

Gamma-Ray Emission from Galactic PeVatrons

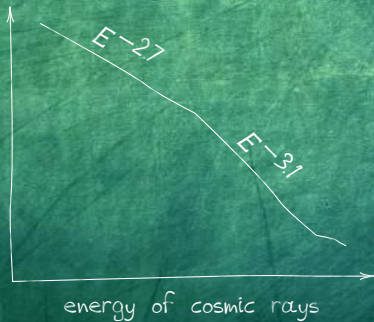
Dmitry Khangulyan

IHEP, Tianfu CRRC

The First China-Europa
Neutrino Astronomy Summer School
Chengdu, September 15th, 2026

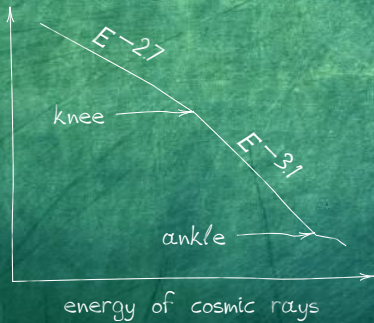
What is it about?

Gamma-Ray Emission from Galactic PeVatrons



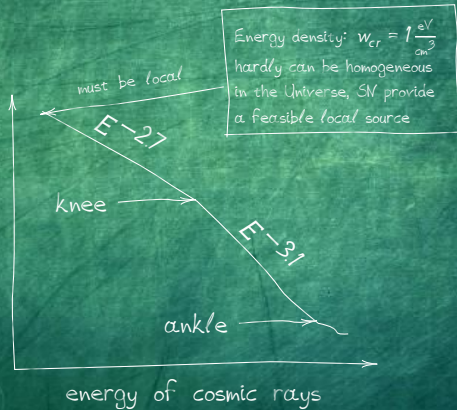
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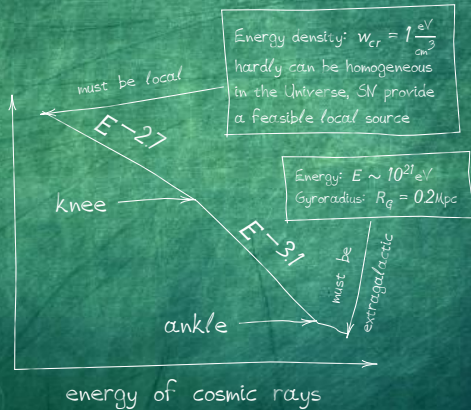
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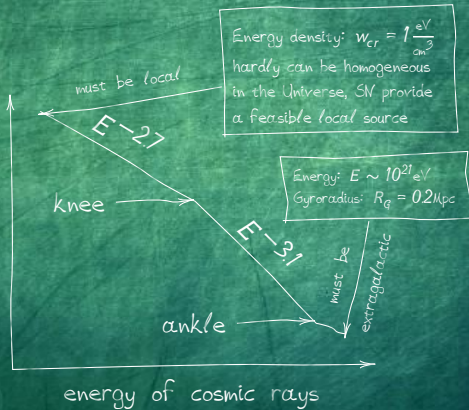
- GeV cosmic rays must be produced locally in the Milky Way
- EeV-ZeV cosmic rays must be produced outside our Galaxy
- there must be a transition between GeV and EeV energies, from the Galactic to extra-Galactic cosmic rays
- a spectral feature "knee" probably marks the onset of the decline of the Galactic component, while the Galactic-to-extragalactic transition occurs at higher energies

So "Galactic PeVatrons" mean

the most efficient Galactic accelerators

Galactic

PeVatrons



What is it about?

Gamma-Ray Emission from Galactic PeVatrons

PeV particles can interact with different targets

- magnetic field (synchrotron)
- photons (inverse Compton, $p\gamma$)
- matter (bremsstrahlung, pp)

the radiation processes vary by the interaction rate and characteristic energy of the radiated photons.

However, there are radiation channels resulting in emission of photons carrying away a significant fraction of the parent particle energy. PeVatrons should produce not just gamma-ray emission, but their emission should extend to the ultra-high-energy band (UHE, $\hbar\omega > 100\text{TeV}$).

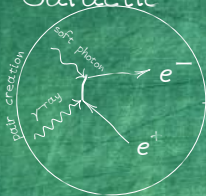
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gamma rays interact with soft photons:

$$E_\gamma = \left(\frac{\omega}{1\text{eV}} \right)^{-1} \text{TeV}$$

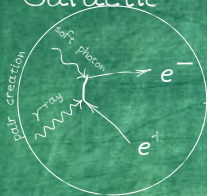
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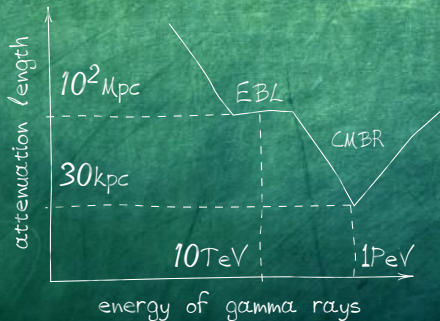
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What is it about?

Gamma-Ray Emission from Galactic PeVatrons

most extreme

most distant for UHE

- UHE gamma-ray telescopes, such as LHAASO, are the ultimate tools for studying the most extreme Galactic sources of cosmic rays
- On the Galactic scale even multi-PeV gamma-rays are moderately attenuated (still there could be significant "internal absorption")
- Compared to neutrino detectors gamma-ray telescopes have superior sensitivity
- Compared to cosmic-ray detectors gamma-ray telescopes allow measuring the spectrum in the source and provide morphological, spectral, and variability information
- Gamma-ray telescopes are best used together with multi-wavelength data

What is it about?

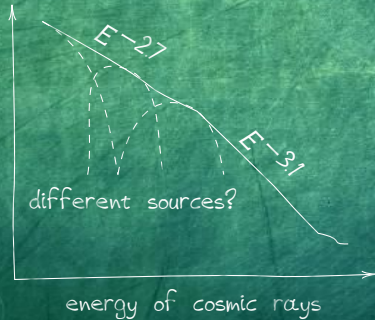
Gamma-Ray Emission from Galactic PeVatrons

Modeling of Galactic PeVatrons aims at

- Understanding the processes and conditions in the most extreme Galactic sources
- Determining the sources contributing to the knee region

While these are important for Galactic sources, detailed study of Galactic source may also help answer more general questions:

- What are the conditions required for efficient particle acceleration?
- What factors do limit the acceleration process?



Boltzmann Equations

$$\boxed{\frac{\partial f}{\partial t} + \mathbf{v} \frac{\partial f}{\partial \mathbf{r}} + \mathbf{F} \frac{\partial f}{\partial \mathbf{p}} = \left[\frac{\partial f}{\partial t} \right]_{\text{col}}}$$

- The collision integral $\left[\frac{\partial f}{\partial t} \right]_{\text{col}}$ accounts for many processes:

- particle injection
- acceleration
- scattering
- energy losses

etc - i.e., for ALL plasma and radiation physics

- In the simplest case, the Boltzmann collision integral is

$$\left[\frac{\partial f_a}{\partial t} \right]_{\text{st}} = \sum_b \int d^3 p_l v_{\text{rel}} d\sigma \left(f_a(x') f_b(x'_l) - f_a(x) f_b(x_l) \right)$$

Boltzmann Equation

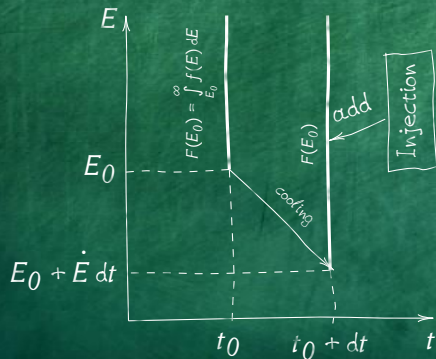
$$\frac{\partial f}{\partial t} + \mathbf{v} \frac{\partial f}{\partial \mathbf{r}} + \mathbf{F} \frac{\partial f}{\partial \mathbf{p}} = \left[\frac{\partial f}{\partial t} \right]_{\text{col}}$$

- The full microscopic collision integral is generally impractical for astrophysical source modeling
- It is possible to divide the physics included in the collision integral in two parts: complex (e.g., acceleration) and simple (cooling, which can be treated under the continuous-loss approximation)
- Also, in most cases particles are isotropic in some system, thus particle energy is a good parameter

Significant simplification in the case of energy losses

Distribution function & Injection

$$dN = f(E, t) dE \quad dN = q(E, t) dE dt$$



$$F(E, t) = \int_E^{\infty} f(E', t) dE'$$

$$F(E + \dot{E} dt, t + dt) =$$

$$F(E, t) + dt \int_E^{\infty} q(E', t) dE'$$

Fokker-Planck Equation

$$\boxed{\frac{\partial f}{\partial t} + \frac{\partial(\dot{E} f)}{\partial E} = q(E, t)}$$

Significant simplification in the case of energy losses

$$F(E + \dot{E}dt, t + dt) = F(E, t) + dt \int_E^{\infty} q(E', t) dE'$$

$$F(E, t) + \frac{\partial F}{\partial E} \dot{E}dt + \frac{\partial F}{\partial t} dt = F(E, t) + dt \int_E^{\infty} q(E', t) dE'$$

$$\frac{\partial}{\partial E} \Rightarrow$$

accounting for $\frac{\partial F}{\partial E} = -f$

$$\frac{\partial}{\partial E} \int_E^{\infty} q(E', t) dE' = -q$$

Fokker-Planck Equation

$$\boxed{\frac{\partial f}{\partial t} + \frac{\partial(\dot{E}f)}{\partial E} = q(E, t)}$$

Particle injection

$$\frac{\partial f}{\partial t} + \frac{\partial(\dot{E}f)}{\partial E} = \boxed{q(E,t)}$$

Here we do not model the acceleration process explicitly; its outcome is parametrized through

the injection term.

Typically one adopts a phenomenological description: a power-law with (super)exponential cutoff

$$q \propto E^{-\alpha} \exp \left[- \left(\frac{E}{E_c} \right)^\beta \right]$$

In the context of PeVatrons, the value of the cutoff energy is exceptionally important. Cutoff energy is typically estimated by balancing the acceleration time to loss/escape time:

$$t_{\text{acc}} \approx t_{\text{loss/esc}} \text{ where } t_{\text{acc}} = \boxed{\eta} R_G/c$$

- Acceleration time:

$$t_{\text{acc}} = \frac{E}{\dot{E}_{\text{acc}}}$$

- Particle energy gain is due to the electric field $\mathcal{E}$:

$$\dot{E}_{\text{acc}} = e\mathcal{E}v$$

- Combining these one obtains:

$$t_{\text{acc}} = \frac{E}{e\mathcal{E}v} = \eta \frac{E}{eBc}$$

since $\mathcal{E} < B$ and $v < c$ we expect $\eta > 1$

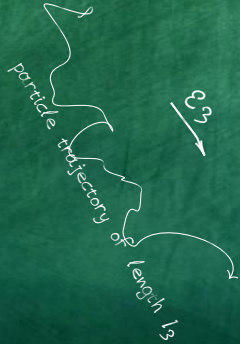
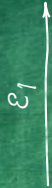
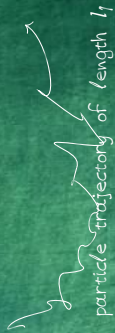
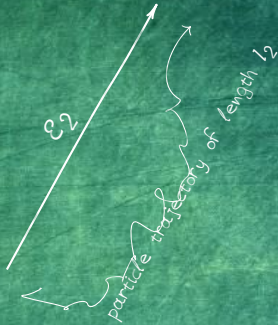
- LHAASO observations of leptonic PeVatrons suggest that $\eta \sim 1$

Acceleration Efficiency

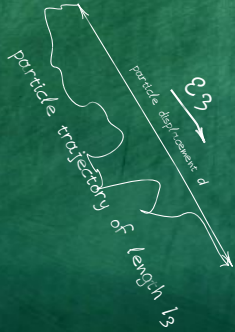
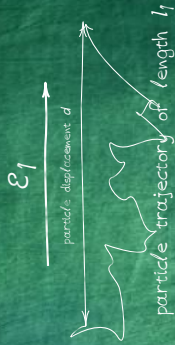
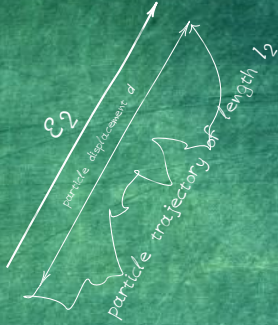
$$\mathcal{E} = -\frac{v}{c} \times B$$



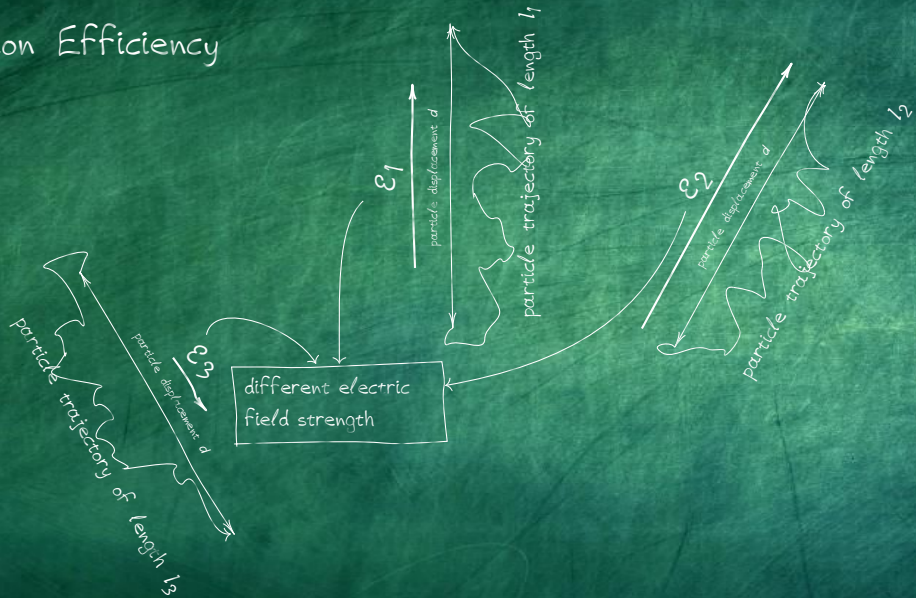
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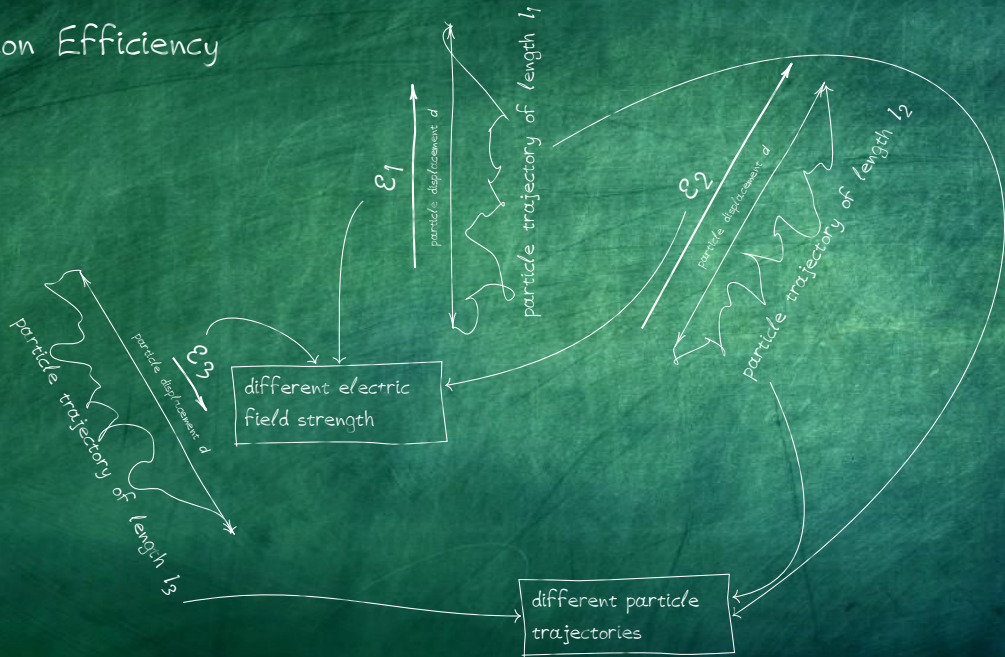
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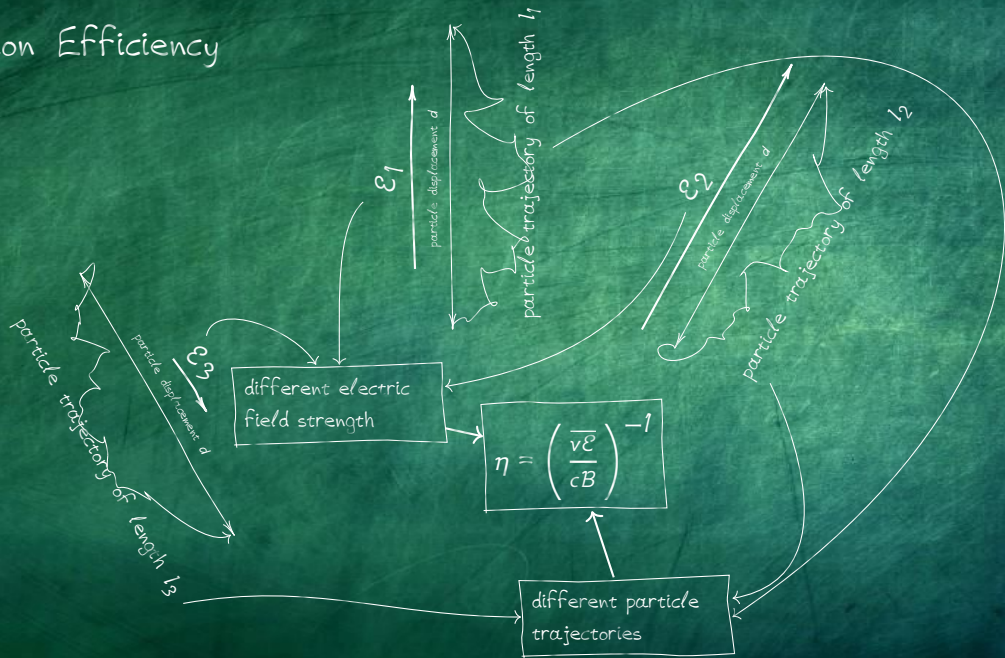
Acceleration Efficiency



Acceleration Efficiency



Acceleration Efficiency



Transport Equation with Diffusion and Escape

$$\frac{\partial f}{\partial t} + \frac{\partial(\dot{E}f)}{\partial E} - \nabla(D\nabla f) + \frac{f}{T} = q(E, \vec{r}, t)$$

also can be solved analytically for homogeneous diffusion provided that the Green function is

$$F = \frac{\delta(t - t_0 - \tau)}{\dot{E}(4\pi\lambda)^{3/2}} \exp\left[-\frac{\tau}{T} - \frac{(\vec{r} - \vec{r}_0)^2}{4\lambda}\right]$$

where

$$\lambda(E, E_0) = \int_E^{E_0} \frac{D(E')}{|\dot{E}'|} dE'; \quad \tau(E, E_0) = \int_E^{E_0} \frac{dE'}{|\dot{E}'|}; \quad q = \delta(E - E_0)\delta(t - t_0)\delta(\vec{r} - \vec{r}_0)$$

$$f = \int dE_0 dt_0 d\vec{r}_0 F q(E_0, \vec{r}_0, t_0)$$

Basic Understanding of Diffusion

$$F = \frac{\overbrace{\delta(t - t_0 - \tau)}^{\tau = t - t_0}}{\dot{E}(4\pi\lambda)^{3/2}} \exp \left[-\frac{\tau}{T} - \frac{\overbrace{(\vec{r} - \vec{r}_0)^2}^{\text{drops when } > 1}}{4\lambda} \right]$$

$$\lambda(E, E_0) = \underbrace{\int_E^{E_0} \frac{D(E')}{|\dot{E}'|} dE'}_{(t-t_0)D}; \quad \tau(E, E_0) = \underbrace{\int_E^{E_0} \frac{dE'}{|\dot{E}'|}}_{t-t_0}; \quad \overline{(\vec{r} - \vec{r}_0)^2} = 6(t - t_0)D \rightarrow v_{diff} \sim \sqrt{\frac{6D}{t-t_0}}$$

Diffusion approximation is valid if $v_{diff} \ll c$ i.e.

$$(t - t_0) \gg \frac{6D}{c^2}$$

$$\overline{(\vec{r} - \vec{r}_0)^2} \gg \left(\frac{6D}{c} \right)^2$$

Typical diffusion regimes

"Bohm limit" $D = \frac{Ec}{3eB} = 10^{25} \frac{E_{TeV}}{B_{5\mu G}} \text{ cm}^2/\text{s}$

"Galactic limit" $D = D_* \left(\frac{E}{E_*} \right)^\delta$

$\delta \approx 0.5$ and $D_* = 10^{29} \text{ cm}^2/\text{s}$ for $E_* = 1 \text{ TeV}$

Diffusion approximation

$$t - t_0 \gg 0.2 D_{27\text{yr}}$$

$$\overline{(\vec{r} - \vec{r}_0)^2} \gg (0.1 D_{27\text{pc}})^2$$

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electrons: $t_{syn} =$

$$500 \left(\frac{B}{5\mu G} \right)^{-2} \left(\frac{E}{1 \text{ PeV}} \right)^{-1} \text{ yr}$$

protons: $t_{pp} =$

$$30 \left(\frac{n}{1 \text{ cm}^{-3}} \right)^{-1} \text{ Myr}$$

Diffusion approximation

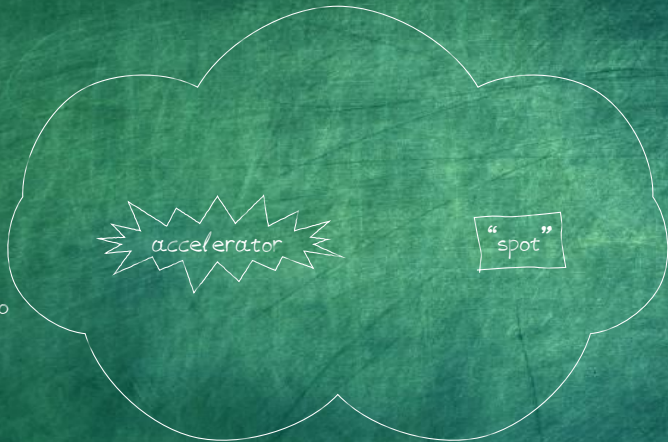
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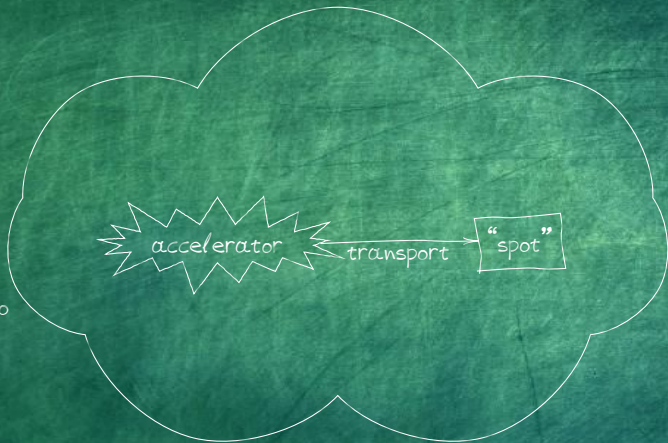
Spectral Morphology

- There is an extended source, which features a localized accelerator
- We can detect emission from two distinct regions inside the source, "accelerator" and "spot" (accumulation of particles or enhanced target)
- How can we use the spectral data to distinguish one another?



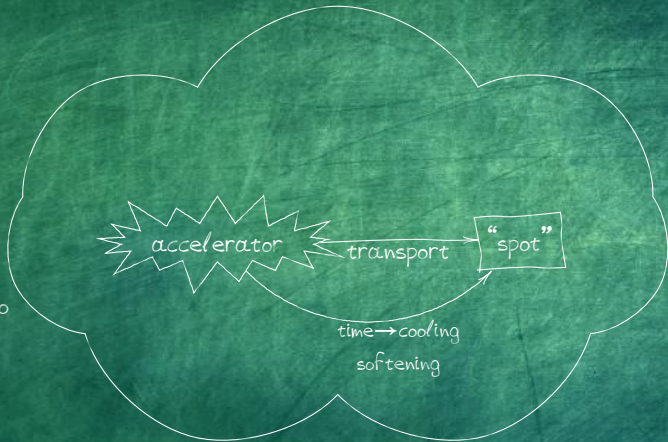
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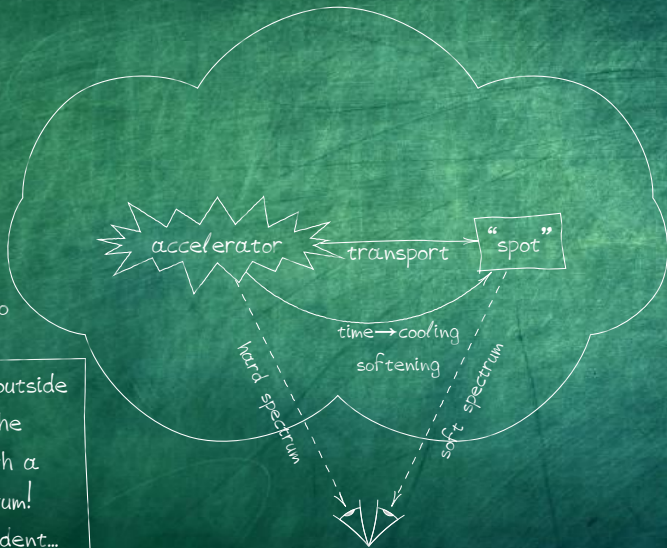
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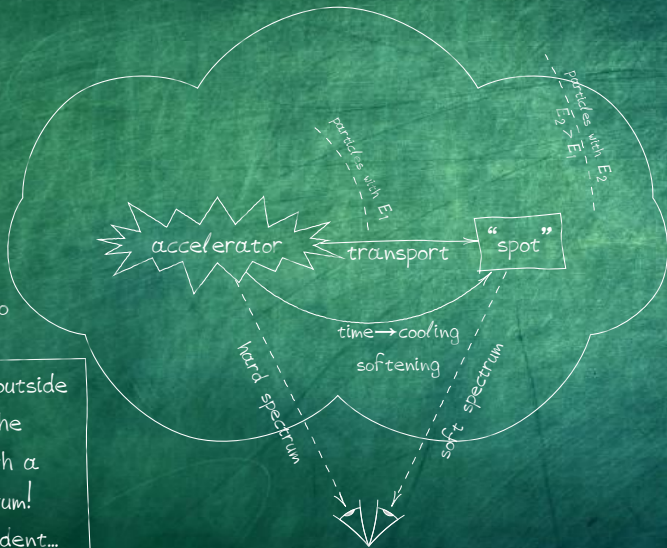
Particle cooling makes the spectra outside the accelerator to be softer, thus the accelerator should be associated with a region that shows the hardest spectrum!
But the transport can energy-dependent...



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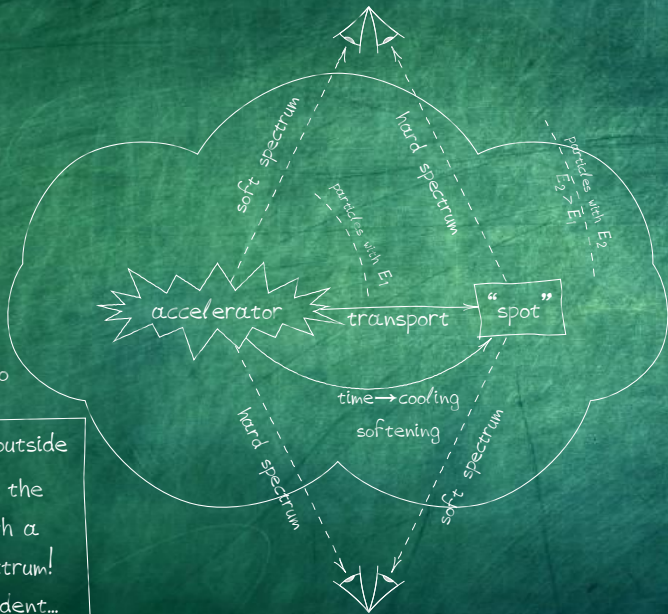
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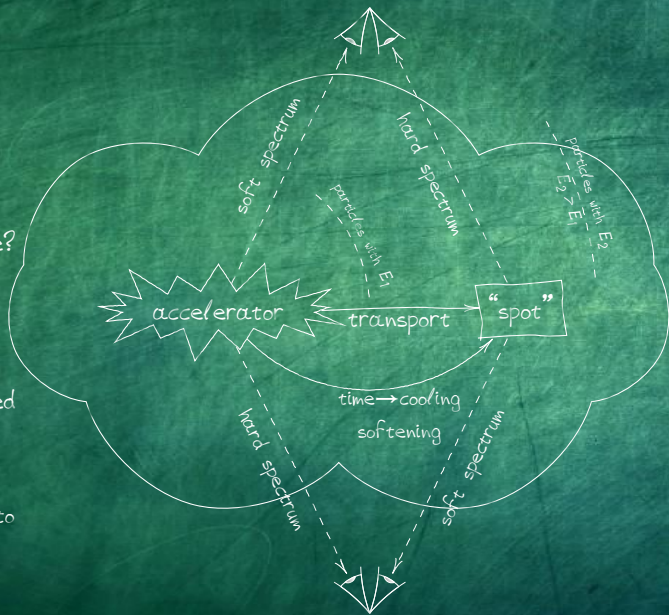
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Particle cooling makes the spectra outside the accelerator to be **harder!** softer, thus the accelerator should be associated with a region that shows the **softest!** ~~hardest~~ spectrum!
But the transport can energy-dependent...



Spectral Morphology

- Does diffusion dominate over advection?
 - * Advection transport is energy-independent
- Is diffusion approximation applicable?
 - * If not, microscopic transport calculations might be required
- Is cooling important on the considered time scale?
 - * In intermediate cases only numerical simulations might help to interpret the data



Emission by Relativistic Particles

Radiation mechanisms are determined by the source of energy (particle) and the target. Different processes are characterized by noticeably different cross-sections and frequencies at which the emission is produced. In addition to electromagnetic emission some processes also enable production of neutrinos. In many cases the energy loss-rate is a more convenient characteristic than the cross-section:

$$\dot{E} = v_{rel} \sigma n_{tar} f E$$

where v_{rel} is relative speed (for a target at rest $v_{rel} = c$), n_{tar} is target density, f is inelasticity (fraction of the particle energy lost in each interaction). Another useful characteristic is cooling time

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If a particle with energy E predominantly emits at $\hbar\omega \propto E^\beta$, and the energy loss-rate is $\dot{E} \propto E^\gamma$, then a power-law distribution of particles render a power-law distribution of photons:

$$\frac{dN_\omega}{d\omega} \propto \int dE \frac{\dot{E}}{\omega} \delta(\omega - E^\beta) E^{-\alpha}$$

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$E = u^{1/\beta}$

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$\frac{du}{E^{\beta-1}} E^{\gamma-\beta} \quad E = u^{1/\beta}$

This δ -functional approximation provides reasonable results in the spectrum is a powerlaw. However, close to the cutoff regions, one should use more accurate approaches. For example, the particle spectrum and single-particle spectra are:

$$\boxed{\frac{dN}{dE} \propto E^{-\alpha_1} \exp\left[-\left(\frac{E}{E_c}\right)^{\alpha_2}\right]} \quad \text{and} \quad \boxed{\frac{dN_\omega^{(0)}}{d\omega} \propto A(E) \omega^{\beta_1} \exp\left[-\left(\frac{\omega}{\omega_c(E)}\right)^{\beta_2}\right]}$$

particles single particle emission

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$$\frac{dN}{d\omega} \propto \int \underbrace{dE}_{\frac{du}{E^{\beta-1}}} \underbrace{\left[\frac{\dot{E}}{\omega} \right]}_{E^{\gamma-\beta}} \underbrace{\delta(\omega - E^\beta)}_{E = u^{1/\beta}} E^{-\alpha} \propto E^{-\frac{\alpha+2\beta-\gamma-1}{\beta}}$$

This δ -functional approximation provides reasonable results in the spectrum is a powerlaw. However, close to the cutoff regions, one should use more accurate approaches. For example, the particle spectrum and single-particle spectra are:

$$\boxed{\frac{dN}{dE} \propto E^{-\alpha_1} \exp\left[-\left(\frac{E}{E_c}\right)^{\alpha_2}\right]} \quad \text{particles} \quad \text{and} \quad \boxed{\frac{dN_{\omega}^{(0)}}{d\omega} \propto A(E) \omega^{\beta_1} \exp\left[-\left(\frac{\omega}{\omega_c(E)}\right)^{\beta_2}\right]} \quad \text{single particle emission}$$

$$\boxed{\frac{dN_{\omega}}{d\omega} = \int dE \frac{dN_{\omega}^{(0)}}{d\omega} \frac{dN}{dE}}$$

Emission by Relativistic Particles

Radiation mechanisms are determined by the source of energy (particle) and the target. Different processes are characterized by noticeably different cross-sections and frequencies at which the emission is produced. In addition to electromagnetic emission some processes also enable production of neutrinos. In many cases the energy loss-rate is a more convenient characteristic than the cross-section:

$$\dot{E} = v_{rel} \sigma n_{tar} f E$$

where v_{rel} is relative speed (for a target at rest $v_{rel} = c$), n_{tar} is target density, f is inelasticity (fraction of the particle energy lost in each interaction). Another useful characteristic is cooling time

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Can we get it analytically?

Shape of the Cutoff

Cutoff energy and the shape of the spectrum in the cutoff region provides very important information about high-energy processes. It is quite common to link the cutoff energy to the emission of highest energy particles in the source, i.e., a proxy for the acceleration efficiency. However, it is also important to remember about other possibilities, e.g.

- the cutoff can be caused by a process external to the source (e.g., EBL attenuation)
- the cutoff can be caused by a change of radiation regime (e.g., Klein-Nishina cutoff)

Let us obtain the intrinsic cutoff caused by the turnover in the particle spectrum. For the sake of simplicity, let us assume that $\omega_c = \Omega_c E^{\beta_3/\beta_2}$.

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Shape of the Cutoff

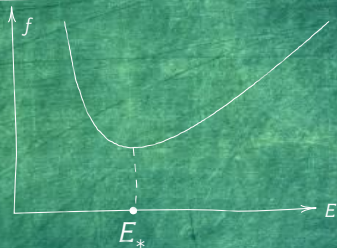
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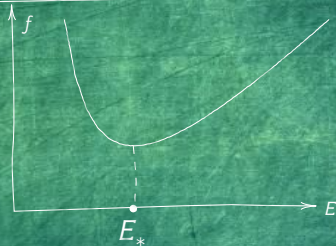
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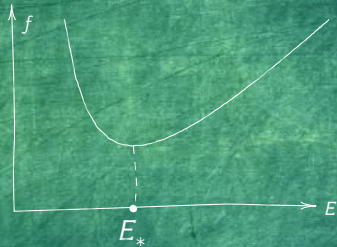
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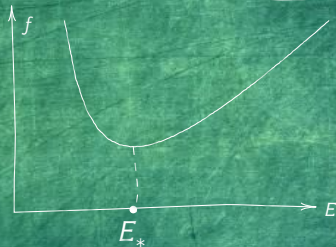
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$$\frac{dN}{d\omega} \propto \underbrace{\left[\frac{\omega^{\beta_1}}{E_*^{\alpha_1}} \frac{A(E_*)}{\sqrt{f''(E_*)}} \right]}_{\text{power factor}} \exp \left[- \left(1 + \frac{\beta_3}{\alpha_2} \right) \left(\frac{\omega}{\Omega_c} \right)^{\beta_2} E_*^{-\beta_3} \right]$$

$$\text{exponent: } \propto \exp \left[- \left(\frac{\omega}{\omega_*} \right)^{-\frac{\alpha_2 \beta_2}{\alpha_2 + \beta_3}} \right]$$

Summary

- PeVatrons represent the most extreme Galactic accelerators
- UHE gamma-ray emission is expected to be a feature of such sources
- $\gamma\gamma$ attenuation limits the scope of UHE astronomy to the Galactic scales
- The Fokker-Planck Equation is the simplest approach that allows to address self-consistently injection and cooling
- Acceleration efficiency parameter can have a simple physical interpretation, which may challenge some phenomenological interpretations
- PeV particles can propagate significant distances implying the necessity for multi-zone models (or solving the transport equations)
- Depending on the dominant transport mechanism one can obtain opposite predictions
- Studying sources close to their acceleration limit requires accurate treatment of the cutoff shapes, which goes beyond the simple δ -functional approximations