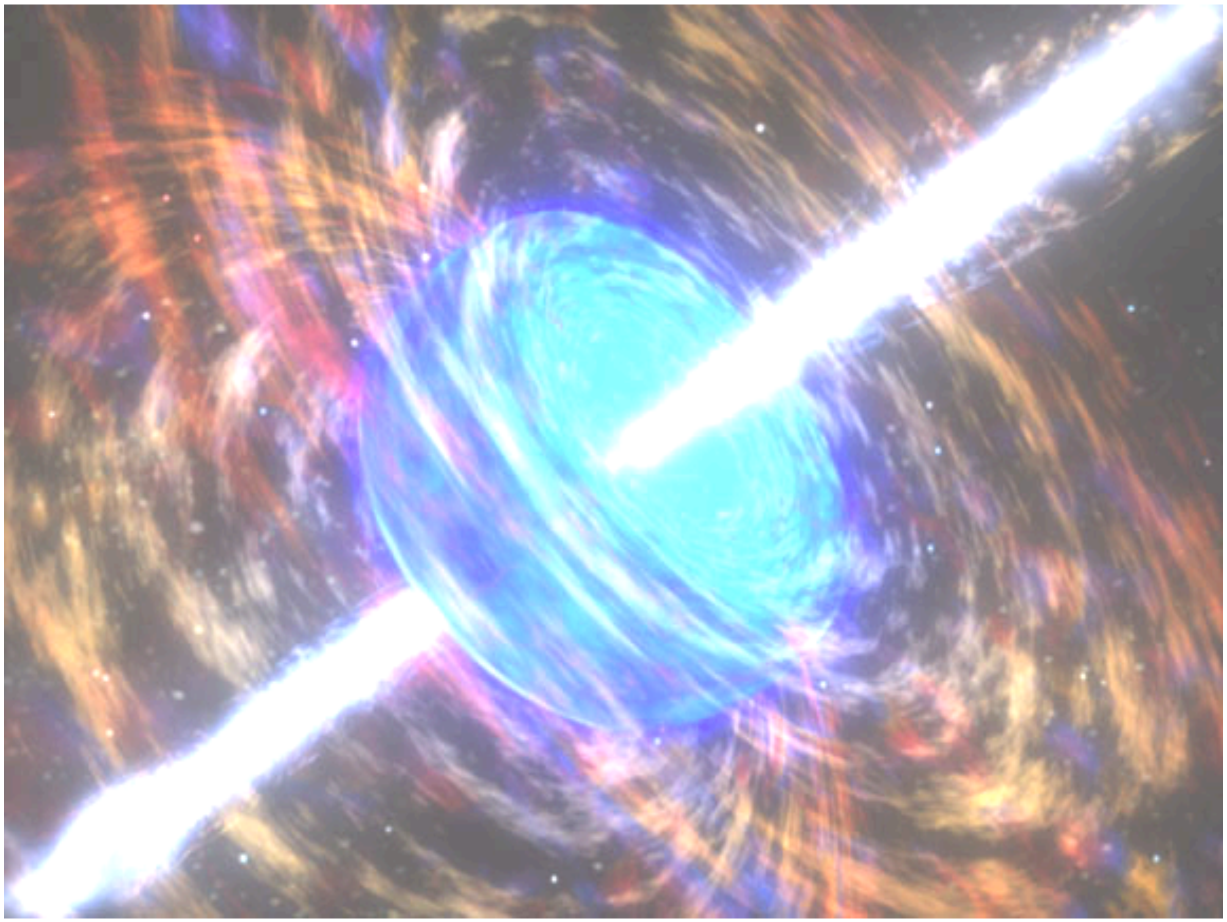
Open Questions in GRB Physics

(Bing Zhang, University of Nevada Las Vegas)

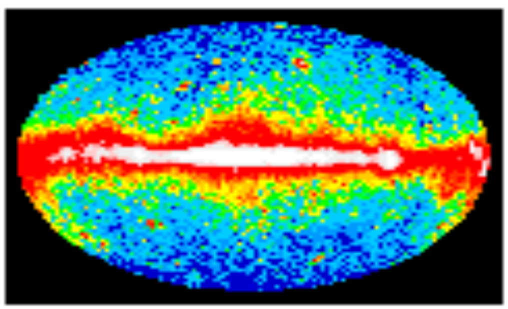
(Zhang 2011, Comptes Rendus Physique, 12, 206-225; arXiv:1104.0932)

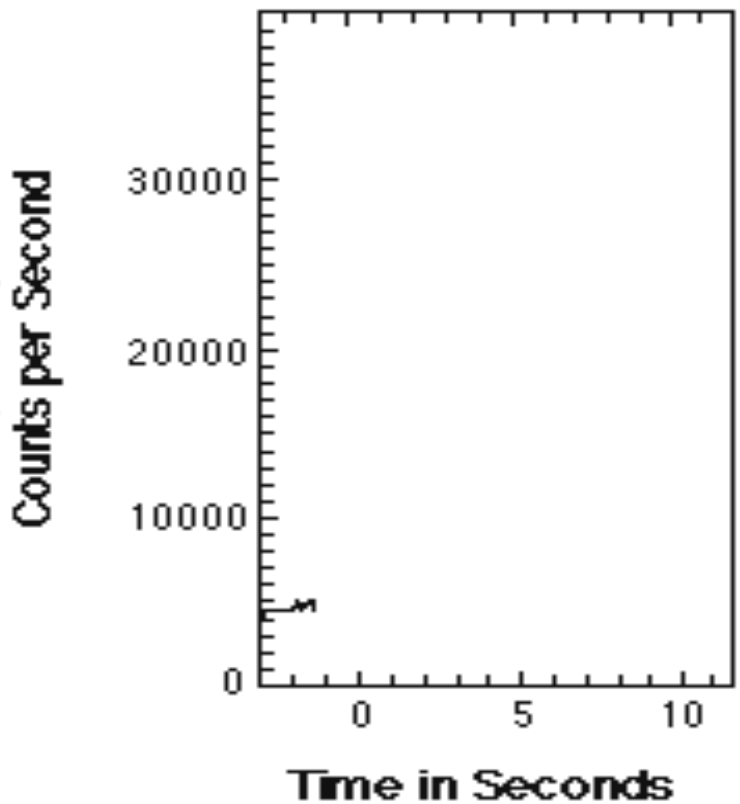


Jul. 10, 2012

Gamma 2012, Heidelberg, July 9-13, 2012

Gamma-ray bursts:
the most luminous explosions in the universe

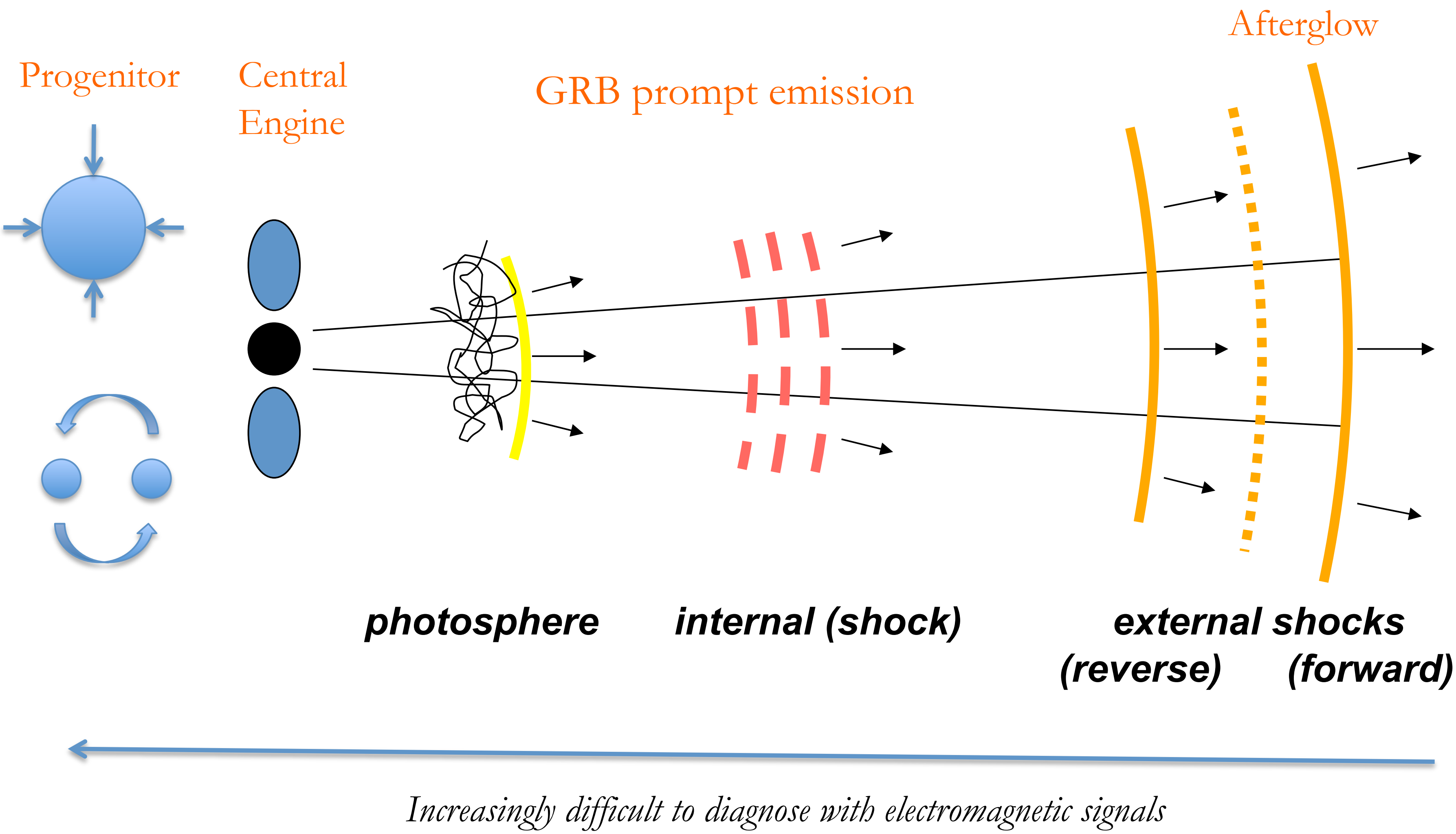




The GRB field

- An active, exciting field
- Due to their elusive nature, it is very difficult to observe GRBs in all the temporal and spectral regimes
- the mystery of GRBs is gradually unveiled when new temporal or spectral windows are opened
- GRBs may be also strong emitters of non-electromagnetic signals (e.g. high energy neutrinos, gravitational waves)
- A sketch of physical picture is available, but many details remain vague – many open questions

Physical Picture: A Sketch



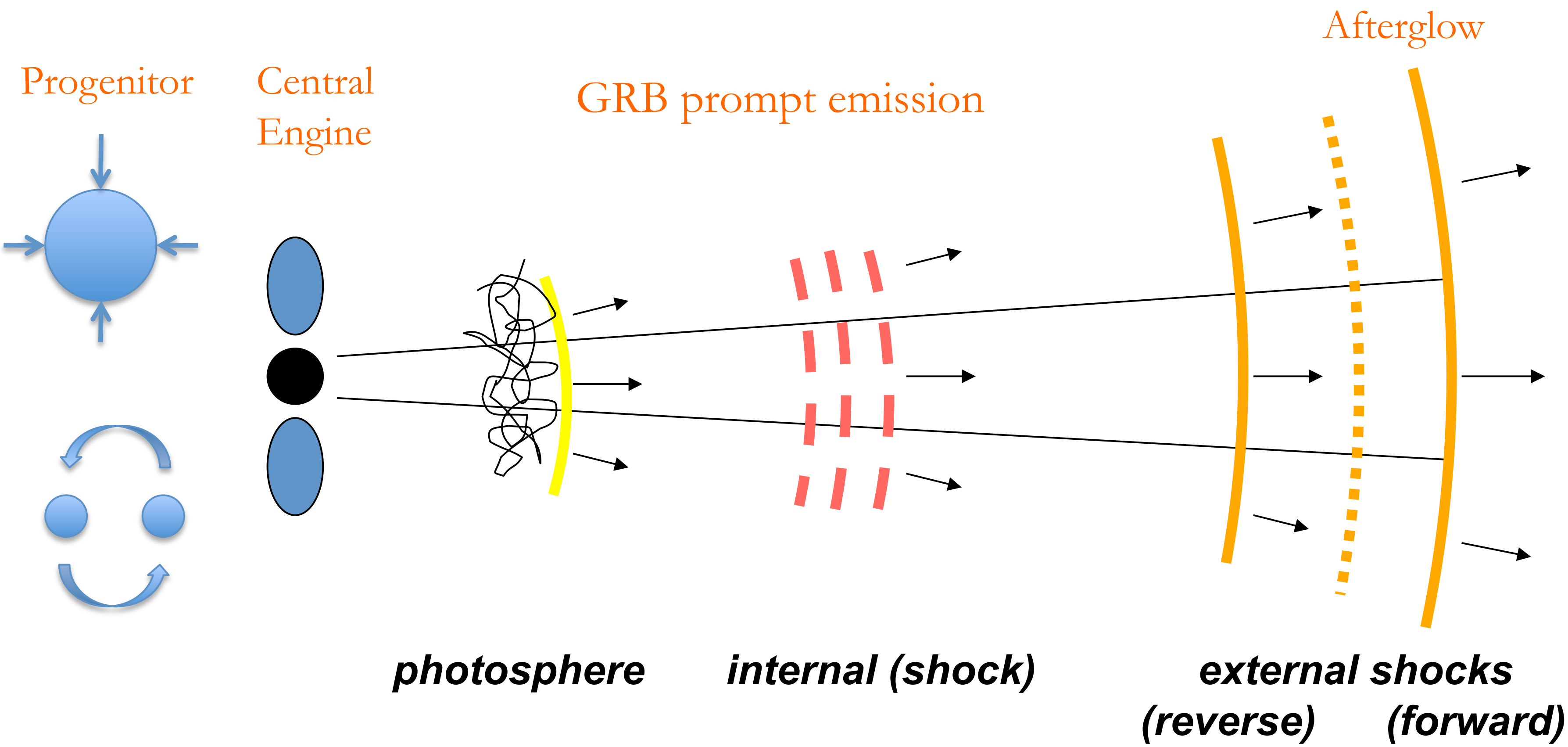
Open Questions in GRB Physics

- Progenitors & classification (massive stars vs. compact stars; others? how many physically distinct types?)
- Central engine (black hole, magnetar?)
- Ejecta composition (baryonic, leptonic, magnetic?)
- Energy dissipation mechanism (shock vs. magnetic reconnection)
- Particle acceleration & radiation mechanisms (synchrotron, inverse Compton, quasi-thermal)
- Afterglow physics (medium interaction vs. long-term engine activity)

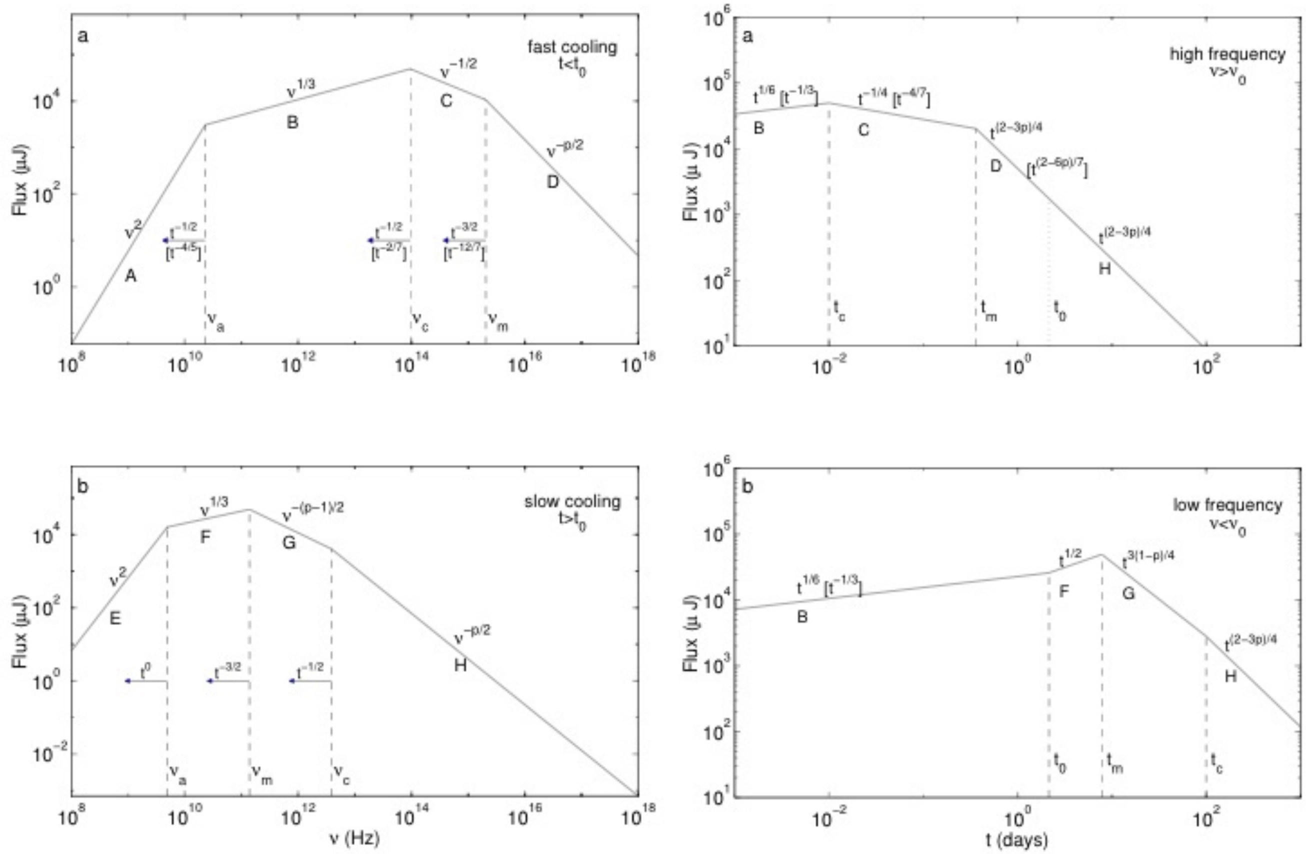
Open Question 1:

Origin of Afterglow

Physical Picture: A Sketch



Standard afterglow model



Sari, Piran & Narayan (1998)

Synchrotron emission from external forward shock: Meszaros & Rees (1997); Sari et al. (1998)

Afterglow Closure Relations

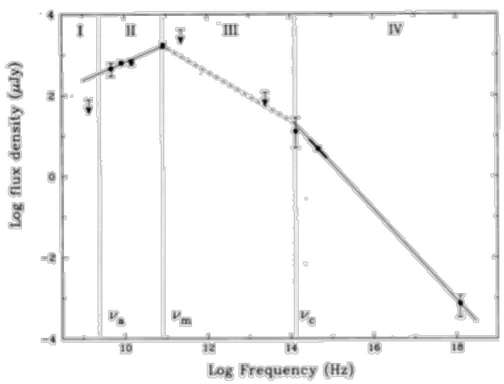
	β	α ($p > 2$, $p \sim 2.3$)	$\alpha(\beta)$	α ($1 < p < 2$, $p \sim 1.5$)	$\alpha(\beta)$
ISM, slow cooling					
$\nu < \nu_a$	2	$\frac{1}{2}$		$\frac{17p-26}{16(p-1)} \sim -0.06$	
$\nu_a < \nu < \nu_m$	$\frac{1}{3}$	$\frac{1}{2}$	$\alpha = \frac{3\beta}{2}$	$\frac{p+2}{8(p-1)} \sim 0.9$	
$\nu_m < \nu < \nu_c$	$-\frac{p-1}{2}$	$\frac{3(1-p)}{4} \sim -1.0$	$\alpha = \frac{3\beta}{2}$	$-\frac{3(p+2)}{16} \sim -0.7$	$\alpha = \frac{3(2\beta-3)}{16}$
$\nu > \nu_c$	$-\frac{p}{2}$	$\frac{2-3p}{4} \sim -1.2$	$\alpha = \frac{3\beta+1}{2}$	$-\frac{3p+10}{16} \sim -0.9$	$\alpha = \frac{3\beta-5}{8}$
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

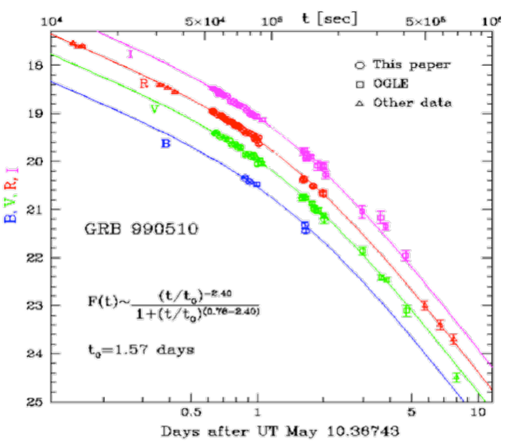
Sari, Piran & Narayan (1998)
Chevalier & Li (2000)
Dai & Cheng (2001)

Zhang & Meszaros (2004)

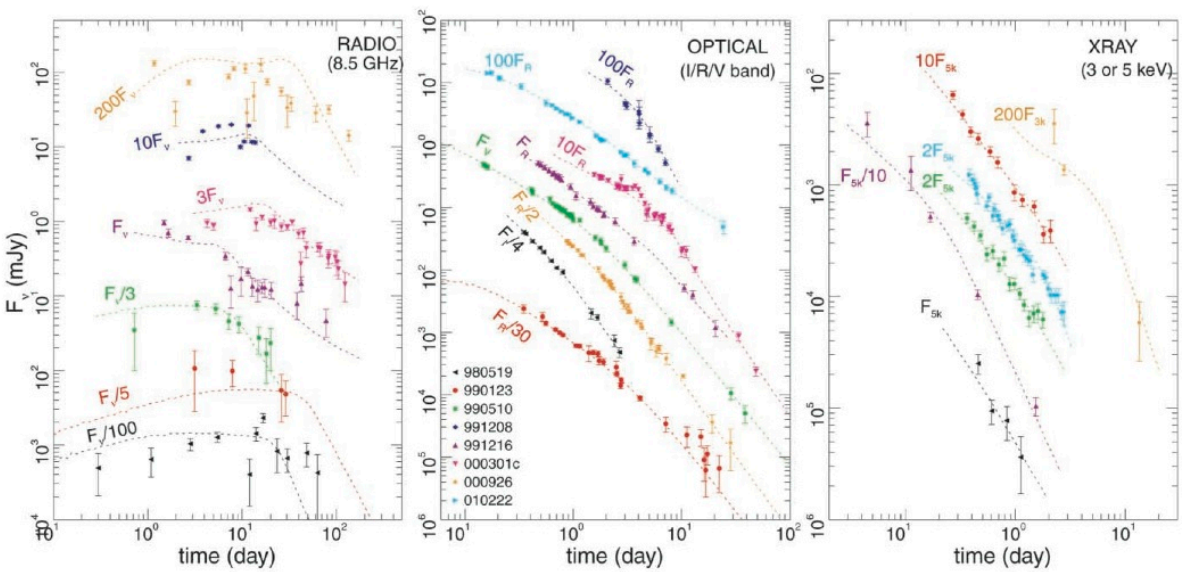
Pre-Swift: Confronting data with theory



Wijers & Galama 99

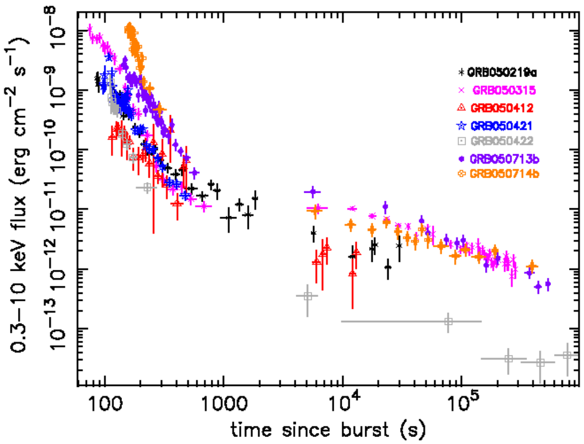


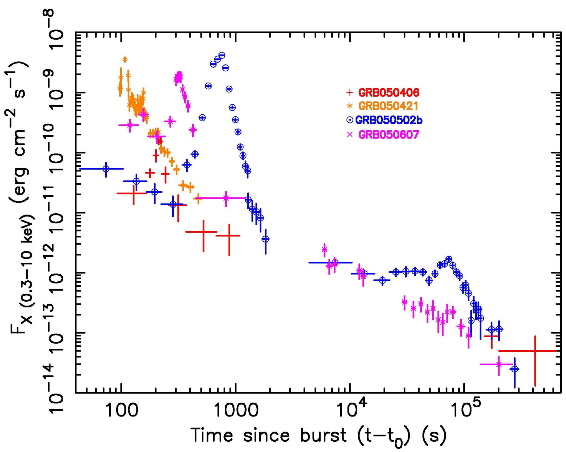
Stanek et al. 99

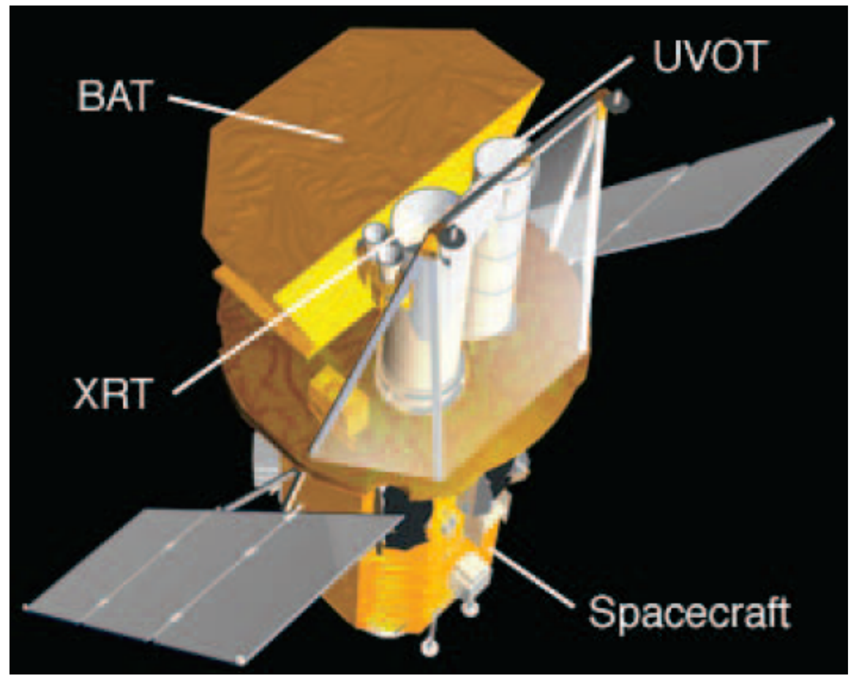


Panaitescu & Kumar (01, 02)

Swift surprise





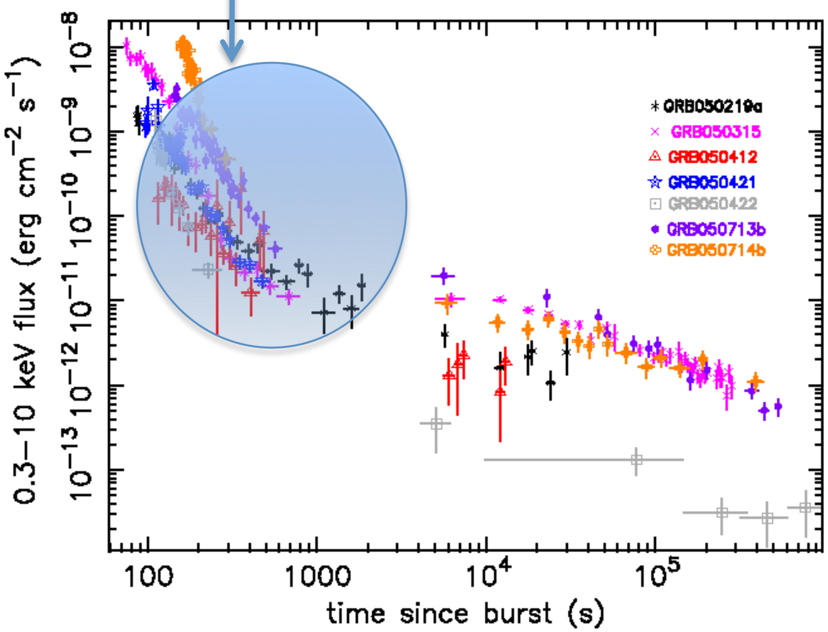


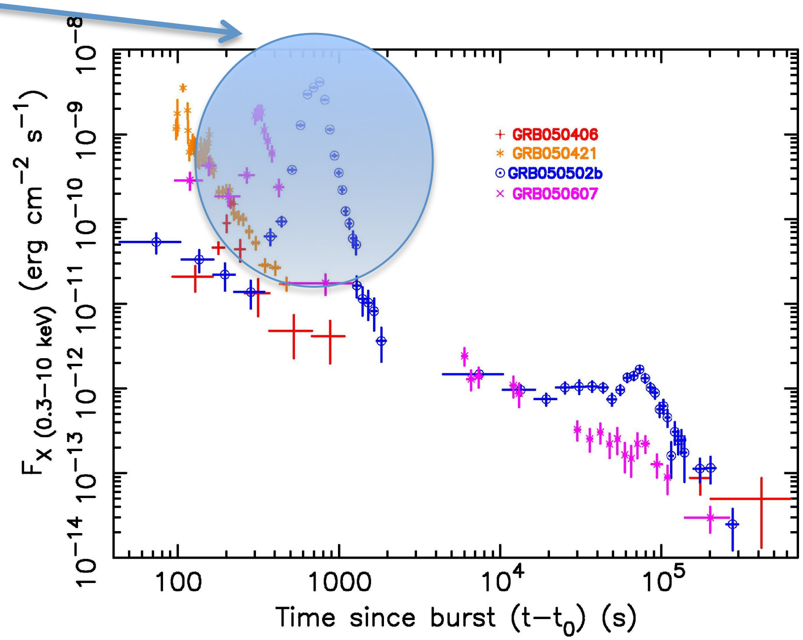
Gehrels et al. (2004)

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

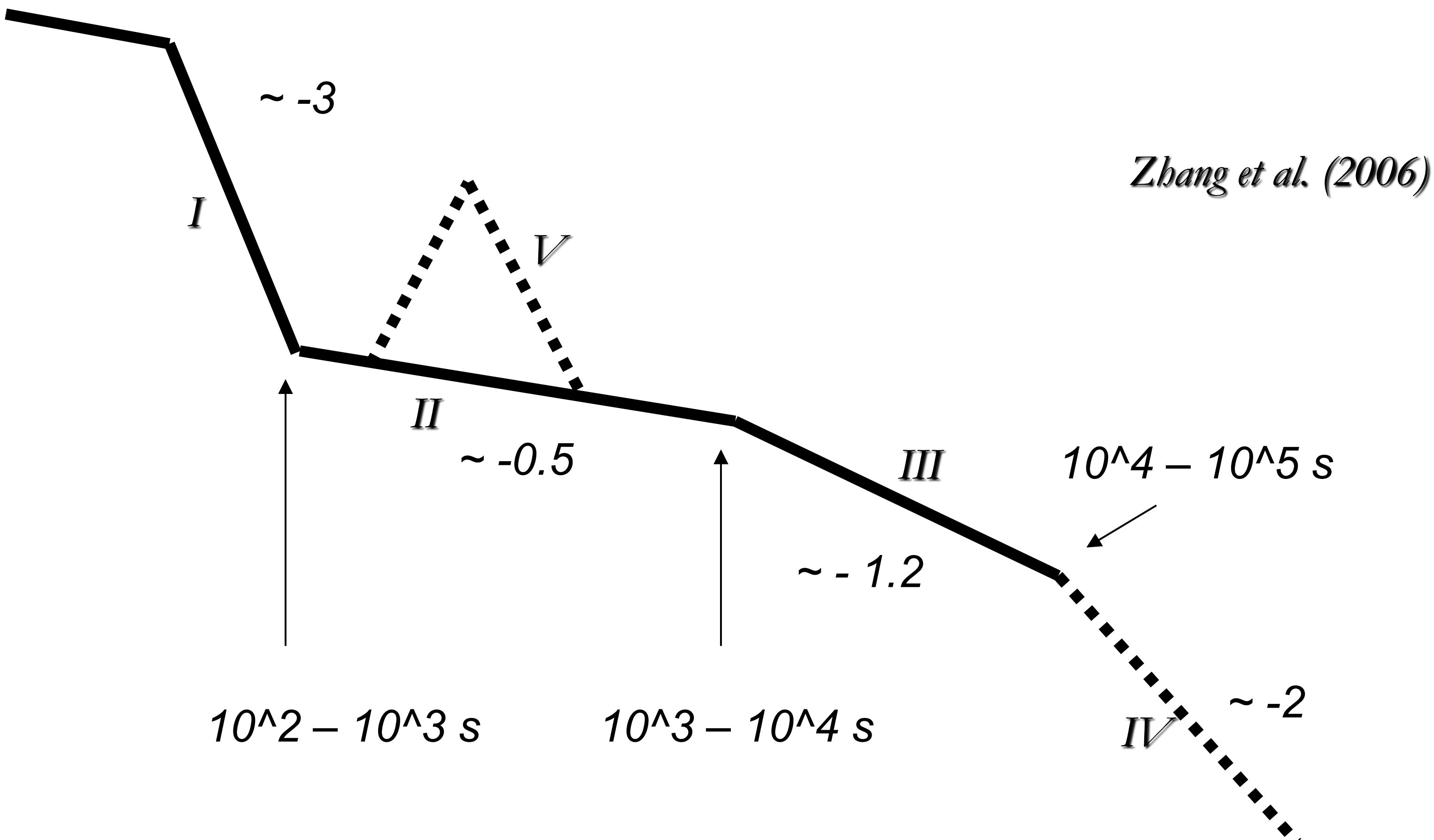
Swift surprise

Not predicted!



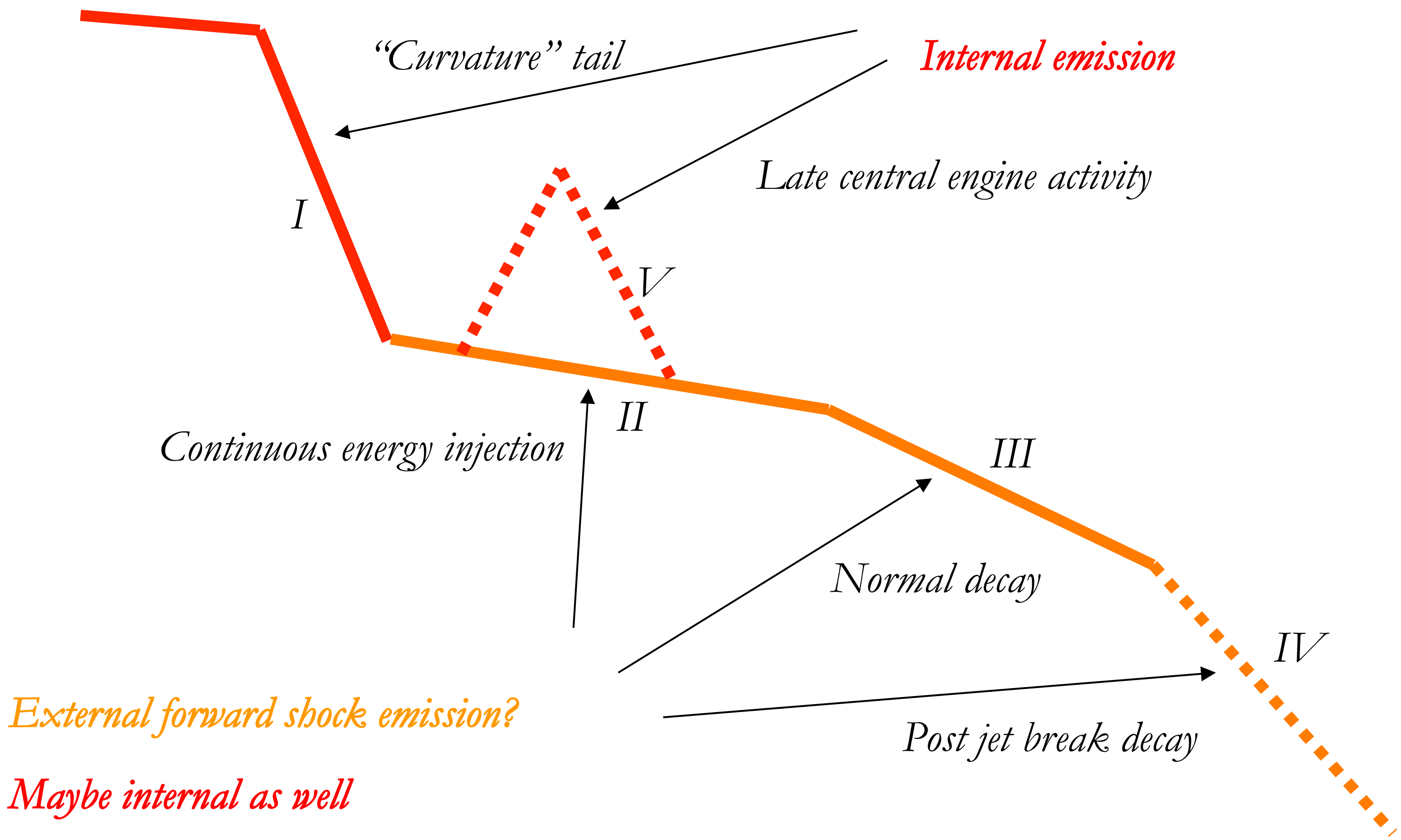


A Five-Component Canonical X-Ray Afterglow

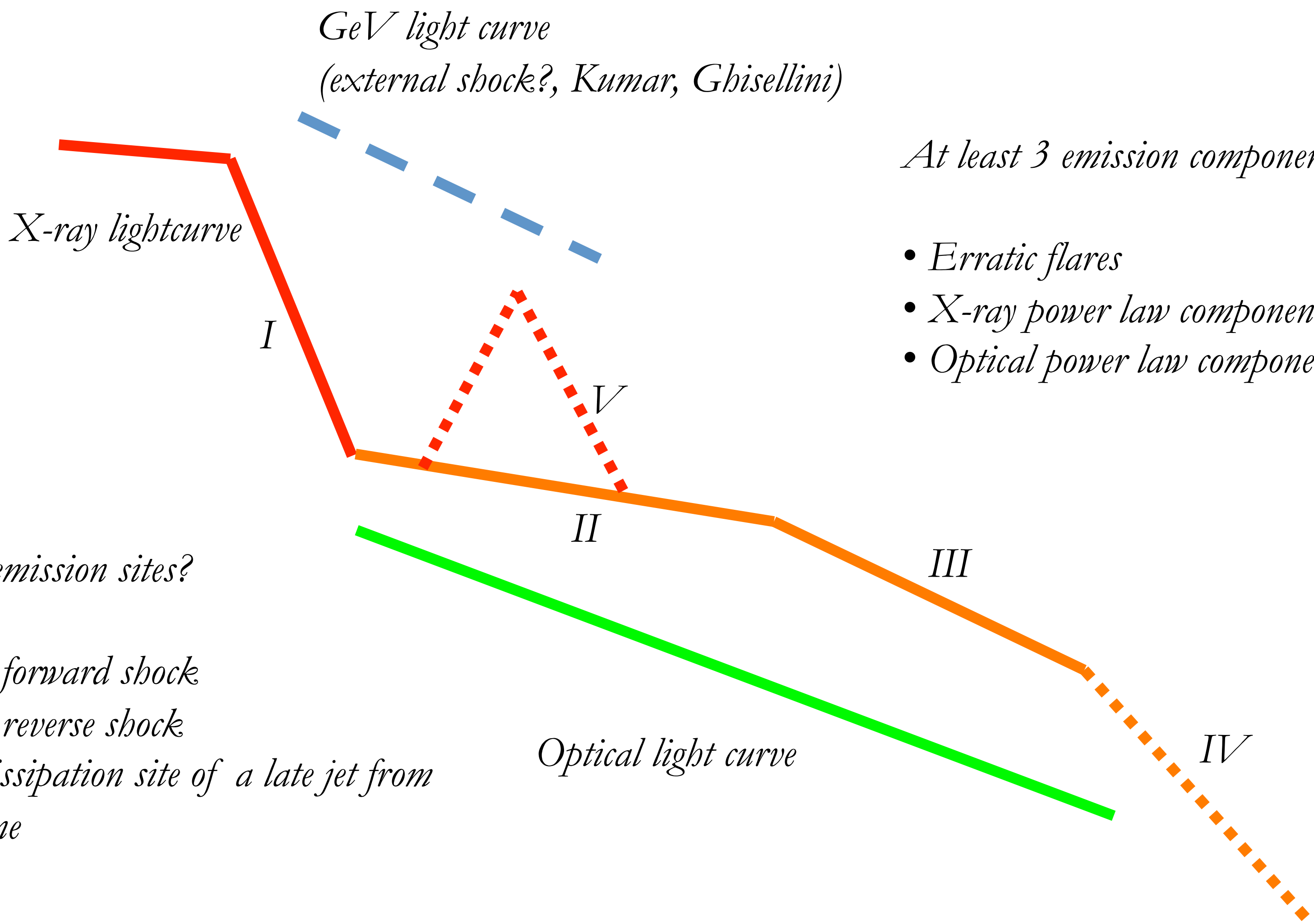


Canonical lightcurves: Internal or external?

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



Puzzling fact: Chromatic breaks



At least 3 emission components:

- *Erratic flares*
- *X-ray power law component*
- *Optical power law component*

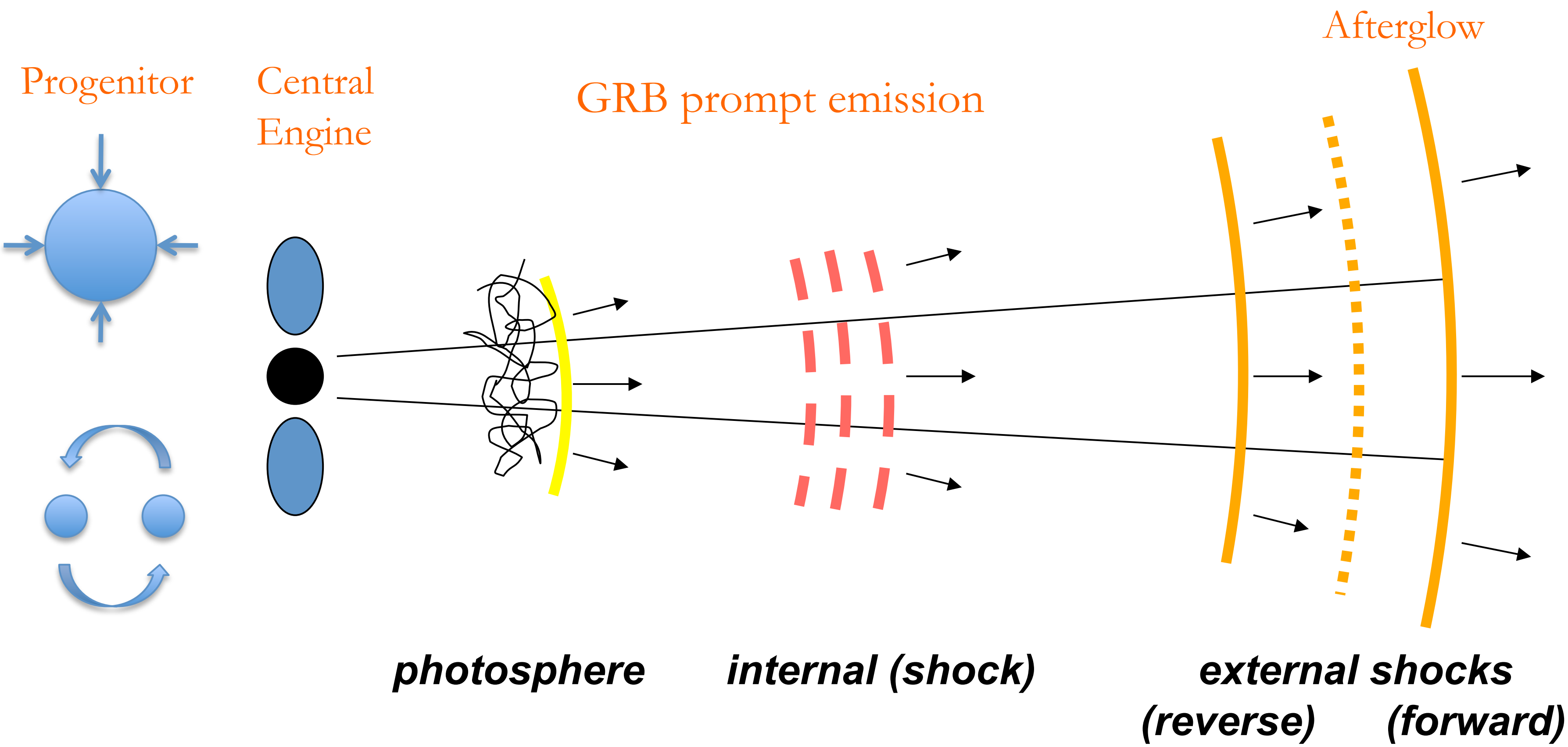
At least 3 emission sites?

- *External forward shock*
- *External reverse shock*
- *Internal dissipation site of a late jet from central engine*
- ……

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



Open Questions 2, 3 & 4:

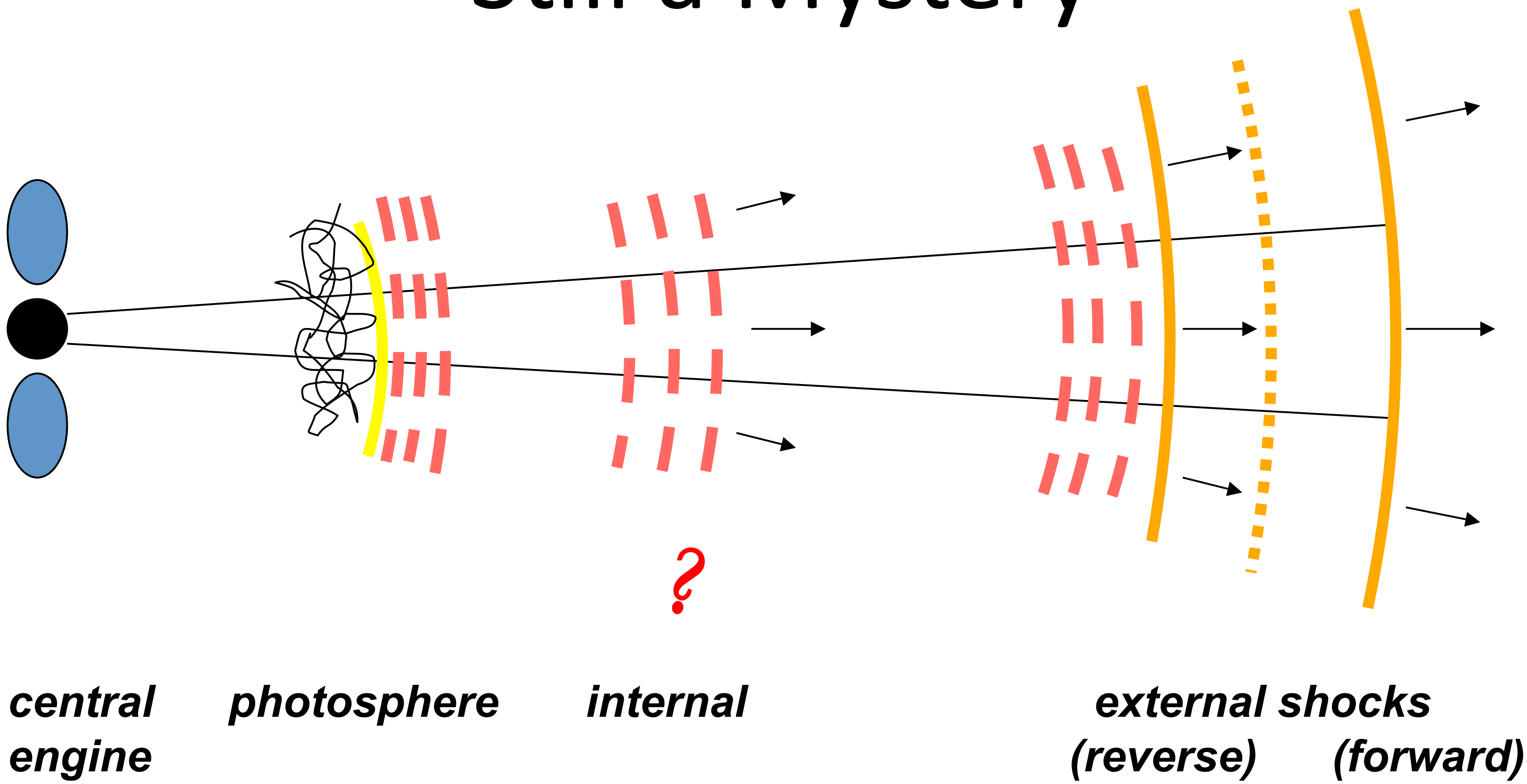
Origin of Prompt Emission:

Jet Composition (matter vs. magnetic)

Energy dissipation (shock vs. reconnection)

Radiation Mechanisms (thermal, synchrotron, inverse Compton)

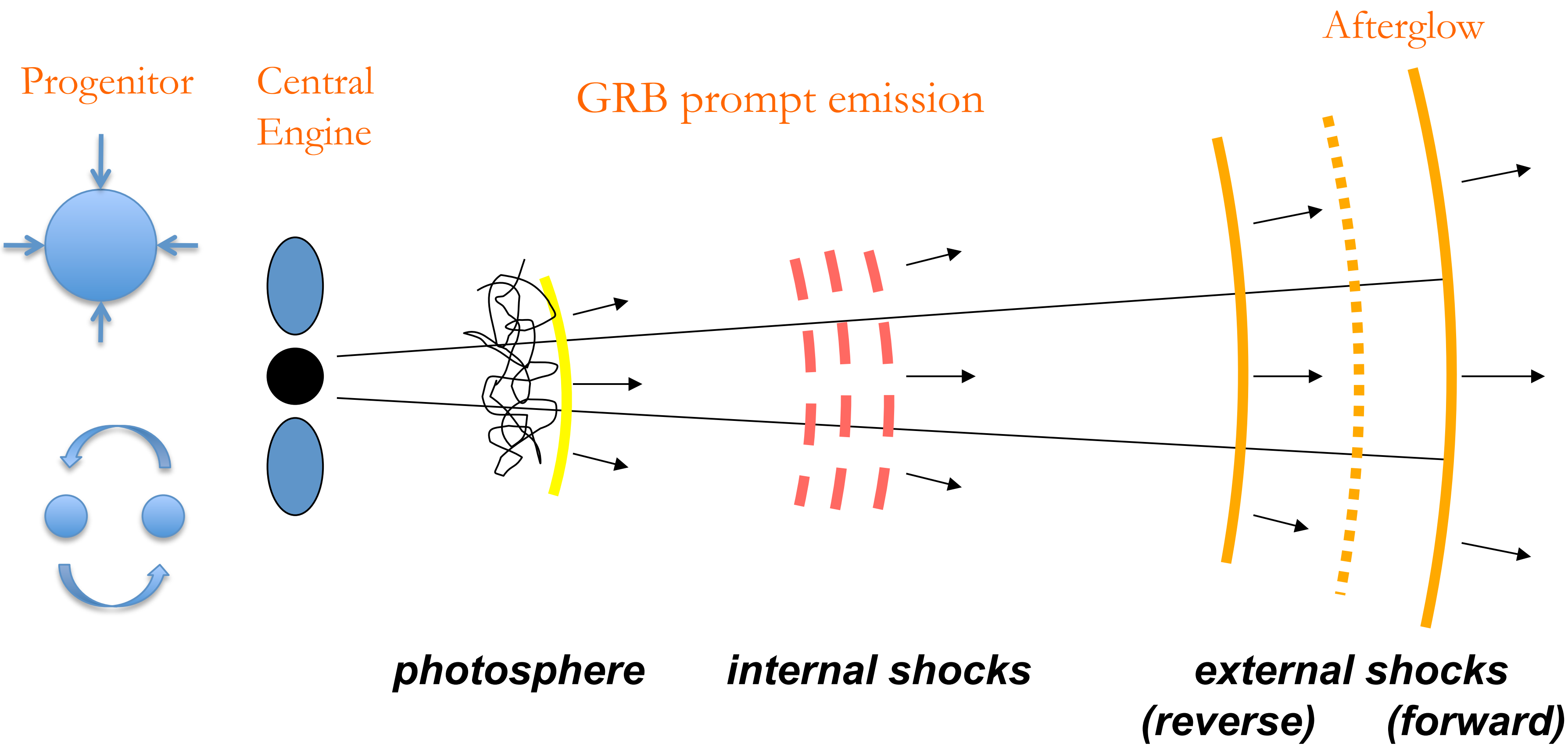
Prompt GRB Emission: Still a Mystery



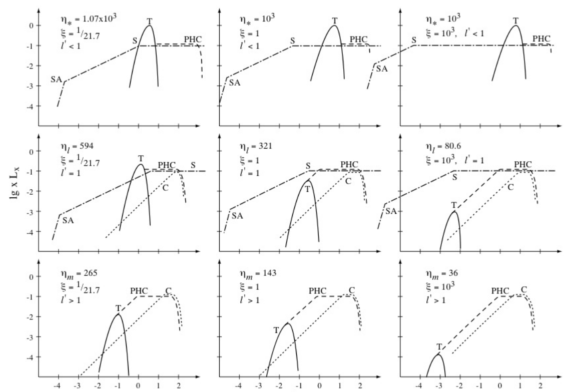
What is the jet composition (baryonic vs. Poynting flux)?
Where is (are) the dissipation radius (radii)?
How is the radiation generated (synchrotron, Compton scattering, thermal)?

Fireball shock model

(Paczynski, Meszaros, Rees, Piran …)

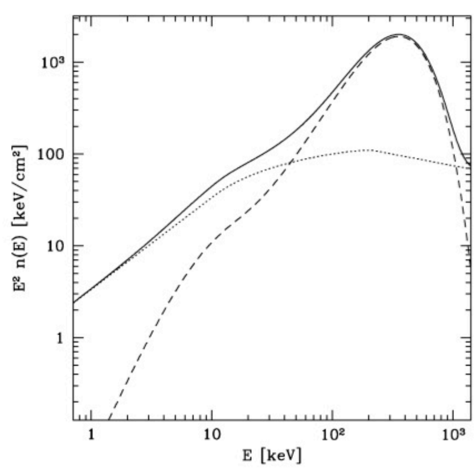


Fireball Predictions: Internal shock vs. photosphere

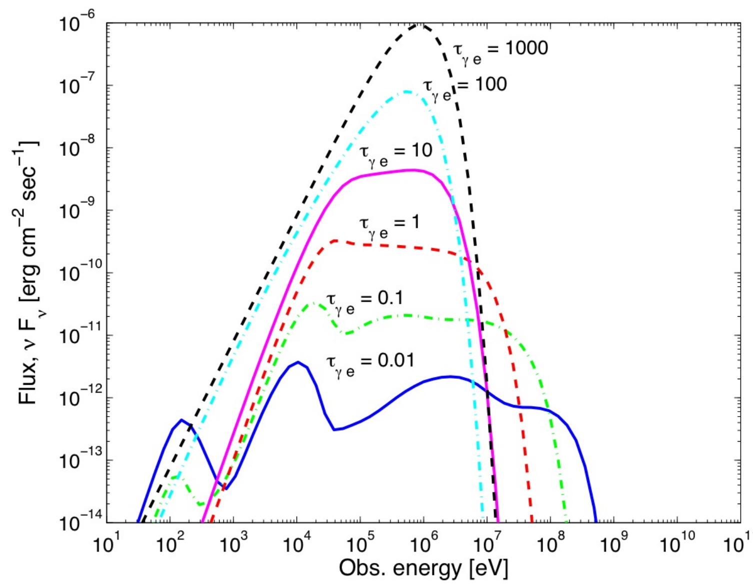


Meszaros & Rees (00)

1276 *F. Daigne and R. Mochkovitch*

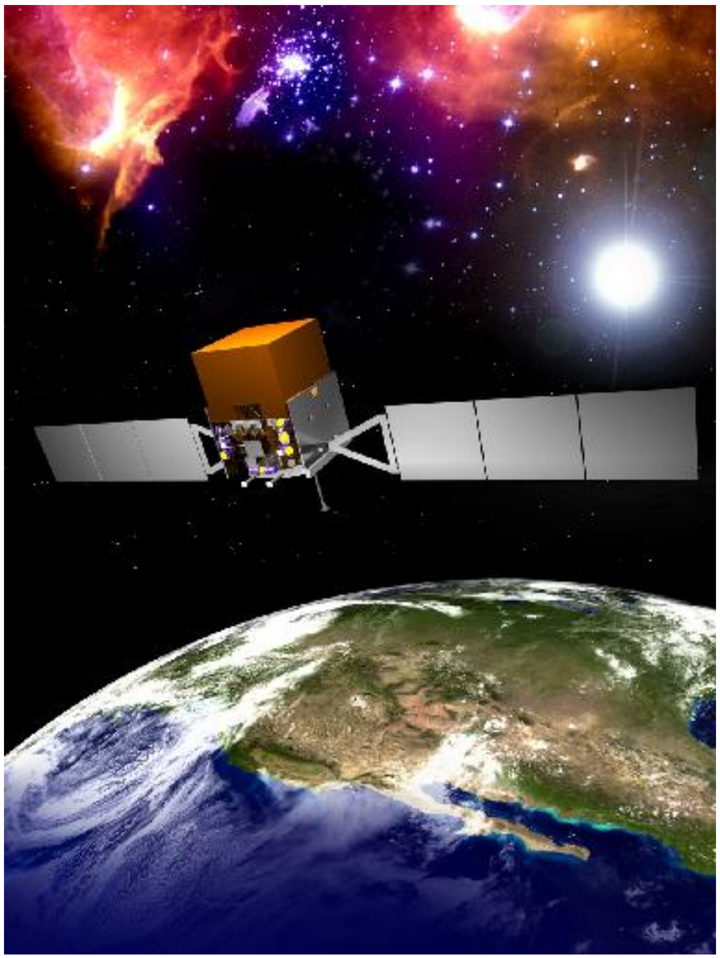


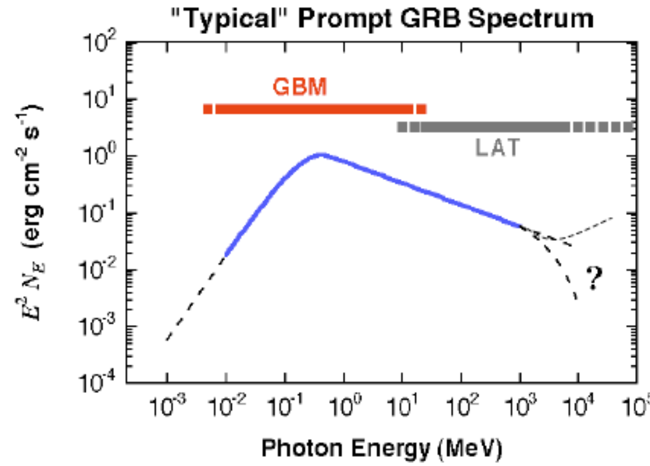
Daigne & Mochkovitch (02)

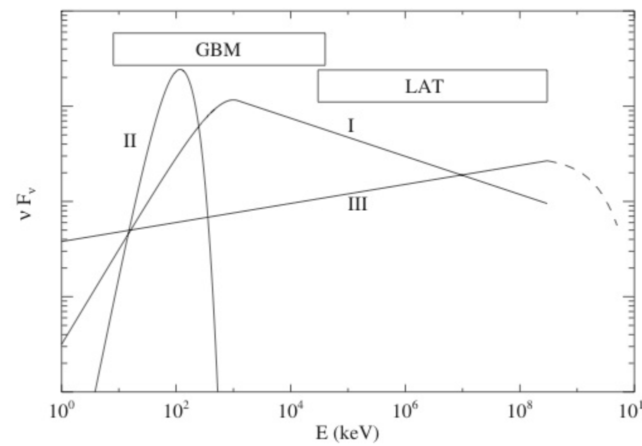


Pe'er et al. (06)

Fermi Satellite:
Broad-Band High Energy Observatory





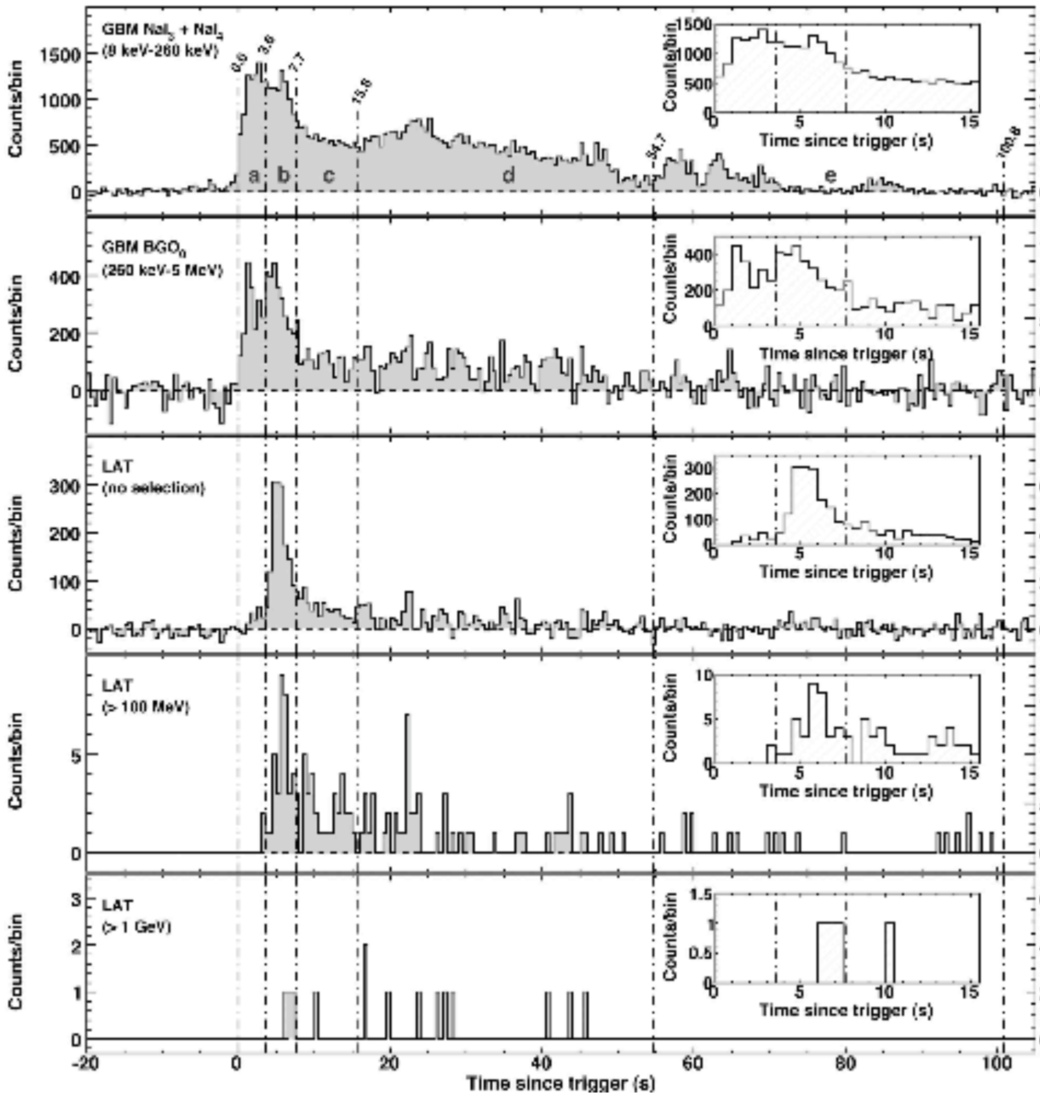


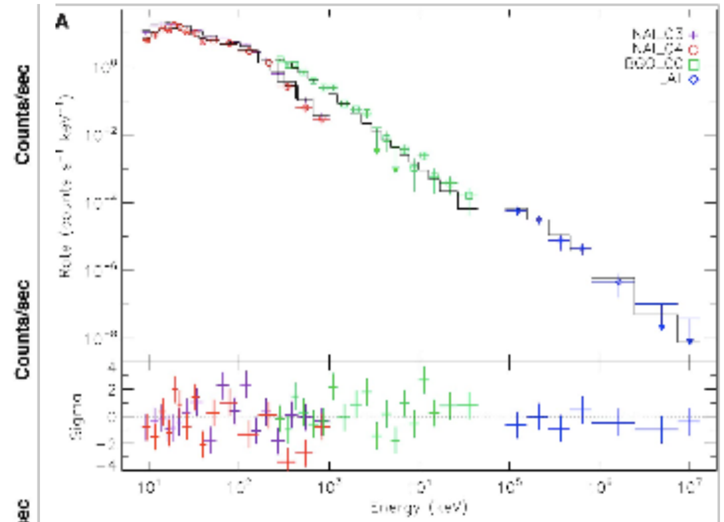
?

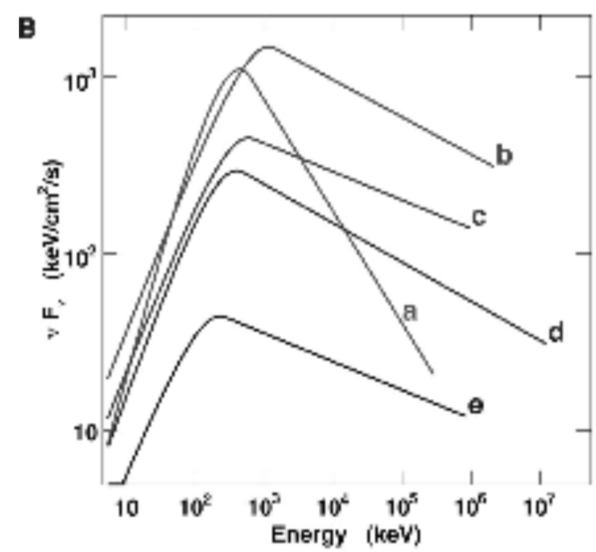
Fermi surprise: GRB 080916C

(Abdo et al. 2009, Science)

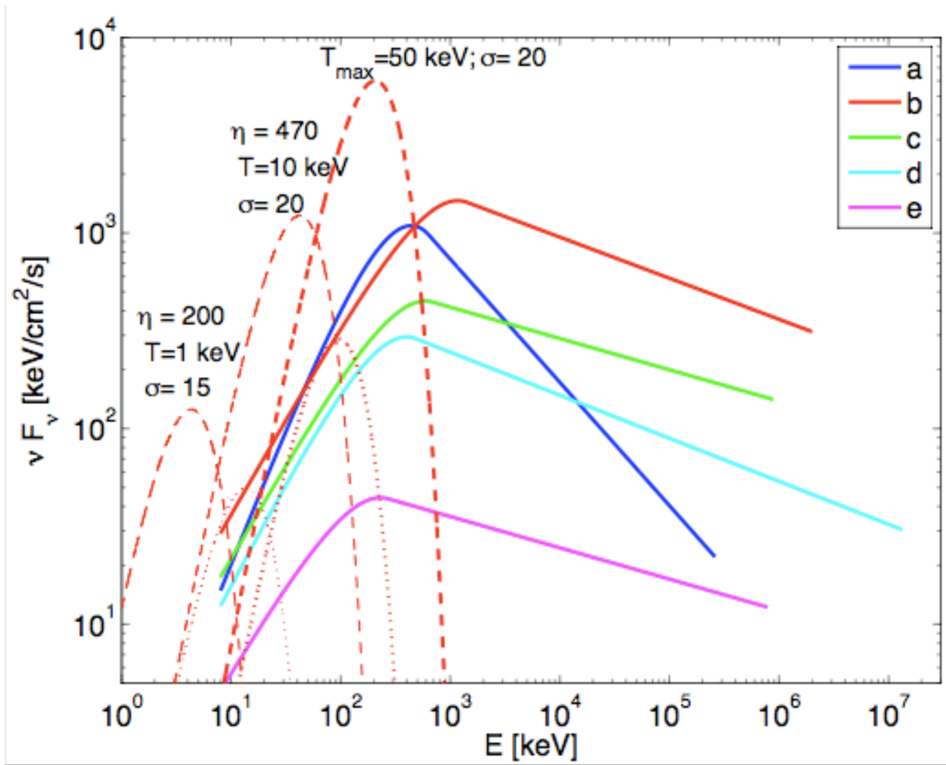
$z = 4.35 \pm 0.15$







Fermi Surprise: Photosphere component missing



Zhang & Pe'er (2009)

Sigma: ratio between Poynting flux and baryonic flux:

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

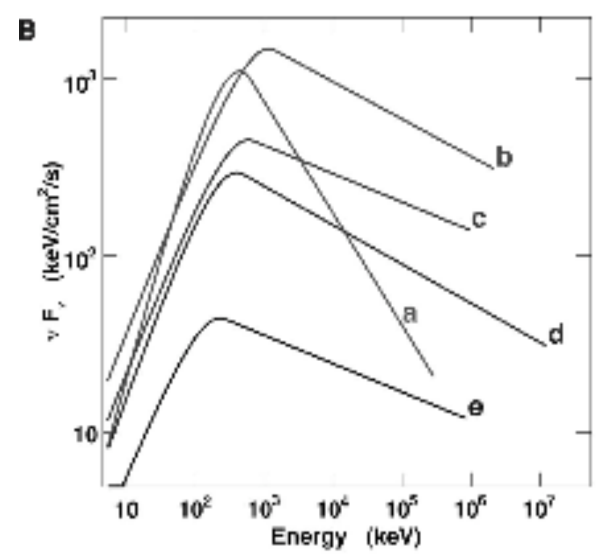
The simplest fireball model does not work!

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

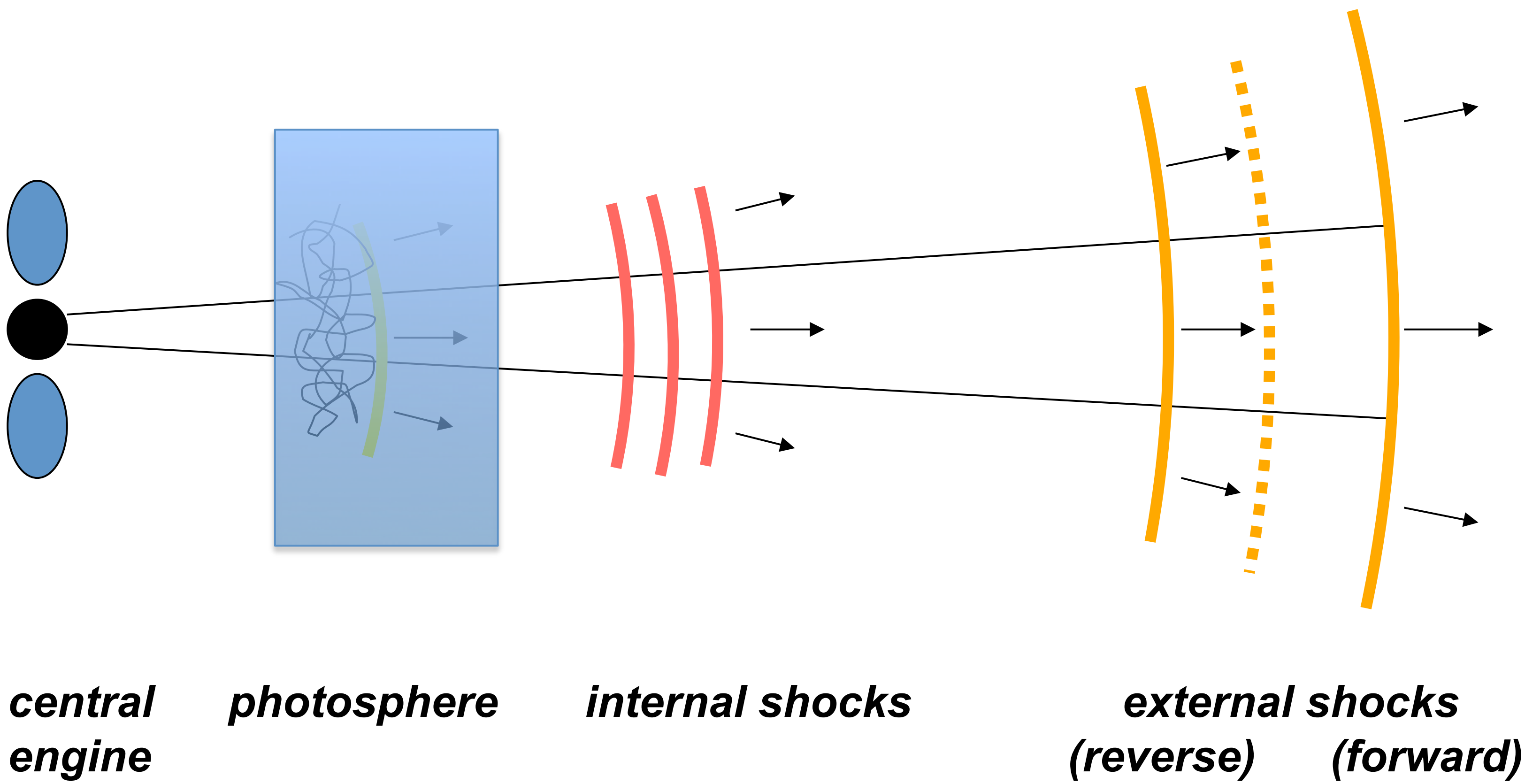
Three distinct views:

The observed component is:

- *The internal shock component*
- *The photosphere component*
- *Neither (Poynting flux dissipation component)*



Modified Fireball Model (1)



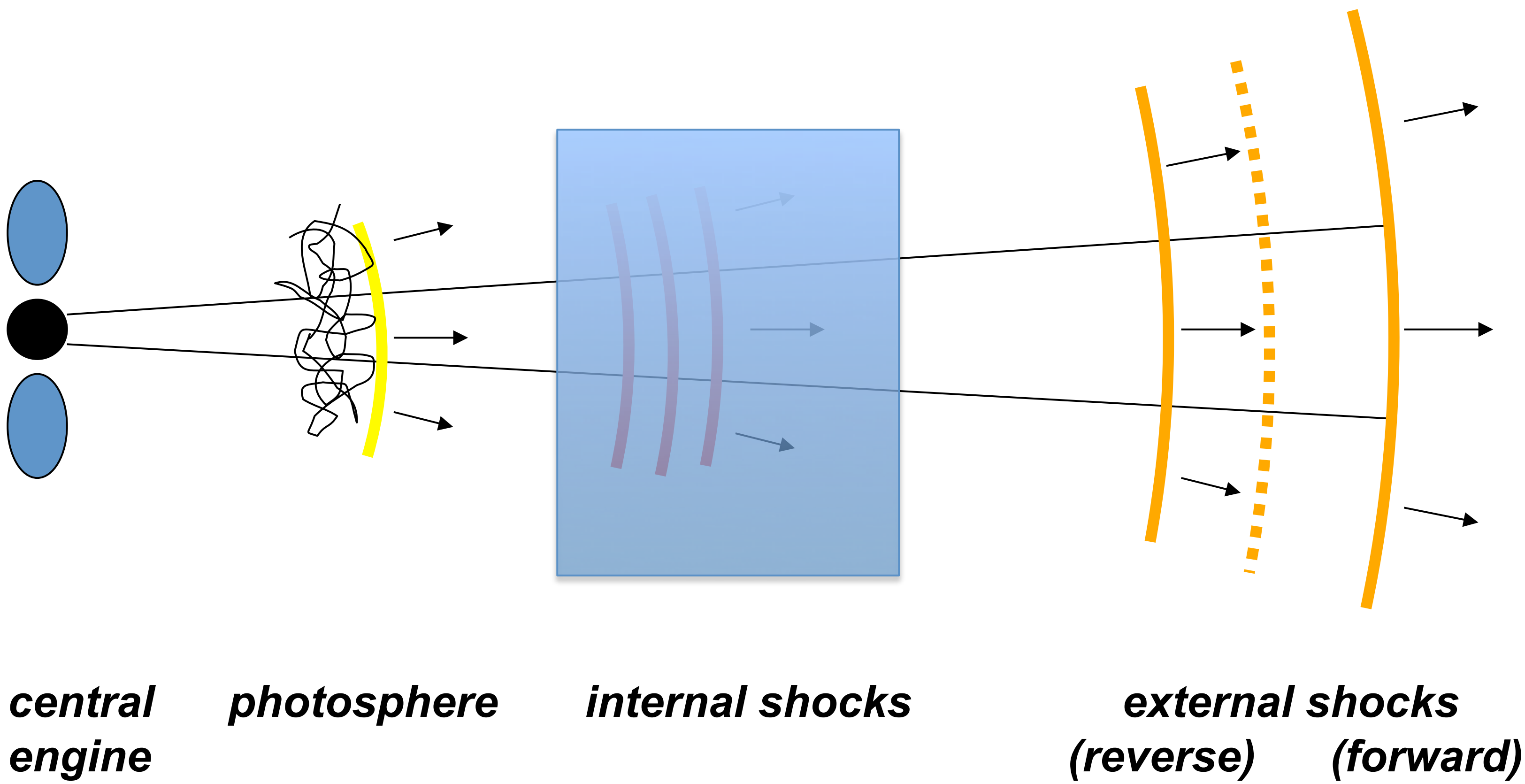
GRB prompt emission is from internal shocks
Photosphere emission suppressed

Internal shock model

- Pros:
  - Naturally expected
  - Variability reflects engine activity, supported by the data
- Cons:
  - Bright photosphere, require a magnetized central engine and fast magnetic acceleration
  - Low efficiency
  - Only a fraction of electrons accelerated
  - Fast cooling problem
  - Ep – Eiso (Liso) correlation inconsistency

Work: Daigne, Mochkovitch, Hacoet …

Modified Fireball Model (2)



GRB prompt emission: from photosphere
Internal shock emission suppressed

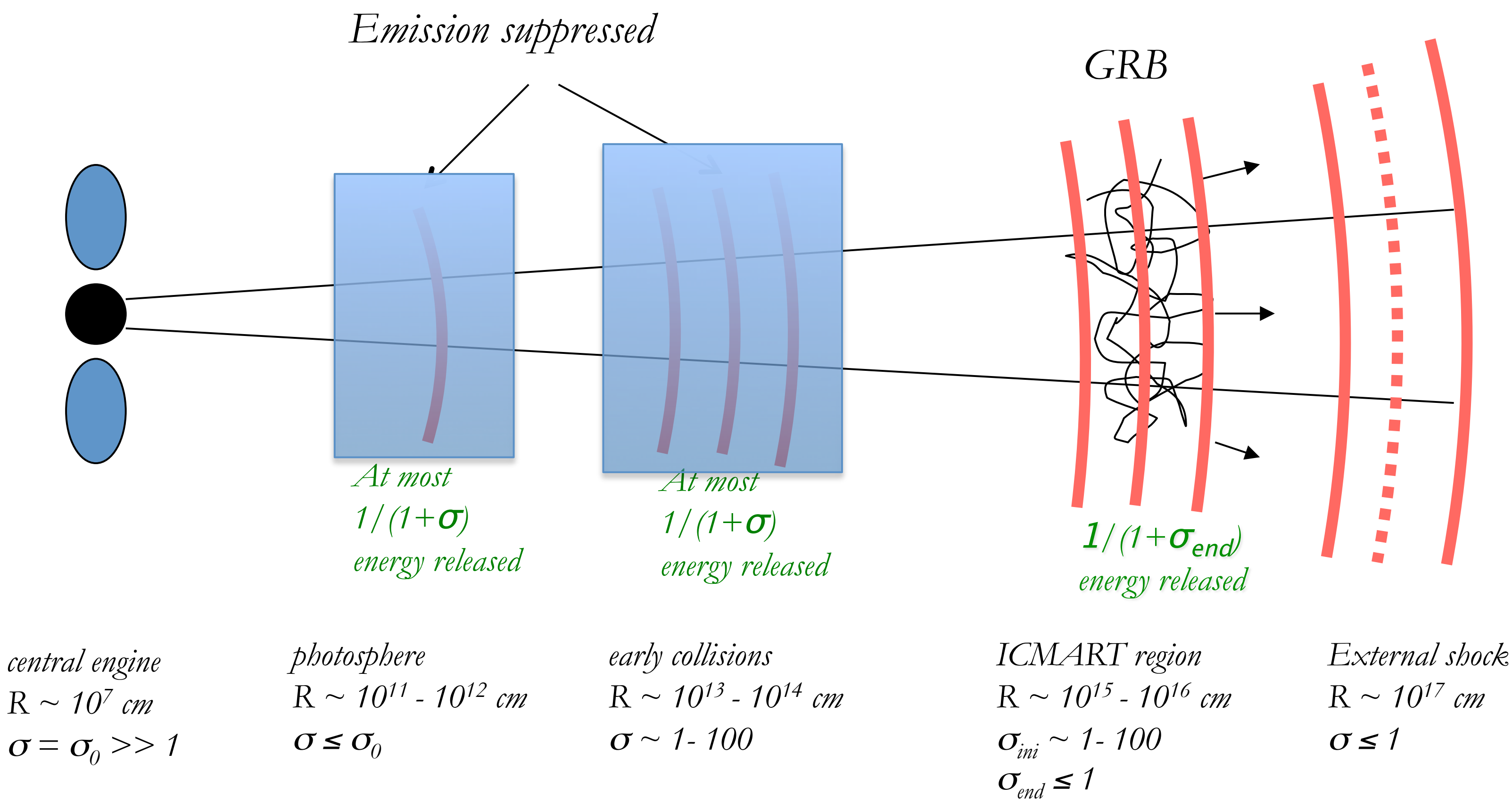
Photosphere model

- Pros:
  - Naturally expected in a hot fireball
  - Roughly right Ep, narrow Ep distribution
  - Roughly right empirical correlations
- Cons:
  - Low energy spectrum too hard (cf. Pe'er's talk)
  - Inconsistent with the 3 independent constraints (X-ray, optical, GeV) of large GRB emission radius

Work: Pe'er, Ryde, Ioka, Beloborodov, Giannios, Lazzati, Toma, Ruffini …

Distance Scales in the ICMART Model

(Internal Collision-induced MAgnetic Reconnection & Turbulence)

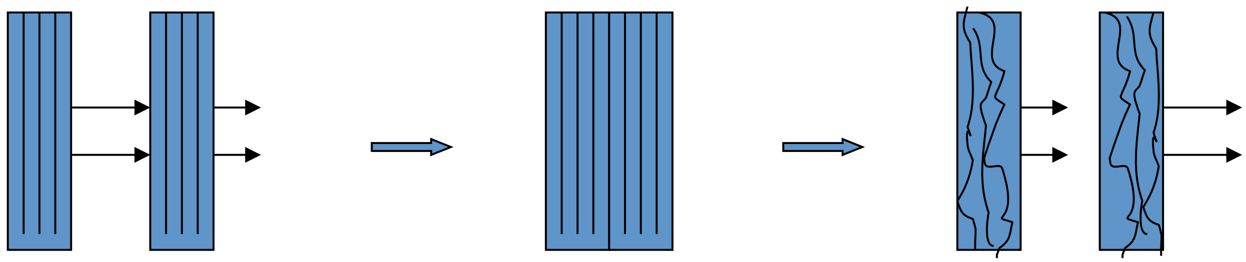


Zhang & Yan (2011)

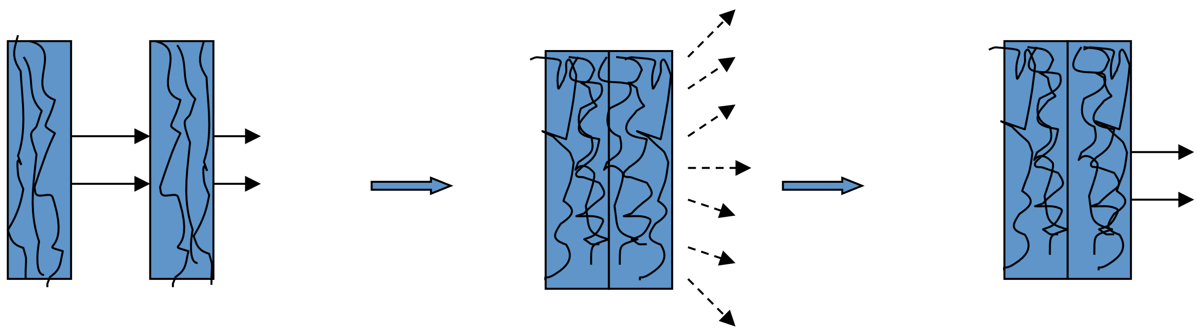
Earlier work: Lyutikoc & Blandford; Narayan & Kumar; Lazarian & Vishniac …

ICMART Model

Zhang & Yan (2011)



(a) Initial collisions only distort magnetic fields

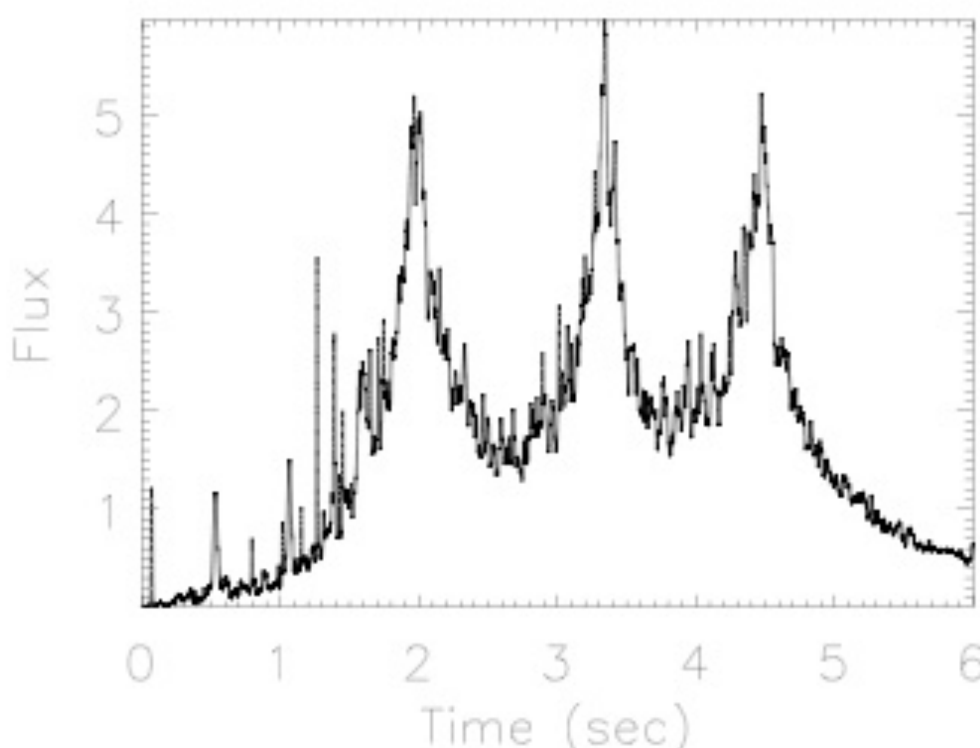


(b) Finally a collision triggers fast turbulent reconnection
- An ICMART event (a broad pulse in GRB lightcurve)

See also
Spitkovsky's talk

ICMART Lightcurves

Bo Zhang & BZ



See also Lyutikov's talk

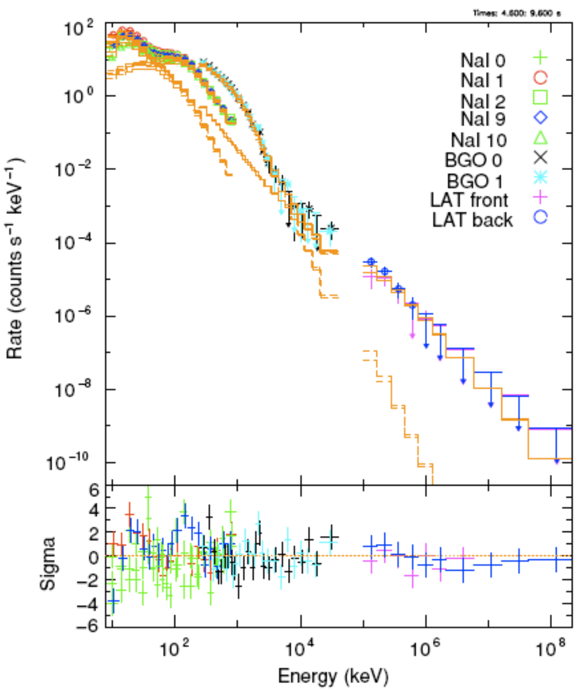
Slow (central engine) vs. fast (turbulent reconnection) components

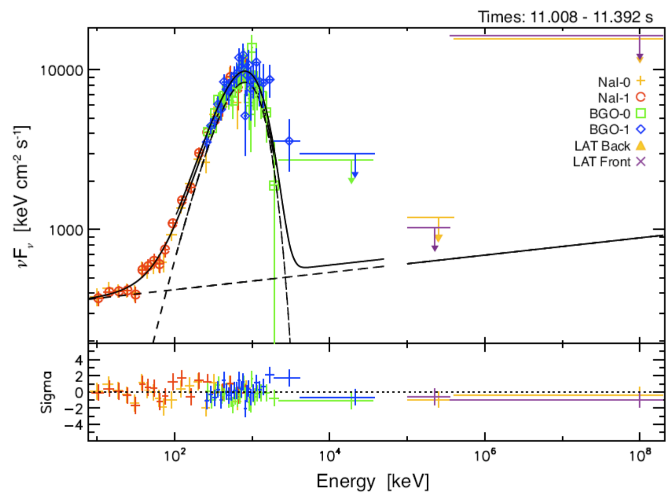
ICMART model

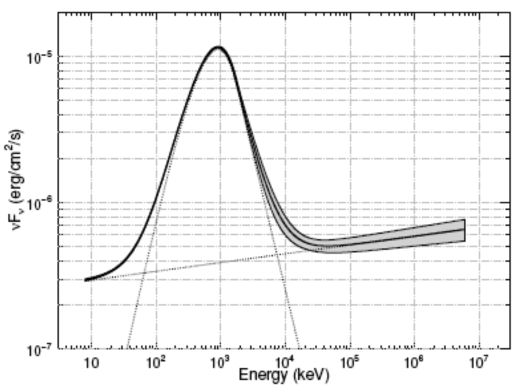
- Pros:
  - Overcome difficulties of the internal shock and photosphere models
  - Inherited strengths of the known models
- Cons:
  - Invoking more complicated physics in the Poynting flux dominated regime (turbulence development, reconnection in high-sigma flow, particle acceleration in reconnection …). Investigations underway.

Less (but still) a surprise: GRB 090902B

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





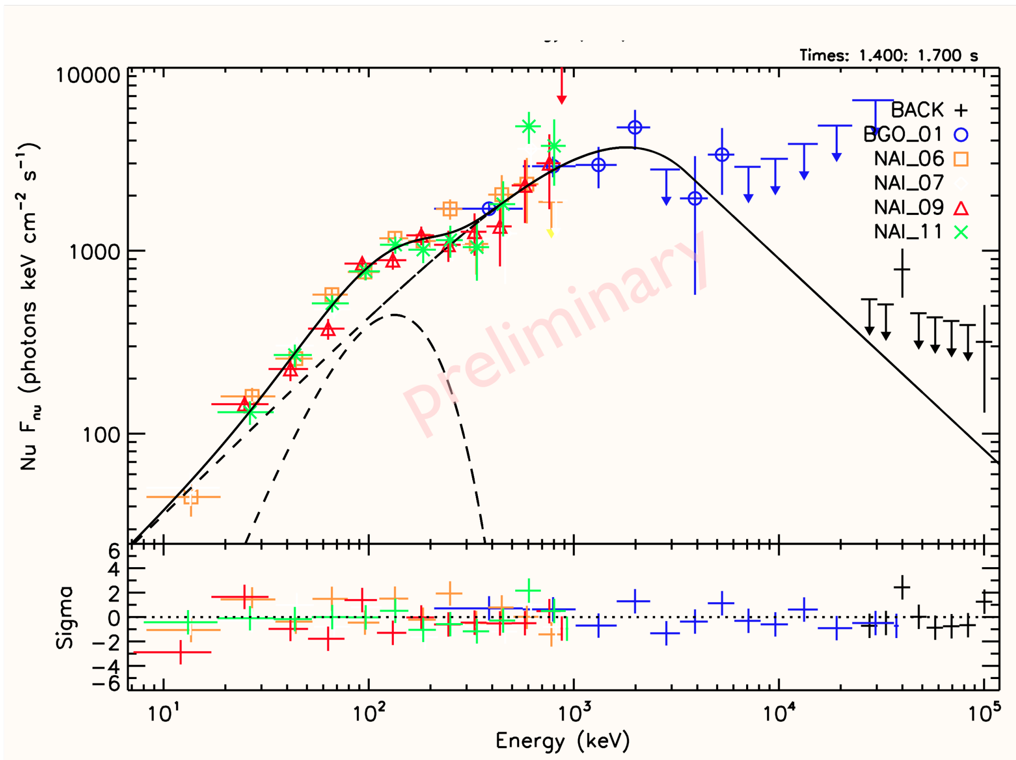


A clear photosphere emission component identified

Very special & rare event!

Something in between: GRB 110721A

(Fermi team: in preparation)



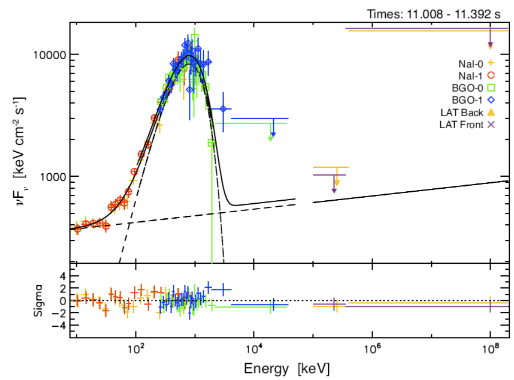
McGlynn et al. in prep.

Mixed thermal & non-thermal components

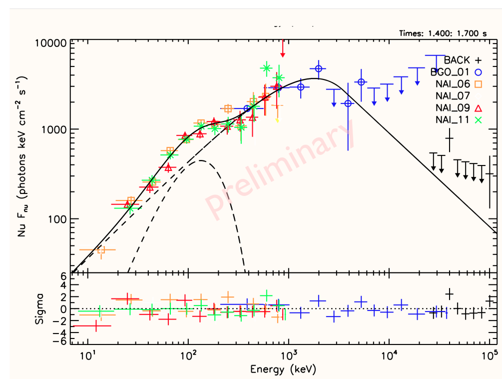
As expected, more common

Big Picture: GRB jet composition

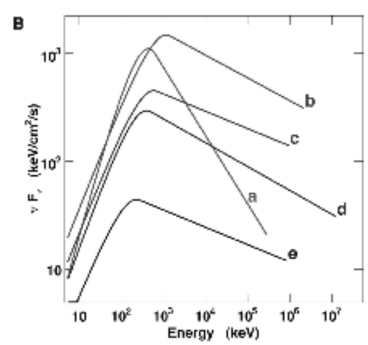
- GRB jets have diverse compositions:
  - Photosphere dominated (GRB 090902B), rare
  - Intermediate bursts (weak but not fully suppressed photosphere, GRB 100724B)
  - Photosphere suppressed, Poynting flux dominated (GRB 080916C)



GRB 090902B



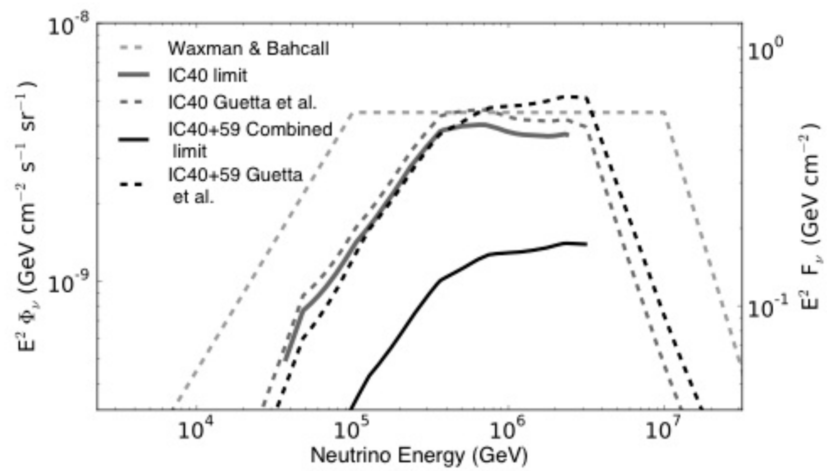
GRB 100724B



GRB 080916C

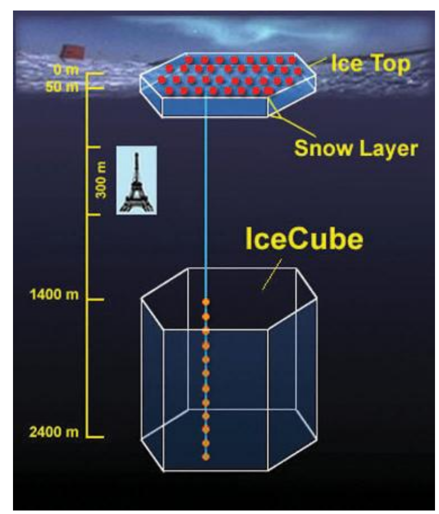
Non-detection of neutrinos by Icecube

- Icecube did not detected GRB neutrinos predicted by the most optimistic internal shock model
- The more conservative internal shock models may be still accommodated by the data



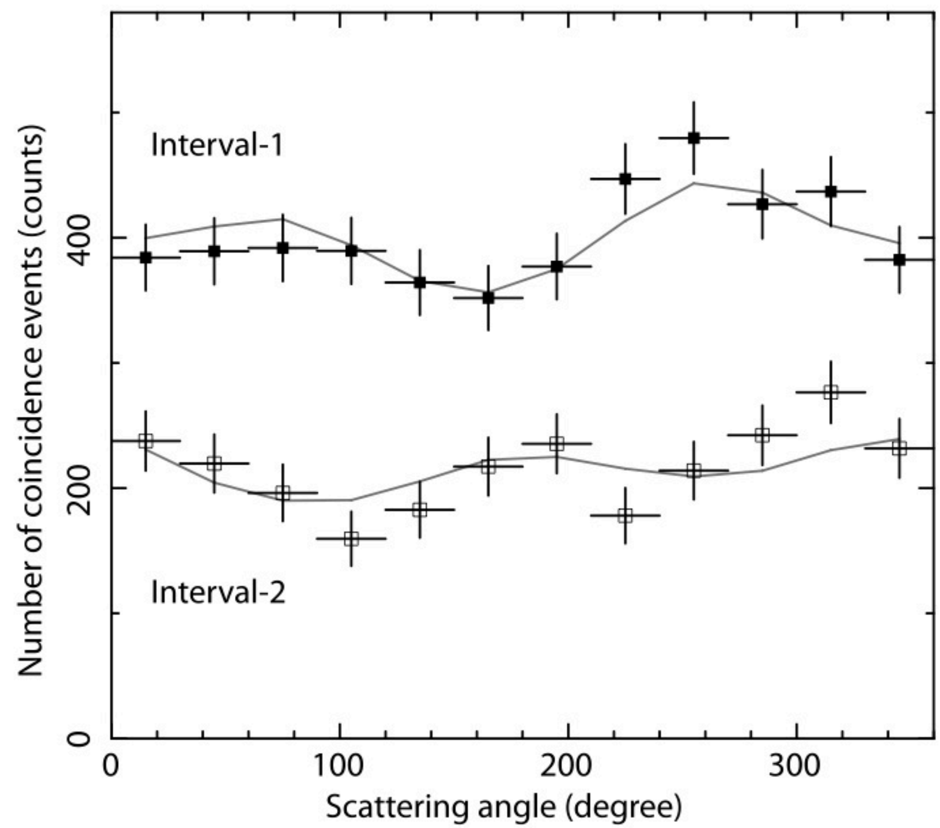
IceCube results

- If most GRBs are magnetically dominated and dissipate energy at large radii (e.g. ICMART model), the predicted neutrino flux level is much lower



Polarization data

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



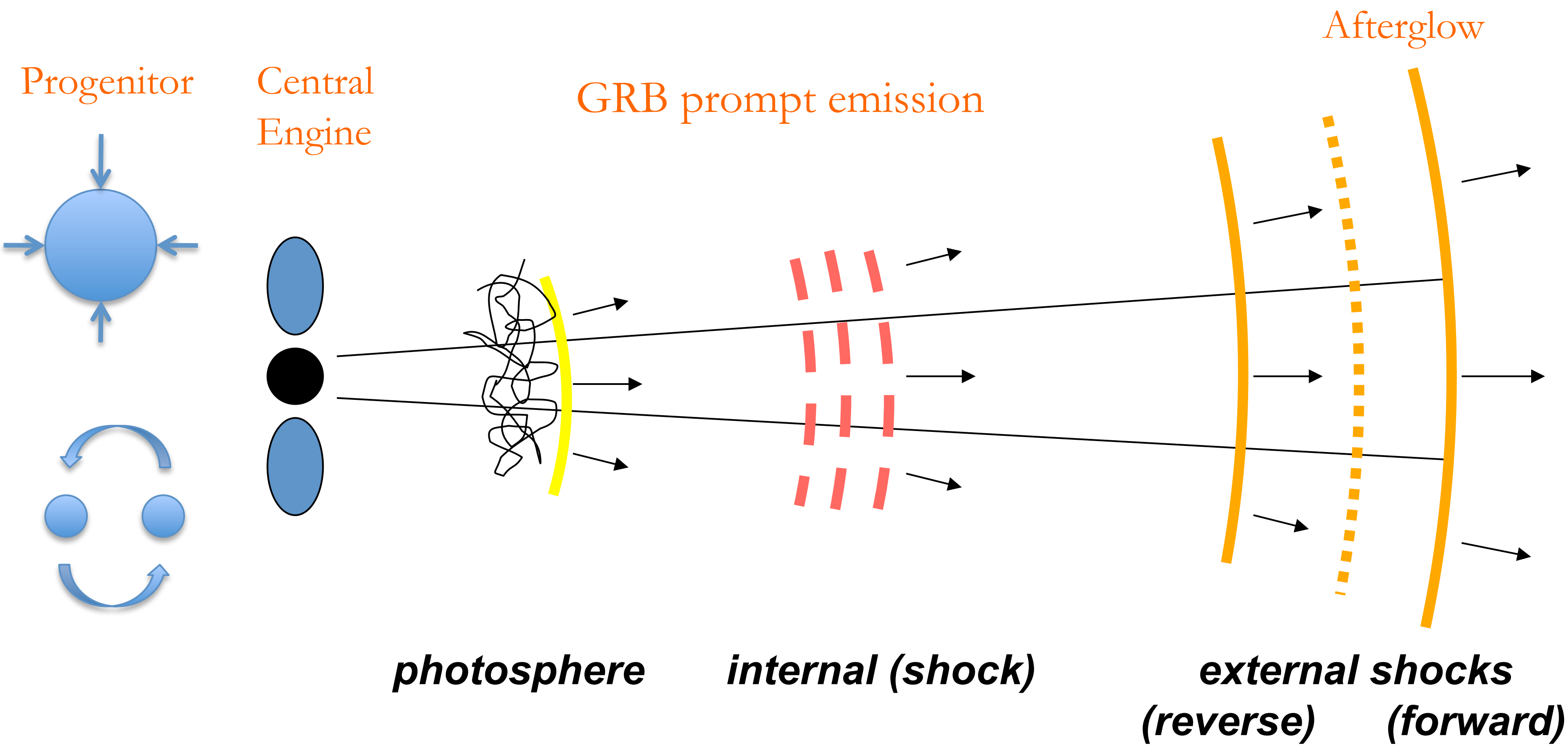
Yonetoku et al. (2011)

Open Questions 5:

Central Engine:

Black holes vs. magnetars?

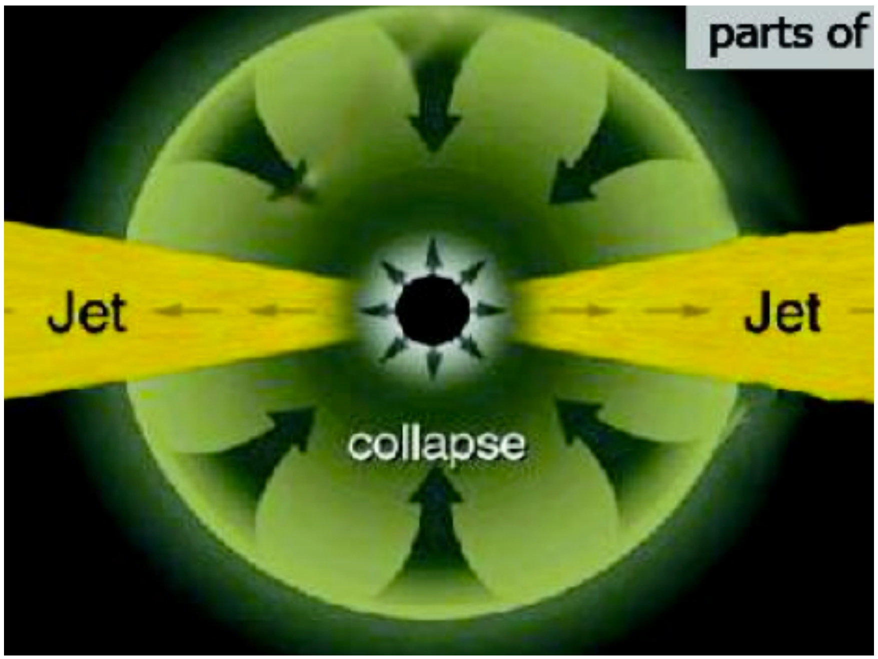
Physical Picture: A Sketch



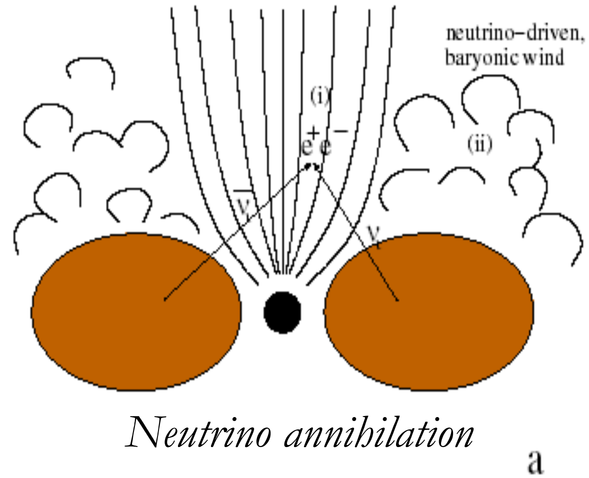
GRB central engine requirements

- Energetic and luminous (E_{iso}~10^{50}-10^{55} erg, L_{iso}~10^{49}-10^{53} erg/s)
- Clean - relativistic ejecta (Γ > ~ 100)
- Rapid variability, diverse temporal behavior
- Intermittent, delayed activity with reducing amplitudes
- A Poynting flux dominated ejecta
- A possible long-lasting steady component in some GRBs (due to spindown?)

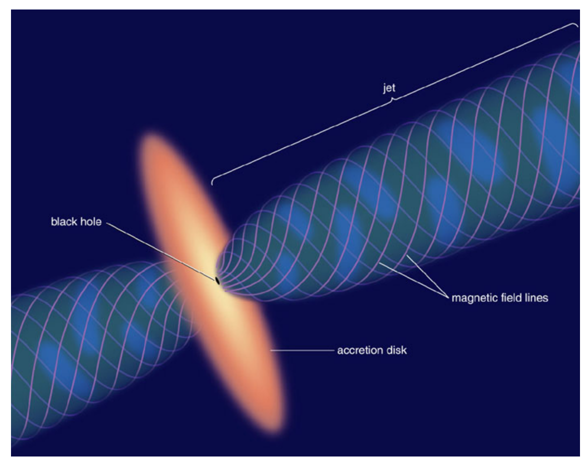
Hyper-Accreting Black Holes



Hyper-Accreting Black Hole

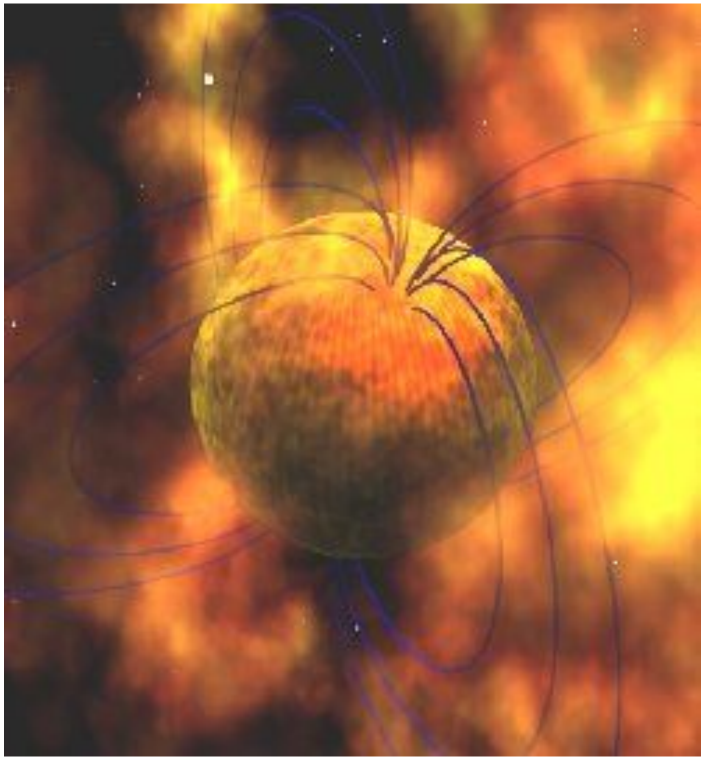


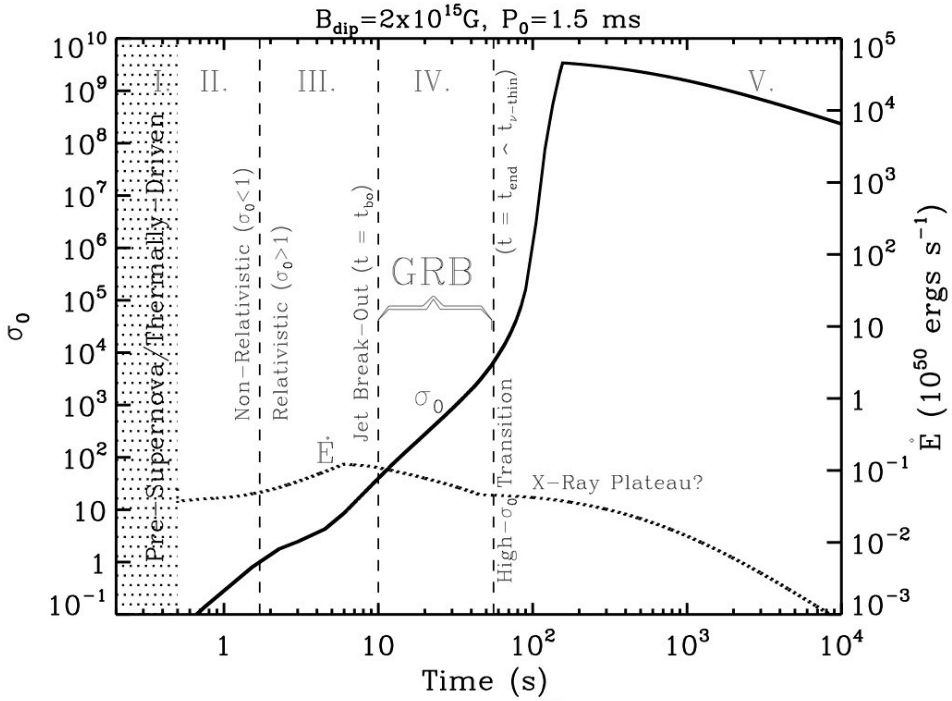
Neutrino annihilation



Magnetically tapping BH spin energy (Blandford-Znajek)

Millisecond Magnetar Central Engine





Metzger et al. (2011)

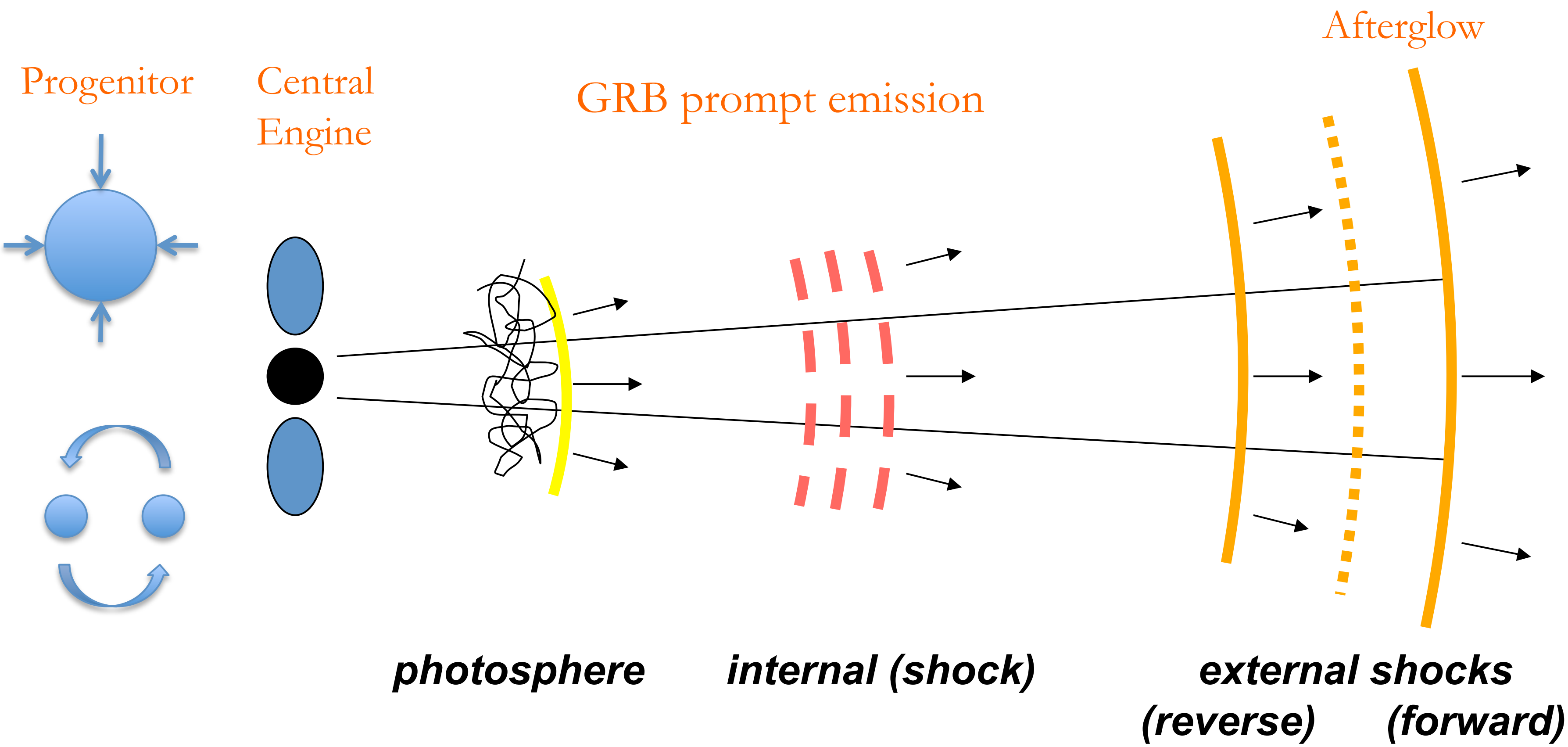
Black Hole or Magnetar?

- BH-torus:
  - More possible for massive progenitors
  - Easy to produce prompt erratic behavior, less easier for very late flares
  - Not easy to produce smooth components
- Magnetars:
  - May need a special channel (event rate too high, progenitor cannot be too massive)
  - Easier to make late flares
  - Maximum energy budget
- Smoking gun? - No
- Clues? - Maybe
  - Plateaus with sharp drops: magnetars
  - Proto black holes?
- A bet: a mix: most BHs, some magnetars

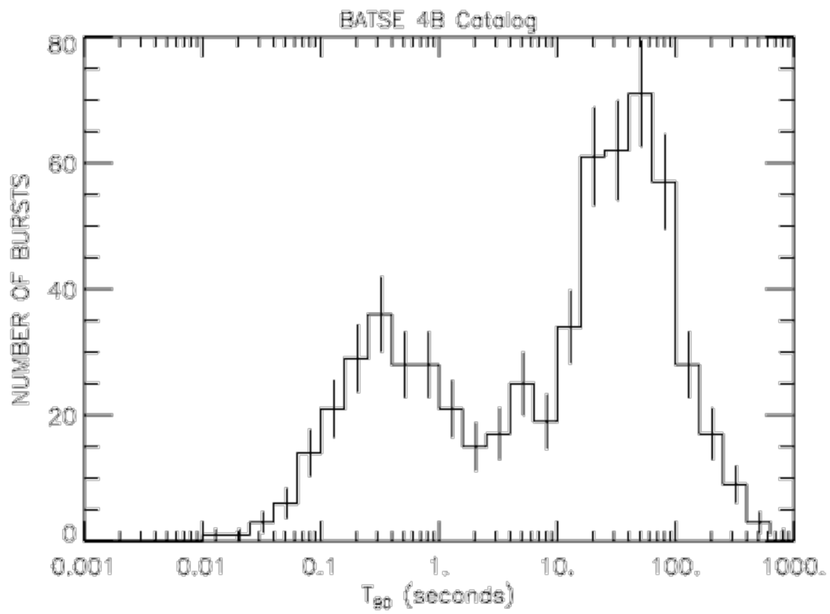
Open Questions 6 & 7:

Progenitors & Classification

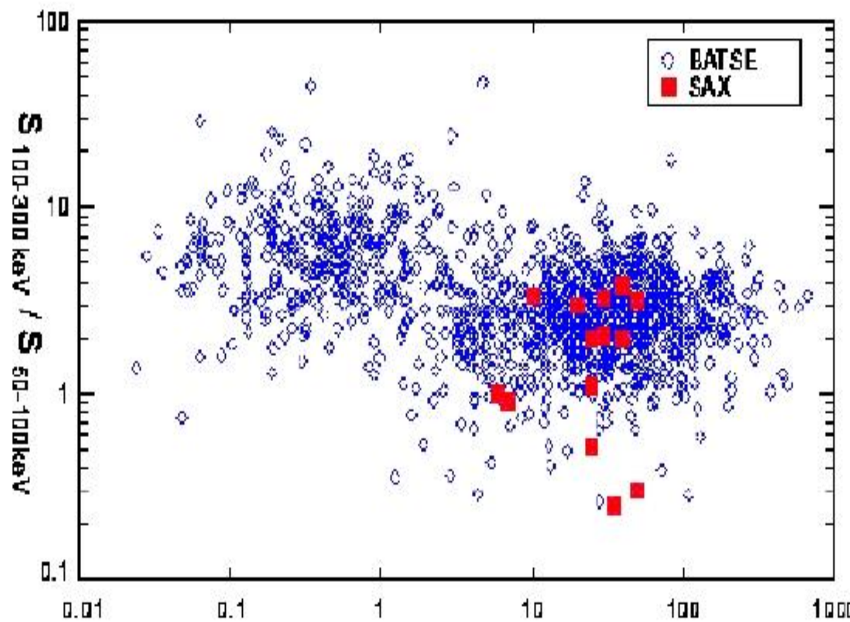
Physical Picture: A Sketch



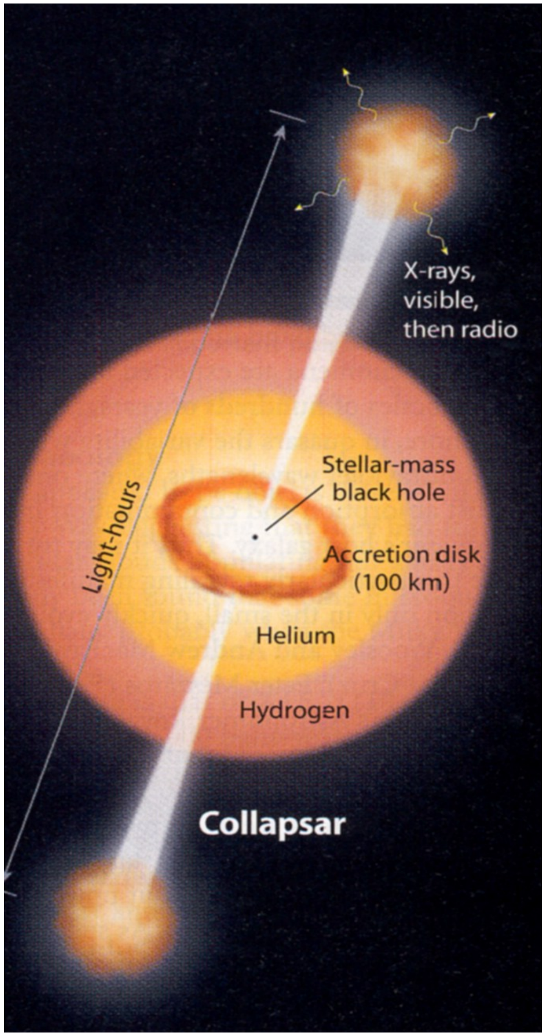
Observation: Long-soft vs. Short-hard

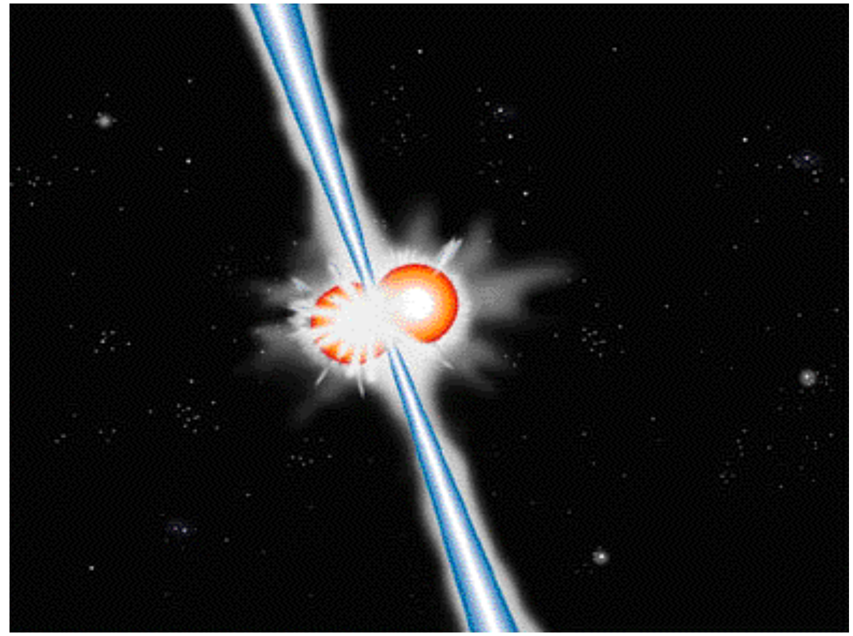


Kouveliotou et al. 1993



Two Progenitor Models





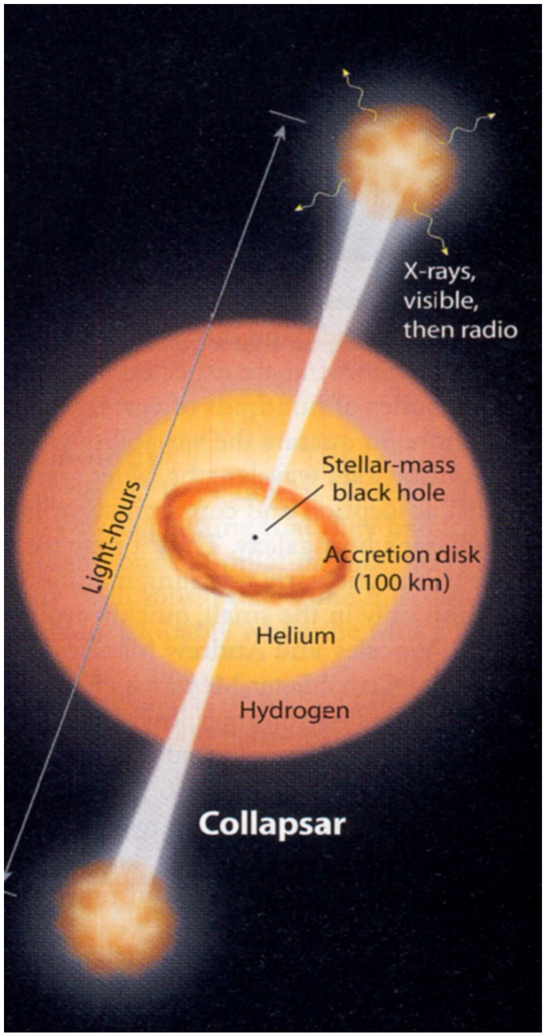
NS-NS Merger

(Eichler et al. 89; Narayan et al. 92 …)

Massive Star Core Collapse

(Woosley 93; Paczynsky 98 …)

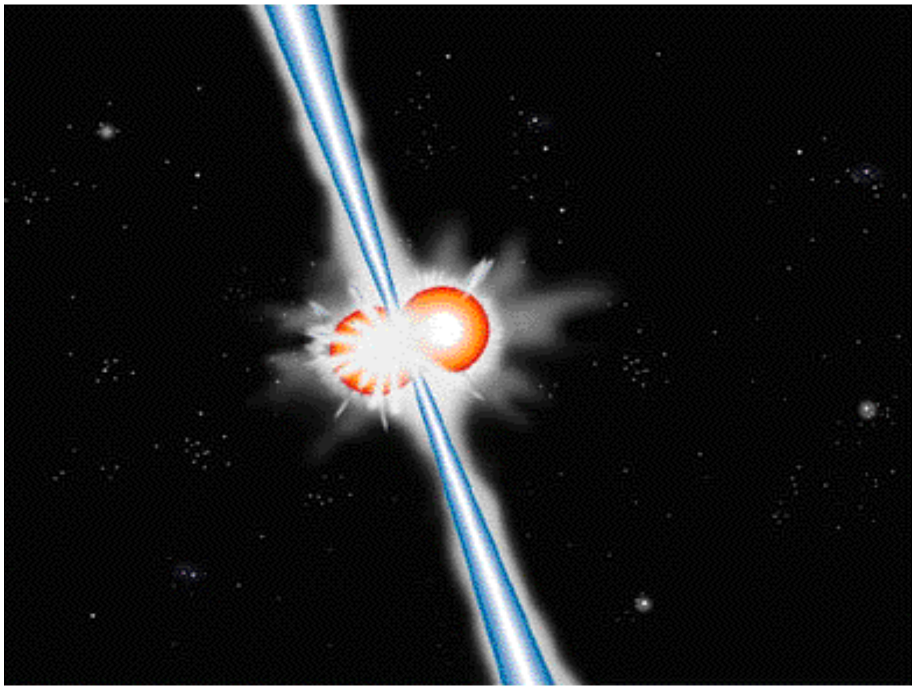
More observations: Massive star GRBs



- Long duration
- A handful secure GRB/SN associations (spectroscopically identified SNe)
- Star formation host galaxies
- Bursts located in active star formation regions.

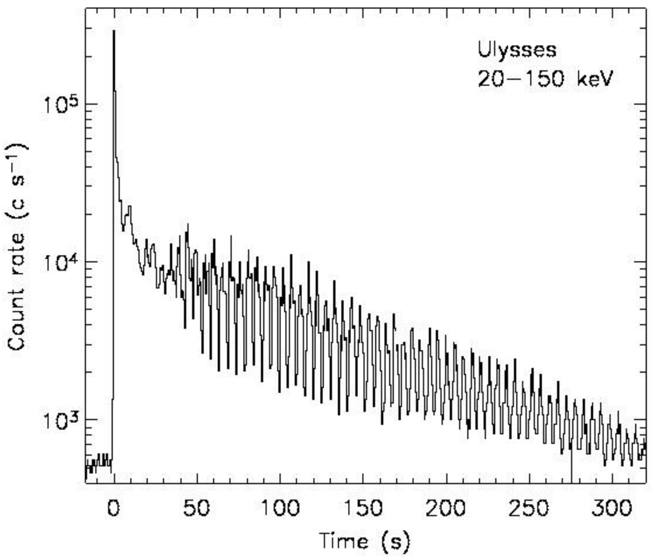
- Possible scenarios:
  - Single star core collapse
  - Binary: merger-induced events
  - Binary: supernova-induced events
  - …

More observations: Compact Star GRBs

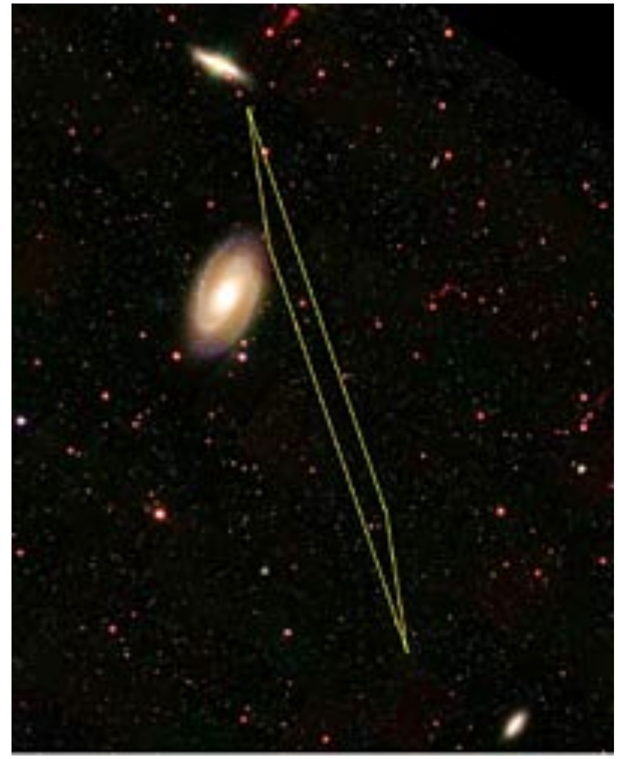


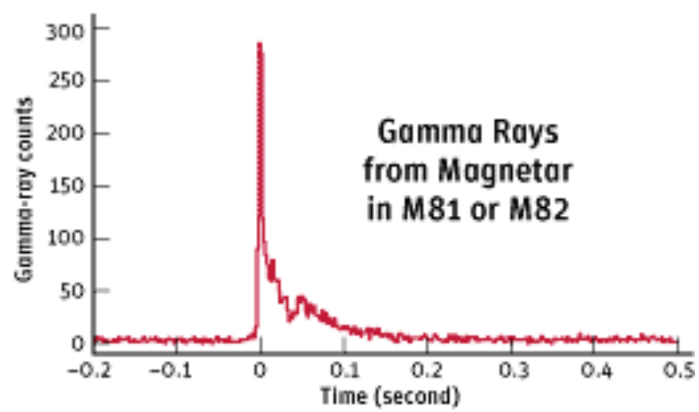
- Most are short
- In different types of host galaxies, including a few in elliptical/early-type galaxies, but most in star-forming galaxies
- Large offsets, in regions of low star formation rate in the host galaxy. Some are outside the galaxy.
- Possible scenarios:
  - NS – NS mergers
  - NS – BH mergers
  - Accretion induced NS collapses
  - Magnetar giant flares
  - …

Magnetar Giant Flares



SGR 1900+14 (Hurley+ 99)

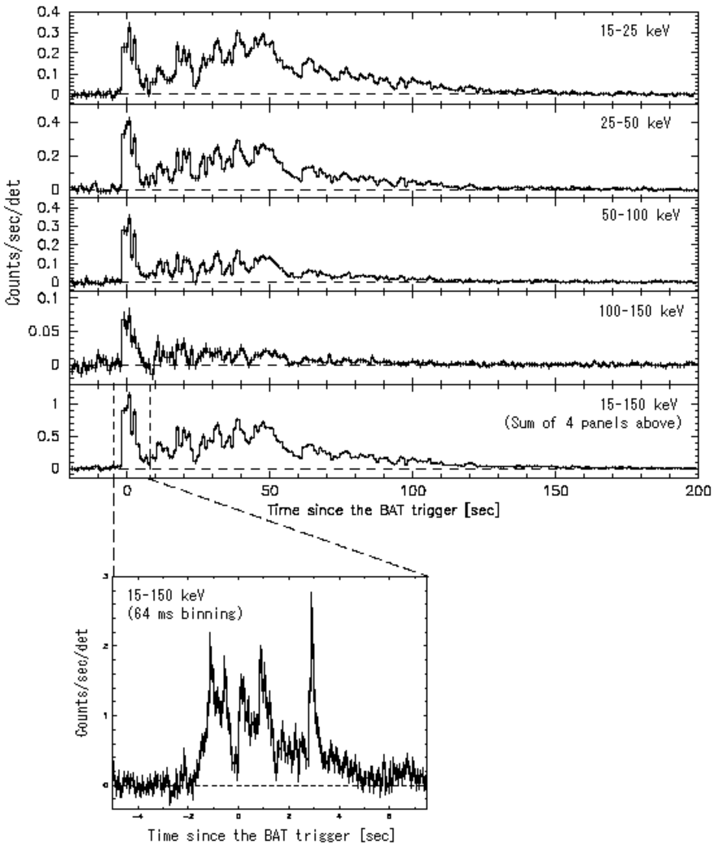


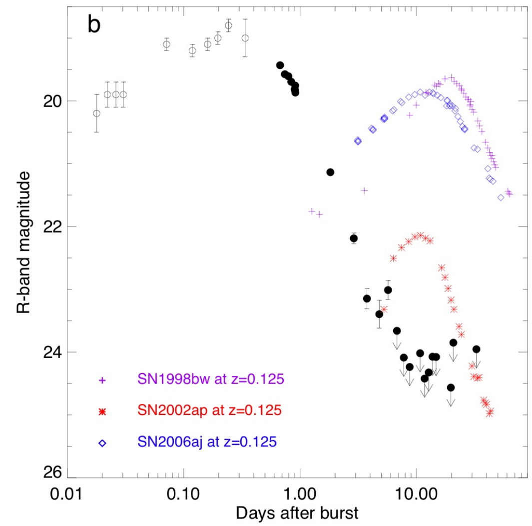


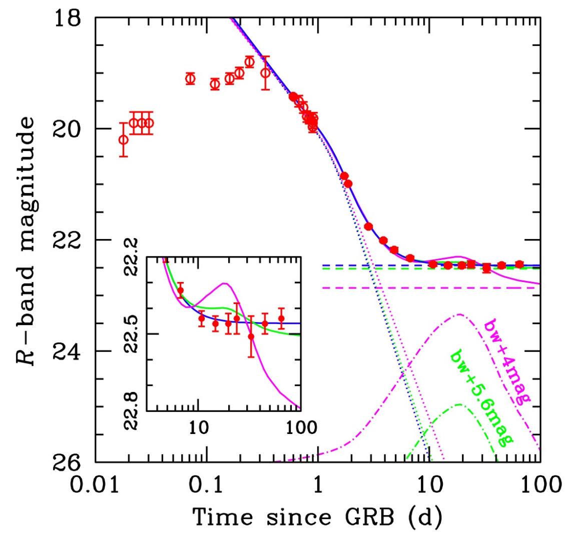
GRB 051103
Ofek+ 06

LIGO team

Oddball: GRB 060614
A nearby long GRB without SN







Gehrels et al. 2006

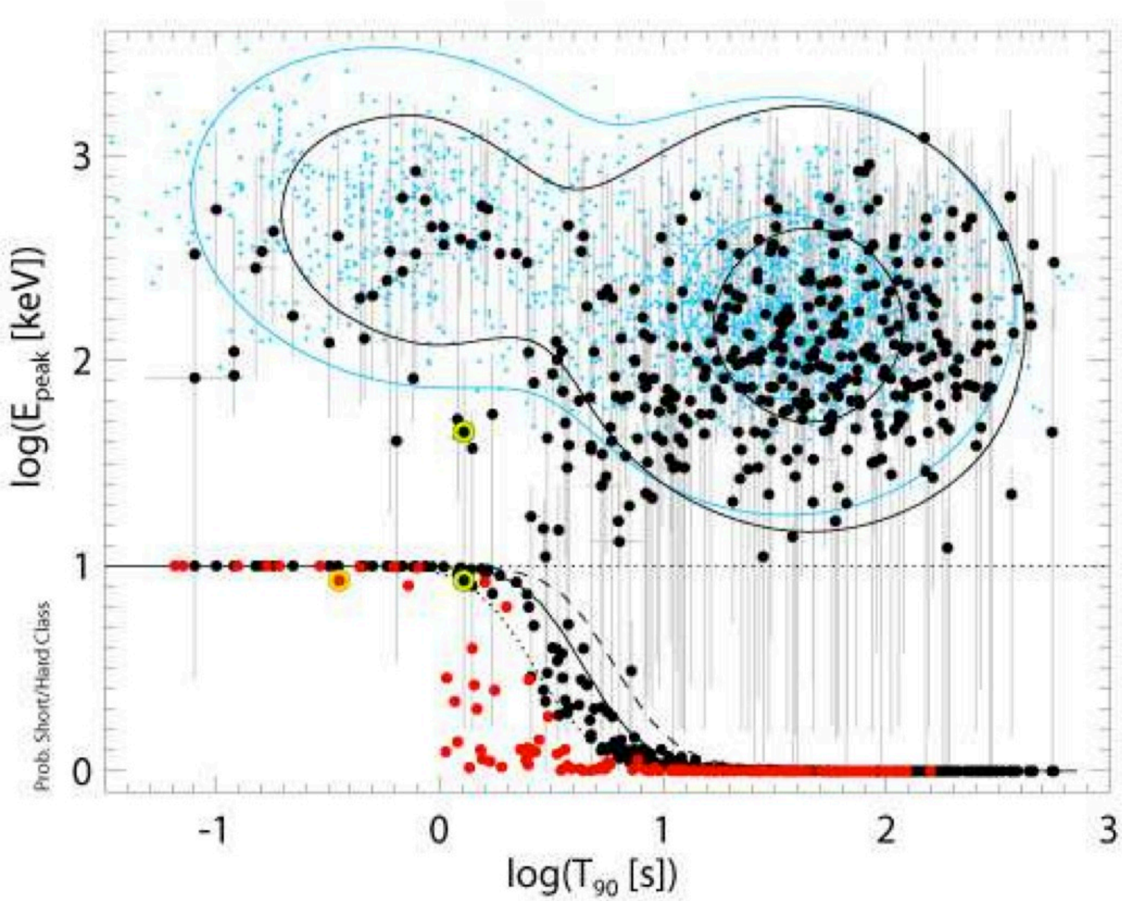
Fynbo et al. 2006

Della Valle et al. 2006

Gal-Yam et al. 2006

Odd ball: GRB 090426

A short GRB likely of a massive star origin



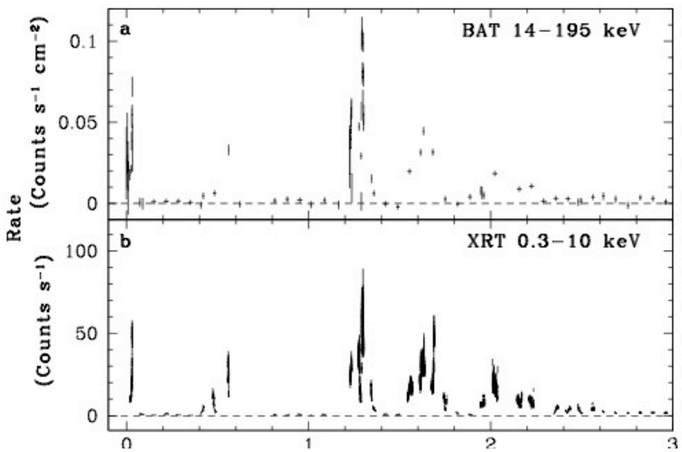
T_{90}=1.28±0.09 s
T_{90}(rest) ~ 0.35 s

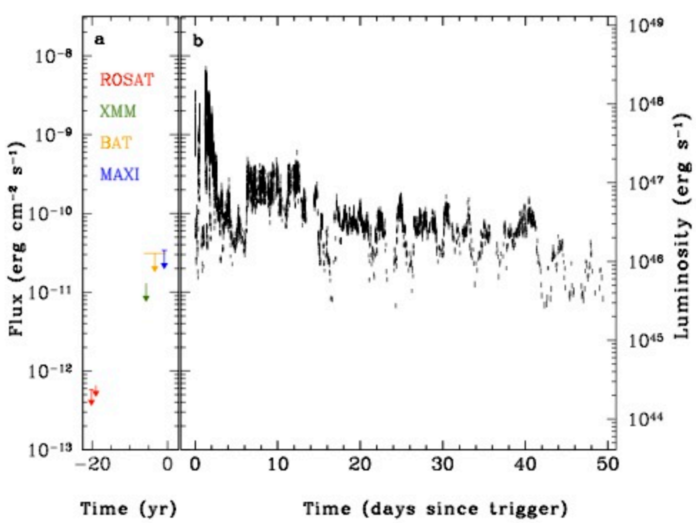
Levesque et al. 2010
Antonelli et al. 2009
Thöne et al. 2011
Xin et al. 2011

Tip of iceberg?
Lü et al. 2012

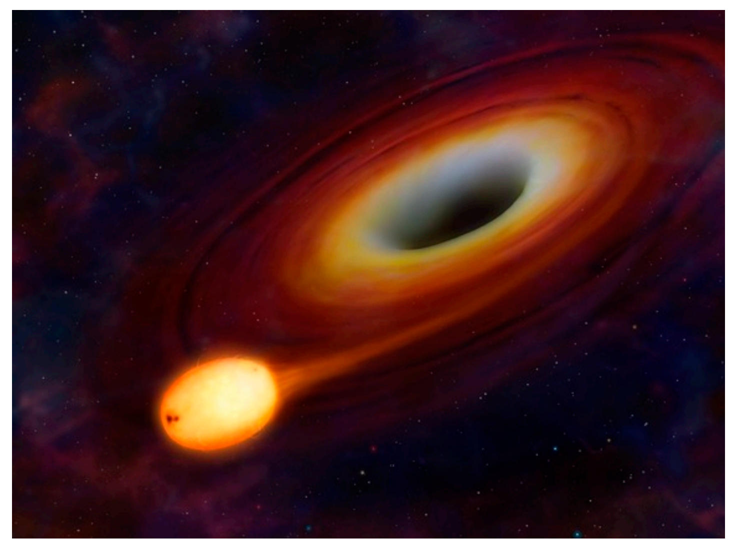
Oddball:
“GRB 110328A”=Swift 1644+57

Burrows et al.; Bloom et al.; Levan et al.; Zauderer et al.

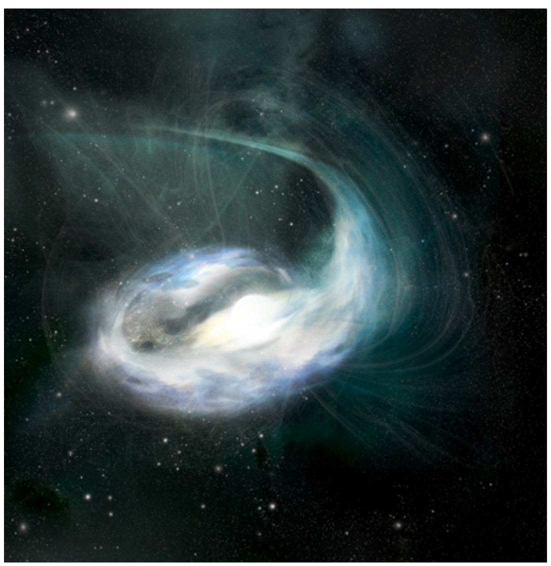




- Triggered BAT multiple times
- Extended X-ray afterglow without significant decay
- Stringent historical X-ray flux upper limits
- z=0.354, source in the center of galaxy
- Minimum variability ~ 100 s: ~ $10^6\ M_\odot$ black hole
- Tidal disruption of a star by a spinning black hole



GRB 101225A="Christmas burst"

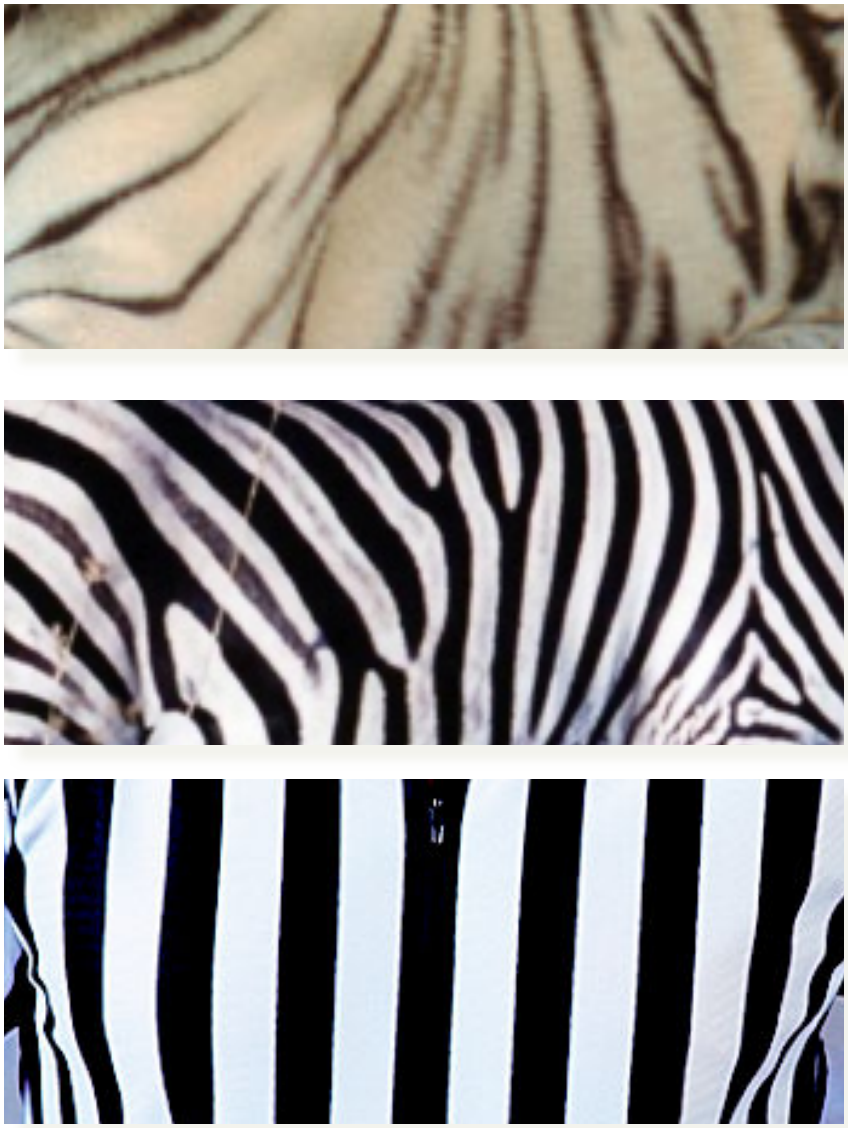


- Super-long GRB
- No SN, no host, no redshift
- Weird afterglow behavior
- Low Galactic latitude (~17^{o})
- Close to Andromeda and Local Group

Two scenarios:

- Cosmological Model: Helium star – neutron star merger (Thone et al. 2011)
- Local Model: NS/comet collision (Campana et al. 2011)

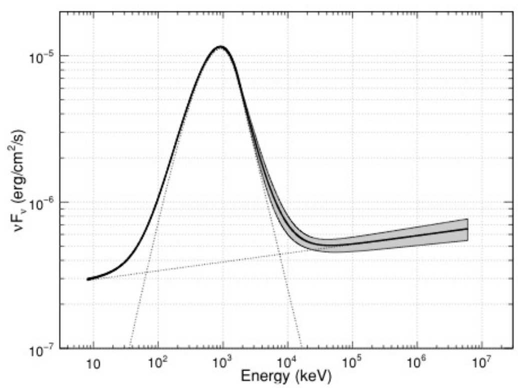
GRBs vs. Striped animals



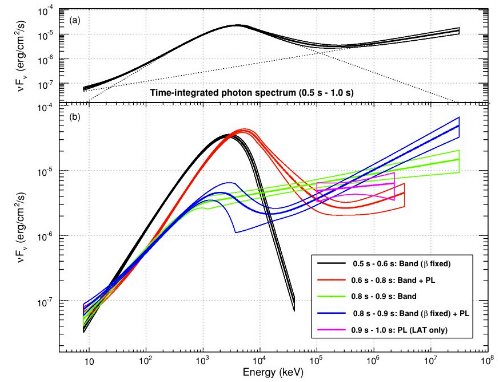
An alien with a narrow field-of-view discovered a specie on earth and named them as "Striped Animals"

Striped animals

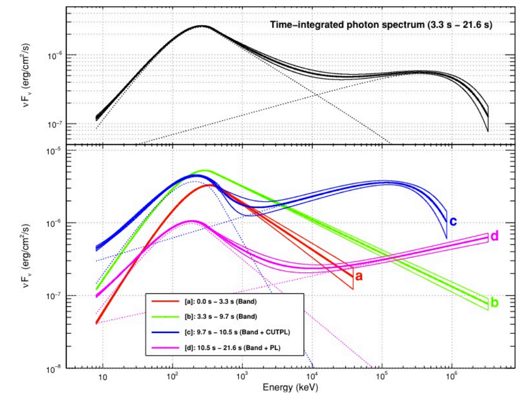
Gamma-Ray Bursts in the "Gamma-Ray" band



GRB 090902B
Abdo et al. 2009

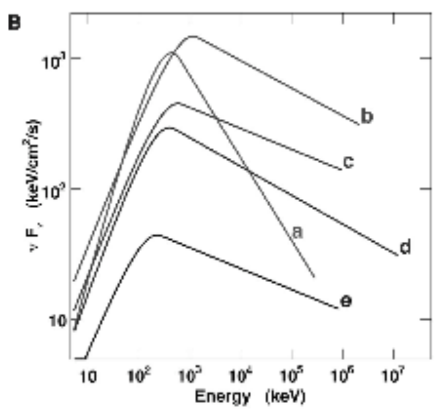


GRB 090510
Ackermann et al. 2010

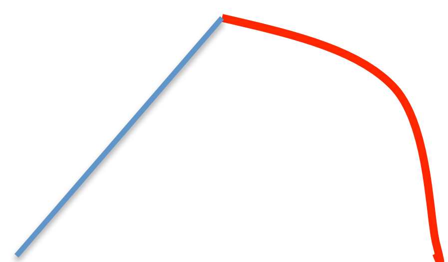


GRB 090926A
Ackermann et al. 2011

Most:

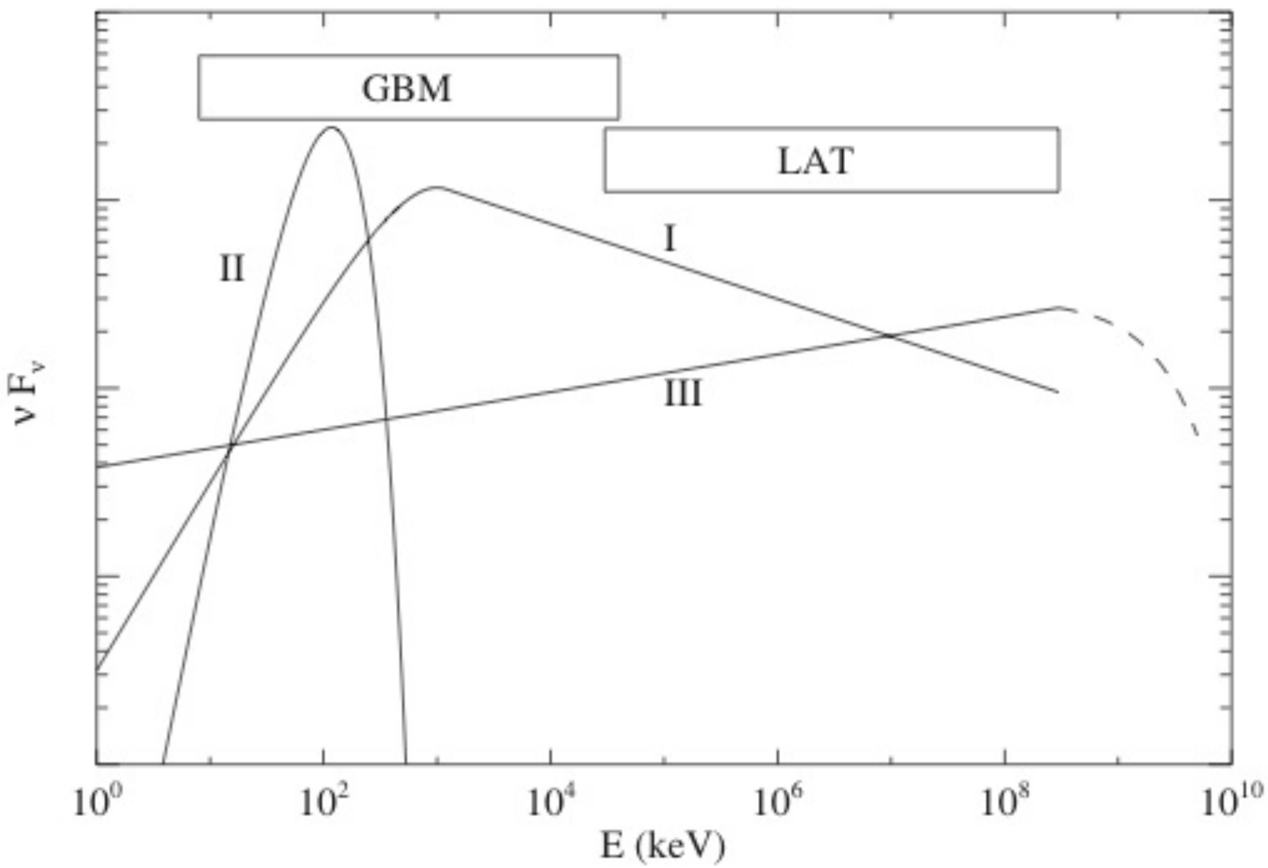


Or:



Not favorable for high energy

Prompt Spectral Components



Zhang et al. (2011)

Gamma-Ray Bursts in the "Gamma-Ray" band

Predictions: with favorable parameters, GRB afterglow can be detected up to TeV

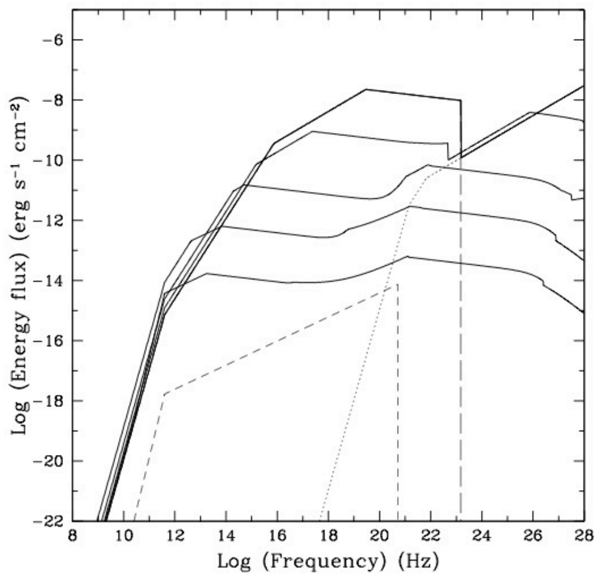
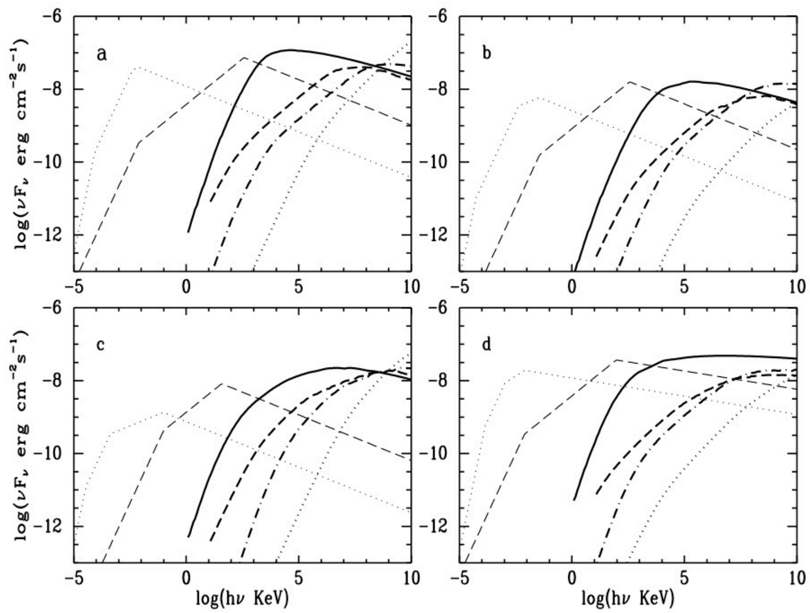


FIG. 2b



Zhang & Meszaros (2001)

Wang et al. (2001)

Future: Multi-messenger Era