How did Fermi revolutionize our physical understanding of GRB prompt emission?

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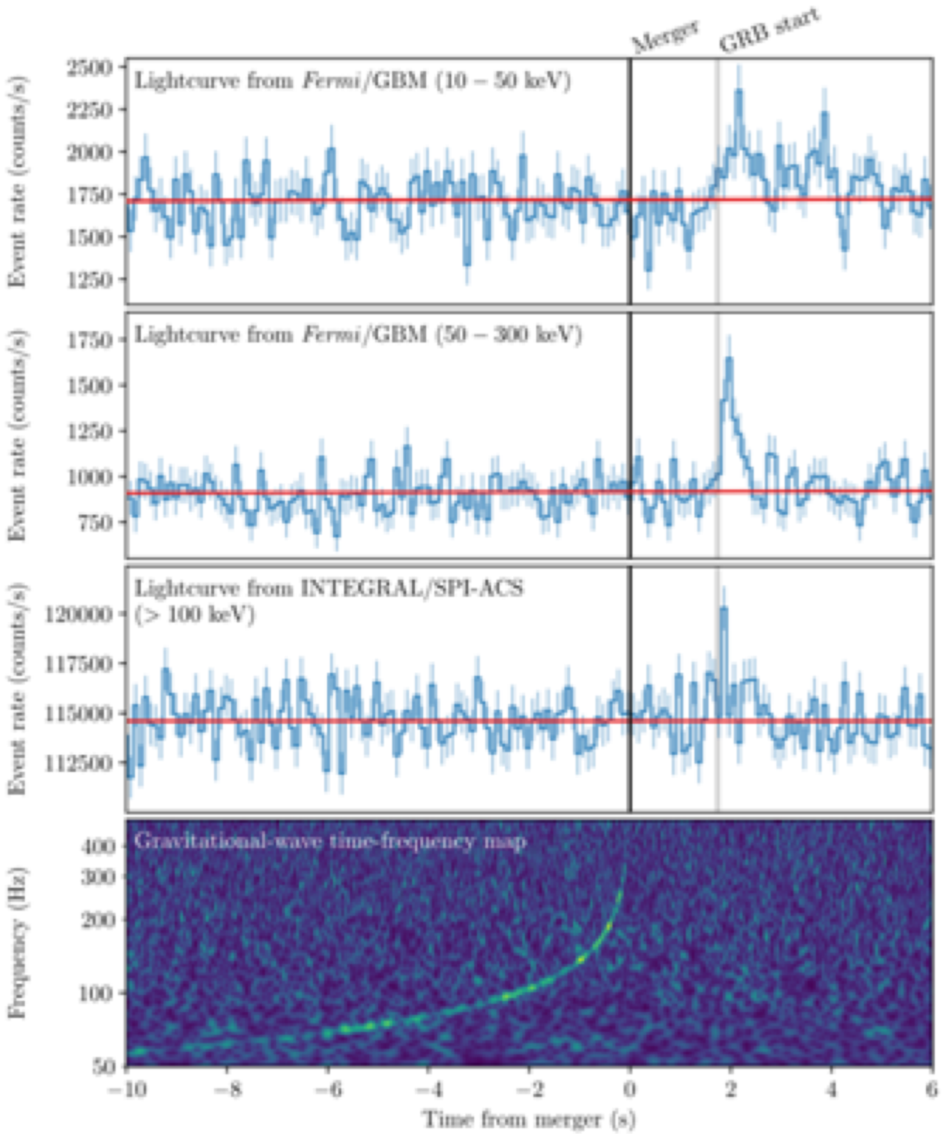
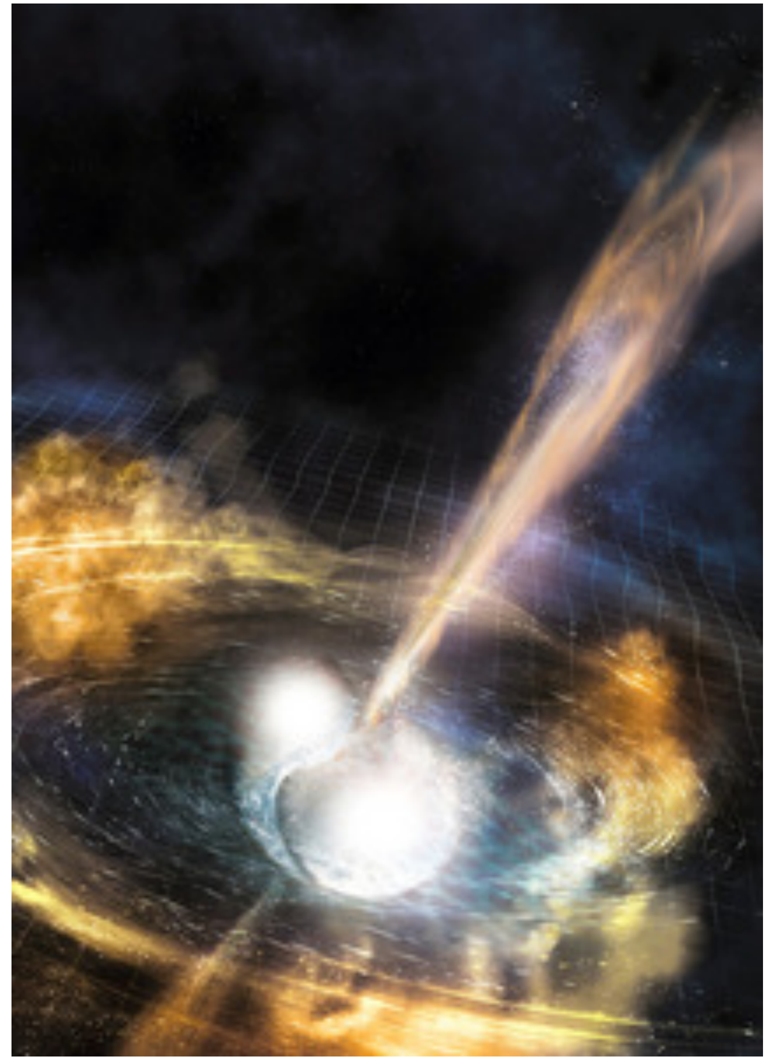
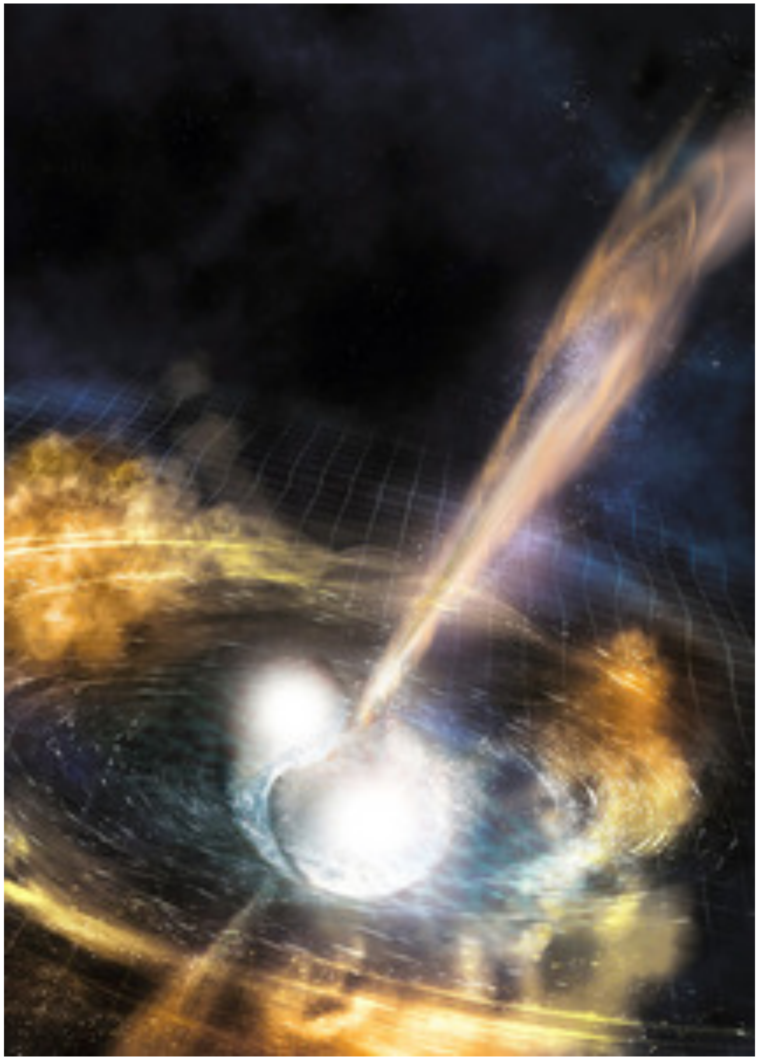
Eighth International Fermi Symposium
(Celebrating 10 Years of Fermi)
Baltimore MD, Oct. 14-19, 2018

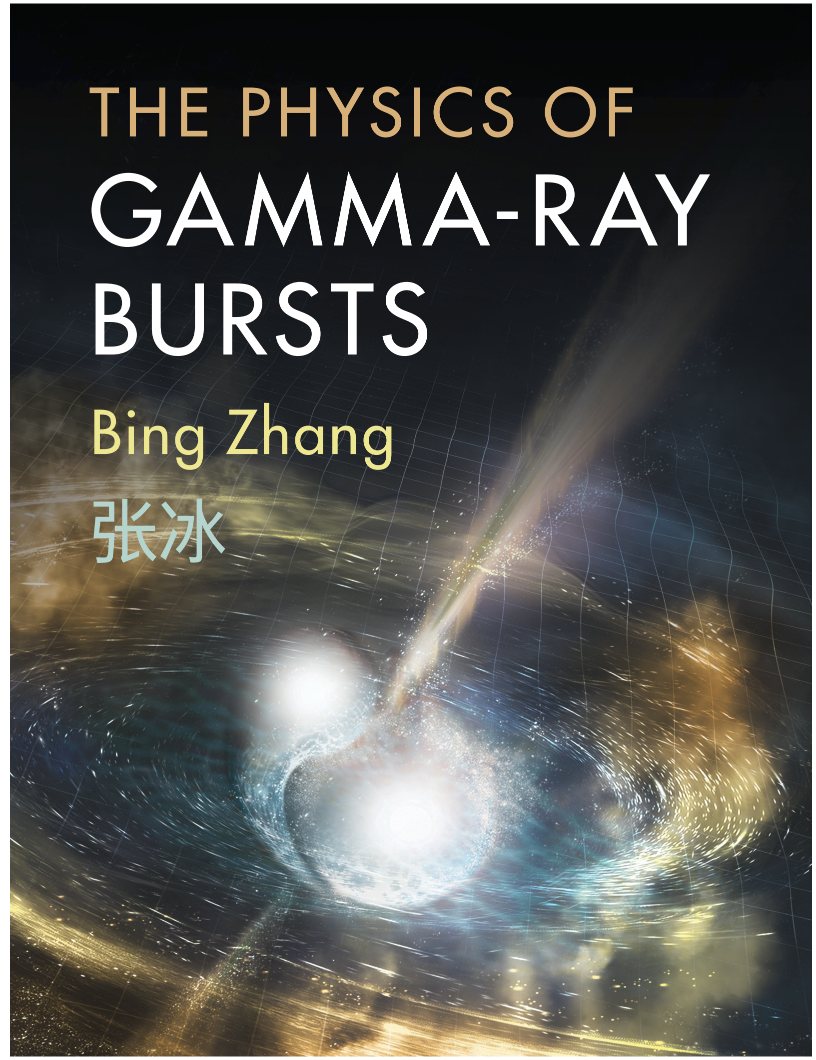
Fermi revolution: Most beautiful figure in astrophysics: GW170817/GRB 170817A



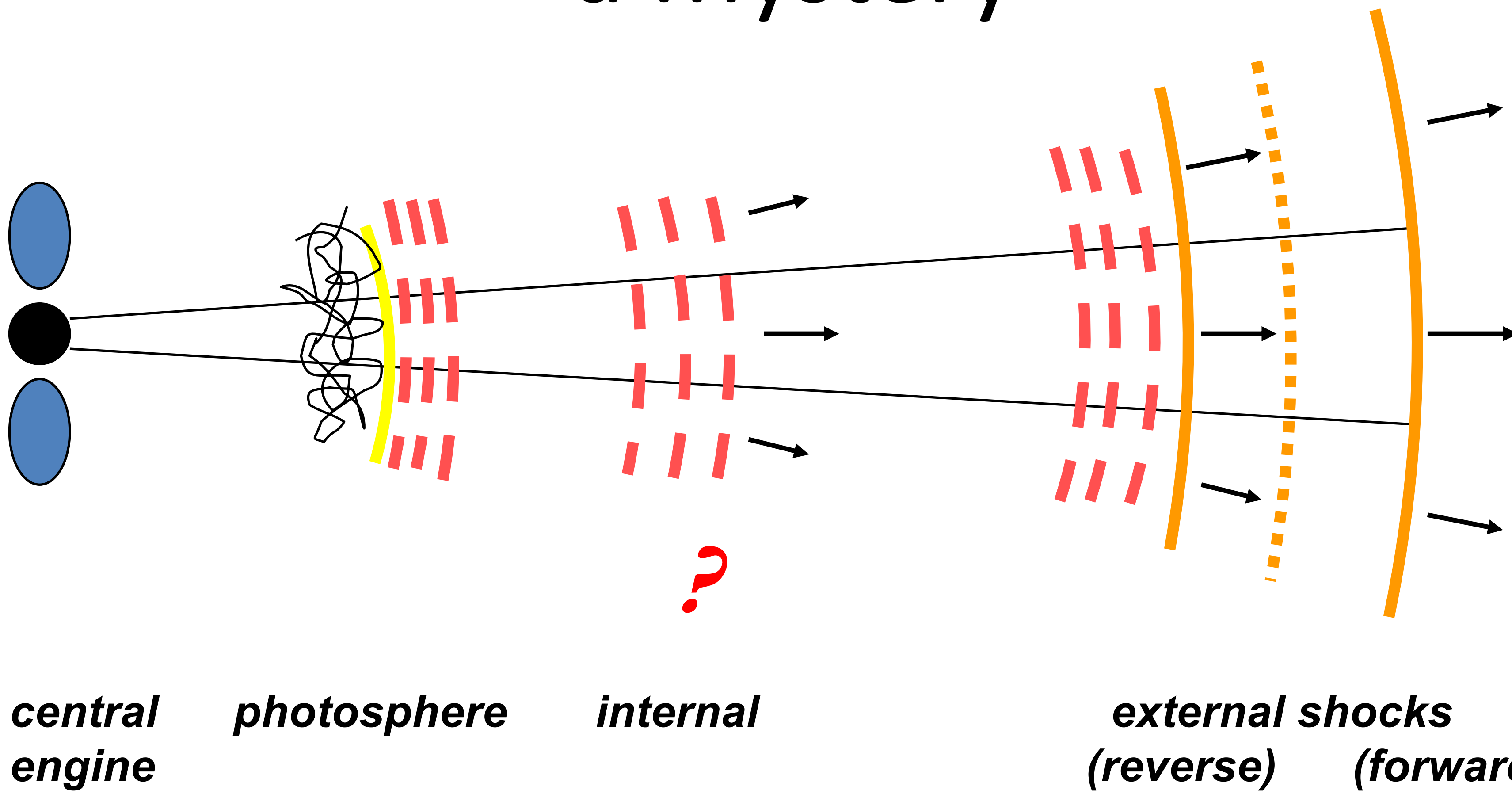


Today's topic:
The Physics of Gamma-Ray Bursts





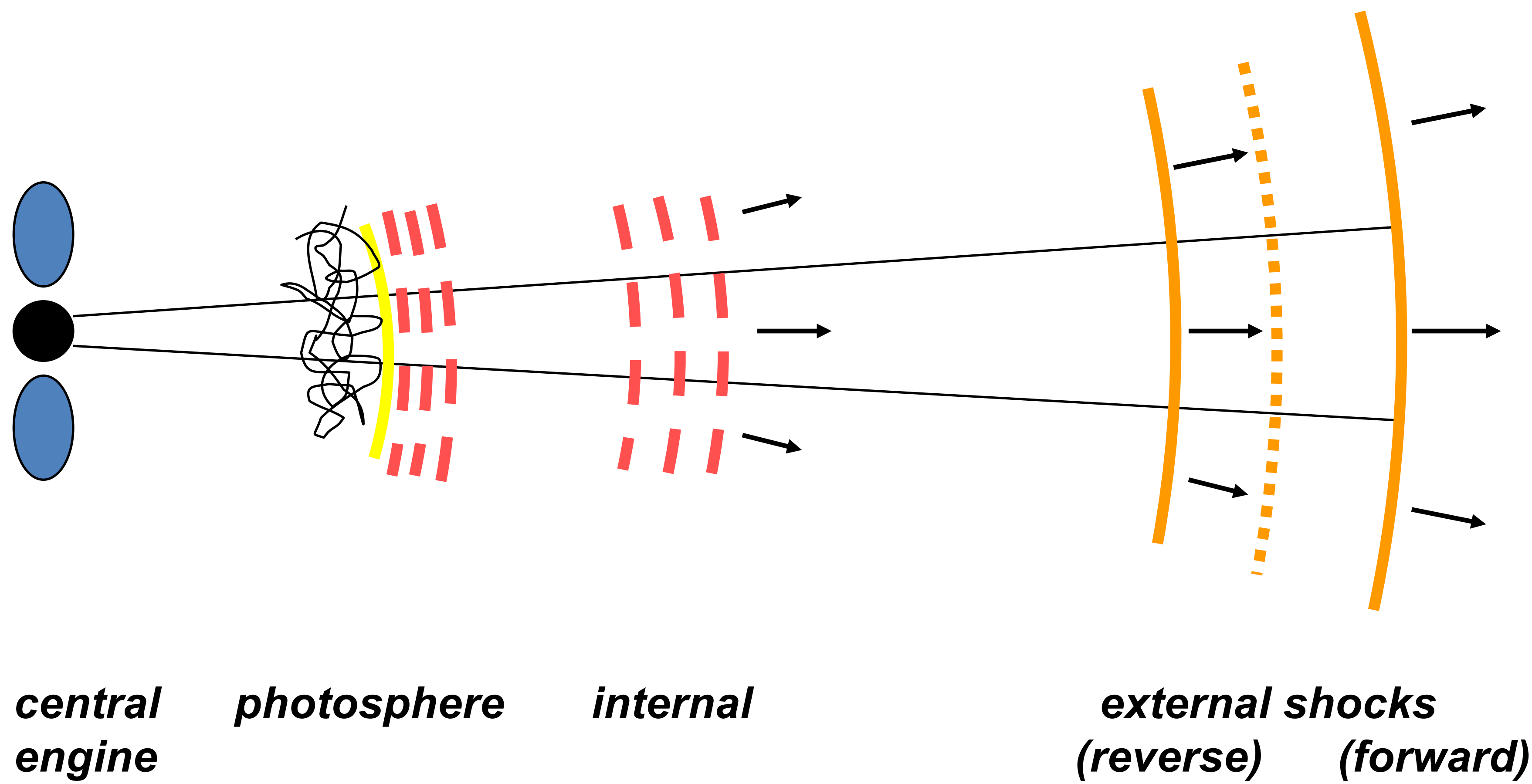
Prompt GRB Emission: a Mystery



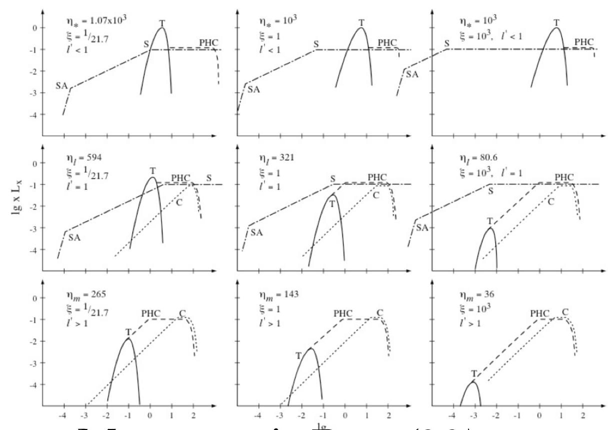
What is the jet composition (baryonic vs. Poynting flux)?
Where is (are) the dissipation radius (radii)?
How is the radiation generated (synchrotron, Compton scattering, thermal)?

Early GRB model:
The fireball shock model

(Paczynski, Meszaros, Rees, Piran, Daigne/Mochkovitch ...)

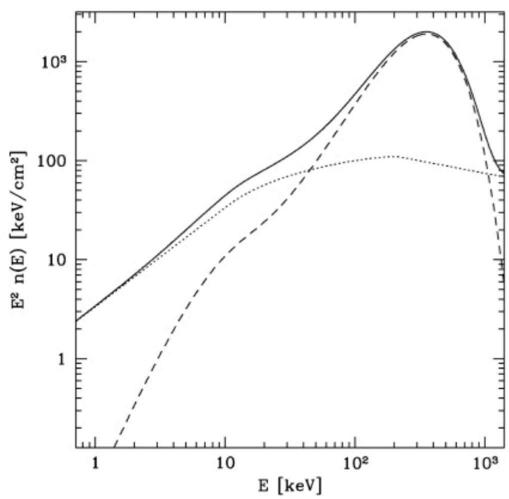


Before Fermi: Fireball Predictions: Internal shock synchrotron vs. photosphere

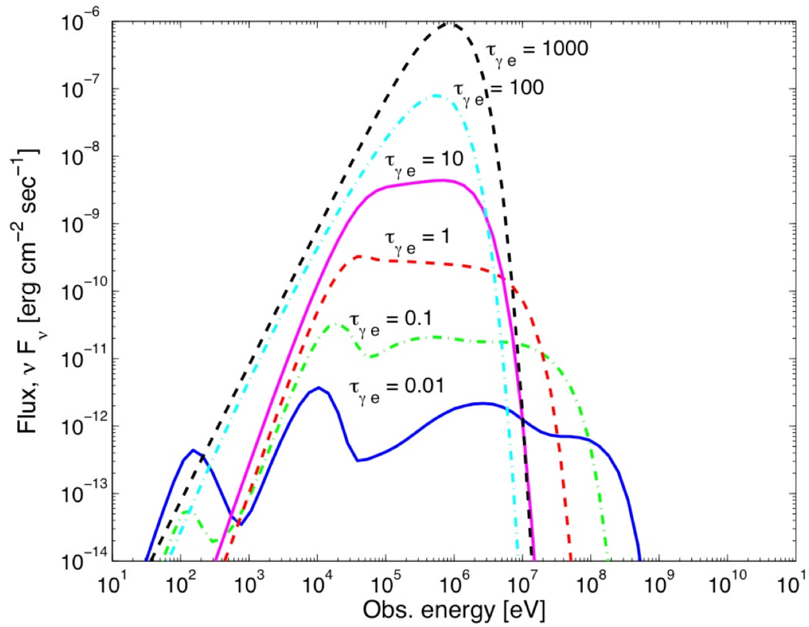


Meszaros & Rees (00)

1276 *F. Daigne and R. Mochkovitch*

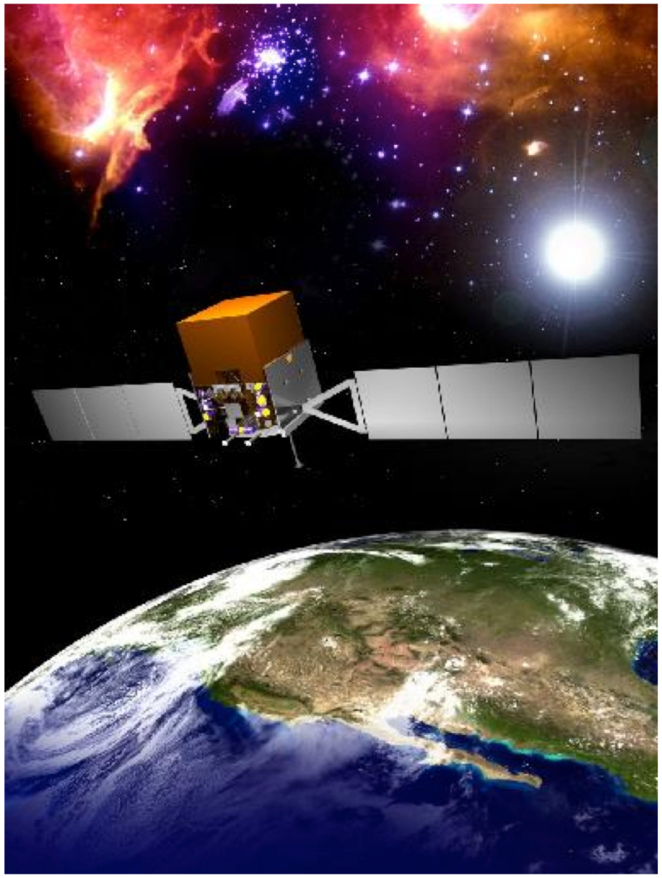


Daigne & Mochkovitch (02)

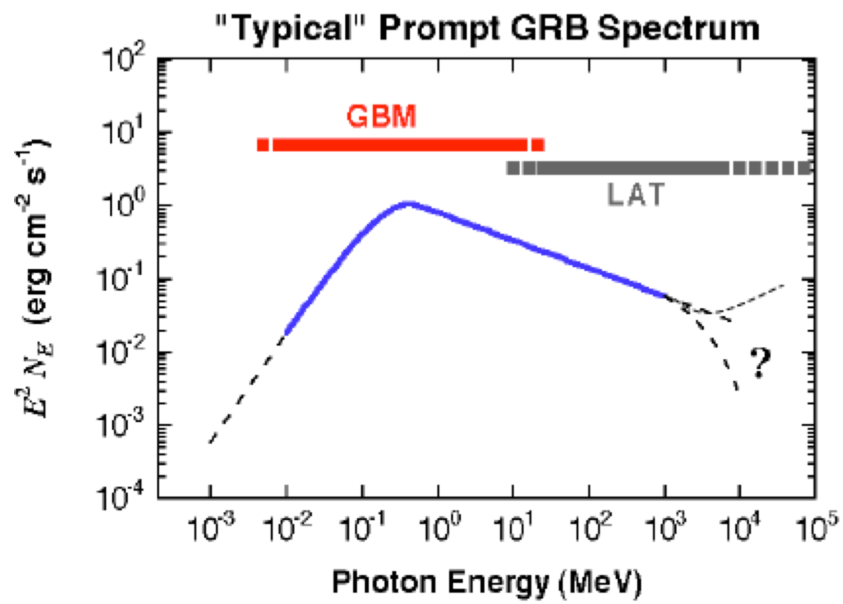


Pe'er et al. (06)

Fermi Revolution:
Much wider spectral window



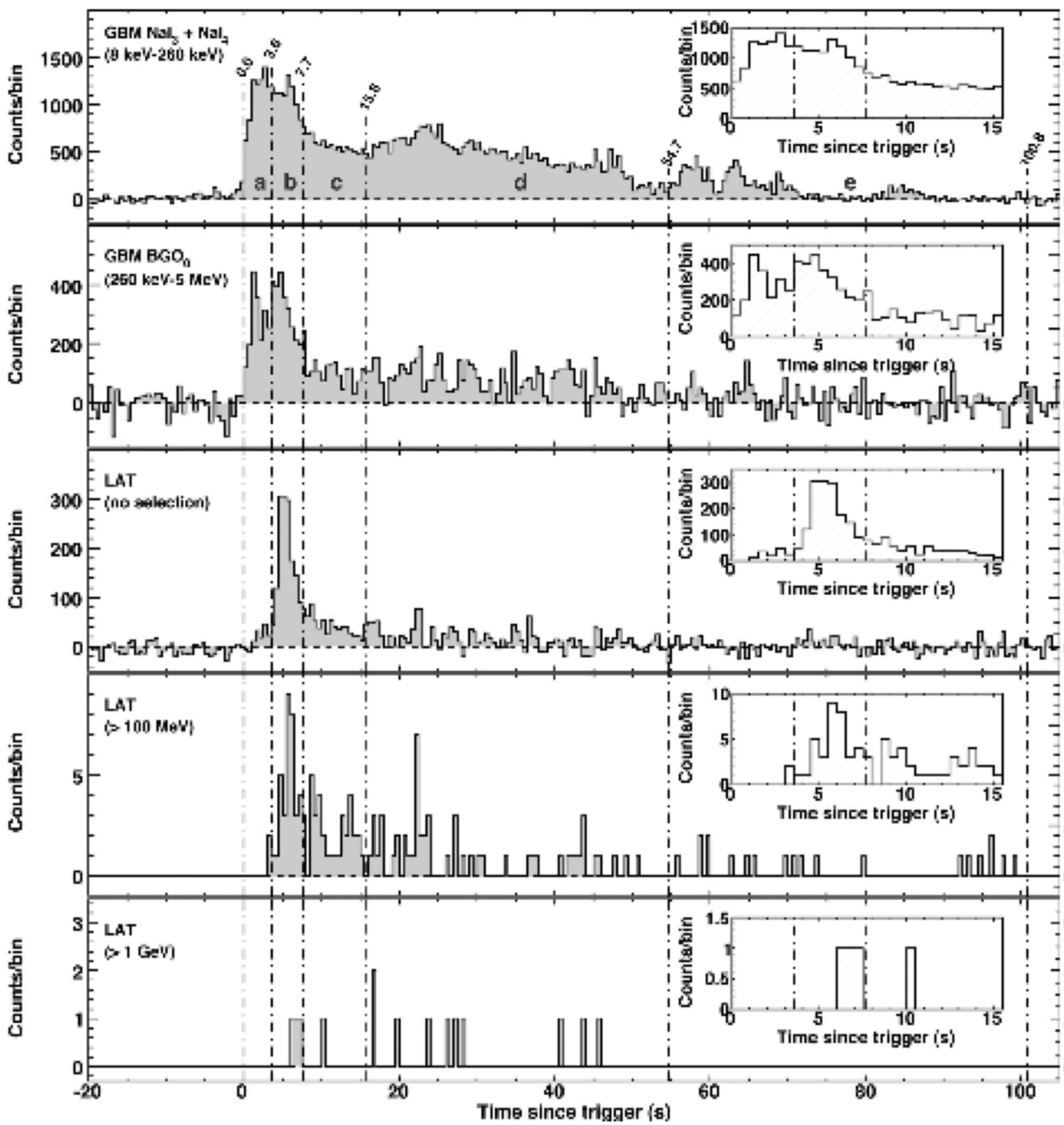
Launched on June 11th, 2008

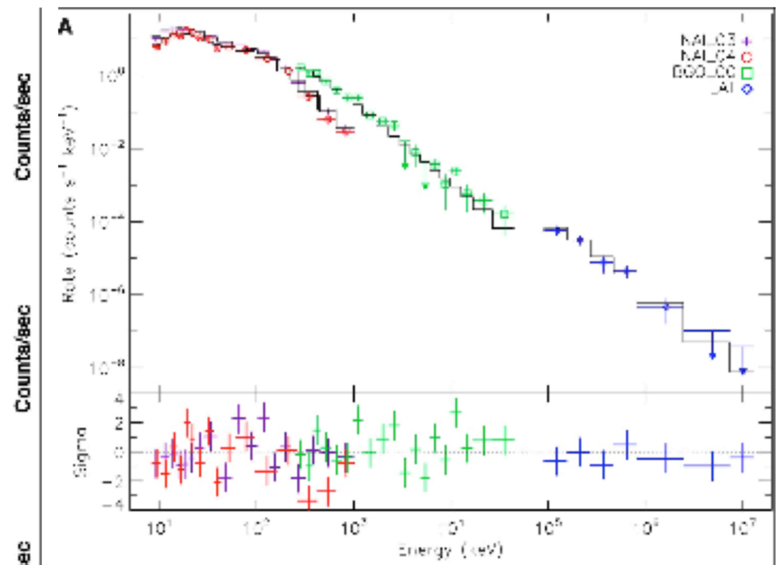


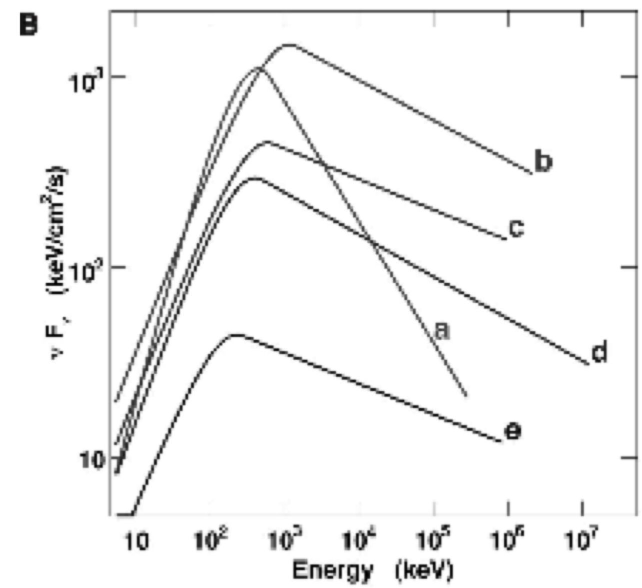
Fermi surprise #1: GRB 080916C

(Abdo et al. 2009, Science)

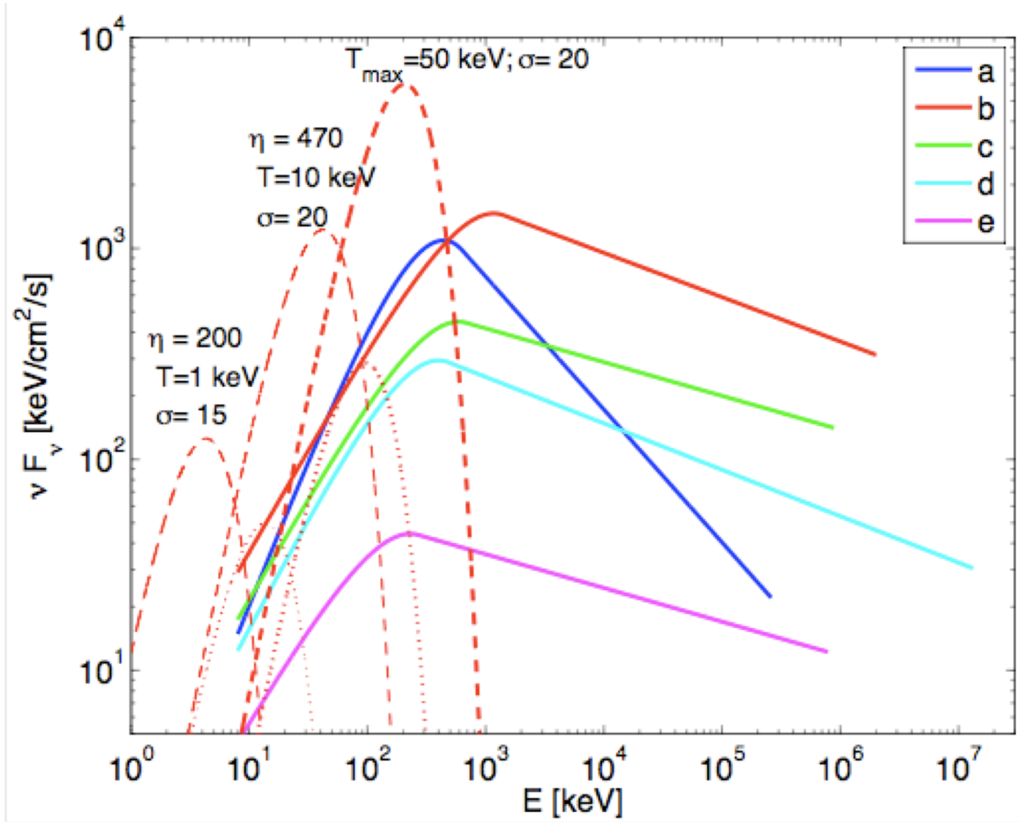
$z = 4.35 \pm 0.15$







Fermi Surprise #1:
Photosphere component missing



Zhang & Pe'er (2009)

Sigma: ratio between Poynting flux and baryonic flux:

Cf. Guiriec et al. (2015)

$\sigma = L_P/L_b$*: at least ~ 20, 15 for GRB 080916C*

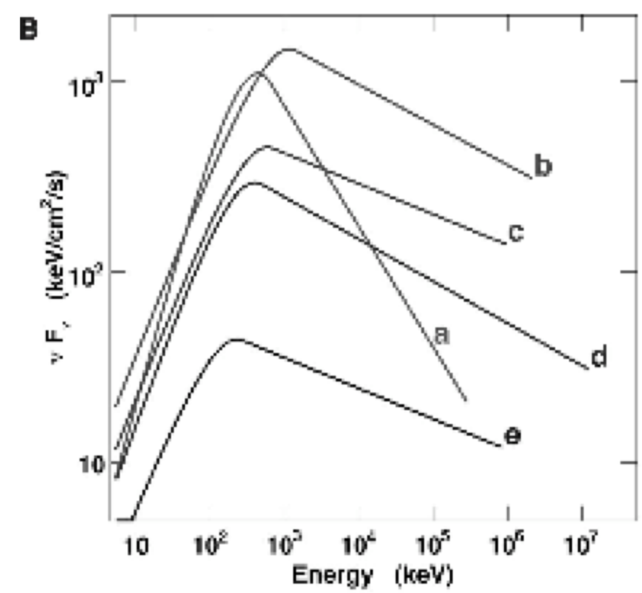
The simplest fireball model does not work!

Theorists' view cannot be more diverse since the establishment of cosmological origin of GRBs!

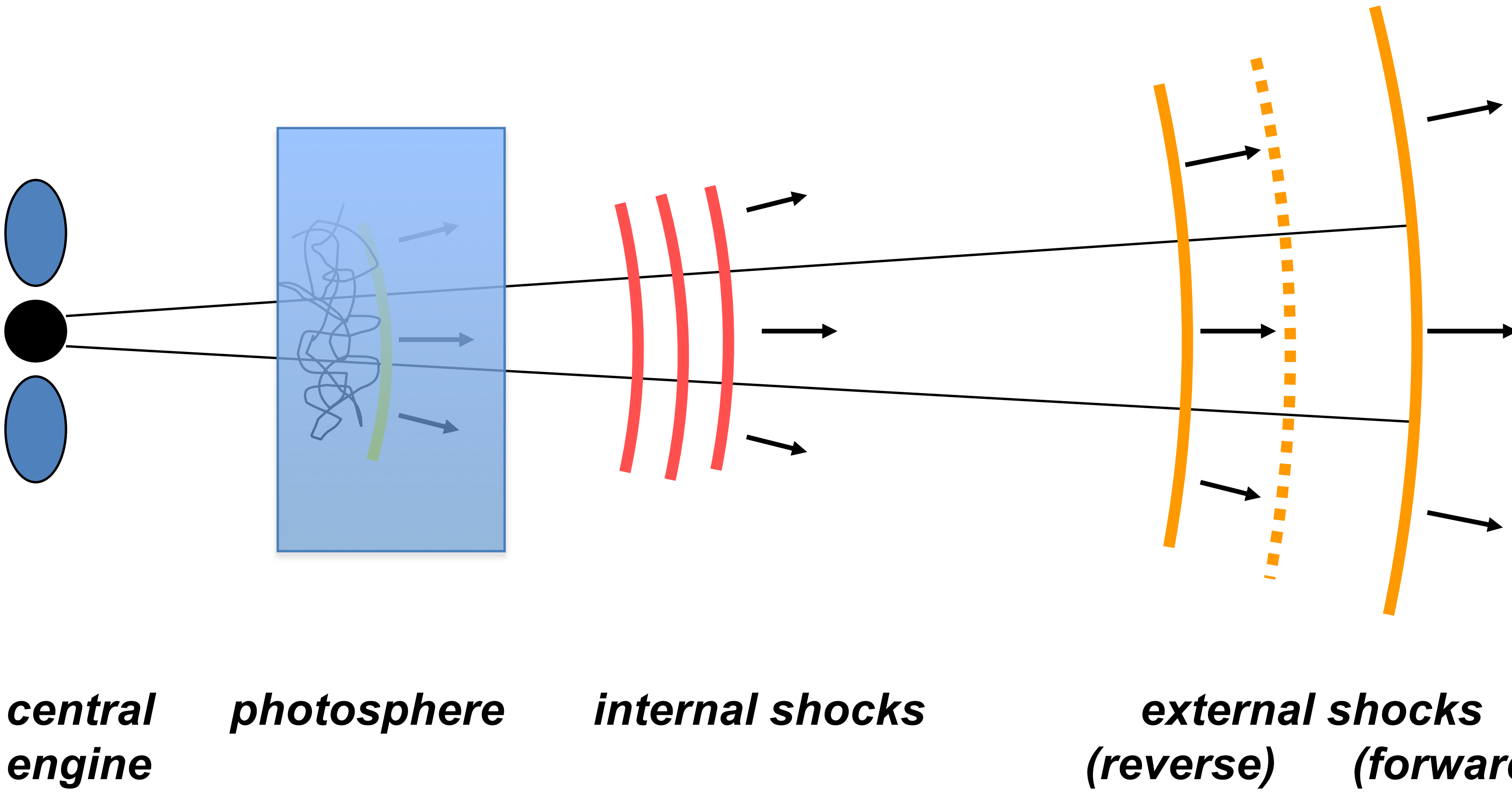
Three distinct views:

The observed component is:

- *The internal shock component*
- *The photosphere component*
- *Neither (Poynting flux dissipation component)*

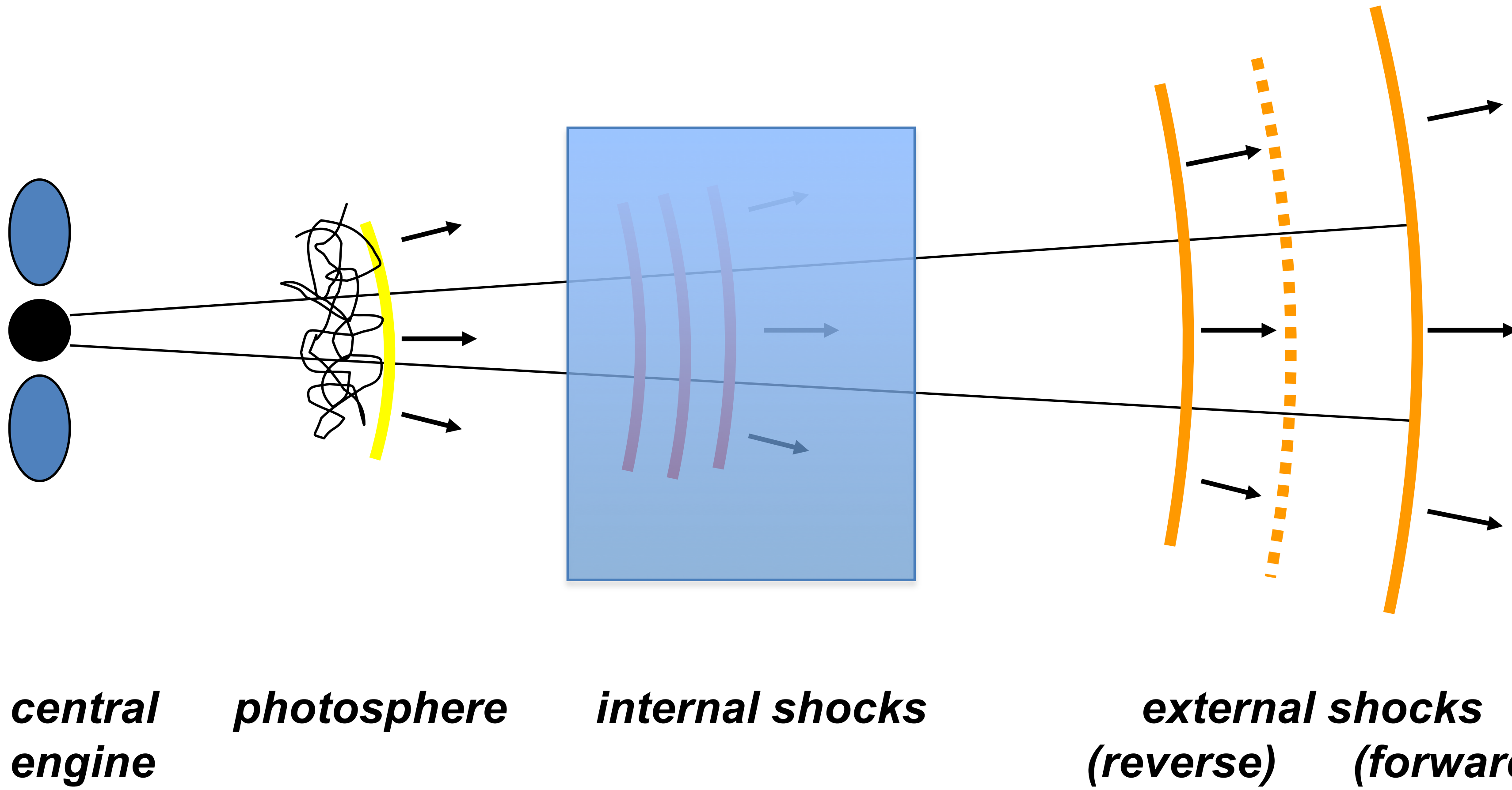


Modified Fireball Model (1)



GRB prompt emission is *from internal shocks*
Photosphere emission suppressed

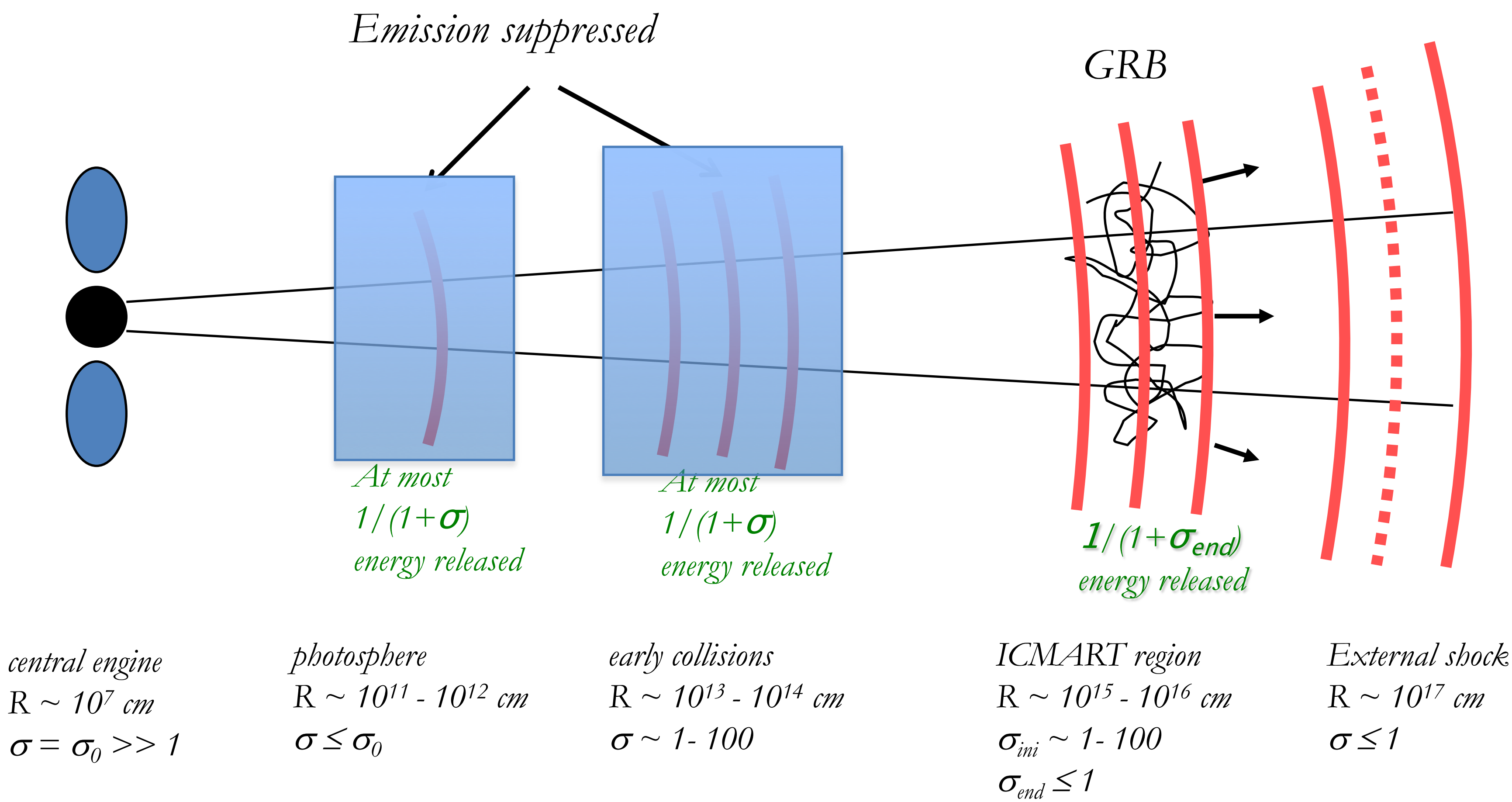
Modified Fireball Model (2)



GRB prompt emission: *from photosphere*
Internal *shock emission suppressed*

The ICMART Model

(Internal Collision-induced MAgnetic Reconnection & Turbulence)



Zhang & Yan (2011)

Earlier work: Lyutikoc & Blandford; Narayan & Kumar …

GRB central engine parameters (η, σ_0)

- Energy per baryon >> 1
- Energy in three forms
  - Thermal: η, Θ
  - Magnetic: σ
  - Kinetic: Γ

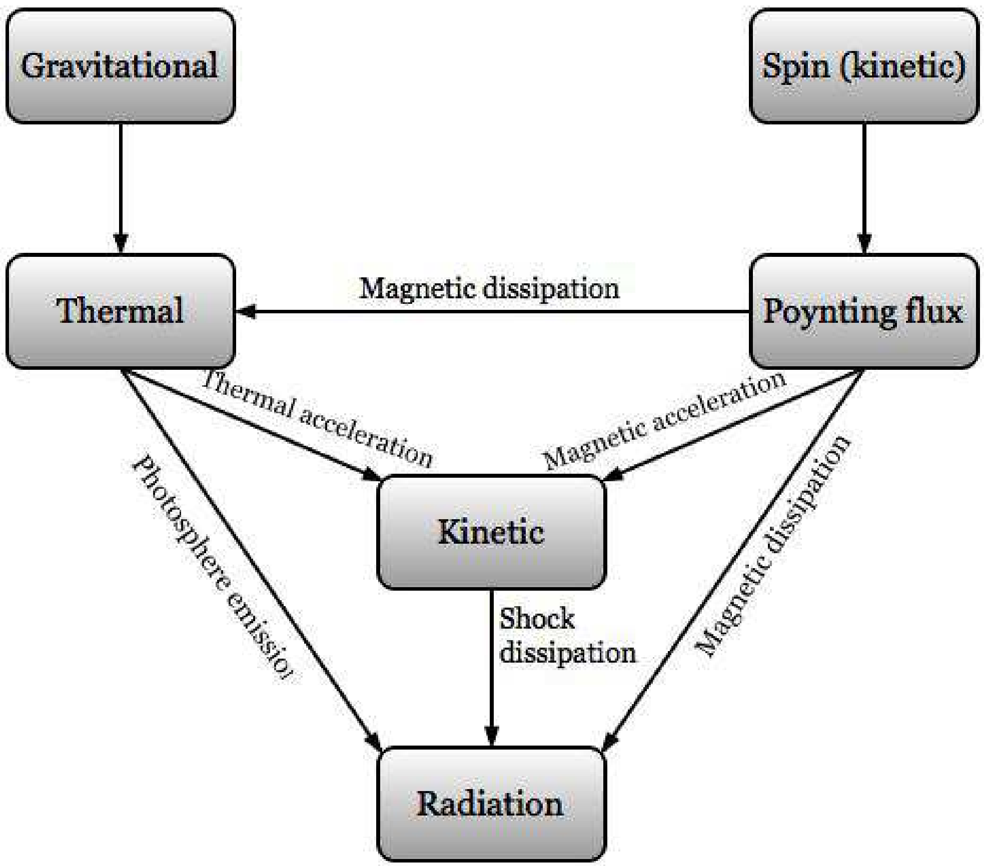
$$\mu_0 = \frac{E_{\rm tot,0}}{Mc^2} = \frac{E_{th,0} + E_{\rm P,0}}{Mc^2} = \eta(1+\sigma_0).$$

Neglect radiation, one has

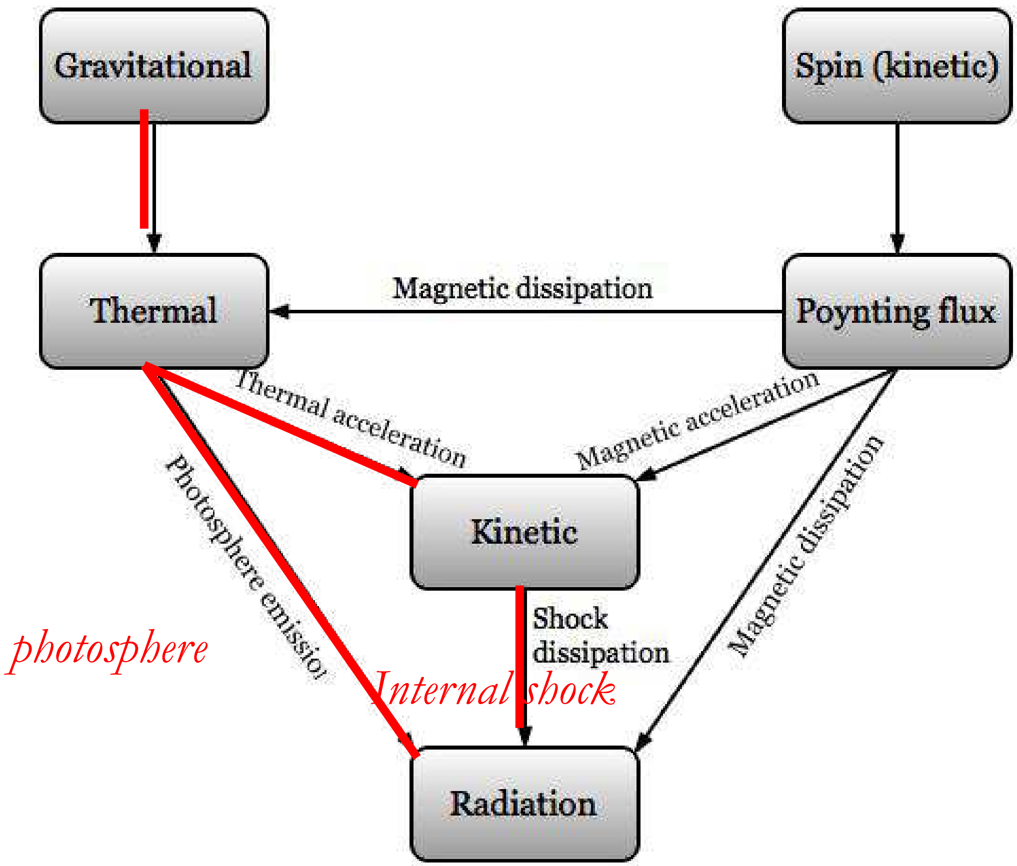
$$\mu_0 = \eta(1+\sigma_0) = \Gamma\Theta(1+\sigma).$$

$$\Gamma_{\rm max} = \mu_0 \simeq \left\{ \begin{array}{ll} \eta, & \sigma_0 \ll 1; \\ \sigma_0, & \eta \sim 1, \sigma_0 \gg 1. \end{array} \right.$$

Energy Flow in GRBs

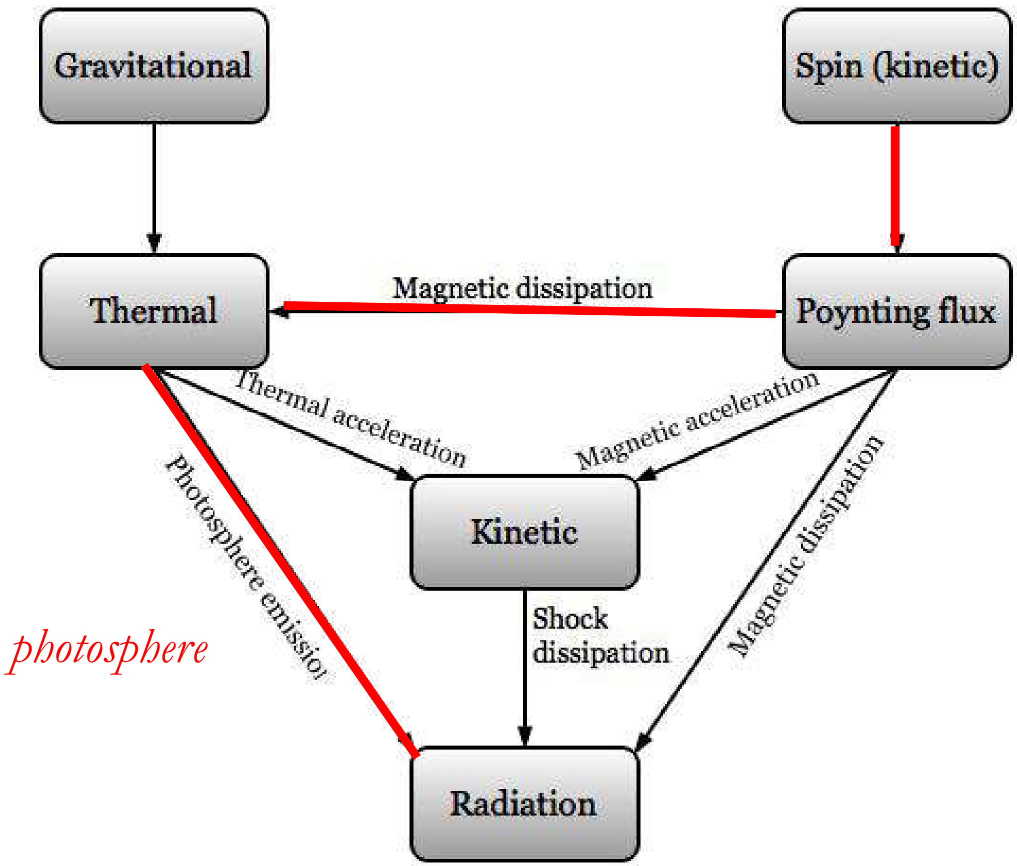


Energy Flow in GRBs



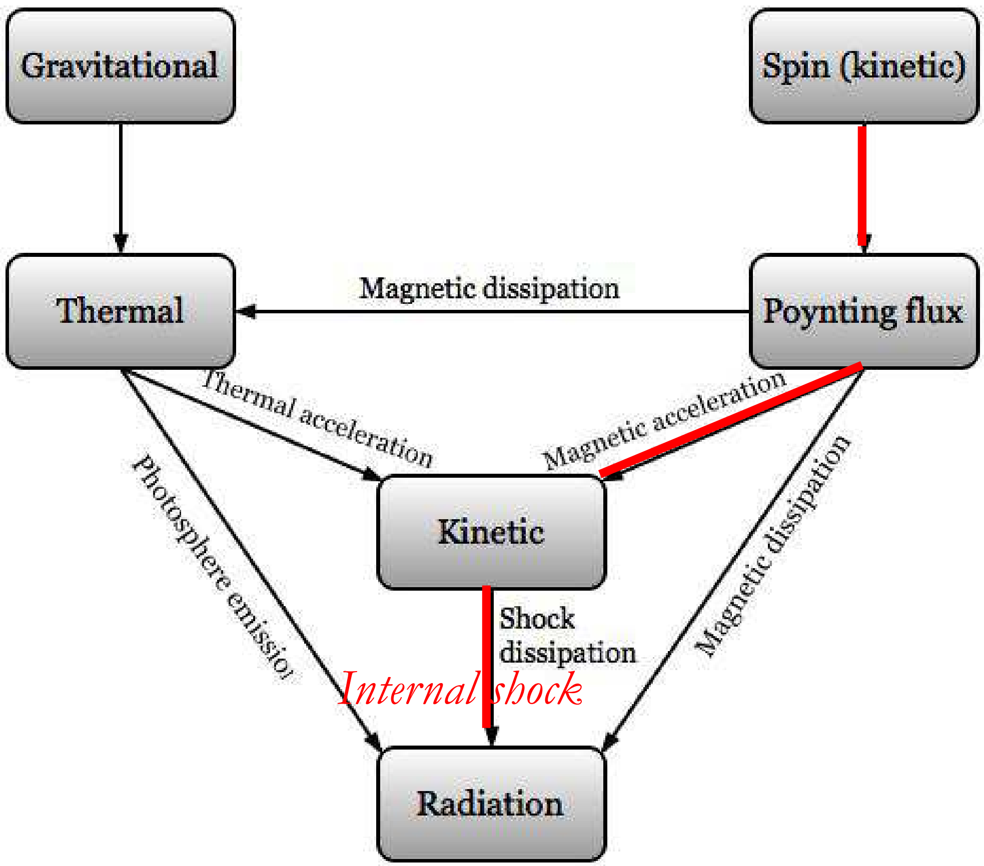
Fireball model

Energy Flow in GRBs



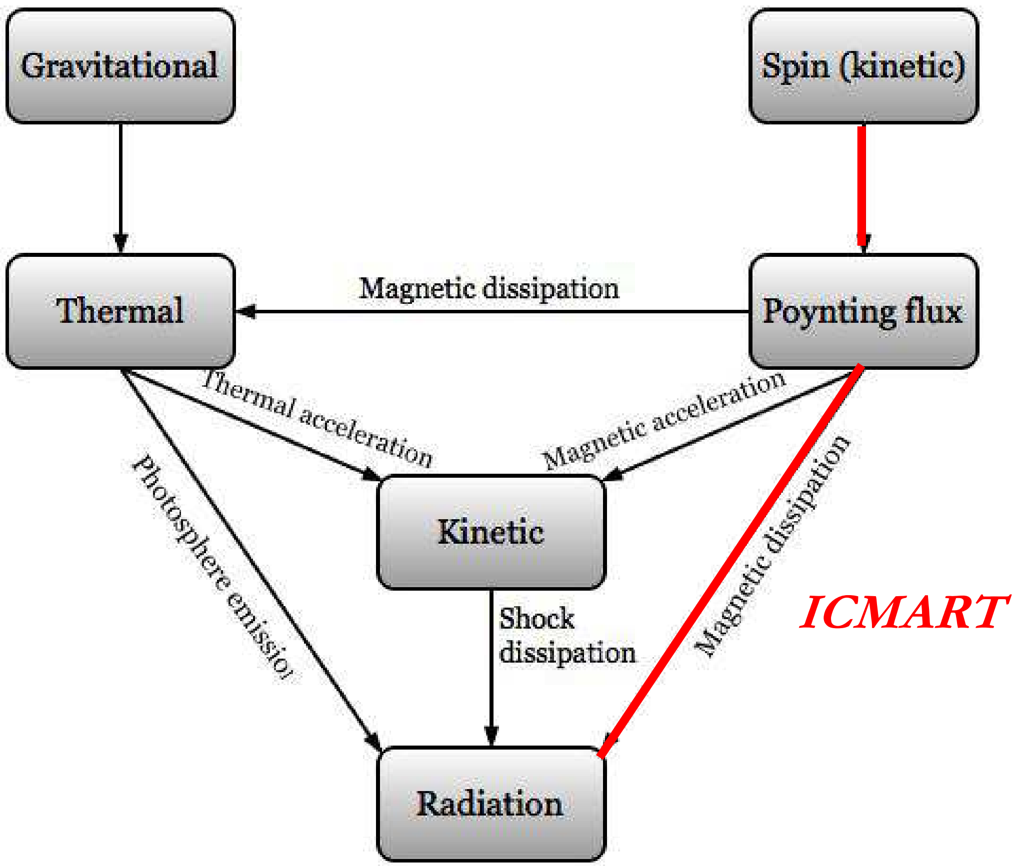
Magnetic photosphere model

Energy Flow in GRBs



Initially magnetized internal shock model

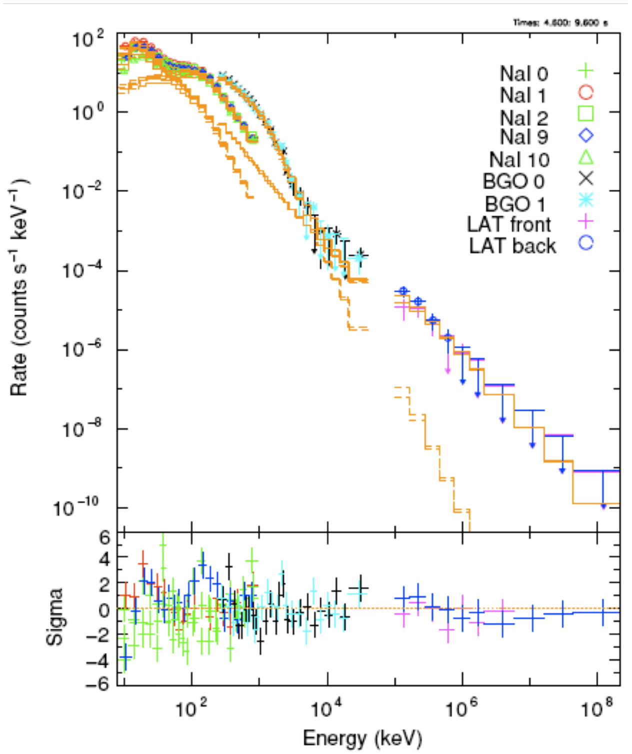
Energy Flow in GRBs

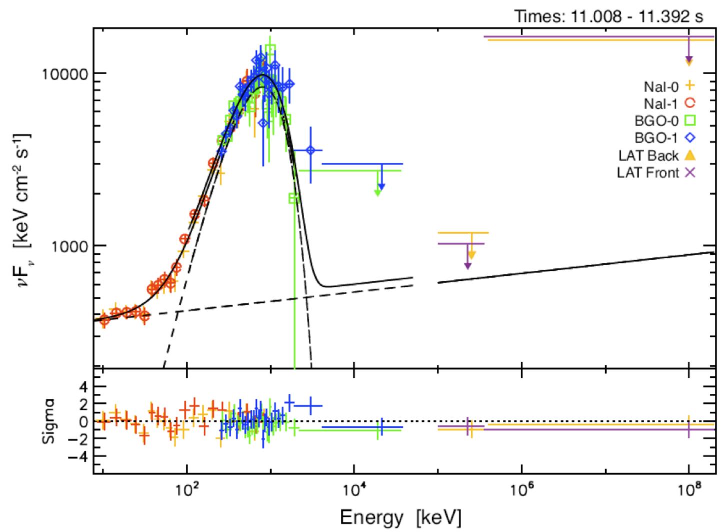


Internal collision-induced magnetic reconnection & turbulence (ICMART) model

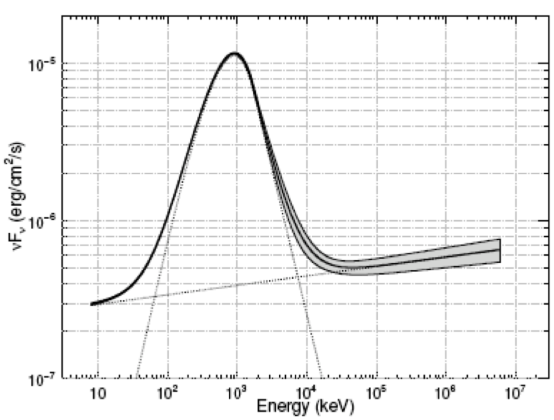
Fermi Surprise #2: GRB 090902B

(Abdo et al. 2009; Ryde et al. 2010; Zhang et al. 2011; Pe'er et al. 2012)





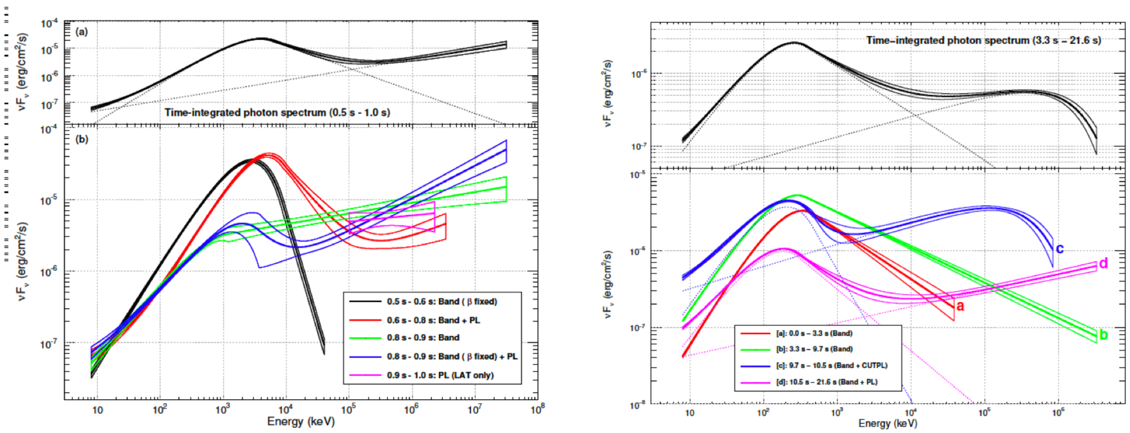
A clear photosphere emission component identified



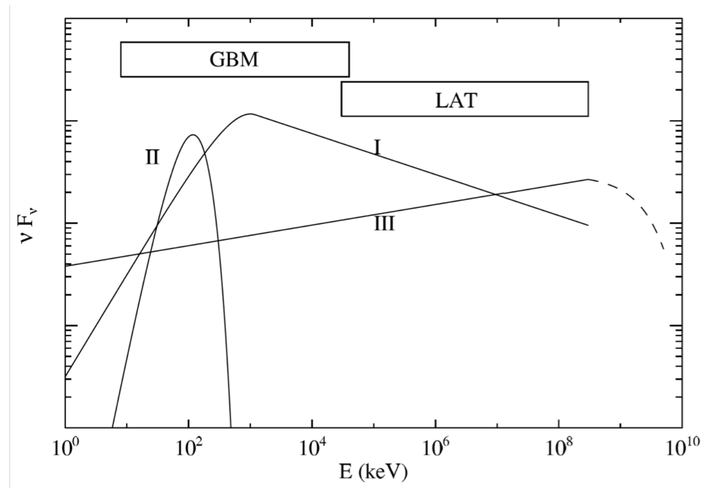
Fireballs do exist!
But are special & rare!

A new high-energy component extending to high energies

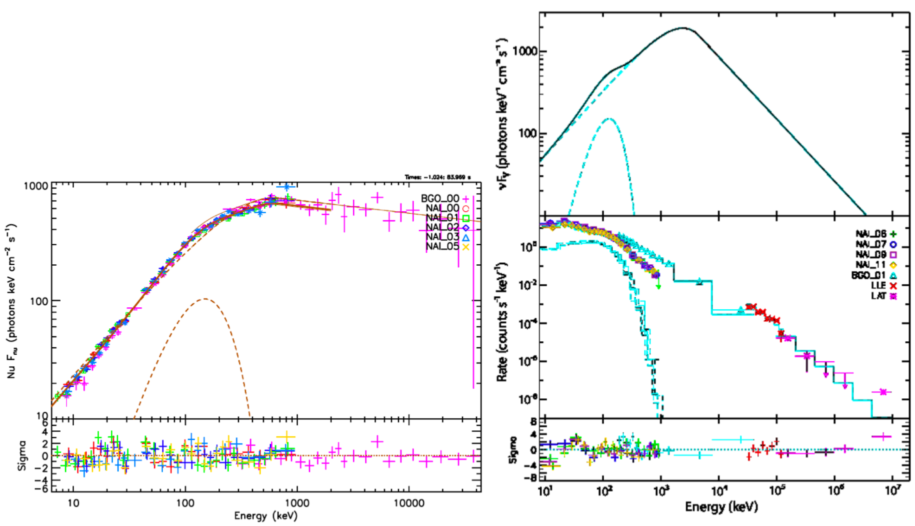
More cases:
Three elemental components?



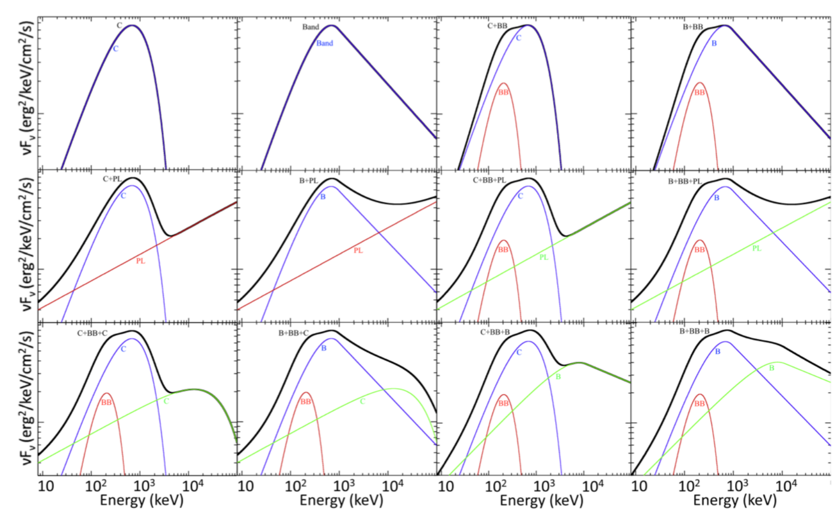
Ackerman et al. 2010, 2011



Zhang et al. 2011

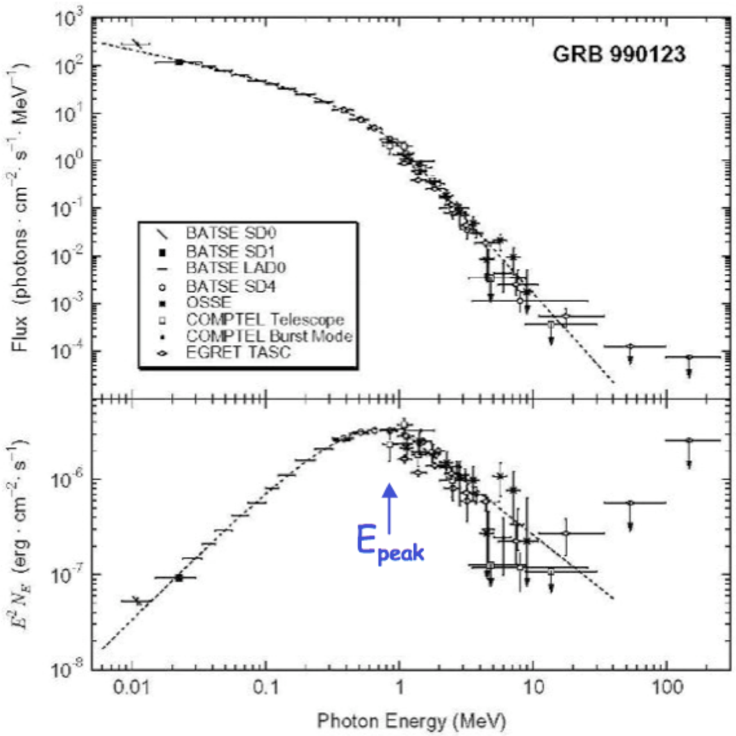


Guiriec et al. 2011; Axelsson et al. 2012



Guiriec et al. 2015

The "Band" function spectrum



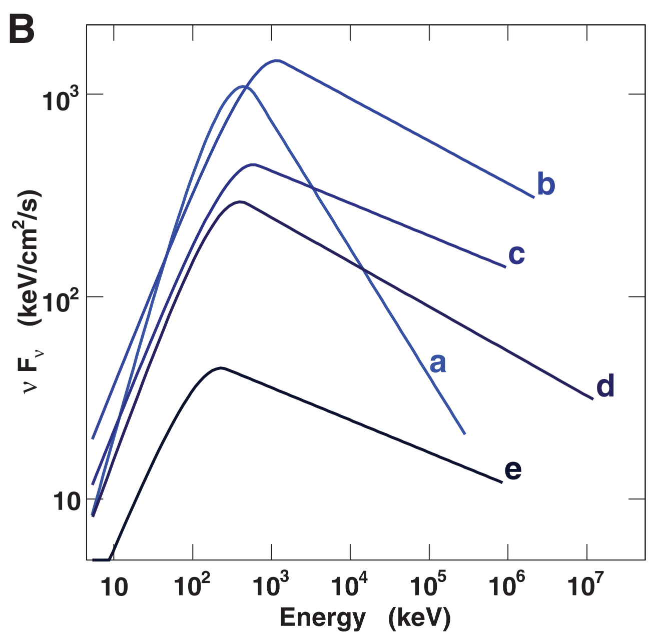
Briggs et al. 1999

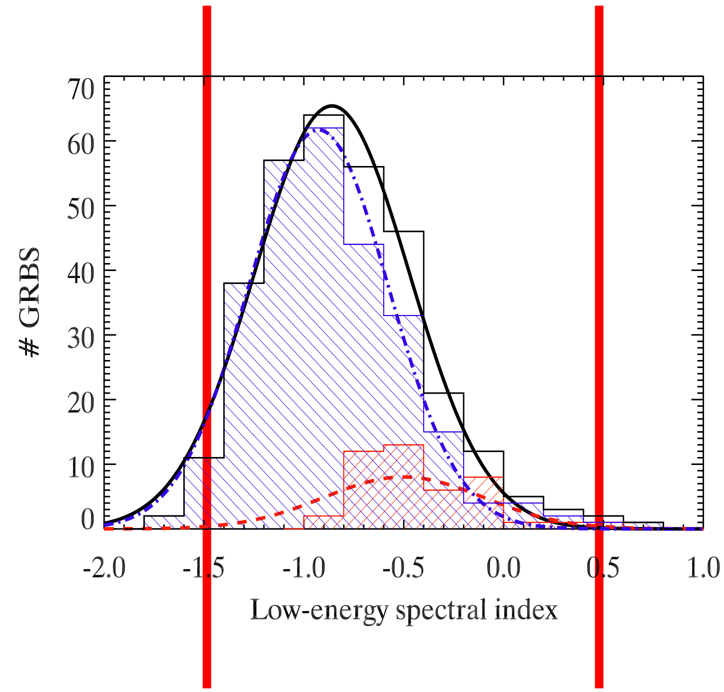
David Louis Band (Jan. 9, 1957 – Mar. 16, 2009)

$$N(E) = \begin{cases} A \left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right) , & E < (\alpha-\beta)E_0 , \\ A \left[\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right]^{\alpha-\beta} \exp(\beta-\alpha) \left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta} , & E \geq (\alpha-\beta)E_0 , \end{cases}$$

Josh Grindley (The 2009 Fermi Symposium, Nov. 2-5, at the David Band special session):
Challenge to theorists: Find the physical meaning of "Band" function in 10 years!

Debate:
What is the origin of the "Band" component?





Simplest synchrotron prediction

Simplest photosphere prediction

Two distinct views:

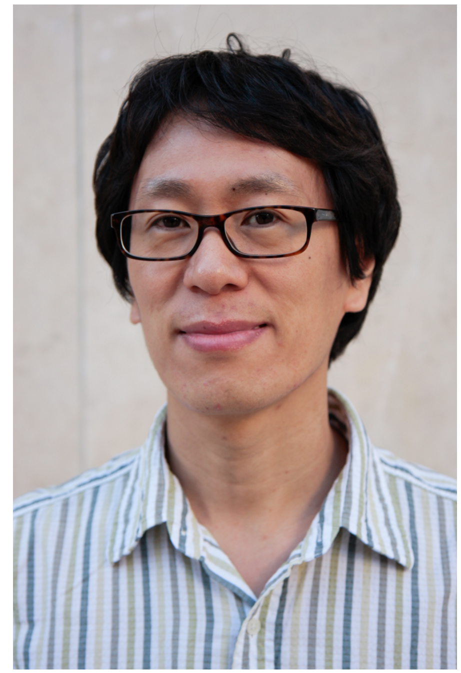
- *The Band component is the synchrotron emission in optically-thin region.*
- *The Band component is reprocessed quasi-thermal emission in a dissipative photosphere.*

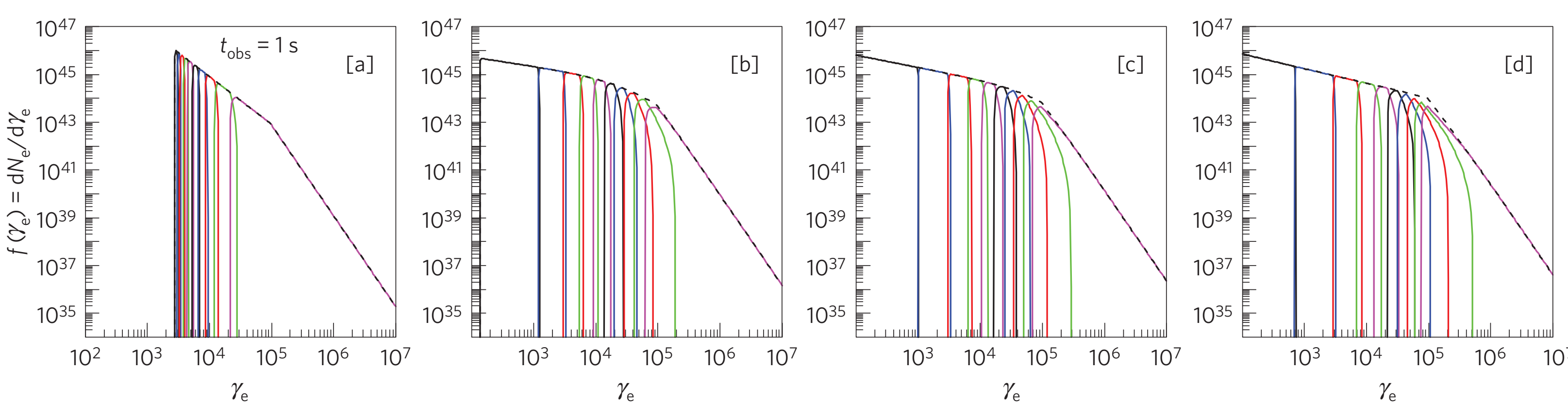
Nava et al. (2011)

Synchrotron Model: Fast Cooling Spectrum Can Be Harder!

(Uhm & Zhang, 2014, Nature Physics, 10, 351)

- B is decreasing with radius
- Electrons are not in steady state
- Electron spectrum deviates significantly from -2 below the injection energy

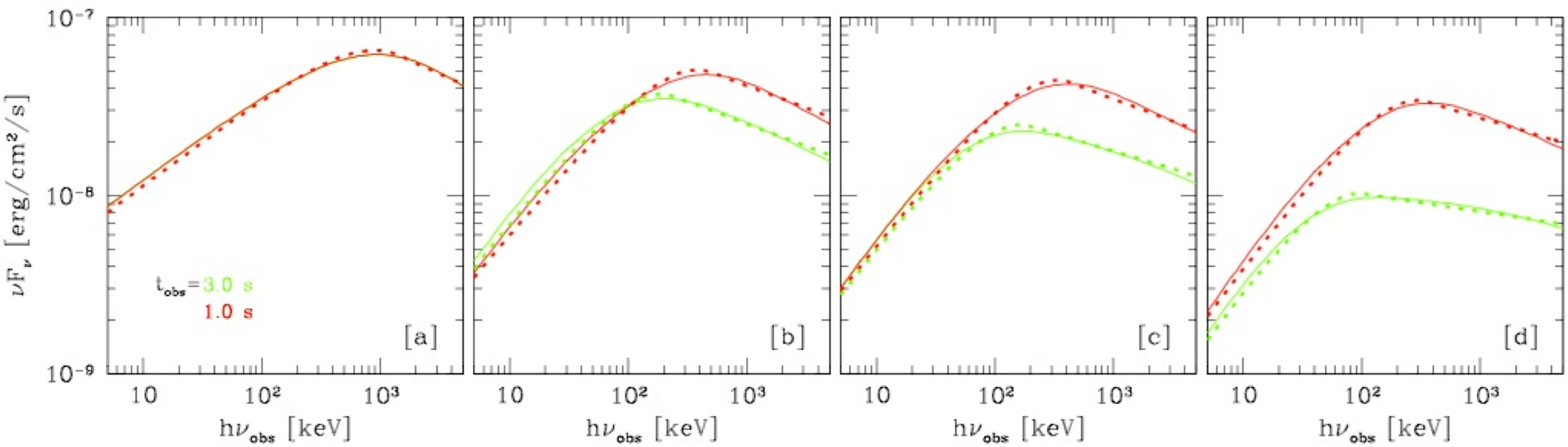




Synchrotron Model: close to (but wider than) the "Band" Function

(Uhm & Zhang, 2014, Nature Physics, 10, 351)

- In the BATSE or GBM band, the spectrum mimics a "Band" function with "correct" indices: α ~ -1, β ~ -2.2

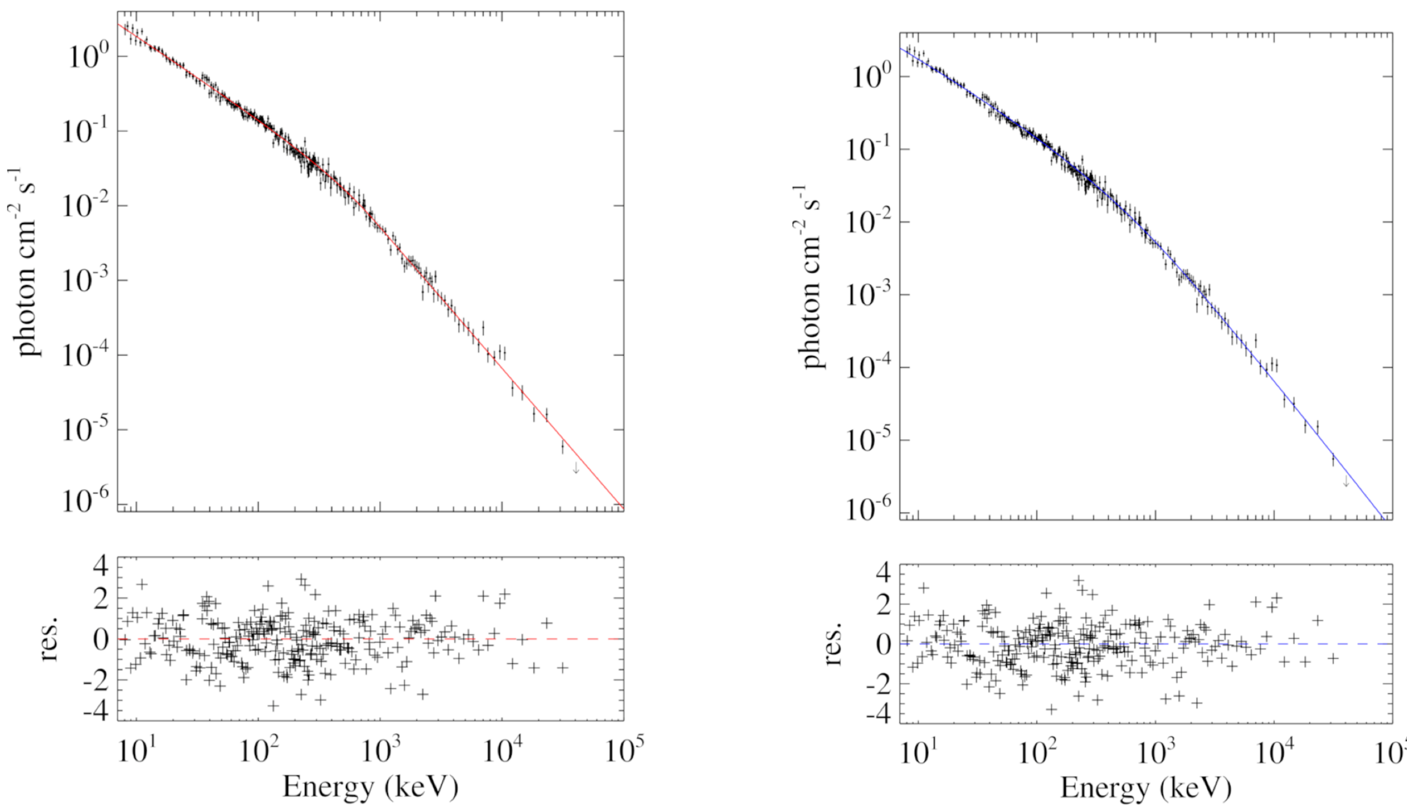


Requirement: Large emission radius where B is low!

“Band” Function is made from synchrotron

(B.-B. Zhang et al., 2016)

- One should apply models directly to data!
- Example: GRB 130606B – no difference between synchrotron and Band models in terms of goodness of fitting



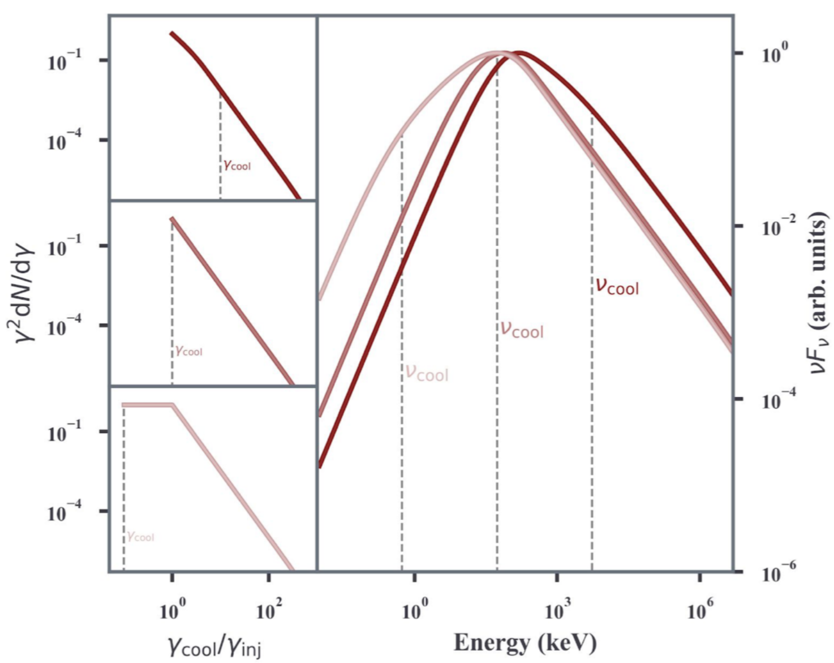
Band & synchrotron model fits

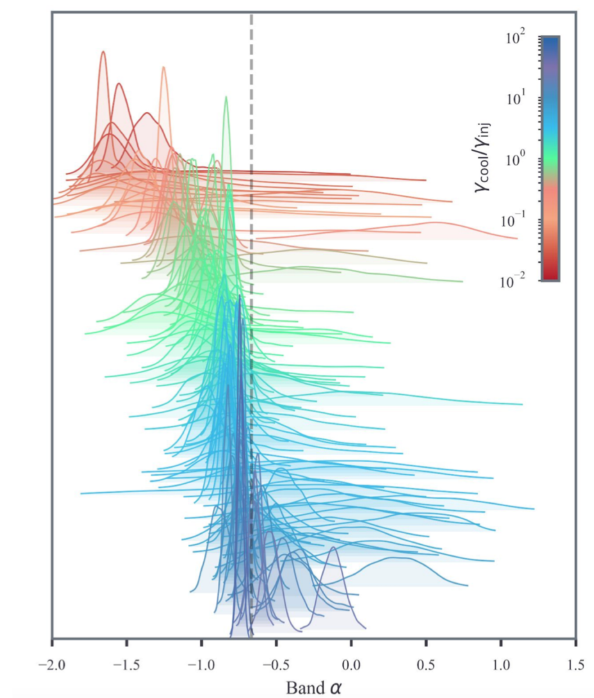
Gamma-ray bursts as cool synchrotron sources

arXiv:1810.06965

J. Michael Burgess[1,2], Damien Bégué[1], Ana Bacelj[1,3], Dimitrios Giannios[4] , Francesco Berlato[1,5], and Jochen Greiner[1,2]

Here we show that idealized synchrotron emission, when properly incorporating time-dependent cooling of the electrons, is capable of fitting ~95% of all time-resolved spectra of single-peaked GRBs as measured with Fermi/GBM. The comparison with spectral fit results based on previous empirical models demonstrates that the past exclusion of synchrotron radiation as an emission mechanism derived via the line-of-death was misleading. Our analysis probes the physics of these ultra-relativistic outflows and the



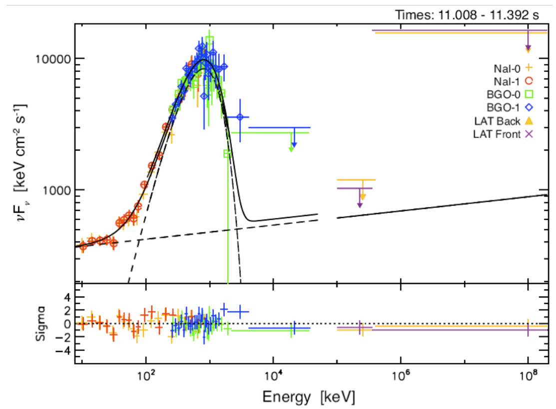


cf. Ryde's talk

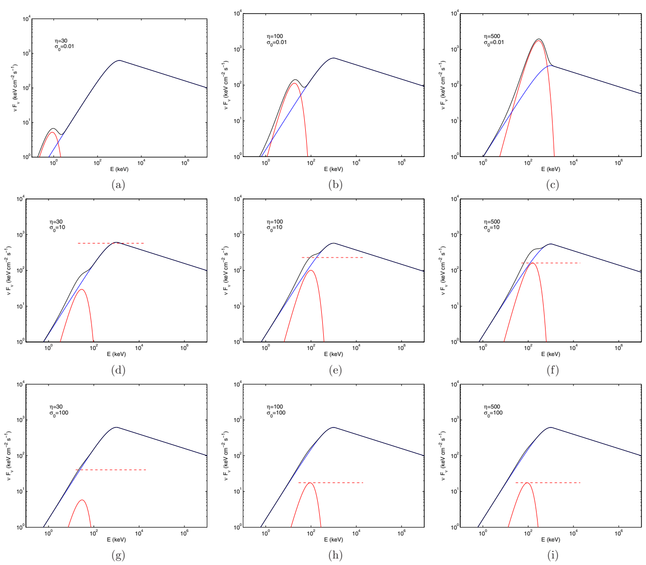
Big Picture: GRB jet composition

- GRB jets have diverse compositions:
  - Photosphere dominated (GRB 090902B), rare
  - Intermediate bursts (weak but not fully suppressed photosphere, GRB 100724B, 110721A)
  - Photosphere suppressed, Poynting flux dominated (GRB 080916C)

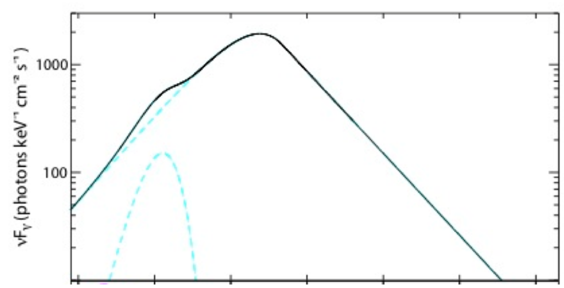
The majority of GRBs have significant magnetization



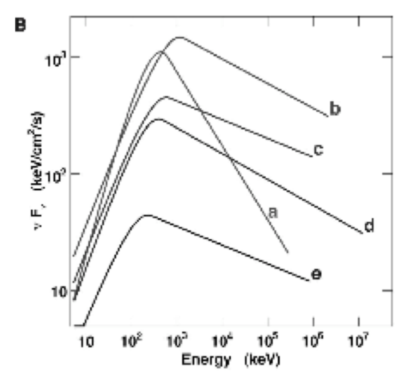
GRB 090902B



Gao & Zhang 2015



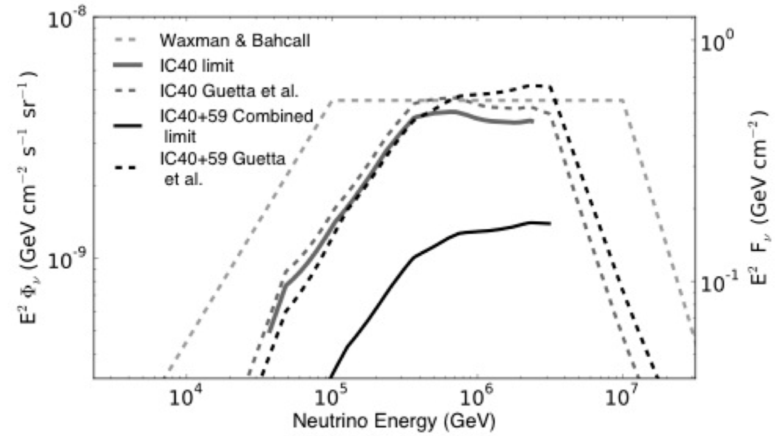
GRB 110721A



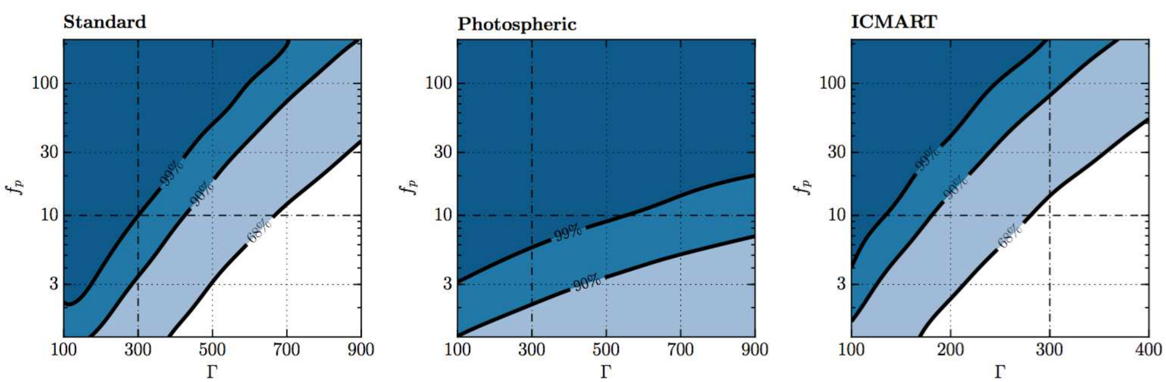
GRB 080916C

Fermi/IceCube Surprise #3: Non-detection of neutrinos by IceCube

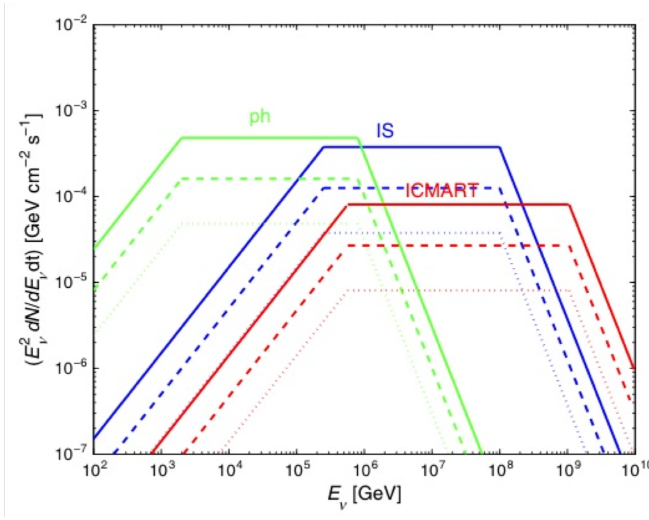
- Icecube so far has not detected any high-energy neutrino associated with GRBs!
- Consistent with a large emission radius (magnetic dissipation)



IceCube 2012



Icecube collaboration 2016



Zhang & Kumar 2013

Smoking gun #1:
Spectral lags & Ep evolutions

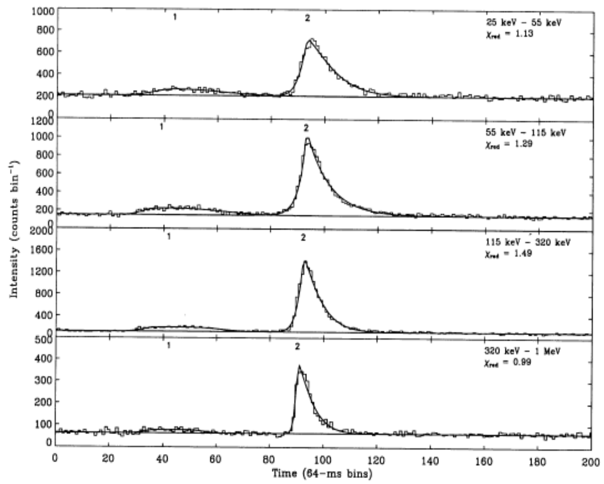
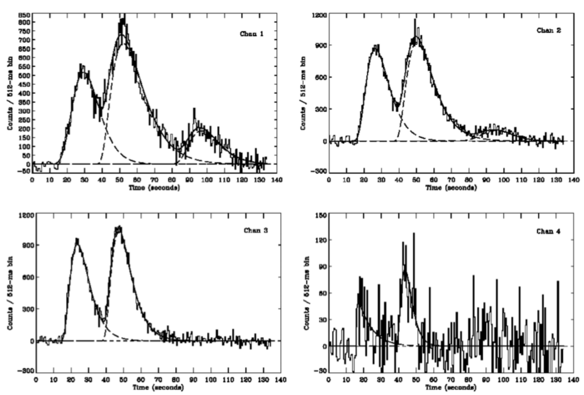
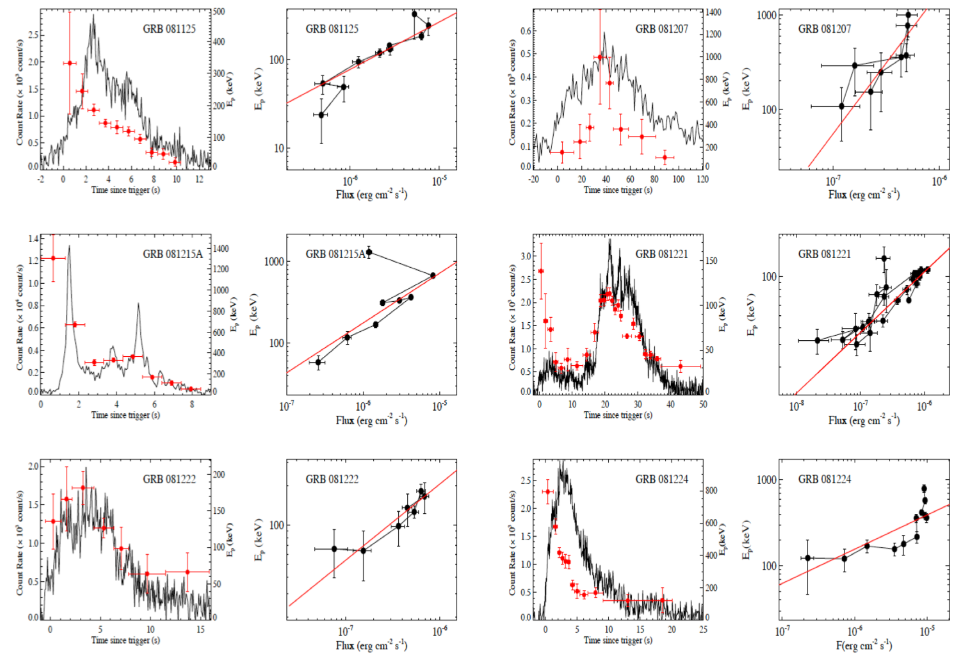


FIG. 16.—BATSE trigger 999: a simple burst profile, with two fitted pulses. Both pulses, identified in all four channels, are considered separable since their overlap is insignificant.

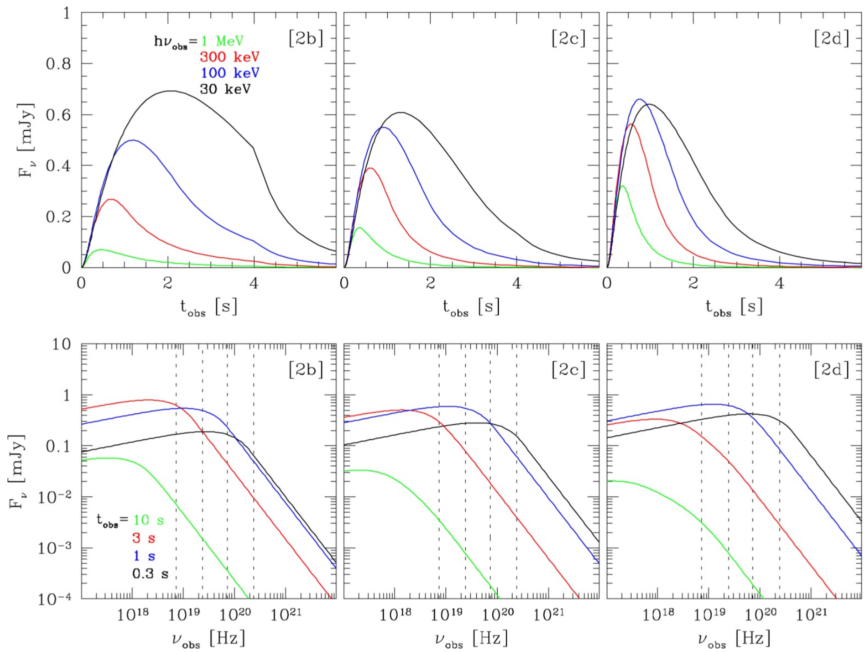


Norris et al. (1996)

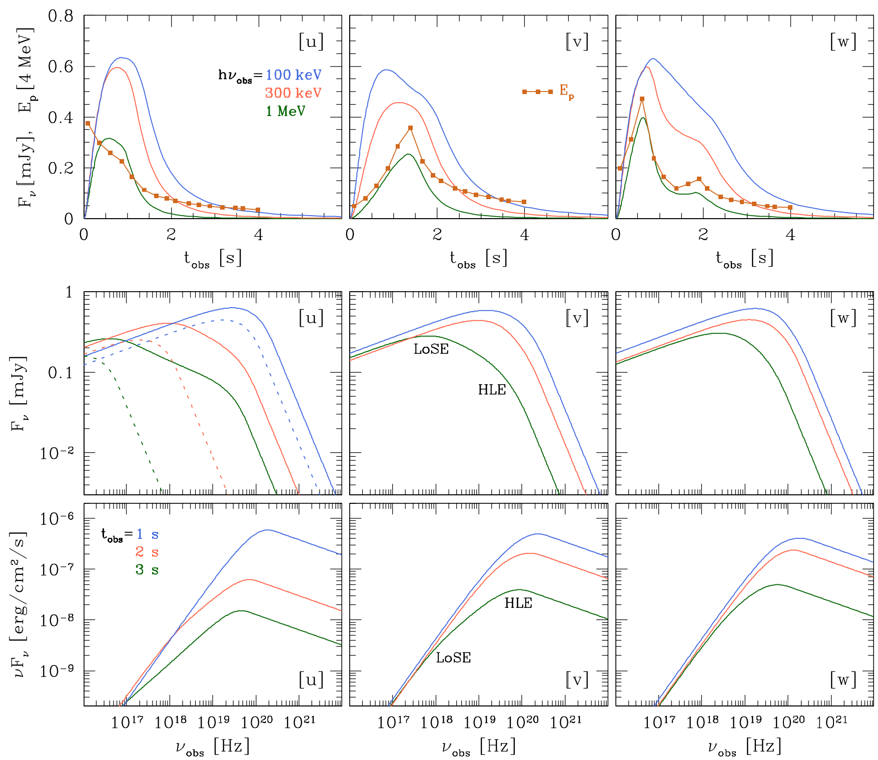


(Lu et al. 2012)

Smoking gun #1: Spectral lags & Ep evolutions



Uhm & Zhang (2016)



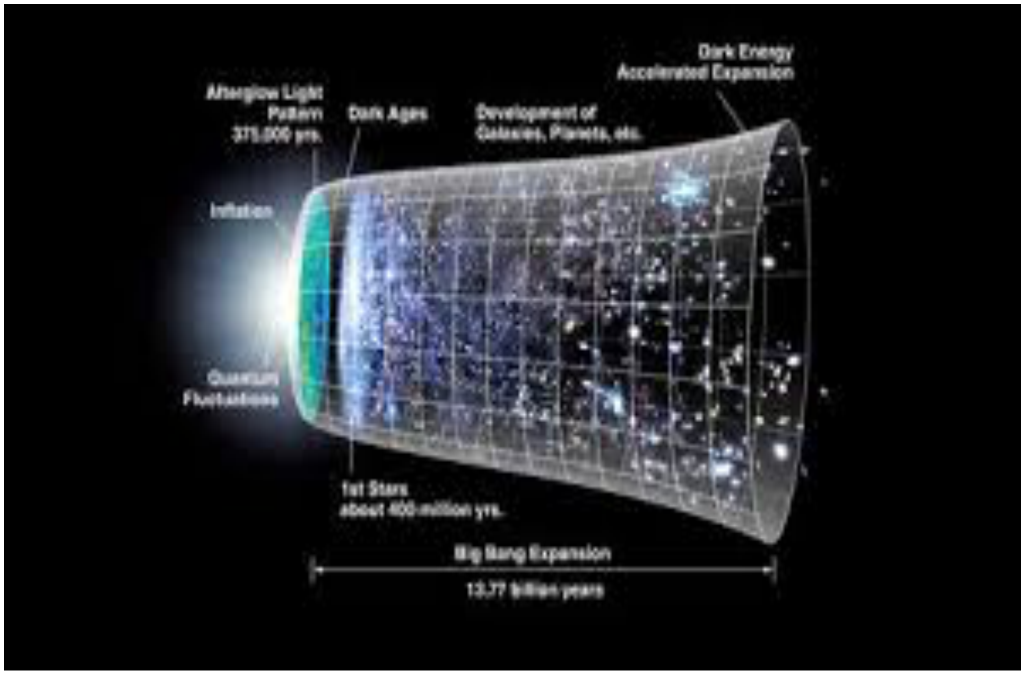
Uhm, Zhang & Racusin (2018)

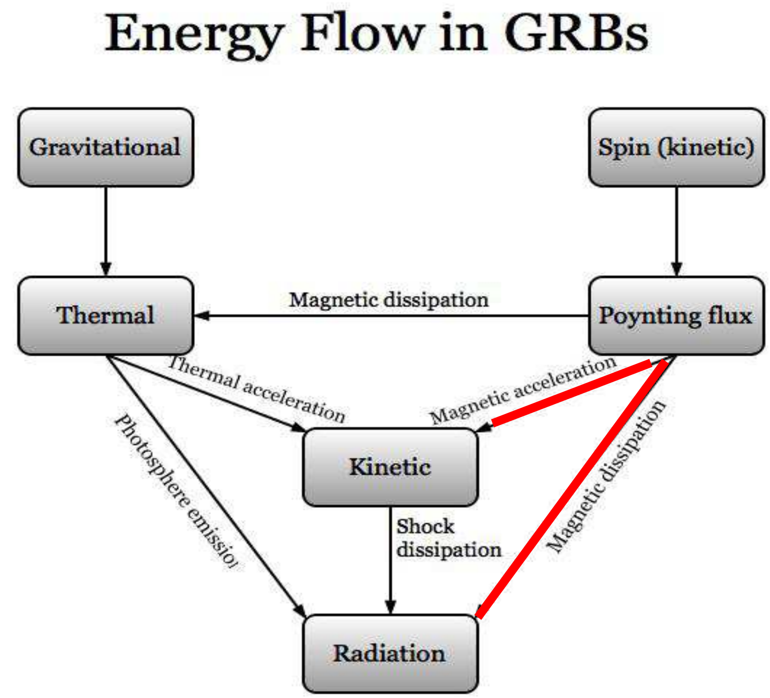
Model requirements:

1. *Large emission region*
2. *Bulk acceleration*

$$r \sim \Gamma^2 c\, t_{\rm pulse} \sim (3 \times 10^{14}\ {\rm cm})\Gamma_2^2 (t_{\rm pulse}/1\ {\rm s}).$$

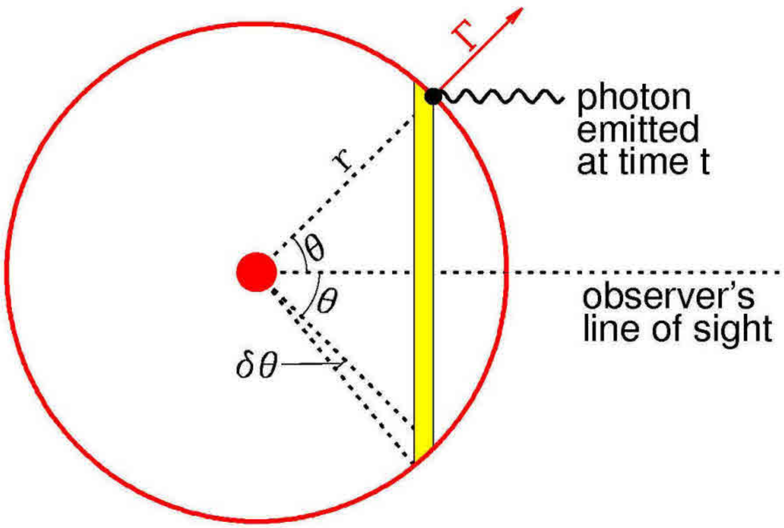
Bulk acceleration & “dark energy”

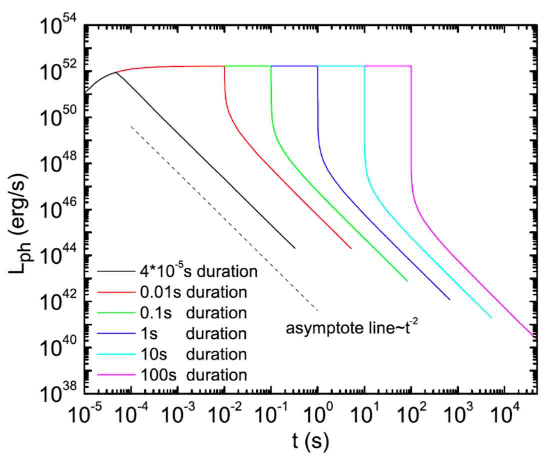




Smoking gun of Poynting flux dissipation:
bulk acceleration *in the emission region*

Smoking gun #2:
High-latitude emission & curvature effect





Not detectable for photosphere emission
Deng & Zhang, 2014

- Predicted features:
  - Lightcurve:

$$F_{\nu_{\rm obs}}^{\rm obs} \propto t_{\rm obs}^{-\hat{\alpha}} \ \nu_{\rm obs}^{-\hat{\beta}},$$

$$\hat{\alpha} = 2 + \hat{\beta},$$

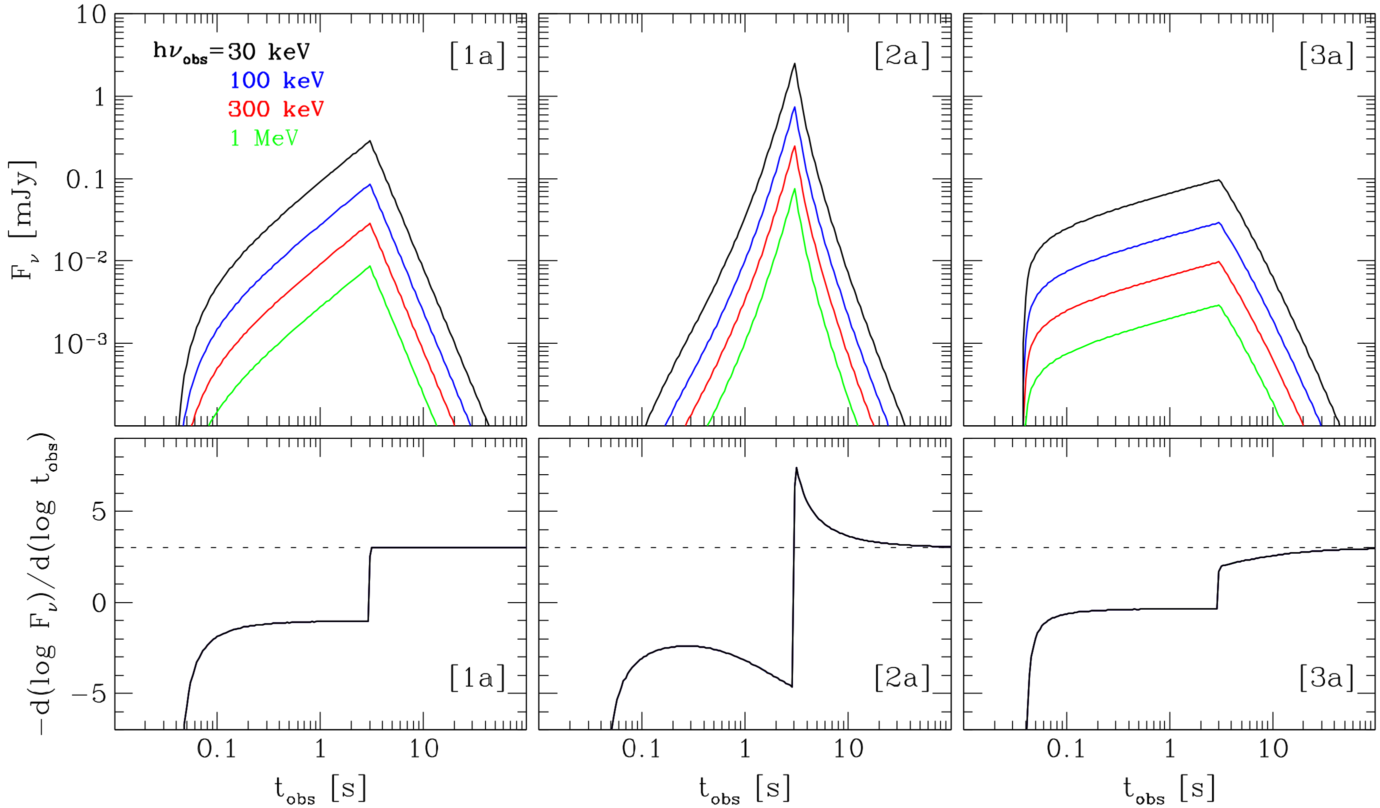
Kumar & Panaitescu (2000)

  - Spectral:

$$F_{\nu,E_p} \propto E_p^2$$

Curvature effect

Uhm & Zhang (2015, ApJ)



Constant Γ *acceleration* *deceleration*

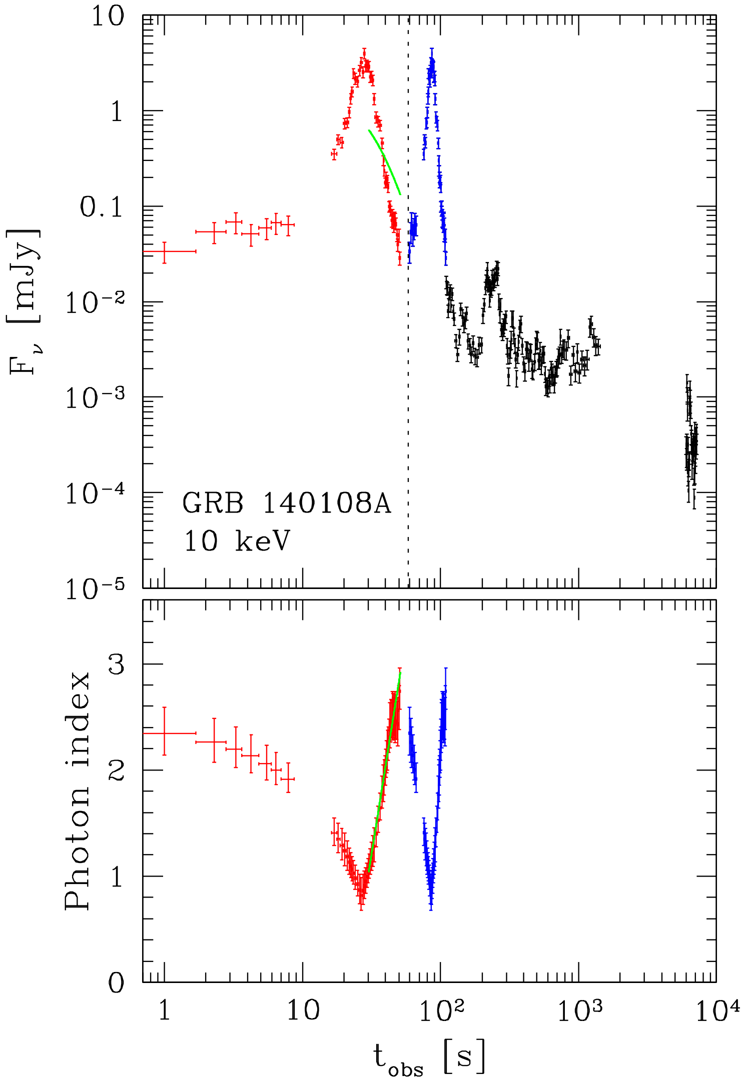
$$F_{\nu_{\rm obs}}^{\rm obs} \propto t_{\rm obs}^{-\hat{\alpha}}\ \nu_{\rm obs}^{-\hat{\beta}}, \qquad \hat{\alpha} = 2 + \hat{\beta},$$

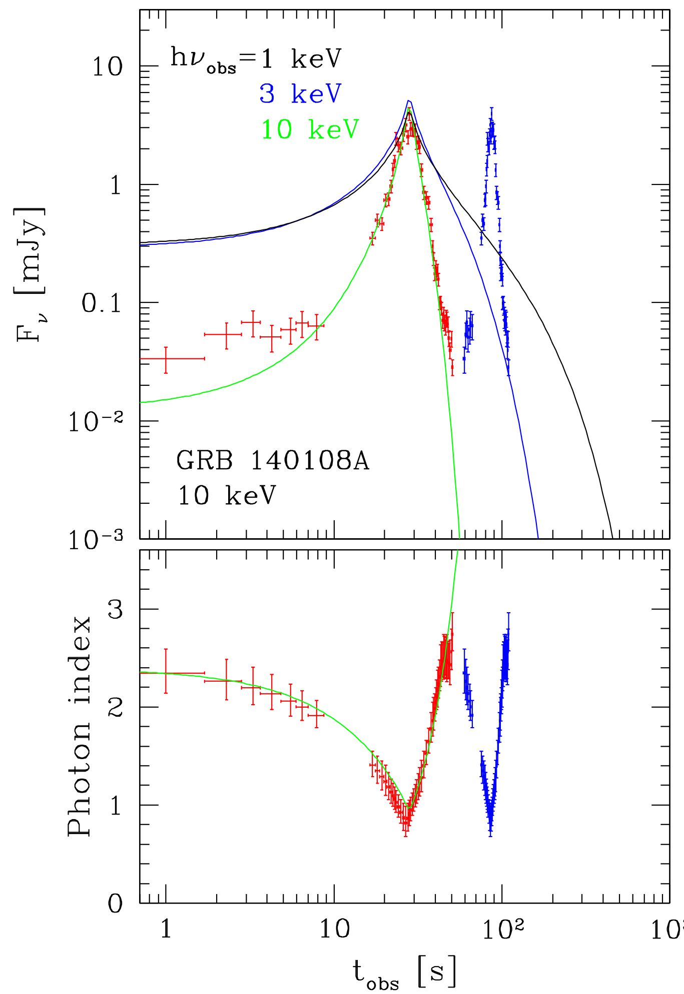
Kumar & Panaitescu (2000)

Only applies for constant Lorentz factor

Steeper with bulk acceleration, shallower with bulk deceleration

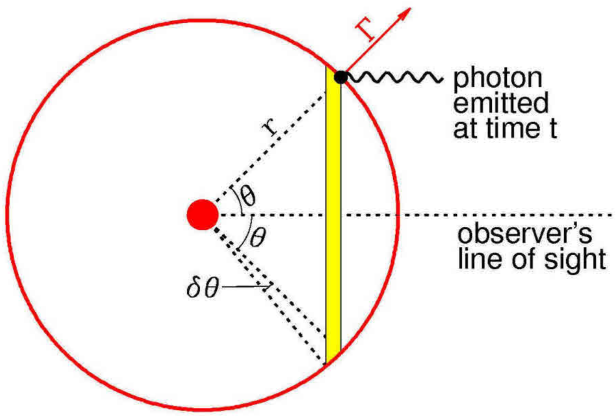
High latitude emission in X-ray flares: again bulk acceleration & Poynting flux

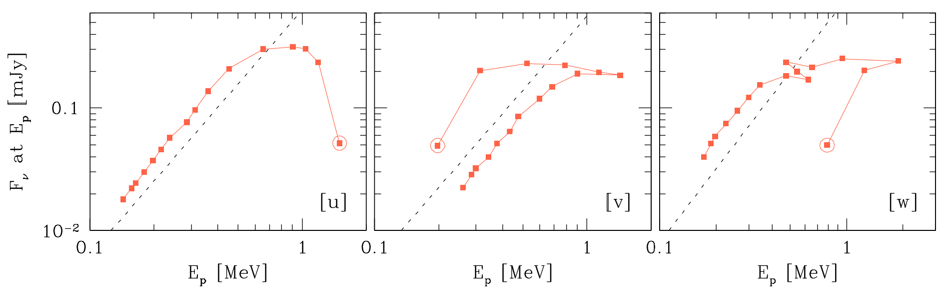


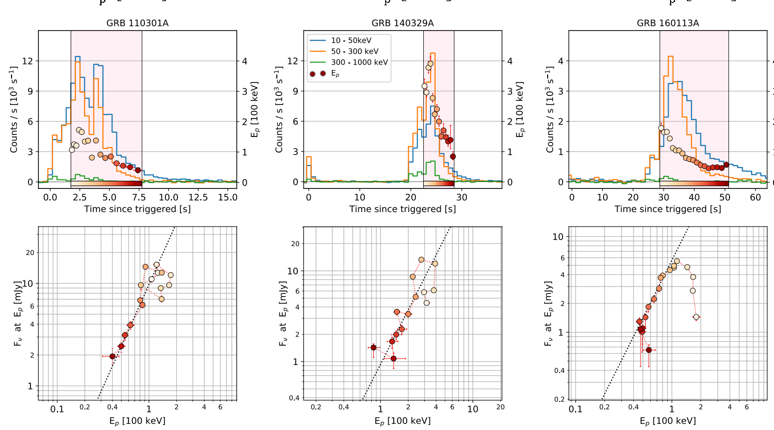


Uhm & Zhang (2016, ApJ, 824, L16)

High-latitude emission in prompt emission







- Not easy to test the lightcurve relation
  - Overlapping
  - Not long enough tail to measure

$$F_{\nu_{\rm obs}}^{\rm obs} \propto t_{\rm obs}^{-\hat{\alpha}} \; \nu_{\rm obs}^{-\hat{\beta}},$$

- Direct & clean test:

$$F_{\nu,E_p} \propto E_p^2$$

Uhm et al. (2018); Tak et al. (2018)

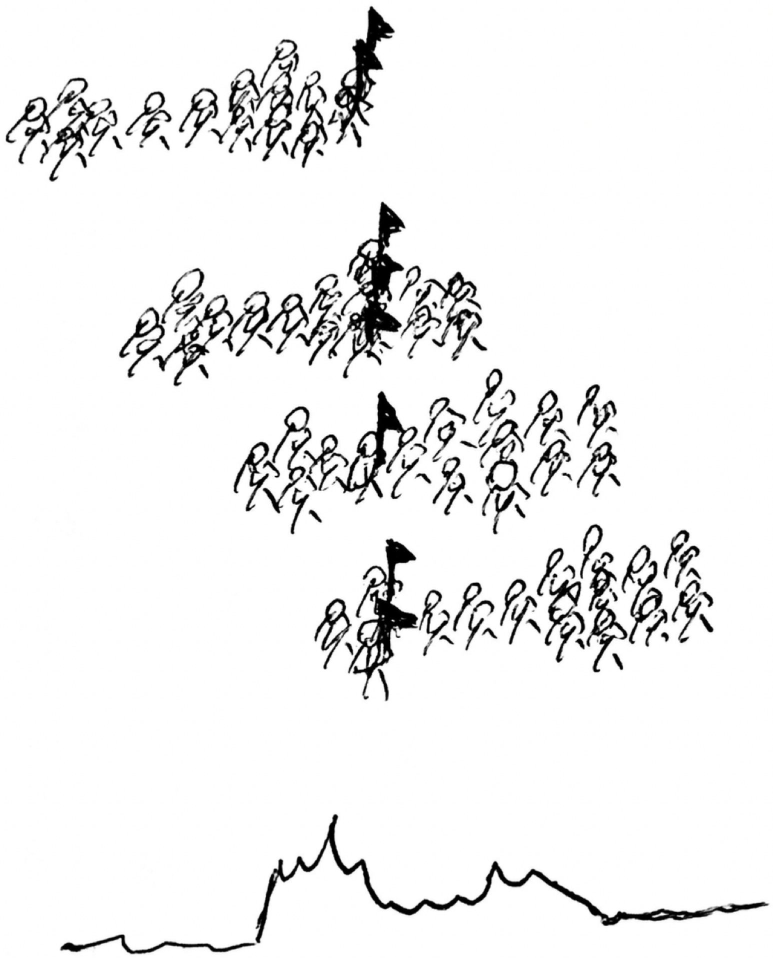
Next talk by Donggeun Tak

Summary

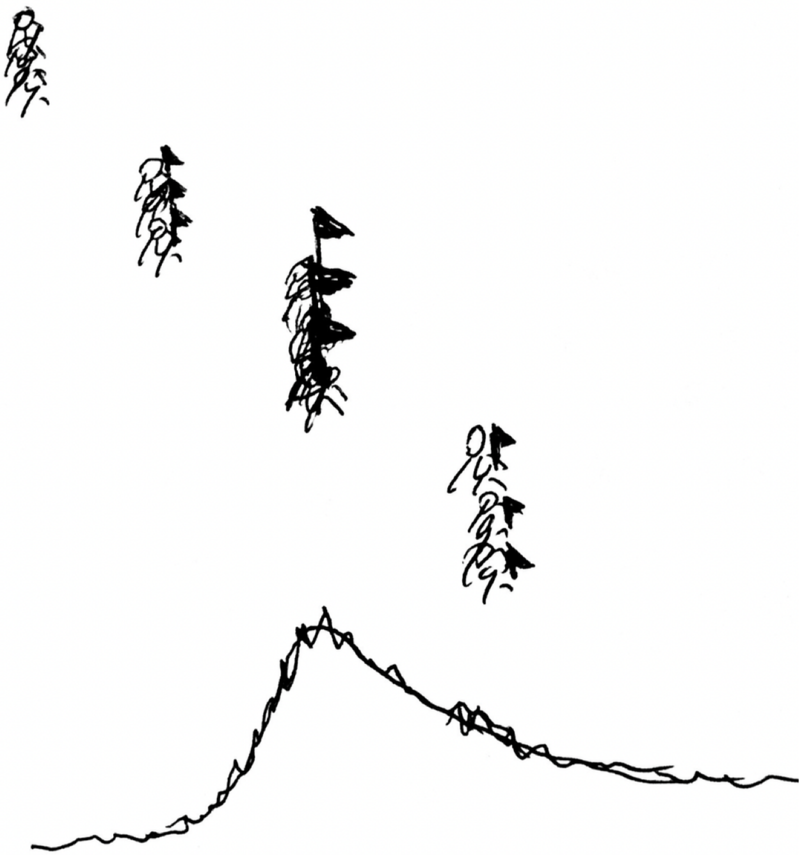
- The excellent GRB data collected by Fermi GBM and LAT have revolutionized our physical understanding of GRB prompt emission
- Data used:
  - Time resolved spectra: ”Band” component, thermal component, high energy component
  - Light curve spectral lags
  - Ep evolution within pulses ($F_{\nu,E_p} \propto E_p^2$)
  - Non-detection of neutrinos
- Conclusions drawn:
  - GRB jet composition is diverse
  - Fireballs are rare, but some GRBs (e.g. GRB 090902B) are dominated by photosphere emission
  - Most GRB outflows are Poynting-flux-dominated at least at the central engine, and are likely still moderately magnetized in the emission region
  - The emission mechanism of the “Band” component is synchrotron radiation from an optically thin region, likely invoking dissipation of magnetic energy, at least for some, possibly most, GRBs.

Future prospects with Fermi (GRB physics)

- More targeted data analysis can answer the following questions:
  - Detections / non-detections of the thermal component can systematically constrain the jet magnetization parameter;
  - Joint spectral and temporal analyses may lead to the identification of two types of GRBs (in terms of jet composition);
  - Comparison of the statistical properties of different types?
  - Short vs. long



photosphere
small-radius IS



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Large-radius IS