Cosmic-ray physics and indirect Dark Matter searches

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"la Caixa"

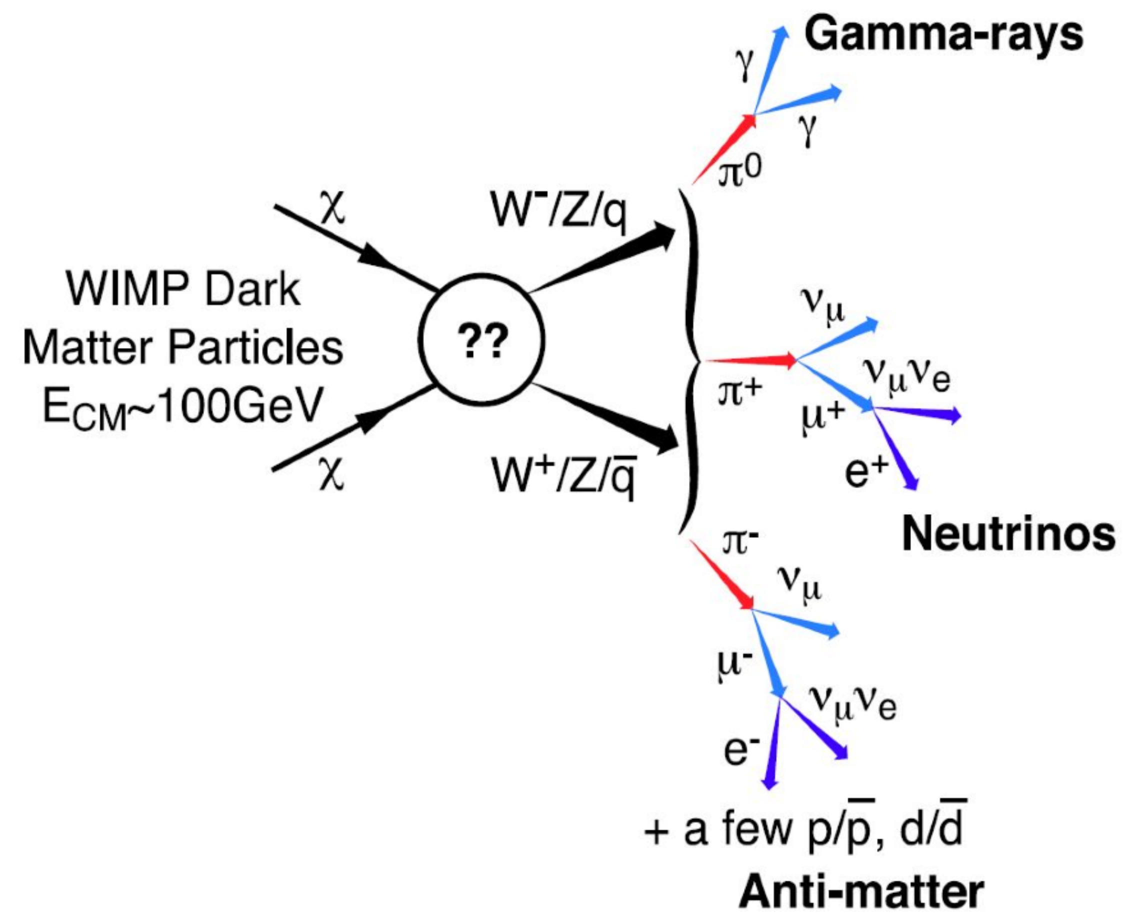
ISAPP school *"Gamma rays to shed light on Dark Matter"*

What did we learn so far?

1) Dark matter is out there!

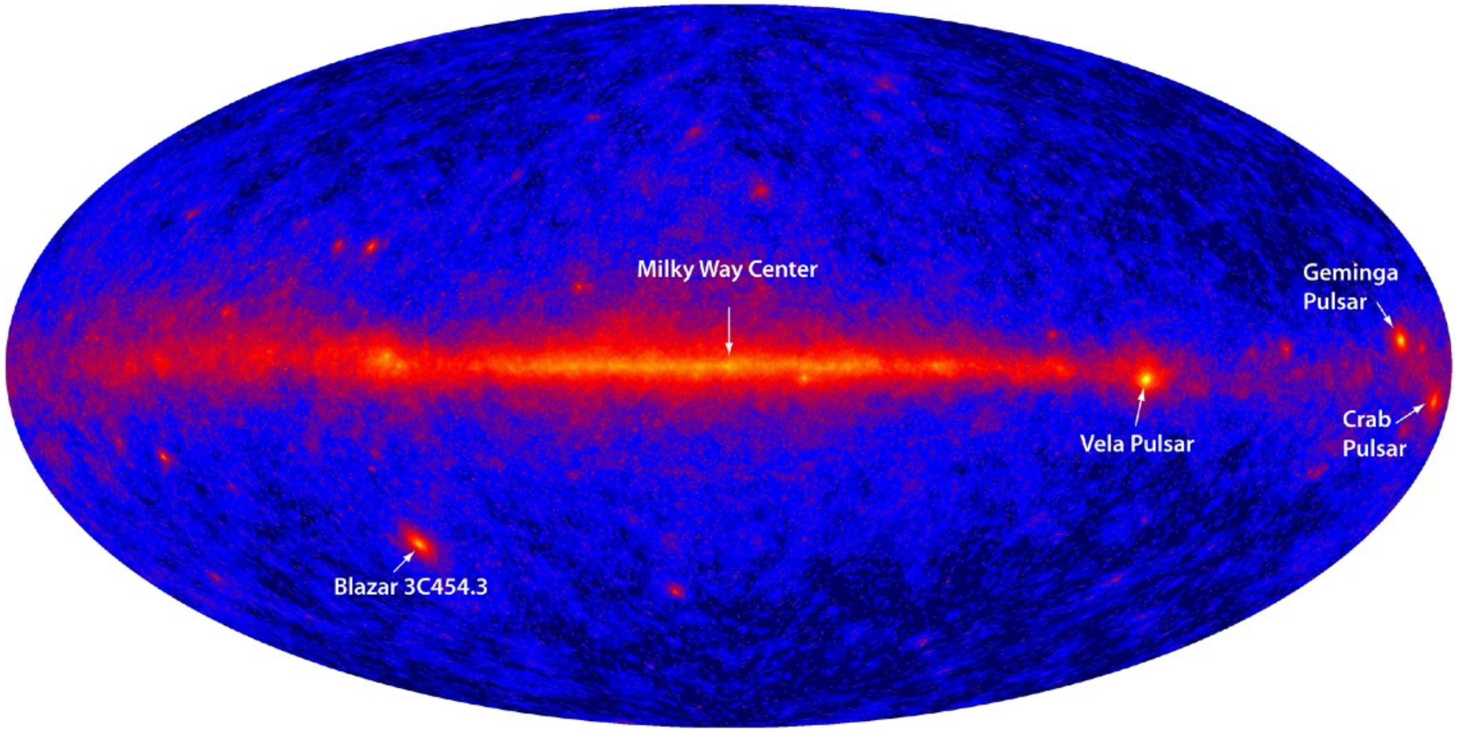
2) A good DM candidate is a ***massive***, ***neutral***, ***cold*** (or not too warm), ***stable*** (or very long-lived), ***feebly interacting*** particle (both with itself and with ordinary matter). No SM particle can fulfill these requirements.

3) The **WIMP paradigm** is a widely studied framework. WIMPs are expected to annihilate into standard model particles



- We have a flux of standard model *particles from outer space* carrying very high energies: we call them **cosmic rays** (CRs)

- We also have a significant gamma-ray emission from our Galaxy and other galaxies, mostly originating from CR interactions



- ***How to disentangle this emission from a DM signal?***

Let's learn more about CRs! Flash of history

Domenico Pacini (1910) observed a *decrease* of the ionization level in the water with increasing depth

PENETRATING RADIATION AT THE SURFACE OF AND IN WATER

Note by D. PACINI

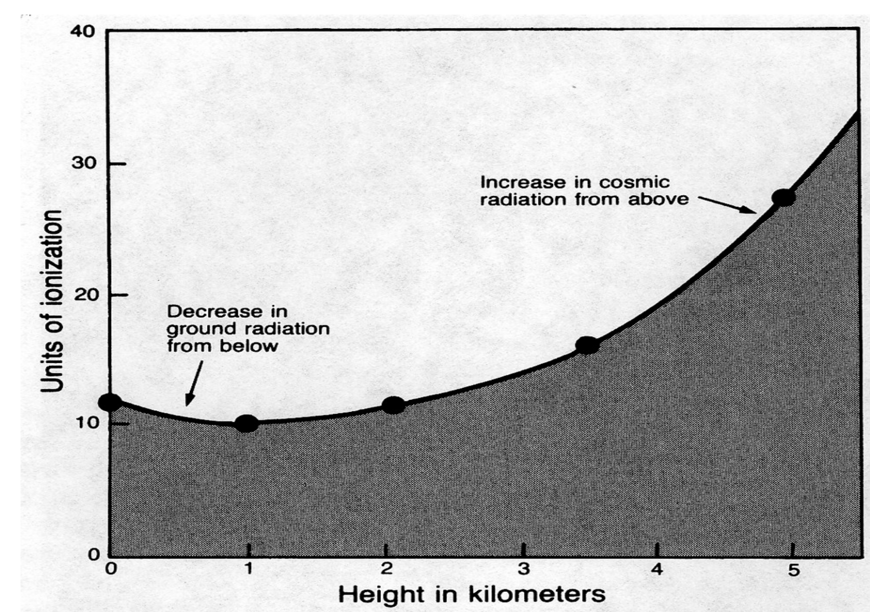
Translated and commented by Alessandro De Angelis
INFN and University of Udine

Observations that were made on the sea during the year 1910[5] led me to conclude that a significant proportion of the pervasive radiation that is found in air had an origin that was independent of direct action of the active substances in the upper layers of the Earth's surface.

Here, I will report on further experiments that support this conclusion.

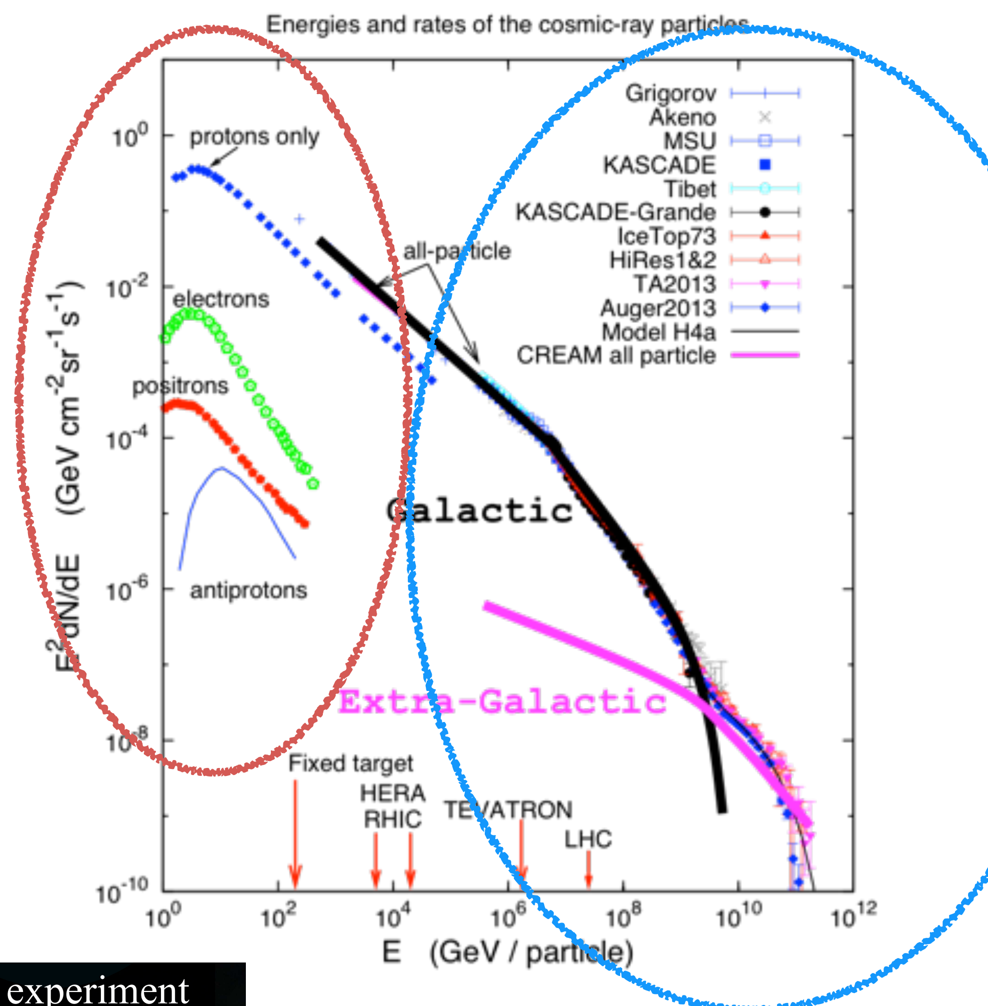
The results that were previously obtained indicated that a source of ionization existed on the sea surface, where possible effects from the soil are small, that had such an intensity that could not be explained on the basis of the known distribution of radioactive substances in water and in air.

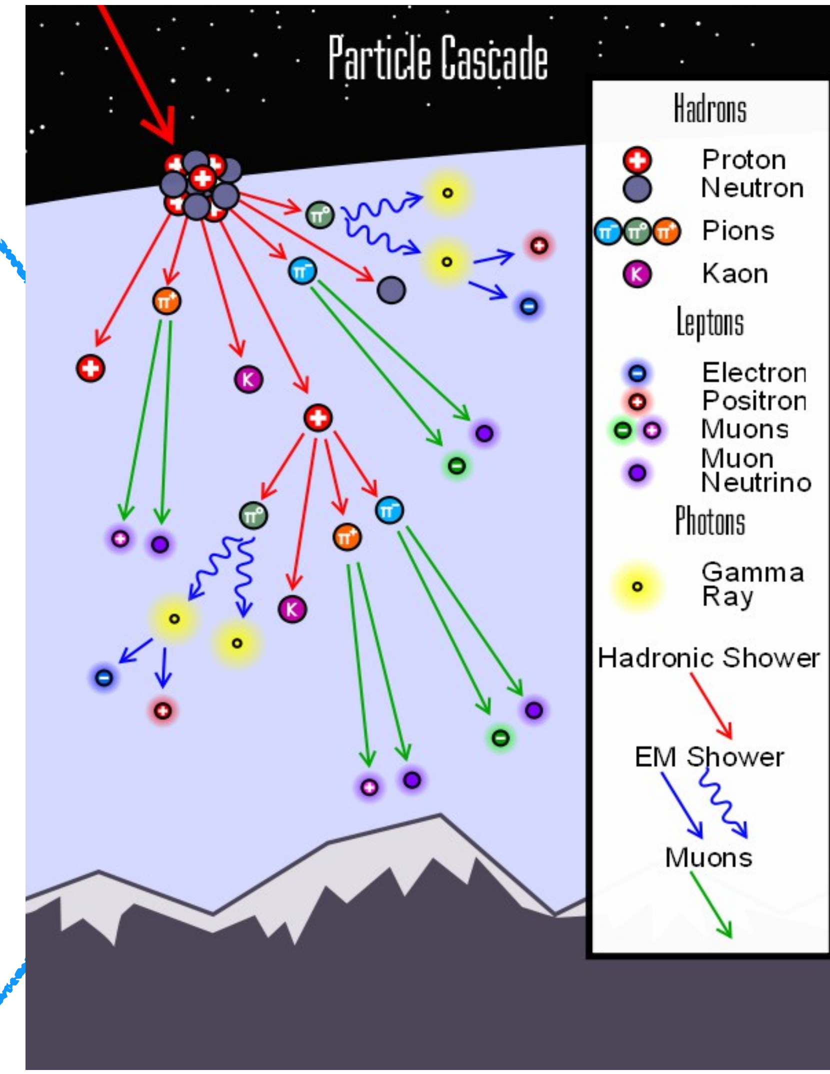
Victor Hess (1912) observed an *increase* of the ionization level in the atmosphere with increasing height (similar studies by **Theodor Wulf** in 1910, on the Eiffel tower)



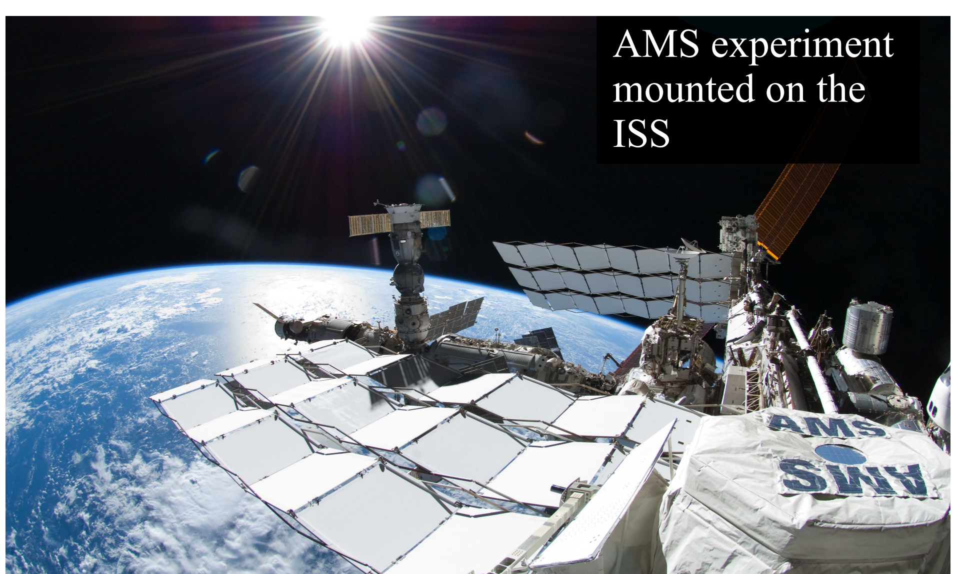
A glimpse on detection techniques

Question 1: how do we distinguish particles from antiparticles? can we do it for all energies?



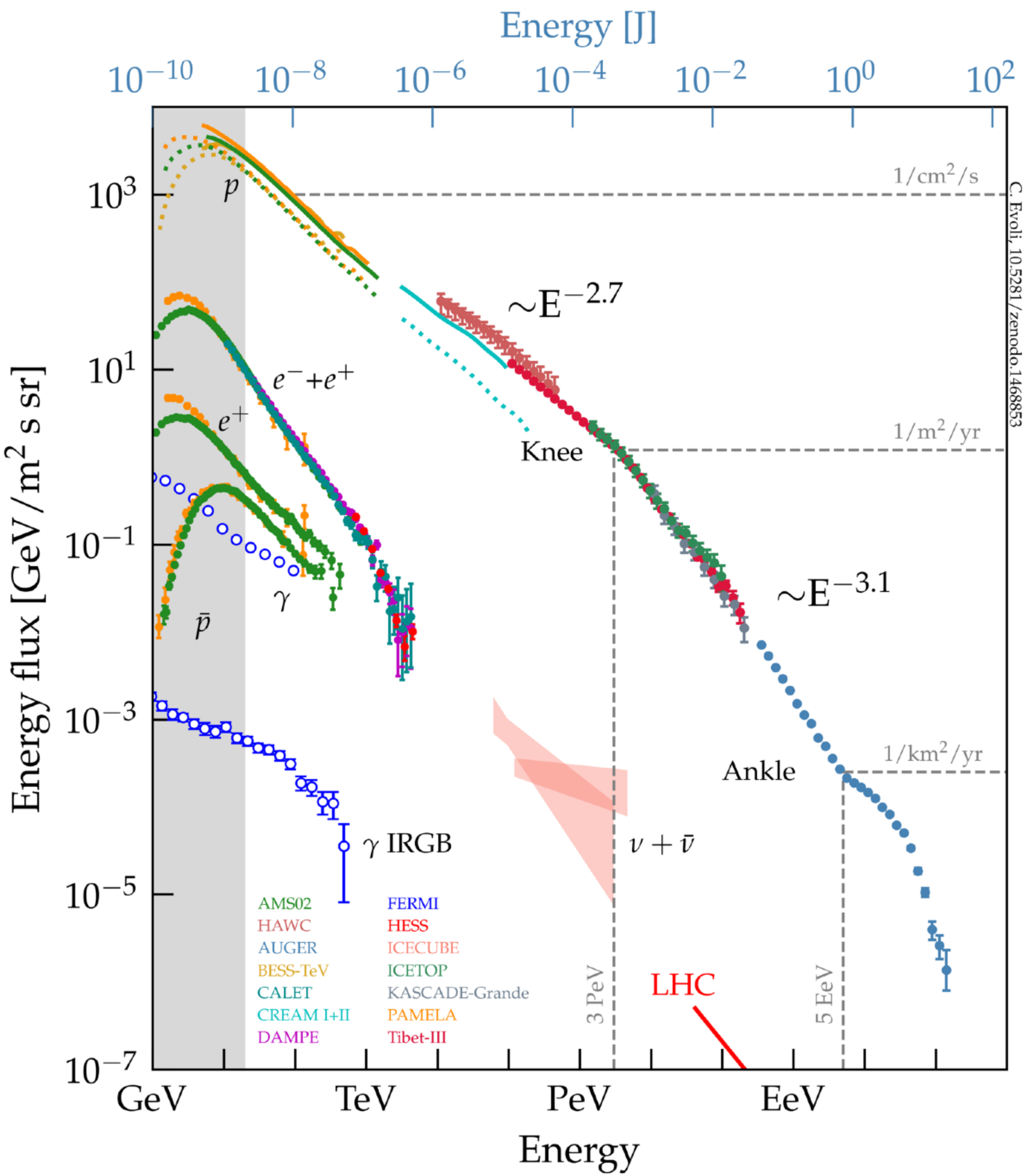


__**Low energy (GeV-TeV):**__
Large fluxes
1 particle/m²/s @100 GeV
mostly measured by **balloon-borne and space-based experiments**


AMS experiment mounted on the ISS

__**High energy (TeV and beyond):**__
Low fluxes
1 particle/km²/y @10^{18} eV
Ground-based experiments measure the ***air shower*** **that CRs generate in the atmosphere**

Properties of the CR flux at Earth



Cosmic rays: a (almost isotropic) flux of high-energy particles from outer space

Huge energy range, 11 decades in energy!

from ~1 GeV to *~10 [20]* eV

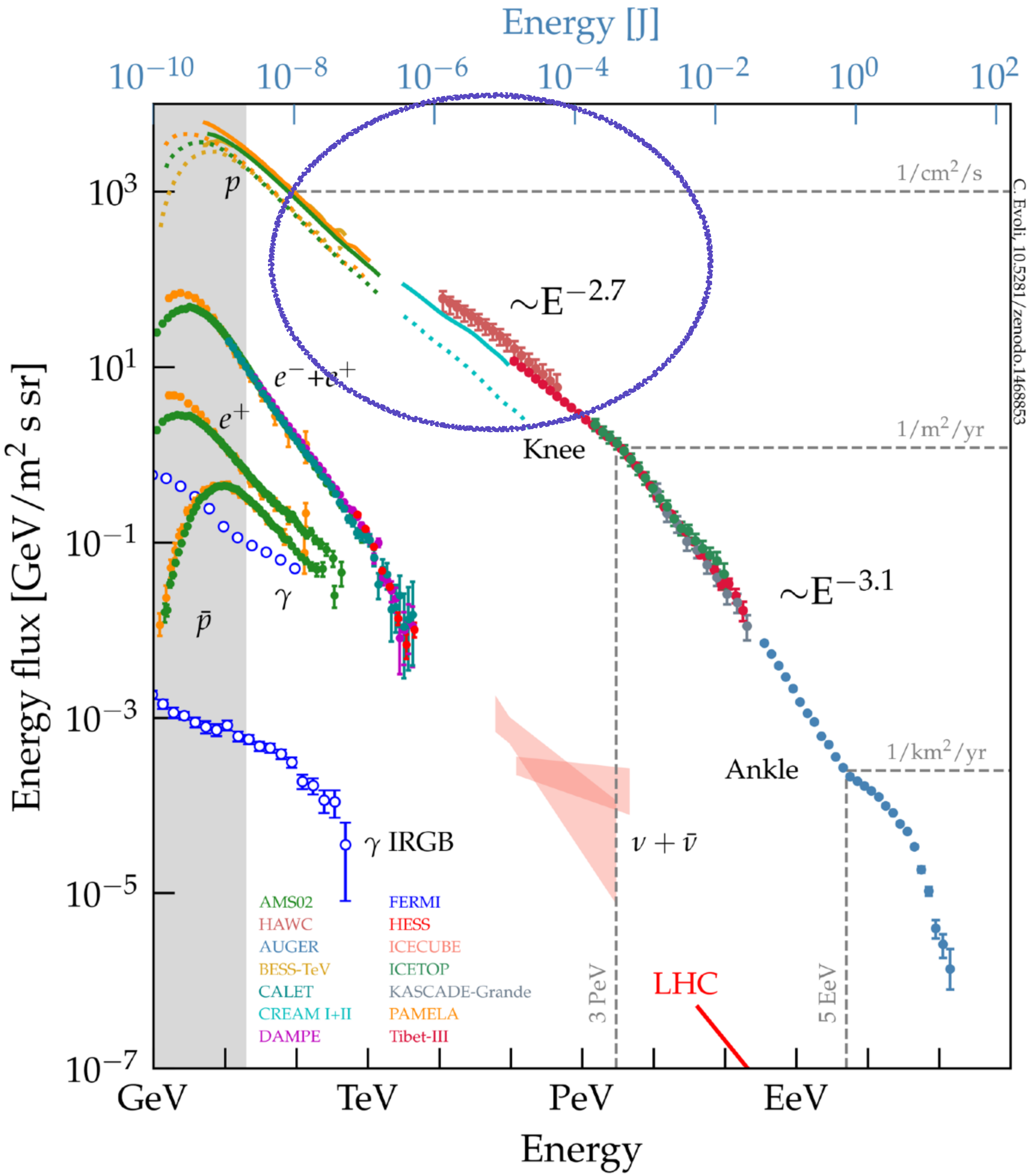
(remember: *1 eV = 1,6 * 10^{-19} J*)

Largest energy ~ 50 J (like a baseball traveling at ~ 100 km/h) Lorentz factor γ ~ 10^{11}

(*"Oh-my-god particle"* recorded in 1991 at Fly's Eye CR detector)

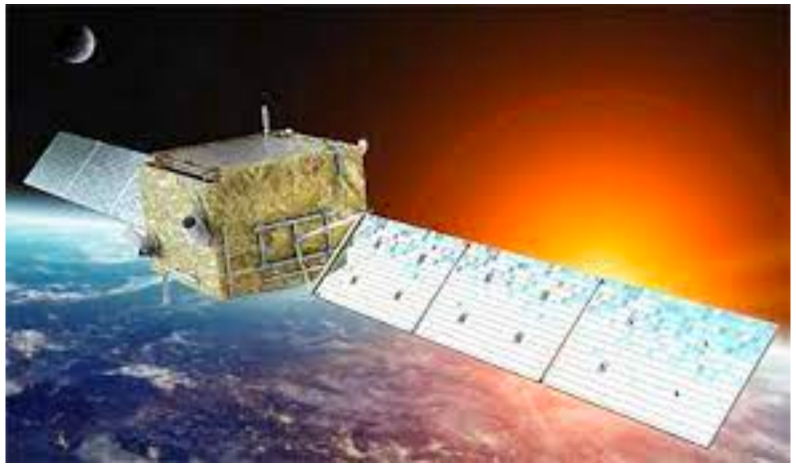
"Non-thermal" spectrum: a power-law in momentum

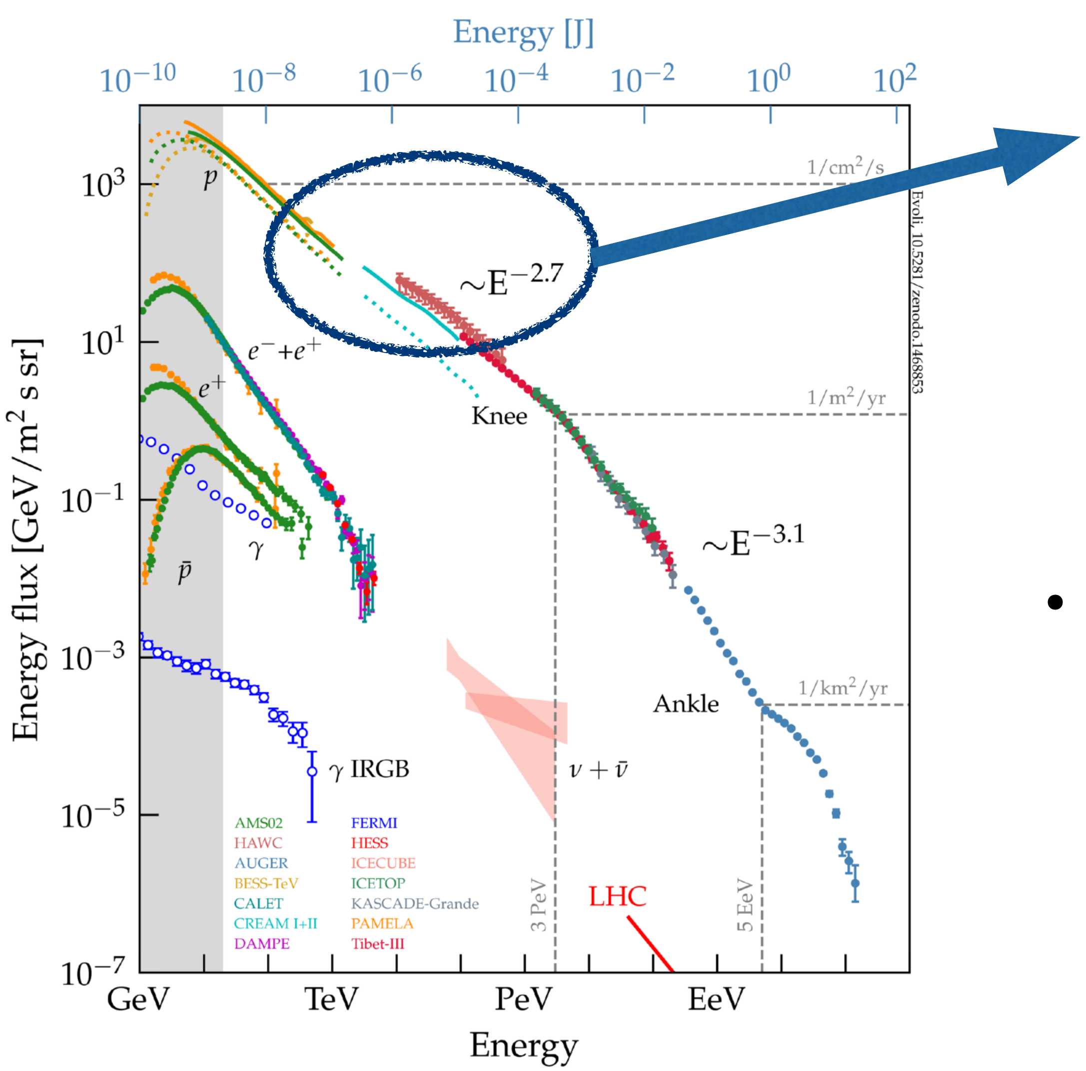
Properties of the CR flux at Earth

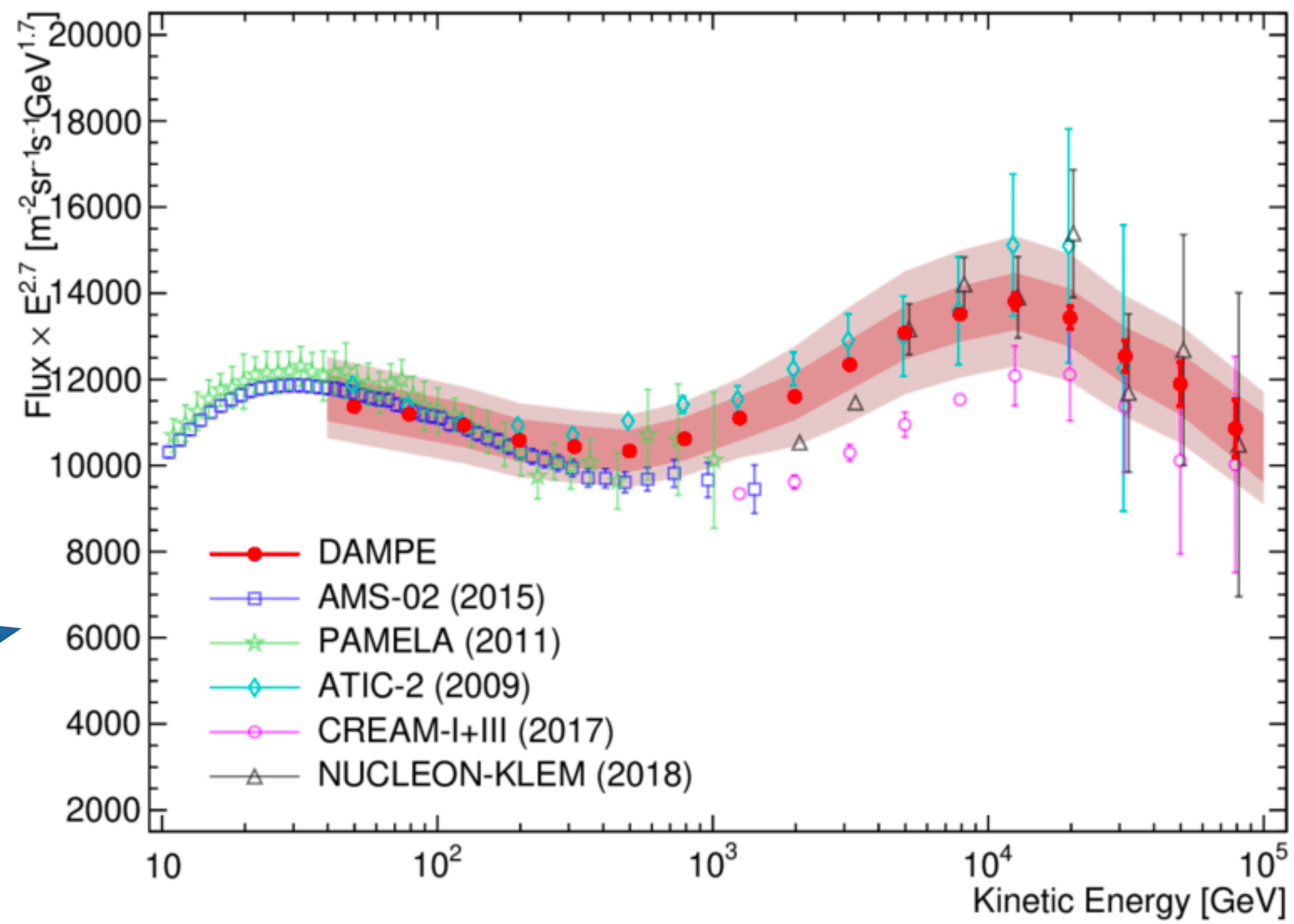


- **The all-particle CR Spectrum** is roughly consistent with a single power law of slope -2.7 spanning from **GeV** to a few **PeV**

Zooming in: new features start to appear

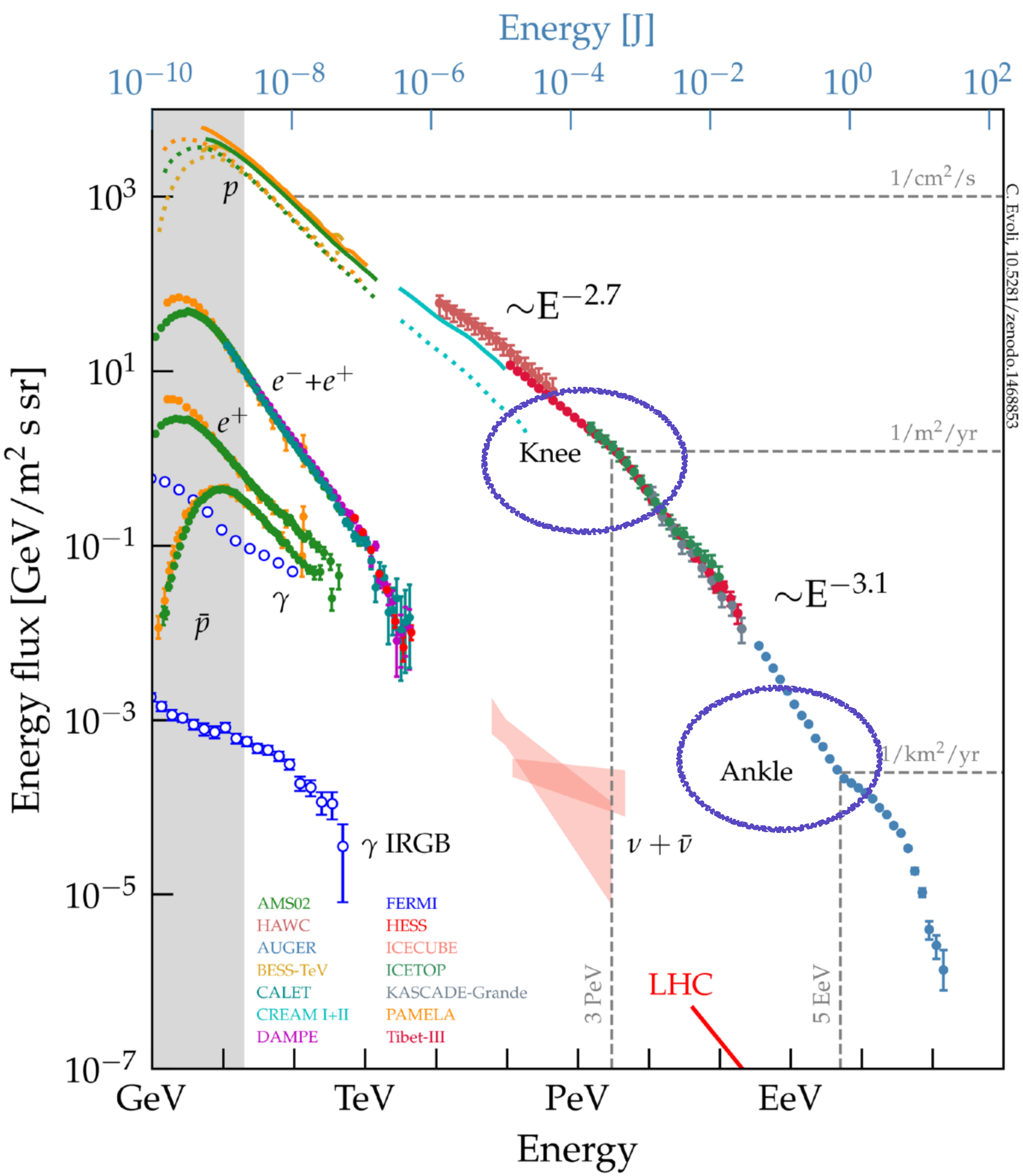






- Possible signature of a single nearby accelerator?

Spectral features: The knee



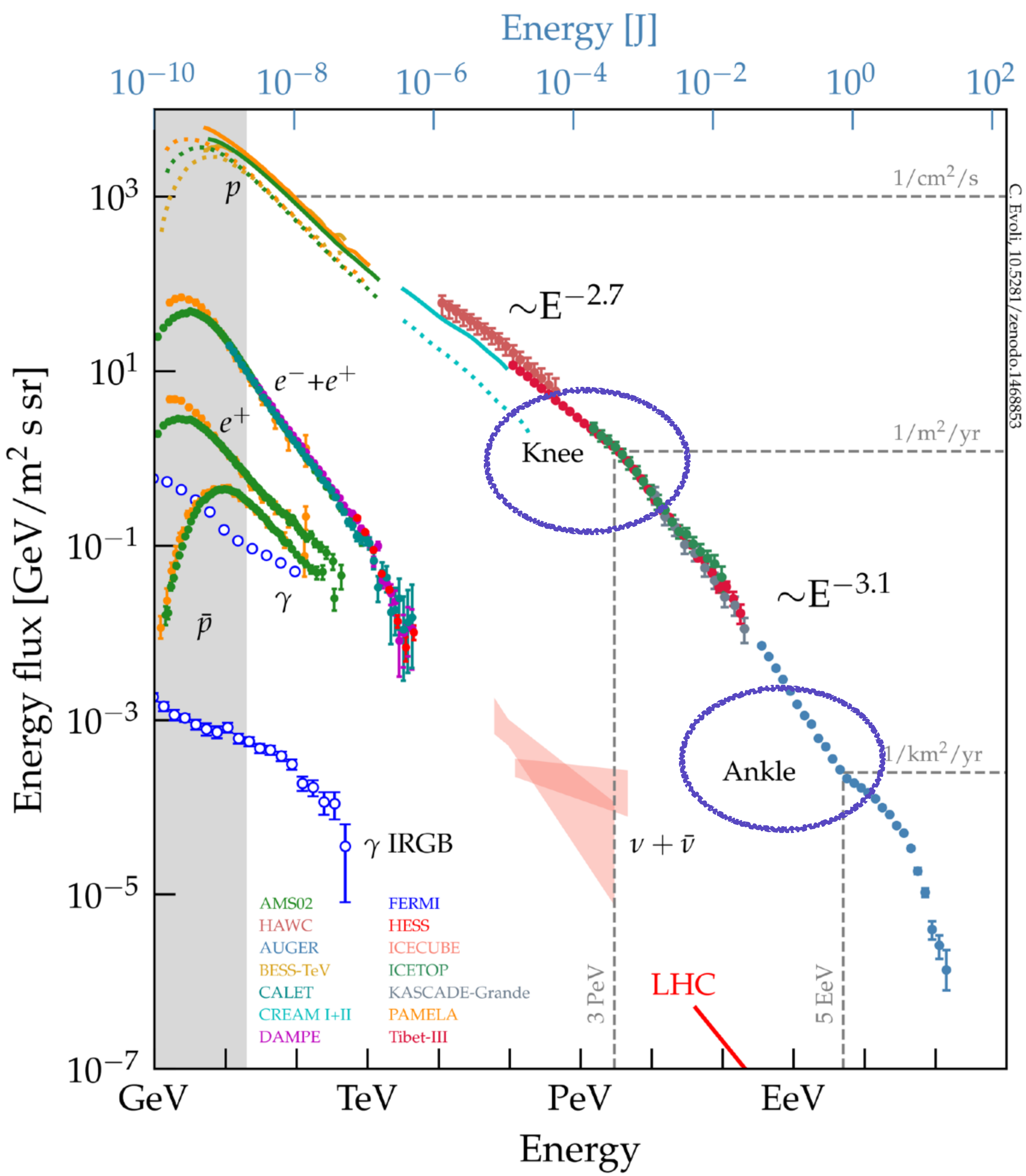
- **The knee is a relevant steepening** that corresponds with a progressive change in composition.

- ***Below the knee:*** the CR composition is largely dominated by protons

- ***Larger energies:*** the presence of heavier elements becomes important.

- The spectral steepening observed above the knee corresponds to a **reduced efficiency** of Galactic CR sources in accelerating particles up to such energies.

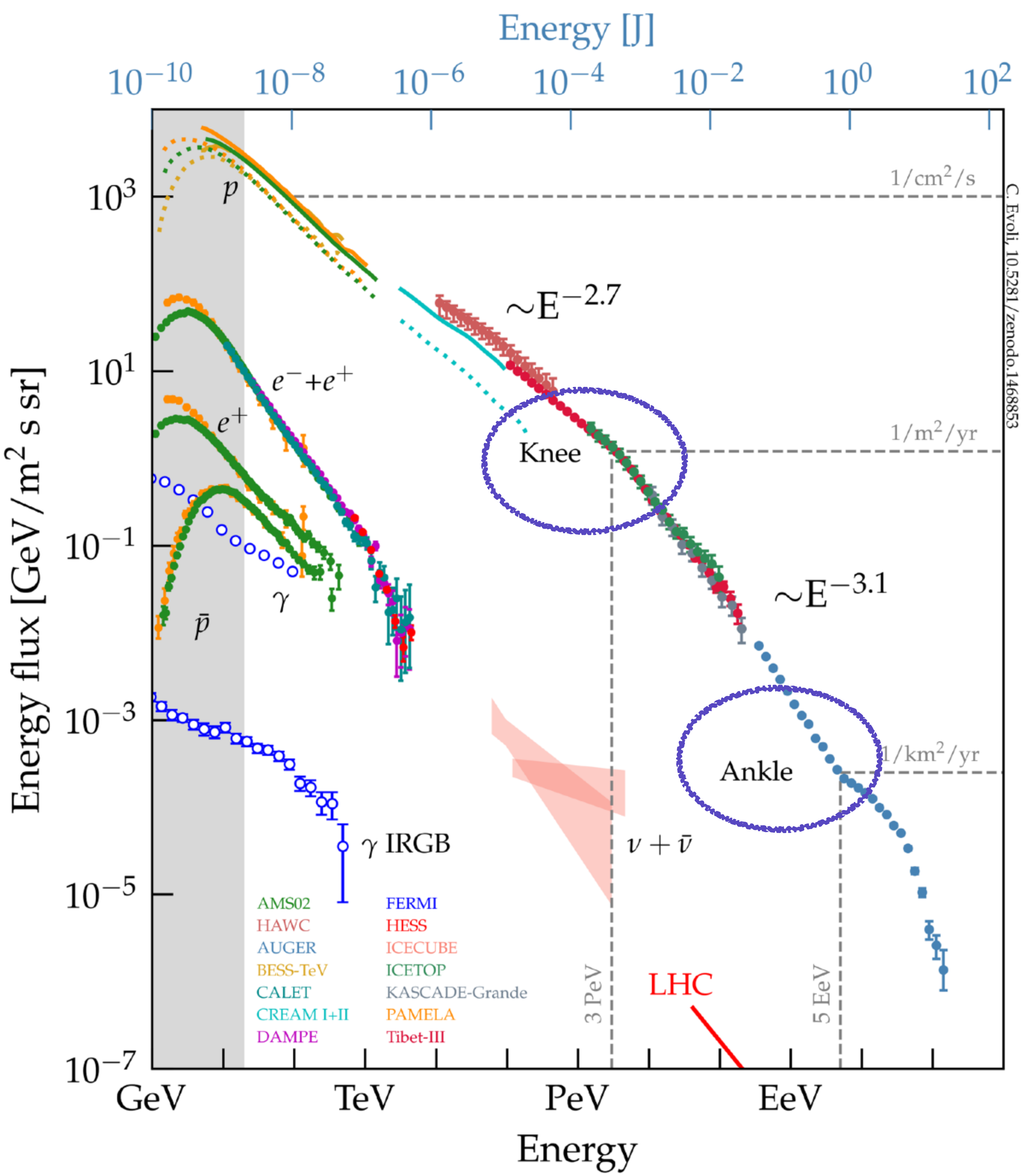
Spectral features: The ankle



- **The** **ankle is a hardening** in the all-particle spectrum at ≈ 5000 PeV (5 EeV)
- It is believed to result from the emergence of the extra-Galactic component of CRs above the Galactic one

Question 2: how can we estimate the maximum energy associated to Galactic confinement?

Spectral features: The ankle



- **The ankle is a hardening** in the all-particle spectrum at ≈ 5000 PeV (5 EeV)

- It is believed to result from the emergence of the extra-Galactic component of CRs above the Galactic one

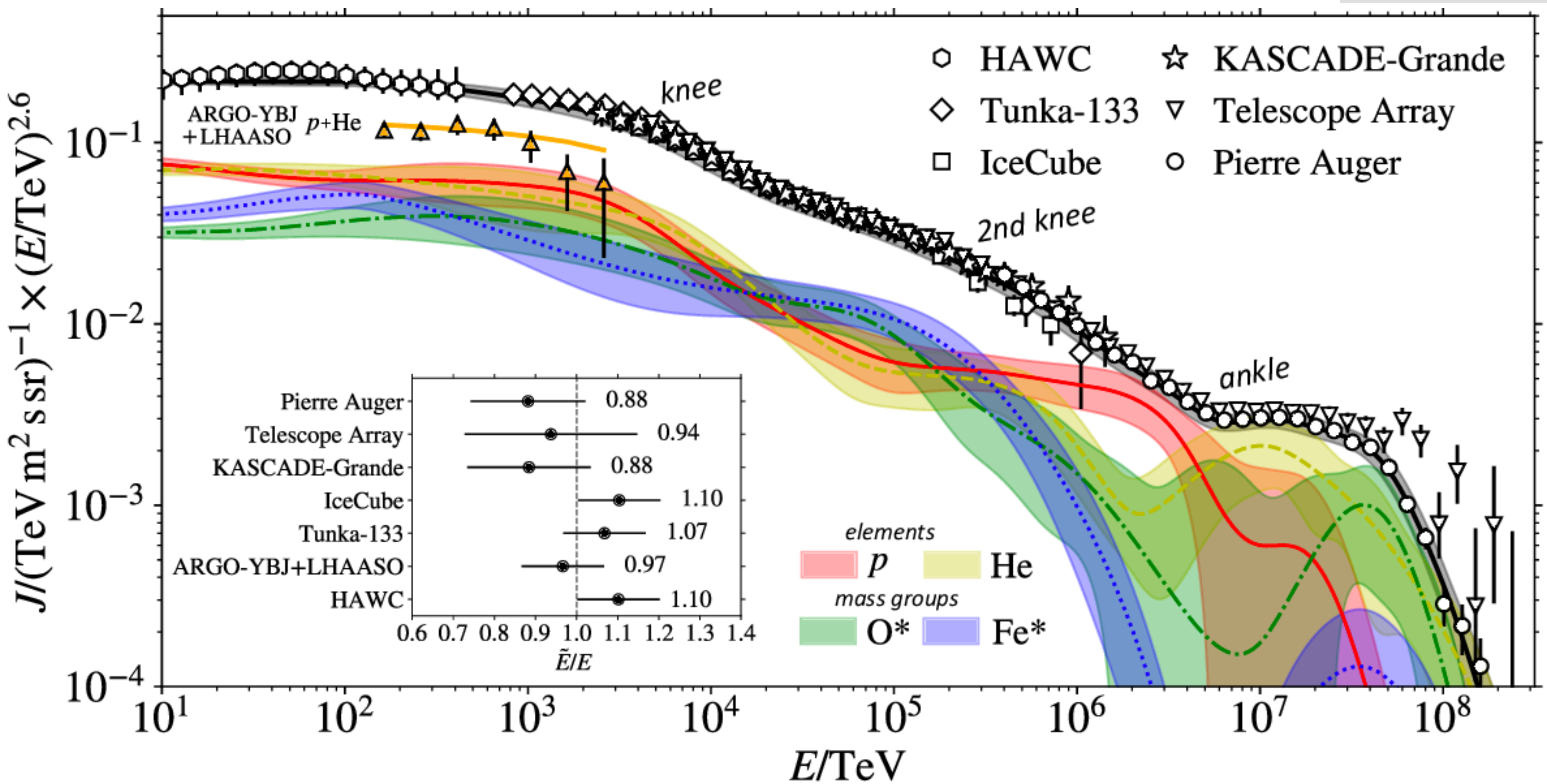
Hint:

$$R_{Larmor}\,[pc] = \frac{E[PeV]}{B[\mu G]}$$

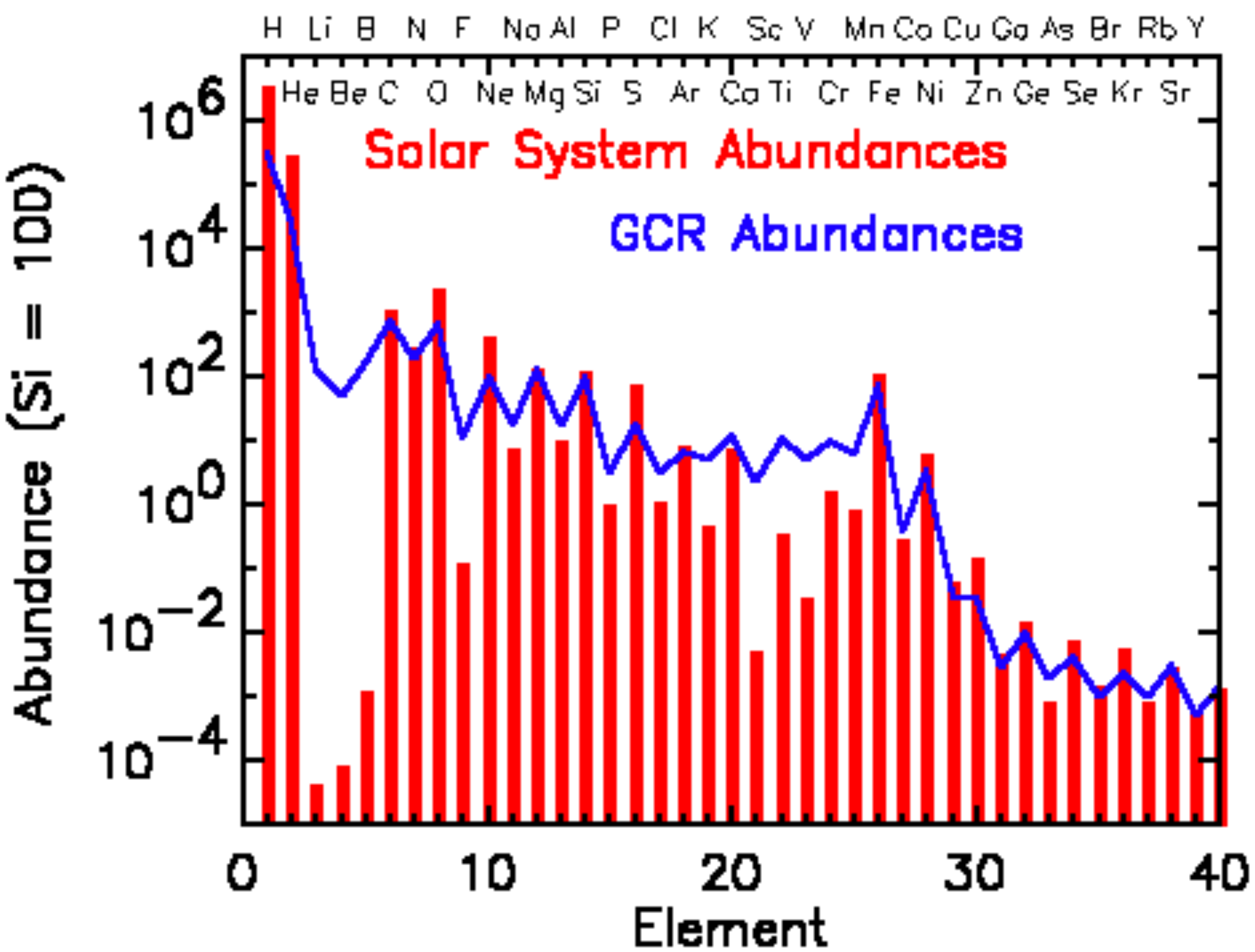
Zooming in on the highest energies

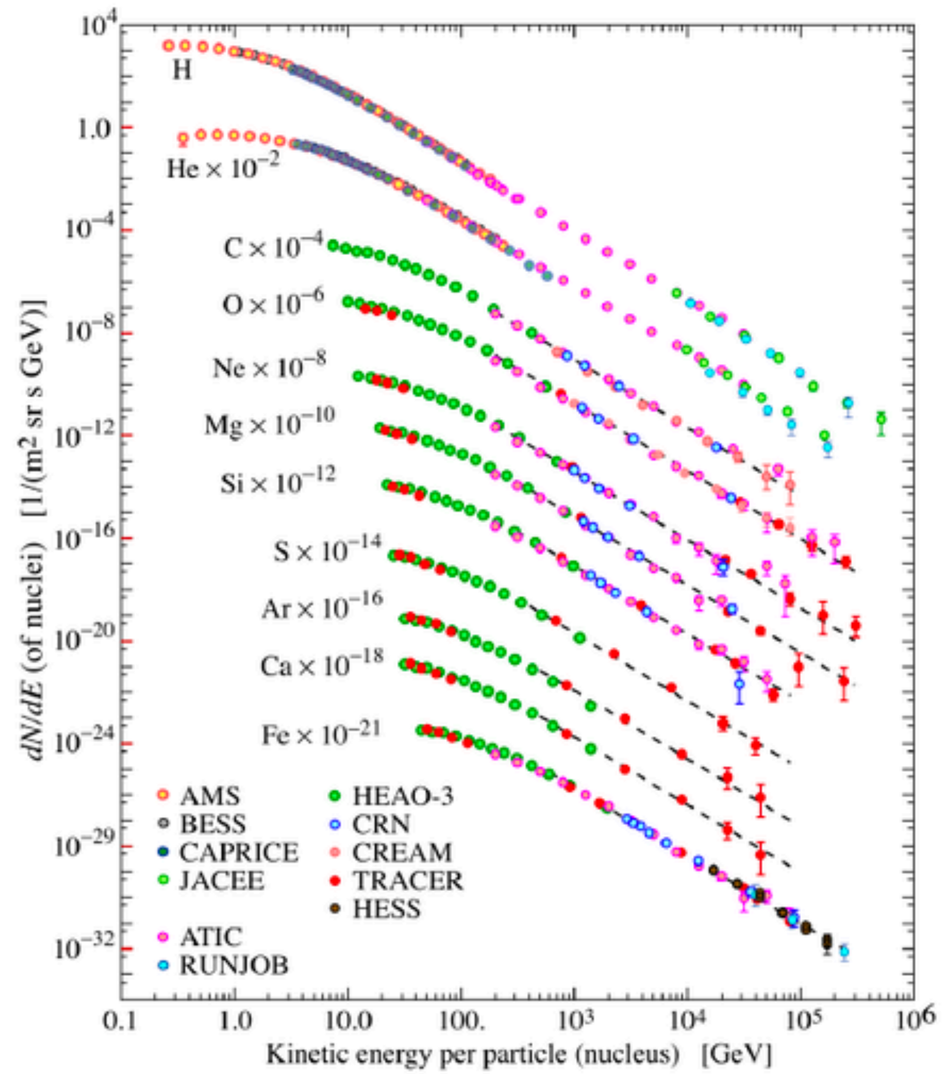
- **Complicated puzzle in the region from the knee to the ankle.** Precise location of Galactic - extra-Galactic transition unclear!

arXiv:1903.07713



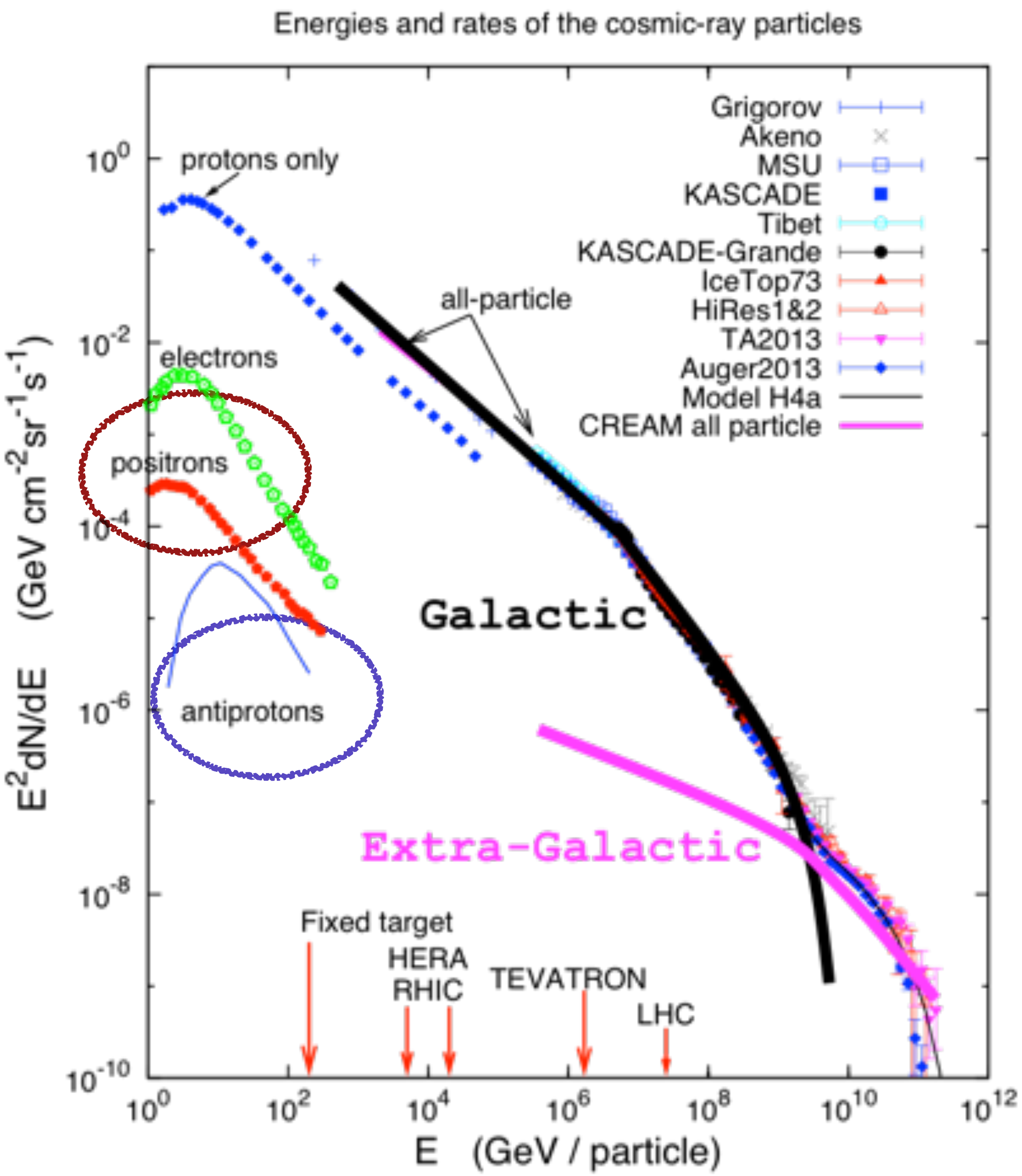
Composition





- 89% are protons
- 10% are He nuclei
- All nuclear species are present
- **Over-abundance of Li, Be, B** (by 5-7 orders of magnitude at 1 GeV) with respect to Solar System abundances
- 1-2% are electrons

Composition



- A very small fraction of CRs are antiparticles (positrons and anti-protons)
- Production channel: Spallation from heavier nuclei
- Ongoing search for anti-deuteron and anti-helium

The "big questions"

1) **Where do they come from? How do they reach these large energies?**

2) **How do they propagate in the interstellar space before reaching us?**

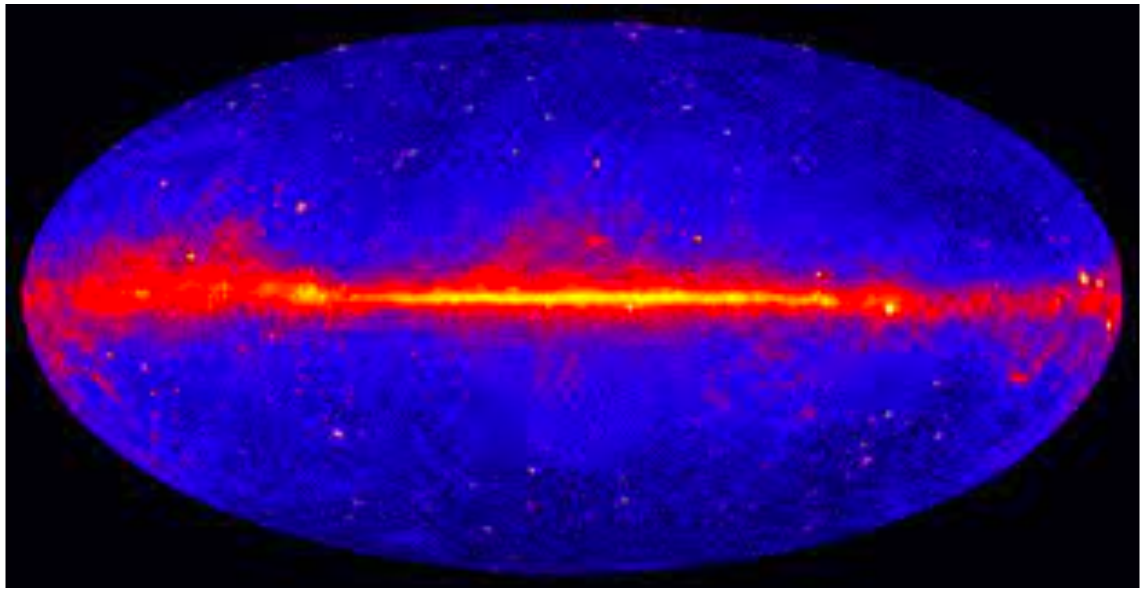
- The answers are still under debate, *after more than 100 years since the discovery*!
- An **interdisciplinary** research field: It requires deep knowledge of particle physics, astrophysics, plasma physics…

The "Orthodox picture"

arXiv:1903.11584

Pillar 1) The **bulk of the energy** of cosmic rays originates from *Supernova Explosions* in the Galactic disk *(other sources may be at work)*

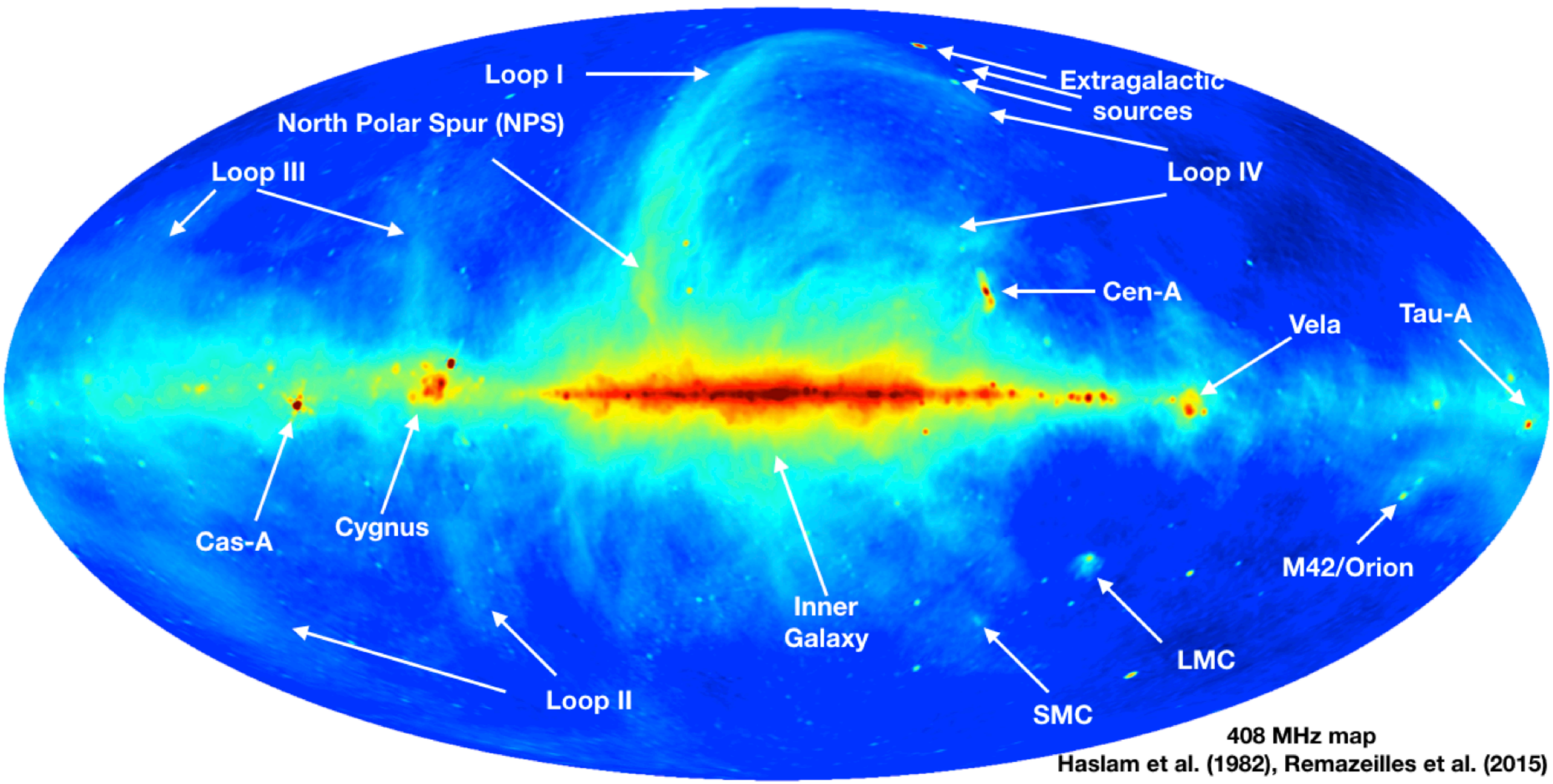
- Measured local energy density of CRs is approximately equal to the other components of the ISM (magnetic field, photon field): 1 eV / cm^3
- Energy budget is compatible with energy injected by SNae
- We have a **theory** that explains CR acceleration at SN shocks: Diffusive Shock Acceleration (DSA) *(other mechanisms may be at work as well)*



The "Orthodox picture"

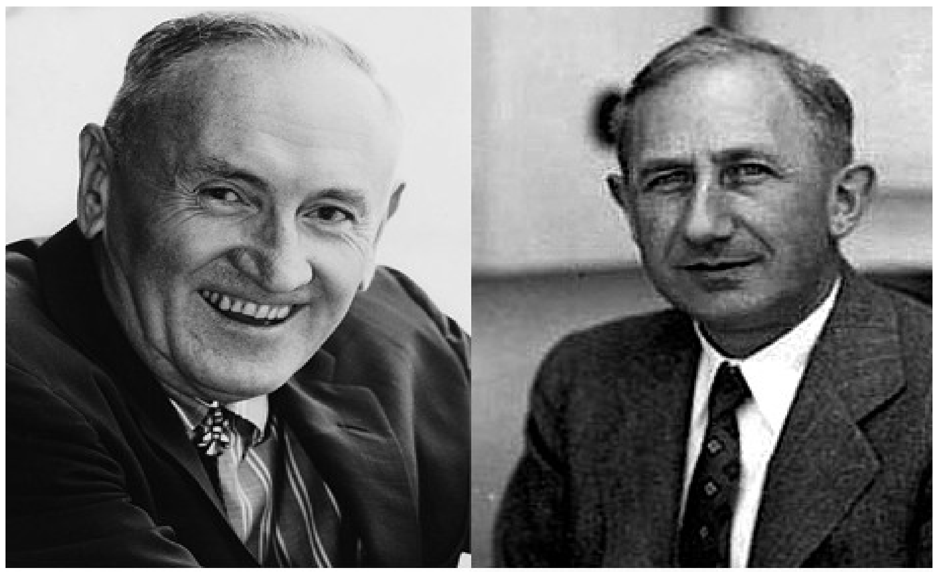
arXiv:1903.11584

Pillar 2) Cosmic rays are **diffusively confined** within an extended, **magnetized Galactic halo**



408 MHz map
Haslam et al. (1982), Remazeilles et al. (2015)

1) A primer on CR acceleration



DR FRITZ ZWICKY — WALTER BAADE, FIZIKUS

1934

Title: Cosmic Rays from Super-novae
Authors: Baade, W.. ; Zwicky, F.
Publication: Contributions from the Mount Wilson Observatory, vol. 3, pp.79-83
Publication Date: 00/1934
Origin: ADS
Keywords: Supernovae
Comment: Reprinted from Proceedings of the National Academy of Sciences, 20, 259-262, 1934.
Bibliographic Code: 1934CoMtW...3...79B

Abstract

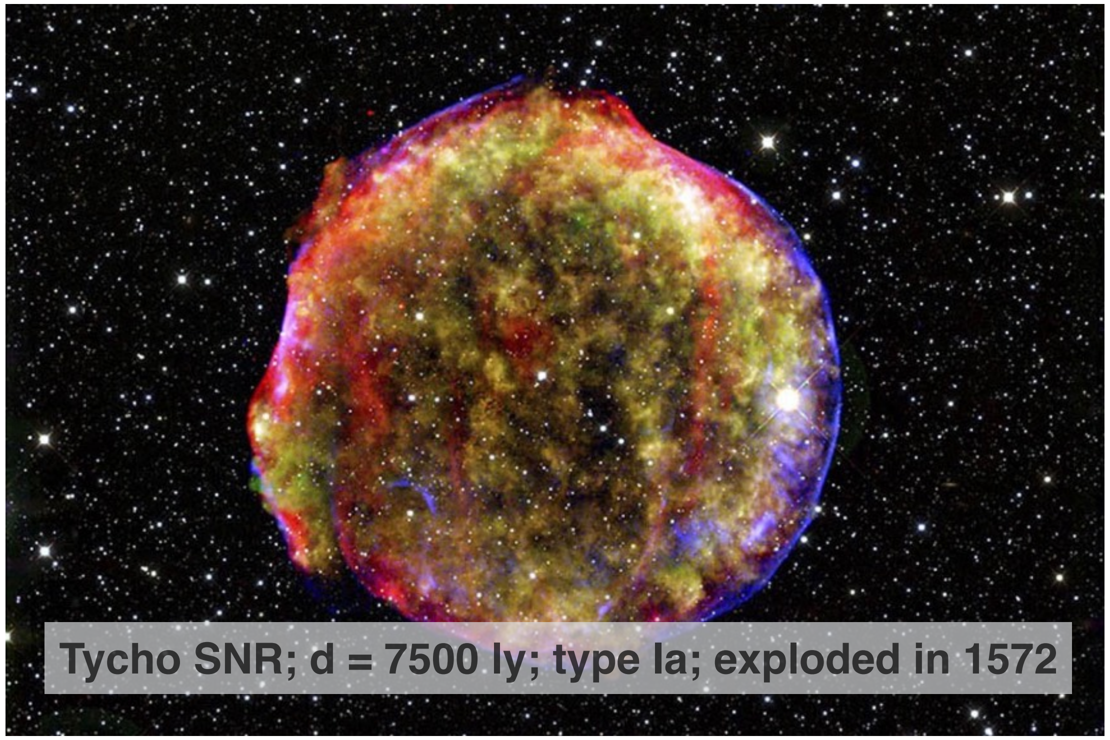
The hypothesis that supernova emit cosmic rays is in reasonable agreement with cosmic ray observations.

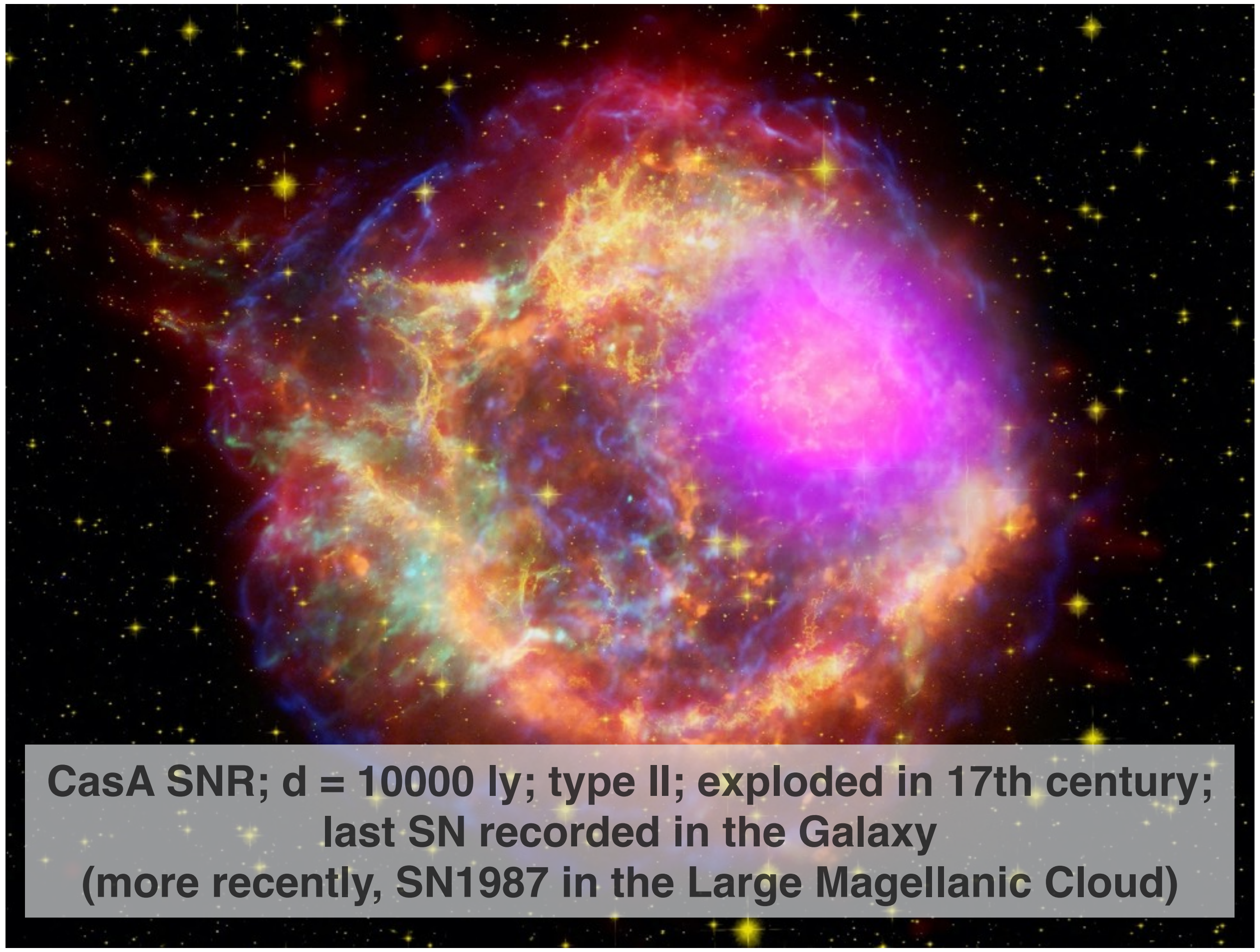
The energy supplied by all Supernova explosions in the Galaxy is enough to sustain the CR flux in the GeV-PeV range (with efficiency of order 1-10%)!

question 3: how can we prove this with a rough order-of-magnitude estimate?

Useful numbers: CR energy density is *~1 eV/ cm³* — CR residence time is ~10 Myr — SN rate is ~3/century in our Galaxy — Volume of the Galaxy?

A primer on CR acceleration: SNRs

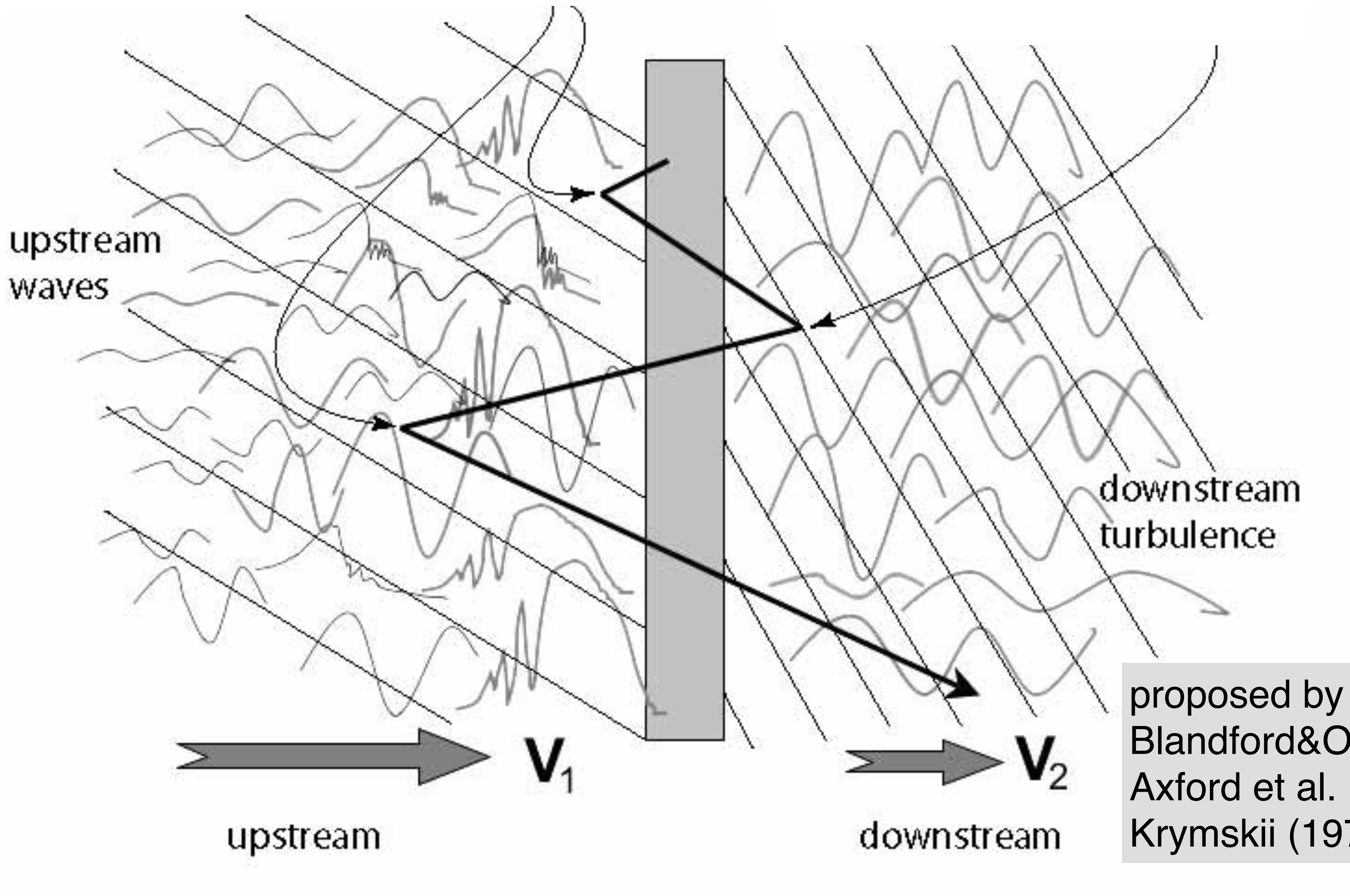

Tycho SNR; d = 7500 ly; type Ia; exploded in 1572


CasA SNR; d = 10000 ly; type II; exploded in 17th century;
last SN recorded in the Galaxy
(more recently, SN1987 in the Large Magellanic Cloud)

- **SNRs** are structures resulting from explosions of supernovae
- **Energy** released in a type II SN ~10^{53} erg (10^{46} J) (99% in neutrinos!)
- A **shock** (density and pressure discontinuity) expands in the interstellar medium: *v ~ 1000 km/s* in the first phase
- Typical SNR lifespan: ~10-100 kyr

A primer on CR acceleration: DSA

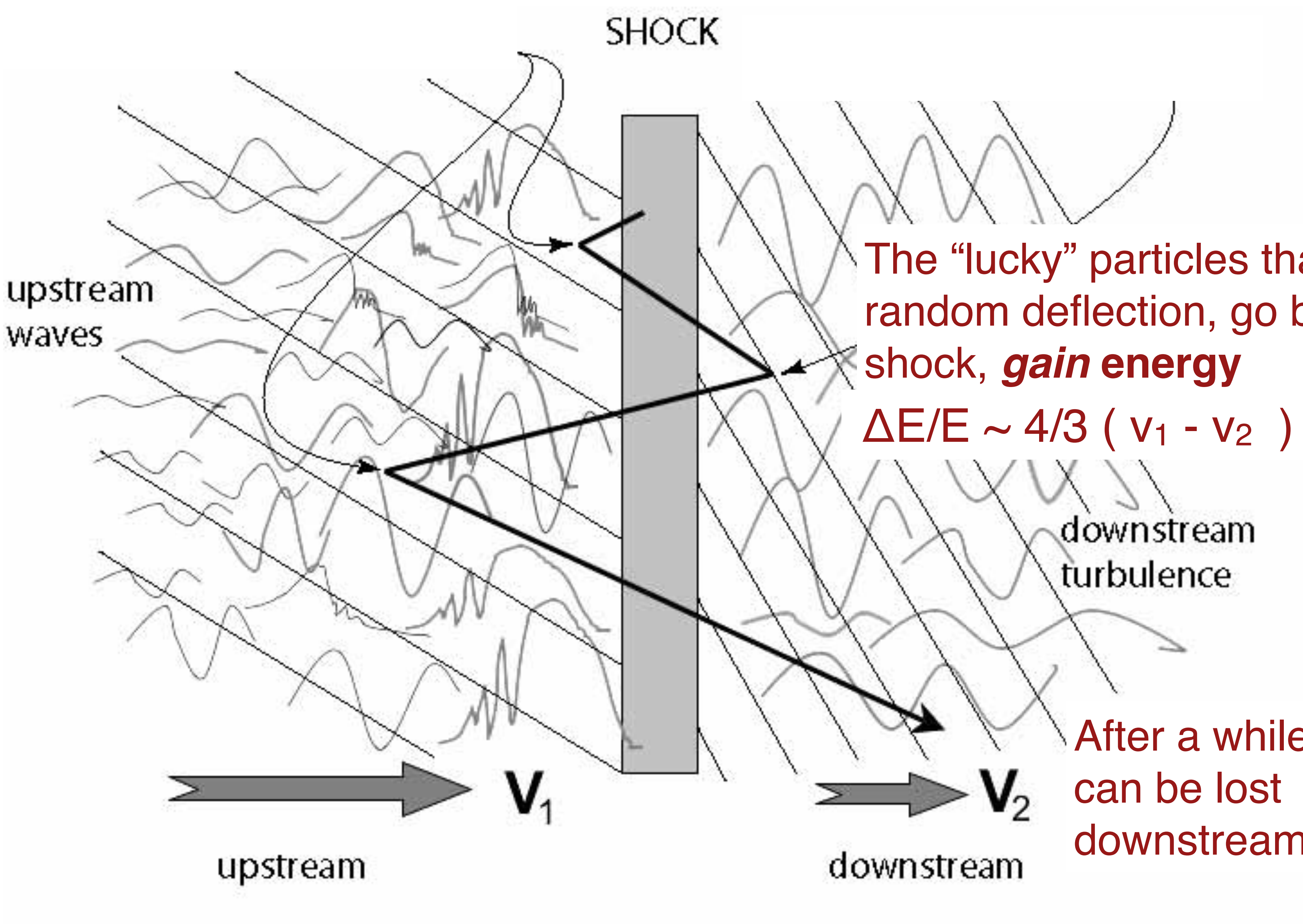
- **Shock front** —> a discontinuity in pressure and temperature travelling in the interstellar medium
- Shocks behave as **efficient heating machines** —> a large fraction of incoming kinetic energy is converted into internal energy of the gas behind the shock front
- This mechanism was not proposed by Fermi



proposed by T.Bell (1978), Blandford&Ostriker (1978), Axford et al. (1977), Krymskii (1977)

A primer on CR acceleration: DSA

- Charged particles interact with the shock front propagating in the interstellar medium
- Turbulent magnetic field —> **particles are deflected in random way** both upstream and downstream the shock



The “lucky” particles that, after the random deflection, go back to the shock, ***gain* energy**

$\Delta E/E \sim 4/3\ (v_1 - v_2) = U$

After a while, they can be lost downstream

Maximal energy: Hillas criterion

The “lucky” particles that interact with the shock many times can reach very large energies:

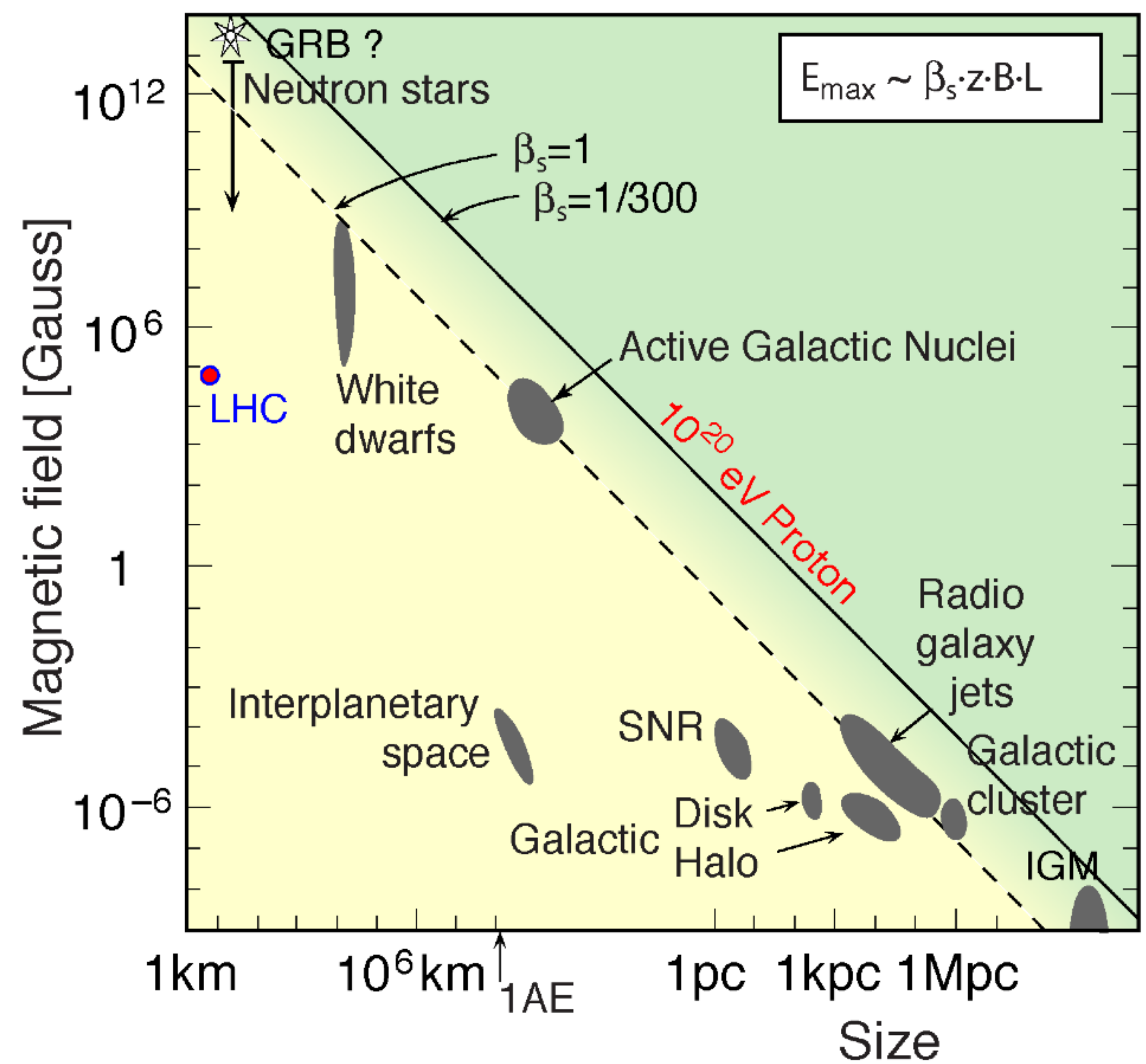
$$\frac{D}{u_s} \sim \frac{r_L c}{u_s} \sim \frac{p\,c\,B_s}{u_s} \sim R_s \qquad r_L \equiv \frac{pc}{ZeB_0} \simeq \frac{E/Z}{10^{15}\ \mathrm{eV}} \left(\frac{B_0}{\mu\mathrm{G}}\right)^{-1} \mathrm{pc}\ .$$

$$E_{max} = \epsilon \left(\frac{R_s}{\mathrm{pc}}\right) \left(\frac{u_s}{1000\ \mathrm{km/s}}\right) \left(\frac{B_s}{\mu\mathrm{G}}\right)\ \mathrm{T}$$

In supernova remnants, if the magnetic field is large enough:

—> CR Protons can reach energies as large as ~ PeV = 10^{15} eV

—> CR Nuclei can reach energies as large as $Z\,E_{max}$ (protons)



Pillar 2) Cosmic-ray are diffusively confined in the Galactic halo

Evidence for CR confinement:

1) Isotropy of the arrival direction

2) Bright diffuse emission in **gamma rays** at GeV-TeV energies

3) Over-Abundance of light elements such as *Lithium*, *Beryllium*, *Boron*

Resulting picture:

- *CRs are confined* for a long time (> 10 Myr) in the Galaxy
- CRs interact with the intestellar gas
- Heavier species produce lighter ones (secondaries) via *spallation*

Pillar 2) Cosmic-ray are diffusively confined in the Galactic halo

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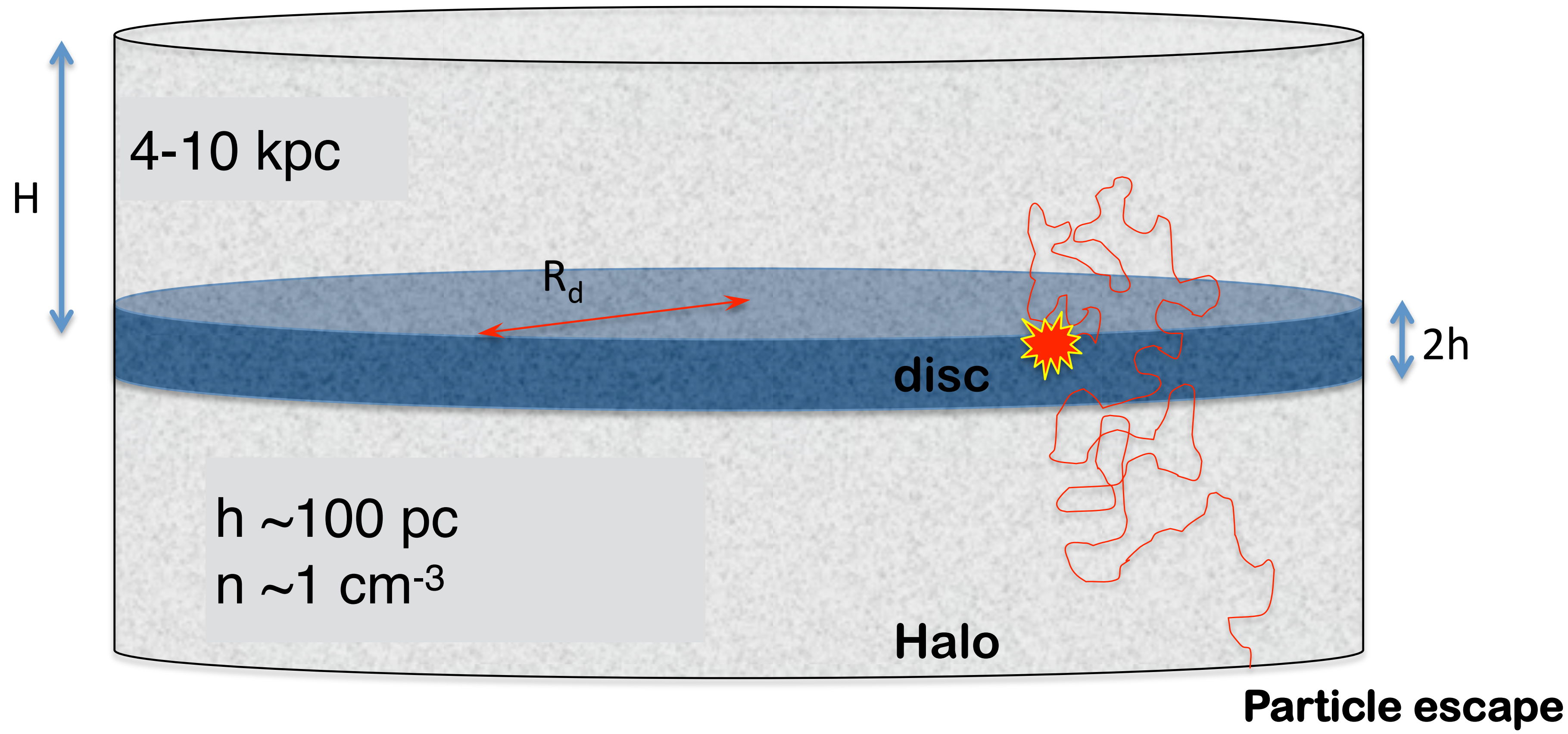

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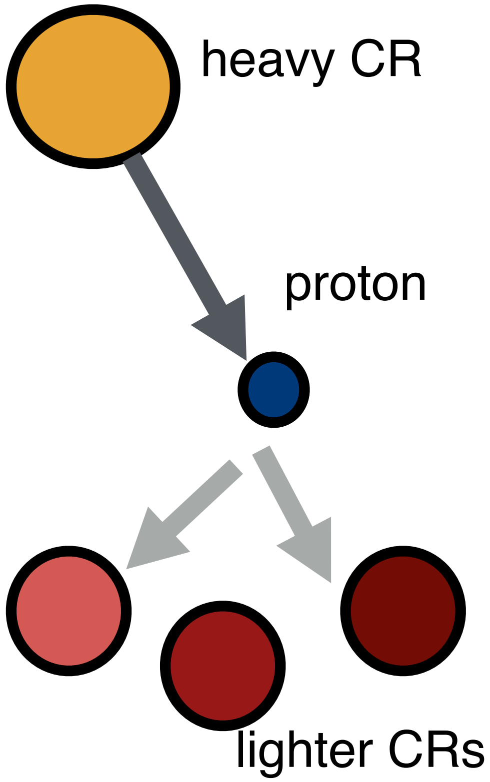

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Resulting picture:

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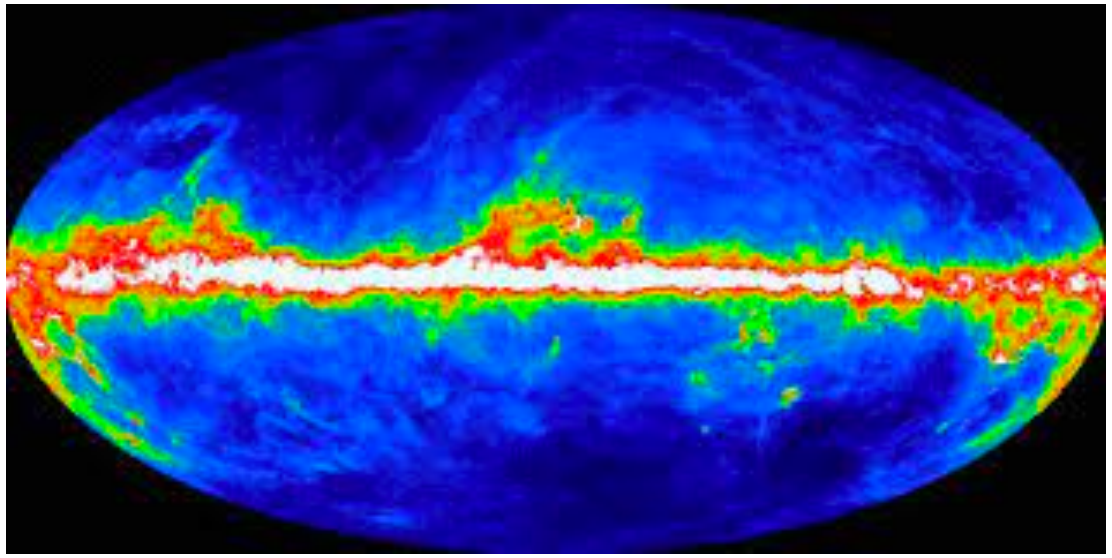
- CRs interact with the intestellar gas
- Heavier species produce lighter ones (secondaries) via *spallation*

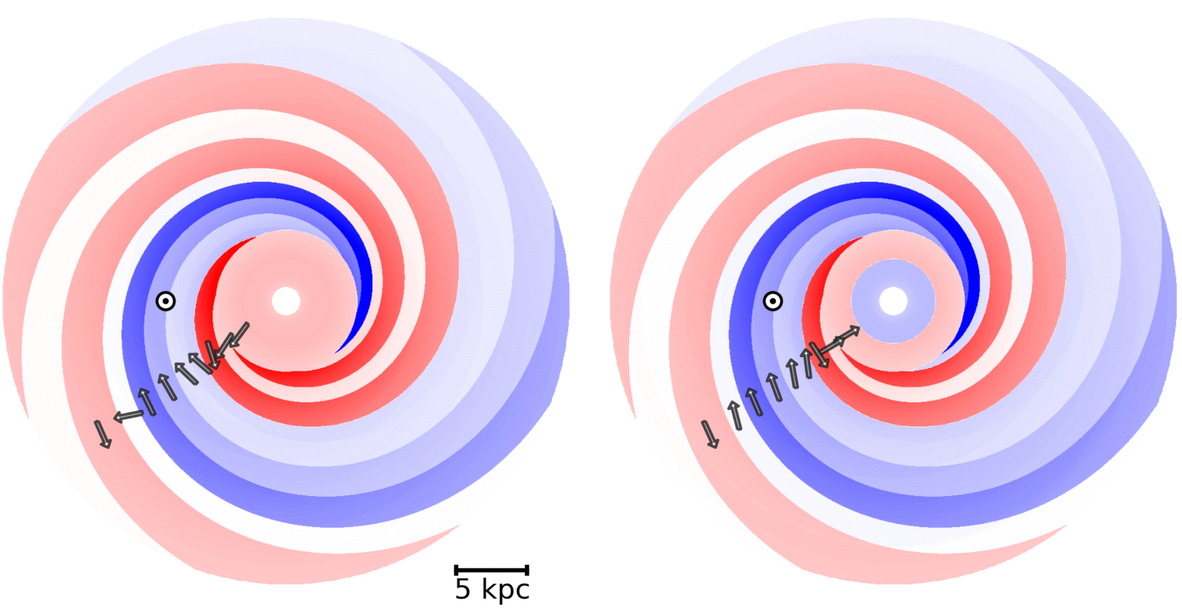
Given the cross section and the relative abundance of secondaries and primaries, ***we can estimate that CRs cross a column density ~3 g/cm²***

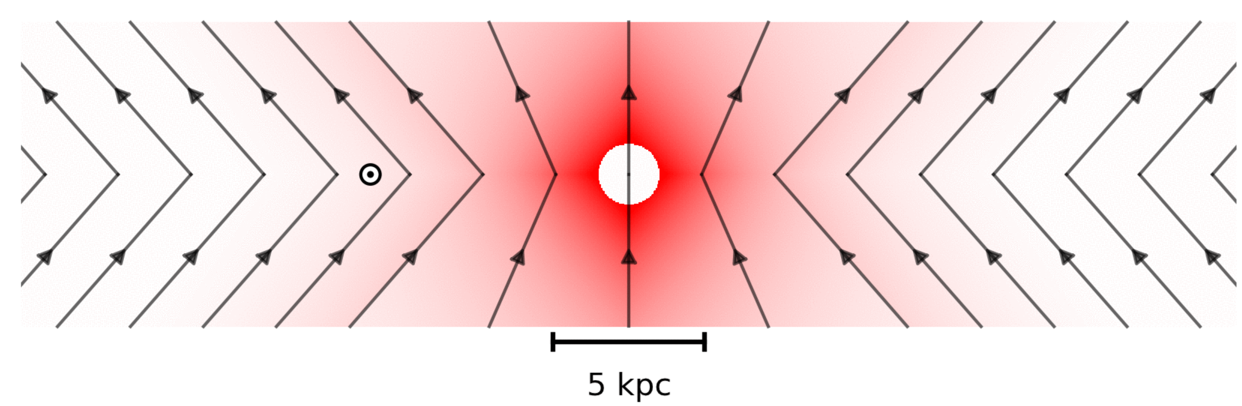


The basic picture: Quasi linear theory of pitch angle scattering

Prologue: Regular and turbulent magnetic field in the Galaxy

Regular field:
- Galactic Plane component (follows spiral arms)
- Vertical X-shaped component



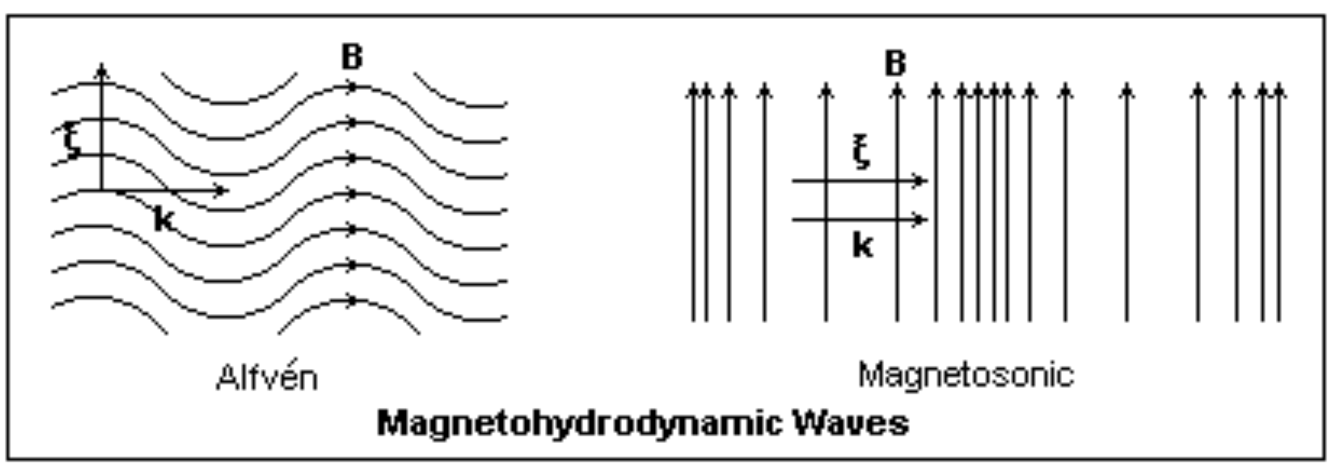


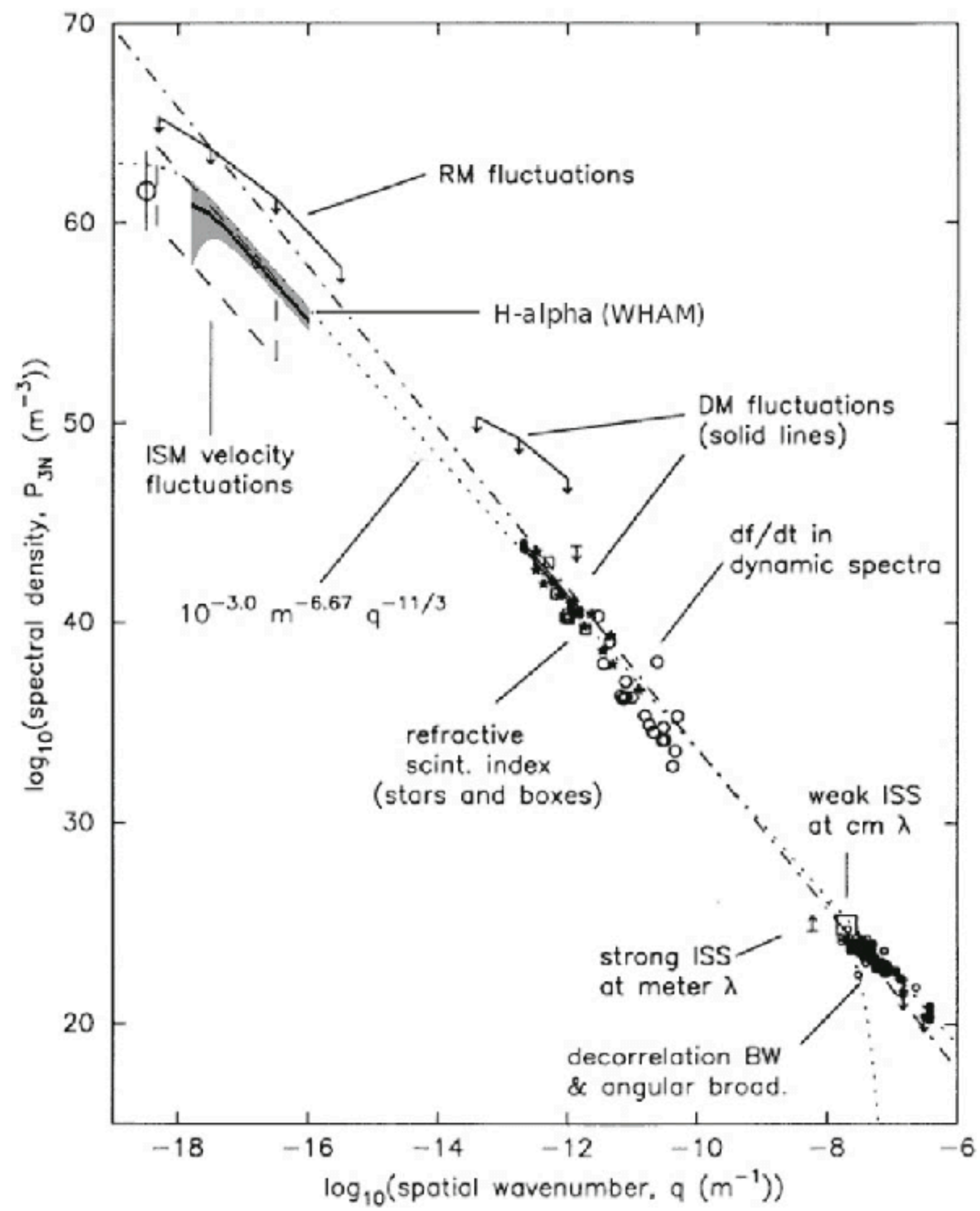
arXiv:1204.3662

The basic picture: Quasi linear theory of pitch angle scattering

Prologue: Regular and turbulent magnetic field in the Galaxy

Turbulent field:
- Superposition of MHD waves
- Power-law power spectrum



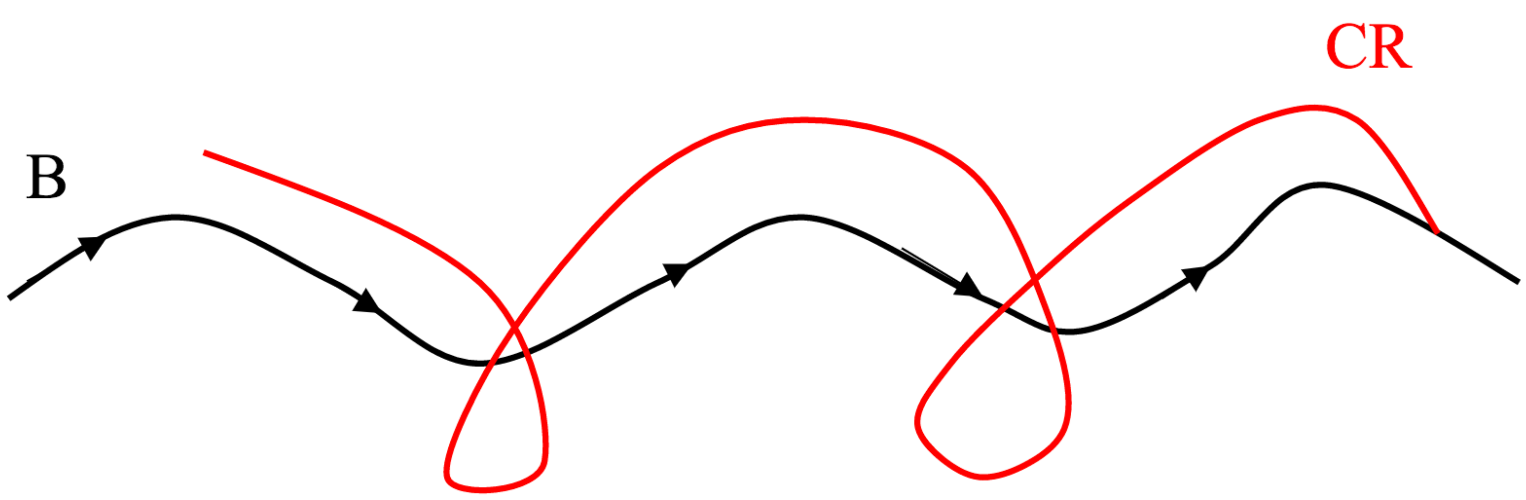


The basic picture: The Quasi-Linear Theory (QLT) of *pitch-angle scattering*

Assumptions:

1) CRs scatter off magnetic inhomogeneities. The inhomogeneities are *Alfvénic*. They are *isotropic* and their **energy density is characterized by a power-law spectrum** as a function of the wavenumber *k*

2) The inhomogeneities are small, at the scale of interest, with respect to the coherent large-scale magnetic field B_0



Recent review: P. Blasi, **arXiv:1311.7346**

- Ginzburg&Syrovatskii *"The origin of cosmic rays"*, 1964
- Berezinskii et al., *"Astrophysics of Cosmic Rays"*, 1990

The basic picture: The Quasi-Linear Theory (QLT) of *pitch-angle scattering*

Key results:

$$< \Delta x > = \sqrt{D \Delta t}$$

1) CRs diffuse mainly **along the regular field**

2) **Resonant** process: the Alfvén wavepackets that contribute to the process have a wavelength comparable to the gyroradius of the particle

3) The parallel diffusion coefficient as a function of the particle rigidity can be written in terms of the turbulent power at the resonant scale as:

$$D(p) = \frac{v^2}{3\Omega_g} \frac{B_0^2/(8\pi)}{k_{\rm res} P(k_{\rm res})}.$$

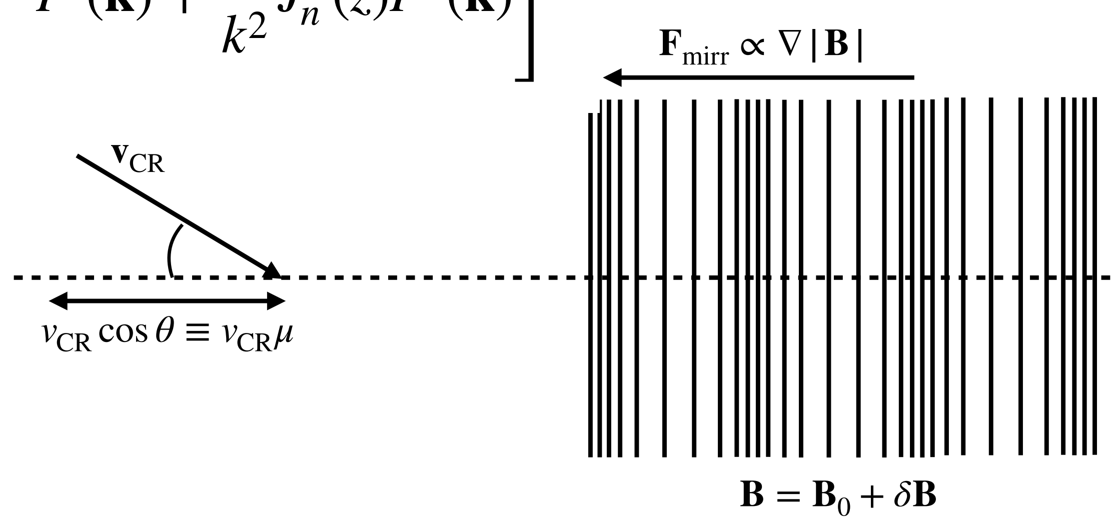
It is convenient to recast the expression in this way, in terms of the turbulence strength at the resonant scale:

$$D(p) = \frac{1}{3} \frac{r_L v}{\mathcal{F}(k_{\rm res})} \qquad \mathcal{F}(k) \equiv \frac{kP(k)}{B_0^2/(8\pi)}.$$

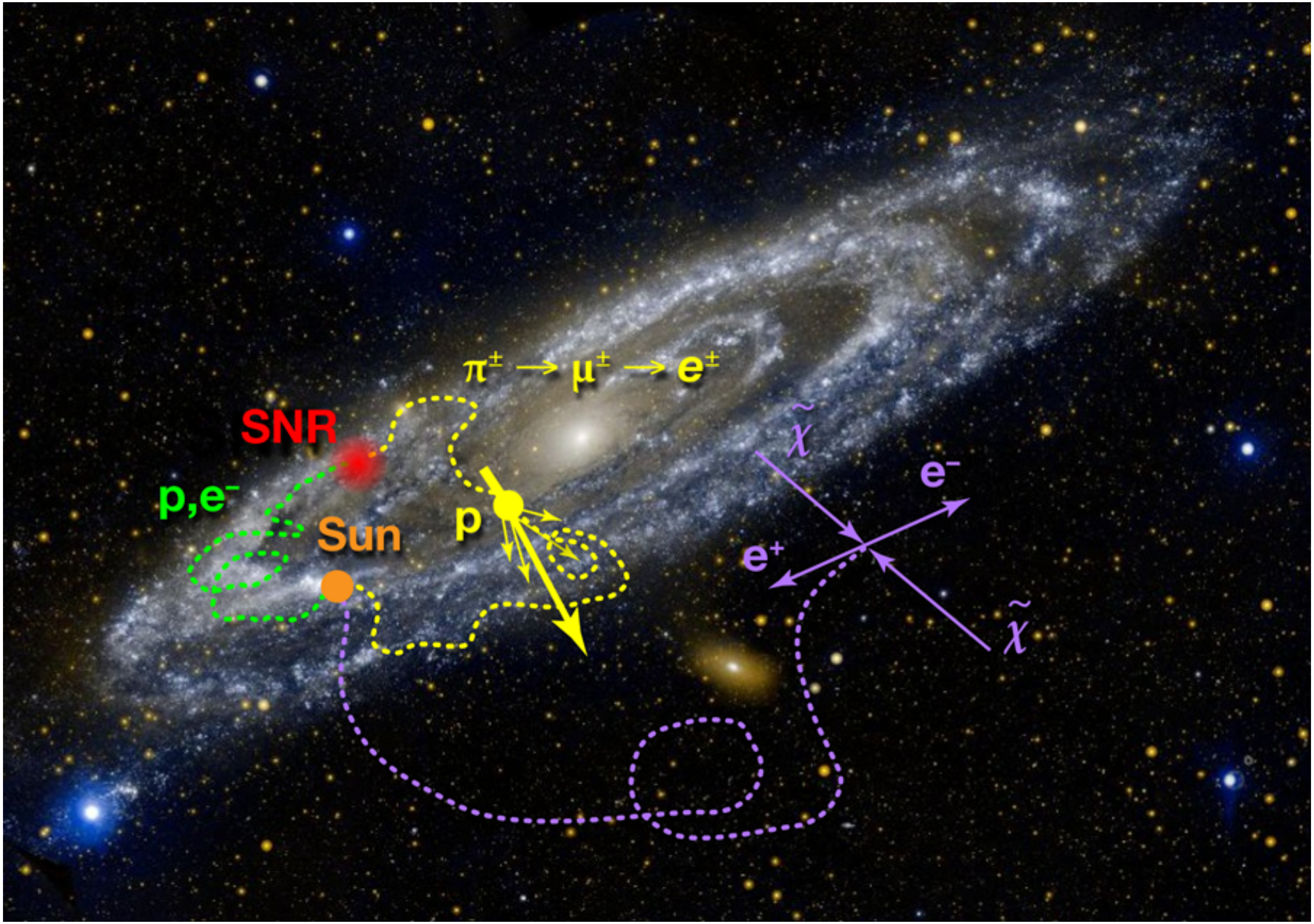
1) Possible important role of **non-linear effects** at low energy: CR self-confinement due to Alfvén waves generated by the CRs themselves!

2) **Anisotropy of the Alfvénic cascade.** Most of the power is transferred to perpendicular scales —> the Alfvénic waves may actually be highly inefficient in confining CRs —> pitch-angle scattering onto **magnetosonic modes** may play the dominant role

$$D_{\mu\mu} = \Omega^2(1-\mu^2)\int d^3\mathbf{k} \sum_{n=-\infty}^{+\infty} \delta(k_\parallel v_\parallel - \omega + n\Omega)\left[\frac{n^2 J_n^2(z)}{z^2} I^{\mathrm{A}}(\mathbf{k}) + \frac{k_\parallel^2}{k^2} J_n'^2(z) I^{\mathrm{M}}(\mathbf{k})\right]$$



“Global” Phenomenological models

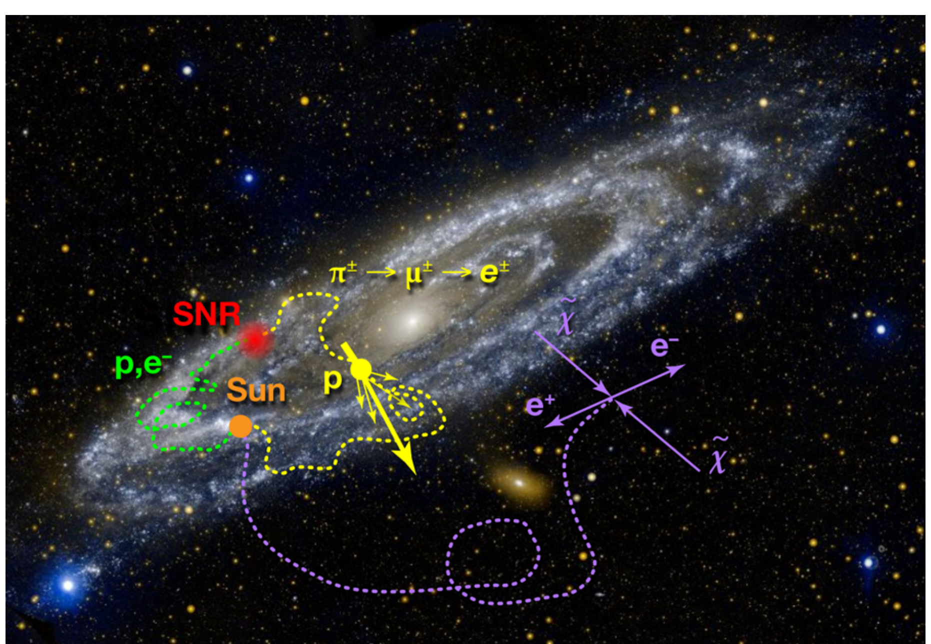


Phenomenological models

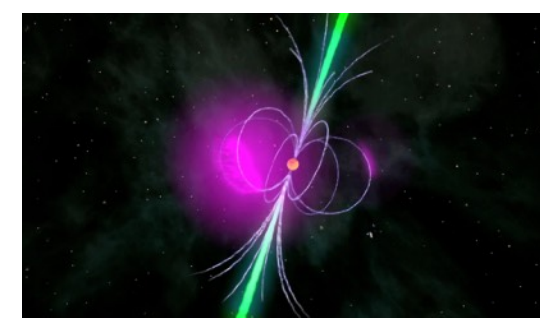
$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla} \cdot \vec{v}_w\right) N_i\right] =$$
$$Q + \sum_{i<j}\left(c\beta n_{\rm gas}\, \sigma_{j\to i} + \frac{1}{\gamma\tau_{j\to i}}\right) N_j - \left(c\beta n_{\rm gas}\, \sigma_i + \frac{1}{\gamma\tau_i}\right) N_i$$

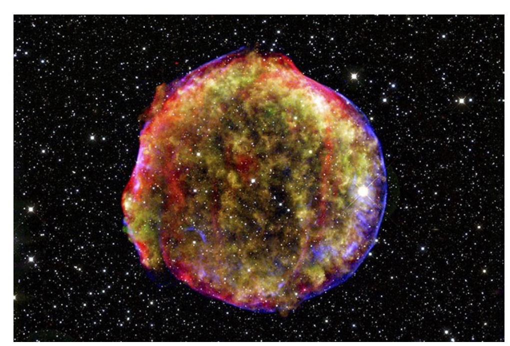
The main ingredient is spatial diffusion

$$J_i = -D_{ij} \nabla_j N$$



Source terms:
- **supernova remnants**
- **pulsars?**
- **dark matter?**

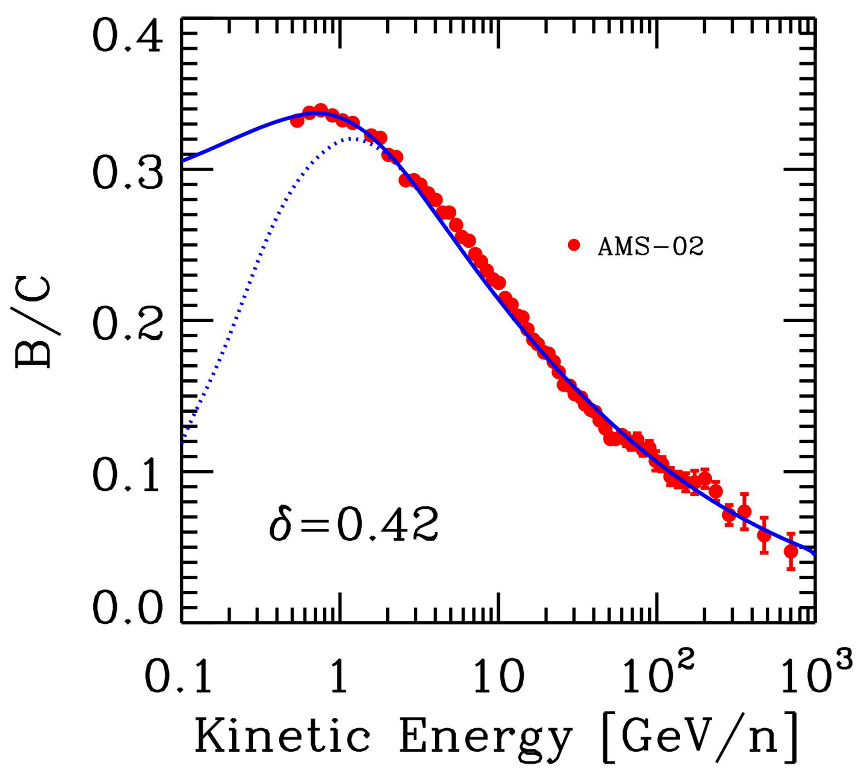


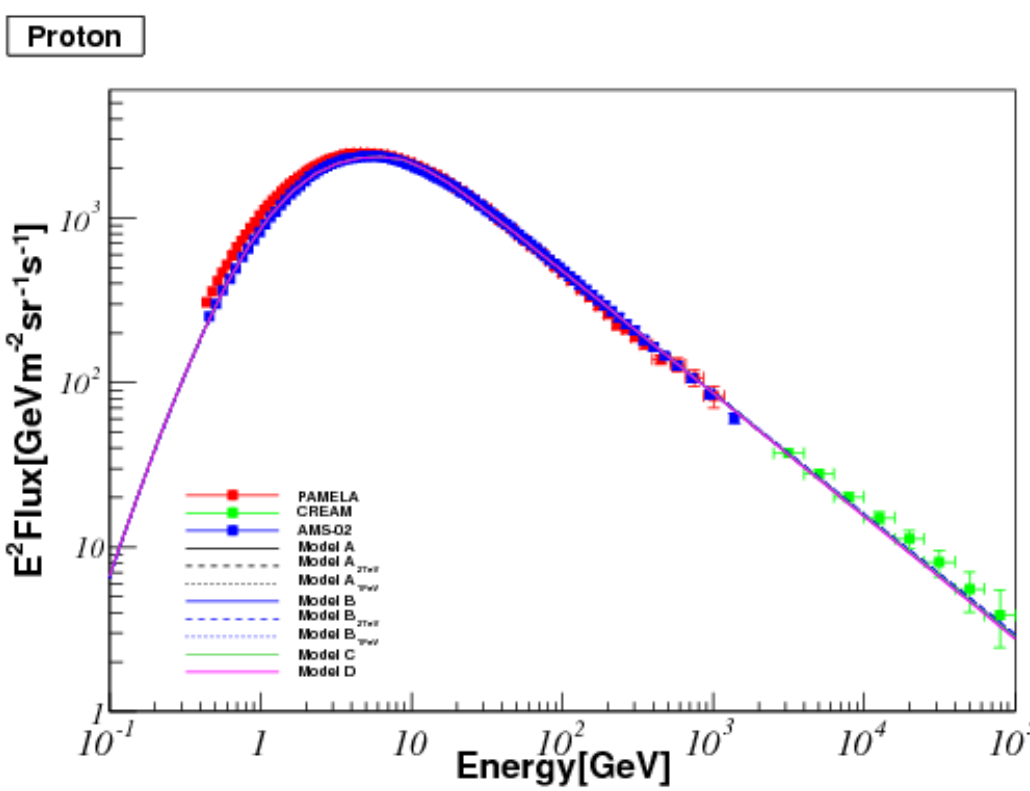


Phenomenological models and global fits

$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla} \cdot \vec{v}_w\right) N_i\right] =$$
$$Q + \sum_{i<j}\left(c\beta n_{\rm gas}\,\sigma_{j\to i} + \frac{1}{\gamma \tau_{j\to i}}\right) N_j - \left(c\beta n_{\rm gas}\,\sigma_i + \frac{1}{\gamma \tau_i}\right) N_i$$

$$J_i = -D_{ij} \nabla_j N \qquad D_{ij} = \left(D_{\|} - D_{\perp}\right) b_i b_j + D_{\perp} \delta_{ij} + \epsilon_{ijk}\; D_A b_k\,,$$





How diffusion shapes the spectrum

A commonly adopted approach (inspired by QLT) is to consider a power-law in momentum for the diffusion coefficient

$$D \propto p^{\delta}$$

A simple way to capture the effect of diffusion: **Leaky-box model**

$$\frac{\partial N}{\partial t} = \frac{N}{\tau_{esc}(p)} + Q(p) \qquad \tau_{esc} \propto p^{-\delta}$$

Primary species (steepening of the spectrum):

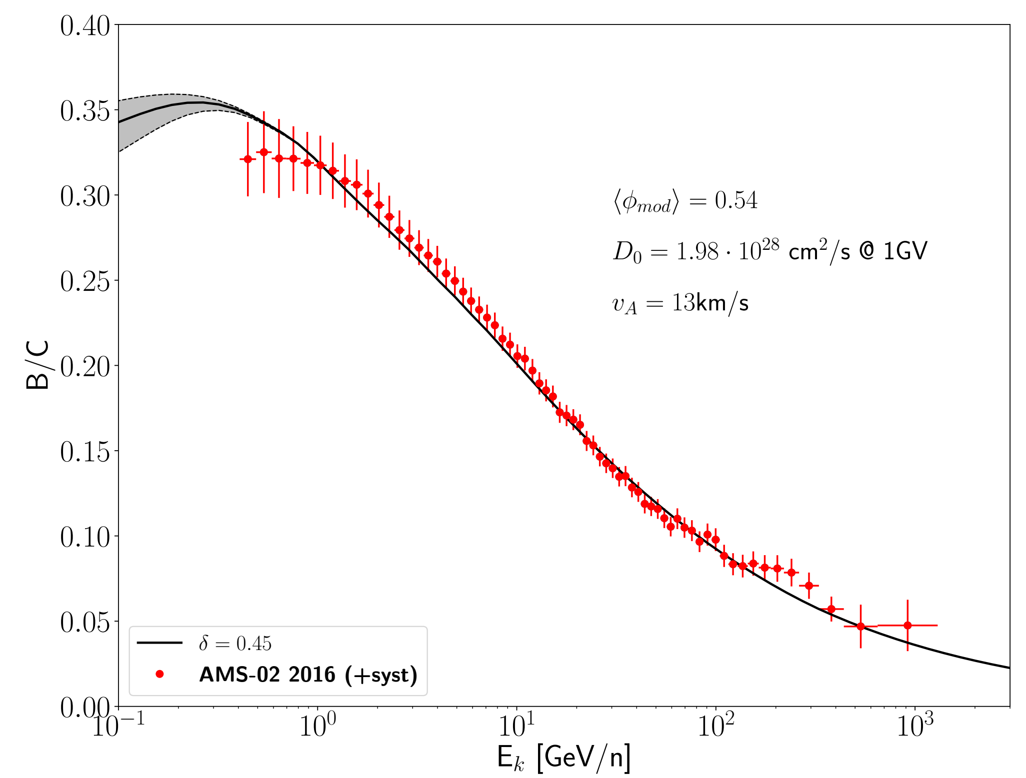
$$Q_{pri}(p) \propto p^{-\alpha} \Rightarrow N_{pri}(p) \propto p^{-\alpha-\delta}$$

Secondary species (further steepening):

$$Q_{sec}(p) \propto p^{-\alpha-\delta} \Rightarrow N_{sec}(p) \propto p^{-\alpha-\delta-\delta}$$

Ratios:

$$\frac{N_{sec}}{N_{pri}} \propto p^{-\delta}$$



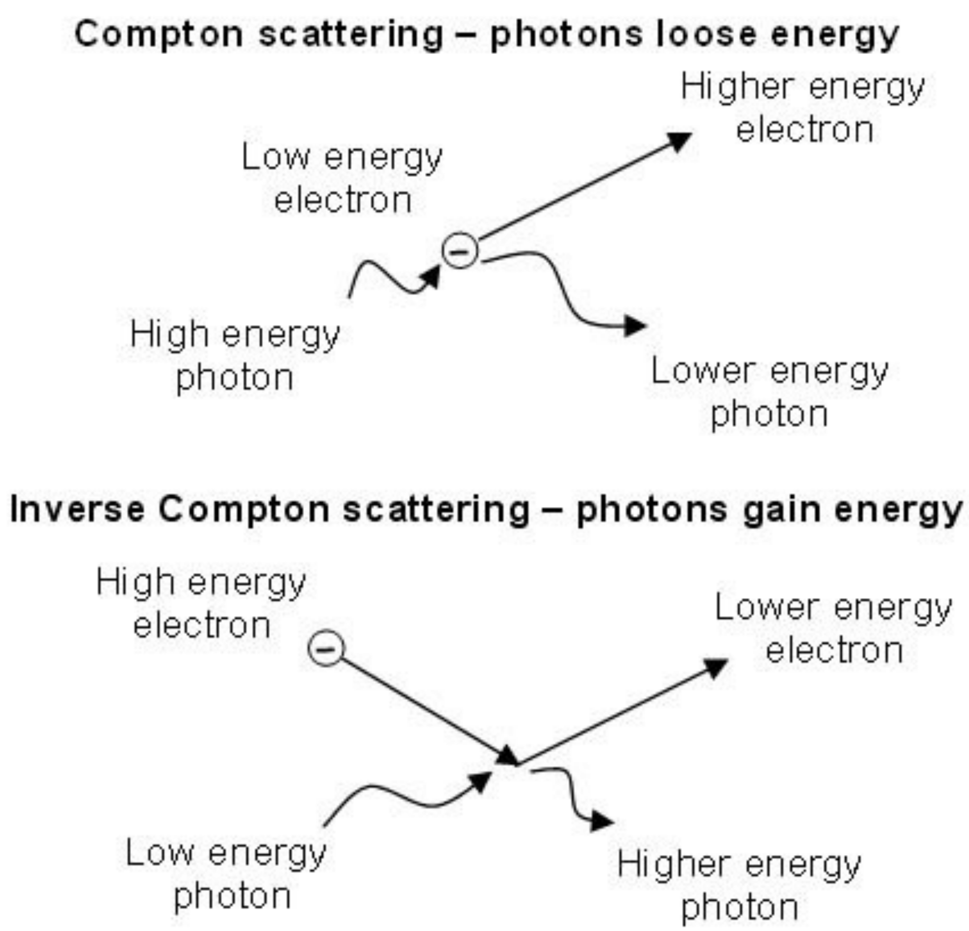
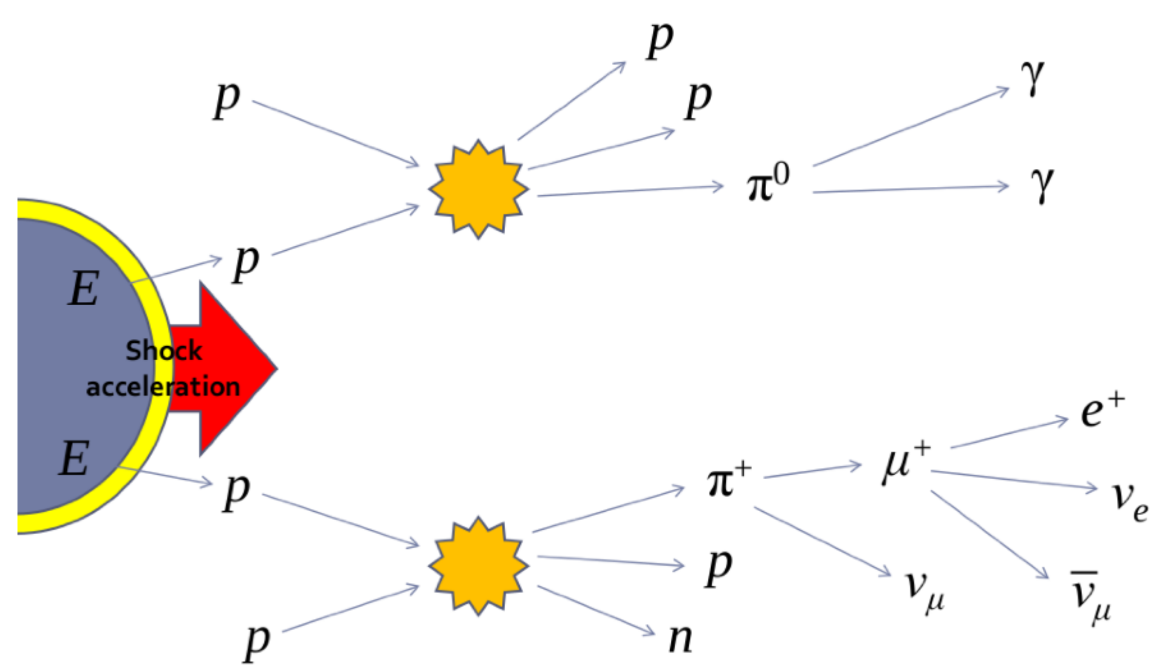
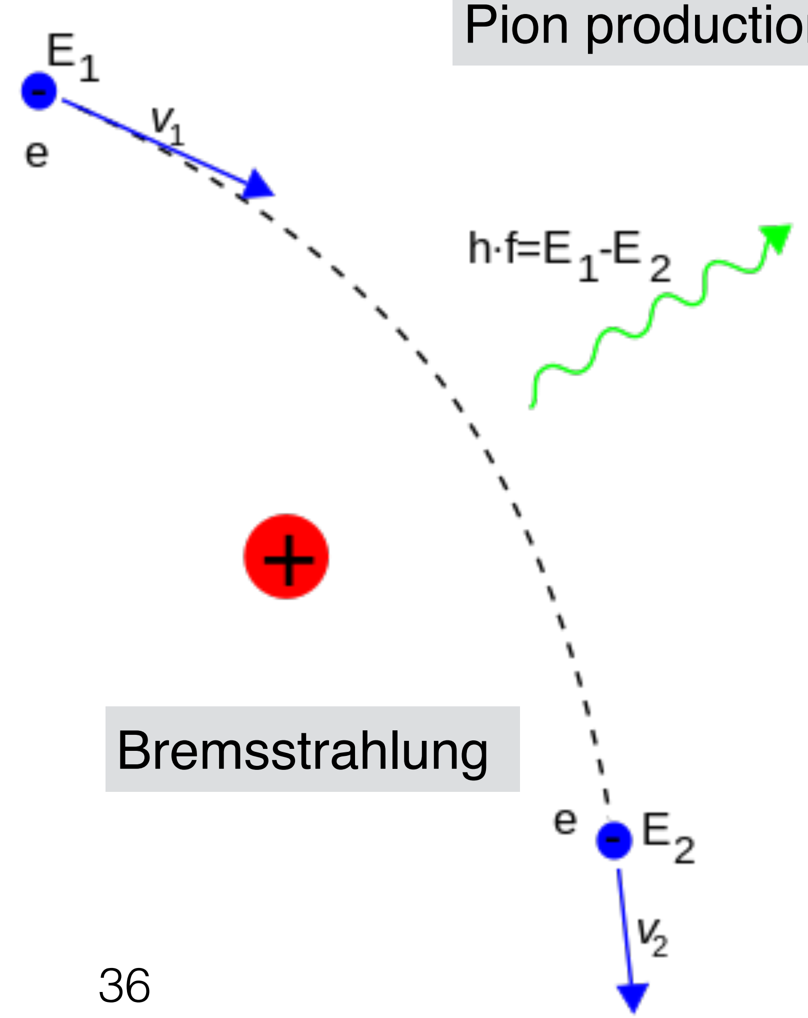


Figure 6: The two Compton scattering processes result in radiation being shifted to lower energies (Compton scattering) or higher energies (inverse Compton scattering). The essential factor

Inverse Compton scattering

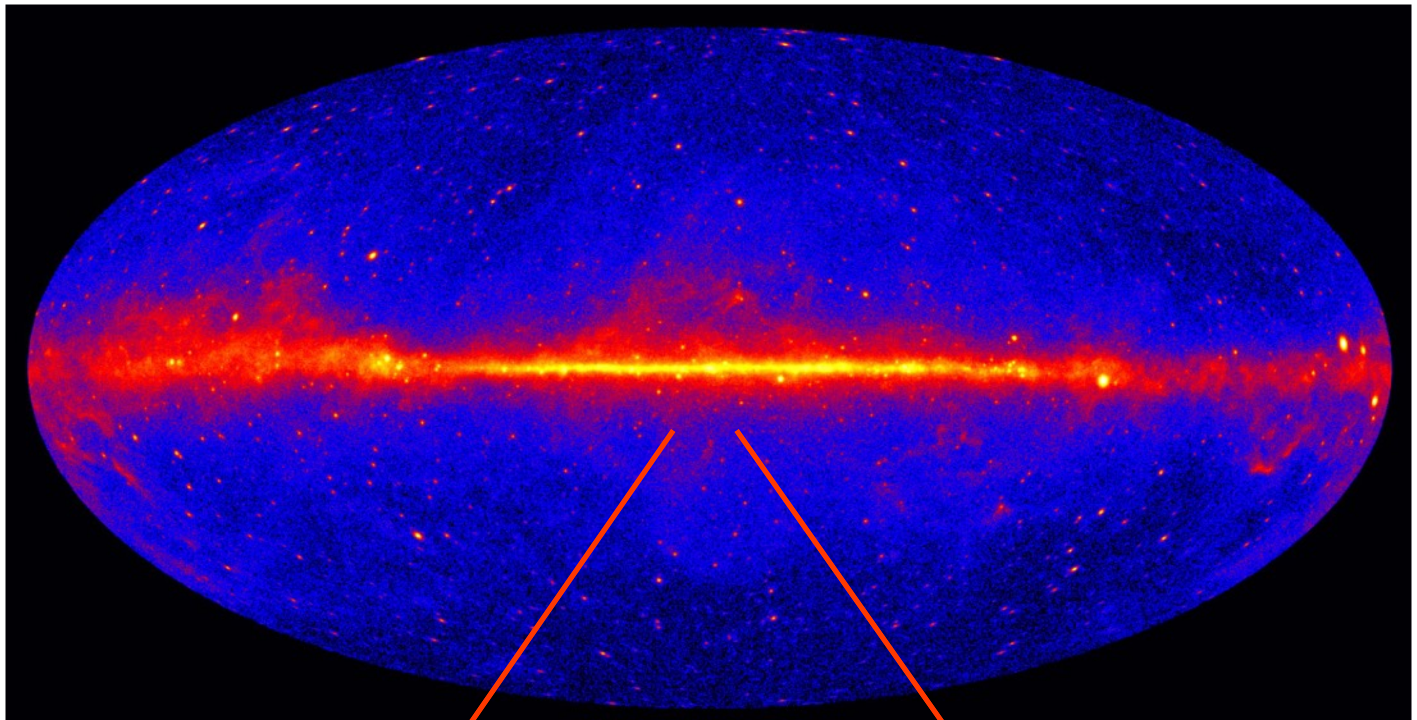


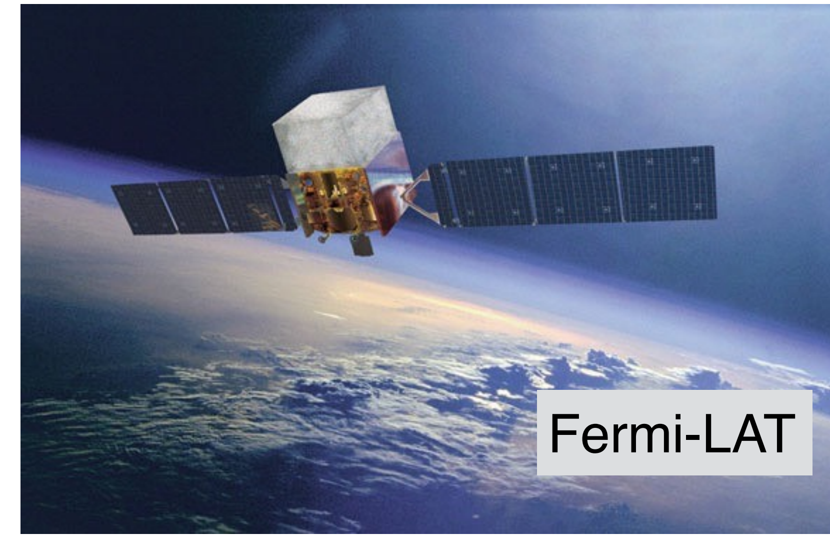
Pion production and decay



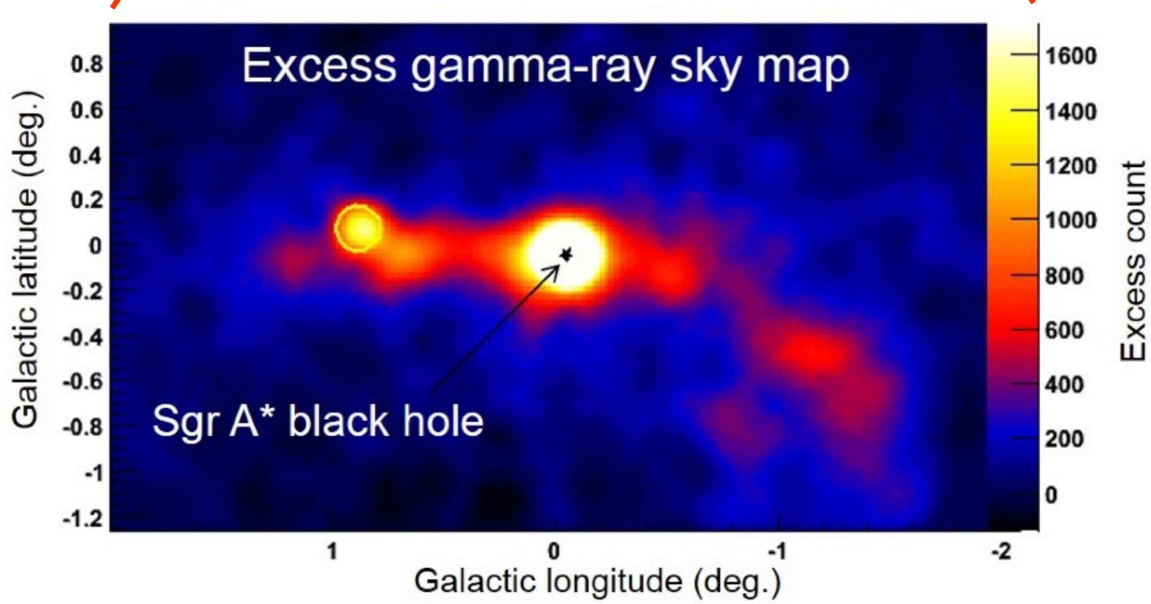
Bremsstrahlung

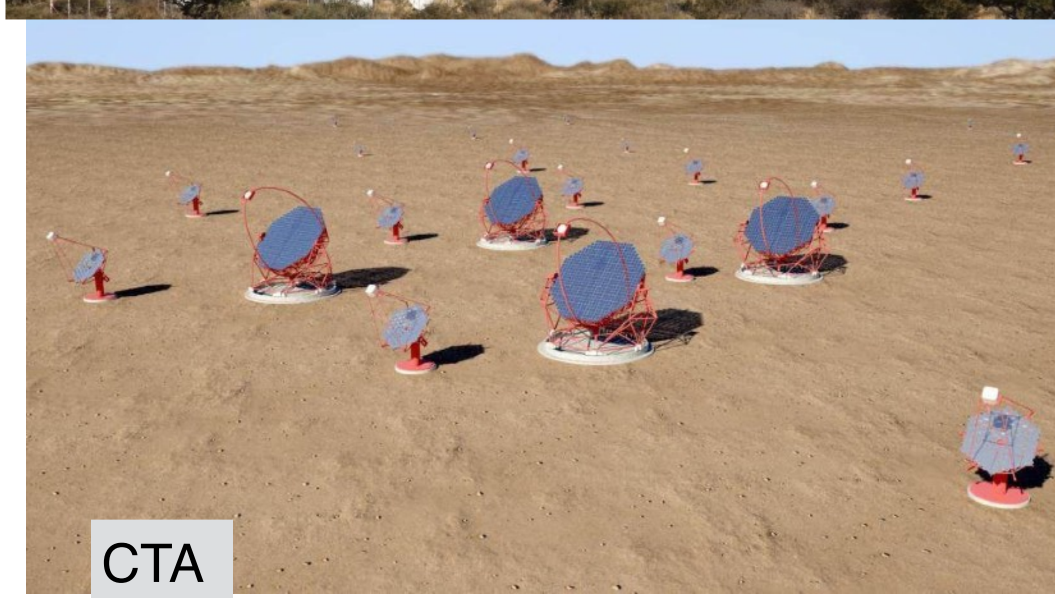
GeV sky





TeV sky





Now let’s go back to Dark Matter searches…

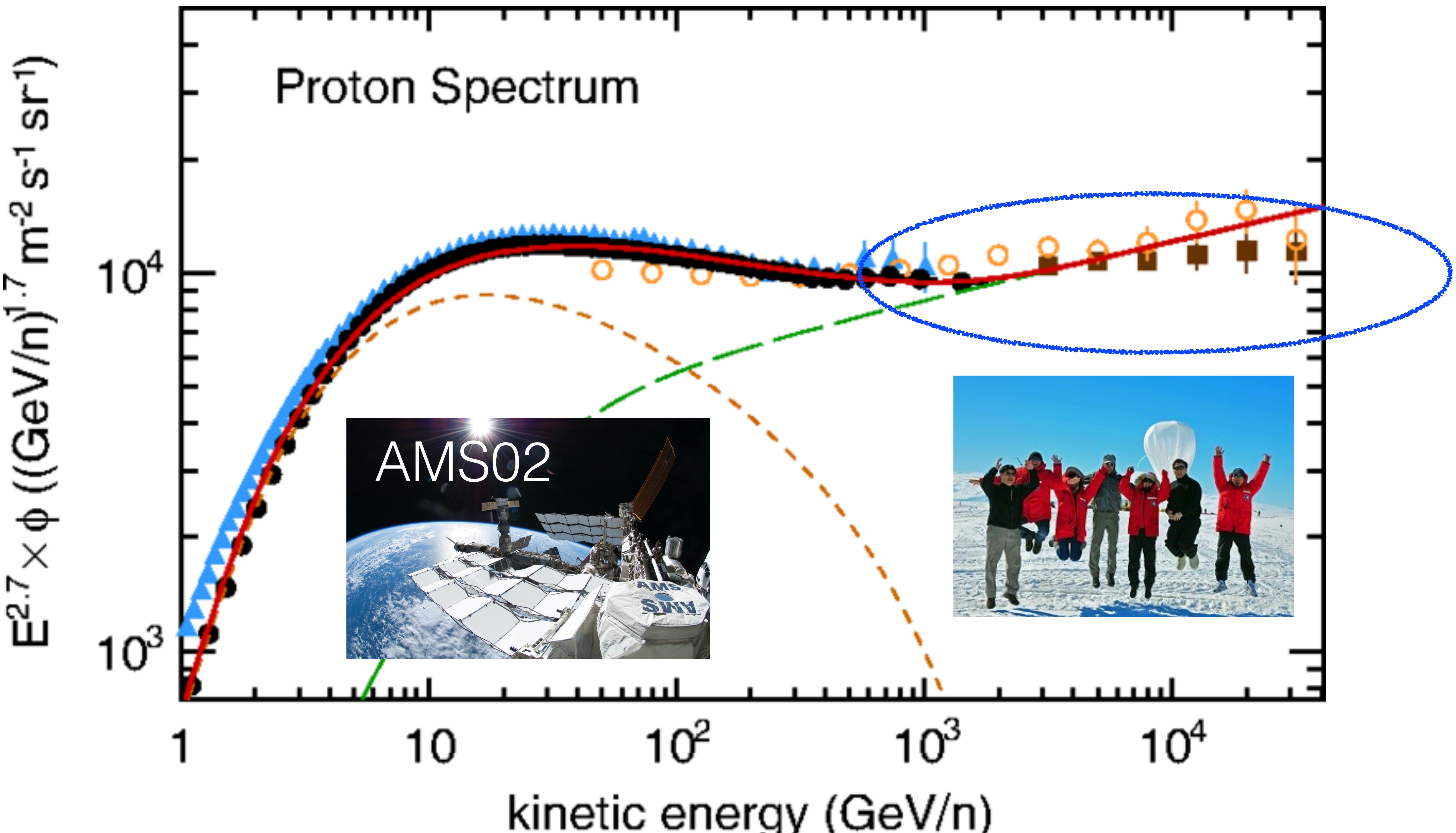
Looking for anomalies in charged CR flux

Looking for anomalies in charged CR flux

We can look at the ***"anomalies"*** in charged particles, in order to search a **potential DM signal.**

Anomalies with respect to what?

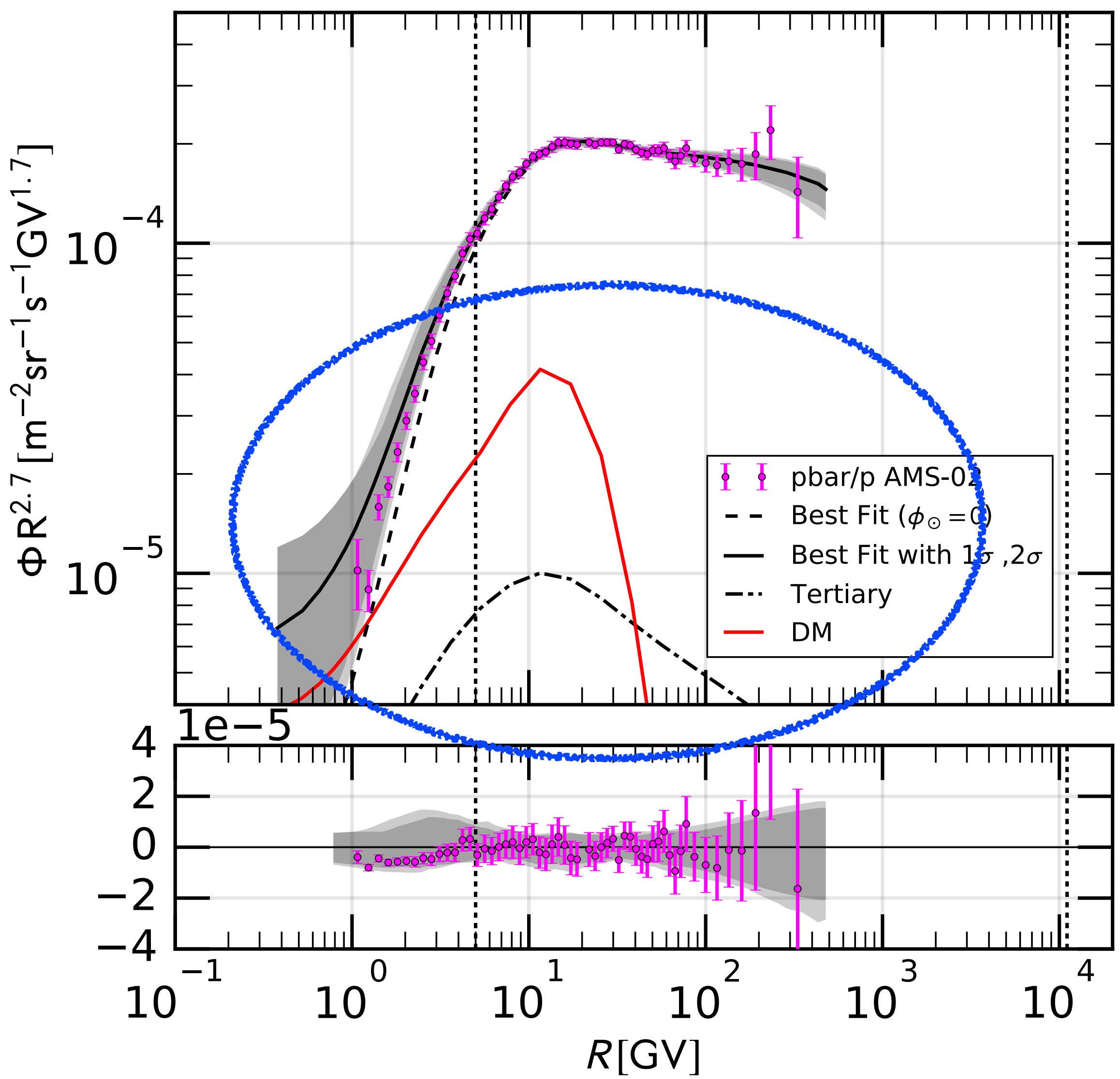
Which ones?



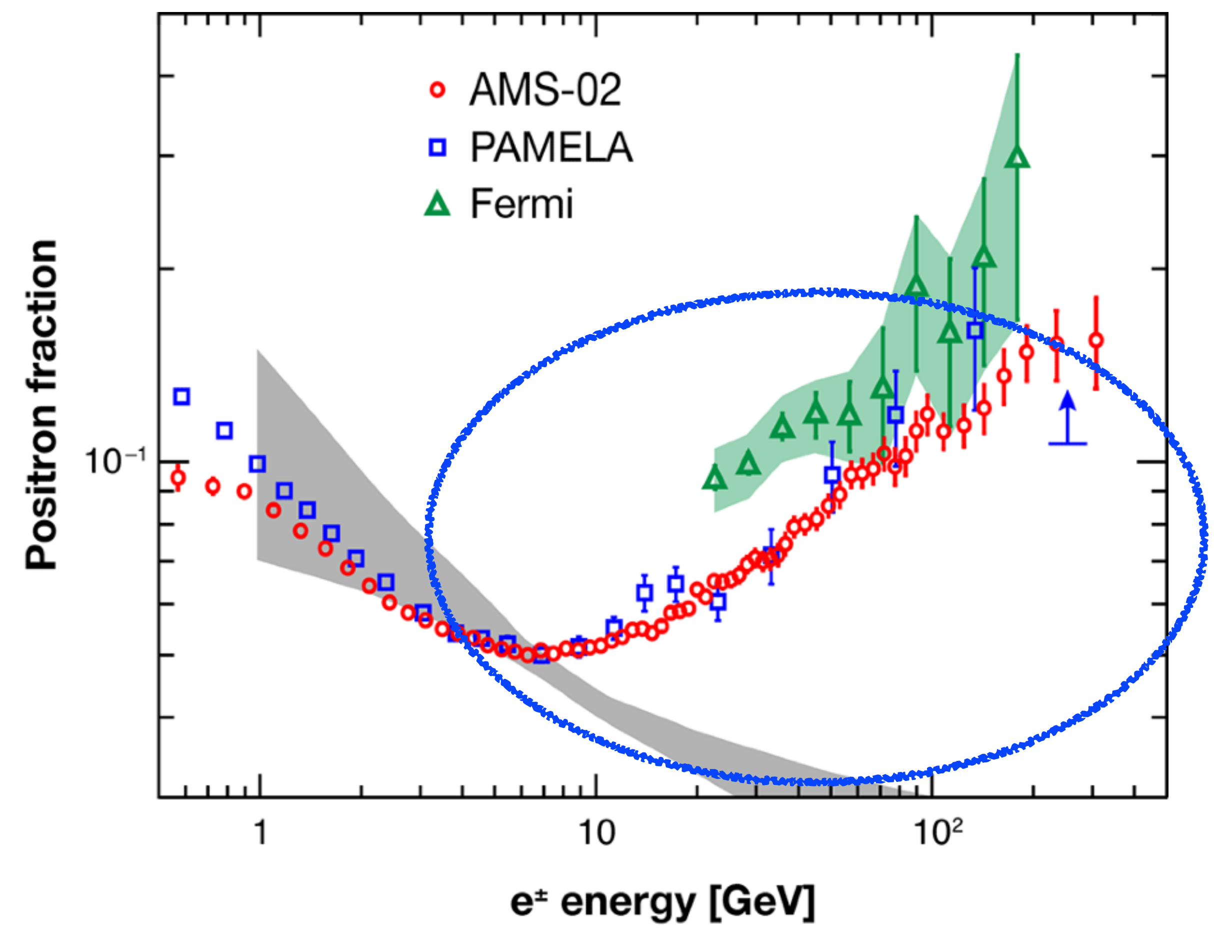
Looking for anomalies in charged CR flux

We can look at the “anomalies” in charged particles. Which ones?

arXiv:1610.03071



ANTIPROTONS



POSITRONS

Looking for anomalies in charged CR flux

We can look at the "anomalies" in charged particles. Which ones?

Hint: Compare the power injected by DM

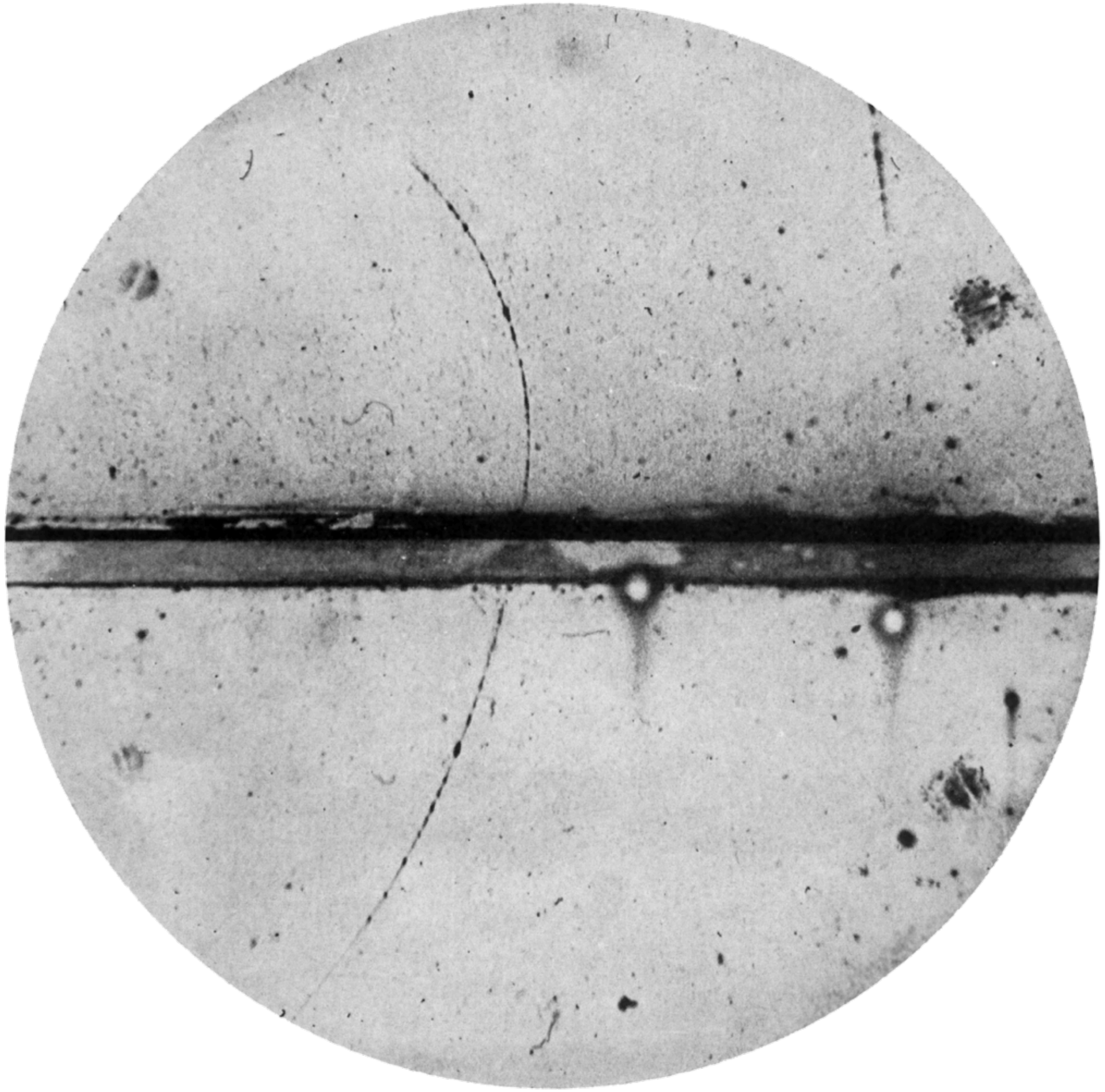
$$L \sim M_{\rm DM} \cdot < \sigma v > \cdot \frac{1}{M_{\rm DM}^2} \cdot \int^{R_{max}} d^3x \; \rho_{NFW}^2(r)$$

With the power injected by SNae into CRs (see previous exercises)

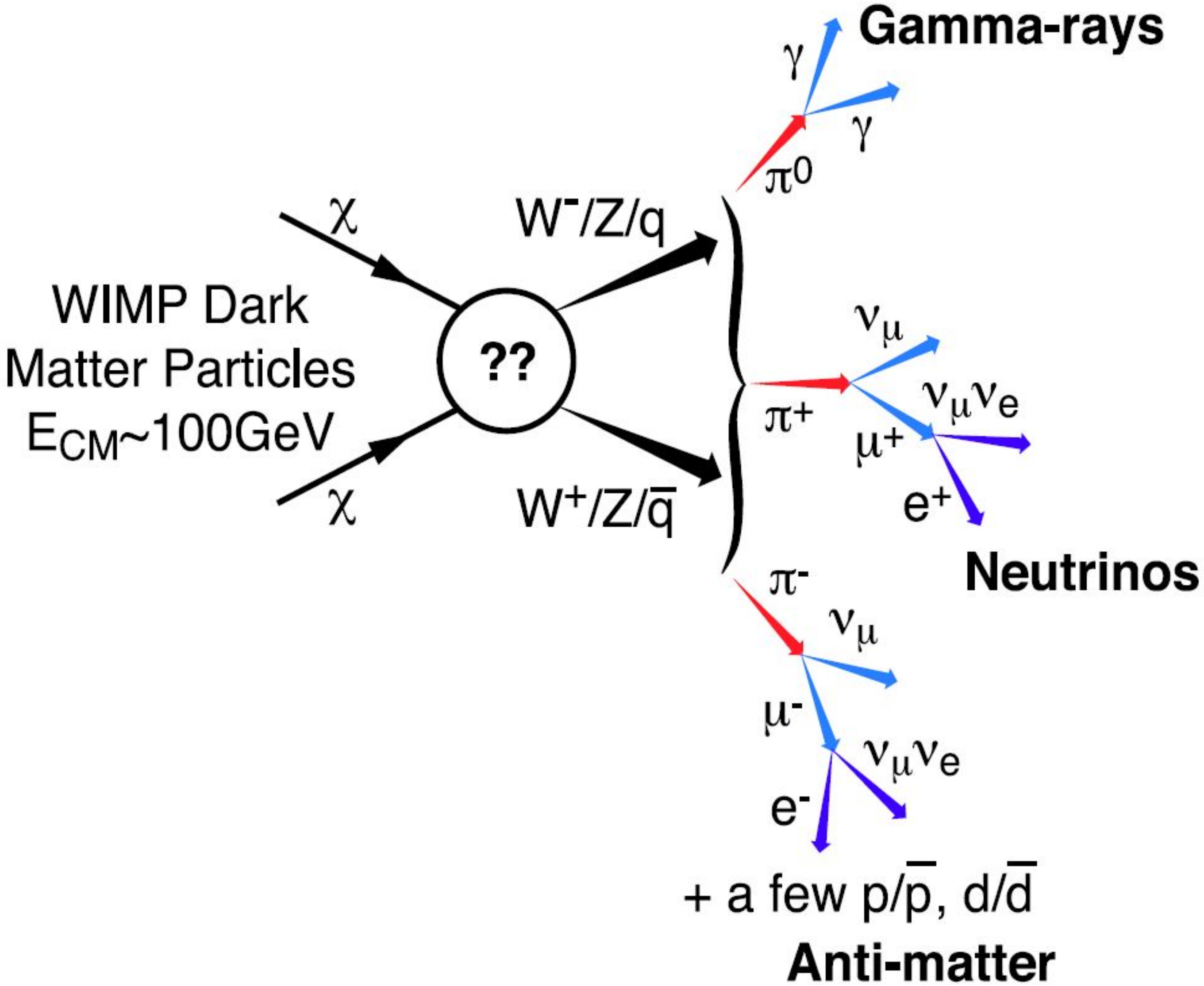
$L_{DM} \sim 10^{37}$ erg/s
$L_{CR} \sim 10^{41}$ erg/s

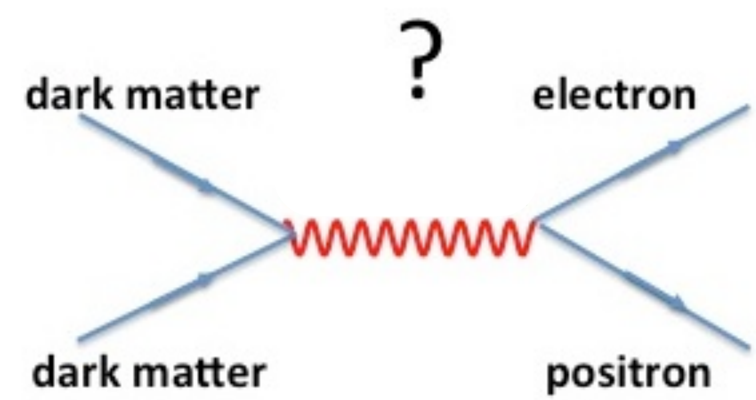
Looking for anomalies in charged CR flux

…antiparticles seem a very interesting channel for DM-related anomalies!



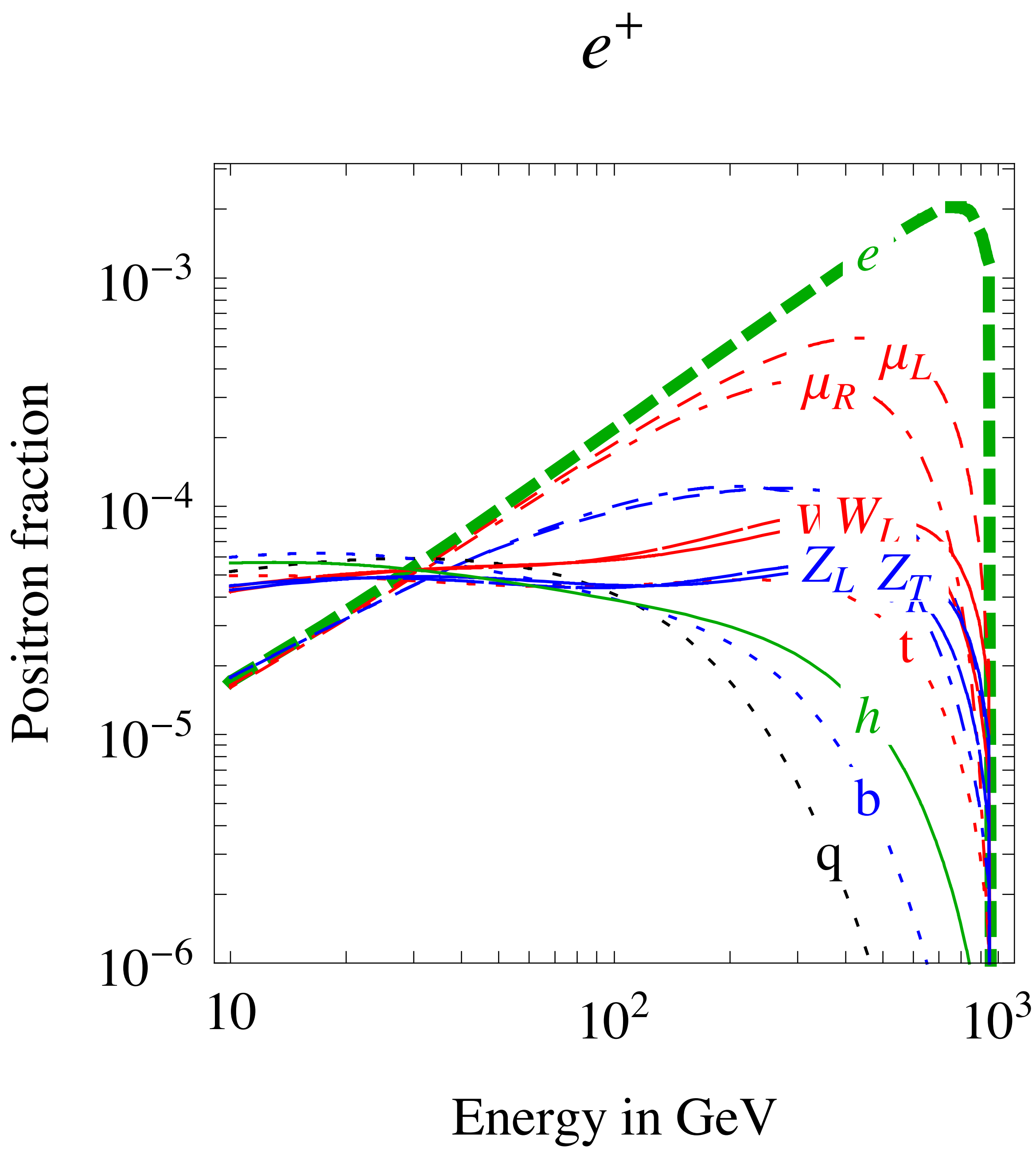
What kind of signal do we expect from DM annihilation into charged particles? It depends on the final state!

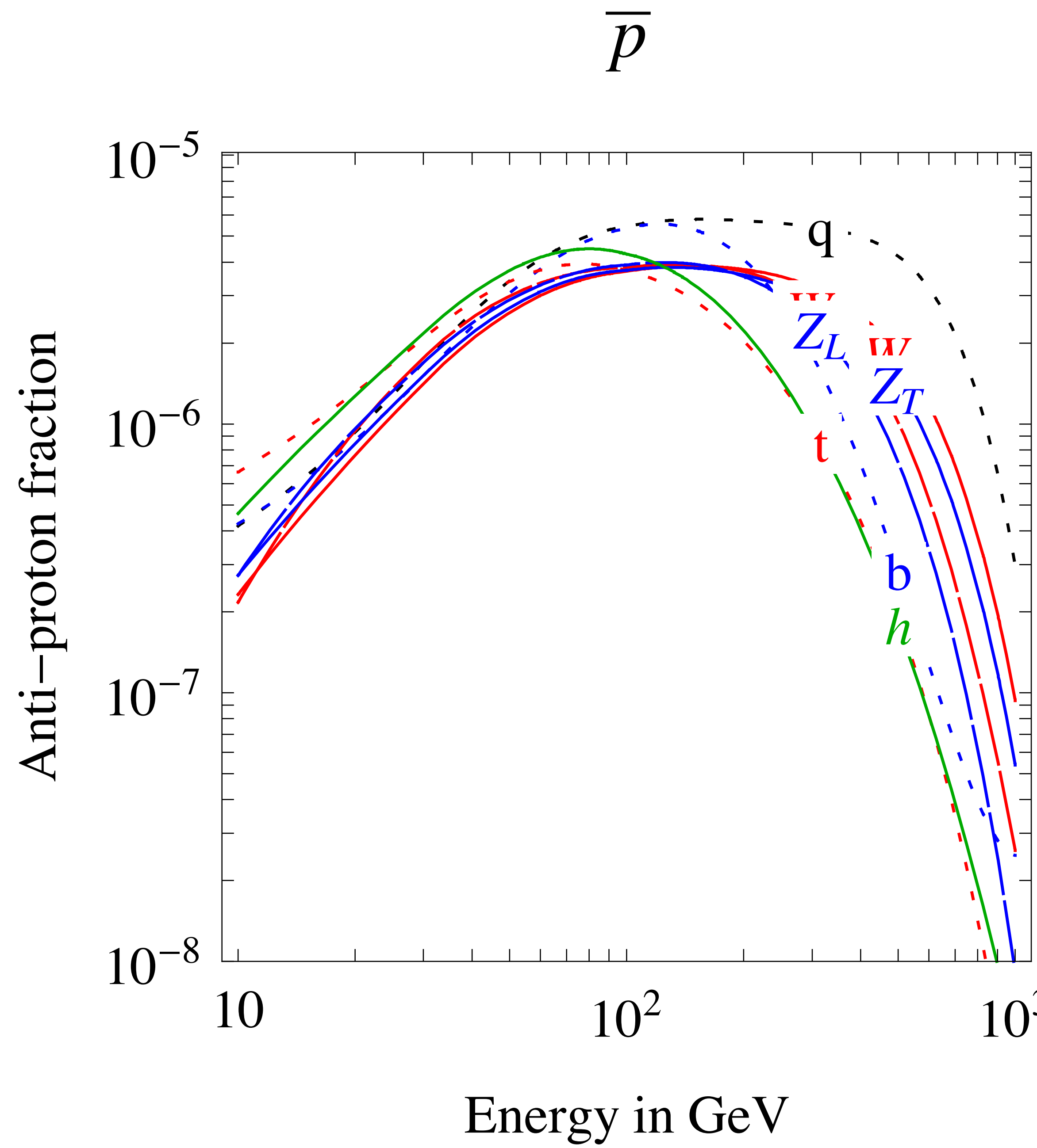




Exotic signals

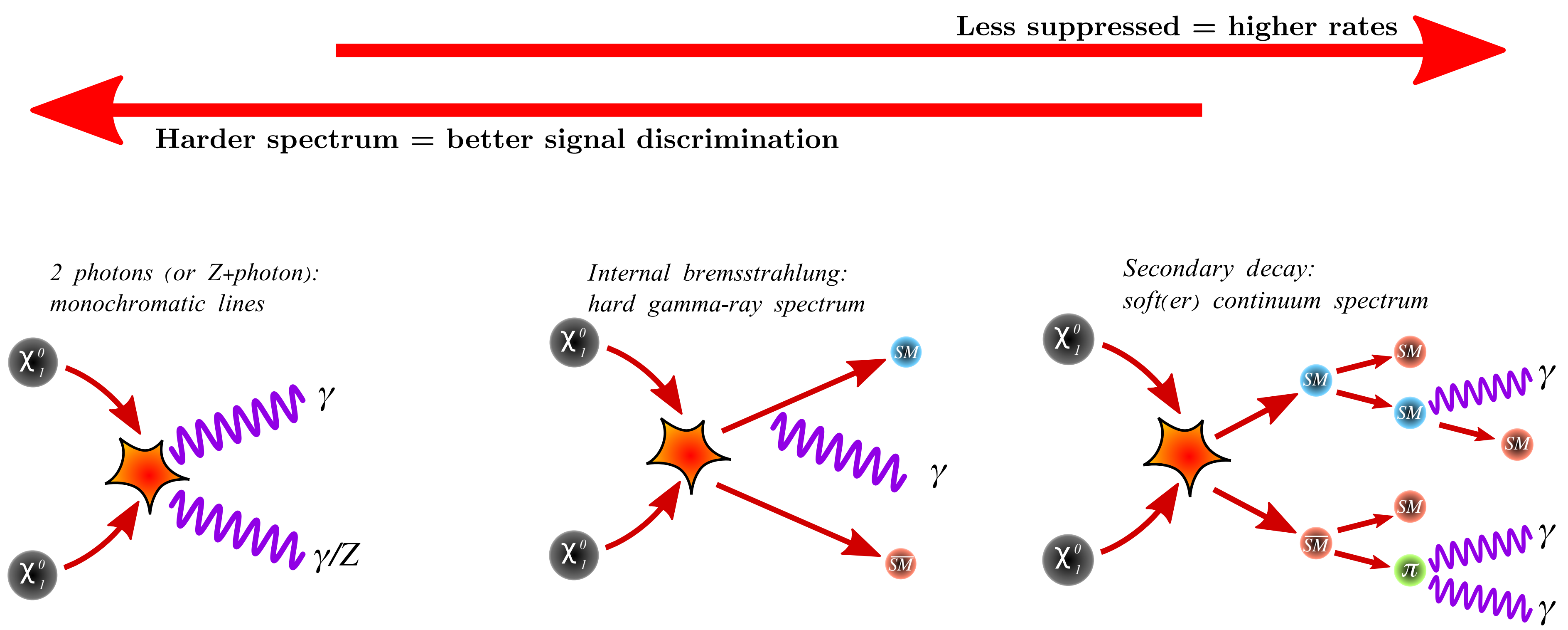
What kind of signal do we expect from DM annihilation into charged particles? It depends on the final state!





What kind of signal do we expect from DM annihilation into gamma rays?

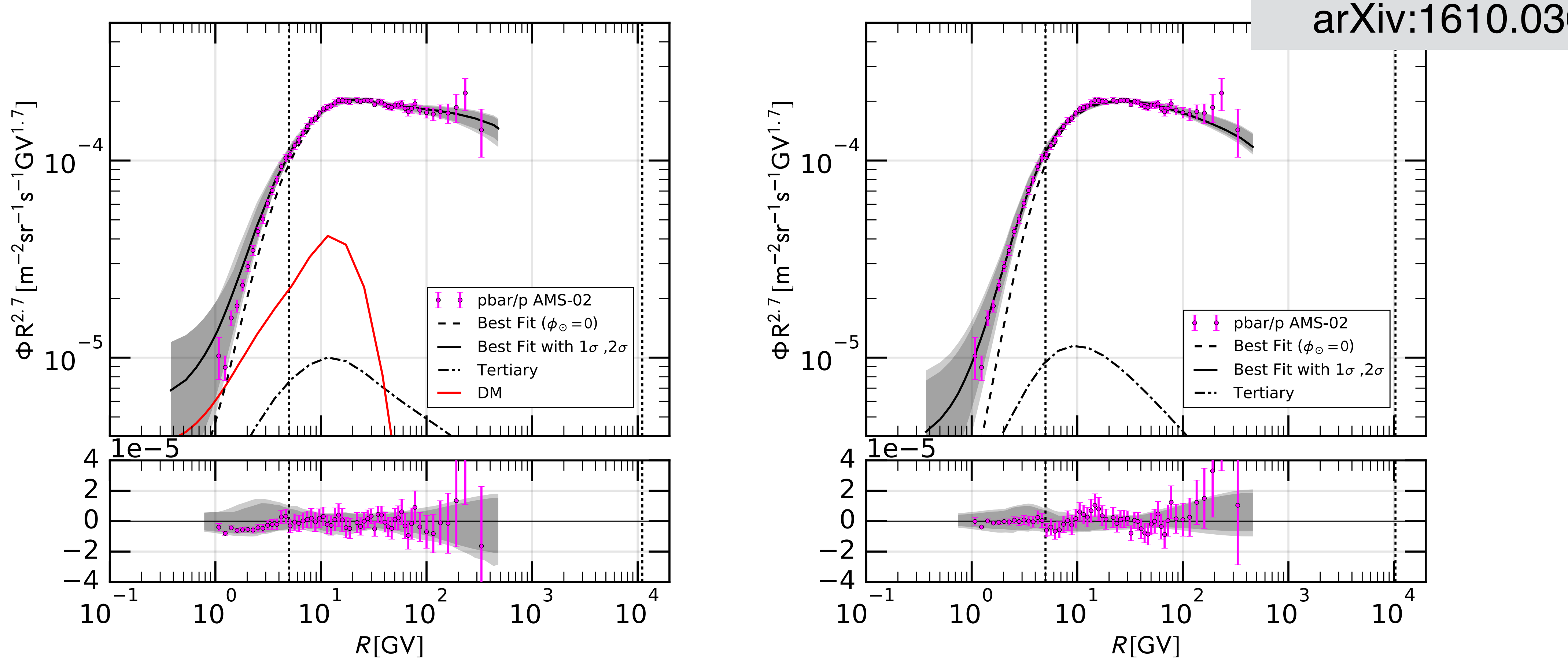
1. *"Prompt"* emission

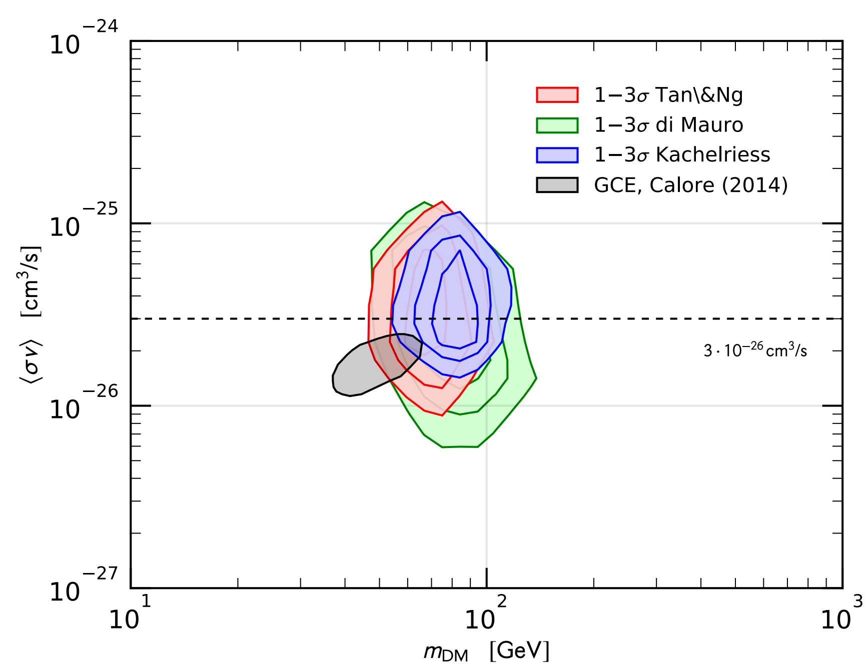


2. *"Secondary"* emission: SM particles in the final state diffuse in the Galaxy and emit gamma rays (mainly due to IC and bremsstrahlung)

Case study: The antiproton anomaly. Role of CR physics

arXiv:1610.03071





An indication for a **DM signal in the antiproton flux**, compatible with the DM interpretation of another claim (the Galactic center gamma-ray GeV excess)?

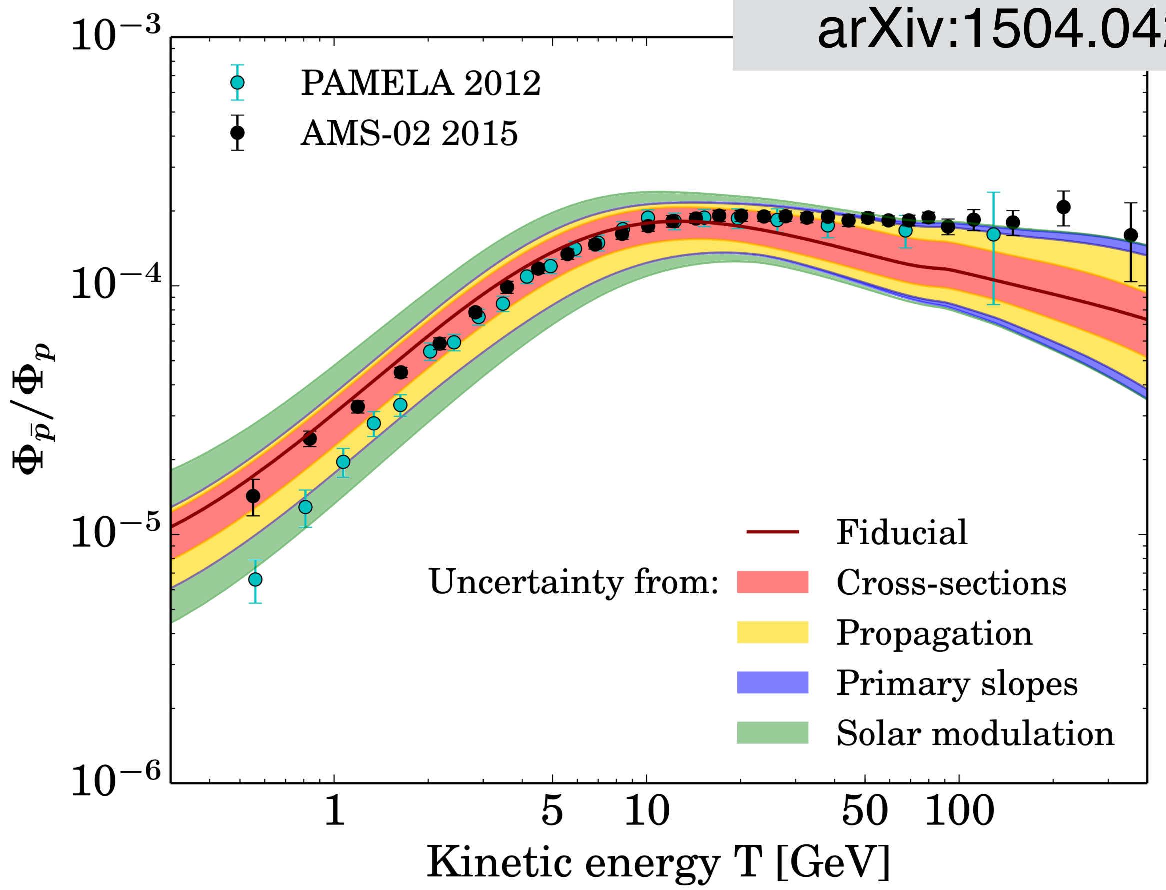
Case study: The antiproton anomaly. Role of CR physics

Under debate!

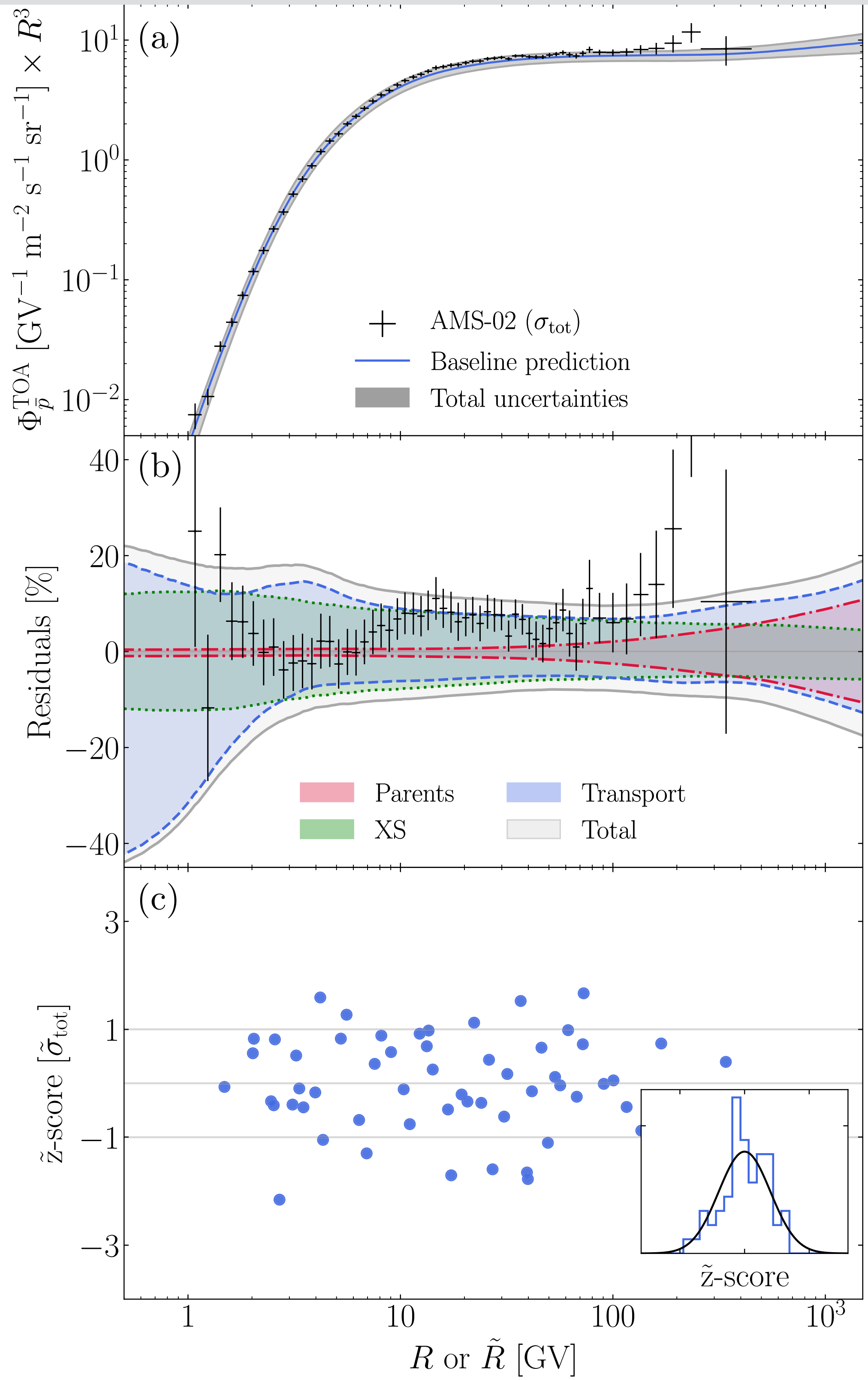
Crucial role of **uncertainties** associated to:

- Cross sections
- CR propagation parameters (within global phenomenological models)
- Solar modulation

arXiv:1504.04276



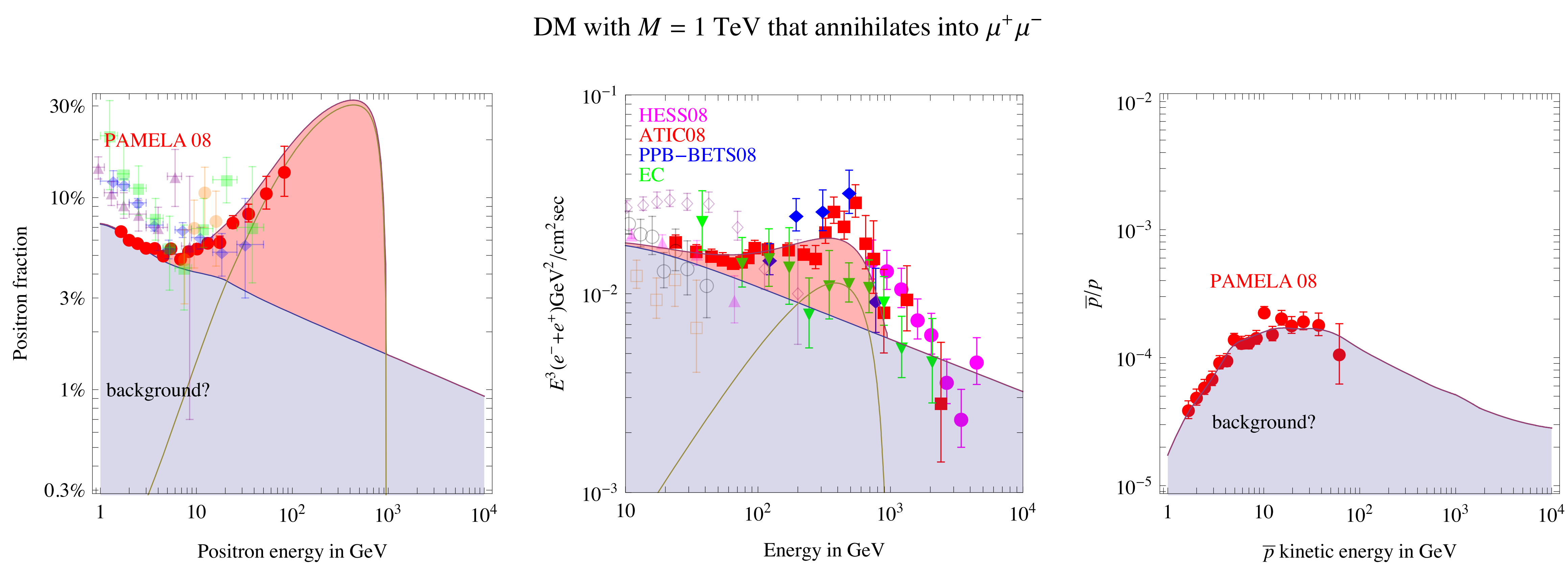
Physical Review Research, Volume 2, Issue 2, article id.023022



Case study: The positron anomaly

- Rise at high energy in the **positron fraction** originally discovered by PAMELA in 2009, and subsequently confirmed by Fermi-LAT and AMS-02 collaborations, is a **substantial deviation** from the standard prediction

- Many **DM scenarios** were invoked: The tough **challenges** for model building are:
  - The large annihilation cross section required to sustain the measured positron flux
  - The strong constraints originating from other channels (gamma rays, CMB, and antiprotons)

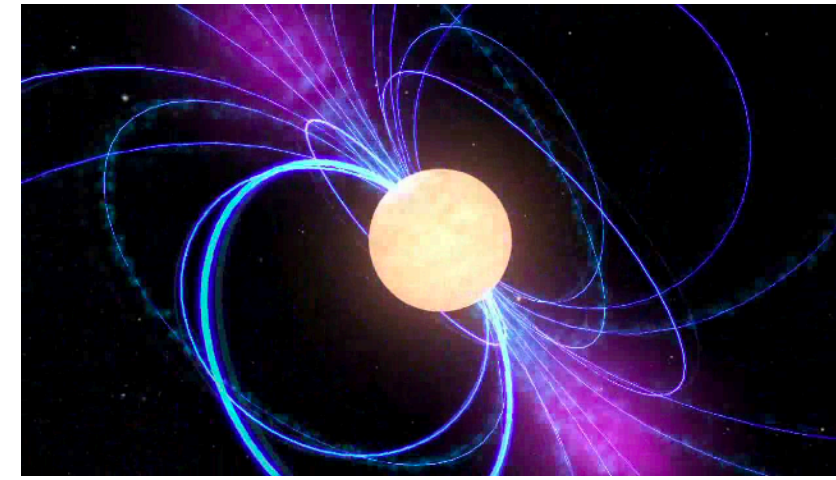


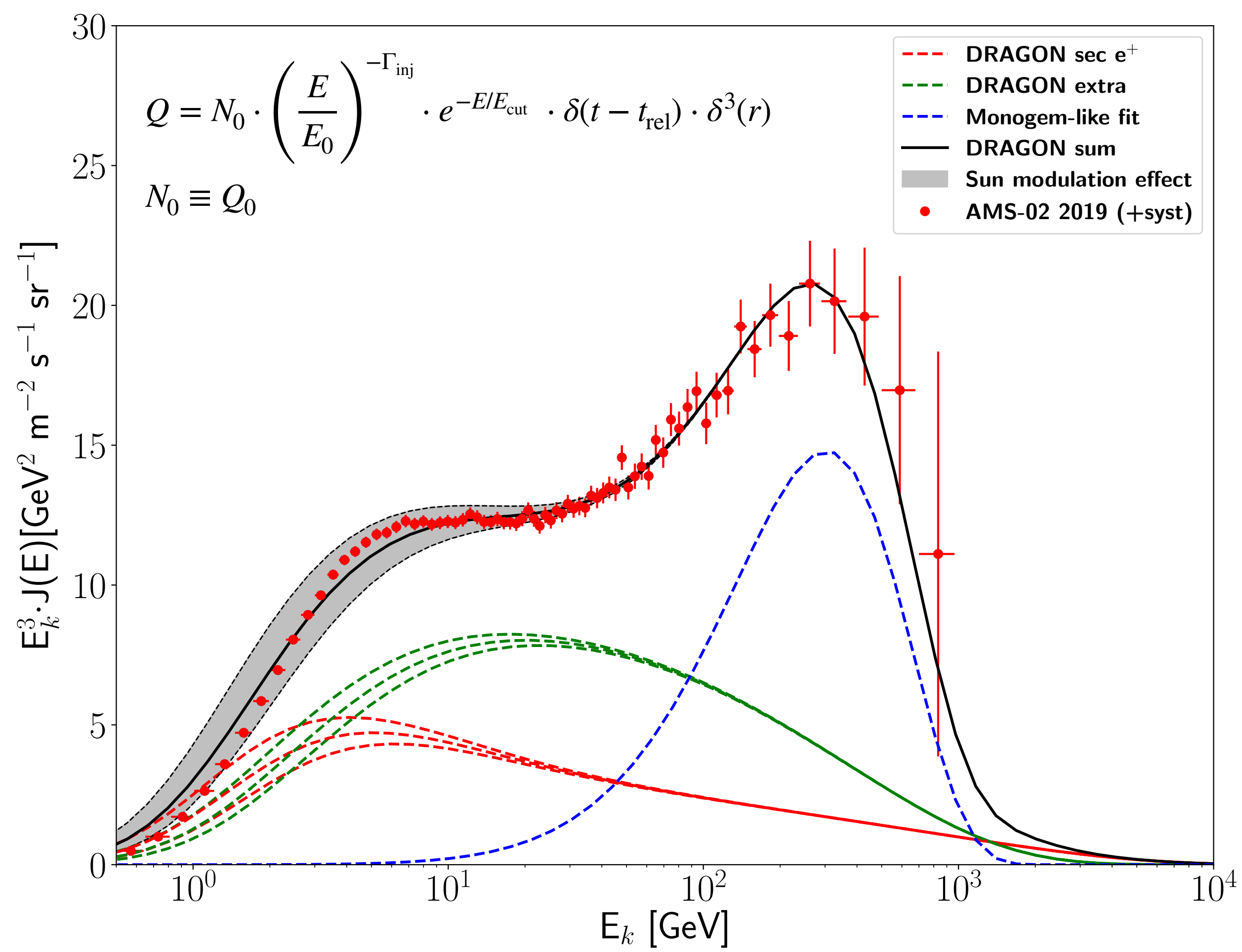
arXiv:0809.2409

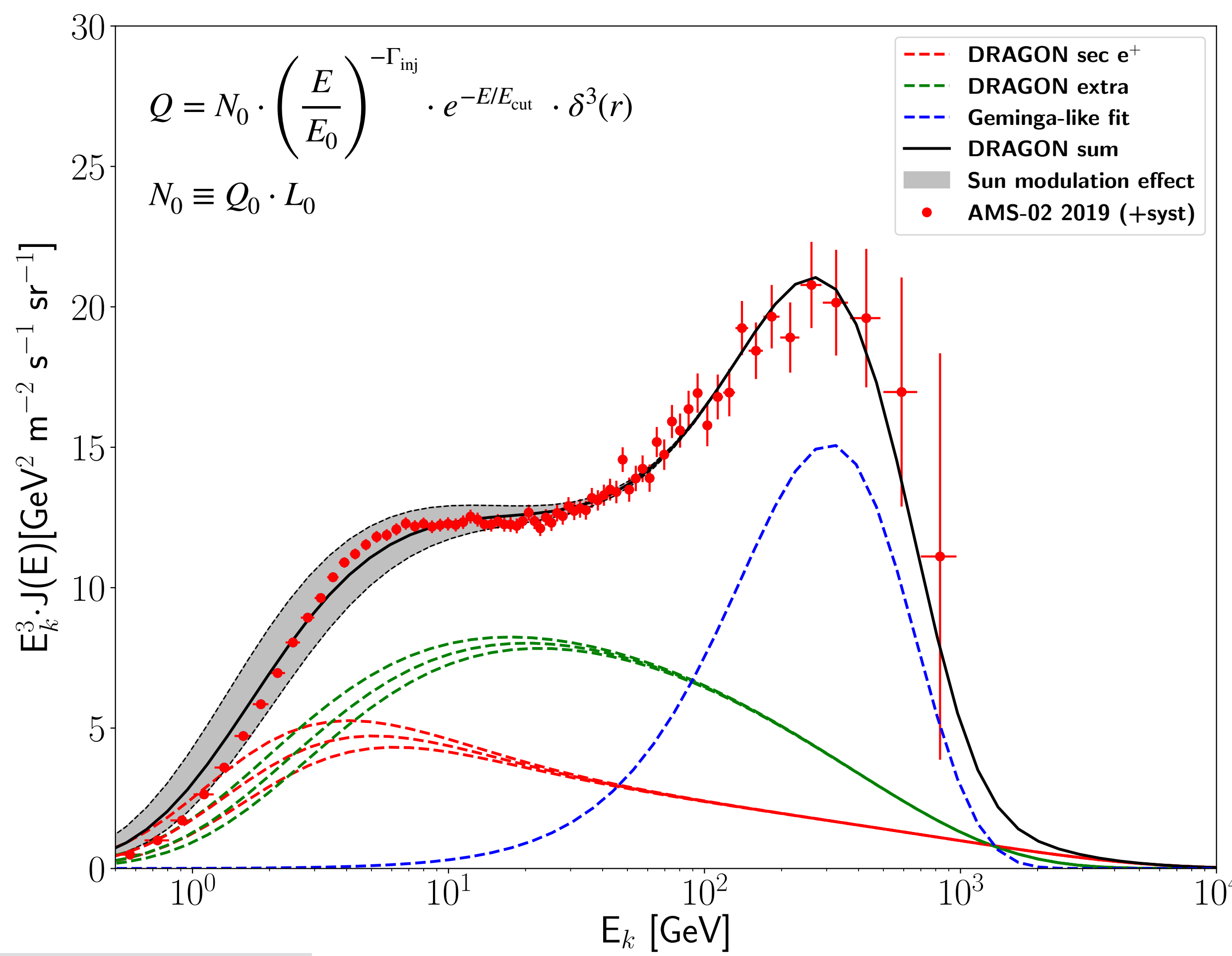
Case study: The positron anomaly

- However: Natural explanation in terms of **nearby astrophysical accelerators** of primary electron+positron pairs, e.g. **pulsar wind nebulae**

- Important: Gamma-ray observatories may now allow to identify the emission from the leptons leaving nearby known pulsars. A detection of a TeV halo around Geminga has recently been reported.

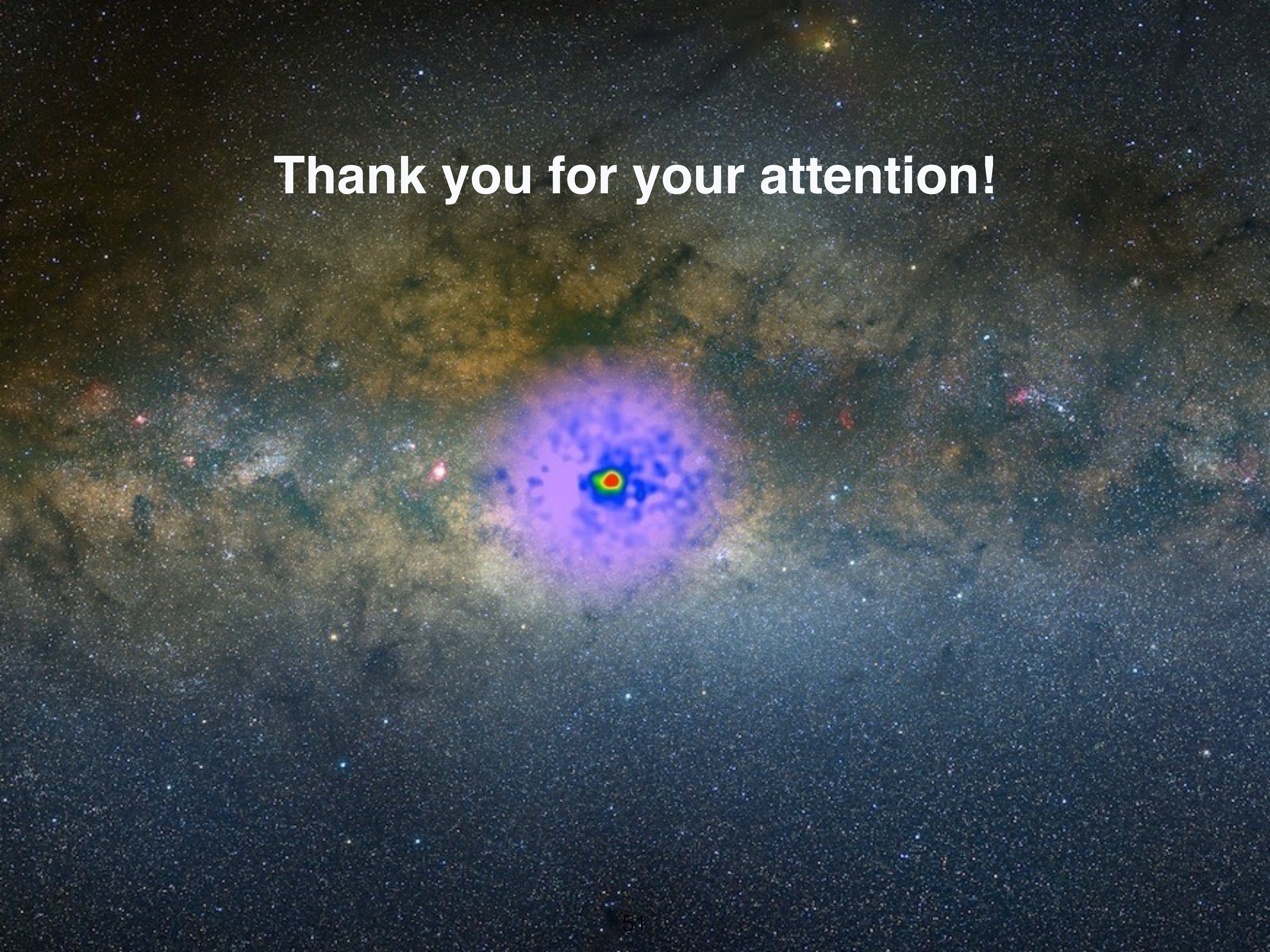






arXiv:1907.03696

Thank you for your attention!



A primer on CR acceleration: Power-law spectrum

Eventually, we get a power law spectrum:

Define $\mathcal{E} = \beta\mathcal{E}_0$ as the average energy of the particle after a collision

Define P as the probability that the particle remains in the acceleration region after a collision

After k collisions there are $N = N_0 P^k$ particles with energies $\mathcal{E} = \mathcal{E}_0\beta^k$

Eliminating k yields

$$\frac{\ln(N/N_0)}{\ln(\mathcal{E}/\mathcal{E}_0)} = \frac{\ln P}{\ln\beta}$$

$$\Rightarrow \frac{N}{N_0} = \left(\frac{\mathcal{E}}{\mathcal{E}_0}\right)^{\ln P/\ln\beta}$$

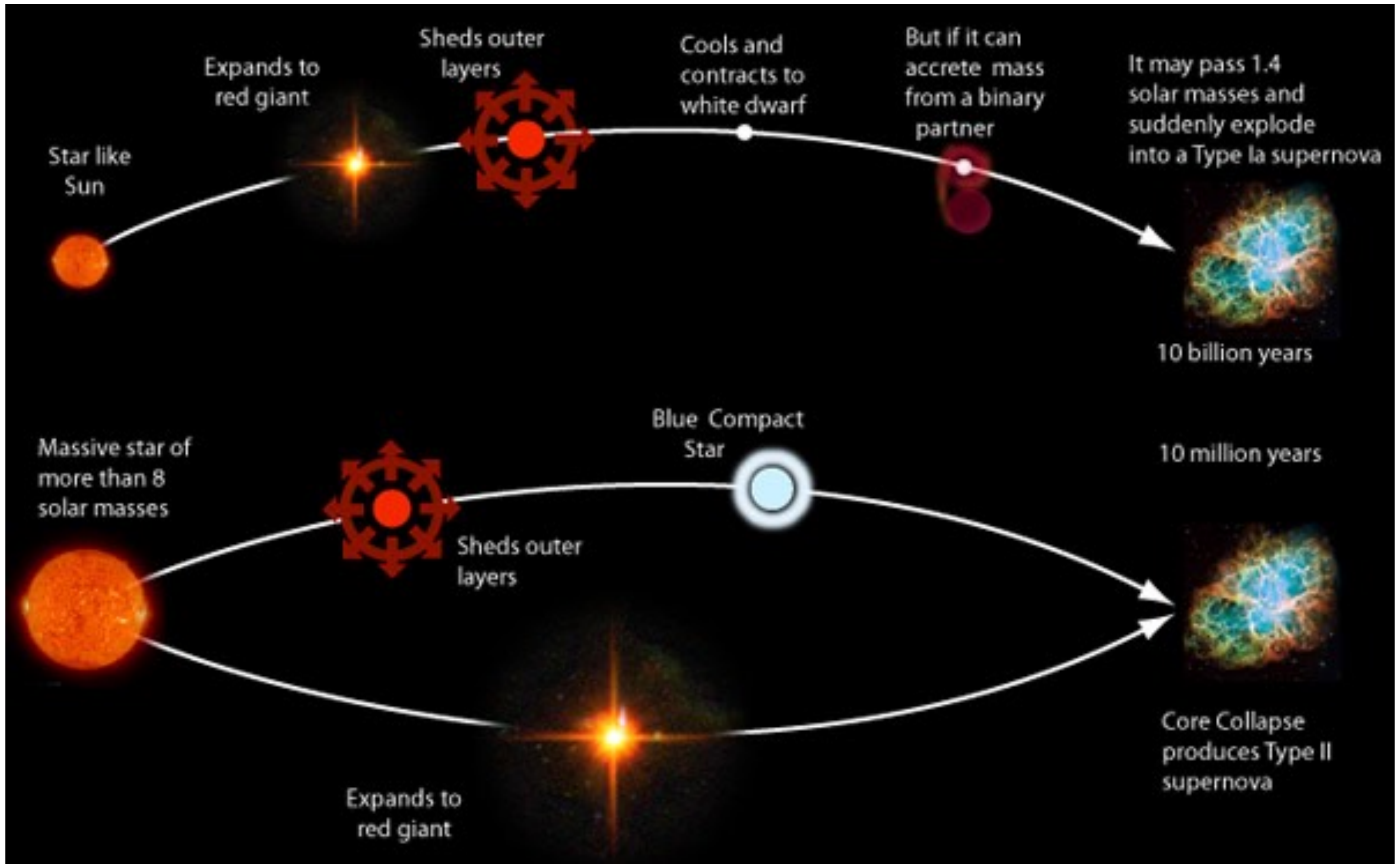
The power spectrum is then

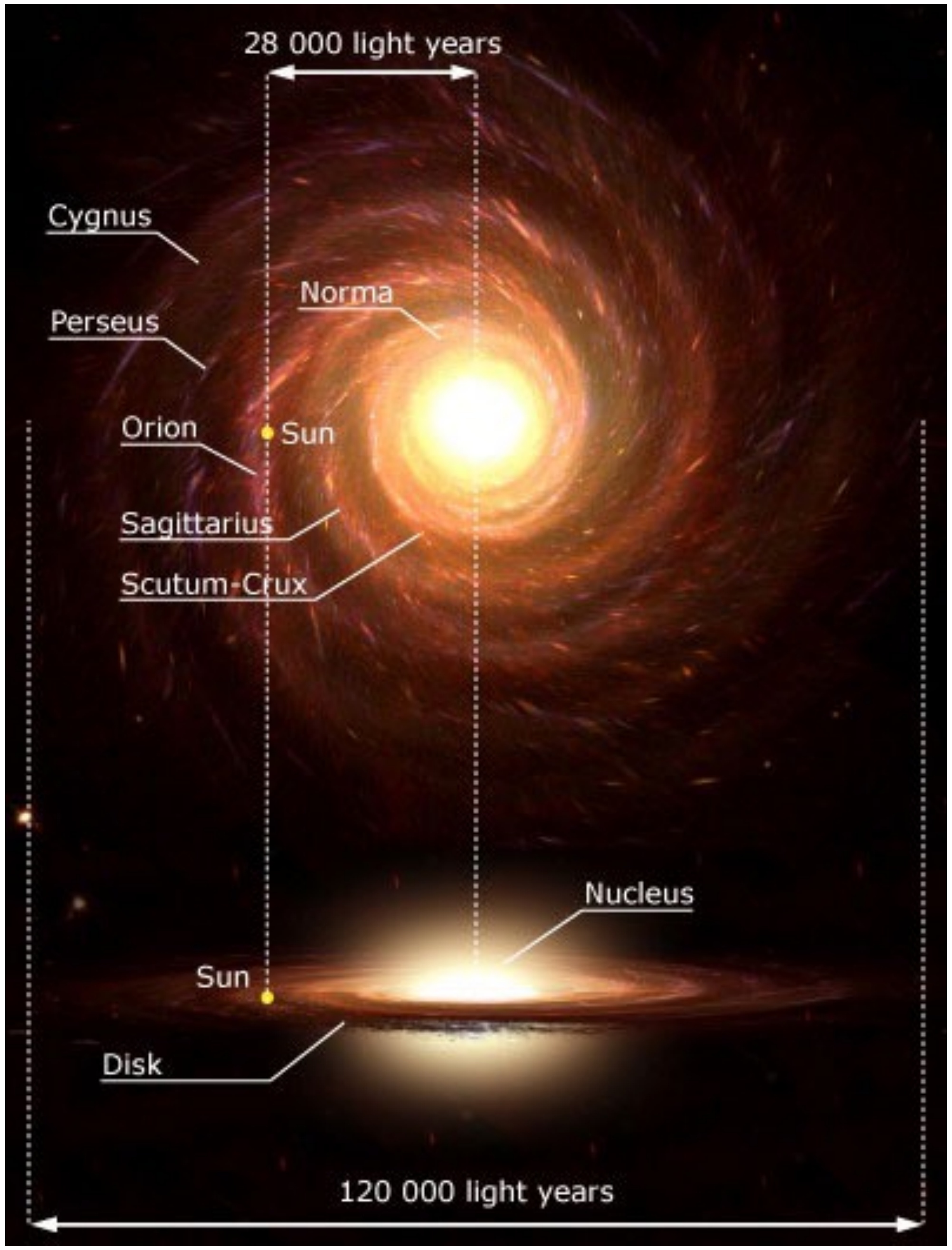
$$N(\mathcal{E})\,\mathrm{d}\mathcal{E} \propto \mathcal{E}^{-1+(\ln P/\ln\beta)}\,\mathrm{d}\mathcal{E}$$

A primer on CR acceleration: SNRs

- Two types of SNae
- SN type II are mostly distributed in the Galactic disk (scale height ~ 100 pc) where star formation is going on.

(remember 1 pc = 3.26 light years)





Backup slides: the diffusion equation in detail

The velocity of the particle in the three spatial dimensions can therefore be written as:

$$v_x(t) = v_\perp \cos(\Omega t + \phi) \tag{22}$$
$$v_y(t) = -v_\perp \sin(\Omega t + \phi) \tag{23}$$
$$v_z(t) = v_\parallel = v\mu = constant, \tag{24}$$

where ϕ is an arbitrary phase and $v_\parallel$ and $v_\perp$ are the parallel and perpendicular components of the particle velocity.

Let us assume now that on top of the background magnetic field $\mathbf{B}_0$ there is an oscillating magnetic field consisting of the superposition of Alfvén waves polarized linearly along the $x-$axis. In the reference frame of the waves ($v_A \ll c$) the electric field vanishes and one can write the individual Fourier modes as

$$\delta\mathbf{B} = \delta B \hat{x} \sin(kz - \omega t) \approx \delta B \hat{x} \sin(kz), \tag{25}$$

where the z coordinate of the particle is $z = v\mu t$. The Lorentz force on the particle in the $z-$ direction is

$$mv\gamma \frac{d\mu}{dt} = -\frac{q}{c}\delta B v_y \rightarrow \frac{d\mu}{dt} = \Omega \frac{\delta B}{B_0}(1-\mu^2)^{1/2} \sin(\Omega t + \phi) \sin(kv\mu t), \tag{26}$$

which can also be rewritten as

$$\frac{d\mu}{dt} = \frac{1}{2}\Omega \frac{\delta B}{B_0}(1-\mu^2)^{1/2} \left\{\cos\left[(\Omega - kv\mu)t + \phi\right] - \cos\left[(\Omega + kv\mu)t + \phi\right]\right\}. \tag{27}$$

Backup slides: the diffusion equation in detail

$$\langle \frac{\Delta\mu\Delta\mu}{\Delta t} \rangle_\phi = \pi \Omega^2 \left(\frac{\delta B}{B_0} \right)^2 \frac{(1-\mu^2)}{\mu} \delta \left(k - \frac{\Omega}{v\mu} \right). \quad (28)$$

The linear scaling of the square of the pitch angle cosine with time is indicative of the diffusive motion of the particles. The rate of scattering in pitch angle is usually written in terms of pitch angle diffusion coefficient:

$$\nu = \langle \frac{\Delta\theta\Delta\theta}{\Delta t} \rangle_\phi = \pi \Omega^2 \left(\frac{\delta B}{B_0} \right)^2 \frac{1}{\mu} \delta \left(k - \frac{\Omega}{v\mu} \right). \quad (29)$$

If $P(k)dk$ is the wave energy density in the wave number range dk at the resonant wave number $k = \Omega/v\mu$, the total scattering rate can be written as:

$$\nu = \frac{\pi}{4} \left(\frac{kP(k)}{B_0^2/8\pi} \right) \Omega. \quad (30)$$

The time required for the particle direction to change by $\delta\theta \sim 1$ is

$$\tau \sim 1/\nu \sim \Omega^{-1} \left(\frac{kP(k)}{B_0^2/8\pi} \right)^{-1} \quad (31)$$

Backup slides: the diffusion equation in detail

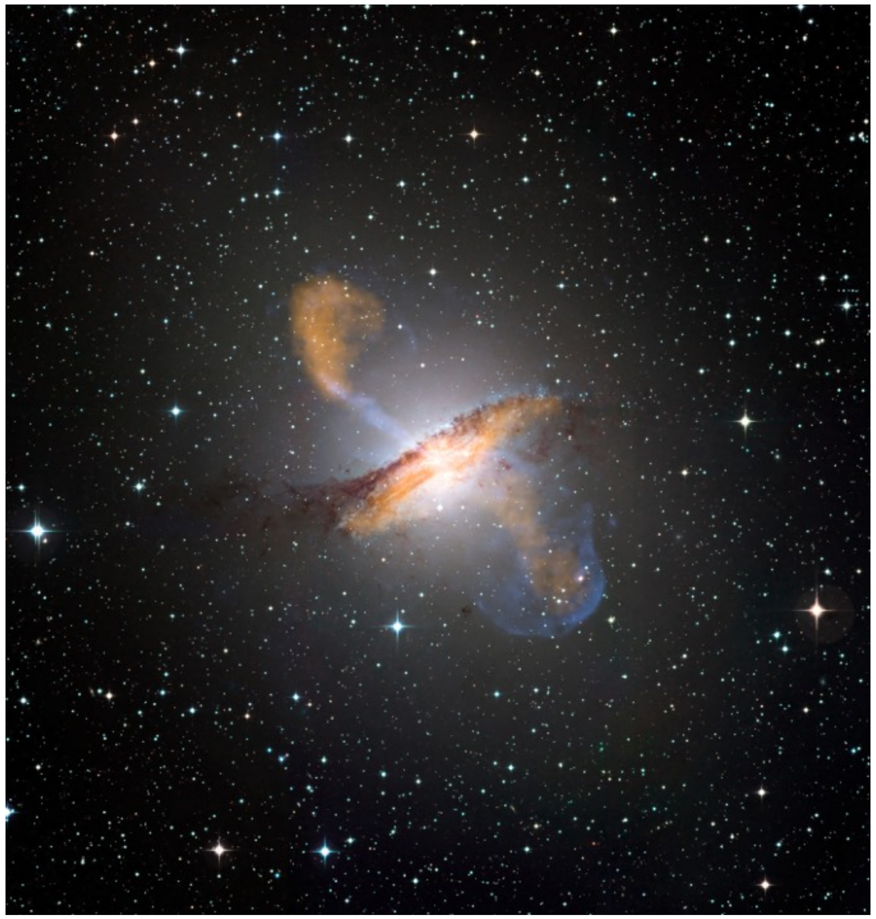
so that the spatial diffusion coefficient can be estimated as

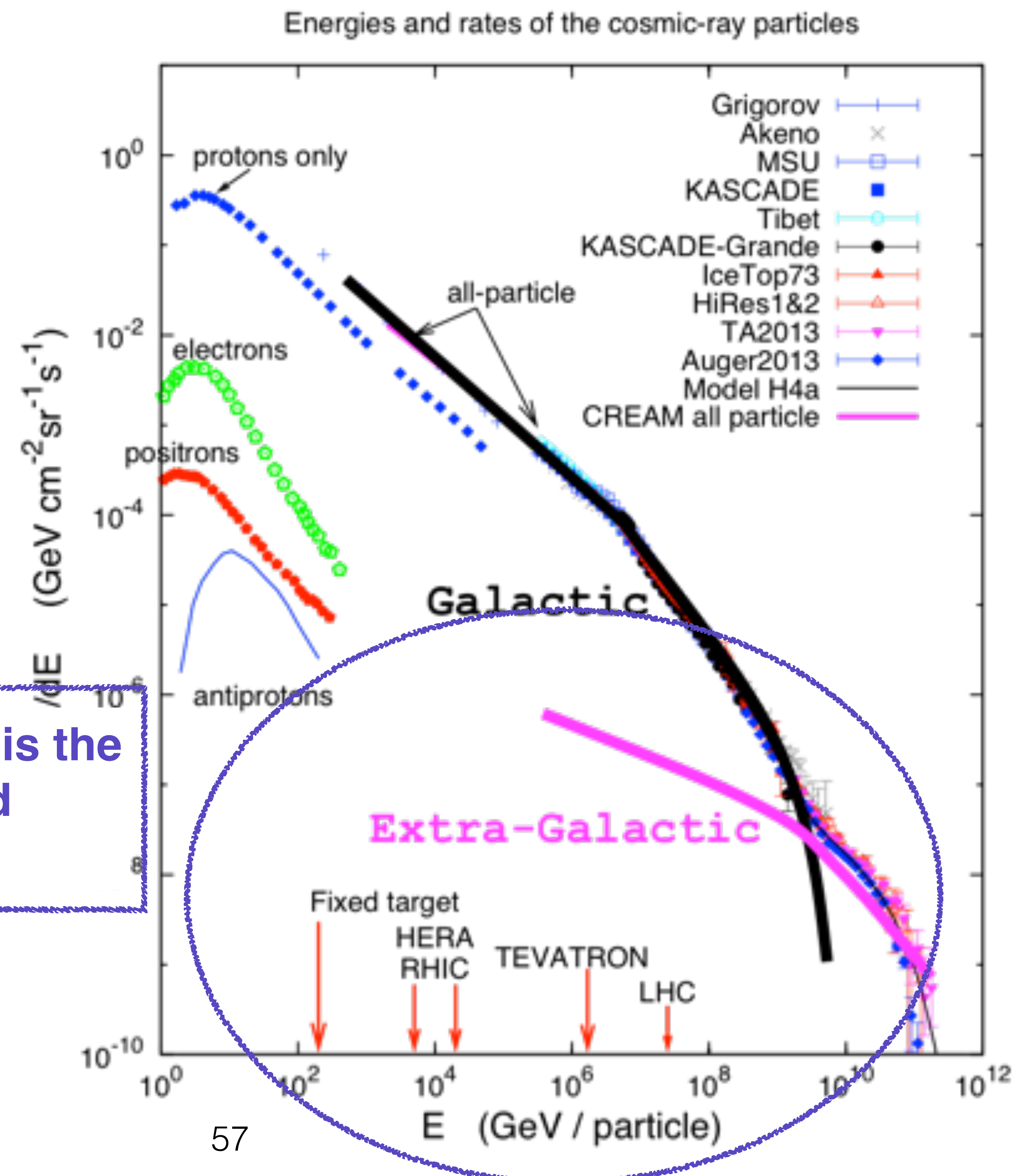
$$D(p) = \frac{1}{3} v(v\tau) \simeq \frac{1}{3} v^2 \Omega^{-1} \left(\frac{kP(k)}{B_0^2/8\pi} \right)^{-1} = \frac{1}{3} \frac{r_L v}{\mathcal{F}}, \tag{32}$$

where $r_L = v/\Omega$ is the Larmor radius of the particles and $\mathcal{F} = \left(\frac{kP(k)}{B_0^2/8\pi} \right)$.

It is interesting to notice that the escape time of CRs as measured from the B/C ratio and/or from unstable elements, namely a time of order 10^7 years in the energy range ~ 1 GeV, corresponds to require $H^2/D(p) \sim 10^7$ years, where $H \sim 3$ kpc is the estimated size of the galactic halo. This implies $D \approx 10^{29} cm^2 s^{-1}$, which corresponds to require $\delta B/B \sim 6 \times 10^{-4}$ at the resonant wave number. A very small power in the form of Alfvén waves can easily account for the level of diffusion necessary to confine CRs in the Galaxy. The requirements become even less demanding when higher energy CRs are considered.

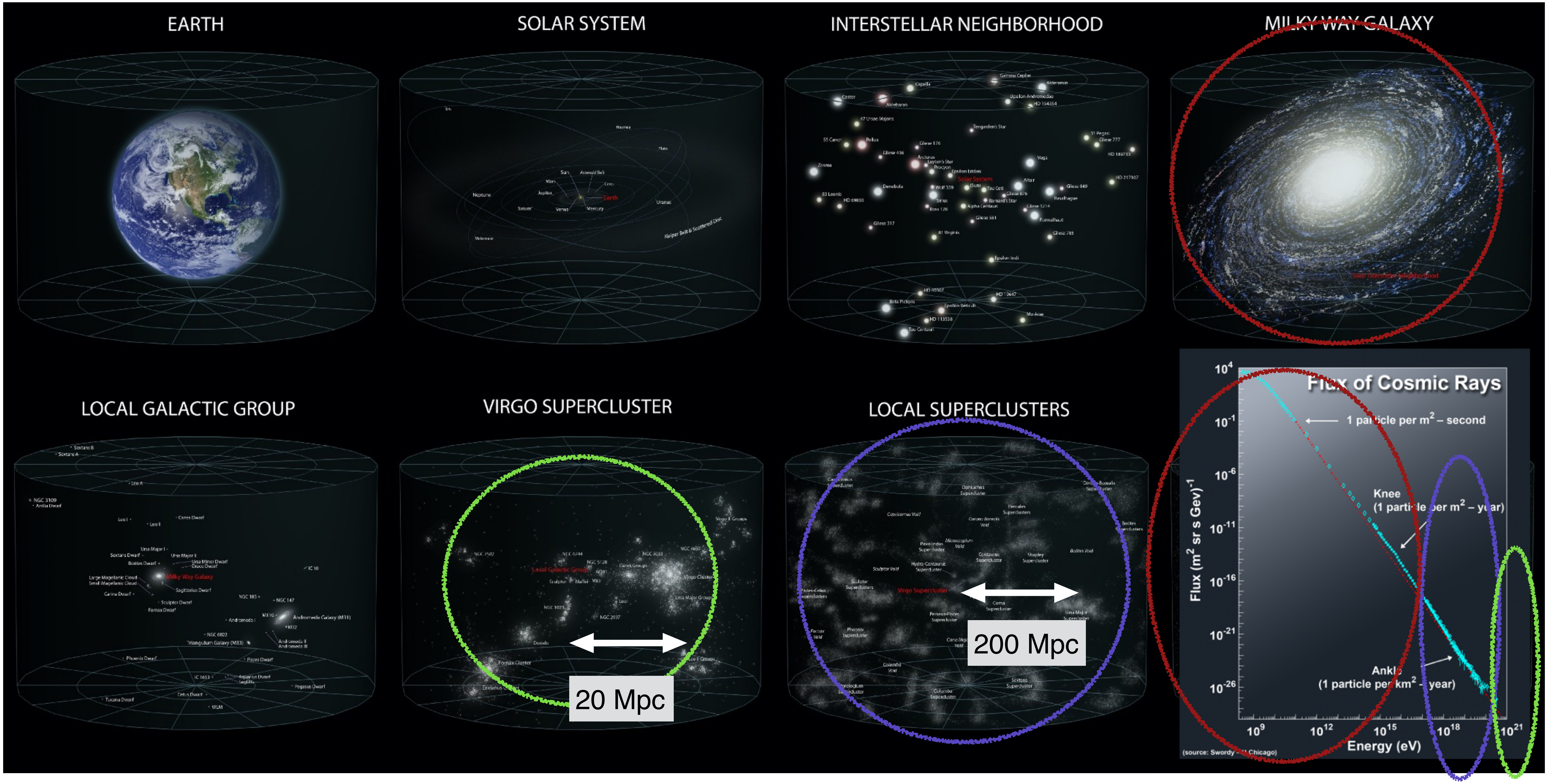
A glimpse on very high energy CRs





remember the question: where is the transition between Galactic and extra-Galactic CRs?

A glimpse on very high energy CRs



A glimpse on very high energy CRs