The Internal Collision-induced MAgnetic Reconnection and Turbulece (ICMART) Model of GRBs

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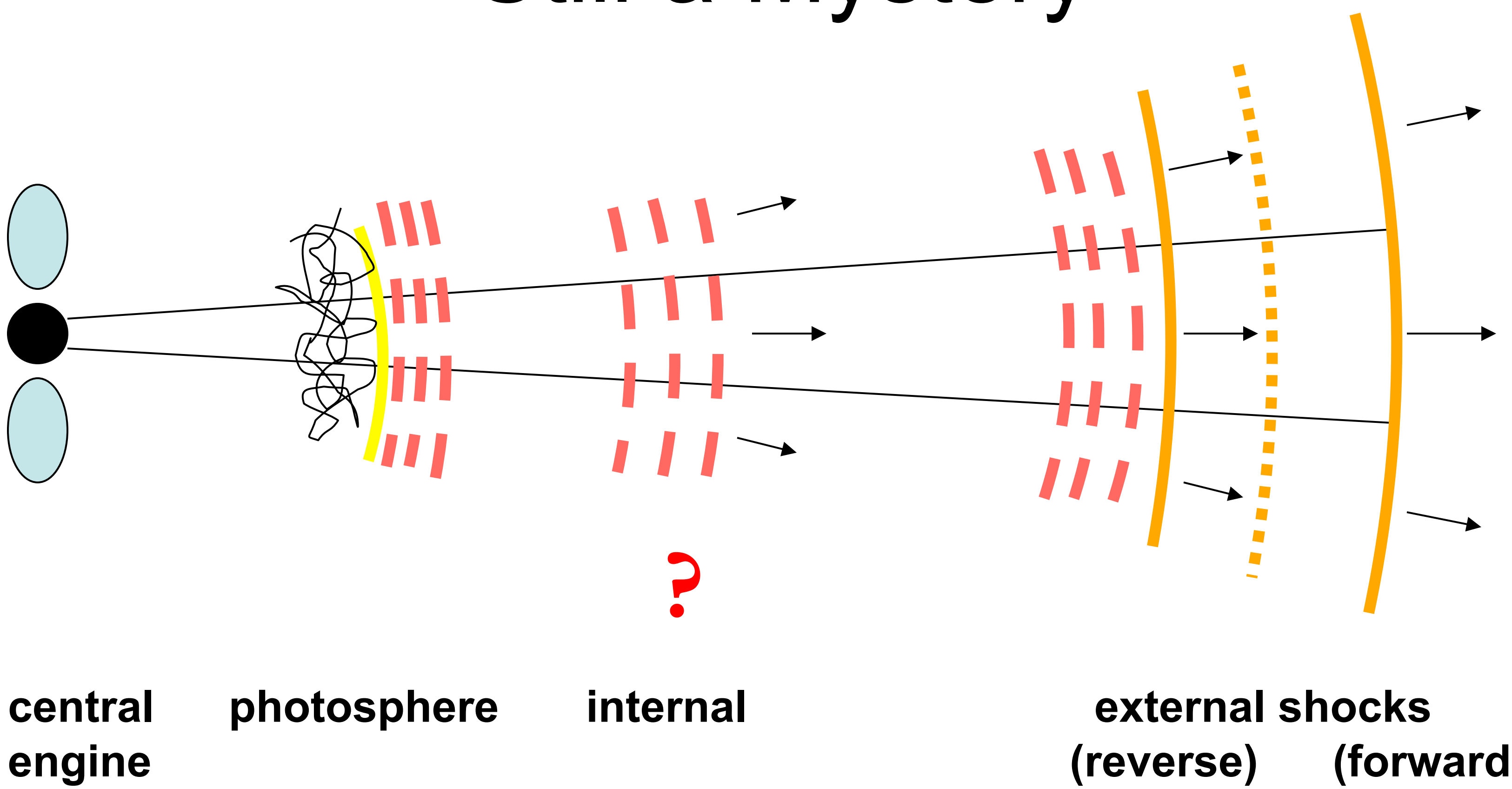
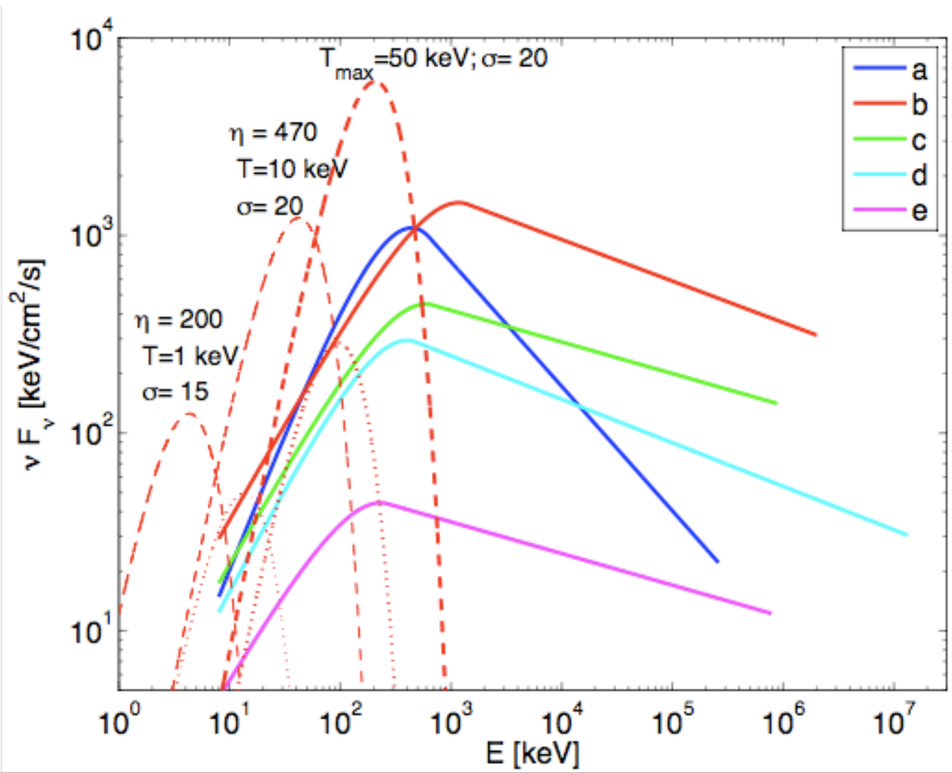
Prompt GRB Emission: Still a Mystery



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)?

Daigne's talk

The Need for a Poynting Flux Dominated Flow in GRB 080916C



Zhang & Pe'er 2009

Featureless Band-function covering 6 orders of magnitude (Abdo et al. 2009; B.-B. Zhang et al. 2010)

Lack of thermal component:

- Most energy is not in the "fireball" form, in the form of a Poynting flux

$$\sigma = L_{poynting}/L_{matter} >> 1$$

Kill Three Birds with One Stone

- Invoking a Poynting flux dominated flow can explain the feature-less Band function (14/17 LAT GRBs, B.-B. Zhang et al. 2010)
  - 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
  - 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 pair cutoff feature is consistent with a large energy dissipation radius

A New Model in the High-σ Regime: The ICMART Model

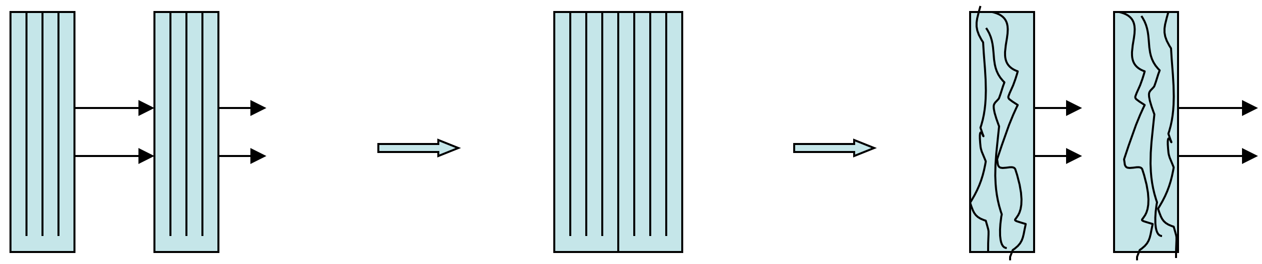
(Internal Collision-induced MAgnetic Reconnection & Turbulence)
(Zhang & Yan 2010, ApJ, accepted)

Basic Assumptions:

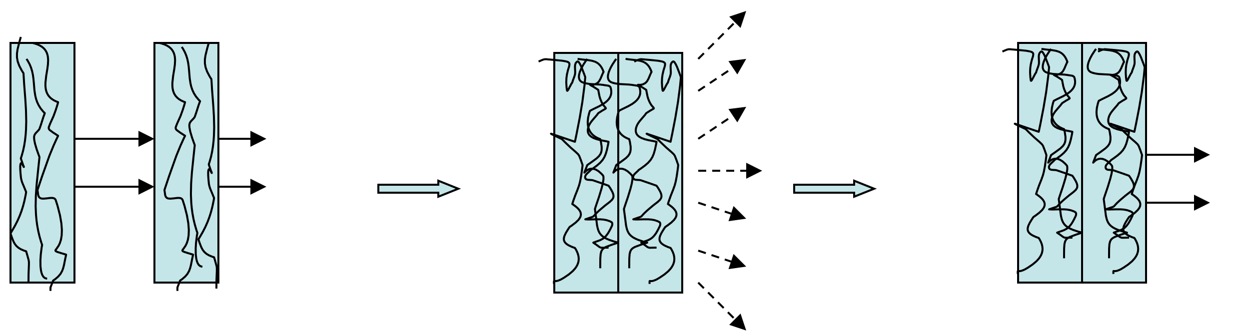
- The central engine launches a high-σ flow. The σ is still ~ (10-100) at R ~ 10^{15} cm.
- The central engine is intermittent, launching an outflow with variable Lorentz factors (less variable in σ).

ICMART Model

Zhang & Yan (2010)

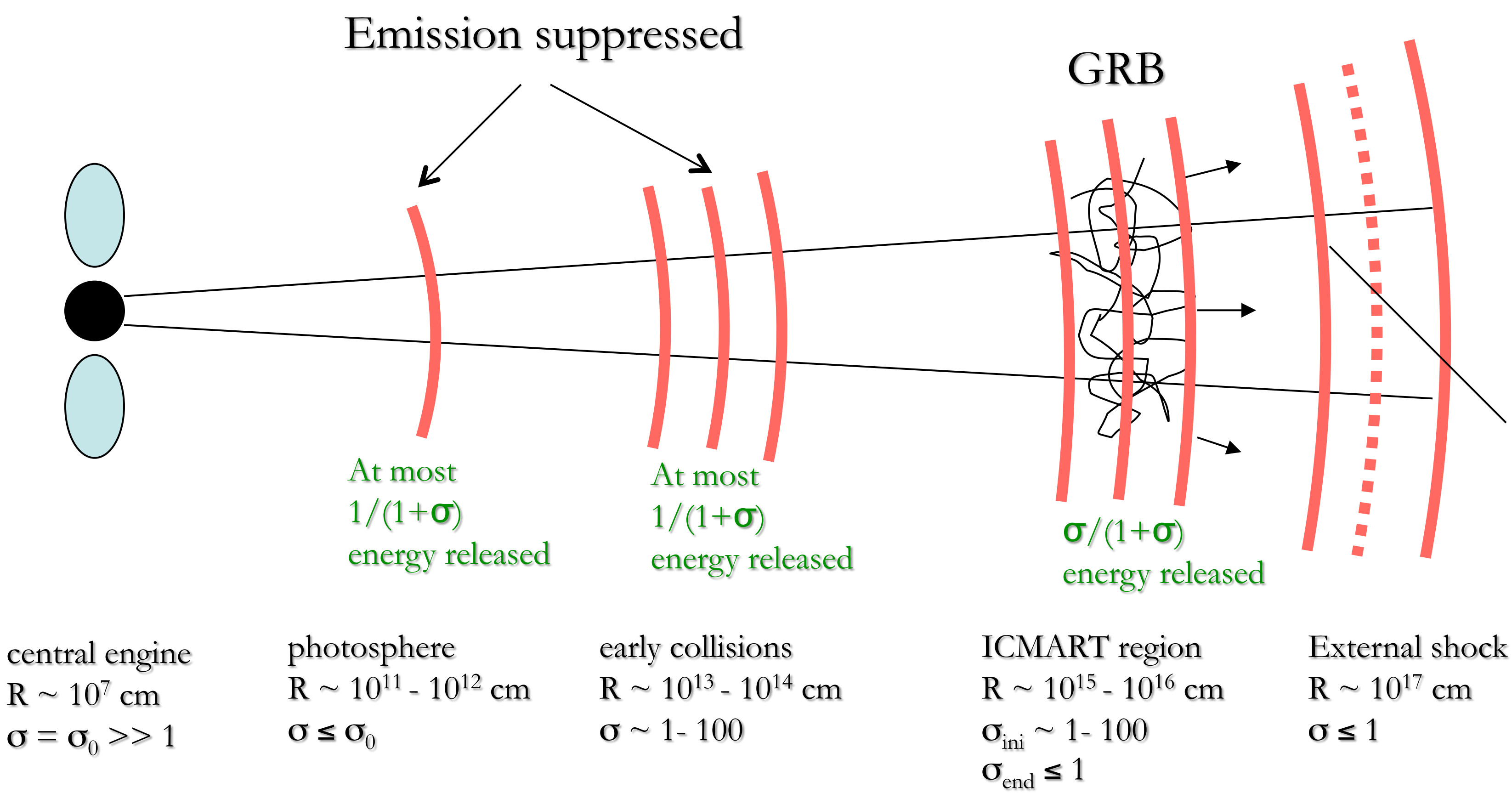


(a) Initial collisions only distort magnetic fields



(b) Finally a collision triggers fast turbulent reconnection
- An ICMART event (a broad pulse in GRB lightcurve)

Distance Scales in the ICMART Model



GRB ejecta is turbulent in nature

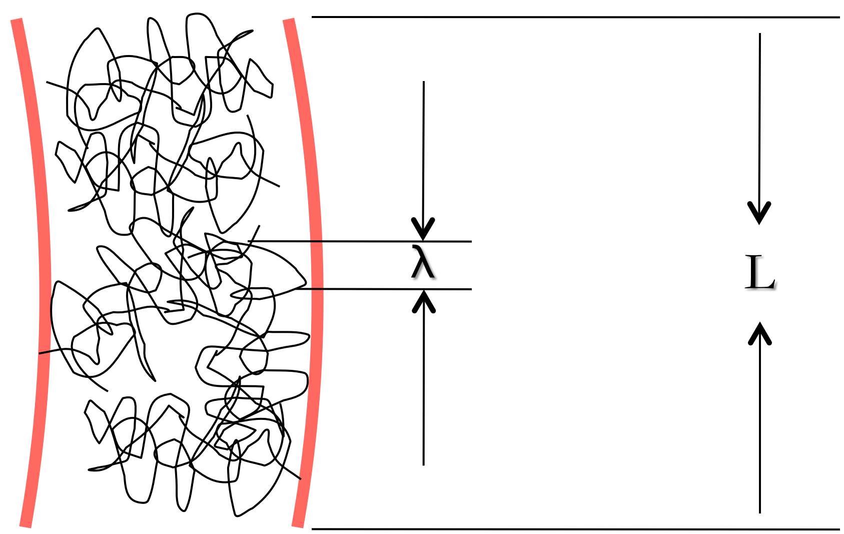
Reynold’s number:

$$R_e \equiv \frac{L\delta V}{\nu} \sim 10^{28} >> 1$$

Magnetic Reynold’s number:

$$R_{m,Bohm} \equiv \frac{L\delta V}{\eta} \sim 3.4 \times 10^{12} >> 1$$

Magnetic fields can be highly distorted and turbulent if turbulent condition is satisfied


λ
L

Turbulent Reconnection is needed to power GRBs

In order to reach GRB luminosity, the effective global reconnection rate has to be close to *c* .

$$\Gamma^2 \frac{B'^2}{8\pi} 4\pi R^2 \frac{\Delta'}{\Delta t'} \sim L_\gamma \qquad V'_{rec,global} = \frac{\Delta'}{\Delta t'} \sim \frac{L_\gamma}{L_w} \frac{1+\sigma}{\sigma} c \sim c$$

Relativistic Sweet-Parker reconnection speed is << *c* (Lyubarsky 2005).

$$V'_{rec,local} = V_A s^{-1/2} << c \qquad s \equiv \frac{\lambda V_A}{\eta} >> 1$$

Turbulent reconnection (Lazarian & Vishniac 1999) can increase reconnection speed by a factor *L/λ* .

$$V'_{rec,global} = V'_{rec,local} (\frac{L}{\lambda})$$

Multiple collisions can distort field lines and eventually trigger turbulence in a high-σ flow

Required condition from the observations (reach GRB luminosity):

$$\lambda \leq 2 \times 10^9 \mathrm{cm}$$

Condition for relativistic turbulence (I): relativistic shock

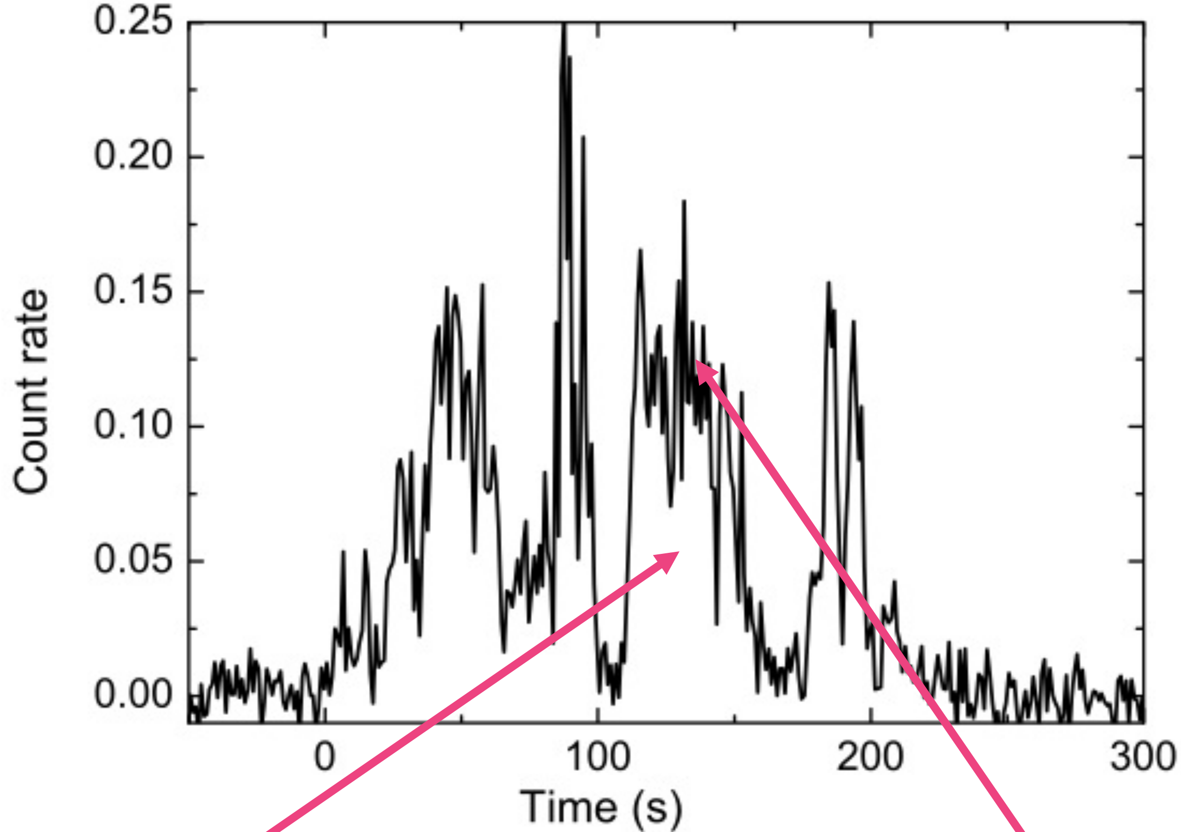
$$\Gamma_{21} \geq \left(\frac{1}{2} \sigma \frac{\rho_1^{'}}{\rho_2^{'}} \right)^{1/2}$$

Condition for relativistic turbulence (II): relativistic reconnection outflow

$$s < \sigma,$$

$$\lambda \leq 10^4 \mathrm{cm}$$

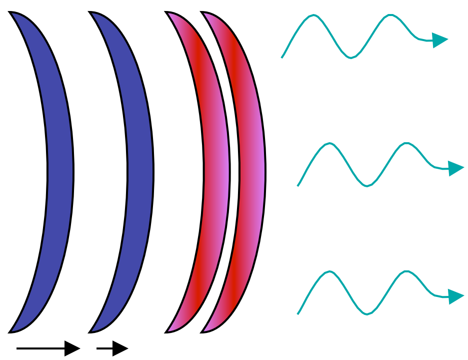
Two-Component Variability in the ICMART Model



slow variability component
related to central engine

fast variability component
related to turbulence

High Efficiency of ICMART



Energy conservation:

$$(\Gamma_2 m_2 + \Gamma_1 m_1)(1+\sigma_{ini}) = \Gamma_m (m_1 + m_2 + U')(1+\sigma_{end})$$

Momentum conservation:

$$(\Gamma_2 \beta_2 m_2 + \Gamma_1 \beta_1 m_1)(1+\sigma_{ini}) = \Gamma_m \beta_m (m_1 + m_2 + U')(1+\sigma_{end})$$

Low efficiency for the internal shock model:

Kobayashi, Piran & Sari 1997
Kumar 1999
Panaitescu, Spada, Meszaros 1999
Maxham & Zhang 2009

Efficiency:

$$\begin{aligned}
\eta_{\rm ICMART} &= \frac{\Gamma_m U'}{(\Gamma_1 m_1 c^2 + \Gamma_2 m_2 c^2)(1+\sigma_{ini})} \\
&= \frac{1}{1+\sigma_{end}} - \frac{\Gamma_m (m_1+m_2)}{(\Gamma_1 m_1 + \Gamma_2 m_2)(1+\sigma_{ini})} \\
&\simeq \frac{1}{1+\sigma_{end}} \qquad (\text{if } \sigma_{ini} \gg 1).
\end{aligned}$$

$\sim 50\%$ if $\sigma_{end} \sim 1$, and can reach 90% if $\sigma_{end} \sim 0.1$

No Electron Number Problem

- Electron number problem of the internal shock model
  - In order to get the right E_p, only a small fraction (~1%) of electrons are accelerated (Daigne & Mochkovitch 1998)
  - 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 (Shen & Zhang 2009)

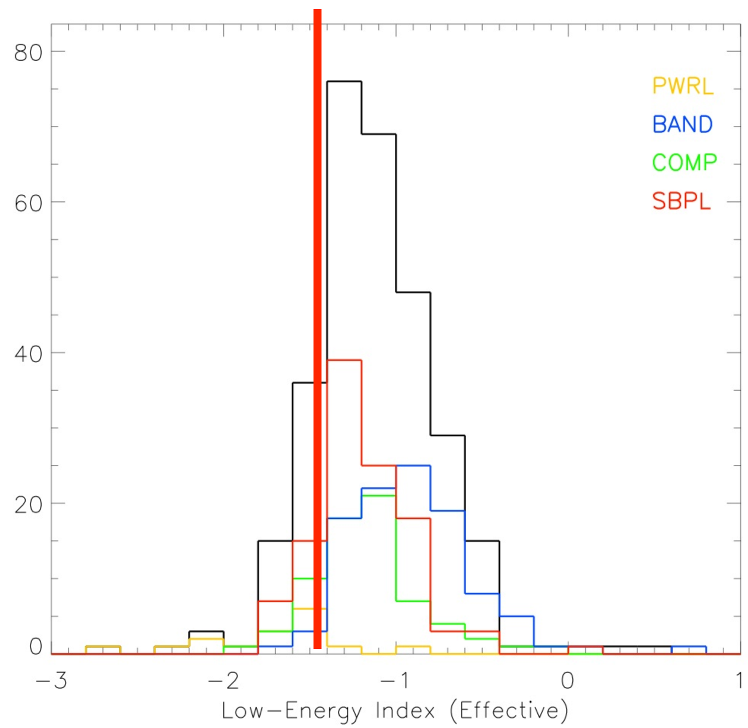
Electron number is smaller by a factor $(1+\sigma)$ naturally in the ICMART model

May overcome the fast cooling problem

Fast cooling problem:

- Theory: α = -3/2
- Data: average α = -1

Ghisellini et al. (00)



If a good fraction of magnetic energy is converted to particle energy through 2nd-order Fermi (turbulent) acceleration, one may have "slow-heating" in the range

$$\gamma_e \leq 3 \times 10^3$$

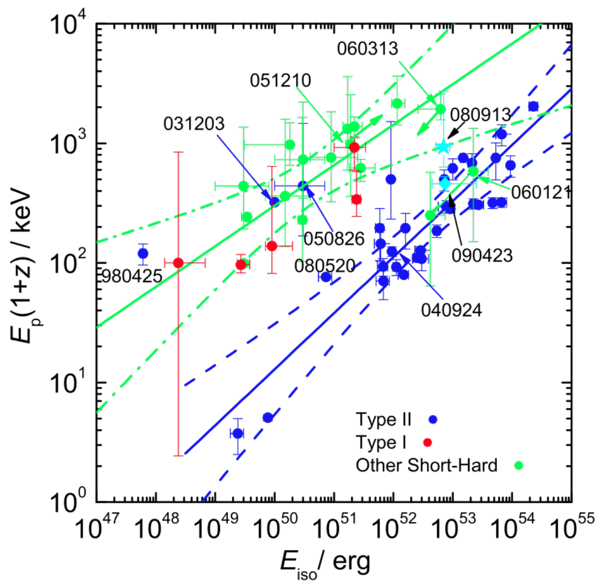
For synchrotron radiation, slow heating is relevant below several 10s of keV – no fast cooling.

Difference from the previous slow heating models: less electrons (more heating) and low B (less cooling)

May better satisfy Amati/ Yonetoku relation

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
- Internal Shock model predicts a wide range of R



ICMART model:

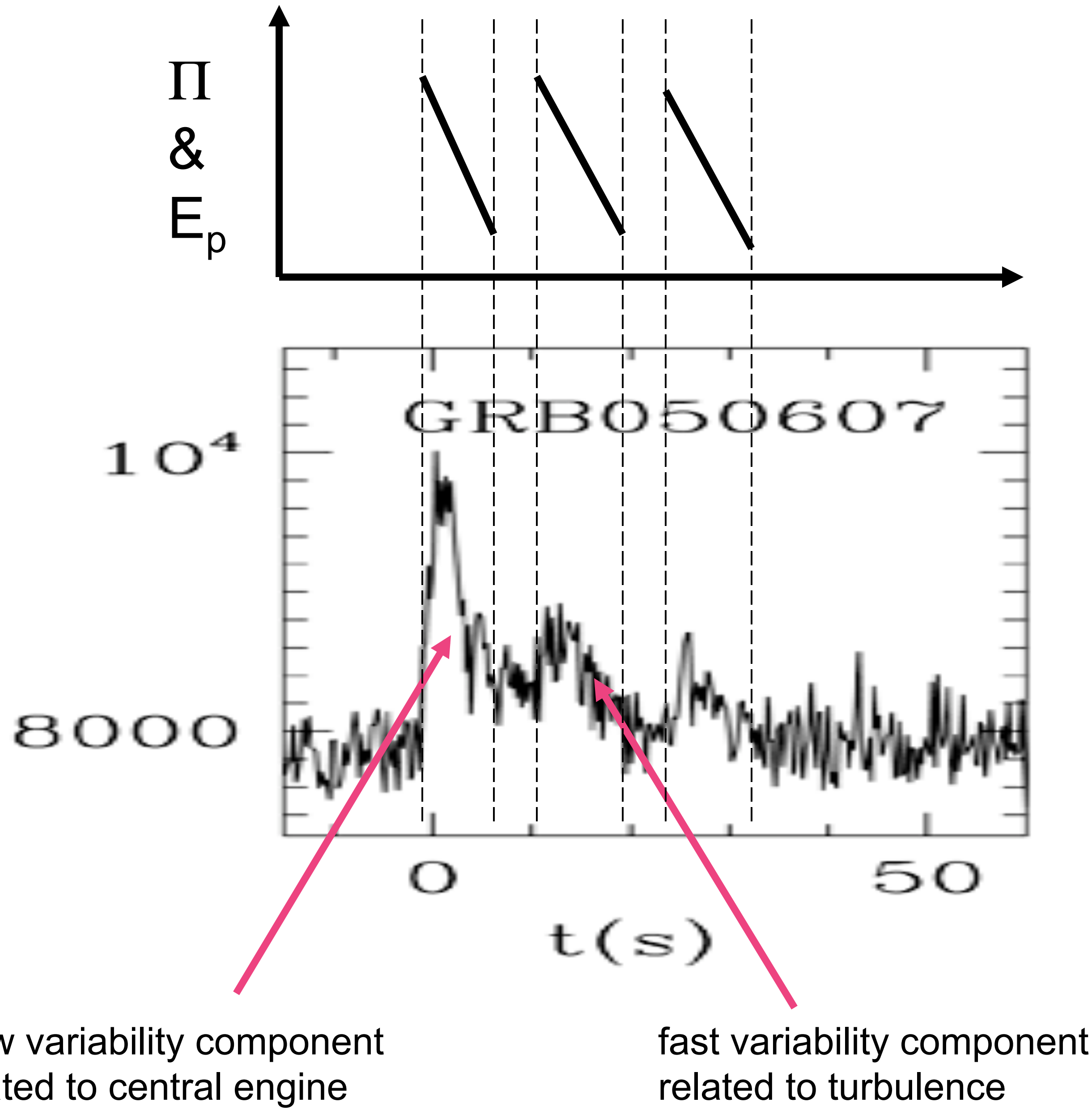
$E_p \sim L^{1/2} \sigma^2 R_{ICMART}^{-1}$

The apparent $R_{ICMART} - \Gamma$ connection is gone. A higher σ tends to give a larger R_{ICMART}. $E_p \sim L^{1/2}$ may be retained.

ICMART predictions:

Evolution of gamma-ray linear polarization across a pulse

Evolution of Ep across a pulse



Conclusions

- Fermi observations suggests that the ejecta of most GRB are likely Poynting flux dominated.
- The ICMART model is a moderately high-σ model that carried the merits of the internal shock model, but overcomes several drawbacks of the internal shock model.
- The model applies to most GRBs (those with Band-only spectrum, or the ones with weak photosphere thermal emission, Guiriec's talk).
- The current model is qualitative. Many ingredients of the model need verification by numerical simulations.