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Announcement of a new journal



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Announcement of a new journal



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Journal is officially open for submissions.

First articles published online, first full issue expected mid-2014.

Journal will appear 4 times per year.

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Radiation Processes in GRBs

Bing Zhang

University of Nevada Las Vegas

In collaboration with:

He Gao, Wei Deng, Z. Lucas Uhm, Hui Li ...

Jun. 17, 2014

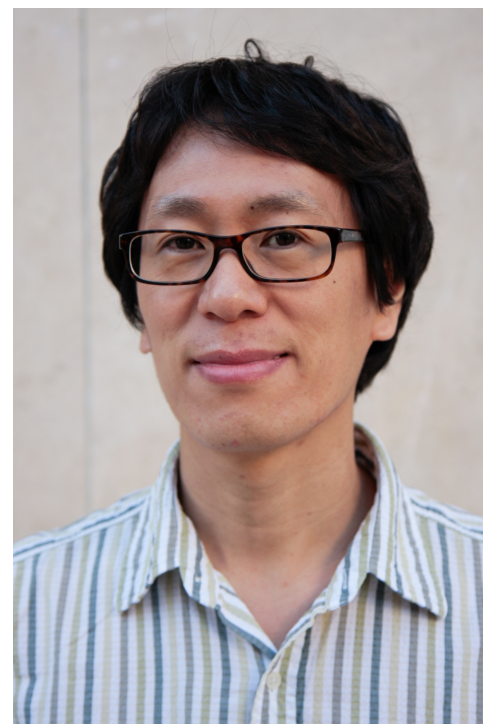
Gamma-Ray Bursts in the Multi-Messenger Era
Paris, France, Jun. 16-19, 2014



He Gao

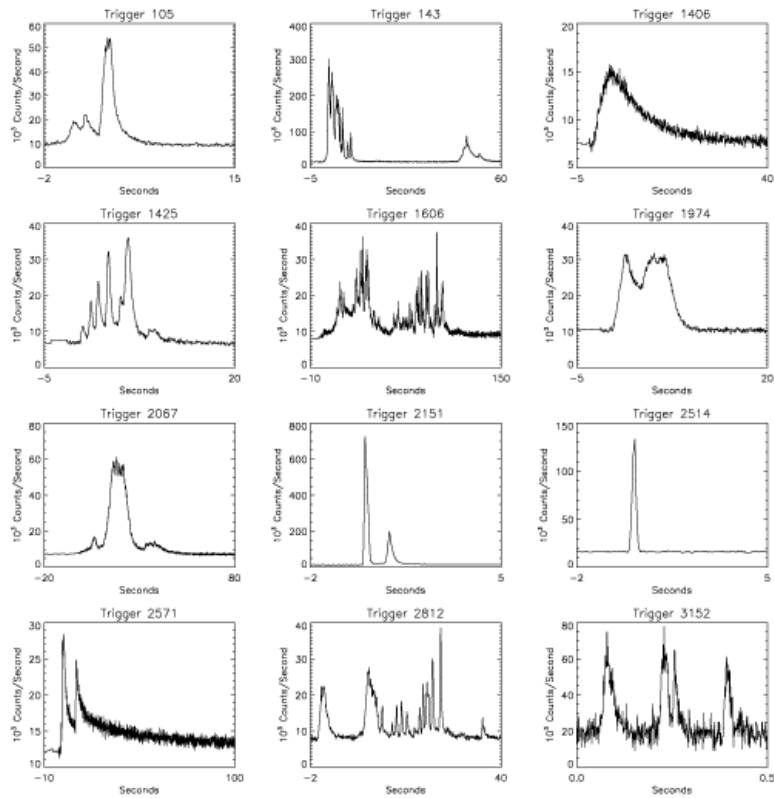


Wei Deng

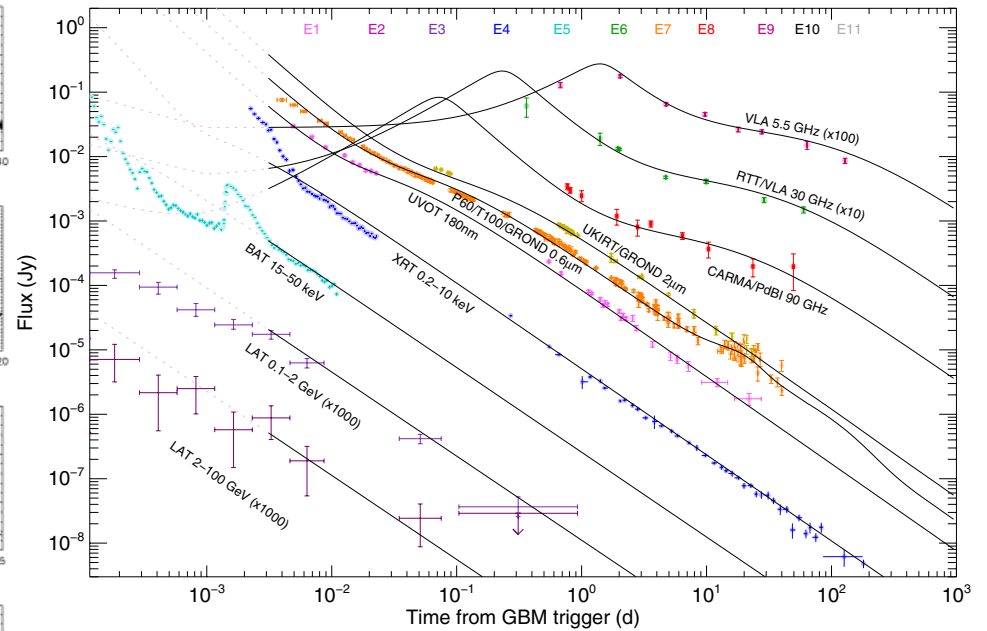


Z. Lucas Uhm

GRB prompt emission & afterglow



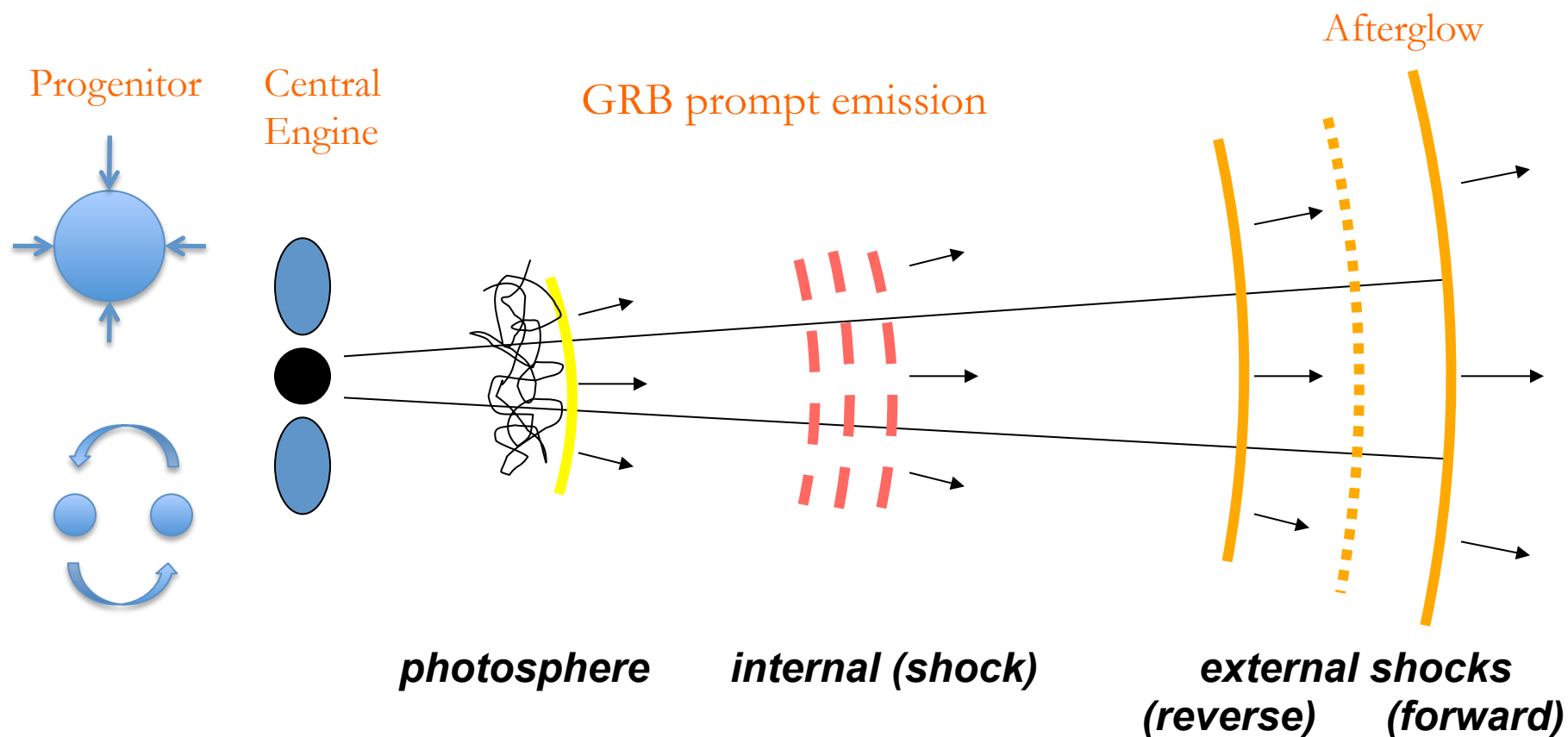
Mészáros (2006)



GRB 130427A

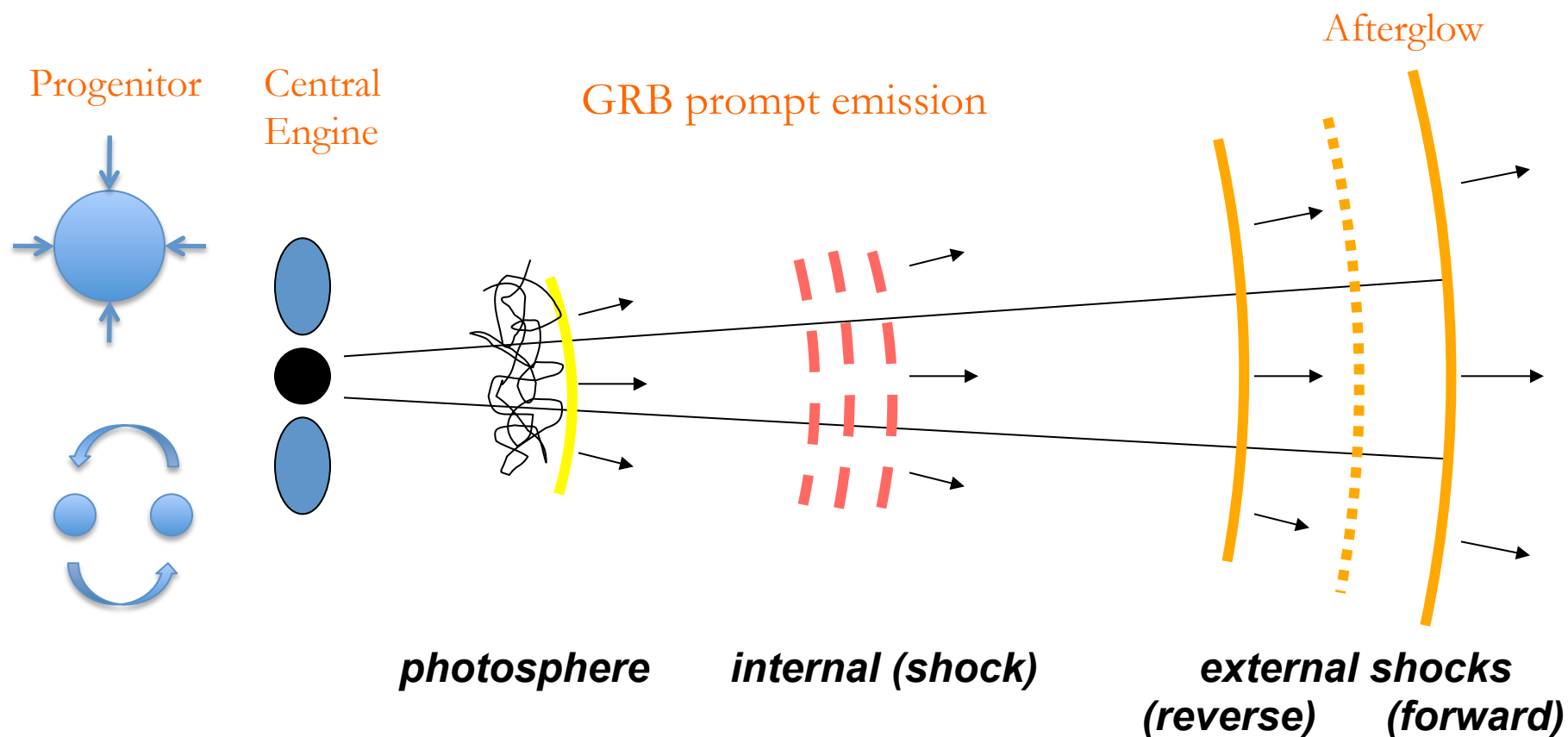
Perley et al. (2014)

Physical Picture: A Sketch



Origin of Afterglow

Physical Picture: A Sketch

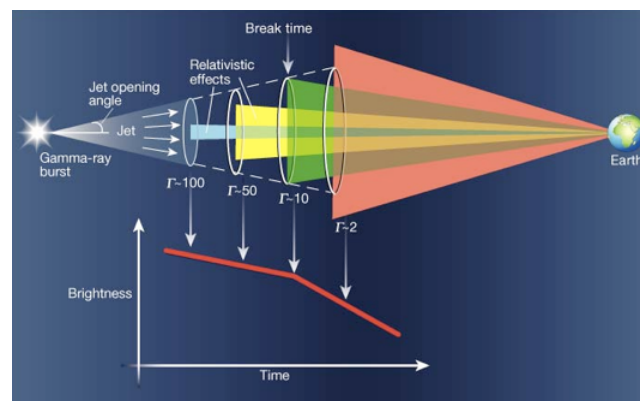
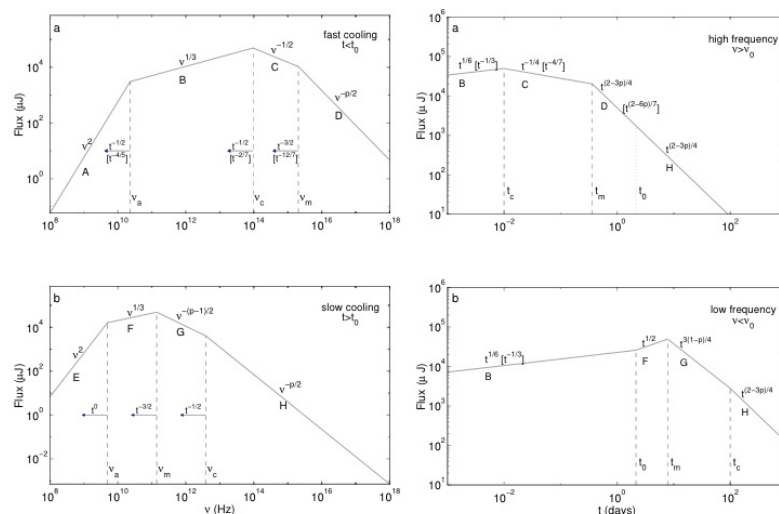


Afterglow Radiation Mechanisms

- Synchrotron radiation
- Synchrotron self-Compton

External forward shock synchrotron afterglow model

- Originated from ejecta – medium interaction
- During the self-similar phase: A **generic** model
- Depend on a few parameters:
 - Ejecta: E or $E(t)$, Γ_0 , and θ_j
 - Medium: n or $n(r)$
 - Shock: ϵ_e , ϵ_B , p
- Jet break



Synchrotron emission from external forward shock: Meszaros & Rees (1997); Sari et al. (1998)
Dynamics of relativistic blastwave: self-similar solution: Blandford & McKee (1976)

Afterglow Closure Relations

| | β | α ($p > 2$, $p \sim 2.3$) | $\alpha(\beta)$ | α ($1 < p < 2$, $p \sim 1.5$) | $\alpha(\beta)$ |
|-----------------------|------------------|-------------------------------------|-------------------------------|---|-----------------------------------|
| ISM, slow cooling | | | | | |
| $\nu < \nu_a$ | 2 | $\frac{1}{2}$ | | $\frac{17p-26}{16(p-1)} \sim -0.06$ | |
| $\nu_a < \nu < \nu_m$ | $\frac{1}{3}$ | $\frac{1}{2}$ | $\alpha = \frac{3\beta}{2}$ | $\frac{p+2}{8(p-1)} \sim 0.9$ | |
| $\nu_m < \nu < \nu_c$ | $-\frac{p-1}{2}$ | $\frac{3(1-p)}{4} \sim -1.0$ | $\alpha = \frac{3\beta}{2}$ | $-\frac{3(p+2)}{16} \sim -0.7$ | $\alpha = \frac{3(2\beta-3)}{16}$ |
| $\nu > \nu_c$ | $-\frac{p}{2}$ | $\frac{2-3p}{4} \sim -1.2$ | $\alpha = \frac{3\beta+1}{2}$ | $-\frac{3p+10}{16} \sim -0.9$ | $\alpha = \frac{3\beta-5}{8}$ |
| ISM, fast cooling | | | | | |
| $\nu < \nu_a$ | 2 | 1 | | 1 | |
| $\nu_a < \nu < \nu_c$ | $\frac{1}{3}$ | $\frac{1}{6}$ | $\alpha = \frac{\beta}{2}$ | $\frac{1}{6}$ | $\alpha = \frac{\beta}{2}$ |
| $\nu_c < \nu < \nu_m$ | $-\frac{1}{2}$ | $-\frac{1}{4}$ | $\alpha = \frac{\beta}{2}$ | $-\frac{1}{4}$ | $\alpha = \frac{\beta}{2}$ |
| $\nu > \nu_m$ | $-\frac{p}{2}$ | $\frac{2-3p}{4} \sim -1.2$ | $\alpha = \frac{3\beta+1}{2}$ | $-\frac{3p+10}{16} \sim -0.9$ | $\alpha = \frac{3\beta-5}{8}$ |
| Wind, slow cooling | | | | | |
| $\nu < \nu_a$ | 2 | 1 | | $\frac{13p-18}{8(p-1)} \sim 0.4$ | |
| $\nu_a < \nu < \nu_m$ | $\frac{1}{3}$ | 0 | $\alpha = \frac{3\beta-1}{2}$ | $\frac{5(2-p)}{12(p-1)} \sim 0.4$ | |
| $\nu_m < \nu < \nu_c$ | $-\frac{p-1}{2}$ | $\frac{1-3p}{4} \sim -1.5$ | $\alpha = \frac{3\beta-1}{2}$ | $-\frac{p+8}{8} \sim -1.2$ | $\alpha = \frac{2\beta-9}{8}$ |
| $\nu > \nu_c$ | $-\frac{p}{2}$ | $\frac{2-3p}{4} \sim -1.2$ | $\alpha = \frac{3\beta+1}{2}$ | $-\frac{p+6}{8} \sim -0.9$ | $\alpha = \frac{\beta-3}{4}$ |
| Wind, fast cooling | | | | | |
| $\nu < \nu_a$ | 2 | 2 | | 2 | |
| $\nu_a < \nu < \nu_c$ | $\frac{1}{3}$ | $-\frac{2}{3}$ | $\alpha = -\frac{\beta+1}{2}$ | $-\frac{2}{3}$ | $\alpha = -\frac{\beta+1}{2}$ |
| $\nu_c < \nu < \nu_m$ | $-\frac{1}{2}$ | $-\frac{1}{4}$ | $\alpha = -\frac{\beta+1}{2}$ | $-\frac{1}{4}$ | $\alpha = -\frac{\beta+1}{2}$ |
| $\nu > \nu_m$ | $-\frac{p}{2}$ | $\frac{2-3p}{4} \sim -1.2$ | $\alpha = \frac{3\beta+1}{2}$ | $-\frac{p+6}{8} \sim -0.9$ | $\alpha = \frac{\beta-3}{4}$ |
| Jet, slow cooling | | | | | |
| $\nu < \nu_a$ | 2 | 0 | | $\frac{3(p-2)}{4(p-1)} \sim -0.8$ | |
| $\nu_a < \nu < \nu_m$ | $\frac{1}{3}$ | $-\frac{1}{3}$ | $\alpha = 2\beta - 1$ | $\frac{8-5p}{6(p-1)} \sim 0.2$ | |
| $\nu_m < \nu < \nu_c$ | $-\frac{p-1}{2}$ | $-p \sim -2.3$ | $\alpha = 2\beta - 1$ | $-\frac{p+6}{4} \sim -1.9$ | $\alpha = \frac{2\beta-7}{4}$ |
| $\nu > \nu_c$ | $-\frac{p}{2}$ | $-p \sim -2.3$ | $\alpha = 2\beta$ | $-\frac{p+6}{4} \sim -1.9$ | $\alpha = \frac{\beta-3}{2}$ |

Well-predicted temporal decay indices and spectral indices

Sari, Piran & Narayan (1998)

Chevalier & Li (2000)

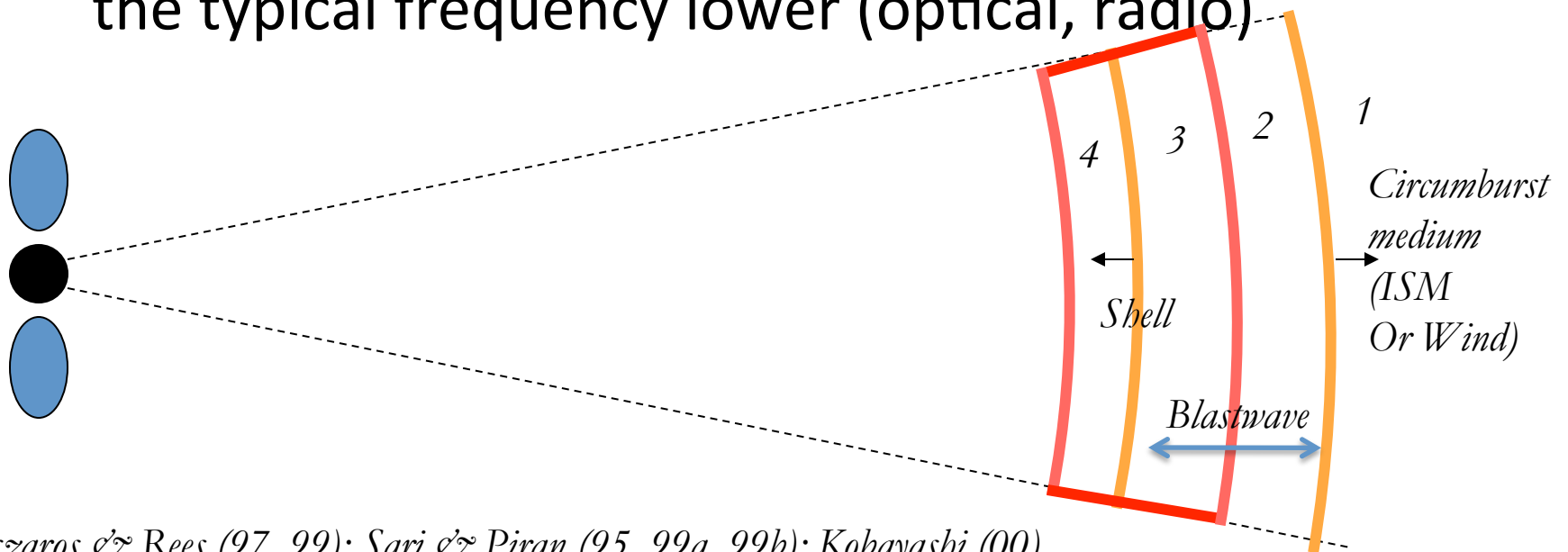
Dai & Cheng (2001)

Zhang & Meszaros (2004)

Gao et al. (2013, New Astron. Rev.)

External reverse shock afterglow

- Since GRBs are short-lived, *if the Lorentz factor of the ejecta is roughly constant*, then there is a short-lived reverse shock
- Similar pressure in 2 & 3; the RS region is denser, the typical frequency lower (optical, radio)



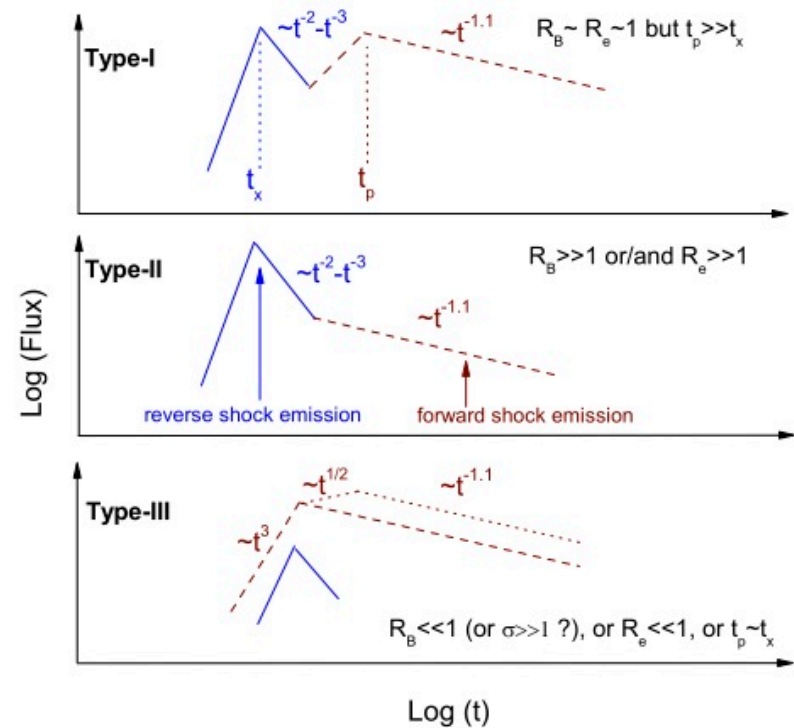
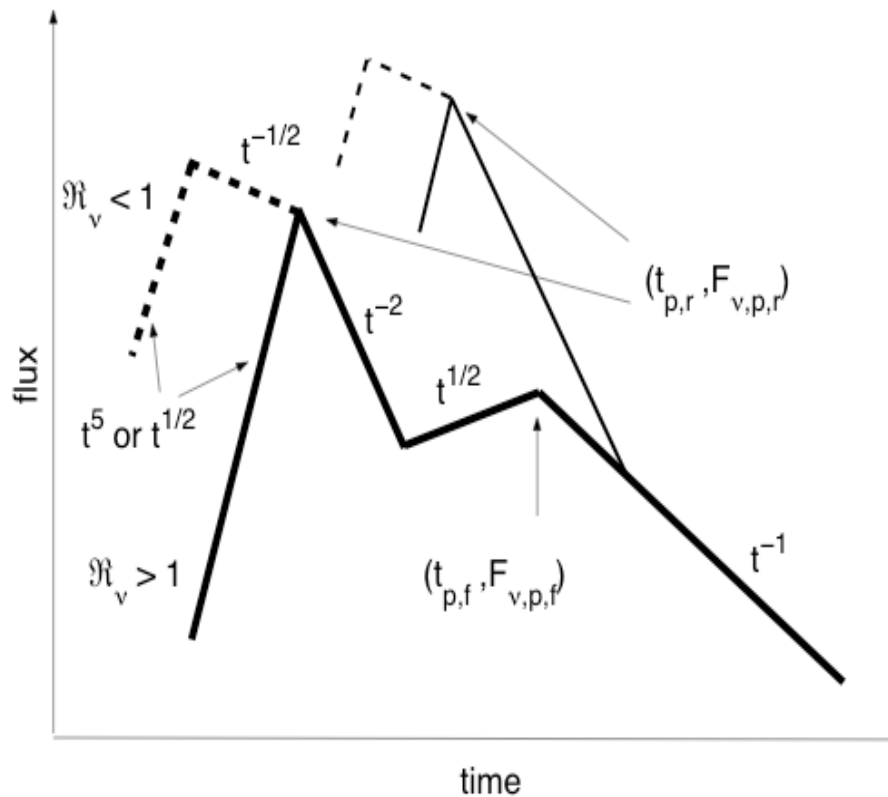
Meszaros & Rees (97, 99); Sari & Piran (95, 99a, 99b); Kobayashi (00)

Kobayashi & Zhang (03); Zhang, Kobayashi & Meszaros (03,05)

Long lasting: Genet et al. (2007); Uhm & Beloborodov (2007); Uhm et al. (2012), Uhm & Zhang (2014)

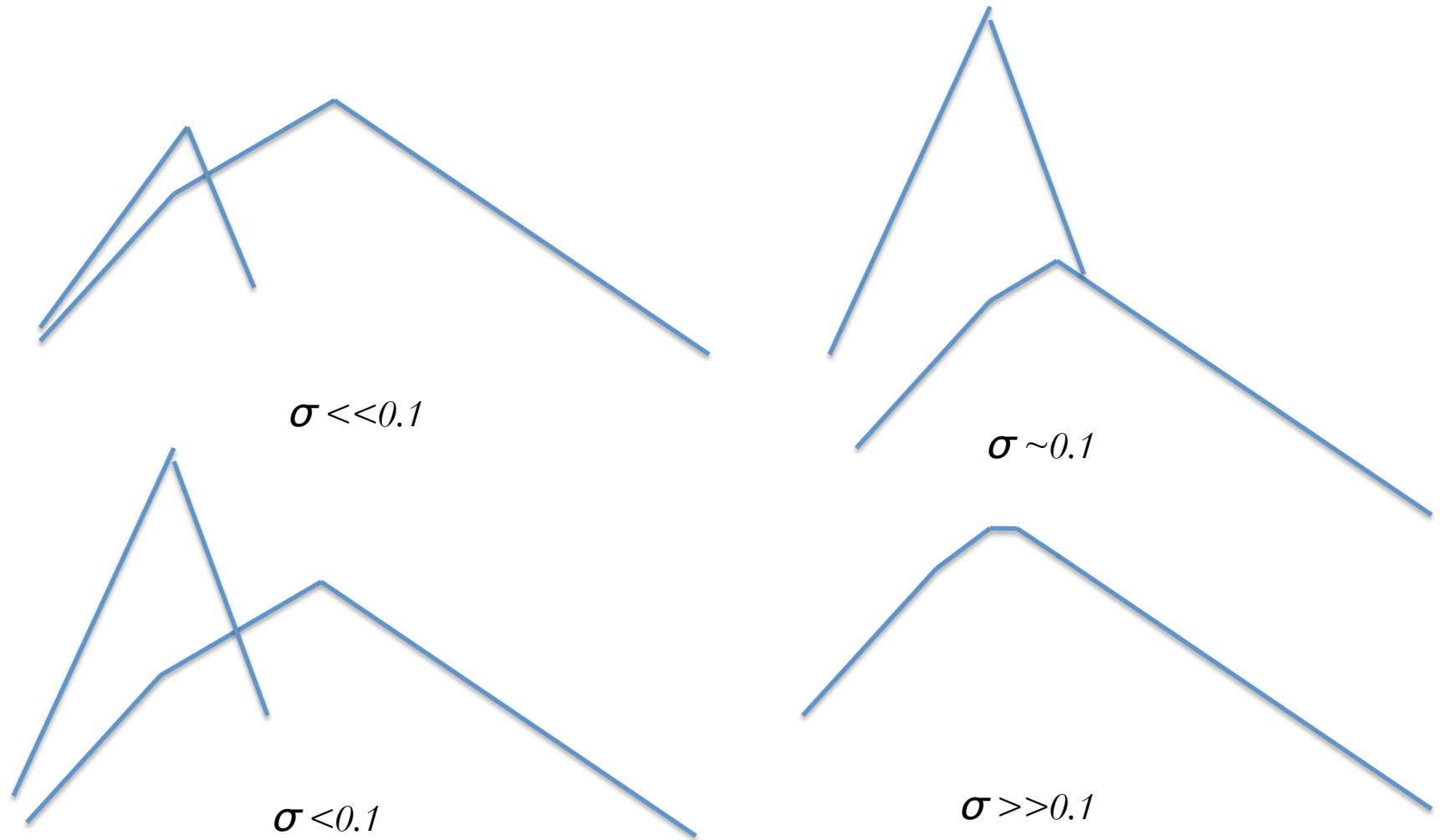
Three types of early optical afterglow lightcurves

(Zhang, Kobayashi & Meszaros 2003; Jin & Fan 2007)

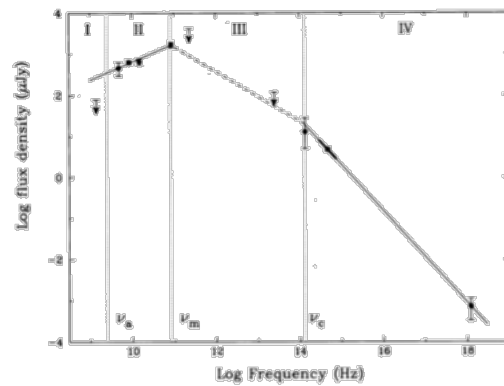


Effect of ejecta magnetization

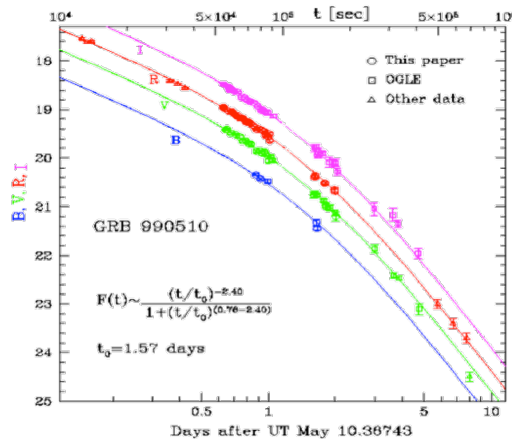
(Zhang & Kobayashi 2005; Mimica et al. 2009)



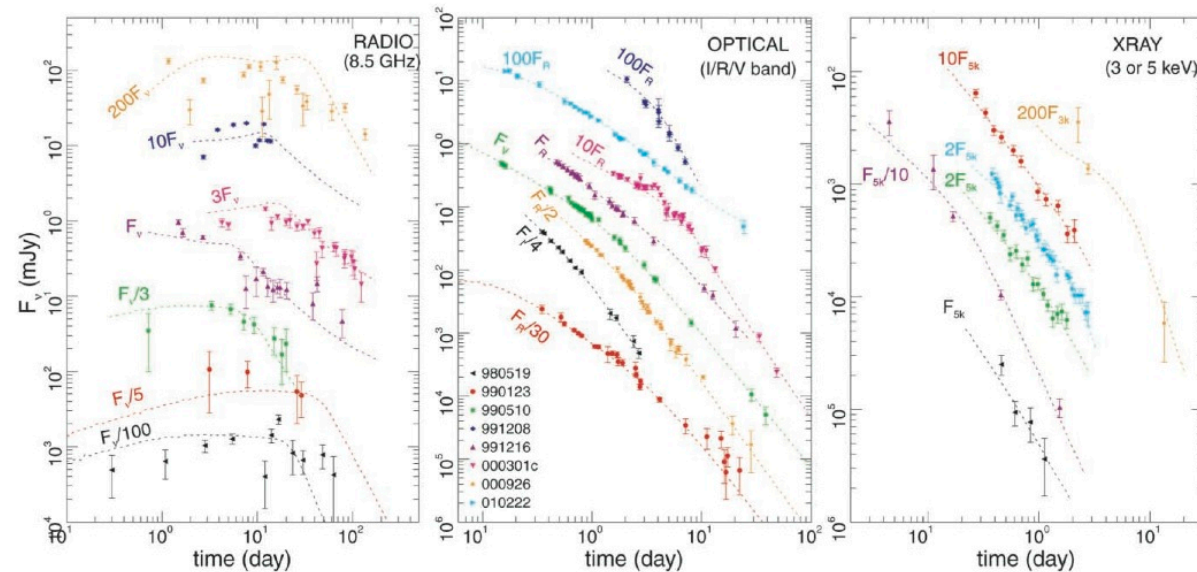
Pre-Swift: Confronting data with theory



Wijers & Galama 99



Stanek et al. 99



Panaitescu & Kumar (01, 02)

Other factors

- Energy injection
 - Long lasting central engine
 - Lorentz factor stratification
- Density inhomogeneity
 - Bumps
 - Voids
 - Fluctuations
- Angular structure
 - Power law or Gaussian jets
 - Patchy or mini-jets
- Two-component / multi-component jets

A “reference book”

New Astronomy Reviews 57 (2013) 141–190



Contents lists available at [ScienceDirect](#)

New Astronomy Reviews

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A complete reference of the analytical synchrotron external shock models of gamma-ray bursts



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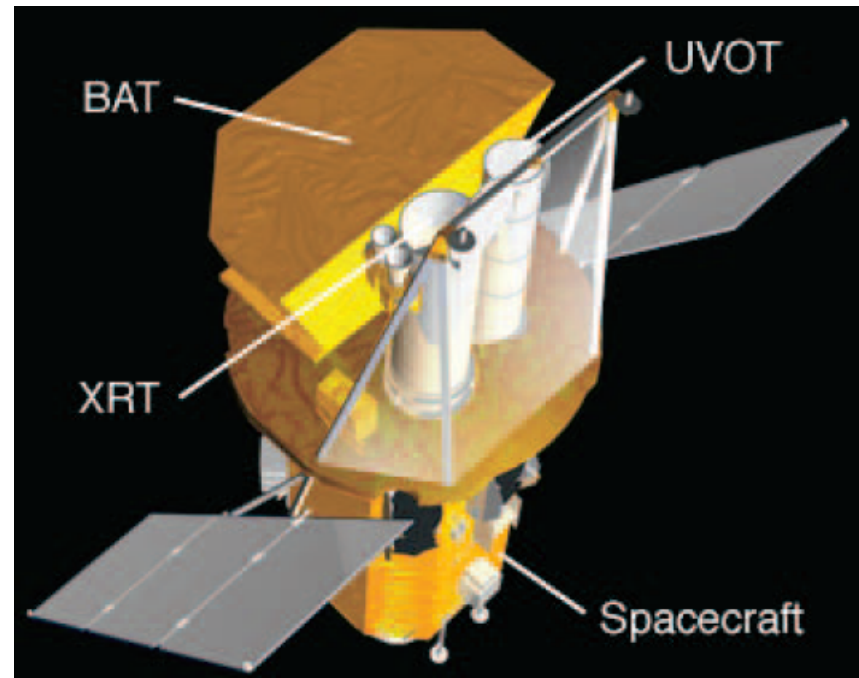
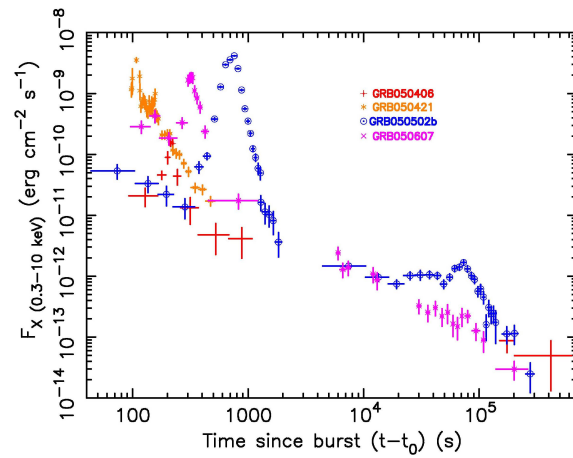
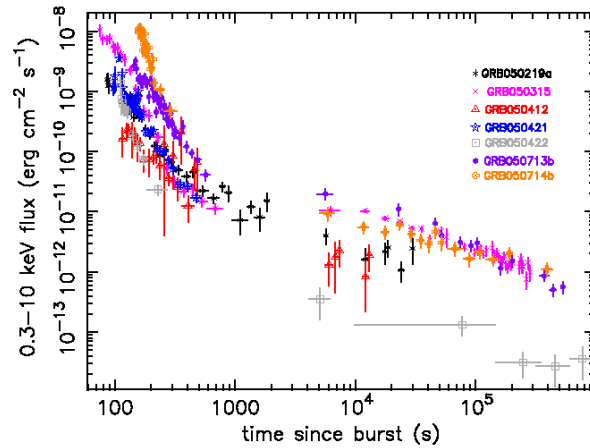
ABSTRACT

Gamma-ray bursts are most luminous explosions in the universe. Their ejecta are believed to move towards Earth with a relativistic speed. The interaction between this “relativistic jet” and a circumburst medium drives a pair of (forward and reverse) shocks. The electrons accelerated in these shocks radiate synchrotron emission to power the broad-band afterglow of GRBs. The external shock theory is an elegant theory, since it invokes a limit number of model parameters, and has well predicted spectral and temporal properties. On the other hand, depending on many factors (e.g. the energy content, ambient density profile, collimation of the ejecta, forward vs. reverse shock dynamics, and synchrotron spectral regimes), there is a wide variety of the models. These models have distinct predictions on the afterglow decaying indices, the spectral indices, and the relations between them (the so-called “closure relations”), which have been widely used to interpret the rich multi-wavelength afterglow observations. This review article provides a complete reference of all the analytical synchrotron external shock afterglow models by deriving the temporal and spectral indices of all the models in all spectral regimes, including some regimes that have not been published before. The review article is designated to serve as a useful tool for afterglow observers to quickly identify relevant models to interpret their data. The limitations of the analytical models are reviewed, with a list of situations summarized when numerical treatments are needed.

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69 equations (302 formulae), 45 figures (216 panels), 22 tables

Swift surprise

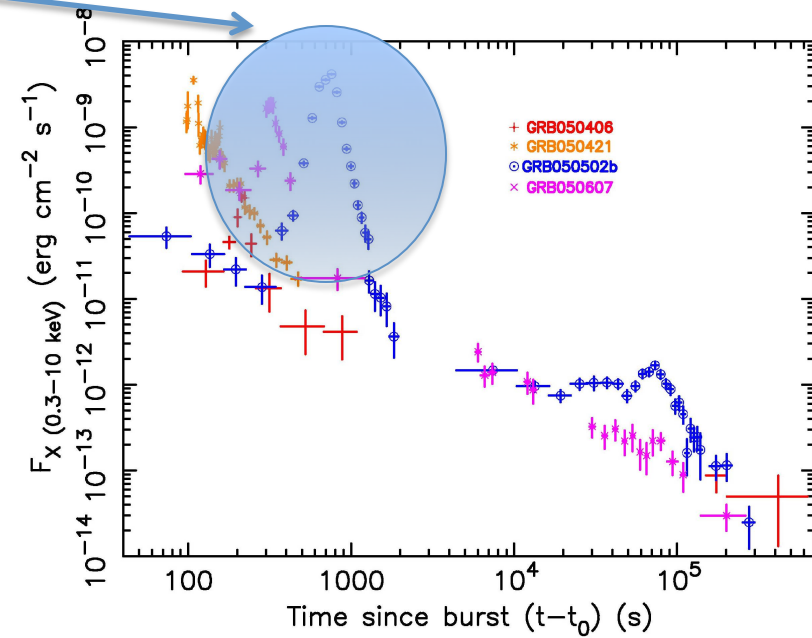
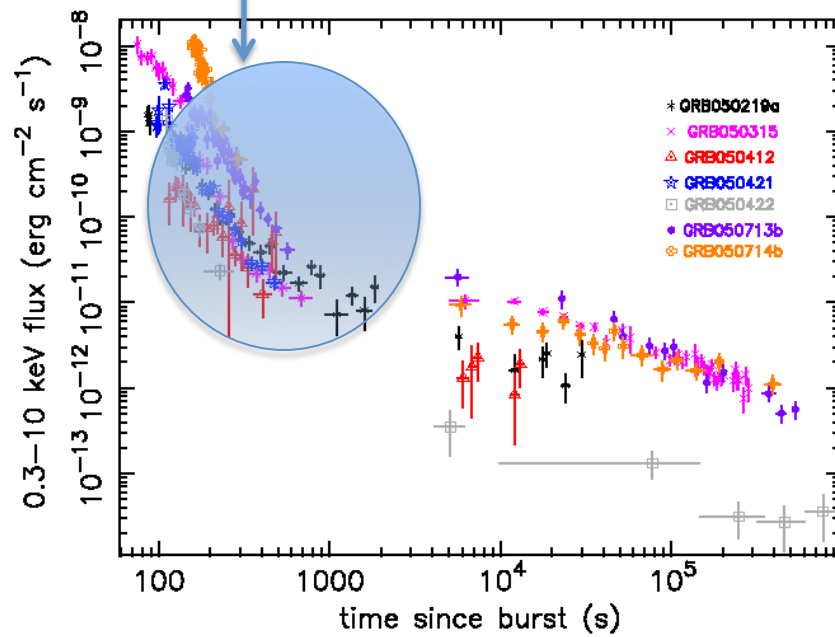


Gehrels et al. (2004)

Nousek et al. (2006), O'Brien et al. (2006)

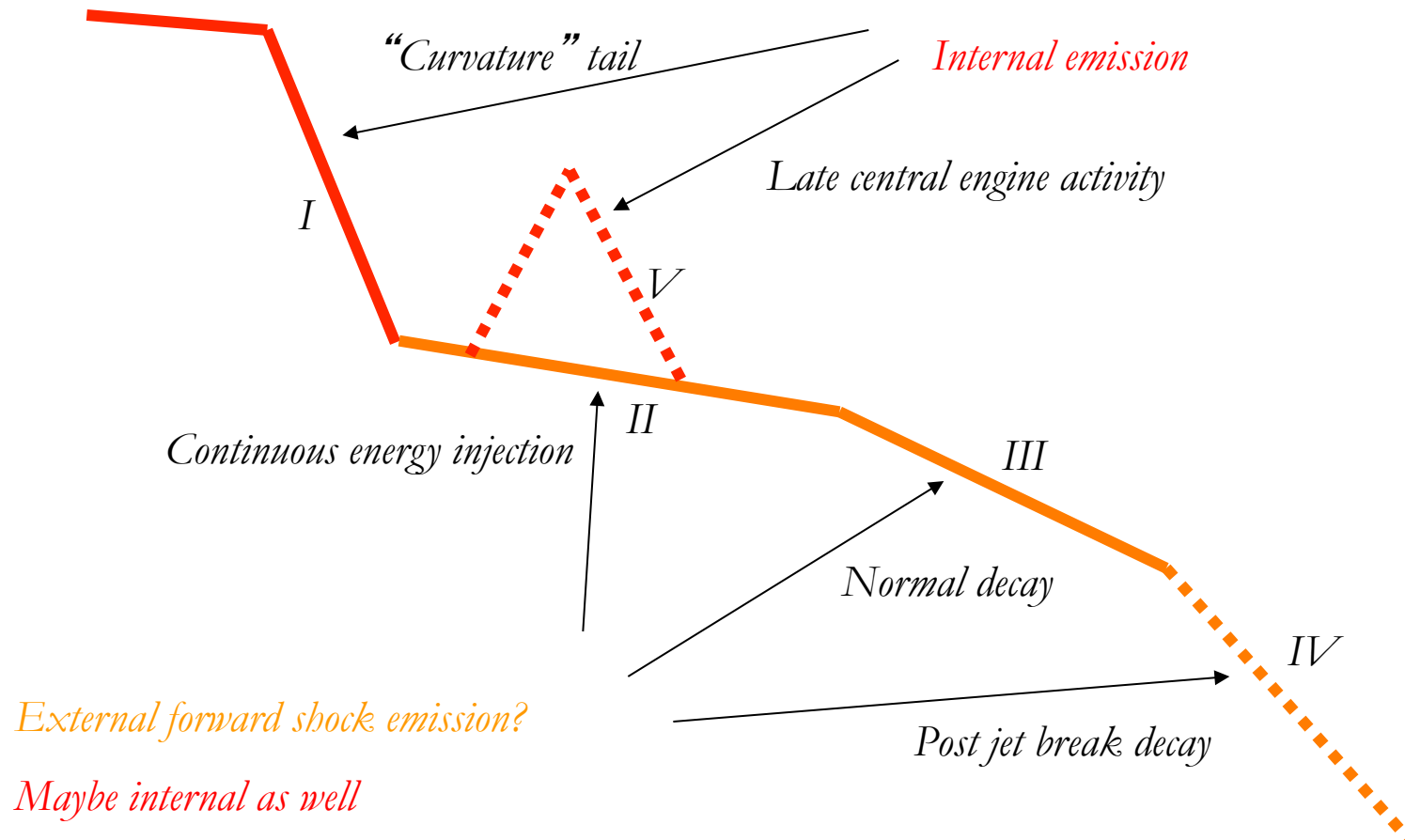
Swift surprise

Not predicted!

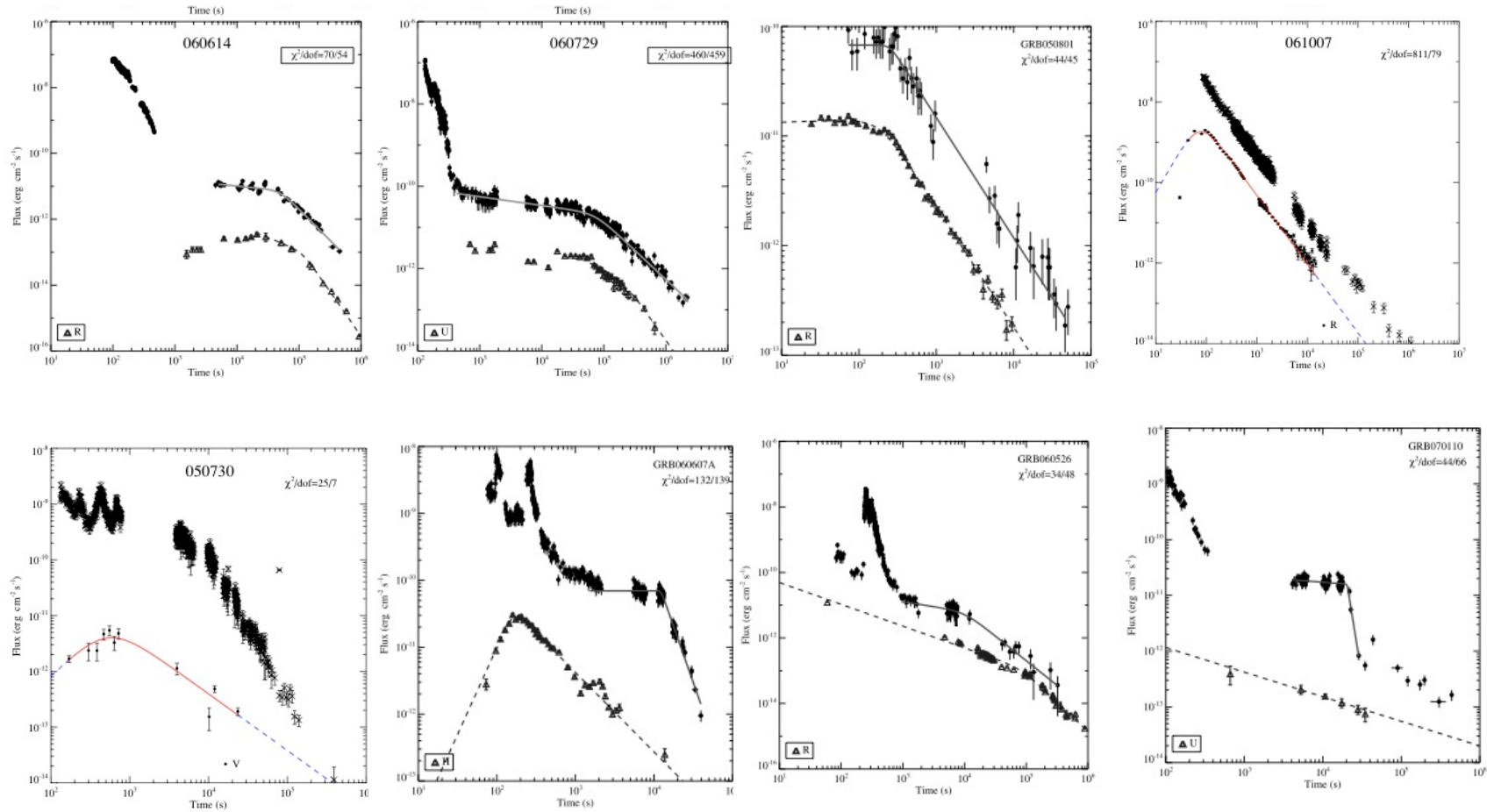


Canonical lightcurves: Internal or external?

(Zhang et al. 2006; Nousek et al. 2006)



Diverse multi-wavelength lightcurves: achromatic vs. chromatic

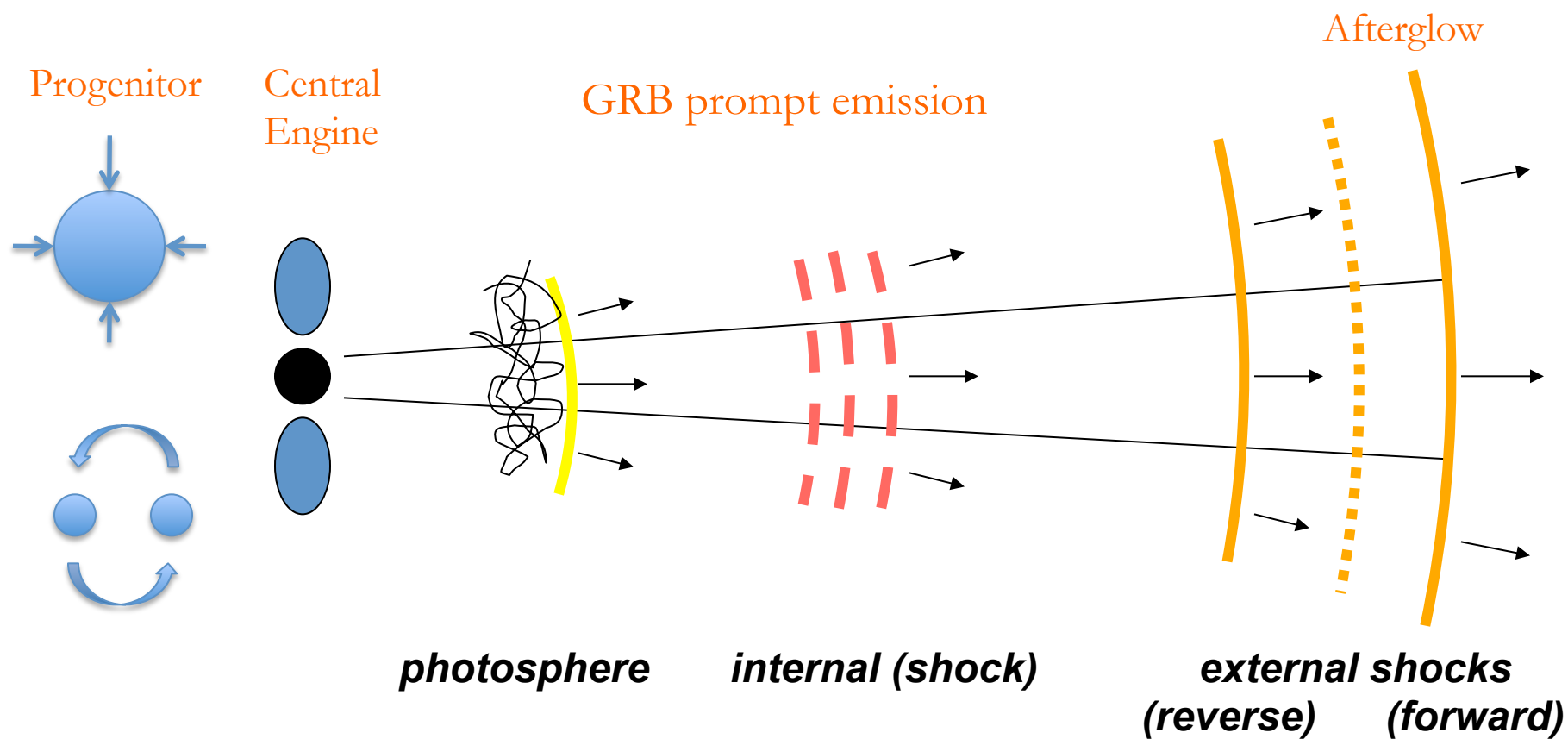


Panaitescu et al. 2006; Troja et al. 2007; Liang et al. 2007, 2008, 2010

Current afterglow picture

- The so-called “afterglow” is a **superposition** of the traditional **external** shock afterglow and **internal** dissipation of a long-lasting wind launched by a gradually dying central engine.
- The GRB cartoon picture no longer just describes a time sequence, but delineates an **instantaneous spatial picture** as well.
- Observed emission comes from **multiple emission sites!**

Physical Picture: A Sketch



How bad is the external forward shock model? – Not too bad

(Wang et al. 2014, in prep, see also Li et al. (2014))

Table 4. The criteria for GRB grades

| Grades | Light curve behavior | Closure-relation | Fraction |
|-----------|--|------------------|----------|
| Grade I | Achromatic break or SPL de | Yes | 39/94 |
| Grade II | Beak missing in one band may due to ob | Yes | 6/94 |
| Grade III | Achromatic break or SPL de | No | 31/94 |
| Grade IV | Beak missing in one band may due to ob | No | 8/94 |
| Grade V | Data is not enough, could not rule out achromatic behavior | No | 6/94 |
| Grade VI | Chromatic | No | 4/94 |

Gold sample
45/94

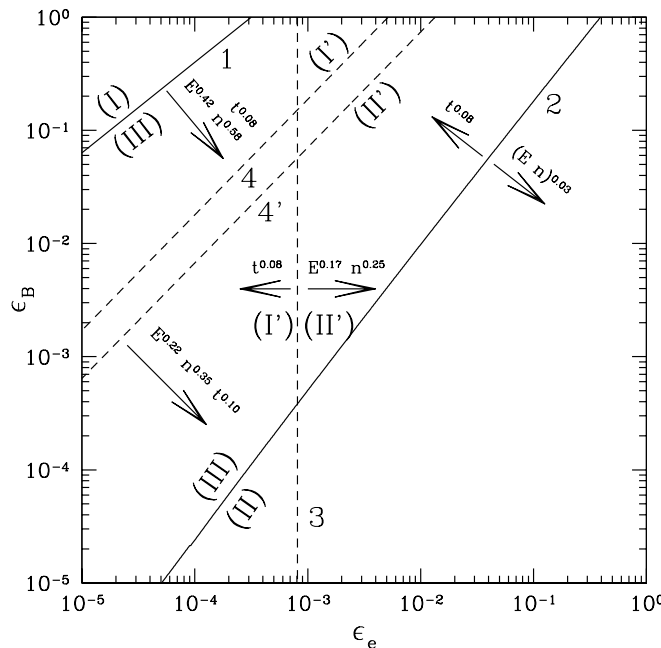
Silver sample
49/94

Chromatic sample
10/94

External shock model Candidates: Gold sample: 45/94 GRBs; Silver sample : 39/94
Chromatic sample : 4/94GRBs

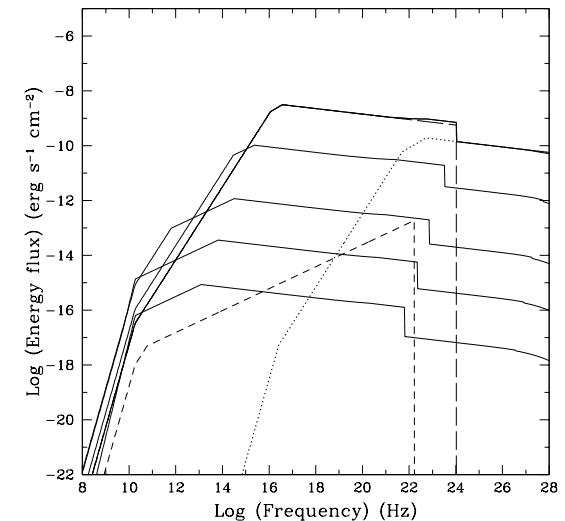
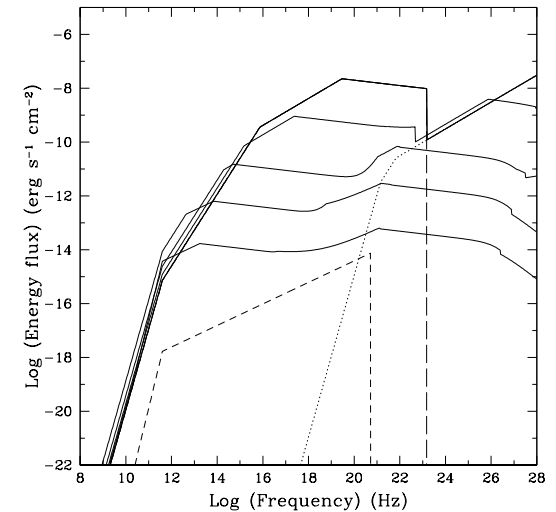
How about SSC?

- Should be there
- Significance depends on micro-physics parameters



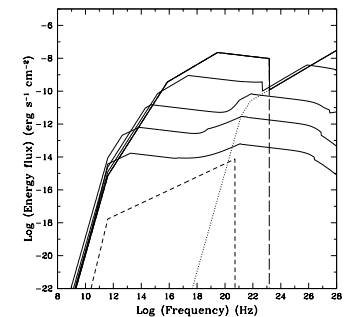
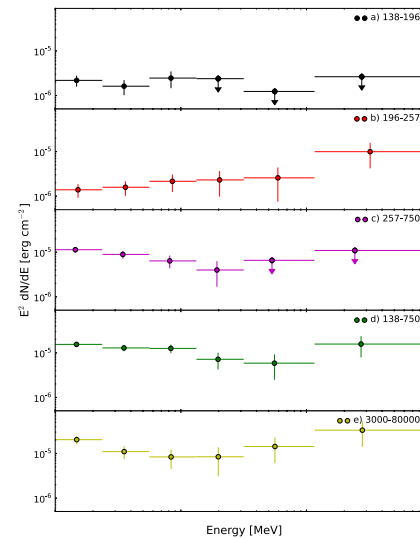
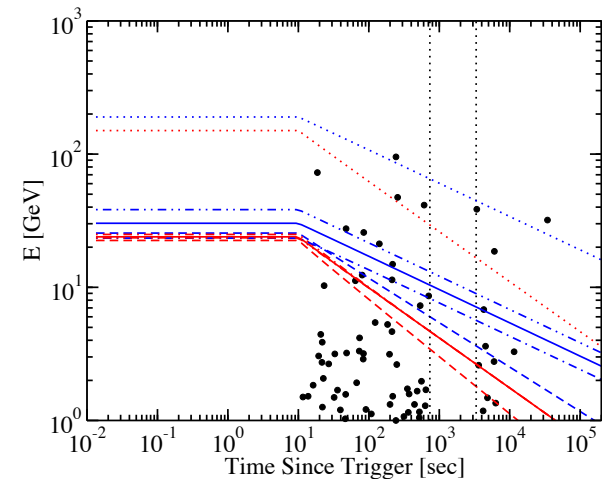
Zhang & Meszaros 2001

See also Dermer et al. (2000); Panaitescu & Kumar (2000); Sari & Esin (2001)



Fermi: mostly synchrotron, probably SSC in GRB 130427A?

- GeV emission from most GRBs are dominated by synchrotron radiation (Kumar & Barniol-Duran; Ghisellini et al.; Gao et al.)
- GRB 130427A:
 - Data may not demand
 - But data consistent with SSC: photon energy too high, slight bending

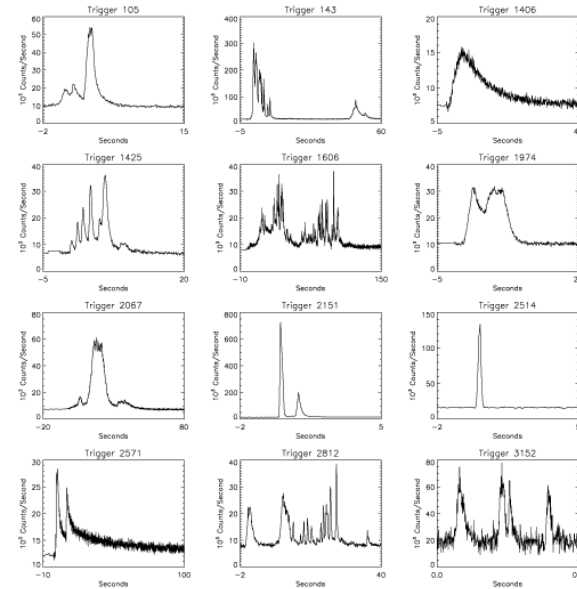


*Ackermann et al. (2014) - See Piron's & Lemoine's talk
(See also Fan et al.; Tam et al.; Liu & Wang)*

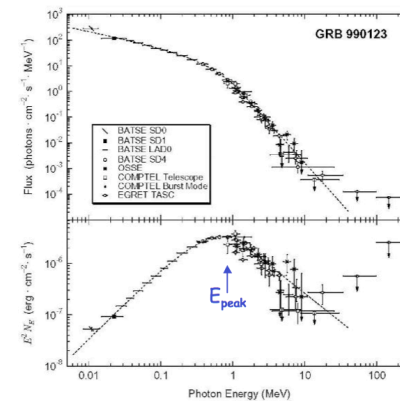
Origin of Prompt Emission

What do we interpret?

- Light Curve
- Spectrum
- Polarization
- Other constraints
 - Ep evolution patterns
 - Correlations
 - Prompt high energy emission
 - Prompt low energy emission
 - Neutrino flux / upper limit
 -



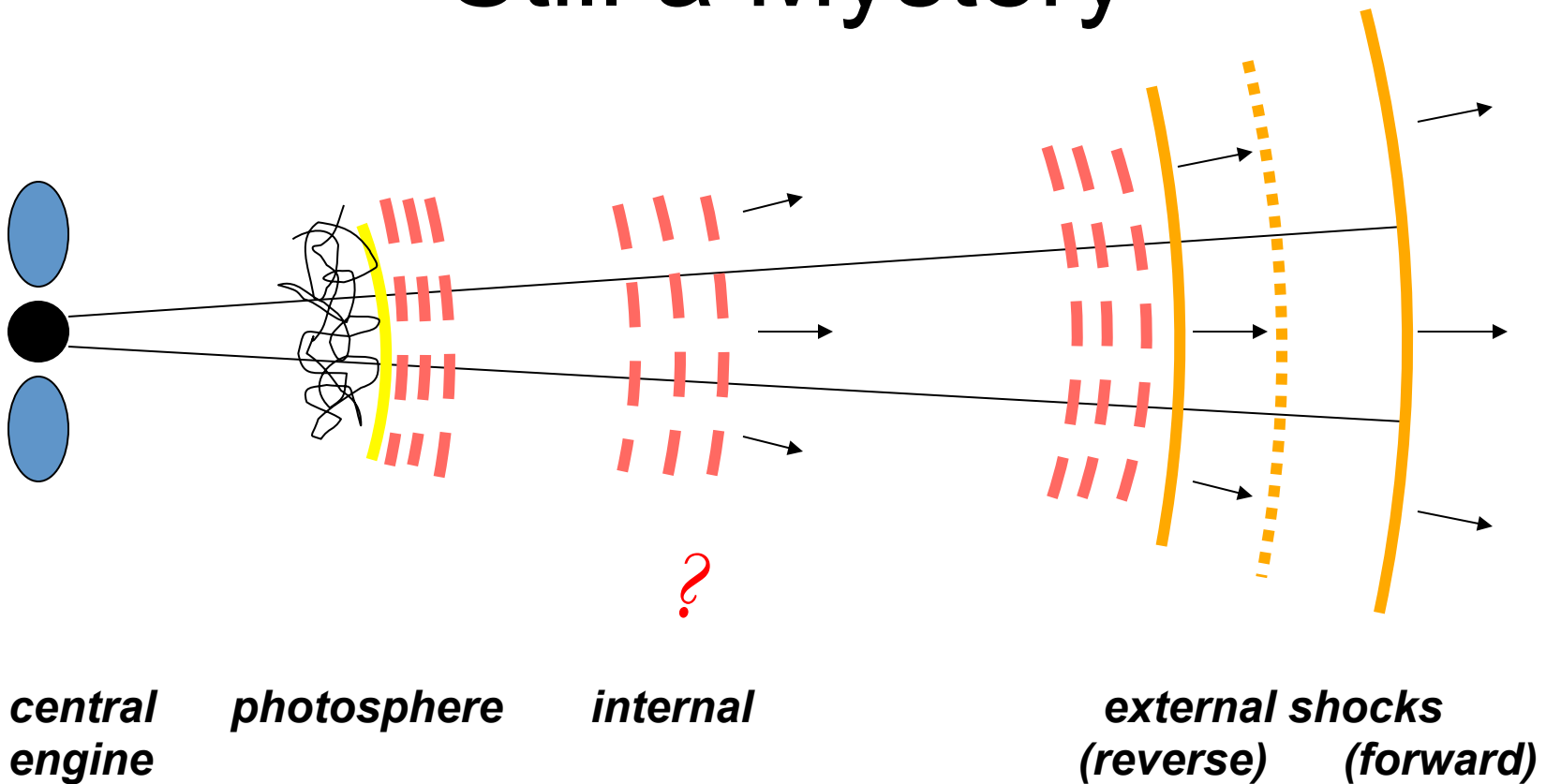
Fishman & Meegan 1996



Briggs et al. 1999

Briggs et al. 1999

Prompt GRB Emission: Still 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)?

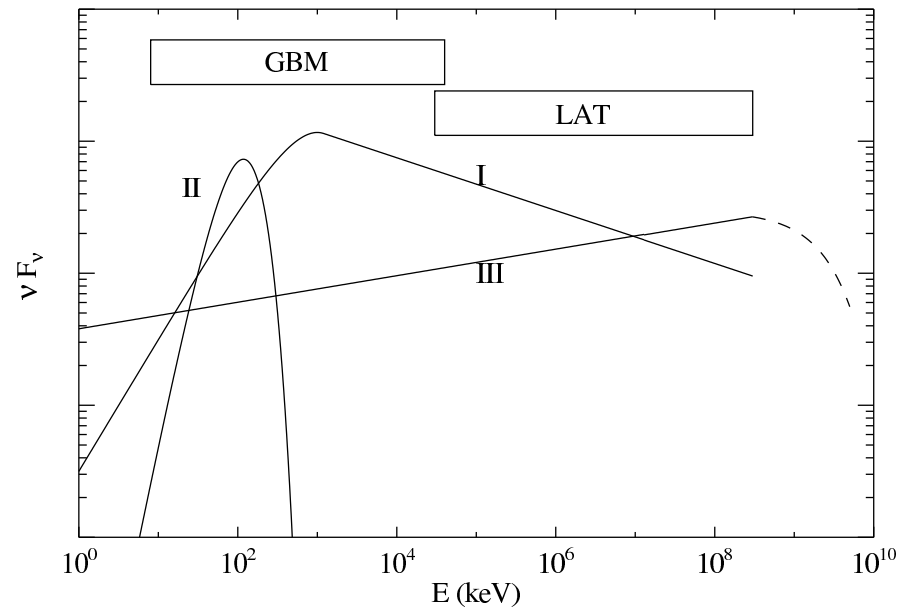
Radiation Mechanisms

- Synchrotron radiation
- Quasi-thermal (with Comptonization)
- Synchrotron Self-Compton (SSC)
- Hadronic processes

Three spectral components?

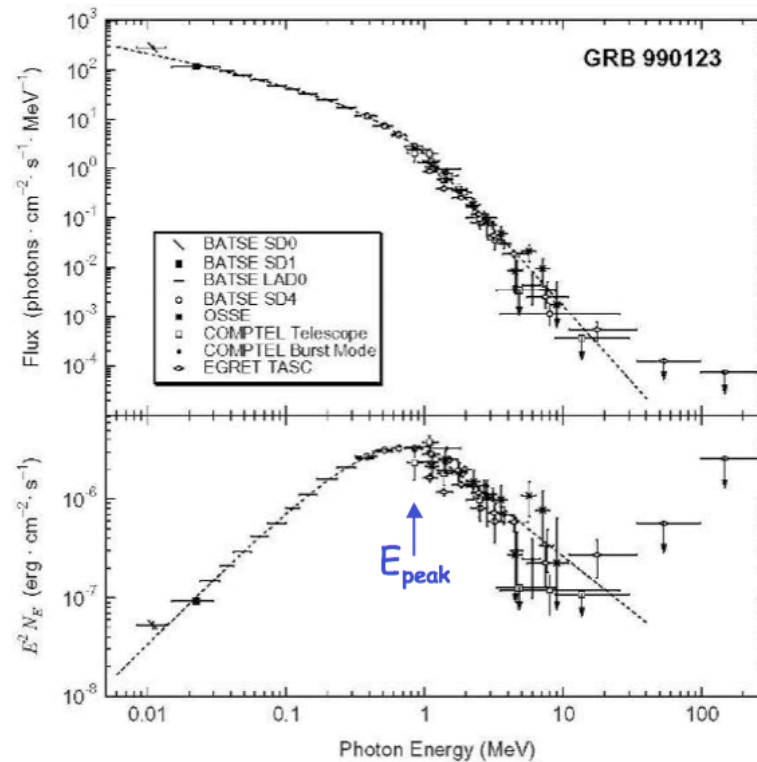
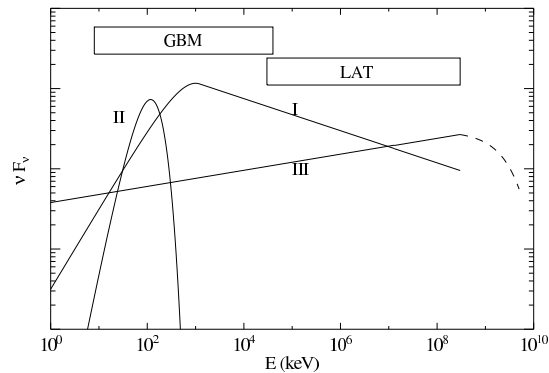
(Zhang et al. 2011; Guiriec et al. 2014)

- Band
- Quasi-thermal
- An extra high-energy component?
- Talk by
Sylvain Guiriec



Zhang et al. (2011)

Origin of the Band component



Briggs et al. 1999

SSC?

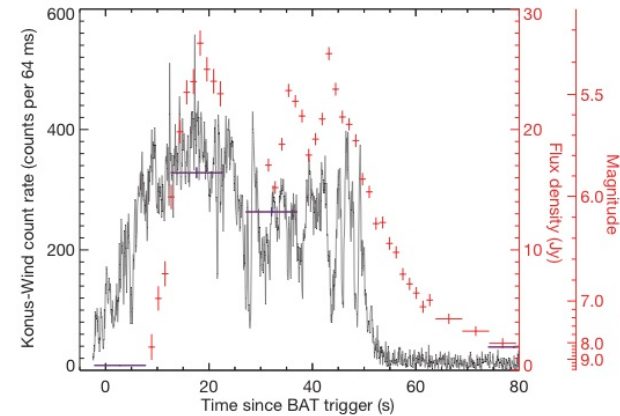
Hadronic?

Photosphere?

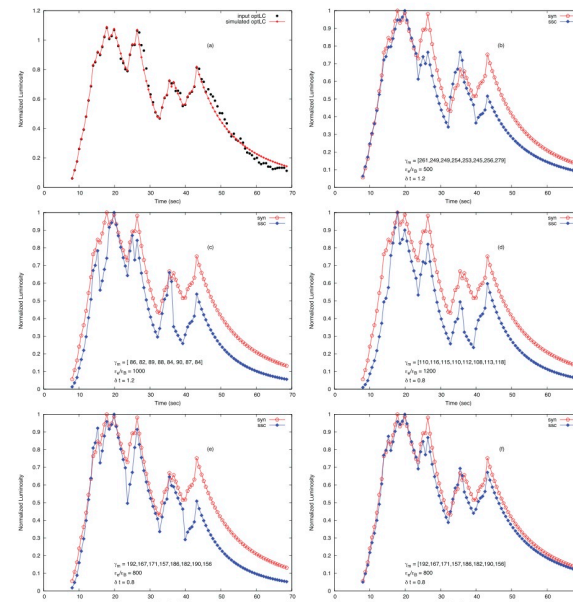
Synchrotron?

SSC? - No

- Motivated by the “naked-eye” GRB 080319B
 - Optical emission much brighter than low-energy extension of the Band component
 - Not common feature among GRBs
- Difficulties
 - Energy budget (Derishev et al. Piran et al.)
 - Ep distribution too broad (Zhang & Meszaros 2002)
 - Gamma-ray vs. optical Variability (Resmi & Zhang, 2012)



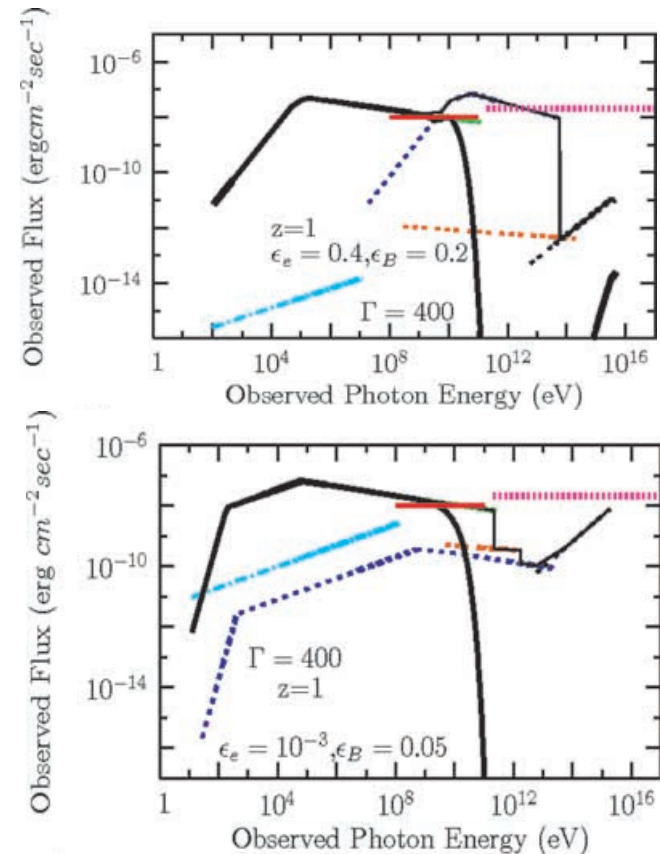
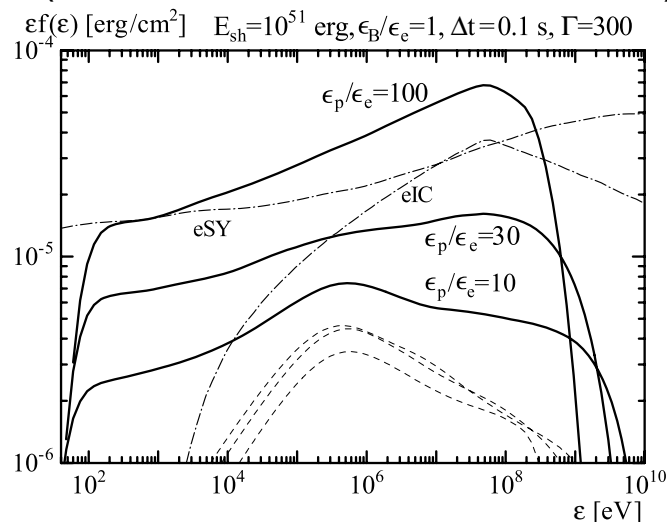
Racusin et al. (2008)



Resmi & Zhang (2012)

Hadronic? - No

- Protons emitting via
 - Synchrotron radiation
 - pY interaction, π^0 decay or secondary leptonic cascade
- Difficulties
 - Inefficient, usually outshone by the leptonic components (Gupta & Zhang 2007)
 - Predicts strong neutrino signals, which are not detected (Asano, Inoue & Meszaros, 2009)



Gupta & Zhang (2007)

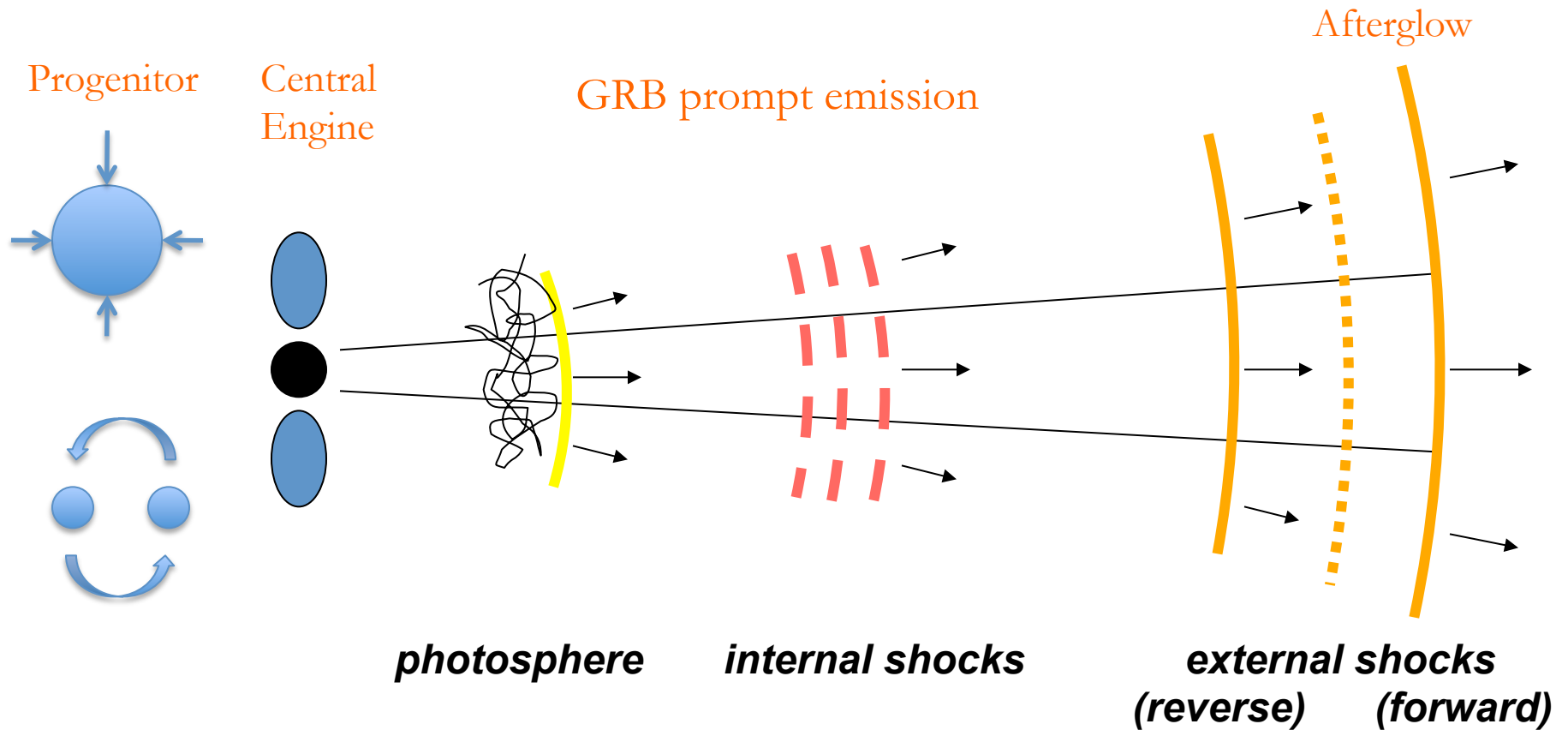
See Asano, Petropoulou ...

Debate:

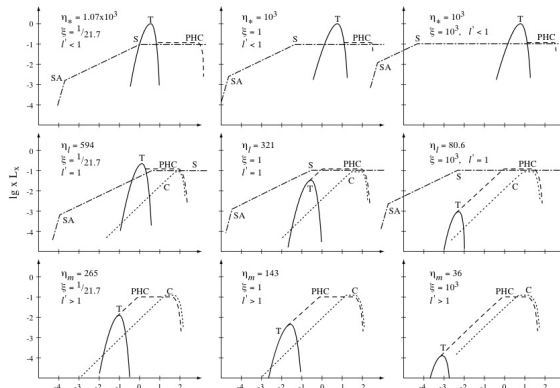
Quasi-Thermal or Synchrotron?

Fireball shock model

(Paczynski, Meszaros, Rees, Piran ...)

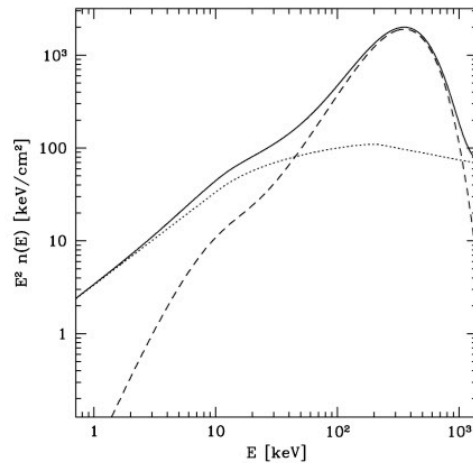


Fireball Predictions: Internal shock vs. photosphere

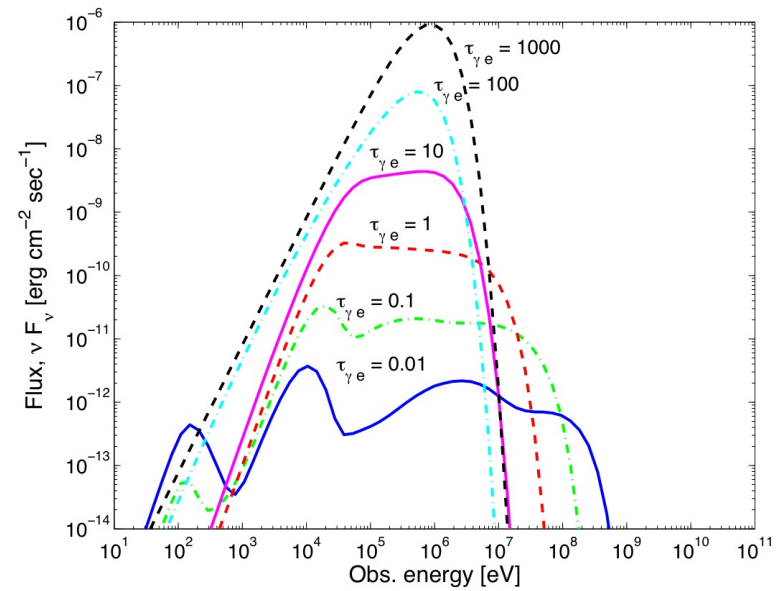


Mészáros & Rees (00)

1276 *F. Daigne and R. Mochkovitch*



Daigne & Mochkovitch (02)

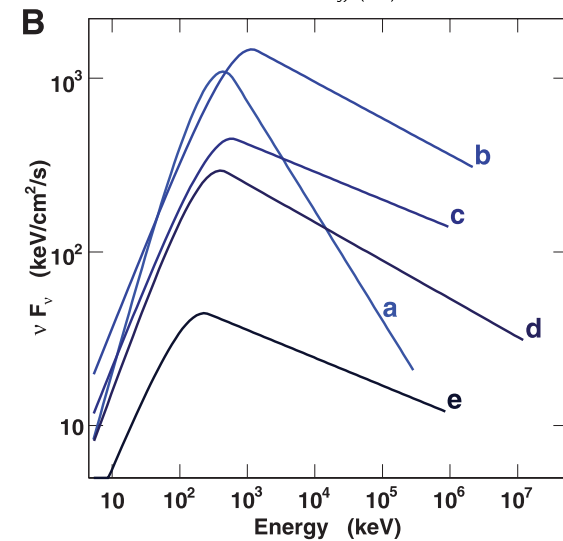
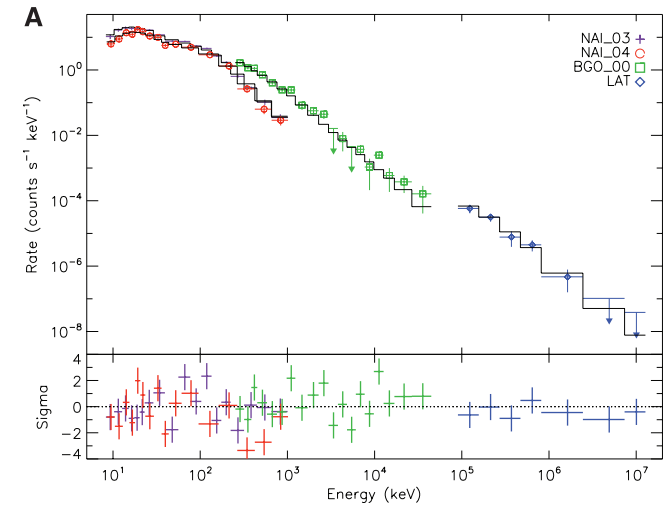
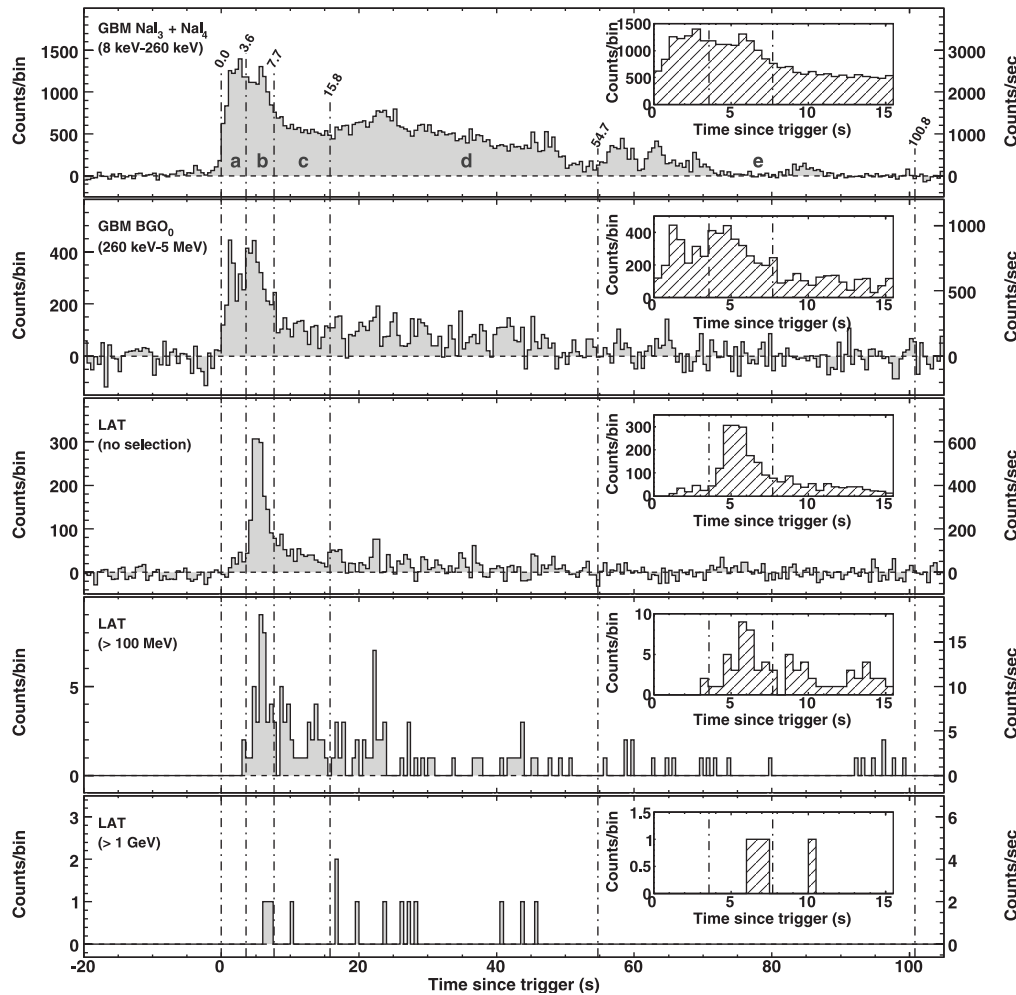


Pe'er et al. (06)

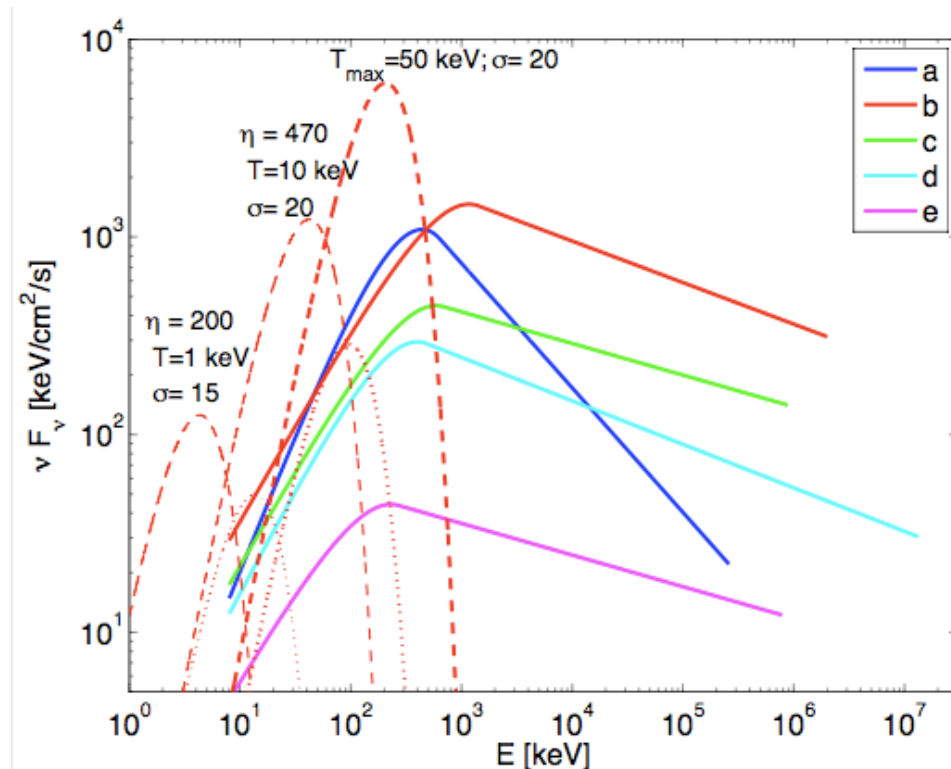
Fermi surprise: GRB 080916C

(Abdo et al. 2009, Science)

$$z = 4.35 \pm 0.15$$



Fermi Surprise: Photosphere component missing



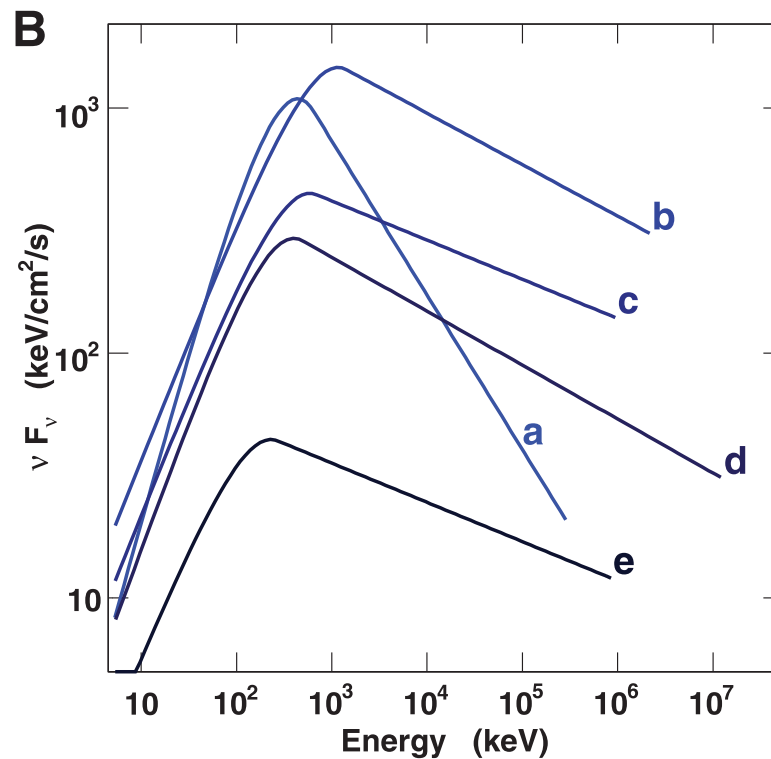
*Zhang & Pe'er
(2009)*

Sigma: ratio between Poynting flux and baryonic flux:

$\sigma = L_p/L_b$: at least $\sim 20, 15$ for GRB 080916C

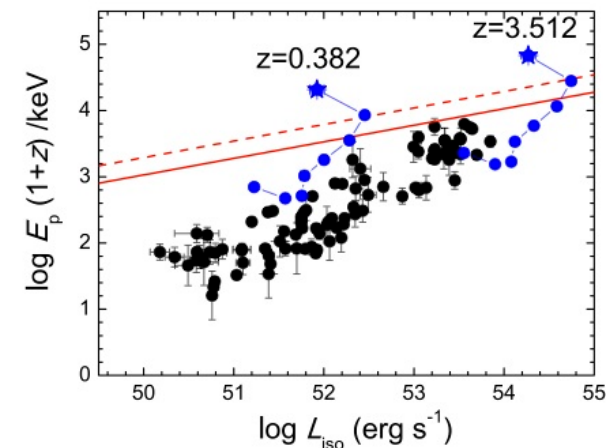
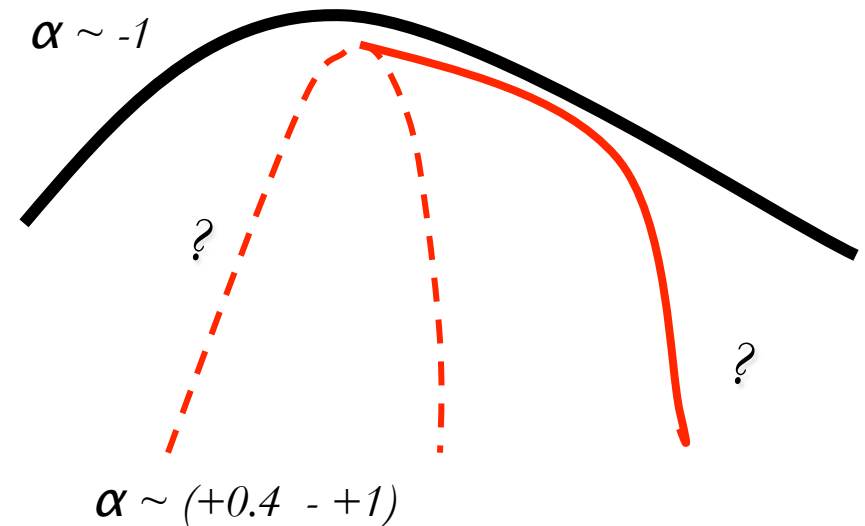
Is the Band component “quasi-thermal” or “synchrotron”?

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



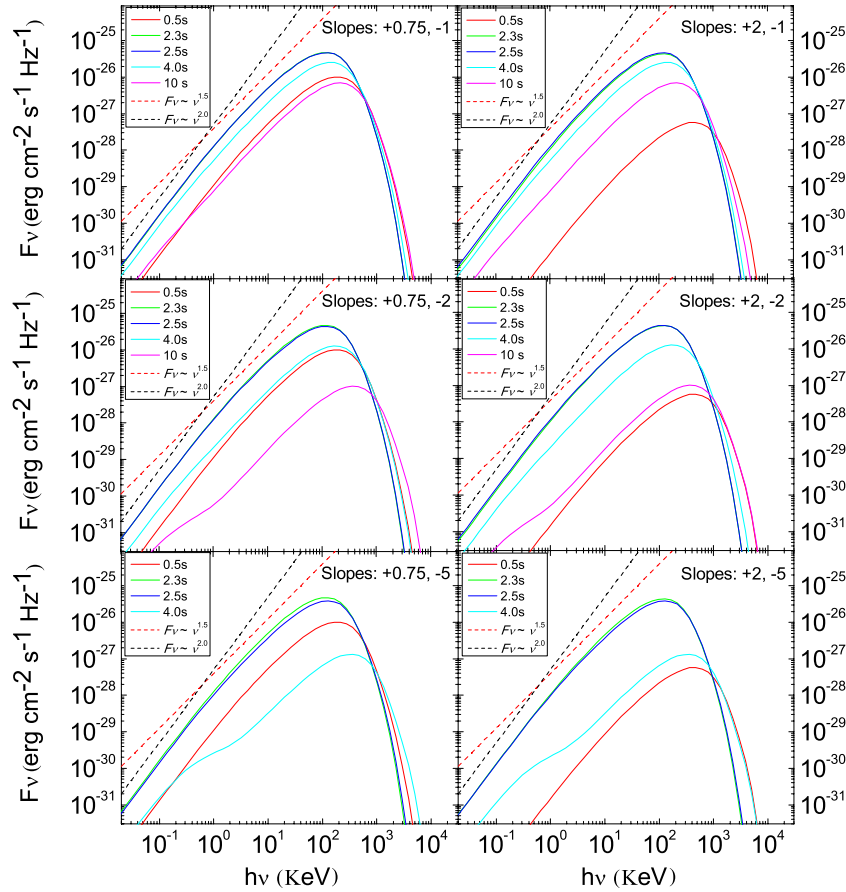
Quasi-thermal photosphere model

- Motivations:
 - Temperature defines E_p , falls into the observed range, can interpret various correlations (Thompson et al.; Rees & Meszaros; Pe'er et al., Ryde, Beloborodov, Giannios, Lazzati et al.; Ioka; Toma et al.; Fan et al.)
 - Naturally bright if matter dominated
- Difficulties
 - Small emission radius inconsistent with other constraints (GeV, X-ray and optical)
 - Low frequency spectral index too hard
 - Maximum E_p for a given L (“death line”, Zhang et al. 2012)
 - Inability to interpret hard-to-soft evolution patterns (Deng & Zhang 2014)

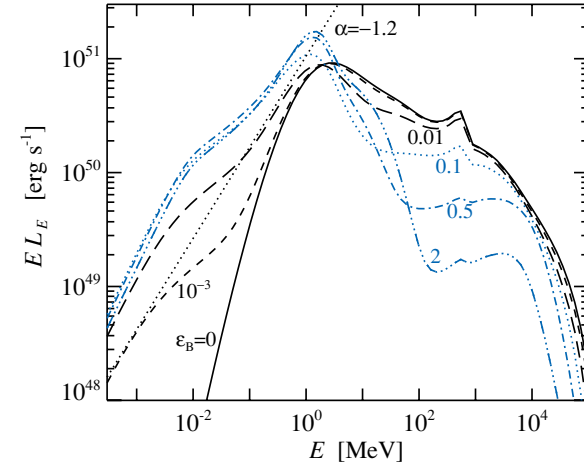


GRB 110721A, Zhang et al. (2012)

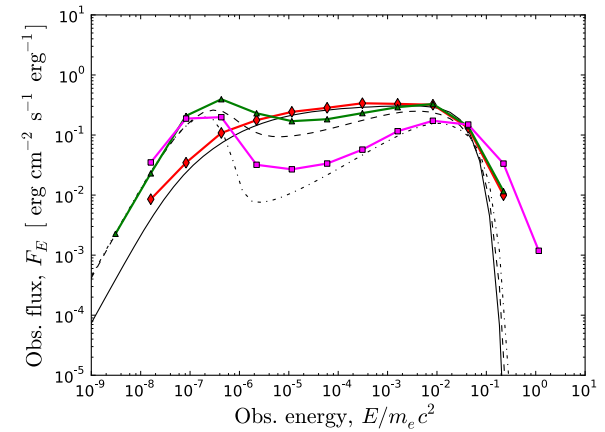
α Problem



(Deng & Zhang, 2014, *ApJ*, 785, 112)

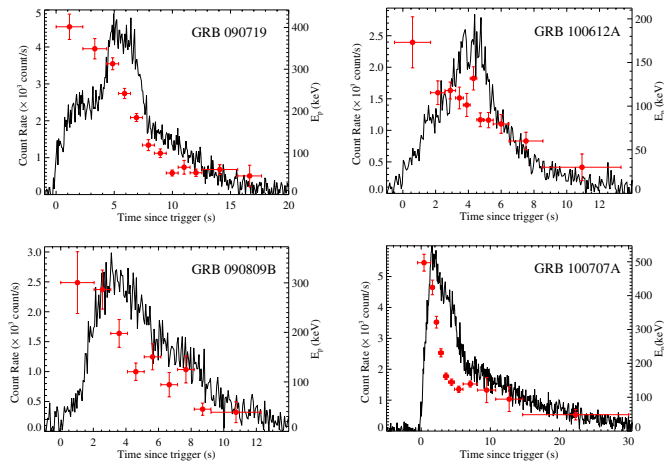


Synchrotron contamination
Vurm et al. 2011

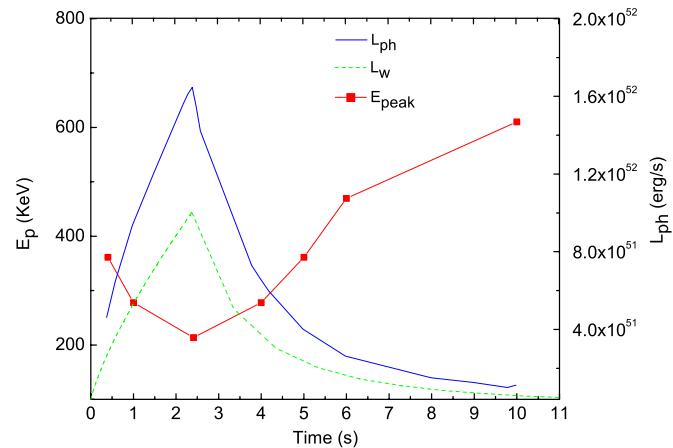


(Special) structured jet
Lundman et al. 2012

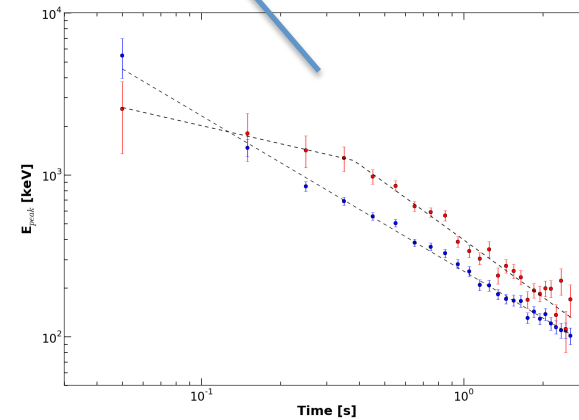
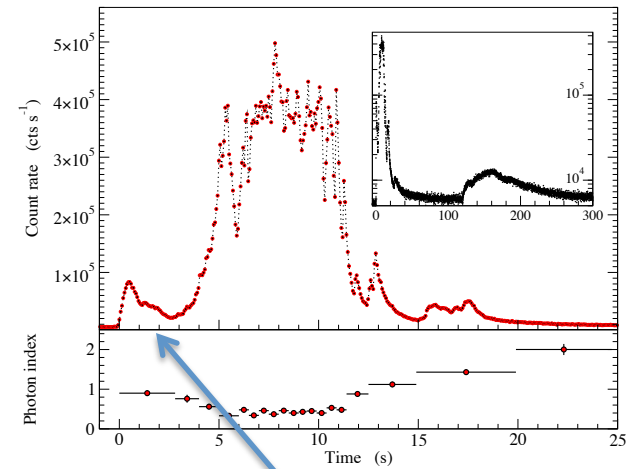
Spectral evolution problem



Li et al. (2012)



(Deng & Zhang, 2014, ApJ, 785, 112)



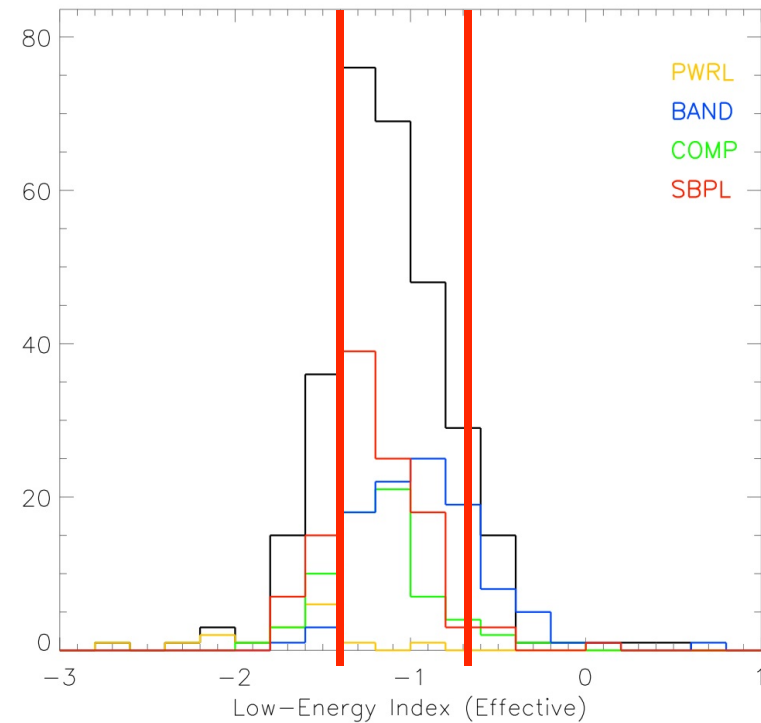
GRB 130427A

Preece et al. (2014)

Maselli et al. (2014)

Synchrotron model

- Motivations:
 - Known to power most other non-thermal astrophysical sources
 - Known to power GRB afterglow
- Difficulties
 - E_p value and distribution
 - “Fast cooling” problem: the predicted low-energy photon index is $\alpha = -1.5$, while observations show a typical value of -1 (Ghisellini et al. 2000; Kumar & McMahon 2008)
 - Synchrotron “death line”: the low energy photon index cannot be harder than $-2/3$, i.e. $\alpha < -2/3$ (Preece et al. 1999)

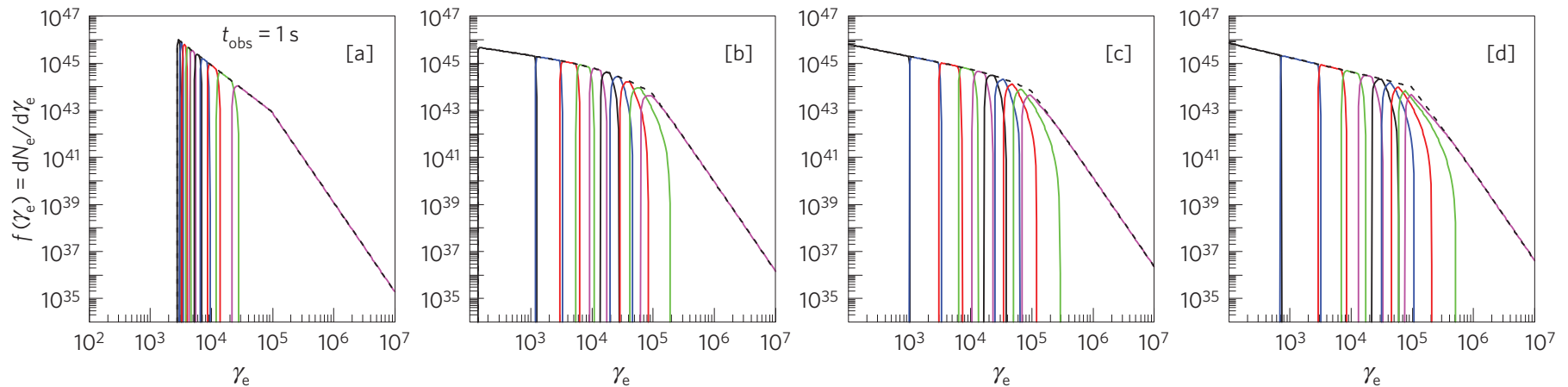


Synchrotron Model:

Fast Cooling Spectrum Can Be Harder!

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

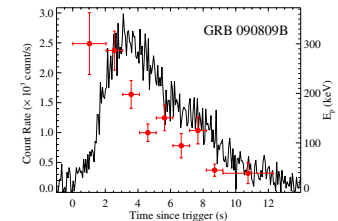
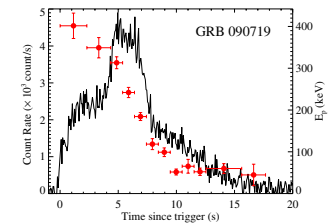
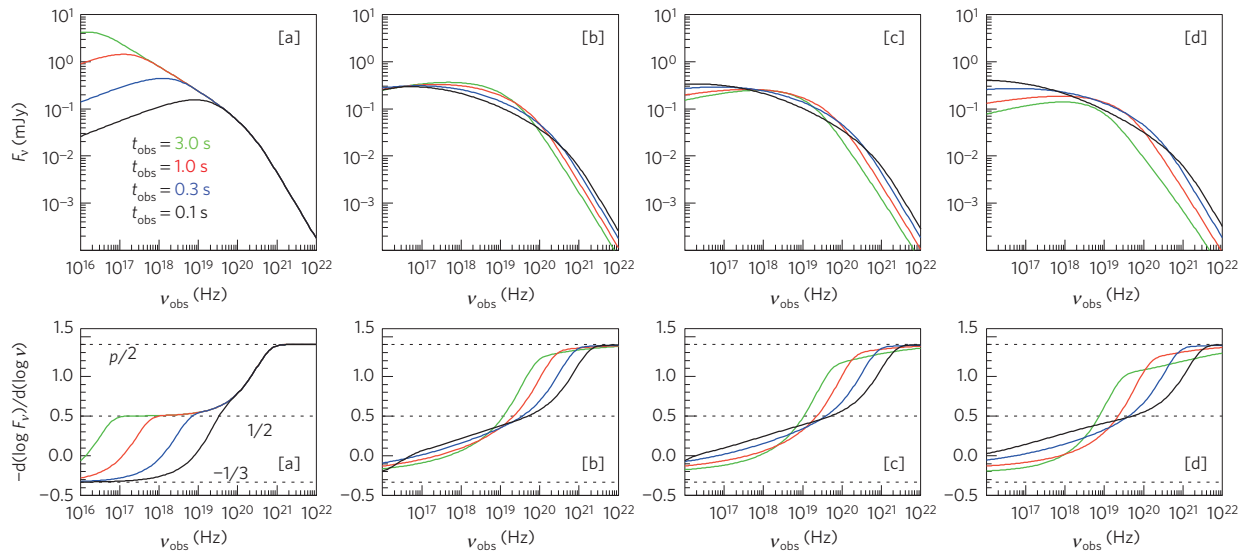
- B is decreasing with radius
- Electrons are not in steady state
- Electron spectrum deviates significantly from -2 below the injection energy



Synchrotron Model: Seems to work well!

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

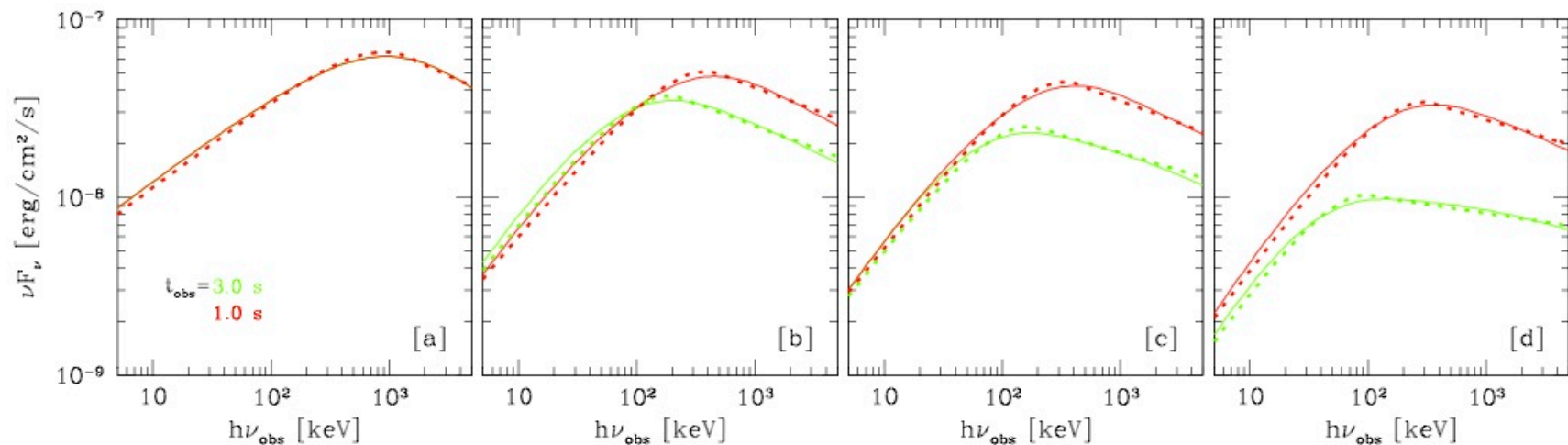
- In the BATSE or GBM band, the spectrum mimics a “Band” function with “correct” indices: $\alpha \sim -1$, $\beta \sim -2.2$
- Clear hard-to-soft evolution during the rising phase and throughout



Synchrotron Model: “Band” Function

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

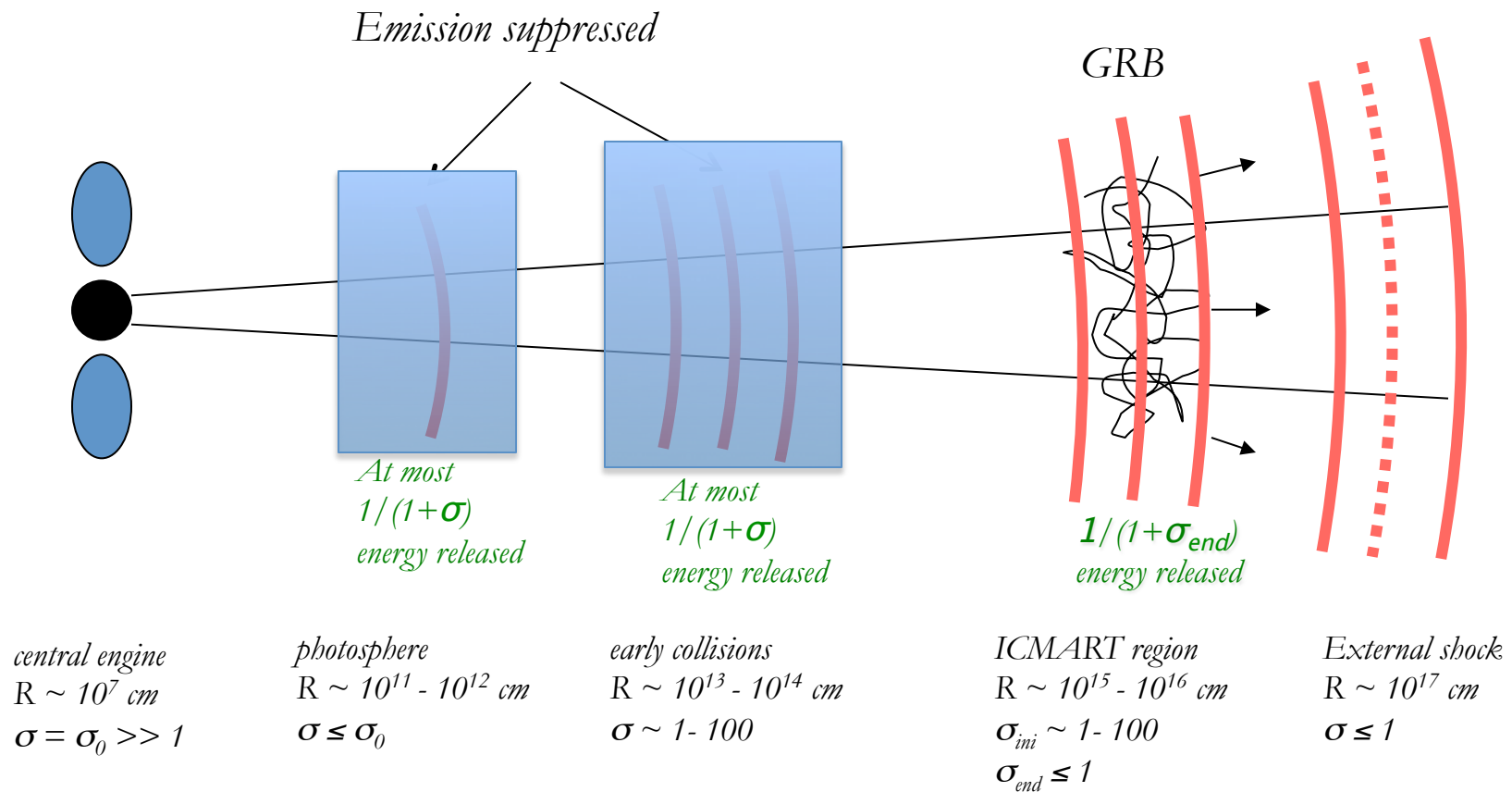
- In the BATSE or GBM band, the spectrum mimics a “Band” function with “correct” indices: $\alpha \sim -1$, $\beta \sim -2.2$



Requirement: Large emission radius where B is low!

The ICMART Model

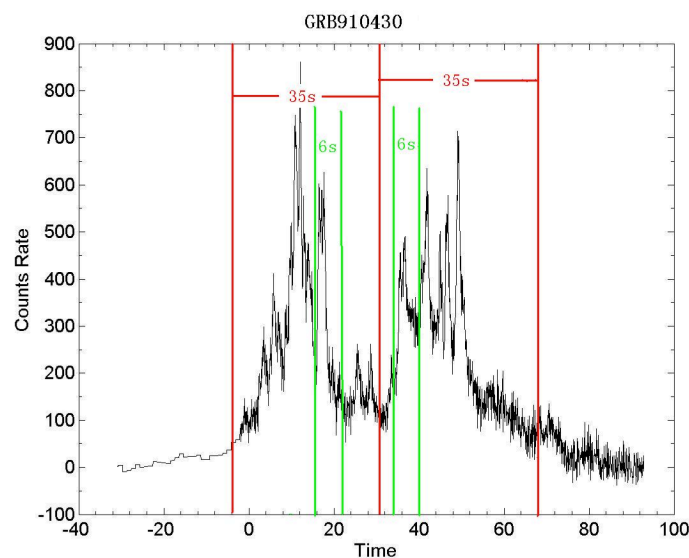
(Internal Collision-induced MAgnetic Reconnection & Turbulence)



Zhang & Yan (2011, *ApJ*, 726, 90)

Emission radius

- Internal shock model: $R = \Gamma^2 c \delta t_{\min}$
- Photosphere model: *probably* $R < \Gamma^2 c \delta t_{\min}$
- Internal Collision-induced MAgnetic Reconnection and Turbulence (ICMART) model: $R = \Gamma^2 c \delta t_{\text{slow}} > \Gamma^2 c \delta t_{\min}$



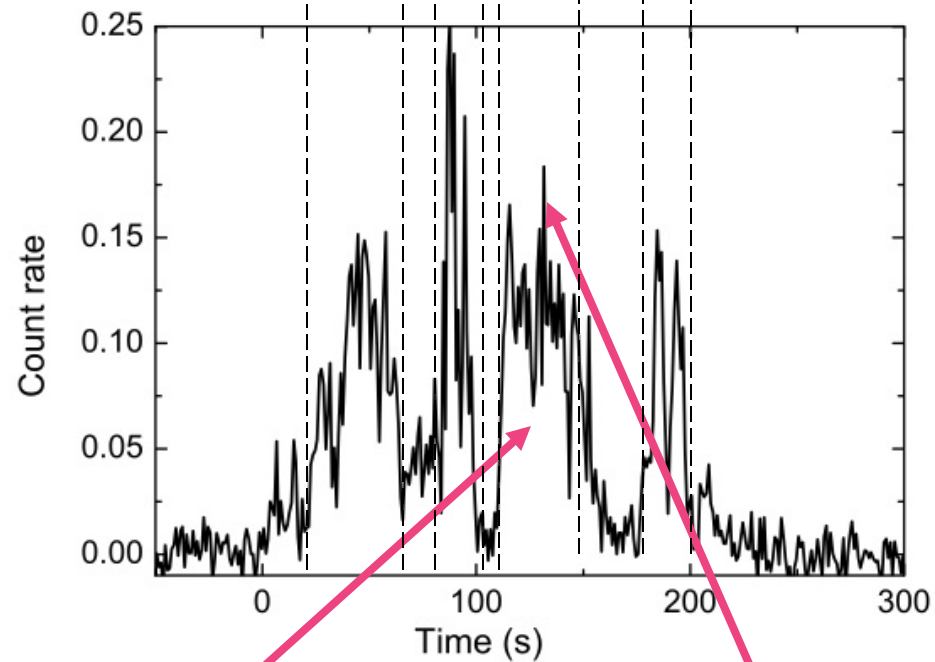
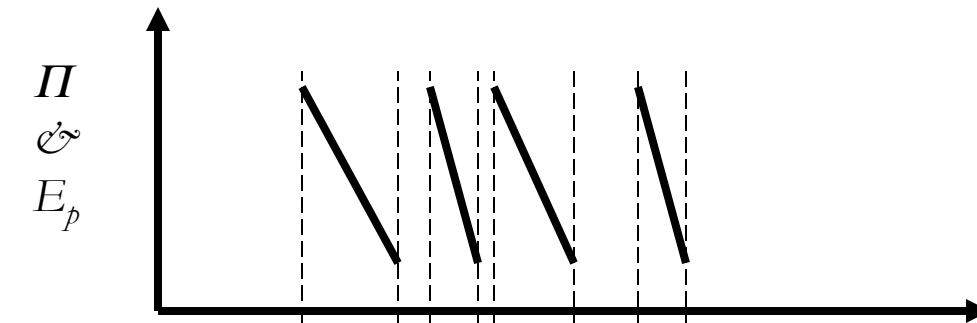
Gao, Zhang & Zhang (2012)

ICMART
predictions:

Two variability components

Evolution of
gamma-ray linear
polarization across
a pulse

Evolution of E_p
across a pulse



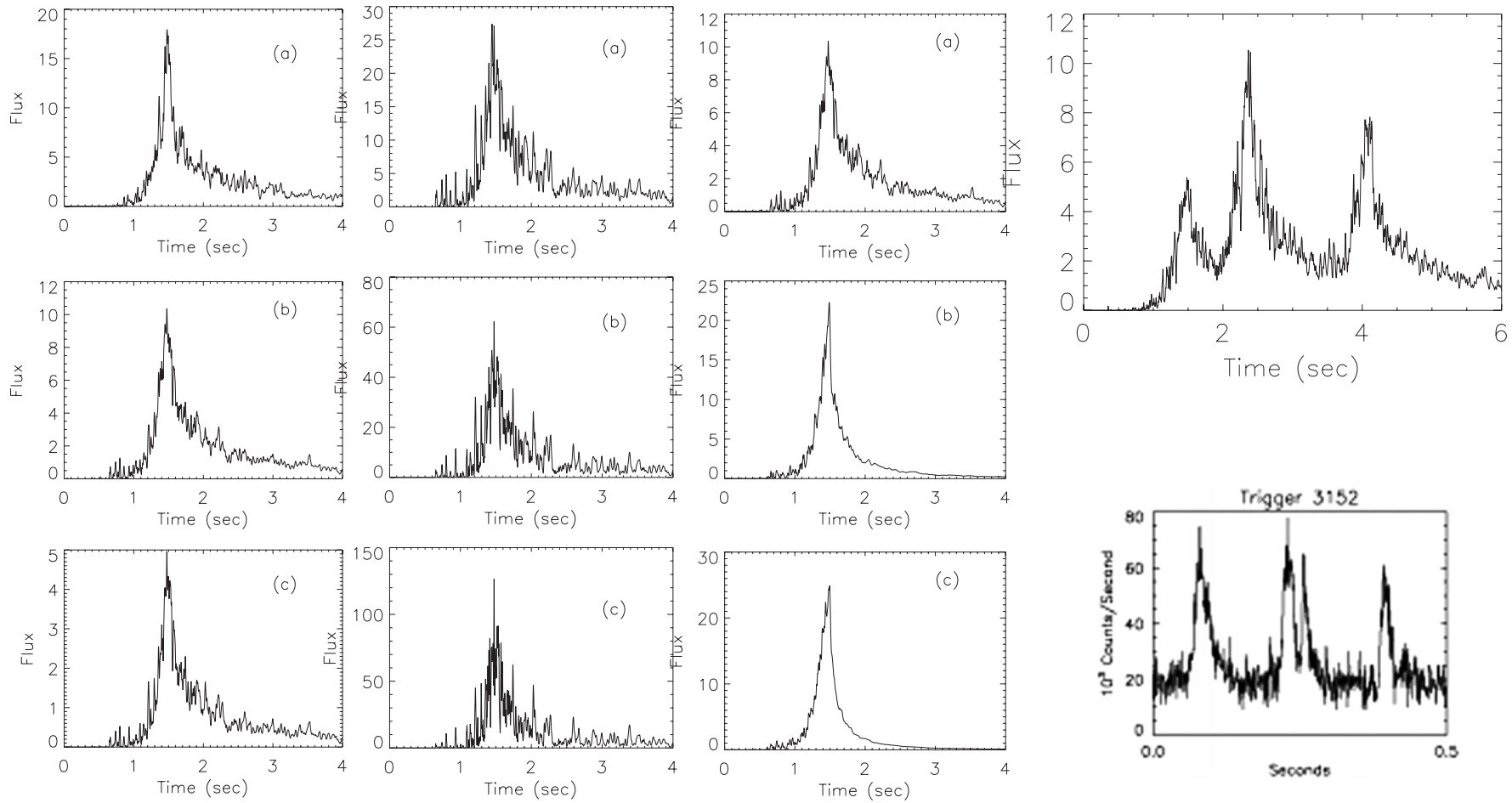
*slow variability component
related to central engine*

*fast variability component
related to turbulence*

Zhang & Yan (2011)

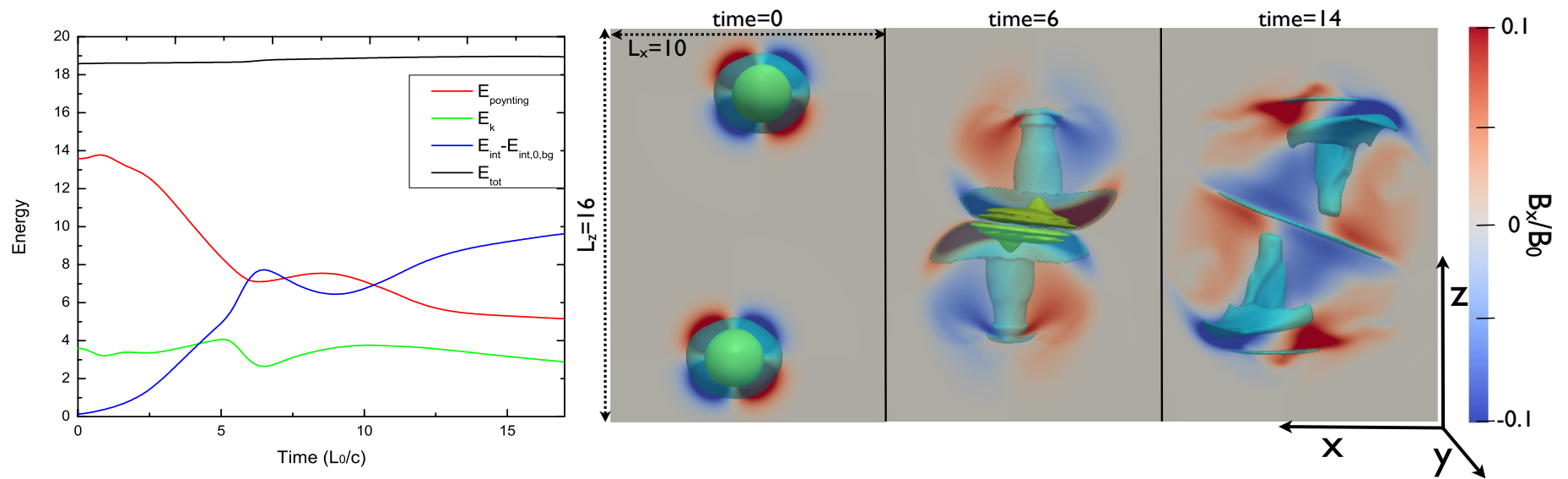
ICMART Lightcurves

Bo Zhang & BZ, 2014, ApJ, 782, 92



ICMART Simulations

Deng, Li & Zhang, 2014, in prep

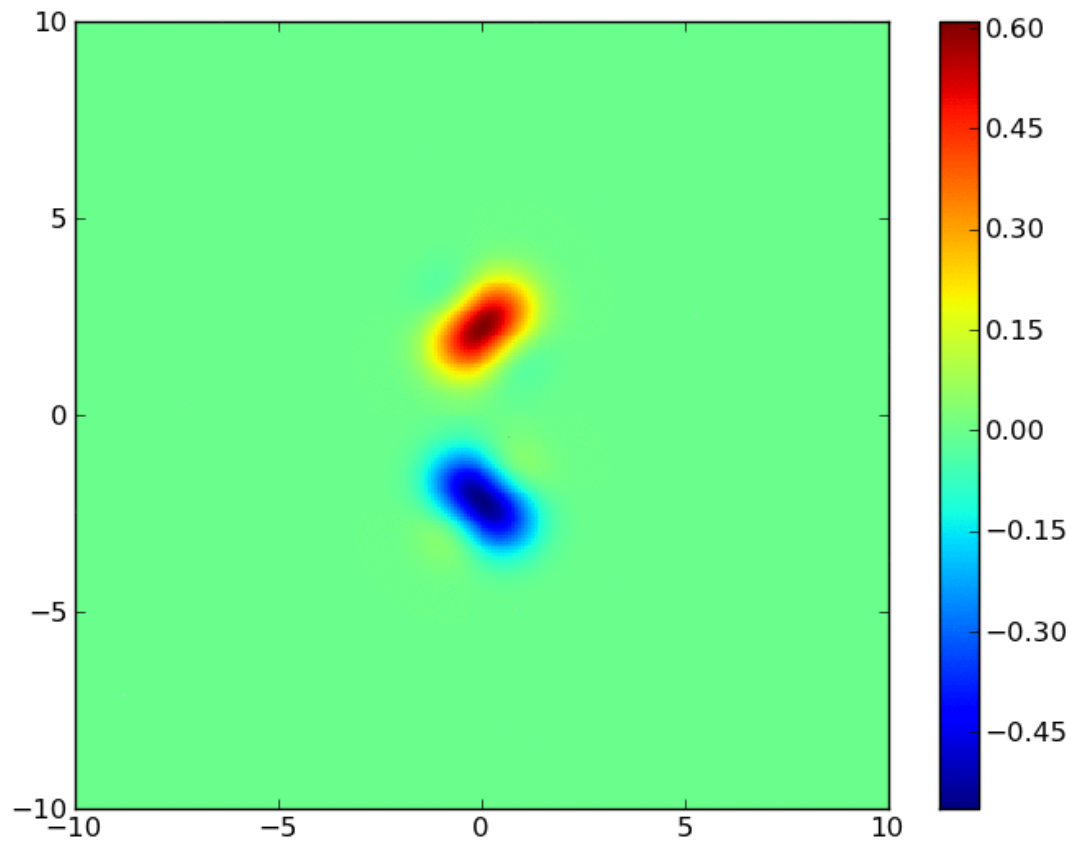


Significant magnetic energy dissipation seen

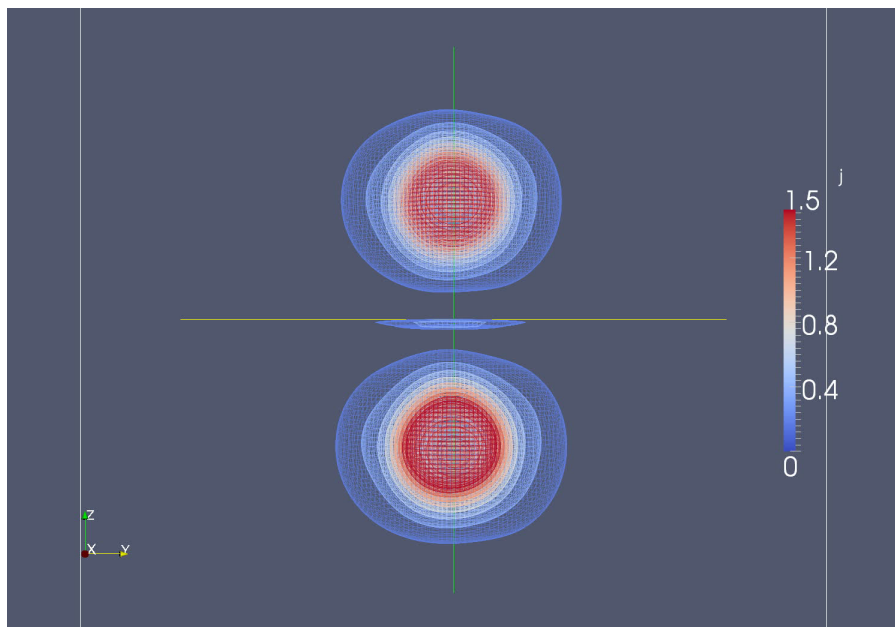
Current intensity evolution

ICMART Simulations

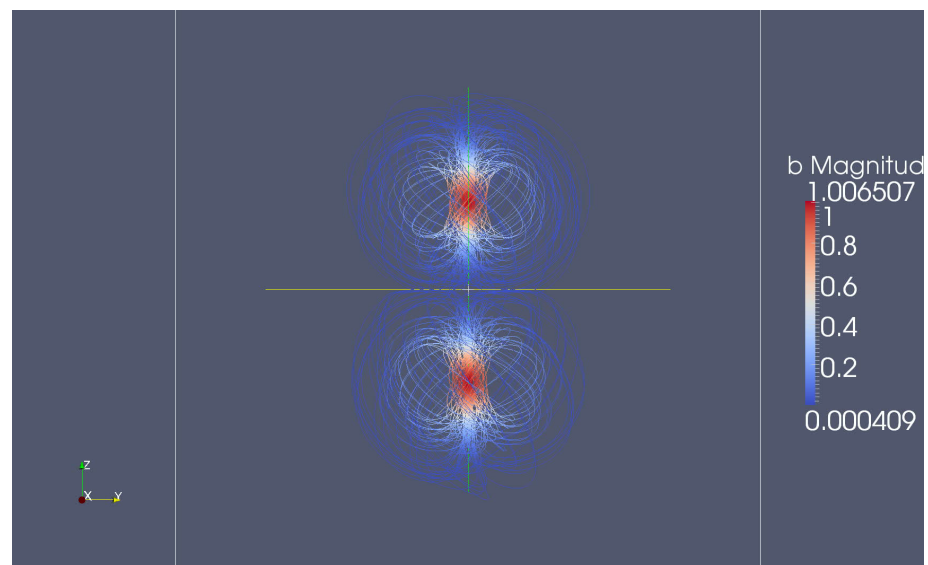
Deng, Li & Zhang, 2014, in prep



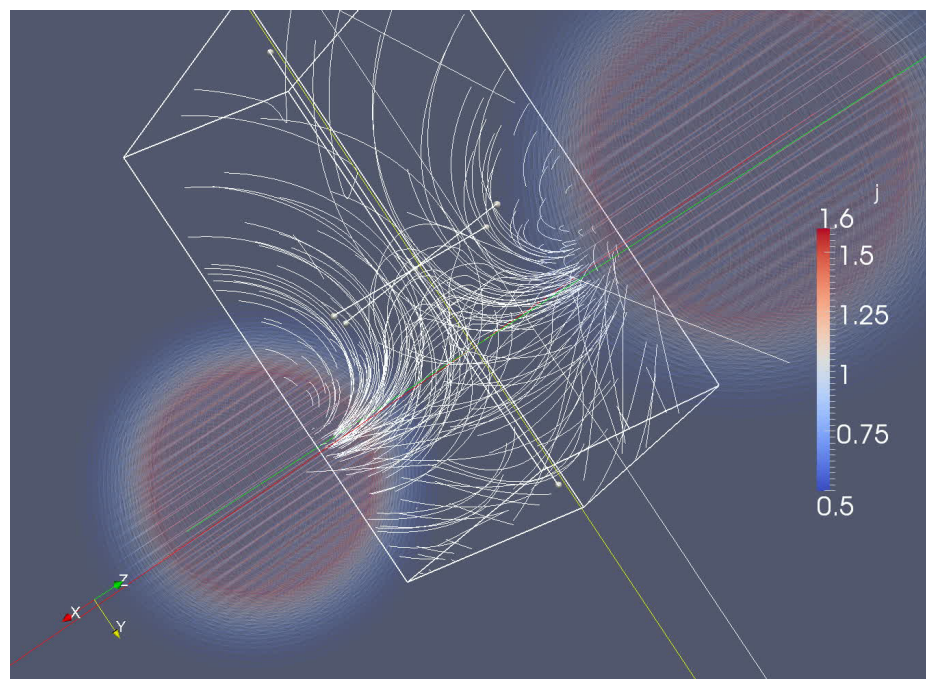
V_y evolution



Current evolution

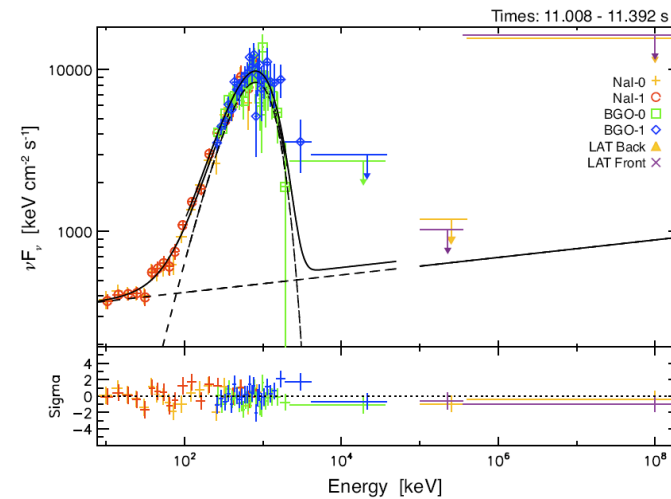
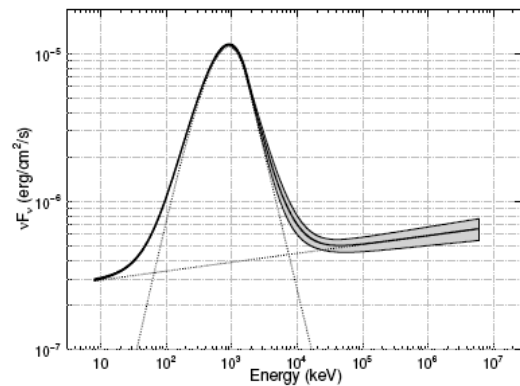
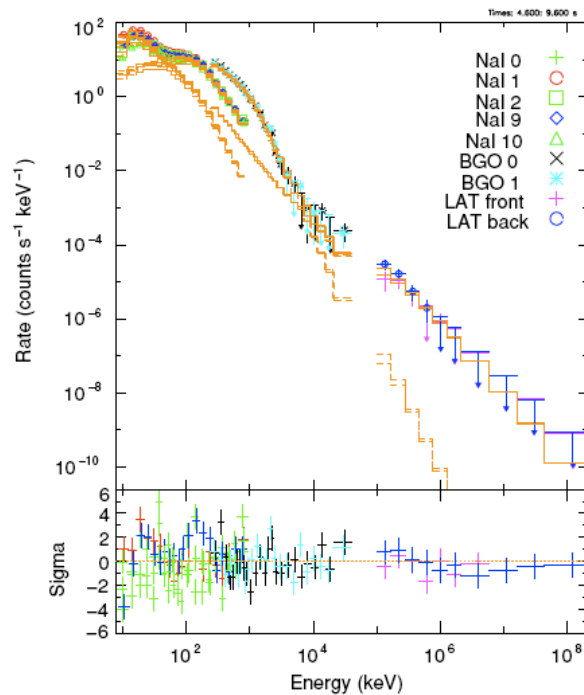


B field line evolution



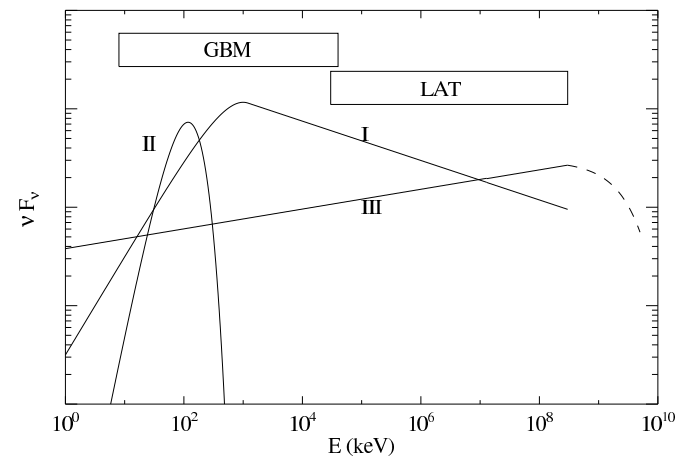
Thermal dominated case: GRB 090902B

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



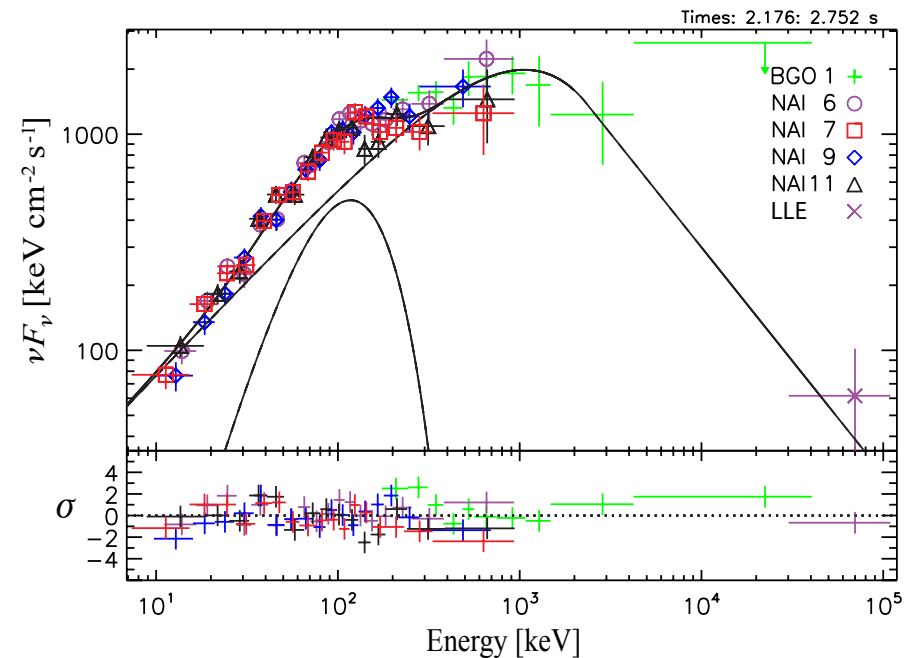
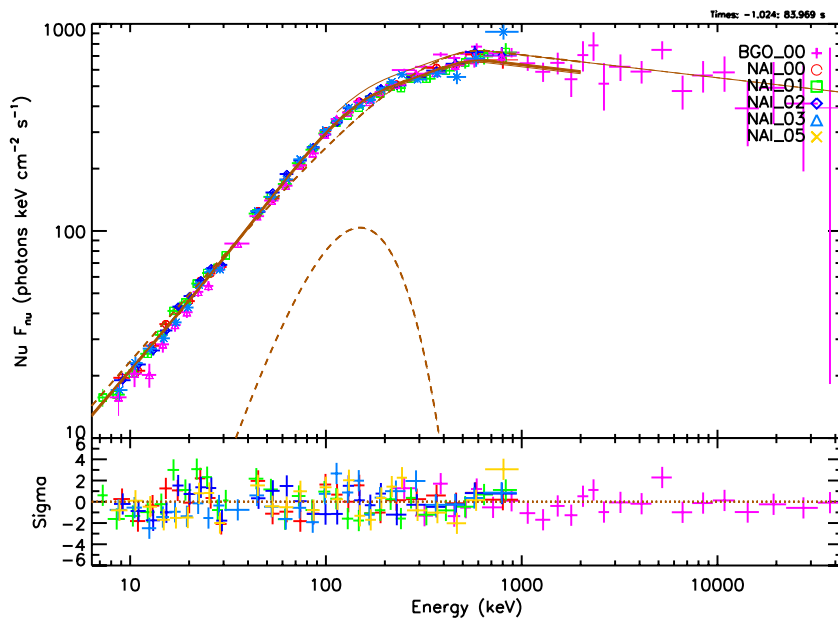
A clear photosphere emission component identified

Very special & rare event!



Something in between: GRB 100724A & GRB 110721A

(Guiriec et al. 2011; Axelsson et al. 2012; Iyyani et al. 2013)

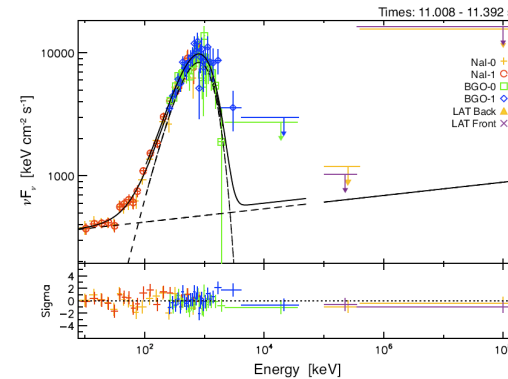


Mixed thermal & non-thermal components
As expected, more common

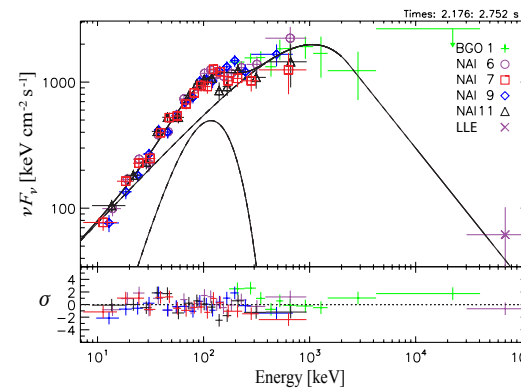
Band component has to be synchrotron

Big Picture: GRB jet composition

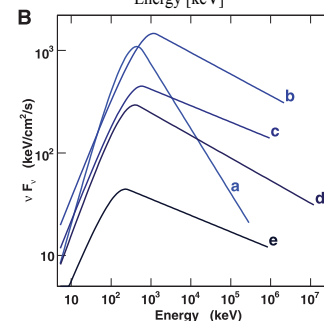
- GRB jets have diverse compositions:
 - Photosphere dominated (GRB 090902B), rare
 - Intermediate bursts (weak but not fully suppressed photosphere, GRB 100724B, GRB 110721A ...)
 - Photosphere suppressed, Poynting flux dominated (GRB 080916C)



GRB 090902B



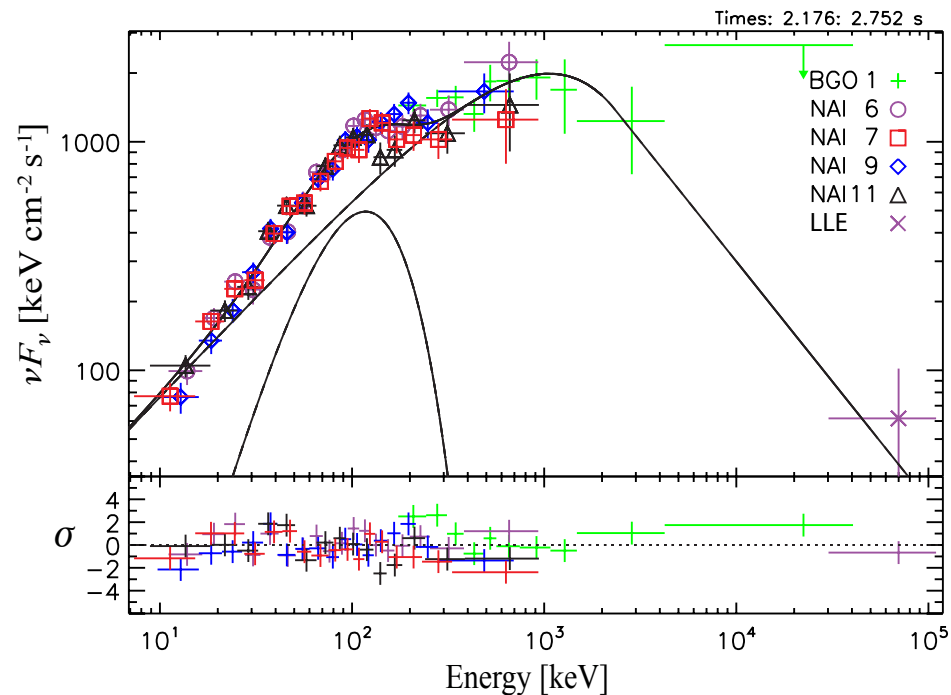
GRB 110721A



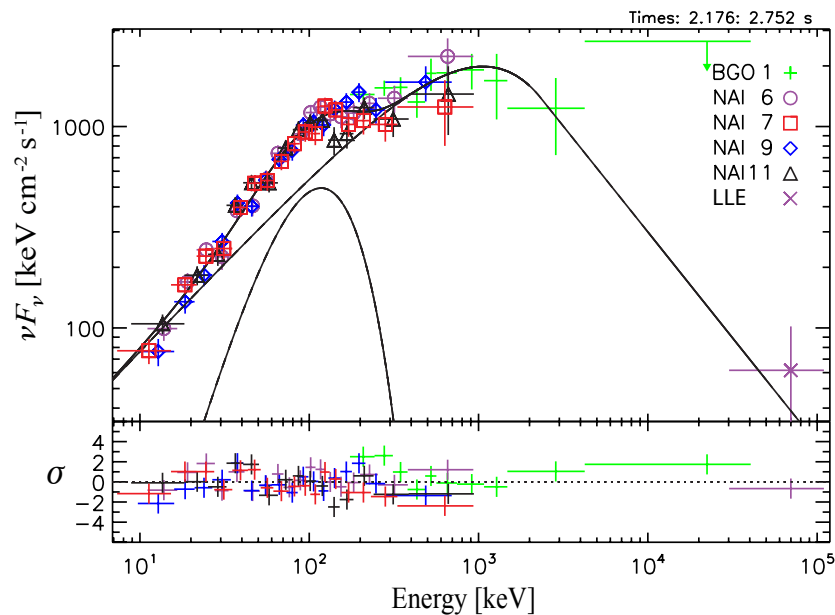
GRB 080916C

A common mis-understanding:

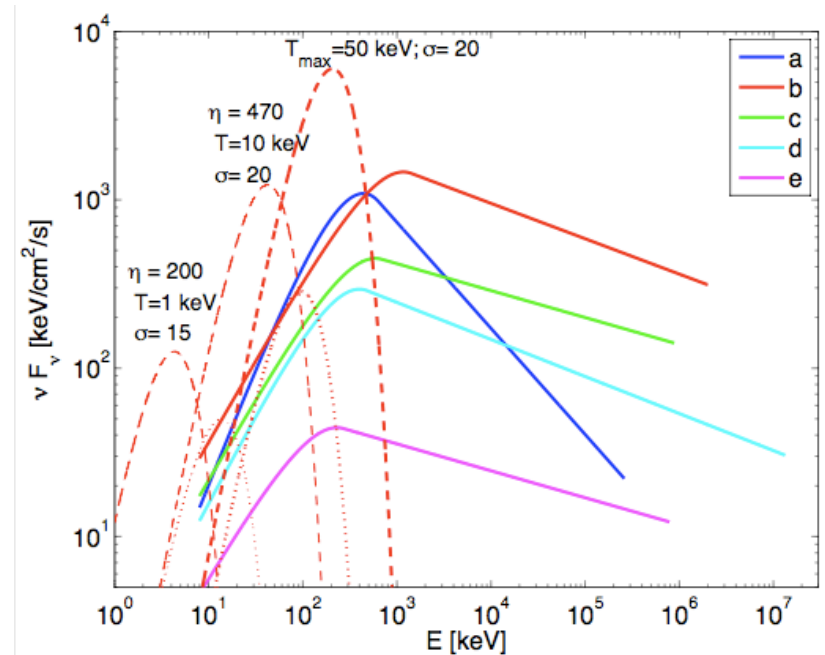
Whenever one sees a photosphere component, it is a fireball



One should check how bright the
photosphere component is with respect
to the non-thermal component!



Iyyani et al. 2013



Zhang & Pe'er 2009

Nice Diagnostic Tool to Study Photosphere Emission (Within fireball theoretical framework)

THE ASTROPHYSICAL JOURNAL, 664: L1–L4, 2007 July 20
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Ⓔ

A NEW METHOD OF DETERMINING THE INITIAL SIZE AND LORENTZ FACTOR OF GAMMA-RAY BURST FIREBALLS USING A THERMAL EMISSION COMPONENT

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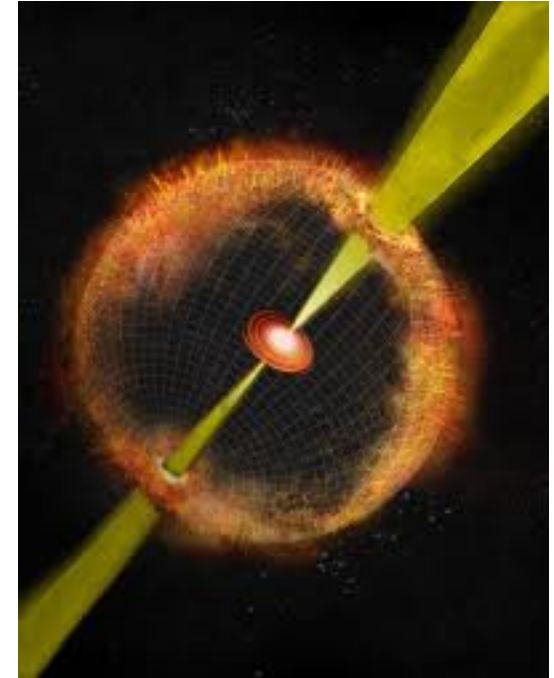
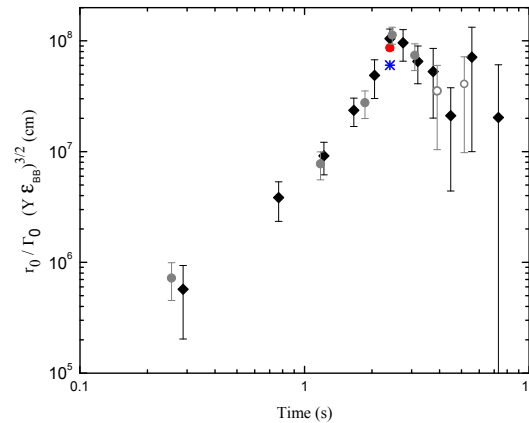
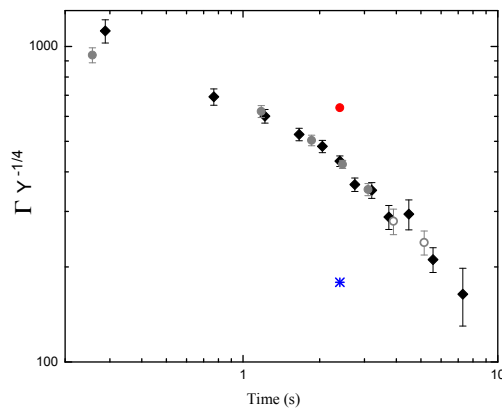
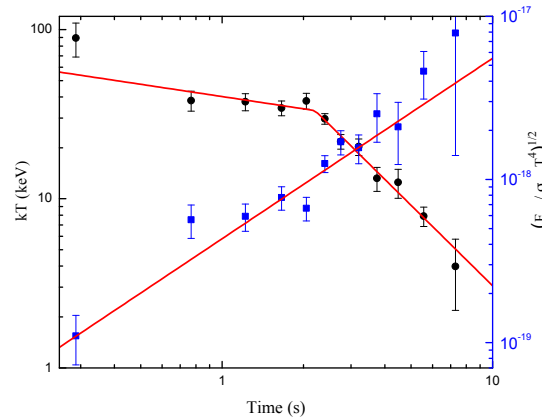
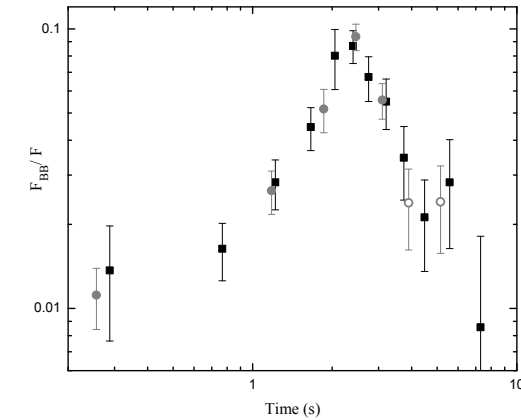
ABSTRACT

In recent years, increasing evidence has emerged for a thermal component in the γ - and X-ray spectrum of the prompt emission phase in gamma-ray bursts. The temperature and flux of the thermal component show a characteristic break in the temporal behavior after a few seconds. We show here that measurements of the temperature and flux of the thermal component at early times (before the break) allow the determination of the values of two of the least restricted fireball model parameters: the size at the base of the flow and the outflow bulk Lorentz factor. Relying on the thermal emission component only, this measurement is insensitive to the inherent uncertainties of previous estimates of the bulk motion Lorentz factor. We give specific examples of the use of this method: for GRB 970828 at redshift $z = 0.9578$, we show that the physical size at the base of the flow is $r_0 = (2.9 \pm 1.8) \times 10^8 Y_0^{-3/2}$ cm and the Lorentz factor of the flow is $\Gamma = (305 \pm 28) Y_0^{1/4}$, and for GRB 990510 at $z = 1.619$, $r_0 = (1.7 \pm 1.7) \times 10^8 Y_0^{-3/2}$ cm and $\Gamma = (384 \pm 71) Y_0^{1/4}$, where $Y = 1Y_0$ is the ratio between the total fireball energy and the energy emitted in γ -rays.

Subject headings: gamma rays: bursts — gamma rays: theory — plasmas —
radiation mechanisms: nonthermal — radiation mechanisms: thermal

However ...

Curious / inconsistent conclusions are obtained



How could r_0 vary so much?

With a decreasing Γ , how to produce internal shocks?

Iyyani et al. 2013

Theory is correct, but **theoretical framework** is wrong!

One should consider:

A general photosphere theory with arbitrary σ

GRB Central Engine

(Zhang 2014; IJMPD)

General description: a hot component and a magnetic field component

$$\eta = \frac{E_{th,0} + Mc^2}{Mc^2} = \frac{U_{th,0}}{nm_p c^2} + 1,$$

$$\sigma_0 = \frac{E_{B,0}}{\eta Mc^2} = \frac{U_{B,0}}{\eta nm_p c^2},$$

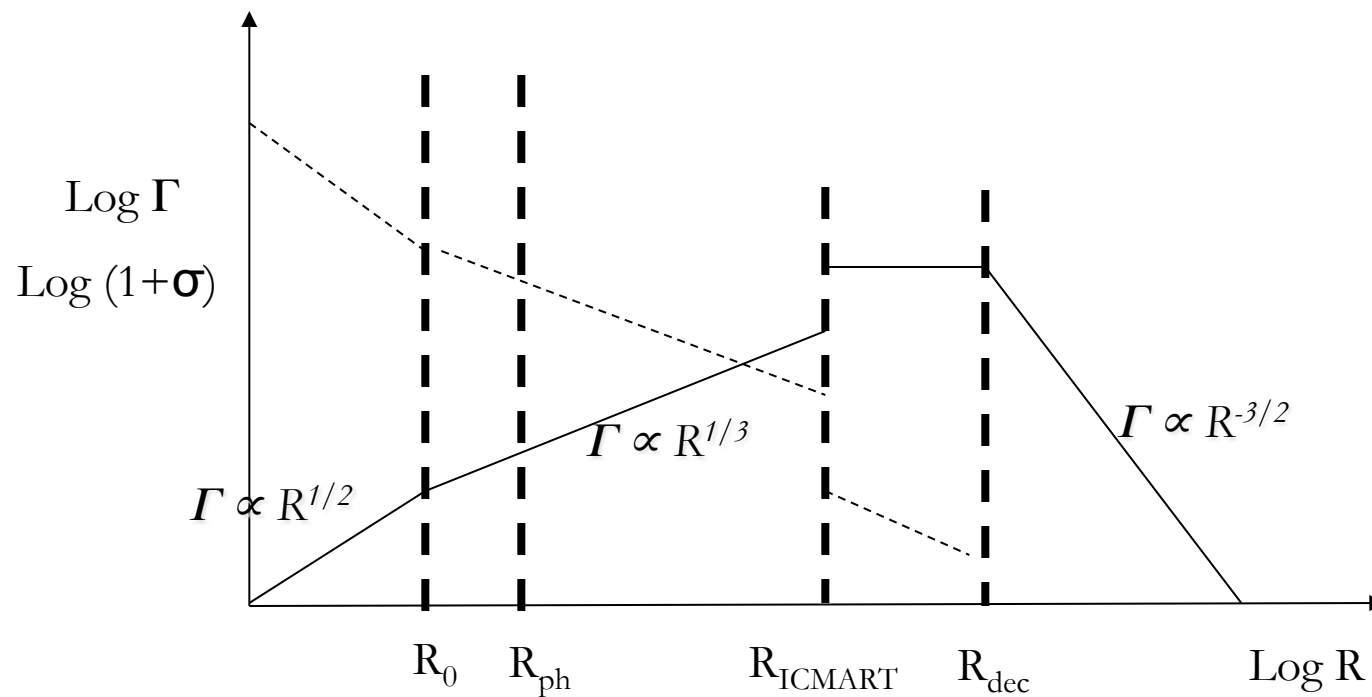
$$\mu_0 = \frac{E_{tot,0}}{Mc^2} = \frac{E_{th,0} + E_{B,0}}{Mc^2} = \eta(1 + \sigma_0).$$

No magnetic dissipation: $\mu_0 = \eta(1 + \sigma_0) = \Gamma(1 + \sigma) = \text{const}$

$$\Gamma_{\text{max}} = \mu_0 \simeq \begin{cases} \eta, & \sigma_0 \ll 1; \\ \sigma_0, & \eta \sim 1, \sigma_0 \gg 1. \end{cases} \quad \begin{array}{l} \text{fireball} \\ \text{Poynting-flux-dominated flow} \end{array}$$

With magnetic dissipation: $\mu = \Gamma(1 + \sigma)$ *decreasing with radius*

Evolution of a Poynting-flux-dominated flow: ICMART



Photosphere theory in an arbitrarily magnetized ejecta

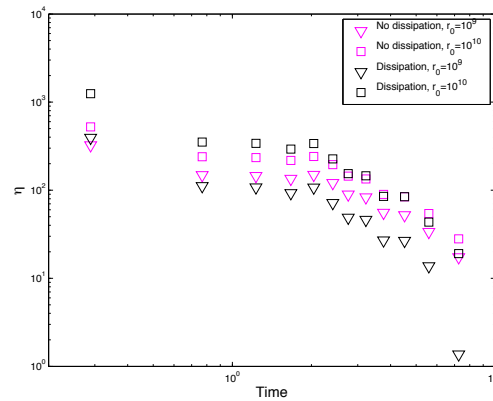
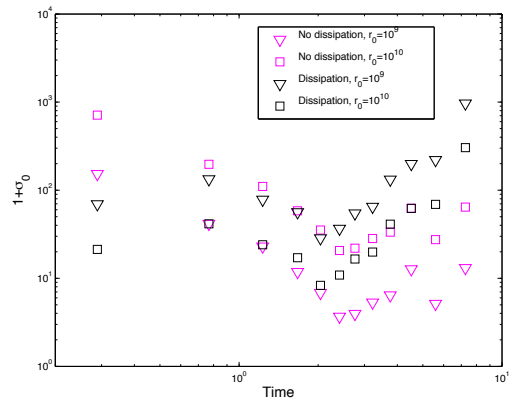
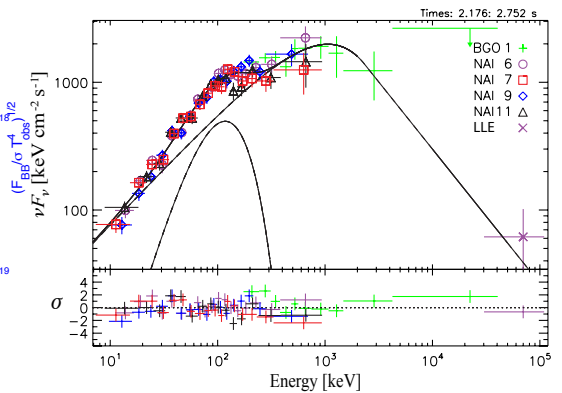
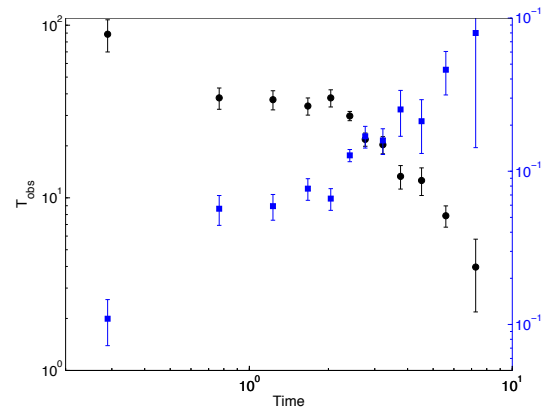
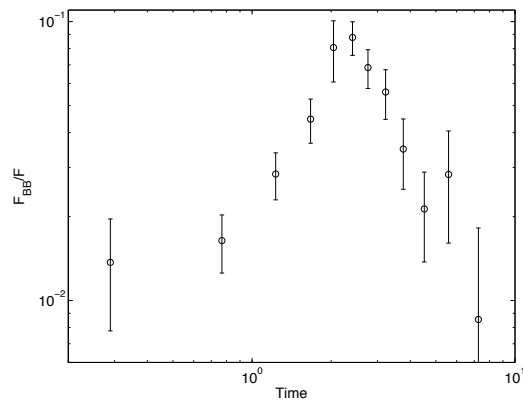
(Gao & Zhang 2014, in prep.)

| | $r_1 < r_{\text{ph}} < r_2$ | $r_{\text{ph}} > r_2$ |
|--|---|---|
| Non-dissipation $\eta > \sigma_0^{1/3}$ | $\frac{1.06^{67/72} \times 1.48^{7/3}}{4^{7/12} A^{1/4}} \frac{r_0^{1/72}}{d_L^{19/72} (1+z)^{17/36}} \frac{F_{\text{ob}}^{1/3} Y^{1/3} \mathcal{R}^{17/72}}{F_{\text{BB}}^{7/12}} < 1$ $\frac{4^3}{1.06^{19/2} \times 1.48^{12}} \frac{d_L^{7/2}}{r_0^{7/2} (1+z)^7} \frac{F_{\text{BB}}^3 \mathcal{R}^{7/2}}{F_{\text{ob}}^3 Y^3} < 1$ | $\frac{1.06^{119/36} \times 1.48^{16/3}}{4^{4/3} A^{1/4}} \frac{r_0^{8/9} (1+z)^{23/18}}{d_L^{41/36}} \frac{F_{\text{ob}}^{13/12} Y^{13/12}}{F_{\text{BB}}^{4/3} \mathcal{R}^{23/36}} < 1$ $\frac{4^2}{1.06^{19/3} \times 1.48^8} \frac{d_L^{7/3}}{r_0^{7/3} (1+z)^{14/3}} \frac{F_{\text{BB}}^2 \mathcal{R}^{7/3}}{F_{\text{ob}}^2 Y^2} > 1$ |
| Non-dissipation $\eta < \sigma_0^{1/3}$ | $\frac{1.06^{67/18} \times 1.48^{28/3}}{4^{7/3} A} \frac{r_0^{1/18}}{d_L^{19/18} (1+z)^{17/9}} \frac{F_{\text{ob}}^{4/3} Y^{4/3} \mathcal{R}^{17/18}}{F_{\text{BB}}^{7/3}} > 1$ $\frac{1.06^{5/3} \times 1.48^{16}}{4^4 A^3} \frac{d_L^{1/3}}{r_0^{10/3} (1+z)^{38/3}} \frac{F_{\text{ob}} Y \mathcal{R}^{19/3}}{F_{\text{BB}}^4} < 1$ | $\frac{1.06^{119/36} \times 1.48^{16/3}}{4^{4/3} A^{1/4}} \frac{r_0^{8/9} (1+z)^{23/18}}{d_L^{41/36}} \frac{F_{\text{ob}}^{13/12} Y^{13/12}}{F_{\text{BB}}^{4/3} \mathcal{R}^{23/36}} > 1$ $\frac{1.06^{5/18} \times 1.48^{8/3}}{4^{2/3} A^{1/2}} \frac{d_L^{1/18}}{r_0^{5/9} (1+z)^{19/9}} \frac{F_{\text{ob}}^{1/6} Y^{1/6} \mathcal{R}^{19/18}}{F_{\text{BB}}^{2/3}} > 1$ |
| Dissipation $\eta > \sigma_0^{1/3}$ | $\frac{1.06^{1/4} \times 1.48^{7/3}}{4^{7/12} A^{1/4}} \frac{d_L^{5/12}}{r_0^{2/3} (1+z)^{11/6}} \frac{F_{\text{ob}}^{1/3} Y^{1/3} \mathcal{R}^{11/12}}{F_{\text{BB}}^{7/12}} < 1$ $\frac{2^9}{1.06^6 \times 1.48^{12}} \frac{F_{\text{BB}}^3}{F_{\text{ob}}^3 Y^3} < 1$ | $\frac{4}{1.06^{35/12} \times 1.48^4 A^{1/4}} \frac{d_L^{5/12}}{r_0^{2/3} (1+z)^{11/6}} \frac{F_{\text{BB}} \mathcal{R}^{11/12}}{F_{\text{ob}}^{5/4} Y^{5/4}} < 1$ $\frac{1.06^3 \times 1.48^6}{4^{3/2}} \frac{F_{\text{ob}}^{3/2} Y^{3/2}}{F_{\text{BB}}^{3/2}} > 1$ |
| Dissipation $\eta < \sigma_0^{1/3}$ | $\frac{1.06 \times 1.48^{28/3}}{4^{7/3} A} \frac{d_L^{5/3}}{r_0^{8/3} (1+z)^{22/3}} \frac{F_{\text{ob}}^{4/3} Y^{4/3} \mathcal{R}^{11/3}}{F_{\text{BB}}^{7/3}} > 1$ $\frac{1.48^{16}}{1.06^3 \times 2^5 A^3} \frac{d_L^5}{r_0^8 (1+z)^{22}} \frac{F_{\text{ob}} Y \mathcal{R}^{11}}{F_{\text{BB}}^4} < 1$ | $\frac{1.06^{35/16} \times 1.48^3 A^{3/16}}{4^{3/4}} \frac{r_0^{1/2} (1+z)^{11/8}}{d_L^{5/16}} \frac{F_{\text{ob}}^{15/16} Y^{15/16}}{F_{\text{BB}}^{3/4} \mathcal{R}^{11/16}} > 1$ $\frac{1.48^{3/2}}{1.06^{9/32} \times 4^{3/8} A^{9/32}} \frac{d_L^{15/32}}{r_0^{3/4} (1+z)^{33/16}} \frac{F_{\text{ob}}^{3/32} Y^{3/32} \mathcal{R}^{33/32}}{F_{\text{BB}}^{3/8}} > 1$ |

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

Photosphere theory in an arbitrarily magnetized ejecta

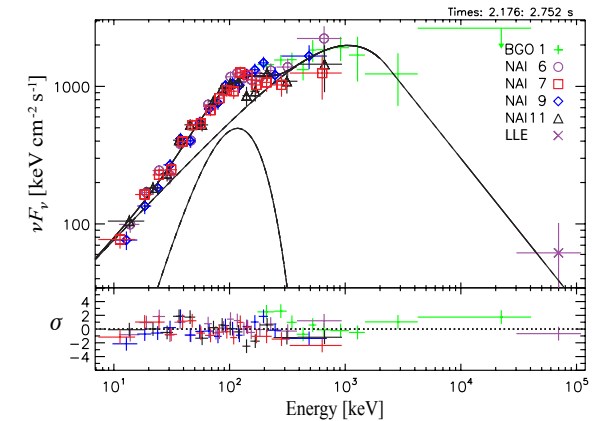
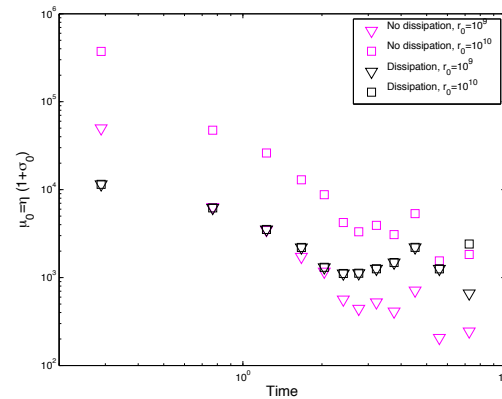
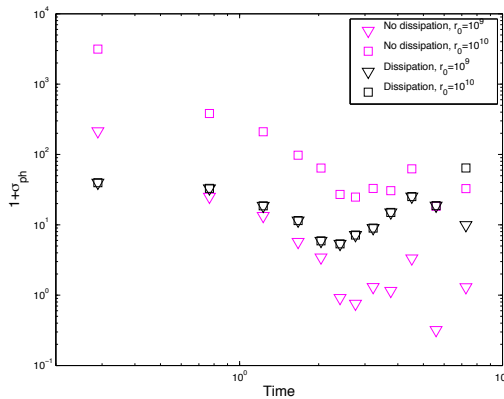
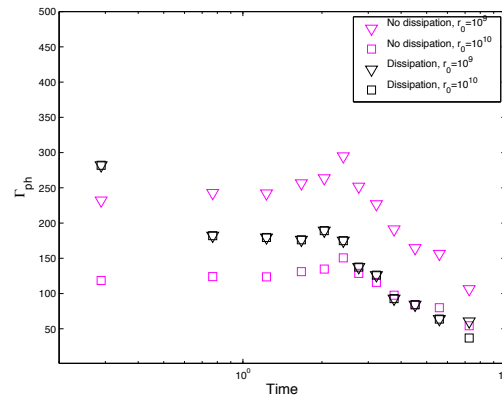
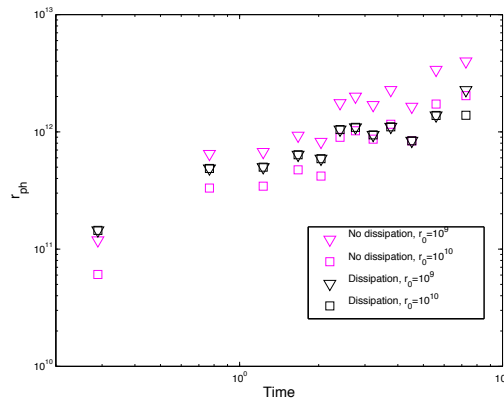
(Gao & Zhang 2014, in prep.)



r_0 not changed, sigma is changing!

Photosphere theory in an arbitrarily magnetized ejecta

(Gao & Zhang 2014, in prep.)



*Magnetized flow
ICMART is operating!*

Non-detection of neutrinos by Icecube

- IceCube did not detect neutrinos from GRBs yet, upper limit 3 times lower than the most optimistic predictions (Waxman & Bahcall)
- What does this mean?
 - Solar neutrino problem:
 - Astrophysics wrong?
 - **Physics wrong?**
 - GRB neutrino problem?
 - **Astrophysics wrong?**
 - Physics wrong?

LETTER

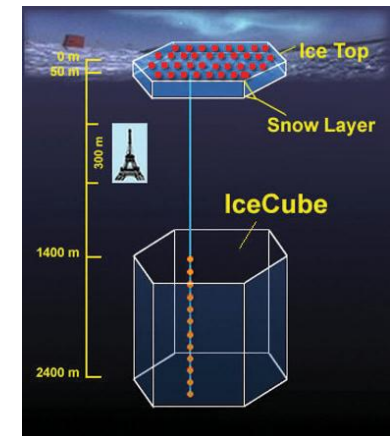
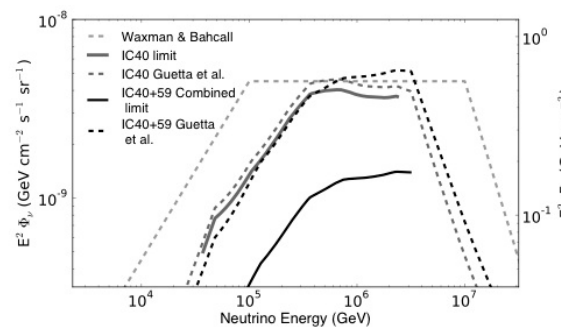
doi:10.1038/nature11068

An absence of neutrinos associated with cosmic-ray acceleration in γ -ray bursts

IceCube Collaboration*

Very energetic astrophysical events are required to accelerate cosmic rays to above 10^{18} electronvolts. GRBs (γ -ray bursts) have been proposed as possible candidate sources^{1–3}. In the GRB 'fireball' model, cosmic-ray acceleration should be accompanied by neutrinos produced in the decay of charged pions created in interactions between the high-energy cosmic-ray protons and γ -rays⁴. Previous searches for such neutrinos found none, but the constraints were weak because the sensitivity was at best approximately equal to the predicted flux^{5–7}. Here we report an upper limit on the flux of energetic neutrinos associated with GRBs that is at least a factor of 3.7 below the predictions^{8,9–10}. This implies either that GRBs are not the only sources of cosmic rays with energies exceeding 10^{18} electronvolts or that the efficiency of neutrino production is much lower than has been predicted.

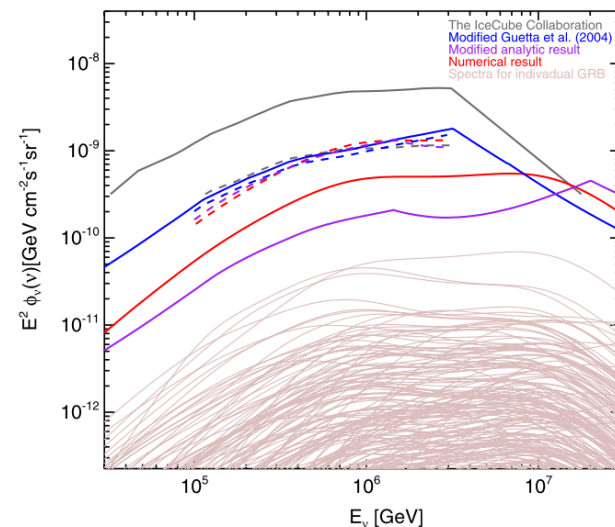
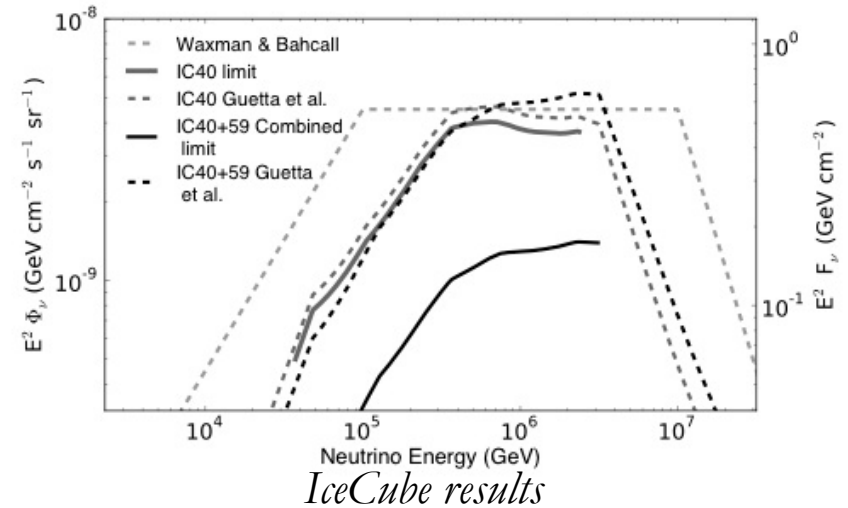
As in our previous study⁷, we conducted two analyses of the IceCube data. In a model-dependent search, we examine data during the period of γ -ray emission reported by any satellite for neutrinos with the energy spectrum predicted from the γ -ray spectra of individual GRBs^{8,9}. The model-independent analysis searches more generically for neutrinos on wider timescales, up to the limit of sensitivity to small numbers of events at ± 1 day, or with different spectra. Both analyses follow the methods used in our previous work⁷, with the exception of slightly changed event selection and the addition of the Southern Hemisphere to the model-independent search. Owing to the large background of downgoing muons from the southern sky, the Southern Hemisphere analysis is sensitive mainly to higher-energy events (Supplementary Fig. 3). Systematic uncertainties from detector effects have been included in the reported limits from both analyses.



IceCube results

Non-detection of neutrinos by Icecube

- IceCube upper limit is 3 times lower than the most optimistic predictions in the internal shock (IS) model (Waxman & Bahcall)
- More careful studies (Li 2012; Hummer et al. 2012; He et al. 2012) suggest that the IS limit is barely violated

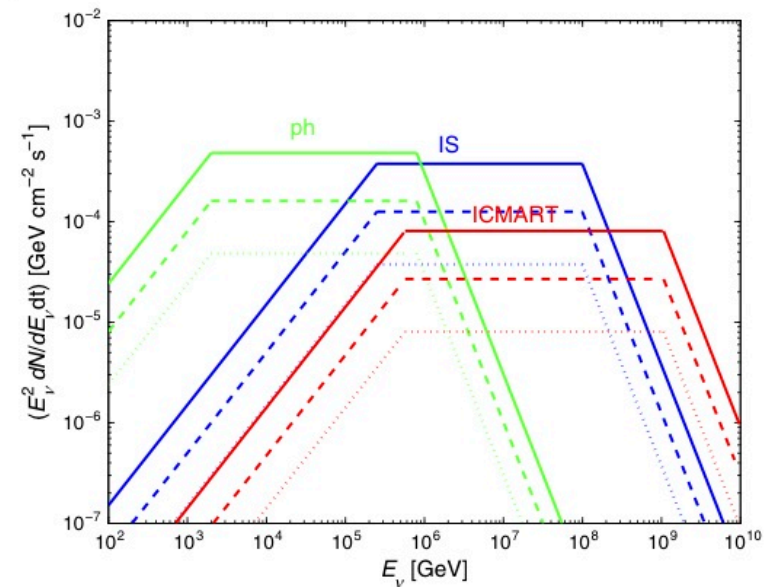


*He et al.
(2012)*

Talk by M. Bustamante

Model-Dependent Neutrino Flux from GRBs

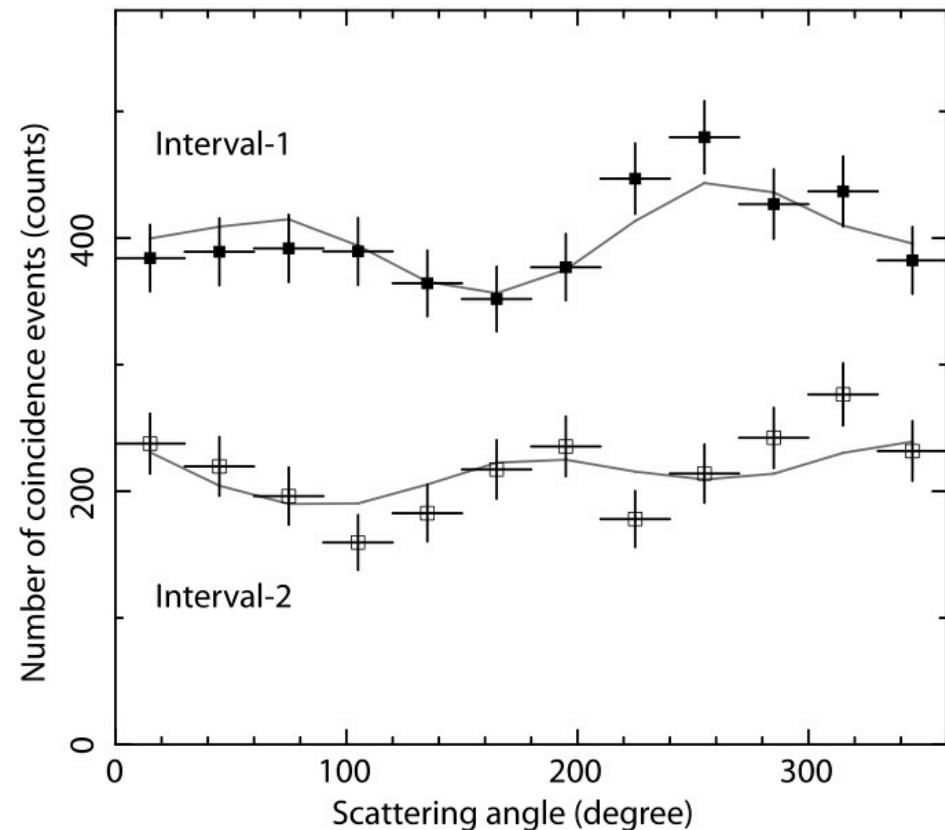
- A highly magnetized ejecta with large dissipation radius (ICMART) predicts a much lower flux
- Recent IceCube limit is another factor ~ 3 lower



Zhang & Kumar, 2013, PRL, 110, 121101

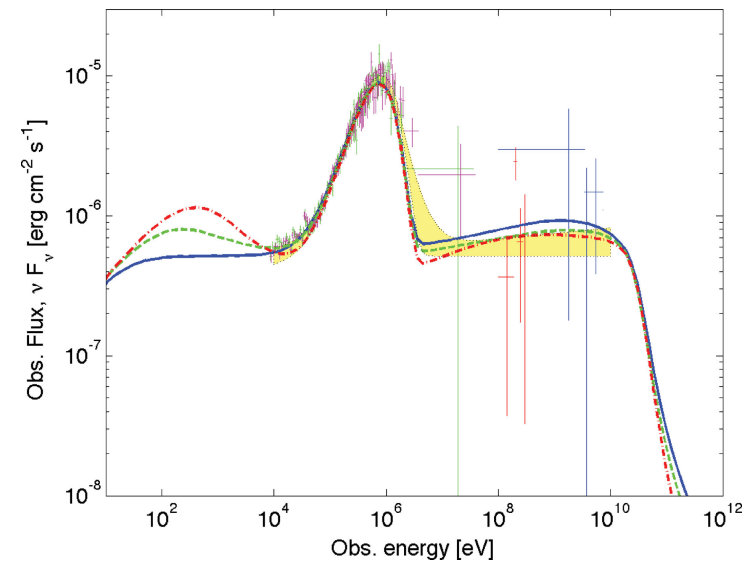
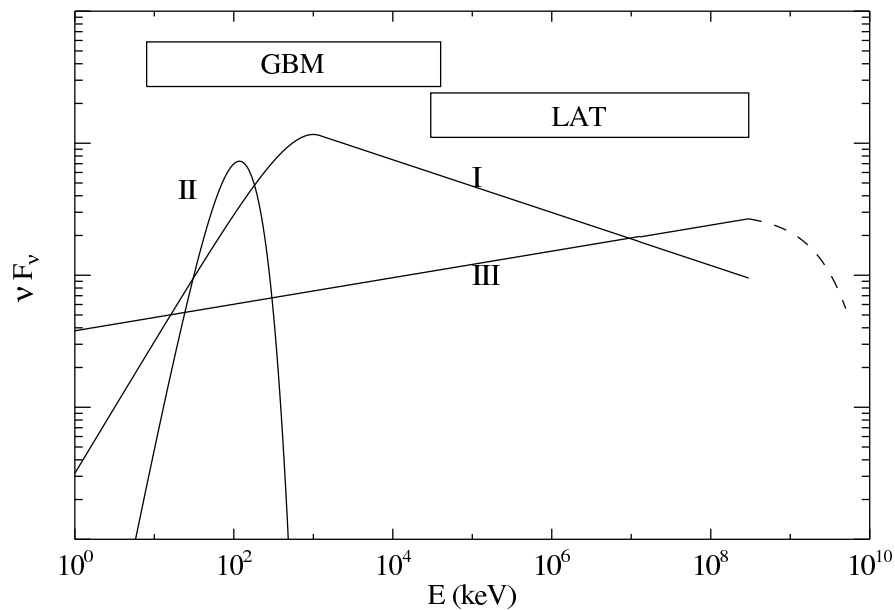
Polarization data

- Three *bright* GRBs with polarization detections in gamma-rays: GRB 100826A: $27\% \pm 11\%$ (Yonetoku et al. 2011)
- Early optical emission has “residual” $\sim 10\%$ polarization from reverse shock (Steele et al. 2009; Uehara et al. 2012)
- Consistent with dissipation of large scale magnetic field



Yonetoku et al. (2011)

Origin of the third component?



I don't know, but inverse Compton of some sort.

Pe'er et al. (2012)

Conclusions

- GRB composition may be diverse. At least some (even most) GRBs are highly magnetized,
- Magnetic dissipation may be an important energy dissipation mechanism to power GRB prompt emission
- GRB spectra likely include contributions from multiple components:
 - A Band component likely of a synchrotron origin in the optically thin region (ICMART / internal shock region)
 - A quasi-thermal component likely of a photosphere origin
 - A mysterious high energy component