Title: The structure of Gamma Ray Bursts: beyond GRB 170817

Speakers: Paz Beniamini

Series: Strong Gravity

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Abstract: Combining information from the first gravitational wave detected gamma-ray burst, GRB 170817 with observations of cosmological GRBs holds important lessons for understanding the structure of GRB jets and the required conditions at the emitting region. It also re-frames our understanding of more commonly observed phenomena in GRBs, such as X-ray plateaus, and sets our expectations for future observations. I will present different lines of argument suggesting that efficient gamma-ray emission in GRBs has to be restricted to material with Lorentz factor > 50 and is most likely confined to a narrow region around the core. GRB jets viewed slightly beyond their jet cores, result in X-ray plateaus that are consistent with observed light-curves and naturally reproduce correlations between plateau and prompt emission properties. For jets viewed further off-axis (that are expected to be detected as future GW triggered events) we provide new analytical modelling that reveals two different types of light-curves that could be observed (single or double peaked) and outlines how the underlying physical properties can be recovered from such observations.

# The structure of Gamma Ray Bursts: beyond GRB 170817


Paz Beniamini

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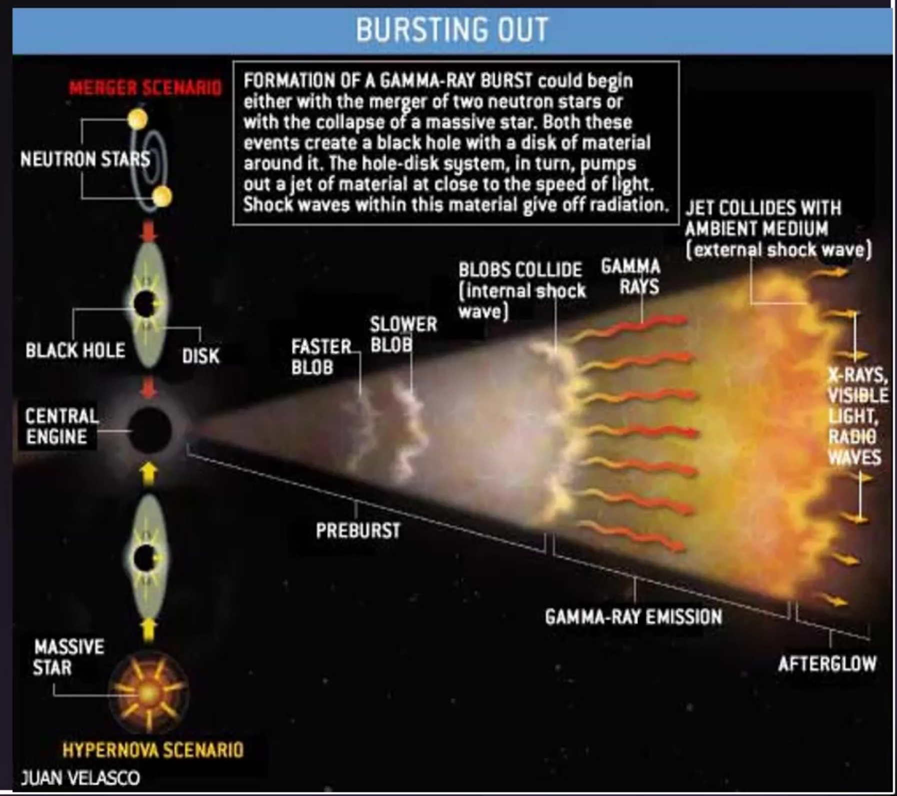
In collaboration with: Jonathan Granot, Ramandeep Gill, Ehud Nakar, Maria Petropoulou, Rodolfo Barniol Duran, Dimitrios Giannios, Raphael Duque, Frederic Daigne and Robert Mochkovitch

# Gamma ray bursts

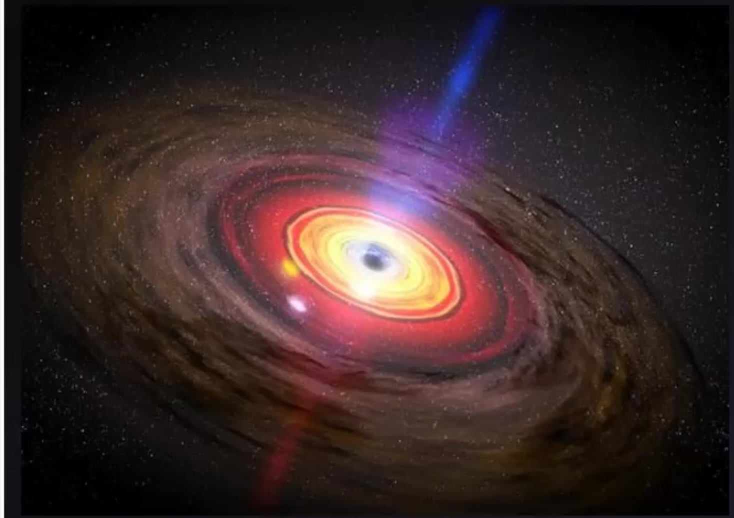
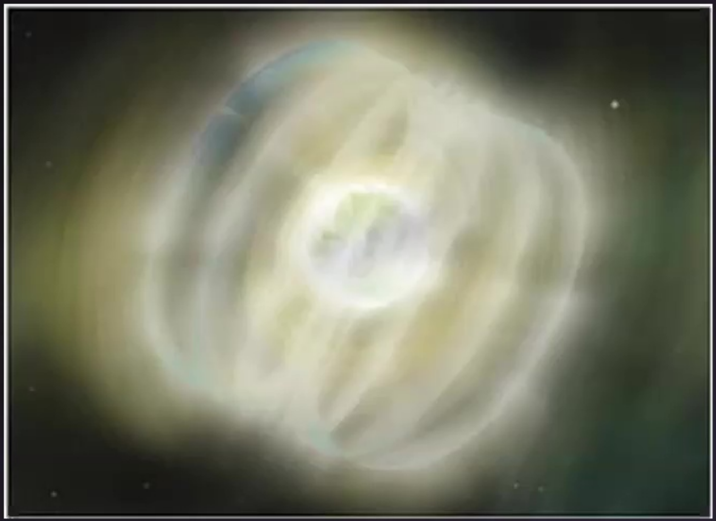
- most extreme explosions in nature (huge luminosities released during seconds)
- Formed by collapse of massive stars or NS-NS (NS-BH) merger
- "prompt" - extremely variable emission peaking at ~0.1MeV and typically lasting tens of seconds
- Followed by a longer and smoother "afterglow", gradually decreasing in frequency with time and observed up to years after the burst



# Introduction

- Main open questions:

1. What is the progenitor?

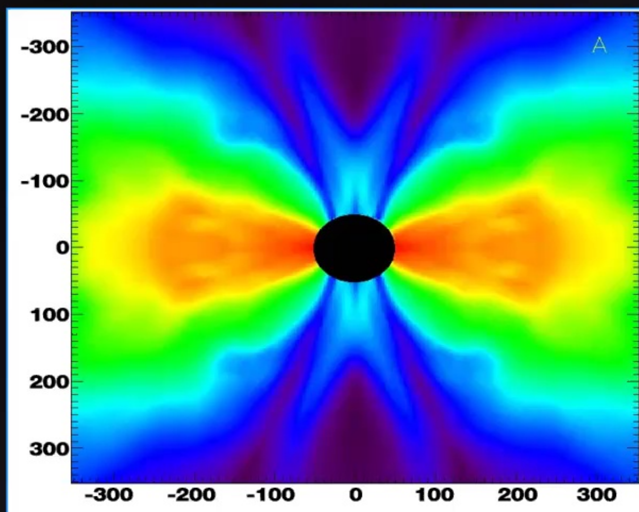
| Black hole | Rapidly rotating magnetar |
| --- | --- |
|  |  |

# Introduction

- Main open questions:

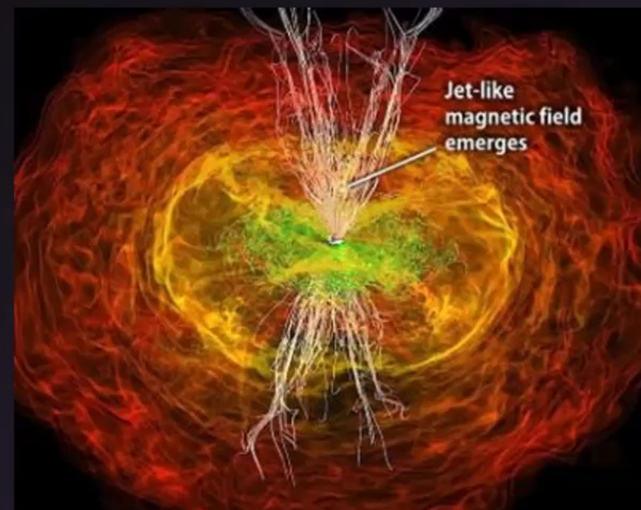
1. What is the composition of the jet?

**Baryonic**




Simulation: Woosley

**Poynting flux (magnetic fields)**

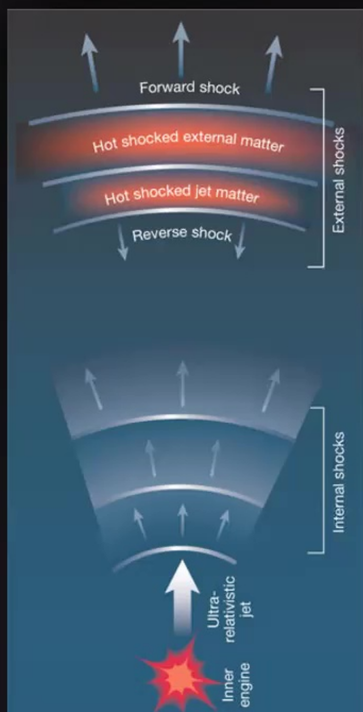
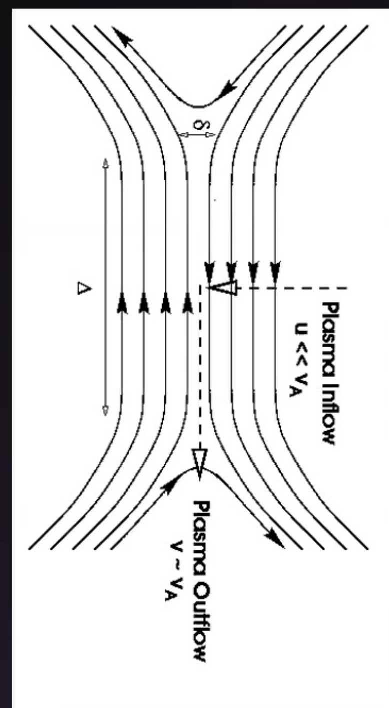



Simulation: Koppitz & Rezzolla

# Introduction

- Main open questions:

1. What is the dissipation mechanism?

| Internal shocks | Reconnection | Other? |
|---|---|---|
|  |  | Neutron – Proton collisions<br>Nuclear collisions<br>Etc. |



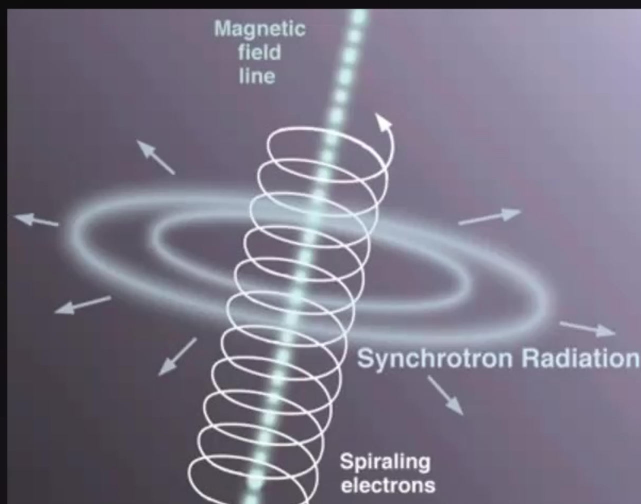


# Introduction

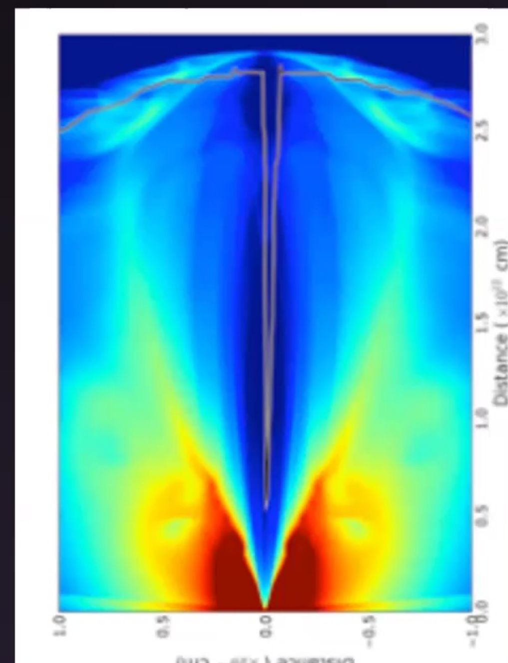
- Main open questions:

1. What is the radiation process?

**Synchrotron**



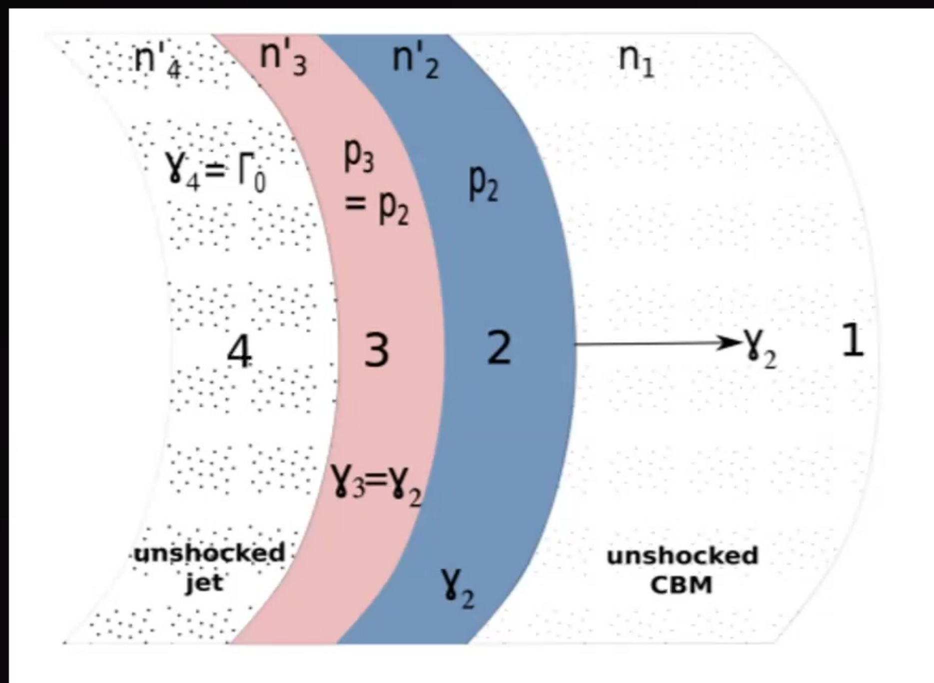

**Photospheric**



Simulation: Lazzati

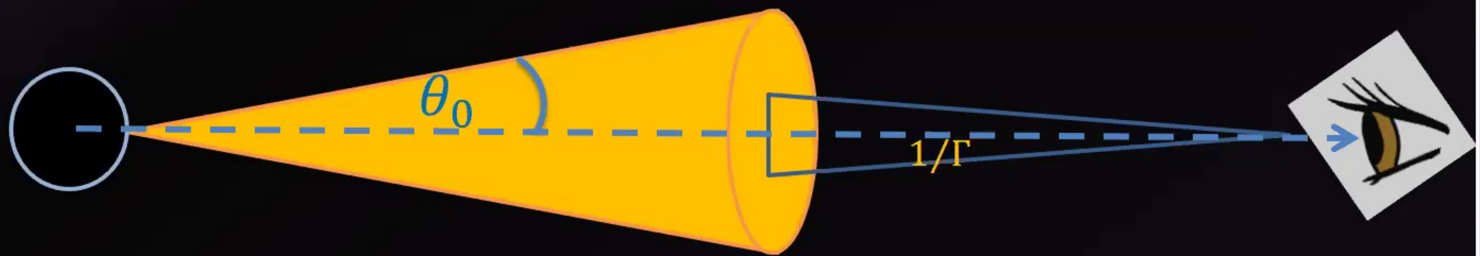
# GRB afterglows

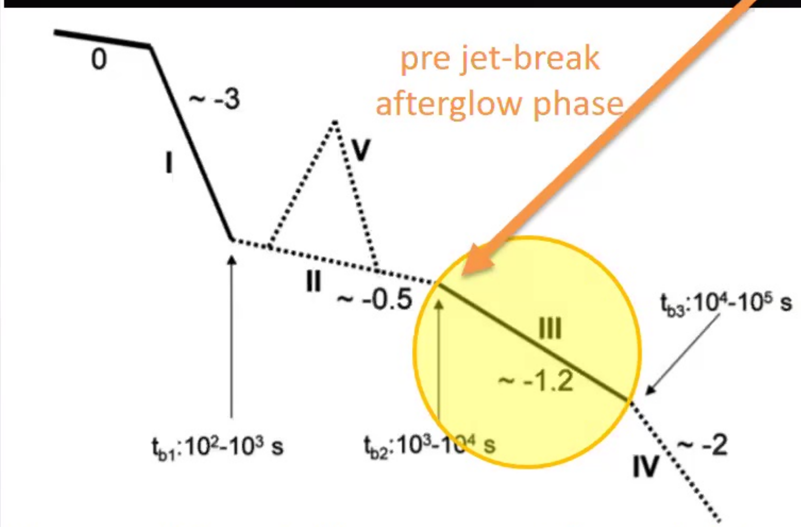
- Dynamics: Self-similar blast wave ultra-relativistic blast wave driving into external density (Blandford & Mckee 76)
- Radiation: Synchrotron from electrons accelerated in the forward shock (Sari, Piran & Narayan 98)



# Regular on-axis GRB afterglows

- Isotropic equivalent energy constant (up to jet break)




'Canonical' X-ray light-curve; from Zhang et al. 06

$L \times t$ almost constant (slightly decreasing)

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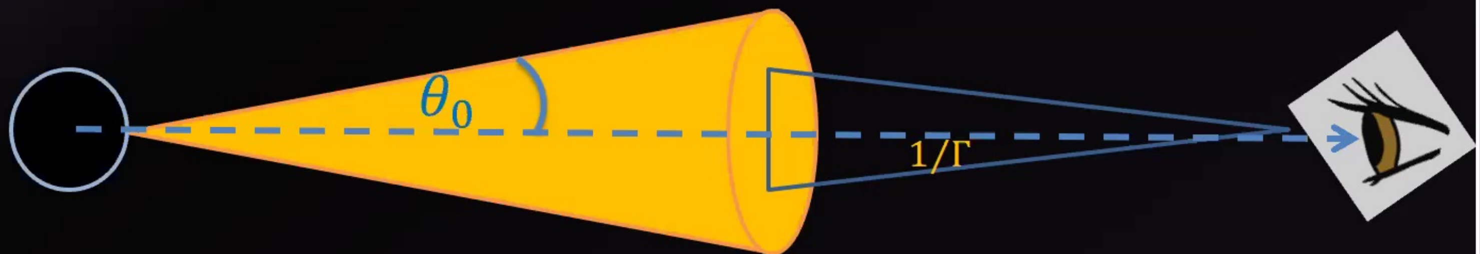


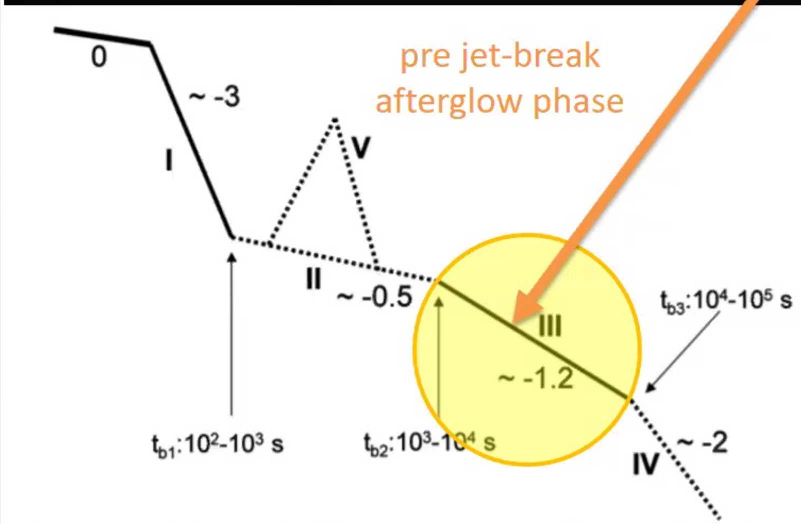


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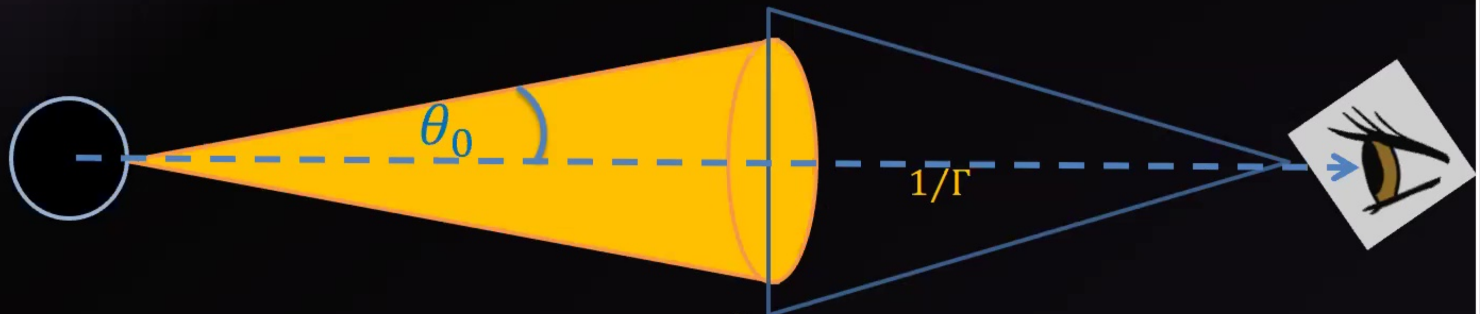


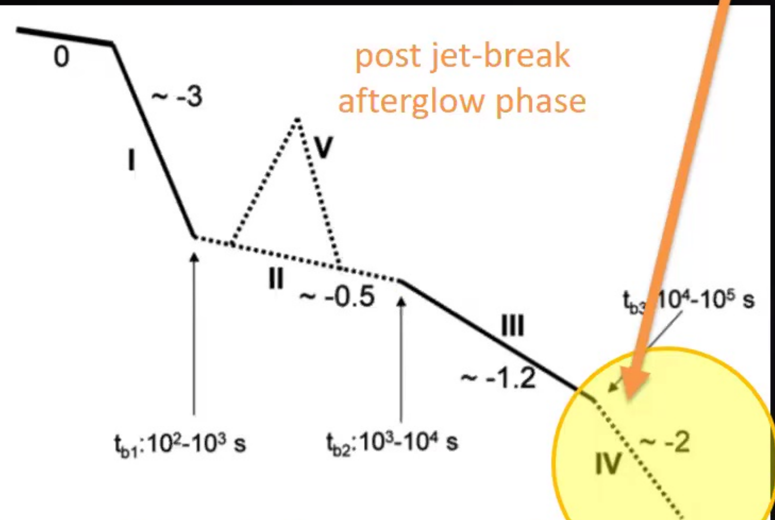


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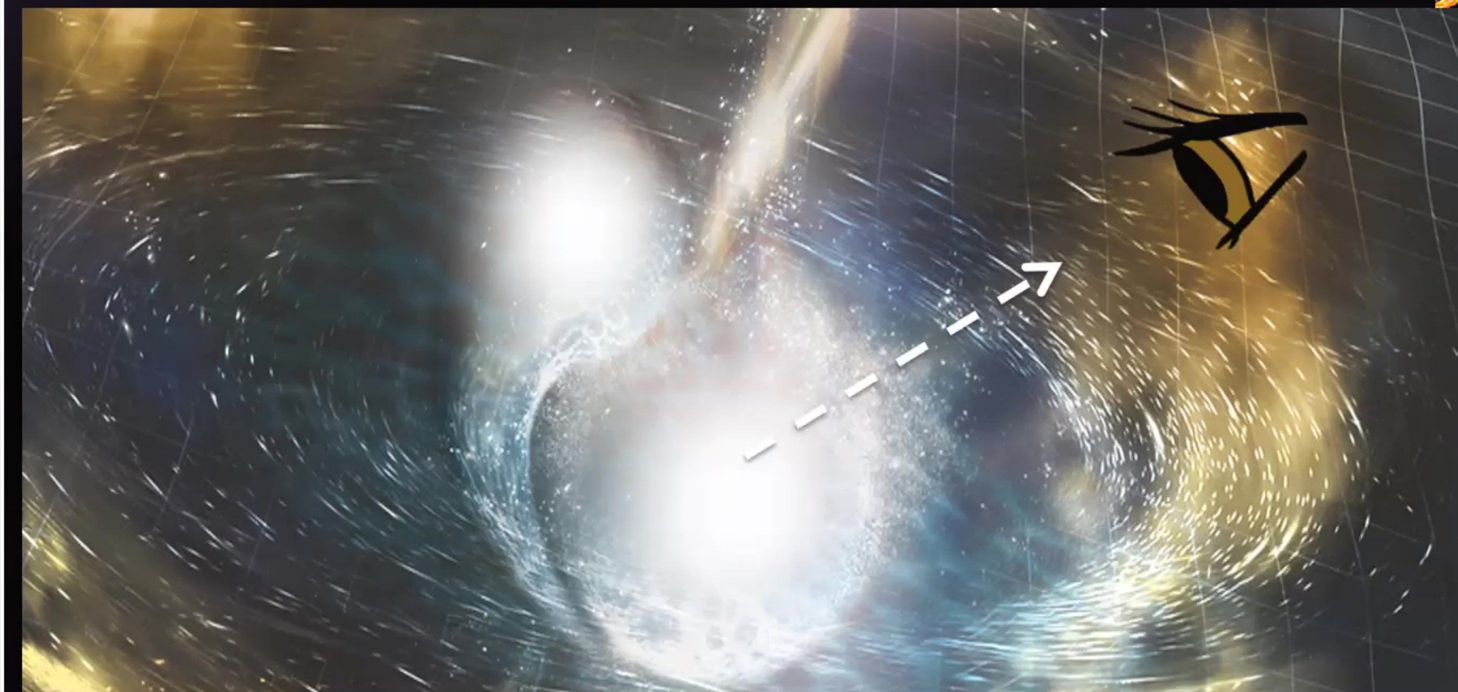
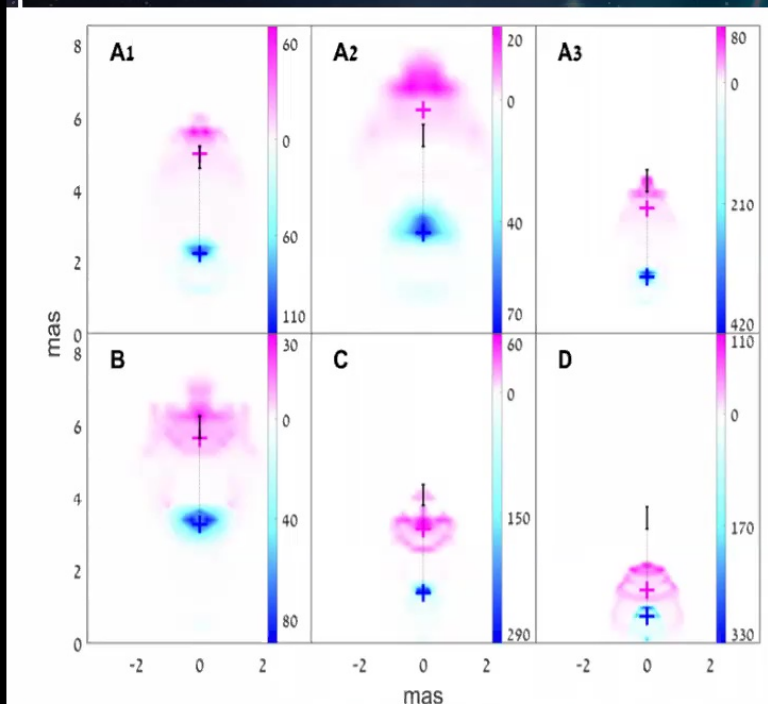
# GRB170817 – First confirmed off-axis GR



- 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

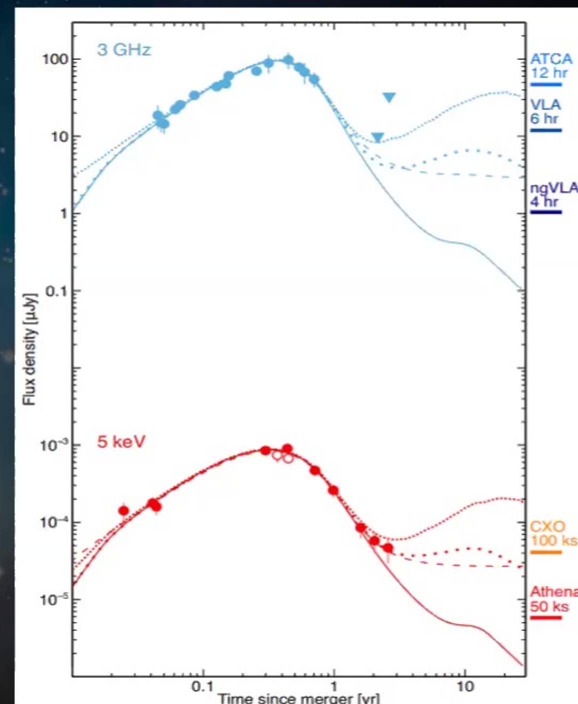
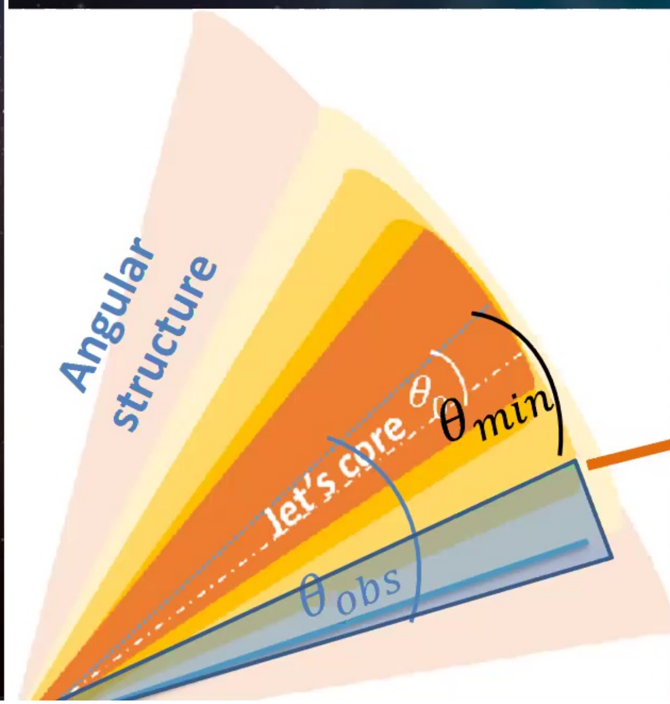
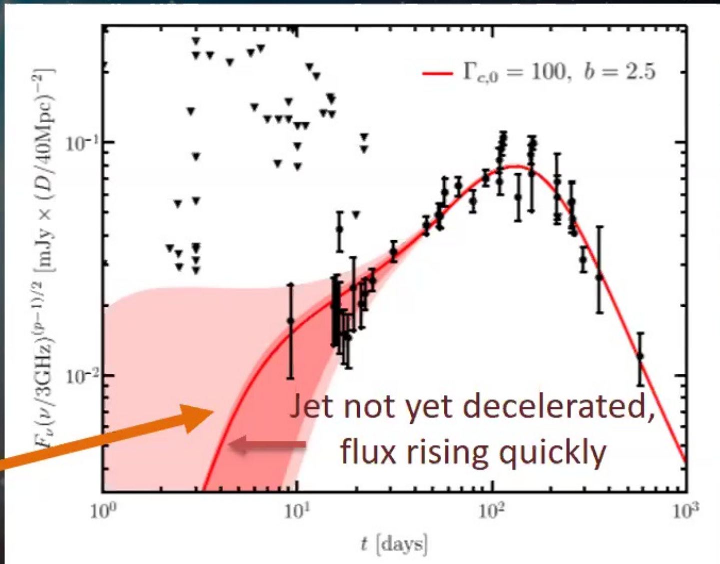



Image from Troja et al 20; See also:
Pooley et al. 18, Troja et al. 18, Ghirlanda et al. 18

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

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




PB, Granot & Gill 20

Light-curve increases as more energetic material contributes

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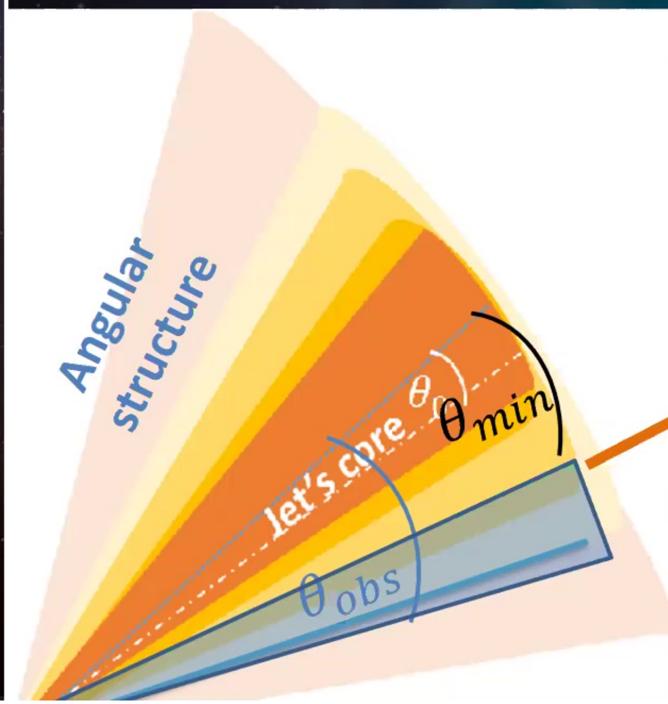


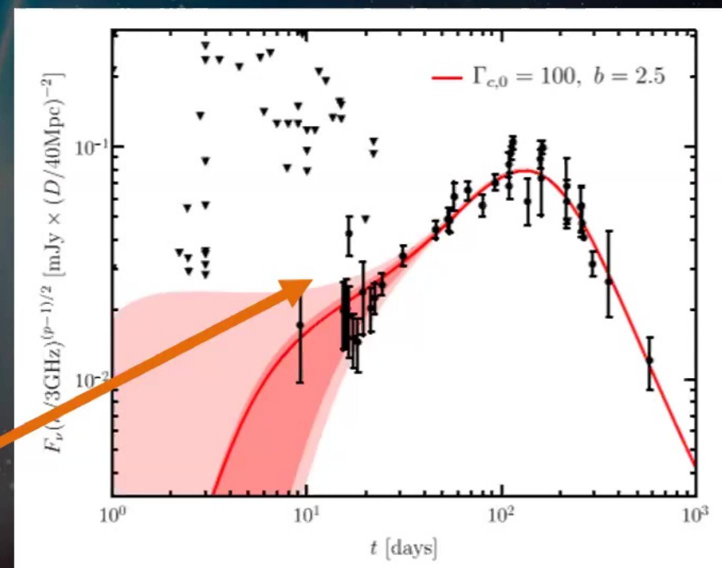


PB, Granot & Gill 20

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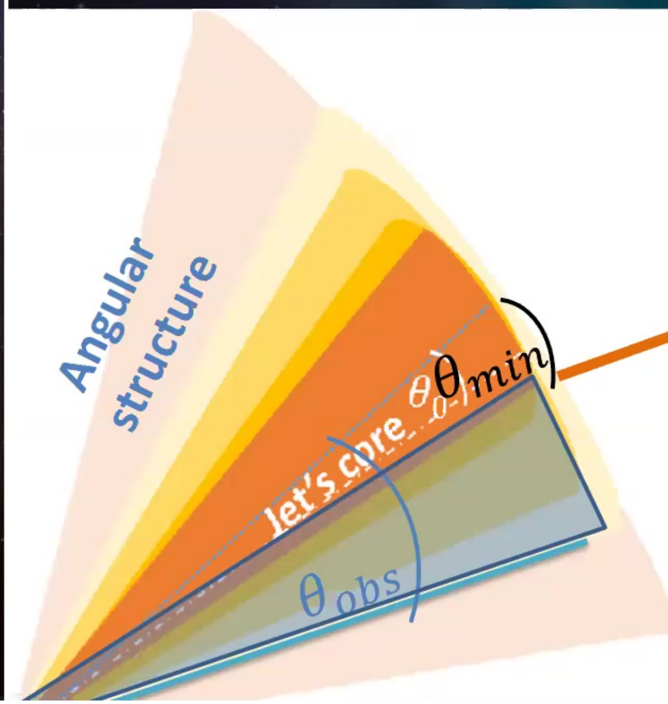


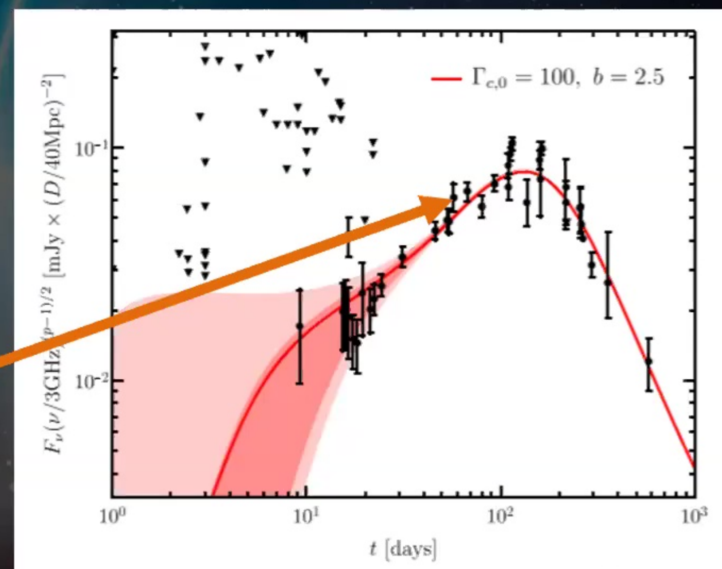


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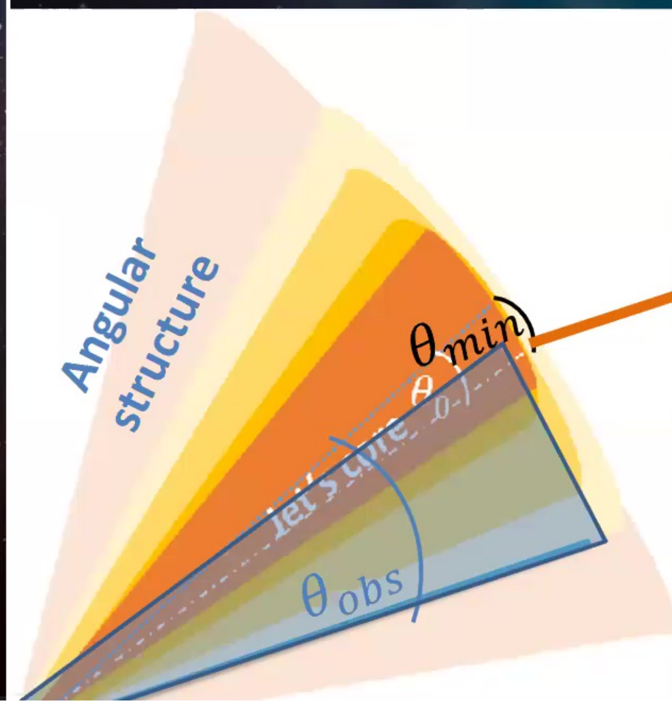


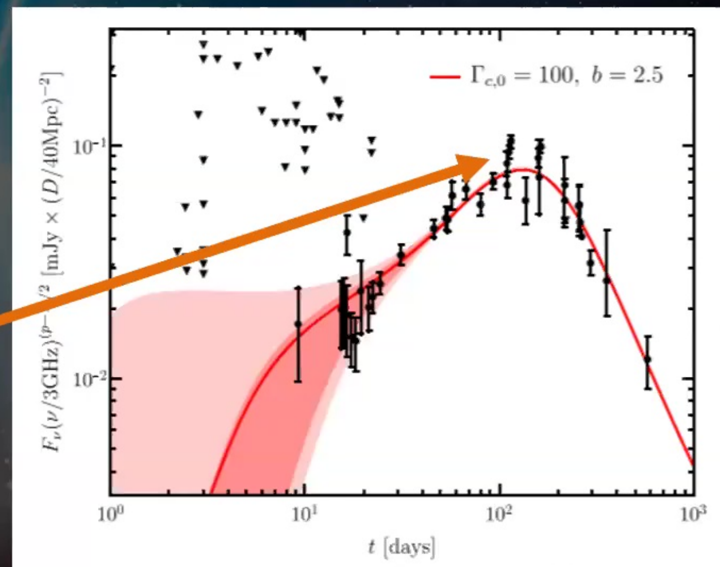


PB, Granot & Gill 20

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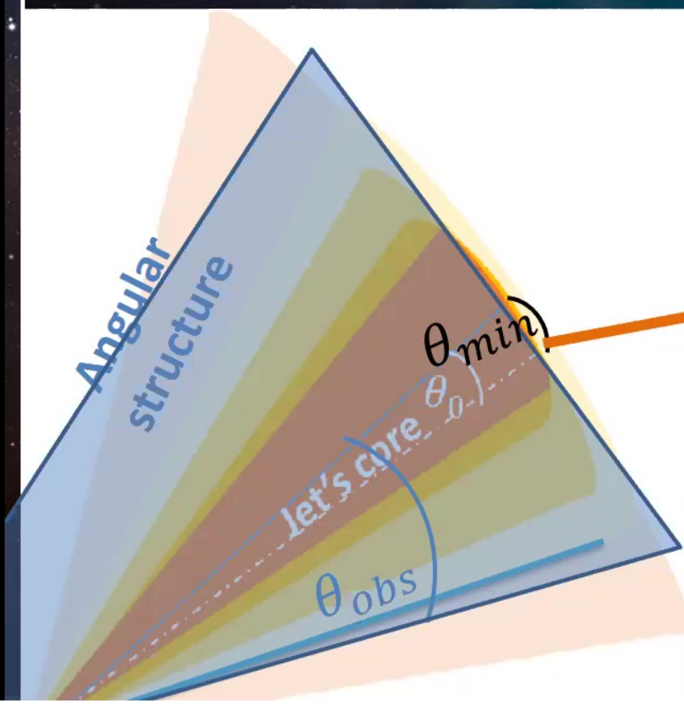


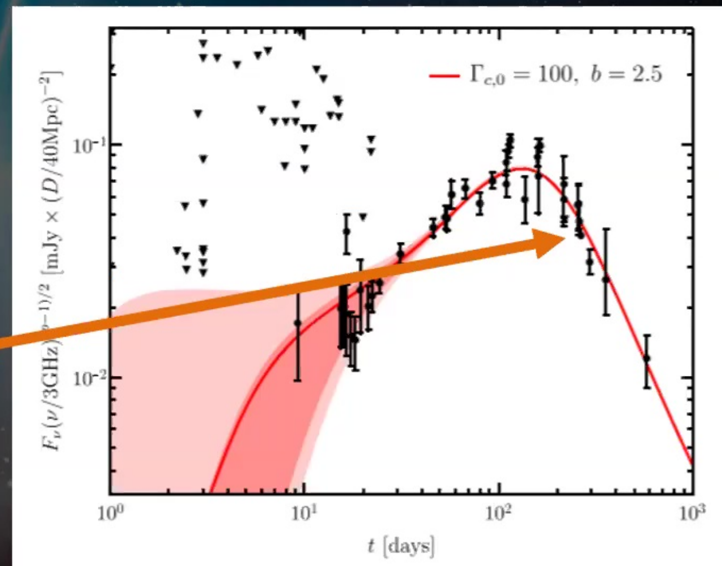


PB, Granot & Gill 20

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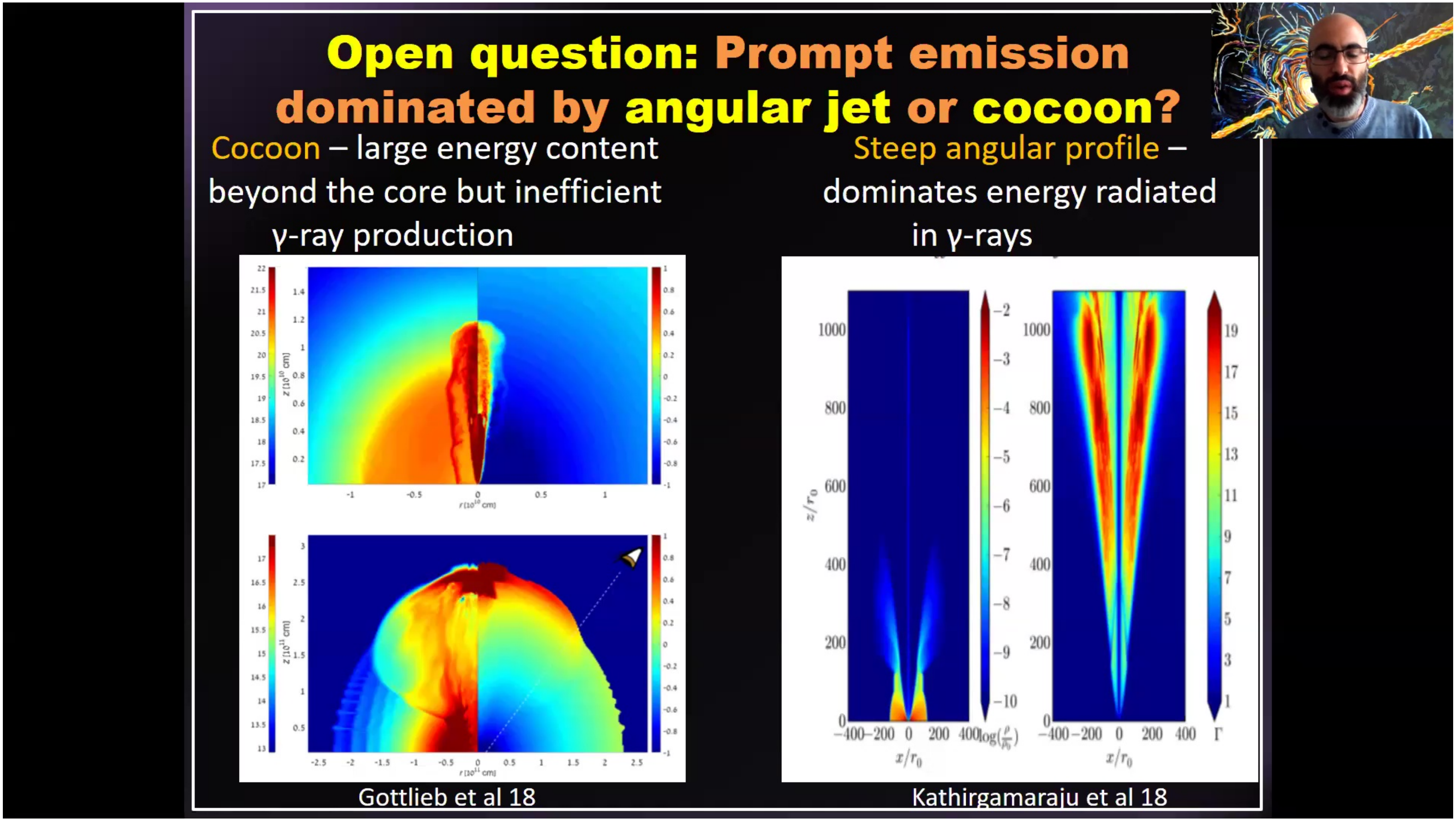
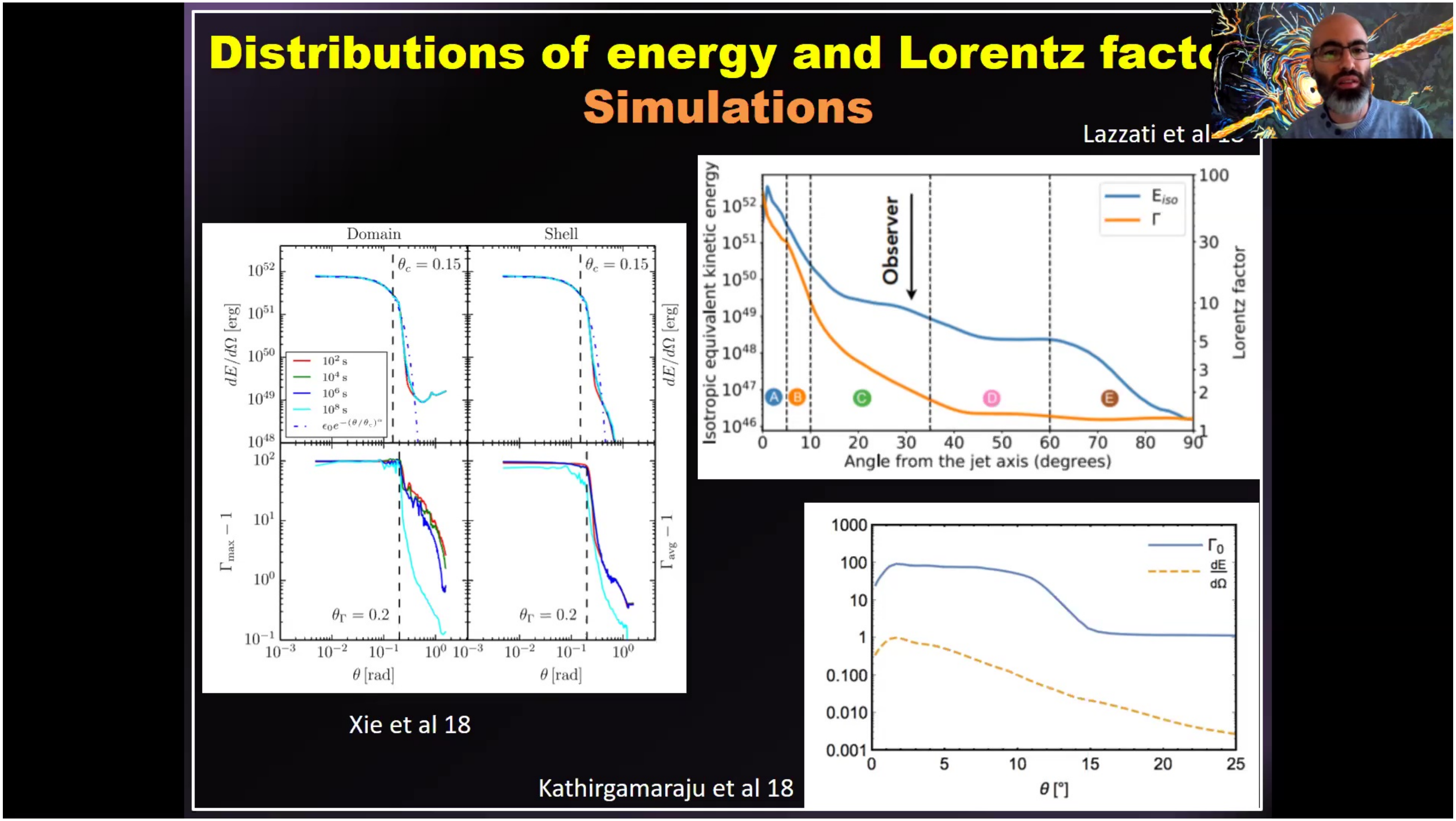
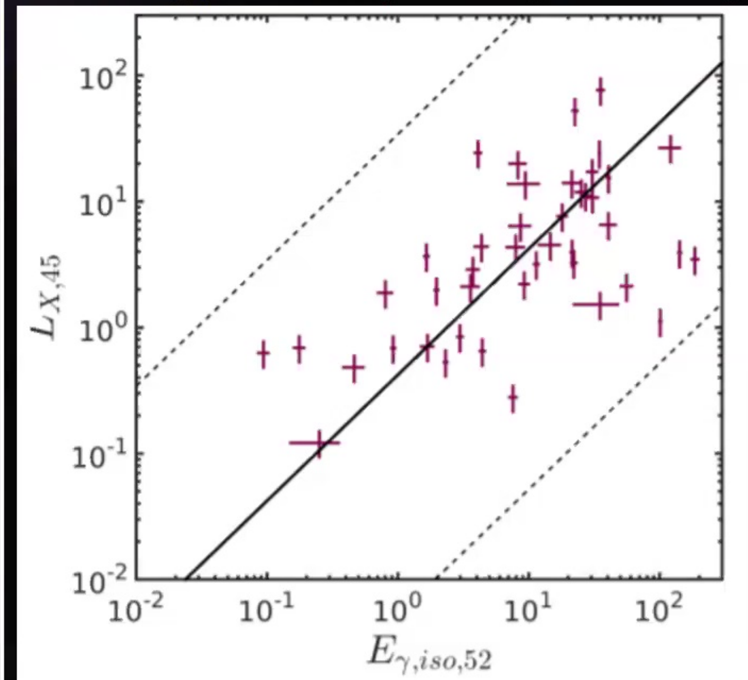
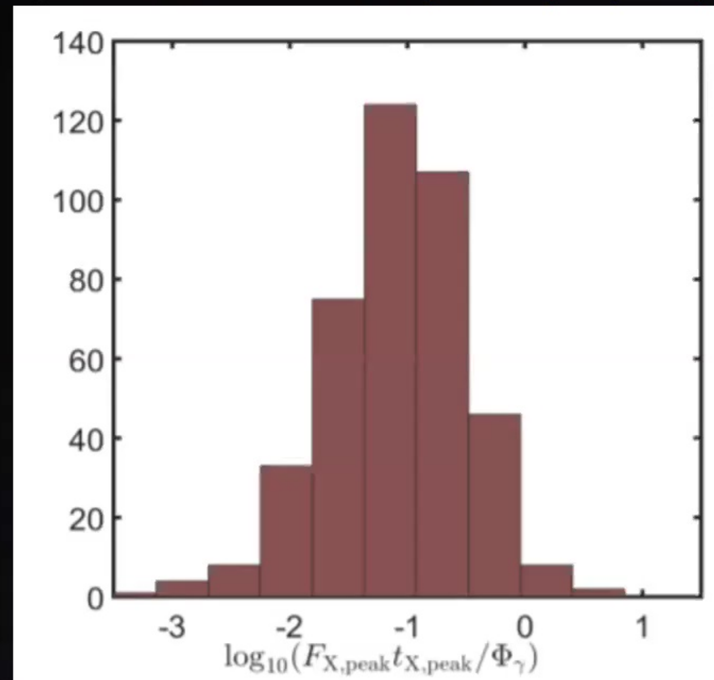

Open question: Prompt emission dominated by angular jet or cocoon?
Cocoon – large energy content beyond the core but inefficient γ-ray production
Steep angular profile – dominates energy radiated in γ-rays
Gottlieb et al 18
Kathirgamaraju et al 18


Distributions of energy and Lorentz facto
Simulations
Lazzati et al
Domain
Shell
$\theta_c = 0.15$
$dE/d\Omega$ [erg]
$10^2$ s
$10^4$ s
$10^6$ s
$10^8$ s
$\epsilon_0 e^{-(\theta/\theta_c)^\alpha}$
$\Gamma_{max} - 1$
$\Gamma_{avg} - 1$
$\theta_\Gamma = 0.2$
$\theta$ [rad]
Xie et al 18
Isotropic equivalent kinetic energy
Lorentz factor
Observer
$E_{iso}$
Γ
A
B
C
D
E
Angle from the jet axis (degrees)
$\Gamma_0$
$\frac{dE}{d\Omega}$
$\theta$ [°]
Kathirgamaraju et al 18

# Typical GRBs observed closed to core ar
# produced by high Lorentz factor materia

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




Redshift complete sample

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

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

All Swift GRBs

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

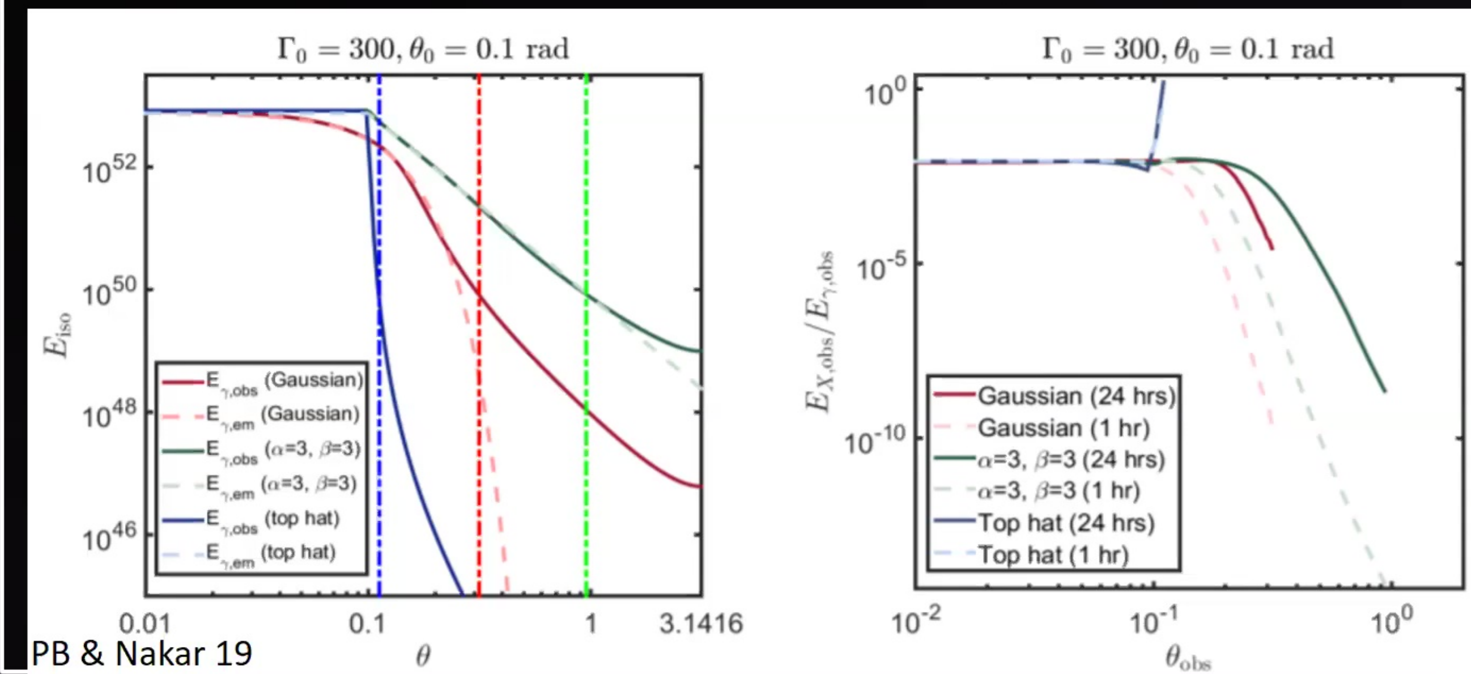
Image from PB & Nakar 19

# Typical GRBs observed closed to core ar produced by high Lorentz factor materia

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

*Very* limiting for energy and Lorentz factor structures:

- Prompt – typically dominated by $E(\theta)$, $E_\gamma \propto E(\theta)$
- Early Afterglow – Dominated by $\Gamma(\theta)$, $L_x \propto \left(\frac{t}{t_{dec}}\right)^3 \propto \frac{E(\theta)}{n}\Gamma(\theta)^8$




PB & Nakar 19

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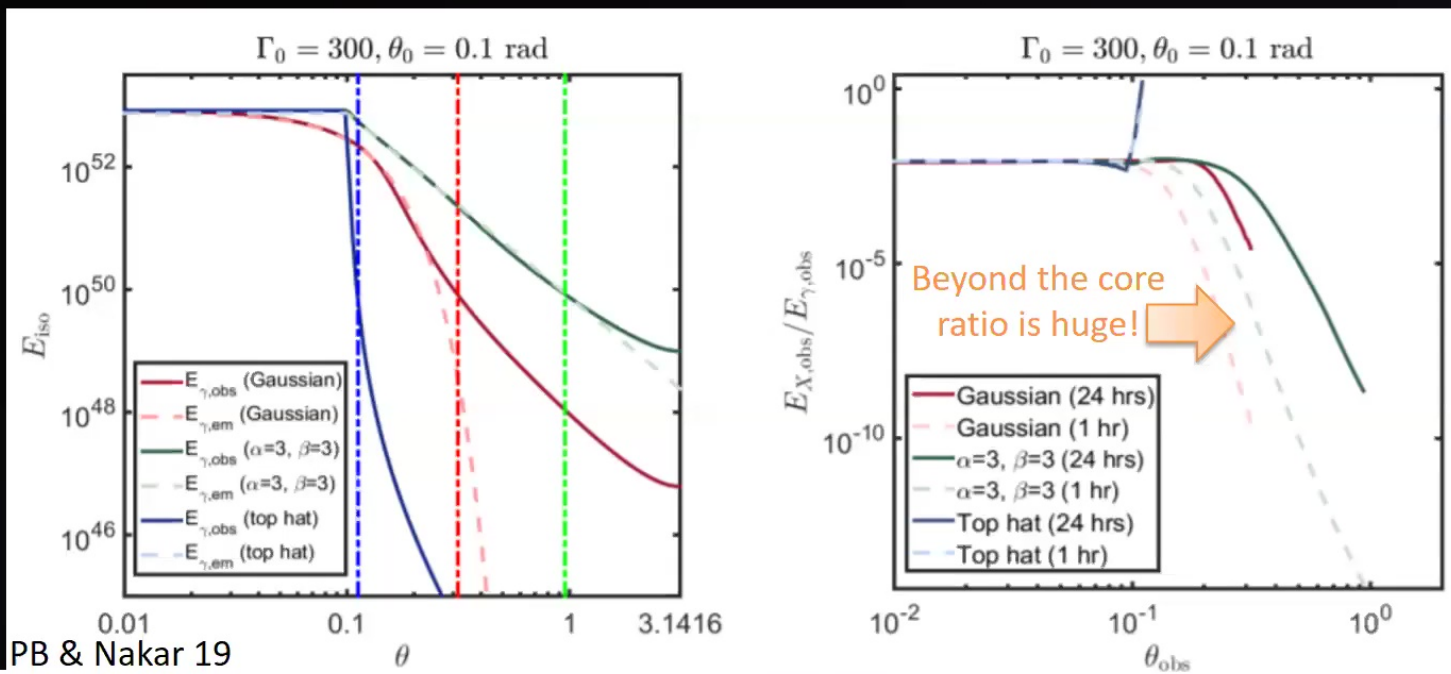
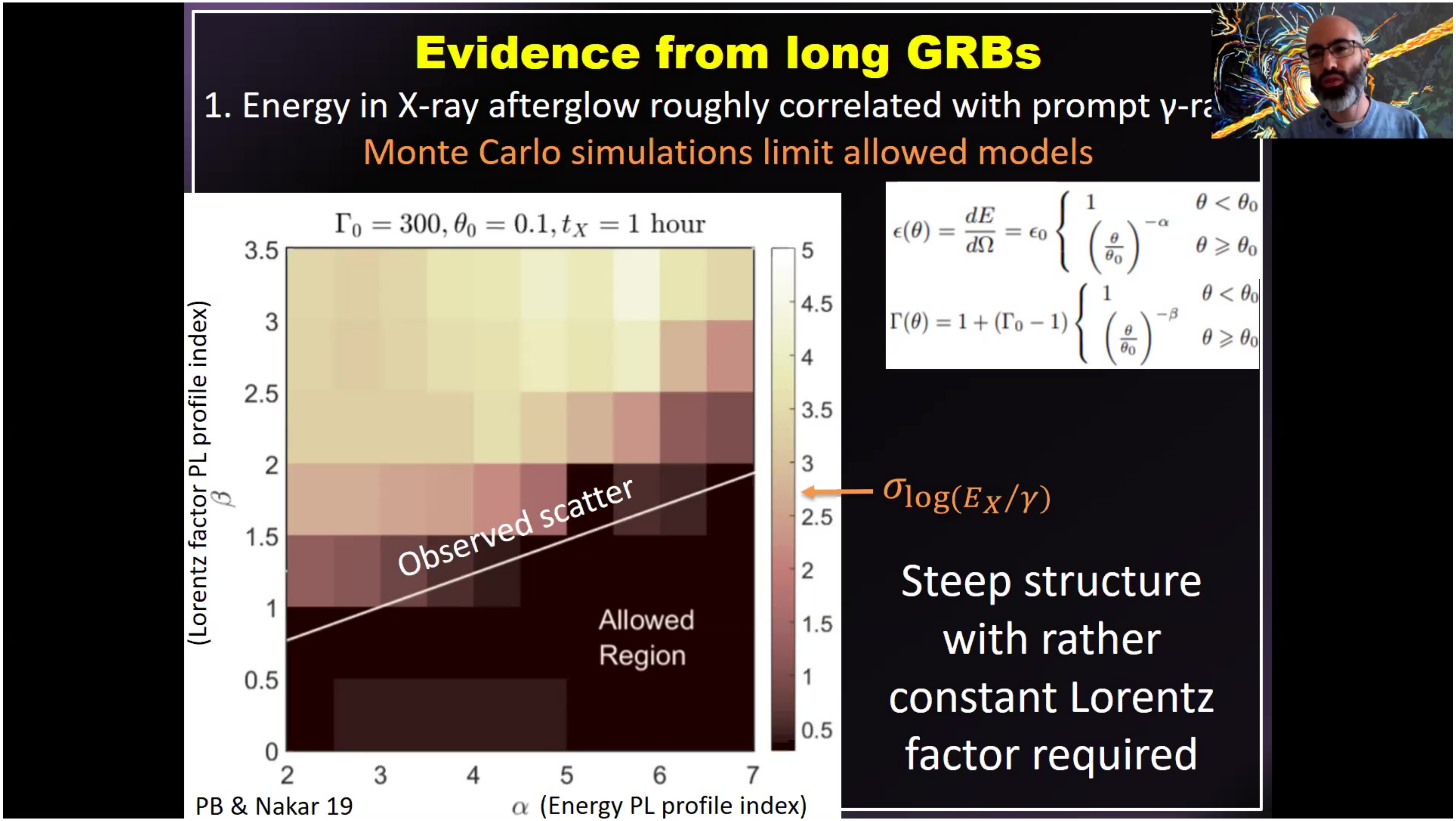
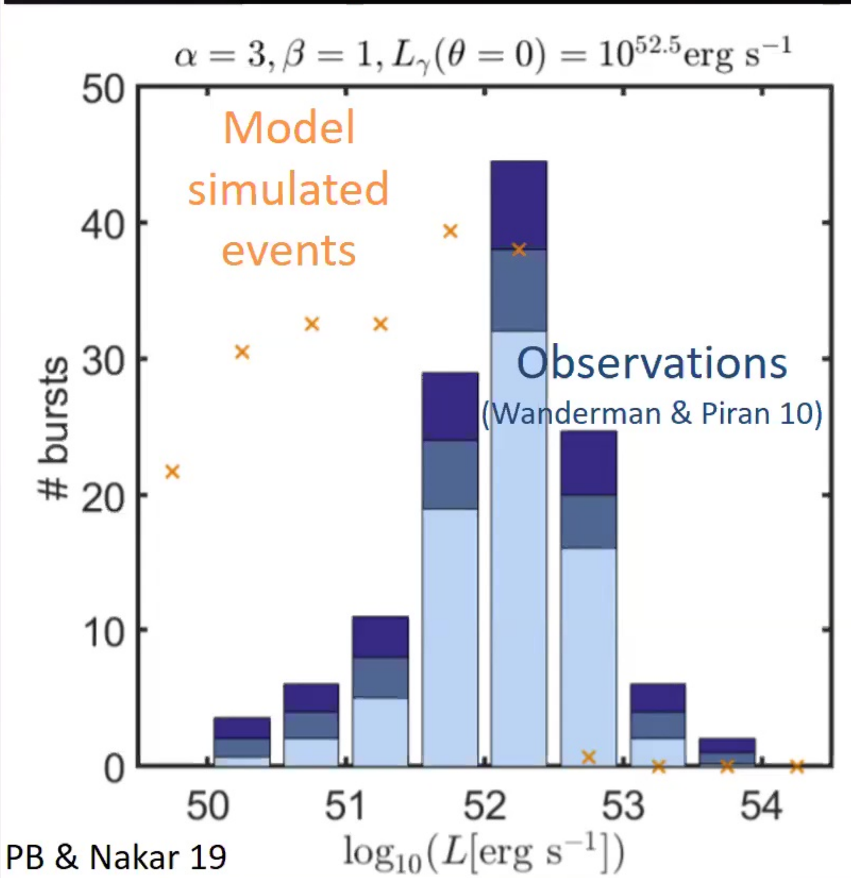



PB & Nakar 19


Evidence from long GRBs
1. Energy in X-ray afterglow roughly correlated with prompt γ-ra
Monte Carlo simulations limit allowed models
$\Gamma_0 = 300, \theta_0 = 0.1, t_X = 1$ hour
Observed scatter
Allowed Region
$\beta$ (Lorentz factor PL profile index)
$\alpha$ (Energy PL profile index)
PB & Nakar 19
$\epsilon(\theta) = \frac{dE}{d\Omega} = \epsilon_0 \begin{cases} 1 & \theta < \theta_0 \\ \left(\frac{\theta}{\theta_0}\right)^{-\alpha} & \theta \geqslant \theta_0 \end{cases}$
$\Gamma(\theta) = 1 + (\Gamma_0 - 1) \begin{cases} 1 & \theta < \theta_0 \\ \left(\frac{\theta}{\theta_0}\right)^{-\beta} & \theta \geqslant \theta_0 \end{cases}$
$\sigma_{\log(E_X/\gamma)}$
Steep structure with rather constant Lorentz factor required

# Typical GRBs observed closed to core ar produced by high Lorentz factor materia

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



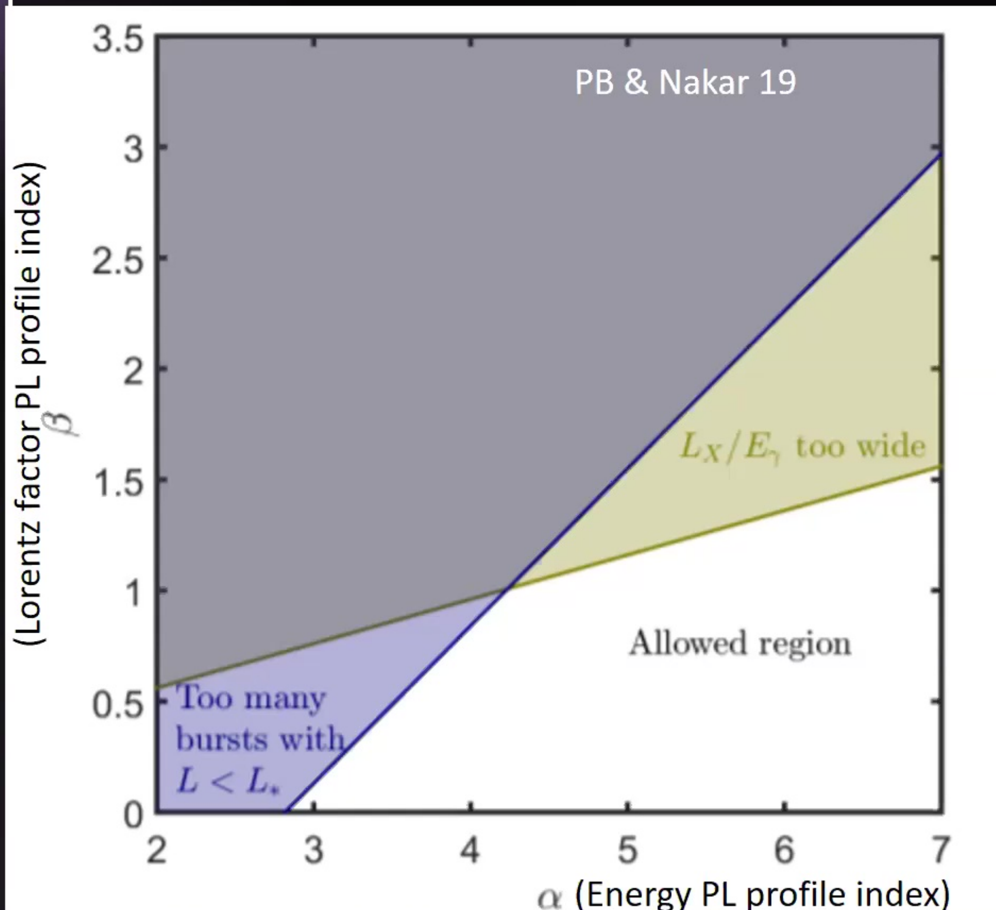

$$\epsilon(\theta)=\frac{dE}{d\Omega}=\epsilon_0\begin{cases}1 & \theta<\theta_0\\ \left(\frac{\theta}{\theta_0}\right)^{-\alpha} & \theta\geqslant\theta_0\end{cases}$$

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

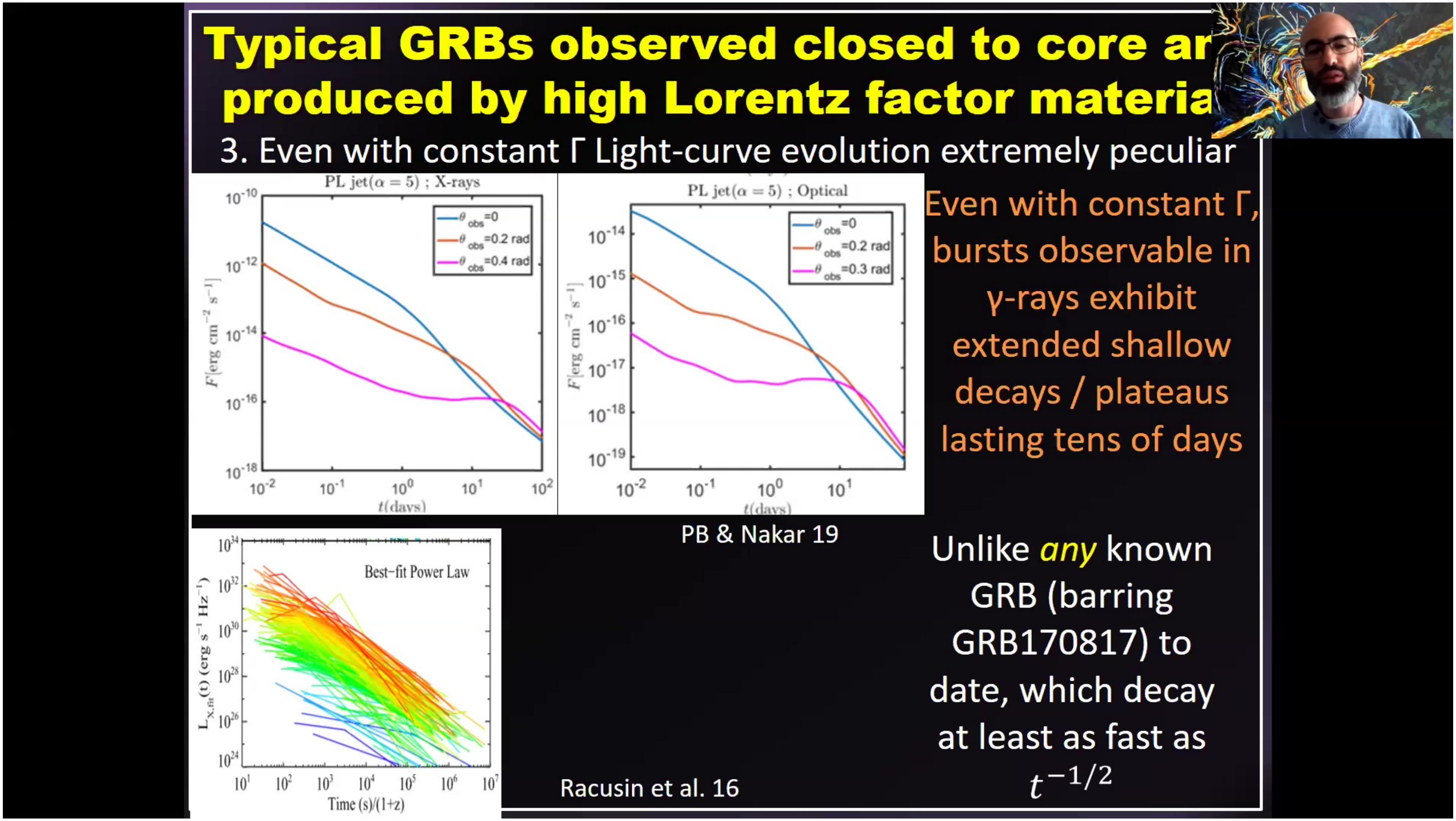
Even if all bursts have $L_*$ at core, lower L bursts are overproduced due to bursts detectable off-axis

# Evidence from long GRBs

Combining both constraints:

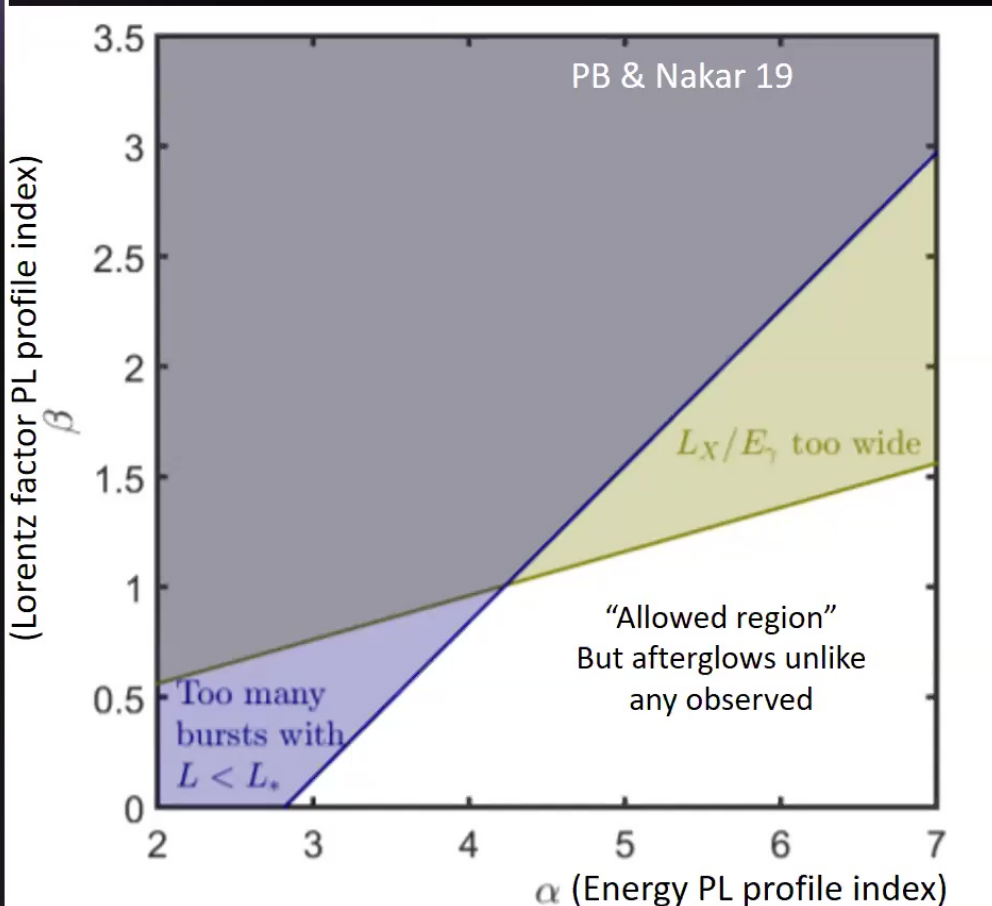



Steep structure with rather constant Lorentz factor required


Typical GRBs observed closed to core ar
produced by high Lorentz factor materia
3. Even with constant Γ Light-curve evolution extremely peculiar
PL jet(α = 5) ; X-rays
θ obs=0
θ obs=0.2 rad
θ obs=0.4 rad
F[erg cm^-2 s^-1]
t(days)
PL jet(α = 5) ; Optical
θ obs=0
θ obs=0.2 rad
θ obs=0.3 rad
F[erg cm^-2 s^-1]
t(days)
Even with constant Γ, bursts observable in γ-rays exhibit extended shallow decays / plateaus lasting tens of days
PB & Nakar 19
Best-fit Power Law
L_X,fit(t) (erg s^-1 Hz^-1)
Time (s)/(1+z)
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

Combining all constraints:

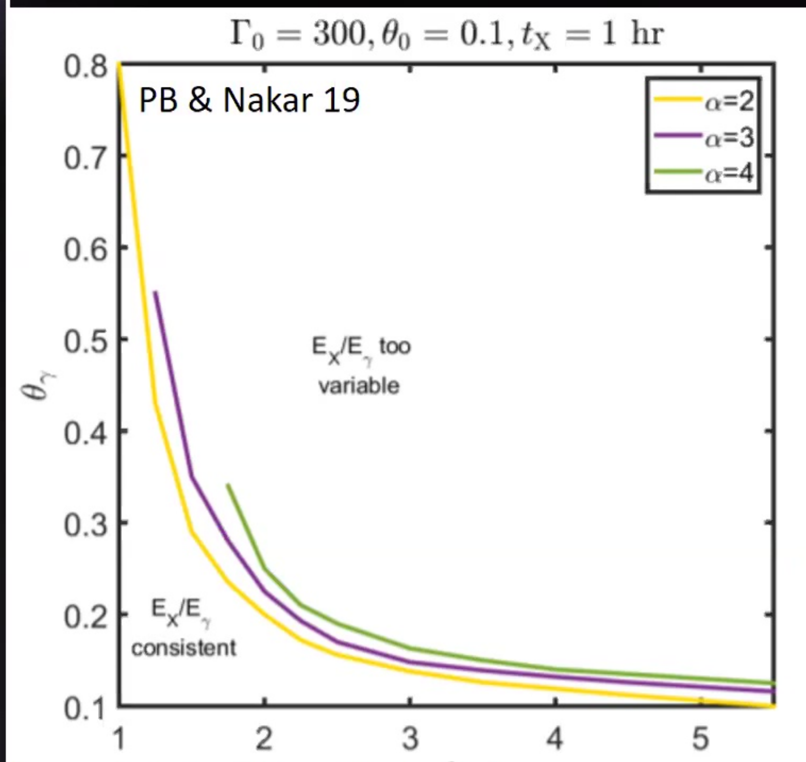



What is the solution?

# Typical GRBs observed closed to core ar produced by high Lorentz factor materia

An alternative possibility: Restrictive γ-ray region

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




(Lorentz factor PL profile index)

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

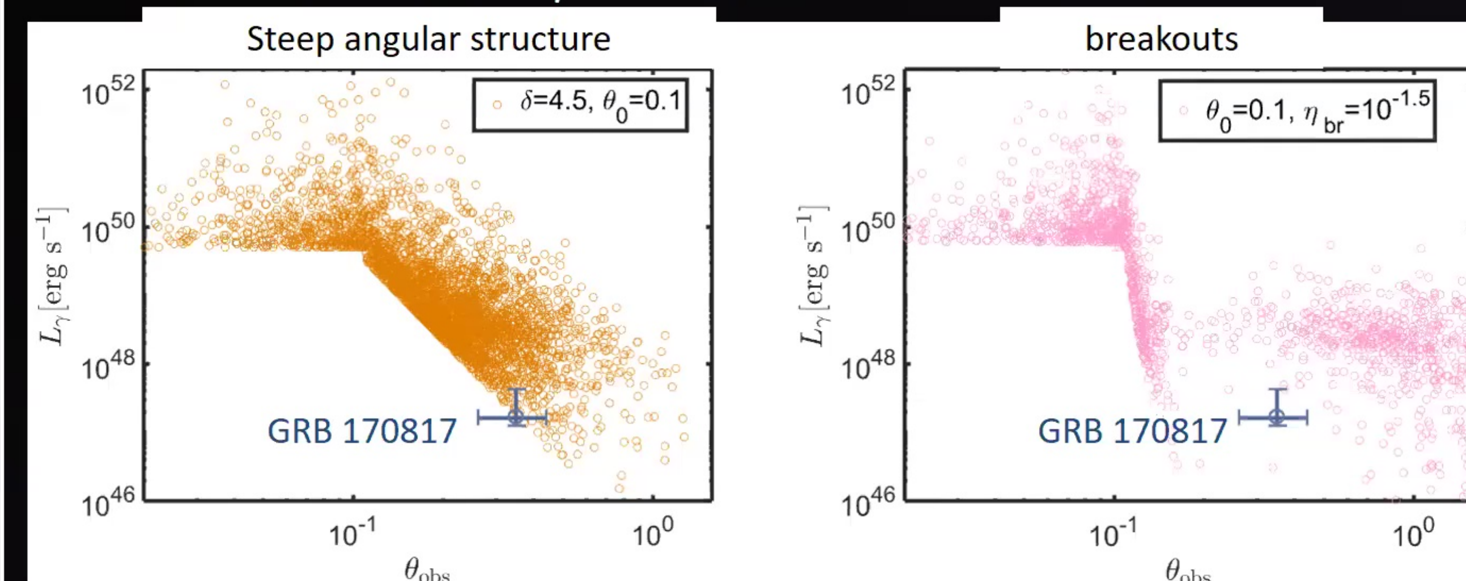
$\Gamma(\theta_{obs}) \gtrsim 50$

$\theta_{obs} \lesssim 1.5\theta_0$

# How can we test this? – Future prospect

Monte Carlo simulations of different structure models

- Most GW detected events up to 220Mpc undetectable in γ-rays
  - Between 1 (breakout) and 10 (steep angular structure) joint detections in next decade
- The distributions of $L_\gamma$ and $\theta_{obs}$ can distinguish between models

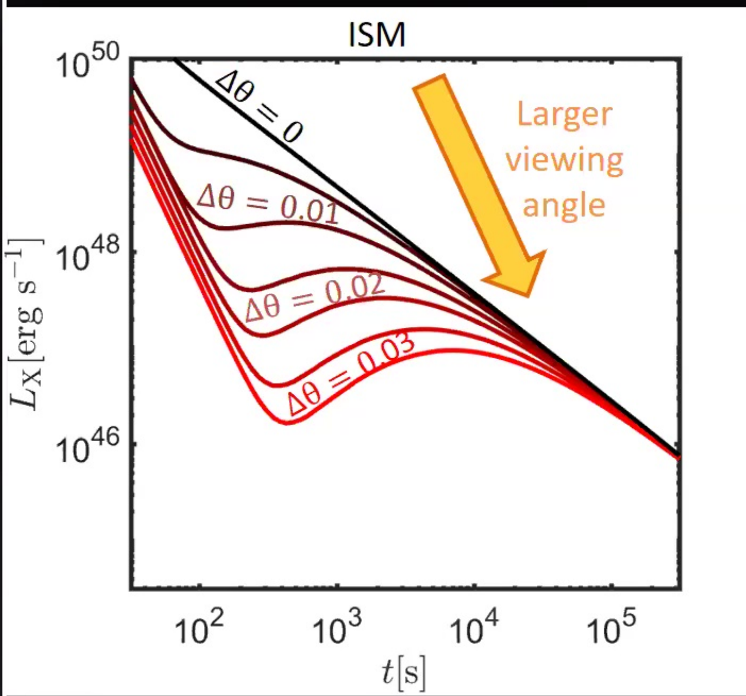


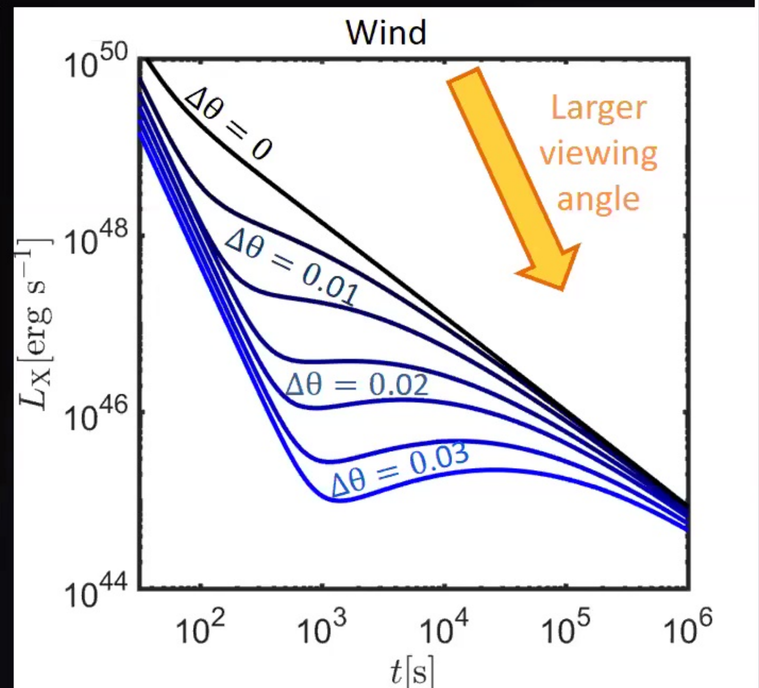

PB, Petropoulou, Barniol Duran, Giannios 19

# X-ray plateaus – Evidence for (mildly) off axis structured GRB jets?

For $\Delta\theta = \theta_{obs} - \theta_c \ll \theta_c$ shallow phase lasts until $\Gamma(\theta_j) \approx \Delta\theta^{-1}$

$$t_p = t_d(\theta_c)[\Delta\theta\Gamma_c]^{(1+2\varepsilon)/\varepsilon} \sim 10^3 \left(\frac{\Delta\theta}{0.02}\right)^{(1+2\varepsilon)/\varepsilon} sec\ ;\ \varepsilon = \frac{1}{2}\ or\ \frac{3}{2}$$




PB, Duque, Daigne, Mochkovitch 20

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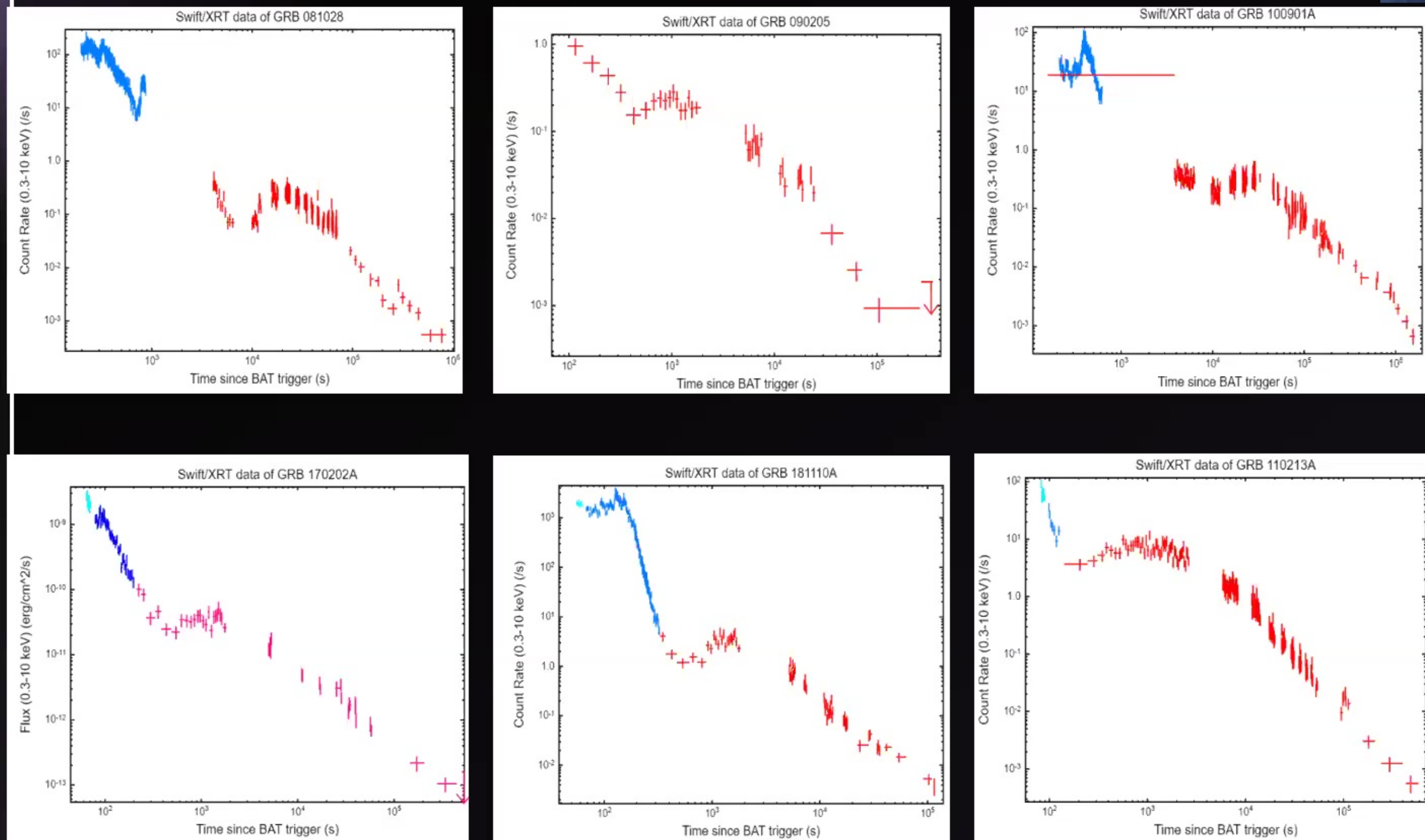

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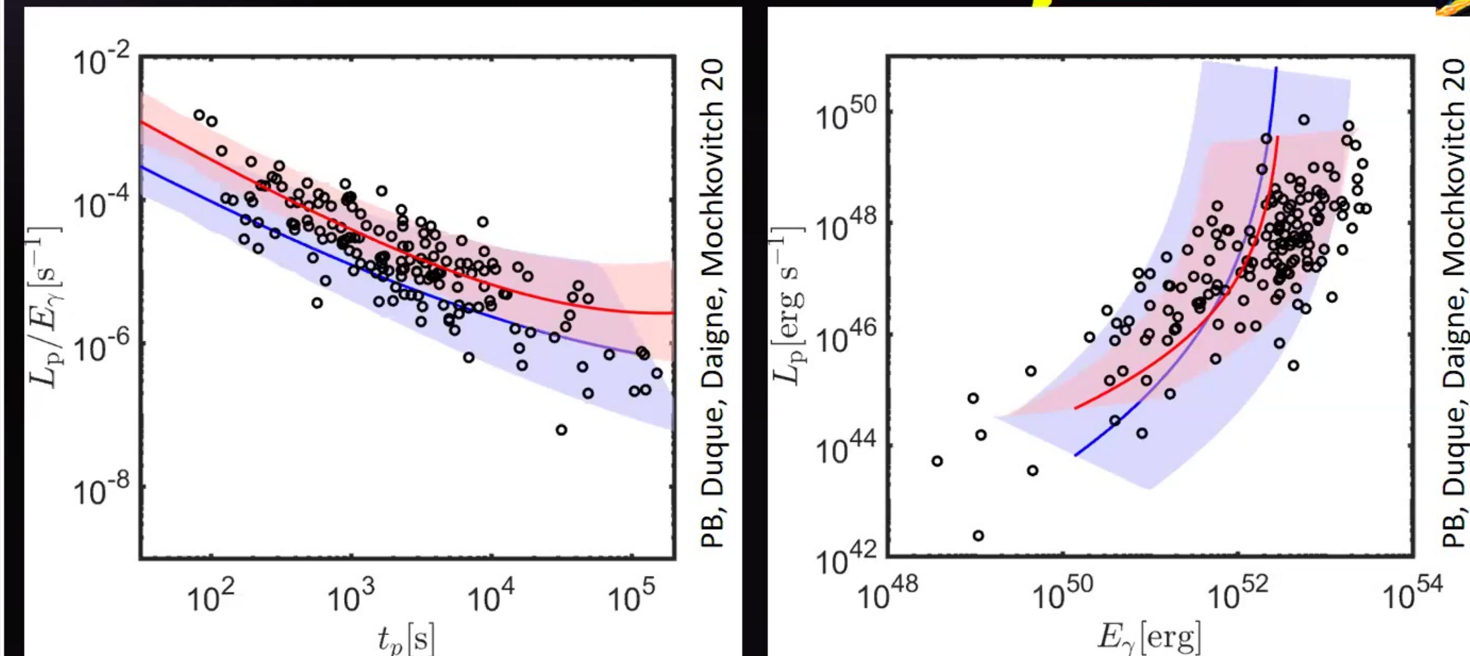



- Observed correlations naturally reproduced:

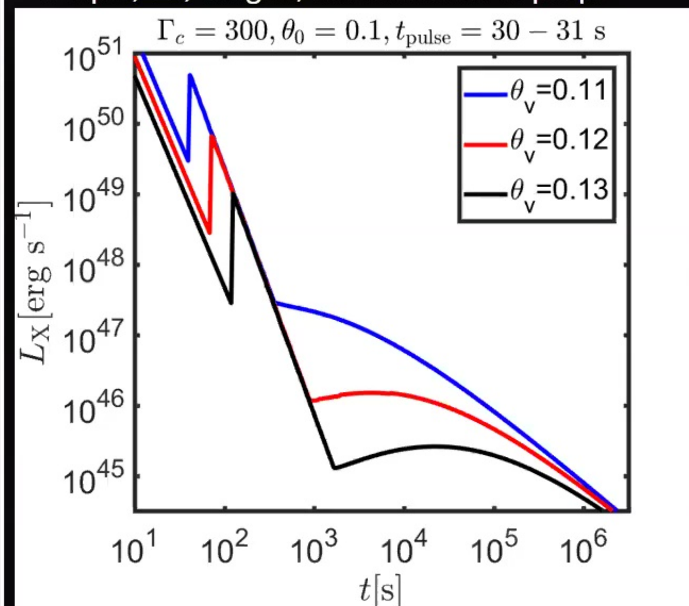
To first order $L_p \propto E_\gamma t_p^{-1}$ as observed (contrary to energy injection!)

- Fraction of bursts with plateaus naturally reproduced $\frac{\theta_{max}^2-\theta_c^2}{\theta_{max}^2}\sim 0.5$
- No spectral break between plateau and post-plateau light-curve

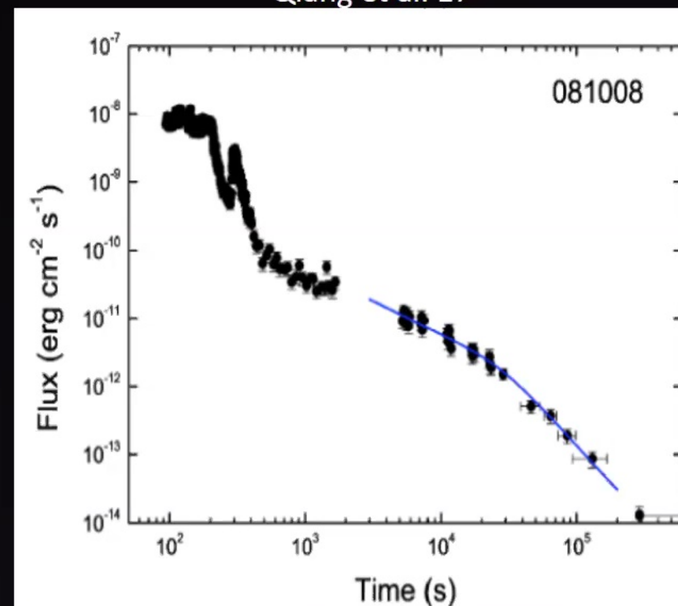
# Evidence for (mildly) off-axis structured GRB jets?

- Same interpretation for plateaus explains X-ray flares as de-boosted off-axis prompt emission spikes

Duque, PB, Daigne, Mochkovitch in prep.




Qiang et al. 17




- Kill two birds with one stone?
- Constraints on structure around the core from cosmological GRBs

# Future prospects - Afterglows

- Likely most common EM counterpart for GW detected BNS merge

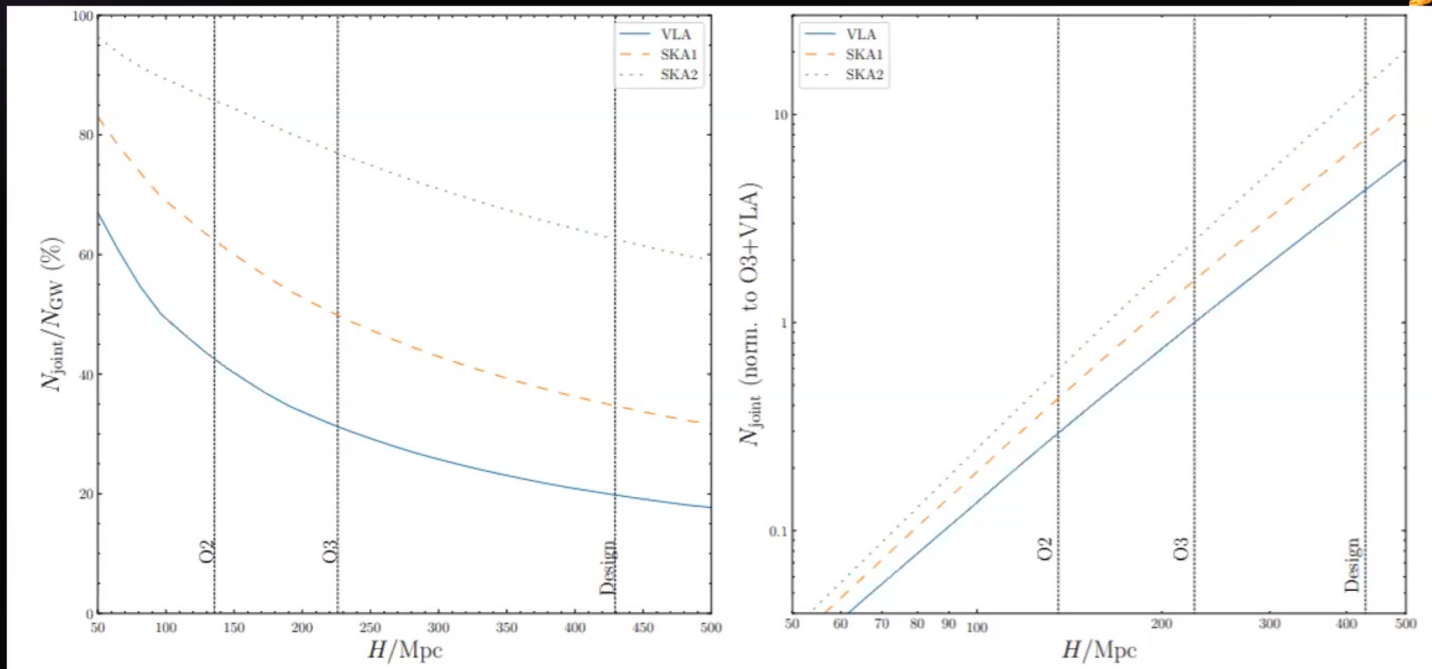
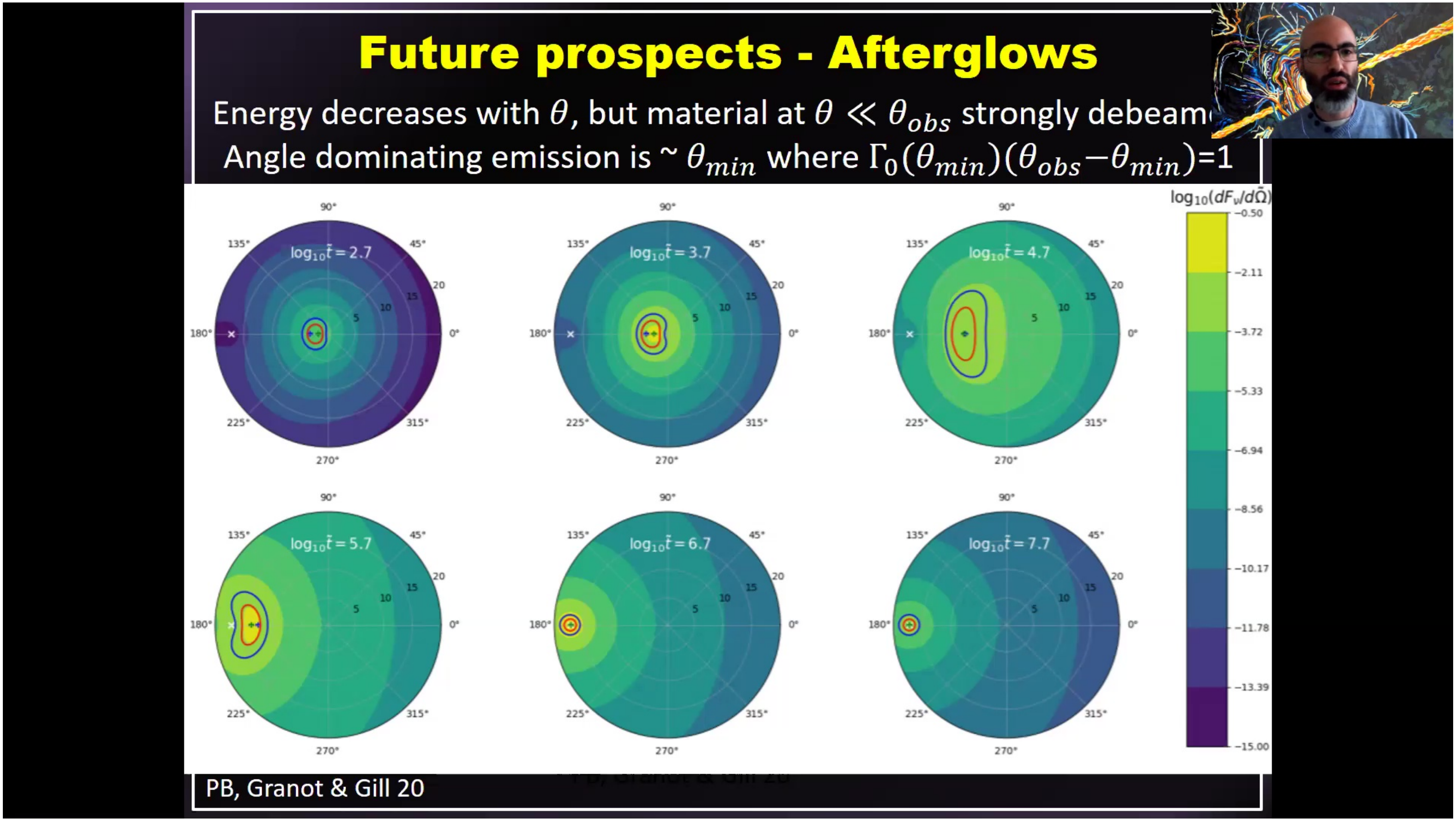
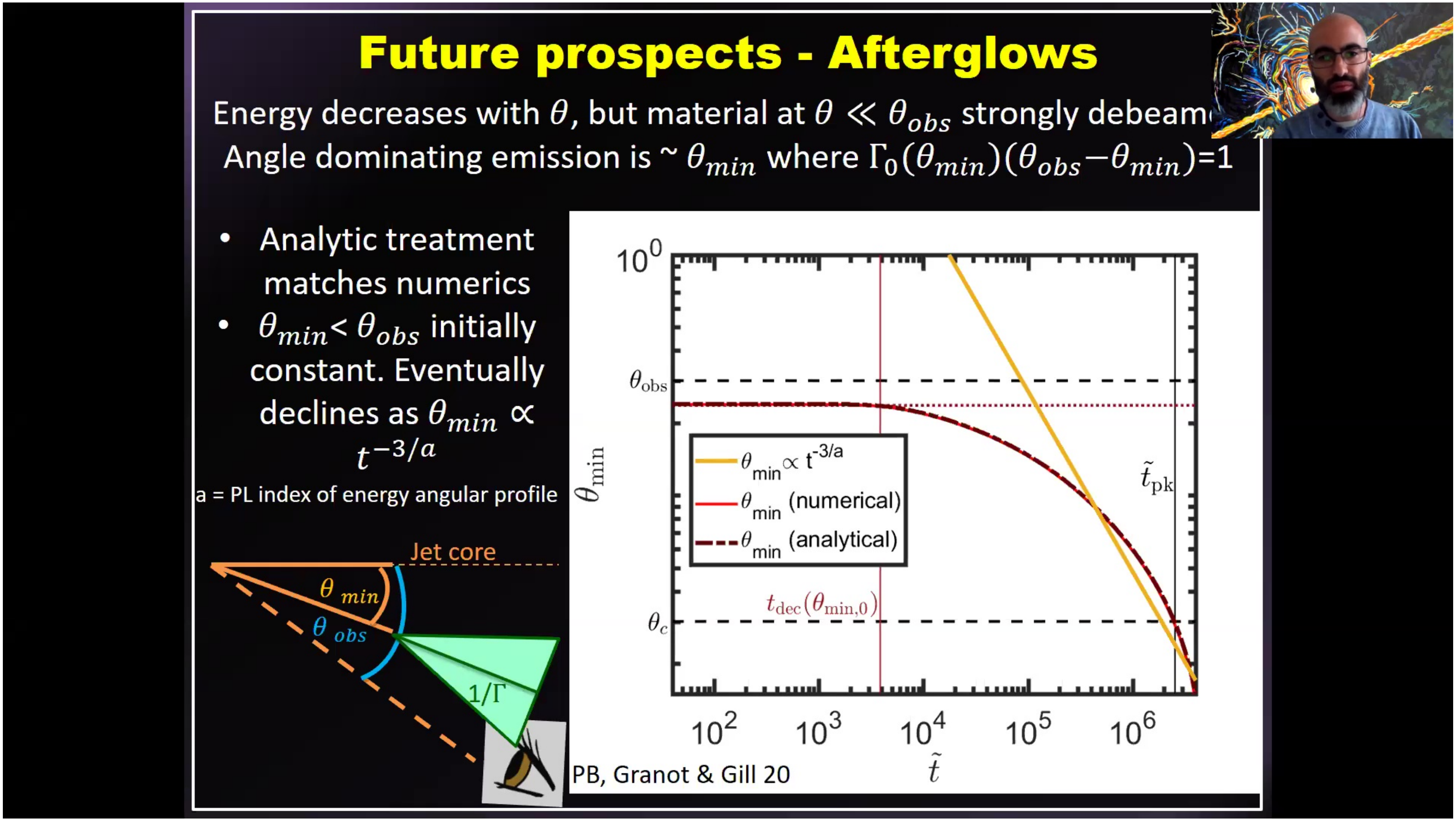



**Fig. 2.** *Left*: Detectable fraction of radio afterglows among gravitational wave events as a function of the *horizon* distance $H = 1.58\bar{H}$. *Right*: Expected number of joint detections normalized to the case of the O3+VLA configuration. In both panels the full (resp. dashed, resp. dotted) lines correspond to the VLA (resp. SKA1, resp. SKA2/ngVLA) being the limiting radio facility.

Duque et al. 19

- We derive simple intuitive tools for analyzing GRB afterglow light-curves that can be used to inform numerical fitting attempts

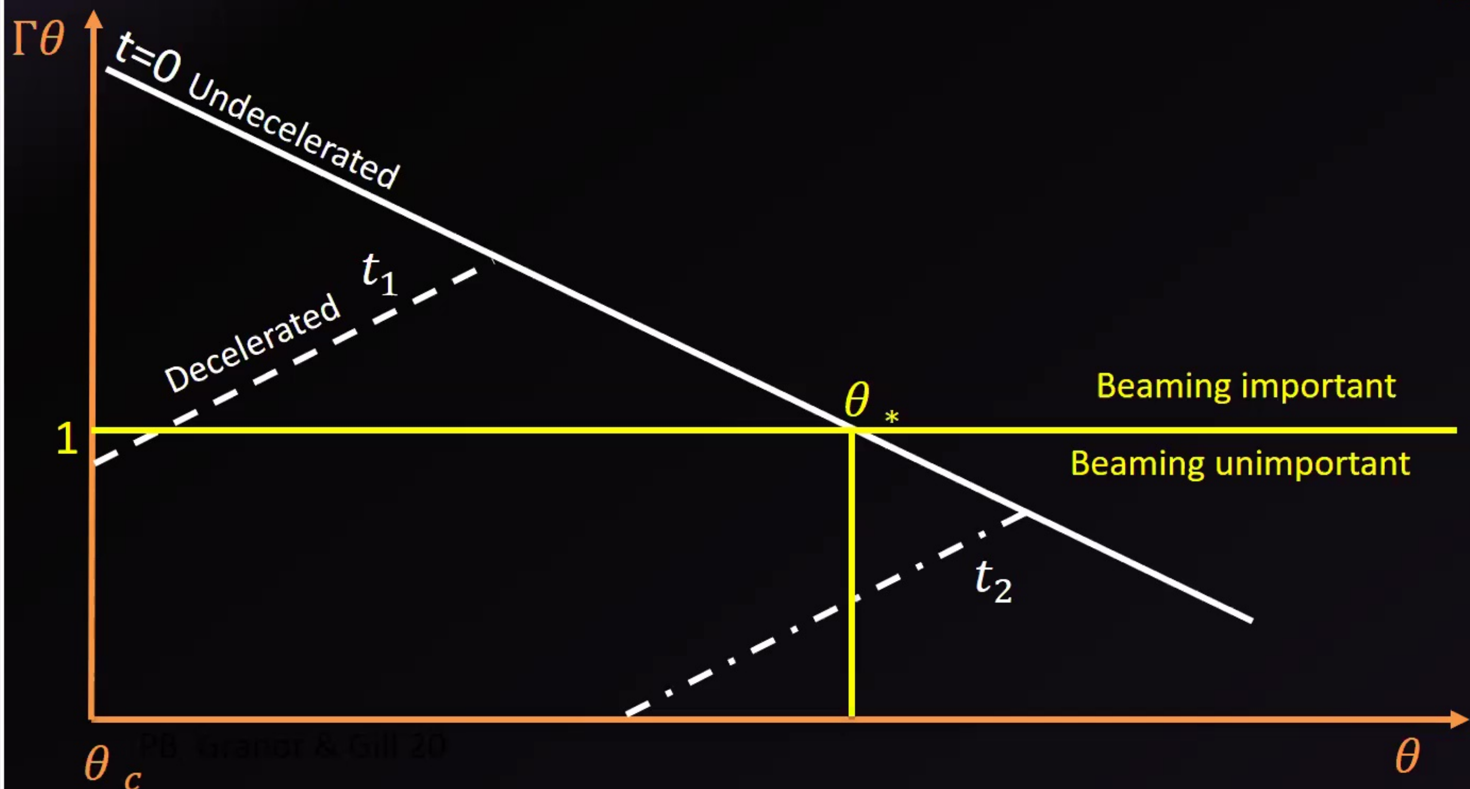

Future prospects - Afterglows
Energy decreases with $\theta$, but material at $\theta \ll \theta_{obs}$ strongly debeam
Angle dominating emission is ~ $\theta_{min}$ where $\Gamma_0(\theta_{min})(\theta_{obs}-\theta_{min})$=1
$\log_{10}\tilde{t} = 2.7$
$\log_{10}\tilde{t} = 3.7$
$\log_{10}\tilde{t} = 4.7$
$\log_{10}\tilde{t} = 5.7$
$\log_{10}\tilde{t} = 6.7$
$\log_{10}\tilde{t} = 7.7$
$\log_{10}(dF_\nu/d\tilde{\Omega})$
−0.50
−2.11
−3.72
−5.33
−6.94
−8.56
−10.17
−11.78
−13.39
−15.00
PB, Granot & Gill 20



Future prospects - Afterglows
Energy decreases with θ, but material at θ ≪ θ_obs strongly debeam
Angle dominating emission is ~ θ_min where Γ_0(θ_min)(θ_obs−θ_min)=1
• Analytic treatment matches numerics
• θ_min< θ_obs initially constant. Eventually declines as θ_min ∝ t^{−3/a}
a = PL index of energy angular profile
Jet core
θ min
θ obs
1/Γ
10^0
θ_obs
θ_c
θ_min
θ_min ∝ t^{-3/a}
θ_min (numerical)
θ_min (analytical)
t_dec(θ_min,0)
t̃_pk
10^2
10^3
10^4
10^5
10^6
t̃
PB, Granot & Gill 20

# Future prospects - Afterglows

A typical case is that $b > 1$ where $\Gamma_0(\theta) \propto \theta^{-b}$ for $\theta > \theta_c$

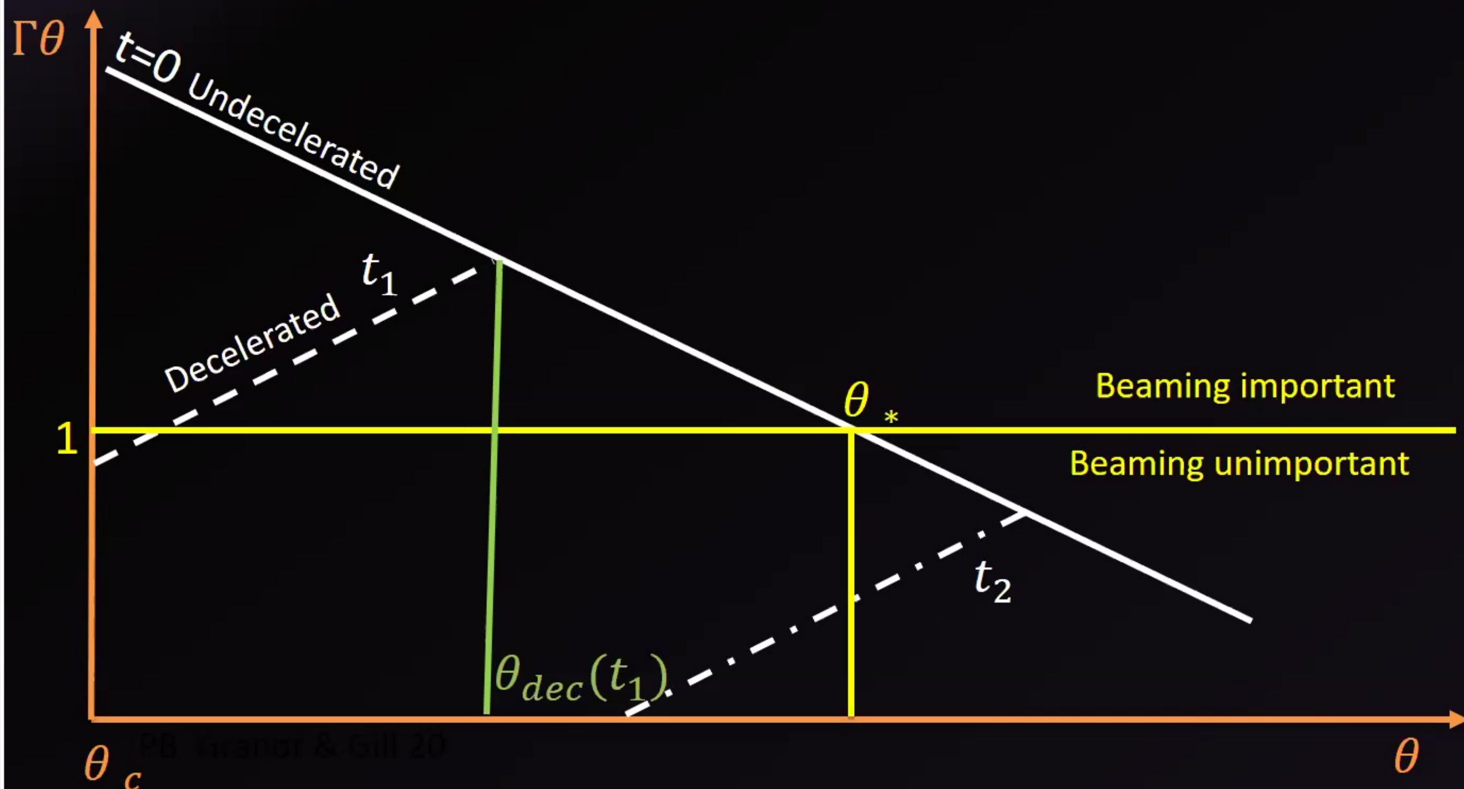



$\Gamma_0(\theta)\theta$ declines with $\theta$ and deceleration progresses from inwards out*

* Unless energy profile is extremely steep

# Future prospects - Afterglows

A typical case is that $b > 1$ where $\Gamma_0(\theta) \propto \theta^{-b}$ for $\theta > \theta_c$




$\Gamma_0(\theta)\theta$ declines with $\theta$ and deceleration progresses from inwards out*

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# Future prospects - Afterglows

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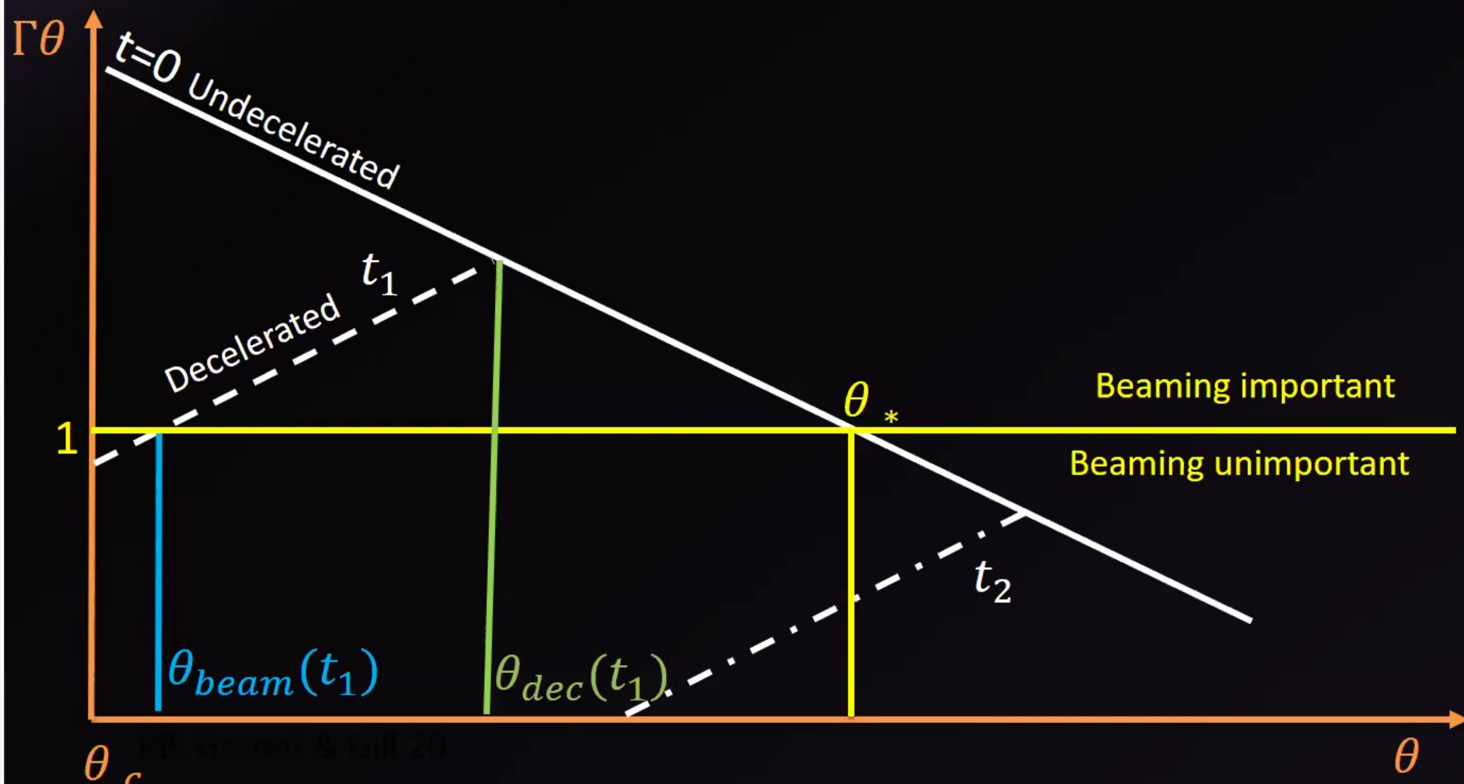


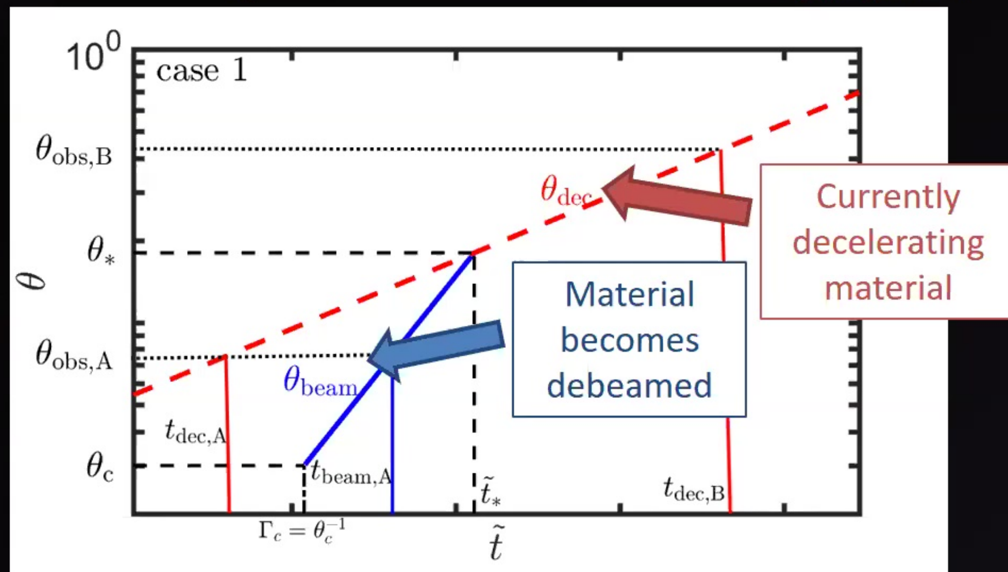

$\Gamma_0(\theta)\theta$ declines with $\theta$ and deceleration progresses from inwards out*

* Unless energy profile is extremely steep

# Future prospects - Afterglows

A critical angle $\theta_*$ is defined such that $\Gamma_0(\theta_*)\theta_*=1$

PB, Granot & Gill 20

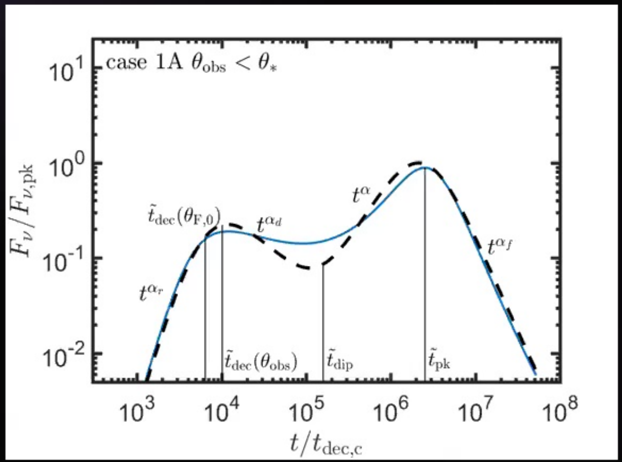


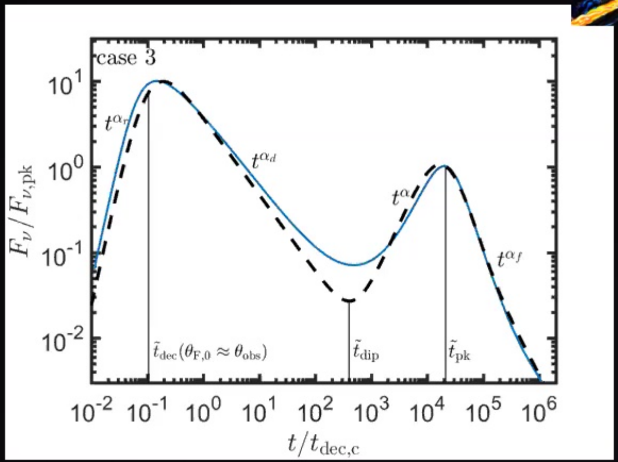

*A.* $\theta_{obs} < \theta_*$ $\rightarrow \Gamma_0(\theta_{obs})\theta_{obs}$>1 Relativistic beaming important from t=0
Initially dominant material decelerates and dominates flux before lower latitudes become exposed and take over

*B.* $\theta_{obs} > \theta_*$ $\rightarrow \Gamma_0(\theta_{obs})\theta_{obs}$<1 Initially dominant angle is significantly smaller than $\theta_{obs}$ and gradually decreases with time

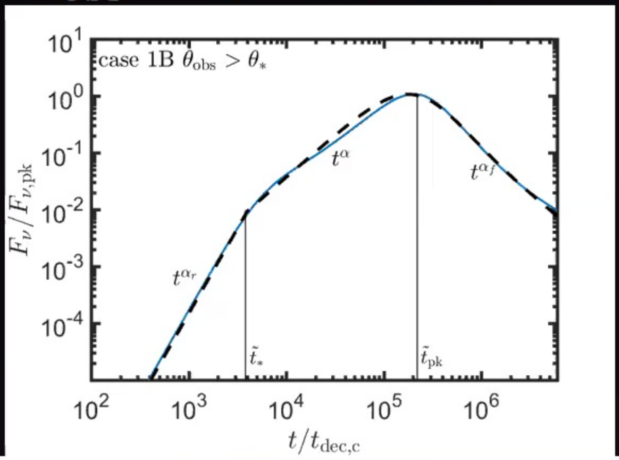
# Future prospects - Afterglows

Case A $\theta_{obs} < \theta_*$ – Double peaked light-curve




Case B $\theta_{obs} > \theta_*$ – Single peaked light-curve




Numerical calculation

Analytic light-curve

PB, Granot & Gill 20

# Future prospects - Afterglows

- Analytic treatment reproduces numerical simulations and provid[e] easy to use and intuitive tools

- Analytics reproduce Temporal slopes, critical times and critical fluxes

  - n, E, $\varepsilon_e$, $\varepsilon_B$ highly degenerate

- $q \equiv \frac{\theta_{obs}}{\theta_c}$, a, b, $\xi_c \equiv (\Gamma_c \theta_c)^2$ robustly constrained from analytics

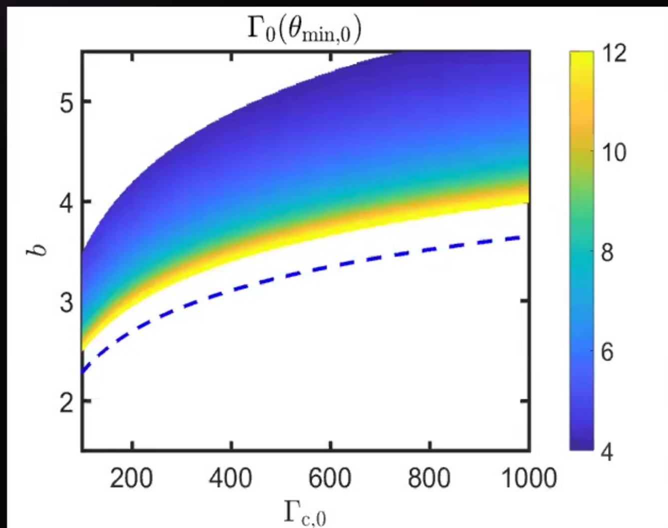
$$q = \left(\frac{F_{1\mathrm{pk}}}{F_{\mathrm{pk}}}\right)^{\frac{4}{8-a(3+p)}} \left(\frac{t_{\mathrm{pk}}}{t_{1\mathrm{pk}}}\right)^{\frac{3(1-p)}{8-a(3+p)}}$$

$$\xi_c \approx 2^{\frac{a}{2(4-k)}} \left(\frac{t_{\mathrm{pk}}}{t_{1\mathrm{pk}}}\right)^{\frac{3-k}{4-k}} q^{2(b-1)-\frac{a}{4-k}}$$

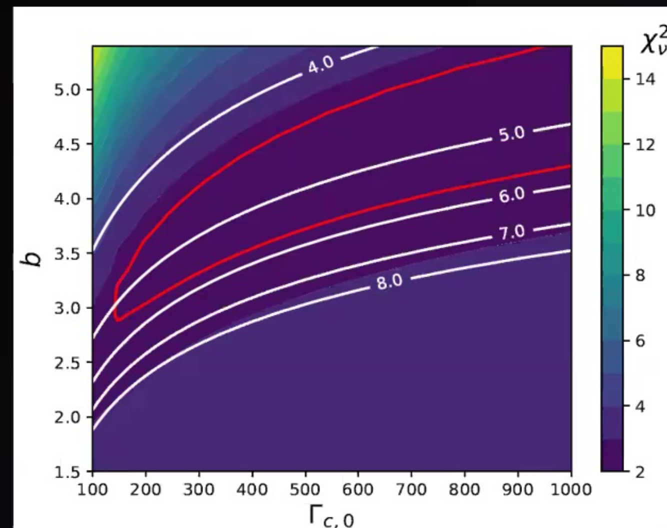
$$\xi_c = \left(\frac{t_{\mathrm{pk}}}{t_*}\right)^{\frac{2(b-1)(k-3)}{8-a-2k}} 2^{\frac{a(1-b)}{8-a-2k}} q^{\frac{4(b-1)(4-k)}{8-a-2k}}$$

# 170817 as a test case

- Single peaked light-curve + shallow rise & $t_{pk} > 7t_{dec}(\theta_{min,0})$ constrains b, $\Gamma_c$, and $\Gamma(\theta_{min,0}) \equiv \Gamma$ of initially dominant material




**Analytics**




**Numerical simulation**

$b \gtrsim 3$ ; $\Gamma_{c,0} > 150$

- $\Gamma(\theta_{min,0}) \approx 5 - 7$ constrained by 3 independent approaches:

Afterglow light-curve analysis

Superluminal motion – Flux centroid velocity

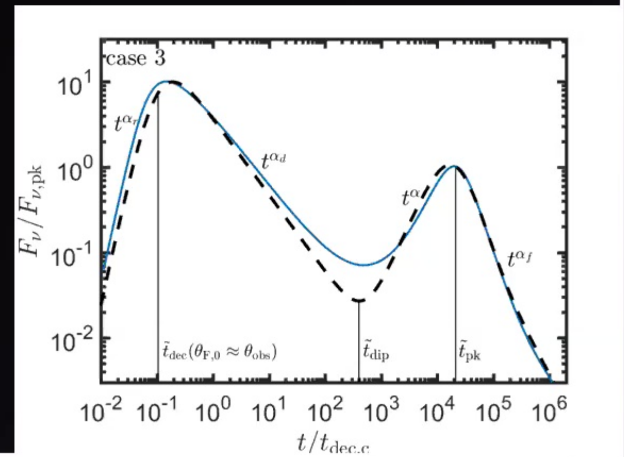
Compactness constraint from prompt emission

# Conclusions

- In lGRBs, if energy drops continuously with latitude,

efficient γ-ray production restricted to material with $\Gamma > 50$, $\theta_{obs} \lesssim 1.5\theta_c$

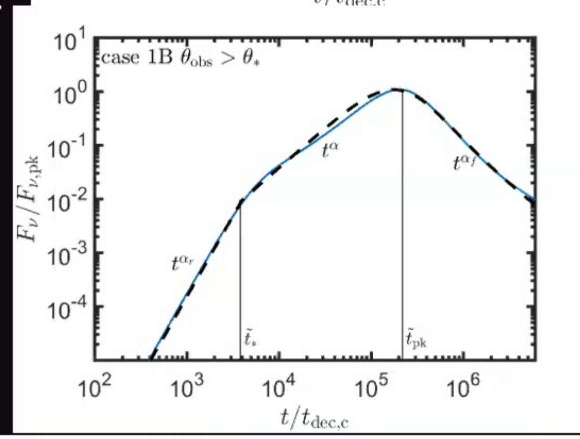
- At $\theta_c \lesssim \theta_{obs} \lesssim 2\theta_c$ plateaus are naturally produced by debeamed emission from core and reproduce observed light-curves, correlations with prompt properties




- sGRBs: Structured jet vs cocoon distinguished by $L_\gamma$ and $\theta_{obs}$ of joint prompt + GW events

- Analytical tools robustly constrain parameters of far off axis afterglows

- Two qualitative types of afterglows predicted




Thank You.