Synchrotron radiation downstream of relativistic shocks and Fermi-LAT gamma-ray bursts

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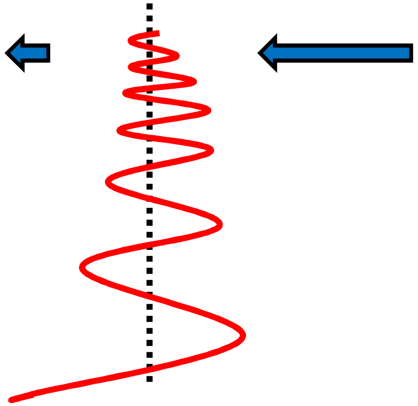


Outline

1. Standard afterglow model for gamma-ray bursts

2. Recent GeV detections of extended emissions in GRBs

3. Interpretation in terms of decaying microturbulence

Introduction

... gamma-ray bursts: burst (<1 sec → 1000sec) of gamma radiation, with erratic time behavior in the MeV range, followed by a slowly decaying afterglow

... at the origin: collapse of massive stars (long?), coalescence of compact objects (short)?

... canonical description: narrow jet accelerated to large Lorentz factor $\Gamma \sim 100\text{-}1000$

... prompt MeV radiation: dissipation of jet bulk kinetic (magnetic?) energy

... afterglow: dissipation of jet energy through a strong collisionless relativistic shock with the surrounding medium
shock heating of swept up electrons and shock acceleration
$\Rightarrow$ very high energy electrons with $\langle\gamma_e\rangle \sim \gamma_{sh}\, m_p/m_e \sim 10^5$!

The standard afterglow model for GRBs

e.g. Meszaros & Rees 97, Piran 04

- Standard picture:

→ as the shock propagates, it sweeps up matter from the external medium and dissipates energy through the shock:

swept up power: $$\frac{\mathrm{d}E}{\mathrm{d}t'} = \gamma_{\mathrm{b}}^2\left(\beta_{\mathrm{b}} + \frac{1}{3}\right) c\,4\pi r^2 \rho_{\mathrm{ext}} c^2$$

→ beyond radius $r_{\mathrm{dec}} \sim \left[E_{\mathrm{ej}}/\left(4\pi\rho_{\mathrm{ext}}c^2\gamma_{\mathrm{b}}^2\right)\right]^{1/3}$ the blast wave decelerates with $\gamma_{\mathrm{b}} \propto (r/r_{\mathrm{dec}})^{-3/2}$ (for uniform external density profile)

→ electrons are heated to large Lorentz factors ~ $\gamma_{\mathrm{b}}\, m_p/m_e$ (downstream frame) and radiate through synchrotron at frequency (observer frame)

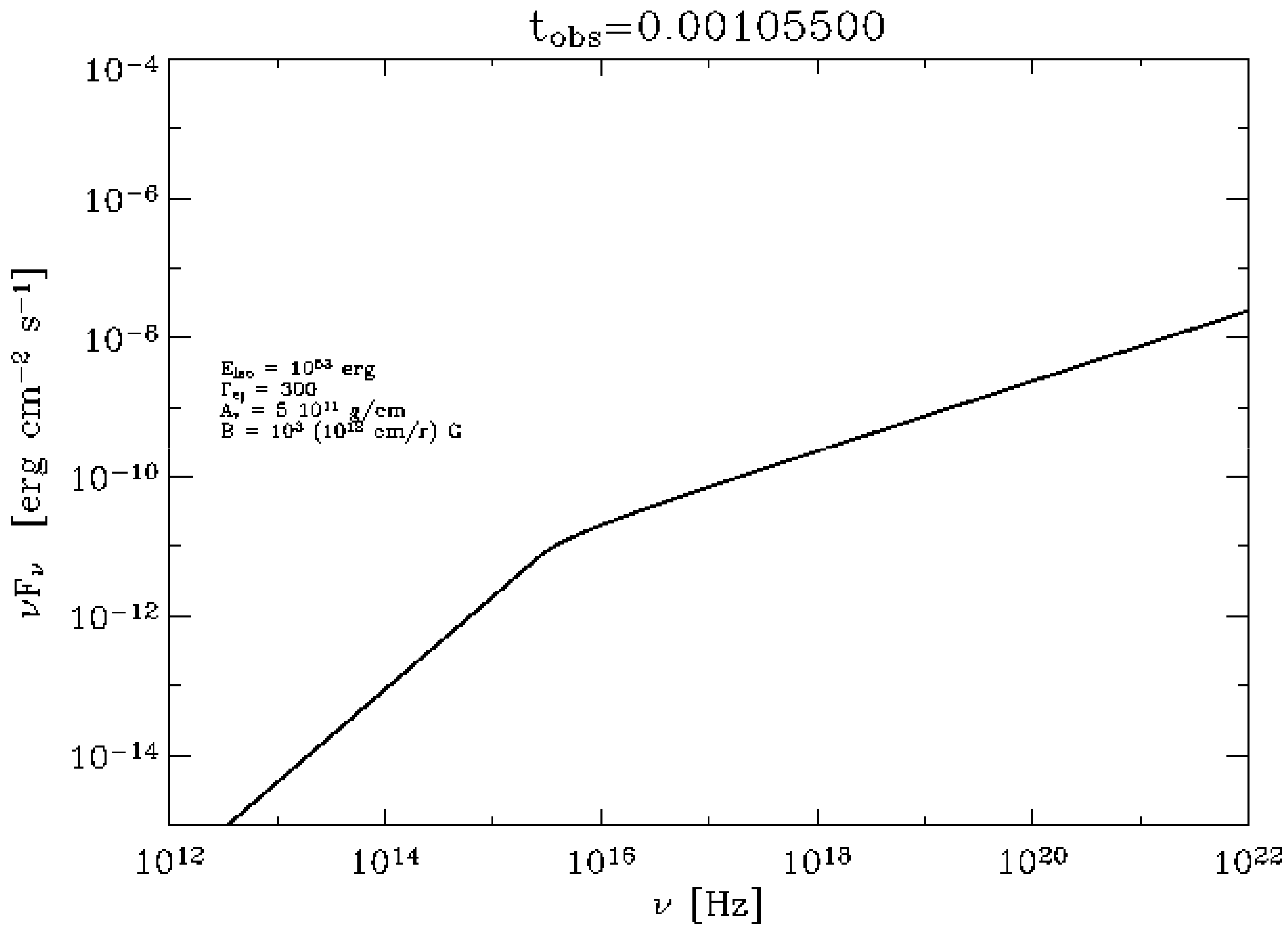
$$\nu_{\mathrm{obs}} \simeq 0.2\frac{eB'}{m_e c}\gamma_{\mathrm{b}}\gamma_e^2 \propto B'\gamma_{\mathrm{b}}^3 \propto t_{\mathrm{obs}}^{-3/2}$$

with flux: $$\nu F_\nu|_{\mathrm{peak}} \simeq \frac{1}{4\pi D_L^2}\frac{4}{3}\gamma_{\mathrm{b}}^2\epsilon_e\frac{\mathrm{d}E'}{\mathrm{d}t'} \propto \gamma_{\mathrm{b}}^4 r^2 \propto t_{\mathrm{obs}}^{-1}$$

→ the photon spectrum is shaped by the electron energy distribution and the cooling efficiency, but the peak frequency moves to lower frequencies as γ_{b} decreases, and the amount of radiated energy also decreases as γ_{b} decreases:

→ decaying afterglow at increasing wavelengths (γ → X → Opt. → IR → radio...)

The standard afterglow model for GRBs



The standard afterglow model for GRBs

Canonical afterglow model:

→ works well at late times $>10^4$sec, with $\varepsilon_B \sim 0.1\% - 1\%$, $\varepsilon_e \sim 1\% - 10\%$, $\gamma_{min} \sim \gamma_b\, m_p/m_e$… i.e. as expected for a weakly magnetized relativistic shock wave (e.g. Sironi & Spitkovsky 11): multiwavelength + time behaviors ~ OK

Problems with the canonical afterglow model… at early times

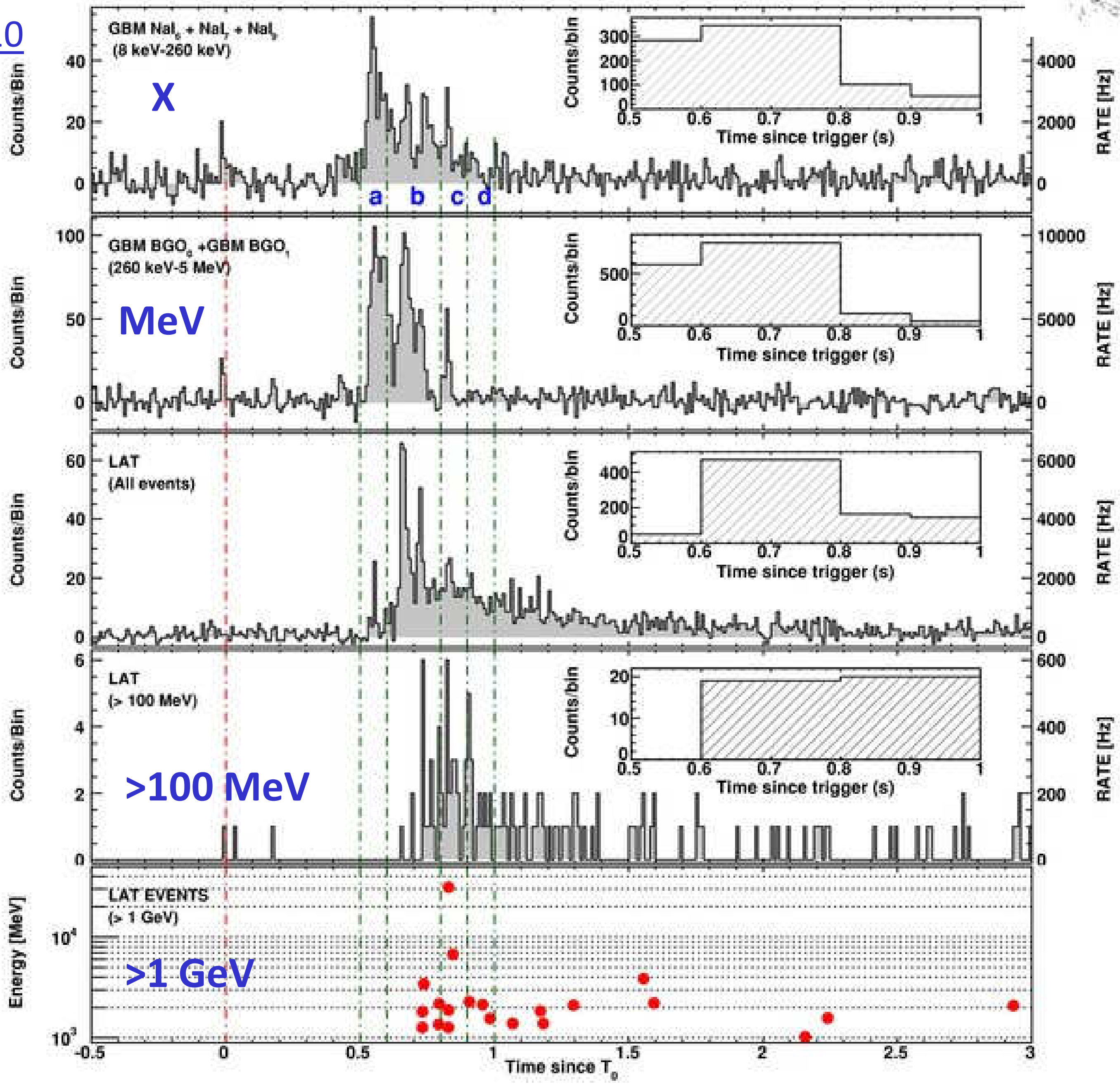
→ most early afterglows in the X-ray band show a non-canonical decay, with fast early decay followed by late shallow decay… the canonical behavior emerges at 10^4 sec… (Nousek et al. 06, O'Brien et al. 06)

→ the Fermi-LAT instrument has detected GeV emission beyond the prompt phase, lasting up to 1000sec…
+ with peculiar properties (faster than expected decay for fast cooling)…
(Ackermann et al. 09,10)

GRB090510

Fermi data GRB090510

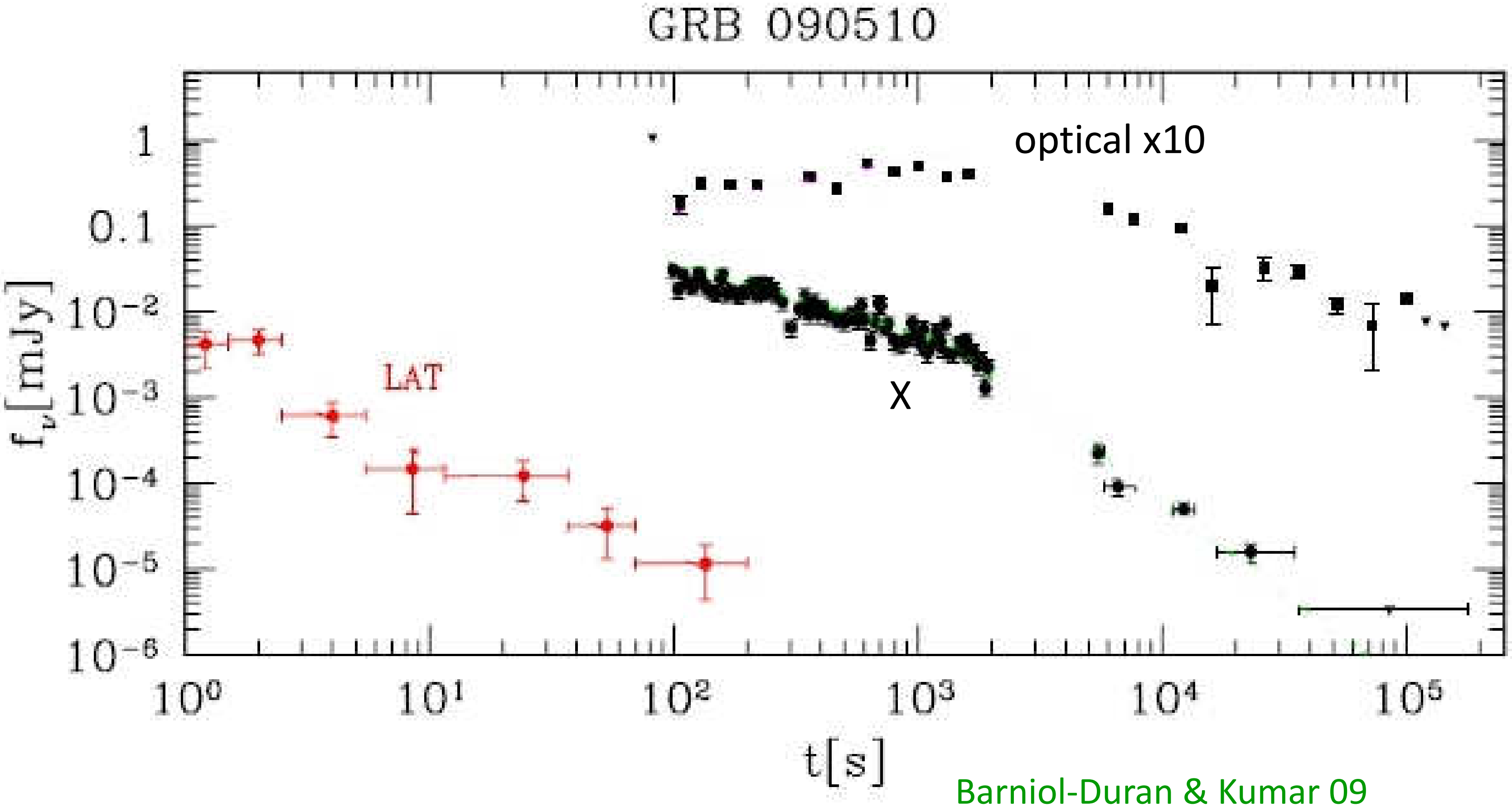
short burst,
duration 0.9sec



Note: production of GeV photons ↔ a true challenge for acceleration

GRB090510

Multiwavelength data for GRB 090510 (prompt duration 0.9sec!)



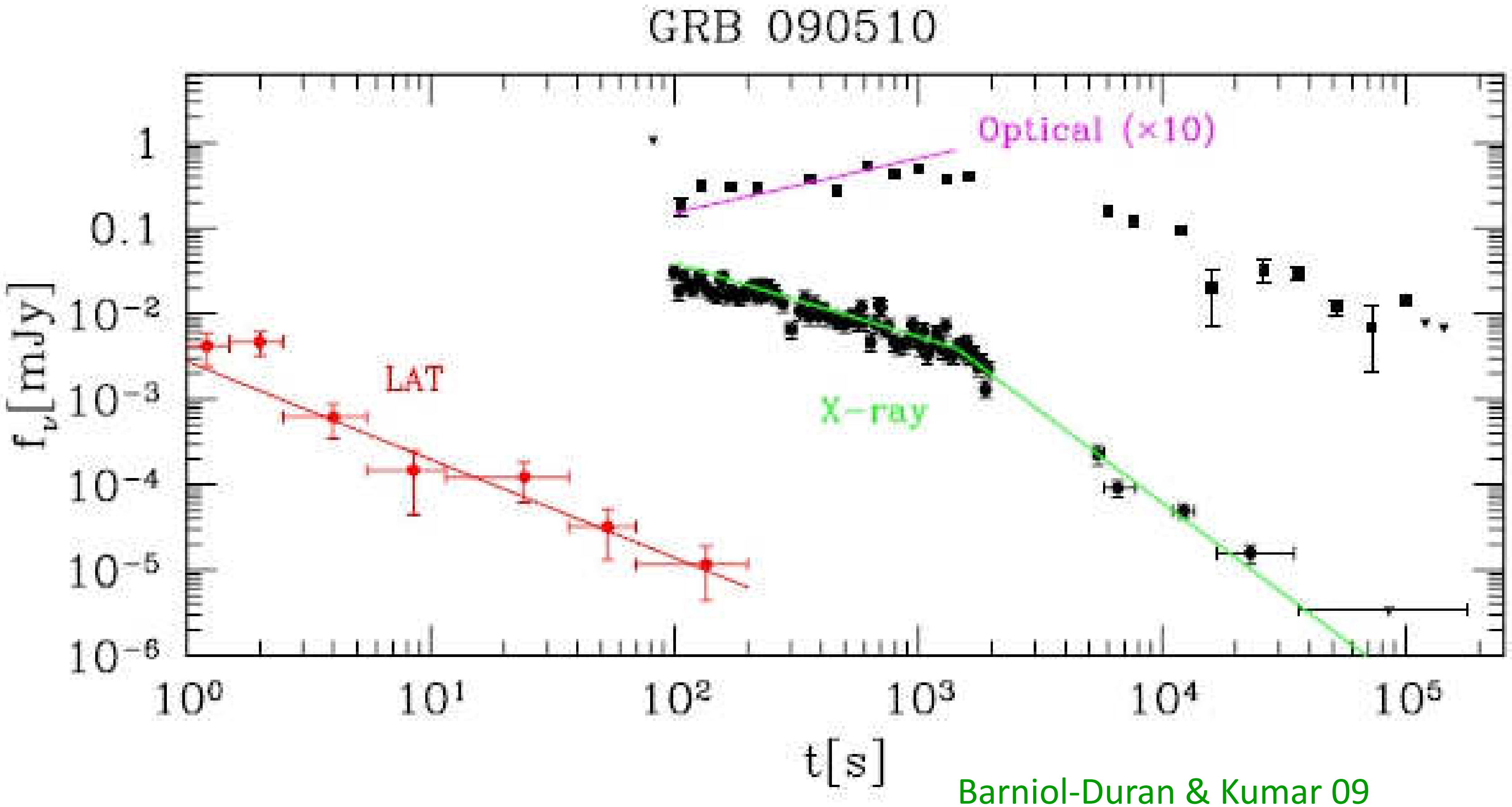
Barniol-Duran & Kumar 09

GRB090510

Barniol-Duran & Kumar 09: afterglow fits quite well the prediction of a "standard " afterglow with inefficient electron cooling, meaning a weakly magnetized blast

$$\mathrm{ISM} < \epsilon_B \sim 10^{-7} - 10^{-6} n_0^{-2/3} \ll \mathrm{Weibel}$$

This corresponds to a magnetic field in the upstream frame : $B_{up} \sim 30$ μG, i.e. weak or no self-generation!

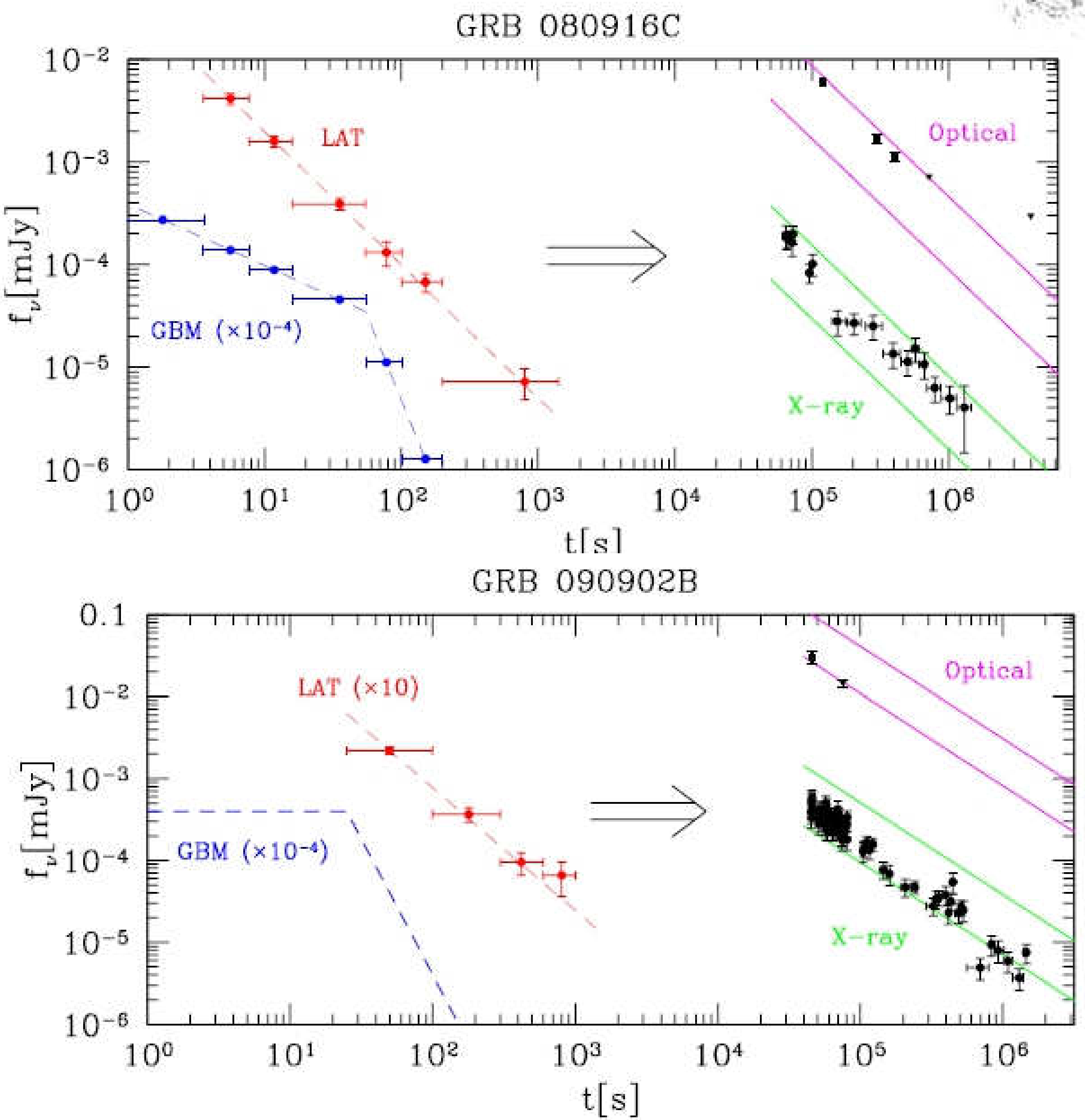


Barniol-Duran & Kumar 09

GeV extended emission GRBs

Two other (long) bursts
with GeV extended emission
give similar results…

$B_{up} \sim 10\ \mu G$


GRB 080916C

GRB 090902B

Barniol-Duran & Kumar 09

Afterglow from GeV extended emission GRBs

Interpretation of GeV extended emission and Barniol-Duran & Kumar model:

→ electrons radiate in a shock compressed magnetic field (no magnetic field self-generation), or at least in a turbulence with $\varepsilon_B \ll 10^{-2}$

→ if $\varepsilon_B < 10^{-5}$, Weibel turbulence should be excited, and it should be present downstream…

→ + in the absence of self-generation of microturbulence, why would acceleration operate?

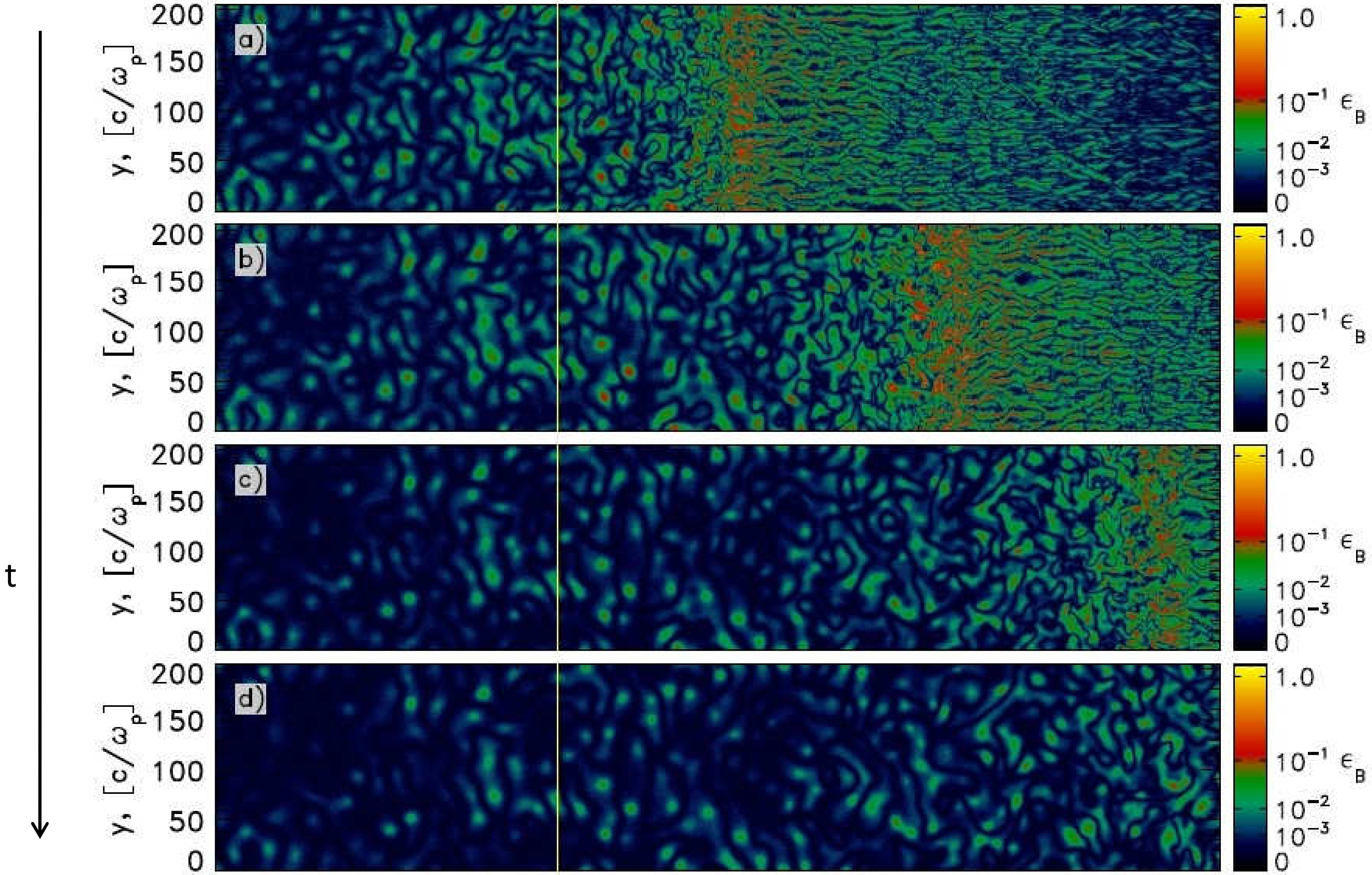
→ possible interpretation: Weibel turbulence is excited, it allows shock acceleration, but it decays on a short length scale behind the shock front, particles cool in a weaker magnetic field where $\varepsilon_B \ll 10^{-2}$

→ how does it connect to early (late 90's) GRB determinations of $\varepsilon_B \sim 10^{-3}$-$10^{-2}$ at late times?

→ does another instability set in at late times and fill the blast with $\varepsilon_B \sim 10^{-2}$

→ P. Kumar: actually, biased estimates, closer to $\varepsilon_B \sim 10^{-4}$

Results from PIC simulations

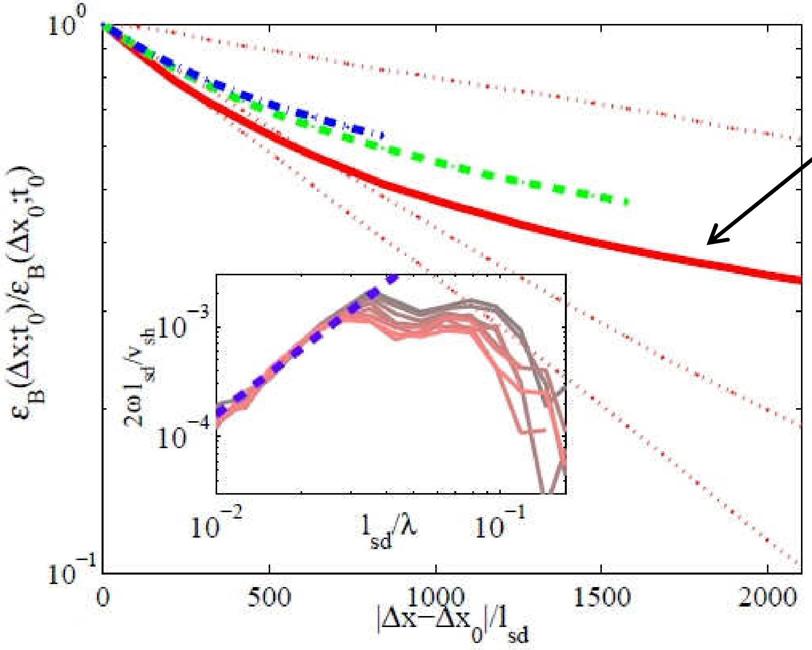


Chang et al. 08: turbulence with typical scale ~ 10-30 c/ω_p, static, small scales dissipate first

$\Rightarrow$ gradual erosion of magnetic power

Results from PIC simulations

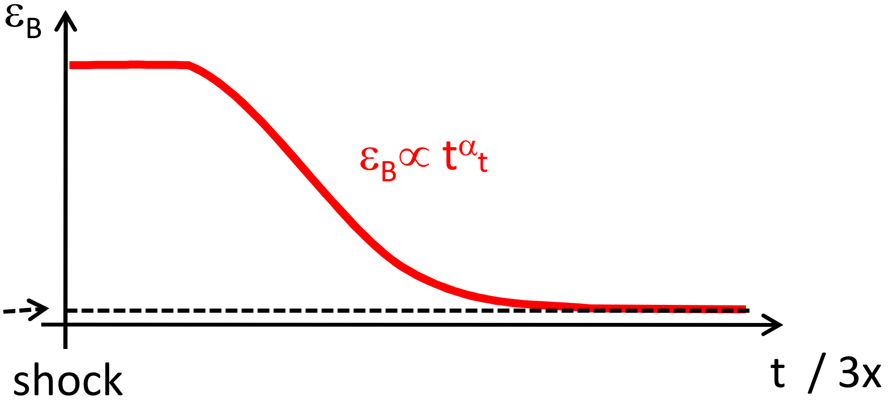
Keshet et al. 09: simulation up to 10^4 c/ω_p (~ 1% of a dynamical timescale for a GRB!)



power law decay of ε_B away from the shock
α_t ~ -0.5

For a small scale turbulent spectrum $\delta B_\lambda{}^2 \propto \lambda^{\alpha_B}$ with damping time $\propto \lambda^{\alpha_\lambda}$,
magnetic power decreases as:

$$\epsilon_B \propto t^{\alpha_t}, \quad \alpha_t = \frac{1+\alpha_B}{\alpha_\lambda} < 0$$

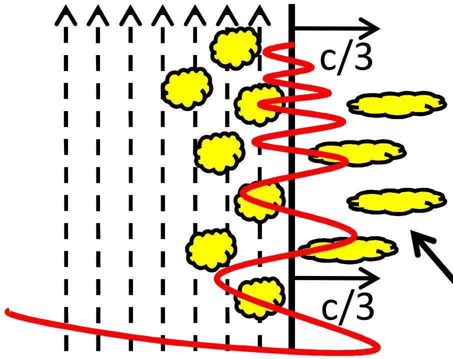


$\varepsilon_{B,-}$
(shock compression of B_{up})

Decaying microturbulence behind the shock front

→ at weakly magnetized shock waves, micro-instabilities can grow and allow Fermi acceleration…
microturbulence controls at least the first cycles of Fermi acceleration:

$$r_{\rm L} \sim \epsilon_B^{-1/2}\frac{\gamma_e}{\gamma_{\rm min}}\,\frac{c}{\omega_{\rm pi}}$$



micro-instabilities associated with the shock : typically on plasma scales c/$\omega_{\rm pi}$

→ low γ particles cool further away from the shock than high γ particles…

$$\frac{l_{\rm cool}}{c/\omega_{\rm pi}} \approx 10^7\, t_2^{9/8} E_{53}^{-3/8} n_{-3}^{-1/8} \epsilon_{B,-2}^{-1}\epsilon_{e,-0.3}^{-1}\frac{\gamma_{\rm min}}{\gamma_e}$$

$$\frac{l_{\rm cool}}{l_{\rm blast}} \approx t_2^{1/2} E_{53}^{-3/8} n_{-3}^{-1/8} \epsilon_{B,-2}^{-1}\epsilon_{e,-0.3}^{-1}\frac{\gamma_{\rm min}}{\gamma_e}$$

→ with decaying microturbulence, particles of different Lorentz factors cool in different magnetic fields…

⇒ direct impact on the synchrotron spectrum

Synchrotron power with decaying microturbulence

Synchrotron power from the blast:

$$P_\nu = \frac{4\gamma_{\rm b}^2}{3}\int_{\gamma_{\rm min}}^{\gamma_{\rm max}} {\rm d}\gamma_{e,0}\,\frac{{\rm d}\dot N_e}{{\rm d}\gamma_{e,0}}\int_0^{t_{\rm dyn}}{\rm d}t\,\frac{{\rm d}E_{\rm syn}}{{\rm d}\nu{\rm d}t}$$

angular beaming

e Lorentz factor distribution at injection

e spectral power during cooling history

e swept up/unit time:

$$\frac{{\rm d}\dot N_e}{{\rm d}\gamma_{e,0}} = \gamma_{\rm b}\left(\beta_{\rm b}+\frac{1}{3}\right)4\pi n r^2\,c\,\frac{p-1}{\gamma_{\rm min}}\left(\frac{\gamma_{e,0}}{\gamma_{\rm min}}\right)^{-p}$$

(depends on observer time through $\gamma_{\rm b}$, $\gamma_{\rm min}$, r)

spectral power per e:

$$\frac{{\rm d}E_{\rm syn}}{{\rm d}t} \approx \frac{\sigma_{\rm T}}{6\pi}\delta B^2\gamma_e^2 c\,\frac{4}{3}\frac{1}{\nu_e}\left(\frac{\nu}{\nu_e}\right)^{1/3}\Theta\left(\nu_e-\nu\right)$$

**(depends on t, time since injection at shock,
i.e. on distance from shock front)
(no diffusive synchrotron radiation at relativistic shocks, but strong impact of decaying turbulence!)**

Spectral flux:

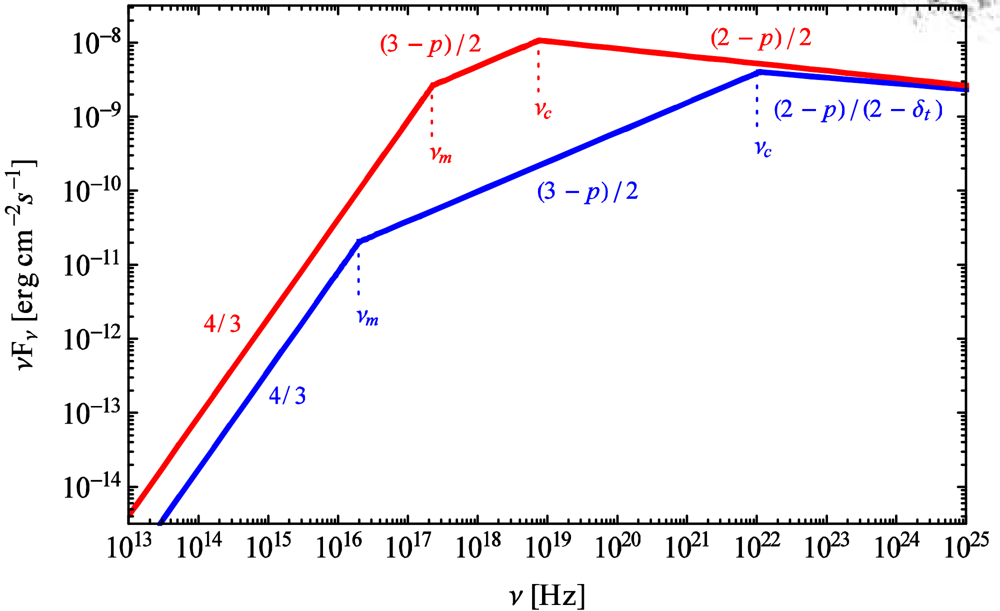
$$F_\nu = \frac{P_\nu}{4\pi D_{\rm L}^2}$$

$\Rightarrow$ multiwavelength lightcurve through $\gamma_{\rm b}(t)$

Synchrotron spectral shapes

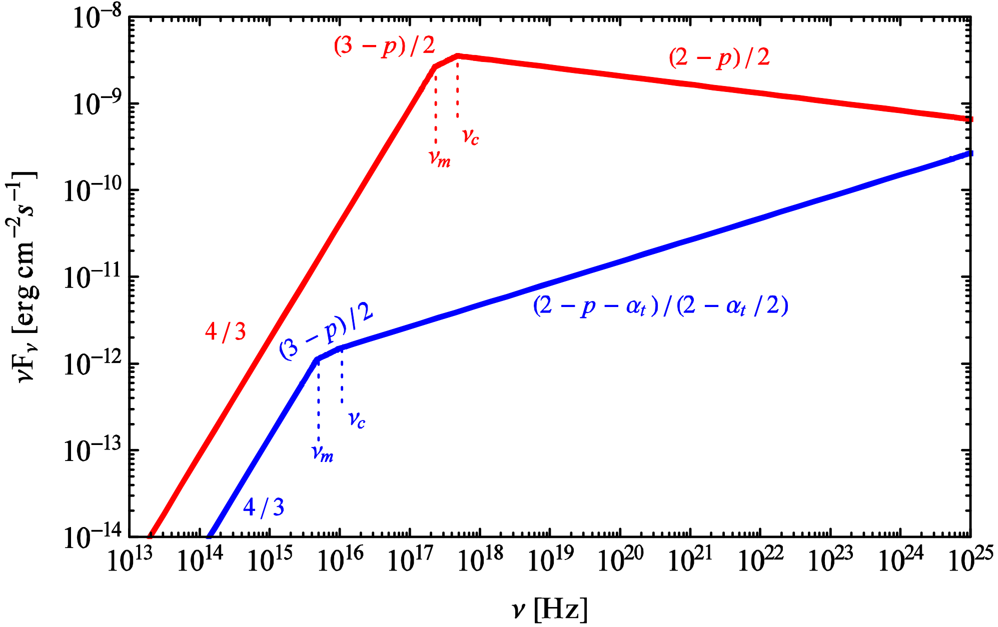
Example 1:

slowly decaying turbulence, α_t = -0.5,
t_{obs} = 100 sec, n = 10^{-3}cm^{-3}, E = 10^{53}ergs,
no inverse Compton losses
vs
homogeneous turbulence, ε_B=10^{-2}



Example 2:

slowly decaying turbulence, α_t = -0.8,
t_{obs} = 100 sec, n = 10^{-3}cm^{-3}, E = 10^{53}ergs,
with inverse Compton losses, Y=3
vs
homogeneous turbulence, ε_B=10^{-2}



Synchrotron spectral shapes

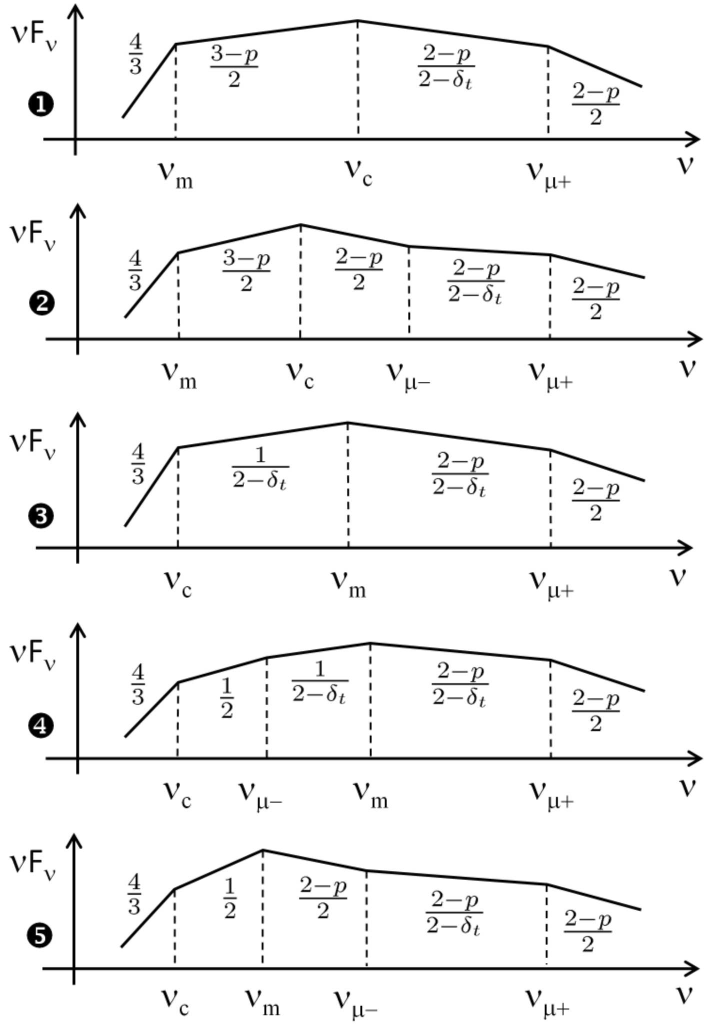
Consequences:

→ decaying turbulence may leave a strong signature in the spectral flux $F_\nu(t_{obs})$ of a decelerating relativistic blast wave…
modifies slopes and characteristic frequencies..

→ application to GRB090510: presently too many new parameters (α_t, slow/fast cooling, with/without inverse Compton losses) to discriminate the models…

→ e.g., for α_t > -1 (slow decay), main constraint from GRB 090510:
$\nu_m = \nu_e(\gamma)$ must cross the optical range at 1000sec, which is obtained for $\alpha_t = -0.6$.

different synchrotron shapes at different times for:
-1 < α_t + no inverse Compton losses



Decaying microturbulence and high energy photons

Consequences (2):

→ decaying turbulence may leave a strong signature in the spectral flux $F_\nu(t_{obs})$ of a decelerating relativistic blast wave…
modifies slopes and characteristic frequencies…

→ **decaying turbulence affects estimates of the maximal energy…** at maximal energy, particles scatter in the decaying part of the turbulence, interact with weaker but larger scale turbulent modes…

→ e.g. , for $\alpha_t = -0.5$, $\alpha_\lambda=2$, $\epsilon_{\gamma,\max} \approx 2\,\mathrm{GeV}\,E_{53}^{0.22}\dots t_2^{-0.66}$

(with power dependence on α_t, α_λ)

whereas in scenario of Barniol-Duran & Kumar: particles scatter in microturbulence but radiate in background field

$$\epsilon_{\gamma,\max} \approx 30\,\mathrm{MeV}\,E_{53}^{1/4} n_{-3}^{-7/12} \lambda_{\mu,1}^{2/3} B_{-5} t_2^{-3/4}$$

Summary

→ gamma-ray bursts with extended GeV emission at early times suggest a weakly magnetized blast wave, $\varepsilon_B << 10^{-2}$…

→ this may be reconciled with the results of PIC simulations, which suggest a decaying microturbulence behind the shock front, leading to $\varepsilon_B << 10^{-2}$ at the back of the blast, where particles radiate their synchrotron spectrum…

→ decaying turbulence may leave a strong signature in the spectral flux $F_\nu(t_{obs})$ of a decelerating relativistic blast wave…
modifies slopes and characteristic frequencies…

→ decaying turbulence affects estimates of the maximal energy… at maximal energy, particles scatter in the decaying part of the turbulence, interact with weaker but larger scale turbulent modes… possibility of radiating GeV photons…

→ origin of the late time magnetization of the blast, of order $\varepsilon_B \sim 10^{-4}$? Signatures of the evolution of magnetization in the light curve? Relation to other non-GeV bursts?