Study on synchrotron cooling of pitch-angle anisotropic electrons in relativistic magnetic reconnection

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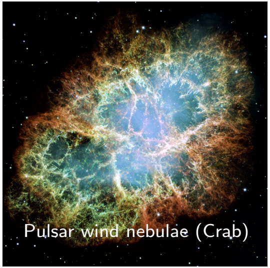
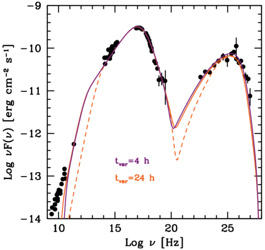
Collaborators:
Maria Petropoulou
Luca Comisso

Synchrotron radiation

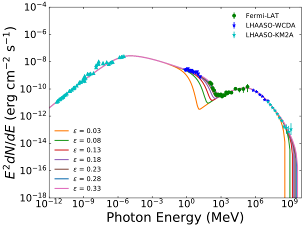
source: Sloan Digital Sky Survey



source: Hubble Space Telescope



Tavecchio, Ghisellini 2016



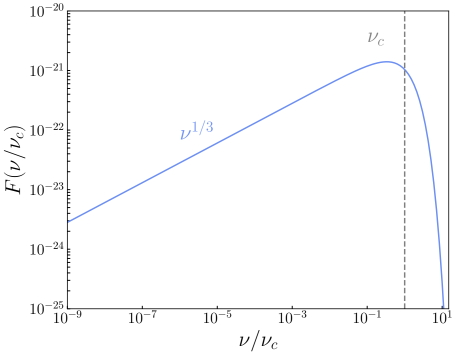
Lu Wen *et al.* 2021

Synchrotron cooling of electrons

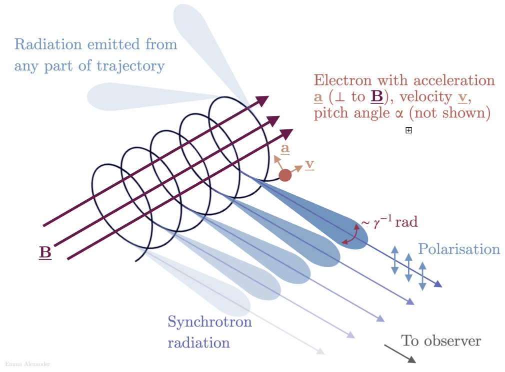
Energy losses for a single particle:

$$\dot{\gamma}_{\rm syn} = -2\frac{\sigma_T U_B \beta^2}{m_e c}\gamma^2 \sin^2\alpha, \quad t_{\rm cool} = \frac{\gamma}{|\dot{\gamma}_{\rm syn}|}$$

Single electron spectrum:



$$\nu_c \propto \gamma^2 \sin\alpha$$



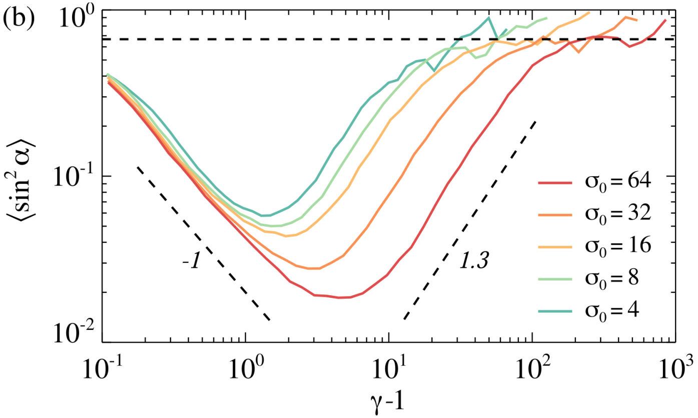
(source: Emma Alexander)

Magnetic Reconnection

Recent results from 2D PIC (Comisso *et al.* 2023)

Evidence of an **energy-dependent pitch-angle anisotropy**

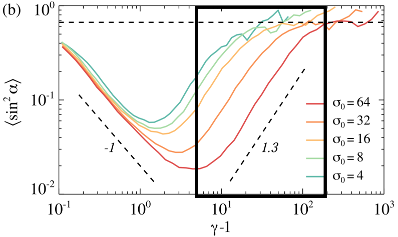
- Significant deviation from the isotropic case.
- Dependent on reconnection parameters $\sigma_0,\ B_g/B_0$.

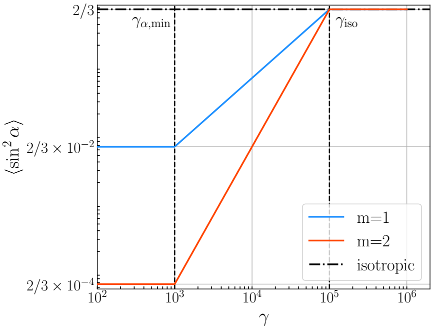


A framework for the anisotropy

Driven by PIC results

$$\langle \sin^2 \alpha \rangle = f(\gamma) = \begin{cases} \frac{2}{3}\left(\frac{\gamma_{\rm min}}{\gamma_{\rm iso}}\right)^m & , \quad \gamma \leq \gamma_{\alpha,\rm min} \\ \frac{2}{3}\left(\frac{\gamma}{\gamma_{\rm iso}}\right)^m & , \quad \gamma_{\alpha,\rm min} \leq \gamma \leq \gamma_{\rm iso} \\ \frac{2}{3} & , \quad \gamma \geq \gamma_{\rm iso} \end{cases}$$





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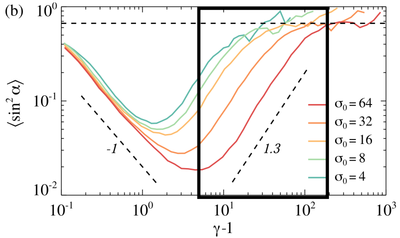

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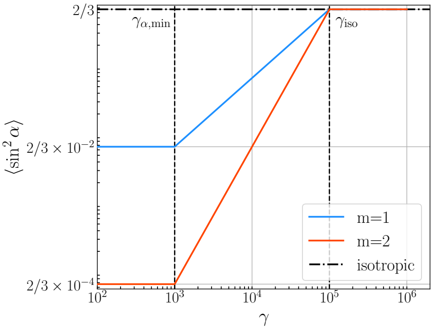


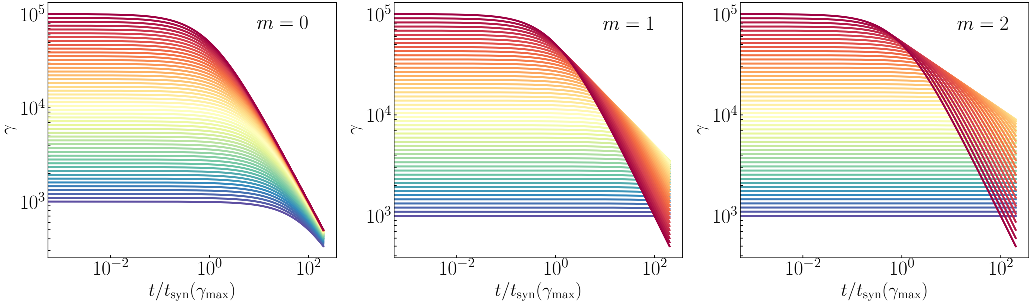
Does pitch-angle change over time?

Numerical treatment of the anisotropic cooling

Method: 2D-grid treatment

- Logarithmic grid in the $\langle \sin^2 \alpha \rangle \ - \ \gamma$ space
- Generate particles inside the cells corresponding to the injection range following a power-law distribution every time-step
- Cool them based on the characteristic and track their final state

$$\dot{\gamma}_{\rm syn} = -2\frac{\sigma_T U_B \beta^2}{m_e c}\gamma^2 \langle \sin^2 \alpha \rangle \longrightarrow \gamma(t) = \frac{\gamma_0}{A_{\rm syn}\gamma_0 f(\gamma_0) + 1}$$



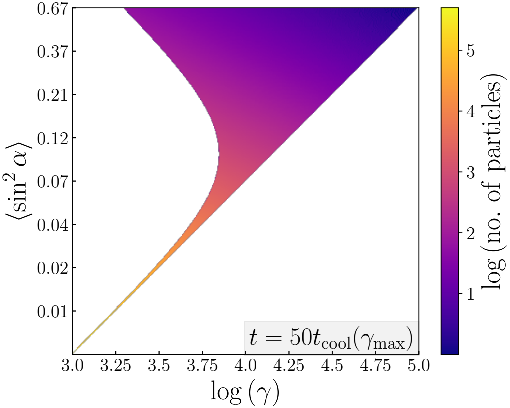
- Different asymptotic value for each γ_0

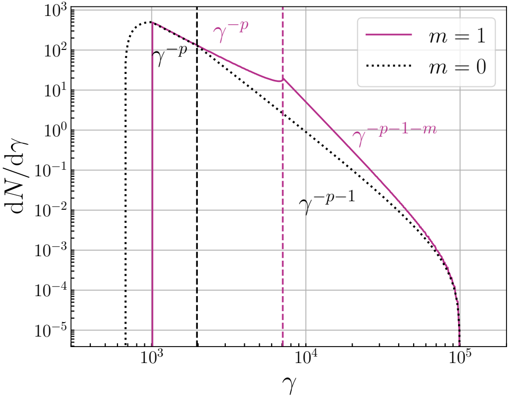
$$\lim_{t\to\infty} \gamma(t) = \left(\frac{\gamma_0}{\gamma_{\rm iso}}\right)^{-m} \frac{1}{A_{\rm syn} t}$$

- Crossing of the characteristics.

Anisotropic cooling distributions (slow cooling)

$$\boxed{Q_{\rm inj} = \gamma^{-p},\ p = 2,\ \gamma_{\min} = 10^3,\ \gamma_{\max} = 10^5}$$





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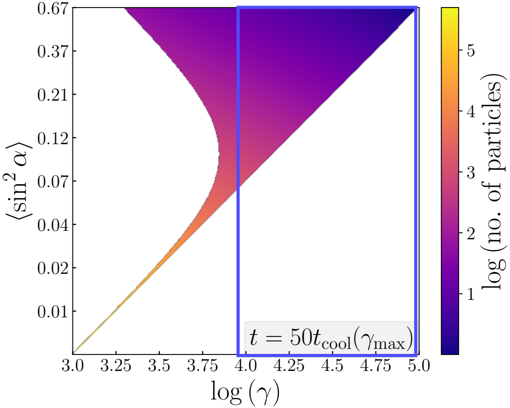

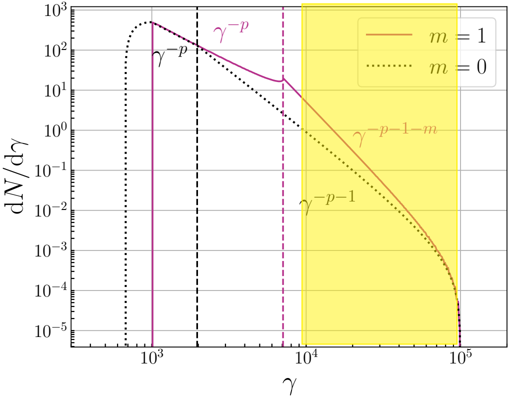

$$\dot{\gamma} \propto \gamma^2 \sin^2 \alpha$$

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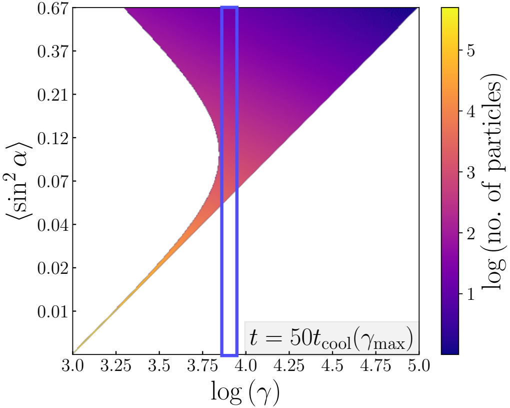
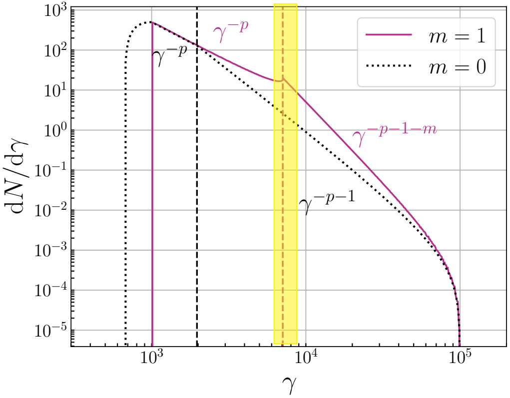


New cooling break accompanied by a bump!



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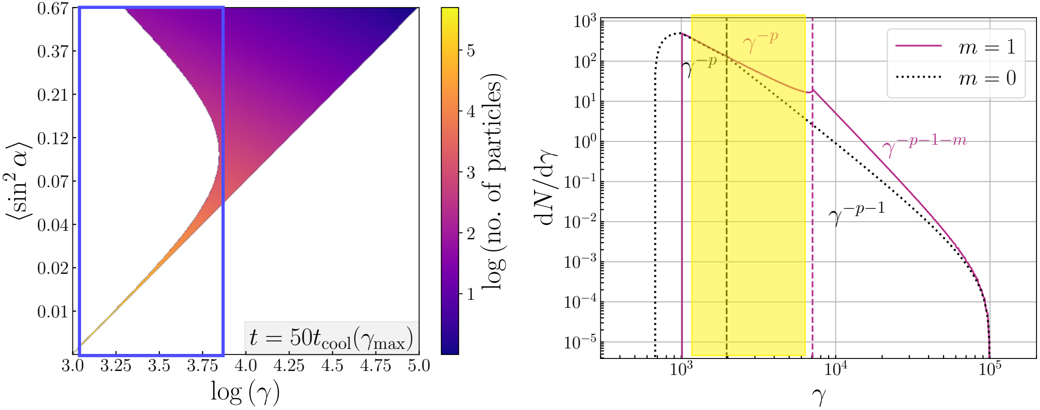

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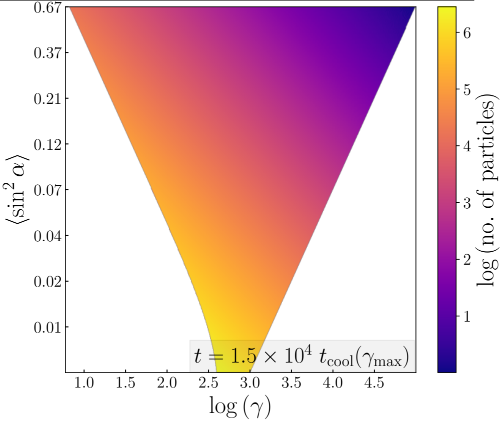

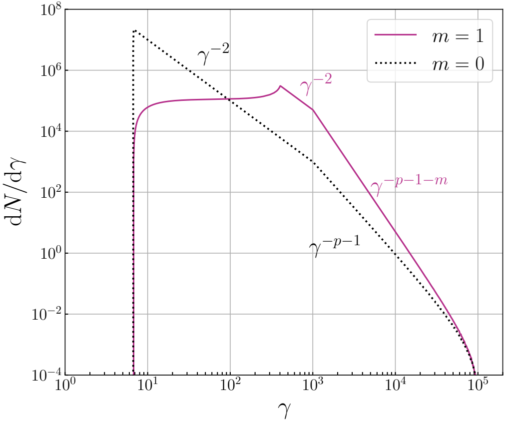

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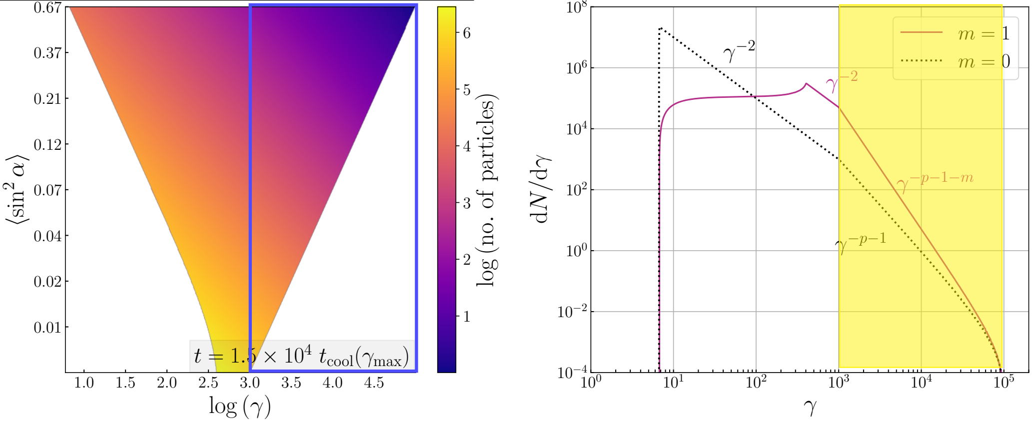

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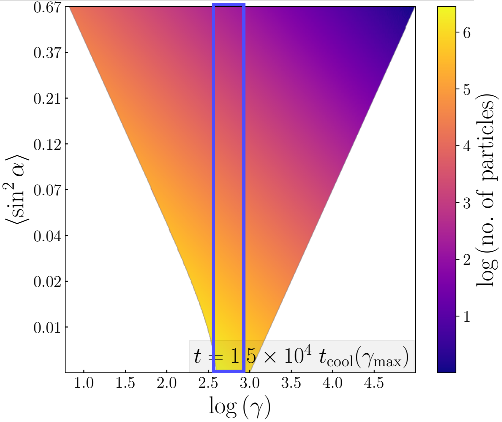

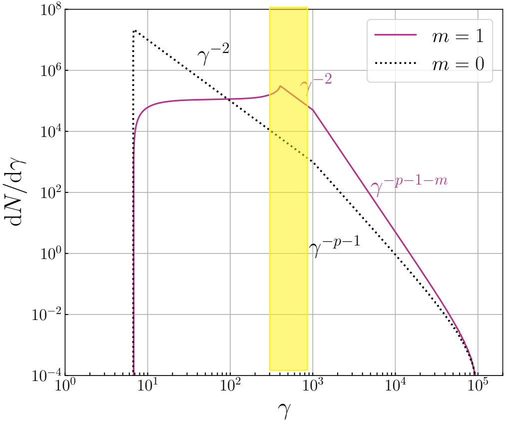

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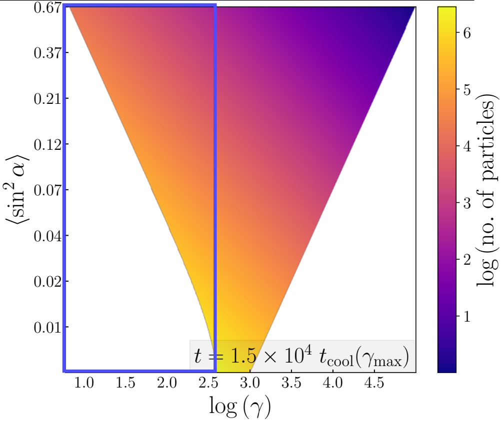
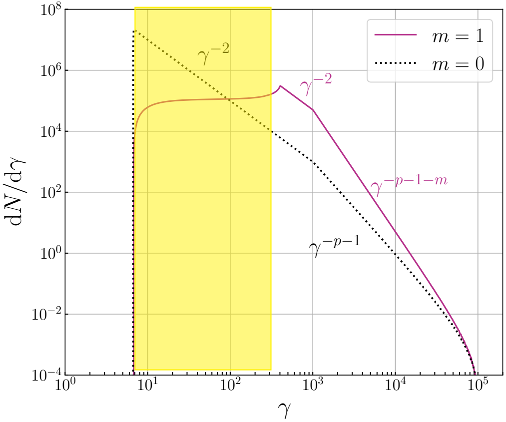


Emergence of a new component!



Anisotropic synchrotron spectra

Using the derived slopes and monoenergetic emission, we can approximate the spectral slopes by considering $\sin^2\alpha \propto \gamma^m$.

$$\nu L_\nu \propto \gamma \frac{\mathrm{d}N}{\mathrm{d}\gamma} \frac{\mathrm{d}\gamma}{\mathrm{d}t}\bigg|_{\mathrm{syn}} \propto \frac{\mathrm{d}N}{\mathrm{d}\gamma}\gamma^{m+3},$$

$$j_\nu = C\delta(\nu - \nu_c)$$

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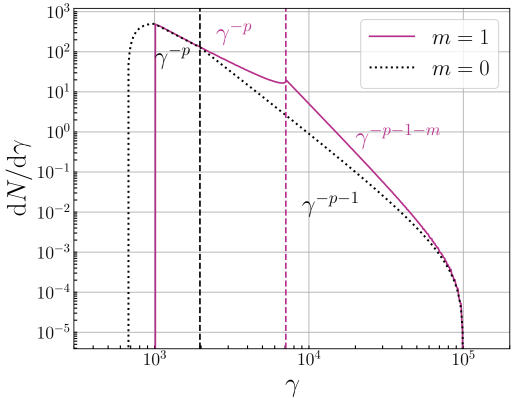
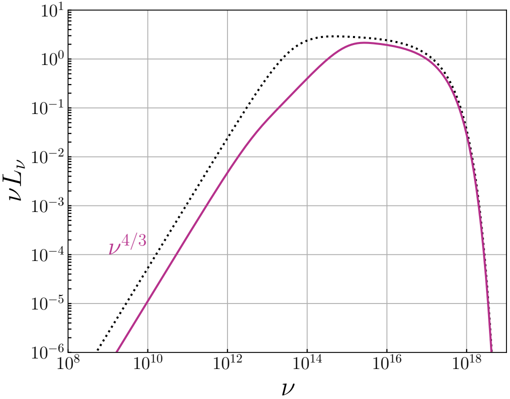
$$\nu L_\nu \propto \begin{cases} \nu^{2(3-p+m)/(m+4)} & , \quad \nu < \nu_c(\gamma_{\mathrm{br}}) \\ \nu^{2(2-p)/(m+4)} & , \quad \nu > \nu_c(\gamma_{\mathrm{br}}) \end{cases} \quad \text{slow}$$

$$j_\nu = C\delta(\nu - \nu_c)$$

$$\nu L_\nu \propto \begin{cases} \nu^{2(2-p)/(m+4)} & , \quad \nu_c(\gamma_{\min}) < \nu < \nu_c(\gamma_{\max}) \\ \nu^{2(m+1)/(m+4)} & , \quad \nu_c(\gamma_{\mathrm{br}}) < \nu < \nu_c(\gamma_{\min}) \end{cases} \quad \text{fast}$$

Anisotropic synchrotron spectra (slow cooling)





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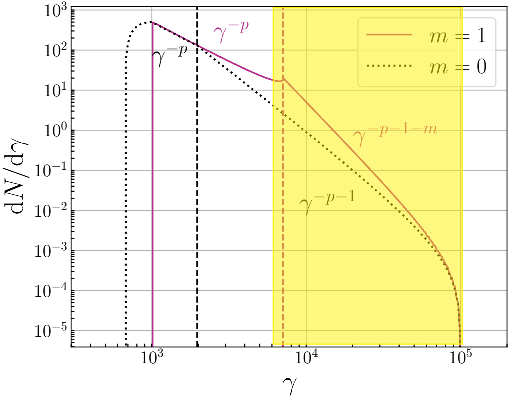

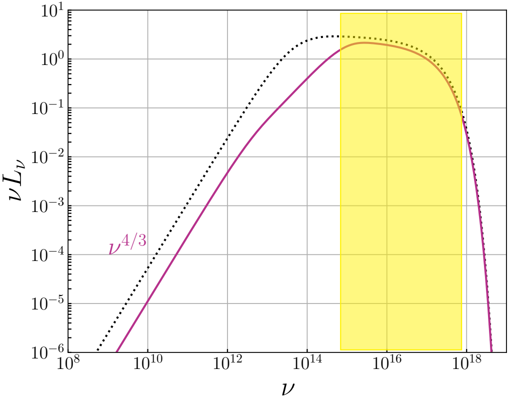

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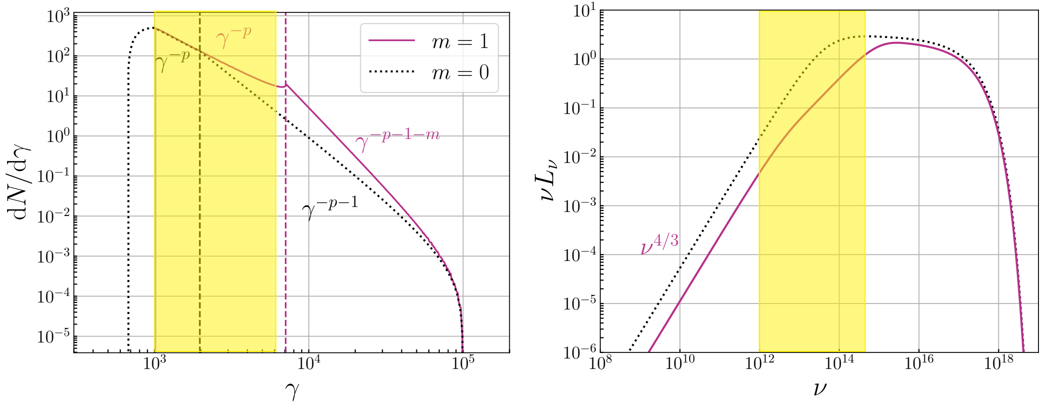
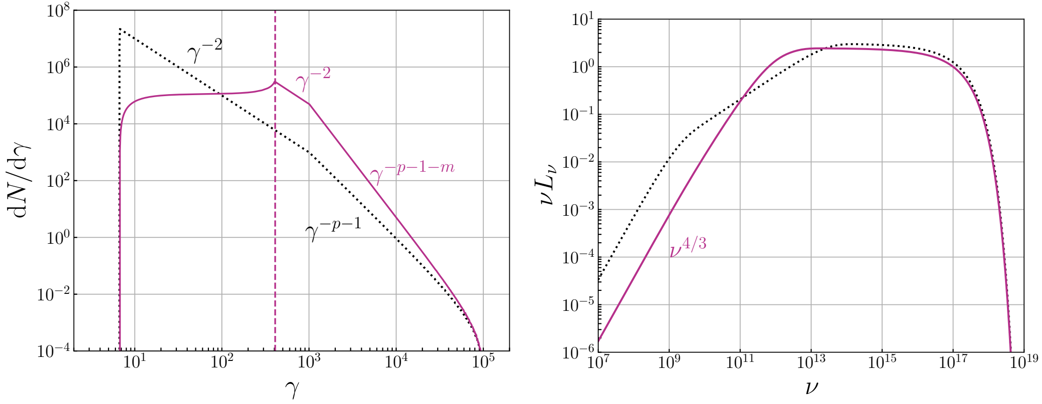


Anisotropic synchrotron spectra (fast cooling)



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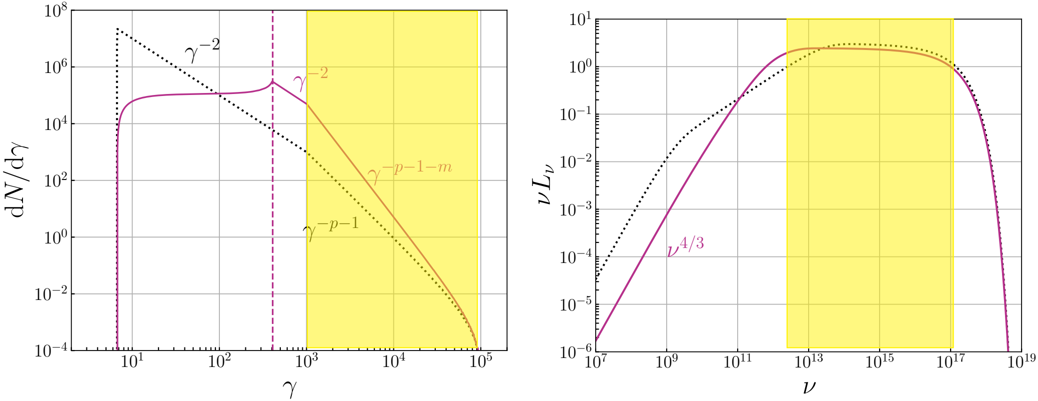

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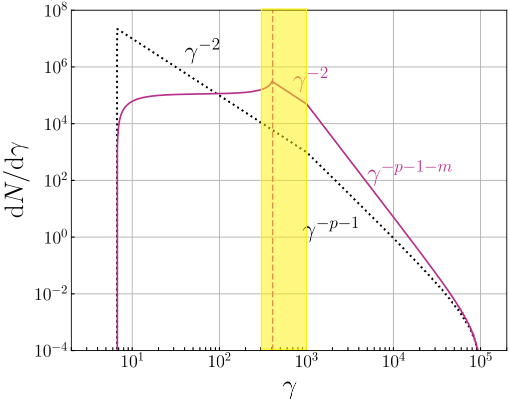

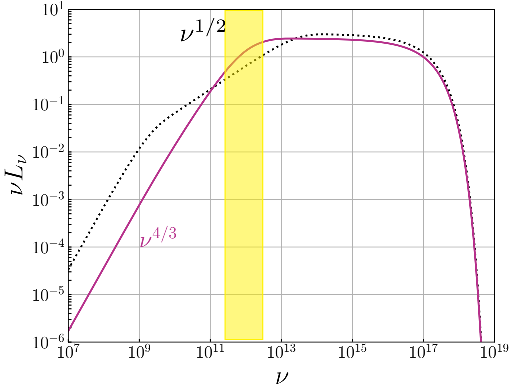

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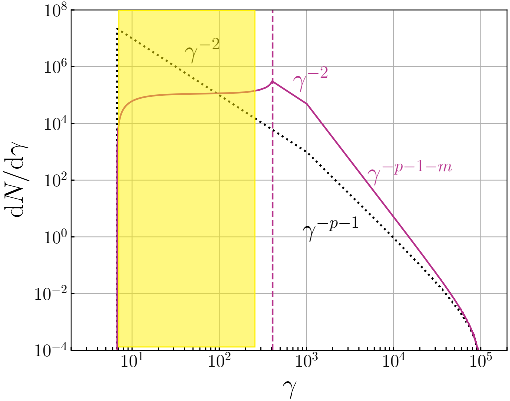

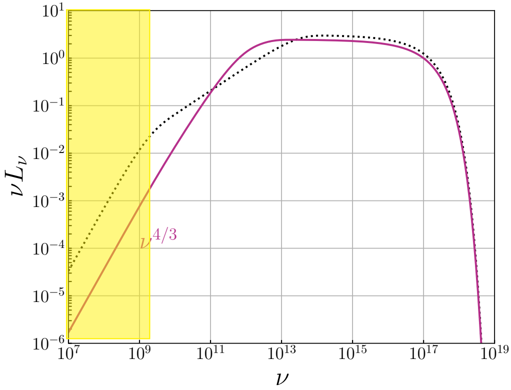

Summary

- Emergence of a new cooling break accompanied by a bump due to the crossing of characteristics.
- Decrease in the bolometric luminosity of the electron population as m increases.
- Hardening of the spectra slope at the injection range, accompanied by a broadening of the frequency range.
- Significant suppression of the non-injection dependent spectral component.
- Narrowing of the overall spectra as m increases, due to decrease of the low energy component $\nu^{4/3}$.

Future work

- Extension of the code, to include broken power-laws both in injection and pitch-angle distribution and benchmark for different σ_0 and B_g/B_0 values. Anisotropy results in 3D PIC simulations (Karavola *et al.* 2026 in prep.).
- Effects on the polarization degree of the time-integrated spectra.
- Application to observed spectra (pulsar wind nebulae, gamma-ray-bursts etc.).

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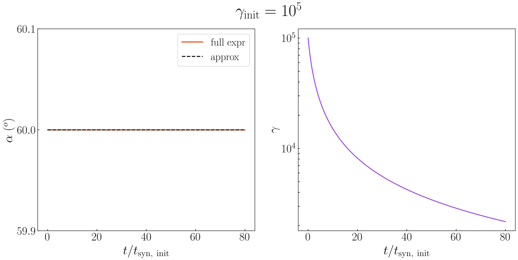
Thank you for your attention:) !

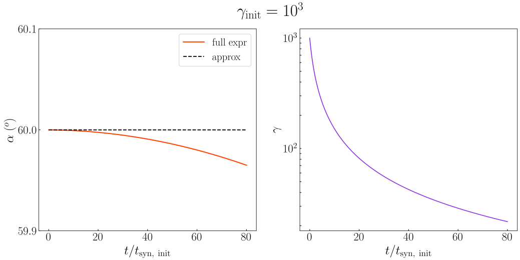
Pitch-angle rate of change

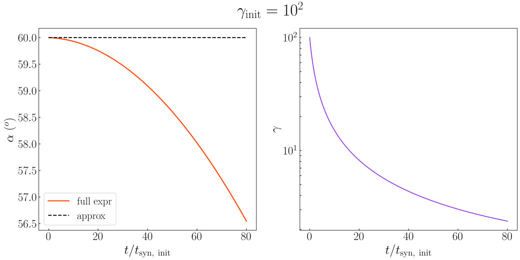
Equations of motion for a relativistic charged particle under the Lorentz force, including radiation damping yields

$$\begin{cases} \dfrac{\mathrm{d}}{\mathrm{d}t}\left(p_\perp^2\right) = -\dfrac{2q^4 B_0^2 \gamma^3}{3mc^3}\beta_\perp^4\left(1+\dfrac{1}{\gamma^2\beta_\perp^2}\right) \\[2ex] \dfrac{\mathrm{d}}{\mathrm{d}t}\left(p_\parallel^2\right) = -\dfrac{2q^4 B_0^2 \gamma^3}{3mc^3}\beta_\perp^2\beta_\parallel^2 \end{cases}$$

Pitch-angle rate of change



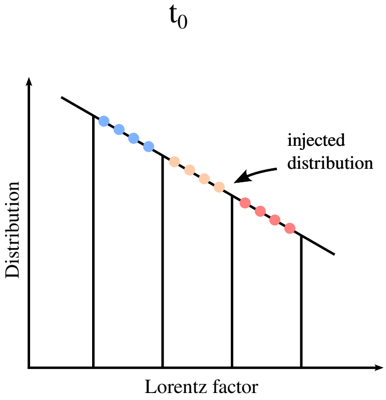


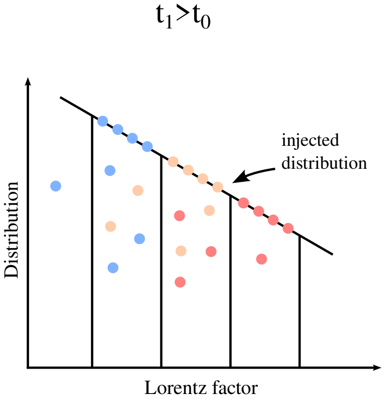


Numerical treatment of the anisotropic cooling

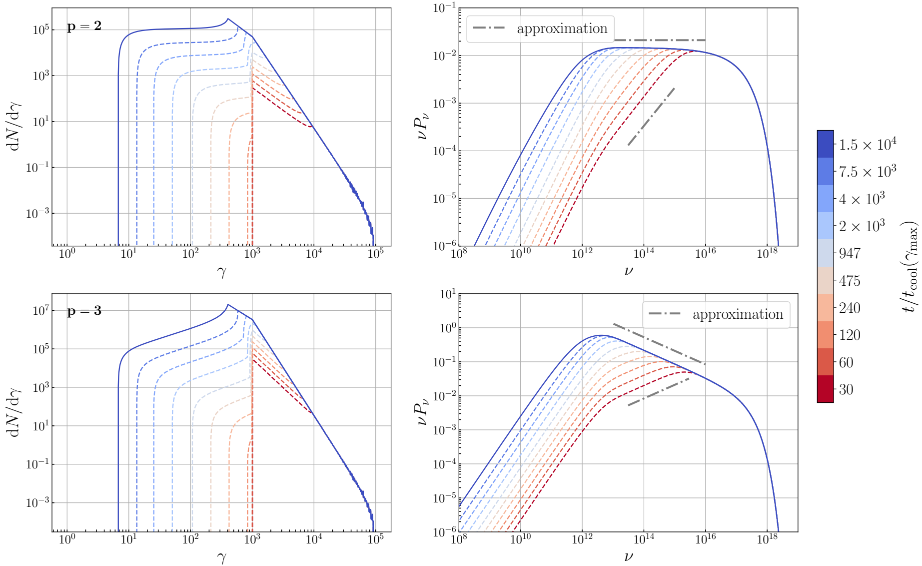
Finite difference schemes implications:

! Mixing of different pitch-angle populations in a single bin.





Time evolution plots



Spectra plots