Acceleration of Particles in Gamma-Ray Bursts

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Sep. 29, 2009

In "Nonlinear Processes in Astrophysical Plasma: Particle Acceleration, Magnetic Field Amplification, and Radiation Signatures"

KITP, Santa Barbara, CA

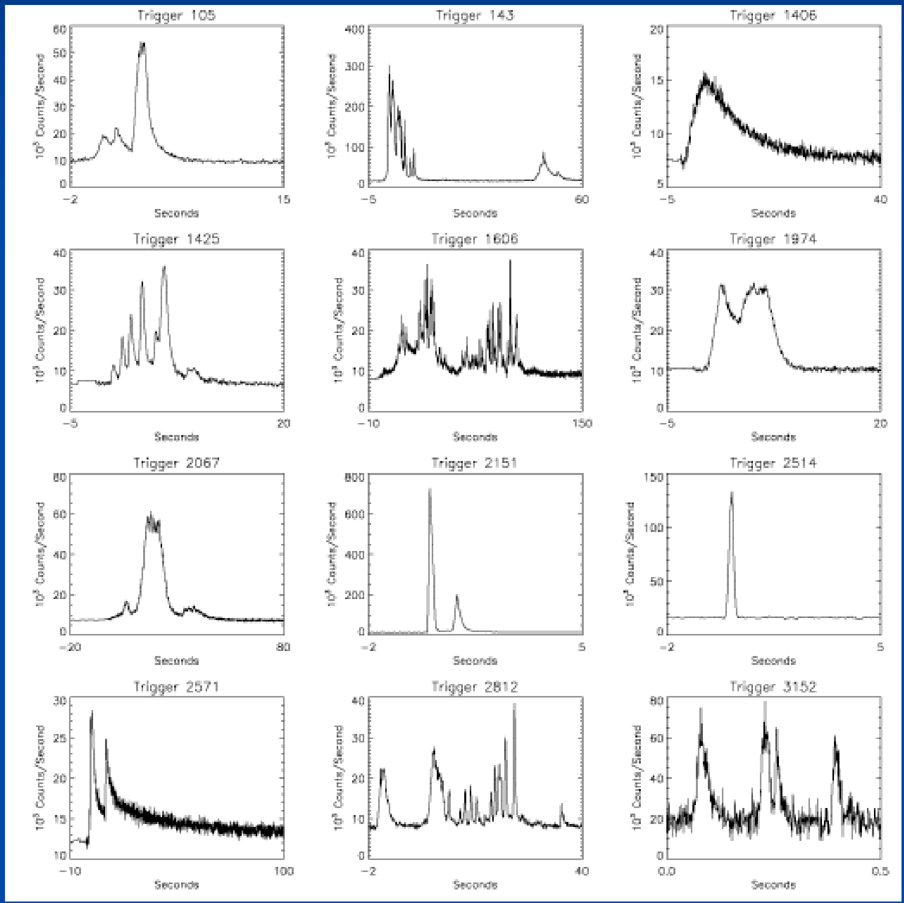
Collaborators: Asaf Pe'er & Huirong Yan

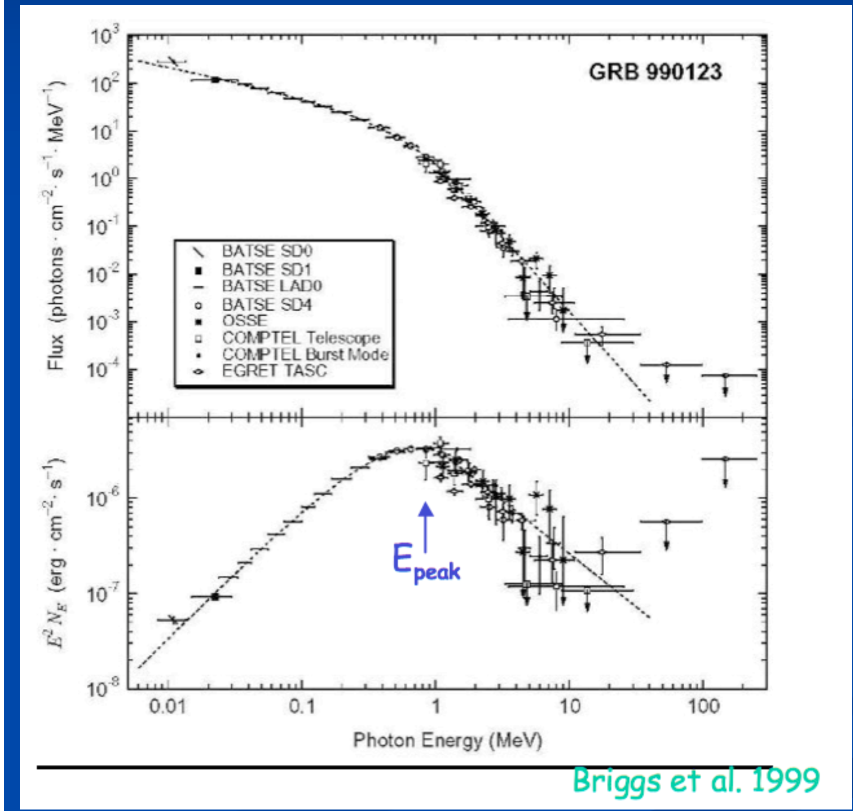
Two approaches to study particle acceleration in GRBs

- "Bottom-up": (Mathematician's approach)
  - Starting with fundamental physics; proceeding through numerical simulations: Particle-in-cell (PIC) (Spitkovsky, Sironi, Nishikawa, Medvedev, et al) or Monte Carlo simulations (Baring, Ellison et al.)
  - Pros: first principle; robust
  - Cons: explored parameter space is limited by computational power; input parameters may not be the right ones in Nature; may not get what is needed to interpret the data; for complicated systems, difficult to incorporate all the effects
- "Top-down": (detective's approach)
  - Starting with observations and phenomenological models; using data and model to infer the requirements to the model
  - Pros: More directly connected to data, allow a much wider parameter space not achievable by the current computational power
  - Cons: Uncertainty involved; conclusions subject to confirmation from the "bottom-up" approach

This talk adopts the latter approach.

GRB Phenomenology (1): Prompt Emission

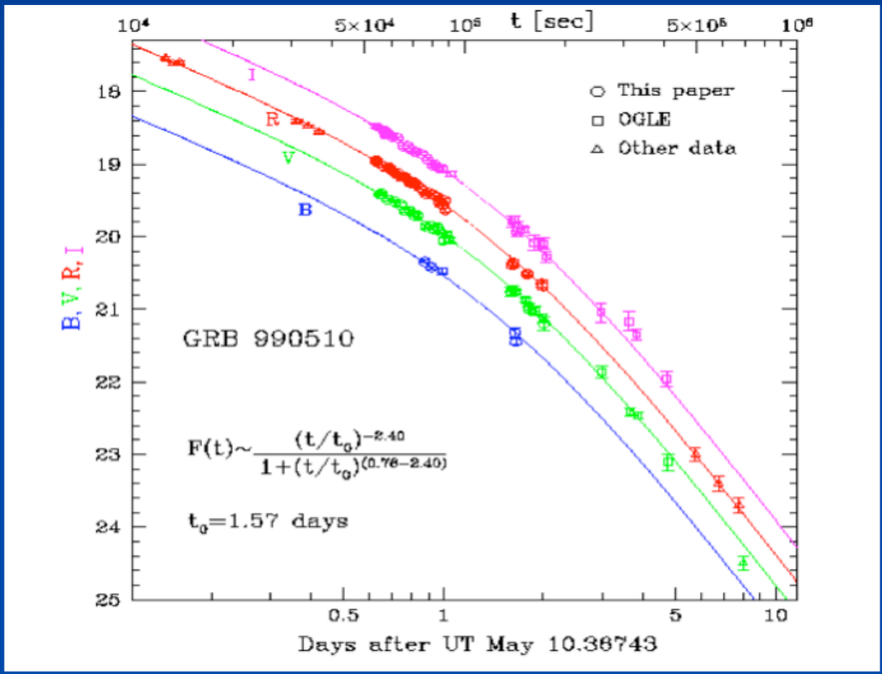


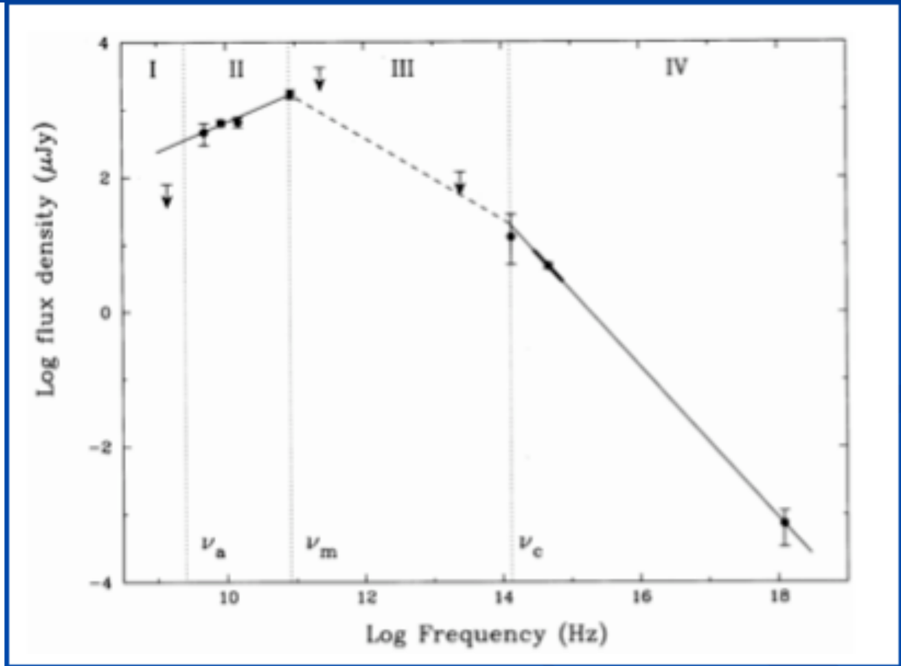


Light curves: irregular

Spectra: non-thermal emission from relativistic particles

GRB Phenomenology (2): Afterglow





Light curves: power law decay with breaks

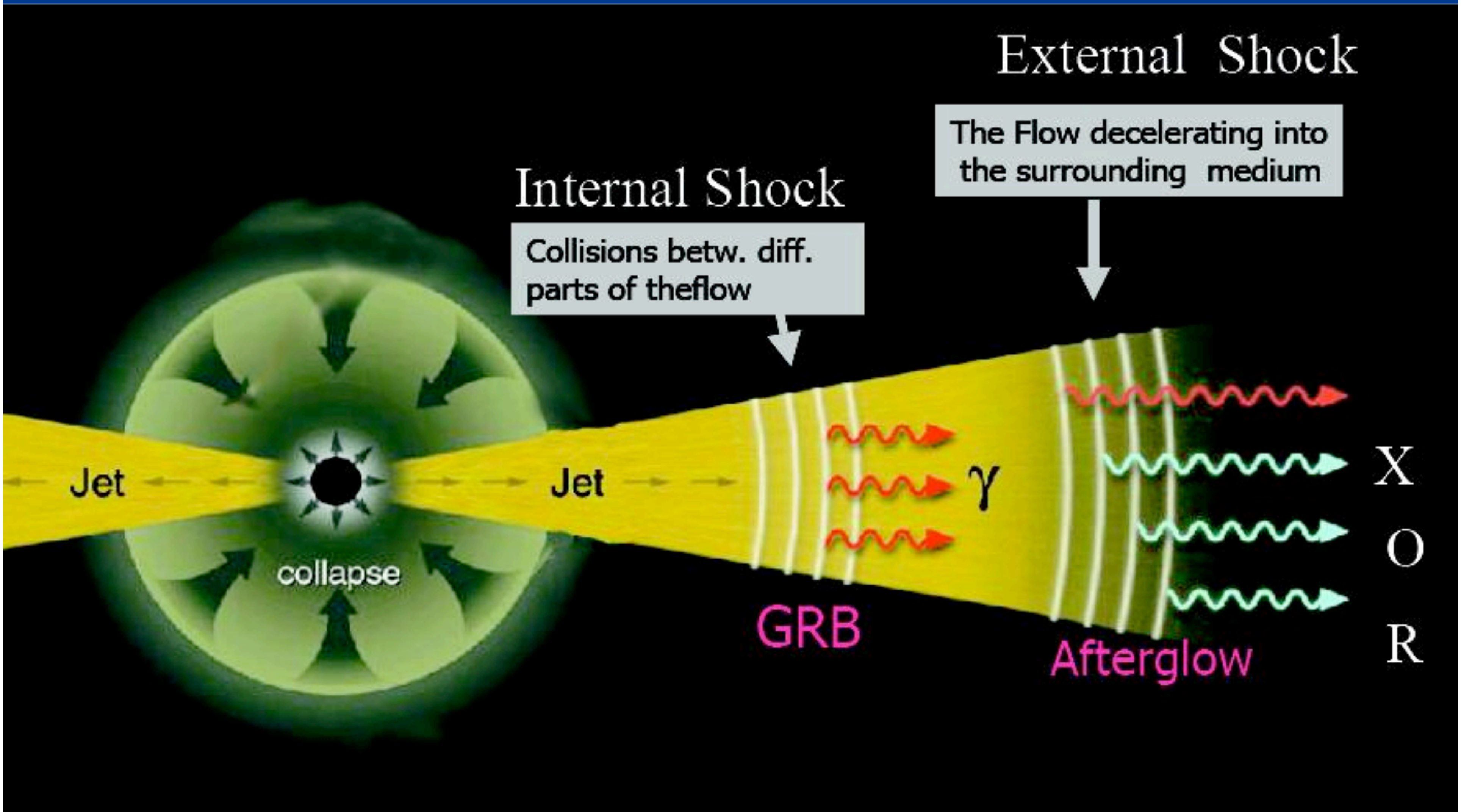
Stanek et al. 99

Spectra: broadband broken power law

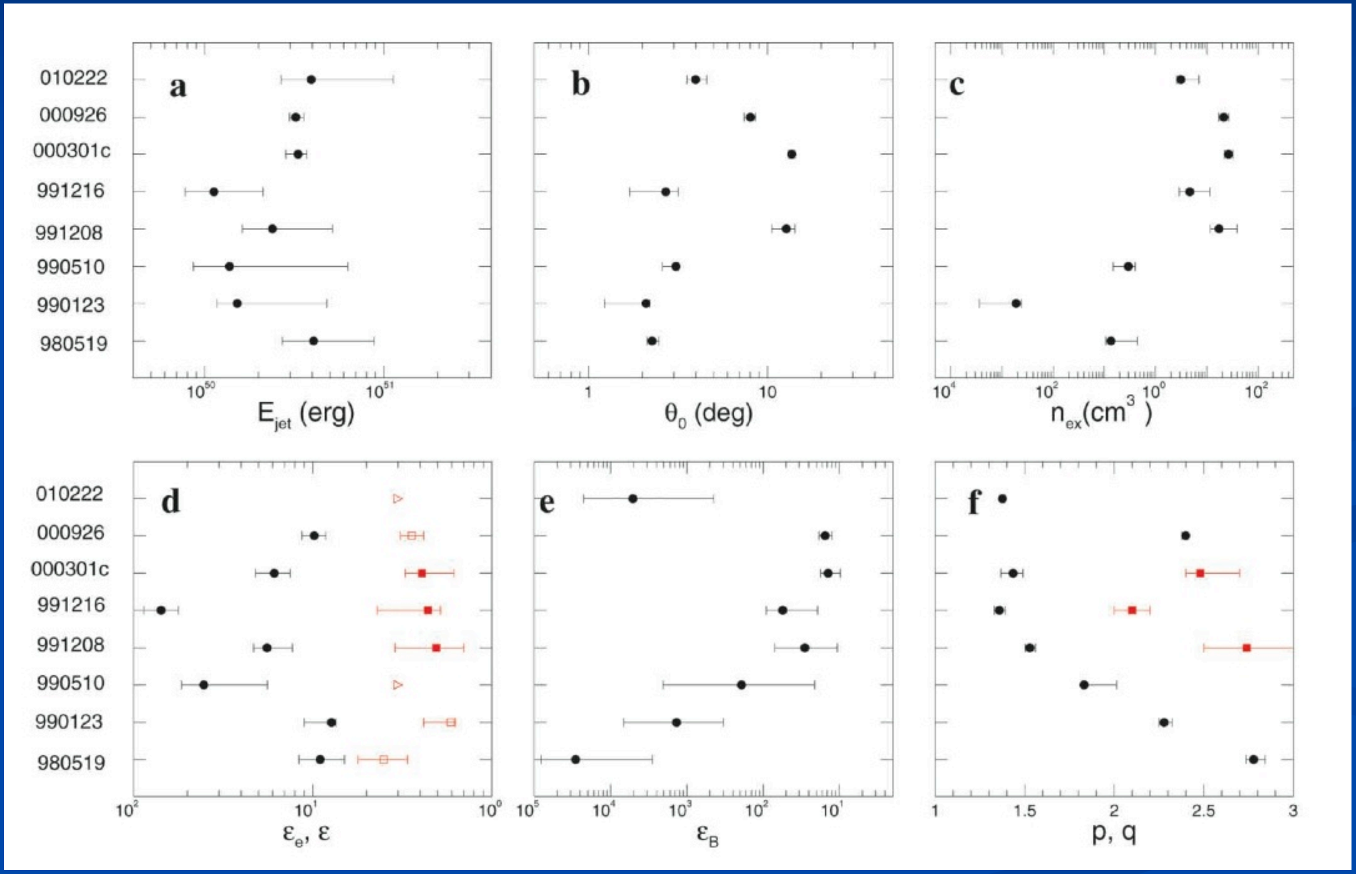
Wijers & Galama 99

An Elegant Picture: "Generic" Fireball Shock Model

(Paczynski, Meszaros, Rees, Sari, Piran, …)



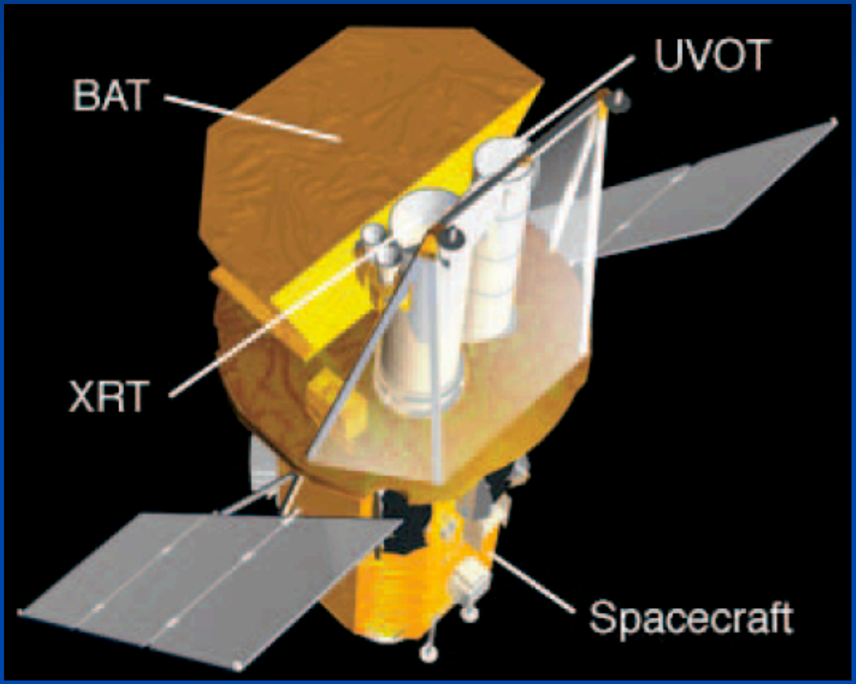
Constraints on External Forward Shock Parameters

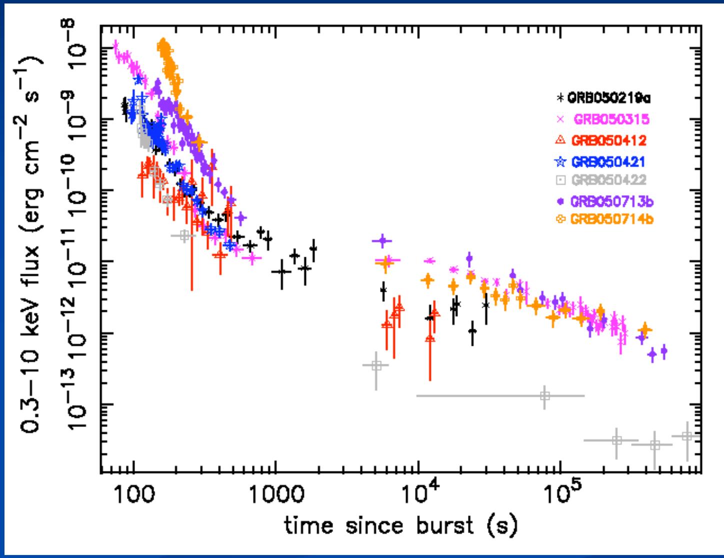


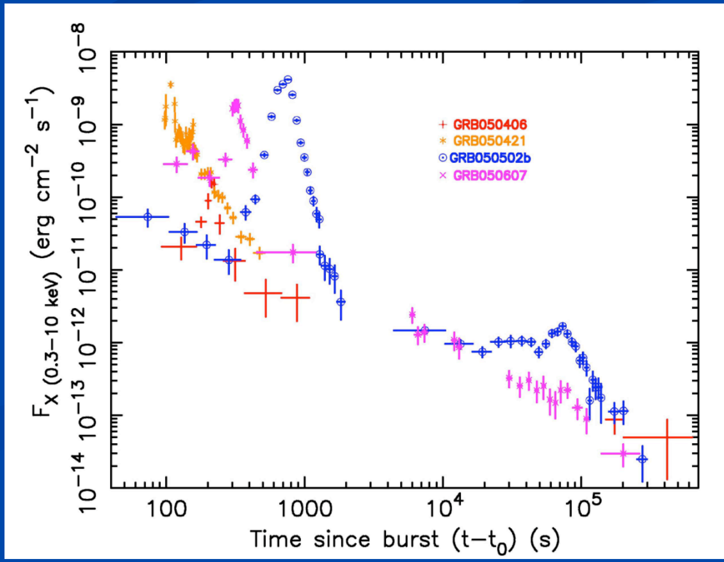
Panaitescu & Kumar (2001, 2002); Yost et al. (2003)

However …
Life is not that simple!

Swift Revolution





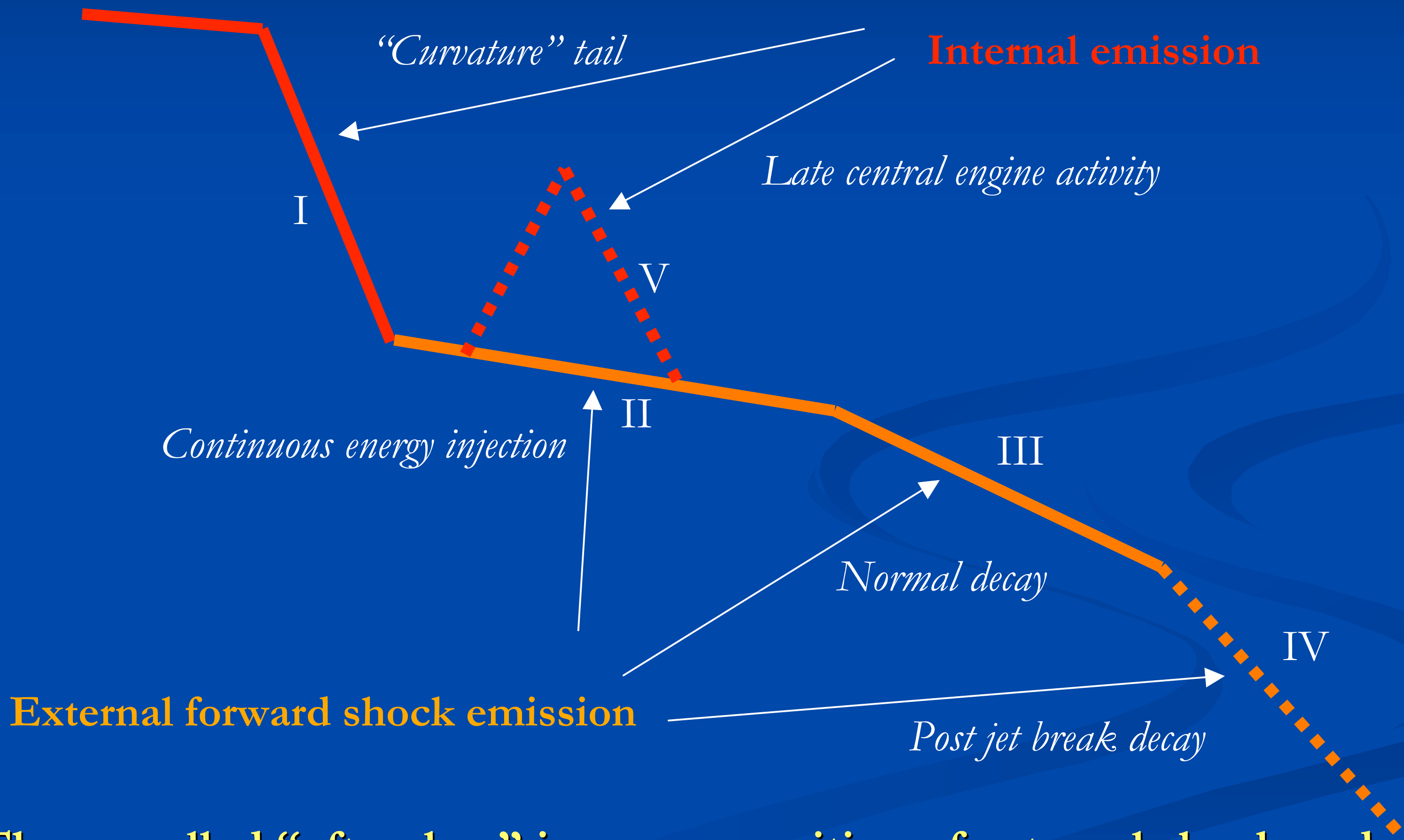


Early X-ray afterglow displays unexpected features

Nousek et al. 2006
Zhang et al. 2006

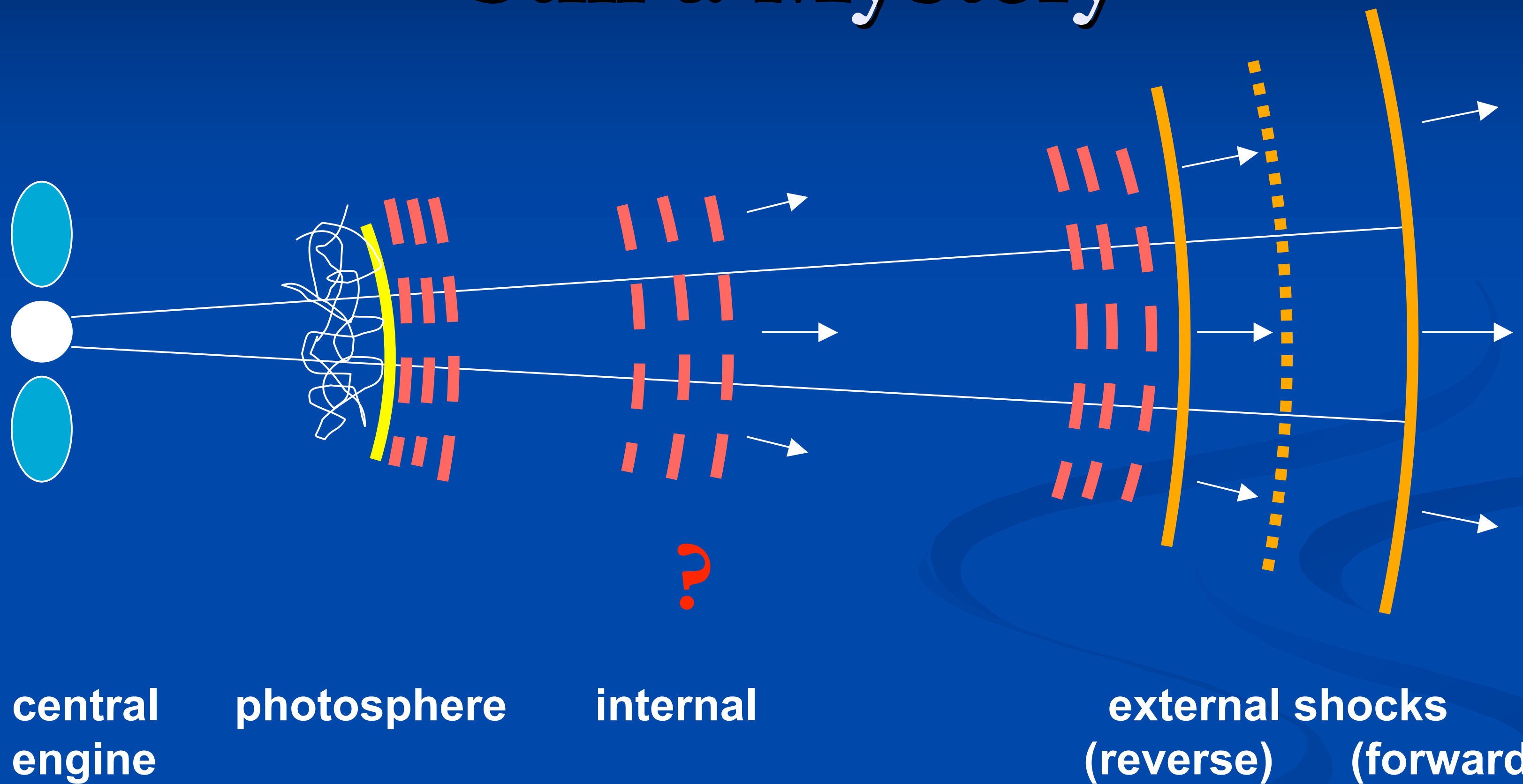
Swift Revolution

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



The so-called "afterglow" is a superposition of external shock and late internal emission powered by late central engine activity!

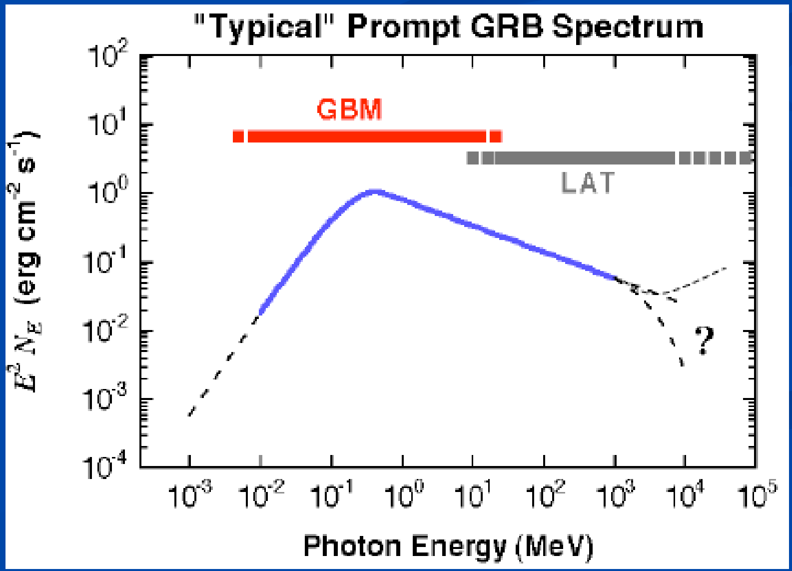
Prompt GRB Emission:
Still a Mystery



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)?

Fermi Revolution:
High energy prompt emission/afterglow

Launched on June 11th, 2008



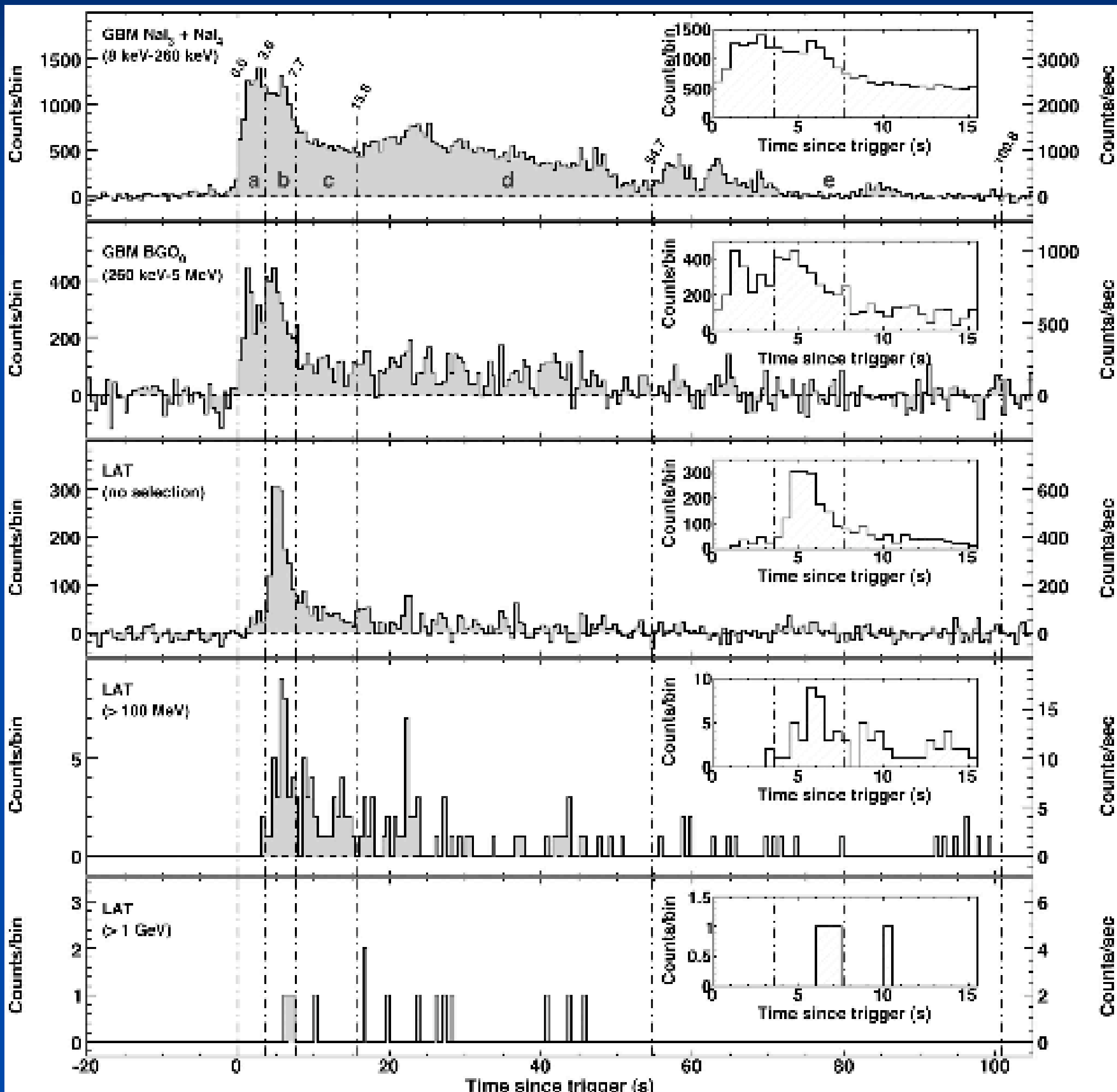
Constrain LIV
Extra spectral component
……

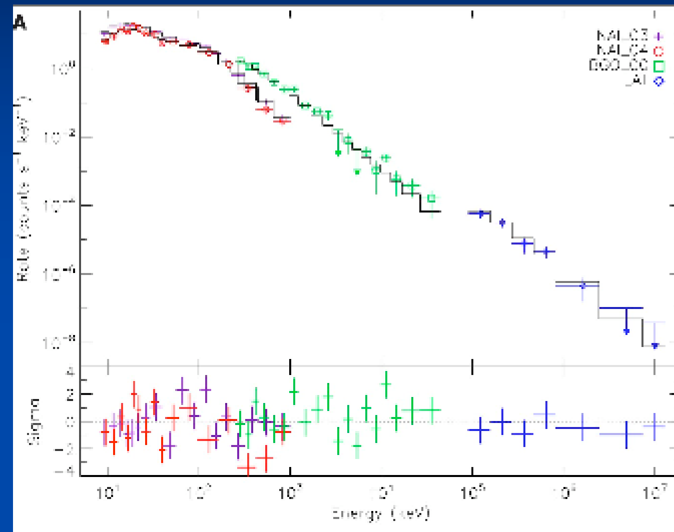
Constrain GRB ejecta composition

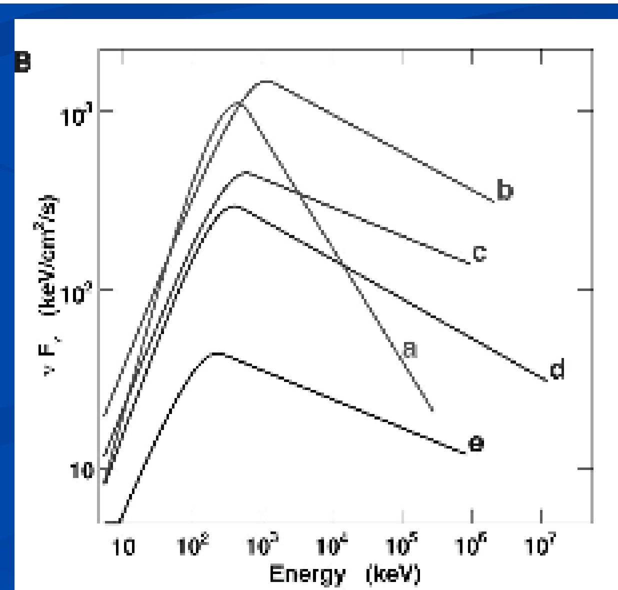
GRB 080916C

(Abdo et al. 2009, Science)

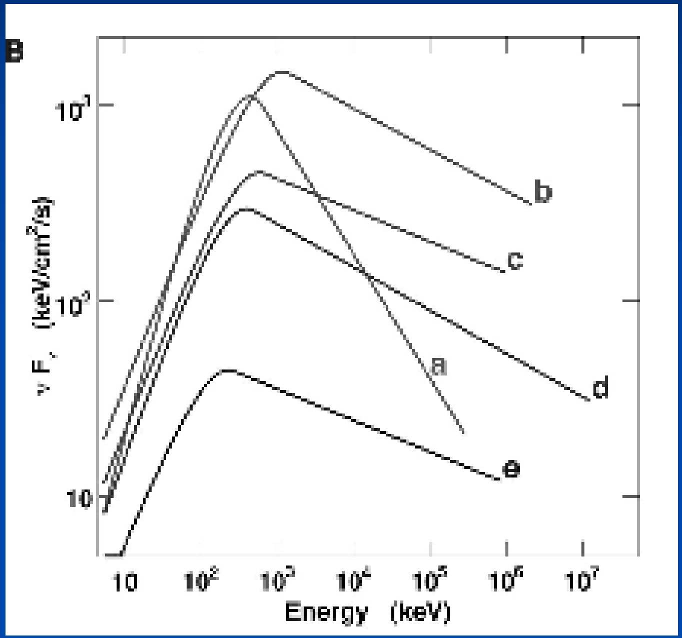
$z = 4.35 \pm 0.15$







What do we learn from GRB 080916C?

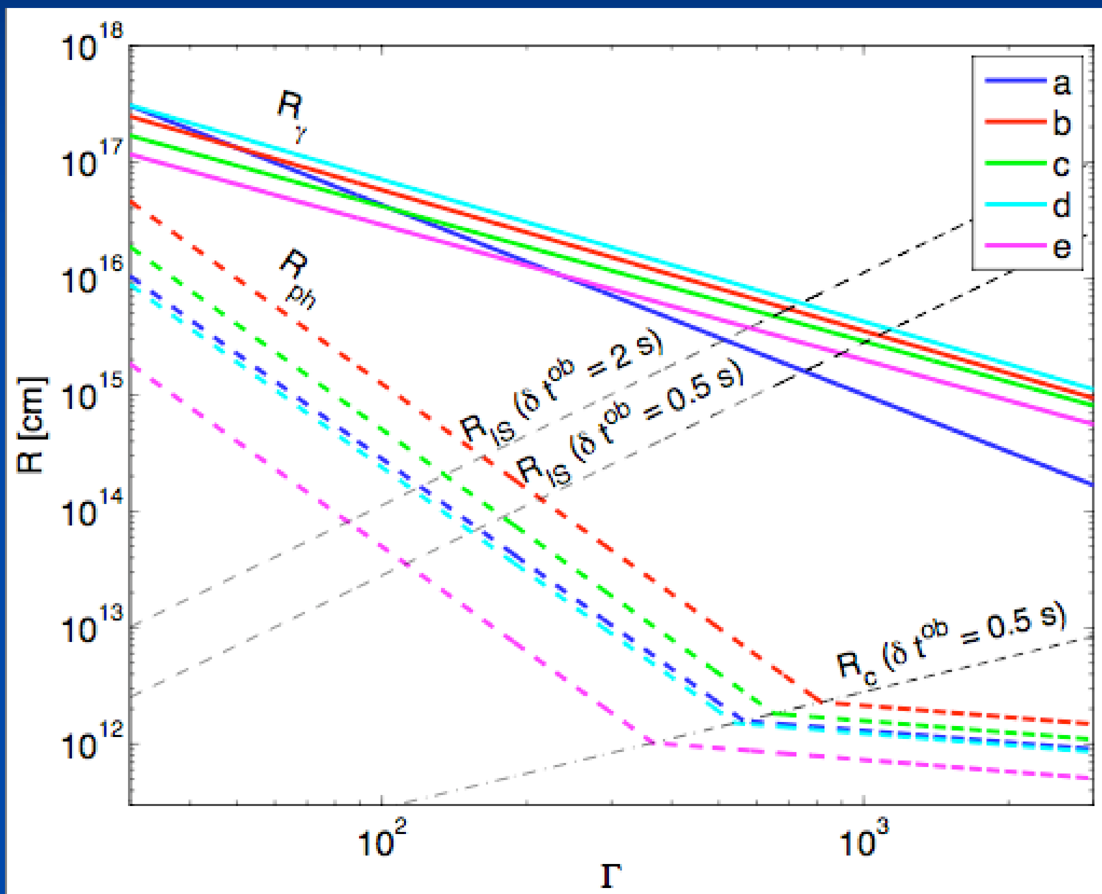


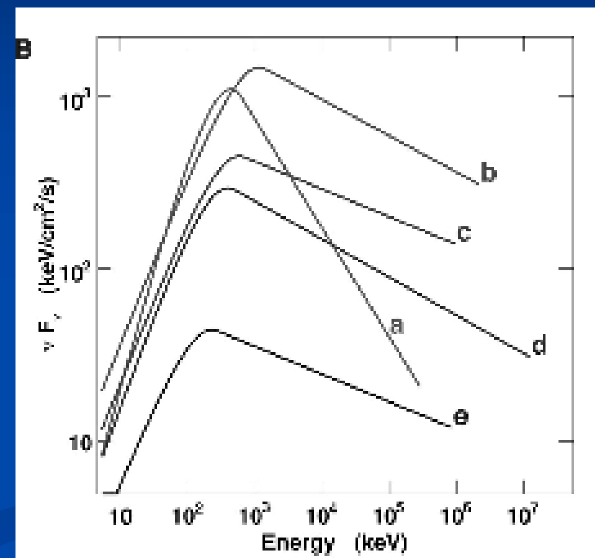
- Featureless Band-function covering 6 orders of magnitude
- Not a surprise? A surprise?
- Three features are missing:
  - No pair cutoff observed
  - No SSC component detected
  - Lack of thermal component

Time bin & Range (s)	A (γ cm^{-2} s^{-1} keV^{-1})	α	β	E_{peak} (keV)	Flux 50-300 keV (γ cm^{-2} s^{-1})	Flux 100 MeV-10 GeV (γ cm^{-2} s^{-1})
a: 0.004 to 3.58	$(55 \pm 2) \times 10^{-3}$	-0.58 ± 0.04	-2.63 ± 0.12	440 ± 27	6.87 ± 0.12	$(2.5 \pm 1.6) \times 10^{-4}$
b: 3.58 to 7.68	$(35 \pm 1) \times 10^{-3}$	-1.02 ± 0.02	-2.21 ± 0.03	1170 ± 140	5.63 ± 0.09	$(4.8 \pm 0.6) \times 10^{-3}$
c: 7.68 to 15.87	$(21 \pm 1) \times 10^{-3}$	-1.02 ± 0.04	-2.16 ± 0.03	590 ± 80	2.98 ± 0.06	$(1.7 \pm 0.2) \times 10^{-3}$
d: 15.87 to 54.78	$(19.4 \pm 0.7) \times 10^{-3}$	-0.92 ± 0.03	-2.22 ± 0.02	400 ± 26	2.44 ± 0.03	$(7.1 \pm 0.9) \times 10^{-4}$
e: 54.78 to 100.86	$(5.2 \pm 0.9) \times 10^{-3}$	-1.05 ± 0.10	-2.16 ± 0.05	230 ± 57	0.54 ± 0.02	$(1.5 \pm 0.4) \times 10^{-4}$

Abdo et al (2009)

Radius constraints
(Zhang & Pe'er 09)





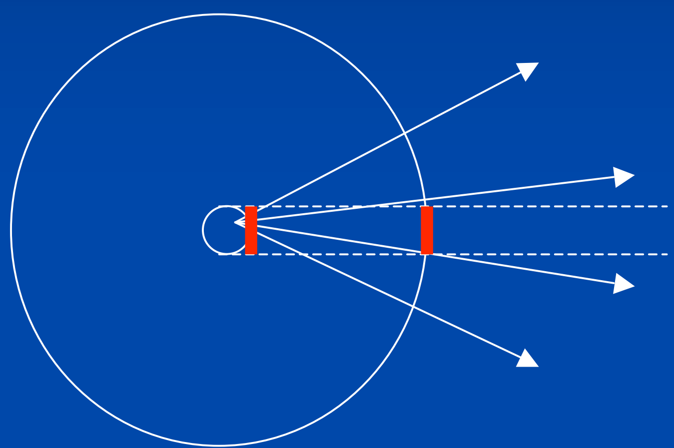
$$\tau_{\gamma\gamma}(E) = \frac{C(\beta)\sigma_T d_z^2 f_0}{-1-\beta}\left(\frac{E}{m_e^2c^4}\right)^{-1-\beta}\frac{1}{R_\gamma^2}\left(\frac{\Gamma}{1+z}\right)^{2+2\beta}$$

$$f_0 = A\cdot\Delta T\left[\frac{E_p(\alpha-\beta)}{(2+\alpha)}\right]^{\alpha-\beta}\exp(\beta-\alpha)(100\ \mathrm{keV})^{-\alpha}$$

Emission must come from a large radius far away from the photosphere.

Expected photosphere emission from a fireball

Meszaros et al. 93
Piran et al. 93



$\Gamma \propto R \quad T' \propto R^{-1}$

$T = \Gamma T' \propto R\,R^{-1} = T_0$

$A \propto R^2 \Gamma^{-2} \propto R^2 R^{-2} = A_0$

$L_{th} \sim L_w > L_\gamma$

$$L_{th} = \begin{cases} L_w, & \eta > \eta_*, \; R_{ph} < R_c, \\ L_w(\eta/\eta_*)^{8/3}, & \eta < \eta_*, \; R_{ph} > R_c. \end{cases}$$

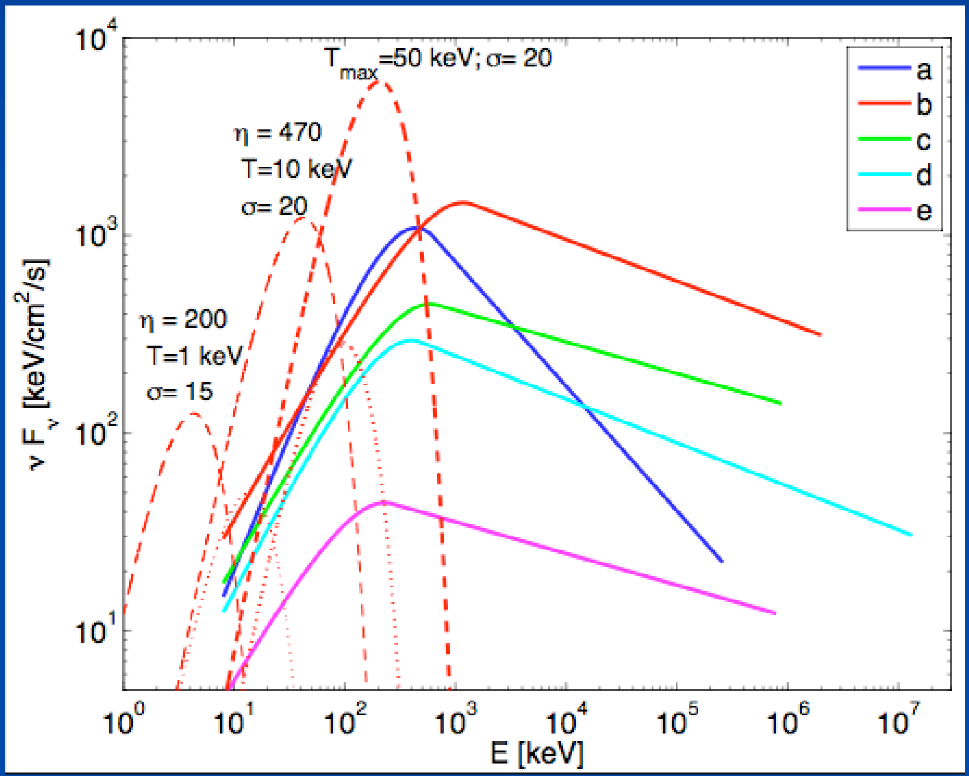
$$\eta_* = (L_w \sigma_T / 8\pi m_p c^3 R_0)^{1/4}$$

Meszaros & Rees (00)

Meszaros, Ramirez-Ruiz, Rees & Zhang (02)

Expected photosphere emission from a fireball

(Zhang & Pe'er 09)



-The thermal residual emission from the fireball is TOO bright to be consistent with the data

- In order to hide the thermal component, a significant amount of ejecta energy is initially not in the thermal form

- **The flow has to be Poynting-flux dominated at the central engine!**

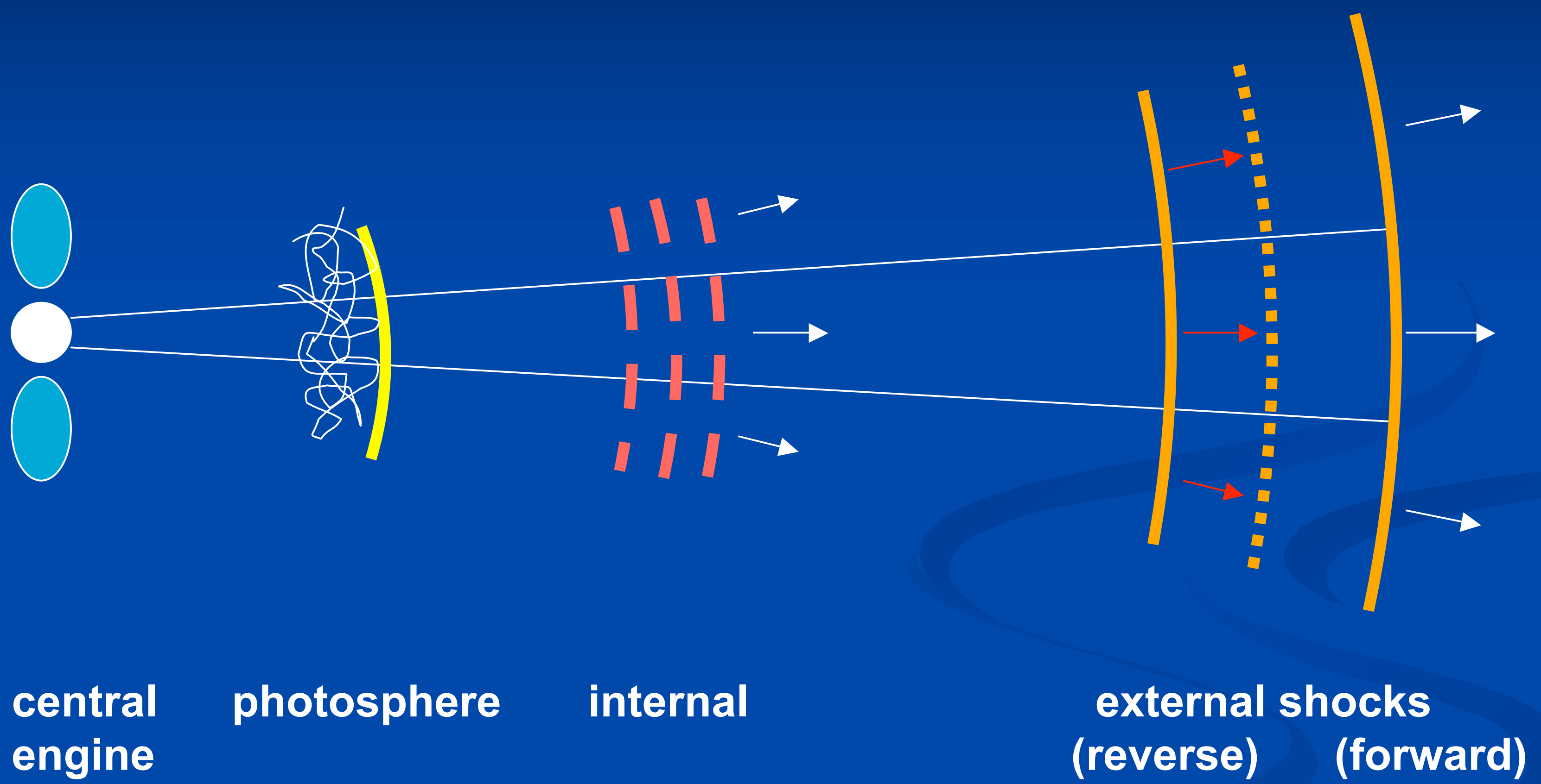
Sigma: ratio between Poynting flux and baryonic flux:
$\sigma = L_P/L_b$

σ At least ~ 20, 15 for GRB 080916C

Kill Three Birds with One Stone

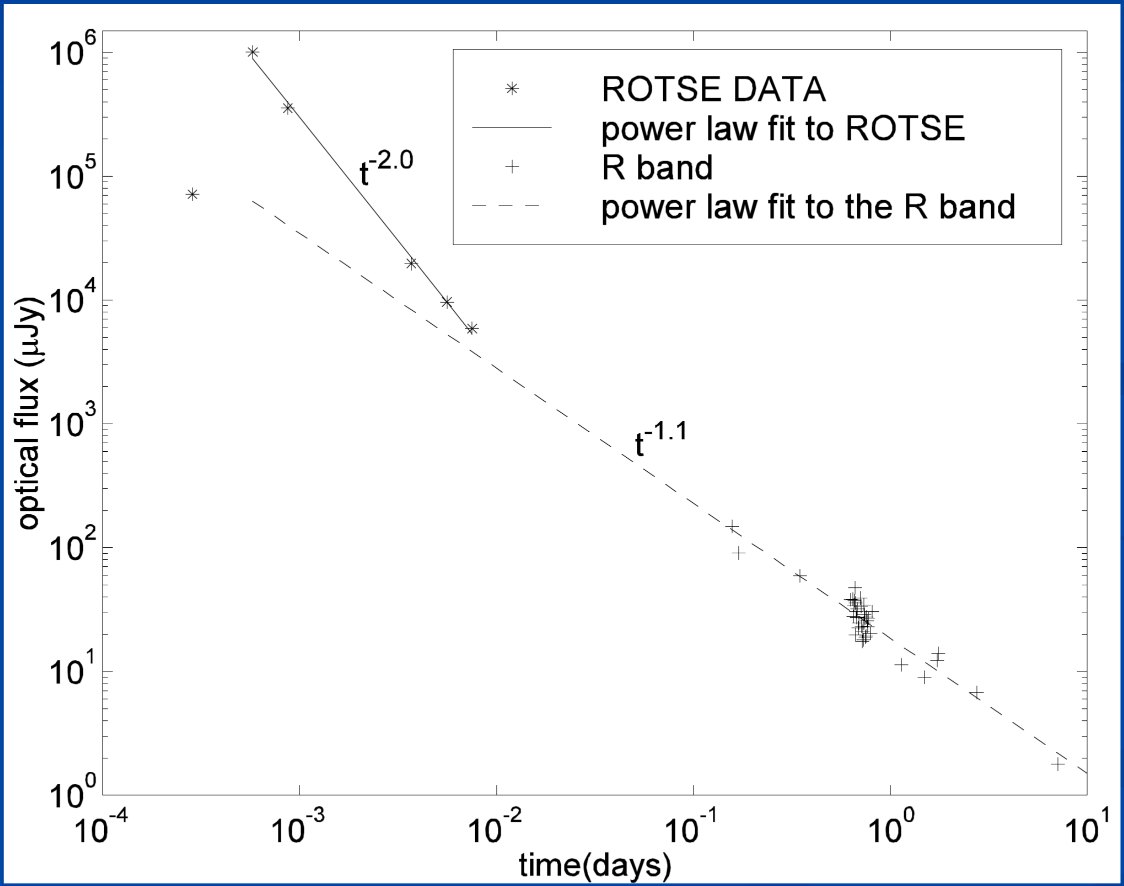
- Invoking a Poynting flux dominated flow can explain the lack of the three expected features
  - Non-detection of the pair cutoff feature is consistent with a large energy dissipation radius
  - Non-detection of the SSC feature is naturally expected, since in a Poynting flux dominated flow, the SSC power is expected to be much less that the synchrotron power
  - Non-detection of the photosphere thermal component is consistent with the picture, since most energy can be retained in the form of Poynting flux energy rather than thermal energy

Magnetized Reverse Shock?



GRB 990123

(Akerlof et al. 1999)



Reverse shock interpretation:
Meszaros & Rees (97, 99)
Sari & Piran (99a, 99b)

Magnetized reverse shock:

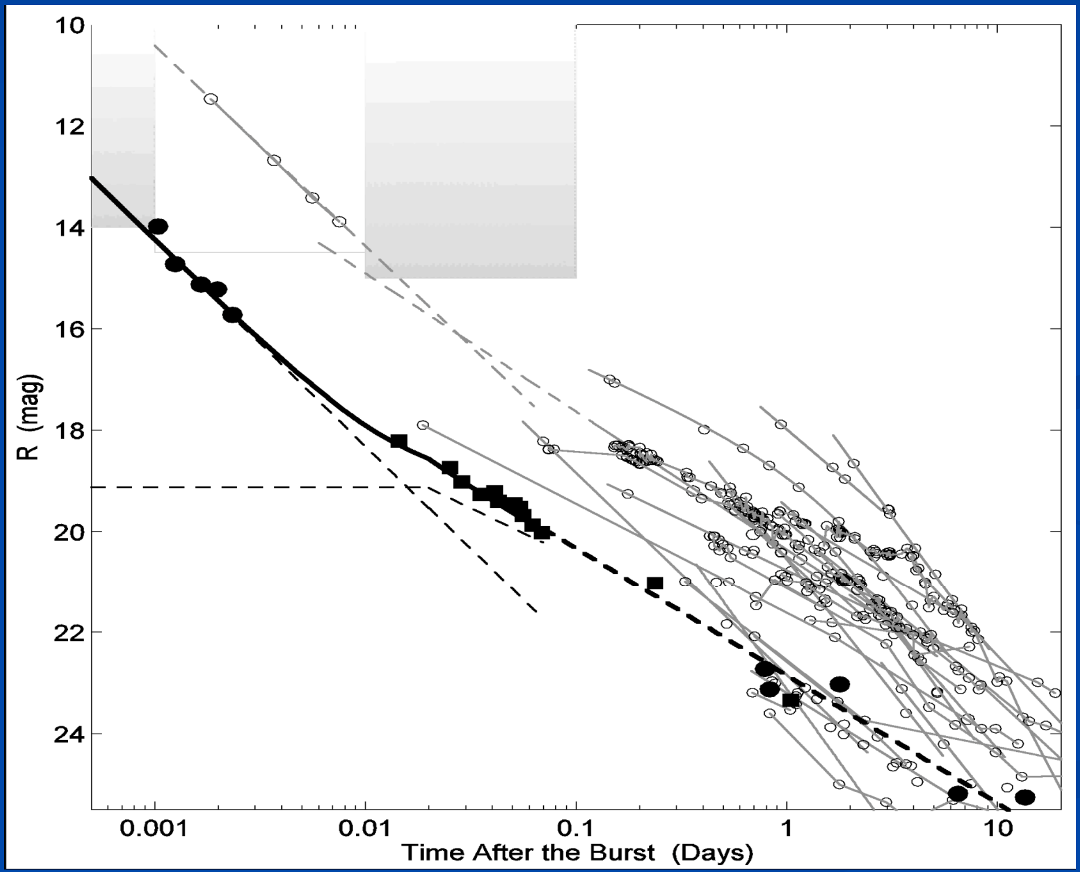
Zhang, Kobayashi & Meszaros, 2003

Fan et al. 2002

$$R_B = B_r / B_f \sim 15$$

GRB 021211

(Fox et al. 2003; Li et al. 2003)



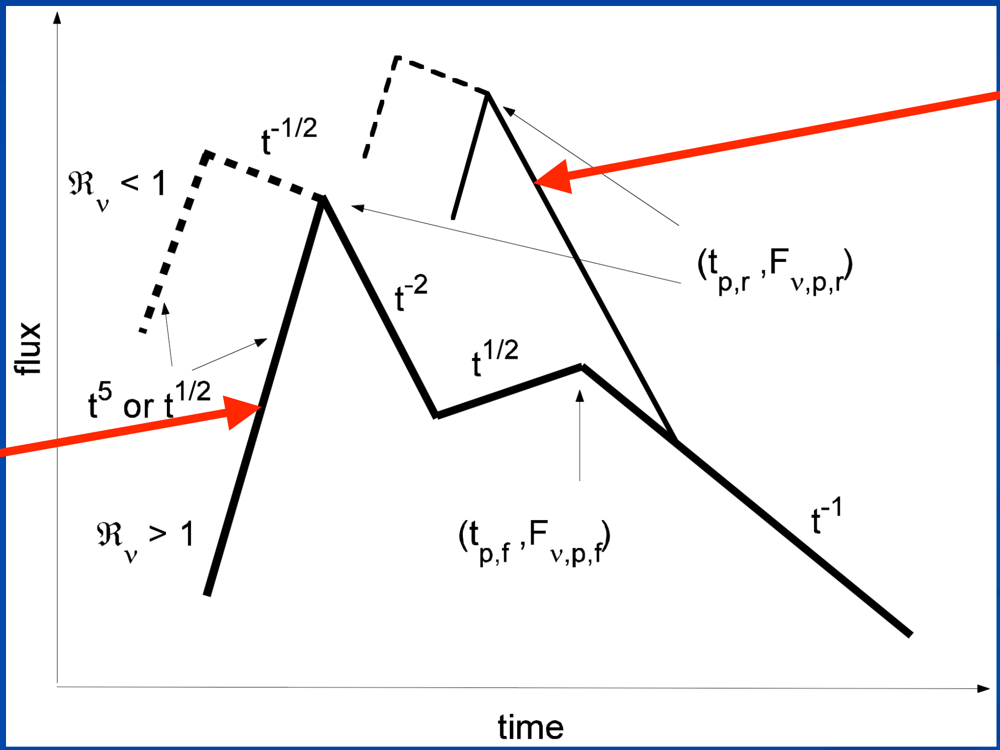
$R_B = B_r / B_f >> 1$

Zhang, Kobayashi & Meszaros, 2003

Kumar & Panaitescu 2003

In general:
early optical afterglow lightcurves

(Zhang, Kobayashi & Meszaros 2003)



If the reverse shock region has a similar magnetization factor as the forward shock region

Requires a more magnetized ejecta (but not Poynting flux dominated)

Should be linearly polarized!

Verified recently in GRB 090102

(10±1)%

Steele et al. Nature, submitted

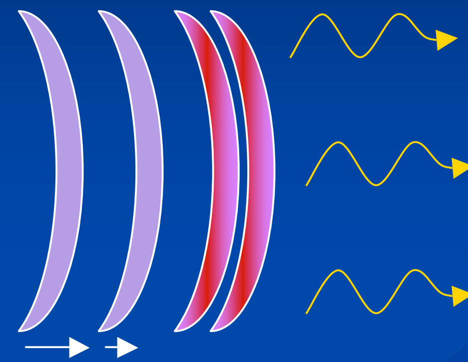
Which model best describes GRB prompt emission?

Three prompt emission models discussed in the literature

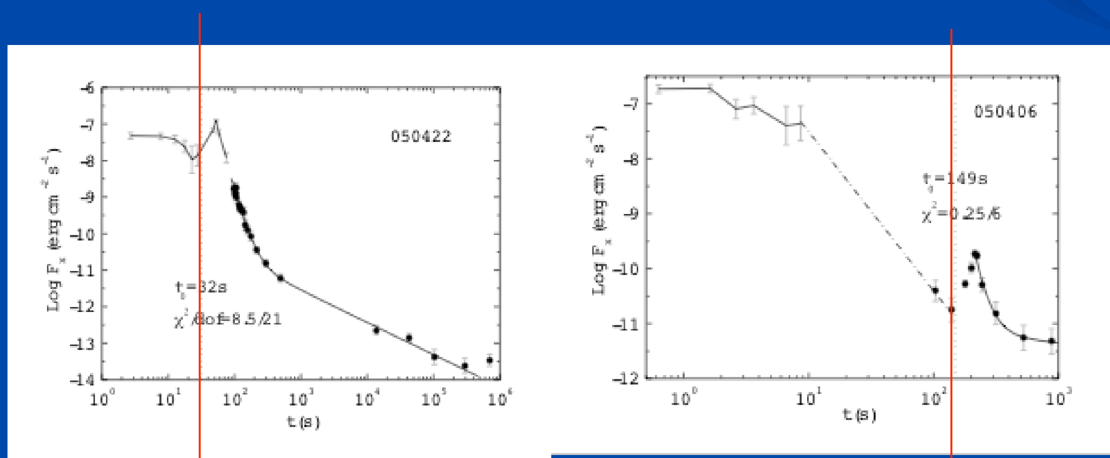
- Low σ:
  - internal shock model:
  - $\sigma << 1$
- Extremely high σ:
  - electromagnetic model
  - $\sigma > \Gamma^2 - 1 \sim 10^5 - 10^6$
- Intermediate σ: MHD model
  - $\sigma > 1$ at the central engine
  - $\sigma \leq 1$ in the emission region

Internal Shock Model: Pros

- Advantages:
  - Naturally expected in an unsteady outflow
  - Variability related to that of the central engine
  - Supported by X-ray flare data



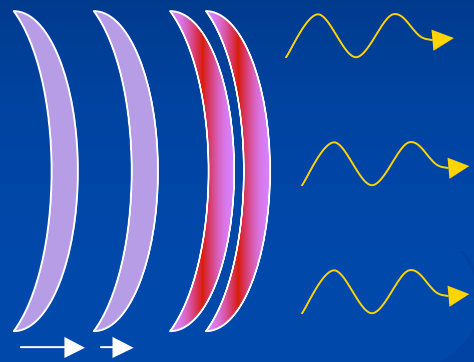
Rees & Meszaros
Paczynski & Xu
Kobayashi, Piran & Sari
Daigne & Mochkovitch
Panaitescu, Spada, Meszaros
……



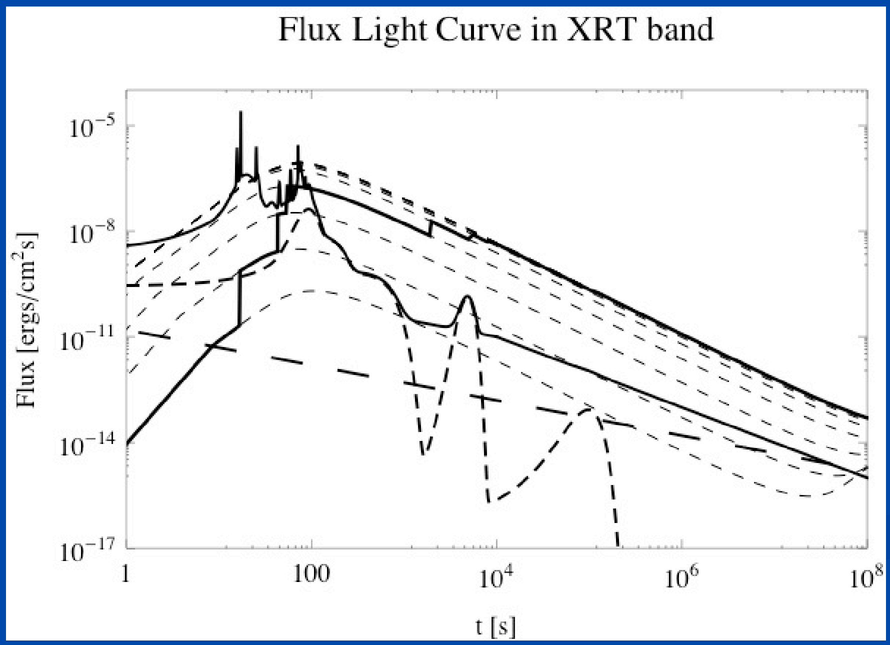
Liang et al. 2006

IS model: Cons (1)

- The low efficiency problem
  - Theory: ~1-10%
  - Data: up to 90% (e.g. Zhang et al. 2007)



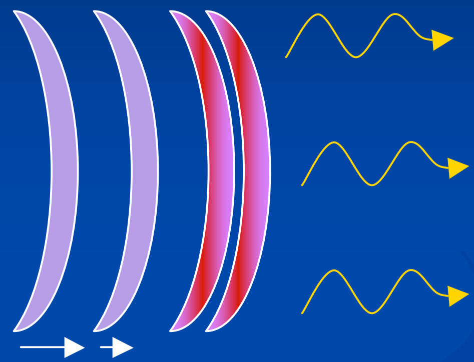
Kumar 1999
Panaitescu, Spada, Meszaros 1999
Beloborodov 2000
Kobayashi & Sari 2001
Guetta et al. 2001



Maxham & Zhang (2009)

IS model: Cons (2)

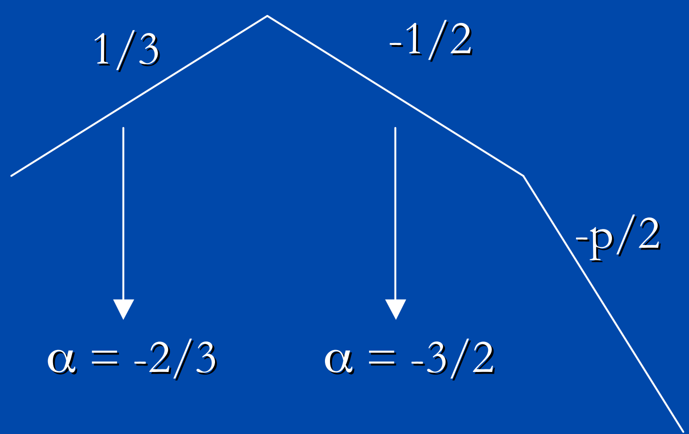
- Missing electron problem
  - In order to get the right E_p, only a small fraction (~1%) of electrons are accelerated
  - In order to correctly derive internal shock synchrotron self-absorption frequency, only a small fraction of electrons are accelerated and contribute to the observed gamma-ray emission

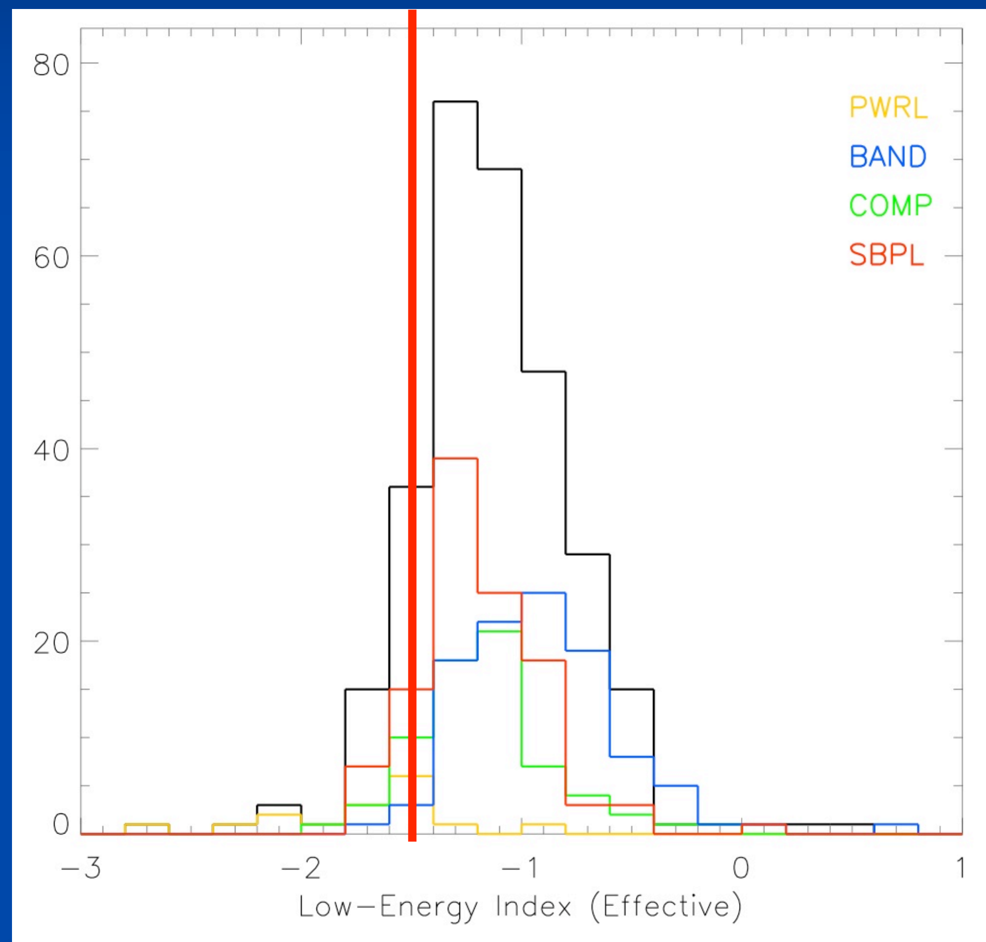


Daigne & Mochkovitch 1998
Shen & Zhang 2009

IS Model: Cons (3)

- Fast cooling problem:
  - Theory: $\alpha = -3/2$
  - Data: average $\alpha = -1$





Ghisellini et al. (00)

Possible solutions:

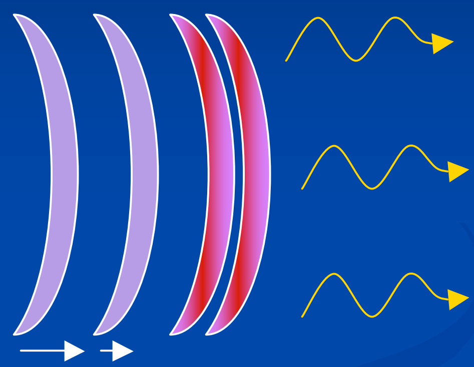
Medevedev (00)

Pe'er & Zhang (06)

Asano & Terasawa (09)

IS model: Cons (4)

- Amati/Yonetoku relation problem:
  - Synchrotron model:
    $E_p \sim \Gamma \gamma_e^2 B' \sim L^{1/2} R^{-1} \sim L^{1/2} \Gamma^{-2} \delta t^{-1}$
  - Requirement: R ~ const for GRBs with different L
  - Model predicts a wide range of R

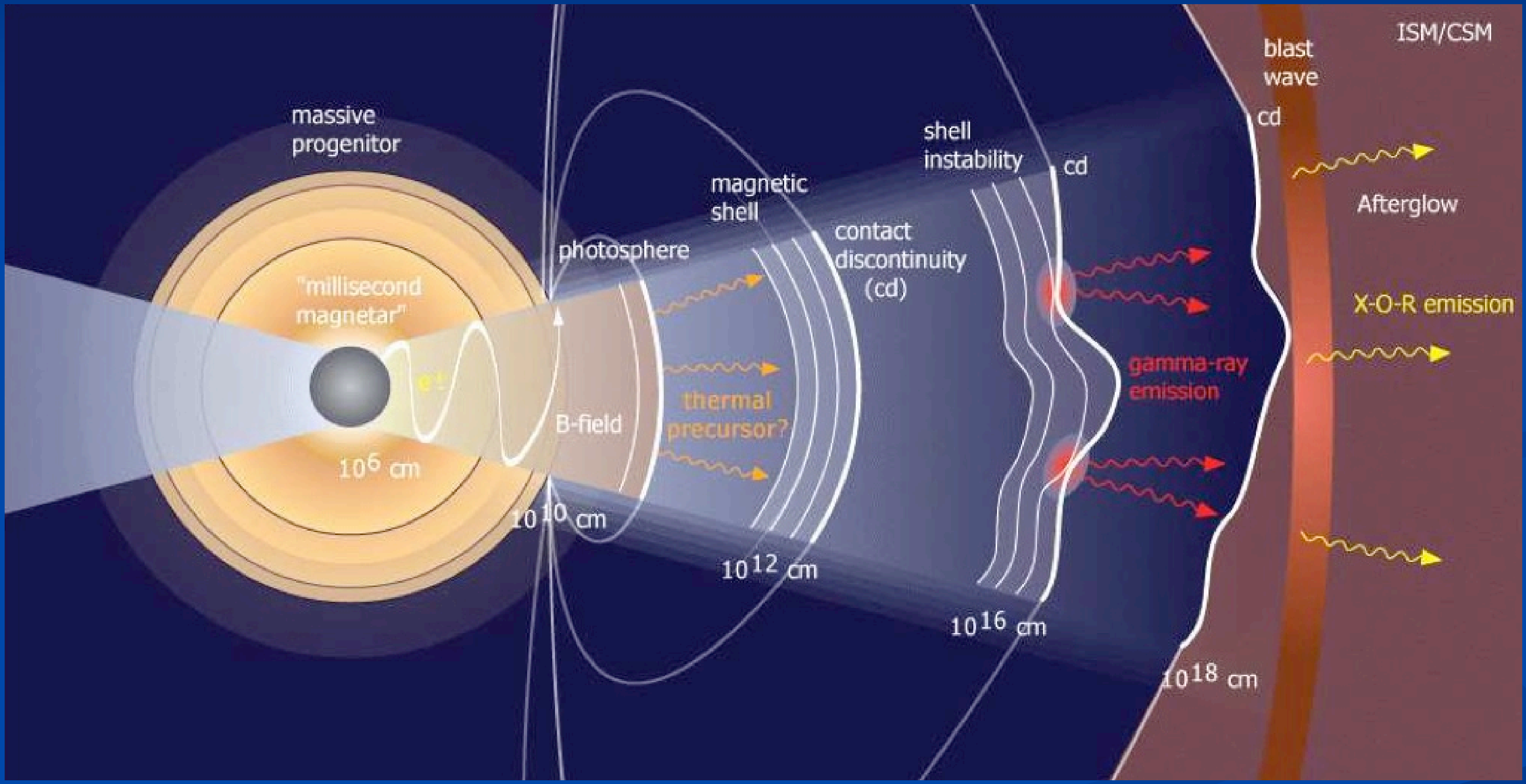


Daigne's talk

IS model: Cons (5)

- Missing photosphere problem (this talk)

Electro-Magnetic (EM) model



Lyutikov & Blandford (2003)

EM model: Pros & Cons

- Pros:
  - High efficiency
  - Weak photosphere
  - Large emission radius (current instability): consistent with several observational constraints
- Cons:
  - Variability is not related to central engine activity
  - Too high σ ($>10^5$-10^6): is it achievable?

MHD models: Pros & Cons

- Quasi-fireball
  - High σ at the central engine
  - Low σ in the emission region
- Share the same pros & Cons of the internal shock model

A New Scenario: Internal Collision-induced MAgnetic Reconnection & Turbulence (ICMART) Model

Zhang & Yan (2009, in preparation)

- Central engine ejecta moderately high-σ shells (several or several 10s)
- Internal inhomogeneity induced collisions (like internal shock model)
- If relative Lorentz factor $\Gamma_{rel} < (1+\sigma)^{1/2}$, no internal shocks, little dissipation (elastic collisions?)
- If relative Lorentz factor $\Gamma_{rel} > (1+\sigma)^{1/2}$, shock may induce turbulence, which may enhance reconnection, leading to a runaway release of magnetic energy. This is the GRB.
- The dissipation process stops when σ drops to around unity. The ejecta is still magnetized, which is consistent with the early optical polarization detection in GRB 090102 (Steele et al.)

Merits of the ICMART model

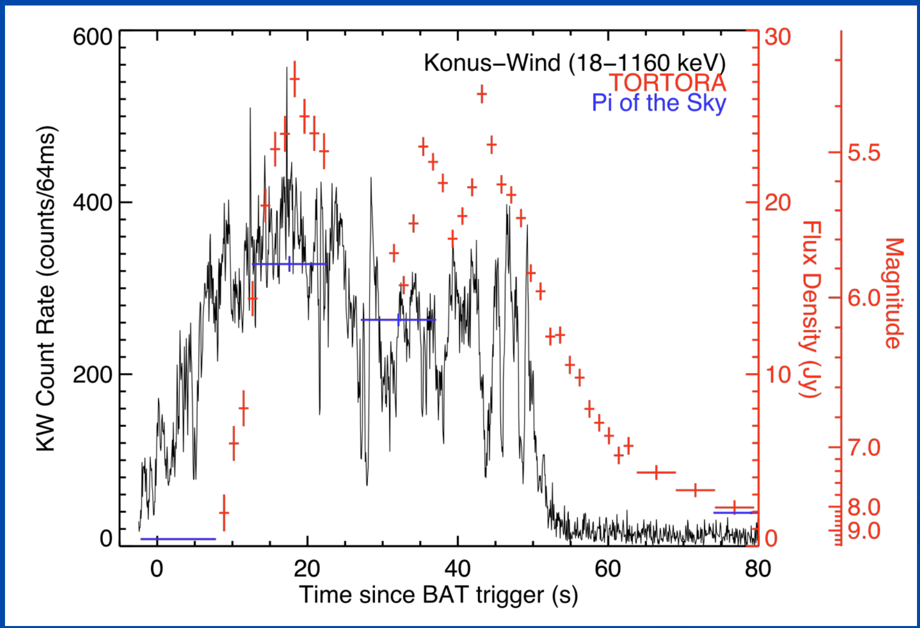
Zhang & Yan (2009, in preparation)

- Carries the merits of the internal shock model (variability related to central engine)
- Overcomes the difficulties of the internal shock model (carries the merits of the EM model)
  - High efficiency ~ 50%
  - Electron number problem naturally solved (electron number is intrinsically small)
  - Turbulent heating may overcome fast cooling problem
  - Amati relation more naturally interpreted (larger R, smaller σ, easier to have reconnection "avalanche")
  - No missing photosphere problem

New feature of the ICMART model

Zhang & Yan (2009, in preparation)

- Two variability components:
  - A slow component related to the central engine
  - A fast component related to turbulence (Nayaran & Kumar 08)



Consistent with data:

Shen & Song (03)
Vetere et al. (06)
Marguitti et al. (09)

Particle Acceleration in GRBs Summary (I):

- A relativistic forward shock plowing into the circumburst medium is believed to be responsible for the power-law decaying afterglow
  - Power law distribution of electrons
  - Non-uniform electron power law index p
  - Non-uniform ε_e and ε_B. Likely $\varepsilon_e > \varepsilon_B$

Seems to be "partially" reproduced by numerical simulations (Nishikawa, Spitkovsky …)

Issues: electron-ion plasma, large density contrast, high Lorentz factor

Particle Acceleration in GRBs Summary (II):

- At least some GRBs (e.g. GRB 090102) display a magnetized (polarized) reverse shock component
  - One probably needs to allow particle acceleration in moderately magnetized shocks (cf. Sironi & Spitkovsky)
  - Maybe 1st order Fermi acceleration allowed in the trans-relativistic regime? Maybe 2nd order stochastic acceleration in downstream turbulence?

Particle Acceleration in GRBs Summary (III):

- At least some GRBs (e.g. GRB 080916C) show strong evidence of a non-baryonic composition in the outflow. The outflow is likely Poynting flux dominated
  - One probably needs to accelerate particles without shocks
  - Reconnection & Turbulence? Can turbulence develop in the high-Γ, high-σ regime?
  - MHD simulation in the high-Γ, high-σ regime is called for (to observe turbulence development)
  - PIC simulation in the high-Γ, high-σ regime is called for (to observe reconnection & particle acceleration)

Many questions for numerical simulations to address!