GRB Prompt Emission Theory

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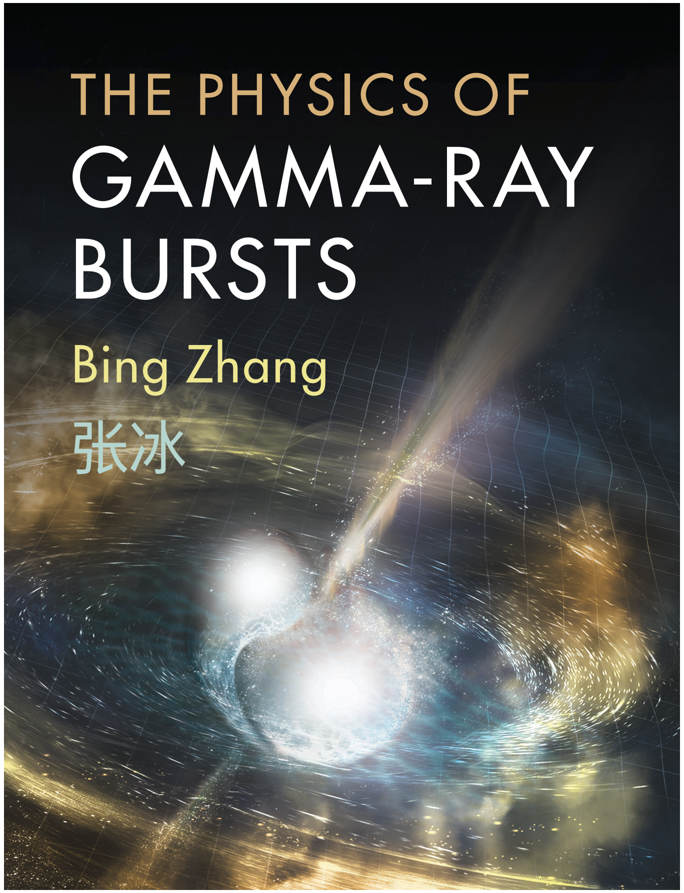
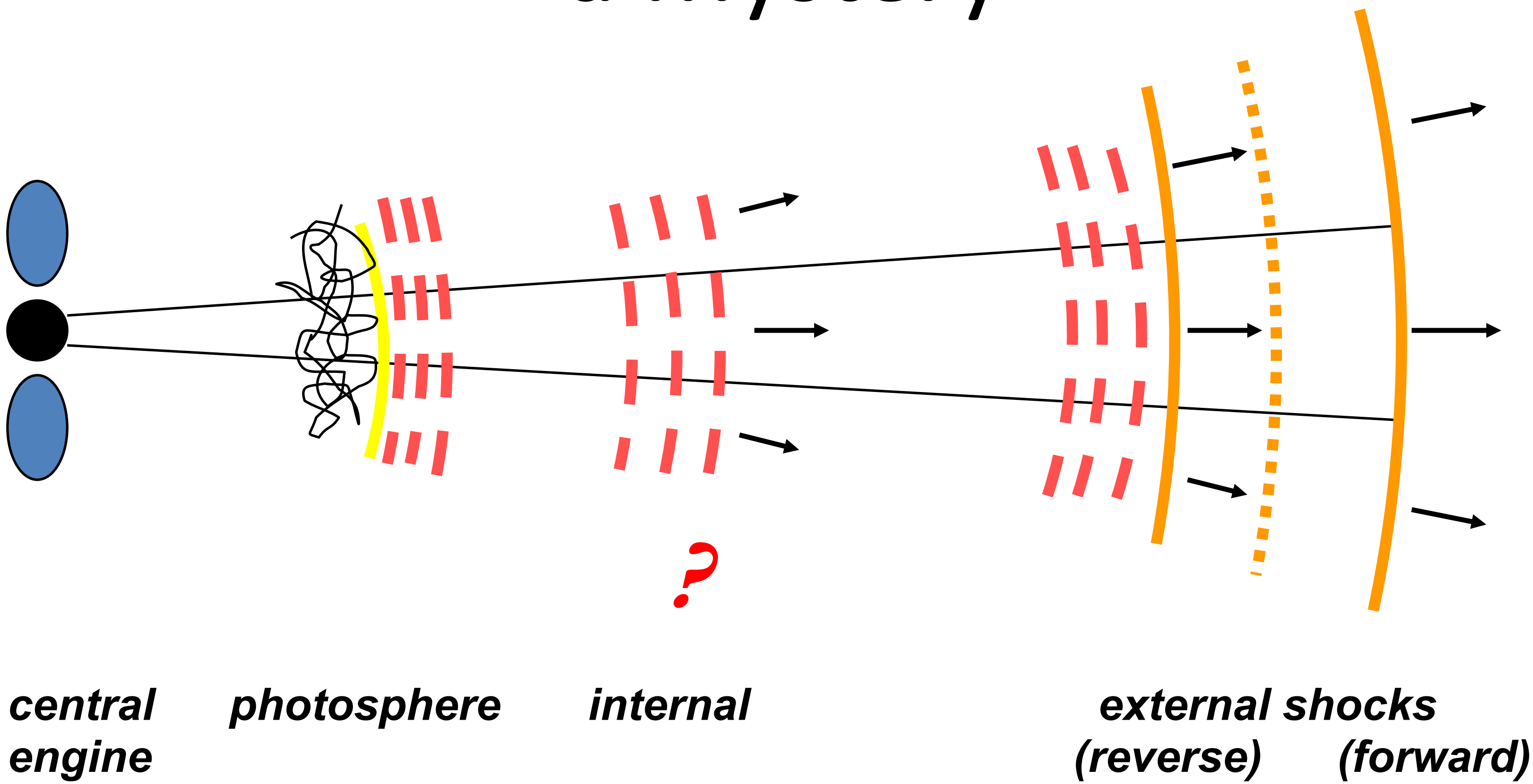


Prompt GRB Emission: a Mystery



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

GRB central engine defined by (η, σ_0)

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

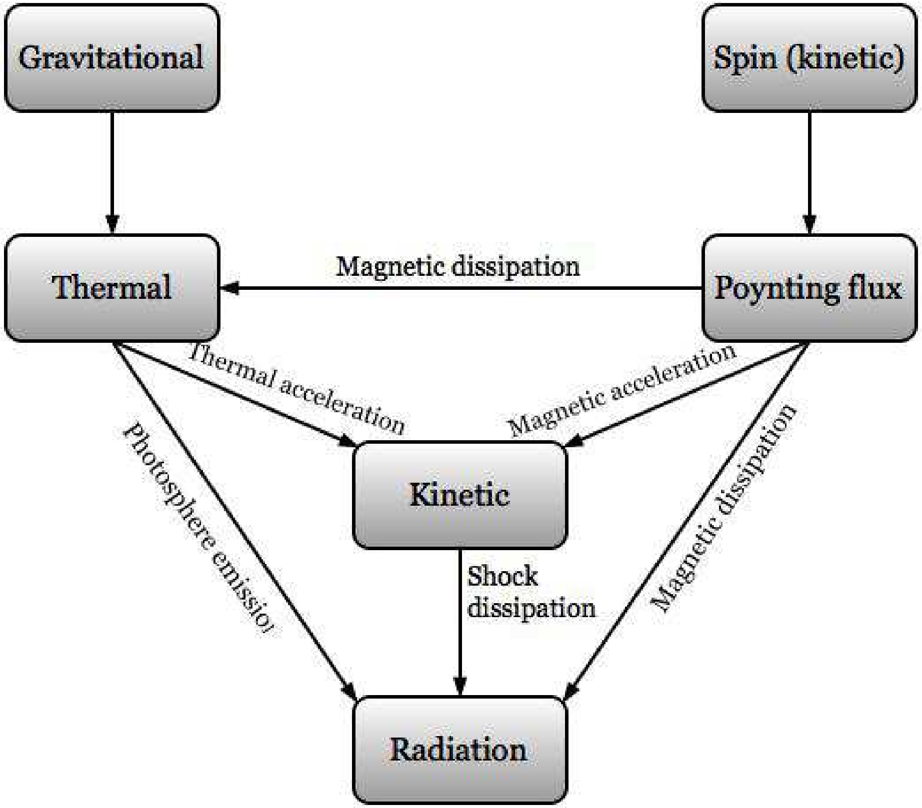
$$\mu_0 = \frac{E_{\rm tot,0}}{Mc^2} = \frac{E_{th,0} + E_{\rm P,0}}{Mc^2} = \eta(1+\sigma_0).$$

Neglect radiation loss, one has

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

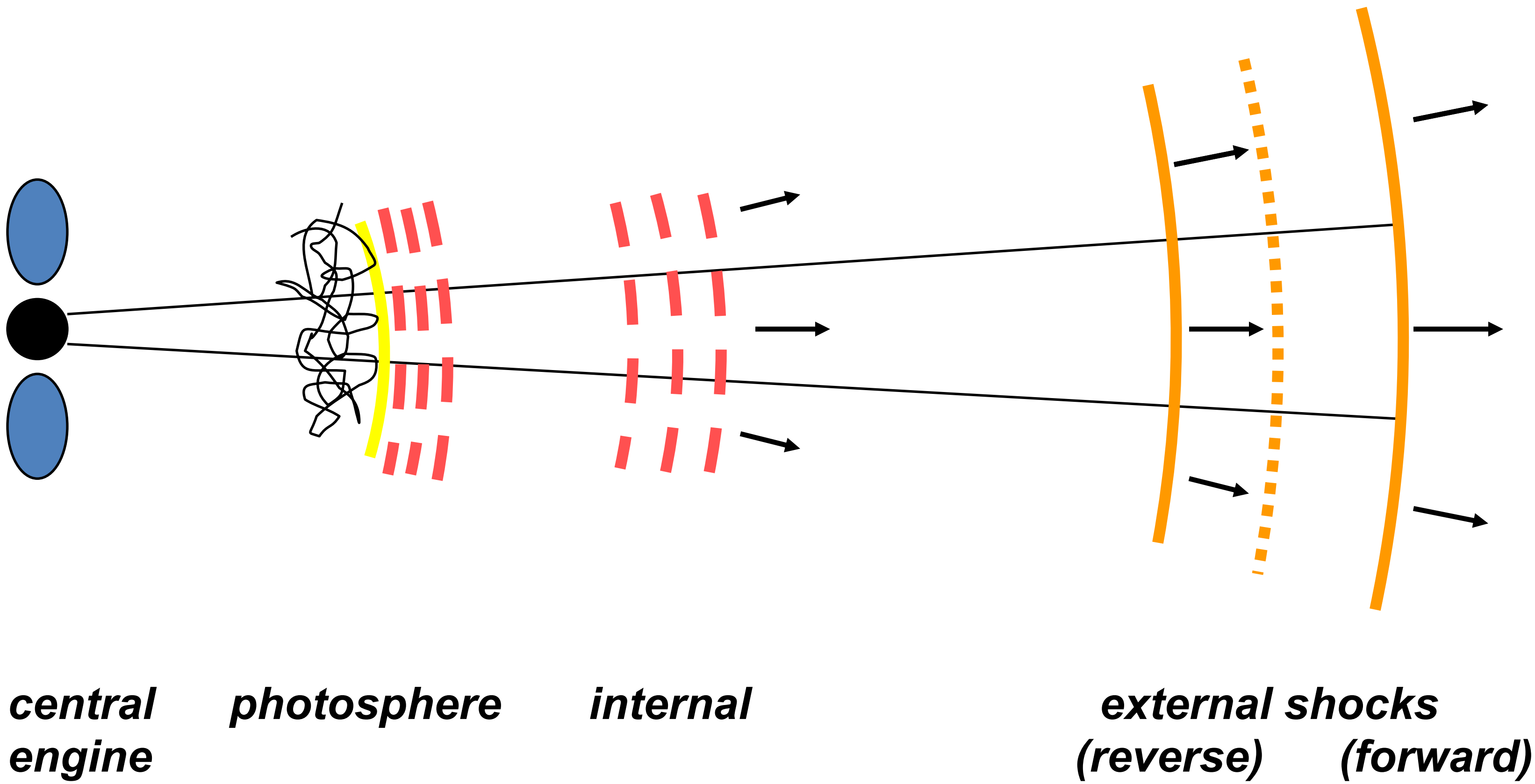
$$\Gamma_{\rm max} = \mu_0 \simeq \begin{cases} \eta, & \sigma_0 \ll 1; \\ \sigma_0, & \eta \sim 1, \sigma_0 \gg 1. \end{cases}$$

Energy Flow in GRBs

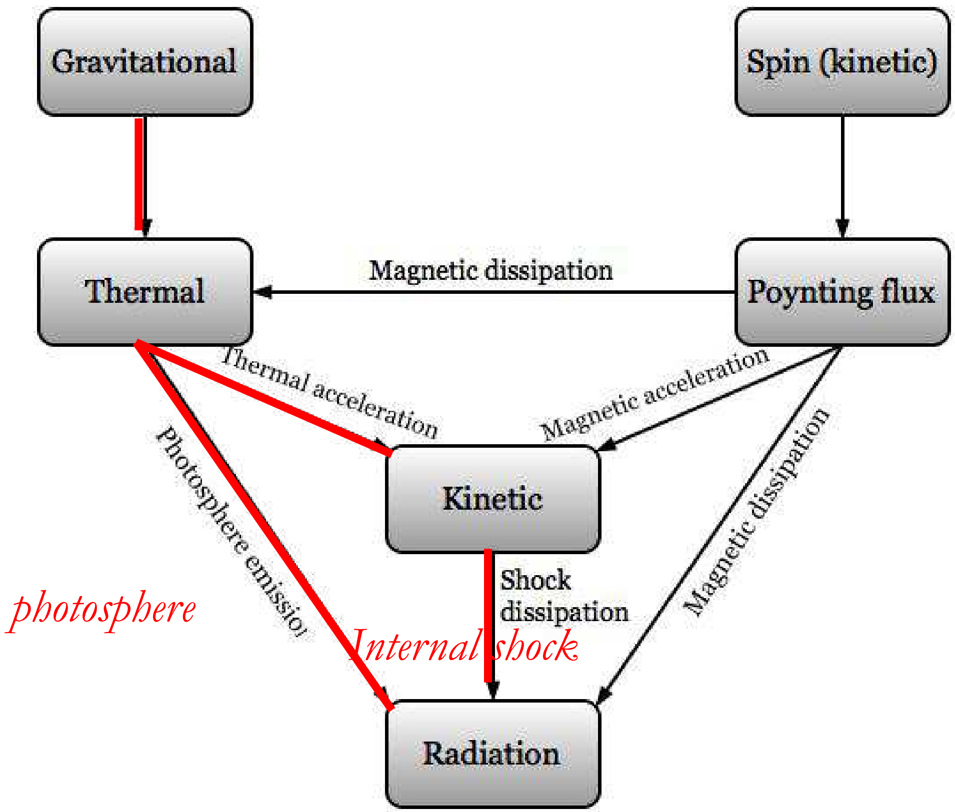


Early GRB model:
The fireball shock model

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

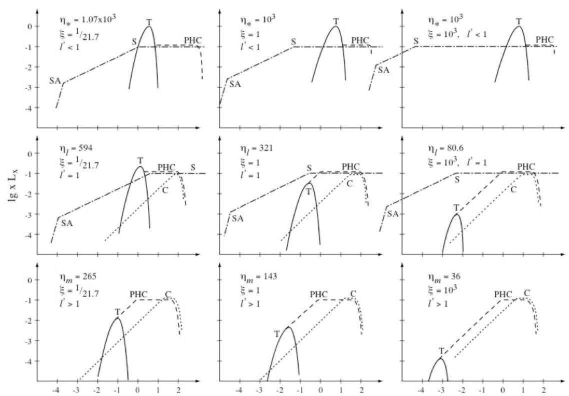


Energy Flow in GRBs



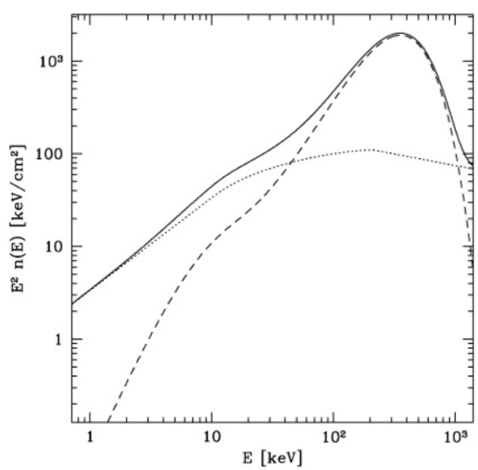
Fireball model

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

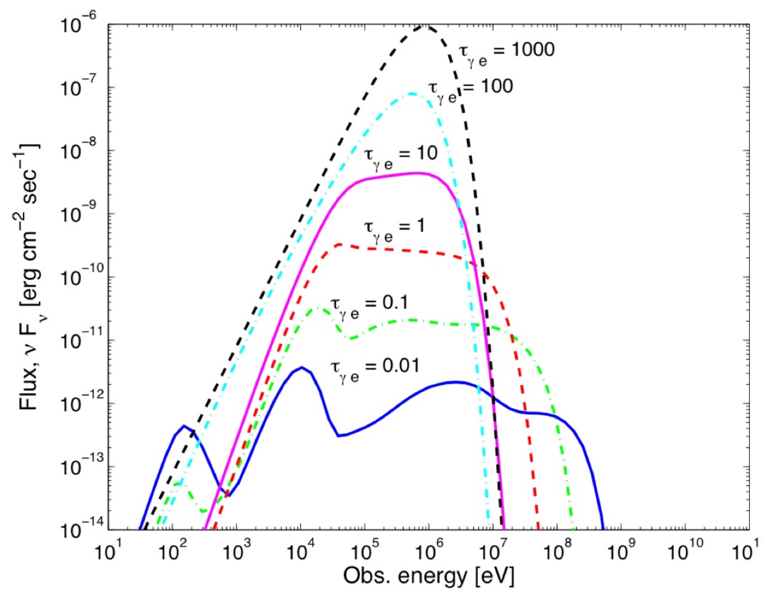


Meszaros & Rees (00)

1276 *F. Daigne and R. Mochkovitch*



Daigne & Mochkovitch (02)

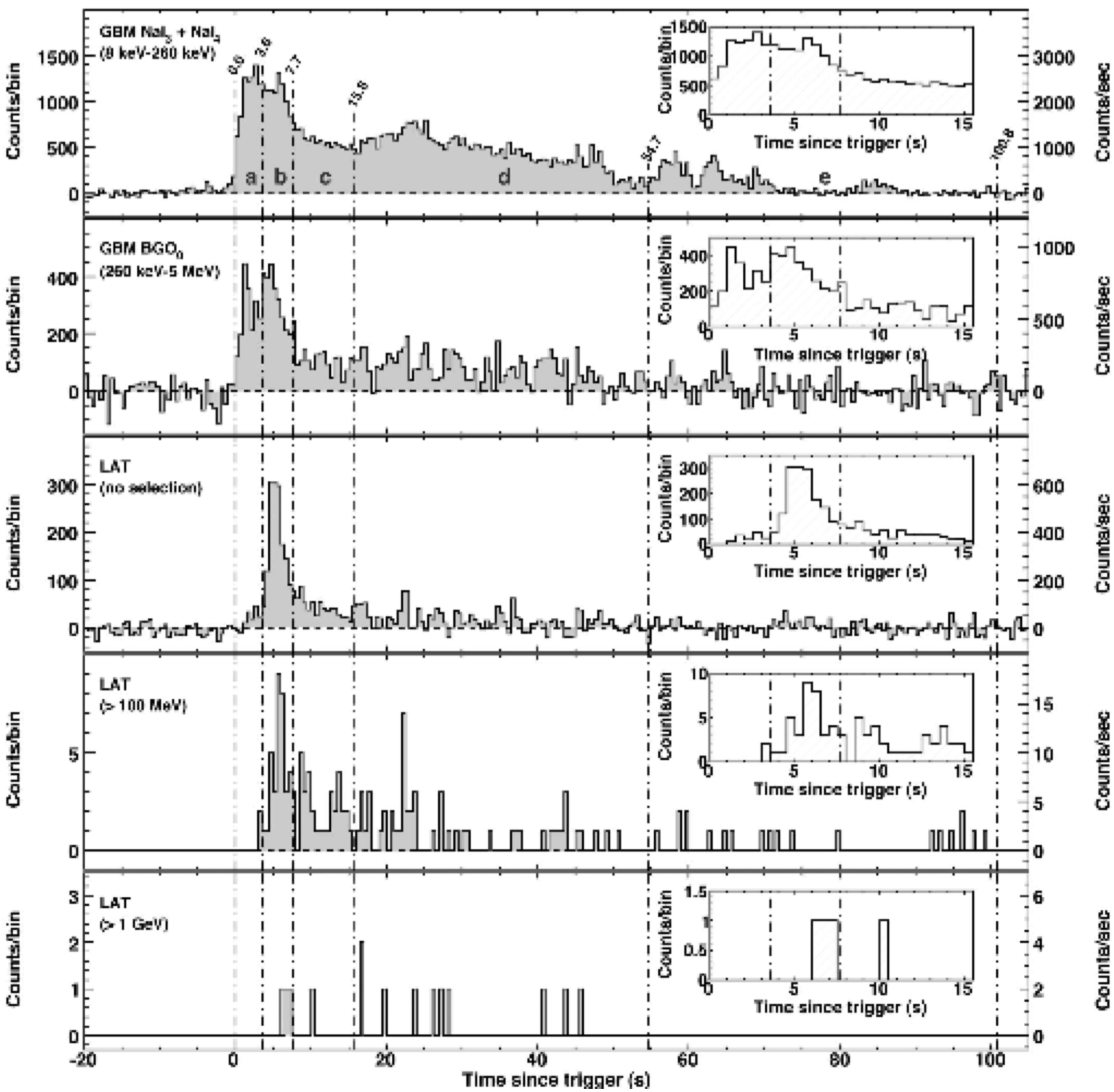


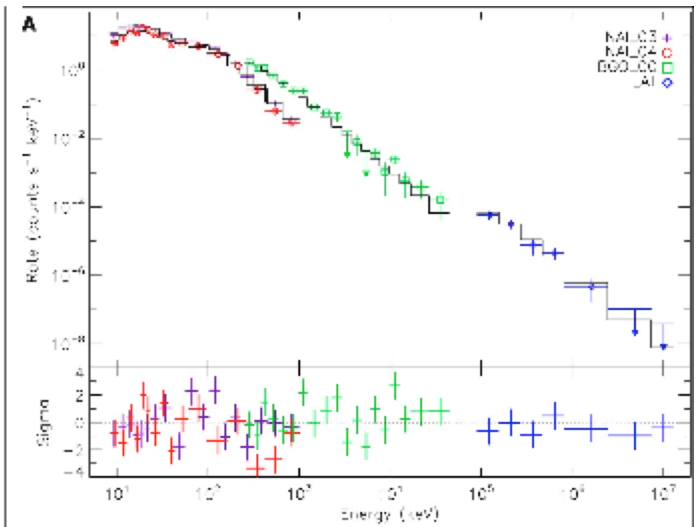
Pe'er et al. (06)

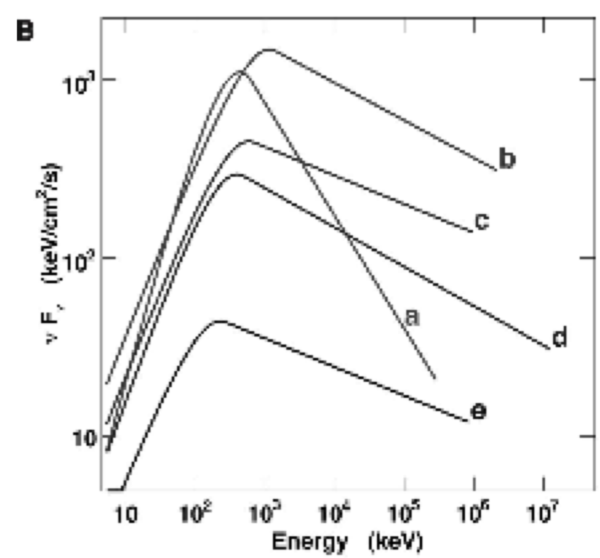
Fermi surprise: GRB 080916C

(Abdo et al. 2009, Science)

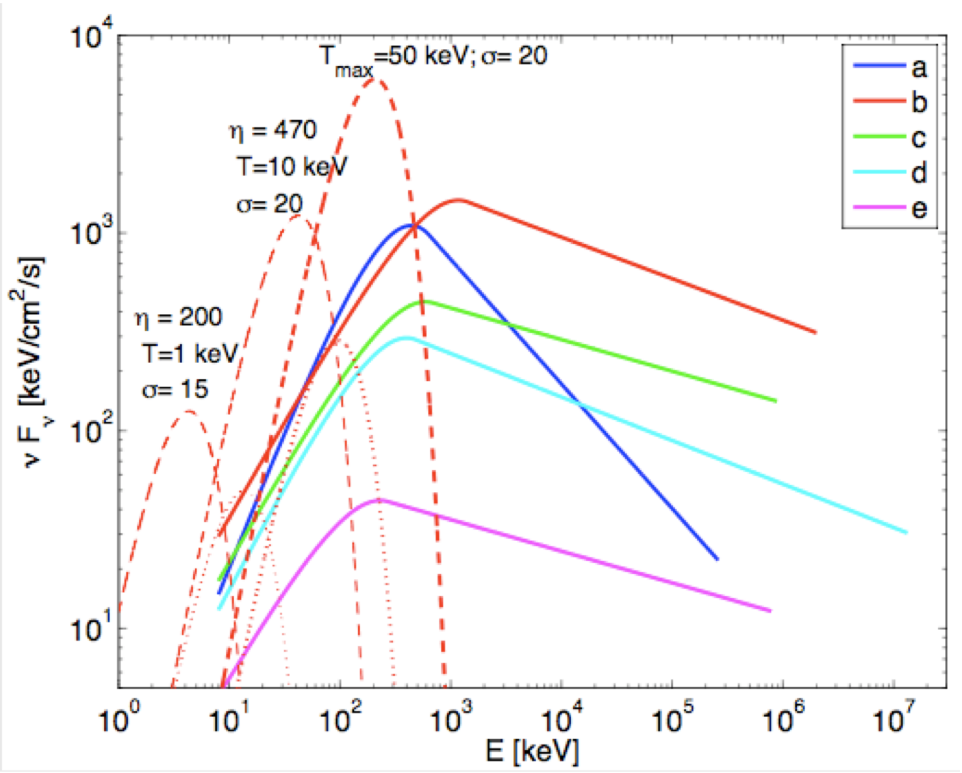
$z = 4.35 \pm 0.15$







Fermi Surprise:
Photosphere component missing



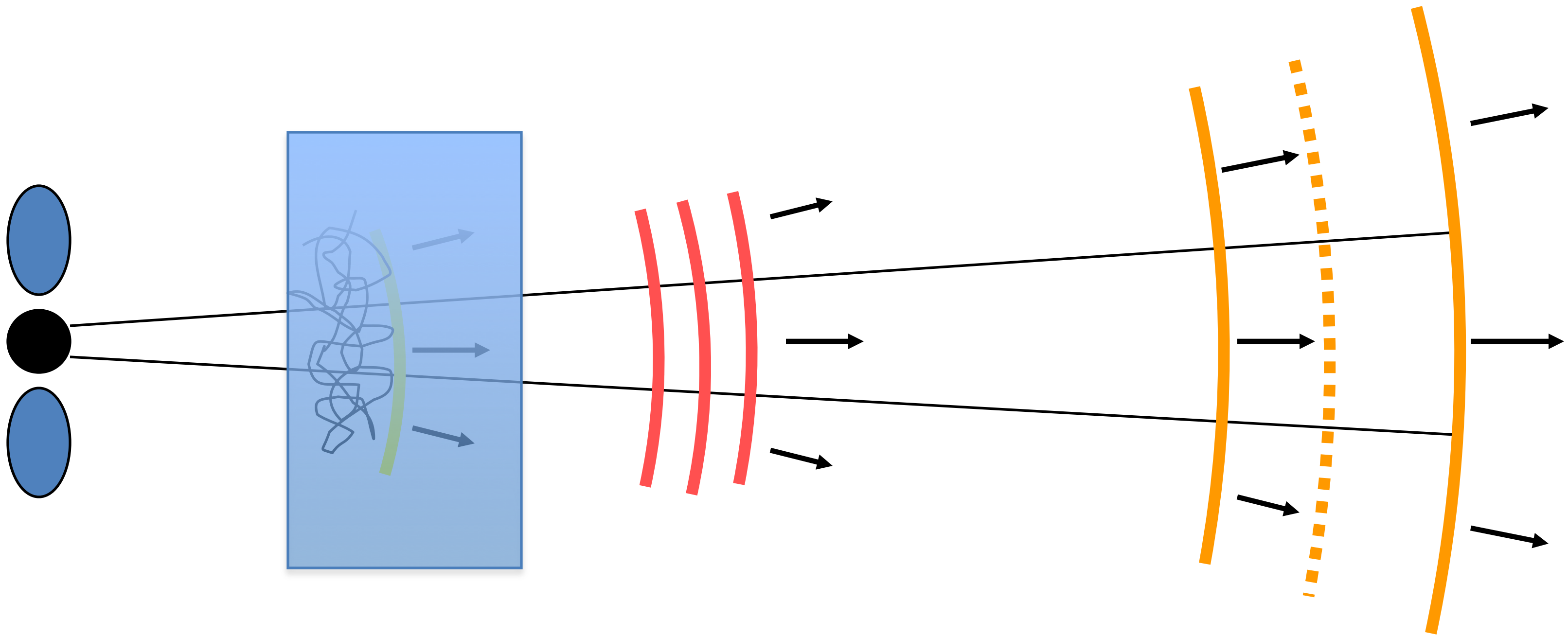
Zhang & Pe'er (2009)

Sigma: ratio between Poynting flux and baryonic flux:

Cf. Guiriec et al. (2015)

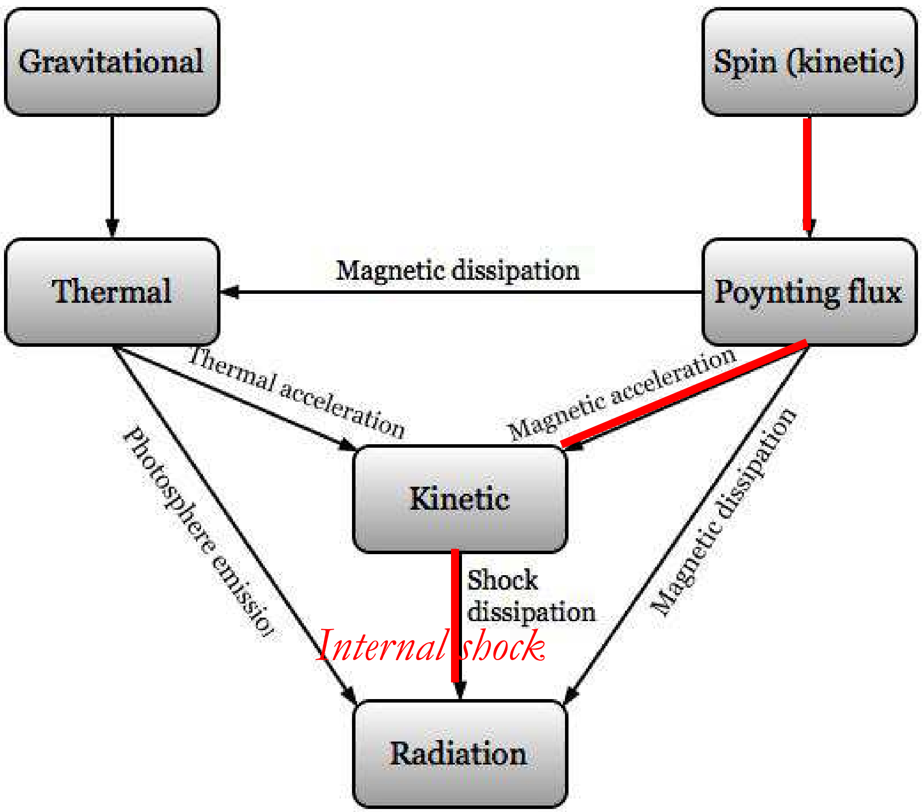
$\sigma = L_P/L_b$: *at least ~ 20, 15 for GRB 080916C*

Modified Fireball Model (1)



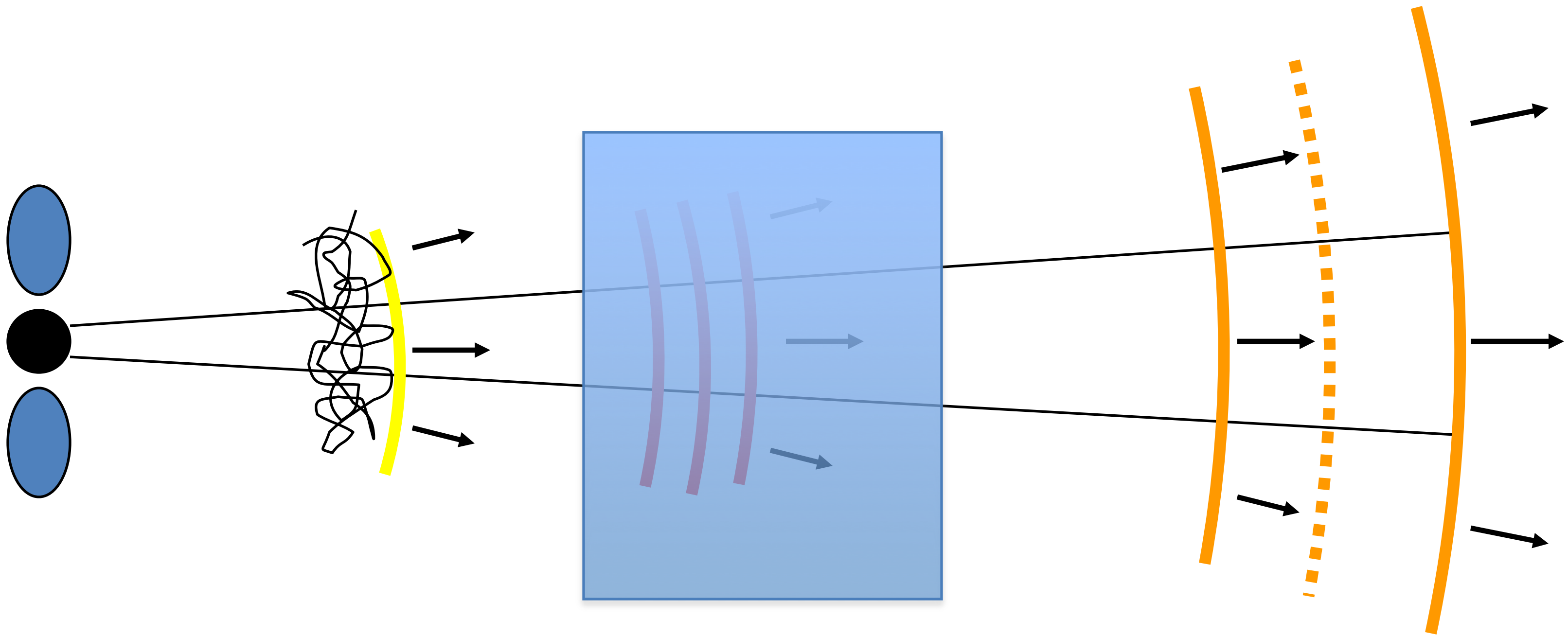
***GRB prompt emission is** from internal shocks*
Photosphere emission suppressed

Energy Flow in GRBs



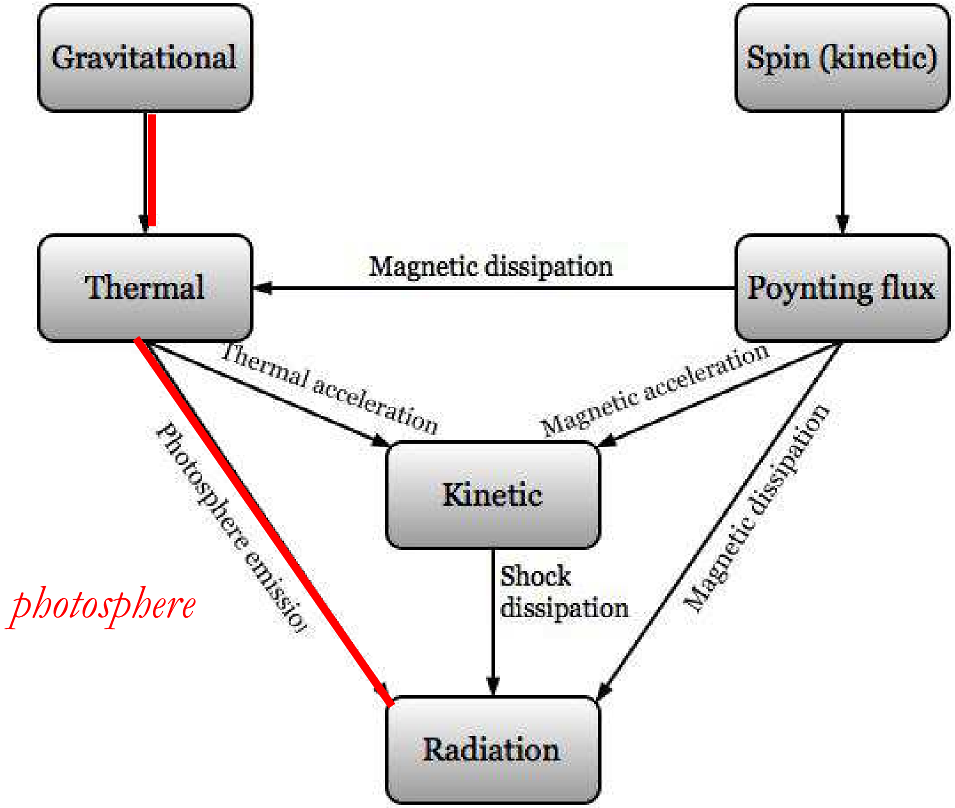
Initially magnetized internal shock model

Modified Fireball Model (2)



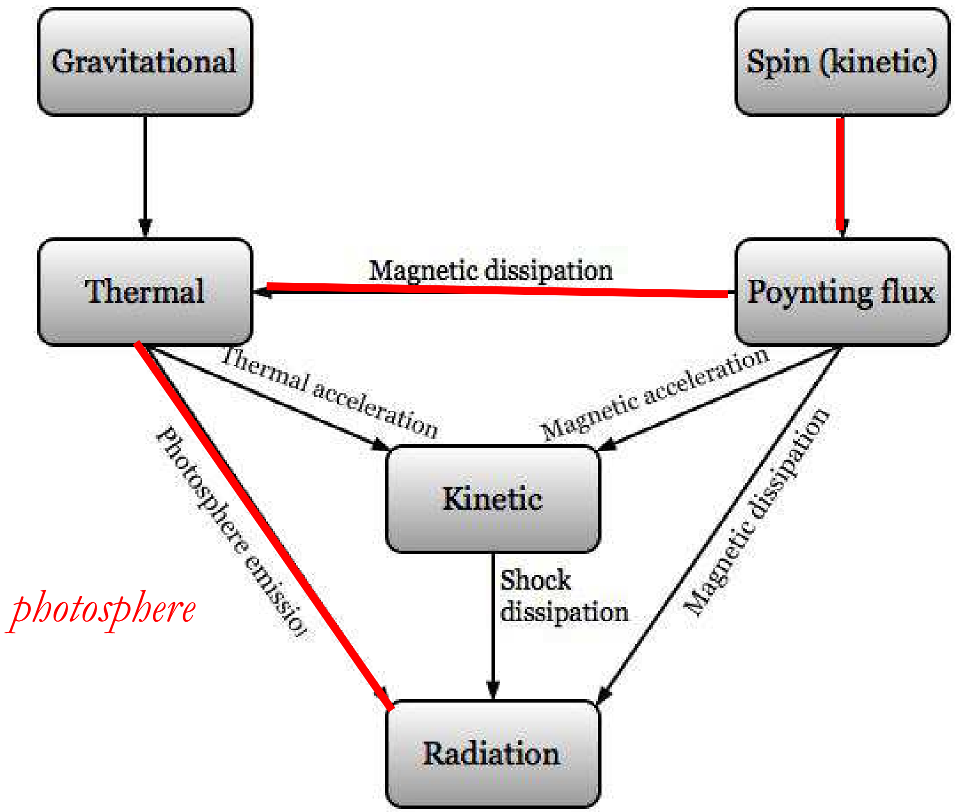
GRB prompt emission: *from photosphere*
Internal *shock emission suppressed*

Energy Flow in GRBs



Dissipative photosphere model

Energy Flow in GRBs

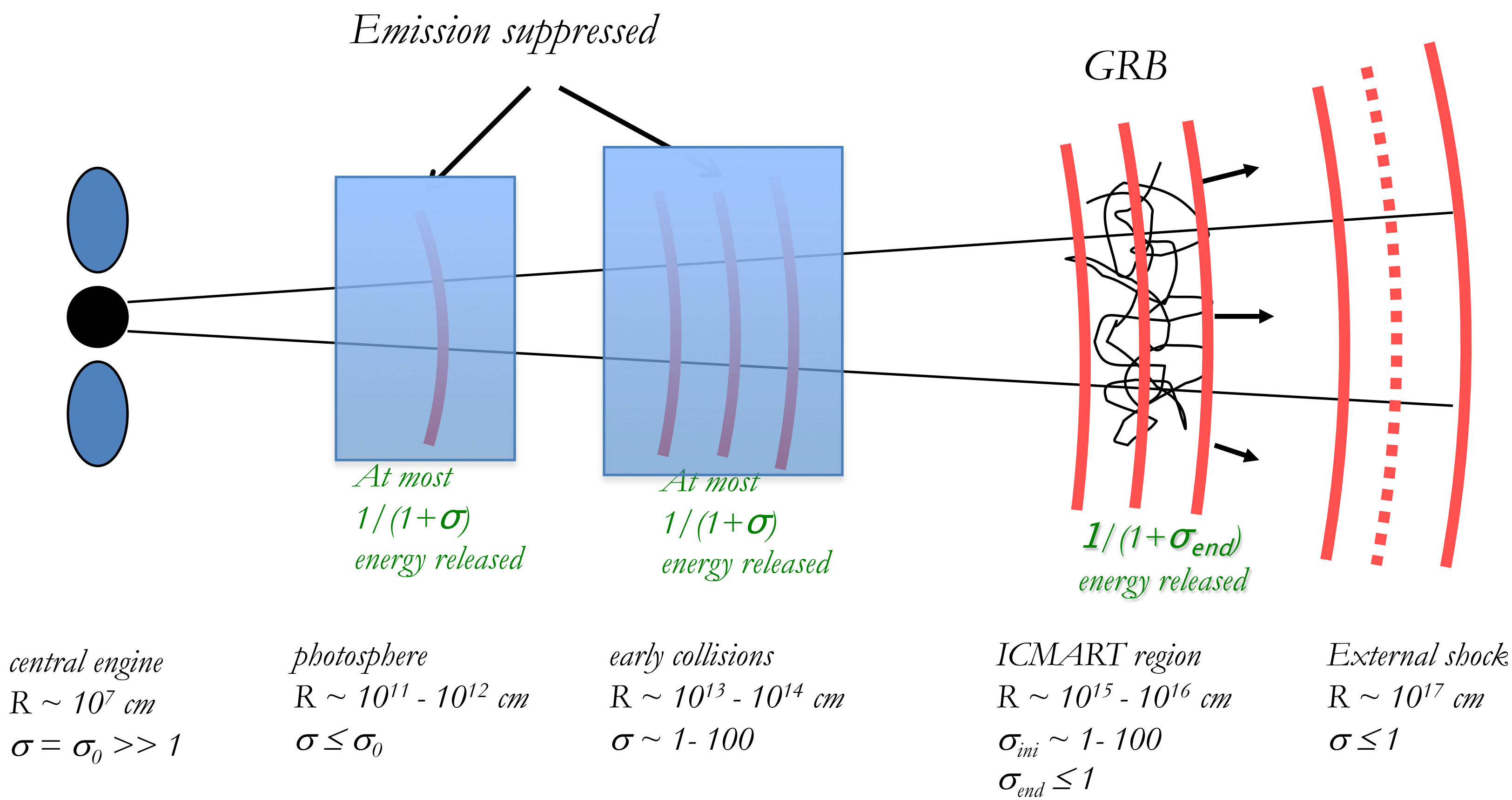


Magnetically dissipative photosphere model

The ICMART Model

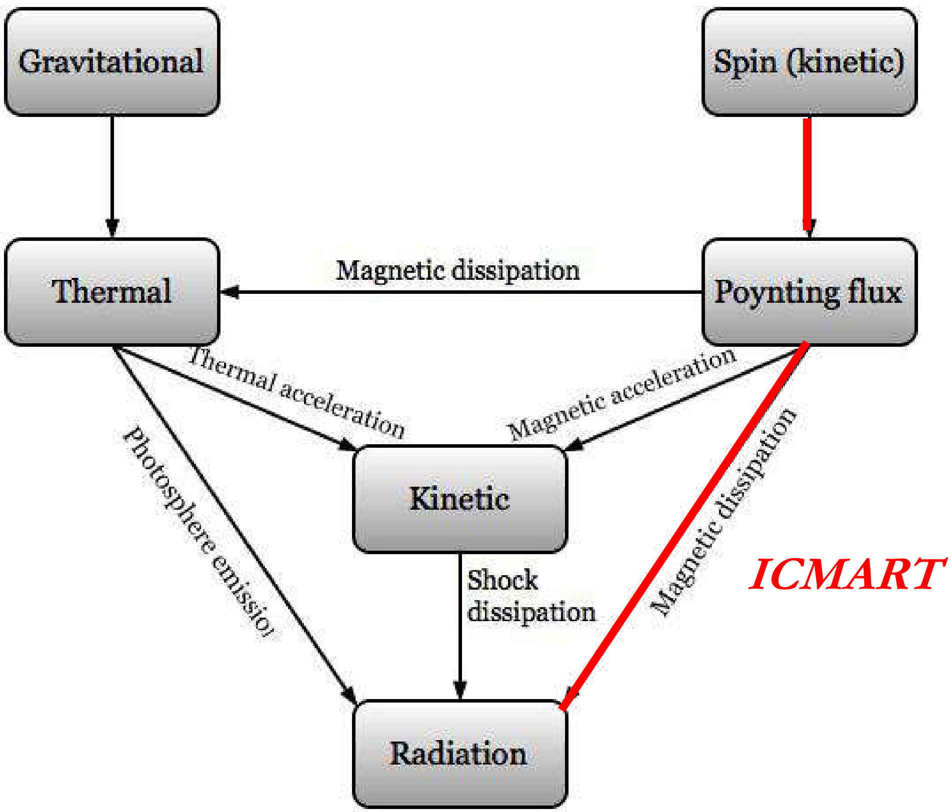
(Internal Collision-induced MAgnetic Reconnection & Turbulence)

Zhang & Yan (2011)

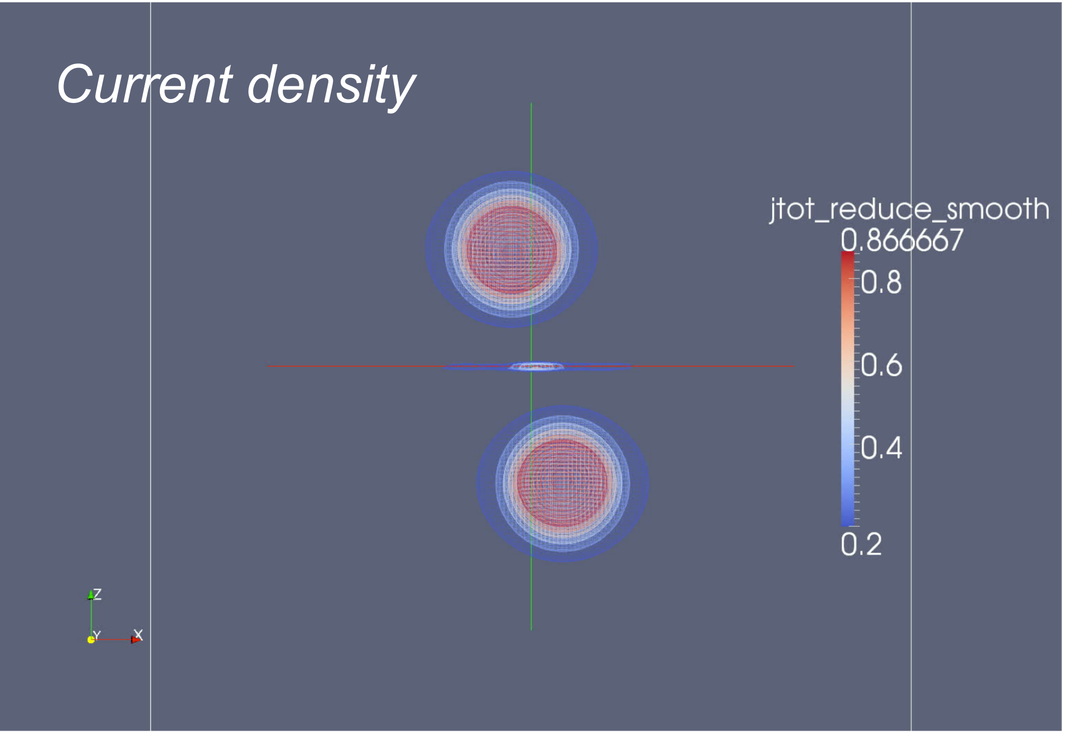


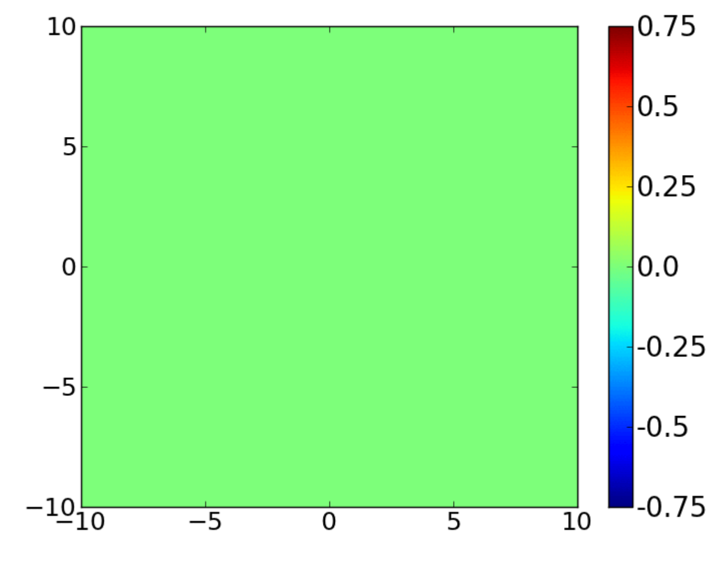
cf: Lyutikoc & Blandford (2003)…

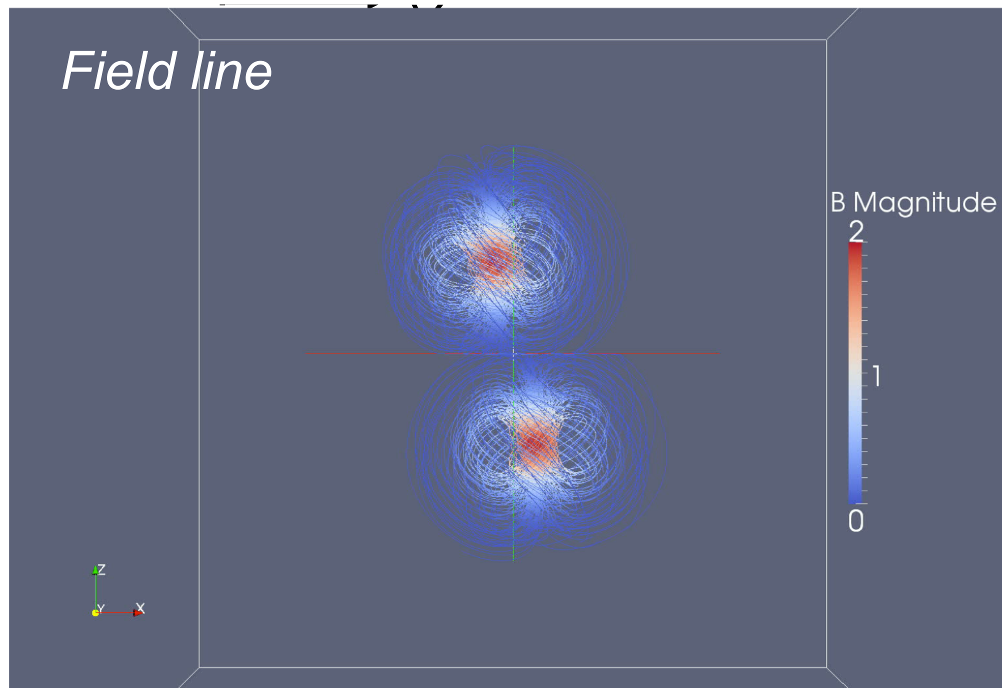
Energy Flow in GRBs



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







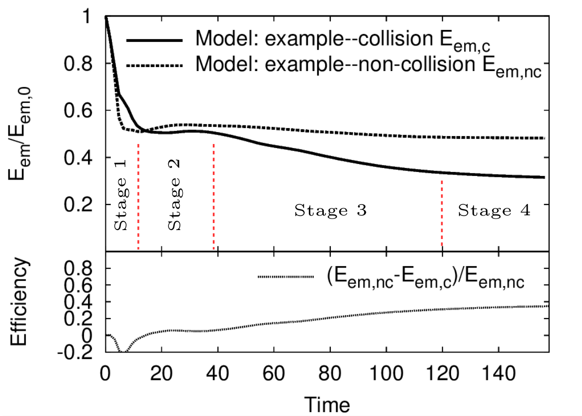
ICMART simulations:

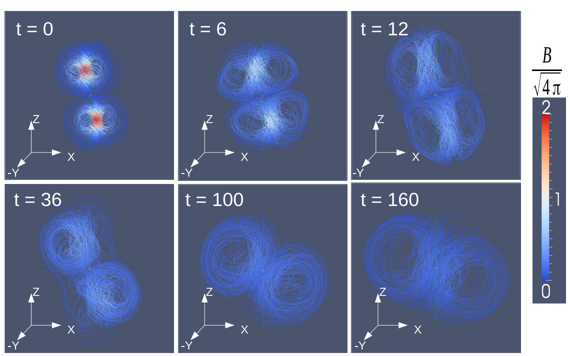
* *High efficiency*
* *Relativistic mini-jets*

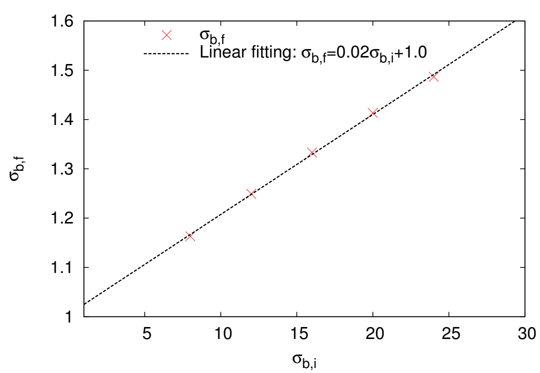
Deng et al. 2015, ApJ, 805, 163

ICMART simulations

(Deng et al., 2015)







$$(\mathbf{\Gamma}_2 m_2 + \mathbf{\Gamma}_1 m_1)(1+\sigma_{\rm ini}) = \mathbf{\Gamma}_m (m_1 + m_2 + U')(1+\sigma_{\rm end})$$

$$(\mathbf{\Gamma}_2 \beta_2 m_2 + \mathbf{\Gamma}_1 \beta_1 m_1)(1+\sigma_{\rm ini}) = \mathbf{\Gamma}_m \beta_m (m_1 + m_2 + U')(1+\sigma_{\rm end})$$

$$\begin{aligned}\eta_{\rm ICMART} &= \frac{\mathbf{\Gamma}_m U'}{(\mathbf{\Gamma}_1 m_1 c^2 + \mathbf{\Gamma}_2 m_2 c^2)(1+\sigma_{\rm ini})} \\ &= \frac{1}{1+\sigma_{\rm end}} - \frac{\mathbf{\Gamma}_m (m_1+m_2)}{(\mathbf{\Gamma}_1 m_1 + \mathbf{\Gamma}_2 m_2)(1+\sigma_{\rm ini})} \\ &\simeq \frac{1}{1+\sigma_{\rm end}} (\text{if } \sigma_{\rm ini} \gg 1).\end{aligned}$$

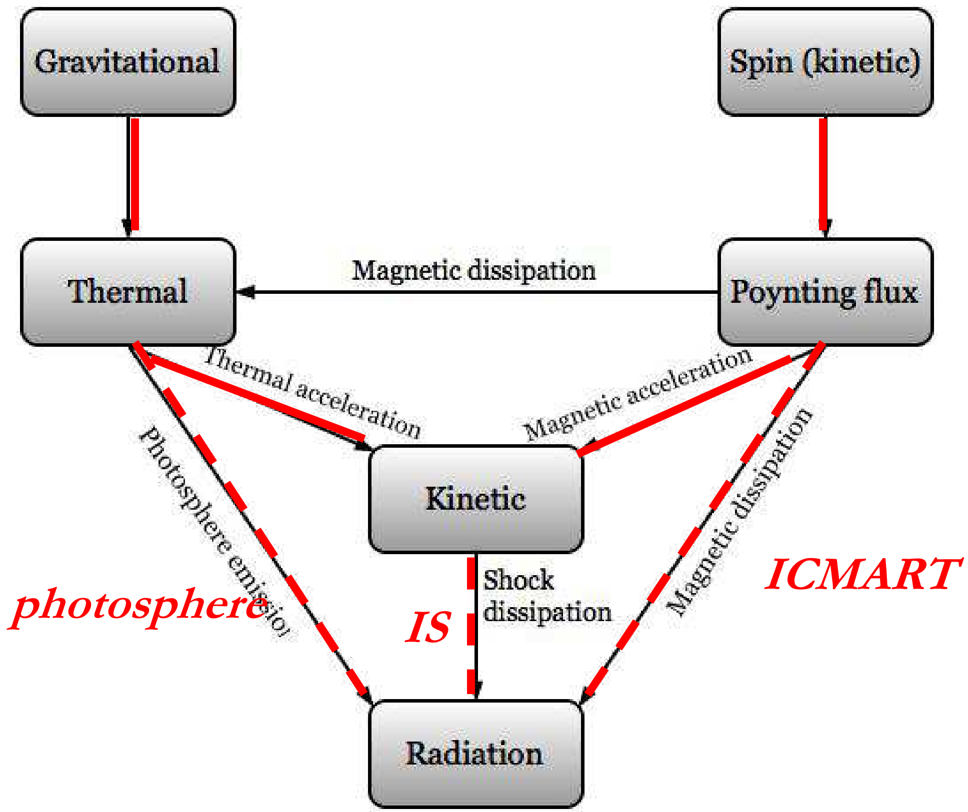
Zhang & Yan (2011)

TABLE 4
$\sigma_{b,f}$ - $\sigma_{b,i}$ RELATION AND THE ANALYTICAL VS. NUMERICAL EFFICIENCIES.

$\sigma_{b,i}$	$\sigma_{b,f}$	Efficiency (analytical)	Efficiency (numerical)
8	1.16	35.7%	33.3%
16	1.33	37.3%	34.4%
24	1.49	36.4%	34.7%

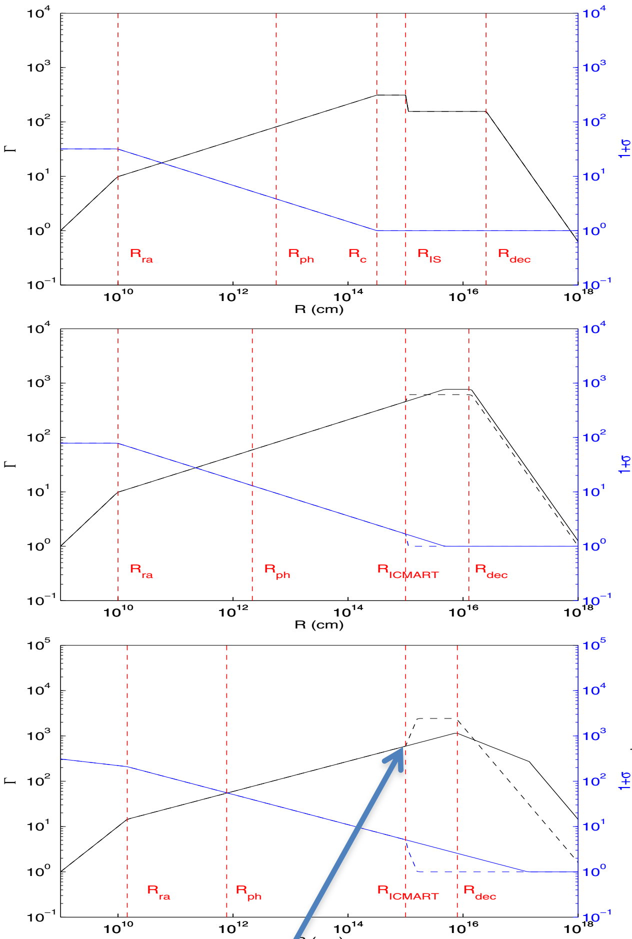
Deng et al. (2015)

Energy Flow in GRBs

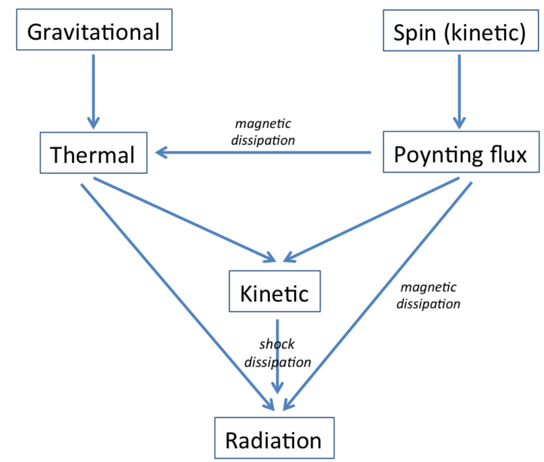


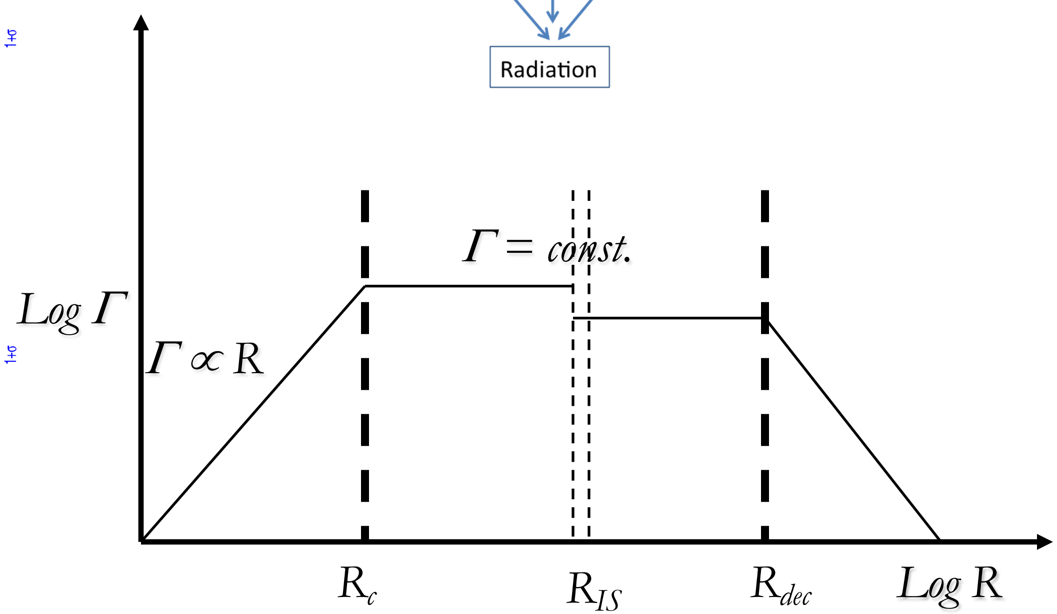
Hybrid models

Initial central engine parameters (η, σ_0) define jet dynamics and dissipation physics



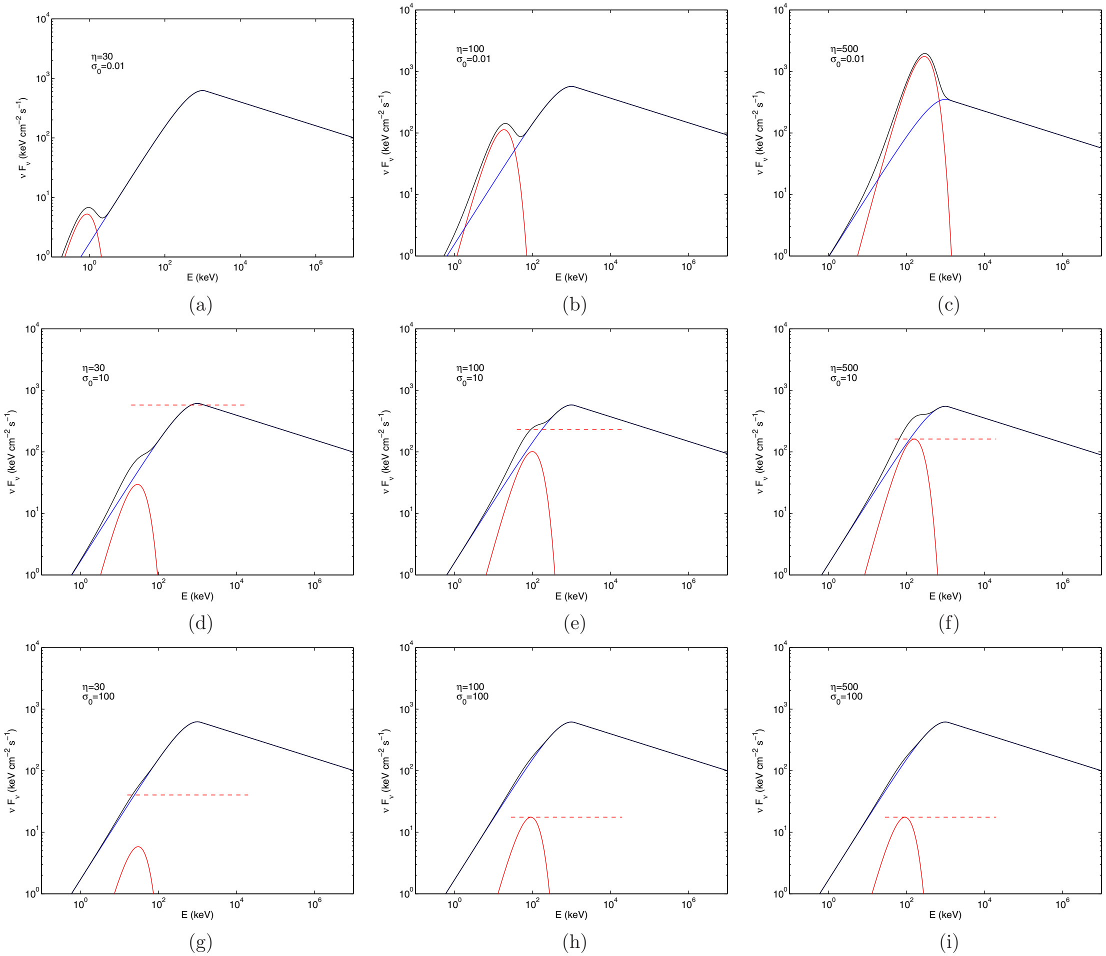
Gao & Zhang (2015)

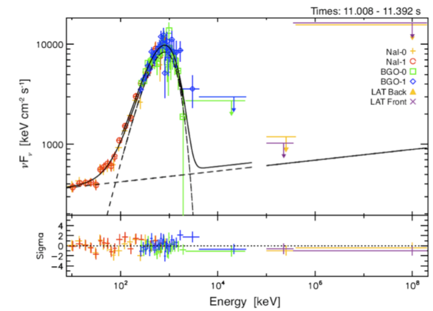


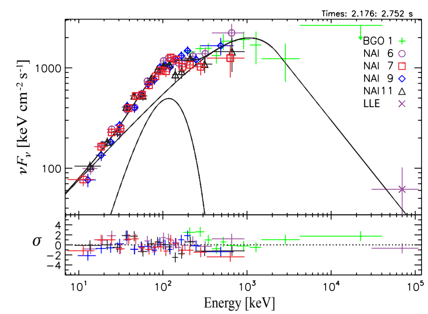


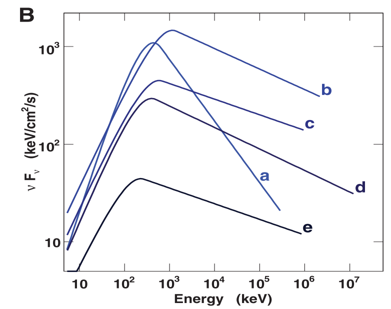
ICMART key prediction: emission site undergo acceleration as magnetic energy is dissipated!

Hybrid model (thermal + non-thermal)







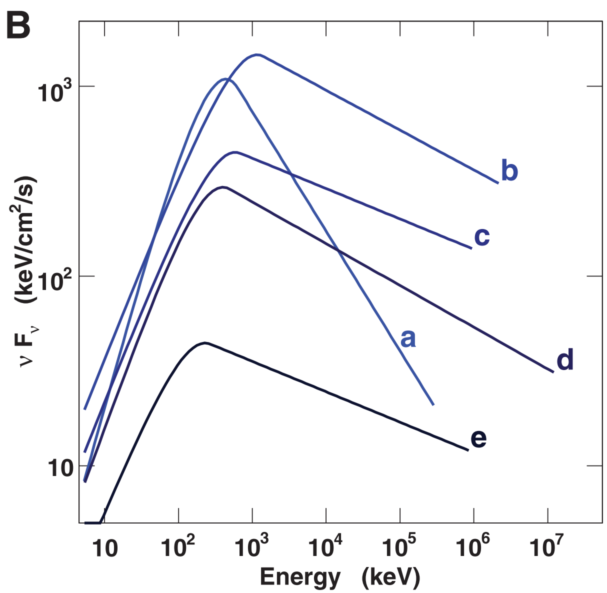


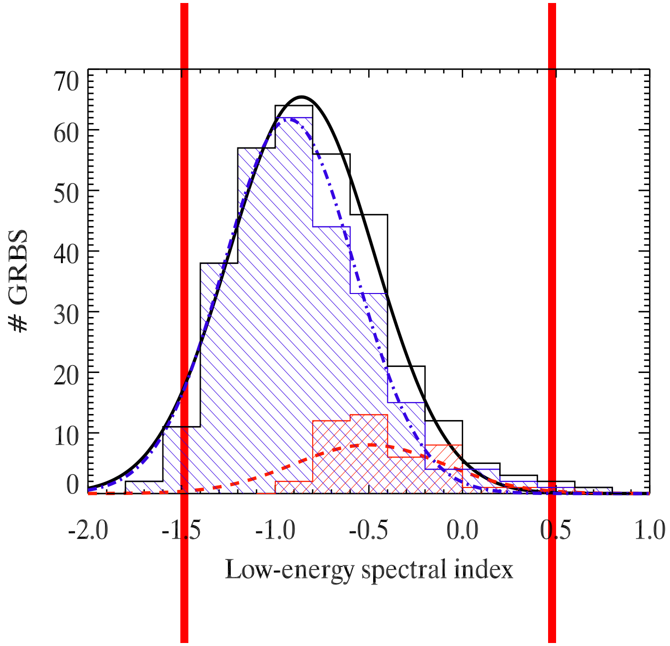
Gao & Zhang (2015, ApJ, 801: 103)

How to tell which picture is correct from the data?

Spectral properties

Debate (**α** battle): What is the origin of the "Band" component?





Simplest synchrotron prediction

Simplest photosphere prediction

Two distinct views:

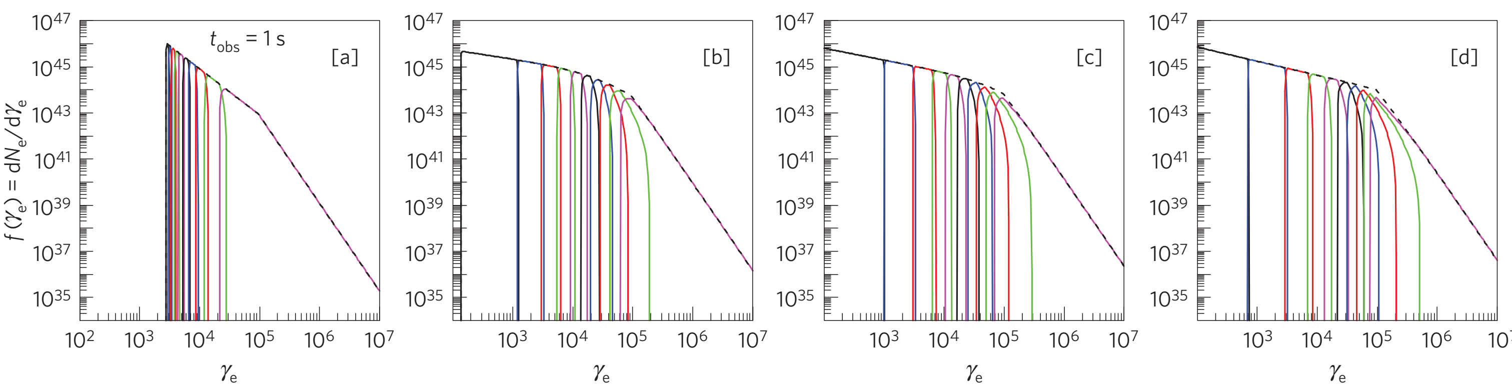
- *The Band component is the synchrotron emission in optically-thin region.*
- *The Band component is reprocessed quasi-thermal emission in a dissipative photosphere.*

Nava et al. (2011)

cf. Burgess' talk, Oganesyan's talk, Ryde's talk

Synchrotron Model:
Fast Cooling Spectrum Can Be Harder!
(Uhm & Zhang, 2014, Nature Physics, 10, 351)

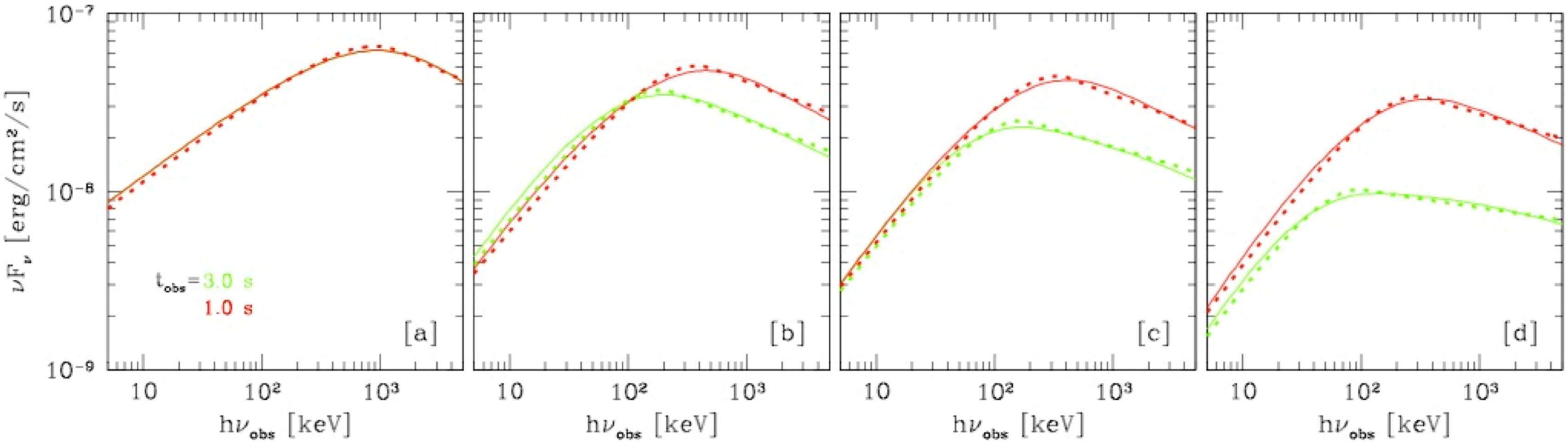
- B is decreasing with radius
- Electrons are not in steady state
- Electron spectrum deviates significantly from -2 below the injection energy



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

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

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

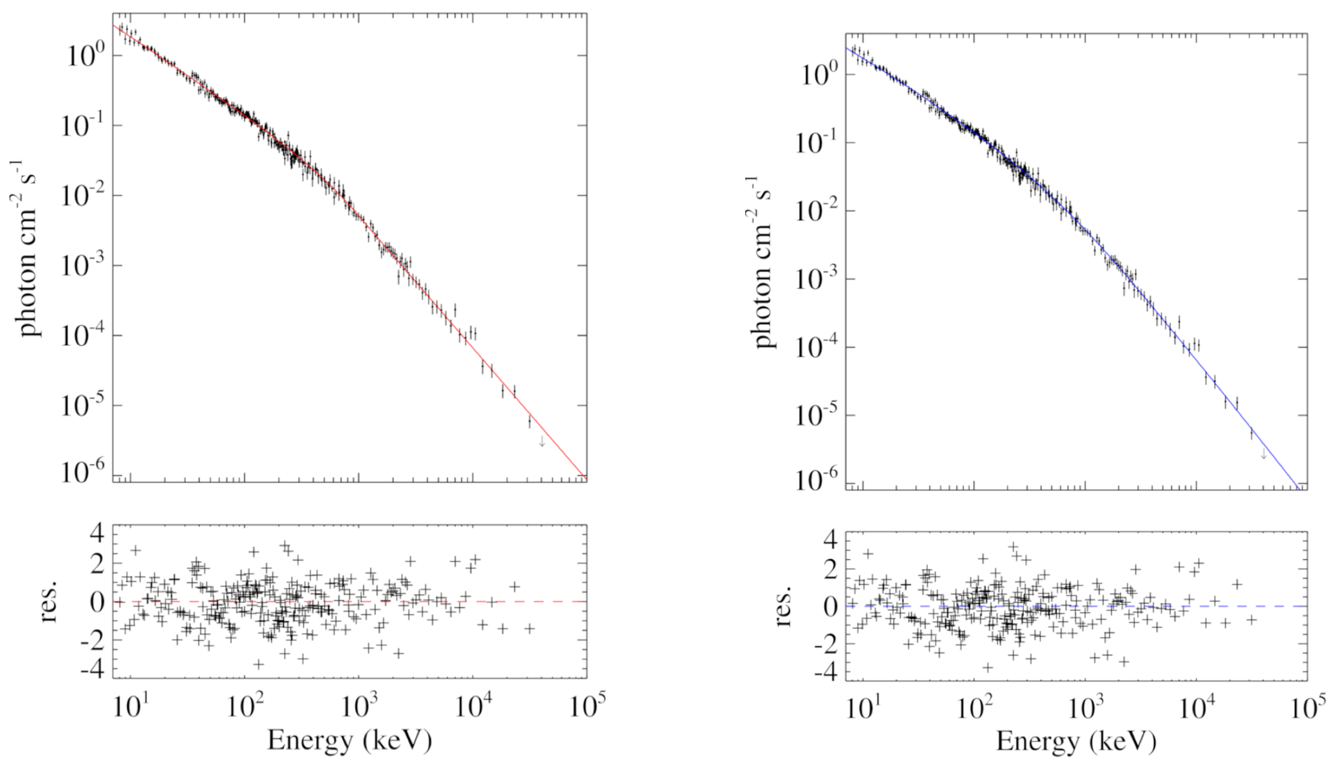


Requirement: Large emission radius where B is low!

“Band” Function is made from synchrotron

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

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



Band & synchrotron model fits

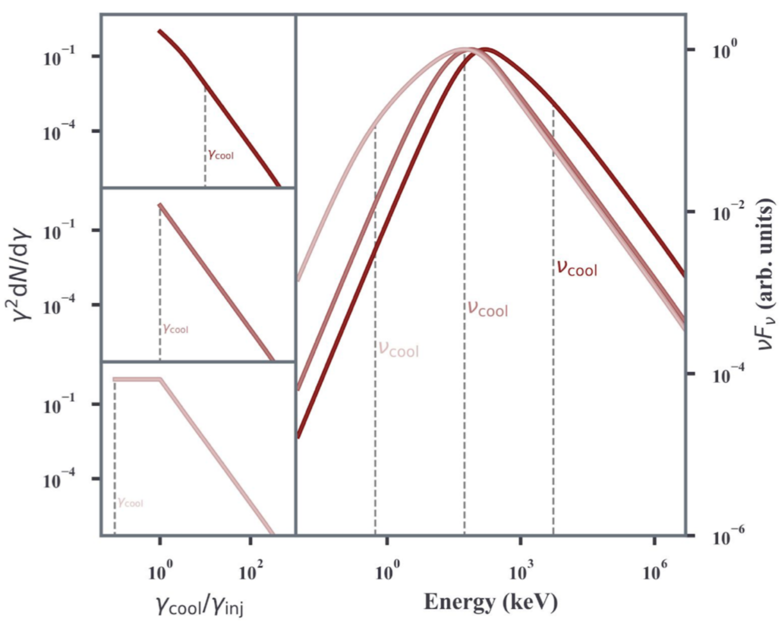
See also talks of Burgess, Guirec, Oganesyan, Ravasio, Piron …

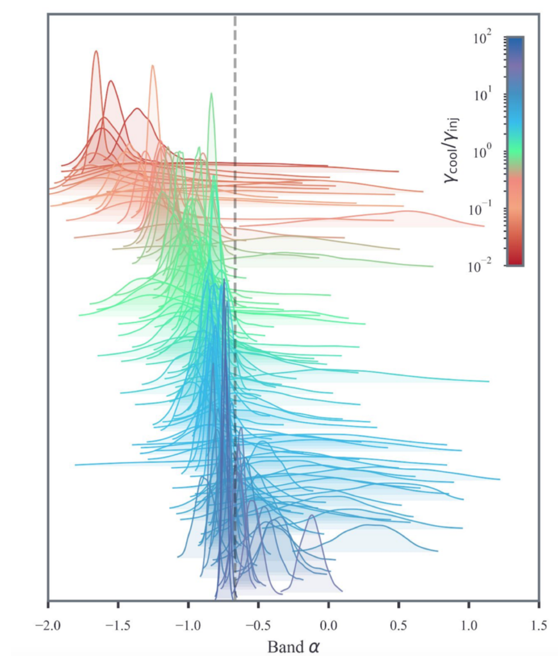
Gamma-ray bursts as cool synchrotron sources

2019, Nature Astronomy

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

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



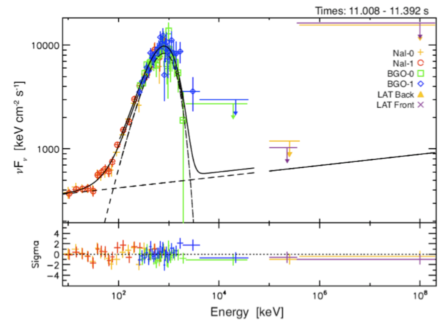


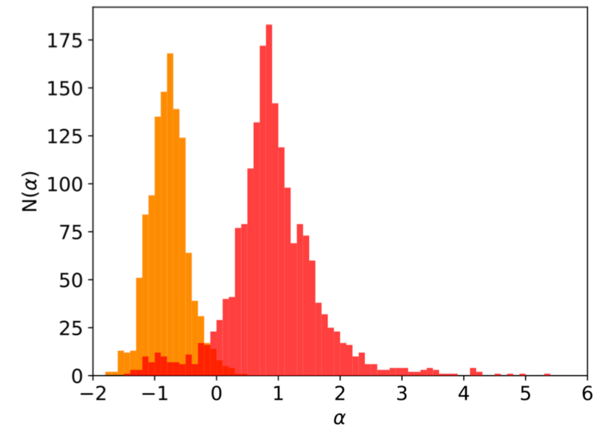
Band Function from Photosphere Emission

- Low-energy photon index
  - Typically hard

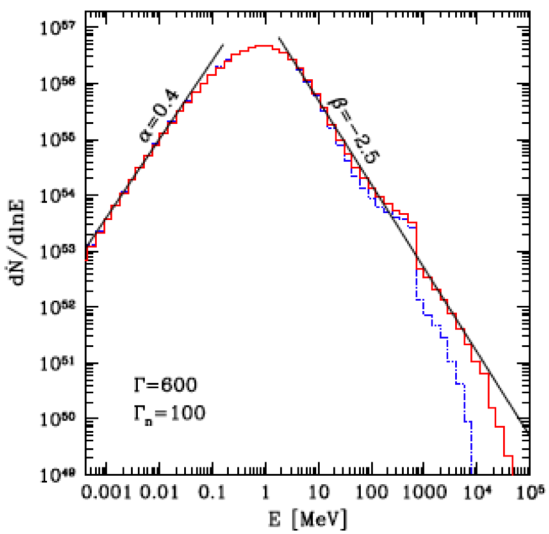
$$F_\nu \sim \nu^{1.5}\ (\alpha \sim +0.5)$$

  - Narrow Peak
- May reach -1 for some special types of structured jets, but not -1.5
- Mechanism for 090902B-like GRBs
- Not easy to interpret "typical" Band

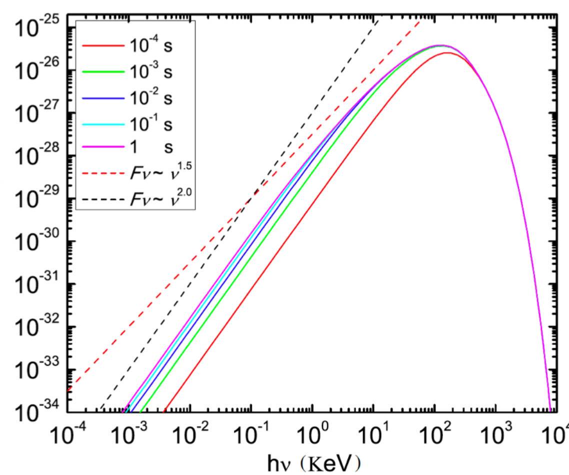




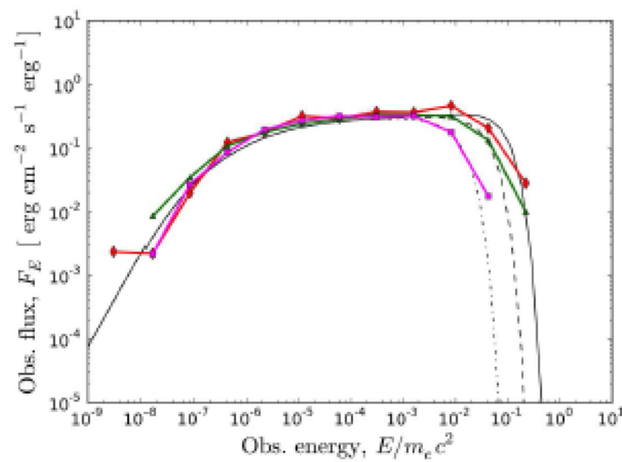
Parsotan et al., 2018, ApJ, 869, 103



Beloborodov, 2010, MNRAS, 407, 1033



Deng & Zhang, 2014, ApJ, 785, 112



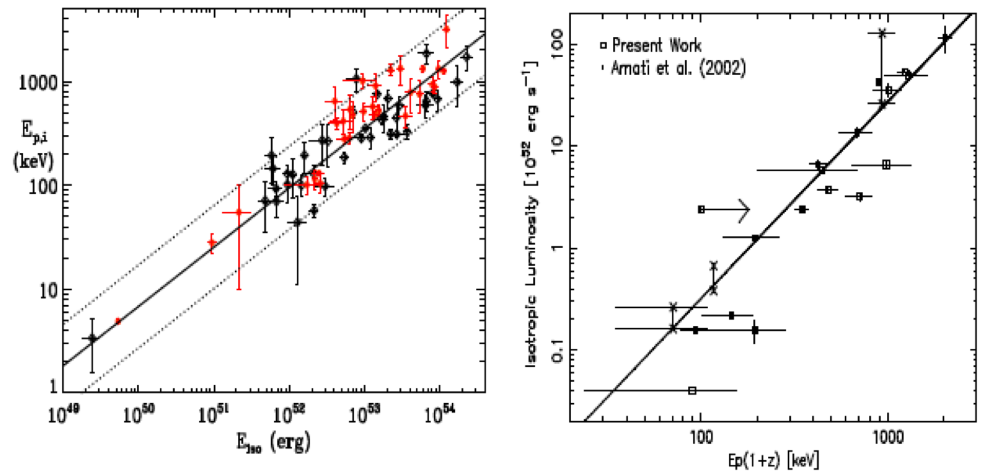
Lundman, Pe'er & Ryde, 2013, MNRAS, 428, 2430

Correlations

(Amati / Yonetoku / Liang)

Amati / Yonetoku relations

- One may not be too proud of reproducing the relations
- In all models, Ep is a function of L and $\mathbf{\Gamma}$. The relations can be reproduced given a particular L-$\mathbf{\Gamma}$ relation.



Amati et al. 2002; Yonetoku et al. 2004

TABLE 1

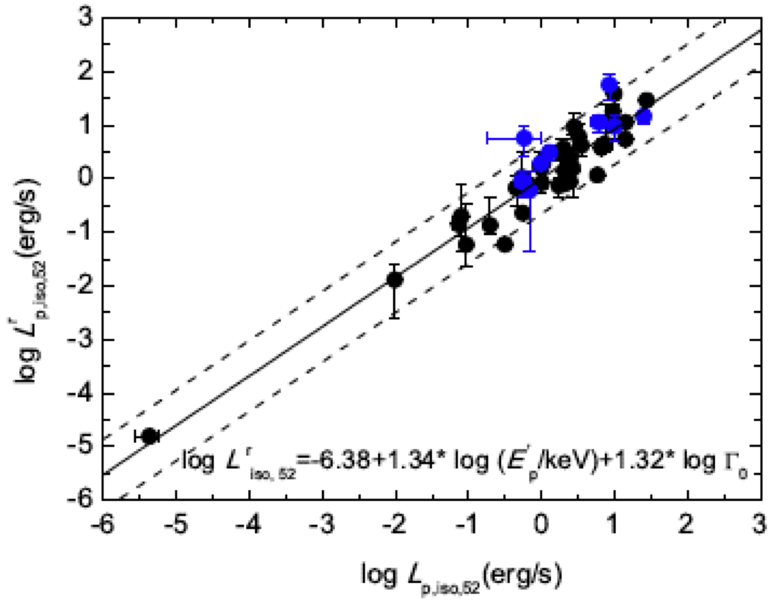
MODEL PREDICTIONS FOR E_p

Models	Subcategories	E_p	Comments
Internal models	Low σ: internal shocks	$\propto \epsilon_{x3} L^{1/2} \Gamma^{-2} t_v^{-1} (1+z)^{-1}$	$\gamma_e^{(1)}$ relevant
	High σ: magnetic dissipation	$\propto \epsilon_{x5} \Gamma (1+z)^{-1}$	$\gamma_e^{(2)}$ relevant
	Pair photosphere	$\propto \Gamma T'_{\pm} / \tau'^{2}_{\pm} (1+z)^{-1}$	Comptonized spectrum
External models	Low σ: external shocks	$\propto \epsilon_{x6} \Gamma^4 n_{\rm ext}^{1/2} (1+z)^{-1}$	B generated in situ
	High σ: plasma-barrier interaction	$\propto \epsilon_{x7} \Gamma^{8/3} L^{1/2} E^{-1/3} n_{\rm ext}^{1/3} (1+z)^{-1}$	B carried from the wind
Innermost models	$\eta < \eta_{c1} \sim 250(1+\sigma)^{-1/5}$	$\propto L^{-5/12} t_{v,m}^{1/6} \Gamma^{8/3} (1+z)^{-1}$	Wind coasting regime
	$\eta_{c1} < \eta < \eta_{c2}$	$\propto L^{-1/12} t_{v,m}^{-1/6} \Gamma (1+z)^{-1}$	Shell coasting regime
	$\eta > \eta_{c2} \sim 10^4 (1+\sigma)^{-1/3}$	$\propto L^{1/4} t_{v,m}^{-1/2} (1+z)^{-1}$	Shell acceleration regime

Zhang & Meszaros, 2002, ApJ, 581, 1236

Liang fundamental-plane relations

- More challenging to reproduce
- Simple photosphere and internal shock models fail
- ICMART possible



$$E_{\rm p,z} \propto T_{\rm ph} \propto L^{-5/4}\Gamma_0^6,$$

$$E_{\rm p,z} \propto L^{1/2}\Gamma_0^{-2}$$

$$E_{\rm p,z} \propto L^{1/2}R^{-1}\sigma^2$$

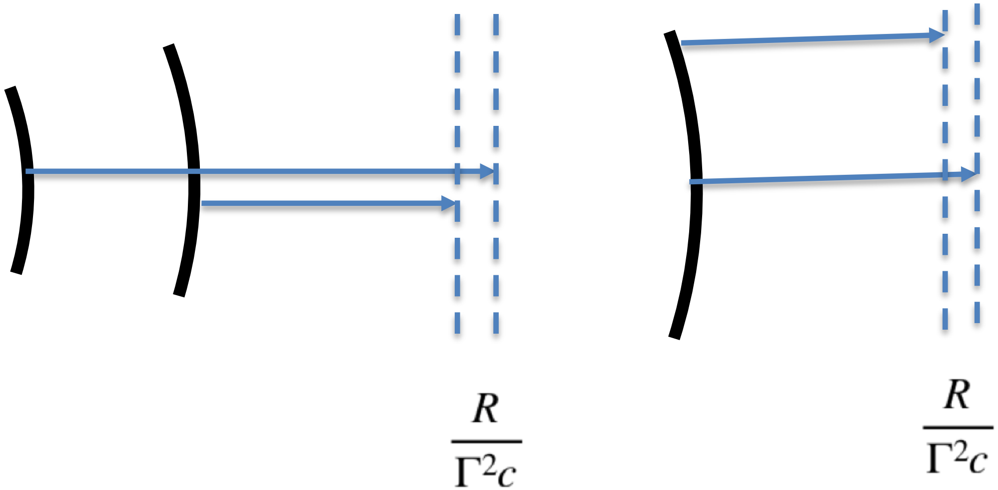
$$L_{\gamma,\rm p,iso,52} = 10^{-6.38\pm0.35}\left(\frac{E_{p,z}}{\rm keV}\right)^{1.34\pm0.14}\Gamma_0^{1.32\pm0.19}$$

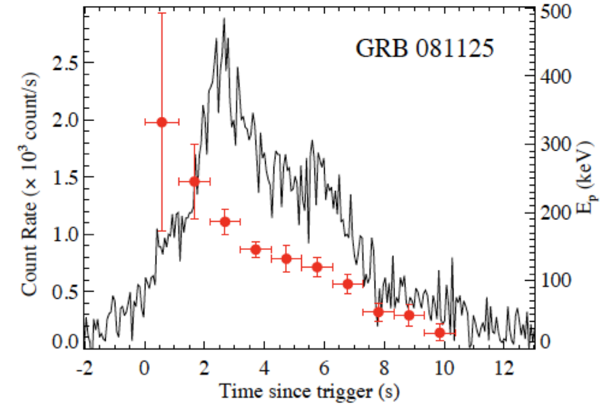
$$E_{p,z} = 10^{3.71\pm0.38}\ {\rm keV}\ L_{\gamma,\rm p,iso,52}^{0.55\pm0.06}\Gamma_0^{-0.50\pm0.17}.$$

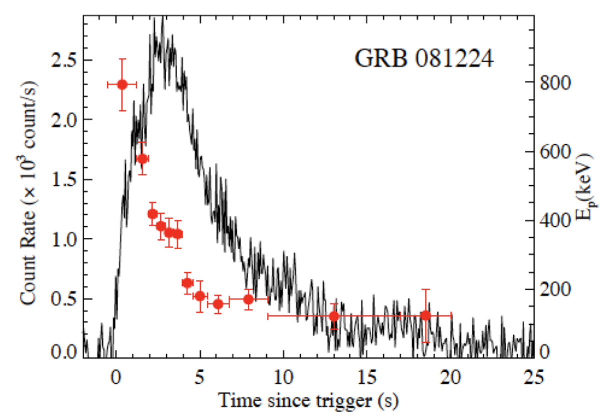
Liang et al. 2015, ApJ, 813, 116

Temporal properties

Characteristic time scale:

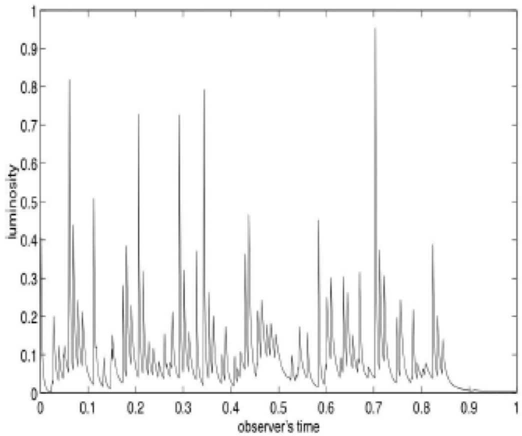


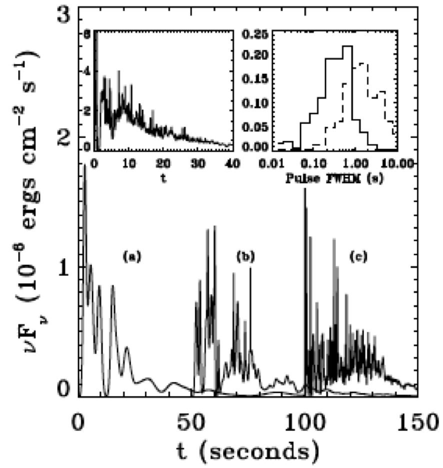


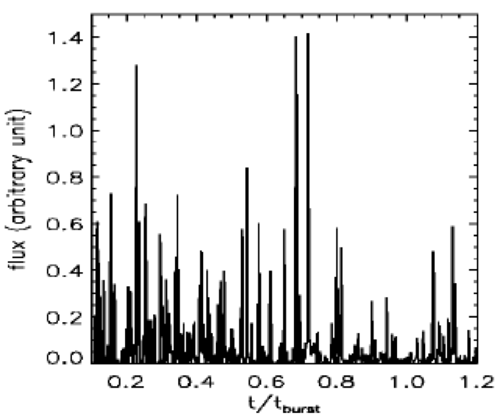


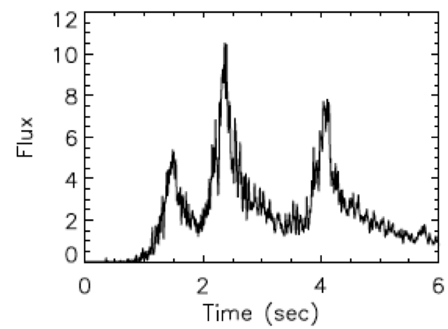
$$\Delta t \sim \frac{R}{\Gamma^2 c} \simeq (0.3\text{ms})\ R_{11}\Gamma_2^{-2} \simeq (30\text{ms})\ R_{13}\Gamma_2^{-2} \simeq (3\text{s})\ R_{15}\Gamma_2^{-2}$$

Model lightcurves

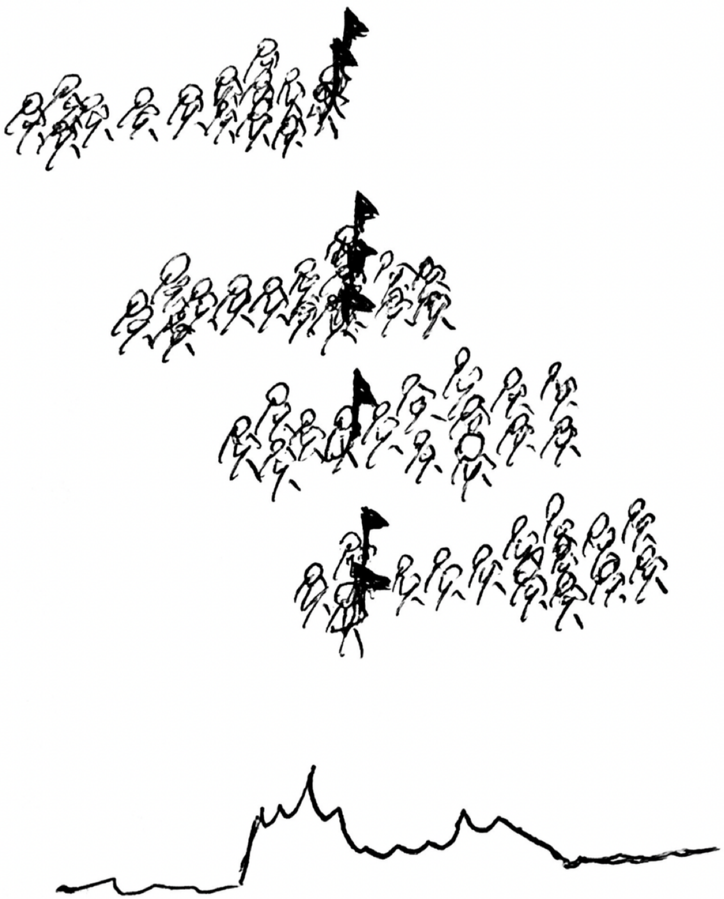




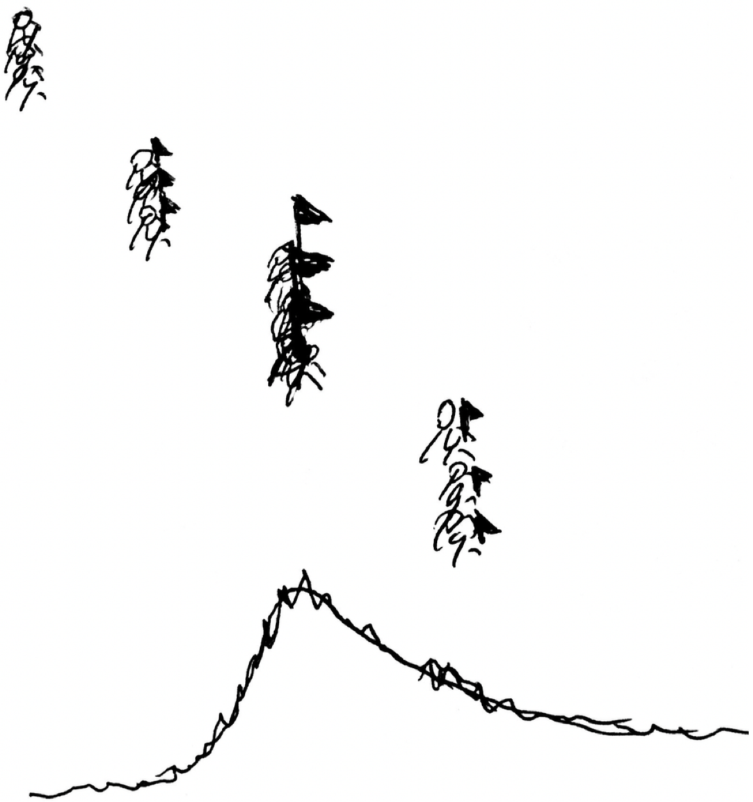




Kobayashi et al. (1997); Dermer & Mitman (1999)
Narayan & Kumar 2009; Zhang & Zhang (2014)



photosphere
small-radius IS



ICMART
Large-radius IS

Joint spectral & temporal properties:

Spectral lags

Ep evolution patterns

Smoking gun #1:
GRB pulses, Spectral lags & Ep evolutions

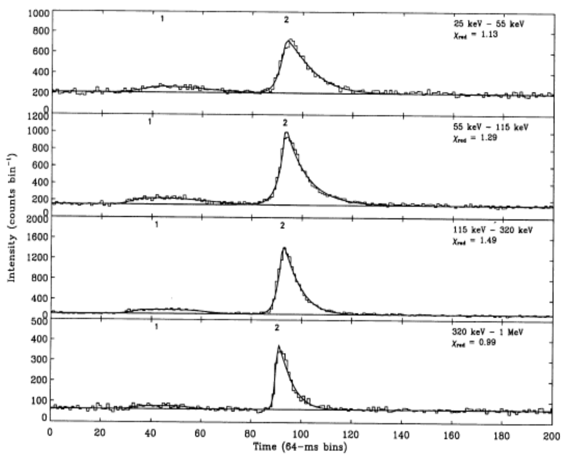
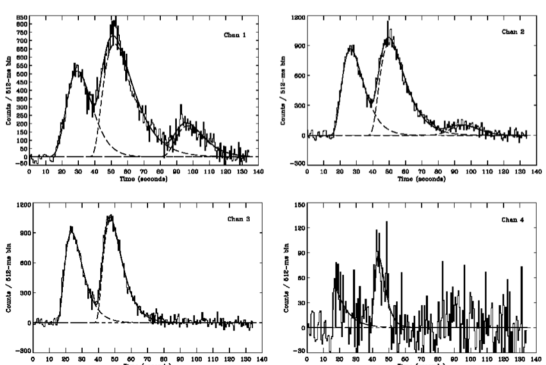
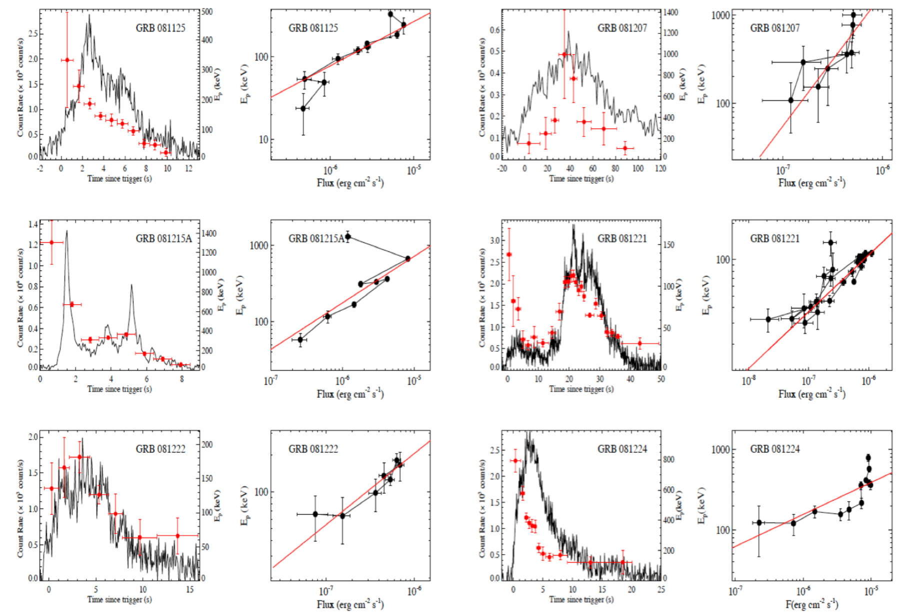


FIG. 16.—BATSE trigger 999: a simple burst profile, with two fitted pulses. Both pulses, identified in all four channels, are considered separable since their overlap is insignificant.

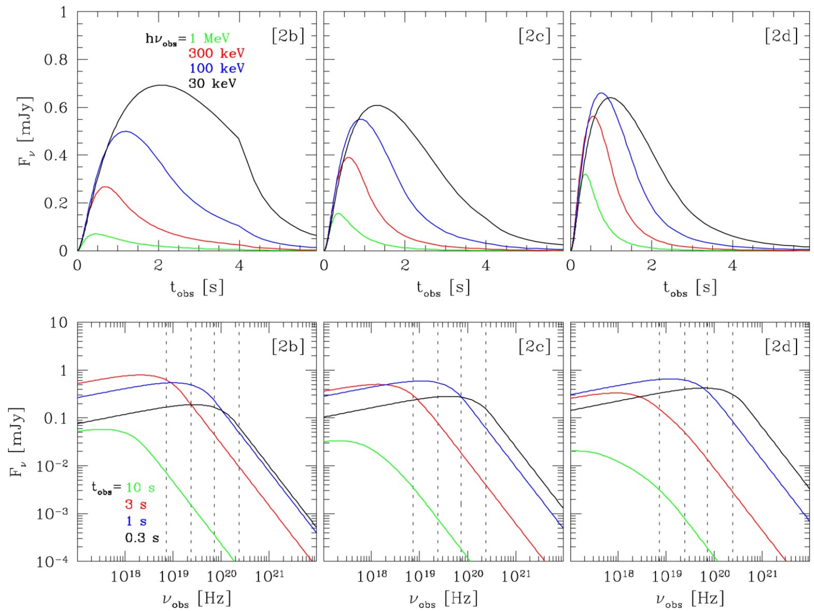


Norris et al. (1996)

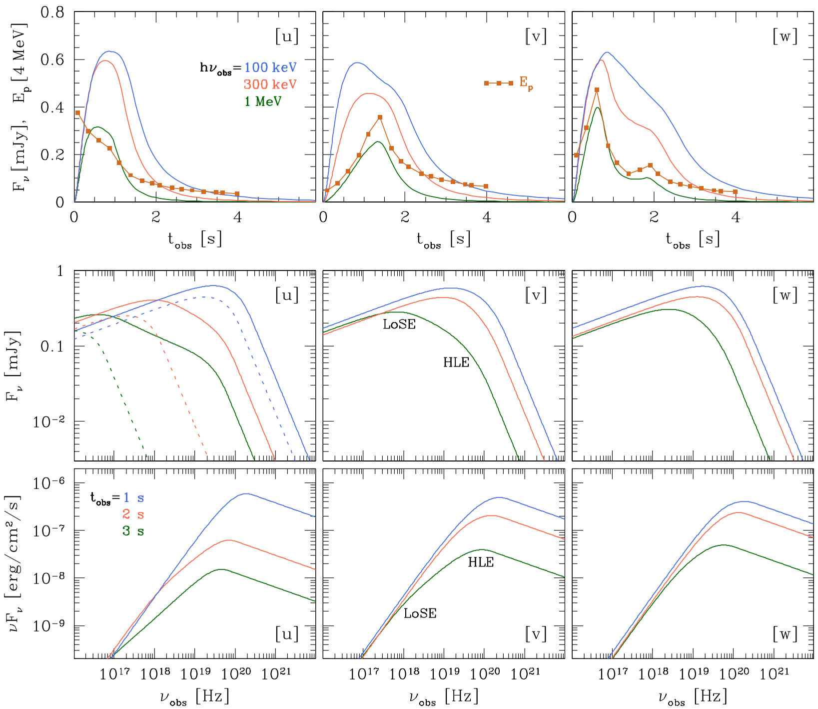


(Lu et al. 2012)

Spectral lags & Ep evolutions



Uhm & Zhang (2016)



Uhm, Zhang & Racusin (2018)

Model requirements:

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

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

Other constraints:

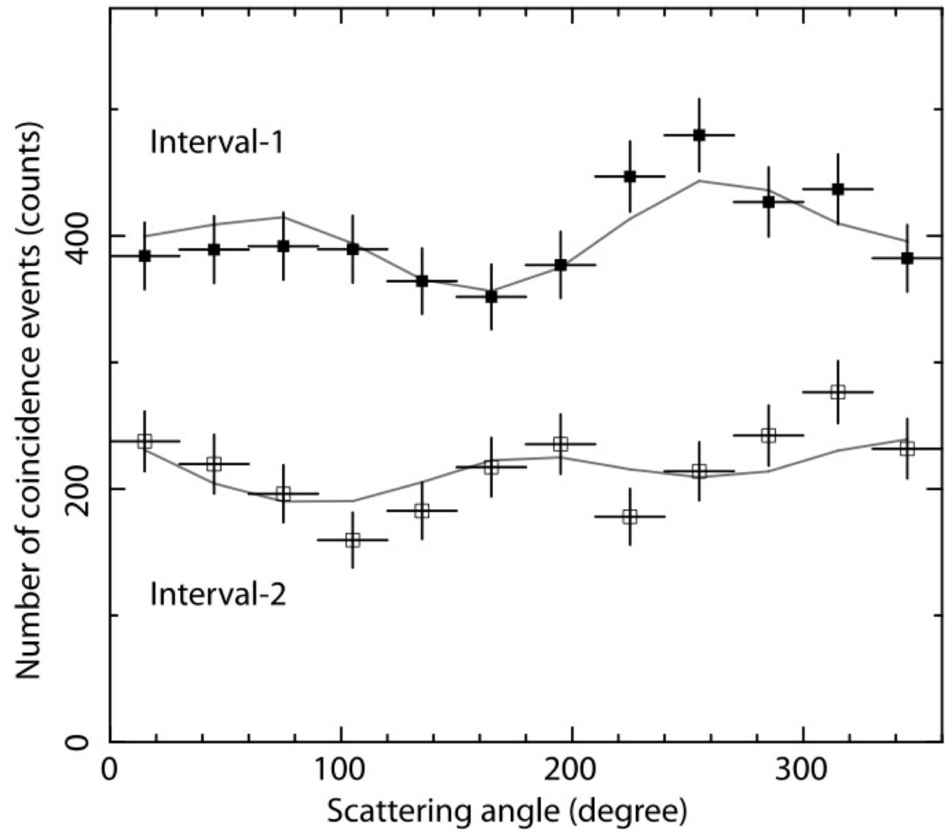
Polarization

Neutrino flux

…

Polarization data

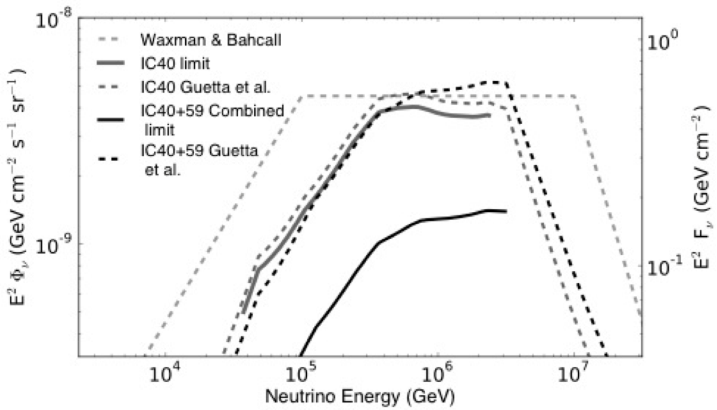
- Bright GRBs with polarization detections in gamma-rays: GRB 100826A: 27%±11% (Yonetoku et al. 2011); POLAR results (S.-N. Zhang et al. 2019);
- Early optical emission has "residual" ~10% polarization from reverse shock (Steele et al. 2009; Mundell et al. 2013)
- Prompt optical emission 8.3%±0.3% polarization (Troja et al. 2017)



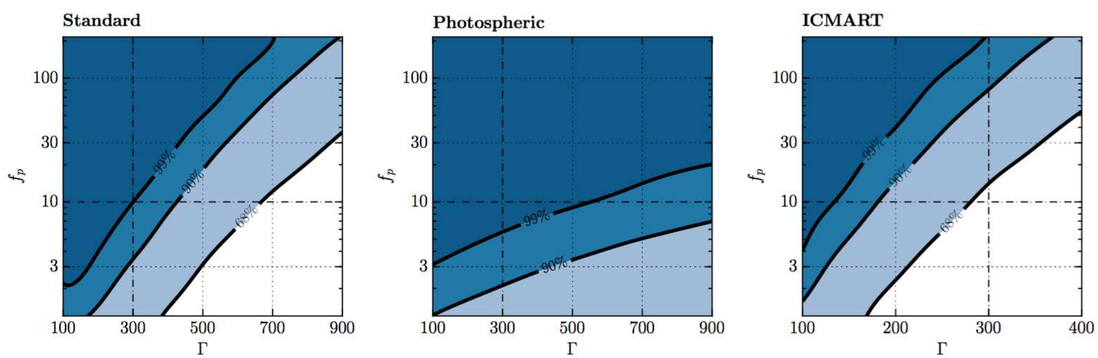
Yonetoku et al. (2011)

Non-detection of neutrinos by IceCube

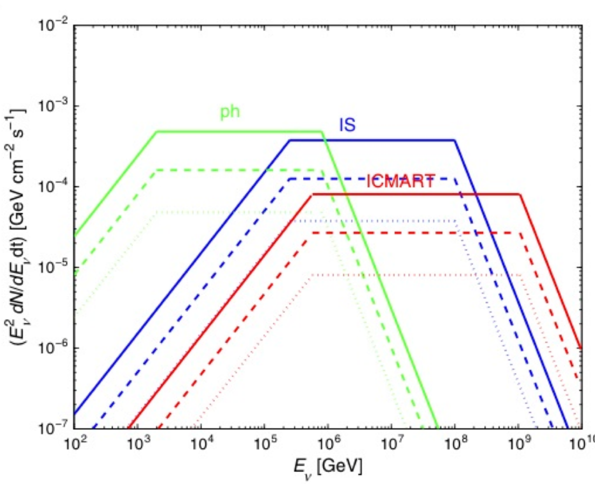
- Icecube so far has not detected any high-energy neutrino associated with GRBs!
- Consistent with a large emission radius (magnetic dissipation)



IceCube 2012



Icecube collaboration 2016

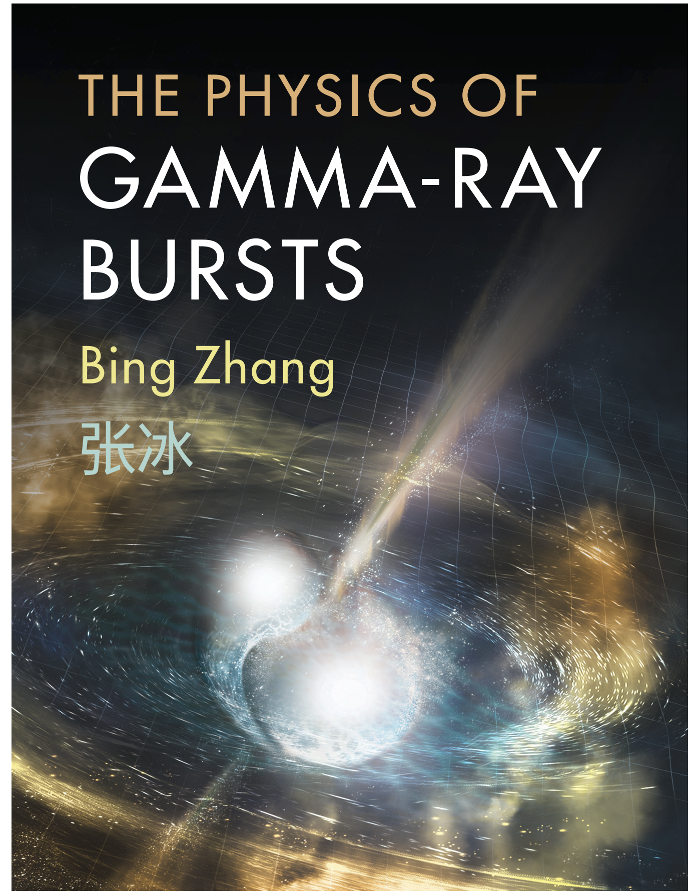


Zhang & Kumar 2013

Liu's talk

Table 9.1 Grading chart for three representative GRB prompt emission models.

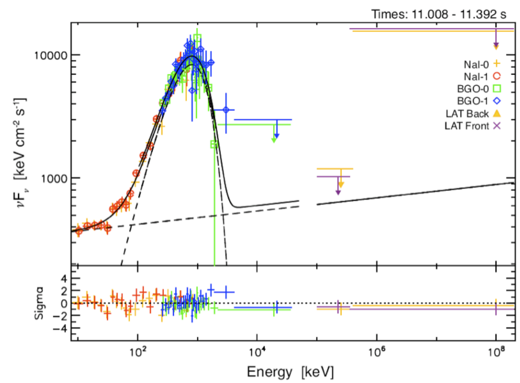
Criterion	photosphere	IS	ICMART
Lightcurve properties:			
Slow variability	Yes	Yes	Yes
Fast variability	Yes	Yes	Yes
Superposition	Yes	Yes	Yes
E_p evolution: hard-to-soft	No	Yes(?)	Yes
E_p evolution: tracking	Yes	Yes(?)	Yes(?)
Spectral lags	No	No(?)	Yes
Power density spectrum	Yes	Yes	Yes
Spectral properties:			
Origin of E_p	Yes	Yes	Yes
$\alpha \sim -1$	Yes(?)	Yes(?)	Yes(?)
$\alpha > -2/3$	Yes	No	No
β	Yes	Yes	Yes
narrowness	Yes	Yes(?)	Yes(?)
E_p distribution	Yes(?)	Yes(?)	Yes(?)
thermal component	Yes	No	No
high-energy component	No(?)	Yes(?)	Yes(?)
Other properties:			
γ-ray radiative efficiency	Yes	Yes(?)	Yes
γ-ray polarization	Yes(?)	Yes(?)	Yes
optical polarization	No(?)	No(?)	Yes
neutrino upper limit	No(?)	No(?)	Yes
three-parameter correlations	No(?)	No(?)	Yes(?)



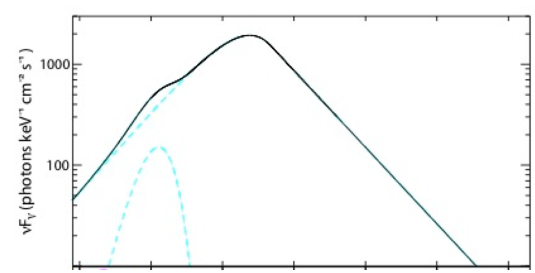
Big Picture: GRB jet composition

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

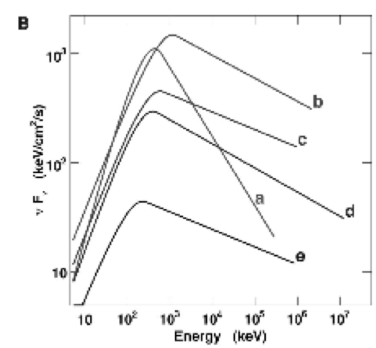
Most GRBs have significant magnetization



GRB 090902B



GRB 110721A

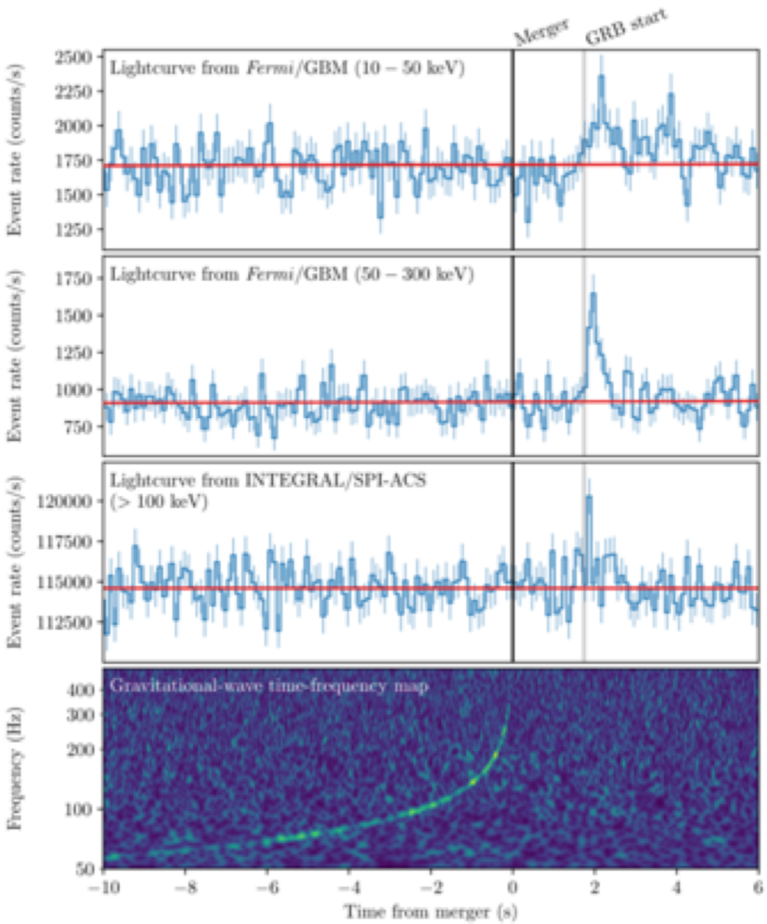


GRB 080916C

GW170817 / GRB 170817A

Provided T0!

Origin of the 1.7 s delay?



$$\Delta t = (\Delta t_{\rm jet} + \Delta t_{\rm bo} + \Delta t_{\rm GRB})(1+z),$$

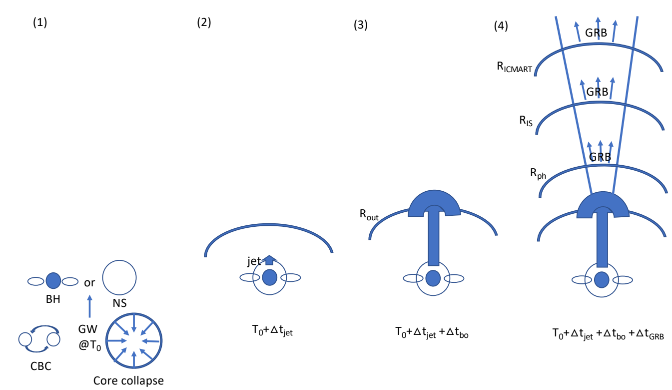
waiting time for jet launching — *jet breakout time* — *Time to reach GRB radius*

$$\Delta t_{\rm GRB} \simeq (1-\beta\cos\theta)\frac{R_{\rm GRB}}{c} \simeq \frac{R_{\rm GRB}}{\Gamma^2 c}.$$

$$T_{\rm GRB} \sim \frac{R_{\rm GRB}}{\Gamma^2 c}.$$

~2 s

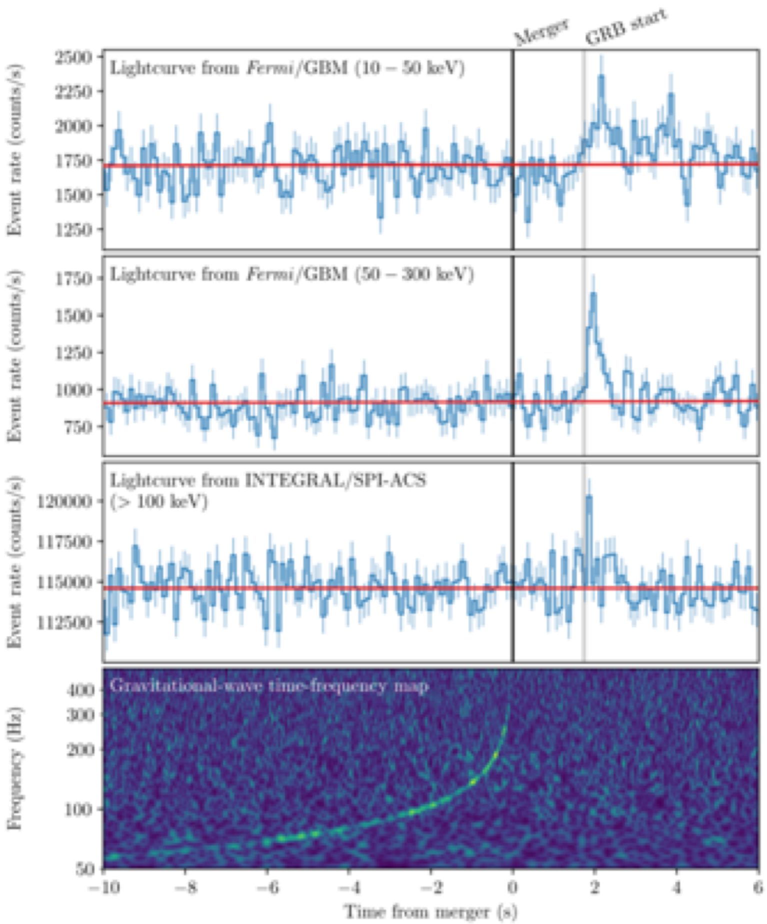
~1.7 s



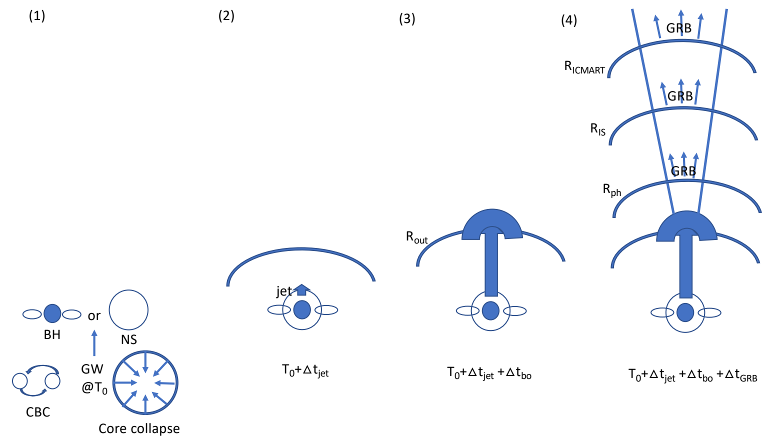
Delay time ~ duration
Not evidence of forming a BH

Zhang, 2019, Frontiers of Physics, 14, 64402, arXiv:1905.00781
Talks of Burns & Hamidani

Origin of the 1.7 s delay?



Delay time ~ duration
Not evidence of forming a BH



- Mostly contributed by

$$\Delta t_{\rm GRB} \simeq (1-\beta\cos\theta)\frac{R_{\rm GRB}}{c} \simeq \frac{R_{\rm GRB}}{\Gamma^2 c}.$$

- Too long for photosphere / small-radius internal shock
- Consistent with ICMART (B.-B. Zhang et al. 2018, Nature Communications, 9, 447)

Summary

- The GRB prompt emission mechanism is still subject to debate.
- Open questions:
  - Jet composition
  - Energy dissipation mechanisms
  - Radiation mechanisms
- My best bet:
  - Jet composition is diverse
  - At least some (or most) GRBs carry significant Poynting flux
  - No model can interpret all GRBs

  Everybody is correct (to some degree)!

  All the models are probably relevant for some GRBs!