Radiative Signatures of Relativistic Shocks

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PIC phenomenology

Magnetized vs *Unmagnetized* dichotomy
(relativistic e^+-e^- plasma, bulk Lorentz factor $\bar{\gamma}$
magnetization parameter $\sigma = B^2/(4\pi\bar{\gamma}nmc^2)$)

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- Reflection at magnetic barrier
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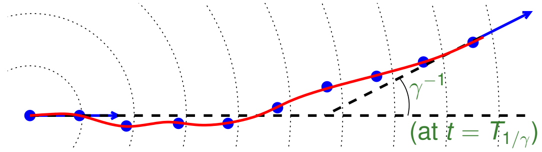
Is there a radiative signature?

Magneto-brems., diffuse synchrotron, jitter...

Incoherent (single particle) radiation determined by trajectory



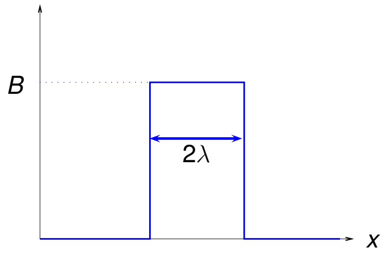
Fundamental concept: formation time T:

- Classically: time for particle to lag $\sim$ 1 wavelength behind wavefront
- QM: time needed to create photon

Formation length can be large: $T = 2\gamma^2 c/\omega$, for $T < T_{1/\gamma}$

Idealized scatterer

Strength parameter: $a = \lambda eB/mc^2$ $\quad (\delta\theta = 2a/\gamma)$



Magnetized: $a \sim \bar{\gamma}$ $\quad$ Unmagnetized: $a \sim \bar{\gamma}\sigma^{1/2}$

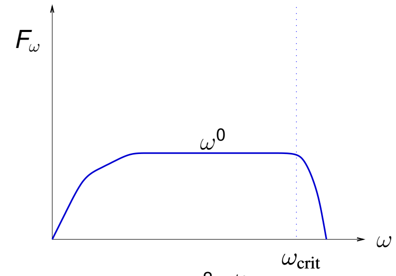
Spectrum: $a \gg 1$

- Fields constant over a formation length
- Can define a local emissivity
- 'Synchrotron' radiation (independent of whether E or B is responsible)
- Integrated over angle, low frequency spectrum is $\omega^{1/3}$, because:

$$\omega\left(t - \frac{1}{c}|\mathbf{r}(t) - \mathbf{r}(0)|\right) \approx \frac{\omega}{2\gamma^2}t - \frac{\omega c^2\kappa^2}{24}t^3$$

Spectrum: $a \ll 1$

$\delta\theta < \gamma^{-1}$, $T < T_{1/\gamma}$, formation time $T = 2\gamma^2/\omega$



$\omega_{\rm crit} = \gamma^2 c/\lambda$

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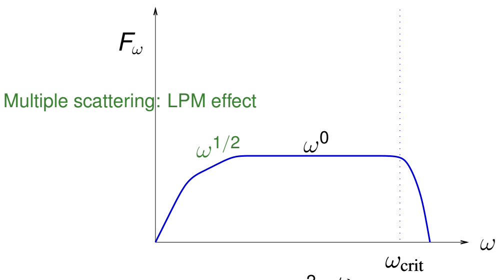

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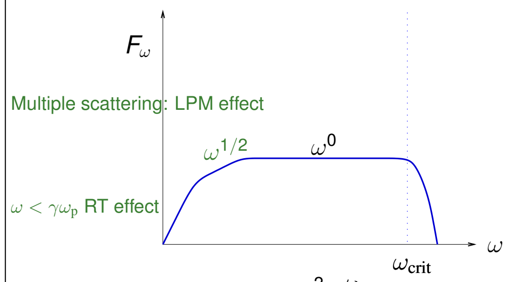

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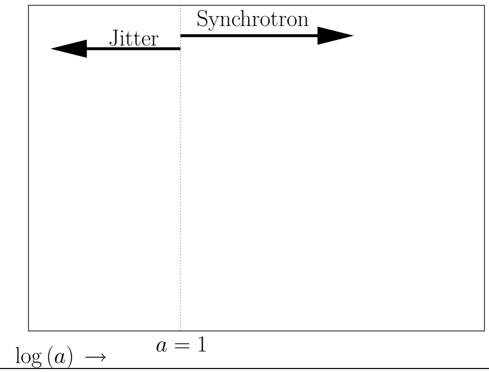
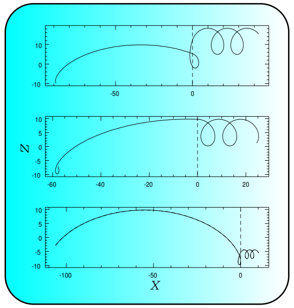
Two kinds of radiation:



1st order Fermi process

Average field orientation: $B_{\parallel} = B'_{\parallel}$, $B_{\perp} = \Gamma_{\mathrm{shock}} B'_{\perp}$.



Short-wavelength turbulence needed ($a < \bar{\gamma}$)

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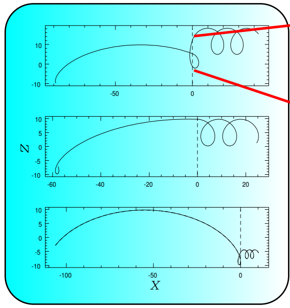

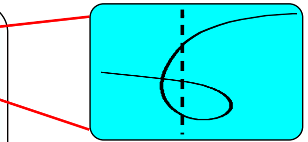

Particle overtaken in small fraction of a gyration

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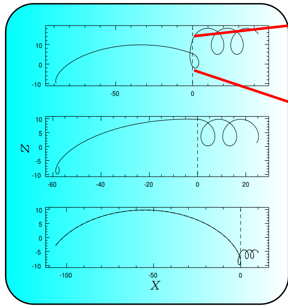

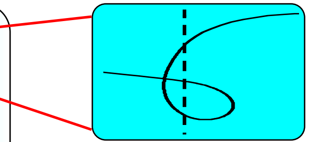

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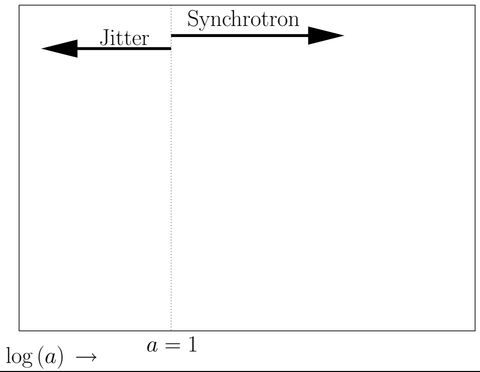

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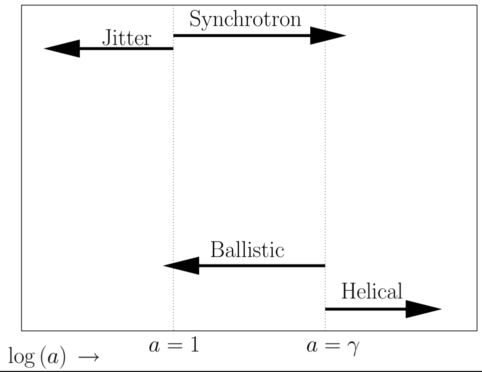

Maximum energy, maximum frequency

- Random small-angle deflections:

$$\Delta\theta = 2a/\gamma \quad (\propto B)$$

- Number of scatterings needed to isotropize:

$$N_{\mathrm{scatt}} \approx (\pi/\Delta\theta)^2$$

- Energy loss per scattering:

$$\Delta\gamma/\gamma = 2\alpha_f a b \gamma/3 \propto B^2$$

$(b = B/B_{\mathrm{crit}} = B/(4.4 \times 10^{13}\,\mathrm{G}))$

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- Acceleration/confinement, requires isotropization rate faster than energy loss rate:

$$\begin{aligned} N_{\rm scatt}\Delta\gamma/\gamma &< 1 \\ \Rightarrow \gamma &< a_{\rm crit} \\ &= \left(\frac{3mc^2\lambda}{2e^2}\right)^{1/3} \\ &= 10^6\left(n/1\,{\rm cm}^{-3}\right)^{-1/6} \end{aligned}$$

- Adding constraint in the helical regime:

$$\gamma_{\rm max} = \begin{cases} a_{\rm crit} & \text{for } a < a_{\rm crit} \\ a_{\rm crit}\sqrt{a_{\rm crit}/a} & \text{for } a > a_{\rm crit} \end{cases}$$

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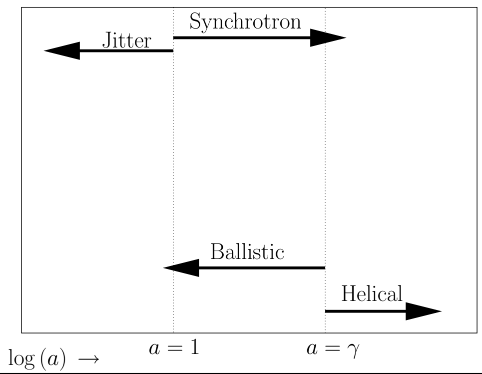

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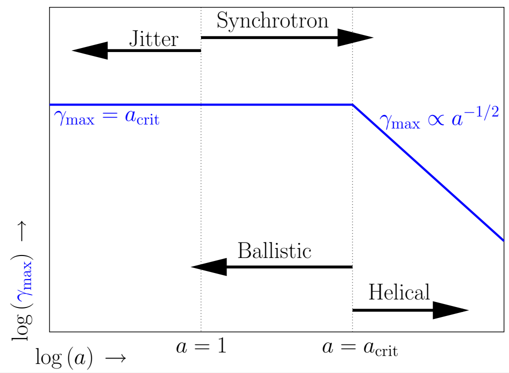

Maximum energy, maximum frequency

- Maximum energy of radiated photon (co-moving frame):

$$\frac{\hbar\omega_{\rm max}}{mc^2} = \begin{cases} (\alpha_{\rm f} a_{\rm crit})^{-1} & a < 1 \\ a\,(\alpha_{\rm f} a_{\rm crit})^{-1} & 1 < a < a_{\rm crit} \\ \alpha_{\rm f}^{-1} & a > a_{\rm crit} \end{cases}$$

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$$\hbar\omega_{\rm max} = \begin{cases} 40\,(n/1\,{\rm cm}^{-3})^{1/6}\,\bar{\gamma}^{1/6}\,{\rm eV} & a < 1 \\ 70\,{\rm MeV} & \text{for } a > a_{\rm crit} \end{cases}$$

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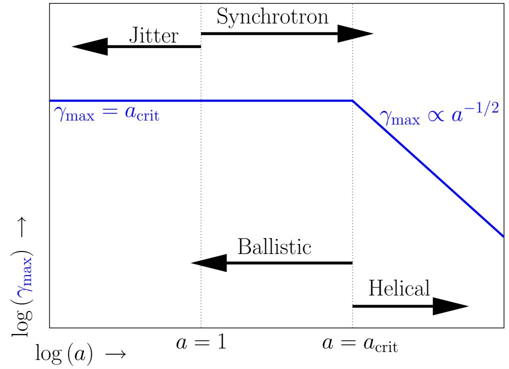

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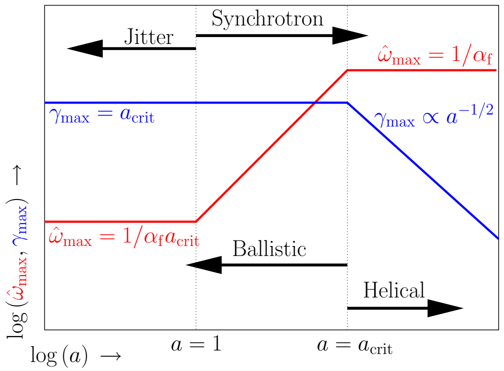

Two kinds of scatterers?

Isotropization (large λ, small B) and radiation (small λ, large B) by different scatterers?

- Define

$$\lambda_{\rm losses} = \frac{\langle B^2\lambda\rangle}{\langle B^2\rangle}$$

$$\lambda_{\rm isotrop}^{-2} = \left\langle \frac{1}{B^2\lambda^2} \right\rangle \left\langle B^2 \right\rangle$$

- Maximum energy increased if $\lambda_{\rm isotrop} \gg \lambda_{\rm losses}$:

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- Two radiation regimes: $a < 1$ (jitter), $a > 1$ (synchrotron)
- Two transport regimes: $a < \gamma$ (ballistic), $a > \gamma$ (helical)
- 1st order Fermi at relativistic shocks requires ballistic transport, $a < \gamma$
- Associated synchrotron/jitter radiation is in optical/UV independent of B (but $\nu_{\rm max} \propto {\rm density}^{1/6}$)
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