Bar-Ilan University
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What can we learn from GRB pulses and their shapes: implications on GRB prompt phase

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With

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erc

Summary

1) Lorentz factor of many GRBs (but not all) **may be only a few tens,** smaller than what many people think.

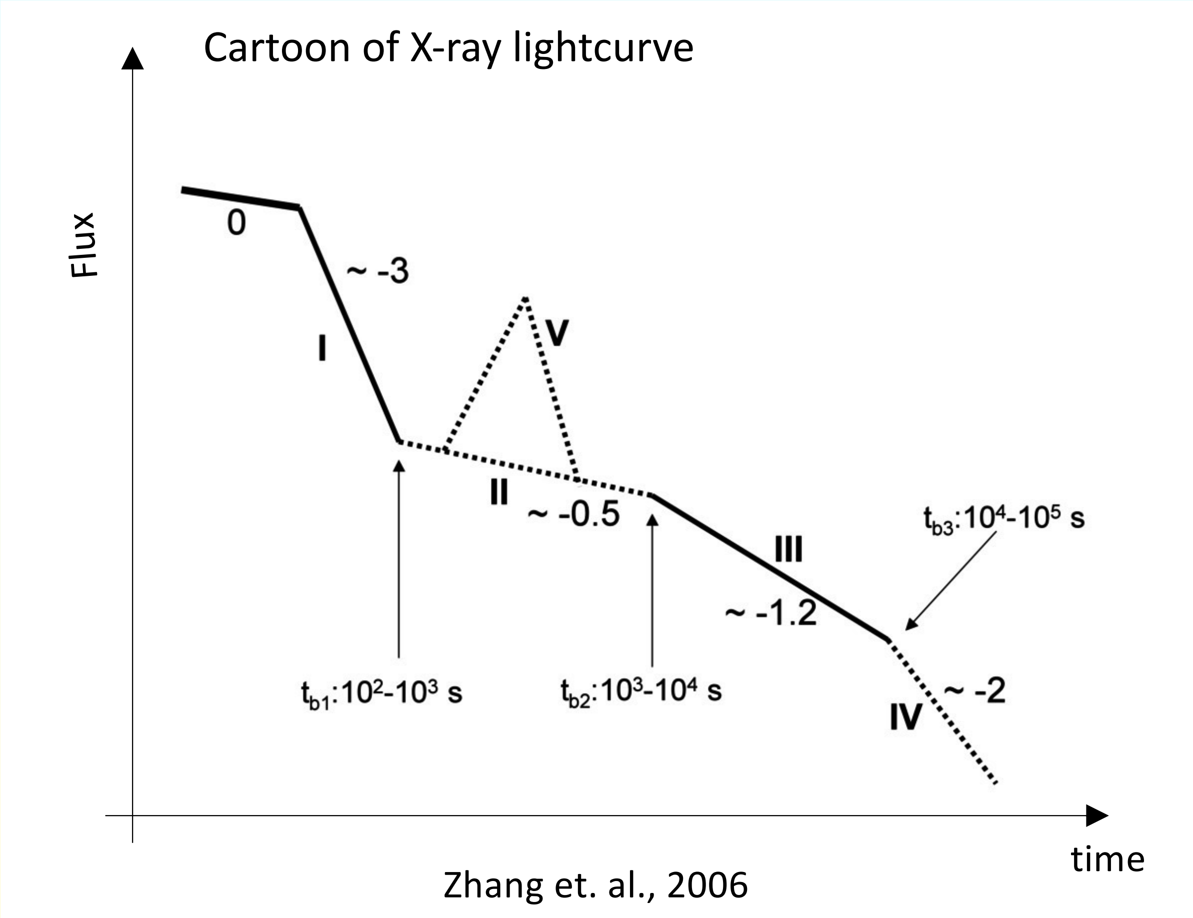
2) As a result, photospheric emission may be pronounced

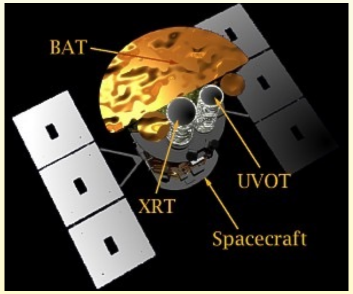
3) The observed spectra is complex, due to
(i) sub-photospheric energy dissipation;
(ii) structured jet that leads to a new mechanism of photon energy gain

4) (if time permits) – revival of proton-synchrotron, and unique conditions for pair annihilation line in GRB221009A

1. Flares during the x-ray plateau

❖ Swift launch: Nov. 2004





<u>Ubiquitous</u>: X-ray plateau seen in 60% of GRBs (Srinivasaragavan + 2020)

X-ray Plateau

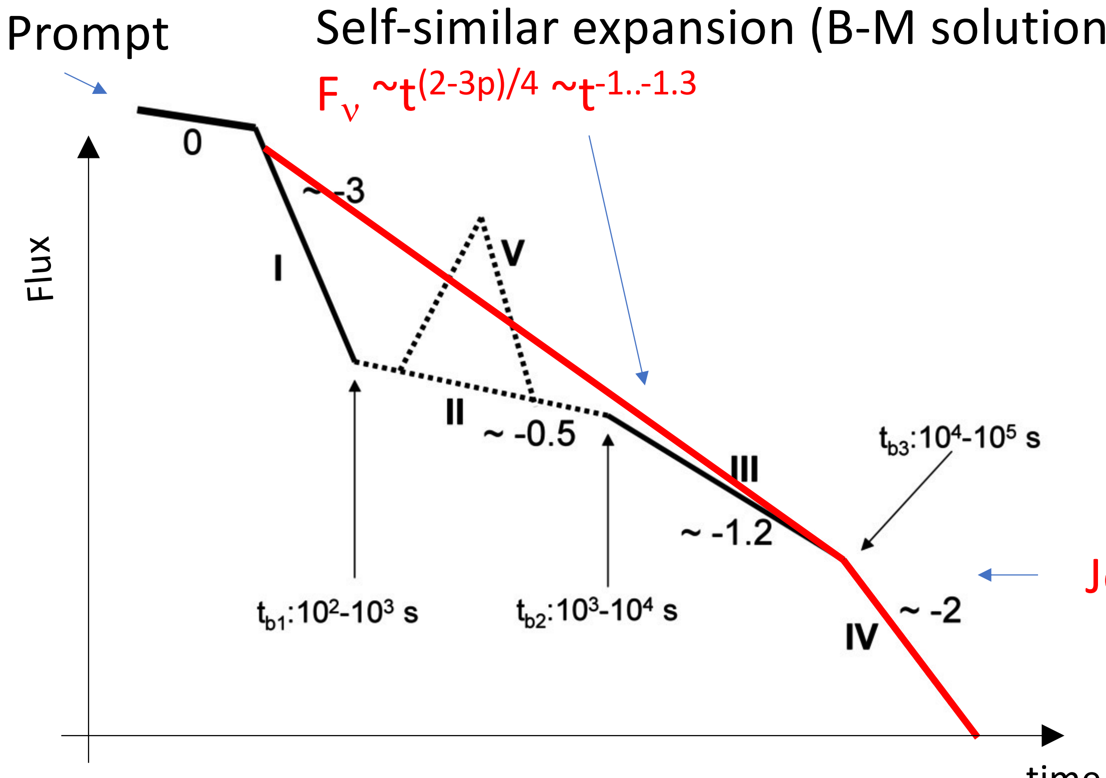
❖ Swift launch: Nov. 2004

Blandford & McKee, 1976

Initial theoretical expectation

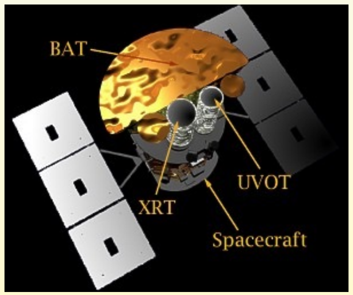
Self-similar expansion (B-M solution)

$F_\nu \sim t^{(2-3p)/4} \sim t^{-1..-1.3}$



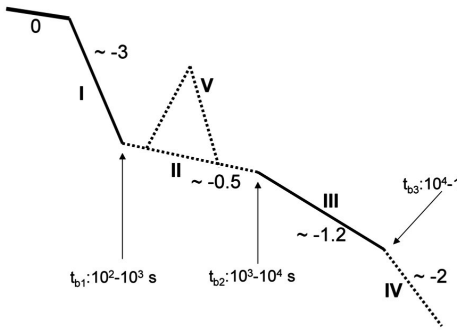
Jet break

Zhang et. al., 2006

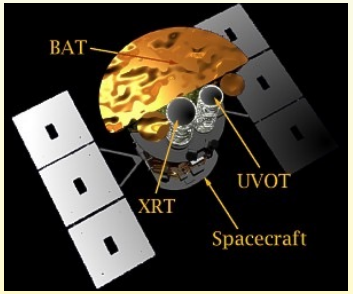


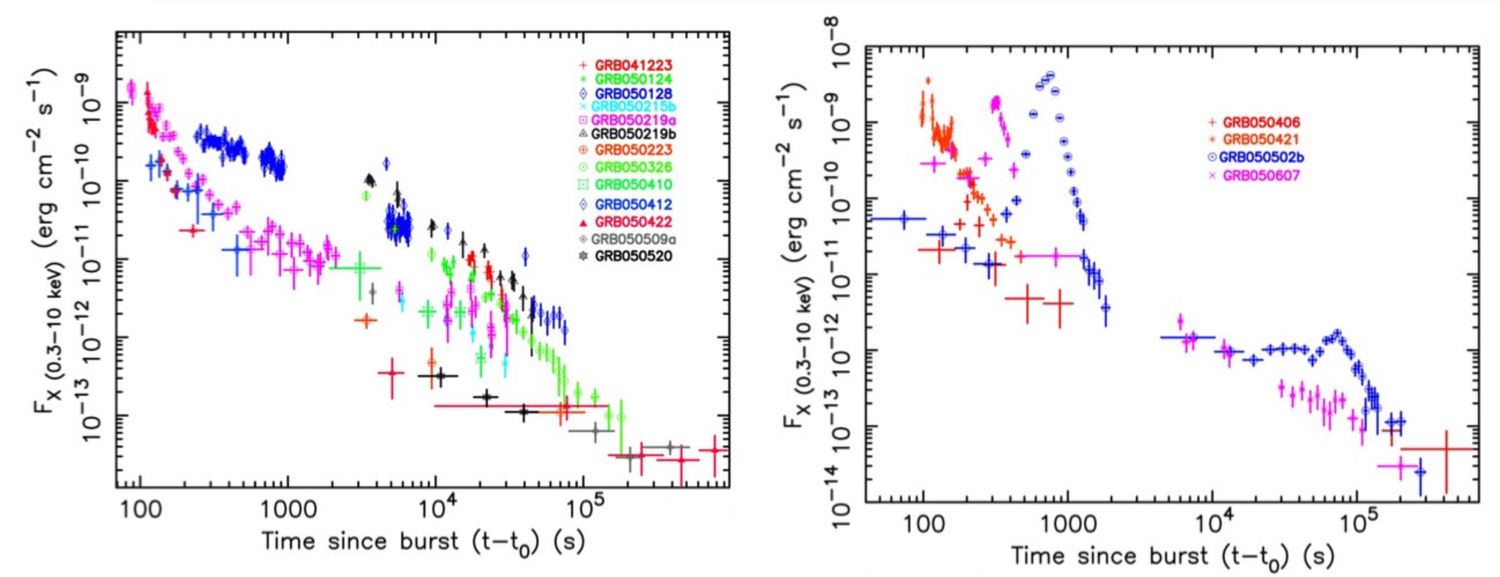
X-ray Plateau

Cartoon of X-ray lightcurve



Zhang et. al., 2006

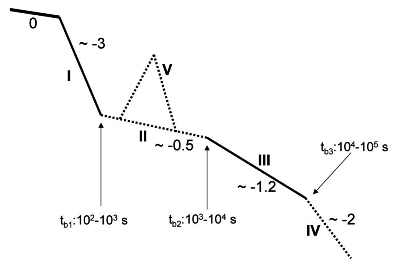




Nousek+2006

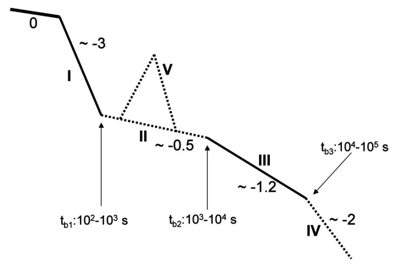
<u>Ubiquitous</u>: X-ray plateau seen in 60% of GRBs (Srinivasaragavan + 2020)

Plethora of ideas…



- **Continuous energy injection** that slows down the acceleration
  Zhang et. al., 2006; Nousek et al., 2006; Panaitescu et. al., 2006 ; Granot et. al., 2006; Fan & Piran, 2006 ; Ghisellini+2007…
- 2 component jet Ramirez-Ruiz + 2002, Granot+ 2006, Racusin et. al., 2008, …
- Forward shock emission in **Inhomogeneous media** Toma et. al. 2006
- Scattering by dust / modification of ambient density by a gamma-ray trigger
  Ioka et. al., 2006, Shao & Dai, 2007..
- Dominant reverse shock emission Uhm & Beloborodov, 2007, Gennet + 2007, Hascoet+2014…
- Evolving microphysical parameters (ε_e, ε_B) Ioka et. al., 2006, Panaitescu, 2006
- **Viewing angle effect**: jets viewed off-axis Eichler & Granot 2006, Toma + 2006, Eichler + 2008, 2014, Oganesyan et. al., 2019, Beniamini et. al., 2020
- Forward shock - before deceleration Shen & Matzner, 2012

Plethora of ideas…



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Requires: (i) explosion into a ”wind”; (ii) $\Gamma_i < 100$; (iii) a-chromatic breaks

Does Γ have to be > 100?

Measure Γ: 1. Opacity; 2. strong thermal; 3. onset of afterglow (reverse shock)

The Astrophysical Journal, 878:52 (61pp), 2019 June 10
https://doi.org/10.3847/1538-4357/ab1d4e

A Decade of Gamma-Ray Bursts Observed by *Fermi*-LAT: The Second GRB Catalog

M. Ajello[1], M. Arimoto[2], M. Axelsson[3,4], L. Baldini[5], G. Barbiellini[6,7], D. Bastieri[8,9], R. Bellazzini[10], P. N. Bhat[11],

(1) 2^{nd} Fermi-LAT catalogue: (Ajello+ 2019):

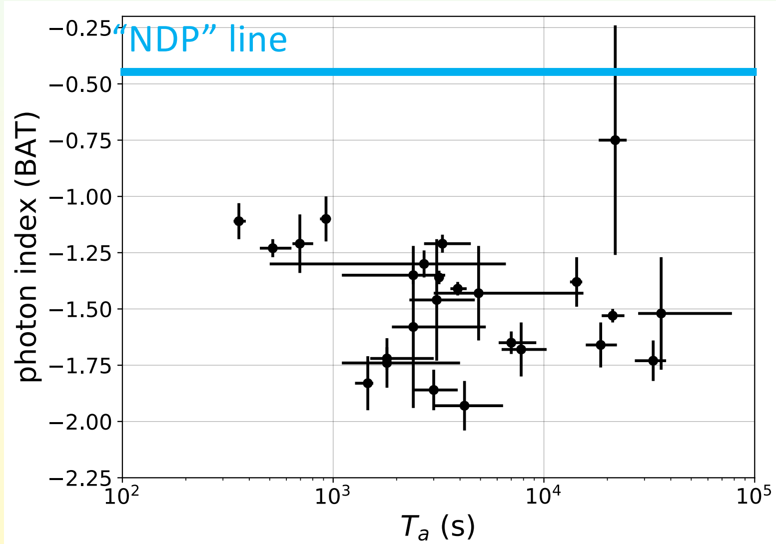
Only 3/186 LAT bursts show any evidence for a “Plateau” !

→ **Opacity argument (γγ →$e^{\pm}$: (GeV) LAT photons necessitates Γ>~100) is not valid** !

(2) +- All Plateau bursts, are below the NDP line –

-Do **NOT** show evidence for a leading thermal component

“Plateau” bursts seem to **anti-correlate** with requirement for high Γ



Dereli-Bégué, **AP**, Ryde 2020; Yu+2020)

Basics of synchrotron (wind)

$\nu_m^{ob.} \sim B\, \gamma_{el}^2\, \Gamma$

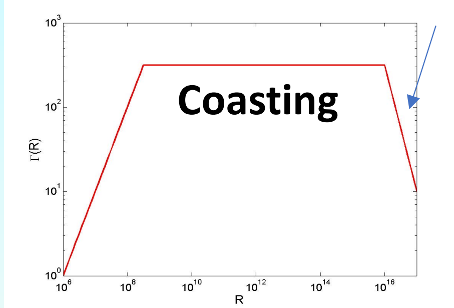
$\nu_c^{ob.} \sim \Gamma^3/(B^3\, r^2)$

$F_{\nu,peak} \sim N_e\, B\, \Gamma$

* Shock generates B field & accelerates particles:

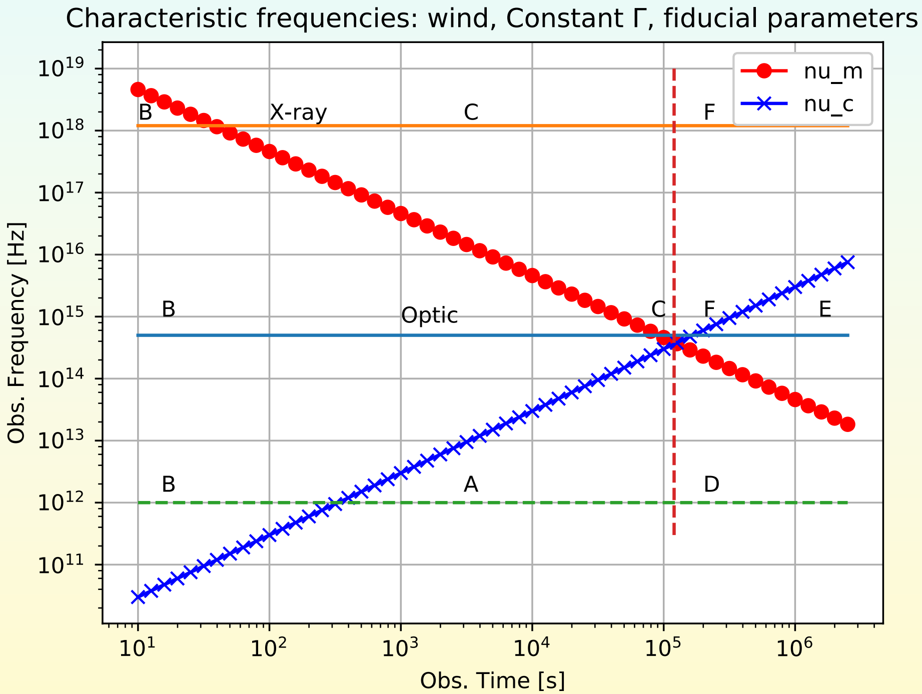
$\gamma_{el} \sim \Gamma\, \varepsilon_e$; $B \sim \varepsilon_B\, u$

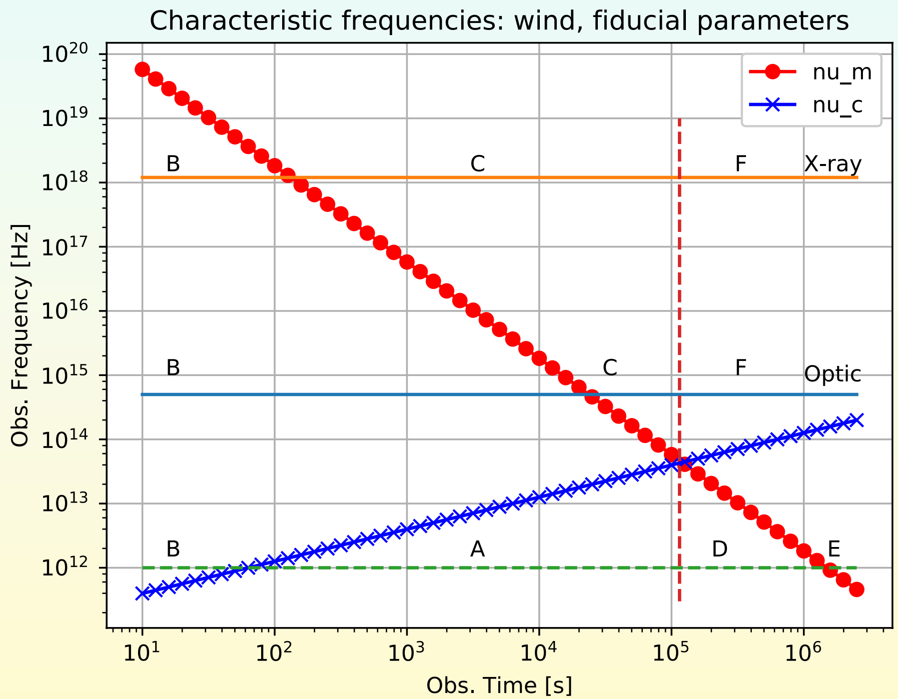
Self-similar



Coasting: $\nu_m^{ob.} \sim t^{-1}$; $\nu_c^{ob.} \sim t$

Self-similar decay: $\nu_m^{ob.} \sim t^{-3/2}$; $\nu_c^{ob.} \sim t^{1/2}$

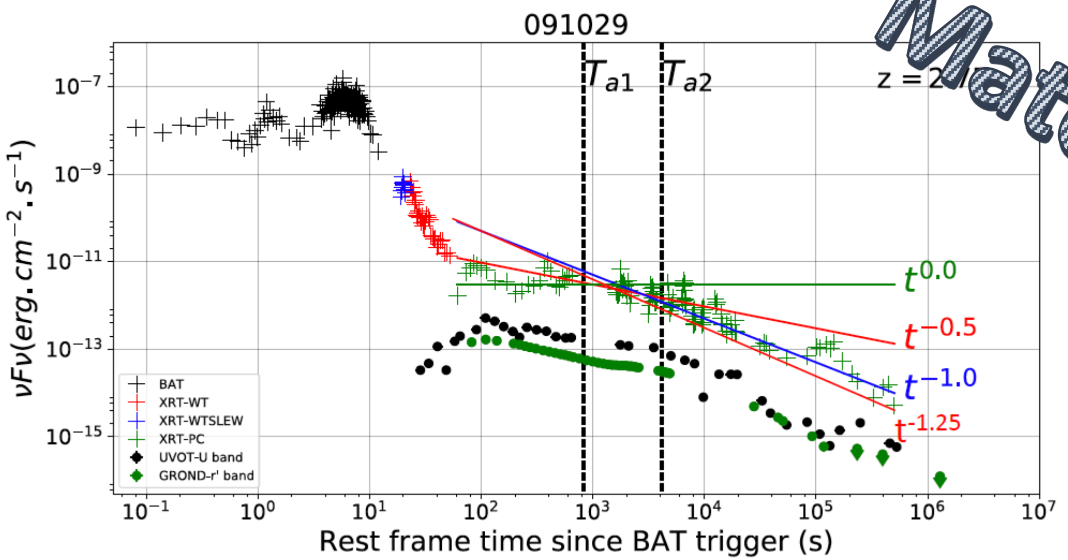




Prediction: Transition from region F ($\nu_c < \nu$) → E ($\nu < \nu_c$); optical first

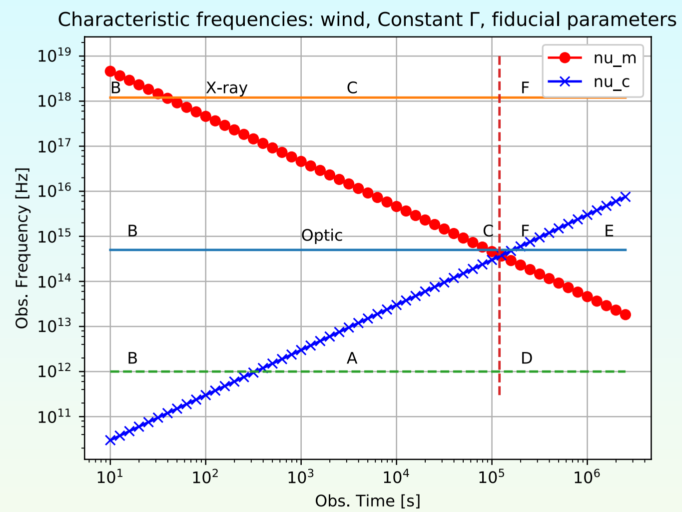
Basics of synchrotron (wind): theory vs. data

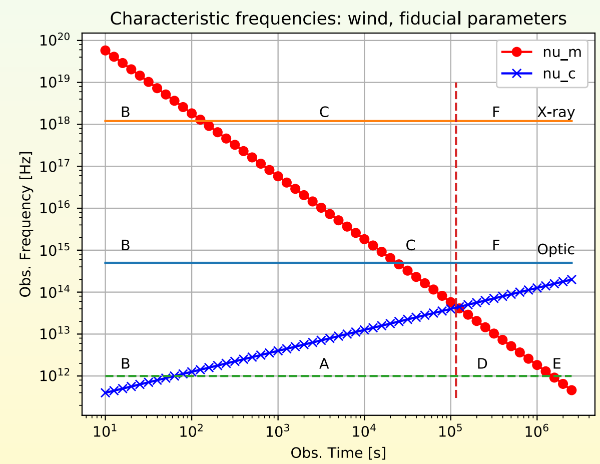
Region	Coasting	Self-similar decay
F ($\nu_c < \nu$):	$F_\nu \sim t^{(2-p)/2}\,\nu^{-p/2} \sim t^0$	$F_\nu \sim t^{(2-3p)/4}\,\nu^{-p/2} \sim t^{-1}$
E ($\nu < \nu_c$):	$F_\nu \sim t^{(1-p)/2}\,\nu^{-(p-1)/2} \sim t^{-0.5}$	$F_\nu \sim t^{(1-3p)/4}\,\nu^{-(p-1)/2} \sim t^{-1.25}$



Match !

Dereli-Bégué+2021, in preparation





A-chromatic breaks are allowed !

Extracting physical information

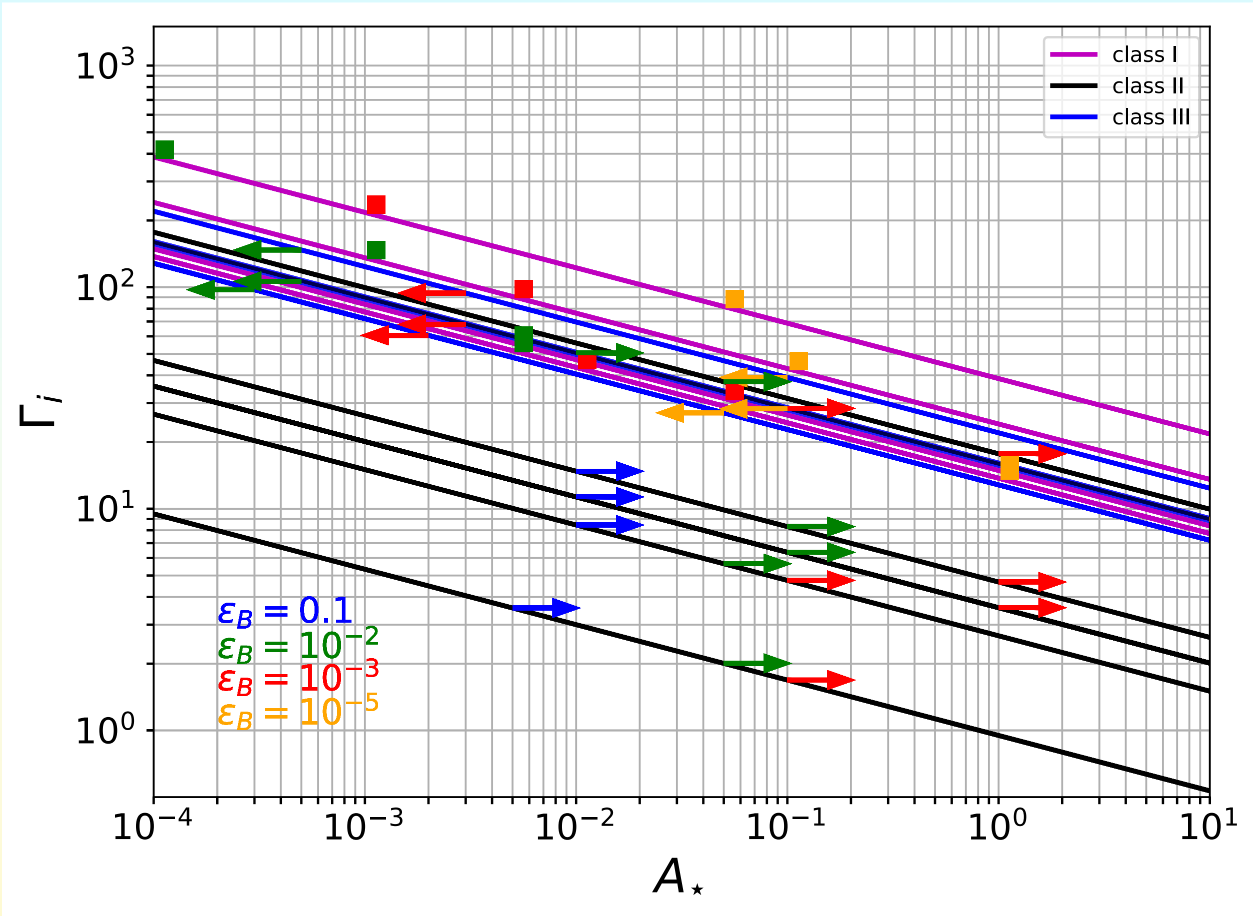
$$t^{ob.}_{trans} = (1+z)\frac{9E}{32\pi A c^3 \Gamma_i^4}$$

→ $A_* \Gamma_{i,1.5}^4$ ~=0.2 (1+z)/2 $E_{52.5}$ $t_{trans,3.5}^{-1}$

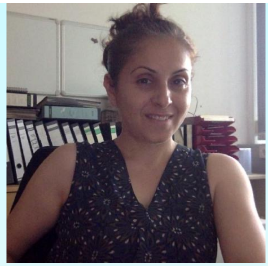
$\rho(r) = 5*10^{11} A_* r^{-2}$

A_* (Wolf-Rayet) ~1

Chevalier+04,..



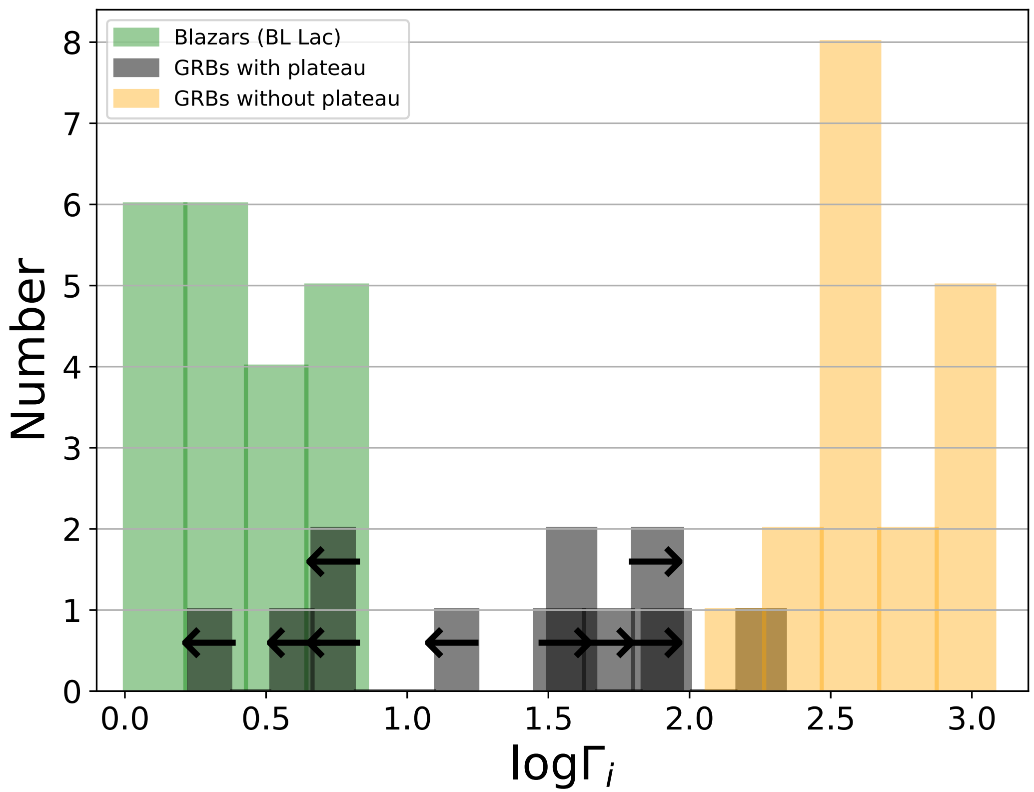
Dereli-Begue, Pe'er et. al., 2022, Nature Com.



Given magnetization 0.1 <ε_B < 10^{-5} → **<A_*>~10^{-2} ; 4<Γ_i<218; <Γ_i>=51**

Bridging an observational gap

Ghisellini+93



Liang+10
Racusin+11

$<\Gamma_i>=51$ bridges an observational gap btw blazars and LAT/ no plateau GRBs
And- can potentially explain polarization angle change

Independent way to discriminate between models ?
1.a. Flares during the early afterglow phase

Sample consists of 89/100 GRBs (11 GRBs are excluded due to special features):

1) **~69% of all GRBs analyzed have flares.**
2) **~64% of all GRBs analyzed have plateau**
3) ~68% of the GRBs with flares have a plateau.
4) ~73% of plateau GRBs have flares.

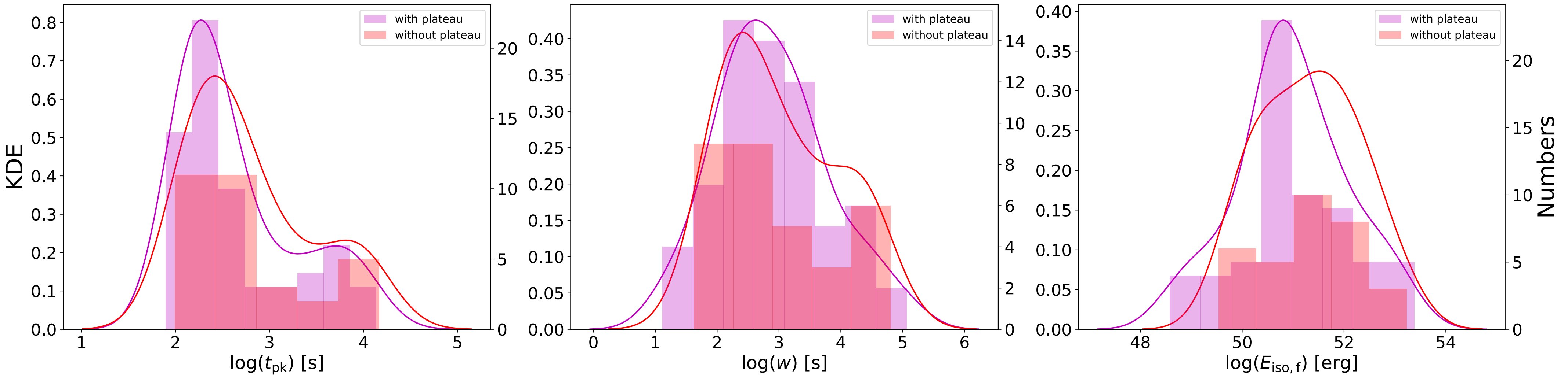
Conclusion- (1): The existence of flares is independent of the existence of a plateau.

Dereli-Begue, AP, Begue, Ryde, 2024, submitted

Results: flare properties (1)

GRBs with plateau

GRBs without plateau



Flare peak time

Flare width

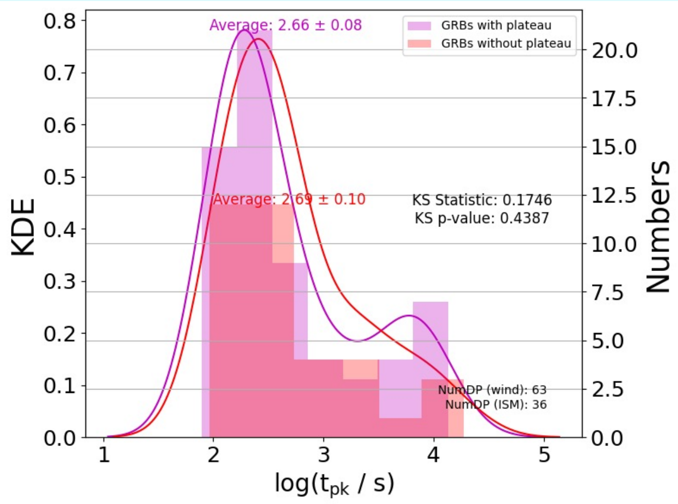
Flare total energy

No notable differences between flare properties

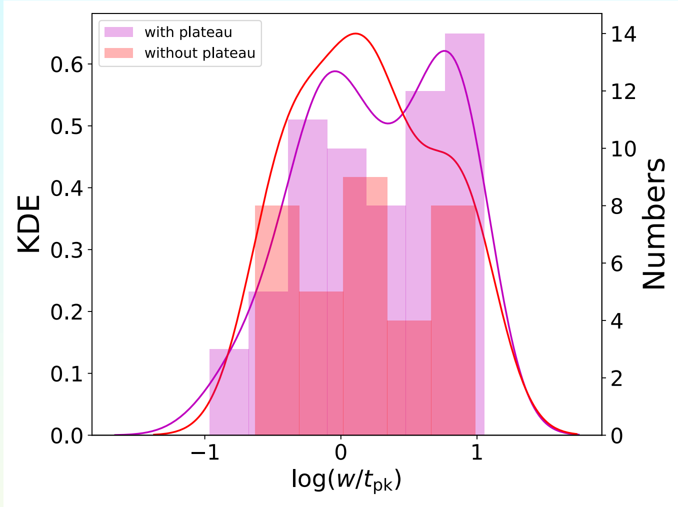
Dereli-Begue, AP, Begue, Ryde, 2024, submitted

Flare properties - implications

Flare peak time



Relative time-scale variability



Main results:

(1) t_{peak} is, on the average, same for both sample

(2) $<\Delta t/t_{peak}>$ ~1, irrespective of the environment.

Implications for Plateau origin:

Late time central engine activity: Flares expected to occur later; $\Delta t/t_{peak}$ have different distributions → contradicts results (1) and (2) x

Viewing angle effect: Flares in plateau GRBs expected at later times → contradicts result (1) x – **similar for density effects** x

Low Lorentz factor during the coasting phase: The dissipation that produces the flares occurs at smaller radii → no contradiction ✓

1.b. Hints from the prompt emission itself ?
Fitting prompt emission: Norris function

408 NORRIS ET AL.

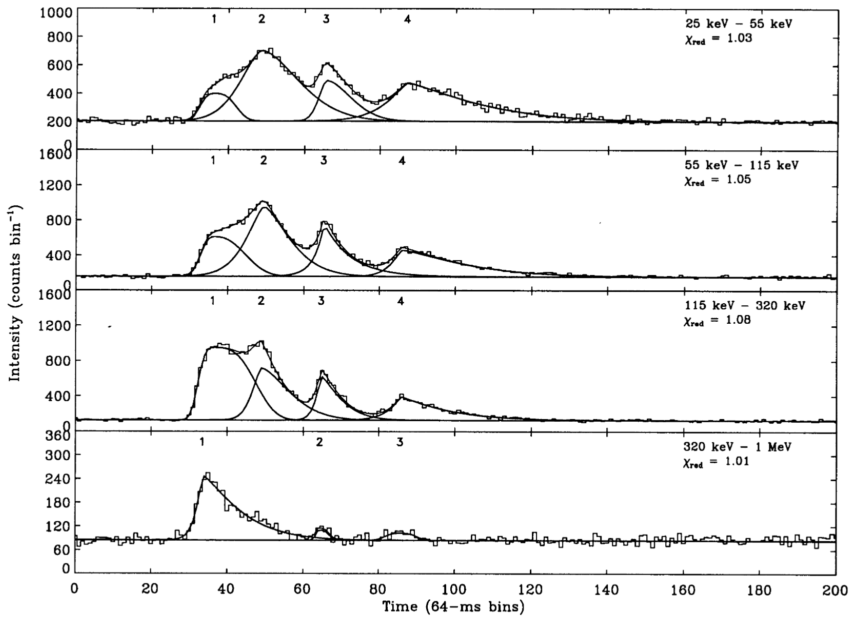


FIG. 17.—BATSE trigger 543. Four pulses are required to fit profiles in channels 1–3, whereas a second pulse is not required in channel 4. Pulse no. 4 in channels 1–3 and pulse no. 3 in channel 4 are separable pulses. Pulses no. 3 (channel 3) and no. 2 (channel 4) are also separable.

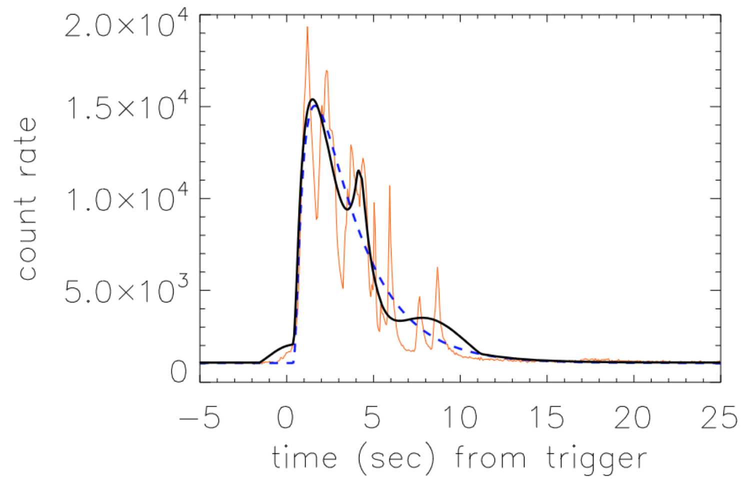
Norris et. al. (1996, 2005,…); Hakkila + 2018; …

ters have relatively simple expressions. A form proportional to the inverse of the product of two exponentials, one increasing and one decreasing with time, satisfies the requirements

$$I(t) = A\lambda/[\exp(\tau_1/t)\exp(t/\tau_2)]$$
$$= A\lambda\exp(-\tau_1/t - t/\tau_2) \quad \text{for } t > 0, \qquad (1)$$

Norris (2005) function:
3 free parameters

Hakkila et al.



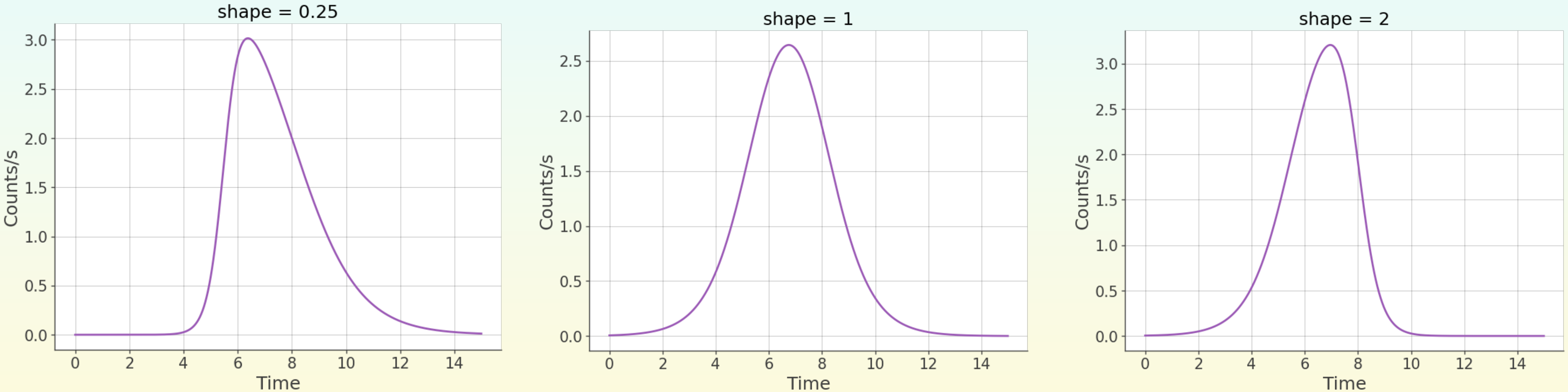
“Fast Rise, Exponential Decay” (FRED)

Fitting prompt emission: new function

$$I(t) = A \times \left[1 - tanh\left(\frac{1}{s_r}(t - r_r)\right)\right] \times \left[1 + tanh\left(\frac{1}{s_l}(t - r_l)\right)\right].$$

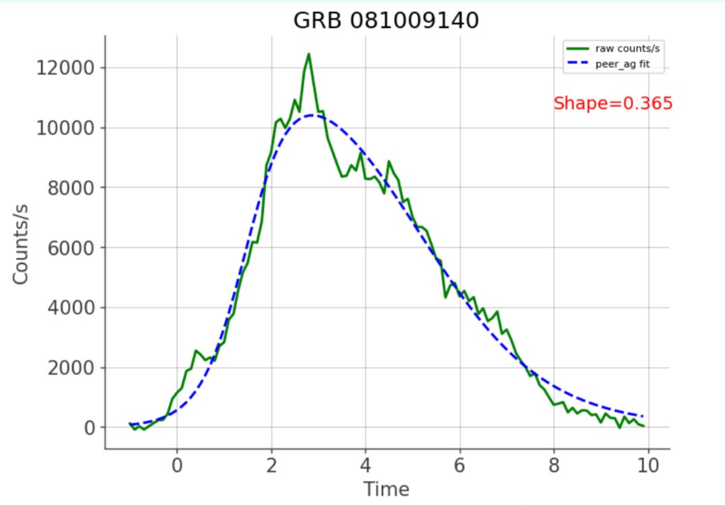
5 (4) degrees of freedon

Shape function = s_l/s_r



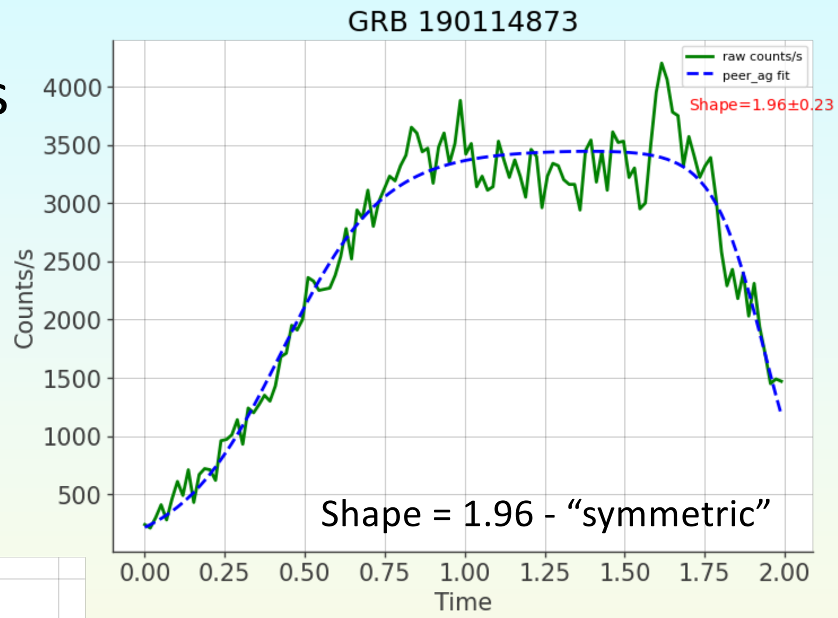
Anil, **AP**, Ryde, Dereli-Begue, 2024, submitted (arXiv:2409.17860)

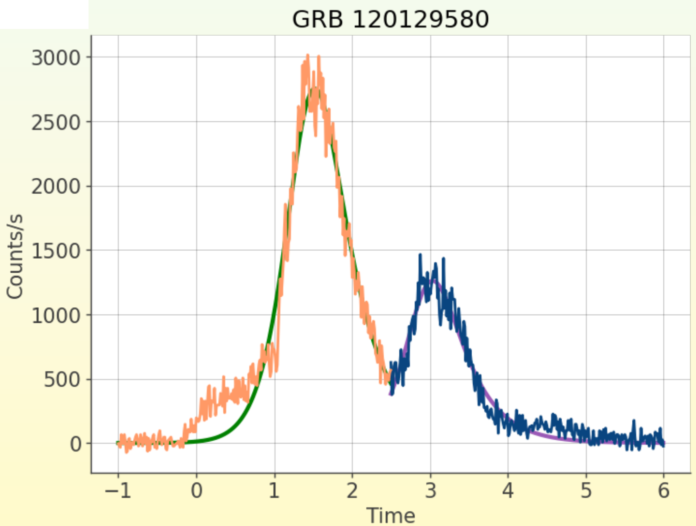
Fitting prompt emission pulses



Shape =0.36 - “FRED”

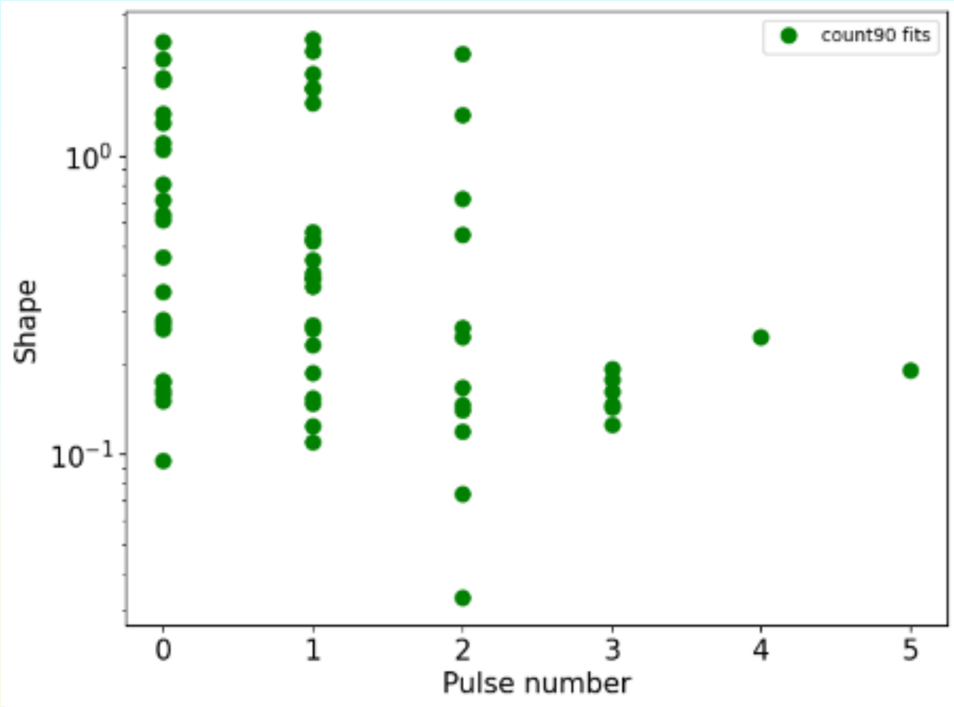
64 pulses / 23 GRBs
(Fermi-GBM)
38/64: “single”
28/64: ”combined”





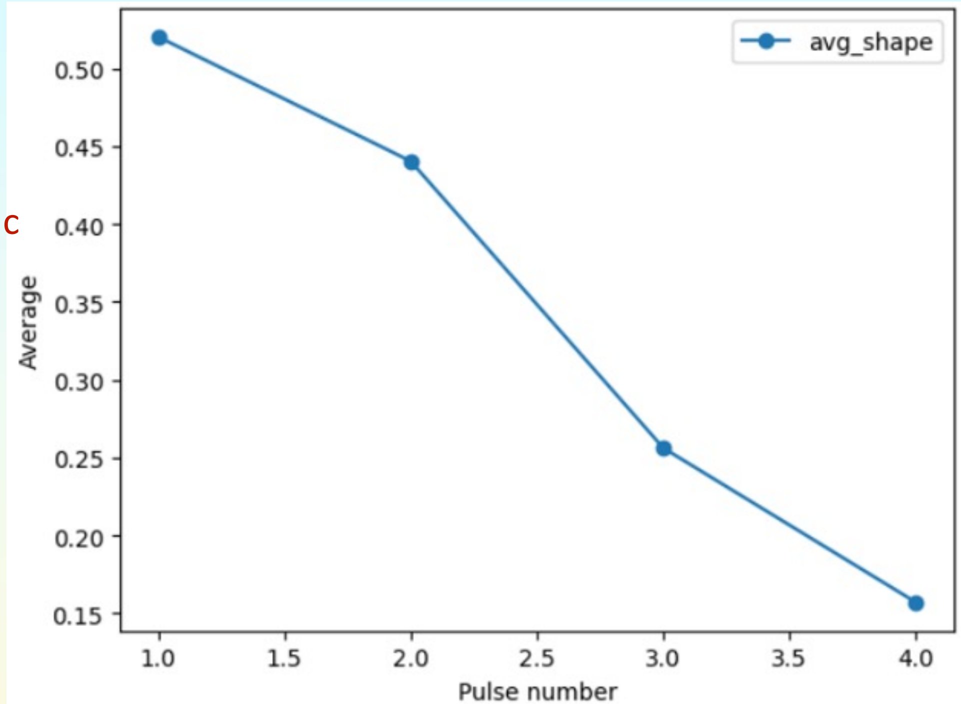
- Distinct pulses
- At least 2 pulses/GRB
- Statistical significance: SNR>20 (Vianello+2018)
- Coefficient of determination: $r^2 > 0.7$

Key result -1: pulse shape evolves !



Symmetric

FRED

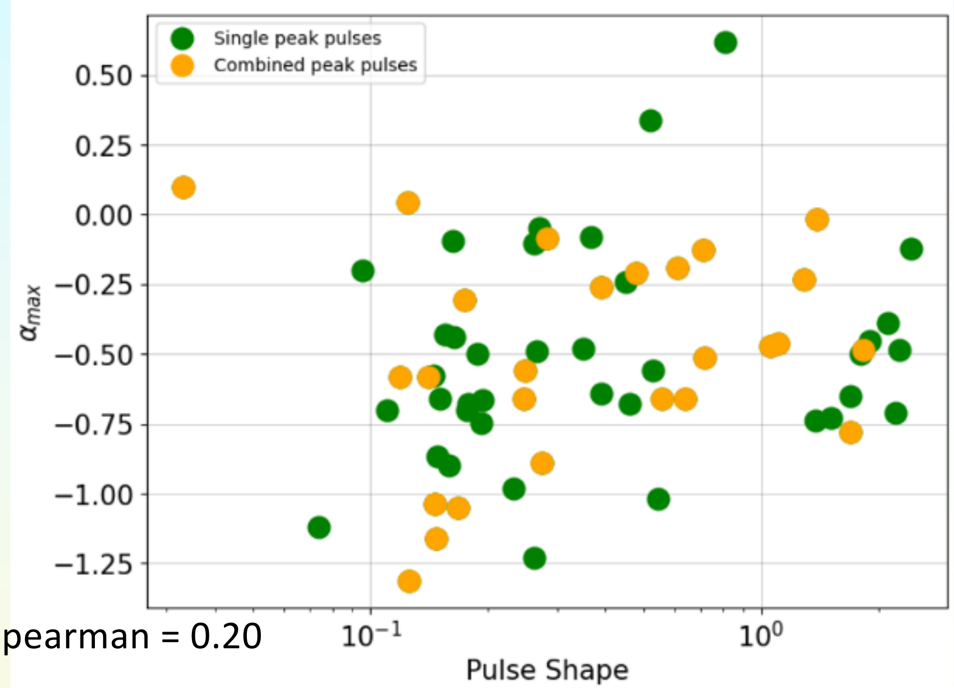


Shape = s_l/s_r

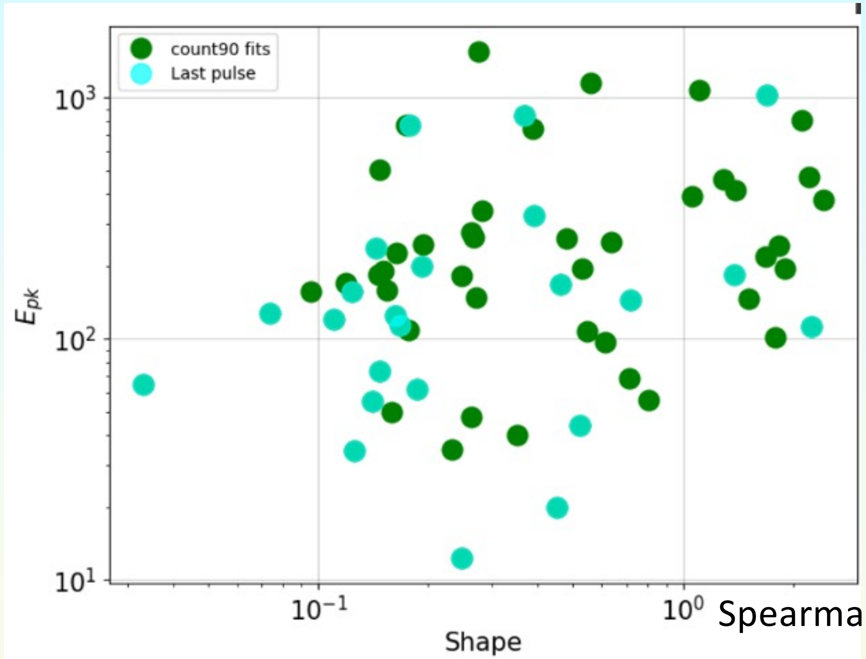
Spearman = -0.36

Early pulses tend to be more symmetric;
Later pulses tend to be more FRED-like !

Key result -2: pulse shape correlates with spectra



Spearman = 0.20



Spearman = 0.30

FRED Symmetric

Shape = s_l/s_r

Symmetric pulses have steeper slopes, higher E_{pk}

Possible interpretation: **Change of radiative mechanism**: thermal → synchrotron

Time scale -? $t = \frac{r_{ph}}{\Gamma^2 c} = \frac{L\sigma_T}{8\pi m_p \Gamma^5 c^4} = 2\ ms\ L_{51}\left(\frac{\Gamma}{100}\right)^{-5} = 1\ s\ L_{51}\left(\frac{\Gamma}{30}\right)^{-5}$

Anil, **AP**, Ryde, Dereli-Begue, arXiv:2409.17860

2. Pronounced photospheric signal – how does it look like ?
"Physical broadening" the photospheric signal

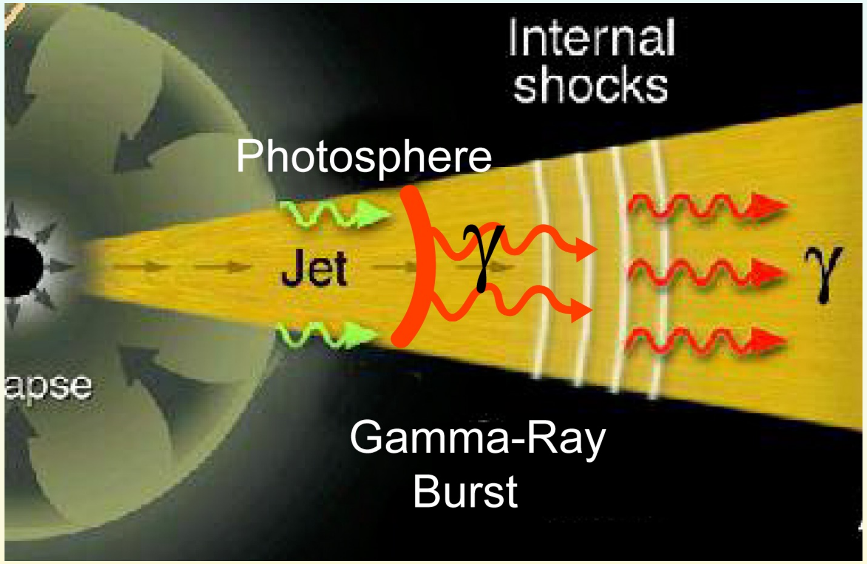
Basic idea:

Sub photospheric energy dissipated (heating plasma at $r_d <= r_{pht.}$)

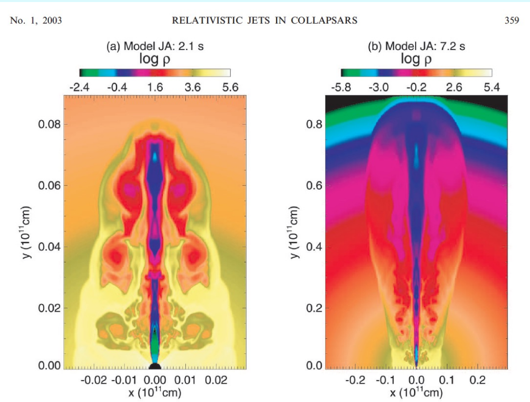
Hot (thermal) electrons, colder photons
(alternative: photon gain energy directly)

Multiple IC scattering

Spectra depends on:
- heating rate
- heating location (crucial!!)
- magnetic field strength

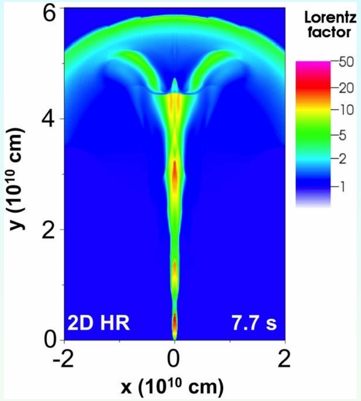


Energy dissipation below the photosphere (Dissipative photosphere)

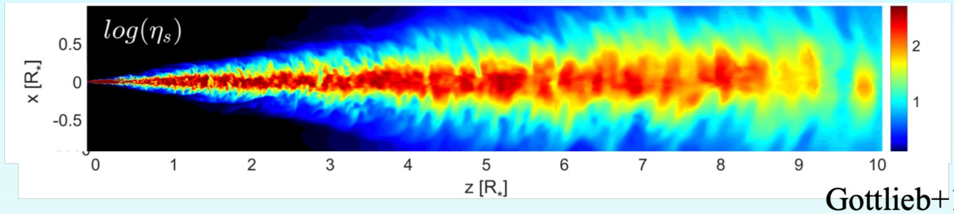


Zhang, Woosley & MacFadyen, 03

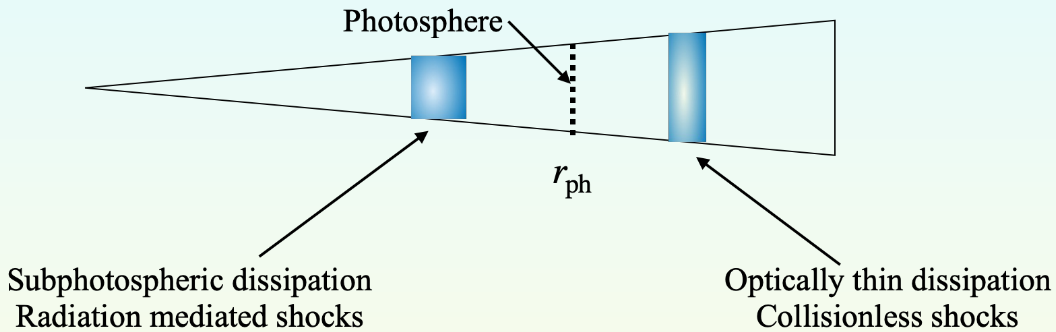
Dissipation $\epsilon_{\rm d}(r)$

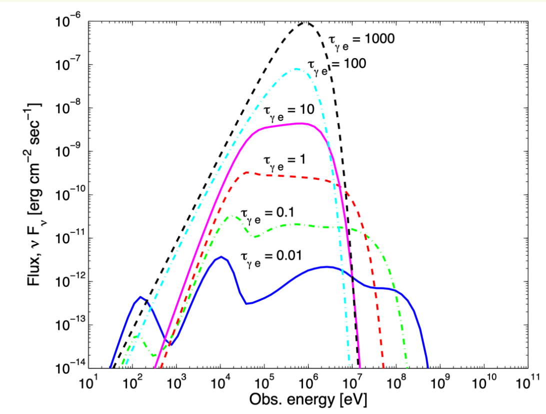


Lopez-Camara et. al., 2013
Aloy, Zheng, Mizuta, Lazatti, …

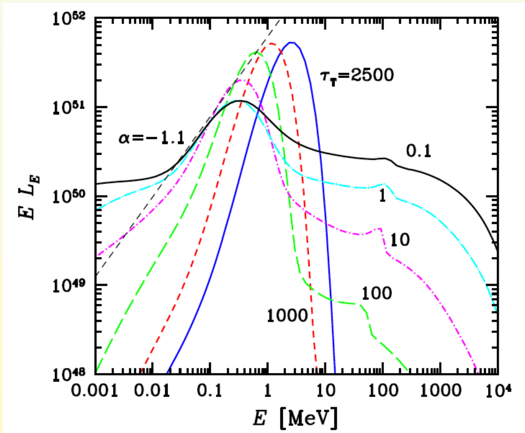


Gottlieb+19

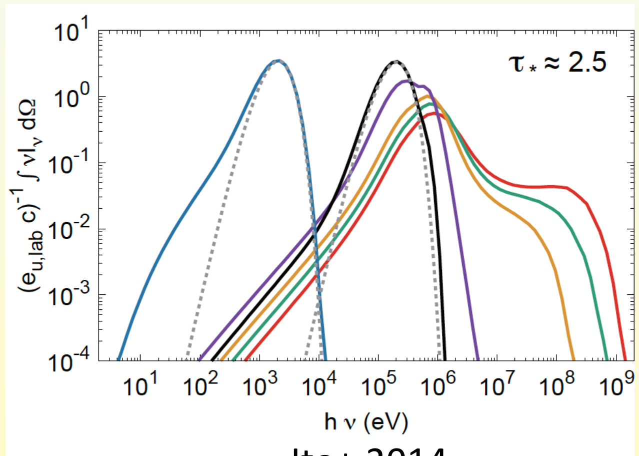




Pe'er, Meszaros & Rees 2006

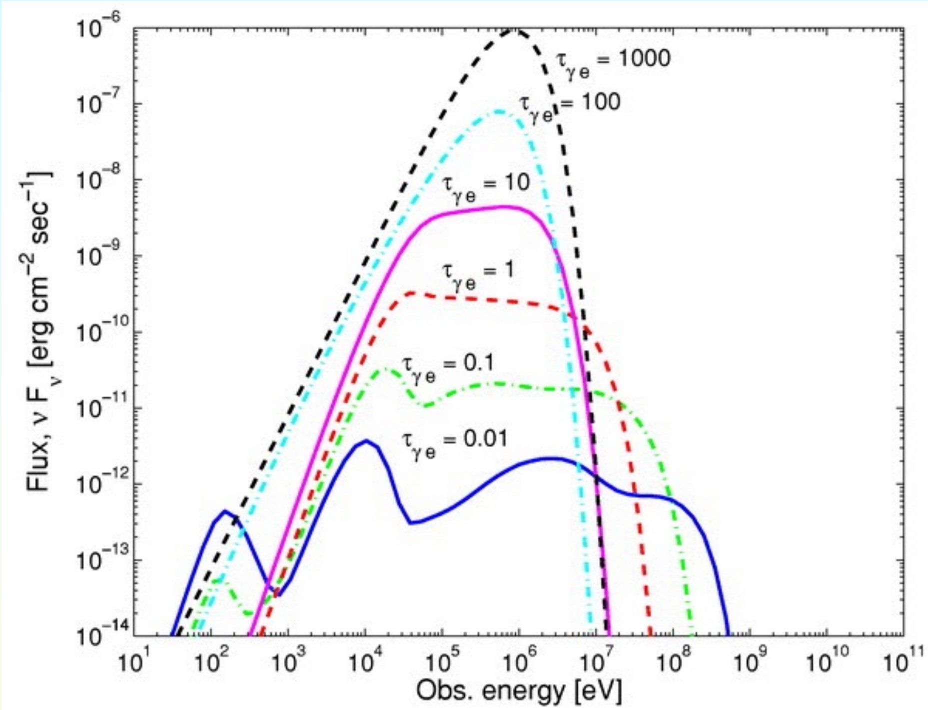


Vurm + 2014



Ito+ 2014

Complex thermal - non thermal emission spectra



Pe'er, Meszaros & Rees 2006

See also

- Giannios 2006, 2012
- Giannios & Spruit 2007
- Ioka + 2007
- Pe'er + 2010
- Beloborodov 2010
- Lazatti & Begelman 2010
- Vurm +11, 12
- Rudolph + 24

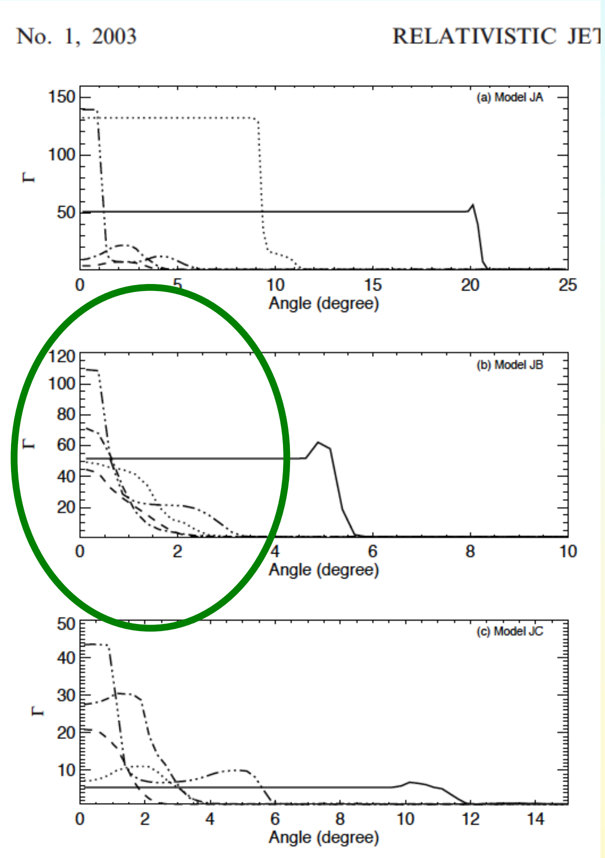
"Quasi steady state": **Electrons distribution is quasi-Maxwellian (not power law)**

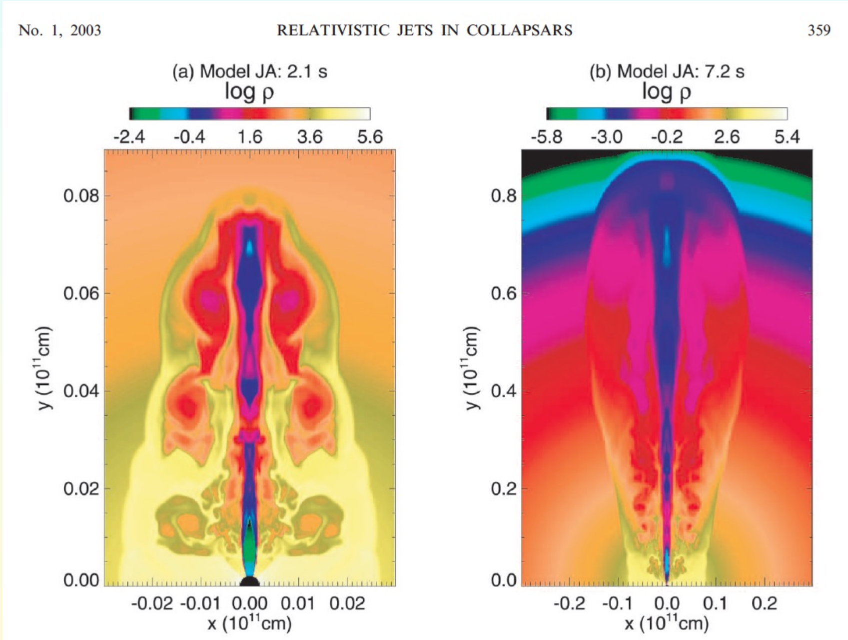
Main rad. Process (above thermal peak): **IC of thermal photons**

spectra is **NOT** thermal, neither a simple broken Power law)

3. Structured jet and its implications

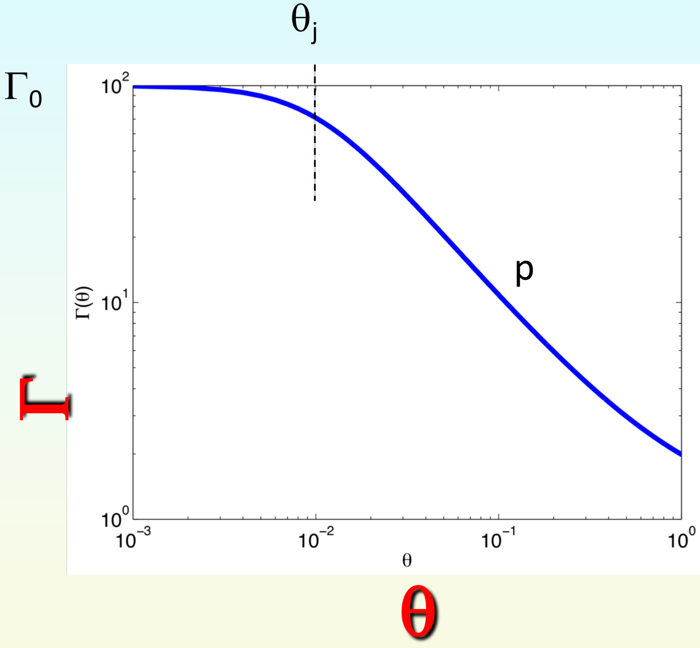
$\Gamma=\Gamma(\theta)$

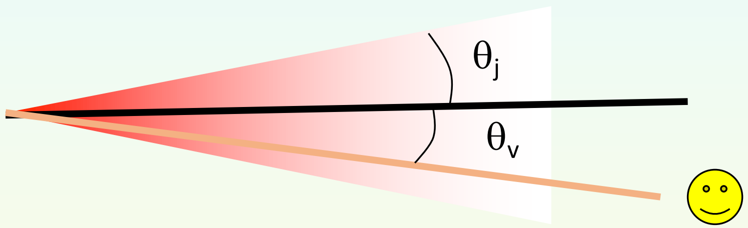




(Zhang, Woosley & MacFadyen, 2003)

Photospheric emission: 'realistic' jet velocity profile



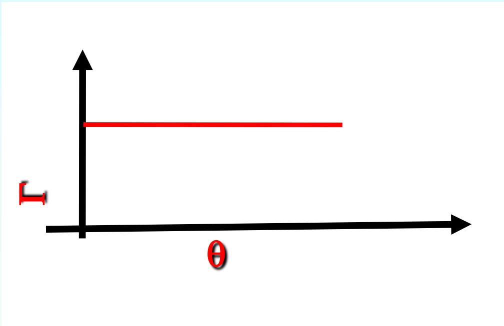


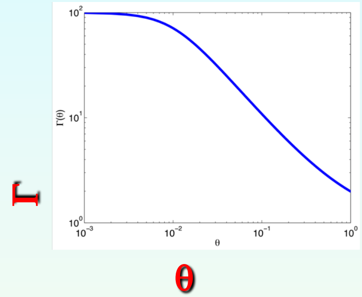
$$[\Gamma(\theta)-1]^2 = \frac{[\Gamma_0 - 1]^2}{1+\left(\frac{\theta}{\theta_j}\right)^{2p}}$$

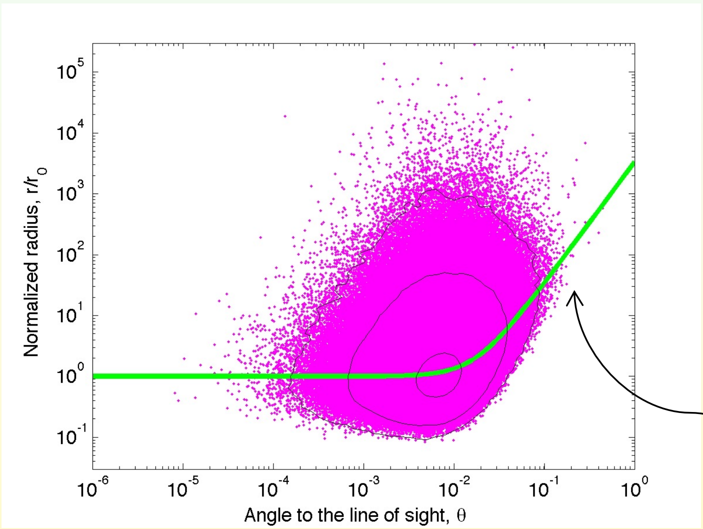
4 free parameters: Γ_0, θ_j, θ_v, p

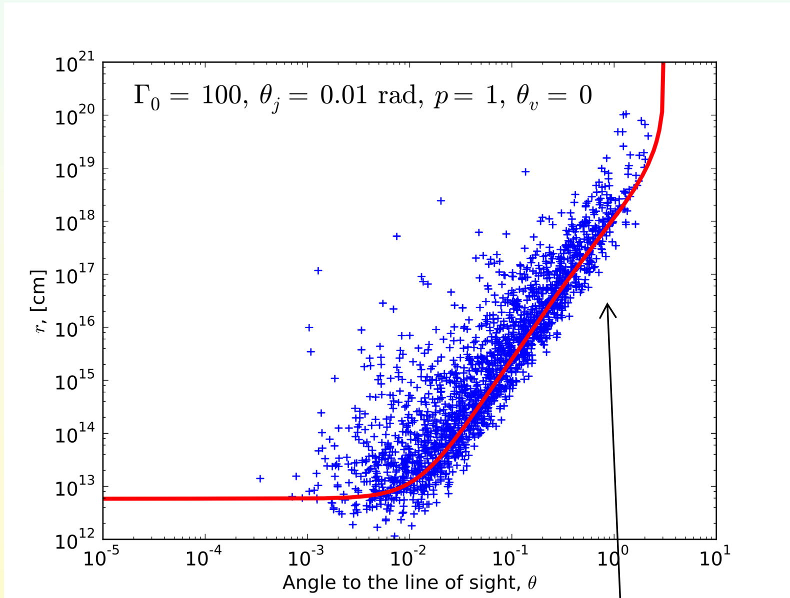
Lundman, AP & Ryde (2013)

Extended emission from high angles





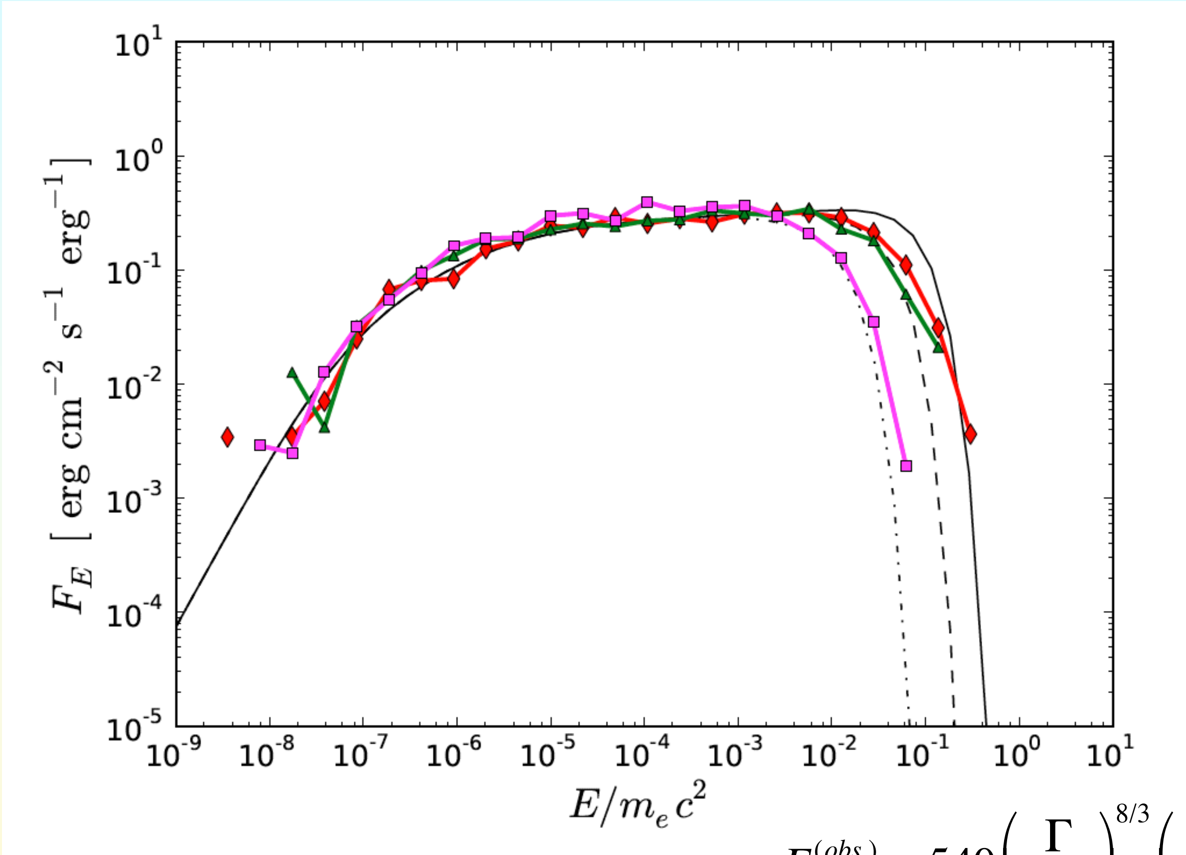




AP 2008; Lundman, AP & Ryde (2013)

Relativistic Limb darkening effect

Flat spectra for different viewing angles (prompt!)



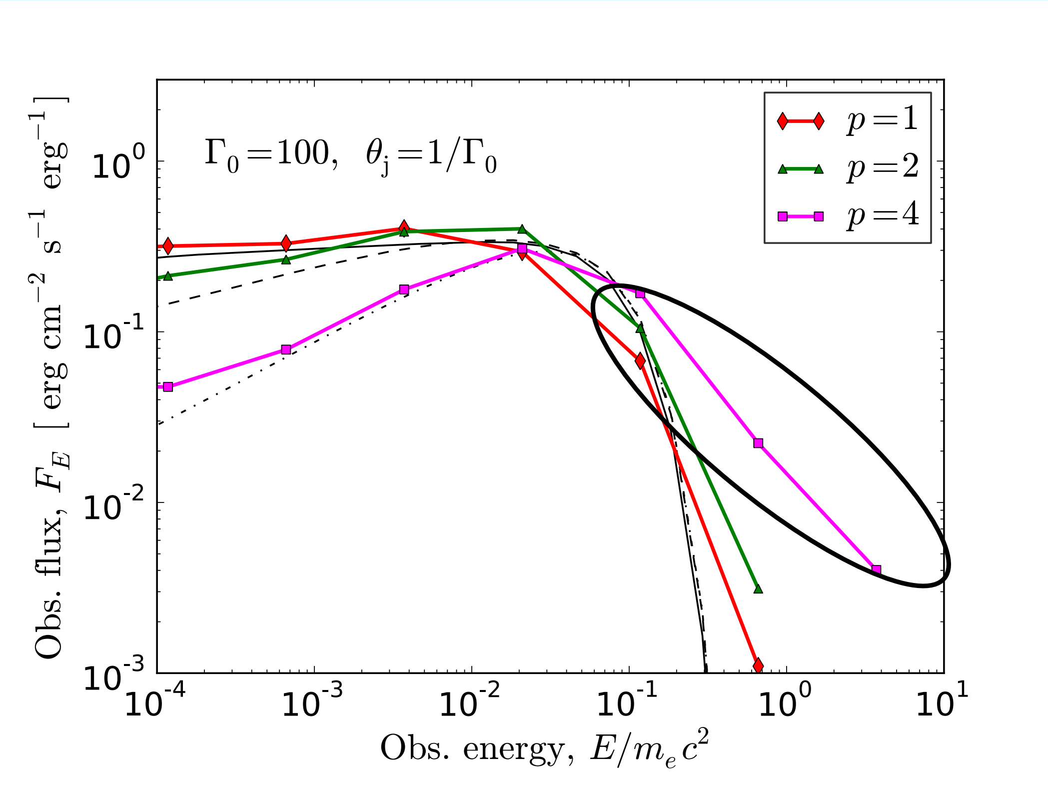
$$E_{pk}^{(obs.)} \approx 540 \left(\frac{\Gamma}{300}\right)^{8/3} \left(\frac{L}{10^{52}}\right)^{-5/12} \text{keV}$$

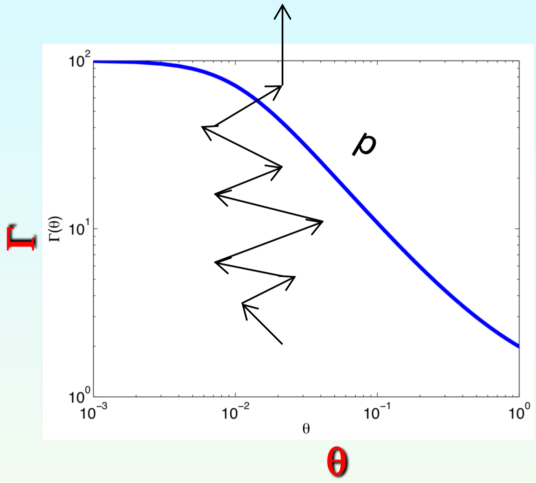
A robust result !

Γ_0=100; $\Gamma_0\theta_j$ = 1; p=1 ; θ_v = {0,1,2} θ_j (red, green, magenta)

Lundman, AP & Ryde (2013)

Photon up-scattering by Fermi-like mechanism





$$\left\langle \frac{\nu_{out,1}}{\nu_{in,2}} \right\rangle \approx \frac{1}{2}\left(1+\left(\frac{\Gamma_2}{\Gamma_1}\right)^2\right)$$

Repeated scattering between regions of different Γ, causes photon energy increase.

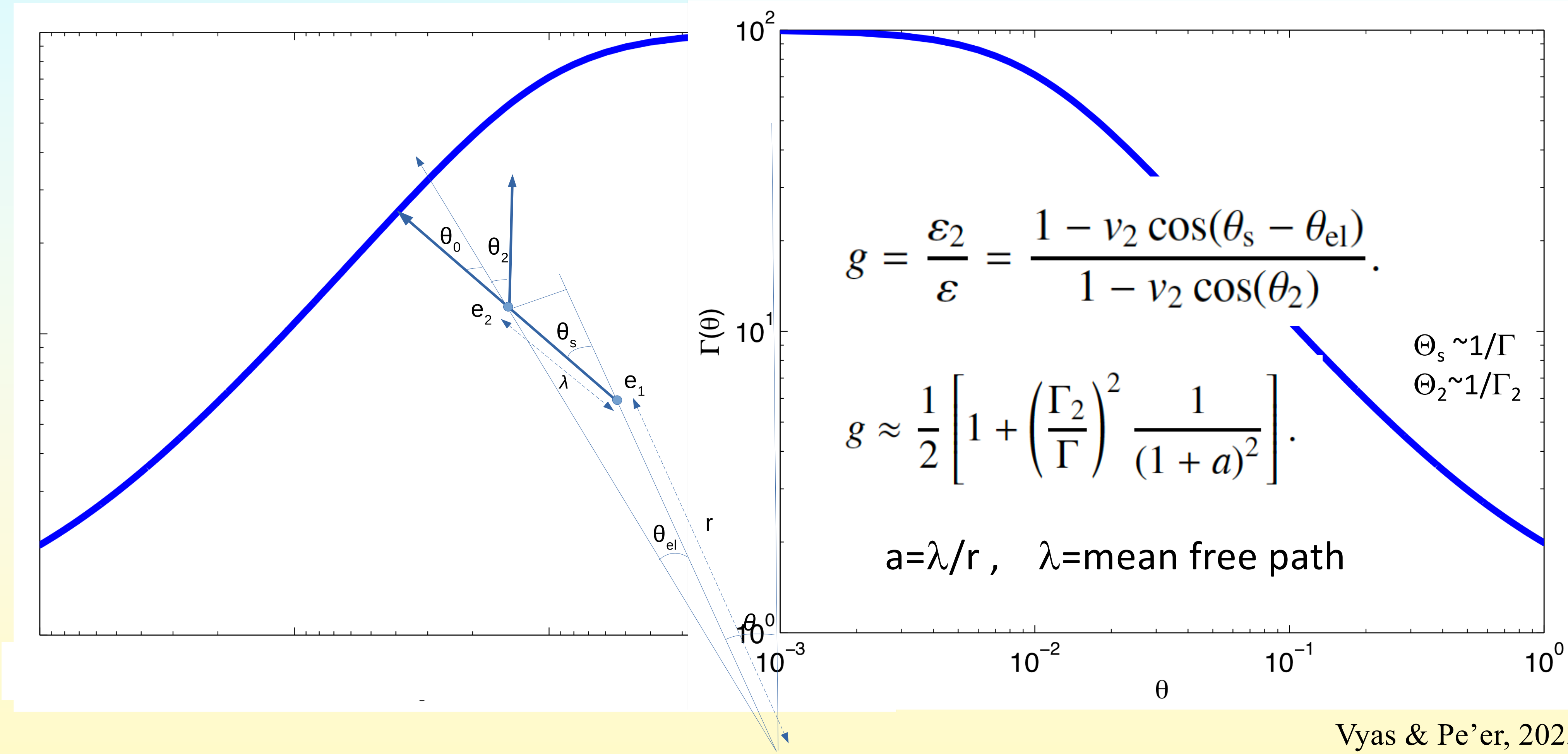
$1 \rightarrow 2 \rightarrow 1$

$$\left\langle \frac{\nu_{out}}{\nu_{in}} \right\rangle \approx \frac{1}{4}\left(1+\left(\frac{\Gamma_2}{\Gamma_1}\right)^2\right)\left(1+\left(\frac{\Gamma_1}{\Gamma_2}\right)^2\right) > 1$$

Lundman, AP & Ryde (2013, 2015); Ito.. Pe'er et. al. (2013)

Full calc. >>

Photon energy gain: basic idea



$$g = \frac{\varepsilon_2}{\varepsilon} = \frac{1 - v_2 \cos(\theta_s - \theta_{el})}{1 - v_2 \cos(\theta_2)}.$$

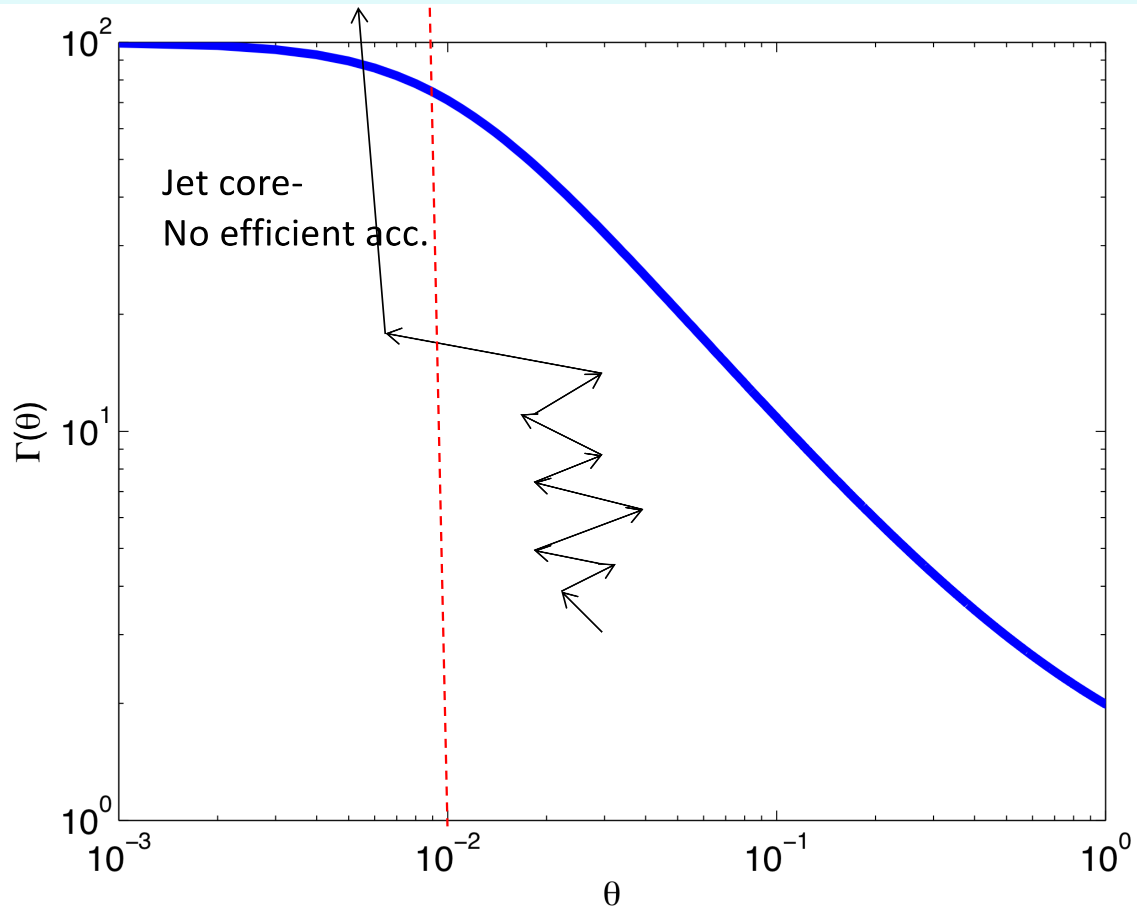
$$g \approx \frac{1}{2}\left[1 + \left(\frac{\Gamma_2}{\Gamma}\right)^2 \frac{1}{(1+a)^2}\right].$$

$a=\lambda/r$, λ=mean free path

$\Theta_s \sim 1/\Gamma$
$\Theta_2 \sim 1/\Gamma_2$

Vyas & Pe'er, 2023

Multiple scattering: obtaining a power law



Expectation value of photon energy gain: $\bar{g} = \frac{1}{V}\int dV \;\; g(r,\theta)$

Prob. of staying in the shear region: $\bar{P} = \frac{1}{V}\int dV \;\; P(r,\theta)$

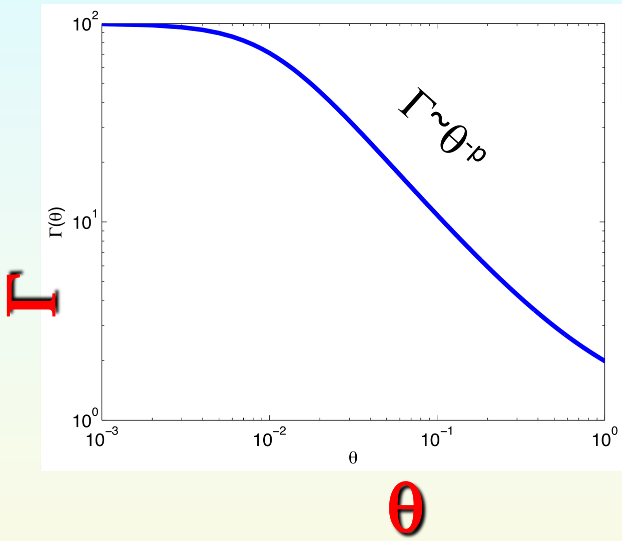
$$P(r,\theta) = 1 - e^{-\tau(r,\theta)}$$

After *k* scattering photon energy is ε_k $\quad N = N_0\bar{P}^k \qquad \frac{N}{N_0} = \left(\frac{\varepsilon_k}{\varepsilon_0}\right)^{\beta'}$

Obs. Photon index

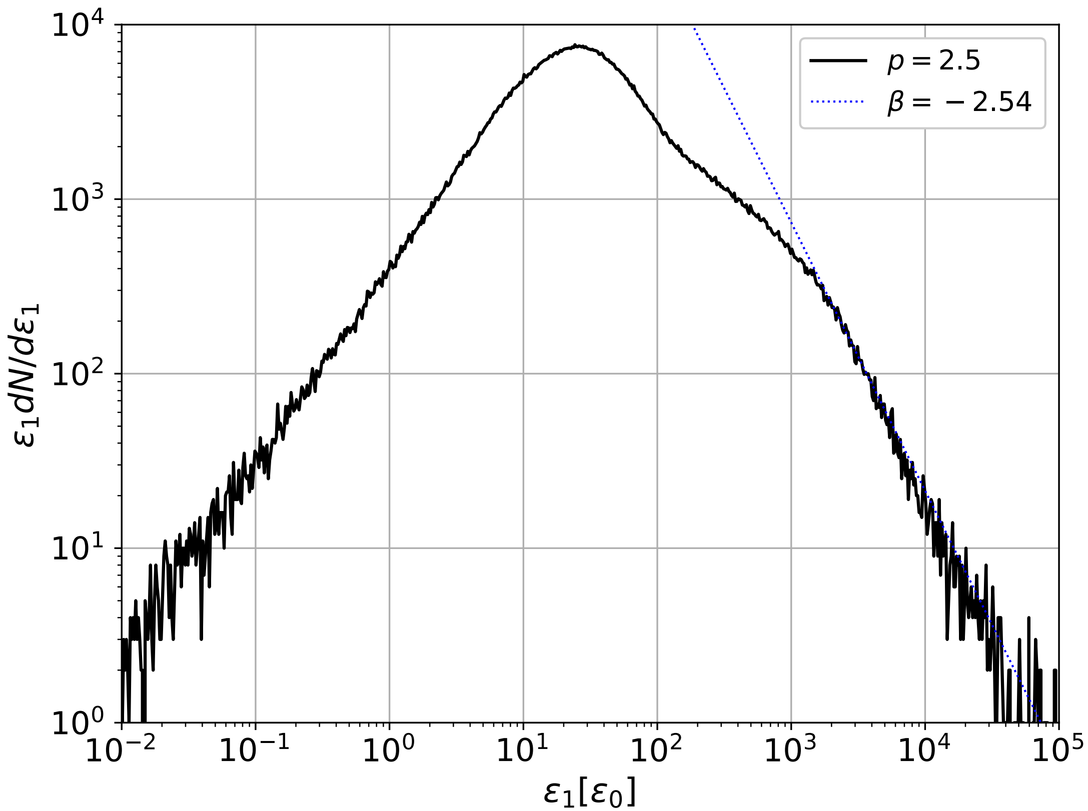
$$\beta = \beta' - 1 = \frac{\ln \bar{P}}{\ln \bar{g}} - 1$$

Results: Monte-Carlo simulation



$$\left[\Gamma(\theta)-1\right]^2=\frac{\left[\Gamma_0-1\right]^2}{1+\left(\frac{\theta}{\theta_j}\right)^{2p}}$$

$N_\gamma=10^{6.5}$, $\Gamma_0=100$, $\theta_j=0.01$ $\varepsilon_0=10^{-6}\ m_e c^2$



Confirm analytic estimate: High energy power law; spectral slope β=-2.54

Semi-analytic expression of the spectral slope

Asymptotic expression:

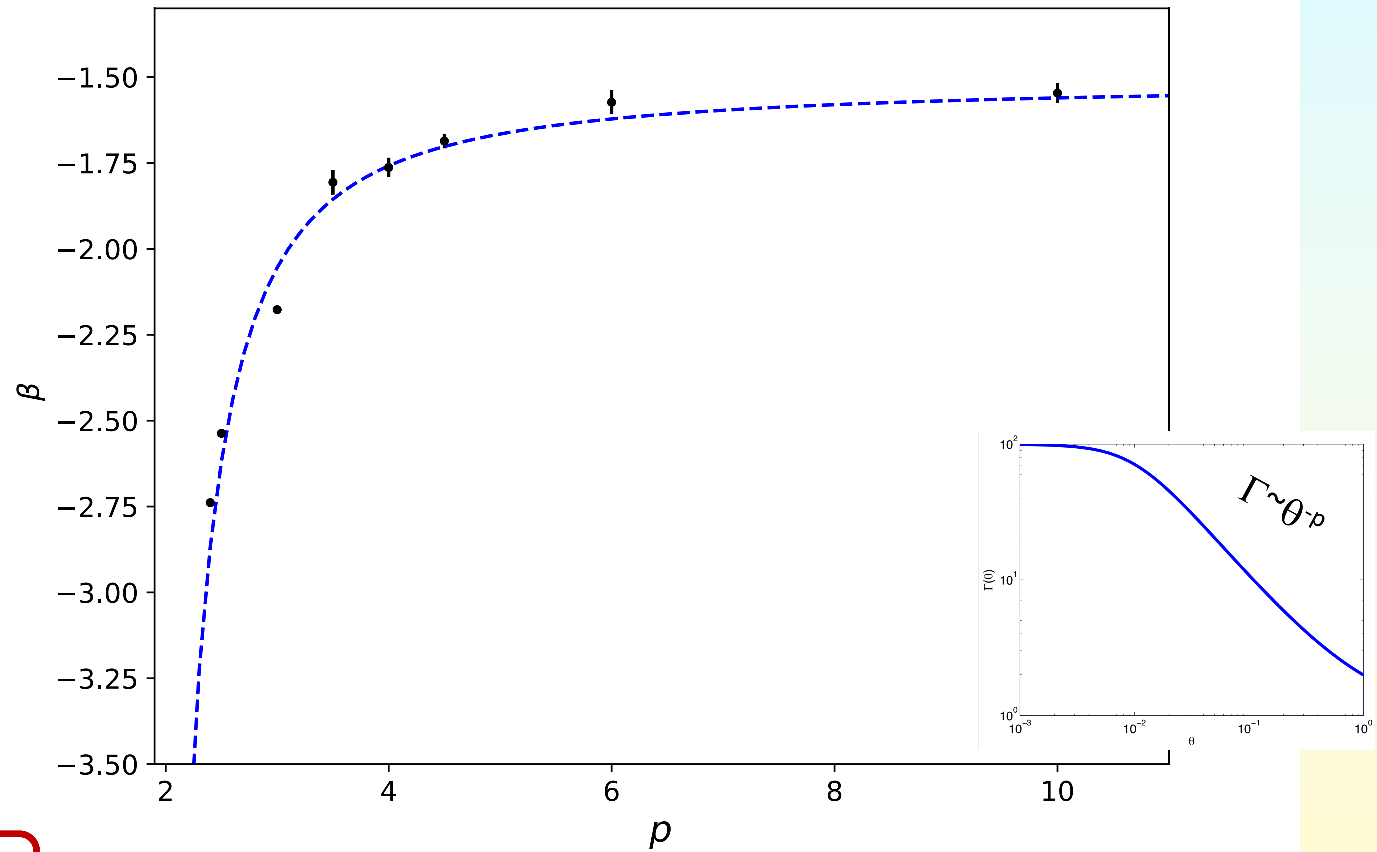
$\tau \ll 1 \rightarrow P(r,\theta) \sim \tau$

$\langle g \rangle \sim p^2$; p = power law

$\langle P \rangle \sim \Gamma_0^{(1/p)} - 1$

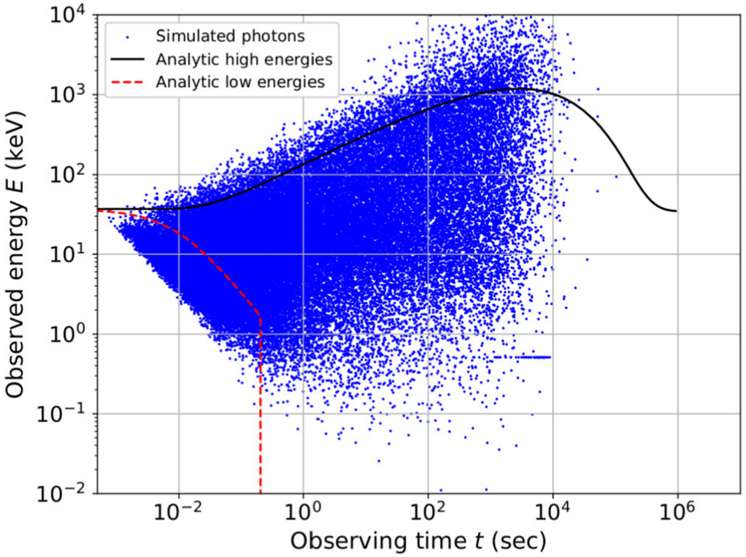
$$\beta = \frac{\ln \bar{P}}{\ln \bar{g}} - 1 \rightarrow -1.5$$

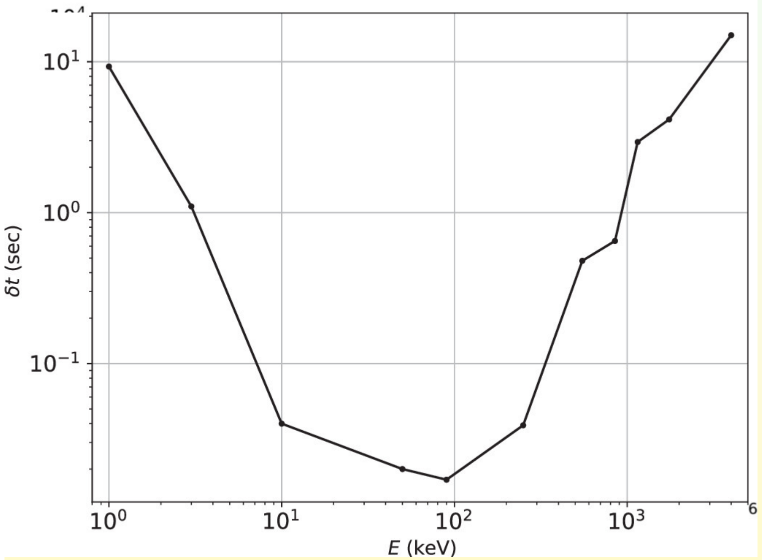
Prediction ! $\beta \le -1.5$

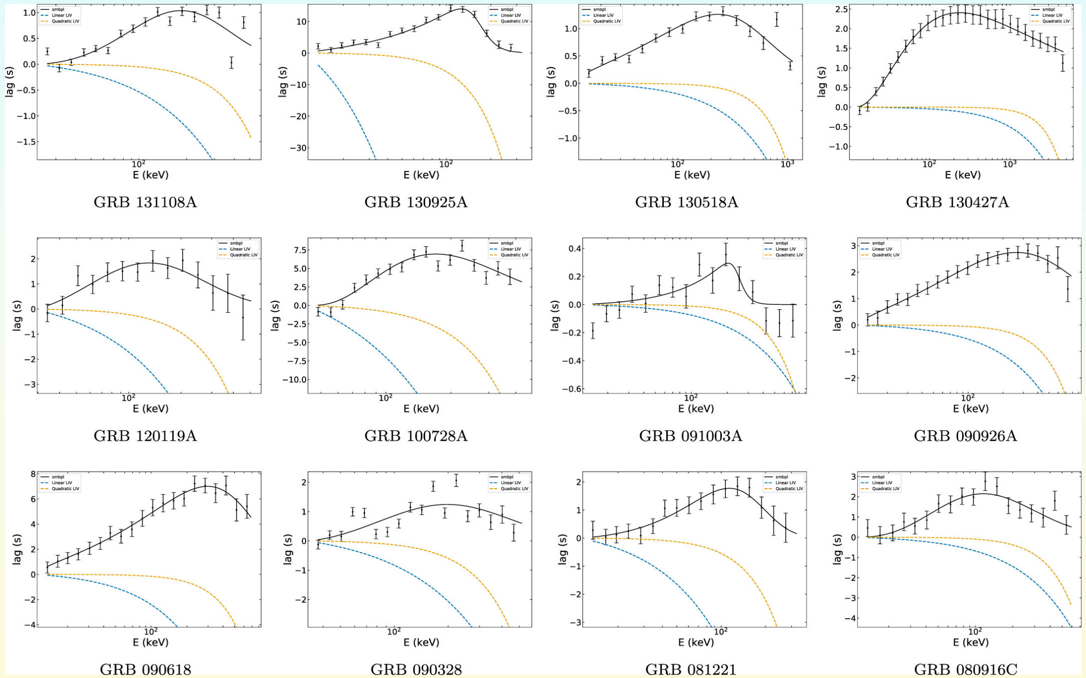


Vyas & Pe'er, 2023

Prediction: energy-dependent spectral lags





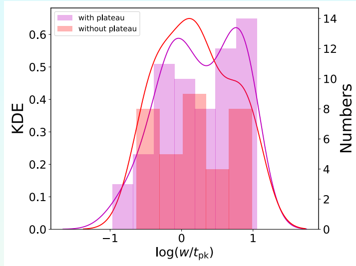


Liu, Zhang, Meng 2022

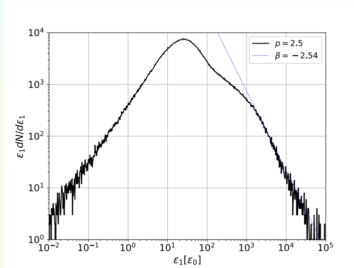
Vyas, AP, Iyyani, Ap.J., 2024

Summary

1) Lorentz factor of many GRBs (but not all) **may be only a few tens,** smaller than what many people think.



2) As a result, photospheric emission may be pronounced



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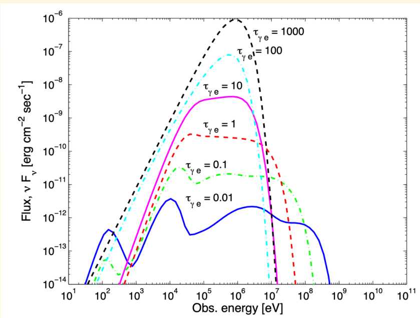
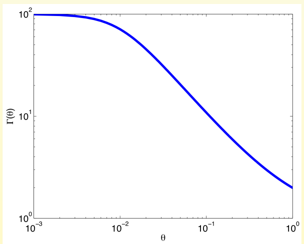
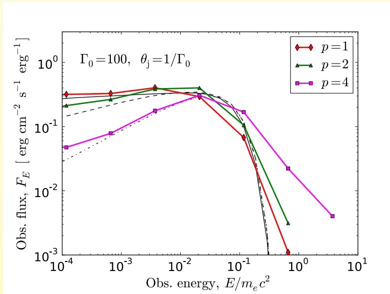
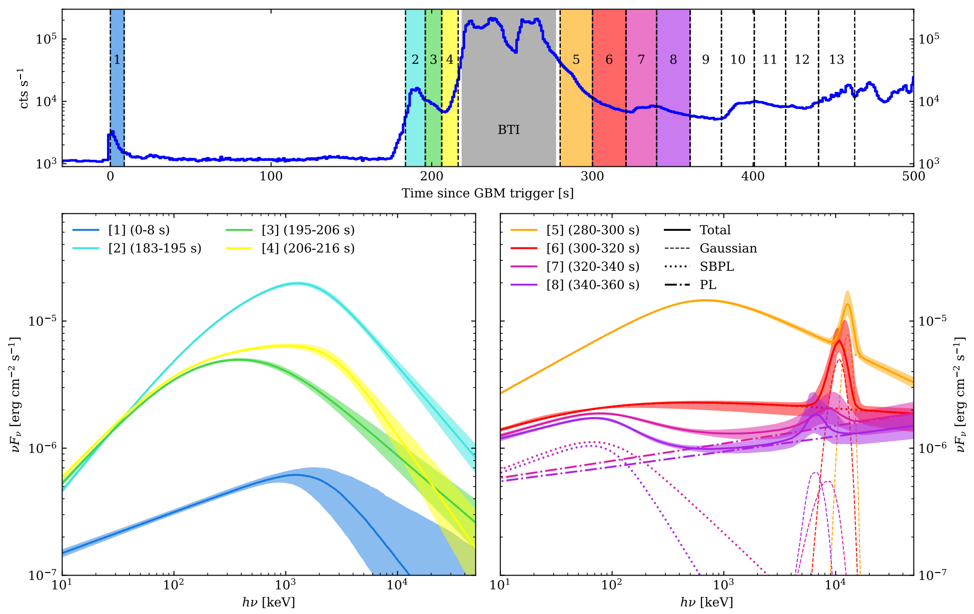
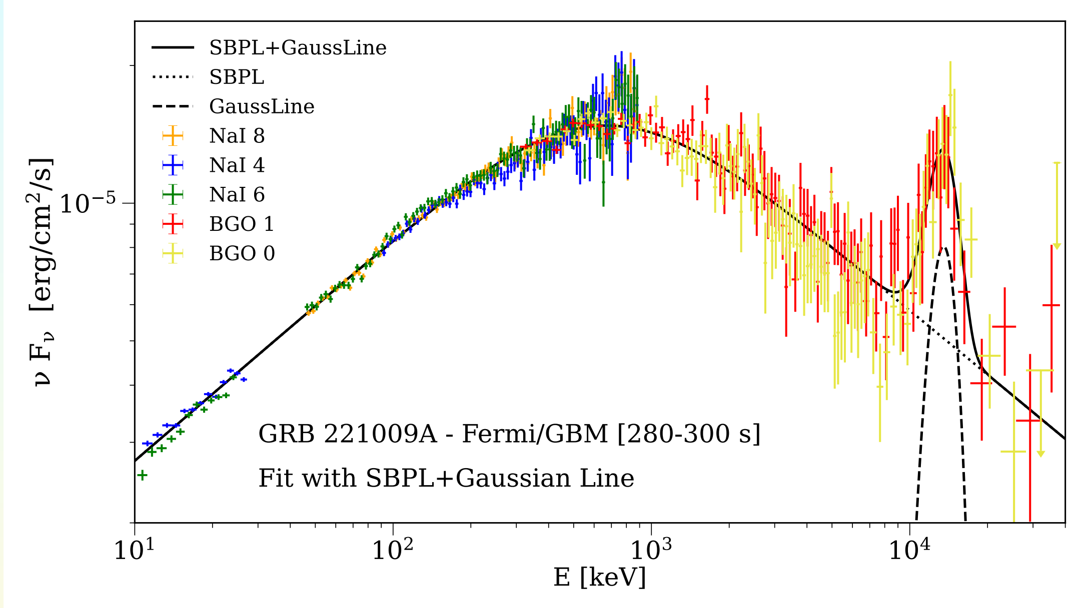






Evidence for pair annihilation line in the BOAT GRB221009A

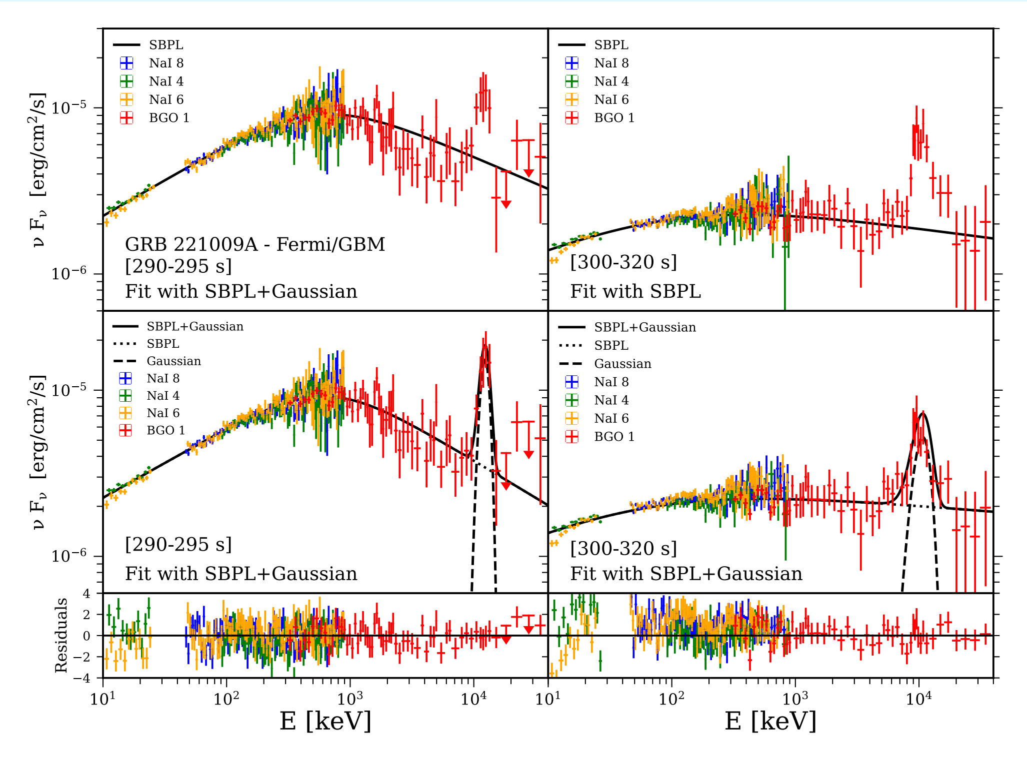




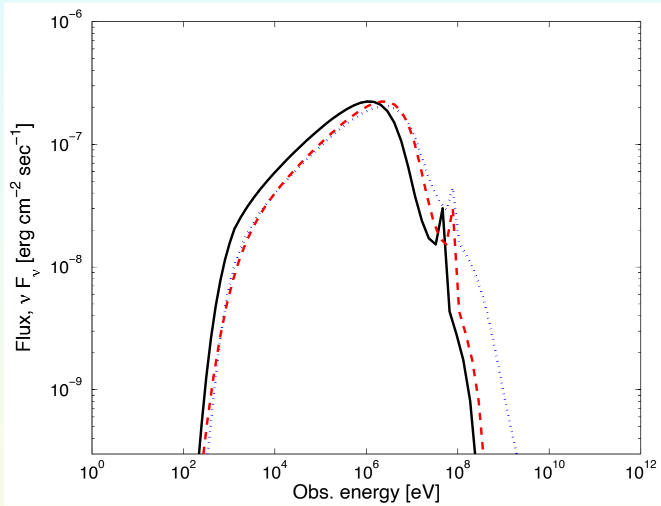
Ravasio et. al. (2023)

GRB 221009A – "brightest of all times" (BOAT) Evidence for pair annihilation line

Narrow, ~10 MeV emission line , detected for ~80 s during the early afterglow phase



Ravasio et. al., 2023

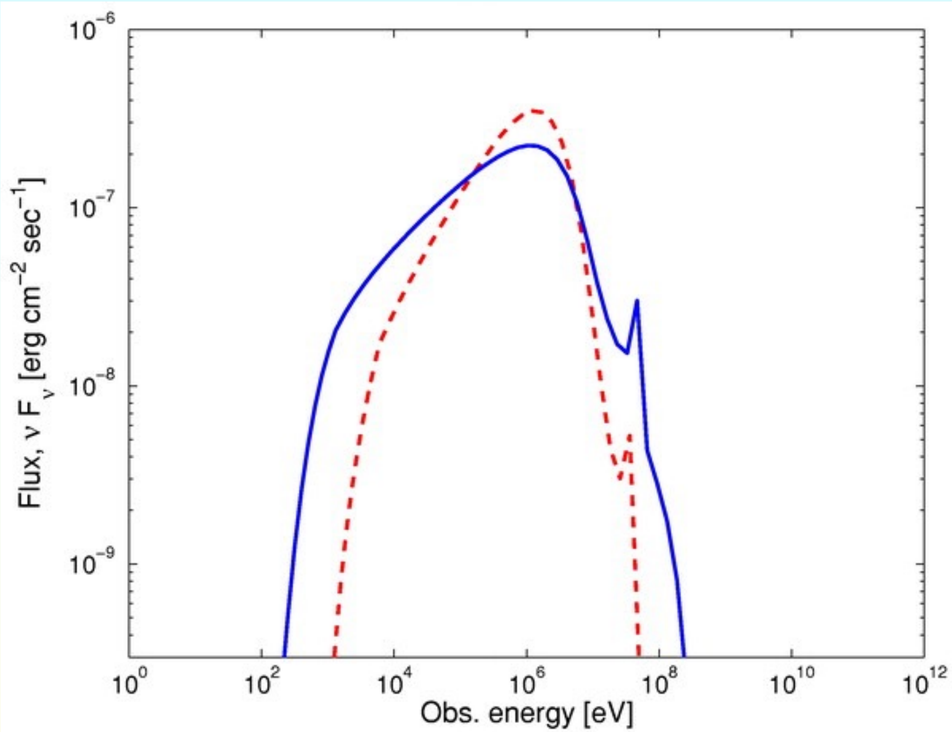


Pe'er & Waxman, 2004

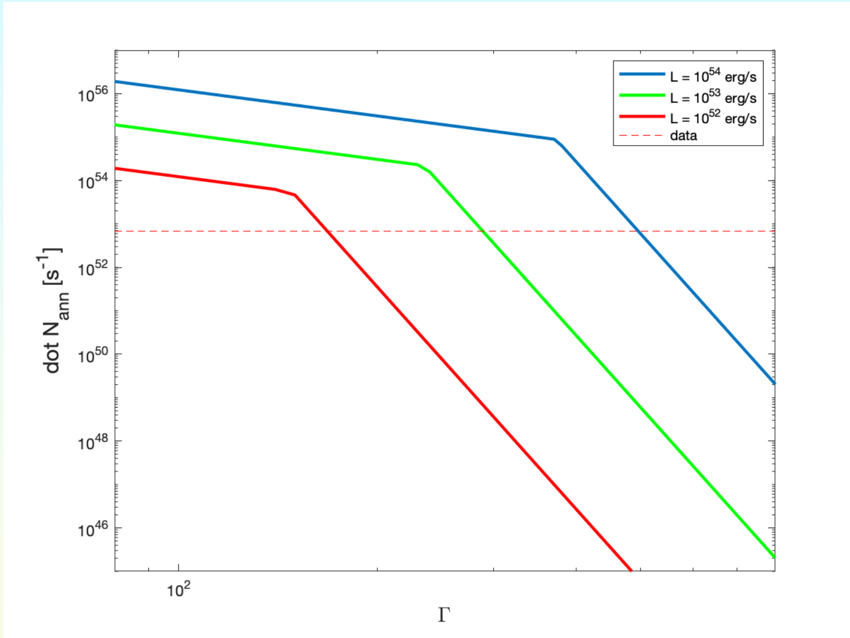
Possible detection of pair annihilation line ?

Consequence: measure of bulk Γ ~ 20 !?

Where was it hiding all these years ?



Pe’er & Waxman, 2004 (!)



Pe’er & Zhang, 2024

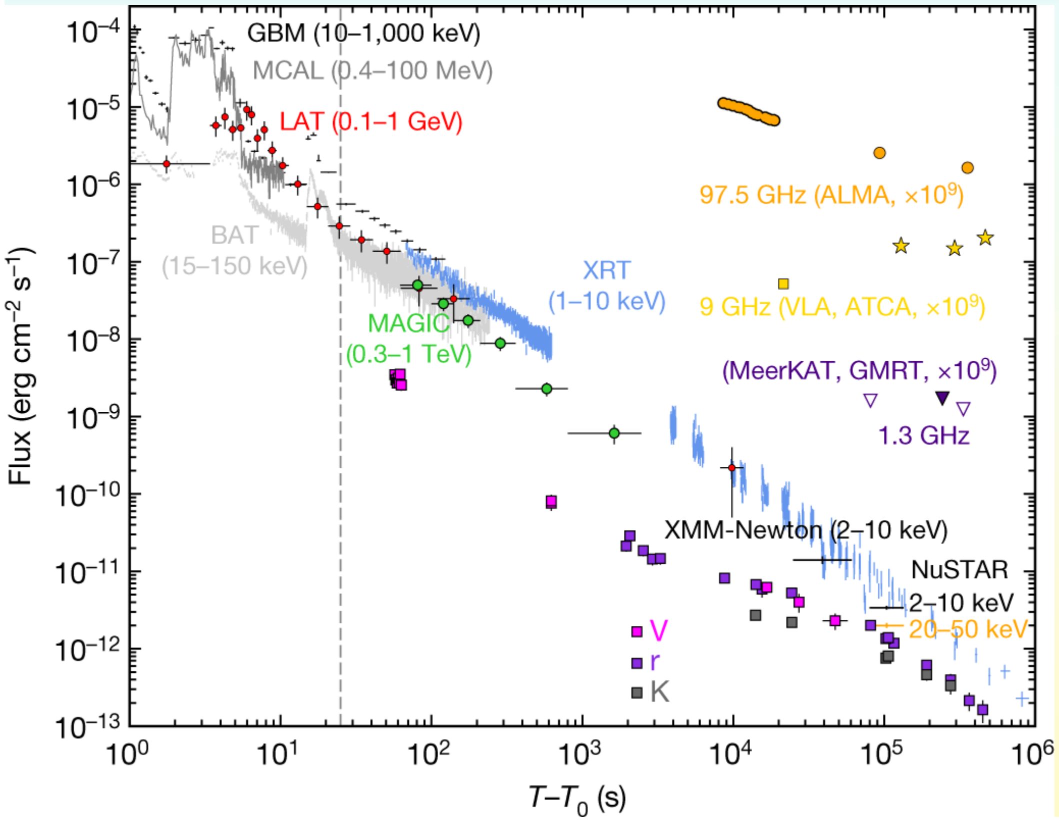
Pair annihilation is expected in a narrow range of parameter space: high L, low Γ

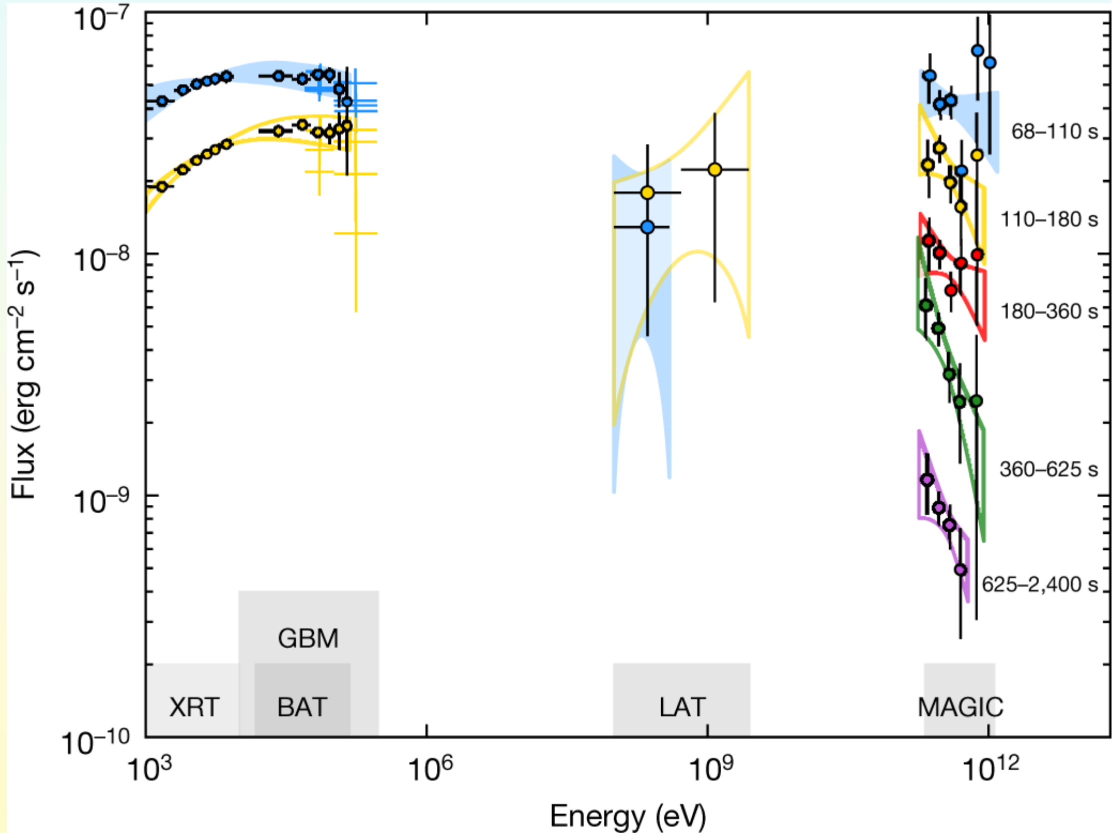
Recent years: available TeV data (and more to come !)

P. Veres et. al. (MAGIC collaboration) 2019

Multi-wavelength light curves of GRB 190114C

Multi-band spectra in the time interval 68–2,400 s.



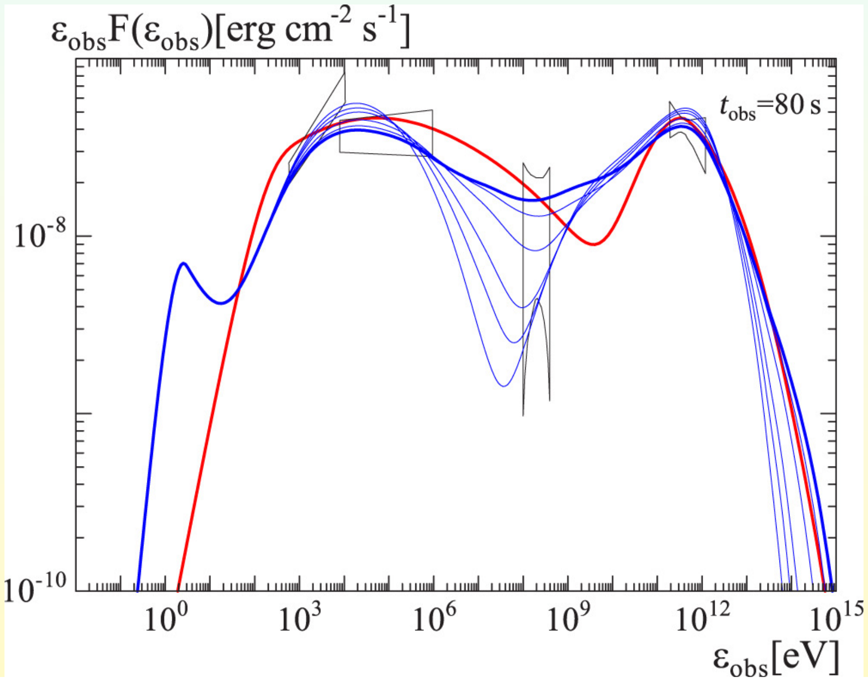


Leptonic model fits (GRB 190114C)- IC

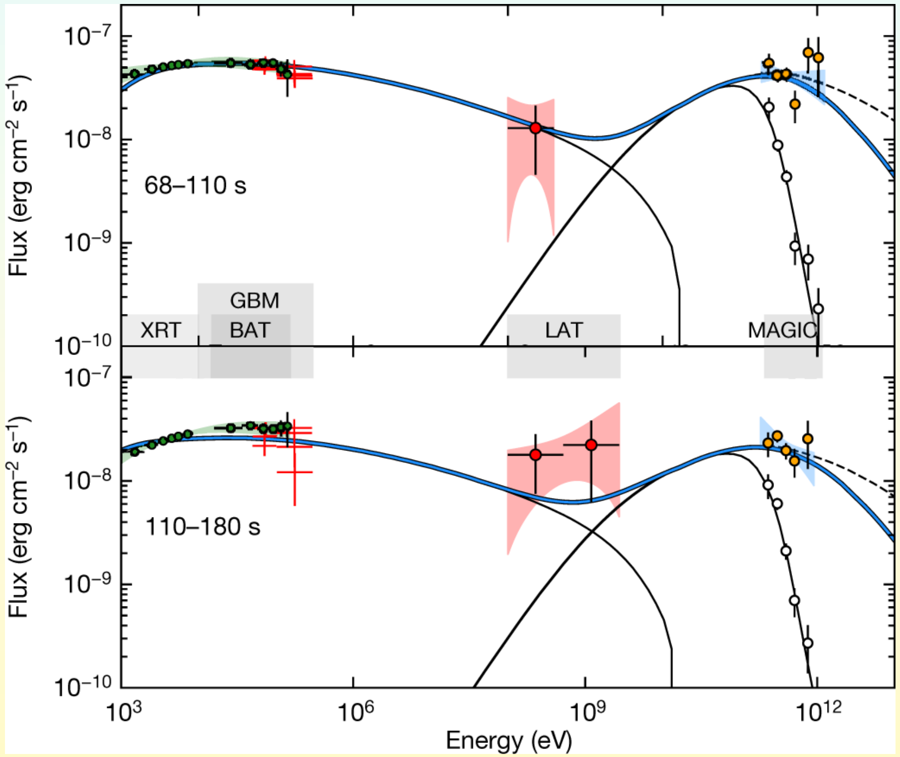
Pros:

- ✓ Natural
- ✓ Minimal freedom
- ✓ Reasonably low energy (compared to proton-synchrotron)
- ✓ Low B-field

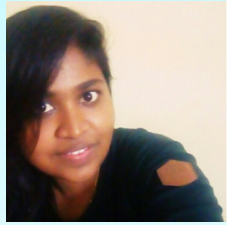
Asano+2020



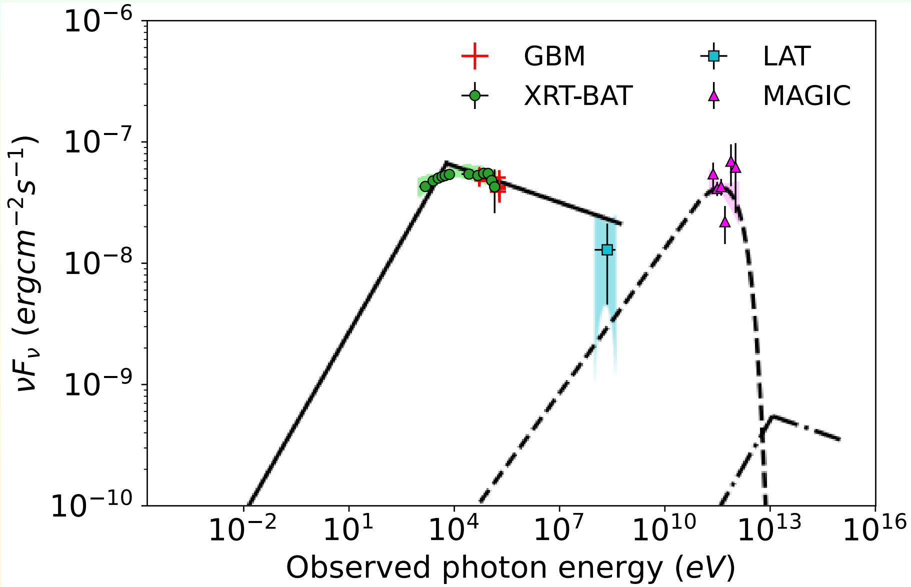
P. Veres et. al. (MAGIC collaboration) 2019



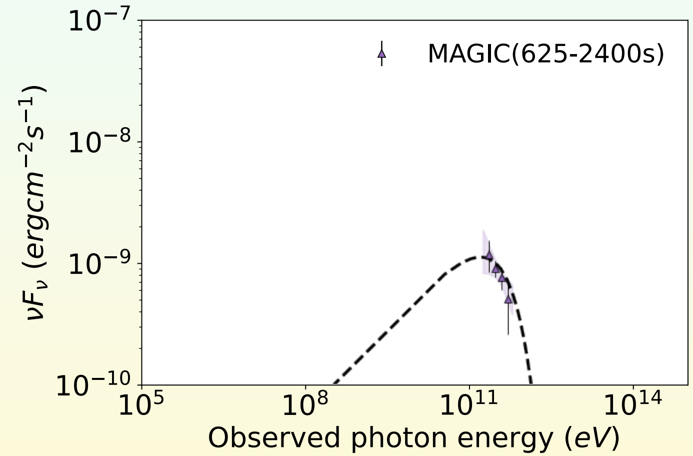
P-synchrotron - ? (GRB 190114C)



- Standard BM76 dynamics
- both electrons and protons are acceleratres by forward shock; → synchrotron. e- slow cooling; p- fast cooling
- (degree of freedom): A fraction ξ_p ~5-20% of protons are accelerated. → $E_{tot, iso}$ ~$10^{54.5}$ erg
- Fit results: $\varepsilon_p = 0.8$, $\varepsilon_e = 0.003$, $\varepsilon_B = 0.13$ (most energy with protons); ξ_p=0.2 (efficiency= E^{ob}/E_{tot} ~5-10%)



t = 90 s



excellent fits to the late time (>~1000's s) broad band spectra

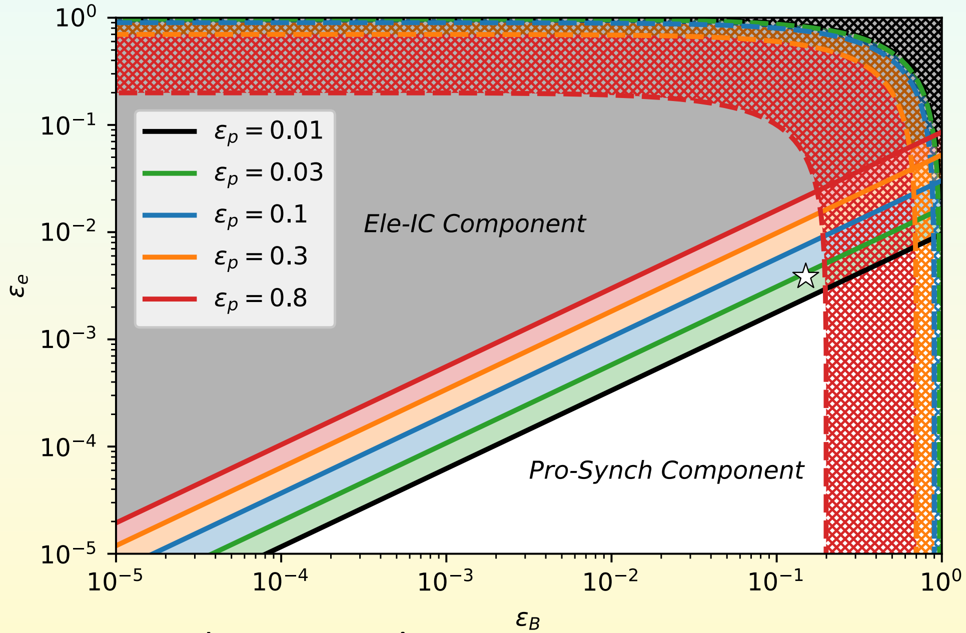
Isravel, Begue, Pe'er, 2023a

P-synchrotron vs. IC

Condition for domination: $\varepsilon_B >> \varepsilon_e$ → P-sync. dominate

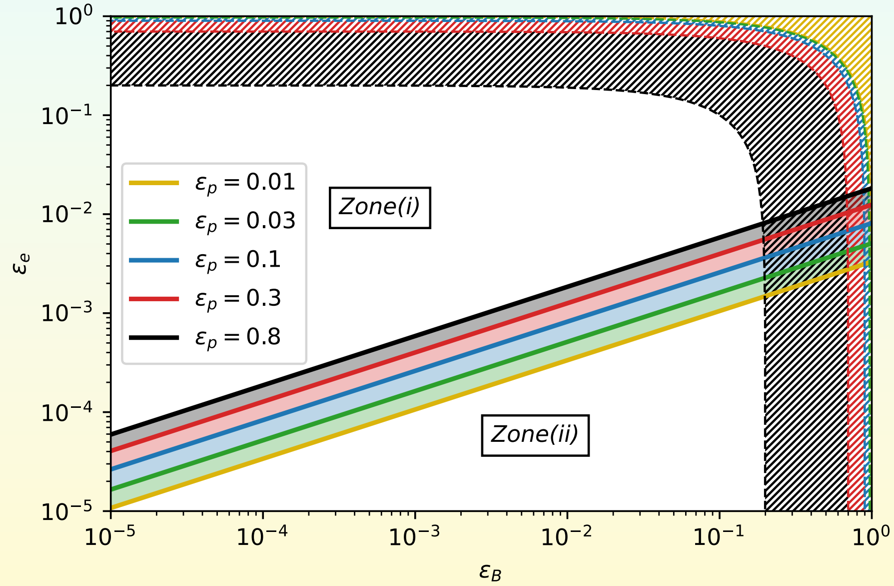
$\varepsilon_B << \varepsilon_e$ → e-IC dominate

GRB190114C



Isravel, Begue, Pe'er, 2023a

GRB221009A



Isravel, Begue, Pe'er, 2023b

Summary

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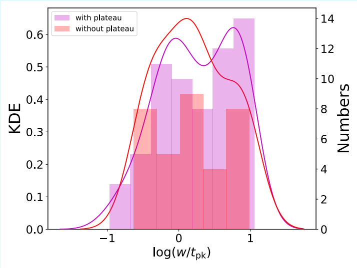
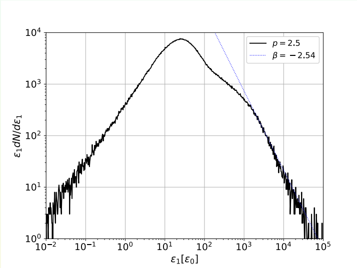


2) As a result, photospheric emission may be pronounced



3) The observed spectra is complex, due to
(i) sub-photospheric energy dissipation;
(ii) structured jet that leads to a new mechanism of photon energy gain

4) (if time permits) – revival of proton-synchrotron, and unique conditions for pair annihilation line in GRB221009A

Summary

❖ **During the prompt phase:**

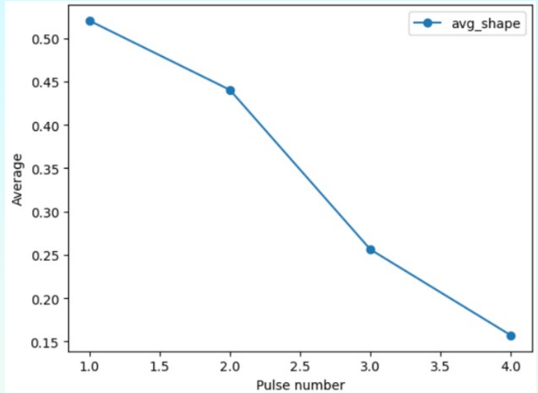
GRB pulses <u>change their shape</u>.

Initial pulses – more symmetric

Later pulses – more FRED-like

Shape correlates with spectra:

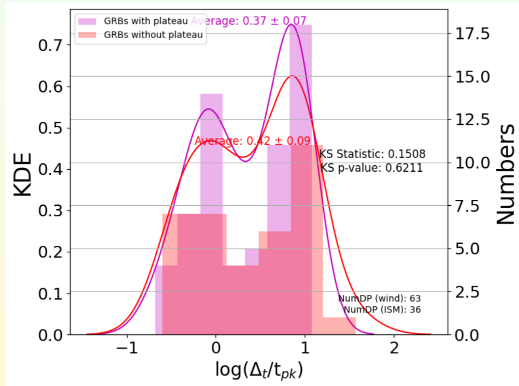
symmetric pulses show steeper slopes



Interpretation: change of radiative mechanism: thermal → synchrotron

❖ **During the early afterglow phase:**

Flares show <u>similar behaviour</u> for GRBs with/ without plateau



→ Strong indication for low Lorentz factor in GRBs with plateau

Many GRB Lorentz factors may be lower than 100 !

Asaf.peer@biu.ac.il

Anil, AP, Ryde, Dereli-Begue, In prep.

Dereli-Begue, AP, Ryde, in prep.