Observational signatures of sub-Larmor scale fields

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Outline

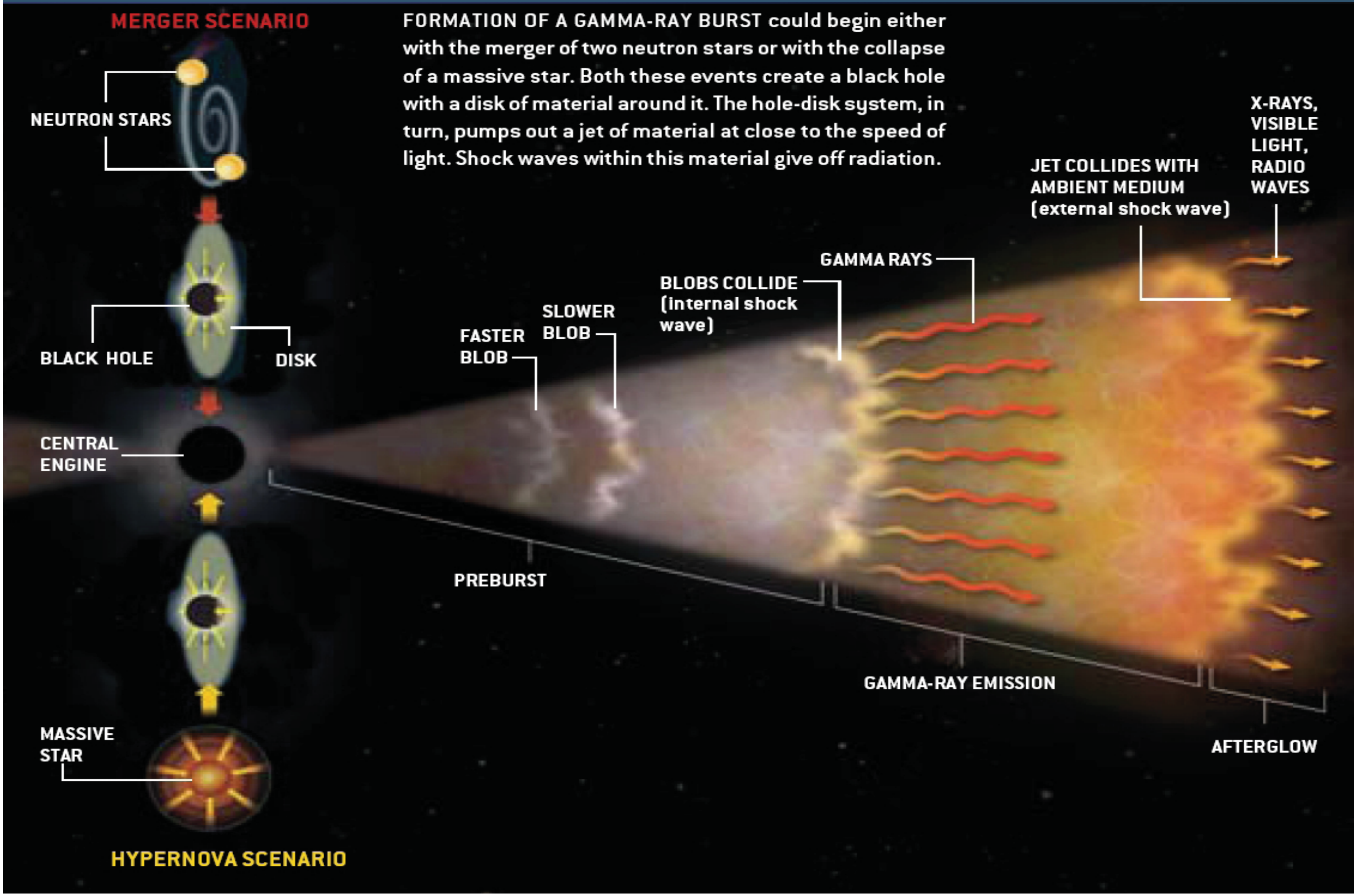
- *Intro: ubiquitous Weibel*
- *Basics: Jitter, Synchrotron, Intermediate*
- *Comparison: PIC, observations*
- *Lessons & homework*

Students:
Sarah Reynolds,
Sriharsha Pothapragada

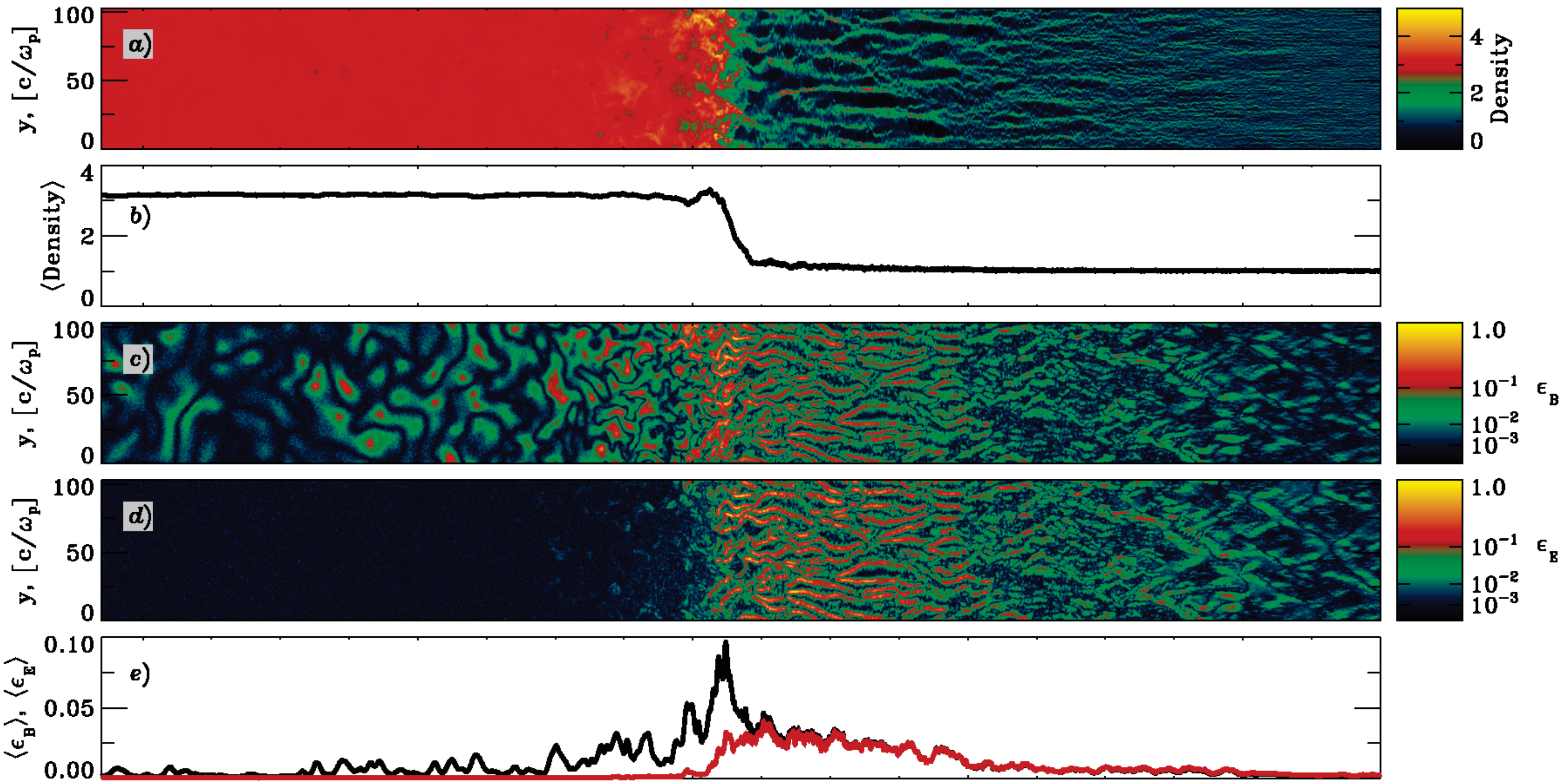
Nonlinear processes in astrophysics

KITP, Santa Barbara, 2009

Baryonic/leptonic jet

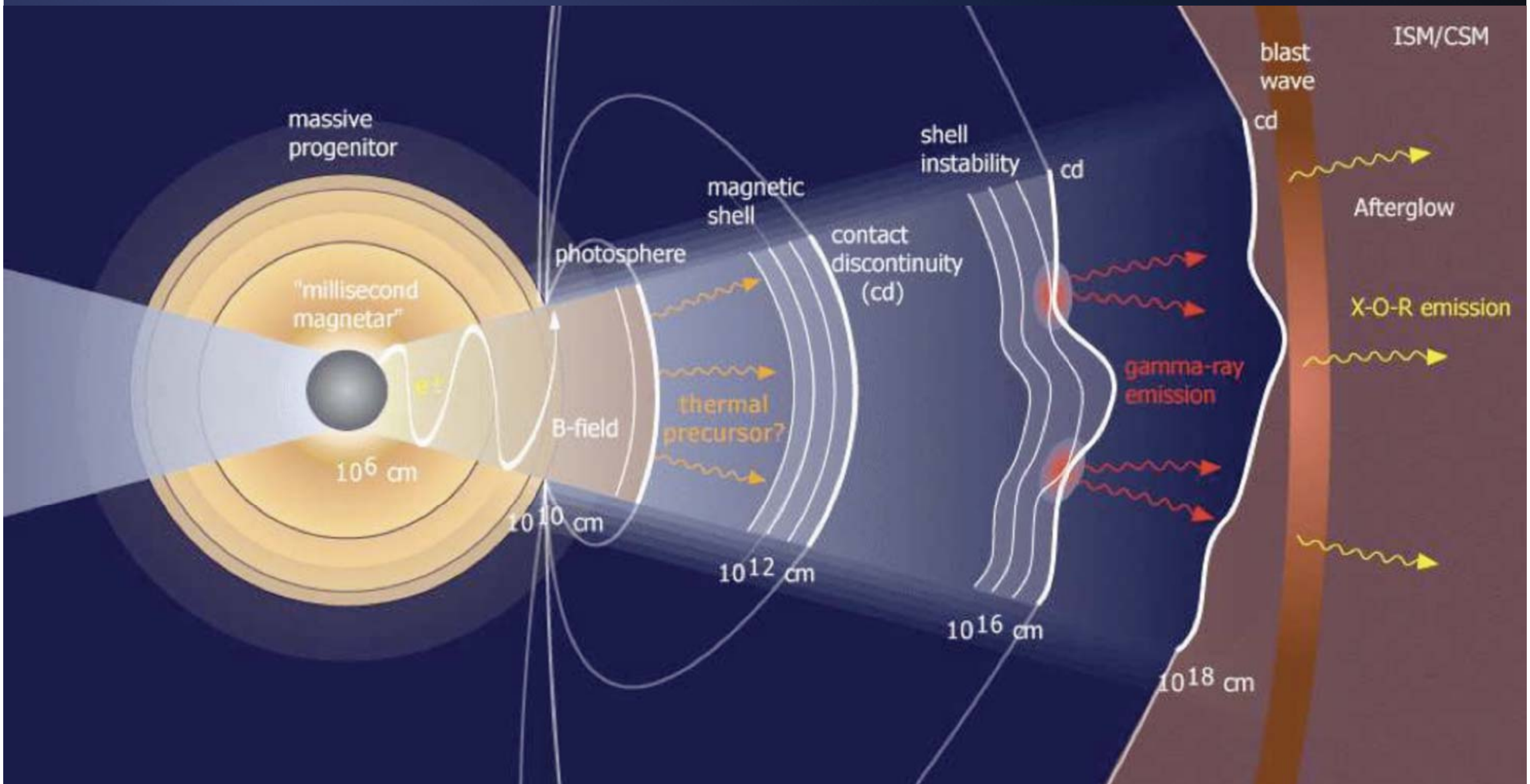


Weibel in shocks



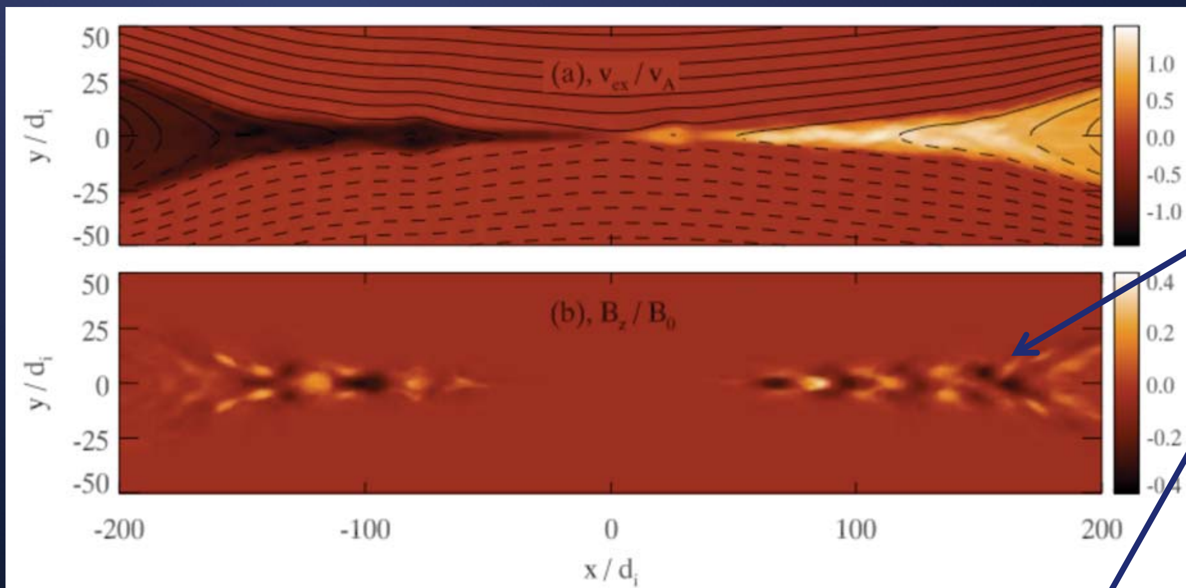
(Sirony &Spitkovsky, 2009)

Magnetically-dominated ejecta



(Lyutikov & Blandford 2003)

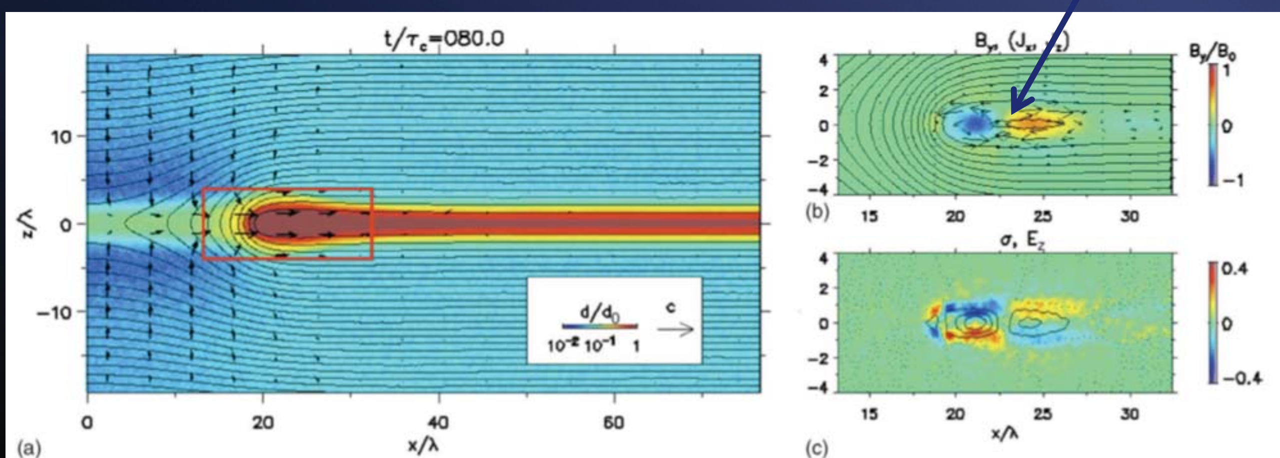
Weibel in reconnection



Weibel fields

Non-relativistic electron-positron pair plasma

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



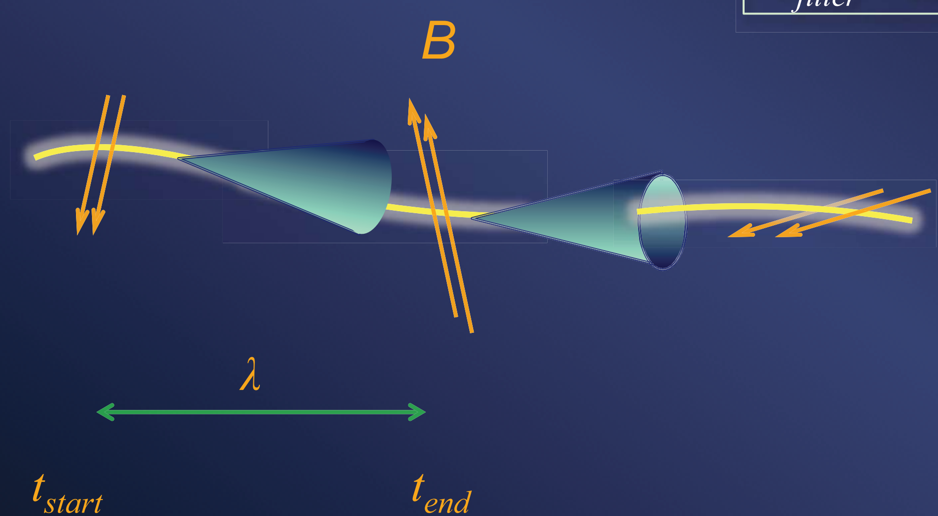
Relativistic electron-positron pair plasma

(Zenitani & Hesse, PoP, 2008)

Jitter radiation

$\delta_{jitter} \sim$ (deflection angle)/(beaming)
$\sim (\Delta p_{perp}/p)/(1/\gamma) \sim (F_L \Delta t)/(mc)$

$\delta_{jitter} \sim eB\lambda/mc^2 \sim 0.6\, B_{kG}\, \lambda_{cm} << 1$

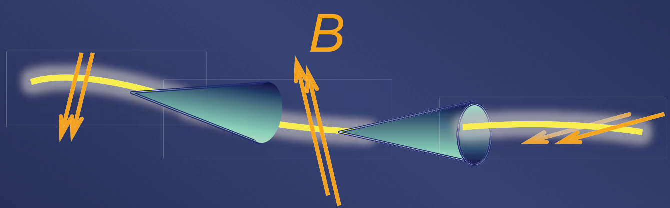


$l_{rad} \sim \lambda$

$\Delta t_{obs} = t_{end} - t_{start}$
$\sim l_{rad}/c\gamma^2$
$\sim \lambda/c\gamma^2$

$\omega_{jitter} \sim 1/\Delta t_{obs}$
$\sim (c/\lambda)\,\gamma^2$

Jitter theory



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

$\mathbf{w}_{\omega'} = \int \mathbf{w} e^{i\omega' t}\,dt$ $\quad \omega' = \omega\,(1-\mathbf{n}\cdot\mathbf{v}/c)$

Fourier transform of $\boldsymbol{w}(\boldsymbol{r}_0+\boldsymbol{v}t, t)$

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

$|\boldsymbol{w}_{\omega'}|^2$ should not depend on the initial point, $\boldsymbol{r}_0$, $\quad \langle|\boldsymbol{w}_{\omega'}|^2\rangle = V^{-1}\int|\boldsymbol{w}_{\omega'}|^2\,d\boldsymbol{r}_0$

$$\left\langle|\boldsymbol{w}_{\omega'}|^2\right\rangle = (2\pi)^{-3}V^{-1}\int|\boldsymbol{w}_{\Omega,\boldsymbol{k}}|^2\delta(\omega'-\Omega+\boldsymbol{k}\cdot\boldsymbol{v})\,d\Omega\,d\boldsymbol{k}.$$

Jitter theory

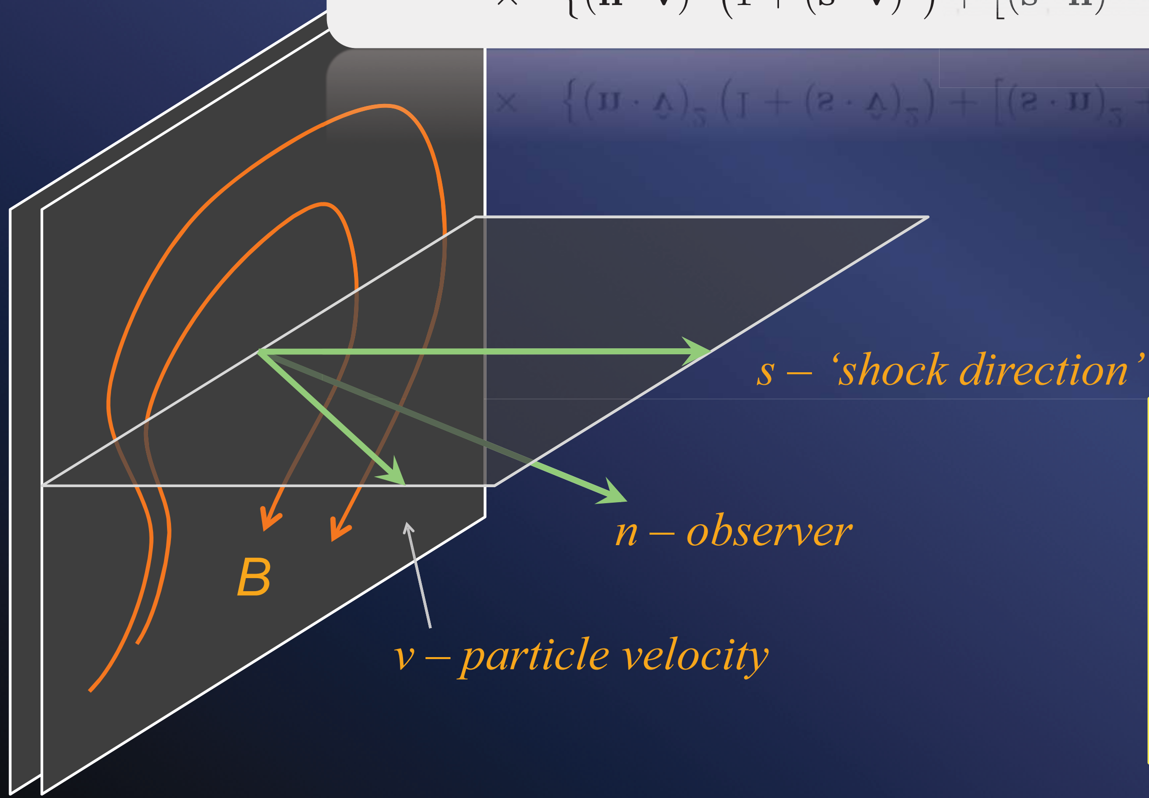
'shock geometry': $B = B_{perp}$ — *$v \times B$ force only*

$$B^{\alpha}_{\Omega,\mathbf{k}} B^{*\beta}_{\Omega,\mathbf{k}} = C(\delta_{\alpha\beta} - s_\alpha s_\beta) f(k_\parallel, k_\perp)$$

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

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

$$\times \left\{ (\mathbf{n}\cdot\hat{\mathbf{v}})^2 \left(1 + (\mathbf{s}\cdot\hat{\mathbf{v}})^2\right) + \left[(\mathbf{s}\cdot\mathbf{n})^2 + (\mathbf{s}\cdot\mathbf{v})^2 - 2(\mathbf{s}\cdot\mathbf{n})(\mathbf{s}\cdot\mathbf{v})(\mathbf{n}\cdot\mathbf{v})\right] \right\}$$



beaming

$$\frac{dW}{d\Omega} \propto \left(1 + (\gamma\vartheta)^2\right)^{-5}$$

spectrum

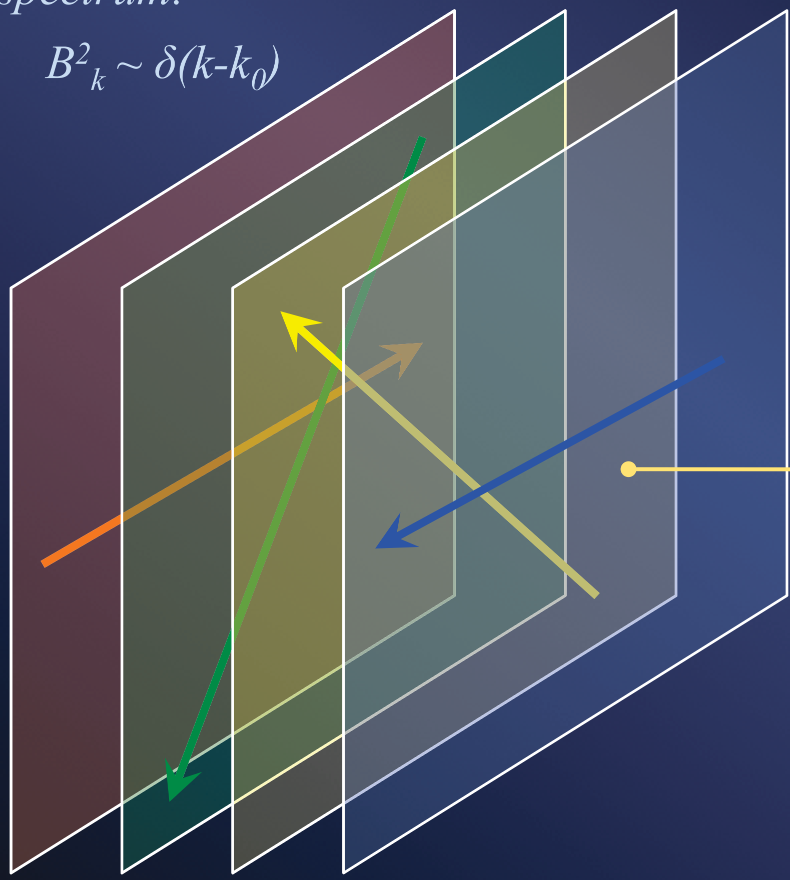
$$\frac{dW_\omega}{d\omega\, d\Omega} \propto |\mathbf{w}_{\omega'}|^2$$

Any spectrum is possible

Jitter in 1D: 'Green's function'

B-field spectrum:

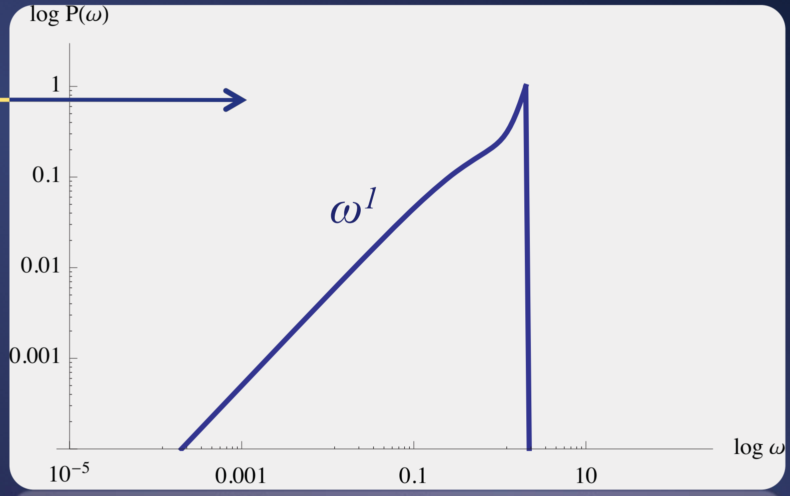
$B^2_k \sim \delta(k-k_0)$



Angle-averaged spectrum

⇔ isotropic PDF

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

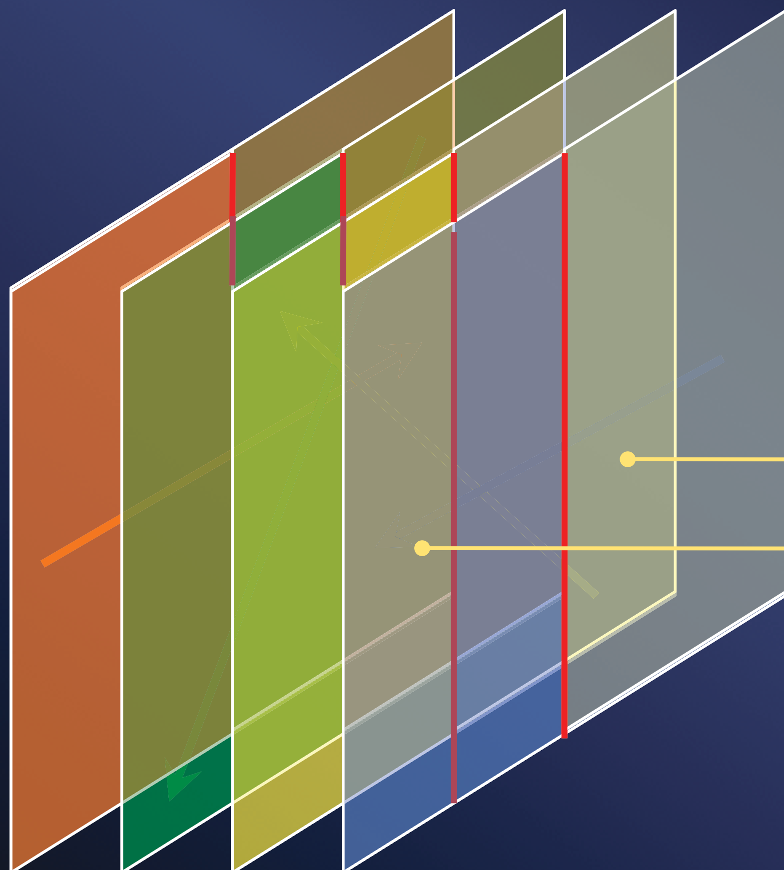


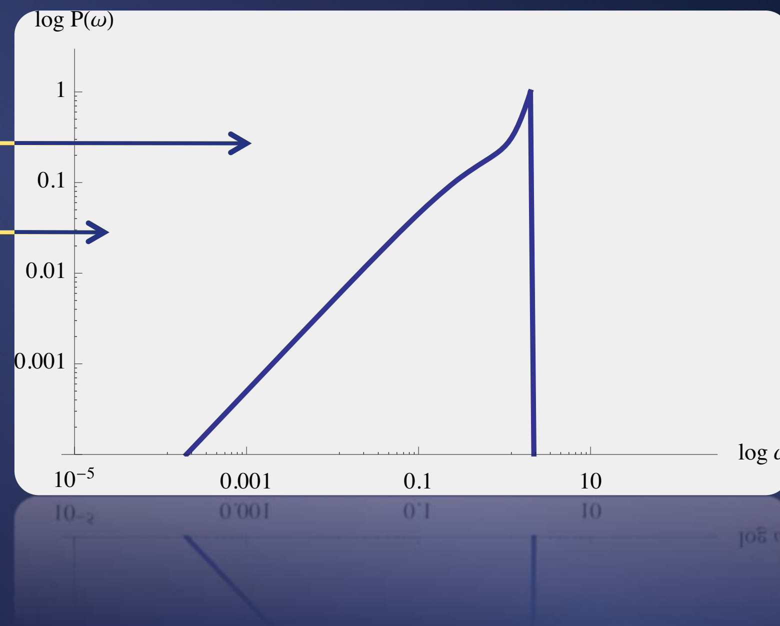
Adding dimensions…

Spectrum = statistical average over paths

Color coding = different field orientation

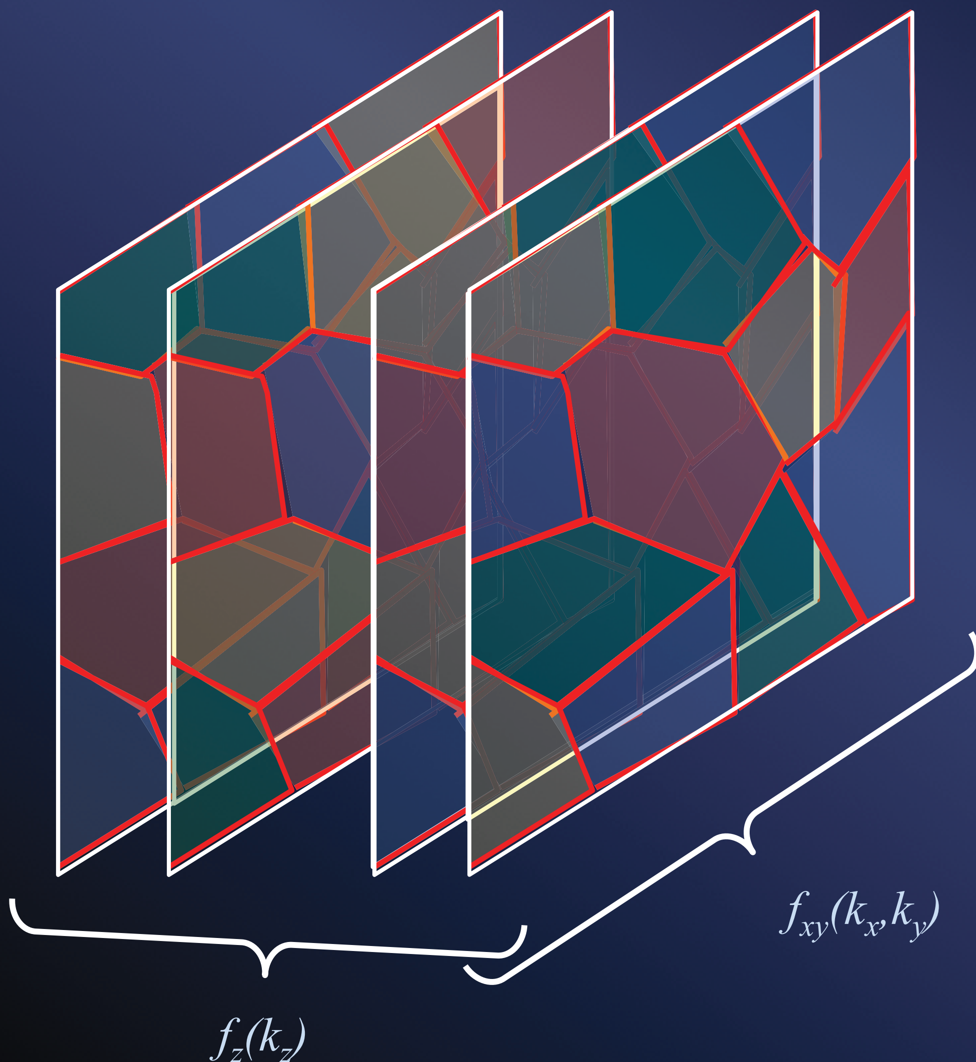
→ does not change

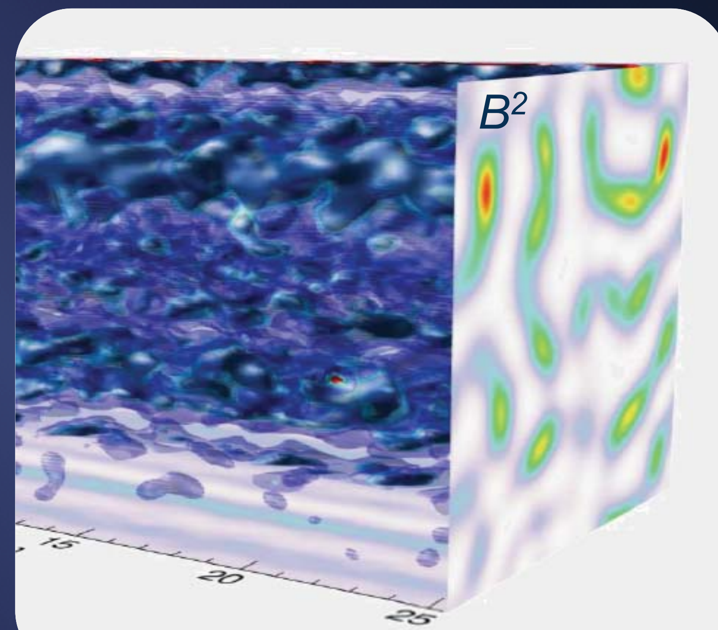




A model of Weibel turbulence

Color coding = different field orientation
Red lines = current sheets



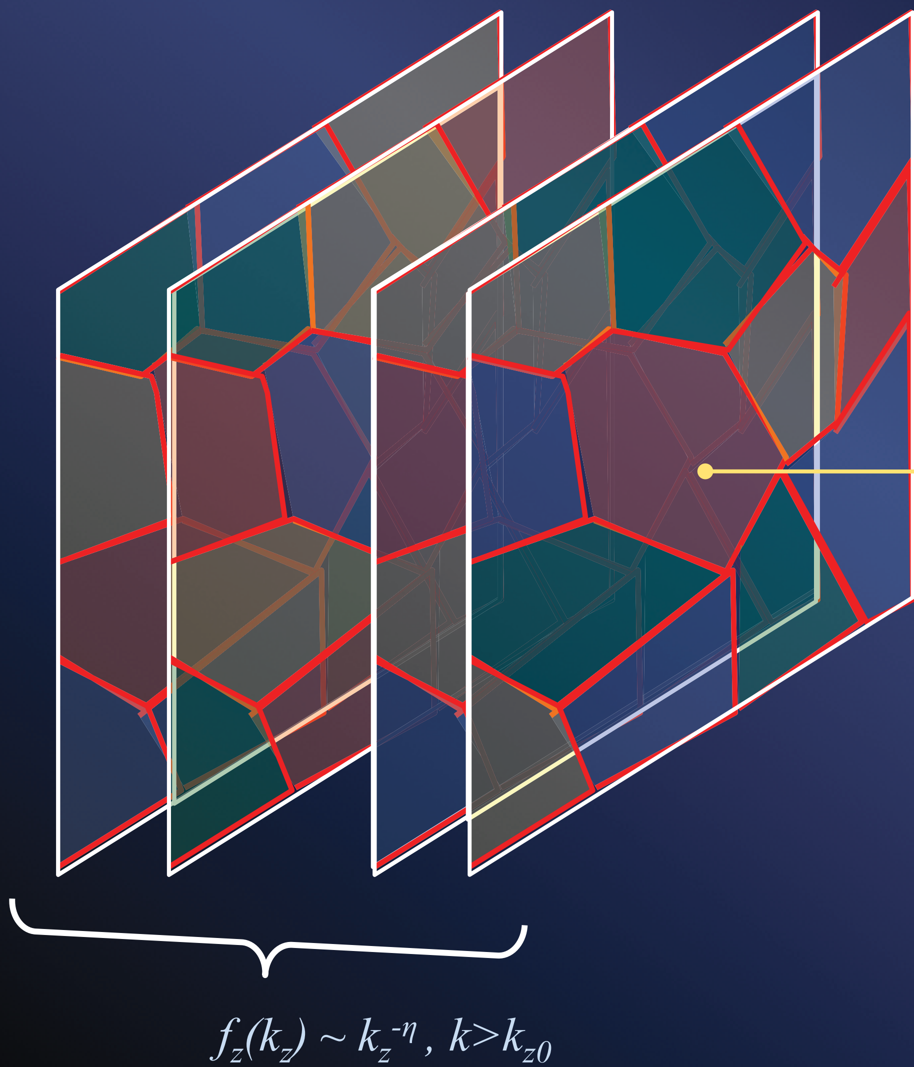


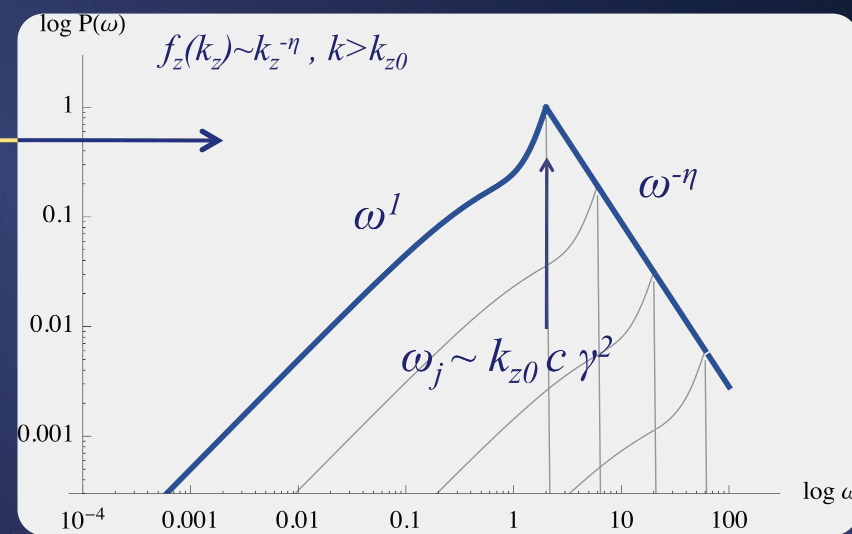
Credit: L Silva

$\nabla \bullet B = 0$

Jitter parallel spectrum

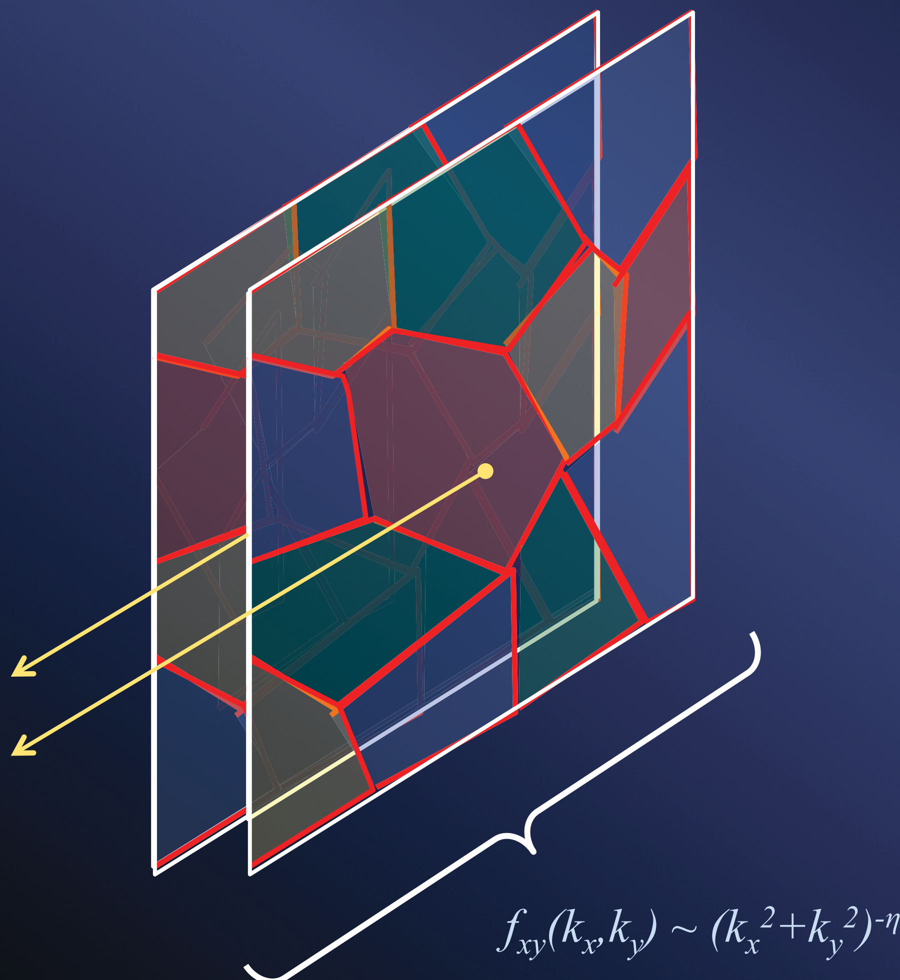
Color coding = different field orientation
Red lines = current sheets

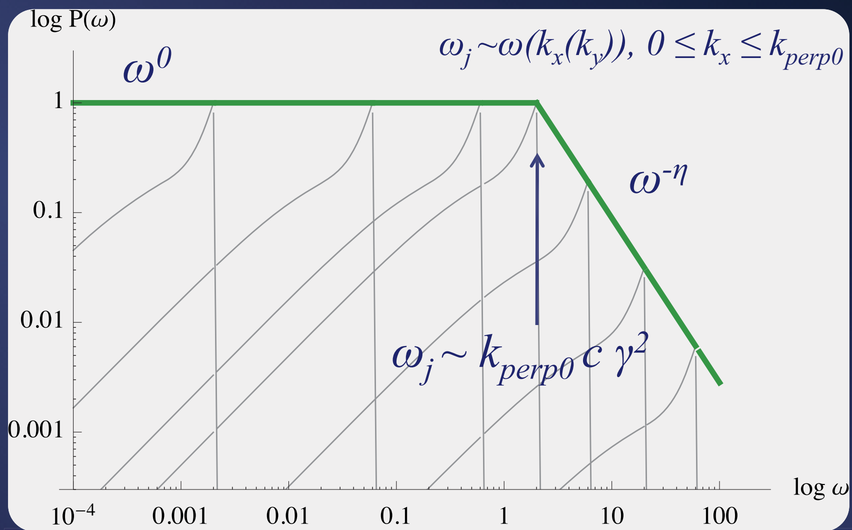




Jitter perpendicular spectrum

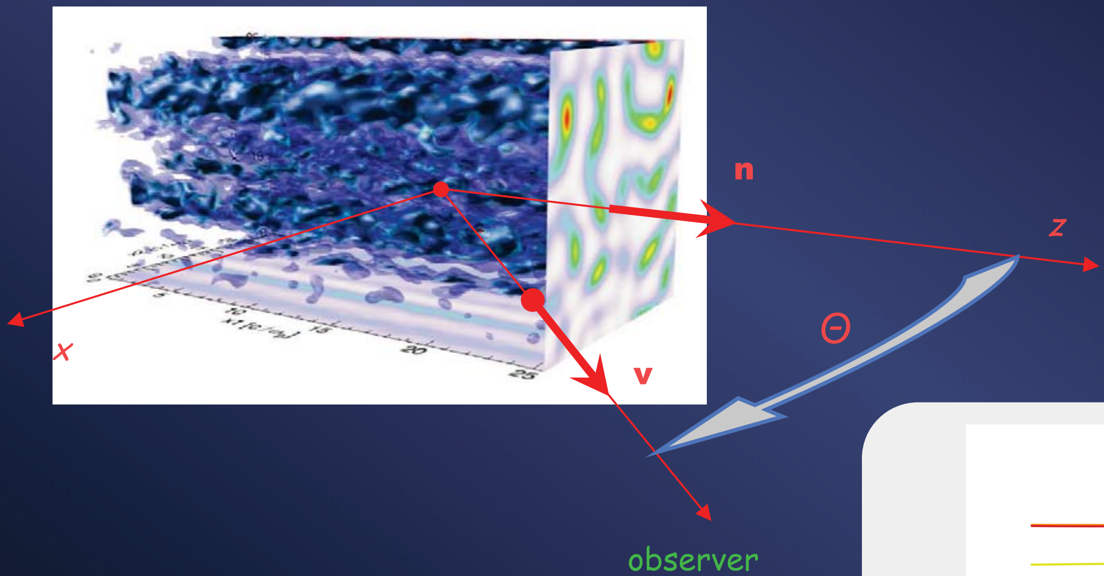
Color coding = different field orientation
Red lines = current sheets

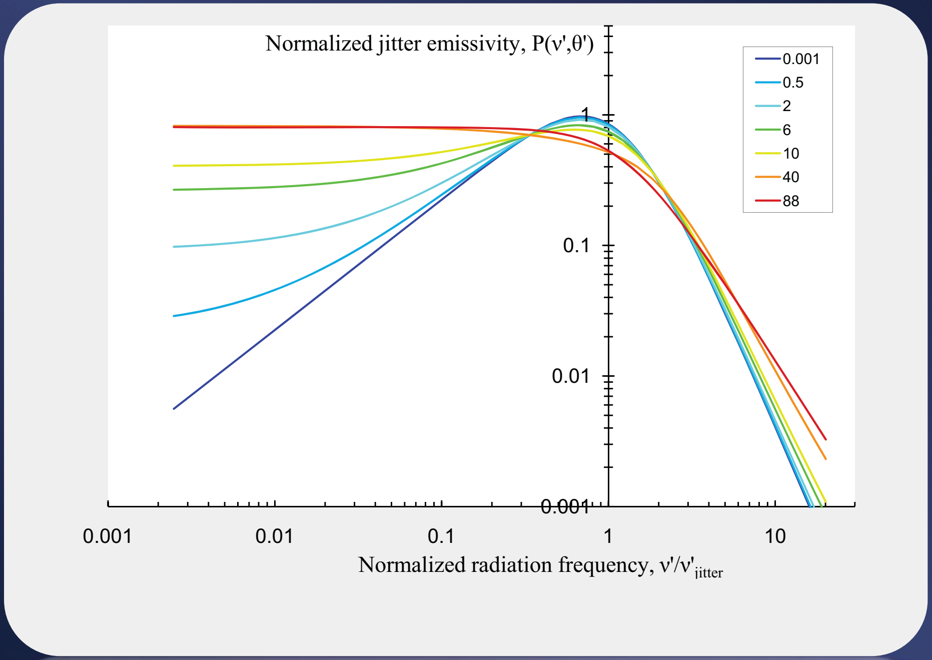




Anisotropic emissivity

Radiation spectrum depends on angle and B-field spatial spectrum



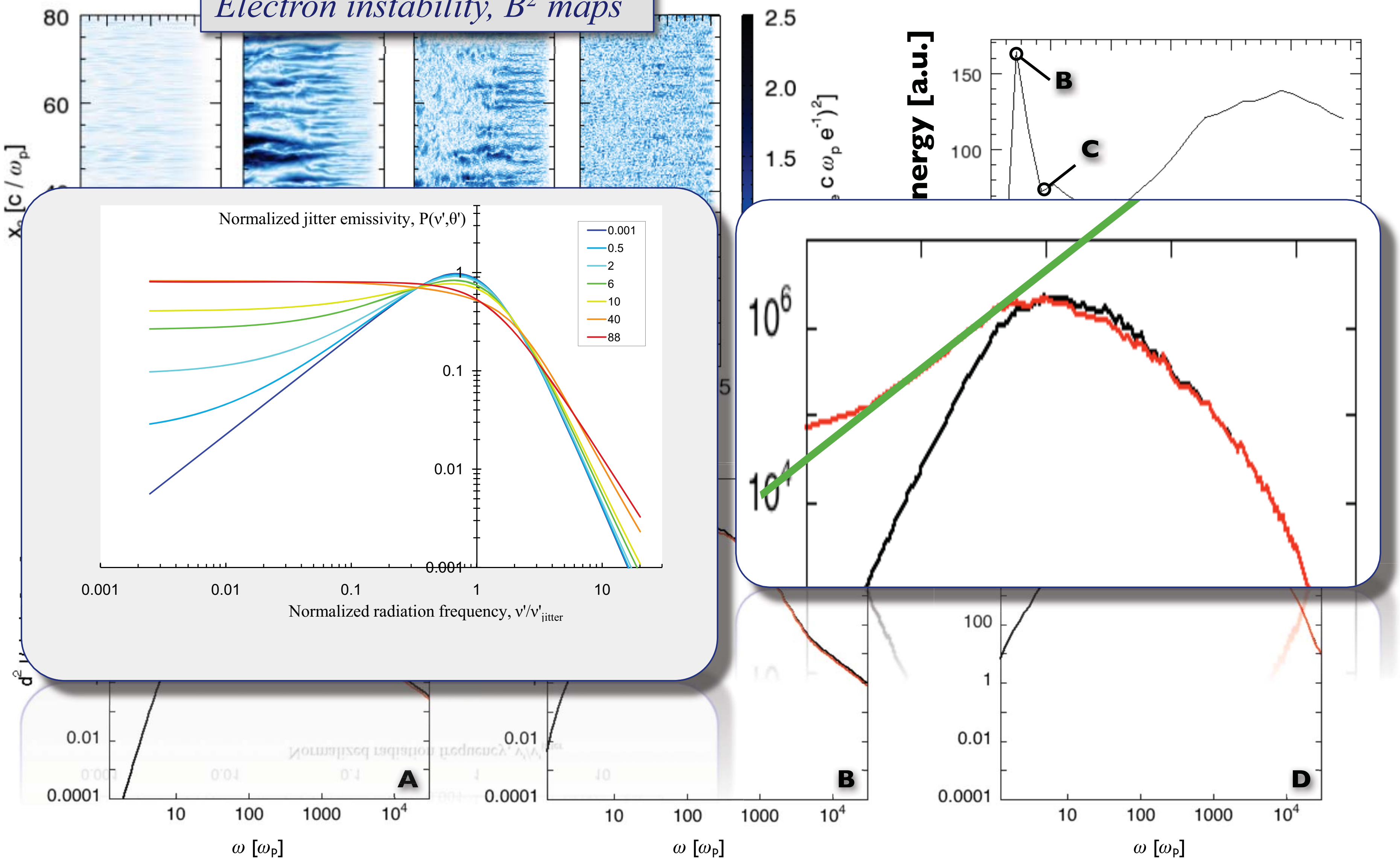


(Medvedev, ApJ 2006,
Reynolds et al 2009, ApJ submitted;
simulations by L. Silva)

Spectrum e^-e^+ scenario

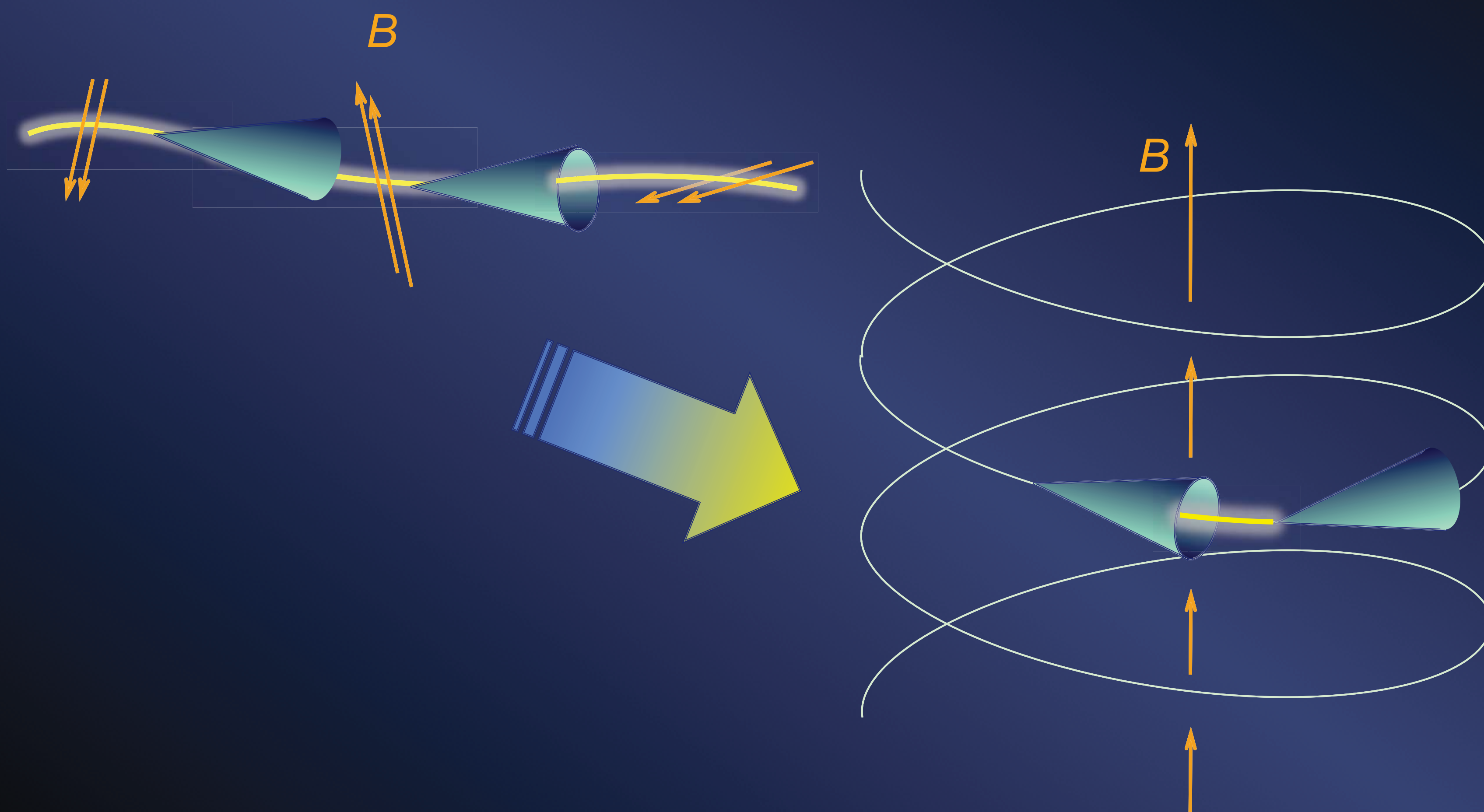
J.Martins, S.Martins, R.Fonseca, L.Silva
Poster here (preliminary results)

Electron instability, B^2 maps

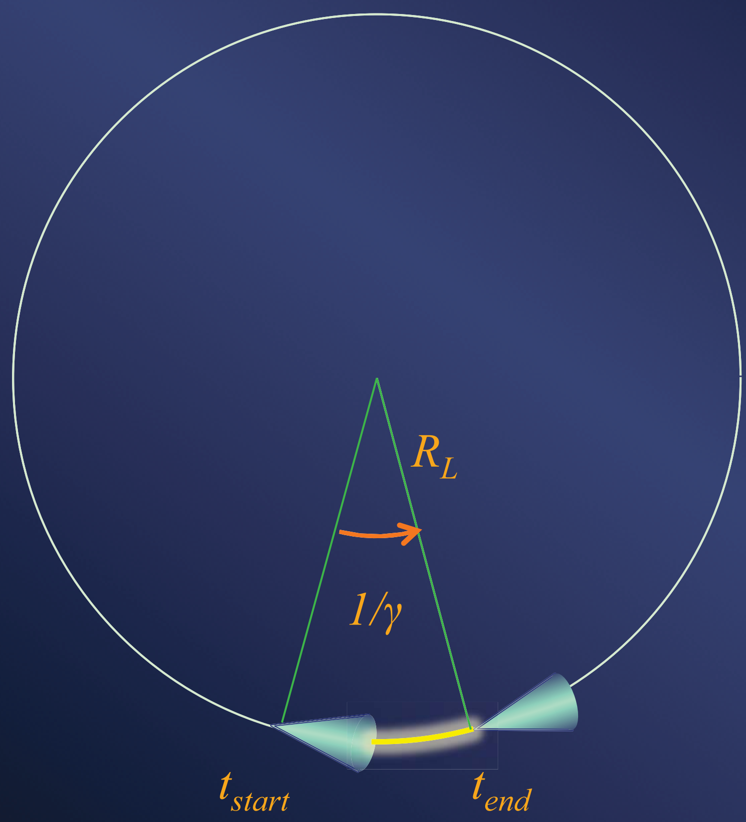


with dispersion — no dispersion

Jitter → Synchrotron transition



Synchrotron



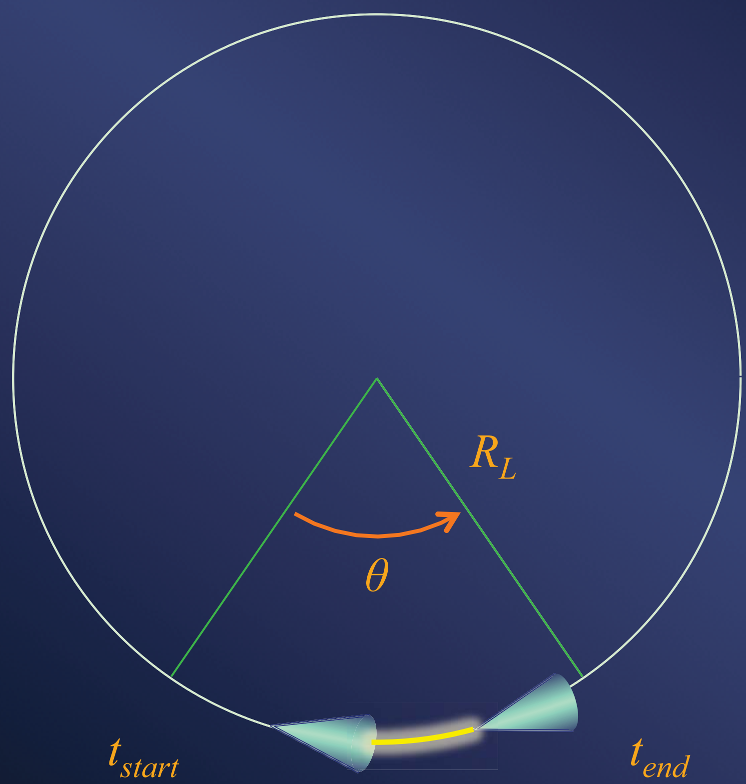
$$\omega_0 = eB/\gamma mc = \omega_B/\gamma$$

$$l_{rad} \sim R_L/\gamma$$

$$\begin{aligned}\Delta t_{obs} &= t_{end} - t_{start} \\ &\sim l_{rad}/c\gamma^2 \\ &\sim R_L/c\gamma^3 \\ &\sim 1/\omega_0\gamma^3\end{aligned}$$

$$\begin{aligned}\omega_{synch} &\sim 1/\Delta t_{obs} \\ &\sim \omega_0\gamma^3 \sim \omega_B\gamma^2\end{aligned}$$

Synchrotron



lower harmonics…

$l_{rad} \sim \theta R_L$

$\gamma_{perp} \sim \theta\gamma$

$\gamma_{mean} \sim \gamma/\gamma_{perp} \sim 1/\theta$

$\Delta t_{obs} = t_{end} - t_{start}$

$\sim l_{rad}/c\gamma^2_{mean}$

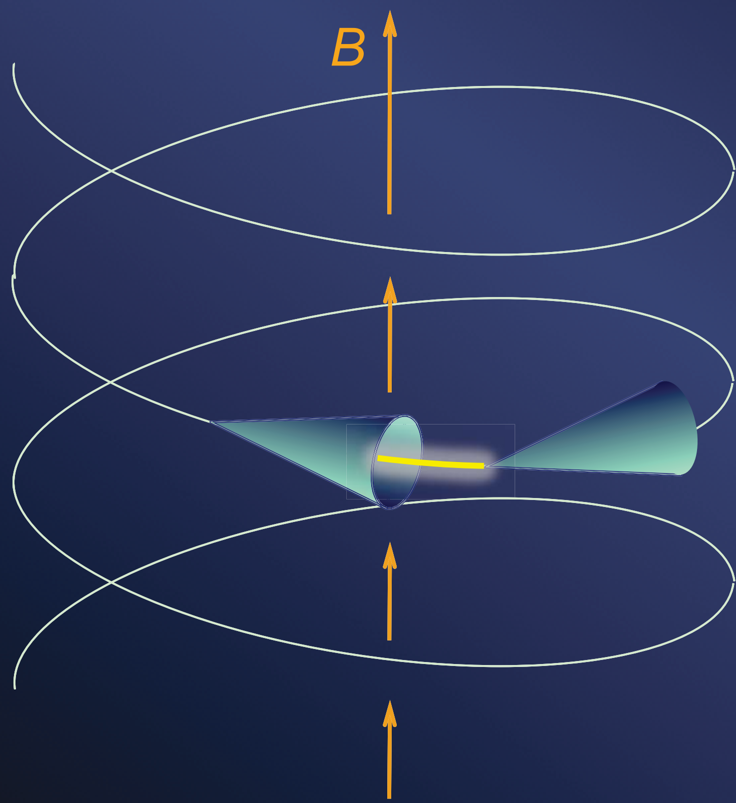
$\sim \theta^3 R_L/c$

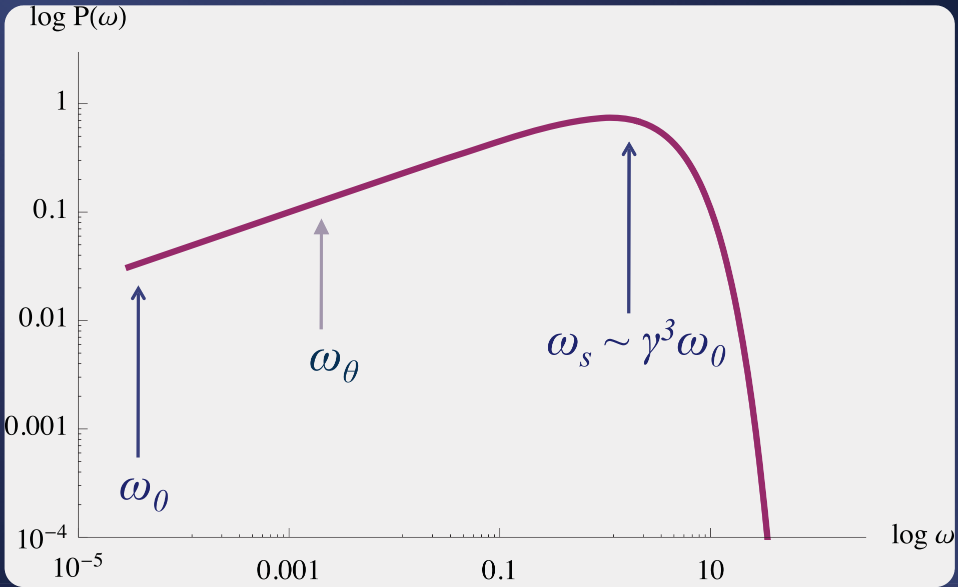
$\sim (\gamma\theta)^3/\omega_0\gamma^3$

$\omega_\theta \sim 1/\Delta t_{obs}$

$\sim (\gamma\theta)^{-3}\omega_{synch}$

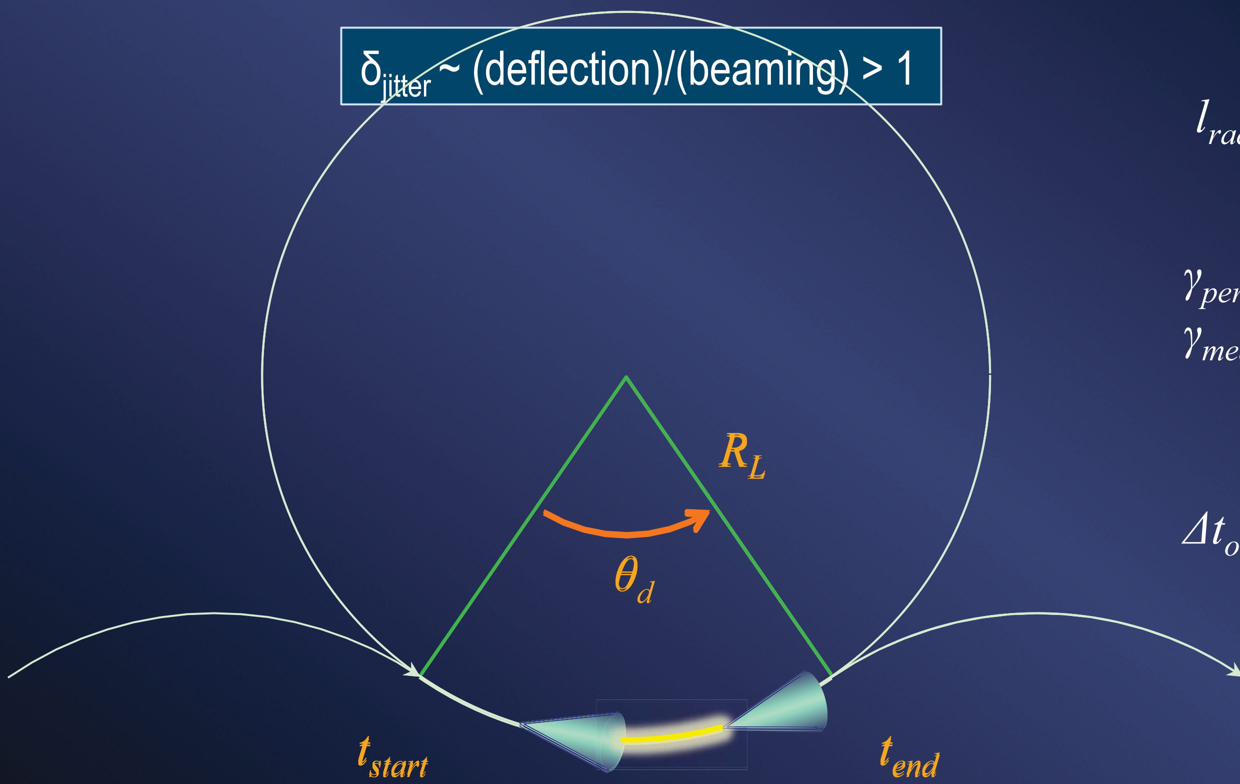
Synchrotron





Transition regime (synchro-jitter)

δ_{jitter} ~ (deflection)/(beaming) > 1



$l_{rad} \sim \theta_d R_L$

$\gamma_{perp} \sim \theta_d \gamma$

$\gamma_{mean} \sim \gamma/\gamma_{perp} \sim 1/\theta_d$

$\Delta t_{obs} = t_{end} - t_{start}$

$\sim l_{rad}/c\gamma^2_{mean}$

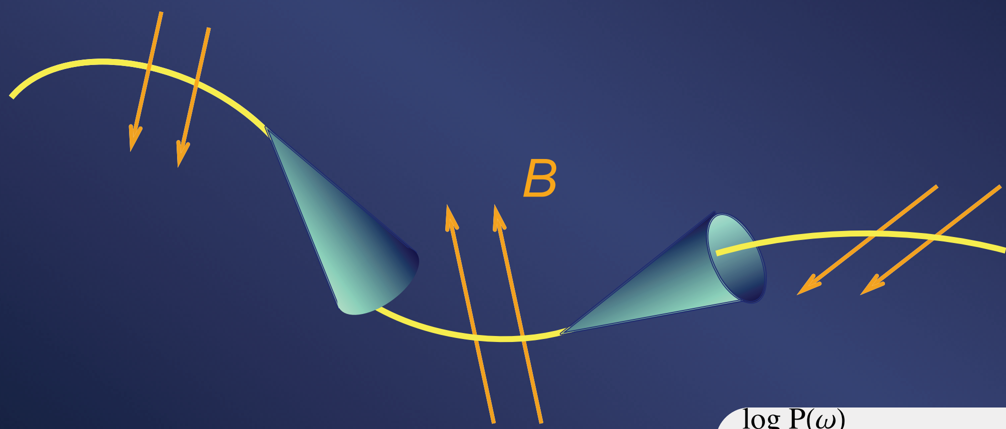
$\sim(\gamma\theta_d)^3/\omega_0\gamma^3$

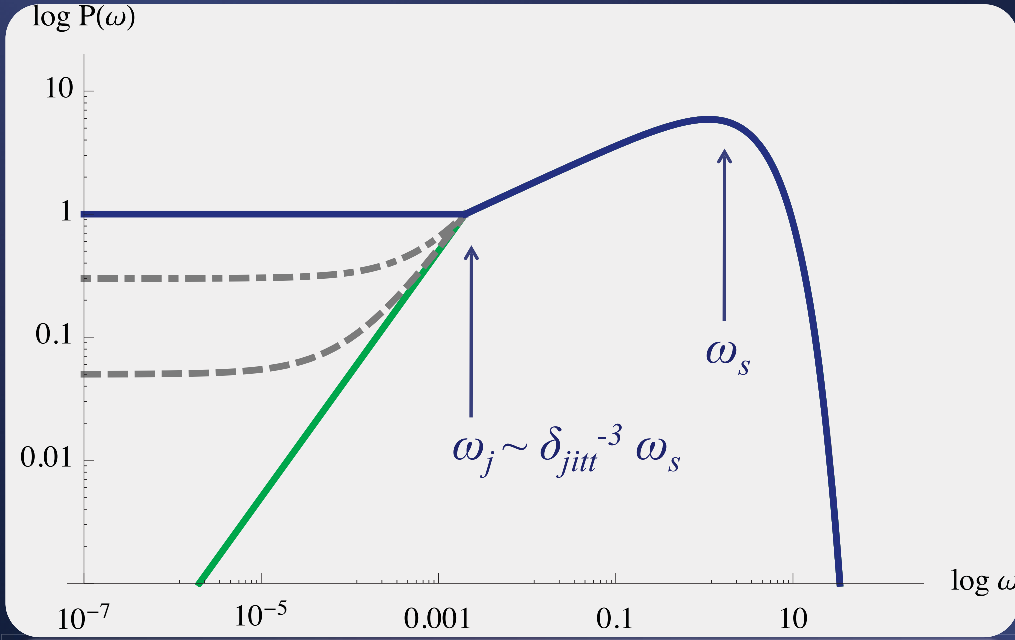
$\omega_\theta \sim 1/\Delta t_{obs}$

$\sim (\gamma\theta_d)^{-3}\omega_{synch} \sim \delta_{jitter}^{-3}\,\omega_{synch}$

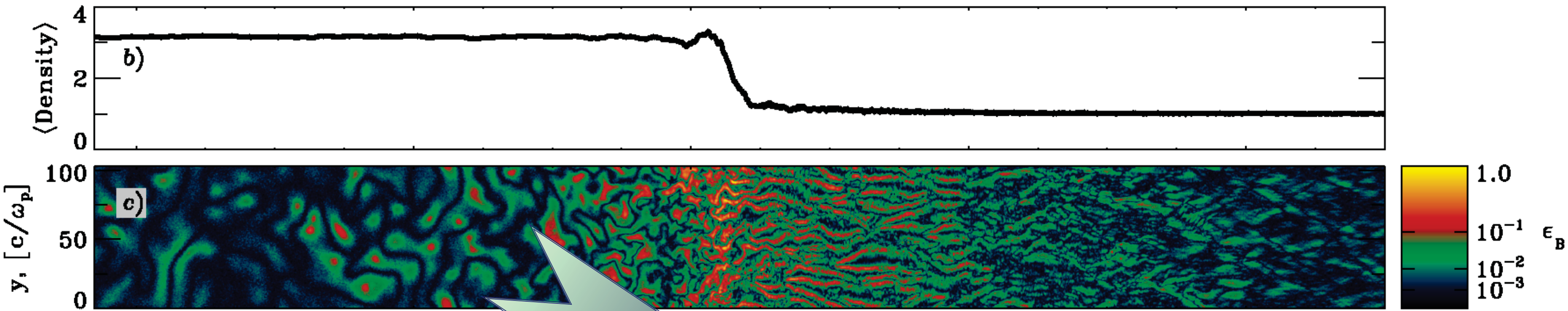
Transition regime (synchro-jitter)

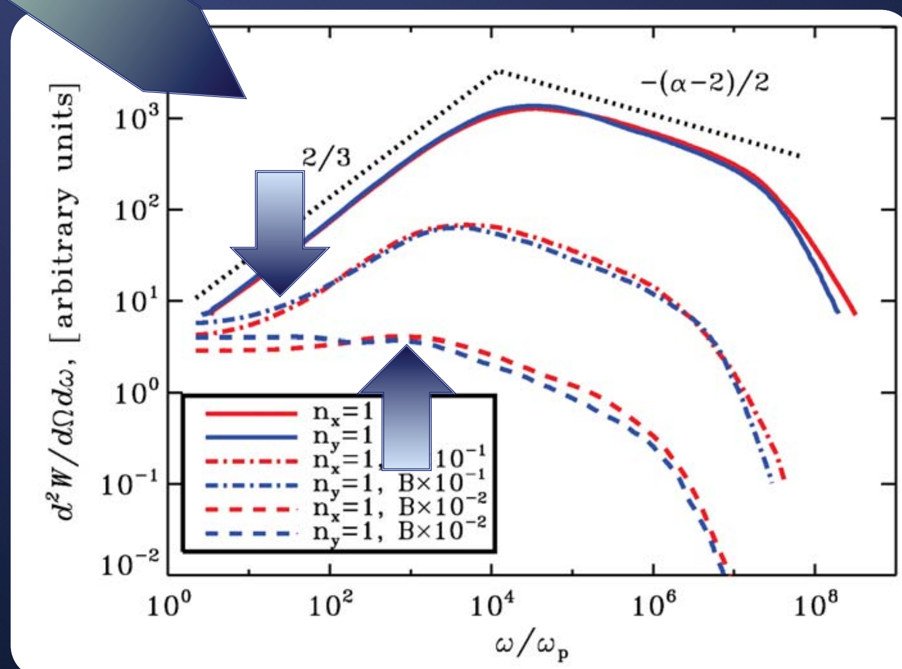
$\delta_{jitter} \sim eB\lambda/mc^2 \sim 0.6\ B_{kG}\ \lambda_{cm}$





Weibel in shocks





δ_{jitter} *(downstream)~ 30…100*

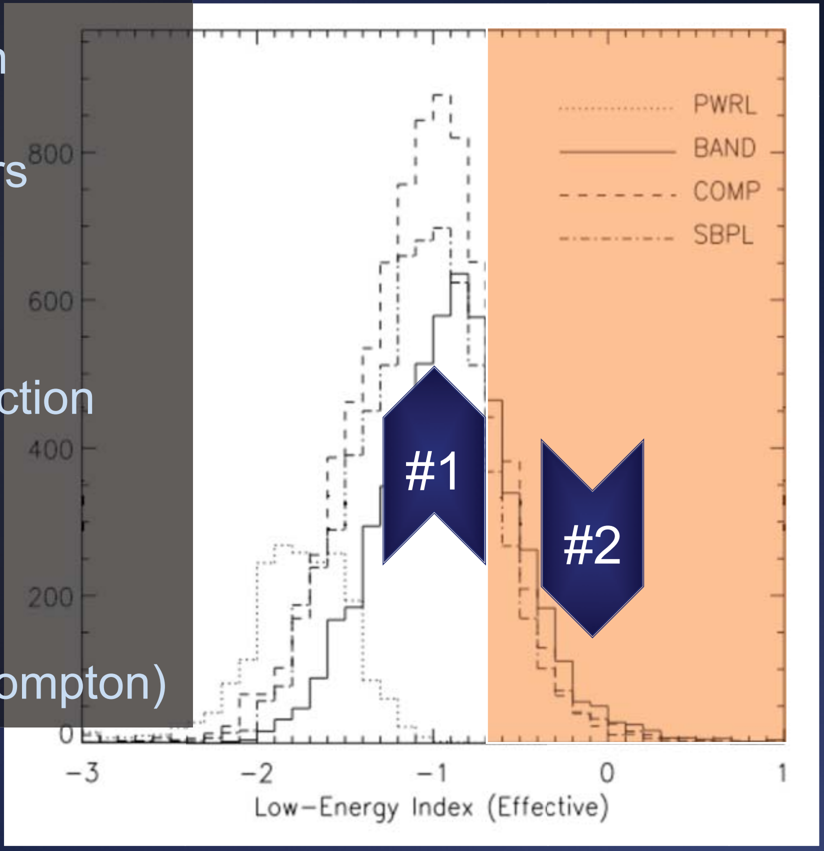
→'aged', isotropic turbulence

→diagnostics: δ_{jitt} → λ → n

(Sirony &Spitkovsky, 2009)

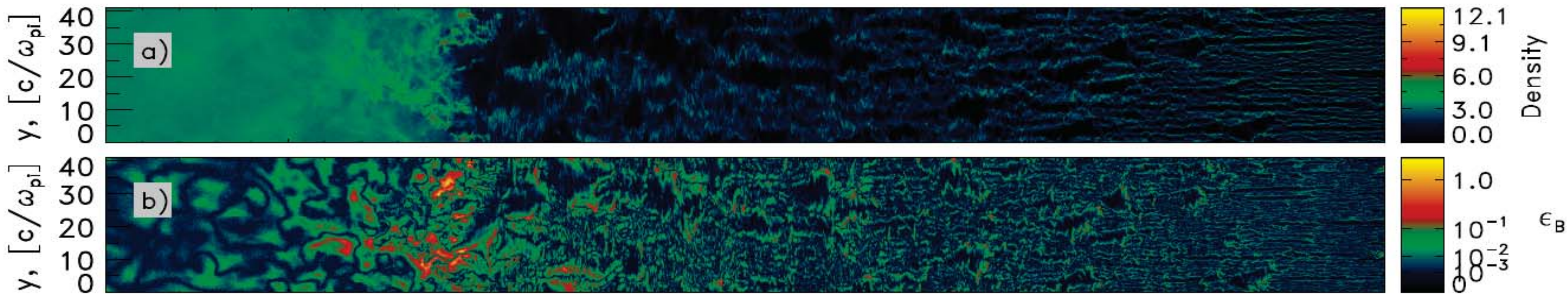
Conclusions

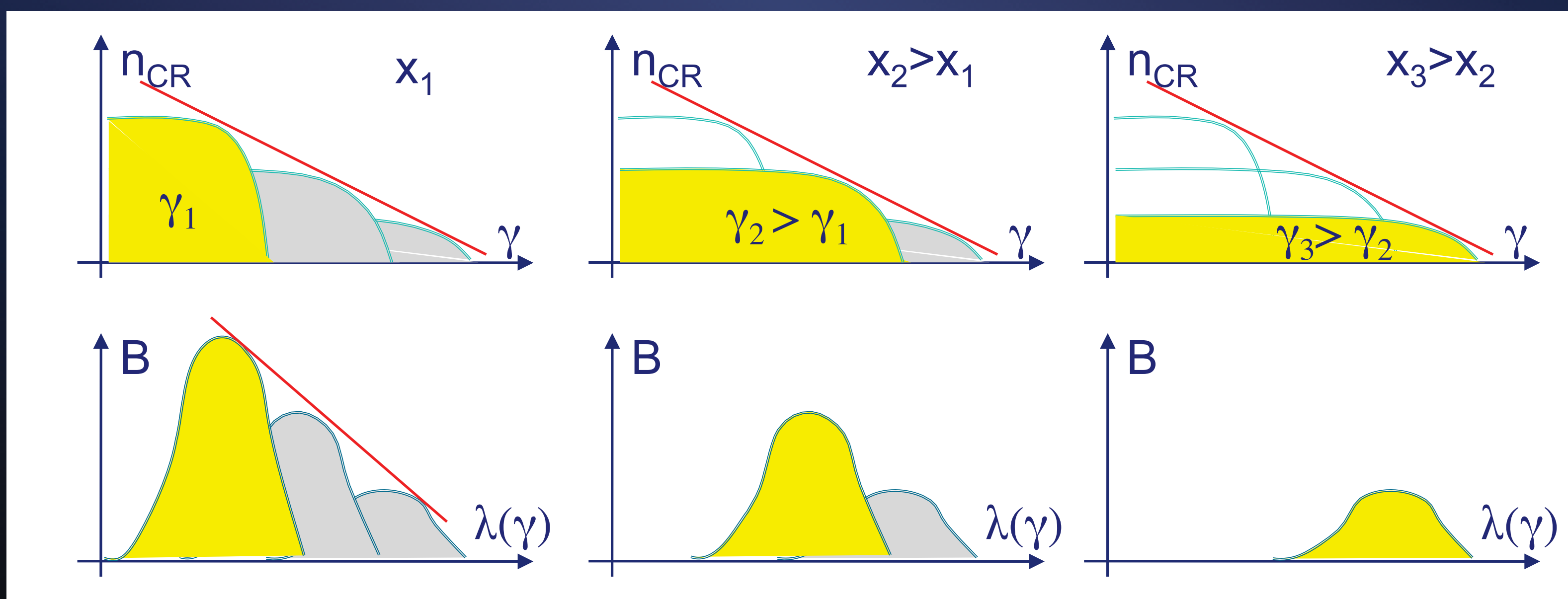
- #1 Flat spectra (~ω^0)
  - ? 'aged' Weibel turbulence → shock
    - 2D, 3D
    - foreshock/precursor contribution
    - low-Γ shocks
    - ambient (ejecta) field → whistlers
    - composition
- #2 Hard (steep) spectra ($\omega^{>1/3}$)
  - ? 'fresh' Weibel turbulence → reconnection
    - 2D, 3D, guiding field
    - reconnection regime
    - field geometry in the ejecta
    - composition
    - alternative (photosphere, self-Compton)



(Kaneko, et al, ApJS, 2006)

The model





(Medvedev & Zakutnyaya, ApJ, 2009)

Self-similar foreshock

Assume steady state and neglect nonlinear effects:

- large region upstream is strongly magnetized
- enough to explain efficient acceleration (Li & Waxman, 2006)
- large-scale fields → long life-time
- increase radiative efficiency of afterglow shocks
- source of magnetic fields in galaxy clusters, at LSS formation shocks (Medvedev, Silva, Kamionkovski, 2005)

Consequences:

- 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

$$B(x) \sim B_0\,(x/x_0)^{-\frac{s-1}{s+1}}$$

$$\lambda(x) \sim x(2\xi_B),$$

B-field spectrum near a shock

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

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

$$x_{\rm max} \sim R/(2\Gamma_{\rm sh}) \sim 5\times10^8\ x_0\ E_{52}^{1/3} n_{\rm ISM}^{-1/3} \Gamma_{\rm sh}^{-5/3}$$

Typical field within ΔR ~ R/(2Γ²):

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

$$\lambda(x_{\rm max}) \sim (10^{16}\ {\rm cm})\ E_{52}^{-1/2} n_{\rm ISM}^{1/2} R_{18}^{5/2}$$

(Medvedev & Zakutnyaya, ApJ, 2009)