Cosmic rays, dark matter, solar modulation

24 May 2019

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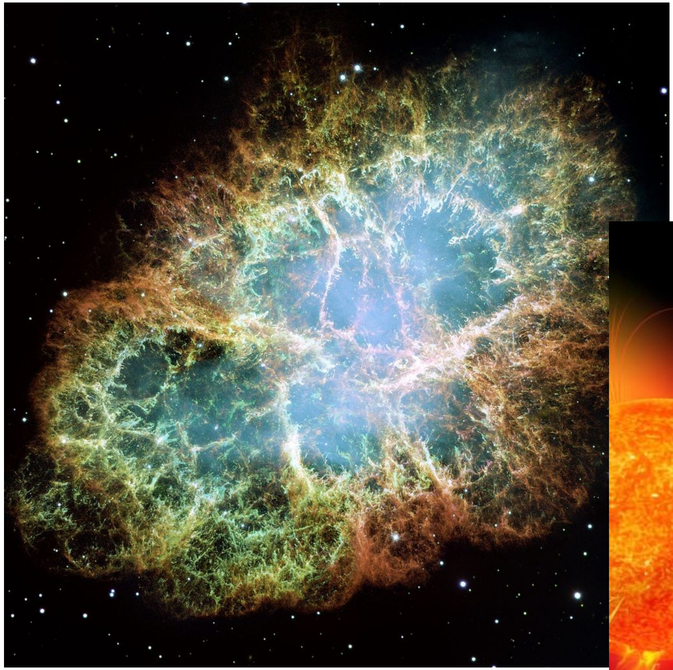
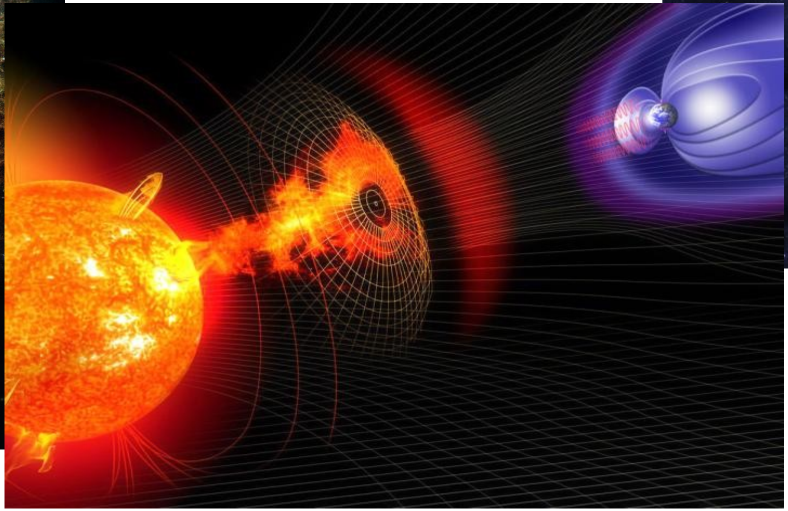
INFN Trieste





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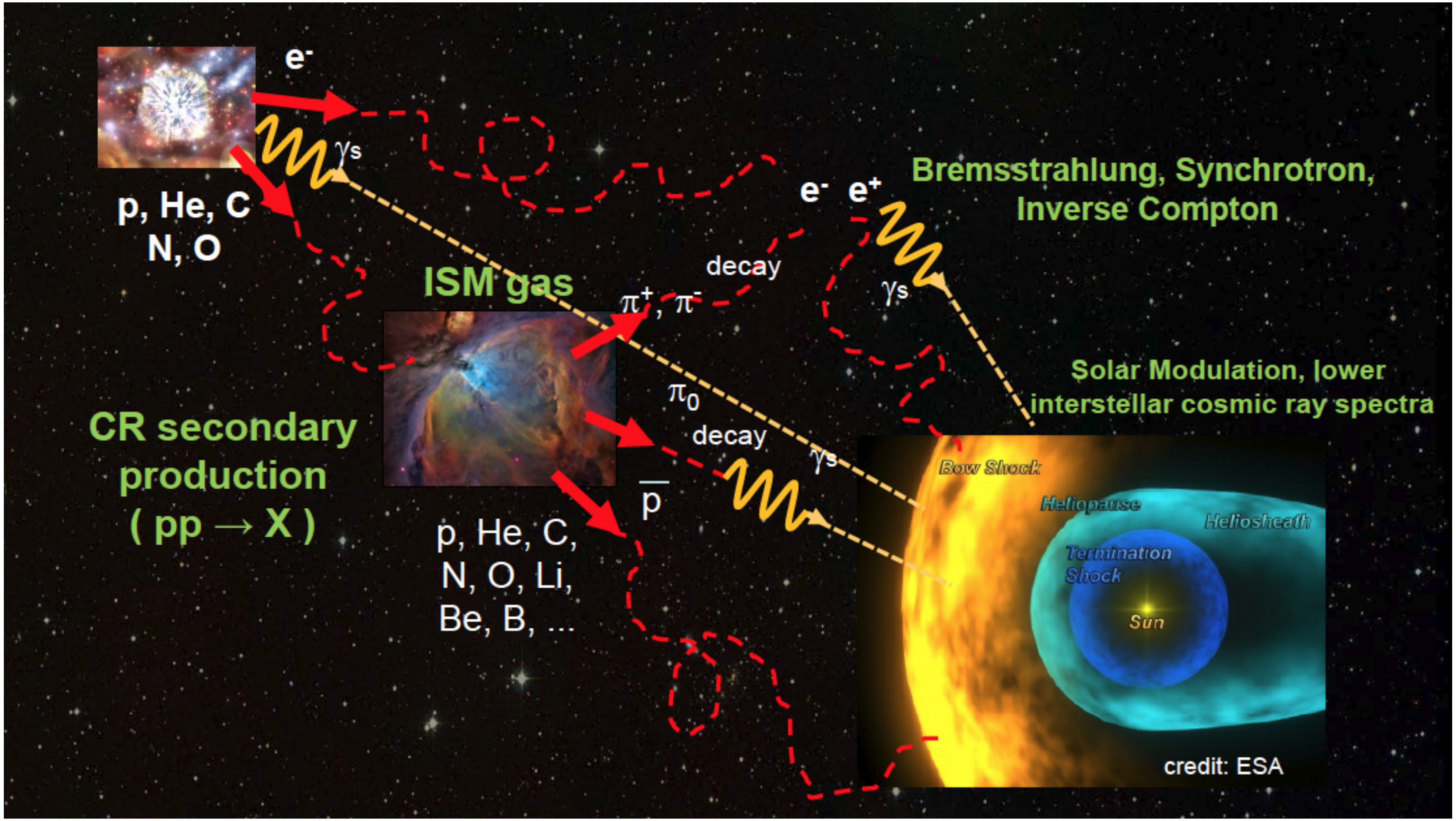
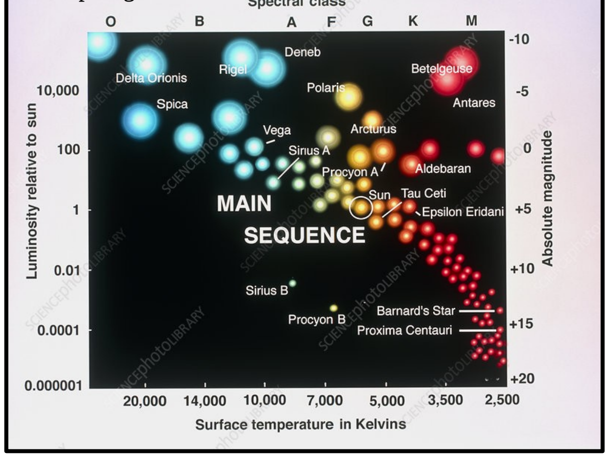
Cosmic rays propagation inside Heliosphere

Propagation of cosmic rays: Heliospere

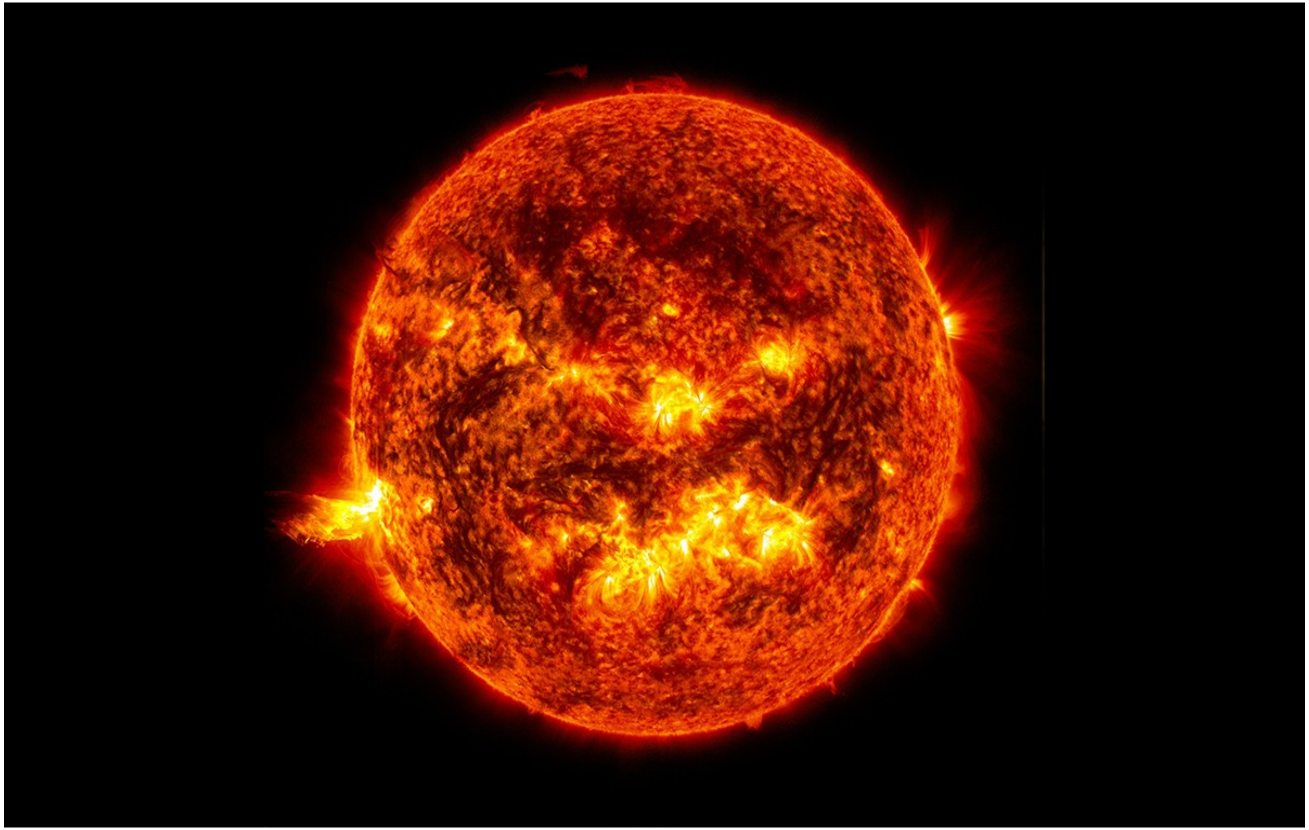


The Sun

Hertzsprung-Russell



Mass: 1.98 10^30 kg
Radius: 692 10^3 km
Temperature surface: 5778 K
Temperature core: 1.57 10^7 K
Spectral classification: G2V
Age: 4.6 10^9 years
Rotation period: 27 days



Solar wind (SW)

The solar wind, consisting of ionised coronal plasma, flows supersonically and radially outward from the Sun due to the large pressure difference between the hot solar corona and the interstellar medium.

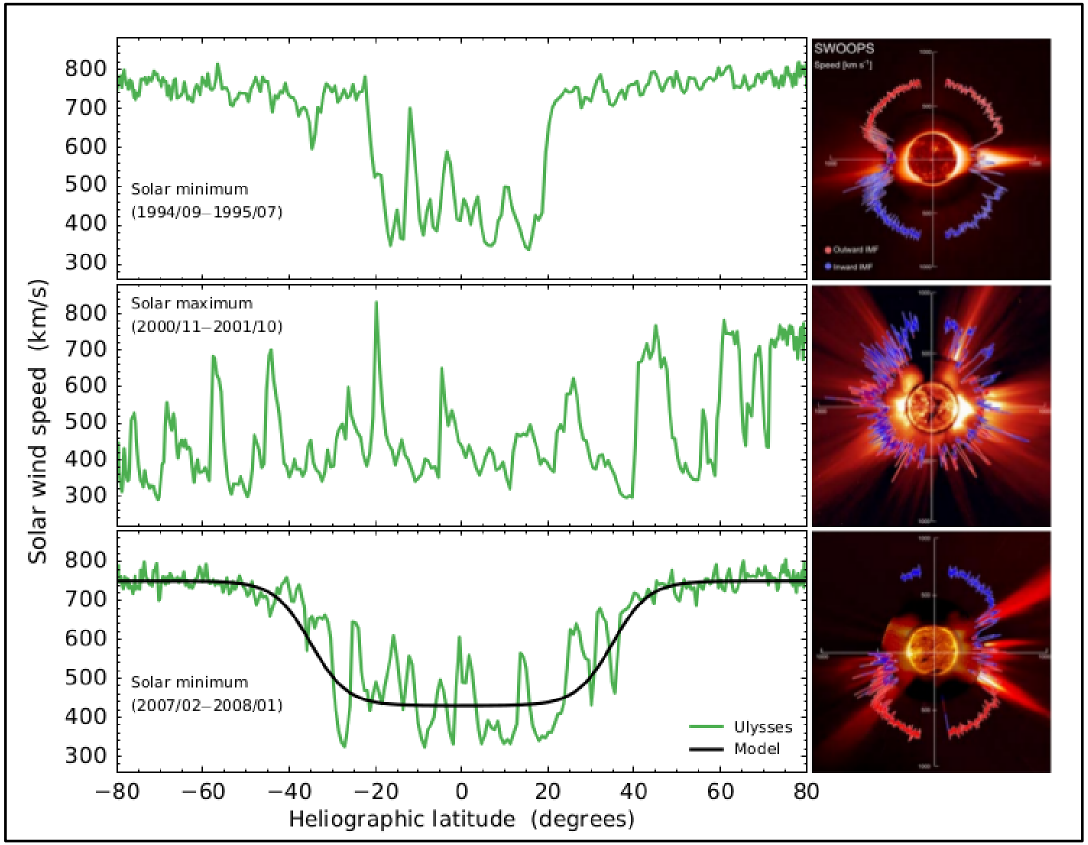
Speed ~ 400-800 km/s

Number density ~10 cm^–3

Flux ~3 10^8cm–2s^–1

Magnetic field ~3 nT

Proton, electron, He ~ 0.5 – 10 KeV

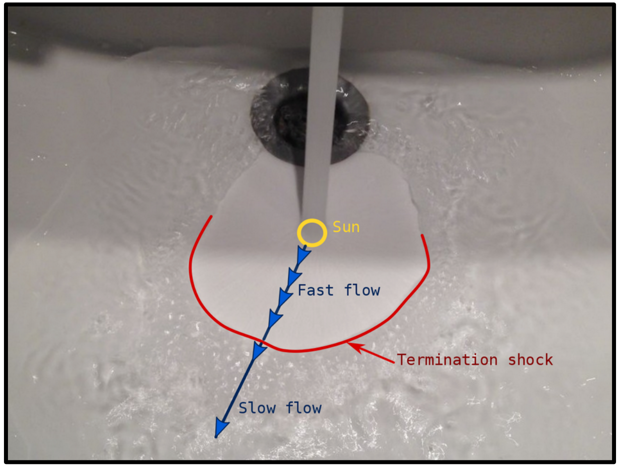


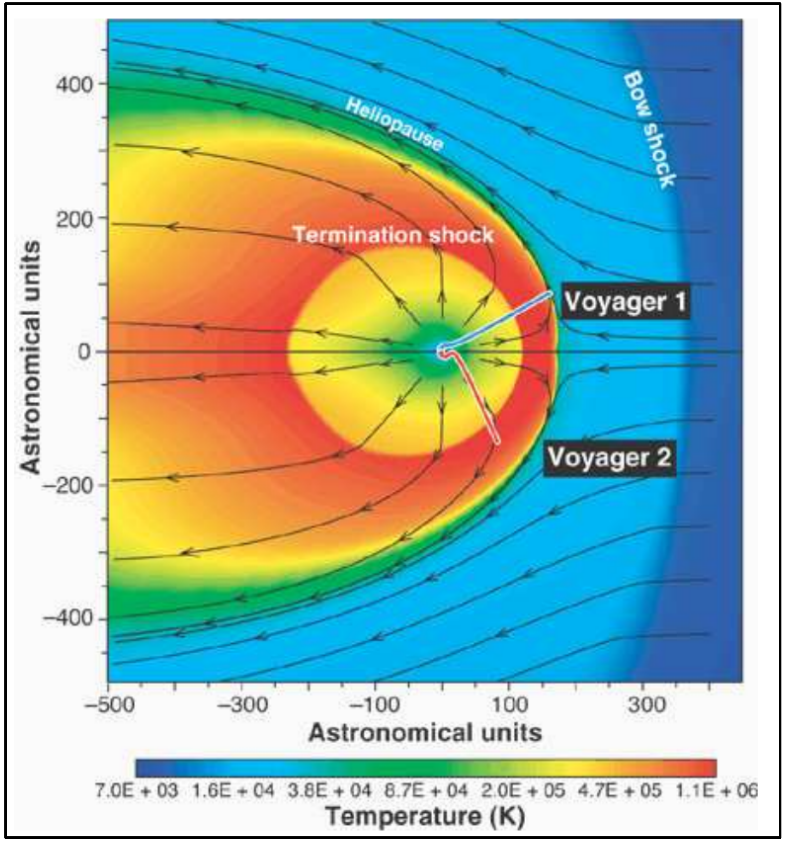
Heliosphere structure

Heliosphere: region of space formed by the expanding SW interacting with the interstellar medium (ISM)

Termination shock (TS): where the SW ram pressure equals the external interstellar thermal pressure

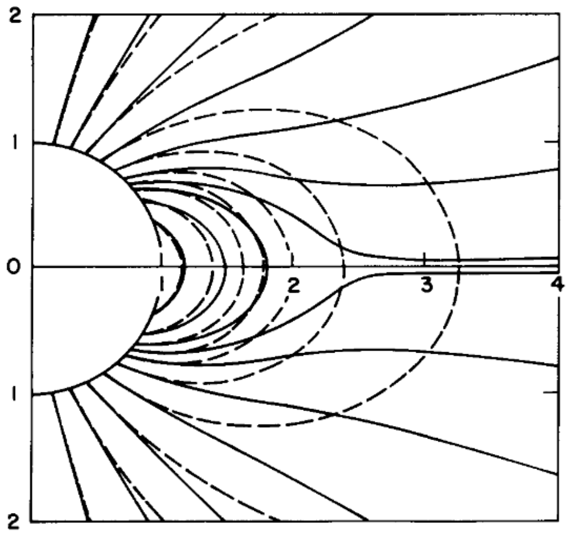
Heliosheat: the region which is between the TS and the **Heliopause** (HP)



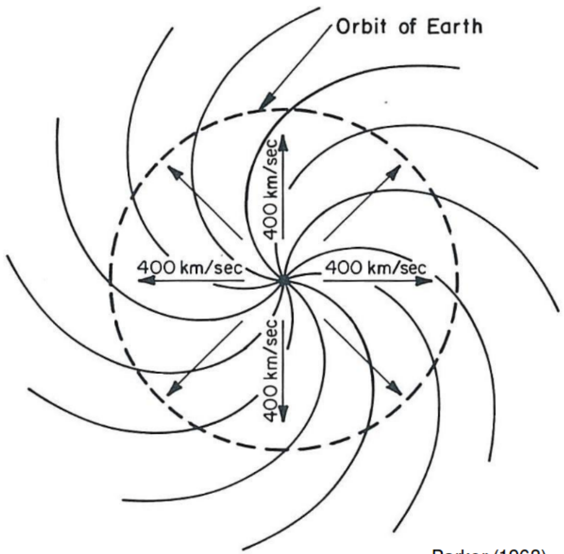


Heliospheric magnetic field (HMF)

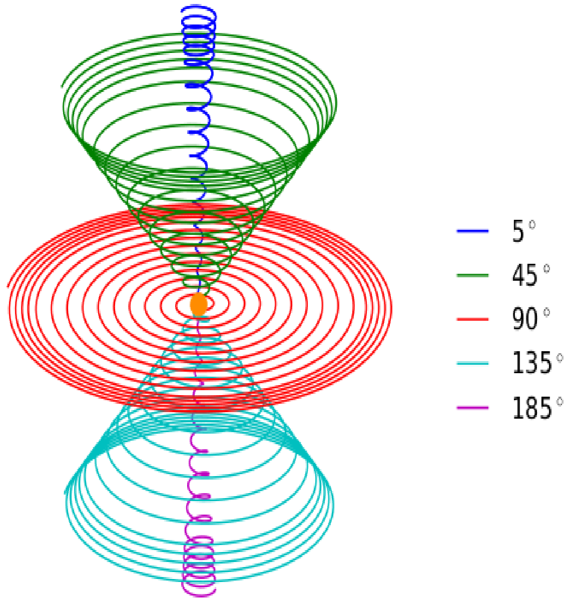
The heliospheric magnetic field is a result of the Sun’s magnetic field being carried outward, frozen in to the solar wind



Model of Pneumann and Kopp (1971)



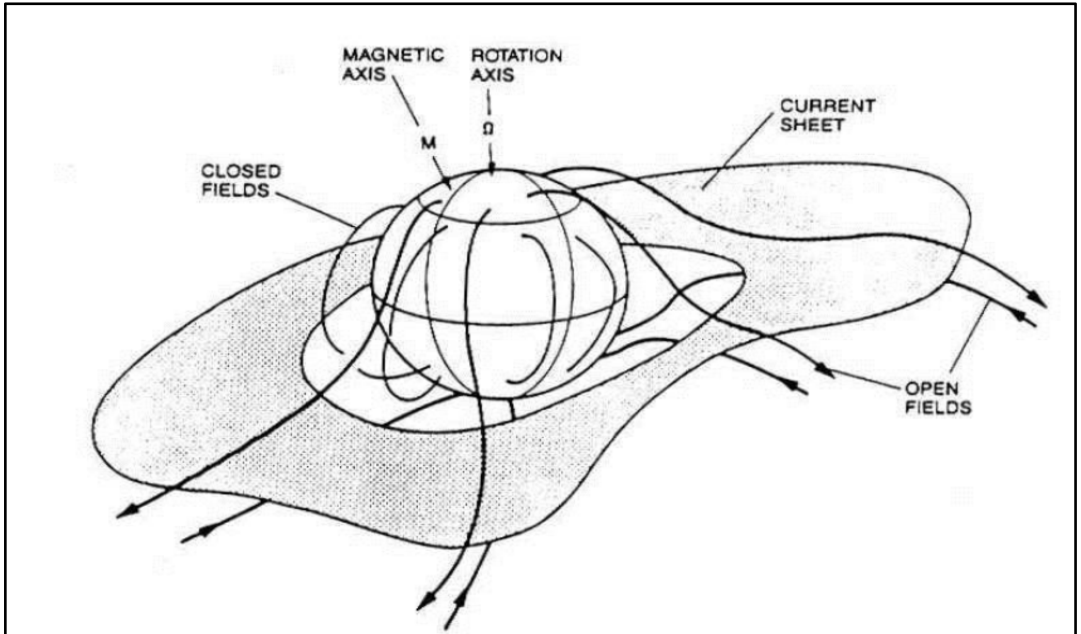
Parker (1963)



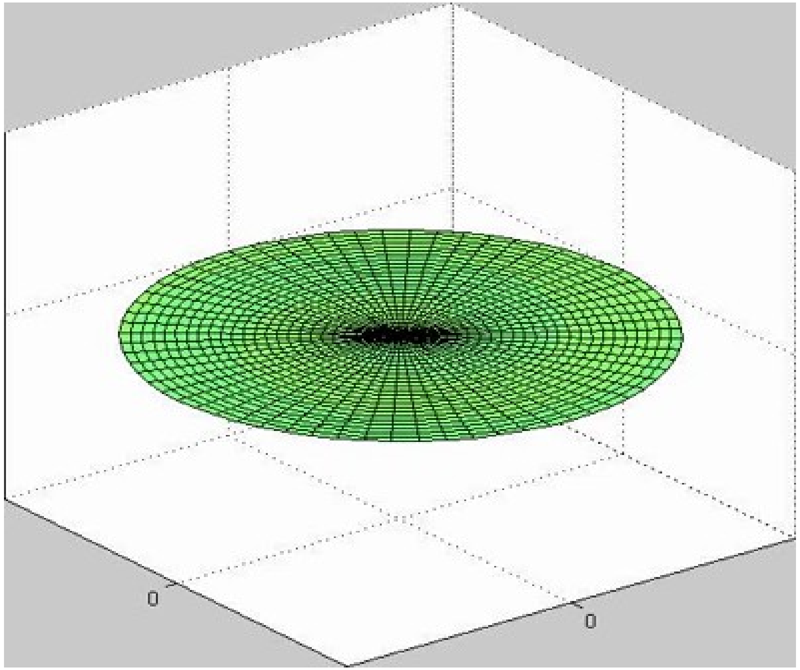
Heliospheric current sheet (HCS)

The heliospheric current sheet forms where outward field lines from one hemisphere meet inward field lines from the other hemisphere.

Tilt angle: inclination angle of the HCS with respect to the ecliptic



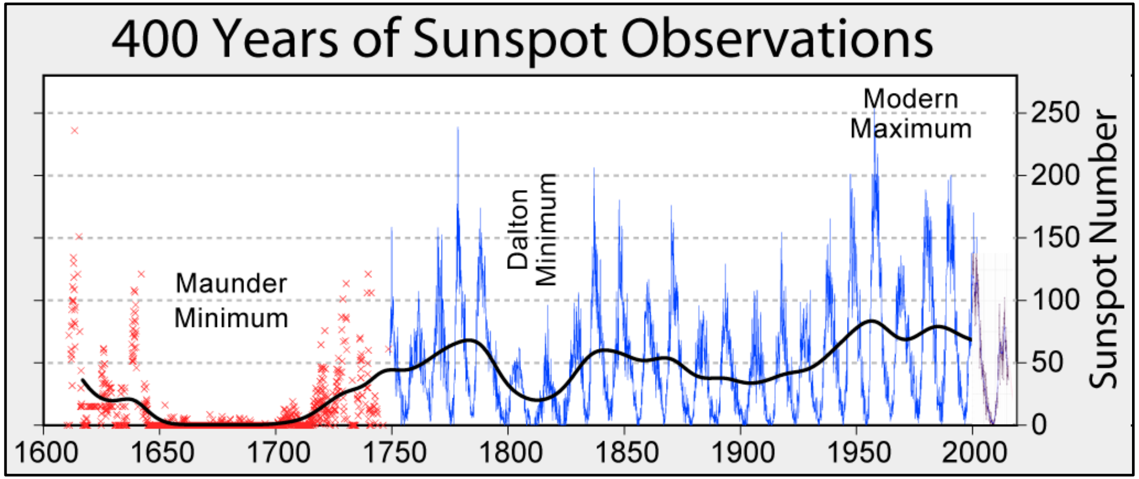
Smith (1997)

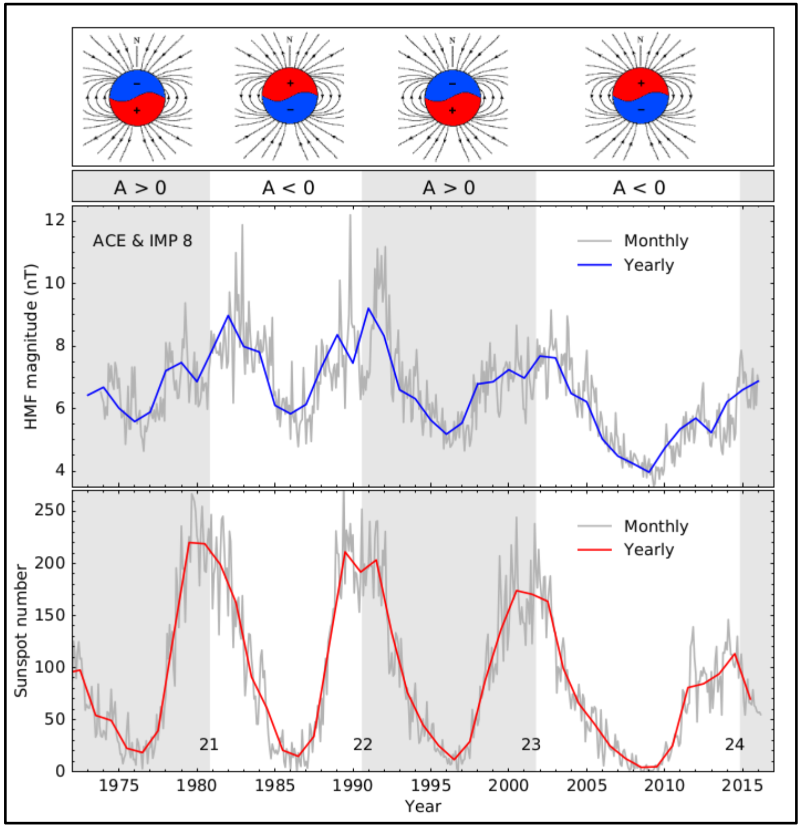


Solar activity cycle

A quasi-periodic variation in solar activity with an apparent periodicity of ∼ 11 years during which the sunspot number fluctuate between successive maxima and minima referred to as solar maximum and minimum.

Polarity reversal every 22 years.

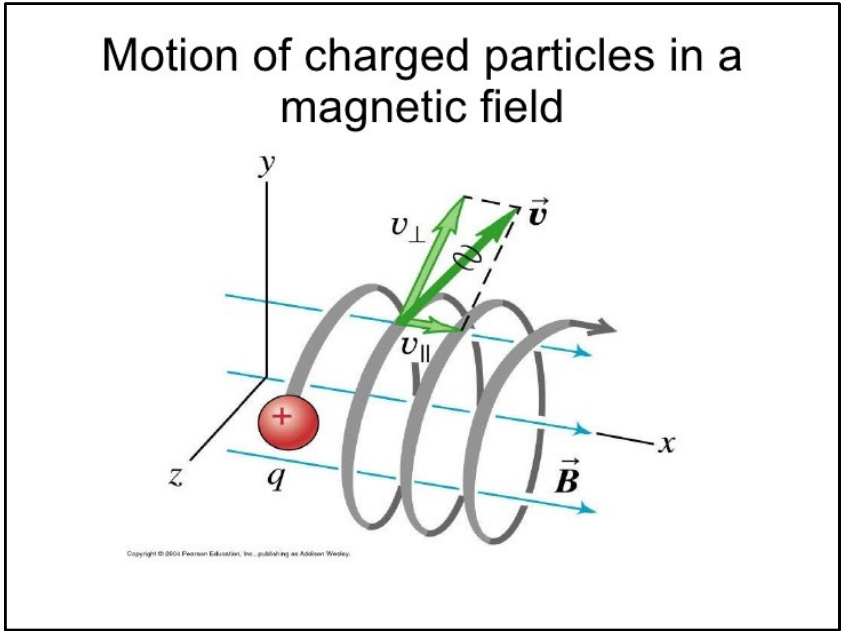




Charge particle motion in magnetic field

For simplicity the motion of a charged particle in magnetic field is described in terms of the guiding center trajectory

Red line: guiding center trajectory



Cosmic rays propagation through Heliosphere

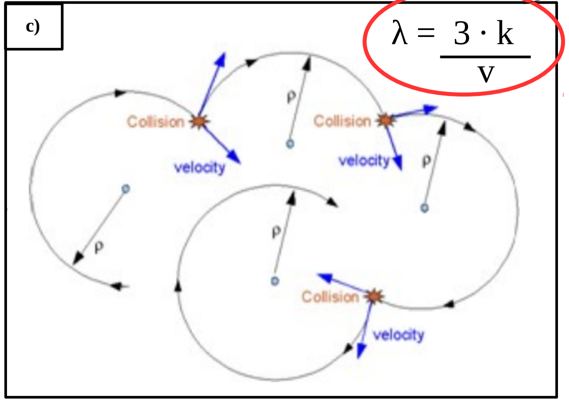
Parker equation

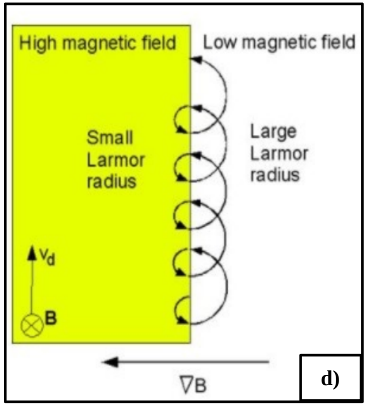
$$\underbrace{\frac{\partial f}{\partial t}}_{a} = -\underbrace{\mathbf{V}\cdot\nabla f}_{b} + \underbrace{\nabla\cdot(\mathbf{K_s}\cdot\nabla f)}_{c} - \underbrace{\langle \mathbf{v_D}\rangle\cdot\nabla f}_{d} + \underbrace{\frac{1}{3}(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial \ln p}}_{e} + \underbrace{Q(\mathbf{x},p,t)}_{f}$$

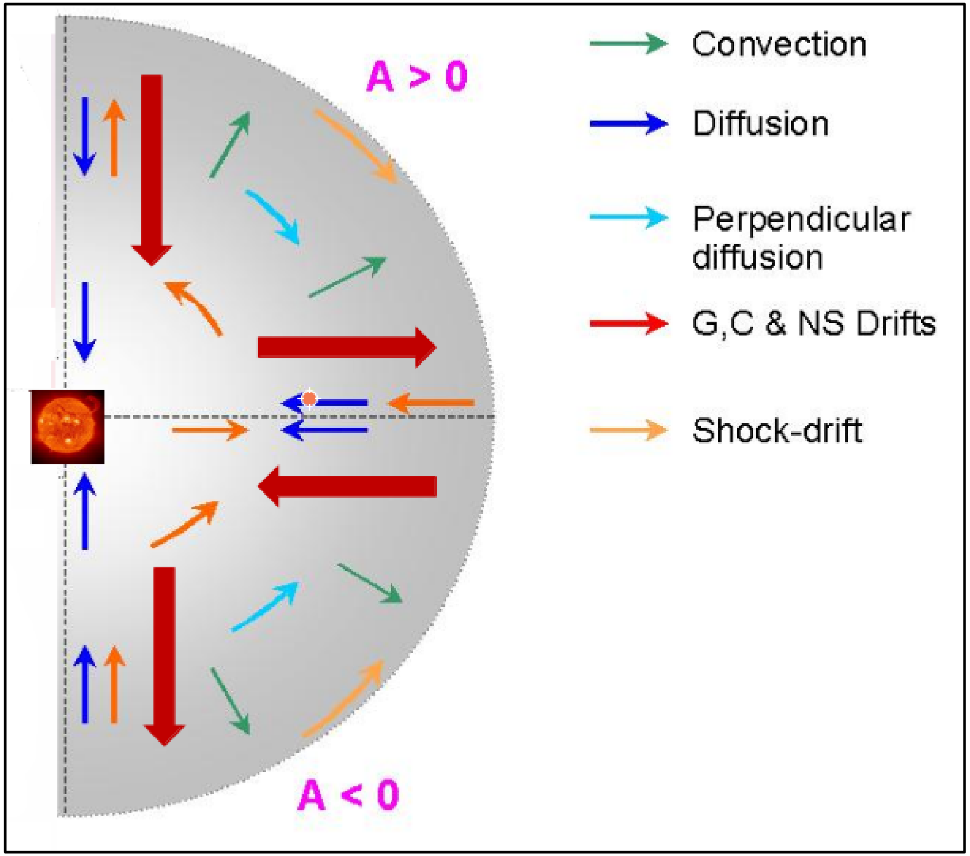
a) Omnidirectional function distribution of CRs
b) Convection with expanding solar wind
c) Diffusion on magnetic field irregularities
d) Drift on magnetic field gradients curvature
e) Adiabatic energy losses
f) Local sources

Mean free path: mean distance between two consecutive collision

$$\lambda = \frac{3\cdot k}{v}$$







3D numerical model for CRs propagation

Parker equation

$$\underbrace{\frac{\partial f}{\partial t}}_{a} = -\underbrace{\mathbf{V}\cdot\nabla f}_{b} + \underbrace{\nabla\cdot(\mathbf{K_s}\cdot\nabla f)}_{c} - \underbrace{\langle \mathbf{v_D}\rangle\cdot\nabla f}_{d} + \underbrace{\frac{1}{3}(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial \ln p}}_{e} + \underbrace{Q(\mathbf{x},p,t)}_{f}$$

Sperical coordinates steady state approximation

$$\overbrace{\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 K_{rr}\right) + \frac{1}{r\sin\theta}\frac{\partial K_{\phi r}}{\partial \phi}\right]\frac{\partial f}{\partial r} + \left[\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(K_{\theta\theta}\sin\theta\right)\right]\frac{\partial f}{\partial\theta}}^{\text{diffusion}}$$
$$+ \overbrace{\left[\frac{1}{r^2\sin\theta}\frac{\partial}{\partial r}(rK_{r\phi}) + \frac{1}{r^2\sin^2\theta}\frac{\partial K_{\phi\phi}}{\partial\phi} - \Omega\right]\frac{\partial f}{\partial\phi}}^{\text{diffusion}}$$
$$+ \overbrace{K_{rr}\frac{\partial^2 f}{\partial r^2} + \frac{K_{\theta\theta}}{r^2}\frac{\partial^2 f}{\partial\theta^2} + \frac{K_{\phi\phi}}{r^2\sin^2\theta}\frac{\partial^2 f}{\partial\phi^2} + \frac{2K_{r\phi}}{r\sin\theta}\frac{\partial^2 f}{\partial r\partial\phi}}^{\text{diffusion}}$$
$$+ \overbrace{\left[-\langle \mathbf{v}_A\rangle_r\right]\frac{\partial f}{\partial r} + \left[-\frac{1}{r}\langle \mathbf{v}_A\rangle_\theta\right]\frac{\partial f}{\partial\theta} + \left[-\frac{1}{r\sin\theta}\langle \mathbf{v}_A\rangle_\phi\right]\frac{\partial f}{\partial\phi}}^{\text{drift}}$$
$$- \overbrace{V_{sw}\frac{\partial f}{\partial r}}^{\text{convection}}$$
$$+ \overbrace{\frac{1}{3r^2}\frac{\partial}{\partial r}\left(r^2 V_{sw}\right)\frac{\partial f}{\partial \ln p}}^{\text{adiabatic energy losses}} = 0.$$

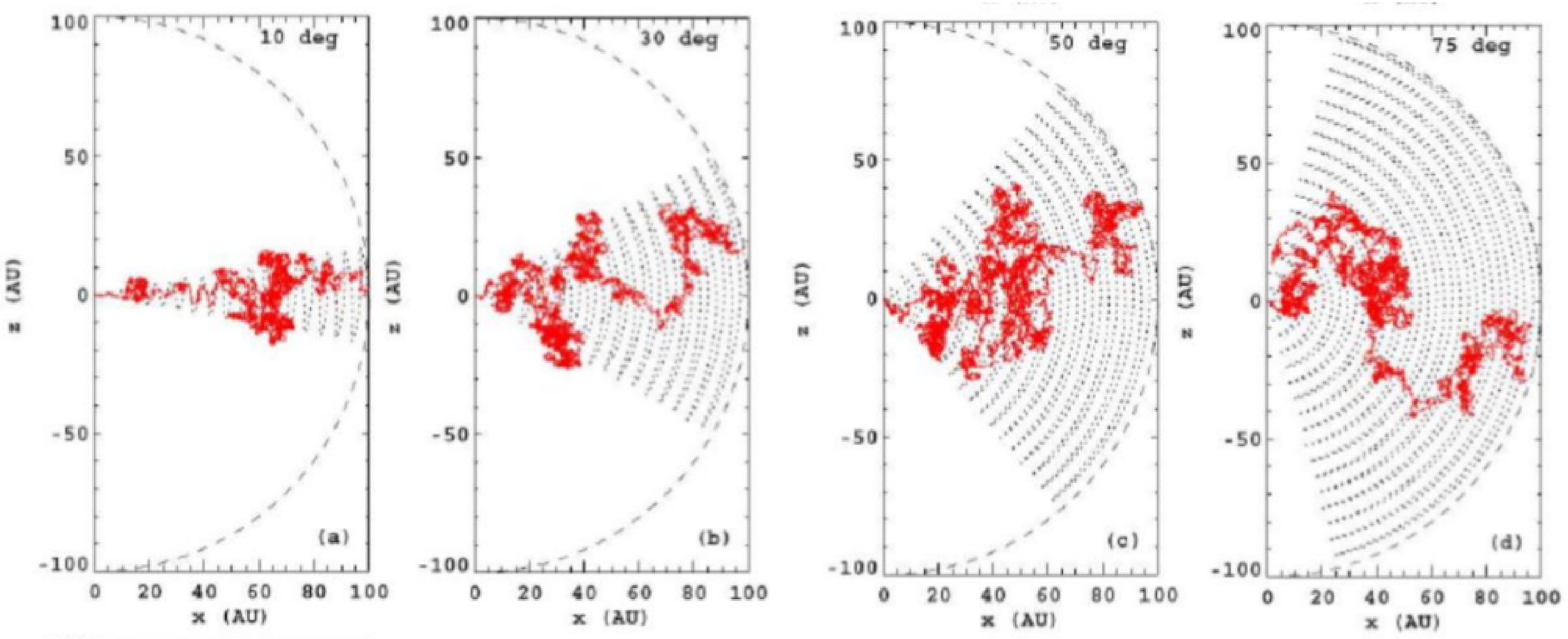
From theory:
- Propagation equation

From data:
- Tune of free parameters

Other approach possible like stochastic differential equation possible and have a time dependent solution

Charge particle motion inside Heliosphere

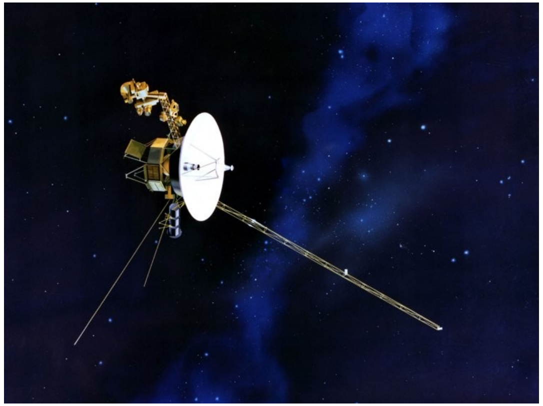
Trajectory of protons propagating from outside the Heliosphere to the Earth during different period of solar activity



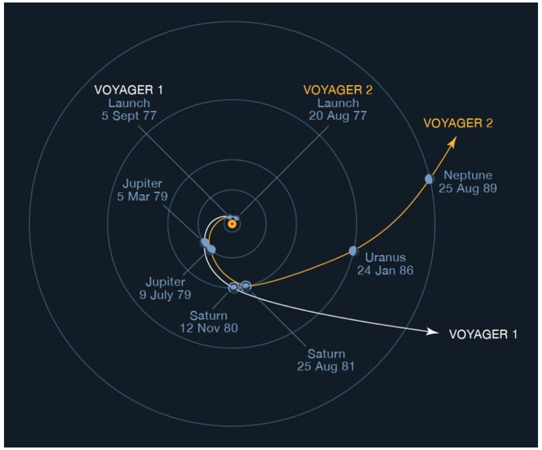
Solar minimum → **Solar maximum**

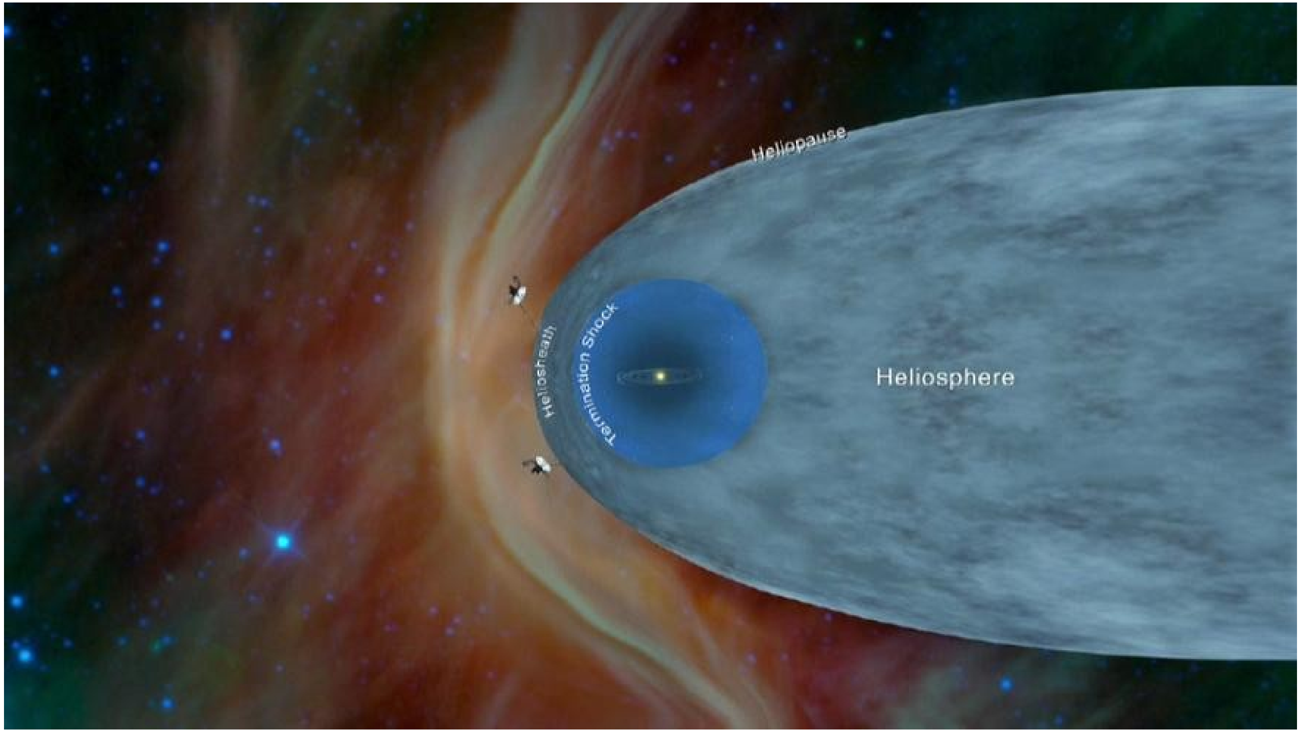
CRs trough Heliosphere

Voyager journey inside (and outside) Heliosphere



Voyager 1-2: space probes launched by NASA on September and August 1977
Exploration of the solar system and beyond the outer limits of the Heliosphere



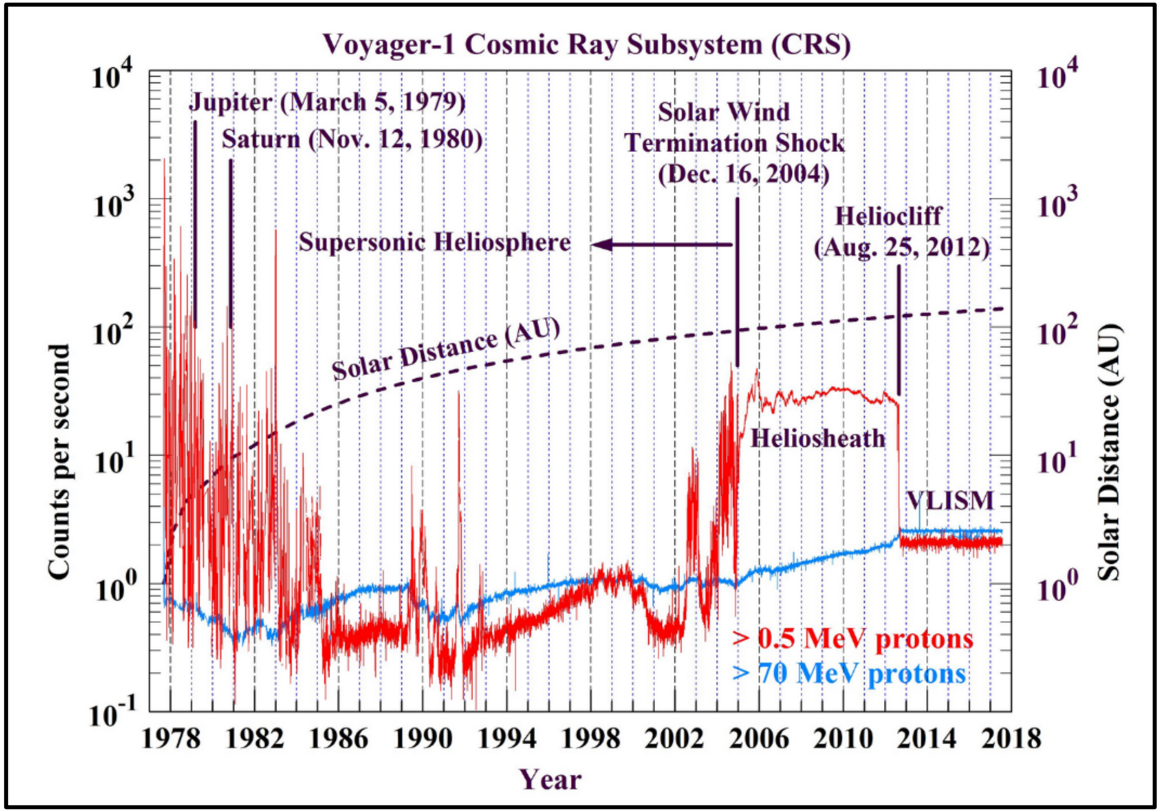


Voyager data trough the Heliosphere

Equipped with several instrument:

- Imaging Science System
- Radio Science System
- Infrared Interferometer Spectrometer
- Ultraviolet Spectrometer
- Triaxial Fluxgate Magnetometer
- Low Energy Charged Particle Instrument
- Cosmic Ray System
- …..

Voyager 1 reach the HP in 2012,
Voyager 2 reach the HP in late 2018



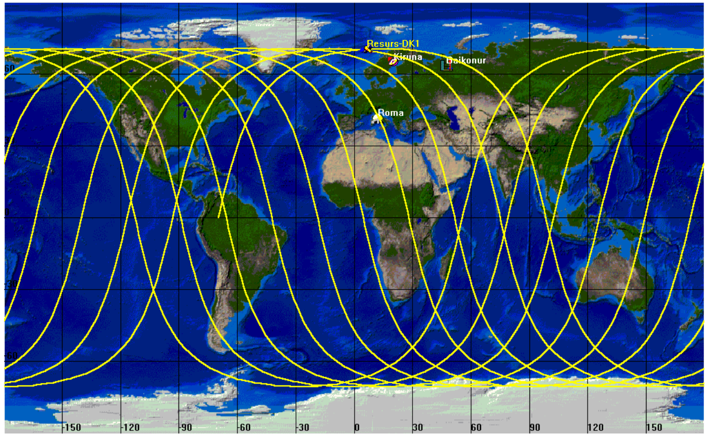
PAMELA and solar modulation

PAMELA: CRs detector deeply inside Heliosphere

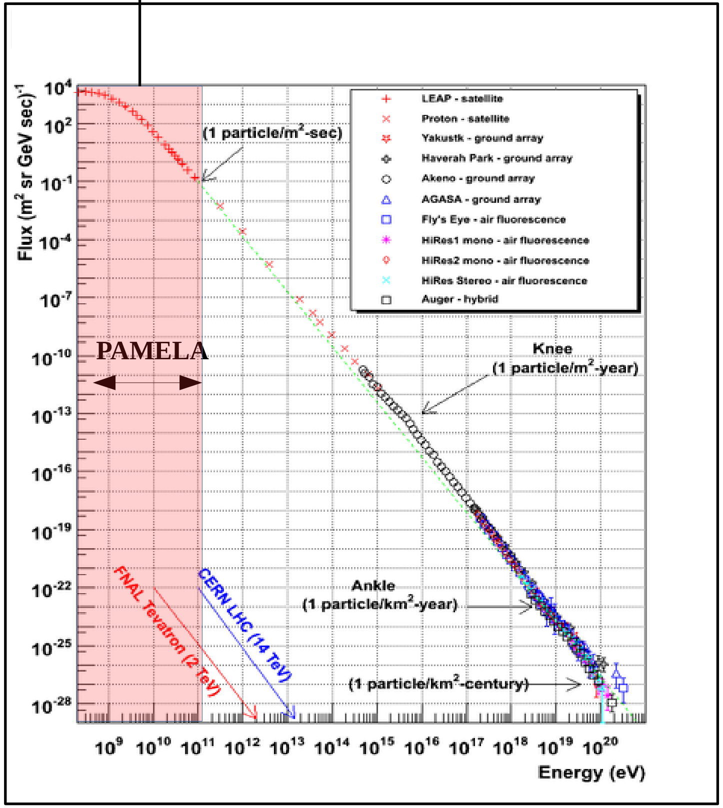
1 AU from the Sun
50 MeV – 1 TeV

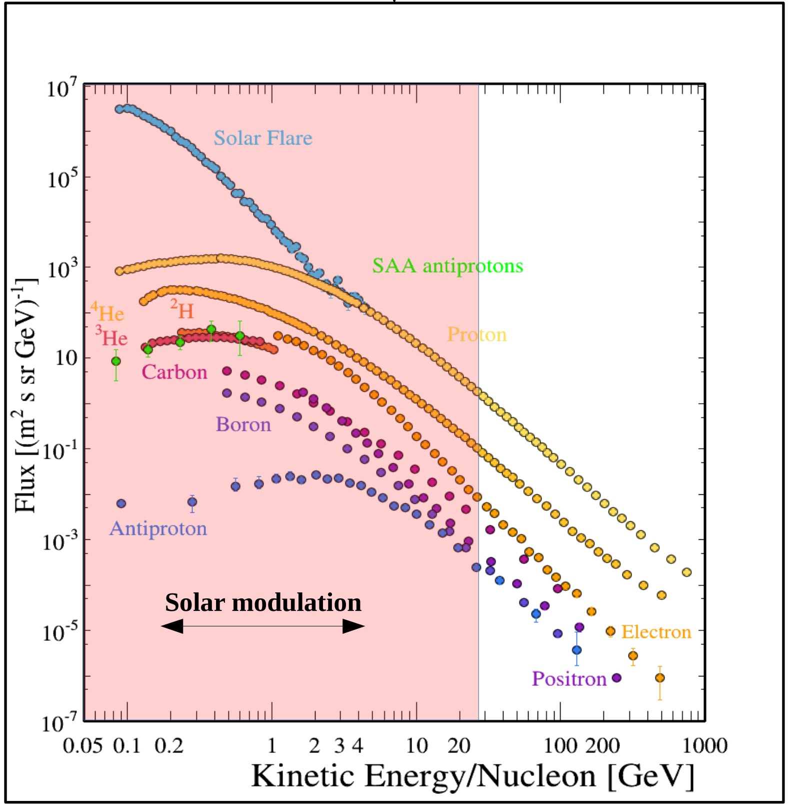
- Multi-particle measurement
- Cosmic ray origin
- Dark matter search

Quasi polar elliptical orbit

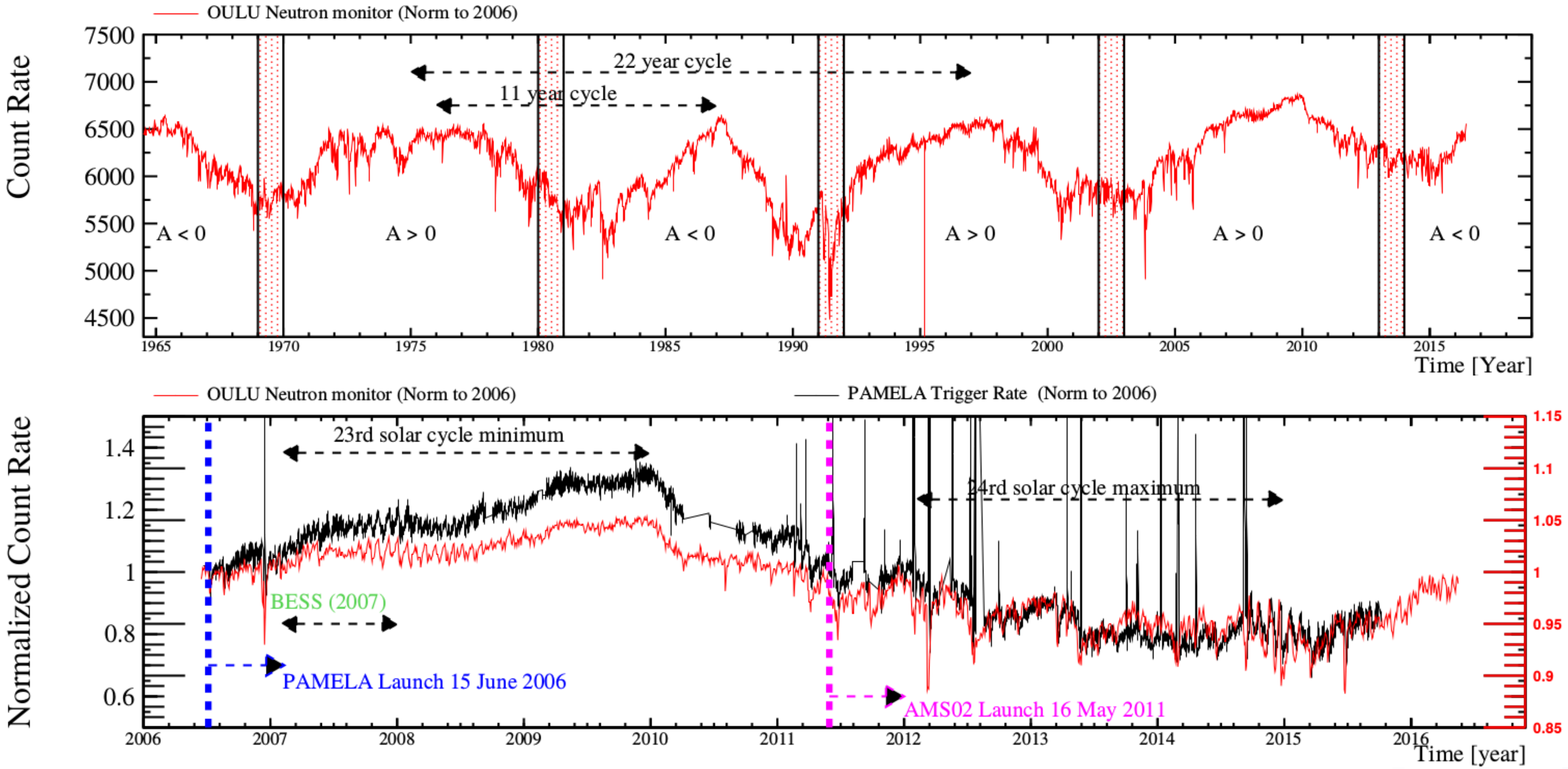


PAMELA: energy range





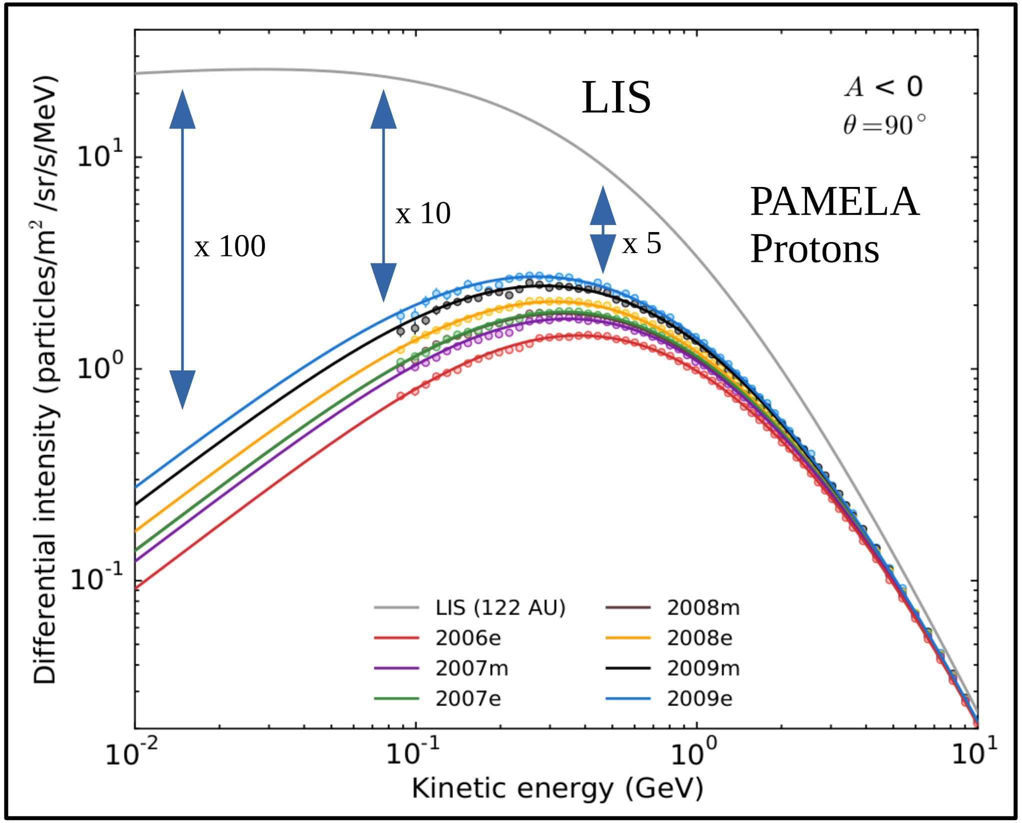
PAMELA trough a solar cycle



Protons modulation modeling

Solar modulation heavely affected cosmic rays propagation below 30 GV.

The local interstellar spectrum (LIS) is changed both in intensity and shape



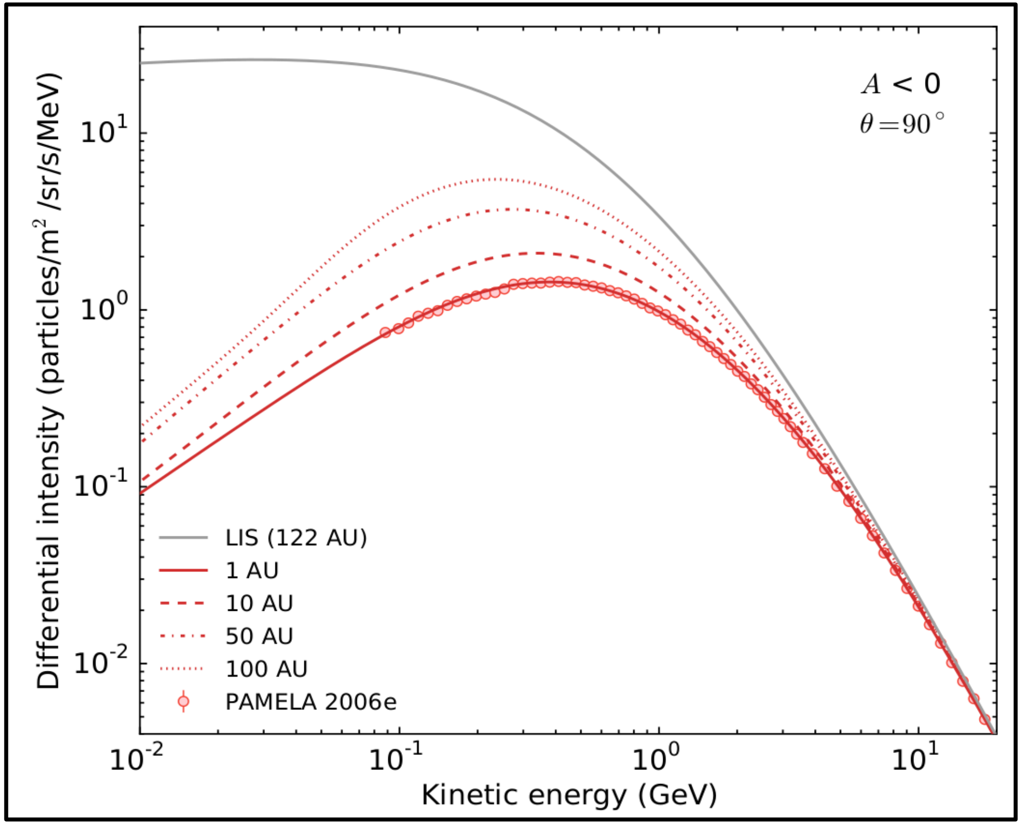
Protons modulation modeling

Solar modulation heavely affected cosmic rays propagation below 30 GV.

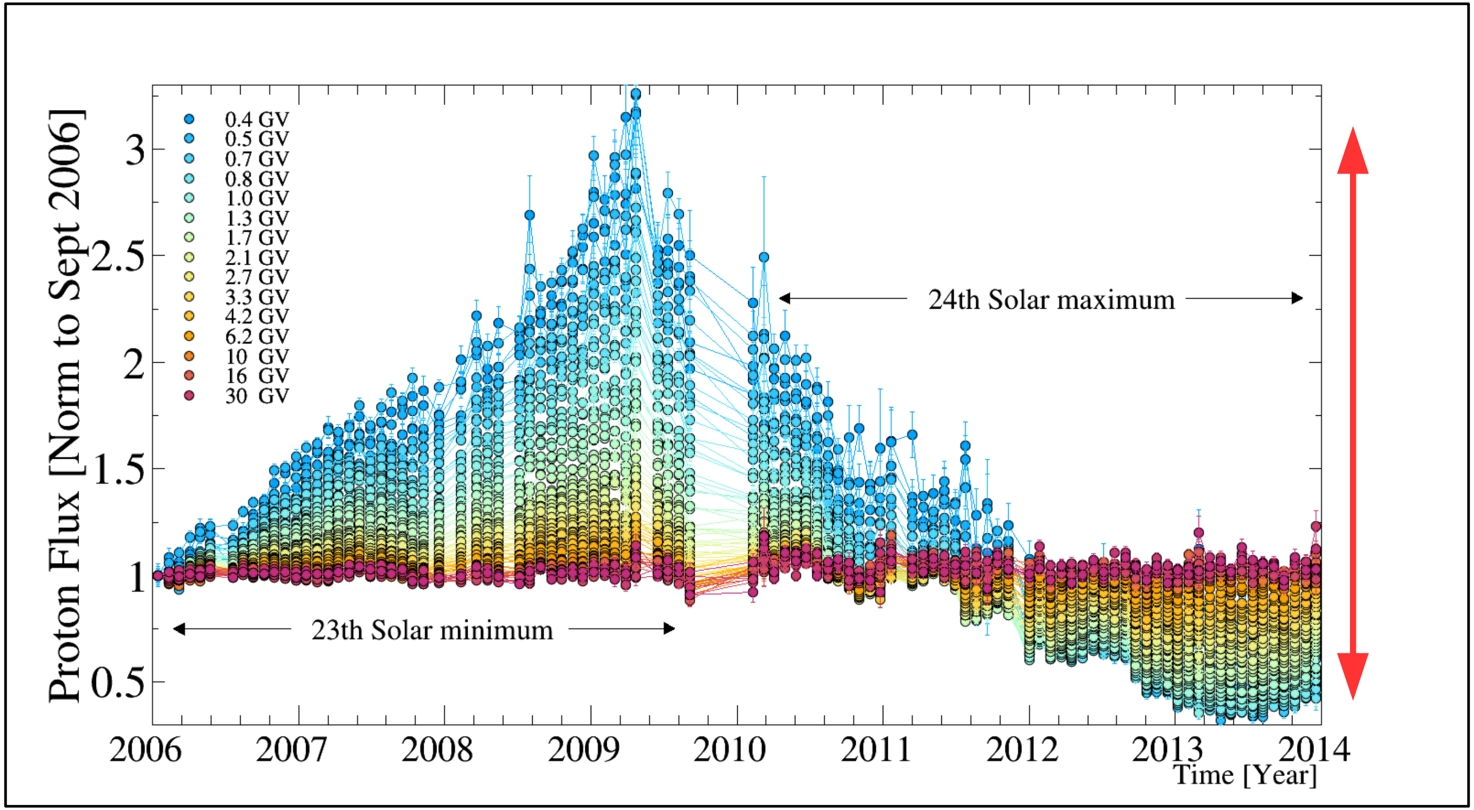
The local interstellar spectrum (LIS) is changed both in intensity and shape

Models which solves numerically the Parker equation are used in order to reproduce the measured intensity at Earth.

Modulated spectra evaluated for different position inside the Heliopshere



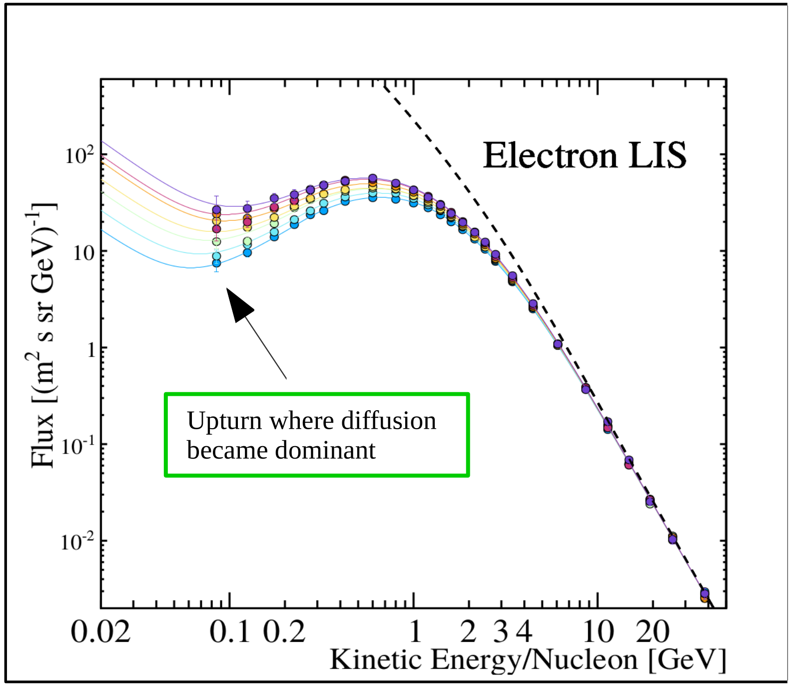
Protons modulation modeling

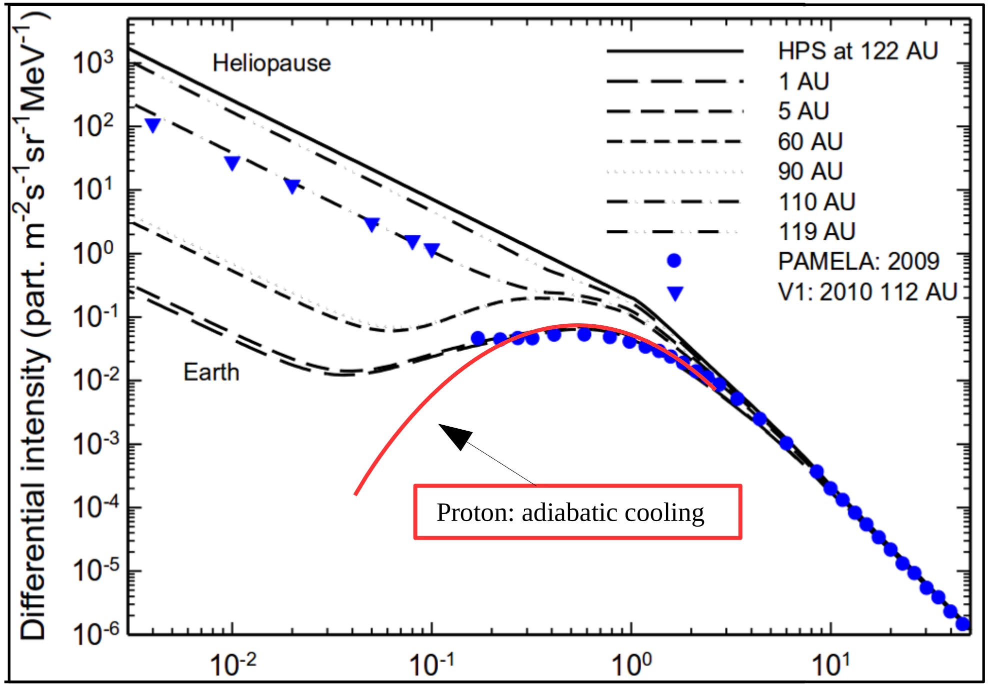


Factor 6 of intensity variation from solar minimum to solar maximum

Electrons modulation modeling

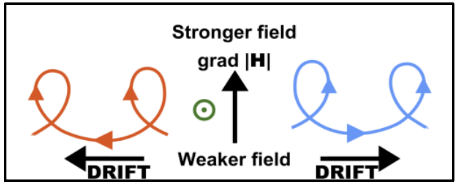
Different modulation mechanism due to mass differences.

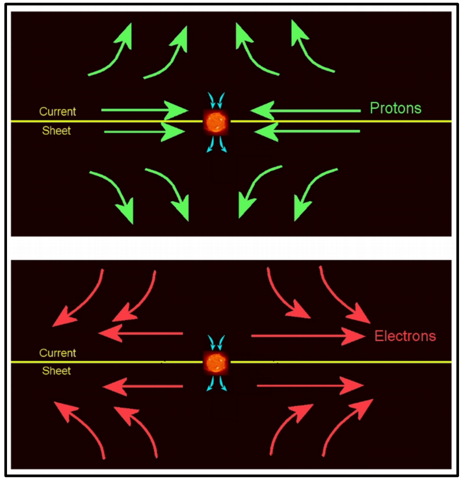




Charge sign dependence in solar modulation

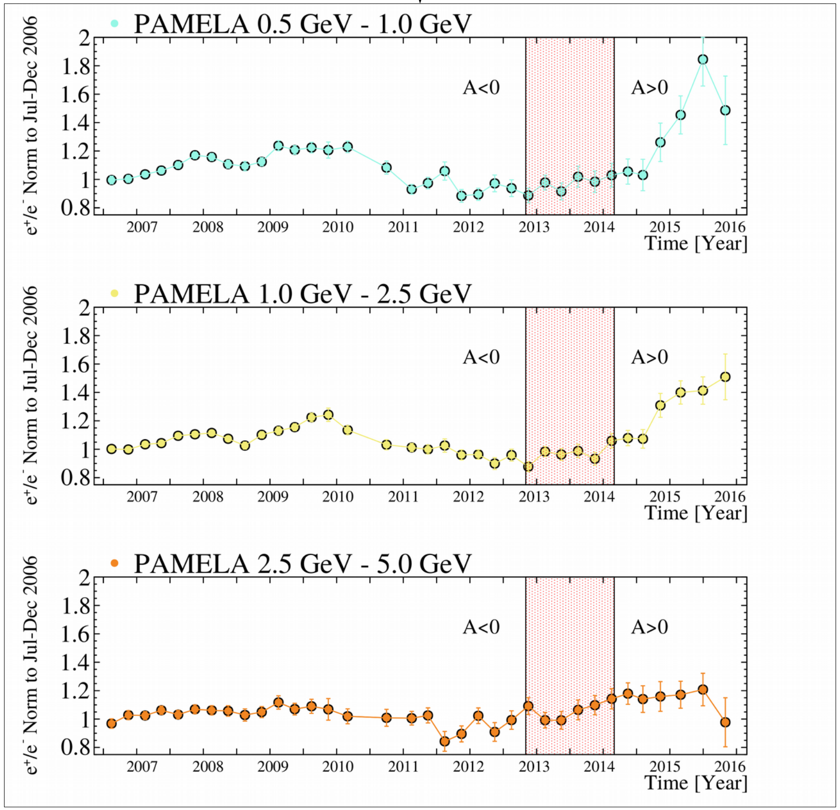
Drift motion is opposite for positively and negatively charged particles





Different pattern of drift motion in the heliosphere for positively and negatively charged particles

Particle with opposite charge propagate preferentially trough different region of the Heliosphere experiencing different amount of modulation



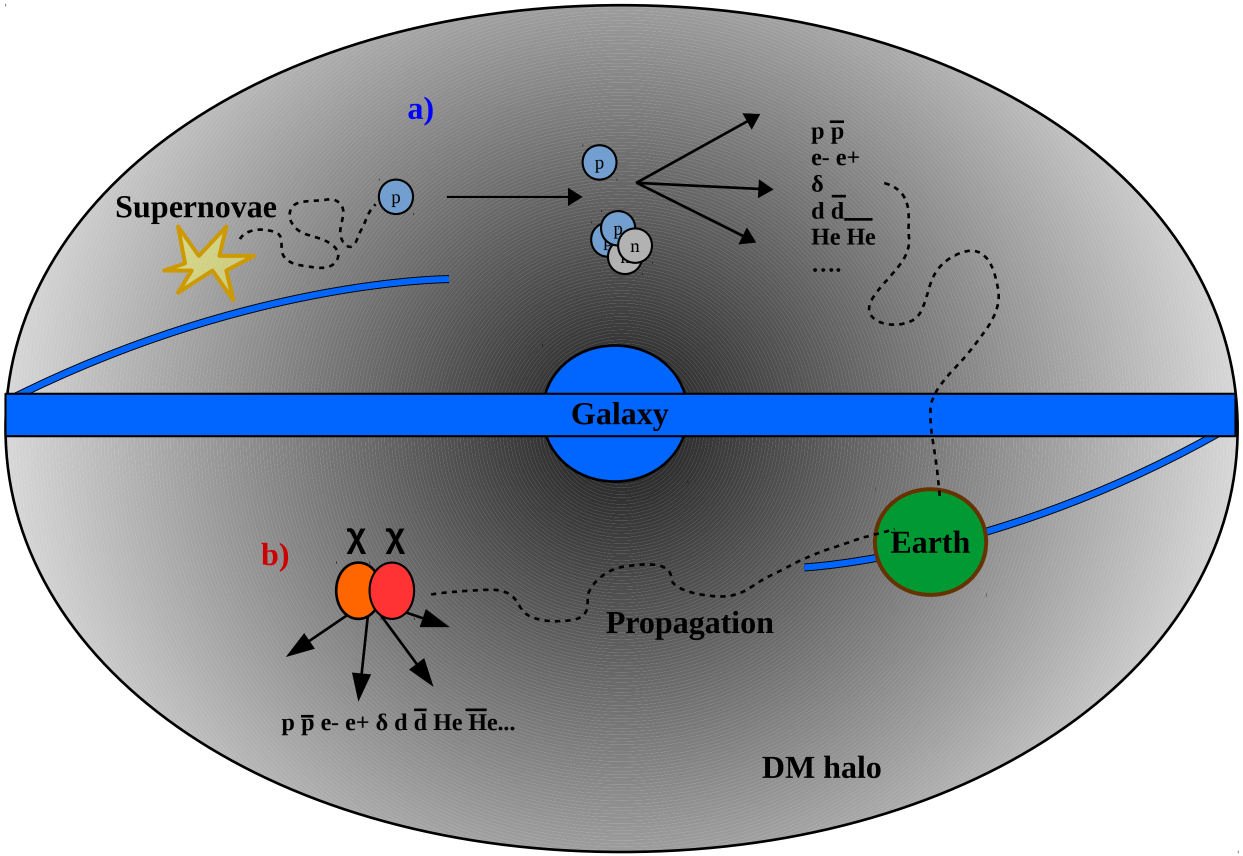
Dark matter search and solar modulation

Antimatter production in CRs

a) Primary Crs interacting with interstellar matter (IM)

b) Decay or annihilation of DM particles in galactic halo (beyond standar model theories)

Antimatter from DM is expected to be of the order or higher with respect to secondaries CRs



Positron fraction: dark matter detection?

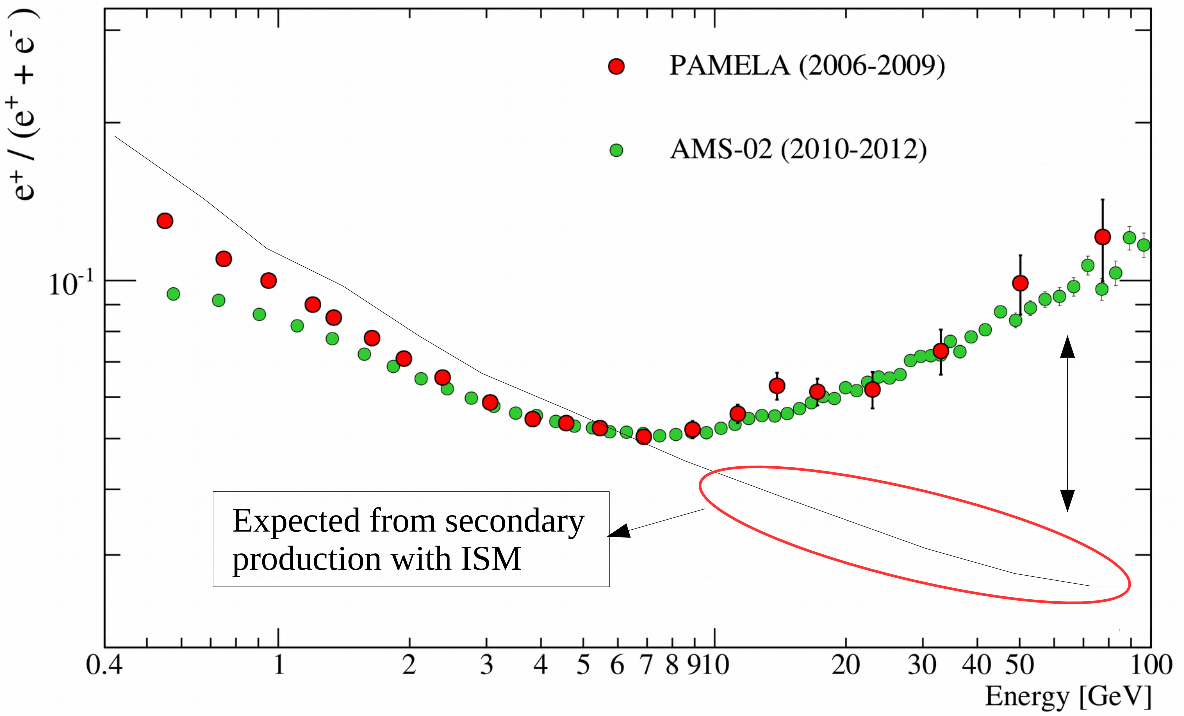
No e+ expected from supernovae explosions!

PAMELA measured a positron excess above 10 GV with respect to a purely secondary production

? ?

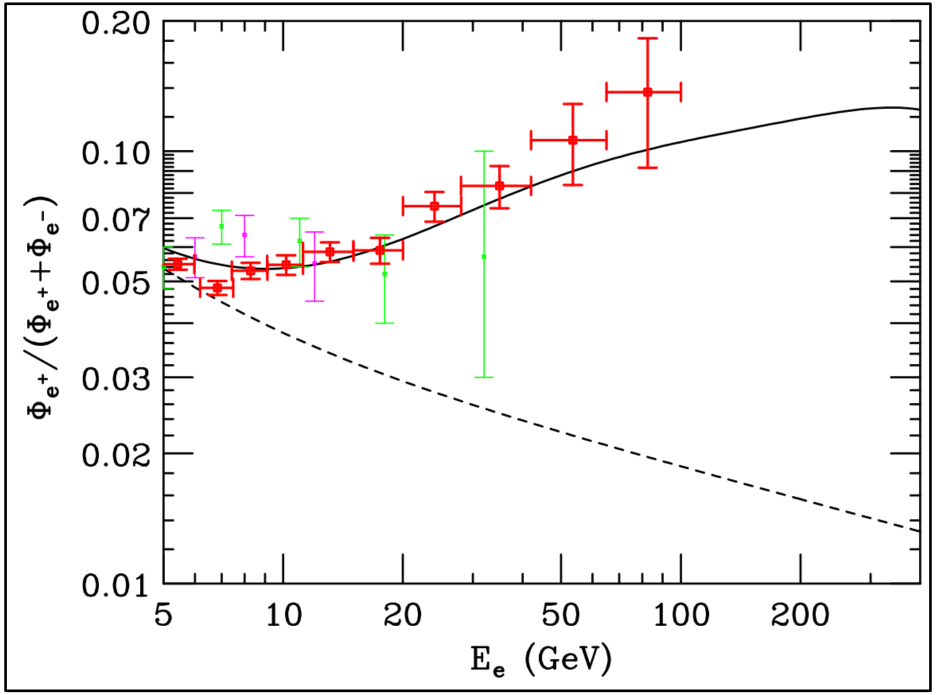
- Wrong propagation?
- Dark matter?
- Astrophysical sources?

Positron excess!



Positron fraction: astrophysical sources?

Contribution from diffuse mature and nearby young pulsars

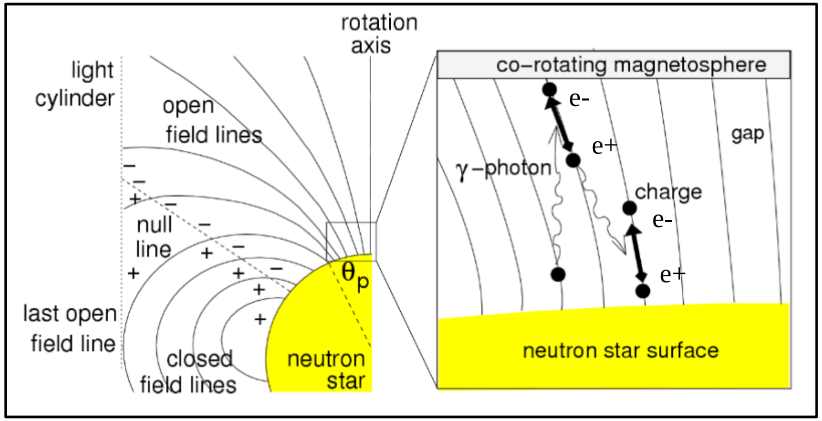


Electrons are stripped off the surface of the neutron star because of the strong electric field.

Perpendicular momentum rapidly dissipated through synchrotron emission.

Photon → pair production on virtual photon of magnetic field.

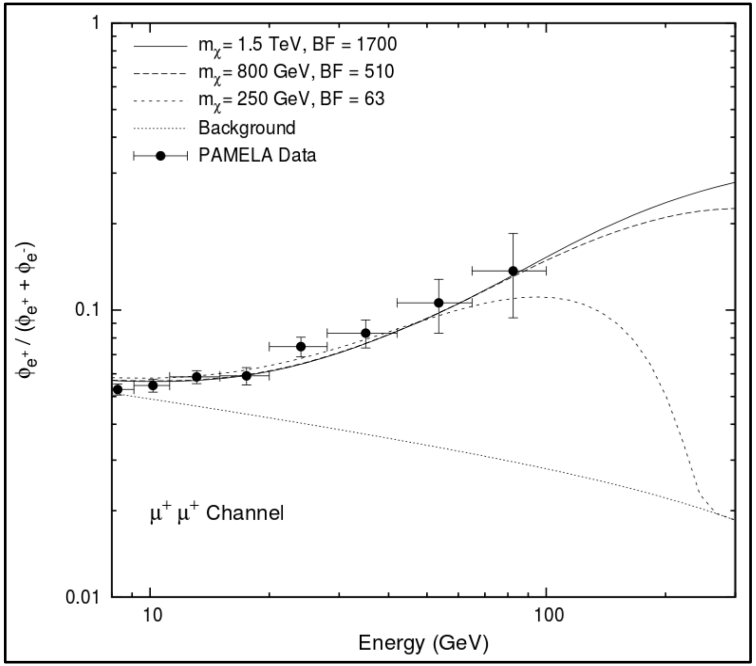
For each electron extracted from the surface the magnetosphere is populated with 10^4 -10^6 pairs .

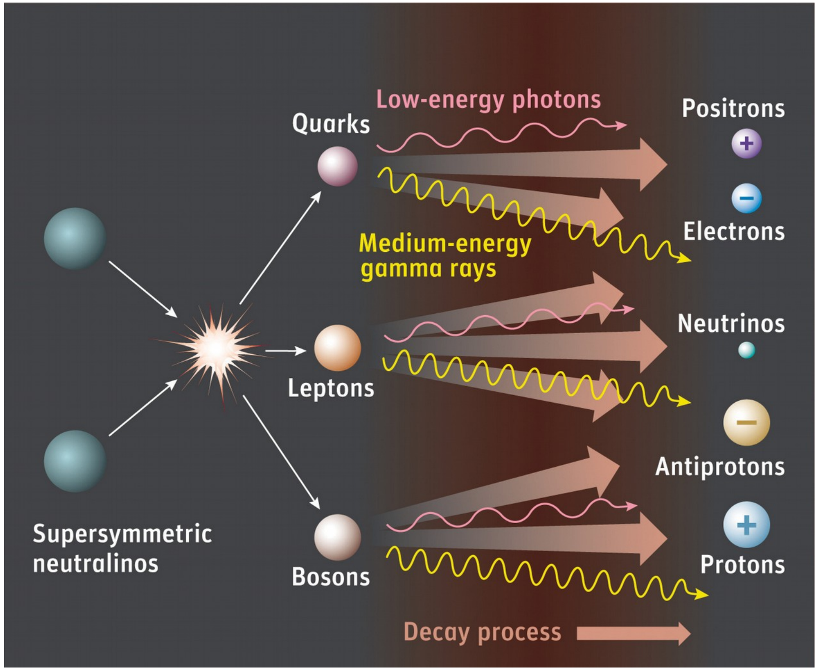


Positron fraction: dark matter detection?

Contribution from dark matter assuming various masses

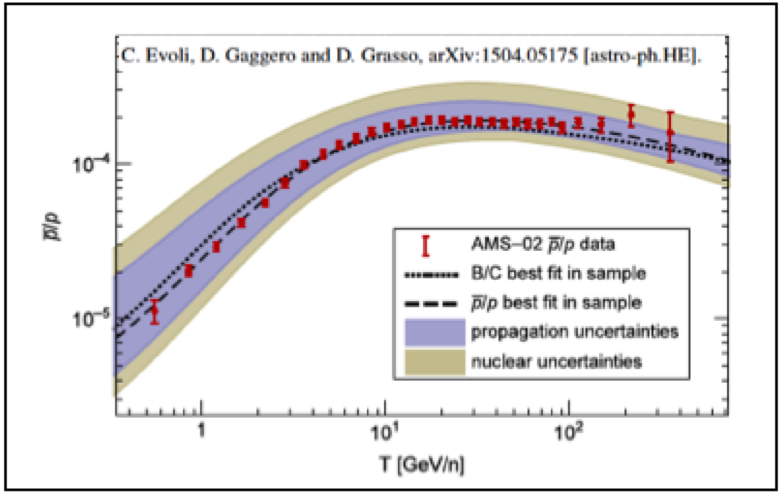
Search for an excess in antimatter component of CRs since standard matter have an astrophysical background orders of magnitude greater than the excpeted signal.

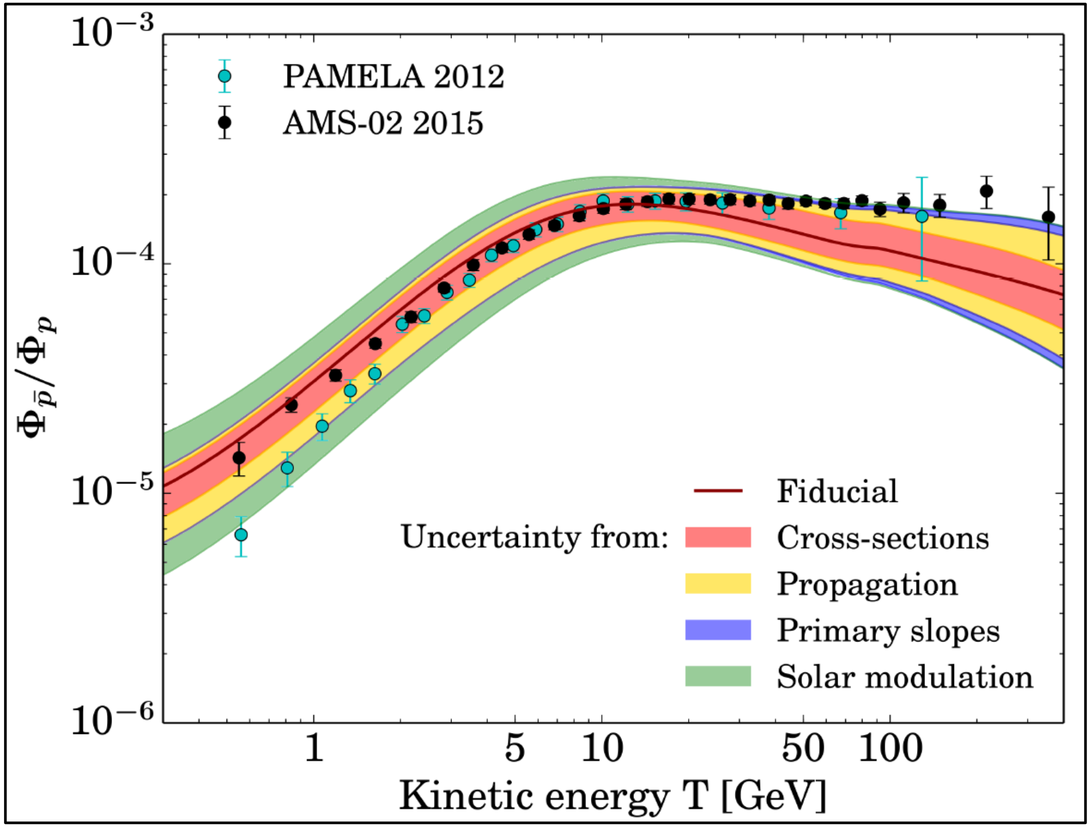




Antiproton: high energy excess?

While for positron the excess is very large for antiproton there is not a clear excess with respect to secondary production at high energie. Good agreement within uncertainties!



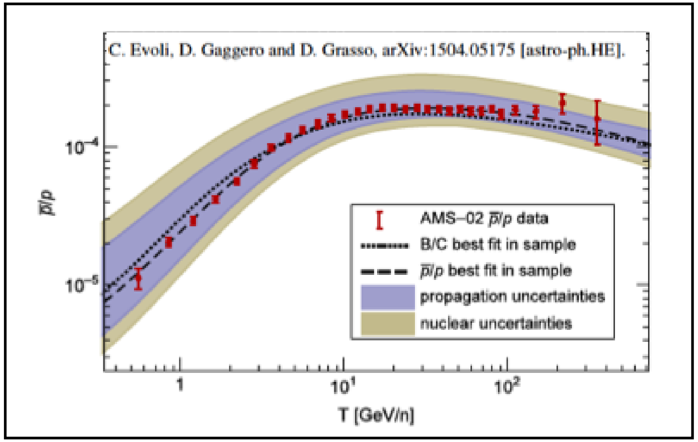


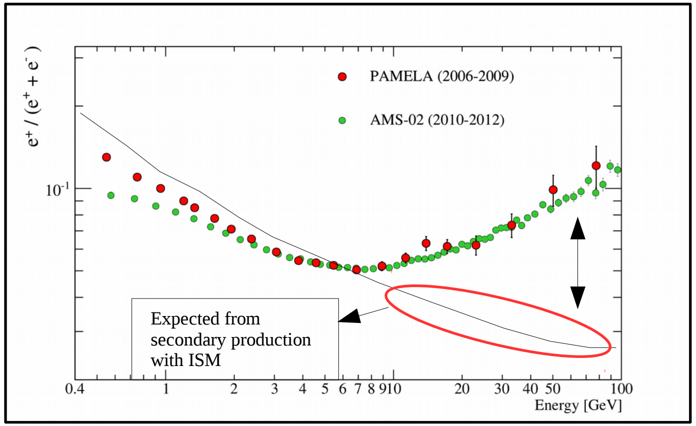
Dark matter?

Difficult to accomodate the DM interpretation of a significant excess in the positron fraction with a not significant excess in antiproton

Why dark matter should preferentially decade in the lepton sector?

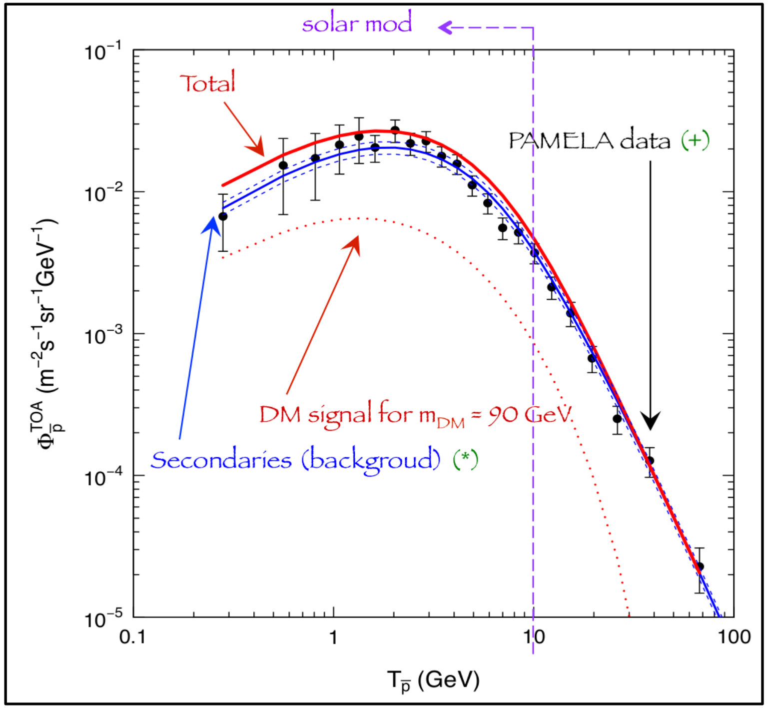
Look other energy range?
Look other particle species?

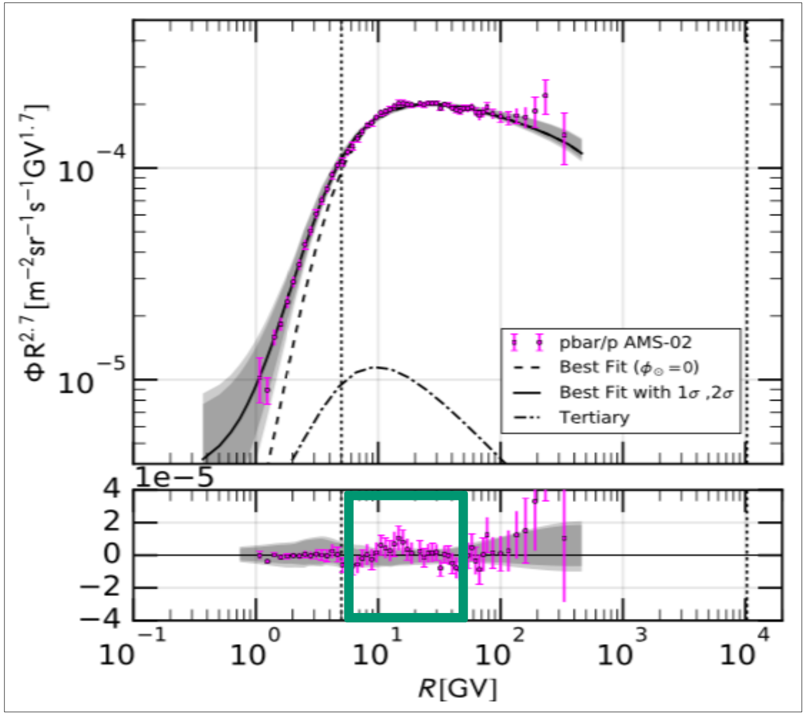




Antiproton: low energy excess?

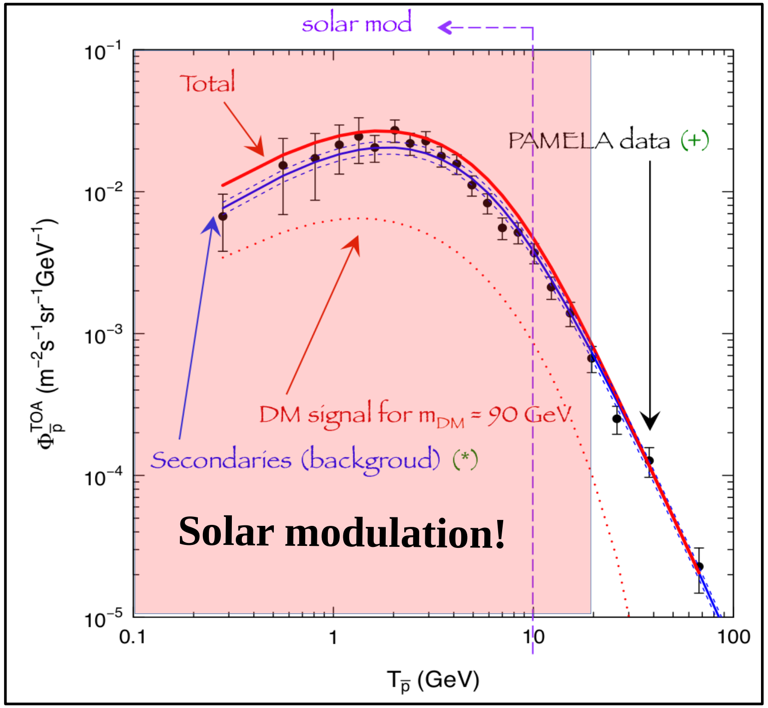
Low energy excess in AMS02 data with respect to secondary production

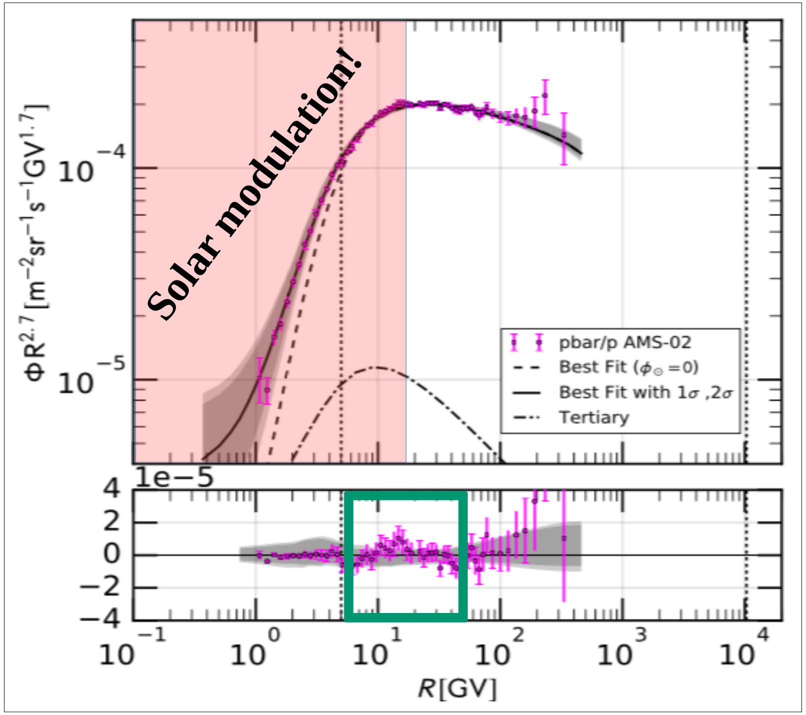




Antiproton: low energy excess?

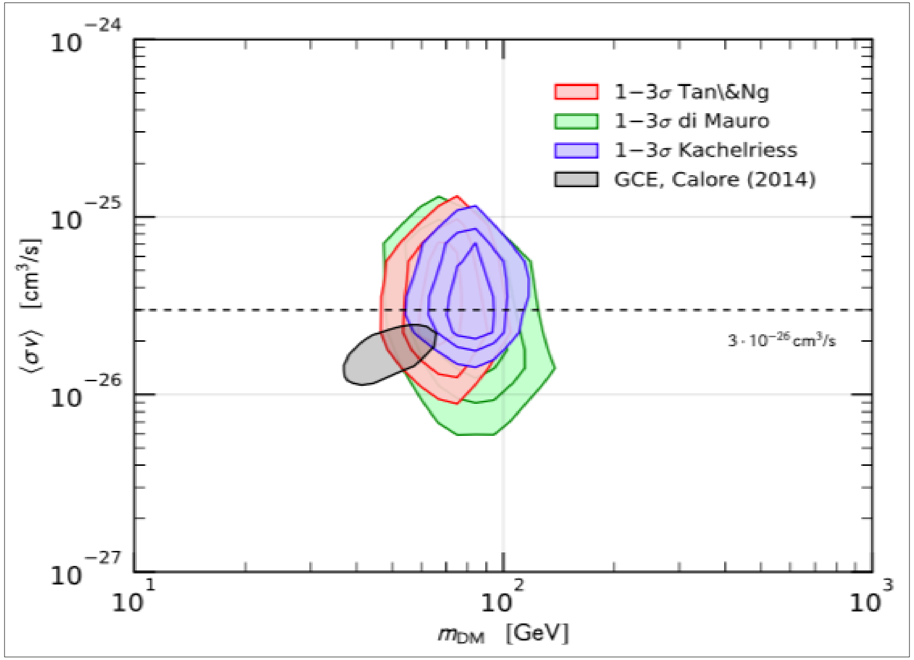
In order to search any DM excess in CR antimatter spectra at low energy is necessary a good modeling of the solar modulation!



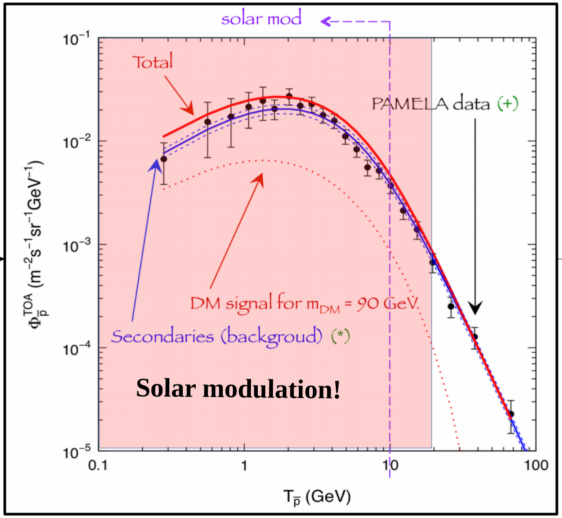


Antiproton: low energy excess?

Range of mass and annihilation cross section which could account for the antiproton excess



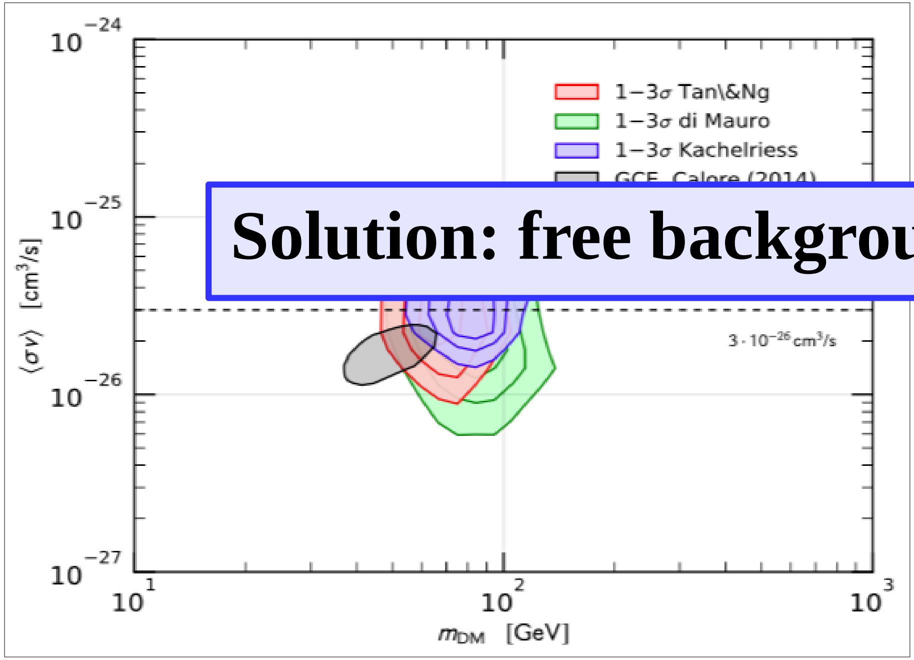
Problem: signal from dark matter only a fraction (10-30%) with respect to secondary CRs.



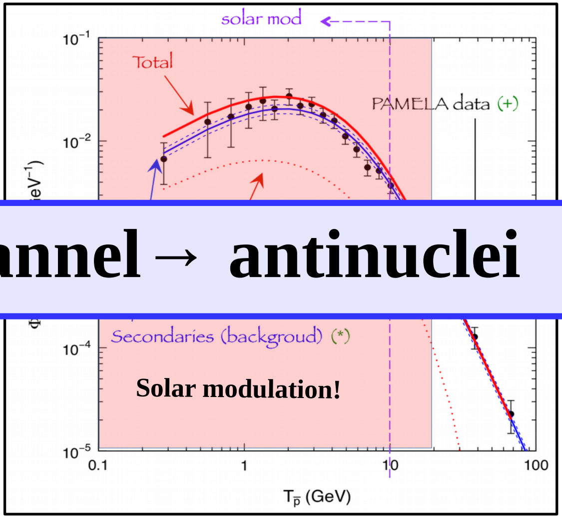
Extremely precise evaluation of background from model is needed, uncertainties of 10-20%

Antiproton: low energy excess?

Range of mass and annihilation cross section which could account for the antiproton excess



Problem: signal from dark matter only a fraction (10-30%) with respect to secondary CRs.



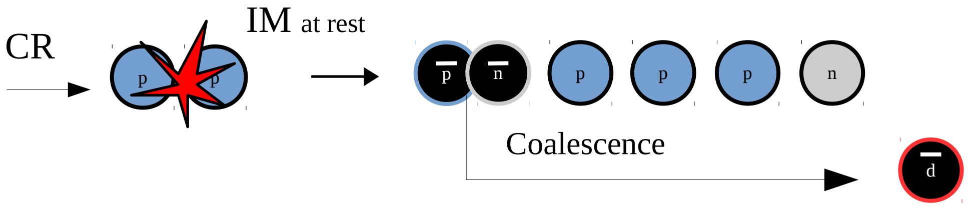
Solution: free background channel → antinuclei

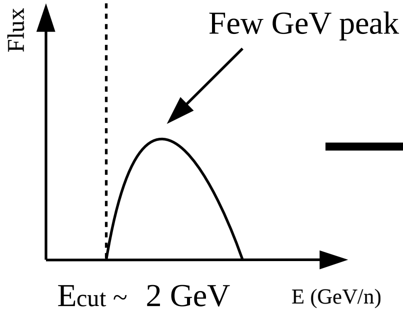
Extremely precise evaluation of background from model is needed, uncertainties of 10-20%

The GAPS experiment

Antimatter production in CRs

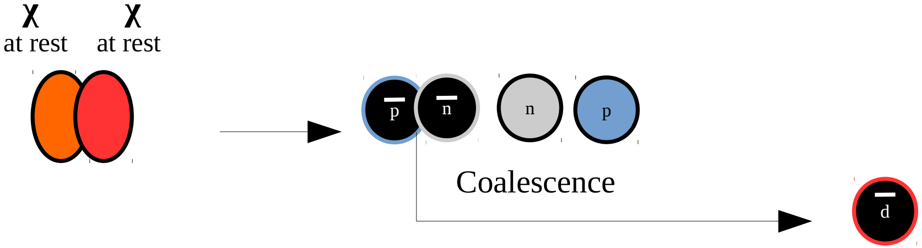
Secondary from CRs

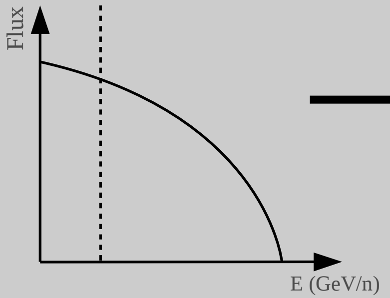




Strongly suppressed below few GeV

Primary from dark matter

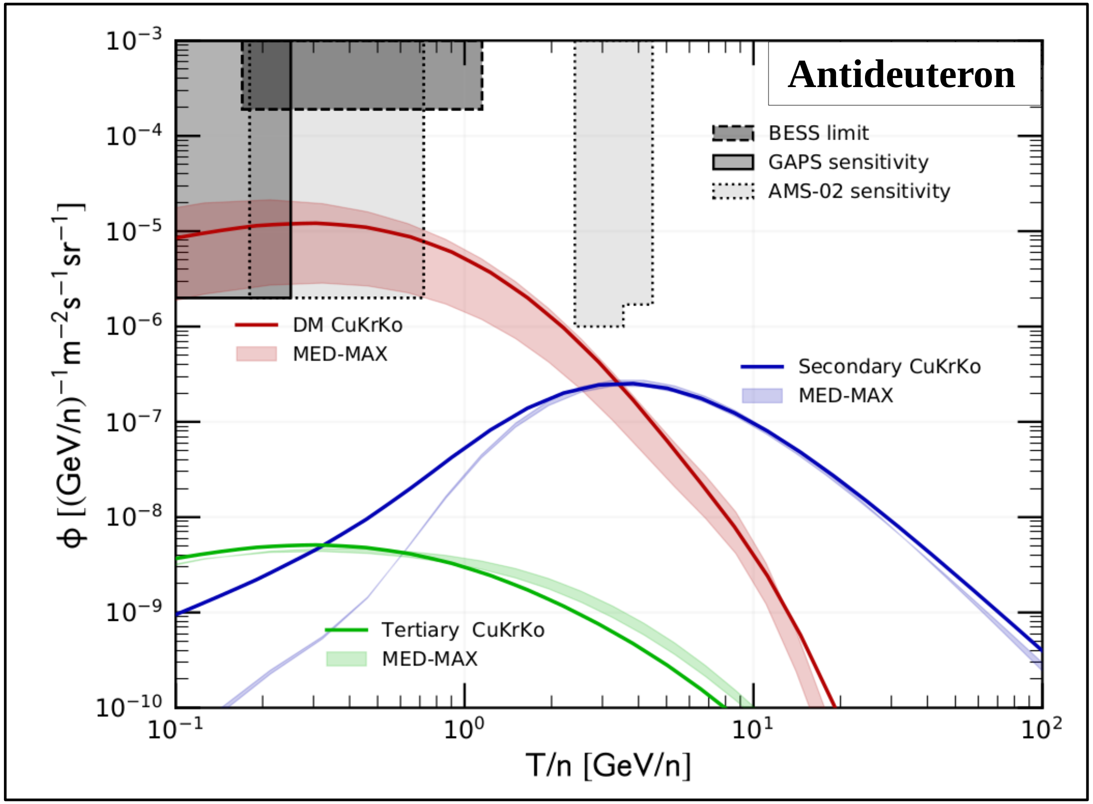




High intensity below few GeV

Why antideuteron for DM search?

Korsmeier et al.,Phys.Rev.D97,103011(2018)



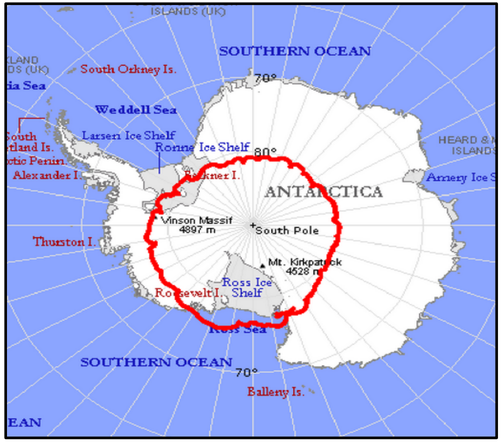
At low energies the background is expected to be 3 orders of magnitude less than the signal expected from DM annihilation

Background free signal!

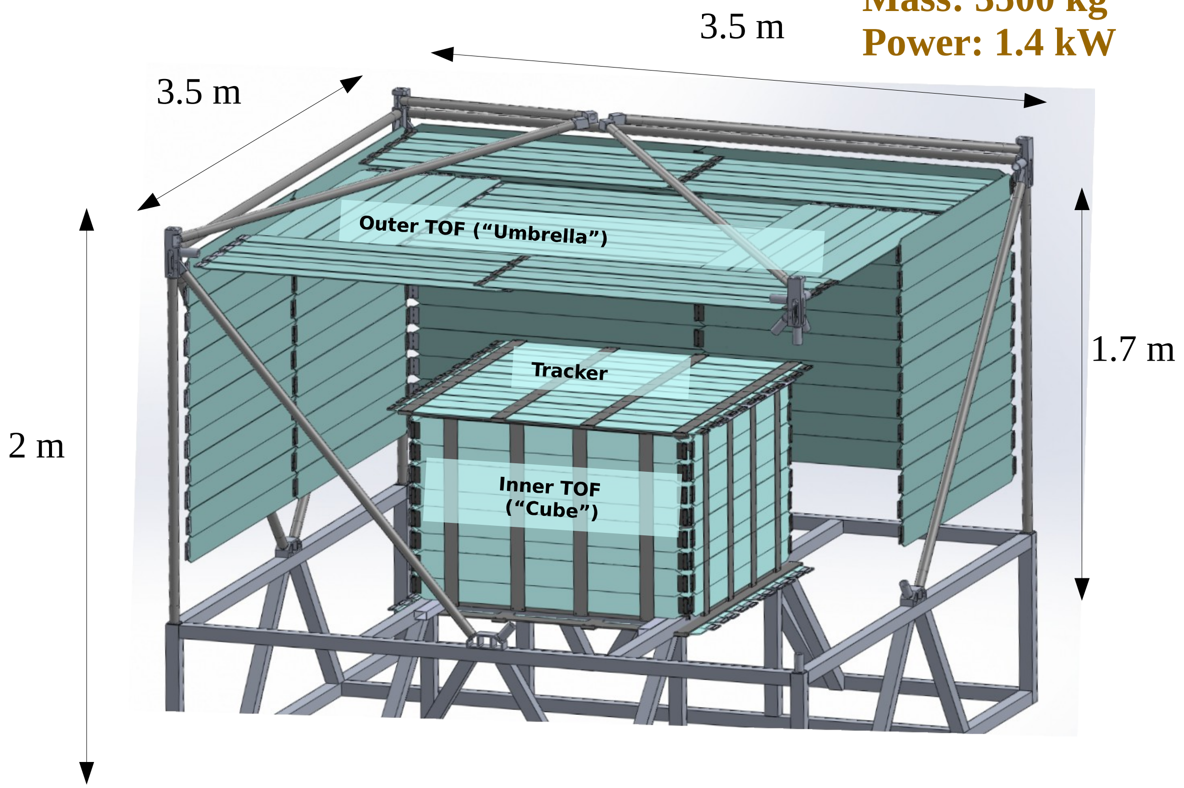
Instrument overview

Time of flight
- Velocity measurement
- Trigger

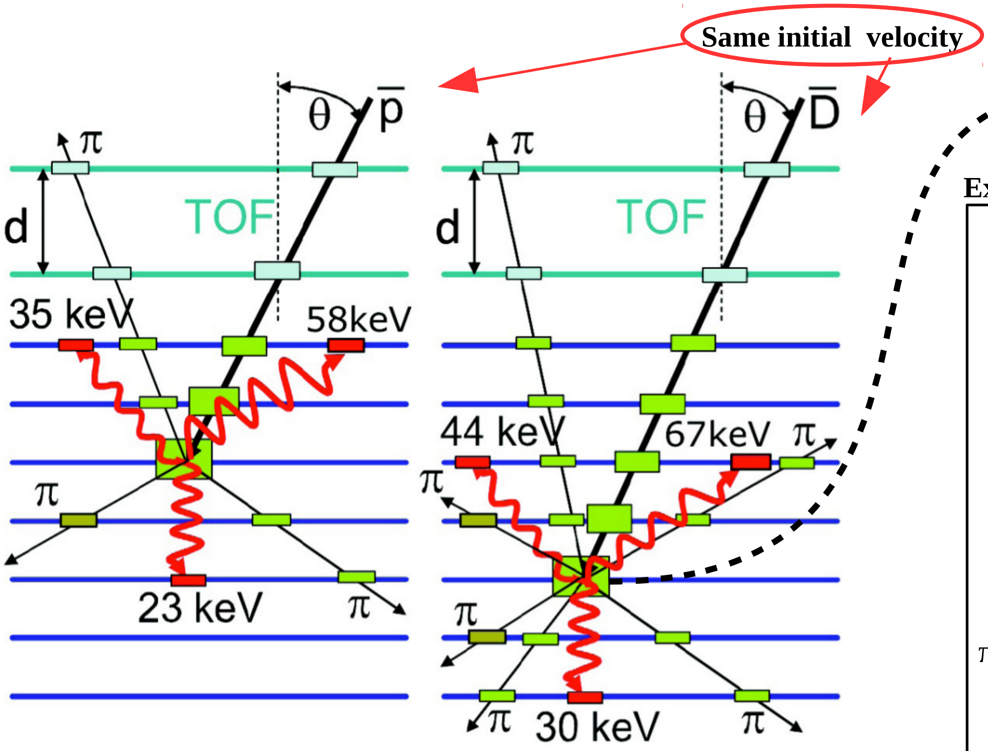
Tracker
- Particle tracking
- X-rays detection

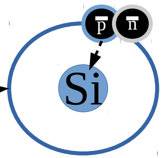


Mass: 3500 kg
Power: 1.4 kW

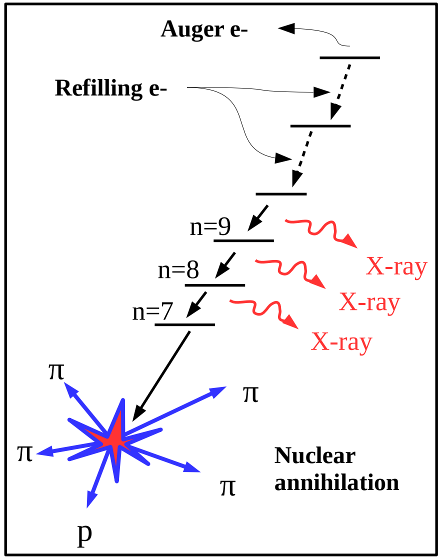


GAPS detection tecnique





Exotic nucleus – atomic transitions

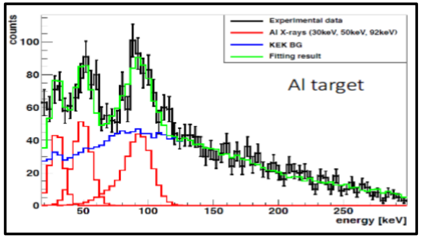


$$E_{X-ray} = (zZ)^2 \frac{M}{m_e} R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

AntiD - antiP identification

- Time of flight
- Depth - multiple dEdx
- X-rays emission
- Pion multiplicity

Aramaki et al. Astro.Ph. 49 (2013) 52

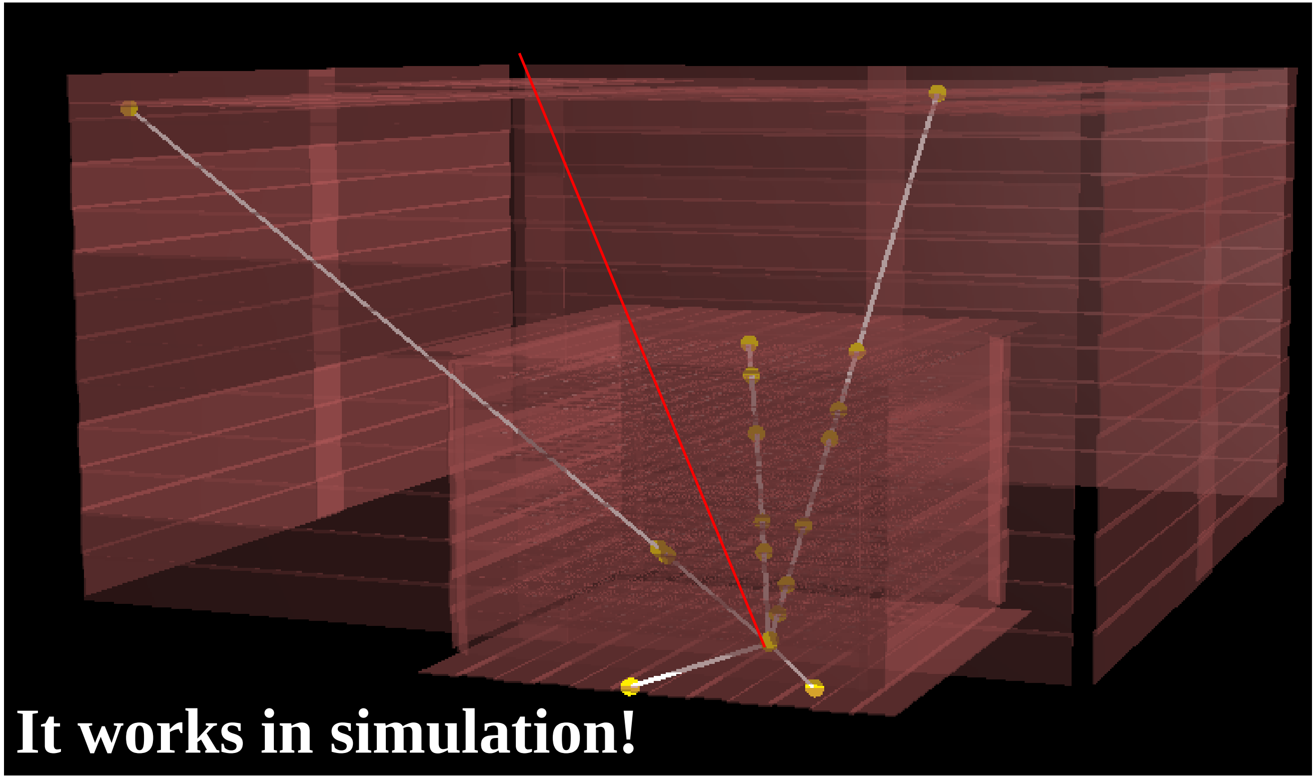


X-raymeasured at KEK in 2004/2005

Stopping particles inside tracker volume

Antideuteron 3D topology

Simulated antideuteron event: beta = 0.4



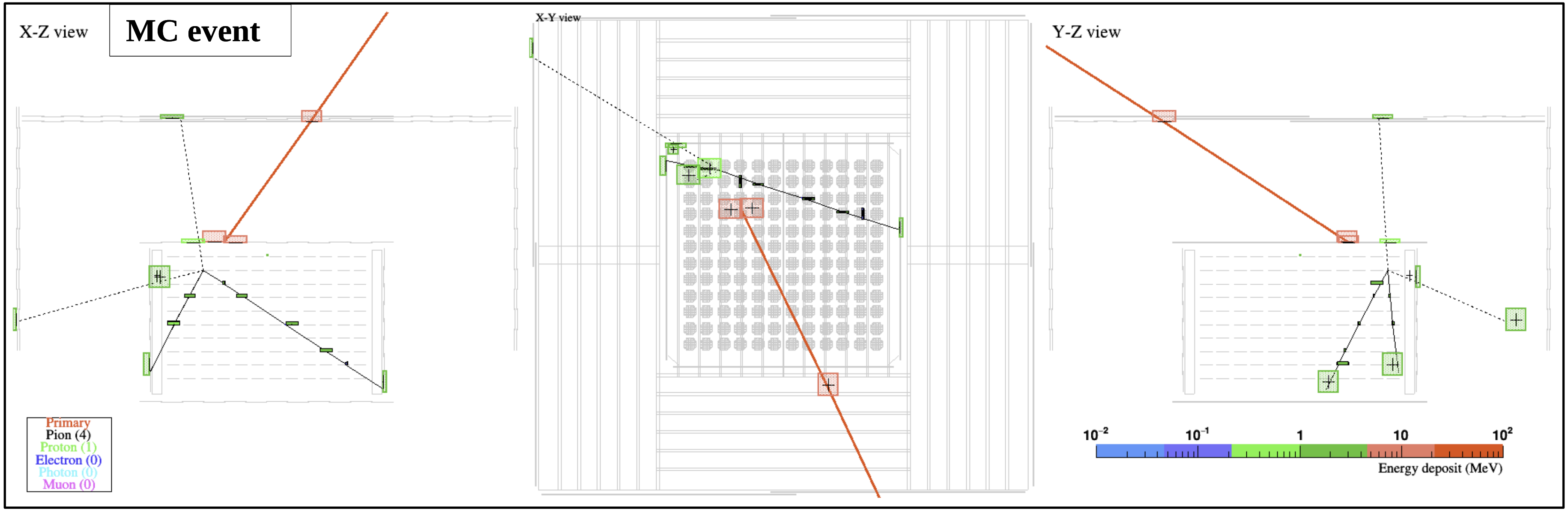
Antideuteron
Pion

GAPS at Trieste: reconstruction

Vertex reconstruction based on:

- Kalman-like filter for primary reconstruction
- Hough transformation for secondaries
- Vertex reconstruction with minimization

Fully detector simulation with (GEANT4)



GAPS at Trieste: reconstruction

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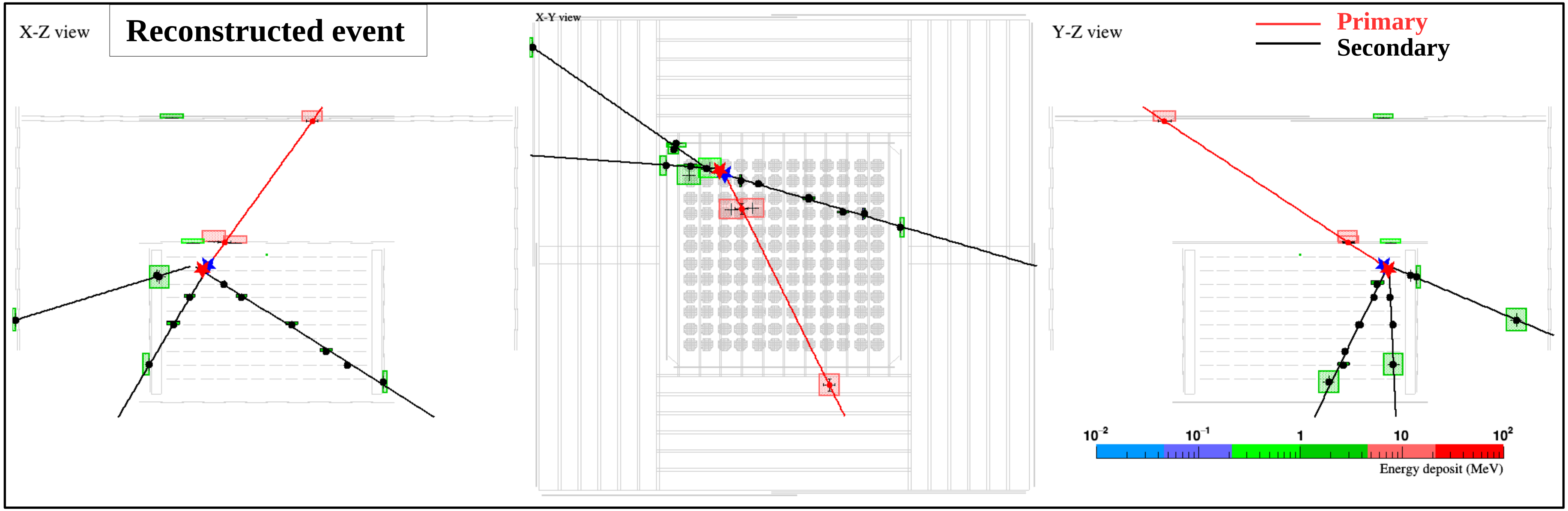
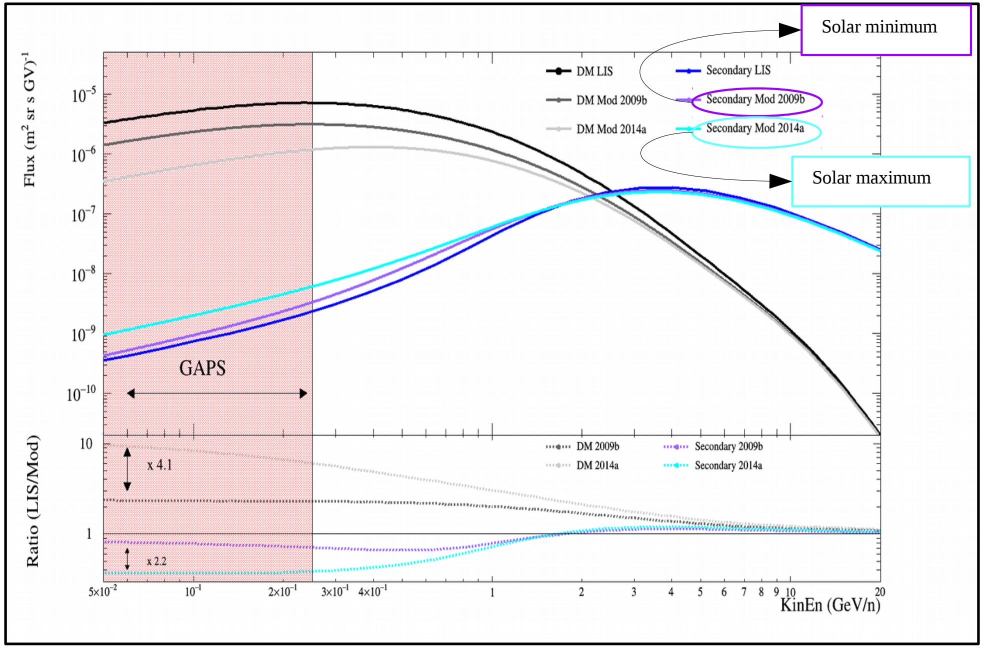
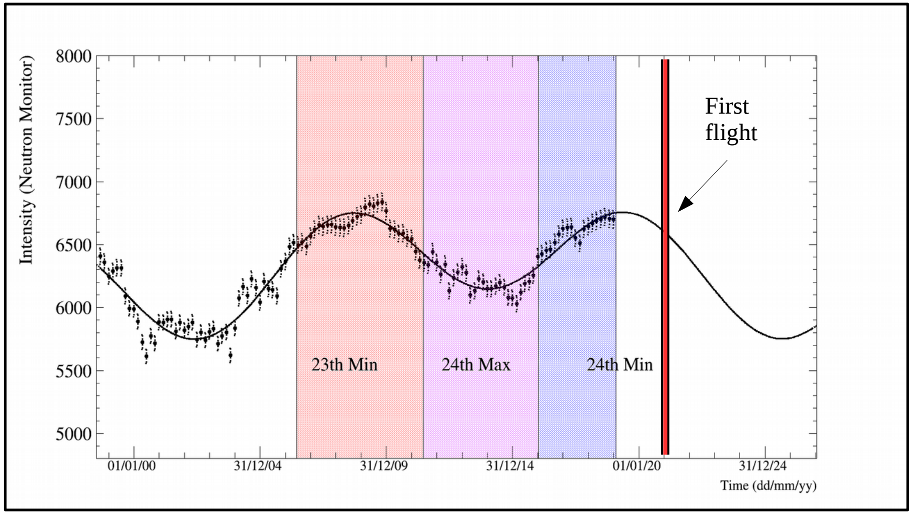


GAPS and solar modulation

GAPS will measure antiP - antiD at energies were CRs are heavily affected by **solar modulation**





Precise modeling of the solar modulation has to be taken into account to interpret the data.

3D numerical model for CRs propagation inside heliosphere: factor 4 of intensity variation for DM antiD between solar minimum and maximum

Master thesis – PhD

Software:
- Reconstruction algorithm development
- Identification analysis
- Solar modulation studies

Hardware:
- Read-out tracker electronics