Structured Jets: Illuminating the Enigma of GRBs

Paz Beniamini – Astrophysics Research Center of the Open University (ARCO),
Open University of Israel

Work with: Jonathan Granot, Ramandeep Gill, Brendan O'Connor, Vikas Chand, Gal Birenbaum, Raphael Duque, Frederic Daigne, Robert Mochkovitch, Tsvi Piran and Tatsuya Matsumoto

ARCO
Astrophysics Research Center of the Open university

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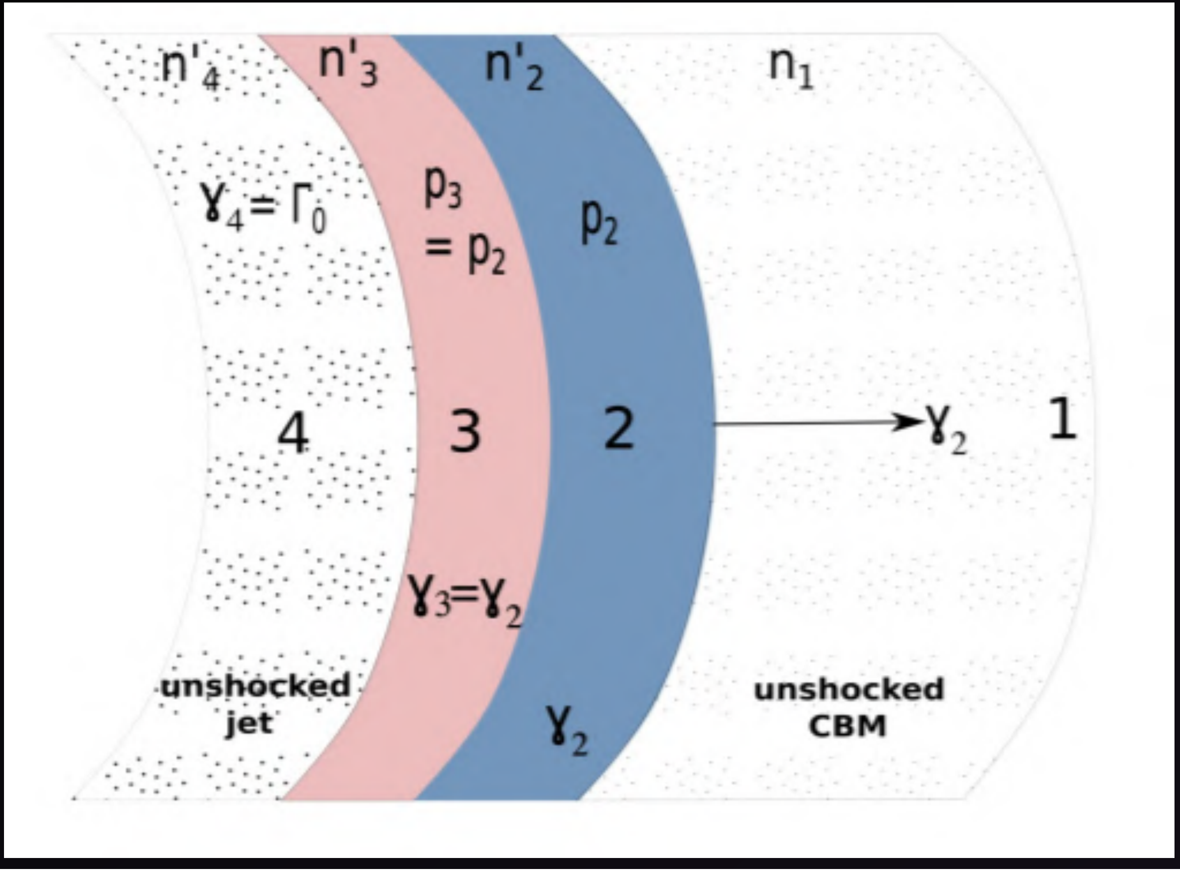
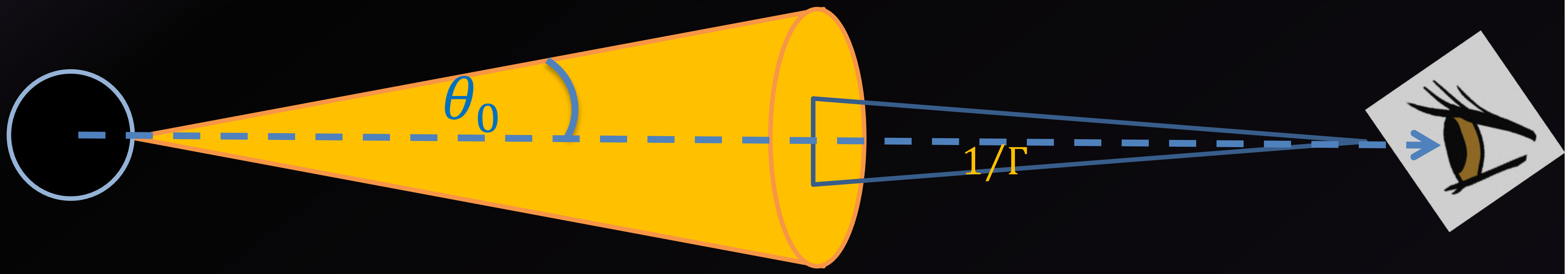
Jet afterglows

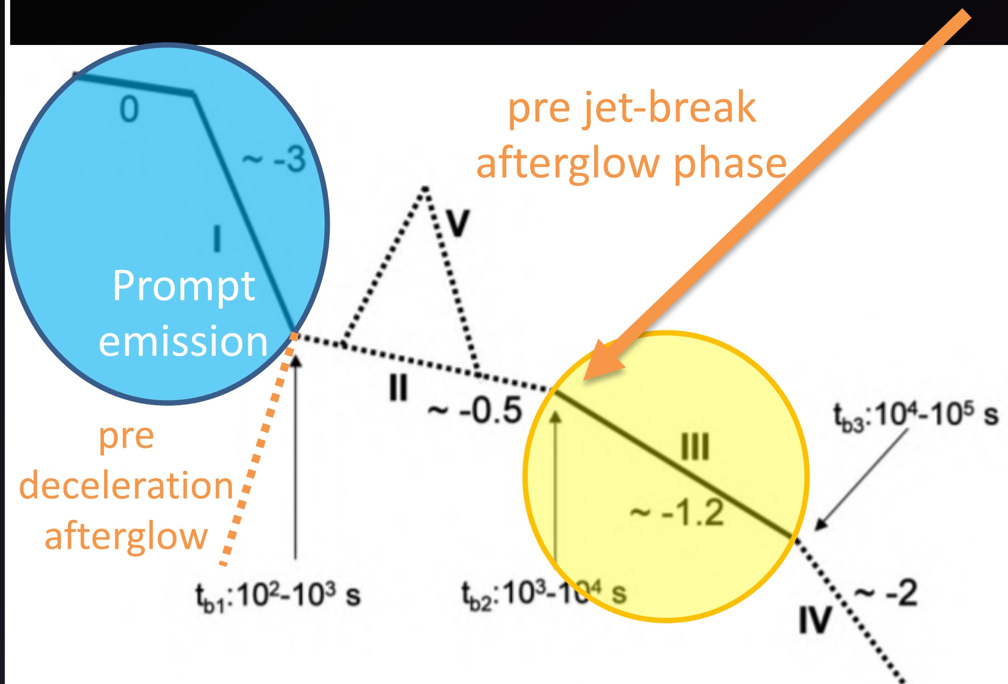
- Dynamics: Self-similar blast wave ultra-relativistic blast wave driving into external density (Blandford & Mckee 76)
- Radiation: Synchrotron from electrons accelerated in the forward shock (Sari, Piran & Narayan 98)



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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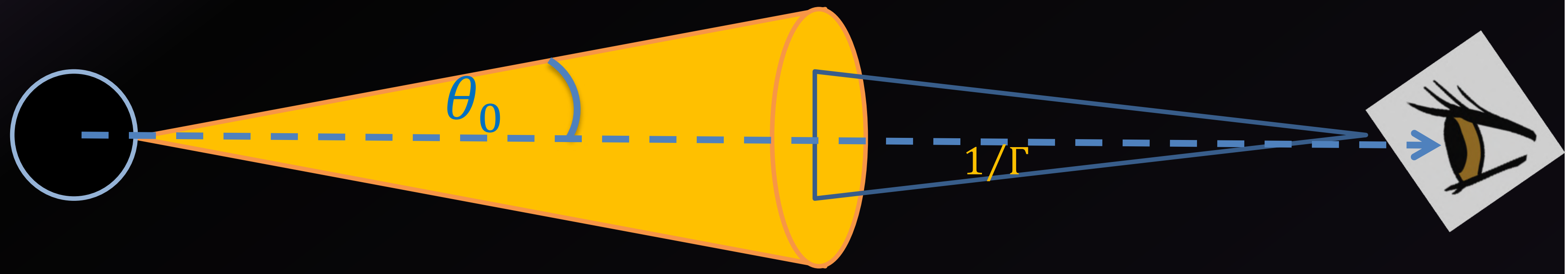

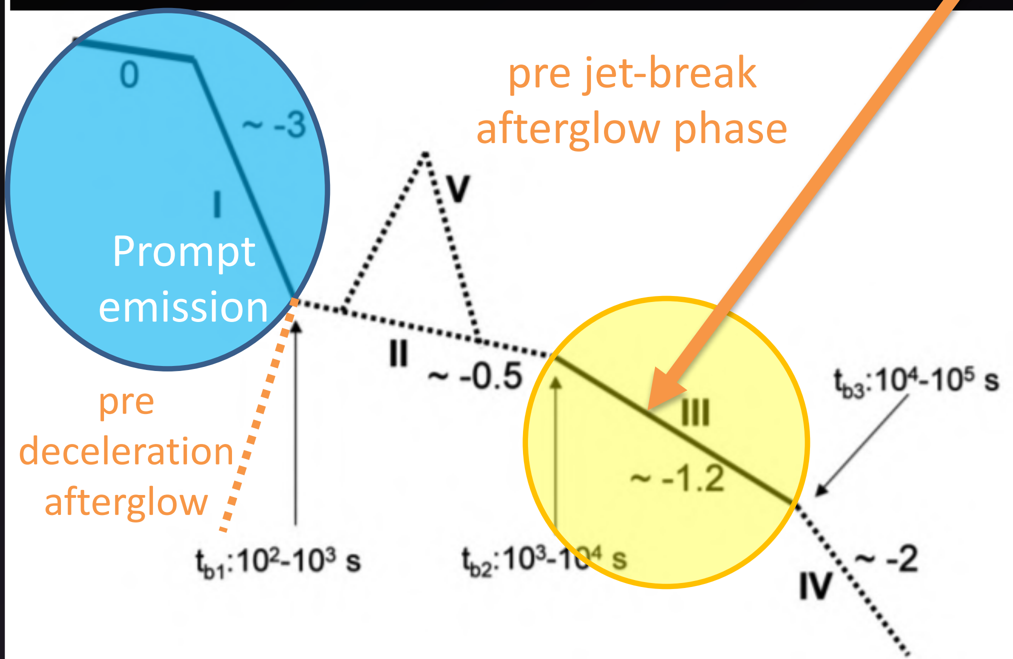

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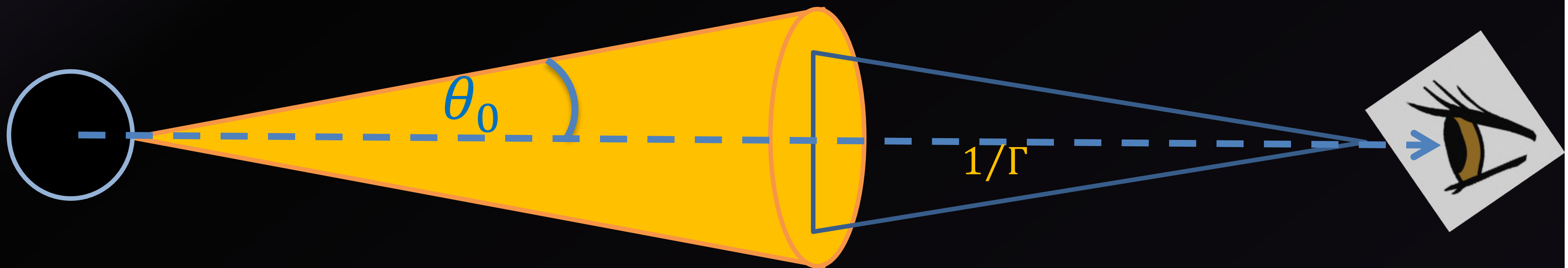

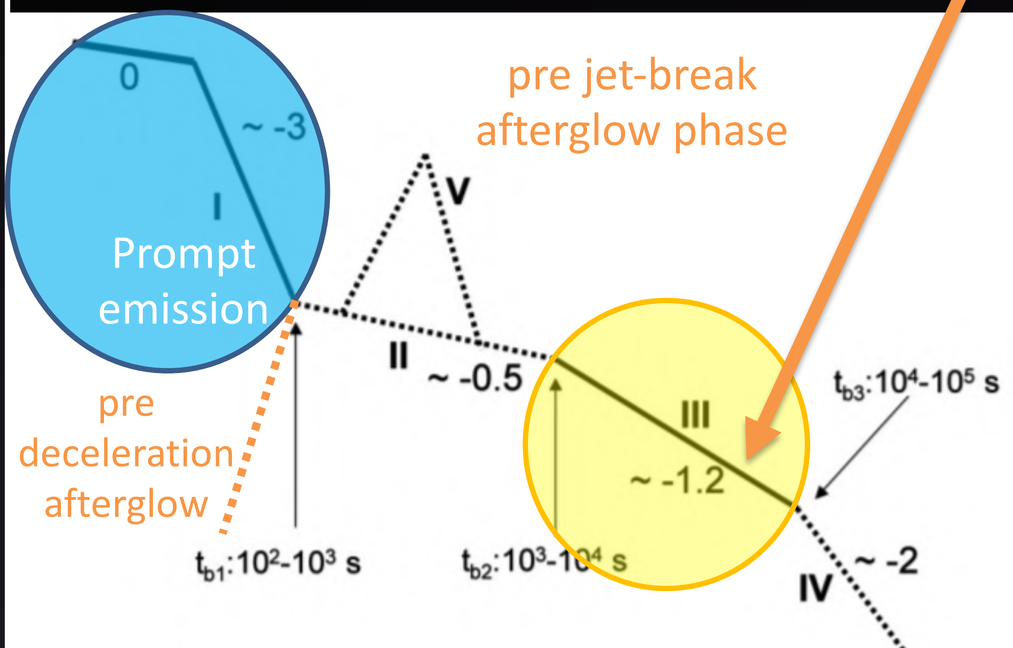

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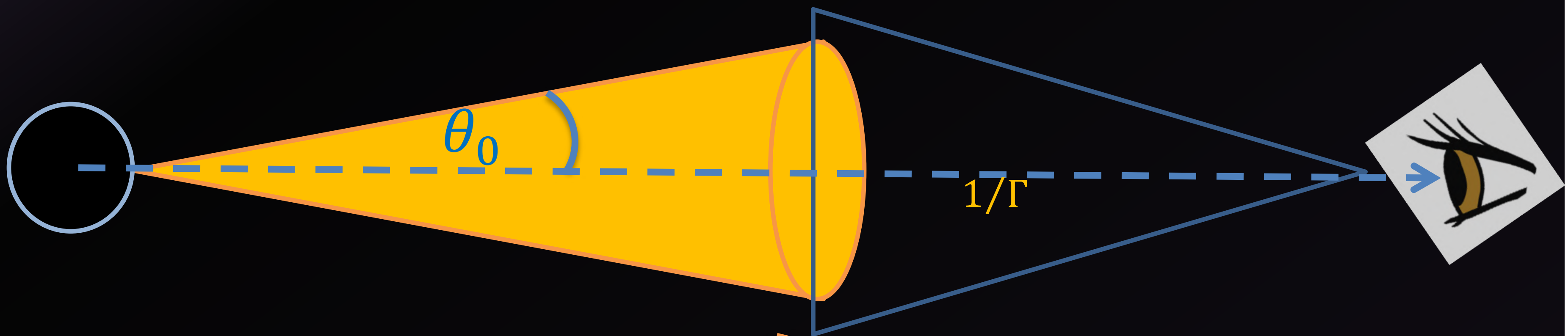

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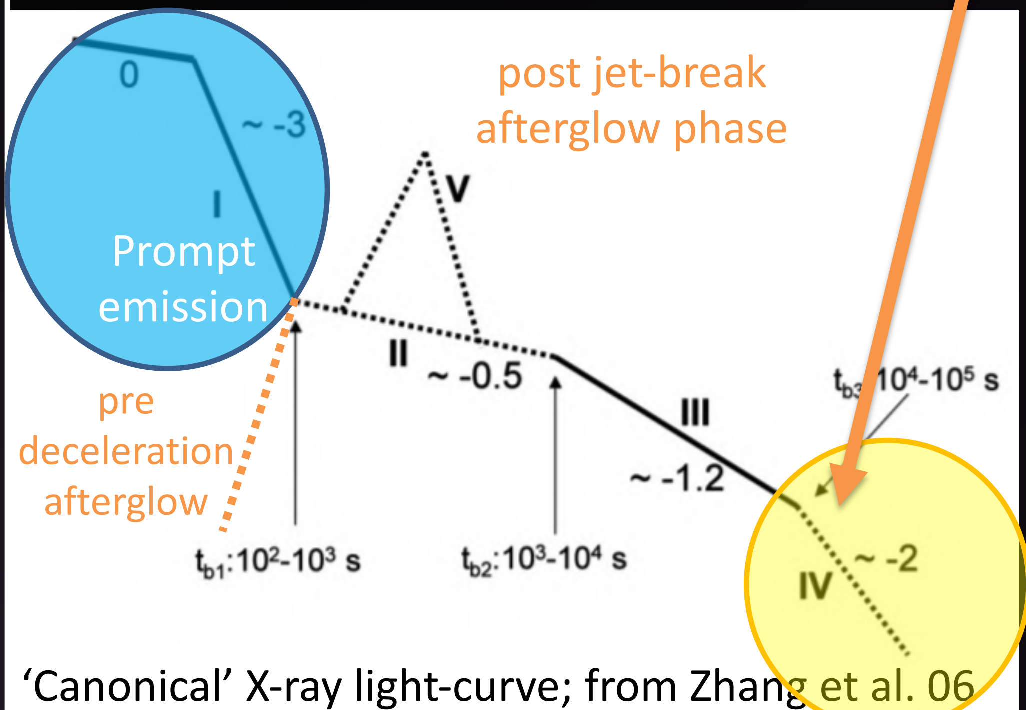

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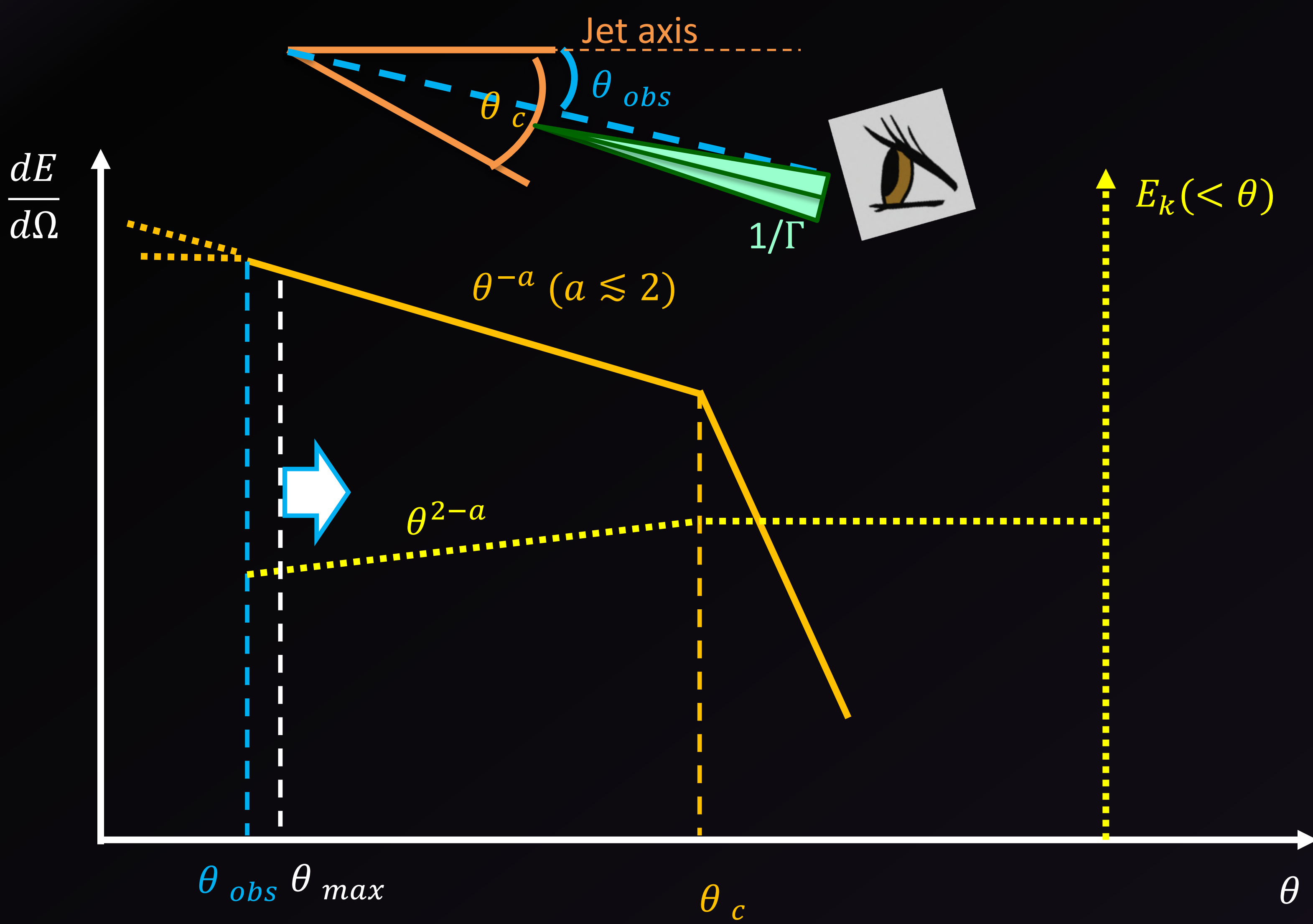
Shallow jets look different even on-axis

Emission dominated by largest visible angle



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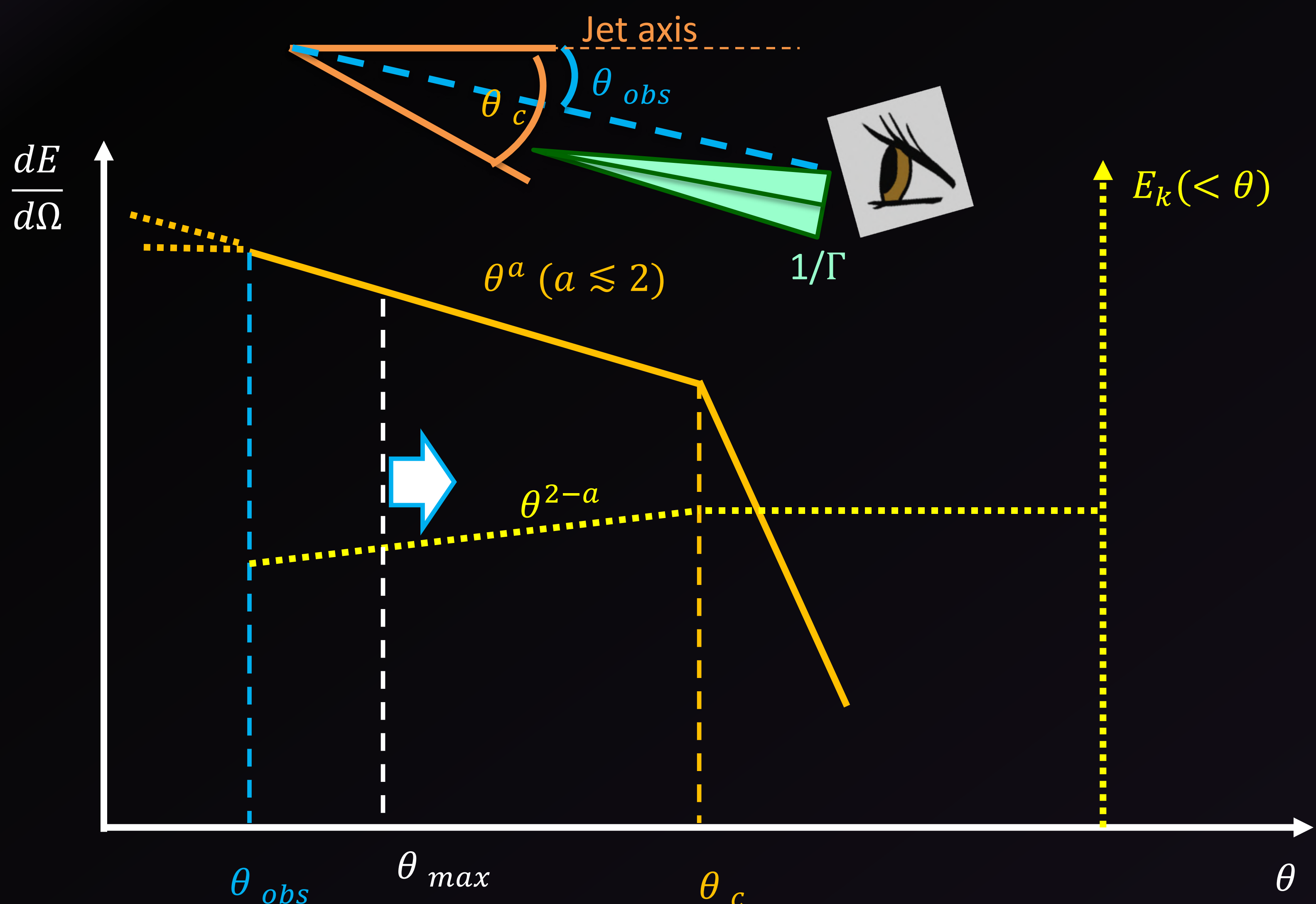

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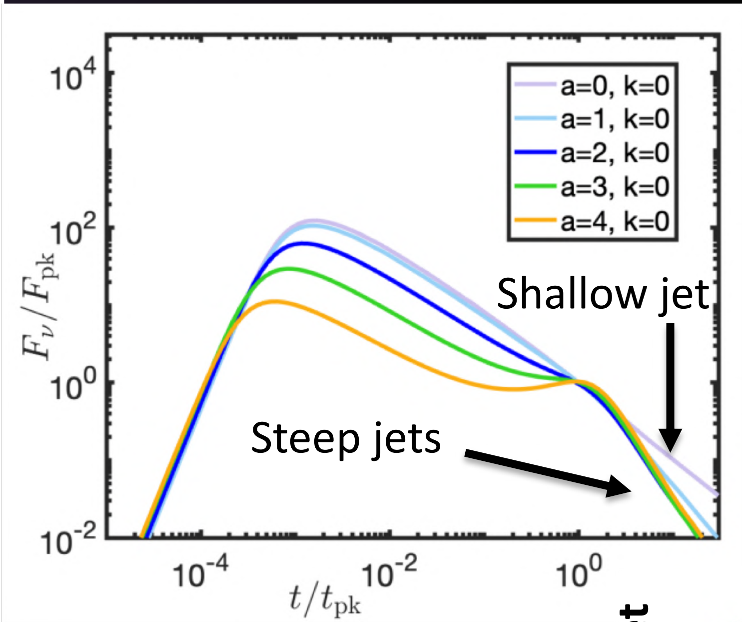
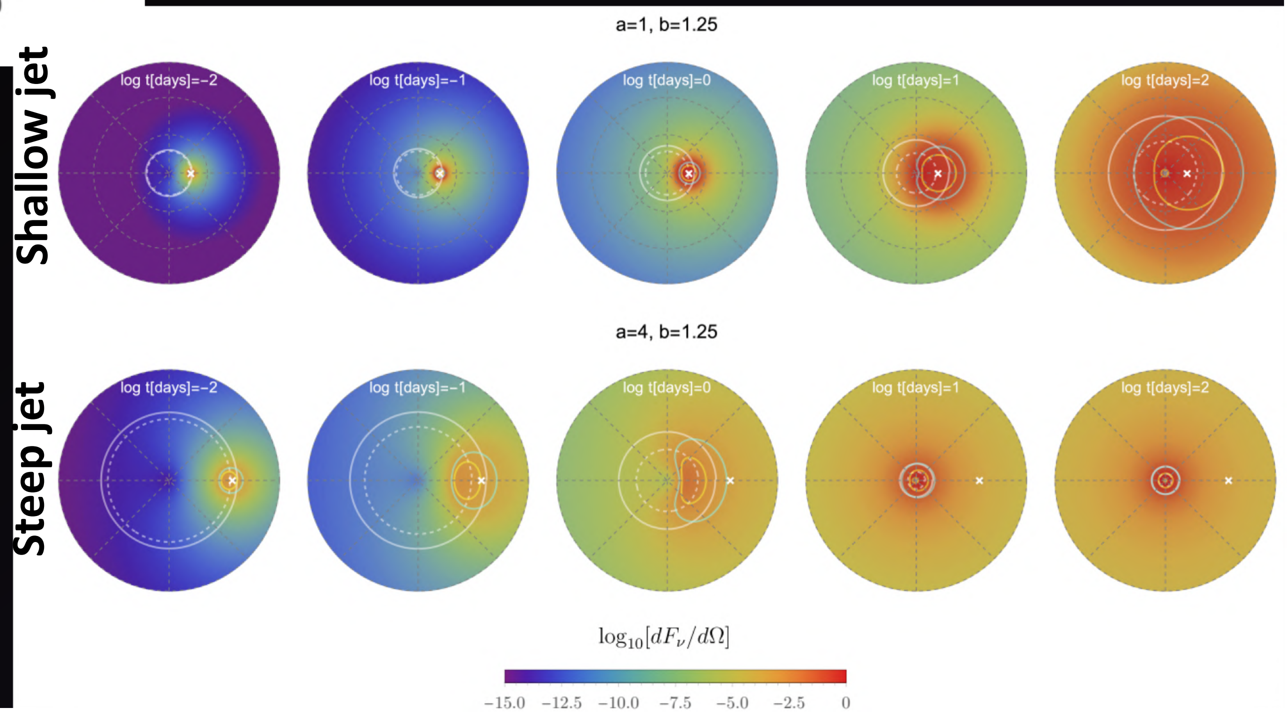


- For $\varepsilon \propto \theta^a$ beyond jet core with $a \lesssim a_{cr} \sim 2$, flux eventually dominated by angles larger than viewing angle.
- $\theta_{obs} = \Gamma(\theta_{obs})^{-1}$ replaces traditional jet break

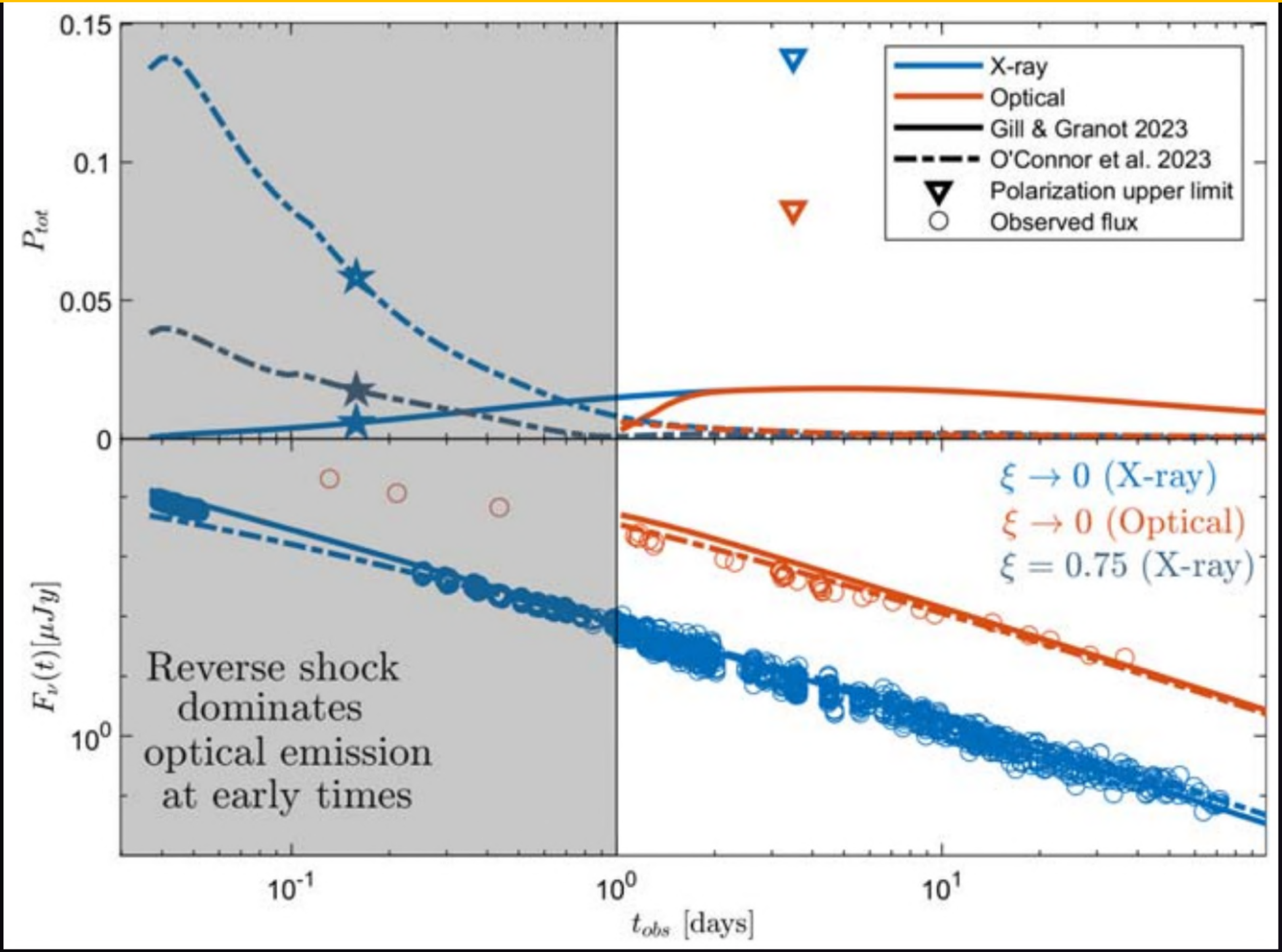
PB, Gill & Granot 22

- Distinct temporal evolution / closure relations
- Potentially chromatic `jet breaks’
- Motion and shape of flux centroid



Little polarization expected for shallow jets

- See talk by Gal Birenbaum



Birenbaum, ... PB... 24

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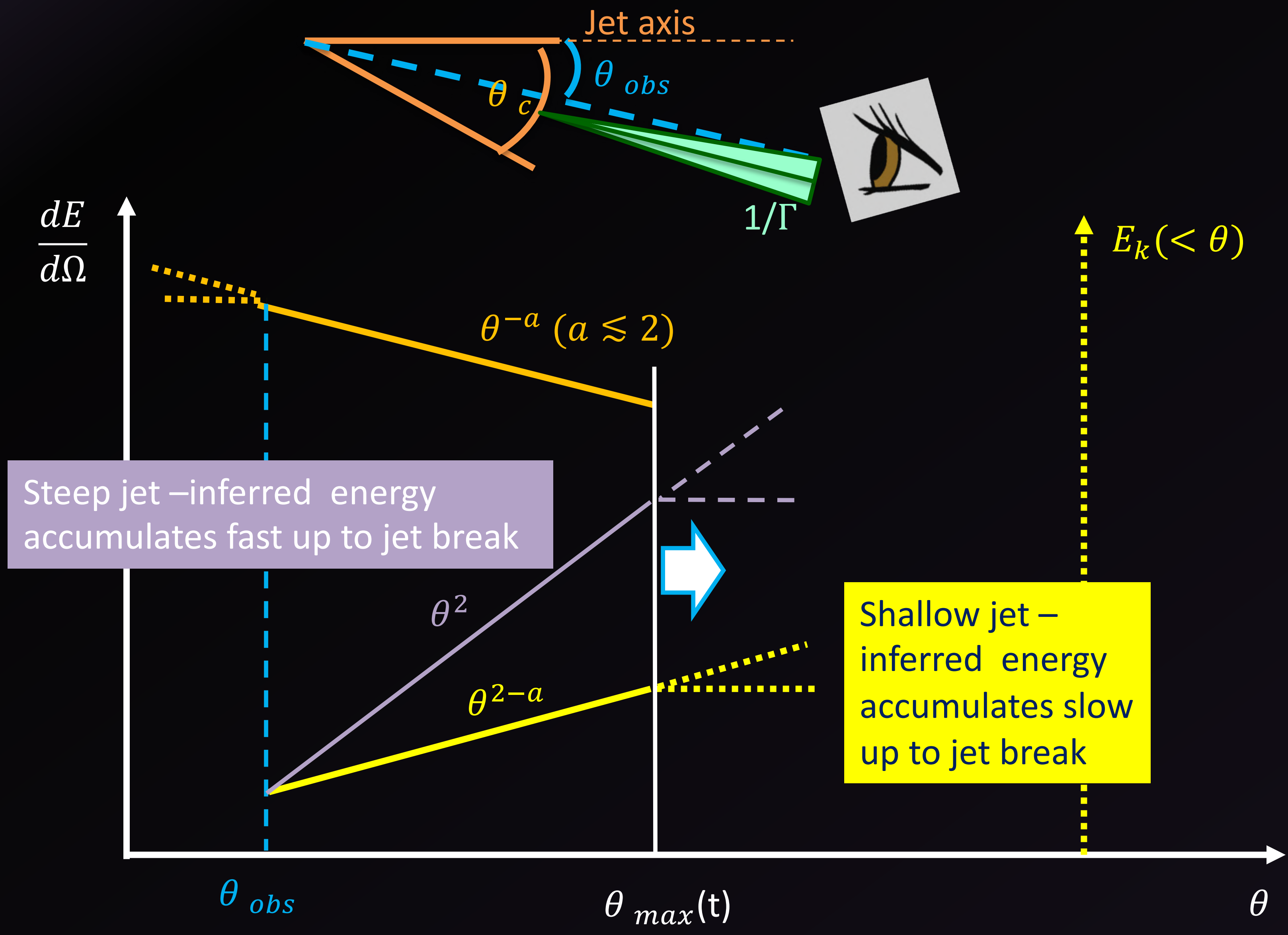
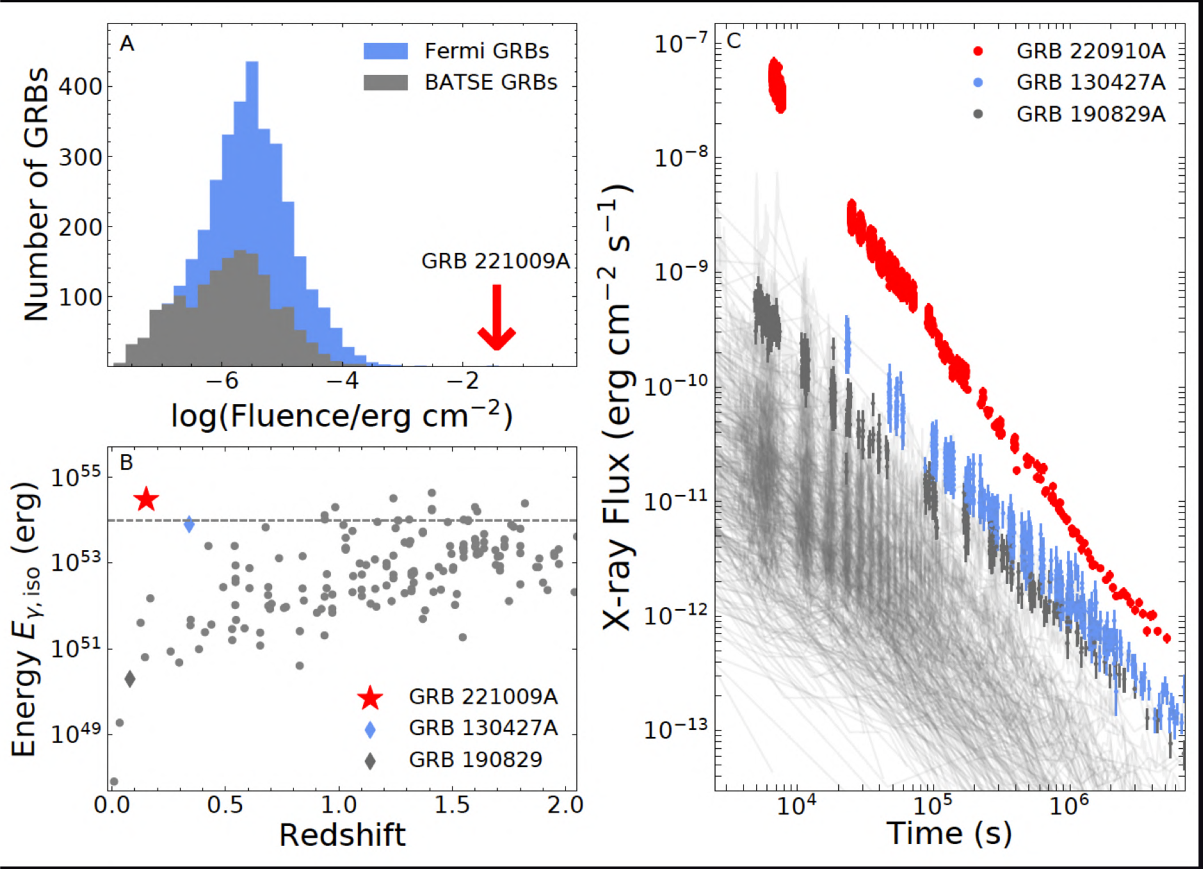


Do shallow jets underlie the most energetic GRBs?

- Very energetic GRBs show no steep jet break until very late times (>120 days in GRB 221009)
- For a 'steep' jet, huge minimum limit on beaming corrected energy

$$E_k > 5 \cdot 10^{53} \left(\frac{t}{120\ d}\right)^{3/4} \left(\frac{n}{1 cm^{-3}}\right)^{1/4} \mathrm{erg}$$



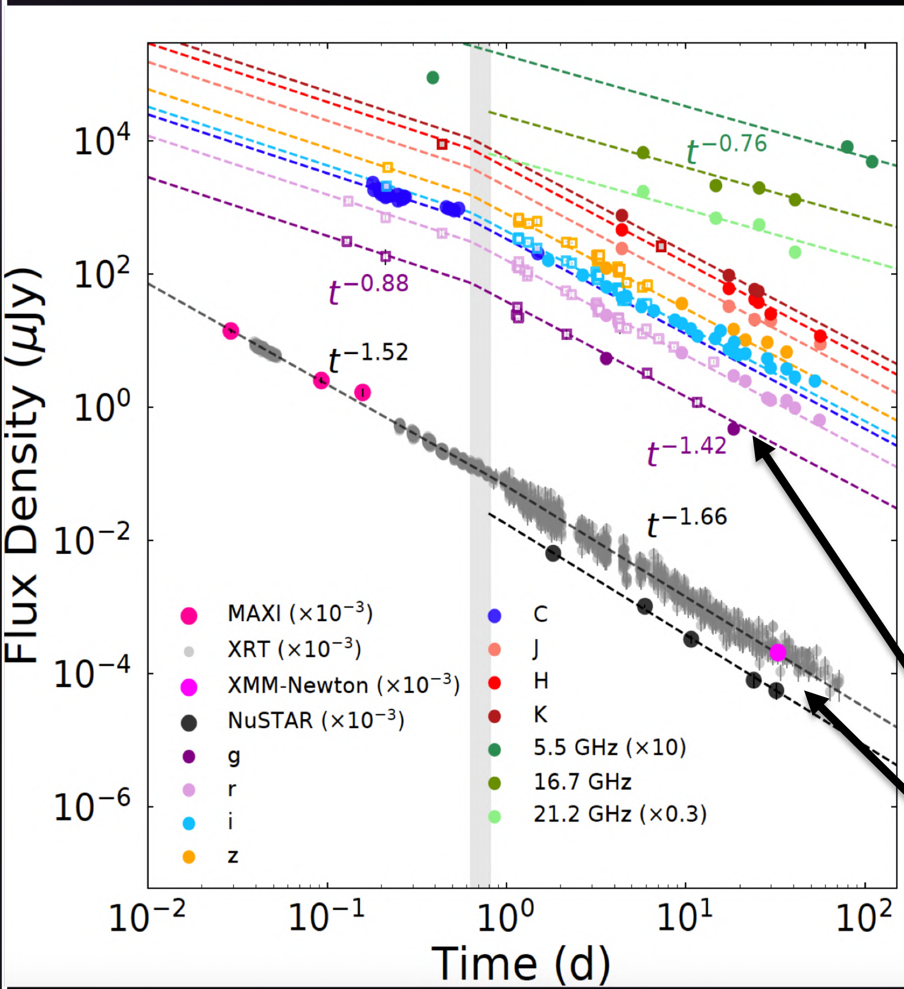
- A `shallow' on-axis jet, explains the spectrum and lightcurve and requires significantly less energy
- $\theta \propto t^{\frac{3}{8}} \rightarrow$

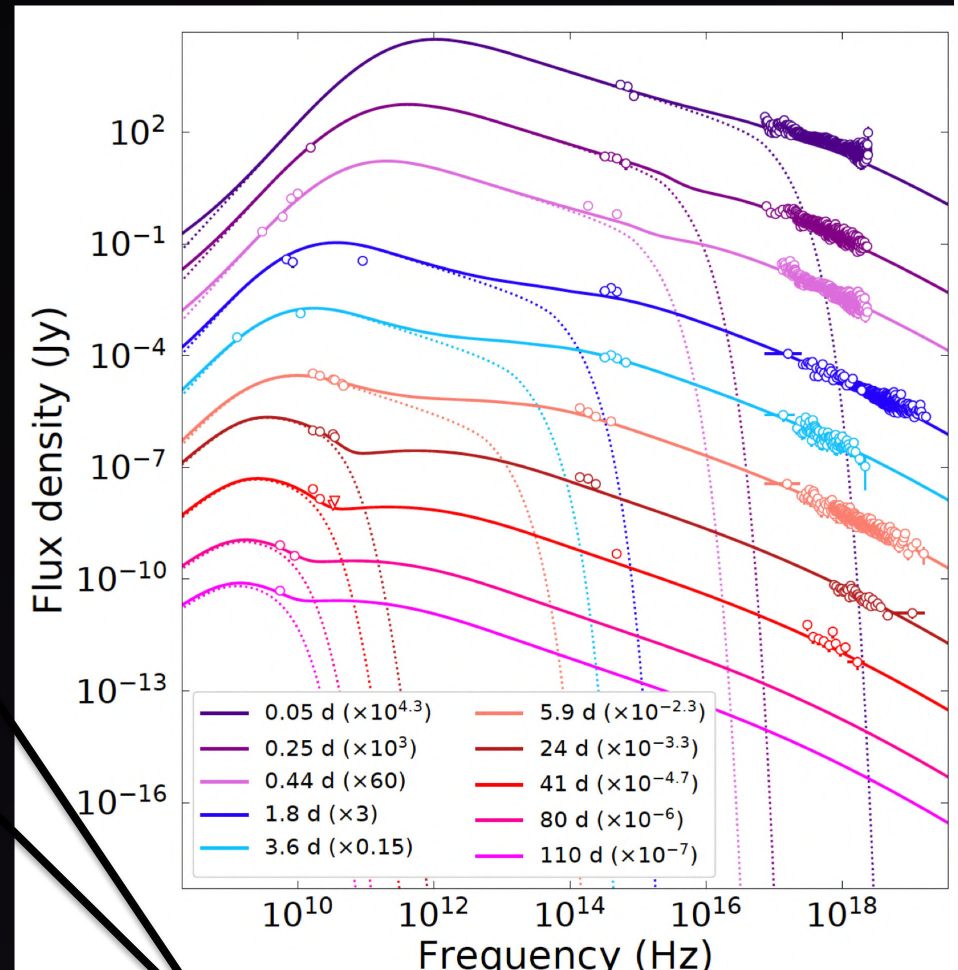
$$E_k \propto \theta^{2-a} \propto t^{\frac{6-3a}{8-a}} \sim t^{0.37}$$

- $E_k \approx 1 - 8 \cdot 10^{52} \left(\frac{t}{120\ d}\right)^{0.37}$

O'connor, .. PB... et al. 23

Do shallow jets underlie the most energetic GRBs?



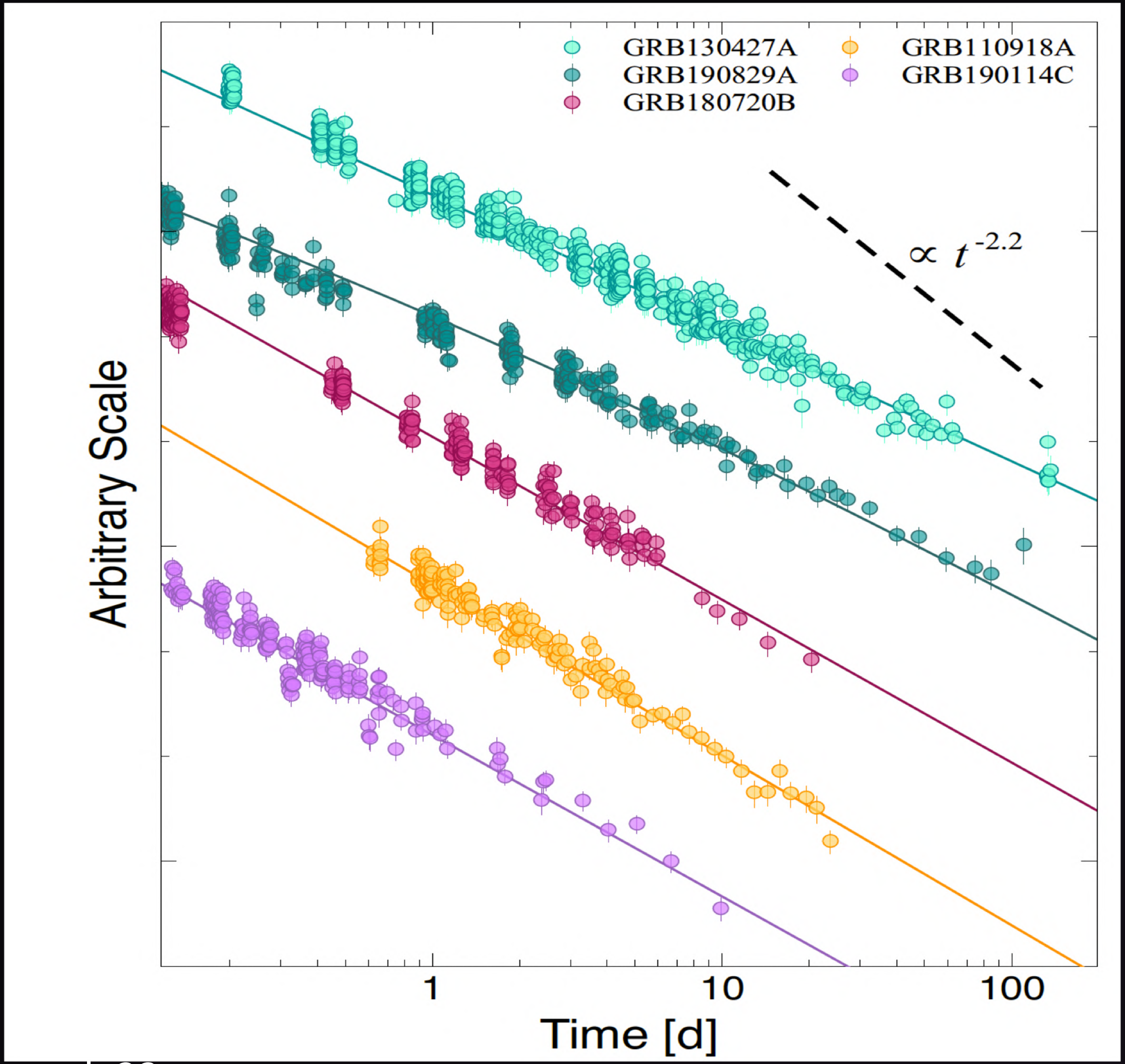


Too steep if $E_{iso}(t)$=const

O'connor, .. PB... et al. 23

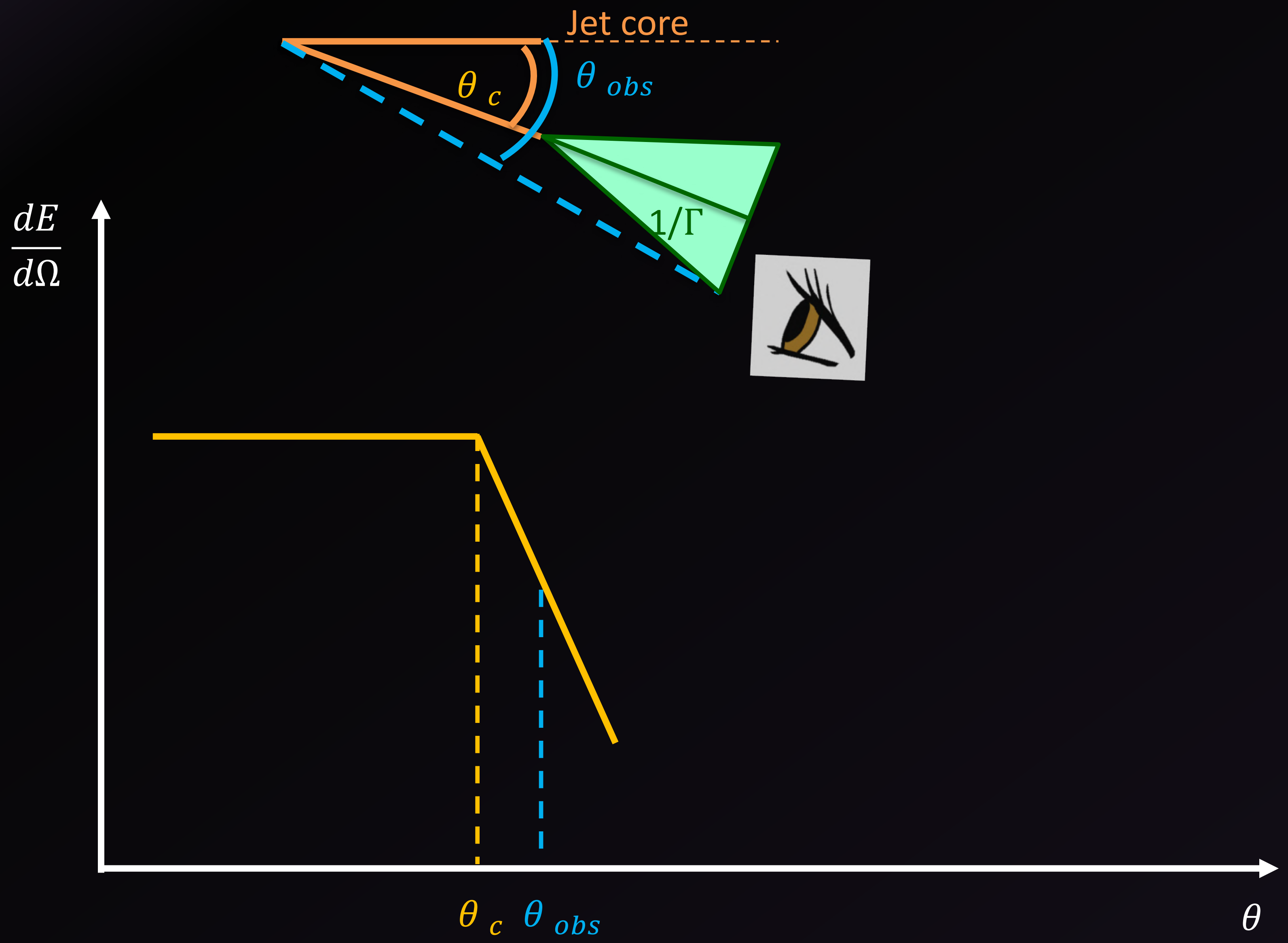
Do shallow jets underlie the most energetic GRBs?

- Other energetic GRBs follow the same trend



O'connor, .. PB... et al. 23

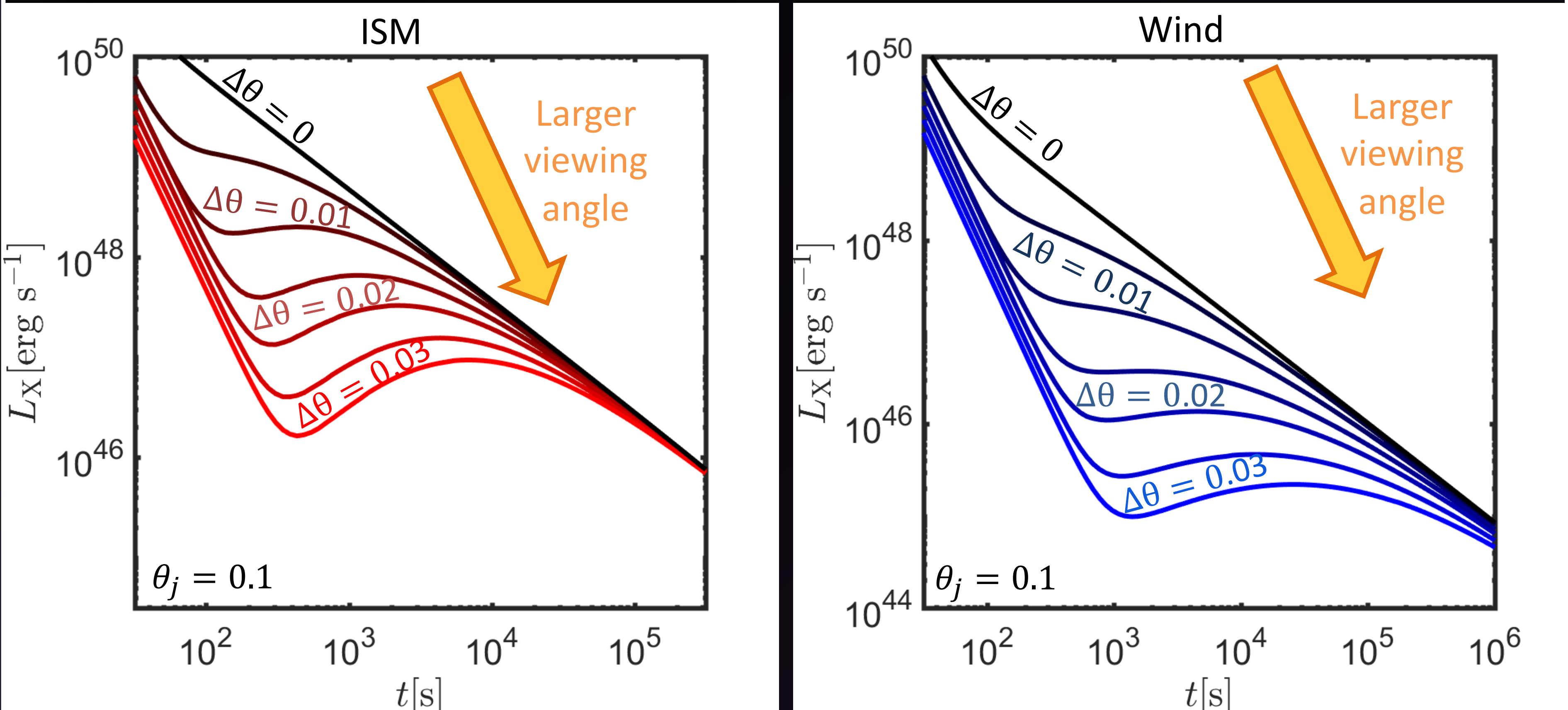
Slightly off-axis jets



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

For $\Delta\theta = \theta_{obs} - \theta_c \lesssim 0.5\theta_c$ shallow phase lasts until $\Gamma(\theta_j) \approx \Delta\theta^{-1}$

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



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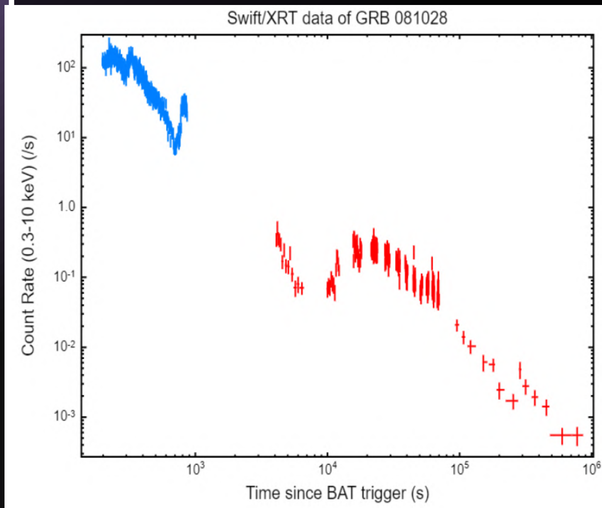
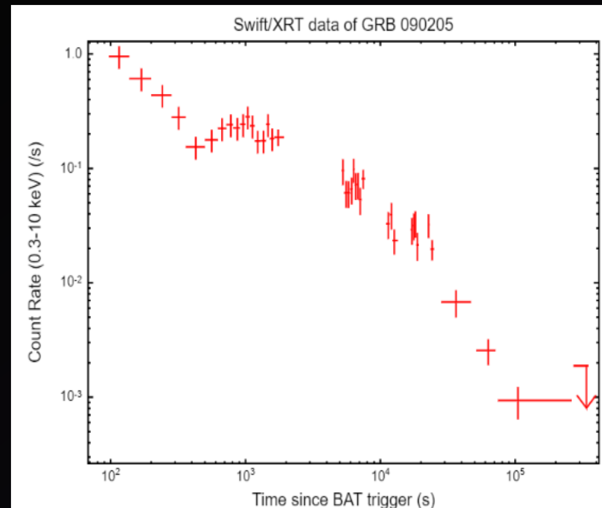
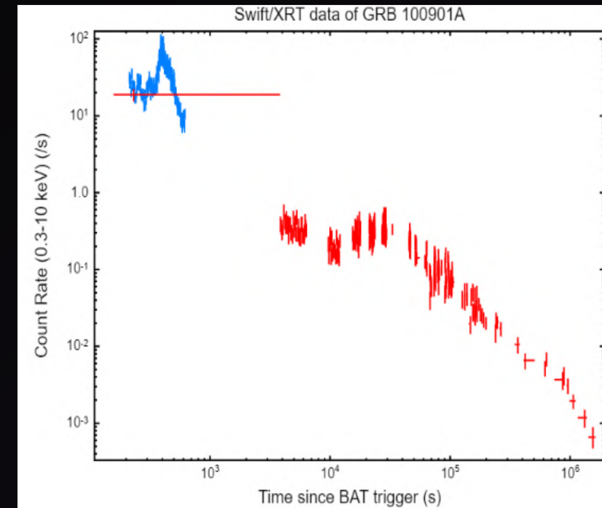
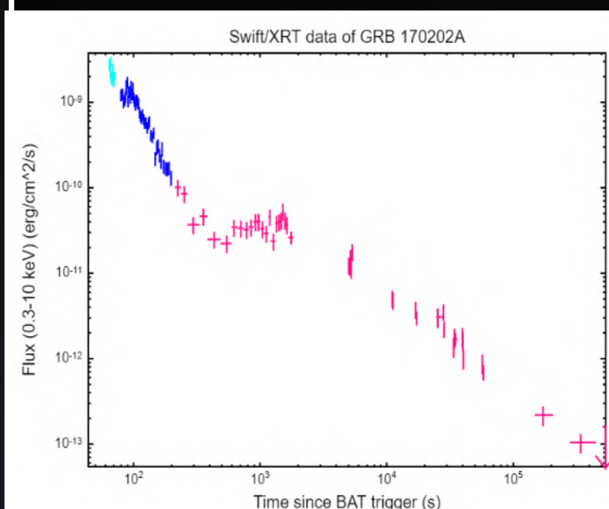
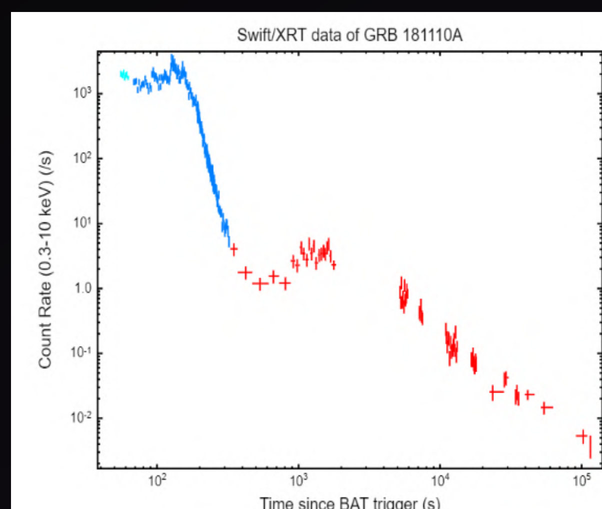
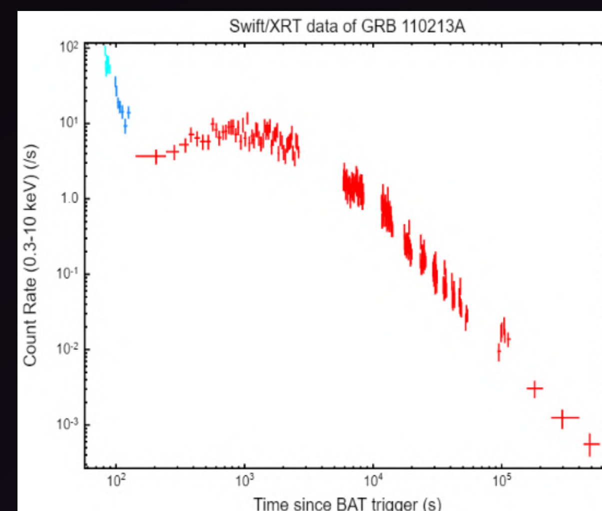




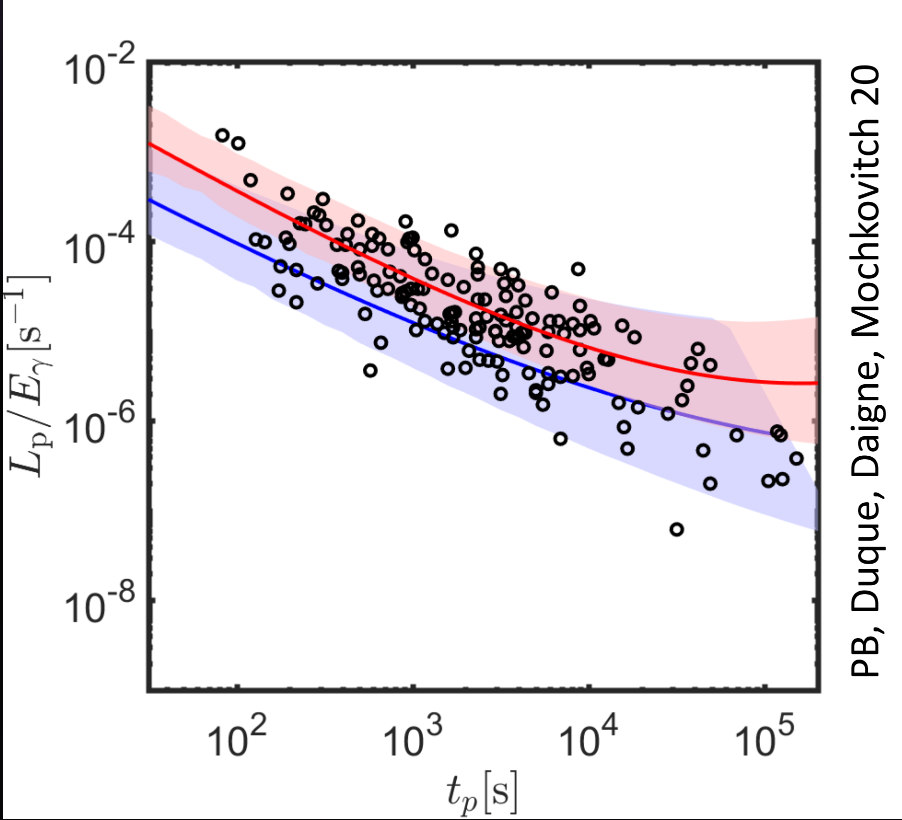


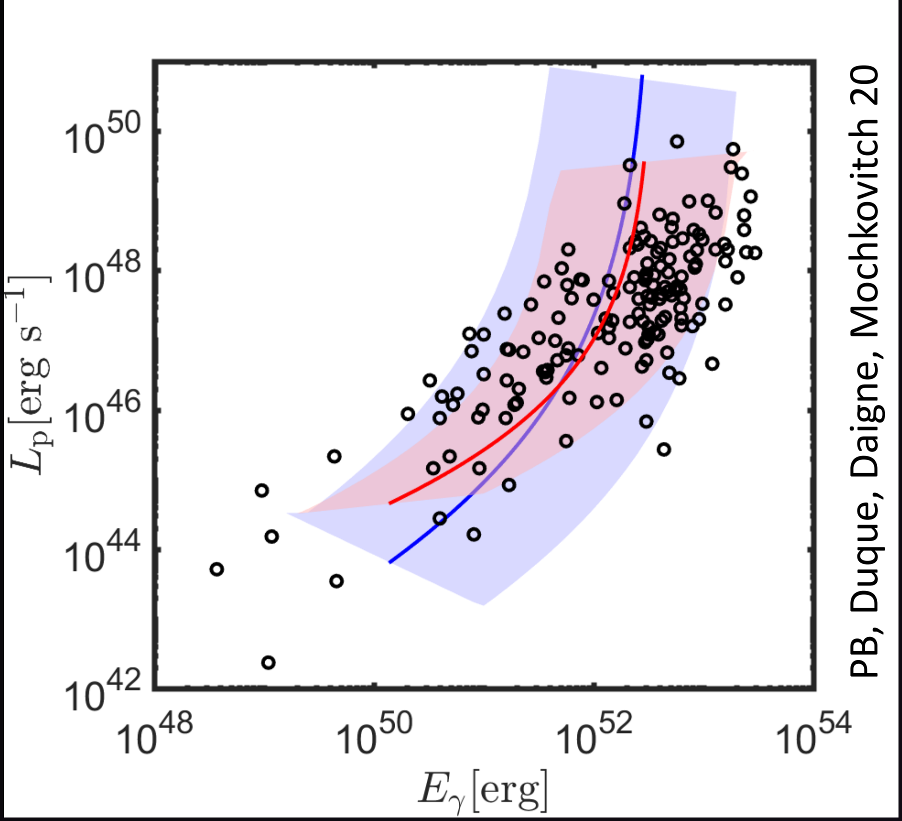






X-ray plateaus – Evidence for (mildly) off-axis structured GRB jets?



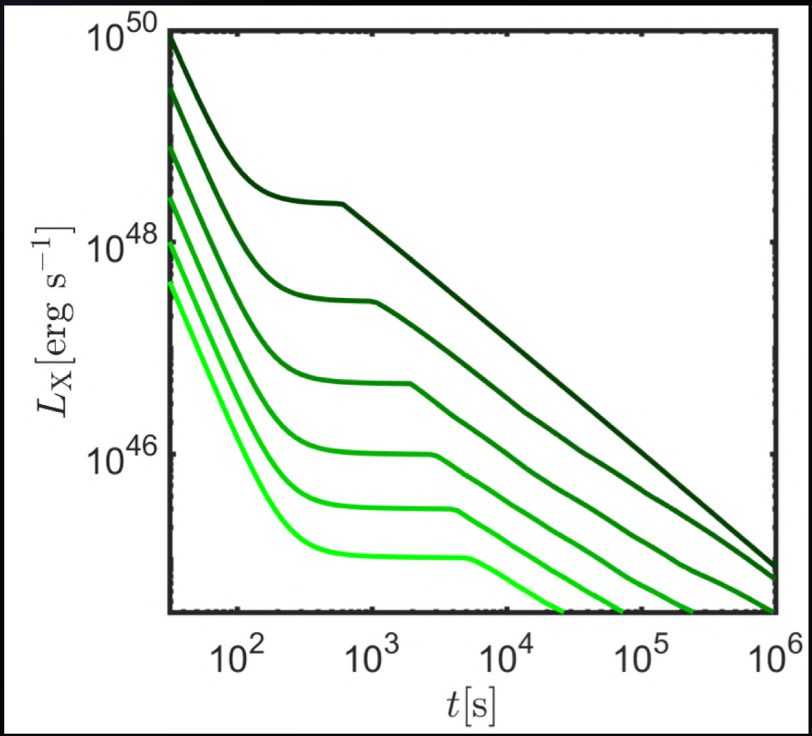


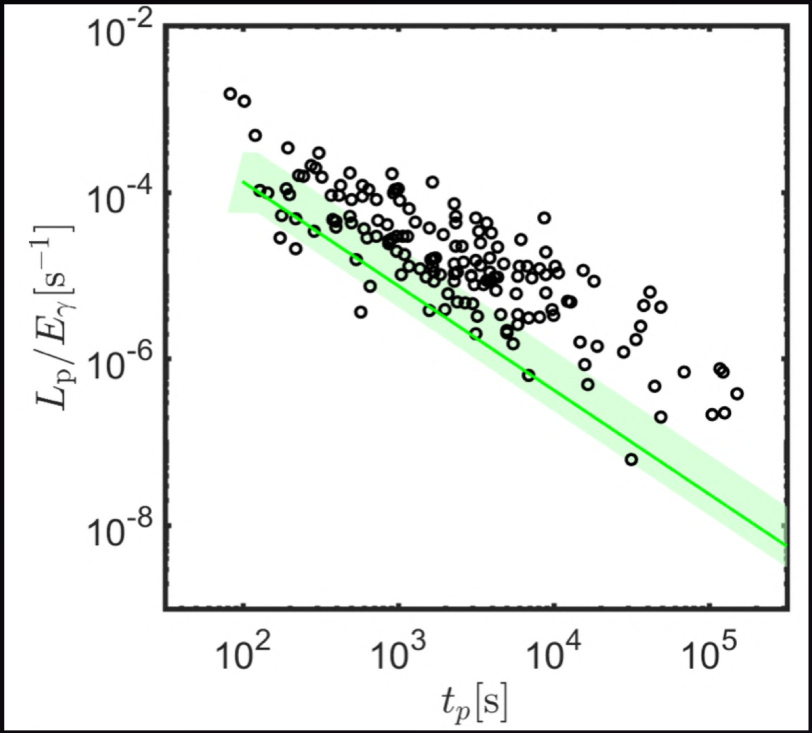
- Observed correlations naturally reproduced:

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

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

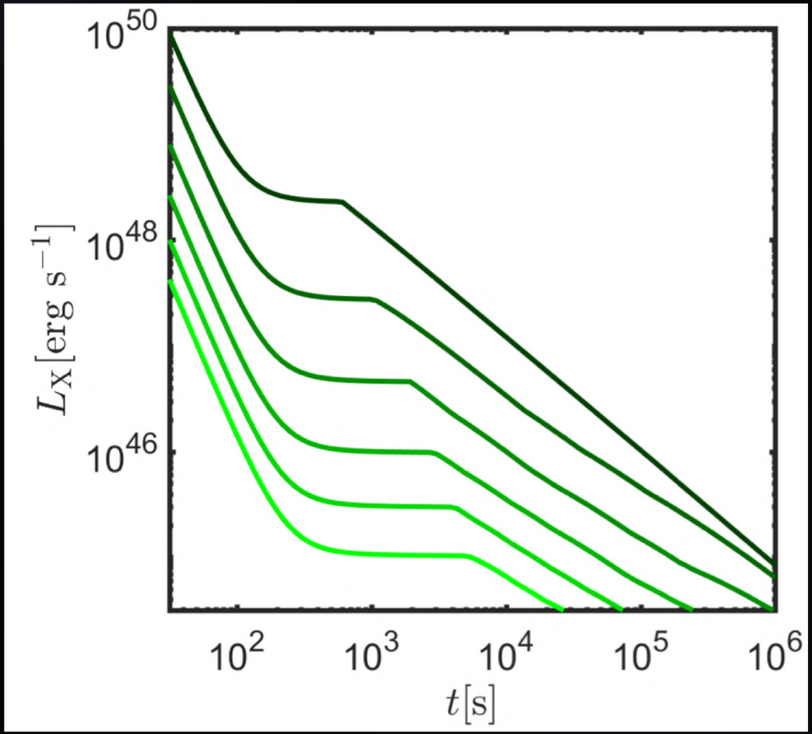


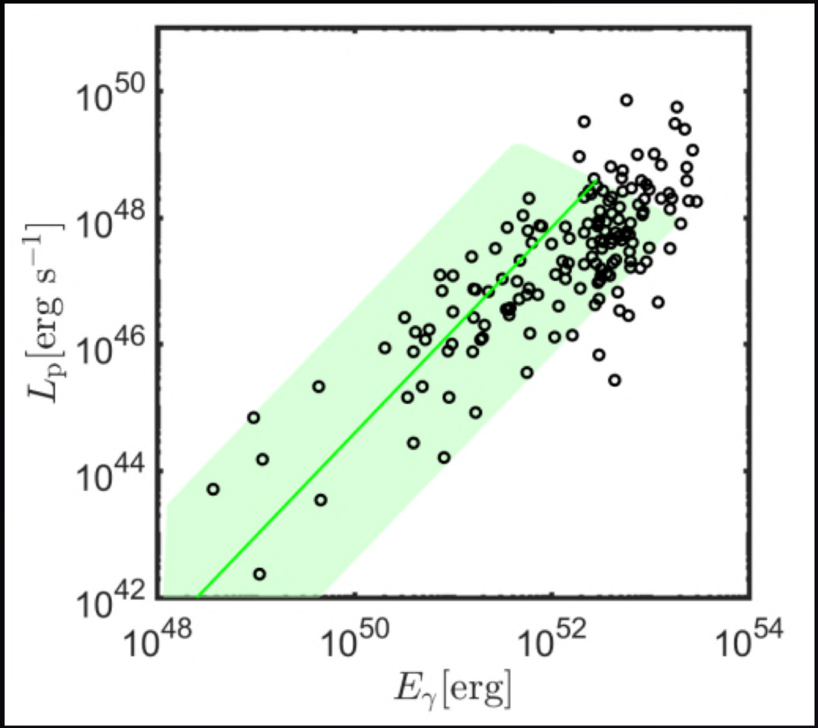


- Γ_0 decreases when θ increases
- In a wind medium, above ν_c, plateau due to deceleration
- Wide range of plateau durations and luminosities
- Narrow range of jet structure parameters with consistent plateaus:

$$3\beta \lesssim \alpha \lesssim 4\beta$$

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



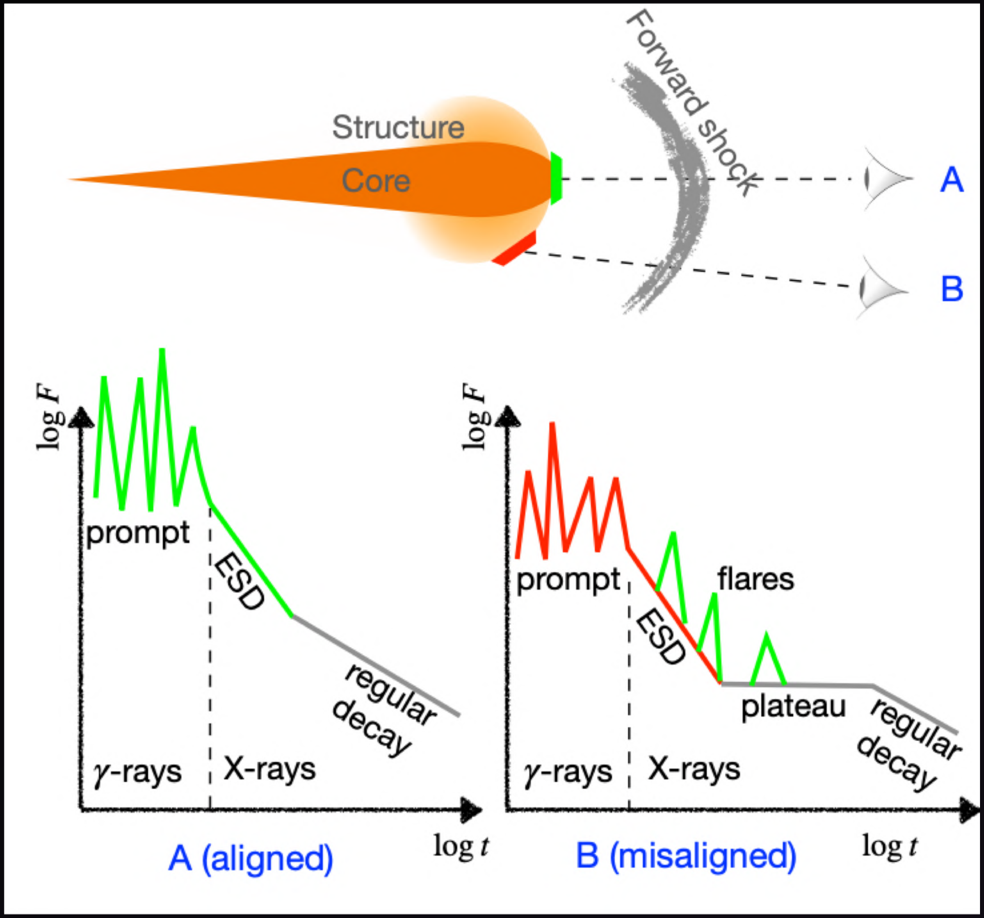


- If plateau dominated by core material, correlation with E_γ unexpected ($L_p \propto E_k^{1-\frac{p}{2}}$)
  - Much flatter plateaus
- Distinct reverse shock and polarization signatures

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 2022



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

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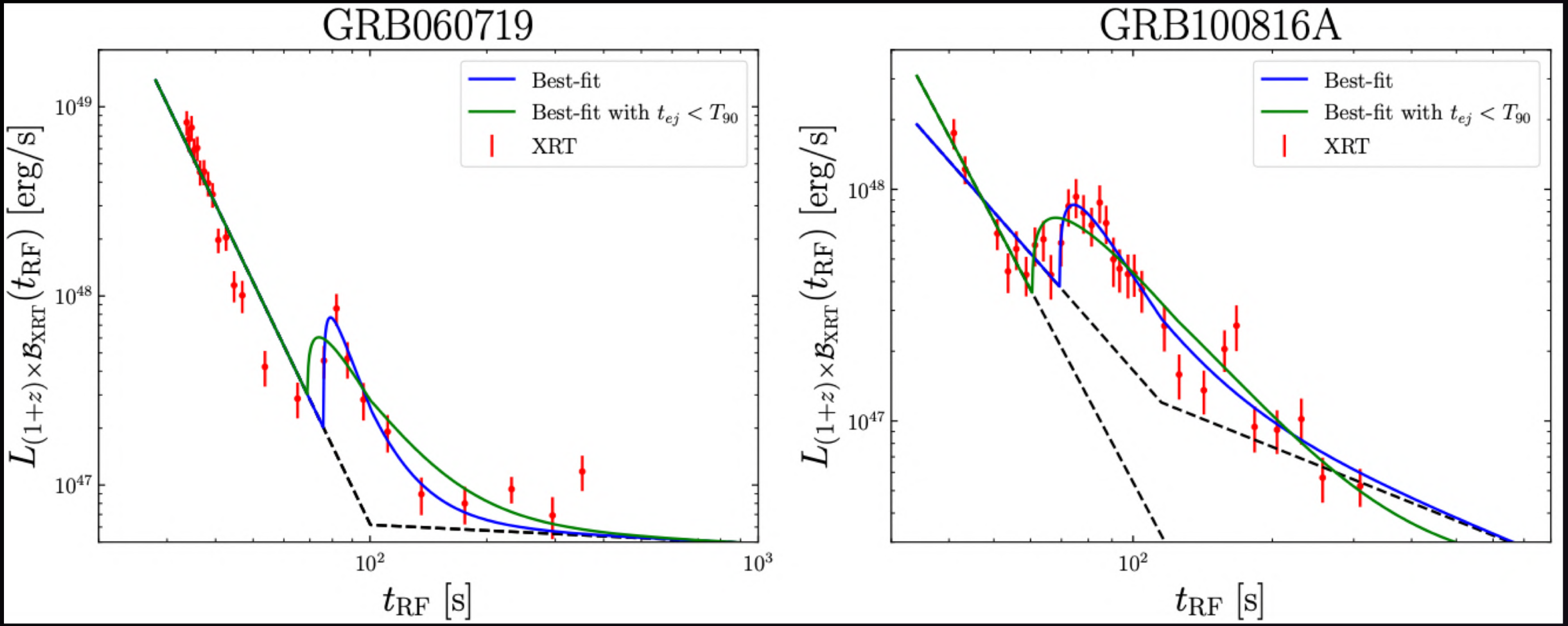
Duque, PB, Daigne, Mochkovitch 2022



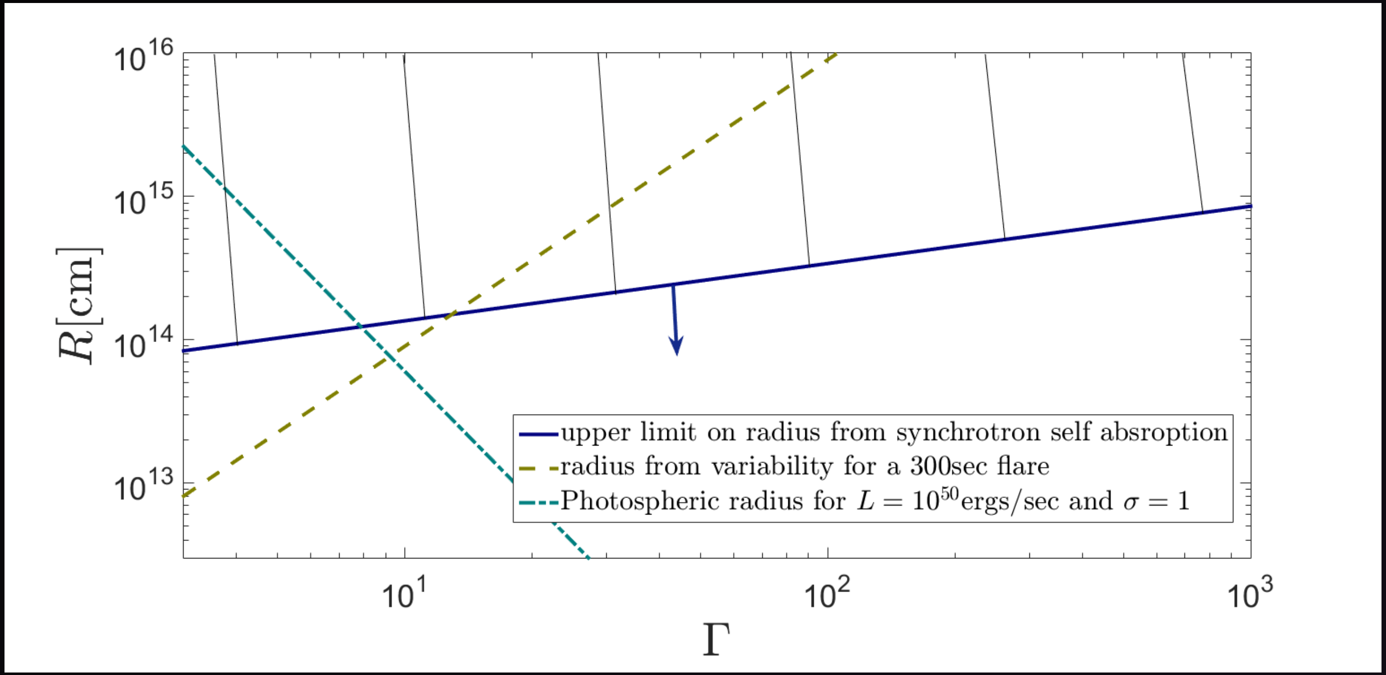
- Kill two birds with one stone?
- Constraints on structure around the core from cosmological GRBs
- *However:* Relevant mostly for early flares – difficult to separate from late prompt, need to select for spectral properties

Peculiar features in GRB afterglows may hint at nature of dissipation

- Photospheric models: $\Delta t \propto L/_{(1+\sigma)\Gamma^5}$ -> flares by moderate Γ material

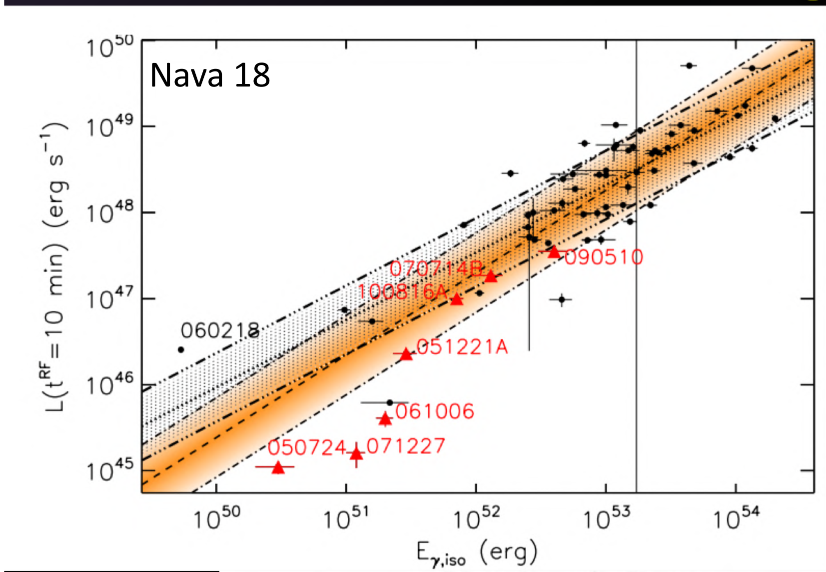
$$\frac{\Delta t_{flare}}{\Delta t_{GRB}} = \left(\frac{L_f}{L_{GRB}}\right)\left(\frac{1+\sigma_{GRB}}{1+\sigma_f}\right)\left(\frac{\Gamma_{GRB}}{\Gamma_f}\right)^5$$

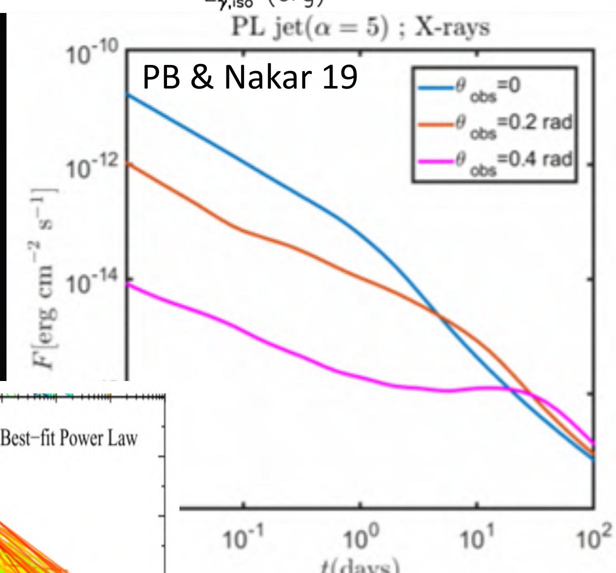
  - Predict thermal spectrum during flare (explains low optical flux)
- Late appearance despite early production (larger energy reservoir)

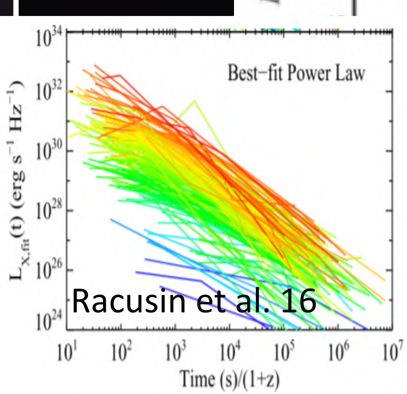


PB & Kumar 2016

Current cosmological GRBs near on-axis







1. Early X-ray afterglow energy correlated with prompt γ-rays

But $L_X(t < \mathrm{t_{dec}})/\mathrm{E_\gamma} \propto \Gamma^{10-11} E_{iso}^{0-1/3}$

So angular structure of Γ + GRBs viewed much beyond jet core -> **ruled out**

2. Far off-axis GRBs overproduce bursts below luminosity function peak

3. GRB afterglows observed at large angles have extended shallow decays / plateaus lasting tens of days

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

See talk by Brendan O'Connor

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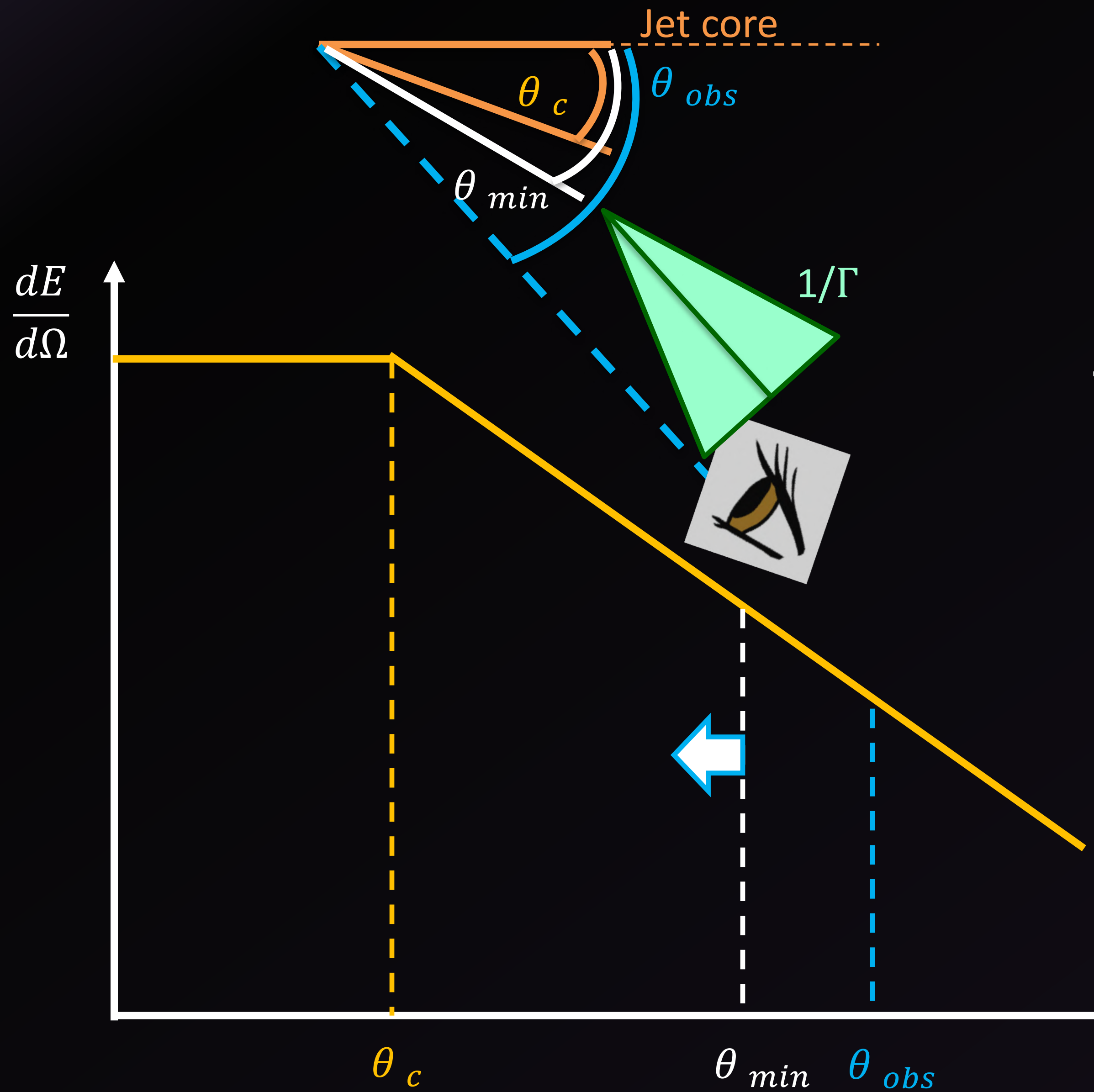
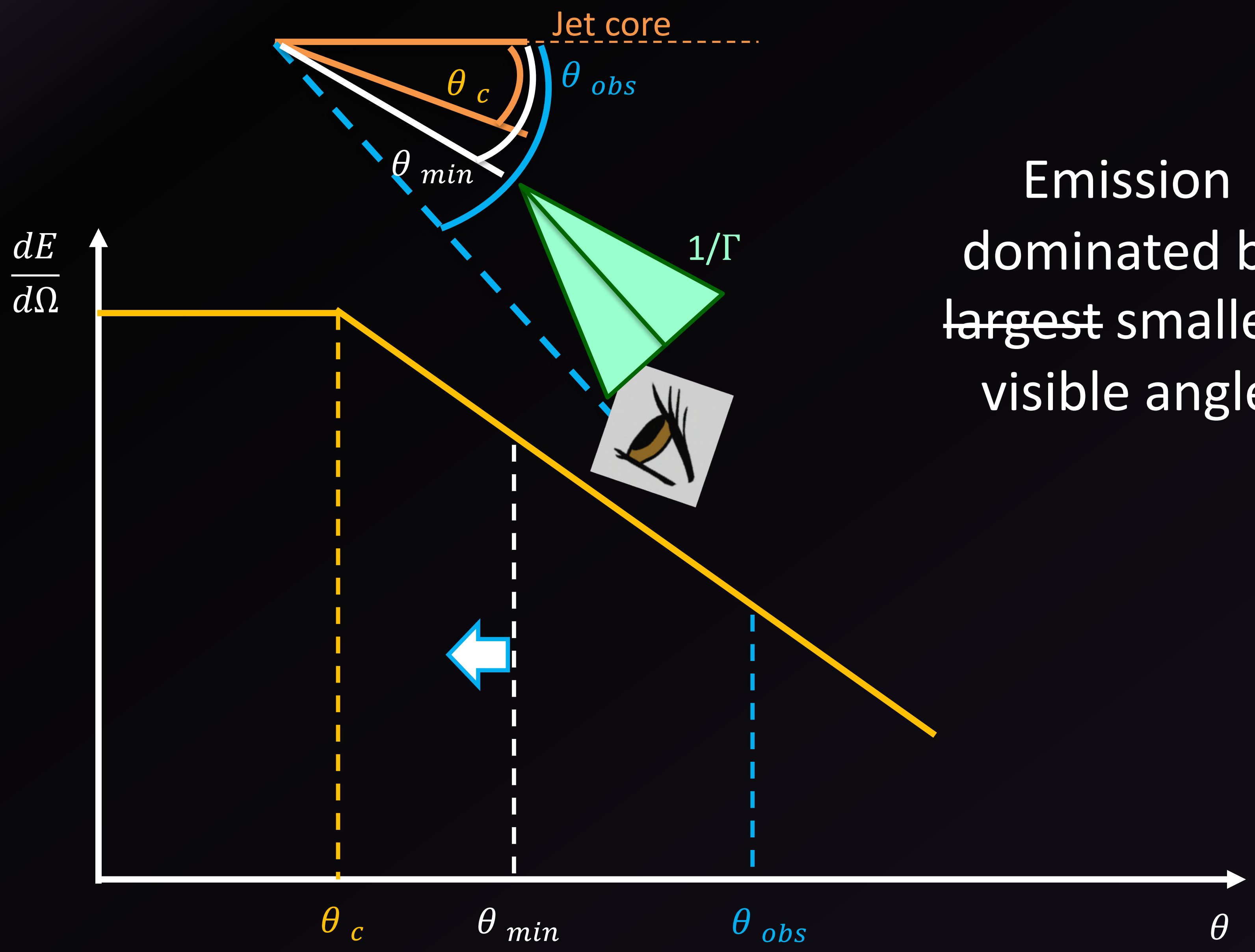
PB & Nakar 19, O'Connor, PB & Gill 24

Far off-axis (steep) jets



Emission dominated by ~~largest~~ smallest visible angle

Far off-axis (steep) jets

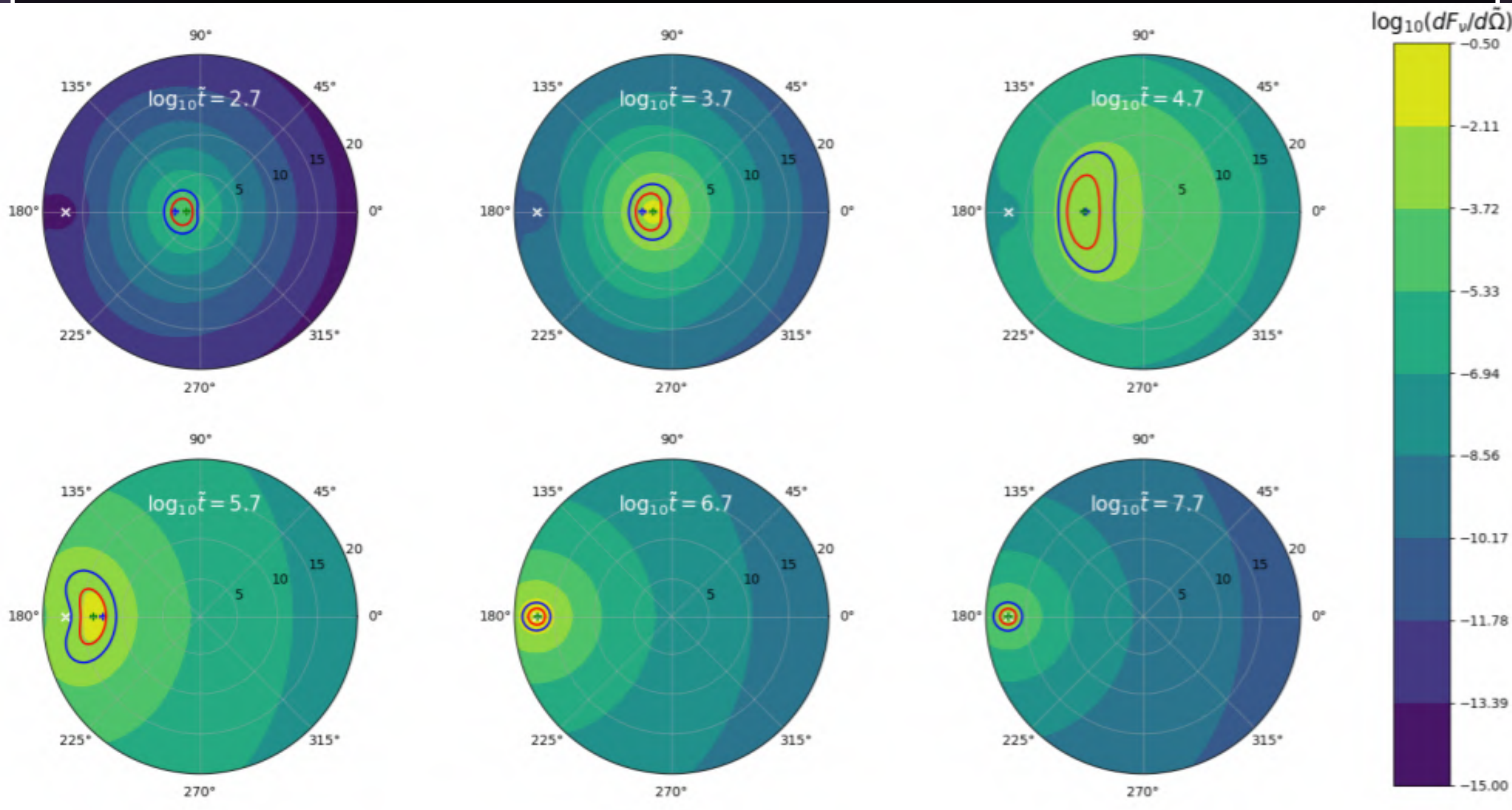


Emission dominated by ~~largest~~ smallest visible angle

Future prospects – off-axis afterglows

Energy decreases with θ, but material at $\theta \ll \theta_{obs}$ strongly debeamed

Angle dominating emission is ~ θ_{min} where $\Gamma_0(\theta_{min})(\theta_{obs}-\theta_{min})=1$



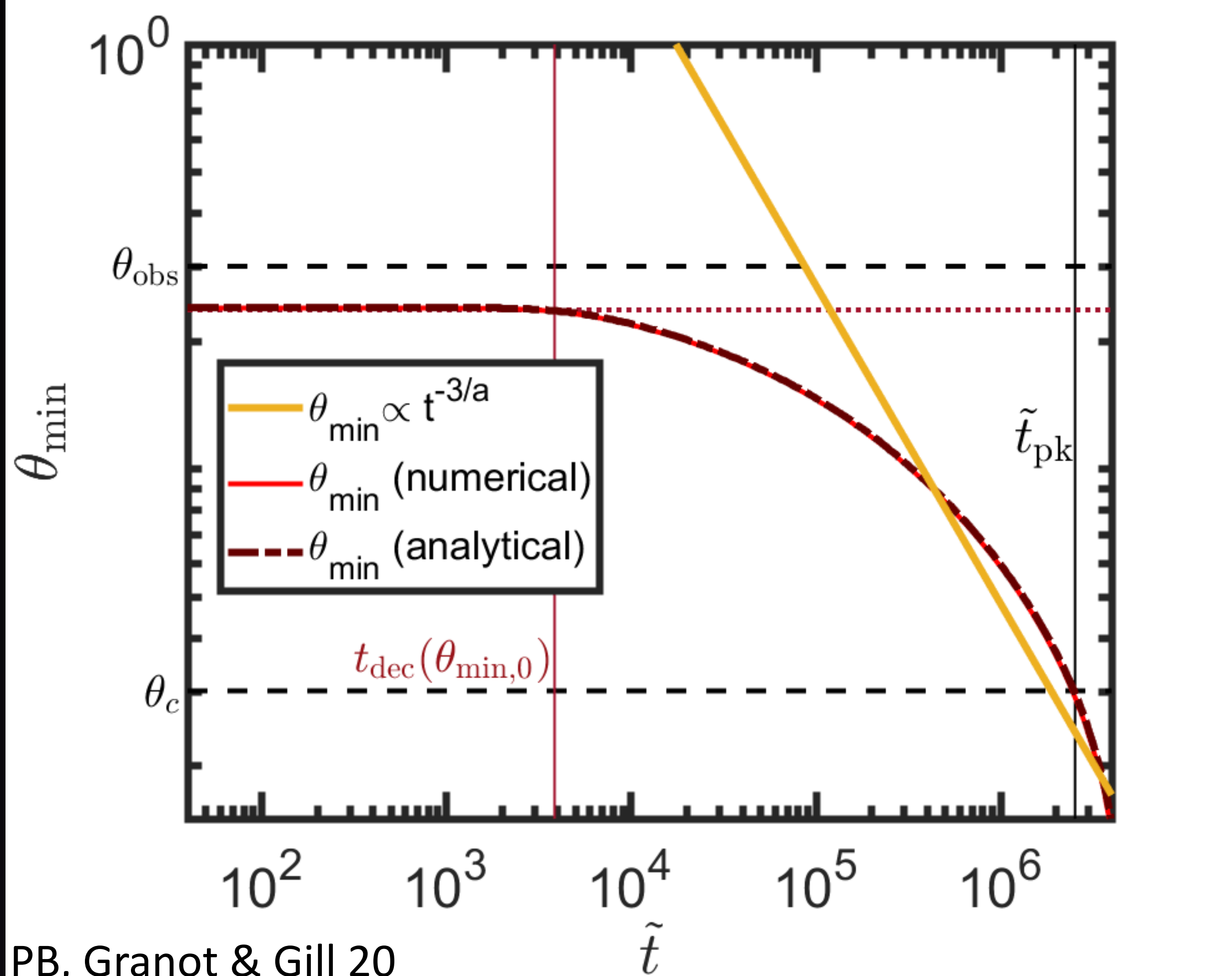
PB, Granot & Gill 20

Future prospects – off-axis afterglows

Energy decreases with θ, but material at $\theta \ll \theta_{obs}$ strongly debeamed
Angle dominating emission is ~ θ_{min} where $\Gamma_0(\theta_{min})(\theta_{obs}-\theta_{min})=1$

- Analytic treatment matches numerics
- $\theta_{min} < \theta_{obs}$ initially constant. Eventually declines as $\theta_{min} \propto t^{-3/a}$

a = PL index of energy angular profile



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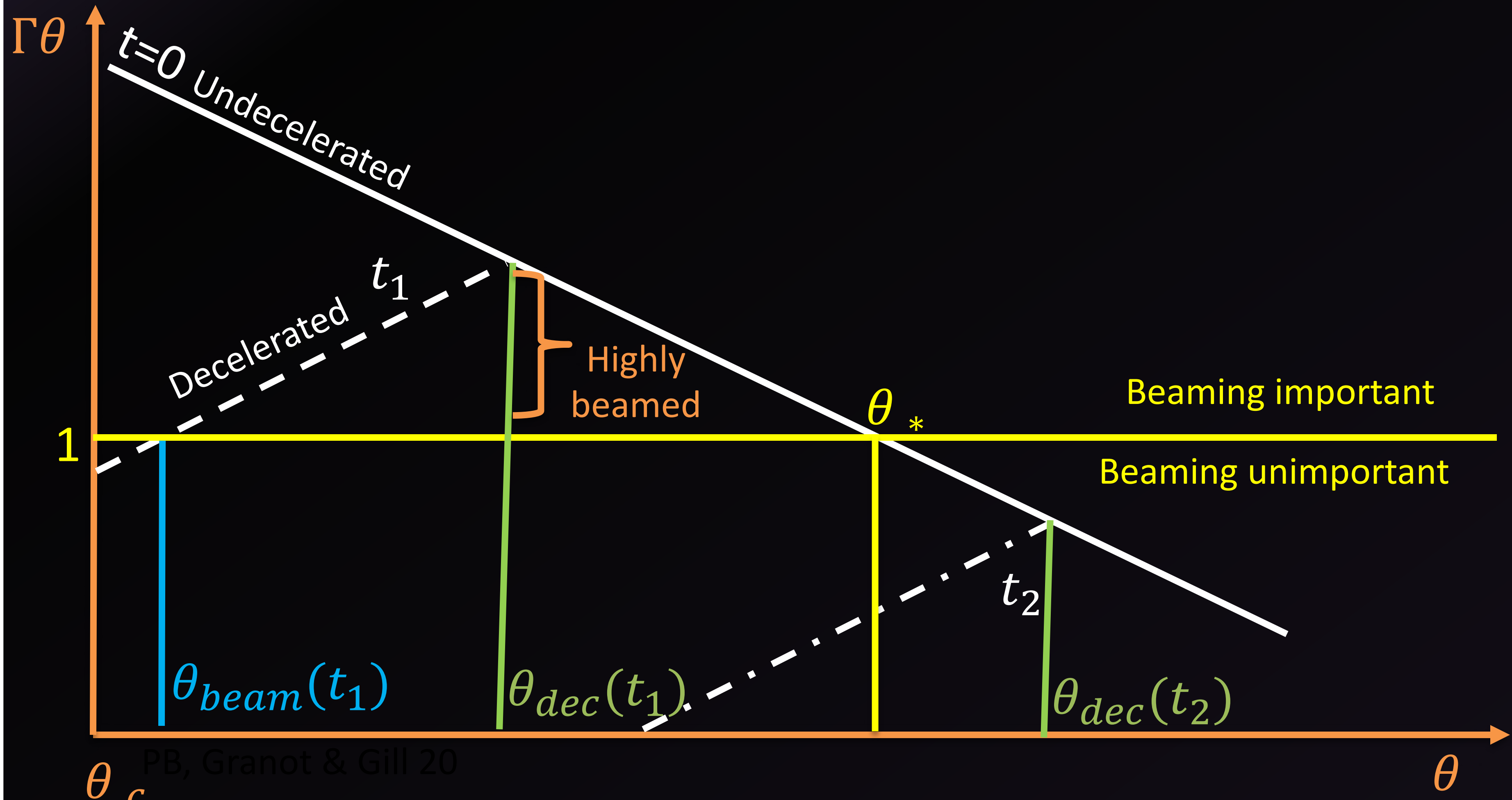
Future prospects - Afterglows

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



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

* Unless energy profile is extremely steep

PB, Granot & Gill 20

Future prospects – off-axis afterglows

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

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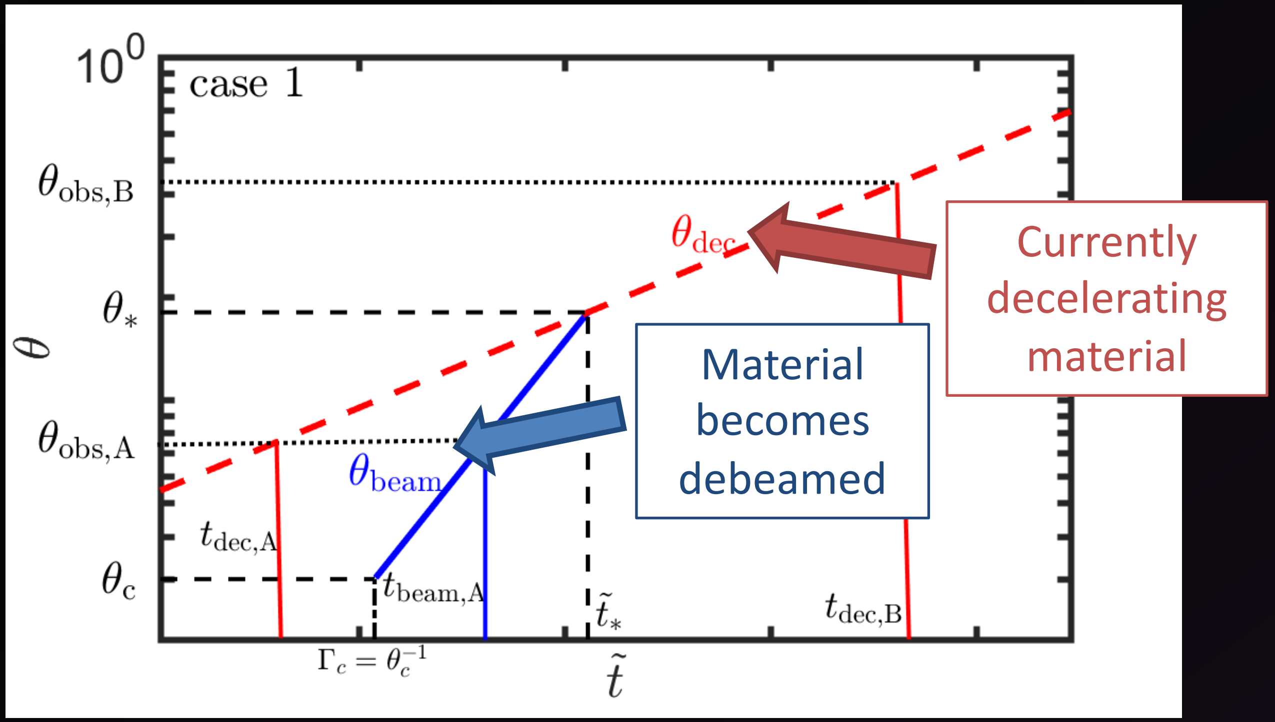


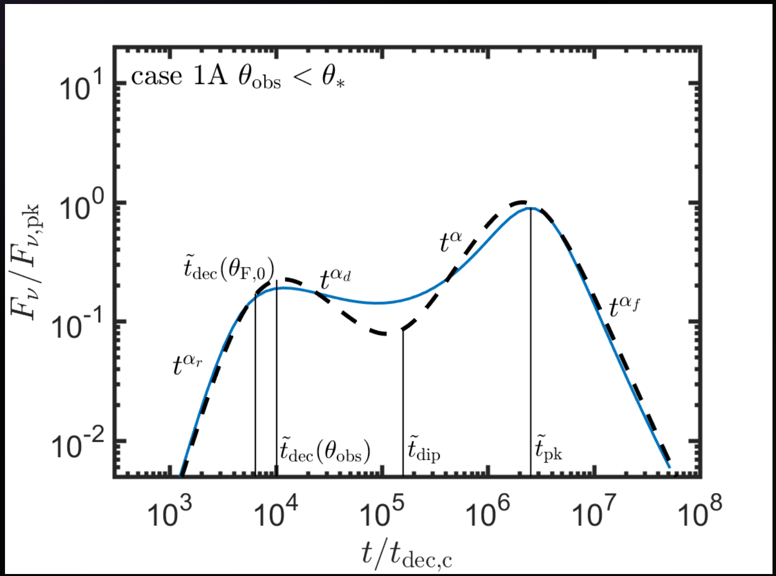
A. $\theta_{obs} < \theta_*$ → $\Gamma_0(\theta_{obs})\theta_{obs}$>1 Relativistic beaming important from t=0

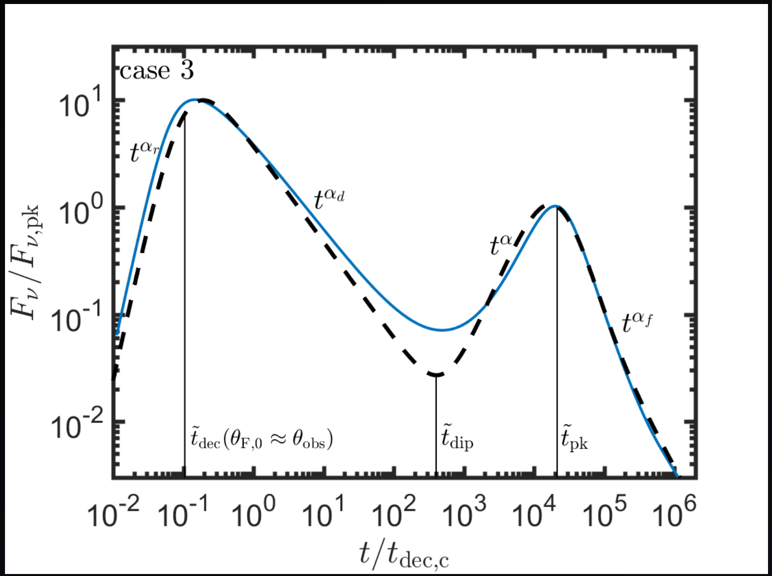
Initially dominant material decelerates and dominates flux before lower latitudes become exposed and take over

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

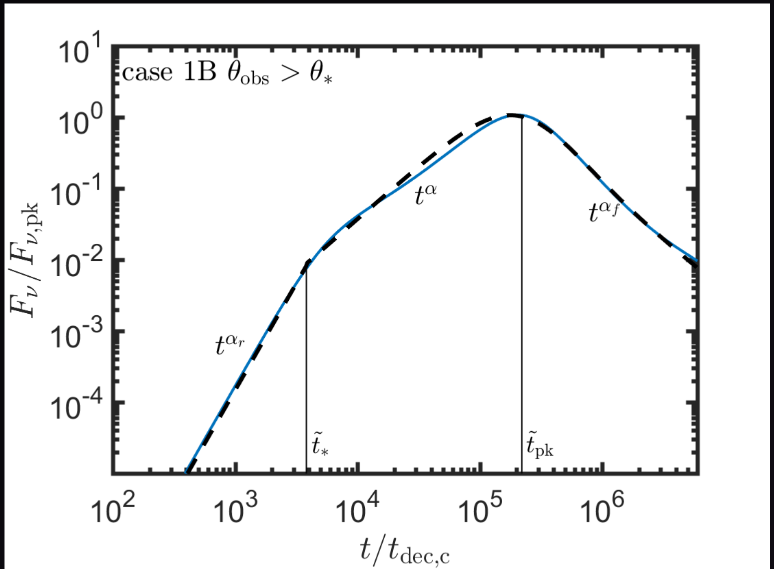
Future prospects – off-axis afterglows

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 – off-axis afterglows

- Analytic treatment reproduces numerical simulations and provides easy to use and intuitive tools

- Analytics reproduce Temporal slopes, critical times and critical fluxes

  - n, E, ε_e, ε_B highly degenerate

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

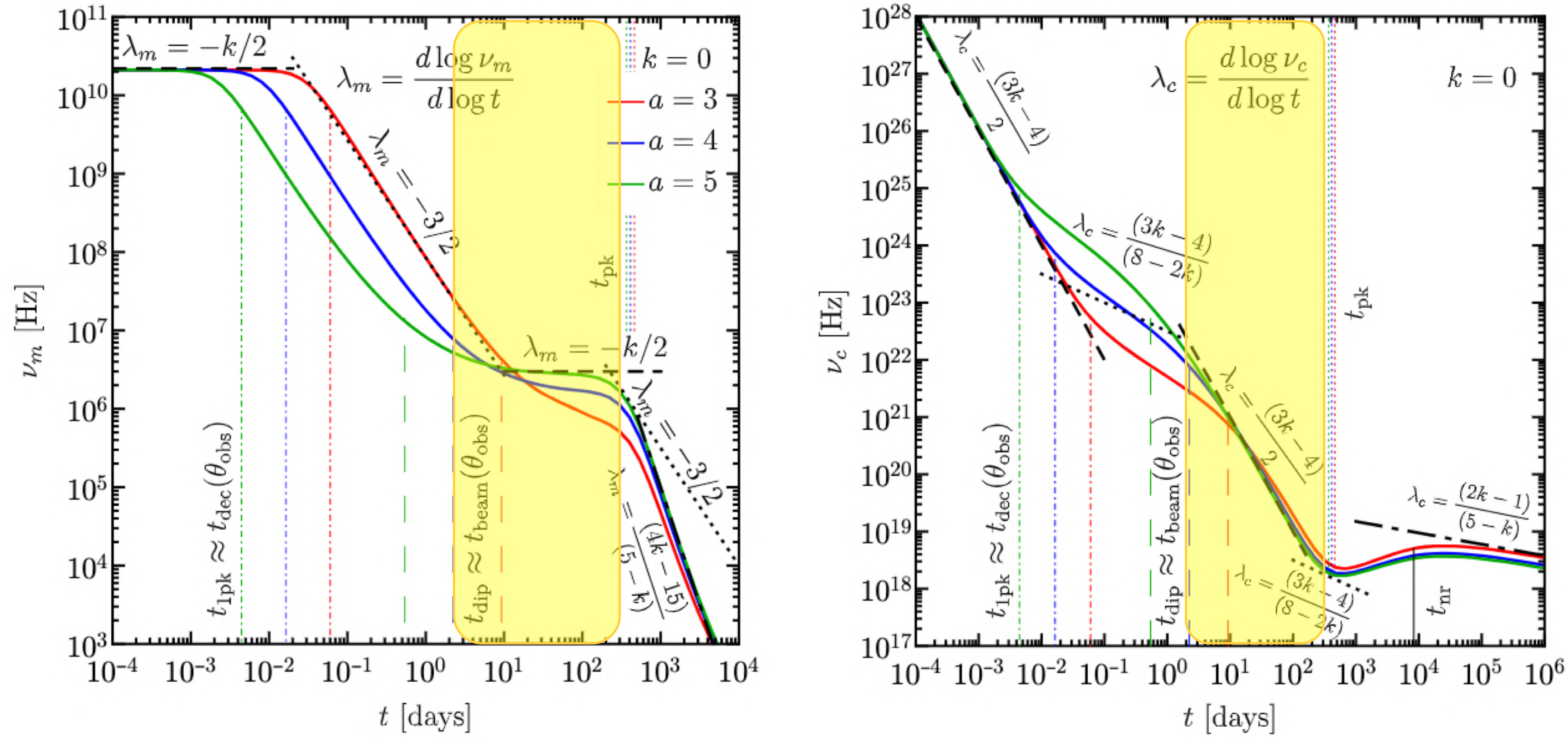
$$q = \left(\frac{F_{1\mathrm{pk}}}{F_{\mathrm{pk}}}\right)^{\frac{4}{8-a(3+p)}} \left(\frac{t_{\mathrm{pk}}}{t_{1\mathrm{pk}}}\right)^{\frac{3(1-p)}{8-a(3+p)}}$$

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

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

PB, Granot & Gill 20

Spectral evolution – Unique regime for structured jets

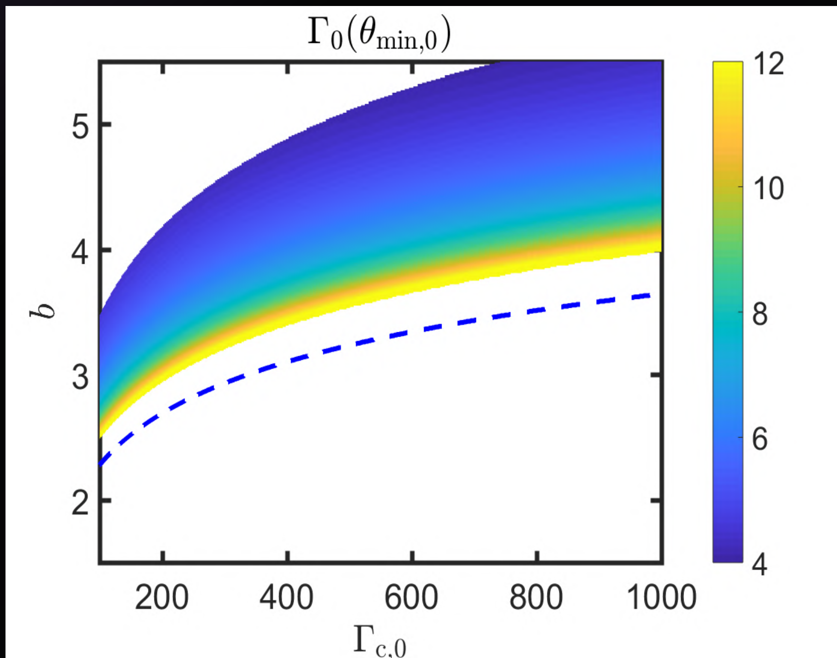


During Angular structure dominated emission phase, $\Gamma(\theta_{obs}) \approx const$ -> Synchrotron frequencies evolve as in pre-deceleration phase

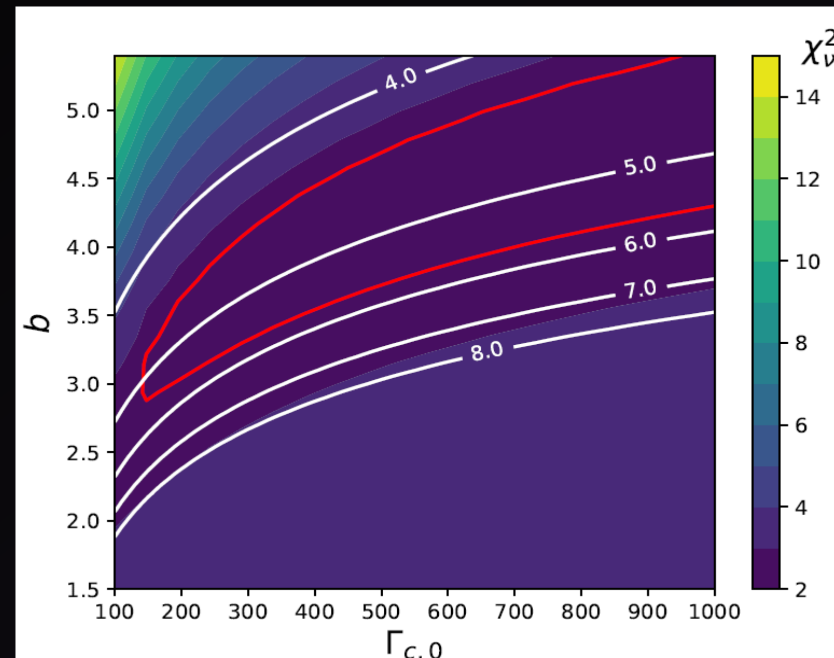
PB, Gill & Granot 22

170817 as a test case

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



Analytics



Numerical simulation

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

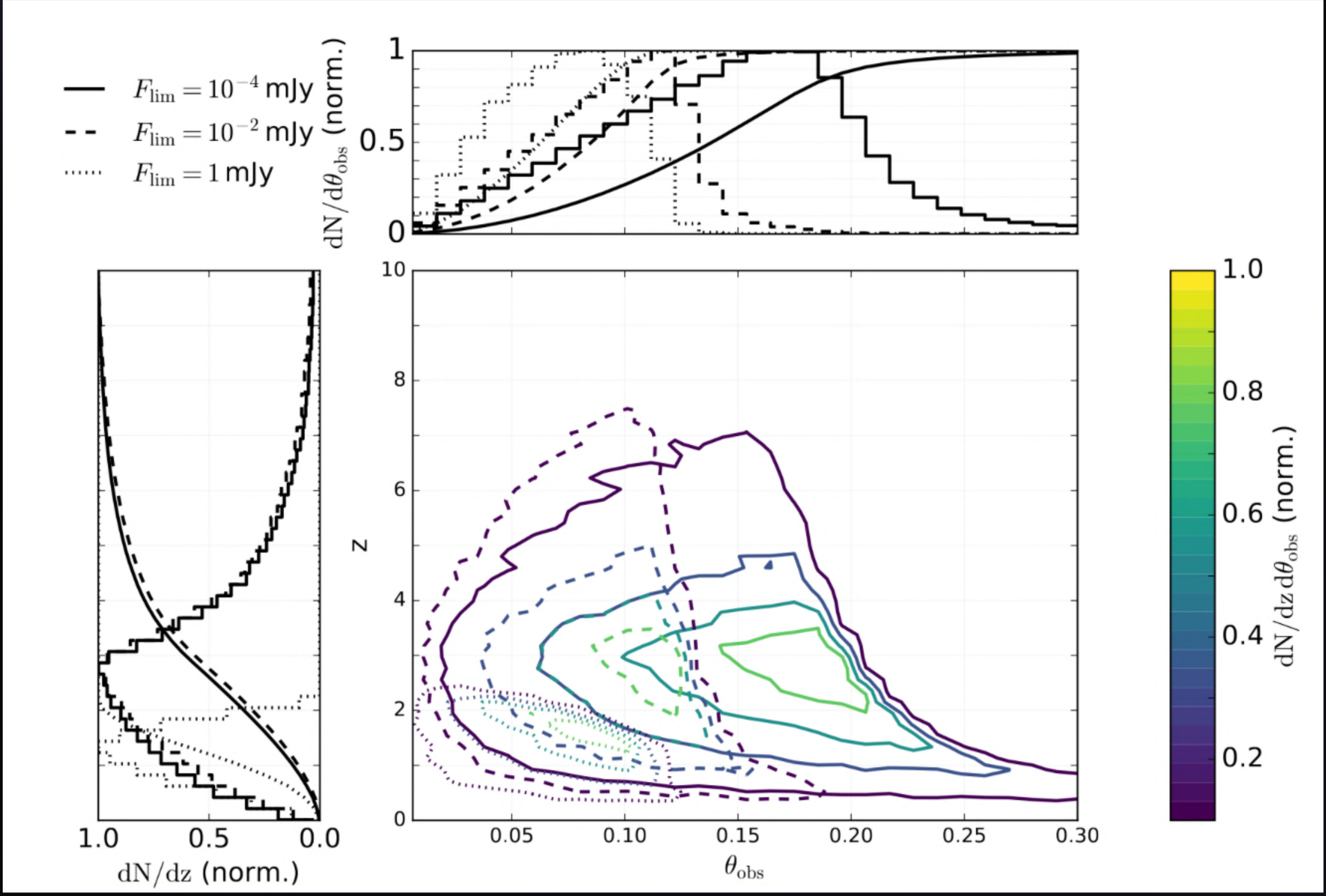
- $\Gamma(\theta_{min,0}) \approx 5-7$ constrained by 3 independent approaches:

Afterglow light-curve analysis

Superluminal motion – Flux centroid velocity

Compactness constraint from prompt emission

Orphan afterglows

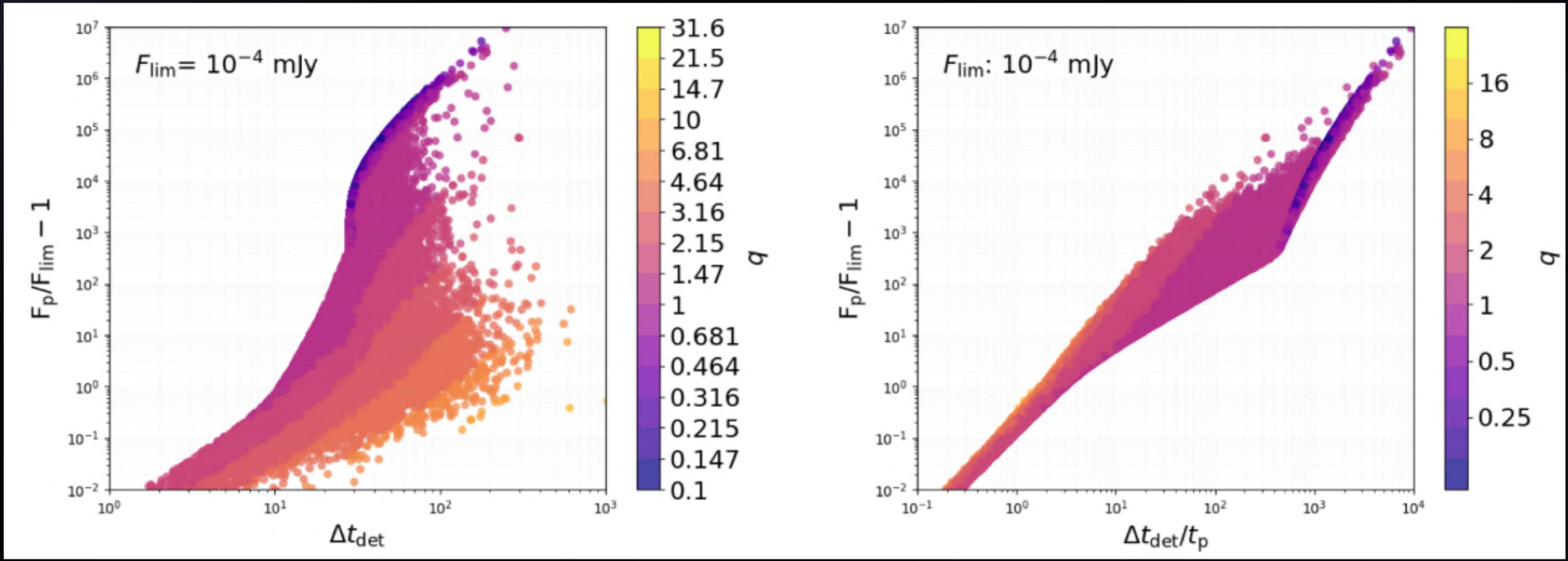


Ratio of off to on axis orphan afterglow detections sensitively depends on survey characteristics (limiting flux, cadence, etc.)

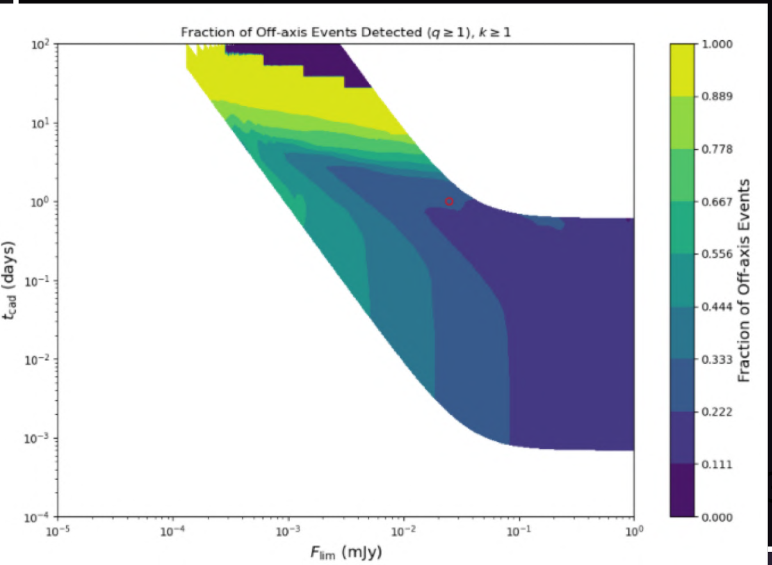
PB, Granot & Gill 20

Chand, Granot, PB (in perp.)

Orphan afterglows



- Well-defined parameter space for orphan afterglows: differentiate from other transients

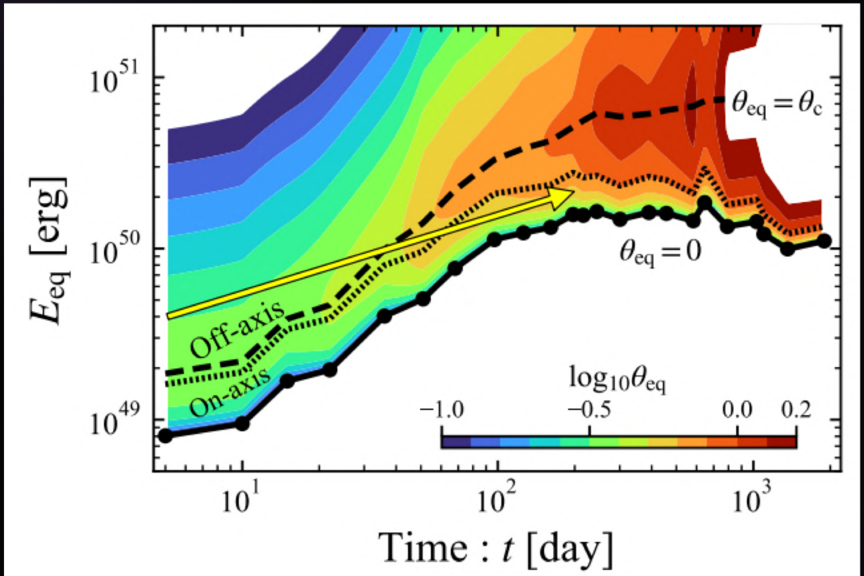


- Surveys can be optimized for specific goals (e.g. off-axis detections)
- Constrain existence of 'dirty fireballs'

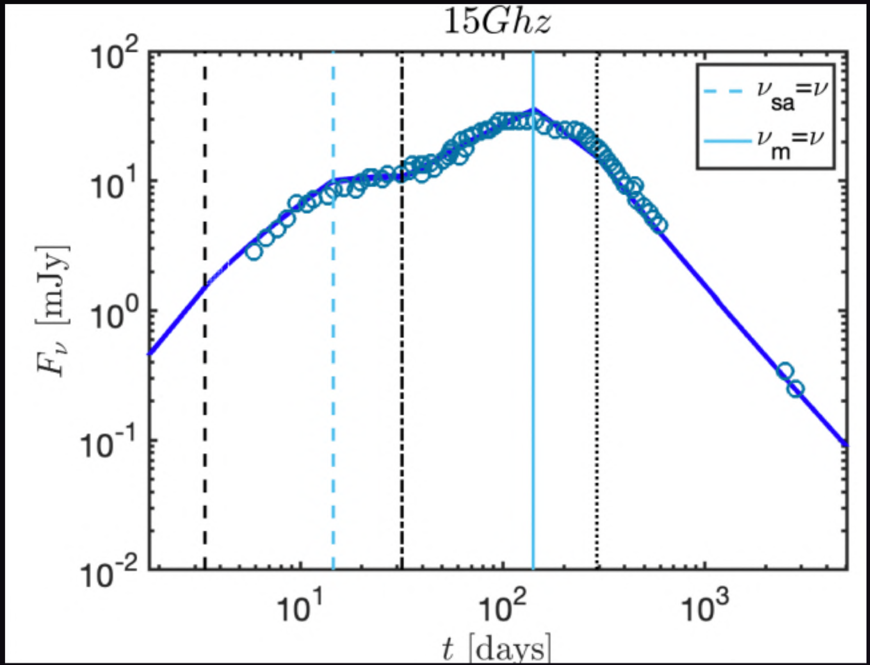
Granot & Gill 20

Chand, Granot, PB (in perp.)

Evidence for (mildly) off-axis TDE jets?



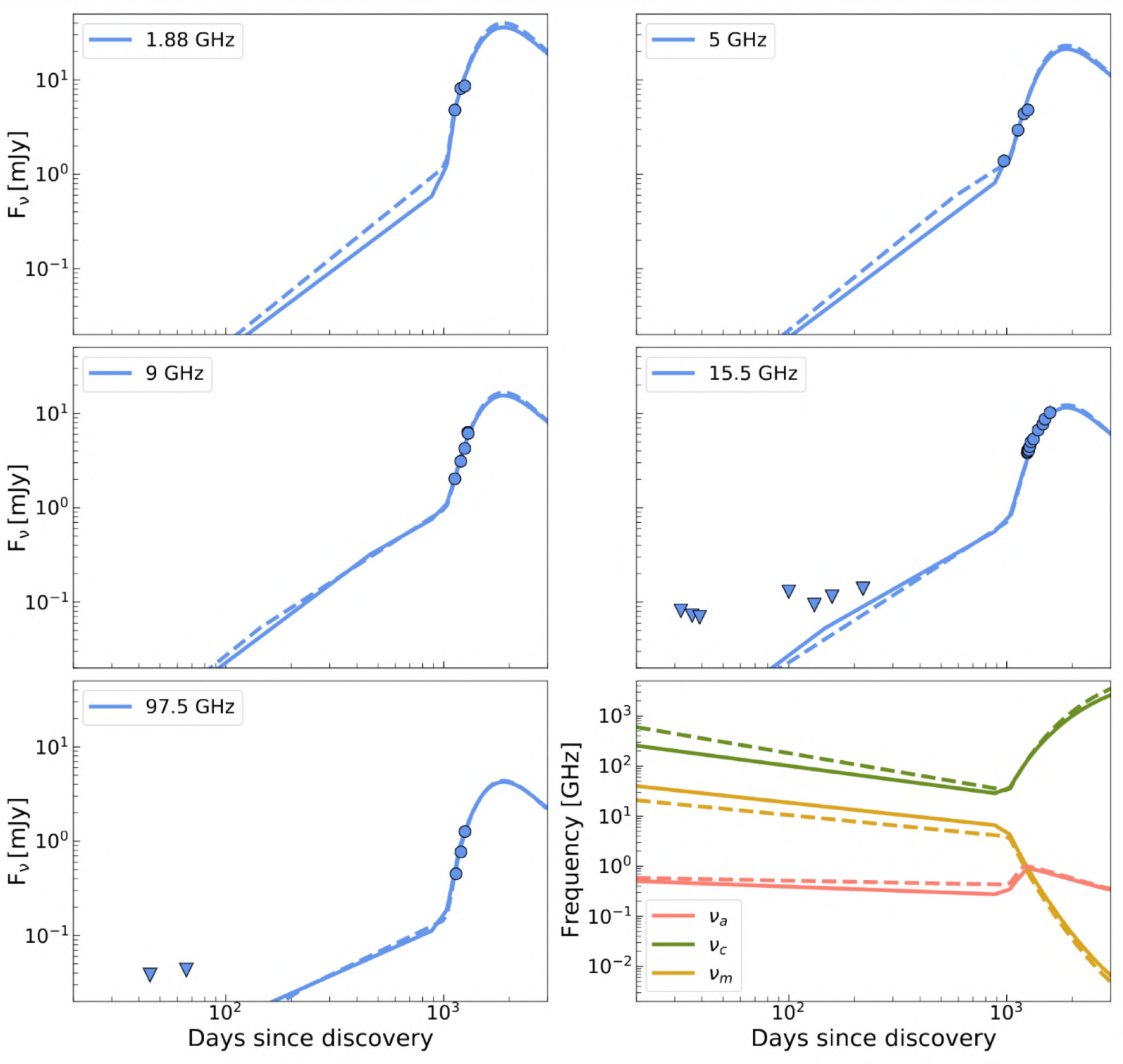
- Swift J1644+57 First jetted TDE
- On-axis equipartition analysis requires increase in energy for over 200 days after trigger



- Simple top hat slightly off-axis can explain radio lightcurve with no energy injection
- Allows estimate of jet opening angle ~21°

PB, Piran, Matsumoto 2023

Very steep jet, far off-axis – AT2018hyz

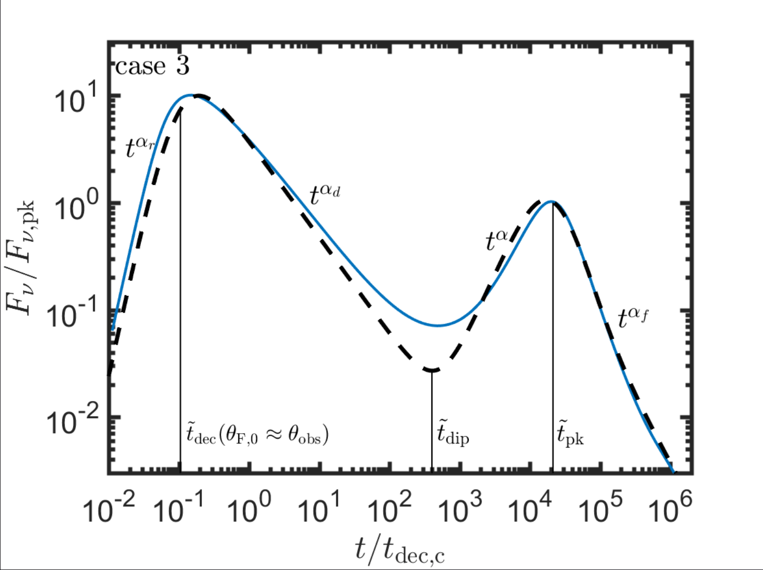


- Flux rises as $t^{4.2\pm0.9}$
- Well fit by forward modeling with far off-axis jet, $\theta_0 \sim 7°$, $\theta_{obs} \sim 42°$
- Large energy required $E_k > 3 \cdot 10^{52}$erg

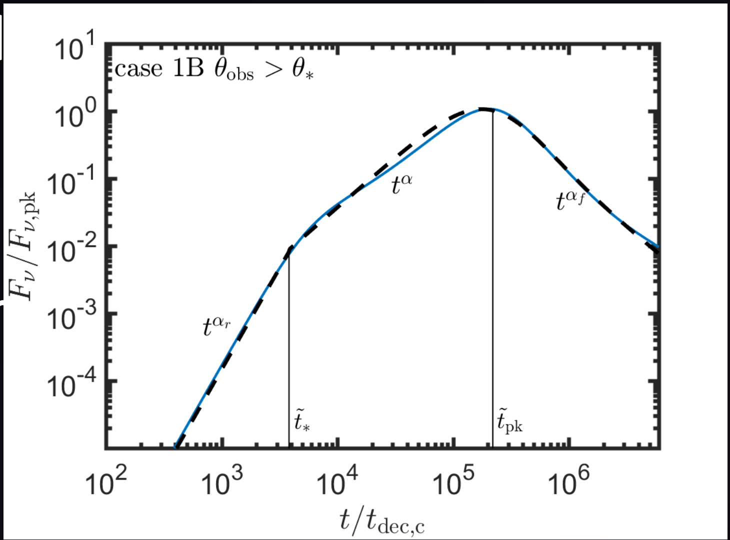
Sfaradi, Horesh, PB, Piran et al. 23

Conclusions

- Shallow jets energy structure important even on-axis – GRB 221009A and other energetic GRBs match this
- At $\theta_c \lesssim \theta_{obs} \lesssim 2\theta_c$ X-ray plateaus and flares are naturally produced by debeamed emission from core and reproduce observed light-curves, correlations with prompt properties

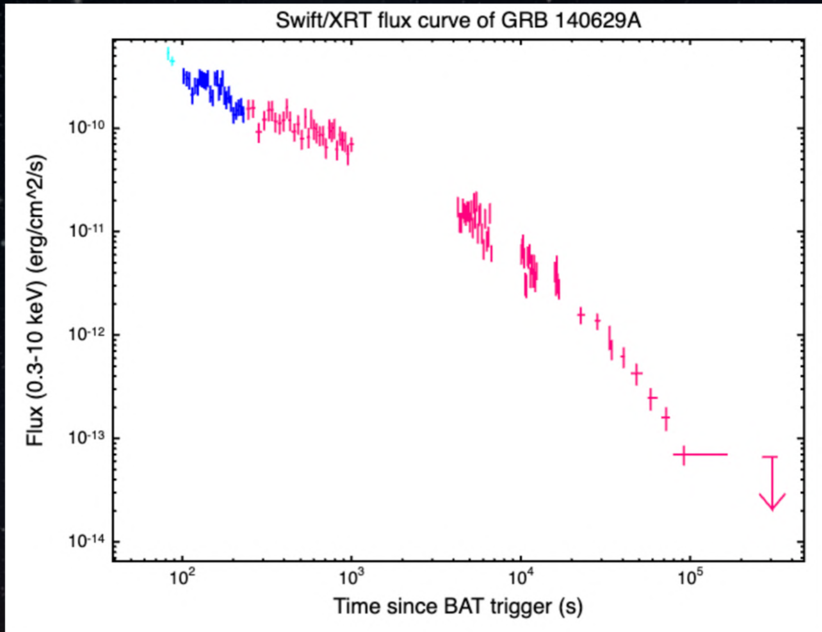


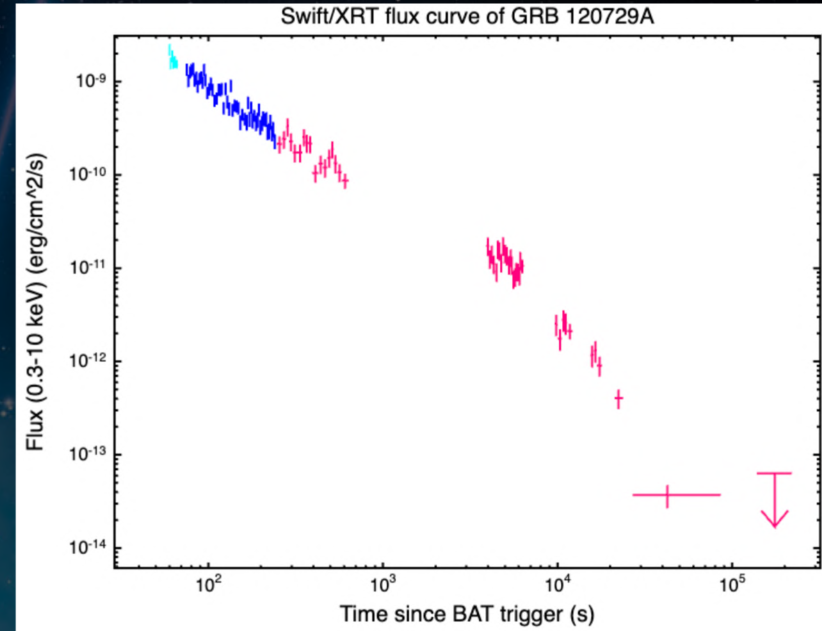
- $\theta_{obs} \gtrsim 2\theta_c$ Two qualitative types of afterglows predicted – single or double peaked. Light-curve shape and spectral evolution determined by few key parameters

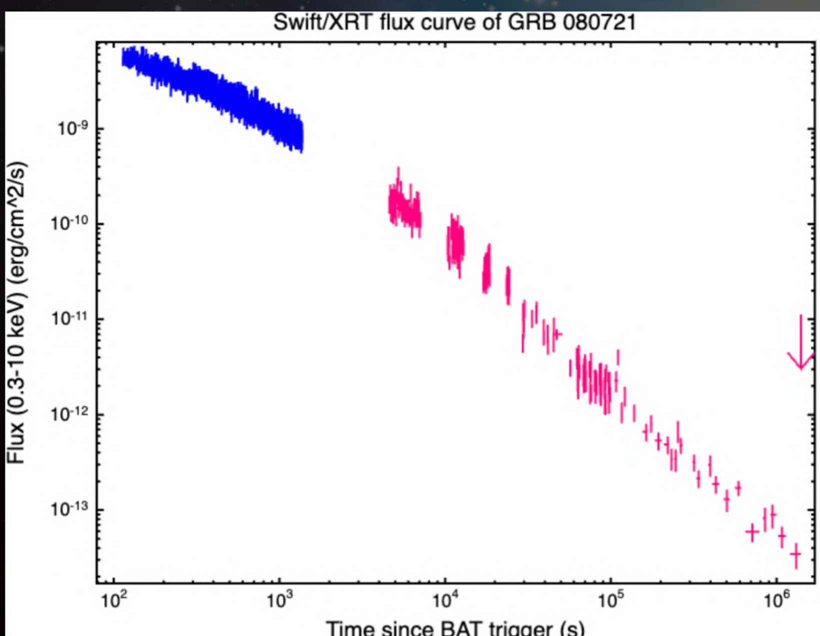


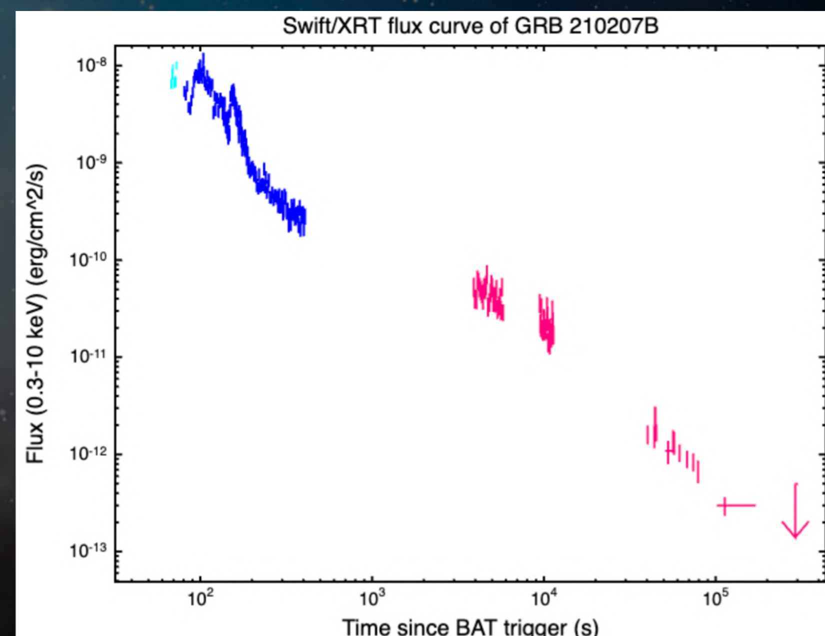
- Orphan afterglows distinct from other transients – surveys can be optimized to find off-axis bursts

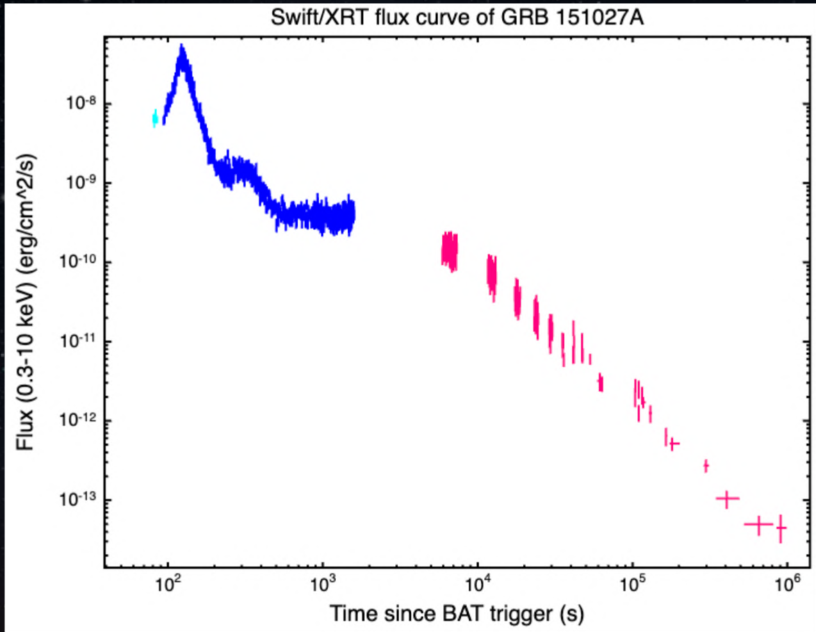

Thank You!

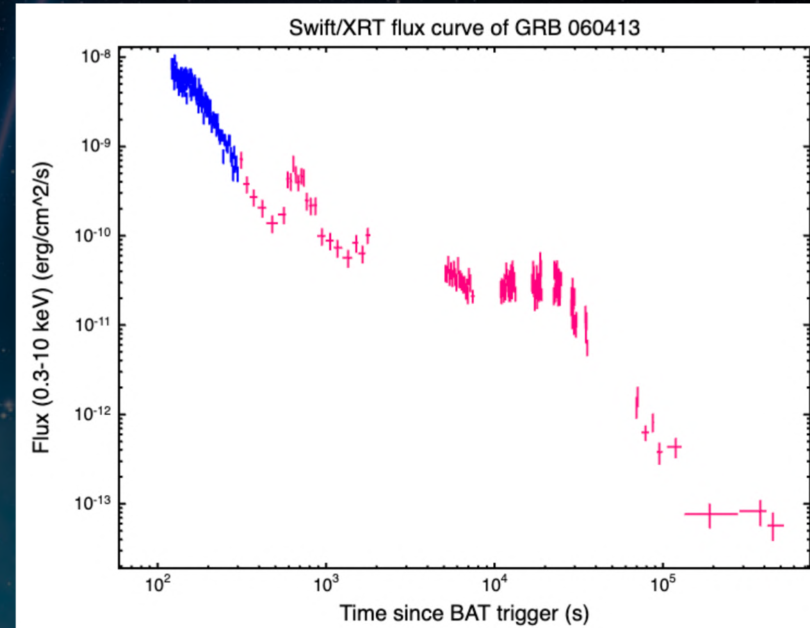

Swift/XRT flux curve of GRB 140629A
Flux (0.3-10 keV) (erg/cm^2/s)
Time since BAT trigger (s)

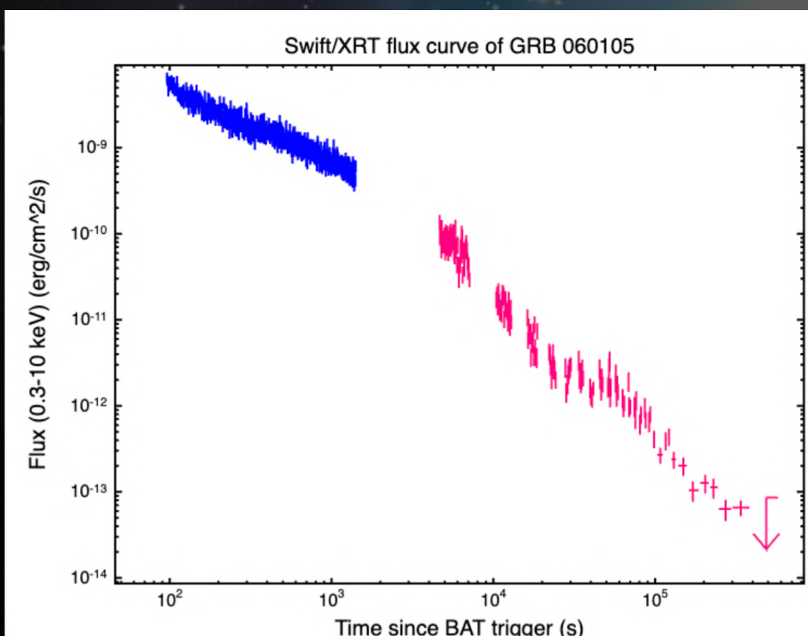

Swift/XRT flux curve of GRB 120729A
Flux (0.3-10 keV) (erg/cm^2/s)
Time since BAT trigger (s)

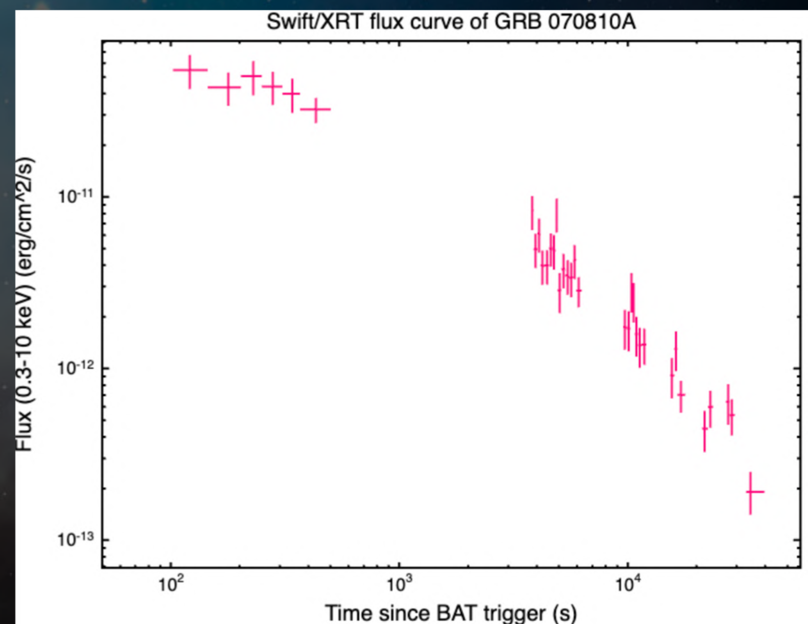

Swift/XRT flux curve of GRB 080721
Flux (0.3-10 keV) (erg/cm^2/s)
Time since BAT trigger (s)


Swift/XRT flux curve of GRB 210207B
Flux (0.3-10 keV) (erg/cm^2/s)
Time since BAT trigger (s)


Swift/XRT flux curve of GRB 151027A
Flux (0.3-10 keV) (erg/cm^2/s)
Time since BAT trigger (s)


Swift/XRT flux curve of GRB 060413
Flux (0.3-10 keV) (erg/cm^2/s)
Time since BAT trigger (s)


Swift/XRT flux curve of GRB 060105
Flux (0.3-10 keV) (erg/cm^2/s)
Time since BAT trigger (s)


Swift/XRT flux curve of GRB 070810A
Flux (0.3-10 keV) (erg/cm^2/s)
Time since BAT trigger (s)