Several aspects of MHD-driven relativistic jets

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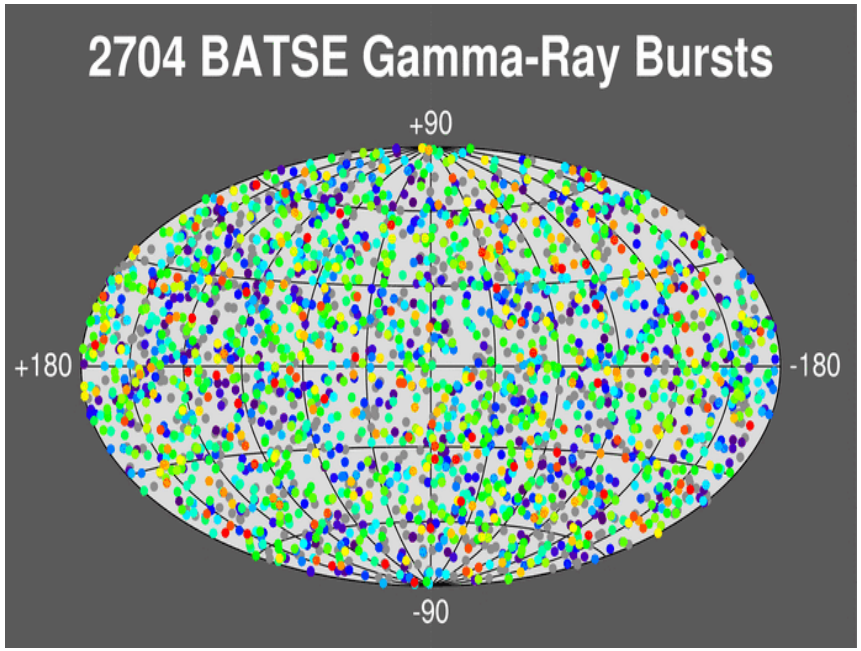
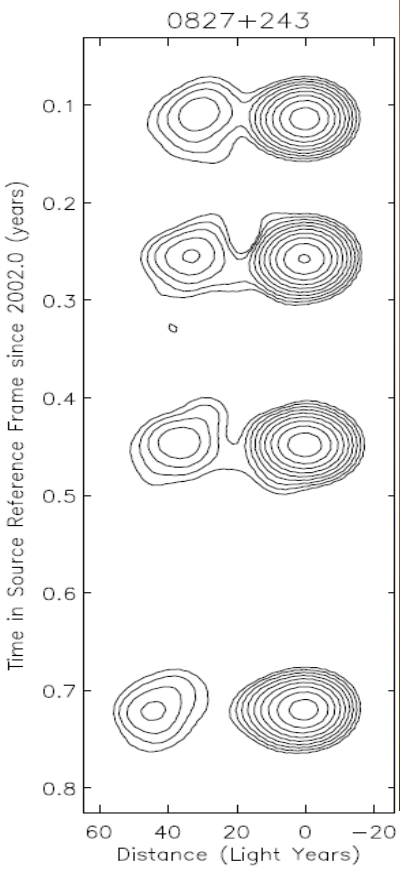
Relativistic jets in GRBs and AGNs

GRBs: powerful cosmic explosions

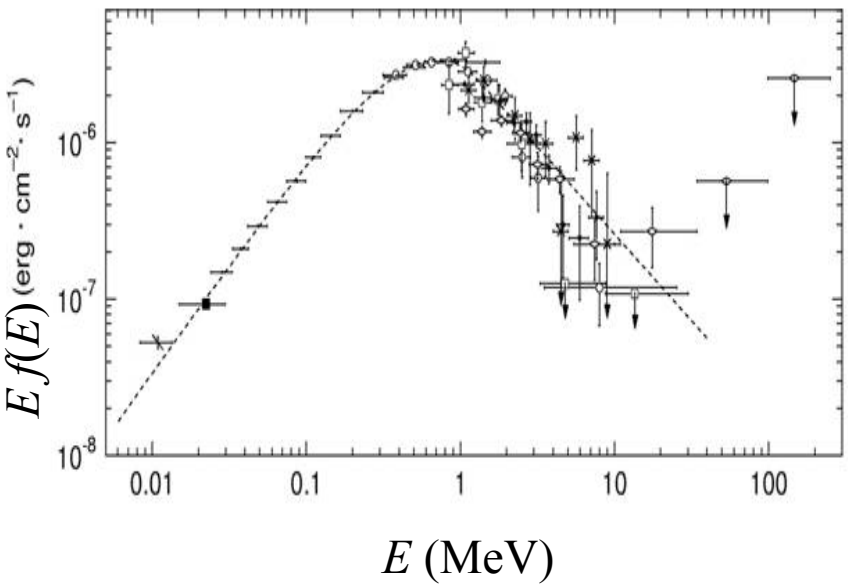


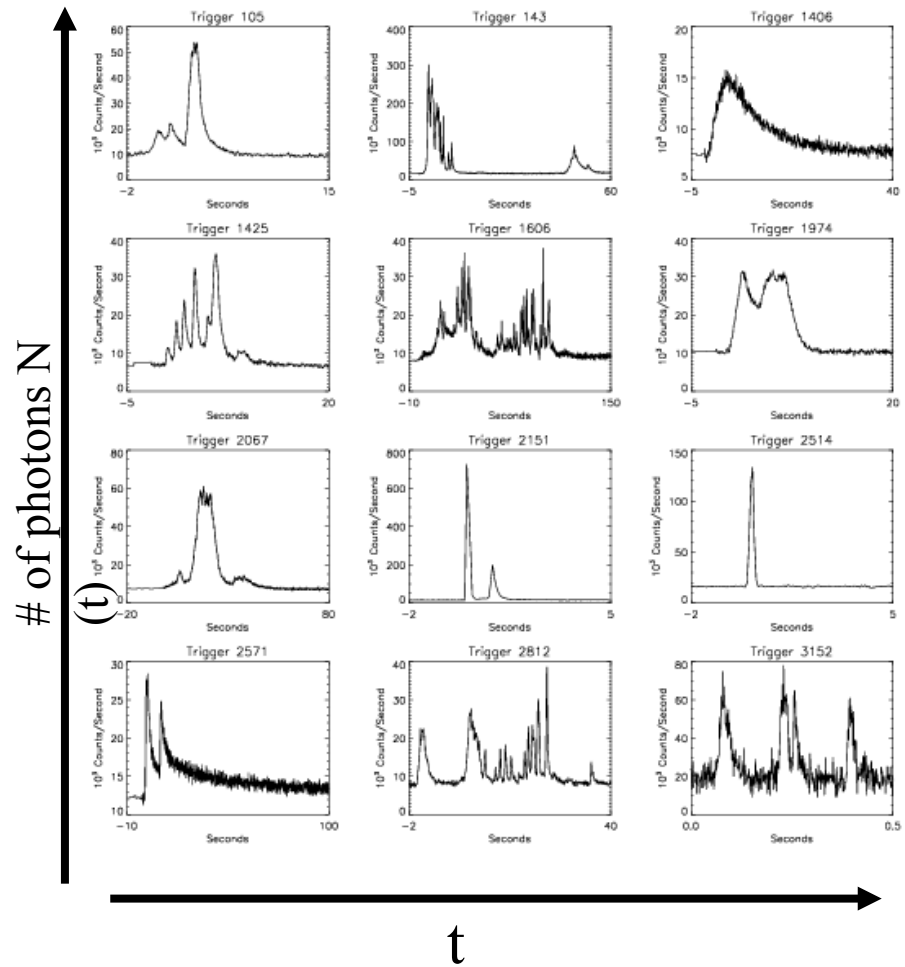
few per day – $E\gamma$~1052-1054 erg

AGN jets



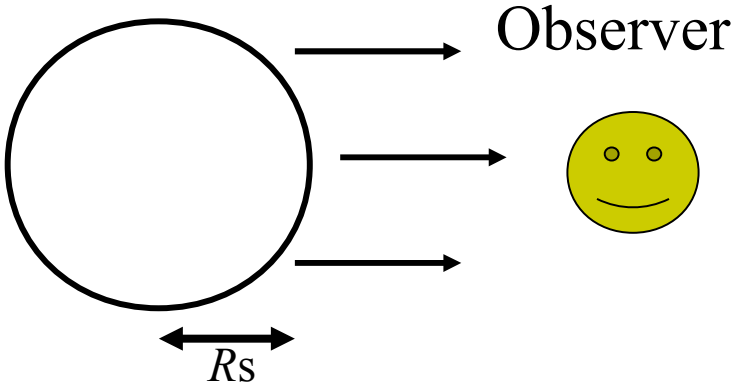
GRB spectra and variability



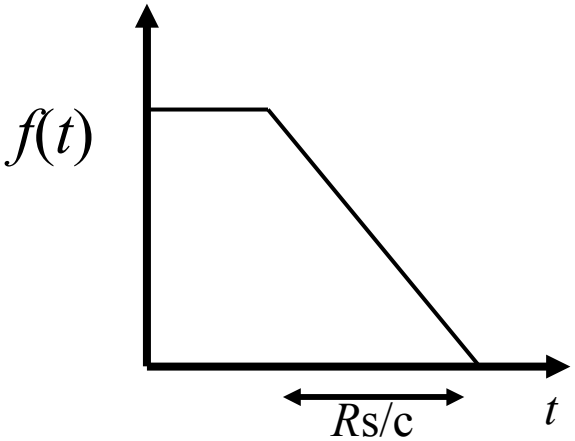


Variability and source size

- The variability constrains the size of the source
  - a source with typical scale of R_S *cannot* vary faster that timescales $t_{var} \sim R_S/c$



- Variability of msec indicates a very compact source of $R_S < c\, t_{var} \sim 3 \cdot 10^7$ cm



- Putting $N \sim E_\gamma / m_e c^2$ photons into a volume of $\sim R_S^3$ one

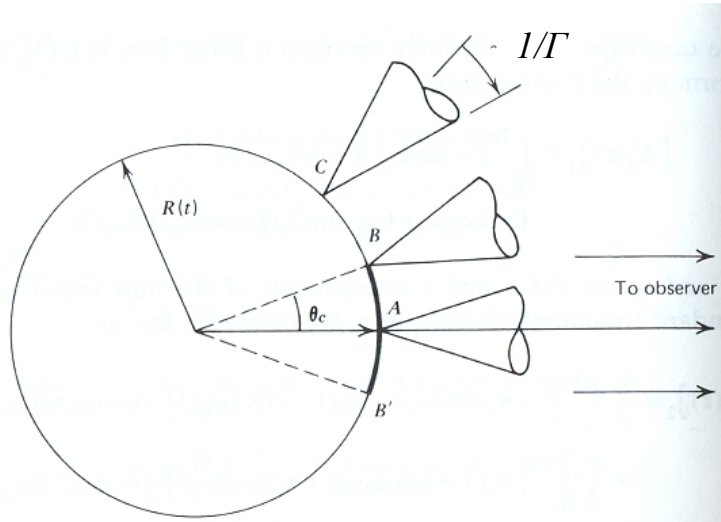
Special relativistic effects help

- For observed variability *t*var the radius of emission is constrained to be

$$Rs < 2 \cdot \Gamma 2 \cdot c \cdot t\mathrm{var}$$

Much larger than the non-relativistic

$$Rs < c \cdot t\mathrm{var}$$



- Larger radius of emission

→ smaller density of γ-rays in the source

→ less optical depth to $\gamma\gamma$ annihilation

Emission Γ>100 (1000?) are needed!

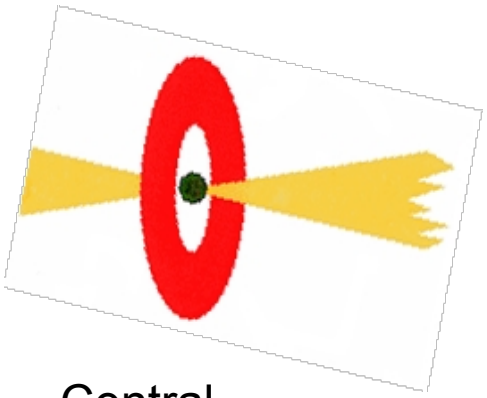
Summary for the GRB emission

- Clues
  - The powerful GRB emission
    - extends well above the pair creation threshold

      Band et al. 1993; Preece et al. 1998; Abdo et al. 2009
    - ***Rapid*** variability
  - The GRB-emitting flow is ***ultrarelativistic*** ($\Gamma>100$)

    e.g. Lithwick & Sari 2001
- *Some big questions*
  - How is the jet launched?
  - How is the flow accelerated?
  - What processes result in the jet emission?
  - What can we learn from the afterglow emission?

The GRB framework

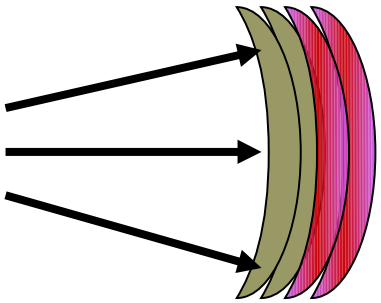


Central Engine

~106cm

GRB emission

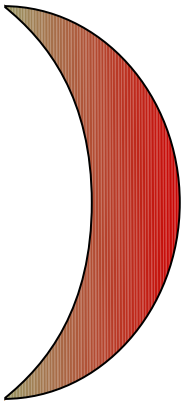
γ–ραψσ



Acceleratio n & internal dissipation

~1011-1016cm

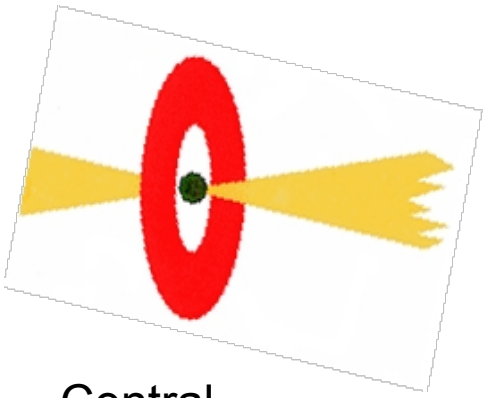
Afterglow



External Shock

~1016-1018cm

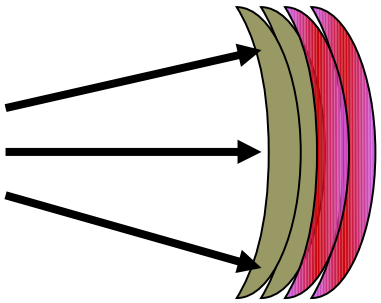
(The AGN jet framework)



Central Engine

~1014cm

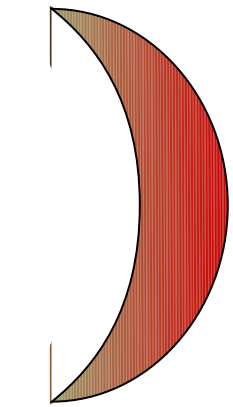
“blazar” zone



Acceleratio n & internal dissipation

~1016-1017cm

e.g. radio lobes

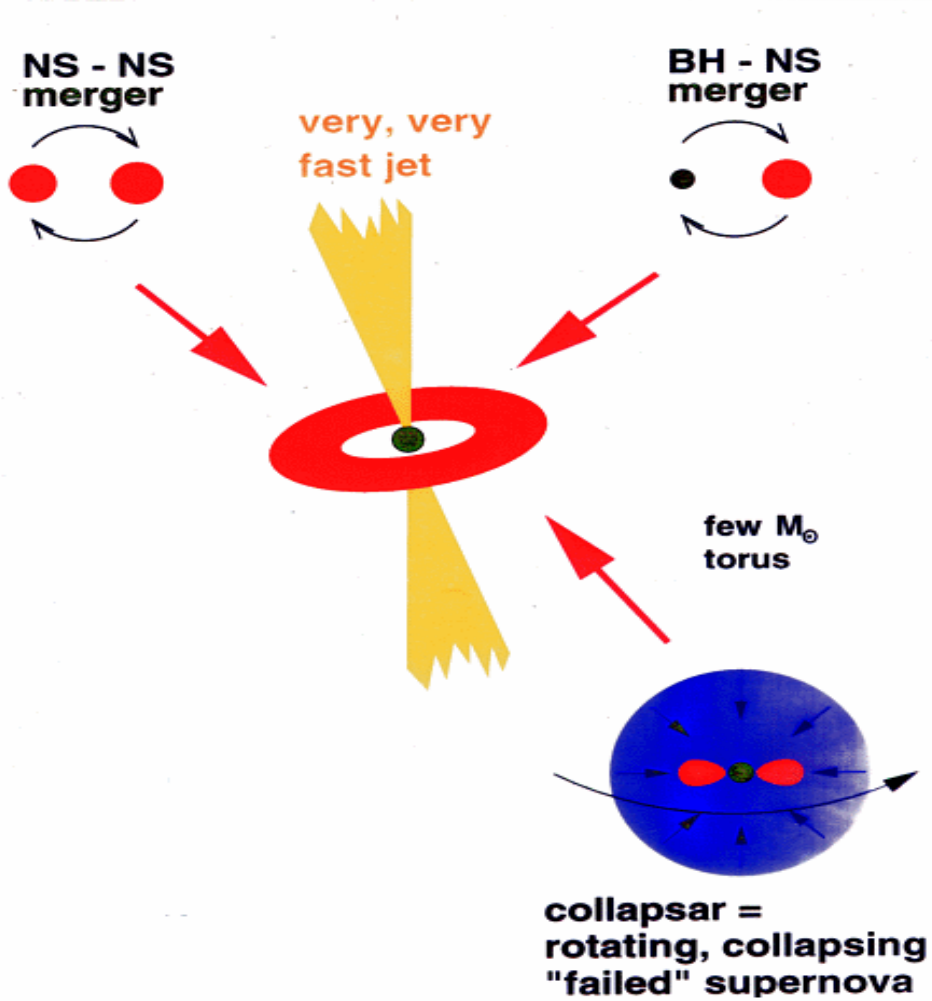


External interactions

~1021-1024cm

The GRB central engine

Short Bursts



Long Bursts

The jet-driving mechanism:
MHD Energy Extraction and/or neutrino annihilation

From the rotational energy of the black hole:

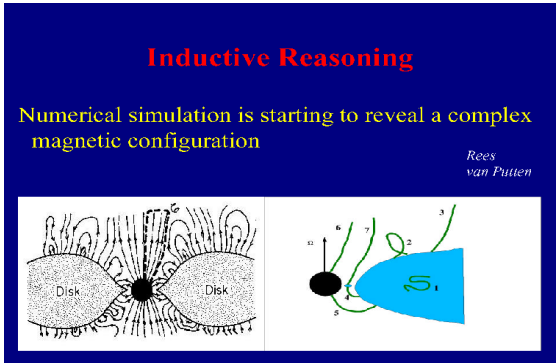
$$L \propto B^2 r_S^{\,2} c \sim 4 \times 10^{51} B_{15}^2 \left(\frac{M}{3 M_e} \right)^2 \text{ erg s}^{-1}$$

Neutrino annihilation energy
deposition rate (erg cm –3 s-1)

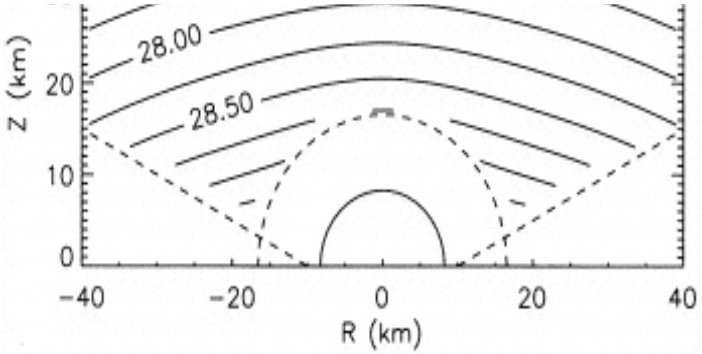
Plausible for GRBs only

B ~ 1015 gauss for 3 solar mass black hole

Well below equipartition in the disk!



Blandford & Znajek 1977
Koide et al. 2001
van Putten 2001
Lee et al. 2001
Barkov & Komissarov 2008



Eichler 1989; Ruffert & Janka 1999; Popham et al. 1999; Aloy et al. 2000; Chen & Beloborodov 2007

Basic properties of the jet

- Important quantities:
  - luminosity L
  - mass flux $\dot{M}$

  Baryon loading $\eta = \frac{L}{\dot{M}c^2} >> 1$
  - Efficient acceleration can lead to $\Gamma sr \sim \eta$

- Depending on the energy extraction mechanism, the flow can initially be dominated by

Thermal energy (*Fireball*) ⇒ thermal acceleration

Paczynski 1986; Goodman 1986; Sari & Piran 1991; Piran 2005

Magnetic energy (*Poynting-flux dominated flow*) ⇒ MHD acceleration

Applicable to all relativistic jets

Usov 1992; Thompson 1994; Mészáros & Rees 1997; Drenkhahn & Spruit 2002; Lyutikov & Blandford 2003

Poynting-flux Dominated flows

- Energy initially stored in the magnetic field

$$\eta \sim B_0^2 / 8\pi \rho_0 c^2 >> 1$$

- The field can be
  - axisymmetric

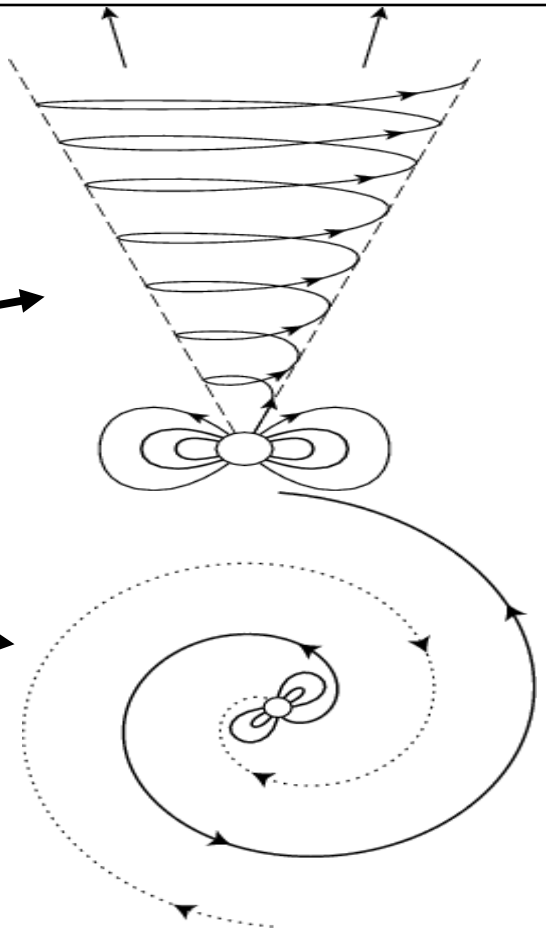
Vlahakis & Königl 2003; Lyutikov & Blandford 2003; Lyutikov 2006; Komissarov et al 2008

  - highly asymmetric

Drenkhahn & Spruit 2002; Thompson 2006

- Extracts the rotational energy of the compact object

- Acceleration of the flow largely model dependent



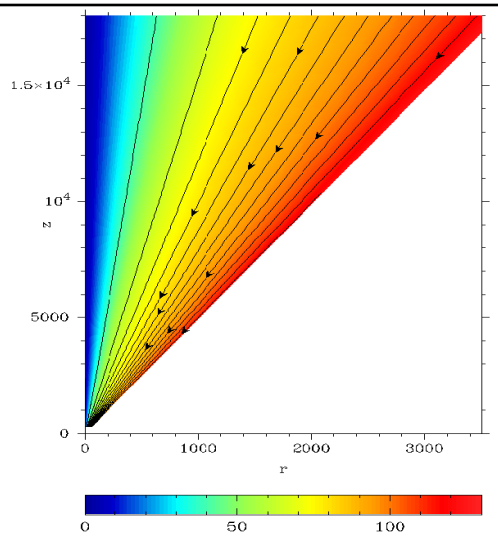
Coroniti 1990;
Lyubarsky & Kirk 2001

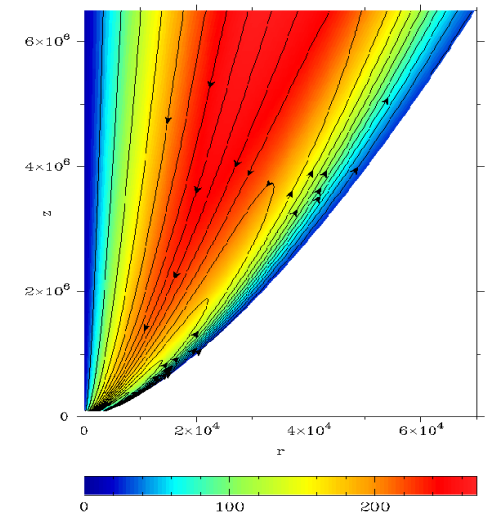
Axisymmetric rotator I

- Large progress in 2D analytical and numerical RMHD simulations

  Vlahakis & Koenigl 2003; komissarov et al 2009; Tchekhovskoy, McKinney & Narayan 2009; Lyubarsky 2010

  - High magnetization flows may accelerate to $\Gamma > 100$, $\sigma \sim 1$
  - Acceleration depends on the funnel shape
- GRB emission produced further out



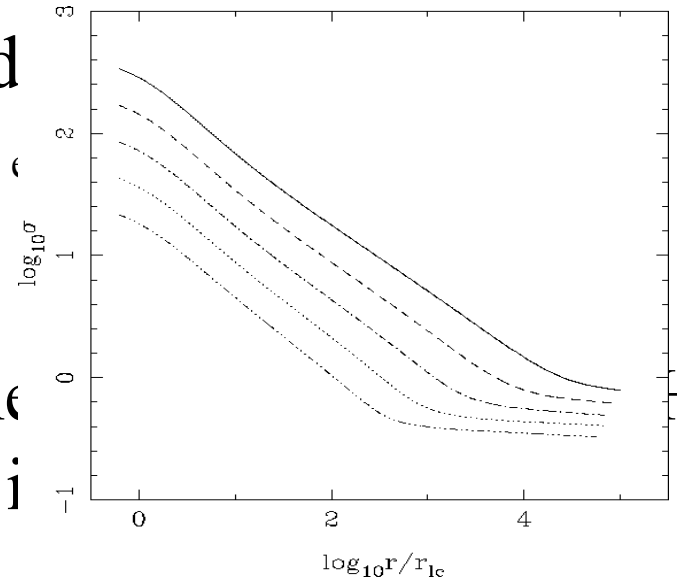


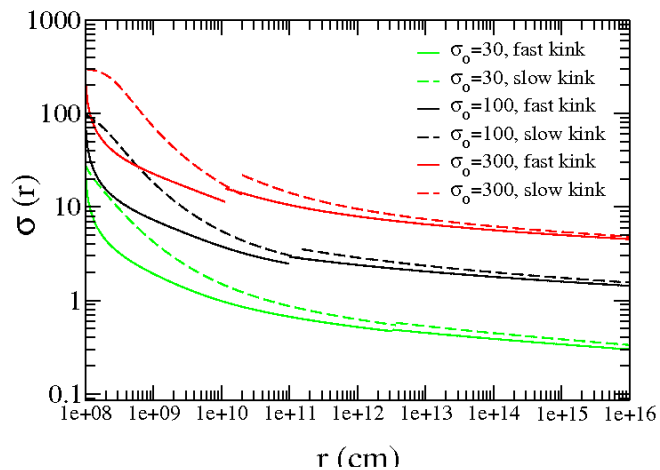
- Are they 3D stable?
  - Current-driven instabilities may appear in 3D and affect the dynamics

  Begelman 1998; DG & Spruit 2006

Axisymmatric rotator II

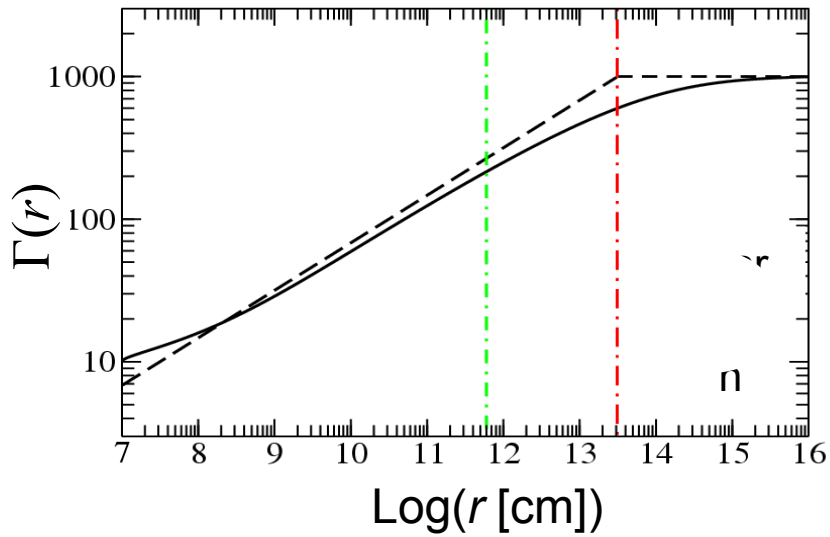
- The magnetization is of ord
  acceleration is over Komissarov e
- Similar estimates may come HD
  current-driven instabilities i





Nonaxisymmetric flow (Striped Wind)

- Magnetic field changes polarity on small scales and reconnects
  Drenkhahn 2002 and Denkhahn & Spruit 2002; see also Lyubarsky & Kirk 2001 for pulsar winds
- Dissipation is gradual and leads to acceleration of the flow *and* emission
- The model *predicts* the rate with which energy is released with radius



$$\Gamma = \Gamma_{sr}(r/r_{sr})^{1/3},$$

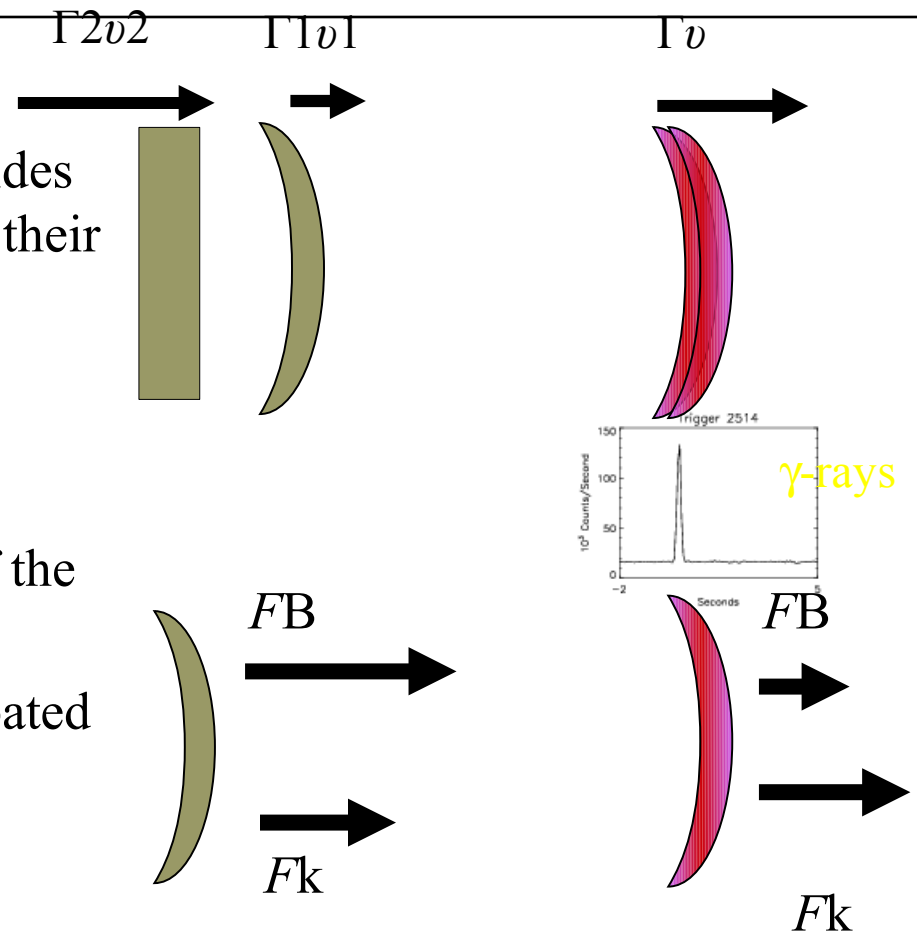
$$B' \propto r^{-4/3},$$

$$n' \propto r^{-7/3},$$

$$P'_{diss} = \frac{(B')^2/8\pi}{t_{diss}} \propto r^{-3}$$

The GRB emission: Internal shocks or Magnetic dissipation?

- Internal shocks
  - A fast shell with $\Gamma 2 > \Gamma 1$ collides with a slower one dissipating their *relative* kinetic energy

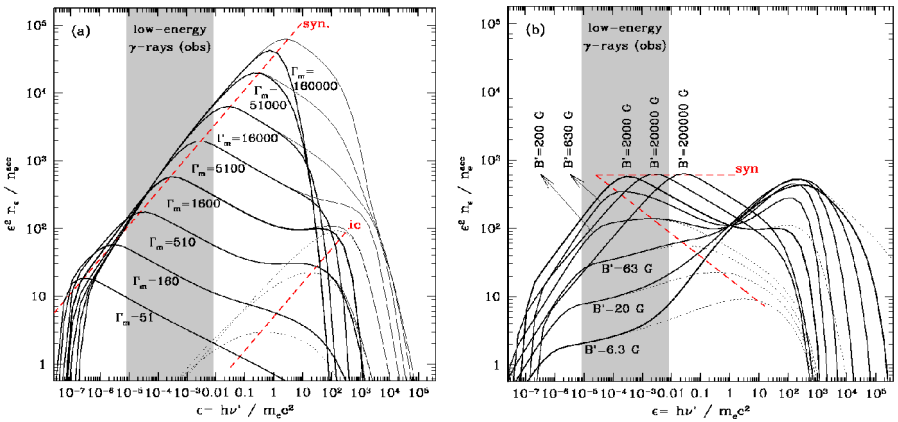


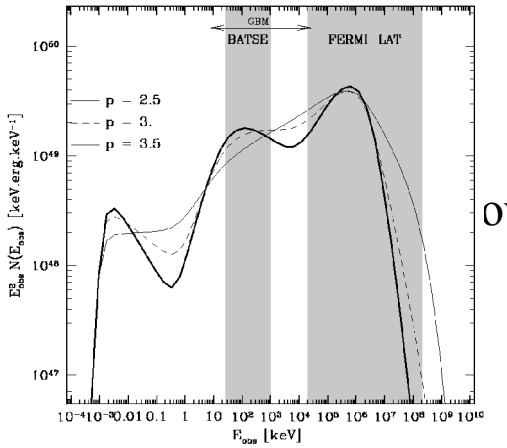
- Magnetic dissipation
  - Magnetic fields carry most of the energy of the flow
  - The magnetic energy is dissipated internally through, e.g., reconnection

The observed variability reflects the central engine activity

Spectra from internal shocks in a fireball

- Shocks accelerate particles and amplif
- Big variety of spectra ***depending*** on th
  - ϵdiss -fraction of dissipated energy
  - ϵB, ϵe -fraction that goes to B-fields,
  - Fraction ζ of accelerated electrons
  - Electron power-law index *p*
  - Distance of collision
- Dominant processes: *Compton scattering* of phc ow; *synchrotron-self-Compton*

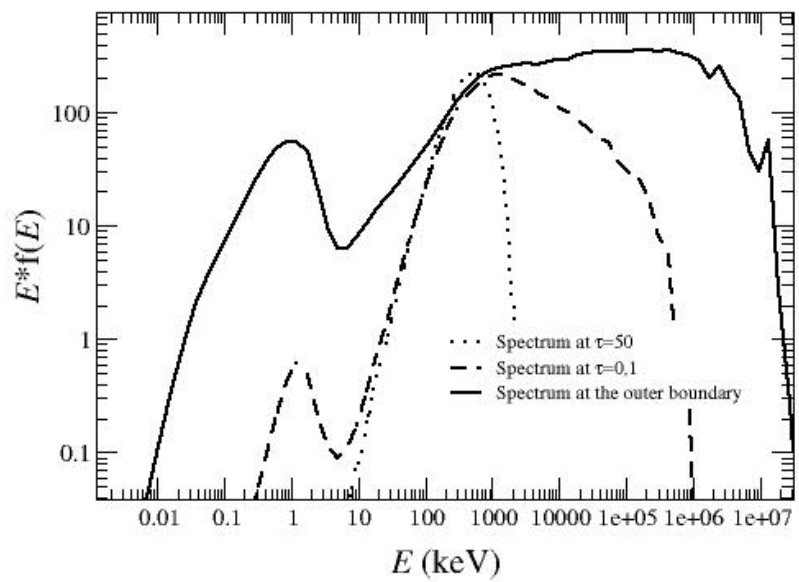




Bosnjak, Daigne & Dubus 2008

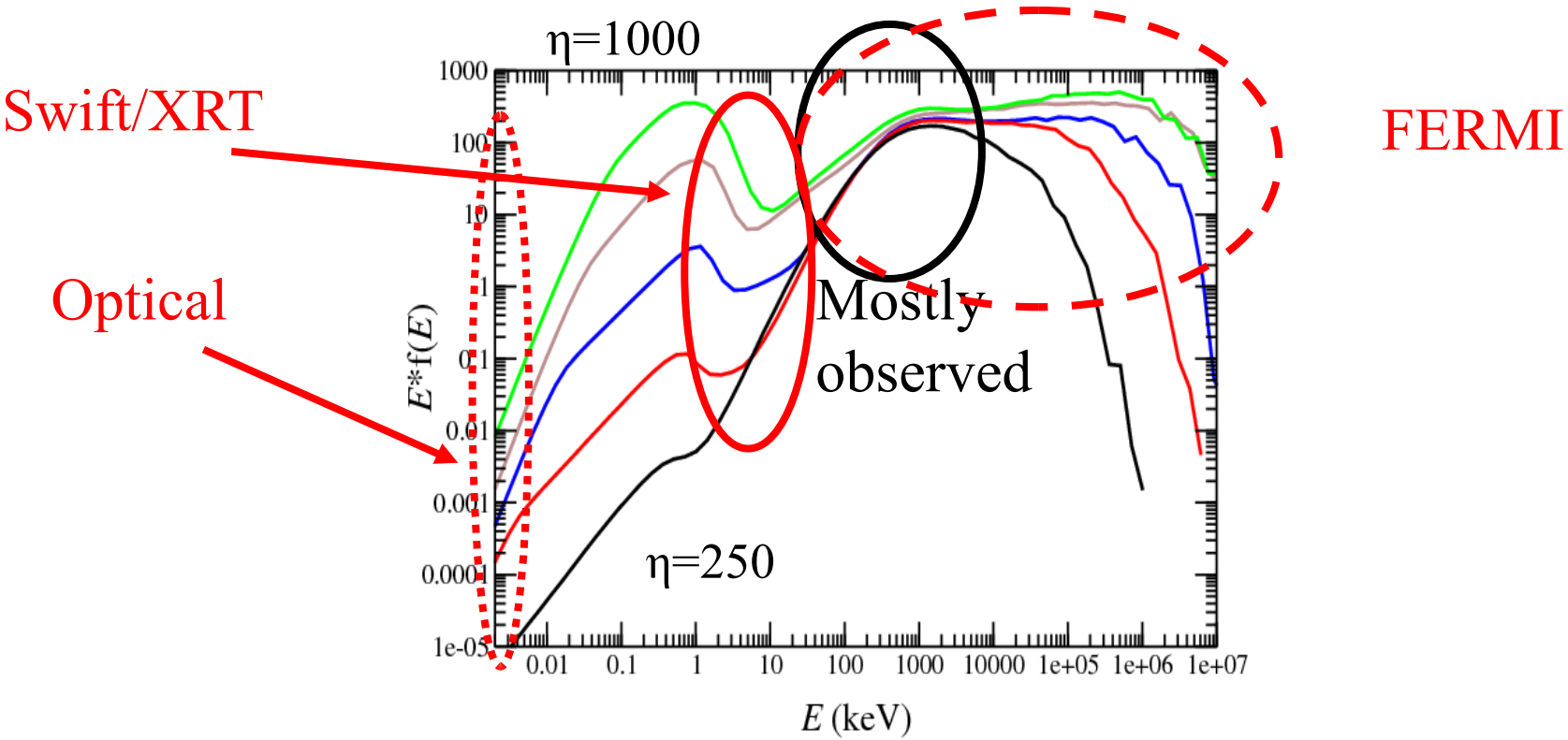
Spectra from the magnetic reconnection model

- Only one new parameter: ϵe
  - Magnetic fields, dissipation predicted by the model
  - Electrons are assumed thermal
- Deep in the flow, radiation & particles are in thermal equilibrium
- Further out balance in heating and cooling determined Te
  - Compton scattering dominates at $\tau \sim 1$
  - Synchrotron-self-Compton emission dominates further out



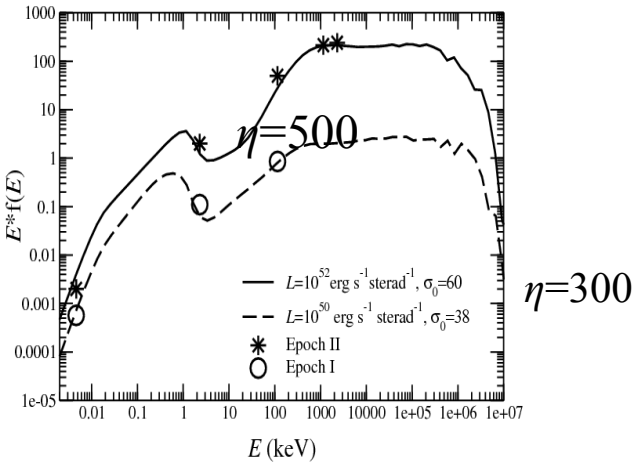
DG 2006; 2008; DG & Spruit 2007

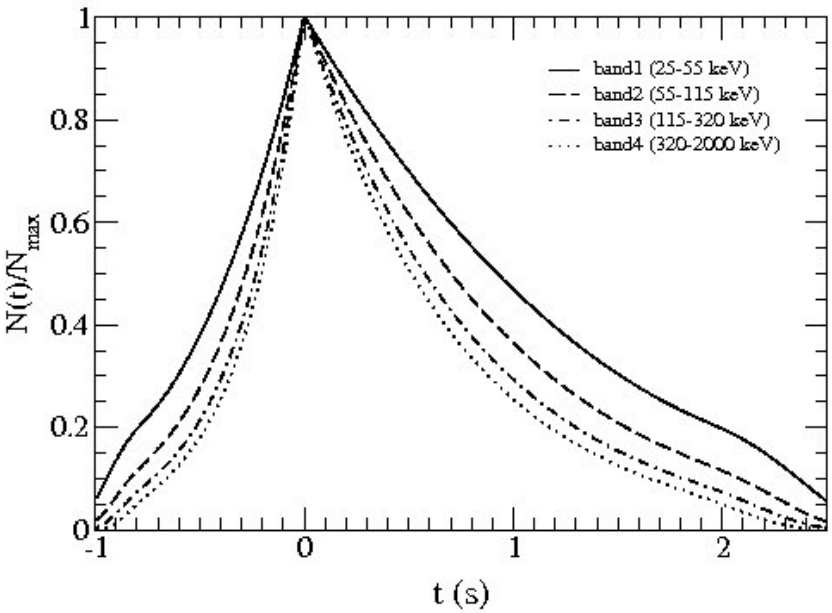
Spectra from gradual magnetic dissipation



Comparison with multi-band spectra, lightcurves

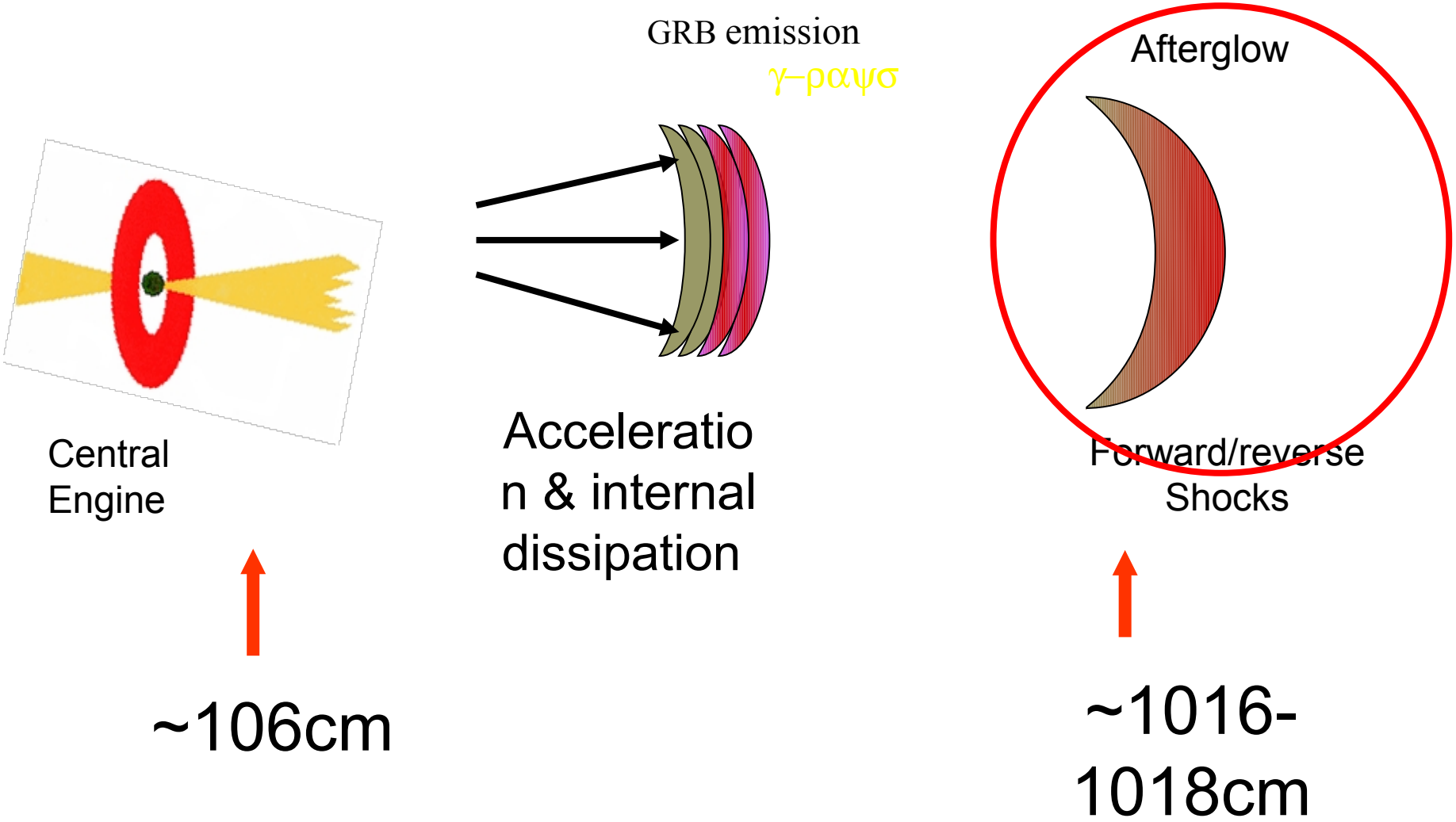
GRB 061121; Page et al. 2007





DG 2006; DG & Spruit 2007; DG 2008

Probing the magnetization through interactions with the external medium

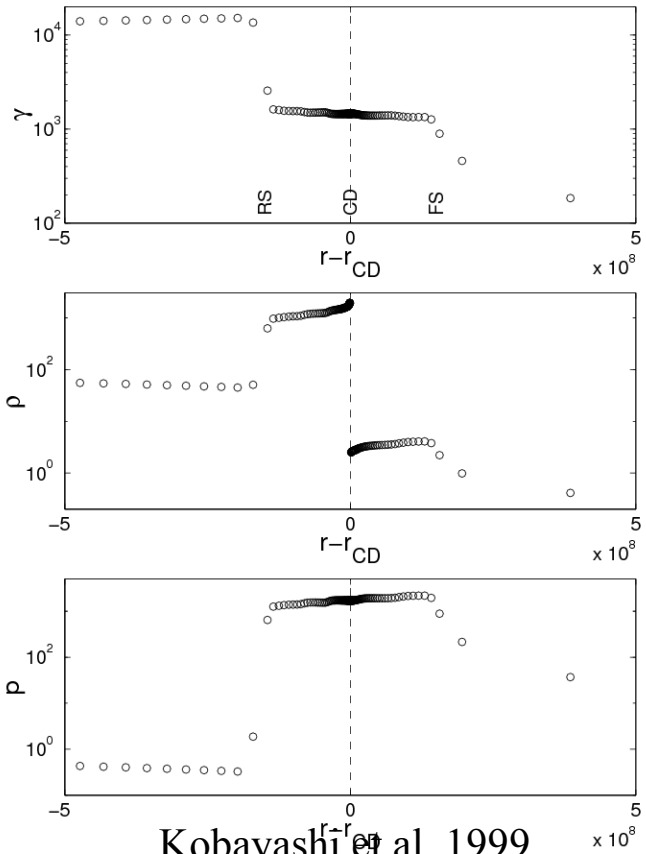


Initial deceleration: hydro $\sigma = 0$ case

- Forward-Reverse shock (FS-RS) structure *always* forms
  Sari & Piran 1995

- The RS emission comes early
  - *Prediction: powerful optical flash in most bursts* (see, however, McMahon, Kumar & Piran 2006)

- It has likely been observed (in *a few* bursts)! eg GRB 990123, 090102
  Akerlof et al. 1999; Gendre 2010

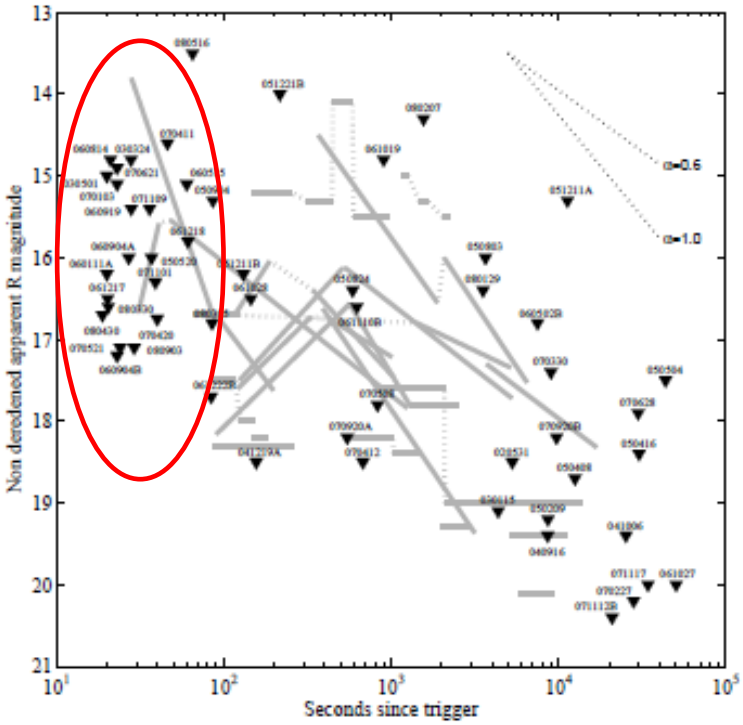


Kobayashi et al. 1999

Where are the other optical flashes?

- Rapid optical follow-ups are now routinely possible
- The large majority of bursts do not show a reverse shock signature
  - Down to ~16th

TAROT; Klotz et al. 2008



Initial deceleration: magnetized ejecta

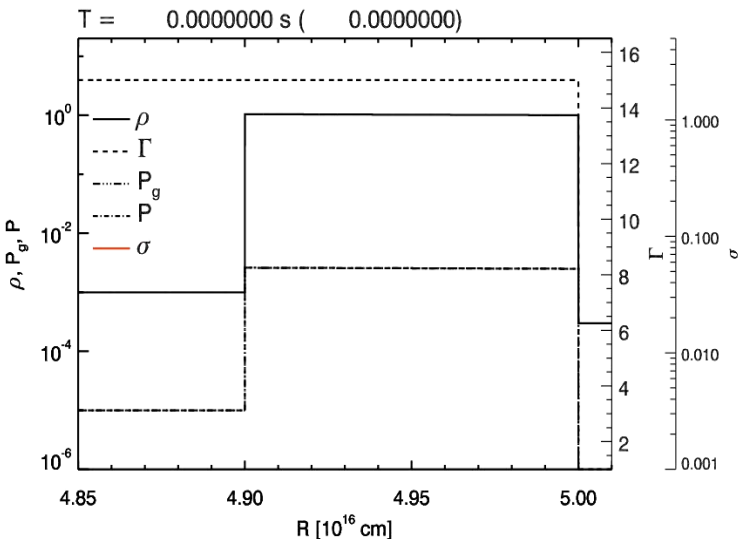
- Far less studied
- Analytical approaches indicate that even moderate magnetization affects the reverse shock strength/emission

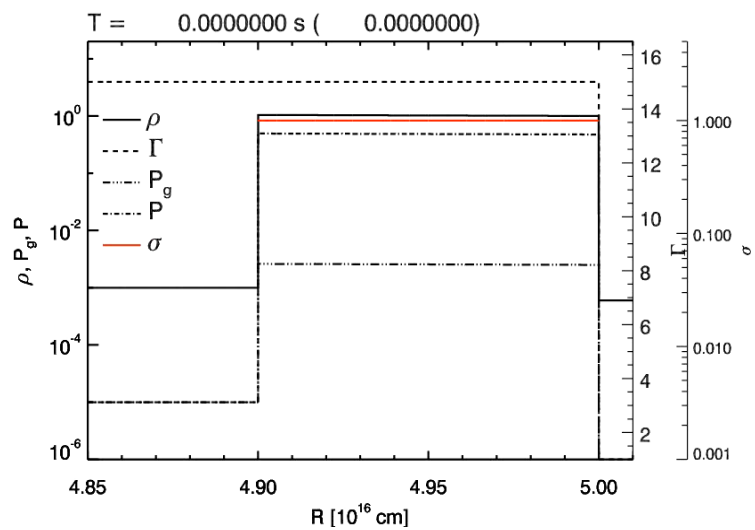
Fan et al. 2004; Zhang & Kobayashi 2005; Lyutikov 2005; DG, Mimica & Aloy 2008; Fan 2009

  - *Leading however to conflicting claims*

  - *The internal evolution of the shell needs to be taken into account*

Relativistic MHD simulations of the early deceleration of magnetized ejecta

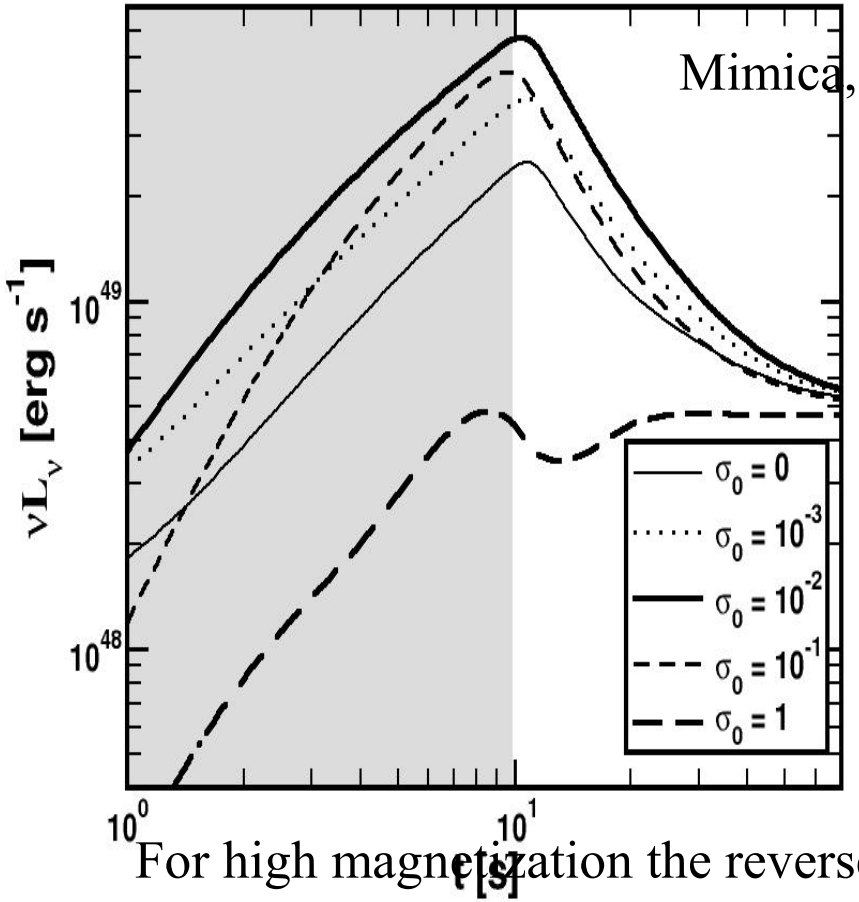


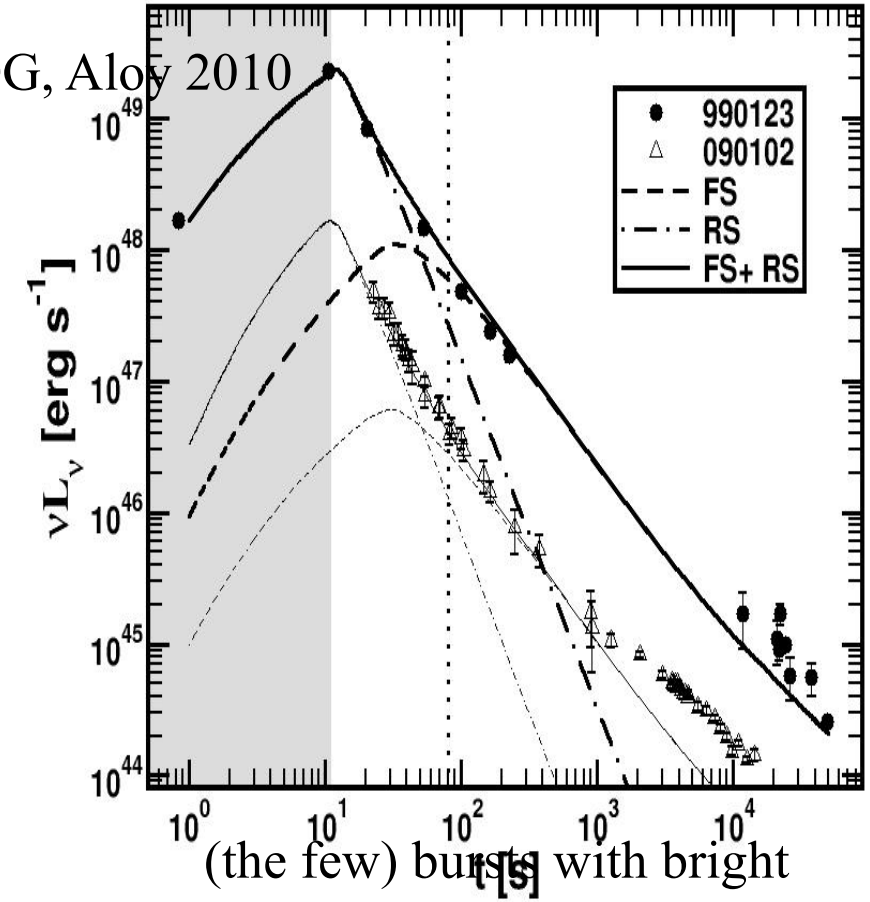


Mimica, DG & Aloy 2009; 2010

Simulated synchrotron lightcurves

Mimica, DG, Aloy 2010





For high magnetization the reverse shock emission is suppressed

(the few) bursts with bright reverse shock have σ ~0.1

Summarizing

- Powerful magnetic fields B~1015 G that thread a rotating BH, accretion disk, ms magnetar can launch the GRB flow
  - The flow is magnetically dominated
- Magnetic dissipation may efficiently power the emission of the burst
- Radiative transfer calculation shows that the observed ~MeV emission (and variability) is well explained
  - The model makes predictions for other bands (optical to GeV) that can be used to test it
- The early afterglow can probe the magnetization
  - The observed lack of RS emission is expected from $\sigma > 1$ ejecta

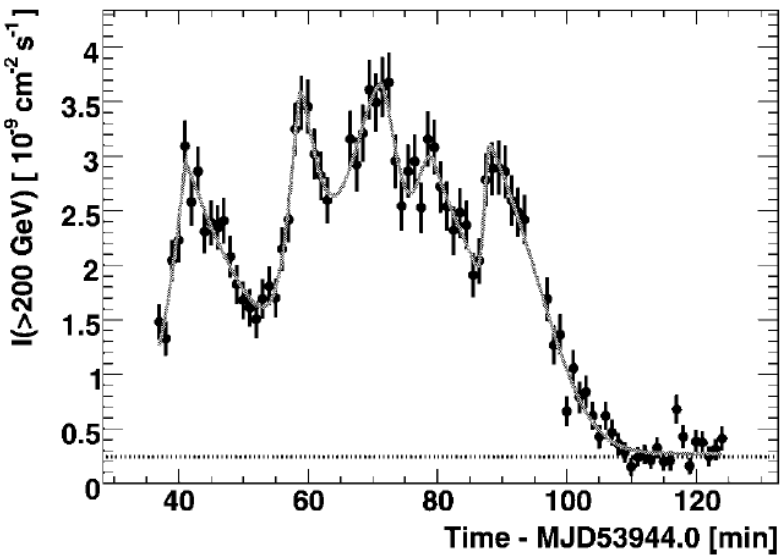
Part II:
Magnetic reconnection powers the blazar emission?

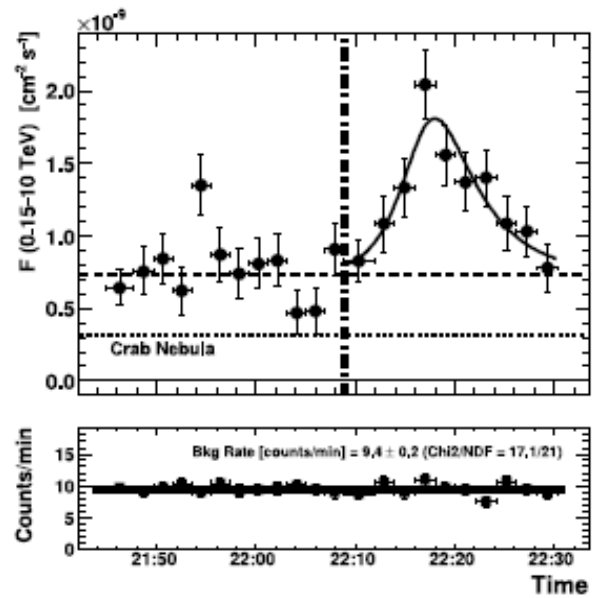
ultrafast TeV blazars

PKS 2155-304 Aharonian et al. 2007

Markarian 501

Albert et al. 2007





Both vary on timescales 3-5 min or tv <<Rg/c!!!

Implications

- Models that associate the observed variability to black hole activity do not work
  - Internal shocks at odds for these flares

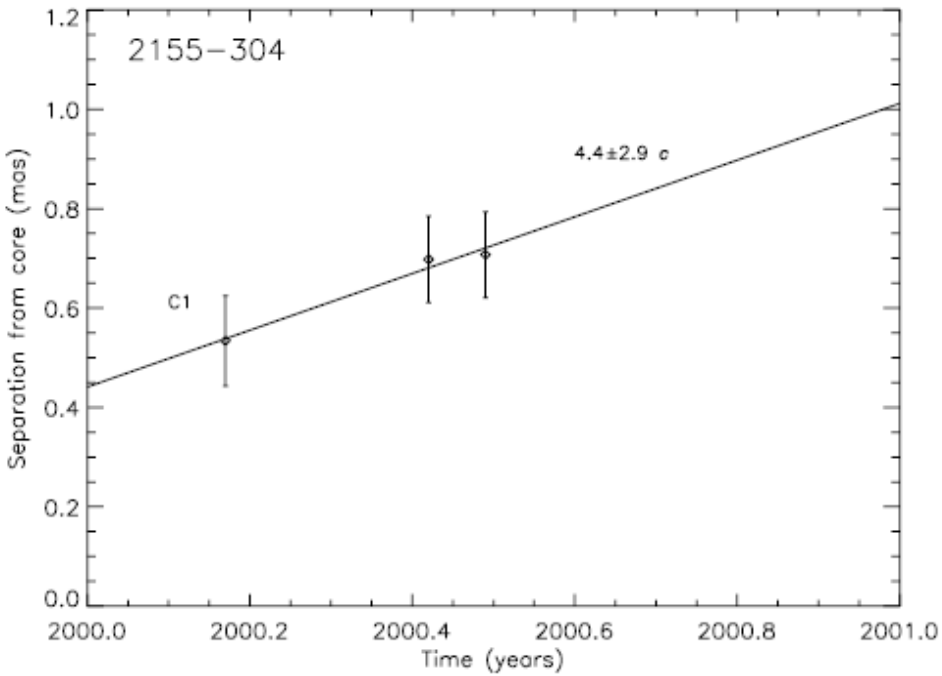
Indicates variability originating from the jet

- For the TeV emission to escape $\Gamma_{em}>50$

  Begelman, Fabian & Rees 2008; Mastichiadis & Moraitis 2008

“Slow” proper motions for these sources

- *BUT* PKS 2155-304, Mrk 501 show “mildly” superluminal ejections indicating Γ<<50
  - on sub-pc (VLBI) scales



Piner & Edwards 2004; Ghiroletti et al. 2004; Piner et al. 2008

Proposed solutions

- The jet decelerates just after the blazar zone

  Kazanas & Georganopoulos 2004

- The jet is slower ($\Gamma j \sim 10$) but contains blobs that move relativistically *within* the jet (jets in a jet)

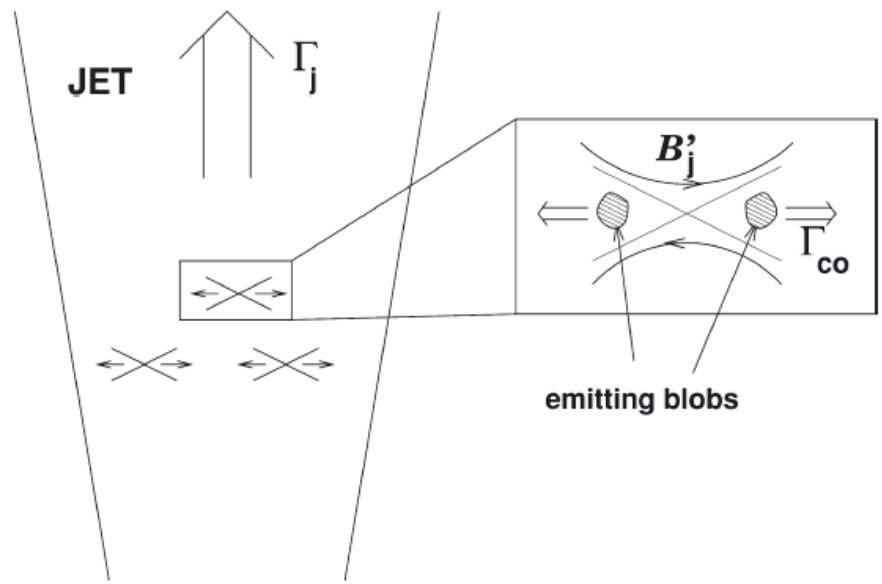
  DG, Uzdensky & Begelman 2009; 2010

Jets in the jet

- Consider a jet moving with Γj~10 and a blob moving with Γco~10, θ'~π/2 w.r.t. the jet

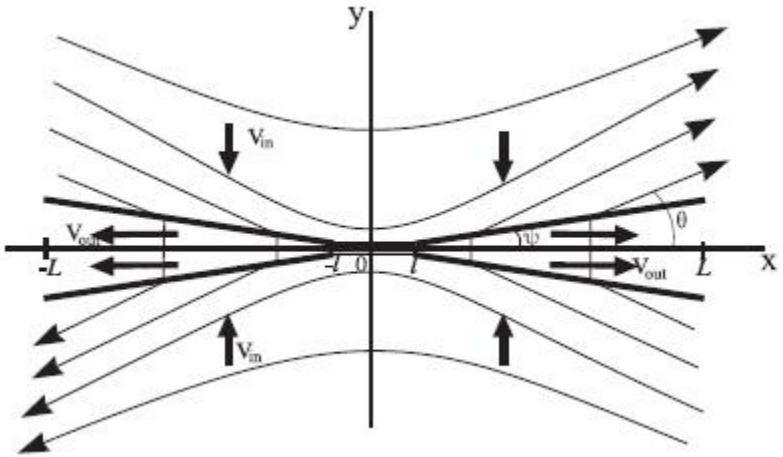
moving with the jet

- The blob moves with l



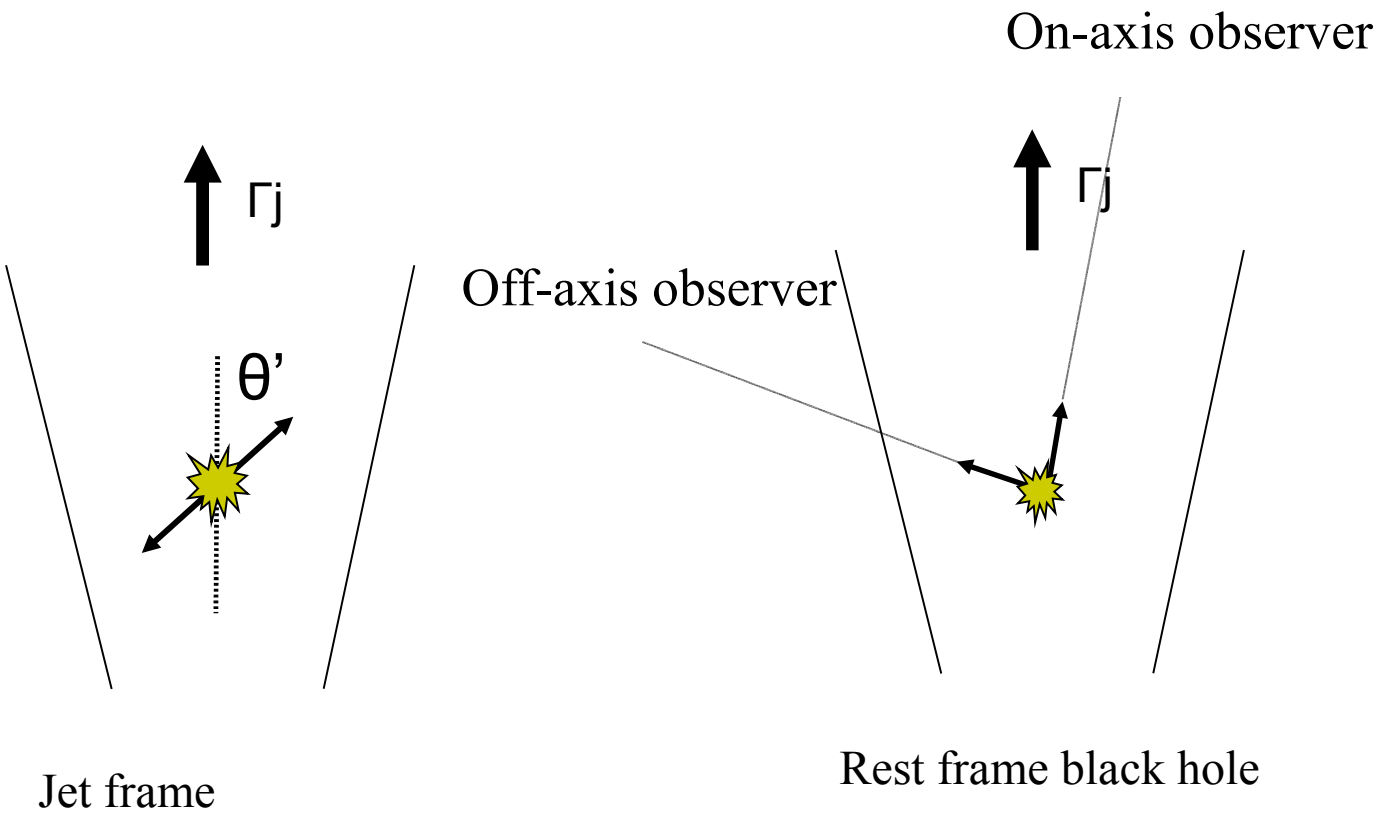
Where could these compact minijets come from?

- Suppose the jet remains Poynting-flux dominated at the blazar emission region (~100 Rg)
- (kink?) Instabilities/ polarity reversals lead to magnetic reconnection
- Material leaves the reconnection region at high speed (Relativistic Petschek reconnection)



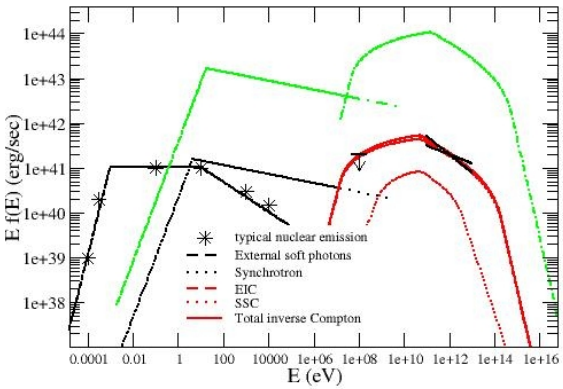
Lyubarsky 2005

Impications: Flares from misaligned jets

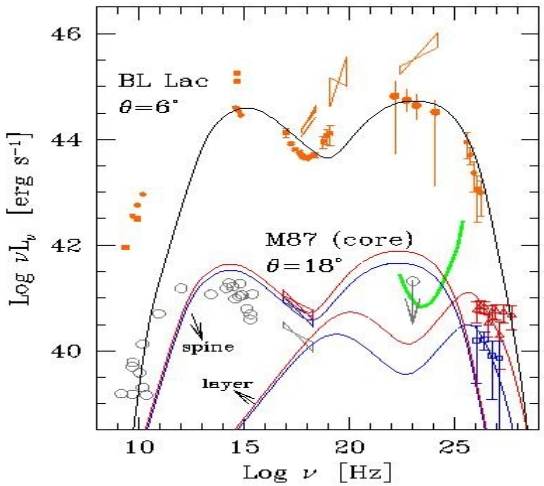


Implications: TeV flares from M87

- A minijet that emits off the jet axis explains the flares much better than a misaligned jet model



DG, Uzdensky & Begelman 2010



Tavecchio & Ghisellini 2008

Concluding

- Magnetic fields can drive the relativistic jets
- Magnetic energy can be used not only to accelerate the jets but also power their emission