Non-Thermal Radiation

Nataly Ospina *(Istituto Nazionale di Fisica Nucleare)*

Non-Thermal Radiation

- Non-Thermal Radiation
- Thermal radiation vs Non-Thermal radiation
- Hadronic Processes:
  - Proton-proton collisions
  - Pion production & decay
  - Gamma-ray and neutrino emission

Thermal radiation:

- Electromagnetic emission produced by matter in (global or local) **thermodynamic equilibrium**
- Spectrum depends only on **temperature**
- Characterized by **blackbody radiation**

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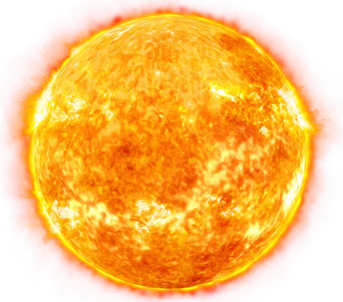
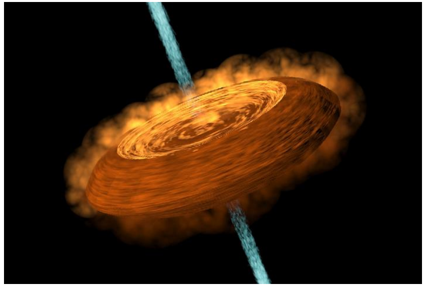
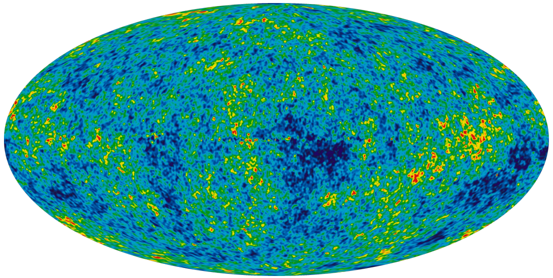


Stars



Accretion disks around BHs or young stars



CMB radiation

Dust emission in IR/sub-mm

Planck spectrum:

$$B_\nu(T) = \frac{2}{c^2}\frac{h\,\nu^3}{e^{\frac{h\nu}{k_B T}} - 1}$$

$$B_\lambda(T) = 2c^2\frac{h/\lambda^5}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

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Integrating over frequency => **Stefan–Boltzmann law:**

energy density: $$u(T) = \frac{4}{c}\sigma_B\, T^4$$

integrated density: $$B(T) = \frac{1}{\pi}\sigma_B T^4$$

emergent flux: $$F(T) = \sigma_B\, T^4$$

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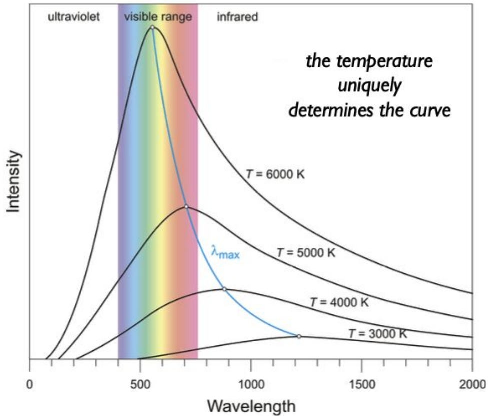
Wien's displacement law:

The peak wavelength of radiation emitted by a BB is inversely proportional to its T



$$\lambda_{max}T = 0.290\ cm\ K$$

$$h\nu_{max} = 2.82\ k_B\ T$$

$$\lambda_{max} \propto \frac{1}{T}$$

$\lambda \gg \lambda_{max}$: *Rayleigh-Jeans law*

$\lambda \ll \lambda_{max}$: *Wien law*

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What is Non-Thermal Radiation?

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Produced when particles are accelerated (it is not determined simply by temperature). It arises from physical processes such as shocks, turbulence, and strong electromagnetic fields

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Hadronic processes are interactions of hadrons (strongly interacting particles such as protons and neutrons) that produce secondary particles, gamma rays, and neutrinos

Hadronic processes:

- Proton-proton collisions
- Pion production & decay
- Gamma-ray and neutrino emission

Leptonic processes:

- Synchrotron emission
- Inverse Compton scattering
- Non-thermal bremsstrahlung

Leptonic processes are interactions of leptons (electrons and positrons) that produce radiation through electromagnetic mechanisms such as synchrotron emission or inverse Compton scattering

Leptonic processes:

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Thermal radiation

- Equilibrium
- Planck spectrum:

$$B_\nu(T) = \frac{2}{c^2}\frac{h\,\nu^3}{e^{\frac{h\nu}{k_B T}} - 1}$$

- Radiation spectrum depends only on *temperature*

Non-thermal radiation

- Out of equilibrium
- Power-law spectrum

$$F_\nu \propto \nu^{-\alpha}, \quad \alpha = \frac{p-1}{2}$$

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Spectrum is determined by the underlying energy distribution of the particles
=> **particle energy distribution**

$$N(E)$$

Thermal radiation

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- Radiation spectrum depends only on *temperature*
- Probes equilibrium properties (*temperature, density*)

Non-thermal radiation

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- Radiation spectrum depends on *acceleration mechanisms*
- Probes acceleration physics (*shocks, turbulence, magnetic fields*)

Non-Thermal Radiation

In *non-thermal* radiation we need to describe how particles are distributed in energy because that distribution controls the emitted radiation.

From Momentum distribution to Energy Distribution: $f(p) \longrightarrow N(E)$

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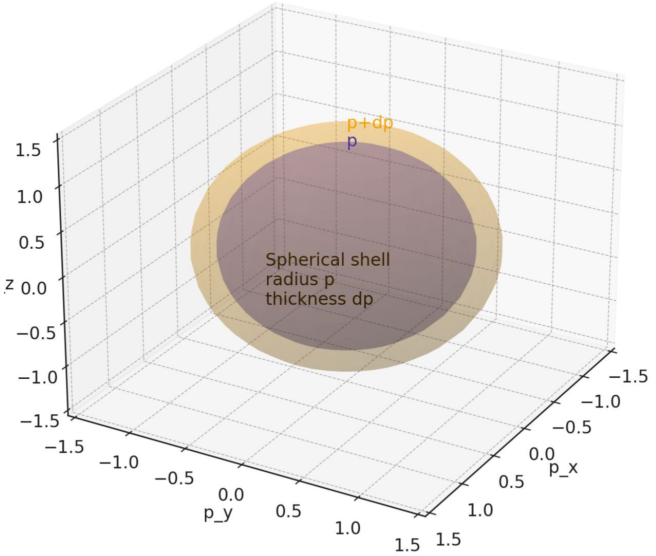

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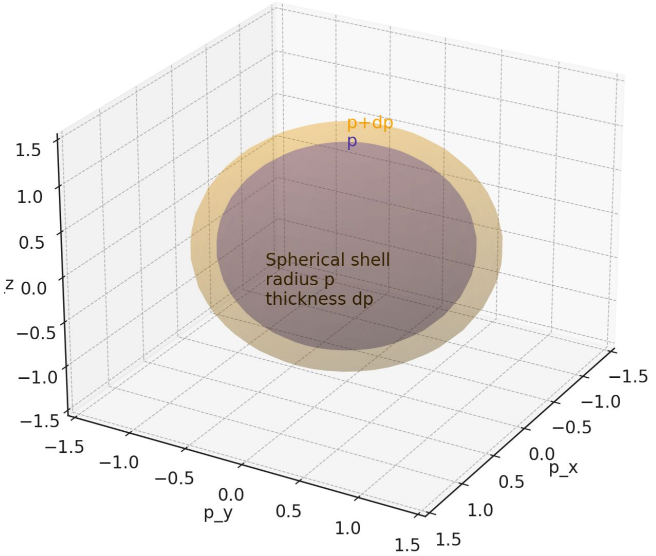

Isotropic momentum distribution $f(p)$

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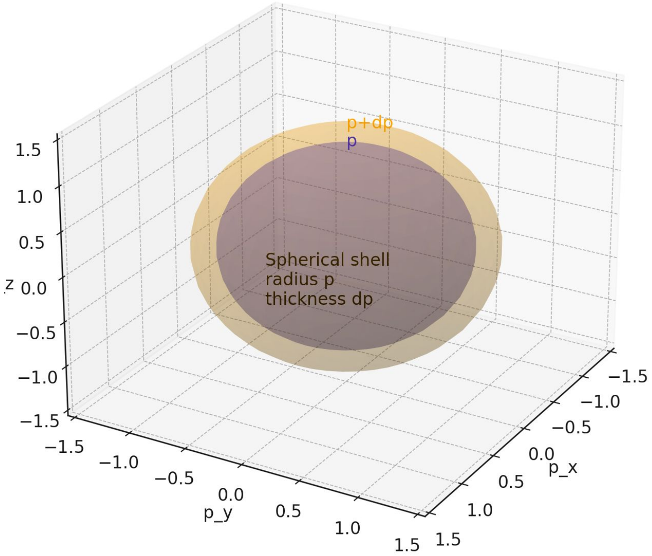

Isotropic momentum distribution $f(p)$

Number of particles per unit volume in $[p, p+dp]$:

$$dn = 4\pi p^2 f(p)\, dp$$

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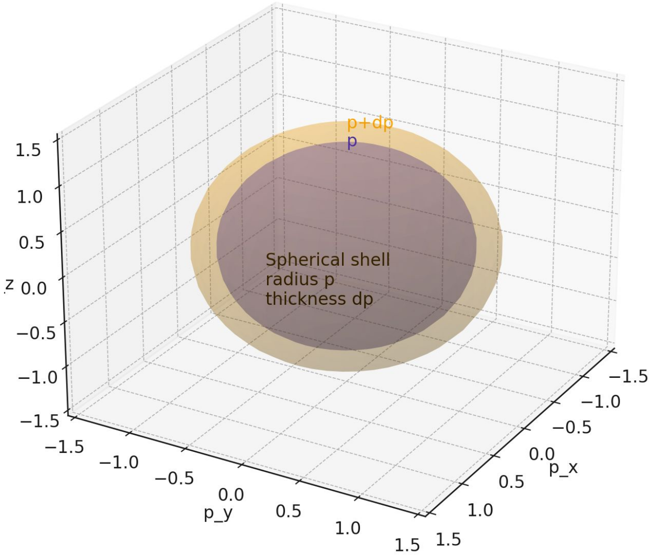

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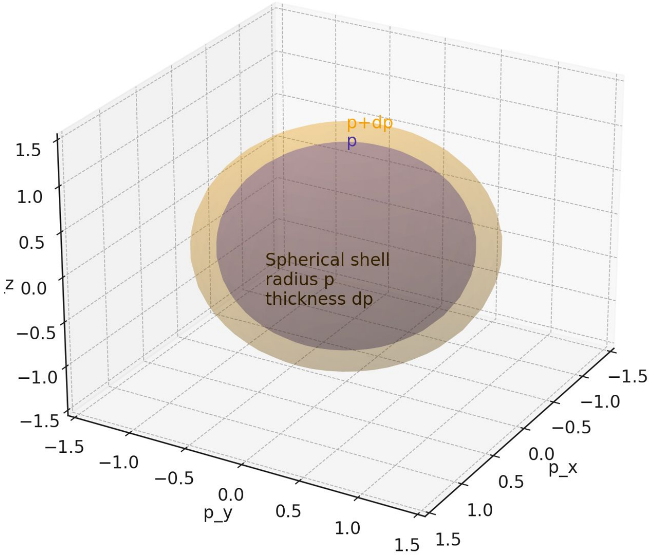

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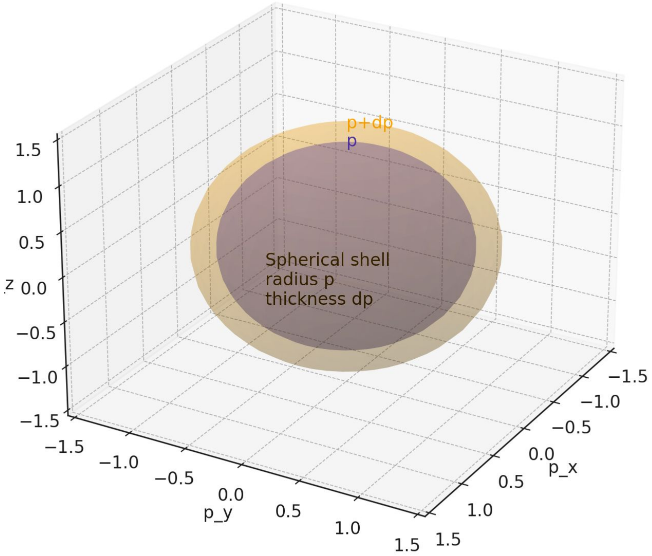

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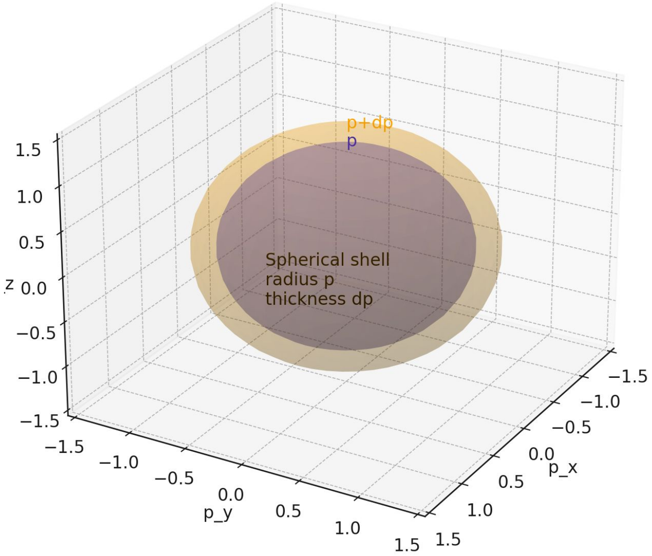

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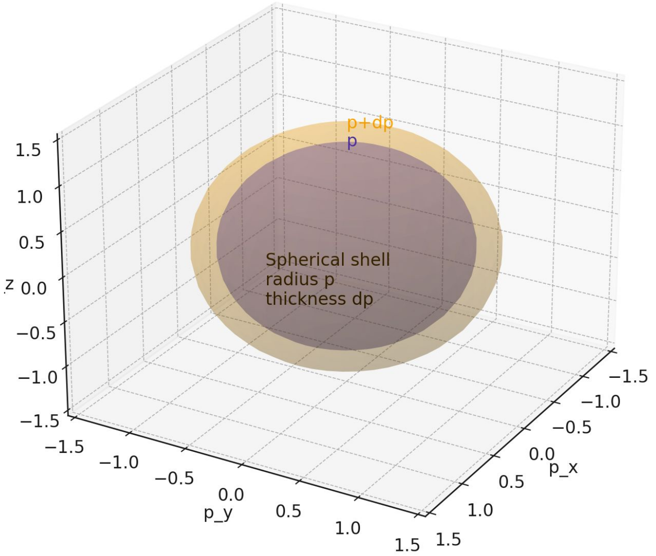

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if $E \simeq pc$: $dp/_{dE} = 1/_{c} \Rightarrow$ $N(E) = \frac{4\pi}{c^3} E^2 f\left(E/_{c}\right)$

Thermal radiation:

Particle distribution is determined by *T* and the relevant quantum statistics. For *non-relativistic*, this reduces to the Maxwell–Boltzmann distribution:

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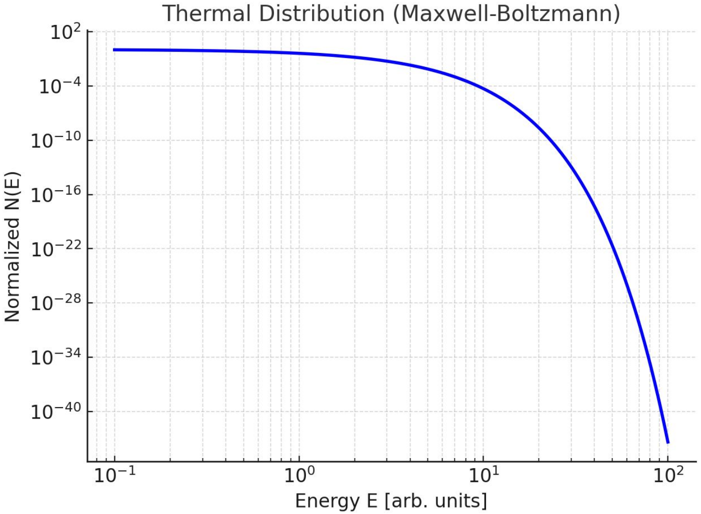
Thermal distributions always have an exponential cutoff at high *E*



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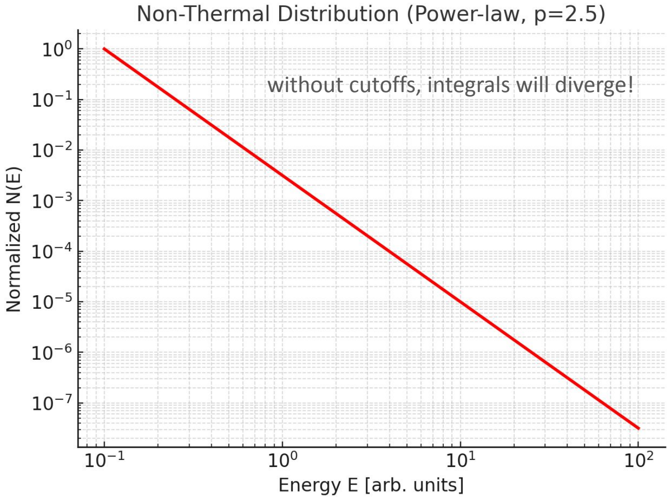

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Thermal distributions are exponential and controlled by T

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Non-thermal distributions are power laws, controlled by acceleration physics

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Observations across high-energy astrophysics evidence → *power-law energy spectra*

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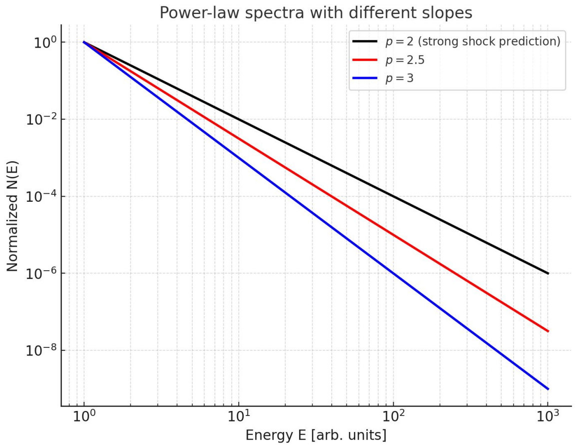

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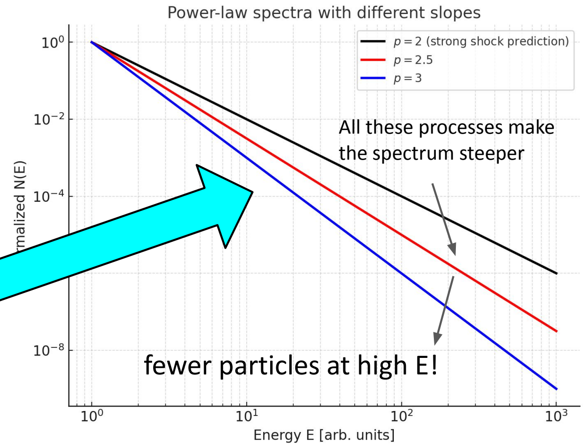

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- The shape of the spectrum (its slope) is determined by *p*
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→ The normalization constant K must be determined!

There are two common ways:

- Normalize to the ***total number density*** of particles *n*
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This allows us to solve for K:

$$K = n\, \frac{1-p}{E_{\max}^{1-p} - E_{\min}^{1-p}}$$

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- Lower cutoff E_{min}: set by ***injection*** – particles need a minimum energy to enter the acceleration process
- Upper cutoff E_{max}: set by ***losses & finite time*** – particles cannot be accelerated indefinitely
  - Radiative losses (synchrotron, inverse Compton)
  - Escape from the acceleration region
  - Limited source lifetime

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we can solve for K:

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if *p < 2*:

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high-energy particles dominate the energy budget

→ A finite E_{max} is required

if $p>2$

- The integrand E^{1-p} grows rapidly towards *low energies*
- As E_{min} approaches zero, the energy integral becomes arbitrarily large

low-energy particles dominate the energy budget

→A finite E_{min} is required

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- A characteristic value for the particle population
- Links the *total energy* to the *particle number*
- Indicates whether the energy budget is dominated by low- or high-energy particles

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It is defined as the ratio between the *total energy density U* and the *number density n:*

$$\langle E \rangle = \frac{U}{n}$$

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- Links the *total energy* to the *particle number*
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It is defined as the ratio between the *total energy density U* and the *number density n:*

$$\langle E \rangle = \frac{U}{n}$$

where:

$$U = \int E\, N(E)\, dE \quad ; \quad n = \int N(E)\, dE$$

The ***mean energy*** provides:

- A characteristic value for the particle population
- Links the *total energy* to the *particle number*
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$$\langle E \rangle = \frac{U}{n} = \frac{\int E\, N(E)\, dE}{\int N(E)\, dE}$$

Substituting for the power law distribution $N(E) = KE^{-p}$:

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Convergence conditions:

- Finite E_{min} required if $p \geq 2 \rightarrow$ limits the influence of low-energy particles
- Finite E_{max} required if $p \leq 2 \rightarrow$ limits the influence of high-energy particles

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Special cases:

- At exactly *p=2*, the mean energy depends logarithmically on the ratio $\ln\left(E_{max}/E_{min} \right)$, meaning both energy limits are important
- For *p>2*, most of the energy is carried by the low-energy particles, so ⟨*E*⟩ is close to E_{min}
- For p<2, a few very energetic particles dominate, so ⟨E⟩ is close to E_{max}

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When we compute the *mean energy* of a power-law distribution, the integral only makes sense if we restrict the energy range.

This result shows which particles control the source energetics: either the low-energy ones or the few very energetic ones

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- A particle with energy *E* radiates a power spectrum at frequency ν:

$$P(\nu, E)$$

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If particles radiated at a single frequency, the spectrum would copy *N(E)*. In reality, each particle radiates over a frequency range, so the observed spectrum is a mixture of particle distribution and emission physics

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Non-thermal sources often show photon spectra as power laws, reflecting the ***underlying particle distribution***

Non-Thermal Radiation

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Hadronic processes* = interactions of relativistic protons and atomic nuclei with matter

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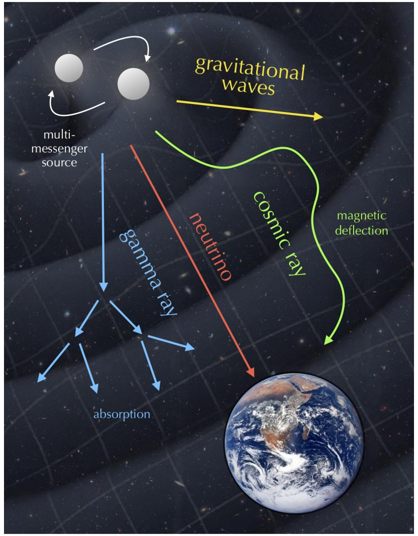
→ hadronic interactions are a natural source of *gamma rays* and *neutrinos*



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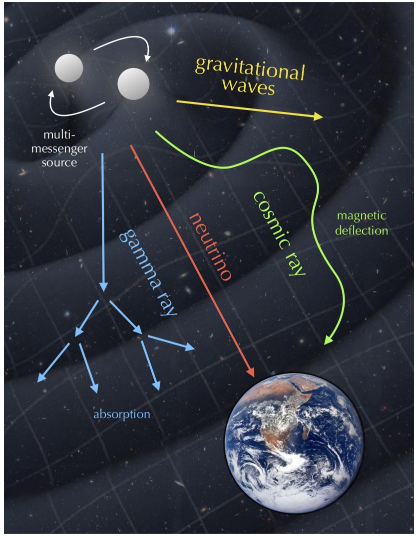
Importance:

- Cosmic rays are mostly protons (~90%)
- Protons can reach ultra-high energies (>10^{20} eV)
- When collide → generate secondary particles
- Explain observed high-energy y-rays
- Produce astrophysical neutrinos (multi-messenger signals)
- Reveal cosmic-ray acceleration in sources (SNRs, AGN, starbursts)



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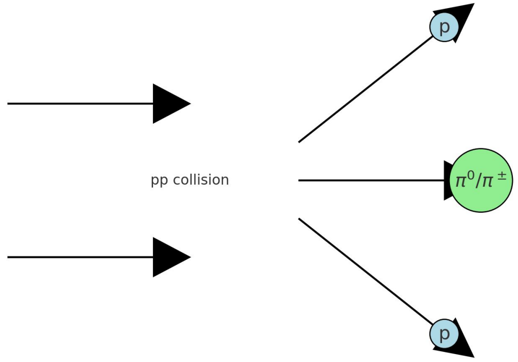
- **Proton–proton (pp):**
  - Dominant channel in astrophysics (ISM, molecular clouds)
  - *Inelastic collisions:*

$$p + p \;\to\; p + p + \pi^0, \pi^{\pm} + \ldots$$



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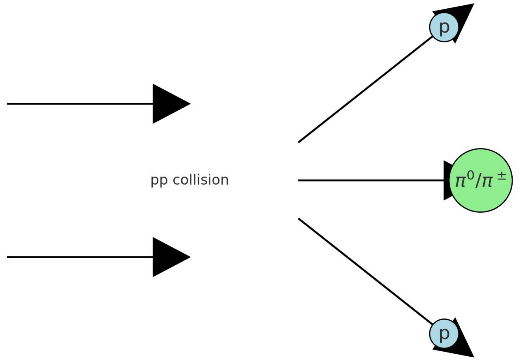

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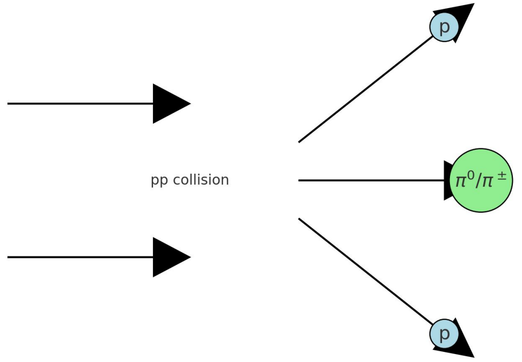

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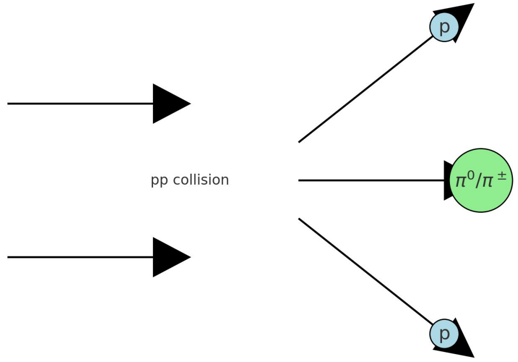

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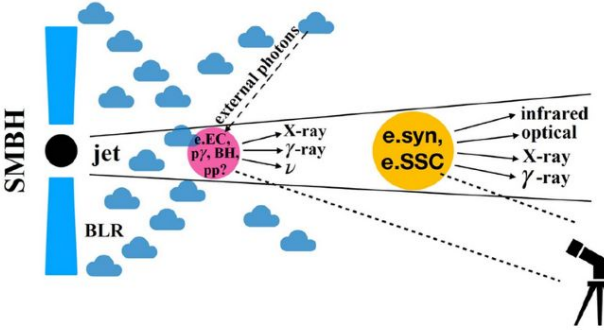
- **Proton–photon (p–γ, photohadronic):**
  - Relativistic proton + photon radiation field
  - Via Δ+ resonance
  - Relevant in GRBs and AGN jets



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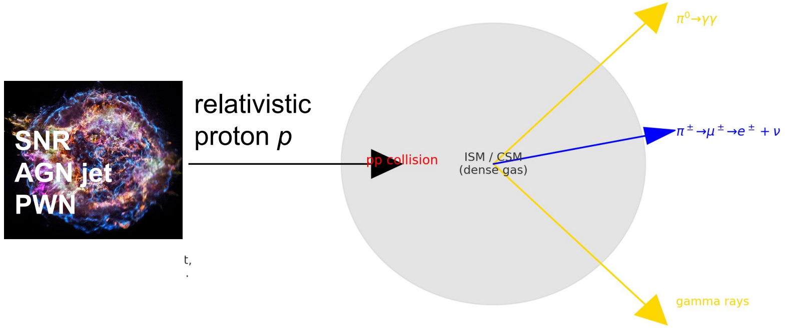

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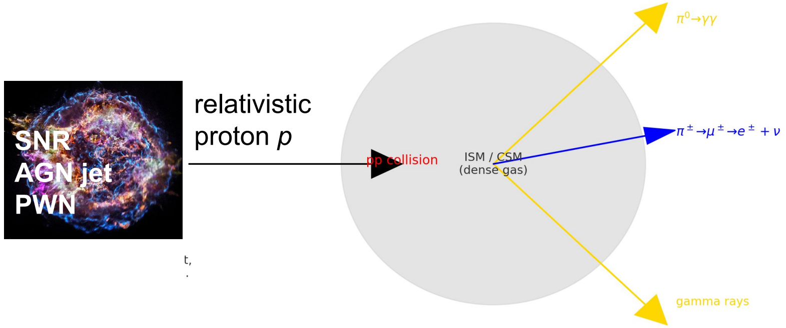

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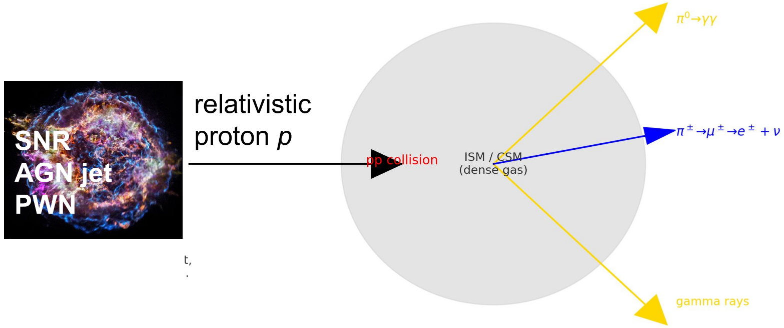

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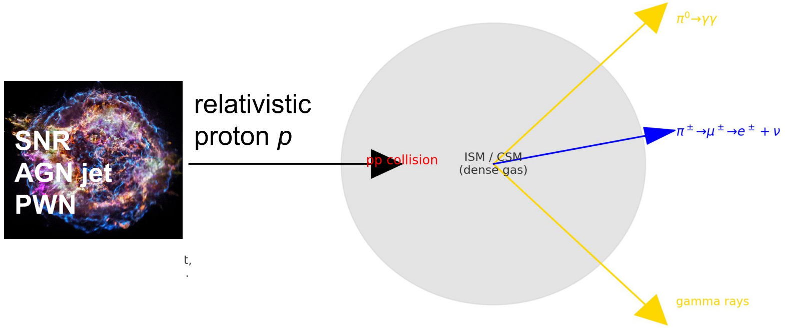

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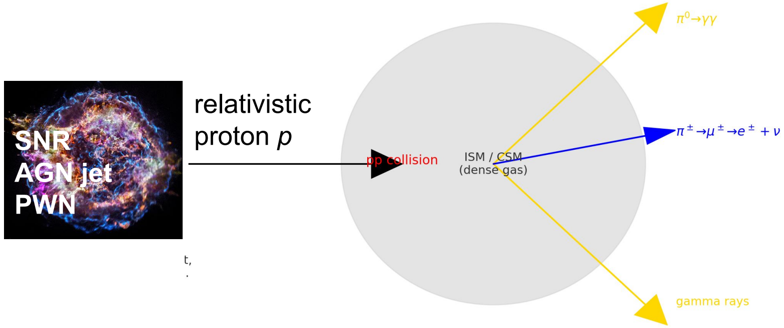

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Inelastic: part of the kinetic energy converted into new particles => ***non-thermal*** radiation via pion production
Elastic scattering: no new particle, only momentum redistribution => **no** *non-thermal* radiation, only scattering

Relativistic cosmic-ray protons collide with medium (cold) protons → pion production

Importance: pions decay into γ rays and neutrinos → key to non-thermal signatures

Threshold Energy for Pion Production

- Defines the *minimum proton energy* to produce pions
- Below threshold $\rightarrow$ no π^0, $\pi^\pm$ $\rightarrow$ no hadronic γ,ν
- Sets the lower integration limit in all emissivity calculations for hadronic γ-ray and neutrino production

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Minimum kinetic energy that an incoming proton must have in the *lab frame* for pion production in a *p-p* collision to be kinematically allowed

Threshold Energy for Pion Production

Mandelstam invariant (s):

It is a relativistic invariant: its value is the same in any reference frame, which makes it ideal to connect the lab frame and the center-of-mass frame.

$$s \equiv (p_1 + p_2)^2$$

square of the total 4-momentum of the system

with p_1, p_2 = 4-momenta of the colliding particles

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If an *incident* proton (CR) collides with a *target* proton at rest (ISM/CSM):

$$s = (p_{\text{inc}} + p_{\text{tar}})^2 = 2m_p^2c^4 + 2m_pc^2E_p^{\text{lab}}$$

Threshold condition (c.m. frame):

$$\sqrt{s_{\mathrm{thr}}} = 2m_p c^2 + m_\pi c^2$$

Solving for incident energy:

$$E_p^{\mathrm{lab}} = m_p c^2 + T_p^{\mathrm{thr}}$$

[T_p = kinetic energy of the incident proton (lab frame)]

$$T_p^{\mathrm{thr}} = 2m_\pi c^2 + \frac{m_\pi^2 c^4}{2m_p c^2}$$

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$$E_p^{\rm lab} = m_p c^2 + T_p^{\rm thr}$$

$$T_p^{\rm thr} = 2m_\pi c^2 + \frac{m_\pi^2 c^4}{2m_p c^2}$$

Solving for π^0:

$$T_p^{\rm thr} \approx 280\ {\rm MeV}$$

⇒

- Only CRs with energies above this value can produce pions!
- It sets the lower integration limit in all emissivity calculations for hadronic γ-ray and neutrino production

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→ Once we know the process is possible, the next question is its probability of occurrence

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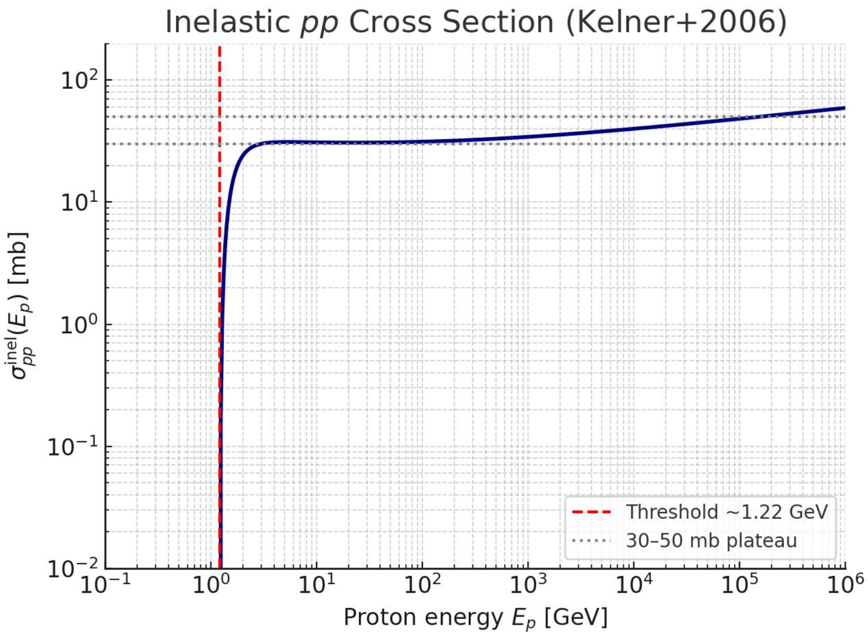
$T_p^{\mathrm{thr}} \approx 280\ \mathrm{MeV}$: kinetic energy of the incident proton in the lab frame

E_{thr} ≈ 1.22 GeV : total energy (rest + kinetic) of the same proton

Cross Section

Energy dependence:

- $\sigma_{pp}^{\mathrm{inel}} \approx 0$ for $E_p < E_{\mathrm{thr}}$
- Rapid rise above threshold
- Plateau at ~30–50 mb for $E_p \gtrsim 10\ \mathrm{GeV}$



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- ***Above threshold*** (higher energies): Multiple pions are produced per collision
- The average multiplicity grows slowly with proton energy
- Roughly:

$$\langle n_\pi \rangle \;\approx\; a + b\,\ln\!\left(\frac{E_p}{E_0}\right)$$

where:

- E_p = incident proton energy (lab)
- $E_0 \sim m_p c^2$ = reference scale
- a,b = constants (order unity)

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★ Final products: neutrinos of several flavors + secondary electrons/positrons

Relevance:

- ***Neutral vs charged pions***

Neutral pions (π^0)

★ Produced abundantly in pp collisions

★ Very short lifetime (~10^{-16} s)

★ Decay almost exclusively into two gamma-ray photons:

$$\pi^0 \to \gamma+\gamma$$

★ Photons typically MeV–TeV energies, detected by Fermi-LAT (GeV), CTA (TeV)

★ π^0 decay is the direct source of hadronic gamma-ray emission

Charged pions ($\pi^\pm$)

★ Longer lifetime (~10^{-8} s)

★ Decay primarily into muons + muon neutrinos:

$$\pi^+ \to \mu^+ + \nu_\mu, \quad \pi^- \to \mu^- + \bar{\nu}_\mu$$

★ Muons then decay further:

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★ Final products: neutrinos of several flavors + secondary electrons/positrons

★ $\pi\pm$ are the main channel for astrophysical neutrino production

Relevance:

- ***Neutral vs charged pions***

➢ Each pp collision produces a mixture of π^0 and $\pi^\pm$

➢ Outcomes:

  ○ Gamma rays (from π^0)

  ○ Neutrinos (from $\pi^\pm$)

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pp collisions are factories of pions → sources of ***multi-messenger*** emission ($\gamma + \nu + e^\pm$)

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How do we calculate the hadronic γ-ray emissivity?

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→ It is obtained by integrating the proton distribution weighted by the differential cross section for pp collisions producing π^0

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Photon emissivity (per Eγ):

$$q_\gamma(E_\gamma) = n_{\rm H}\, c \int_{E_{p,\rm thr}}^{\infty} N_p(E_p)\, \frac{d\sigma_{pp\to\gamma}(E_p, E_\gamma)}{dE_\gamma}\, dE_p$$

***γ**-ray emissivity is the convolution of the proton spectrum with the differential cross section, weighted by the target density and c*

$$q_\gamma(E_\gamma) \;=\; n_{\mathrm{H}}\, c \int N_p(E_p)\, \frac{d\sigma_{pp\to\pi^0\to\gamma}(E_p, E_\gamma)}{dE_\gamma}\, dE_p$$

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γ-ray emissivity includes both:

- ***proton spectrum*** and the detailed ***photon production cross section***
- The ***differential cross section*** $\frac{d\sigma}{dE_\gamma}$, which comes from complex nuclear physics. In principle, this cross section is difficult to compute and contains many details.

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With the scaling approximation, the photon spectrum directly inherits the slope of the proton spectrum: $N_p(E_p) \propto E_p^{-p}$

Thus, if cosmic-ray protons follow a power law with slope p, the produced γ-rays will also follow a power law with the same slope p.

$$q_\gamma(E_\gamma) \;=\; n_{\rm H}\, c \int N_p(E_p)\, \frac{d\sigma_{pp\to\pi^0\to\gamma}(E_p, E_\gamma)}{dE_\gamma}\, dE_p$$

This is a fundamental result for HE astrophysics:

By measuring the ***hadronic γ-ray spectrum***, we can directly infer the slope of the underlying proton population – a bridge between what we cannot see (CR protons) and what we can observe (photons)

Observational Signatures: the pion bump

Hadronic models predict a very specific spectral feature: ***pion bump*** around **100 MeV**.

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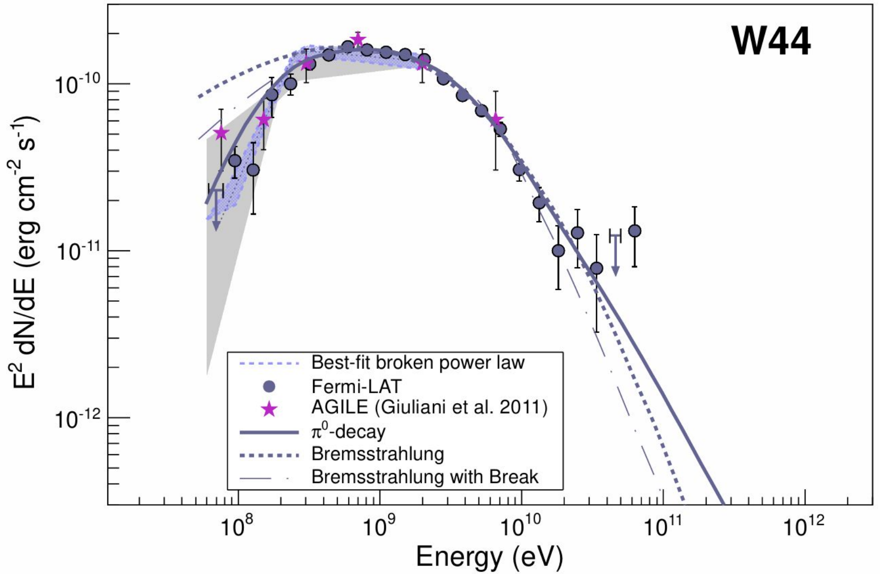
If the pion is moving (e.g. in a SNR), this value is ***broadened*** by relativistic effects (Doppler, boosting), and in the spectrum it appears as the ***pion bump*** around 100 MeV.



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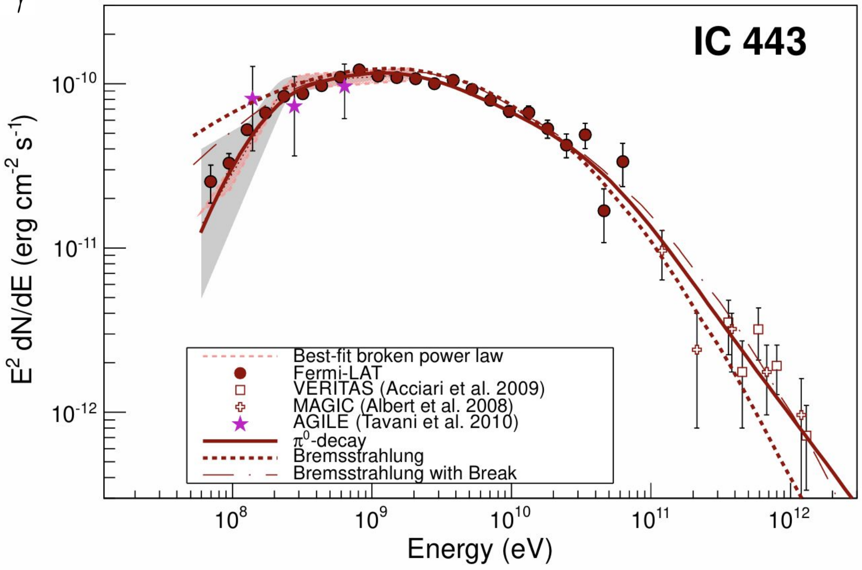
2013: Fermi-LAT detected this spectral shape in IC443 and W44, and it was considered the ***first direct evidence*** that ***SNRs*** produce gamma rays through hadronic collisions!



The pion bump is considered a **smoking-gun signature of hadronic emission**

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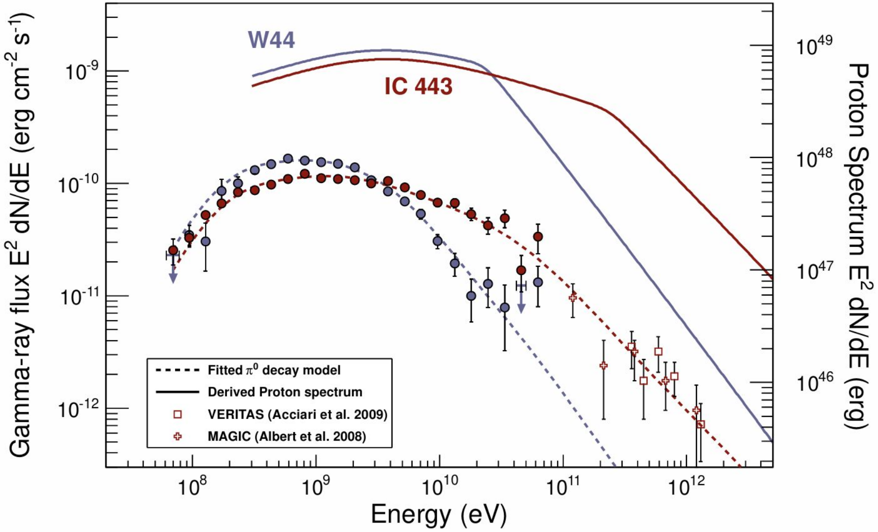
No ***leptonic process*** (bremsstrahlung, synchrotron, inverse Compton) produces such a pronounced feature around 100 MeV



The pion bump is considered a **smoking-gun signature of hadronic emission**

Pion decay → photons + neutrinos

pp collision

$\quad \hookrightarrow \; \pi^0 \;\rightarrow\; \gamma + \gamma$

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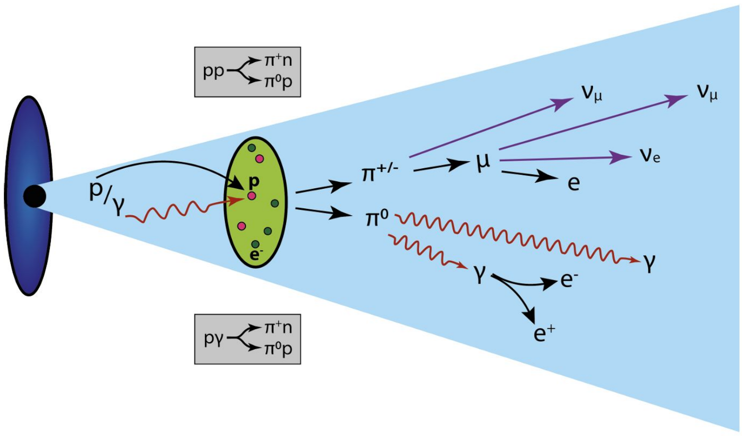
(But at the same time, $\pi^{\pm}$ are produced)

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \longrightarrow \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



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$$\pi^+ \rightarrow \mu^+ + \nu_\mu \longrightarrow \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

For every γ-ray from π^0, we expect a comparable flux of neutrinos from $\pi^{\pm}$

Both originate from the same hadronic process (pp or pγ). Therefore, the **γ-ray** and **neutrino spectra *are linked***

Pion decay → photons + neutrinos

pp collision

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(But at the same time, $\pi^{\pm}$ are produced)

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \longrightarrow \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Each $\pi^{\pm}$ produces **3 neutrinos:**

- 2 muon-type
- 1 electron-type

Non-Thermal Radiation

neutrino production and gamma ray connection

Pion decay → photons + neutrinos

pp collision

→ $\pi^0 \rightarrow \gamma + \gamma$

(But at the same time, $\pi^{\pm}$ are produced)

→ $\pi^+ \rightarrow \mu^+ + \nu_\mu$ ⟶ $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

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Each $\pi^{\pm}$ produces **3 neutrinos:**

- 2 muon-type
- 1 electron-type

- Detecting γ-rays alone does not guarantee a hadronic origin (they may also be leptonic)
- ***Detecting γ + ν simultaneously*** = unambiguous evidence of hadronic processes.
- Neutrinos travel unaffected by magnetic fields → direct tracers of acceleration sites → MM

Pion decay → photons + neutrinos

pp collision

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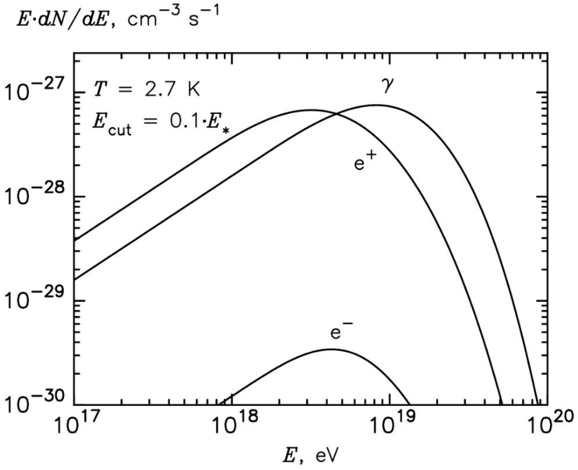

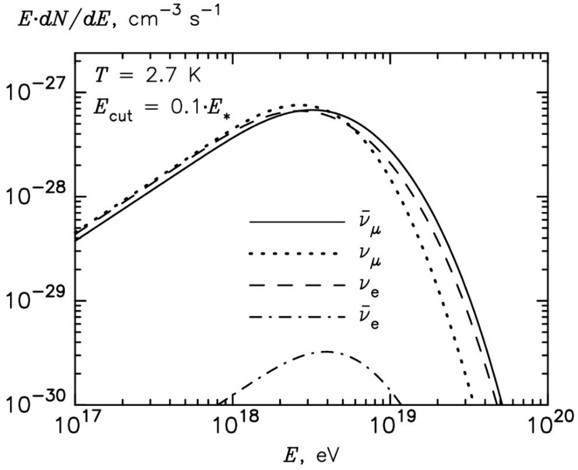

Cosmic rays

Nataly Ospina *(Istituto Nazionale di Fisica Nucleare)*

"IT'S DOWN. THE PARTICLES ARE SUPPOSED TO COLLIDE WITH OTHER PARTICLES, NOT WITH THE PHYSICISTS."

Cosmic rays

- Cosmic ray definition
- Production of Cosmic rays
- Cosmic ray propagation in the Galaxy

Cosmic rays

- **Cosmic ray definition**
- Production of Cosmic rays
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Cosmic rays

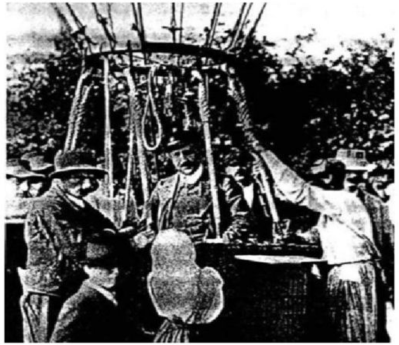
What are Cosmic rays?

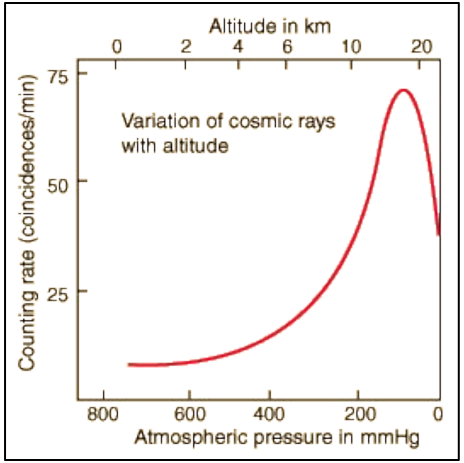
Cosmic rays

Cosmic rays **are not radiation**, but non-thermal particles (relativistic protons and nuclei). Their interactions produce non-thermal radiation (γ-rays, synchrotron, neutrinos)

Cosmic rays

- First discovered by Victor Hess (1912, balloon experiments)



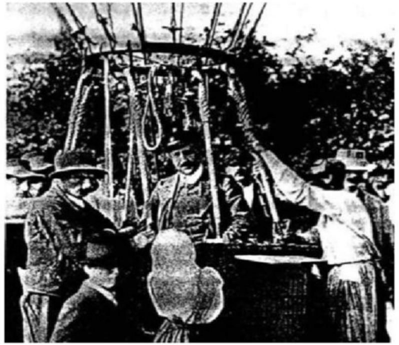


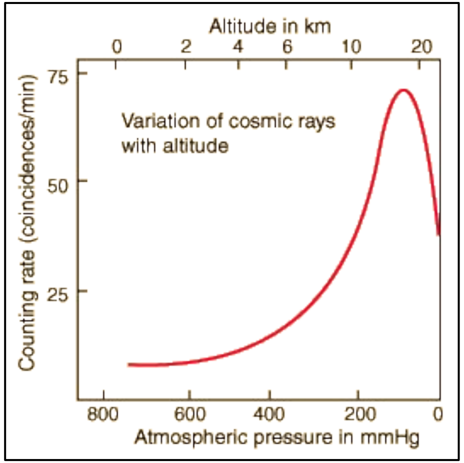
Cosmic rays

- First discovered by Victor Hess (1912, balloon experiments)
- Relativistic charged particles traveling at relativistic velocities
- Composition:
  - ~ 90% protons
  - ~ 9% helium nuclei (α-particles)
  - ~ 1% heavier nuclei (C, O, Fe, …)
  - < 1% electrons and positrons
- Energy range:

$$E \sim 10^9\,\mathrm{eV}\ (\mathrm{GeV})\ \ \text{to}\ \ > 10^{20}\,\mathrm{eV}$$ UHE

- Cosmic rays have a **non-thermal** power-law energy spectrum





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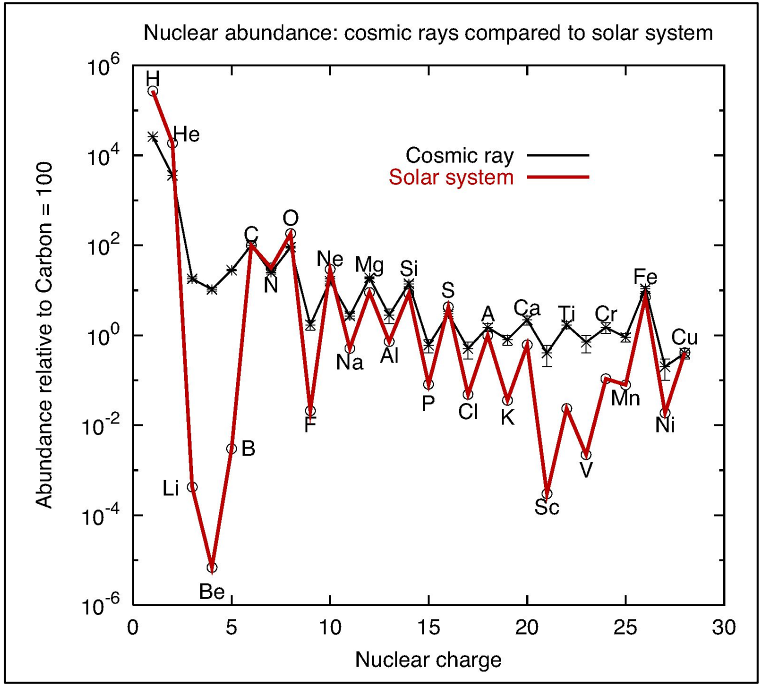


- Cosmic-ray composition is *similar to the solar*
- There is an **overabundance of Li, Be, and B**. These arise from *spallation reactions*
- This detail connects CR physics with nuclear processes in the ISM.

Cosmic rays

Primary Cosmic Rays (p, He, C, O, ...):

Primary CRs carry information about their original spectra and propagation

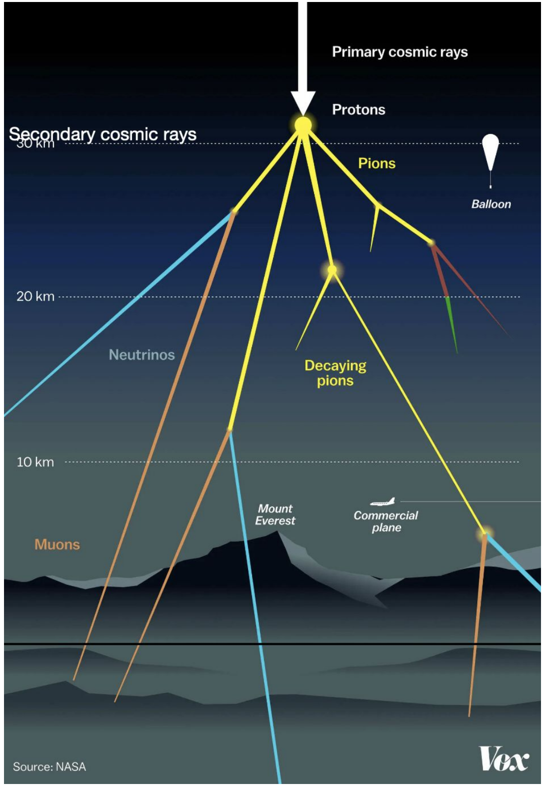
⇒When the primary CRs from the outer space hits the upper atmosphere, produces a *shower of other particles*. Particles in the shower are called secondary CRs.

Secondary Cosmic Rays (Li, Be, B, ...):

Secondary CRs carry information about propagation of primaries, secondaries and interactions in the ISM.

→ Creating:

- Electromagnetic shower: mainly γ-rays
- Hadronic shower: mainly muons and neutrinos



Energy Spectrum

One of the most remarkable features of CRs is their energy spectrum:

It extends over *~14 orders of magnitude*, from GeV energies up to 10^{20} eV

$$E \sim 10^{9}\,\mathrm{eV}\ (\mathrm{GeV}) \quad \rightarrow \ > 10^{20}\,\mathrm{eV}$$

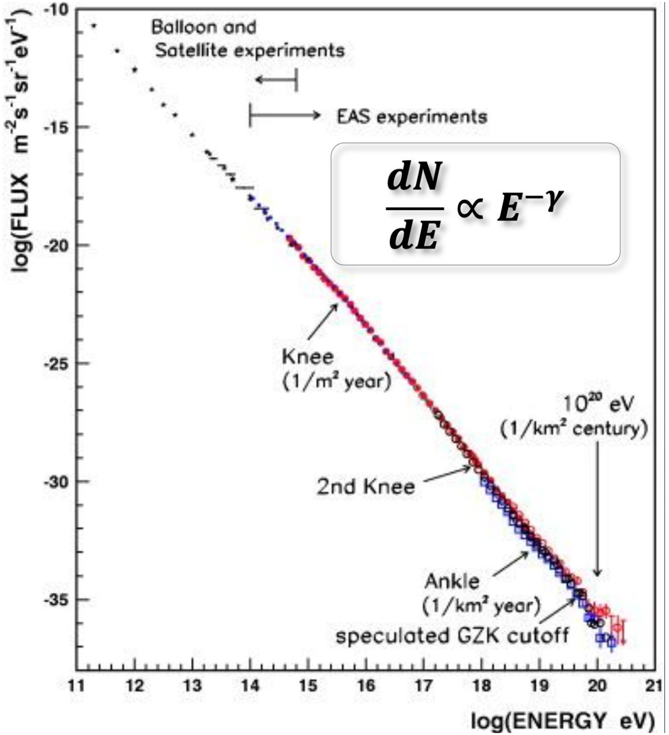
The flux is usually expressed as a differential intensity, $J(E)$, which follows a power law:

$$J(E) \ \propto \ E^{-\gamma}$$

Cosmic rays

The slope, or spectral index γ, is not constant:

- At energies below the **knee** (~3×10^{15} eV), the spectrum has slope γ≈2.7



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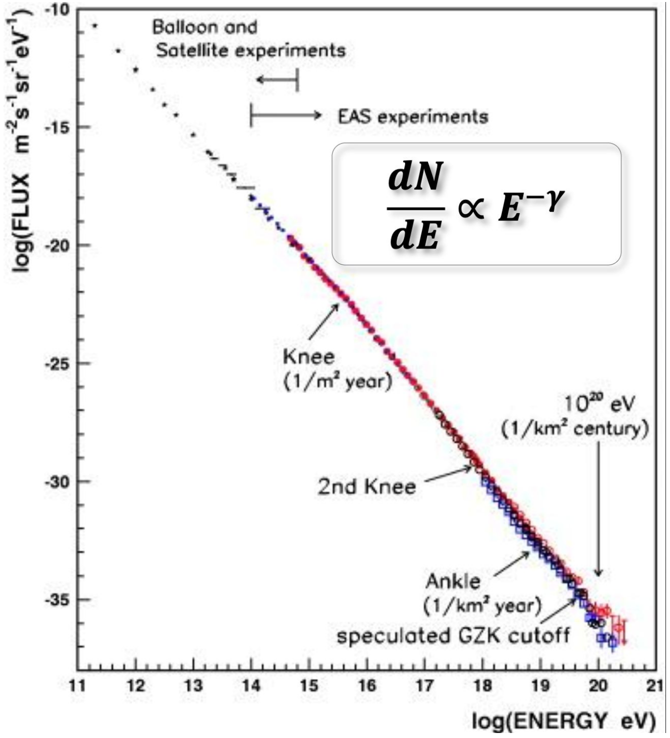

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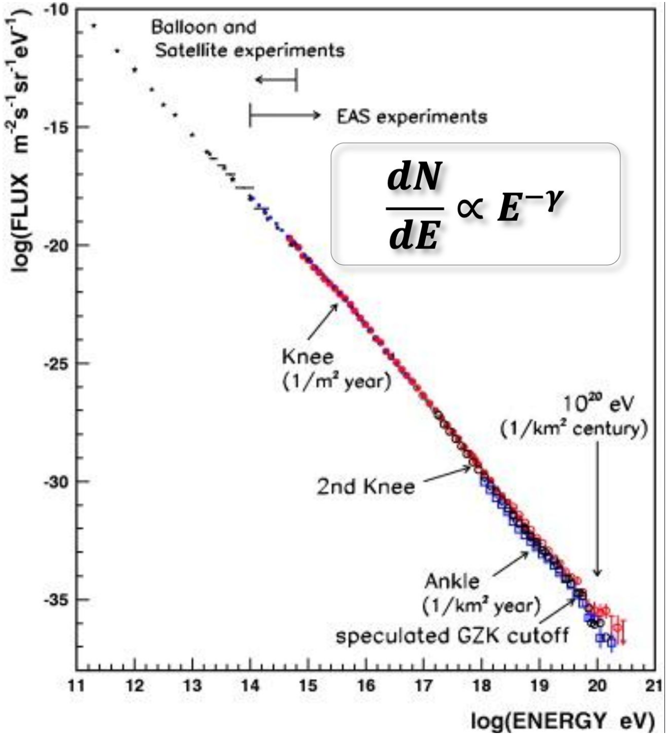

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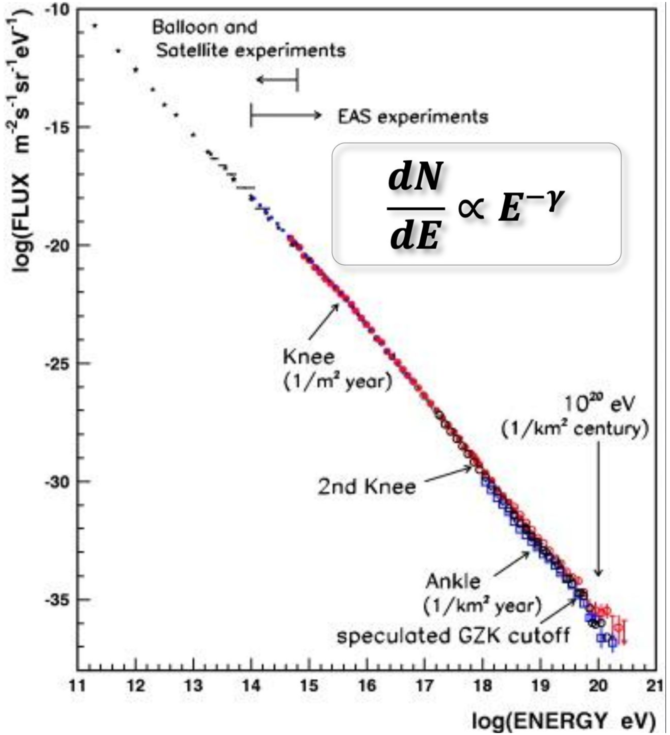
- Finally, above 5×10^{19} eV, we observe a suppression known as the **GZK cutoff**, due to interactions of UHE CRs with the CMB



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Cosmic rays

Energy Spectrum

Direct measurements (space-based/balloon-borne):

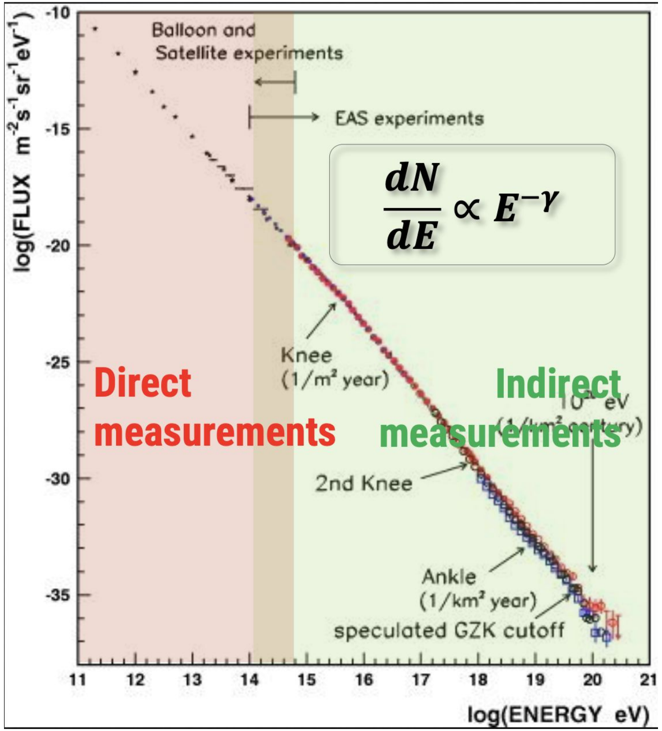
☺ Particle identification

✗ Weight/size constraints: limits in the energy range

Indirect measurements (ground-based):

☺ Extended energy range

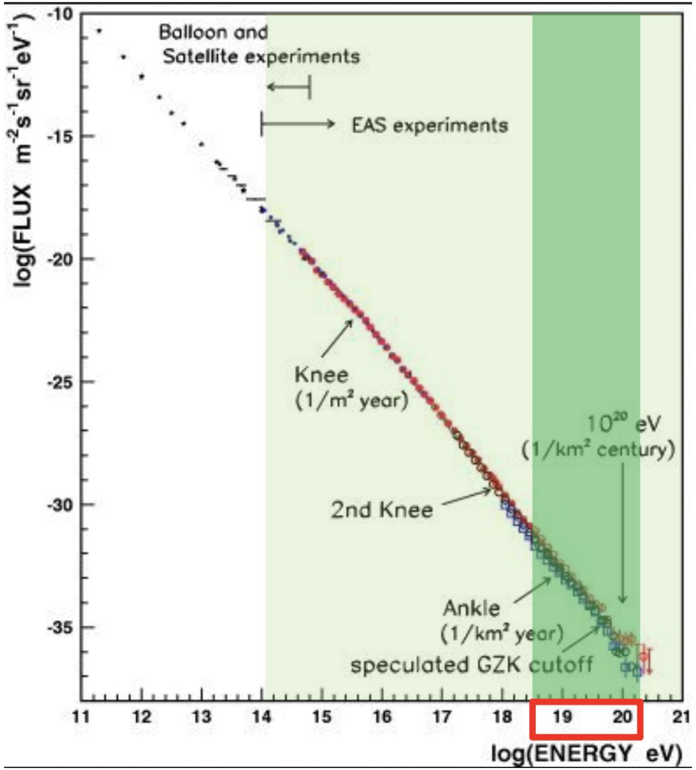
✗ Particle identification: dependence on models about atmospheric interactions



Direct & Indirect Measurements
Provide Complementary Information

(Some) open questions in CRs physics

1. Energy spectrum: the ankle and the suppression
2. Mass composition of UHECRs



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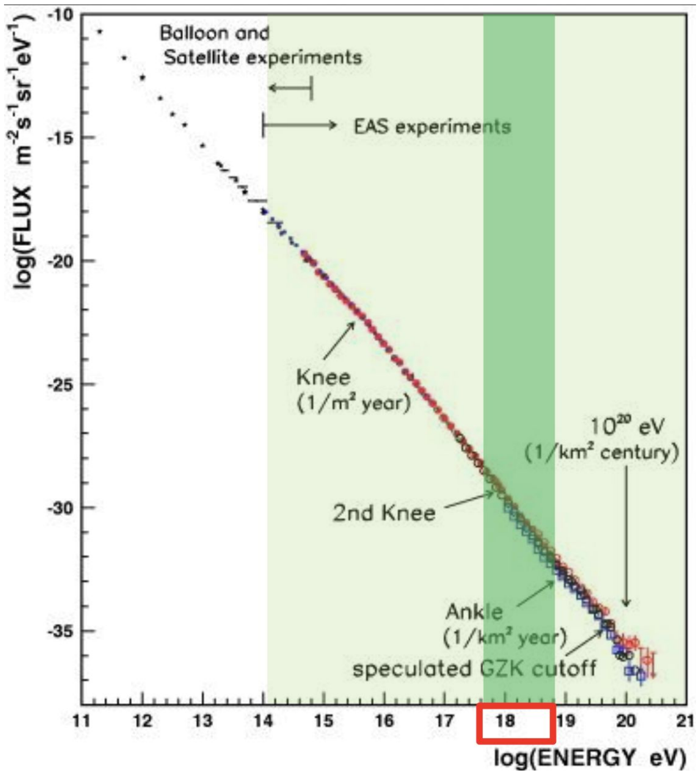
3. Galactic-Extragalactic transition
4. Sources of high energy CRs



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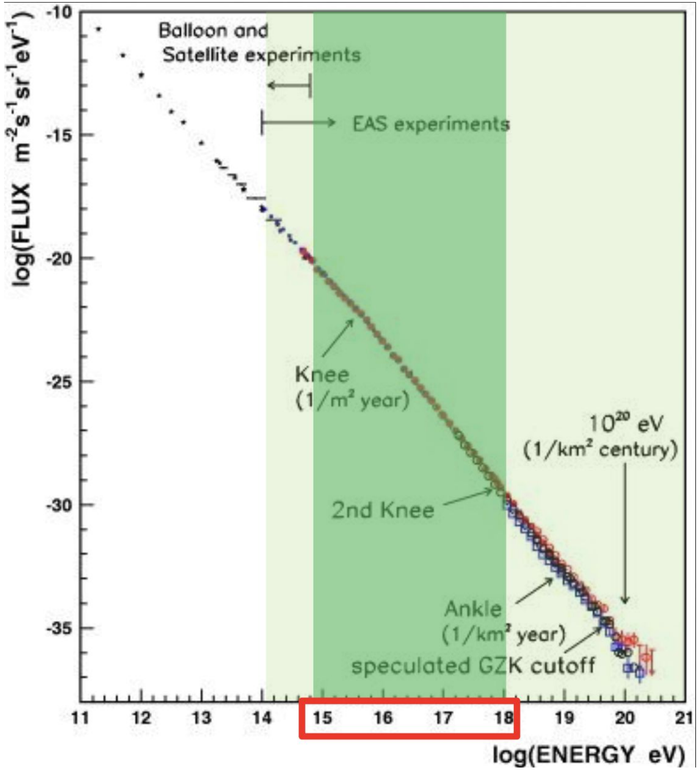

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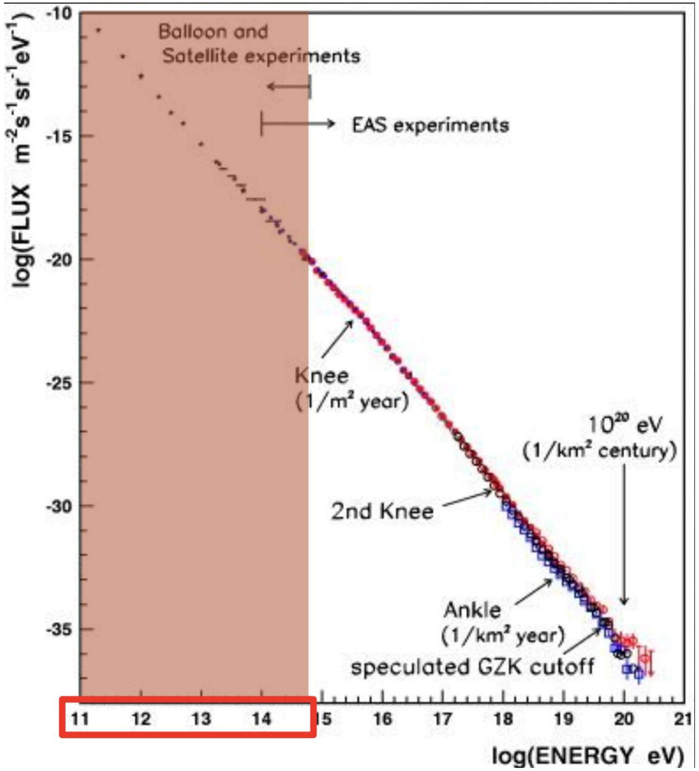
6. Propagation of GCRs in the Galaxy
7. Energy spectrum of GCRs
8. Antimatter in CRs and indirect search for DM



Cosmic rays

Importance of Cosmic Rays

Energetics:

- Energy density of CRs in the ISM is comparable to that of magnetic fields and thermal gas
- Contribute significantly to the pressure balance in galaxies

Cosmic rays

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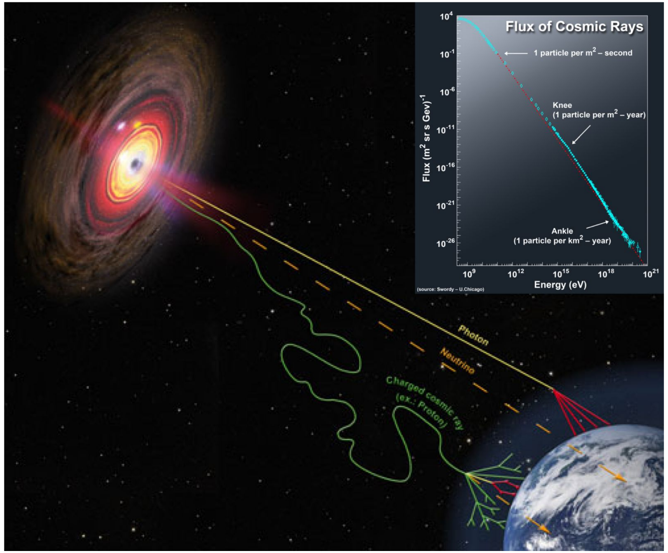
Non-thermal messengers:

- CR interactions produce **γ-rays** ($\pi^0 \rightarrow 2\gamma$)
- Produce **neutrinos** ($\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm} + \nu$)
- Essential for multi-messenger astrophysics



Importance of Cosmic Rays

Energetics:

- Energy density of CRs in the ISM is comparable to that of magnetic fields and thermal gas
- Contribute significantly to the pressure balance in galaxies

Non-thermal messengers:

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- Probe ***acceleration physics*** (shocks, turbulence, magnetic reconnection).
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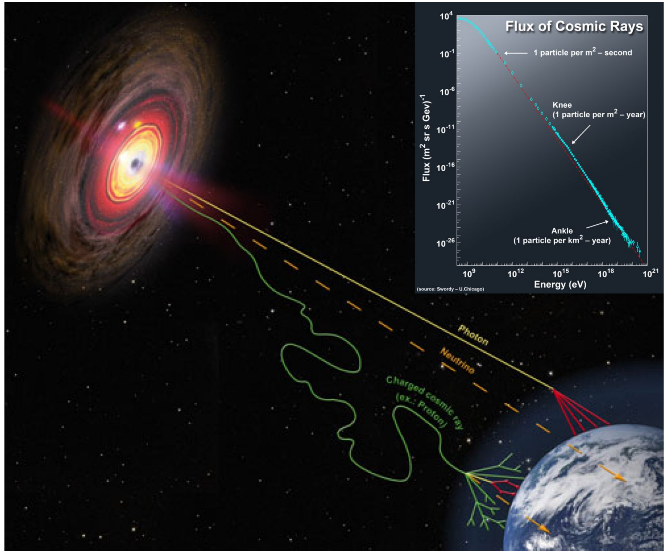

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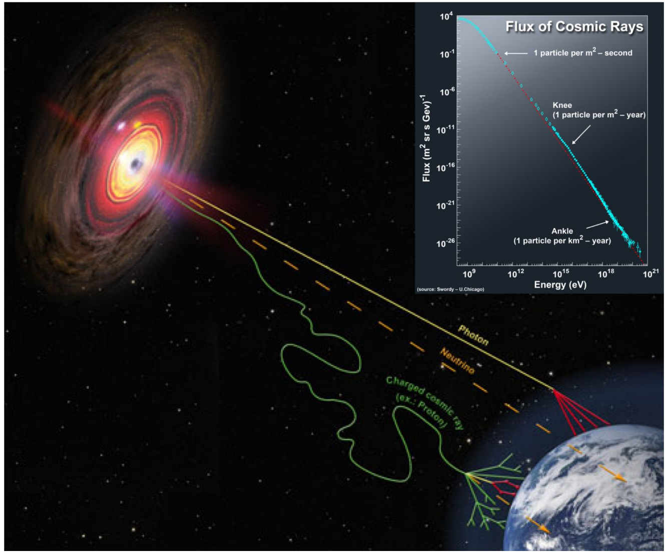
Astrobiological/space relevance:

- CRs ionize the interstellar medium, affecting chemistry.
- Radiation hazard for space exploration.



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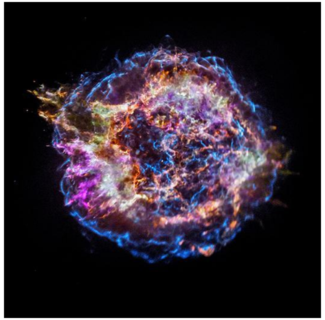

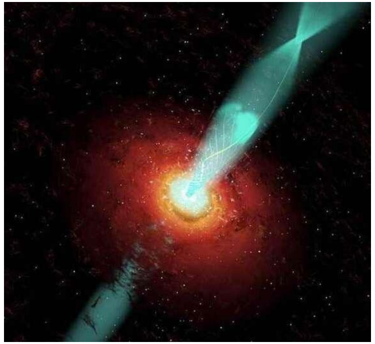

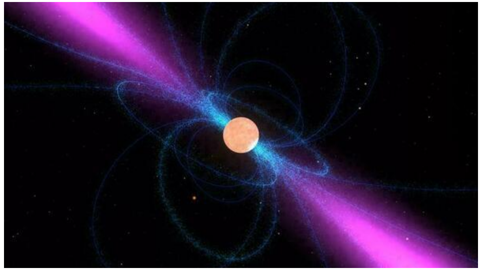

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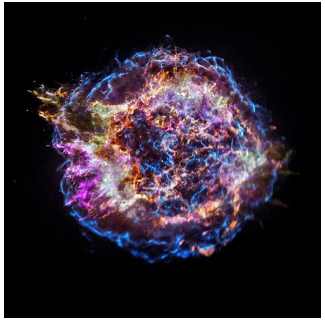
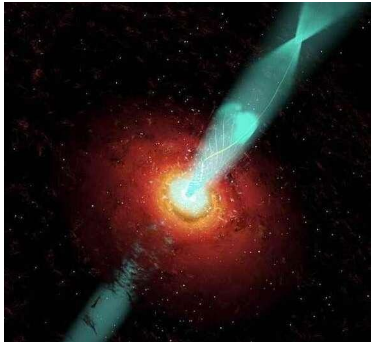
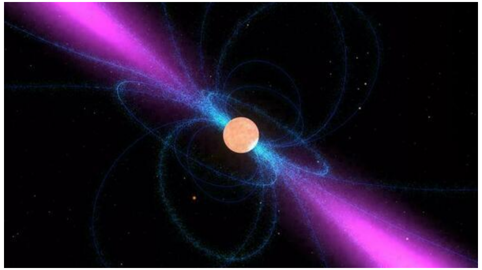

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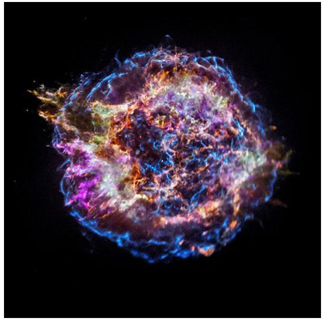

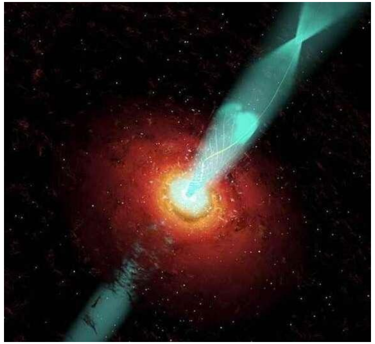

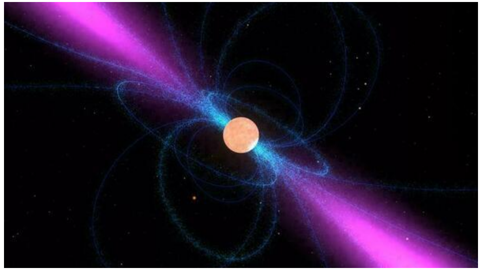

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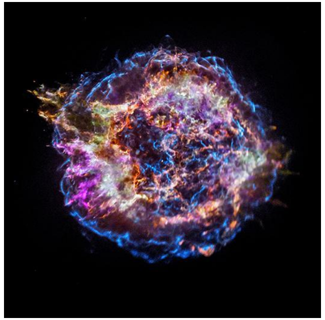

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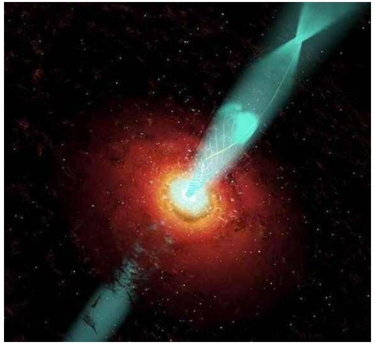

Pulsars & magnetars:
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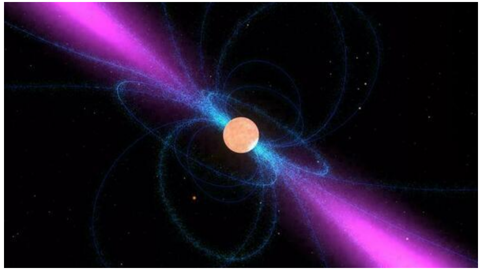
Gamma-ray bursts (GRBs):
- Short-lived ultra-relativistic shocks
- Possible sources of highest-energy CRs (>10^19 eV)



Different types of sources are responsible at different *E* ranges, and the observed spectrum is a superposition of these contributions

Cosmic rays

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The most widely accepted mechanism is ***Diffusive Shock Acceleration (DSA)***

- Let's imagine a charged particle near a shock wave, like in a SNR
- Magnetic turbulence on both sides of the shock scatters the particle
- The particle crosses the shock back and forth many times
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After many such cycles, the particle distribution becomes a *power law in energy*

We can derive the slope *p* from the shock compression ratio r. For a strong, non-relativistic shock, r=4.

This gives:

$$p = \frac{r+2}{r-1} = \frac{6}{3} = 2$$

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Non-thermal distribution!

We know that SNR shocks can explain Galactic CRs up to the knee, but the origin of UHE cosmic rays remains an open problem!

Cosmic rays

Candidate accelerators:

- SNRs: main sources below the “knee” (10^{15} eV)
- AGN jets, GRBs: plausible for ultra-high-energy CRs (> 10^{18} eV)
- Pulsars/magnetars: contribute mainly leptons (electrones y positrones)

Acceleration mechanism:

- Diffusive Shock Acceleration (DSA):
  - Particles scatter across shocks, gaining energy
  - Predicts a power-law spectrum $N(E) \propto E^{-p}$ with p~2
- The ***spectrum*** observed ***at Earth is softer*** ($p \approx 2.7$) because propagation in the Galaxy alters the slope produced at the sources ($p \approx 2.0$–2.2)

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Propagation of Cosmic Rays in the Galaxy

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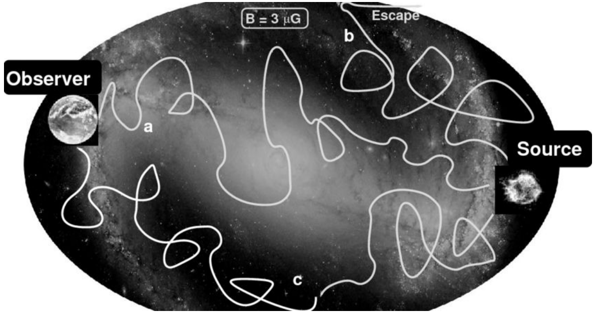
Instead, they remain confined in the Galaxy for millions of years, undergoing repeated scattering in turbulent magnetic fields ⟵ this process is described as ***diffusion***



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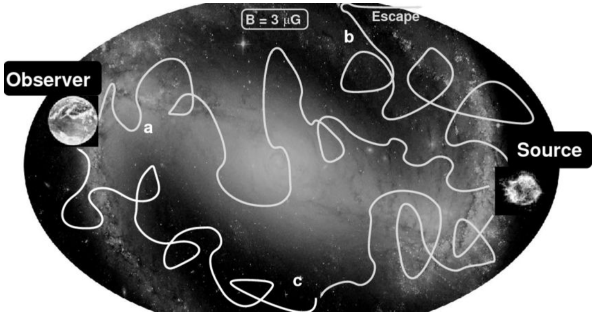

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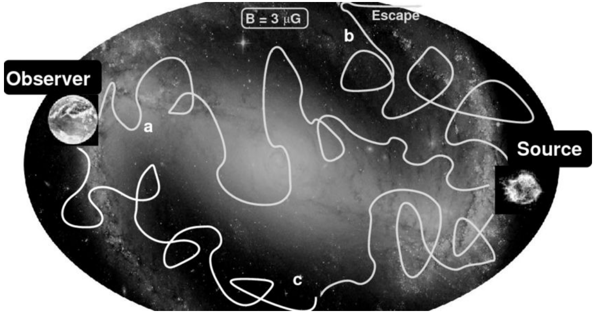

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⇒ This is why the spectrum we observe at Earth is ***softer*** than the source spectrum

Interactions with gas and radiation produce **γ-rays** and **neutrinos**

Cosmic rays

Interactions with gas and radiation produce **γ-rays** and **neutrinos**

- With gas (pp collisions):
  - Production of neutral pions:

    $\pi^0 \rightarrow 2\gamma \rightarrow$ hadronic γ-rays
  - Production of charged pions:

    $\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm} + \nu$ → neutrinos + $e^{\pm}$ pairs

- With photons ($p\gamma$ *interactions)* :
  - Processes via Δ^+ resonance → also neutral and charged pions → γ-rays + neutrinos

CRs diffuse through the Galaxy with an energy-dependent escape time. During propagation they interact with gas and radiation, producing γ-rays, neutrinos, and secondary nuclei (e.g. Li, Be, B)