Constraining GRB jet composition using Fermi data

Bing Zhang

Department of Physics and Astronomy

University of Nevada, Las Vegas

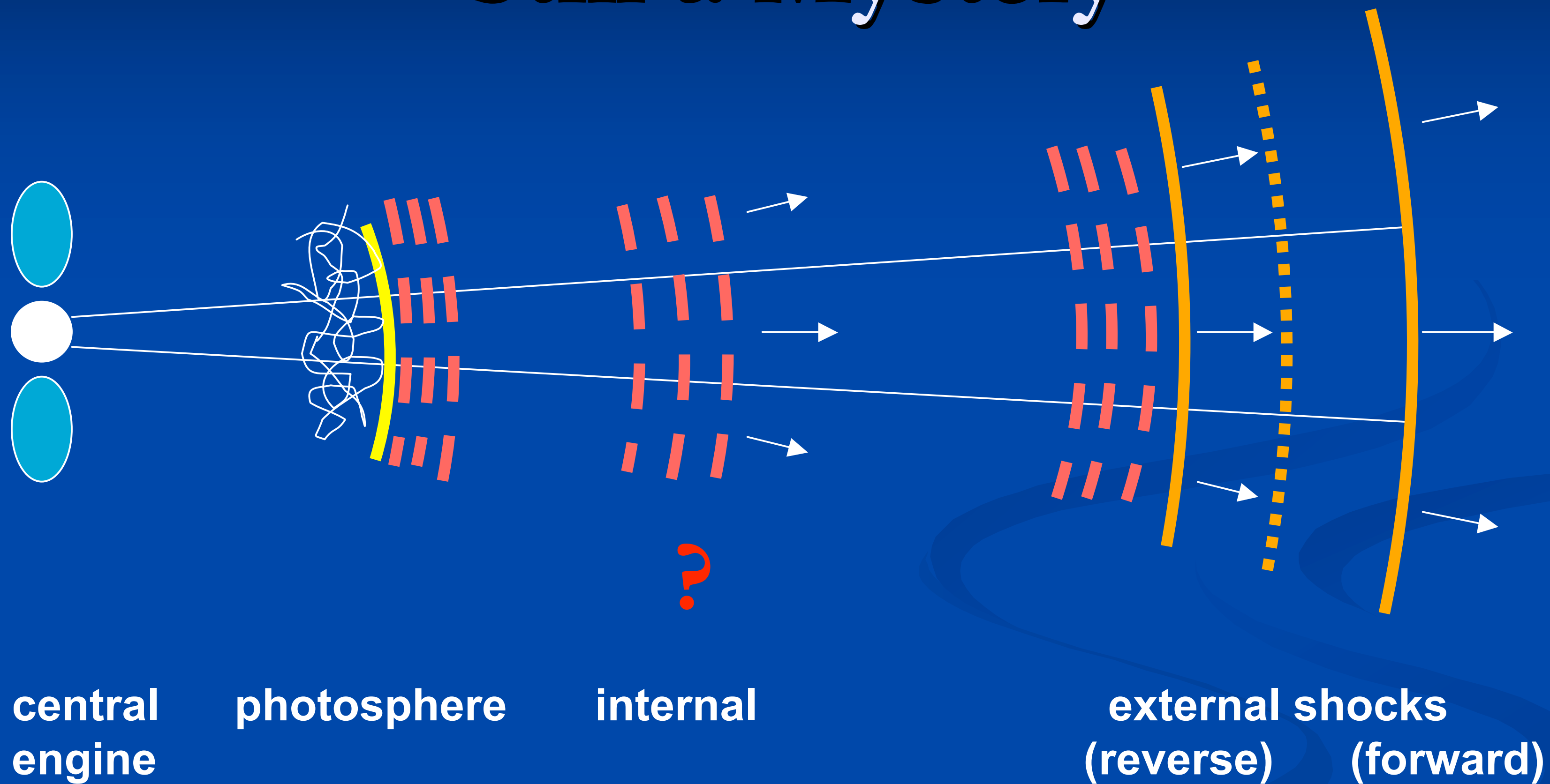
Collaborators:

Asaf Pe'er (STScI), Huirong Yan (Univ. Arizona), Bin-Bin Zhang (UNLV)

Nov. 4, 2009

2009 Fermi Symposium, Hyatt Regency Washington, Capitol Hill

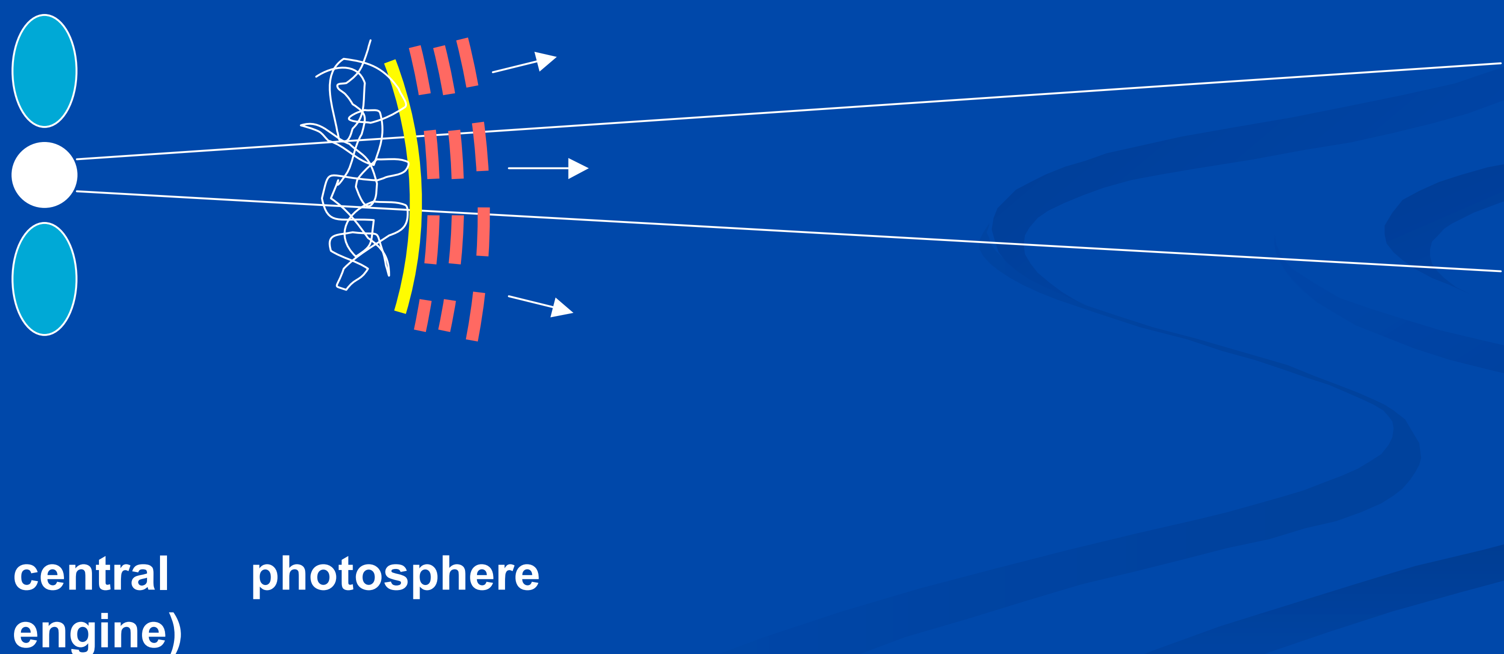
Prompt GRB Emission: Still a Mystery



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)?

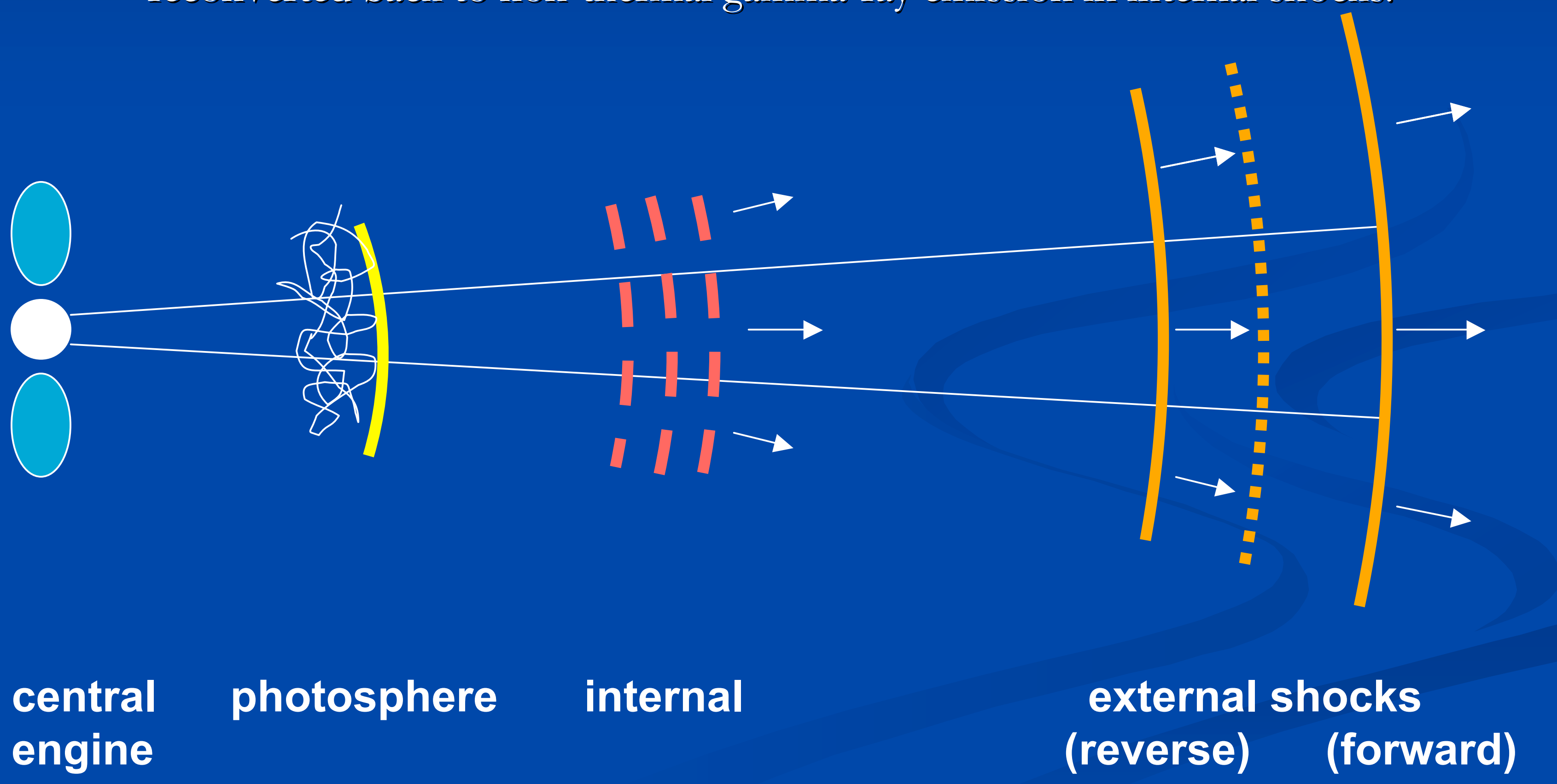
Historical Remark (1)

- Paczynski (86) & Goodman (86): a fireball of photons, electron-positron pairs expands freely. When it becomes optically-thin → gamma-ray burst, but a blackbody, not Band spectrum!
- Shemi & Piran (90): add some baryons, energy is converted to kinetic energy



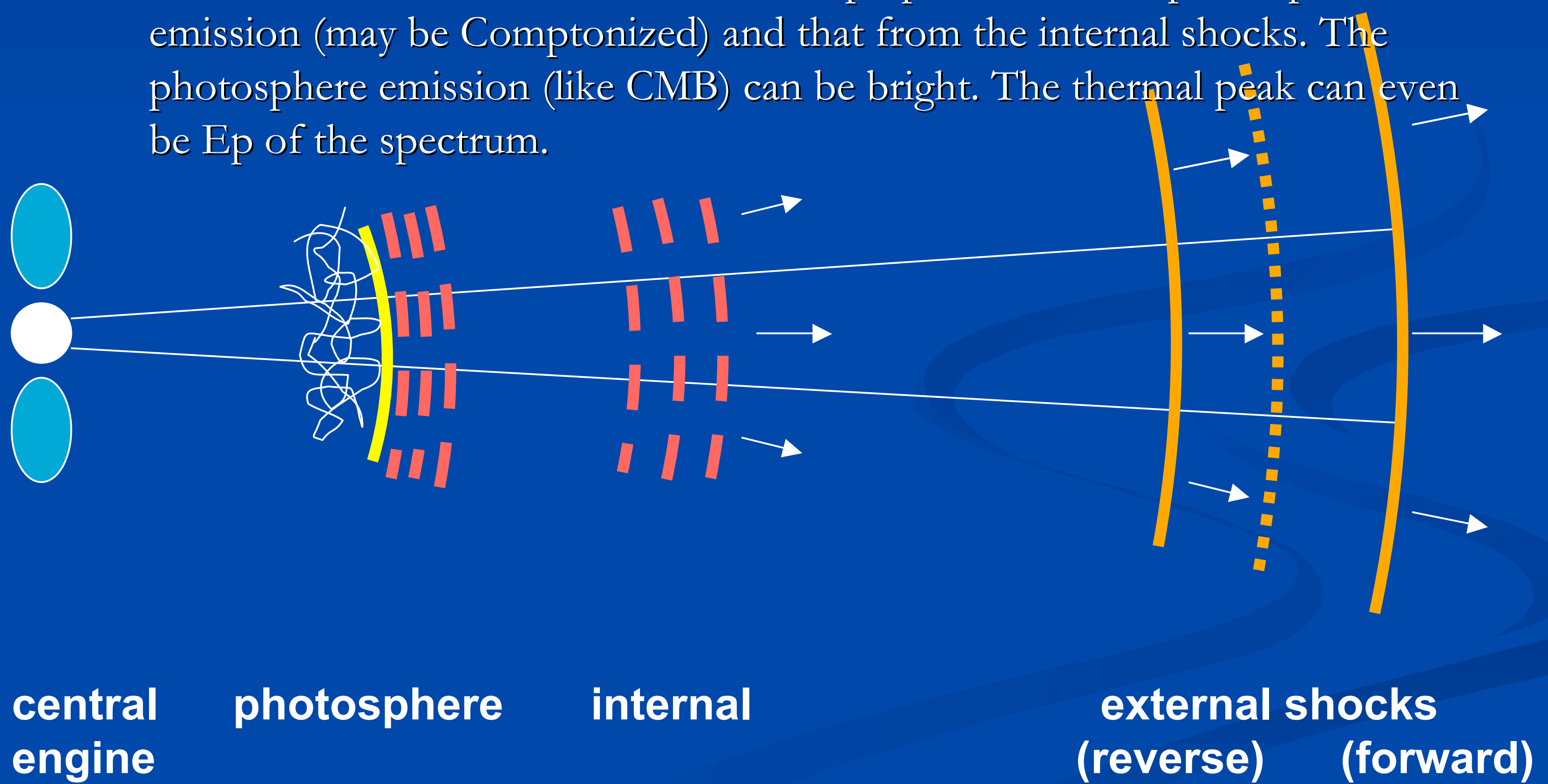
Historical Remark (2)

- Rees & Meszaros (92), Meszaros & Rees (93): the kinetic energy is reconverted back to non-thermal gamma-ray emission in external shock.
- Rees & Meszaros (94), Paczynski & Xu (94): the kinetic energy is reconverted back to non-thermal gamma-ray emission in internal shocks.

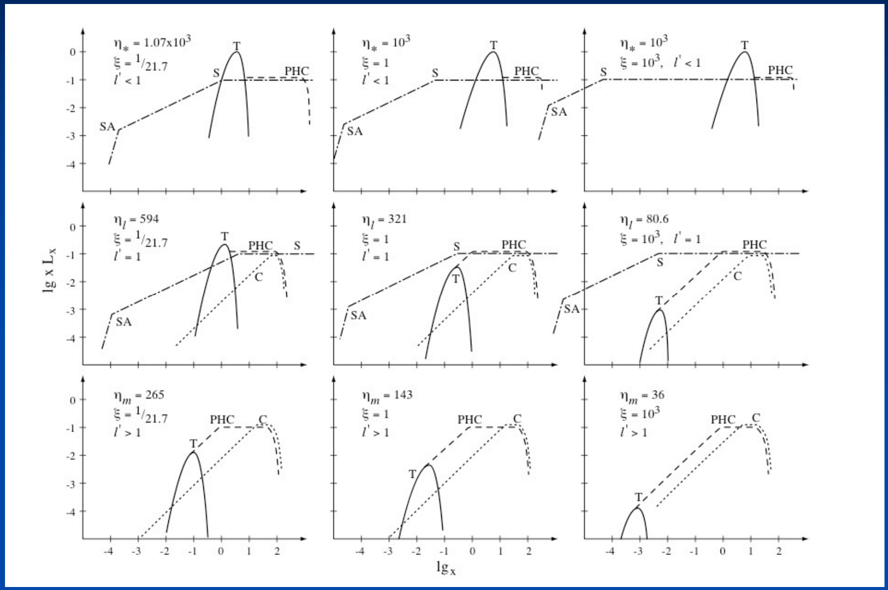


Historical Remark (3)

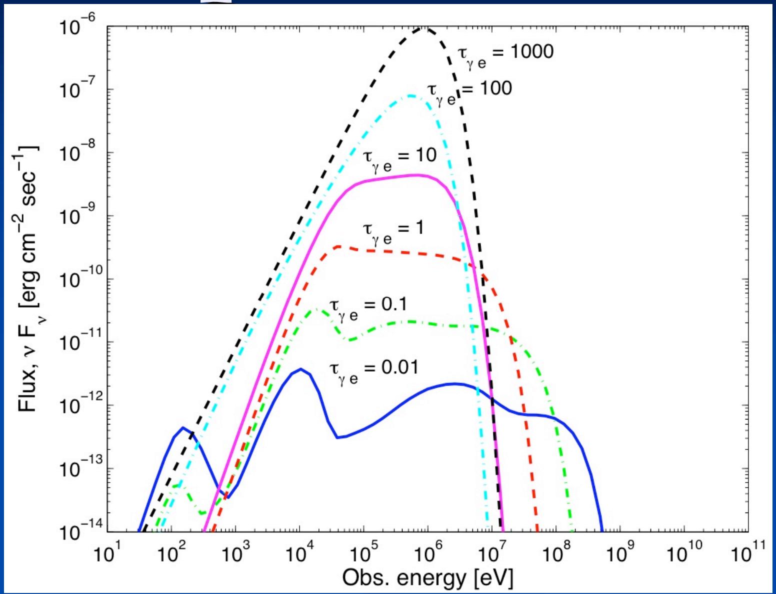
- Meszaros & Rees (00), Meszaros et al. (02), Daigne & Mochkovitch (02), Zhang & Meszaros (02), Rees & Meszaros (05), Pe'er et al. (06), Thompson et al. (07), Ioka et al. (07), Pe'er (08):
the observed GRB emission could be superposition of the photosphere emission (may be Comptonized) and that from the internal shocks. The photosphere emission (like CMB) can be bright. The thermal peak can even be Ep of the spectrum.



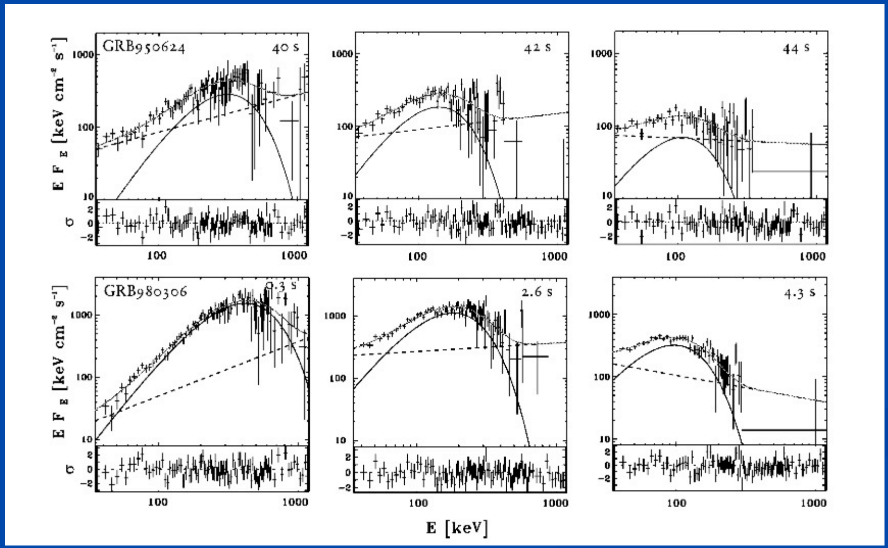
Superposition spectra?



Meszaros & Rees (00)



Pe'er, Meszaros, Rees (06)

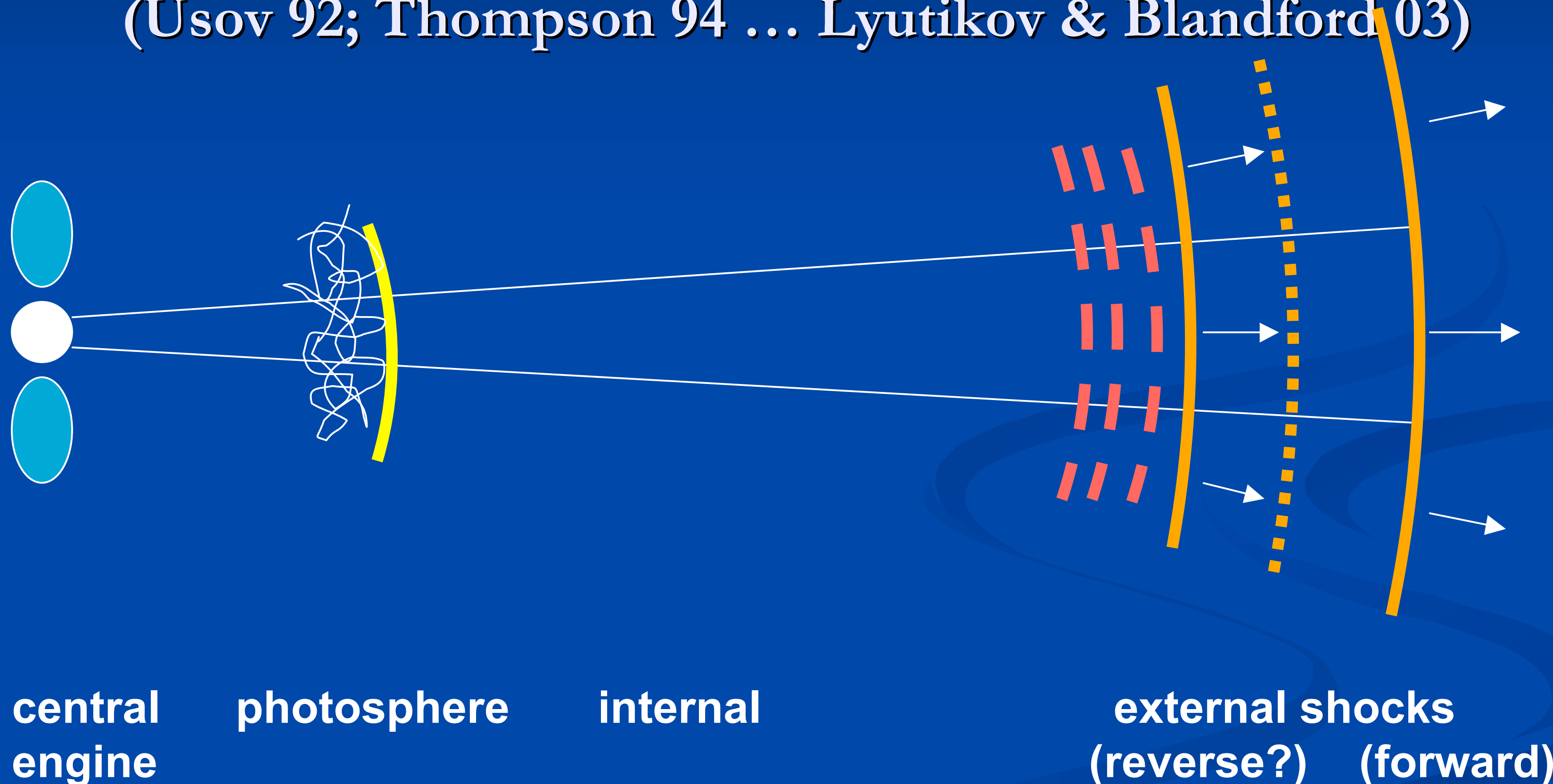


Ryde 05

Alternative view:

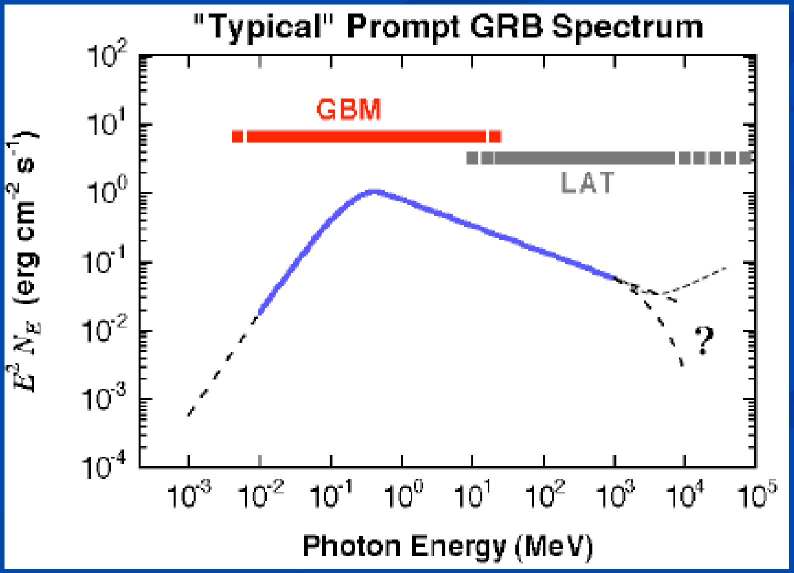
Magnetic dissipation in a Poynting-flux dominated flow

(Usov 92; Thompson 94 … Lyutikov & Blandford 03)



Fermi Revolution:
High energy prompt emission/afterglow

Launched on June 11th, 2008



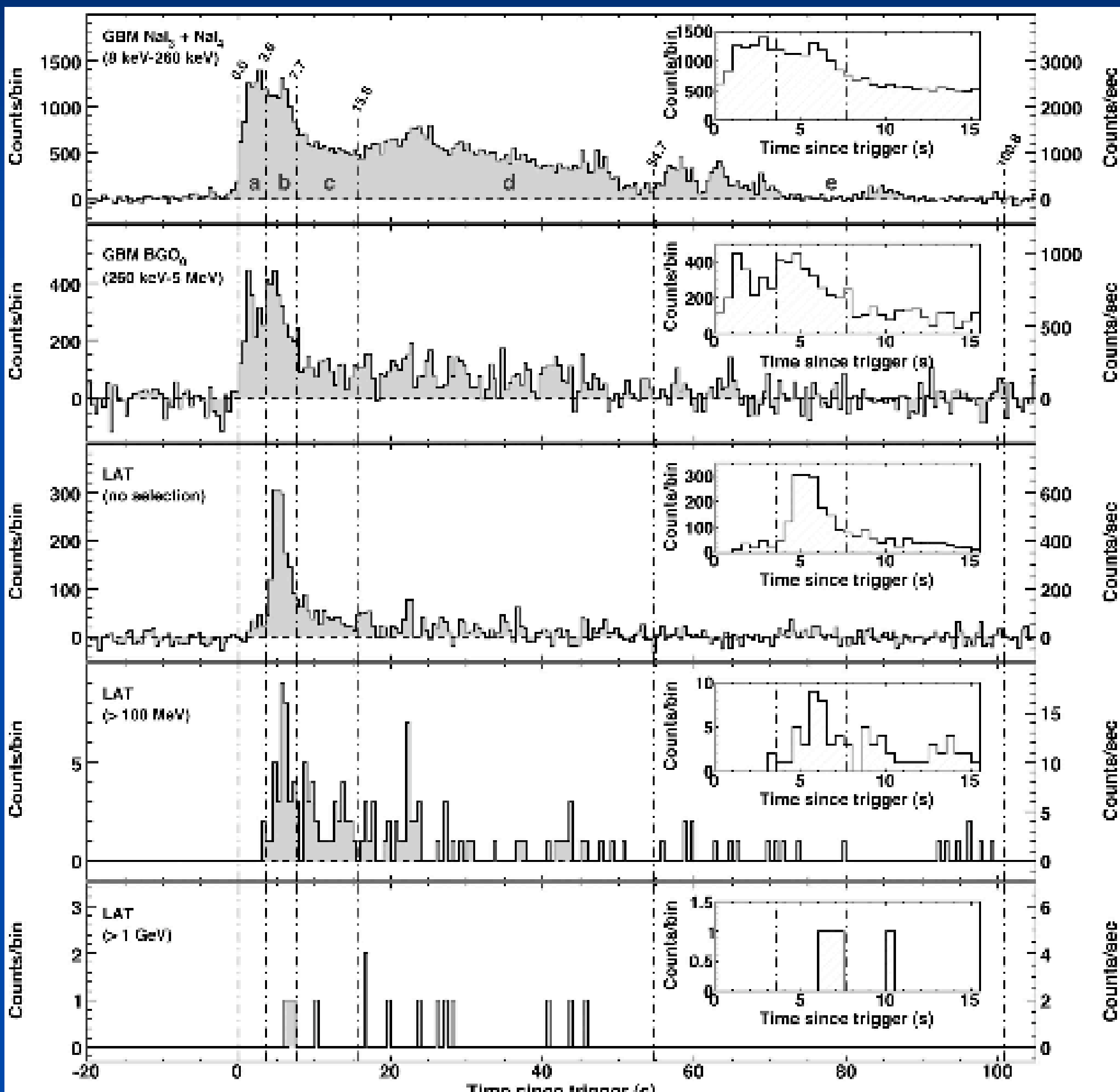
Constrain LIV
Extra spectral component
Minimum Γ??
……

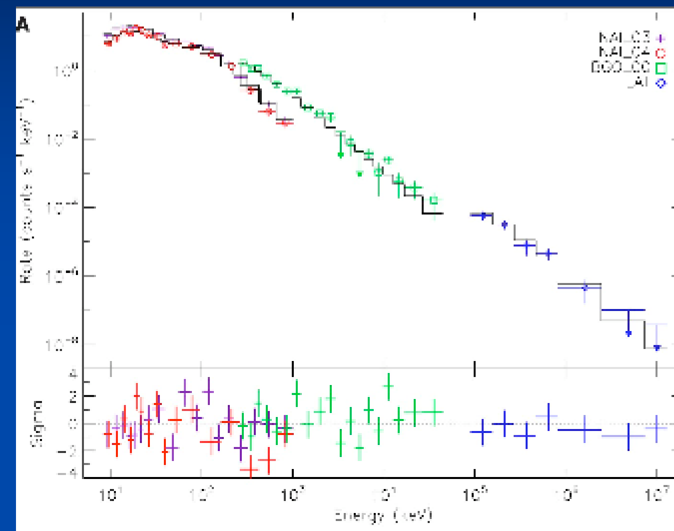
Constrain GRB ejecta composition

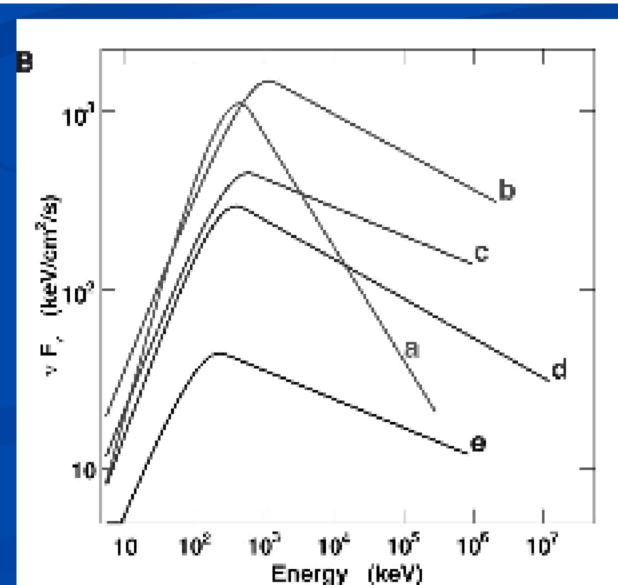
GRB 080916C

(Abdo et al. 2009, Science)

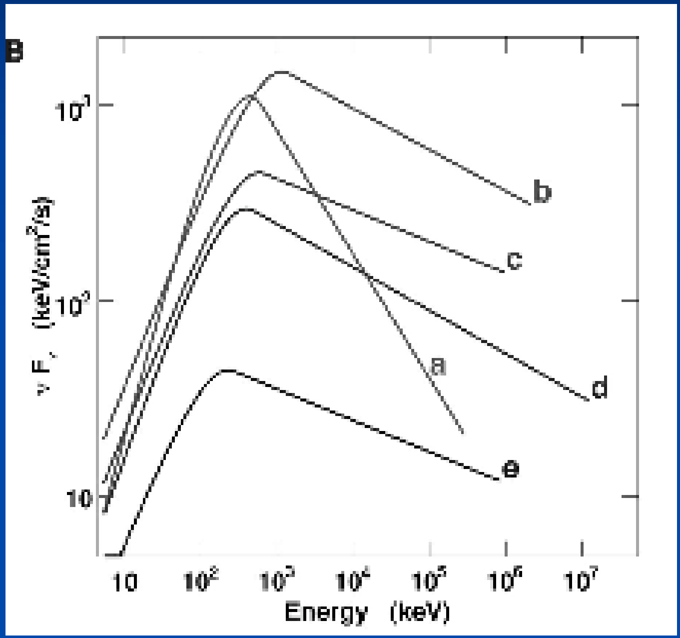
$z = 4.35 \pm 0.15$







What do we learn from GRB 080916C?



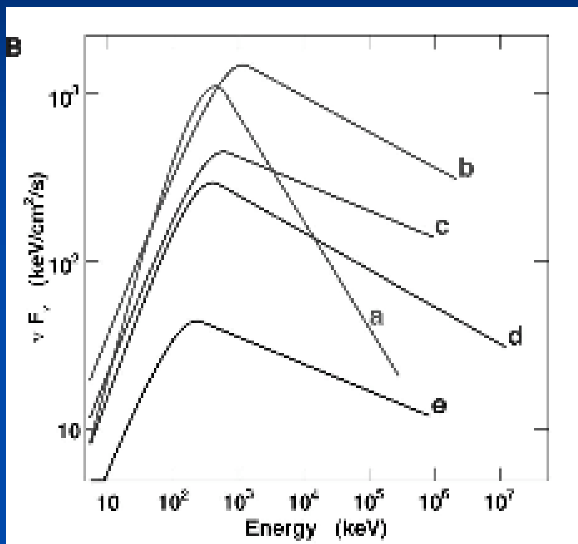
- Featureless Band-function covering 6 orders of magnitude
- Not a surprise? A surprise?
- Three features are missing:
  - No pair cutoff observed
  - No SSC component detected
  - Lack of thermal component

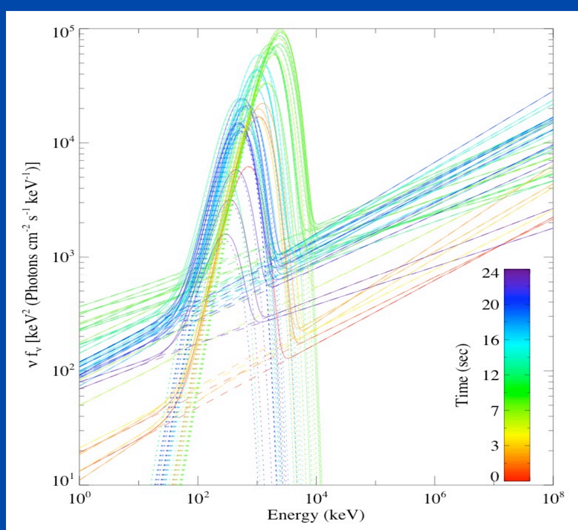
Time bin & Range (s)	A (γ cm^{-2} s^{-1} keV^{-1})	α	β	E_{peak} (keV)	Flux 50-300 keV (γ cm^{-2} s^{-1})	Flux 100 MeV-10 GeV (γ cm^{-2} s^{-1})
a: 0.004 to 3.58	$(55 \pm 2) \times 10^{-3}$	-0.58 ± 0.04	-2.63 ± 0.12	440 ± 27	6.87 ± 0.12	$(2.5 \pm 1.6) \times 10^{-4}$
b: 3.58 to 7.68	$(35 \pm 1) \times 10^{-3}$	-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	$(1.5 \pm 0.4) \times 10^{-4}$

But see Kumar & Barniol Duran (2009); Beloborodov (2009)

Abdo et al (2009)

A few comments on estimating Γ

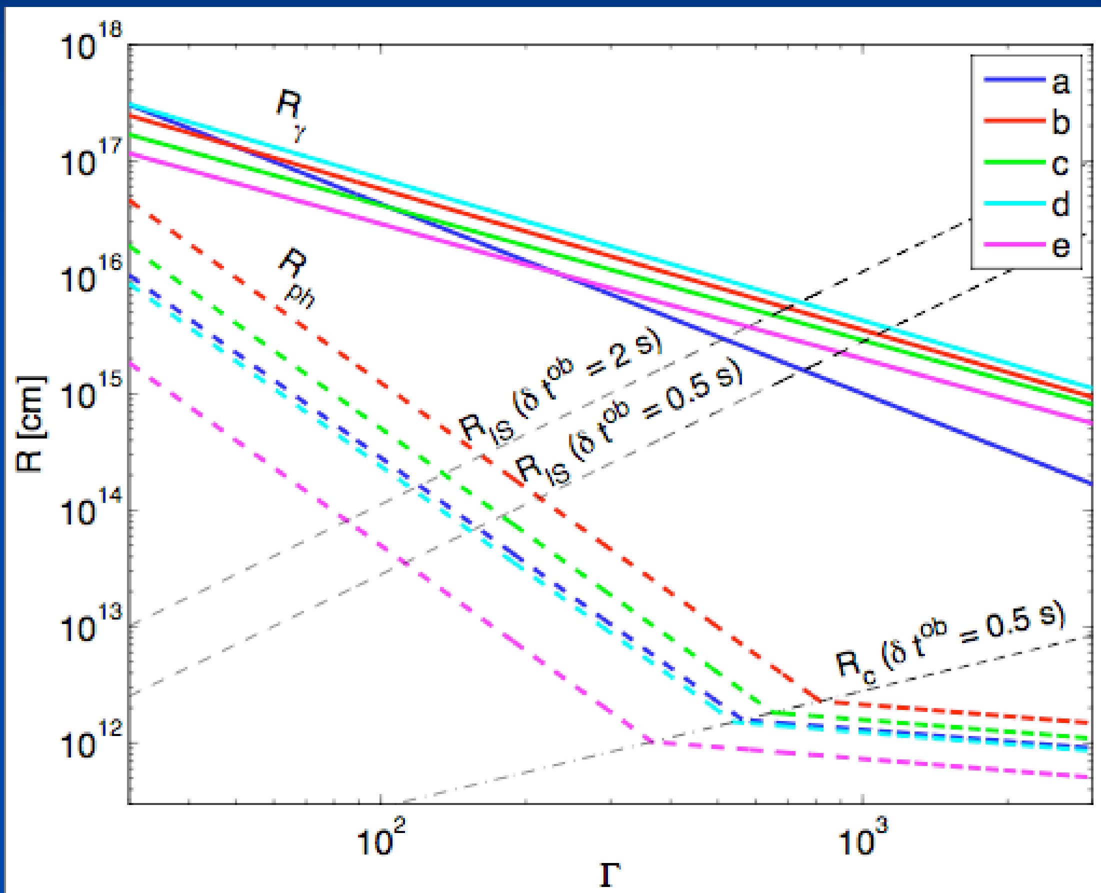


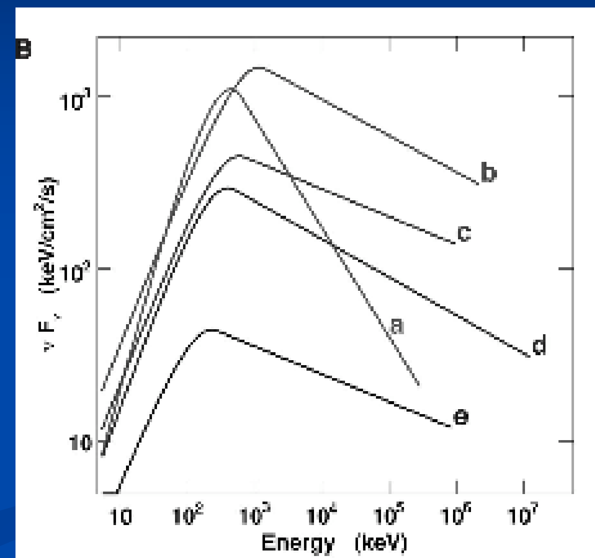


- Fermi team claims $\Gamma > 1000$ for 3 GRBs, based on the assumptions
  - All prompt emission is from the same R
  - $R = \Gamma^2 c\, \delta t$ (internal shock radius)
- Two other methods of estimating Γ
  - Deceleration time estimate (pre-Fermi), about 20 cases: Γ ~ several hundreds
  - Photosphere method (Pe'er et al. 2007), for GRB 090902B, a few hundreds
- The issue of the opacity argument
  - Maximum photon energy depends on both R and Γ (Gupta & Zhang 2008)
  - R can be both smaller (photosphere) or larger (magnetic turbulence) than $\Gamma^2 c\, \delta t$
  - The high-E component can be at higher R
  - One needs to be more conservative!

GRB 080916C: Radius constraints

(Zhang & Pe'er 09)



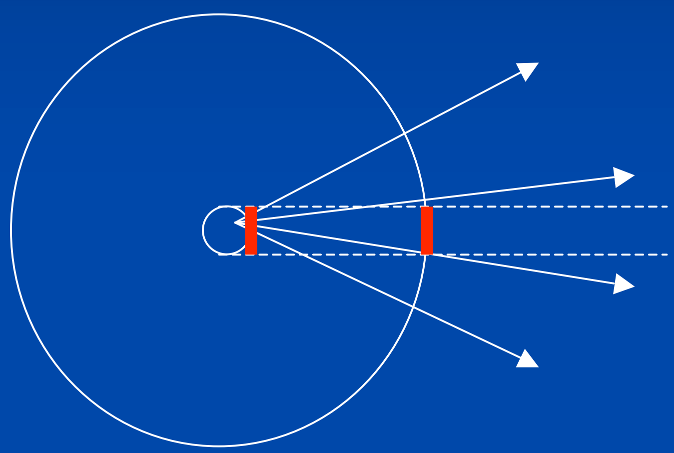


$$\tau_{\gamma\gamma}(E) = \frac{C(\beta)\sigma_T d_z^2 f_0}{-1-\beta}\left(\frac{E}{m_e^2c^4}\right)^{-1-\beta}\frac{1}{R_\gamma^2}\left(\frac{\Gamma}{1+z}\right)^{2+2\beta}$$

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

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

Expected photosphere emission from a fireball



Piran et al. 93
Meszaros et al. 93

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

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

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

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

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

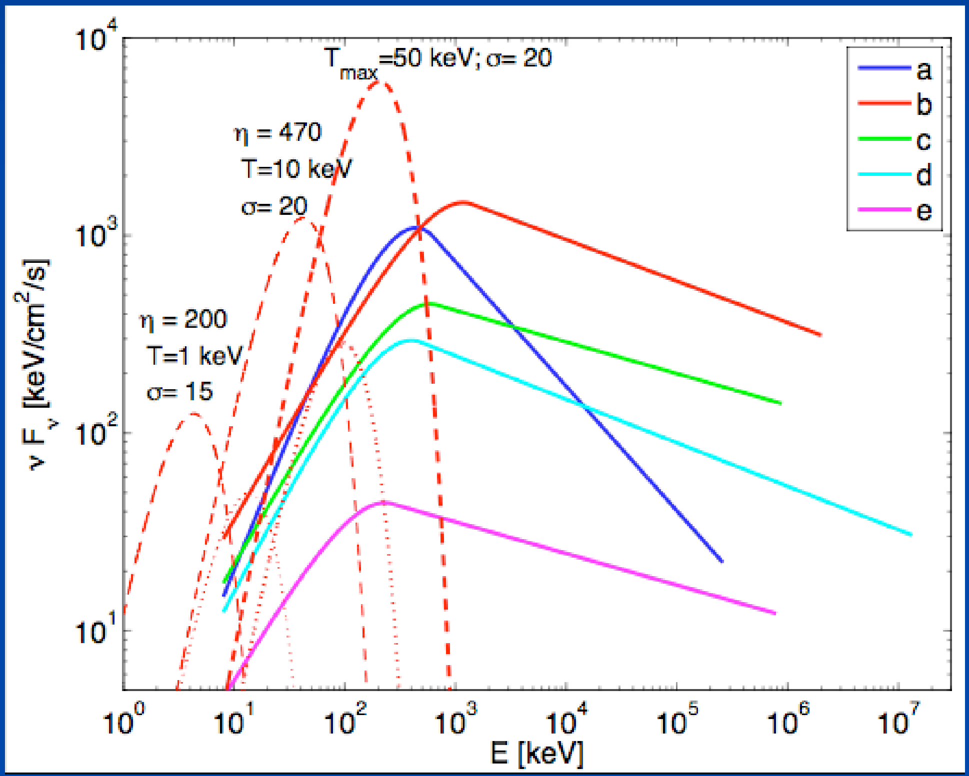
$$\eta_* = (L_w \sigma_T / 8\pi m_p c^3 R_0)^{1/4}$$

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

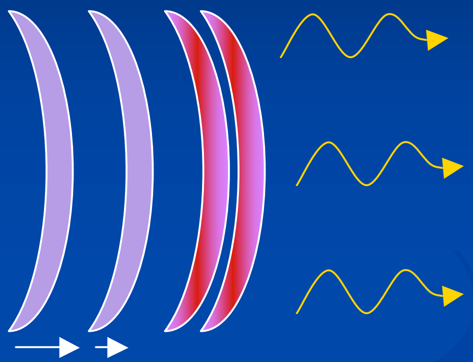
- Invoking a Poynting flux dominated flow can explain the lack of the three expected features
  - Non-detection of the pair cutoff feature is consistent with a large energy dissipation radius
  - Non-detection of the SSC feature is naturally expected, since in a Poynting flux dominated flow, the SSC 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
- Also consistent with
  - Numerical modeling
  - Polarization observation of early optical afterglow of GRB 090102 (Steele et al.)

Is there any way to hide the thermal component?

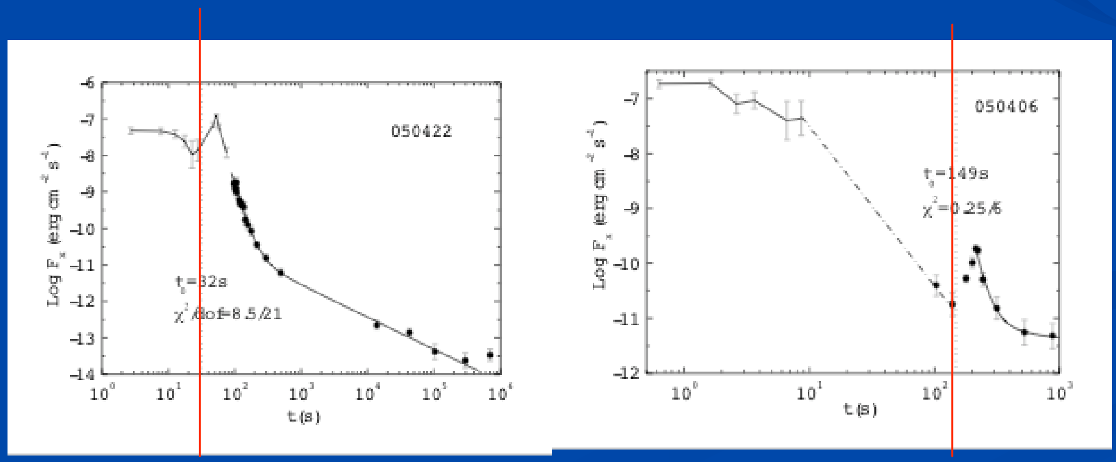
- Change R_0?
  - $R_0 = c\,\delta t \sim 3\times10^9$ cm (based on the observed variability)
  - If R_0 is smaller (10^6 cm - not observed, not favored for a massive star progenitor), the thermal component is weaker, but still difficult to hide (Fan 2009; Toma et al. 2009)
- Magnetic acceleration
  - In a MHD flow, a Poynting flux is gradually converted to a baryonic flux (Vlahakis & Konigl 2003; Komissarov et al. 2009; Narayan et al. 2009; Tchekhovskoy et al. 2009)
  - Without confinement the conversion is not complete.
  - With confinement the conversion process is not fully cold.

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



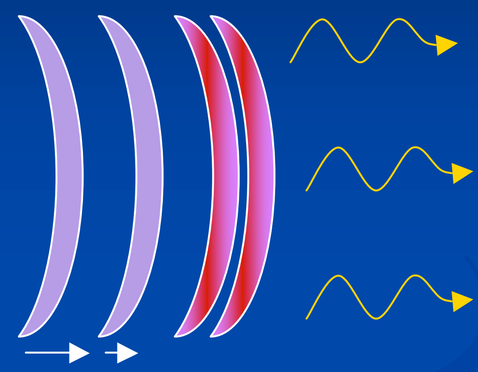
Rees & Meszaros
Paczynski & Xu
Kobayashi, Piran & Sari
Daigne & Mochkovitch
Panaitescu, Spada, Meszaros
……

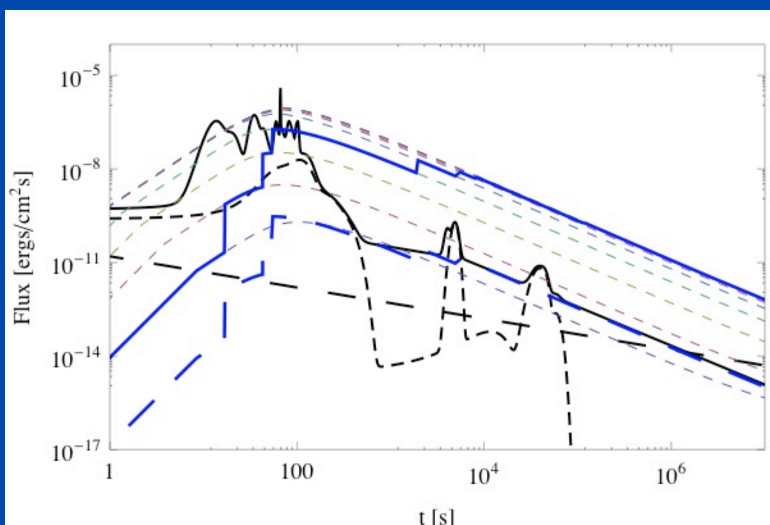


Liang et al. 2006

Internal shock model: Cons

- The low efficiency problem
- Missing electron problem
- Fast cooling problem
- Amati/Yonetoku relation
- Missing photosphere



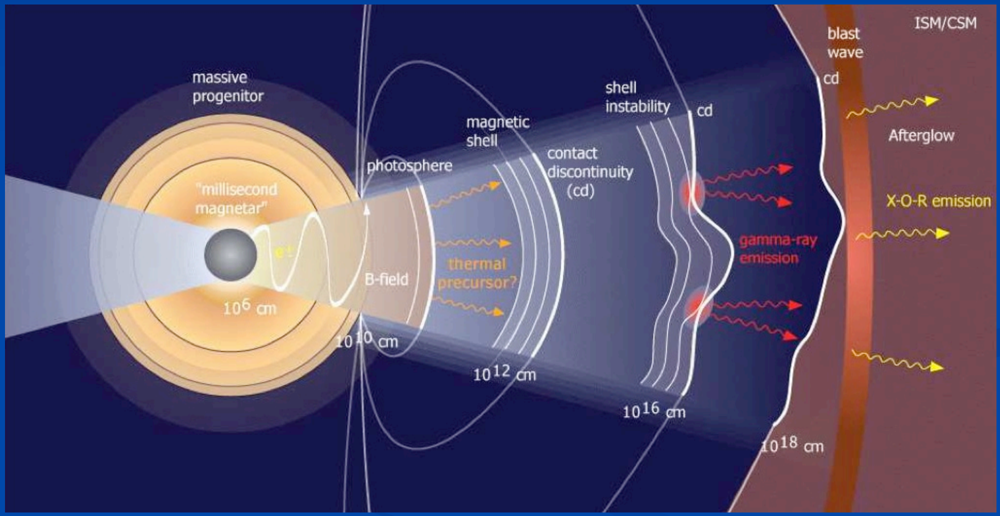


Kumar 1999
Panaitescu, Spada, Meszaros 1999
Beloborodov 2000
Kobayashi & Sari 2001
Daigne & Mochkovitch 1998
Shen & Zhang 2009
Ghisellini et al. 2000

Maxham & Zhang 2009

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?



Lyutikov & Blandford 2003

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

Zhang & Huirong 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 shock or very weak shock, little dissipation
- If relative Lorentz factor $\Gamma_{rel} > (1+\sigma)^{1/2}$, turbulence may develop, which may enhance reconnection, leading to a catastrophic 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. 2009).
- Prediction: gamma-ray polarization degree drops during each pulse. POET!

Merits of the ICMART model

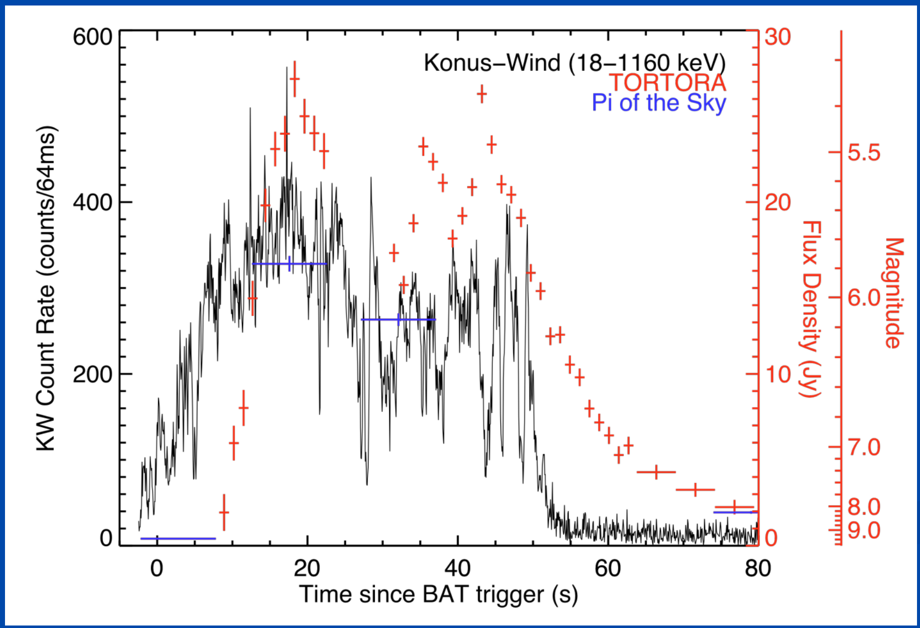
Zhang & Yan (2009, in preparation)

- 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)

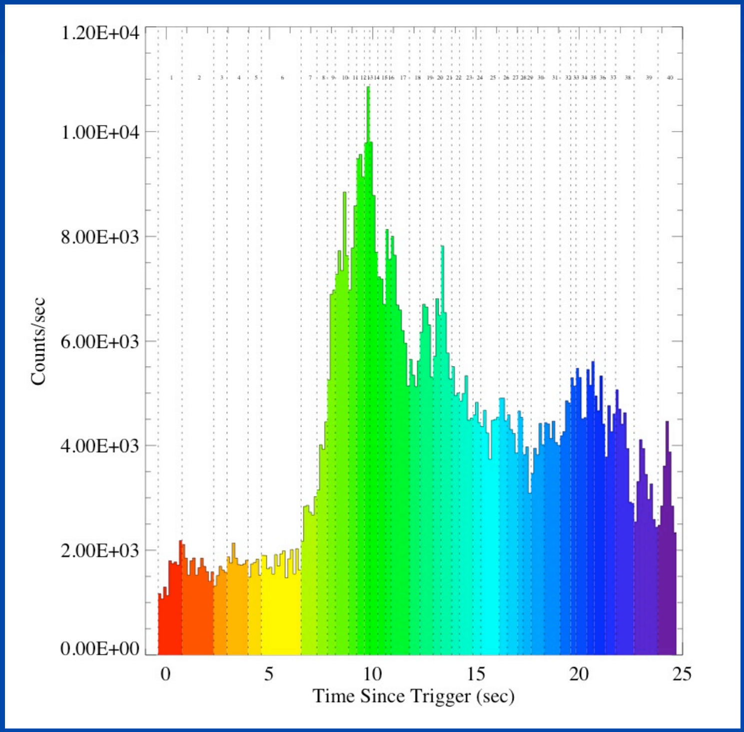


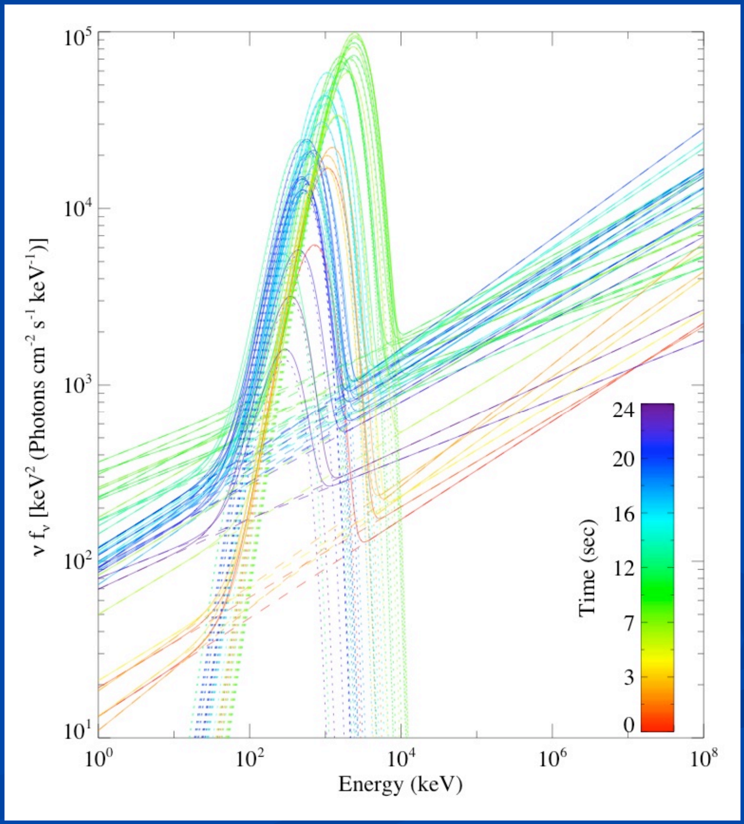
Consistent with data of some GRBs

Shen & Song (03)
Vetere et al. (06)
Marguitti et al. (09)
Gao et al. (09, in prep)

New Surprise:
Thermal emission in GRB 090902B!

Poster: P3 159; Ryde et al. (2009); Pe'er, B.-B. Zhang et al. (2009) in preparation

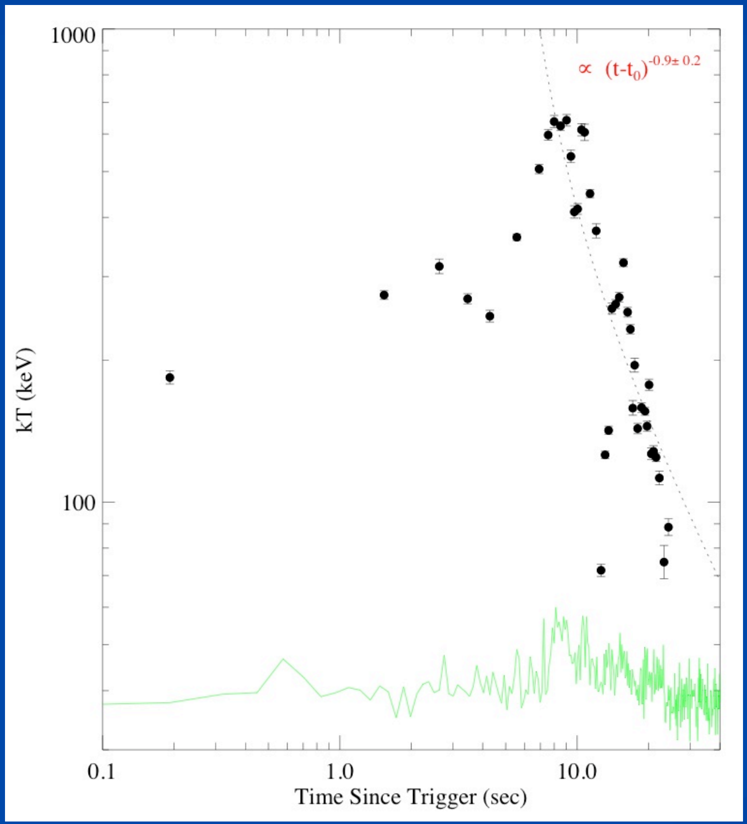


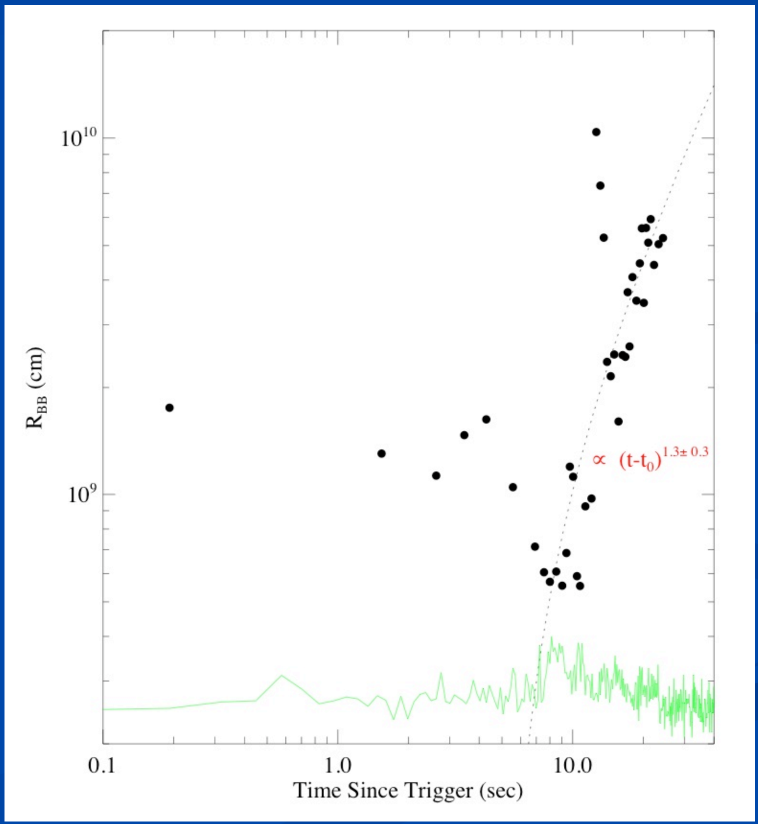


This is a Paczynski-Goodman "fireball"!

GRB 090902B - cont.

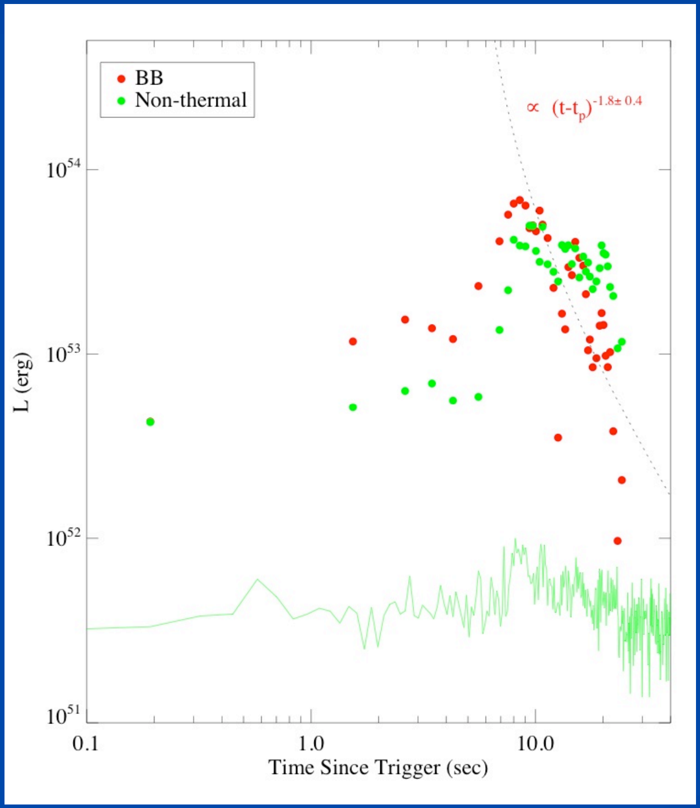
Poster: P3 159 (Zhang & Zhang)

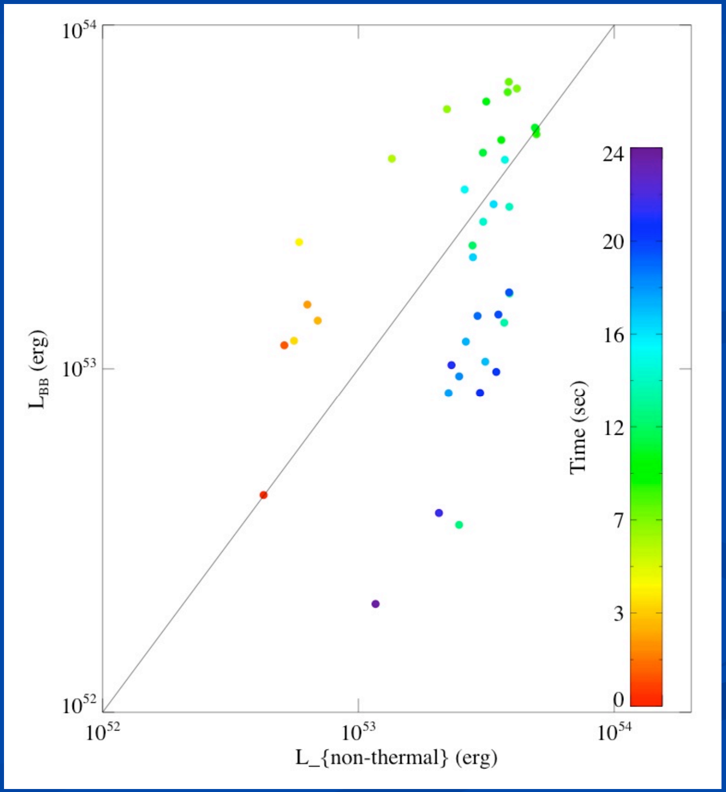




GRB 090902B - cont.

Poster: P3 159 (Zhang & Zhang)





Conclusions

- The broad-band Fermi GBM/LAT data can be used to constrain GRB jet composition.
- GRB composition is diverse. Magnetization parameter σ may vary in a wide range.
- At least GRB 080916C is very likely Poynting flux dominated at the central engine; at least GRB 090902B is very likely a hot fireball.
- For a moderately magnetized outflow, the ICMART model carries the merits of both the IS model and EM model, and can be an attractive possibility. Needs verification by numerical simulations.