Physics of collisionless shocks in SN and GRBs: Weibel Instability

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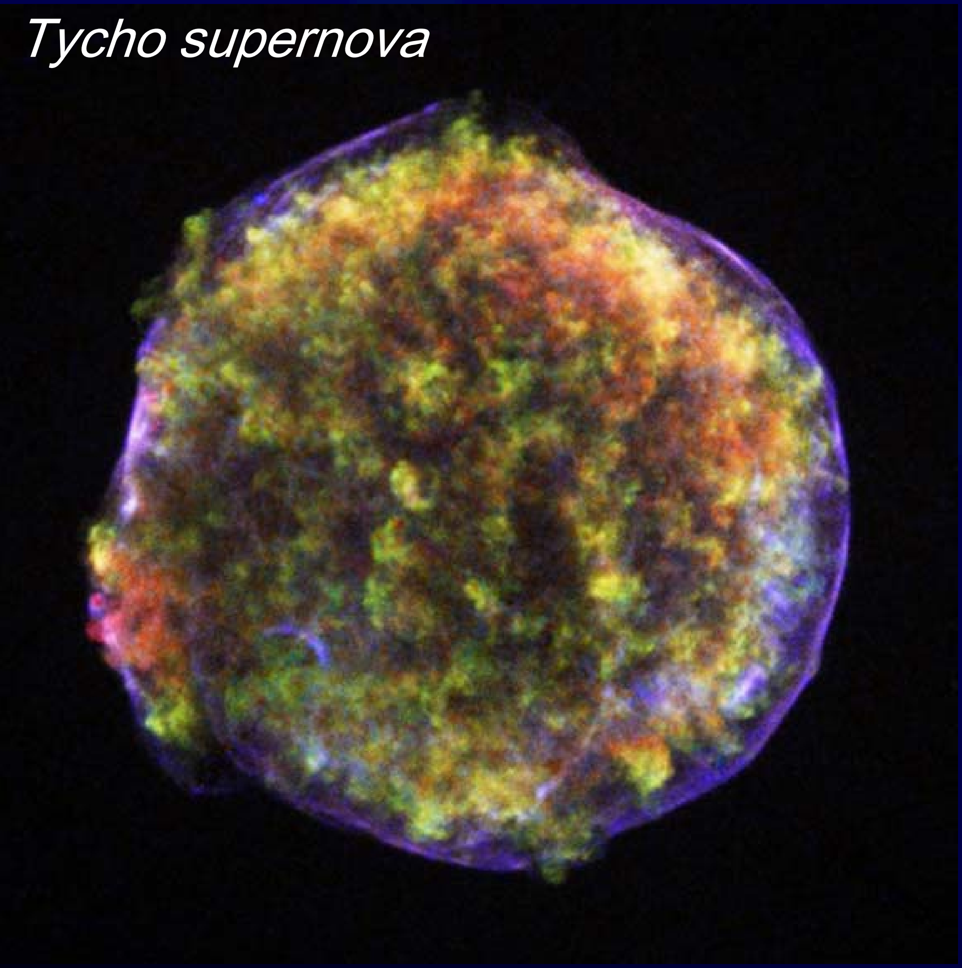
Christian Hededal,
Troels Haugboelle,
Aake Nordlund (Niels Bohr Institute, Copenhagen, Denmark)

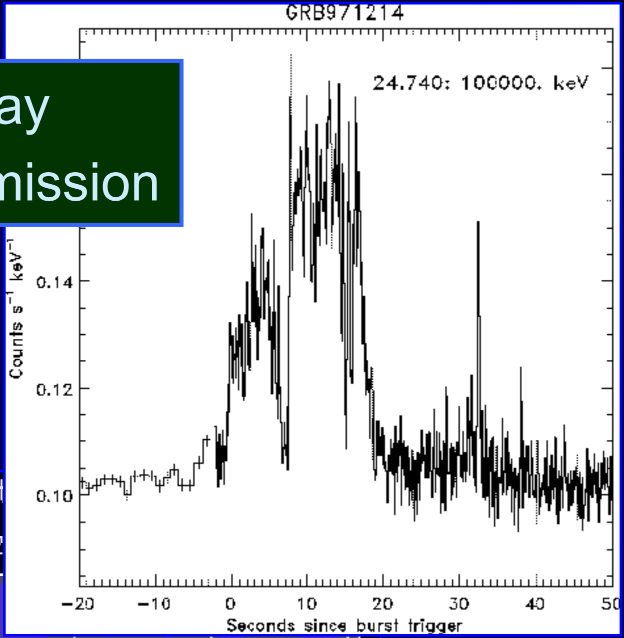
Outline

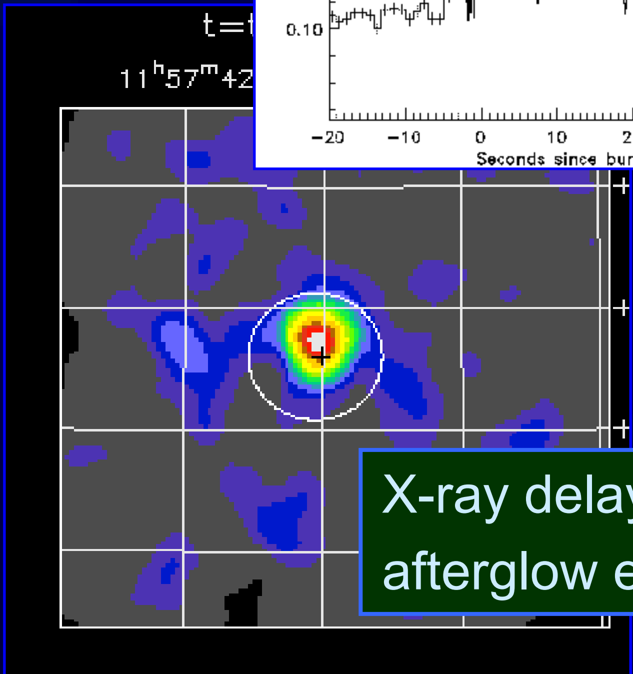
Collisionless shocks:
GRB/SN "Standard Model"

- Introduction
- Microphysics of collisionless relativistic unmagnetized shocks
- Realistic modeling of shocks
- Particle acceleration…
- Can the produced fields really populate large volumes?
- How do the shocks shine?
- Spectral variability
- Polarization of radiation
- Summary

Collisionless shocks DO exist







How a collisionless shock can form?

Collisionless shock ➔ NO COLLISIONS
which transport momentum
from downstream to upstream

Electromagnetic fields can mediate
interactions between plasma particles

Why collisionless shocks radiate?

- ***Shock jump conditions***
- ***Strong magnetic fields in the shock***
- ***Very efficient particle acceleration***

Synchrotron emission of
-- energetic electrons in
-- magnetic fields

Best model

Speculative !

Outline

Starting from the first principles

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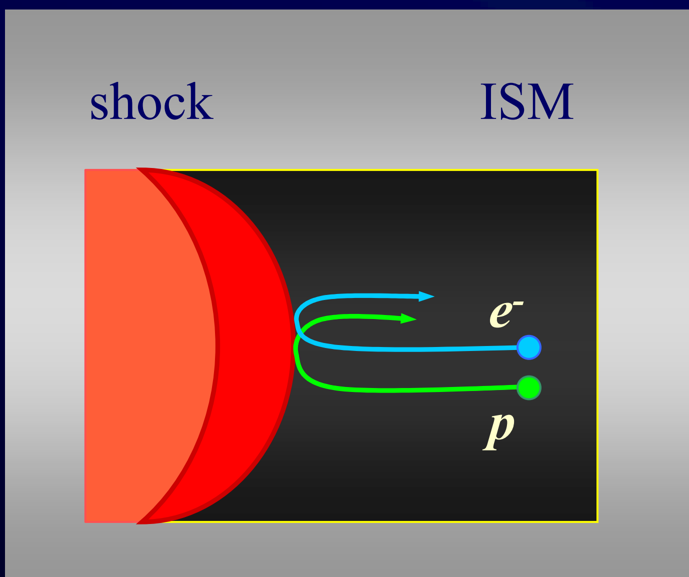
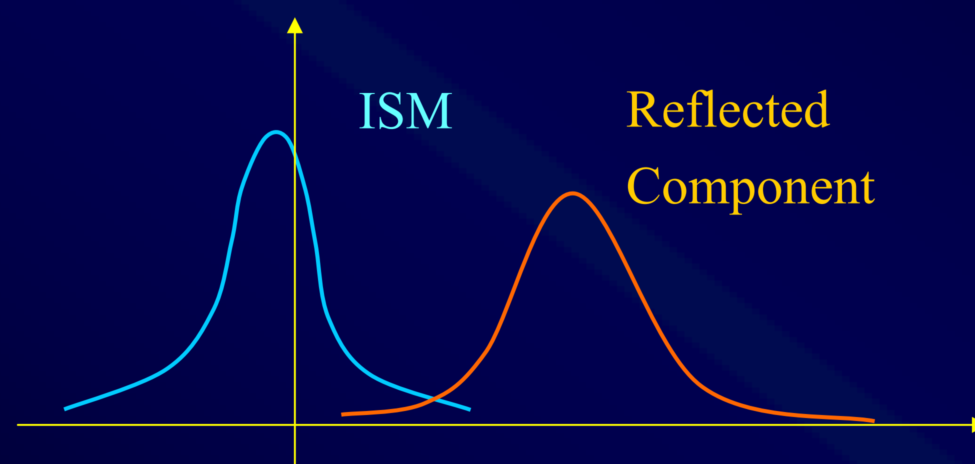
Conditions at a shock



Anisotropic distribution of particles (counter-propagating streams) at the shock front



General description

Anisotropy: $\varepsilon_{||} > \varepsilon_{\perp}$ characteristic energies (e.g., T) in the directions parallel and perpendicular to the shock propagation direction

Introduce: plasma frequency

$$\omega_{p(e,p)} = \sqrt{4\pi e^2 n / m_{(e,p)}} \sim 10^{(4.7,\,3)}\, n^{1/2}$$

anisotropy parameter

$$A = (\varepsilon_{||} - \varepsilon_{\perp})/\varepsilon \sim (\mathcal{M}-1)/(\mathcal{M}+1)$$

Growth rate	Field scale	Field strength
$\gamma \sim (v/c)\, \omega_p\, A$	$1/k \sim c/(\omega_p\, A)$	$B^2/8\pi \sim (\varepsilon_{||} - \varepsilon_{\perp})\, \eta$

efficiency (from simulations) (η)

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3D relativistic plasma PIC simulations

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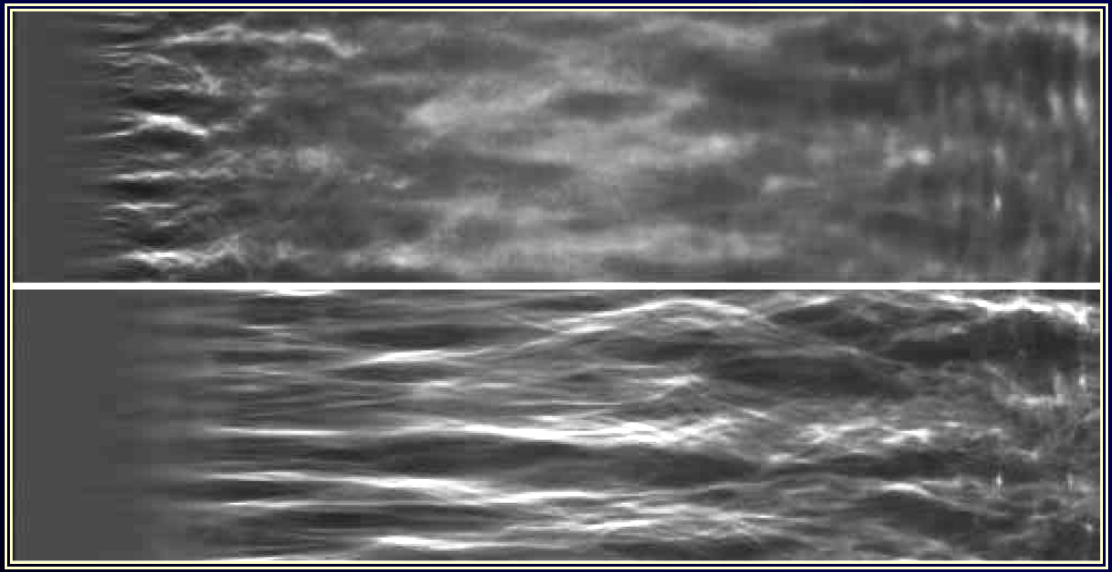
Relativistic e^-p shock (GRB)

Proton density



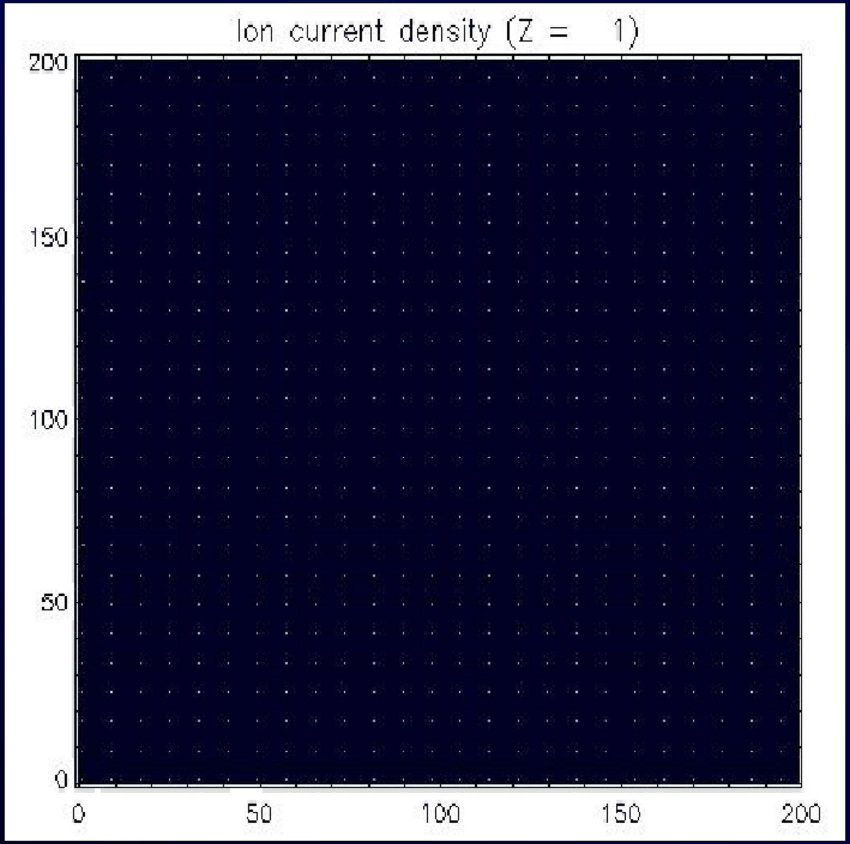
Electron currents

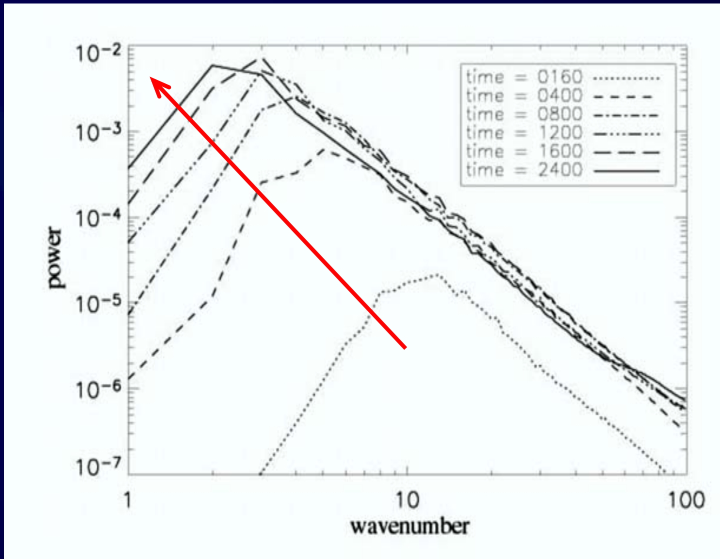
Proton currents

(Frederiksen, et al., 2003)

Currents and fields

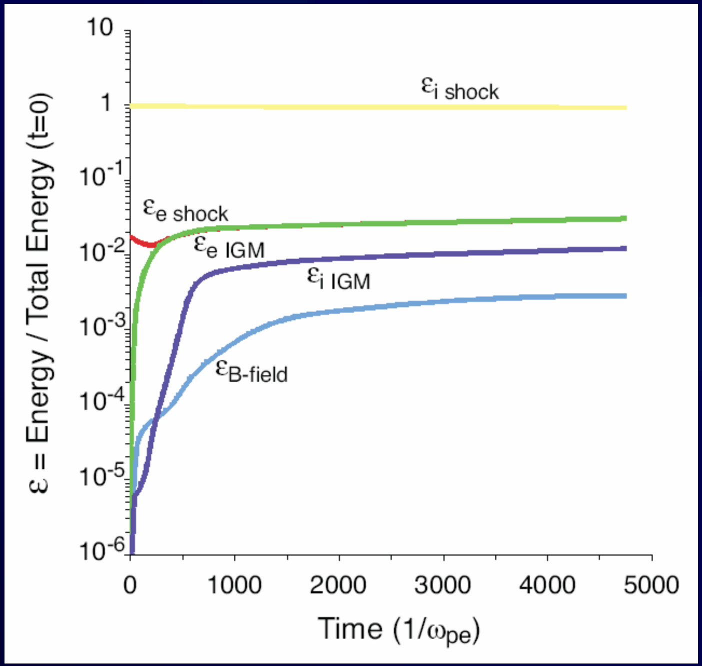
B-field scale grows downstream, where $\varepsilon_B \sim constant$

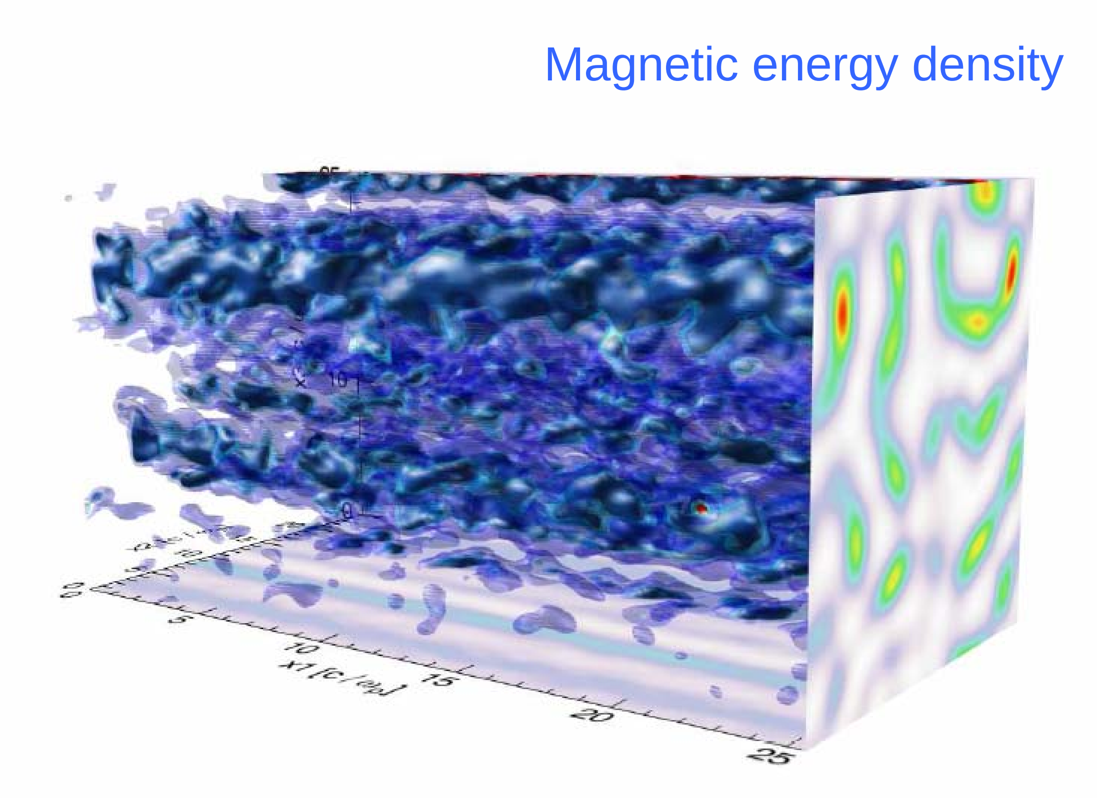




(Frederiksen, PhD thesis, 2005)

Nonrelativistic e^-p shock (SN)





(Medvedev, Silva, Kamionkowski, 2005)

Rule of thumb

Magnetized vs. Unmagnetized external medium

Critical parameter: *magnetization* σ

< 1% = unmagnetized → Weibel

> 1% = magnetized → no Weibel

+ shock front ~ Larmor
+ field amplification is still possible via Alfvenic-type instability

[talk by *Jacco Vink*, poster by *Malkov & Diamond*]

(Spitkovski, still in preparation)

Outline

A hint…

More: talk by Matthew Baring

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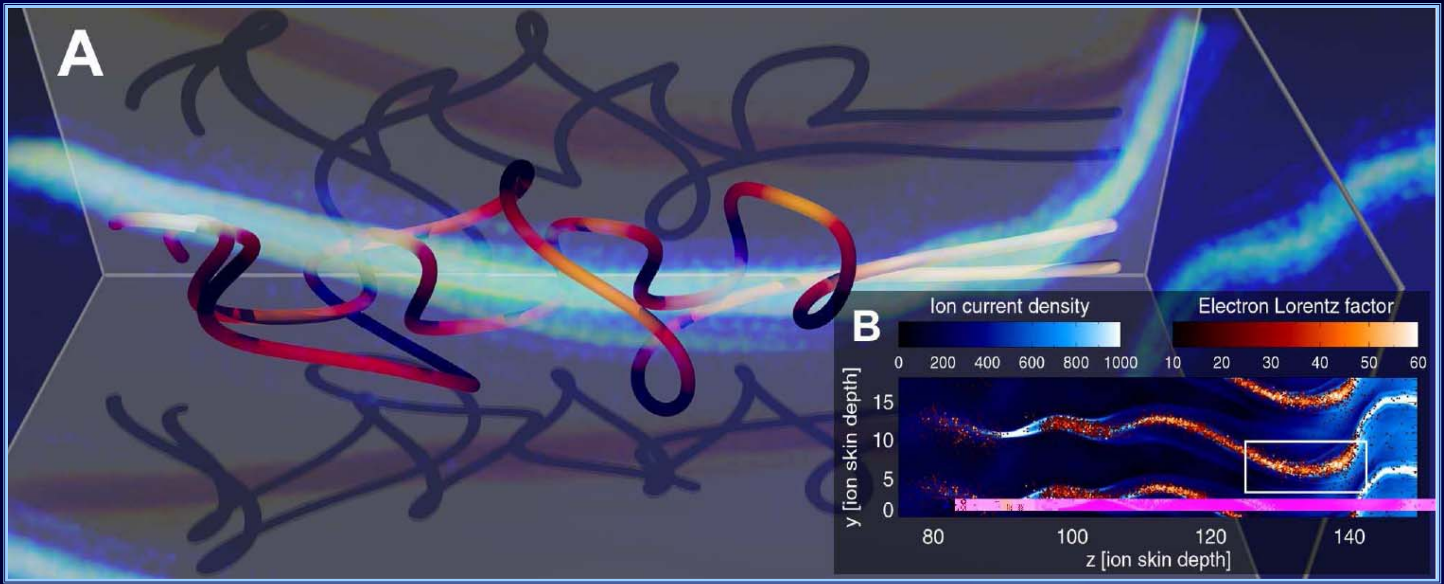
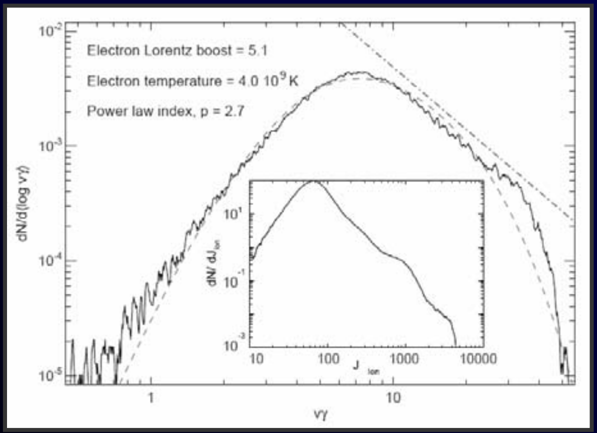
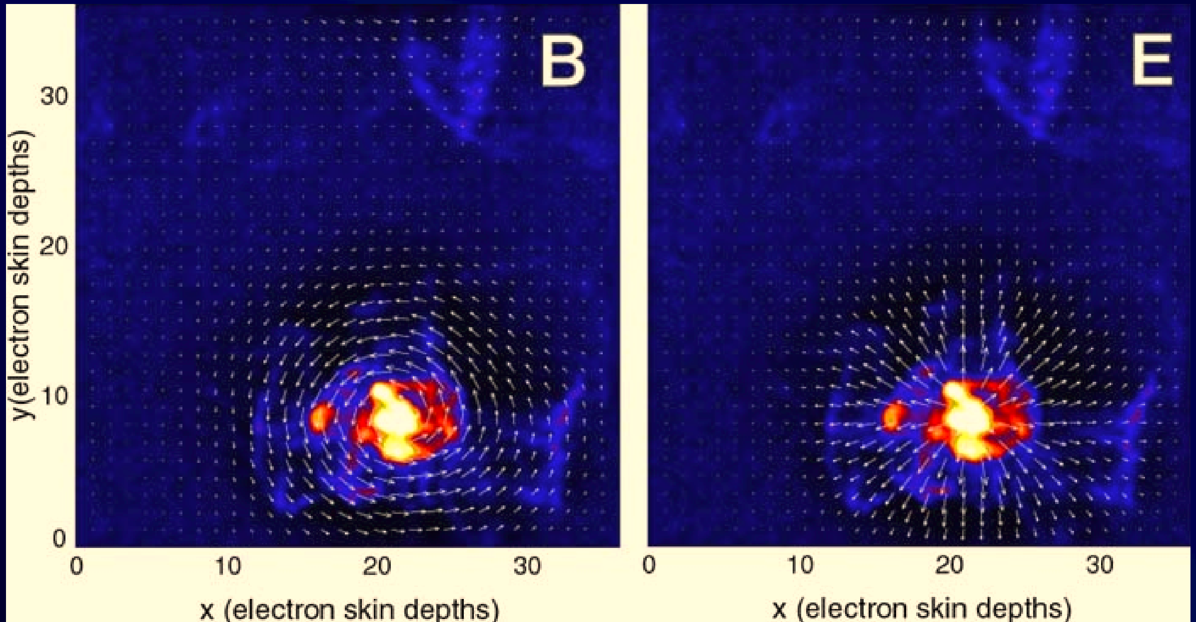
Particle acceleration *e⁻p*





(Hededal, et al, 2005, PhD)



Outline

Fields must populate large volumes downstream in order to explain observations:

Synchrotron-type radiation from shocks

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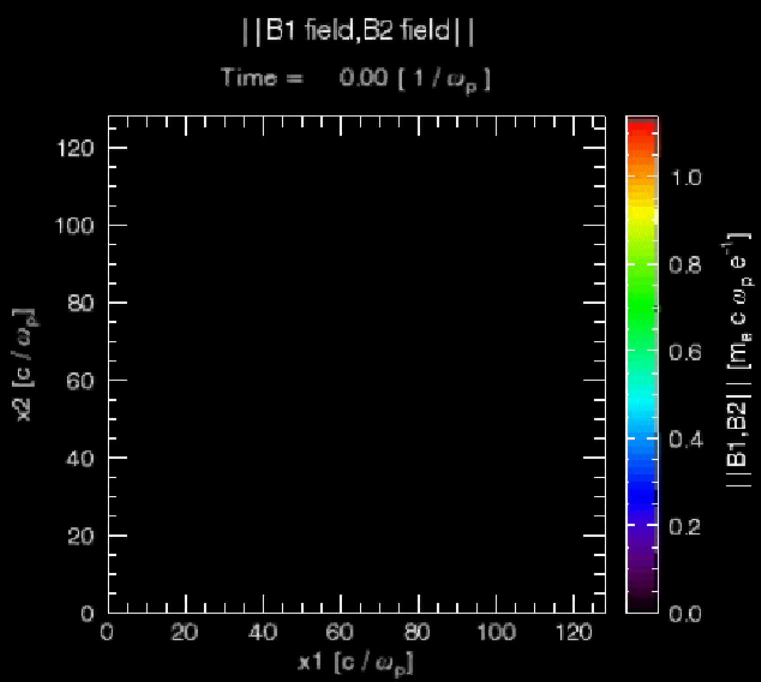
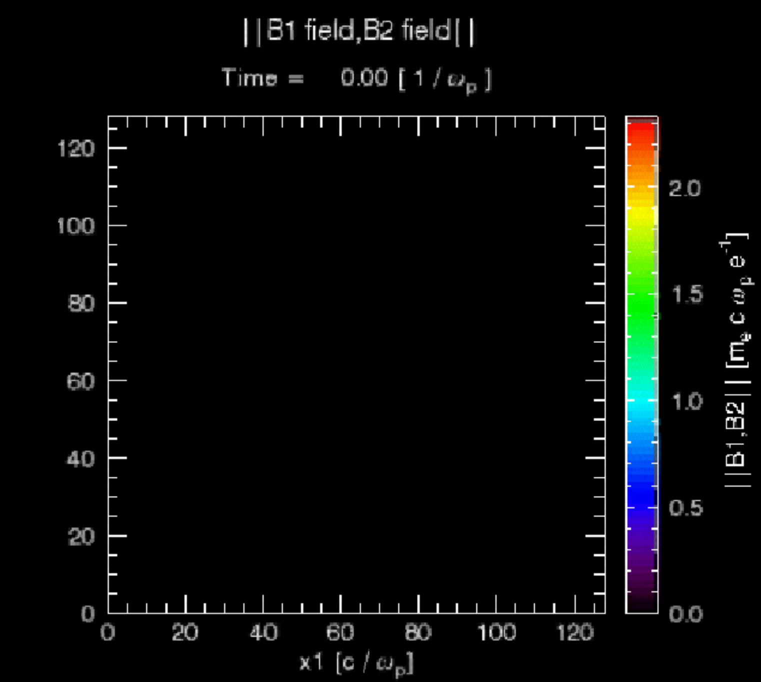
Evolution of $B_\perp$

Electron-positron simulations

Electron-proton simulations

$m_p/m_e = 1860$

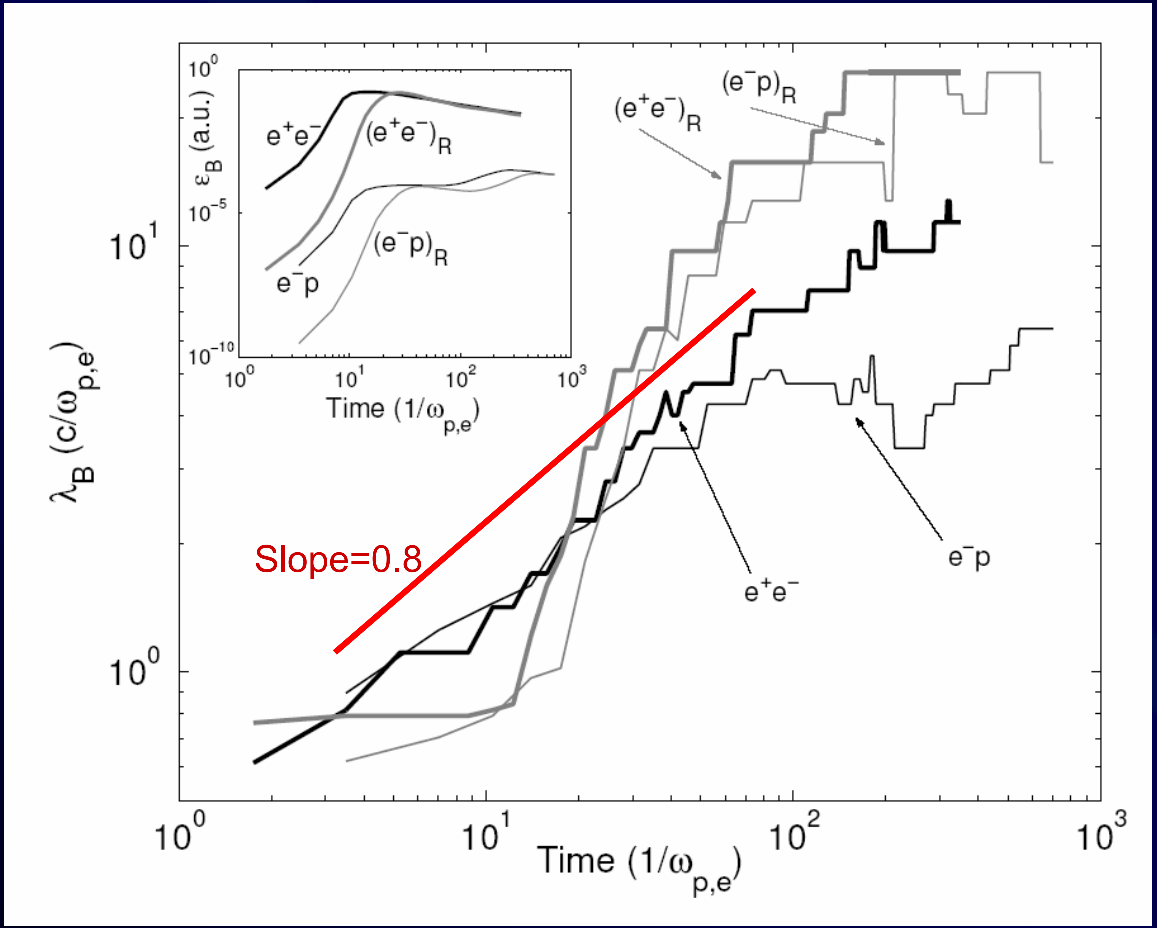




B-field *E-field* *B-field* *E-field*

(Silva, et al 2005)

The evolution of λ_B



- $e^- e^+$ medium
- $e^- p$ medium

Black – non-relativistic
Grey – relativistic (R)

$$\lambda_B \sim t^{0.8\text{-}1.1}$$

As the spatial scale grows "super-diffusively", the standard (diffusive) dissipation quenches

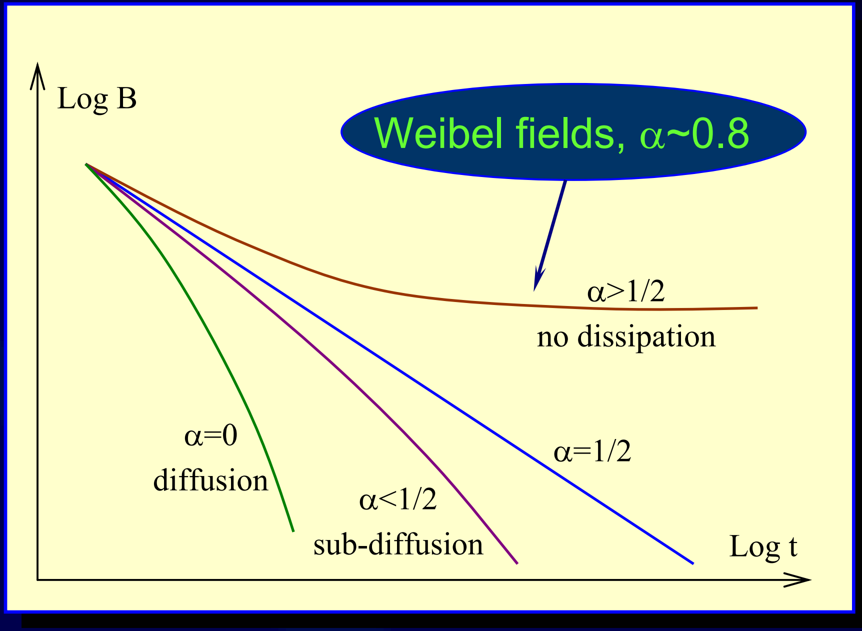
Field dissipation

Diffusive dissipation:

$$\frac{\partial B}{\partial t} = -\kappa \frac{\partial^2 B}{\partial x^2} \sim -\frac{\kappa}{\lambda_B^2} B$$

Field scaling:

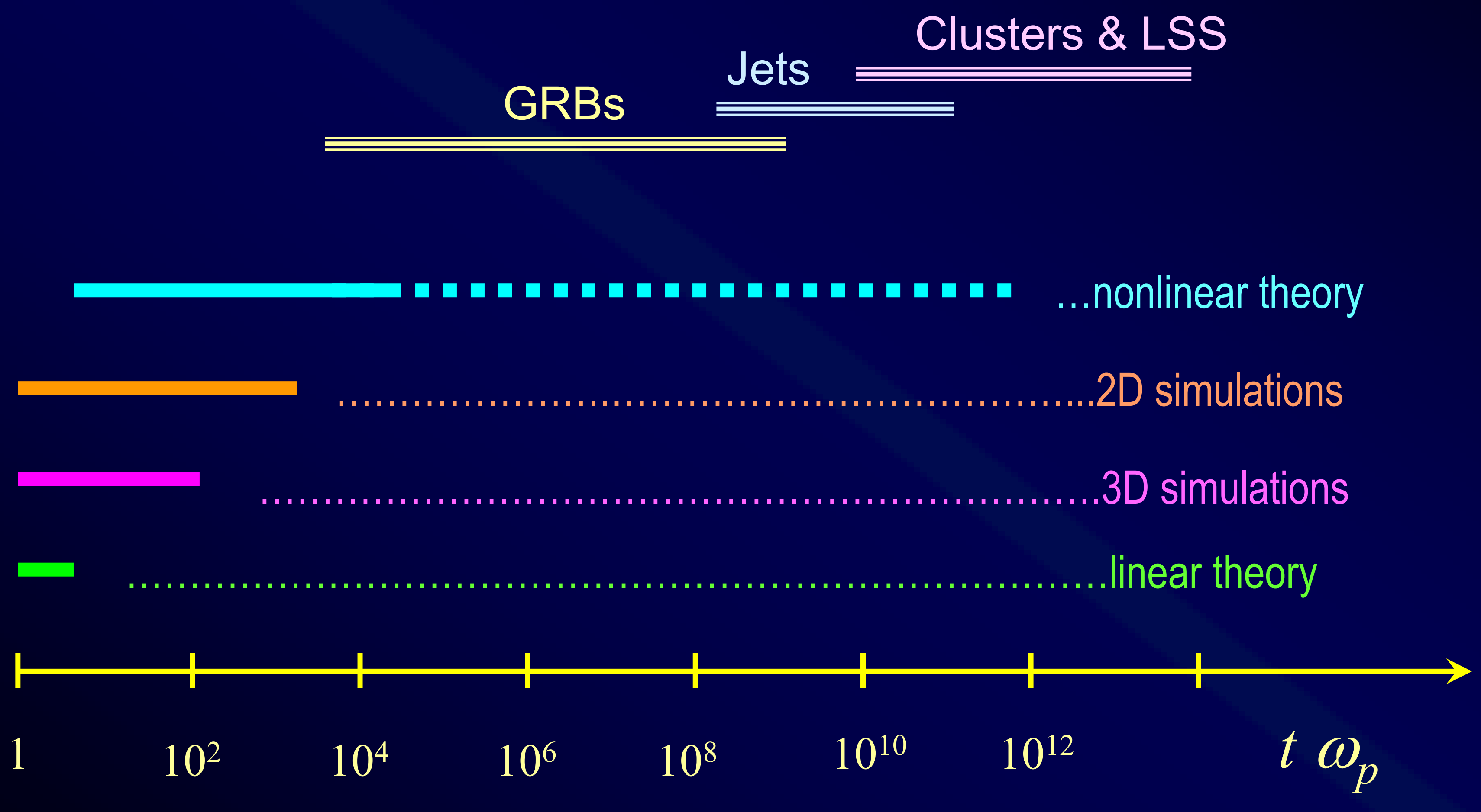
$$\lambda_B \propto t^{\alpha}$$



Solution:

$$B \propto \exp\left[-\int \lambda_B^{-2}(t)\, dt\right] \propto \begin{cases} \exp\left(-t^{1-2\alpha}\right), & if\ \alpha < 1/2 \\ t^{-A}, & if\ \alpha = 1/2 \\ \exp\left(\frac{1}{t^{2\alpha-1}} - \frac{1}{t_0^{2\alpha-1}}\right), & if\ \alpha > 1/2 \end{cases}$$

Science vs. Nature



Outline

Radiation from small-scale random fields

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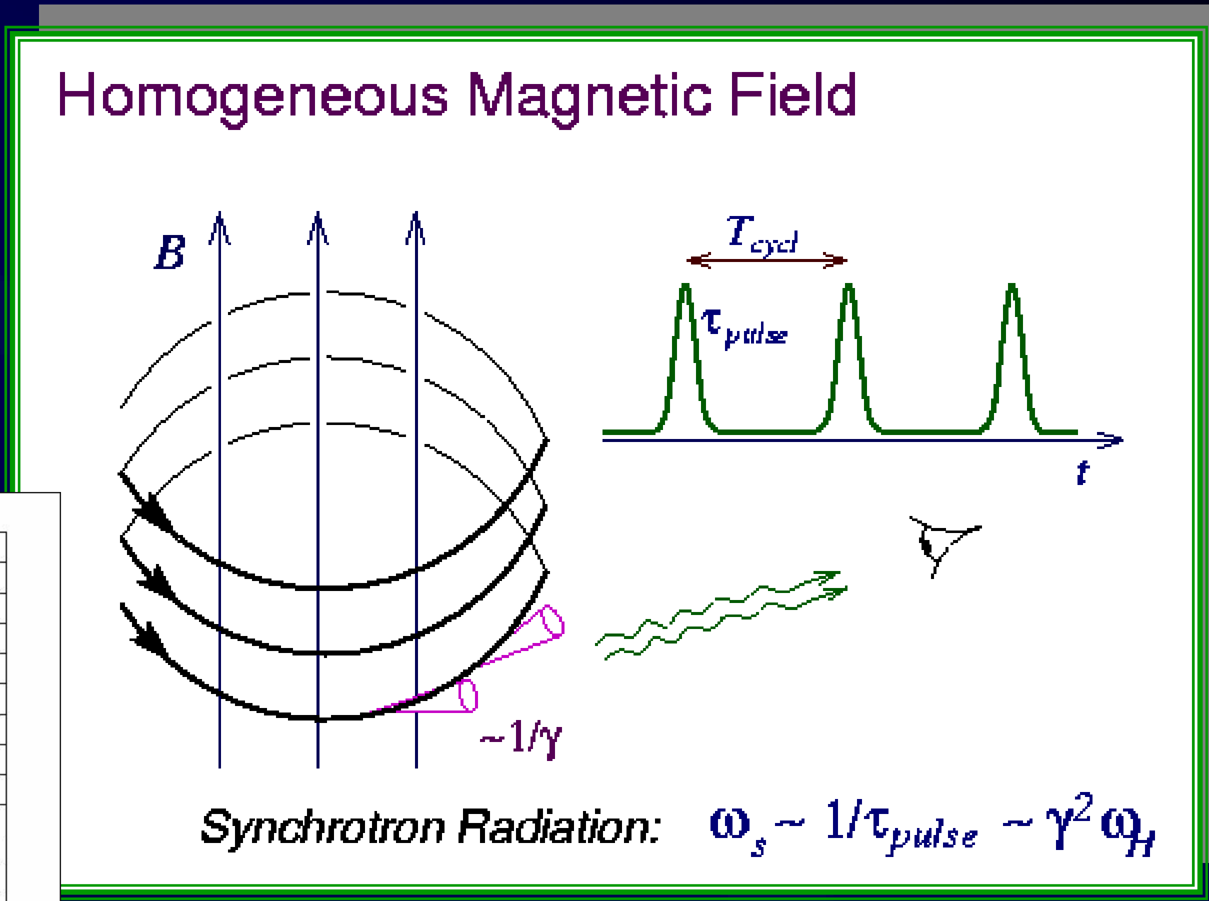
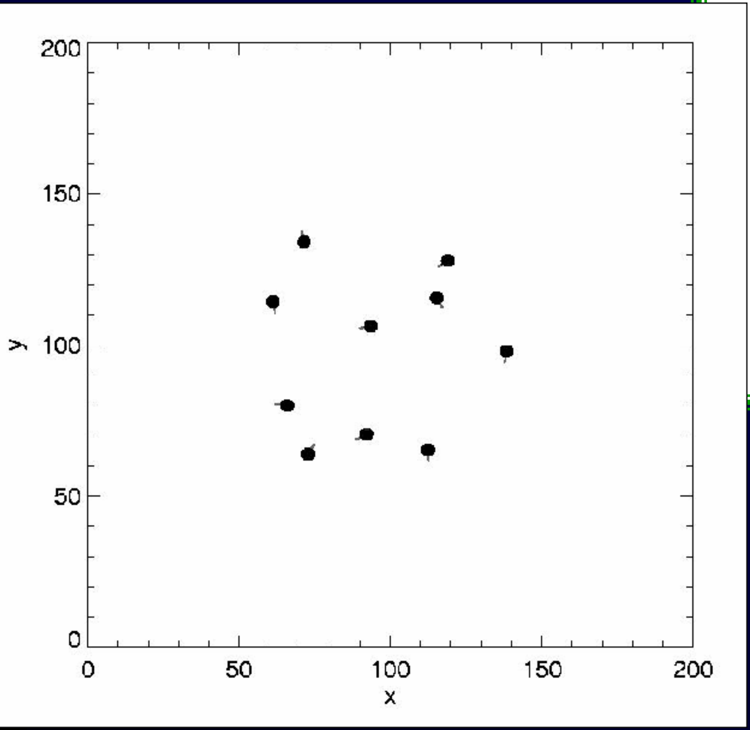
Synchrotron Radiation

$B(r)=B_0=const$

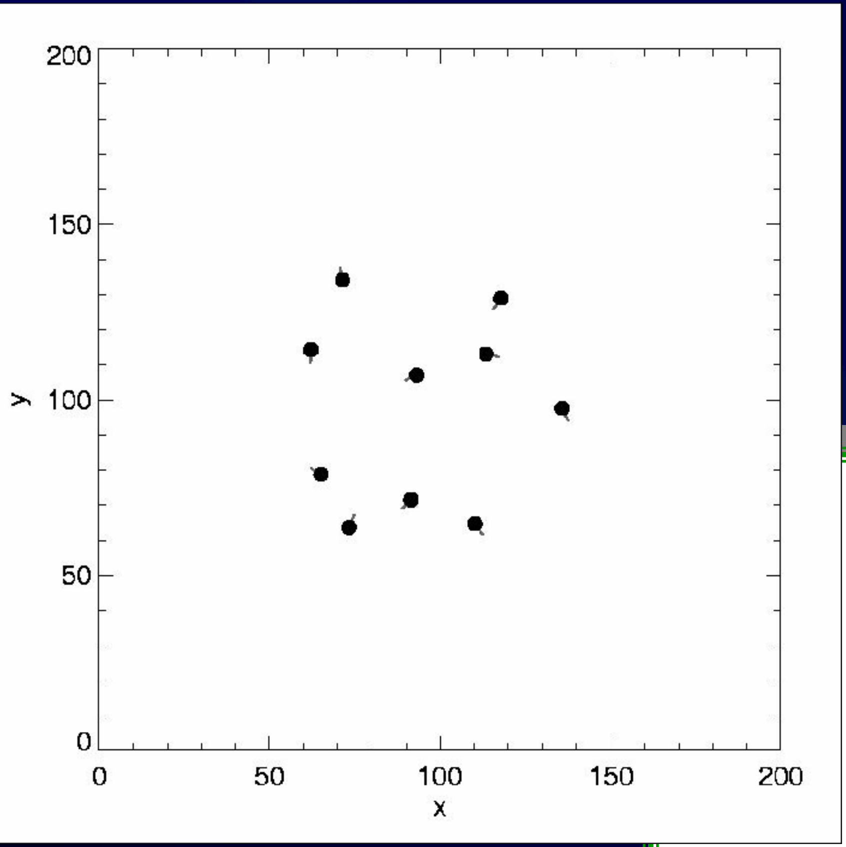
(homogeneous)





(Frederiksen, 2005, PhD thesis)

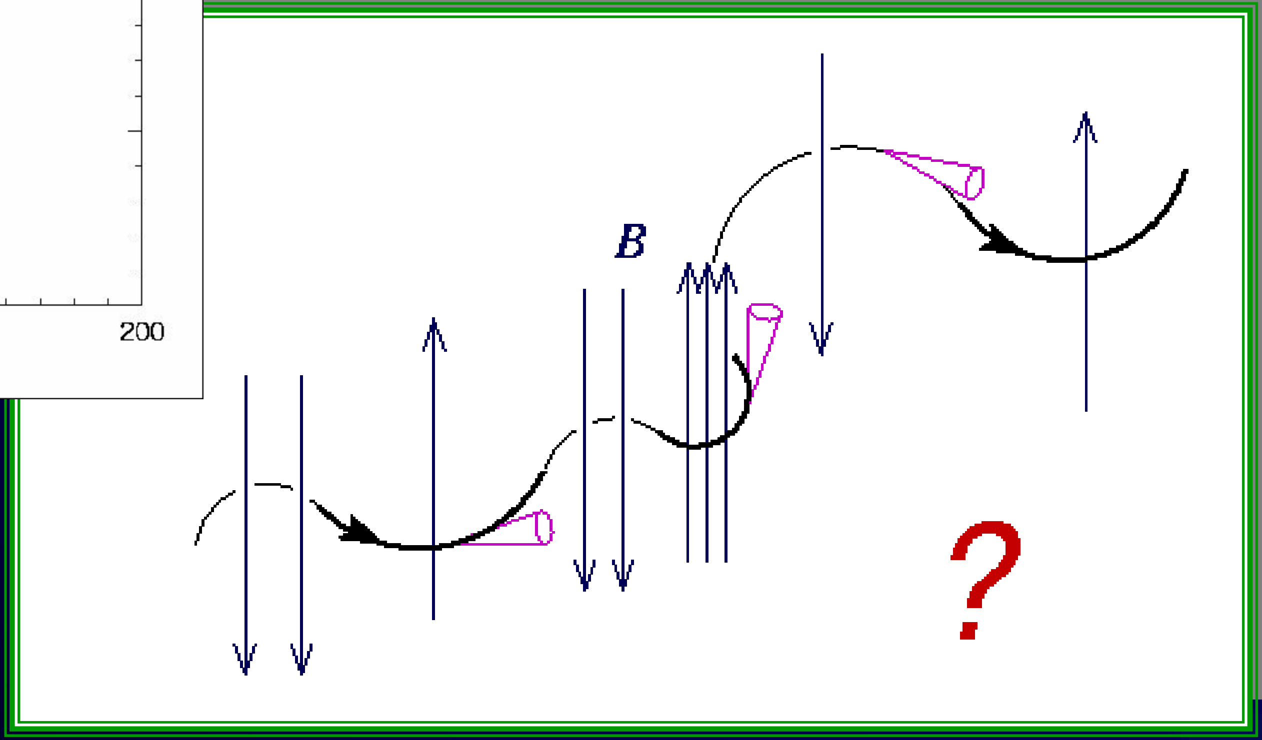
Synchrotron Vs. Jitter Radiation



$B(r)=B_1(r)\ , \quad B_0=0$

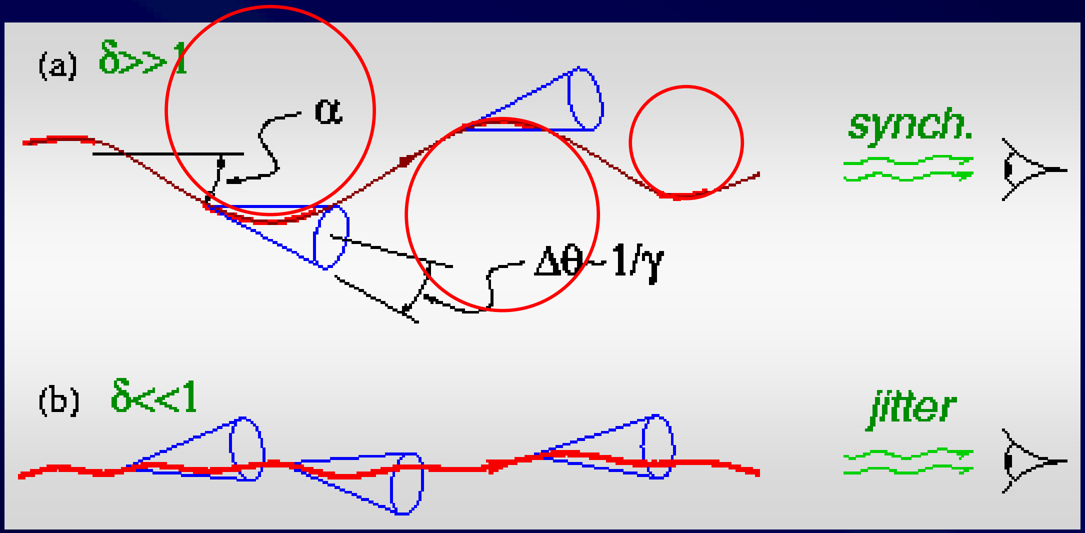
(highly inhomogeneous, random)

(Frederiksen, 2005, PhD thesis)



(Medvedev 2000, ApJ)

Regimes



$$\omega_s \sim \gamma^2\, \omega_H$$

$$\omega_j \sim \gamma^2\, c/\lambda$$

Deflection parameter:

$$\delta = \frac{\alpha}{\Delta\theta} = \frac{eB\lambda}{mc^2}$$

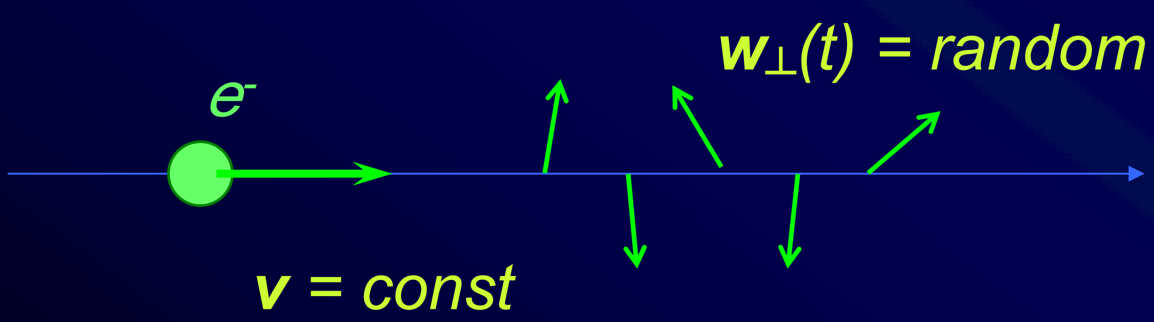
... independent of γ !

(Medvedev, 2000, ApJ)

Jitter regime

When $\delta << 1$, one can assume that

- particle is highly relativistic $\gamma >> 1$
- particle's trajectory is *piecewise-linear*
- particle velocity is nearly constant $r(t) = r_0 + c\,t$
- particle experiences random acceleration $\mathbf{w}_\perp(t)$



Jitter radiation. Theory

Lienard-Wichert potentials

$$dW = \frac{e^2}{2\pi c^3}\left(\frac{\omega}{\omega'}\right)^4 \left| \boldsymbol{n} \times \left[\left(\boldsymbol{n} - \frac{\boldsymbol{v}}{c}\right) \times \boldsymbol{w}_{\omega'}\right]\right|^2 d\Omega \frac{d\omega}{2\pi}$$

where $\boldsymbol{w}_{\omega'} = \int \boldsymbol{w} e^{i\omega' t} dt$ is the Fourier component of the particle's acceleration, $\omega' = \omega(1 - \boldsymbol{n} \cdot \boldsymbol{v}/c)$, and $\boldsymbol{n}$ is the unit vector pointing toward the observer.

Small-angle approximation

The dominant contribution to the integral comes from small angles $\theta \sim 1/\gamma$

$$\omega' \simeq \omega(1 - v/c + \theta^2/2)$$
$$\simeq \omega/2(1 - v^2/c^2 + \theta^2)$$
$$= \omega/2(\theta^2 + \gamma^{-2})$$

$$\frac{dW}{d\omega} = \frac{e^2\omega}{2\pi c^3}\int_{\omega/2\gamma^2}^{\infty} \frac{|\boldsymbol{w}_{\omega'}|^2}{\omega'^2}\left(1 - \frac{\omega}{\omega'\gamma^2} + \frac{\omega^2}{2\omega'^2\gamma^4}\right)d\omega'$$

Spectral power

(Landau & Lifshitz, 1963; Medvedev, ApJ, 2000)

Jitter radiation. Theory (cont.)

Fourier image of the particle acceleration from the 3D "(vxB) acceleration field"

We need to express the temporal Fourier component of the acceleration $\mathbf{w} \equiv F_L/\gamma m$ taken along the particle trajectory in terms of the Fourier component of the field in the spatial and temporal domains. Taking the Fourier transform of $\mathbf{w}(\mathbf{r}_0 + \mathbf{v}t, t)$, we have

$$\mathbf{w}_{\omega'} = (2\pi)^{-4} \int e^{i\omega' t}\, dt \left(e^{-i(\Omega t - \mathbf{k}\cdot\mathbf{r}_0 - \mathbf{k}\cdot\mathbf{v}t)} \mathbf{w}_{\Omega,\mathbf{k}}\, d\Omega d\mathbf{k} \right)$$
$$= (2\pi)^{-3} \int \mathbf{w}_{\Omega,\mathbf{k}} \delta(\omega' - \Omega + \mathbf{k}\cdot\mathbf{v})\, e^{i\mathbf{k}\cdot\mathbf{r}_0}\, d\Omega d\mathbf{k},$$

where we used that $\int e^{i\omega t}\, dt = 2\pi\delta(\omega)$. In a statisti-

$$\mathbf{w} = (e/\gamma mc)\mathbf{v} \times \mathbf{B}$$

Lorentz force

$$w_\alpha = (e/\gamma mc)\tfrac{1}{2} e_{\alpha\beta\gamma}(v_\beta B_\gamma - v_\gamma B_\beta).$$

$$\overline{|\mathbf{w}_{\Omega,\mathbf{k}}|^2} = (ev/\gamma mc)^2 (\delta_{\alpha\beta} - v^{-2} v_\alpha v_\beta)\, \overline{B^\alpha_{\Omega,\mathbf{k}} B^{*\beta}_{\Omega,\mathbf{k}}}.$$

Ensemble-averaged acceleration spectrum

$$\overline{B^\alpha_{\Omega,\mathbf{k}} B^{*\beta}_{\Omega,\mathbf{k}}} = C(\delta_{\alpha\beta} - n_\alpha n_\beta) f_z(k_\parallel) f_{xy}(k_\perp),$$

B-field spectrum

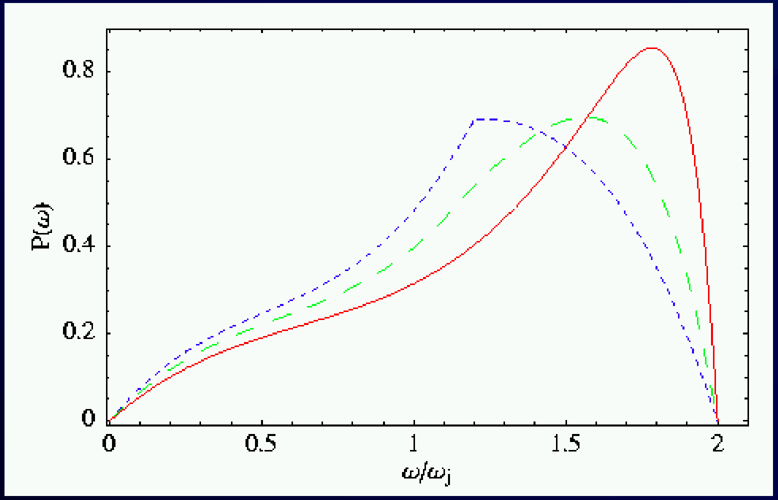
(Landau & Lifshitz, 1963; Medvedev, ApJ, 2000; Fleishman, ApJ, 2006, Medvedev, ApJ, 2006)

Jitter Spectra: F_ν (1D)

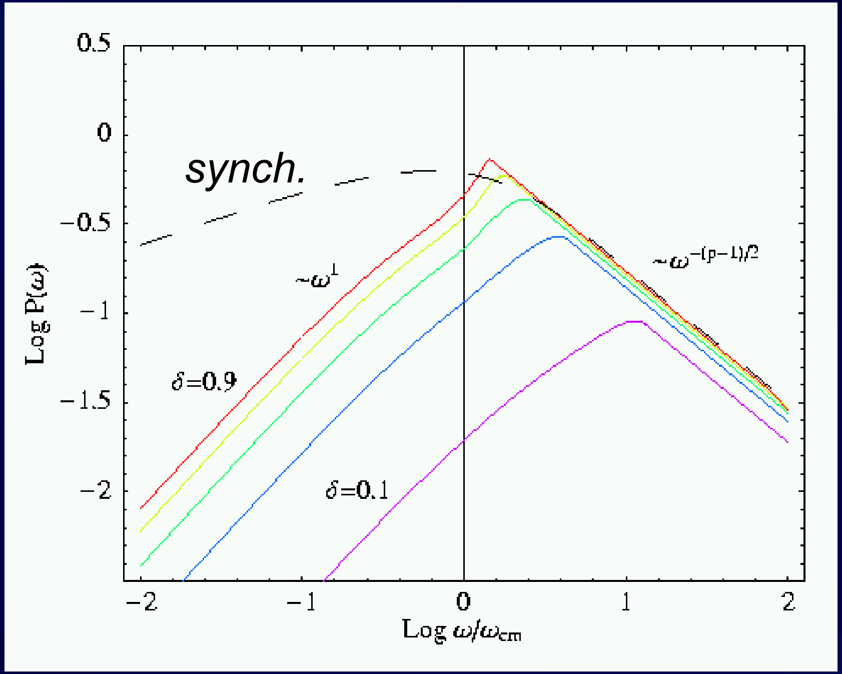
Weibel instability: $0 < k < k_{max} \sim \omega_{p,e}/c$

Assume, for illustration: $\langle B_k^2 \rangle \sim k^{2\mu}$, $\mu > 1$

Single electron



Power-law electrons

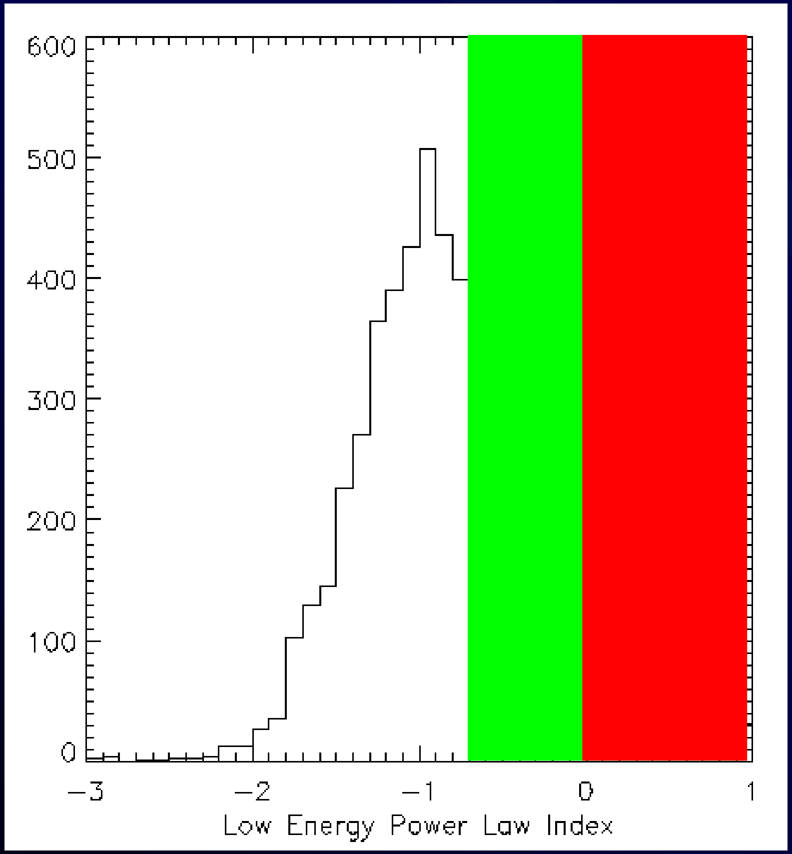


$N(\gamma) \sim \gamma^{-p}$, $\gamma > \gamma_{min}$

(Medvedev, ApJ, 2000)

Synchrotron "Line of Death"

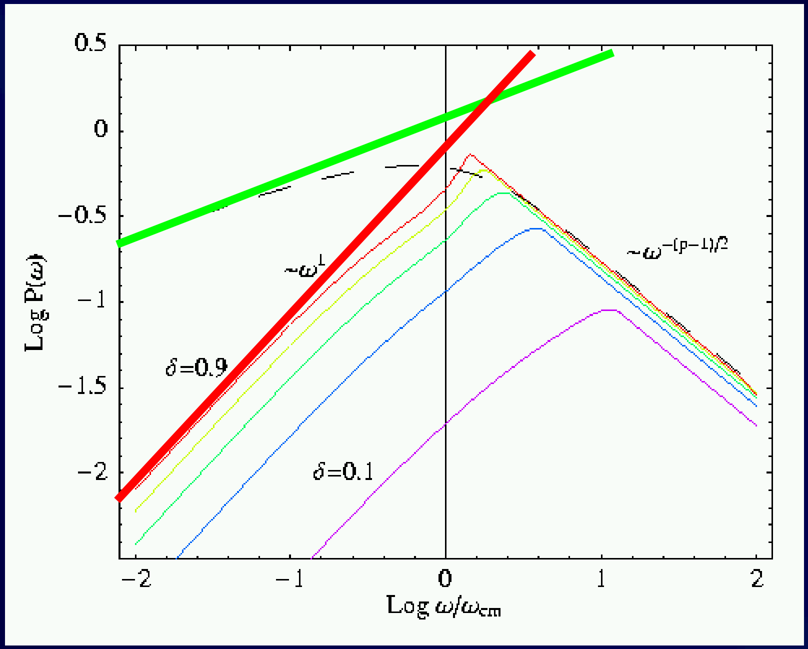
About 30% of BATSE GRBs and 50% of BSAX GRBs have photon soft indices α greater than –2/3, inconsistent with optically thin Synchrotron Shock Model



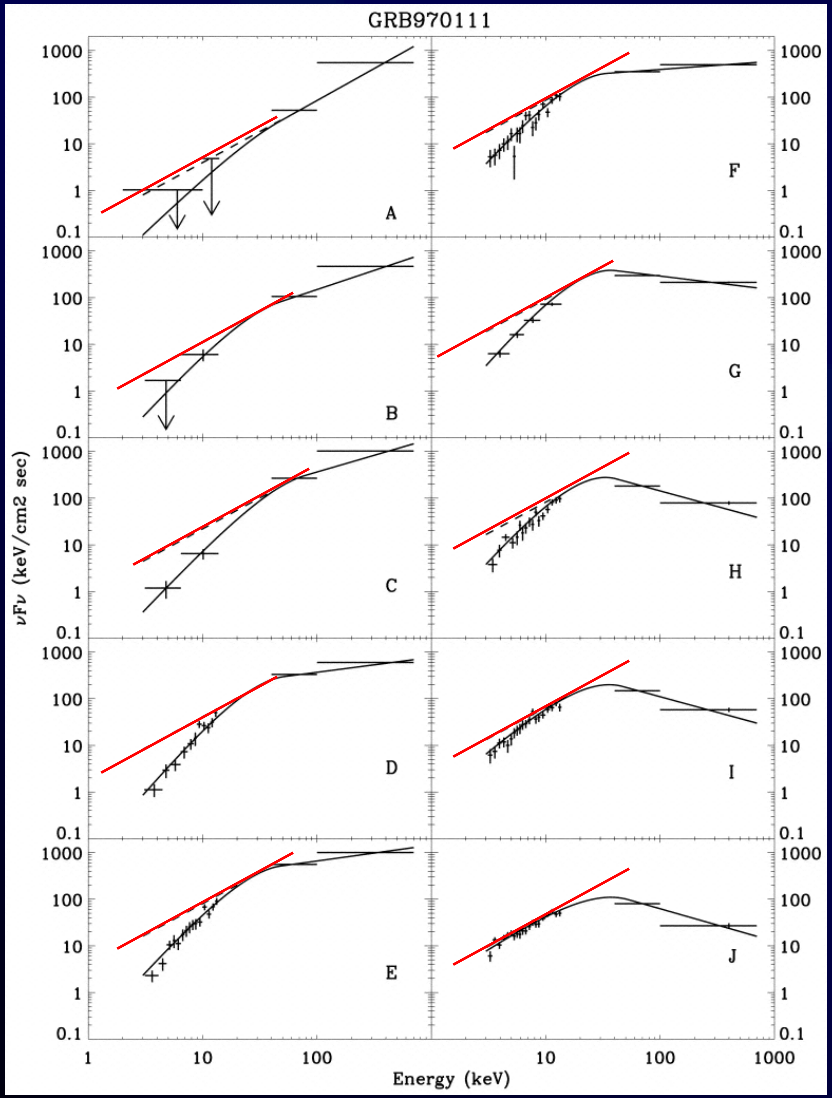
(Preece, et al., ApJS, 2000)

$$F_\nu \sim \nu^{\alpha+1}$$

(Medvedev, 2000)

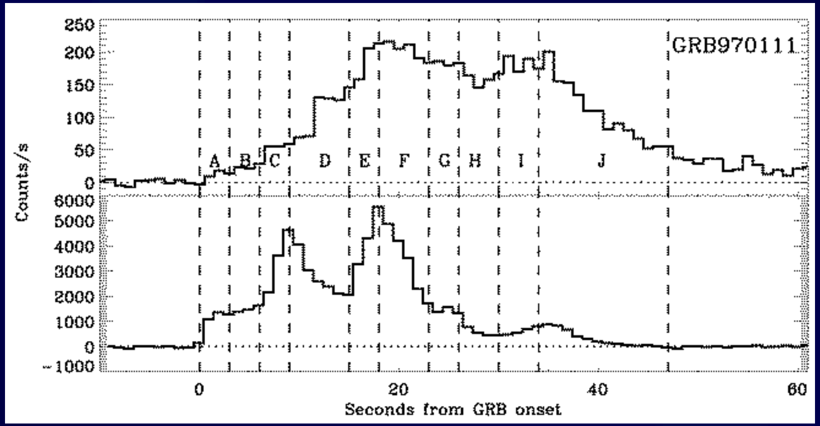


Beppo-SAX spectra



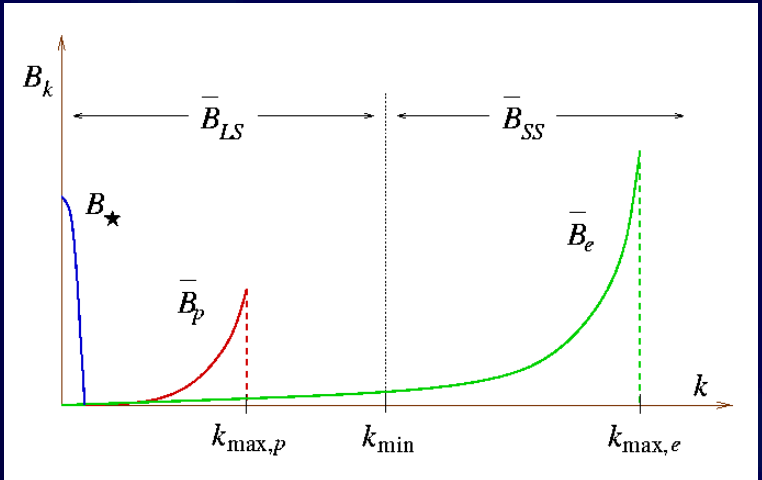
In a sample of 8 GRBs (2-700keV)
50% *violate* synchrotron limit

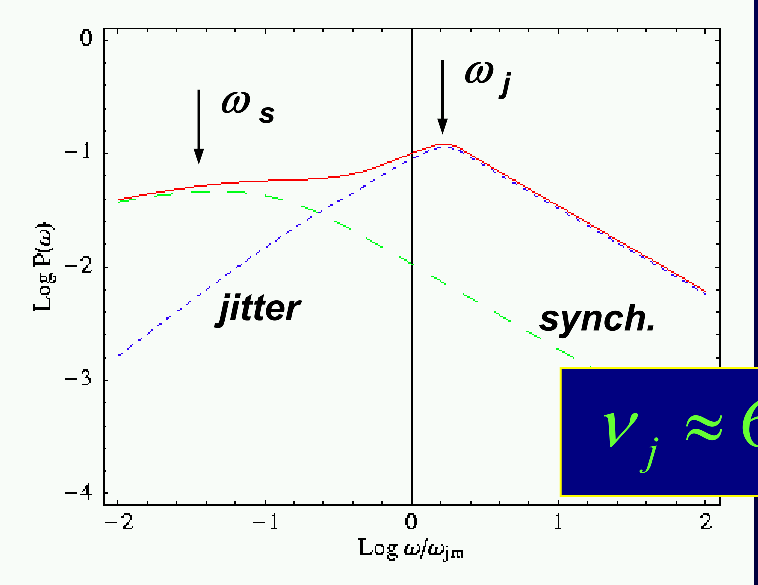
GRB 970111
soft photon index *violates*
synchrotron limit for the entire burst



(Frontera, et al., ApJ, 2000)

Composite Model of Spectra





(Medvedev, ApJ, 2000)

Frequencies

$$\frac{\omega_s}{\omega_j} = \frac{3}{2}\frac{B_{LS}}{B_{SS}}\delta$$

Fluxes

$$\frac{F_{J,\max}}{F_{S,\max}} = f(p,\mu)\,\delta^2$$

$$\delta \approx \sqrt{(m_p/m_e)\varepsilon_B}$$

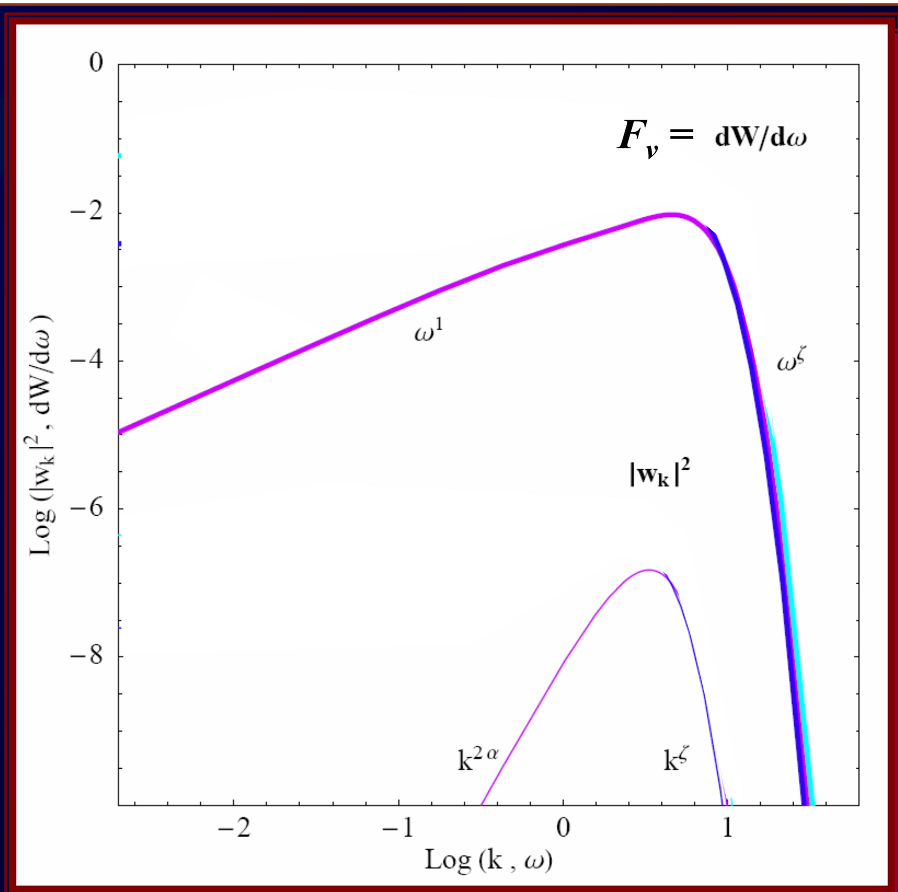
Break

$$\nu_j \approx 6\times10^9\ \gamma_{\min}^2\ \Gamma_{\rm sh}\ \Gamma_{\rm int}\ \bar{\gamma}_e^{-1/2}\ n_{e,10}^{1/2}\quad \text{Hz}$$

Jitter does not work?

Fleishman, ApJ, astro-ph/0502145

• a low-frequency spectrum, $dI_\omega/d\omega \propto \omega^1$, valid in the presence of *ordered* small-scale magnetic field fluctuations, does not occur in the general case of small-scale *random* magnetic field fluctuations.



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- diffusive synchrotron radiation arising from the scattering of fast electrons on small-scale *random* magnetic or/and electric fields produces a broad variety of low-frequency spectral asymptotes – from $dI_\omega/d\omega \propto \omega^0$ to $\propto \omega^2$ – sufficient to interpret the entire range of low energy spectral indices observed from GRB sources, while the high-frequency spectrum $dI_\omega/d\omega \propto \omega^{-\nu}$ may affect the corresponding high energy spectral index distribution.

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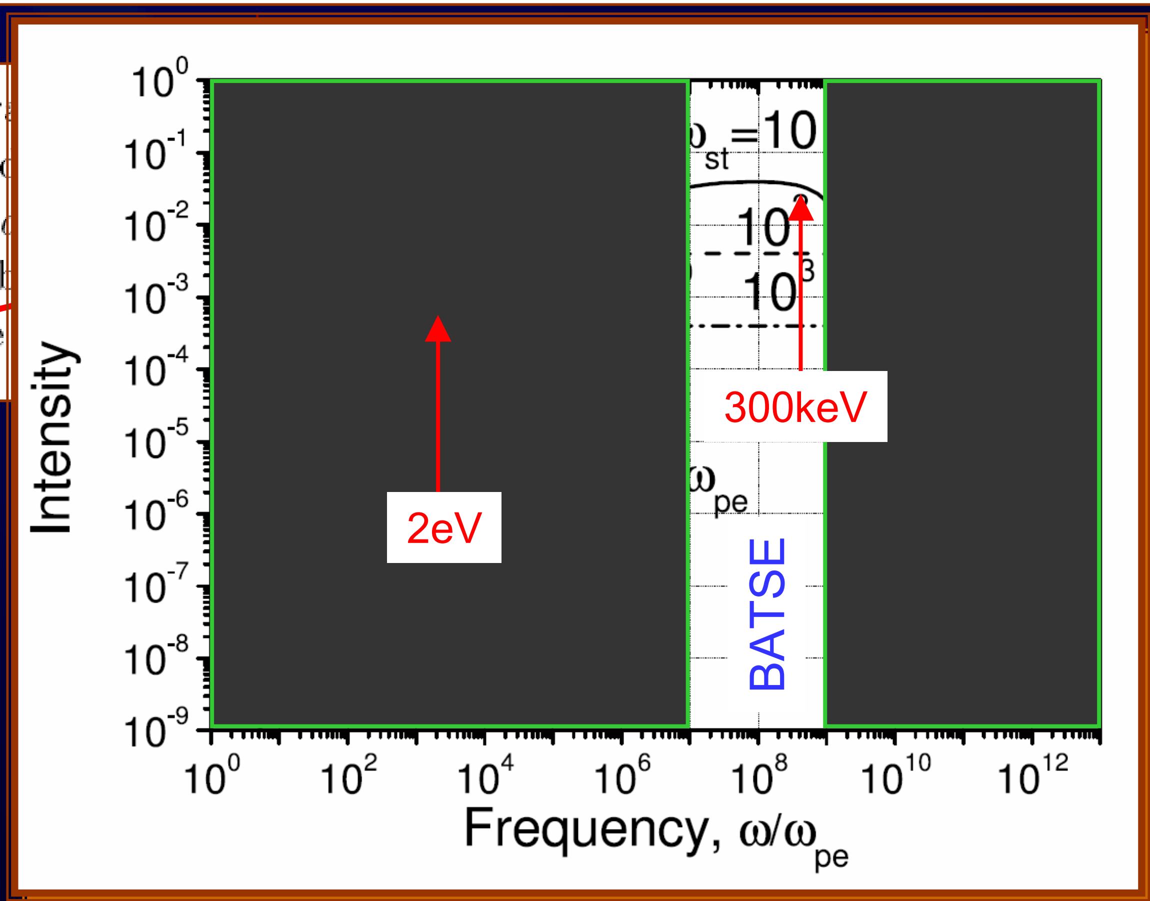

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All "diffusive synchrotron" calculations

(perturbative and non-perturbative)

assume isotropic (!) field distribution.

→→ irrelevant for Weibel turbulence !!!

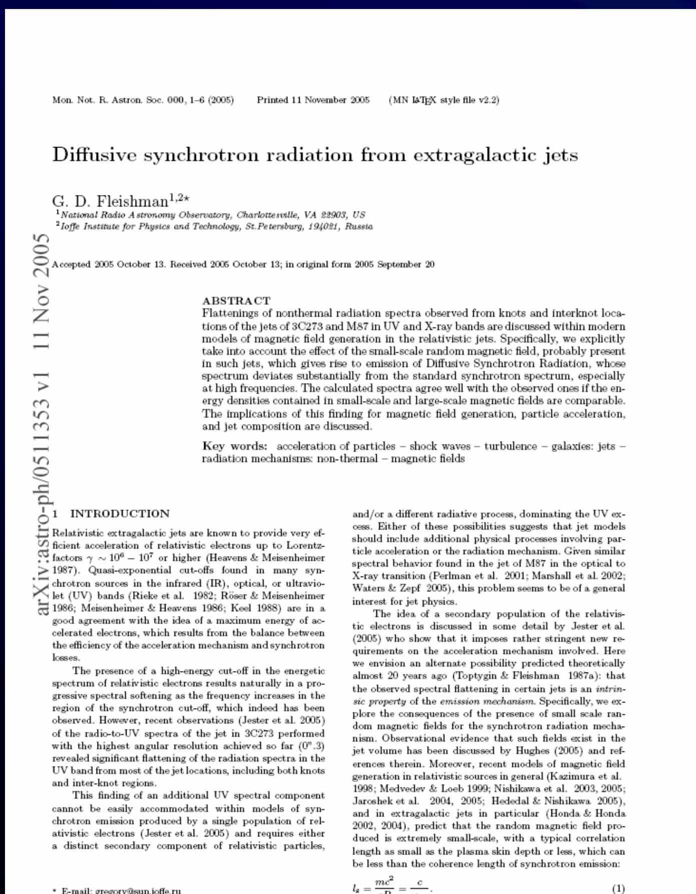
“Jitter” vs. “Diffusive Synchrotron”

No difference:
Same physical mechanism !

[redacted] We will refer the synchrotron radiative process in the presence of small-scale magnetic fields as *Diffusive Synchrotron Radiation* (DSR), [redacted]

[redacted] The second component is DSR (called also “3D jitter radiation”, Hededal (2005)) resulting from the interaction of the ultrarelativistic electrons with small-scale random fields. [redacted]

(Fleishman, 2005, MNRAS (in press), astro-ph/0511353)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Diffusive synchrotron radiation from extragalactic jets

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ABSTRACT
Flattenings of nonthermal radiation spectra observed from knots and interknot locations of the jets of 3C273 and M87 in UV and X-ray bands are discussed within modern models of magnetic field generation in the relativistic jets. Specifically, we explicitly take into account the effect of the small-scale random magnetic field, probably present in such jets, which gives rise to emission of Diffusive Synchrotron Radiation, whose spectrum deviates substantially from the standard synchrotron spectrum, especially at high frequencies. The calculated spectra agree well with the observed ones if the energy densities contained in small-scale and large-scale magnetic fields are comparable. The implications of this finding for magnetic field generation, particle acceleration, and jet composition are discussed.

Key words: acceleration of particles – shock waves – turbulence – galaxies: jets – radiation mechanisms: non-thermal – magnetic fields

1 INTRODUCTION

Relativistic extragalactic jets are known to provide very efficient acceleration of relativistic electrons up to Lorentz-factors $\gamma \sim 10^6 - 10^7$ or higher (Heavens & Meisenheimer 1987). Quasi-exponential cut-offs found in many synchrotron sources in the infrared (IR), optical, or ultraviolet (UV) bands (Rieke et al. 1982; Röser & Meisenheimer 1986; Meisenheimer & Heavens 1986; Keel 1988) are in a good agreement with the idea of a maximum energy of accelerated electrons, which results from the balance between the efficiency of the acceleration mechanism and synchrotron losses.

The presence of a high-energy cut-off in the energetic spectrum of relativistic electrons results naturally in a progressive spectral softening as the frequency increases in the region of the synchrotron cut-off, which indeed has been observed. However, recent observations (Jester et al. 2005) of the radio-to-UV spectra of the jet in 3C273 performed with the highest angular resolution achieved so far (0".3) revealed significant flattening of the radiation spectra in the UV band from most of the jet locations, including both knots and inter-knot regions.

This finding of an additional UV spectral component cannot be easily accommodated within models of synchrotron emission produced by a single population of relativistic electrons (Jester et al. 2005) and requires either a distinct secondary component of relativistic particles, and/or a different radiative process, dominating the UV excess. Either of these possibilities suggests that jet models should include additional physical processes involving particle acceleration or the radiation mechanism. Given similar spectral behavior found in the jet of M87 in the optical to X-ray transition (Perlman et al. 2001; Marshall et al. 2002; Waters & Zepf 2005), this problem seems to be of a general interest for jet physics.

The idea of a secondary population of the relativistic electrons is discussed in some detail by Jester et al. (2005) who show that it imposes rather stringent new requirements on the acceleration mechanism involved. Here we envision an alternate possibility predicted theoretically almost 20 years ago (Toptygin & Fleishman 1987a): that the observed spectral flattening in certain jets is an *intrinsic property* of the *emission mechanism*. Specifically, we explore the consequences of the presence of small scale random magnetic fields for the synchrotron radiation mechanism. Observational evidence that such fields exist in the jet volume has been discussed by Hughes (2005) and references therein. Moreover, recent models of magnetic field generation in relativistic sources in general (Kazimura et al. 1998; Medvedev & Loeb 1999; Nishikawa et al. 2003, 2005; Jaroshek et al. 2004, 2005; Hededal & Nishikawa 2005), and in extragalactic jets in particular (Honda & Honda 2002, 2004), predict that the random magnetic field produced is extremely small-scale, with a typical correlation length as small as the plasma skin depth or less, which can be less than the coherence length of synchrotron emission:

$$l_s = \frac{mc^2}{eB} = \frac{c}{\omega_{Be}}. \quad (1)$$

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Outline

Viewing angle effect

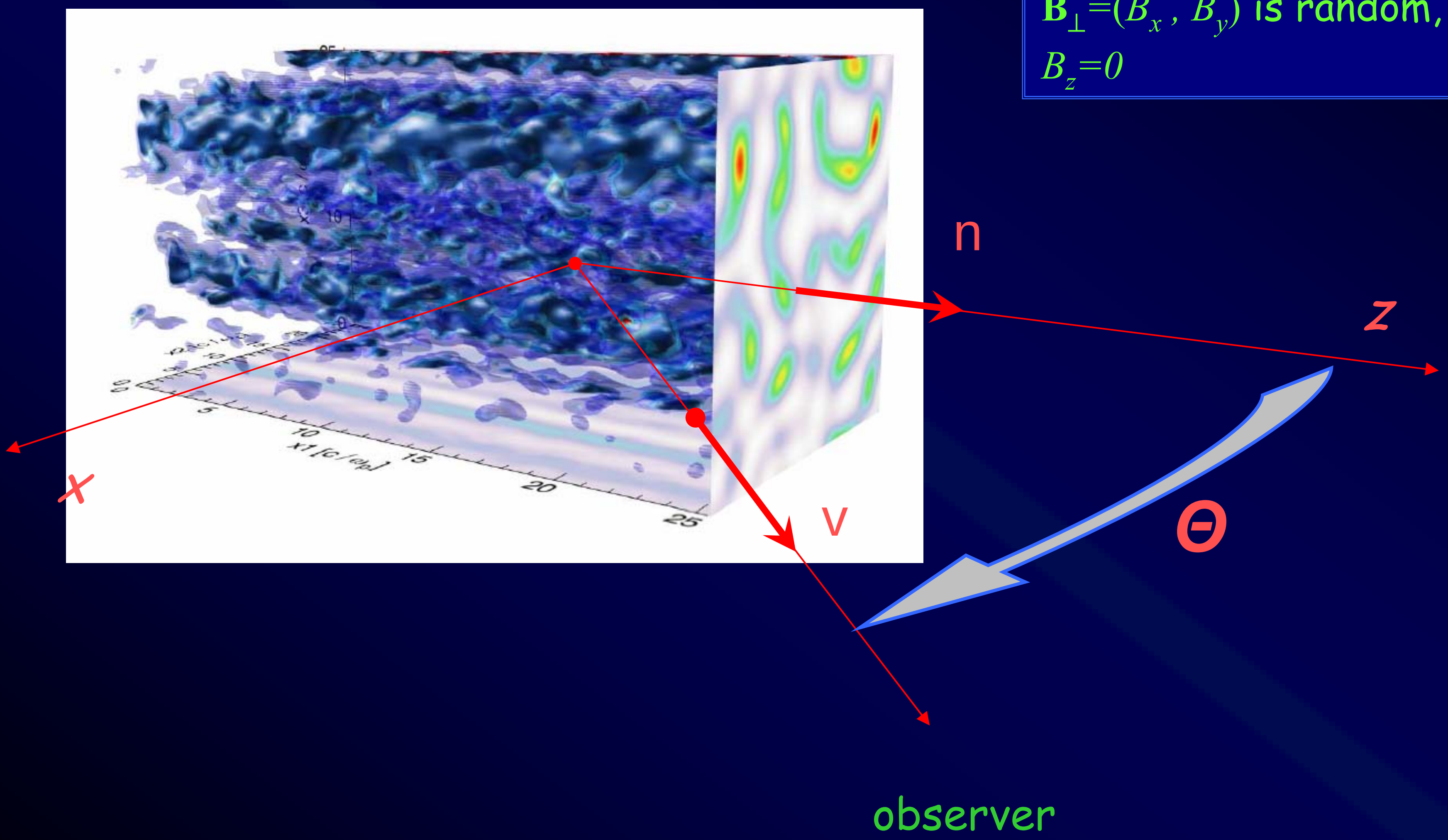
- Introduction
- Microphysics of collisionless relativistic inmagnetized shocks
- Realistic modeling of shocks
- Particle acceleration…
- Can the produced fields really populate large volumes?
- How do the shocks shine?
- Spectral variability
- Polarization of radiation
- Summary

Radiation vs Θ

B-field is anisotropic:

$\mathbf{B}_\perp=(B_x\,,\,B_y)$ is random,

$B_z=0$



(Medvedev, Silva, Kamionkowski 2006; Medvedev 2006)

Jitter + Weibel theory -- summary

Spectral power of radiation

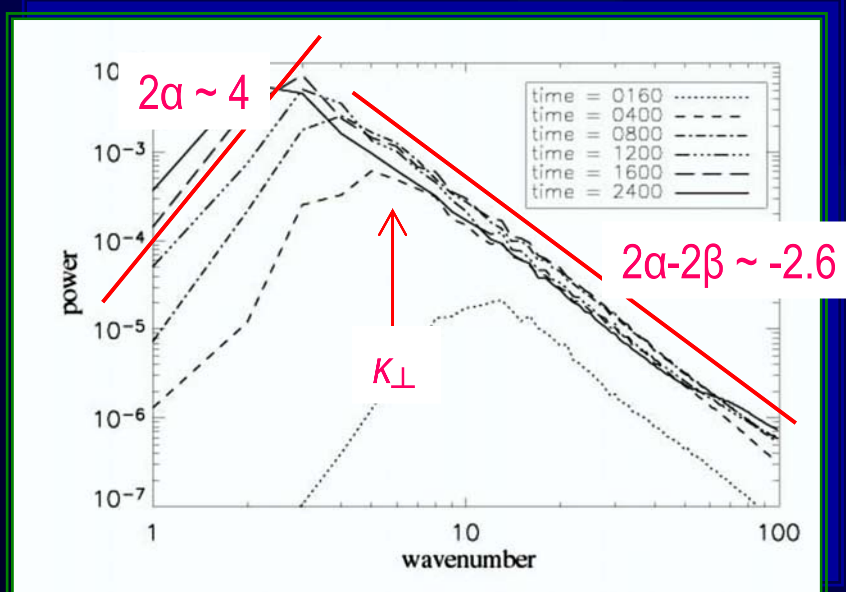
$$\frac{dW}{d\omega} = \frac{e^2\omega}{2\pi c^3}\int_{\omega/2\gamma^2}^{\infty}\frac{|\mathbf{w}_{\omega'}|^2}{\omega'^2}\left(1-\frac{\omega}{\omega'\gamma^2}+\frac{\omega^2}{2\omega'^2\gamma^4}\right)d\omega',$$

Electron's acceleration spectrum

$$\langle|\mathbf{w}_{\omega'}|^2\rangle = \frac{C}{2\pi}(1+\cos^2\Theta)\int f_z(k_\parallel)f_{xy}(k_\perp)\delta(\omega'+\mathbf{k}\cdot\mathbf{v})\,dk_\parallel d^2k_\perp.$$

Models of field spectra, independent in *z* and *xy* (!)

$$f_z(k_\parallel) = \frac{k_\parallel^{2\alpha_1}}{(\kappa_\parallel^2+k_\parallel^2)^{\beta_1}},\quad f_{xy}(k_\perp) = \frac{k_\perp^{2\alpha_2}}{(\kappa_\perp^2+k_\perp^2)^{\beta_2}},$$



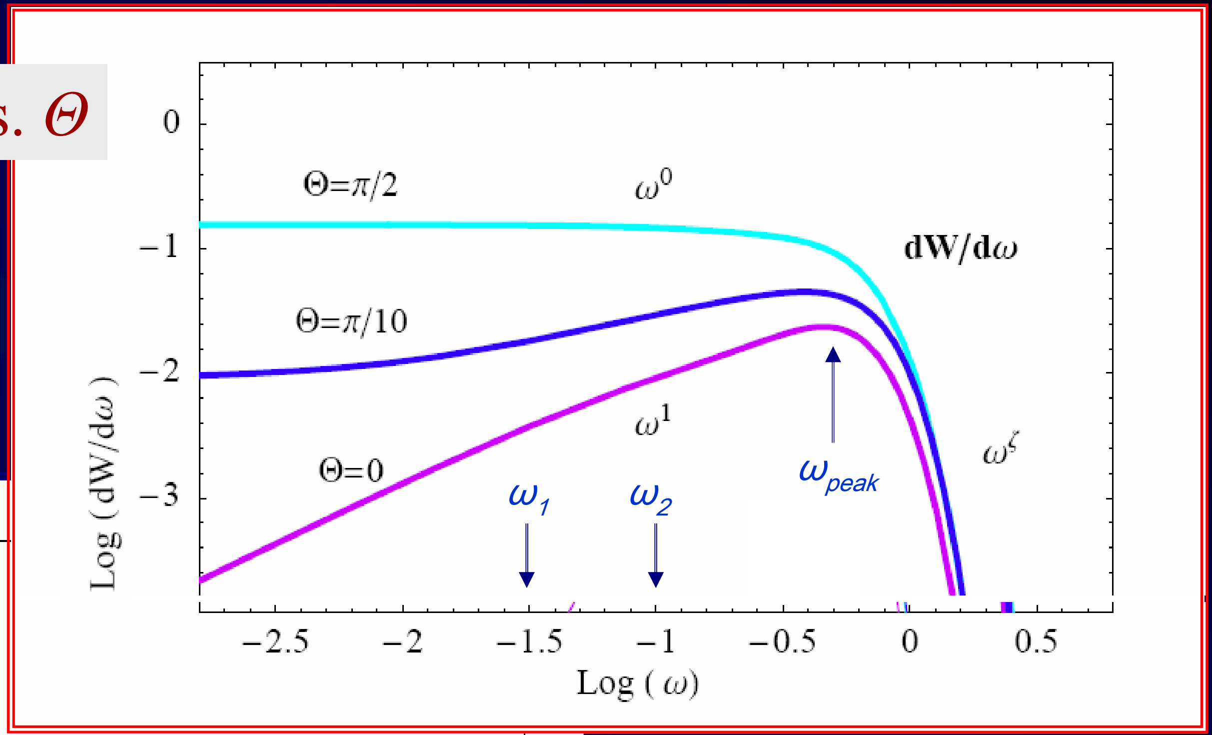
$\alpha_2 \sim 2$

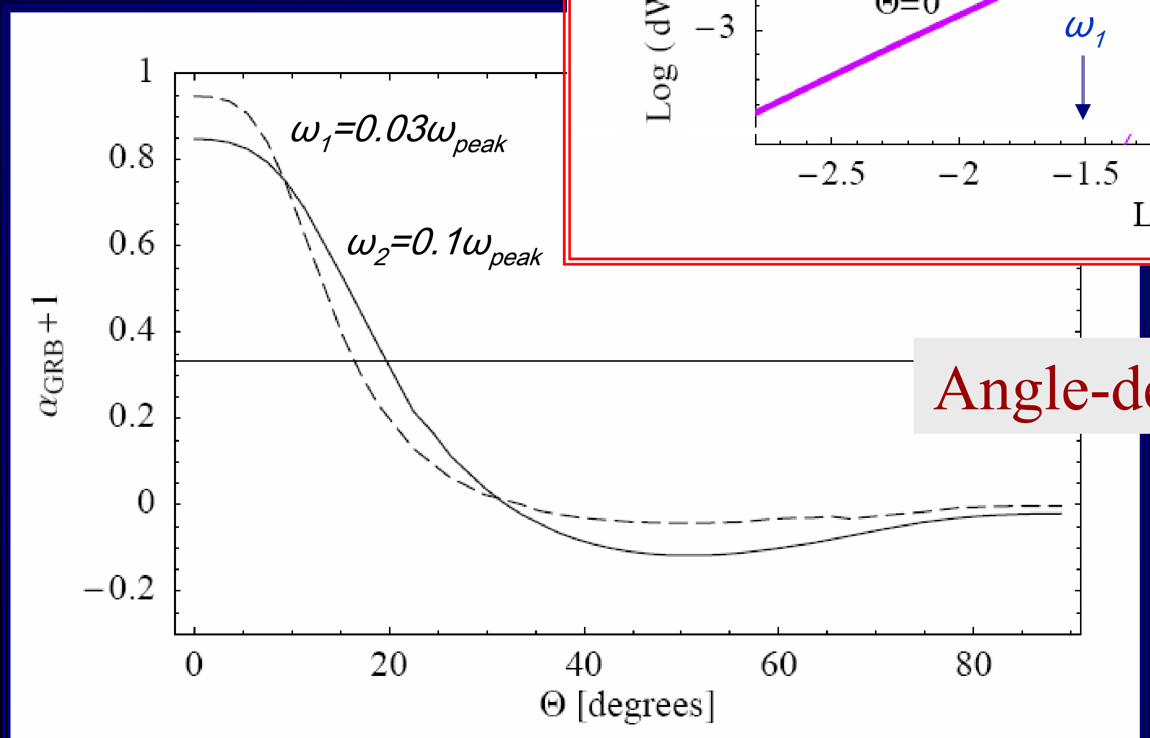
$\beta_2 \sim -3.3$

$\kappa_\perp \sim$ const. $(\omega_{p,e}/c)$

(Frederiksen, ApJL, 2004)

Spectrum vs. viewing angle

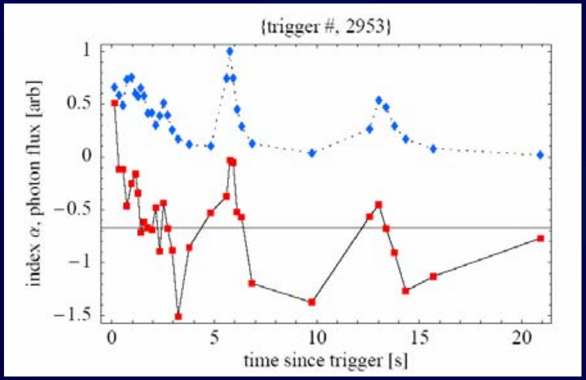


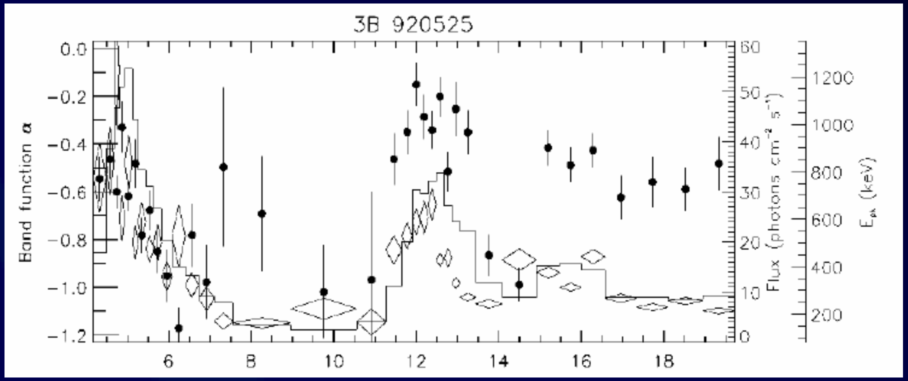


(Medvedev, ApJ, 2006)

“Tracking” GRBs

Also, “hardness – intensity” correlation ; *Also, “tracking behavior”*



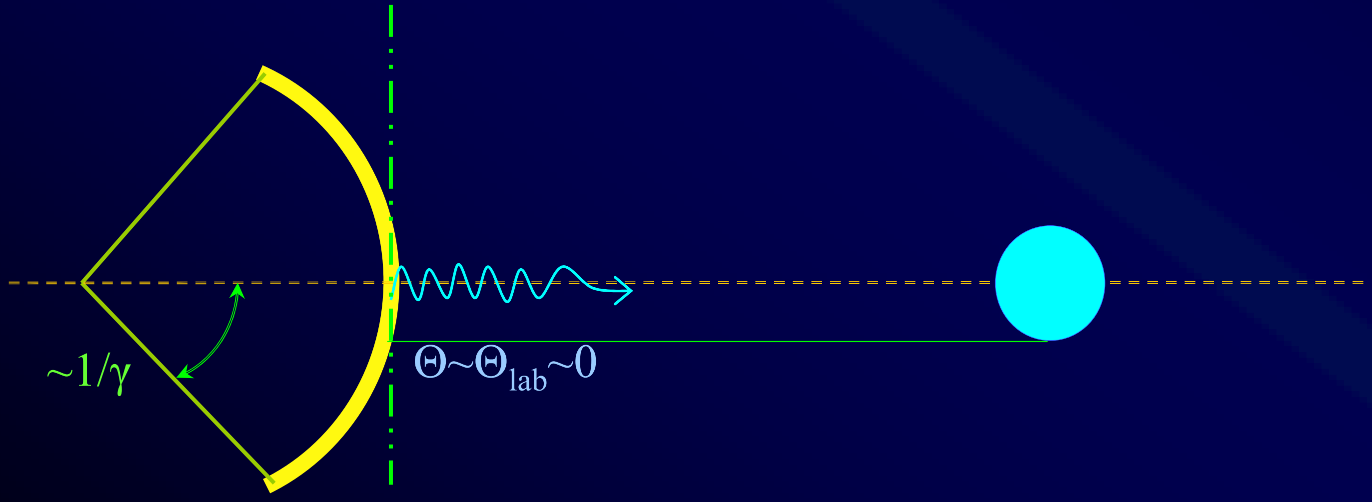


● = α

◊ = E_{peak}

— = Flux

t_1 , bright,
high E_{peak},
α~0



“Tracking” GRBs

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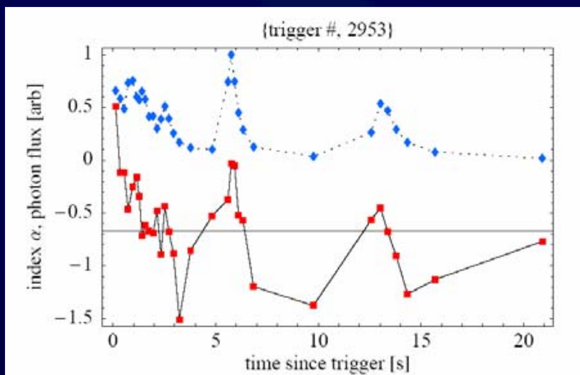
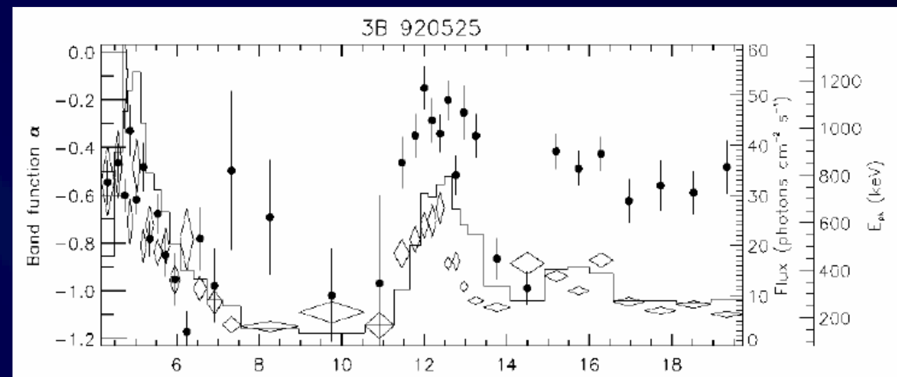
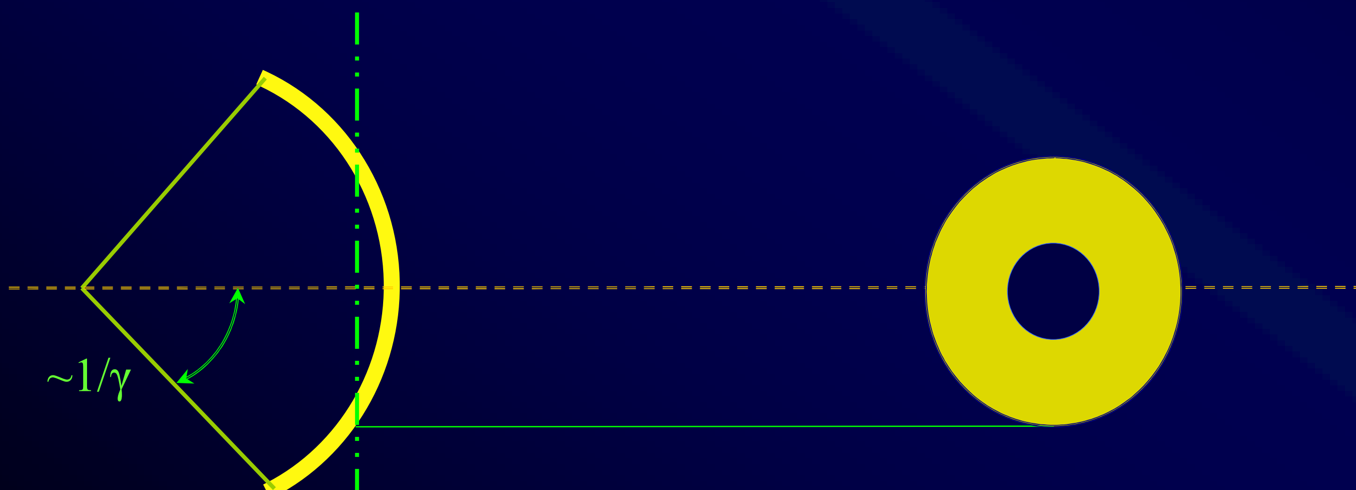




● = α

◊ = E_{peak}

— = Flux

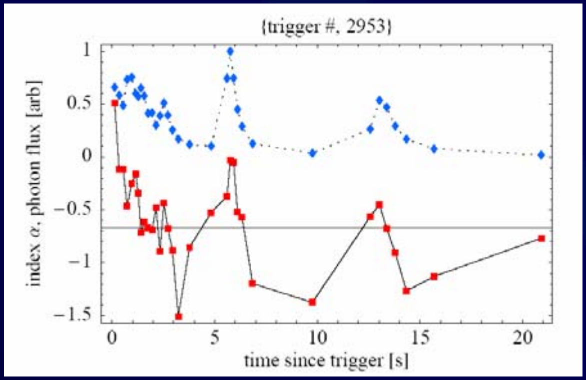


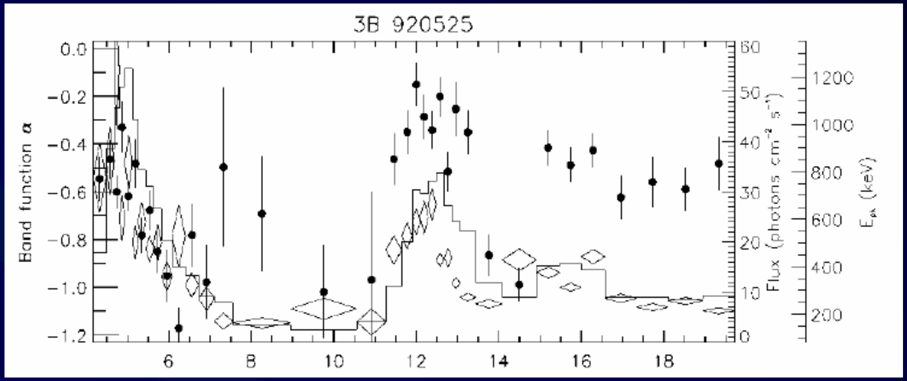
t_2 , intermediate

α~ -2/3

“Tracking” GRBs

Also, “hardness – intensity” correlation ; *Also, “tracking behavior”*

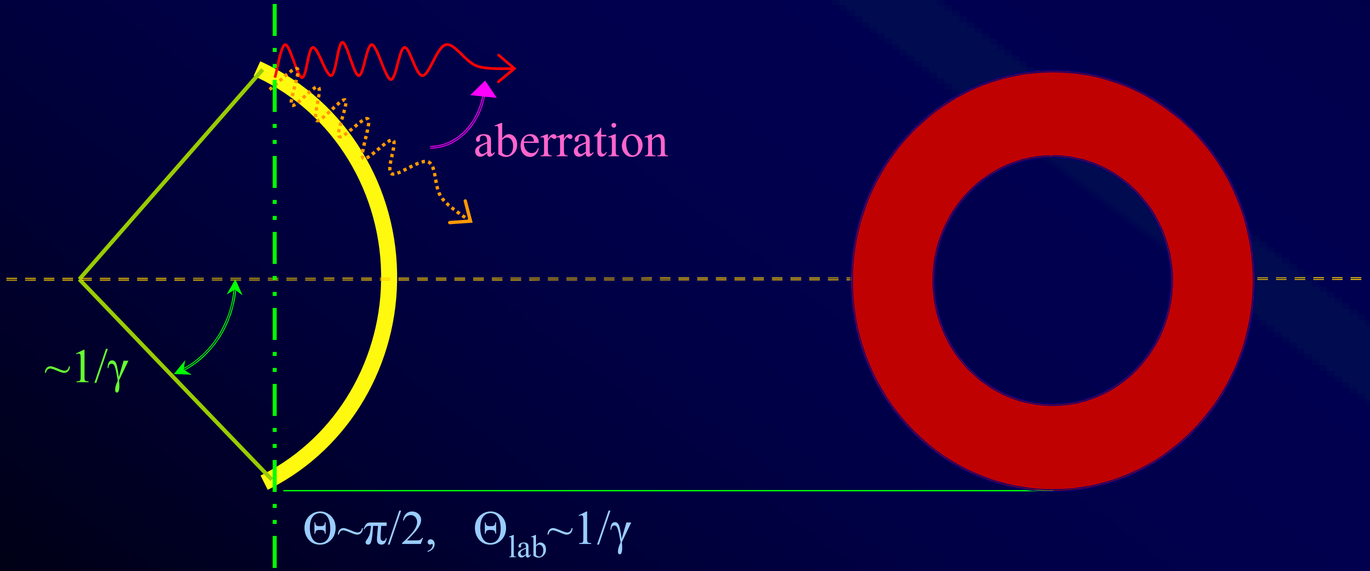




● = α

◊ = E_{peak}

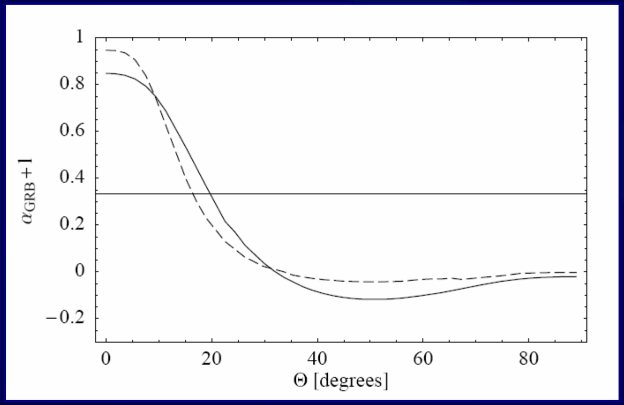
— = Flux



t_3 , faint,
low E_{peak},
α~ -1

Flux – α correlation

Also, "hardness – intensity" correlation ;   Also, "tracking behavior"



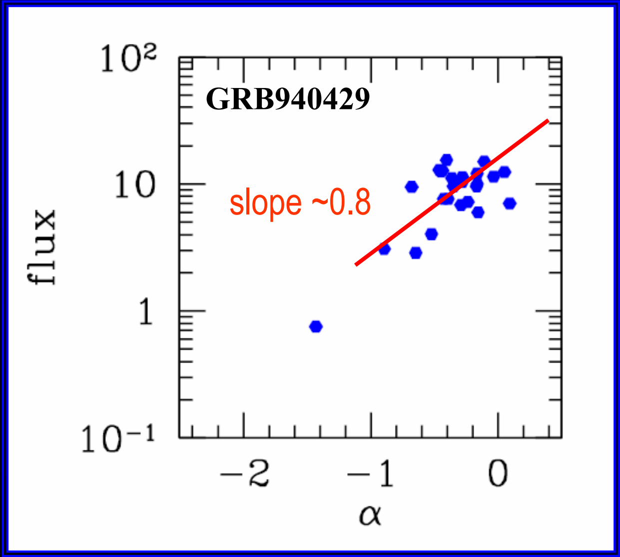
index α depends on Θ

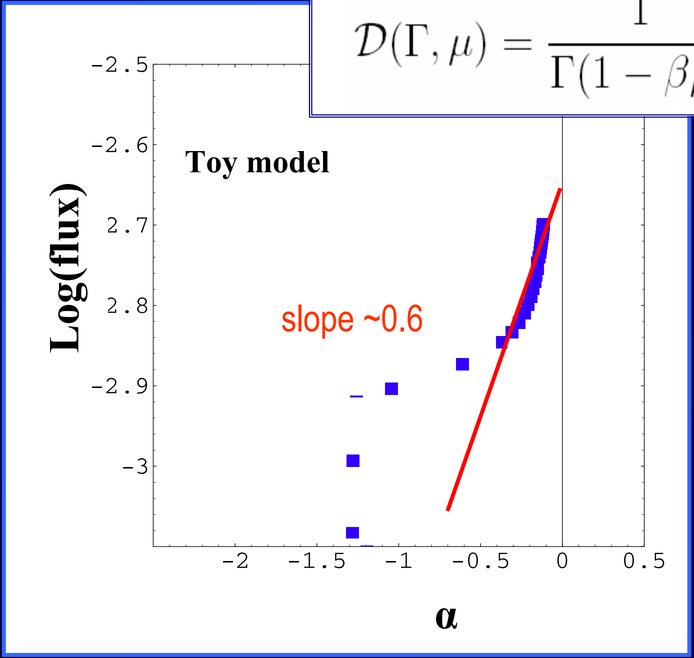
bolometric flux depends on Θ

$$F_{\rm bol}(t) = F_0 \mu \mathcal{D}^2(\mu)/\Gamma^2,$$

where the Lorentz boost is Θ-dependent

$$\mathcal{D}(\Gamma,\mu) = \frac{1}{\Gamma(1-\beta\mu)} \qquad \mu = \cos\theta$$

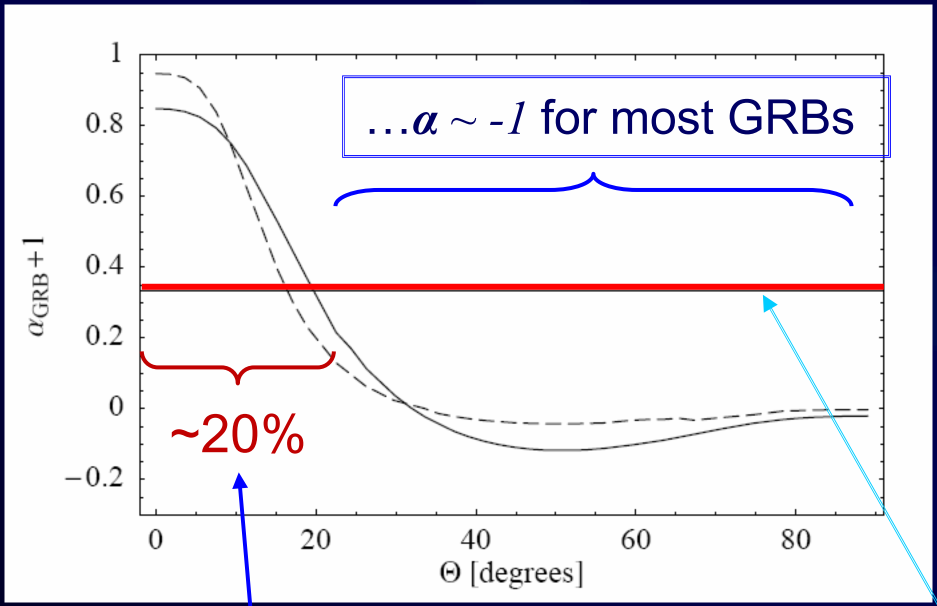


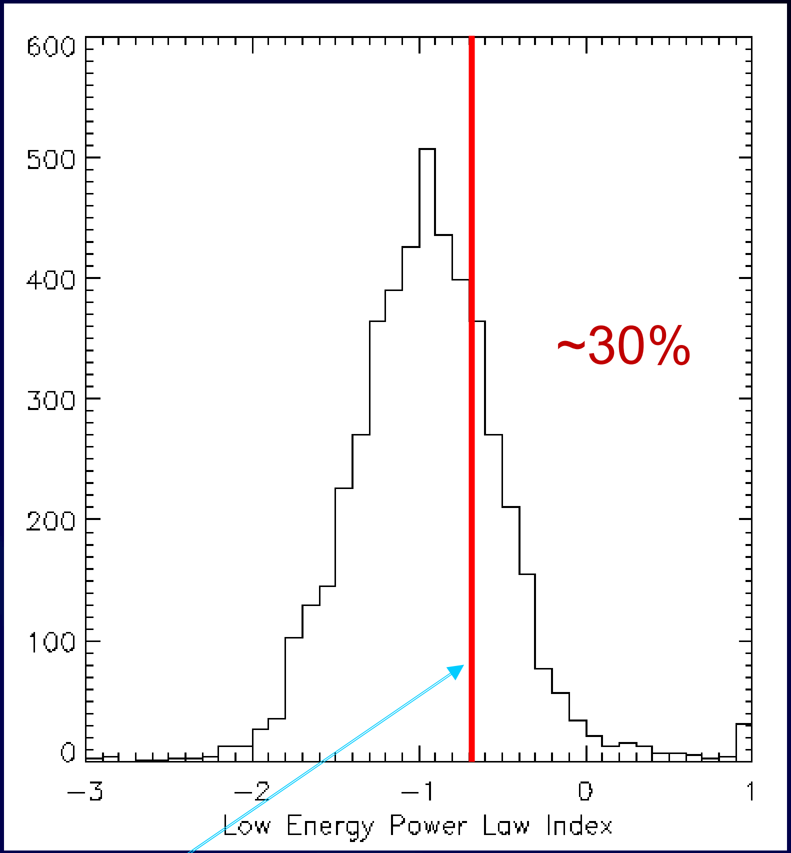


(Medvedev, ApJ, 2006)

Statistics of α

index α depends on Θ





…of GRB spectra violate SLoD

Synchrotron "Line of Death"

(Medvedev, ApJ, 2006)

(Preece, et al. 2000, ApJS)

Summary

- shock theory & simulations:
  - magnetic field generation
  - shock formation and evolution
  - e^+e^- and e^-p plasmas
  - particle acceleration (*heating*)
  - long-term evolution of the fields
- radiation production
  - jitter radiation
  - violation of the Synchrotron LoD
  - sharp spectral peaks
  - *flux*-α correlation (*hardness-intensity* correlation)
  - peak of α distribution at $\alpha \sim -1$
  - spectral variability (+ *"tracking"* behavior)
  - net polarization
  - polarization scintillations