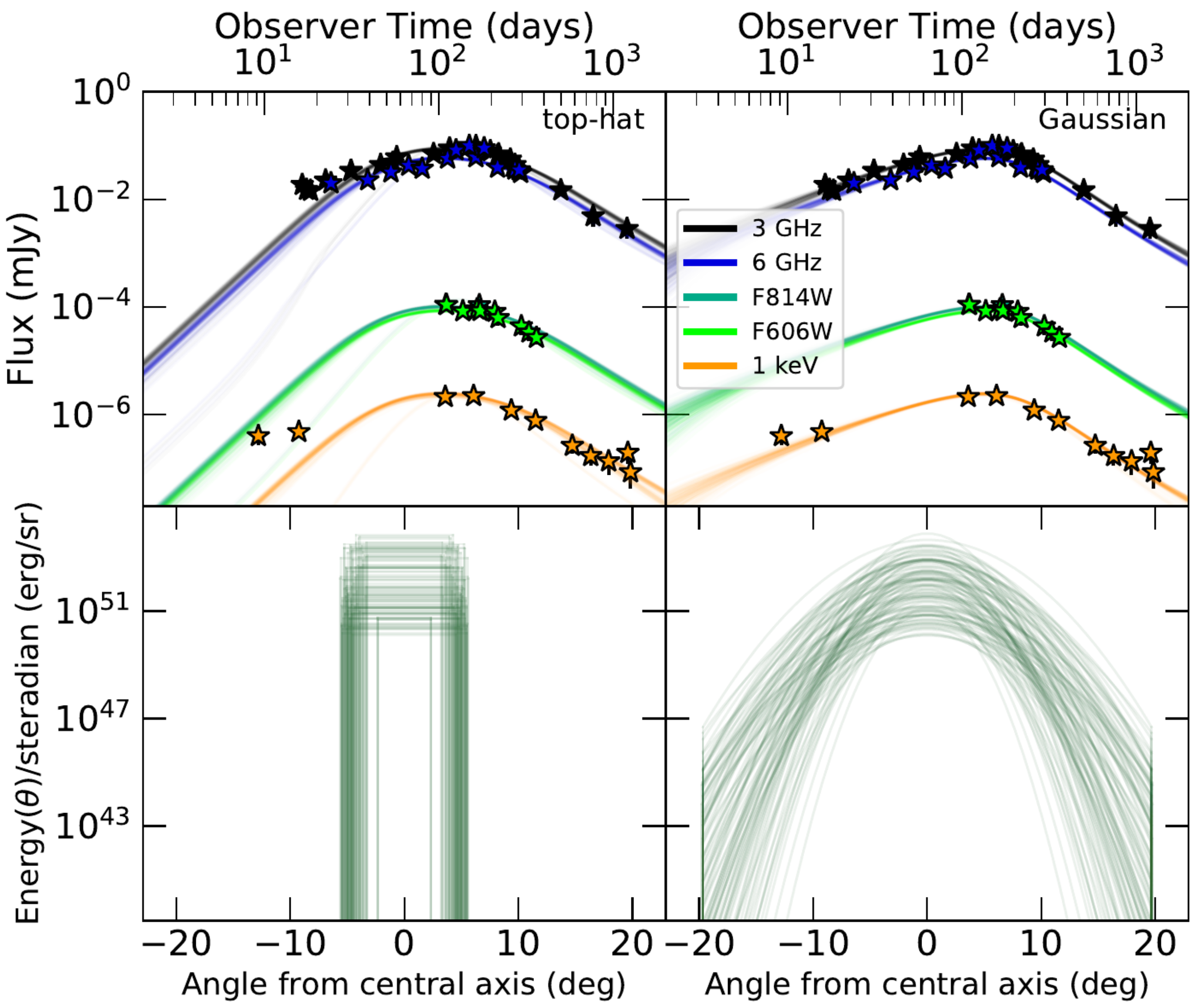
Temporal index

$$\alpha = \frac{d \log F}{d \log t'}$$

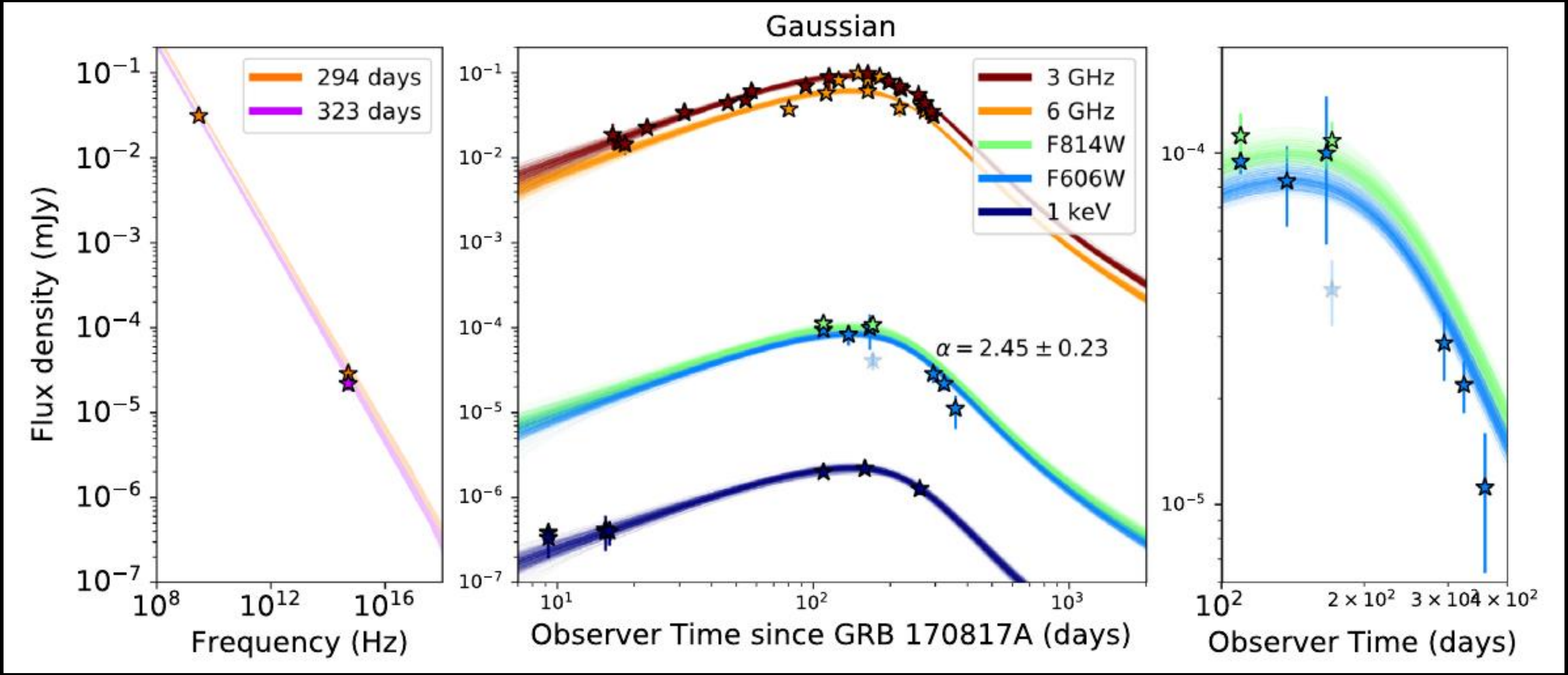
Flux

Observer time

See also: Xie ea 2018, Resmi ea 2018, Troja ea 2018, Margutti ea 2018, Lazzati ea 2018, Granot ea 2018, etc.

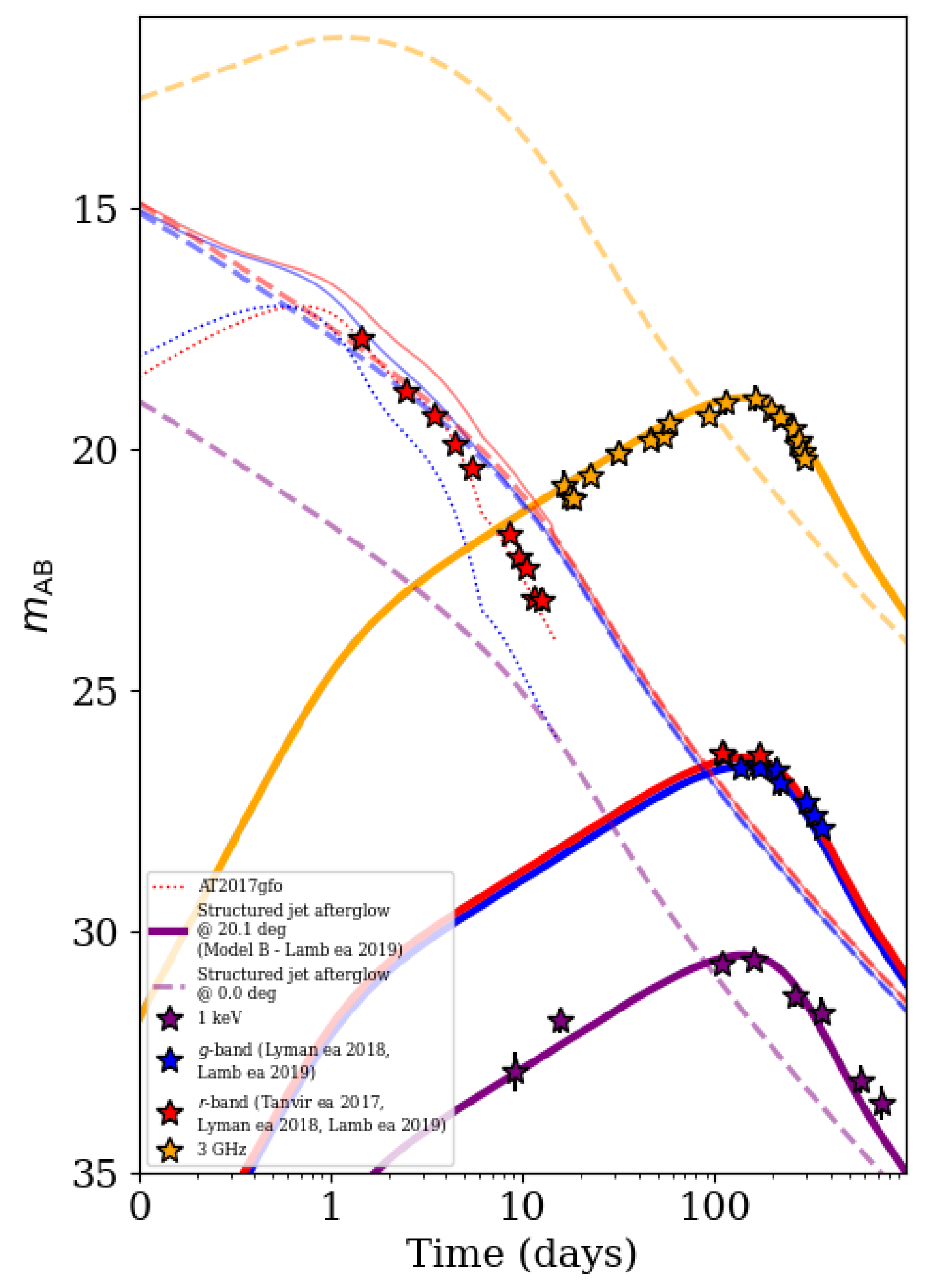

Observer Time (days)
10^1
10^2
10^3
Observer Time (days)
10^1
10^2
10^3
top-hat
Gaussian
Flux (mJy)
10^0
10^{-2}
10^{-4}
10^{-6}
3 GHz
6 GHz
F814W
F606W
1 keV
Energy(θ)/steradian (erg/sr)
10^{51}
10^{47}
10^{43}
−20
−10
0
10
20
Angle from central axis (deg)
−20
−10
0
10
20
Angle from central axis (deg)

GW170817 – a successful, and ultra-relativistic jet



Lamb, Lyman et al. 2019

See also: Troja ea 2019-2022, Dobie ea 2019, Ghirlanda ea 2019, Balasubramanian ea 2021, etc.



GRB 170817A and AT2017gfo – off- vs on-axis

- Model afterglow at **~20 degrees** off-axis – thick solid lines
- Kilonova – dotted lines
- The same model afterglow, but viewed at 0 degrees, on-axis – dashed lines

Off-axis, kilonova and afterglow are clearly separated. The shape of the afterglow indicates some lateral jet structure. On-axis, kilonova is buried in the afterglow emission. No obvious evidence for jet structure.

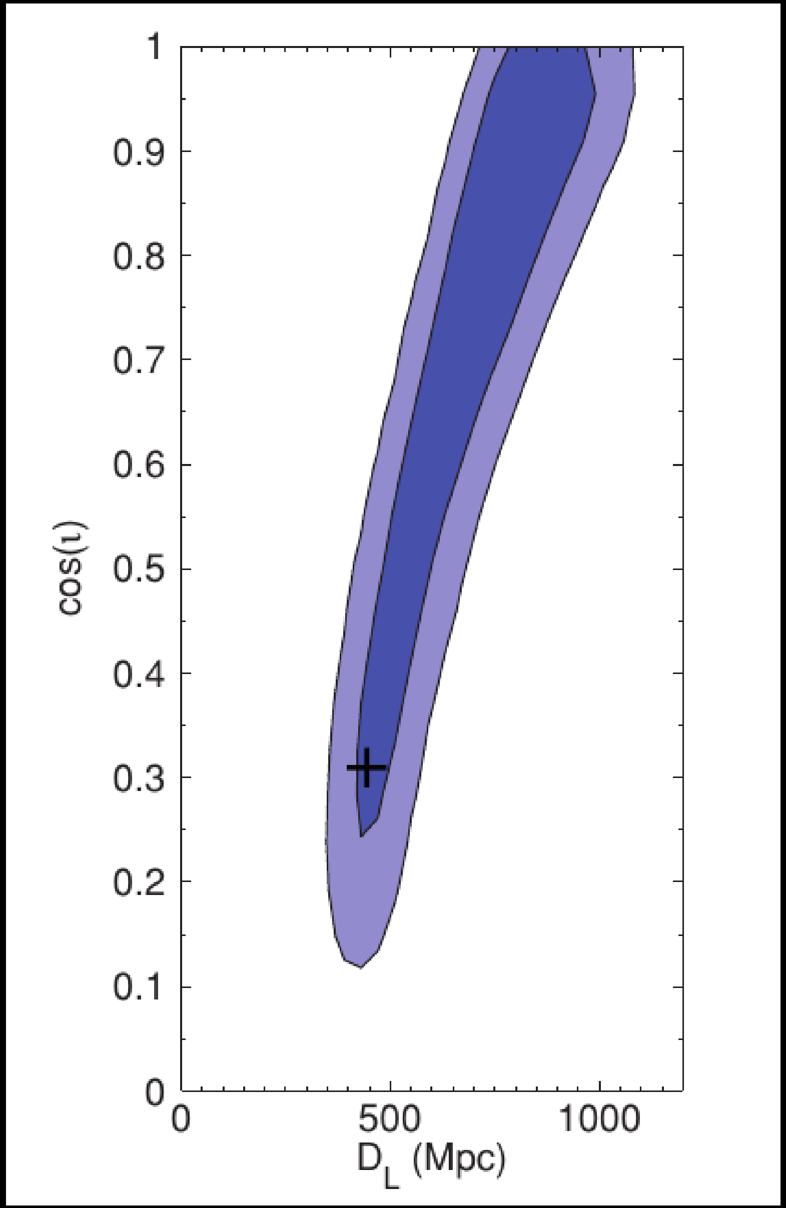
What can we do with GW-EM?

Other than the structure and diversity of relativistic jets:

- Cosmology
- DL(GW) vs z(GRB... well, host galaxy)
- DL(GW) proportional to the inclination – most of the uncertainty in GW distance estimates comes from this degeneracy

$$h_\times \propto 2\cos i \qquad h_+ \propto 1+\cos^2 i$$

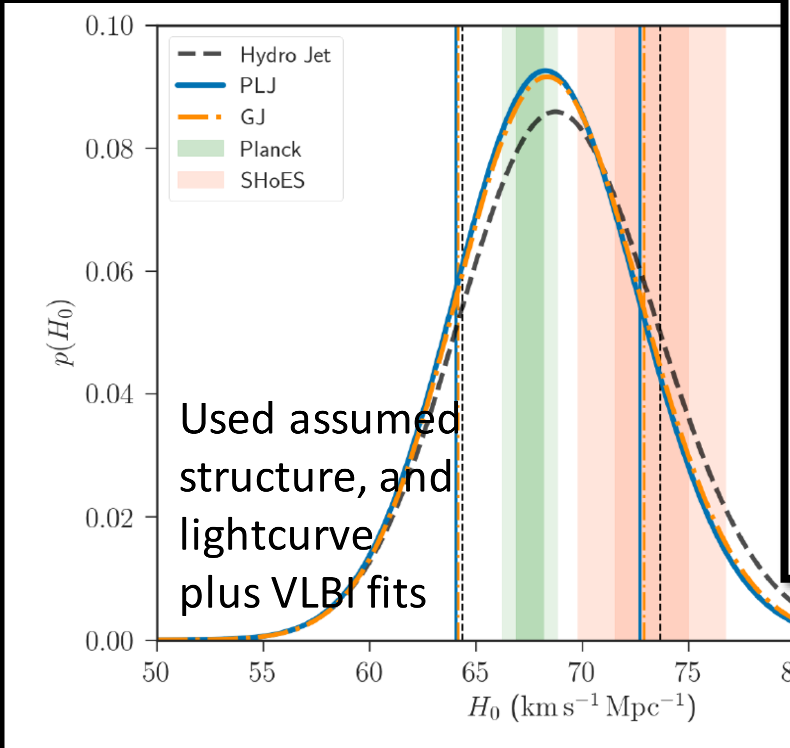
- Afterglow modelling can give the inclination – but with some cautionary tales



Nissanke et al. 2010

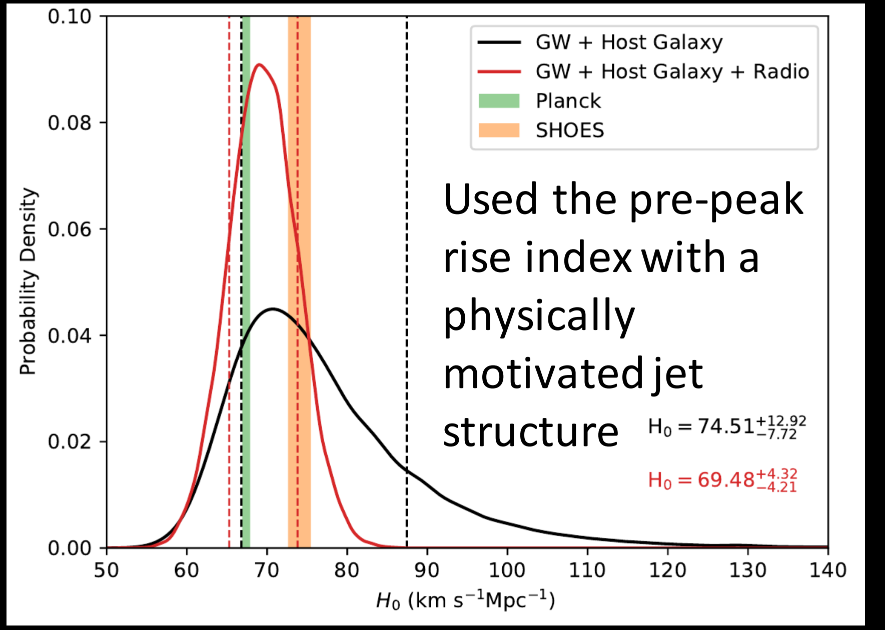
Inclination estimates, and use to estimate H_0

- Inclination from modelling – quite a broad range!



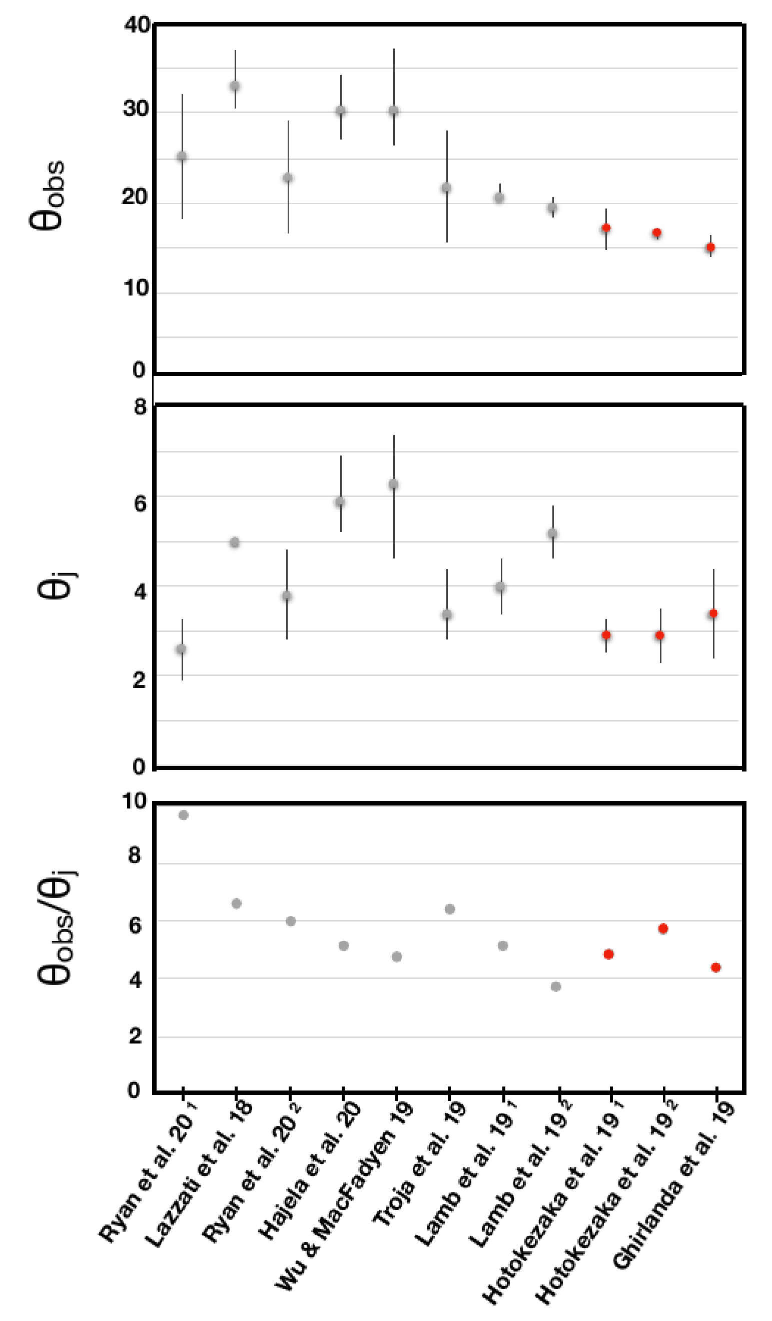
Used assumed structure, and lightcurve plus VLBI fits

Hotokezaka et al. 2019, H_0 = 68.9 +/-4.7



Used the pre-peak rise index with a physically motivated jet structure

Wang & Giannios 2021,
H_0 = 69.5 +/-4.3
θ_{obs} = 21.8 +/- 1.1 deg



Nakar & Piran 2021

The problem with afterglow modelling…

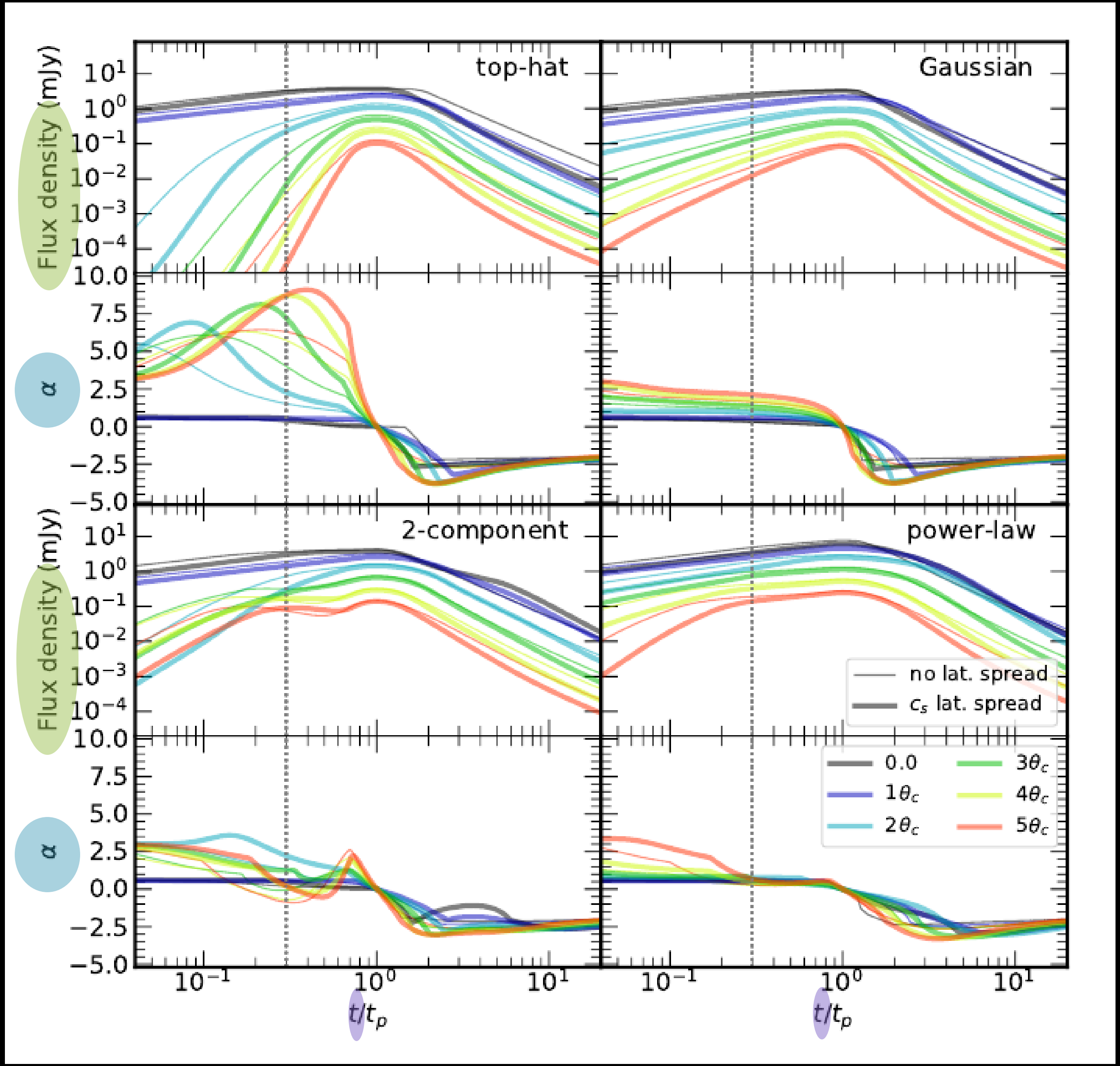
- Commonly, afterglow models neglect lateral expansion
- Claimed to only effect the lightcurve post-peak or jet-break
- **THIS IS NOT TRUE FOR OFF-AXIS AFTERGLOWS!**
- Identical model parameters, with (thick line) and without (thin line)

Temporal index

$$\alpha = \frac{d\log F}{d\log t'}$$

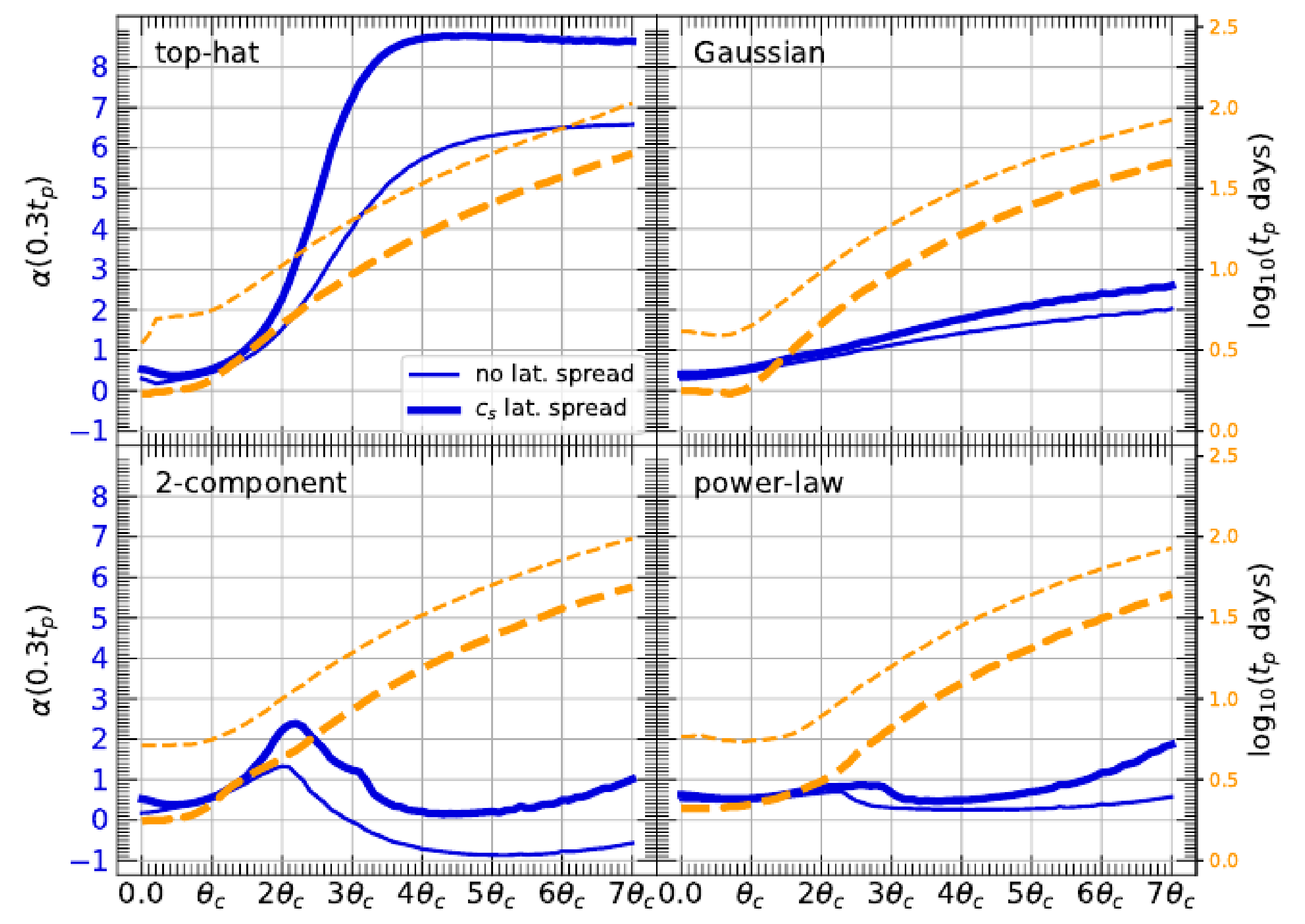
Flux

Observer time

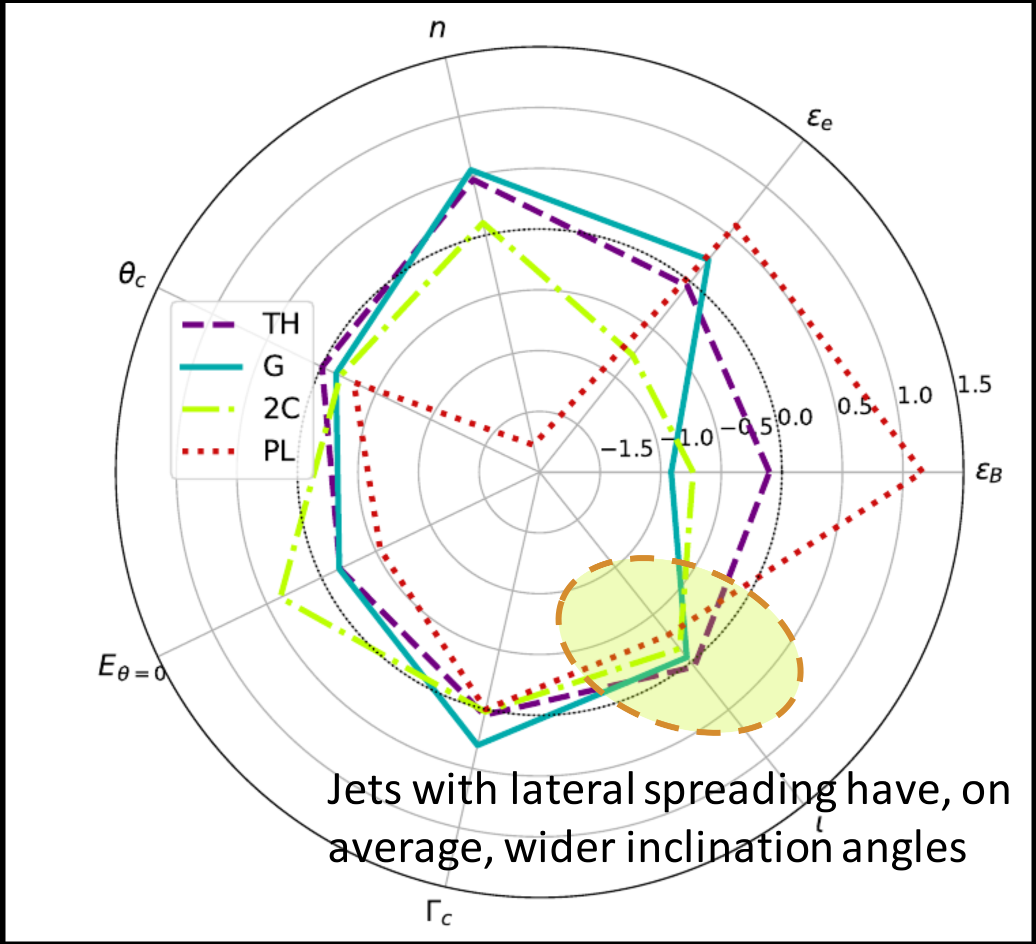


Lamb, Fernandez, Hayes et al. 2021

The problem with afterglow modelling for inclination estimation…



The log ratio of afterglow parameters for jet fits to GW170817 data without/with lateral spreading effects

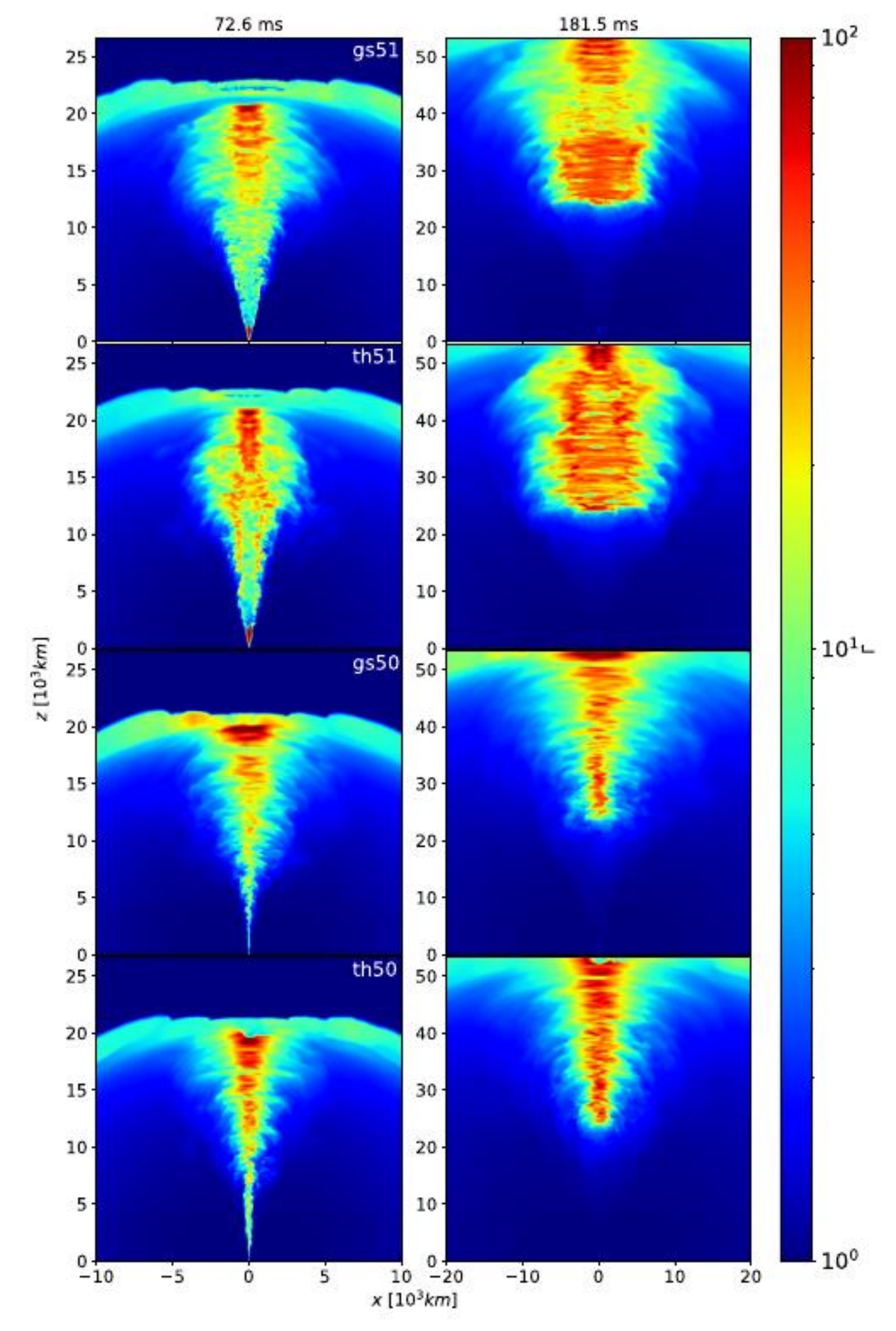


Jets with lateral spreading have, on average, wider inclination angles

Lamb, Fernandez, Hayes et al. 2021

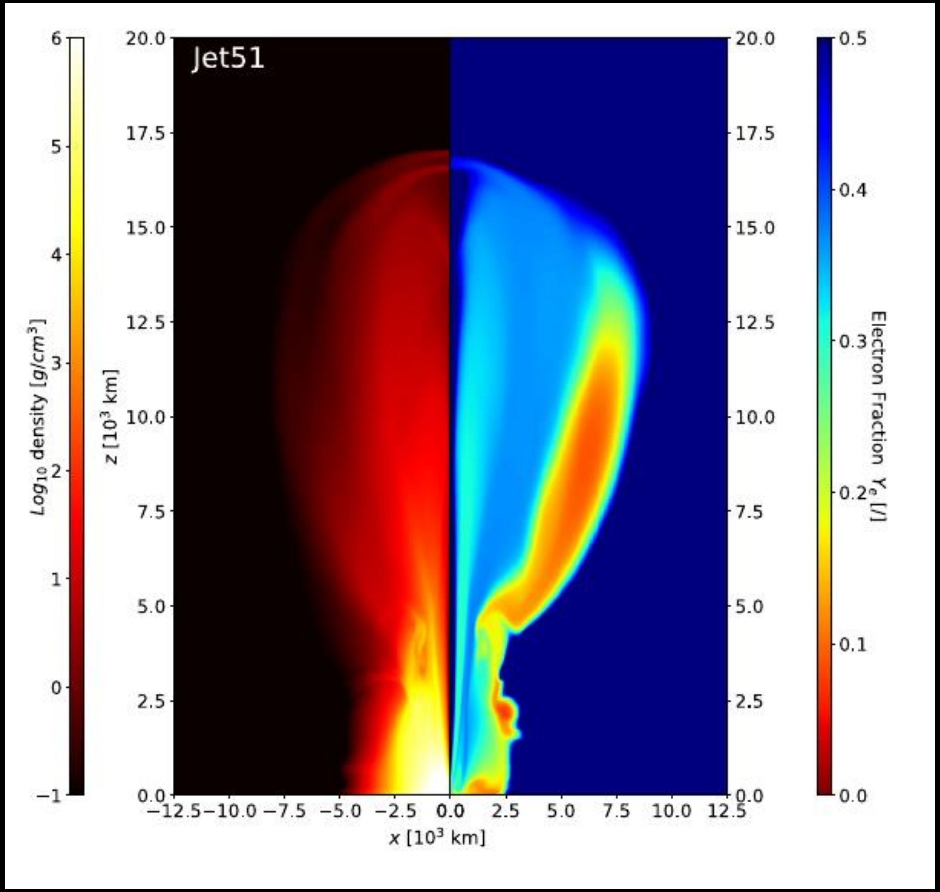
Simulations of Merger Jets

- What shapes the emergent jet structure?
- Is the emergent jet entirely shaped by the ejecta interaction or does the intrinsic structure of the jet survive?
- Using the same merger ejecta and environment:
  - Four jets – two profiles, two jet powers (top-hat, Gaussian | 10^{50}, 10^{51} erg/s)
  - Jets have injected half opening angles of 15 degrees
  - Jets are injected for 100ms
  - Initial $\Gamma_0 = 5$, and specific enthalpy $h_c = 30$, giving an asymptotic $\Gamma_\infty = 150$

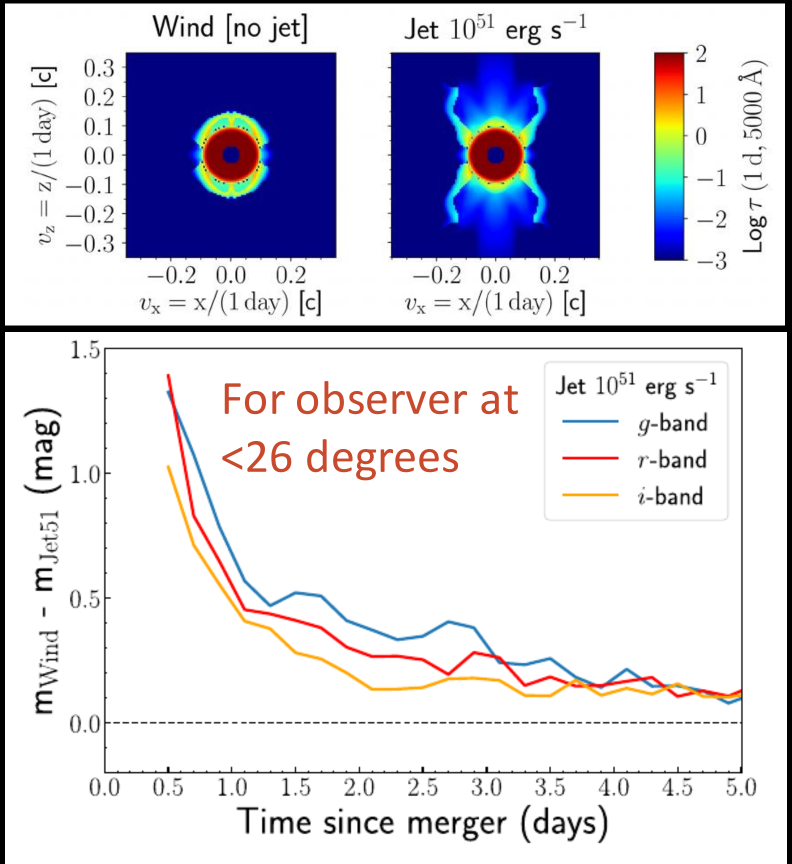


Nativi, **Lamb** et al. 2022

Physically motivated jets



Jet at 65ms, [left] rest-mass density (log), [right] electron fraction



For observer at <26 degrees

- 3D simulations using AMUN
- Jets in a neutrino driven wind and merger ejecta
- The effect on the kilonova
- Jets make kilonova brighter and bluer (towards the pole)

Nativi [incl. **Lamb**] et al. 2021

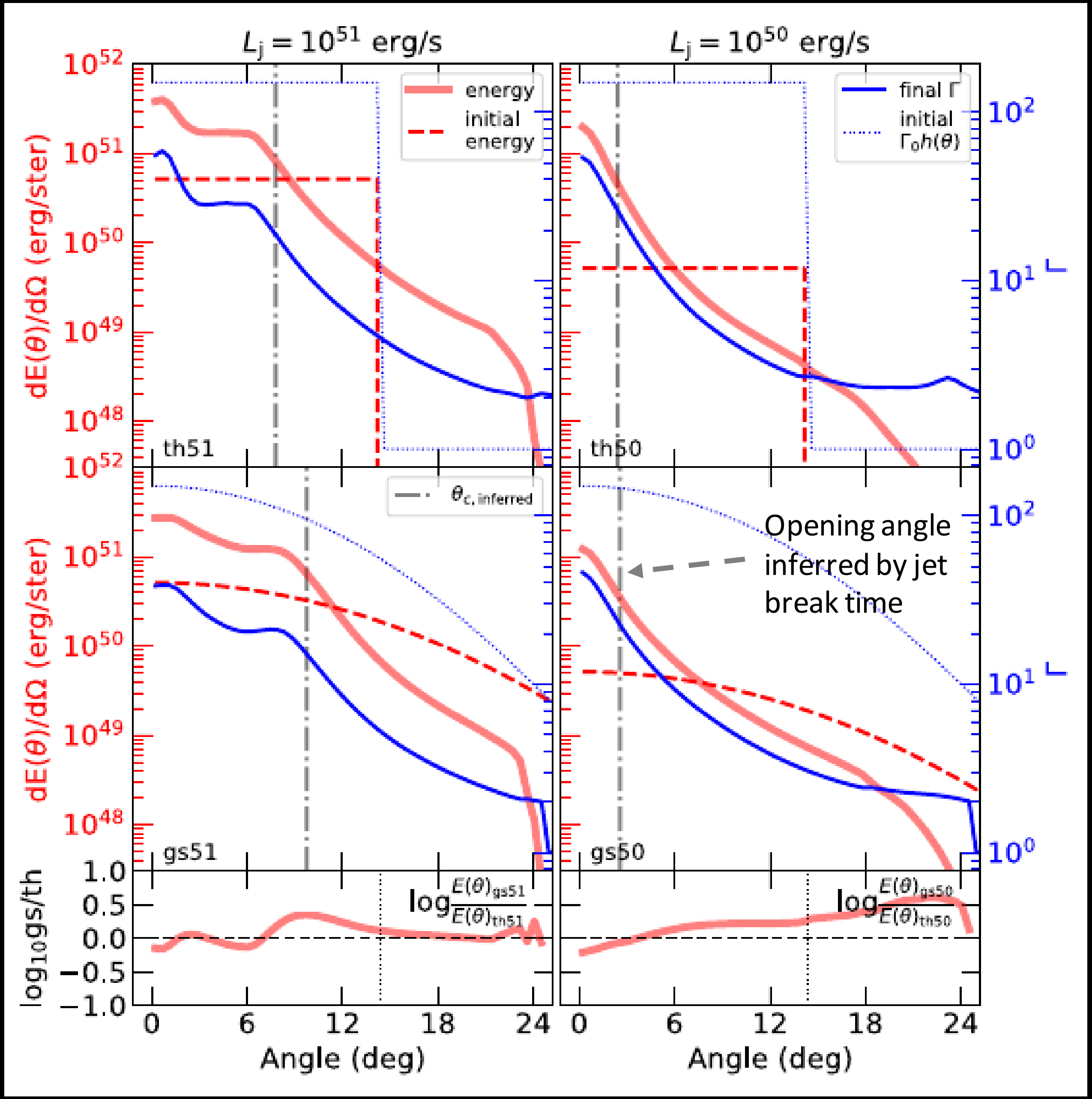
Physically motivated jets

- Resultant, rotationally averaged jet profiles
- Differences are largely due to chaotic, turbulent effects
- Less powerful jets are more collimated
- All jet profiles can reproduce the temporal shape of GW170817
- No fit was made to the VLBI
- NOTE – the merger ejecta and wind is inconsistent with the kilonova seen in GW170817! (Ejecta masses are lower)

Initially top-hat

Initially Gaussian

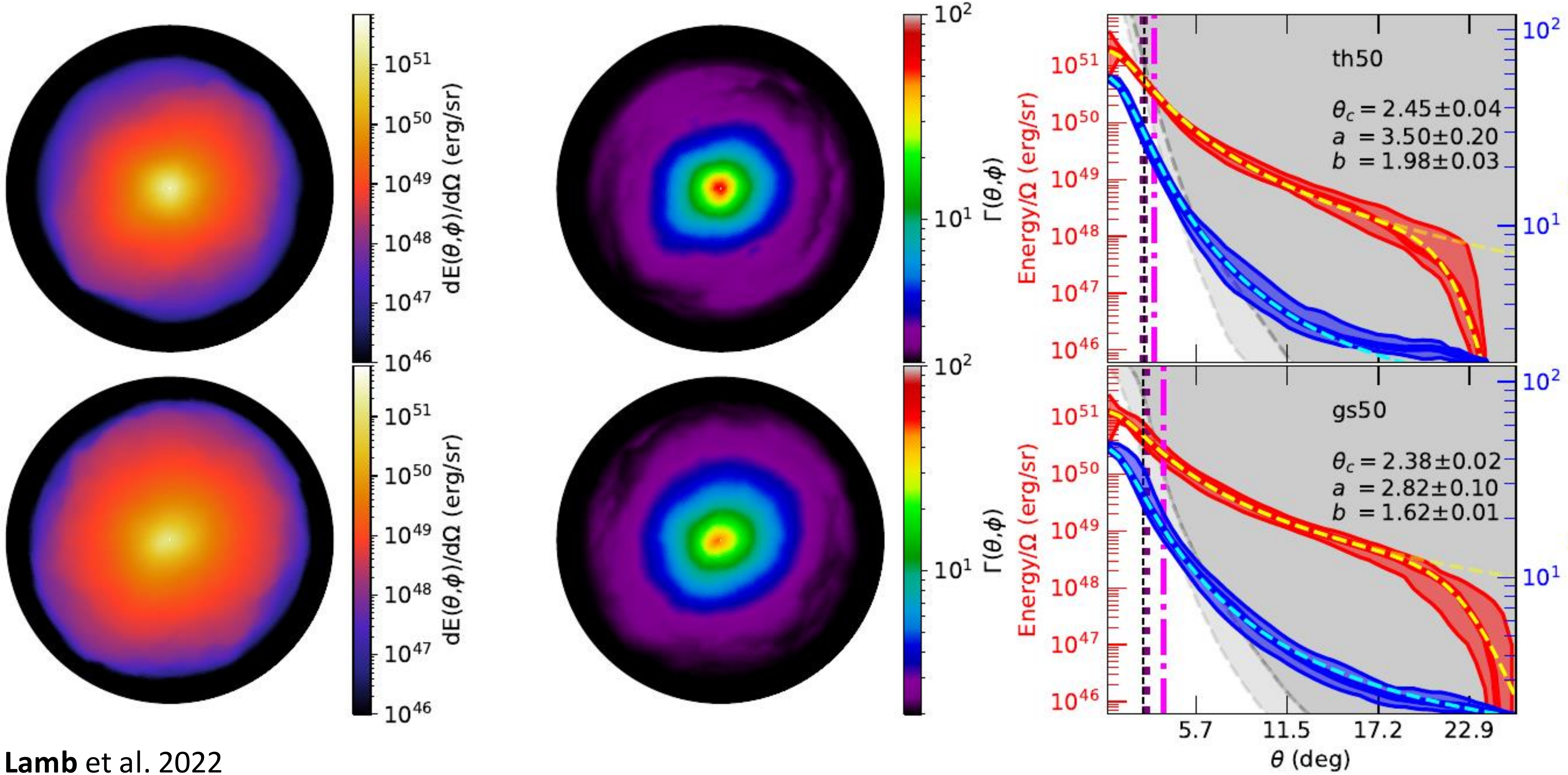
Difference at same jet power



Opening angle inferred by jet break time

Nativi, **Lamb** et al. 2022

Inhomogeneity within the jet!



Lamb et al. 2022

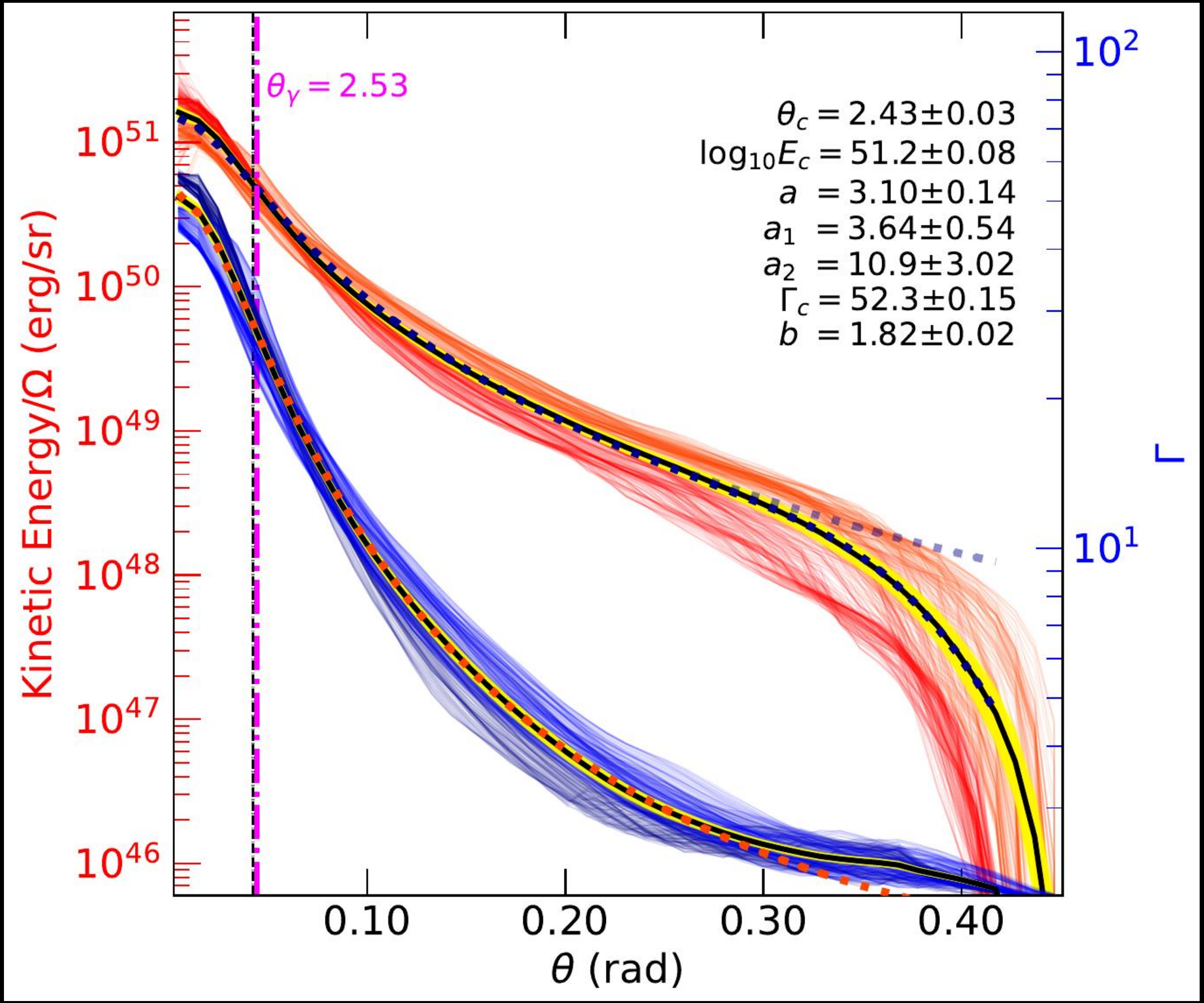
A physically motivated jet structure-function?

- All profiles through φ
- Bootstrap to approximate distribution
- Find median of medians (black lines)

$$\begin{aligned}\Theta &= \left[1+\left(\frac{\theta}{\theta_c}\right)^2\right]^{1/2},\\ E(\theta) &= E(\theta=0)\Theta^{-a},\\ \Gamma(\theta) &= 1+\left[\Gamma(\theta=0)-1\right]\Theta^{-b}.\end{aligned}$$

Energy cut-off at wide angles as:

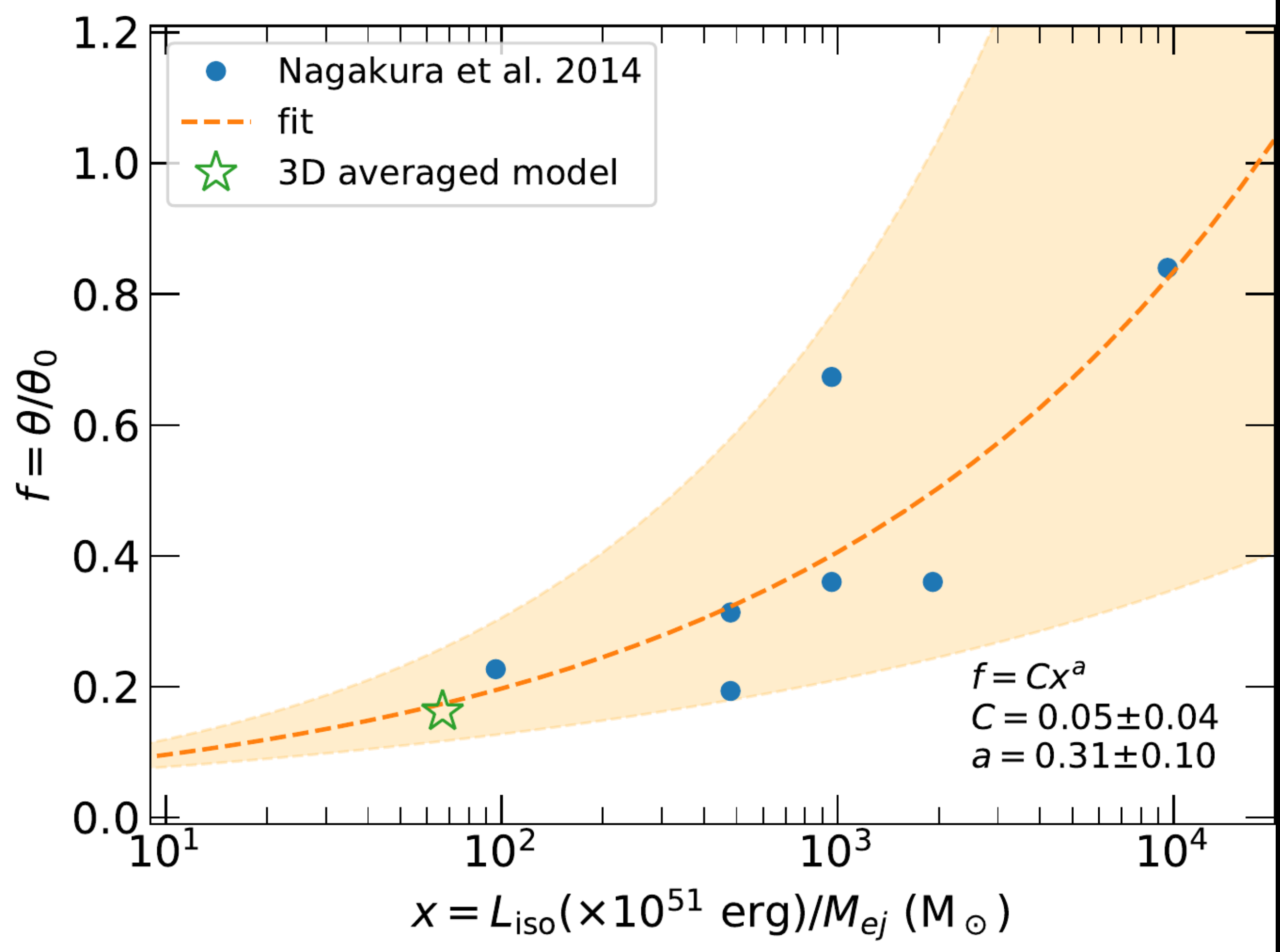
$$(1+(\theta/\theta_j)^{a_2})^{-a_1}.$$



Lamb et al. 2022

- An approximation for the collimation efficiency
- Many simulations with different ejecta/wind configurations – computationally expensive
- Look at past simulations – best published sample, Nagakura et al. 2014
  - 7 consistent simulations
- Use output to fit mass vs collimation

$$\theta_c = 0.05\ \theta_0\ (L_{iso}/M_{ej})^{0.31}$$



The ratio of jet power to ejecta mass versus the degree of collimation from initial jet opening angle to resultant angle

Lamb et al. 2022

A Universal Profile?

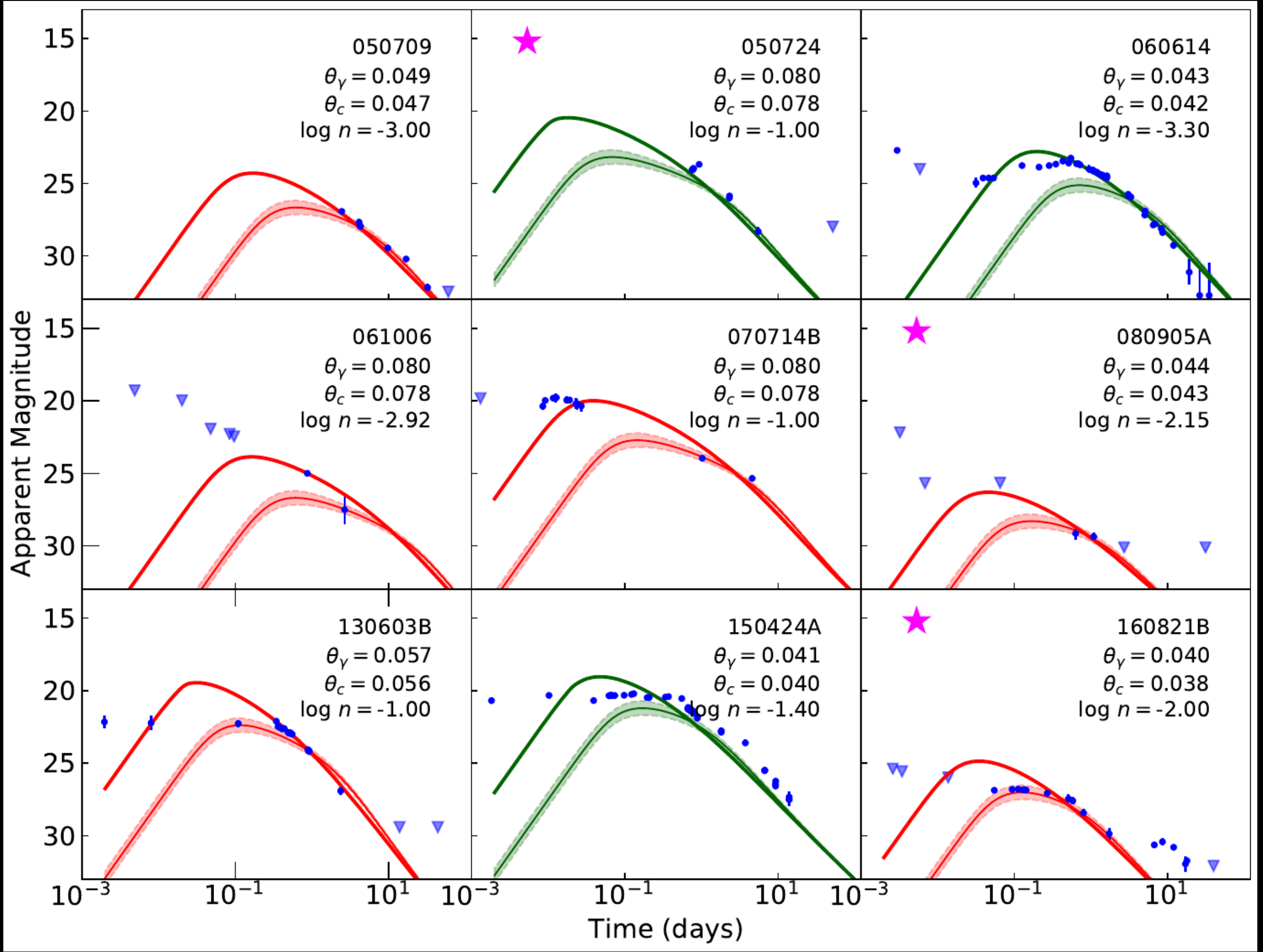
- A universal structure for all GRBs has been a popular idea.
- Here we see that chaotic mixing processes add an uncertainty to any profile
- The core size is a function of the ejecta mass!
- Even if all jets have an identical energy reservoir, the observed properties of KN are quite broad
- One possible origin for much of the jet diversity seen in GRB population is the degree of collimation and mixing from the ejecta – this would depend on the ejecta density (at the poles)

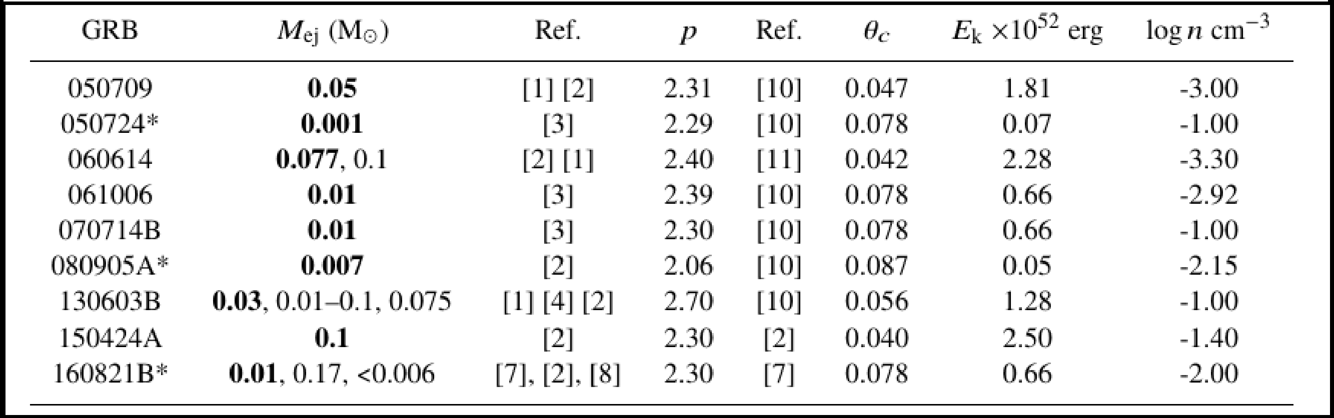
A universal profile NOT a universal jet!??

Comparison

- 9 GRB afterglows with KN candidates
- Use literature ejecta mass to set θ_c
- Initially, alter only ambient density (red)
- Change magnetic microphysical parameter (green), from 0.01 to 0.1
- Models with pink star have one tenth jet energy – note GRB 160821B is consistent with refreshed shock model energies

- NOT fits!
- Phenomenological comparison – indicates consistency with an intrinsically narrow energy reservoir for short GRB jets.





GRB	$M_{\rm ej}$ ($M_\odot$)	Ref.	p	Ref.	θ_c	$E_{\rm k}$ $\times 10^{52}$ erg	$\log n$ cm^{-3}
050709	**0.05**	[1] [2]	2.31	[10]	0.047	1.81	-3.00
050724*	**0.001**	[3]	2.29	[10]	0.078	0.07	-1.00
060614	**0.077**, 0.1	[2] [1]	2.40	[11]	0.042	2.28	-3.30
061006	**0.01**	[3]	2.39	[10]	0.078	0.66	-2.92
070714B	**0.01**	[3]	2.30	[10]	0.078	0.66	-1.00
080905A*	**0.007**	[2]	2.06	[10]	0.087	0.05	-2.15
130603B	**0.03**, 0.01–0.1, 0.075	[1] [4] [2]	2.70	[10]	0.056	1.28	-1.00
150424A	**0.1**	[2]	2.30	[2]	0.040	2.50	-1.40
160821B*	**0.01**, 0.17, <0.006	[7], [2], [8]	2.30	[7]	0.078	0.66	-2.00

Lamb et al. 2022

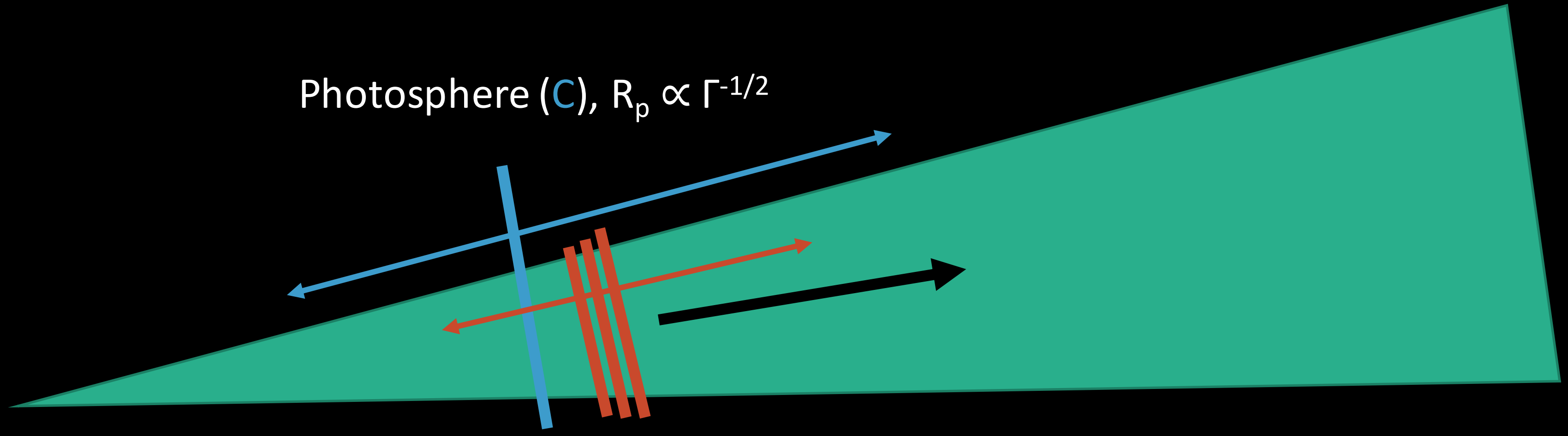
Summary

- GW170817 has made structured jets the "normal"
- Next steps in modelling – confidence for cosmology from GW-EM
  - The afterglow physics is important – **lateral spreading must be considered for off-axis modelling**
- Simulations show that jets:
  - **…jet ejecta interaction makes the kilonova, bluer and brighter**
  - ...and **shapes the resultant jet structure**
- **Simulations are helping refine the viable jet structure profiles and understand the processes that are shaping the jets!**

Opacity in GRBs

- Pair production – annihilation of highest energy photons (A)
- Scattering by pair produced electrons (B)
- Scattering by electrons that accompany baryons – requires baryonic jets (C)

Depend on spectrum of prompt emission

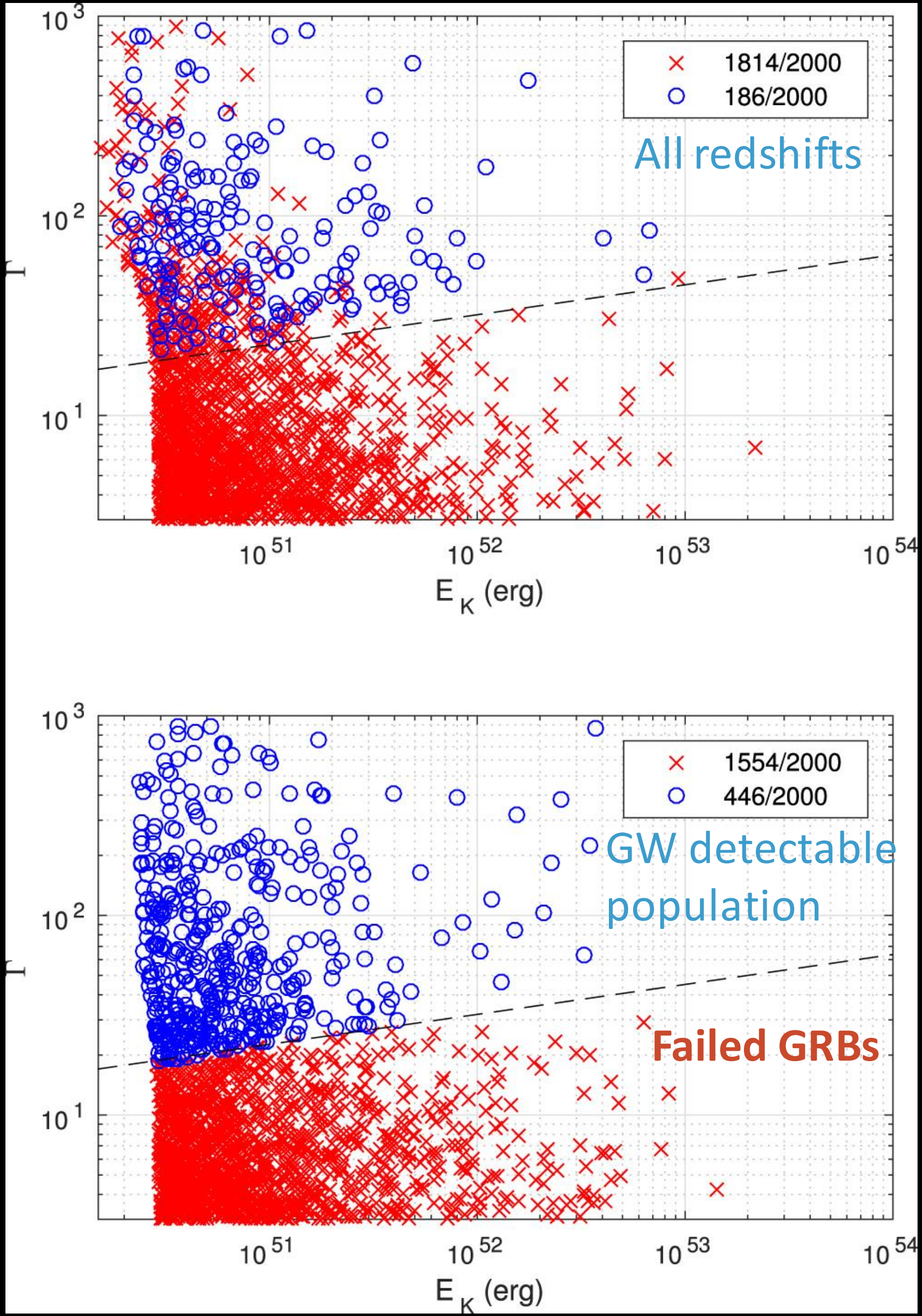


Photosphere (C), $R_p \propto \Gamma^{-1/2}$

Dissipation radius (internal shocks), $R_d \propto \Delta t\, \Gamma^2$

A population of failed GRBs?

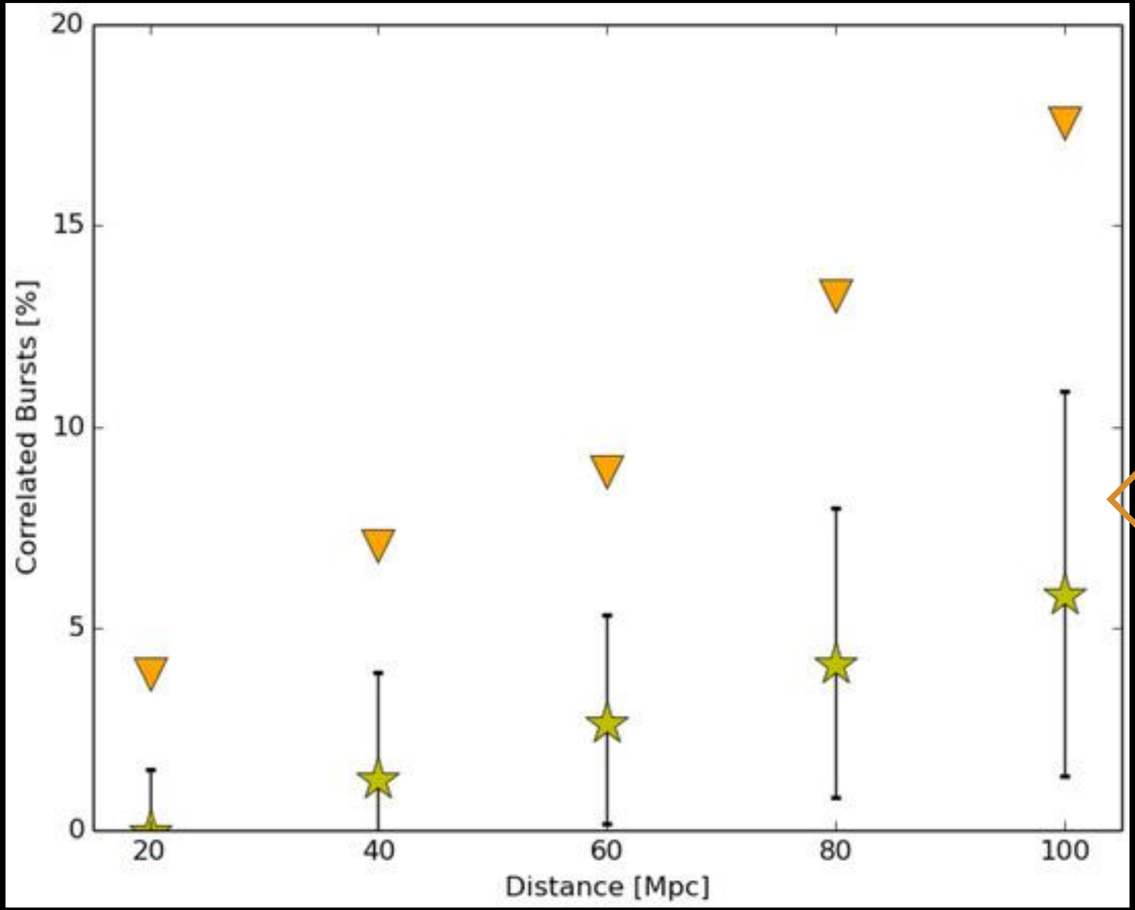
- No bright GRBs (like the choked jet scenario)
- Afterglows!?
- The rate of GW detected neutron star mergers is starting to rule this out(?)



Lamb & Kobayashi 2016

What about a low luminosity population?

- Little evidence for any nearby short GRBs! See, Mandhai et al. 2018



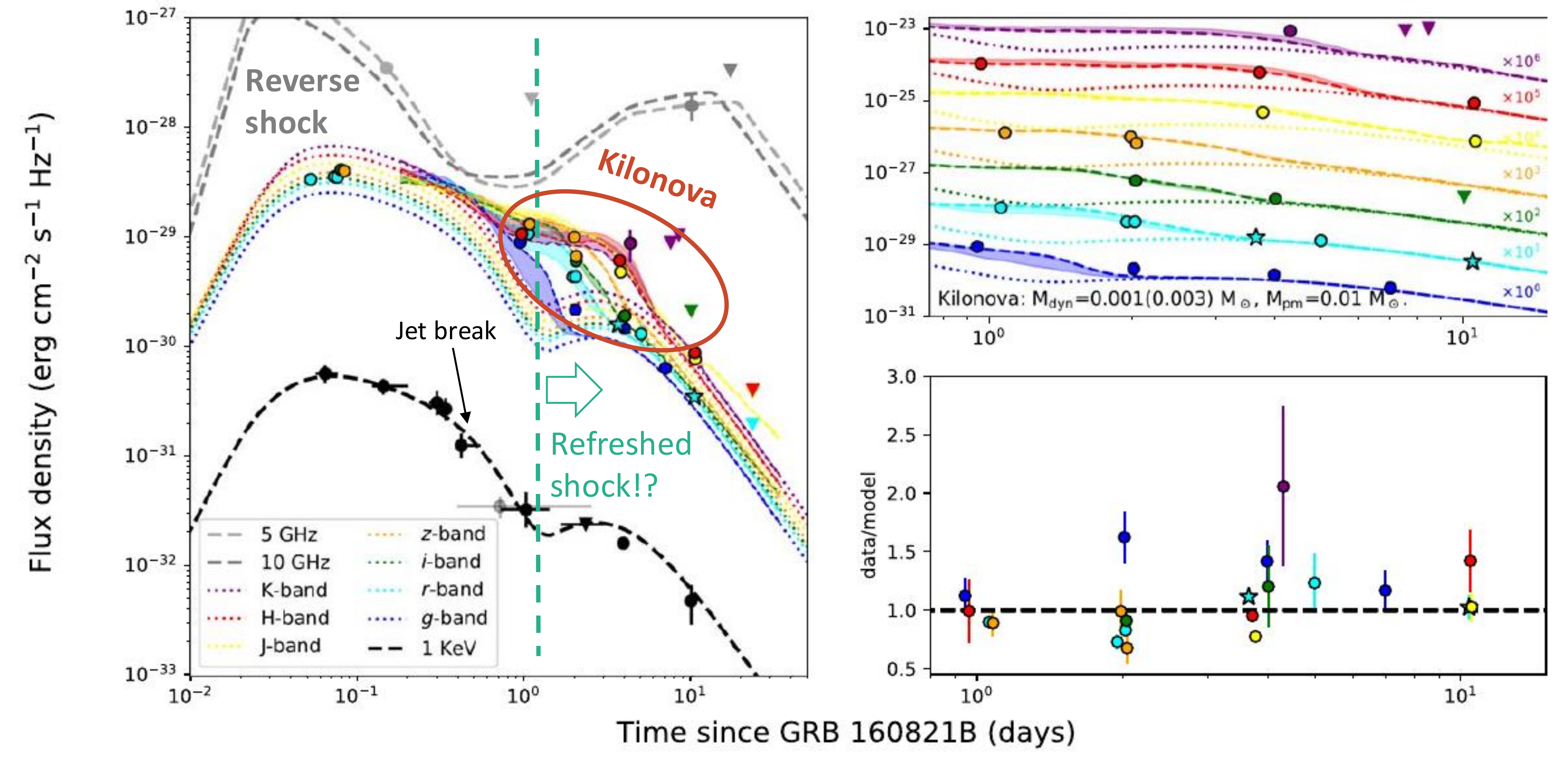
Mandhai, Tanvir, **Lamb**, Levan & Tsang 2018

BATSE and *Fermi* short GRBs sky localisation correlated with galaxies (consistent with zero)

– *Swift* bursts show an even smaller fraction!

An aside – the case of GRB 160821B

$z = 0.162$
$\theta_j \sim 1^\circ.9$
$E_j \sim 0.9\times10^{49}$ erg
$E_{K,iso} \sim 1.6\times10^{52}$ erg
$E_{\gamma,iso} \sim 2.1\times10^{50}$ erg



Reverse shock

Kilonova

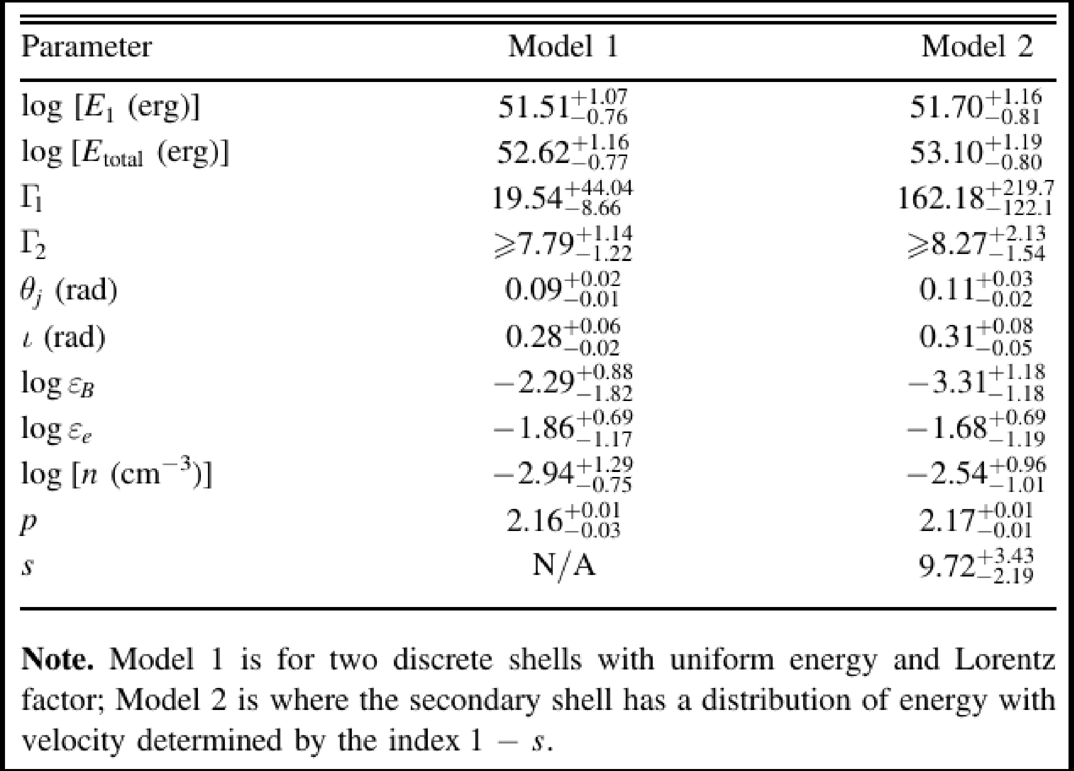
Jet break

Refreshed shock!?

Lamb, Tanvir, Levan et al. 2019

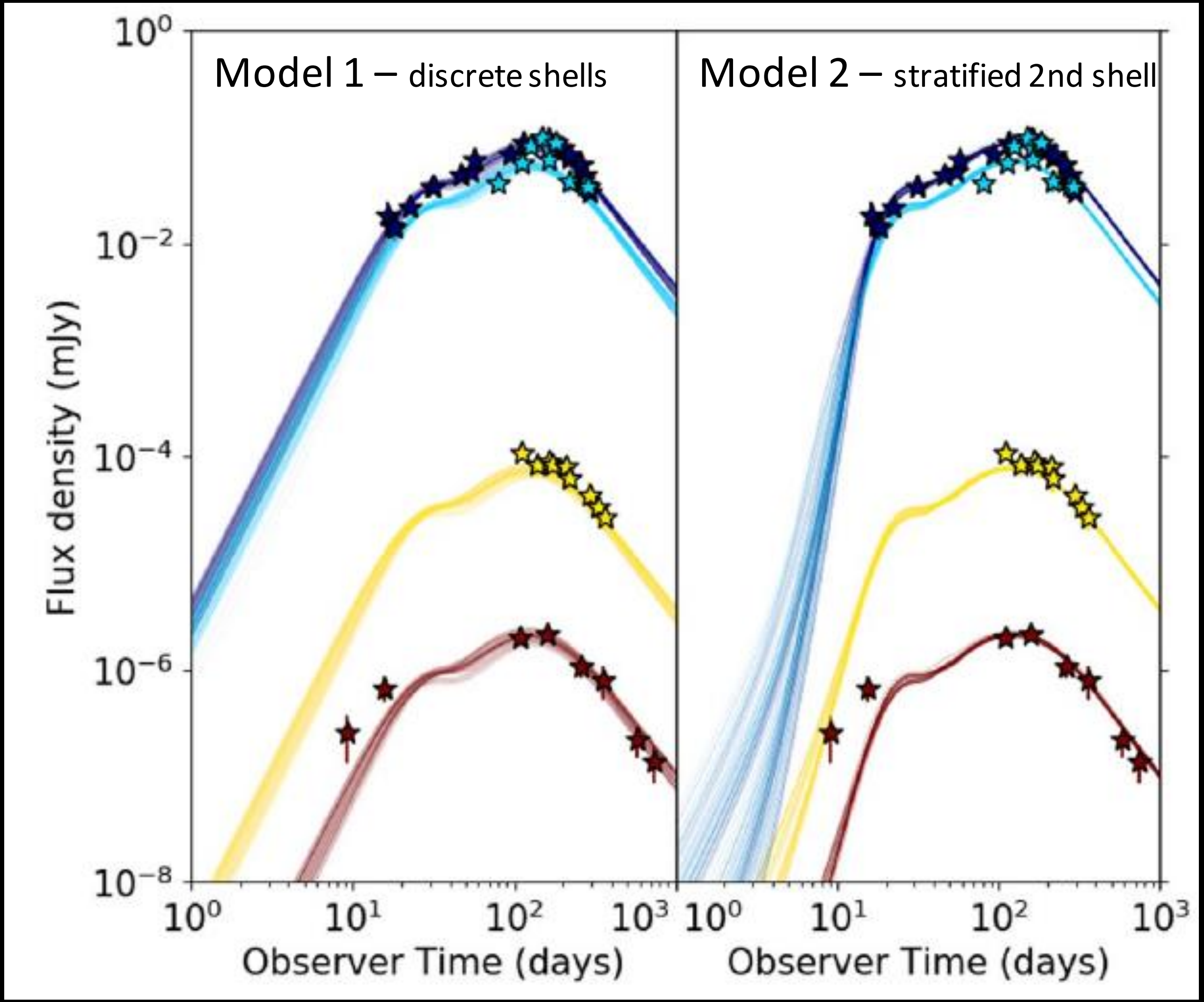
The refreshed shock model for GW170817?

- It works!
- A real alternative to purely structured jets... but some structure is expected!



Parameter	Model 1	Model 2
log [E_1 (erg)]	$51.51^{+1.07}_{-0.76}$	$51.70^{+1.16}_{-0.81}$
log [$E_{\rm total}$ (erg)]	$52.62^{+1.16}_{-0.77}$	$53.10^{+1.19}_{-0.80}$
Γ_1	$19.54^{+44.04}_{-8.66}$	$162.18^{+219.7}_{-122.1}$
Γ_2	$\geqslant 7.79^{+1.14}_{-1.22}$	$\geqslant 8.27^{+2.13}_{-1.54}$
θ_j (rad)	$0.09^{+0.02}_{-0.01}$	$0.11^{+0.03}_{-0.02}$
ι (rad)	$0.28^{+0.06}_{-0.02}$	$0.31^{+0.08}_{-0.05}$
log ε_B	$-2.29^{+0.88}_{-1.82}$	$-3.31^{+1.18}_{-1.18}$
log ε_e	$-1.86^{+0.69}_{-1.17}$	$-1.68^{+0.69}_{-1.19}$
log [n (cm^{-3})]	$-2.94^{+1.29}_{-0.75}$	$-2.54^{+0.96}_{-1.01}$
p	$2.16^{+0.01}_{-0.03}$	$2.17^{+0.01}_{-0.01}$
s	N/A	$9.72^{+3.43}_{-2.19}$

Note. Model 1 is for two discrete shells with uniform energy and Lorentz factor; Model 2 is where the secondary shell has a distribution of energy with velocity determined by the index $1 - s$.

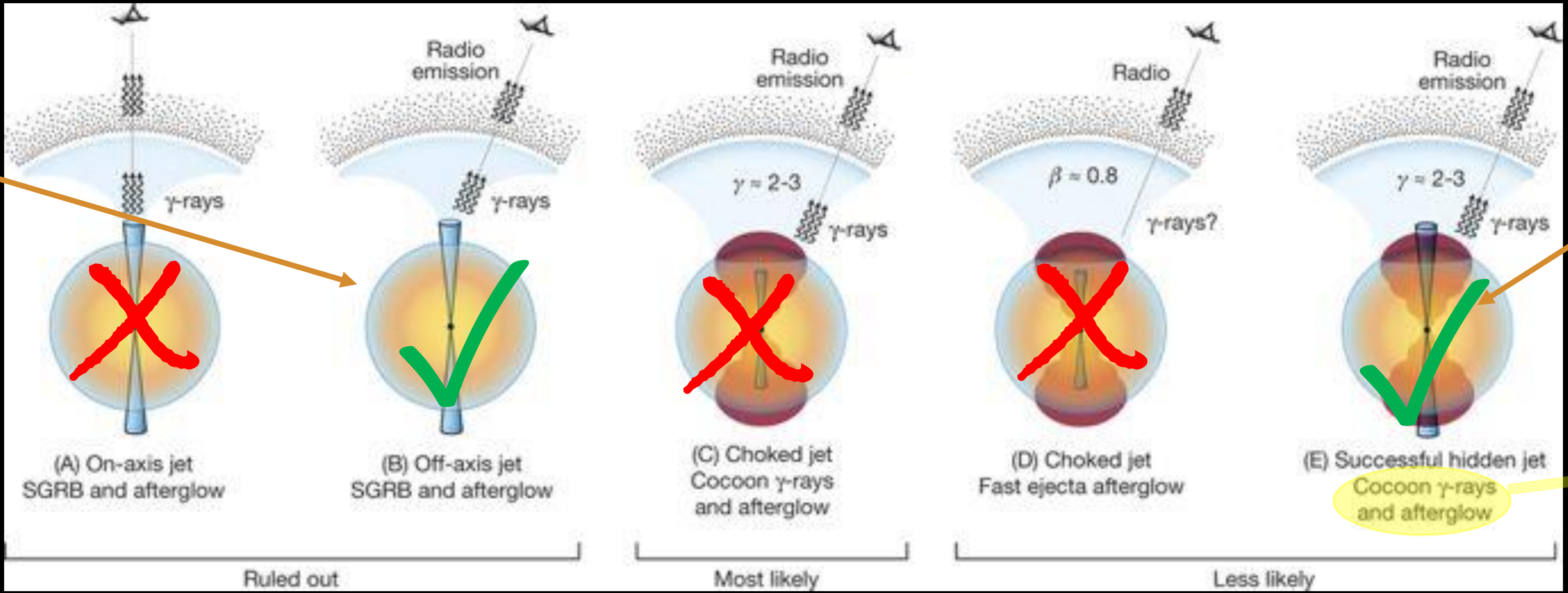


Lamb, Levan & Tanvir 2020

Recap GRB 170817A afterglow origin

- No observational evidence for a large, nearby population of low-luminosity short GRBs e.g., failed GRBs or choked jets
- Strong evidence from GW170817 for structured jets in short GRBs
- Refreshed shocks, as seen in GRB 160821B, can recreate the off-axis afterglow of GW170817 – an alternative (still needs some lateral structure e.g., a cocoon)

Successful jet SGRB and afterglow viewed off-axis



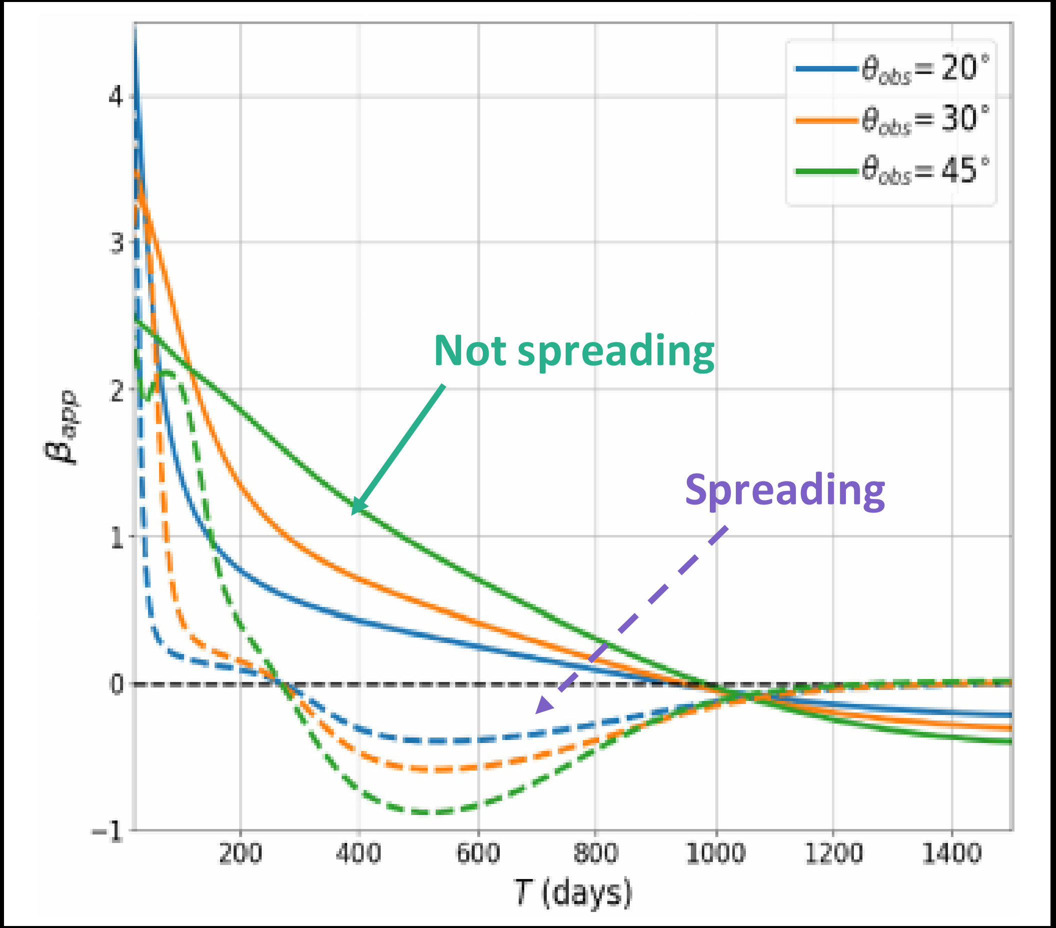
Successful jet and afterglow viewed off-axis, γ-rays from cocoon

Jet afterglow NOT cocoon afterglow

Fig from Mooley et al. 2018

Imaging – radio VLBI and superluminal motion

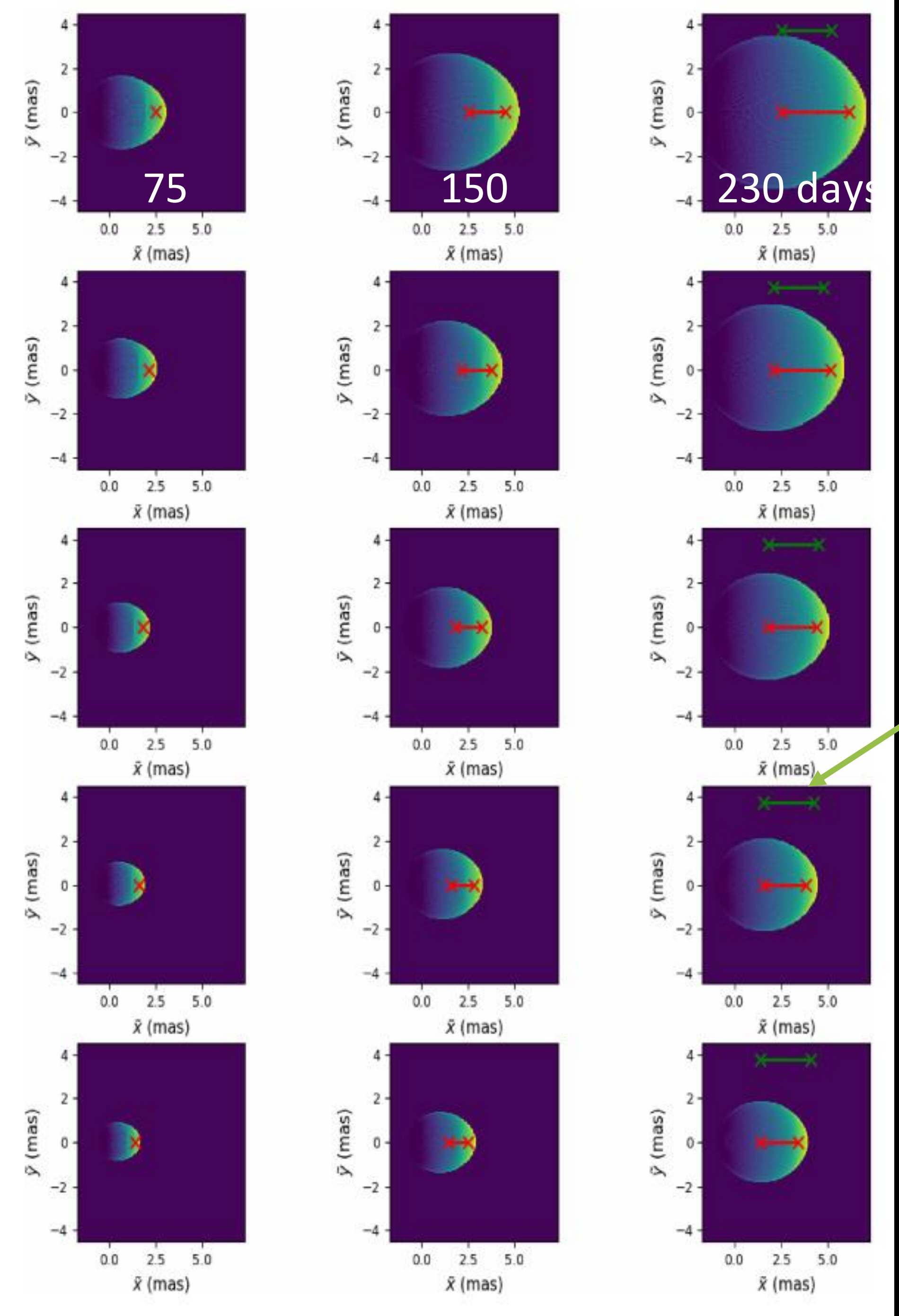
- Radio imaging of superluminal motion can constrain the inclination
- Again, spreading is often neglected in modelling – underestimate the inclination
- Often, a point approximation is used… how accurate is this?



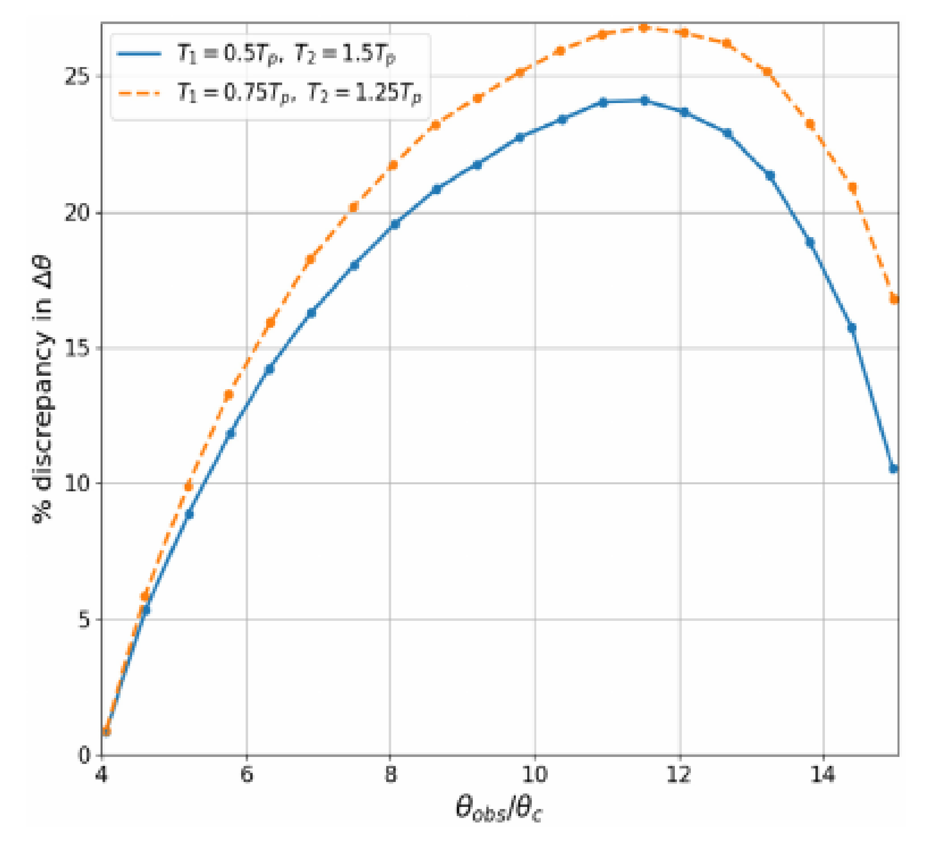
Apparent superluminal velocity for the same jet parameter models – dashed is with spreading, solid without spreading

Fernandez, Kobayashi & **Lamb** 2022

Imaging – radio VLBI and superluminal motion



- [left] 5 models with spreading that fit the temporal afterglow lightcurve of GW170817
- The centroid position at 75, 150, and 230 days
- The green bar indicates the observed centroid shift in GW170817
- [right] The percentage discrepancy between the point approximation estimate for the viewing angle versus the model parameters
- For small θ_{obs}/θ_c, the approximation is okay e.g., for GW170817

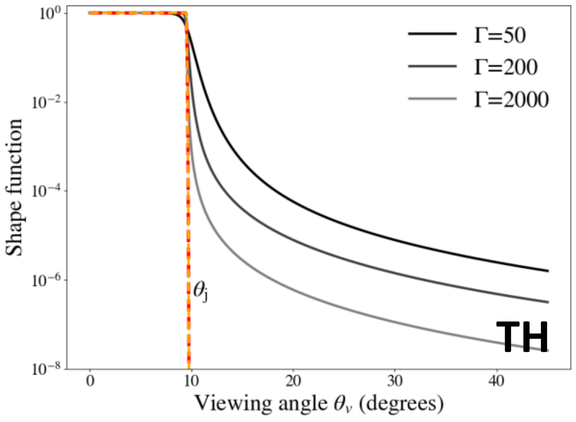


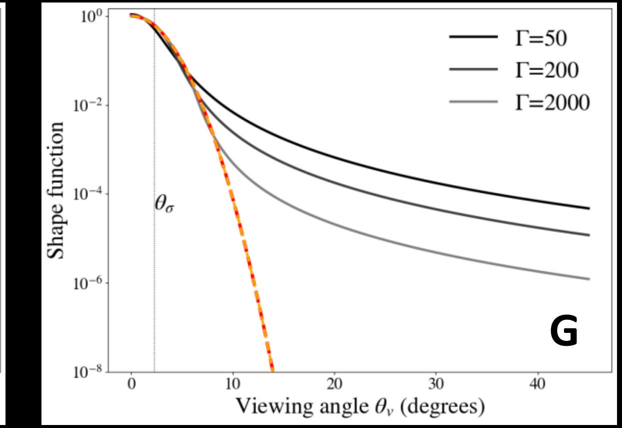
Error in the estimation of θ_{obs} from synthetic images as a function of θ_{obs}/θ_c for two different observing windows

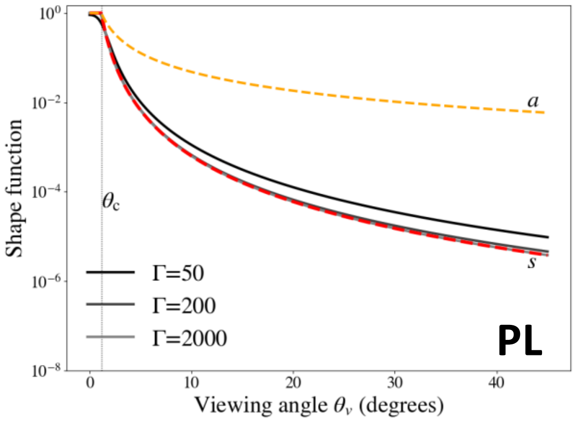
Fernandez, Kobayashi & **Lamb** 2022

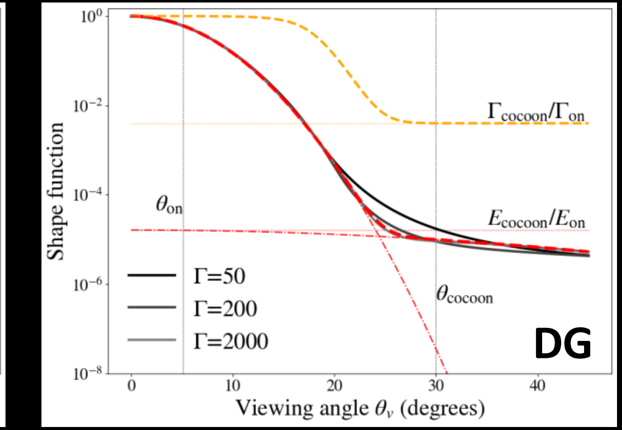
Inferred jets – a Bayesian approach (in prep)

- Use Bayesian framework to compare short GRB rates with GW merger rates
- Add the Fermi GRB 170817A
- Add the non-detection for GW190425
- Infer luminosity function
- Assume one of four jet-structures – top-hat (TH), Gaussian (G), powerlaw (PL), or double-Gaussian (DG)



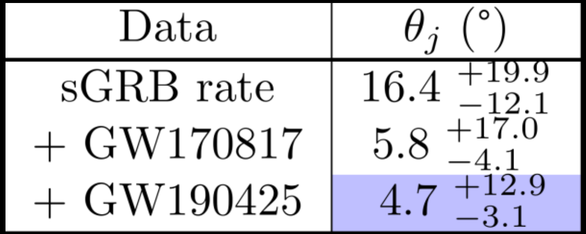






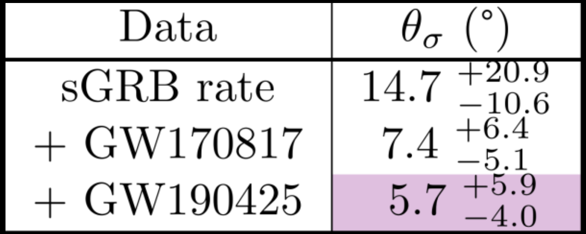
Hayes, Heng, **Lamb** et al. (in prep.)

Inferred jets – a Bayesian approach (in prep)



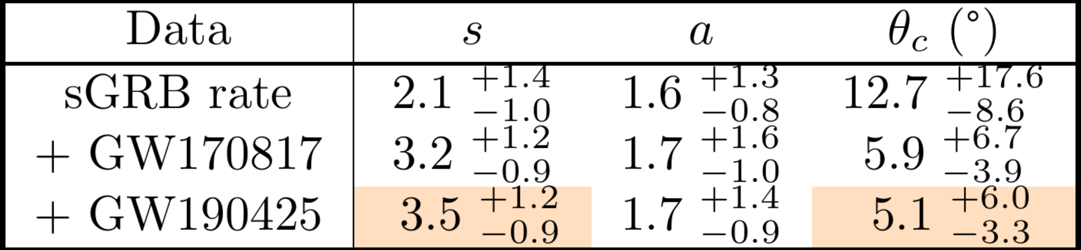
Data	θ_j (°)
sGRB rate	$16.4^{+19.9}_{-12.1}$
+ GW170817	$5.8^{+17.0}_{-4.1}$
+ GW190425	$4.7^{+12.9}_{-3.1}$

TH jets, population parameters



Data	θ_σ (°)
sGRB rate	$14.7^{+20.9}_{-10.6}$
+ GW170817	$7.4^{+6.4}_{-5.1}$
+ GW190425	$5.7^{+5.9}_{-4.0}$

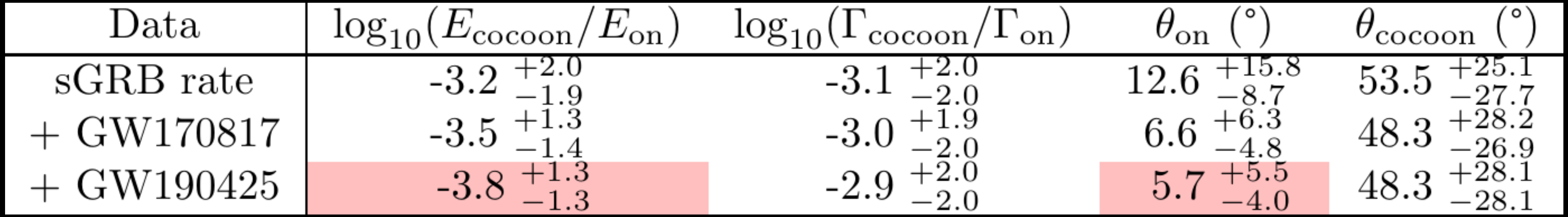
G jets, population parameters



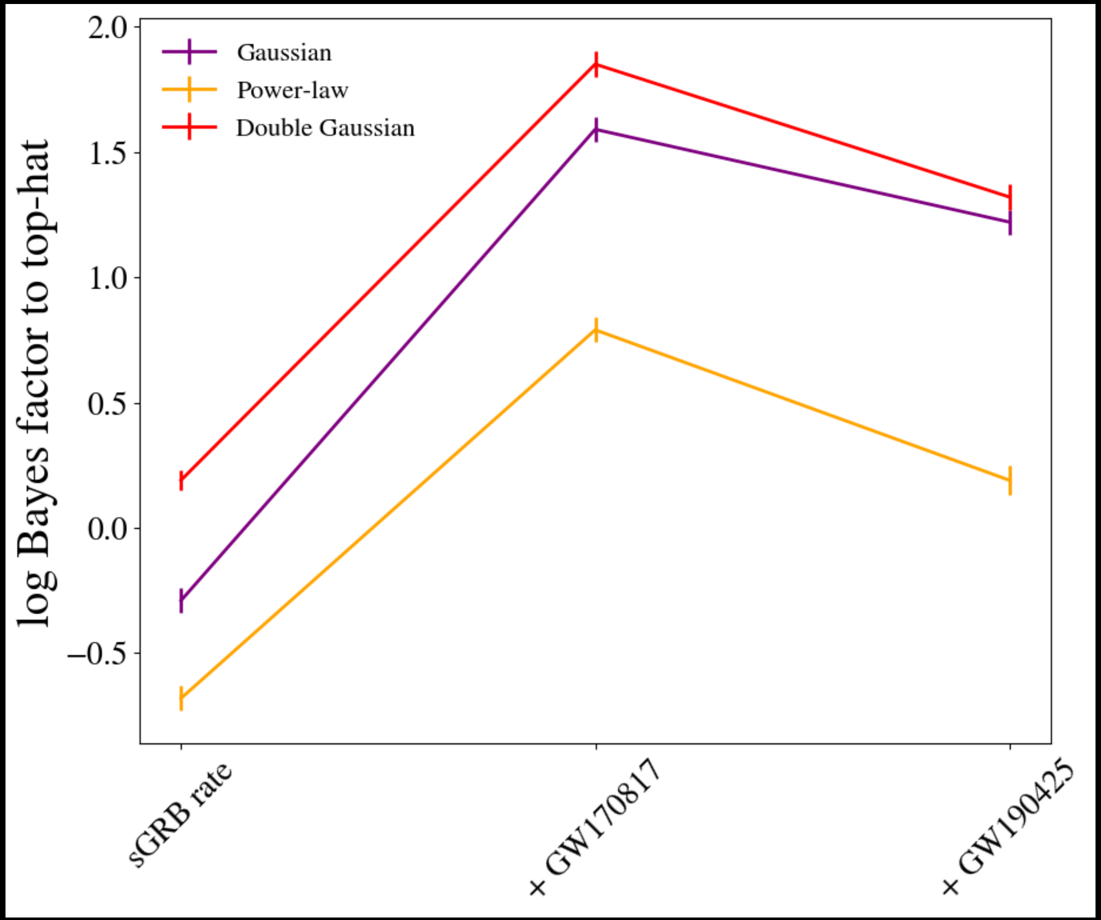
Data	s	a	θ_c (°)
sGRB rate	$2.1^{+1.4}_{-1.0}$	$1.6^{+1.3}_{-0.8}$	$12.7^{+17.6}_{-8.6}$
+ GW170817	$3.2^{+1.2}_{-0.9}$	$1.7^{+1.6}_{-1.0}$	$5.9^{+6.7}_{-3.9}$
+ GW190425	$3.5^{+1.2}_{-0.9}$	$1.7^{+1.4}_{-0.9}$	$5.1^{+6.0}_{-3.3}$

PL jets, population parameters

DG jets, population parameters



Data	$\log_{10}(E_{\rm cocoon}/E_{\rm on})$	$\log_{10}(\Gamma_{\rm cocoon}/\Gamma_{\rm on})$	$\theta_{\rm on}$ (°)	$\theta_{\rm cocoon}$ (°)
sGRB rate	$-3.2^{+2.0}_{-1.9}$	$-3.1^{+2.0}_{-2.0}$	$12.6^{+15.8}_{-8.7}$	$53.5^{+25.1}_{-27.7}$
+ GW170817	$-3.5^{+1.3}_{-1.4}$	$-3.0^{+1.9}_{-2.0}$	$6.6^{+6.3}_{-4.8}$	$48.3^{+28.2}_{-26.9}$
+ GW190425	$-3.8^{+1.3}_{-1.3}$	$-2.9^{+2.0}_{-2.0}$	$5.7^{+5.5}_{-4.0}$	$48.3^{+28.1}_{-28.1}$

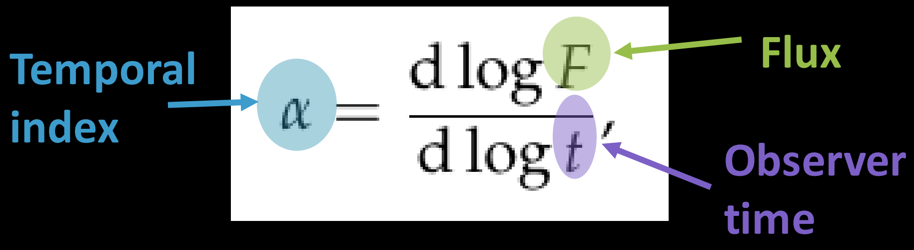


Bayes factor model selection – when GW data is included, a structured jet model is preferred

Hayes, Heng, **Lamb** et al. (in prep.)

Observed in GRBs?

- The jet break can measure the structure!
- Solid lines, with spreading
- Dashed lines, without spreading
- Four jet structure models

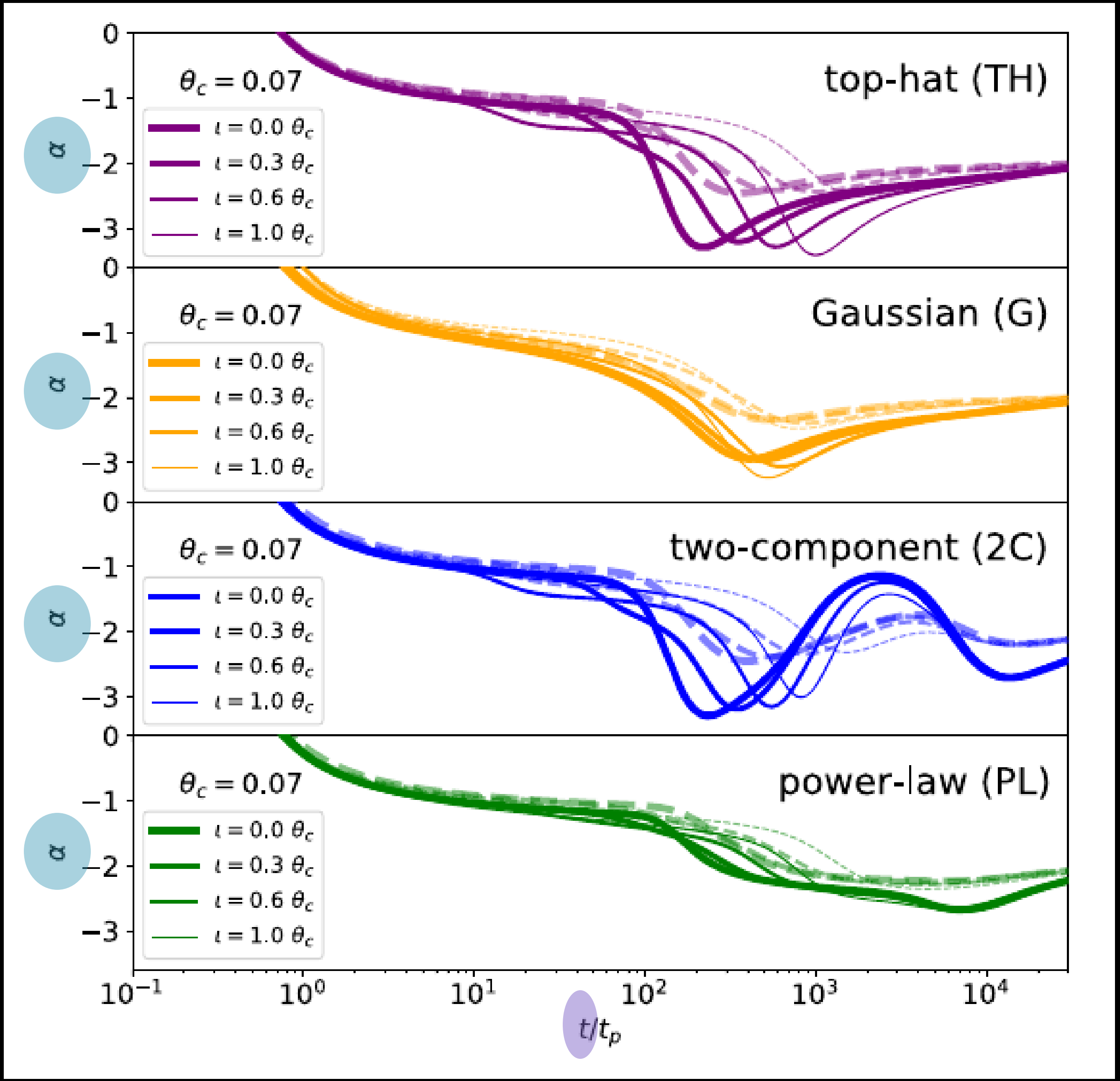


Temporal index

$$\alpha = \frac{d \log F}{d \log t},$$

Flux

Observer time

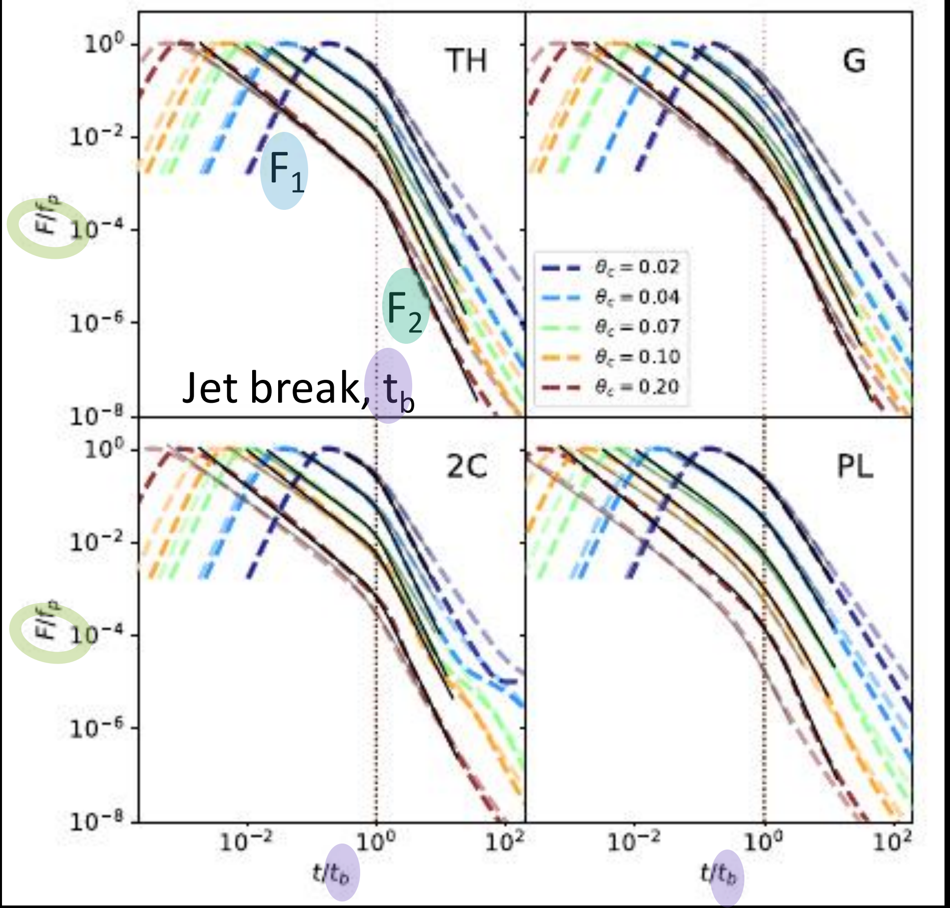


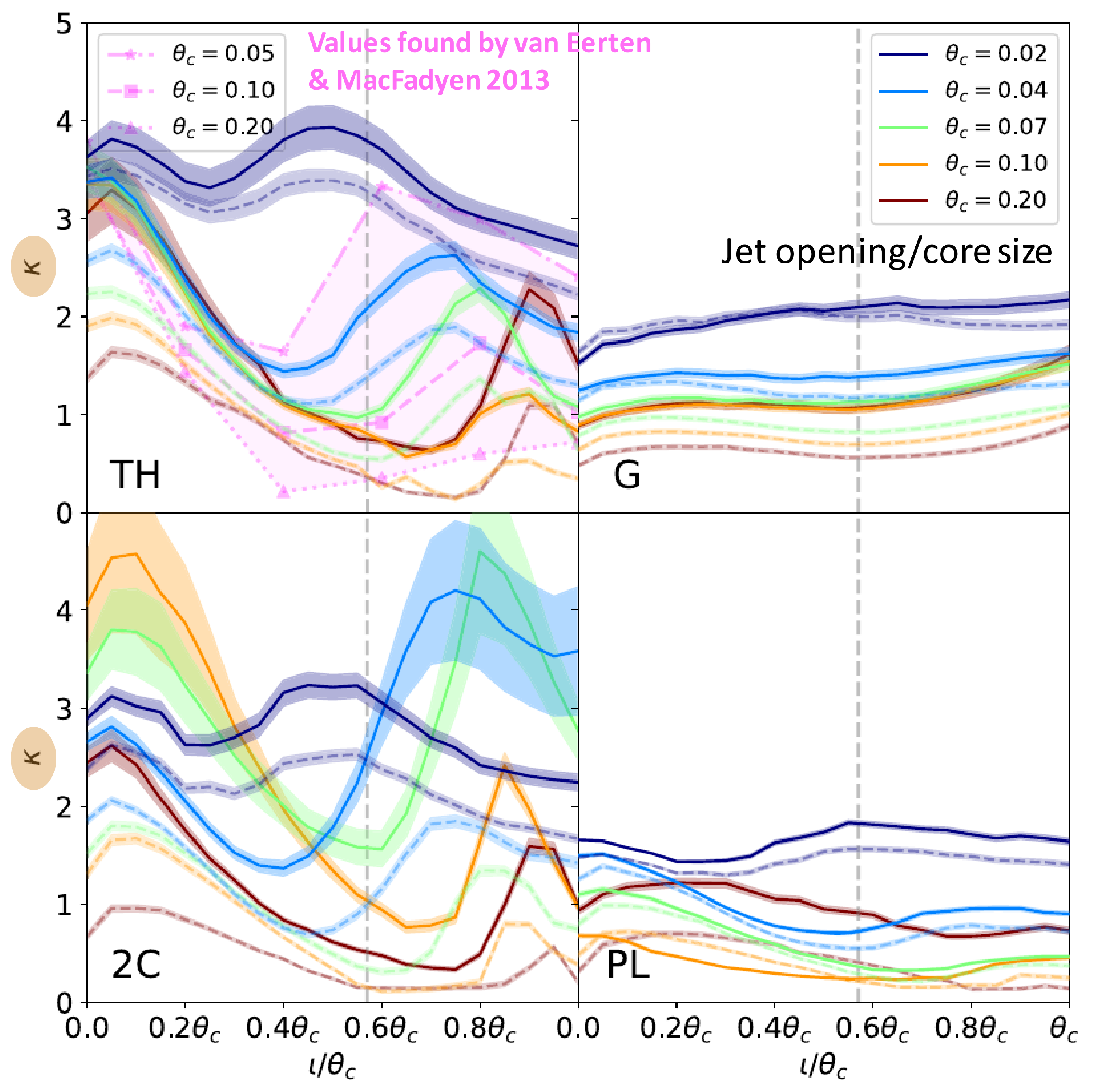
Lamb, Kann et al. 2021

Observed in GRBs?

$$F(t) = \left[F_1^{\kappa} + F_2^{\kappa}\right]^{-1/\kappa},$$

$$F_x = f_{\rm b}(t/t_{\rm b})^{\alpha_x}$$





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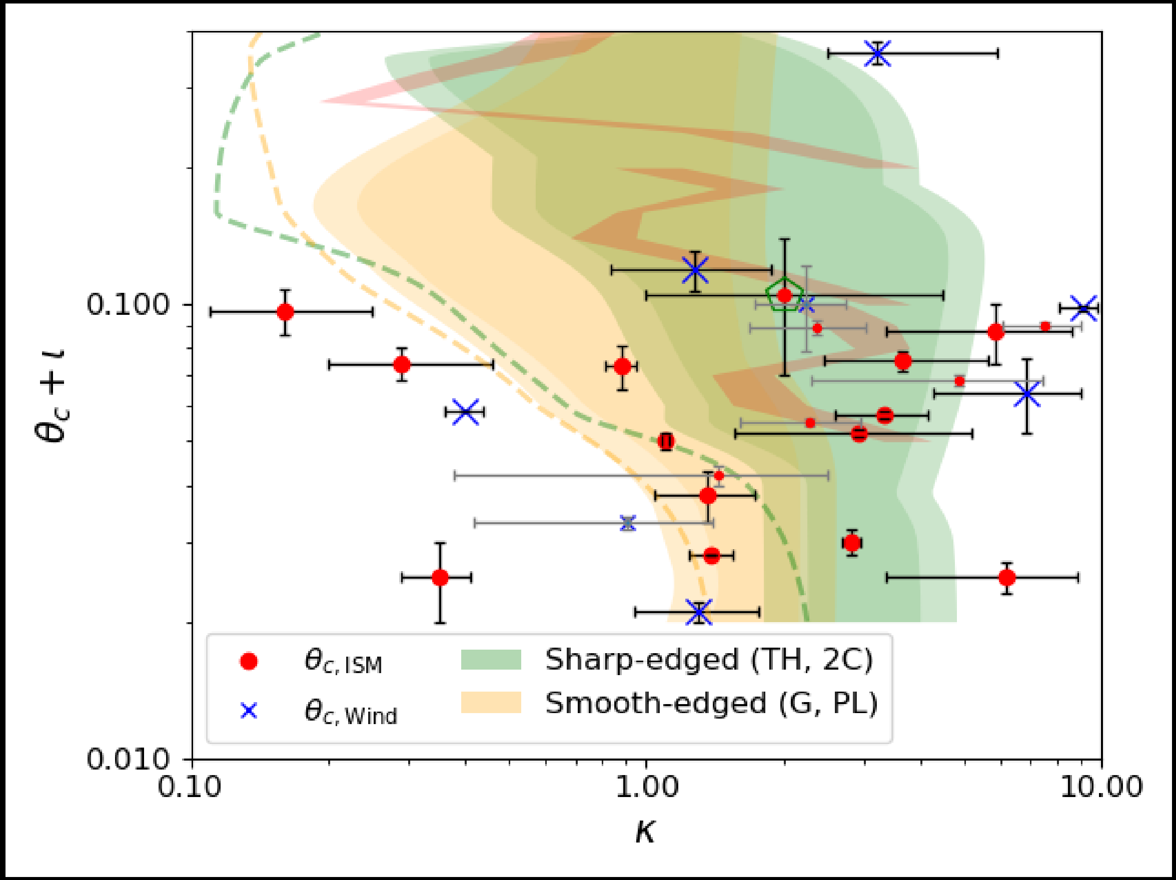
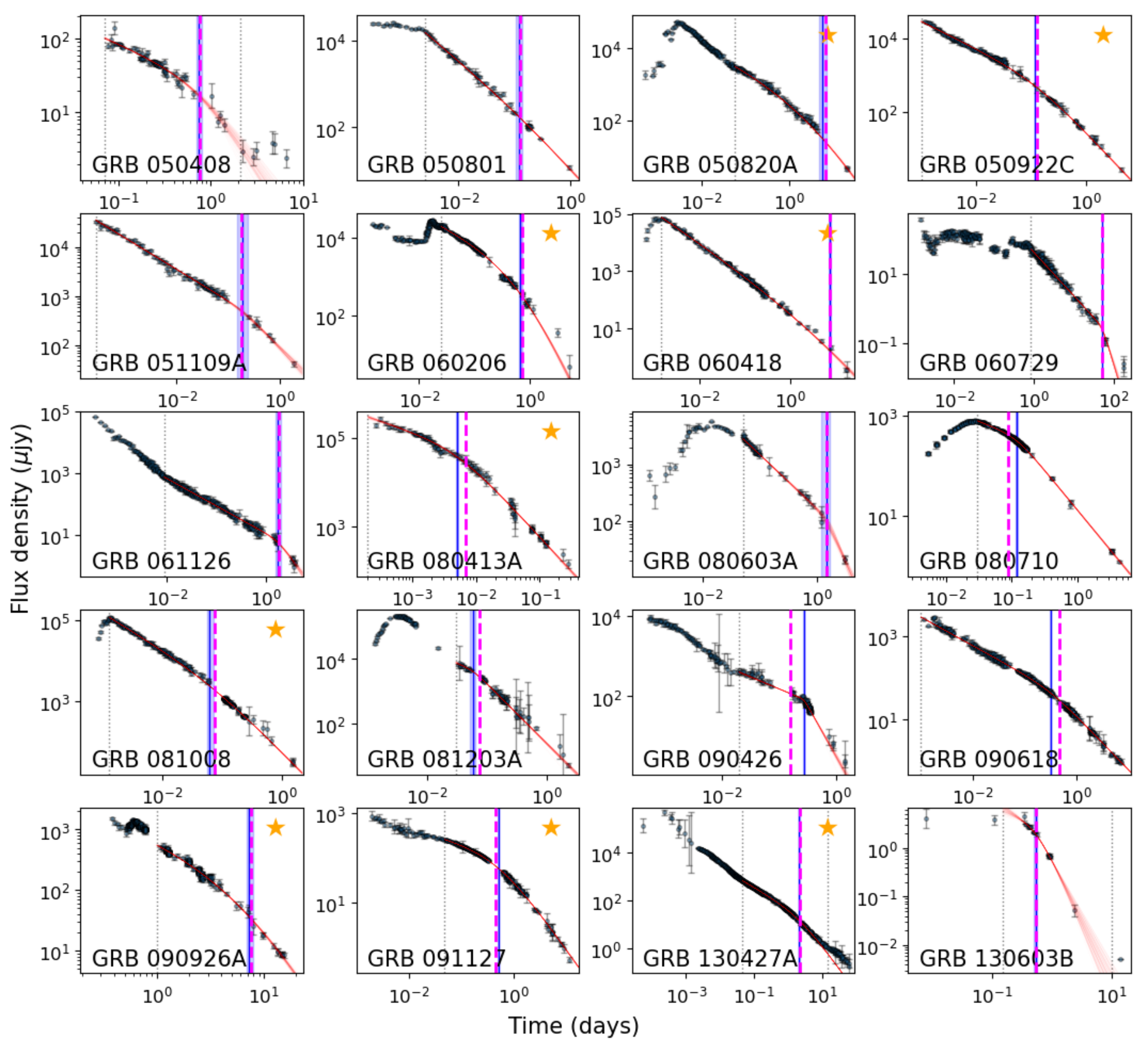
Observed in GRBs? - hints of diverse jet structures





19 long GRBs, 1 short GRB – jet break, redshift, follows closure relations:

9 "smooth" edged jets

8 "sharp" edged jets

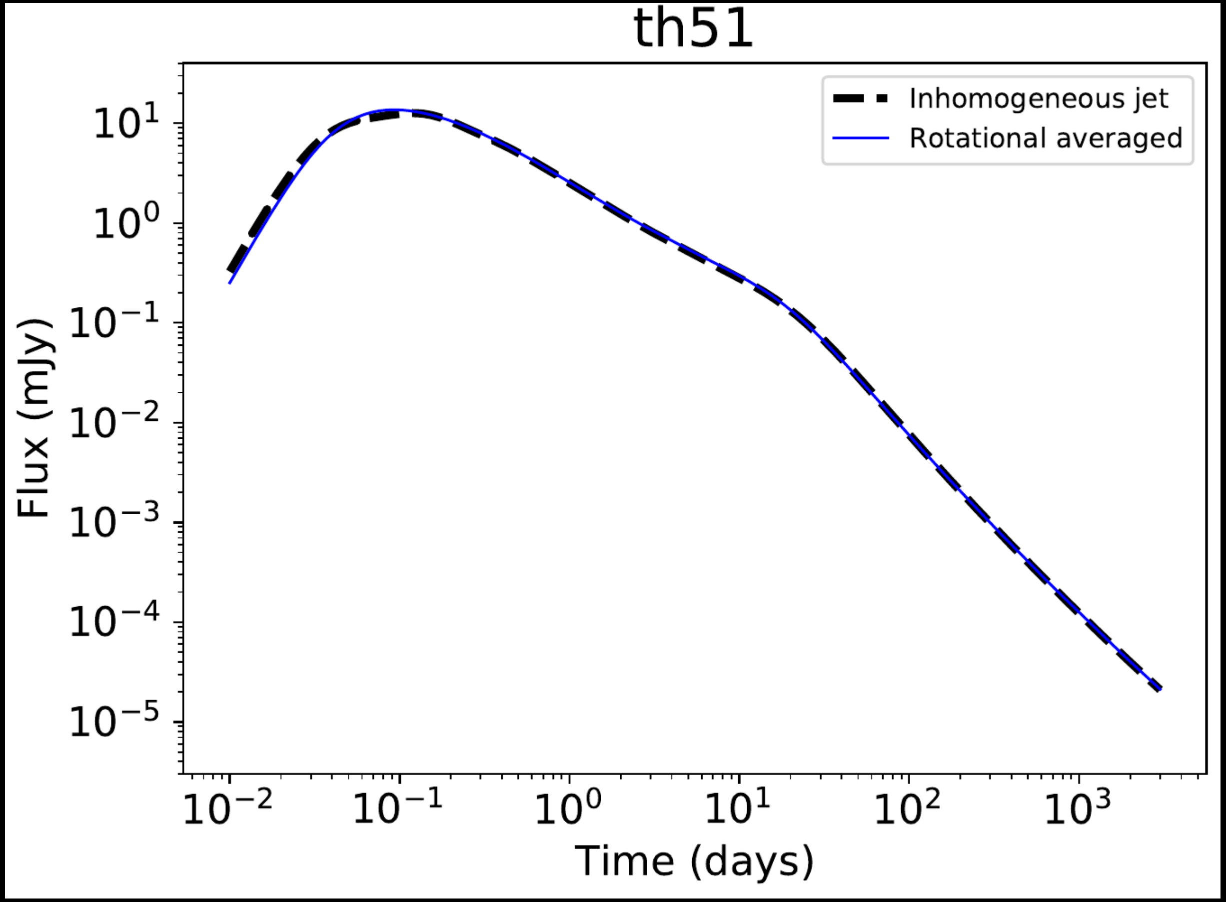
3 indeterminate jets

Lamb, Kann et al. 2021

What is the effect of this inhomogeneity?

- 3D simulations – the jet profile is traditionally averaged through 360 degree rotation, φ.
- This loses the jet structure in φ
- Could preserving this φ structure produce some variability in the afterglow?

- **No**; not a significant difference

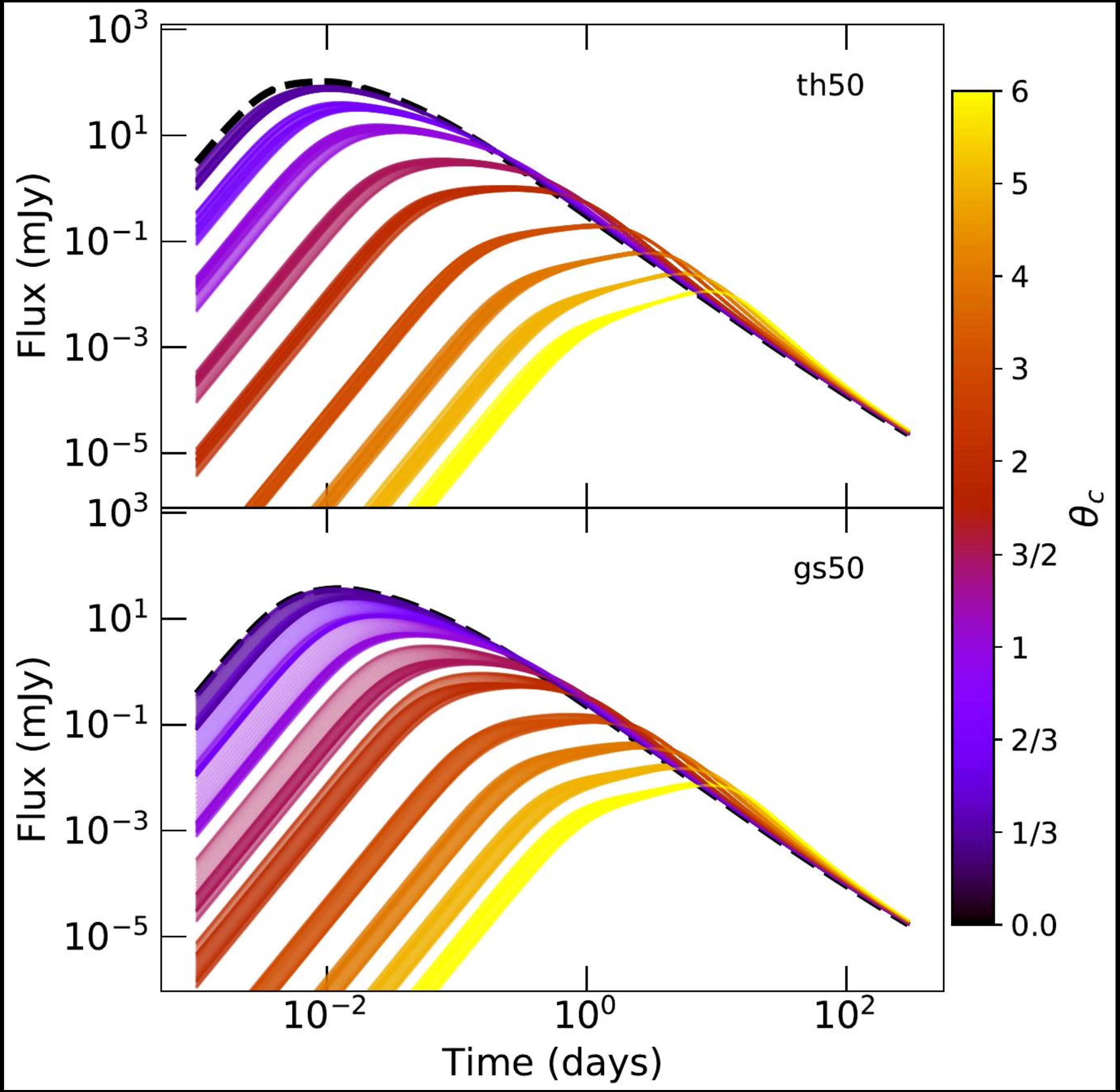


Comparison of an afterglow using the rotationally averaged profile, versus one example where the rotational structure is preserved

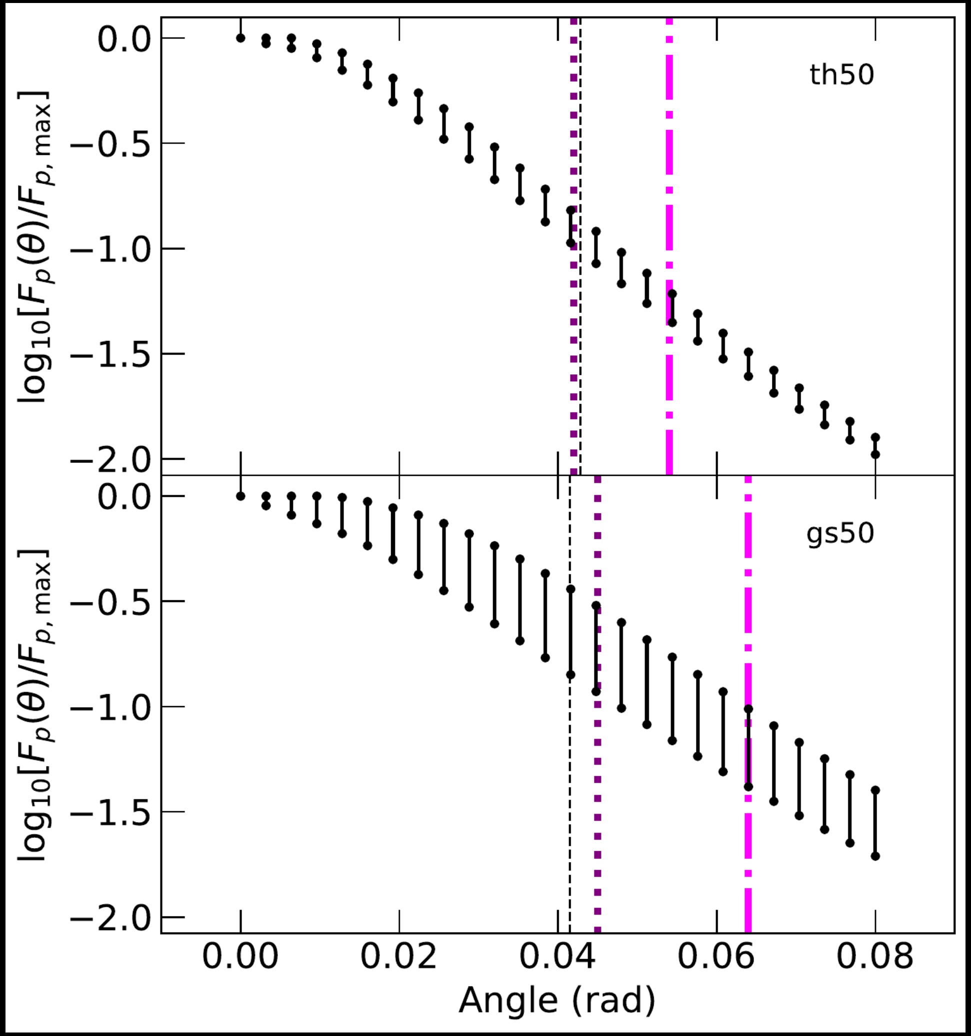
How does this inhomogeneity appear?

- At a fixed polar angle, the rotational orientation effects the observed, peak afterglow flux
- This is more pronounced for the initially Gaussian jet in our two simulations
- This is expected, as turbulence is more dominant for jet components with lower energy

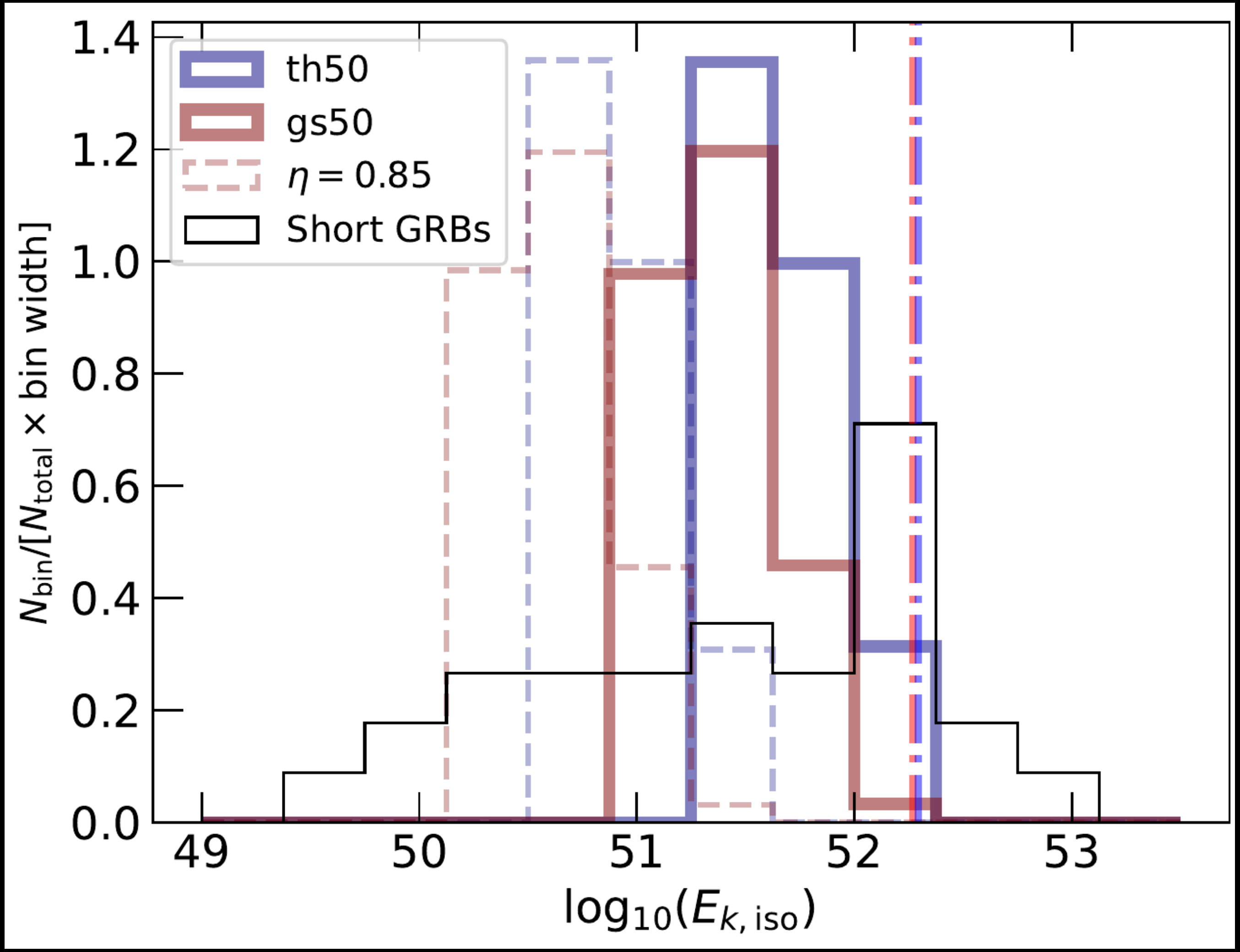
How does this effect our understanding of the short GRB population?



Lamb et al. 2022



The afterglow peak flux is proportional to the kinetic energy, $F_p \propto E_k^{(3+p)/4}$
The range of F_p for a fixed polar angle through the jet rotation in φ.

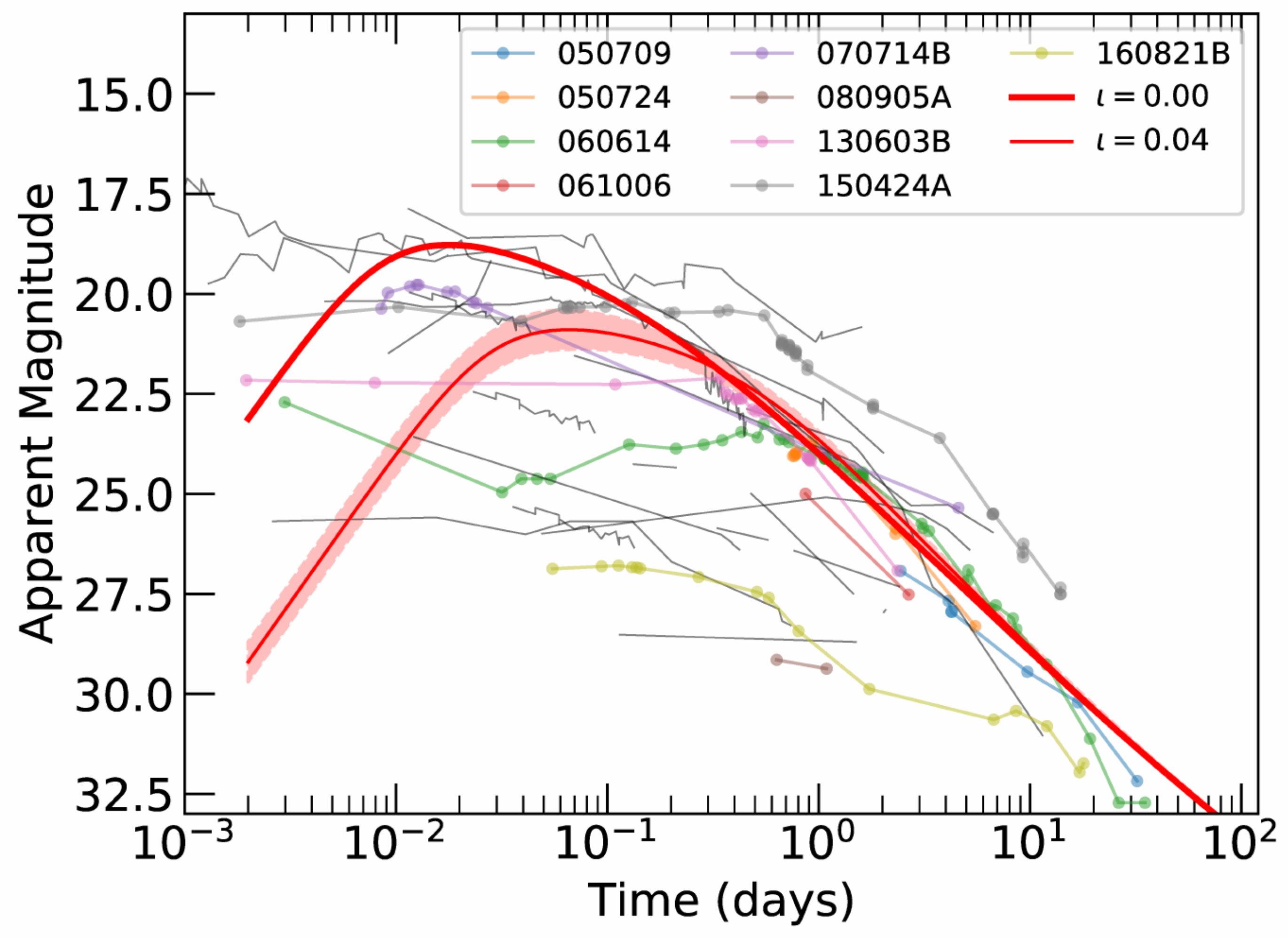


Inferred E_K for each of the afterglow lightcurves from a unique population of structured jets viewed at a random angle within the gamma-ray bright region (optically thin) jet.
Short GRB population shown for comparison.

Lamb et al. 2022

How to relate this to GRB afterglows!?

- Kinetic energy distribution assumed fixed parameters: ambient density, microphysics, etc.
- Real afterglow population is quite diverse too...
- Using an averaged structure profile, with fixed parameters – lightcurve broadly consistent with population
- BUT!!! Is it one for all?



Lamb et al. 2022