# Astroparticle experiment

## 1) Charged cosmic rays (CRs) and AMS-02 experiment

## 2) High-energy gamma rays: H.E.S.S. and Fermi-LAT

**Goal of the lectures**

- Selected topics and instruments in astroparticle physics
- Scientific debates (historical illustration with CRs)
- Complexity of data analysis (illustration with AMS-02)
- Variety of detection principles, 'research activities', etc.

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22 July 2019

# Astroparticle experiment 1

## Charged cosmic rays (CRs) and AMS-02 experiment




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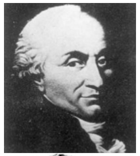
# Ionic conductivity of gas

Study of atmospheric electricity

**1785** – Charles Coulomb
*Charge loss ("electricity dispersion") occurs mainly through air*



**1879** – William Crookes
*Speed of discharge decreases with P: ionization of air is the direct cause*

Natural radioactivity

**1895** – Wilhelm Röntgen (Nobel 1901)
*Discovery of X-rays (or Röntgen rays)*

**1896** – Henri Becquerel, Marie & Pierre Curie (Nobel 1903)
*Discovery of spontaneous radioactivity*

**1897** – Joseph John Thomson (Nobel 1906)
*Discovery of electron*

**1900** – Henri Becquerel
$\beta$ *radioactivity = electrons*

**1903,1914** – Ernest Rutherford (Nobel 1908)
$\alpha$ *radioactivity = helium*
$\gamma$ *radioactivity = similar to X-rays but shorter wavelength*

End of 19th century – J.J. Thomson

*Electric conductivity of gasses increases with X-rays and radioactivity*

Theory of ionic conductivity of gasses

# Nature of the source of ions

**Start of 20th century**

- Radiation constantly ionizing the air
- Discharge of an electroscope explained by an insignificant number of ions in air

→ **What is the nature of the unknown source of ions?**

Electroscope designs, speed of leakage

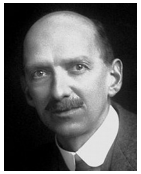
**1900 – J. Elster and H. Geitel**

Data: conductivity of air strongly fluctuates vs P and h

→ *radioactivity from Earth's crust + accumulation in atmosphere*

**1901 – C.T.R. Wilson (invented later the cloud chamber, Nobel 1927)**

Data: same speed of leakage for +/- charges, proportional to P



→ *"future [...] will show that formation of ions in air [...] is caused by radiation which arises out of our atmosphere to similarly X-ray or cathodic rays, but possesses considerably bigger penetrating ability"*

N.B.: Curie (1898,1899): "*it is necessary to imagine that all space is crossed by the beams similar to beams of the X-ray, but considerably more penetrating*"

… but then changed his mind

Data: speed of ionization in a tunnel, no reduction w.r.t. usual conditions

→ *"It is improbable therefore that ionization is caused by radiation passing through our atmosphere. Most likely, as has concluded Geitel, this is property of air"*

# Proof of an extraterrestrial radiation

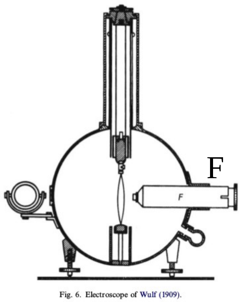
- **A decade of unrewarded efforts...**

  1902-1909 – Improvements of apparatus, data at ground, sea, mountain level... w/o shielding
  Review of Kurtz (1909)
    - ~~γ-radiation from the earth's crust;~~
    - ~~radiation coming from the atmosphere;~~
    - radiation from space.

  Resolutely rejected as improbable!

- **Ionisation constant with altitude (whereas decrease expected)**

  1909-11 – A. Gockel: 3 balloon flights @ 4500 m (unpressurised detector)
  1909-10 – T. Wulf: electroscope + measurements at Eiffel tower
  1909-12 – D. Pacini: underwater (require non-terrestrial radiation)



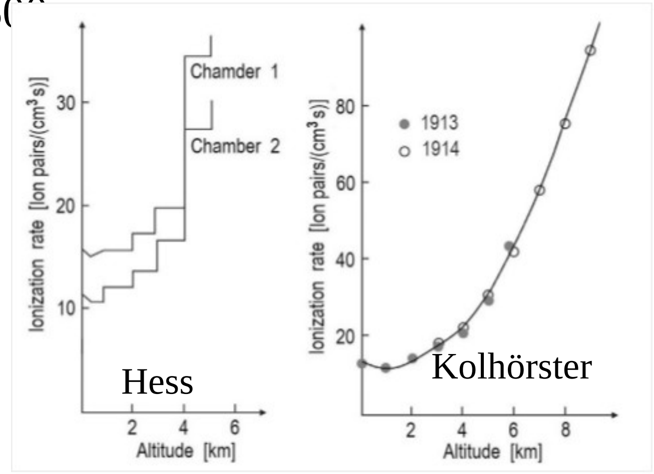

Electroscope: speed of discharge related to distance change between the wires (microscope F)

- **Proof of existence: V. Hess (1911-1912)** → *"ultra-gamma radiation"*

  1911: First measure of γ-ray attenuation in air, predict absorption for d≥5
  → *"there should be other source of a penetrating radiation in addition to γ-radiation from radioactive substances in earth crust"*

  1912: flights at ≠ times, ≠ atmospheric conditions (wind, pressure, T)
  [3 Wulf electroscopes: (non-)hermetic, w/o shield (sensitive to γ-rays)]
  → *"can be explained by the assumption that radiation of the big penetrating ability is coming into our atmosphere from above and even its bottom layers"*

**… and confirmation by Kolhörster (1913-1914)**



# Characterization of the radiation

- **First World War... delayed interest until 1921 (USA), 1923 (Germany)**

- **Another period of doubt... [Millikan = Nobel 1923]**

  1922 – Millikan & Bowen: unmanned balloons (15 500 m reached)
  → High altitude radiation (10 km), but 4x smaller than expected

  1923 – Millikan: absorption factor of high-altitude radiation in lead
  → “*The radiation for the most part nevertheless has a local origin*”

  Pushed for alternative explanation
  - High altitude radioactive pollution
  - Particle acceleration up to high energies during thunderstorms

  1926 – Millikan & Cameron
  → *“These rays do not occur from our atmosphere and consequently can be rightfully named by **‘cosmic rays’**”*

- **Another heated debate: neutral (Millikan) or charged (Compton) particles?**

  1930s

  - Latitude surveys (Clay, Compton, Rossi...) + Störmer’s theory (1910-1911)
    → cosmic rays are charged particles

  - West–East CR asymmetry (Johnson, Seidl, Burbury, Fenton)
    → the largest part of primary CR are positively charged particles

# Human nature and ethics

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- **Another heated debate: neutral (Millikan) or charged (Compton) particles?**

  Clay (discoverer of latitude effect in 1927): "*Mr Millikan [...] is violating the truth, as he does, for his own profit, without any scruples*"

  Alvarez (Nobel 1968, PhD student of Compton) on Millikan: *"First of all, I do not believe latitude effect, but if you really have this effect, then I first discovered it"*


The New York Times

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

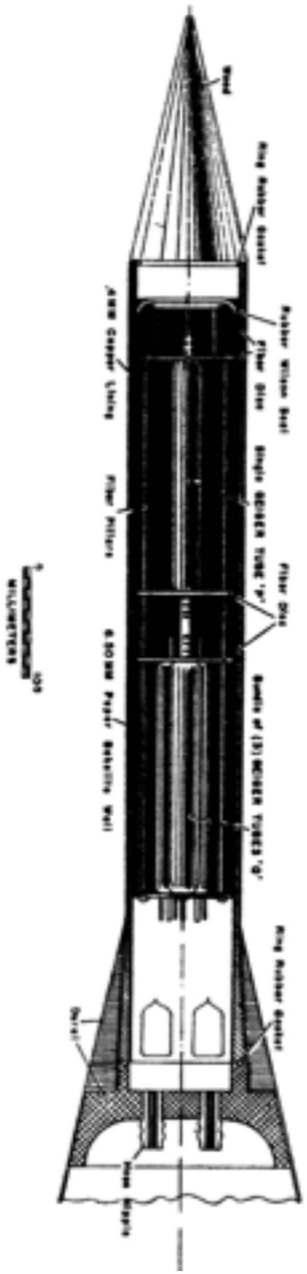
New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

*CR Romancing: The Discovery of the Latitude Effect and the Compton-Millikan Controversy*
Historical Studies in the Physical and Biological Sciences 19, No. 2 (1989) 211-266
M. De Maria and A. Russo

*The Discovery of CRs: Rivalries and Controversies between Europe and the US*
Historical Studies in the Physical and Biological Sciences 22 (1991) 165-192
M. De Maria, M. G. Ianniello and A. Russo

# Opening the space age

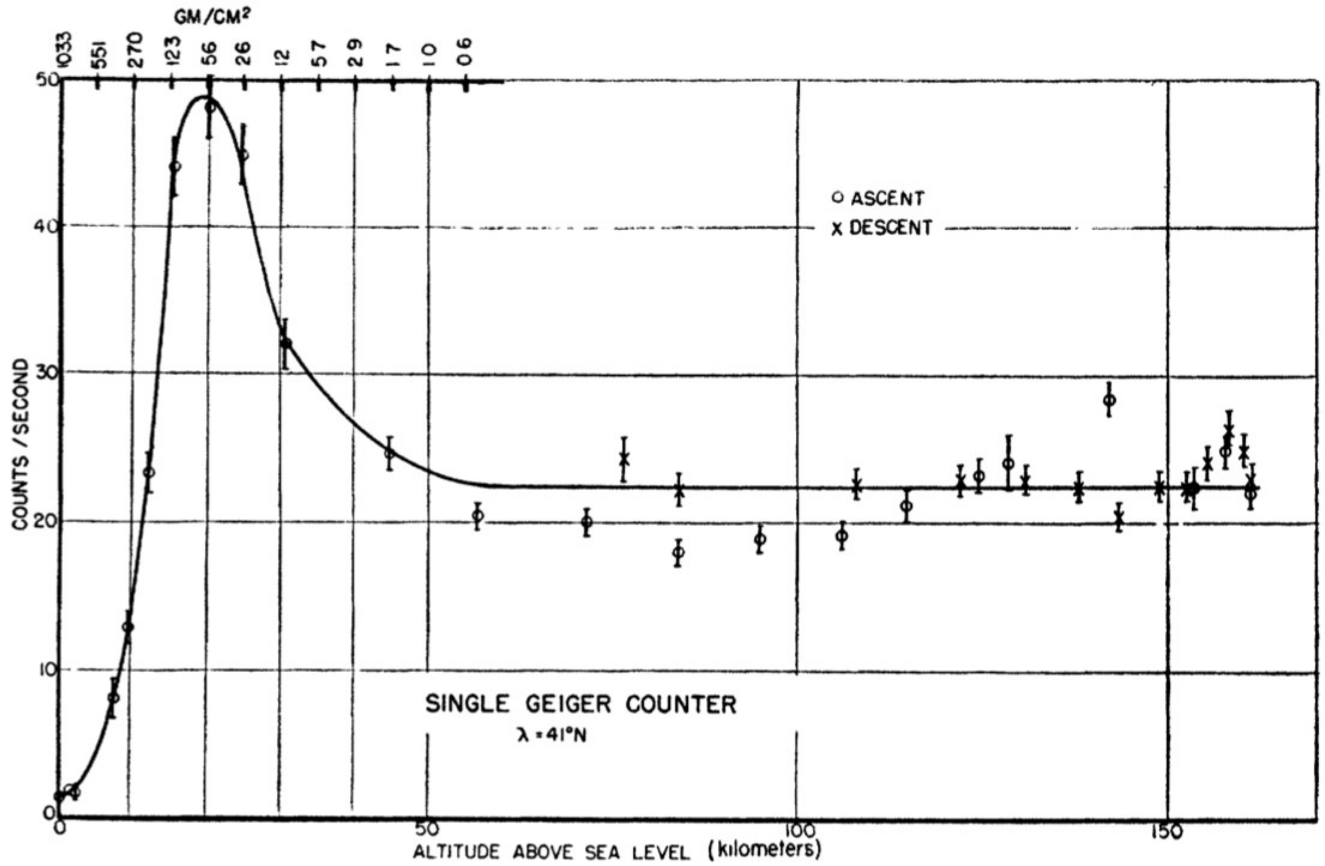
PHYSICAL REVIEW VOLUME 73, NUMBER 3 FEBRUARY 1, 1948



## 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)



I. Cosmic ray discovery

**II. Cosmic ray puzzle: sources, transport...**

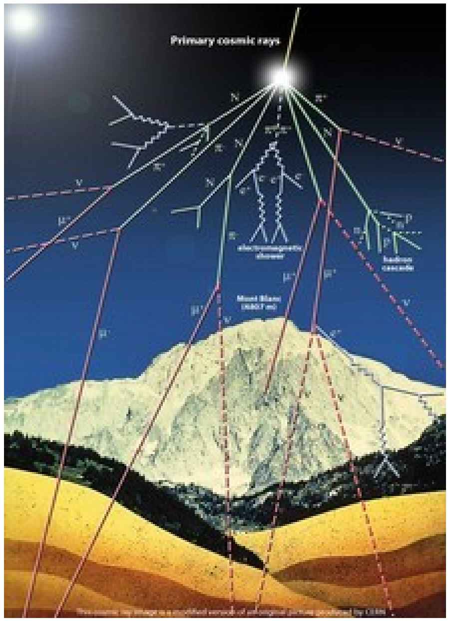
III. CR experiments: overview

IV. AMS experiment: data analysis

V. Recent results

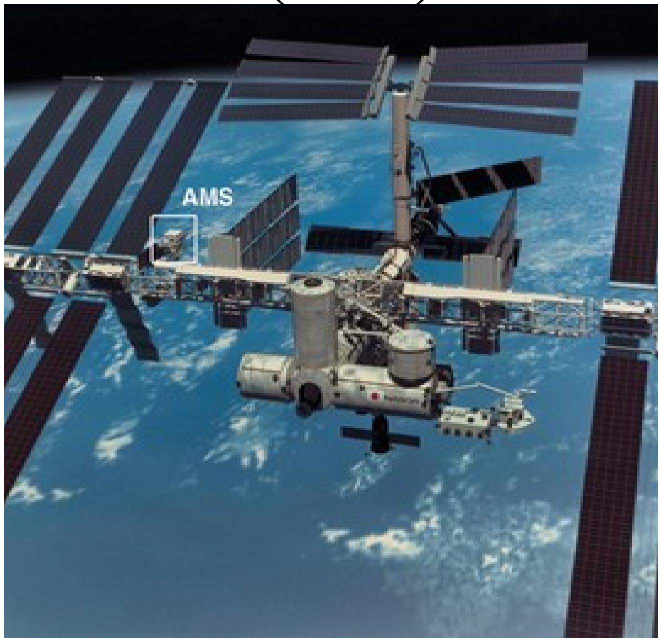
# Experimental milestones

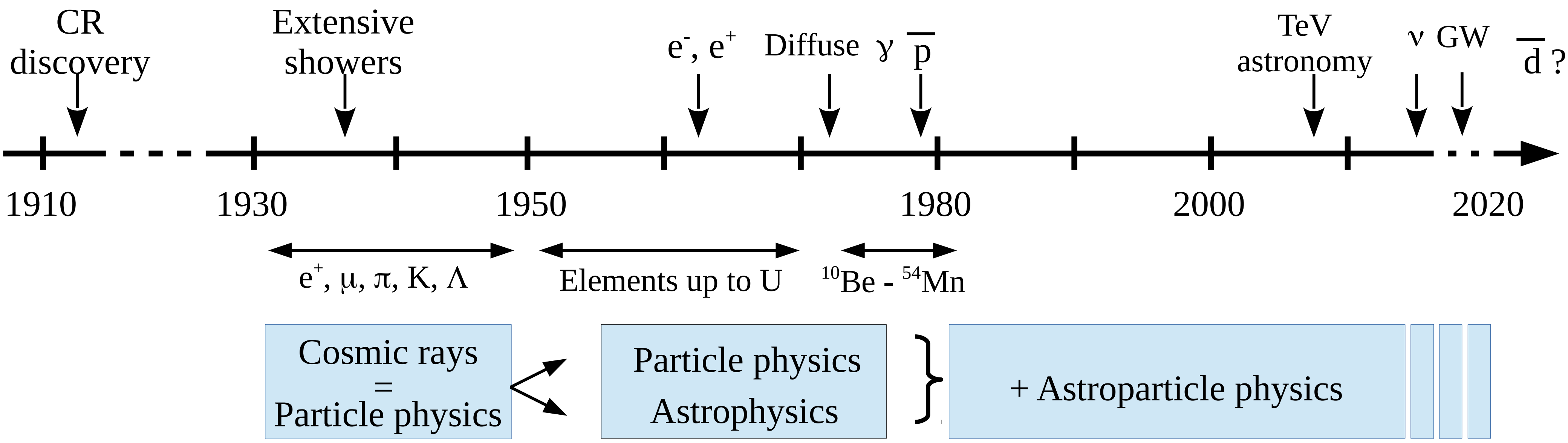
Mountain altitude < 5 km




CREAM balloon ~ 40 km

AMS-02 (on ISS) ~ 300 km



# Charged vs neutral cosmic rays

## Two categories

- *Neutral species*
  - ✓ Gamma-rays
  - ✓ Neutrinos

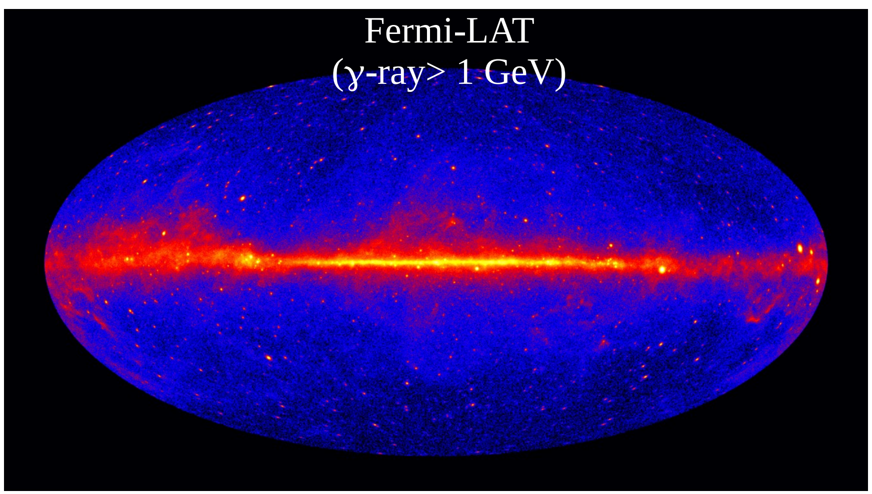
Multi-messenger approaches
Multi-wavelength observations

- *Charged species*
  - ✓ Leptons
  - ✓ Nuclei

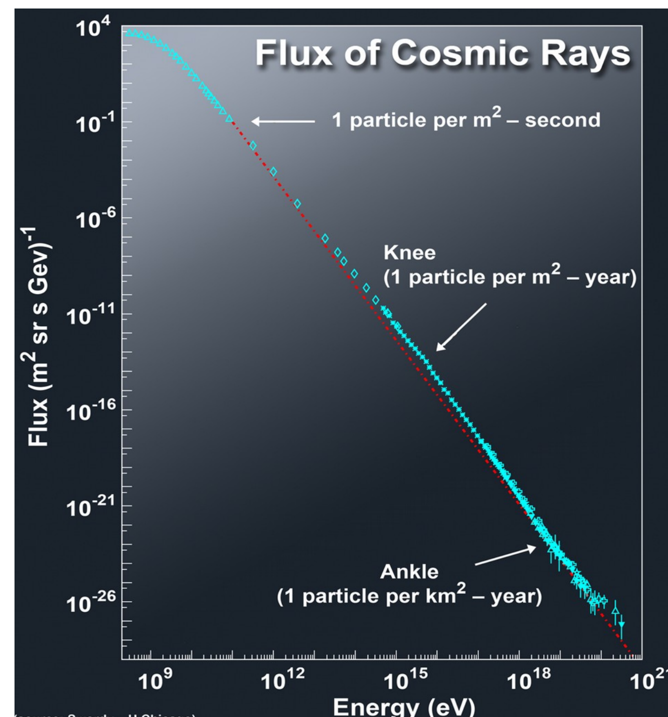
## Observation types

→ *Astronomy*
point-like, extended, diffuse emissions

→ *Spectra & anisotropy maps*
(diffusion/deflection in B)

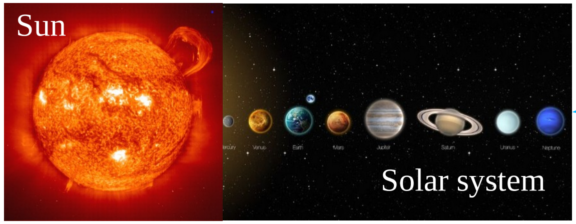


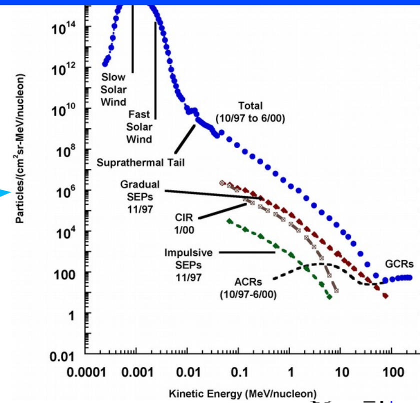

30 orders of magnitude

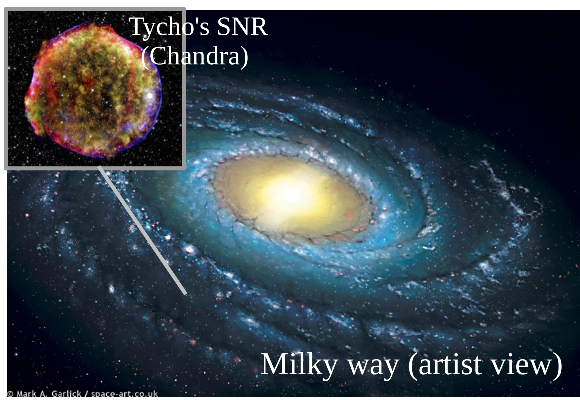


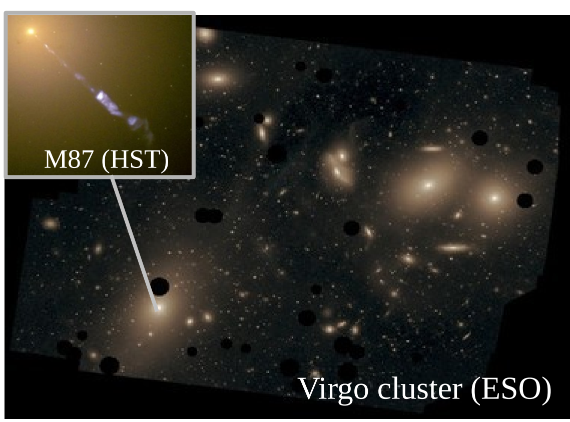

12 orders of magnitude

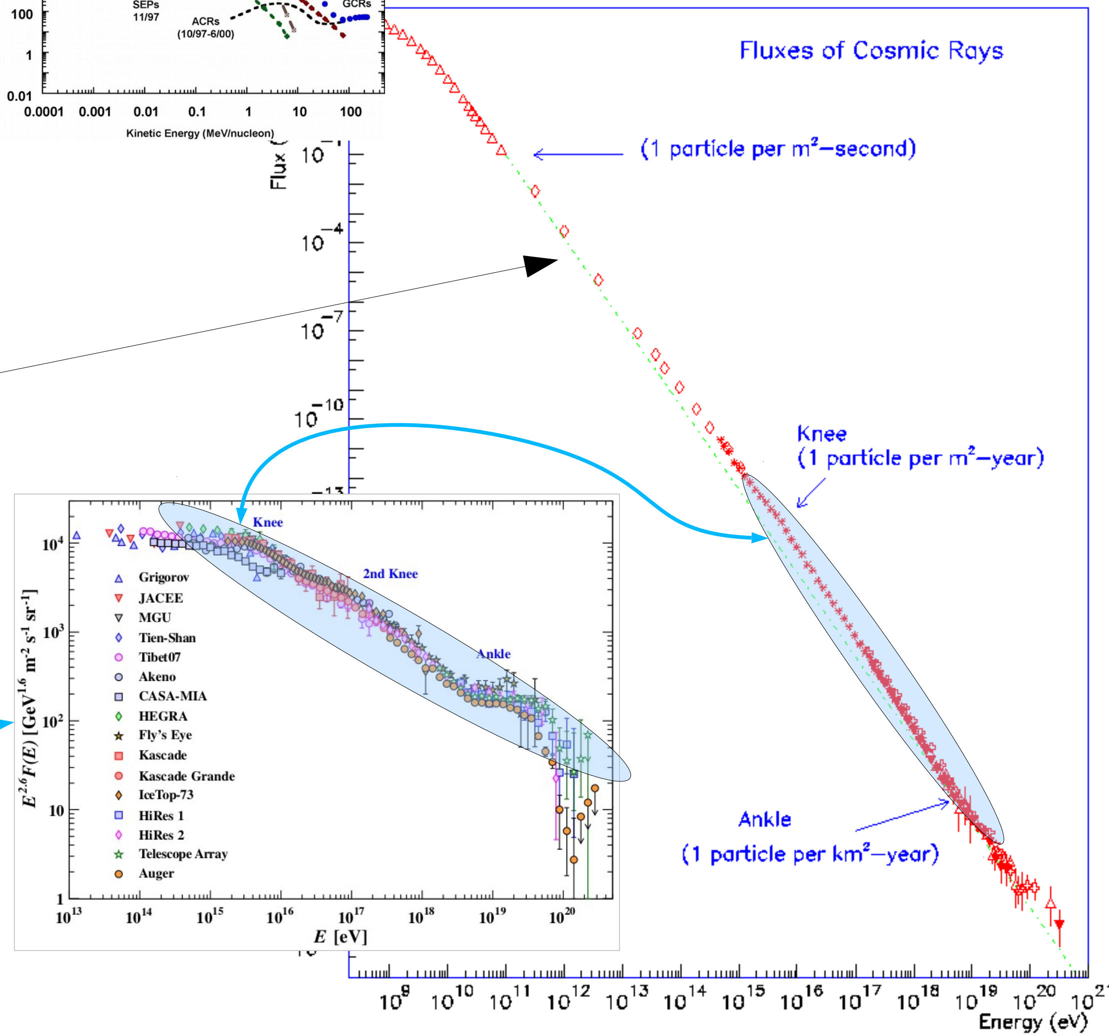
# Cosmic ray sources?



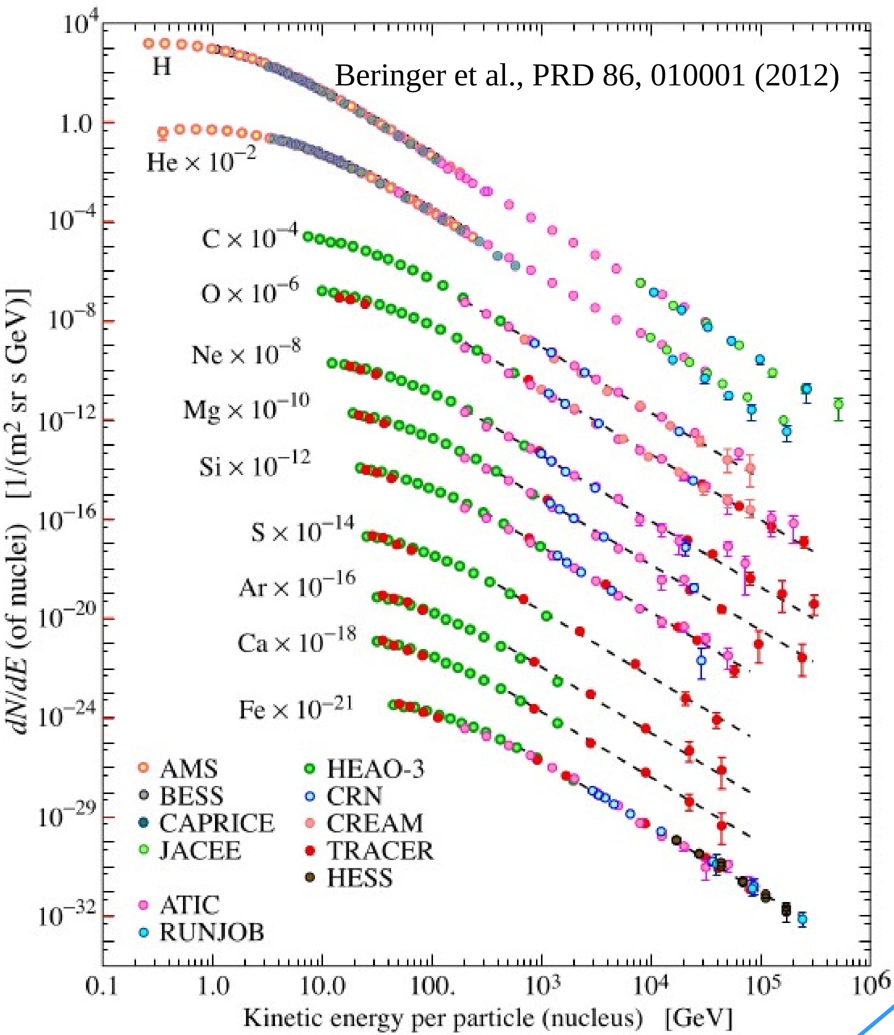

**Transition galactic vs extragalactic**

→ CR sources and transport?

→ Origin of spectral features, composition, anisotropy?

# Galactic CR data ($E \sim 10^8 - 10^{15}$ eV)

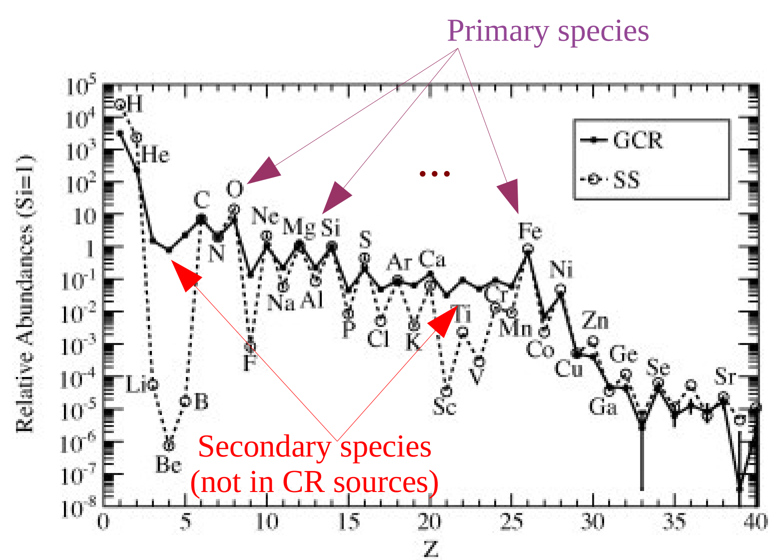
Elemental spectra




→ Origin of 'universal' power law ($E^{-2.8}$)?
→ Abundances of elements/isotopes?
→ CR anisotropy ($\delta < 10^{-3}$)

## Energy units

| E type | Expression | Unit | *Natural for* |
|---|---|---|---|
| Rigidity | $R = \frac{pc}{Ze} = \frac{p}{Z} = r_l B$ | [GV] | *Magnet (AMS)* |
| Total E | $E^2 = p^2 + m^2$ | [GeV] | *Calorimeter (CREAM)* |
| Ek per nucleon | $E_{k/n} (= T) = \frac{E_k}{A}$ | [GeV/n] | *Nuclear reaction* |

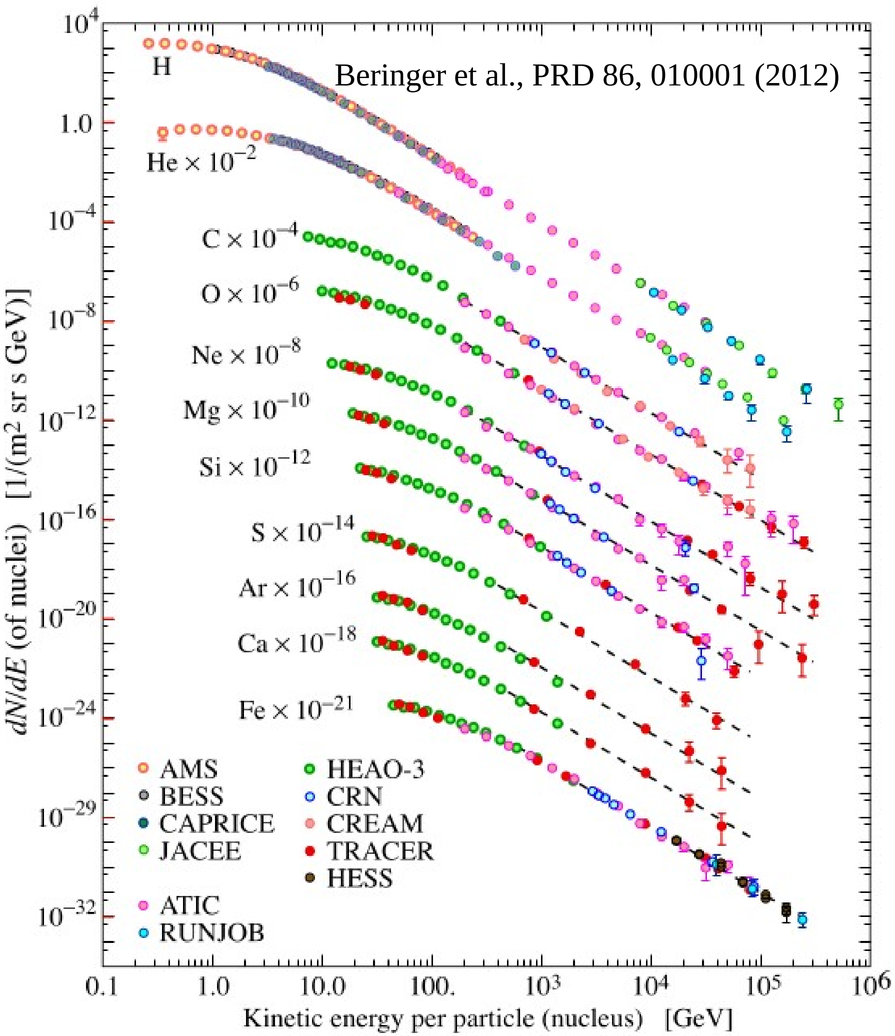



Bauch et al., AdSR 53 (2014)

**Antiprotons, e+, e-, gamma: primary or secondary?**

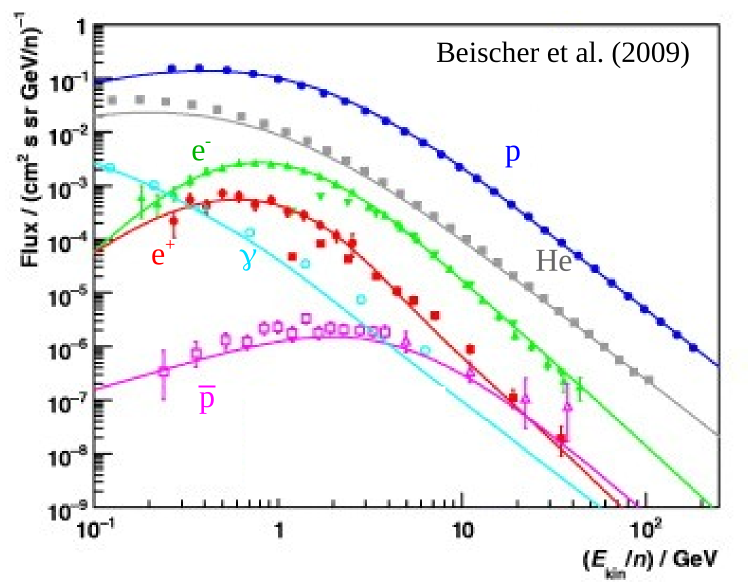
# Galactic CR data ($E \sim 10^{8}$-$10^{15}$ eV)

Elemental spectra



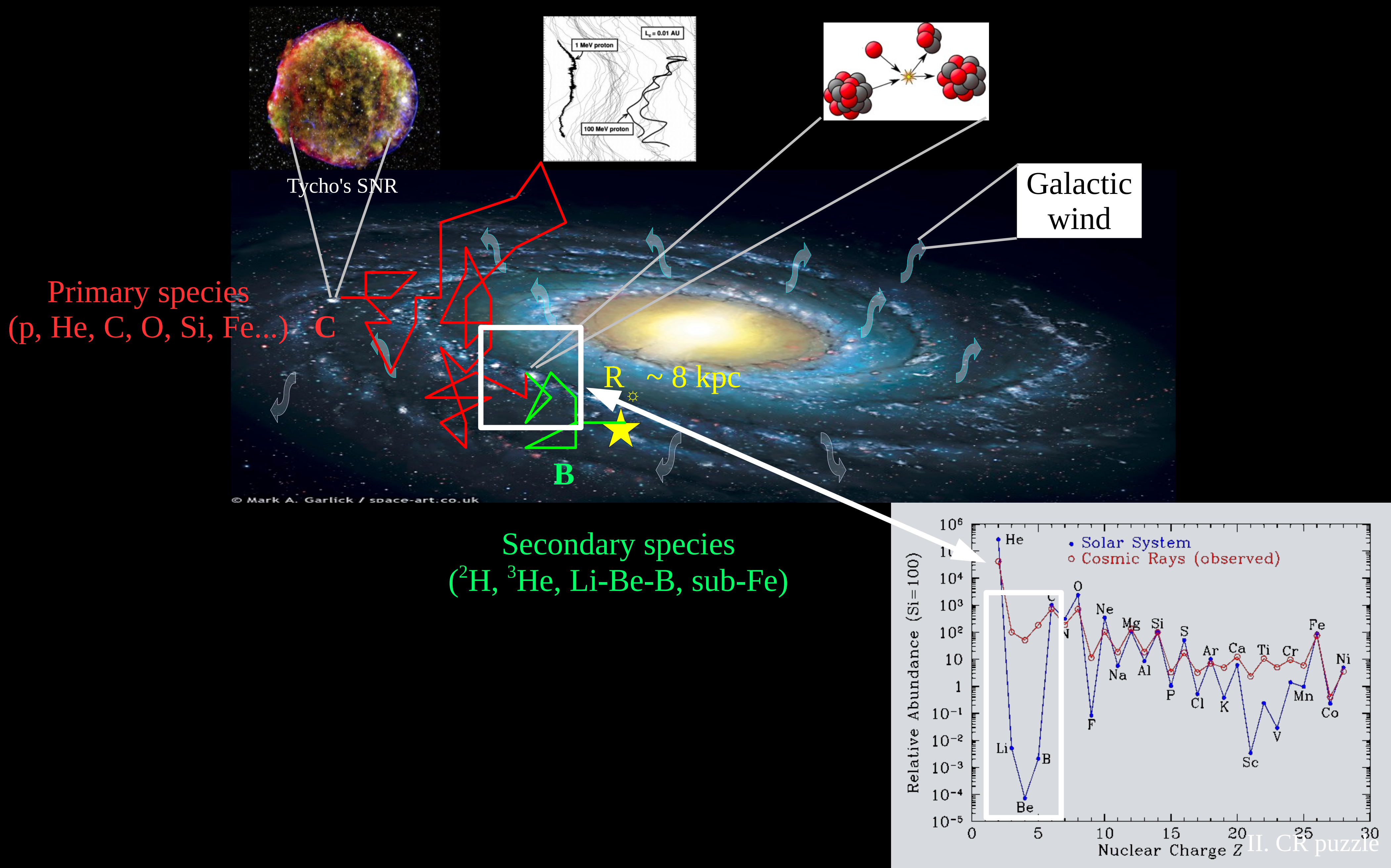

→ Origin of 'universal' power law ($E^{-2.8}$)?
→ Abundances of elements/isotopes?
→ CR anisotropy ($\delta < 10^{-3}$)

Protons and He
*vs*
diffuse γ-rays, pbar, $e^-$ and $e^+$

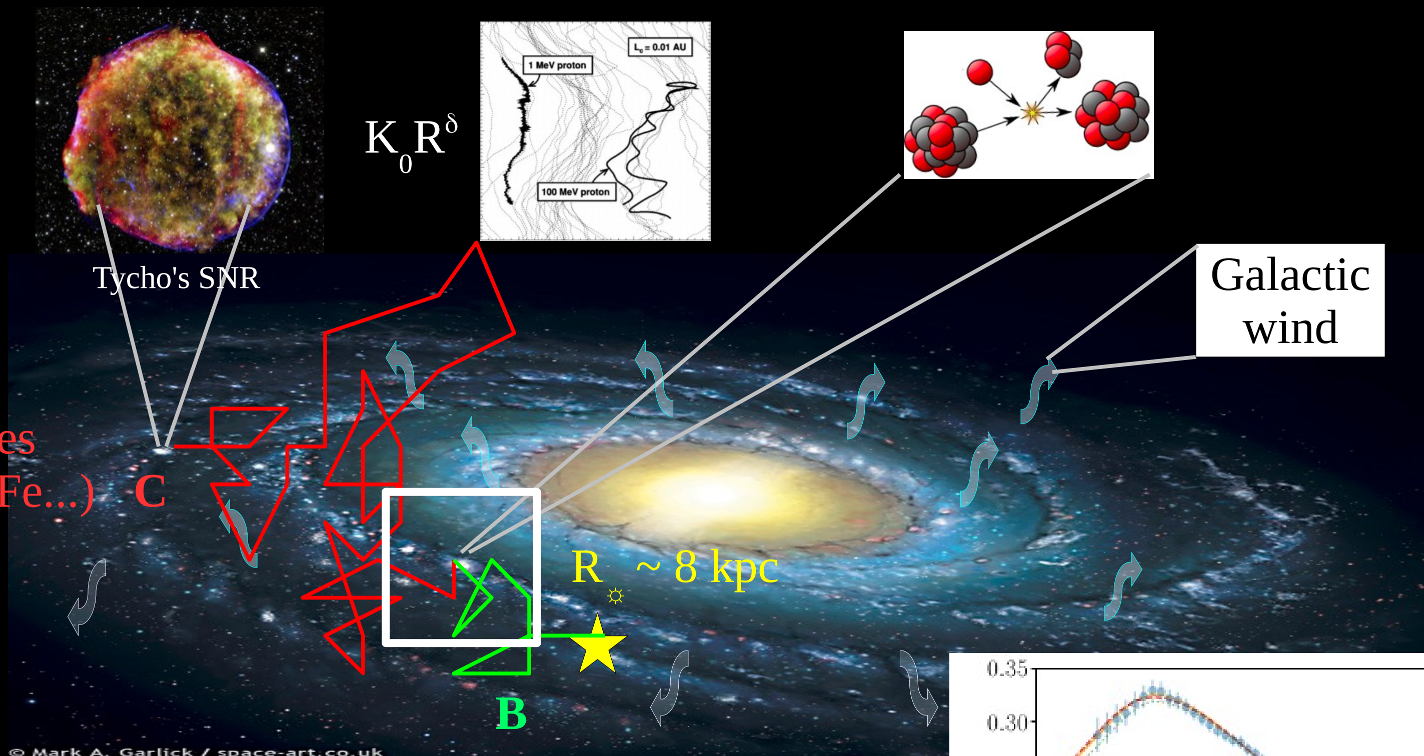



N.B.: rare CRs produced by H,He + ISM
→ How well do we know the astro. production?
→ Is it a good place to look for dark matter?

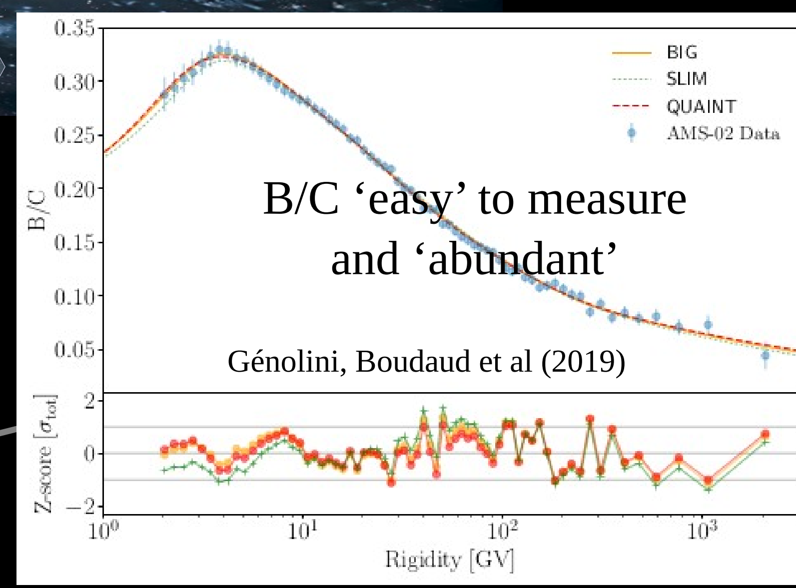
# Nuclear interactions and abundances



# Diffusion: secondary-to-primary ratio




Secondary species
($^2$H, $^3$He, Li-Be-B, sub-Fe)




B/C 'easy' to measure and 'abundant'

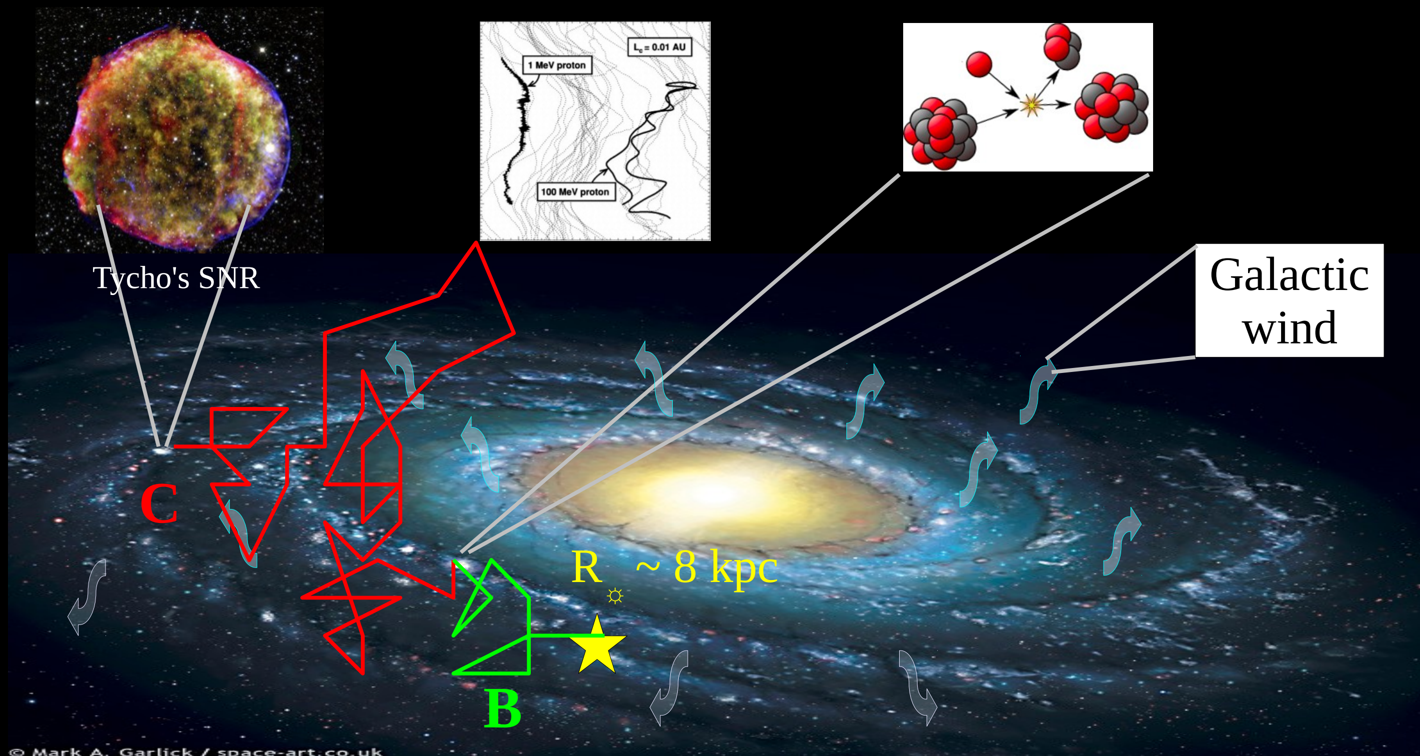
Génolini, Boudaud et al (2019)

Primary species P: source/diffusion ~ $R^{-(\alpha+\delta)}$

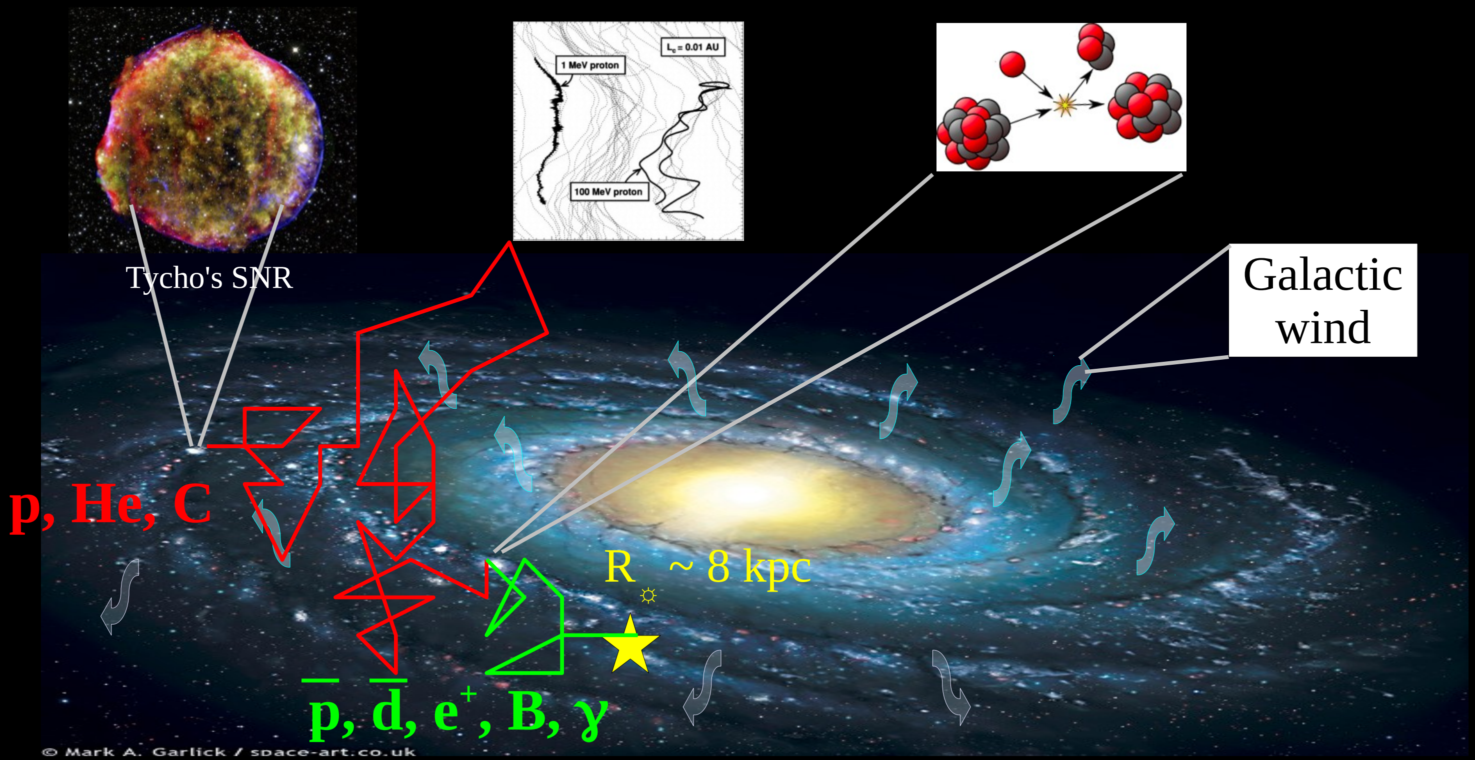
Secondary species S: ($\sigma^{P\rightarrow S}$ . P)/diffusion ~ $R^{-(\alpha+2\delta)}$

**→ Secondary to primary ratio ~ $\sigma^{P\rightarrow S}$ . $R^{-\delta}$**

# Dark matter search: (i) tranport calibrated on B/C

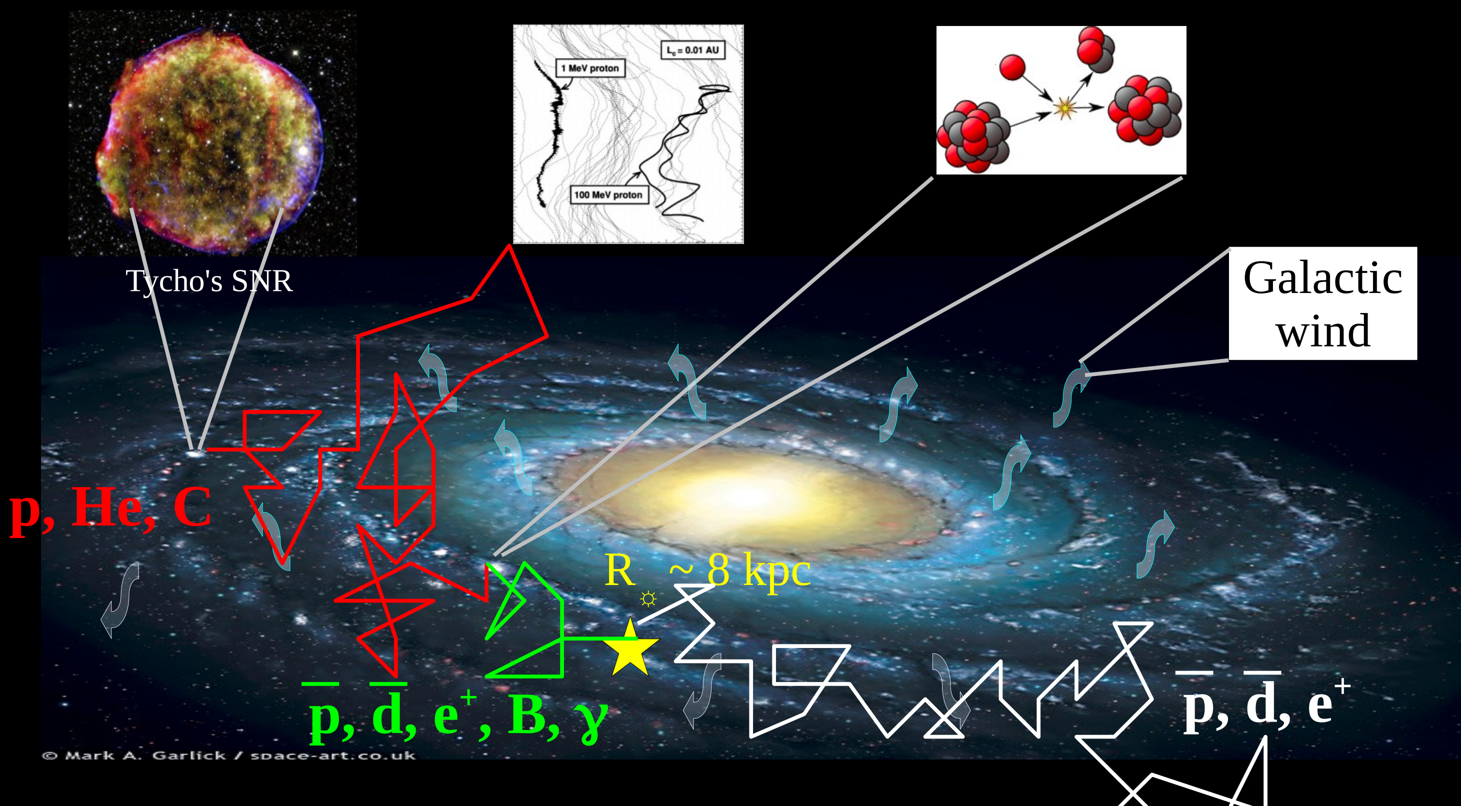


# Dark matter search: (ii) “background” for rare channels




→ Same propagation history for B/C, or pbar/p
(apply previously derived parameters)

# Dark matter search: (iii) “signal” for rare channels



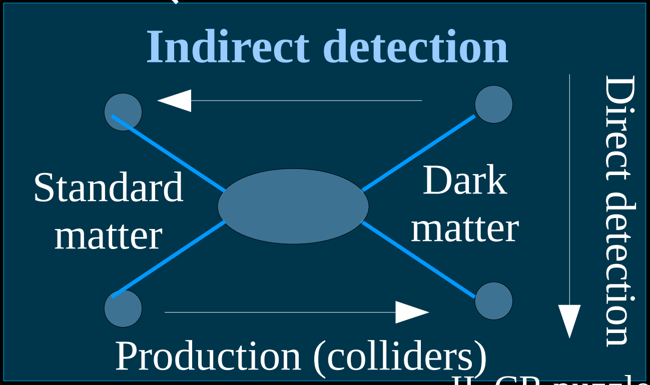

→ Same transport but different origin (from DM halo)

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

→

**Milky-Way dark matter halo**
- ~ spherical halo
- radius ~300 kpc

→

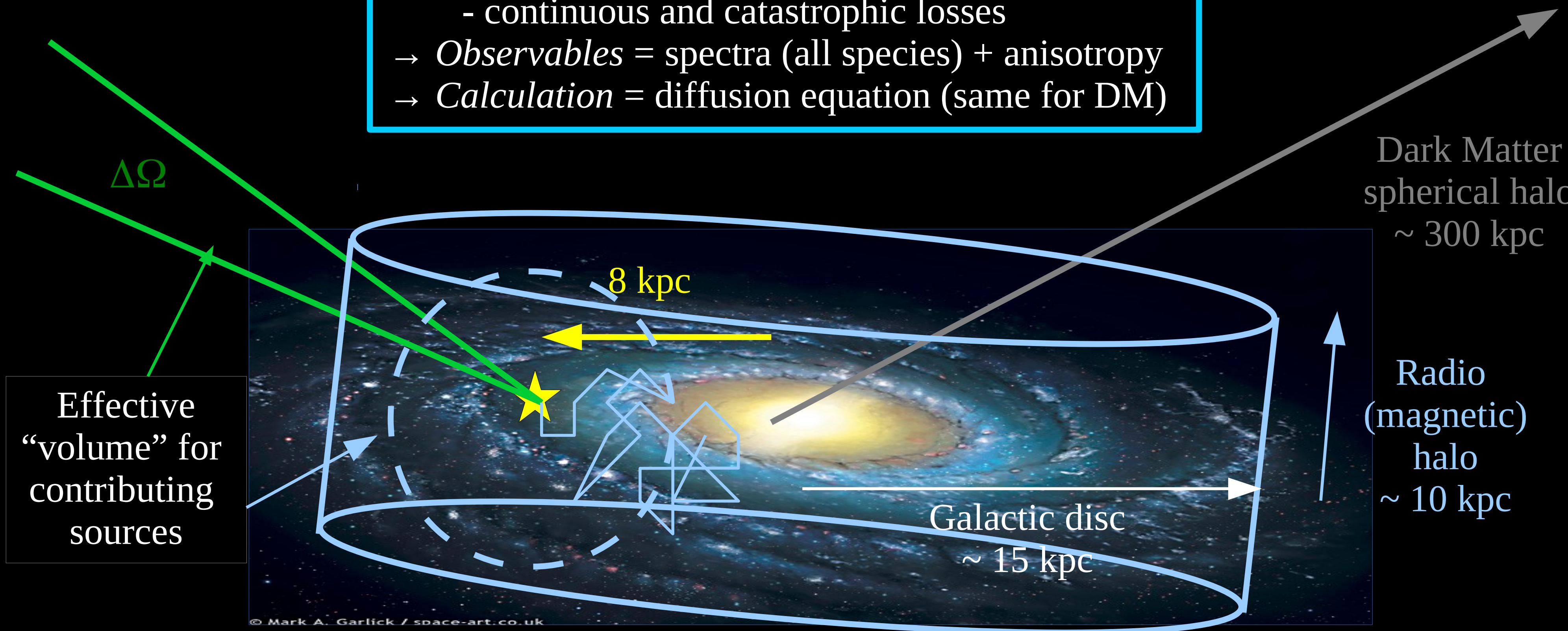


# Indirect DM search: gamma-ray astronomy

**Charge particles**

- diffusion in turbulent B
- continuous and catastrophic losses

→ *Observables* = spectra (all species) + anisotropy
→ *Calculation* = diffusion equation (same for DM)




**Neutral particles**

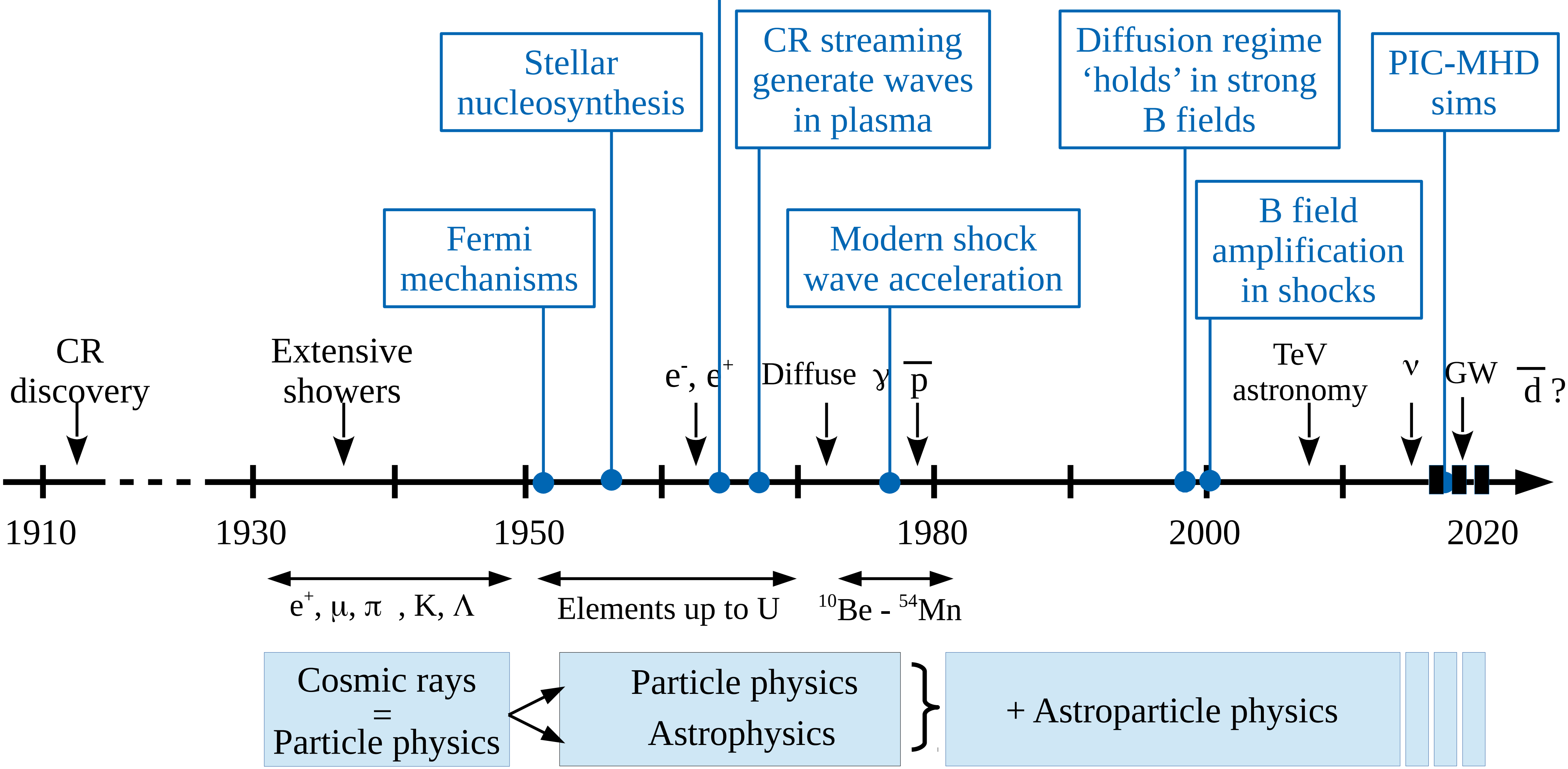
- propagate in straight line
- absorption ~ negligible at GeV-TeV in the Galaxy

→ *Observables* = skymaps + spectra
→ *Calculation* = line-of-sight integration on ΔΩ

# Theoretical milestones

Transport parameters: $K_0$ and $\delta$ (diffusion normalisation and slope), L (diffusive halo size), $V_c$ (convection)

$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Transport (diff+conv)}} N^j + \overbrace{(\Gamma_{\rm rad}+\Gamma_{\rm inel})}^{\text{catastrophic losses}}\, N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j\frac{\partial N^j}{\partial E}\right)}^{\text{E gain/losses}} = \overbrace{Q^j(E,\vec{r}) + \sum_{m_i>m_j}\Gamma^{i\to j}N^i}^{\text{Sources (prim+sec)}}$$



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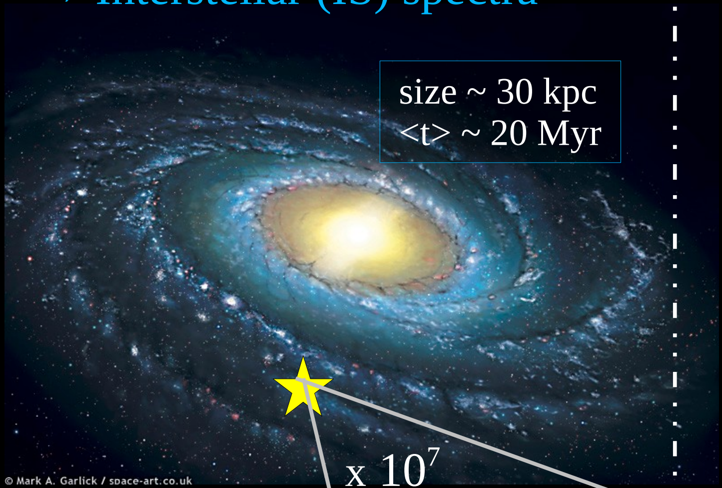
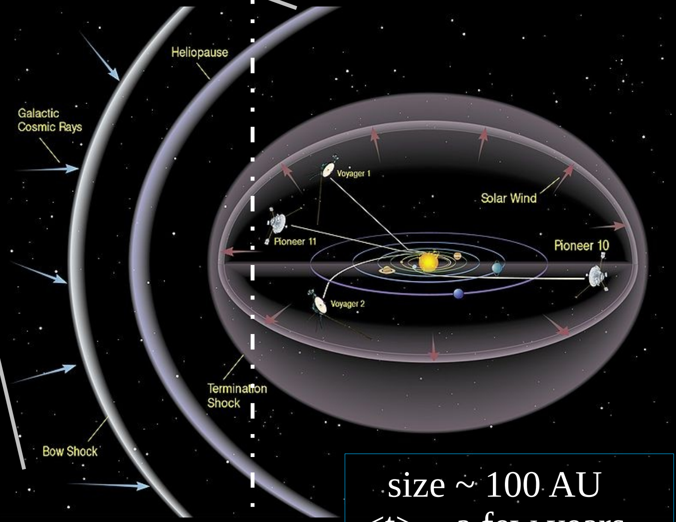
# Last steps before detection… Solar modulation

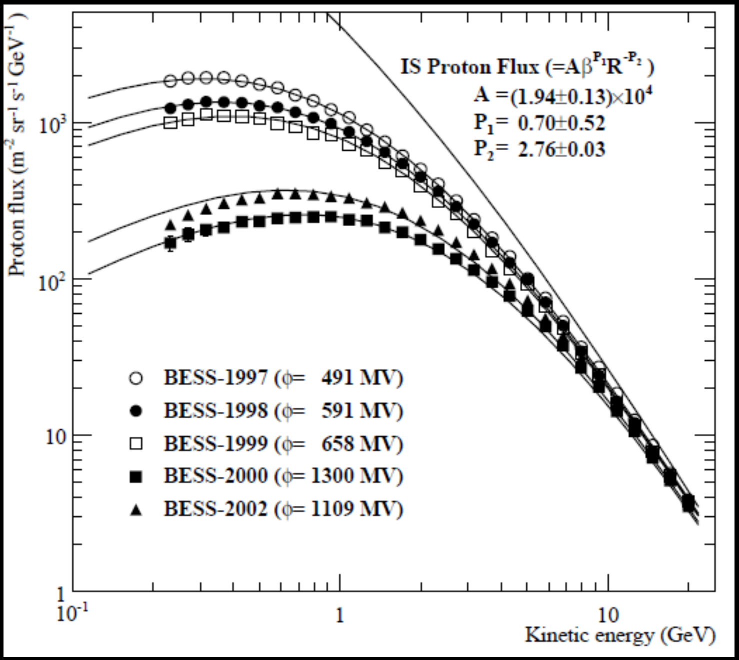
1. Transport in the Galaxy
→ Interstellar (IS) spectra




x $10^7$




size ~ 100 AU
<t> ~ a few years

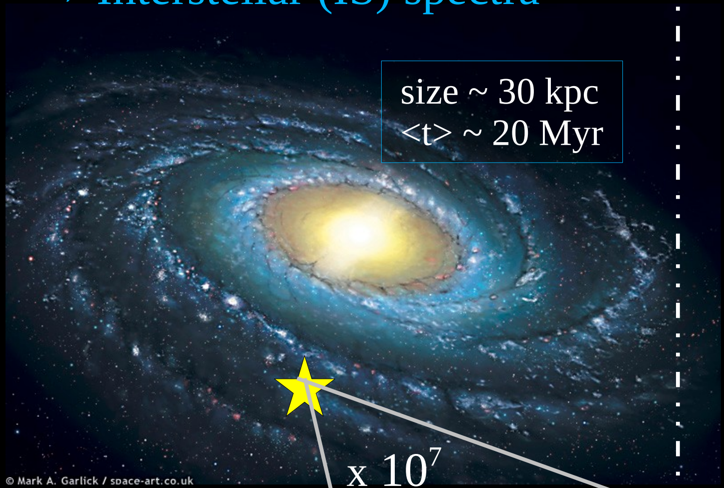



2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)

**[time-independent]** **[time-dependent]**

# Last steps before detection… R cutoff

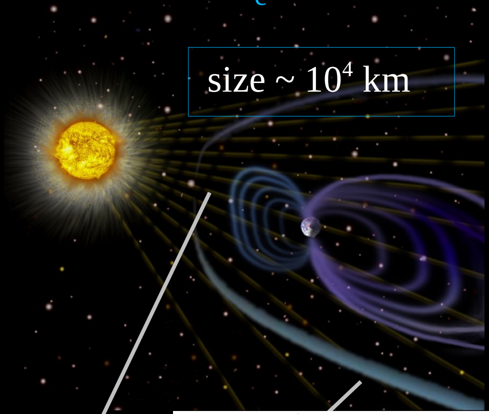
1. Transport in the Galaxy
→ Interstellar (IS) spectra




size ~ 30 kpc
<t> ~ 20 Myr

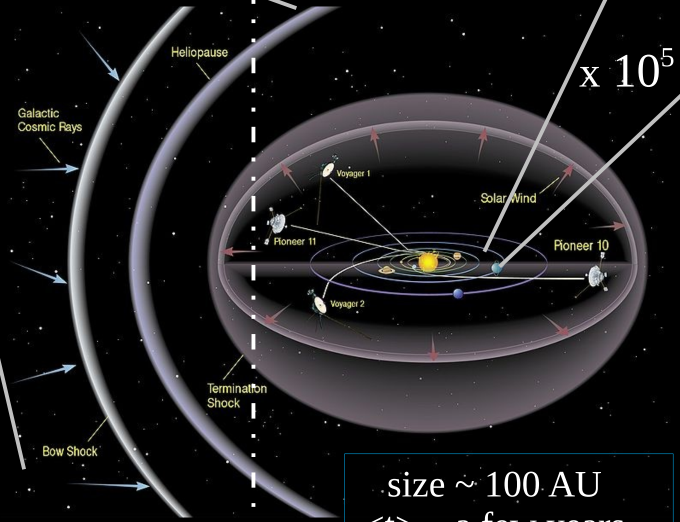
x $10^7$

3. Earth magnetic shield
→ Cut-off rigidity $R_c$ (at Earth)



size ~ $10^4$ km

x $10^5$




size ~ 100 AU
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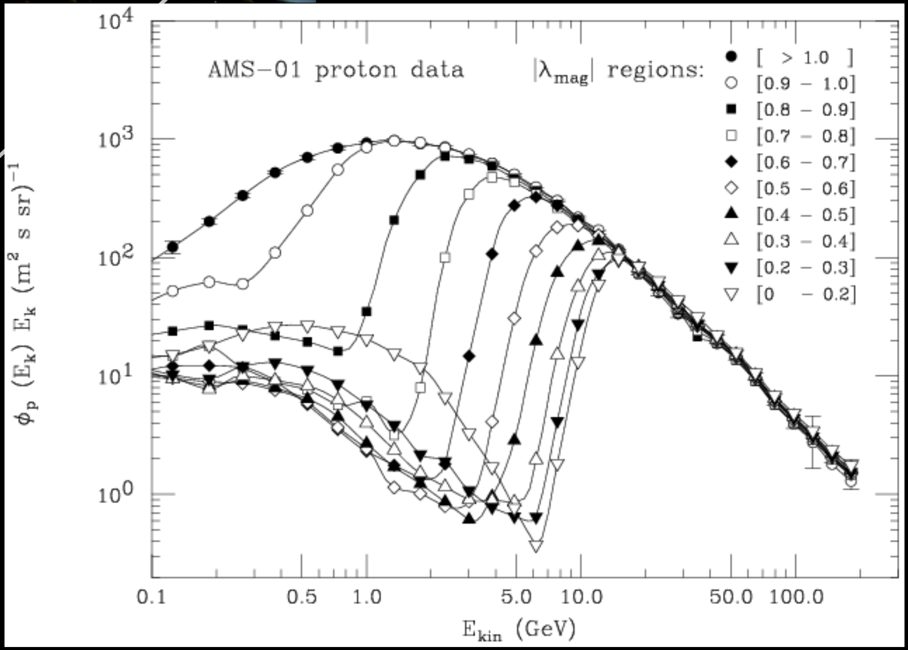
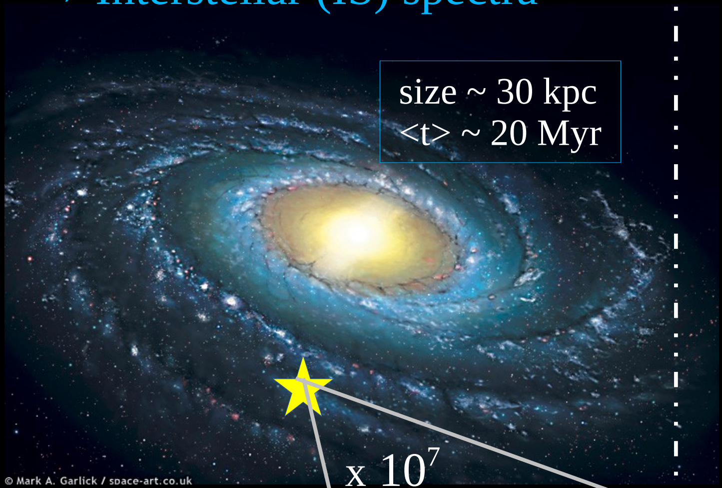



2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)

**[time-independent]** **[time-dependent]**

# Last steps before detection… atmosphere

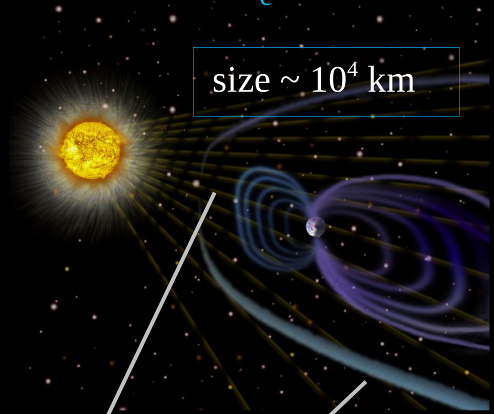
1. Transport in the Galaxy
→ Interstellar (IS) spectra




size ~ 30 kpc
<t> ~ 20 Myr

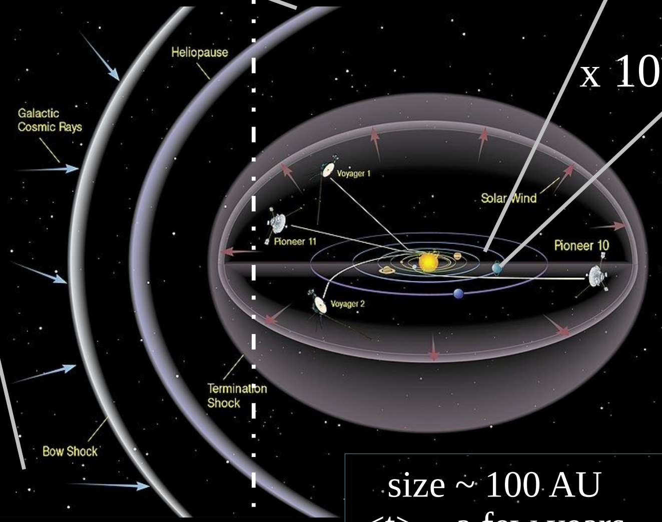
x $10^7$

3. Earth magnetic shield
→ Cut-off rigidity $R_c$ (at Earth)



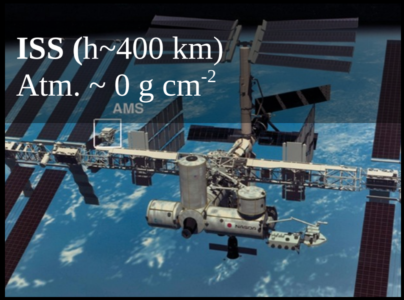
size ~ $10^4$ km

x $10^5$



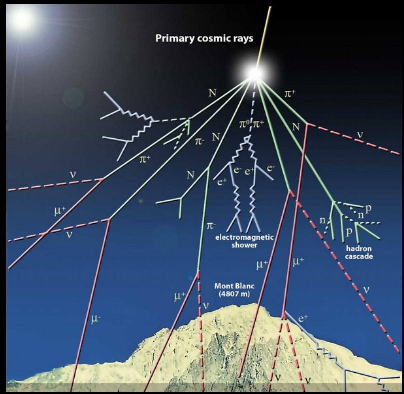

size ~ 100 AU
<t> ~ a few years

2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)




**ISS** (h~400 km)
Atm. ~ 0 g $cm^{-2}$

**Balloon** (h~40 km)
Atm. ~ 5 g $cm^{-2}$




**Neutron monitor** (h<2 km)
Atm. ~ 600-1000 g $cm^{-2}$

4. Atmosphere
→ CR showers

**[time-independent]**

**[time-dependent]**

# Detection: direct vs indirect

**“Direct” CR detection** (< $10^{15}$ eV ~ PeV)

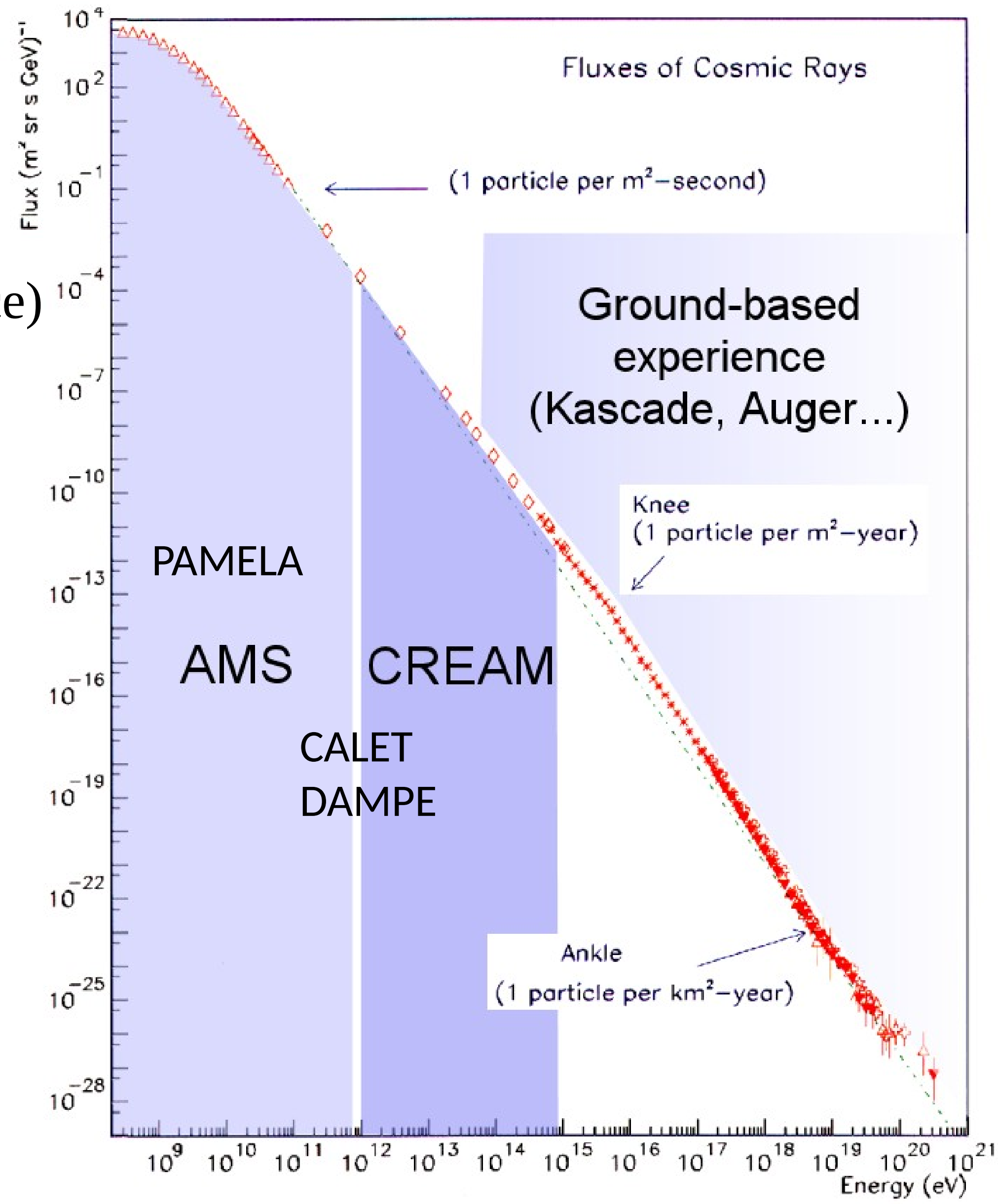
- Detectors “above” atmosphere (balloon or space)
- “Particle physics”-like detectors

→ Identification of CR nature and energy

**“Indirect” CR detection** (> $10^{15}$ eV)

- Ground-based detectors
- Use atmosphere as “calorimeter”
- Measure shower properties

→ Reconstruct CR most likely nature and energy



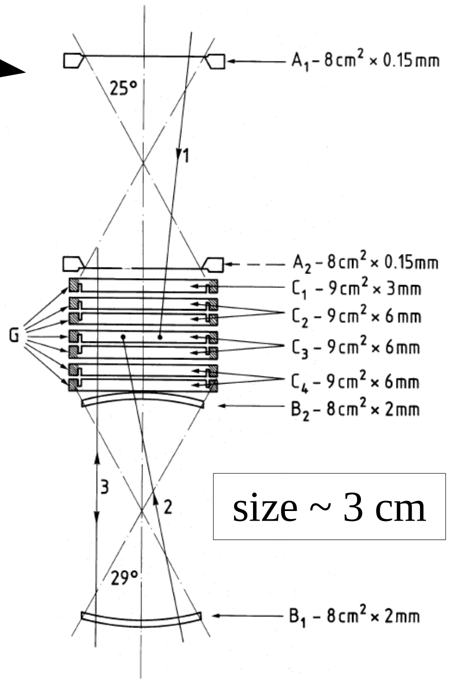
# Major GCR experiments

Balloon-borne experiments

Magnetic Spectrometer
« Calorimeter »

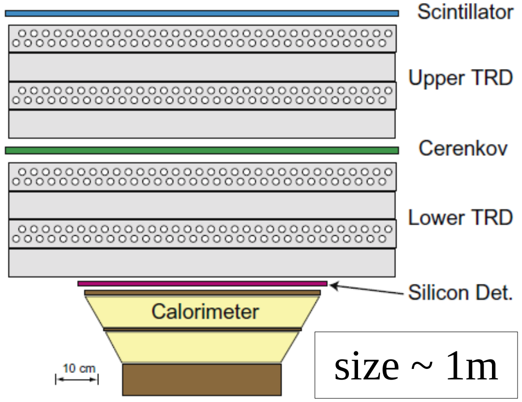
Experiments in space

Voyager (1976-...)
HEAO3 (1979-1981)




size ~ 3 cm

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




size ~ 1m

AMS01 (1998)
FERMI (2008-...)
PAMELA (2006-2016)
AMS02 (2011-...)
CALET (2015-...)
DAMPE (2015-...)
ISSCREAM (2017-2019)
ALADINO, AMS-100 (2050)?

→ slides adapted from L. Derome (LPSC)

**Installed on ISS in May 2011**

- → Circular orbit, 400 km, 51.6°
- → Continuous operation 24/7
- → Average rate ~700 Hz (60 millions particles/day)

**More than 100 billion events so far!**

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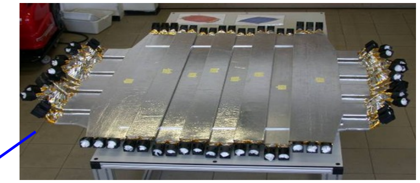
**More than 100  billion events so far!**

# A(lpha) M(agnetic) S(pectrometer)

A TeV precision, multipurpose spectrometer in space.

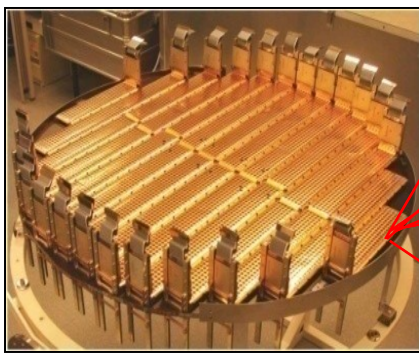
**TRD**
**Identify $e^+$, $e^-$**

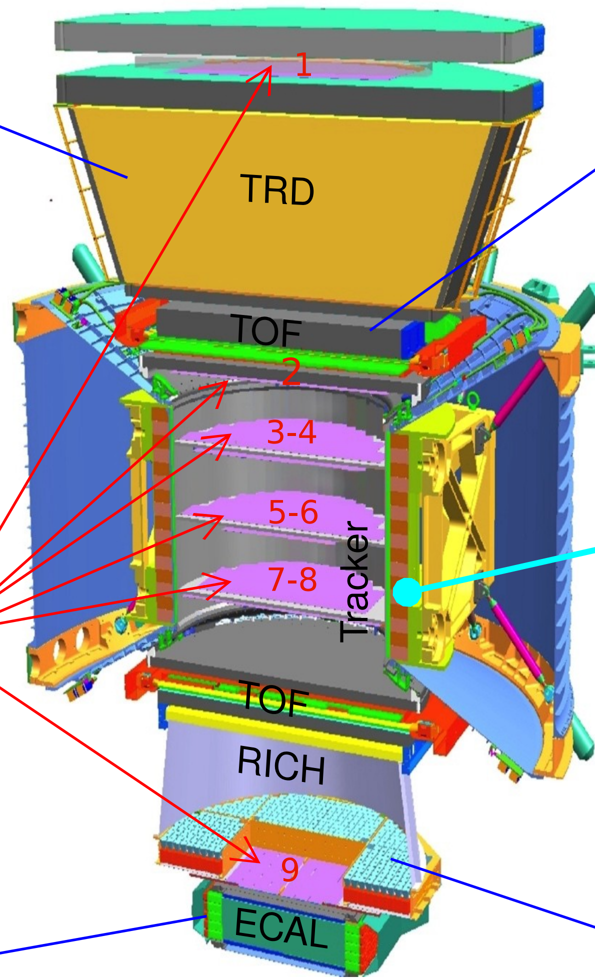
**TOF**
**Z, β**



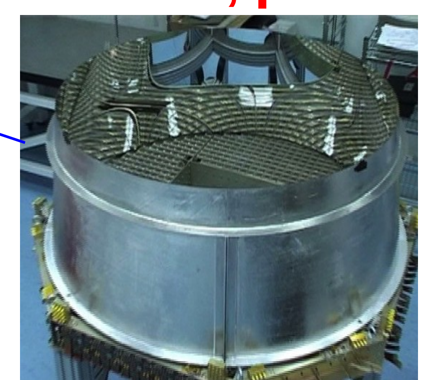
**Magnet**
**R, ±Z**

**Silicon Tracker**
**Z, p**






**RICH**
**Z, β**



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

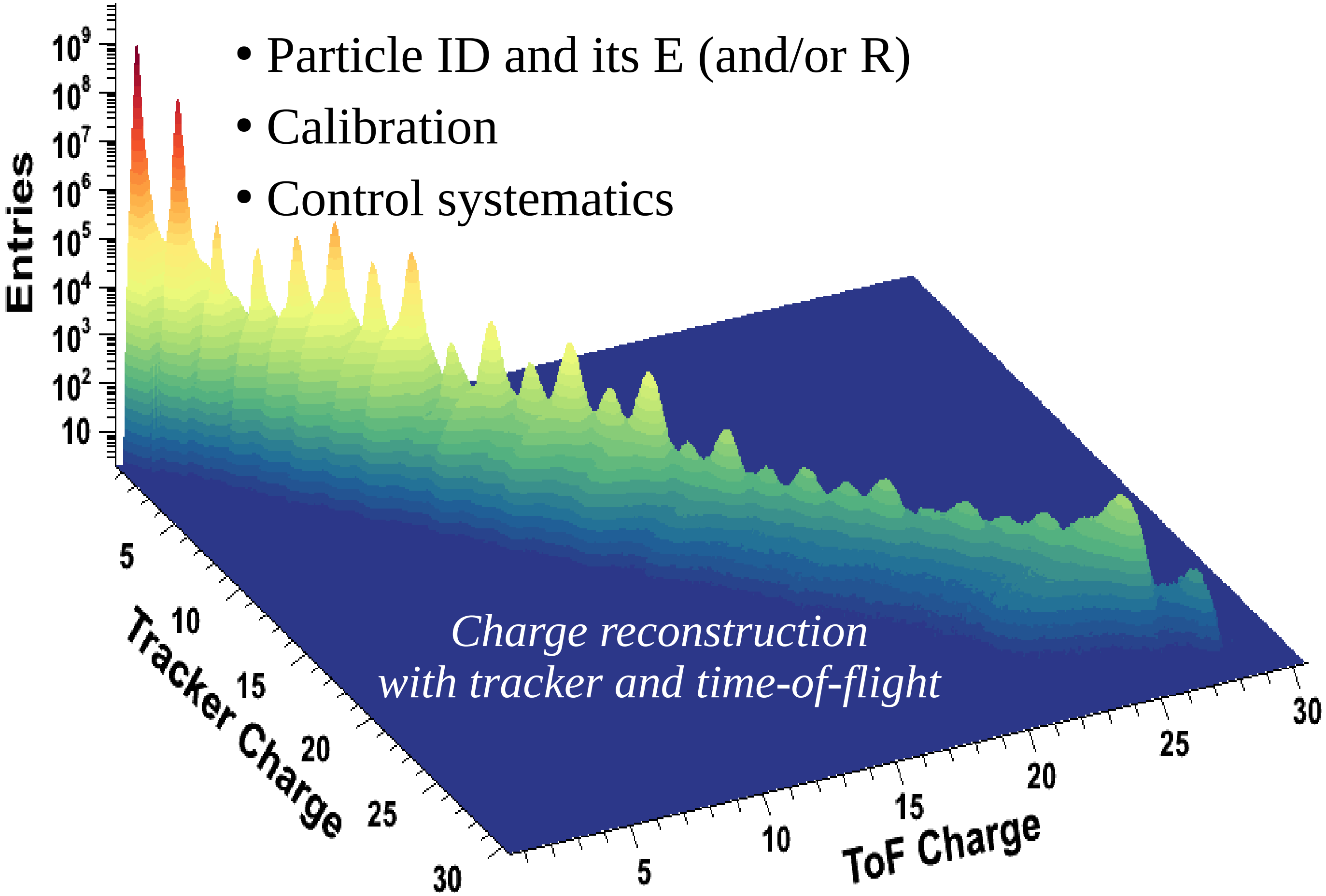
5m x 4m x 3m

7.5 tons

# A(lpha) M(agnetic) S(pectrometer)

**Sub-detector redundancy**

- Particle ID and its E (and/or R)
- Calibration
- Control systematics




*Charge reconstruction*
*with tracker and time-of-flight*

**Each analysis specific** (flux/ratio, leptons/nuclei)

- ID and E (or R) measurement
- Background from other particles
- Background from interaction in detector

**+ rely on**

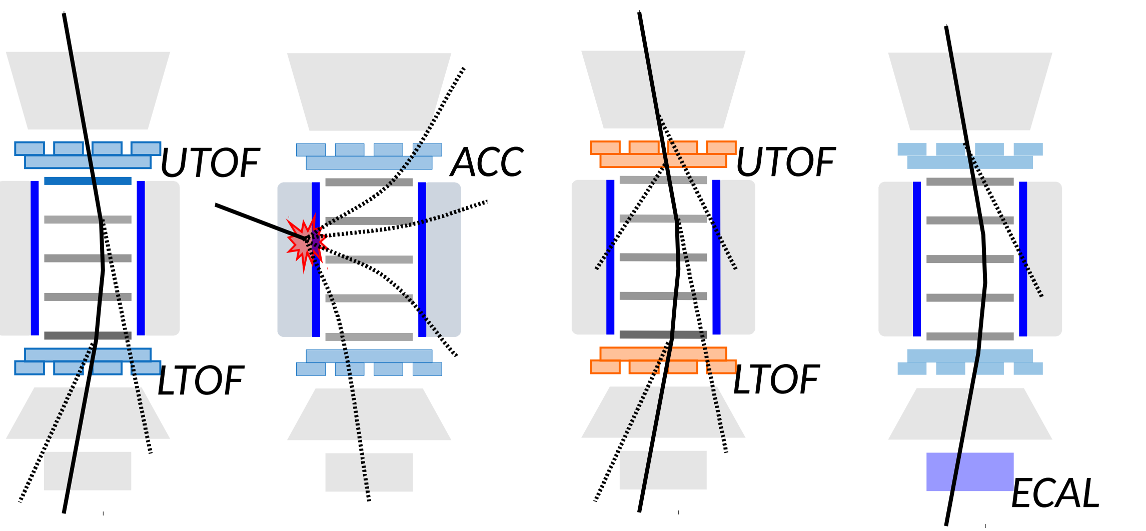
- Beam test
- In-flight data
- Monte Carlo sims

# AMS data analysis: proton flux

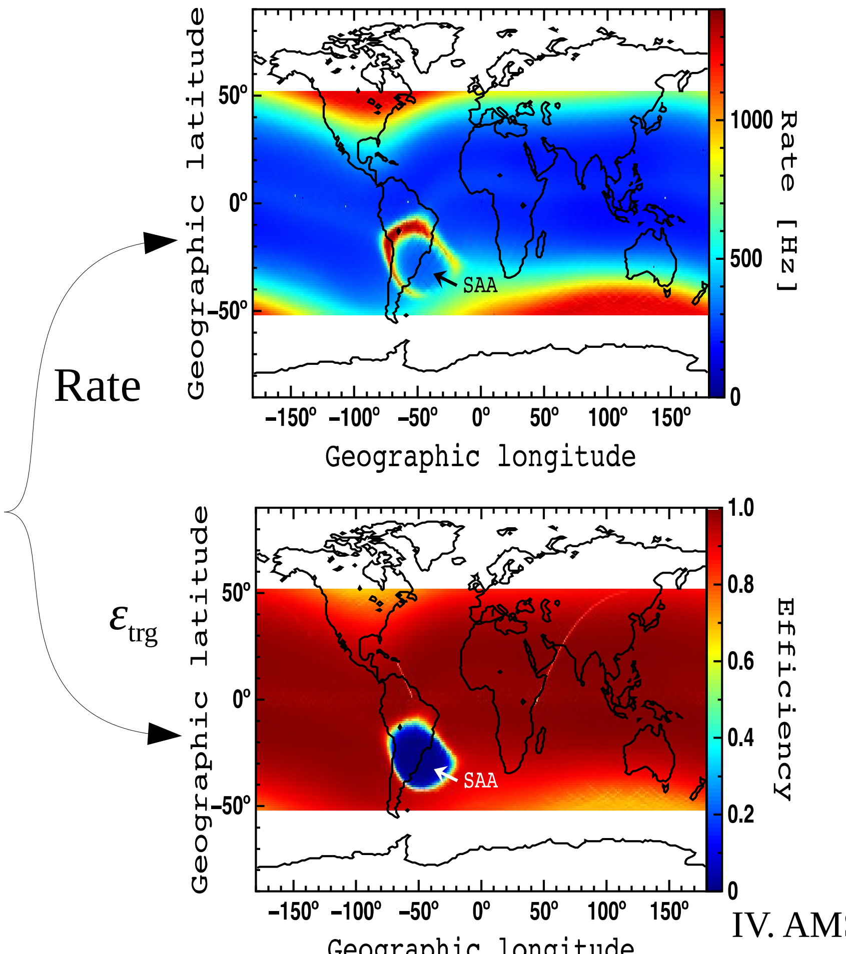
$$F(R) = \frac{N_{obs.}(R)}{T_{exp.}(R)\,A_{eff.}(R)\,\varepsilon_{trig.}(R)\,dR}$$

| | |
|---|---|
| $F$ | Differential flux ($m^{-2}\,sr^{-1}\,s^{-1}\,GV^{-1}$) |
| $R$ | Measured rigidity (GV) |
| $N_{obs}$ | #Events after proton selection |
| $T_{exp}$ | Exposure life time (s) |
| $A_{eff}$ | Effective acceptance ($m^2$ sr) |
| $\varepsilon_{trg}$ | Trigger efficiency |
| $dR$ | Rigidity bin (GV) |

Trigger




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



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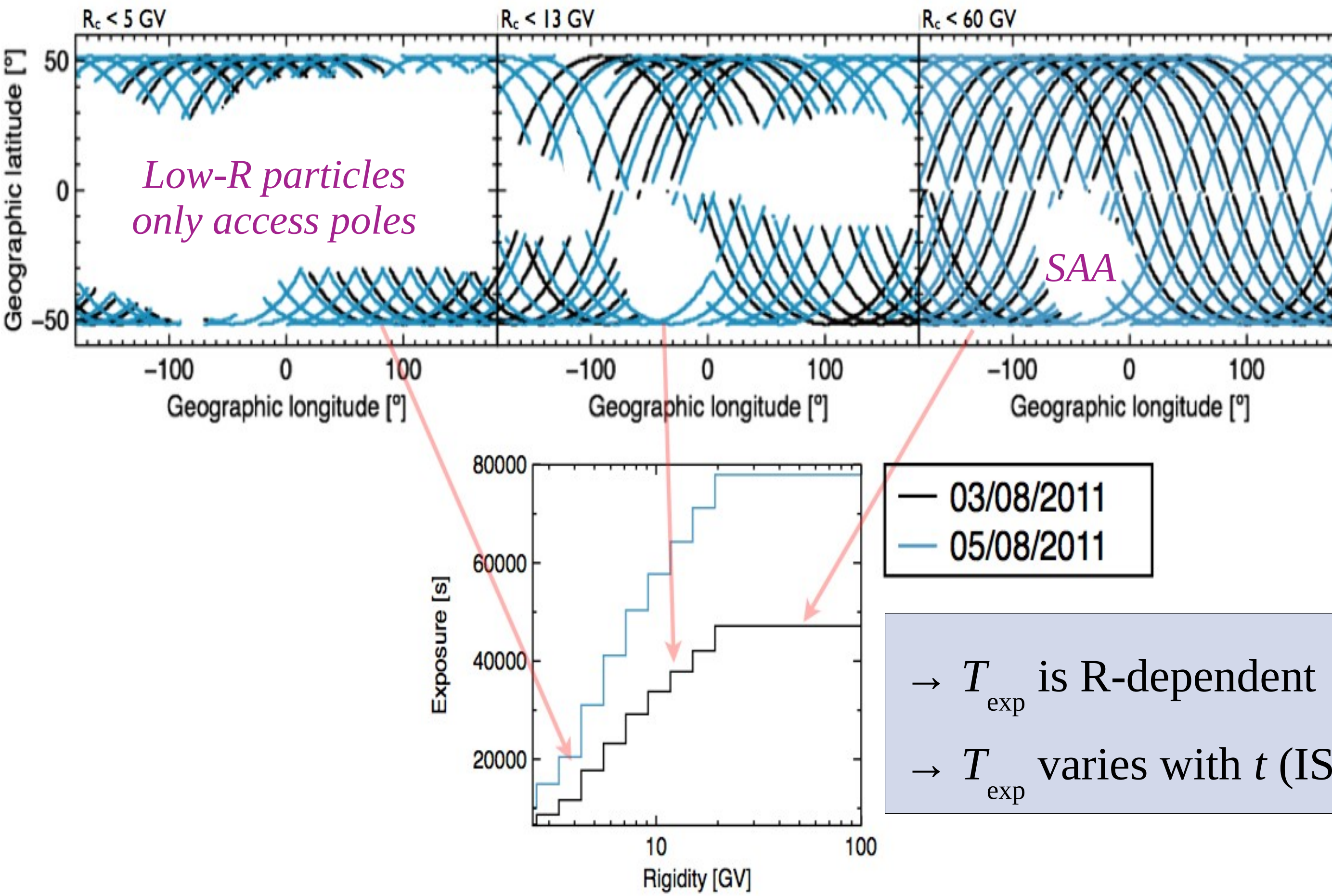


→ $T_{exp}$ is R-dependent

→ $T_{exp}$ varies with $t$ (ISS orbit)

# AMS data analysis: proton flux

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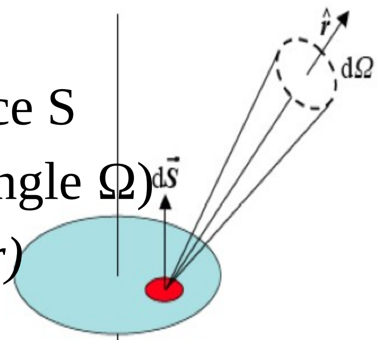
| $dR$ | Rigidity bin (GV) |

- Differential flux (to measure)

$$\phi(E) = \frac{dN}{d\Omega dS dt dE}$$

- Number of events N(E)
  - crossing the detector surface S
  - from all directions (solid angle Ω)
  - with detector efficiency *ε(r)*

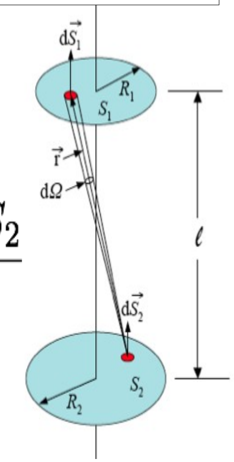



**→ for CR flux (cst & isotropic)**

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

**Simple telescope** ($\varepsilon$=1)

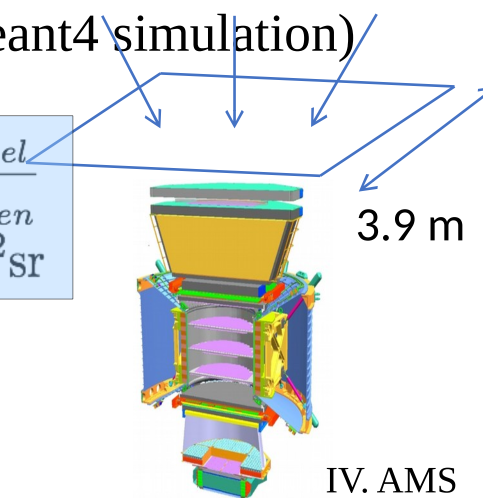
$$Acc(E) = \int_{S_2}\int_{\Omega_2} d\vec{\Omega}.d\vec{S} \approx \frac{S_1 S_2}{l^2}$$




**Real detector** (Geant4 simulation)

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

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



3.9 m

# AMS data analysis: proton flux

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**Rigidity measurement**

"Trace curvature in B" α 1/R

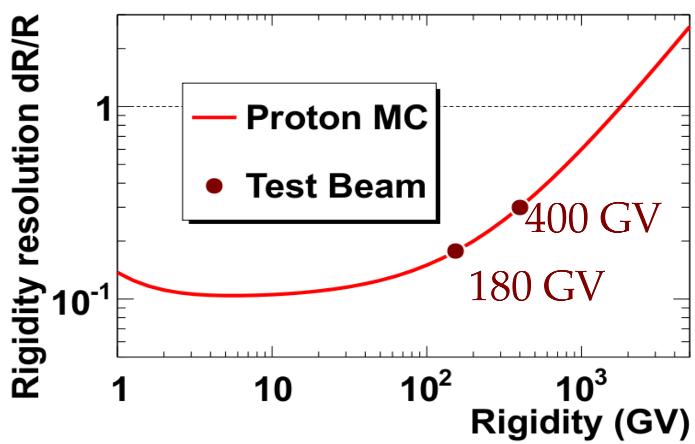
N.B.: MDR=max. detectable R

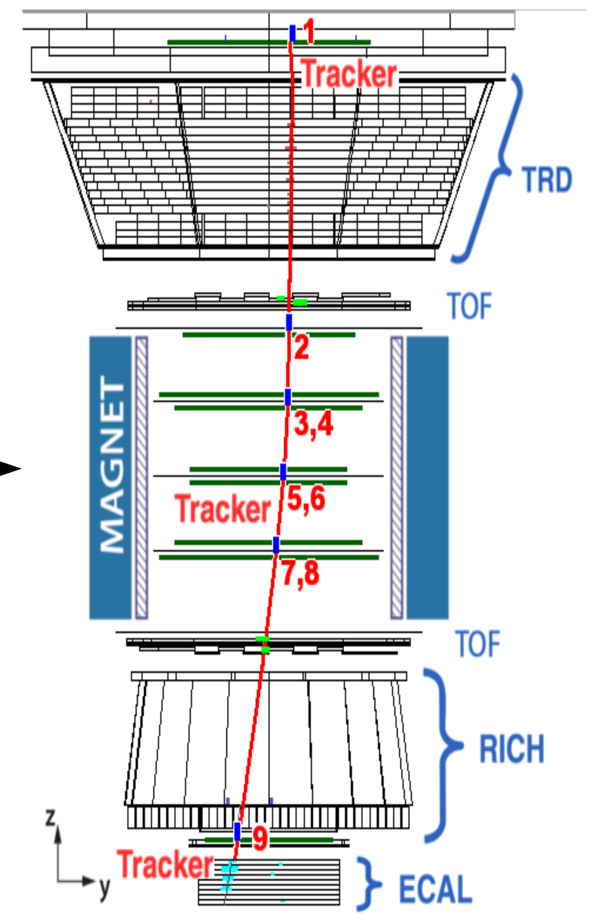
$B_x$ = ~0.14 T
$L$ = ~3 m
$\Sigma_y$ = ~10 μm
MDR : ~2 TV

**Uncertainty on R**

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

$$\frac{\Delta R}{R} = \frac{R}{MDR}$$



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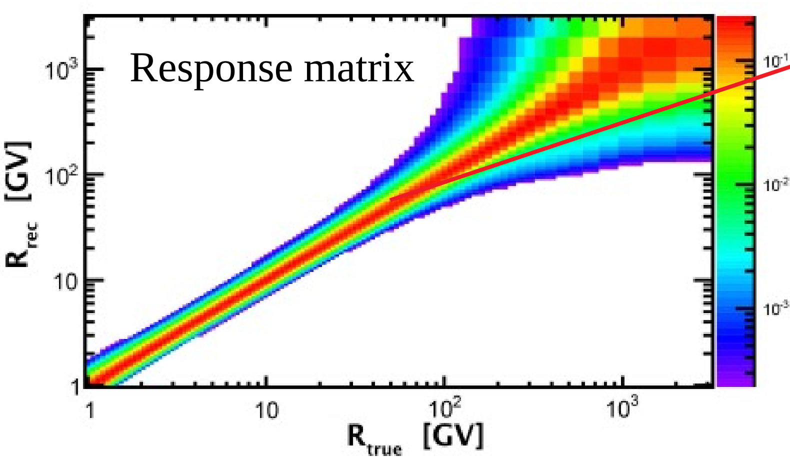
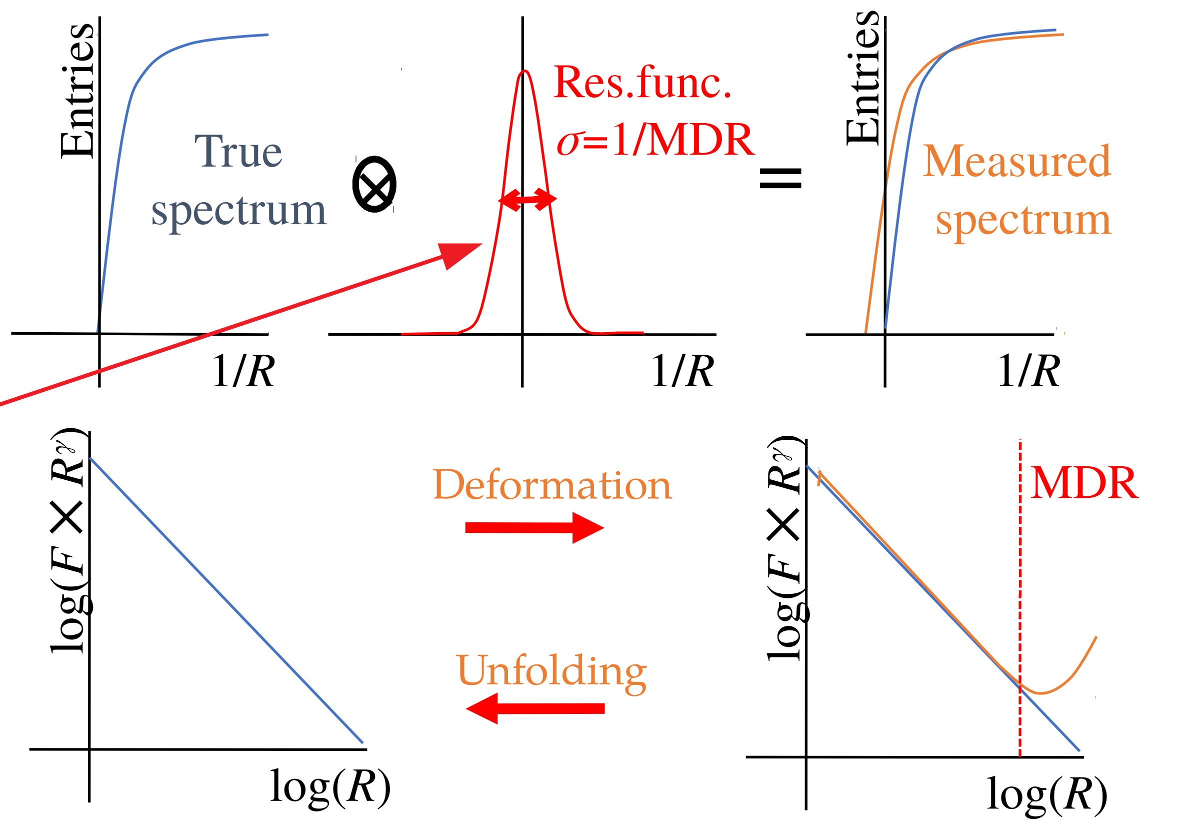
| d$R$ | Rigidity bin (GV) |

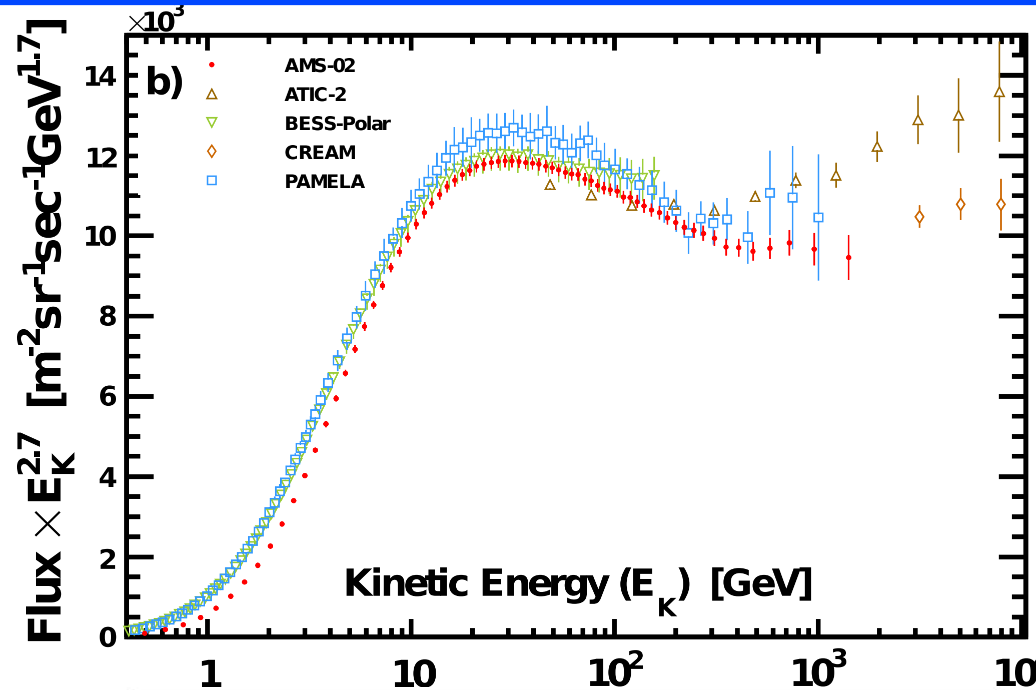
**Finite energy resolution**
→ bias measured spectra
Unfolding necessary...



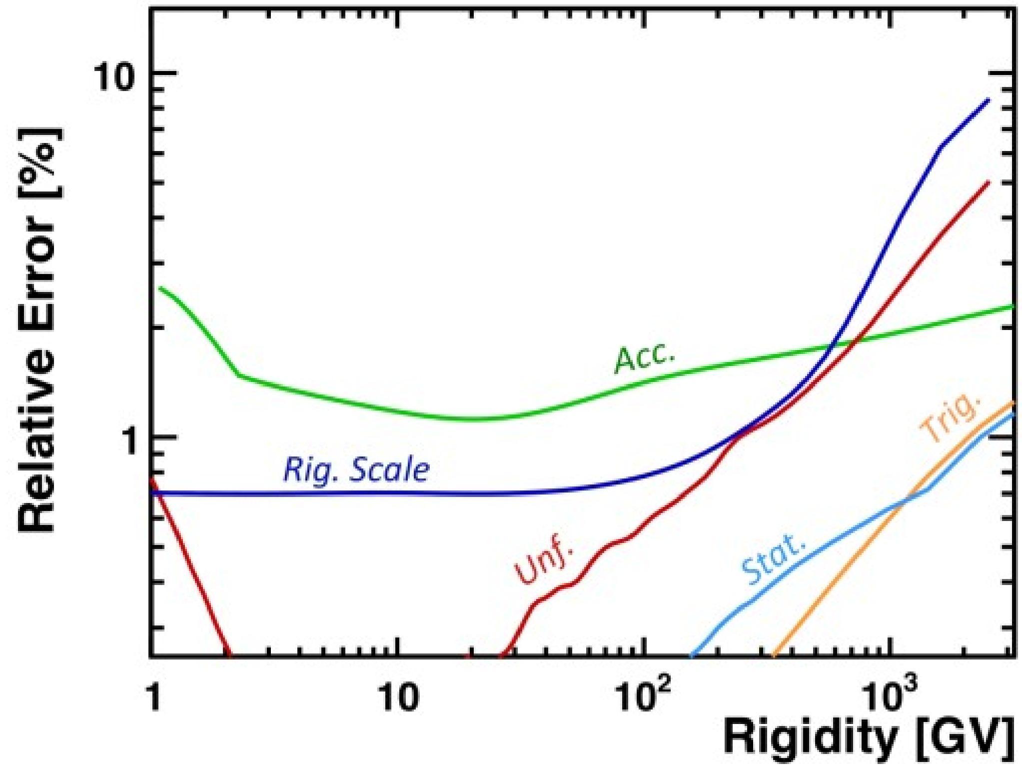
# AMS data analysis: proton flux

**AMS-02 proton flux**
Aguilar et al., PRL 114 (2015)
→ *based on 300 million events*




**… and uncertainties**

→ most difficult part of the analysis
→ stat. uncertainties sub-dominant



I. Cosmic ray discovery

II. Cosmic ray puzzle: sources, transport...

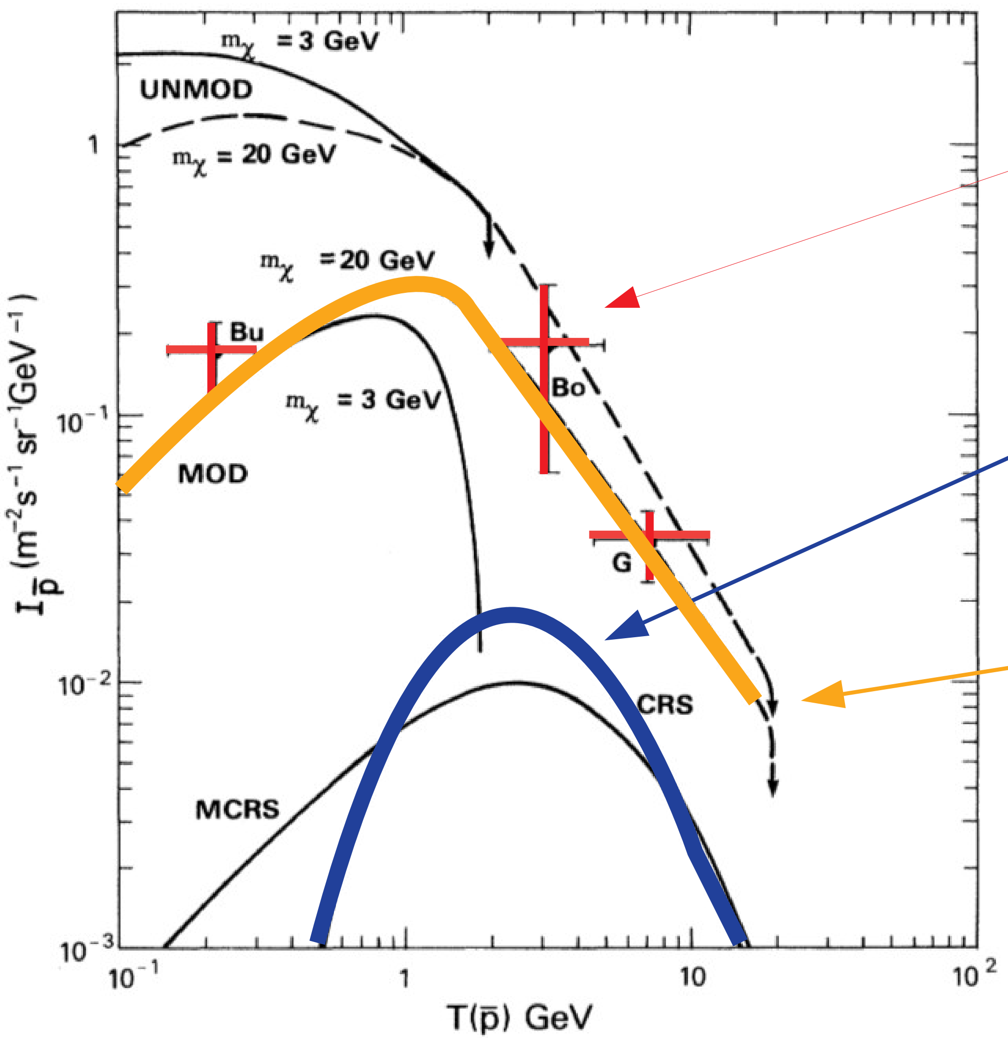
III. CR experiments: overview

IV. AMS experiment: data analysis

V. Recent results

# Dark matter detection in CRs?

Stecker, Rudaz & Walsh, PRL **55**, 2622 (1985)




First pbar data (ballon-borne)

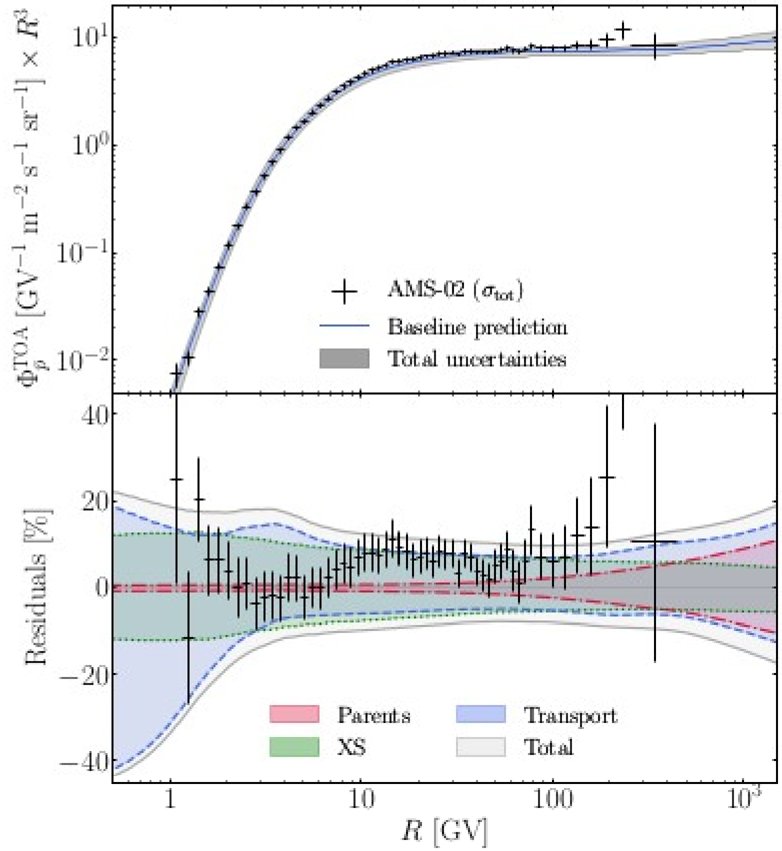
Astrophysical "background" (secondary pbar)

Dark matter contribution ($m_\chi$ = 20 GeV)

Give me 3 possible conclusions from this plot?

# Dark matter detection with AMS-02?

Boudaud, Génolini et al. (2019)

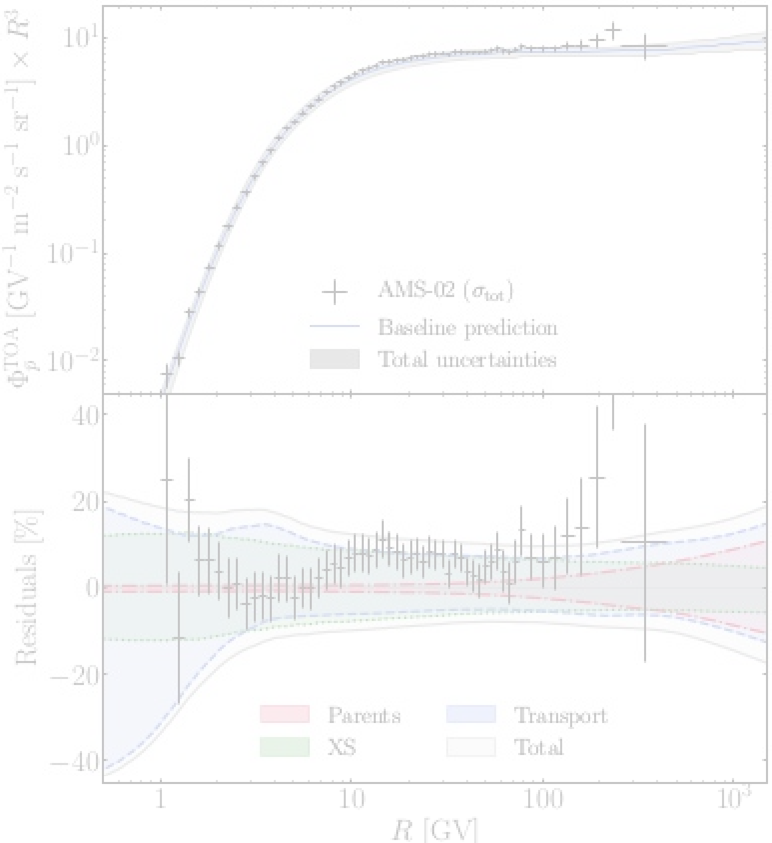



**Antiprotons**

→ Seems consistent with astrophysics only
→ Several groups working on X-sections

# Dark matter detection with AMS-02?

Boudaud, Génolini et al. (2019)

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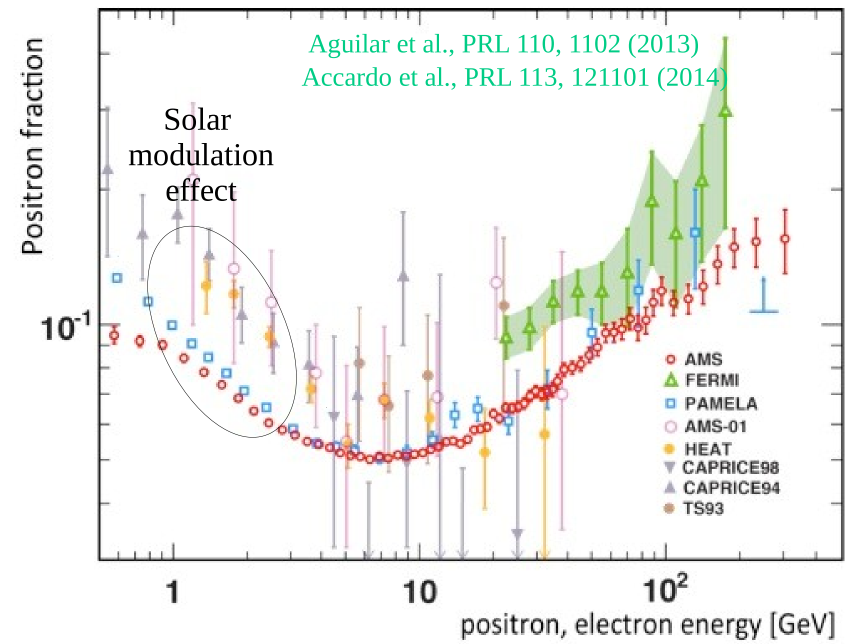



**Positron fraction, $e^-$, $e^+$ and $e^-+e^+$ spectra used to test astrophysical and/or dark matter hypothesis**

- Contribution from local SNRs/pulsars?
  → e.g., Delahaye et al., A&A 524, A51 (2010)

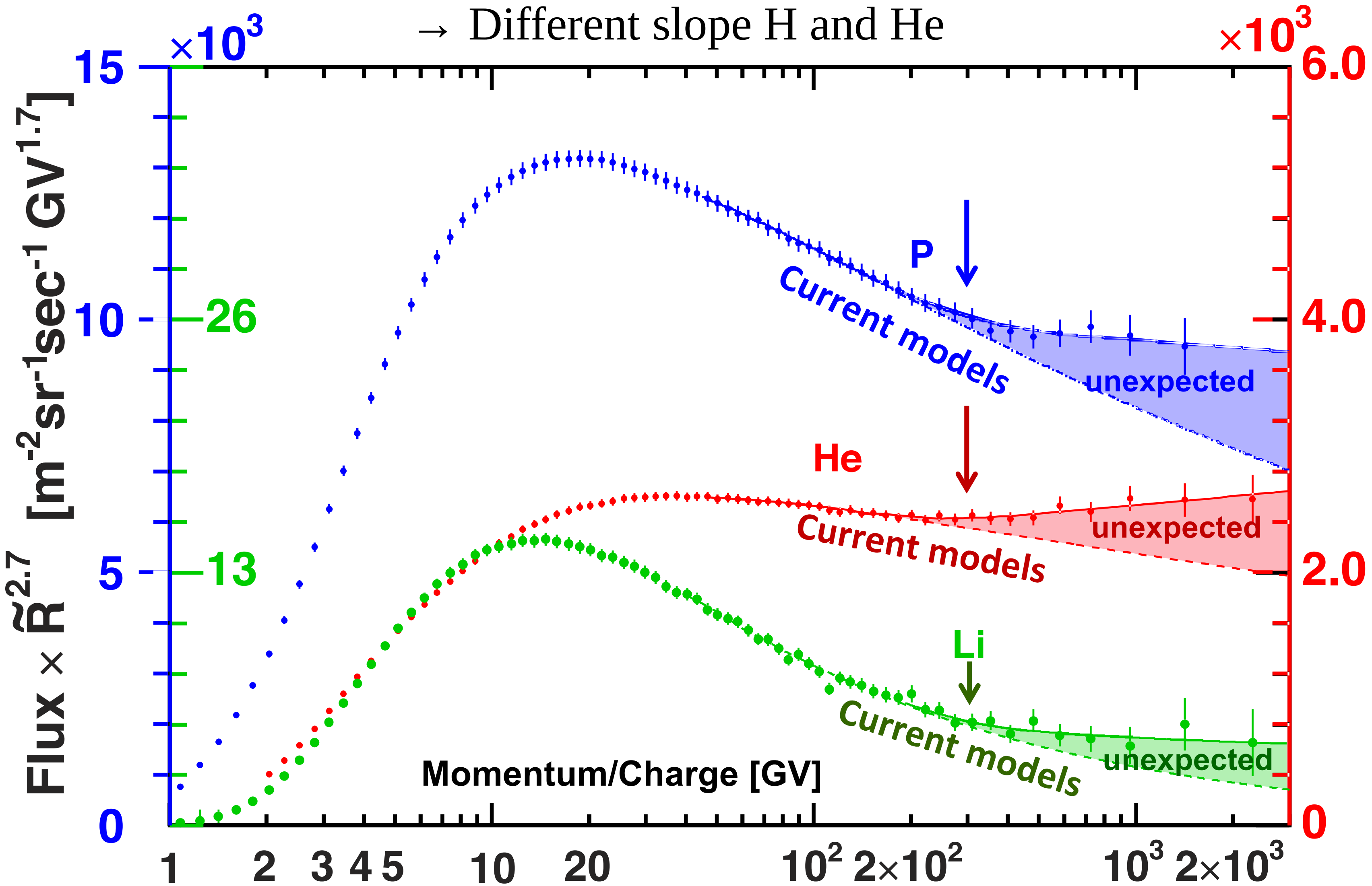
- Dark matter hypothesis?
  → e.g., Boudaud et al., A&A 575, 67 (2015)
  [N.B.: no boost, Lavalle et al., A&A 479, 427 (2008)]

N.B.: see also e- and e+ in Aguilar et al., PRL 113, 121102 (2014)

# Unexpected results: breaks

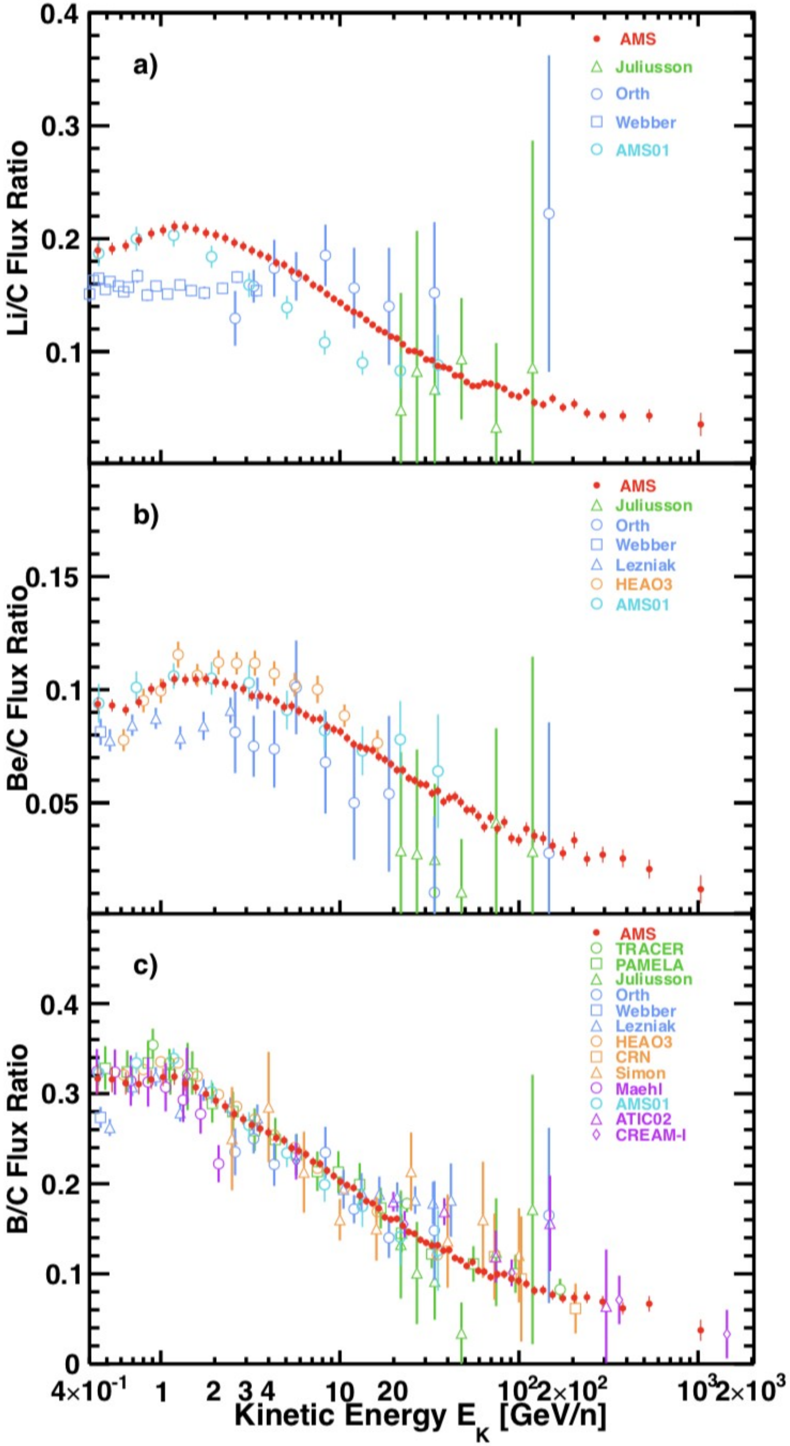
→ Spectral break at ~ 300 GV

→ Different slope H and He



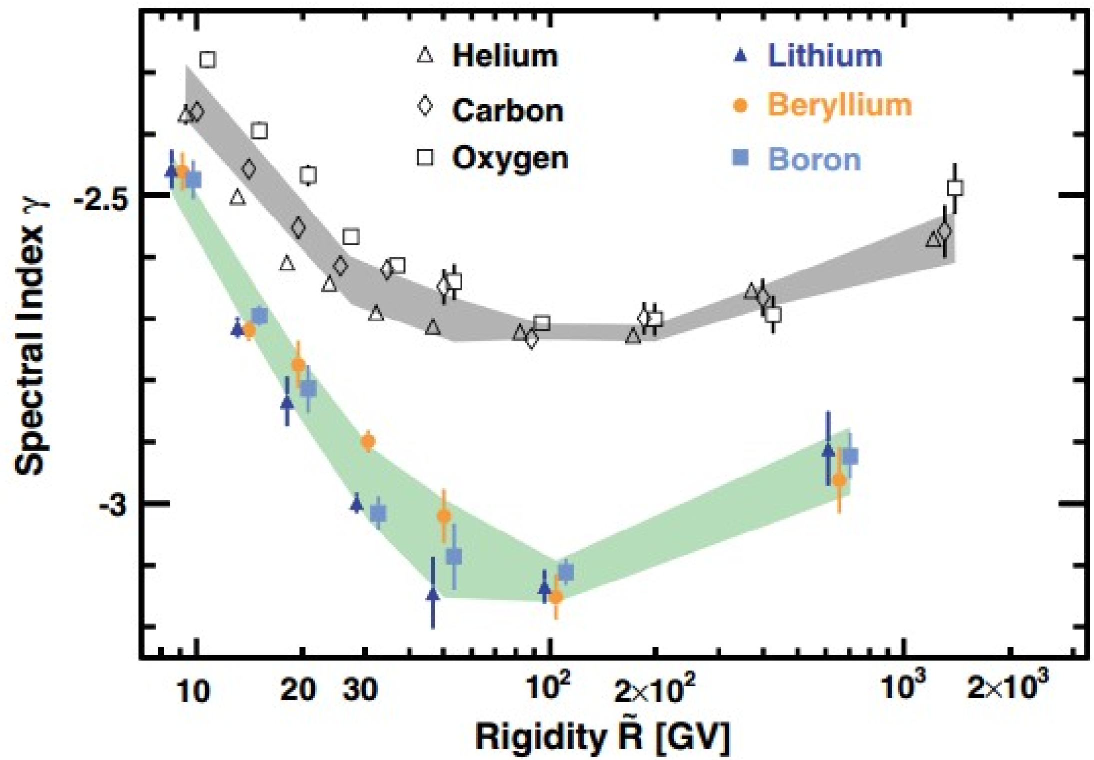

Origin of the break?

# Unexpected results: breaks




→ Break seen in all data (primary and seconday species)

Aguilar *et al.*, PRL 120, 021101 (2018)

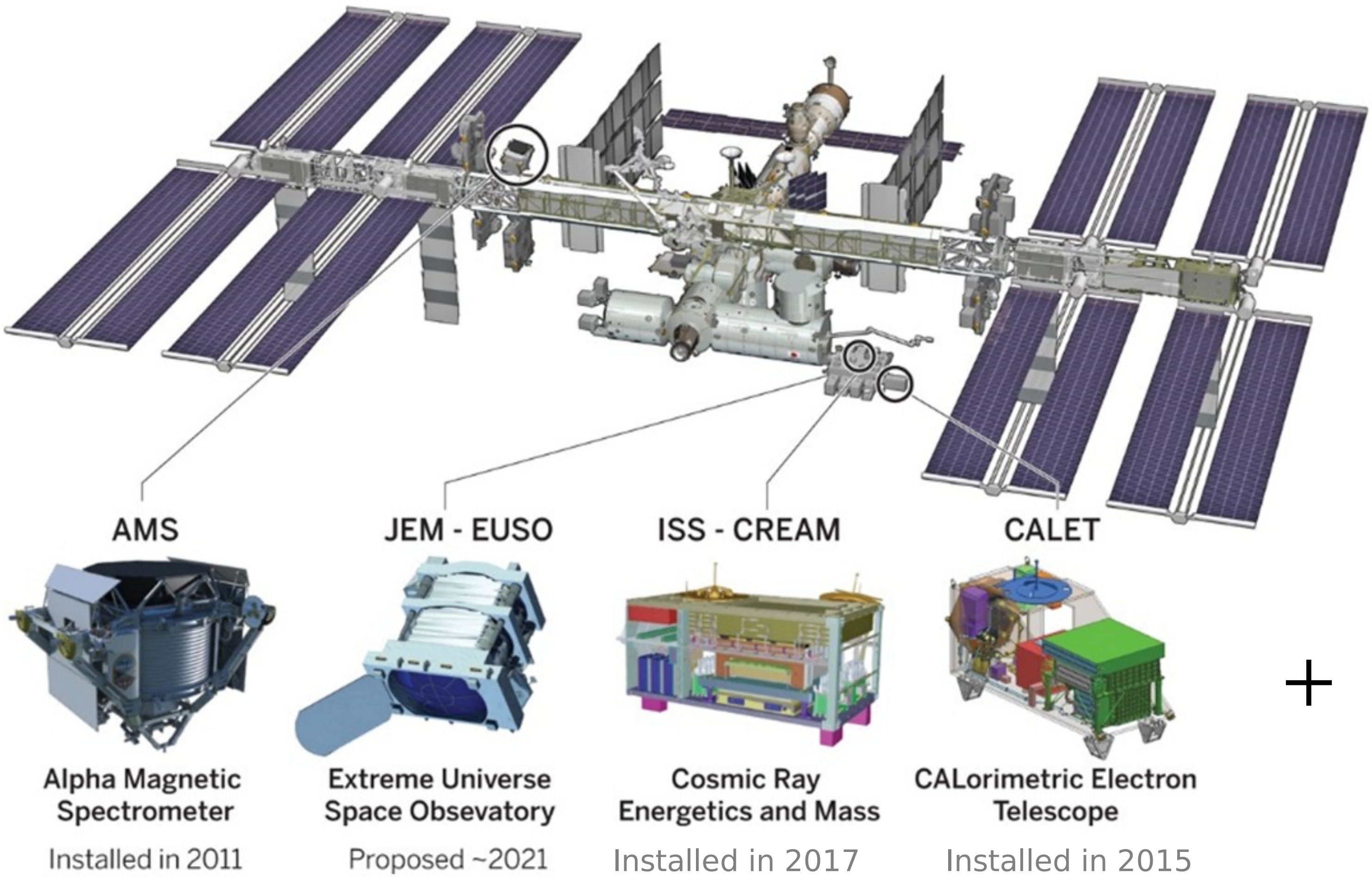



→ most likely transport (not source spectrum)

[coupling CR/B/gas via MHD]

# Conclusions

→ A bright present (and near future) for HE cosmic-rays




\+

**DAMPE satellite**

Launched in 2015

… and a lot of theoretical work to understand the data!

*For more on CR phenomenology,*
*play with the propagation code USINE*

https://lpsc.in2p3.fr/usine/