Very-High-Energy Emission from Relativistic Jets

Dimitrios Giannios
Lyman Spitzer, Jr. Fellow
Princeton, Department of Astrophysical Sciences

Black Hole Astrophysics: tales of power and destruction
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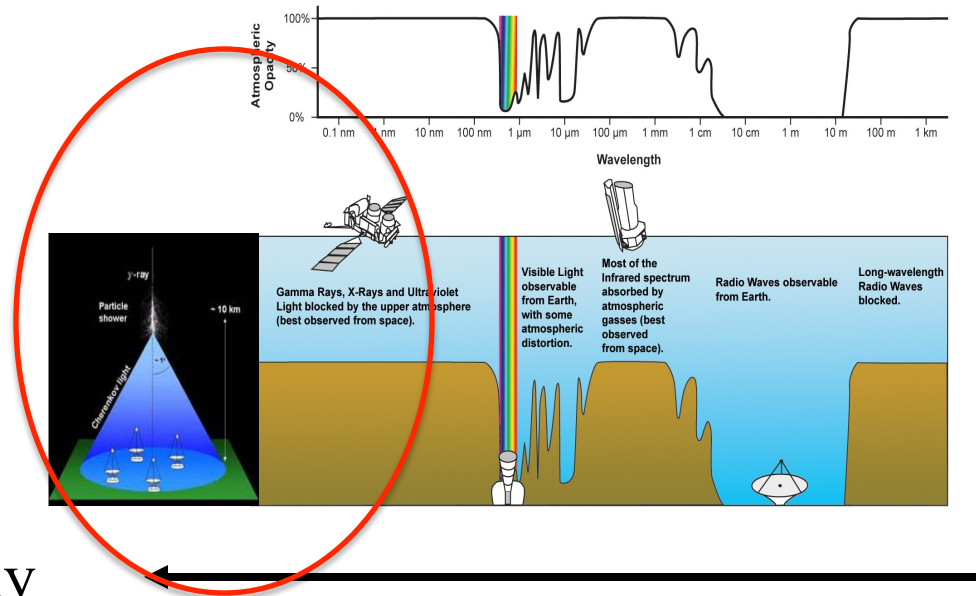
Electromagnetic radiation:
Our main window to the universe

- Until 1950's we had only access to optical and radio wavelengths
  - Limited by our atmosphere
- Satellites opened new exciting windows filling the gaps in the '60s
- In X-rays/γ-rays many, many extreme objects appeared



Higher Energies

VHE emission photons of E > GeV - TeV

Relativistic jets: the big, the small, the strong

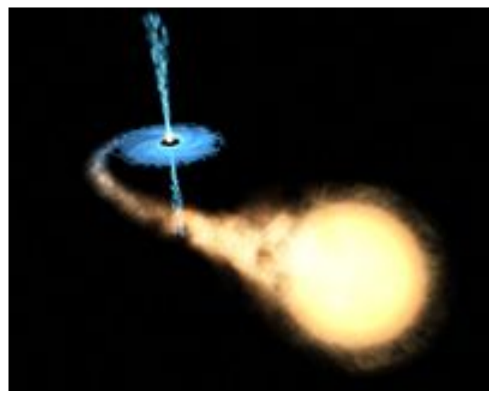
jets in galactic centers

M87; NASA/Hubble

$M_{BH} \sim 10^9 M_\odot$

Power $\sim 10^{44} \ldots 10^{49}$ erg/s

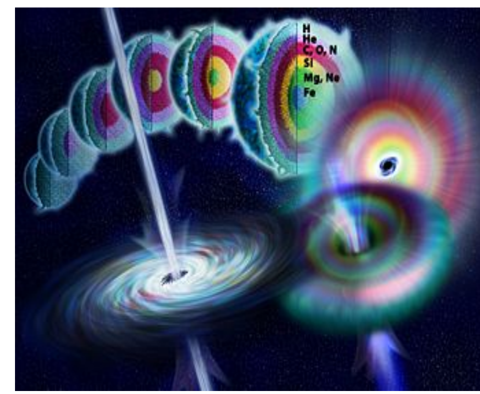
X-ray binaries



$\sim 10 M_\odot$

$\sim 10^{38}$ erg/s

gamma-ray bursts



$\sim 3 M_\odot$

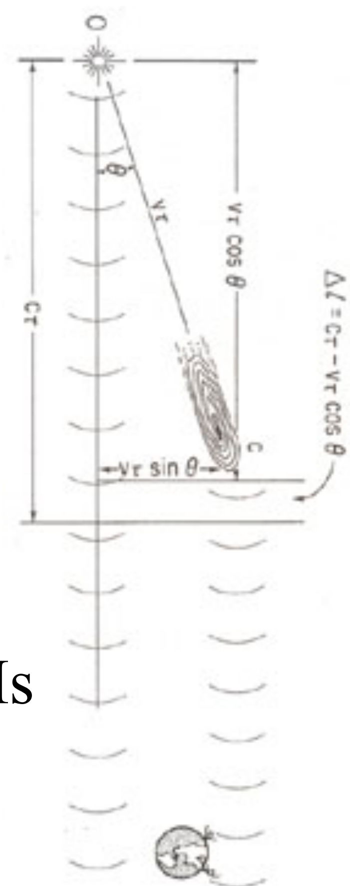
$\sim 10^{52}$ erg/s

How relativistic are jets?

$$\Gamma = \frac{1}{\sqrt{1-\beta^2}}, \beta = v/c$$

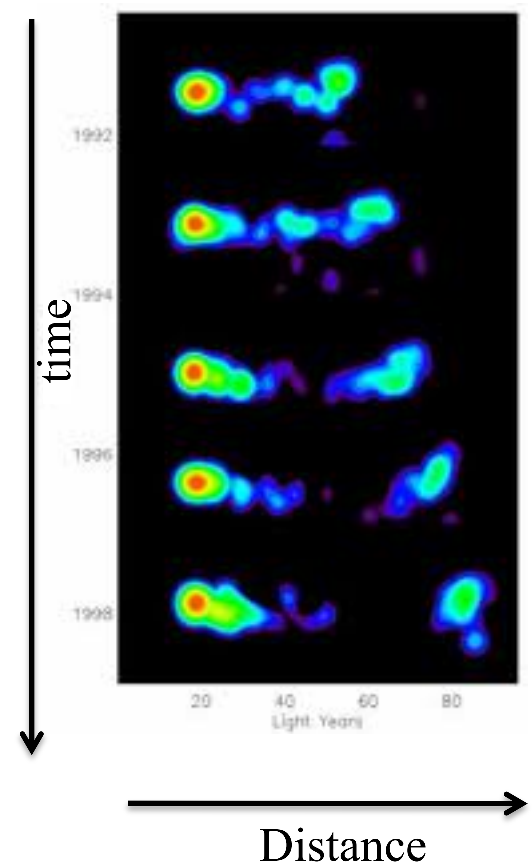
$$\Gamma \geq \beta_{app} = \frac{\beta \sin\theta}{1 - \beta\cos\theta} >> 1$$

Rees 1966



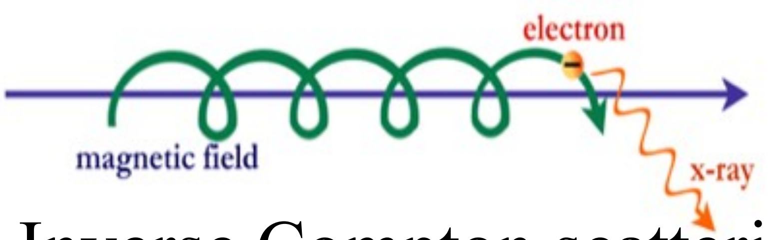
Γ~10 in jets from SMBHs
Γ~a few in binaries
Γ~100-1000 in GRBs

Biretta, Moore, Cohen 1986;
3C279 Wehrle et al. 2001



Basics: radiative processes

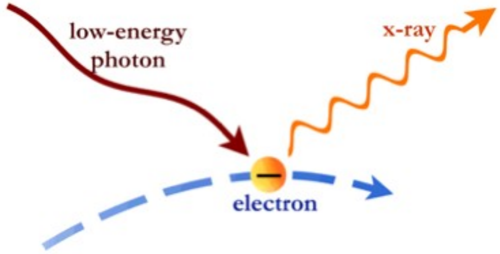
- TeV radiation requires at least E~TeV particles *e.g.* $\gamma \sim E/m_e c^2 \sim 10^6$ for electrons
- fast particles + B-fields give
  - Synchrotron emission



$$E_{syn} \approx \frac{\gamma^2 eB}{mc}$$

  - Inverse Compton scattering

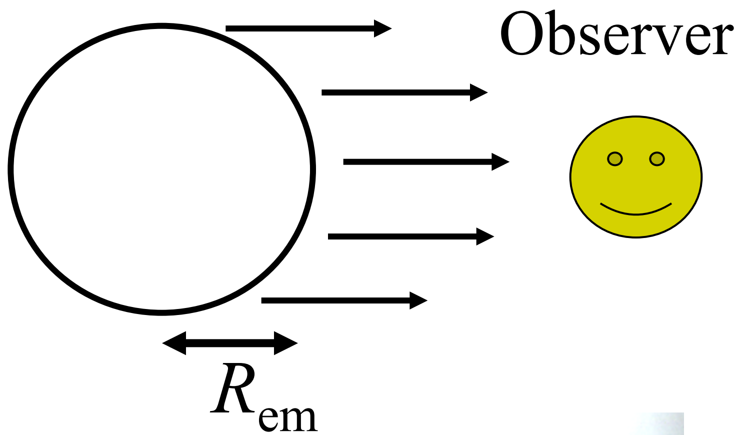
$$e + \gamma \longrightarrow e + \gamma$$

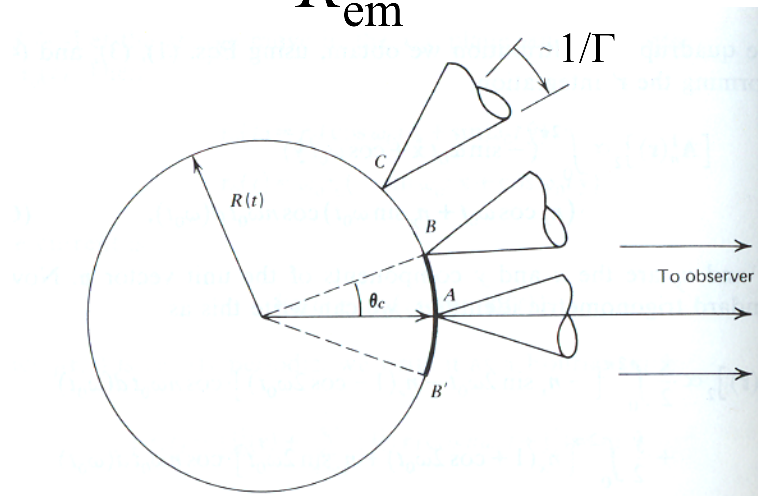


$$E_{eic} \approx \gamma^2 E_{ext}, \qquad E_{ssc} \approx \frac{\gamma^4 eB}{mc}$$

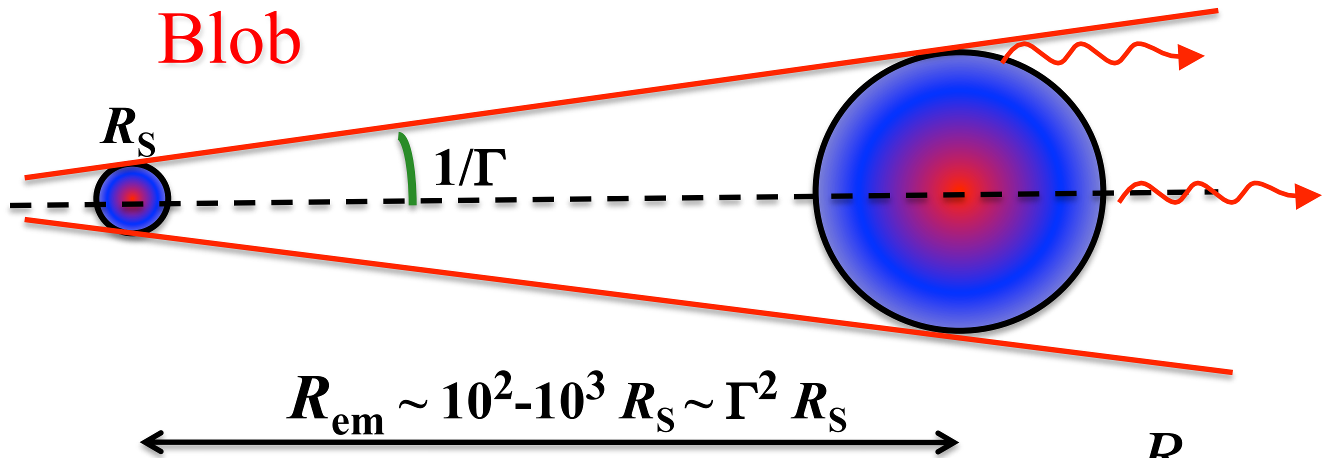
Basics: variability and source size

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

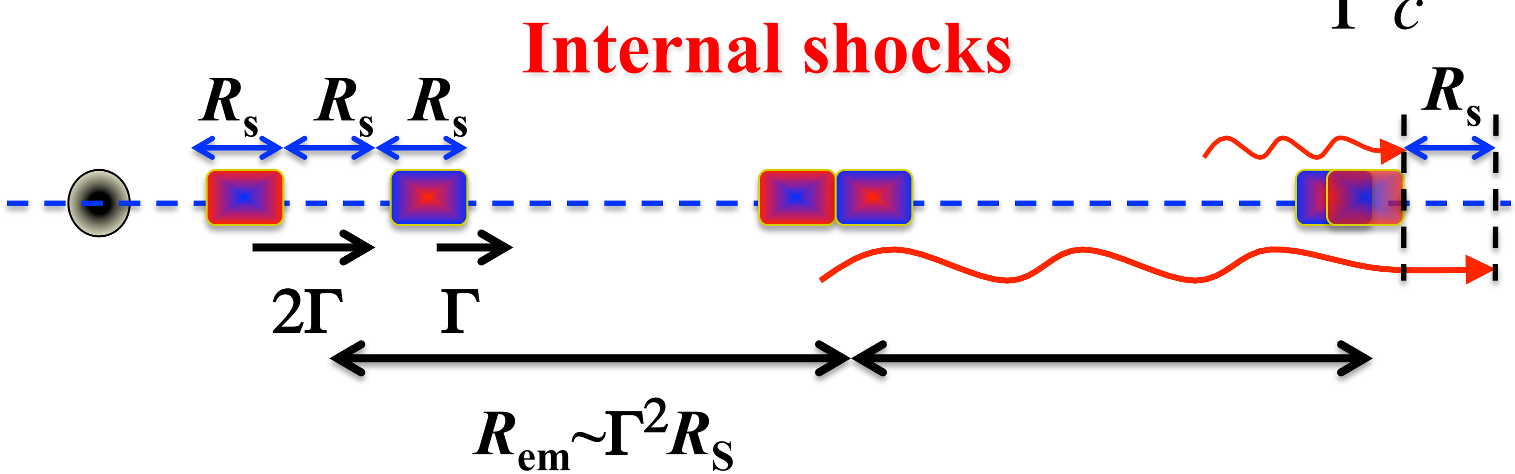




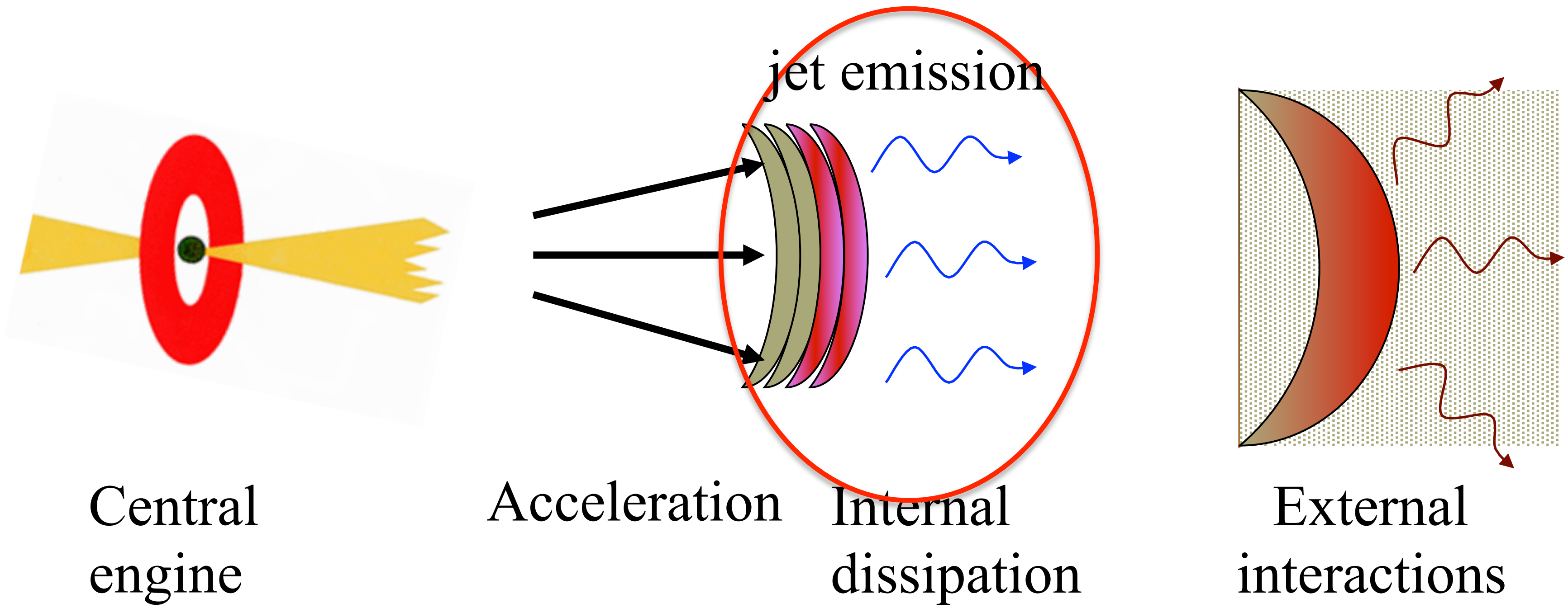
Relativistic effects preserve variability from the central engine but do NOT shorten it



$$t_{var} \sim \frac{R_{em}}{\Gamma^2 c} \sim \delta t_{bh} \geq \frac{R_s}{c}$$

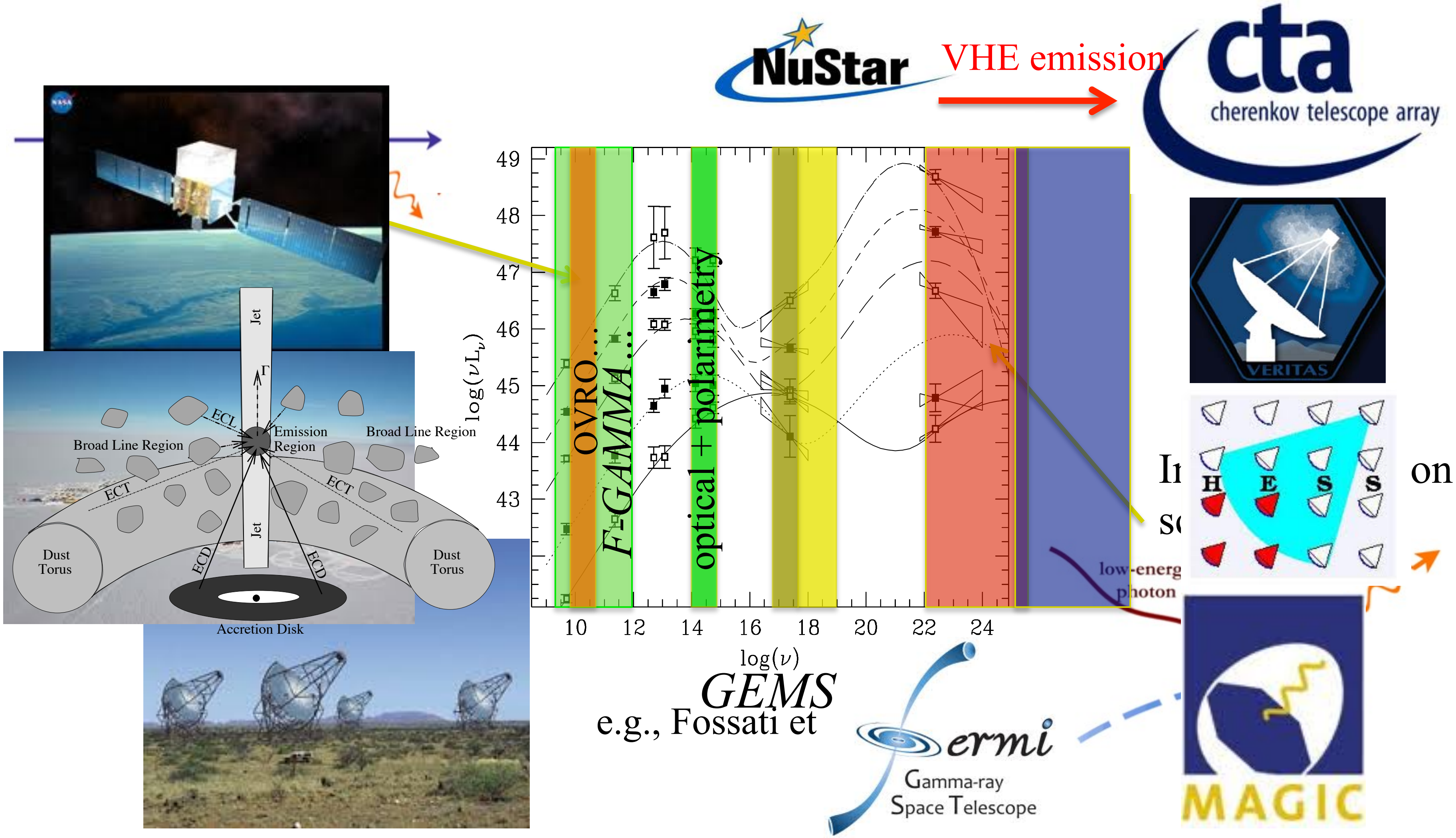


Focus: why and how do jets radiate?



Observations: *What do we see?*

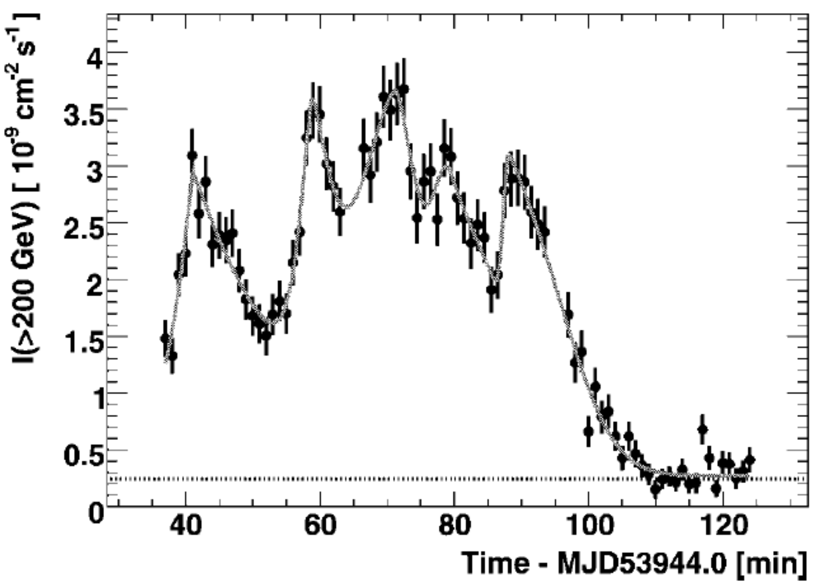
Blazars: bright at all energy bands



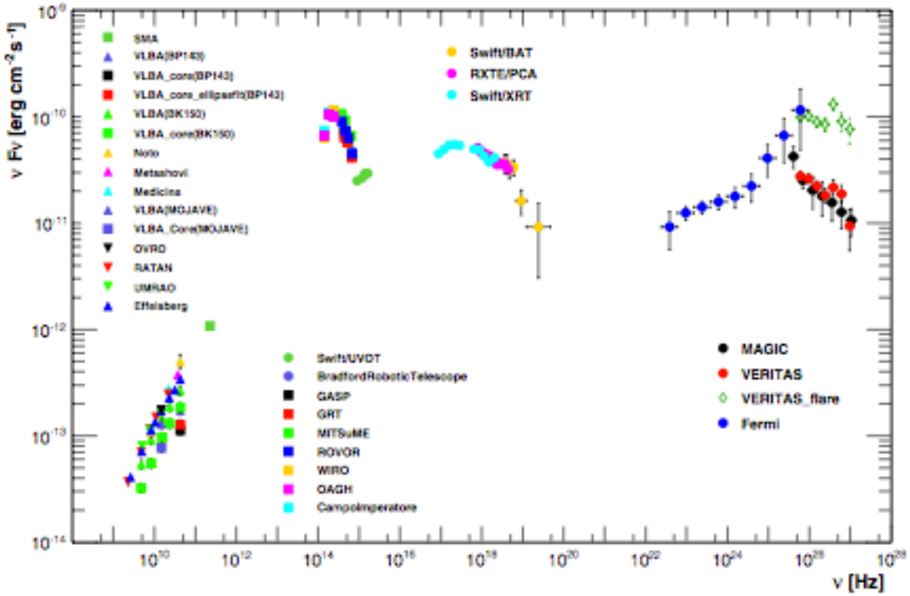
e.g., Fossati et

Recent Developments

- ultra-fast varying TeV blazars (eg. PKS 2155-304; Mrk 501)
- multi-wavelength campaigns (e.g. 3C 66A)

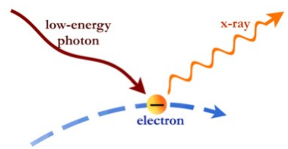


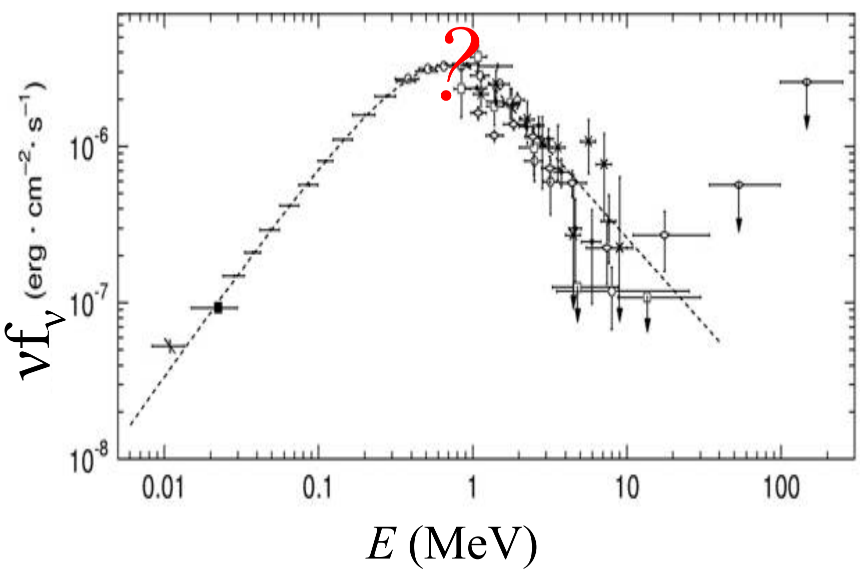
Aharonian et al. 2007; Albert et al. 2007; Aleksic 2011

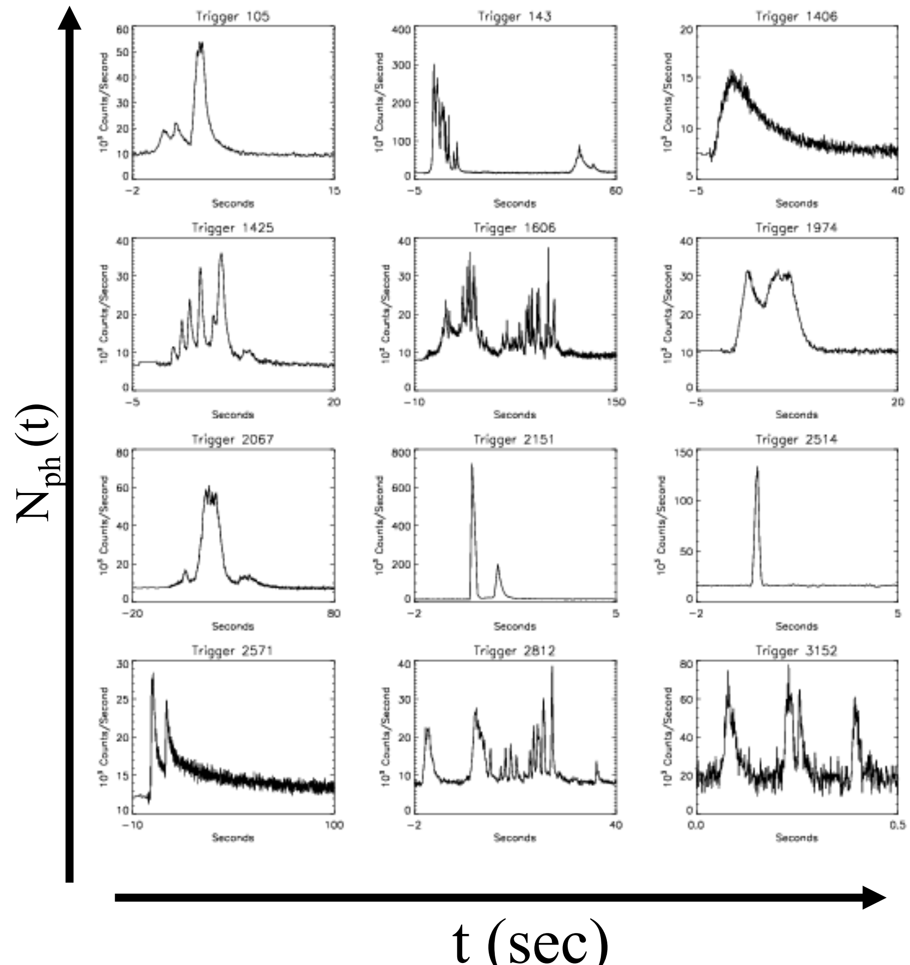


Abdo et al. 2011; Agudo et al. 2011 …

Gamma-ray bursts: spectra and variability



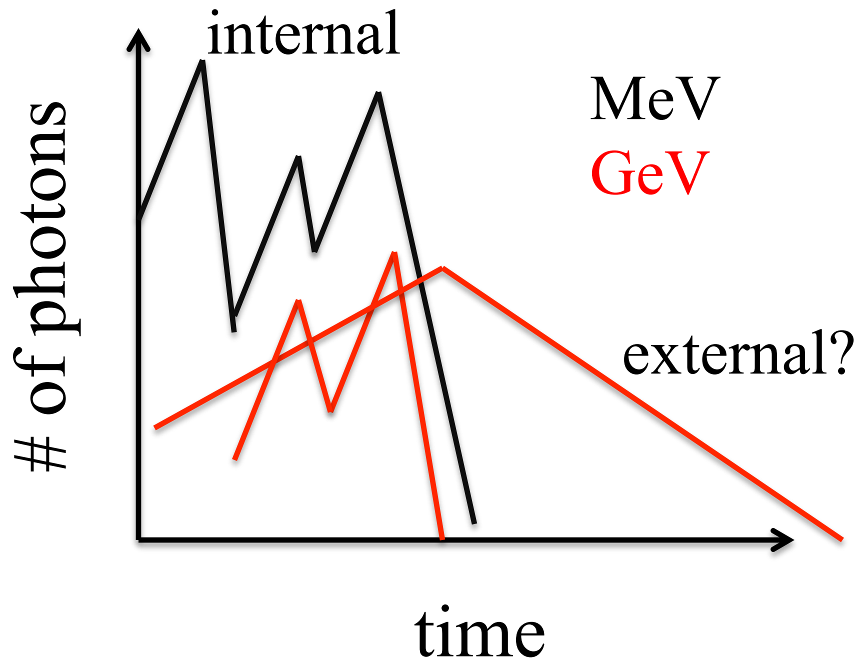




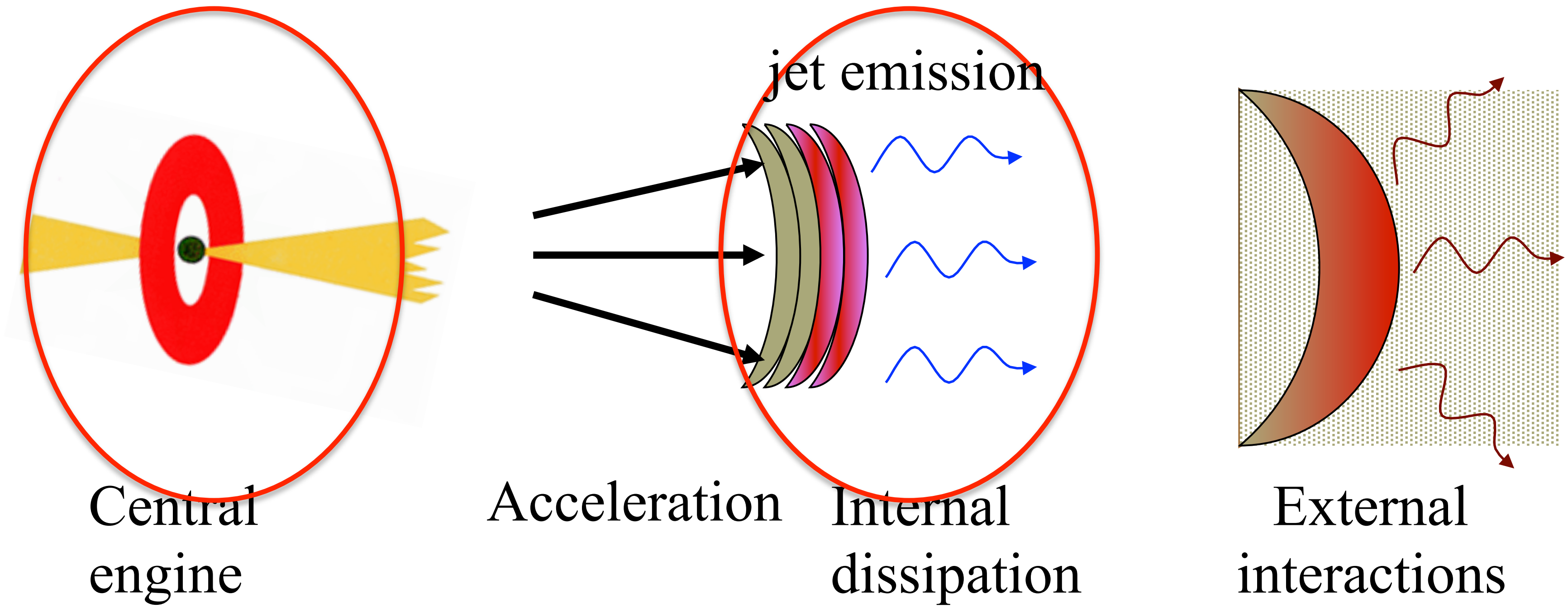
Recent Developments: GeV emission

GeV emission: peaking with (late) MeV ***but*** lasts longer!

Abdo et al. 2009; Ghisellini et al. 2009 …



focus: why and how do jets radiate?



Some big questions:

Which process accelerates the particles that radiate?

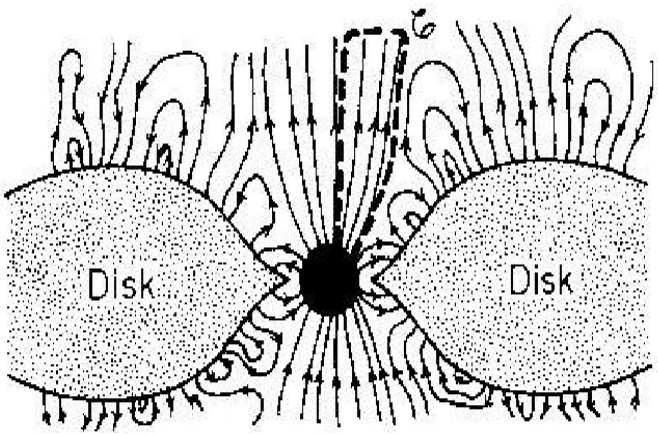
Where the dissipation takes place? How do they radiate?

The Central Engine

B-fields extract rotational energy from the compact object/inner accretion disk at a rate $\dot{E}_{EM} \approx \frac{B^2 R^6 \Omega^4}{c^3} \propto B^2 R^2$

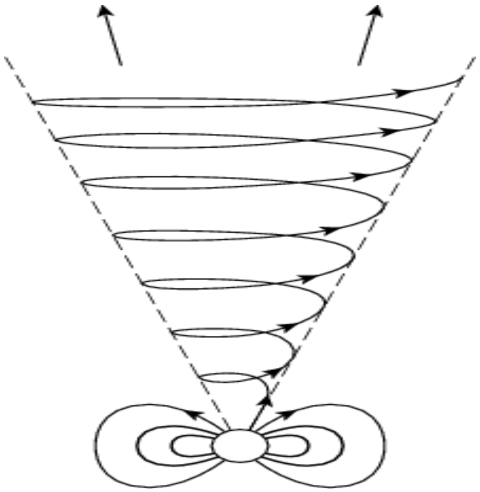
Most of the energy initially stored in the magnetic field!

Blandford & Znajek 1977
Begelman & Li 1992
Meier et al. 2001
Koide et al. 2001
van Putten 2001
Barkov & Komissarov 2008
…



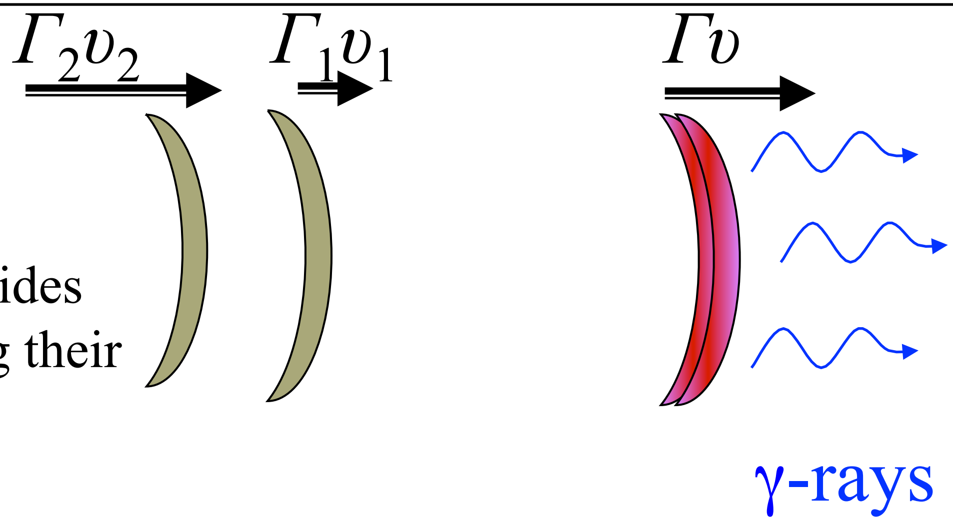
Acceleration of jets

- Recent progress in 2D axisymmetric relativistic MHD simulations & theory
  Vlahakis & Koenigl 2003; Komissarov et al. 2009; 2010; Tchekhovskoy et al. 2009; 2010; Lyubarsky 2009; 2010
  - High magnetization flows accelerate to $\Gamma \gg 1$, *But* most of the energy remains in the B field
  - No clear mechanism to power the emission; *shocks are weak!*
- ***After acceleration: internal dissipation responsible for the emission***

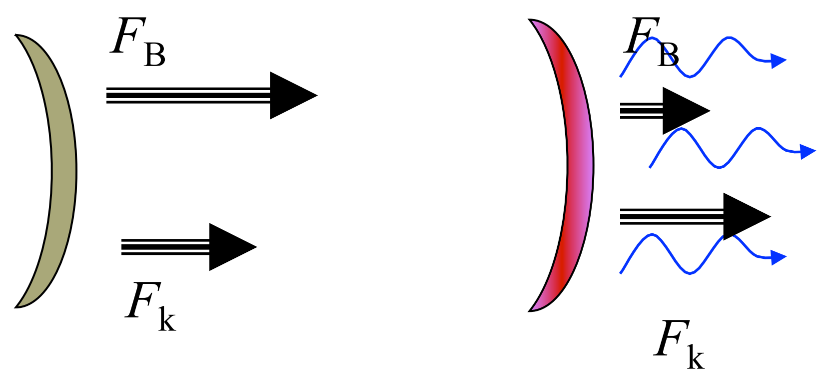


Jet radiation: Internal shocks vs Magnetic dissipation

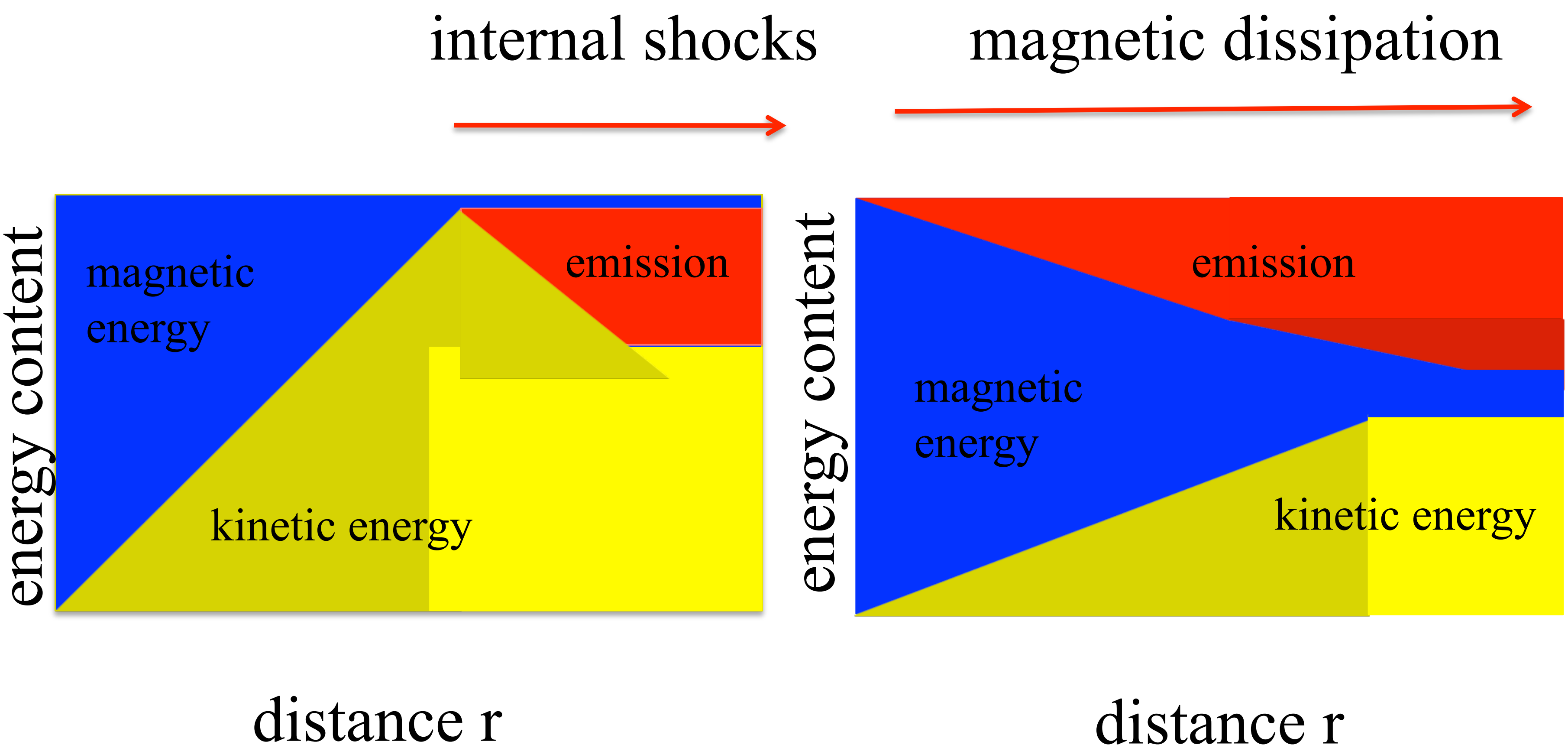
- Internal shocks
  - Unsteady flow composed by shells
  - A fast shell with $\Gamma_2 > \Gamma_1$ collides with a slower one dissipating their *relative* kinetic energy



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

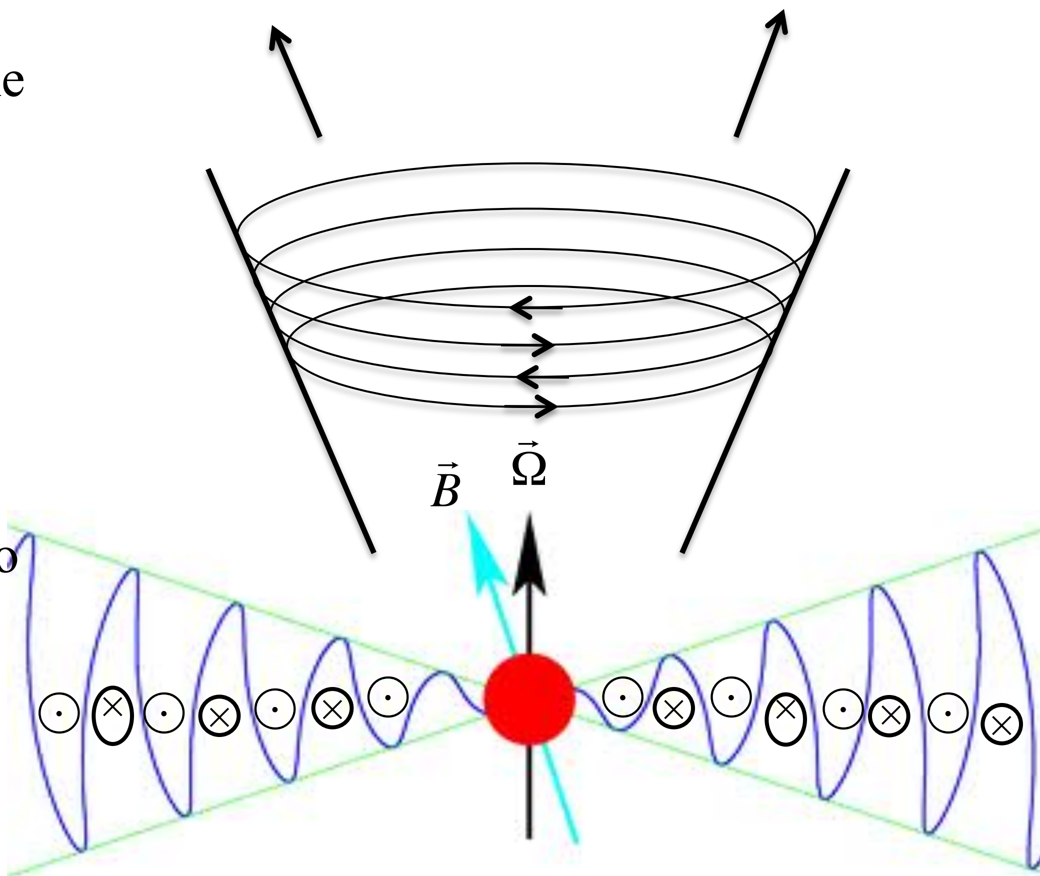


Internal shocks or Magnetic dissipation?

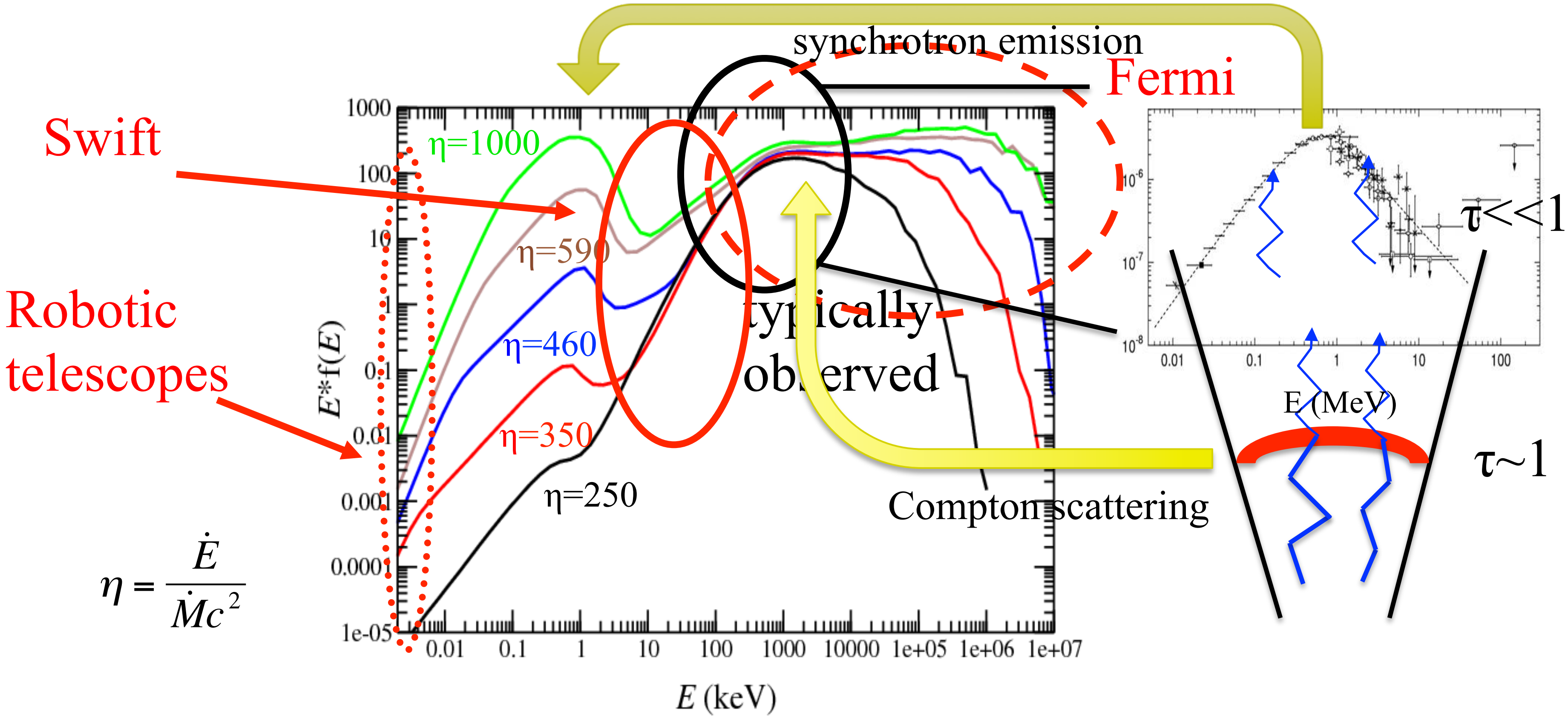


The reconnection model for GRBs

- The field is in general not axisymmetric at the central engine
- *Model for GRBs*: Magnetic field changes polarity on small scales and reconnects $v_{rec}=\varepsilon c$
  Drenkhahn 2002 and Denkhahn & Spruit 2002; Lyubarsky 2011
- Dissipation is gradual and leads to acceleration of the flow *and* heating of plasma
- The model *predicts* a strong photospheric component and optically thin dissipation



Radiative transfer study in the magnetic reconnection model

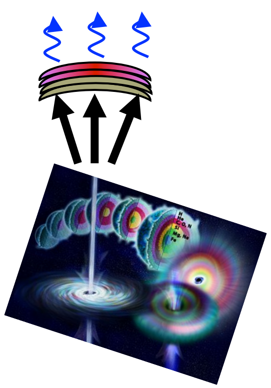


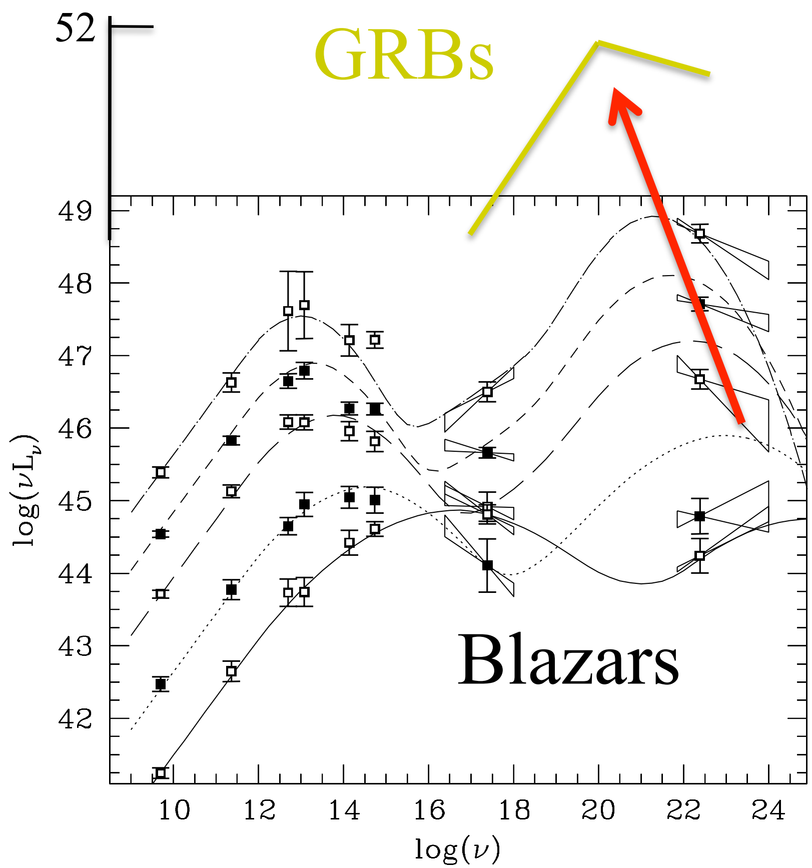
$$\eta = \frac{\dot{E}}{\dot{M}c^2}$$

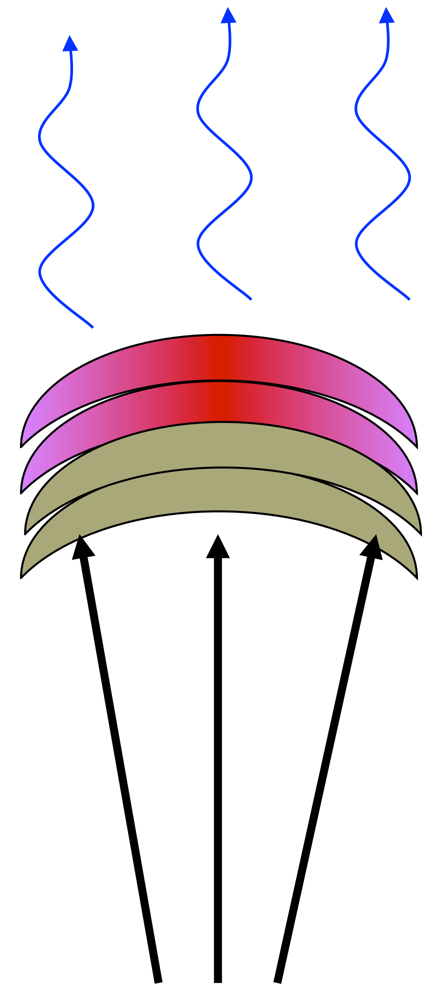
Giannios 2006; Giannios & Spruit 2007; Giannios 2008

more "*dissipative photospheres*": Thompson 1994; Pe'er et al. 2006; Ioka et al. 2007; Ioka 2010; Lazzati & Begelman 2010; Beloborodov 2010; Ryde et al. 2011; Vurm et al. 2011…

From GRBs to blazars?

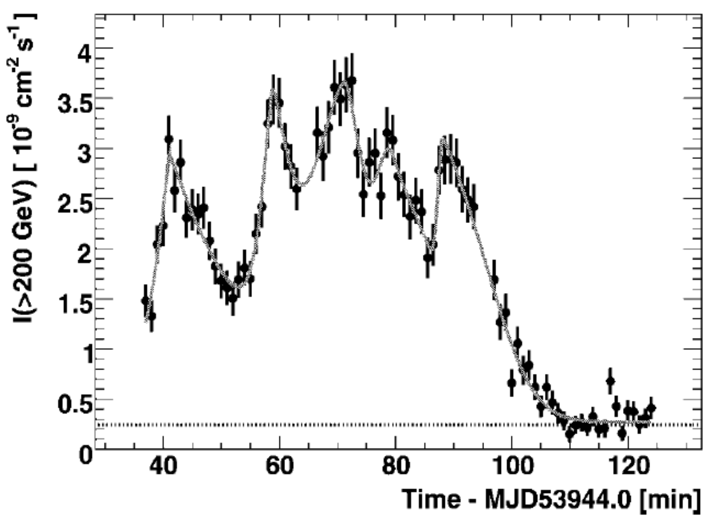






Hints for reconnection: ultrafast TeV blazars

PKS 2155-304 (Aharonian et al. 2007); see also Mrk 501 (Albert et al. 2007); PKS 1222+21 (Aleksic et al. 2011)



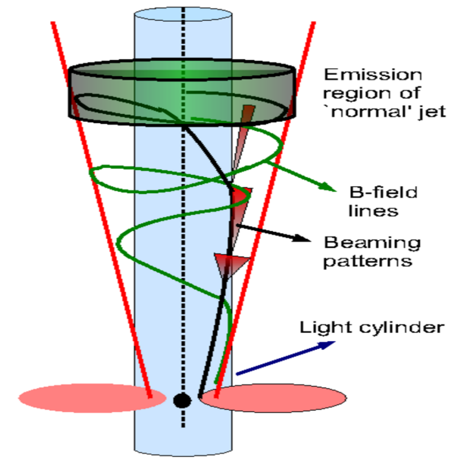
vary on timescales as sort as t_v~3 min << R_s/c ~ 3 hours!!!

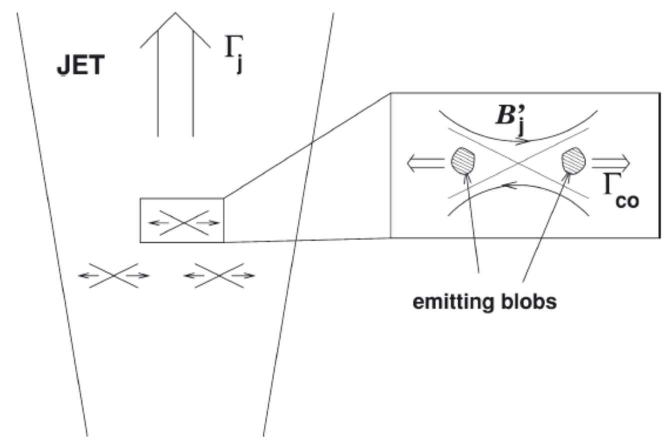
Implications from ultrafast TeV flaring

- Models that associate the variability to black hole activity do not work

→ Strongly indicates variability originating from the jet Tavecchio & Ghisellini 2008

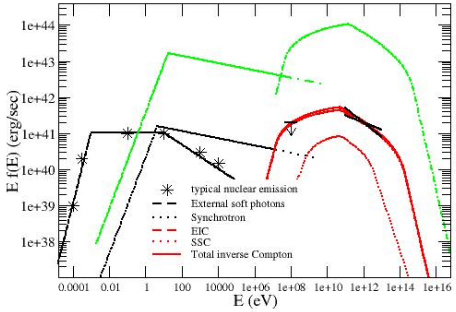
- We see small-scale, fast moving regions!
Ghisellini et al. 2009; Giannios, Uzdensky & Begelman 2009; 2010; Nalewajko et al. 2011 …





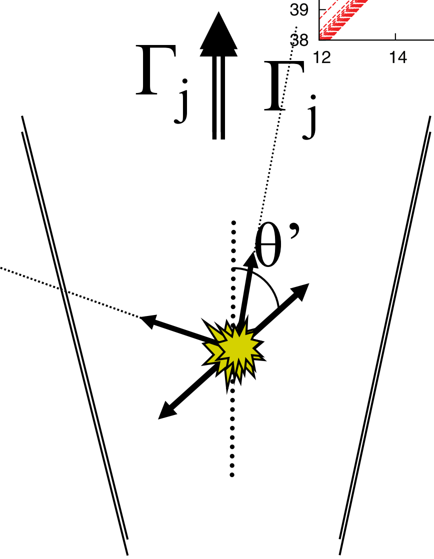
Prediction: flares from jets viewed off axis

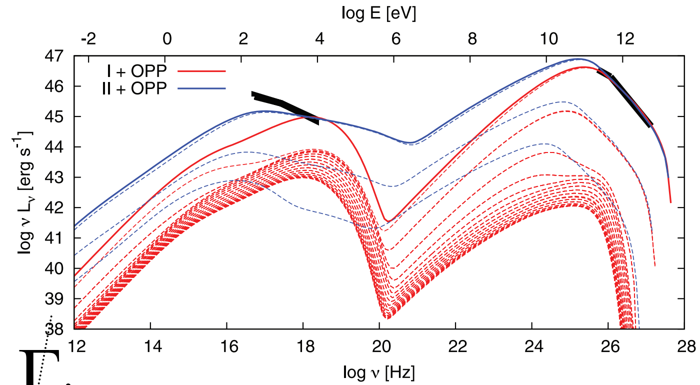
Giannios, Uzdensky & Begelman 2010



Off-jet axis

infra-day M87 flaring





Nalewajko et al. 2011

Jet axis

flares from
Mrk 501
PKS 2155-304
PKS 1222-21

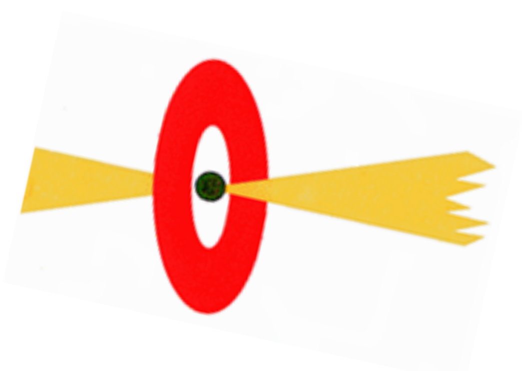
Rest frame of black hole

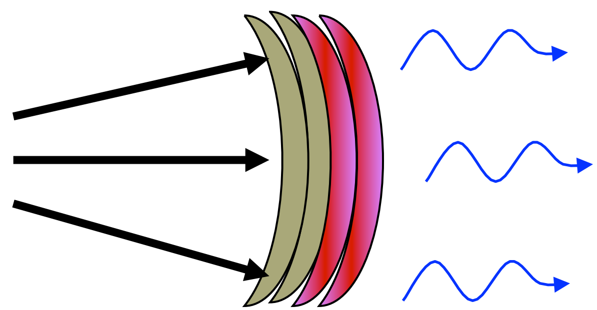
Rest frame of jet

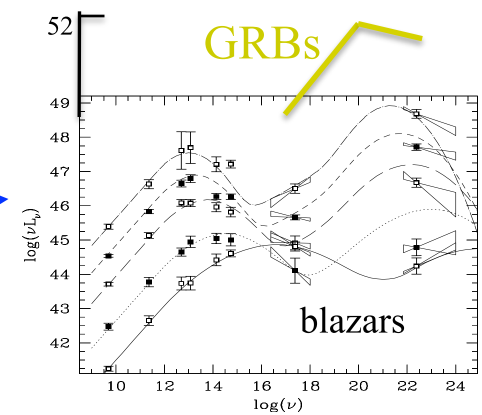
Outlook - How should we proceed?

- Relativistic jets: a multi-scale problem of many physical processes

central engine ⟷ jet structure ⟷ dissipation zone ⟷ particle heating ⟷ radiative transfer ⟷ observations



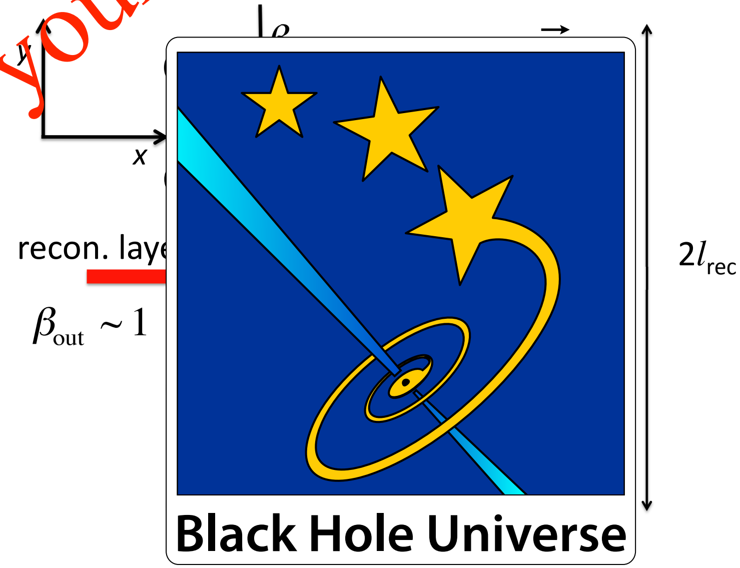




(instead of) Summary: why I like jets

- Exciting (extreme) physics
  - (general) relativity, MHD, plasma physics, radiative transfer…
- Can accelerate UHECRs
  - shocks or magnetic reconnection may be efficient accelerator
- May reveal tidal disruptions (
- Provide EM counterparts to t
- Produce TeV photons that ma
  B-fields
- Deposit energy/momentum a

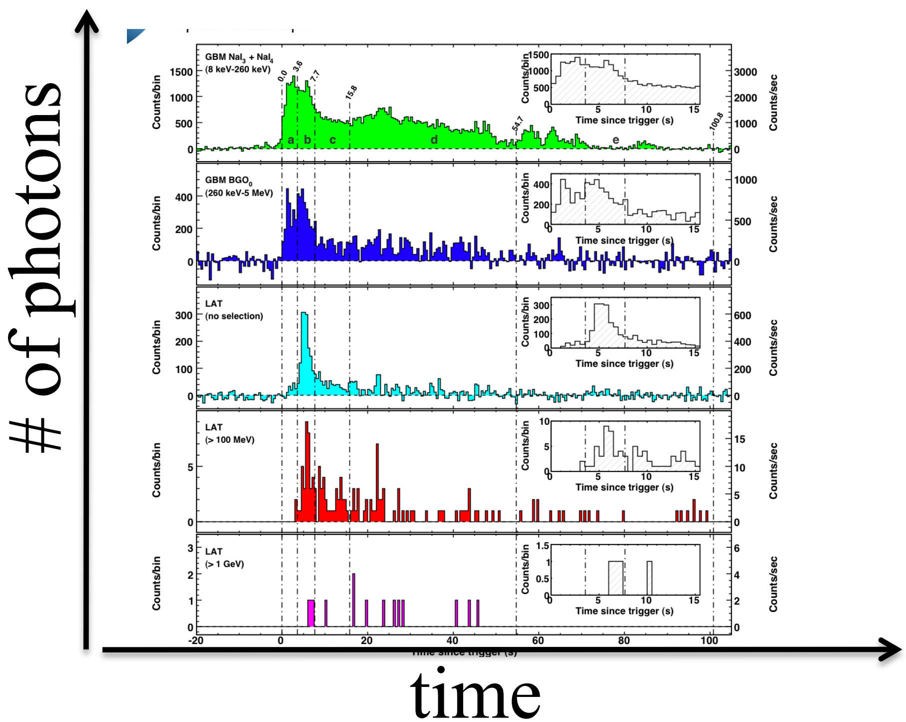
Thank you for your attention!



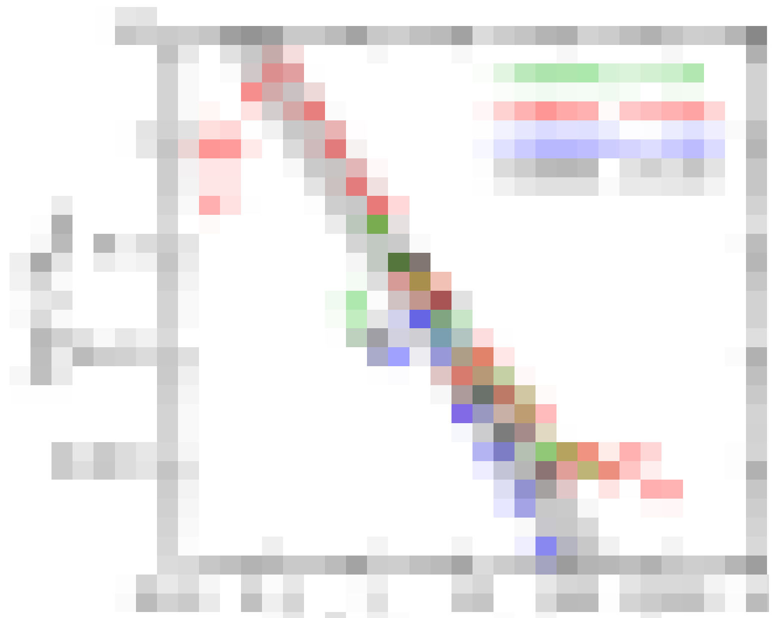
Giannios 2010; Metzger 2011 & Giannios et al 2011

Recent Developments: GeV emission

GeV emission: peaking with (late) MeV ***but*** lasts longer!



GRB 080916C; Abdo et al. 2009



Ghisellini et al. 2009