Radiation processes in relativistic shocks

bonus: CRs + B-fields in a Foreshock

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Simulations:
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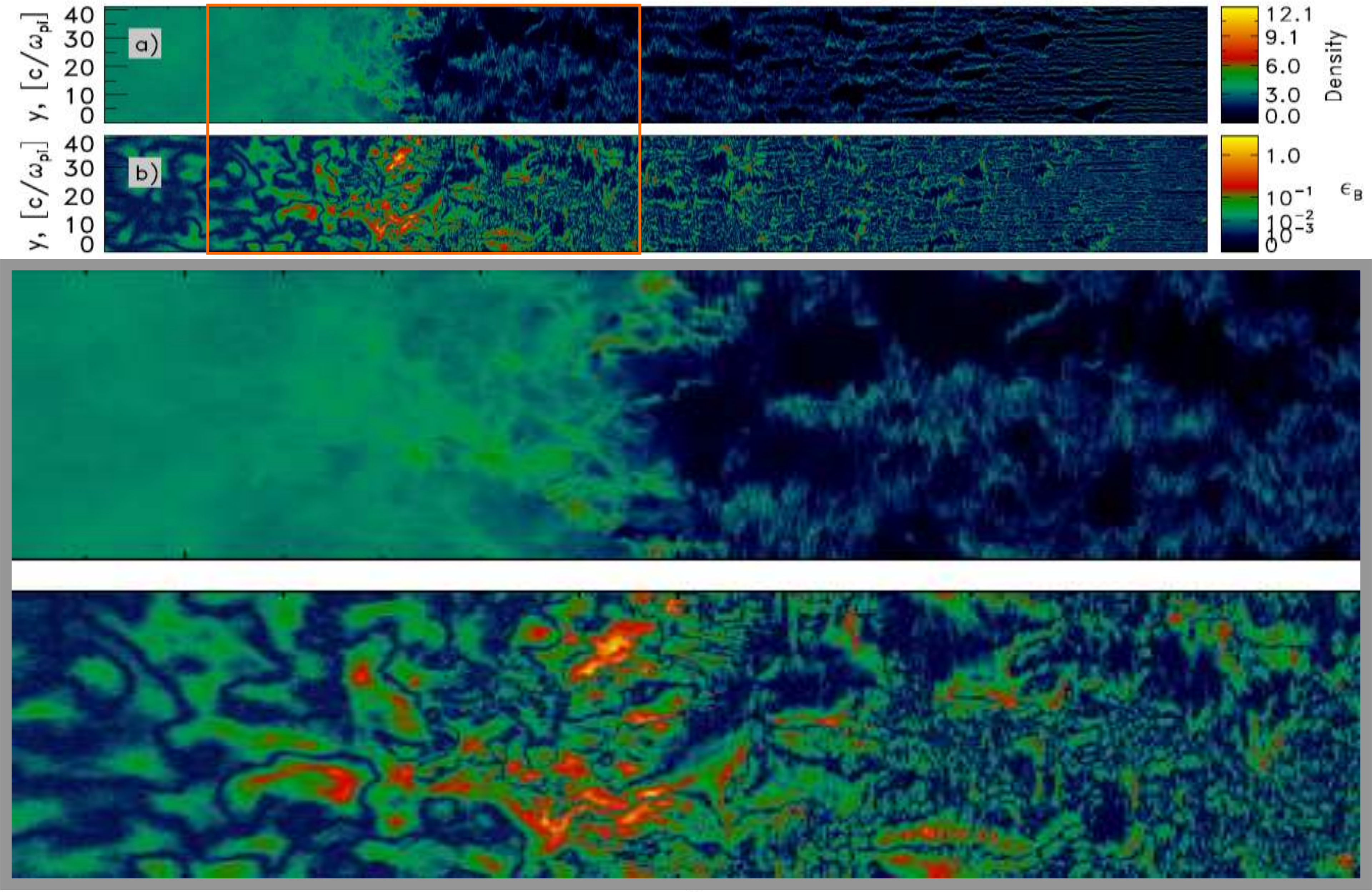
Anatoly Spitkovsky (Princeton)
Luis Silva and the Plasma Simulation Group (Portugal)
Aake Nordlund and his group (Niels Bohr Institute, Copenhagen, Denmark)

Theory:
Davide Lazatti and his group at U.Colorado Boulder

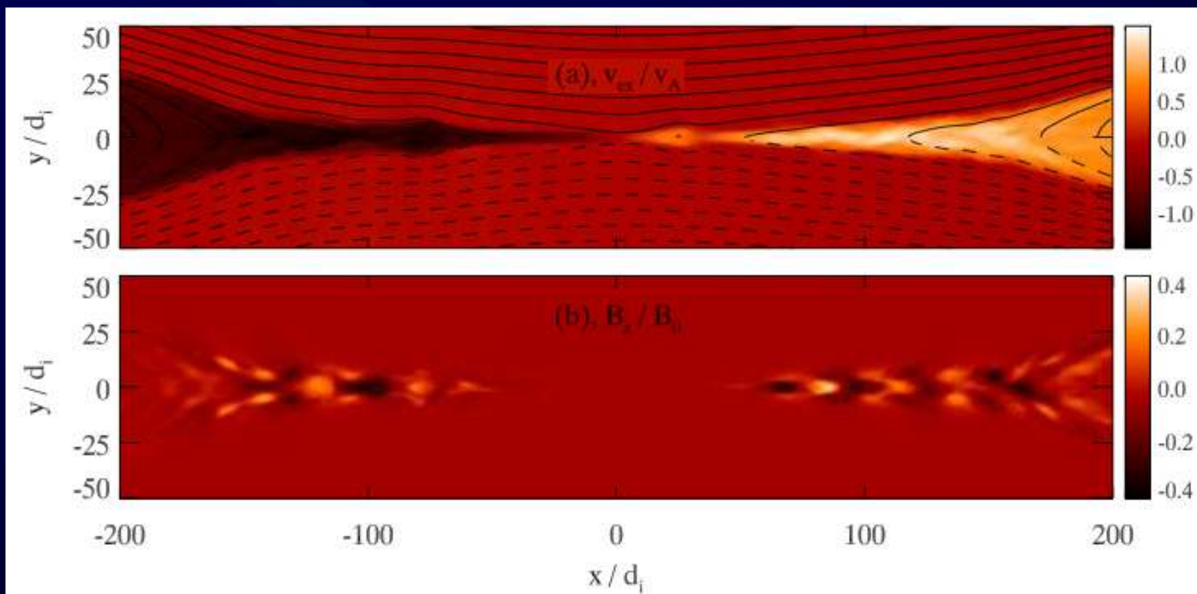
Motivation: ubiquitous Weibel – sub-Larmor-scale fields

Weibel shock: 2D PIC $e^{-}p$, $\Gamma=15$



Magnetized outflow: reconnection

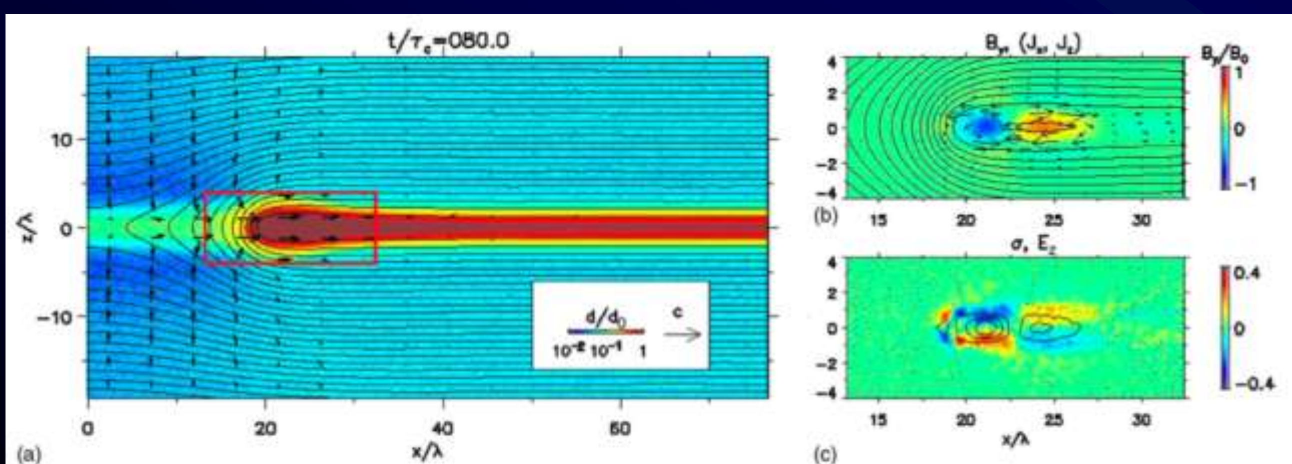
Small-scale field generation (Weibel instability) at a reconnection site



…see talks at this conference

Non-relativistic electron-positron pair plasma

(Swisdak, Liu, J. Drake, ApJ, 2008)

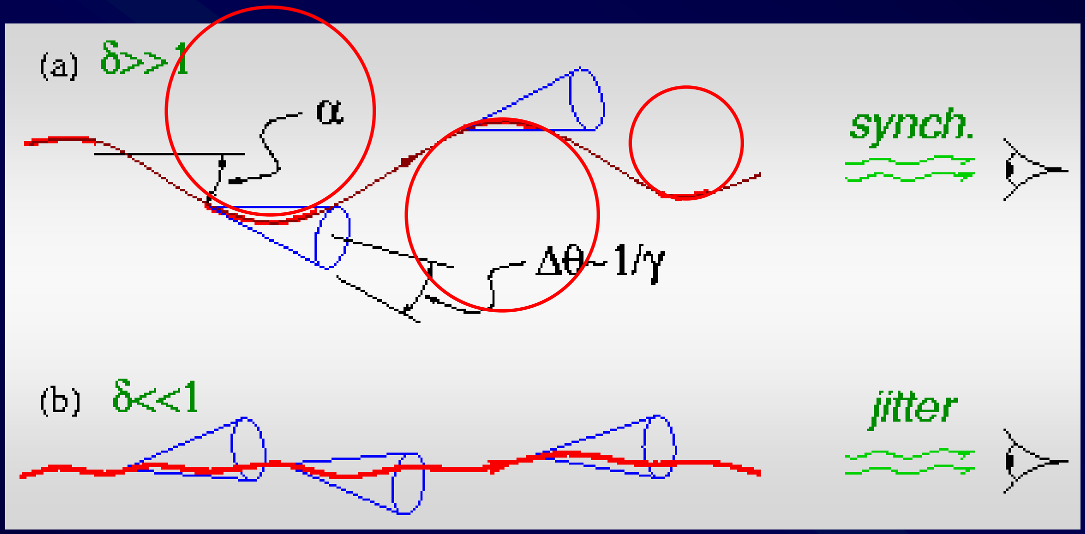


Relativistic electron-positron pair plasma

(Zenitani & Hesse, PoP, 2008)

Jitter radiation

Radiation in random fields



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

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

Deflection parameter:

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

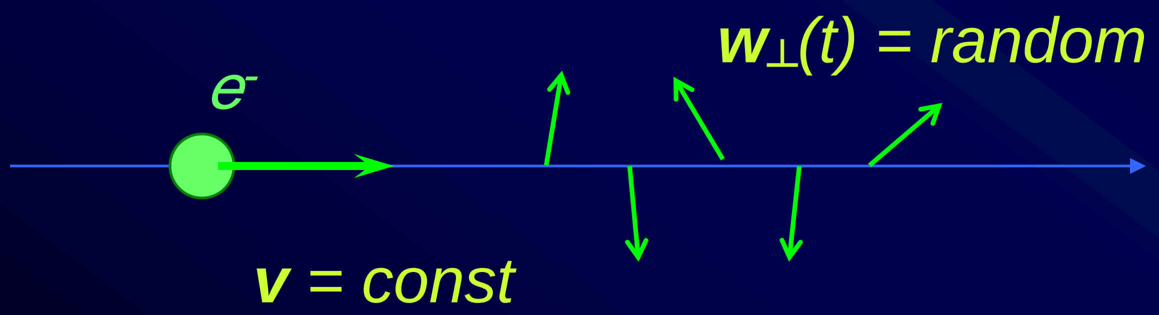
… independent of γ

(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 $\mathbf{r}(t) = \mathbf{r}_0 + \mathbf{c}\, t$
- particle experiences random acceleration $\mathbf{w}_\perp(t)$



(Medvedev, ApJ, 2000; 2006)

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 $\theta \sim 1/\gamma$

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

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

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

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

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

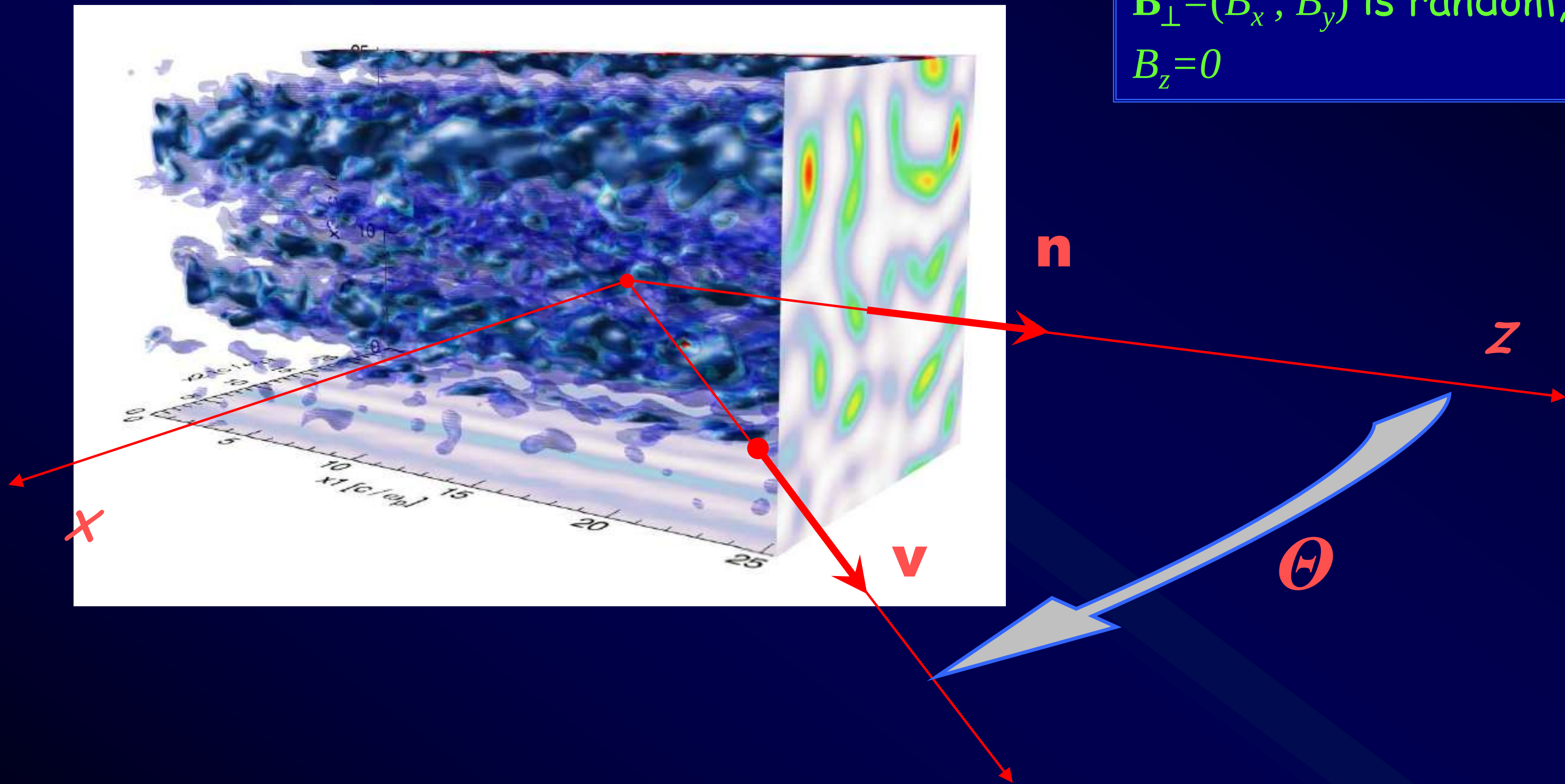
$$\overline{B^\alpha_{\Omega,\mathbf{k}} B^{*\beta}_{\Omega,\mathbf{k}}} = C(\delta_{\alpha\beta} - n_\alpha n_\beta) f_z(k_{||}) f_{xy}(k_\perp),$$

B-field spectrum

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

Radiation vs Θ

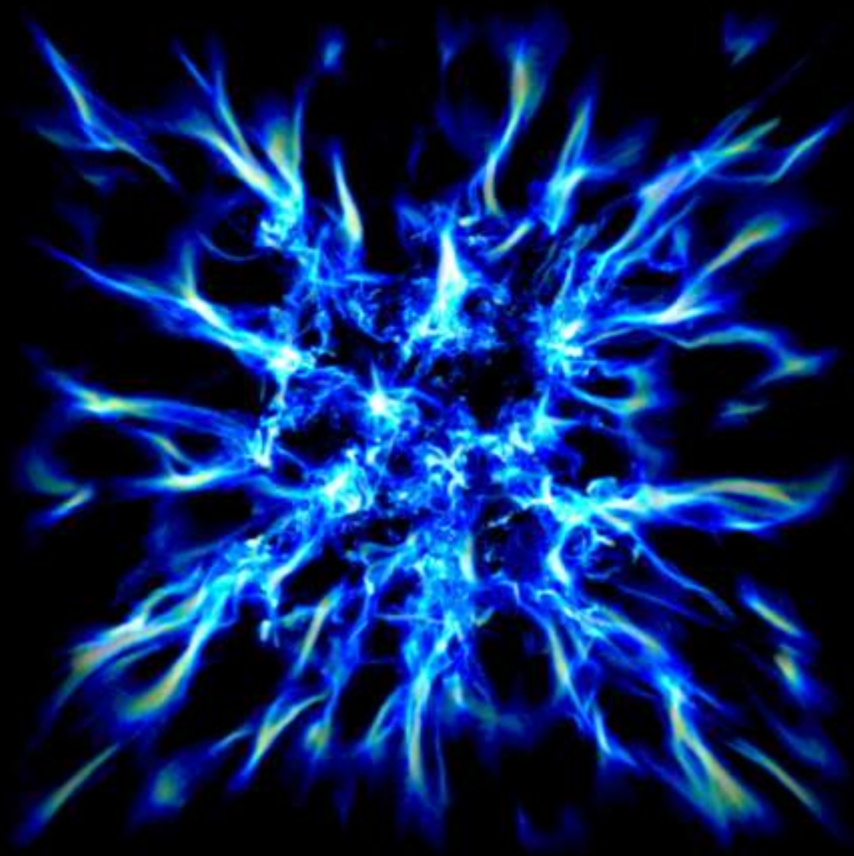
B-field is anisotropic:
$\mathbf{B}_\perp=(B_x , B_y)$ is random,
$B_z=0$



observer

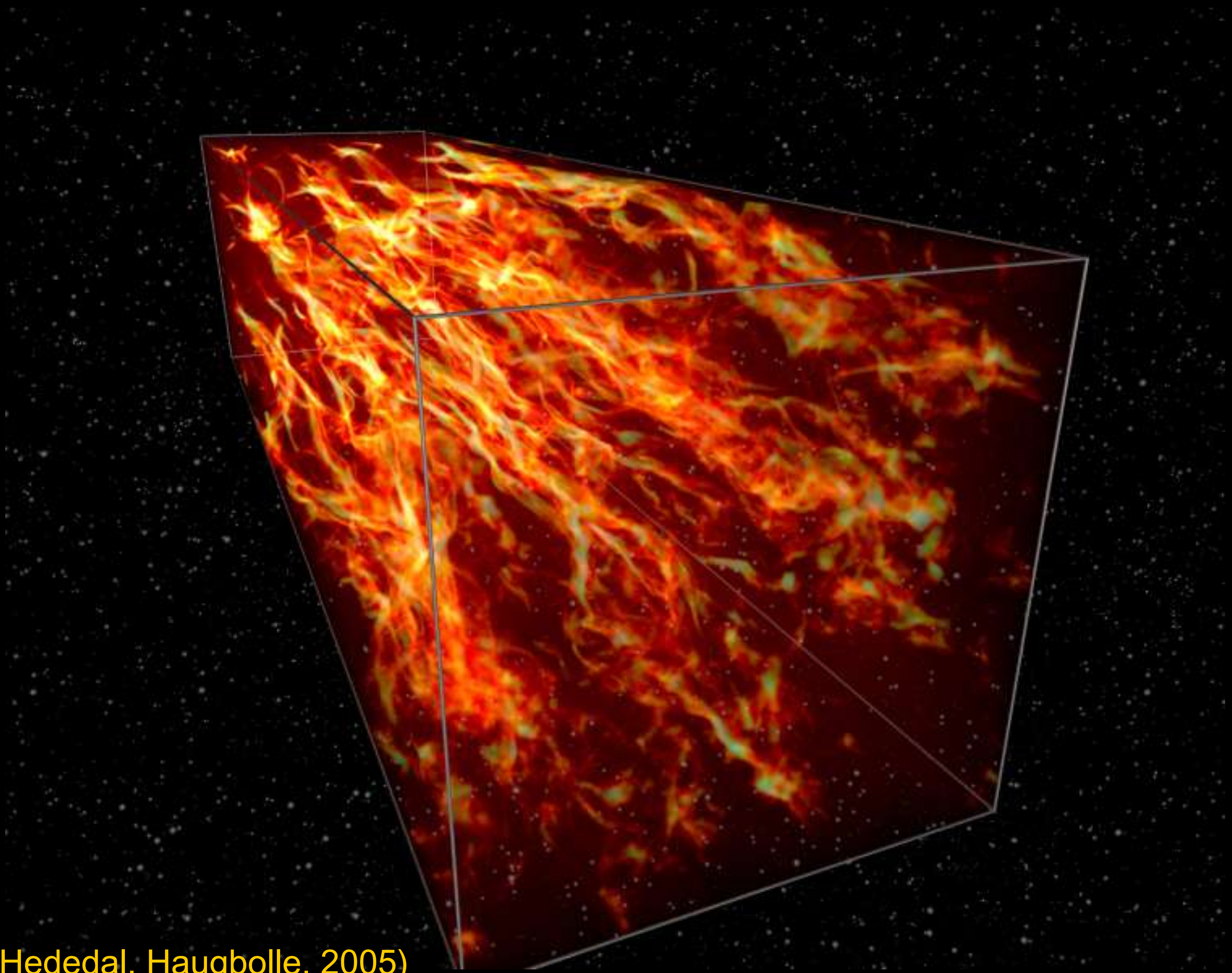
(Medvedev, Silva, Kamionkowski 2006; Medvedev 2006)

Face-on view



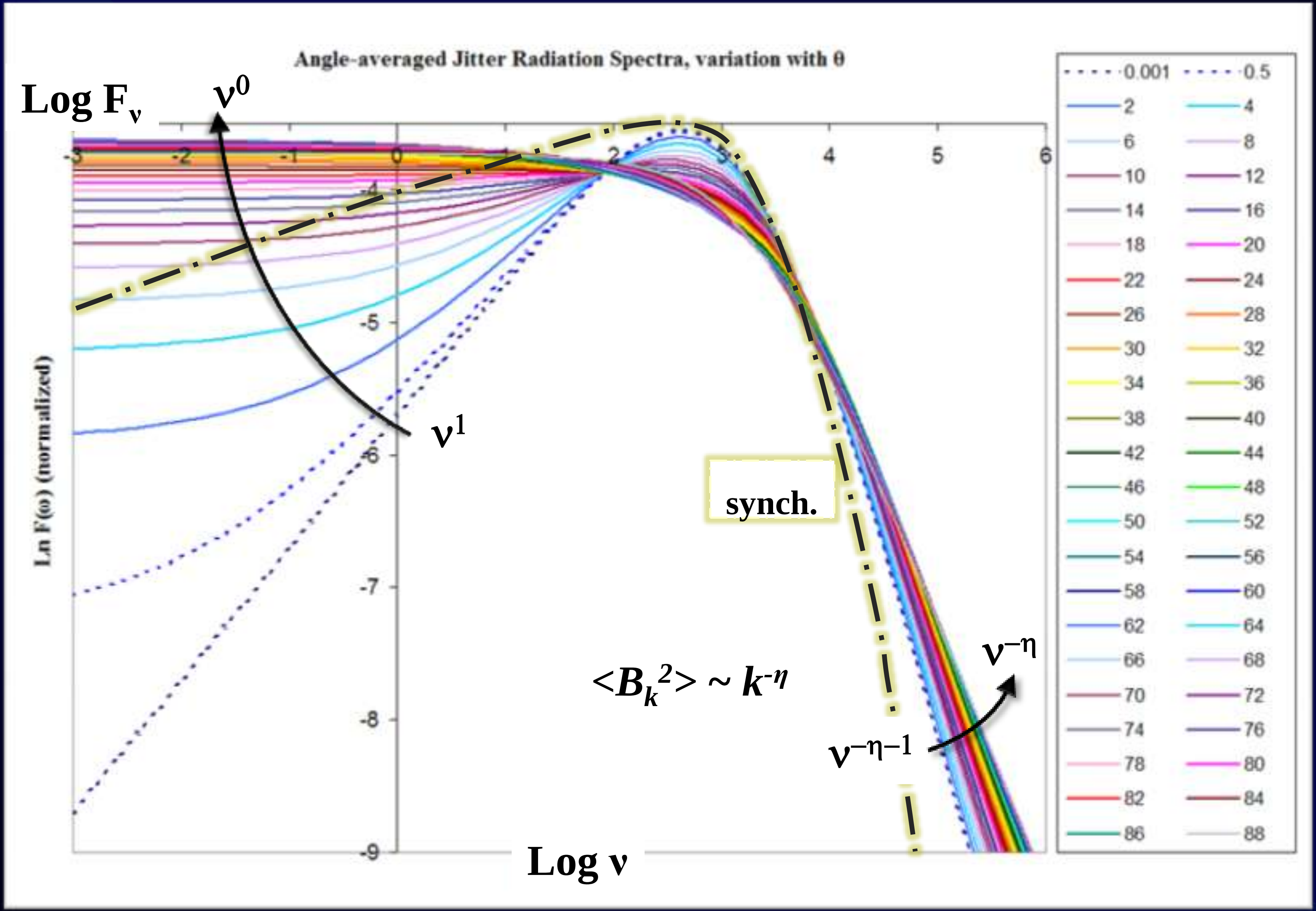
(credit: Hededal, Haugbolle, 2005)

Oblique view



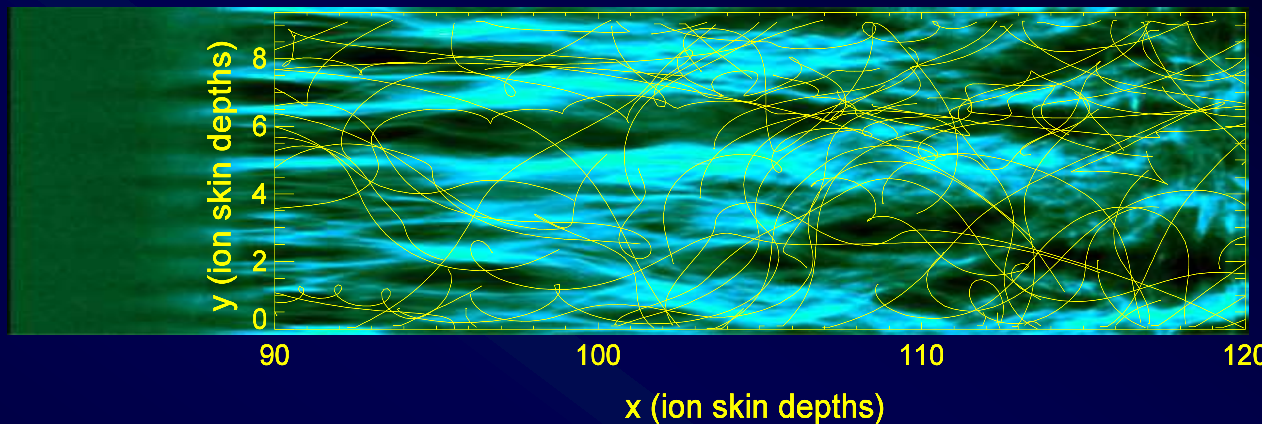
(credit: Hededal, Haugbolle, 2005)

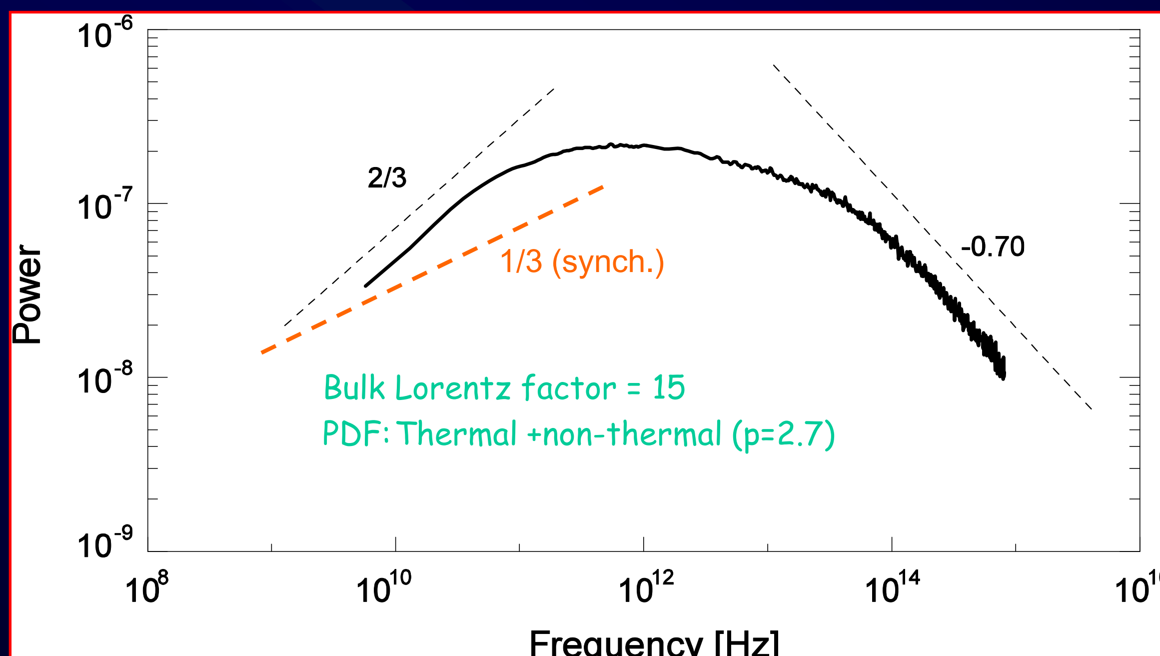
Spectra vs. viewing angle



(Medvedev 2006; S. Reynolds, S. Pothapragada, Medvedev, in prep.)

Jitter spectra from 3D PIC

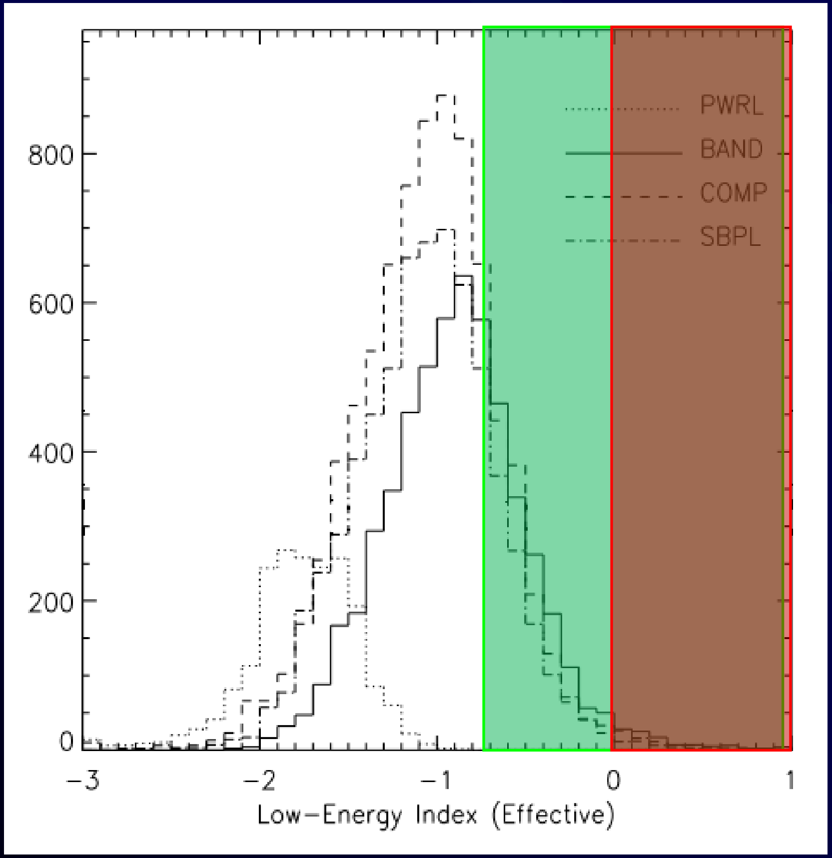




(Hededal, PhD thesis 2005)

Synchrotron "Line of Death"

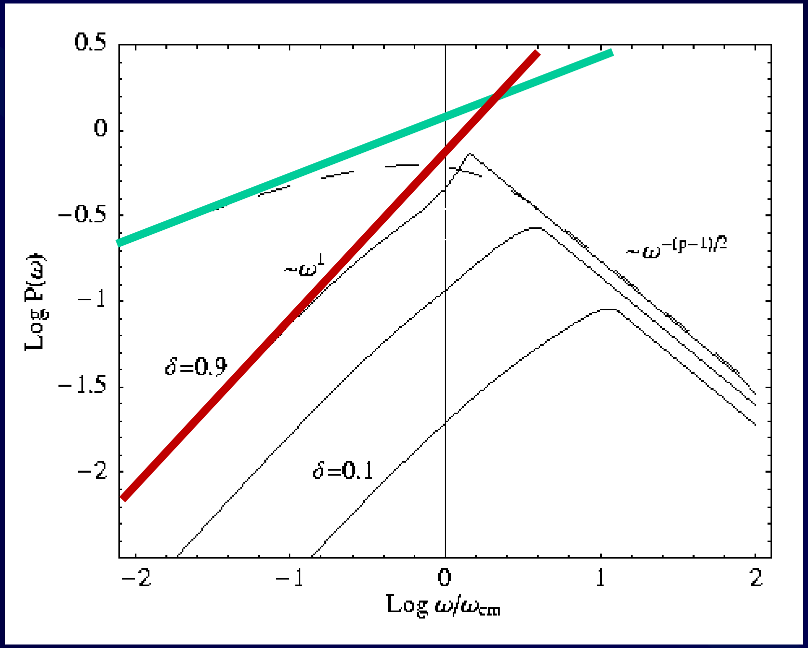
Statistics is large:
About 30% of over 2700 GRBs *violate* synchrotron limit at low energies



(Kaneko, et al, ApJS, 2006)

$P(\omega) \sim \omega^{\alpha+1}$

(Medvedev, 2000)



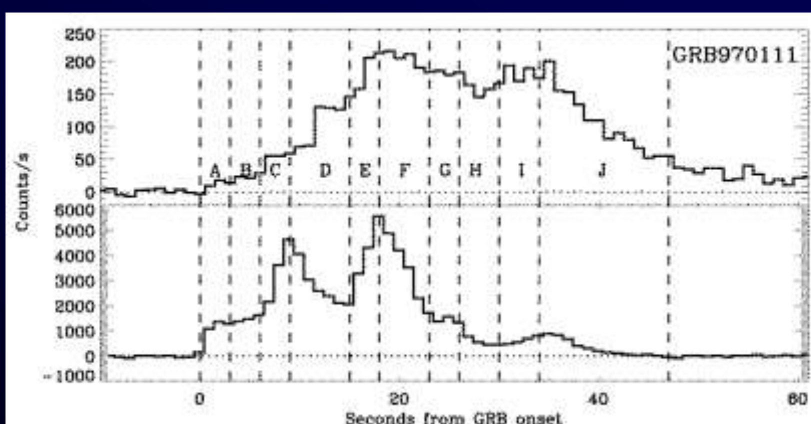
Non-synchrotron GRB spectra

Some GRBs *cannot* be synchrotron

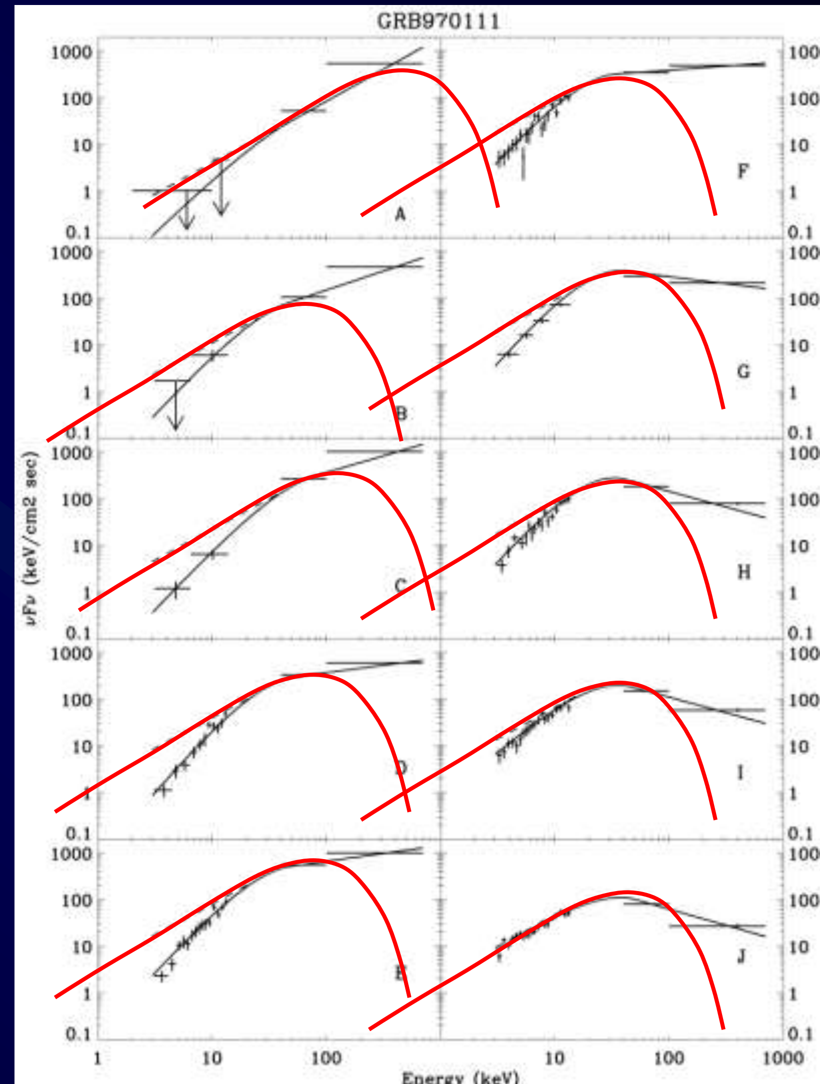
GRB 970111

soft photon index *violates*

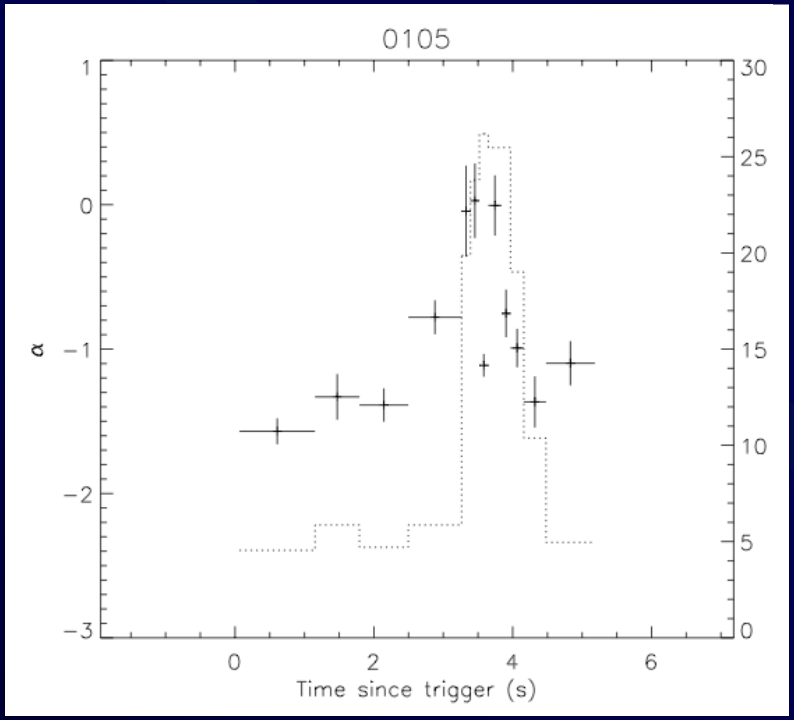
synchrotron limit for the entire burst

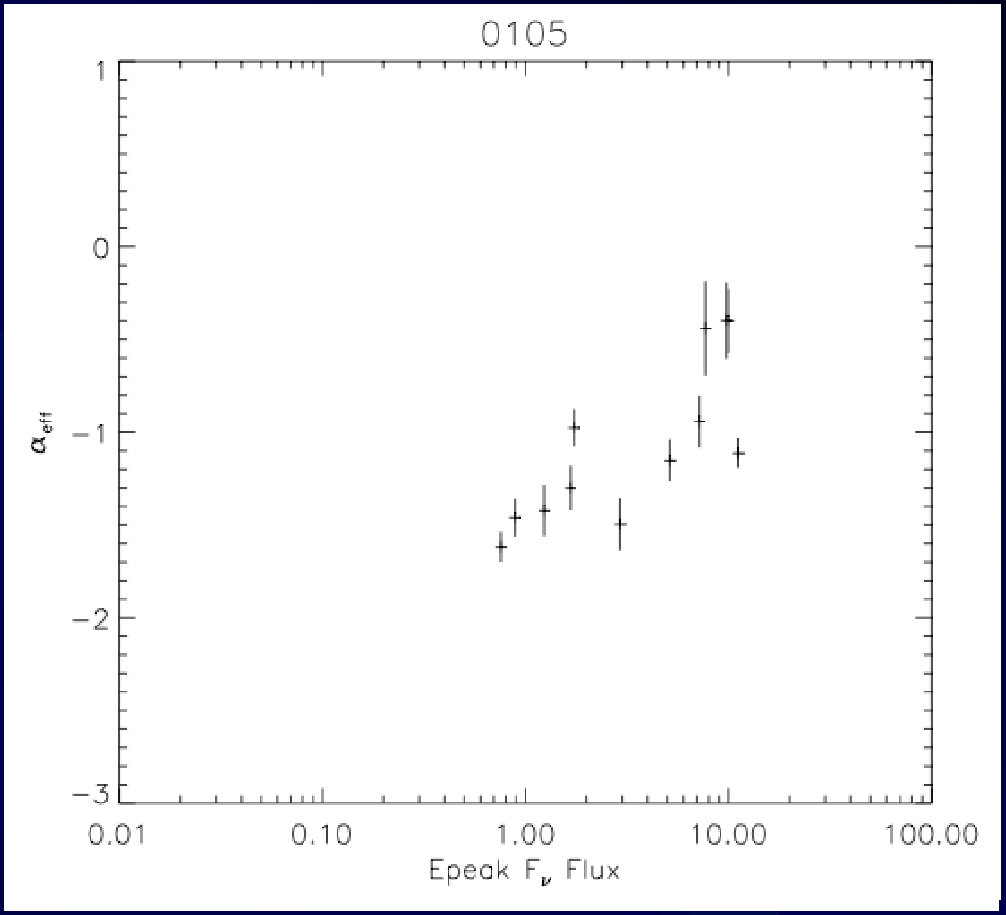


(Beppo-SAX observatory: Frontera, et al., ApJ, 2000)



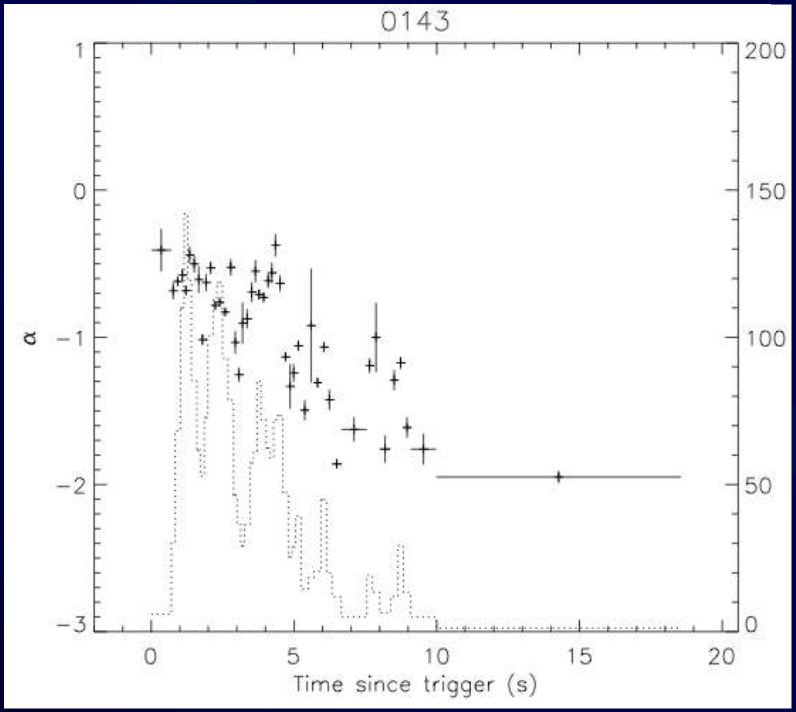
Multi-peak prompt GRB

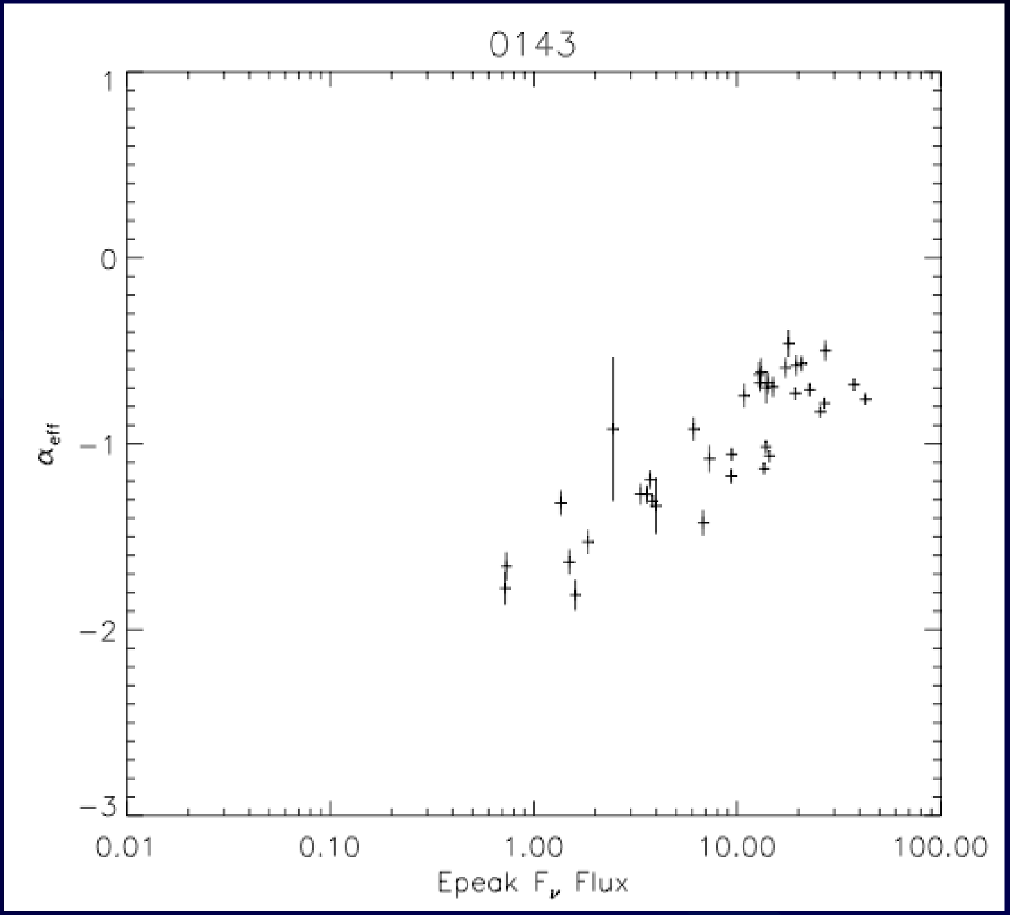




(Kaneko, et al. ApJS 2006; PhD thesis)

Multi-peak prompt GRB





(Kaneko, et al. ApJS 2006; PhD thesis)

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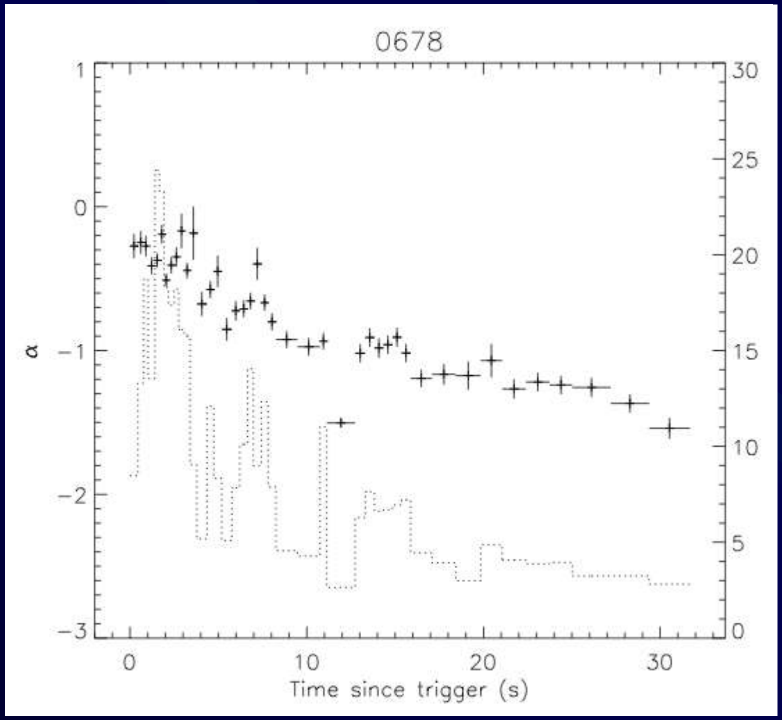

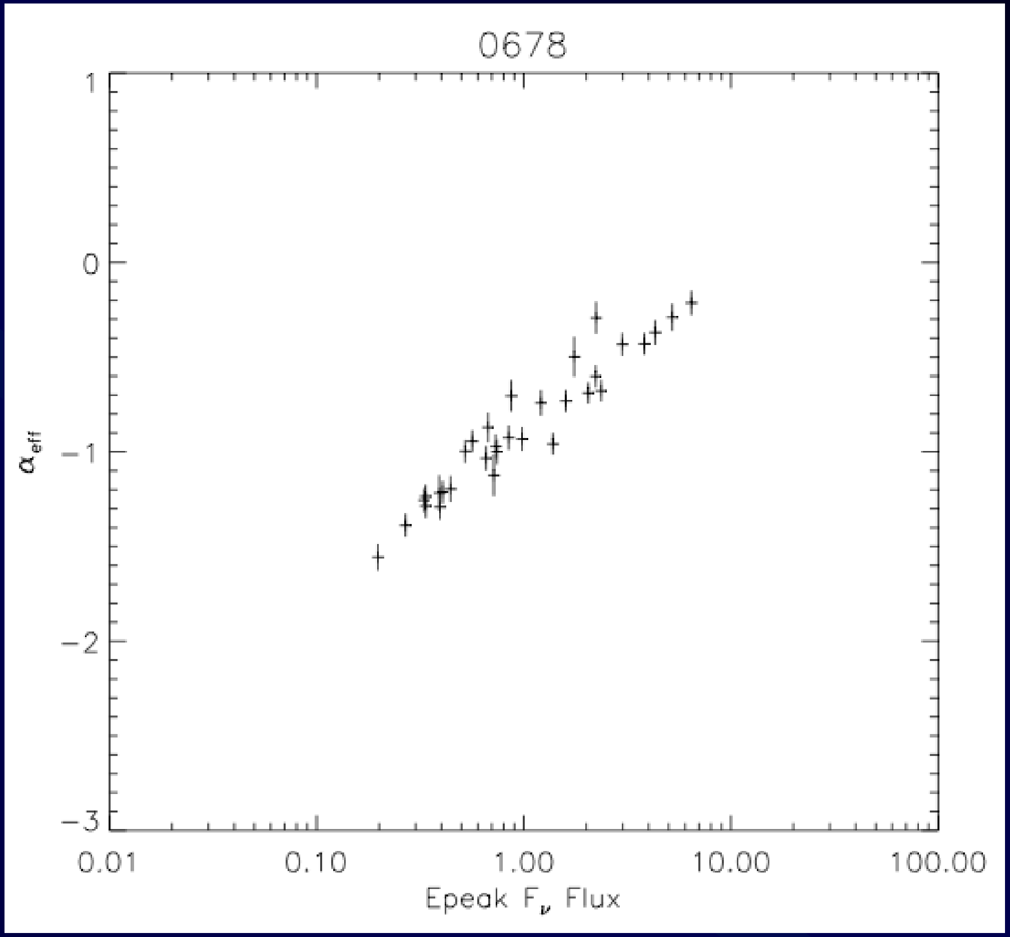

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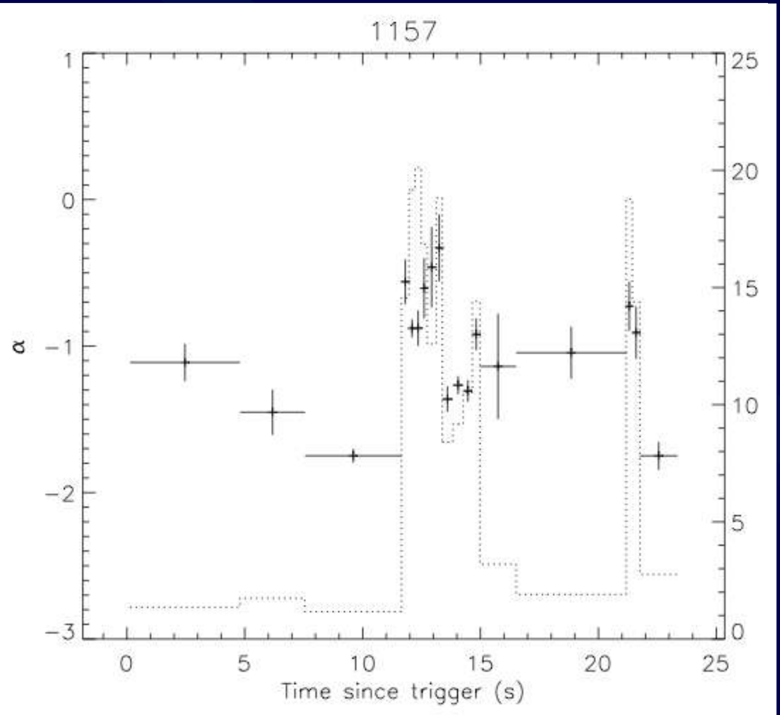
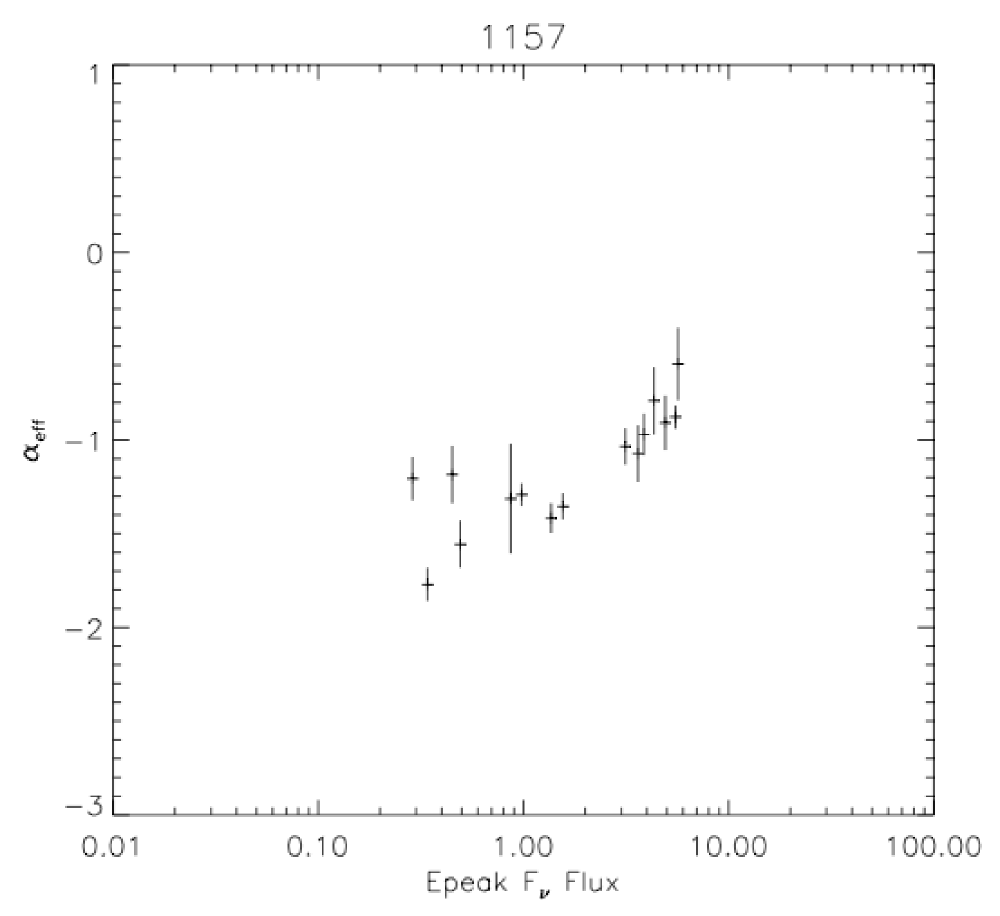
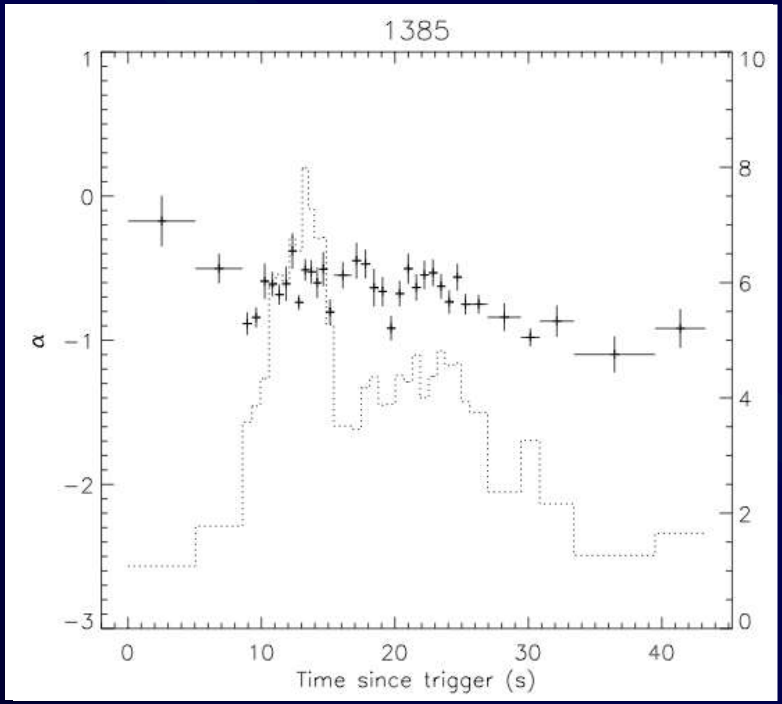
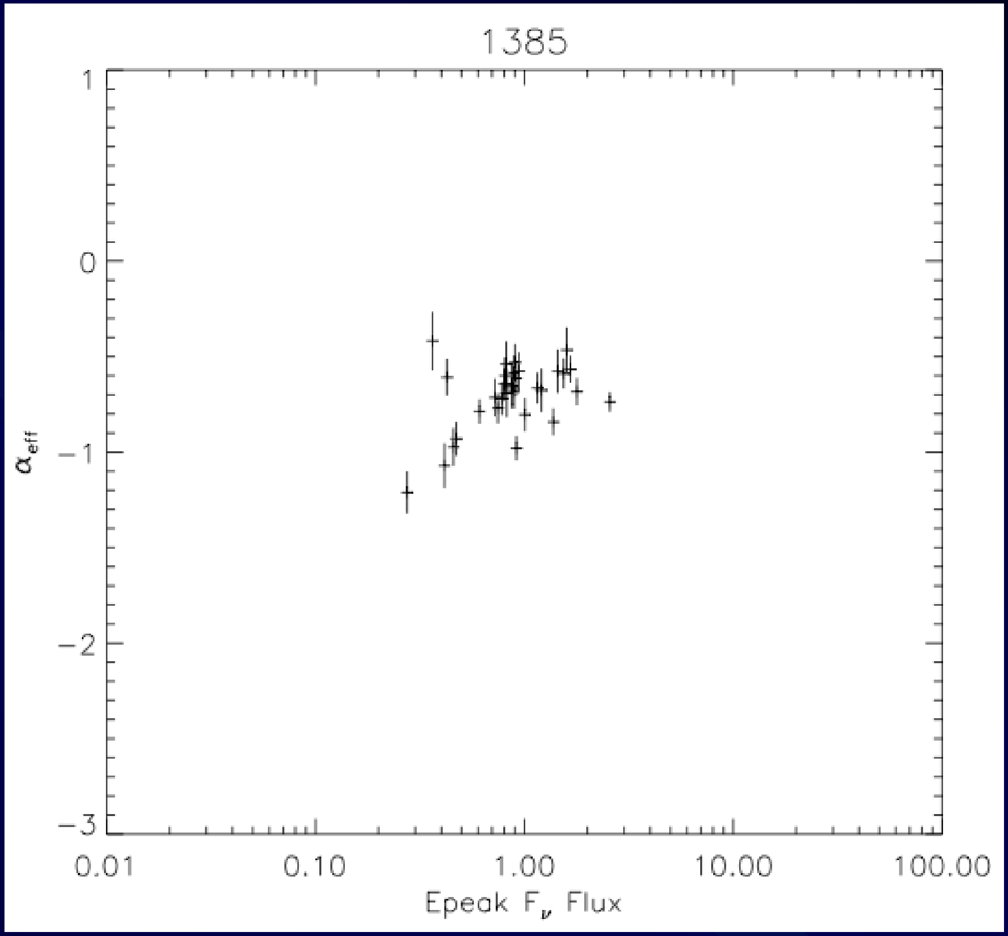




(Kaneko, et al. ApJS 2006; PhD thesis)

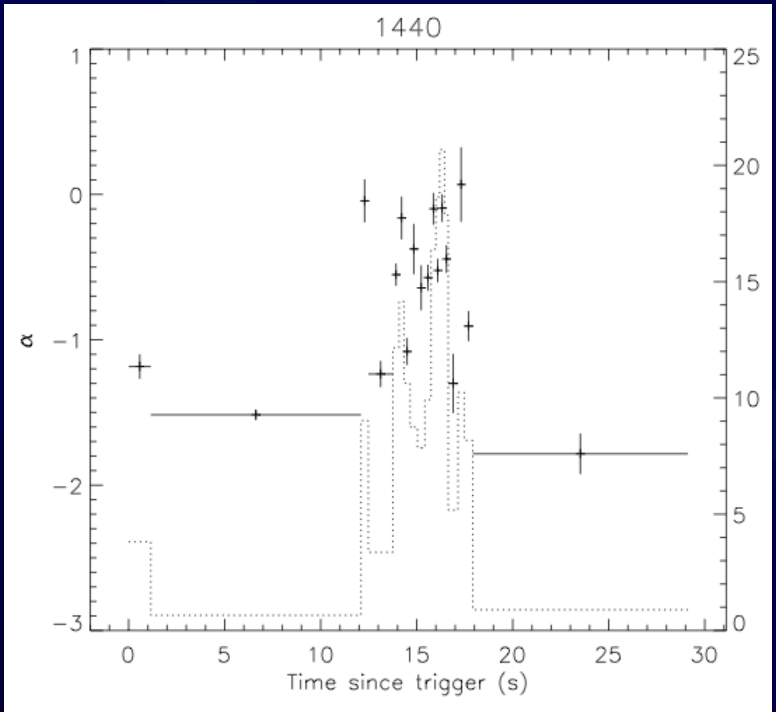
Multi-peak prompt GRB

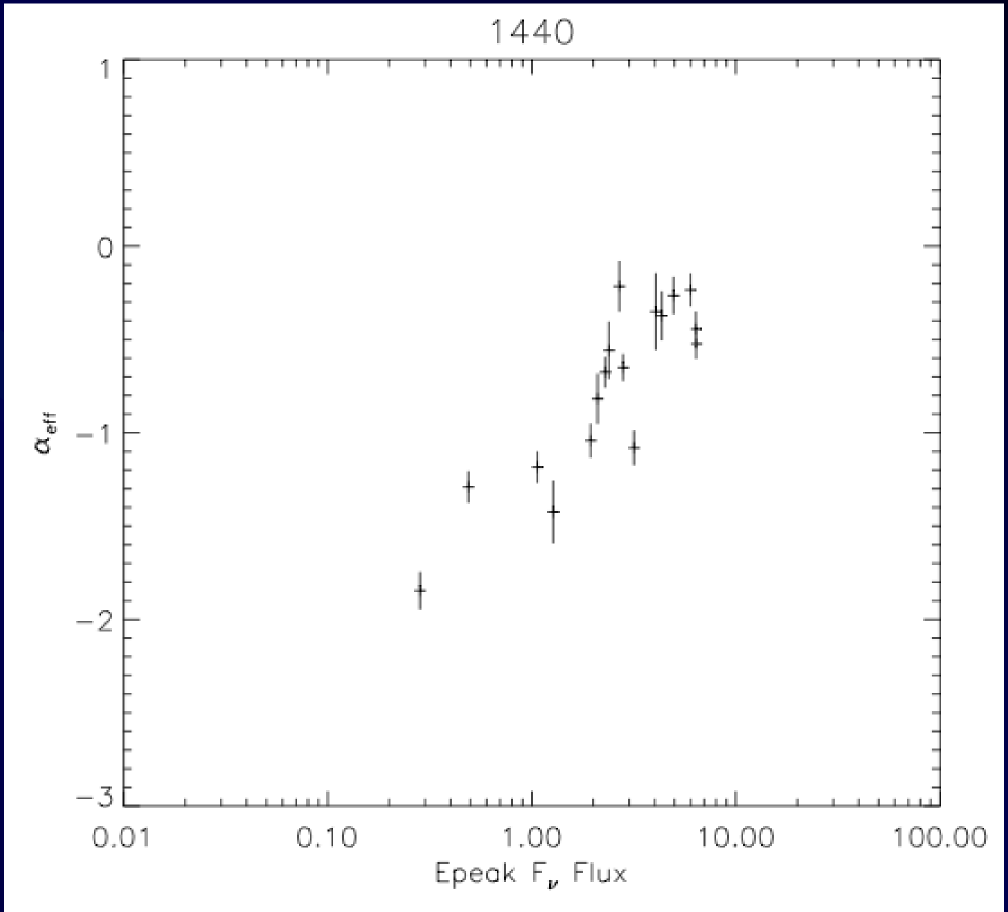




(Kaneko, et al. ApJS 2006; PhD thesis)

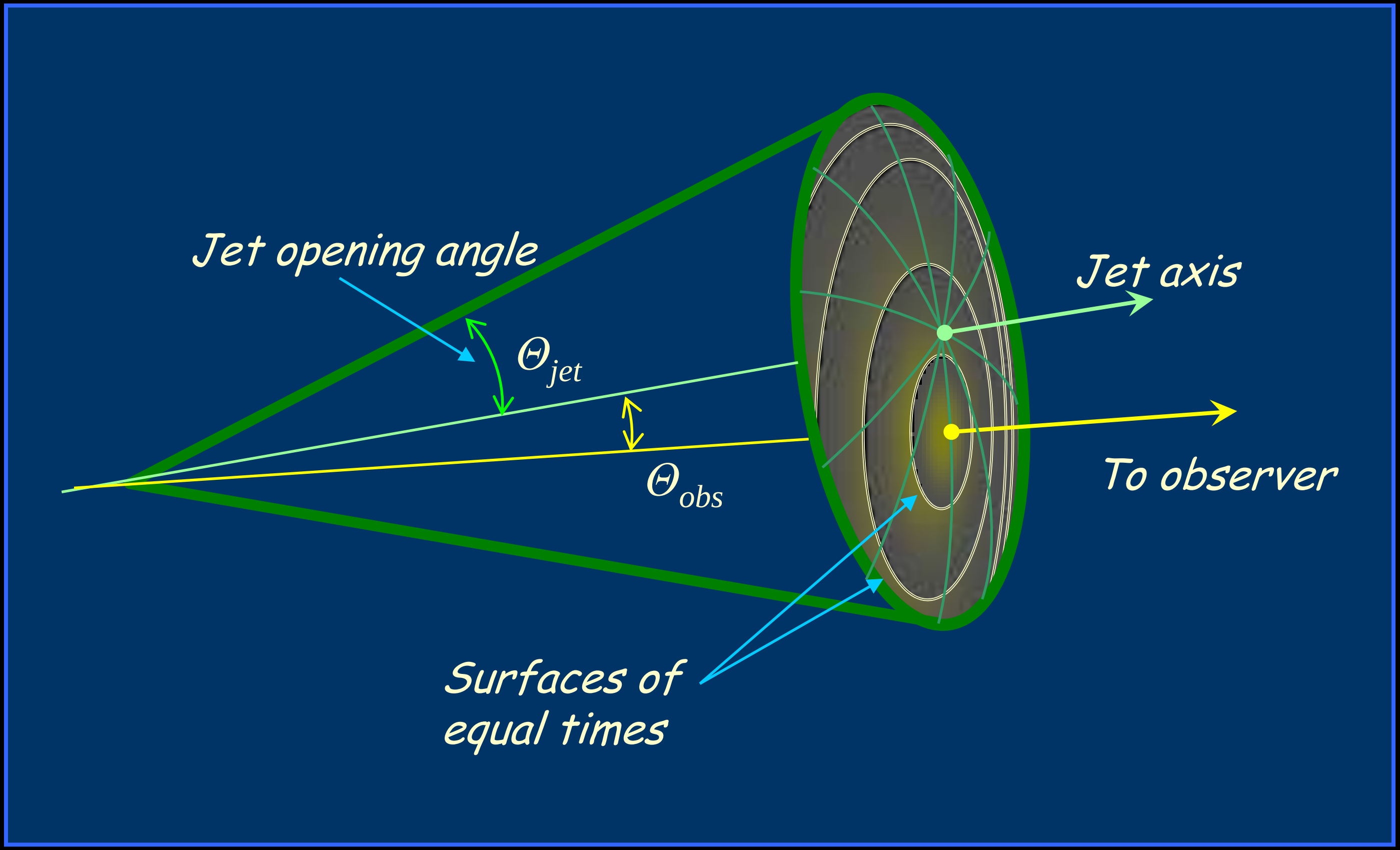
Multi-peak prompt GRB





(Kaneko, et al. ApJS 2006; PhD thesis)

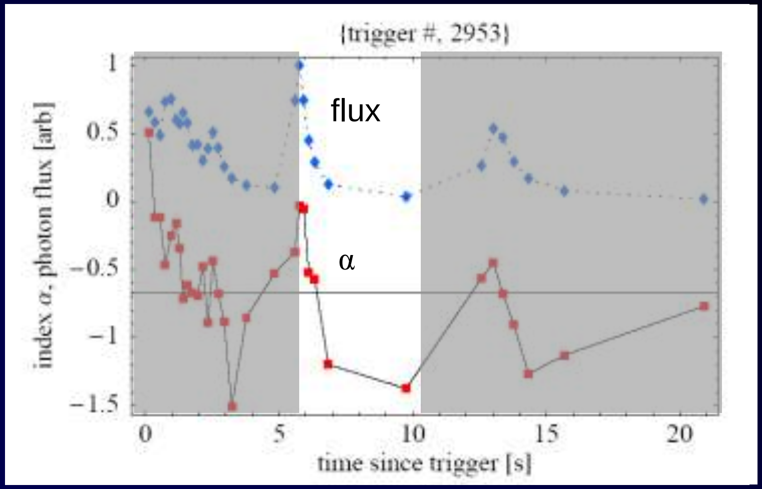
Jet viewing angle effect

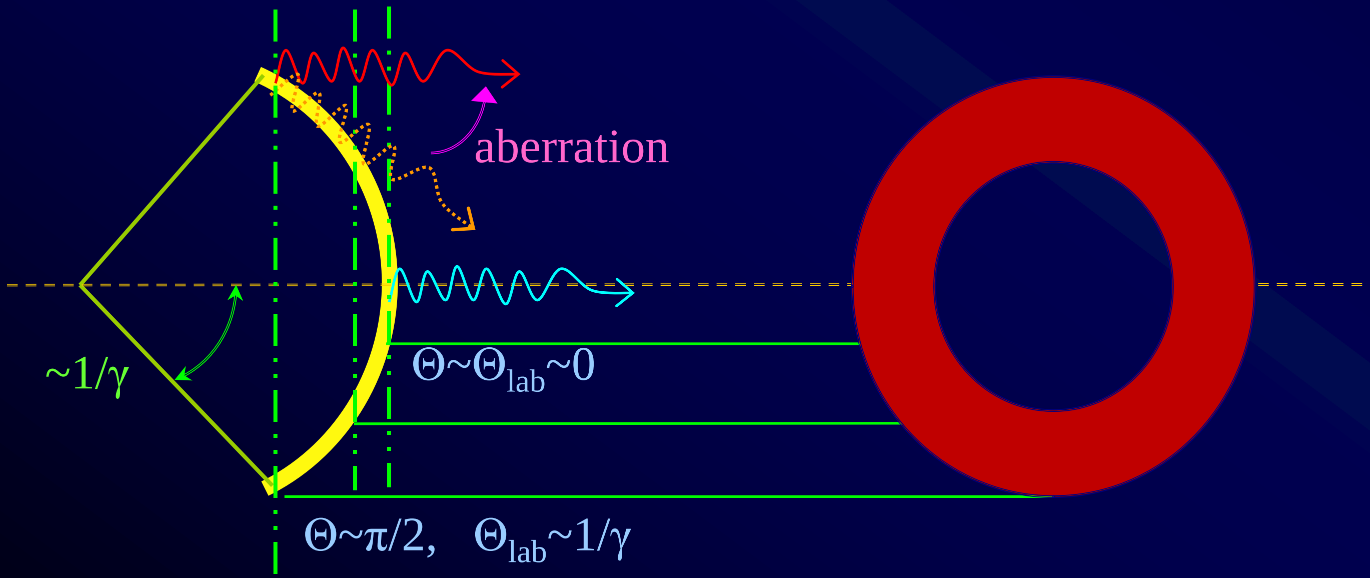


"Tracking" GRBs

Also, "hardness – intensity" correlation ;

Also, "tracking behavior"



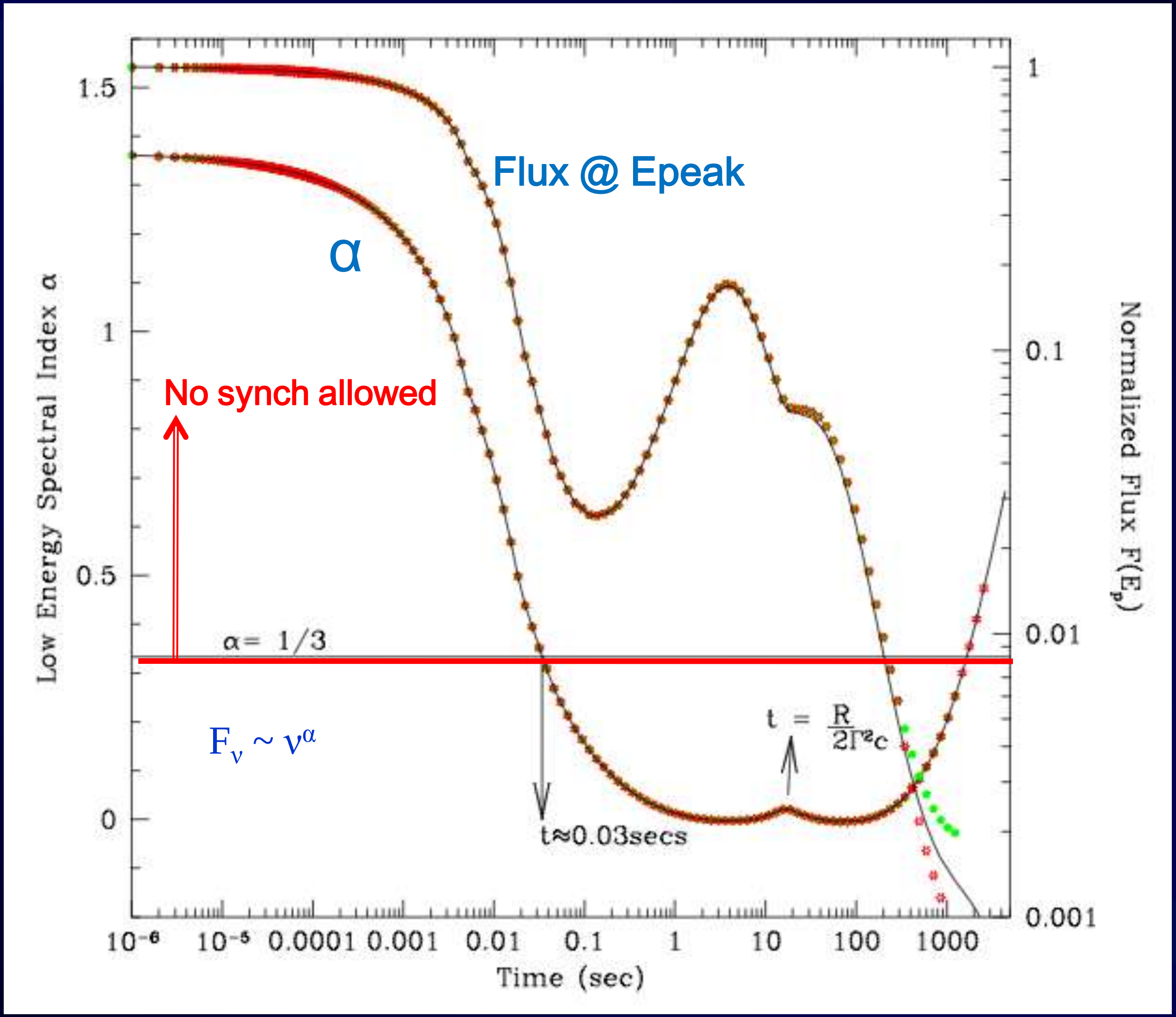


t_1 , bright,
high E_{peak},
α~0

t_2 , intermediate
α~ -2/3

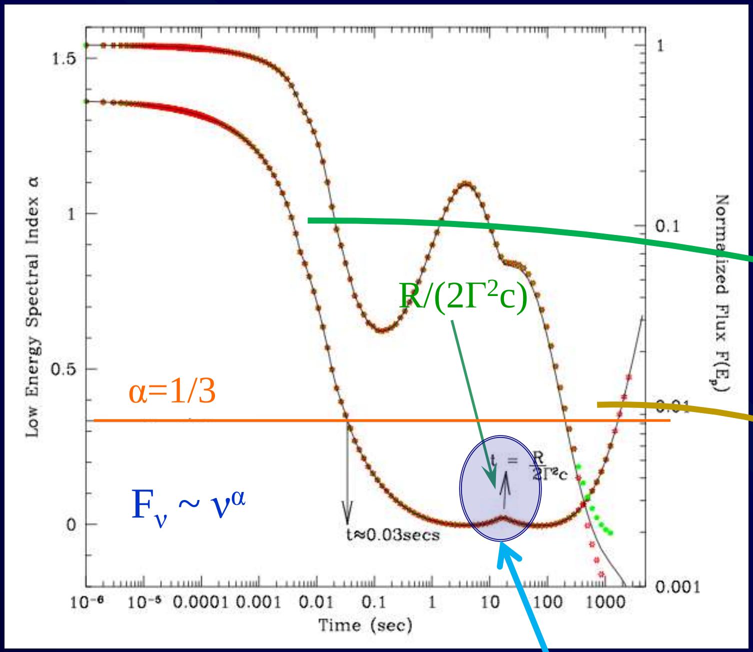
t_3 , faint,
low E_{peak},
α~ -1

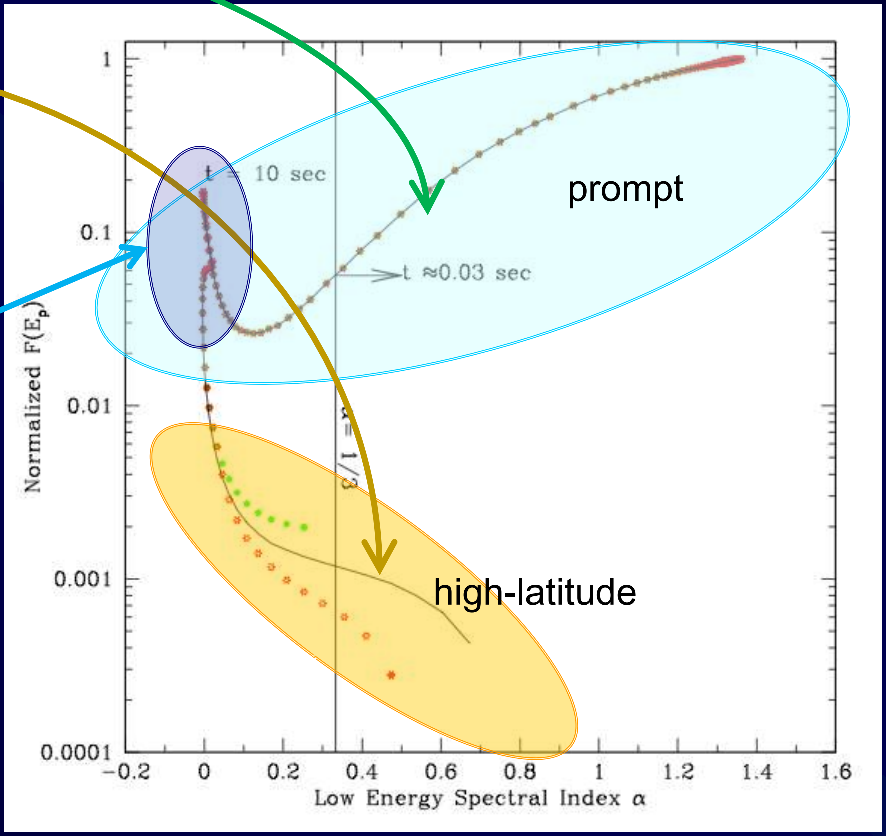
Single pulse: F & alpha "lightcurves"



Prompt spectral variability

a single pulse



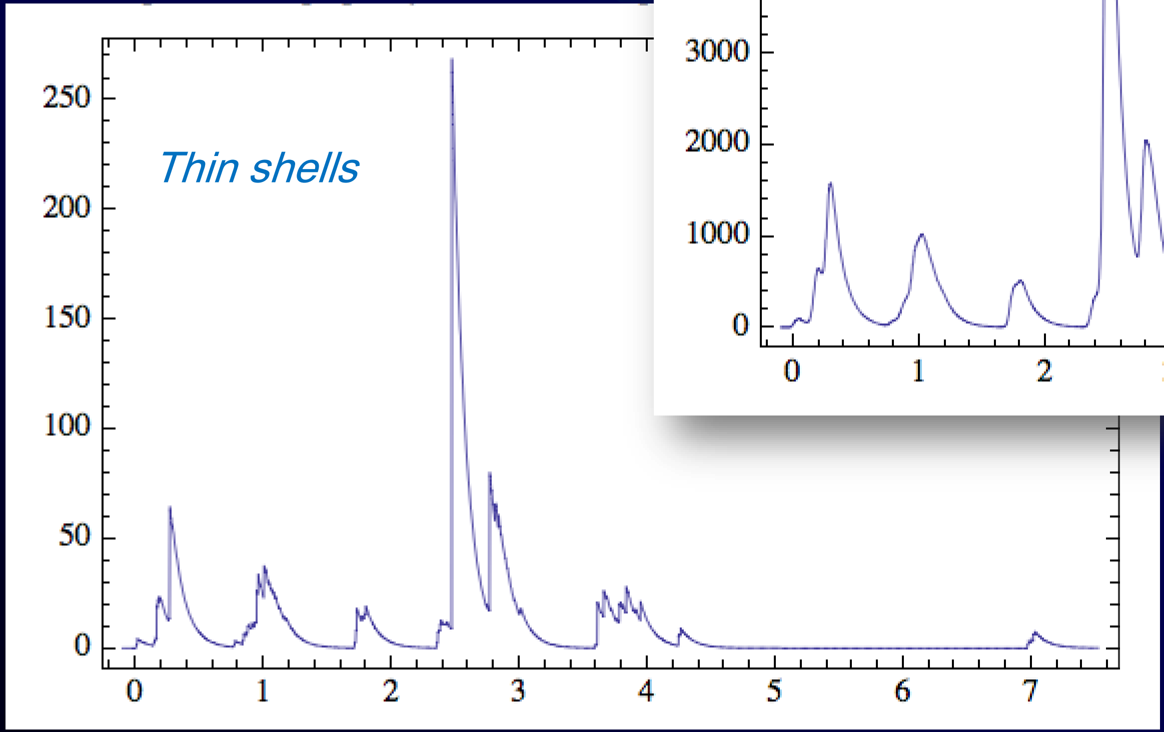


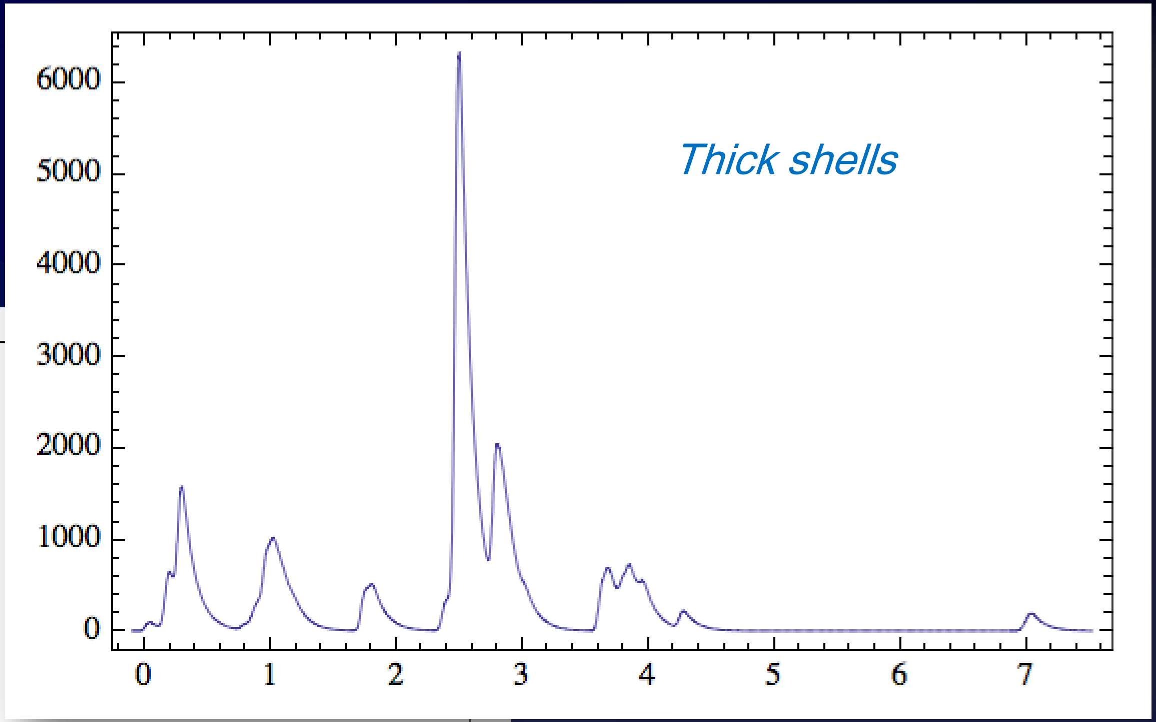
Polarization may be expected, if jet is misaligned

(Medvedev, 2006)

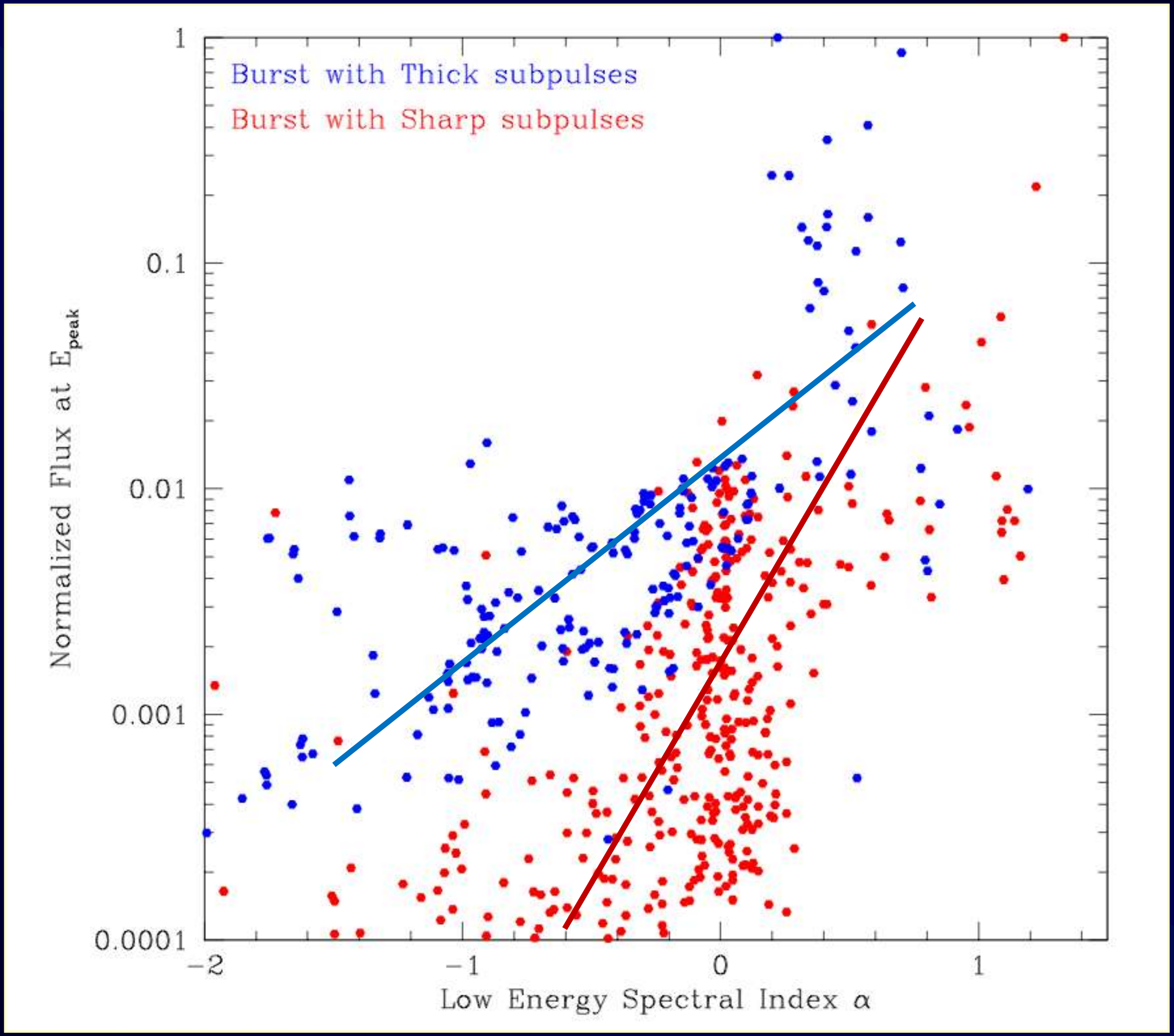
(Pothapragada, Reynolds, Medvedev, in prep)

Model lightcurves





Flux @ Epeak vs alpha -correlation



Are shock simulations relevant for GRBs?

Cooling & Weibel time-scales

Inside the ejecta:

$$n = \frac{L}{4\pi R^2\Gamma^2 m_p c^3} \simeq (1.8\times 10^{15}\ \mathrm{cm}^{-3}) L_{52} R_{12}^{-2}\Gamma_2^{-2},$$

from simulations

Downstream an internal shock:

$$n' = 4\Gamma_i n.$$

$$B' = (8\pi\Gamma_i m_p c^2 n'\epsilon_B)^{1/2} \simeq (1.6\times 10^7\ \mathrm{G}) L_{52}^{1/2}\Gamma_2^{-1} R_{12}^{-1}\epsilon_B^{1/2} \quad (7)$$

$$\gamma_e = (m_p/m_e)\Gamma_i\epsilon_e \simeq 1.8\times 10^3\Gamma_i\epsilon_e. \quad (8)$$

Synchrotron cooling time

$$\tau_{cool} = \frac{6\pi m_e c}{\sigma_T \gamma_e B^2}$$

Electron/proton dynamical time

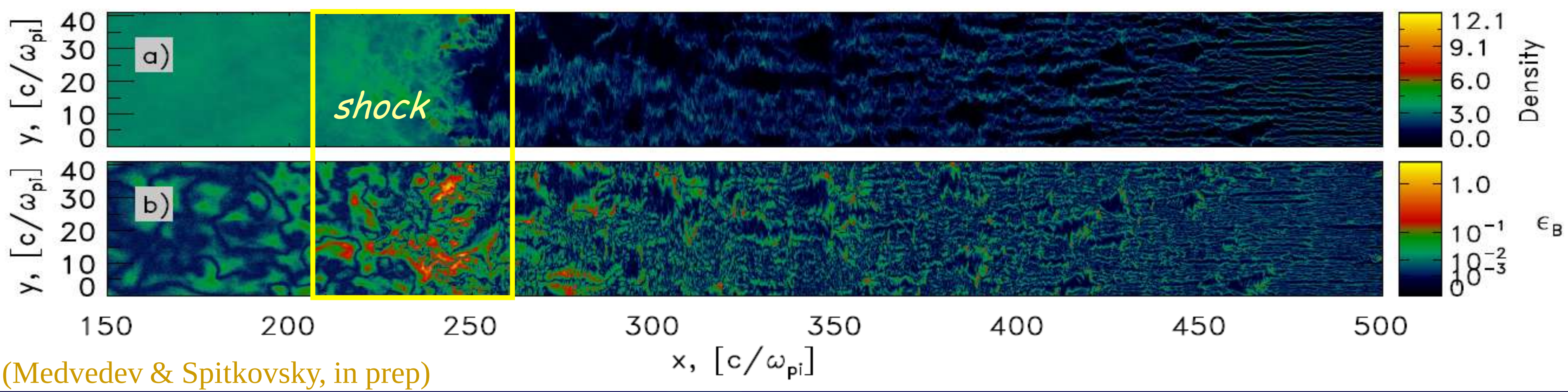
$$\omega_{ps,rel} = \left(\frac{4\pi e^2 n}{\Gamma_{int} m_s}\right)^{1/2}$$

$$\epsilon_B = \frac{B^2/4\pi}{m_p c^2 n\Gamma},$$

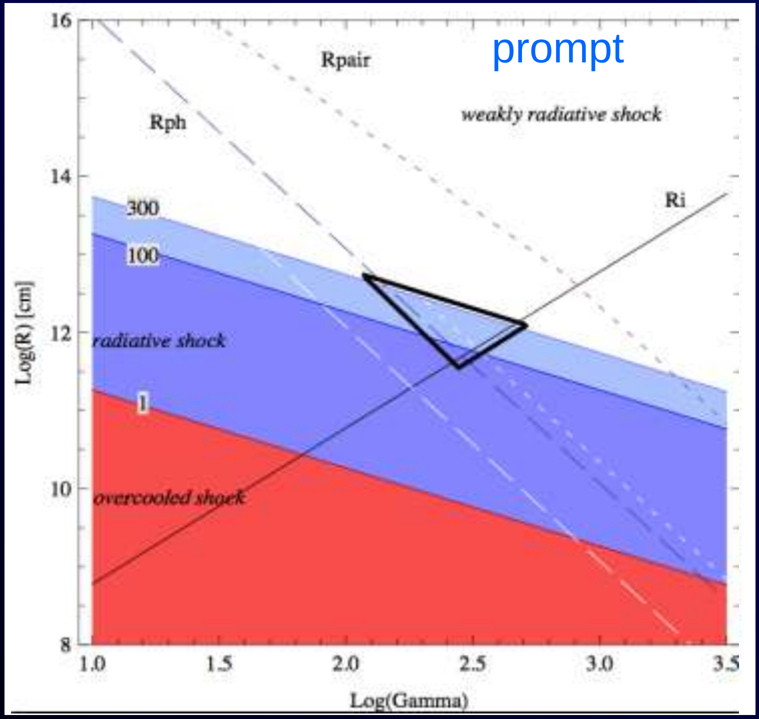
$$\epsilon_e = \frac{U_e}{m_p c^2 n\Gamma}.$$

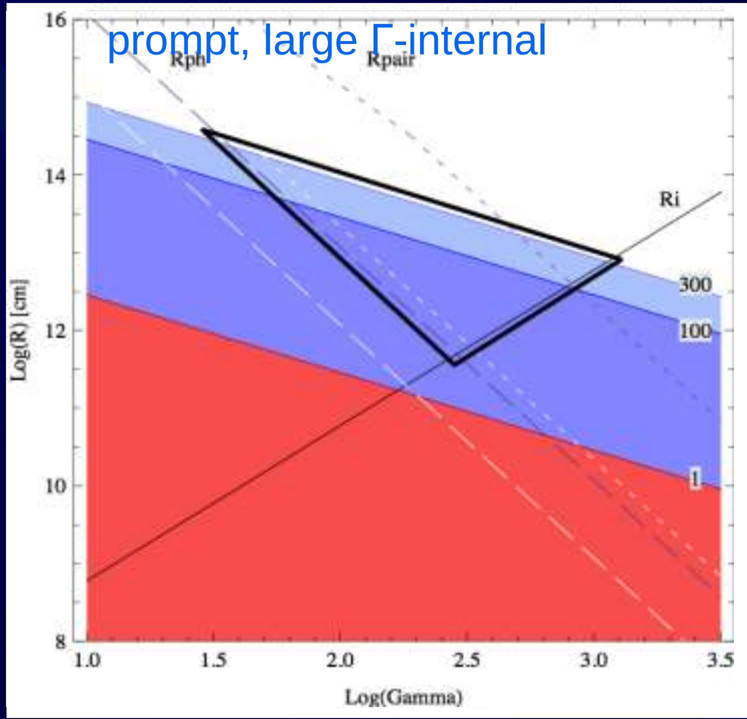
$$n = \frac{L_{kin}}{4\pi R^2\Gamma_{blast}^2 m_s c^2}$$

Cooling & Weibel time-scales

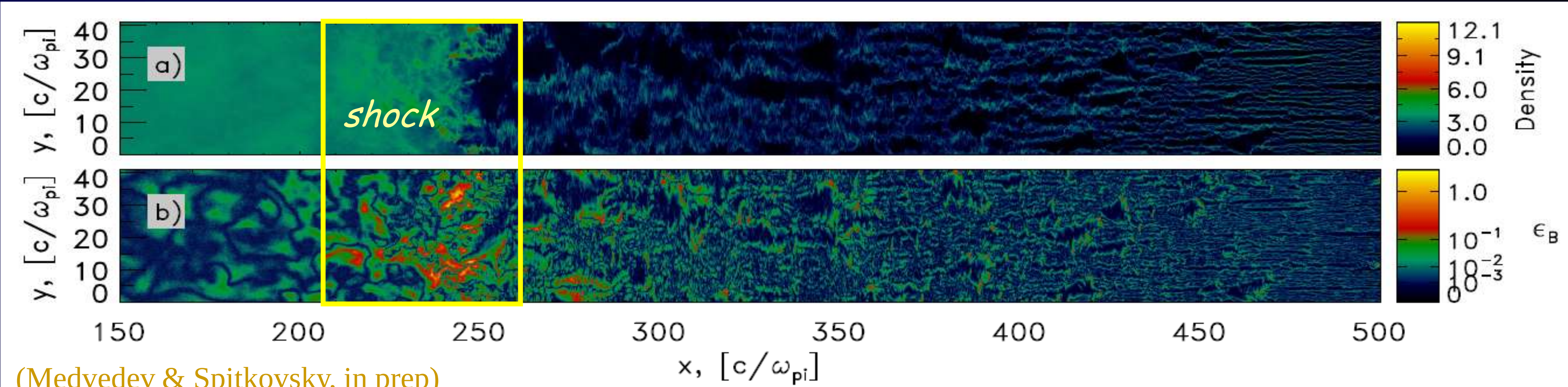


(Medvedev & Spitkovsky, in prep)

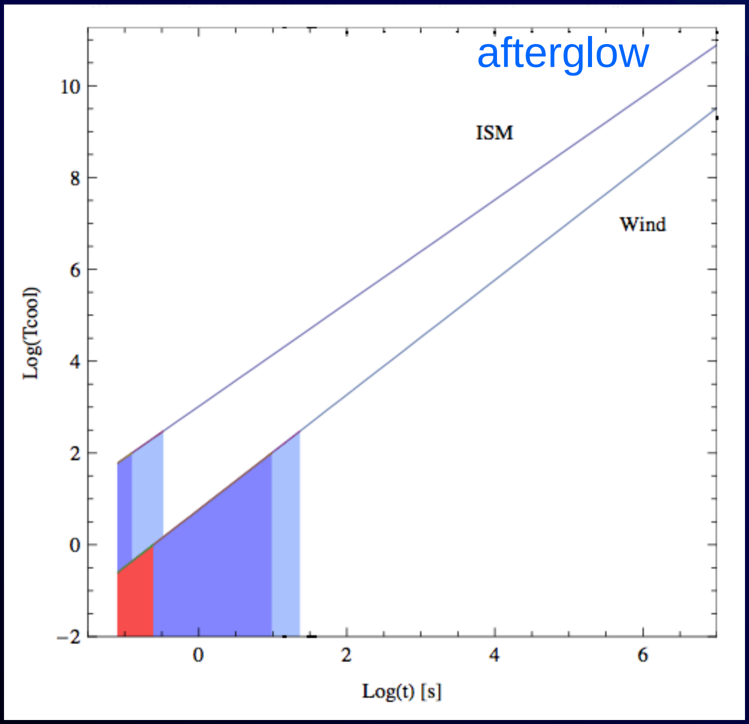


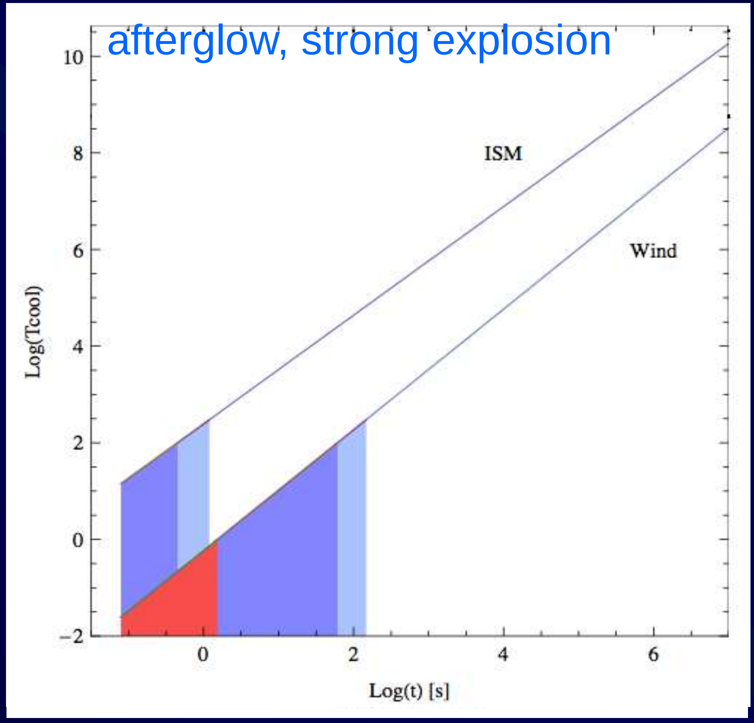


Cooling & Weibel time-scales



(Medvedev & Spitkovsky, in prep)



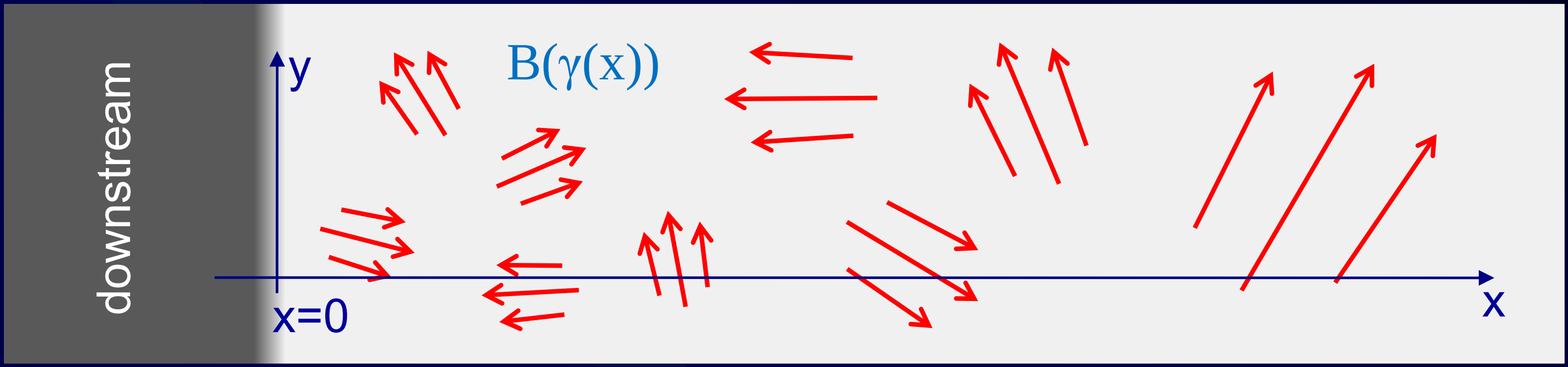


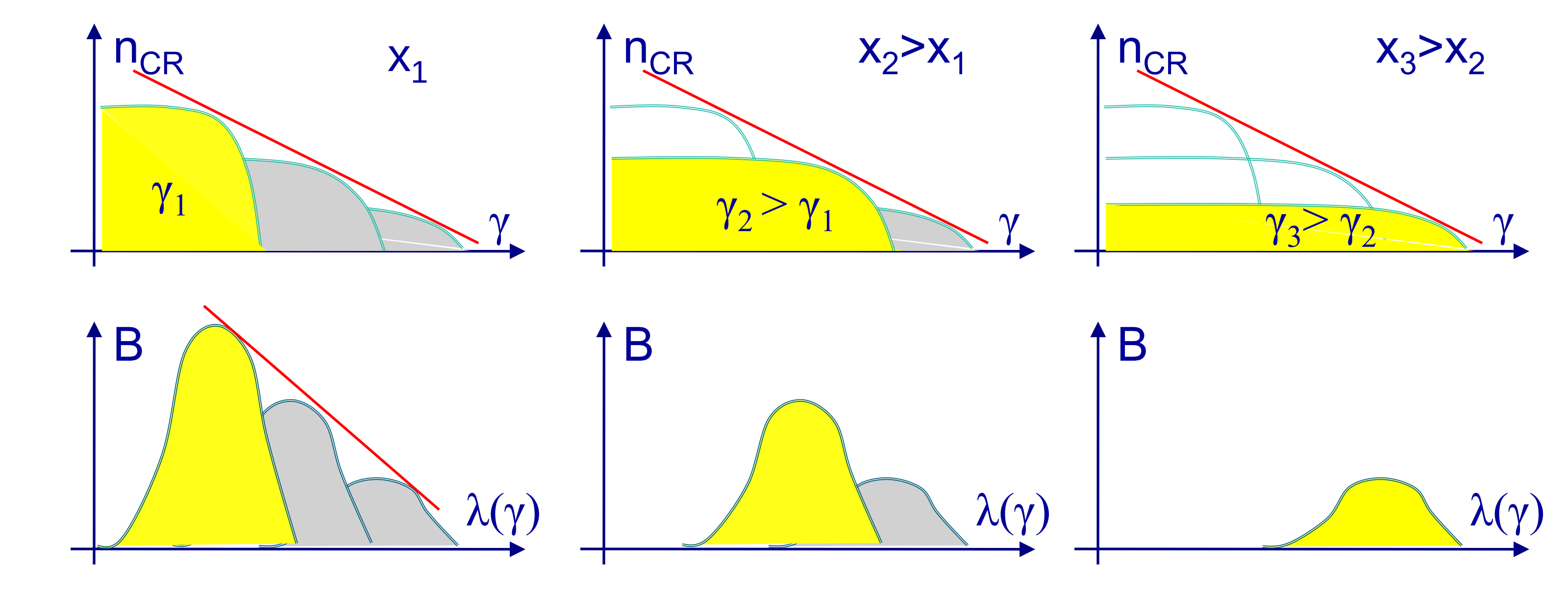
Bonus:

Self-similar foreshosk model with

CR generated B-field

The model





(Medvedev & Zakutnyaya, in prep)

Self-similar foreshock

Assume *steady state* and neglect nonlinear effects:

- effect of pre-conditioning of upstream on Weibel instability
- nonlinear feedback of B-fields on
    - CR distribution function
    - Shock structure
    - CR acceleration
- time evolution of generated fields

$$\boxed{\begin{gathered}B(x) \sim B_0\,(x/x_0)^{-\frac{s-1}{s+1}}\\ \lambda(x) \sim x(2\xi_B).\end{gathered}}$$

$$s = p - 1 \sim 1.2$$

$$x_0 \sim (2\times 10^7\ \mathrm{cm})\, n_{\rm ISM}^{-1/2}/(2\xi_B) \sim (10^9\ \mathrm{cm})\, n_{\rm ISM}^{-1/2},$$

$$B_0 \sim (0.2\ \mathrm{gauss})\, \xi_B^{1/2} n_{\rm ISM}^{1/2}\Gamma_{\rm sh} \sim (1\ \mathrm{gauss})\, E_{52}^{1/2} R_{17}^{-3/2}$$

Valid at $x \lesssim x_{\rm max}$.

$$x_{\rm max} = \mathrm{Min}\,[R/(2\Gamma_{\rm sh}),\ X] = \mathrm{Min}\left[R/(2\Gamma_{\rm sh}),\ x_0\,(B_0/B_{\rm ISM}\Gamma_{\rm sh})^{\frac{s+1}{s-1}}\right]$$

$$x_{\rm max} \sim R/(2\Gamma_{\rm sh}) \sim 5\times 10^8\ x_0\ E_{52}^{1/3} n_{\rm ISM}^{-1/3}\Gamma_{\rm sh}^{-5/3}$$

Typical field:

$$B(x_{\rm max}) \sim (0.2\ \mathrm{gauss})\ E_{52}^{0.45} n_{\rm ISM}^{0.09} R_{18}^{-1.3}$$

$$\lambda(x_{\rm max}) \sim x_{\rm max}/(2\xi_B) \sim (5\times 10^{17}\ \mathrm{cm})\ E_{52}^{-1/2} n_{\rm ISM}^{1/2} R_{18}^{5/2}$$

B-field spectrum near a shock

$$B_\lambda \propto \lambda^{-\frac{s-1}{s+1}} \sim \lambda^{-0.091}$$

(Medvedev & Zakutnyaya, in prep)

Conclusions

- Magnetic field with small spatial coherence length are ubiquitous. They form due to the *Weibel-type instability* via the current filament formation

- Radiation emitted by electrons in Weibel-generated magnetic fields – Jitter radiation – has spectral properties that make it more favorable over synchrotron models. *The Weibel+Jitter shock model can be tested against GRB data: e.g., spectral variability and afterglow lightcurves*

- A model of a self-similar foreshock magnetized by streaming CRs is presented, but more understanding is needed on B-field evolution and acceleration/heating→ larger and longer PIC simulations are needed

- More understanding is still needed for external shocks of afterglows (Weibel vs vorticity models, post-shock turbulence) and prompt emission (magnetized outflows)