Universidad
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DM HUNTERS

lawphysics
Latin American Webinars on Physics

Astroparticle physics

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Winter School HEP-PUC 2019 “Topics on Graviticulas”

The Plan

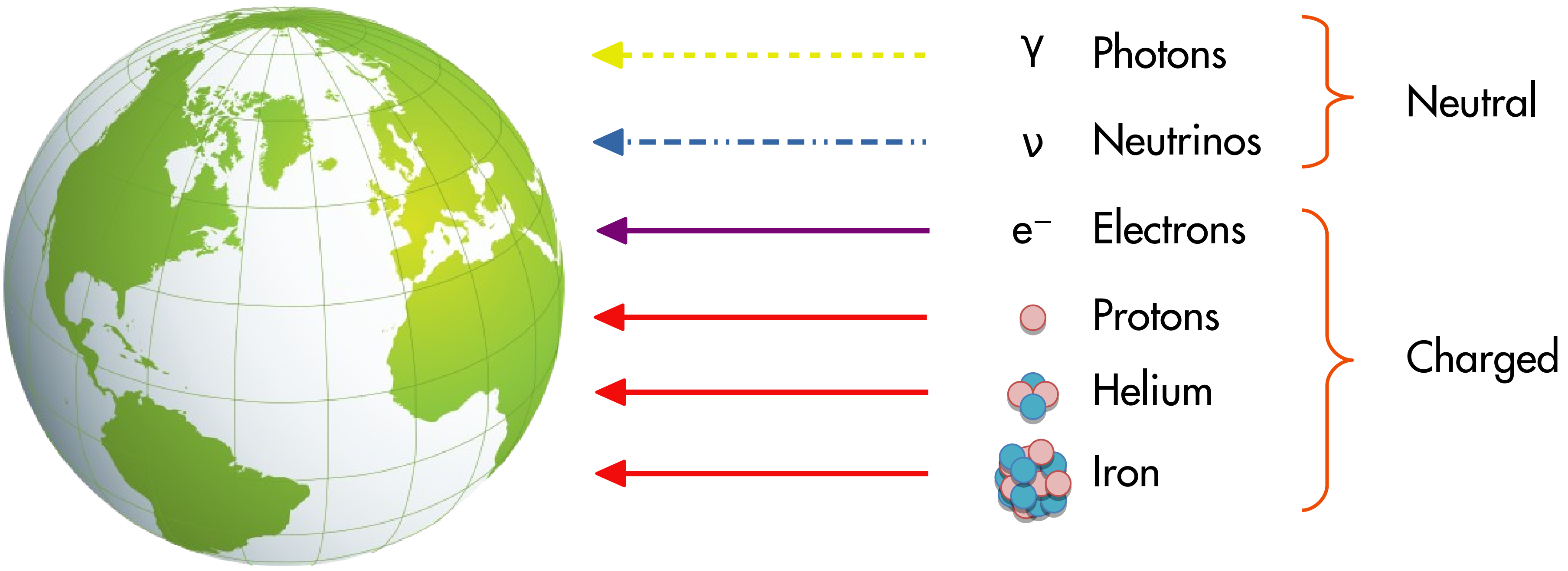
1. Astroparticles
2. Cosmic-rays
3. Neutrinos
4. Gamma-rays
5. Gravitational Waves

Dark Matter

Astrophysical Sources

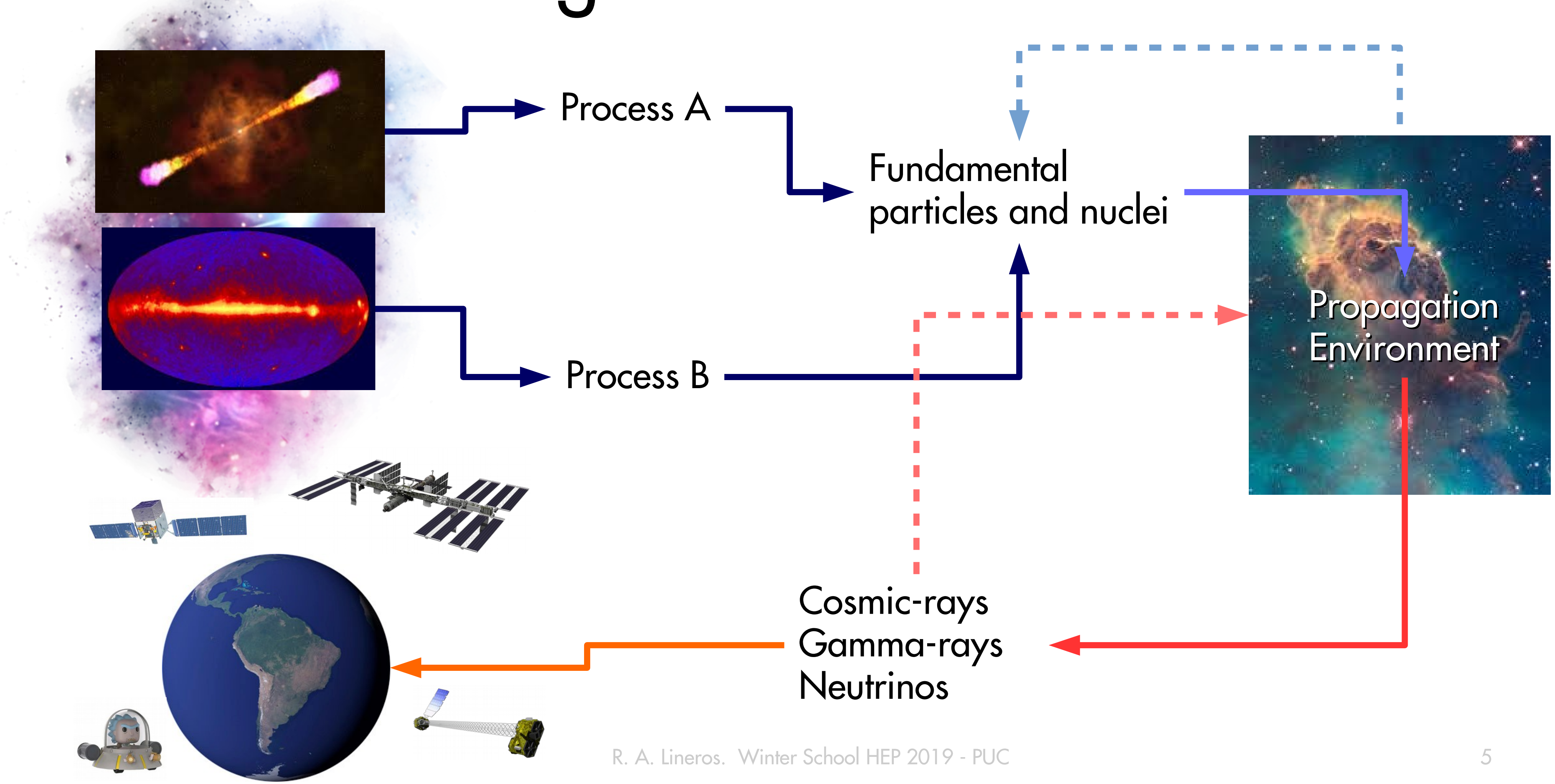
Previously

Particles from outer space

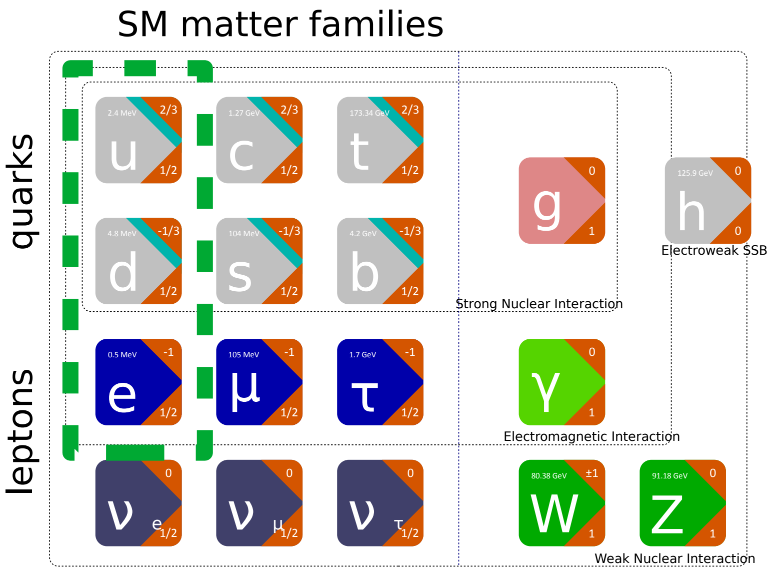


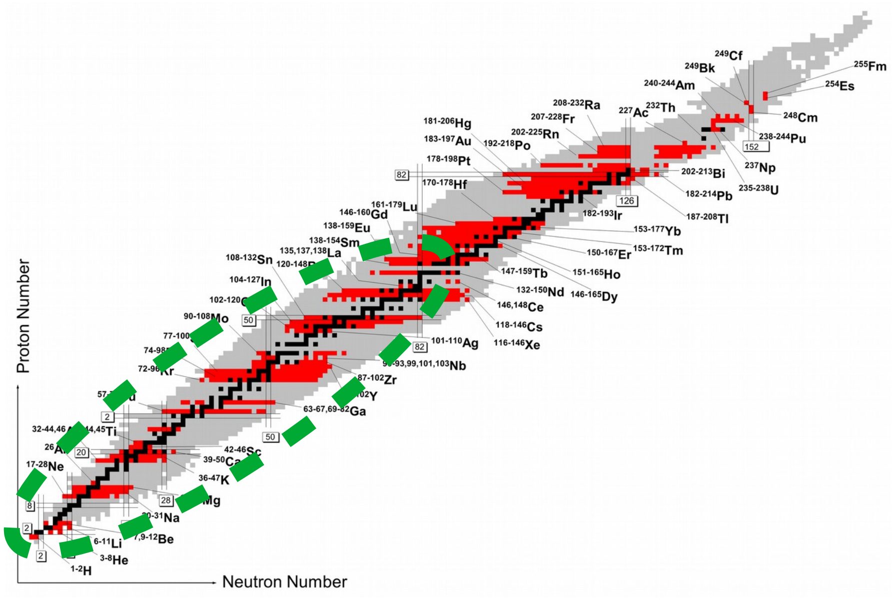
Astroparticles = Multimessenger and Multiwavelength

Multimessengers



Particle cosmic-rays

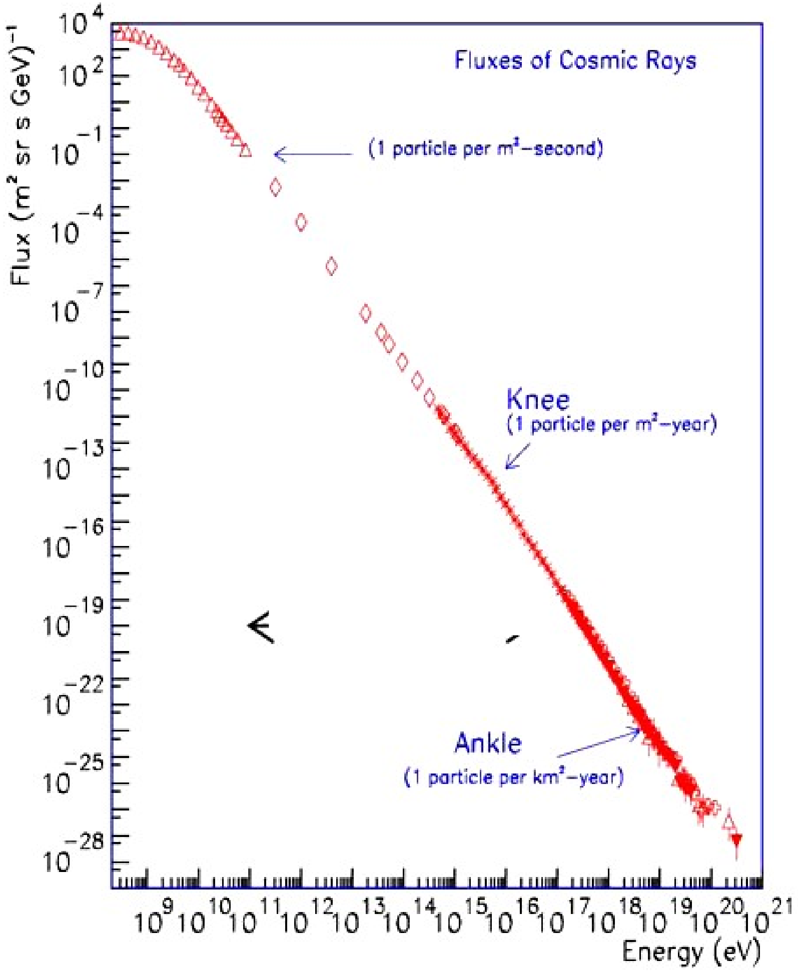




Stable and long-lived charged particles form the cosmic-ray pool.

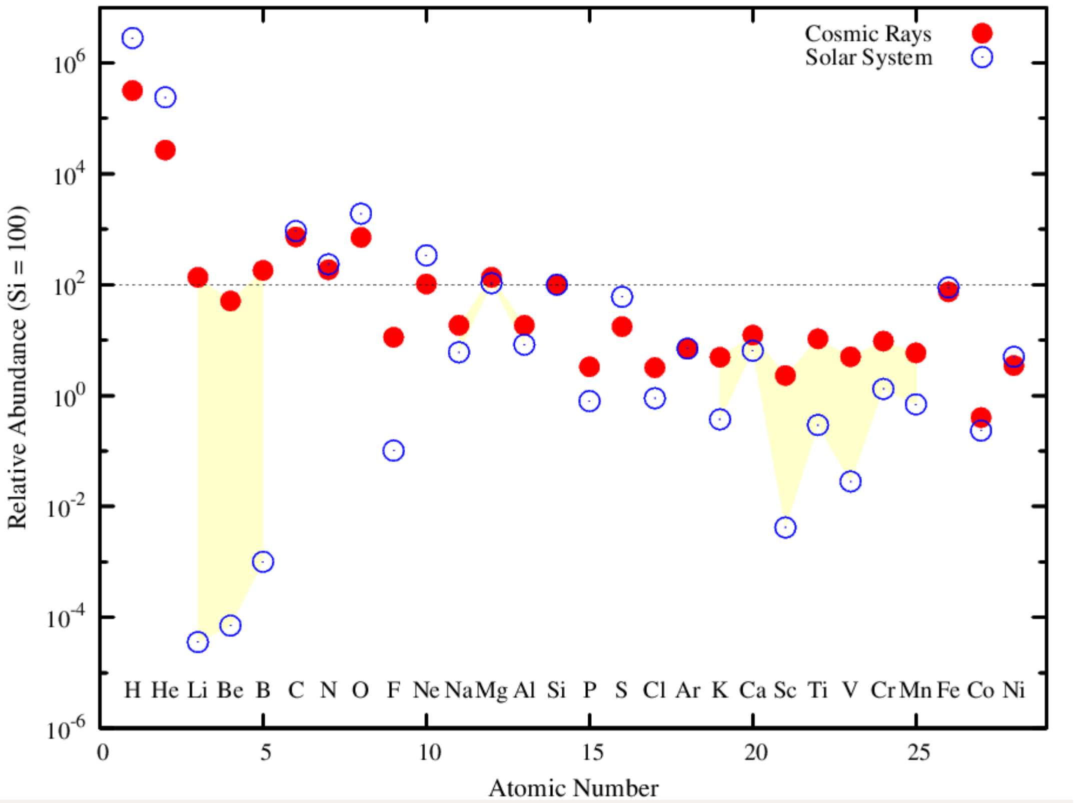
Cosmic-ray Physics

Energy spectra



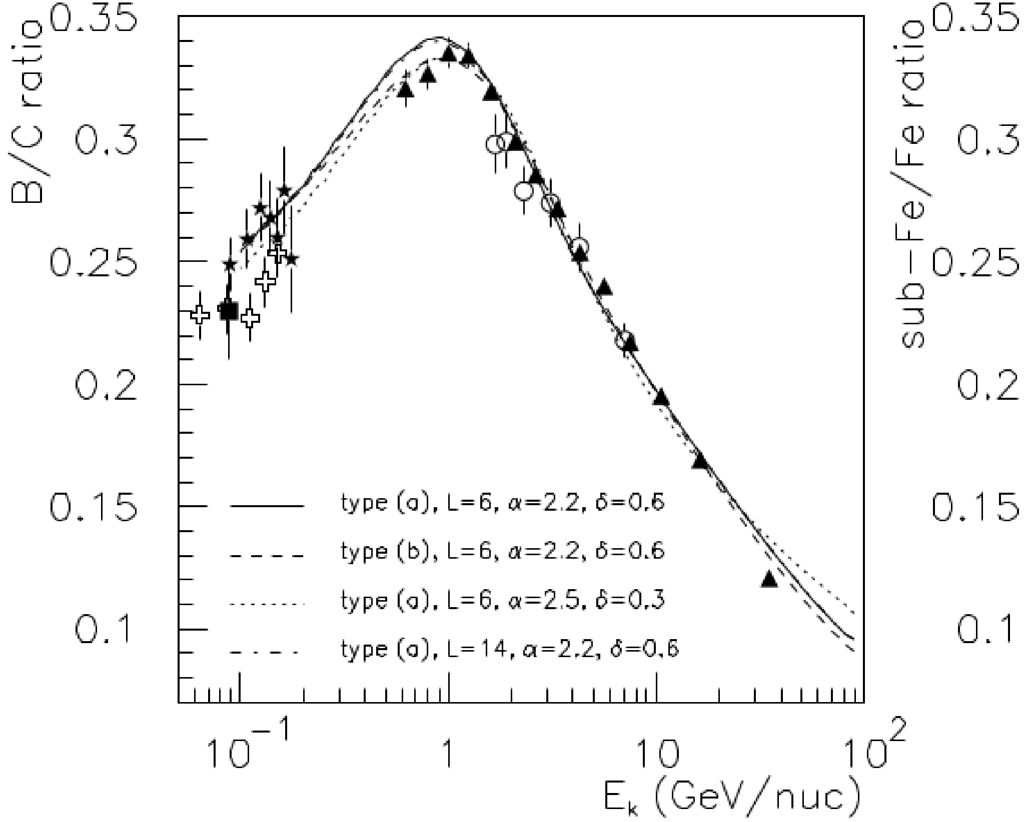
- The observed flux spans from 10^6 to 10^{21} eV
- A power law for 32 orders of magnitudes
- The energy of the CR allows to estimate its origin

Composition



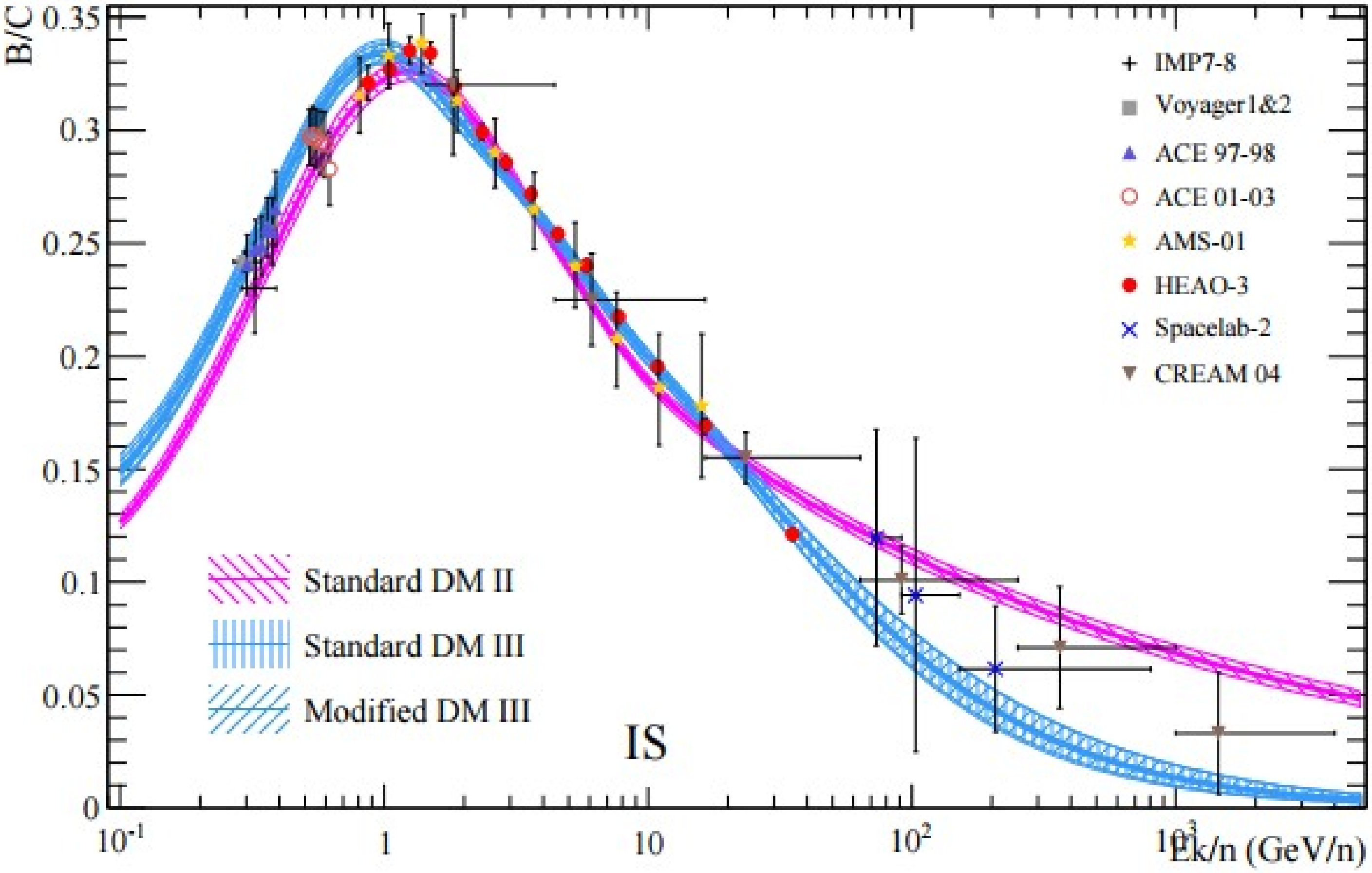
Relative abundances allows to understand the processes behind astro-ph/0212111

Composition



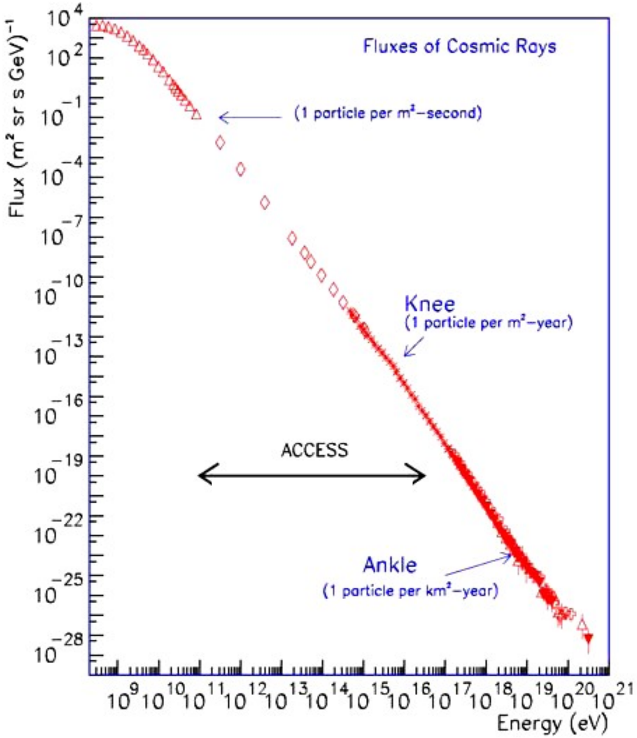
Composition

arxiv:1001.0551



Observing Cosmic-rays

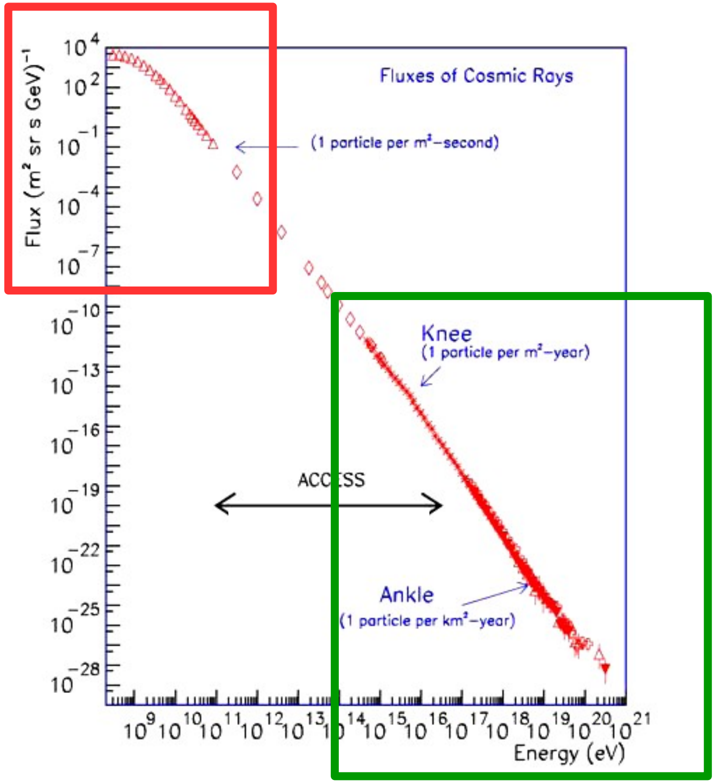
Earth's atmosphere stop most of the CR protecting life from harmful effects



Observing Cosmic-rays

This fact establishes basic rules on how to measure cosmic rays

Balloons
Space probes



Surface detectors

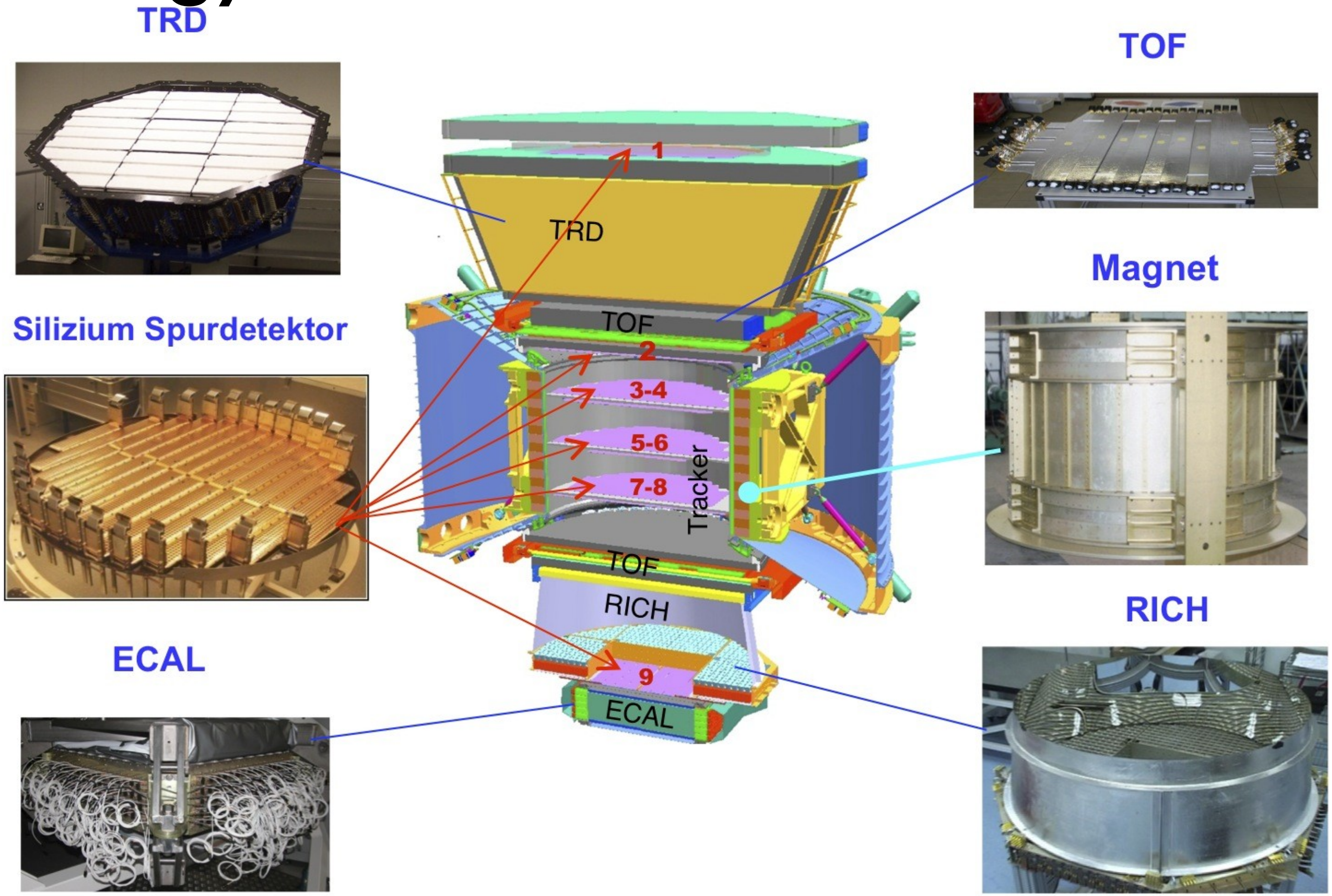
Low Energy Observatories

ATIC (antartida)

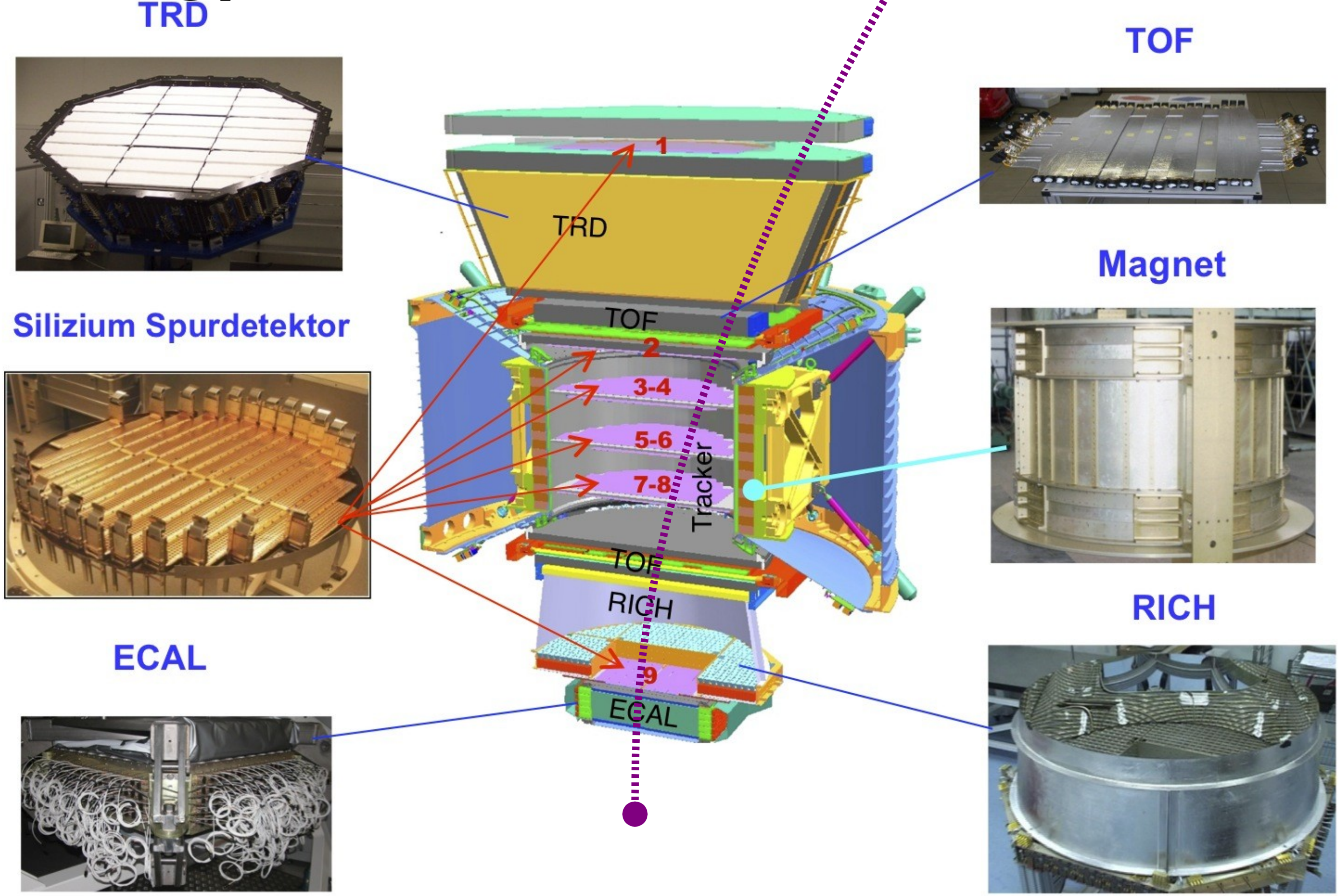
PAMELA (satélite)

AMS02 (ISS)

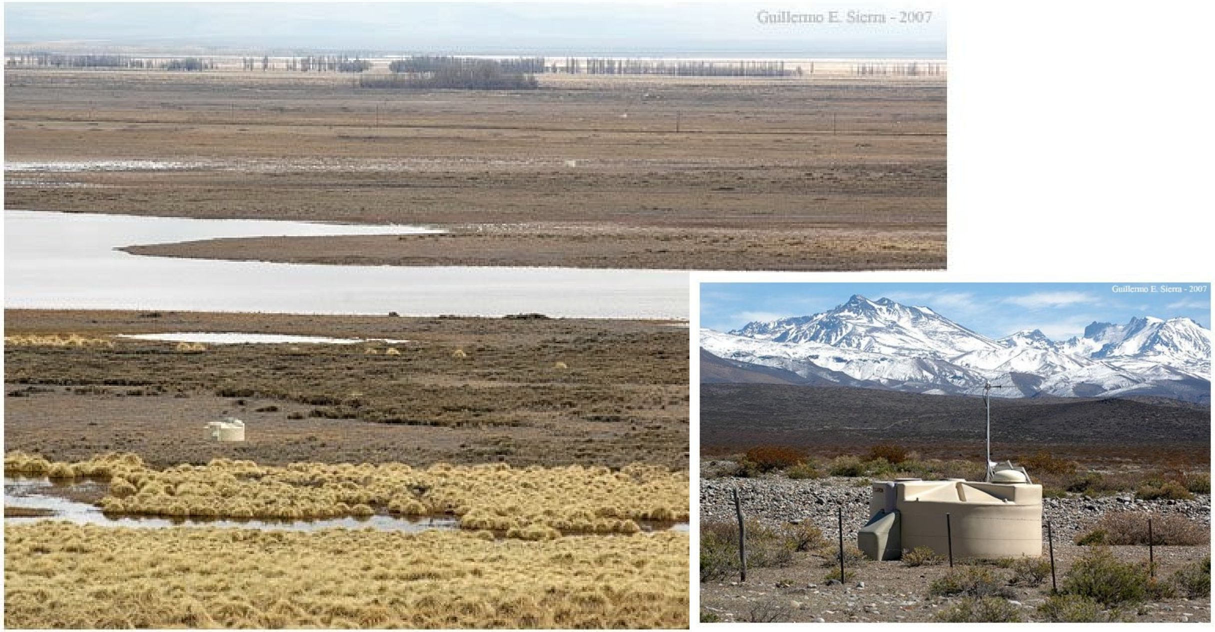
Low Energy Observatories



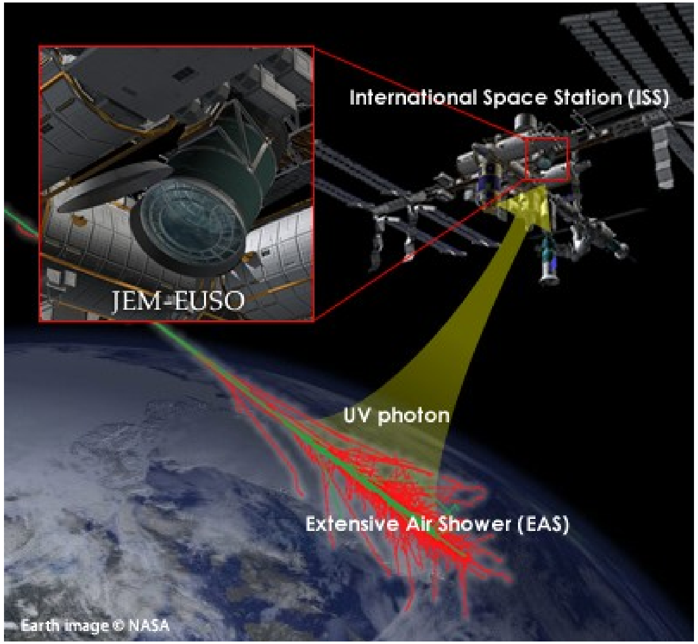
Low Energy Observatories



(Ultra) High Energy Observatories



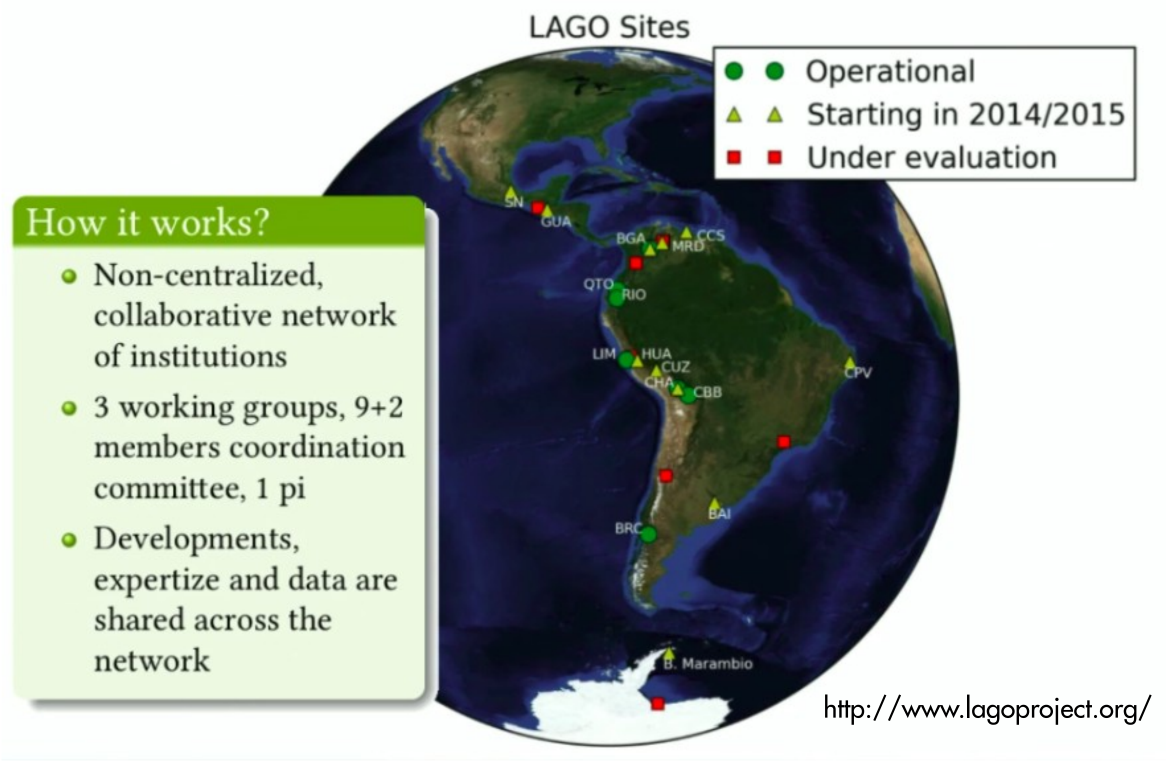
Pierre Auger (Argentina)



JEM-EUSO (ISS)

(Ultra) High Energy Observatories

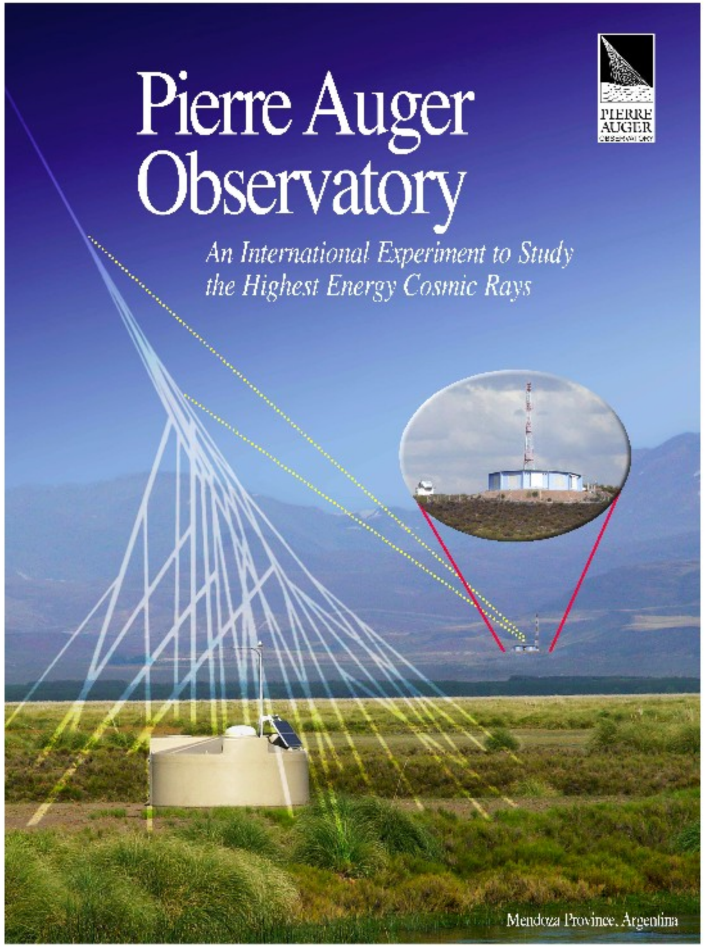
LAGO



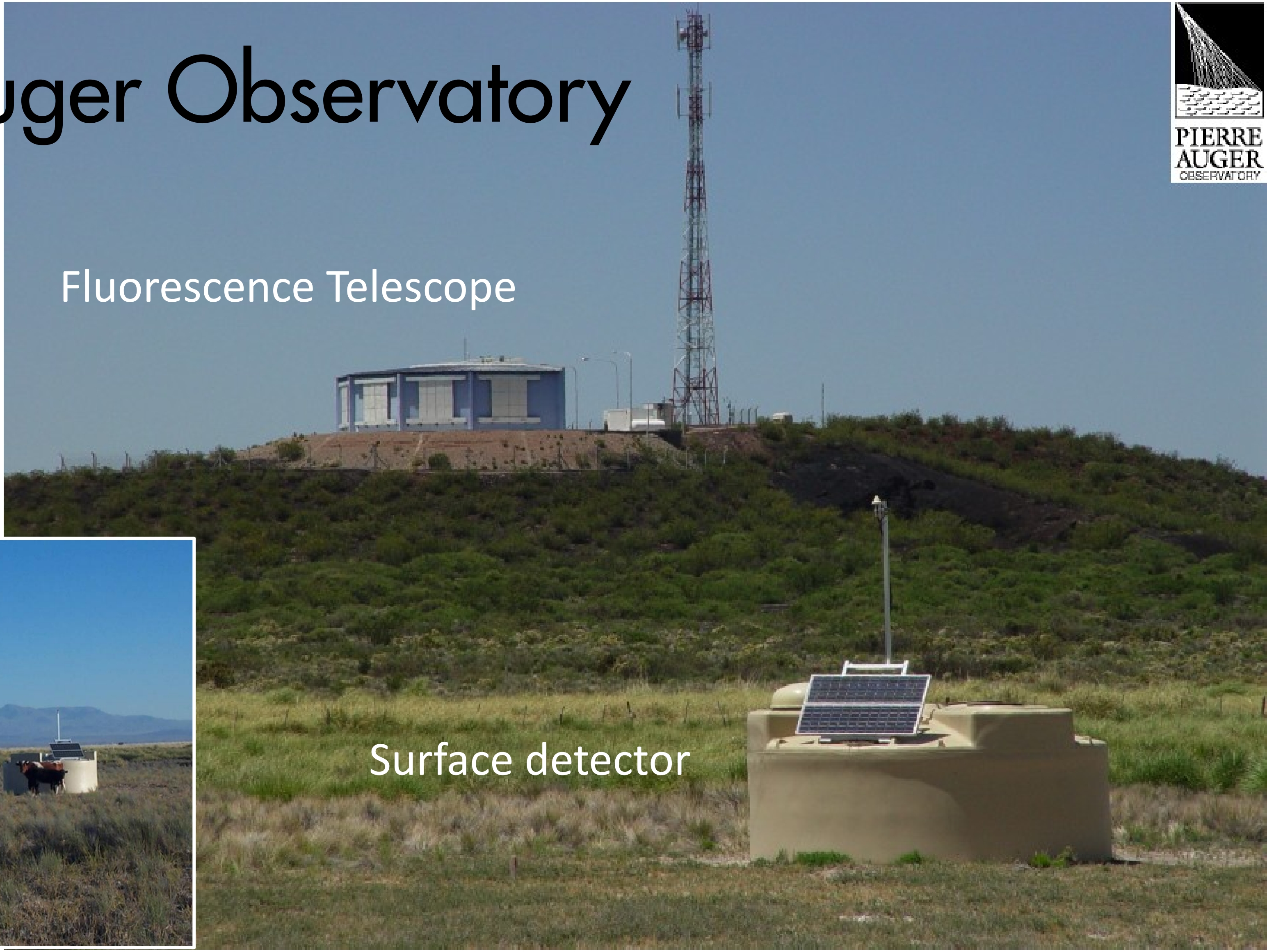
http://www.lagoproject.org/

Pierre Auger Observatory

~ 400 scientists y technician from 70 institutions over 17 countries

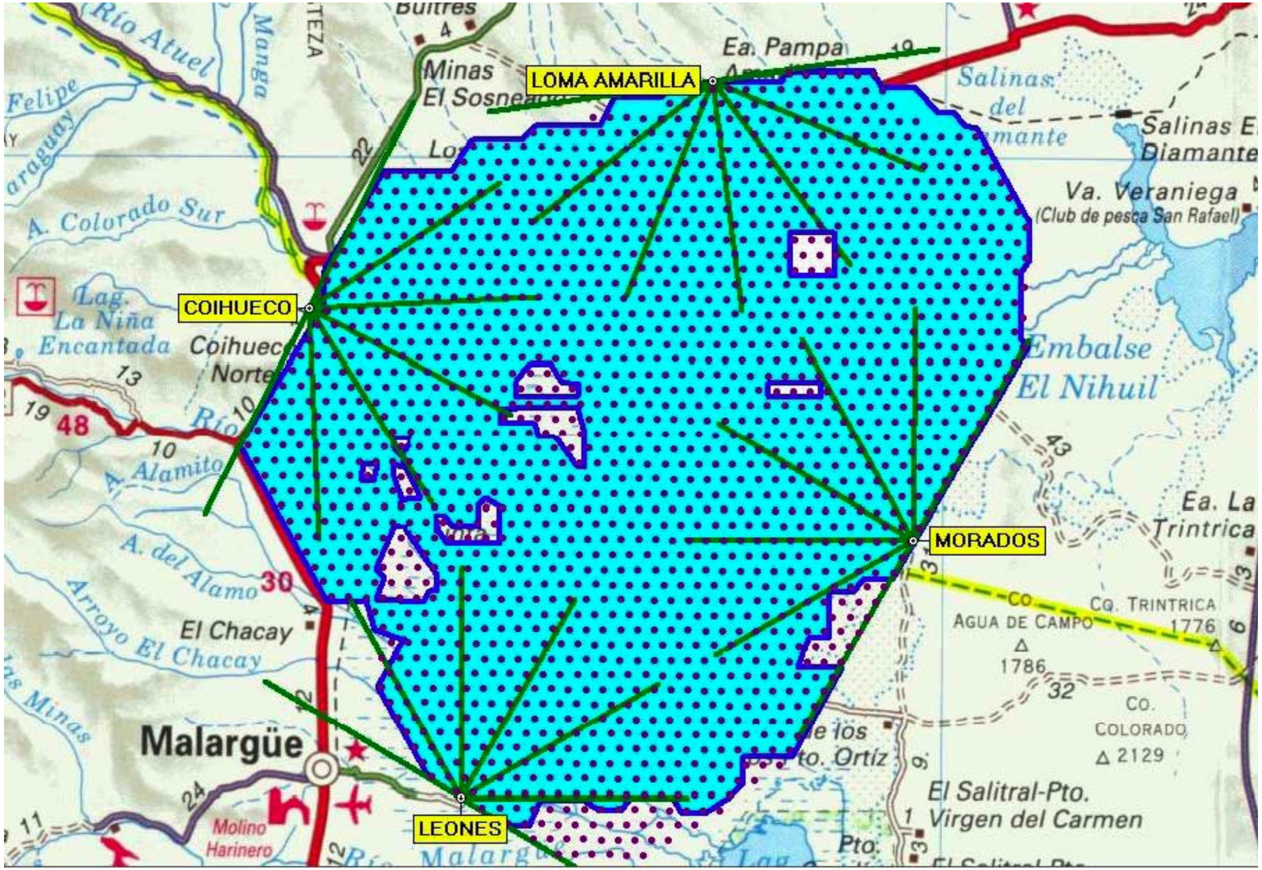


Pierre Auger Observatory



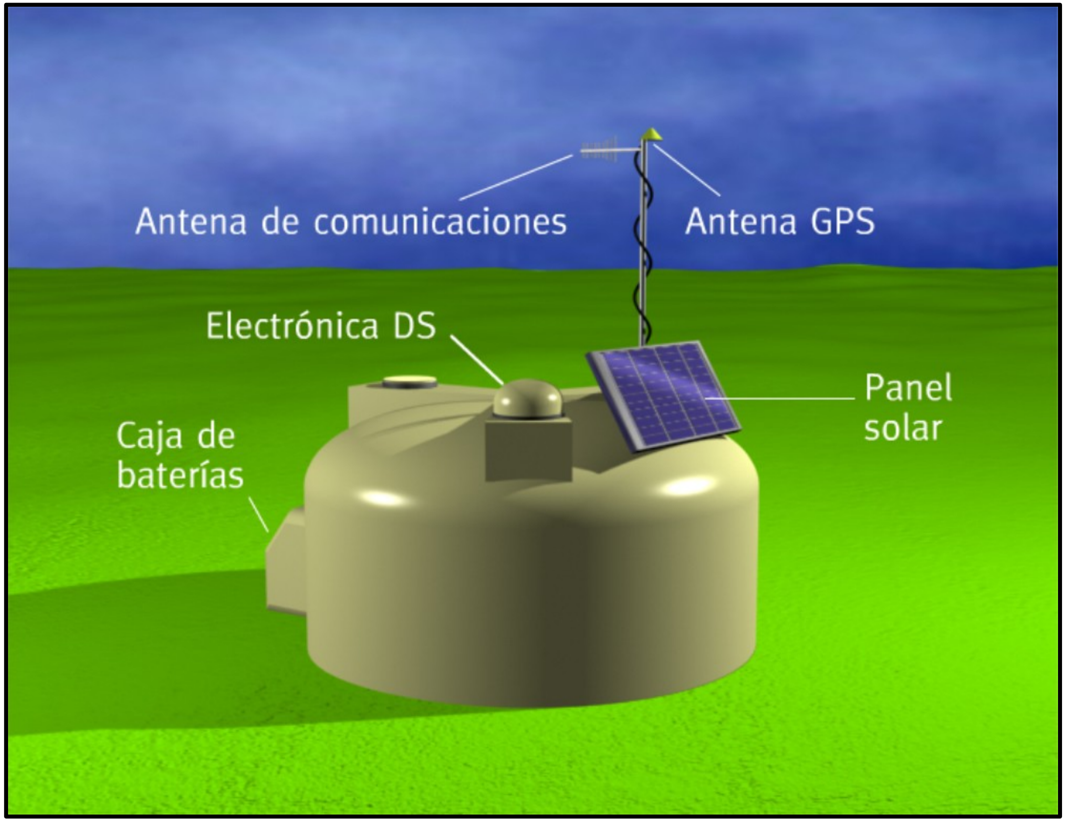
Surface detector

Surface detector

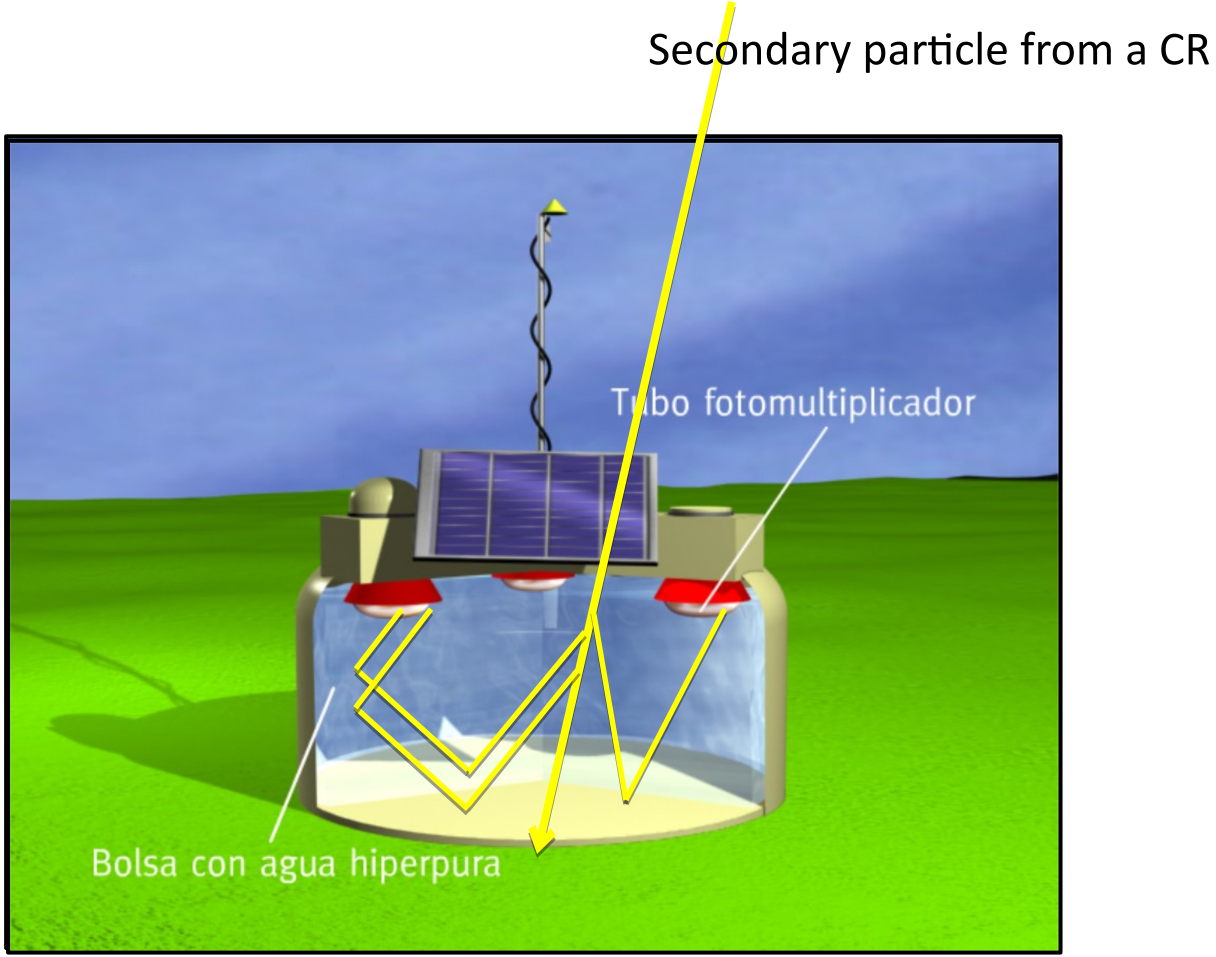


- Array of over 1660 stations
- 1.5 km of separation
- Covers 3000 km^2

Surface detector



Surface detector



Cosmic ray shower

- The atmosphere is part of the detector.
- It triggers a chain reaction starting with the arrival of a primary cosmic rays

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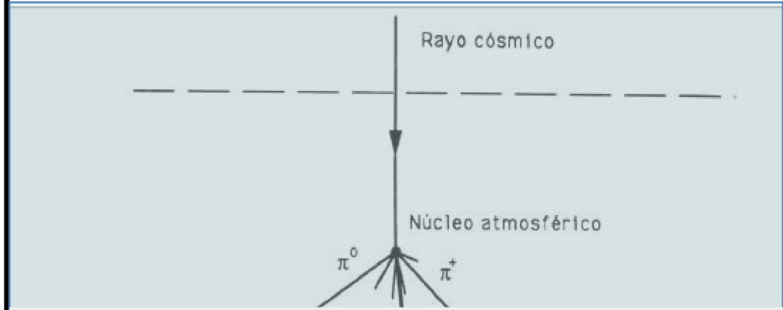

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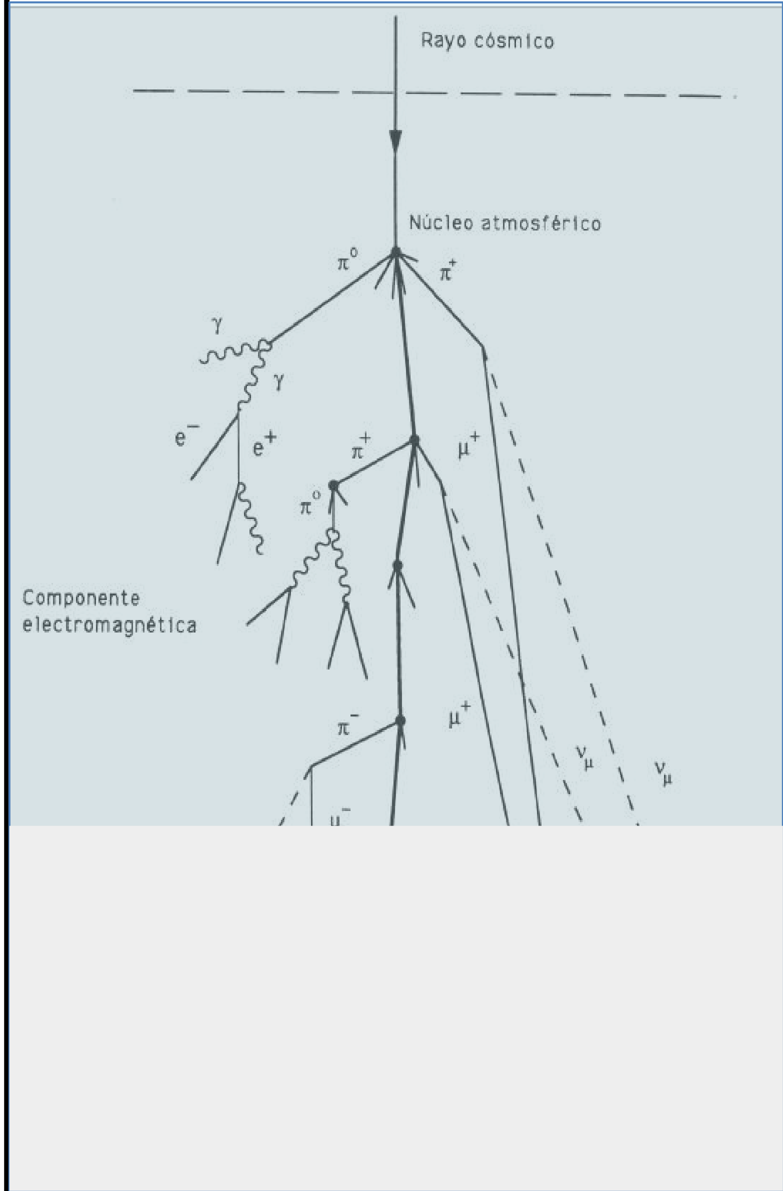

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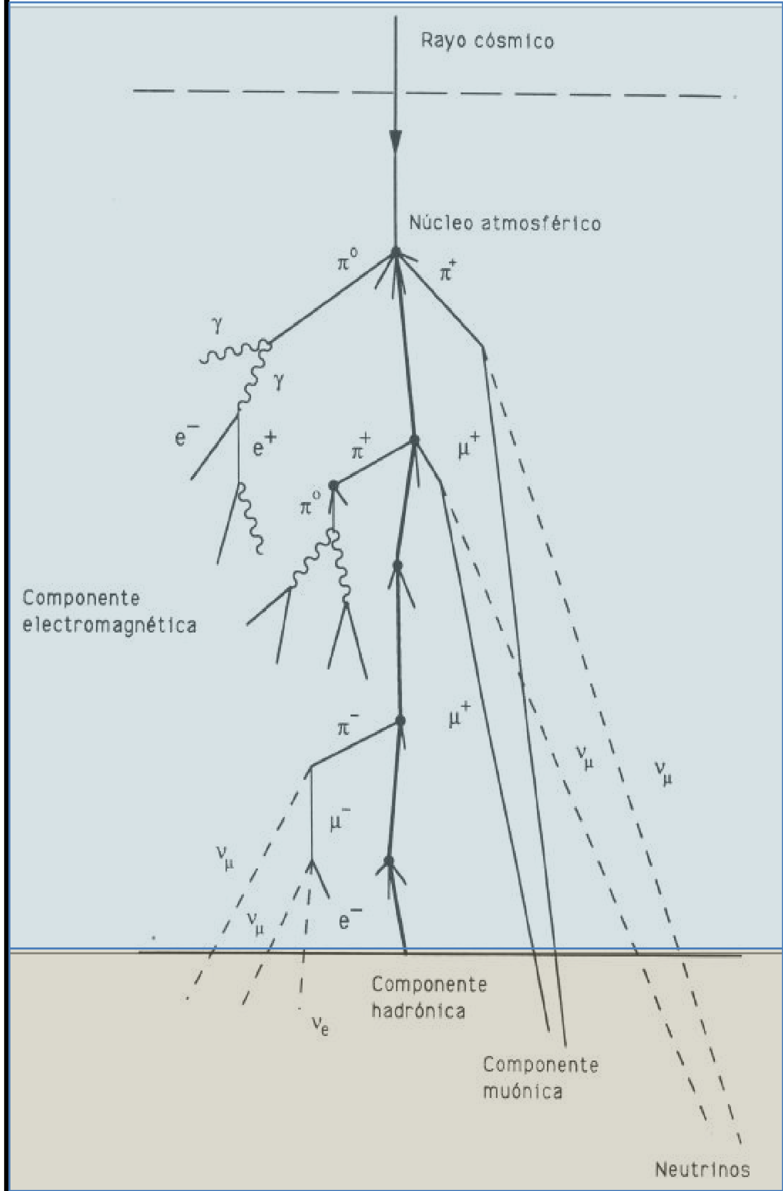
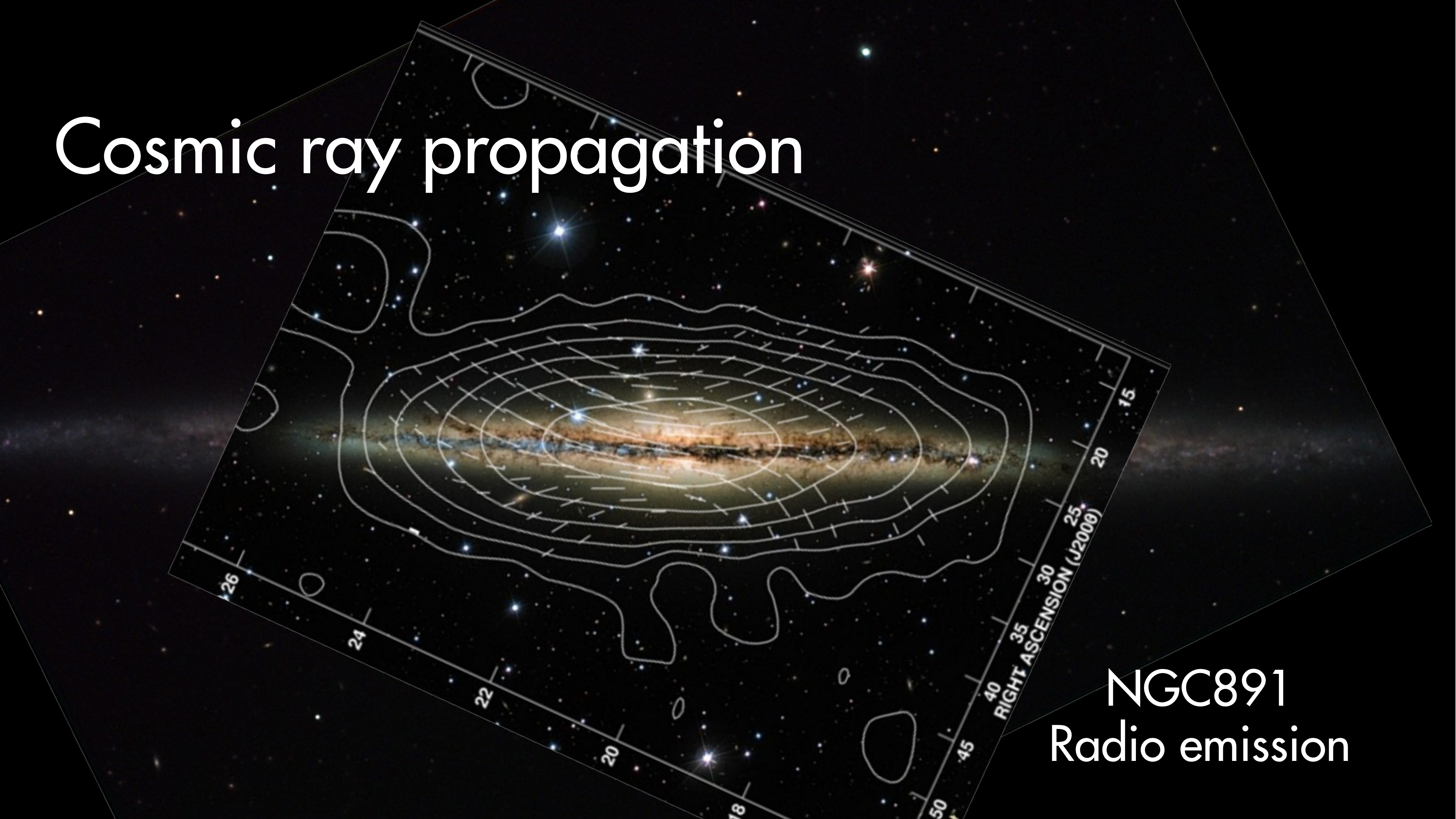


Cosmic ray propagation

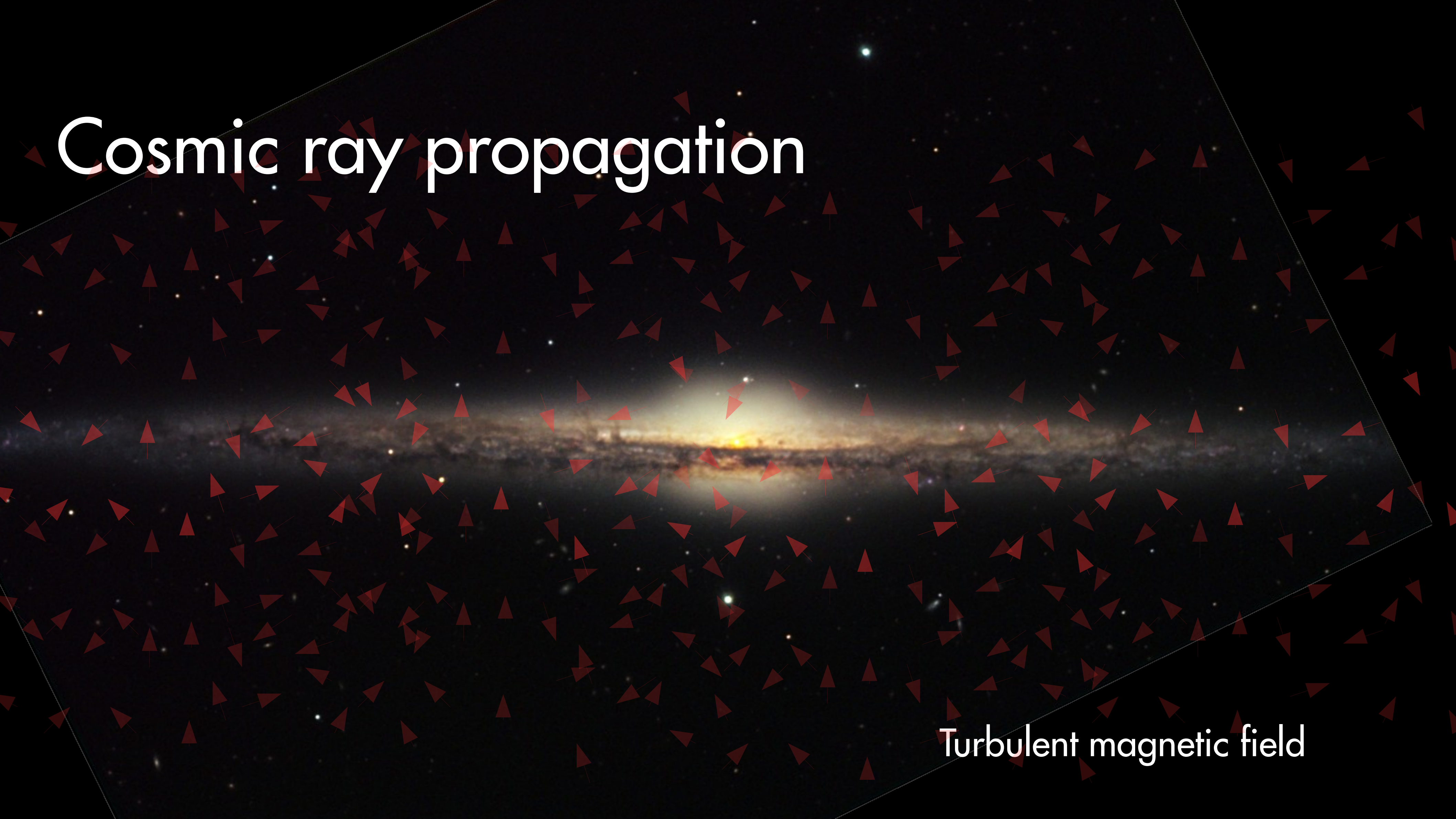
Cosmic ray propagation

Cosmic ray propagation



NGC891
Radio emission

Cosmic ray propagation



Cosmic ray propagation

Cosmic ray propagation

Cosmic ray propagation

The transport equation describes the evolution of the density of cosmic rays

Cosmic-ray transport equation

$$\frac{D\Psi}{Dt} = s$$

Source term due to

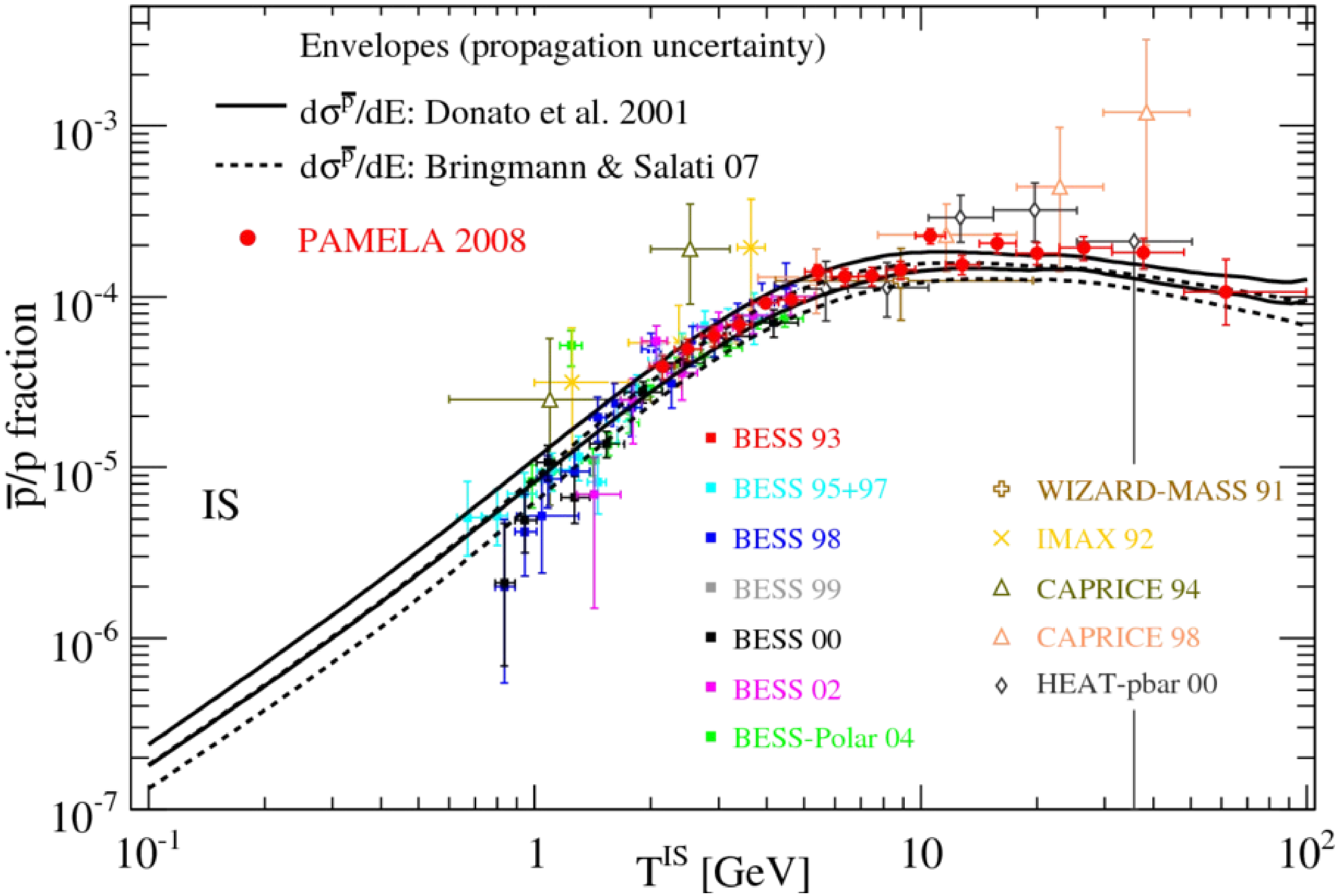
- Dark Matter
- Astrophysical source
- Astroparticle interactions

Cosmic ray propagation

The transport equation describes the evolution of the density of cosmic rays

$$\underbrace{\frac{\partial \psi}{\partial t}}_{\text{Time evolution}} + \nabla \cdot (\underbrace{-K_0 \epsilon^{\delta} \nabla \psi}_{\text{Diffusion}} + \underbrace{\mathbf{V}_c \psi}_{\text{Convection}}) + \underbrace{\frac{\partial J_\epsilon}{\partial \epsilon}}_{\text{Energy evolution}} = \underbrace{q_{\rm src}}_{\text{Sources}}$$

Each specie has its own transport equation usually coupled

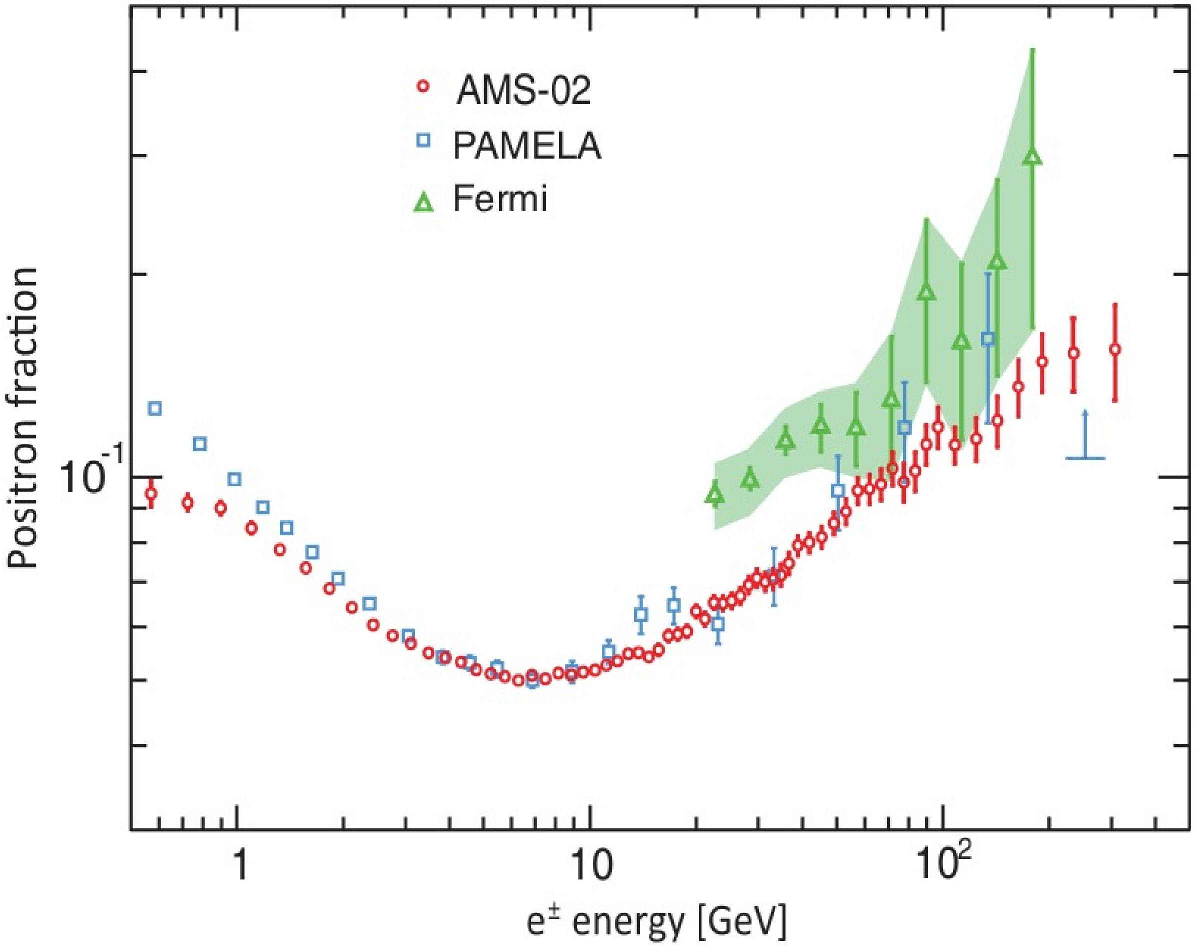


Mod.	**prop. parameters**		
	L [kpc]	K_0 $\left[\frac{\text{kpc}^2}{\text{Myr}}\right]$	δ
min	1	0.0016	0.85
med	4	0.0112	0.70
max	15	0.0765	0.46

There is some degeneracy in the propagation's parameter space

Let's focus on the electron and positron cosmic-rays

AMS' positron fraction



Electron positron cosmic rays

Transport equation

$$\frac{\partial \psi}{\partial t} + \nabla \cdot \left(-K_0 \epsilon^{\delta} \nabla \psi + \mathbf{V}_c \psi\right) + \frac{\partial J_\epsilon}{\partial \epsilon} = q_{\rm src}$$

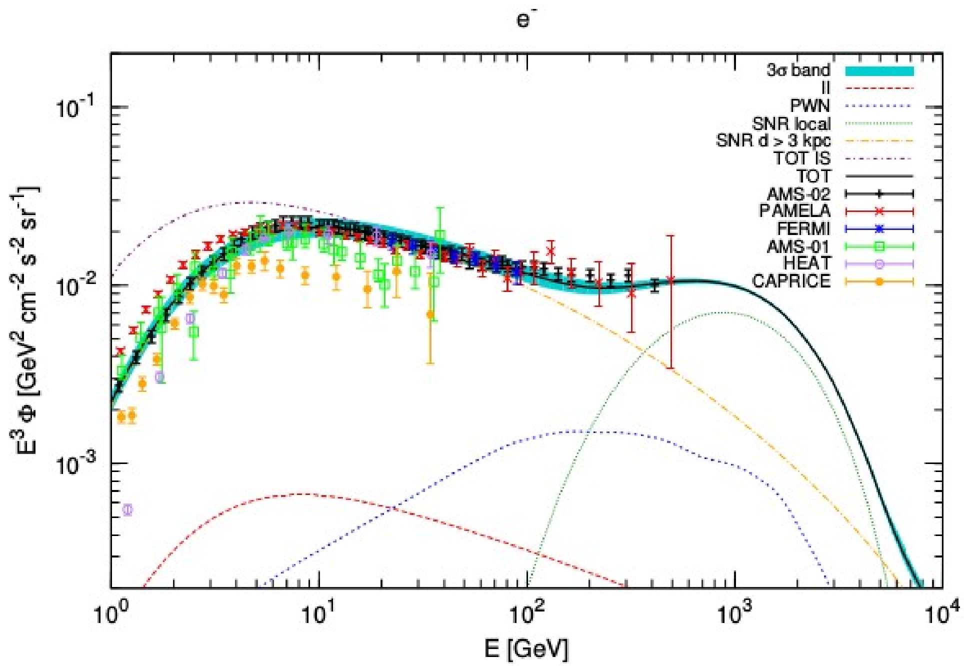
Secondaries from spallations

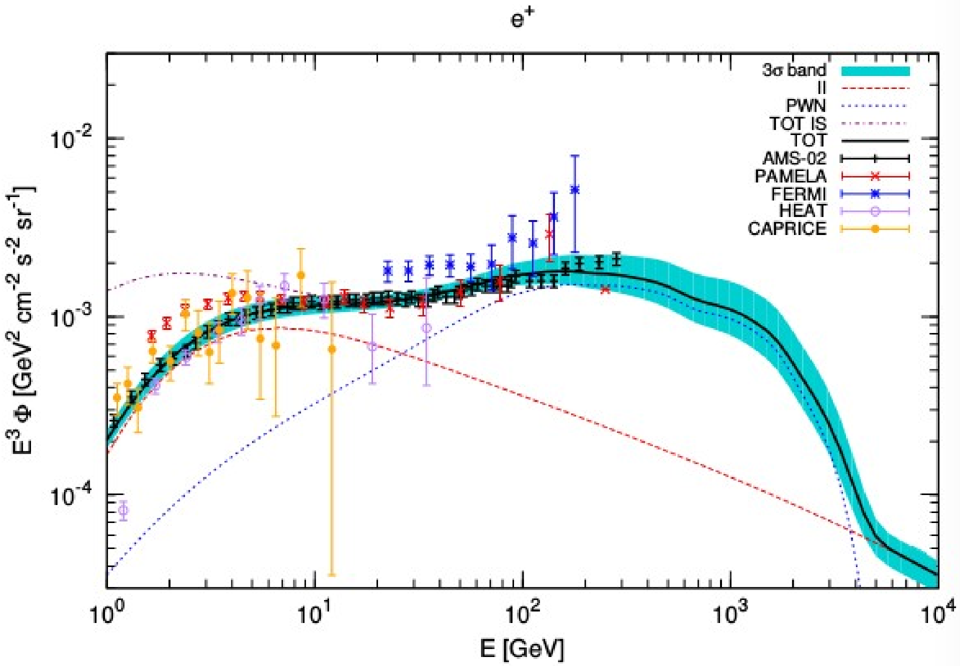
$$q_{e^\pm}(\mathbf{x}, E_e) = 4\pi \, n_{\rm ISM}(\mathbf{x}) \int dE_{\rm CR} \Phi_{\rm CR}\left(\mathbf{x}, E_{\rm CR}\right) \frac{d\sigma}{dE_e}(E_{\rm CR}, E_e)$$

Primaries from SNR and pulsars

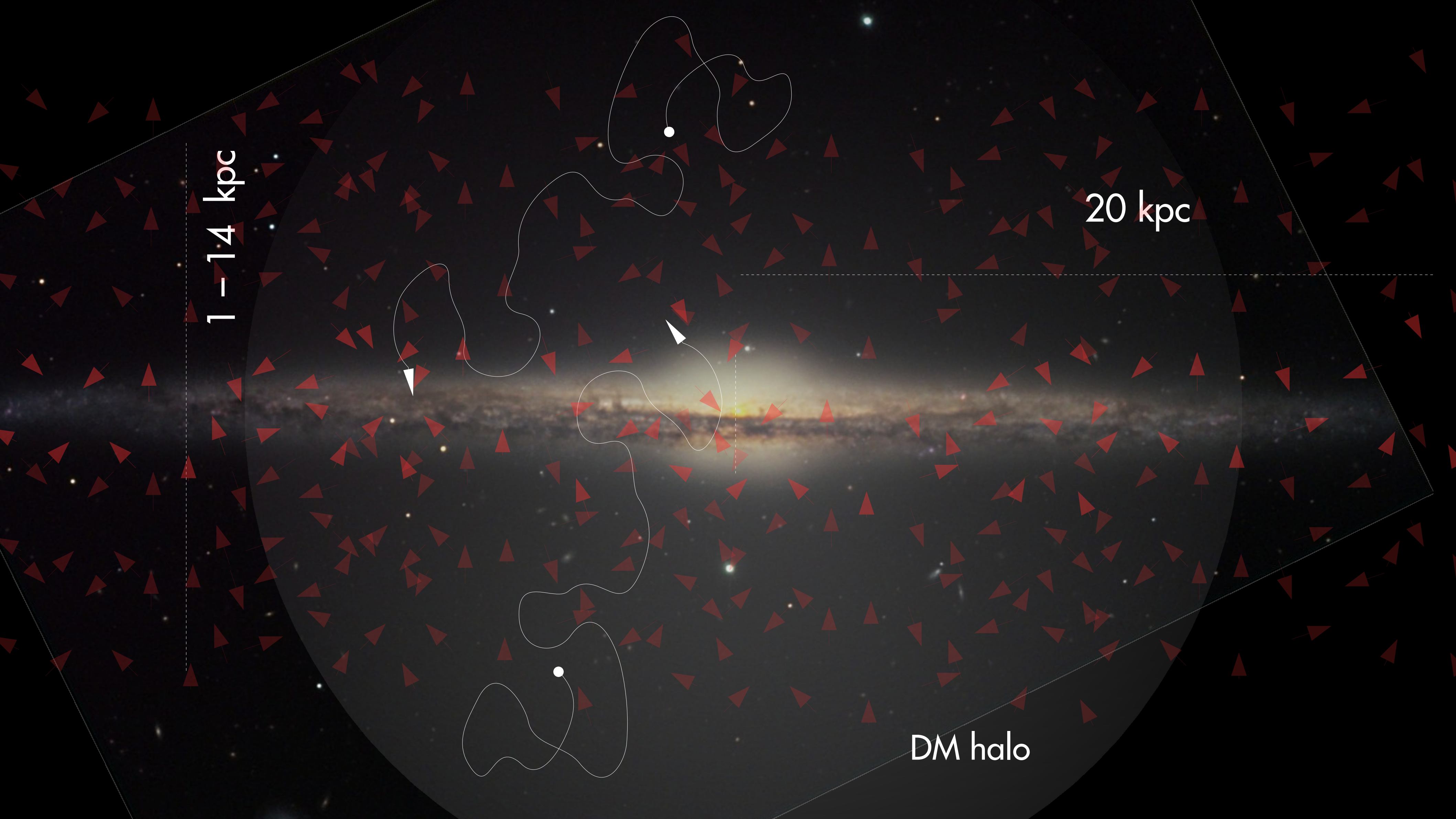
$$\begin{cases} \mathcal{Q}(E) = \mathcal{Q}_0 \epsilon^{-\gamma} \exp\left\{-\frac{E}{E_c}\right\} \\ \rho(r,z) = \rho_0 \, r^a \, \exp\left\{-\frac{r}{r_0}\right\} \exp\left\{-\frac{|z|}{z_0}\right\} \end{cases}$$

Electron positron cosmic rays





arxiv:1402.0321


1 – 14 kpc
20 kpc
DM halo

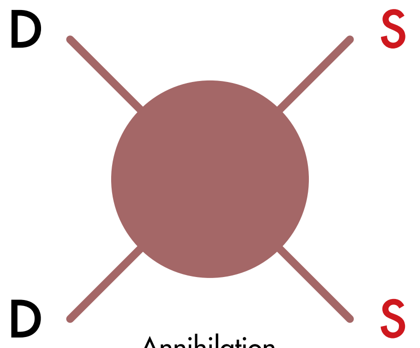
Electron positron cosmic rays

Transport equation

$$\frac{\partial \psi}{\partial t} + \nabla \cdot \left(-K_0 \epsilon^{\delta} \nabla \psi + \mathbf{V}_c \psi\right) + \frac{\partial J_\epsilon}{\partial \epsilon} = q_{\rm src}$$

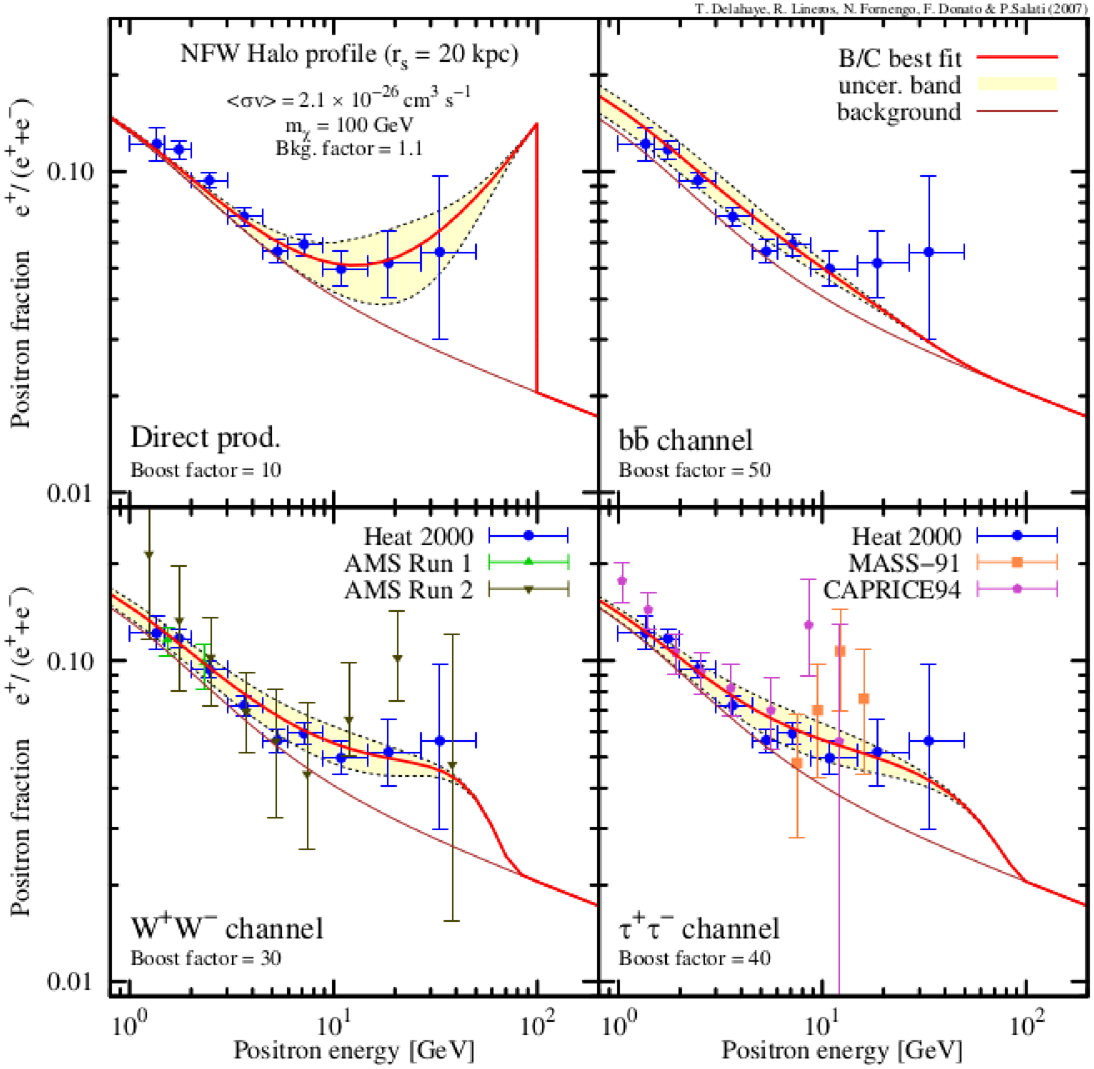
Source from DM annihilation

$$s_{\rm DM}(\vec{x}, \epsilon) = \eta \left\langle \sigma v \right\rangle \frac{\rho^2_{\rm DM}(\vec{x})}{m^2_{\rm DM}} \frac{dn_X}{d\epsilon}(\epsilon)$$



Annihilation

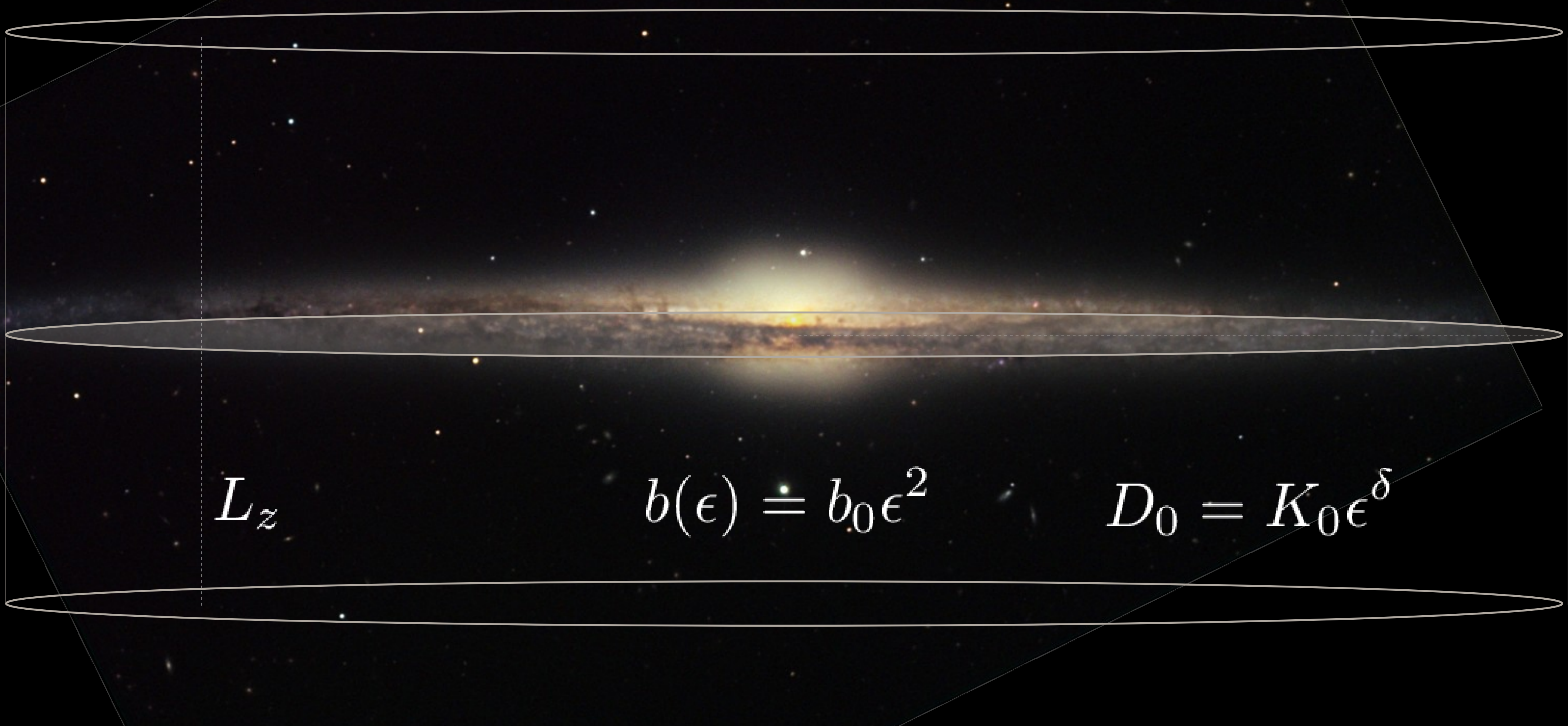
DM is a source which is spherically distributed



arxiv:0712.2312

Analytical calculation

Propagation zone



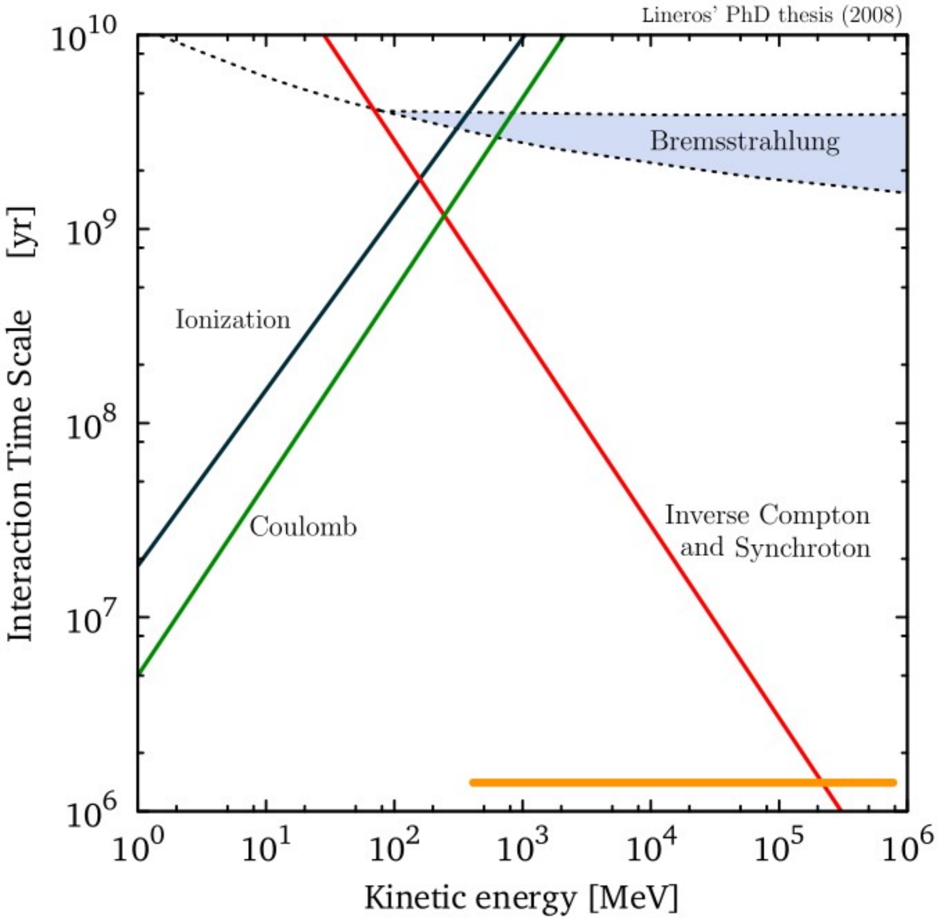
Energy losses

$$J_\epsilon = \dot{\epsilon}\psi = b(\epsilon)\psi$$

At GeV, energy losses are due to

- Synchrotron
- Inverse compton

$$b(\epsilon) = -\epsilon^2 \times 10^{-16}\,\mathrm{GeV\,s^{-1}}$$



Simplified transport

Steady state without convection term:

$$-K_0\epsilon^\delta\nabla^2\psi - \partial_\epsilon(b_0\epsilon^2\psi) = s$$

Remember that the Green's function means to solve:

$$-K_0\epsilon^\delta\nabla^2 G - \partial_\epsilon(b_0\epsilon^2 G) = \delta(\epsilon - \epsilon_s)\delta^3(x - x_0)$$

Simplified transport

Propagation distance

$$\lambda = \frac{2K_0}{b_0}\sqrt{\frac{\left(\epsilon_s^{\delta-1} - \epsilon^{\delta-1}\right)}{\delta - 1}}$$

$$\widetilde{G}(\vec{x}, \vec{x}_s, \lambda) = \frac{1}{\pi^{3/2}\lambda^3} \exp\left(-\frac{(\vec{x} - \vec{x}_s)^2}{\lambda^2}\right)$$

Función de Green
$$G(\vec{x}, \vec{x}_s, \epsilon, \epsilon_s) = \frac{1}{b_0 \epsilon^2}\widetilde{G}(\vec{x}, \vec{x}_s, \lambda)$$

Simplified transport

The Green's method allows to find any solution

$$\psi(\vec{x}, \epsilon) = \int_{\epsilon}^{\infty} d\epsilon_s \int d^3x_s \, s(x_s, \epsilon_s) G(\vec{x}, \vec{x}_s, \epsilon, \epsilon_s)$$

Boundary conditions

A more realistic case must include boundary conditions:

$$\psi(\vec{x} = R_g \hat{r}, \epsilon) = \psi(\vec{x} = \pm L_z \hat{z}, \epsilon) = 0$$

The Green's function must also fulfill the conditions:

$$\widetilde{G}(\vec{x} = R_g \hat{r}, \vec{x}_s, \lambda) = G(\vec{x} = \pm L_z \hat{z}, \vec{x}_s, \lambda) = 0$$

Method of images

Fulfill condition by adding charges outside the region of interest

Veritical borders:

$$\widetilde{G}_v(\vec{x}, \vec{x}_s, \lambda) = \sum_{n=-\infty}^{\infty} (-1)^n \widetilde{G}(\vec{x}, \vec{x}_{s,n}, \lambda)$$

$$\vec{x}_{s,n} = (x_s, y_s, L_z n + (-1)^n z_s)^T$$

Method of images

At the border of the cyllinder

$$\widetilde{G}_r(\vec{x},\vec{x}_s,\lambda) = \widetilde{G}(\vec{x},\vec{x}_s,\lambda) - \widetilde{G}(\vec{\sigma},\vec{\sigma}_s,\lambda)$$

$$\vec{\sigma} = (\beta x, \beta y, z)^T \qquad \beta = \frac{x_s^2 + y_s^2}{R_g^2}$$

$$\vec{\sigma}_s = (x_s/\beta, y_s/\beta, z_s)^T$$

Eigenfunction expansion

Another way is to use eigenfunctions to solve the problem

$$\widetilde{G}_{cb}(\vec{x}, \vec{x}_s, \lambda) = \sum_g \chi_g^\dagger(\vec{x}_s)\chi_g(\vec{x}) \exp\left(-\frac{1}{4}g^2\lambda^2\right)$$

$$\chi_g(z) = \frac{1}{\sqrt{L_z}} \sin\left(\frac{g\pi}{2L_z} z\right) \quad g: \text{ par}$$

$$\chi_g(z) = \frac{1}{\sqrt{L_z}} \cos\left(\frac{g\pi}{2L_z} z\right) \quad g: \text{ impar}$$

Calculating fluxes

The flux and the density are related by

$$\frac{d\Phi}{d\epsilon}(\epsilon) = \frac{\beta c}{4\pi}\psi(\vec{x}, \epsilon)$$

where

$$\psi(\vec{x}, \epsilon) = \int_{\epsilon}^{\infty} d\epsilon_s \int d^3x_s\, s(x_s, \epsilon_s) G(\vec{x}, \vec{x}_s, \epsilon, \epsilon_s)$$

Calculating fluxes

In general, the source term can be divided into 2 parts.

$$s(\vec{x}_s, \epsilon_s) = \frac{dn}{d\epsilon}(\epsilon_s) \times \rho(\vec{x}_s)$$

And then:

$$\psi(\vec{x}, \epsilon) = \frac{1}{b_0 \epsilon^2} \int_{\epsilon}^{\infty} d\epsilon_s \frac{dn}{d\epsilon}(\epsilon_s) \int d^3 x_s \, \rho(\vec{x}_s) \widetilde{G}(\vec{x}, \vec{x}_s, \lambda)$$

Calculating fluxes

$$s(\vec{x}_s, \epsilon_s) = \frac{dn}{d\epsilon}(\epsilon_s) \times \rho(\vec{x}_s)$$

$$\psi(\vec{x}, \epsilon) = \frac{1}{b_0 \epsilon^2} \int_\epsilon^\infty d\epsilon_s \frac{dn}{d\epsilon}(\epsilon_s)\, \tilde{I}(\vec{x}, \lambda(\epsilon, \epsilon_s))$$

The so-called "halo function" allows us to save time!

Astrophysical sources of electrons and positrons

- Primary sources: Supernovae remnants and pulsars
- Secondary sources: Nuclear CR interaction with the ISM gas

Secondaries

The source term depends on the gas and CR density, and the CR energy spectra.

$$s_{pH}(\vec{x}, \epsilon_e) = 4\pi n_H(\vec{x}) \int d\epsilon_p \Phi(\epsilon_p) \frac{d\langle \eta \sigma_{pH} \rangle}{d\epsilon_p}(\epsilon_p, \epsilon_e)$$

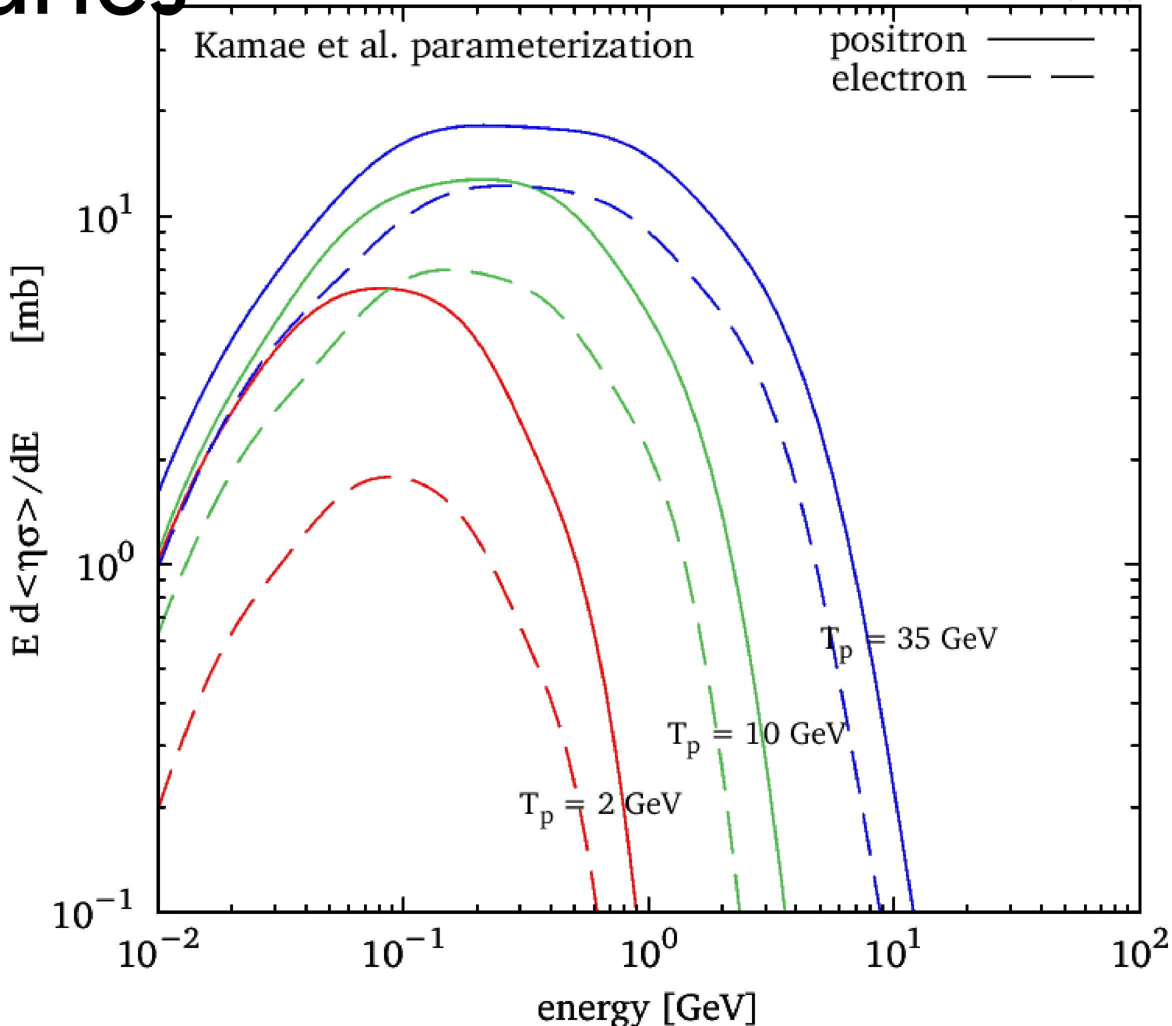
Secondaries

The source term depends on the gas and CR density, and the CR energy spectra.

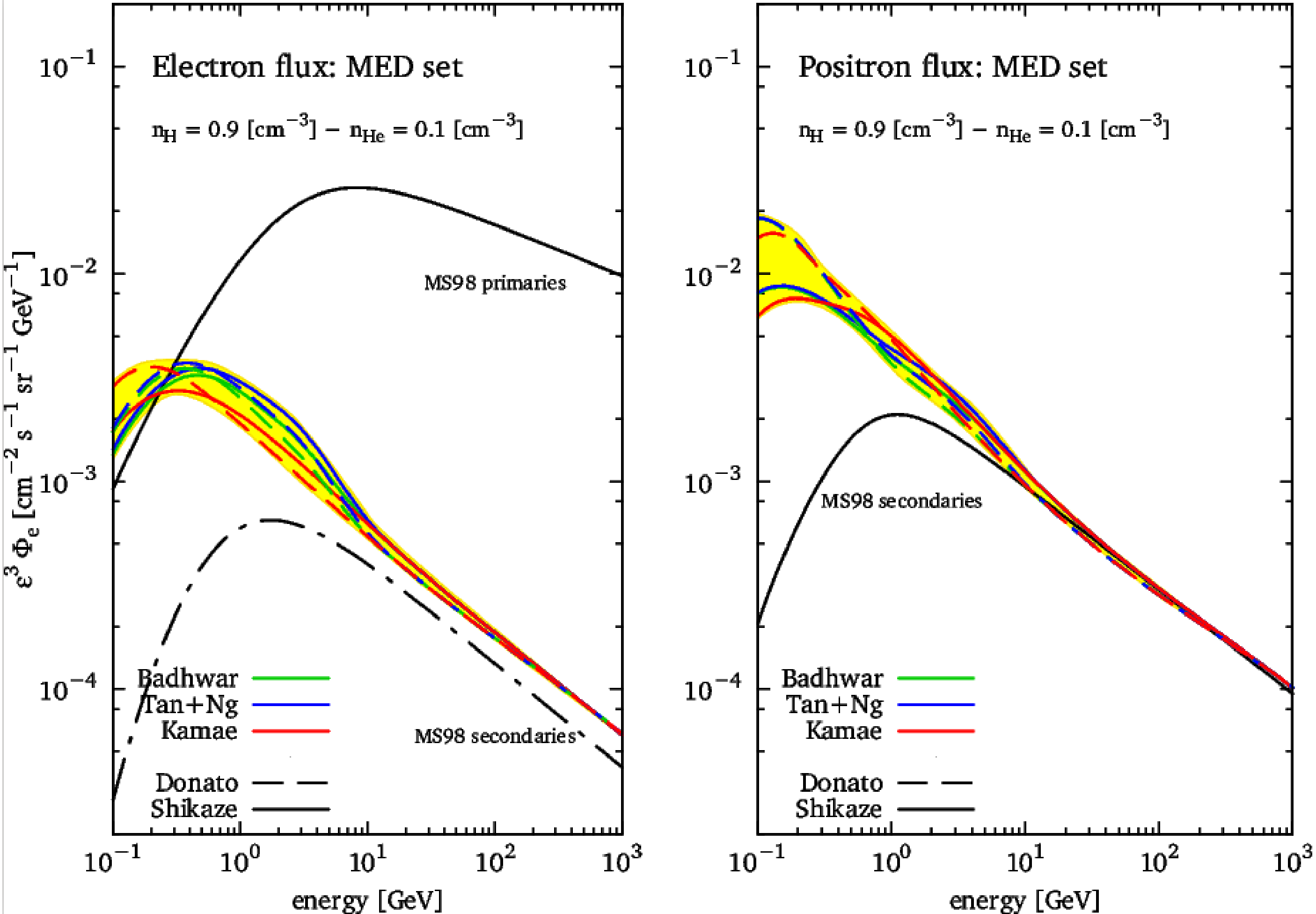
$$s_{full}(\vec{x}, \epsilon_e) = 4\pi \sum_{i=H,He} \sum_{j=p,\alpha} n_i(\vec{x}) \int d\epsilon_j \Phi(\epsilon_j) \frac{d\langle \eta \sigma_{ji} \rangle}{d\epsilon_j}(\epsilon_j, \epsilon_e)$$

Secondaries

$$p + (p, n) \rightarrow X + \pi^{\pm} + K^{\pm} \rightarrow X + e^{\pm}$$



Secondaries



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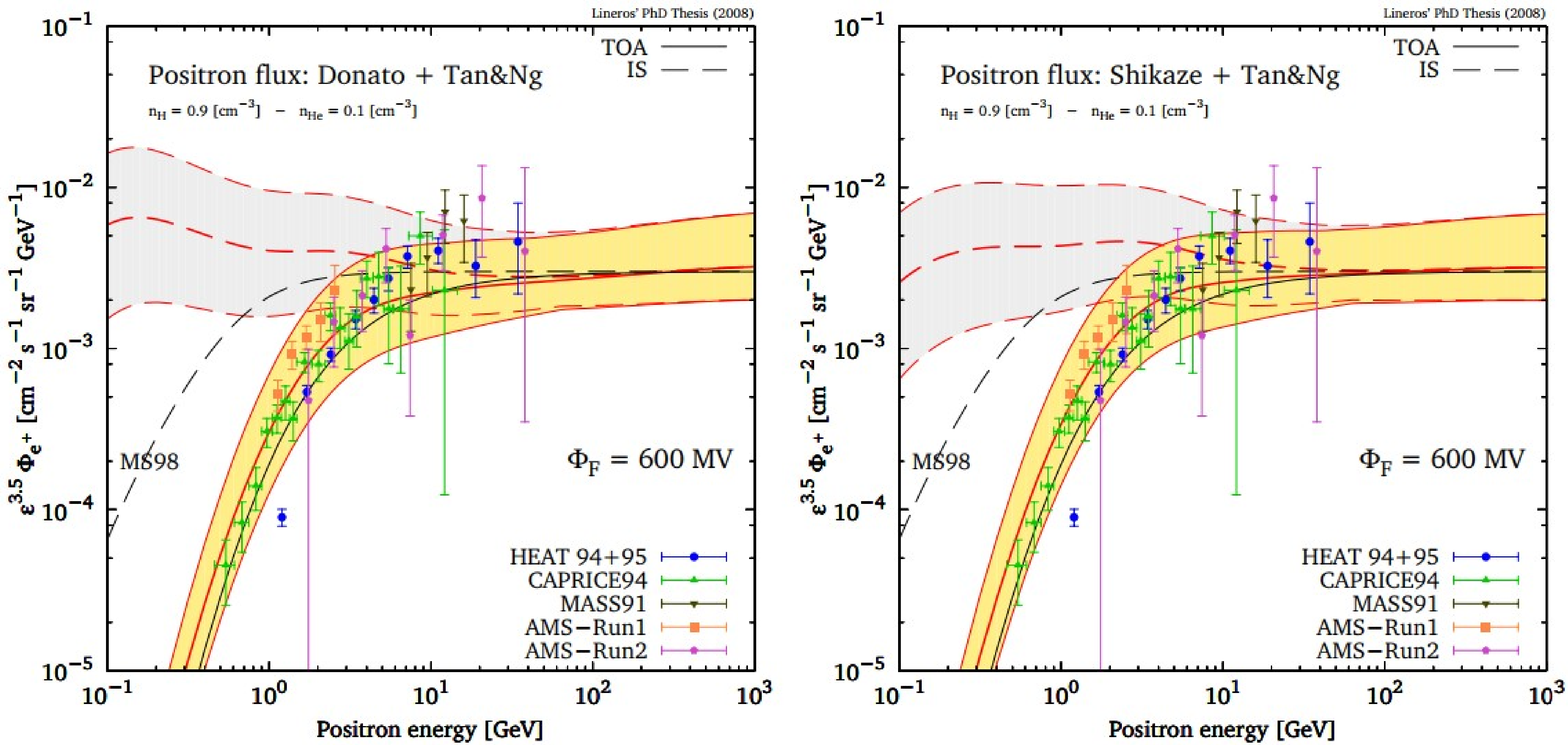
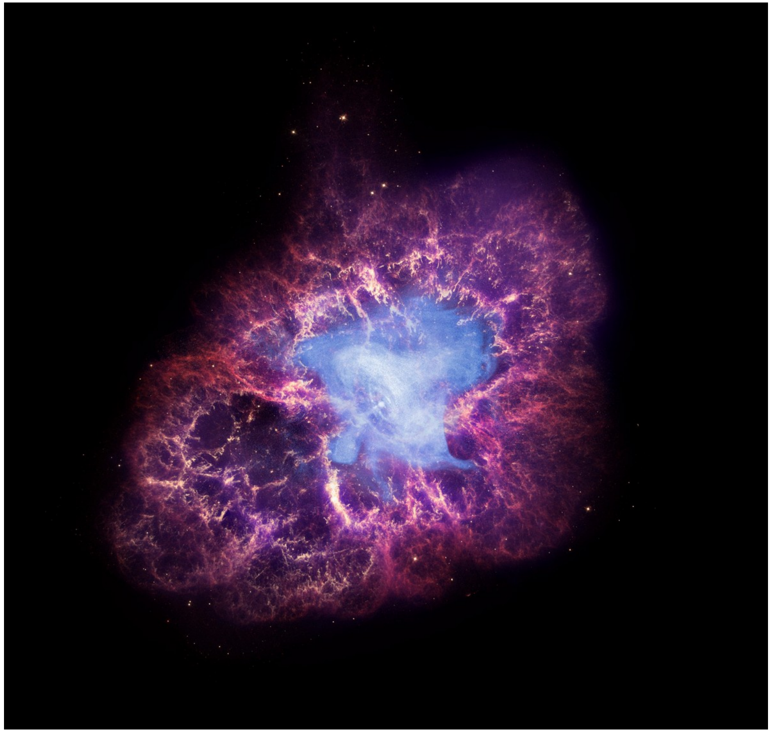


Primary cosmic rays

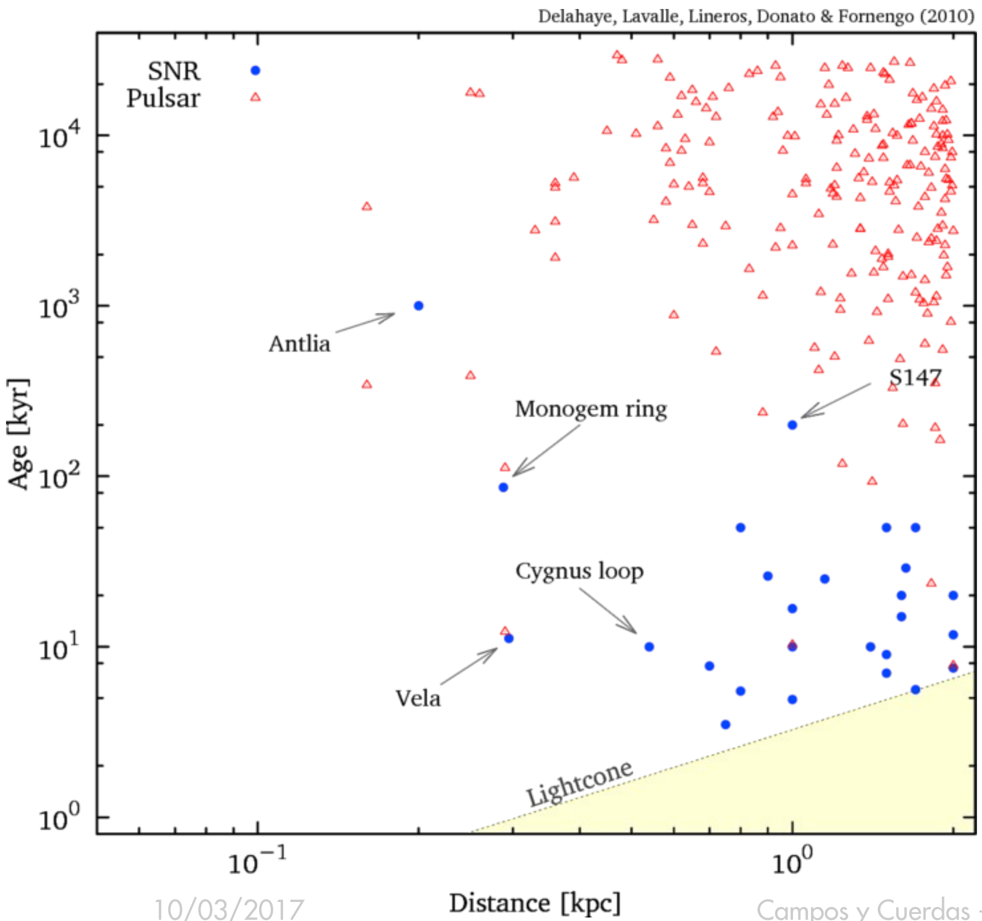


Produced due to astrophysical activities

Common sources:

- Supernovae remnants
- Pulsars

Primary cosmic rays



The difference is they are discrete in time

In a sphere of 2 kpc

- 20 SNRs
- 200 Pulsars

$$\Gamma_{\rm SN} \sim 3/\text{siglo}$$

Transport equation (time dependent)

Not the transport equation is:

$$\partial_t\psi - D(\epsilon)\nabla^2\psi - \partial_\epsilon\left(b(\epsilon)\psi\right) = s(t,\vec{x},\epsilon)$$

And the corresponding Green's function:

$$\partial_t G - D(\epsilon)\nabla^2 G - \partial_\epsilon\left(b(\epsilon)G\right) = \delta(t-t_s)\delta^3(\vec{x}-\vec{x}_s)\delta(\epsilon-\epsilon_s)$$

Transport equation (time dependent)

The Green's function time dependent is easy to find:

$$G(t, t_s, \vec{x}, \vec{x}_s, \epsilon, \epsilon_s) = \delta(t - t_s - \tau_c)\, G(\vec{x}, \vec{x}_s, \epsilon, \epsilon_s)$$

Where the cooling time:

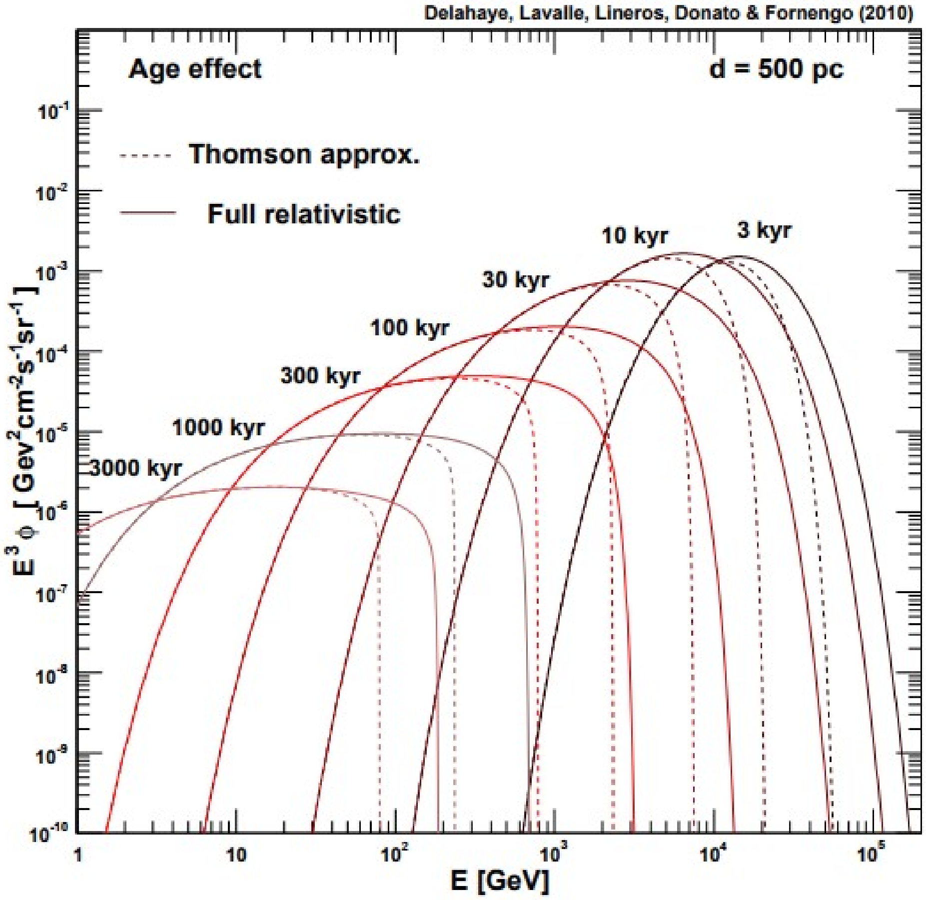
$$\tau_c(\epsilon, \epsilon_s) = \int_{\epsilon}^{\epsilon_s} \frac{d\varepsilon}{b(\varepsilon)}$$

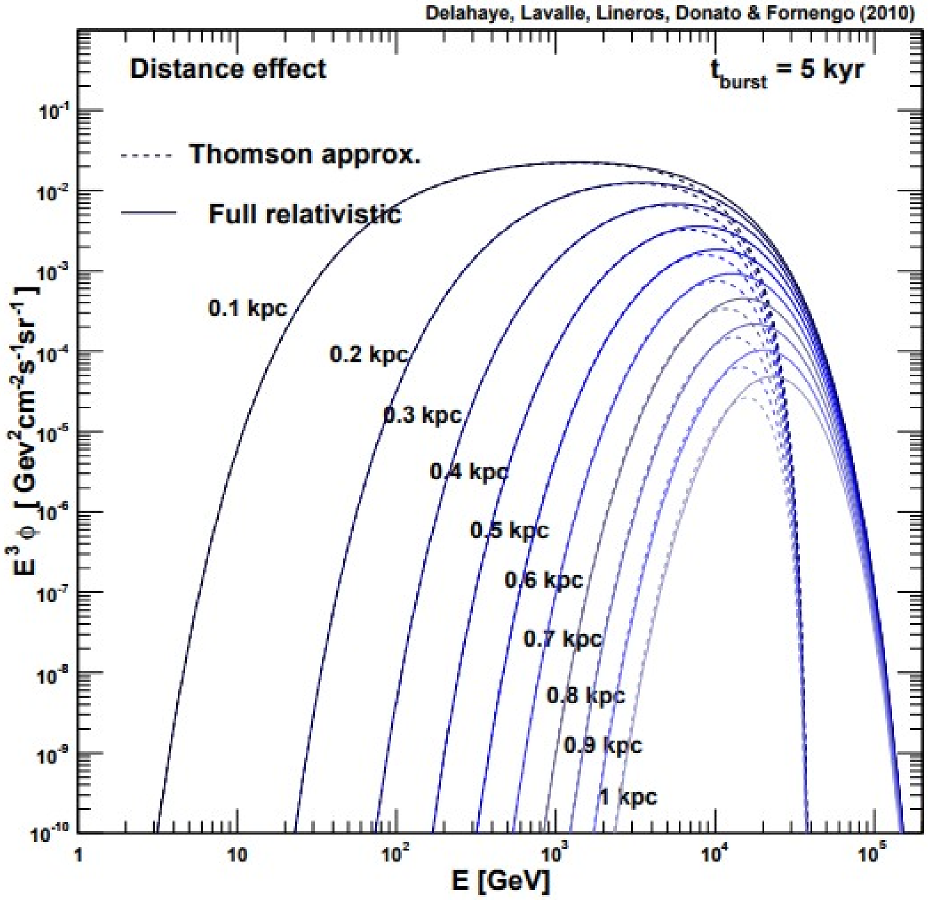
Transport equation (time dependent)

And the general solution is:

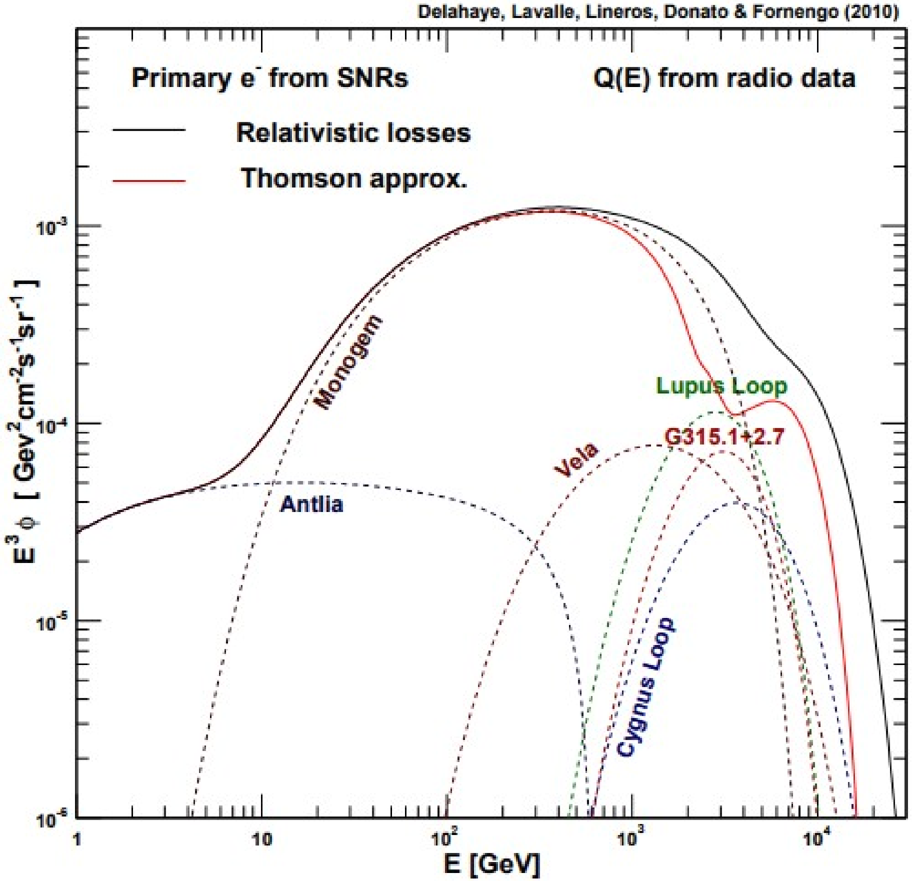
$$\psi(t, \vec{x}, \epsilon) = \int_{-\infty}^{t} dt_s \int_{\epsilon}^{\infty} d\epsilon_s \int d^3x_s \, s(t_s, x_s, \epsilon_s) G(t, t_s, \vec{x}, \vec{x}_s, \epsilon, \epsilon_s)$$

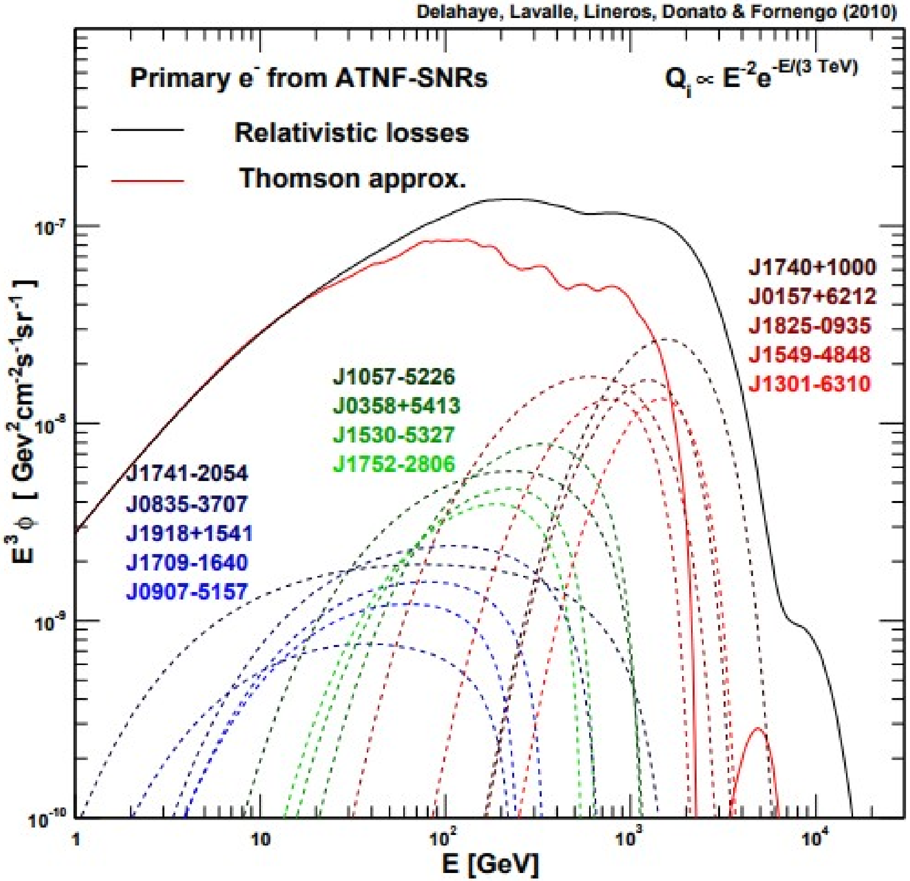
Time dependent solutions



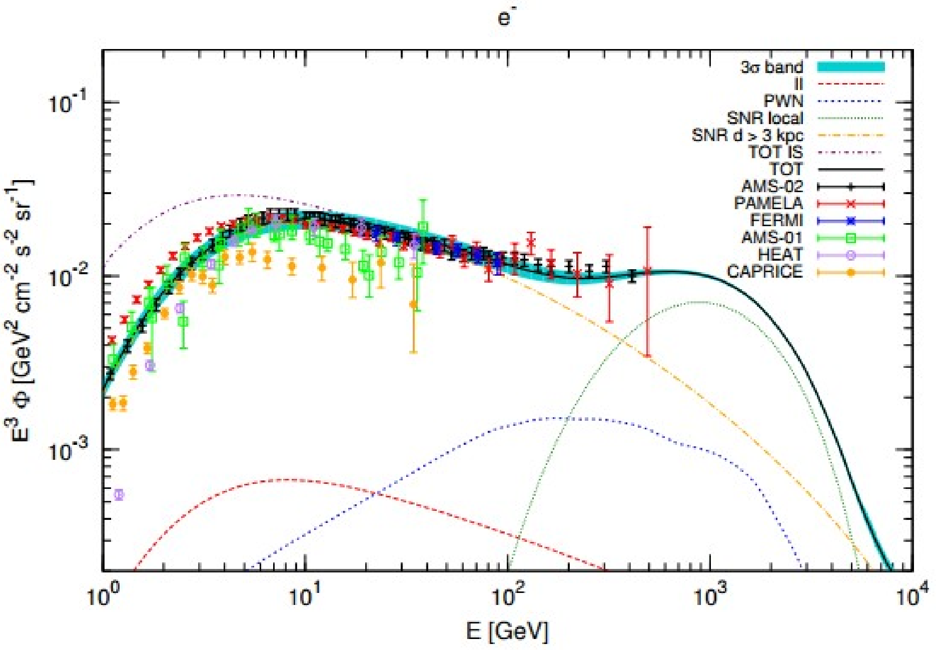


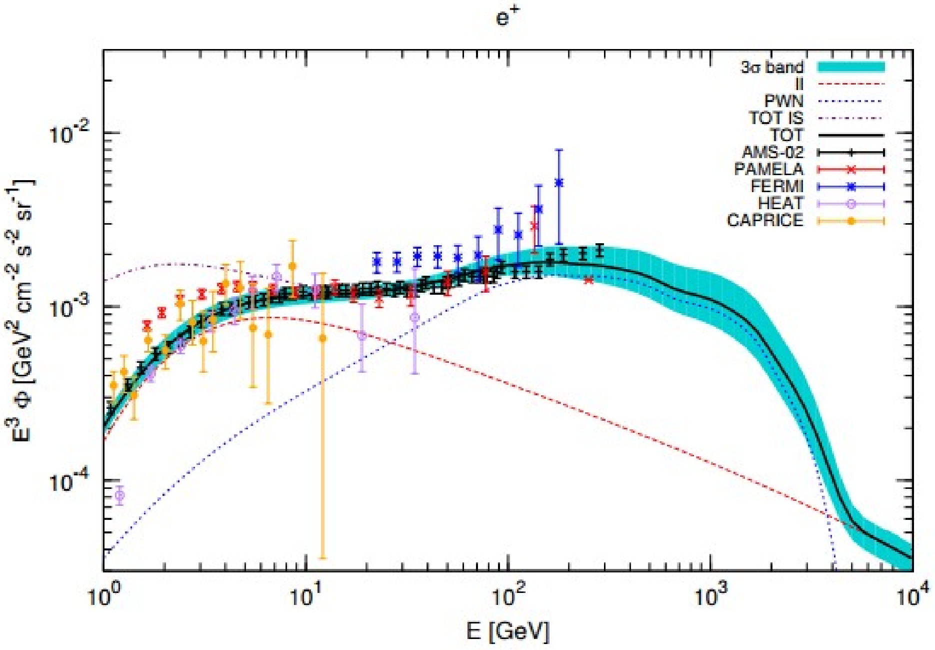
CR fluxes from primary sources



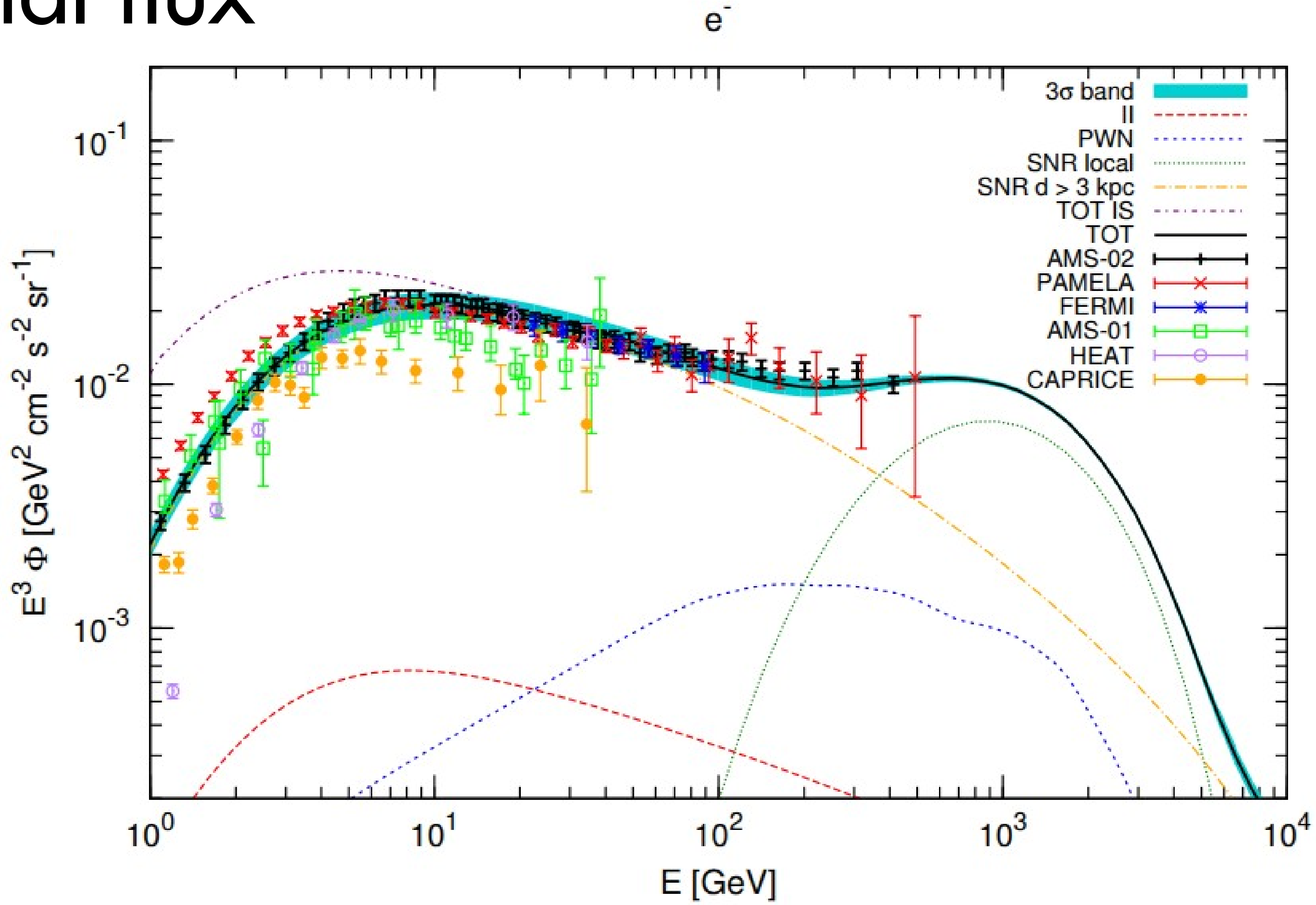


Total flux


e-
3σ band
II
PWN
SNR local
SNR d > 3 kpc
TOT IS
TOT
AMS-02
PAMELA
FERMI
AMS-01
HEAT
CAPRICE
E [GeV]

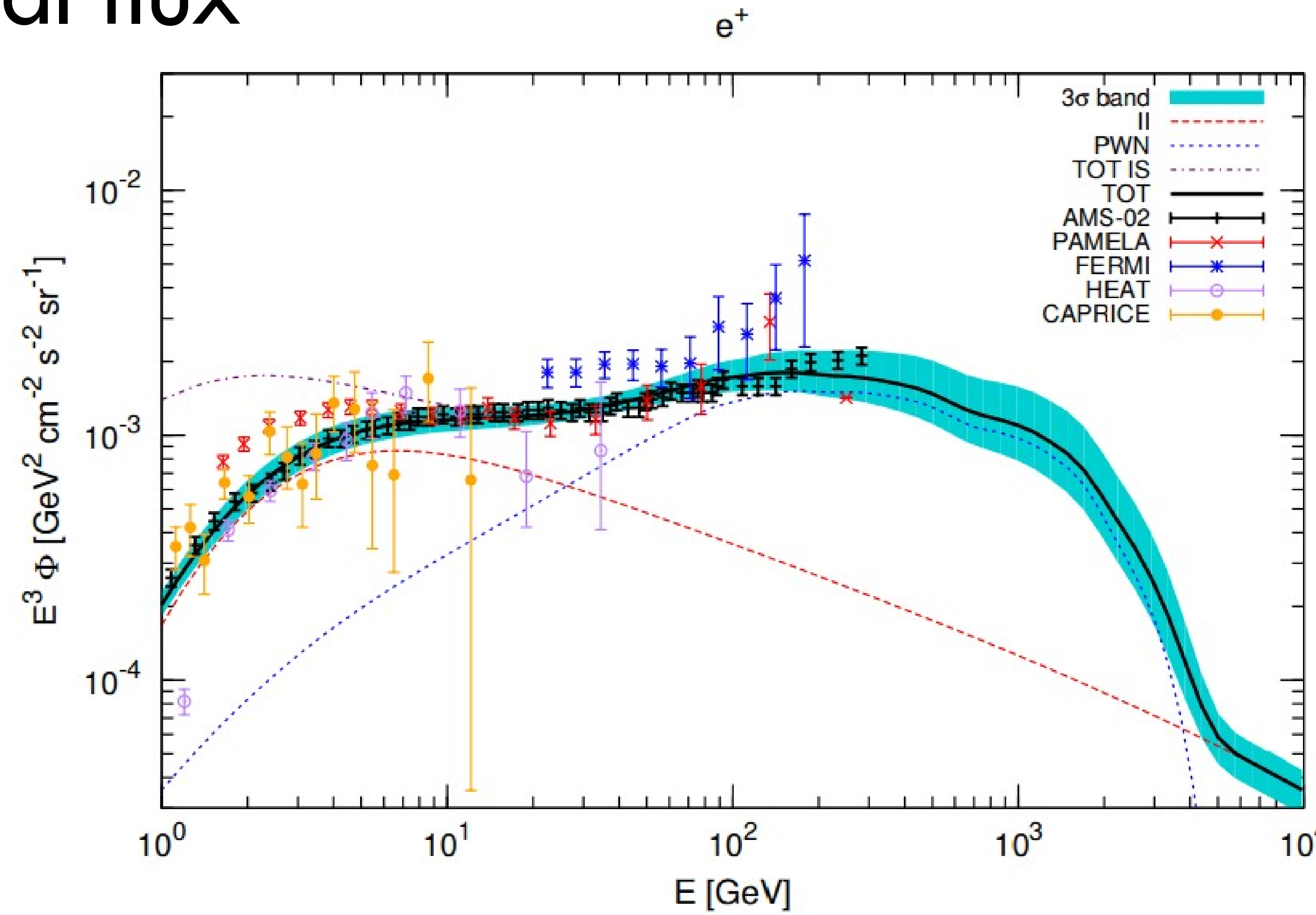

e+
3σ band
II
PWN
TOT IS
TOT
AMS-02
PAMELA
FERMI
HEAT
CAPRICE
E [GeV]

Total flux



e-
3σ band
II
PWN
SNR local
SNR d > 3 kpc
TOT IS
TOT
AMS-02
PAMELA
FERMI
AMS-01
HEAT
CAPRICE
$E^3 \Phi$ [GeV^2 cm^{-2} s^{-2} sr^{-1}]
E [GeV]

Total flux



e+
3σ band
II
PWN
TOT IS
TOT
AMS-02
PAMELA
FERMI
HEAT
CAPRICE
$E^3\ \Phi$ [GeV^2 cm^{-2} s^{-2} sr^{-1}]
10^{-2}
10^{-3}
10^{-4}
10^0
10^1
10^2
10^3
10^4
E [GeV]

The Tools

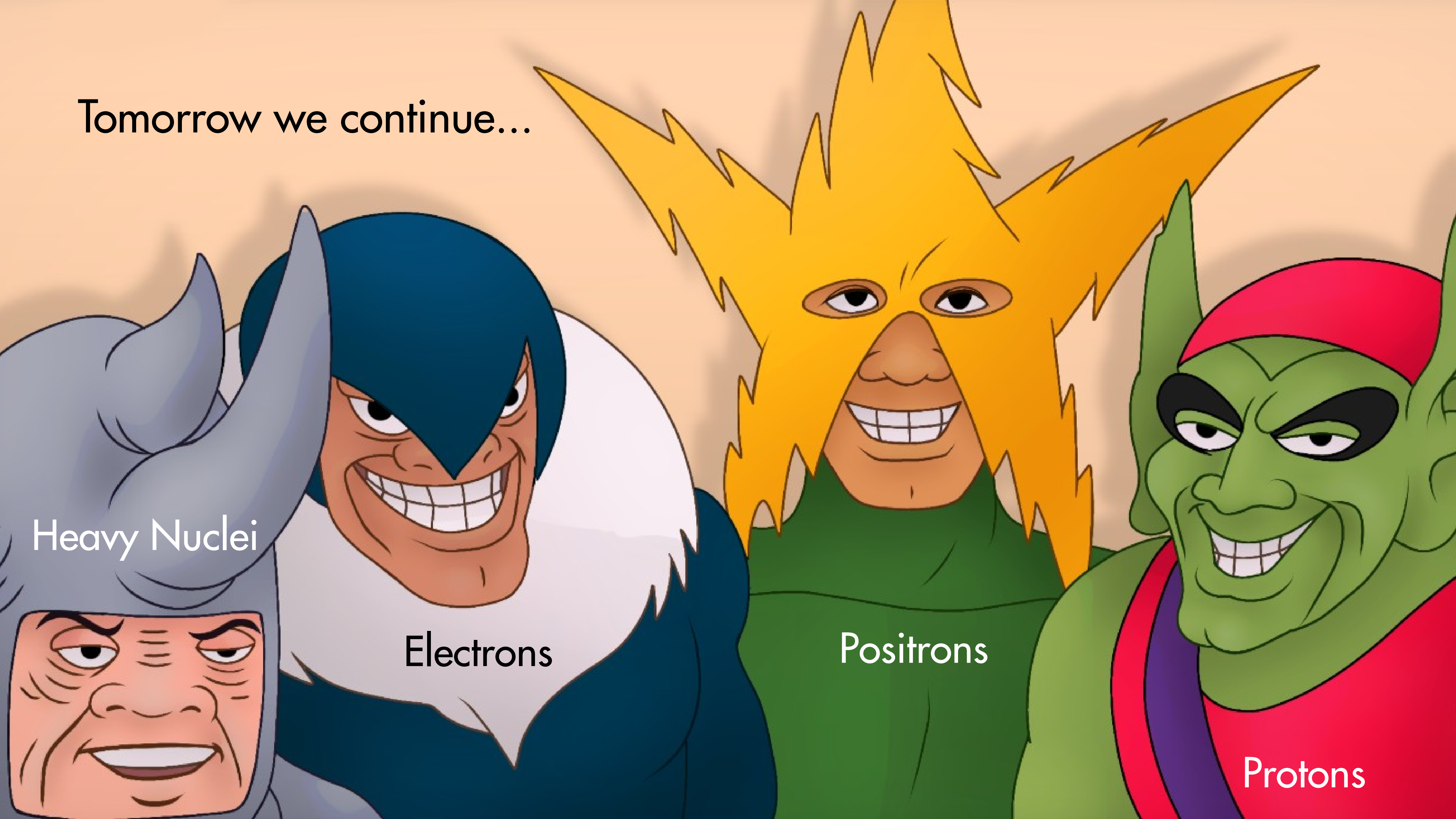
Codes for Cosmic ray progagation

Low Energy Cosmic Rays

- Galprop (Numerical) https://galprop.stanford.edu/
- Dragon (Numerical) https://github.com/cosmicrays
- Usine (Semianalytical) https://dmaurin.gitlab.io/USINE/

High Energy Cosmic Rays

- Simprop (Numerical) https://arxiv.org/abs/1204.2970
- CRpropa (Numerical) https://crpropa.desy.de/


Tomorrow we continue...
Heavy Nuclei
Electrons
Positrons
Protons