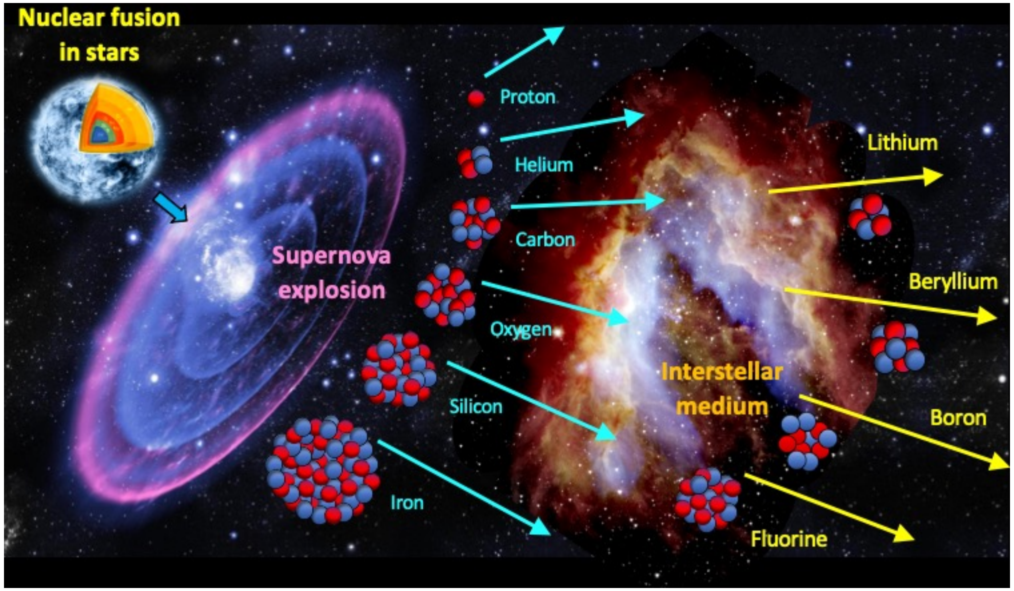
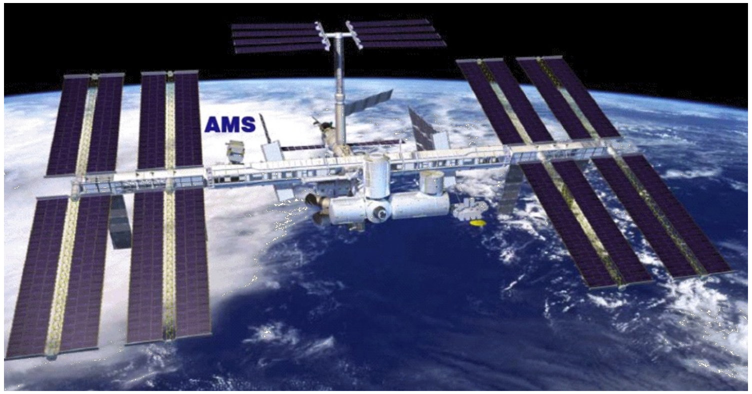
EPFL Physics and Applied Physics master programs - A.Y. 2024-2025

Introduction to astroparticle physics

Part 2 – Lesson 2 – May 2, 2025





Prof. **Chiara Perrina**

E-mail: Chiara.Perrina@epfl.ch

Learning outcomes and goals

Describe the cosmic ray (CR) energy spectrum and composition. Discuss CR origin, acceleration and propagation.

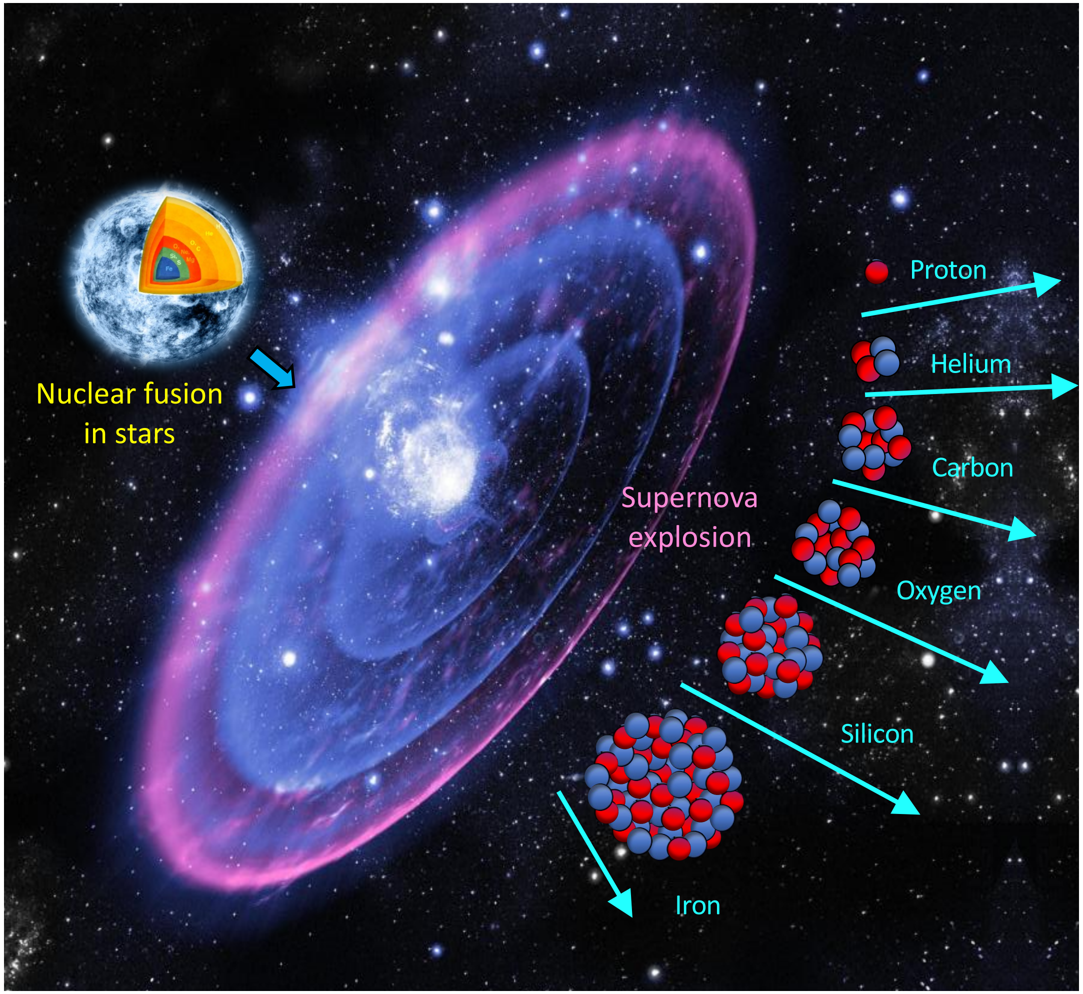
Explain the relationship between charged CRs, gamma-rays and neutrinos.

Discuss the detection principles and measured quantities (mass, charge, momentum, energy, rigidity, direction, …) of astroparticle physics experiments.

Interpret the main results of selected experiments

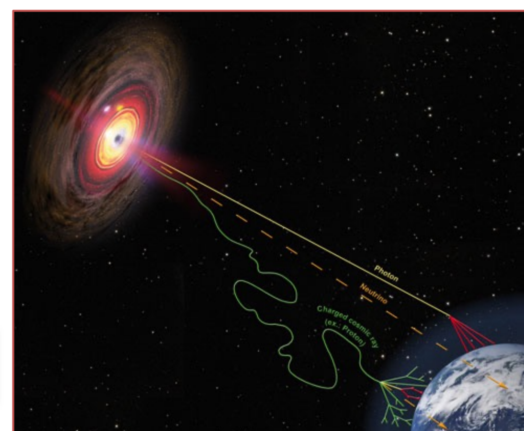
Assess / Evaluate the state of the art of astroparticle physics

Primary cosmic rays



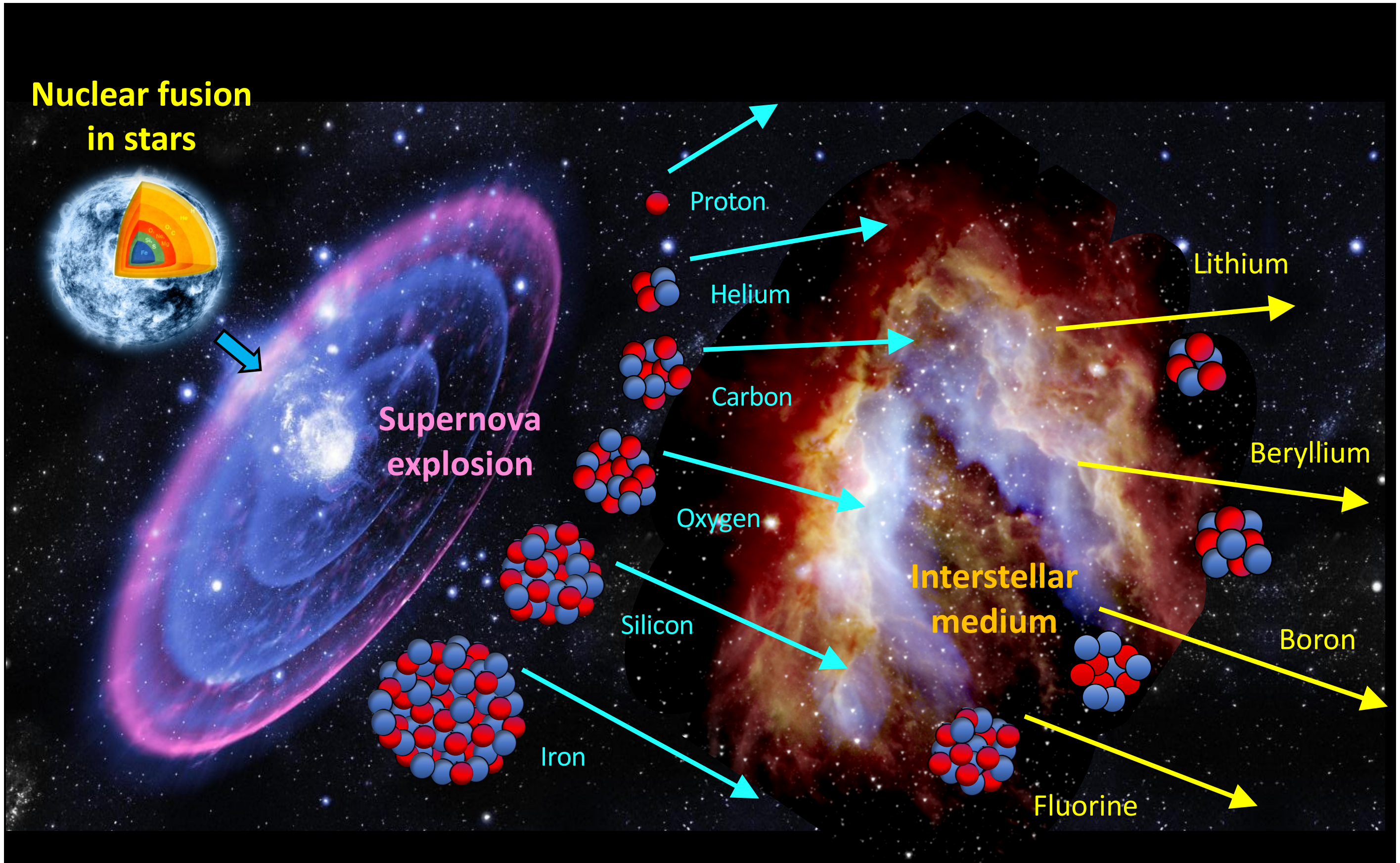
Primary elements,
(protons, nuclei of He, C, O, Ne, Mg, Si..., Fe)
are **produced**
during the lifetime of **stars**.

They are **accelerated in supernovae explosions**
and
expelled in the interstellar medium where they **propagate diffusively through the galaxy**.



The CR propagation is not ballistic.

Secondary cosmic rays

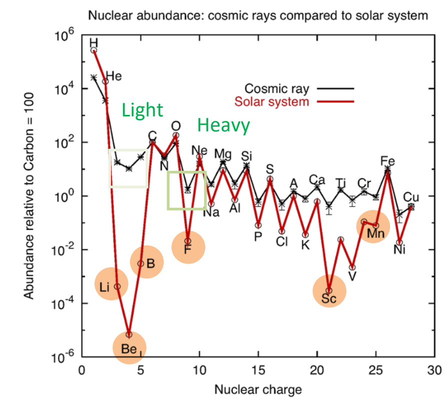


C, O, … + ISM → Li + X
C, O, … + ISM → Be + X
C, O, … + ISM → B + X

Ne, Mg, Si, … + ISM → F + X

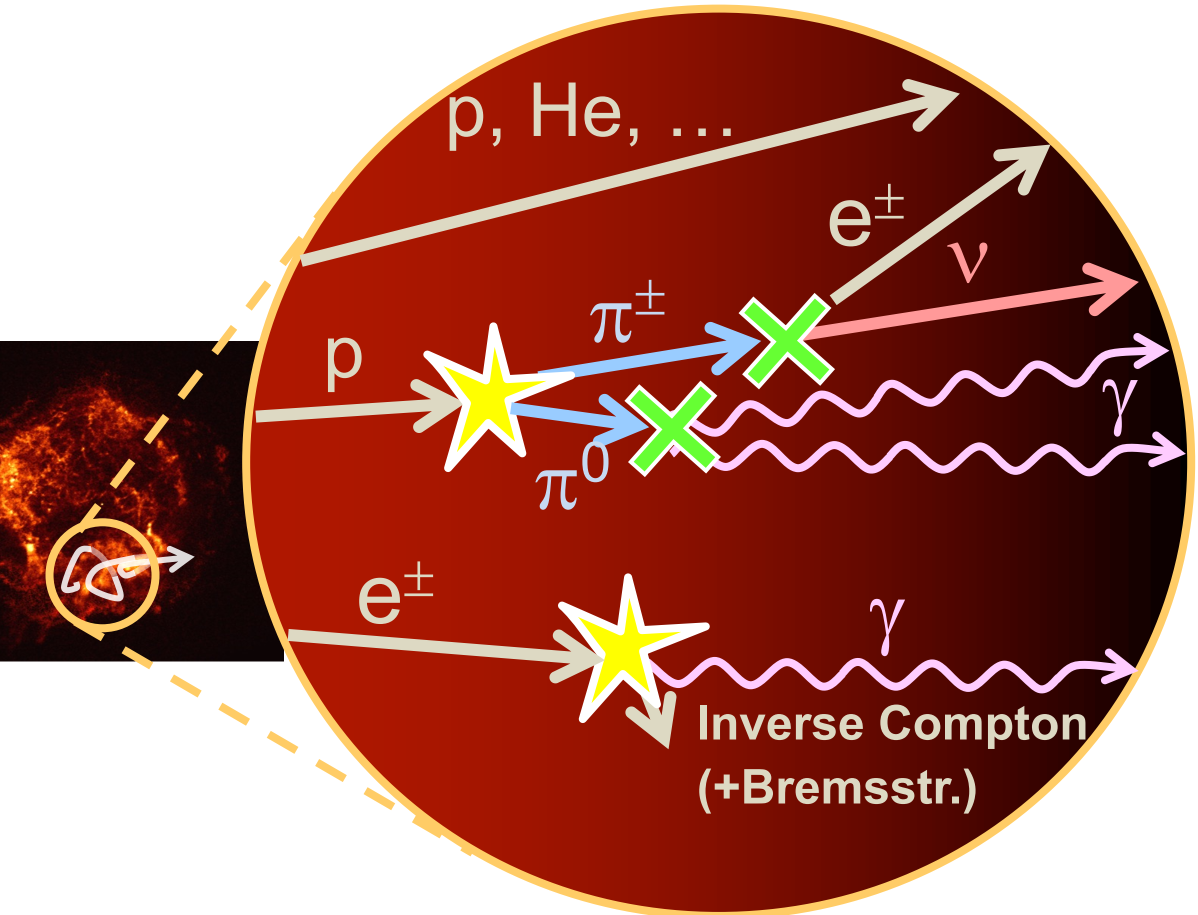
Fe, … + ISM → Sc, … ,Mn + X

Secondary cosmic rays Li, Be, B, F, sub-Fe nuclei are produced by the collision of primary cosmic rays, C, O, Si, … , Fe, with the interstellar medium (ISM).



They propagate **diffusively** through the galaxy.

Elementary particles



While primary cosmic rays get **accelerated**, they interact with the environment and generate other particles. If the interaction happen in the vicinity of the source, the produced particles are still "**primary**". If the interactions occurs with the ISM, they are called **"secondaries"** (or CR from CR collisions/diffuse term).

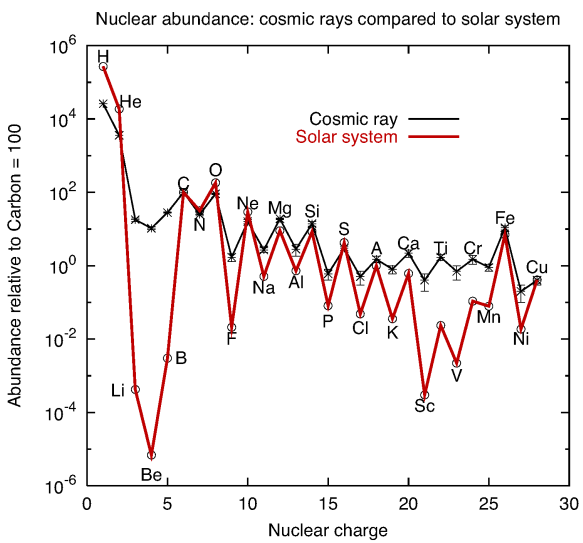
The daughter particles can be:

- **Electrons and positrons**
  Mainly $\pi^{\pm}$ decays
- **Neutrinos**
  Mainly $\pi^{\pm}$ decays
- **Photons**
  Synchrotron, ICS, bremsstrahlung, π^{0} decays
- **Antiprotons**
  Inelastic hadronic interactions

Why can we say that charged CRs propagate diffusively?

From the observation of the “**cosmic clocks**” which provide estimates of the CR residence time in the Galaxy.

1) Existence of secondary nuclei

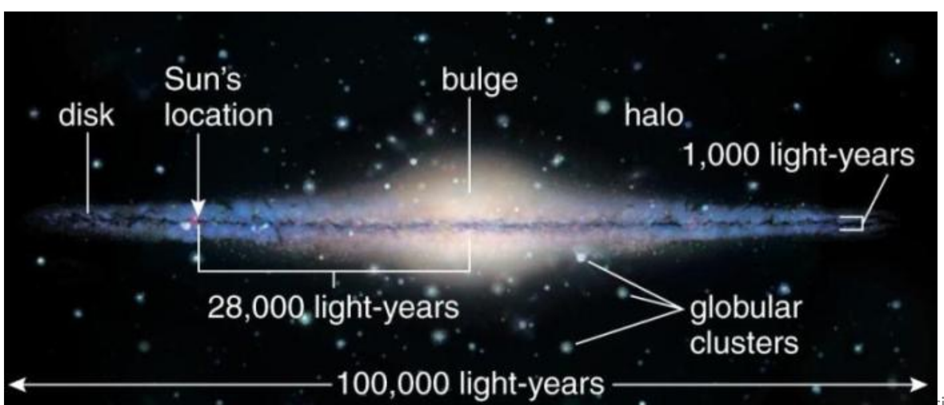


$$(\mathrm{A,Z}) + \mathrm{nucleon_{ISM}} \rightarrow (\mathrm{A}-1, Z') + \mathrm{other}$$

$$\sigma_{\mathrm{spallation}} \propto A^{0.7}\,\mathrm{mb}$$

$$\tau_{\mathrm{spallation}} = \frac{1}{n_{gas}\, c\, \sigma_{\mathrm{spallation}}} = \mathcal{O}(1, 10 \text{ to } 100 \text{ Myr})$$

$$\tau_{\text{primary CR in MW}} > \tau_{\mathrm{spallation}}$$



If CRs propagated ballistically at a speed close to that of light, they would escape from the Galaxy in about 10^4 years

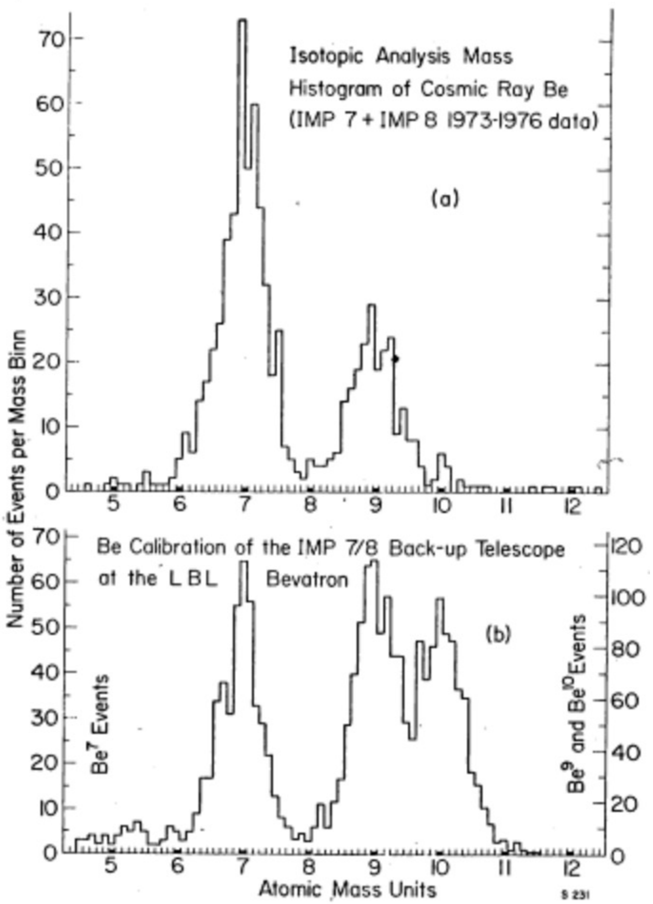
$$R_{\mathrm{disc}} = 15\ \mathrm{kpc}$$

$$1\ \mathrm{pc} = 3\times10^{16}\ \mathrm{m}$$

→ The CR propagation is not ballistic.

Cosmic clocks (2)

2) Disappearance of unstable nuclei



^{10}Be is unstable.
It decays β^- with a half-life $\tau_{1/2}$ = 1.5 Myr.
http://barwinski.net/isotopes/query_select.php

$$\tau_{\mathrm{Be-10\ in\ MW}} > \gamma\tau_{1/2}$$

→ The CR propagation is not ballistic.

Cosmic rays cannot travel in straight lines, nor can they simply follow helical trajectories around magnetic field lines.
CRs must have much more complex trajectories.

CR propagation in the Galaxy is accurately described by **diffusion**

Garcia-Munoz, M., Mason, G. M., & Simpson, J. A. The isotopic composition of galactic cosmic-ray lithium, beryllium, and boron. In: International Cosmic Ray Conference 1977. https://articles.adsabs.harvard.edu//full/1977ICRC....1..307G/A000307.000.html

CR diffusion: random walk

- Diffusion: many random deflections leading to a random walk in space (Brownian motion)
- CR diffusion is not due to collisions, but interactions with turbulent magnetic fields.

P.cle speed: β
Target numeric density: n
Interaction cross section: σ

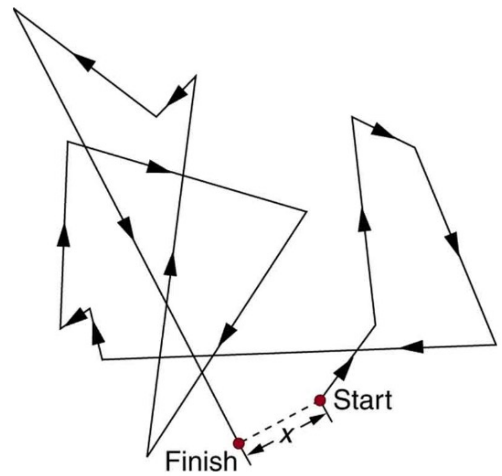


FIG. 2: Typical displacement vectors in a random motion.

Particle mean free path

$$\lambda = \frac{1}{\sigma n}$$

Interaction period

$$\tau = \frac{\lambda}{\beta}$$

$$t = \tau N$$

$$\langle \vec{r}(N) \rangle = \left\langle \sum_{i=1}^{N} \vec{r_i} \right\rangle = 0$$

$$\langle \vec{r}^2(N) \rangle = \left\langle \left(\sum_{i=1}^{N} \vec{r_i} \right) \cdot \left(\sum_{j=1}^{N} \vec{r_j} \right) \right\rangle = \sum_{i=1}^{N} \left\langle \vec{r_i}^2 \right\rangle + \lambda^2 \sum_{i \neq j} \langle \cos \theta_{ij} \rangle = N\lambda^2$$

$$\langle \vec{r}^2(N) \rangle = N\lambda^2$$

Discrete version of a diffusive propagation, with N proportional to the time elapsed

Mean free path

The mean free path depends on

1. **The rigidity of the particle**

2. **The turbolence of the magnetic fields**

$$\lambda \propto r_{\mathrm{L}}^{\delta}$$

$$R = \frac{pc}{Ze} \qquad pc = r_{\mathrm{L}} B Z e \qquad r_{\mathrm{L}} \propto \frac{pc}{B} \qquad r_{\mathrm{L}} \propto \frac{E}{B}$$

$$\lambda \propto E^{\delta}$$

The diffusion equation

Let’s consider a one-dimention random walk, the diffusion equation is given by

$$\frac{\partial P(x,t)}{\partial t} = \boldsymbol{D} \frac{\partial^2 P(x,t)}{\partial x^2}$$

D is the diffusion coefficient of the particle due to interactions in turbulent magnetic fields.

It is a parabolic differential equation, its fundamental solution is the **normalized Gaussian**

$$P(x,t) = \frac{1}{\sqrt{4\pi D t}} e^{-\frac{x^2}{4Dt}} \qquad t > 0$$

$$\mu = \langle x(t) \rangle = 0$$
$$\sigma^2 = \langle (x - \langle x(t) \rangle)^2 \rangle = \langle x^2(t) \rangle = 2Dt$$

For a three-dimention random walk

$$\langle \vec{r}^2(t) \rangle = 2Dt \times 3$$

Motion:

- ✓ Linear
- ✓ uniform
- ✓ isotropic

In general

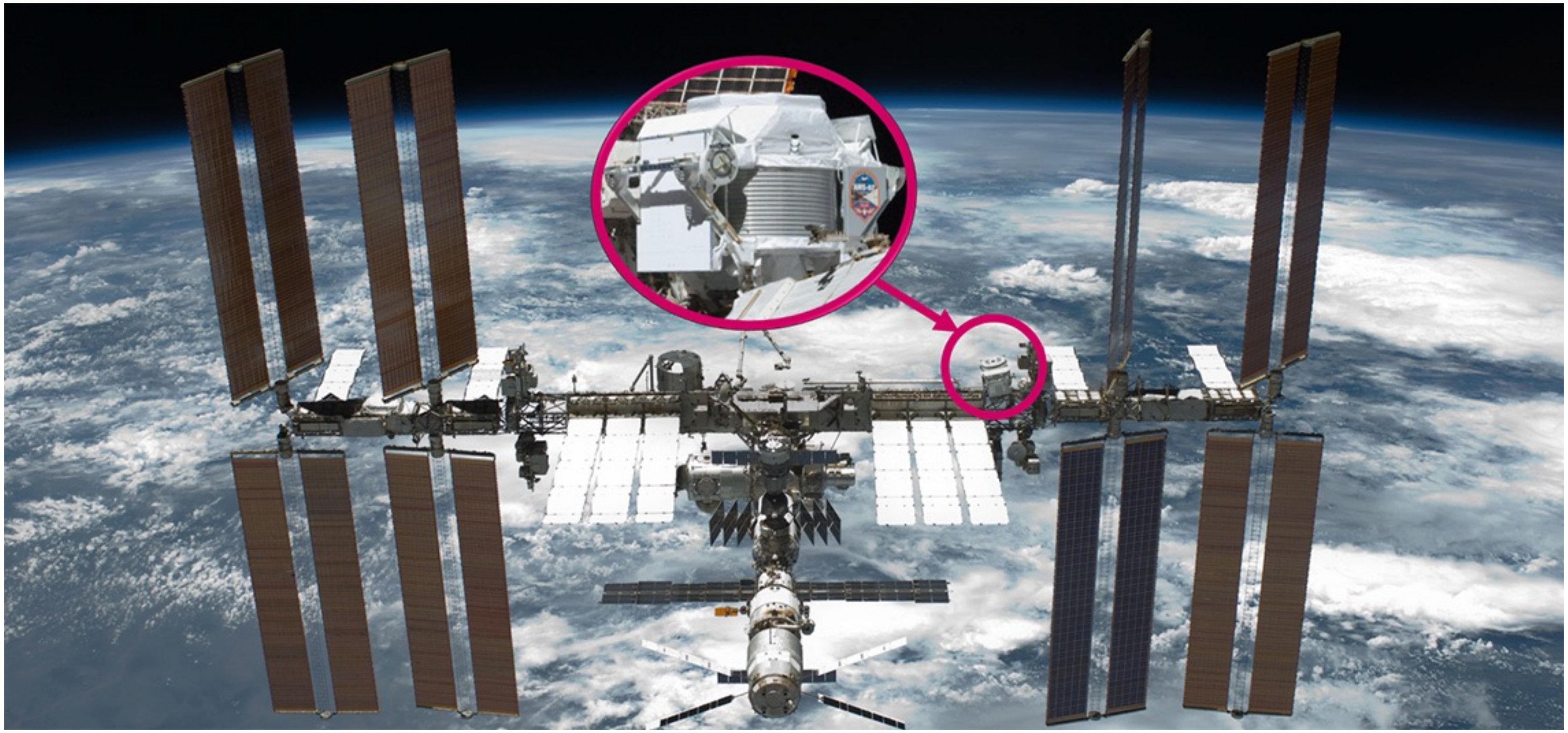
$$\langle \vec{r}^2(t) \rangle \propto Dt \Rightarrow D \propto \frac{\langle \vec{r}^2(t) \rangle}{t}$$

$$\langle \vec{r}^2(N) \rangle = N\lambda^2$$

$$D \propto \frac{N\lambda^2}{t} = \frac{N\lambda^2}{N\tau} = \frac{\lambda^2 \beta}{\lambda} = \lambda\beta$$

$D \propto \lambda\beta$ | $\lambda \propto E^{\delta}$ | $\mathrm{D}(E) \propto E^{\delta}$

AMS (2011 - now)



The Alpha Magnetic Spectrometer (AMS)
on the International Space Station (ISS)

https://ams02.space
https://www.nasa.gov/mission_pages/station/main/index.html

From the launch to the future

AMS was launched with the Space Shuttle Endeavour on May 16, 2011

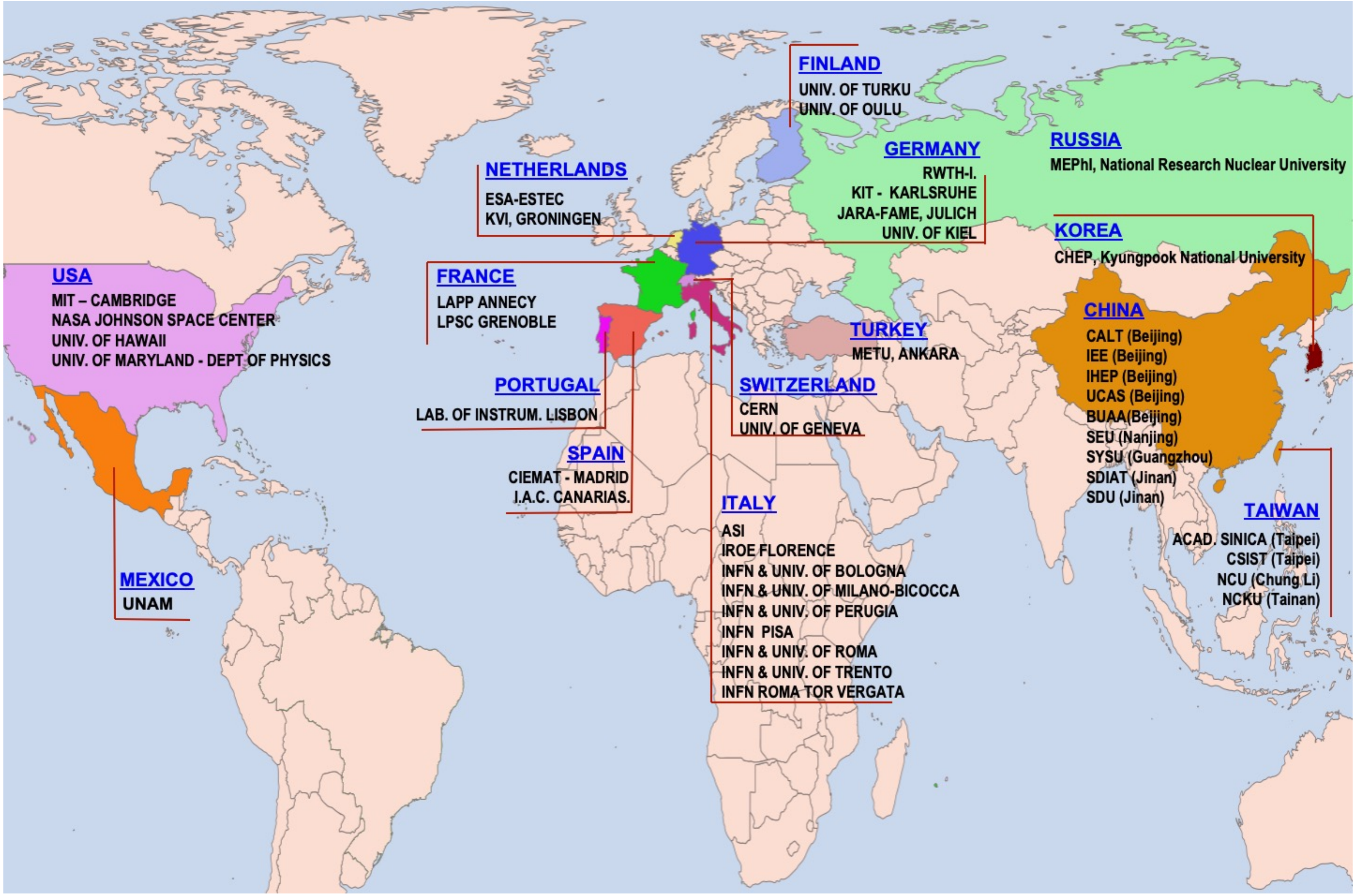
and installed on the ISS on May 19, 2011

AMS studies the universe and its origin by searching for antimatter, dark matter while performing **precision measurements of cosmic-ray** fluxes and composition.

AMS mission duration: entire ISS lifetime (up to 2030)

The AMS Collaboration

AMS is an international collaboration of institutions from America, Europe and Asia.

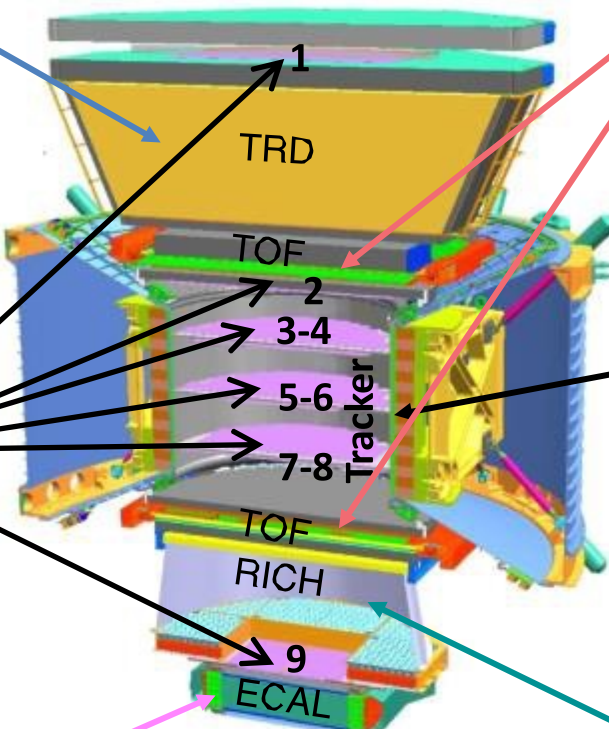


AMS: a TeV precision spectrometer in space

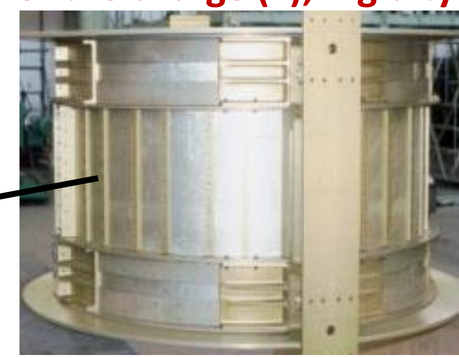
Transition Radiation Detector (TRD):
Discriminate e^+, e^- (TR) out of p and anti-p (no TR), |Z|

Z and E
are measured independently by several subdetectors

Time Of Flight (TOF): |Z|, speed



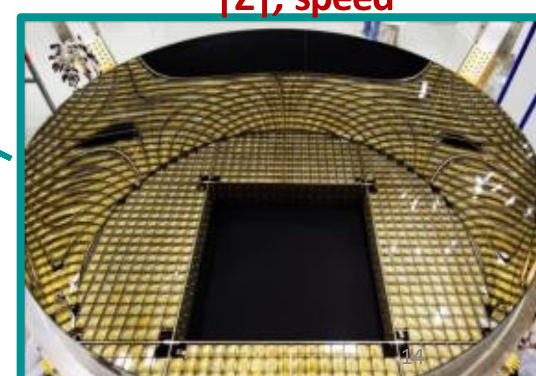
Magnet (0.14 T): Identify the sign of the charge (Z), Rigidity



Silicon Tracker: |Z|, Rigidity = *p/Ze*

Electromagnetic Calorimeter (ECAL):
***Energy* of e^+, e^-**

Ring Imaging Cherenkov (RICH): |Z|, speed



7.5 tons
5 m × 4 m × 3 m

AMS Publications

https://ams02.space/publications

In this lecture:

1. **AMS electrons**: Towards Understanding the Origin of Cosmic-Ray Electrons
   Phys. Rev. Lett. 122, 101101 (2019)

2. **AMS positrons**: Towards Understanding the Origin of Cosmic-Ray Positrons
   Phys. Rev. Lett. 122, 041102 (2019)

3. **AMS Iron**: Properties of Iron Primary Cosmic Rays: Results from the Alpha Magnetic Spectrometer
   Phys. Rev. Lett. 126, 041104 (2021)

4. **AMS report**: The Alpha Magnetic Spectrometer (AMS) on the International Space Station: Part II - Results from the First Seven Years
   Phys. Rep. 894, 1 (2021)

5. **AMS fluorine**: Properties of Heavy Secondary Fluorine Cosmic Rays: Results from the Alpha Magnetic Spectrometer
   Phys. Rev. Lett. 126, 081102 (2021)

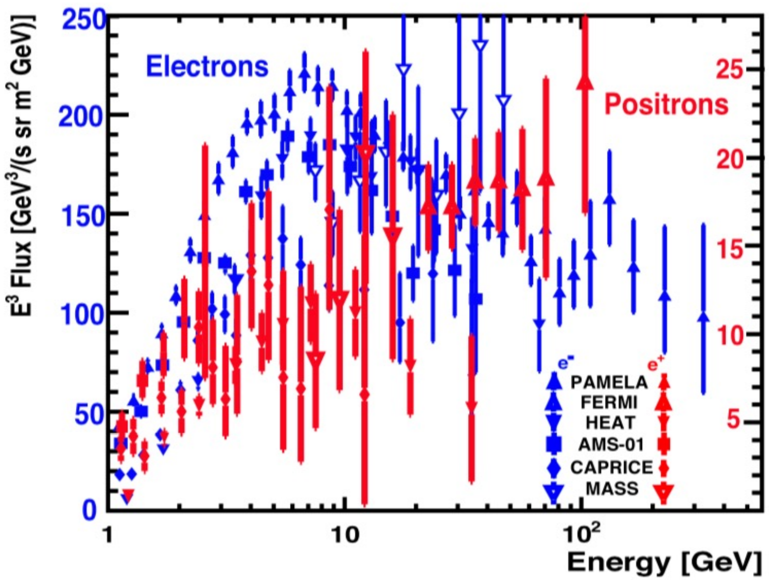
6. **AMS N Na Al:** Properties of a New Group of Cosmic Nuclei: Results from the Alpha Magnetic Spectrometer on Sodium, Aluminum, and Nitrogen
   Phys. Rev. Lett. 127, 021101 (2021)

Cosmic electrons and positrons

Before AMS:

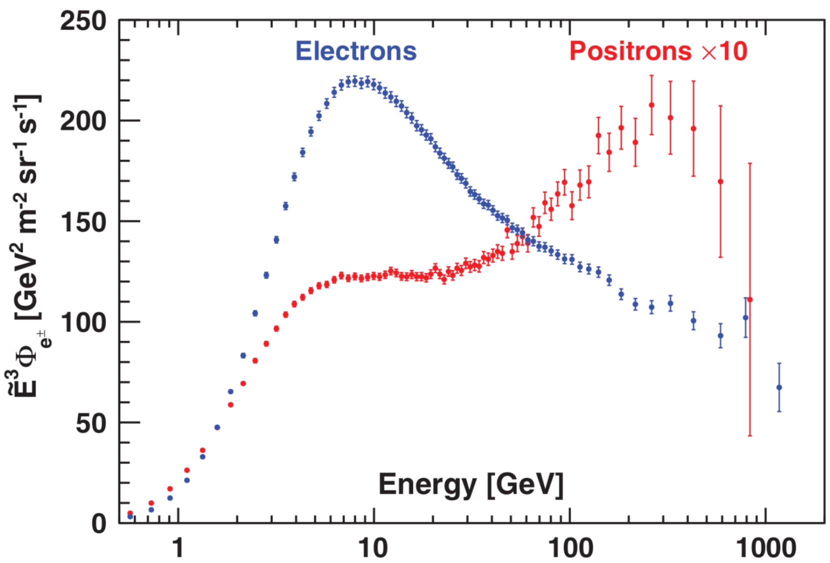
AMS latest results: **~28 M electrons** and **~2 M positrons**

AMS report



The electron spectrum has **different magnitude** compared to that of positrons.

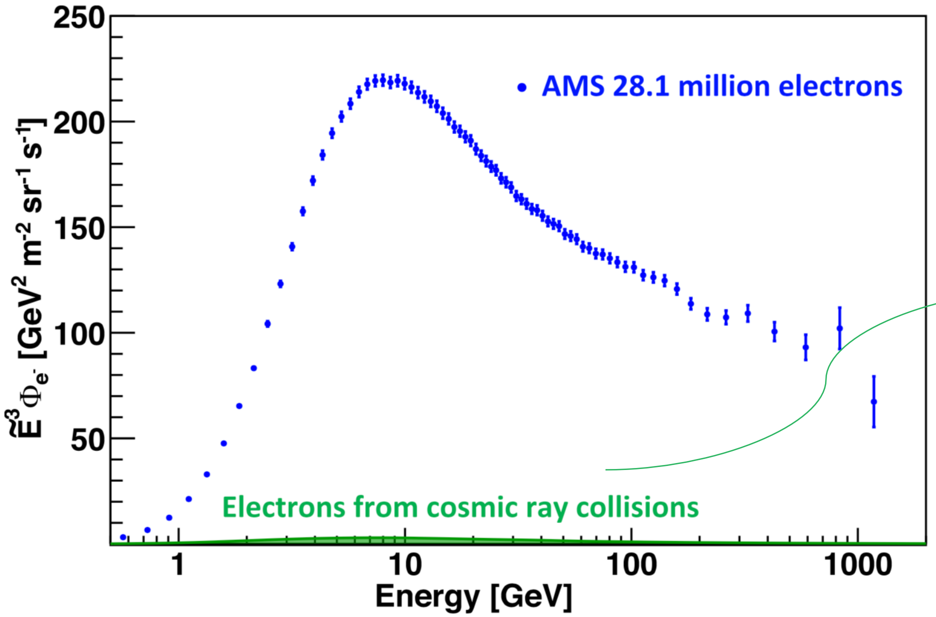
AMS electrons



The electron spectrum has **different magnitude,** and a **different shape** (energy dependence) compared to that of positrons.

The origin of cosmic electrons

AMS report



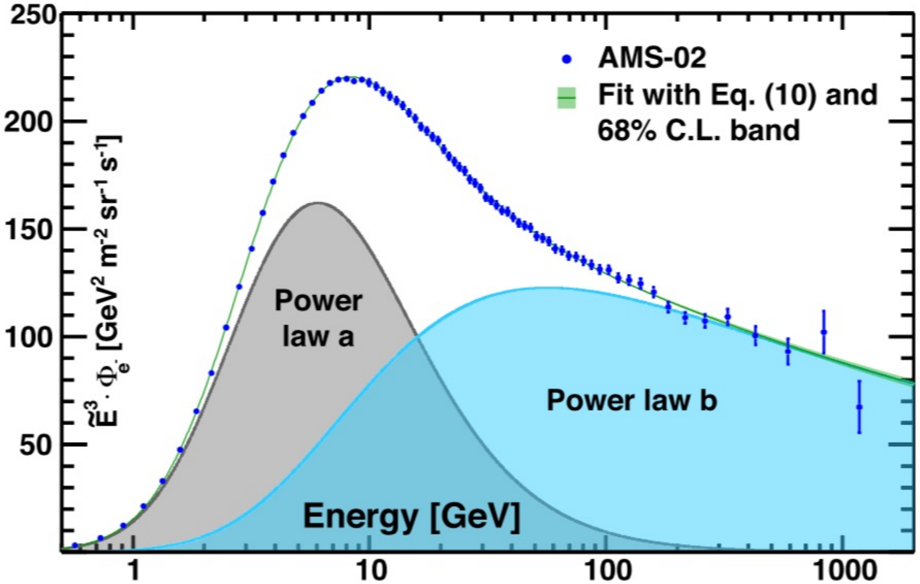
The contribution from cosmic ray collisions is negligible.

GALPROP prediction.

There are many models predicting the flux of secondaries (GALPROP, Dragon, Usine, …). They differ in their assumptions. GALPROP is widely regarded as the standard model for prediction of fluxes of secondaries based on the data from accelerator experiments and from cosmic-ray studies

The origin of cosmic electrons

AMS report



In the energy range [0.5 – 1400] GeV the electron flux is very well described by the sum of **2 power law** functions.

$$\Phi_{e^-}(E) = \frac{E^2}{\hat{E}^2}[1 + (\hat{E}/E_t)^{\Delta\gamma_t}]^{-1}[C_a(\hat{E}/E_a)^{\gamma_a} + C_b(\hat{E}/E_b)^{\gamma_b}]$$

$$\hat{E} = E + \varphi_{e^-}$$

φ_{e^-} is the "effective solar modulation potential" to take into account the solar modulation effects.

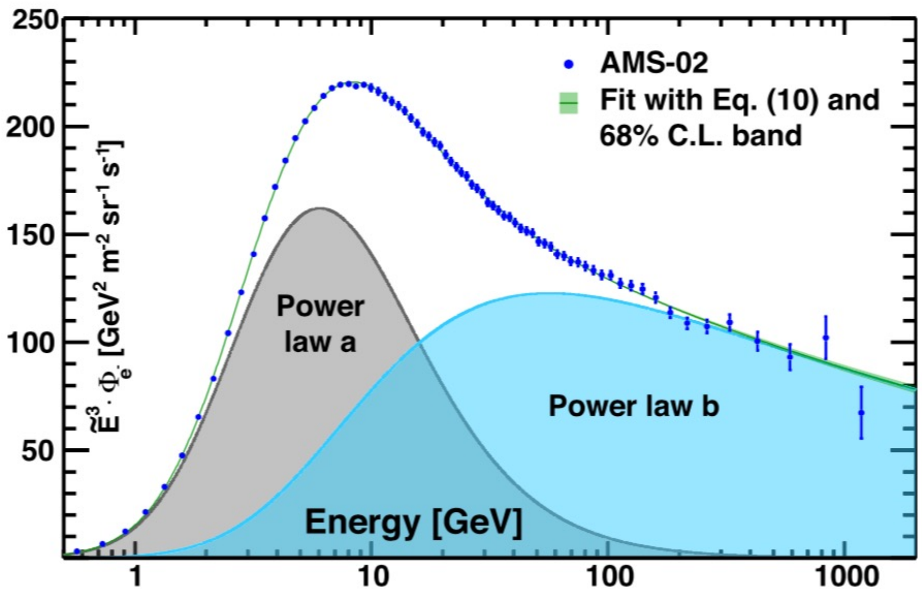
$$E_t = 3.94 \pm 0.21\,\mathrm{GeV},$$
$$\Delta\gamma_t = -2.14 \pm 0.09,$$
$$C_a = (1.13 \pm 0.08) \times 10^{-2}\,\mathrm{m^{-2}sr^{-1}s^{-1}GeV^{-1}},$$
$$\gamma_a = -4.31 \pm 0.13,$$
$$C_b = (3.96 \pm 0.04) \times 10^{-6}\,\mathrm{m^{-2}sr^{-1}s^{-1}GeV^{-1}},$$
$$\gamma_b = -3.14 \pm 0.02,$$
$$\varphi_{e^-} = 0.87 \pm 0.12\,\mathrm{GeV},$$
with $\chi^2/\mathrm{d.o.f.} = 36.5/68.$

$E_{a(b)} = 20\ (300)$ GeV
to minimize the correlation between $C_{a(b)}$ and $\gamma_{a(b)}$

What is the origin of power law a and power law b?

Contributions to the electron flux

AMS report



AMS electrons

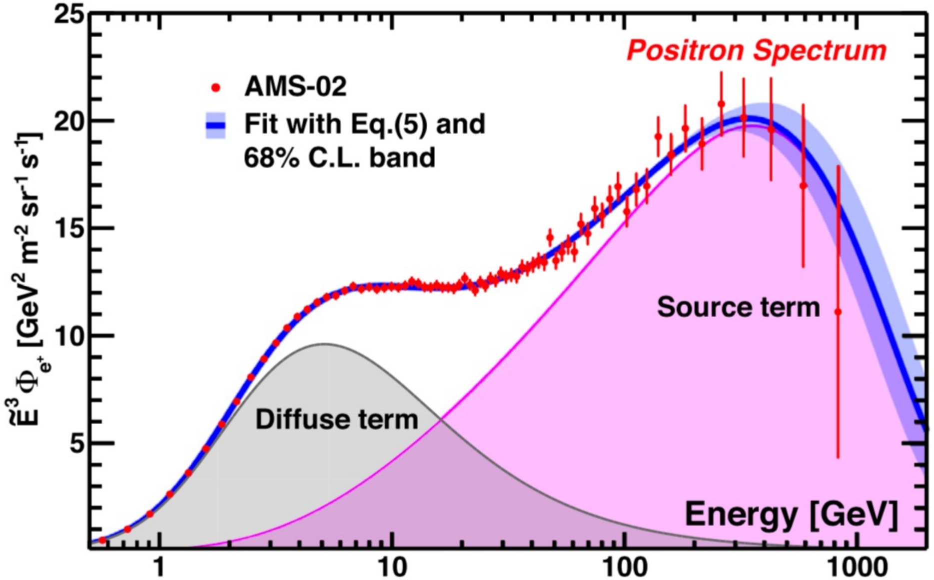
In addition to a small contribution of secondary electrons produced in the collisions of ordinary cosmic rays with the interstellar gas [40], there are several astrophysical sources of primary cosmic-ray electrons. It is assumed that there are only a few astrophysical sources of high energy electrons in the vicinity of the Solar System each making a power-law-like contribution to the electron flux [41,42]. In addition, there are several physics effects which may introduce some spectral features in the original fluxes [43,44]. Therefore, it is important to know the minimal number of distinct power law functions needed to accurately describe the AMS electron flux.

[42]: Astrophys. J. 601, 340 (2004)

Some nearby sources (< 1 kpc distance), *such as Vela, Cygnus Loop, or Monogem, could leave unique signatures in the form of identifiable structure in the energy spectrum of TeV electrons and show anisotropies toward the sources, depending on when the electrons were liberated from the remnant.*

The origin of cosmic positrons

AMS report



At **low energies** positrons come from cosmic ray collisions (secondary positrons).
At **high energies** the positron flux is consistent with the existence of an astrophysical source of positrons (primary positrons) or with a dark matter origin of positrons.

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)]$$

$$1/E_s = 1.23 \pm 0.34\,\mathrm{TeV}^{-1},$$
$$C_s = (6.80 \pm 0.15) \times 10^{-5}\,\mathrm{m}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{GeV}^{-1},$$
$$\gamma_s = -2.58 \pm 0.05,$$
$$C_d = (6.51 \pm 0.14) \times 10^{-2}\,\mathrm{m}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{GeV}^{-1},$$
$$\gamma_d = -4.07 \pm 0.06,$$
$$\varphi_{e^+} = 1.10 \pm 0.03\,\mathrm{GeV},$$
with $\chi^2/\mathrm{d.o.f.} = 50/68$.

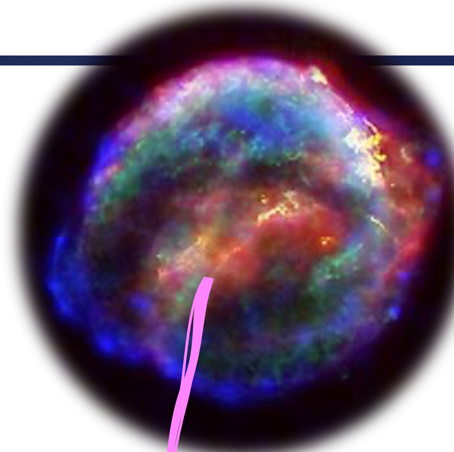
Source term exhibits an exponential cut-off at E_s = 813 GeV with 4$\boldsymbol{\sigma}$ significance.

$$\hat{E} = E + \varphi_{e^+}$$

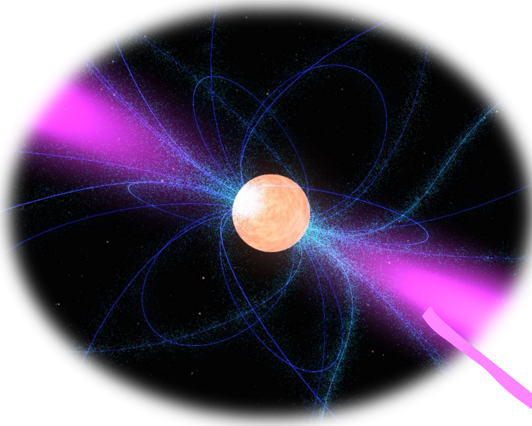
$$E_{1(2)} = 7\ (60)\ \mathrm{GeV}$$
to minimize the correlation between $C_{\mathrm{d(s)}}$ and $\gamma_{\mathrm{d(s)}}$

The origin of cosmic positrons

Supernovae



Astrophysical Sources: Pulsars, …

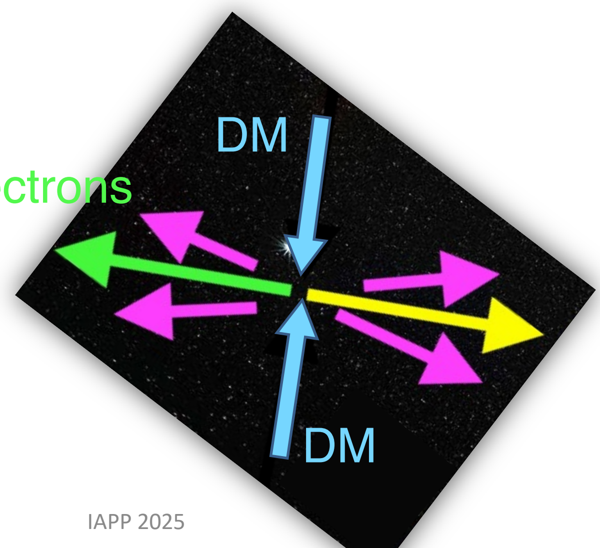


Protons,
Helium, …

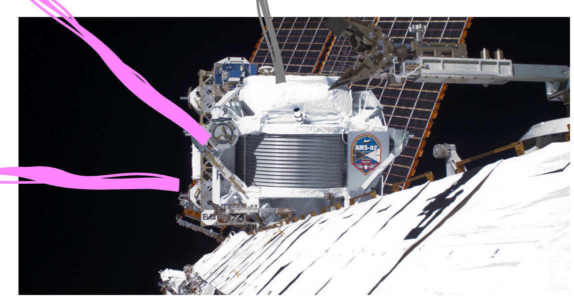
Positrons
from Pulsars

Interstellar
Medium

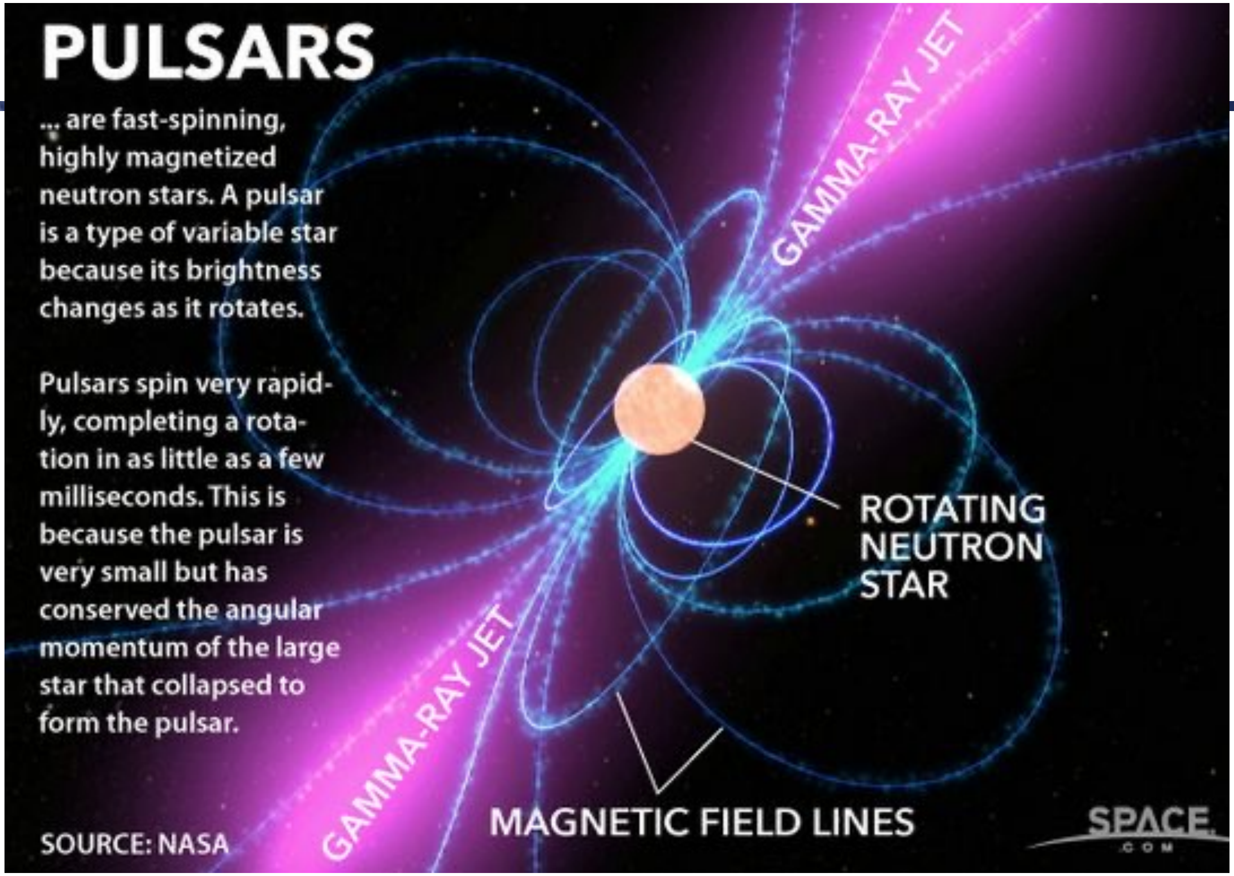
Positrons
from CR collisions



Positrons
from Dark Matter
annihilation



Positrons from



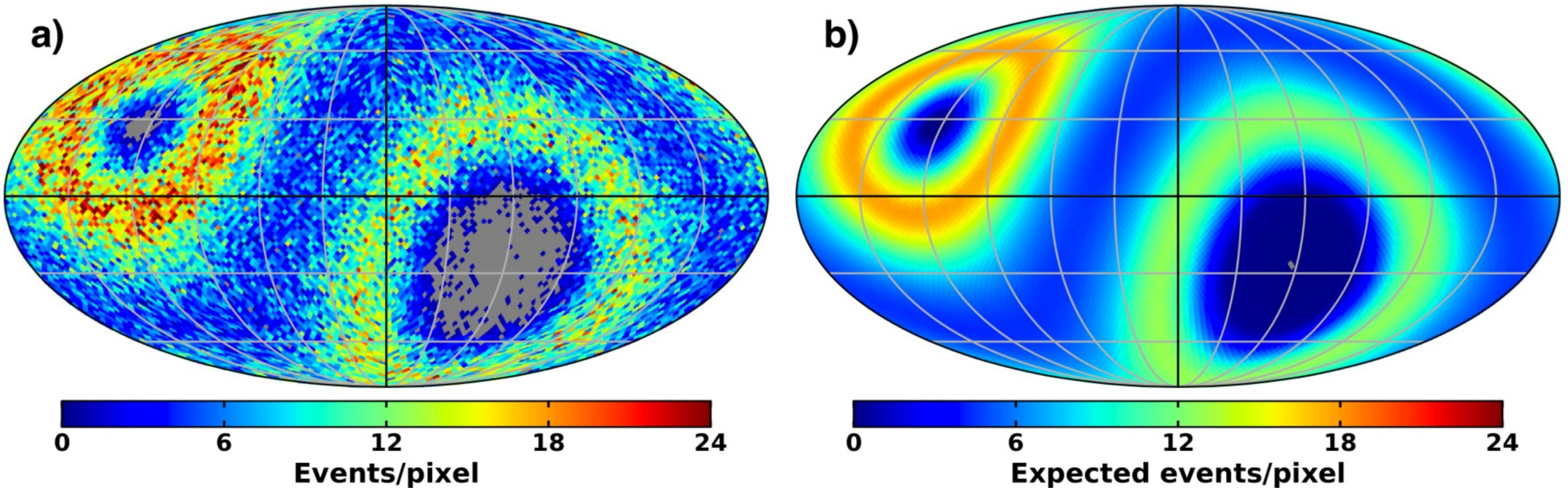
NASA | What is a pulsar video: https://www.youtube.com/watch?v=gjLk_72V9Bw

Pulsars produce and accelerate positrons to high energies.

With respect to Dark Matter:
1. Arrival direction of **positrons** from pulsars should exhibit higher **anisotropy**;
2. Pulsars do **not** produce **antiprotons**.

Positron anisotropy

AMS report



Map in galactic coordinates of the **observed** incoming positron directions

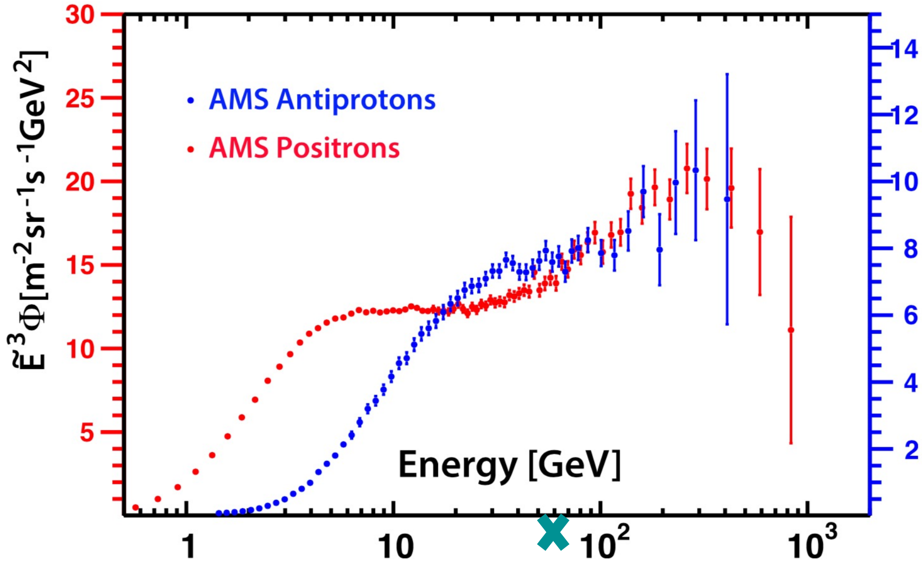
Map in galactic coordinates of the **expected** directions for an isotropic distribution of positrons

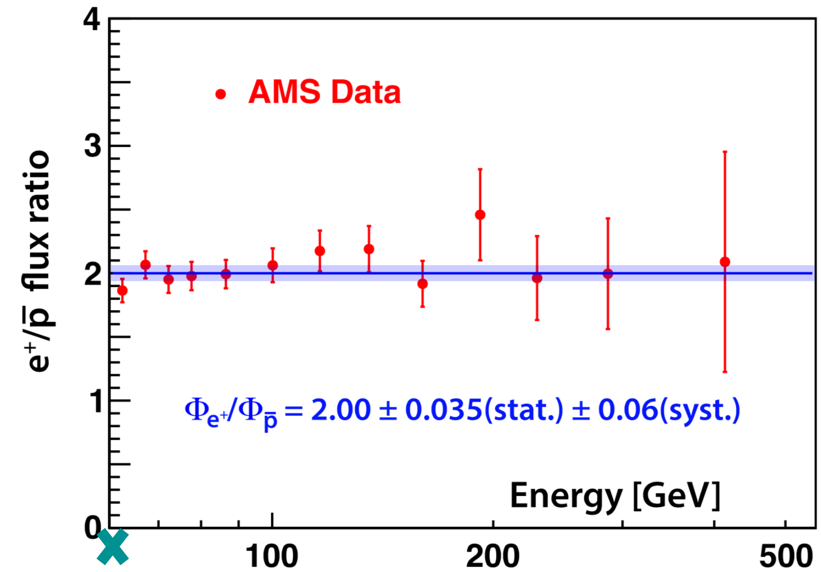
The observed **positron flux is consistent with isotropy**.
The upper limit on the amplitude of the positron dipole anisotropy for any axis in galactic coordinates is $\delta < 0.019$ at the 95% C.L.

No anisotropy → Positrons do not come from pulsars

Antiproton – positron flux comparison

AMS report





Above 60 GeV antiprotons exhibit a **spectral shape similar** to that of positrons

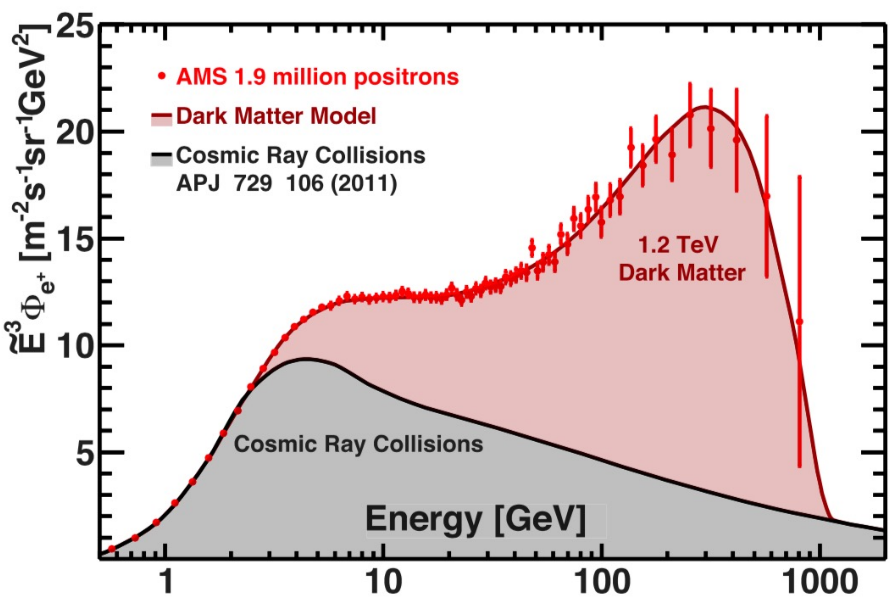
The positron-to-antiproton **flux ratio is constant** (does not depend on energy).

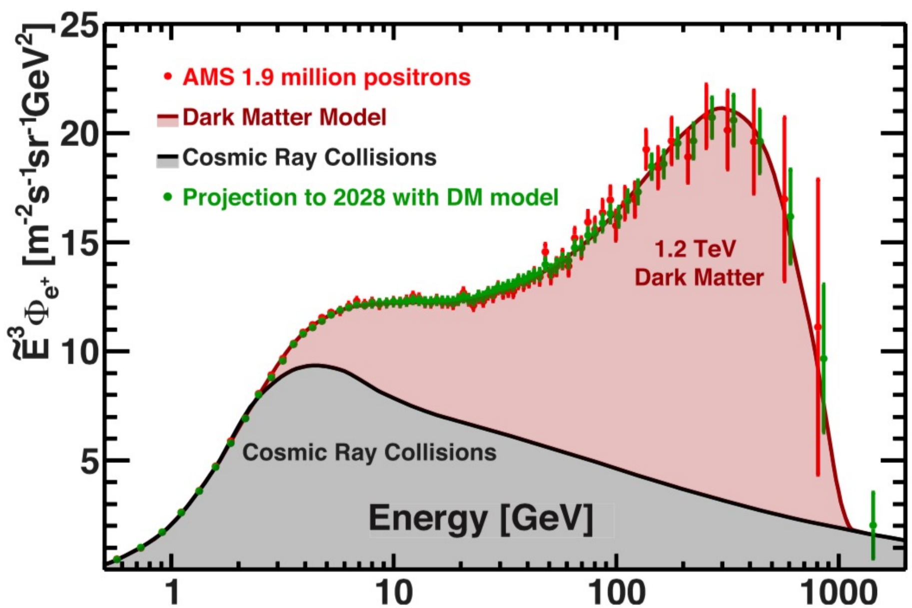
This suggests a possible **common source** of high energy positrons and antiprotons.
Antiprotons cannot come from pulsars.

Common source of positrons and antiprotons → Positrons do not come from pulsars

Positrons and a Dark Matter model

AMS report

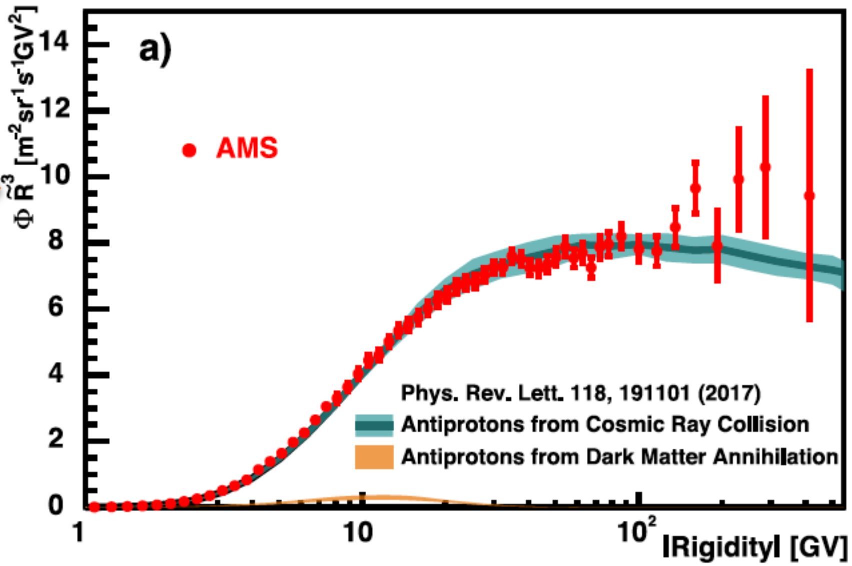




With the increase in statistics, AMS will extend the measurement up to 2 TeV, which will enable to determine the origin of the positron excess, i.e. to distinguish the dark matter origin of the excess from other astrophysical explanations.

Antiproton flux

AMS report

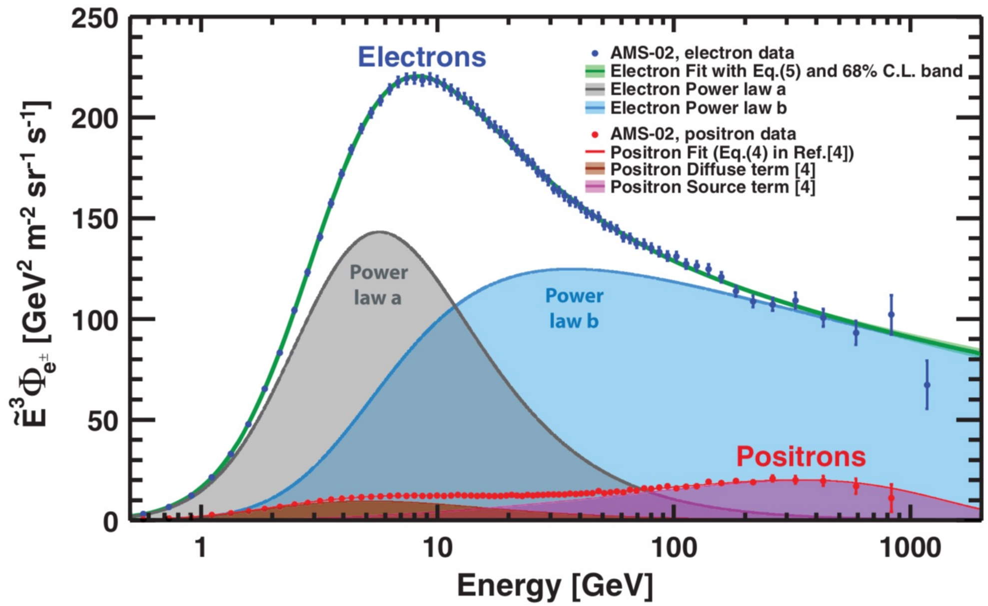


The continuation of data taking through the lifetime of the ISS will provide an important understanding of the origin of high energy positrons and antiprotons.

What's on the x-axis?

Cosmic electrons, positrons, antiprotons

AMS electrons



1. Electrons originate from different sources than positrons.

2. The electron spectrum comes from two power laws.

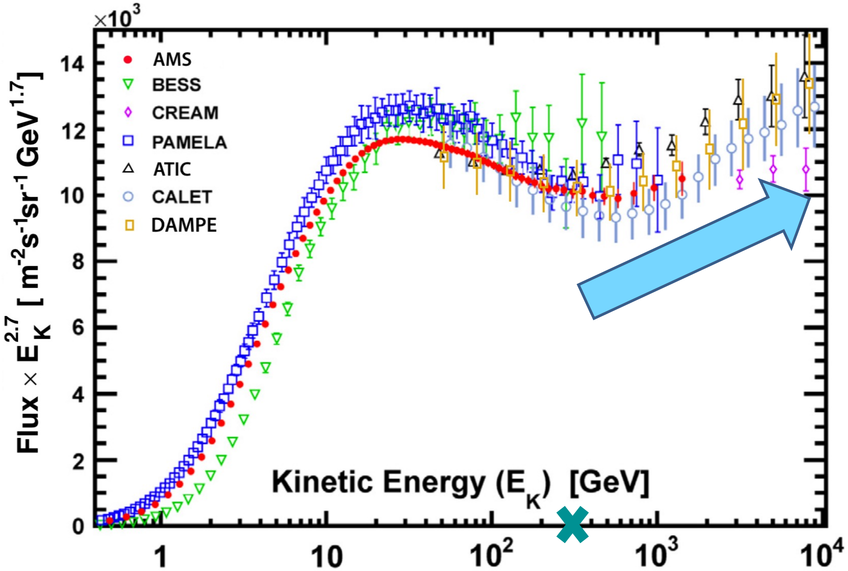
3. The positron flux is the sum of a low-energy part from cosmic ray collisions plus a high energy part with a cut-off energy E_S from an astrophysical source or dark matter.

4. The antiproton spectrum rules out the pulsar origin of positrons.

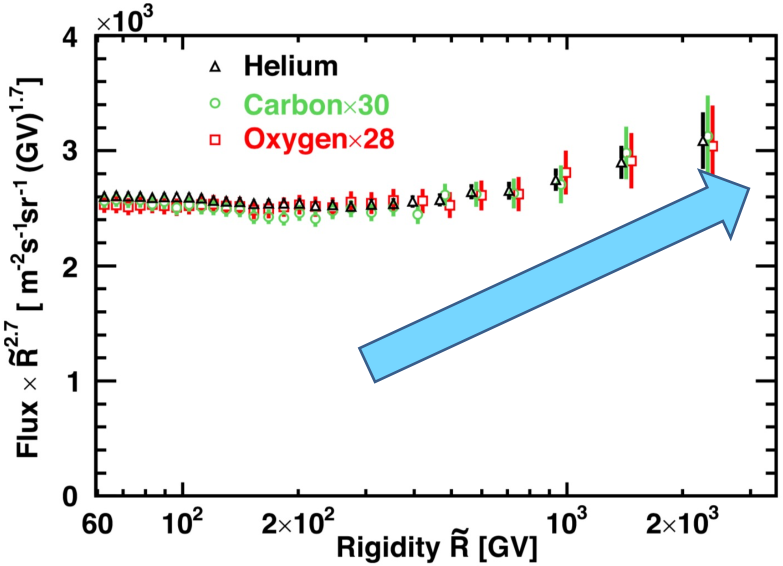
Light Primaries: p, He, C, O

AMS Report

Protons, one billion proton events collected by AMS



The proton flux does not follow a single power law: above 200 GV **the flux hardens**.



Above 60 GV, the primary cosmic rays have identical rigidity dependence.
Also the spectra of He, C, and O harden above 200 GV.

Which is the origin of the spectral hardening?

Lesson 2 -- Bibliography

- **Elements of Nonequilibrium Statistical Mechanics**

  V. Balakrishnan

  Springer Cham

  Chapter 7: The Diffusion Equation

  https://link.springer.com/book/10.1007/978-3-030-62233-6

- **High Energy Cosmic Rays**

  Todor Stanev

  Springer Cham

  4.2.1 Particle Diffusion

  https://link.springer.com/book/10.1007/978-3-030-71567-0

- **The Review of Particle Physics**

  S. Navas et al. (Particle Data Group) Phys. Rev. D **110**, 030001 (2024)

  https://pdg.lbl.gov

- **AMS Publications**

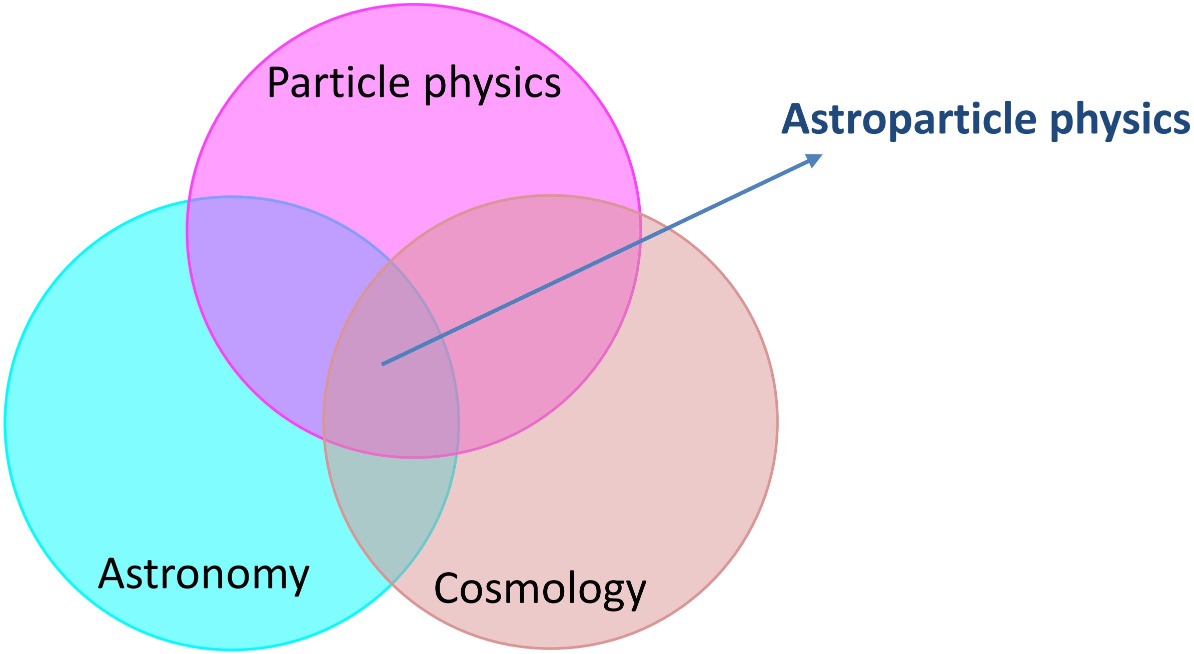
  https://ams02.space/publications

Exercises

What is Astroparticle Physics?

Astroparticle physics is the fascinating field of research at the intersection **of** astronomy, particle physics **and** cosmology.

It simultaneously **addresses** challenging **questions relating to the micro-cosmos** (the world of elementary particles and their fundamental interactions) **and the macro-cosmos** (the world of celestial objects and their evolution) and, as a result, is well-placed to advance our understanding of the Universe beyond the Standard Model of particle physics and the Big Bang Model of cosmology.



https://www.appec.org/

Interaction processes

Charged particles

- Ionization
- Bremsstrahlung
- Cherenkov effect
- Excitation

Photons

- < 100 keV
  Photoelectric effect
- 100 keV - 5 MeV
  Compton scattering
- > 5 MeV
  Pair production

https://pdg.lbl.gov/2023/reviews/rpp2023-rev-passage-particles-matter.pdf

Ionization energy loss: mean value

Charged particles traversing matter lose energy in the collisions with atomic electrons, leading to the ionization of the atoms. **Bethe-Bloch formula** describes the mean energy loss rate (per unit path length) due to this ionization.

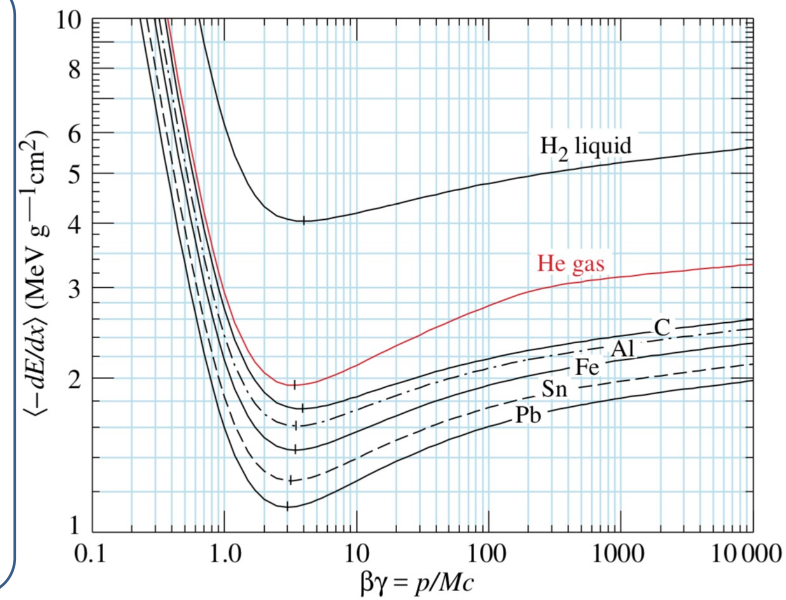
$$\left\langle -\frac{dE}{dx}\right\rangle = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

z	charge number of incident particle	
Z	atomic number of absorber	
A	atomic mass of absorber	$\mathrm{g\ mol^{-1}}$
K	$4\pi N_A r_e^2 m_e c^2$ (Coefficient for dE/dx)	$0.307\,075\ \mathrm{MeV\ mol^{-1}\ cm^2}$
I	mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	density effect correction to ionization energy loss	
M	incident particle mass	

$$W_{\max} = \frac{2m_ec^2\,\beta^2\gamma^2}{1+2\gamma m_e/M + (m_e/M)^2}$$

Maximum possible energy transferred to an electron in a single collision

For $2\gamma m_e \gg M$, $W_{\max} = Mc^2\,\beta^2\gamma$



- ✓ $Z/A \cong 0.5$ in most materials → the energy loss does not depend much on the medium.
- ✓ It decreases as $1/\beta^2$ at low speed ($\beta\gamma < 1$).
- ✓ It reaches a minimum at about βγ ~ 3.5 where the energy los is between 1 and 2 MeV/(g/cm^2).
- ✓ It increases logarithmically until it reaches the «Fermi plateau».

Ionization energy loss: stochastic process

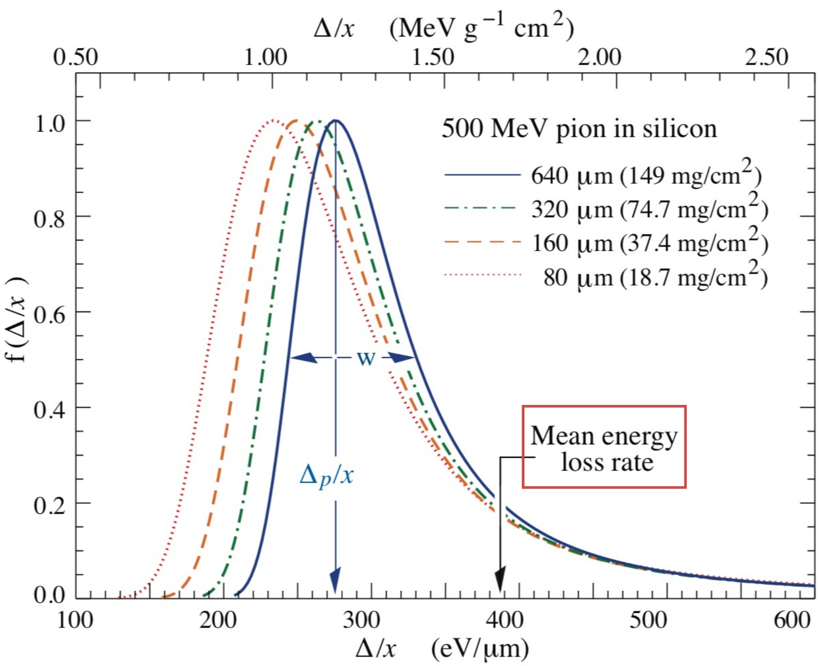
Bethe-Bloch formula

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

The Bethe-Bloch formula expresses the mean energy loss rate, which is a stochastic process involving many elementary collisions and is subject to fluctuations.

For absorber with small thickness or low density, the energy loss distribution exhibits a long tail toward high energy losses, described by the Landau distribution.

For absorber with large thickness, the energy loss distribution approaches a Gaussian.



Range

The “range” is defined as the distance a particle travels before it loses all its kinetic energy.

Energy deposited in *dx:* $$dE = \left(-\frac{dE}{dx}\right)_{\text{ion}} dx$$

$$dx = \frac{dE}{-\left(\frac{dE}{dx}\right)_{\text{ion}}}$$

The range can be obtained by integrating *dx* over all the energy deposited, that is, from 0 to the total initial kinetic energy *E.*

$$R(E) = \int dx = \int_0^E \frac{dE}{-\left(\frac{dE}{dx}\right)_{\text{ion}}}$$

Stopping Powers and Ranges for Protons and Alpha Particles:
http://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html and
http://physics.nist.gov/PhysRefData/Star/Text/ASTAR.html.

Multiple Coulomb scattering

As a charged particle crosses a finite thickness x of material, it loses energy primarily through ionization—transferring energy to the electrons of the medium—and undergoes numerous small-angle deflections due to elastic scattering with nuclei, a process known as multiple Coulomb scattering. The distribution of the resulting deflection angle is approximately Gaussian, with a root mean square (RMS) angle given by:

$$\theta_{\text{plane}}^{\text{rms}} = \theta_0 = \frac{13.6\ \text{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x z^2}{X_0 \beta}\right)\right]$$

Where X_0 is the radiation length:

$$\frac{1}{X_0} = 4 r_e^2 \alpha \frac{N_{\text{A}} Z^2 \rho}{A} \ln(183\, Z^{-1/3})$$

Bremsstrahlung or radiation energy loss

For electrons, the Bethe-Bloch formula must be modified to account for the fact that the projectile and the target are identical particles. At high energies, a more significant energy loss mechanism is Bremsstrahlung ("braking radiation"): when electrons are deflected in the electric field of nuclei, they undergo acceleration, resulting in the emission of electromagnetic radiation.

$$\left(-\frac{dE}{dx}\right)_{rad} \simeq \frac{E}{X_0} \simeq 4r_e^2\alpha\frac{N_A Z^2 \rho}{A}\ln\left(183Z^{-1/3}\right)E$$

$$E(x) = E_0\, e^{-x/X_0}$$

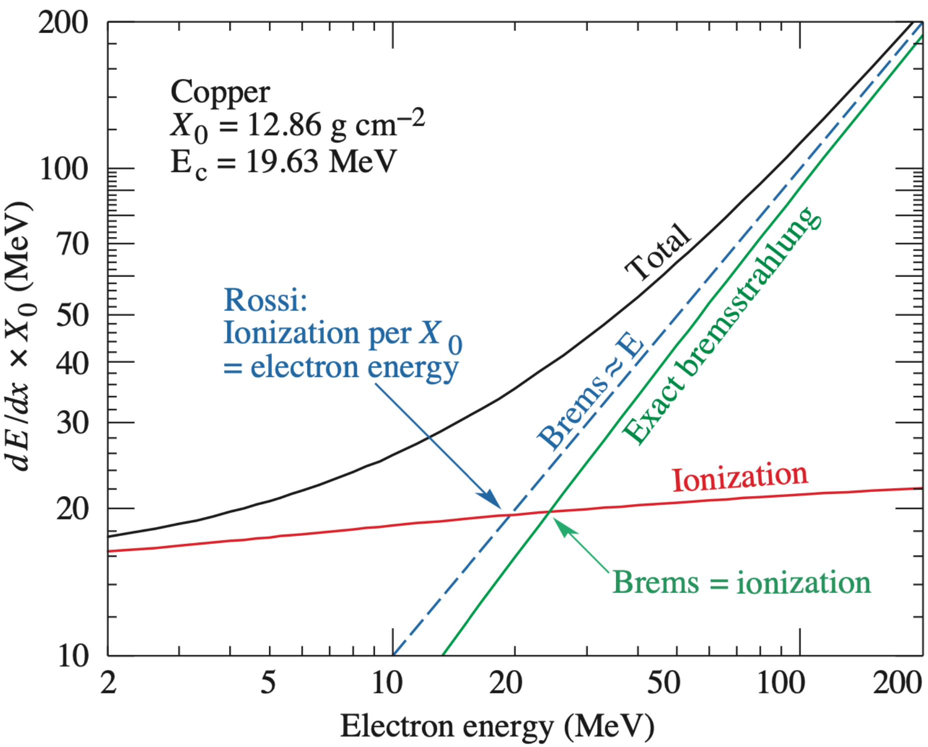
$$E(X_0) = E_0 e^{-1}$$

Radiation length (X_0) is the distance at which the energy is reduced by a factor of 1/*e* due to only the radiation energy loss.

Bremsstrahlung or radiation energy loss

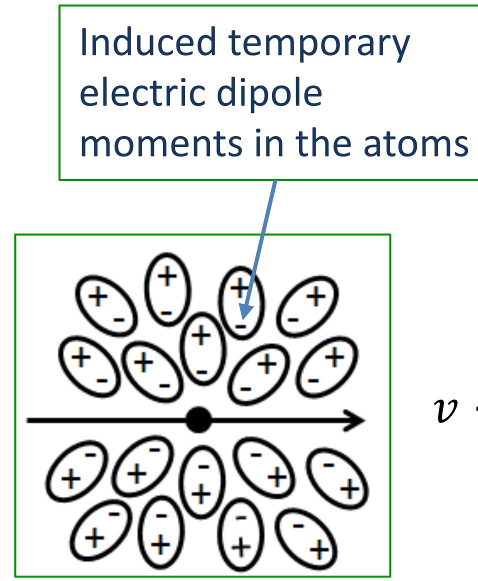
$$\left(-\frac{dE}{dx}\right)_{rad} \simeq \frac{E}{X_0} \simeq 4r_e^2\alpha\frac{N_A Z^2\rho}{A}\ln\left(183Z^{-1/3}\right)E$$

This energy loss is added to the ionization energy loss.
The radiative contribution to the energy losses is **linear in *E***, and therefore for a certain value of *E* these losses will exceed those due to ionization, which instead tend to become constant. The value of *E* for which the losses due to ionization equal those due to radiation is called critical energy, E_c.



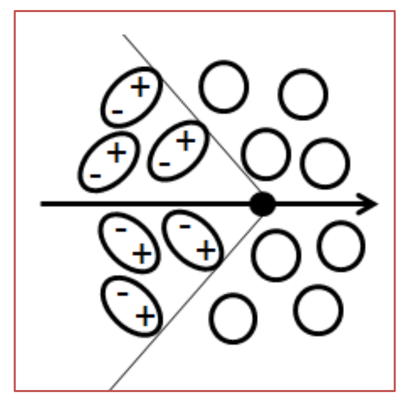
Cherenkov effect

When a charged particle crosses a dielectric medium (with refractive index n), it polarizes the atoms of the medium close to its trajectory. After the particle passes, the atoms return to their initial position through the emission of an electromagnetic radiation.



If the speed (v) of the particle is smaller than the speed of light in the medium (c/n), the radiation emitted by the atoms of the medium interfere destructively with each other, producing a damped radiation with an intensity that decreases exponentially with the distance.

$$v < \frac{c}{n}$$

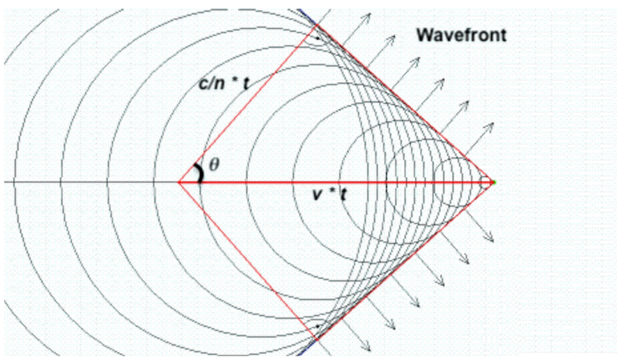


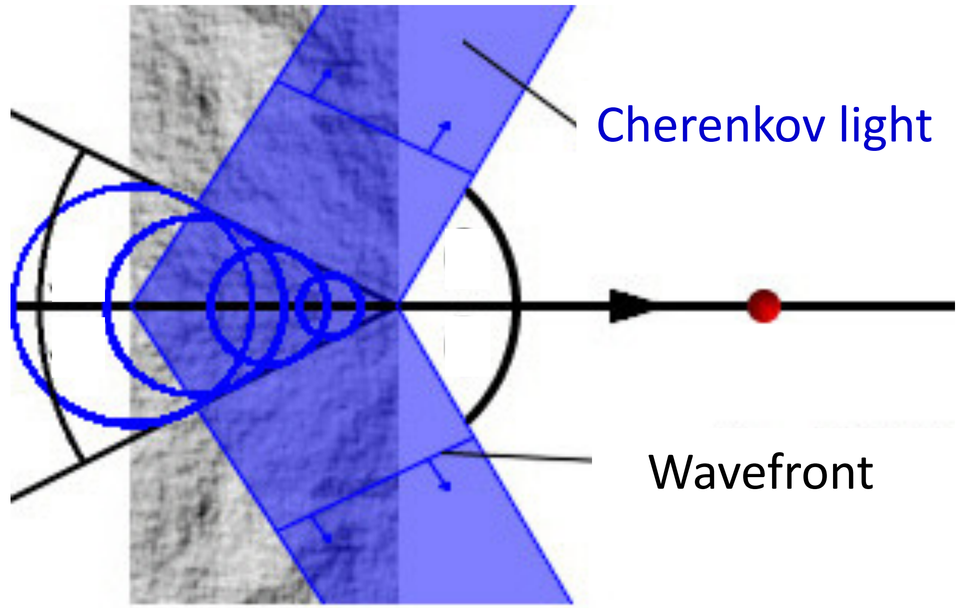
If the speed (v) of the particle is larger than the speed of light in the medium (c/n), there is the production of spherical waves that interfere constructively with each other to form a wave front detectable even at a large distance. The radiation emitted is called **Cherenkov radiation**.

$$v \geq \frac{c}{n}$$

Cherenkov effect: a threshold effect

From the geometric construction of Huygens it is possible to determine the angle that the Cherenkov photons form with the direction of propagation of the particle:





$$\frac{c}{n}t = vt\cos\theta$$

$$\cos\theta = \frac{c}{vn}$$

$$\beta = v/c$$

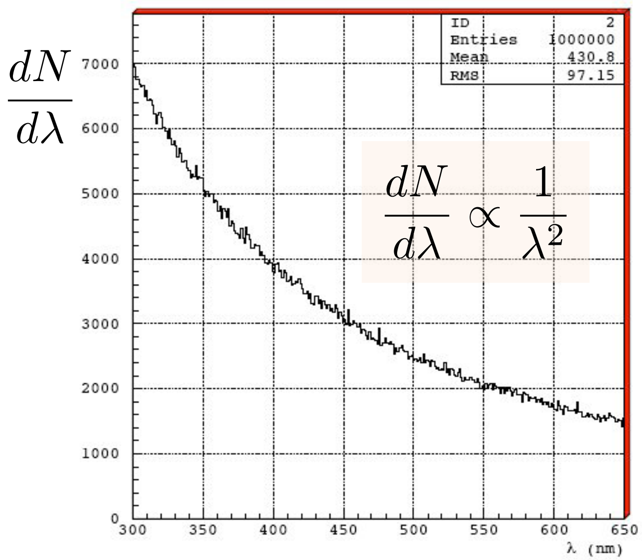
$$\cos\theta = \frac{1}{\beta n} \leq 1$$

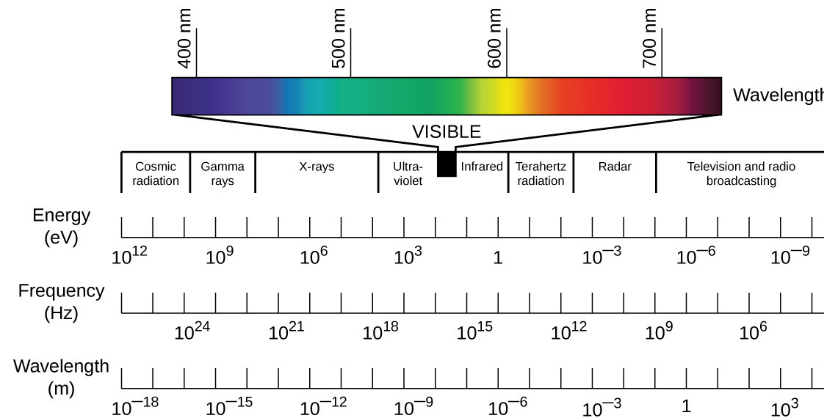
$$\beta \geq \frac{1}{n}$$

$$\beta_{\text{thrs}} = \frac{1}{n}$$

The wavelength of the Cherenkov photons

The Cherenkov spectrum is continuous extending from the ultraviolet region into the visible part of the spectrum. Only a negligible amount of photon emissions is found in the infrared or microwave regions.





To detect the Cherenkov light,
the dielectric medium must be transparent.

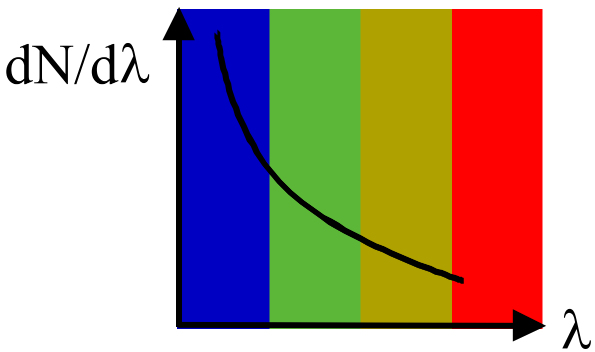
The Frank-Tamm formula: Cherenkov photon yield (it depends on charge and speed of particle) :

$$\frac{d^2N}{dx d\lambda} = z^2 \frac{2\pi\alpha}{\lambda^2} \sin^2\theta$$

$$\cos\theta = \frac{1}{\beta n}$$

fine-structure constant
$\alpha = e^2/4\pi\epsilon_0\hbar c$
$1/137.035\ 999$

The energy of the Cherenkov photons

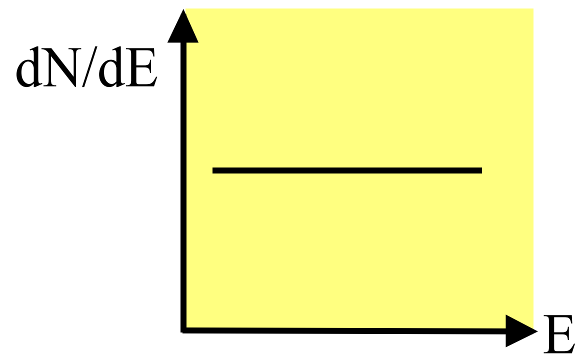


$$\frac{dN}{d\lambda} \propto \frac{1}{\lambda^2}$$

$$c = \lambda\nu$$

$$\lambda = \frac{c}{\nu} = \frac{hc}{h\nu} = \frac{hc}{E}$$

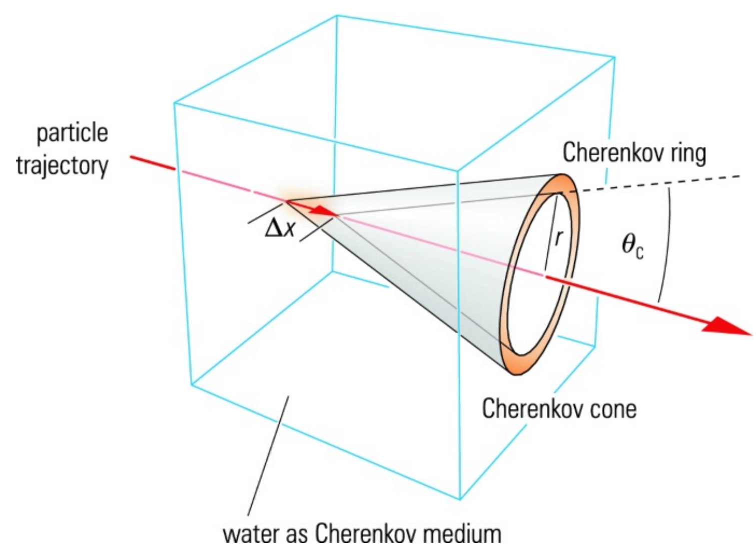
$$\frac{d\lambda}{dE} \propto \frac{1}{E^2}$$



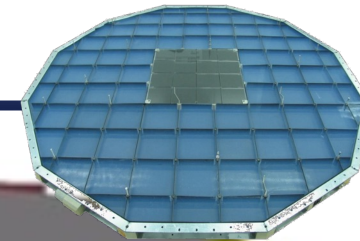
$$\frac{dN}{dE} = \text{const.}$$

The emitted energy per unit length of the particle path and per unit wavelength of the photons is:

$$\frac{d^2E}{dx\,d\lambda} = z^2\frac{4\pi^2\alpha\hbar c}{\lambda^3}\sin^2\theta$$



RICH of AMS



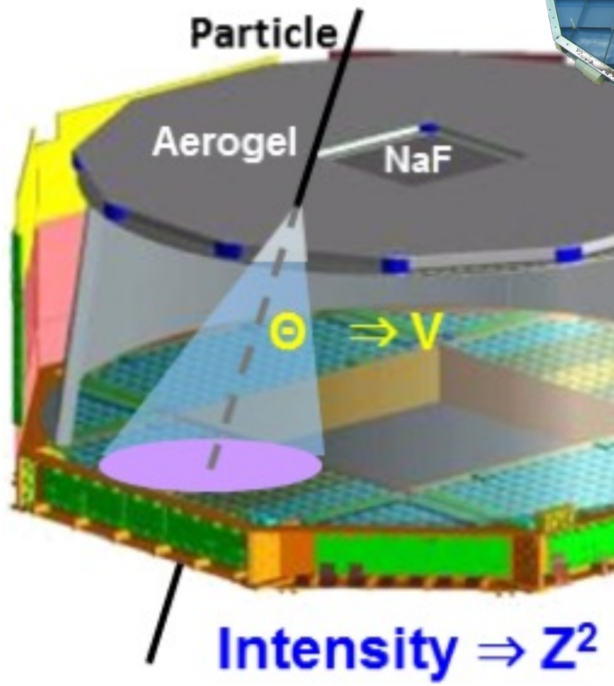
It consists of :

- 2 radiators:
  - The central one made of sodium fluoride with refractive index *n* = 1.33 (this allows the detection of particles with $\beta > 0.75$);
  - The external one made of silica aerogel with refractive index *n* = 1.05 (this allows the detection of particles with $\beta > 0.95$).

- The expansion volume extends vertically for 470 mm, surrounded by a high reflectivity mirror to increase detection efficiency.

- The photodetection plane is an array of 10’880 photosensors in multi-channel photomultiplier tubes with an effective spatial granularity of 8.5 x 8.5 mm^2.

- **The opening angle of the Cherenkov radiation cone is a measure of the speed of the incoming charged particle. The sum of the signal amplitudes is proportional to z^2 thus it is a charge measurement.**



$$\cos\theta = \frac{1}{\beta n}$$