Cosmic-rays

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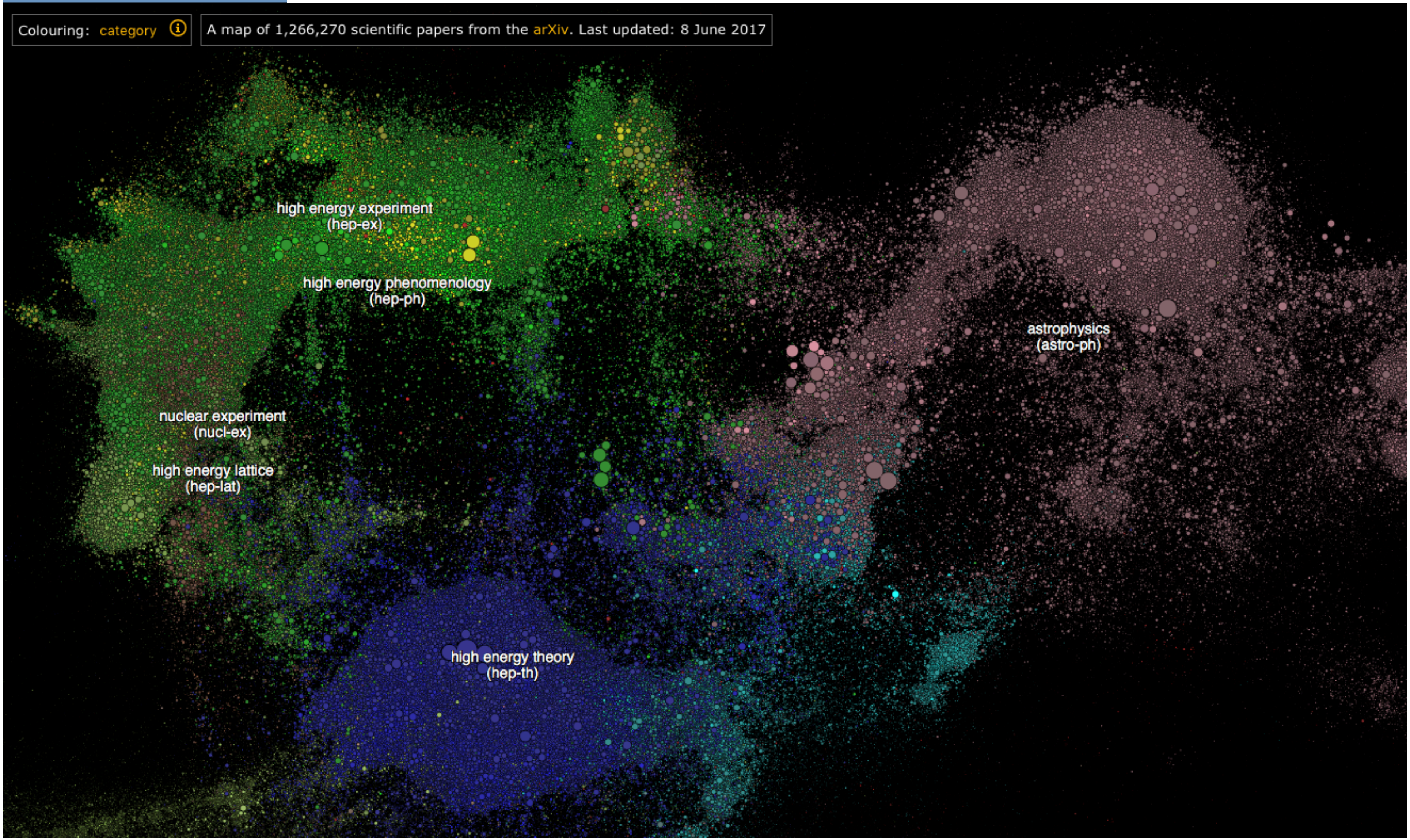
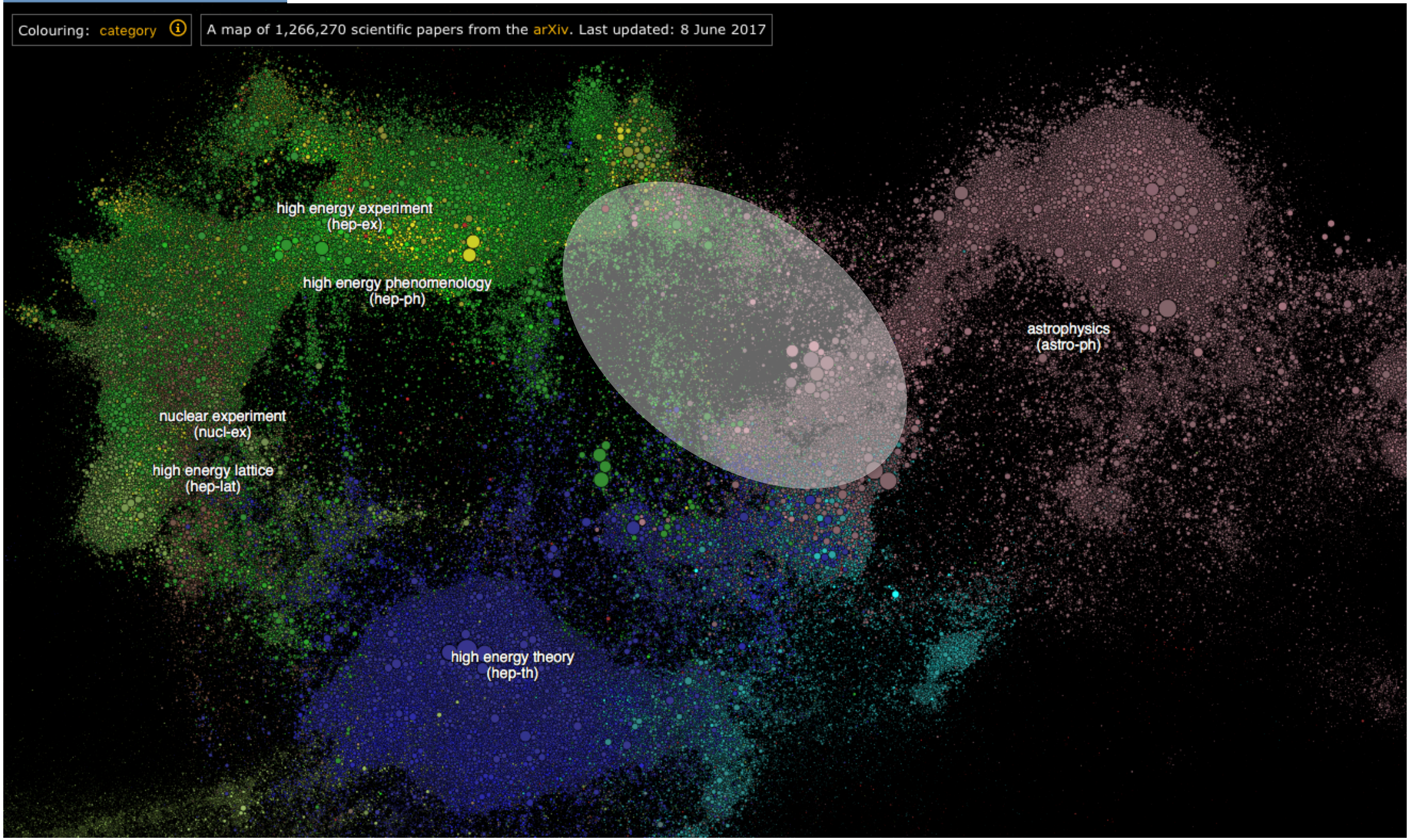
Physics landscape: http://paperscape.org/

- Each point represents a paper from arXiv, size is prop. to citations
- Clustered according to how they reference each other



Cosmic rays – astroparticles physics

At the interface between Astrophysics, Cosmology, Particle (Nuclear) Physics



Purpose and Goals of the lecture

To present you:

- Short overview of CR discovery
- What are the main observables used to characterize the CRs (different particles, distribution of energy/Fluxes, anisotropy)
- What are the mains physical processes: Acceleration/ Propagation of cosmic-rays.
- What is the current knowledge on CRs
- What are the open questions related to CRs
- Different strategies used to measure CRs for the different types of CRs/Energy ranges
- How instruments are built to detect/characterize the CRs. Some basic concepts for CRs detections : Acceptance/Trigger/ Monte Carlo simulations

Summary

Introduction

I. Brief history of cosmic ray discovery

II. Cosmic rays : what are they ?

III. Galactic Cosmic Rays (GCRs)

1. From source to the detector
2. Earth environment (atmosphere, geomagnetic field)
3. Detection of GCRs
4. Concrete example : Measurement of proton flux with AMS-02
5. Recent results
6. CR Solar modulation

IV. From Galactic to Extra-Galactic Cosmic Rays

1. Extended Atmospheric Shower
2. Detection
3. The transition from Galactic to Extra-Galactic
4. GZK, The endpoint of the CR spectrum ?

Today

Tomorrow

Acknowledgment: Large part of the material used for this presentation come from lectures given by

- *Fernando Barao (LIP)*
- *David Maurin (LPSC)*

Summary

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Tomorrow

Please don't hesitate to interrupt me to ask questions.
If something is not clear, it is better to take time to explain it again.

I-Cosmic Rays: historical background

- Before 1900 : the spontaneously ionization of air
- Crookes (1879) : showed that an electrically charged object in a sealed container air-filled gradually looses its charge ! charge is retained if no air exists (vacuum) → *Ionization of air is the direct cause*
- 1896 : the discovery of the radioactivity by Becquerel → *This could explain the spontaneous discharge... !*
- 1900-1910 : many observations were made ; among them Pacini, an Italian meteorologist, point evidences that ionization could have an origin independent of the direct action of radioactive substances contained in the upper layers of the earth crust.
- Pacini's estimate of the excess ionization : 2 ion pairs / cm^3/s corresponds to the ionization of cosmic rays at sea level !

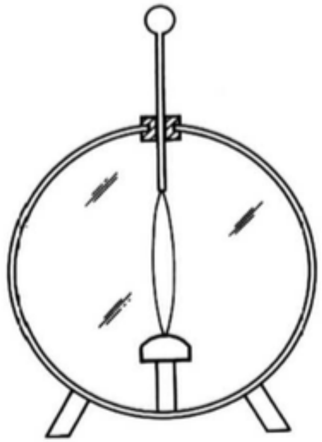
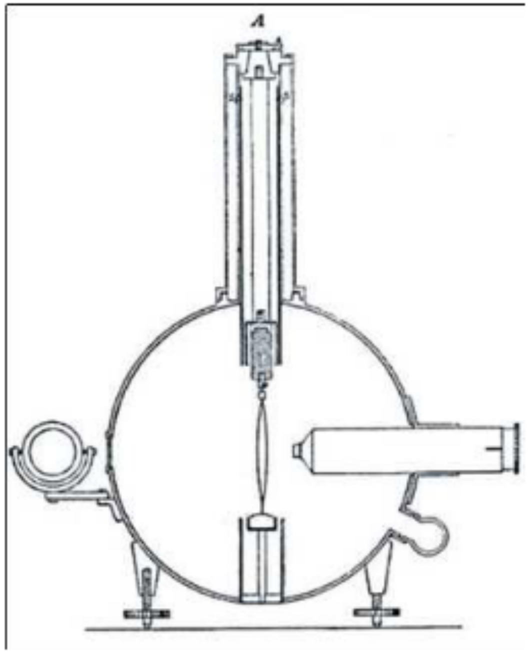


Fig. 6. Schematic view of the Wulf electrometer.

I-Cosmic Rays: historical background

- The hypothesis of the earth surface radioactivity as ionization source suggested that measurements could be made in altitude.
- One should detect a decrease in the intensity on this radiation and therefore an ionization decrease would be expected...
- **Jesuit priest Theodor Wulf (1910) :** improved the electroscope replacing the gold leaves with two slender metal wires whose separation was measured with a microscope and carried it to the top of the Eiffel Tower (330 meters)



Datum	Ort	Ionen / ccm sec
28. März	Valkenburg	22,5
29. "	Paris, Boden	17,5
30. "	" Eiffelturm	16,2
31. "	" "	14,4
1. April	" "	15,0
2. "	" "	17,2
3. "	" Boden	18,3
4. "	Valkenburg	22,0

Daraus ergeben sich als Mittelwerte für die drei Orte

Valkenburg	22,25	$\frac{\text{Ionen}}{\text{ccm} \cdot \text{sec}}$
Paris Boden	18,0	"
Paris Eiffelturm . .	15,7	"

I-Cosmic Rays: Hess discovery

Gockel, 1909-1911: Swiss physicist flew electrometers on balloon flights to 2500 and 2800m

no significant variation of the ionization rate recorded

Hess, 1911-1912: Austrian physicist made several balloon flights

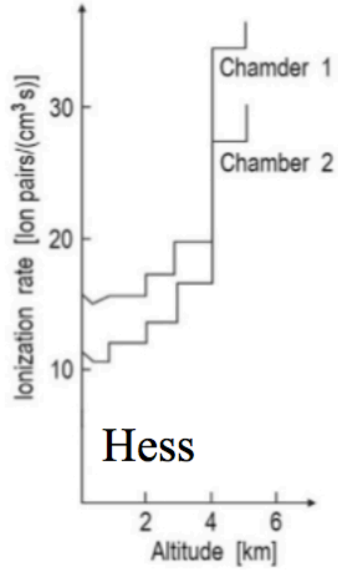
last flight took place on 7 August 1912 in a hydrogen-filled balloon. It lasted 6 hours and reached the altitude of 5350m.

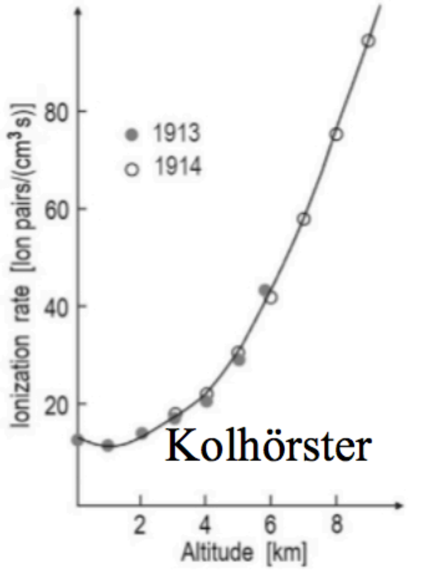
Three Wulf electrometers carried, 2 at atmospheric pressure and one opened

Balloon "Böhmen" (1680 cbm hydrogen)
Meteorological observer: E. Wolf.

Leader: Captain W. Hoffory.
Electr. observer: V. F. Hess

No.	Time	Mean height abs. m	Mean height rel. m	Observed radiation: Inst. 1 q_1	Inst. 2 q_2	Inst. 3 q_3	Inst. 3 red. q_3	Temp.	Rel. humidity %
1	15^h15–16^h15	156	0	17.3	12.9	...	...	1½ days before the ascent (in Vienna)	
2	16^h15–17^h15	156	0	15.9	11.0	18.4	18.4		
3	17^h15–18^h15	156	0	15.8	11.2	17.5	17.5		
4	6^h45–7^h45	1700	1400	15.8	14.4	21.1	25.3	+6.4°	60
5	7^h45–8^h45	2750	2500	17.3	12.3	22.5	31.2	+1.4°	41
6	8^h45–9^h45	3850	3600	19.8	16.5	21.8	35.2	−6.8°	64
7	9^h45–10^h45	4800 (4400–5350)	4700	40.7	31.8	(ended by accident)		−9.8°	40
8	10^h45–11^h15	4400	4200	28.1	22.7			...	...
9	11^h15–11^h45	1300	1200	(9.7)	11.5			...	...
10	11^h45–12^h10	250	150	11.9	10.7			+16.0°	68
11	12^h25–13^h12	140	0	15.0	11.6	(After landing at Pieskow, Brandenburg)			

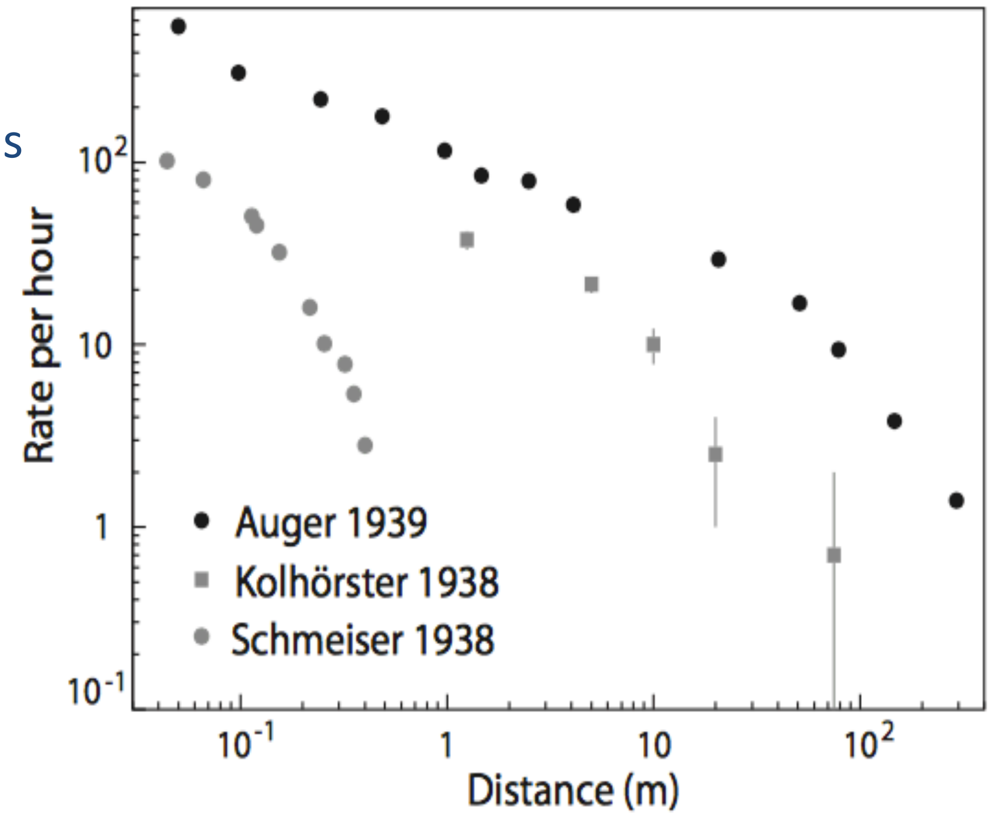




I-Discovery of extended air showers

- Detection of coincidences between distant Geiger Counters (Rossi 1934)
- Kolhoster (1938): Decoherence curve as function of the distance between detectors.
- Auger (1939): measurements performed at the Jungfraujoch in the Swiss Alps (3450 m). They were able to separate their detectors by up to 300 m.

→ Estimation of energy based on the number of particles in the showers, assuming that each particle carried, on average, the critical energy : ~10^{15} eV.



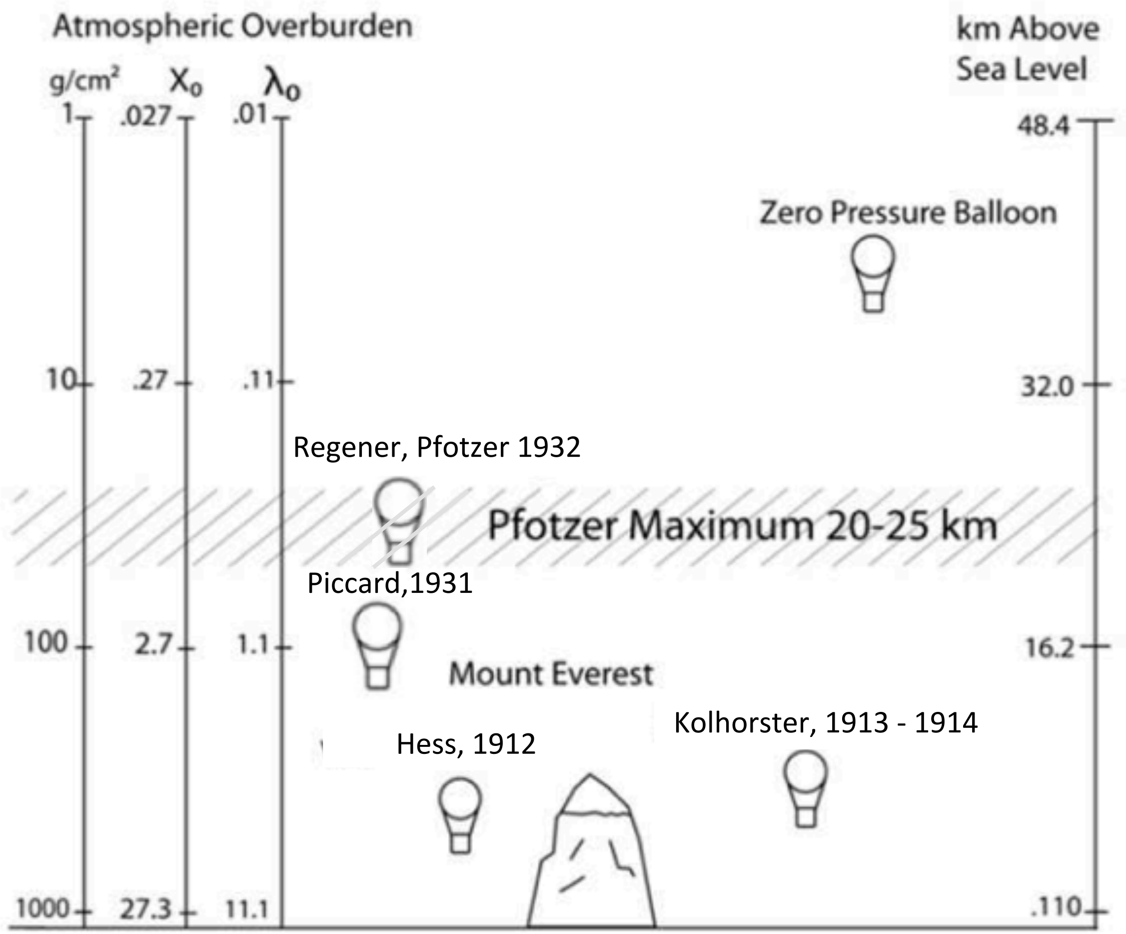
I-Before space age…

In the first decades after CR discovery by Hess, balloon flights at increasingly altitude with more and more complex payloads:

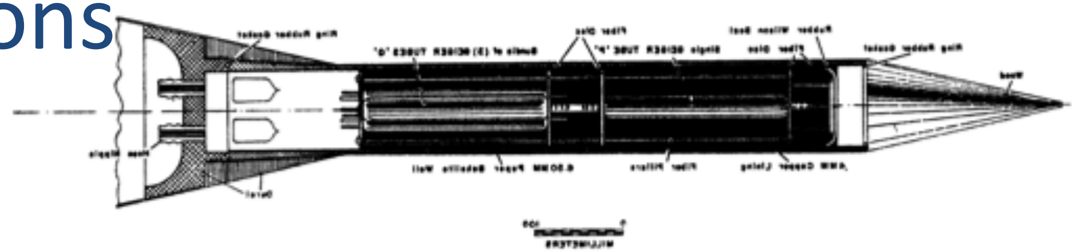
- Allowed the understanding of interaction of particles in the atmosphere.
- Gave birth to particle physics.

→ Until WWII: Study of atmospheric secondary particles. No direct detection of CR.

→ Nature of cosmic rays determined by the properties of atmospheric secondary particles (Latitude effect, East-West effect).



I- First Direct detections



- Just after WWII, US scientists equipped German V-2 rockets with Geiger counters to measure radiation up to 161 km.

PHYSICAL REVIEW VOLUME 73, NUMBER 3 FEBRUARY 1, 1948

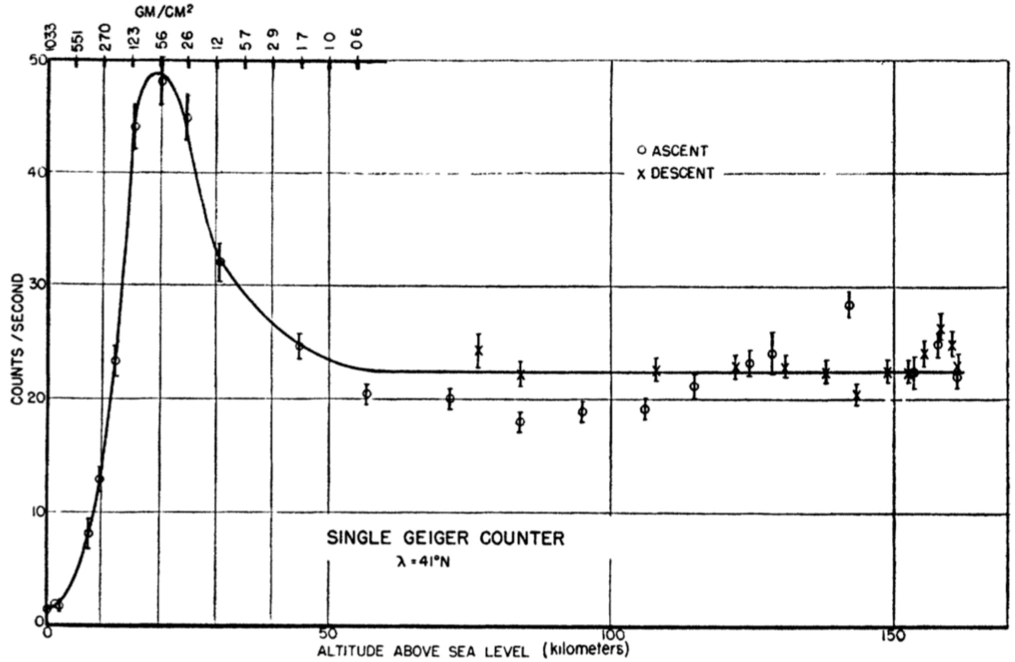
The Cosmic-Ray Counting Rate of a Single Geiger Counter from Ground Level to 161 Kilometers Altitude

J. A. VAN ALLEN AND H. E. TATEL*

Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Maryland

(Received October 16, 1947)

- Plateau above 50 km → First direct measurement of CR out of the atmosphere.

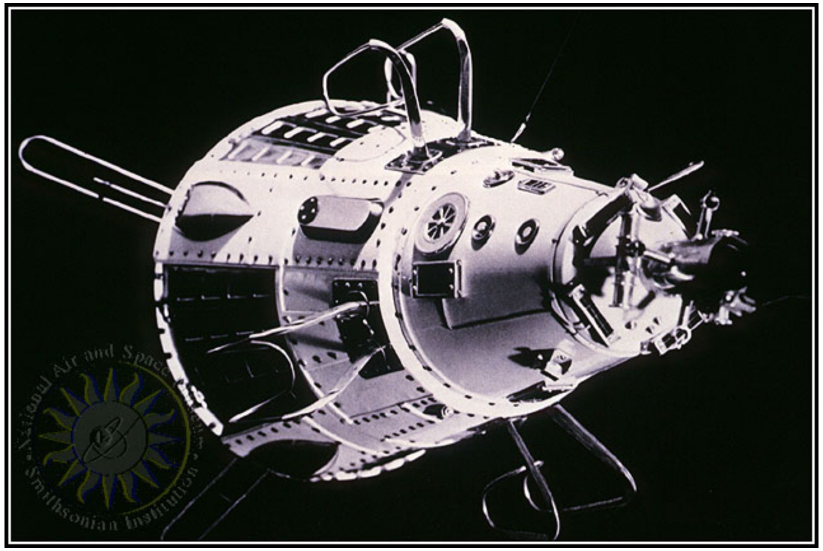


- In the same years more large and complex apparatus flying on balloons up to 30 km were able to study CR composition.

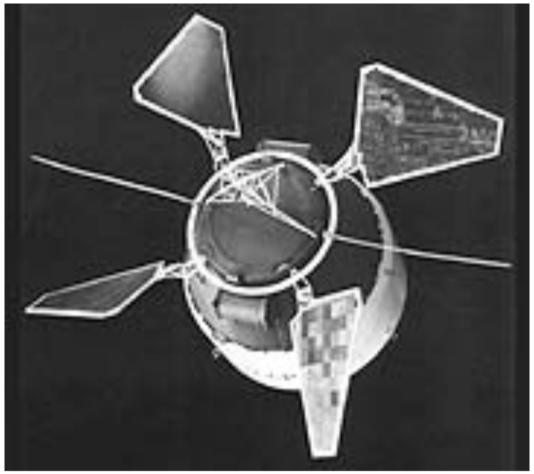
(Freier, Ney, Oppenheimer, Peters, Lofgren, Bradt (1948))

I- Space age...

- From the beginning of space age, cosmic-ray physics naturally went hand in hand with the development of space exploration:
  - Vernov et al (URSS) arranged the first CR space experiment on Sputnik II.
  - Van Allen et al. used the Explorer I satellite to discover the Van Allen belts.
- Starting from the mid 60's, possibility to launch satellites with equipment weighting several tons.
- Large sets of CR experiments onboard satellites and on high altitude balloons allowed to study the cosmic ray spectra and composition up to the knee region...



Sputnik II (1957)

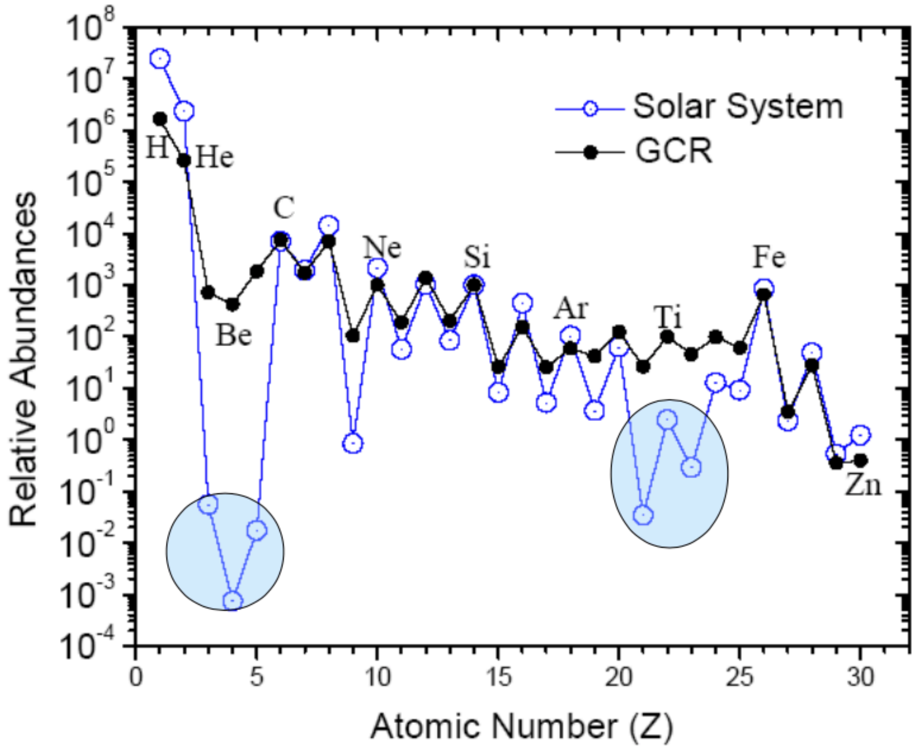


Proton 4 Satellite (1968), 16 tons payload

II- What we know about CR today

1 - Composition

- ~90 % proton
- ~9 % helium
- ~1% heavier elements
- But also e-, e+, anti-p
- Similar features on solar and cosmic rays abundances
  → CR Sources: similar nucleosynthesis + Acceleration
- Some elements result from CRs interactions with the interstellar medium (spallation)
  → Confinement of CRs in the Galaxy.



Definitions:

- Primary species: accelerated at the source (e.g., H, He, C, O)
- Secondary species: absent of source → fragmentation of heavier primary nuclei (e.g., →B)
- Mixed species (e.g., N): both contributions

II- What we know about CR today

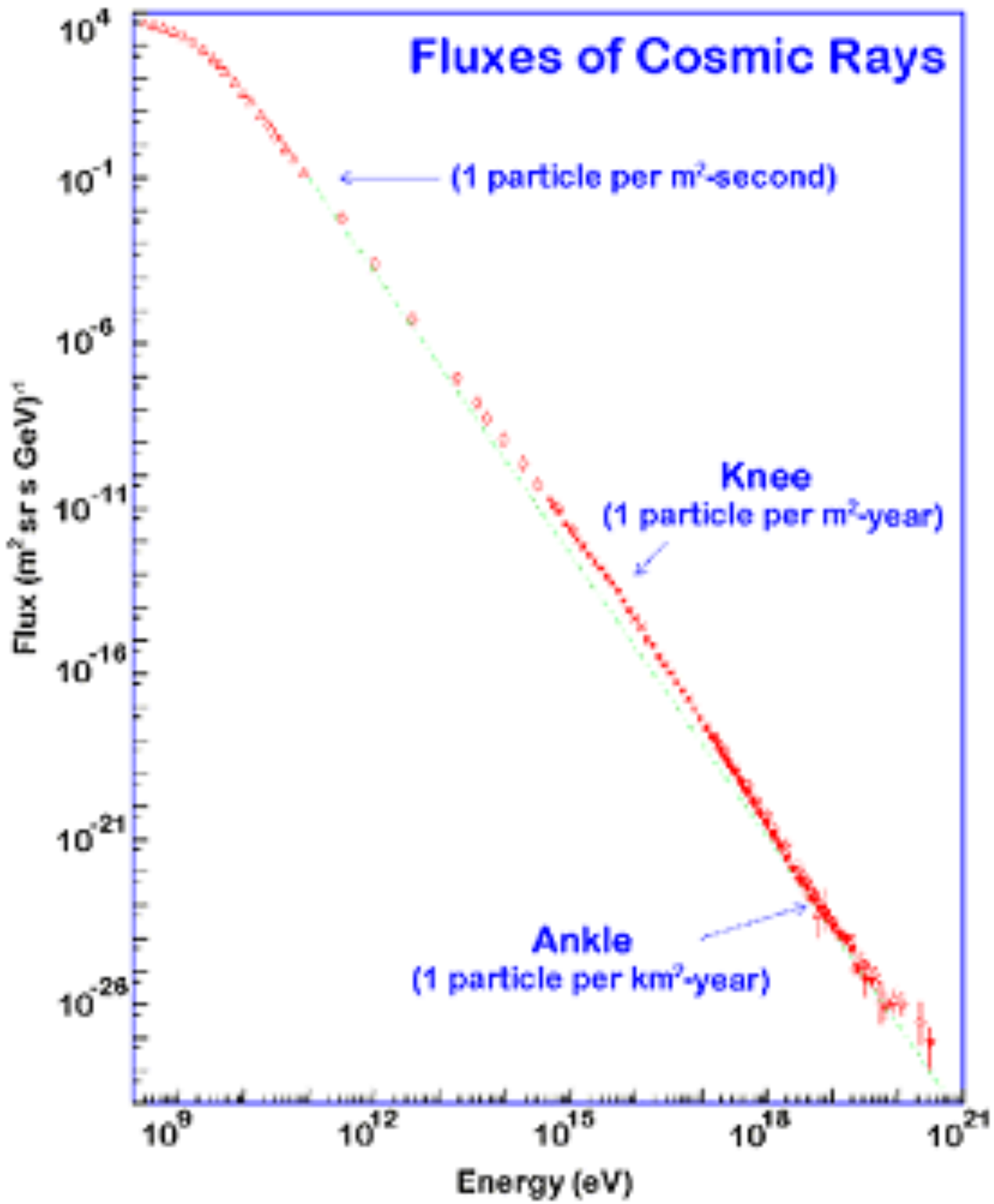
2 – Energy spectra :

- Featureless and universal power-law energy spectra above 2 GeV/n

  Flux ≈ $E^{-\gamma}$ with $\gamma = 2.7\text{-}3$

- Extend over 12 orders of magnitude on Energy, 30 orders of magnitudes in fluxes.

→ evidence of very powerful astrophysical accelerators

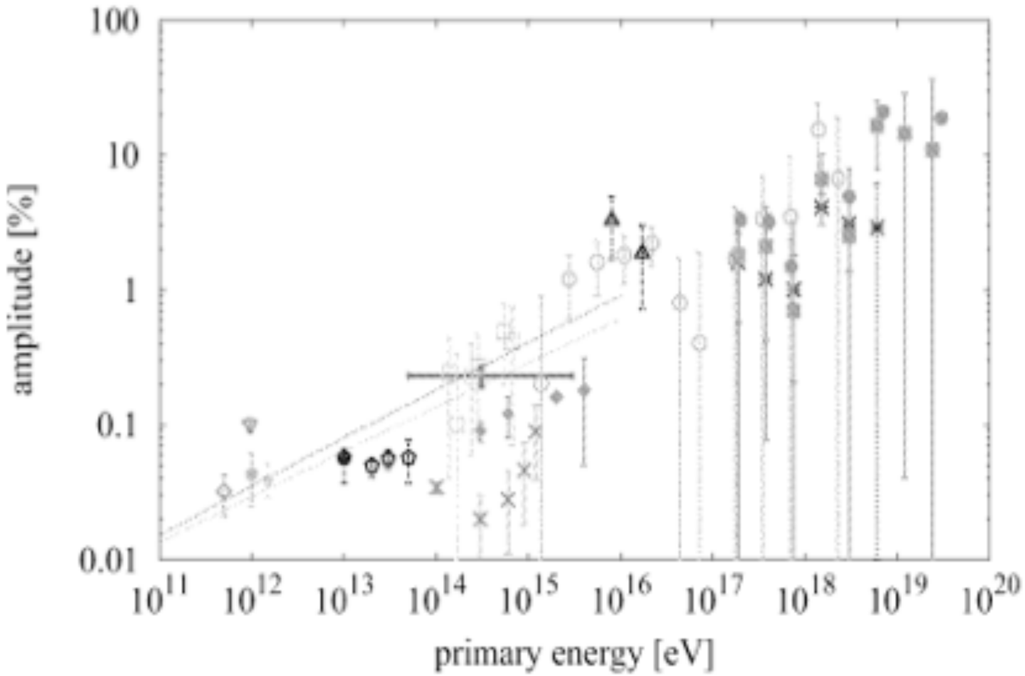


II- What we know about CR today

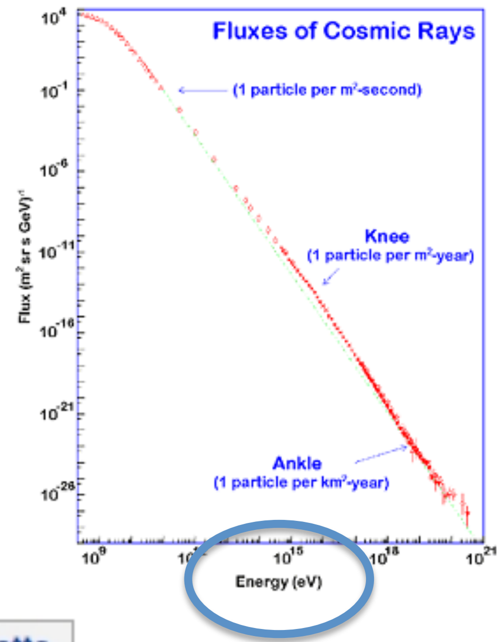
2 – Isotropy

- At low energy, the flux looks isotropic :
  - Sources uniformly distributed (not so simple)
  - Propagation of GCRs → Confinement and isotropisation of CRs.
- More anisotropy with energy : less confinement and extra-galactic cosmic-rays

Dipole anisotropy



II- Useful Units/Definitions



Nucleus: $^{A}_{Z}X$

A = Atomic number

Z = Charge of the Nucleus

$M(^{A}_{Z}X) \approx A\,u$, where $u = 931\ \mathrm{MeV}/c^2$

Energy Units: CRs 100 MeV → 100 EeV

Metric Prefixes:

Name		kilo-	mega-	giga-	tera-	peta-	exa-	zetta-	yotta-
Symbol		k	M	G	T	P	E	Z	Y
Factor	10^0	10^3	10^6	10^9	10^{12}	10^{15}	10^{18}	10^{21}	10^{24}

Energy: $E = \gamma Mc^2$ [eV] → *Calorimeter (Atmosphere)*

Energy per nucleon: $E_{/n} = \gamma Mc^2/A = \gamma uc^2$ [eV/n]

Kinetic energy: $T = (\gamma\text{-}1)\,Mc^2$ [eV]

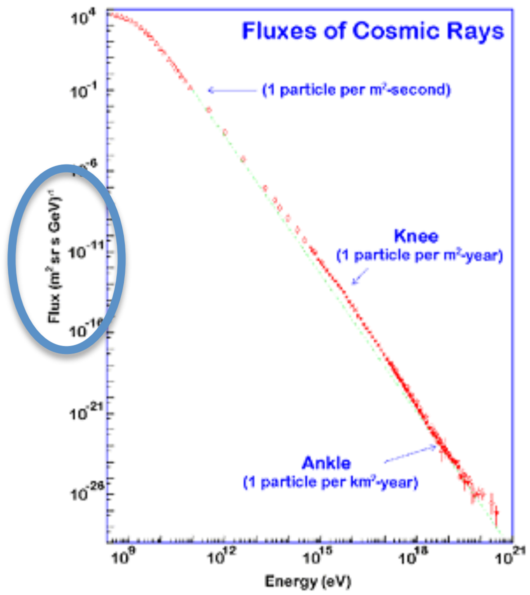
Kinetic energy per nucleon: $T_{/n} = (\gamma\text{-}1)\,uc^2$ [eV/n] → *Velocity (Cherenkov, TOF)*

Momentum: $P = \gamma\beta Mc$ [eV/c] $\boldsymbol{E^2 = P^2 + M^2}$

Rigidity: R = (Pc)/(Ze) [V] → *Curvature in magnetic field (tracker)*

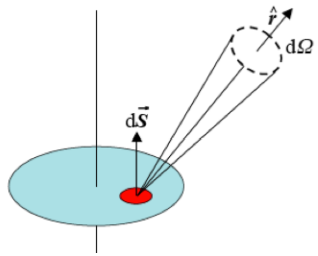
Note: With $e = c = 1$, at high energy $E = AE_{/n} \approx P = Z\,R$

II- Useful Units/Definitions



Flux (CR intensity):

- Detector Rate : R = (# particles < E) /s



- Intensity: I = (# particles < E) [$m^{-2}\ sr^{-1}\ s^{-1}$]
- Differential Intensity: dI/dE = #particles [$m^{-2}\ sr^{-1}\ s^{-1}\ GeV^{-1}$]
- Very usual to display : E^a x dI/dE with a = 2.7-3 : [$m^{-2}\ sr^{-1}\ s^{-1}\ GeV^{-1+a}$]
- For a 1 m^2 and 2π sr ideal detector : expected number of particles between E_1 and E_2 for a duration T:

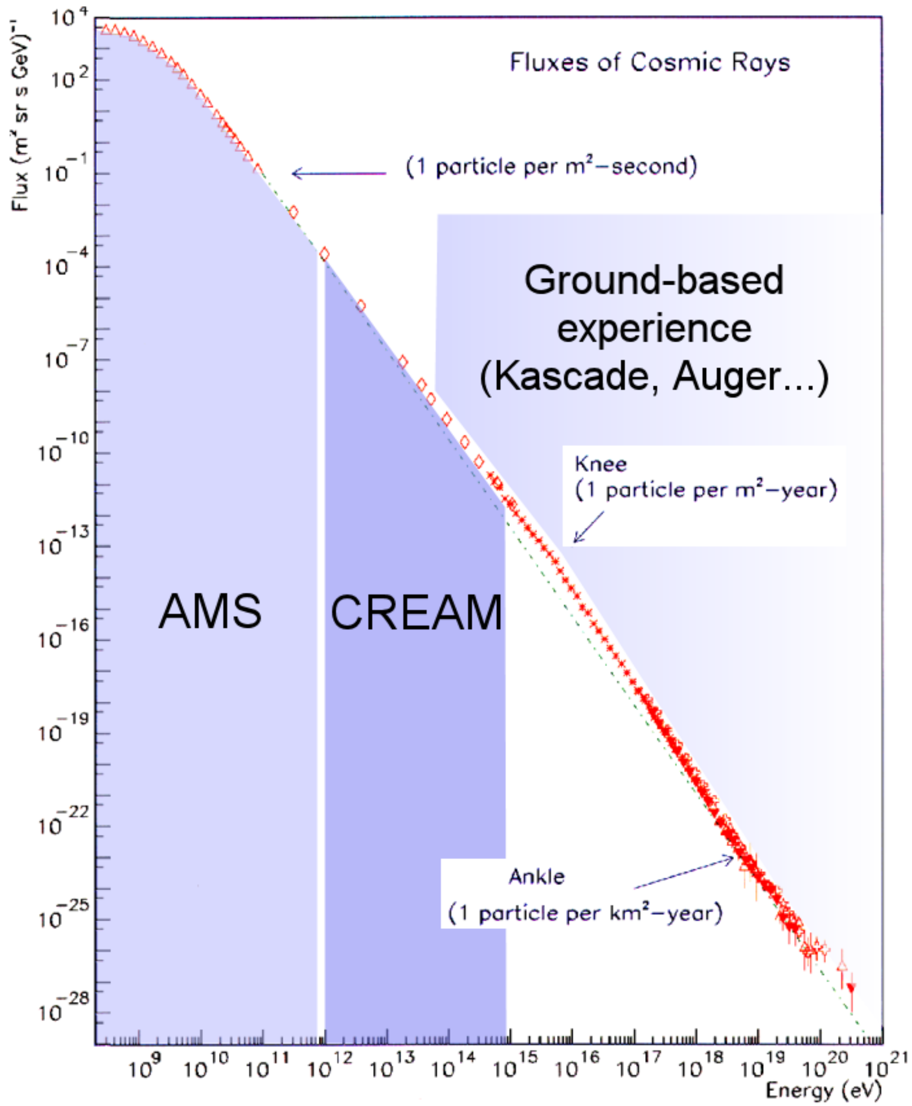
$$N = 2\pi T \int_{E_1}^{E_2} \frac{dI}{dE} dE$$

- Be cautious:
  - $dI/dP = E/P\ dI/dE$ [$m^{-2}\ sr^{-1}\ s^{-1}\ (GeV/c)^{-1}$]
  - $dI/dR = Z\ dI/dP$ [$m^{-2}\ sr^{-1}\ s^{-1}\ GV^{-1}$]
  - $dI/dE_{/n} = A\ dI/dE = (PZ)/(EA)\ dI/dR$ [$m^{-2}\ sr^{-1}\ s^{-1}\ (GeV/n)^{-1}$]

II- Detection of Cosmic rays

- E < 10^{15} ev : Cosmic rays are absorbed in the upper layer of atmosphere but the flux is large
  - → Direct detection above atmosphere.
  - → Identification of CR/Energy measurement with particle physics detectors
- E > 10^{15} ev : Shower produced by CRs is detectable from ground

  → Atmosphere as a « calorimeter » : Measurement of the shower from ground.

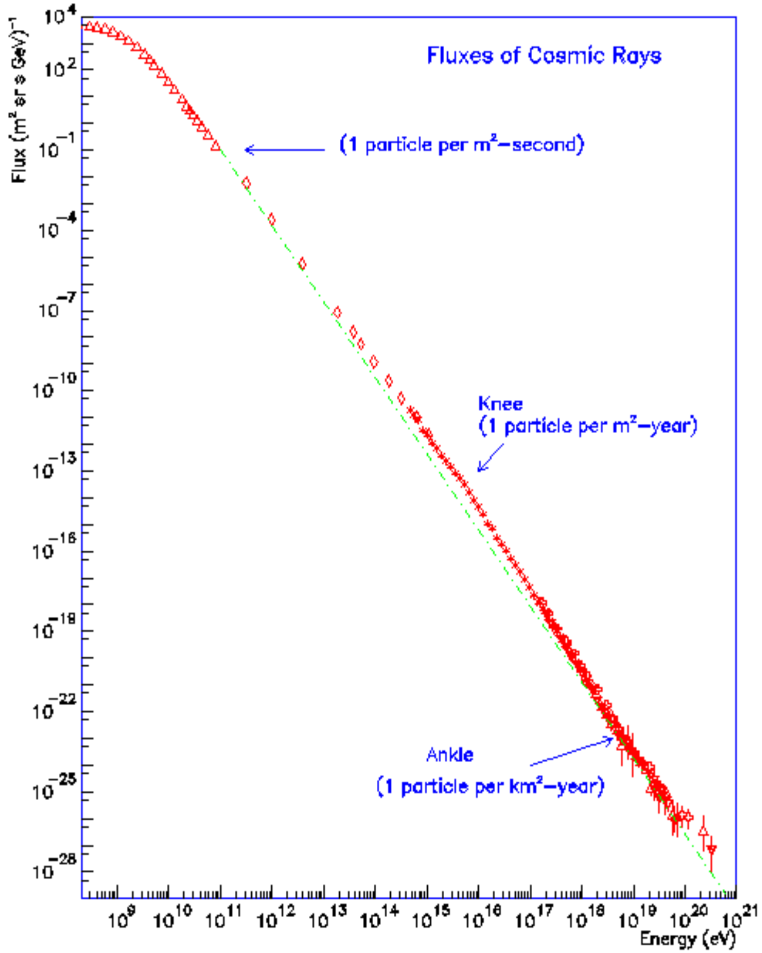


II- Cosmic Rays : open questions

CRs are measured since more than one century. Even a lot has been learned on the nature and the properties of CRs, central questions remain:

- What are the sources of CRs
- What are the acceleration processes
- Propagation of CRs in the Galaxy
- Origin of the knee?
- Where is the transition from Galactic to extragalactic ?
- What are the sources of extragalactic CRS ?
- Do we see the end point (GZK cutoff) ?

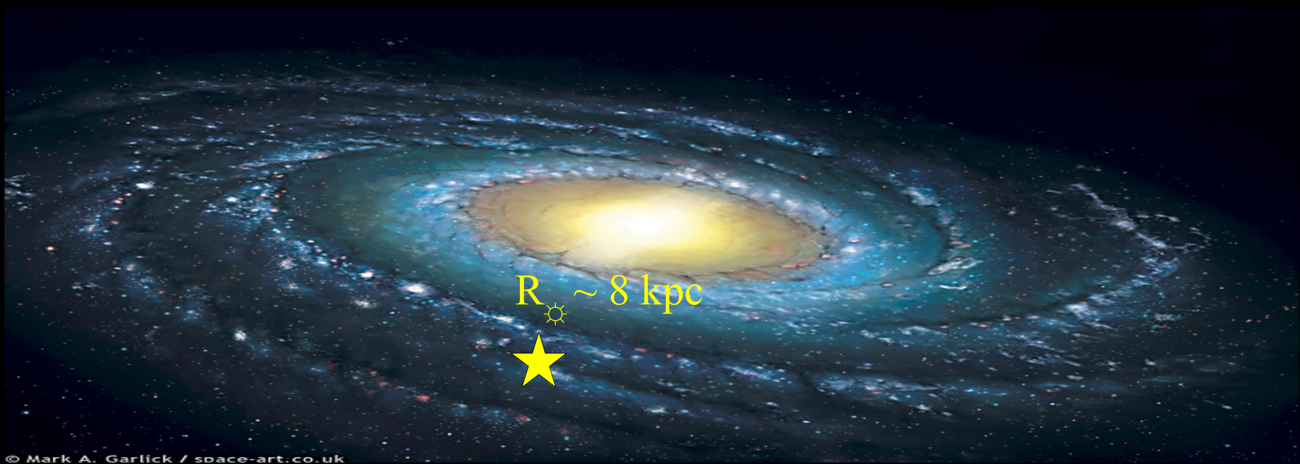
+ What could be the contribution from Dark Matter annihilation (positron, antiproton,...)



III- Galactic Cosmic Rays (GCR)

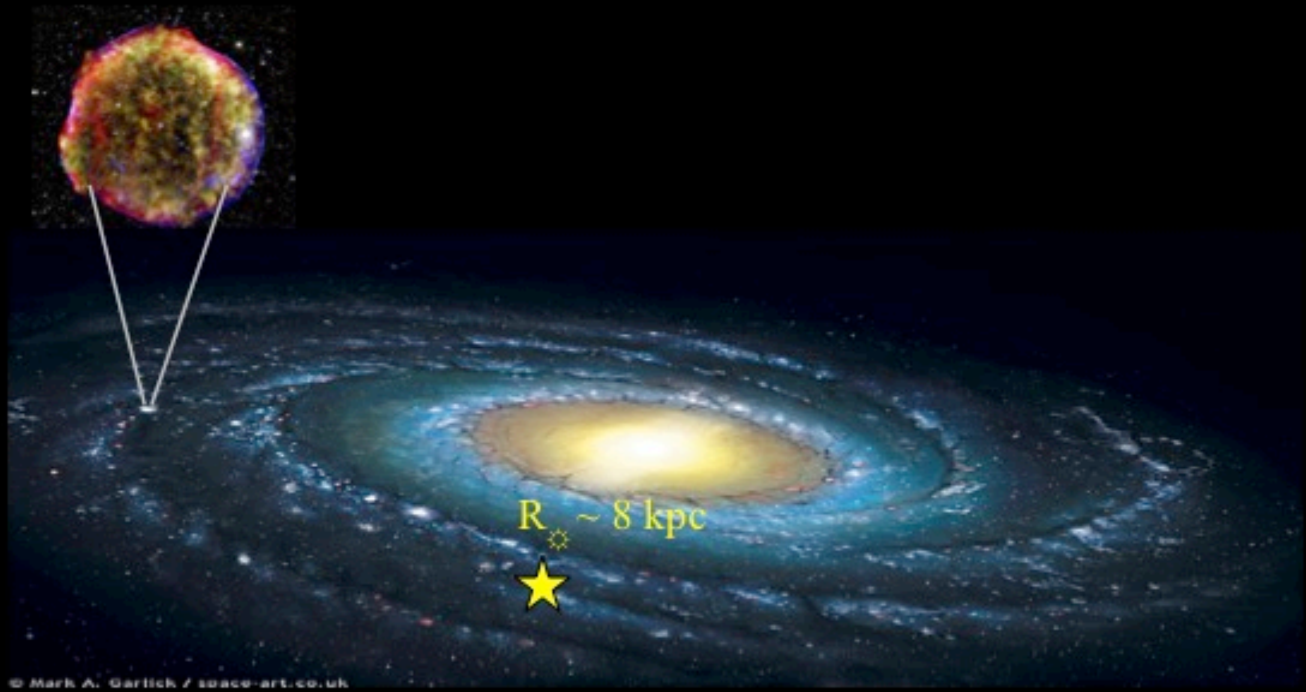
1. GCR journey: From source to the detector

Charged cosmic rays in the Galaxy



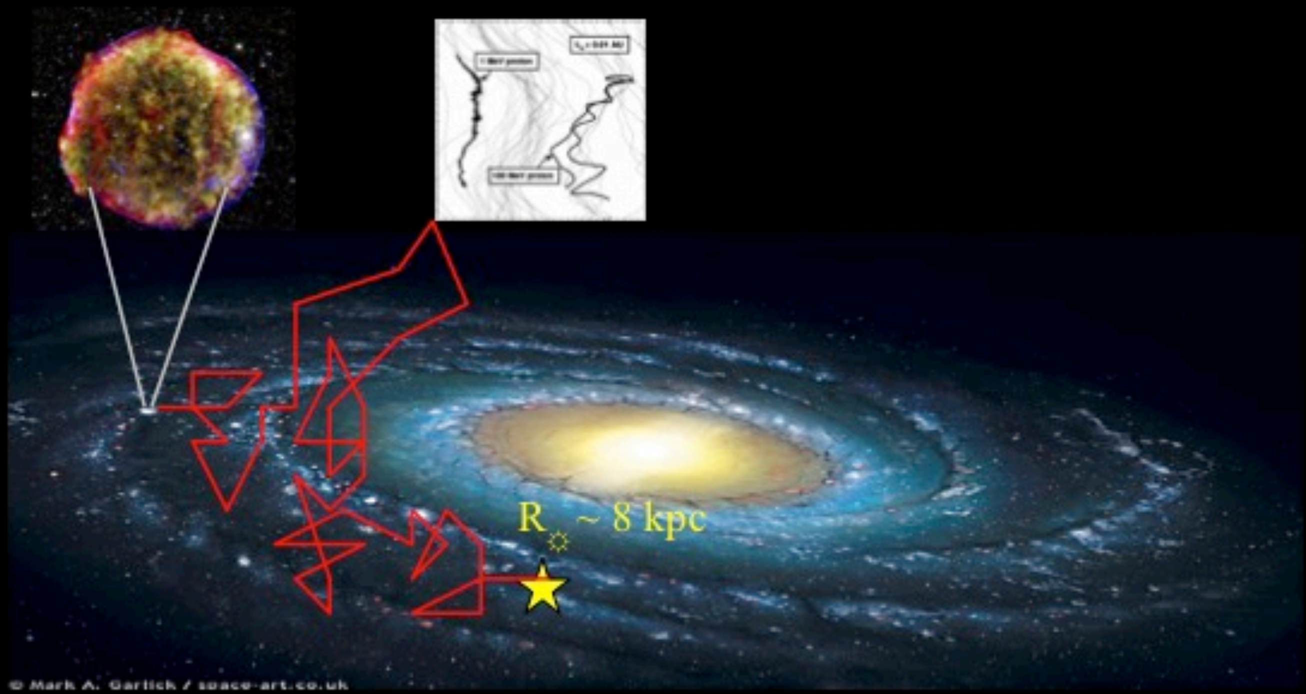
Charged cosmic rays in the Galaxy: sources

1. Source injection
- spectrum ~ R^{-2}
- abundances



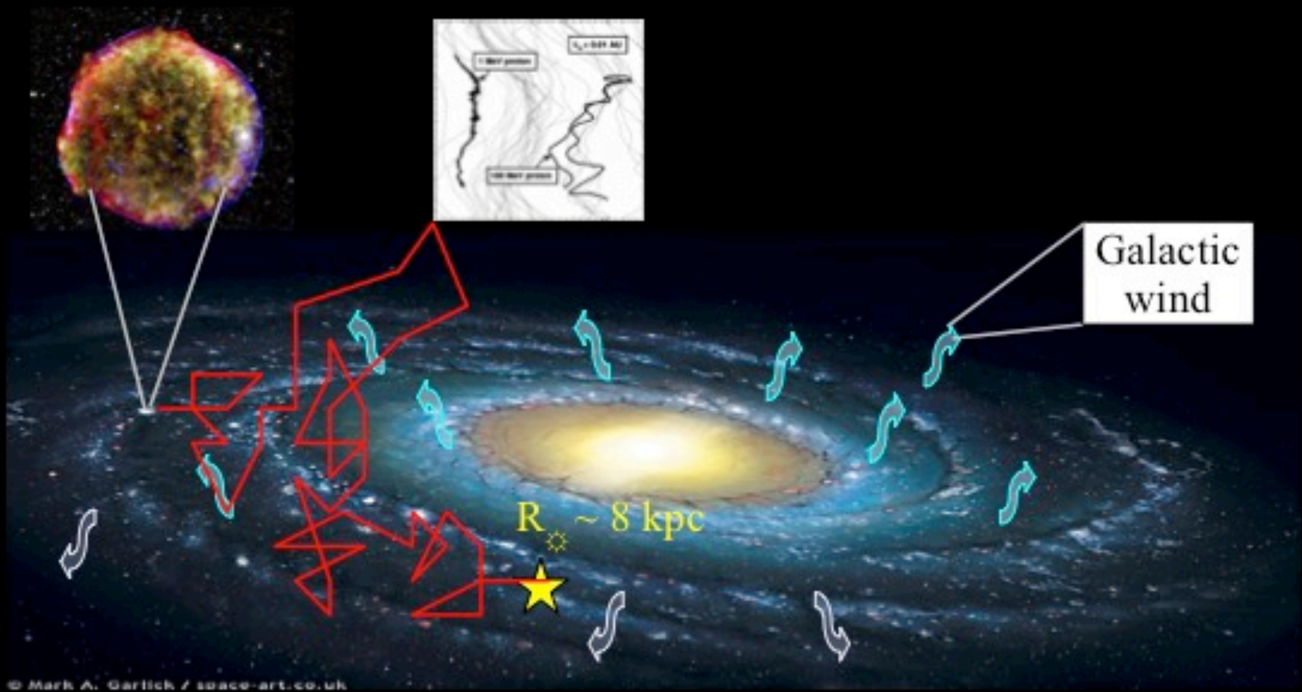
Charged cosmic rays in the Galaxy: diffusion

1. Source injection
- spectrum ~ R^{-2}
- abundances



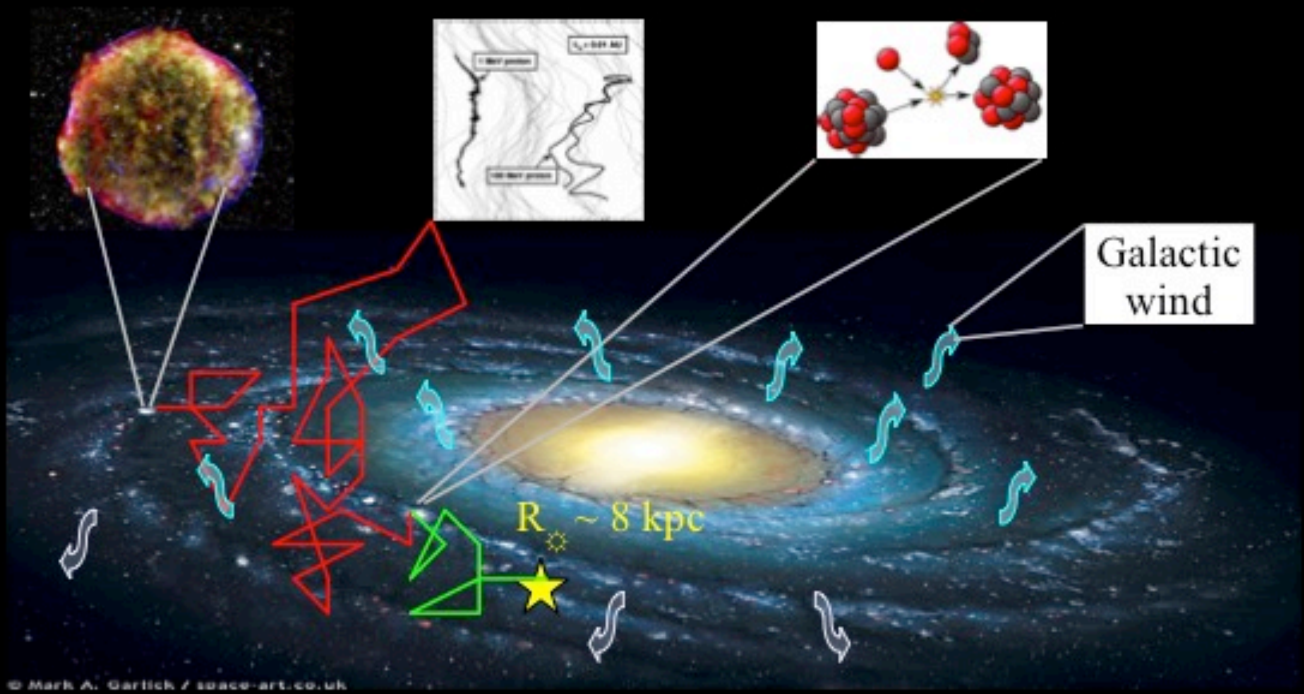
Charged cosmic rays in the Galaxy: convection

1. Source injection
- spectrum ~ R^{-2}
- abundances



Charged cosmic rays in the Galaxy: interactions

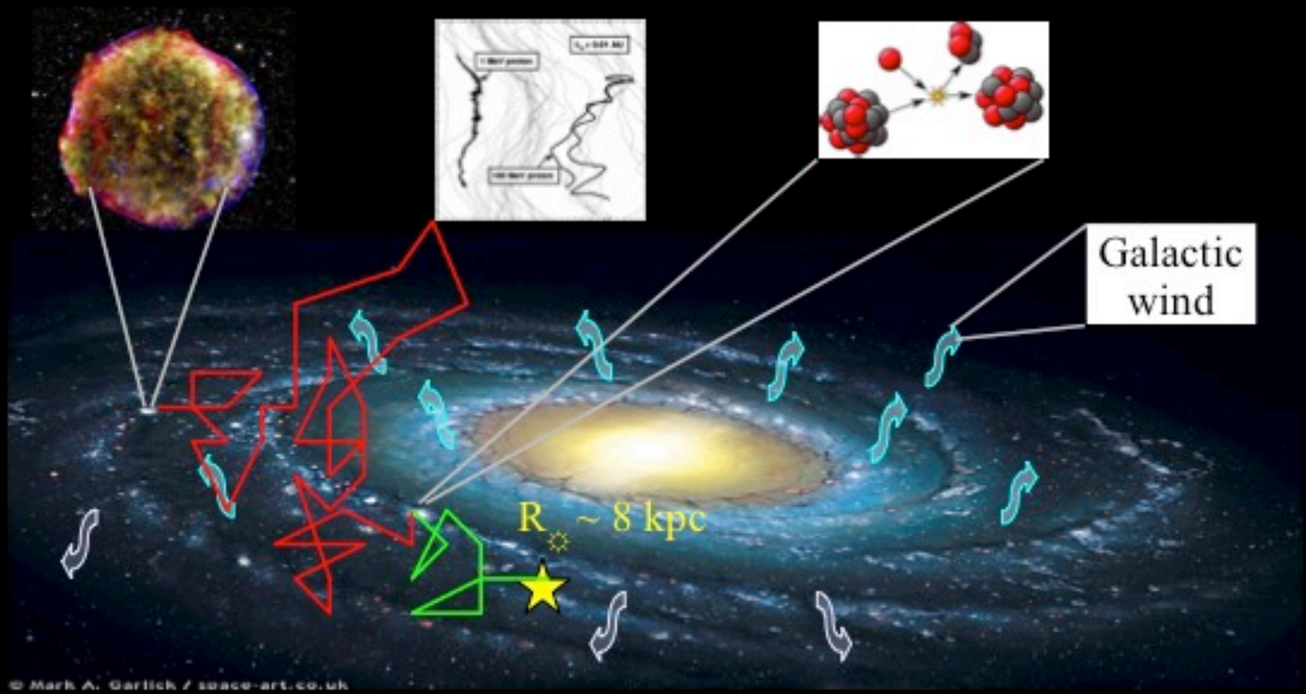
1. Source injection
- spectrum ~ R^{-2}
- abundances



Charged cosmic rays in the Galaxy: all together

1. Source injection
- spectrum ~ R^{-2}
- abundances

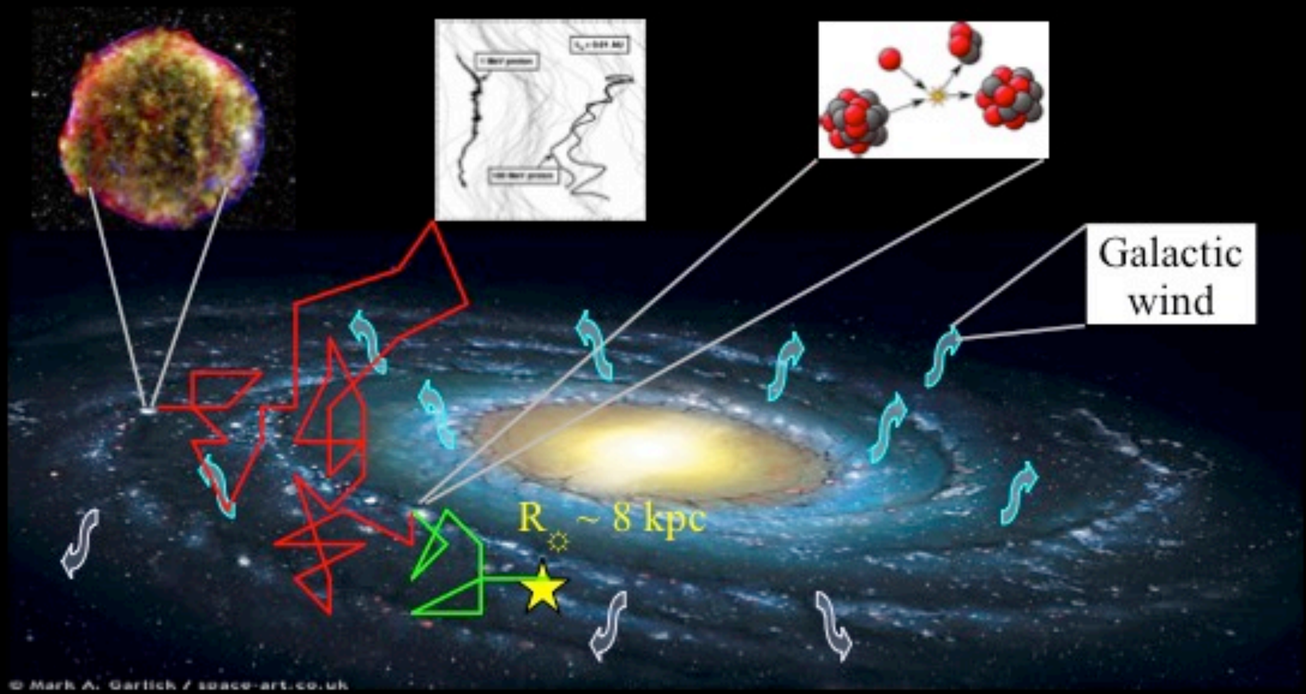
2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay



Charged cosmic rays in the Galaxy: phenomenology

1. Source injection
- spectrum ~ R^{-2}
- abundances

2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay



Particles reaching Earth come from:

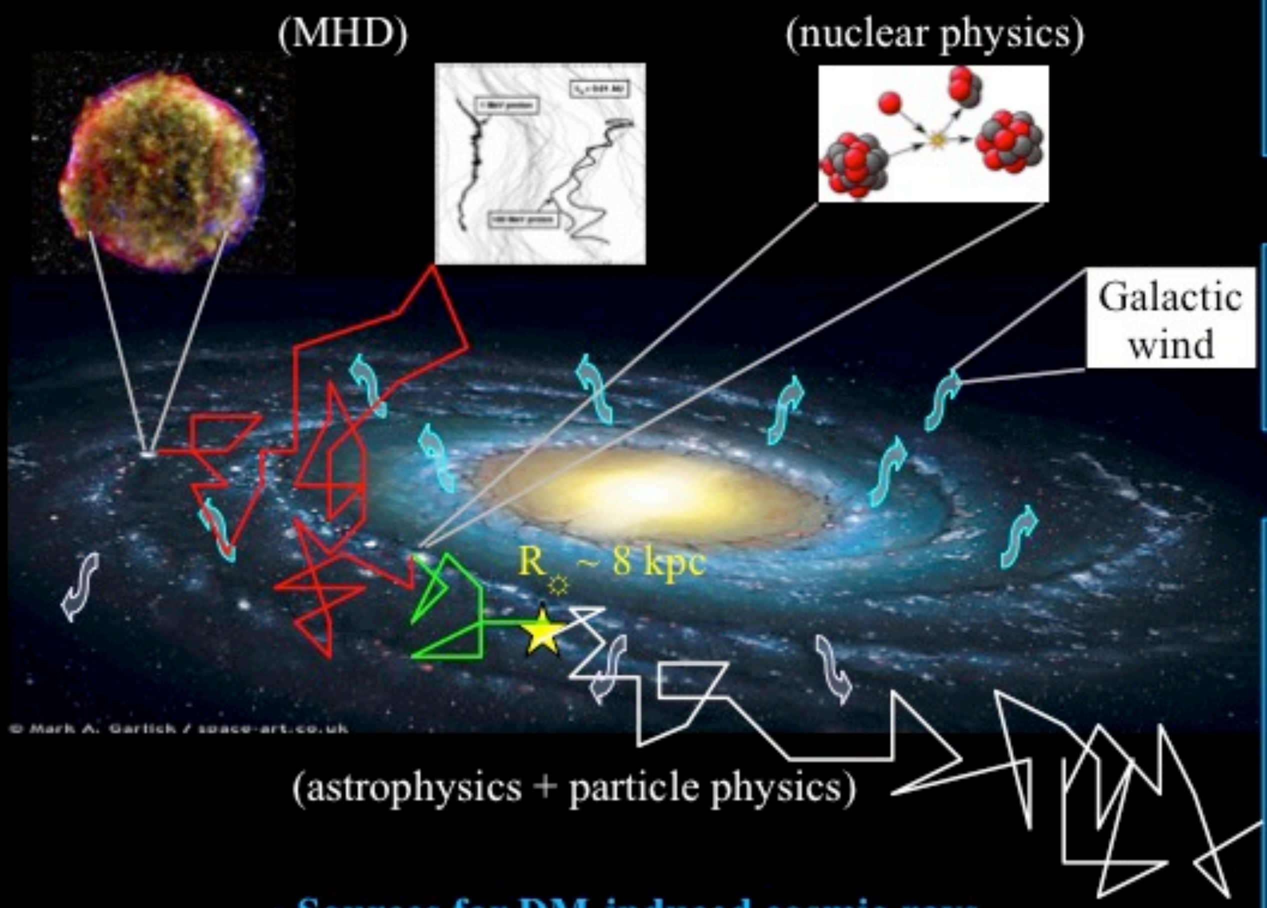
- whole diffusive volume for stable species
- small volume (~ 100 pc) for radioactive nuclei and high energy electrons

→ different species sample different regions of the Galaxy

Charged cosmic rays in the Galaxy: DM indirect detection

1. Source injection
- spectrum ~ R^{-2}
- abundances

2. Transport in the Galaxy
- diffusion: R^{δ}
- convection
- energy gains/losses
- fragmentation/decay



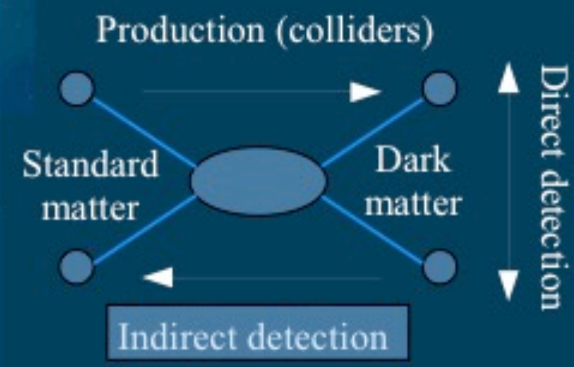
→ Sources for DM-induced cosmic rays from DM halo (not only disc)

What about dark matter?

Universe (after Planck)
- 68.3 % dark energy
- 26.8 % dark matter
- 4.9 % ordinary matter

MW dark matter halo
- ~ spherical halo
- radius ~300 kpc

How to detect dark matter?



An unexpected journey: processes and typical scales

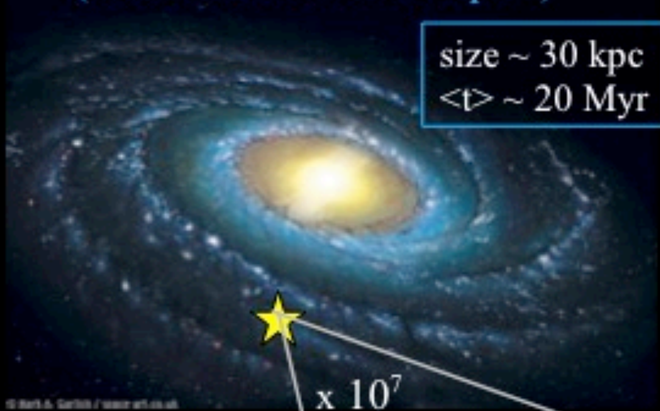
1. Cosmic rays in the Galaxy

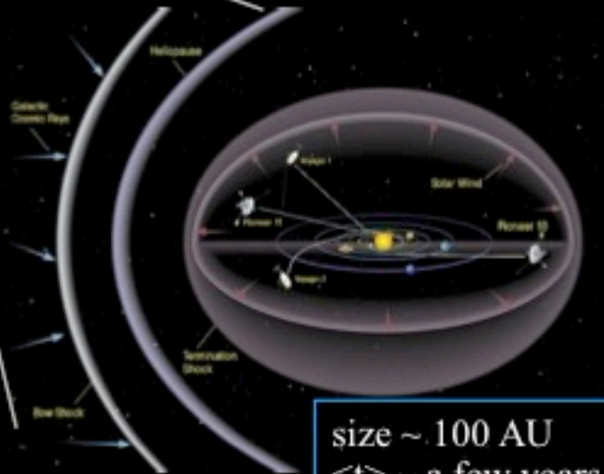
→ Spectra and abundances
(acceleration and transport)

An unexpected journey: across the Solar cavity

1. Cosmic rays in the Galaxy

→ Spectra and abundances
(acceleration and transport)





2. Transport in the Solar cavity

→ flux modulation < 10 GeV/n
→ time dependence

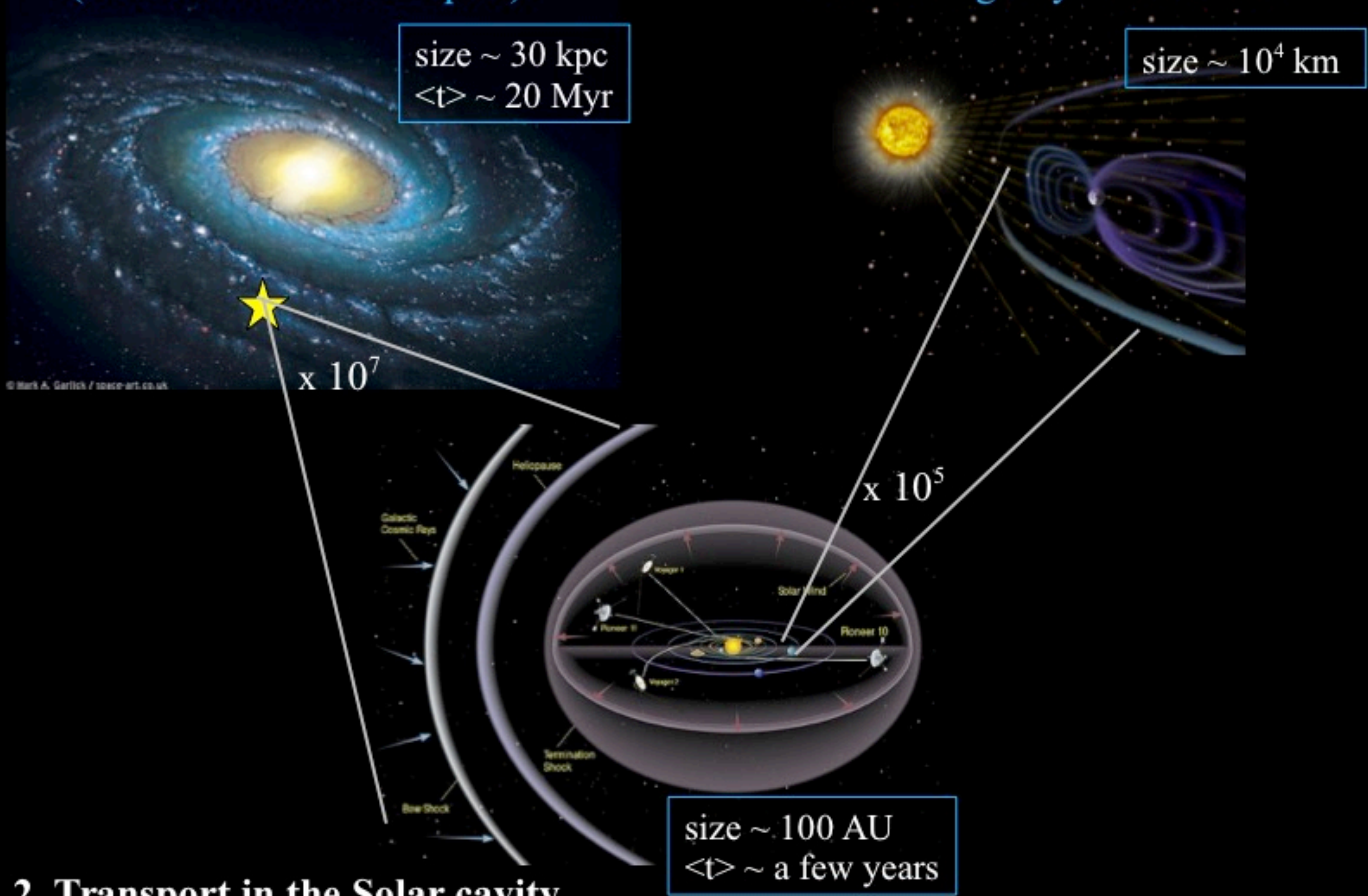
An unexpected journey: across the Earth magnetosphere

1. Cosmic rays in the Galaxy

→ Spectra and abundances (acceleration and transport)

3. Earth magnetic shield

→ Cut-off rigidity for detectors



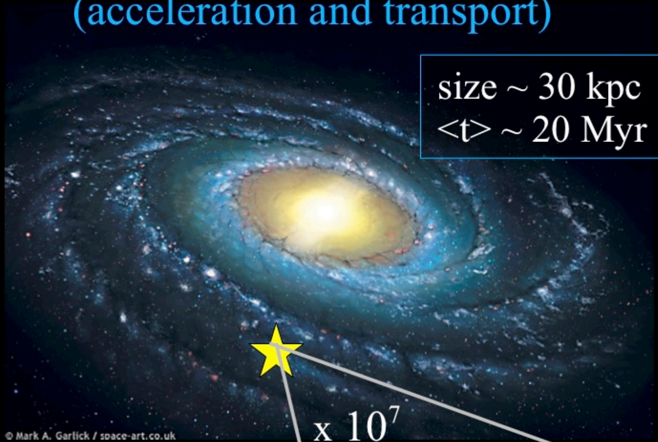
2. Transport in the Solar cavity

→ flux modulation < 10 GeV/n
→ time dependence

An unexpected journey: across the Earth atmosphere

1. Cosmic rays in the Galaxy

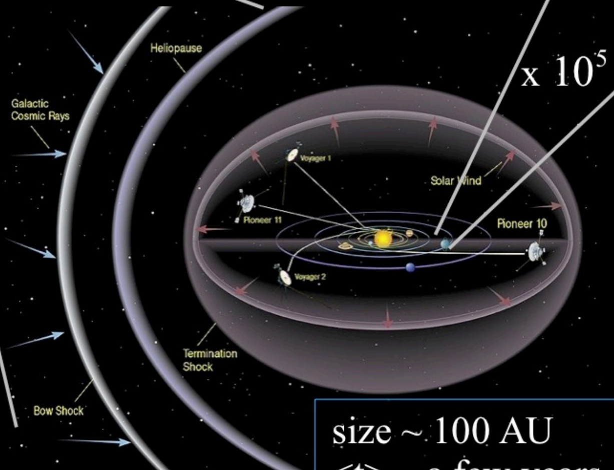
→ Spectra and abundances
(acceleration and transport)



size ~ 30 kpc
<t> ~ 20 Myr

x 10^7

2. Transport in the Solar cavity



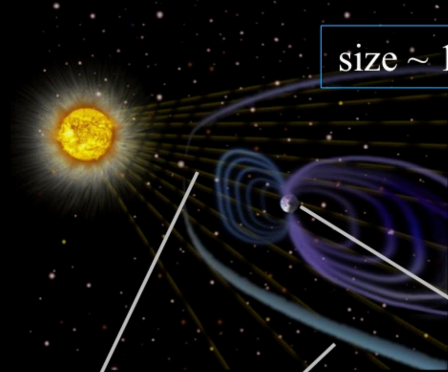
size ~ 100 AU
<t> ~ a few years

→ flux modulation < 10 GeV/n
→ time dependence

x 10^5

3. Earth magnetic shield

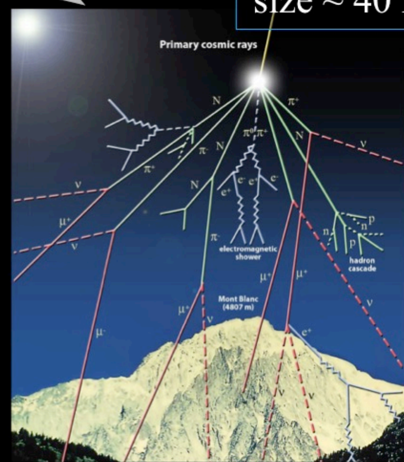
→ Cut-off rigidity for detectors



size ~ 10^4 km

x 10^2

4. Atmospheric showers

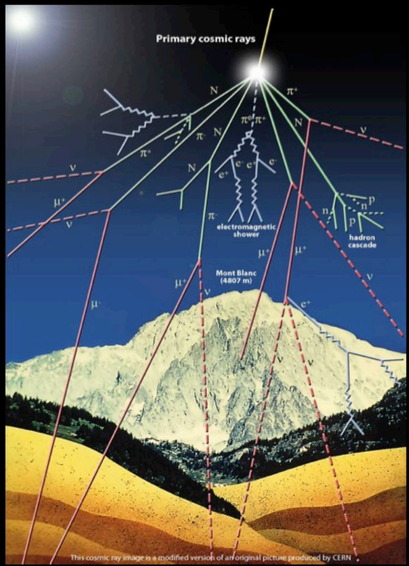


size ~ 40 km

→ Ground-based detection
→ Solar activity monitoring
[N.B.: Čerenkov flash ~ 10^{-8} s]

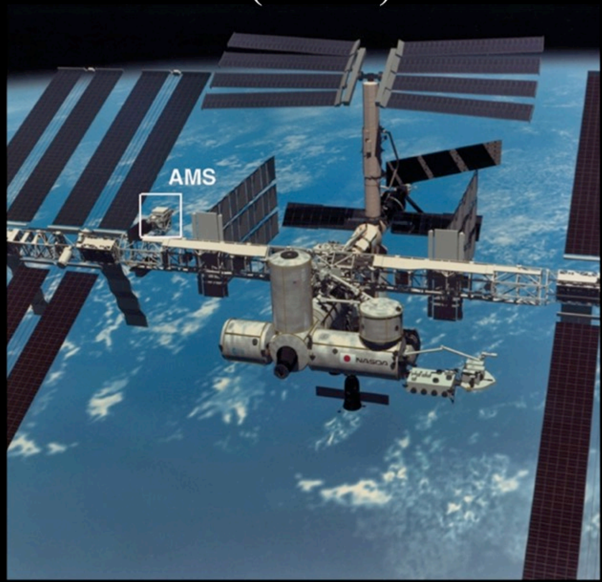
Timeline: CR identification

Mountain altitude < 5 km



CREAM balloon ~ 40 km

AMS-02 (on ISS) ~ 300 km



CR discovery — 1910

e^-, e^+ — Diffuse γ — $\bar{p}$ — TeV astronomy — ν — $\bar{d}$?

1910 — 1930 — 1950 — 1980 — 2000

e^+, μ, π , K, Λ (1930–1950)

Elements up to U (1950–1970)

^{10}Be - ^{54}Mn (1970–1980)

Cosmic rays = Particle physics

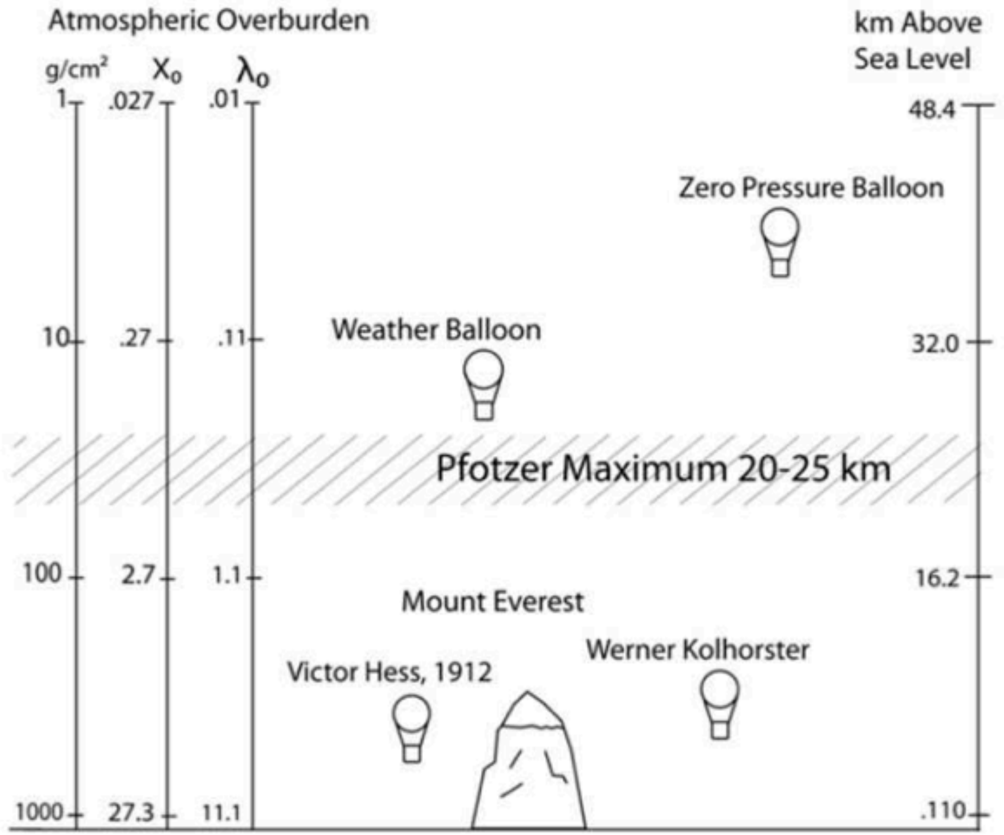
Particle physics

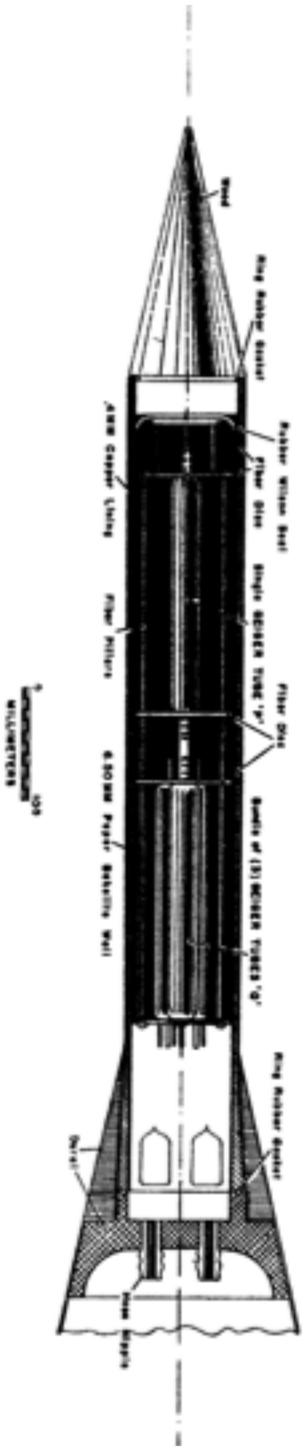
Astrophysics

+ astroparticle physics

III- GCR detection: 2-Earth Environment
i- Earth atmosphere

- Earth atmosphere represents a thickness of 1000 $g.cm^{-2}$:
  - 11.5 nuclear interactions lengths
  - 28 radiation lengths
- primary cosmic rays will undergo nuclear and electromagnetic interactions, producing a lot of secondary particles : pions, kaons, neutrons, electrons, muons, photons, neutrinos,...



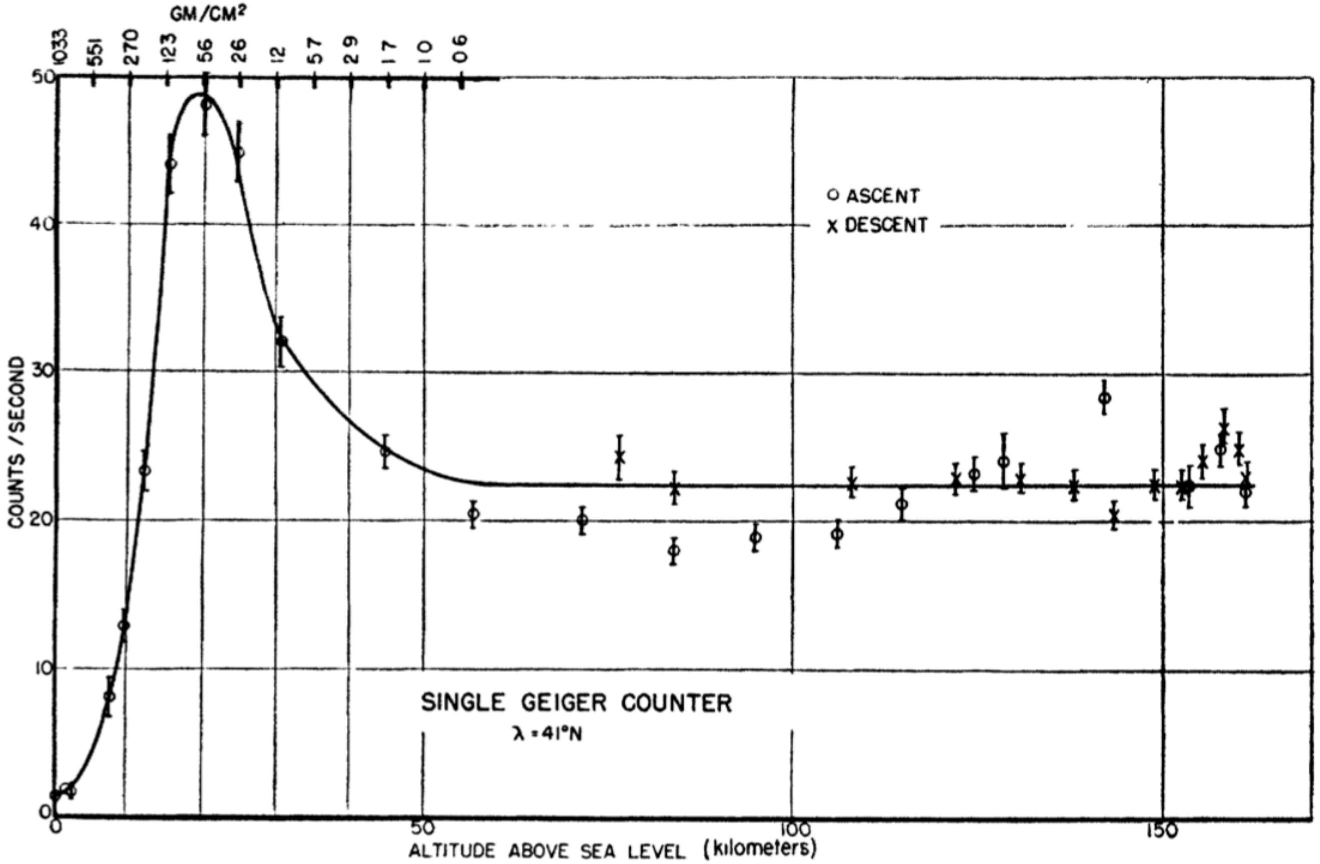


PHYSICAL REVIEW VOLUME 73, NUMBER 3 FEBRUARY 1, 1

The Cosmic-Ray Counting Rate of a Single Geiger Counter from Ground Level to 161 Kilometers Altitude

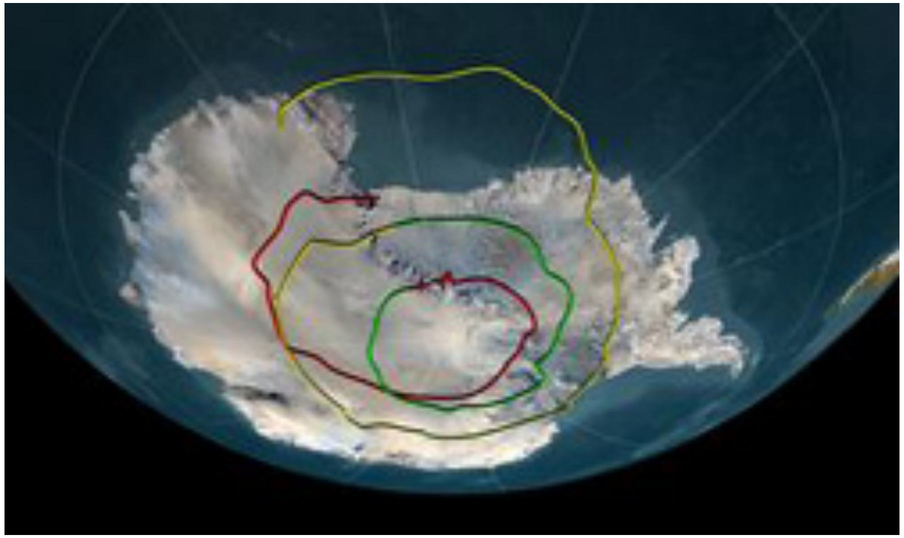
J. A. VAN ALLEN AND H. E. TATEL*
Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Maryland

(Received October 16, 1947)



III- GCR detection: 2- Earth Environment
i- Earth atmosphere

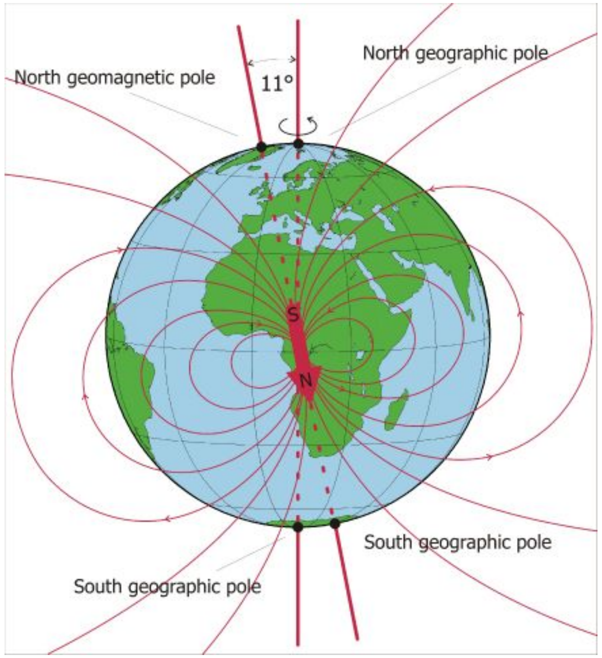
- Direct detection of primary cosmic rays implies the transport of detectors to at least 30 km from earth
- "Zero-Pressure" balloons developed in the late 1940's could carry several tons detectors to altitudes of 30 to 45 Km
  - few days flight
  - LDB: long-duration balloon flights several weeks flight
- Space : Rockets / Satellite / Space station

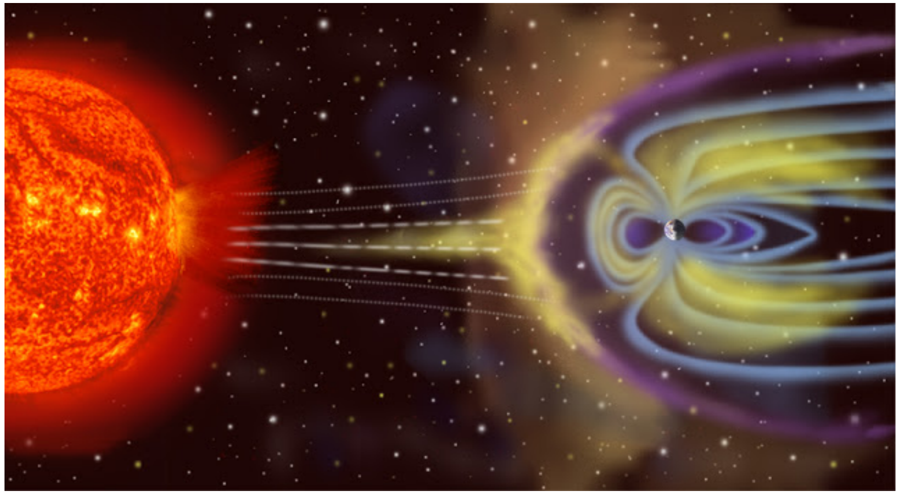


III- GCR detection: 2- Earth Environment
ii- Magnetic Field

The earth has a magnetic field - geomagnetic field the zone of influence is called the **magnetosphere**

- Main source : inside earth, there are electrical currents related to the rotating metallic nucleus
- outer sources : ionosphere currents, ring current (charged particles trapped in radiation belts)
- As a first approximation it can be represented by a magnetic dipole
- The geomagnetic equator is tilted 11.5° wrt. geographic equator
- not centered with earth *(eccentric dipole)*
- more complete model : IGRF + external field model

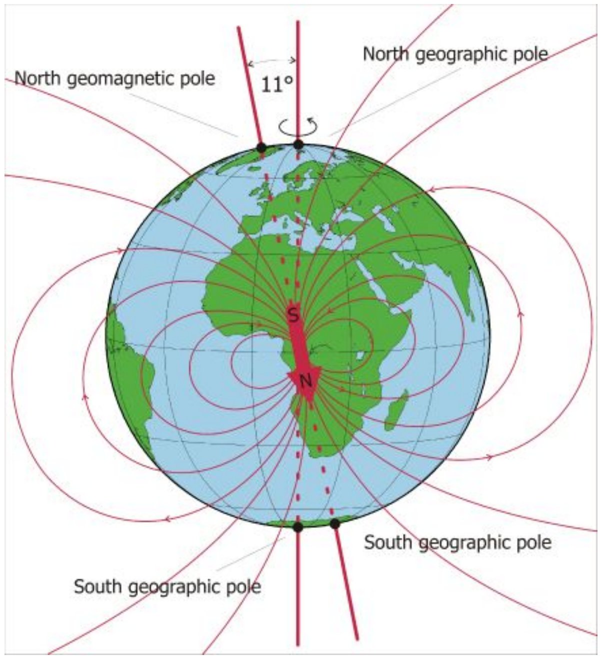


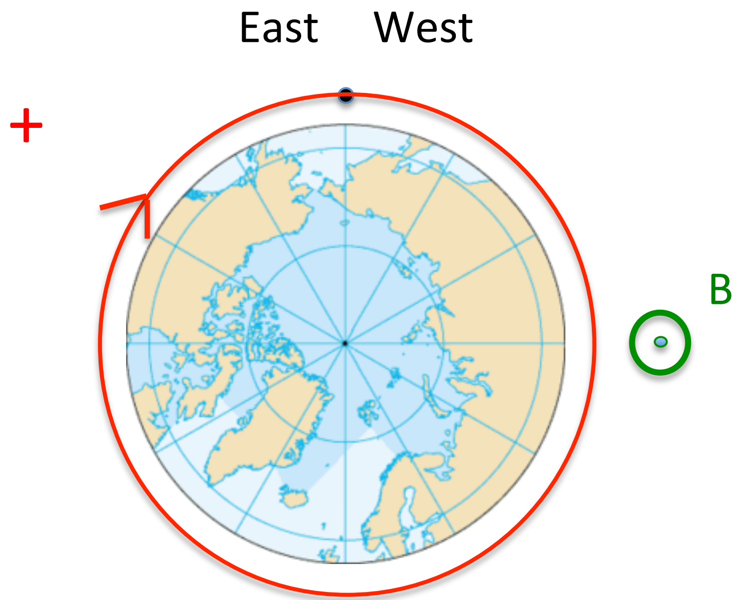


III- GCR detection: 2- Earth Environment
ii- Magnetic Field

In the equatorial plane : circular trajectory of radius r_E corresponds to the rigidity:

$$R = \frac{P}{eZ} = \frac{\mu_0}{4\pi}\frac{M}{r_E^2} = 57\ \text{GV}$$





III- GCR detection: 2- Earth Environment
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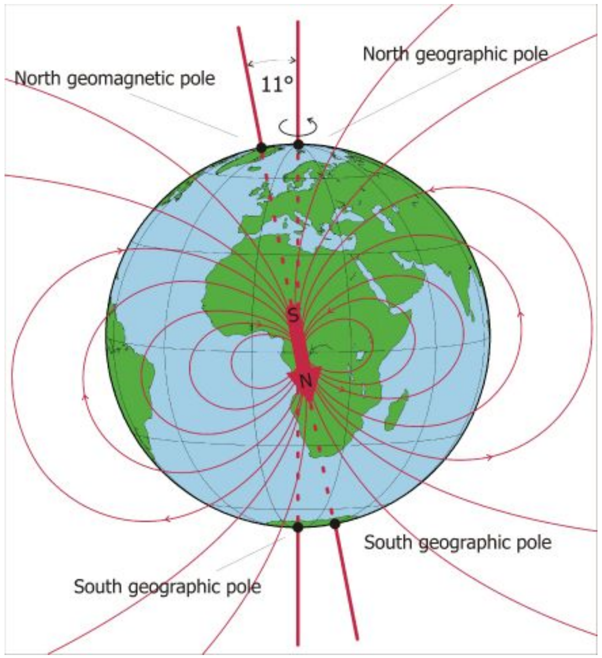

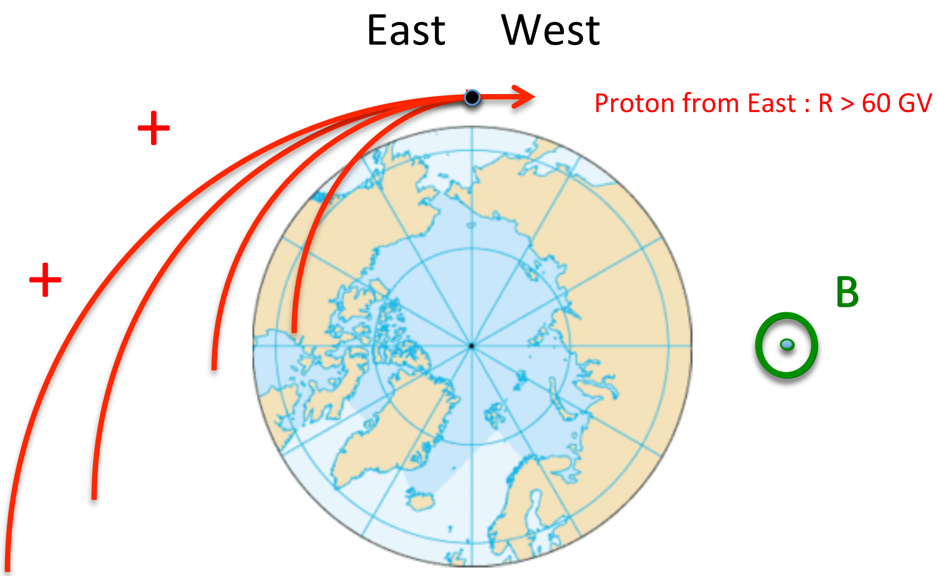

- East-West effect: Cutoff effect → More proton from West vs East
- Equatorial corresponds to the extreme case: perp. To the field lines
  → Decrease of the cutoff with increasing latitude

III- GCR detection: 2- Earth Environment
ii- Magnetic Field

In the equatorial plane : circular trajectory of radius r_E corresponds to the rigidity:

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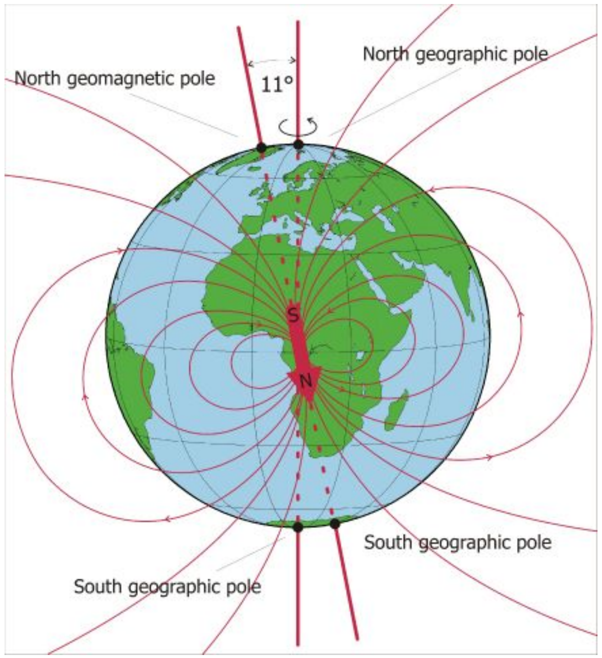

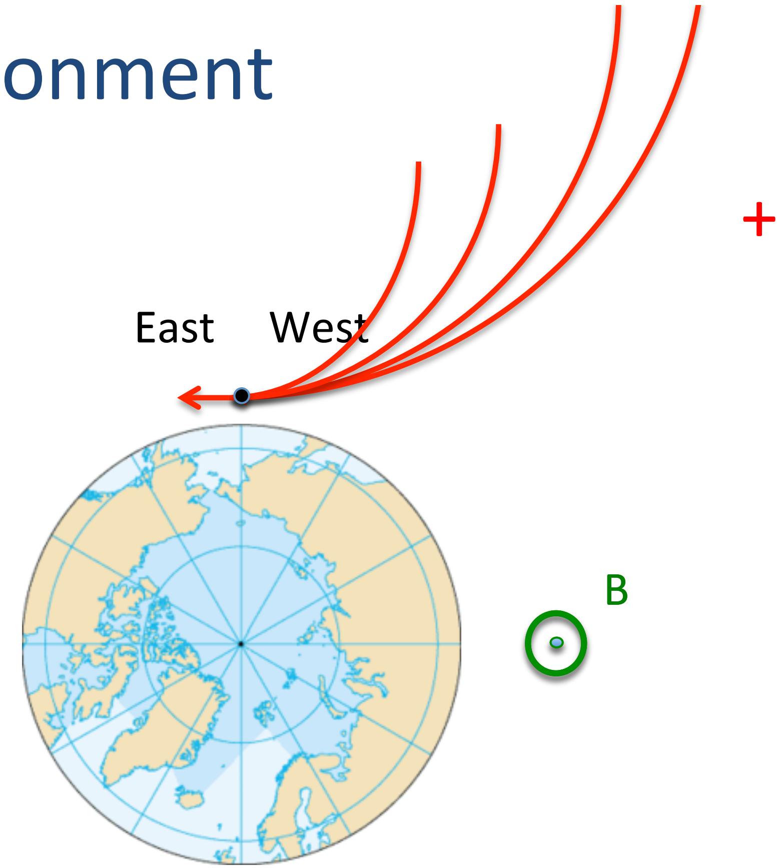

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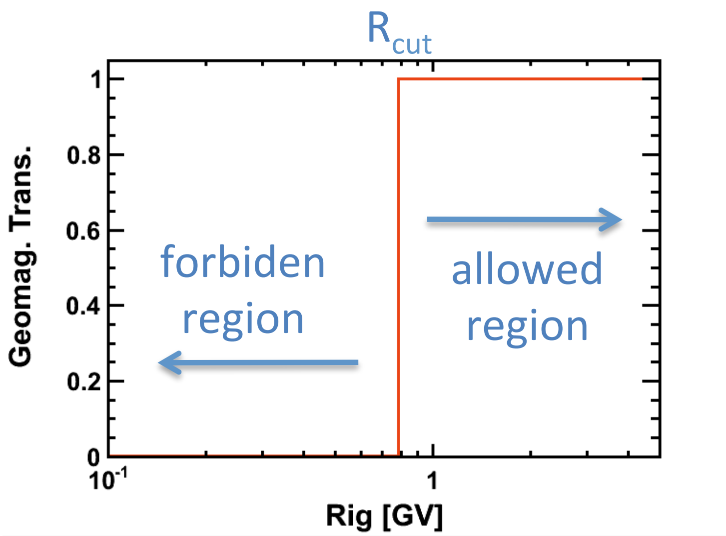
- Equatorial corresponds to the extreme case: perp. To the field lines
  → Decrease of the cutoff with increasing latitude

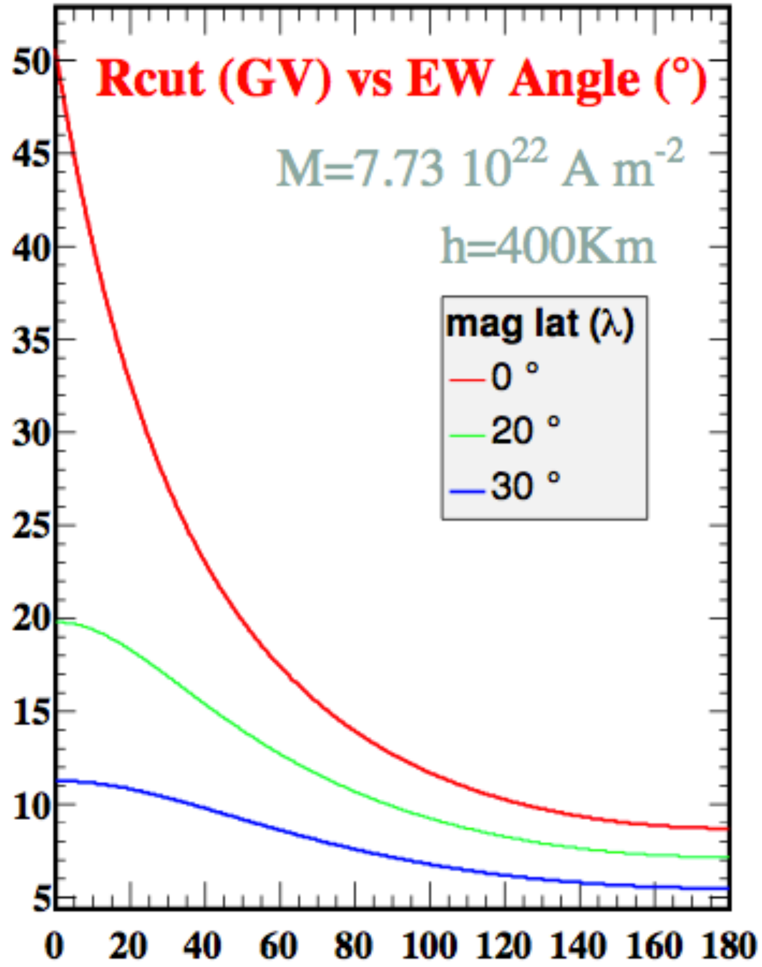
III- GCR detection: 2- Earth Environment
ii- Magnetic Field

- Störmer Formula:

$$P_c = P_E \left(\frac{R_E}{r}\right)^2 \frac{\cos^4 \lambda}{\left[1 + \left(1 - \frac{z}{|z|} \cos\alpha \cos^3 \lambda\right)^{1/2}\right]^2}$$

- Geomagnetic transmission for a given position and direction:

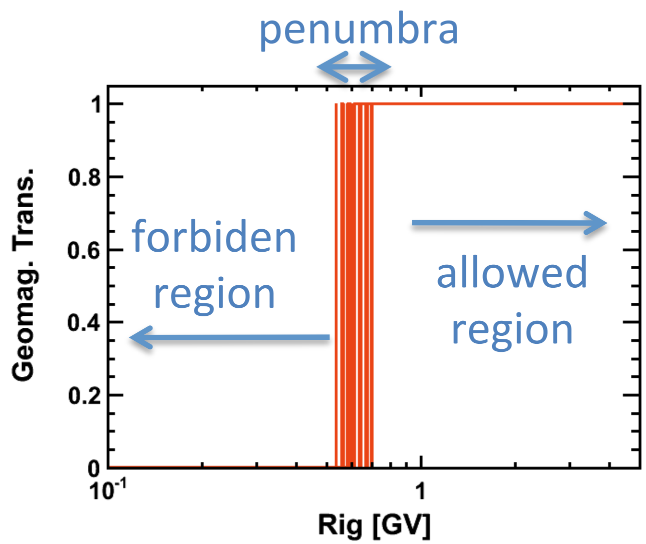


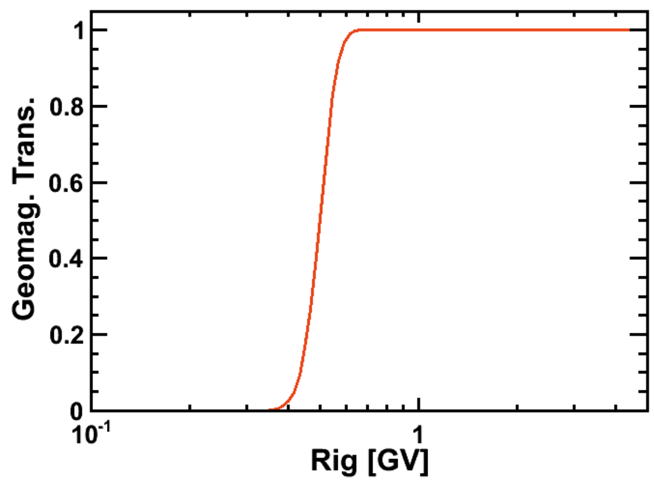


α: East-West Angle

III- GCR detection: 2- Earth Environment
ii- Magnetic Field

- With the real geomagnetic field, the transmission function is more complex. The penumbra region includes allowed and forbiden trajectories.
- Its size, structure depends on position and can evolve with time (solar flare)
- In practice, smoothing of the penumbra region due to the finite energy and direction resolution of the detector.

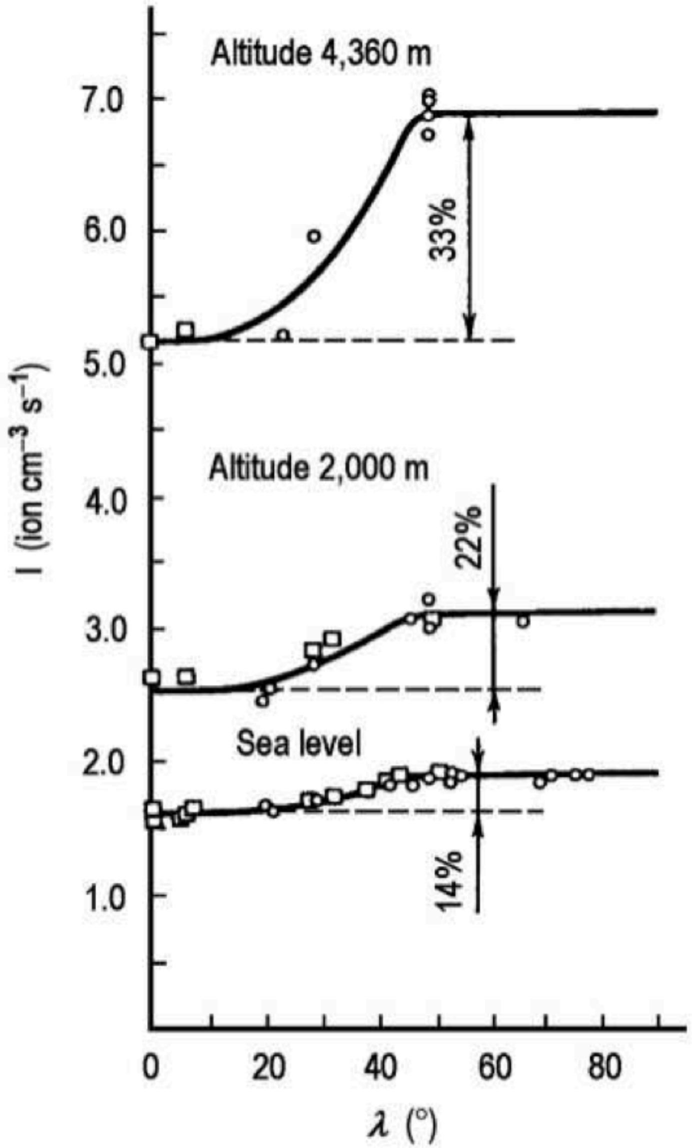




III- GCR detection: 2- Earth Environment
ii- Magnetic Field

Until the end of 1920s was not clear if CRs were charged or neutral (γ rays) particles
→ Millikan and Compton dispute !

- The geomagnetic effect in cosmic rays was observed in 1927 by J. Clay, using an ionization chamber when travelling from Java island to Holland (Slamat ship)
- In 1932, Compton organized eight expeditions for cosmic ray intensity measurements at several locations (latitude and longitude different)
  → a clear dependence with the latitude was observed providing the charged nature of the CRs !
- West–East CR asymmetry (Johnson, Seidl, Burbury, Fenton)
  → the largest part of primary CR are positively charged particles



Recent GCR experiments

balloons

- MASS (1989-1991)
- IMAX (1992)
- CAPRICE (1994-1998)
- HEAT (1994-1995)
- BESS (1994-2000)
- ATIC (2000-2007)
- TRACER (2006)
- CREAM (2004-2010)

space

- HEAO3 (1979-1981)
- AMS01 (1998)
- PAMELA (2006-2016)
- FERMI (2008-?)
- AMS02 (2011-?)

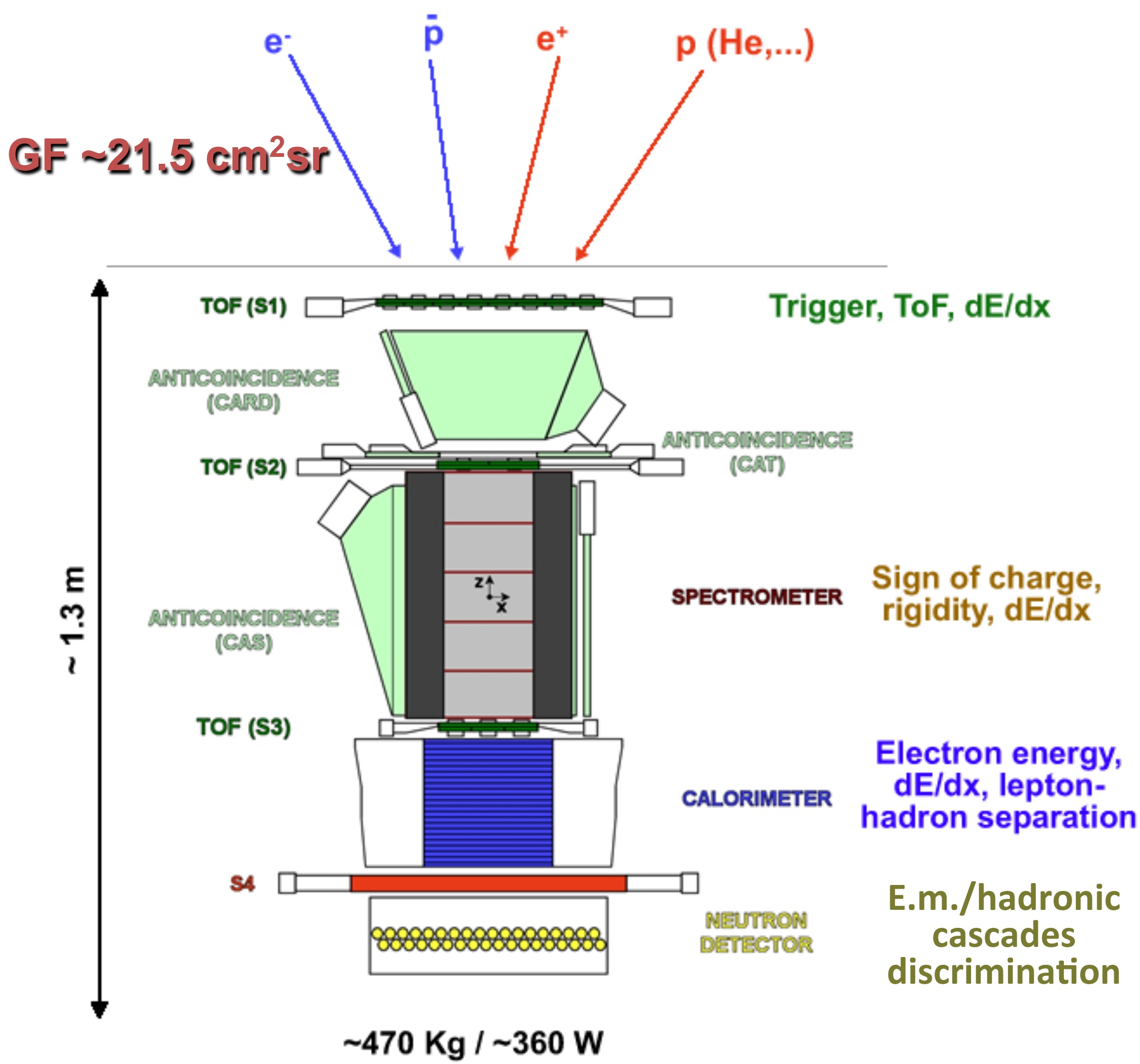
Spectrometer
Calorimeter

In the following, I will use AMS02 to illustrate the detection of GCRs

PAMELA Mission

- PAMELA installed on Russian satellite Resurs-DK1, inside a pressurized container.
- Launch in June 2006, continuously taking data up to last year.
- Circular orbit (70.0°, 600 km).

PAMELA Detector



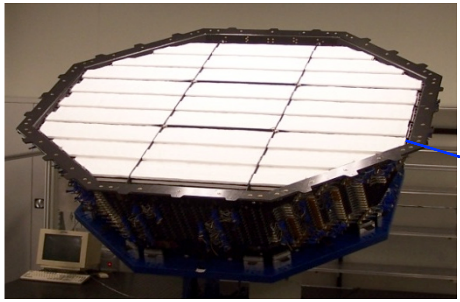
- AMS installed on ISS in May 2011


Alpha Magnetic Spectrometer
AMS-02
ELC2

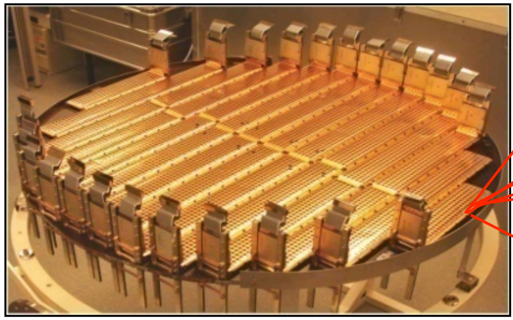
AMS

A TeV precision, multipurpose spectrometer in space.

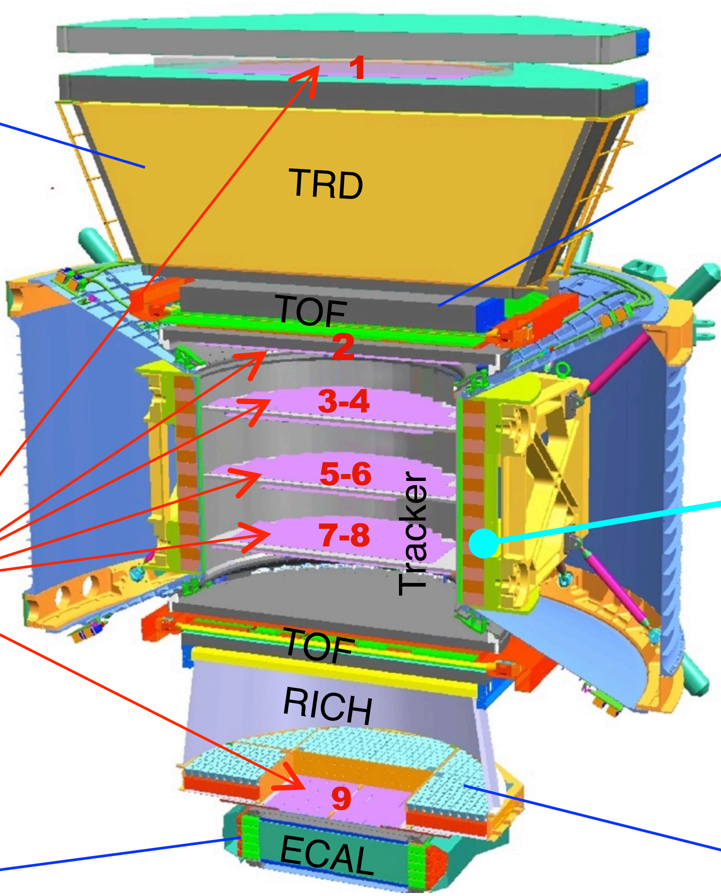
TRD
Identify e^+, e^-



Silicon Tracker
Z, P



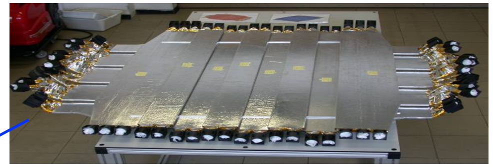
ECAL
Identify e^+,e^-
E of e^+, e^-, γ



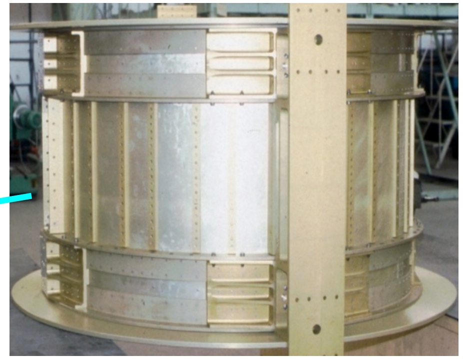
5m x 4m x 3m   7.5 tons

GF ~ 5000 $cm^2 sr$

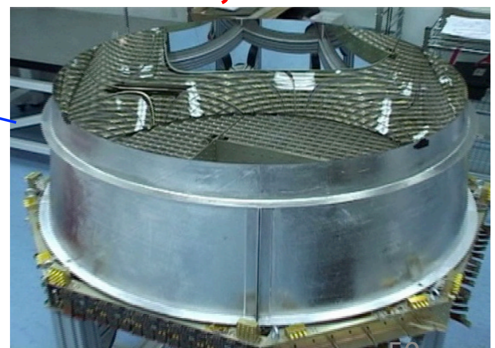
TOF
Z, Beta



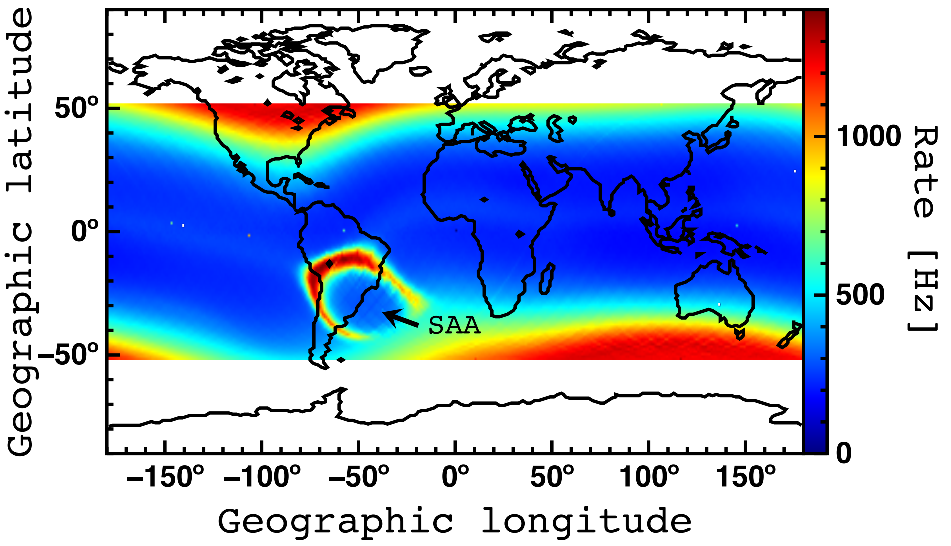
Magnet
±Z

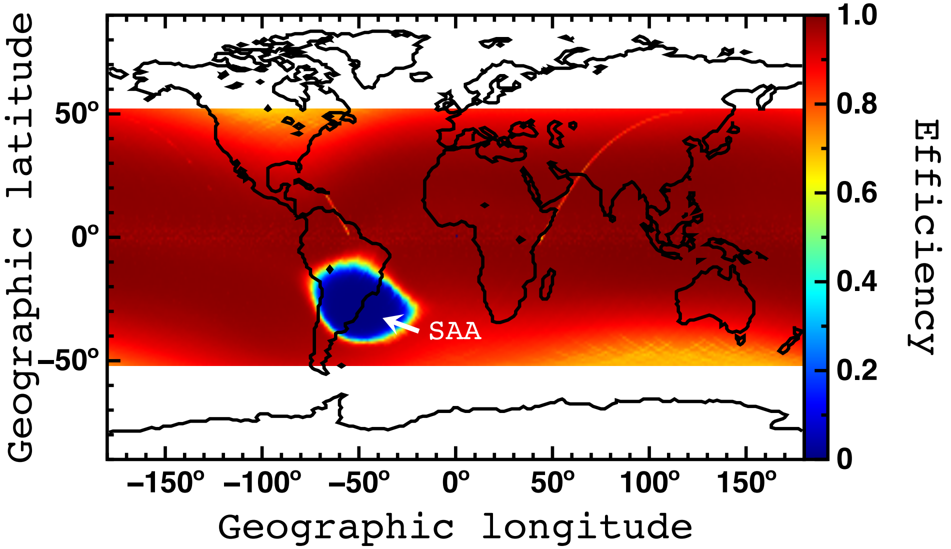


RICH
Z, Beta



In flight operations

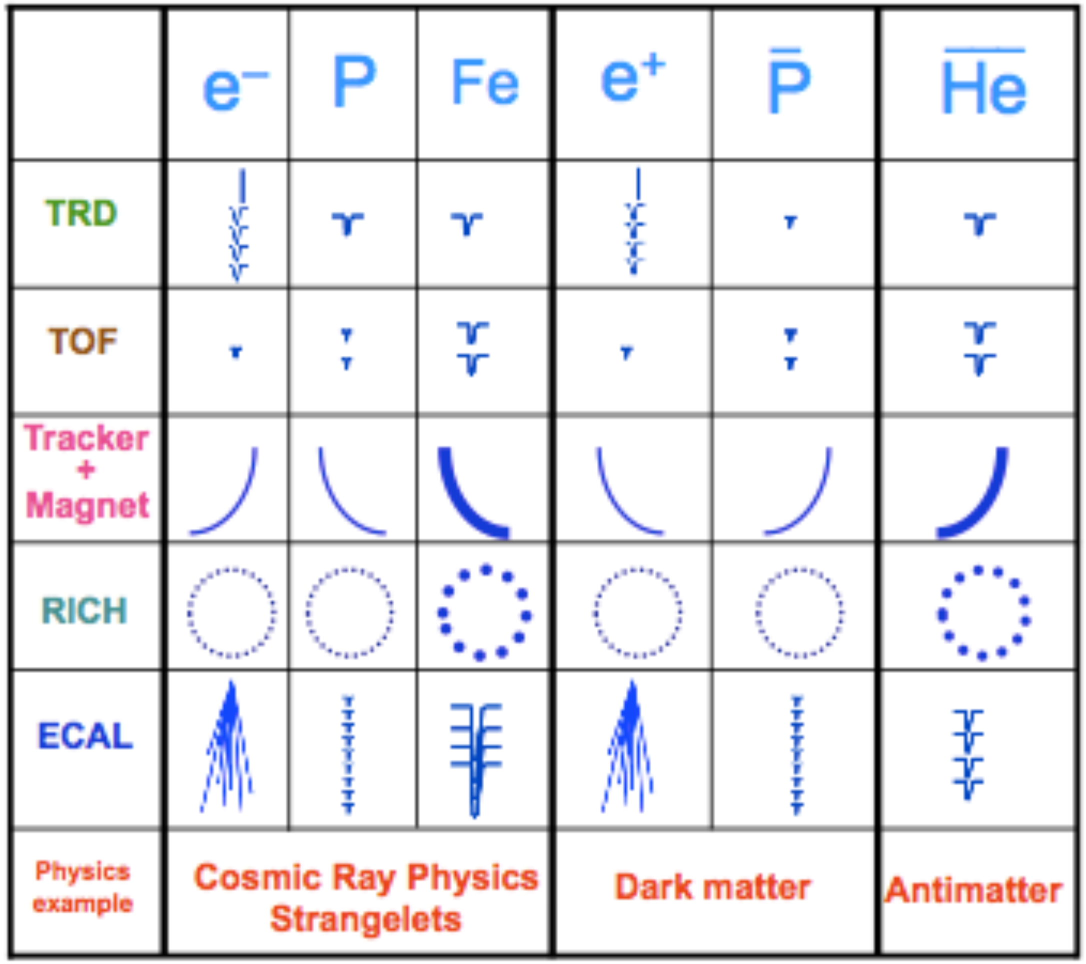




- AMS installed on ISS in May 2011
- Circular orbit, 400 km, 51.6°, 90 mn
- Continuous operation 24/7
- Average rate ~700 Hz
- 60 millions particles/day
- 39 TB raw data/yr
- 200 TB rec. data/yr
- More than 100 milliards of events collected so far

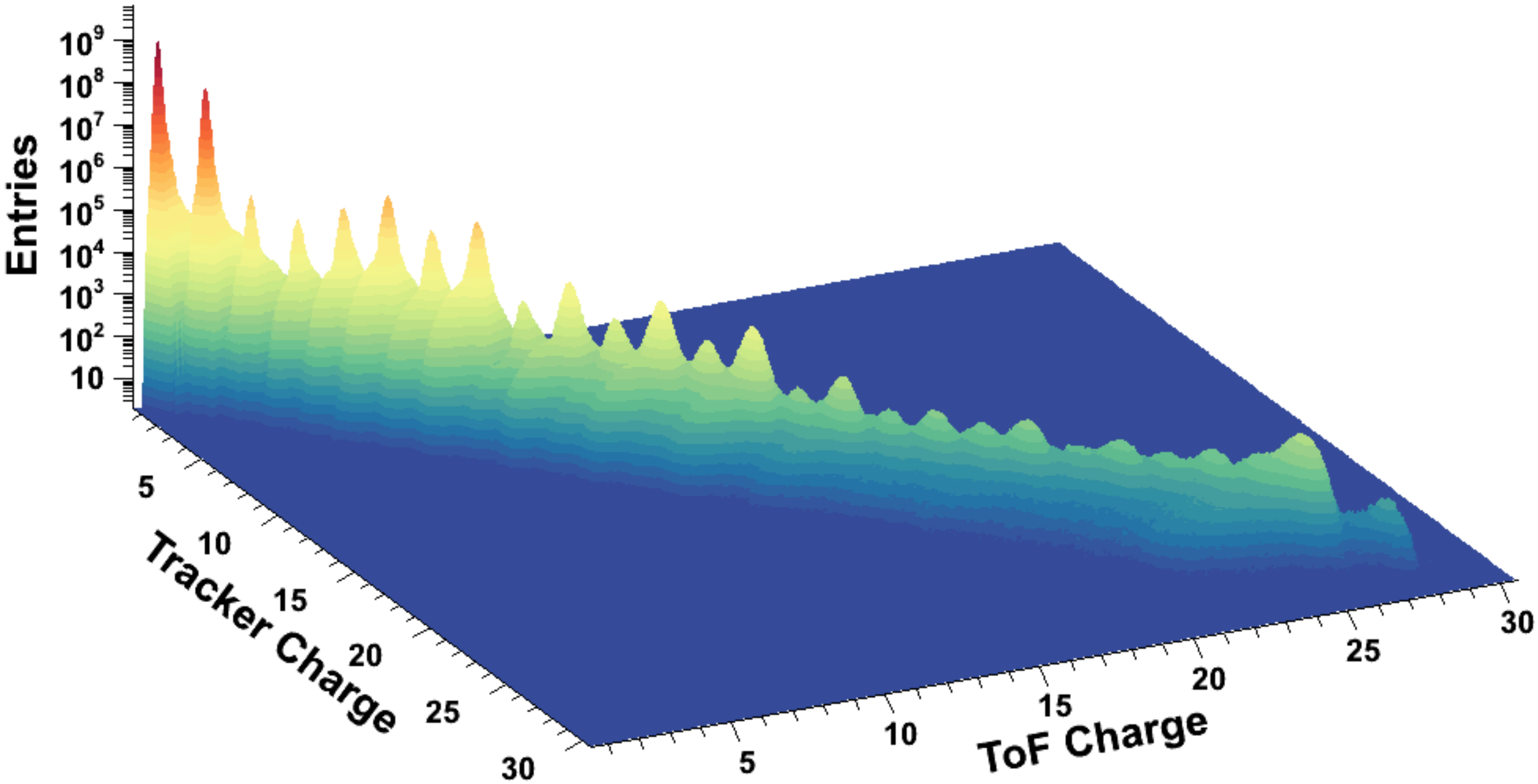
CR Analyses

- Combination of measurement from sub-detectors to identify particles and to measure their Energy/Rigidity



CR Analyses

- Combination of measurement from sub-detectors to identify particles and to measure their Energy/Rigidity



CR Analyses

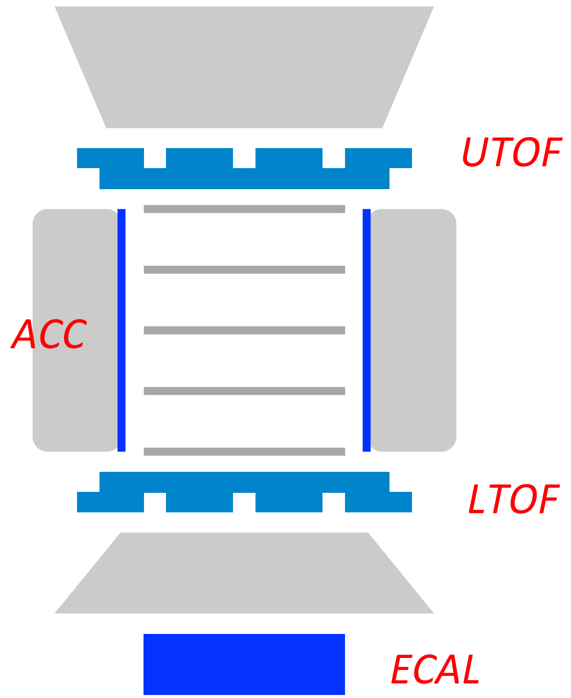
- Combination of measurement from sub-detectors to identify particles and to measure their Energy/Rigidity
- Redundancy of AMS measurements allows:
  - To estimate the efficiencies
  - To build reference distributions (templates)
  - To control systematics
- Each analysis is specific:
  - Observable: Flux / ratio of fluxes flux

    Ex: Flux e^+, e^- -- $e^+/(e^+ + e^-)$ -- Flux $(e^+ + e^-)$
  - Background from other particles
  - Background from interaction in the detector
  - Energy/Rigidity measurement

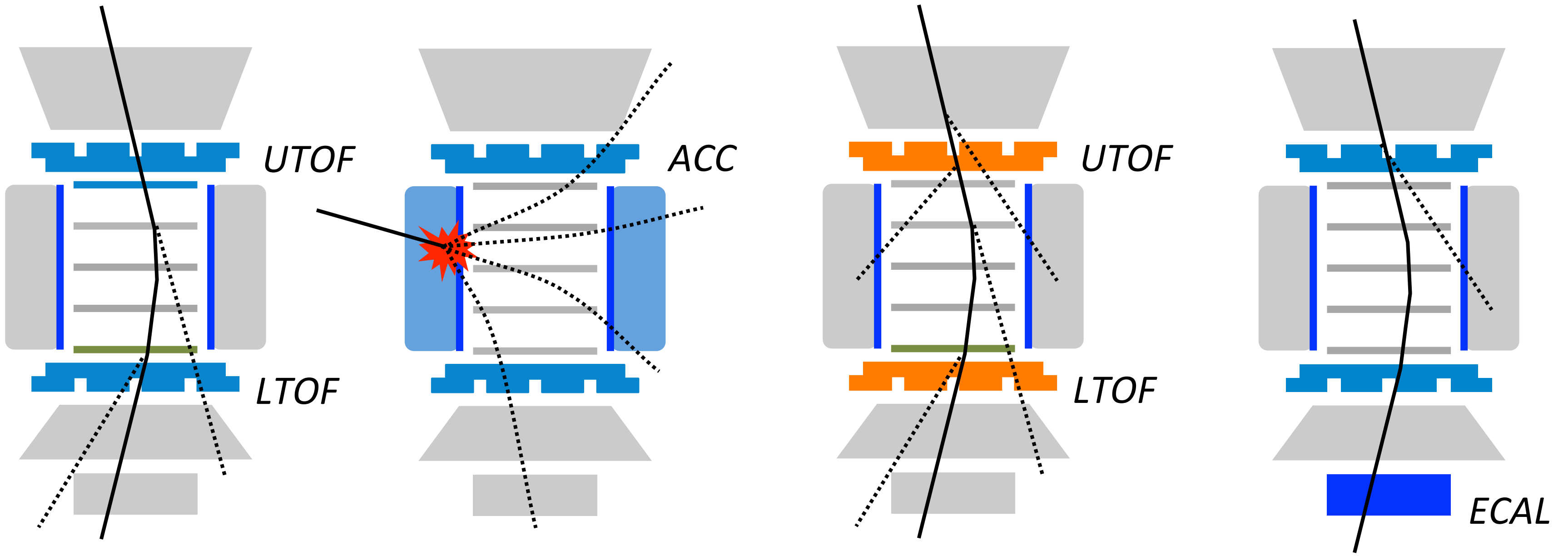
AMS Trigger

- As a particle detector, the instruments should acquire a signal only if a particle is passing trough: Trigger system
- Should be fast enough to trigger readout system of the other sub-detectors.
- Should have the largest efficiency but should also keep the detector rate < 2kHz (Bandwidth limitation)
- AMS: Combination of signals from TOF, de l'ACC et du ECAL.
- Global Trigger = OR between following triggers:
  - « unbias » : TOF 3/4 , scaled by 100

    → Efficiency close to 100%, no energy dependance, use to estimate the efficiency of other triggers
  - « proton » : TOF 4/4, $N_{acc} = 0$
  - « ion » : TOF 4/4 Signal>(Z=1), $N_{acc} < 3$
  - « electron » : TOF 3/4 HT, ECAL shower



Trigger



Z=1 particle | *Horizontal Particle* | *High-Z particle* | *TOF + ECAL Trigger*

Accepted | ***Rejected*** | ***Accepted*** | ***Accepted***

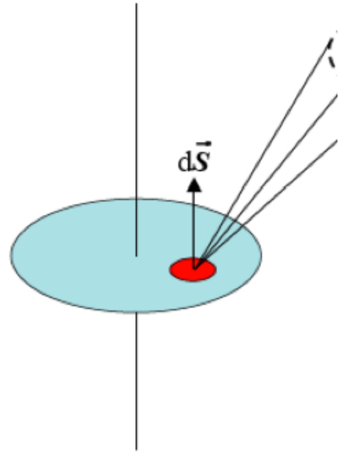
III- GCR detection: 4- Estimation of proton Flux with AMS

- Proton: dominant component in CR
  - No contamination
  - Not limited by statistics

  → High precision measurement

  → Need for precise estimation and control of the systematics ⇦ MC
- Rigidity measurement with the tracker
- Flux Estimation
  - Exposure time / Lifetime
  - Detector acceptance / Selection cuts efficiency ⇦ MC
  - Trigger efficiency

Detector Acceptance



- Flux of particles [(m^{2}sr s GeV)$^{-1}$]: $\phi(E) = \dfrac{dN}{d\Omega dS dt dE}$

- In practice in on bin on energy, the expected number of events is given by

$$N(E) = \int_S \int_\Omega \int_t \int_{E-\frac{\Delta E}{2}}^{E+\frac{\Delta E}{2}} \phi(E')\epsilon(E', x, y, \theta, \phi) d\vec{\Omega}.d\vec{S} dt dE'$$

where ε is the detector effeciency for the corresponding direction and the integration is over the full detector surface and accecible directions.

- With a constant and isotropic flux

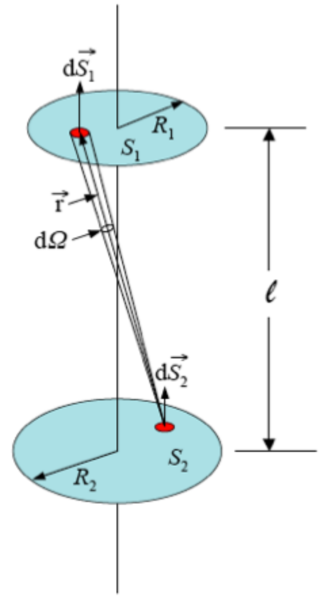
$$N(E) = T\phi(E)\Delta E \underbrace{\int_S \int_\Omega \epsilon(E, x, y, \theta, \phi) d\vec{\Omega}.d\vec{S}}_{Acc(E)\ :\ \text{Acceptance [m}^2\text{sr]}}$$

Detector Acceptance

For a simple telescope with $\varepsilon = 1$

$$Acc(E) = \int_{S_2} \int_{\Omega_2} d\vec{\Omega}.d\vec{S}$$

$$Acc(E) \approx \frac{S_1 S_2}{l^2}$$

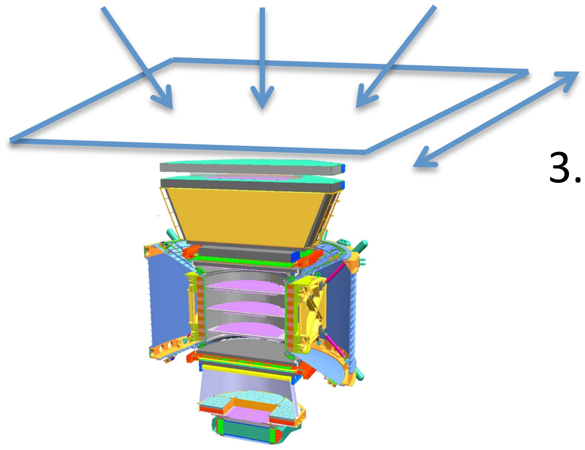


For real detectors, full MC simulation (Geant4) are used:

$$Acc(E) = Acc_{gen} \frac{N_{sel}}{N_{gen}}$$

Where:

$$Acc_{gen} = \pi \ 3.9^2 \ \mathrm{m}^2\mathrm{sr}$$



Proton flux analysis in AMS-02

$$F(R) = \frac{N_{\mathrm{obs.}}(R)}{T_{\mathrm{exp.}}(R)\, A_{\mathrm{eff.}}(R)\, \varepsilon_{\mathrm{trig.}}(R)\, \mathrm{d}R}$$

(For isotropic flux with $\theta_{\mathrm{zen}} < 20°$)

- F : Absolute differential flux ($\mathrm{m^{-2}sr^{-1}s^{-1}GV^{-1}}$)
- R : Measured rigidity (GV)
- $N_{\mathrm{obs.}}$: Number of events after proton selection
- $T_{\mathrm{exp.}}$: Exposure life time (s)
- $A_{\mathrm{eff.}}$: Effective acceptance ($\mathrm{m^2\ sr}$)
- $\varepsilon_{\mathrm{trg.}}$: Trigger efficiency
- $\mathrm{d}R$: Rigidity bin (GV)

Proton flux analysis in AMS-02

$$F(R) = \frac{N_{obs.}(R)}{T_{exp.}(R)\, A_{eff.}(R)\, \varepsilon_{trig.}(R)\, dR}$$

- F : Absolute differential flux ($m^{-2}sr^{-1}s^{-1}GV^{-1}$)
- R : Measured rigidity (GV)
- $N_{obs.}$: Number of events after proton selection
- $T_{exp.}$: Exposure life time (s)
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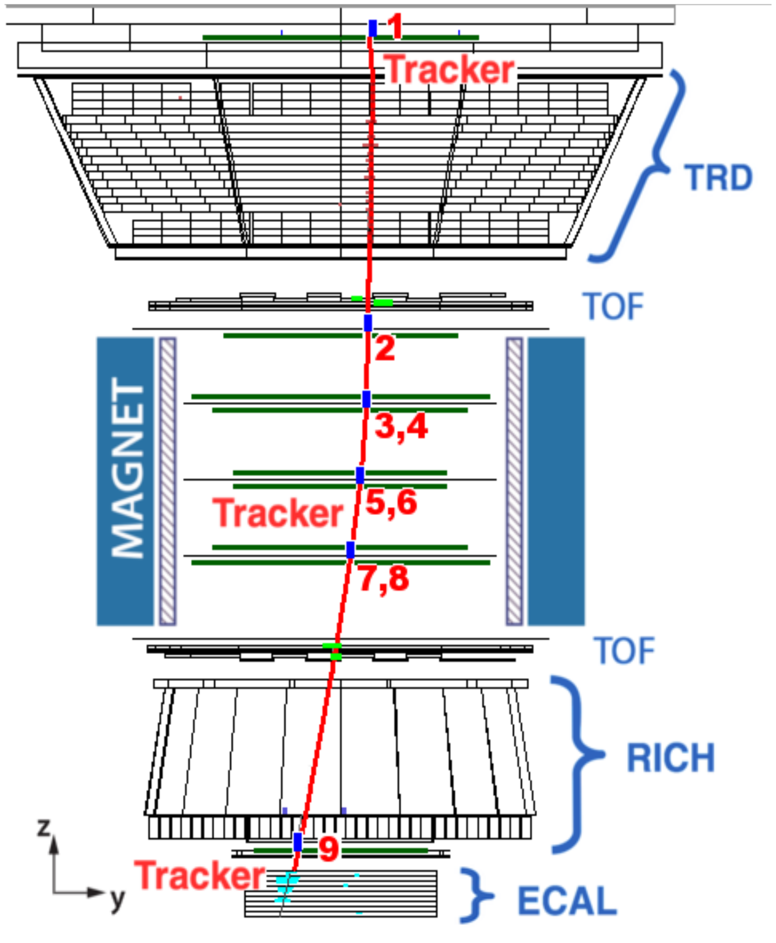
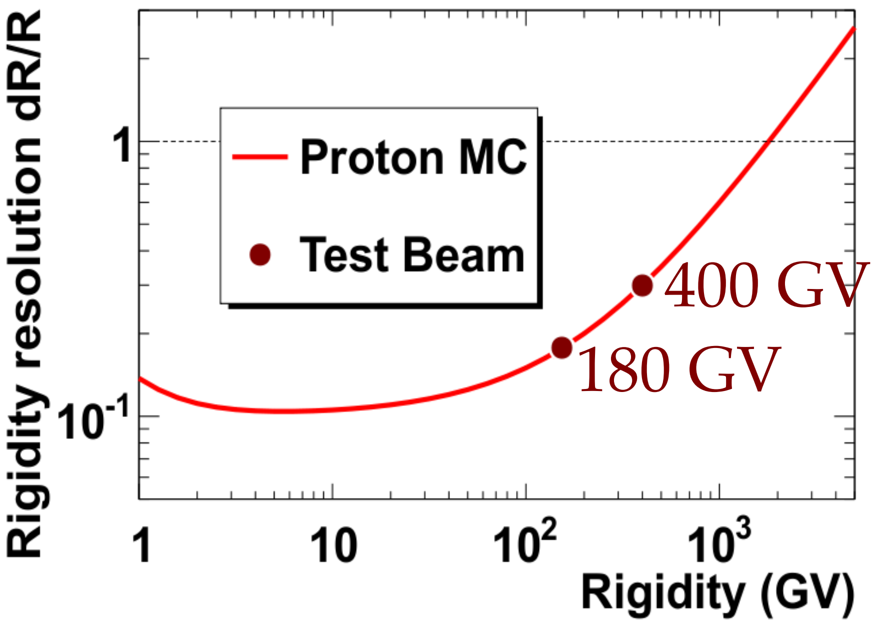
- $\varepsilon_{trg.}$: Trigger efficiency
- dR : Rigidity bin (GV)

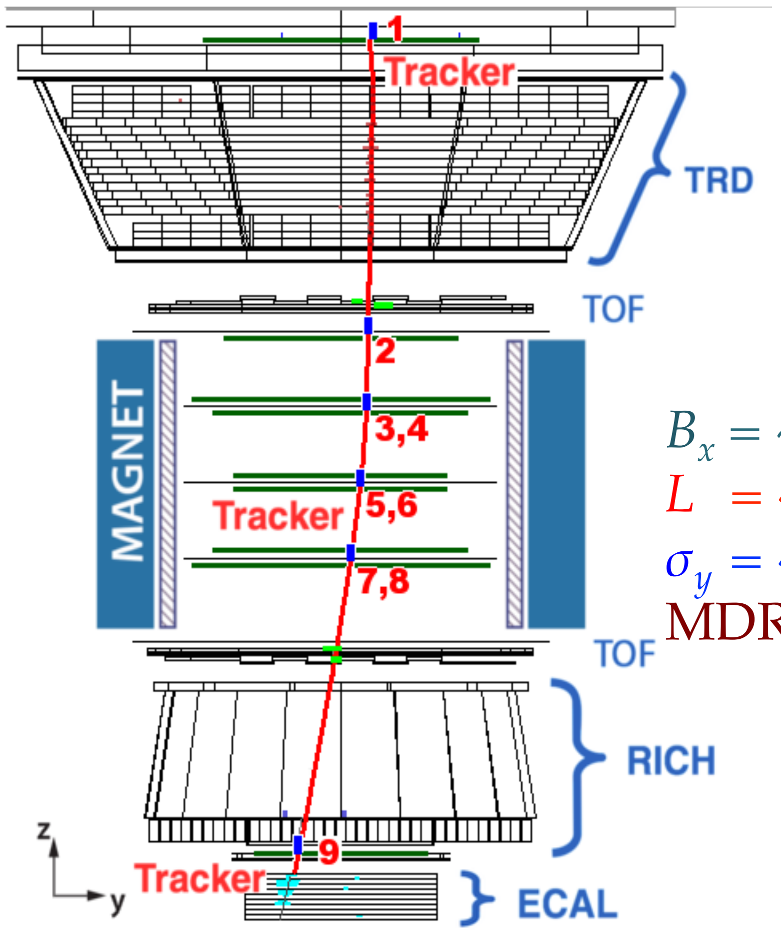
Rigidity measurement



B_x = ~0.14 T
L = ~3m
σ_y = ~10μm
Maximum Detectable Rigidity (MDR) : ~2TV



Rigidity measurement

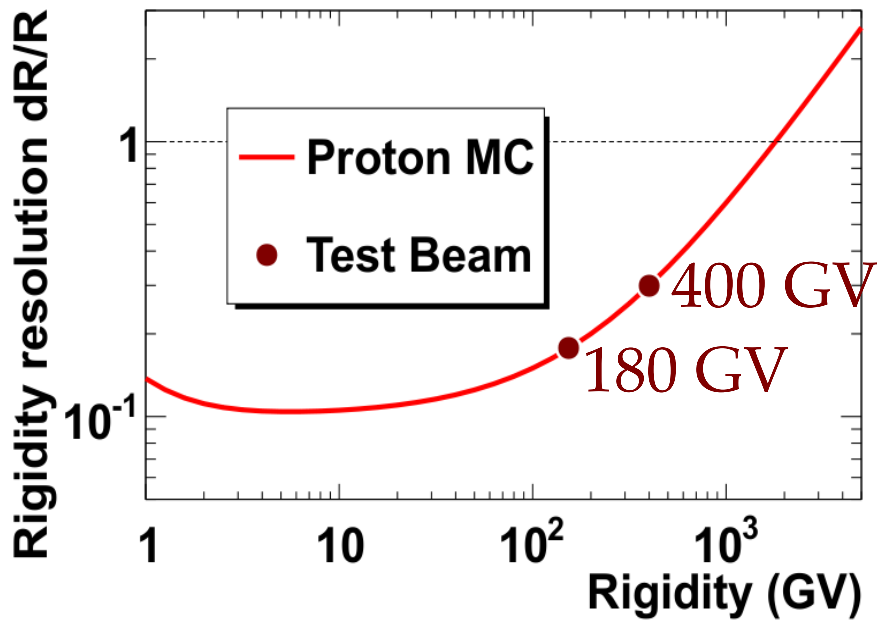


B_x = ~0.14 T
L = ~3m
σ_y = ~10μm
MDR : ~2TV

Measurement of the trace curvature in the magnetic field (x 1/R) :

$$\Delta\left(\frac{1}{R}\right) = \mathrm{cst} = \mathrm{MDR} \rightarrow \frac{\Delta R}{R} = \frac{R}{MDR}$$

MDR: Maximum Detectable Rigidity



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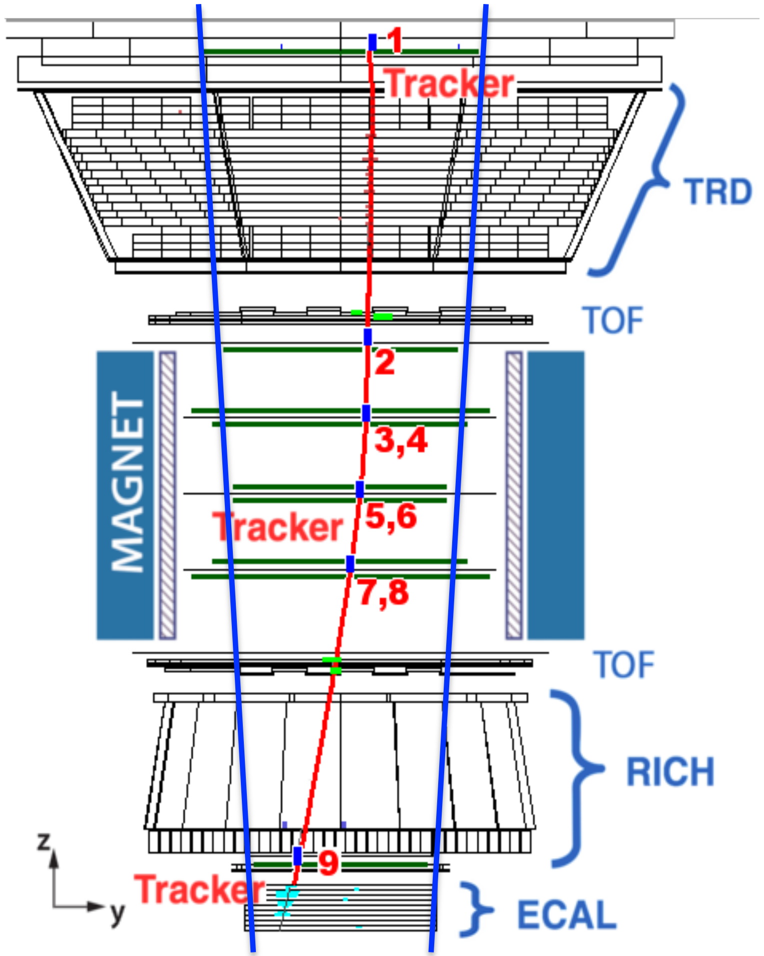
- $N_{\mathrm{obs.}}$: Number of events after proton selection
- $T_{\mathrm{exp.}}$: Exposure life time (s)
- $A_{\mathrm{eff.}}$: Effective acceptance ($\mathrm{m^2\,sr}$)
- $\varepsilon_{\mathrm{trg.}}$: Trigger efficiency
- $\mathrm{d}R$: Rigidity bin (GV)

Pre selection

- Velocity measured by at least 3 TOF counters (out of 4)

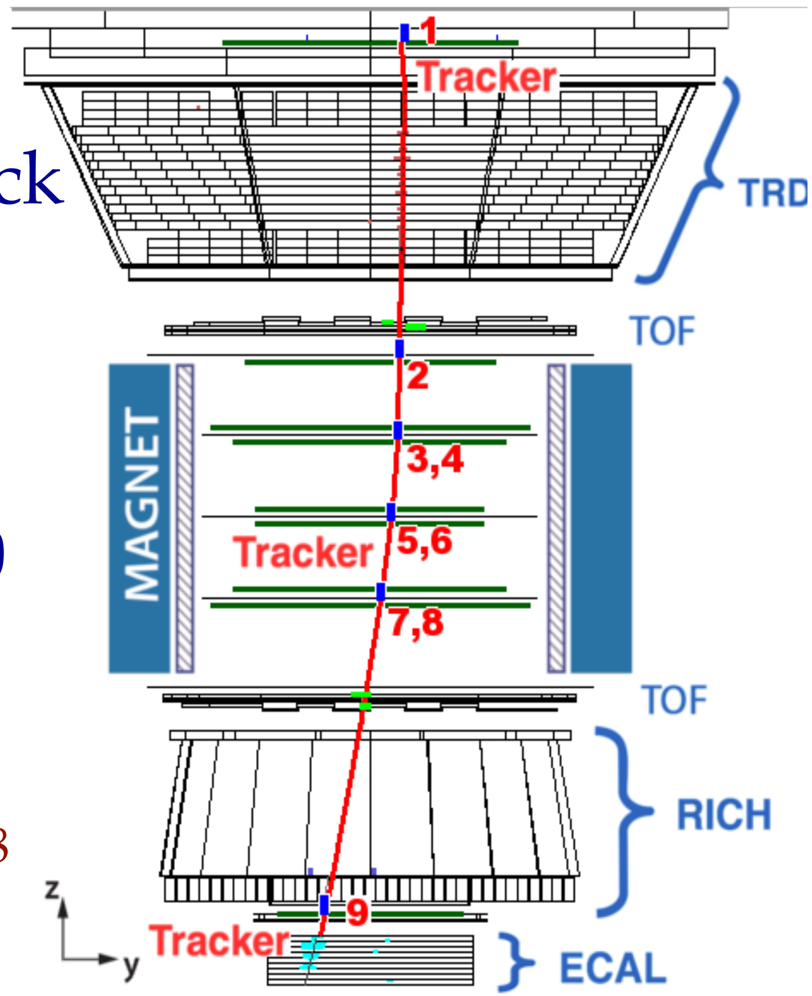
- TOF track pass both Tracker L1 and L9



Full span track selection

- Events with at least one track with measured hit points both in Layer 1 and 9
- Normalized χ^2 of the track fitting : $\chi^2 < 10$

- Final selected events : $N_{obs.}(R > 1\text{ GV}) = 3.03 \times 10^8$



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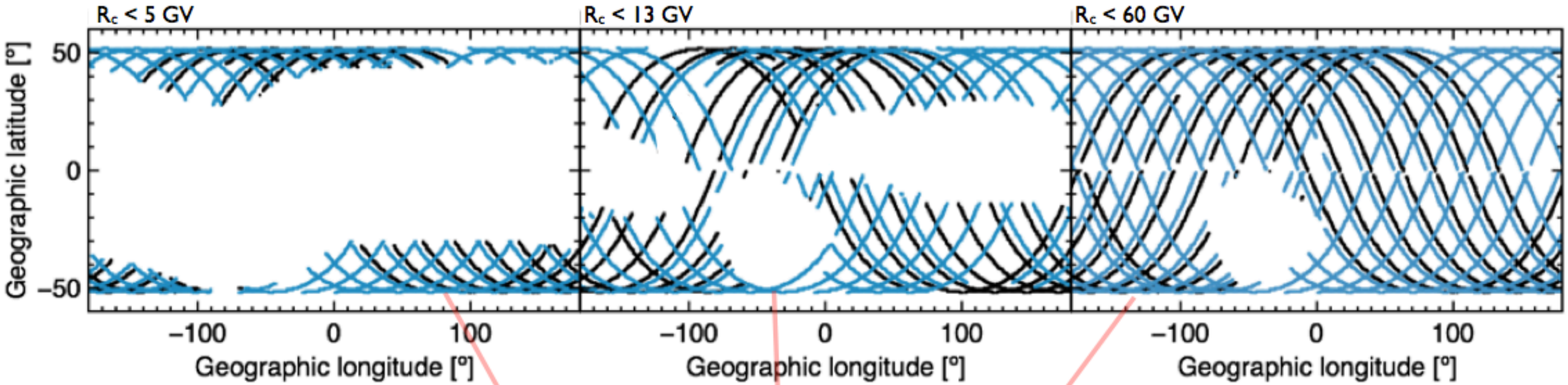
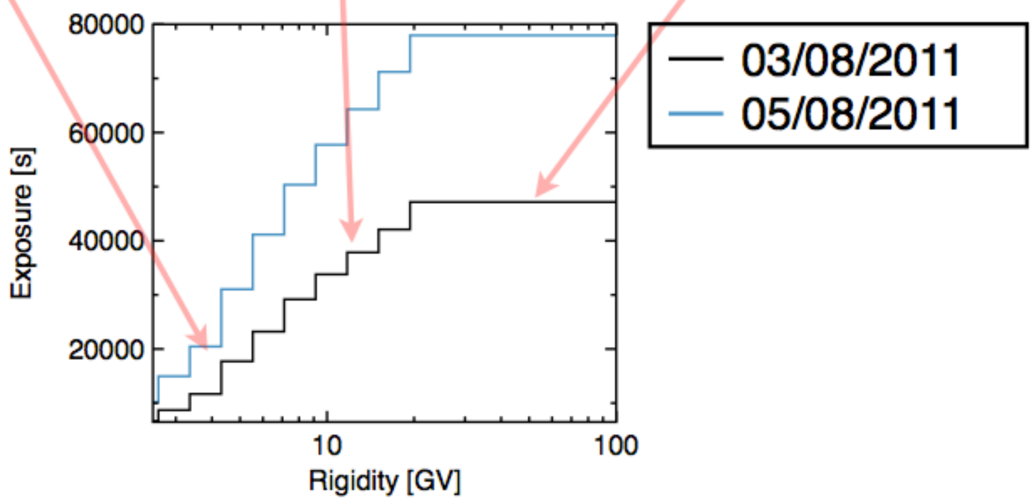
- $T_{\mathrm{exp.}}$: Exposure life time (s)
- $A_{\mathrm{eff.}}$: Effective acceptance ($\mathrm{m^2\, sr}$)
- $\varepsilon_{\mathrm{trg.}}$: Trigger efficiency
- $\mathrm{d}R$: Rigidity bin (GV)

Exposure time

Exposure time is rigidity dependent: For a given rigidity, it corresponds to the time for which the detector is in a position where all the direction within the AMS acceptance are allowed (above geomagnetic cutoff)



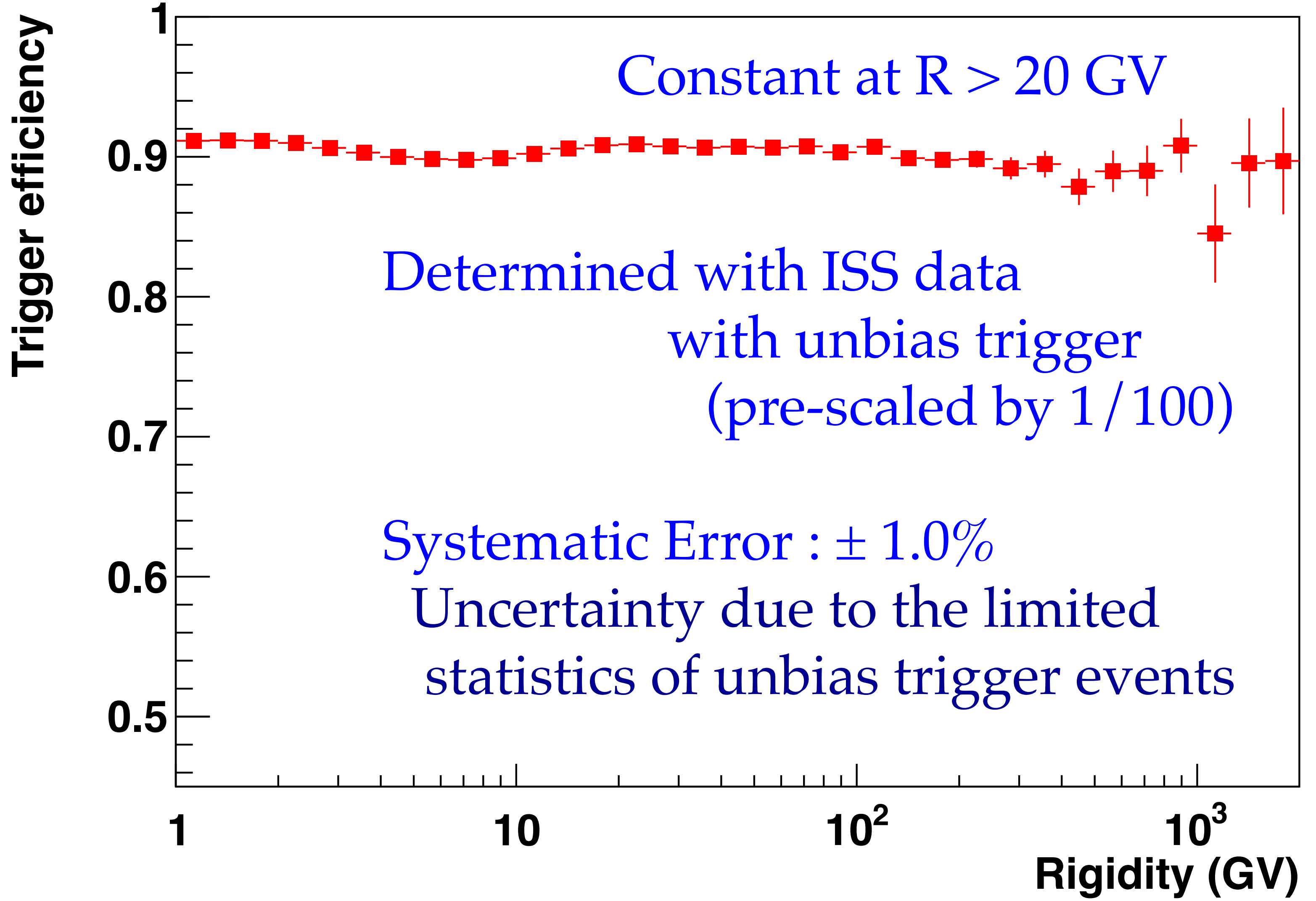


Proton flux analysis in AMS-02

$$F(R) = \frac{N_{\mathrm{obs.}}(R)}{T_{\mathrm{exp.}}(R)\, A_{\mathrm{eff.}}(R)\, \varepsilon_{\mathrm{trig.}}(R)\, \mathrm{d}R}$$

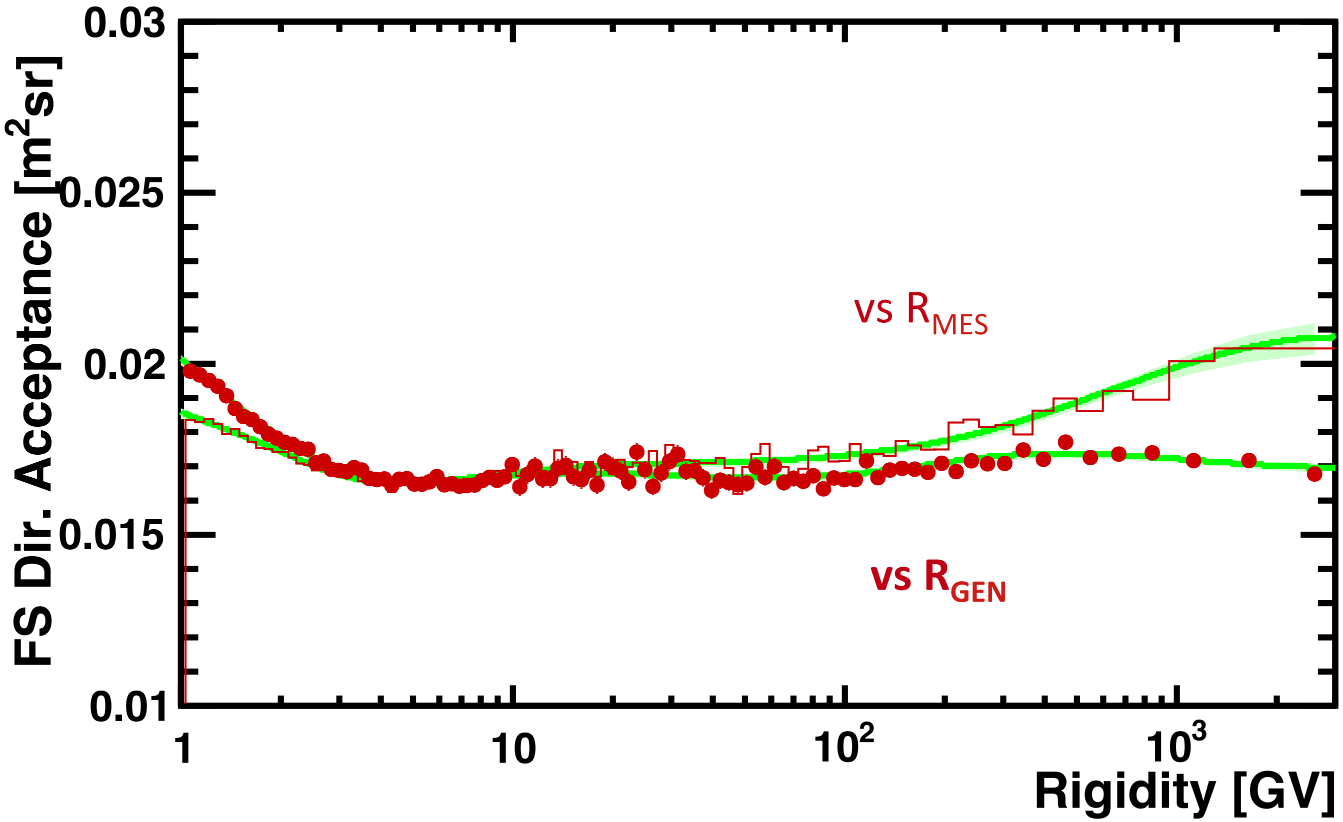
- F : Absolute differential flux ($\mathrm{m^{-2}sr^{-1}s^{-1}GV^{-1}}$)
- R : Measured rigidity (GV)
- $N_{\mathrm{obs.}}$: Number of events after proton selection
- $T_{\mathrm{exp.}}$: Exposure life time (s)
- $A_{\mathrm{eff.}}$: Effective acceptance ($\mathrm{m^2\,sr}$)
- $\varepsilon_{\mathrm{trg.}}$: Trigger efficiency
- $\mathrm{d}R$: Rigidity bin (GV)

Trigger efficiency



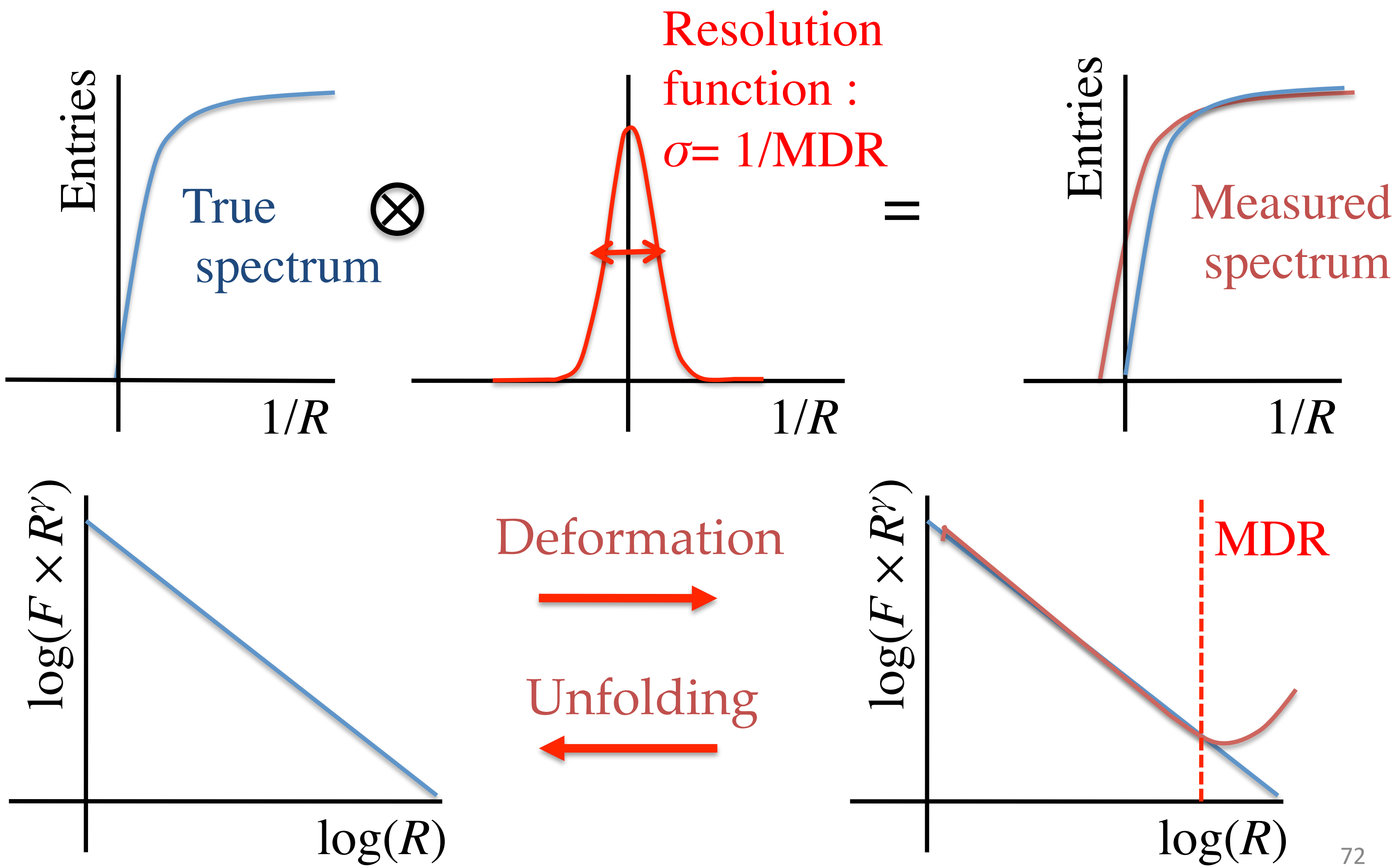
Acceptance

Computed from MC simulation of the detector and corrected for Data/MC differences:



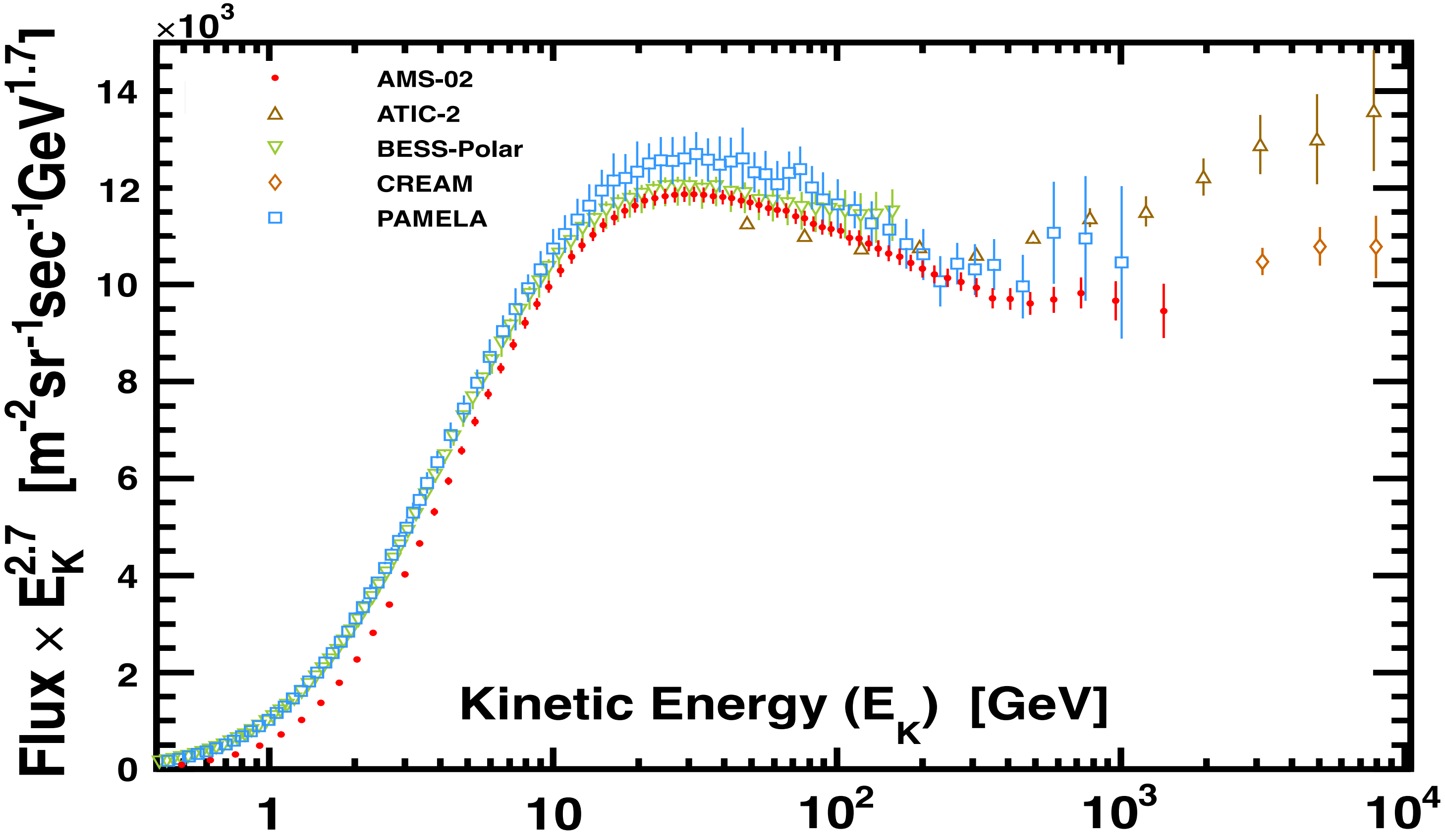
But should also take into account the finite rigidity resolution of the detector

Spectrum unfolding



Proton Flux Measurement

- Proton flux from AMS based on 300 million events (PRL 114 (2015)) compared to PAMELA and recent measurements:

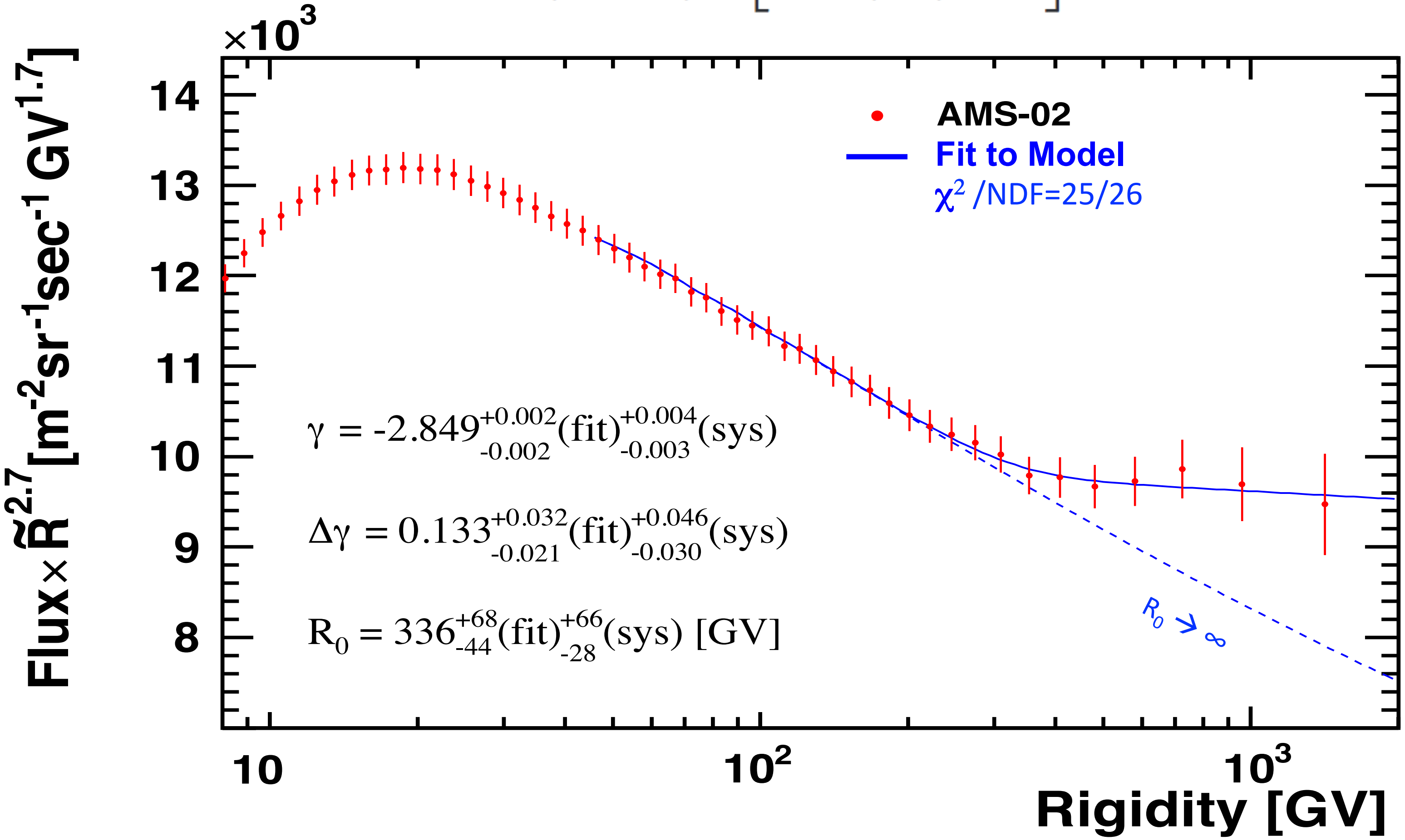


→ Hardening of the proton flux around 300 GeV.
→ Precision of AMS data allowed to characterize the shape of the transition.

AMS: Proton Flux Measurement

- Fit of the AMS flux with a double power model with smooth transition:

$$\Phi = C\left(\frac{R}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$



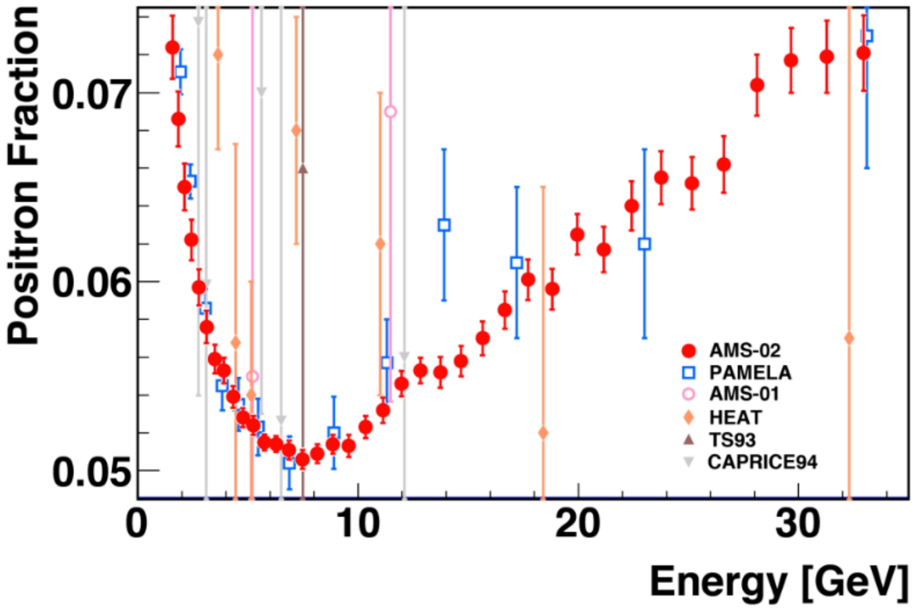
AMS: Positron Fraction

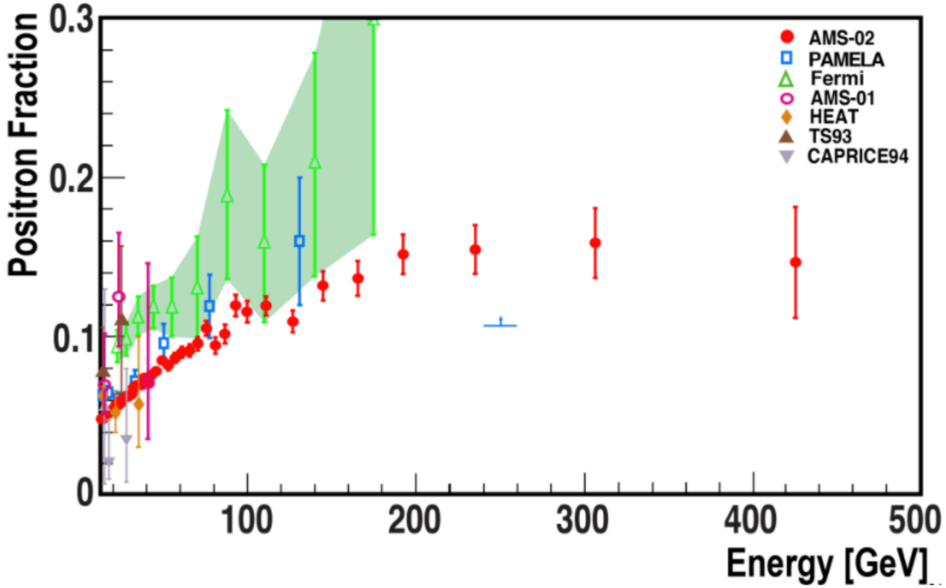
Phys. Rev. Lett. 113 (2014)

- Conclusive evidence of positron excess published by PAMELA in 2009 and then by Fermi.
- Confirmed with improved precision and extended energy range by AMS:

→ Positron fraction:

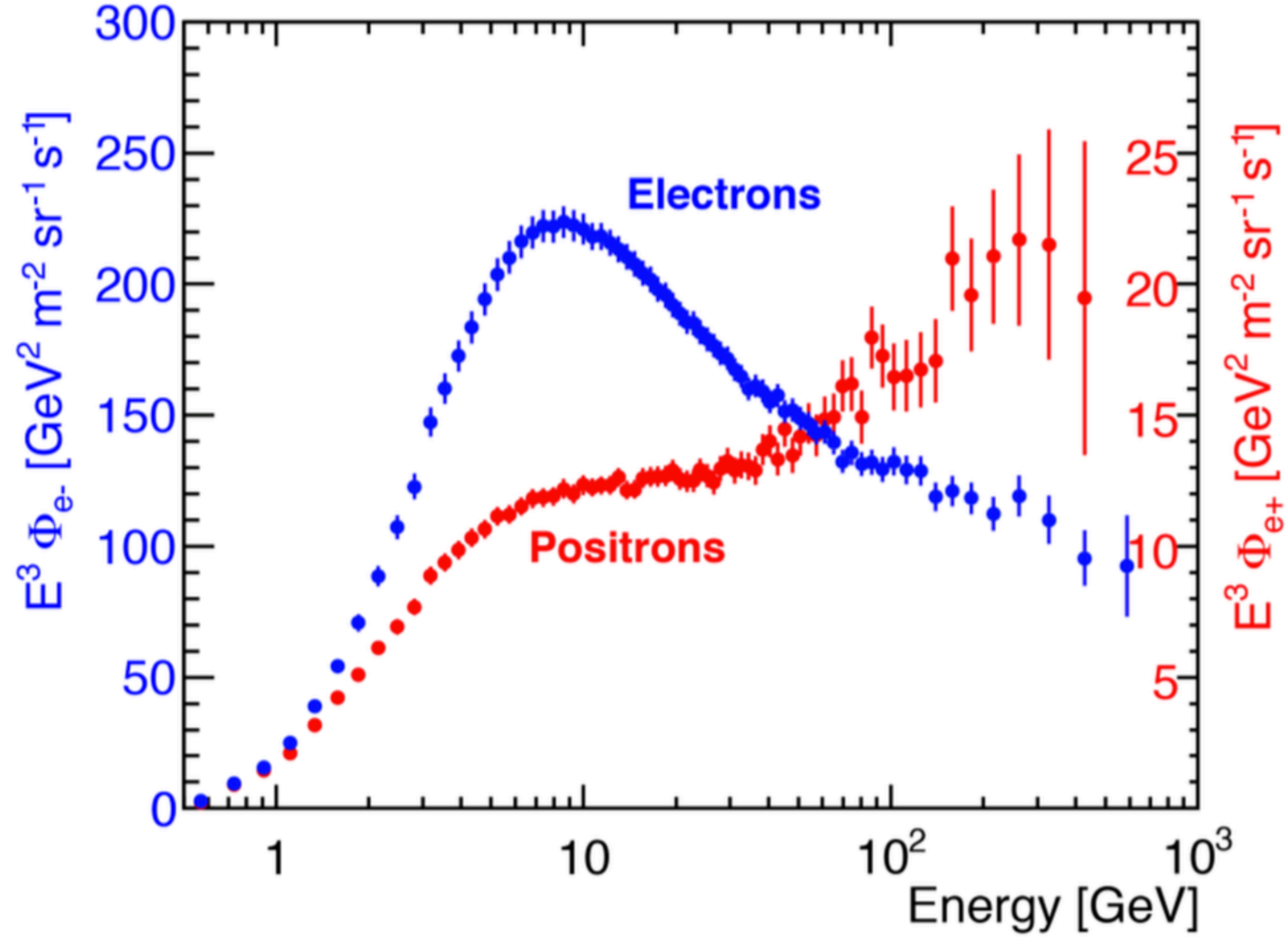
  - reaches its minimum at 8 GeV,
  - steadily increases from 10 to ~250 GeV, no fine structures.
  - At 275±32 GeV the fraction reaches its max.





Electron and Positron Fluxes from AMS

Phys. Rev. Lett. 113 (2014)

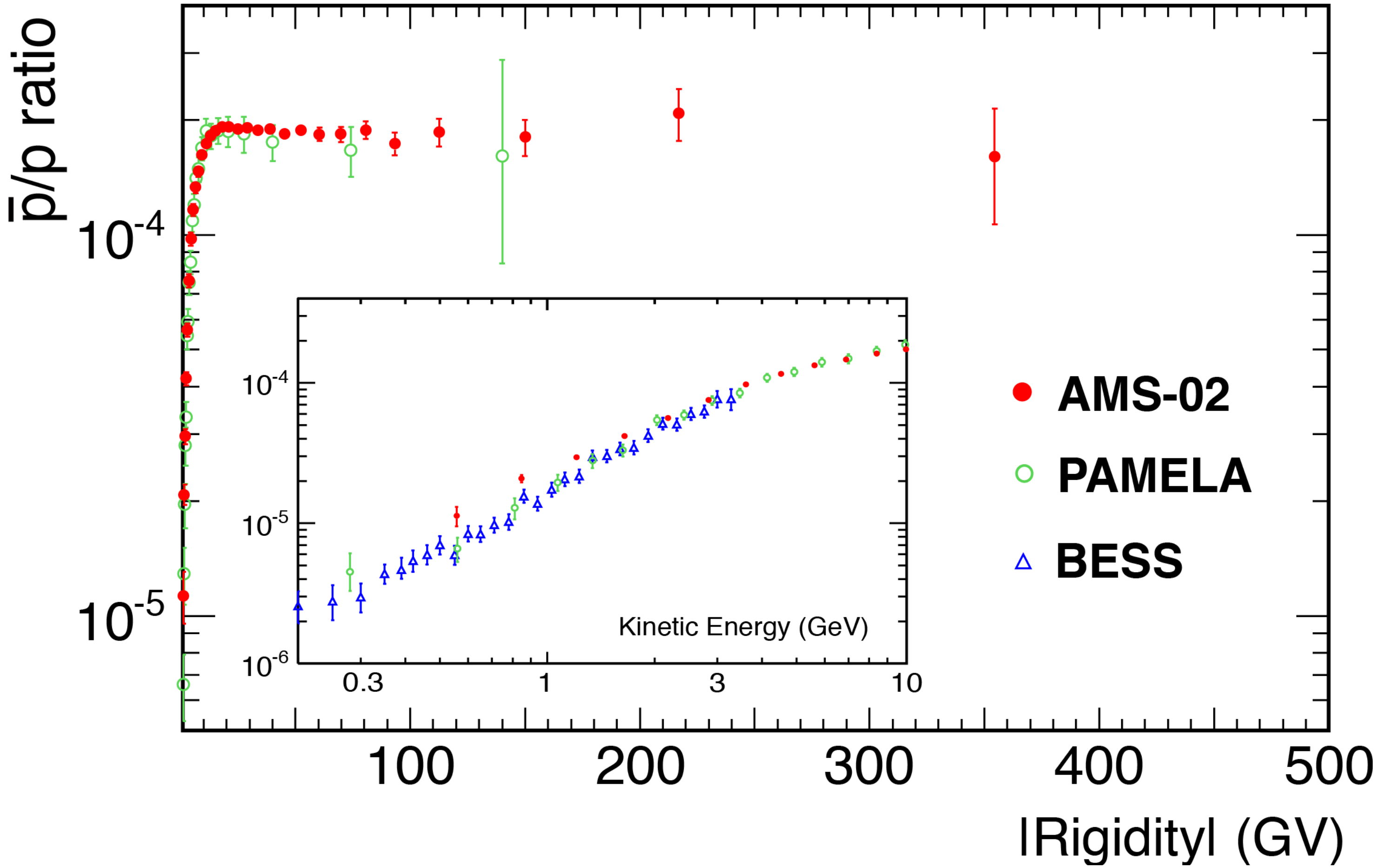


→ Shows that the rise of positron fraction is due to positron excess.

→ Nerby sources (pulsar) ? Or Dark-matter annihilation ?

Antiproton/Proton

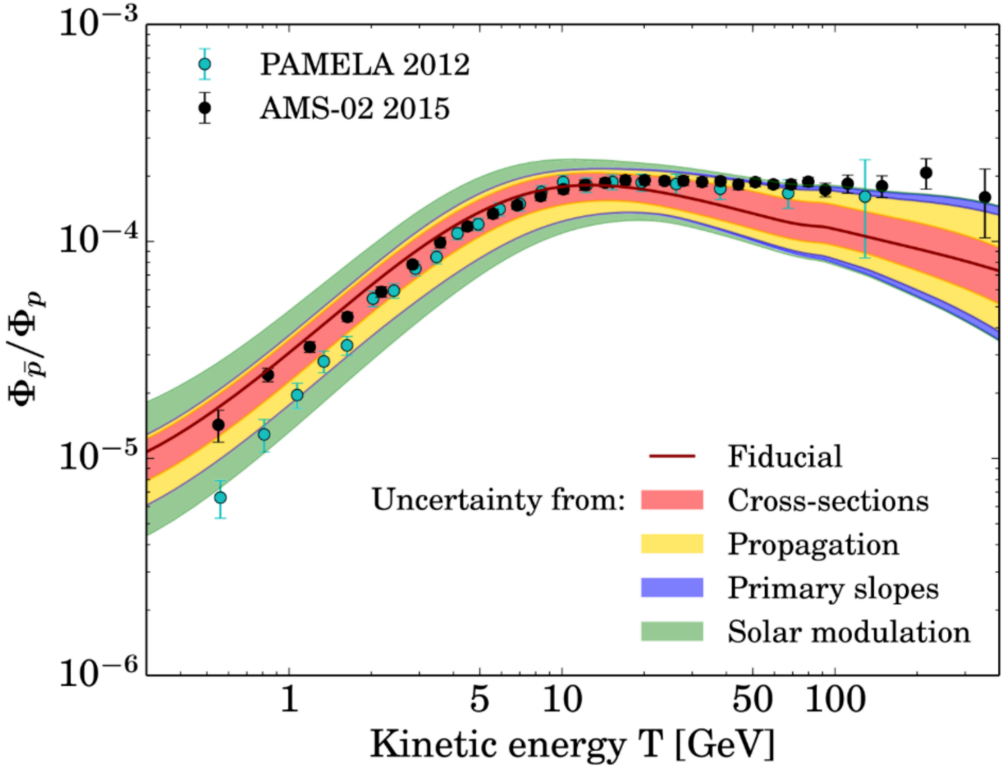
Result from AMS based on 290000 events between 1 and 450 GV presented at ICRC:



→ Flat Antiproton/proton ratio at high energy not expected from standard secondary production

Antiproton/Proton and modeling

Secondary production of CR antiproton: [G. Giesen, et al. arXiv:1504.04276]



- Large uncertainty in the estimation of secondary antiproton.
- Data from AMS should help to reduce the propagation uncertainty.
- More statistics and work needed on models to know if extra sources (DM annihilation) are needed to reproduce the flat pbar/p ratio at high energy

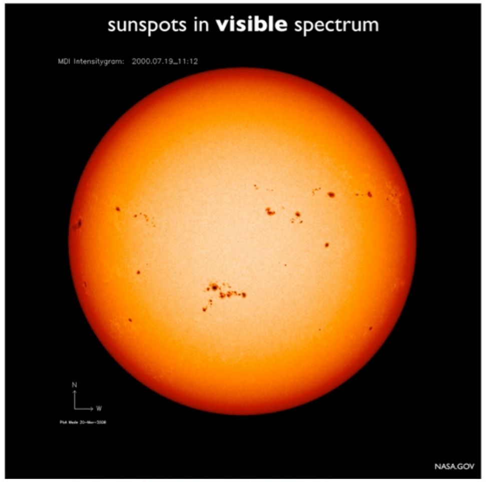
CR "anomalies" from recent Data

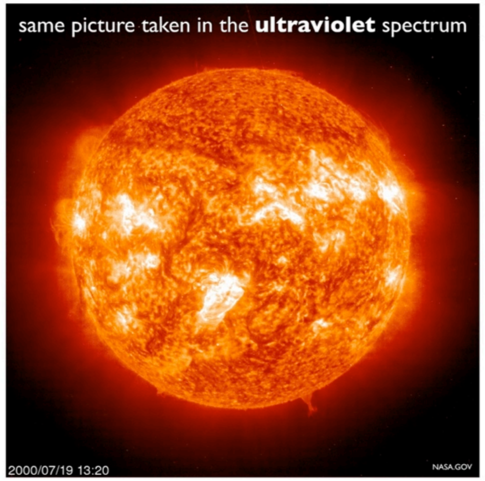
- Questions triggered by recent CR measurements:
  - What is the origin of the spectral hardening?
  - What is the origin of the slopes difference between protons and heliums (and heaviest nuclei)?
  - Flattening of pbar/p at high energy?
  - Positron fraction excess.
- Large classes of models to explain the "anomalies":
  - Propagation mechanism (space and energy-dependent diffusion coefficient, non-linear coupling of CRs with diffusion coefficient,…)
  - CR sources:
    - Acceleration process (non-linear DSA, distributed acceleration on multiple sources).
    - Nearby sources contribution.
    - Secondary production in the source.
  - Dark Matter contributions

→ Lot of modeling activity but no consensus yet. Difficult to reproduce all features with a single explanation.

Cosmic ray modulation

- At low Energy (<20GV) cosmic ray spectrum affected by its propagation in the Solar cavity and the interaction with the plasma emitted by the sun.
- This produces a modulation of the spectrum which follows 11-year cycle in antiphase with Solar activity (Sunspot number)
- Simplest model for Solar Modulation: Force-Field approximation:



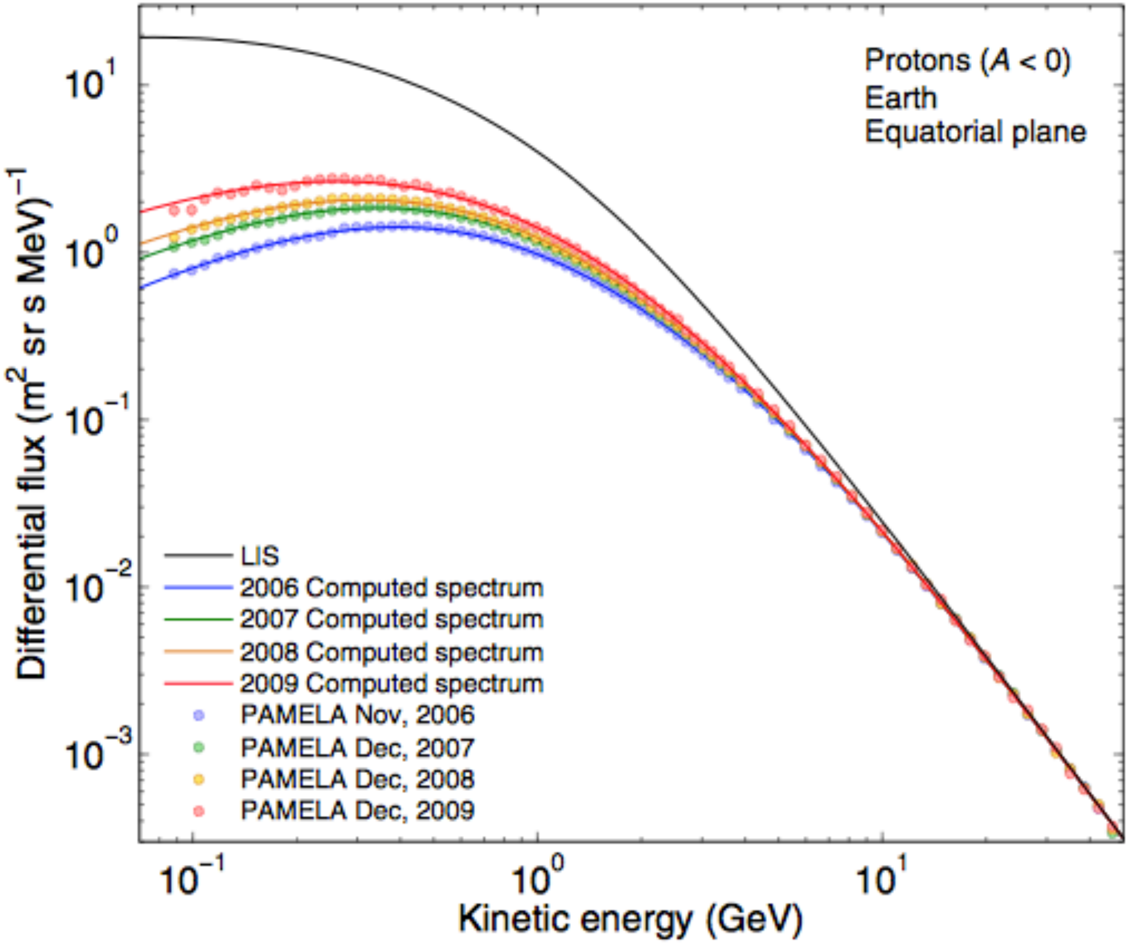


$$J(E,t) = \frac{E^2 - M^2}{(E + \Phi(t))^2 - M^2} J^{IS}(E + \Phi(t))$$

→ Precise measurement of the different components of CR over long period of time with the same detector needed to understand the solar modulation process.

Time dependence of the proton flux

Measured by PAMELA during the July 2006 - December 2009 solar minimum:

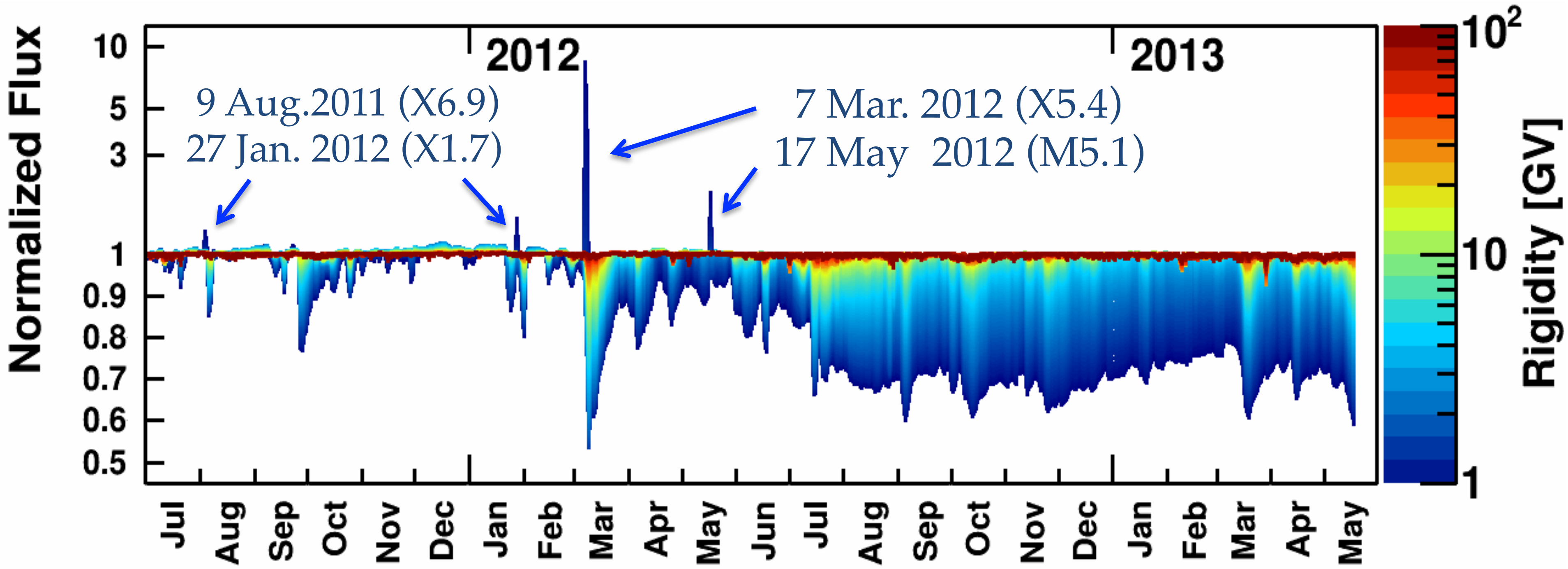


[Adriani, O. *et al.* Astrophys.J. 765 (2013)]()

AMS02 - Daily normalized flux

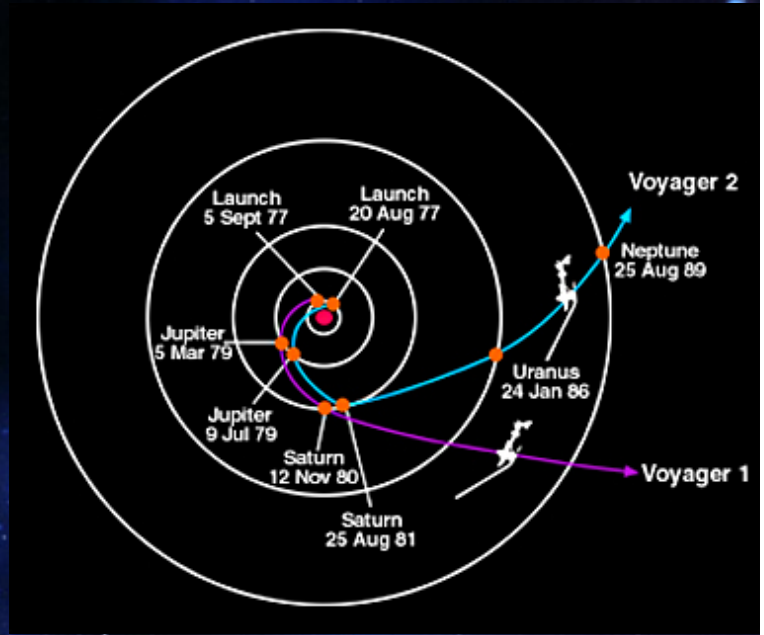
Time fluctuation of proton rate for different rigidities from AMS02 data:

R < ~3 GV : Peaks associated with Solar flares (SEP)



→ Precise Monthly/Daily fluxes over long periods to understand Solar modulation

Voyager

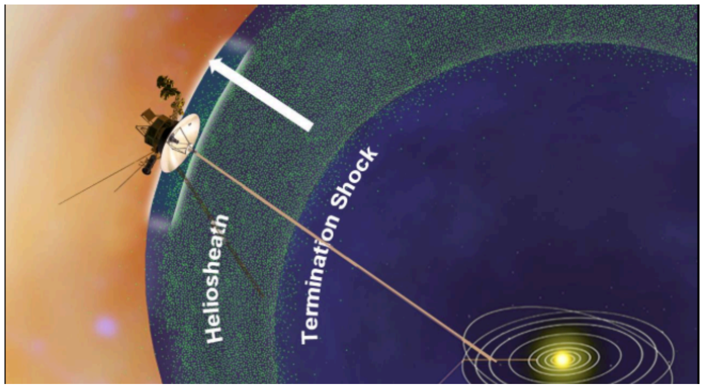


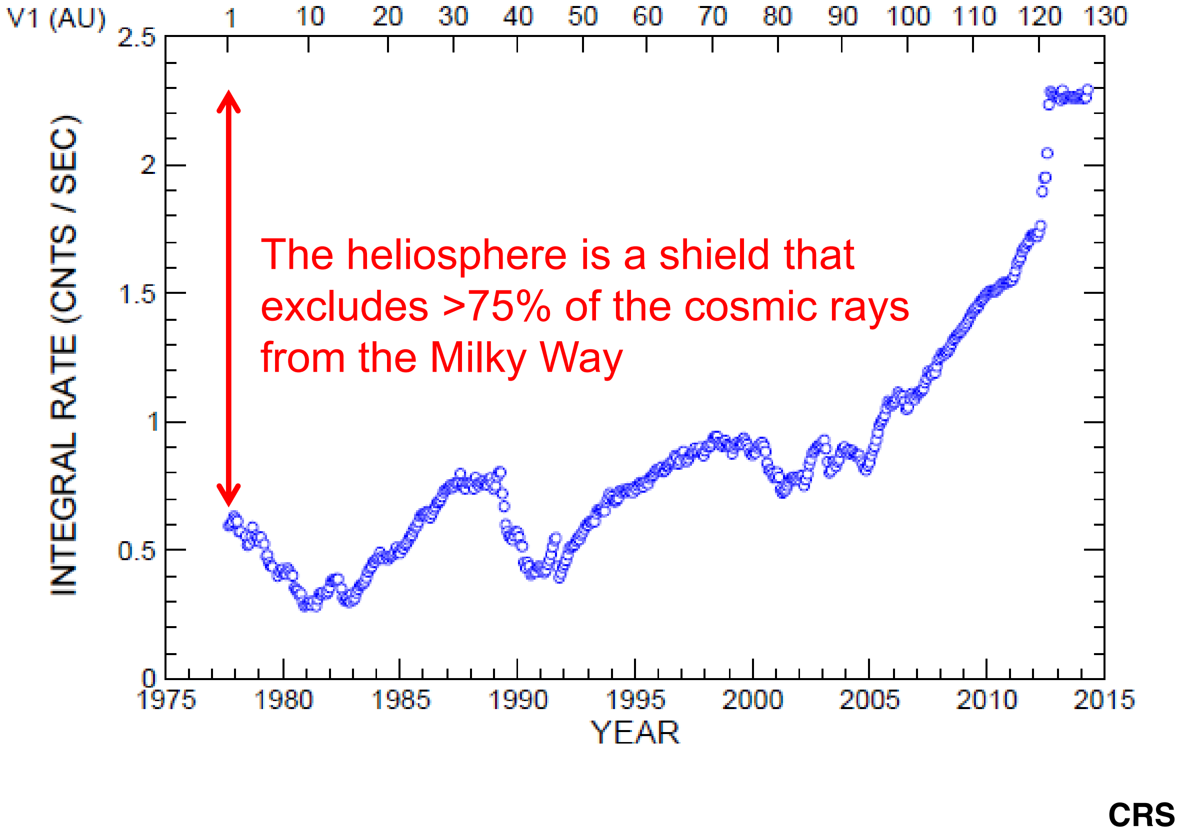
- Voyager 1&2 launched in 1977
- **Used the gravity slingshot method to catapult itself to the furthest planets and eventually beyond the Heliosphere.**
- Payloads still active…**cosmic ray telescopes (CRS) measure the Low energy CR intensity for almost 40 years.**

Voyager 1

Measures CR intensity as it travels to the interstellar space:

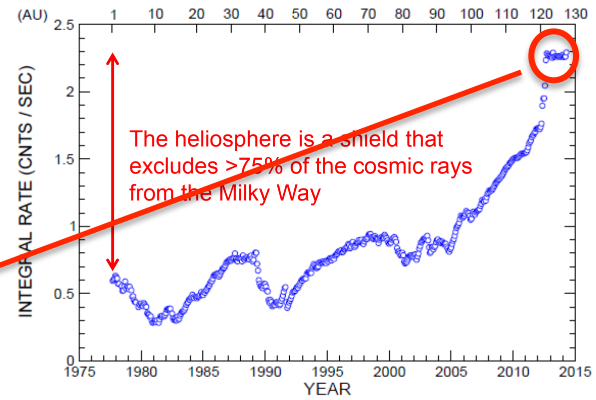
Variation due to:
- 11-years cycles due to solar activity
- Global rise as Voyager go out from the sun.

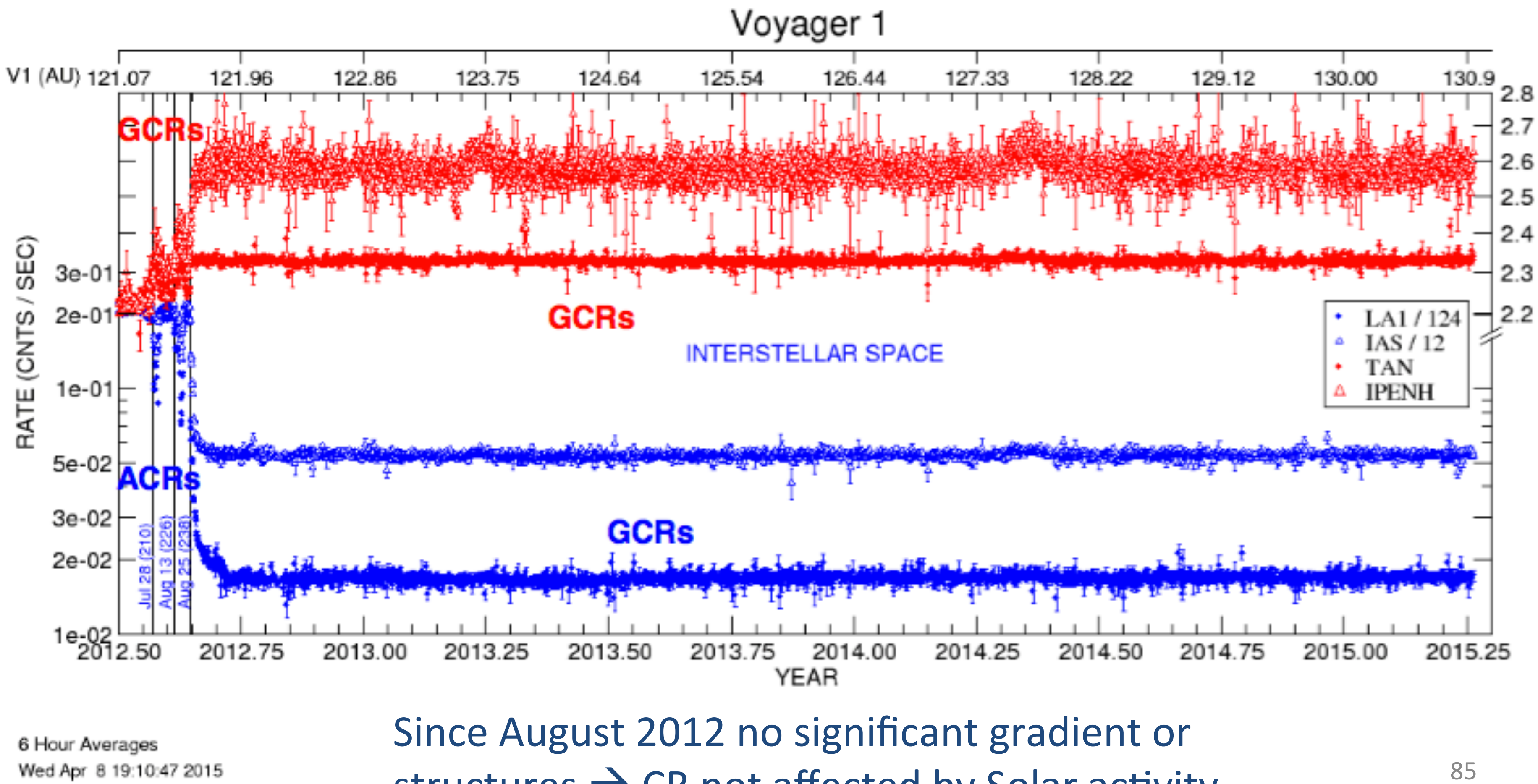




On August 2012, Voyager 1 reached interstellar space at 121 AU.

Voyager 1

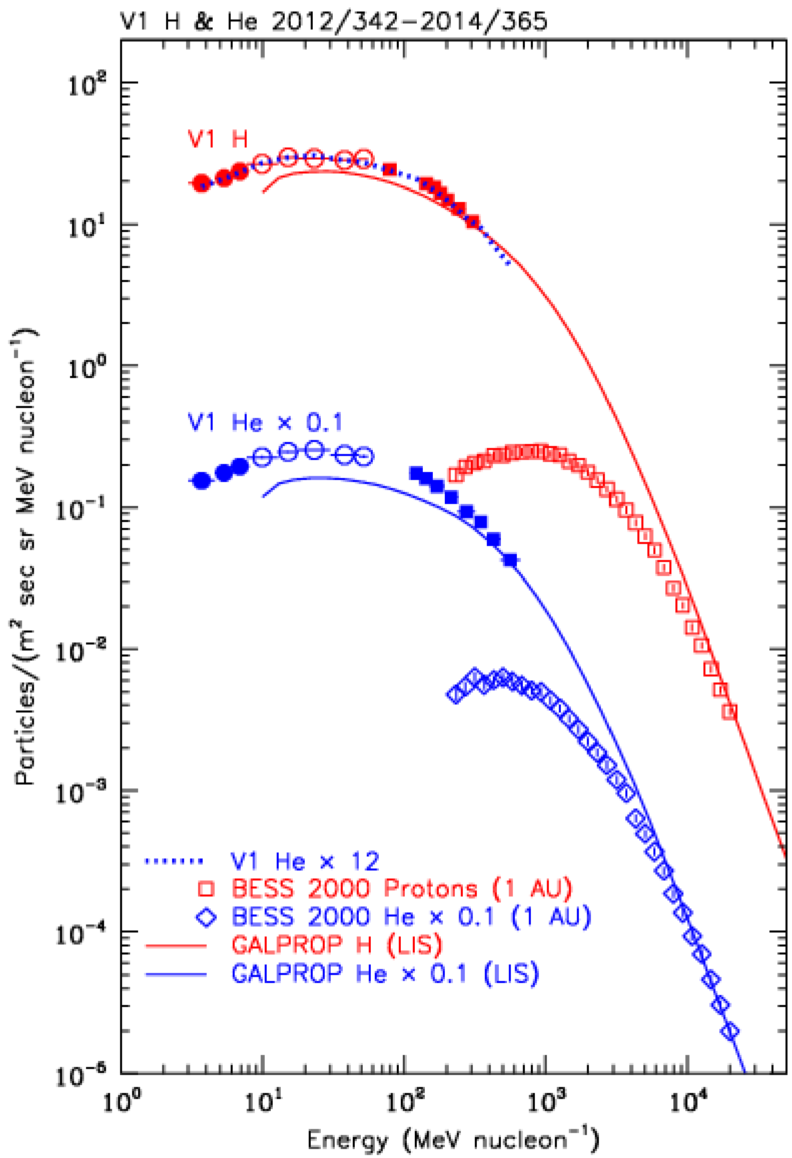




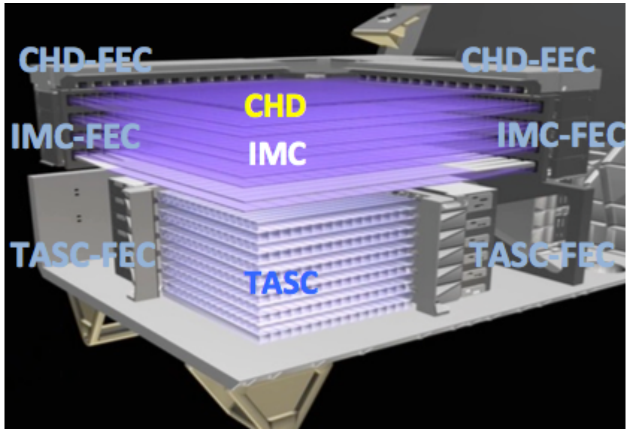
Since August 2012 no significant gradient or structures → CR not affected by Solar activity….

Voyager 1

- Voyager1 measured for the first time the Inerstellar (unmodulated) CR spectra.
- Also measured electron and higher charge nuclei (not shown)



Future experiments

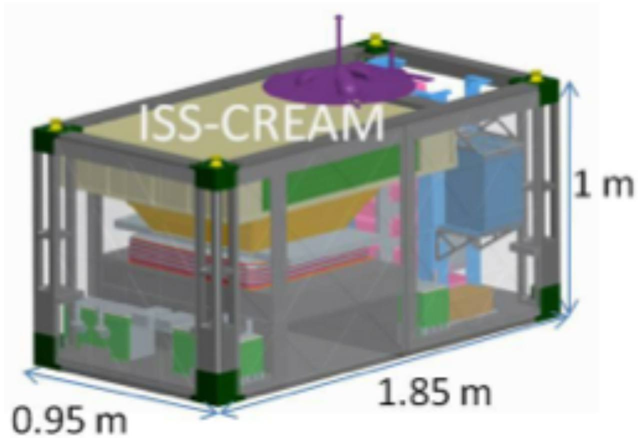


CALET: Launched in HTV-5 Aug. 19 and docked at the ISS Aug. 25. Sending its first signals from ISS. [P.S. Marrocchesi, HE-CR session Sept/8]

- Charge Detector (CHD) Z=1-40
- Imaging Calorimeter (IMC)
- Total Absorption Calorimeter (TASC)

ISS-CREAM: Launch (Space X Dragon cargo) in 2016, to be installed on JEM-EF (ISS):

- 4 layers of Silicon Charge Detector
- Tungsten Calorimeter
- Neutron detector for e/h separation



DAMPE: Satellite (launch Dec 2015)

- Silicon-Tungsten Tracker
- BGO Calorimeter
- Neutron detector

→ Detailed shape of the electron spectrum above 1 TeV to test the presence of nearby astronomical sources

→ Extend the present data to higher energies and measure accurately the curvature of the spectrum for individual nuclear species. Extend Secondary/Primary ratios up to high energy.

Conclusions: results from the past years

- Modulation of CRs by Solar activity:
  - High accuracy monthly/daily proton over long periods (PAMELA, AMS)
  - Measurement of IS fluxes from Voyager

- Propagation of cosmic rays:
  - Precise B/C ratio, approching TeV/n, Light isotopes ratio (AMS, PAMELA, BESS)

- Source/Acceleration of cosmic rays:
  - Precise measument up to TeV region p & He (PAMELA, AMS, CREAM)

- Indirect search of DM
  - Positron fraction, pbar/p up to 450 GV (PAMELA, AMS)

Conclusions: prospects

- Modulation of CRs by Solar activity:
  - High accuracy monthly/daily proton over long periods (PAMELA, AMS)
  - Measurement of IS fluxes from Voyager

    + other species: He, e^- and e^+ → charge sign dependence (PAMELA, AMS)
- Propagation of cosmic rays:
  - Precise B/C ratio, approching TeV/n, Light isotopes ratio (AMS, PAMELA, BESS)

    + Li, B, Be, C, N, O (AMS) + higher energy (CALET, ISS-CREAM,..)
- Source/Acceleration of cosmic rays:
  - Precise measument up to TeV region p & He (PAMELA, AMS, CREAM)

    + High energy measurement (CALET, ISS-CREAM,..)
- Indirect search of DM
  - Positron fraction, pbar/p up to 450 GV (PAMELA, AMS)

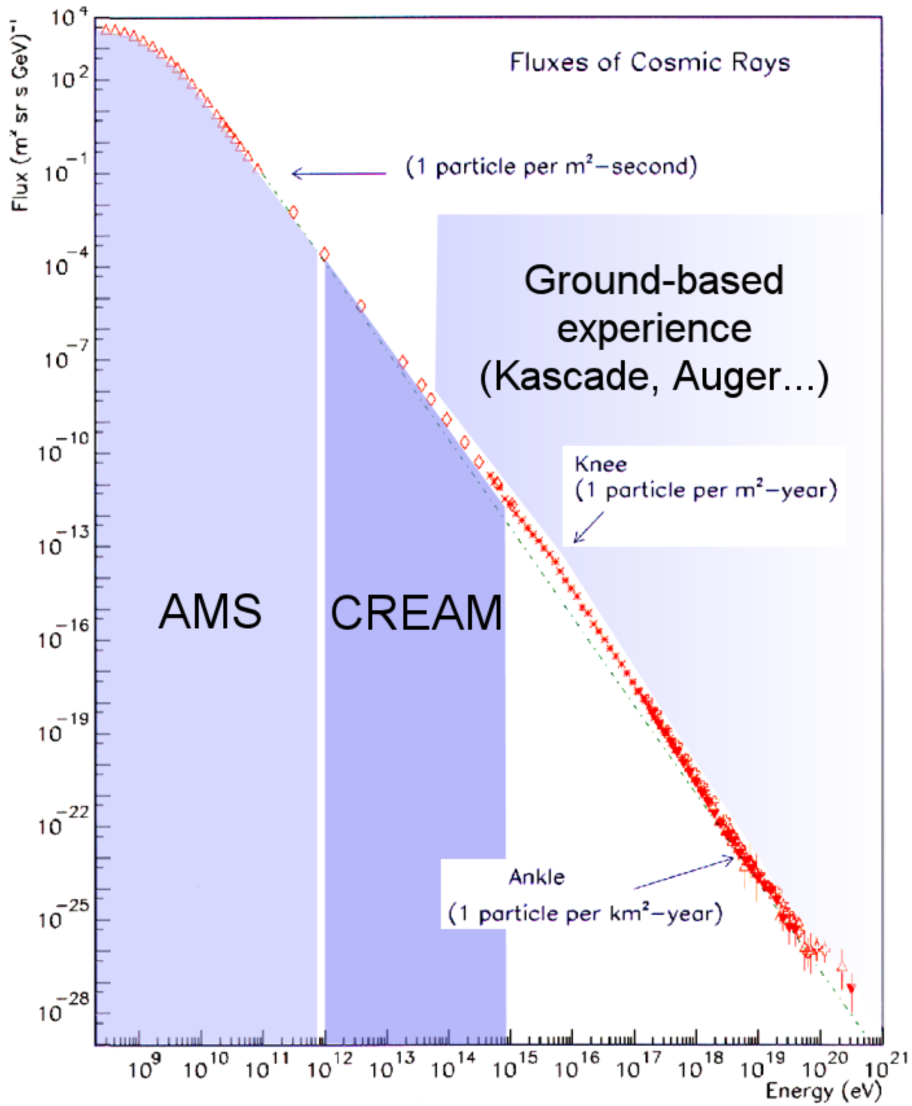
    + up to higher energies, more stat, pbar flux, Dbar (AMS)

IV- From Galactic to Extra-Galactic CRs

Dectection of Cosmic rays

- E < 10^{15} ev : Cosmic rays are absorbed in the upper layer of atmosphere but the flux is large
  - → Direct detection above atmosphere.
  - → Identification of CR/Energy measurement with particle physics detectors
- E > 10^{15} ev : Shower produced by CRs is detectable from ground

  → Atmosphere as a « calorimeter » : Measurement of the shower from ground.



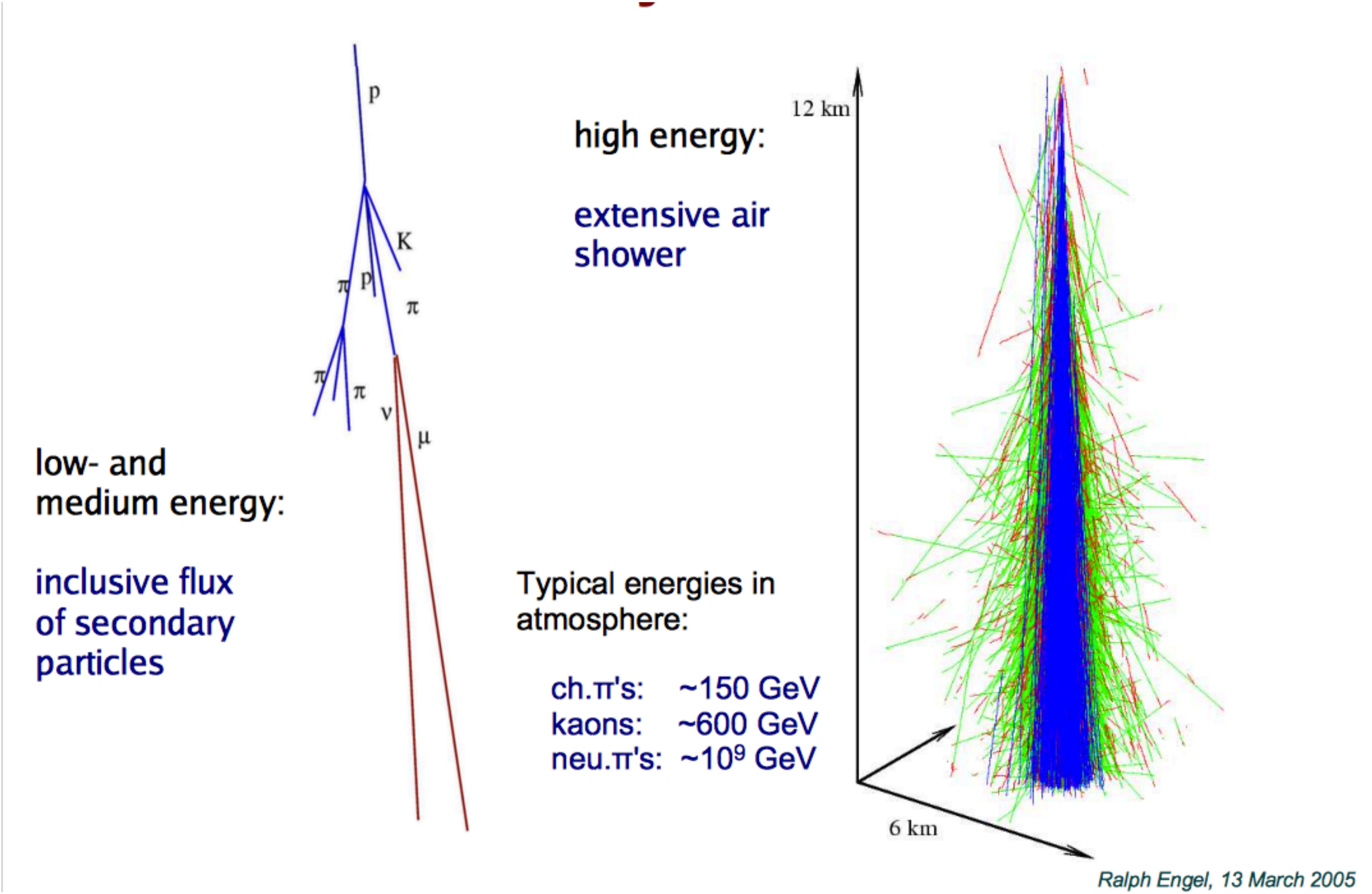
IV- Definition of energy regions.

The terms HE, VHE, UHE, EHE are highly relative and are changed in time.

At present, the following definition can be suggested.

Term	Energy: In center-of-mass system	Energy: In cosmic rays	Remarks
HE	< 2 TeV	$< 2 \cdot 10^{15}$ eV	Existing accelerators
VHE	(2 – 14) TeV	$(2 \cdot 10^{15} - 10^{17})$ eV	LHC; the knee
UHE	(14 – 140) TeV	$(10^{17} - 10^{19})$ eV	The ankle
EHE	>140 TeV	$>10^{19}$ eV	Cut-off

IV- Extensive Air Showers



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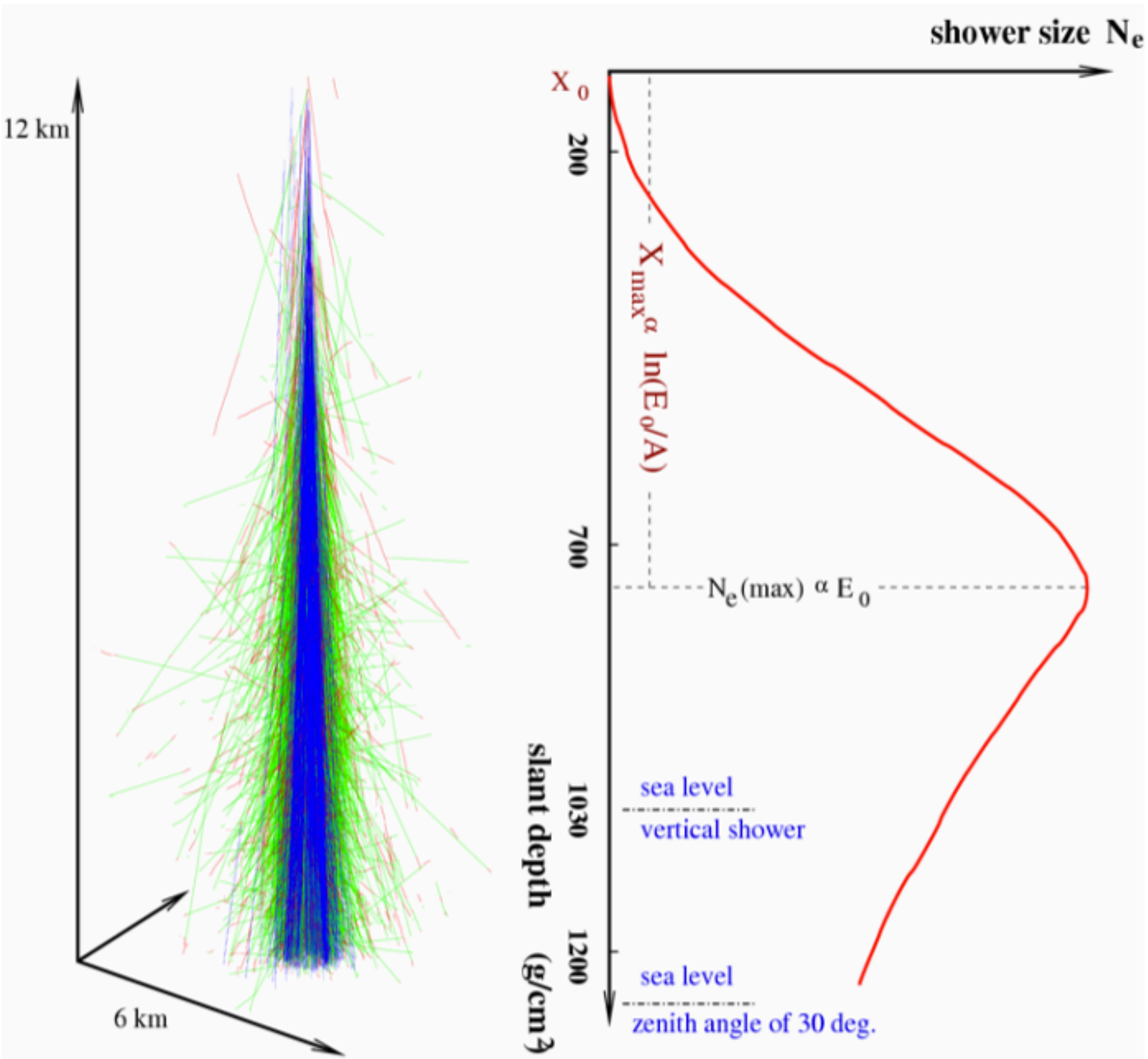


Atmospheric depth:

$$\int_h^{\infty} \rho(l)\, dl = X(h)$$

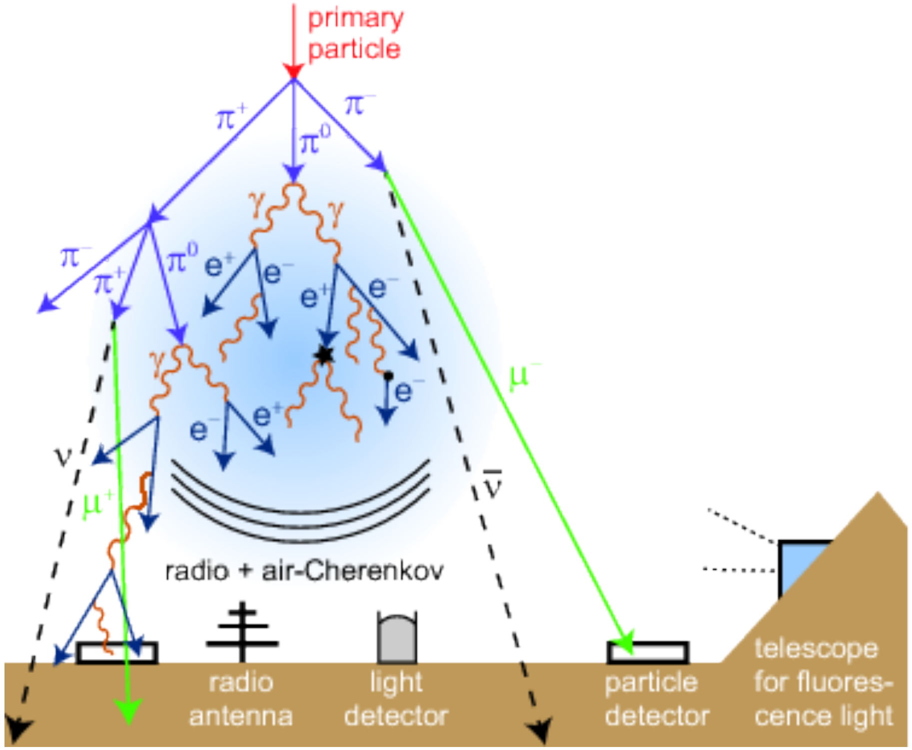
- Shower particles: mainly $e^{\pm}, \gamma$
- 80 – 95% of primary energy converted to ionization energy
- Up to 10^{11} charged particles

Ralph Engel, 13 March 2005

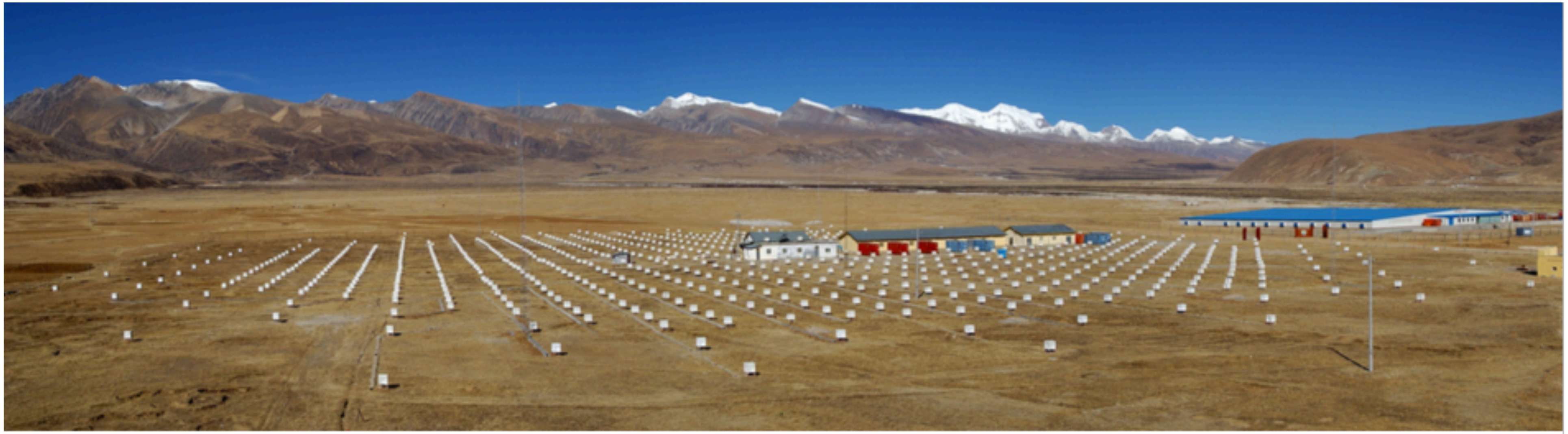
IV- Air Shower Detection

Main methods:

1. Air shower arrays
   - Observe shower structure from single observation level.
   - Timing information can be used to reconstruct arrival direction.
   - Particle density, profile → Energy
   - Particle identification: N_μ/N_e
2. Fluorescent light detectors: Isotropic emission. 4 photons/m.
   - Run only on cloudless, moonless nights
   - Detect full longitudinal development of shower : direction and energy, X_{max} (particle identification)
3. Radio detectors
   - Important R&D effort still ongoing.
   - radio footprint of the shower can be used to measure the energy and the X_{max}

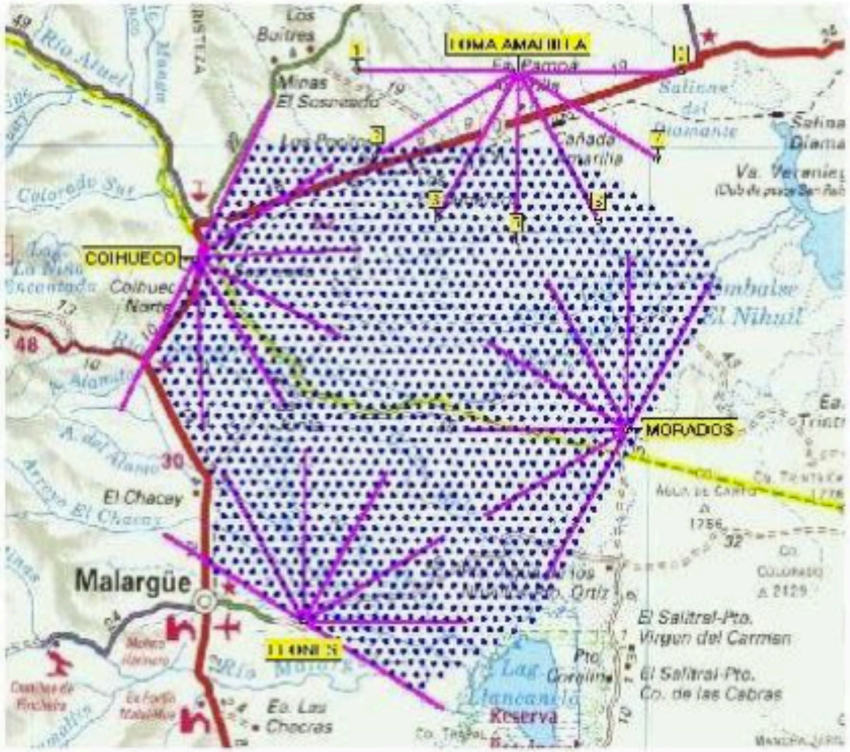


Key points: Duty cicle, Energy resolution, Energy Calibration, Xmax resolution, Detector density, cost.



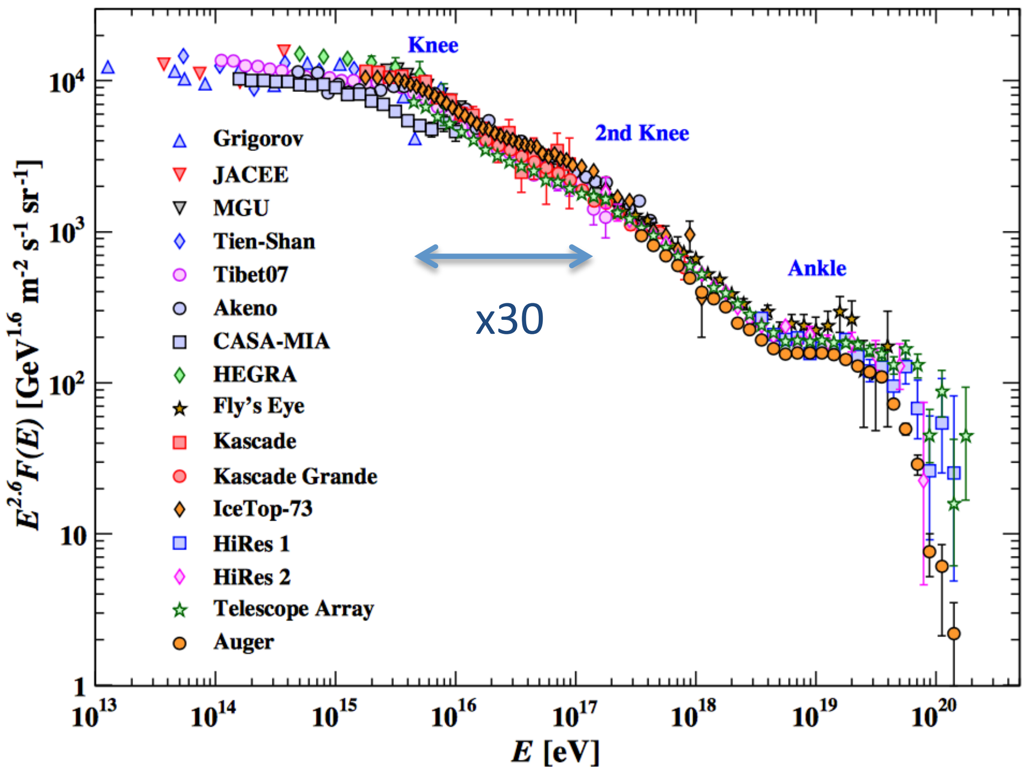
Top: the Tibet III air shower array at an altitude of 4,300 m above sea level.

Right: map of the Auger Southern Observatory in Argentina. The enclosed are of the experiment is 3,000 sq.km.



IV- The knee and the ankle problems.

- Acceleration, propagation
  - depend on B: $r_{gyro} = R/B$
  - Rigidity, $R = E/Ze$
  - $E_c(Z) \sim Z\, R_c$
- $r_{SNR} \sim$ parsec
  - $\rightarrow E_{max} \sim Z * 10^{15}$ eV
  - $1 \leq Z \leq 30$ (p to Fe)
- Slope change should occur within factor of 30 in energy
- Problem: continuation of smooth spectrum to EeV : Models of galactic particles E >> knee:
  - reacceleration by multiple SNR
  - reacceleration by shocks in galactic wind
  - Local source at knee on top of smooth galactic spectrum



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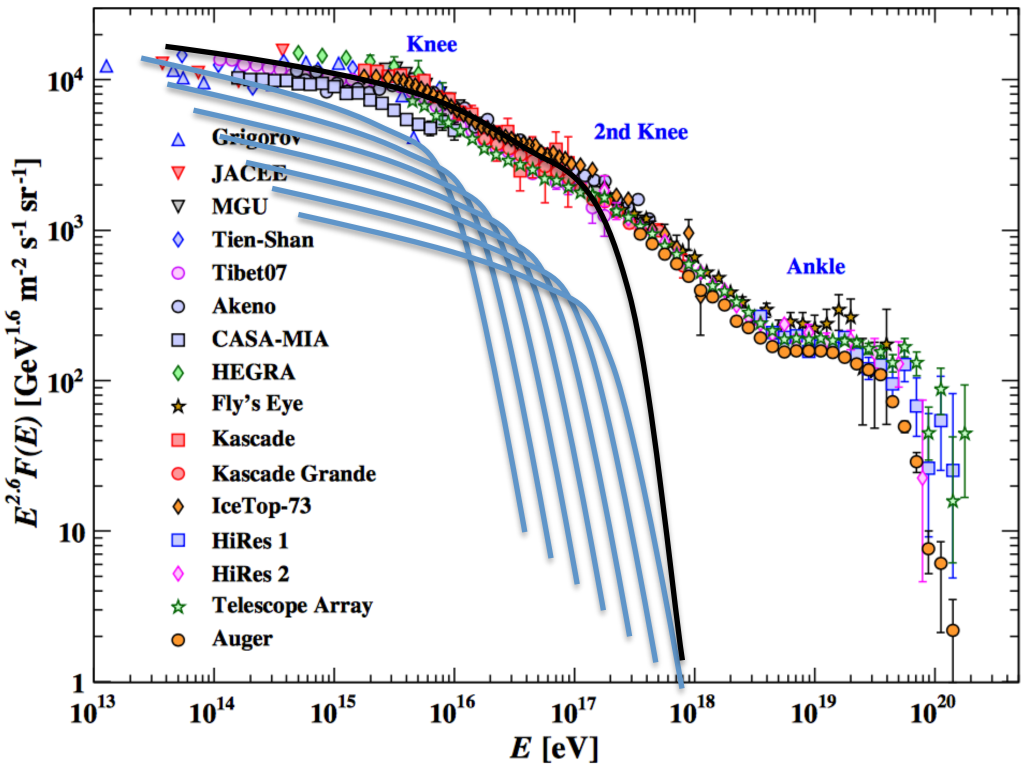

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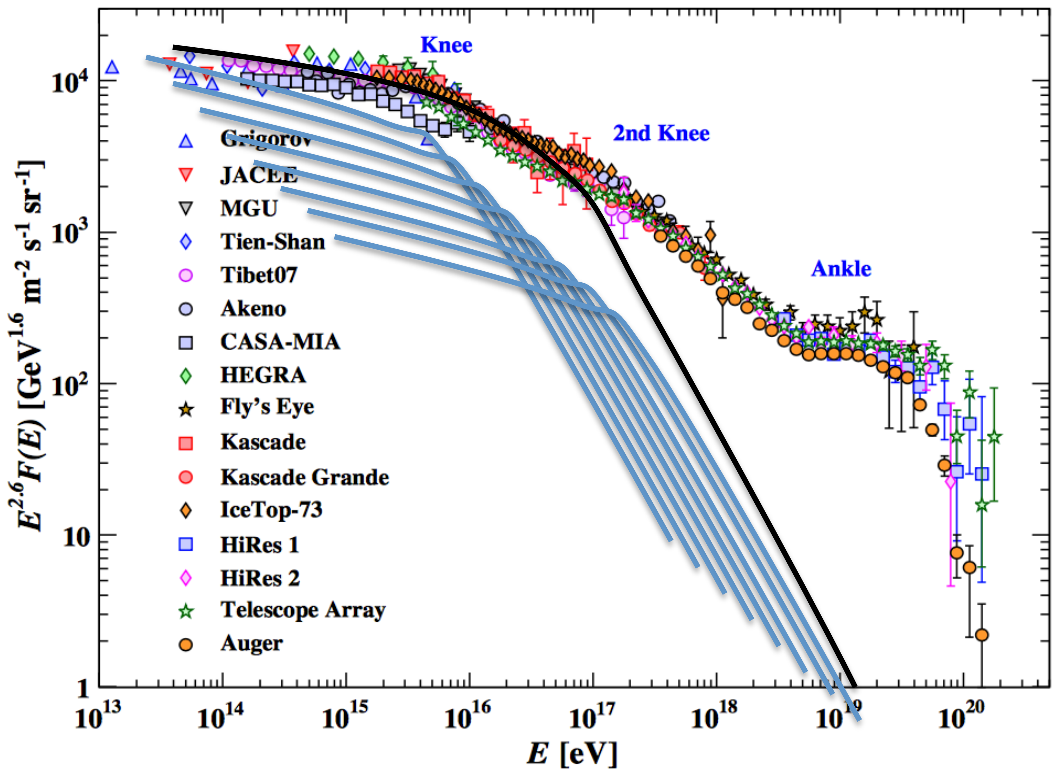

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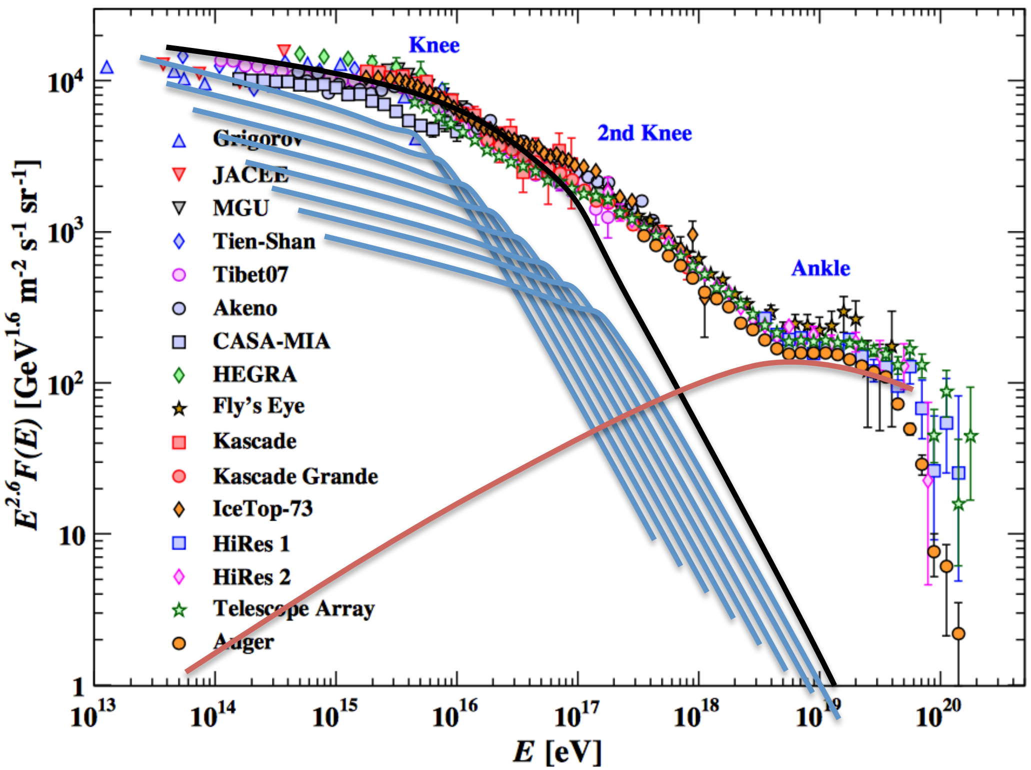
\+ Extragalactic sources



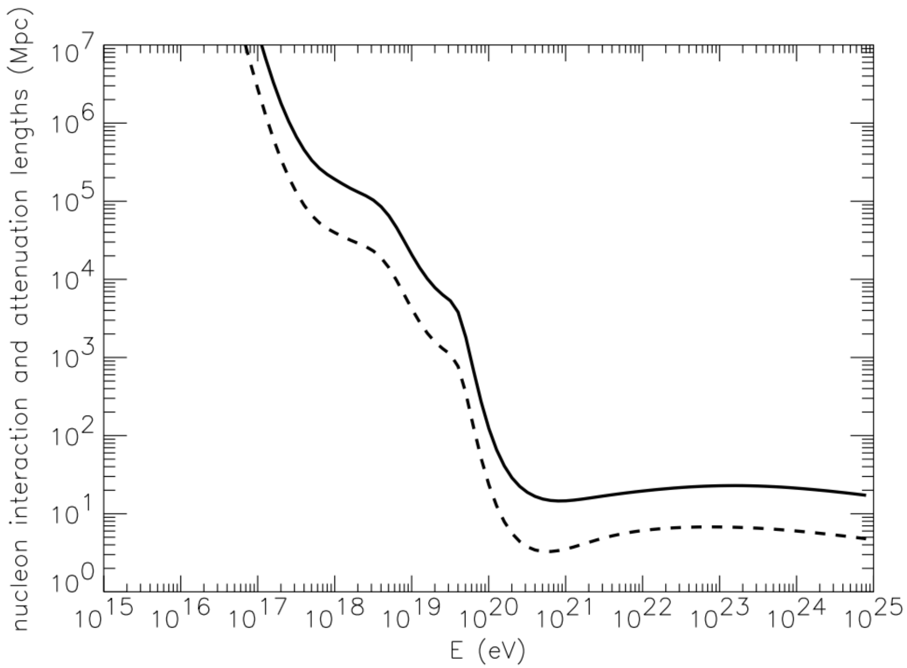
IV- GZK cutoff

- The CMB has a blackbody spectrum with T=2.7 K corresponding to mean energy of 6.34×10^{-4} eV. A proton of high enough energy (> 7×10^{19} eV) will interact inelastically with CMB photons producing pions via

$$\gamma + p \rightarrow n\pi^{+}$$

$$\gamma + p \rightarrow p\pi^{0}$$

- With each collision, the proton would lose roughly 20% of its energy
- Similar behaviors for other particles:
  - nuclei photo-dissociate
  - $\gamma\gamma_{CMB} \rightarrow e^{+}e^{-}$
- This only happens for cosmic rays that have at least 6×10^{19} eV of energy, and this is the predicted GZK cutoff.

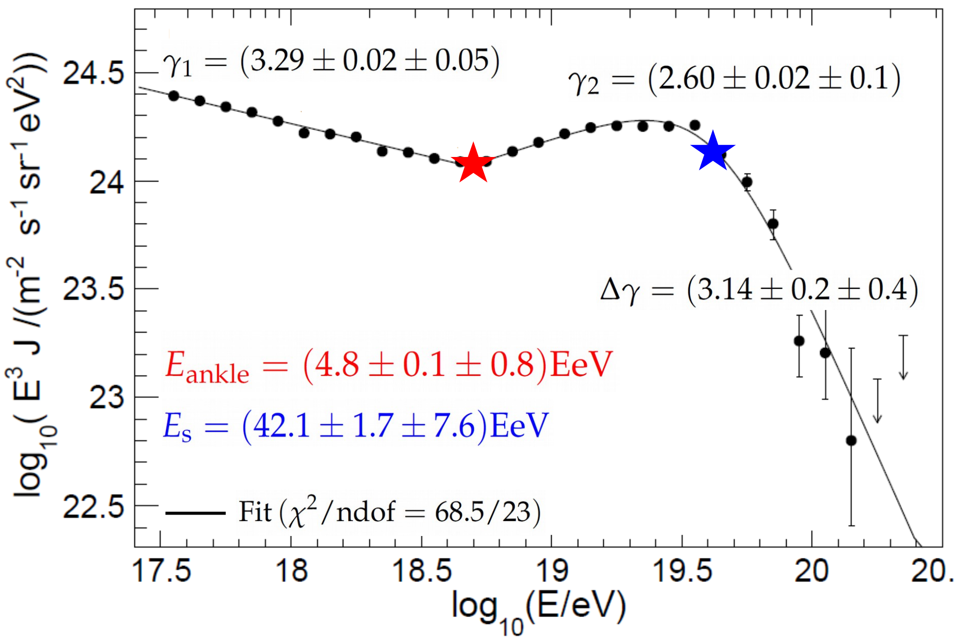


No Local sources → $E_{cutoff} = 10^{20}$ eV

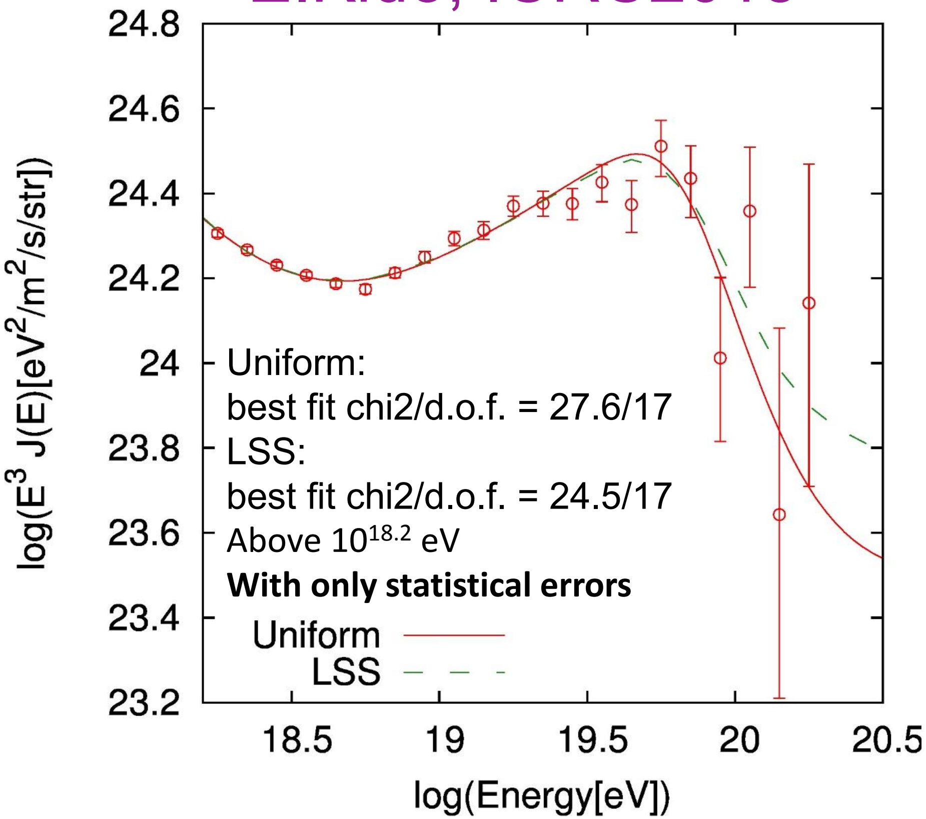
GZK Cut-off or Source Effect?

- Progress in observation: the CR spectrum does not extend beyond 10^{20}eV - First reported by HiRes, and confirmed by Auger and TA.
- Interpretation: the GZK effect, or the acceleration limit, or ?

Auger,
I. Valino, ICRC2015



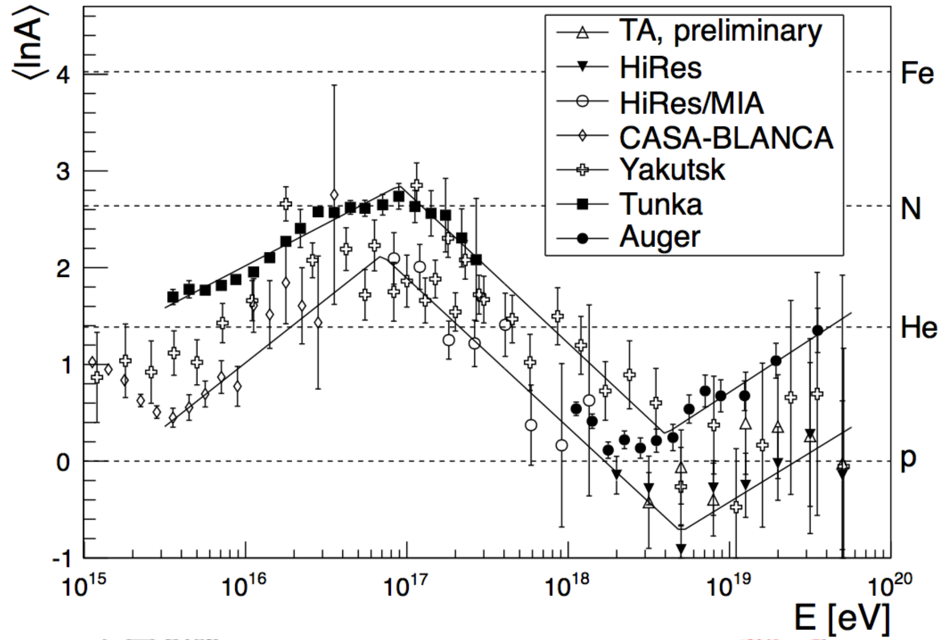
TA,
E.Kido, ICRC2015

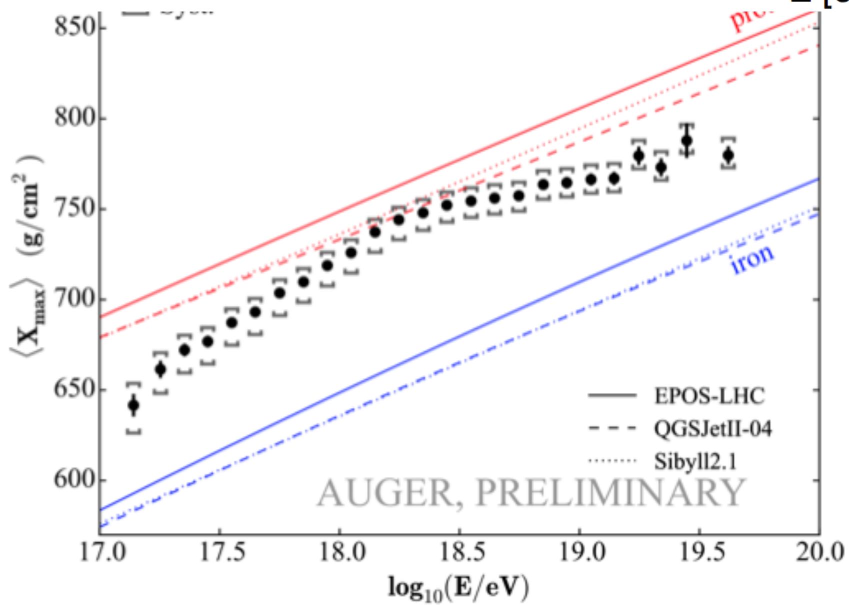


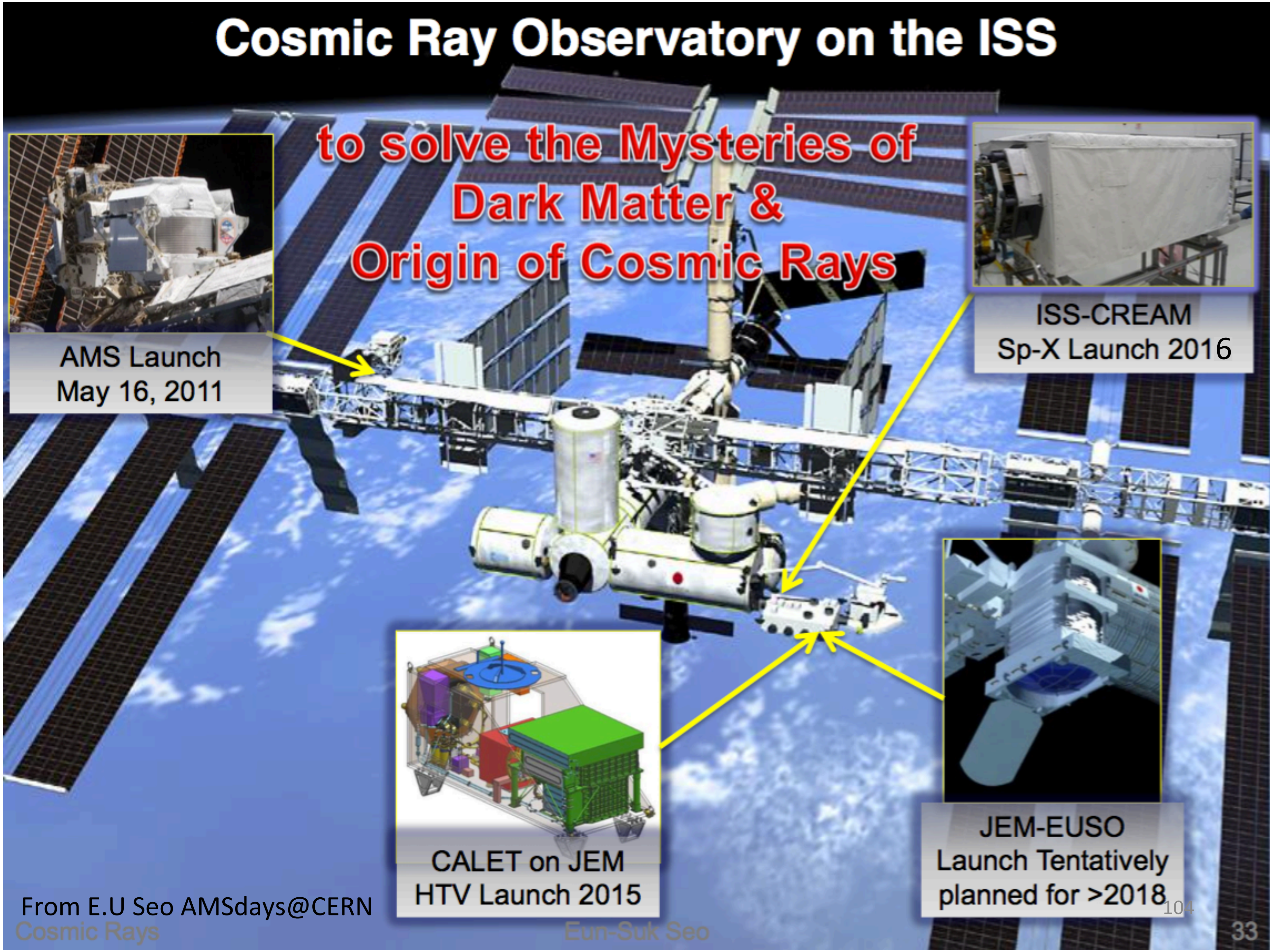
IV- EAS Mass composition

Identification of incident CR :

- Critical observable to understand the transition from galactic to extra-galactic
- Limited precision from EAS measurement.
- Large statistical fluctuation
- Only averaged quantities ($<X_{max}>$ or $<\ln A>$ vs Energy
- Model dependent
- Statistically limited at high energy







From E.U Seo AMSdays@CERN

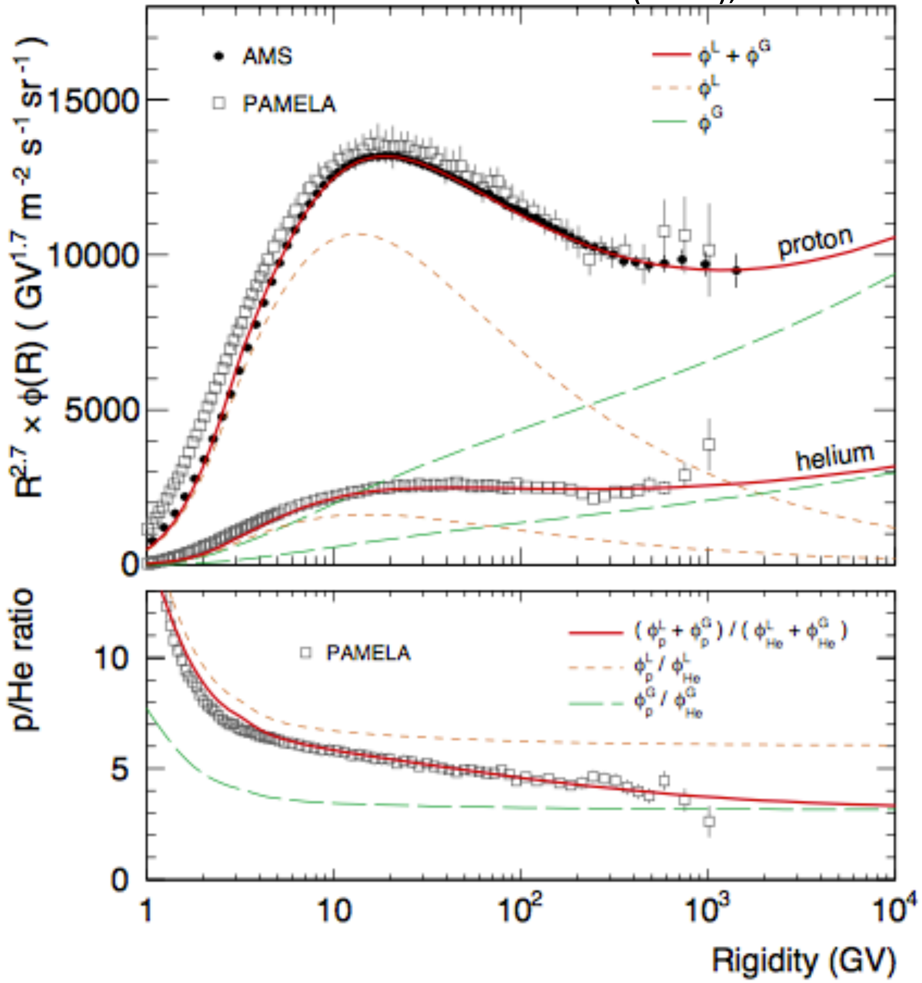
Purpose and Goals of the lecture

To present you:

- Short overview of CR discovery
- What are the main observables used to characterize the CRs (different particles, distribution of energy/Fluxes, anisotropy)
- What are the mains physical processes for the propagation of cosmic-rays.
- What is the current knowledge on CRs
- What are the many open questions related to CRs
- Different strategies used to measure CRs for the different type of CRs/Energy range
- How instruments are built to detect/characterize the CRs / some basic concepts for CRs detections : Acceptance/Trigger/ Monte Carlo simulations

p/He ratio anomaly as signature of a nearby source

N. Tomassetti & F. Donato (2015), NT ICRC15



The idea. Two different classes of sources contribute to the CR flux. Each class has different spectra and composition.

Low-energy flux (GeV-TeV energies)

Nearby old SNRs. The shock is weaker, the B-field are damping, the DSA is not efficient

→ **The injection spectra may be steeper**

Higher background density for p+p interactions (to explain the e+ excess), e.g. due a molecular cloud

→ **It may be well a hidrogen-rich source**

High-energy flux (TeV-PeV energies)

Galactic SNR ensemble. Younger SNRs, with stronger shock and B-field amplification

→ Efficient DSA woring up to PV rigidities.

→ Hard acceleration spectra: slope ~2-2.1.

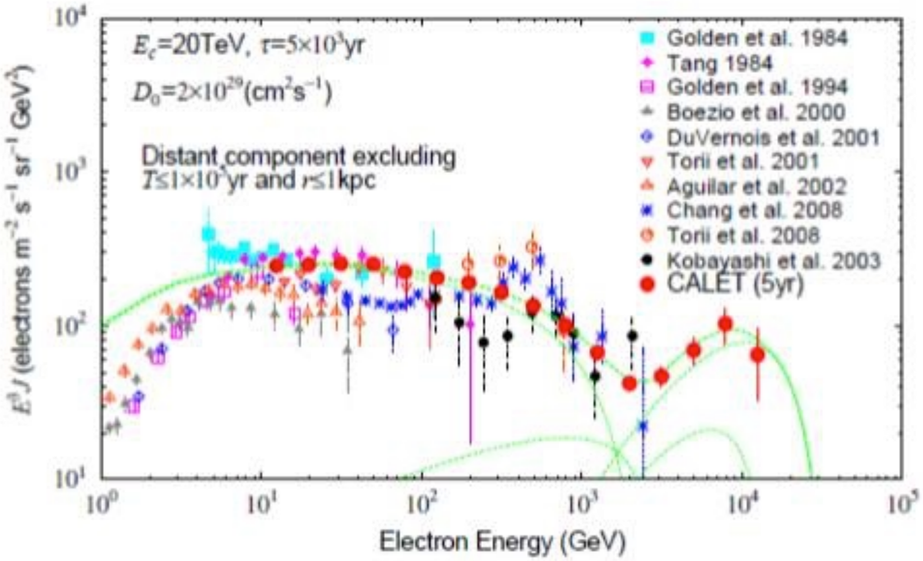
Composition = average Galactic SNRs properties

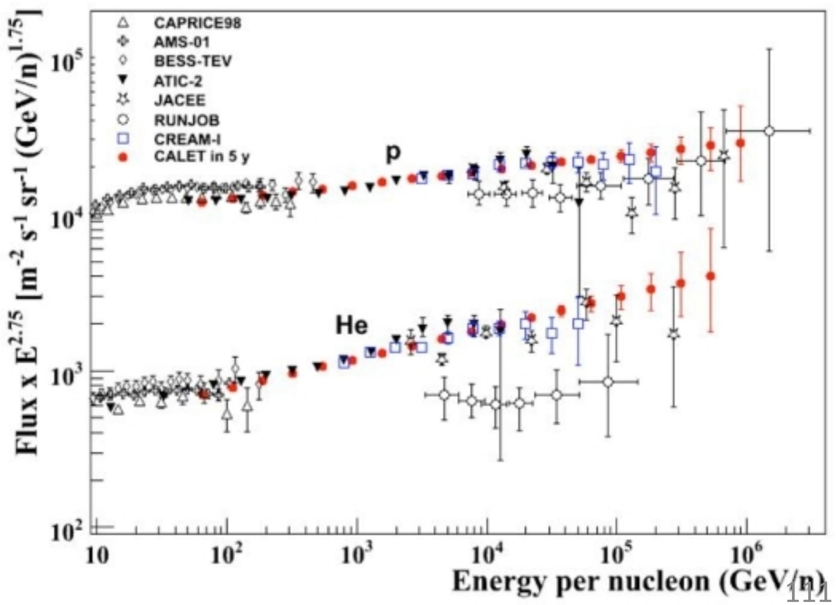
→ p & He hardening: Transition from different DSA spectra

→ pHe ratio: signature of transition to different composition of H & He in the medium

CALET (2015-...)

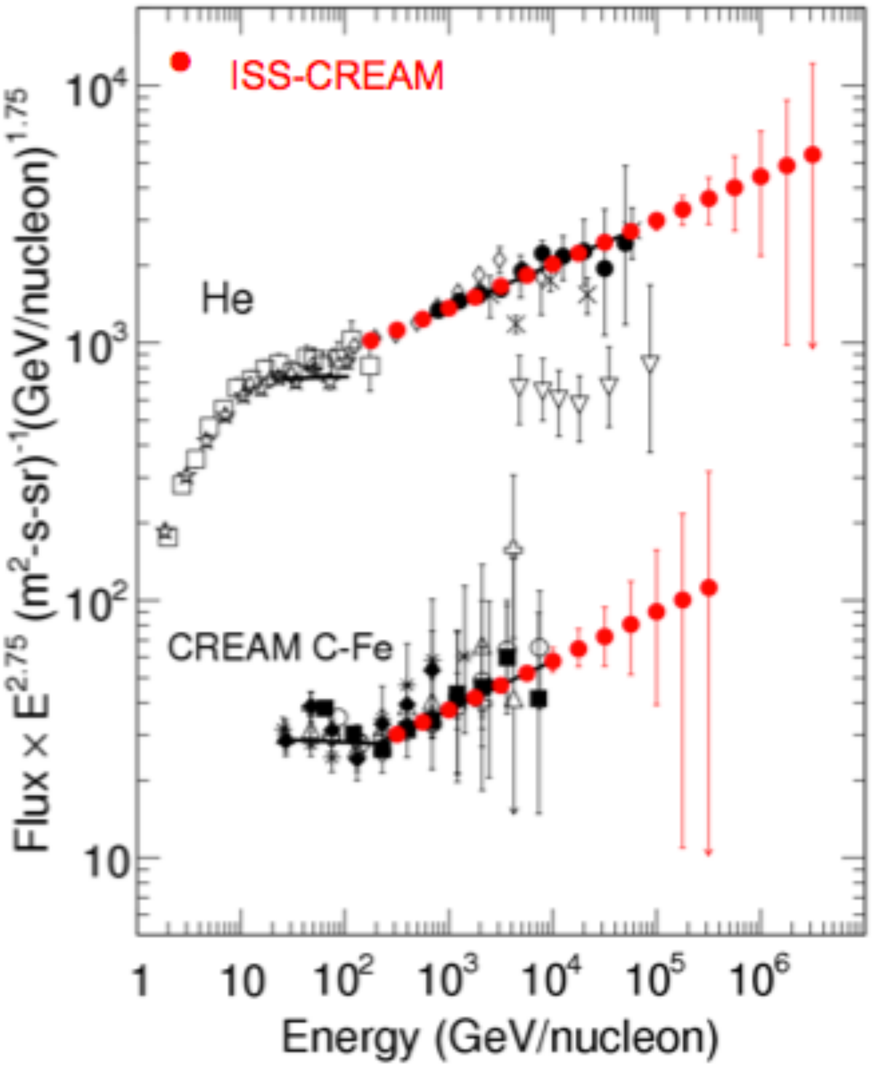
- Detailed shape of the electron spectrum above 1 TeV to test the presence of nearby astronomical sources
- CALET will be able to extend the present data to higher energies and measure accurately the curvature of the spectrum and the position of the spectral break-point for individual nuclear species





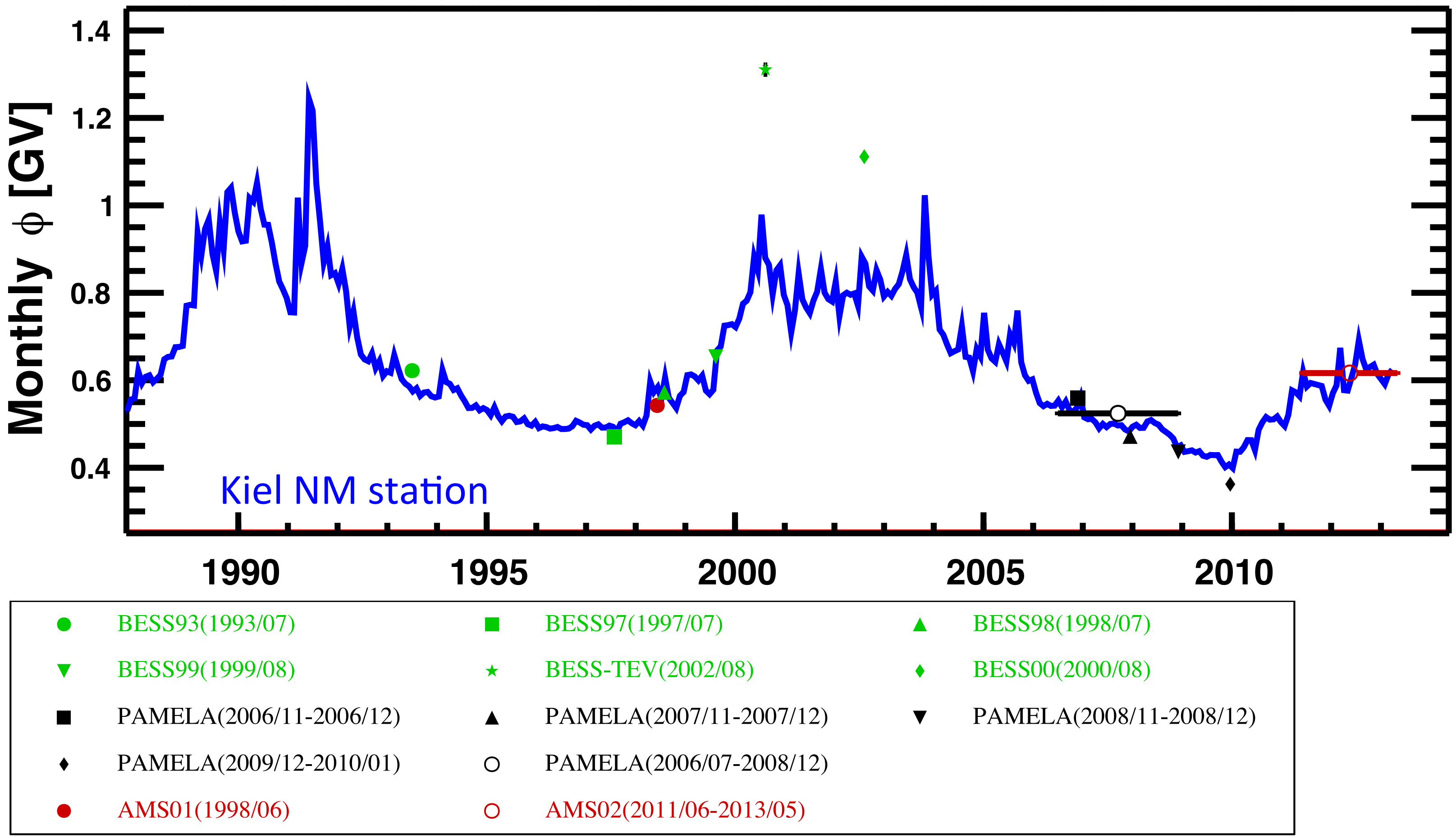
Future experiments: ISS-CREAM

- Launch (Space X Dragon cargo) in 2016
- To be installed on JEM-EF for a period of at least three year
- The elemental spectra for Z = 1–26 nuclei over the energy range 10^{11} to 10^{14} eV
- Additional capability for electron separation from protons.



Modulation of CR spectra

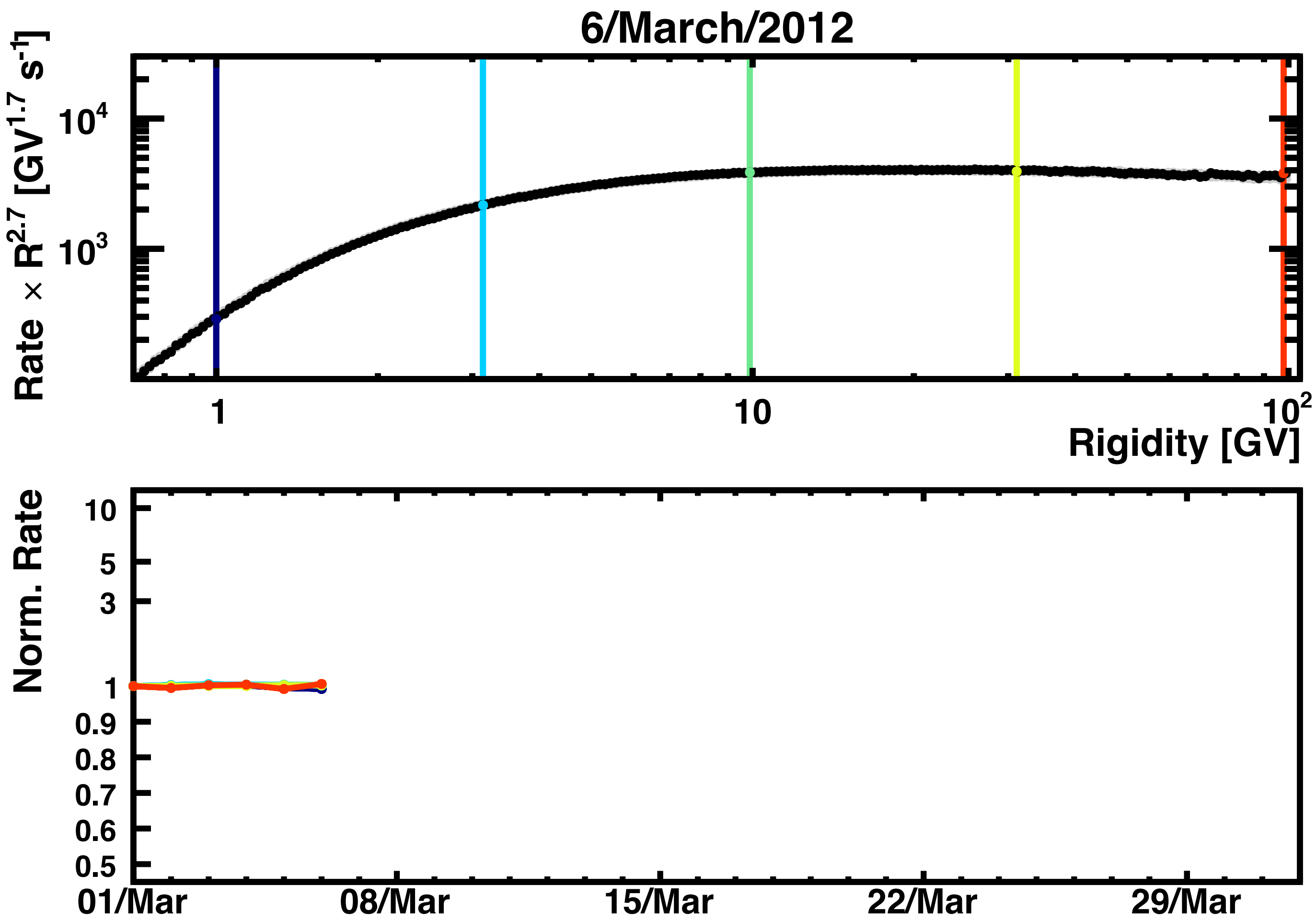
Comparison between Neutron Monitor and Direct measurements:



→ High statistics of AMS: possibility to reconstruct a flux for each day and then to study the time fluctuation.

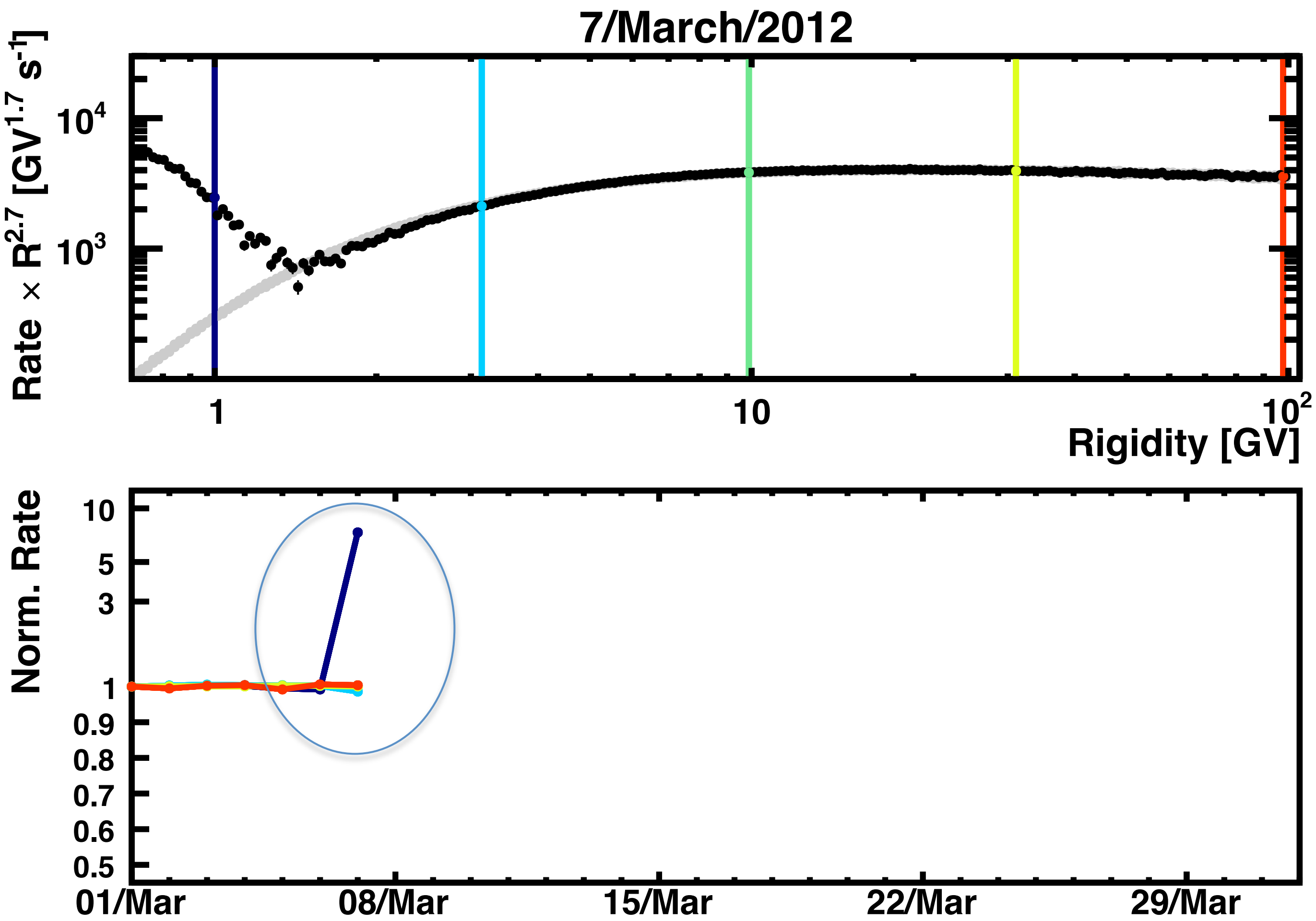
March 2012 solar event

Daily proton rate reconstructed from AMS02 data:



March 2012 solar event

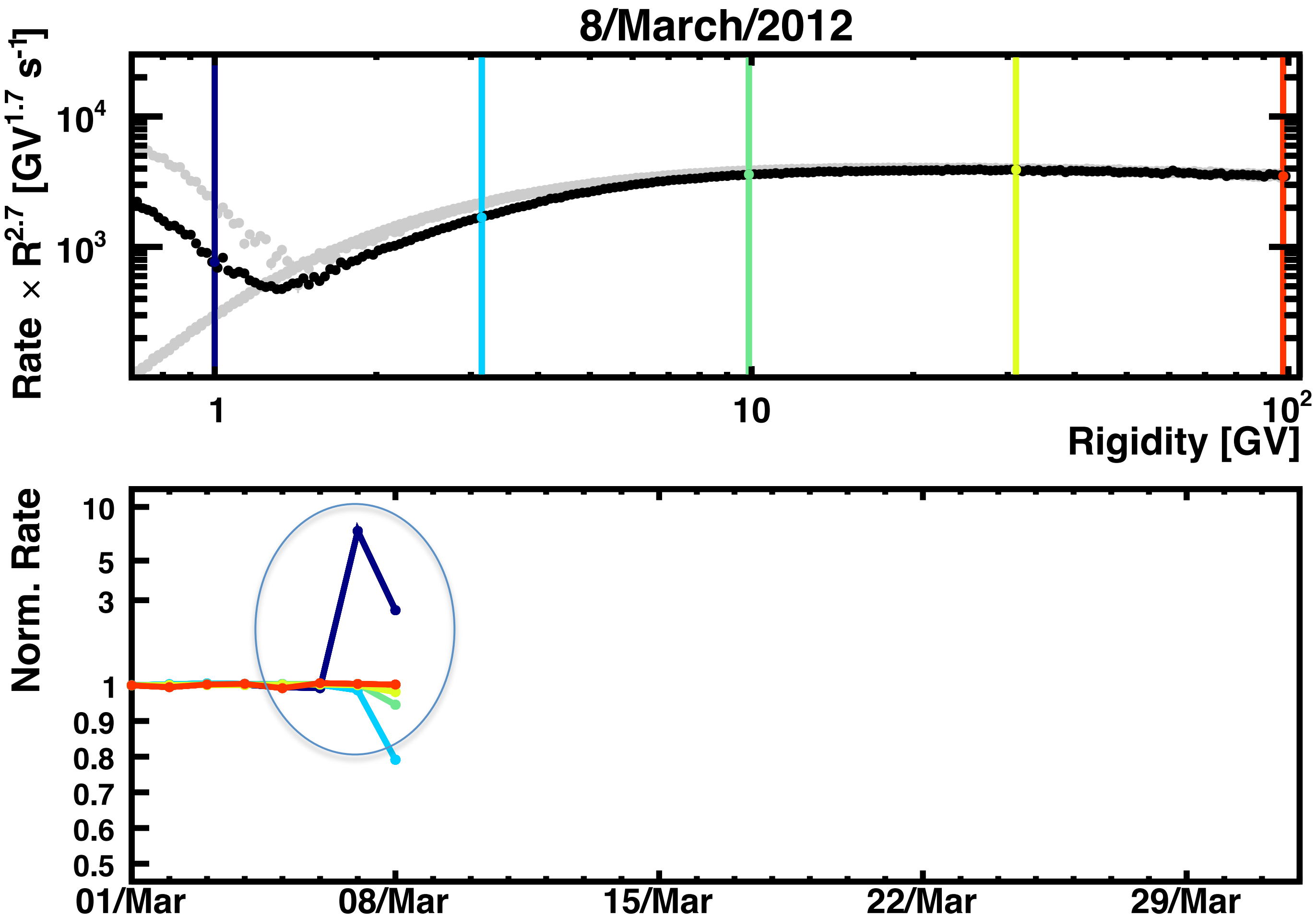
Daily proton rate reconstructed from AMS02 data:



Bunch of low energy particle produced by the flare

March 2012 solar event

Daily proton rate reconstructed from AMS02 data:



Bunch of low energy particle produced by the flare

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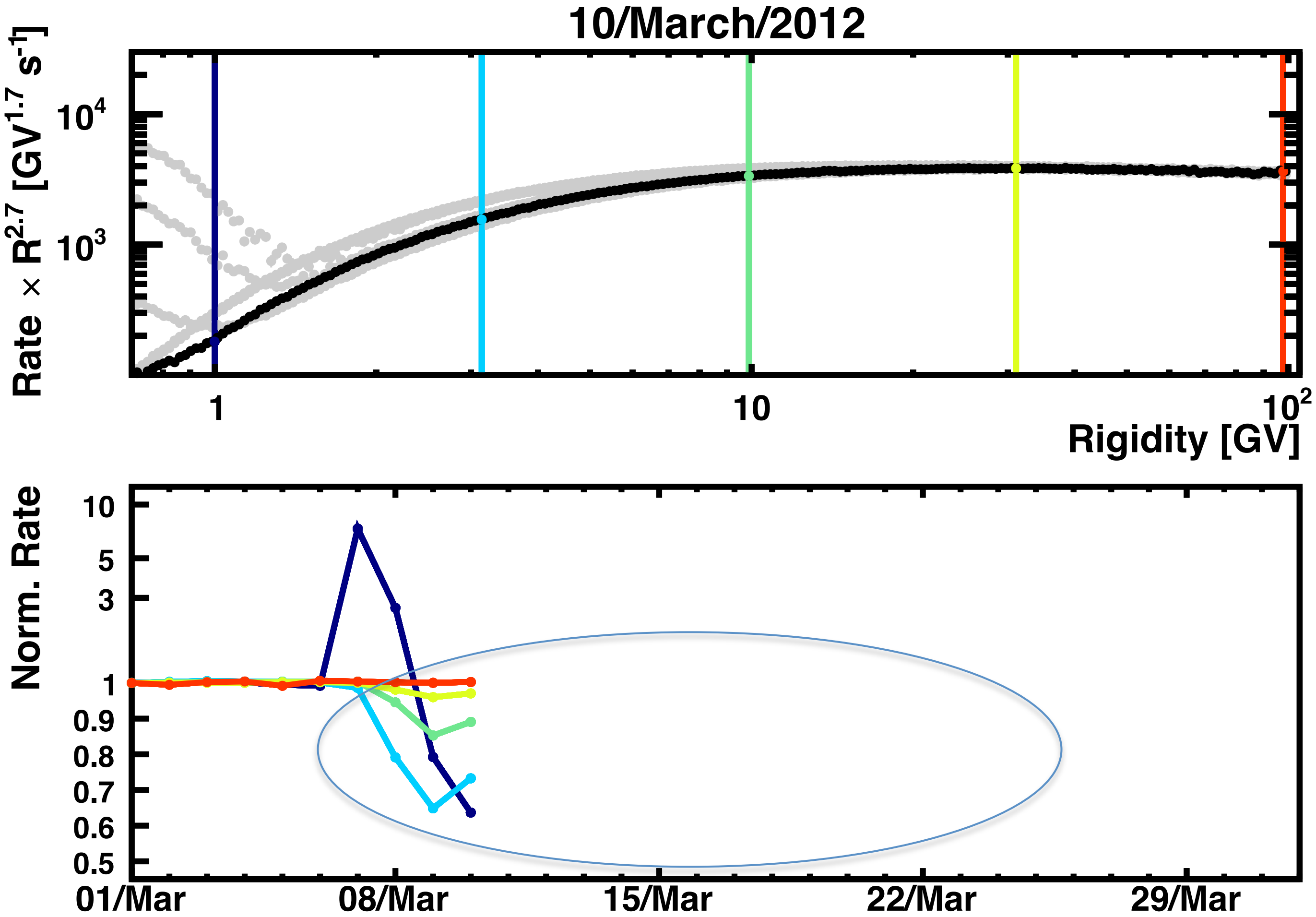
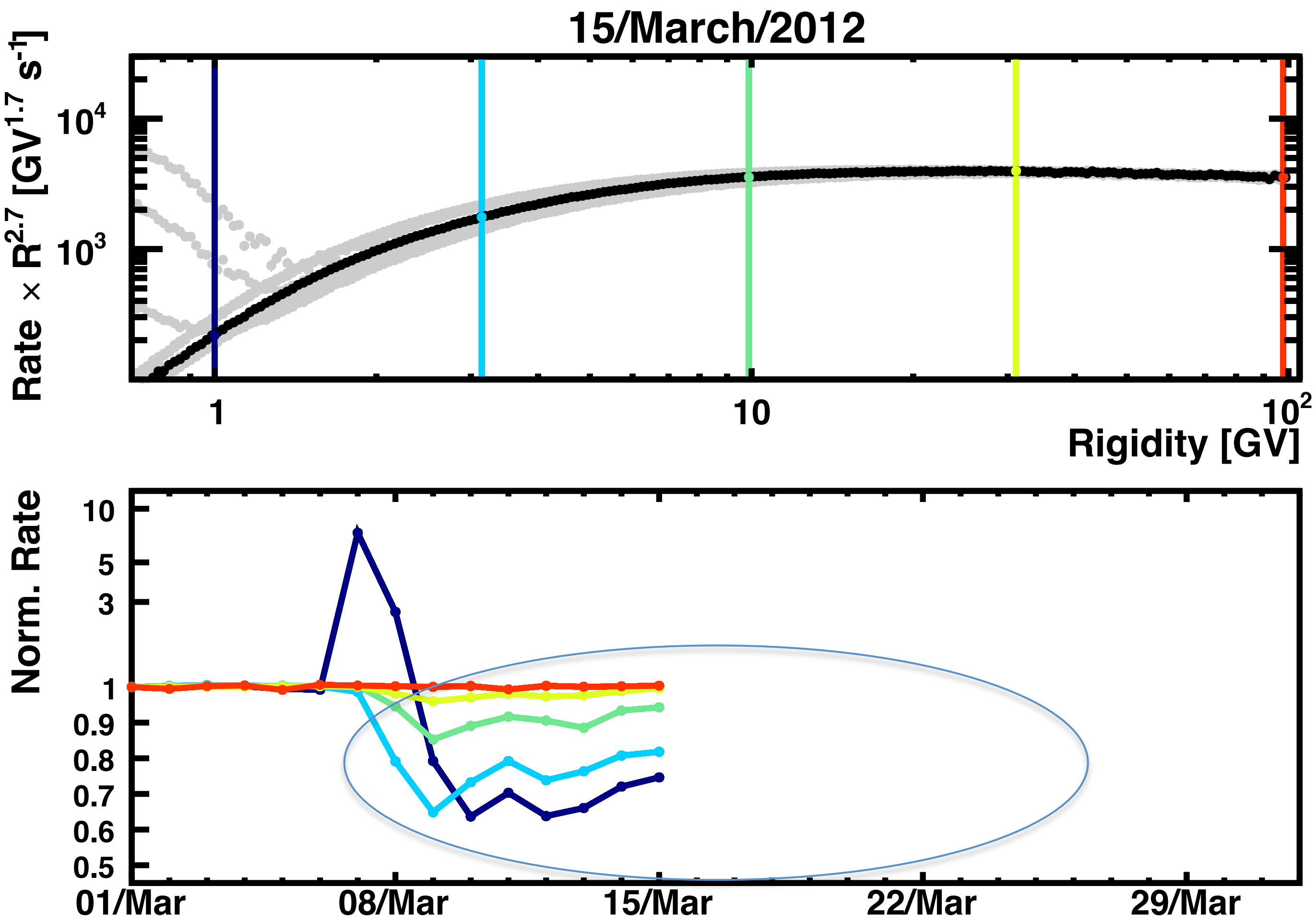
Daily proton rate reconstructed from AMS02 data:



Forbush decrease (due to the large magnetic disturbance) lasting ~20 days

March 2012 solar event

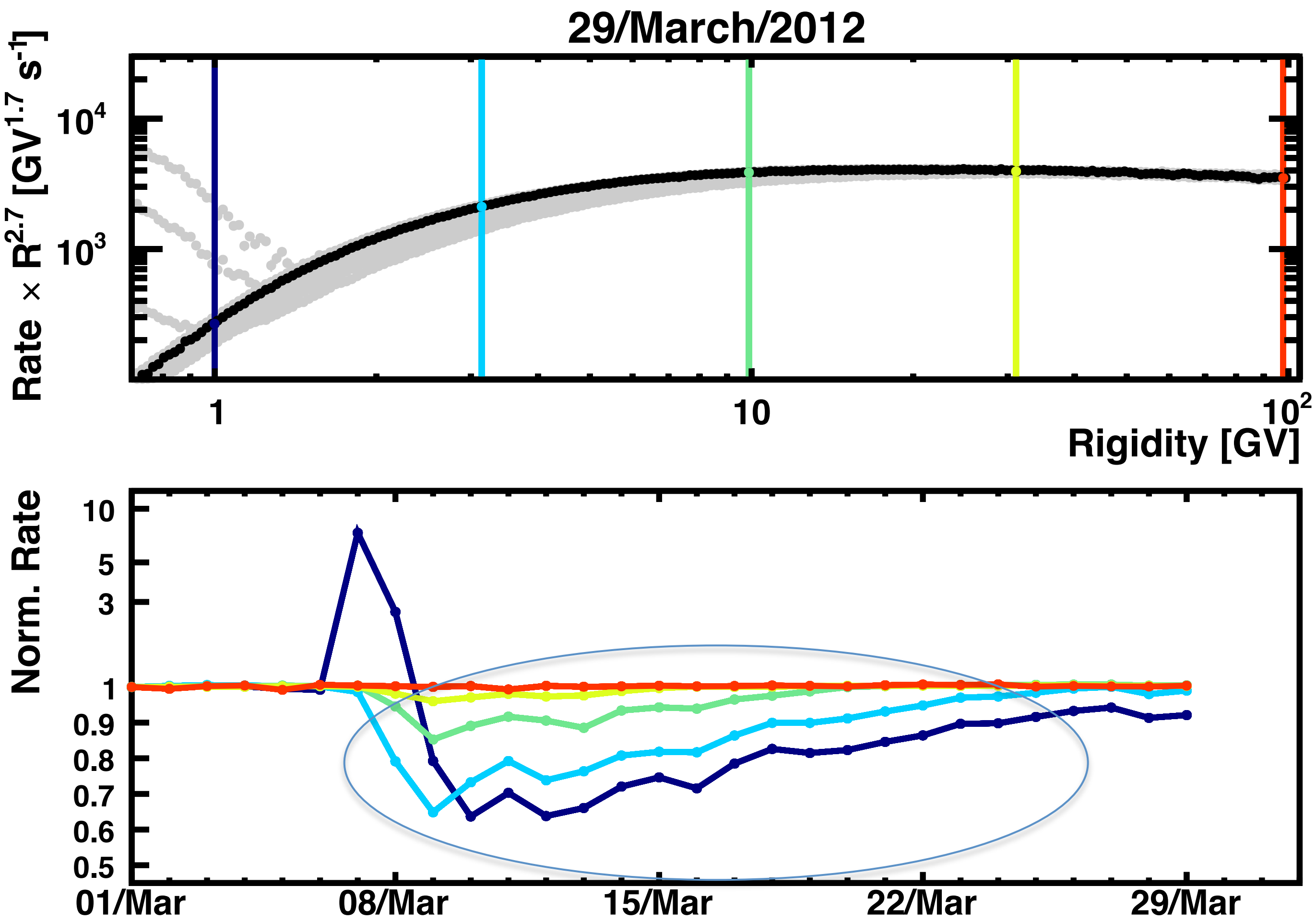
Daily proton rate reconstructed from AMS02 data:



Forbush decrease (due to the large magnetic disturbance) lasting ~20 days

March 2012 solar event

Daily proton rate reconstructed from AMS02 data:

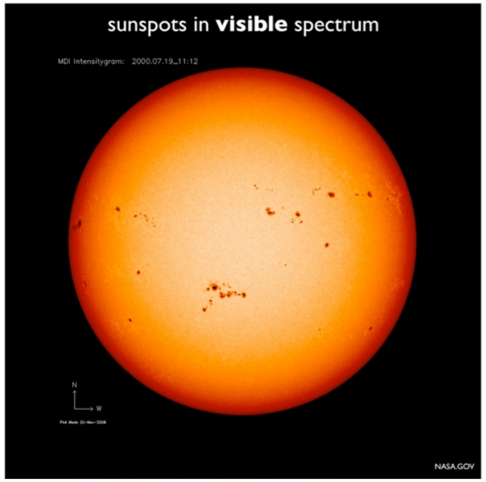


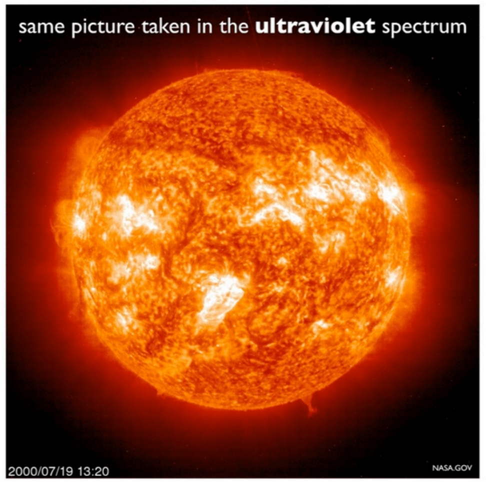
Forbush decrease (due to the large magnetic disturbance) lasting ~20 days

Cosmic ray modulation

- At low Energy (<20GV) cosmic ray spectrum affected by its propagation in the Solar cavity and the interaction with the plasma emitted by the sun.
- This produces a modulation of the spectrum which follows 11-year cycle in antiphase with Solar activity (Sunspot number)
- Simplest model for Solar Modulation: Force-Field approximation:

$$J(E,t) = \frac{E^2 - M^2}{(E+\Phi(t))^2 - M^2} J^{IS}(E+\Phi(t))$$

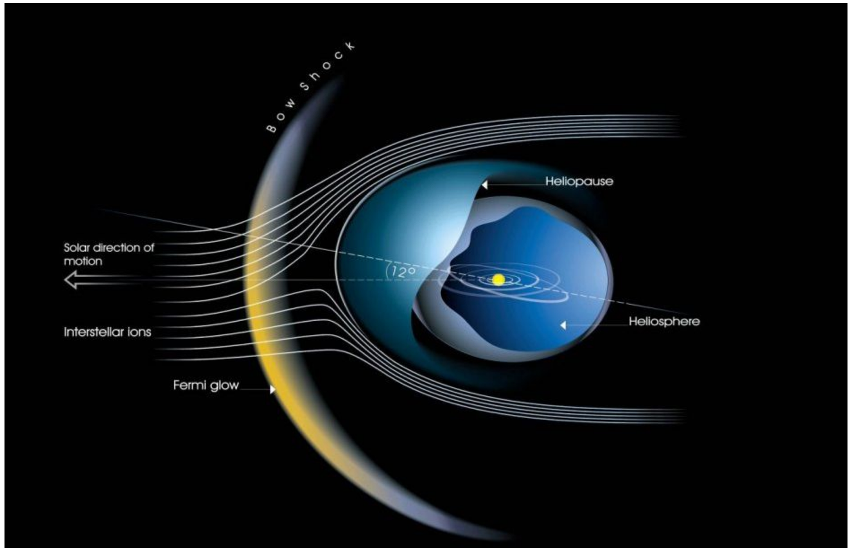


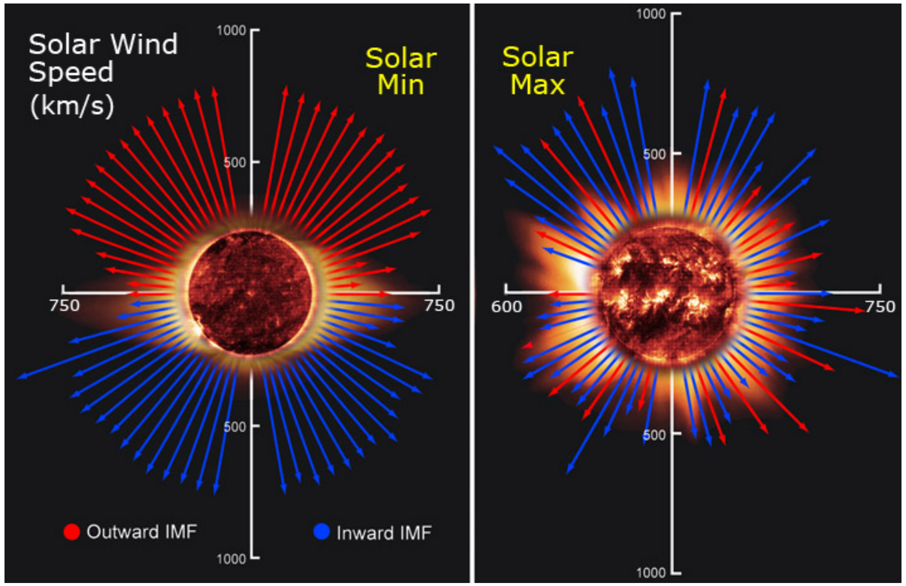


Cavité solaire – l'héliosphère

A region of space influenced by the sun and its expanding **Corona** :
solar wind *size : 100-150 AU*

- Solar wind: a continuous flow of charged particles from SUN with velocities around 400 Km/s
  - mainly composed of electrons and protons
  - flux ~10^{12} particles/m^2.s
- Solar magnetic field



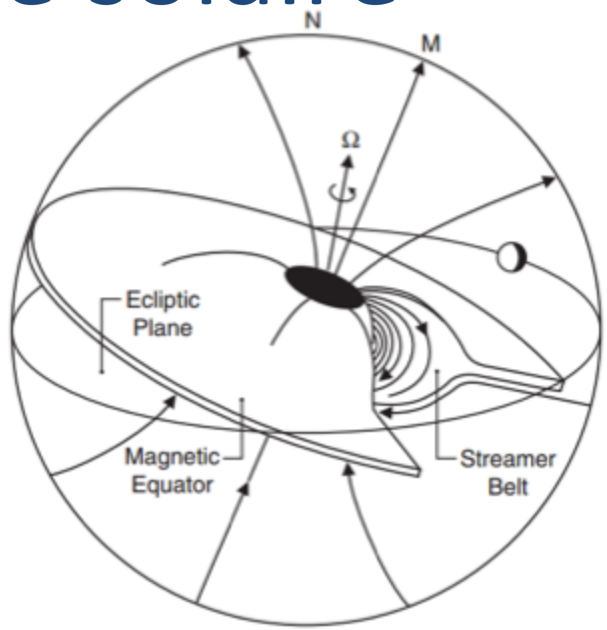


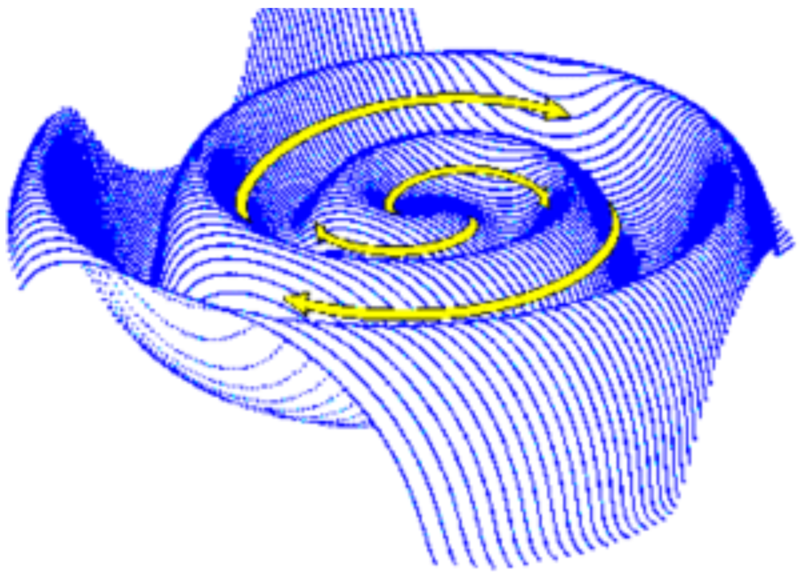
Champ magnétique solaire

- Le soleil tourne sur lui-même avec une période de ≃ 27.27 days (Carrington rotation)
- Le champ magnétique est proche d’un champ dipolaire près des pôles.
- Le vent solaire transporte le champ dans l’espace interplanétaire.
- Offset entre l’axe du champ et l’axe de rotation qui augmente quand on passe du minimum au maximum solaire.

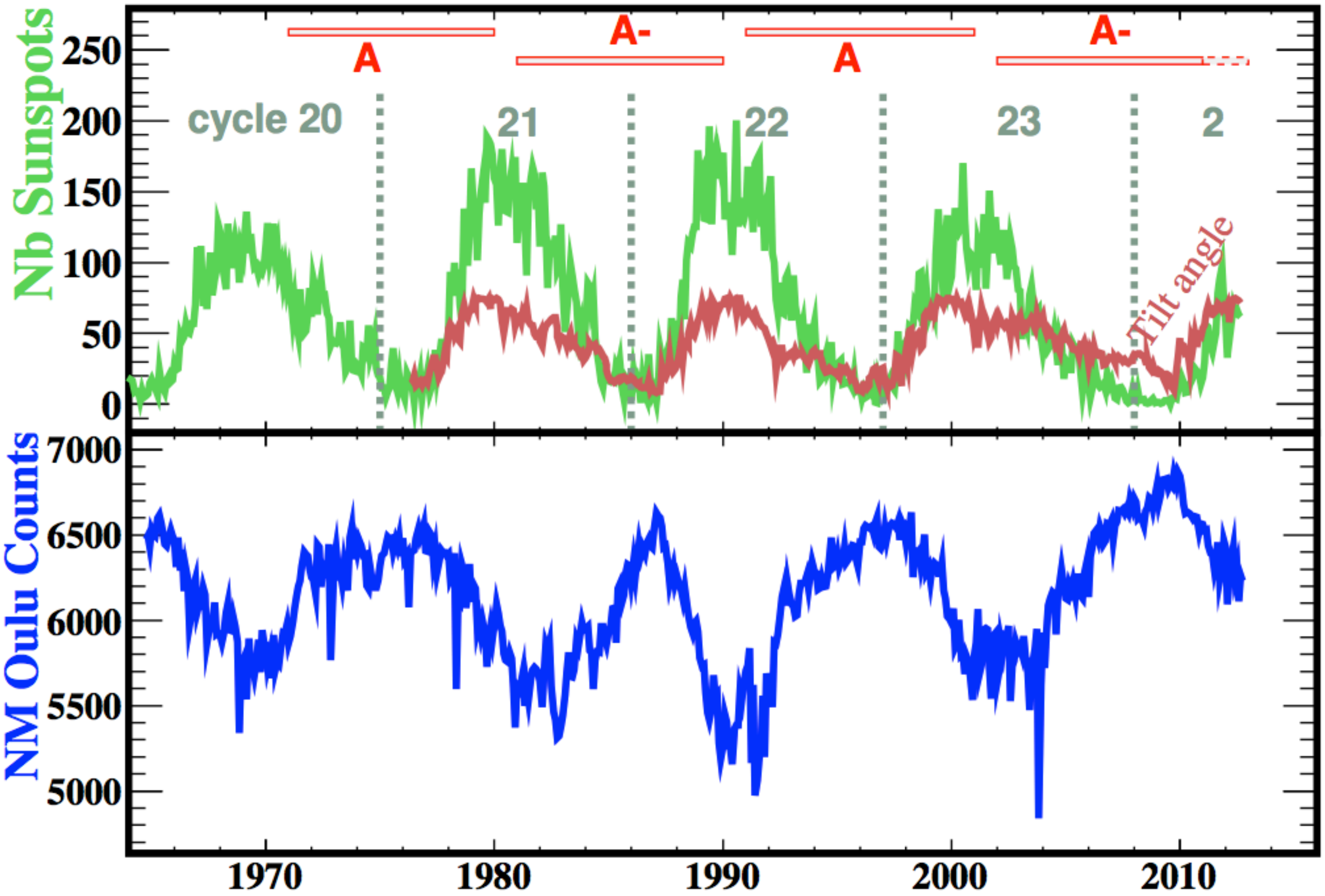
  → Spirale de Parker
- Structure du champ plus complexe quand on approche du maximum

  → Renversement de la polarité





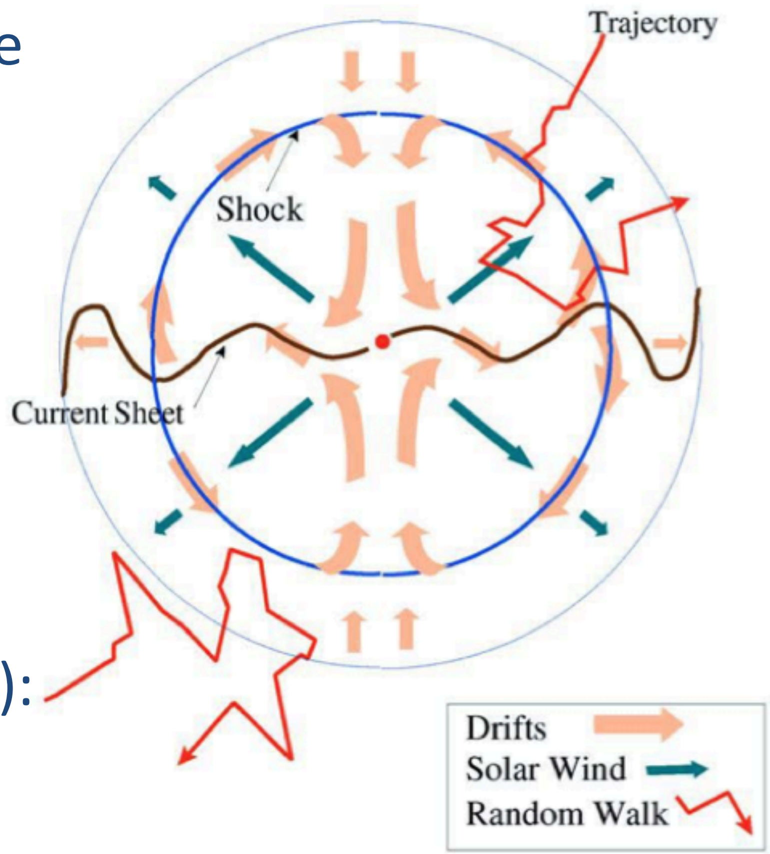
Cycles du soleil



Modulation solaire

Une particule entrant dans l'héliosphère va interagir avec :

- Le vent solaire
- Les irrégularités du champ magnétiques
- Le champ magnétique à plus échelle **(Spirale de Parker)**



Simplifications (Gleeson et Axford 1968):

- Vent solaire radial et de vitesse constante
- Symétrie sphérique de l'héliosphère.
- Pas de dérive – Pure diffusion
- Système à l'équilibre

Approximation Force field

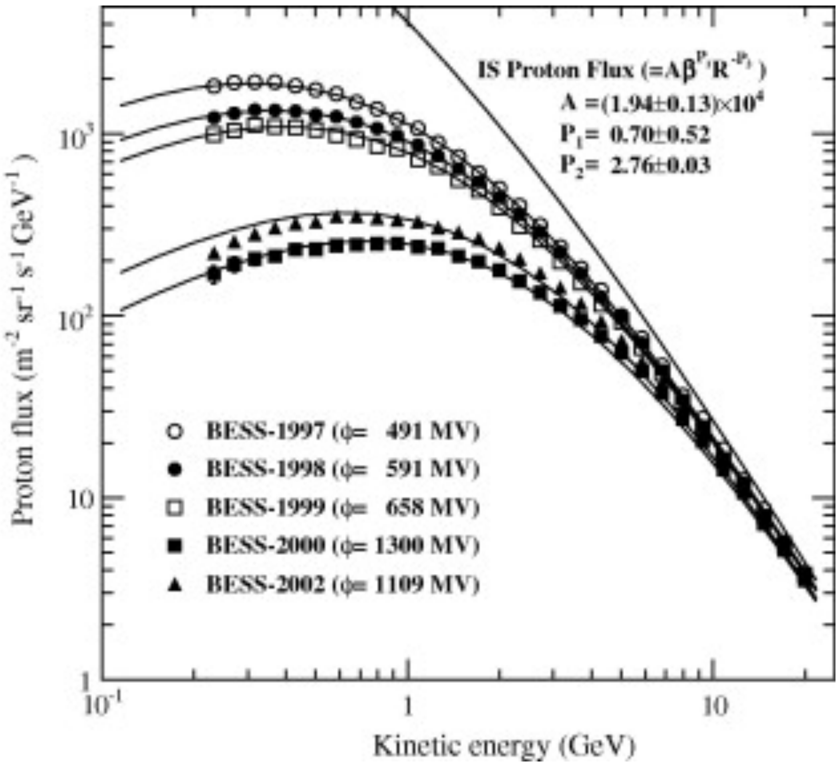
- Modèle le plus simple : Force-Field

$$J(E,t) = \frac{E^2 - M^2}{(E + \Phi(t))^2 - M^2} J^{IS}(E + \Phi(t))$$

Où $\Phi(t)$ est la paramètre de modulation
→ Toute la dépendance en temps est contenue dans $\Phi(t)$

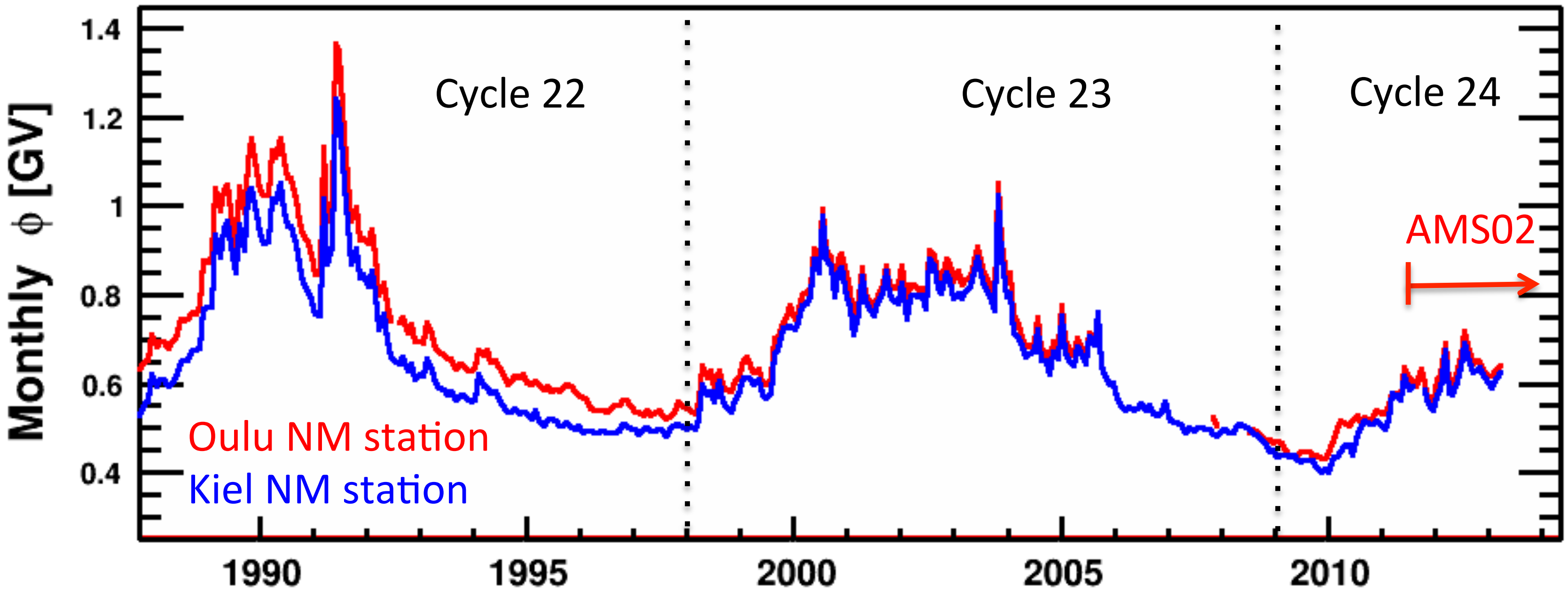
eZ x $\Phi(t)$: Energie moyenne perdue par le RC lors du transport dans la cavité solaire.

Shikaze 2007



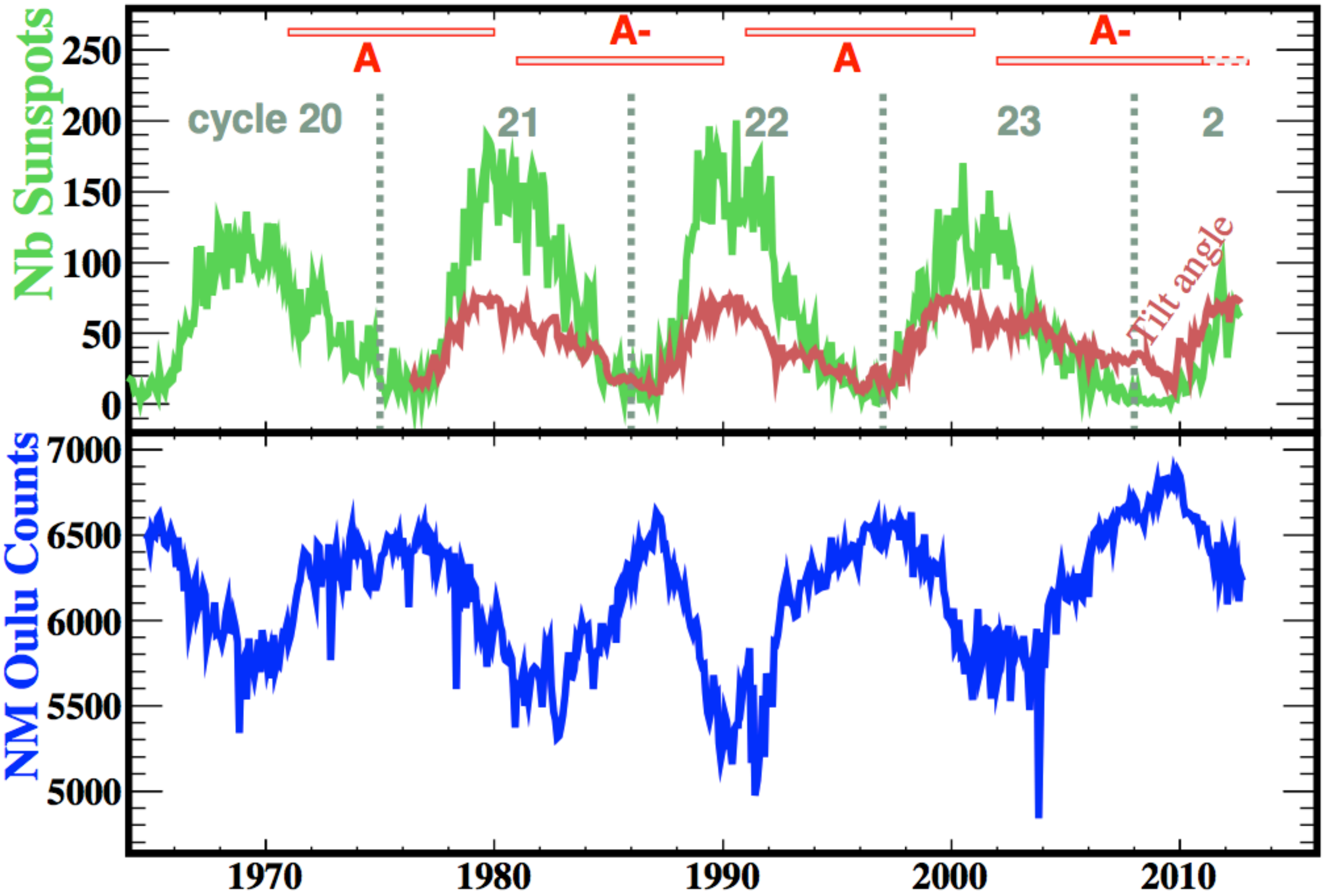
Ground-based Neutron Monitor

- ~30 active stations all over the world (different latitudes and altitudes)
- Some in operation for decades
- Cannot measure the energy spectrum or the composition of cosmic-rays
- Energy integrating device: Monitor the Neutron rate ∝ Integral of fluxes folded with atmosphere and detector response.
- NM counts can be used to compute the modulation parameter ϕ(t):



→ Provide a reference to compare the different experiments.

Cycles du soleil



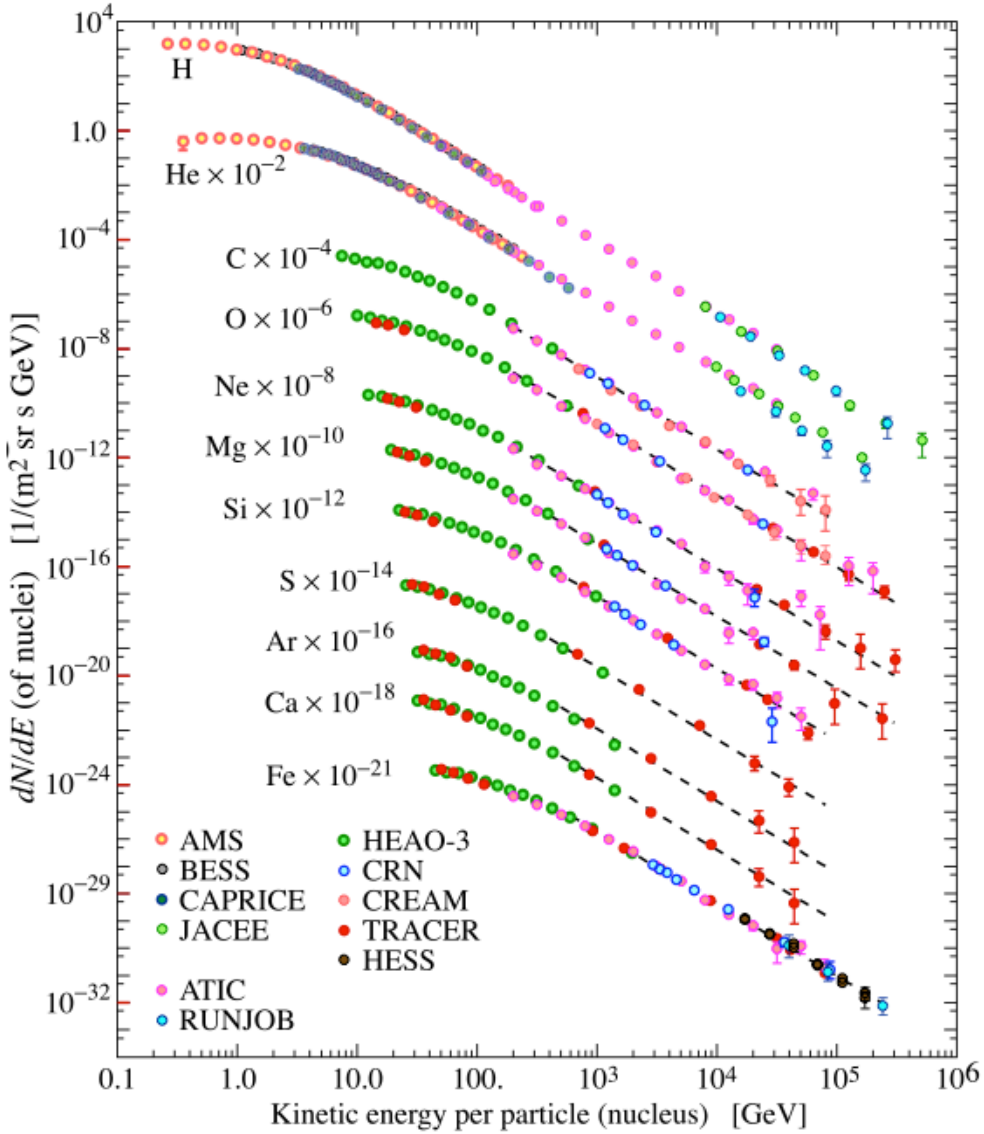
Galactic CRs status ~10 years ago

Main properties:

- Featureless and universal power-law energy spectra above 2 GeV/n
- Abundances for primary species related to Solar system ones.
- Abundances of secondary species explained by nuclear interaction on ISM.

→ Global features could be well describe by diffusion model with universal power-law injection in the sources

→ Recent data, reaching an unprecedented precision are challenging this “simple” picture.



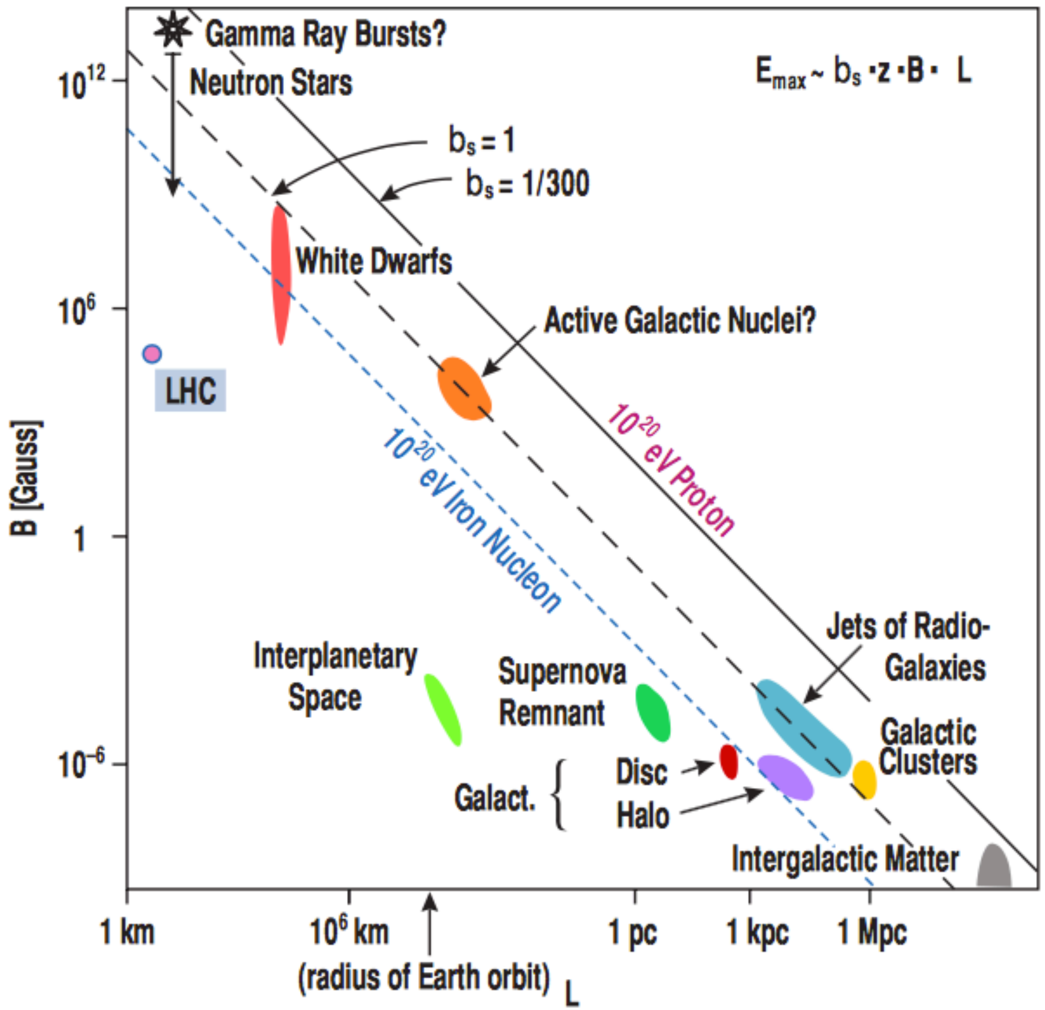
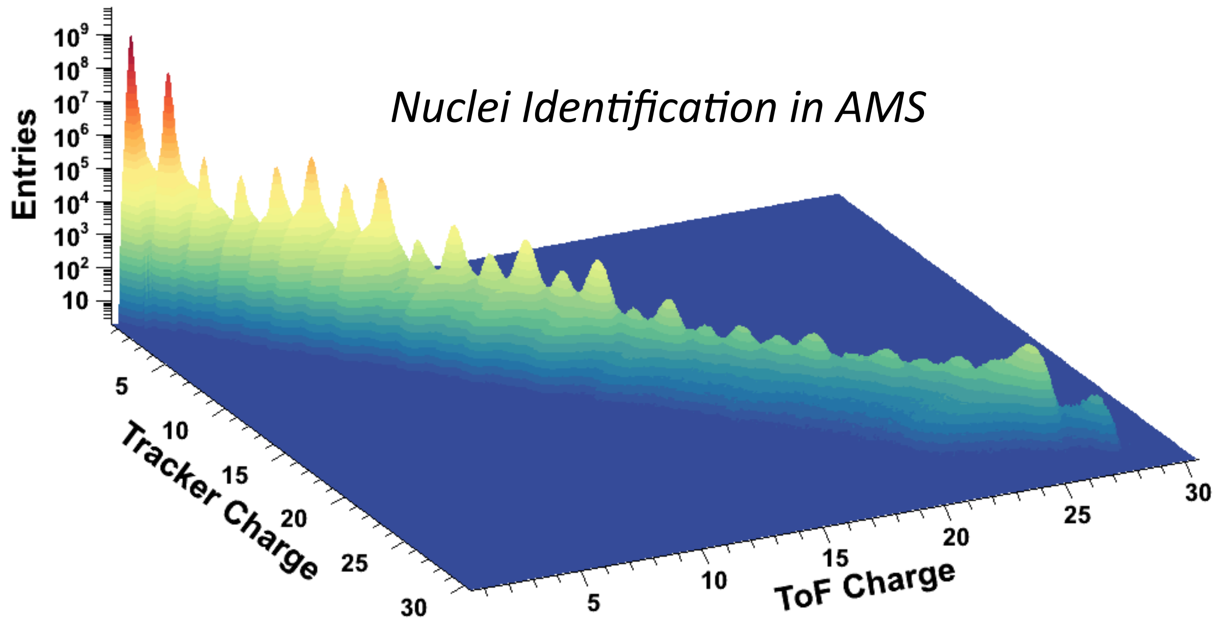


Figure 1.7: Hillas diagram indicating different classes of astrophysical objects capable of accelerating cosmic rays up to very high energies. The maximum energy that can be achieved while containing particles in the acceleration region depends on the size of the source and its magnetic field strength. (Adapted from [27].)

Cosmic-Ray Nuclei



Each cosmic-ray nucleus provides specific information:

- Protons and Helium are the most abundant charged particles in cosmic rays. Knowledge of the precise behavior of the spectrum is important to understand the origin, acceleration, and propagation of cosmic rays.
- Li, Be, B, … are produced by the spallation of cosmic rays in the interstellar medium: The flux of these secondaries or secondary/primary ratios (like B/C) are key measurements to understand propagation.
- Other primary (C,N,O,..) can be used to test the universality of propagation/acceleration.
- Precise knowledge of both primary fluxes and propagation mechanisms is mandatory to assess background (e^+,pbar,…) and expected signal for DM searches.