Bar-Ilan University
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The structure of relativistic jets and their magnetic fields

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Relativistic Fluids around Compact Objects

Summary

1) Relativistic jets are (i) ubiquitous; (ii) fragmented; (iii) filled with radiators; (iv) structured

2) Two leading models for jet formation:
   (i) BZ→ Pointing-dominated → need to entrain the jet with material
   (ii) Collapsar → neutrino/ photon dominated (better align with fits).
   Numerical studies lack crucial physics

3) Energy dissipation: internal shocks (efficiency), magnetic reconnection.

4) Photosphere: (i) solves efficiency issue; (ii) photon energy gain by repeated scattering; (iii) polarization

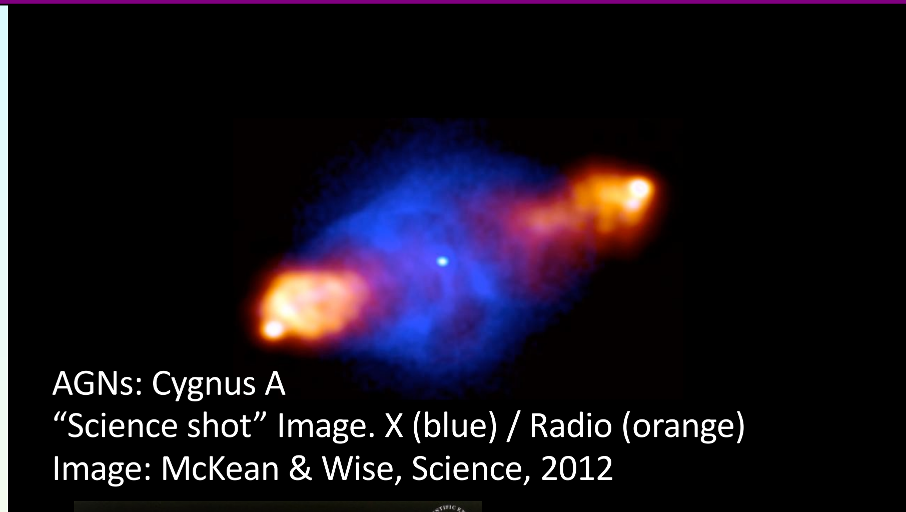
5) Flat radio spectrum in AGNs/XRBs can be obtained from a Maxwellian

What do we know about astrophysics Jets ?

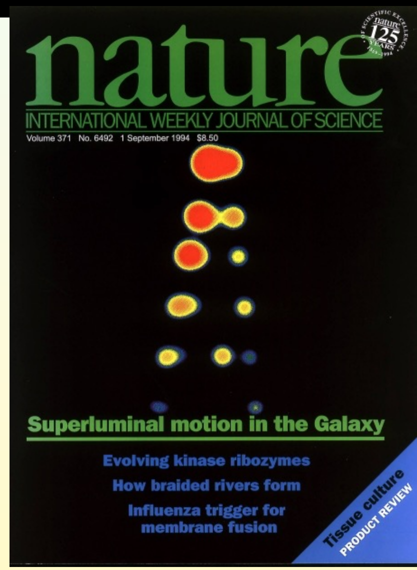
- Jets are observed in a wide range of accreting systems

- Active galactic nuclei (AGNs):
  $M \sim 10^6 - 10^9\ M_\odot$
  X-Ray binaries (XRBs), GRBs:
  $M \sim 10\ M_\odot$

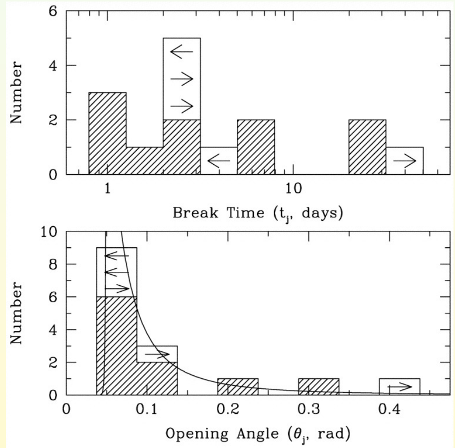
- Evidence for jets in non-BH systems



AGNs: Cygnus A
“Science shot” Image. X (blue) / Radio (orange)
Image: McKean & Wise, Science, 2012



XRBs: GRS 1915+105
Mirabel & Rodriguez, 1994



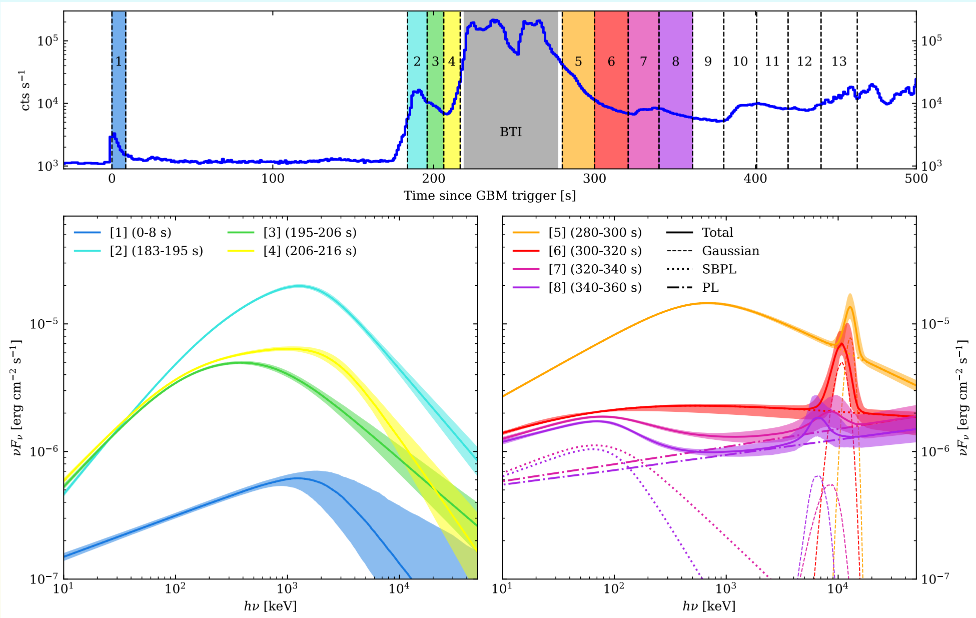
GRBs (indirect)
Frail et. al., 2001

1. Jets are ubiquitious
2. They can be (likely) fragmented

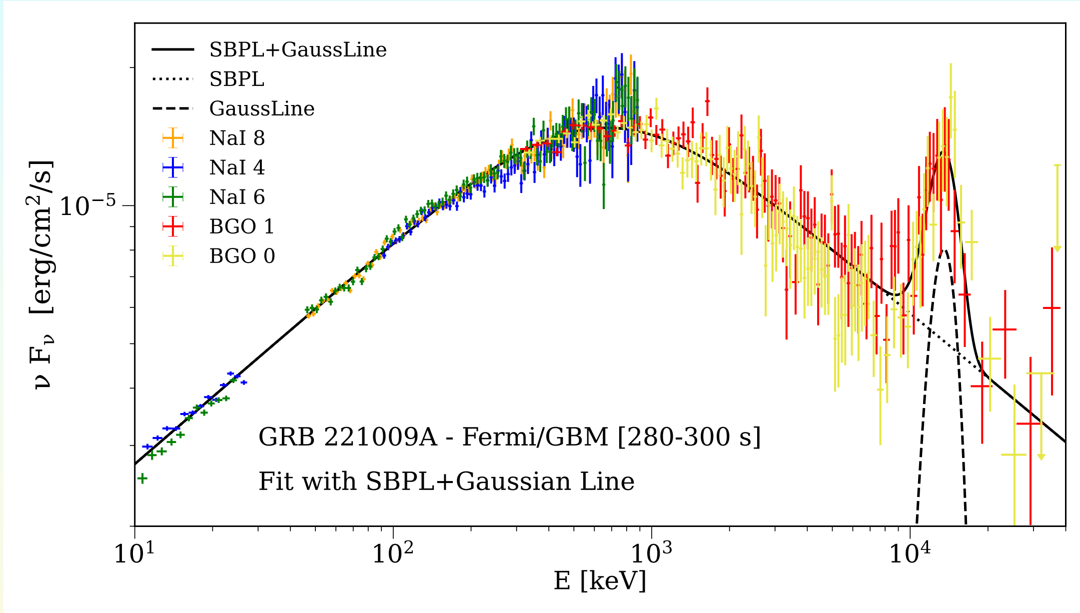
What do we know about astrophysics Jets ?

Evidence for pair annihilation line in the BOAT GRB221009A

Max fluence = 0.21 +- 0.02 erg / cm^2 → $E_{iso} > 10^{55}$ erg (in γ-rays !)



Burns + 2023; Lesage+23; Ravasio et. al. (2024)



Pe'er & Zhang, 2024

Opacity argument: $\gamma\gamma$→ $e^{\pm}$ (GeV) [LAT] photons necessitate Γ>100

Krolik & Pier 1991, Fenimore+93, Woods & Loeb 1995…

$$\Gamma = E/Mc^2$$

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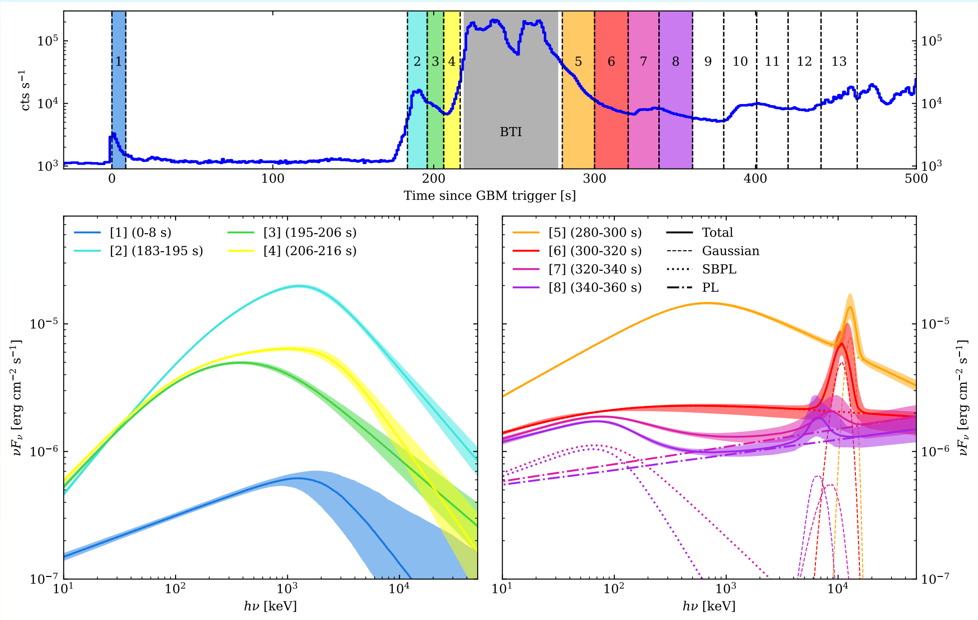

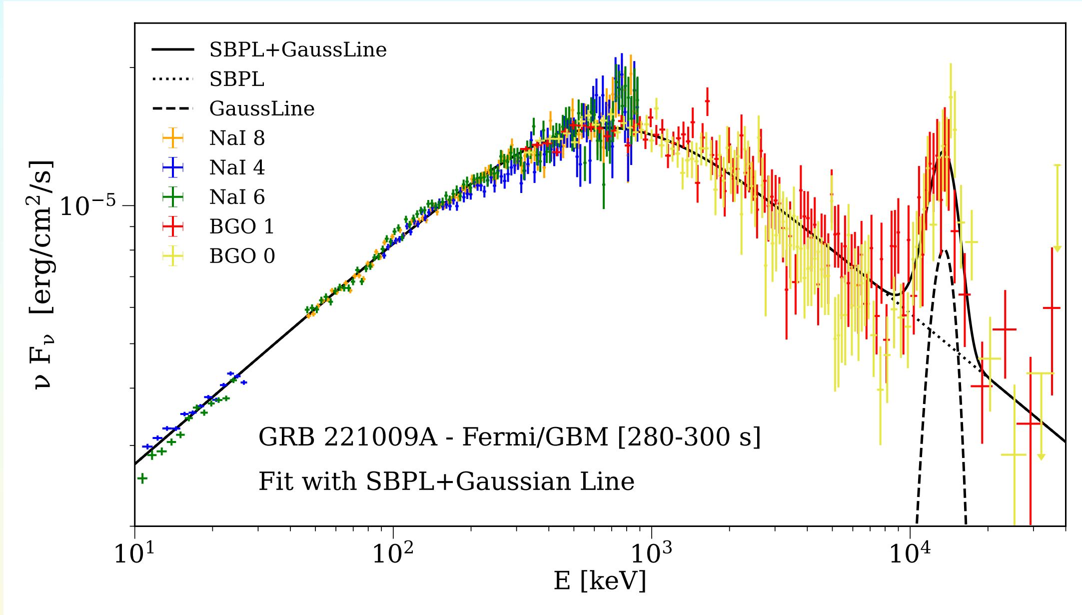

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Opacity argument: $\gamma\gamma$→ e$^\pm$ (GeV) [LAT] photons necessitate ~~Γ >100~~

$$D = \frac{1}{\Gamma(1-\beta\cos\theta)} > 100$$

Krolik & Pier 1991, Fenimore+93, Woods & Loeb 1995…

Γ=E/Mc^2

3. Jets are filled with radiators (GRBs)
4. Velocity direction θ~1/Γ

Chercher l'énergie

Source of energy

Grav. accretion: (i) collapse; (ii) merger – VS – BH rotation

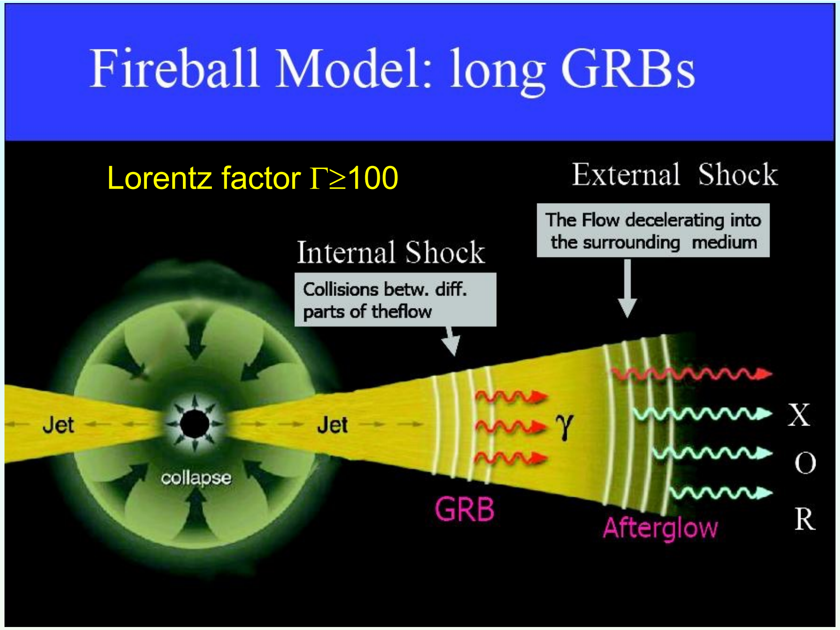
Magnetic energy (GRB?)

Kinetic energy (jet)
At relativistic speeds

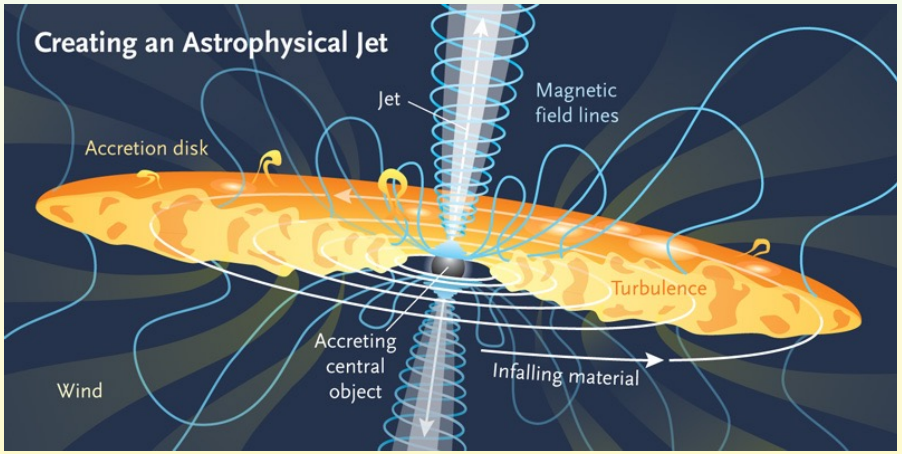
Dissipation / reconnection→
heating / accelerating particles

Observed radiative signal
(temporal, spectral, polarization)

Additional, non-EM signals:
cosmic rays, ν's, GWs



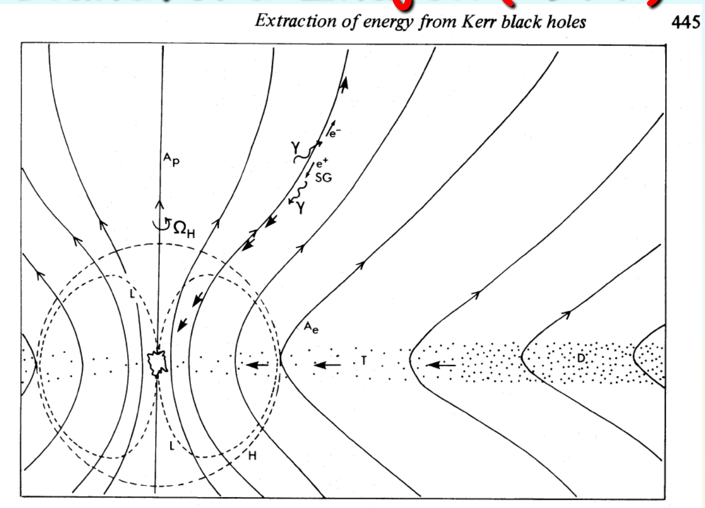
Rees & Meszaros, 1992,1994, 2001



J. McKinney / Sky & Telescope (Apr 2010)

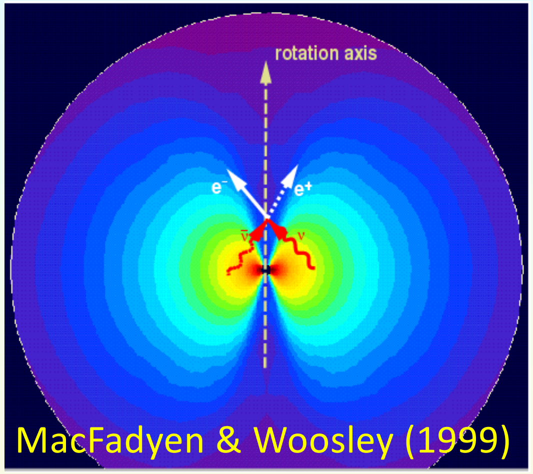
Jet production: two leading models

AGNs, XRBs: Blandford-Znajek (1977)



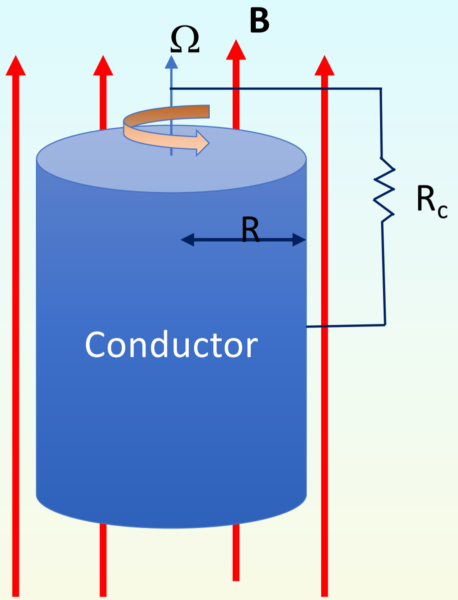
- B-field lines confined by disk
- BH rotation → helical magnetic springs; expand by self-pressure → accelerate plasma
- ⇒BH rotation energy converted into jet (strongly depends on disk state & configuration of B-field)

GRB's: Collapsar (?) (Woosley 1993) Mergers (Eichler+1989)



- Collapse of massive (~30 $M_{\odot}$ WR), rotating star
- Viscous accretion → strong heating
- Thermal νν-annihilating $\nu + \bar{\nu} \rightarrow e^{+} + e^{-}$ (preferentially around the axis) ⇒ formation of a relativistic jet

Blandford & Znajek mechanism: classical analogue rotating conductor in magnetic field



Lorentz force $F = q(r\Omega \times B)$

Voltage $V = \int_0^R d\rho \rho \Omega B = \frac{1}{2} \Omega B\, R^2 = \frac{\Omega \Phi_B}{2\pi}$

$$Power = \frac{V^2}{4R_c} = \frac{\Omega^2 \Phi_B^2}{16\pi^2 R_c}$$

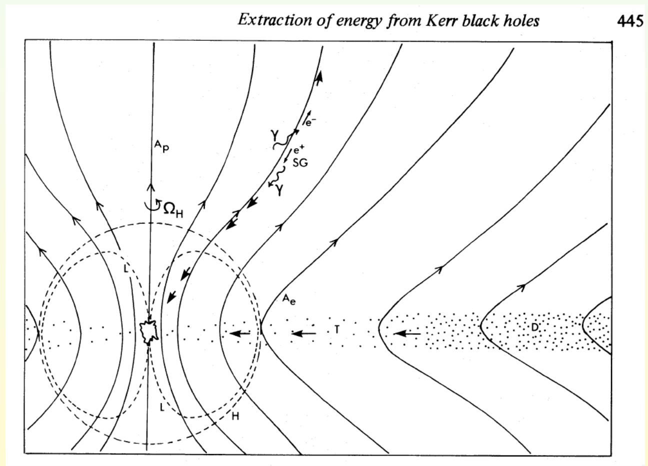
Rotating BH:

B- field lines: attached to the disk

Resistivity: inpedance of free space

Voltage: $\Omega B\, R^2$ ~10^{20} Volts for 10^9 $M_\odot$

→ Accelerate electrons, produce a $e^\pm$ pair cascade (electric circuit)



Consequence: no charged BH in nature

Numerical simulations: accretion disks & jets

- Early 2000's: GRMHD codes

  Koide, Komissarov, De Villiers, Hawley, Gammie, McKinney, Noble, Fragile, Tchekhovskoy, Porth, Shibata, Del Zanna, Zachariah, Shapiro…

  2003: **HARM** (*Gammie*+)

- Many important applications to relativistic jets

- 2014: Radiative-MHD (GR**R**MHD)

  Oshuga: Radiative-MHD (pseudo-Newtonian disks)

  KORAL (Sadowski), HARMRAD (McKinney), Heroic (Narayan+), INAZUMA (Asahina & Ohsuga)

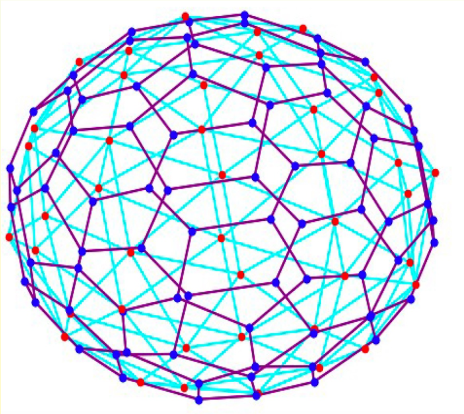
- In parallel: radiative transfer codes (Astroray, GRMONTY (2009), BHLight, GRTrans, CARTOON…)

- 2017: Use of GPU, AMR (Chandra+, Liska+, **Begue, Pe'er et. al., 2023**)
  -Applications to M87

cuHARM: why a new code ?

✓Independently developed:
- ✓ Well understood
- ✓ Easy to modify
- ✓ Highly optimized

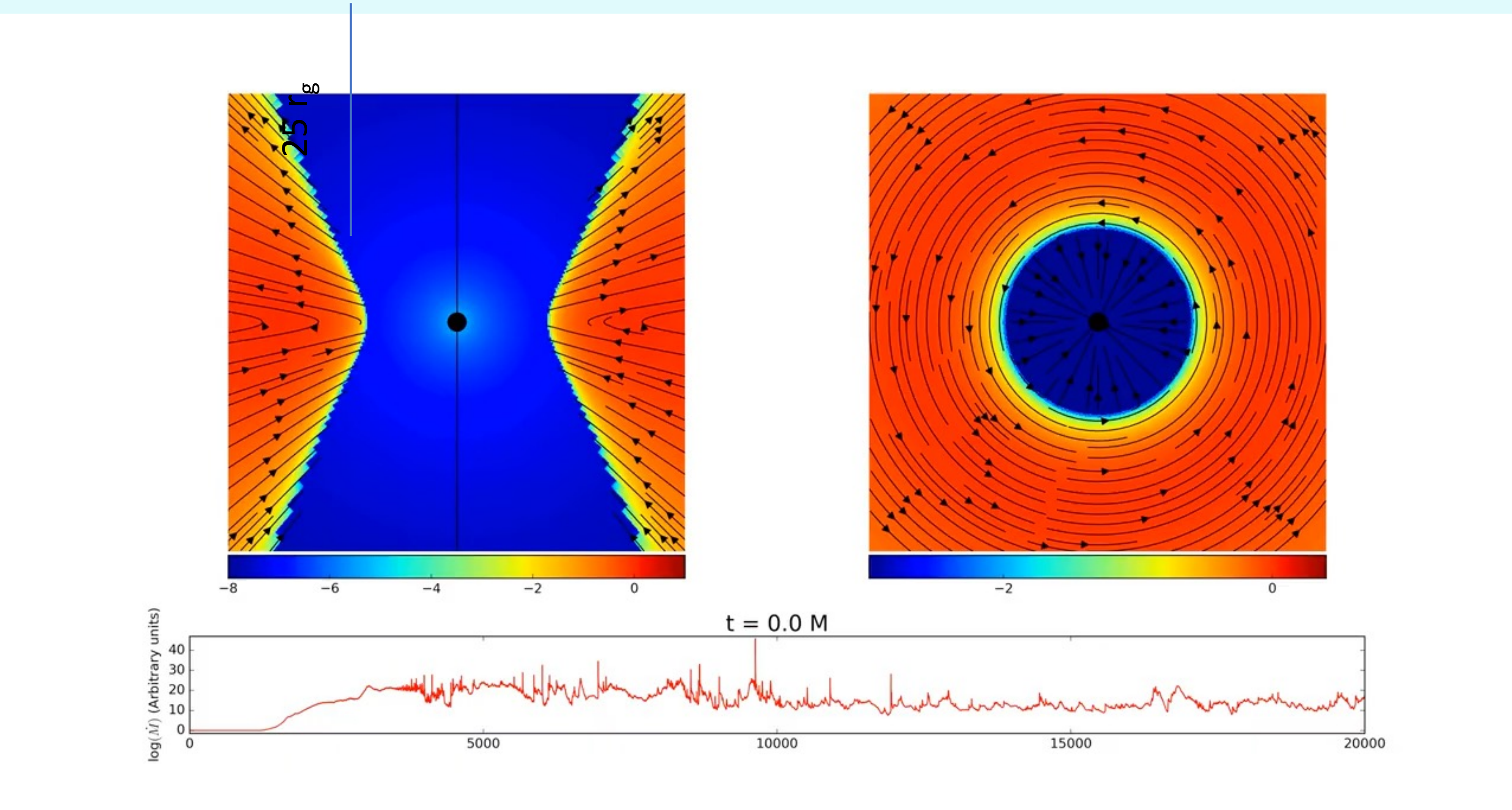
✓Additional physical ingredients:
- Radiation (currently under construction)
- Unconstrained mesh at the pole:
enables accurate calculations of jets –
high resolution without time step reduction.
(future construction)



Bégué, Pe’er et. al., 2023 Zhang, Bégué, Pe’er & Zhang., 2024

Disk and jet evolution (MAD) – using cuHARM

Highly optimized: > 2* 10^8 cells update /s on H100



256 *128*128

$$\beta_0 = \frac{p_g}{p_b} = \frac{2p_g}{B^2} = 100$$

$$\frac{E_B}{M} = 2 \times 10^{-5}$$

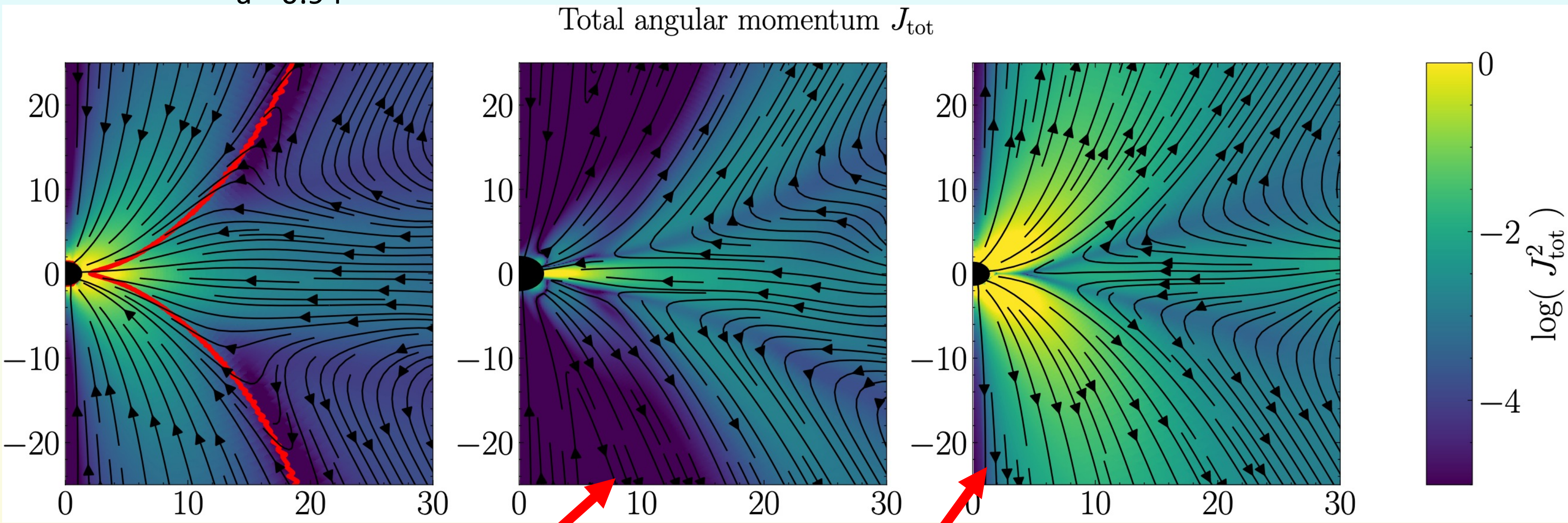
Bégué, Pe'er et. al., 2023 Zhang, Bégué, Pe'er & Zhang., 2024

Angular momentum flux

$$j^i_{total}(r,\theta) = \langle T^i_\phi \rangle_{\phi,t}$$

$$j^i_{total}(r,\theta) = j^i_{stress}(r,\theta)[Maxwell + Reynolds] + j^i_{adv}(r,\theta)$$

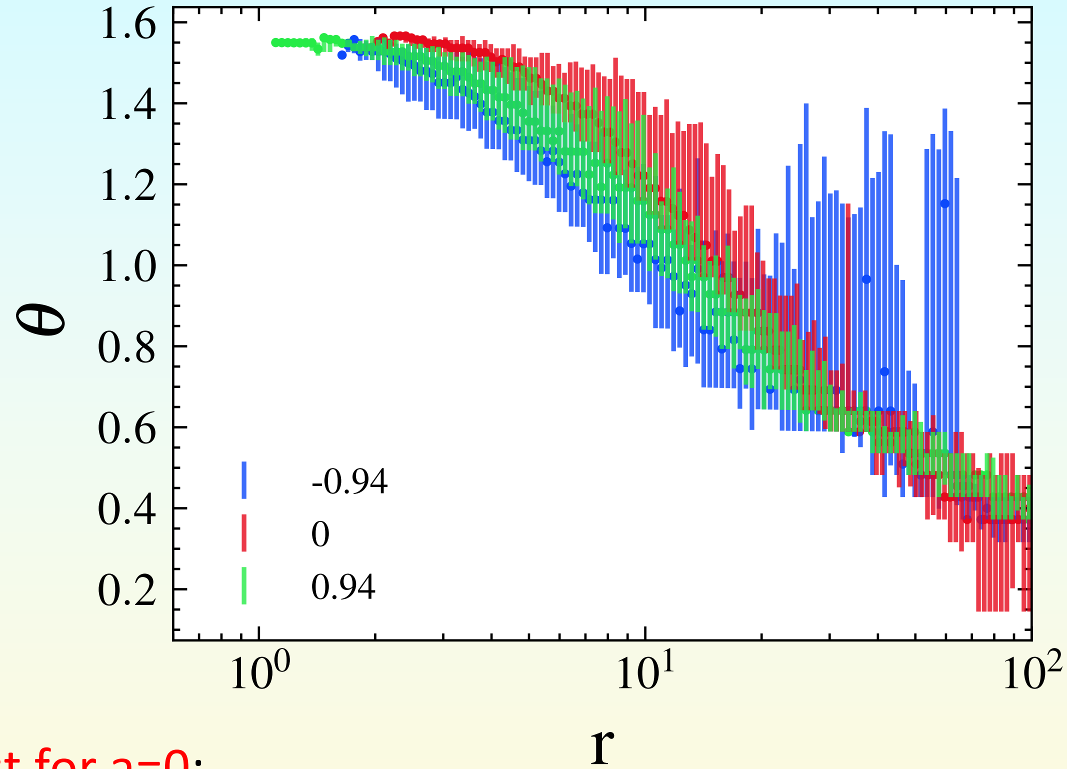
a=-0.94 a=0 a=+0.94

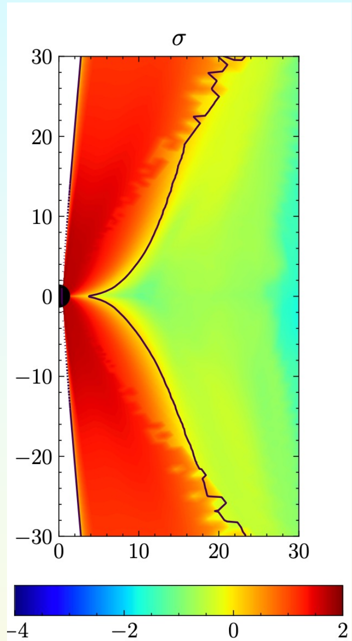


Non rotation BH:
disk angular momentum
transported by MRI (disk) + wind

<u>Rotating BH:</u>
BH angular momentum is transported to
infinity in the form of Maxwell stress in the jet
large ang. momentum transport by wind

Jet structure (MAD)





- Jet is widest for a=0;
- prograde disks produce wider jets than retrograde (<20 r_g); retrogrades are wider for r>20r_g
- Retrograde disks produce highly variable jets

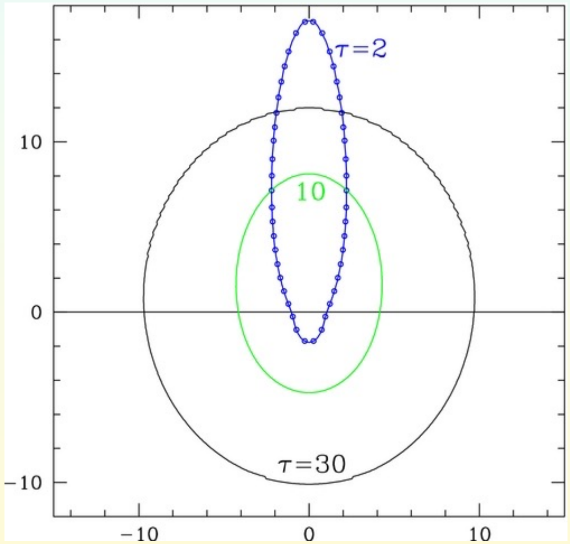
-BUT -
plenty of missing physics

GRMHD: limitations

- **Plenty of missing physics**: neutrino, photons, heavier elements….
- Rad. Transfer – highly degenerated; often limited to thermal, rad. angular distribution is not resolved.
- Most popular schemes (closure schemes) can't handle intermediate optical depths
- Rad. Cooling is not always physical ("target h/r")
- Unknown initial conditions: often "merge" (remapping) simulations
- Emerging jets are always pointing-flux dominated:
  - flooring (numerical)
  - where is material entrained into the jet ?
  - magnetic energy dissipated (requires non-ideal MHD) ?
- Faraday rotation measurements at large radii: helical B-fields, sub-dominant in simulations

GR-R-MHD vs. rad. transfer

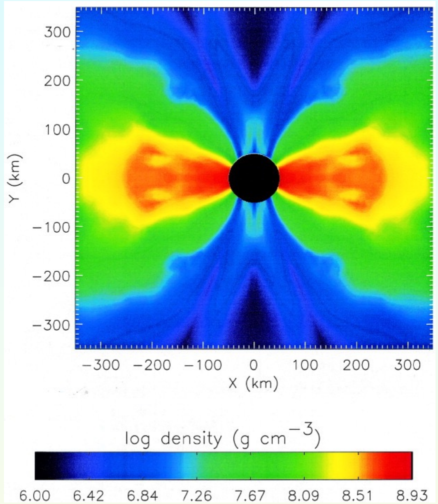
- GRRMHD: (e.g., HARMRAD, HAMR)
  Add rad. stress-energy tensor → incorporate rad. In the dynamics.
  integrate over (θ,ϕ,ν) → Moments of rad. transfer
  Need to close the set of equations; various schemes, most popular – "M1" (alternative: flux-limited diffusion, FLD).
- **Advantage of M1** (minimum entropy): **correct answer for $\tau \rightarrow \infty$, $\tau \rightarrow 0$**
- **Disadvantages:**
  not clear it is accurate for any τ;
  requires the existence of a frame in which rad. is isotropic
  - does not exist in jets !
  - Thermal distribution.
  - not good for neutrino transport
- **cuHARM- see talk by Begue**
- Ray tracing codes- (e.g., GRMONTY – MC):
  Full GR (Kerr metric): integrate along geodesics.
  Broad-band spectrum, temporal variability
- **Disadvantages:**
  Optically thin plasma
  "Stand alone"
  (most schemes) assume thermal dist. of particles for absorption



Beloborodov 2011

Collapsar: jet inside collapsing star

Woosley, 93; MacFadyen & Woosley, 1999, Popham+99, Hager, Zhang, …

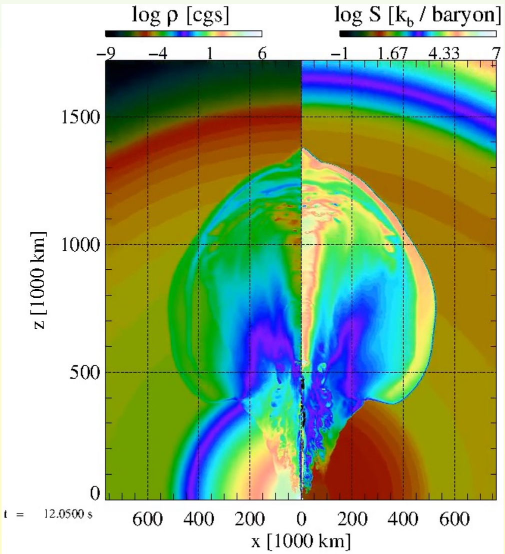


MacFadyen & Woosley, 1999

Two requirements:

• Core collapse produces a black hole - either promptly or very shortly thereafter.

• Sufficient angular momentum exists to form a disk outside the black hole (this virtually guarantees that the hole is a Kerr hole)



Aloy+15

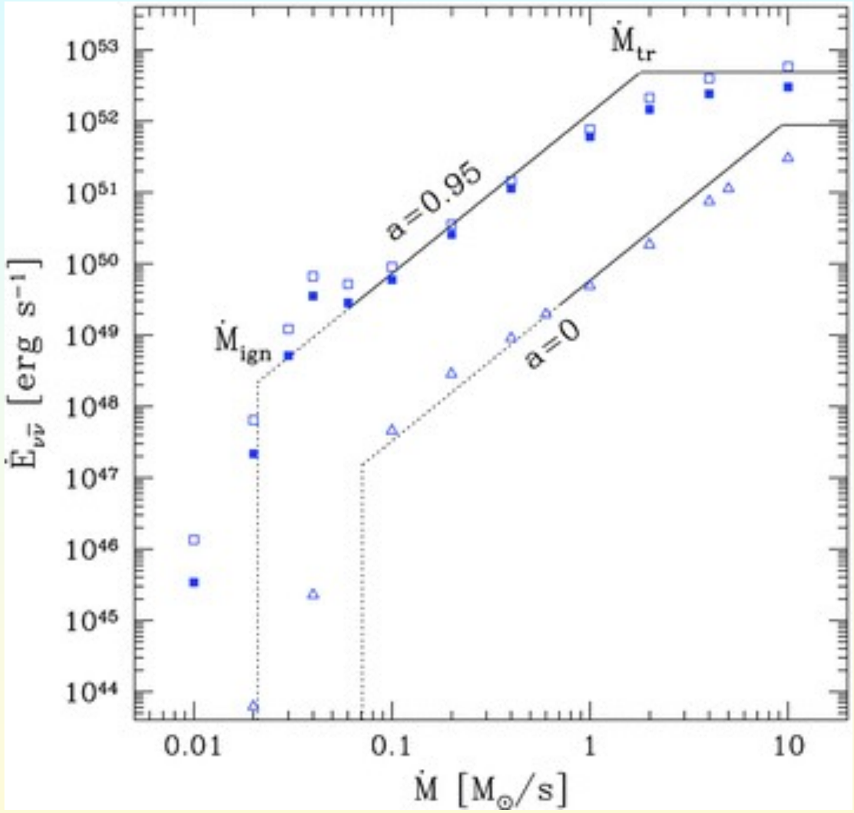
• Many (Rel-MHD) models of jets propagation inside collapsing star (Aloy, Lazatti, Zhang, Mizuta, ..)

•Dynamics: **shaped by topology & strength of B-field; jets are highly variable.**

Rad. + neutrinos play a key role…

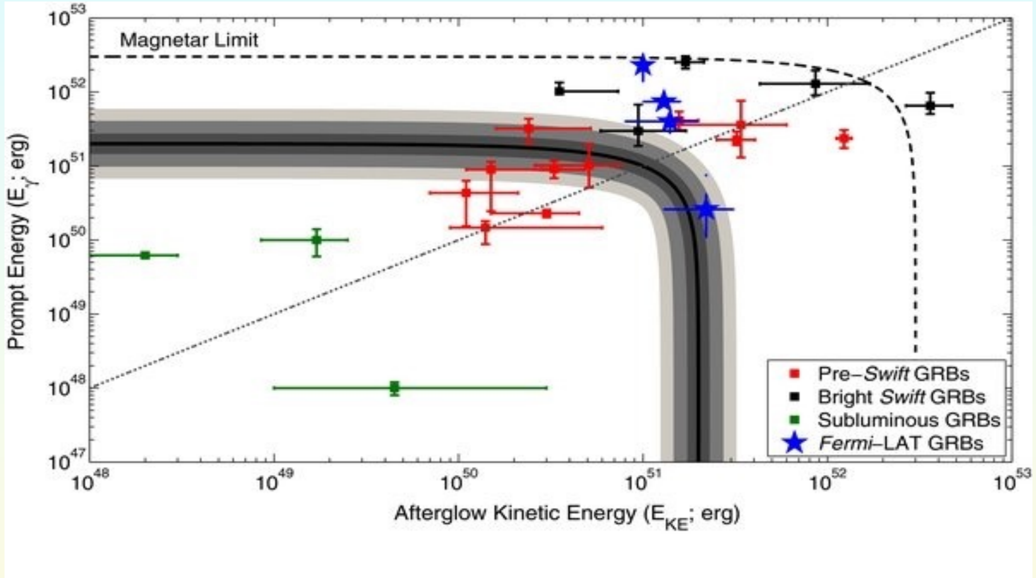
BUT - Initial conditions – put by hand

Neutrino contribution



Zalamea & Beloborodov, 2011

cenko+11



In most GRBs (16/22~70%), $L_{prompt} > L_{AG}$

In hyper accretion disks, neutrino contribution >~10^{52} erg/s

Chercher l'énergie

Source of energy

Grav. accretion: (i) collapse; (ii) merger – VS – BH rotation

Magnetic energy (GRB?)

Kinetic energy (jet)
At relativistic speeds

Dissipation / reconnection→
heating / accelerating particles

Observed radiative signal
(temporal, spectral, polarization)

Additional, non-EM signals:
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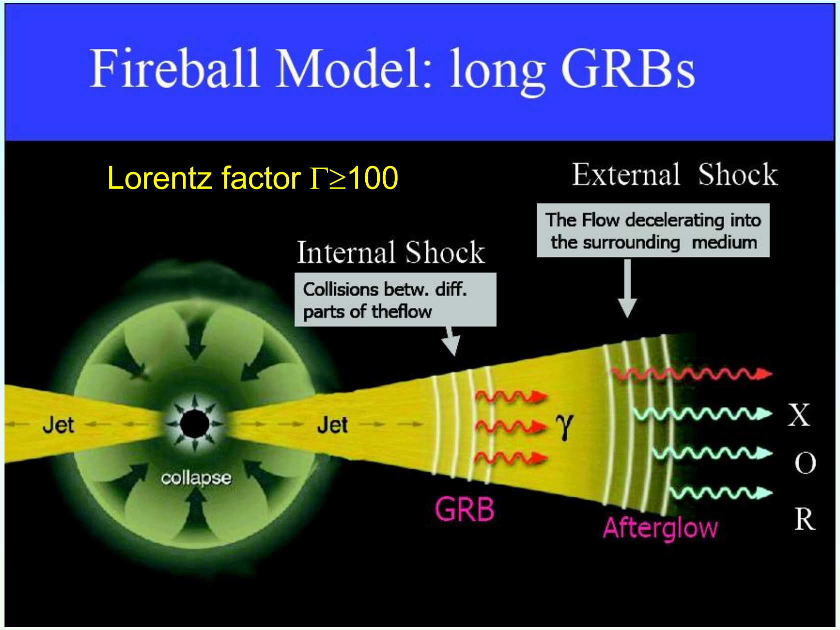
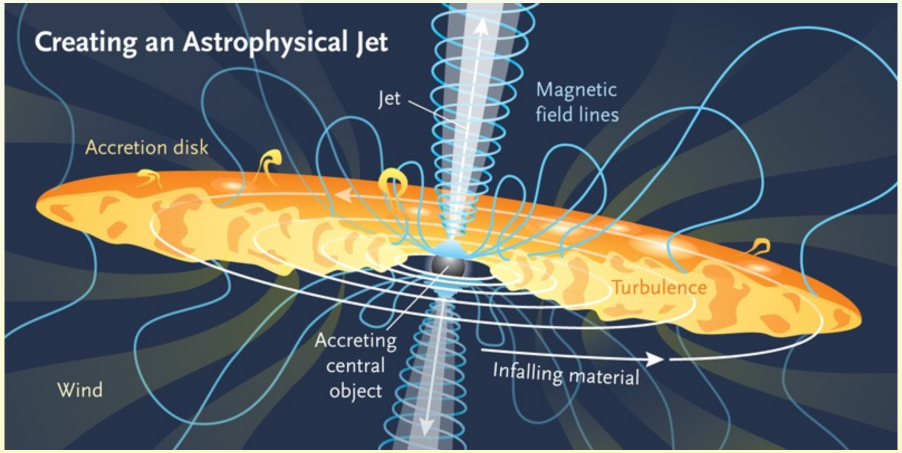


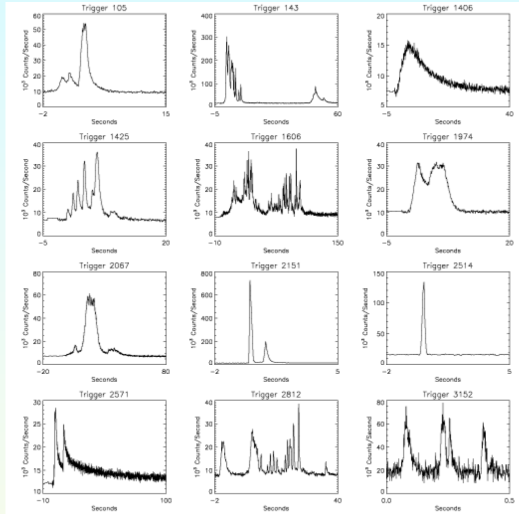
Rees & Meszaros, 1992,1994, 2001



J. McKinney / Sky & Telescope (Apr 2010)

Clumpy jets produce variable lightcurve

internal shocks

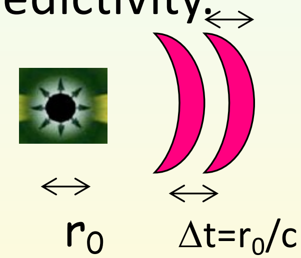


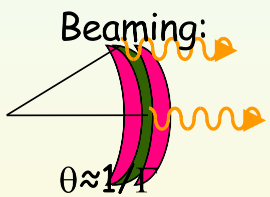
Pro's:

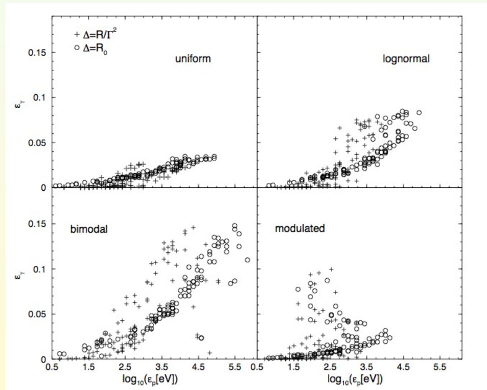
- Naturally expected
- Rad. From external shock / reverse shock observed→ shocks are known to accelerate particles & produce B field

Co's:

- conceptual: lacking predictivity.
- Highly inefficient







Guetta, Spada & Waxman, 2001

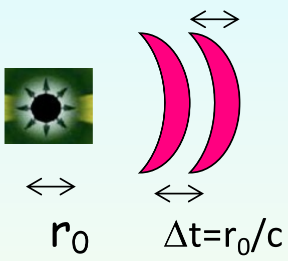
Only the differential kinetic energy is available;
Typical efficiency: ~few % (+ conversion to γ-rays !)

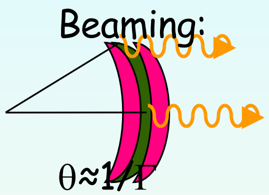
Observed: E_γ / E_{AG}: ~50%

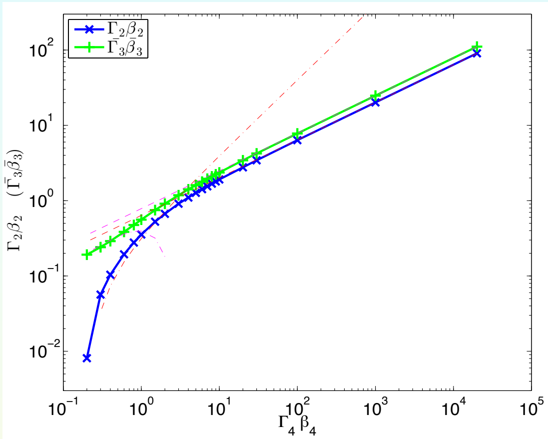
(but see talk by Granot)

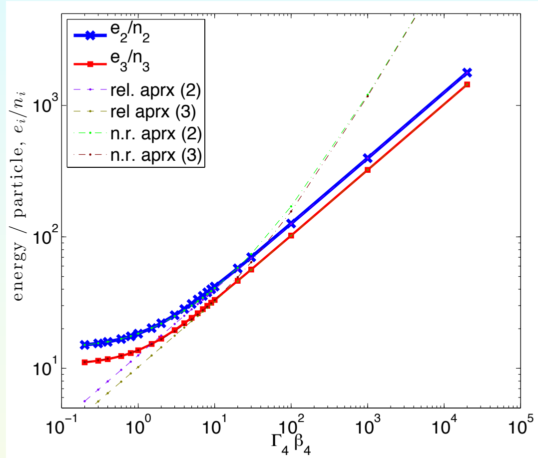
Clumpy jets produce variable lightcurve

internal shocks









Hot plasmas, **magnetized** plasmas - are even less efficient !
Typical efficiency: ~<few % (+ conversion to γ-rays !)

Pe'er, Long, Casella 2016
Bret, Pe'er et. al., 2016

Observed: E_γ / E_{AG}: ~50%

Alternatives: 1. Photosphere; 2. magnetic energy dissipation (magnetized jets) - [GR-MHD + non-ideal + dissipation…]

Production of thermal photons: recollimation shocks (?)

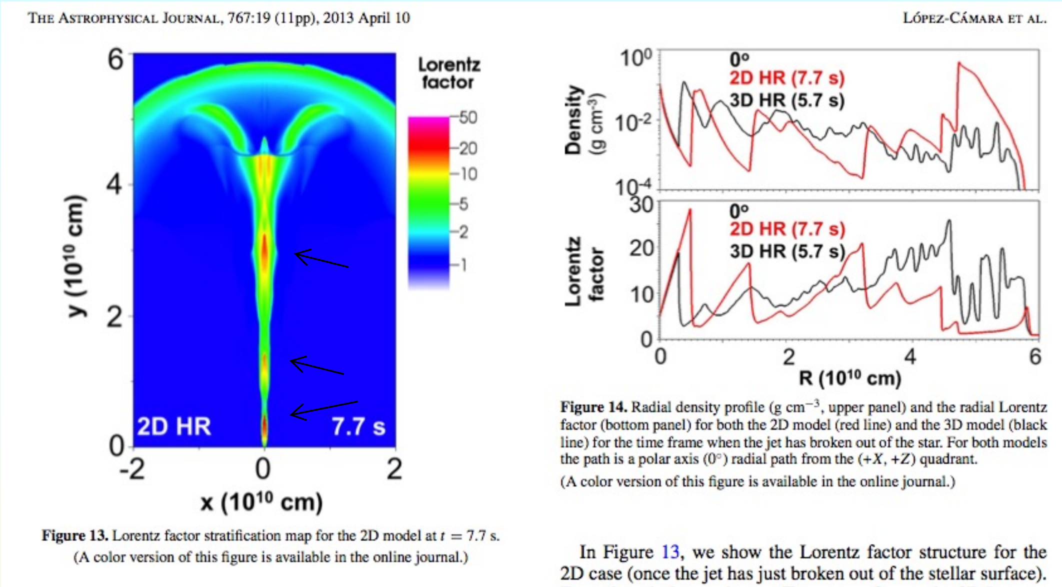


Figure 13. Lorentz factor stratification map for the 2D model at $t = 7.7$ s. (A color version of this figure is available in the online journal.)

Figure 14. Radial density profile (g cm^{-3}, upper panel) and the radial Lorentz factor (bottom panel) for both the 2D model (red line) and the 3D model (black line) for the time frame when the jet has broken out of the star. For both models the path is a polar axis (0°) radial path from the $(+X, +Z)$ quadrant. (A color version of this figure is available in the online journal.)

In Figure 13, we show the Lorentz factor structure for the 2D case (once the jet has just broken out of the stellar surface).

(Lopez-Camara+ 13) ~steady recollimation shocks at ~10^9 cm

Conditions for thermalization:
R_d~10^{10}-10^{11} cm, Γ<~20
(Vurm, Lyubarski, Piran 13)

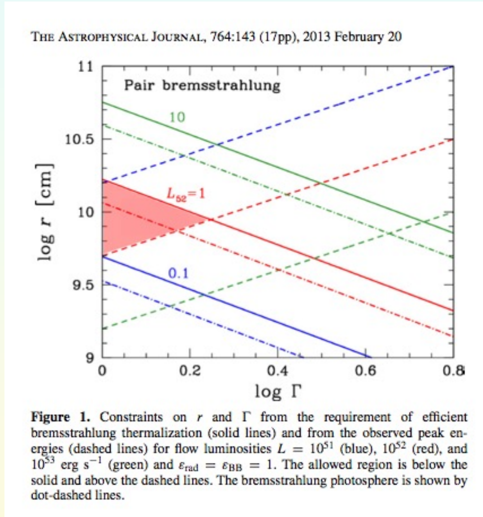
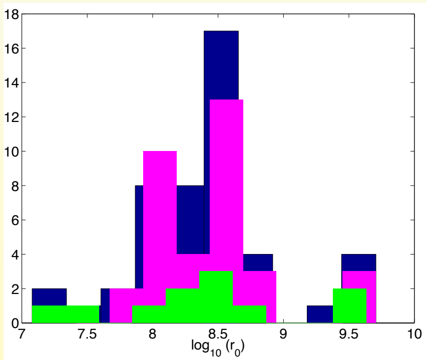


Figure 1. Constraints on r and Γ from the requirement of efficient bremsstrahlung thermalization (solid lines) and from the observed peak energies (dashed lines) for flow luminosities $L = 10^{51}$ (blue), 10^{52} (red), and 10^{53} erg s^{-1} (green) and $\varepsilon_{rad} = \varepsilon_{BB} = 1$. The allowed region is below the solid and above the dashed lines. The bremsstrahlung photosphere is shown by dot-dashed lines.



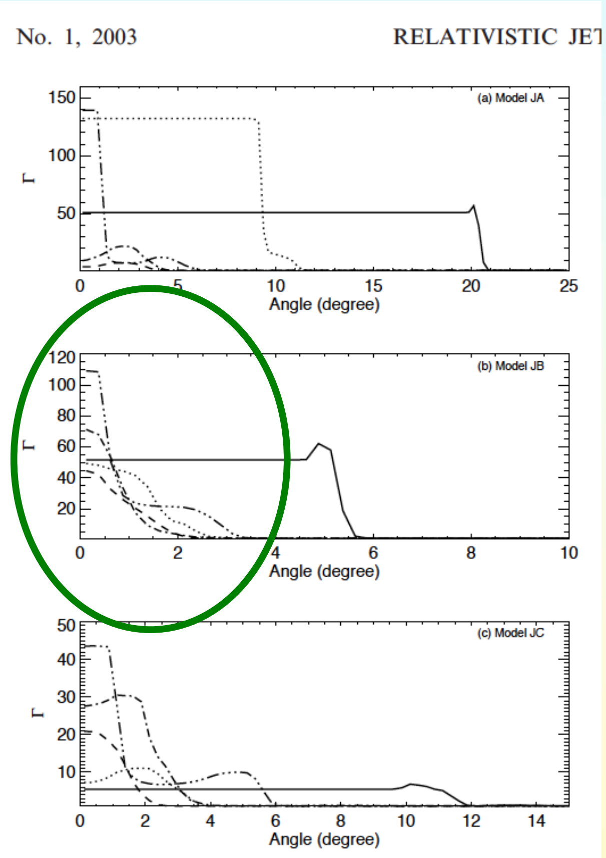
Evidence for recollimation shocks at ~ 10^2 - 10^3 $r_{Sch.}$ May be observed in data

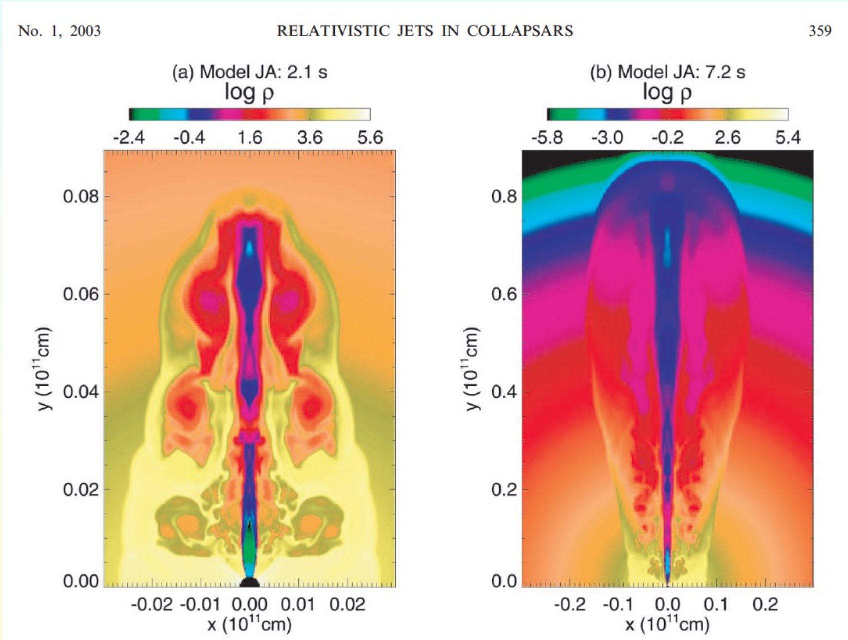
Pe'er et. al., 2015

See talk by Ryde

Obs. consequence: phot. emission from a structured jet

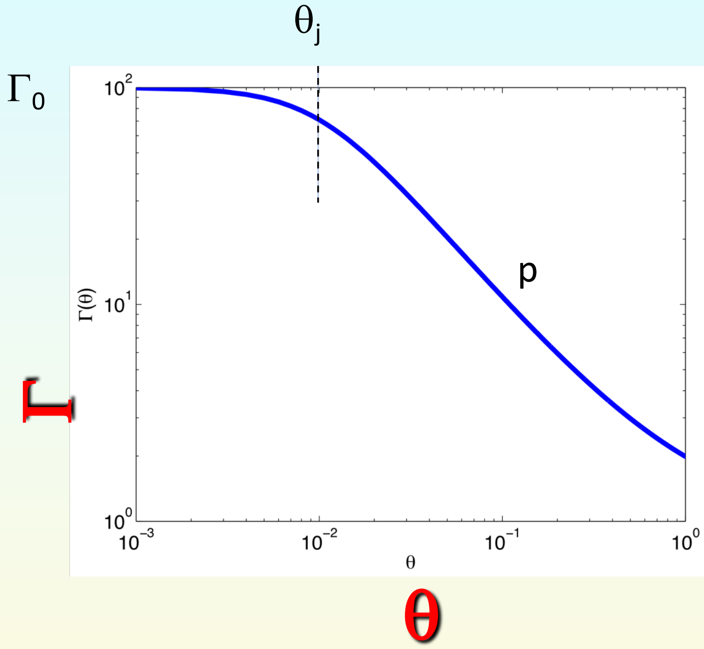
structured jet is a natural outcome

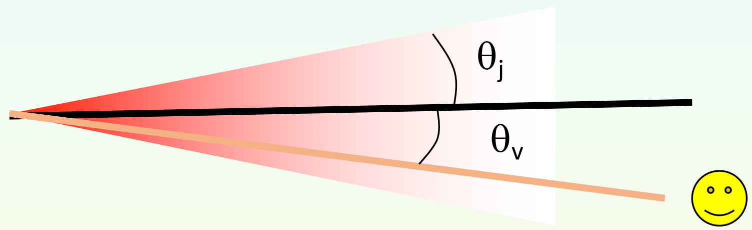




(Zhang, Woosley & MacFadyen, 03)

Photospheric emission: jet velocity profile (cocoon, etc….)



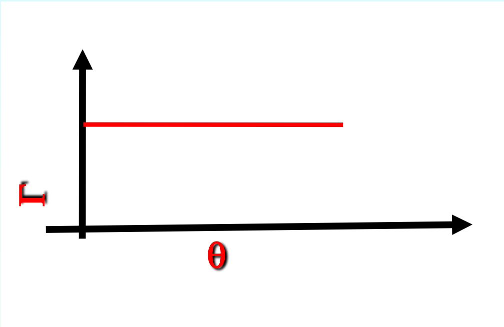


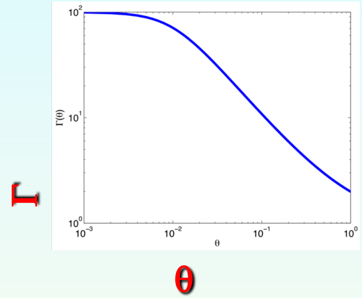
$$[\Gamma(\theta)-1]^2 = \frac{[\Gamma_0-1]^2}{1+\left(\frac{\theta}{\theta_j}\right)^{2p}}$$

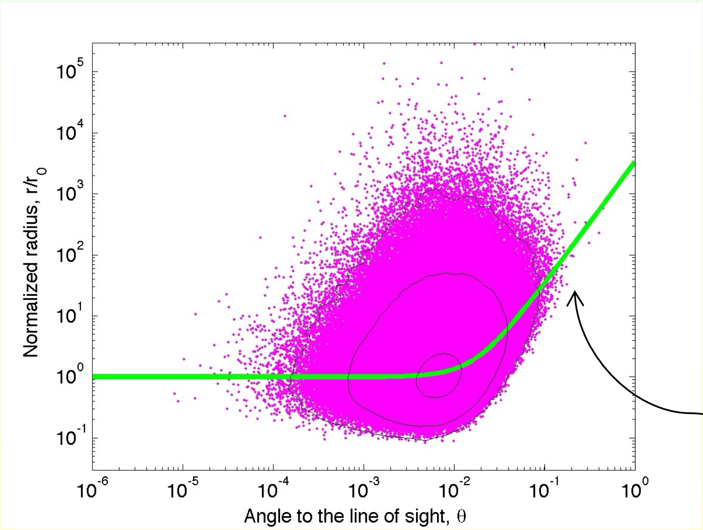
4 free parameters: Γ_0, θ_j, θ_v, p

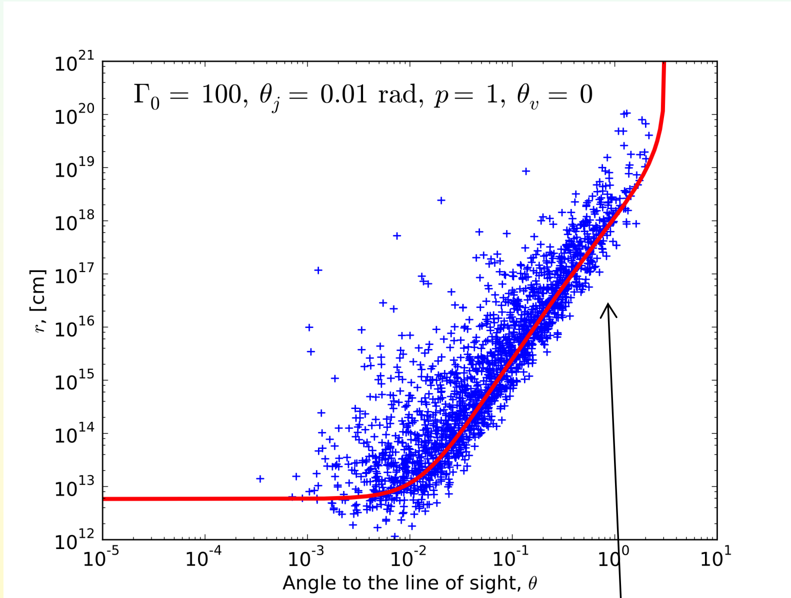
Lundman, AP & Ryde (2013)

Extended emission from high angles



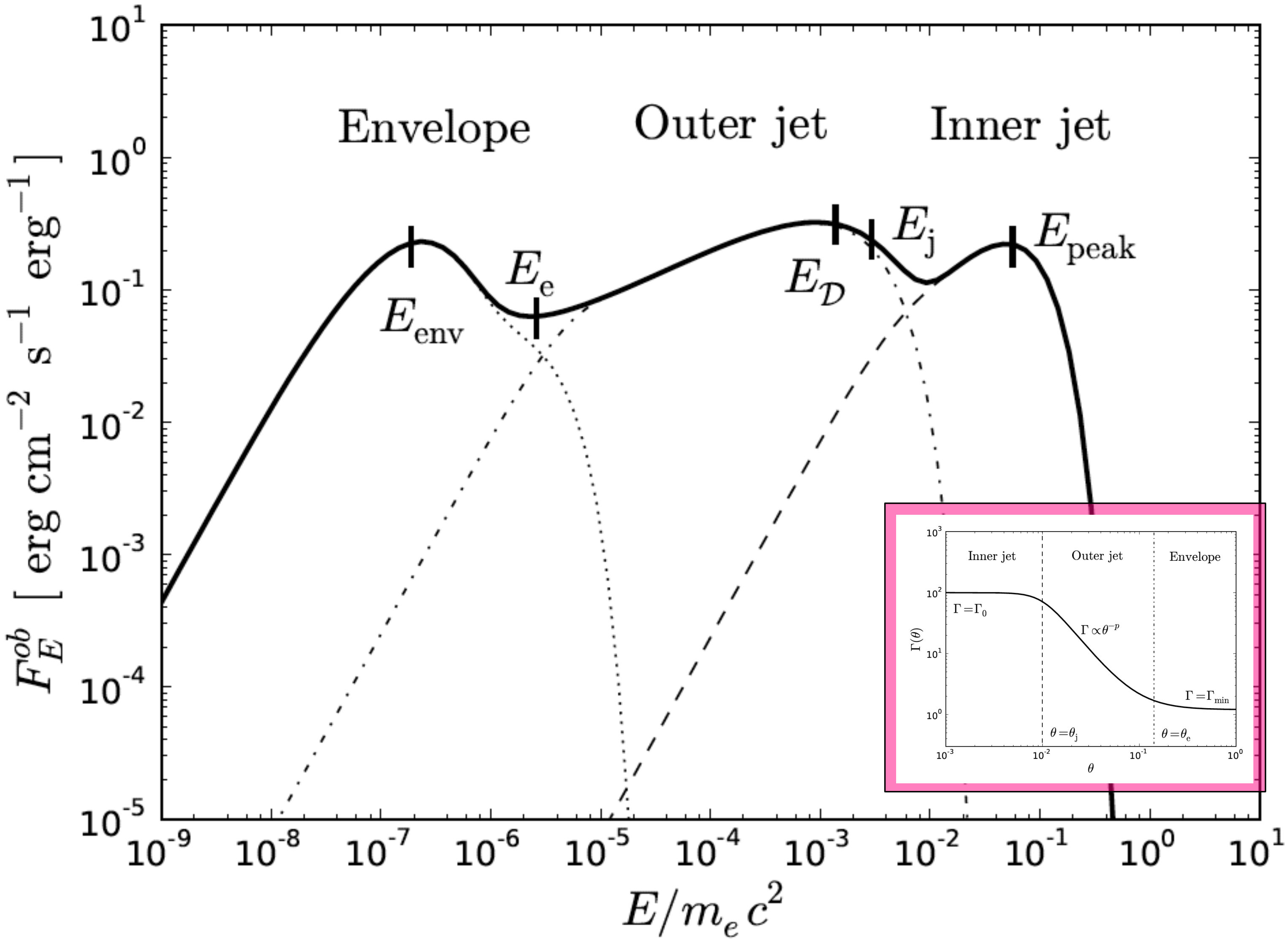






Pe'er 08; Lundman, AP & Ryde (2013)

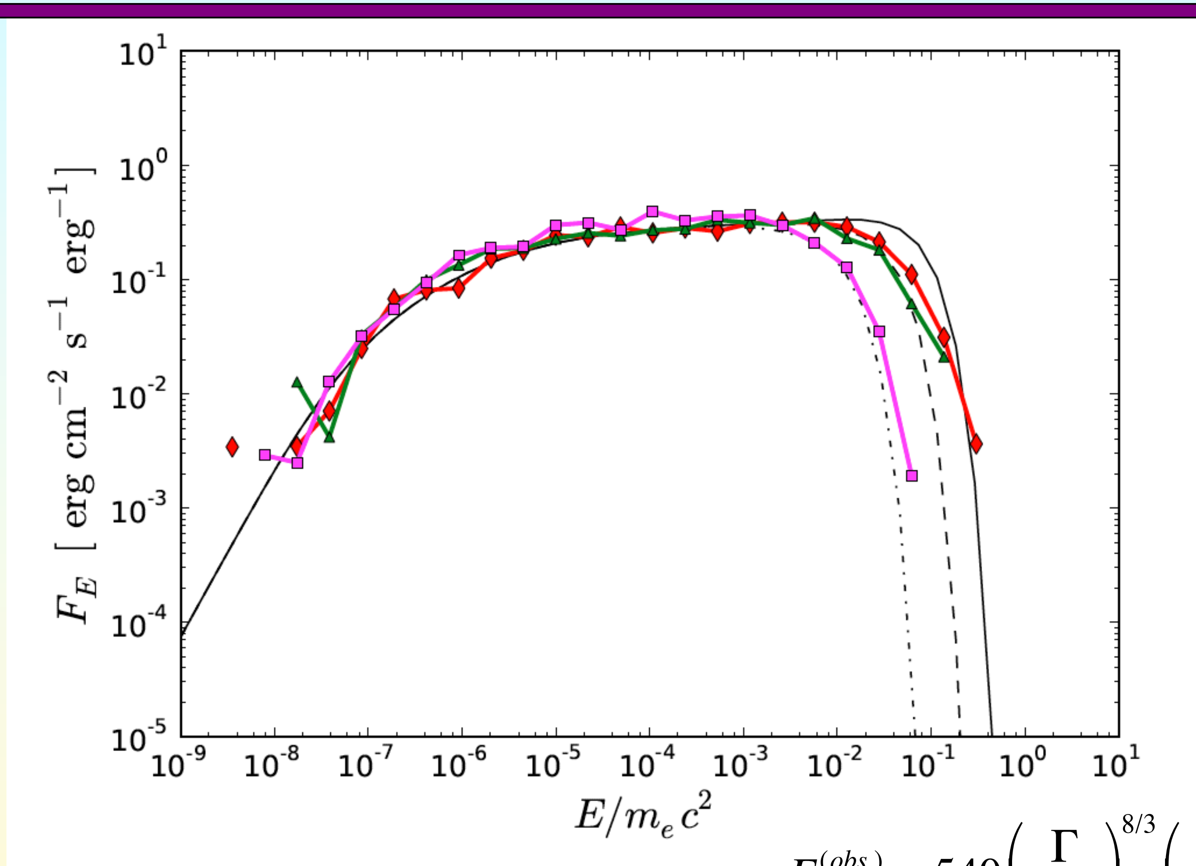
Relativistic Limb darkening effect



Γ_0=100; $\Gamma_0\theta_j$ = 3; θ_v =0 ; p=4

Lundman, AP & Ryde (2013)

Flat spectra for different viewing angles



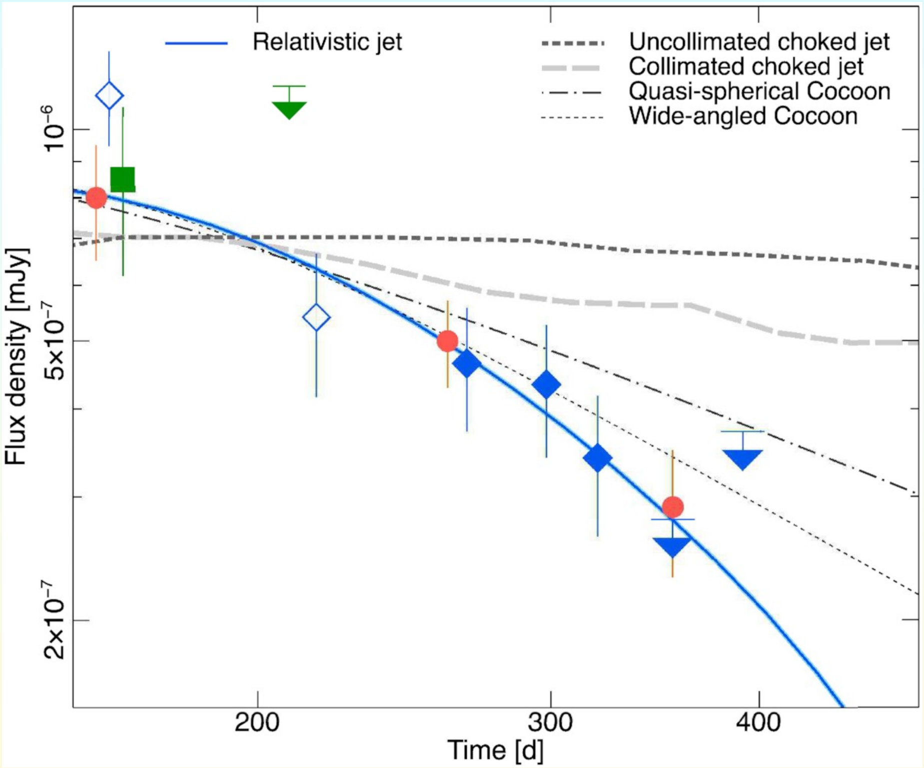
$$E_{pk}^{(obs.)} \approx 540 \left(\frac{\Gamma}{300}\right)^{8/3} \left(\frac{L}{10^{52}}\right)^{-5/12} \text{keV}$$

A robust result !

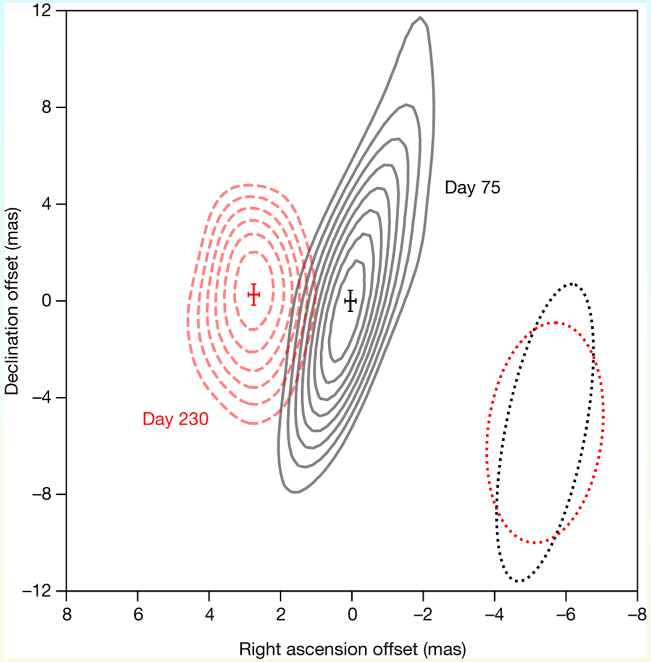
Γ_0=100; $\Gamma_0\theta_j$ = 1; p=1 ; θ_v = {0,1,2} θ_j (red, green, magenta)

Lundman, AP & Ryde (2013)

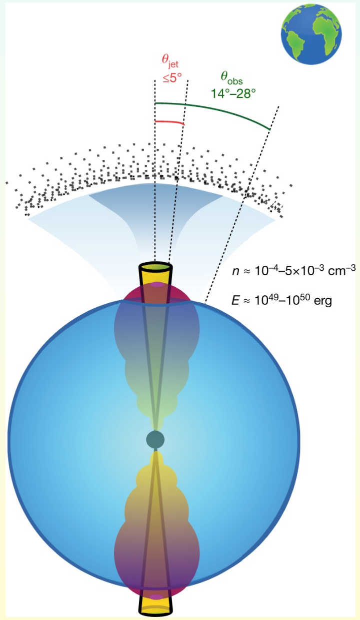
GRB/GW170817 (year): evidence for a structured jet viewed off-axis



D'Avanzo+2018, Troja+2019



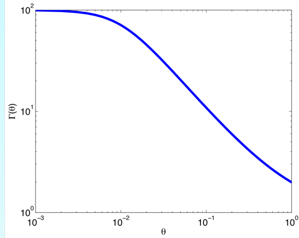
Mooley et. al., 2019

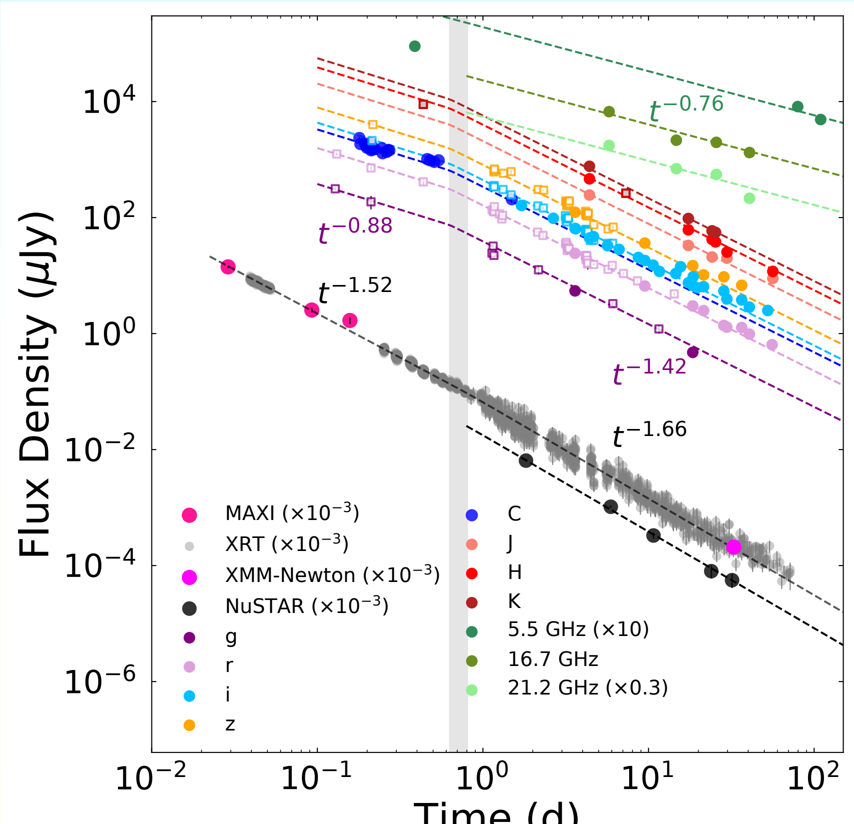


Structured jet, viewed 22^0 from jet axis

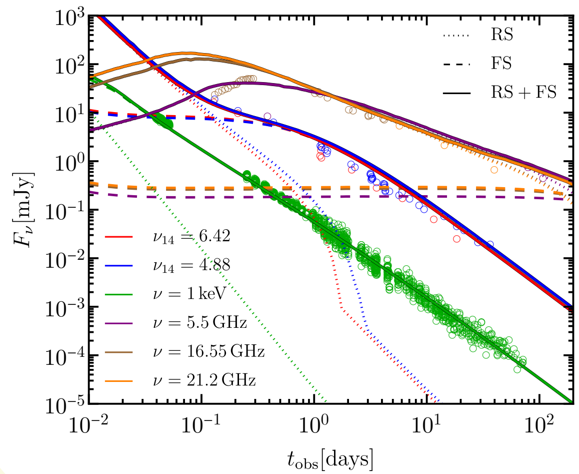
Rad. mechanism: synchrotron (→ energetic electrons + B-field << Pointing dominated)

Late time afterglow of GRB 221009A
Evidence of structured jet





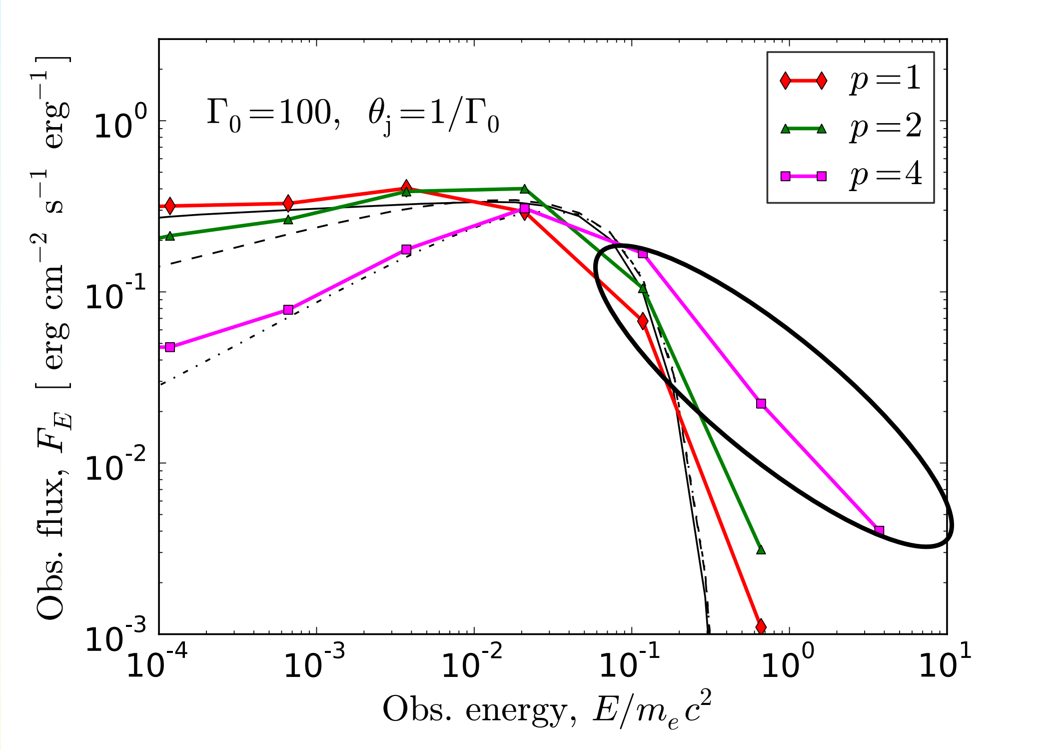
O'Connor et. al., 2023

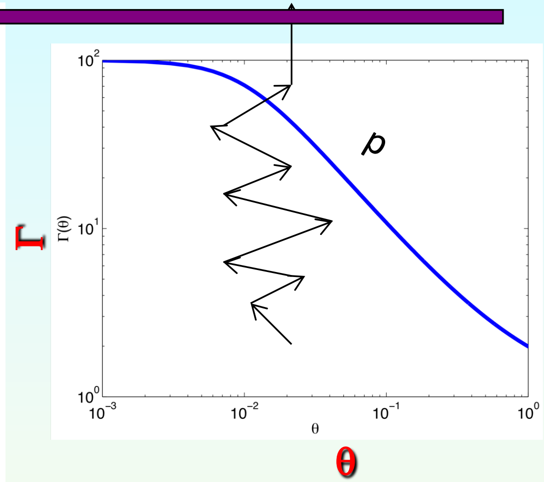


Gill & Granot, 2023 $$\left[\Gamma(\theta)-1\right]^2 = \frac{\left[\Gamma_0-1\right]^2}{1+\left(\frac{\theta}{\theta_j}\right)^{2p}}$$

The idea of structured jet is widely accepted (extra 1-2 deg. of freedom)
- Flow is not pointing flux

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.

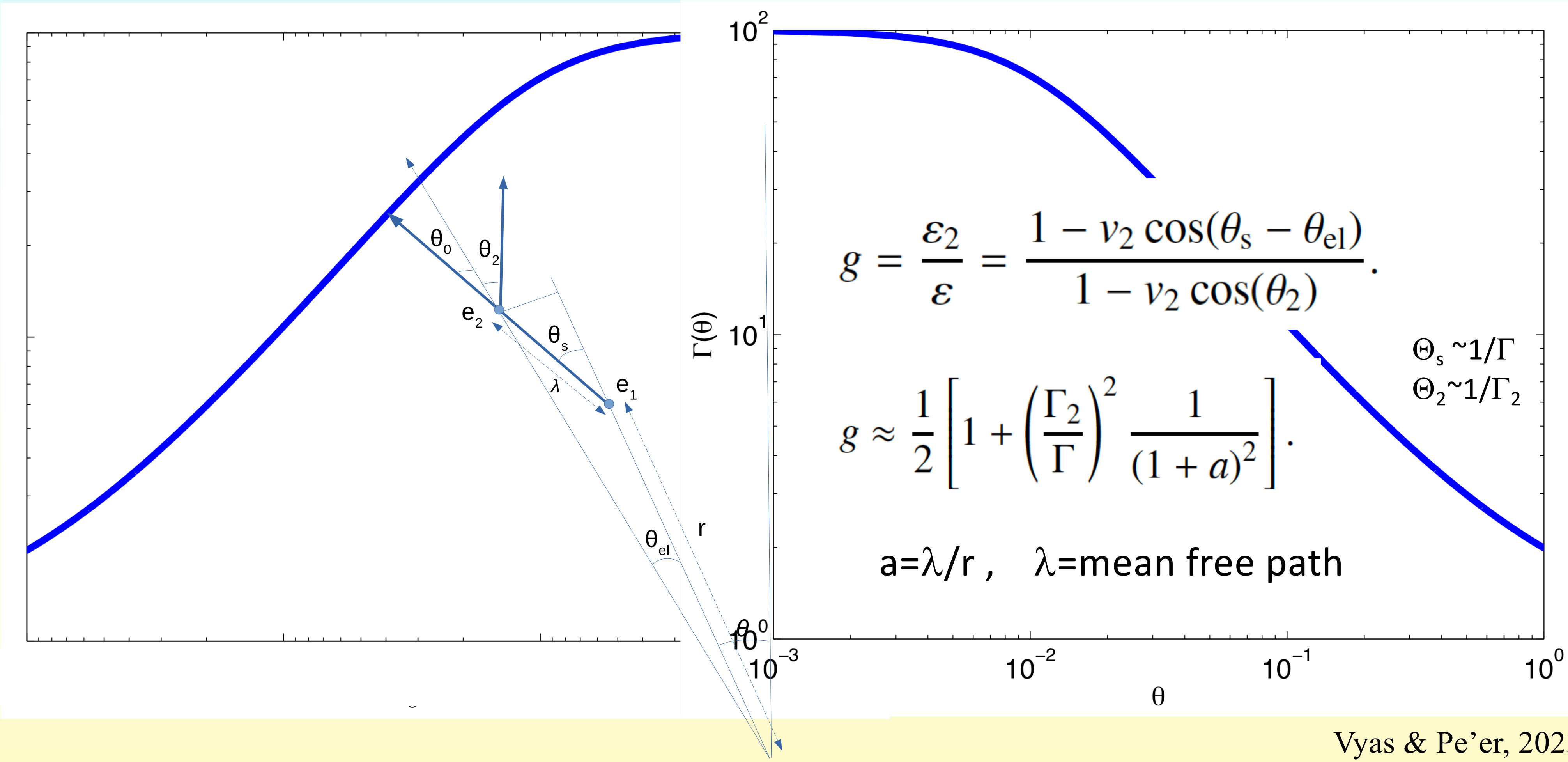
$1 \rightarrow 2 \rightarrow 1$

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

Lundman, AP & Ryde (2013); Ito et. al. (2013);

Full calc. >>

Photon energy gain: basic idea



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

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

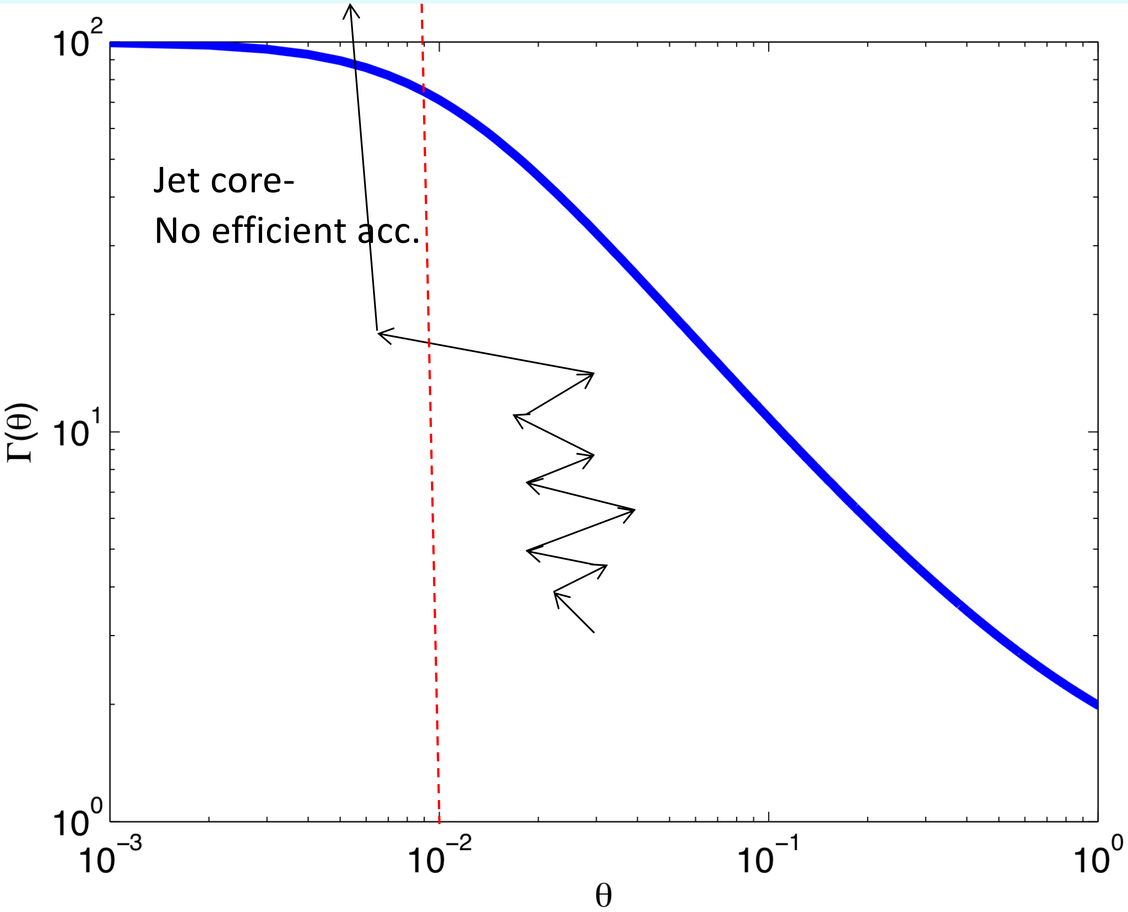
$a = \lambda / r$, λ=mean free path

$\Theta_s \sim 1/\Gamma$

$\Theta_2 \sim 1/\Gamma_2$

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

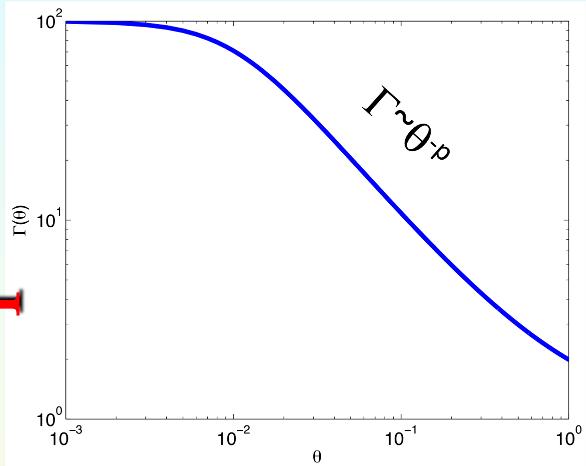
$$N = N_0 \bar{P}^k \qquad \frac{N}{N_0} = \left(\frac{\varepsilon_k}{\varepsilon_0}\right)^{\beta'}$$

Obs. Photon index

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

Results: Monte-Carlo simulation

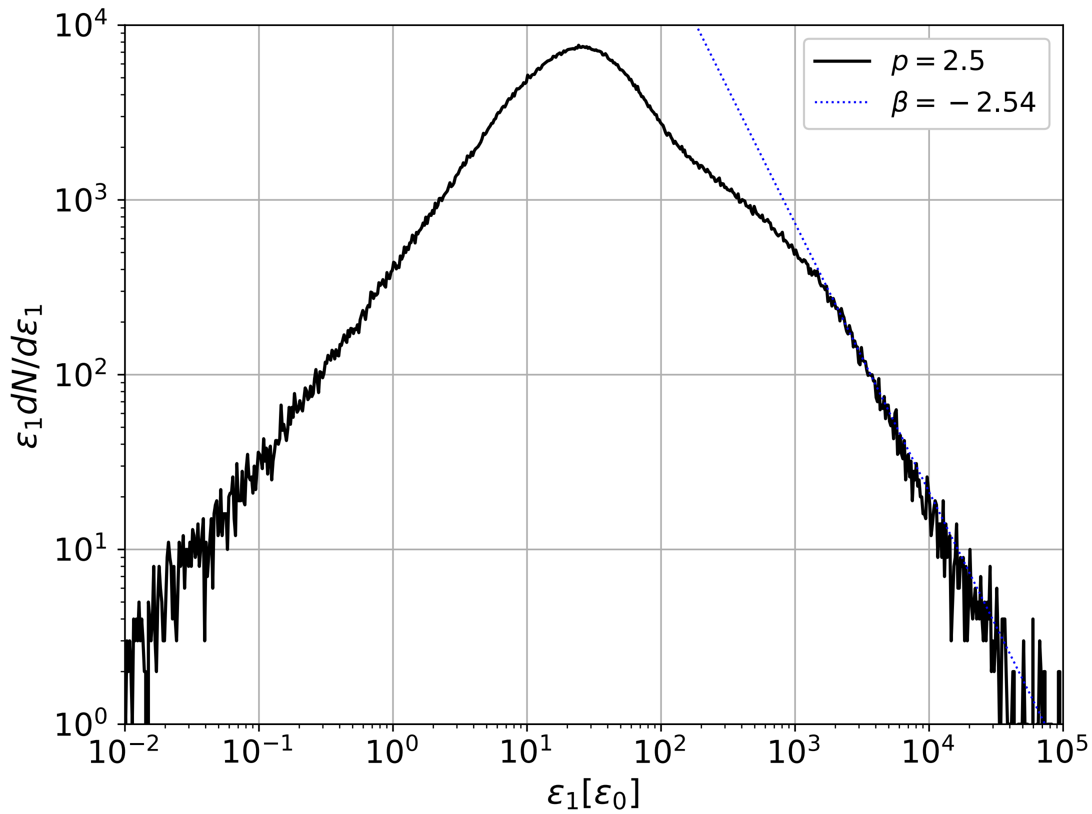
Γ



θ

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

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



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

Semi-analytic expression of the spectral slope

Asymptotic expression:

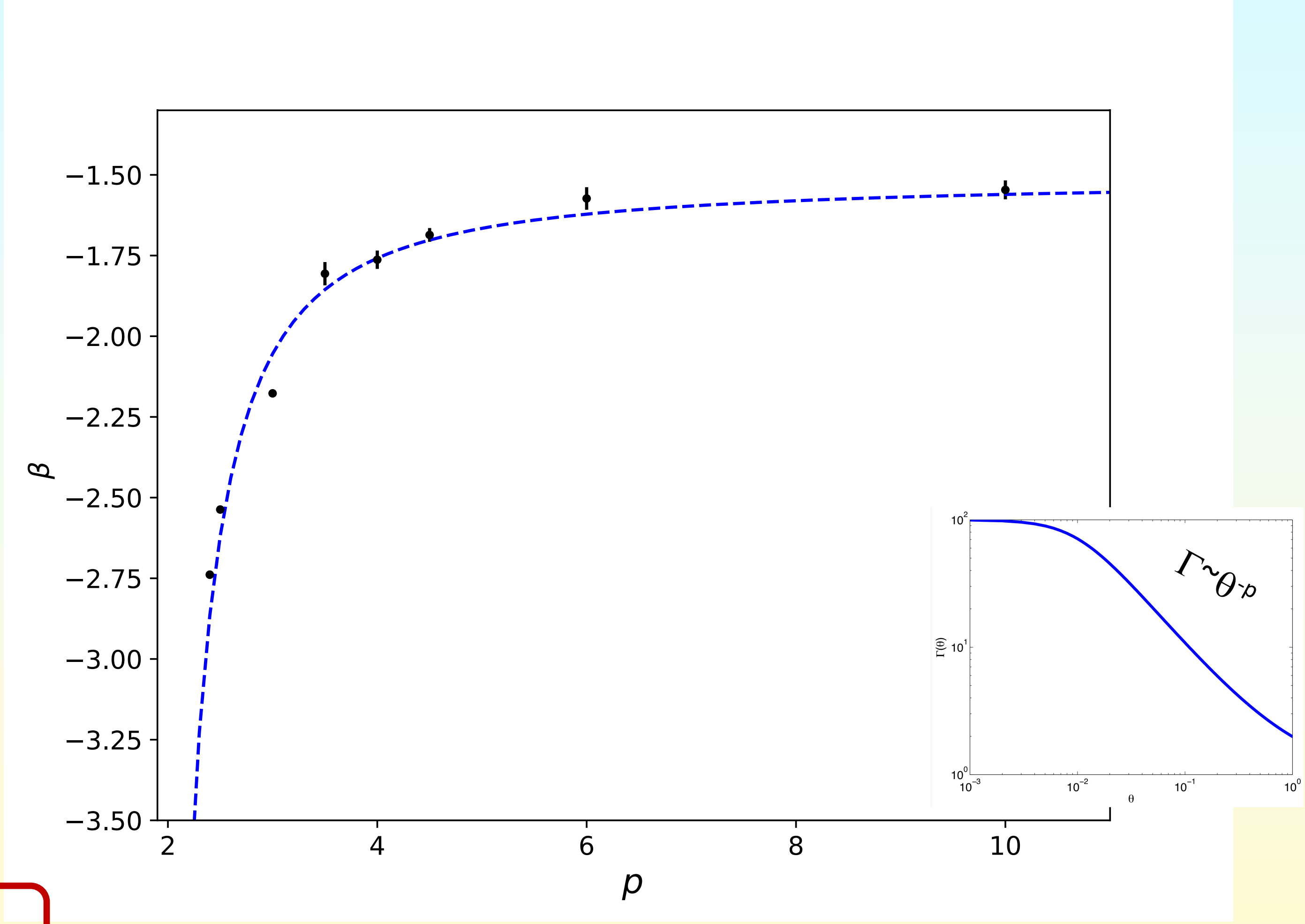
$\tau << 1 \rightarrow P(r,\theta) \sim \tau$

$<g> \sim p^2$; p = power law

$<P> \sim \Gamma_0^{(1/p)} - 1$

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

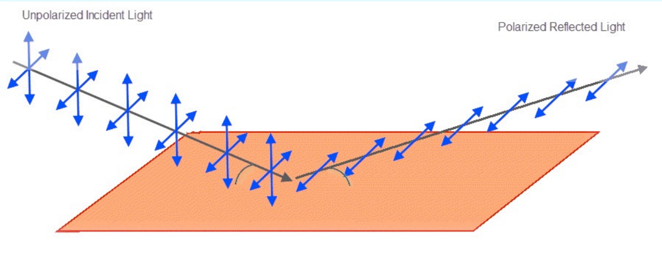
Prediction ! $\beta <= -1.5$



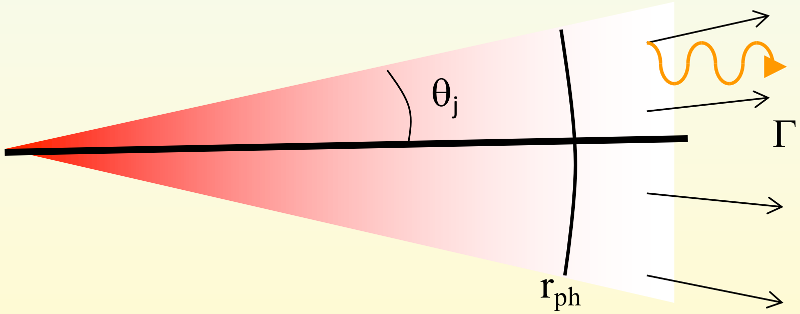
Vyas & Pe'er, 2023

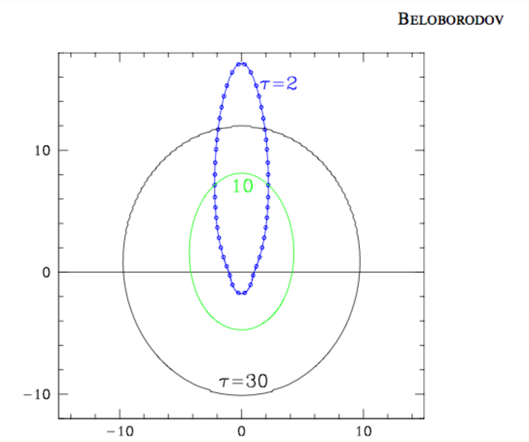
Photospheric emission: polarization ?

1. Thomson scattering produces linearly polarized light.



2. Necessary condition: anisotropic photon field.
fulfilled near the photosphere **(beaming)**



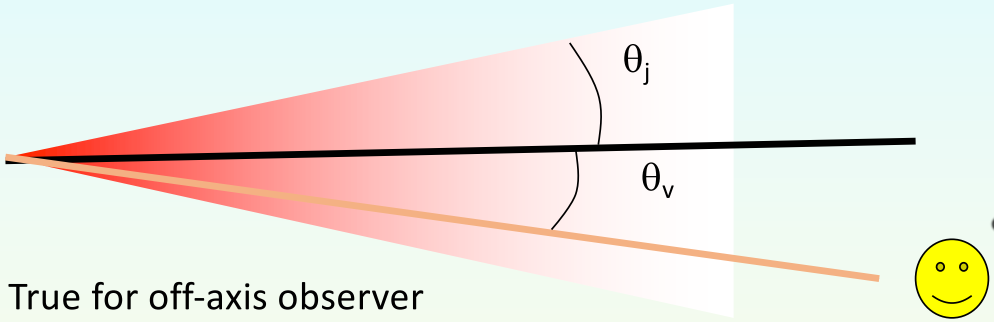


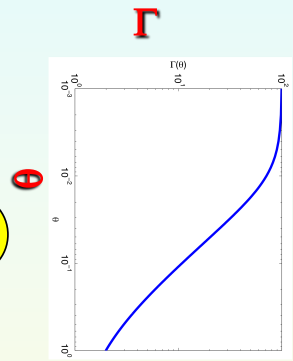
Beloborodov (11)

Spherical outflow:
Emission from θ~1/Γ is fully (100%) polarized

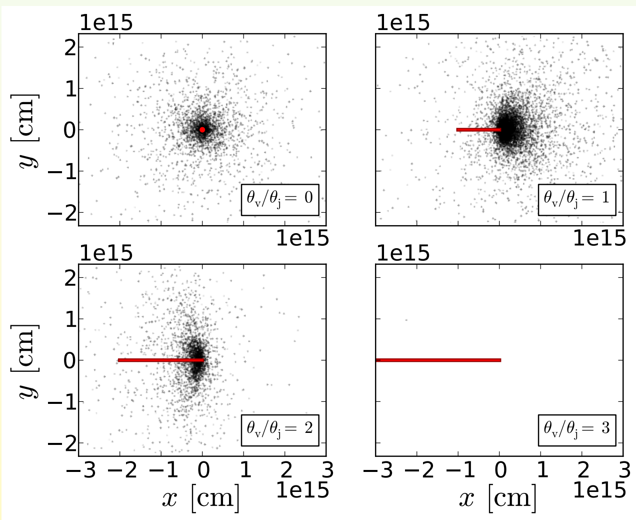
Photospheric emission: polarization ?

3. Necessary condition for unresolved sources:
breaking of the rotational symmetry:



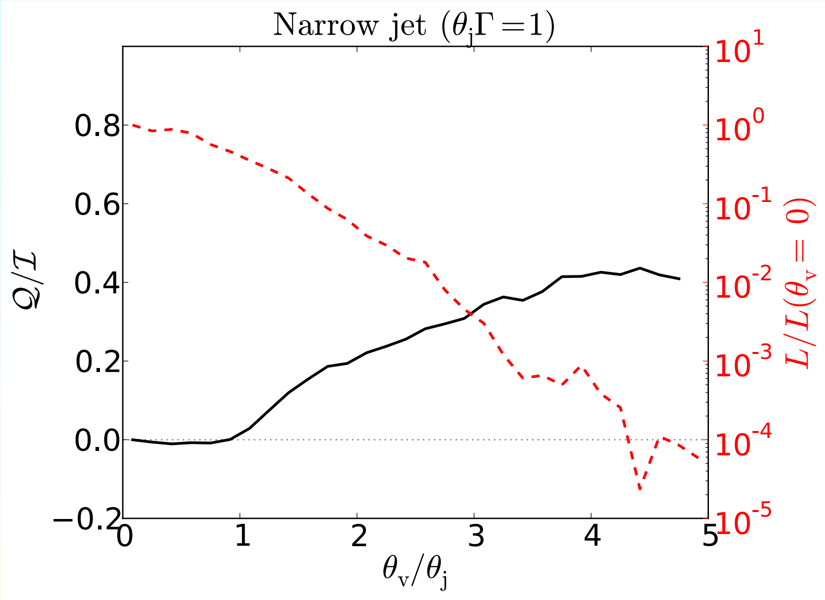


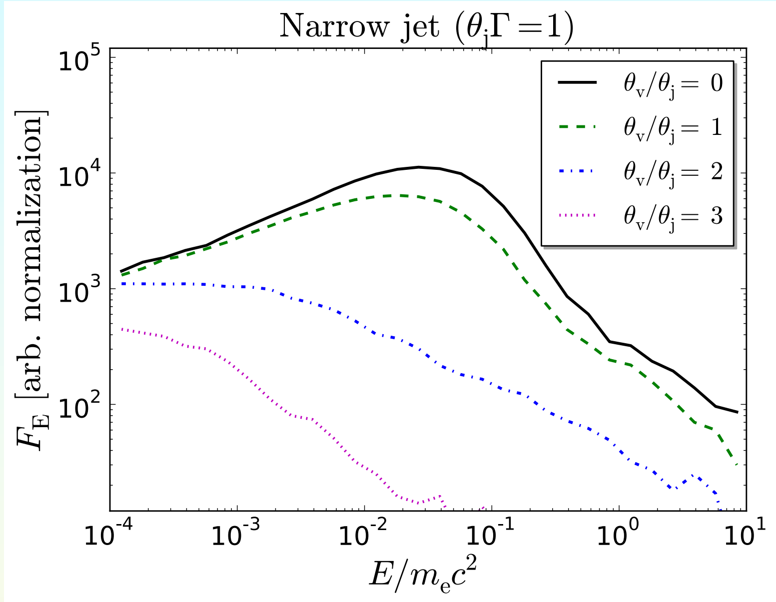
True for off-axis observer



Lundman, AP & Ryde (2014)

Photospheric emission: polarization !





Off- axis observer:

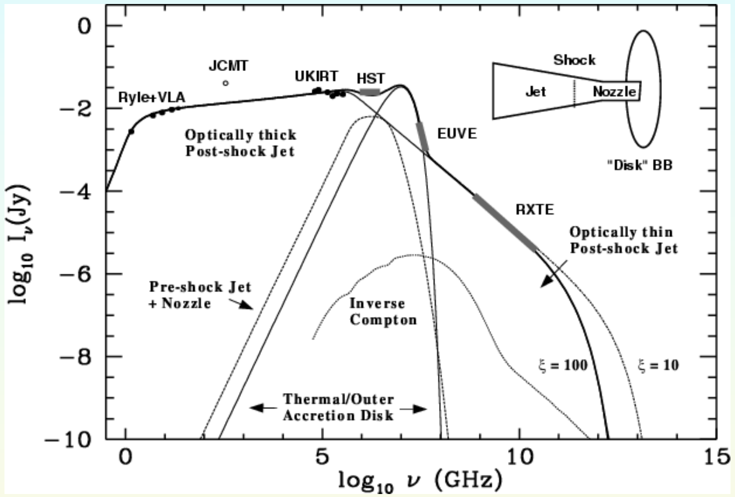
- <~40% linear polarization
- Significant flux
- Natural prediction:
  π/2 shift in polarization angle
  (observed in GRB100826A)

Broad spectra:

- **Does not look like Plank !!**
- Low energies: extended emission from shear layer-> **flat spectra**
- High energies: repeated scattering between core and shear layers -> **Power law**

Lundman, AP & Ryde (2014)

Basic model for radio emission from jets in XRB's: synchrotron



Markoff, Falcke & Fender, 2001

Blandford & Konigl (1979)

1. Basic assumptions:

$n = c\gamma^{-p} \sim r^{-2}$

$B(r) \sim r^{-1}$

2. Basic Synchrotron Theory:

$j_\nu \sim nB^{(p+1)/2}\ \nu^{-(p-1)/2}$

$\alpha_\nu \sim nB^{(p+2)/2}\ \nu^{-(p+4)/2}$

$\tau_\nu \sim r\alpha_\nu \sim rr^{-2}\ r^{-(p+2)/2}\ \nu^{-(p+4)/2}$

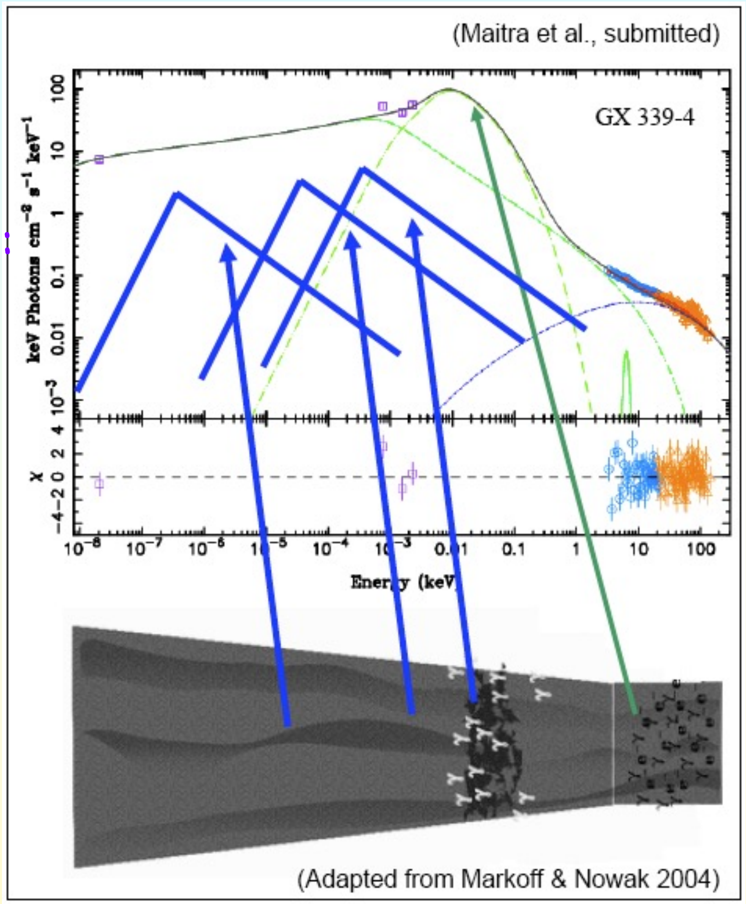
$\nu_{break} = \nu|\tau_\nu = 1 \sim r^{-1}$

$dF_\nu \sim r^2\ (j_\nu/\tau_\nu)\ dx$

$\sim r\ B^{-1/2}\ \nu^{5/2}\ dx$

$dF_\nu|\ \nu_{break} \sim r^0 \sim \nu_{break}{}^0$

Flat radio spectrum

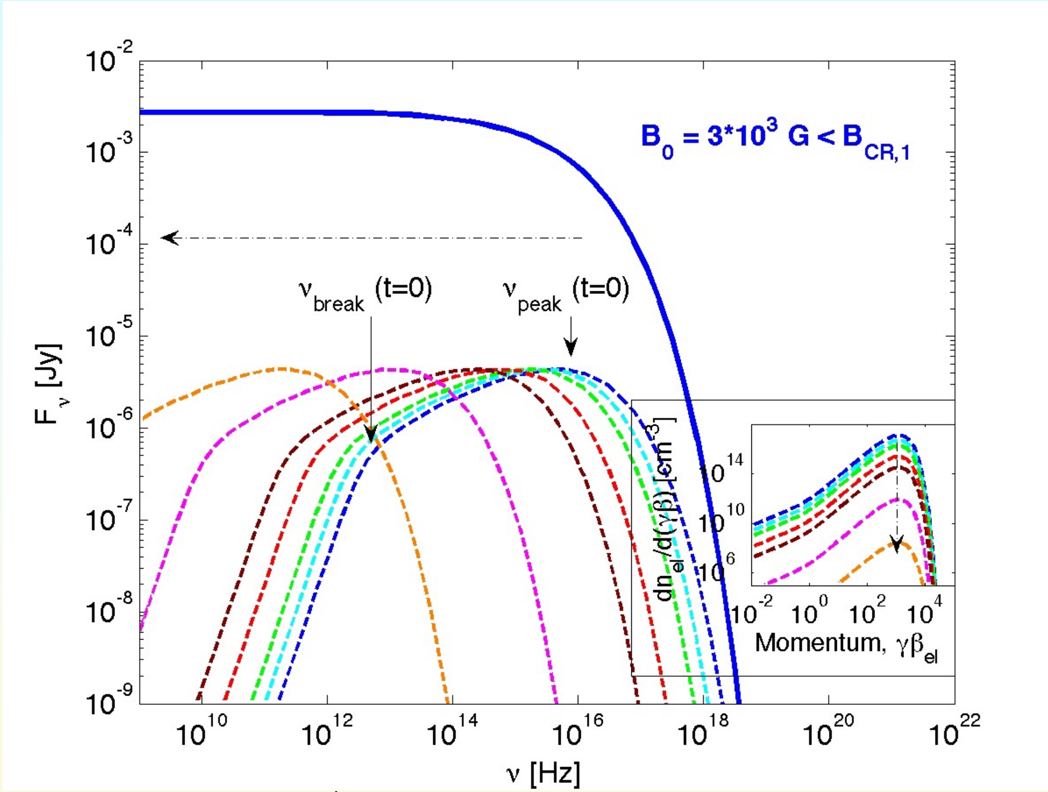


Alternative: no need for SSA. Spectrum from a Maxwellian: only sync.

Two frequencies at the jet base:

$\nu_{peak} \sim B\,\gamma_{min}^2$

$\nu_{break} = \nu|\tau_\nu = 1 \sim \gamma_{min}^{-1}$



Only synchrotron:

$\nu_{peak} \sim B\,\gamma_{min}^2 \sim r^{-1}$

$\nu_{break} \sim r^{-1}$

$n \sim r^{-2}$

$dF_\nu \sim r^2\, n\, P_{\nu|\nu_{peak}}\, dx$

$F_\nu \sim B_0 \nu^{1-1/a}$

For conical jet (a=1), flat radio spectra
Same result as in BK79 …
but different physical origin !

Pe'er & Casella, 2009

Summary

1) Relativistic jets are (i) ubiquitous; (ii) fragmented; (iii) filled with radiators; (iv) structured

2) Two leading models for jet formation:
(i) BZ→ Pointing-dominated → need to entrain the jet with material
(ii) Collapsar → neutrino/ photon dominated (better align with fits).
Numerical studies lack crucial physics

3) Energy dissipation: internal shocks (efficiency), magnetic reconnection.

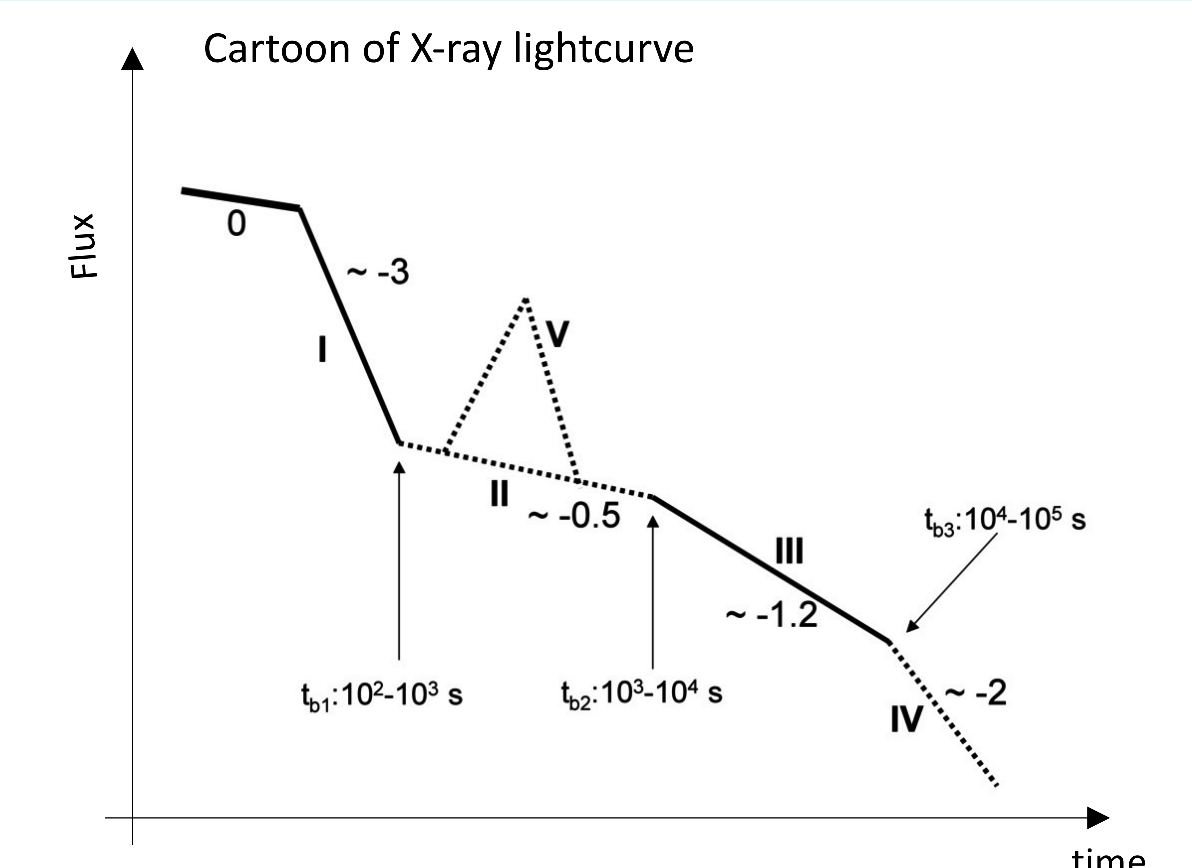
4) Photosphere: (i) solves efficiency issue; (ii) photon energy gain by repeated scattering; (iii) polarization

Implication on particle acceleration

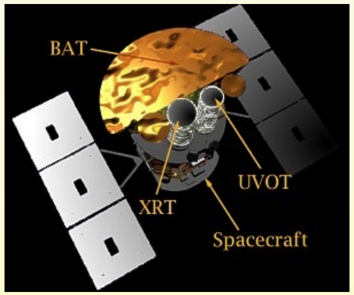
5) Flat radio spectrum in AGNs/XRBs can be obtained from a Maxwellian

1. Flares during the x-ray plateau

❖ Swift launch: Nov. 2004



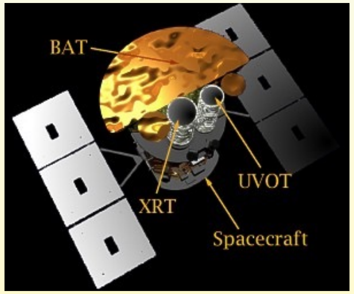
Zhang et. al., 2006

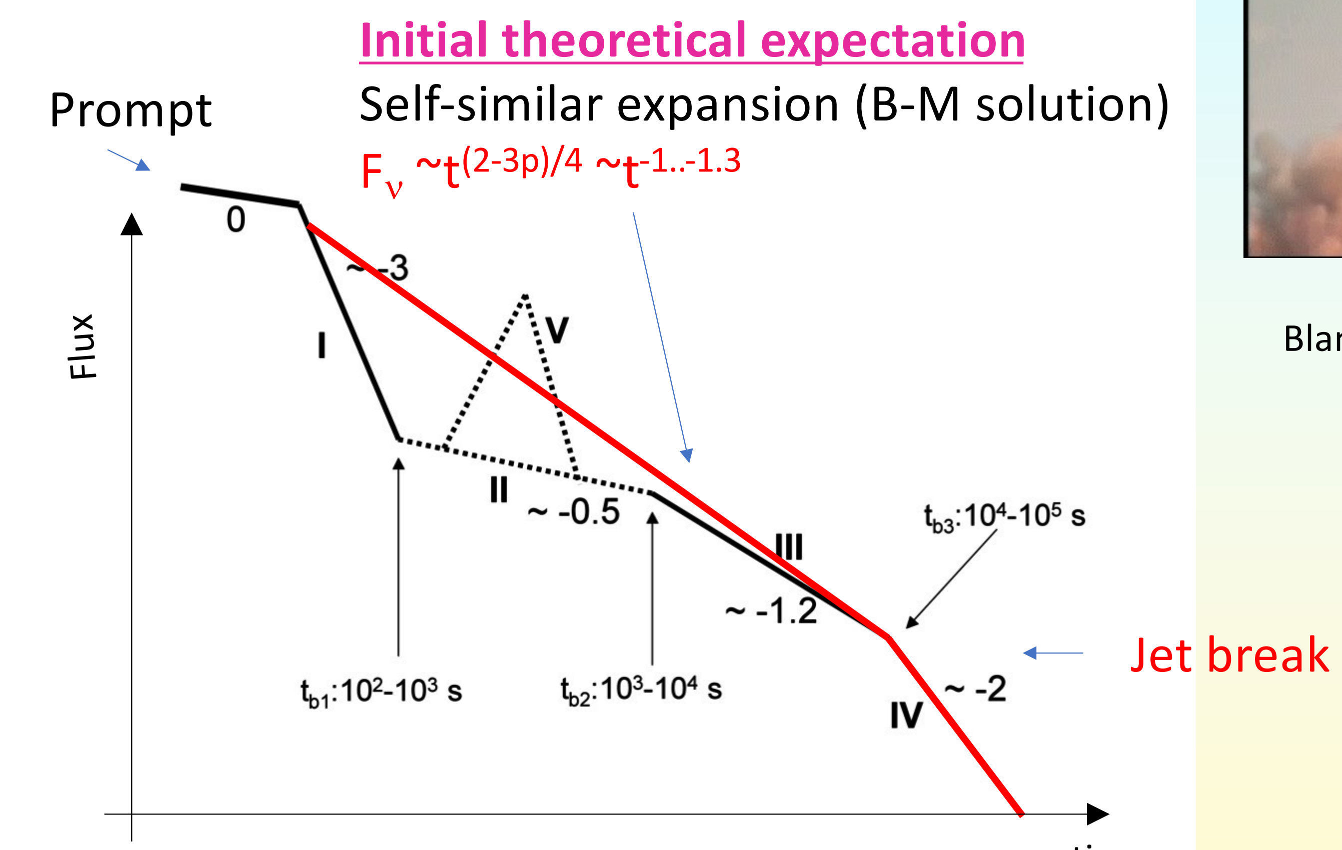


<u>Ubiquitous</u>: X-ray plateau seen in 60% of GRBs (Srinivasaragavan + 2020)

X-ray Plateau

❖ Swift launch: Nov. 2004



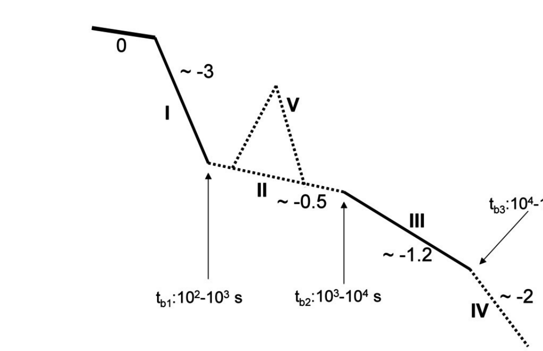


Zhang et. al., 2006

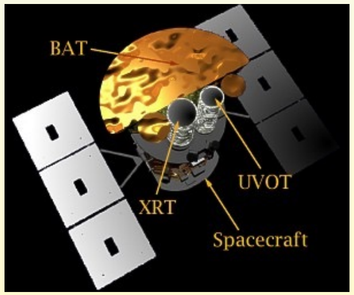
Blandford & McKee, 1976

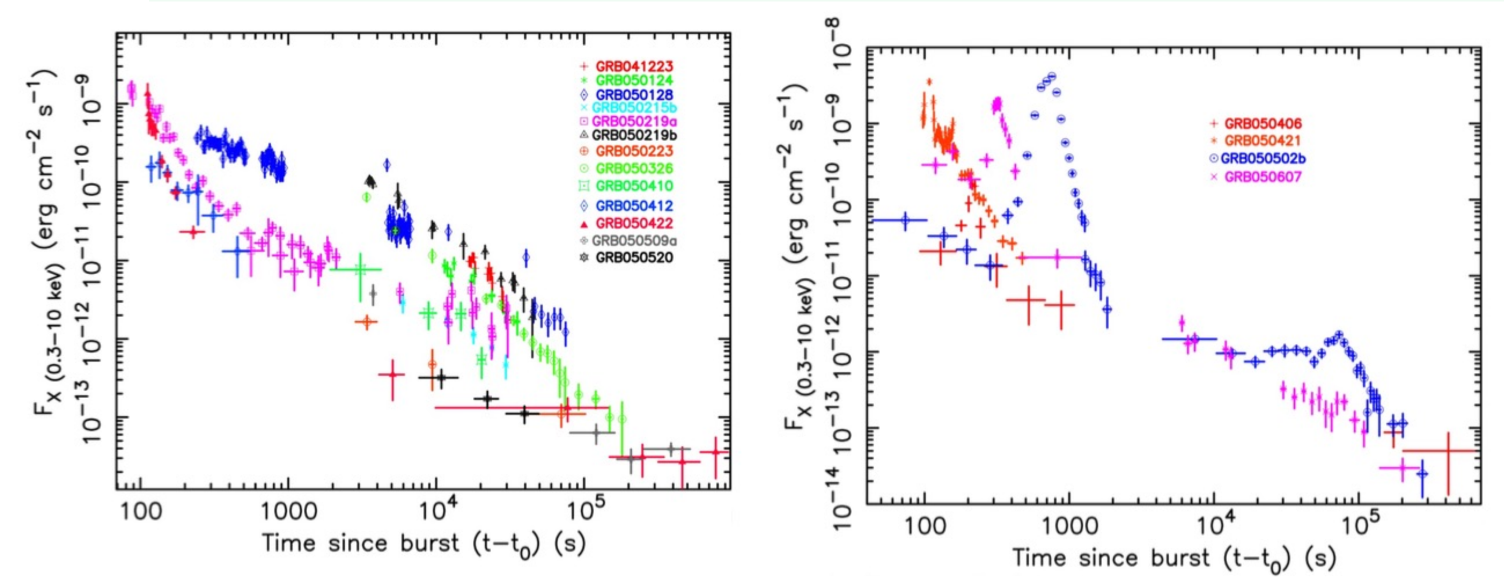
X-ray Plateau

Cartoon of X-ray lightcurve



Zhang et. al., 2006

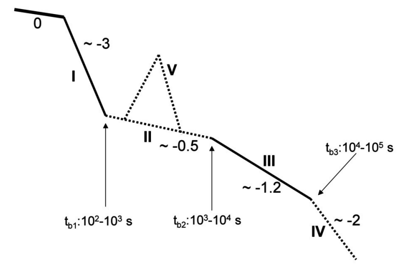




Nousek+2006

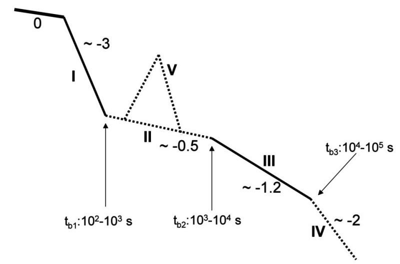
<u>Ubiquitous</u>: X-ray plateau seen in 60% of GRBs (Srinivasaragavan + 2020)

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…



- **Continuous energy injection** that slows down the acceleration
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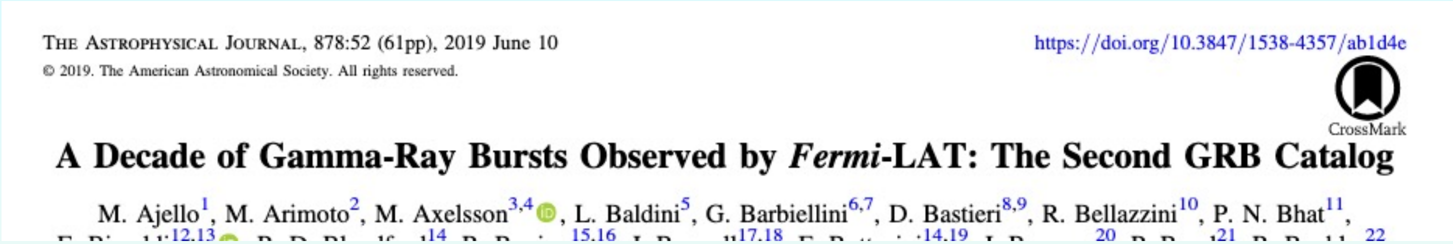
- Forward shock - before deceleration Shen & Matzner, 2012

Requires: (i) explosion into a ”wind”; (ii) Γ_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):

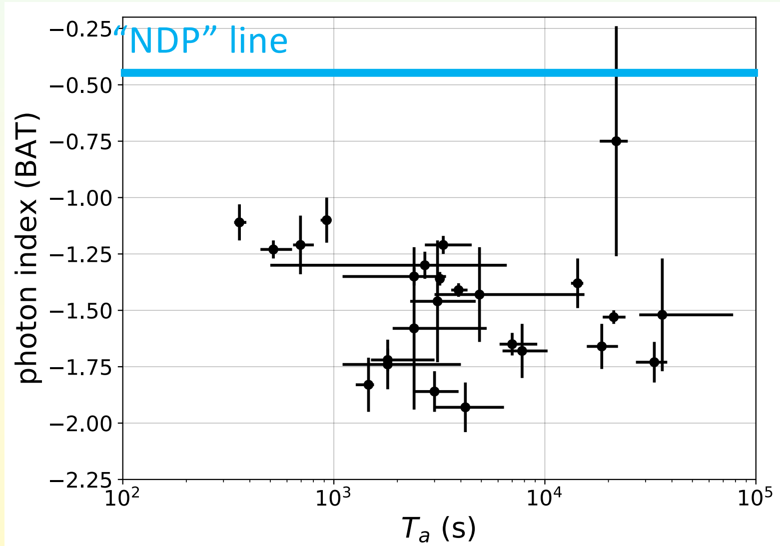
Only 3/186 LAT bursts show any evidence for a "Plateau" !

→ **Opacity argument** ($\gamma\gamma \rightarrow e^{\pm}$: (GeV) LAT photons necessitates $\Gamma >\sim 100$) **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)

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

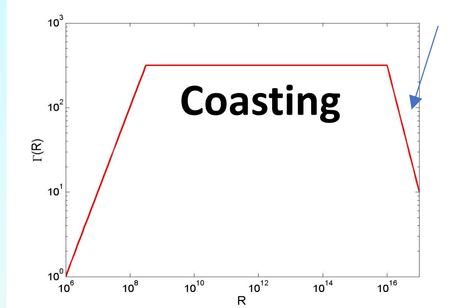
$\nu_c^{ob.} \sim \Gamma^3/(B^3\, r^2)$

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

* Shock generates B field & accelerates particles:

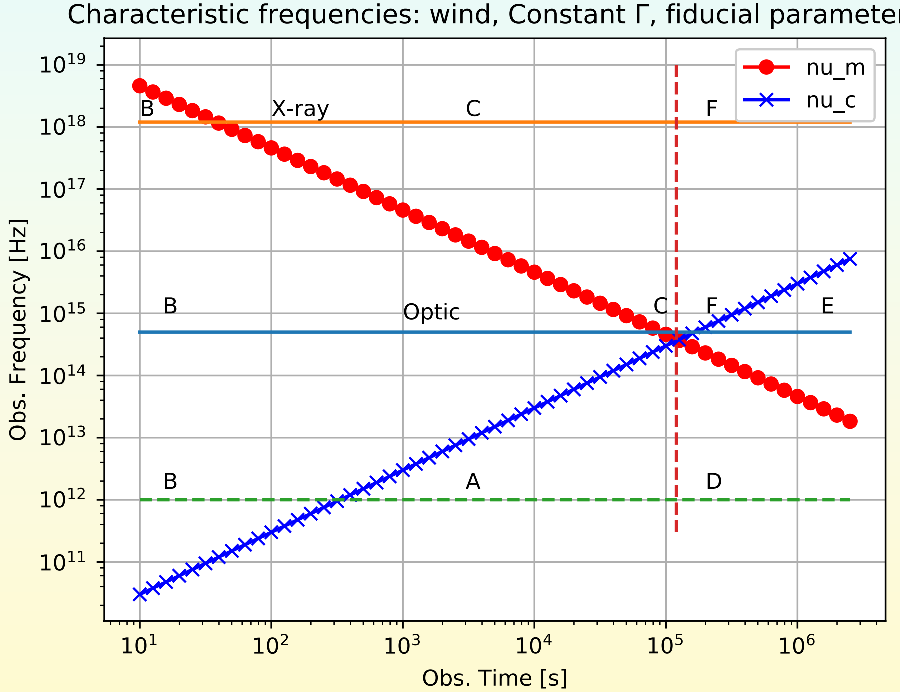
$\gamma_{el} \sim \Gamma\, \varepsilon_e; \quad B \sim \varepsilon_B\, u$

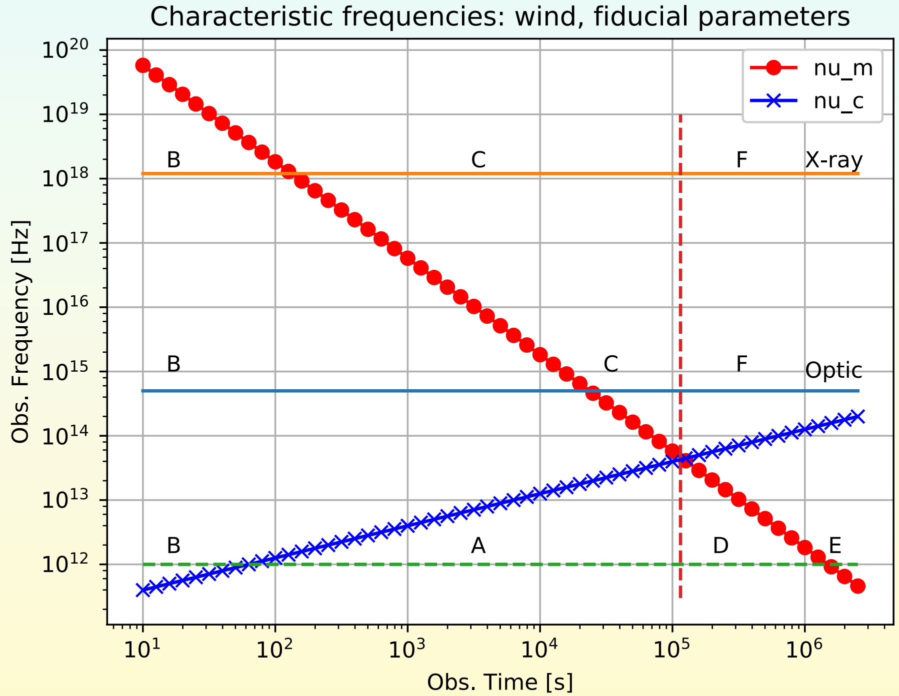
Self-similar



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

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

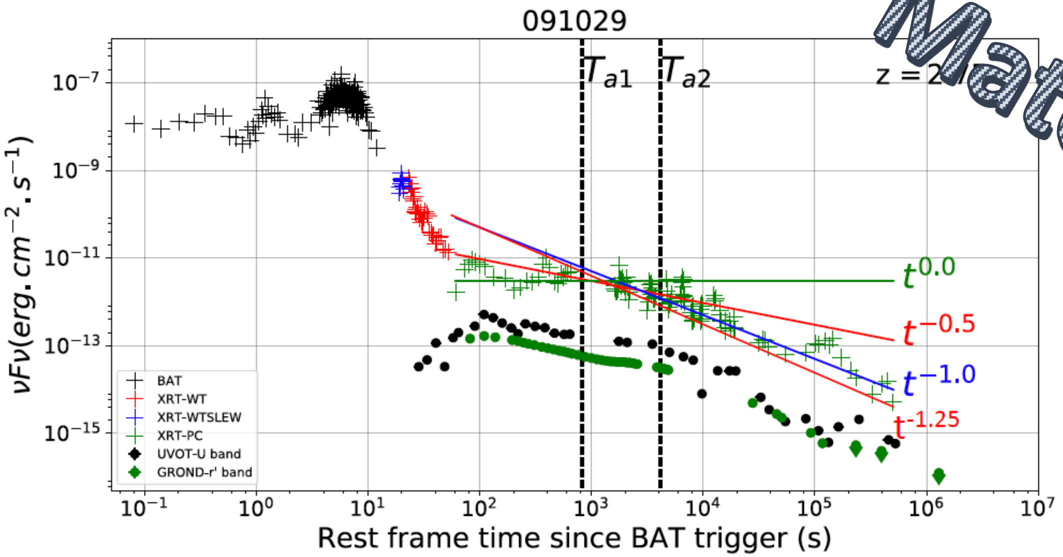




Prediction: Transition from region F ($\nu_c < \nu$) → E ($\nu < \nu_c$); optical first

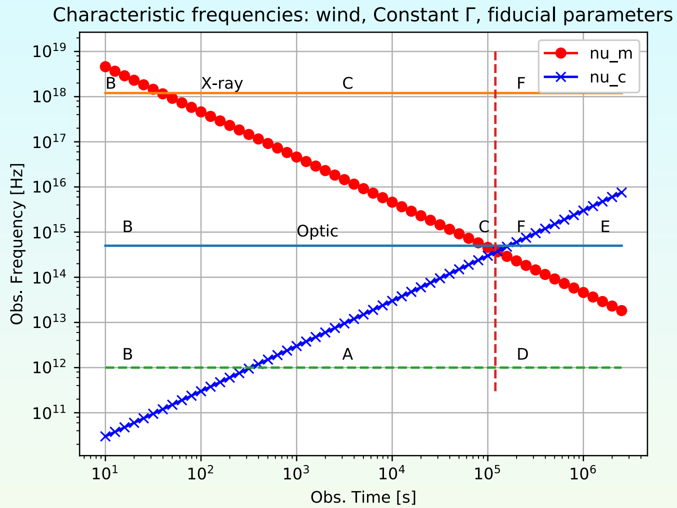
Basics of synchrotron (wind): theory vs. data

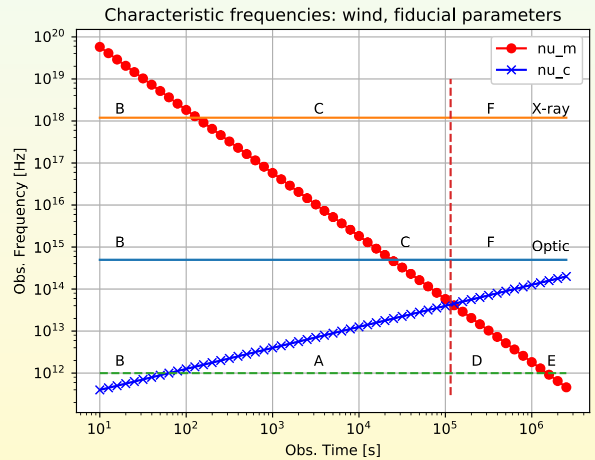
Region	Coasting	Self-similar decay
F ($\nu_c < \nu$):	$F_\nu \sim t^{(2-p)/2}\,\nu^{-p/2} \sim t^0$	$F_\nu \sim t^{(2-3p)/4}\,\nu^{-p/2} \sim t^{-1}$
E ($\nu < \nu_c$):	$F_\nu \sim t^{(1-p)/2}\,\nu^{-(p-1)/2} \sim t^{-0.5}$	$F_\nu \sim t^{(1-3p)/4}\,\nu^{-(p-1)/2} \sim t^{-1.25}$



Match !

Dereli-Bégué+2021, in preparation





A-chromatic breaks are allowed !

Extracting physical information

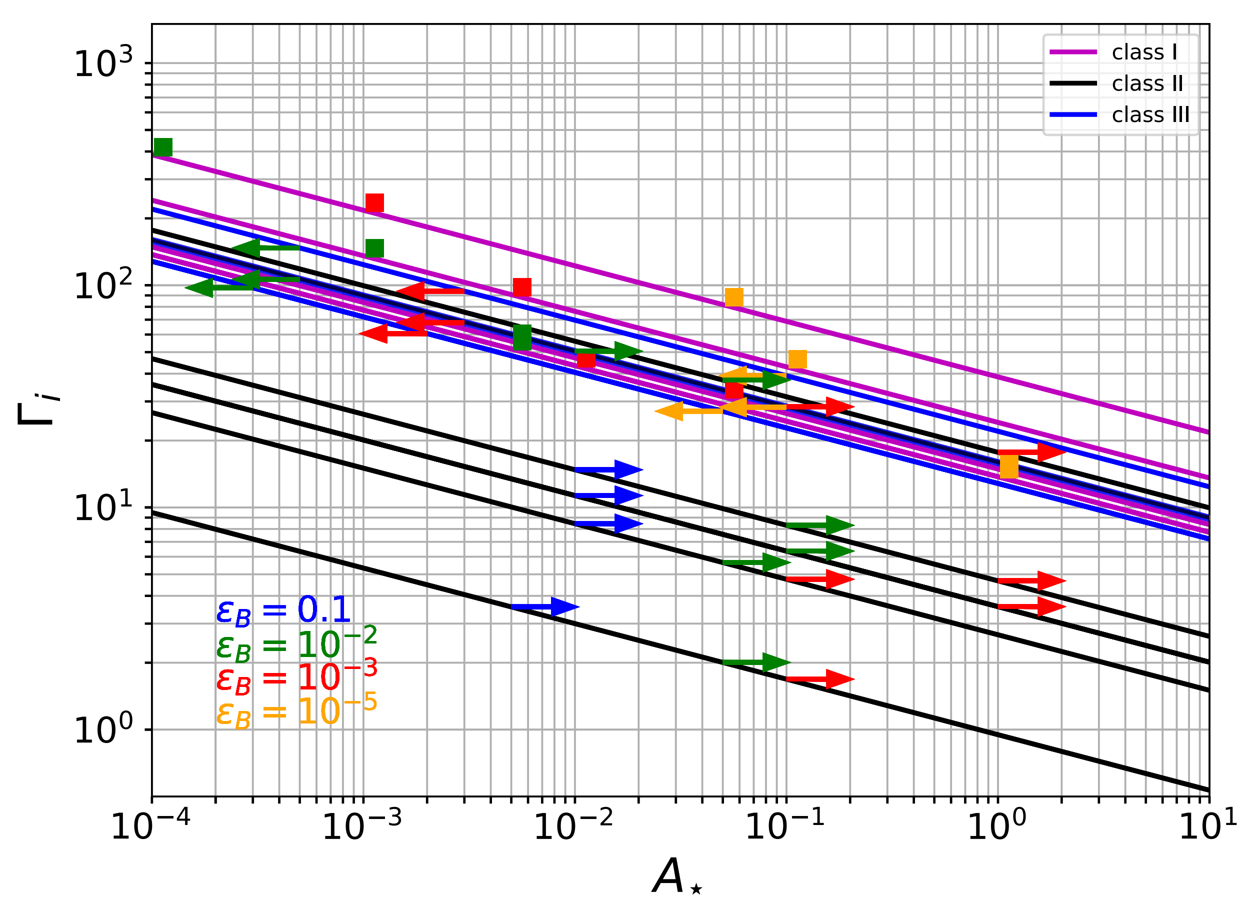
$$t^{ob.}_{trans} = (1+z)\frac{9E}{32\pi A c^3 \Gamma_i^4}$$

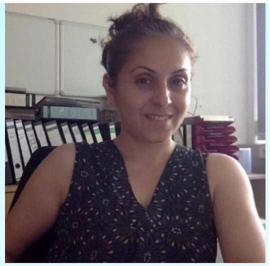
→ $A_* \Gamma_{i,1.5}^4 \sim= 0.2\ (1+z)/2\ E_{52.5}\ t_{trans,3.5}^{-1}$

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

A_* (Wolf-Rayet) ~1

Chevalier+04,..



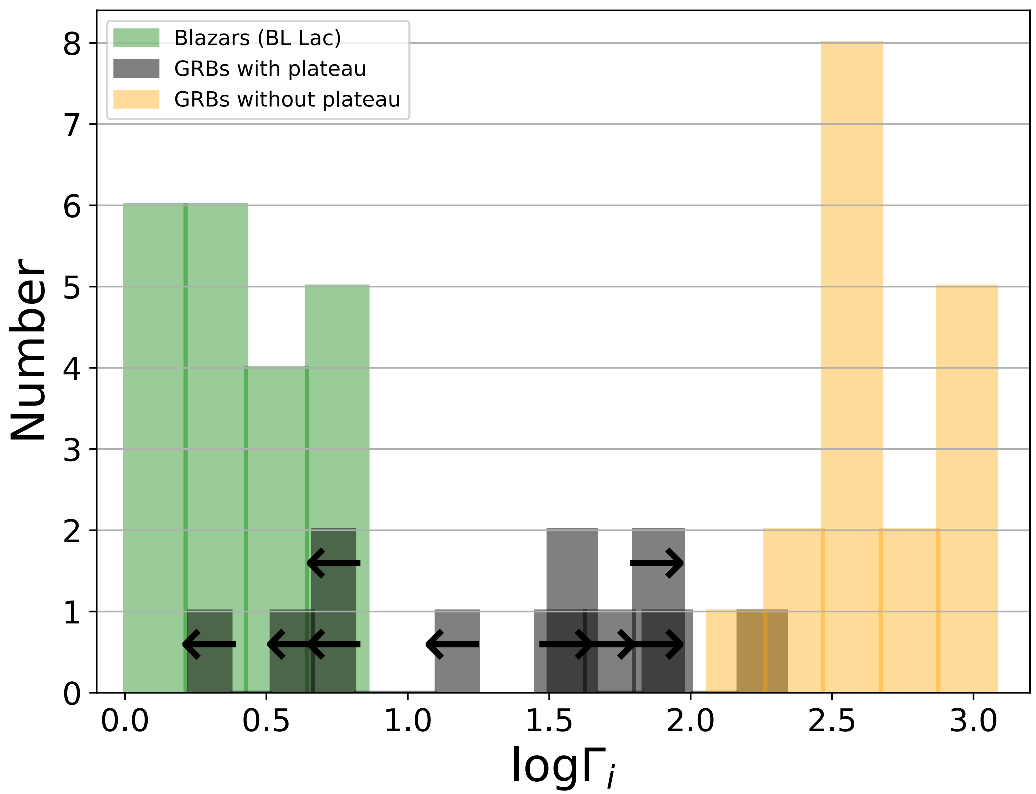


Dereli-Begue, Pe'er et. al., 2022, Nature Com.

Given magnetization $0.1 < \varepsilon_B < 10^{-5}$ → **$\langle A_* \rangle \sim 10^{-2}$; $4 < \Gamma_i < 218$; $\langle \Gamma_i \rangle = 51$**

Bridging an observational gap

Ghisellini+93



Liang+10
Racusin+11

$\langle\Gamma_i\rangle$=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.

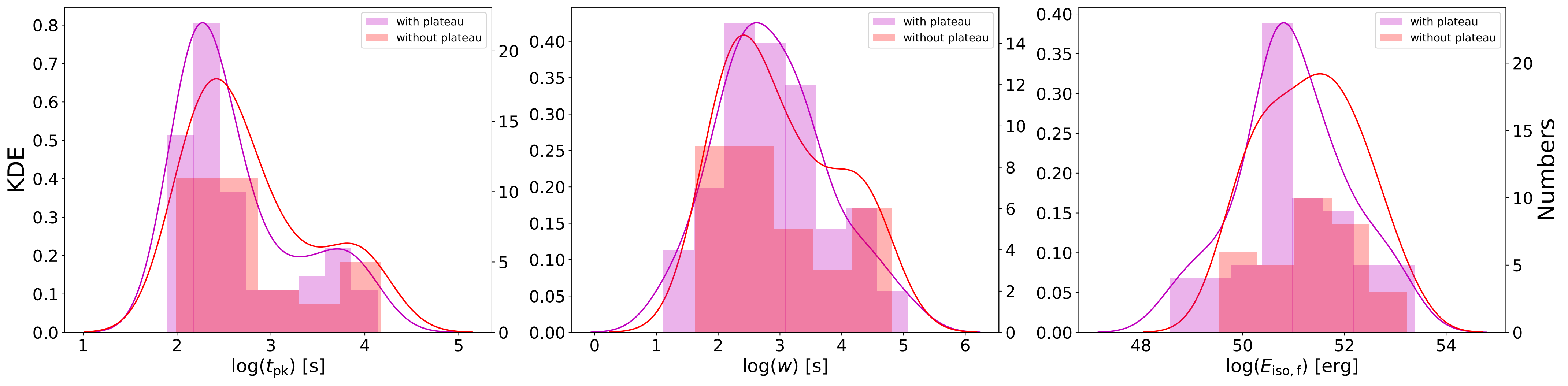
Conclusion- (1): The existence of flares is independent of the existence of a plateau.

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

Results: flare properties (1)

GRBs with plateau

GRBs without plateau



Flare peak time

Flare width

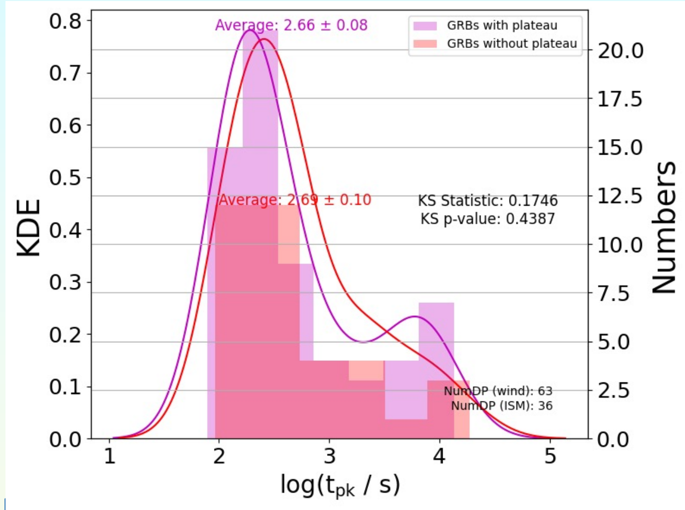
Flare total energy

No notable differences between flare properties

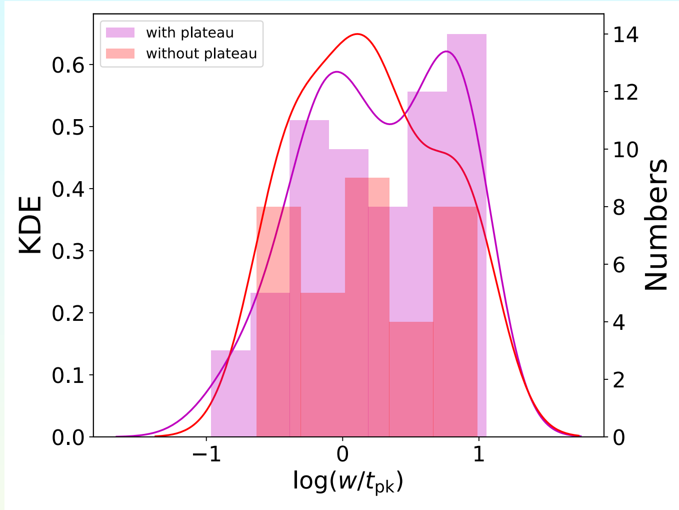
Dereli-Begue, AP, Begue, Ryde, 2024, submitted

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 ✓