Observational constraints on the structure of GRB jets and lessons from GW170817

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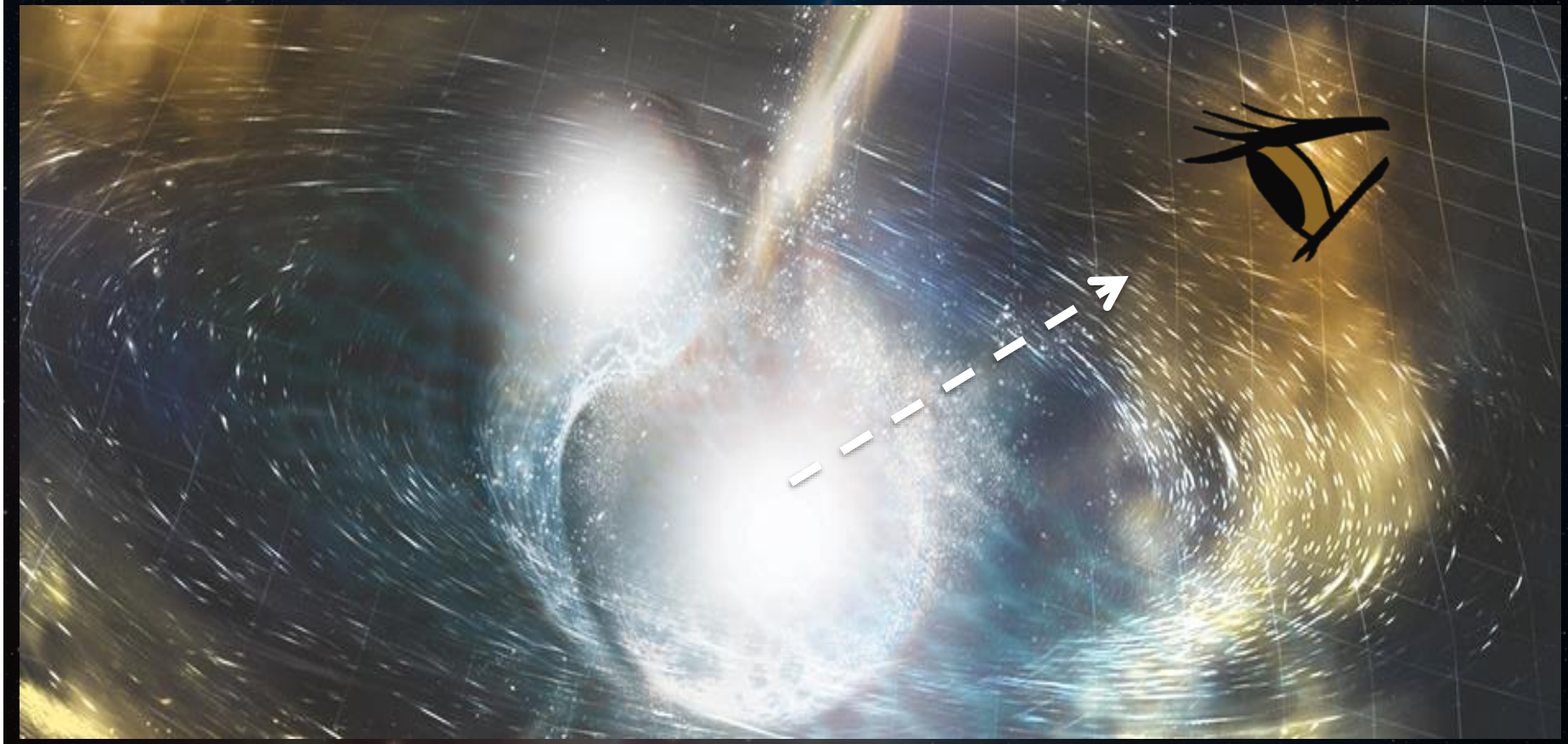
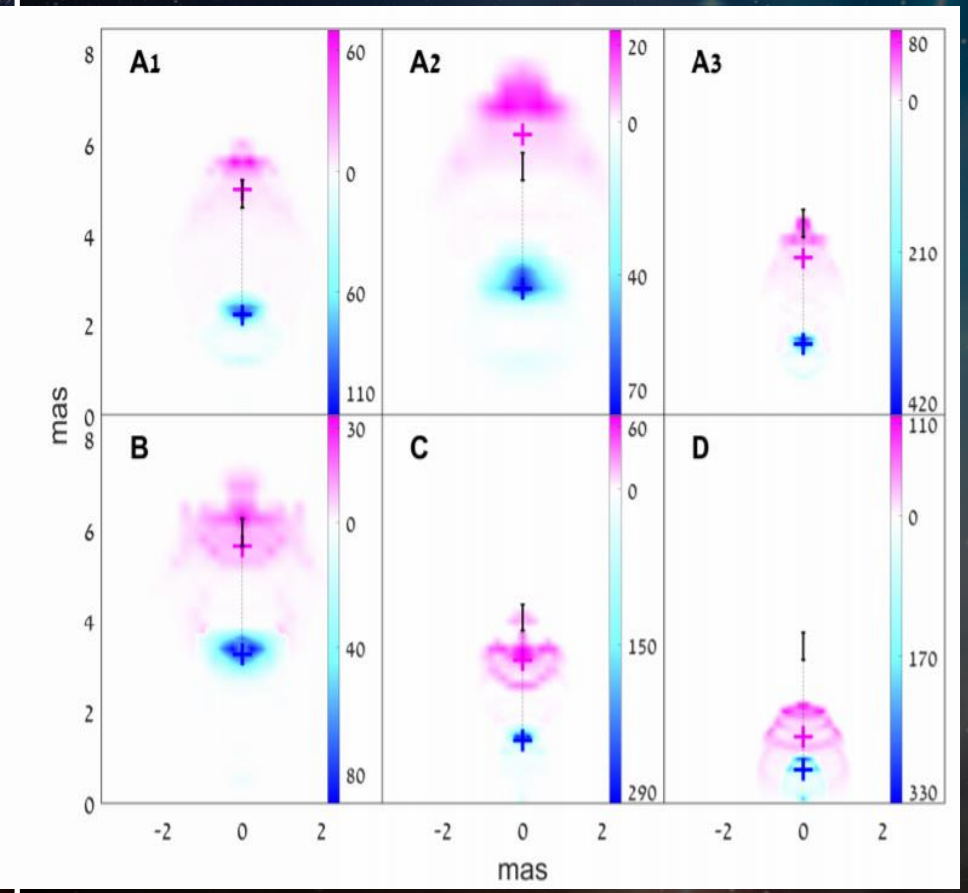
GRB170817 – First confirmed off-axis GRB



- Trigger by GW – detection and follow-up of very faint GRB

Lessons from the afterglow – Successful narrow jet viewed off-axis

Superluminal motion



Mooley et al 18

Rapid decline post peak

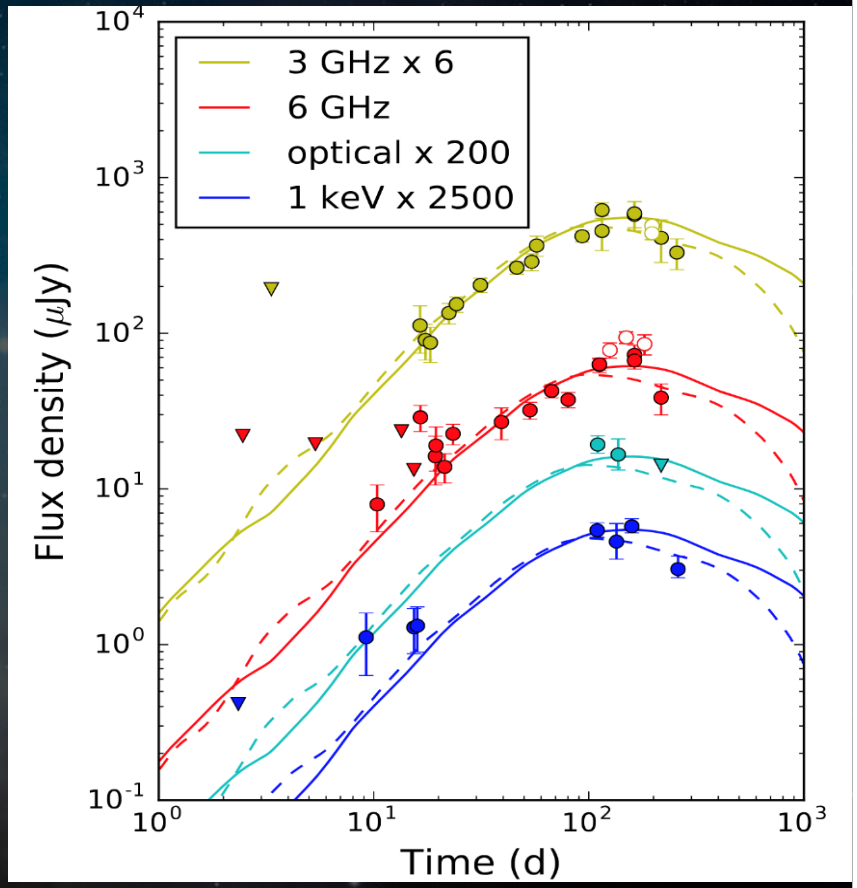
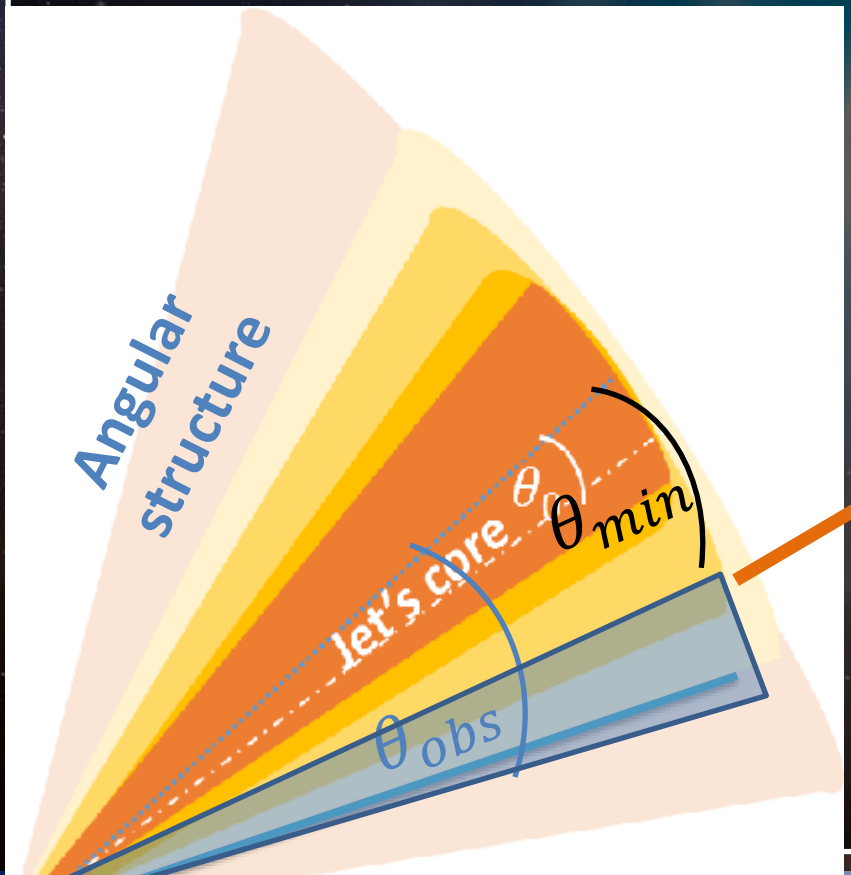
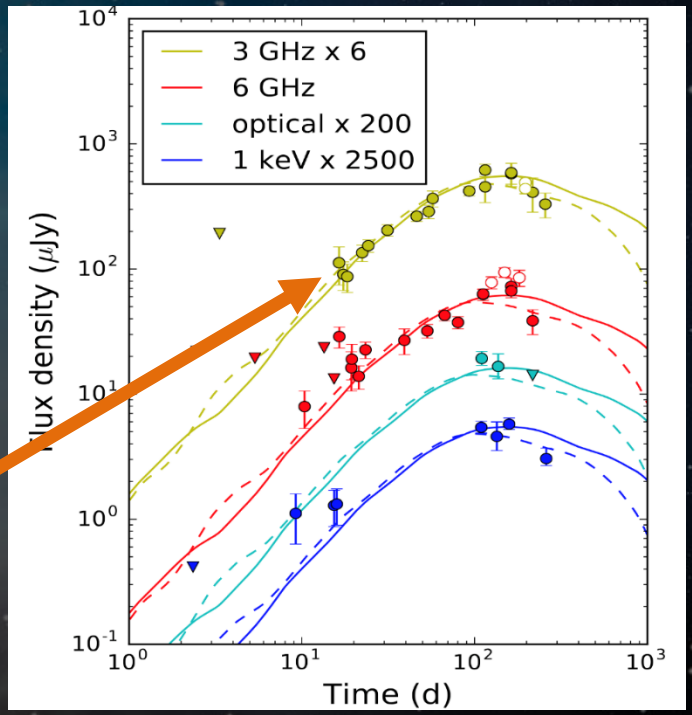


Image from Alexander et al 18; See also: Pooley et al. 18, Troja et al. 18, Ghirlanda et al. 18

Lessons from the afterglow – Successful narrow jet viewed off-axis

- Afterglow dominated by angular profile of E and Γ
- Initial view off-axis. With time inner material with more energy becomes visible.





Light-curve increases as more energetic material contributes

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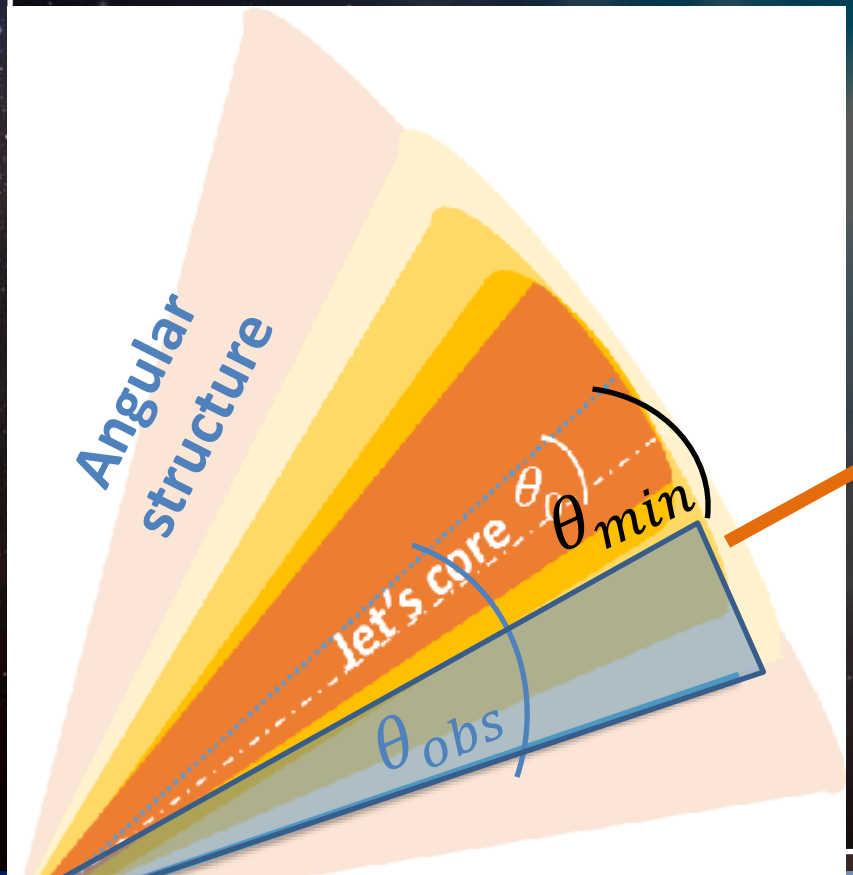

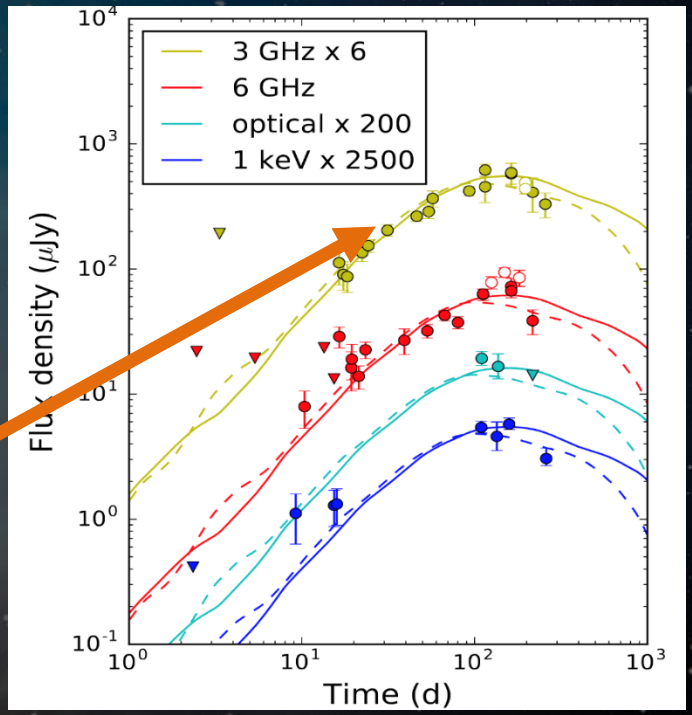

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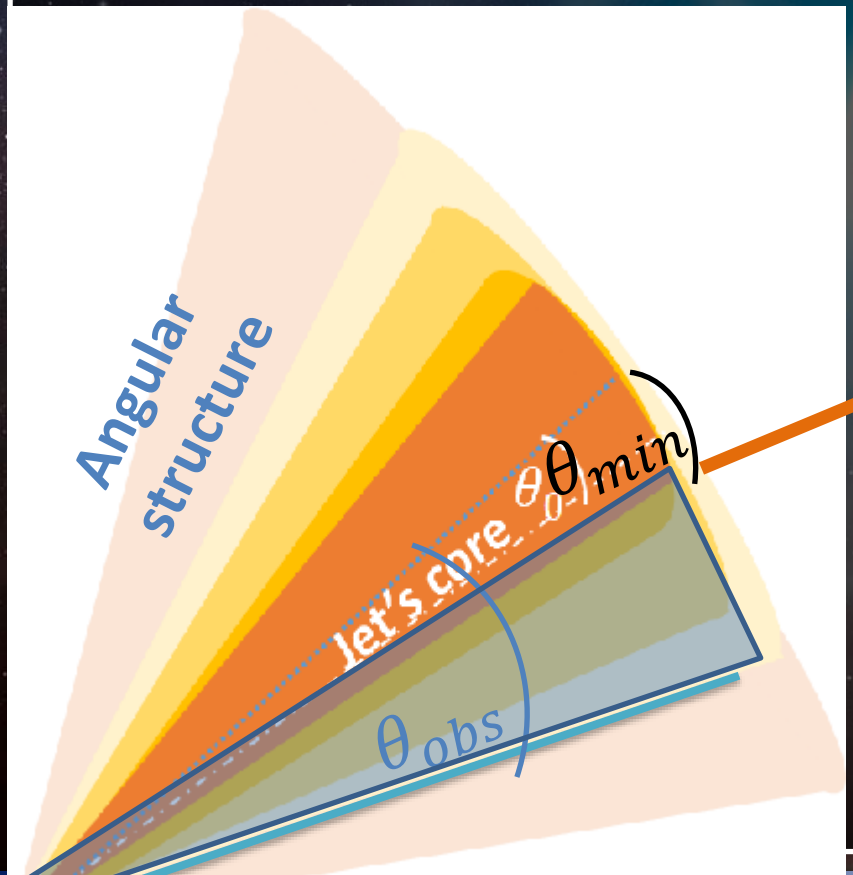

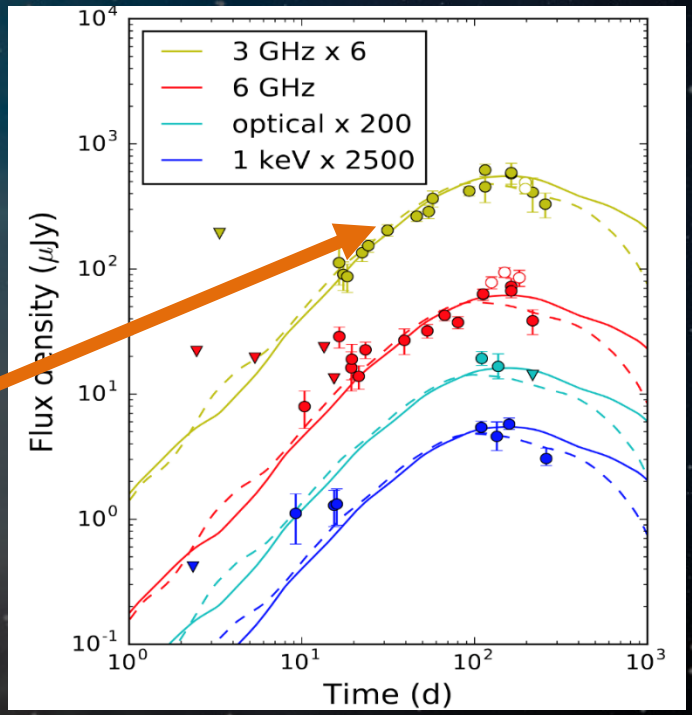

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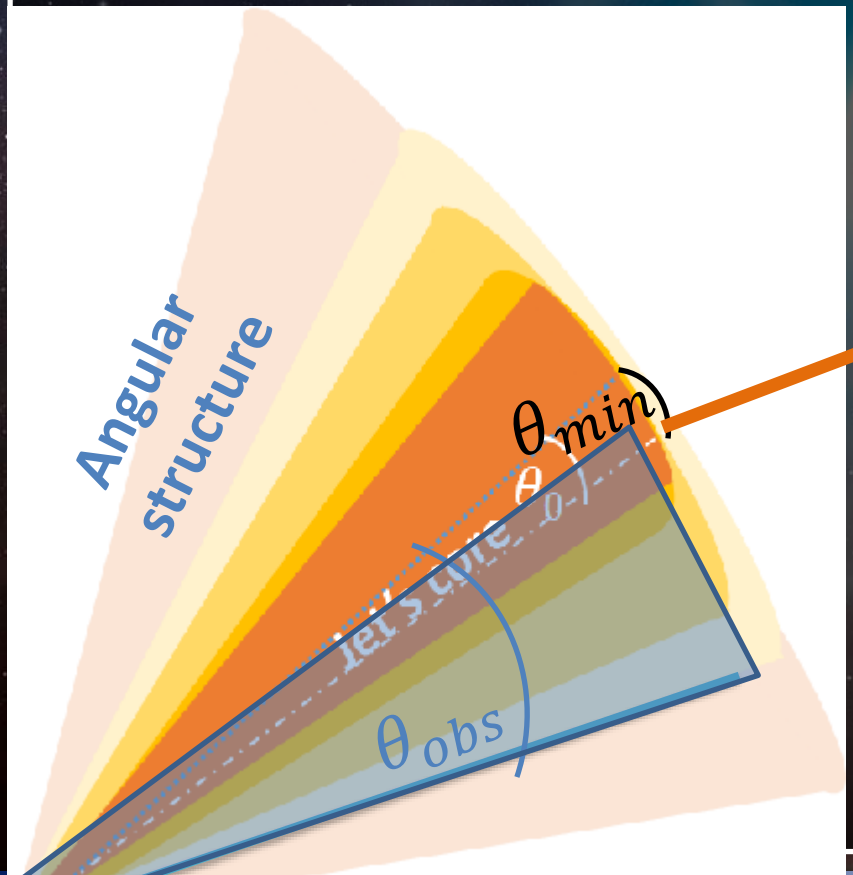
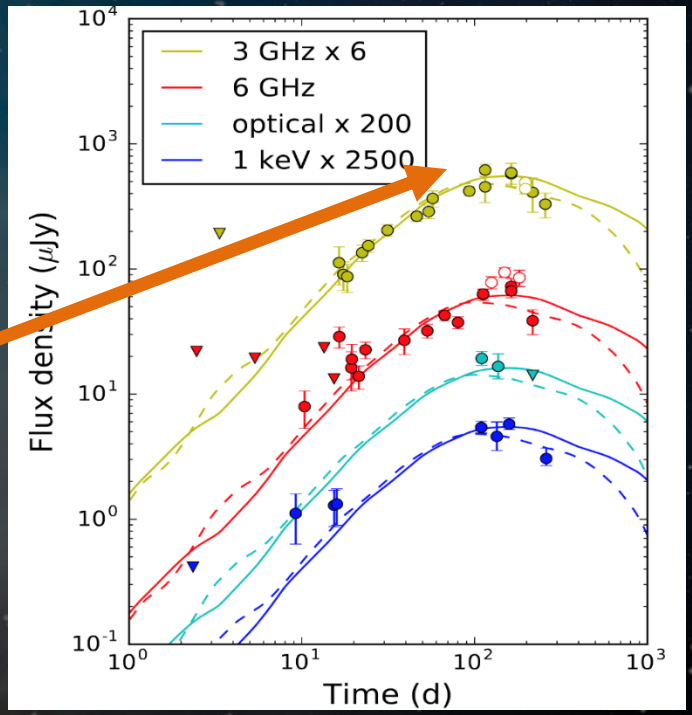


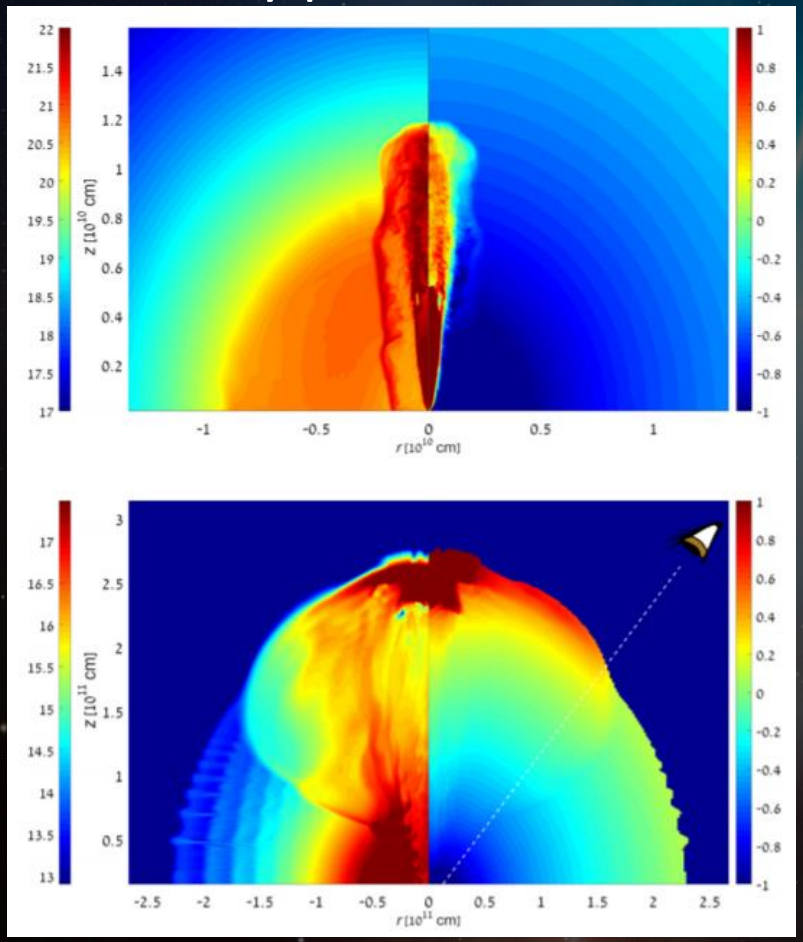


Light-curve increases as more energetic material contributes

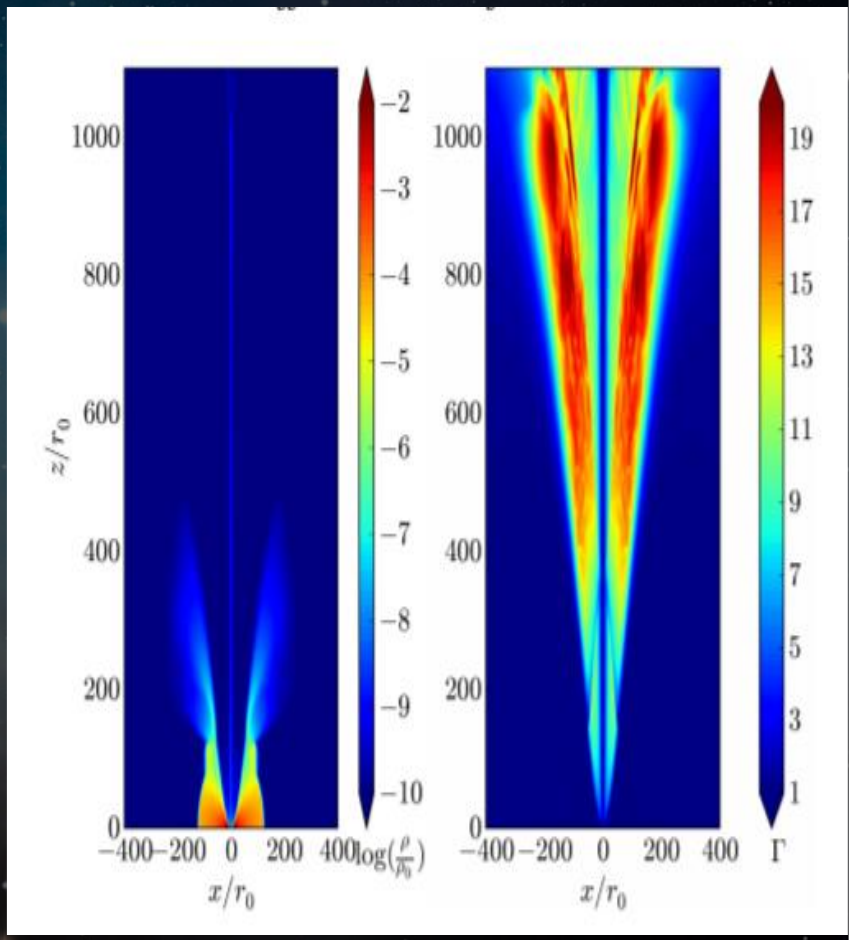
Open question: Prompt emission dominated by angular jet or cocoon?

Cocoon – large energy content beyond the core but inefficient γ-ray production

Steep angular profile – dominates energy radiated in γ-rays



Gottlieb et al 18

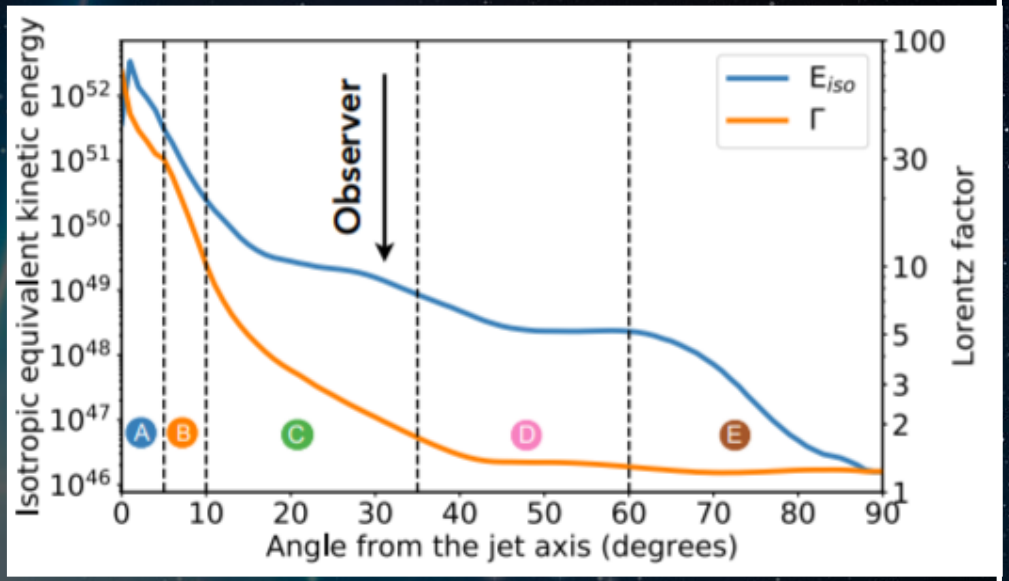


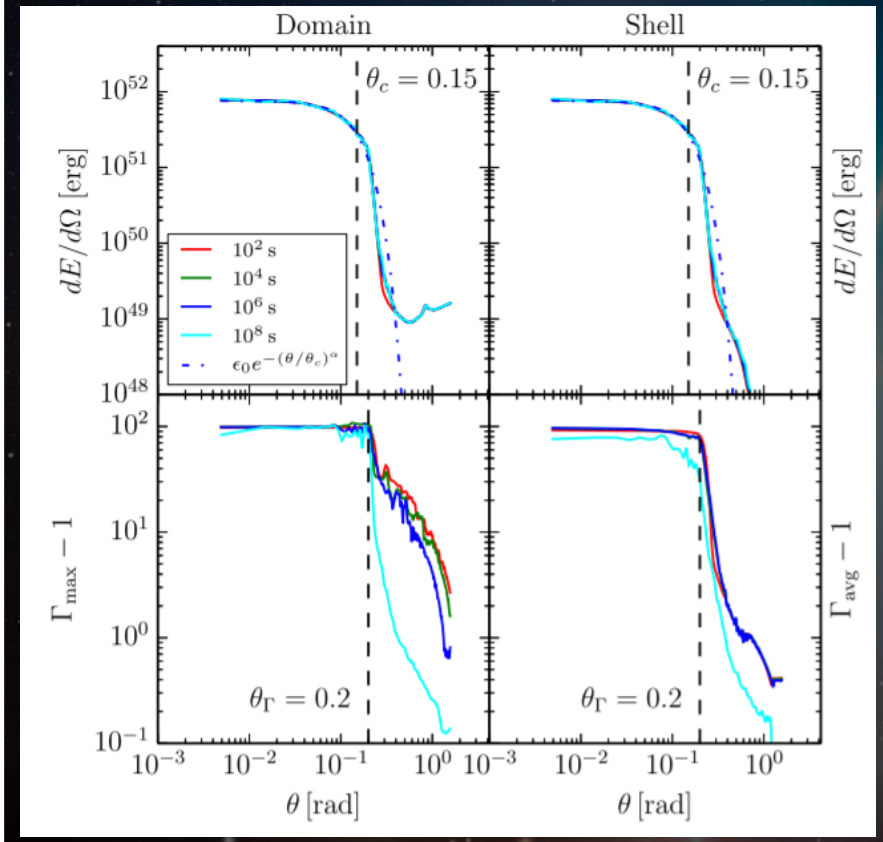
Kathirgamaraju et al 18

Distributions of energy and Lorentz factor

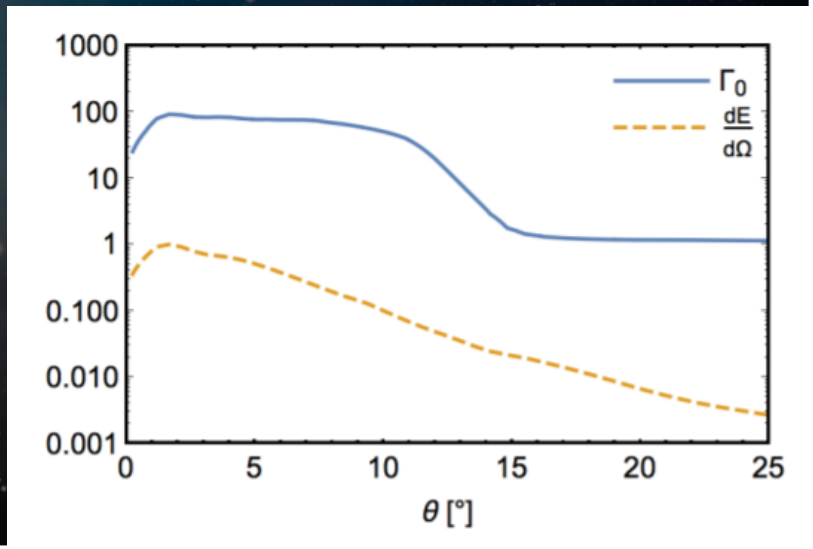
Simulations

Lazzati et al 18





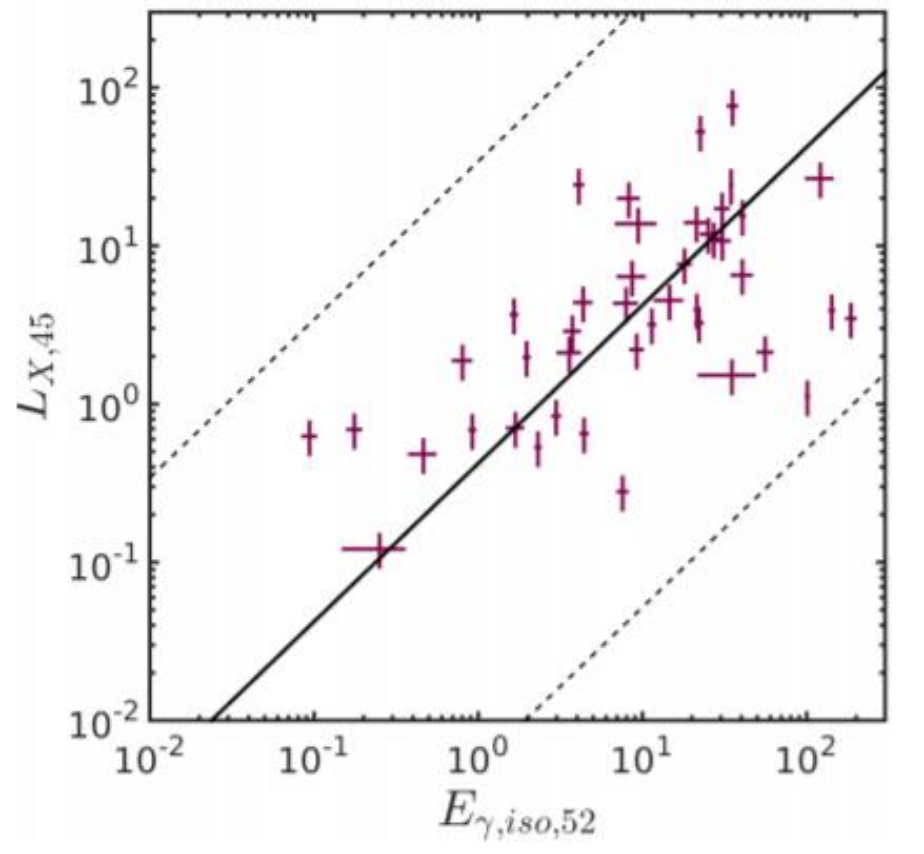
Xie et al 18



Kathirgamaraju et al 18

Evidence from long GRBs

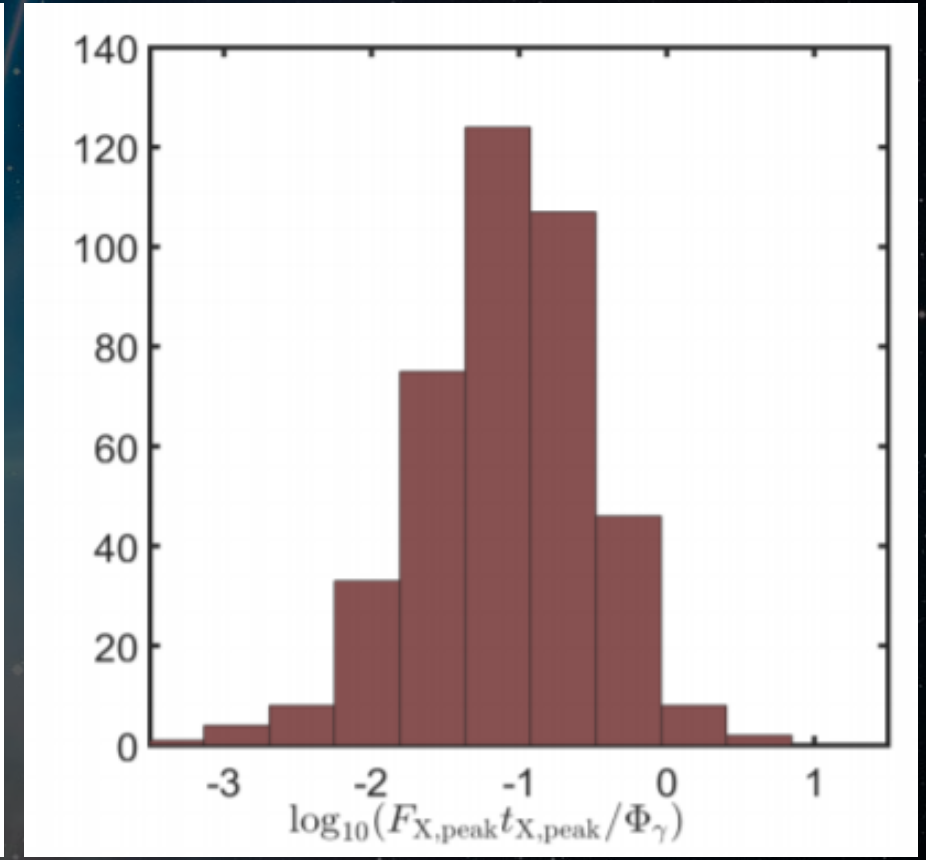
1. Energy in X-ray afterglow roughly correlated with prompt γ-rays



Redshift complete sample

$L_{X,45} = 11\, E_{\gamma,52} \quad \sigma_{log(L_X/E_\gamma)} = 0.51$ at 1 hour

Image from Beniamini, Nava, Piran 16;
data from D'Avanzo et al. 12



All Swift GRBs

$\sigma_{log(F_{X,peak}\, t_{X,peak}/\Phi_\gamma)} = 0.59$

Image from Beniamini & Nakar 18

Evidence from long GRBs

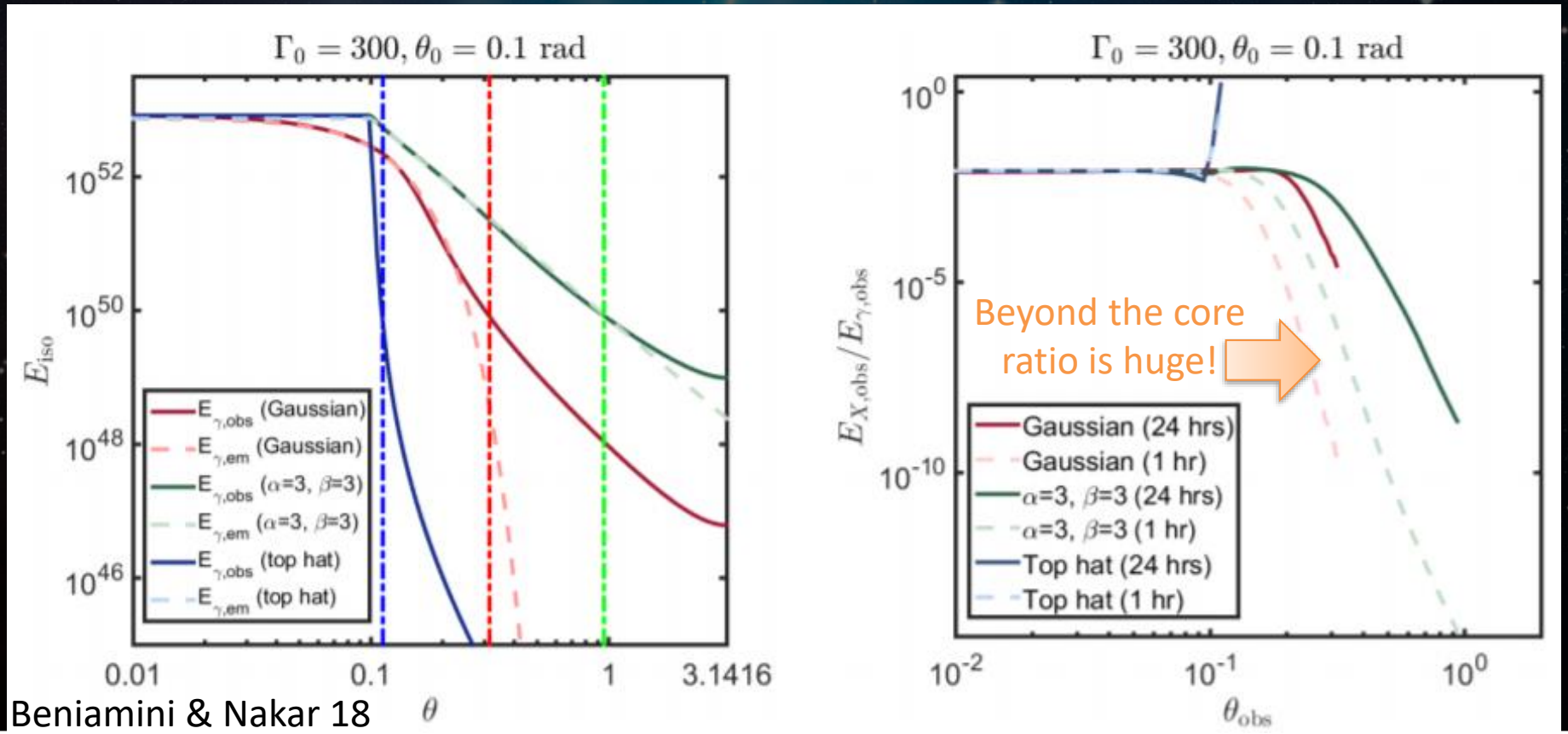
1. Energy in X-ray afterglow roughly correlated with prompt γ-rays

Very limiting for energy and Lorentz factor structures:

- Prompt – typically dominated by $E(\theta)$
- Afterglow – Dominated by $\Gamma(\theta)$

$$E_\gamma \propto E(\theta)$$

$$L_x \propto \frac{E(\theta)}{n}\Gamma(\theta)^8$$



Beniamini & Nakar 18

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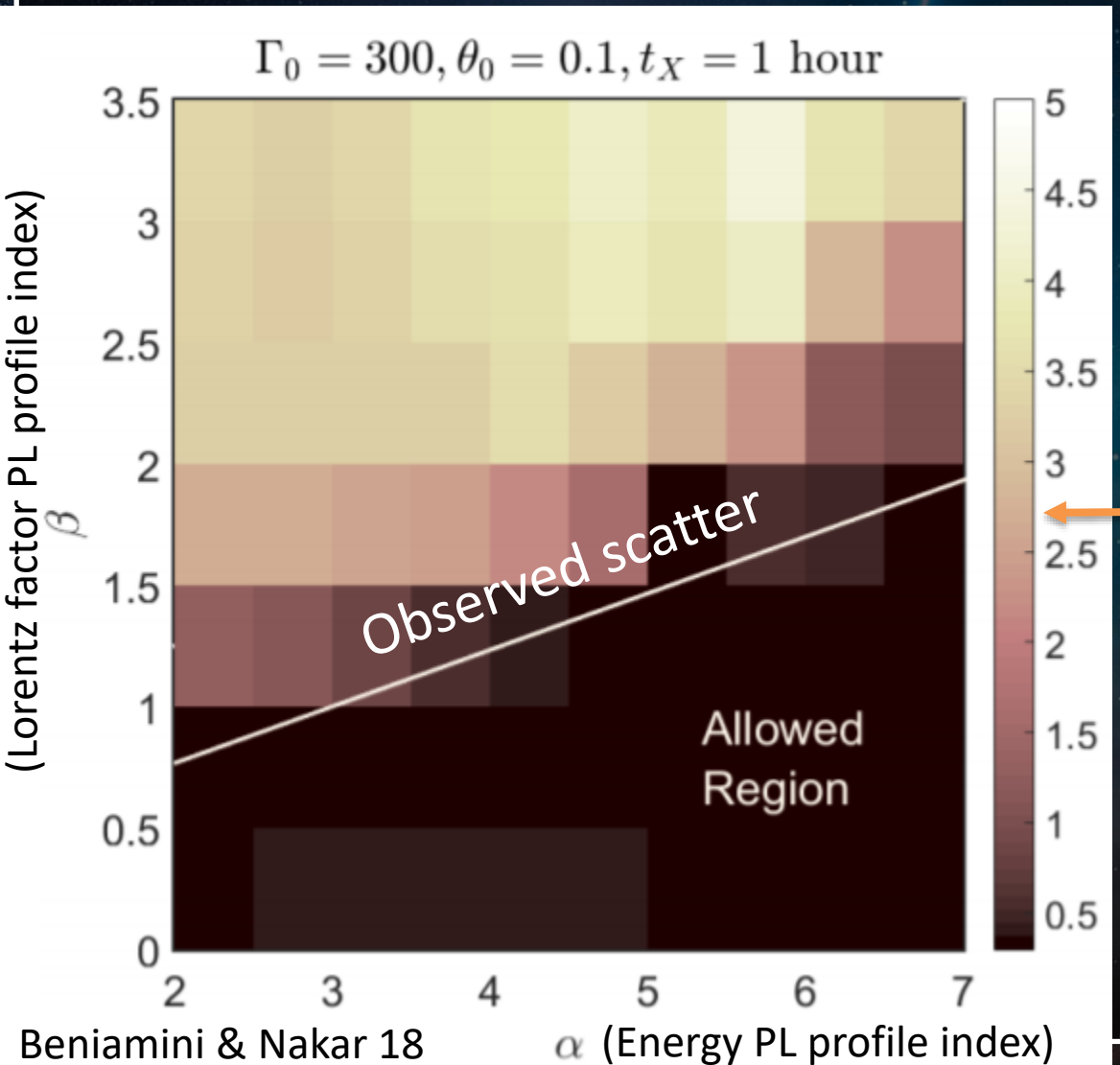
1. Energy in X-ray afterglow roughly correlated with prompt γ-rays

Monte Carlo simulations limit allowed models



Beniamini & Nakar 18

$$\epsilon(\theta) = \frac{dE}{d\Omega} = \epsilon_0 \begin{cases} 1 & \theta < \theta_0 \\ \left(\frac{\theta}{\theta_0}\right)^{-\alpha} & \theta \geqslant \theta_0 \end{cases}$$

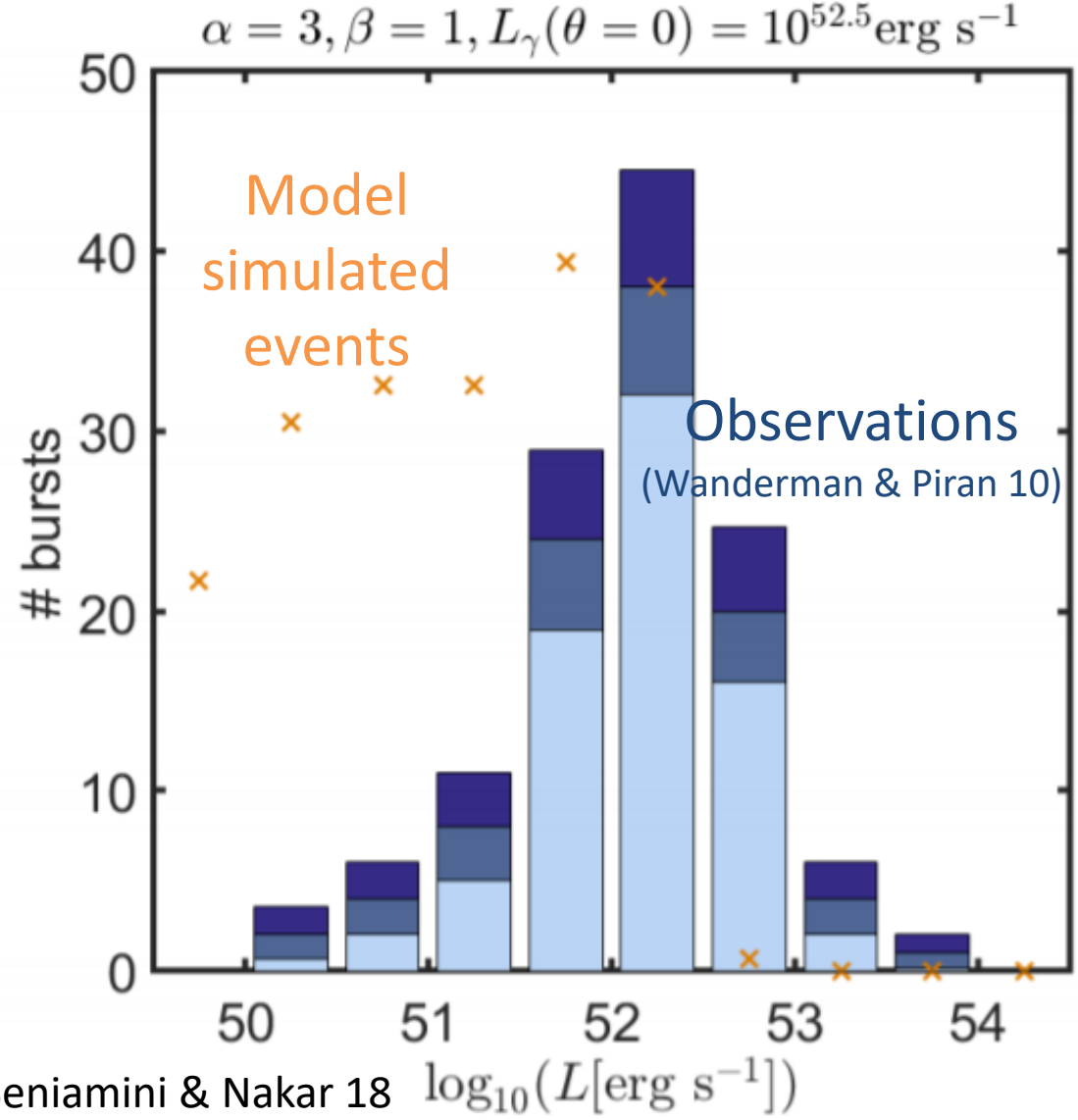
$$\Gamma(\theta) = 1 + (\Gamma_0 - 1) \begin{cases} 1 & \theta < \theta_0 \\ \left(\frac{\theta}{\theta_0}\right)^{-\beta} & \theta \geqslant \theta_0 \end{cases}$$

$\sigma_{\log(E_X/\gamma)}$

Steep structure with rather constant Lorentz factor required

Evidence from long GRBs

2. Mustn't overproduce GRBs below γ-ray luminosity function peak



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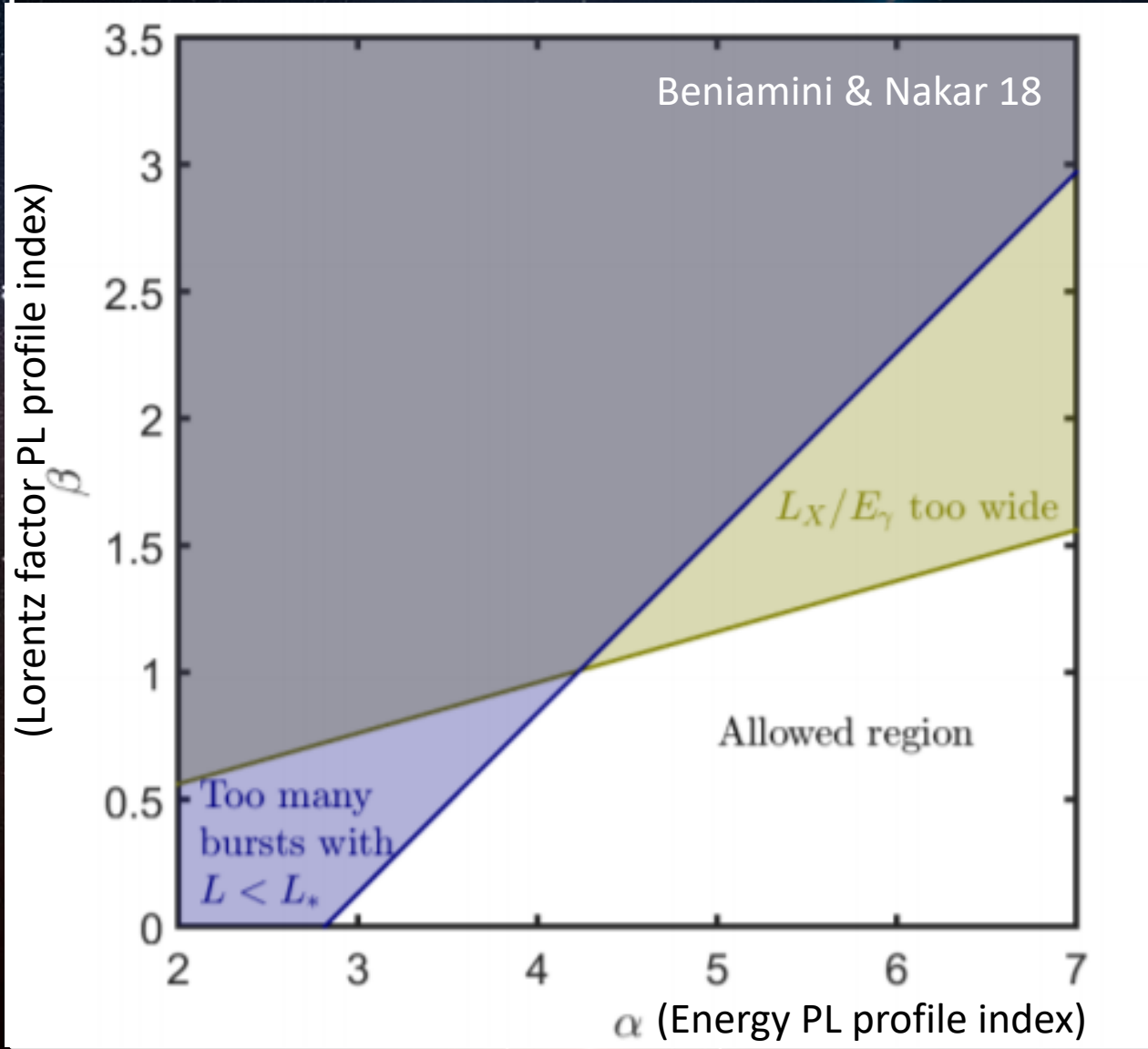
Even if all bursts have L_* at core, lower L bursts are overproduced due to bursts detectable off-axis

Evidence from long GRBs

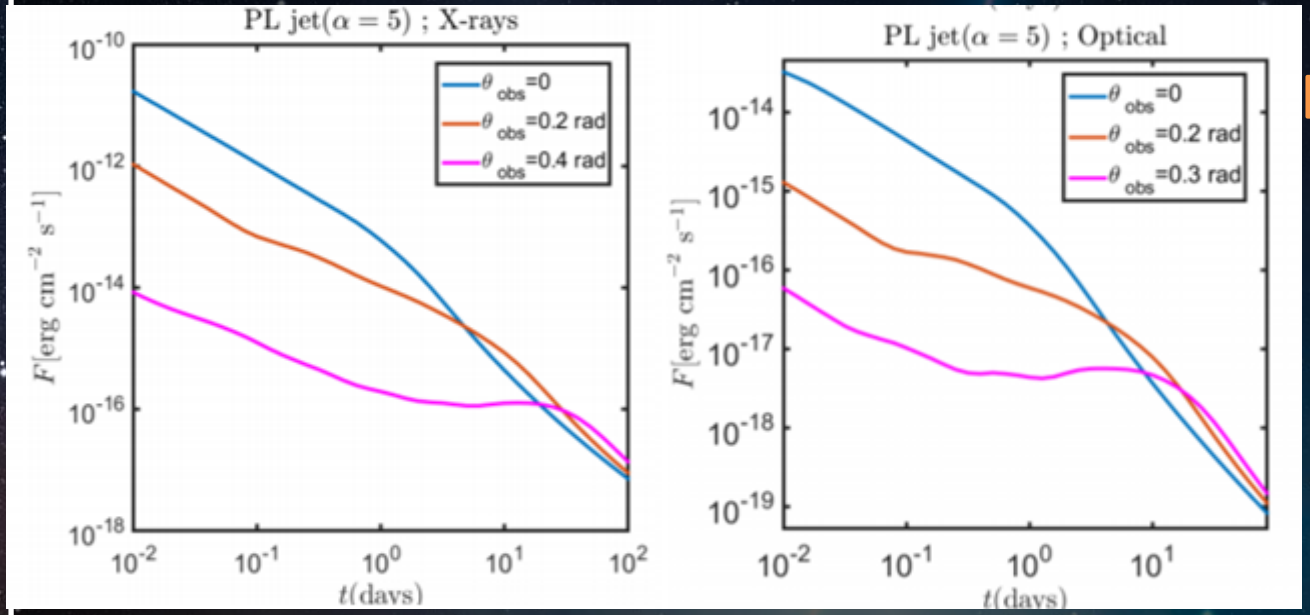
Combining both constraints:



Steep structure with rather constant Lorentz factor required

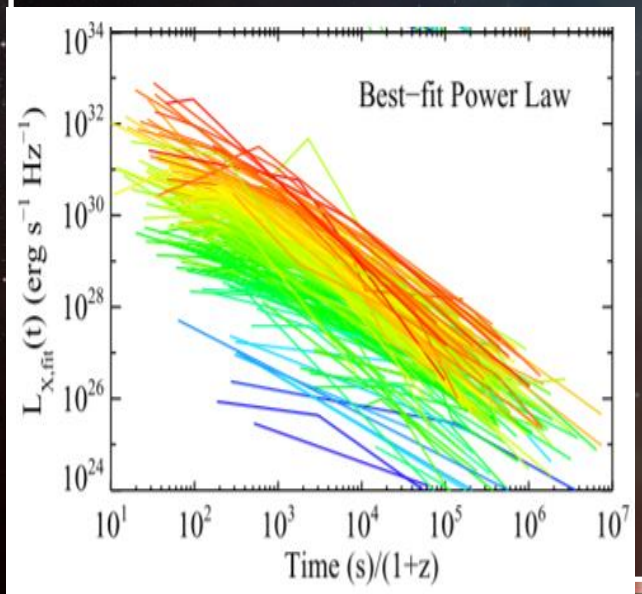
Evidence from long GRBs

3. Even with constant Γ Light-curve evolution extremely peculiar



Even with constant Γ, bursts observable in γ-rays exhibit extended shallow decays / plateaus lasting tens of days

Beniamini & Nakar 18

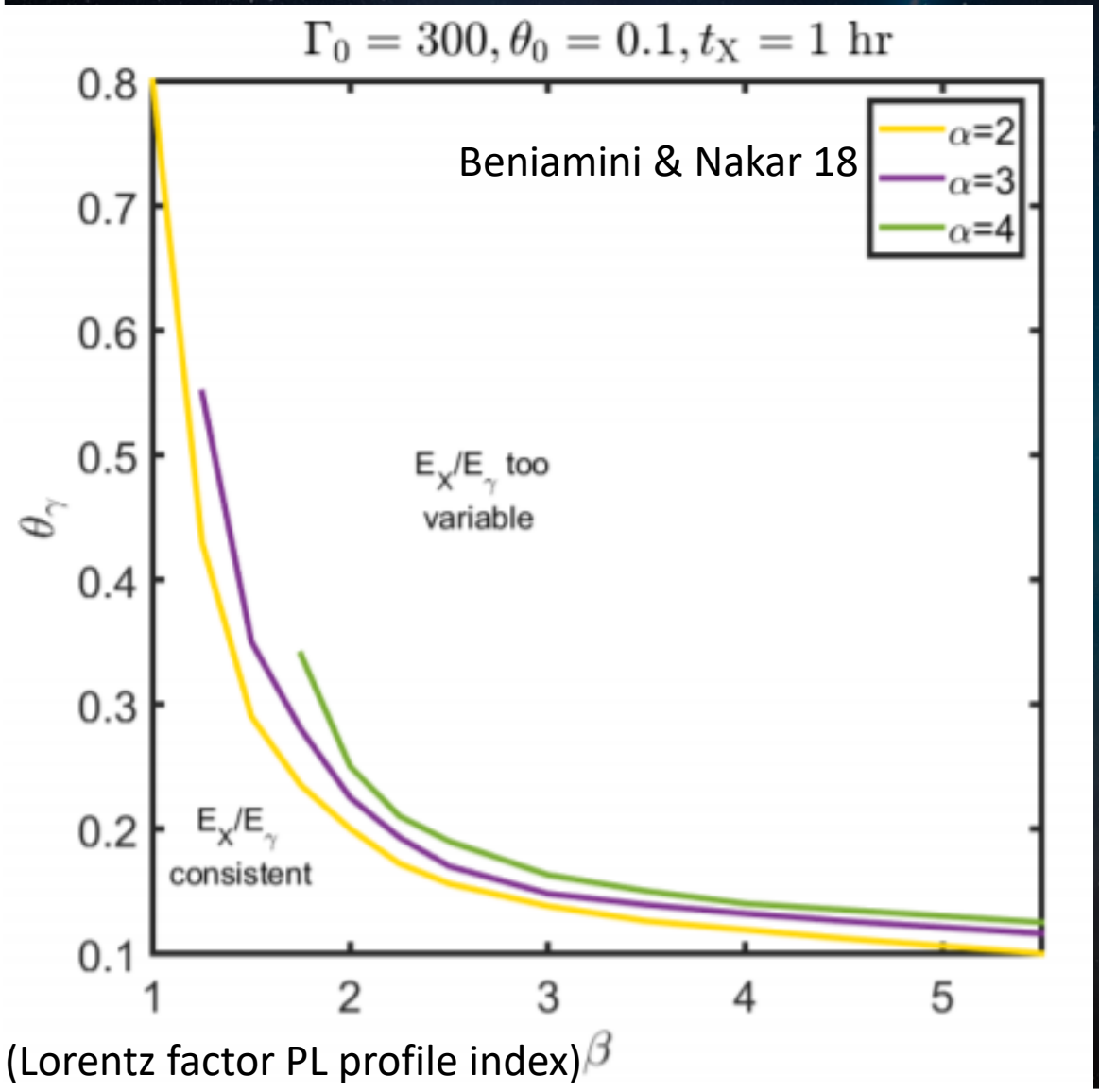


Racusin et al. 16

Unlike *any* known GRB (barring GRB170817) to date, which decay at least as fast as $t^{-1/2}$

Evidence from long GRBs

An alternative possibility: Restrictive γ-ray region



$$E_\gamma \propto \Theta(\theta_\gamma - \theta)$$

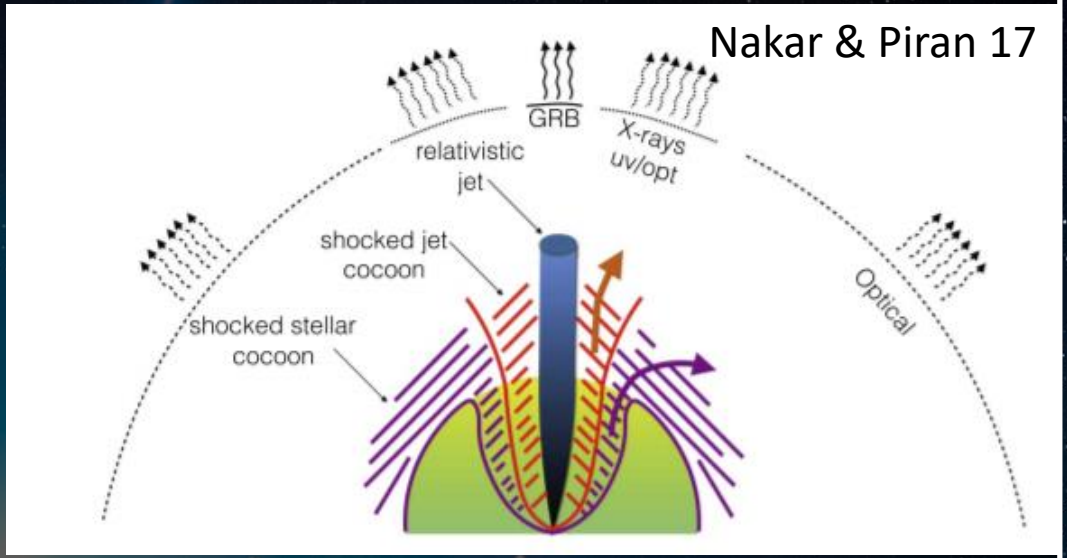
If γ-ray efficiency drops strongly beyond core, results consistent with observations – Shock breakout from a cocoon?

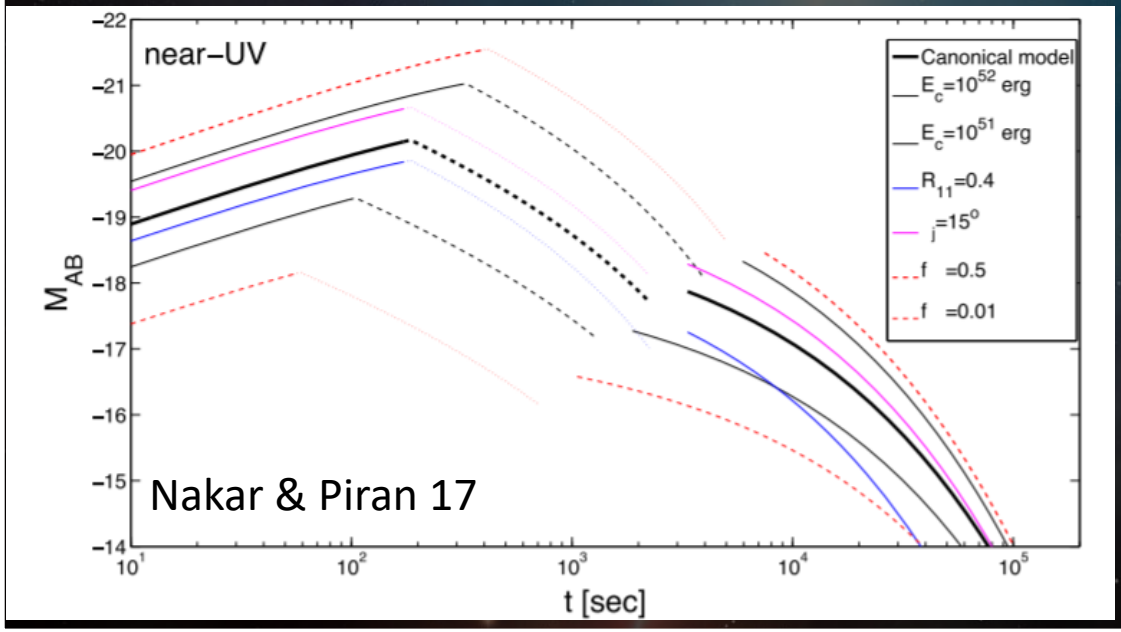
$$\Gamma(\theta_{obs}) \gtrsim 50$$

How can we test this?

For GW detected events the cocoon's large thermal energy is observable directly in UV at $10^{2-3}s$ after GRB

(see Nakar & Piran 17; Beniamini et al. 18)





However

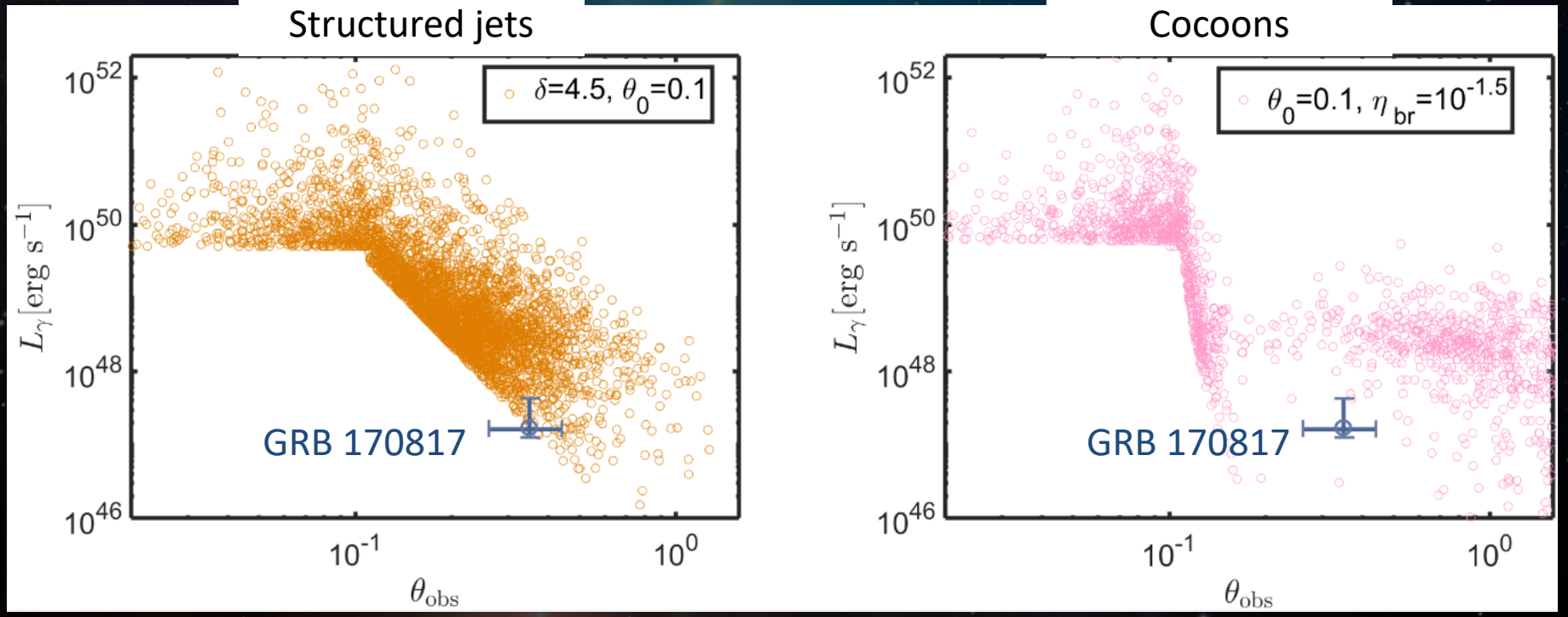
rapid follow-up required

How can we test this? – Future prospects

Nakar & Piran 17

Monte Carlo simulations of different structure models

- Most GW detected events up to 220Mpc undetectable in γ-rays
- Between 1 (cocoon) and 10 (structured jet) joint detections in next decade
- The distributions of L_γ and θ_{obs} can distinguish between models



Beniamini, Petropoulou, Barniol Duran, Giannios 18

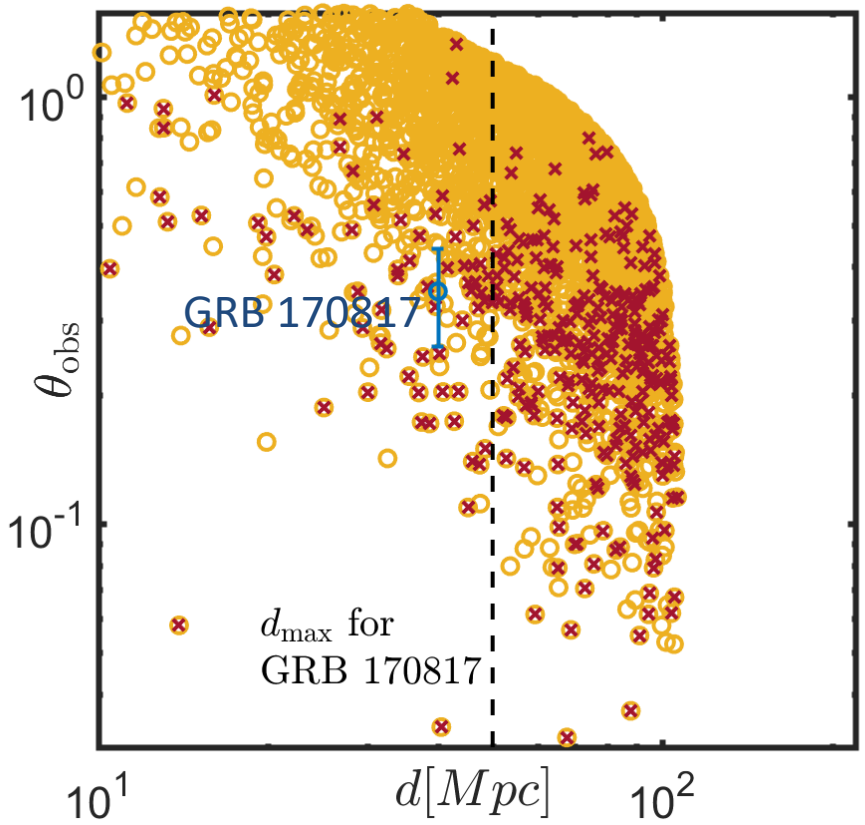
How can we test this? – Future prospects

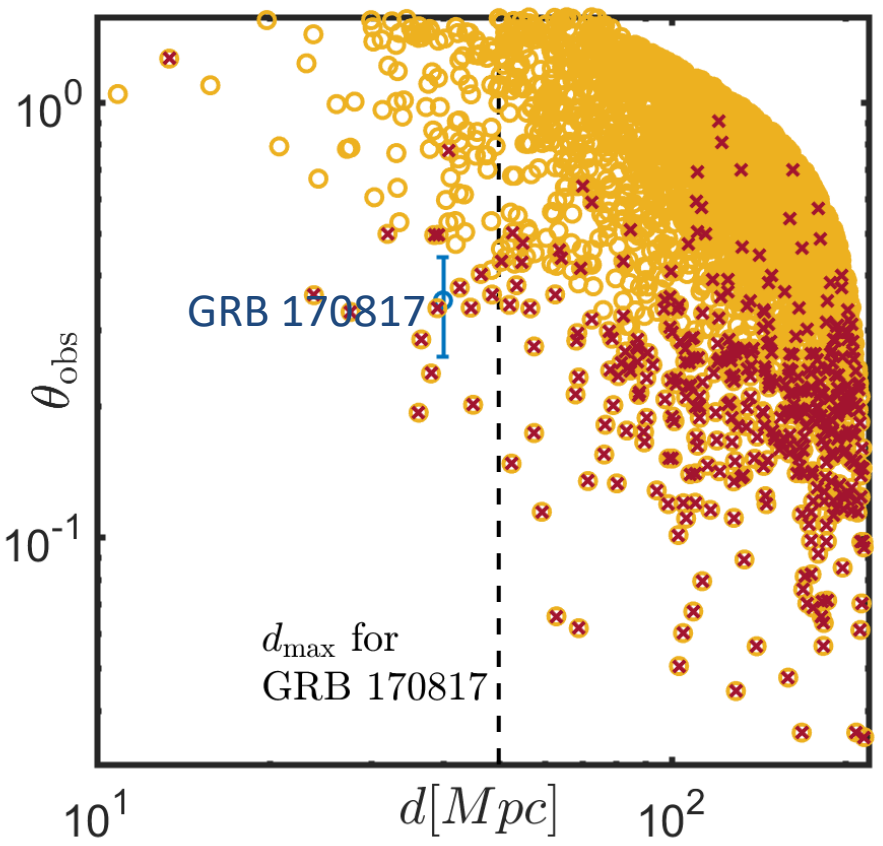
- Events similar to GRB 170817 will be rare!

GW detected events

GW + gamma-ray detected events

110Mpc GW Horizon



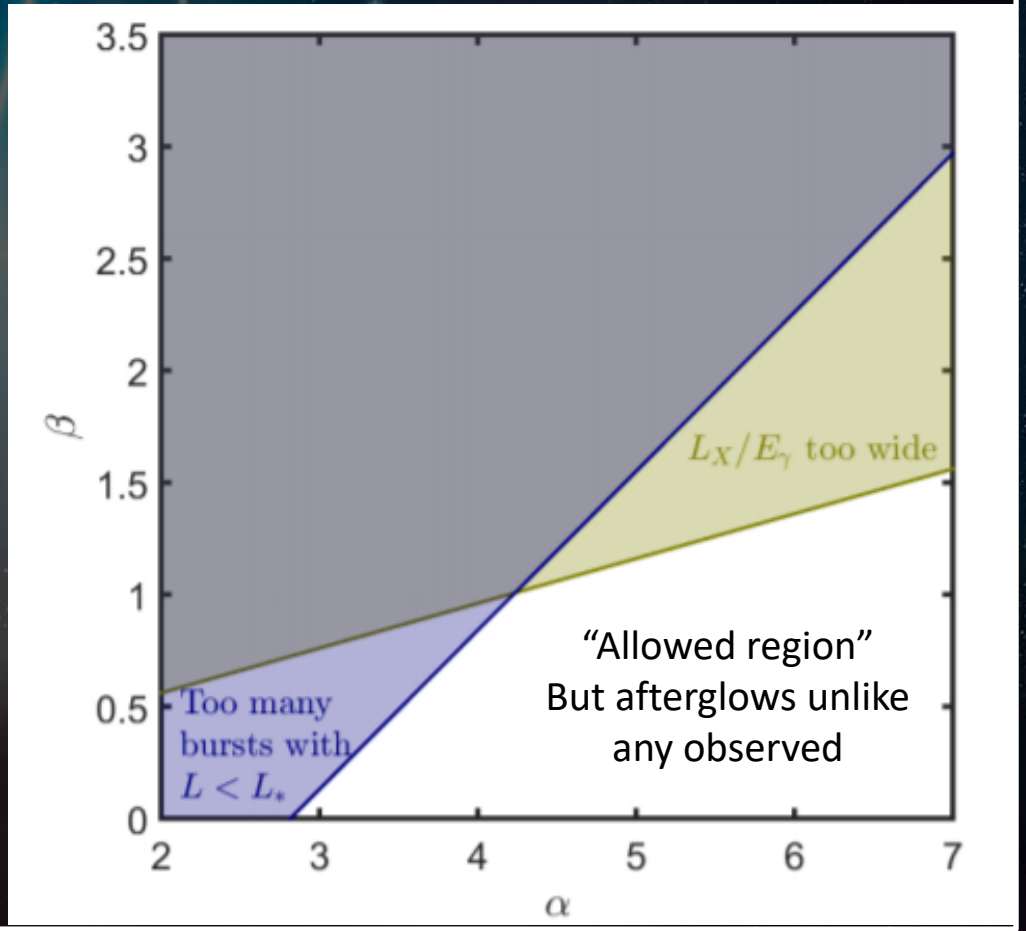


220Mpc GW Horizon

Beniamini, Petropoulou,
Barniol Duran, Giannios 18

Conclusions

- In lGRBs, if energy drops continuously with latitude, efficient γ-ray production restricted to material with $\Gamma > 50$
- Cocoon cooling emission detectable in UV at $\sim 10^{2-3} s$
- sGRBs: Structured jet vs cocoon distinguished by L_γ and θ_{obs} of joint prompt + GW events
- Future events similar to GRB 170817 will be rare




Thank You!

Backup slides

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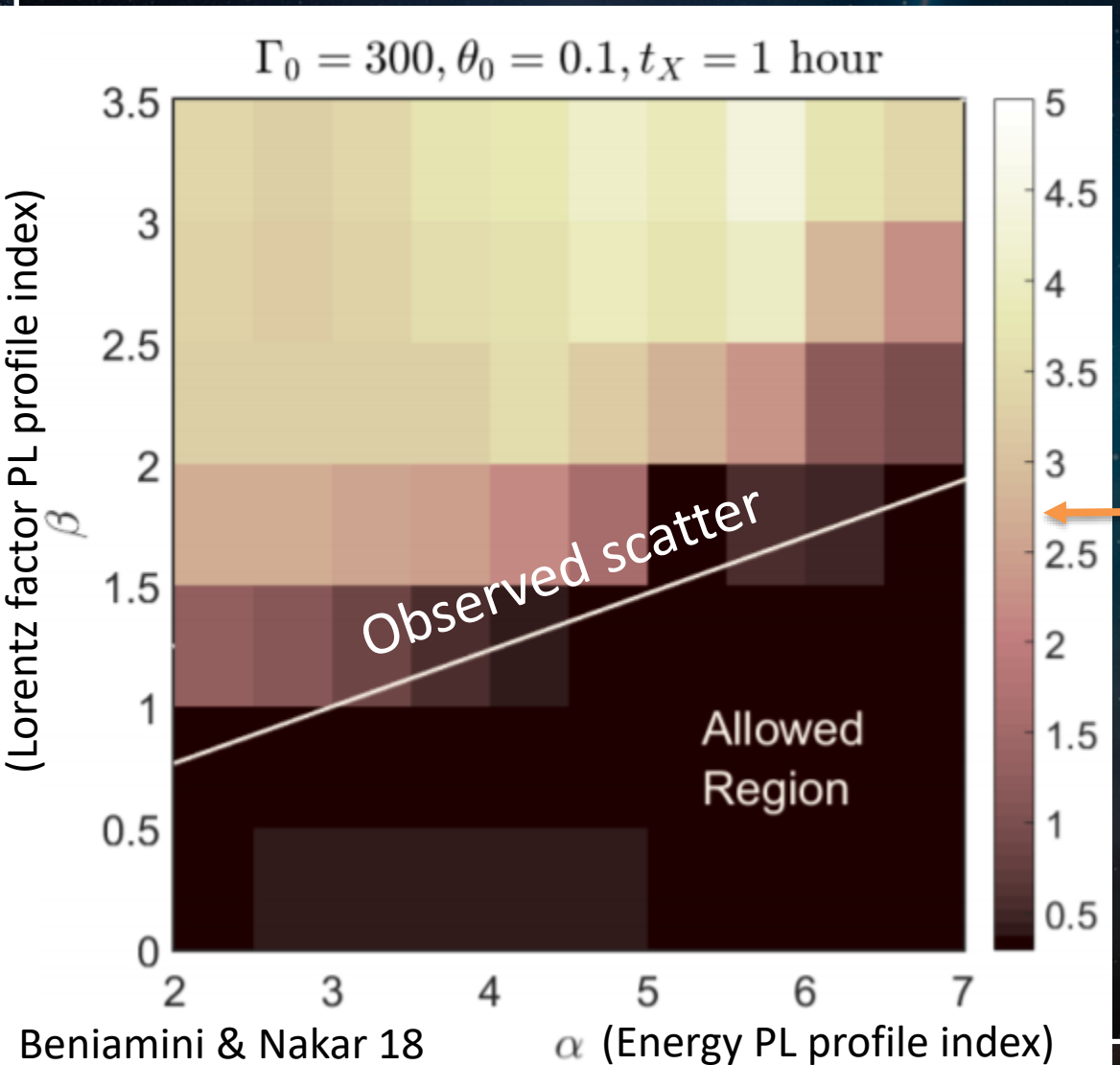

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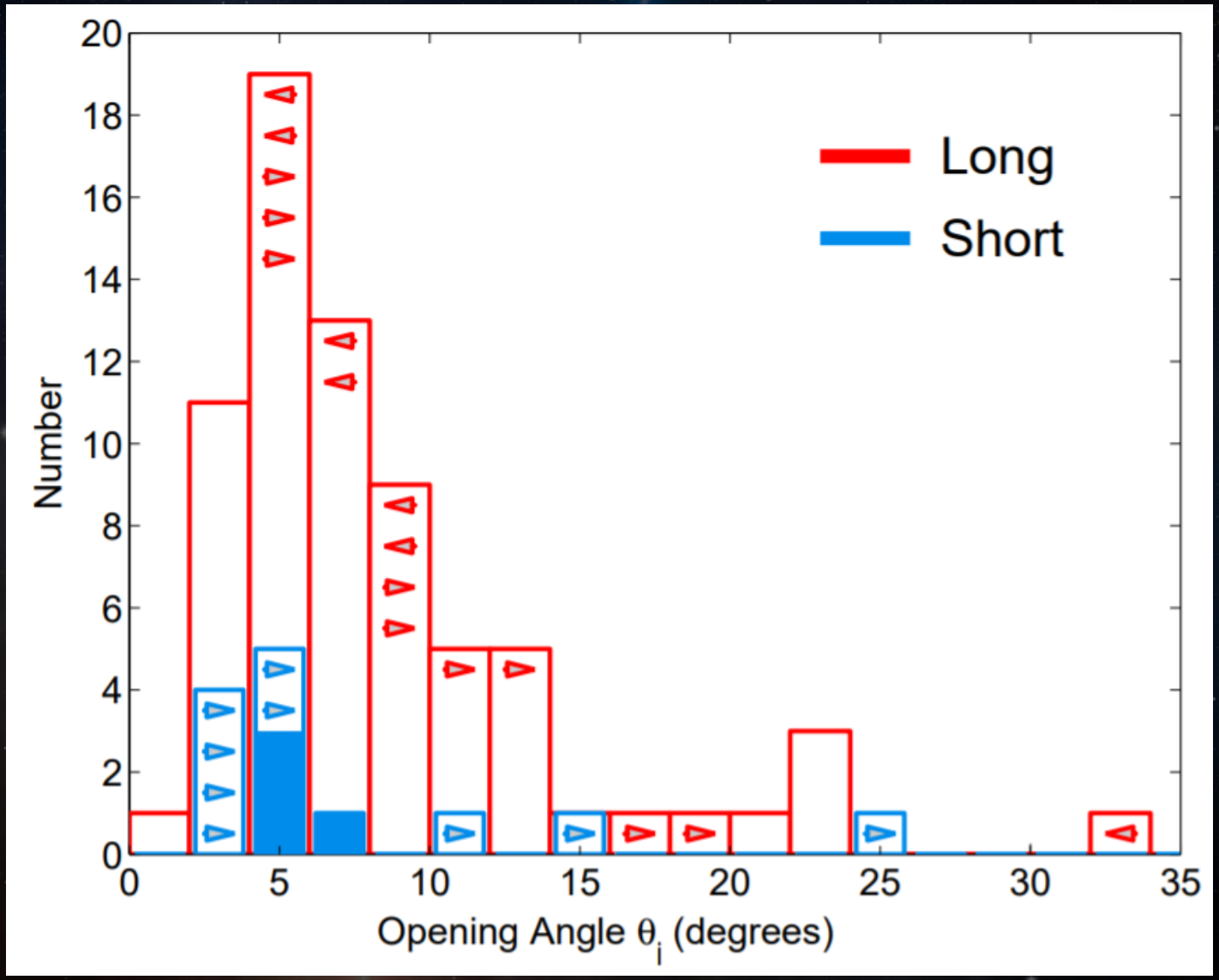
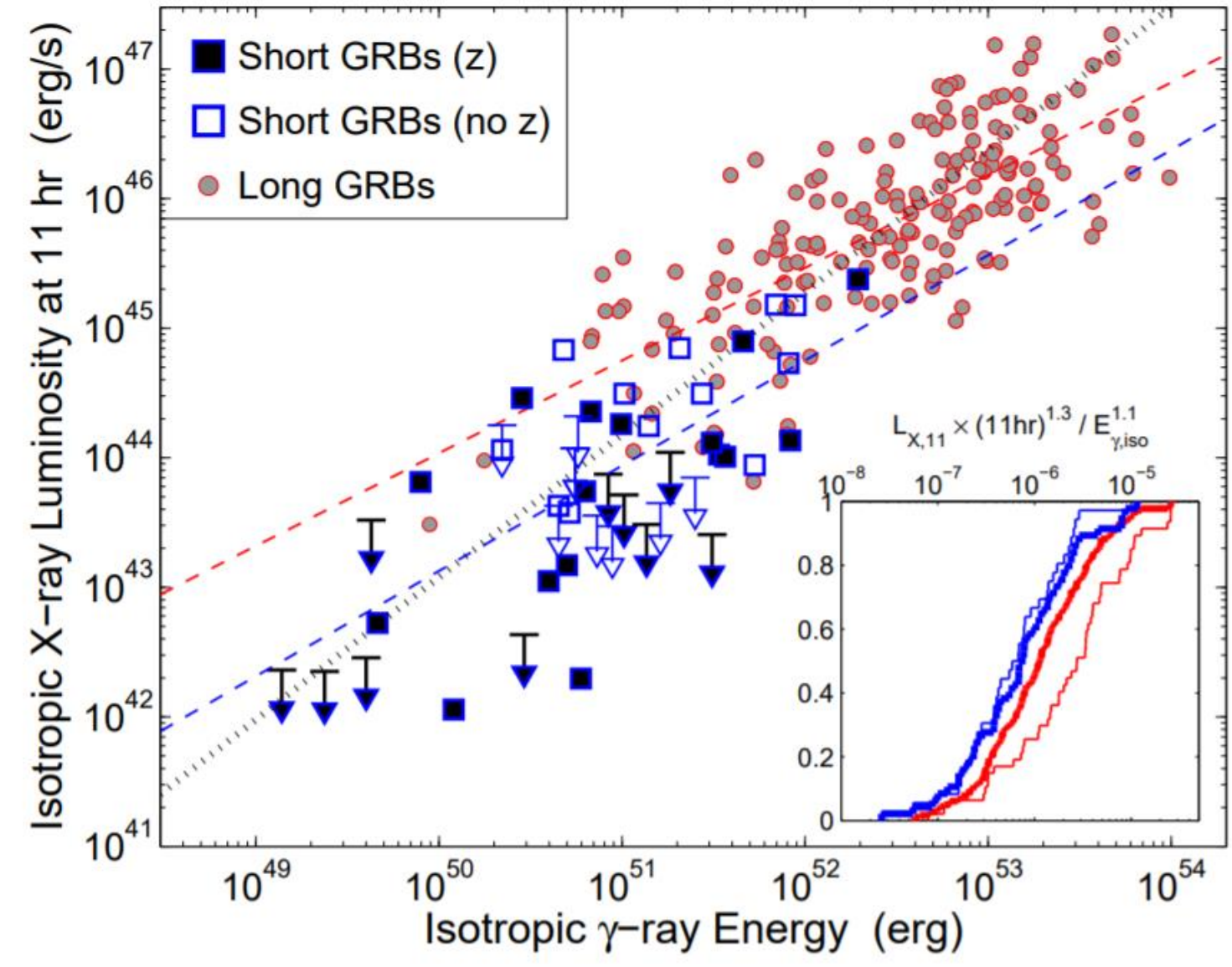
$\sigma_{\log(E_X/\gamma)}$

GRB opening angles from jet breaks



Fong et al. 13

X-ray luminosity to γ-ray energy ratio



Berger et al. 15