Models of GRB Prompt Emission

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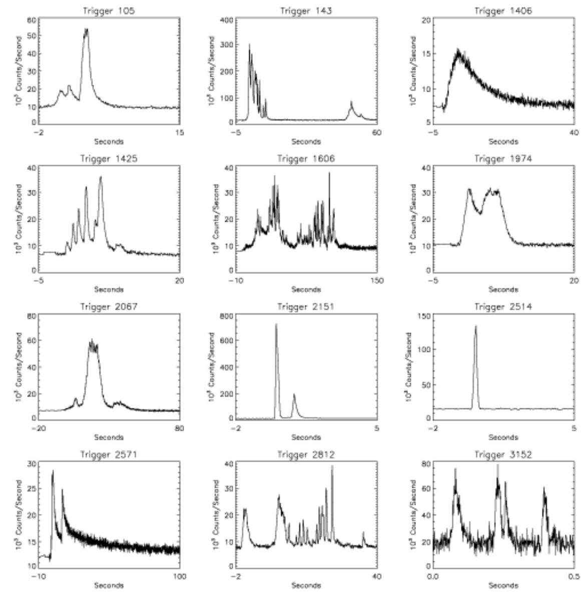
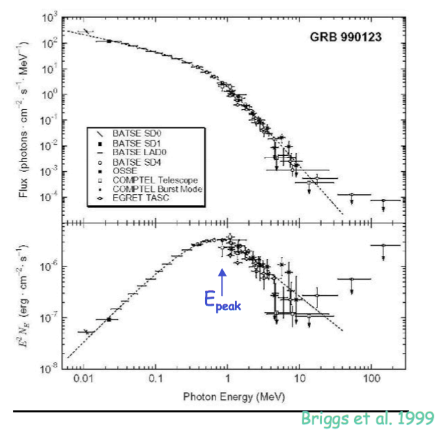
GRB Prompt Emission: What do we interpret?

- Light Curve
- Spectrum
- Polarization
- Other constraints
  - Spectral parameter distributions
  - Ep evolution patterns
  - Correlations
  - Prompt high energy emission
  - Prompt low energy emission
  - connection to afterglow
  - Neutrino flux
  - ……



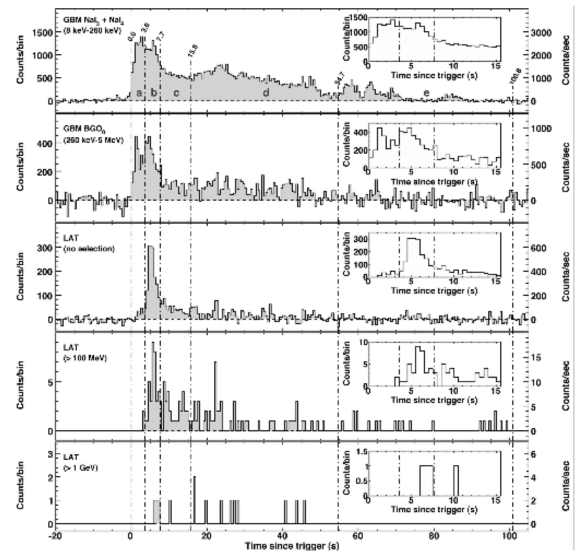
Fishman & Meagan 1996



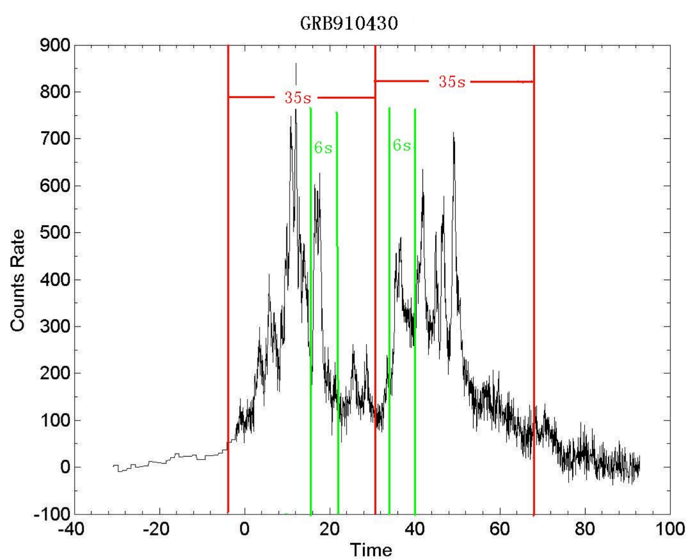
Briggs et al. 1999

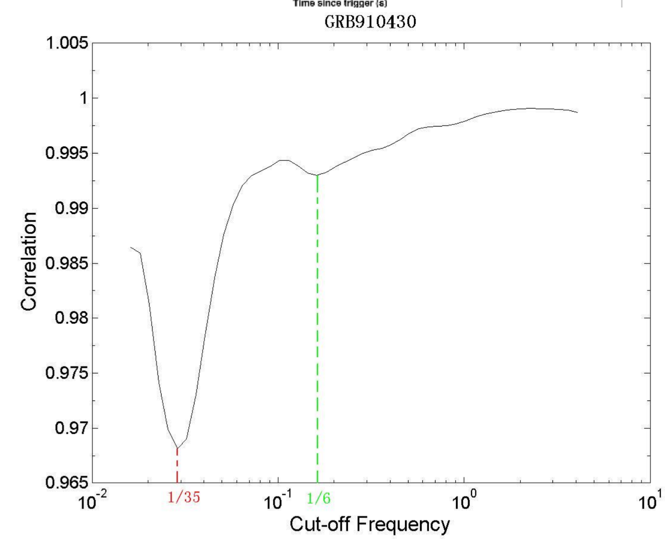
More on light curves

- Erratic, sometimes smooth
- Fast rise exponential decay
- Spectral lag
- Fast vs. slow components
- ……



Abdo et al. 2009

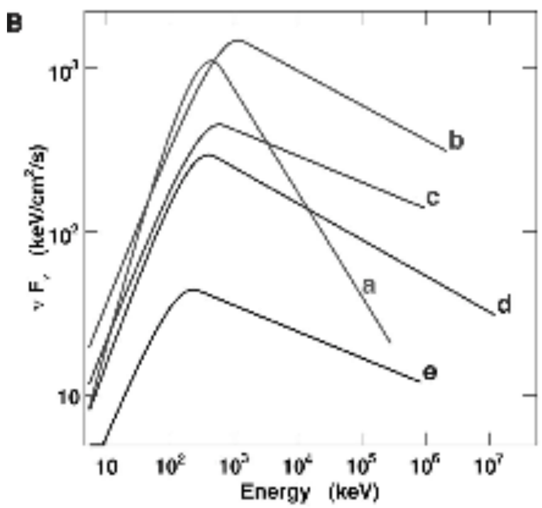




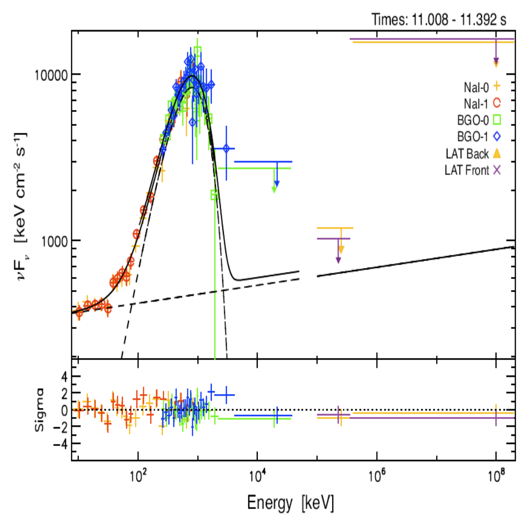
Gao, Zhang & Zhang (2012, ApJ, 748, 134)

More on spectra

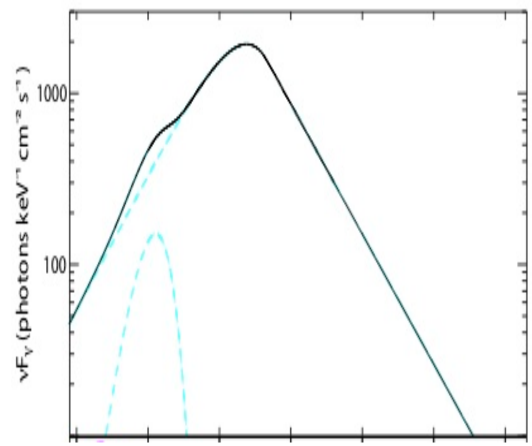
- Phenomenologically dominated by “Band”
  - α ~ -1, β ~ -2.2
- Existence of (probably) two more components
  - Quasi-thermal
  - High energy component



080916C (Abdo et al. 2009)



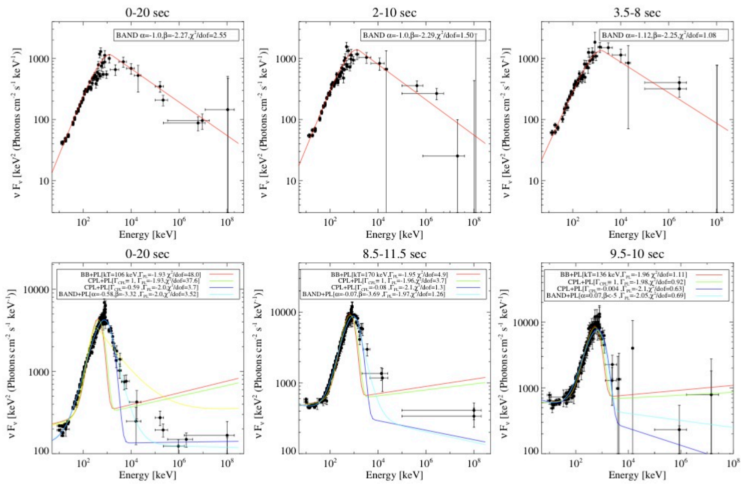
090902B (Ryde et al. 2010)



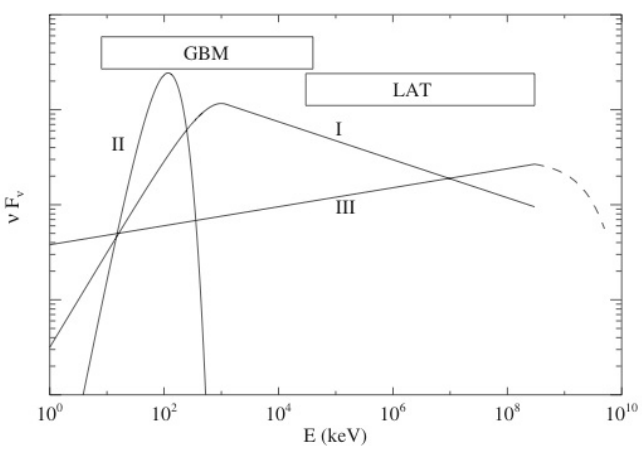
110721A (Axelsson et al. 2012)

More on spectra

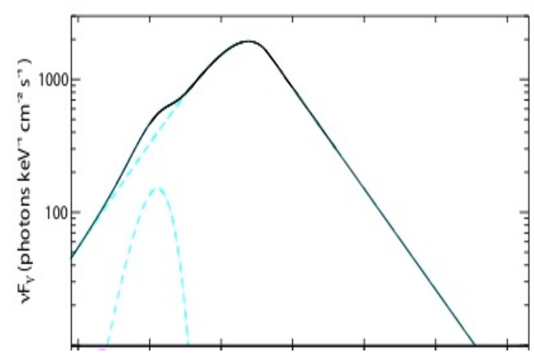
- Difference between 080916C and 090902B
  - 080916C: α ~ -1, spectrum does not narrow when time bin gets smaller
  - 090902B: α ~ 0 to -0.5, spectrum does narrow when time bin gets smaller
- Bursts with superposed components: 100724B, 110721A, 120323A …, suggesting that "Band" and "thermal" are different components
- A three-component spectrum



GRB 080916C vs. GRB 090902B



B.-B. Zhang et al. (2011)

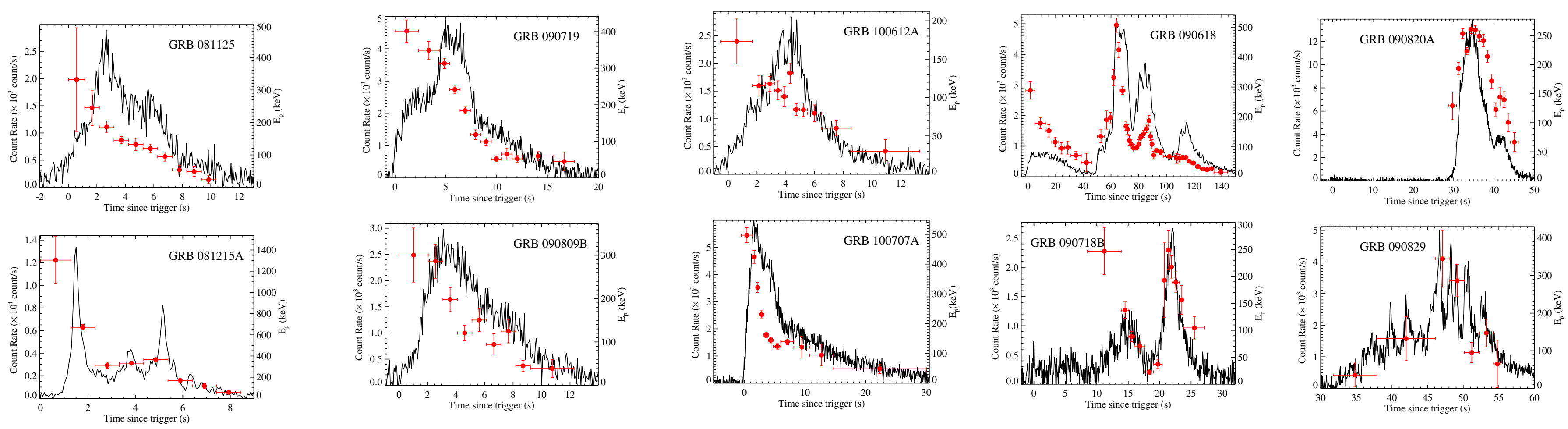


Axelsson et al. (2012)

Spectral Evolution

- Two patterns of Ep-evolution
  - Hard-to-soft evolution
  - Intensity tracking
- In correlation with the broad variability component, not the rapid variability component

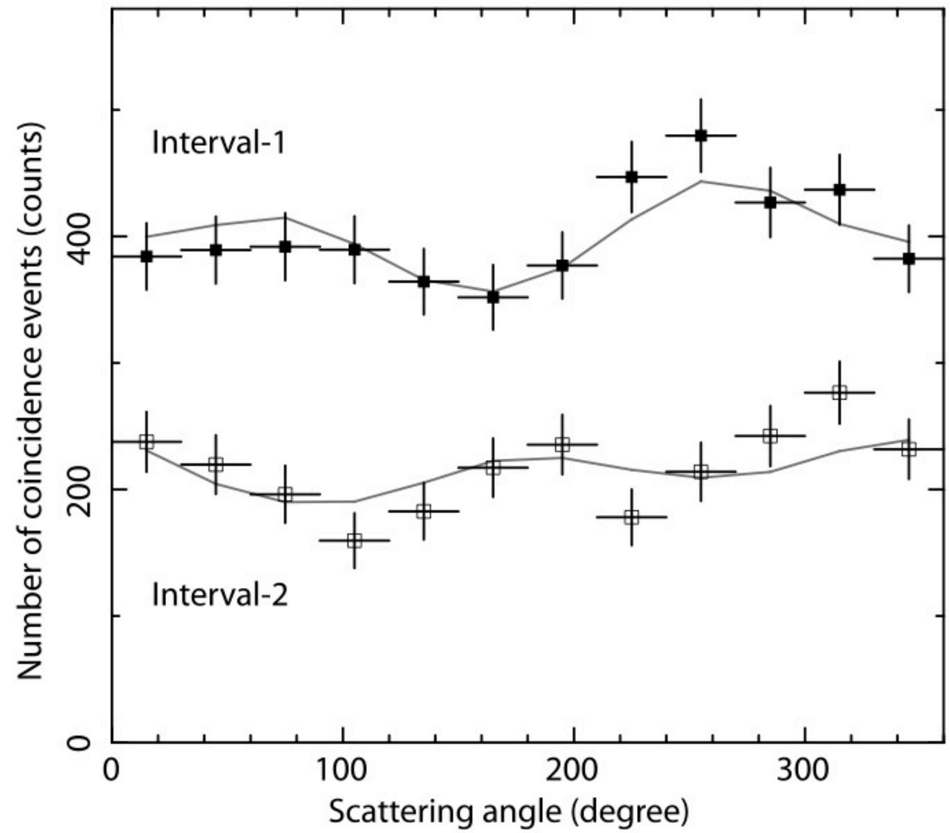
$$R_\gamma \sim \Gamma^2 c\, \Delta t_{broad} \sim 10^{15}\ \mathrm{cm} >> \Gamma^2 c\, \Delta t_{min} \sim 10^{13}\ \mathrm{cm}$$



Lu et al., 2012, 756, 112

Polarization

- 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; but see Uehara et al. 2012)



Yonetoku et al. (2011)

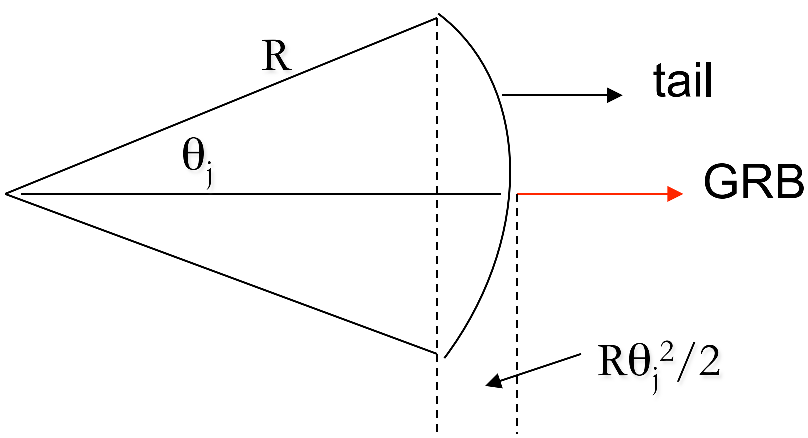
Emission in other wavelengths

- Indirect way to constrain R_γ (if from the same emission region)
- Three independent constraints on R_γ
  - The duration of the X-ray steep decay phase if due to high-latitude emission
  - The condition that the prompt optical emission is not self-absorbed
  - The condition that the GeV photons are not attenuated

X-rays

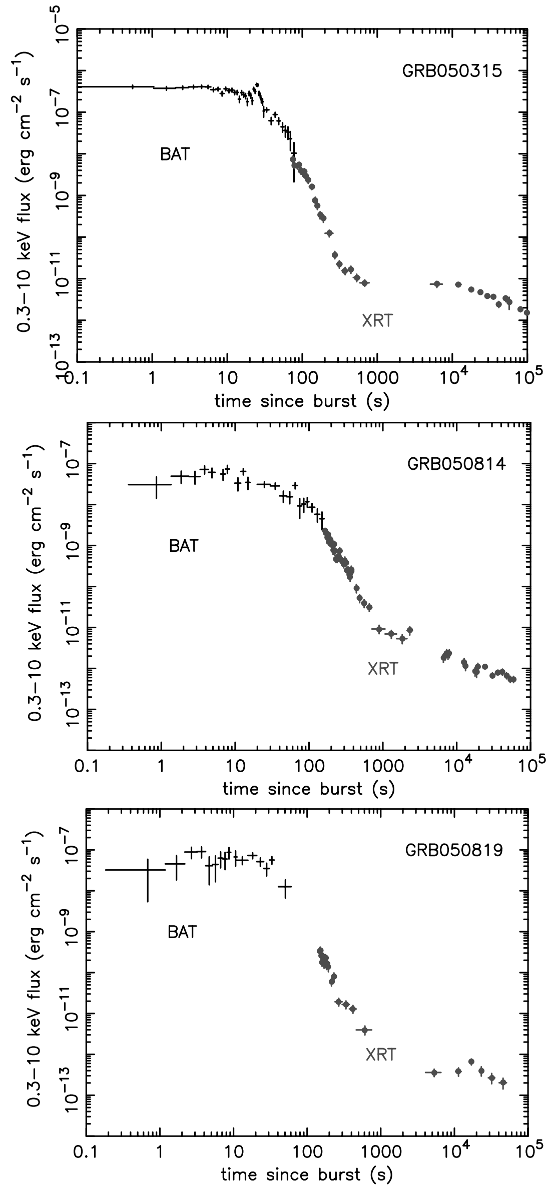
If the steep-decay phase of the X-ray tail is defined by the high-latitude emission, one has:

$$R > \frac{2ct_{tail}}{(1+z)\theta_j^2} \sim 10^{15}\text{cm}\left(\frac{t_{tail}}{1000}\right)\frac{2}{1+z}\left(\frac{\theta_j}{10^{\text{o}}}\right)^2$$



Require large emission radius!

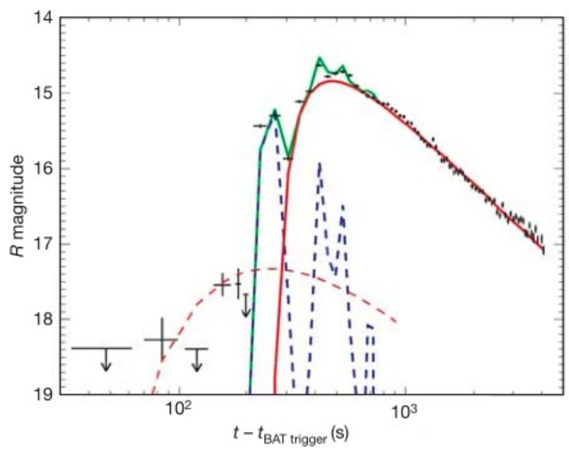
Zhang et al. (2006); Lyutikov (2006); Kumar et al. (2007); Hascoet et al. 2012)



O'Brien et al. (2006)

Optical

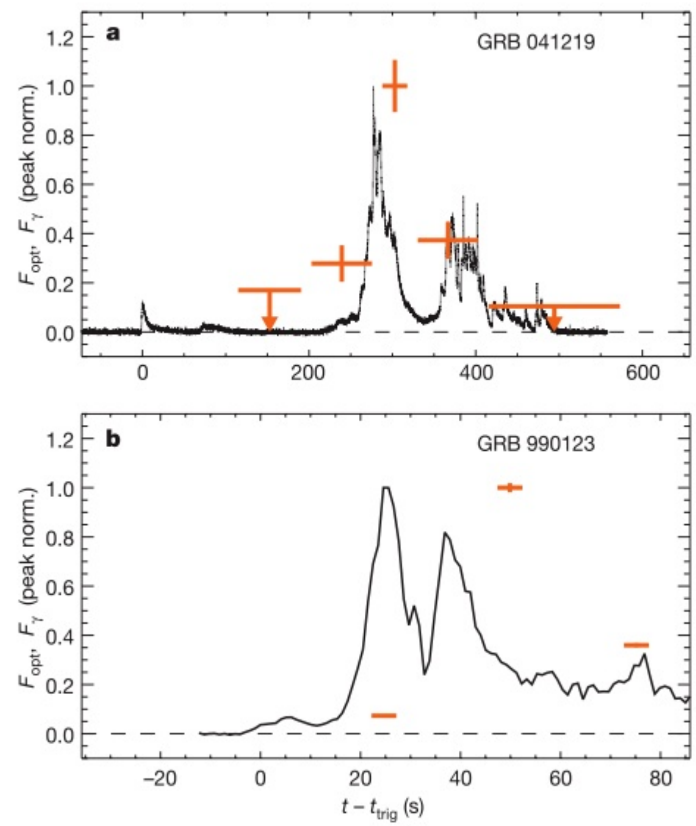
"Tracking" optical band detection constraints the self-absorption frequency and, hence, the emission radius. Most optical emission is consistent with extension of gamma-rays to optical (Naked eye GRB special)



GRB 050820A

Shen & Zhang (08):

$$R_{\gamma,opt} > \text{several } 10^{14} \text{ cm}$$

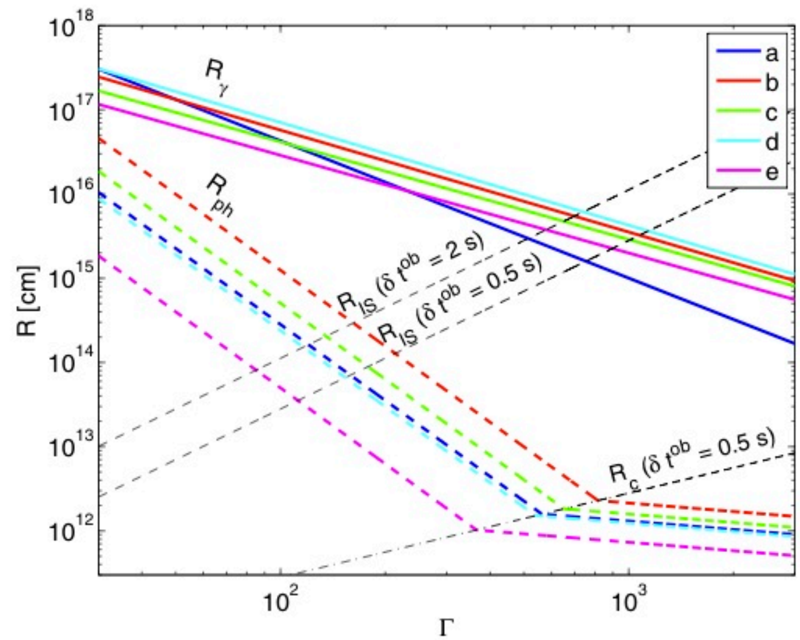


Vestrand et al. 2006a,b

GeV

Pair cutoff feature depends on both bulk Lorentz factor (Baring & Harding 1997; Lithwick & Sari 2001) and the unknown emission radius (Gupta & Zhang 2008).

When Γ is independently measured, the pair cutoff (or its non-existence) can be used to constrain R



GRB 080916C, Zhang & Pe'er (2009)

What do we know & not know about GRB prompt emission

- We are confident about:
  - Non-thermal, not thermalized, need energy dissipation and particle acceleration, emission site must be at or above photosphere
  - “Internal” for most GRBs, emission site should be below deceleration radius
- We are not sure about:
  - Jet composition
  - Energy dissipation mechanism
  - Particle acceleration mechanism
  - Radiation mechanism

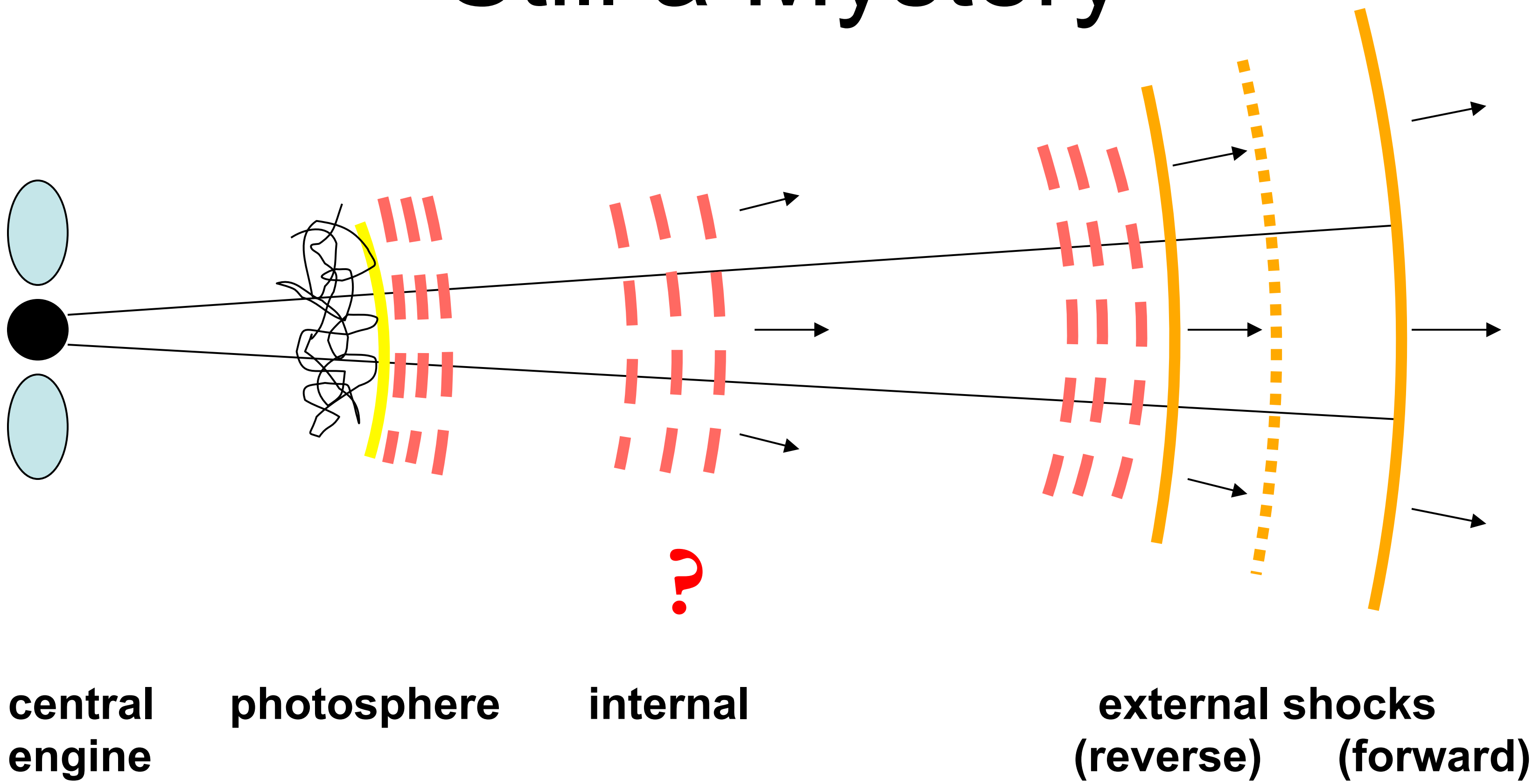
Radiation mechanisms

- Synchrotron radiation
  - Fast cooling, Ep defined by injection energy
- Quasi-thermal with a Comptonized tail
  - Ep defined by photosphere temperature
- Synchrotron self-Compton
  - Ep is defined by the SSC, the synchrotron peak is in optical
  - Problems: energy budget, Ep distribution, variability…
- Hadronic cascade
  - Ep defined by complicated cascade effect
  - Problems: energy budget, neutrino flux constraints…

Physical models

- Traditional fireball model
  - Non-thermal emission from internal shocks
  - Quasi-thermal emission from a baryonic phosphere
- Dissipative photosphere model
  - The entire spectrum is re-processed quasi-thermal emission at the photosphere
  - Dissipation can be either baryonic (p-n collisions or internal shocks) or magnetic (reconnection)
- Large-radius magnetic dissipation model (e.g. ICMART model)
  - Suppressed photosphere emission
  - Bulk of emission comes from large radii due to magnetic dissipation

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)?

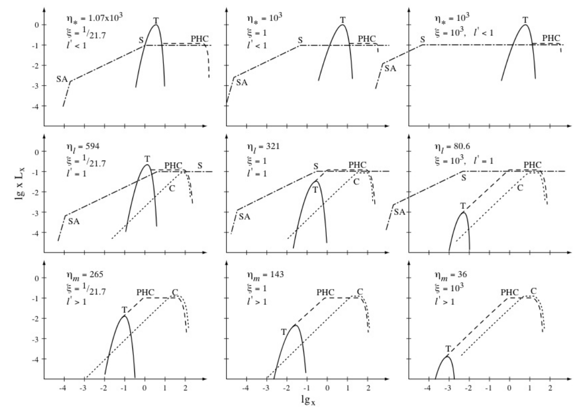
Photosphere model

(model to interpret the entire GRB spectrum with photosphere emission)

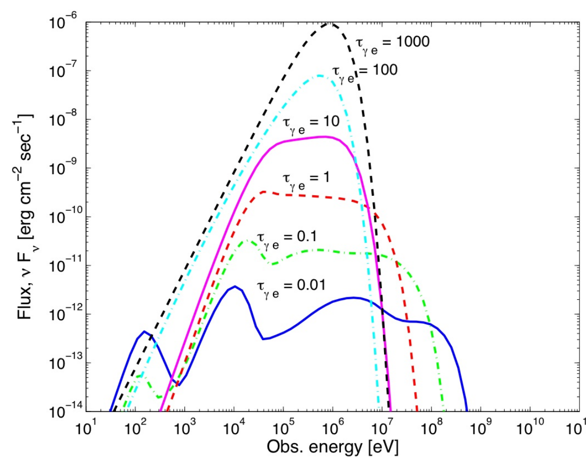
- Usually bright, should be there.
- Temperature defines E_p, falls into the observed range
- Narrow Ep, narrow Ep distribution
- Good to interpret various correlations
- Should have contribution to the observed spectrum.

- But can photosphere interprets everything?

Thompson; Meszaros & Rees; Pe'er et al.,Ryde, Beloborodov, Giannios, Lazzati et al.; Ioka; Toma et al.; Fan et al.; Mizuta & Nagataki; Lundman et al.



Meszaros & Rees (2000)

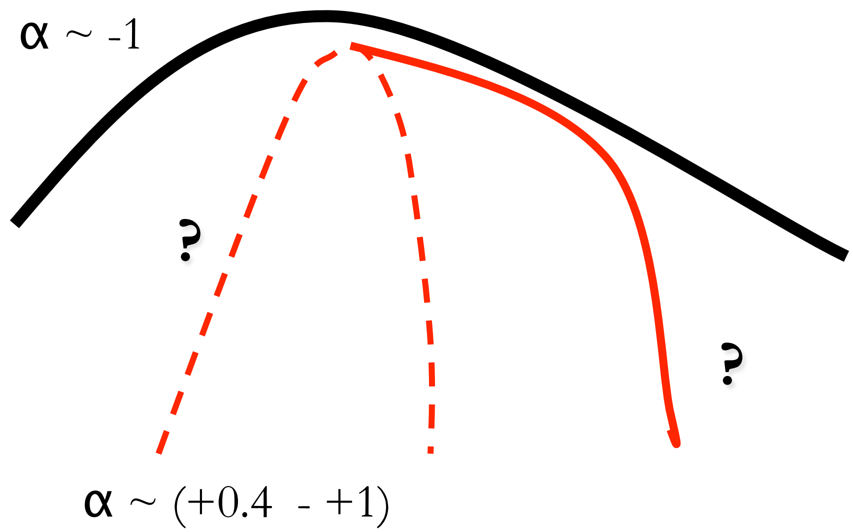


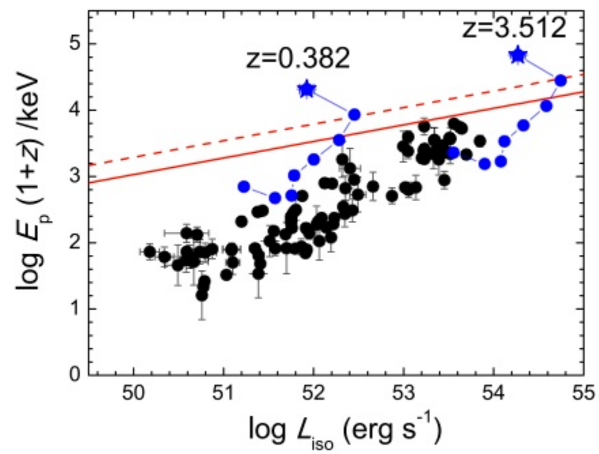
Pe'er, Meszaros & Rees (2006)

Photosphere model: Issues

- Spectral shape
  - Low frequency spectral index: how to produce α ~ -1?
    - Usually too hard α ~ +0.4
    - -1 may be achieved in a structured jet with special structure (Lundman et al. 2013)
  - High energy emission needs an extra component

- Maximum Ep ("death line")
  - Ep defined by temperature for original photosphere model
  - Temperature cannot exceed a certain value give a luminosity
  - GRB 110721A was beyond the death line early on: the "Band" component should be non-thermal (synchrotron) emission in the optically thin region (Zhang et al. 2012; Veres et al. 2012)

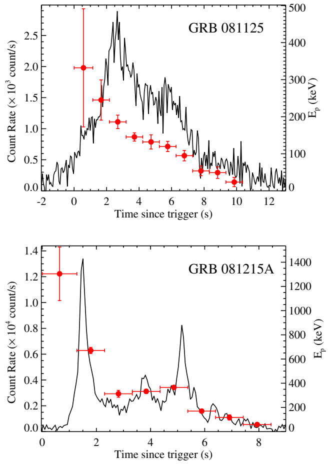


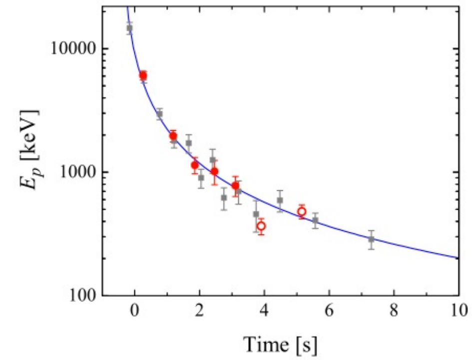


Zhang et al. (2012)

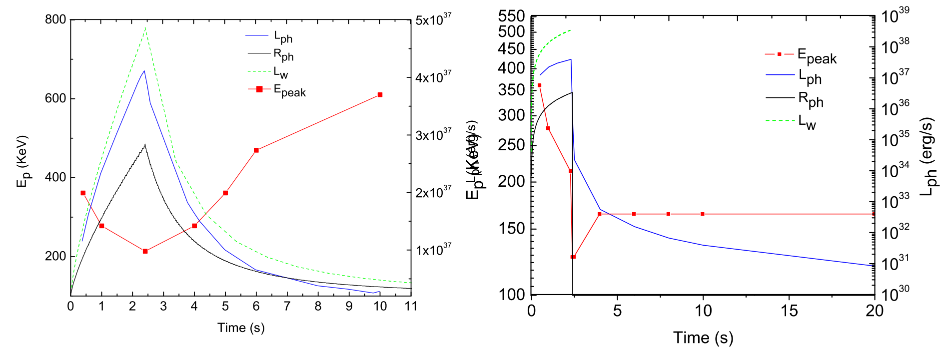
Photosphere model: Issues

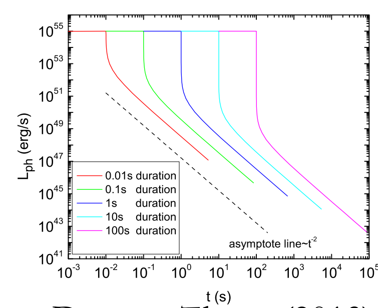
- Ep evolution
  - How to interpret hard-to-soft evolution during the pulse rising phase (Ep initially outside death line)?
- X-ray tail emission
  - Cannot be high-latitude emission
- Contrived condition for dissipation (Asano & Meszaros 13; Vurm et al. 13; Kumar & Zhang 13)
- Polarization
  - Usually un-polarized
  - Polarized emission may be obtained from the synchrotron component of photosphere emission (Vurm et al. 2011), but how to maintain an ordered B-field in a dissipative photosphere?
  - Polarized emission can be obtained in a special structured jet at large viewing angle (Lundman et al. 2012)





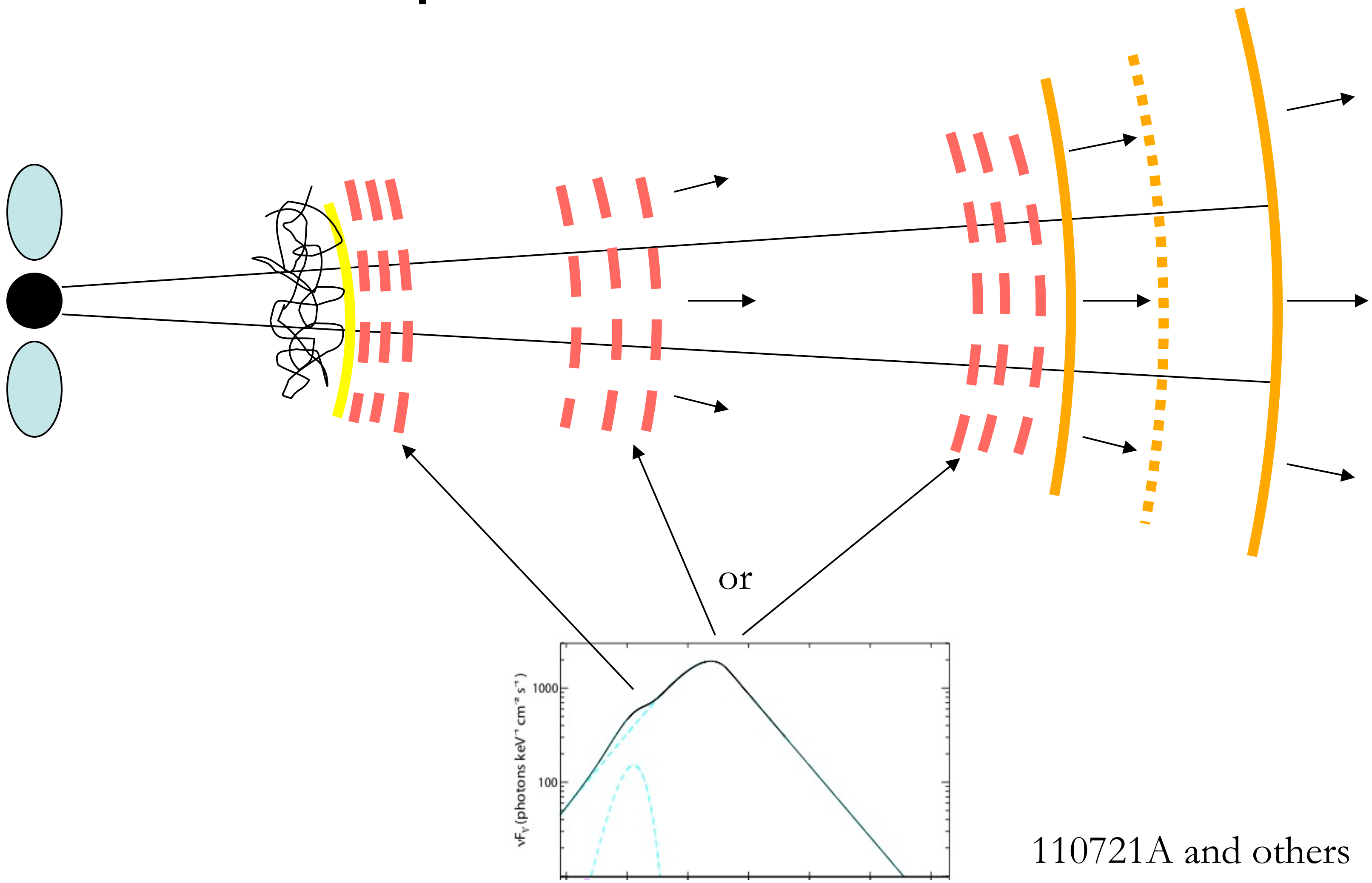
GRB 110721A, Axelsson et al. (2012)





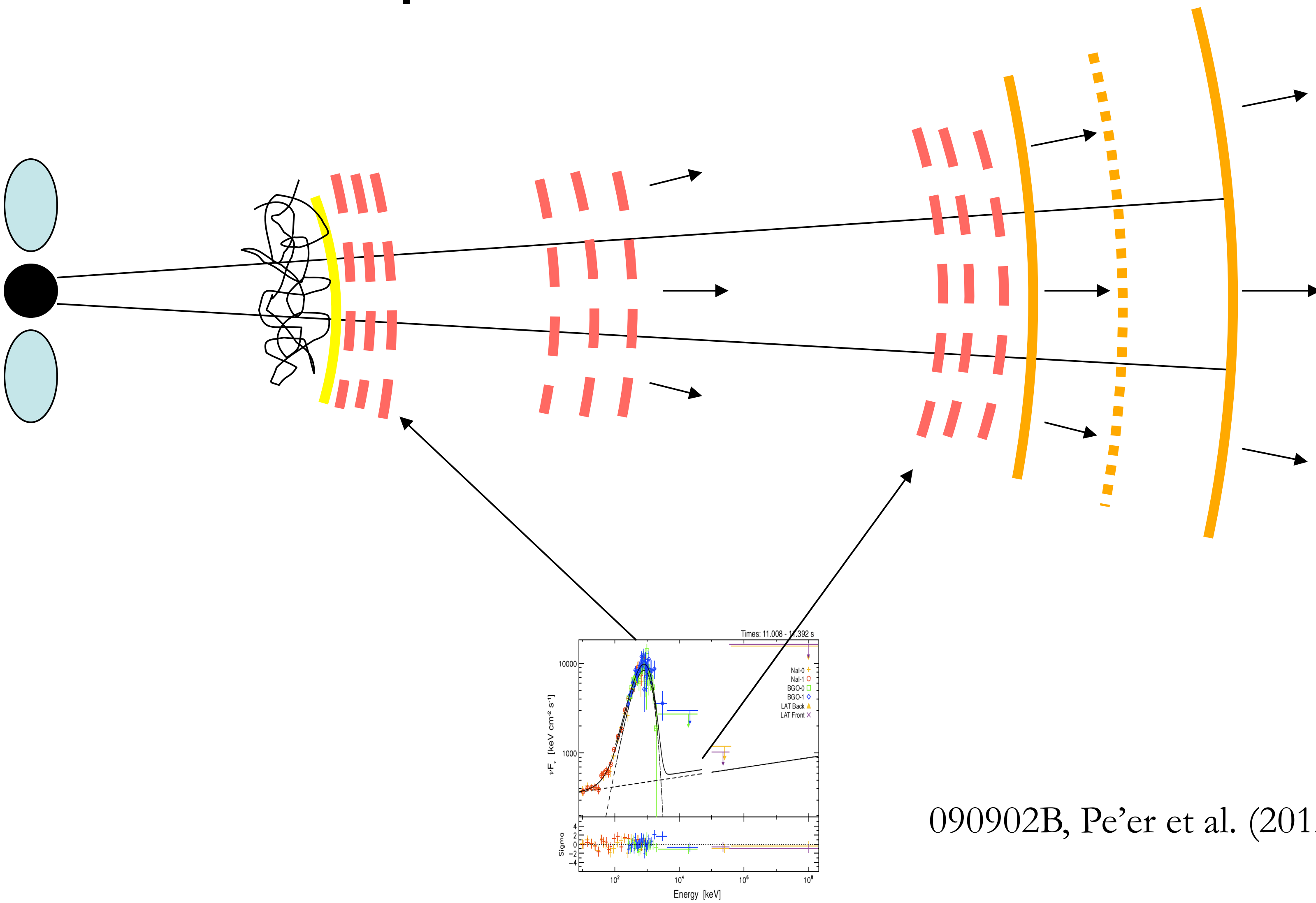
Deng & Zhang (2013)

Let photosphere only contribute to part of spectrum we observe



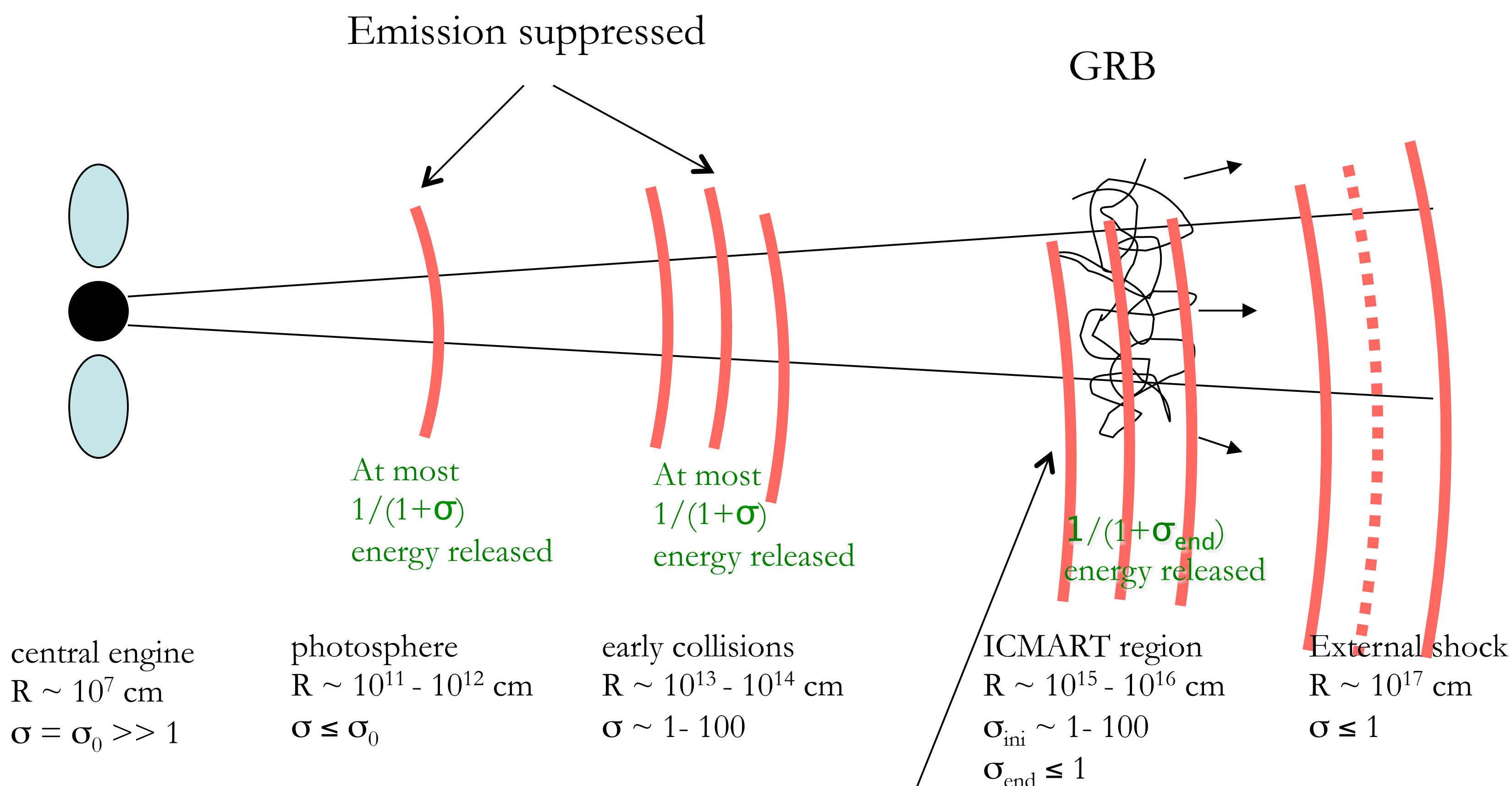
110721A and others

Let photosphere only contribute to part of spectrum we observe

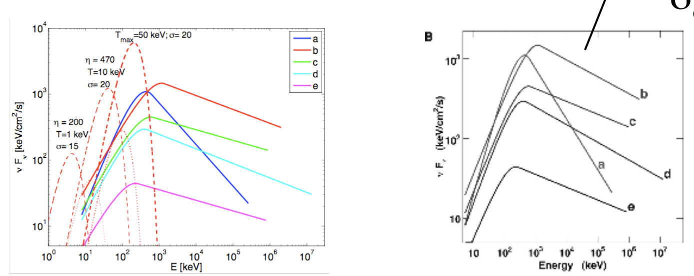


090902B, Pe'er et al. (2012)

Let photosphere only contribute to part of spectrum we observe

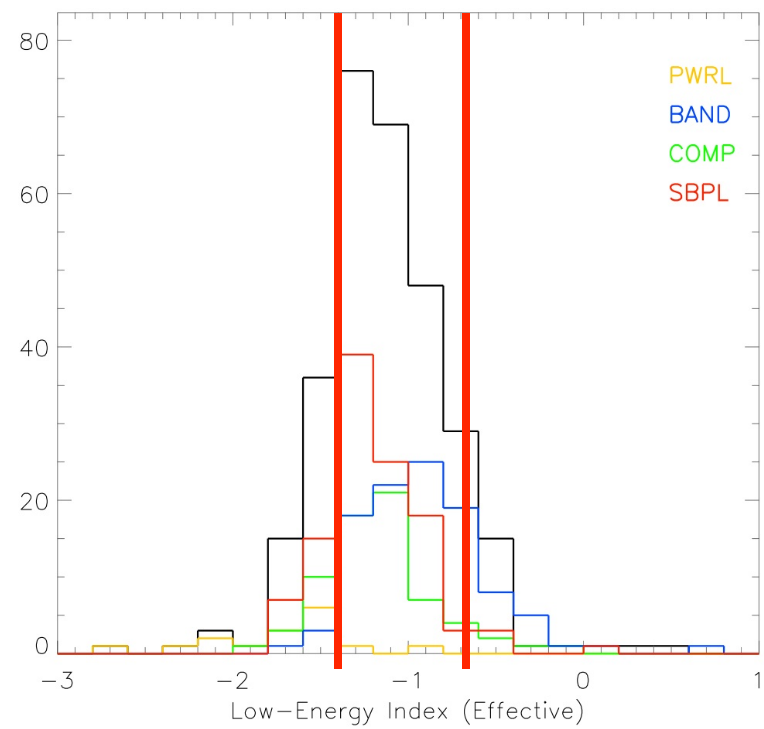


Zhang & Pe'er (2009)



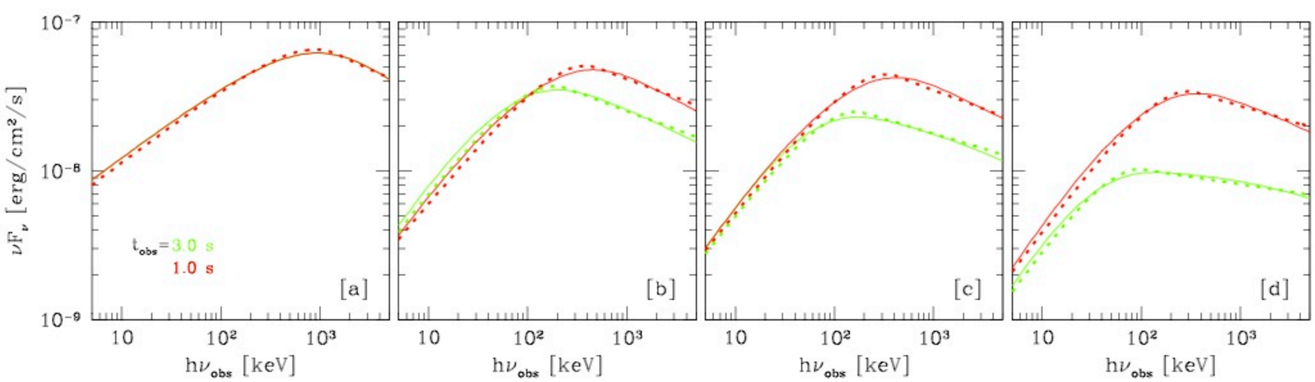
Synchrotron to account for "Band" component

- Motivations:
  - Most common non-thermal mechanism (Meszaros et al. 1994; Daigne & Mochkovitch 1998; Wang et al. 2009; Zhang & Yan 2011; Daigne et al. 2011)
  - Known to power most other non-thermal astrophysical sources
  - Known to power GRB afterglow
- Difficulties
  - Ep value and distribution
  - Broader than "Band"? (Beloborodov; Burgess et al.)
  - "Fast cooling" problem: the predicted low-energy photon index is α=-1.5, while observations show a typical value of -1 (Ghisellini et al. 2000; Kumar & McMahon 2008)
  - Synchrotron "death line": the low energy photon index cannot be harder than -2/3, i.e. α < -2/3 (Preece et al. 1999)



Recent progress:
Fast cooling synchrotron radiation can have a harder spectrum than -1.5!
(Uhm & Zhang, 2013, arXiv:1303.2704)

- B is decreasing with radius
- Electrons are not in steady state
- Electron spectrum deviates significantly from -2 below the injection energy
- In the BATSE or GBM band, the spectrum mimics a "Band" function with "correct" indices: α ~ -1, β ~ -2.2

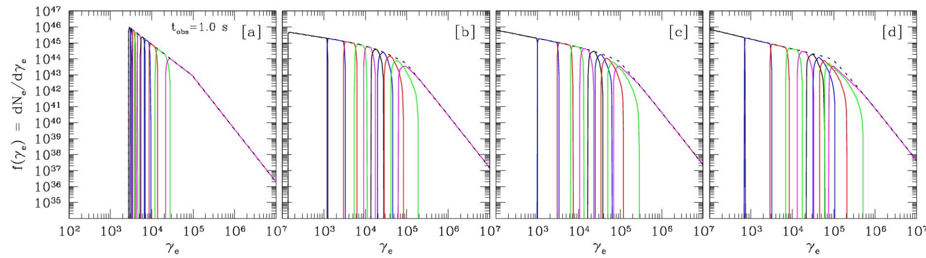


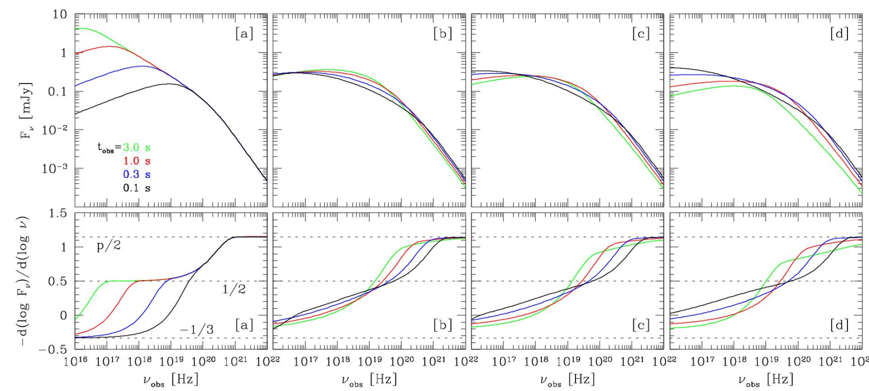
Z. Lucas Uhm's poster

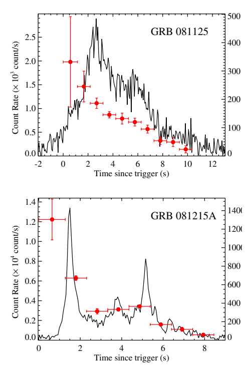
(Moderately) fast cooling synchrotron radiation as origin of the "Band" component

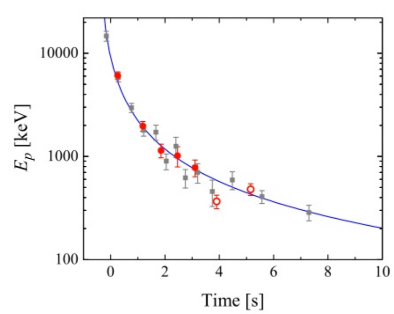
(Uhm & Zhang, 2013, arXiv:1303.2704)

- Requirement: electrons continuously being accelerated all the way to 10^{15} cm
- The "Broad" variability component is one radiation unit
- Naturally interpret hard to soft evolution





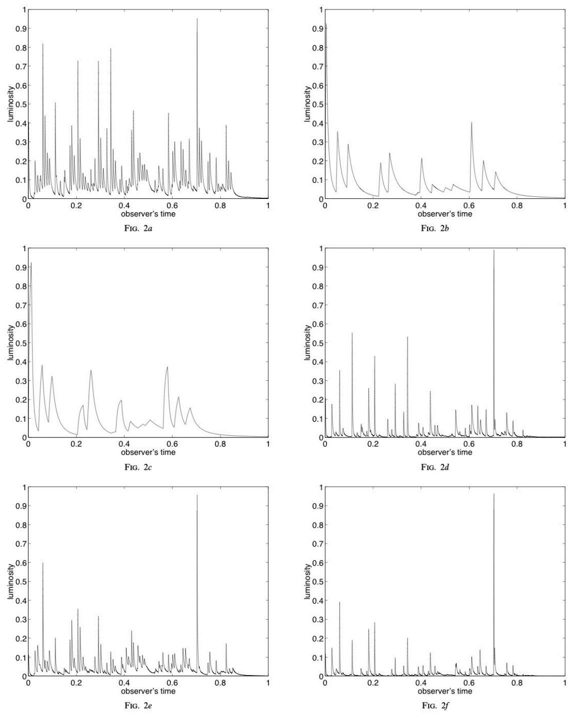




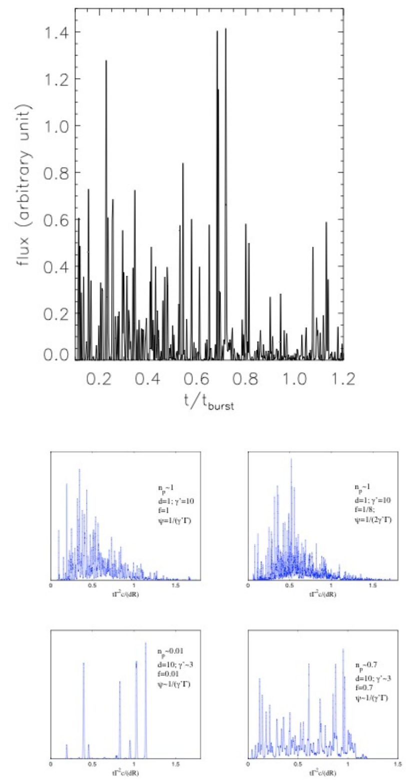
Shocks vs. Reconnection

- Both are possible, both can accelerate high energy particles
- Internal shocks:
  - Naturally expected for a non-steady central engine
  - Relatively low efficiency
  - Particle acceleration suppressed in moderately strong magnetic fields
- Magnetic dissipation (reconnection):
  - Naturally expected in a jet launched from a magnetized central engine (very likely)
  - Can have high efficiency
  - Can be spontaneous (in a striped wind B geometry, Mckinney & Uzdensky) or be forced via collision (in a helical B geometry, Zhang & Yan)

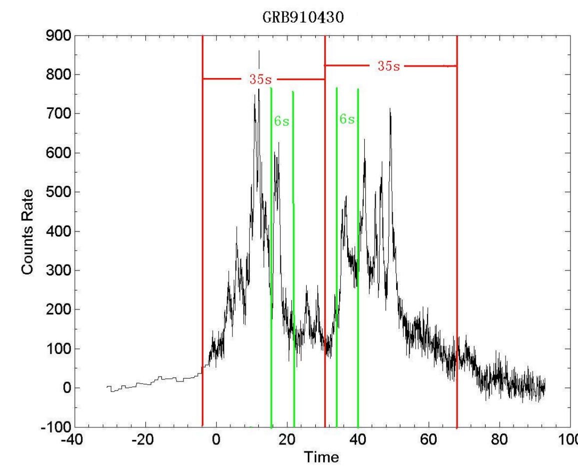
How to account for slow and fast light curve components?



Internal shocks
(Kobayashi et al. 1997)

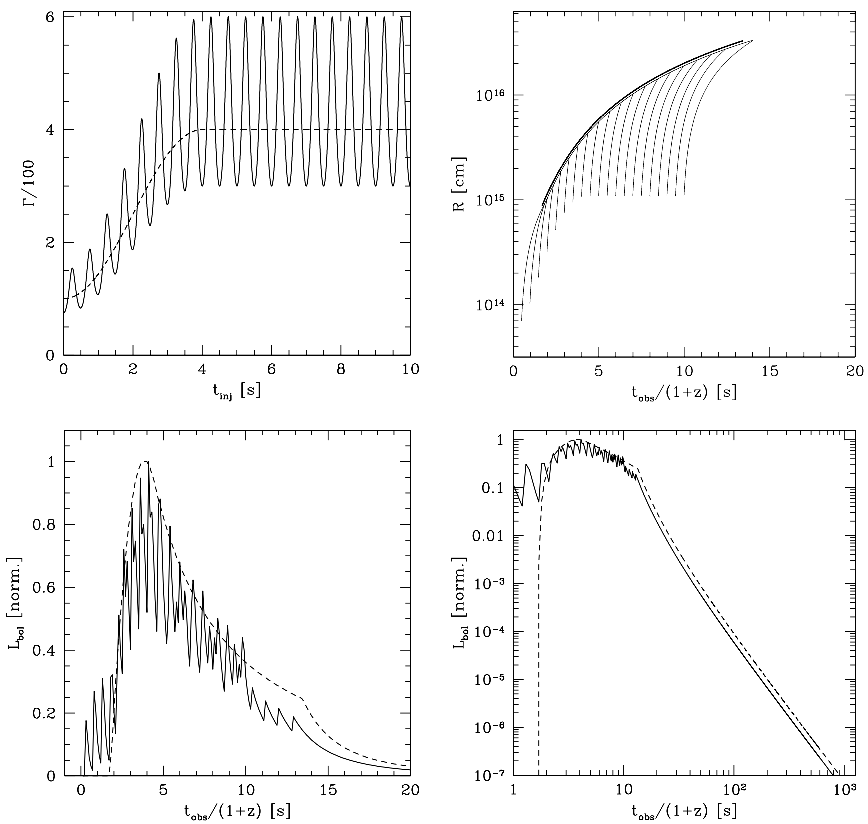


Relativistic turbulence
(Narayan & Kumar 2009,
Lazar et al. 2009)

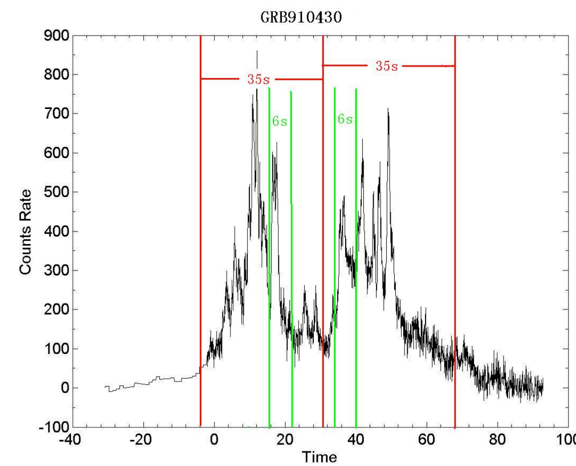


Real data

Improved internal shock model

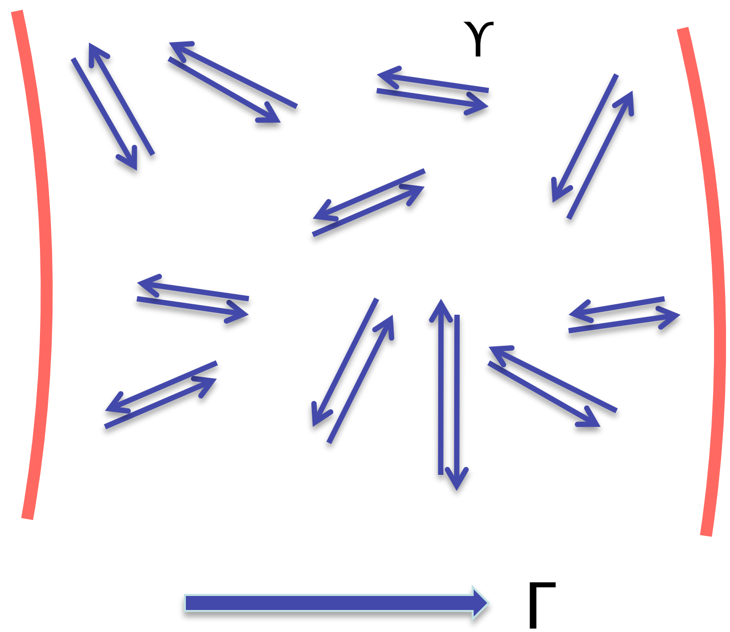


Hascoet et al. (2012)



Real data

Slow and fast light curve components: ICMART



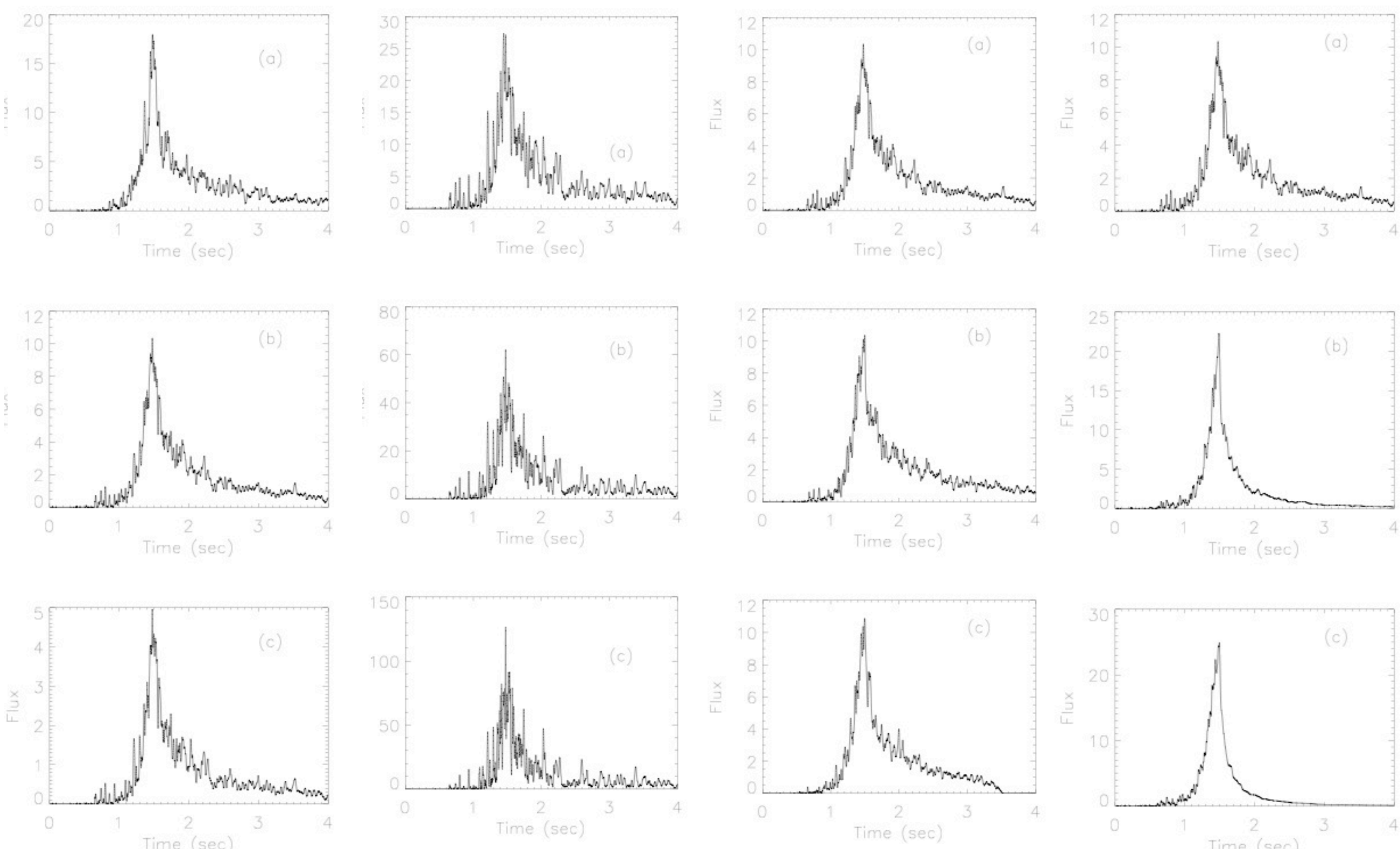
cf. Lyutikov 03
Narayan & Kumar 09
Lazar et al. 09

Prescriptions:

Many fundamental emitters (mini-jets) due to turbulent reconnection
Distribution of the size of the fundamental emitters
Rest-frame same emissivity for each mini-jet
Different mini-jets have same Lorentz factor, but different orientations (different Doppler factors)
Number of mini-jets exponentially increases with time
Observed emission is superposition of all the mini-jets
ICMART end when most magnetic energy dissipated (decay dominated by high latitude effect)

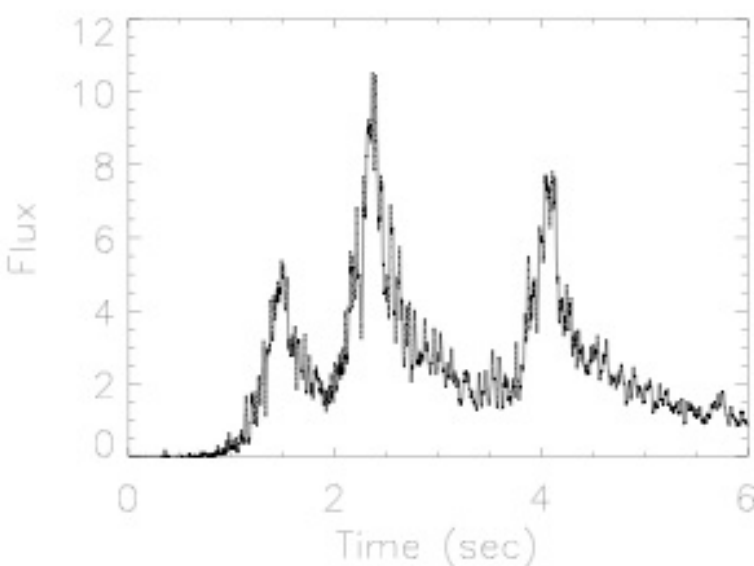
ICMART Lightcurves

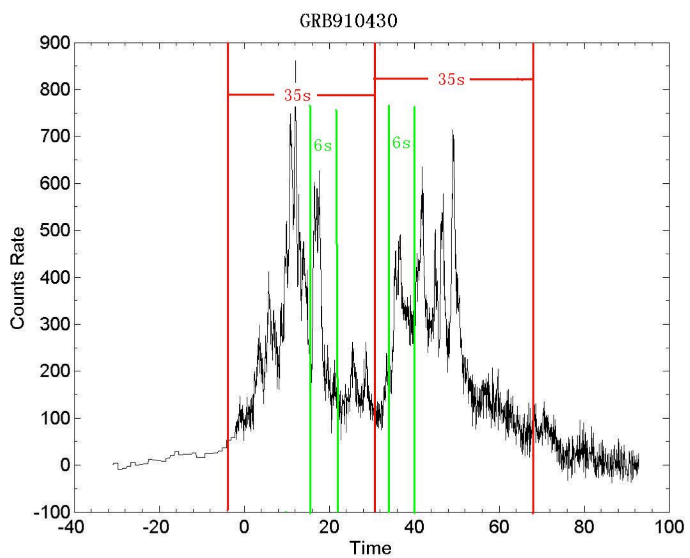
Bo Zhang & BZ



ICMART Lightcurves

Bo Zhang & BZ





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

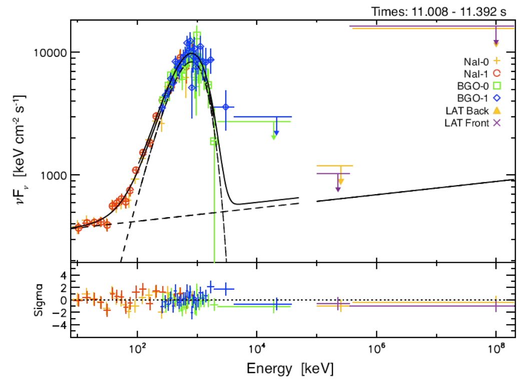
PeV neutrinos

- Guaranteed neutrino component: photon component: ~MeV photons observed from GRBs
- If cosmic rays are accelerated in GRB sources, neutrinos must be there!
- Neutrino flux depends on proton flux and $p\gamma$ optical depth
  - Proton flux depends on L_p (normalized to L_γ)
  - Optical depth depends on L_γ, Γ and R

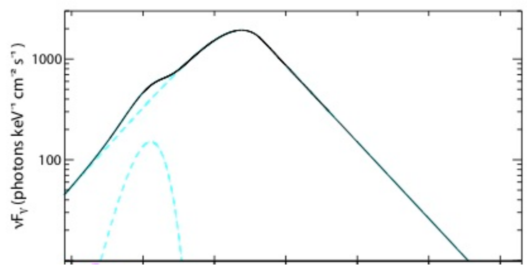
(Waxman & Bahcall, Razzaque, Meszaros, Murase & Nagataki, many others)

Big Picture: GRB jet composition

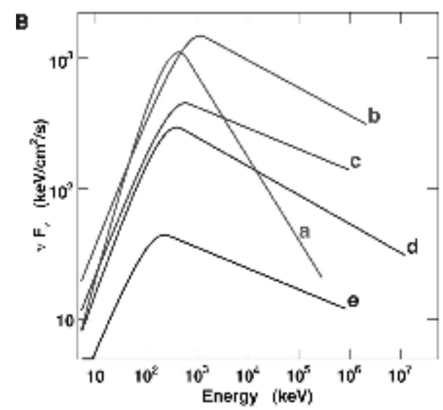
- GRB jets may have diverse compositions:
  - Photosphere dominated (GRB 090902B) (Ryde et al. 2010; Zhang et al. 2011)
  - Intermediate bursts (weak but not fully suppressed photosphere, GRB 100724B, 110721A) (Guiriec et al. Axelsson et al.)
  - Photosphere suppressed, Poynting flux dominated (GRB 080916C)(Zhang & Pe'er 2009)



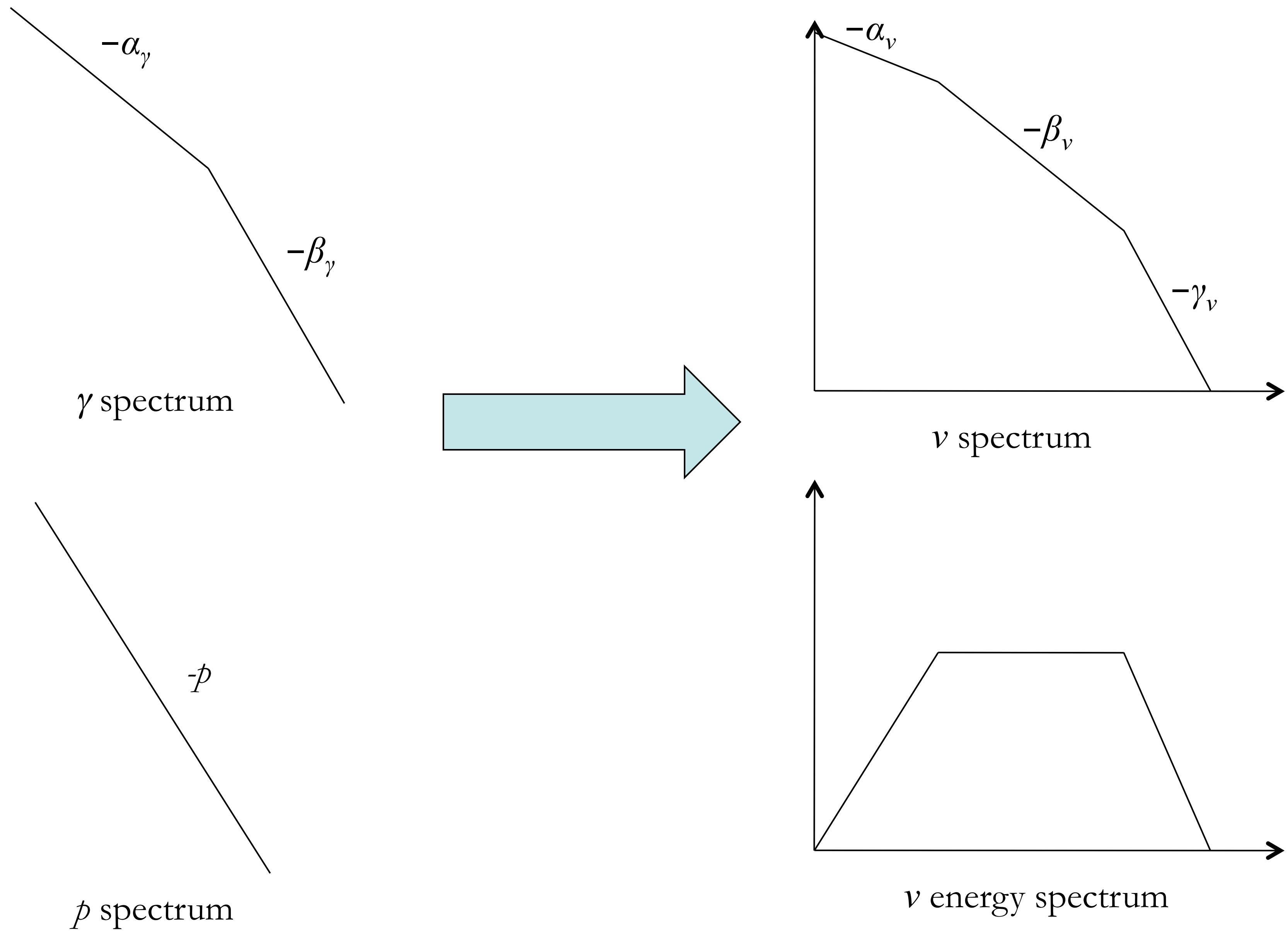
GRB 090902B



GRB 110721A



GRB 080916C



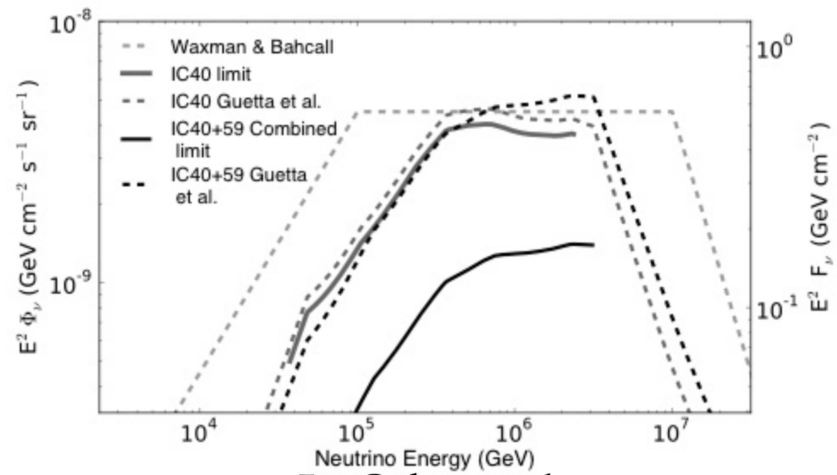
$$\alpha_\nu = p + 1 - \beta_\gamma, \quad \beta_\nu = p + 1 - \alpha_\gamma, \quad \gamma_\nu = \beta_\nu + 2,$$

Model-dependent PeV neutrino flux

- Different models may have different $f_{\gamma/p} = L_\gamma / L_p$
- Given the same observed L_γ and Γ, different models invoke different R
  - Internal shock model: $R = \Gamma^2 c \delta t_{\rm min}$
  - Photosphere model: probably $R < \Gamma^2 c \delta t_{\rm min}$
  - ICMART model: $R = \Gamma^2 c \delta t_{\rm slow} > \Gamma^2 c \delta t_{\rm min}$

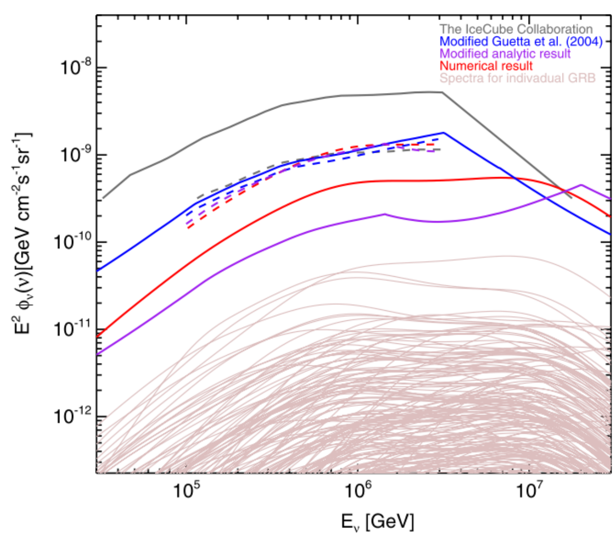
Non-detection of neutrinos by Icecube

- IceCube did not detect neutrinos from GRBs yet, upper limit 3 times lower than the most optimistic predictions (Waxman & Bahcall)



IceCube results

- More careful studies suggest that the internal shock model just barely violates the upper limit (Li 2012; Hummer et al. 2012; He et al. 2012)



He et al. (2012)

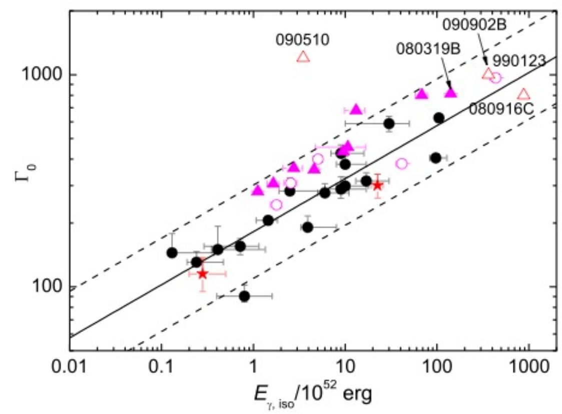
Non-detection of neutrinos by Icecube

- In internal shock model, flux is sensitive to Lorentz factor: Γ^{-4}. "Benchmark" value Γ = 300
- Observations show E (L) correlates with Γ. For low E, L bursts, neutrino flux is enhanced

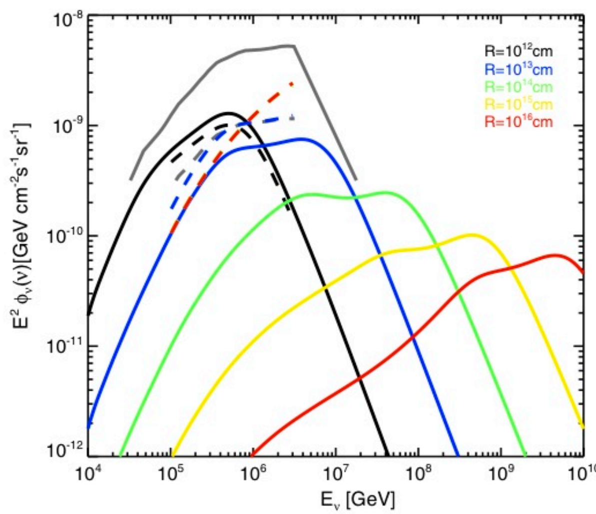
$$\Gamma_0 \simeq 91 E_{\gamma,\mathrm{iso},52}^{0.29}$$

$$\Gamma_0 \simeq 249 L_{\gamma,\mathrm{iso},52}^{0.30}.$$

- Consider such a correlation, internal shock model just barely violates the upper limit (He et al. 2012)



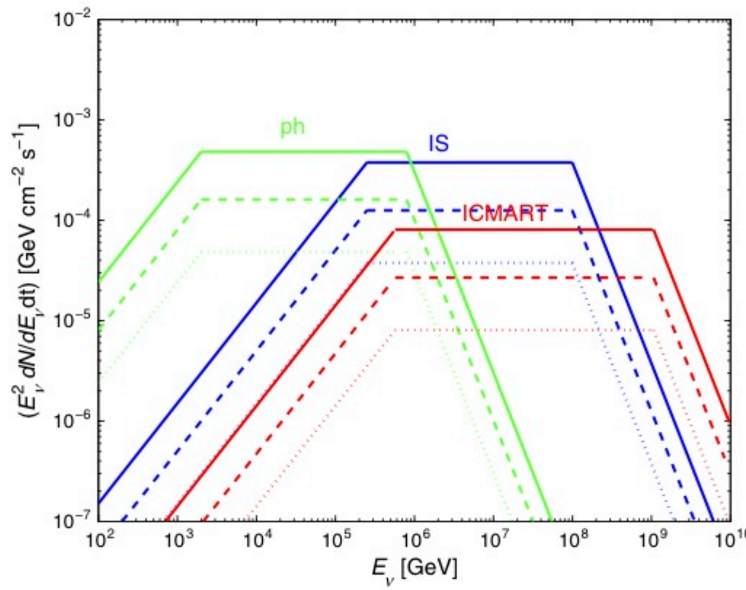
Liang et al. (2010); Lv et al. (2012)



He et al. (2012)

Model-Dependent Neutrino Flux from GRBs

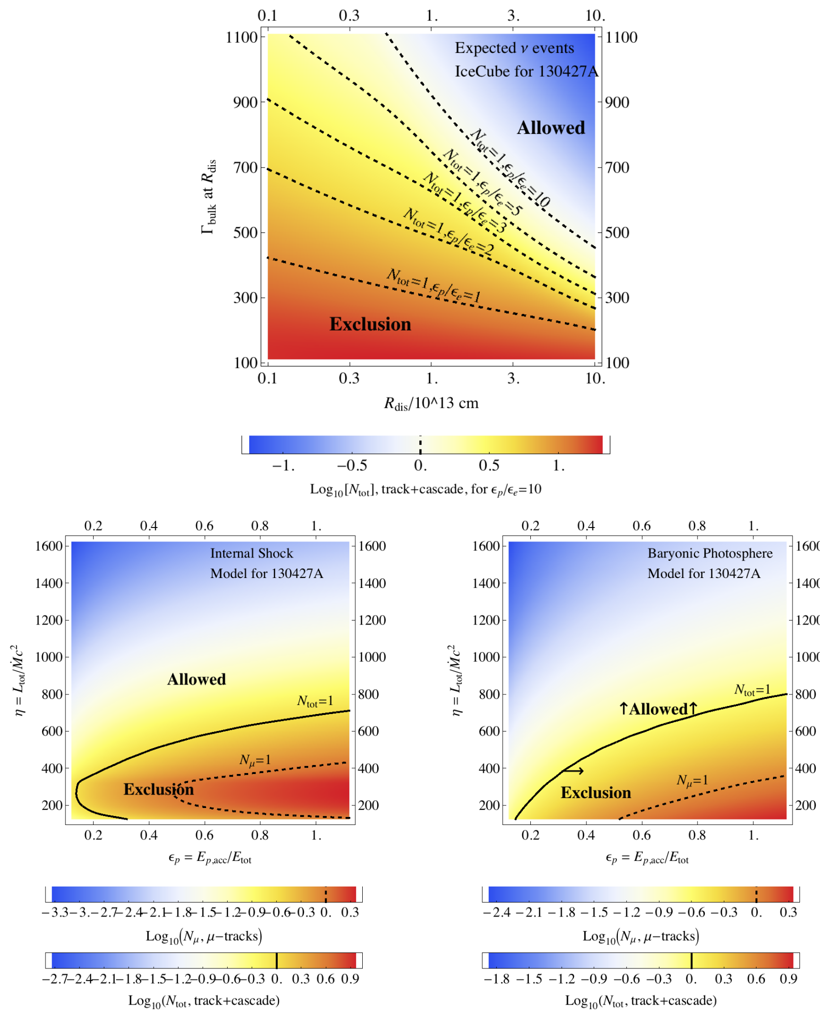
- Internal shock (with observed *E(L) – Γ* correlations) already starts to be constrained. $f_{\gamma/p} = L_\gamma / L_p$ needs to be above 0.1 (He et al. 2012)
- Photosphere model $f_{\gamma/p}$ has to be above 0.1 (see also S. Gao et al. 2012)
- ICMART is consistent with data



Zhang & Kumar, 2013, PRL, 110, 121101

Non-detection of neutrinos from GRB 130427A

- Stringent constraints on models on its own (S. Gao et al. 2013)
- More stringent constraints by combining upper limits on other GRBs
- More interesting constraints available in a few more years
- If neutrinos continue not to be detected, GRB composition may be magnetically dominated with emission coming from large radii



Gao, Kashiyama & Meszaros (2013)

Conclusions

- GRB prompt emission is still not fully understood. Open questions include:
  - Jet composition
  - Energy dissipation and particle acceleration mechanisms
  - Radiation mechanism
- GRB spectra likely include contributions from multiple components from multiple emission sites:
  - A Band component is likely of a synchrotron origin in the optically thin region
  - A quasi-thermal component is likely of photosphere origin
  - A high energy component, whose origin remains unclear
- GRB jet composition (in the emission region) may be diverse
- Internal (collision induced) magnetic dissipation may play an important role to power GRB prompt emission.