# 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
- Complexity of data analysis (illustration with AMS-02)
- Variety of detection principles, 'research activities', etc.


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25 July 2022

# Astroparticle experiment 1

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



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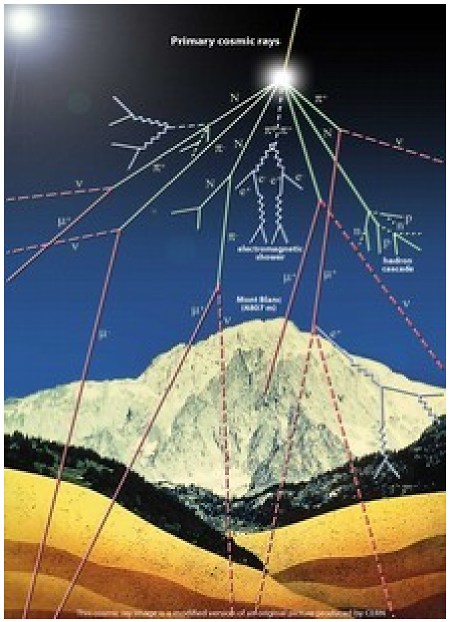
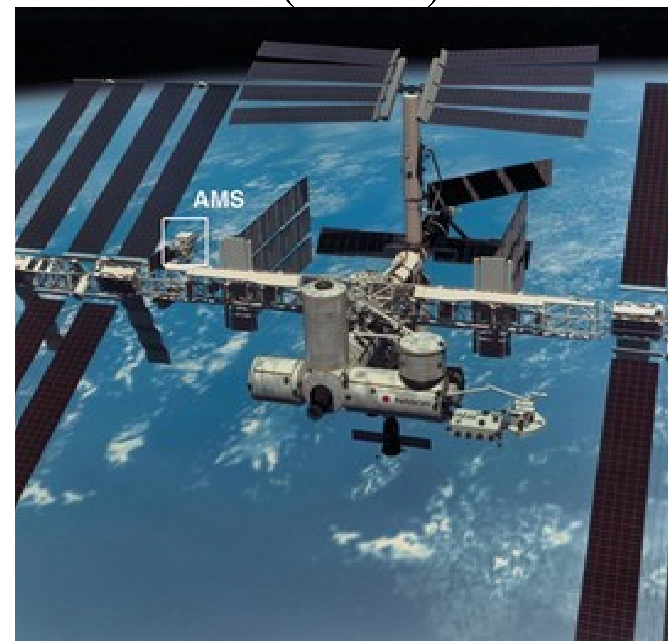
# Experimental milestones

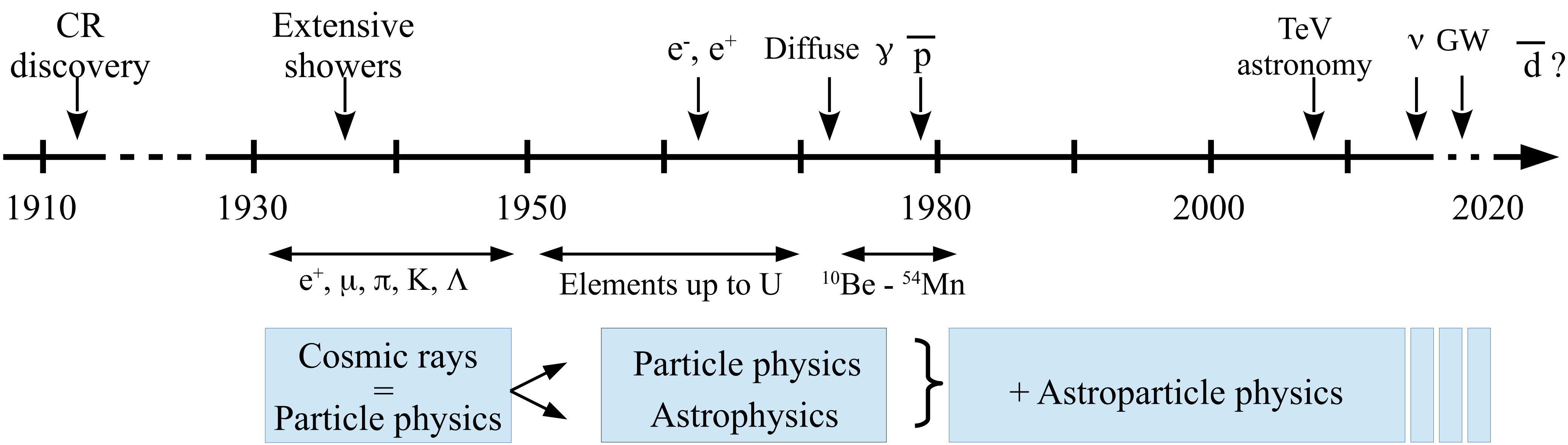
Mountain altitude < 5 km




CREAM balloon ~ 40 km

AMS-02 (on ISS) ~ 300 km



# Charged vs neutral cosmic rays

## Two categories

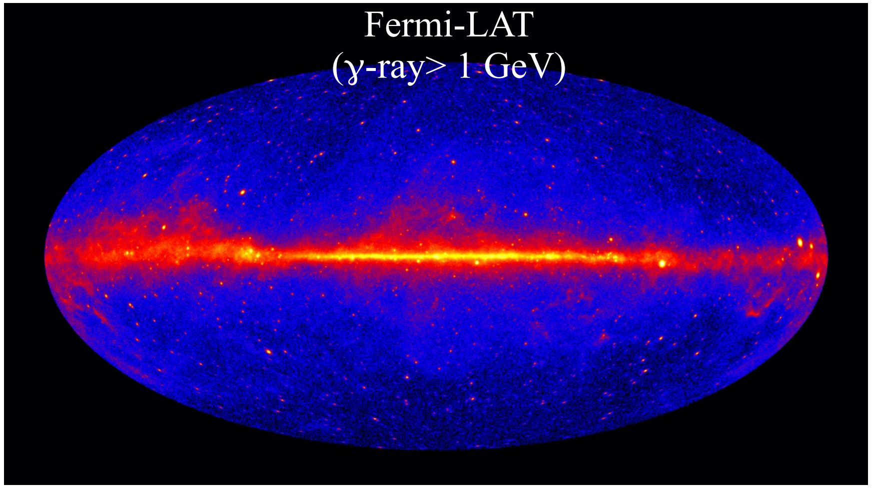
- *Neutral species*
  - ✓ Gamma-rays
  - ✓ Neutrinos

Multi-messenger approaches
Multi-wavelength observations

- *Charged species*
  - ✓ Leptons
  - ✓ Nuclei

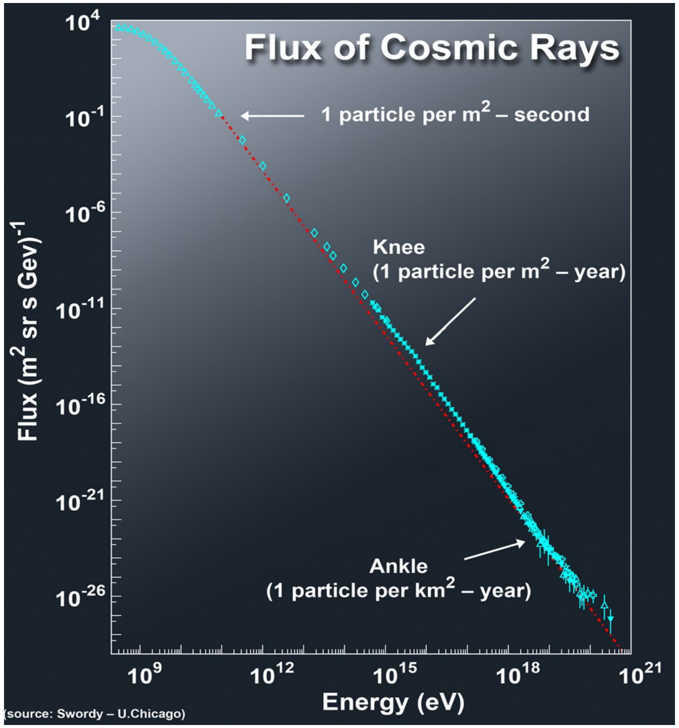
## Observation types

→ *Astronomy (position and spectrum)*
N.B.: point-like, extended, diffuse emissions (see 2nd lecture)



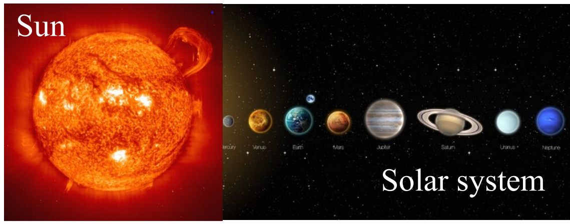

→ *"Isotropic" spectrum & anisotropy sky maps*
(diffusion/deflection in B)

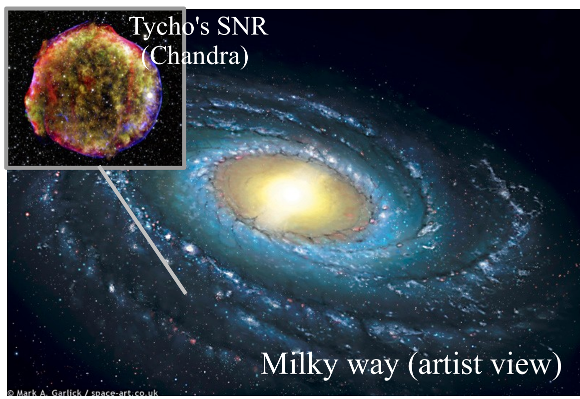
30 orders of magnitude

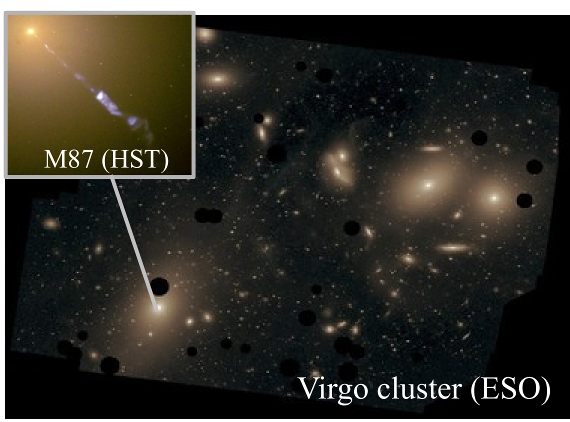


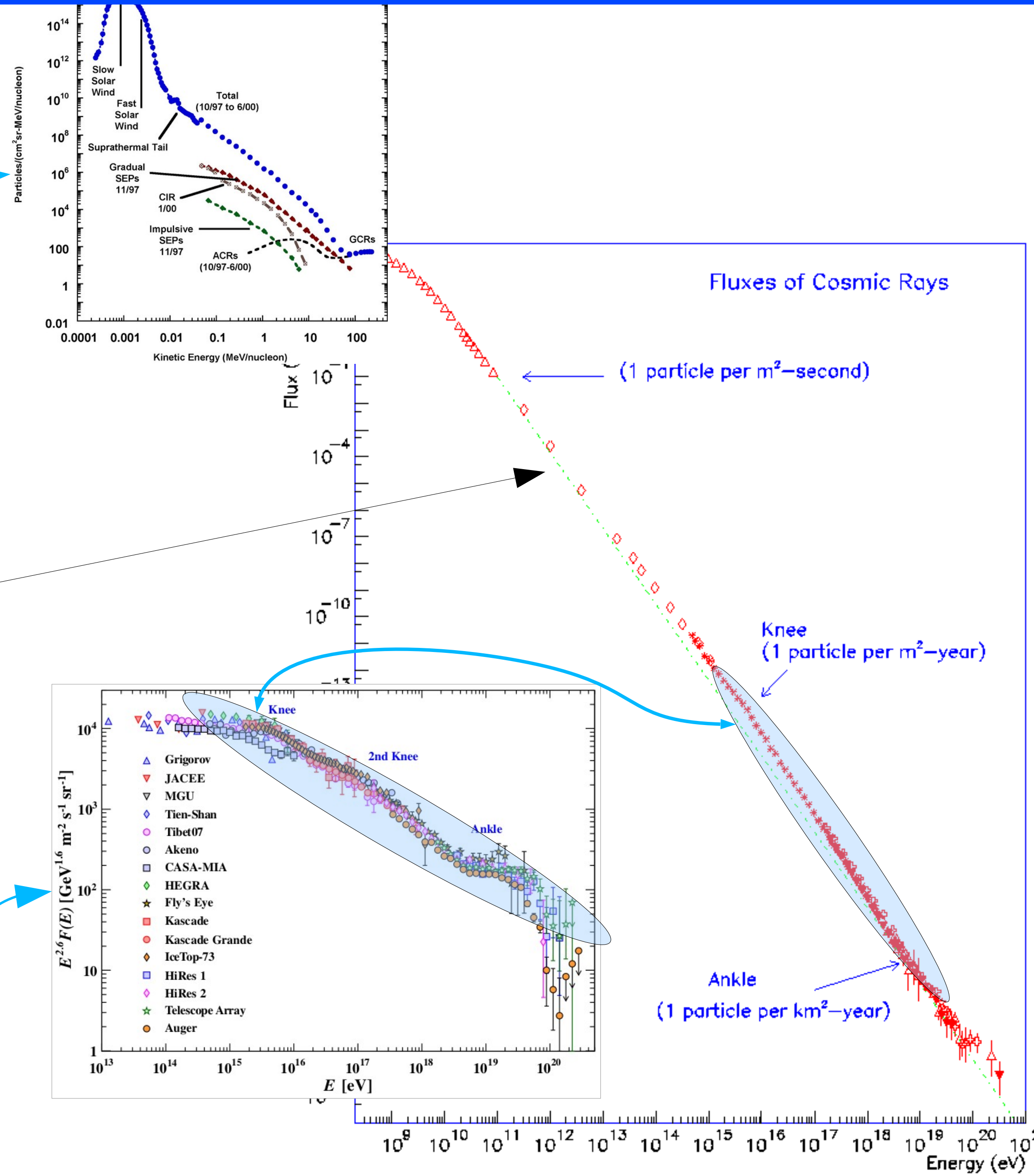

12 orders of magnitude

# Cosmic ray sources?



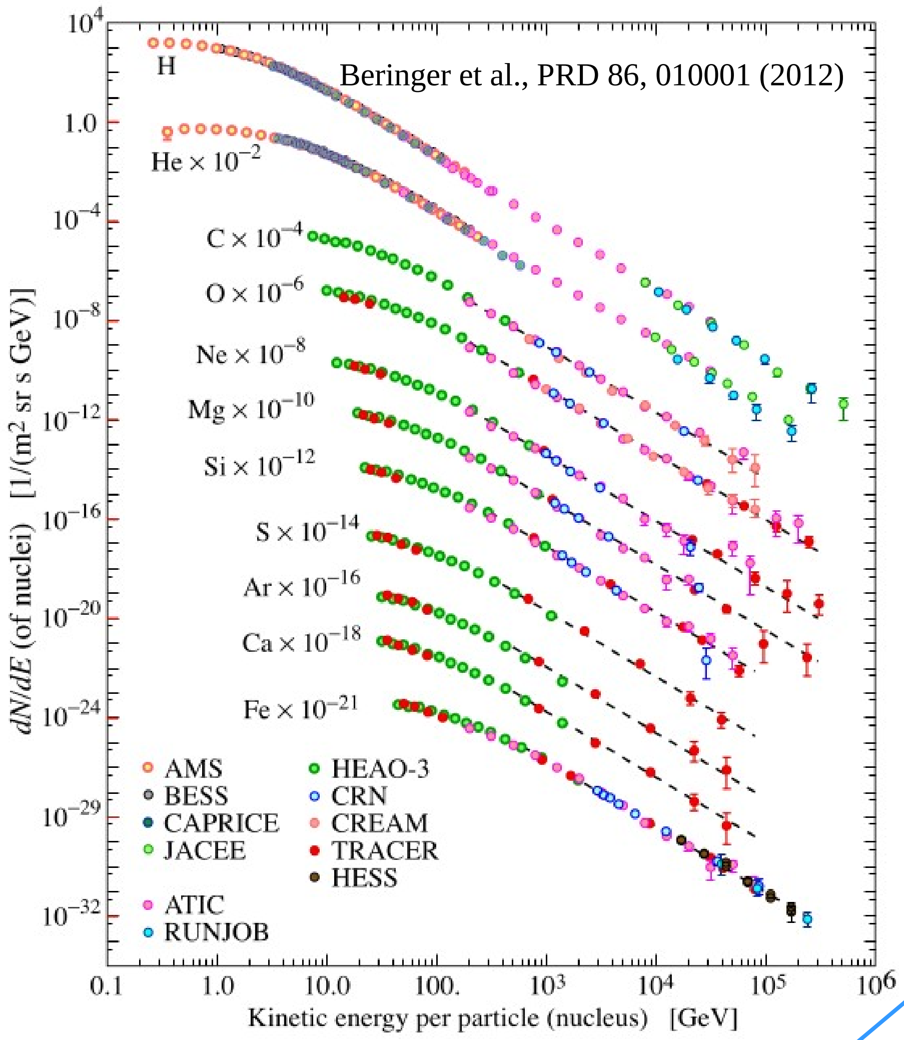

**Transition galactic vs extragalactic**

→ CR sources and transport?

→ Origin of spectral features, composition, anisotropy?

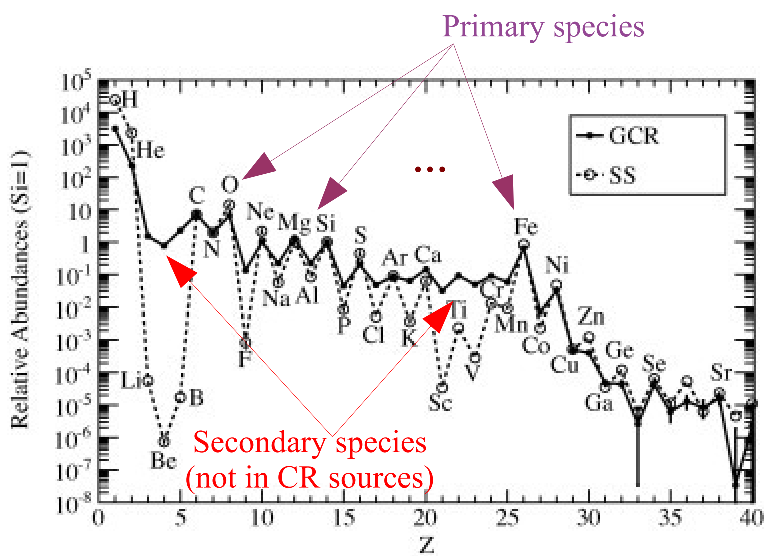
# Galactic CR data (E~$10^8$-$10^{15}$ eV)

Elemental spectra




**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* |



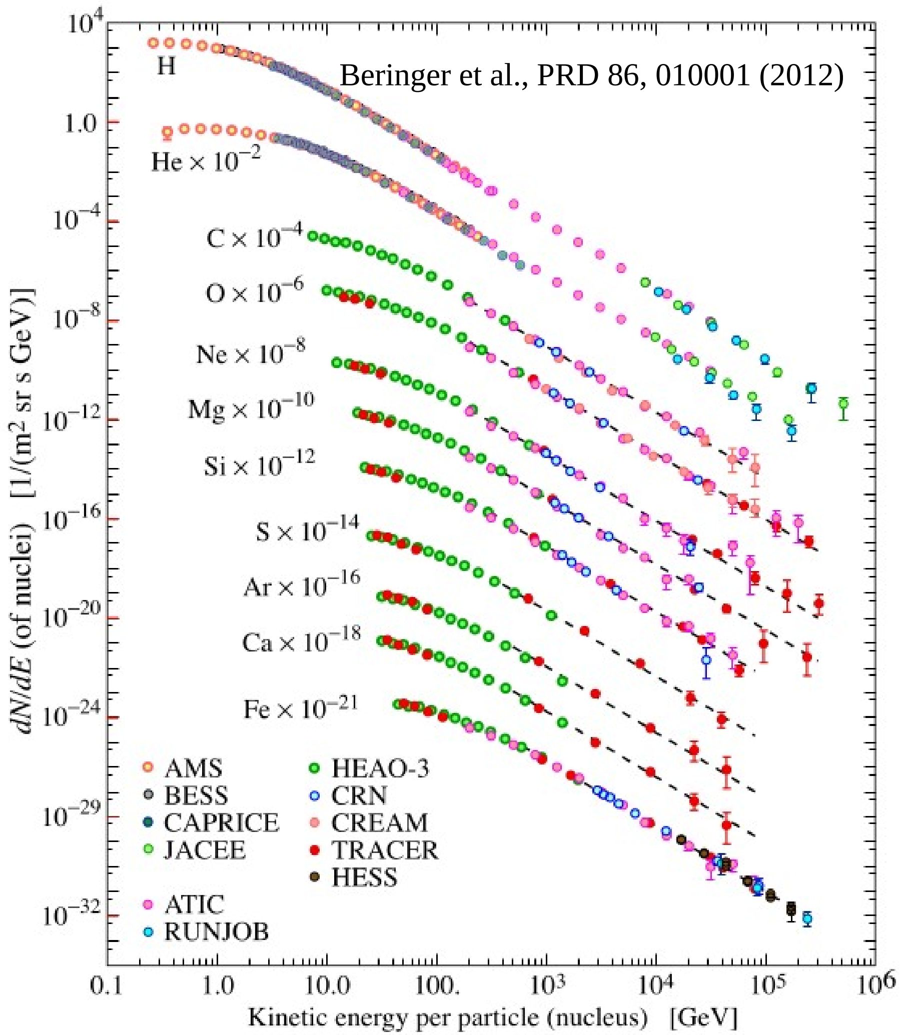

Bauch et al., AdSR 53 (2014)

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

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

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

Elemental spectra




→ Origin of 'universal' power law ($E^{-2.8}$)?
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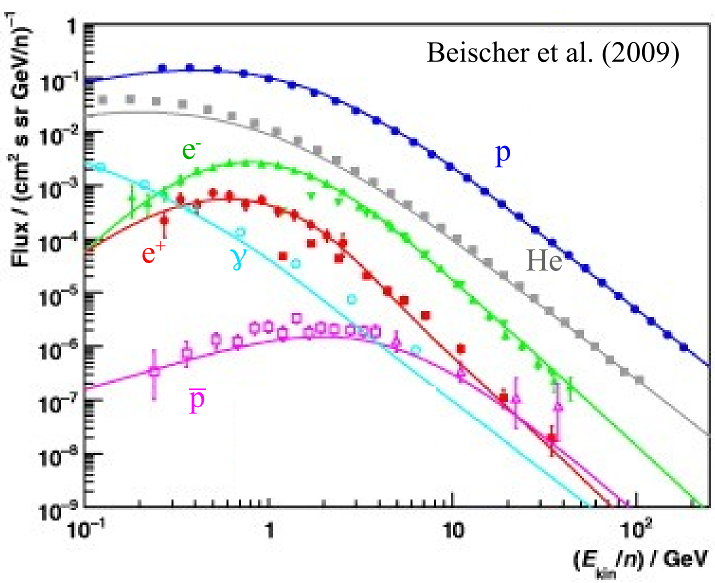
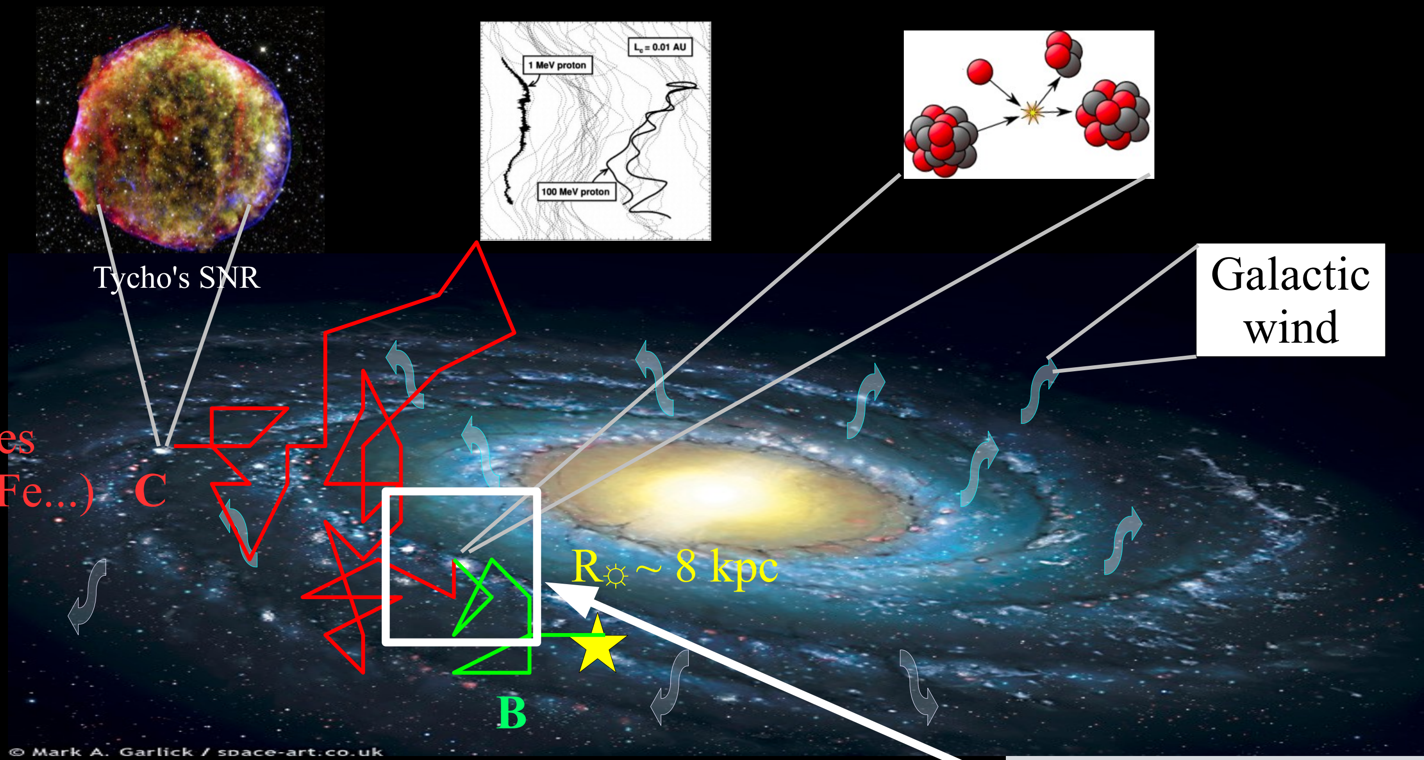
Protons and He
*vs*
diffuse γ-rays, pbar, $e^-$ and $e^+$



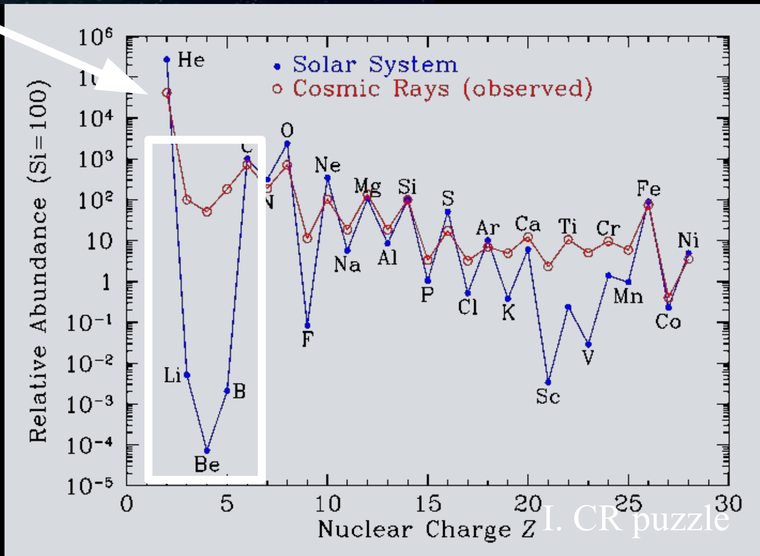

N.B.: rare CRs produced by H,He + ISM
→ How well do we know the astro. production?
→ Is it a good place to look for dark matter?

# Nuclear interactions and abundances

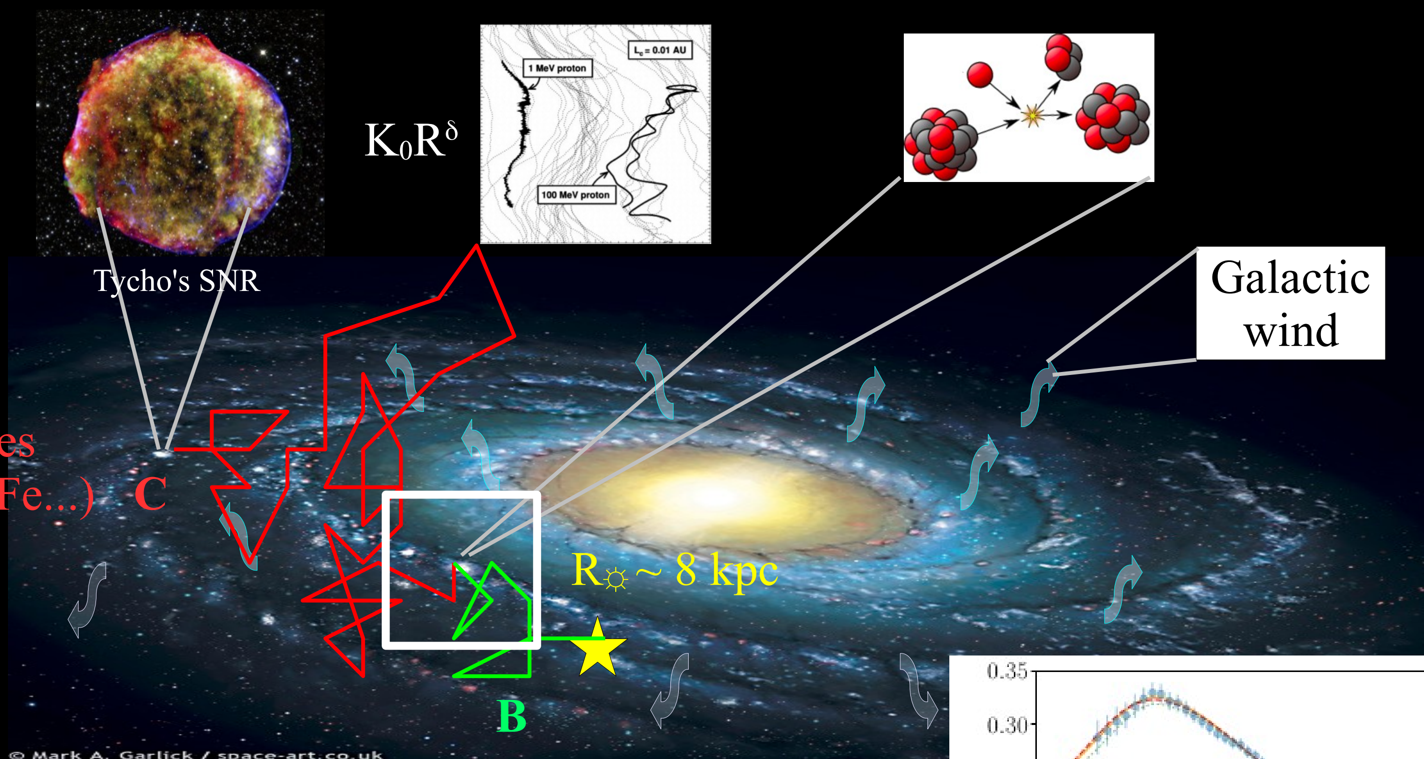



Primary species
(p, He, C, O, Si, Fe...)

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



# Diffusion: secondary-to-primary ratio




Primary species
(p, He, C, O, Si, Fe...)

Secondary species
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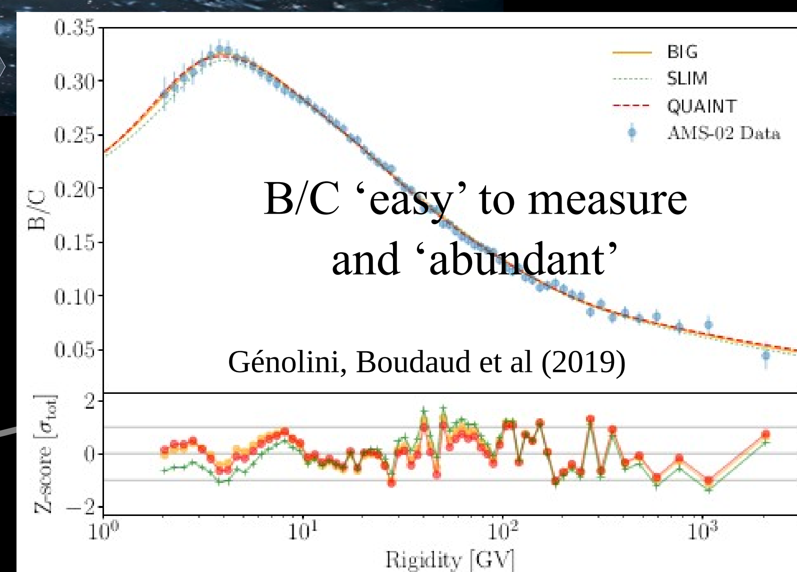
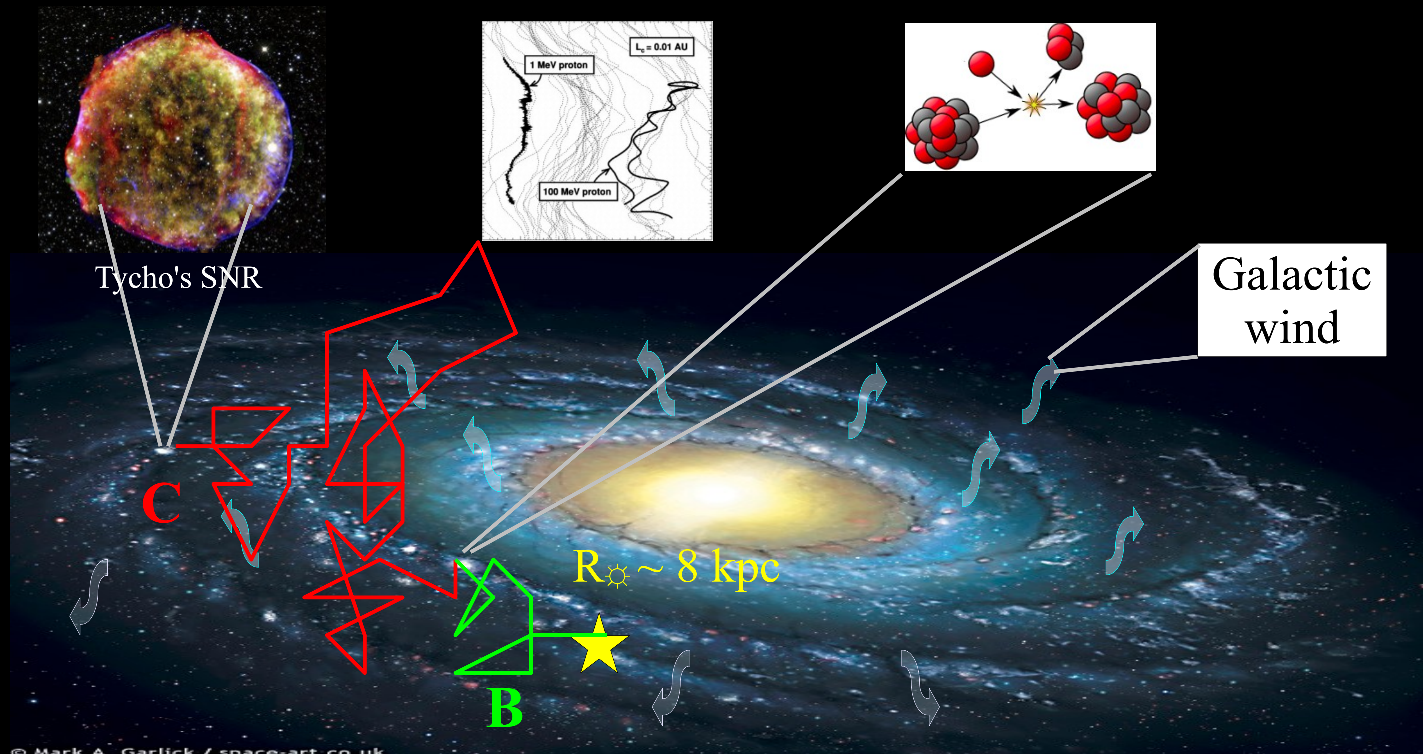



Primary species P: source/diffusion ~ $R^{-(\alpha+\delta)}$

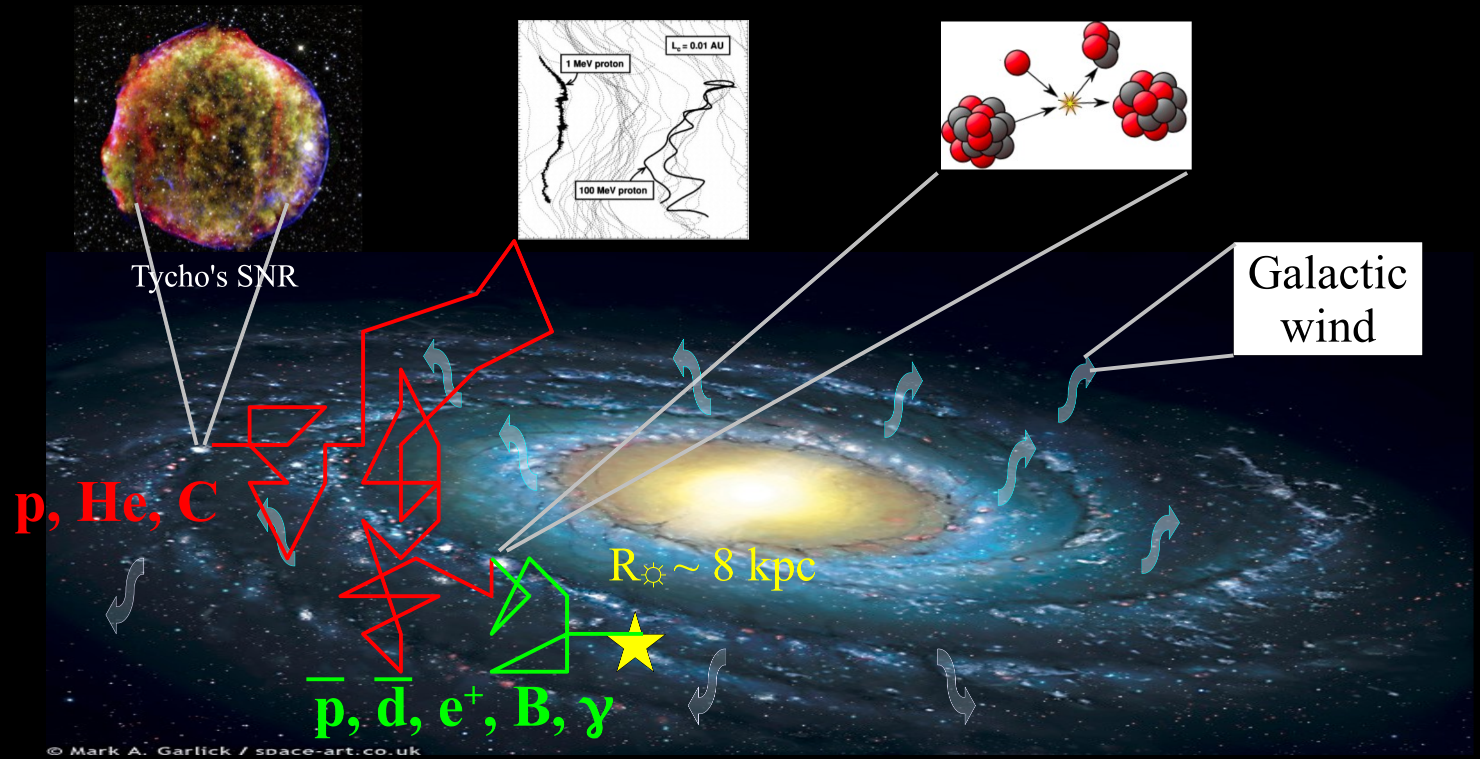
Secondary species S: ($\sigma^{P\rightarrow S}$ . P)/diffusion ~ $R^{-(\alpha+2\delta)}$

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

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

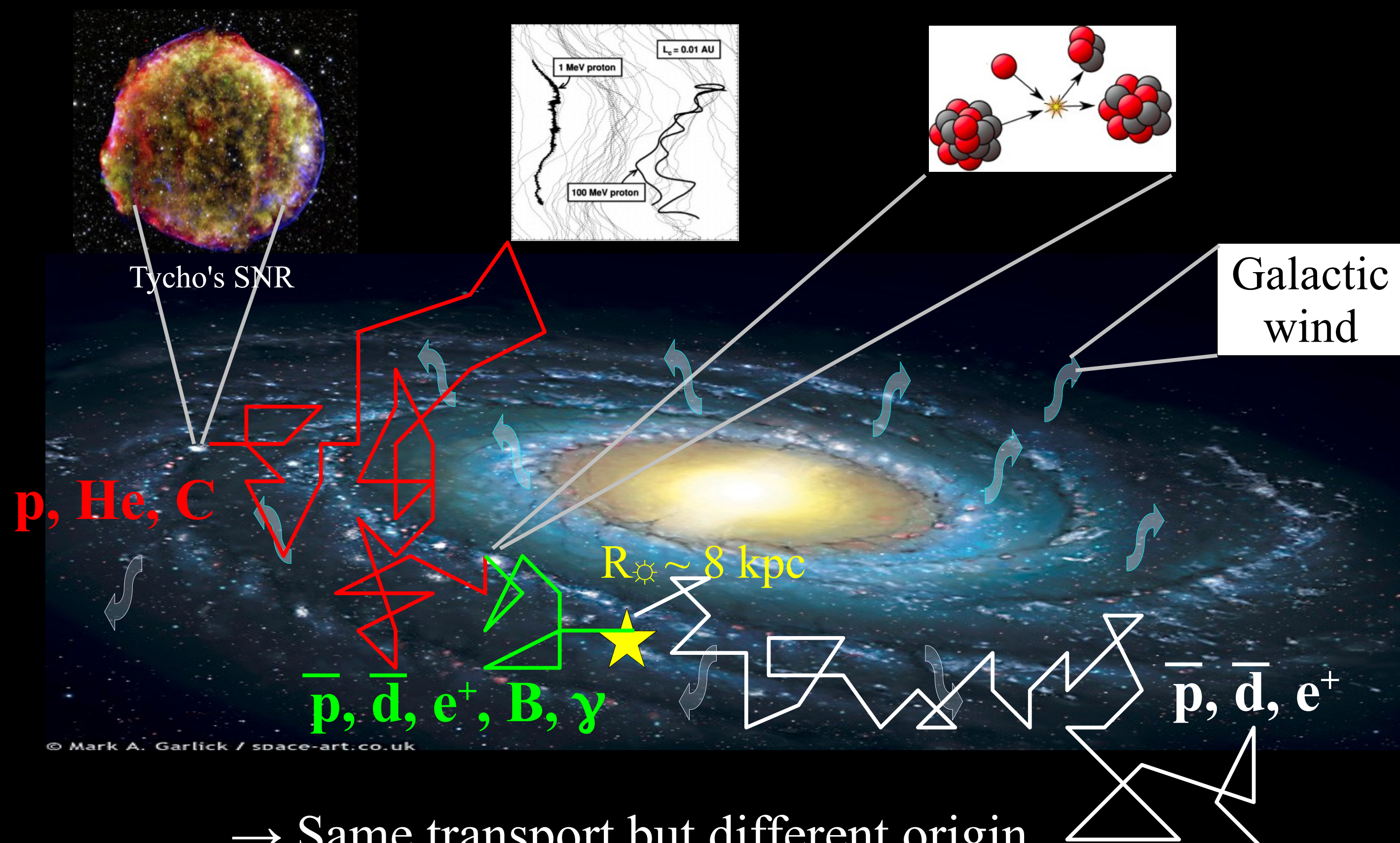


# Dark matter search: (ii) "background" for rare channels




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

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



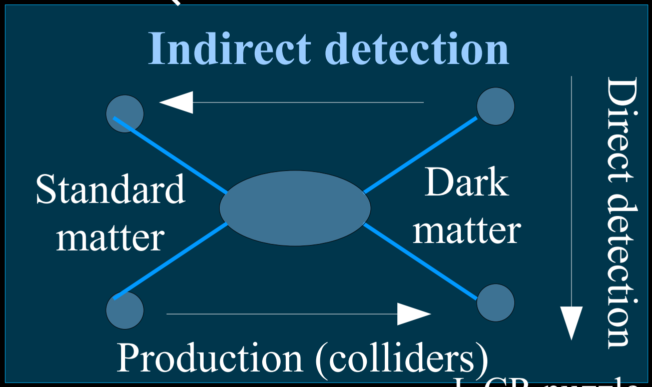

→ Same transport but different origin
(from DM halo)

**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

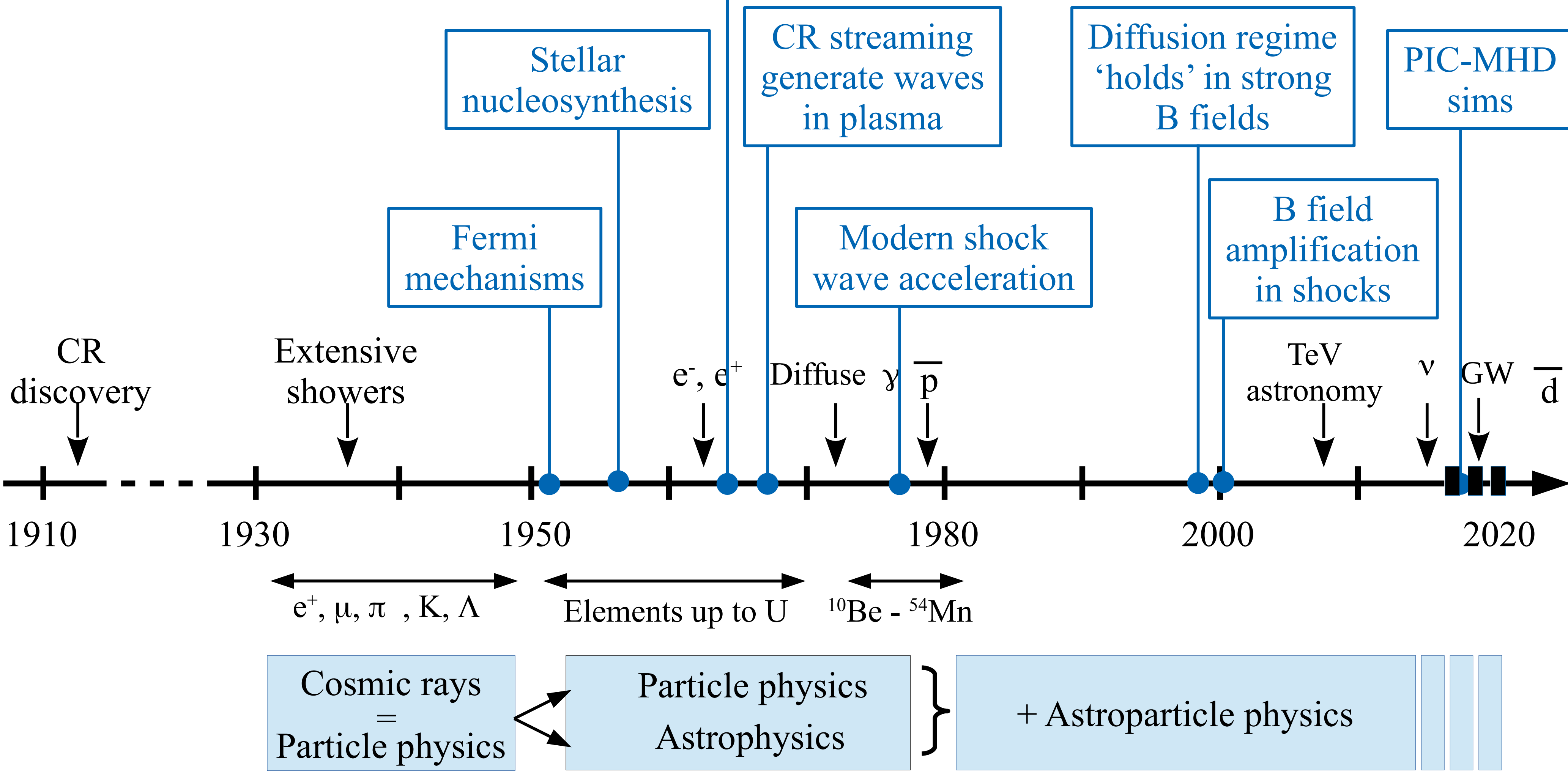
→



# Theoretical milestones

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

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



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

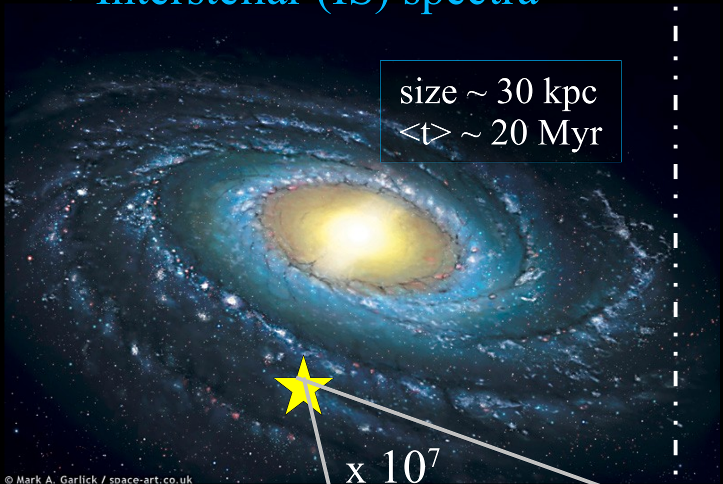
II. CR experiments: overview

III. AMS-02 experiment: data analysis

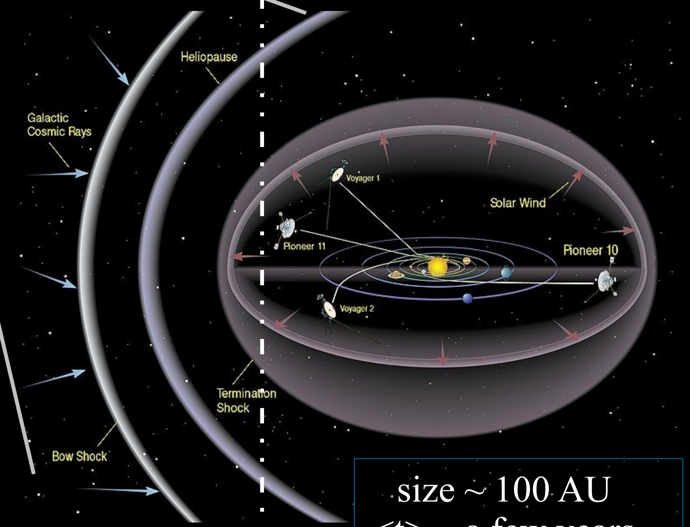
IV. Dark matter in AMS-02 data?

# Last steps before detection… Solar modulation

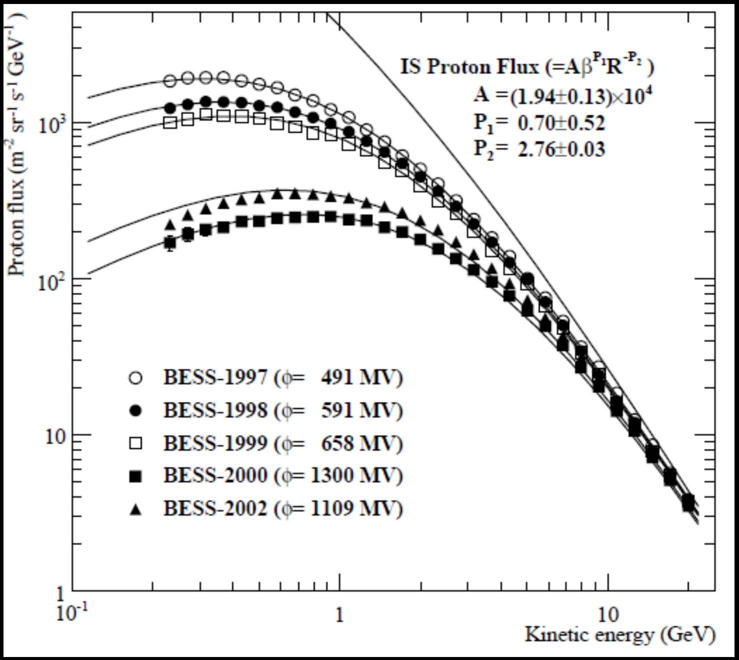
1. Transport in the Galaxy
→ Interstellar (IS) spectra




x $10^7$




size ~ 100 AU
<t> ~ a few years

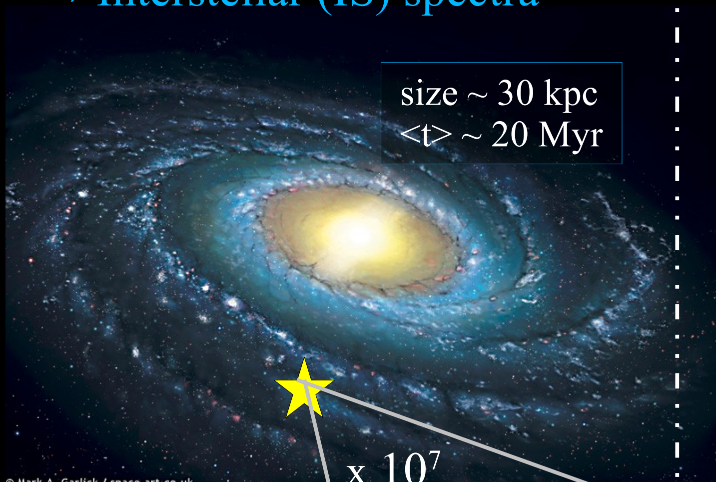



2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)

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

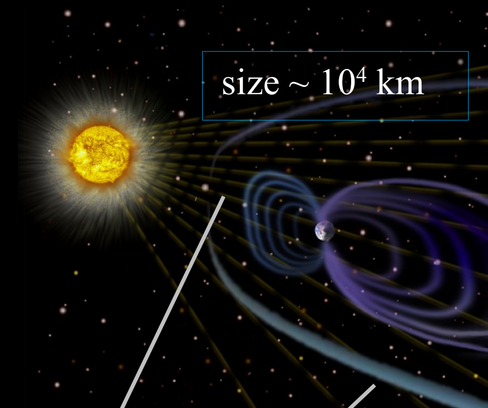
# Last steps before detection… R cutoff

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

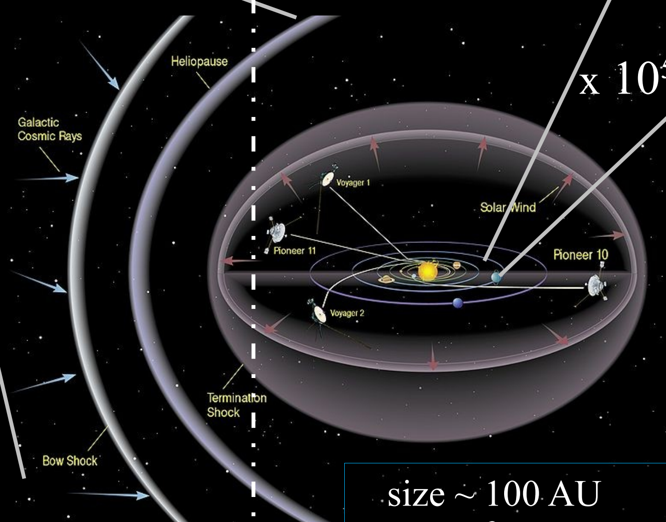


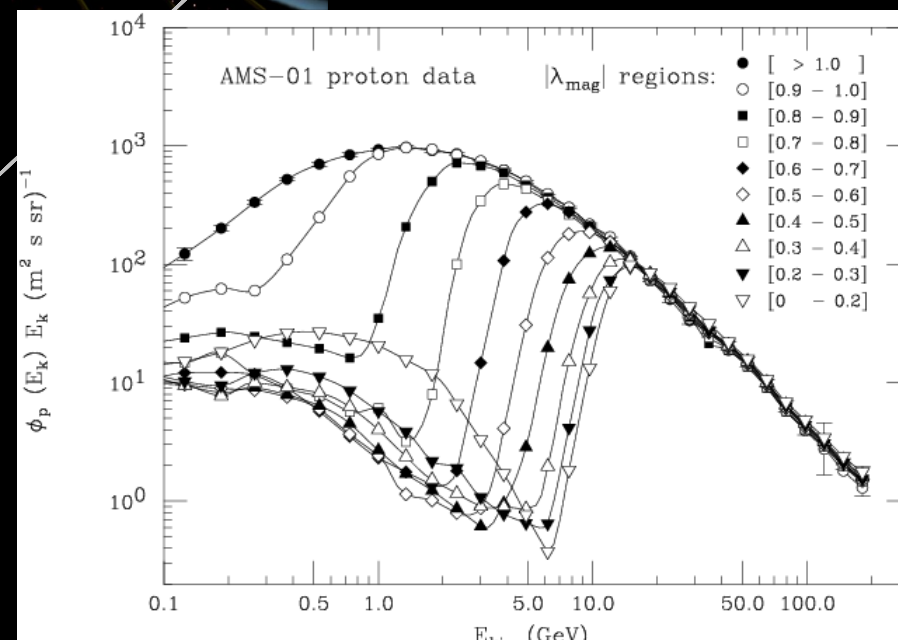

x $10^7$

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




x $10^5$



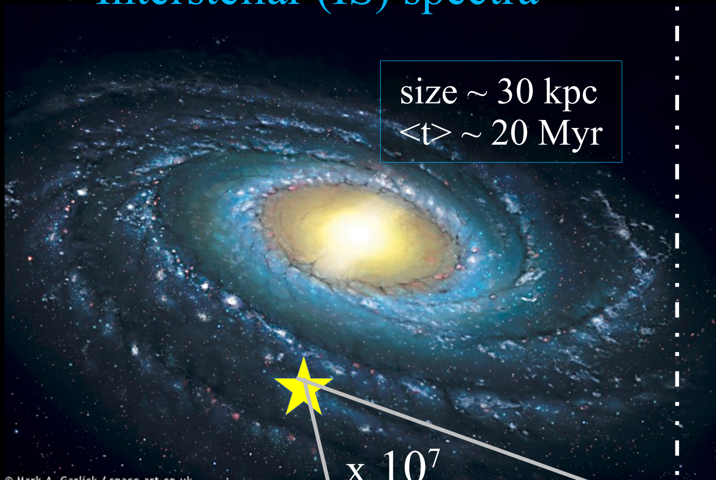




2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)

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

# Last steps before detection… atmosphere

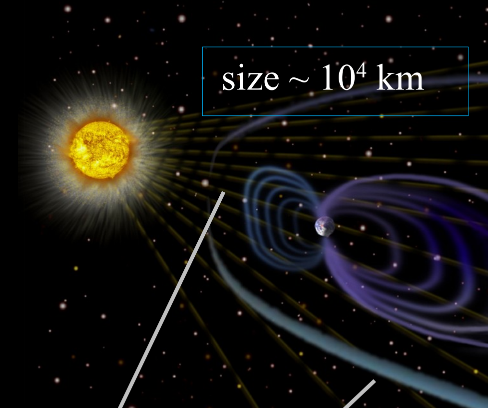
1. Transport in the Galaxy
→ Interstellar (IS) spectra




size ~ 30 kpc
<t> ~ 20 Myr

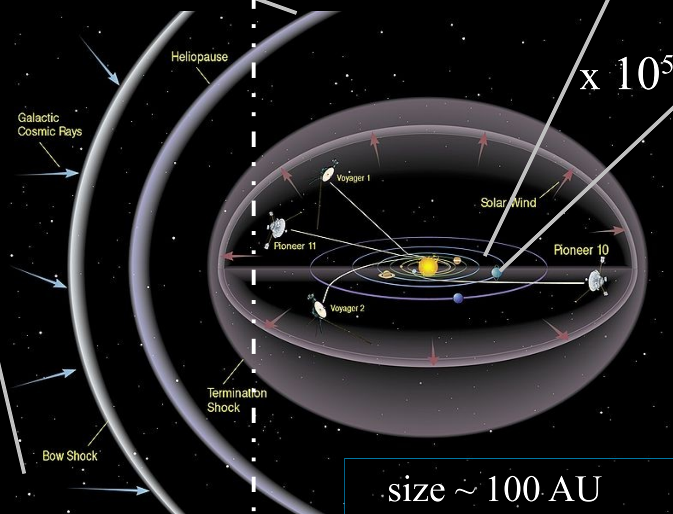
x $10^7$

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



size ~ $10^4$ km

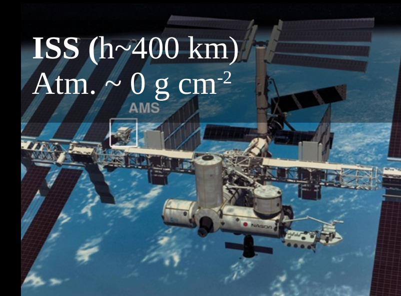
x $10^5$



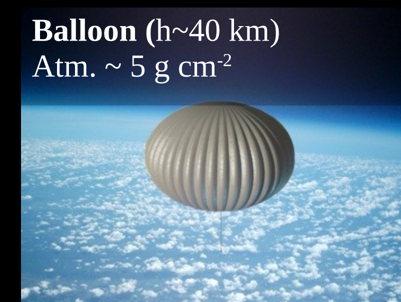

size ~ 100 AU
<t> ~ a few years

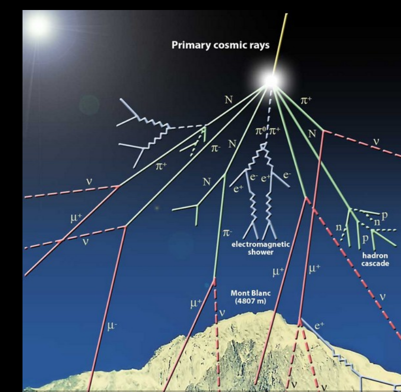
2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)

**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)

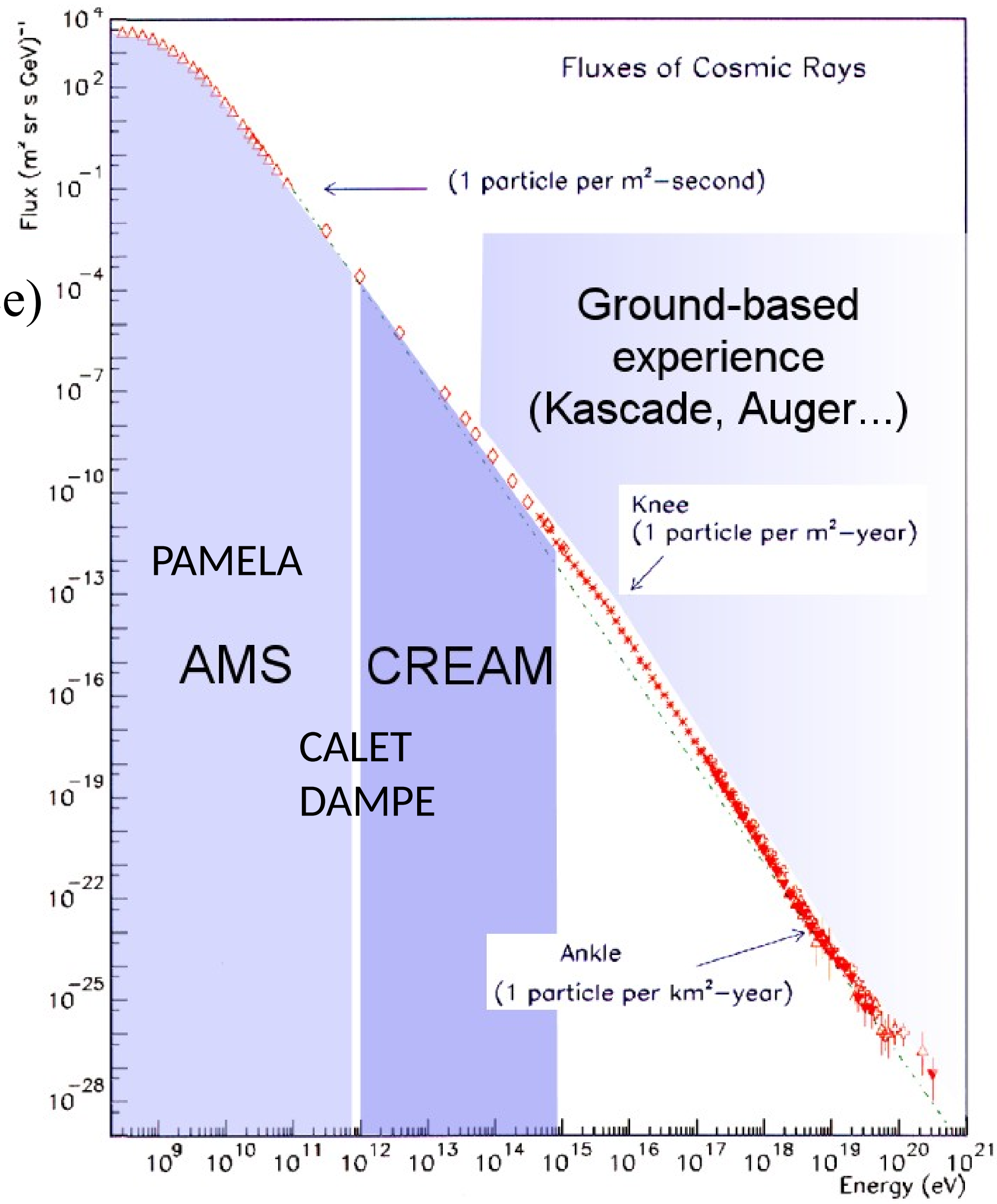
- Detectors “above” atmosphere (balloon or space)
- “Particle physics”-like detectors

→ 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



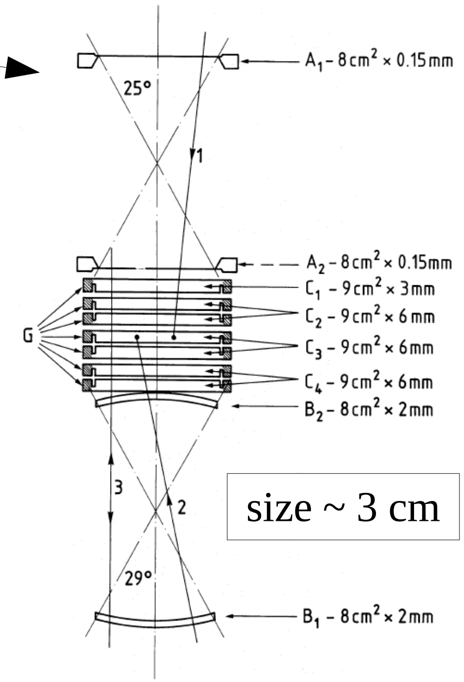
# Major GCR experiments

Balloon-borne experiments

Magnetic Spectrometer
Calorimeter

Experiments in space

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

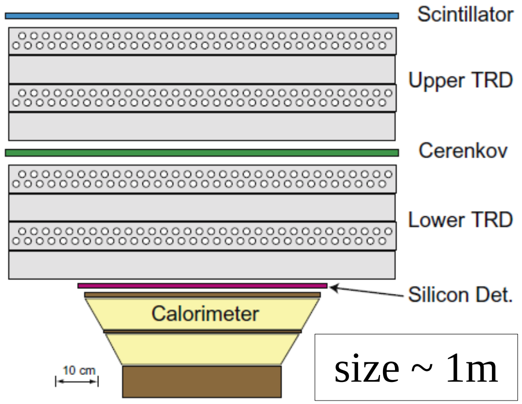



MASS (1989-1991)
IMAX (1992)
CAPRICE (1994-1998)
HEAT (1994-1995)
BESS (1994-2000)
ATIC (2000-2007)
TRACER (2006)
CREAM (2004-2010)

AMS01 (1998)

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

*Still taking data (+ongoing analyses)*



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→ 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 200  billion events so far!**

*To go further:*
- https://ams02.space/
- Aguilar et al., Phys. Rep. 894, 1 (2021)

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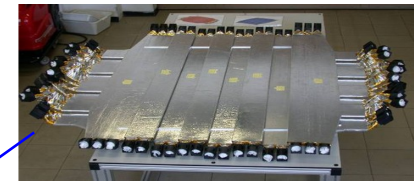
N.B.: Modern astroparticle detectors = particle physics detectors
→ **Use properties of particle-matter interactions to characterise the measured particles**

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

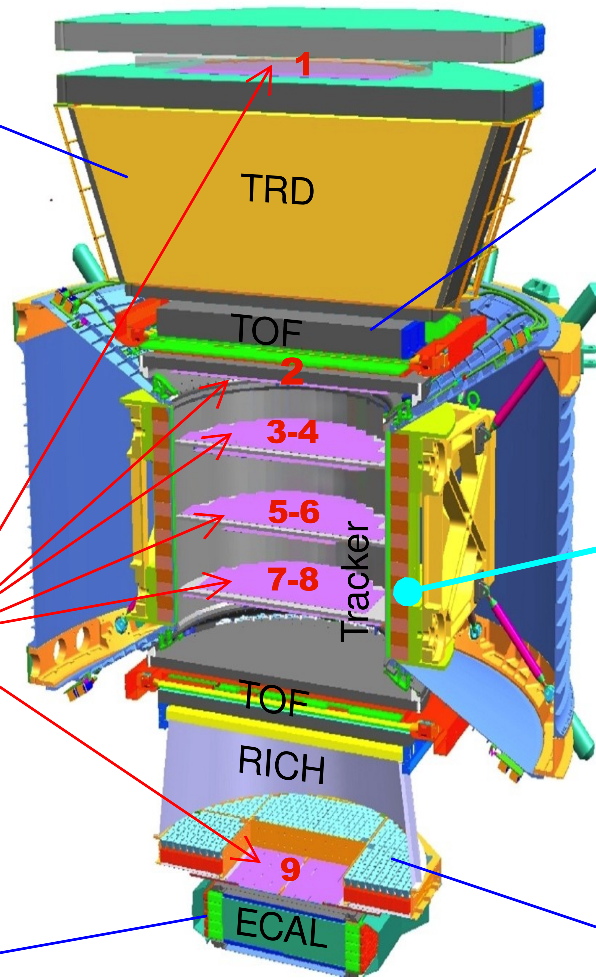
A TeV precision, multipurpose spectrometer in space.

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

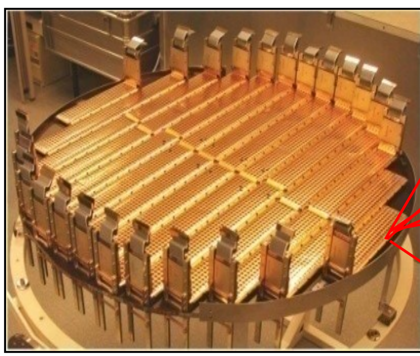
**TOF**
**Z, β**



**Magnet**
**R, ±Z**

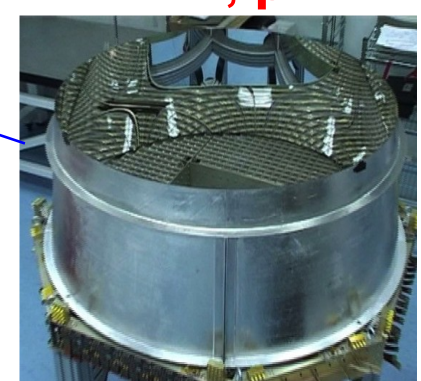



**Silicon Tracker**
**Z, p**



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

**RICH**
**Z, β**



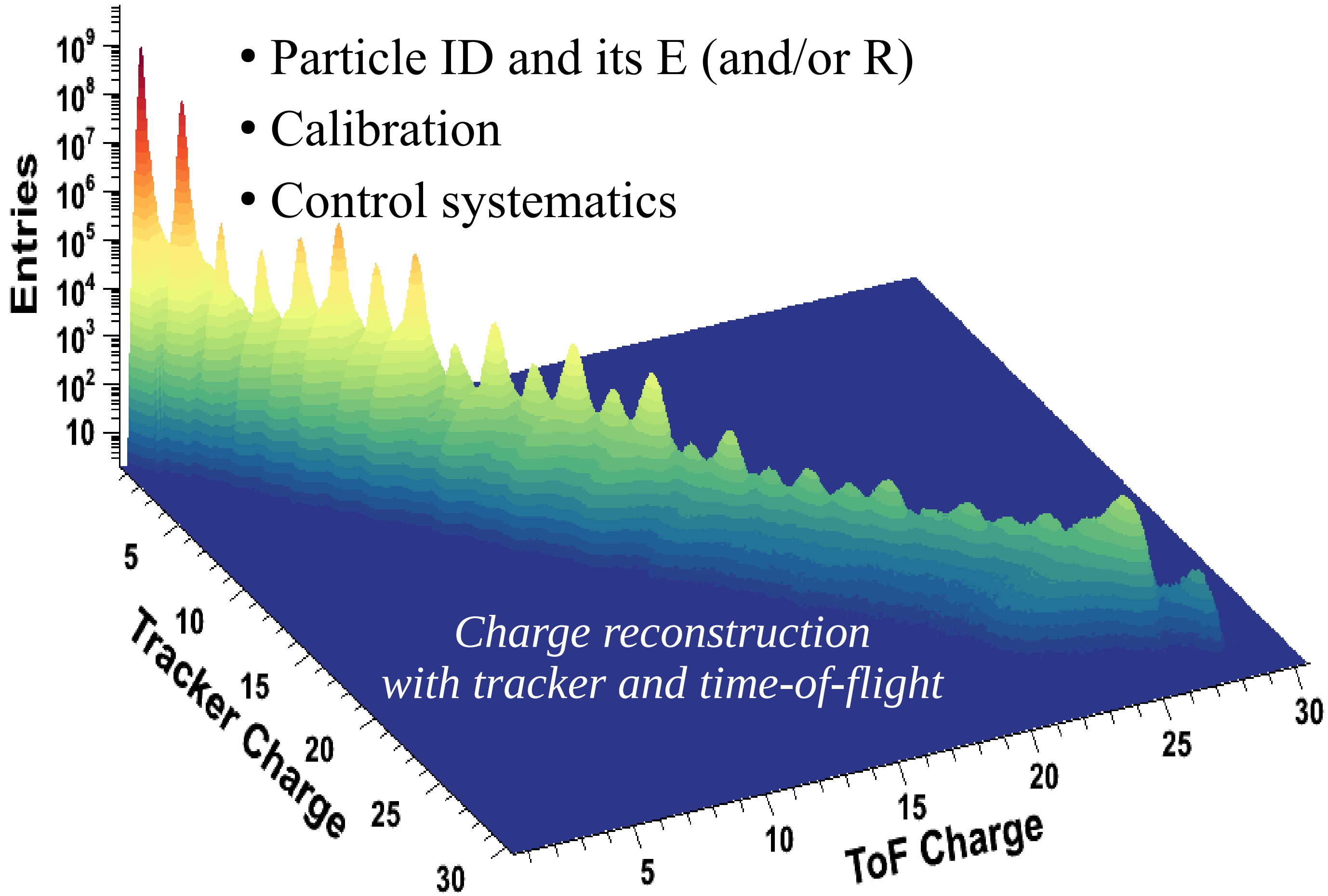
5m x 4m x 3m

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**

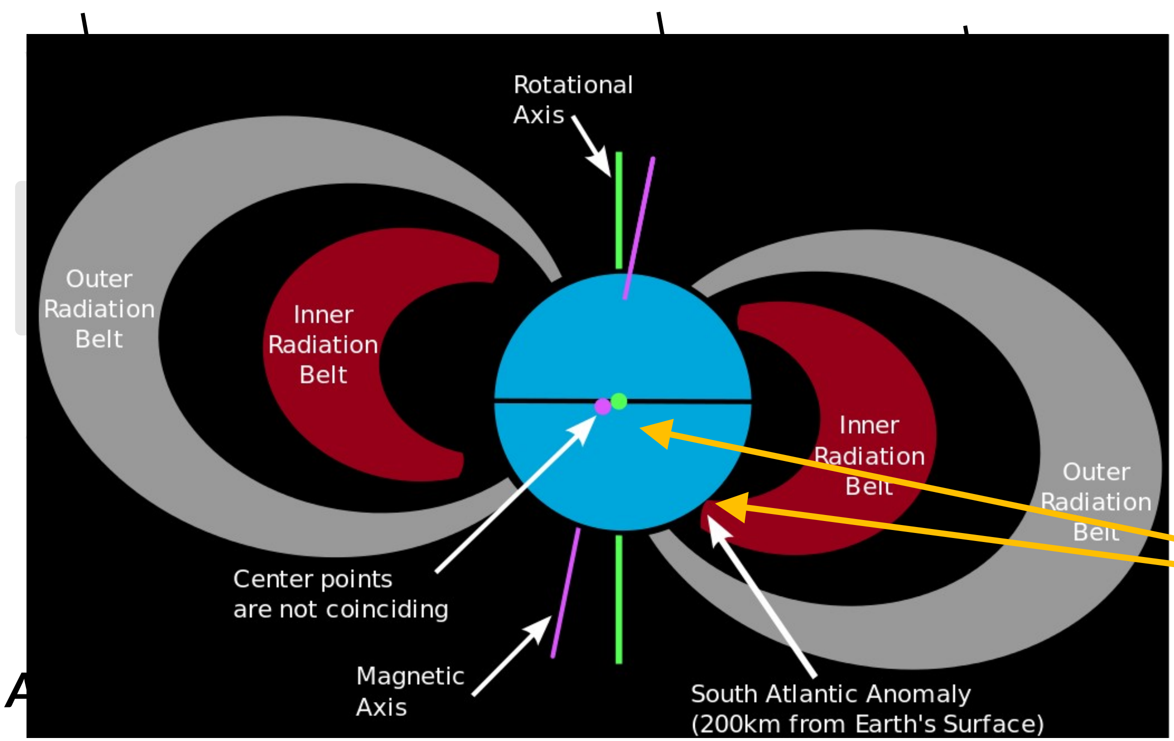
- Beam test
- In-flight data
- Monte Carlo sims

# AMS data analysis: proton flux

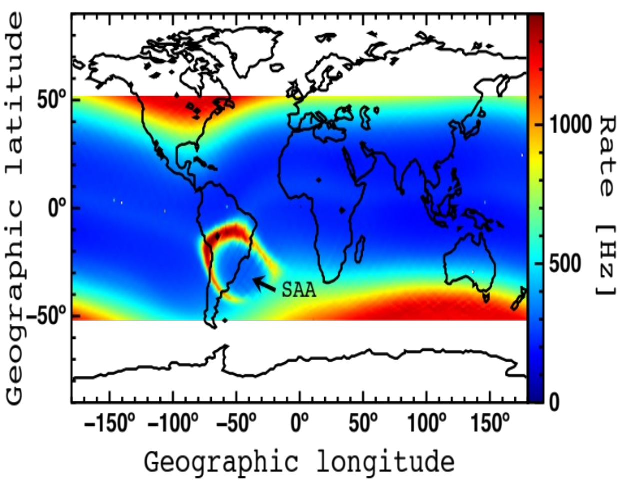
$$F(R) = \frac{N_{obs.}(R)}{T_{exp.}(R)\, A_{eff.}(R)\, \varepsilon_{trig.}(R)\, dR}$$

| | |
|---|---|
| $F$ | 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) |

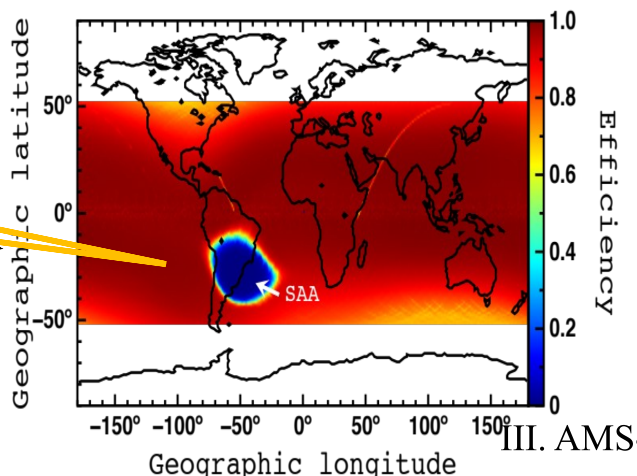
Trigger




Rate




$\varepsilon_{trg}$



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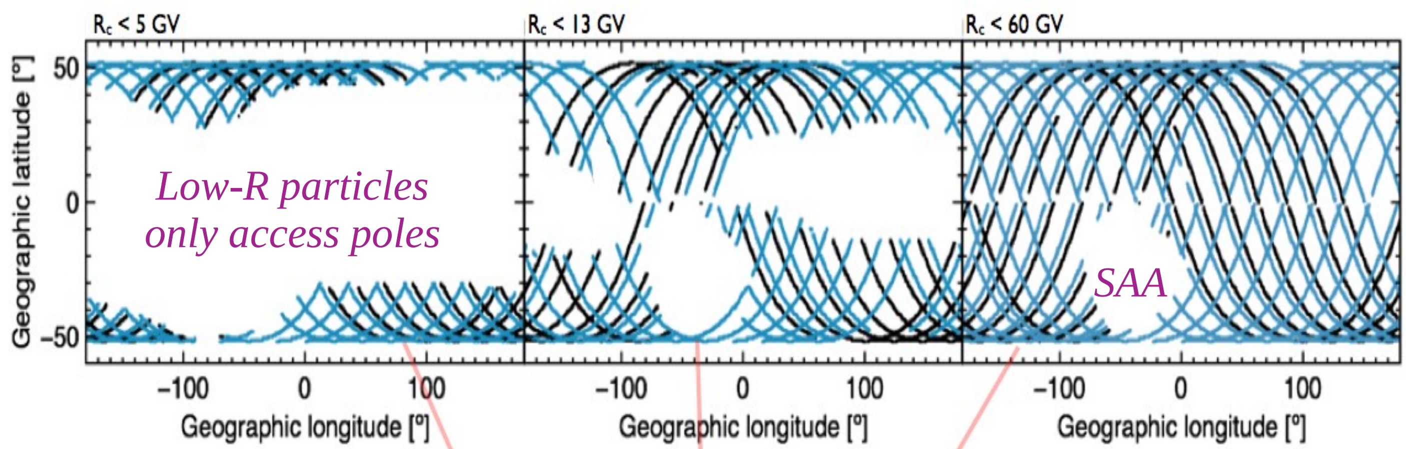
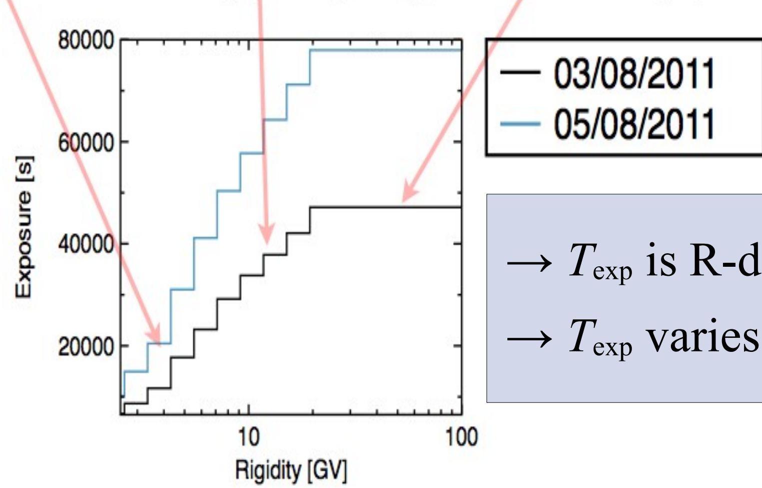
| $dR$ | Rigidity bin (GV) |




→ $T_{exp}$ is R-dependent

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

# AMS data analysis: proton flux

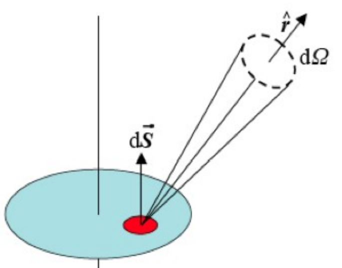
$$F(R) = \frac{N_{obs.}(R)}{T_{exp.}(R)\, A_{eff.}(R)\, \varepsilon_{trig.}(R)\, dR}$$

| | |
|---|---|
| $F$ | 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) |

- 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)*



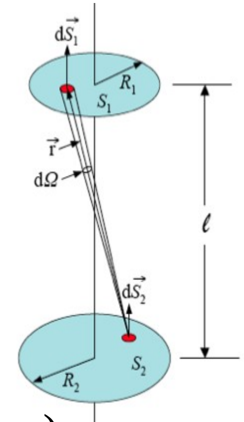

$$N(E) = \int_S \int_\Omega \int_t \int_{E-\frac{\Delta E}{2}}^{E+\frac{\Delta E}{2}} \phi(E')\epsilon(E', x, y, \theta, \phi)\underbrace{d\vec{\Omega}.d\vec{S}}\, dt\, dE'$$

- Acceptance of the detector

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

**Ideal telescope** (ε =1)

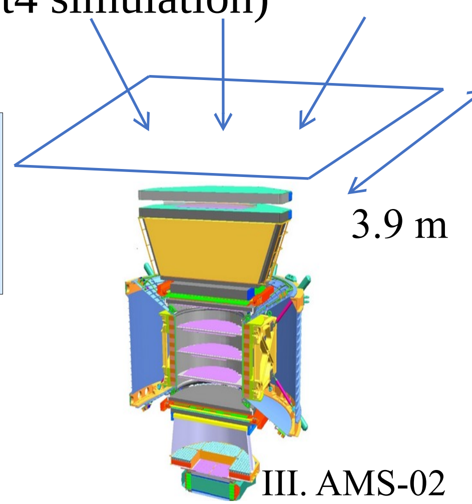
$$Acc(E) \approx \frac{S_1 S_2}{l^2}$$




**Real detector** (Geant4 simulation)

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

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



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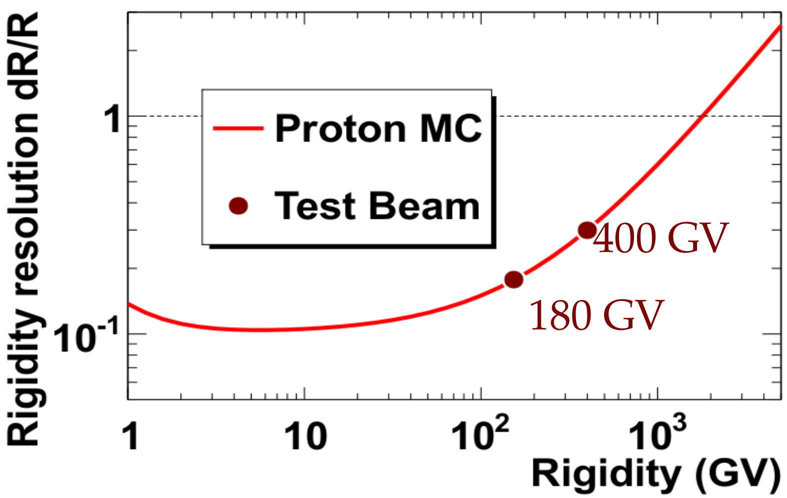
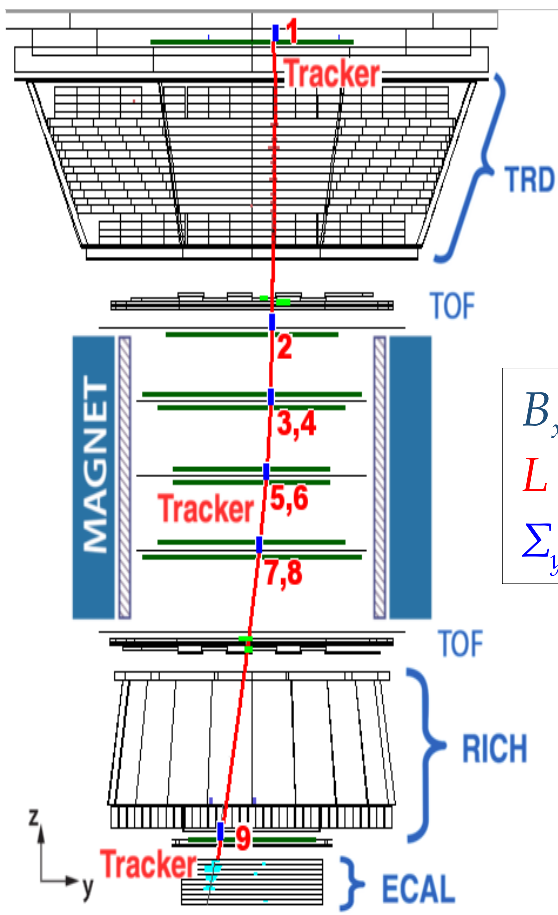
| d$R$ | Rigidity bin (GV) |

**Rigidity measurement**: trace curvature α 1/R

- Rigidity precision: related to trace reconstruction
- Max. detectable R: ~2 TV ("pixel" resolution)




$B_x$ = ~0.14 T
$L$ = ~3 m
$\Sigma_y$ = ~10 μm

# AMS data analysis: proton flux

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

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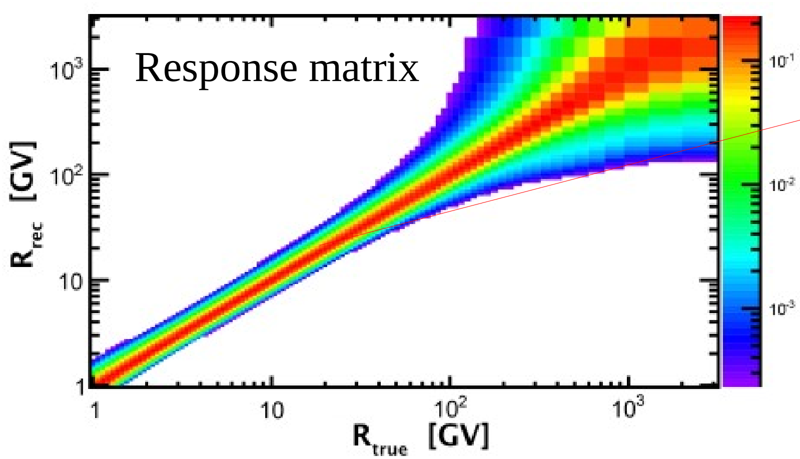
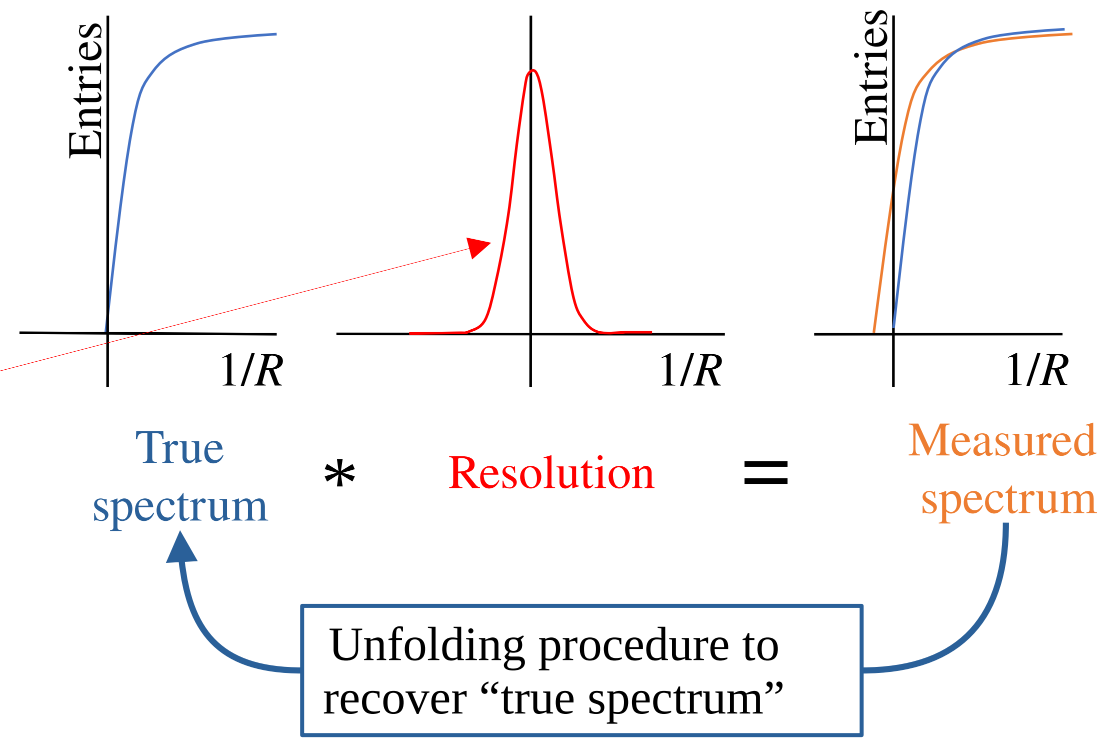
**Rigidity measurement**: trace curvature α 1/R

- Rigidity precision
- Max. detectable R

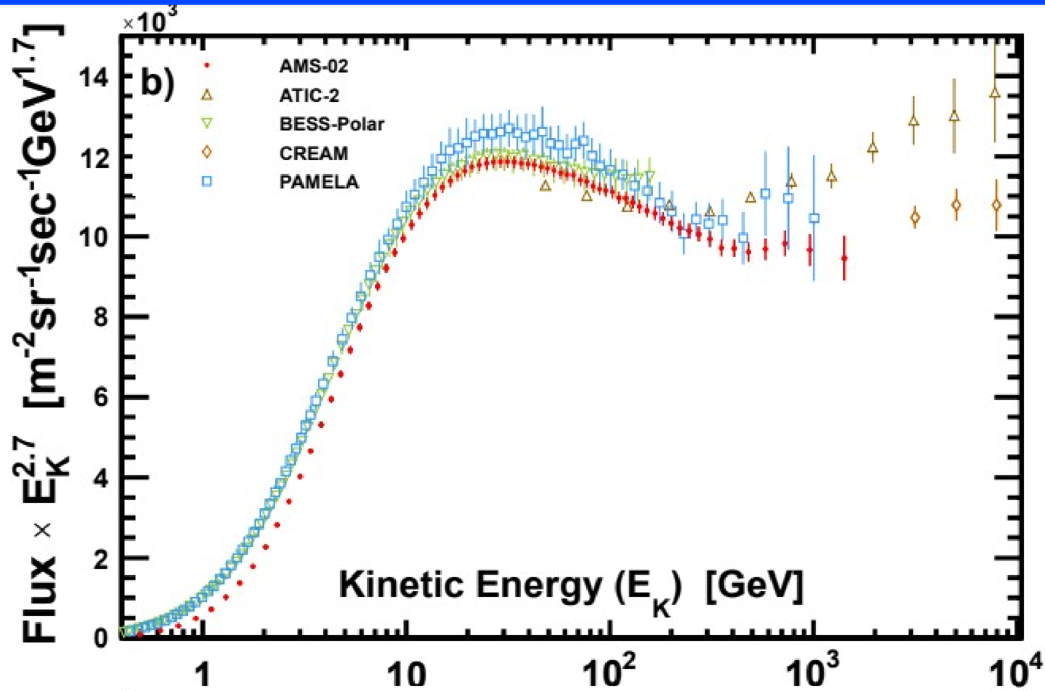
→ **Finite energy resolution!**



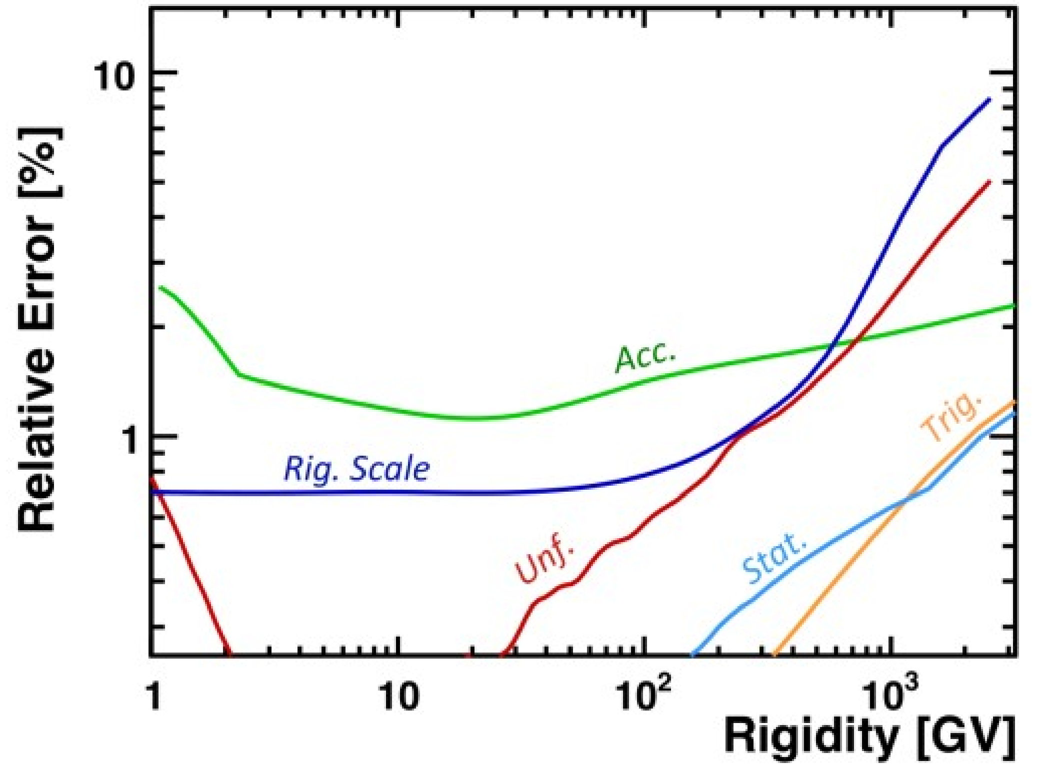
# AMS data analysis: proton flux

**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 puzzle: sources, transport...

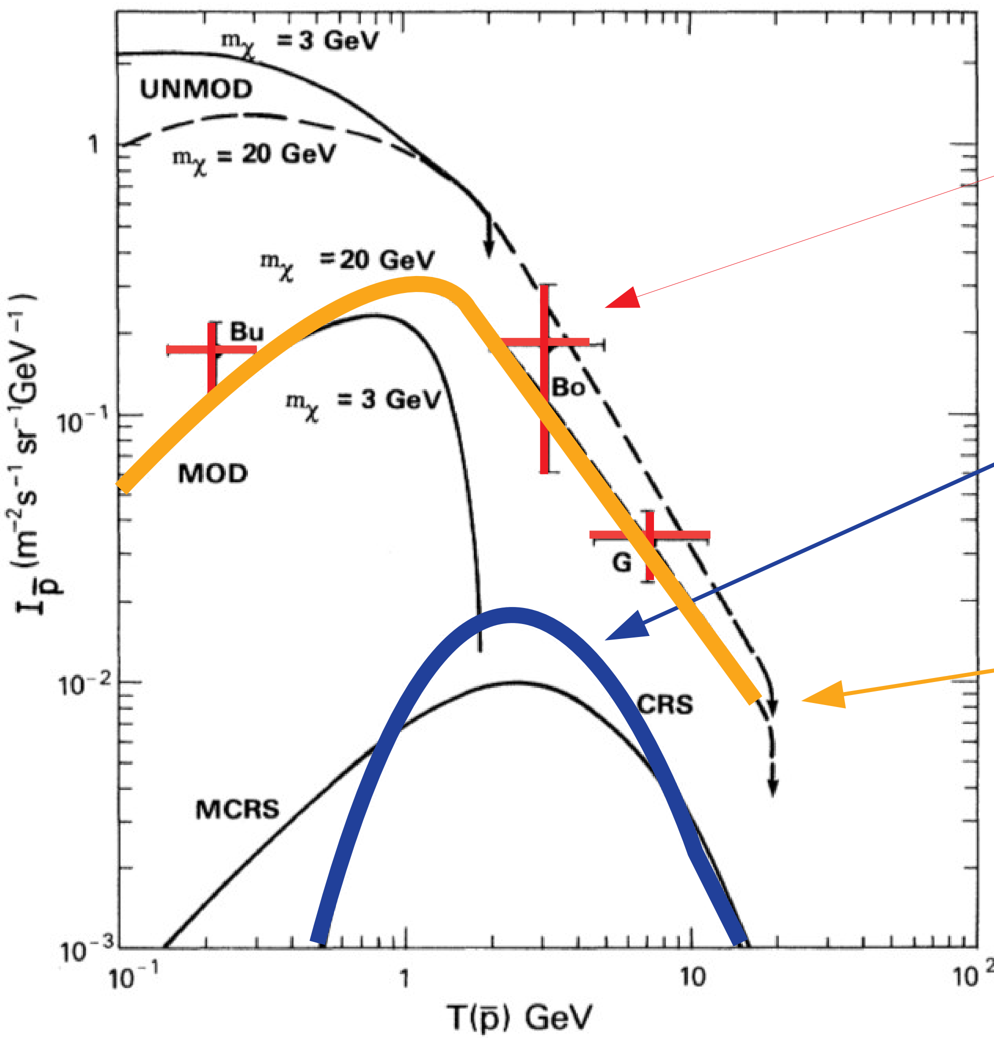
II. CR experiments: overview

III. AMS-02 experiment: data analysis

IV. Dark matter in AMS-02 data?

# Dark matter detection in CRs?

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




First pbar data
(ballon-borne)

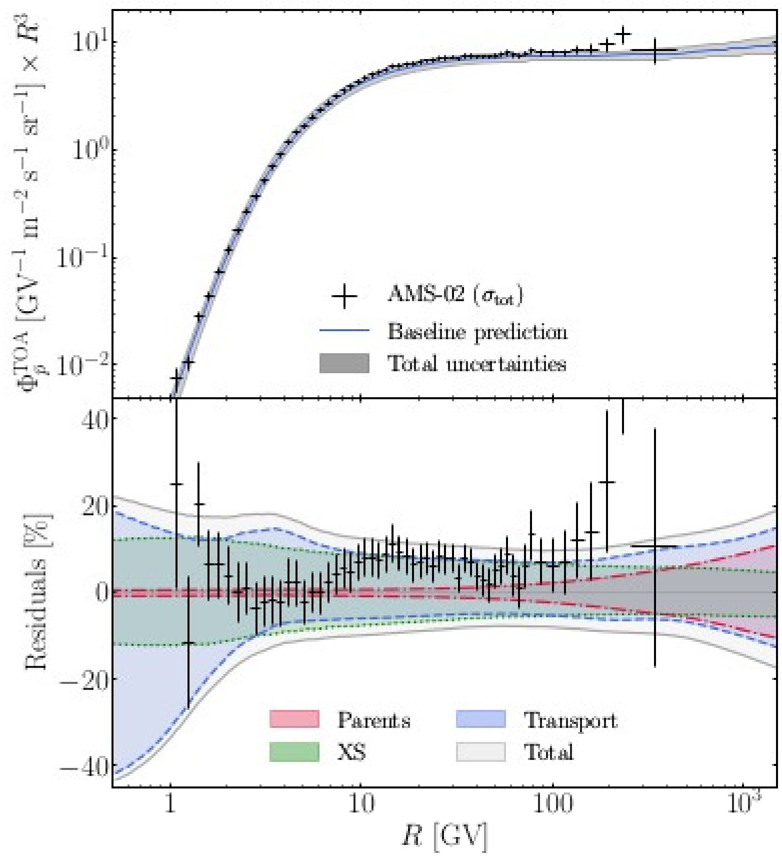
Astrophysical
“background”
(secondary pbar)

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)

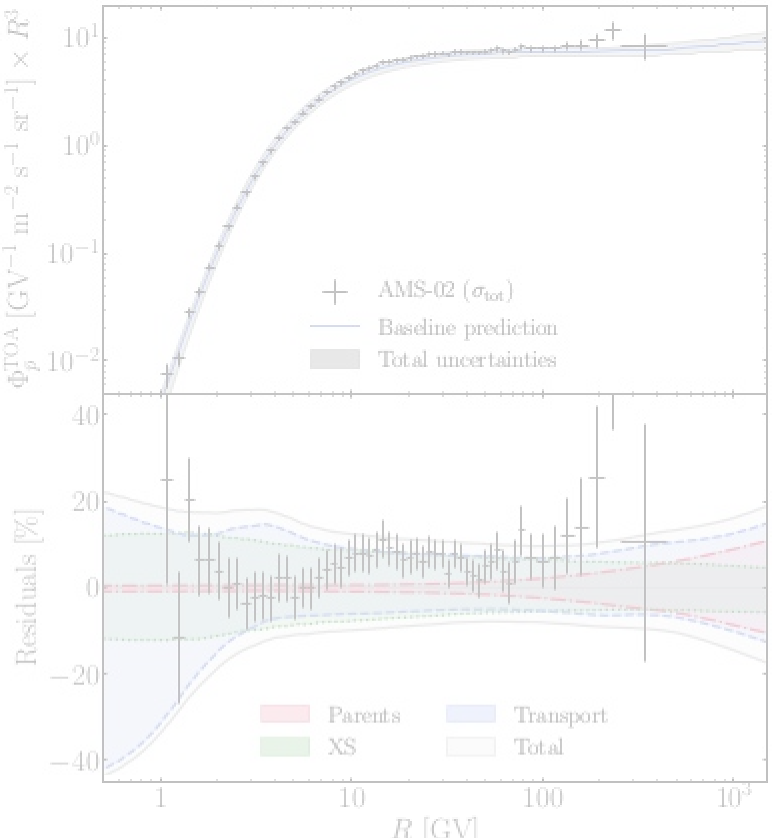



**Antiprotons**

→ Uncertainties dominated by nuclear cross sections
→ Data consistent with astrophysics only
→ Constraints can be set of dark matter candidates (e.g. Calore et al., 2022)

# Dark matter detection with AMS-02?

Boudaud, Génolini et al. (2019)

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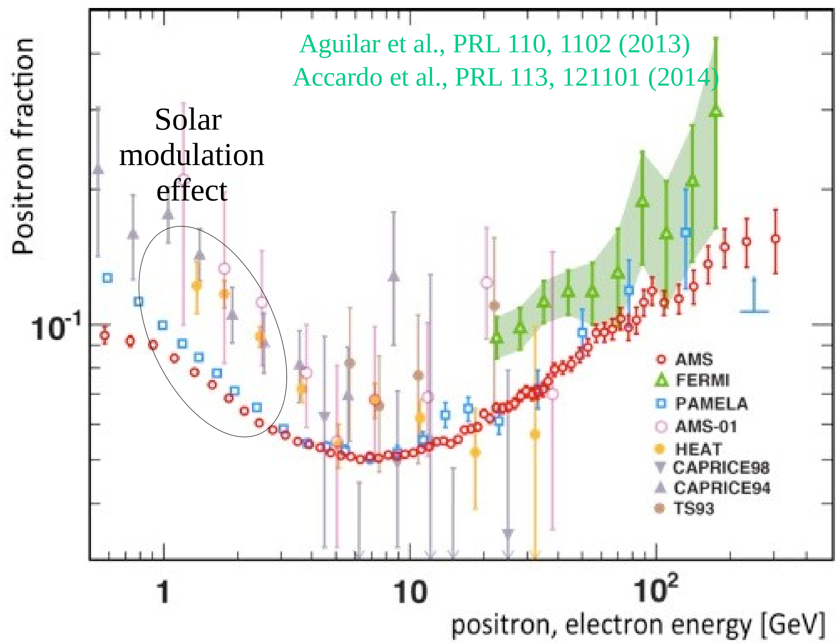



**Positron fraction, $e^-$, $e^+$ and $e^-$+$e^+$ spectra used to test astrophysical and/or dark matter hypothesis**

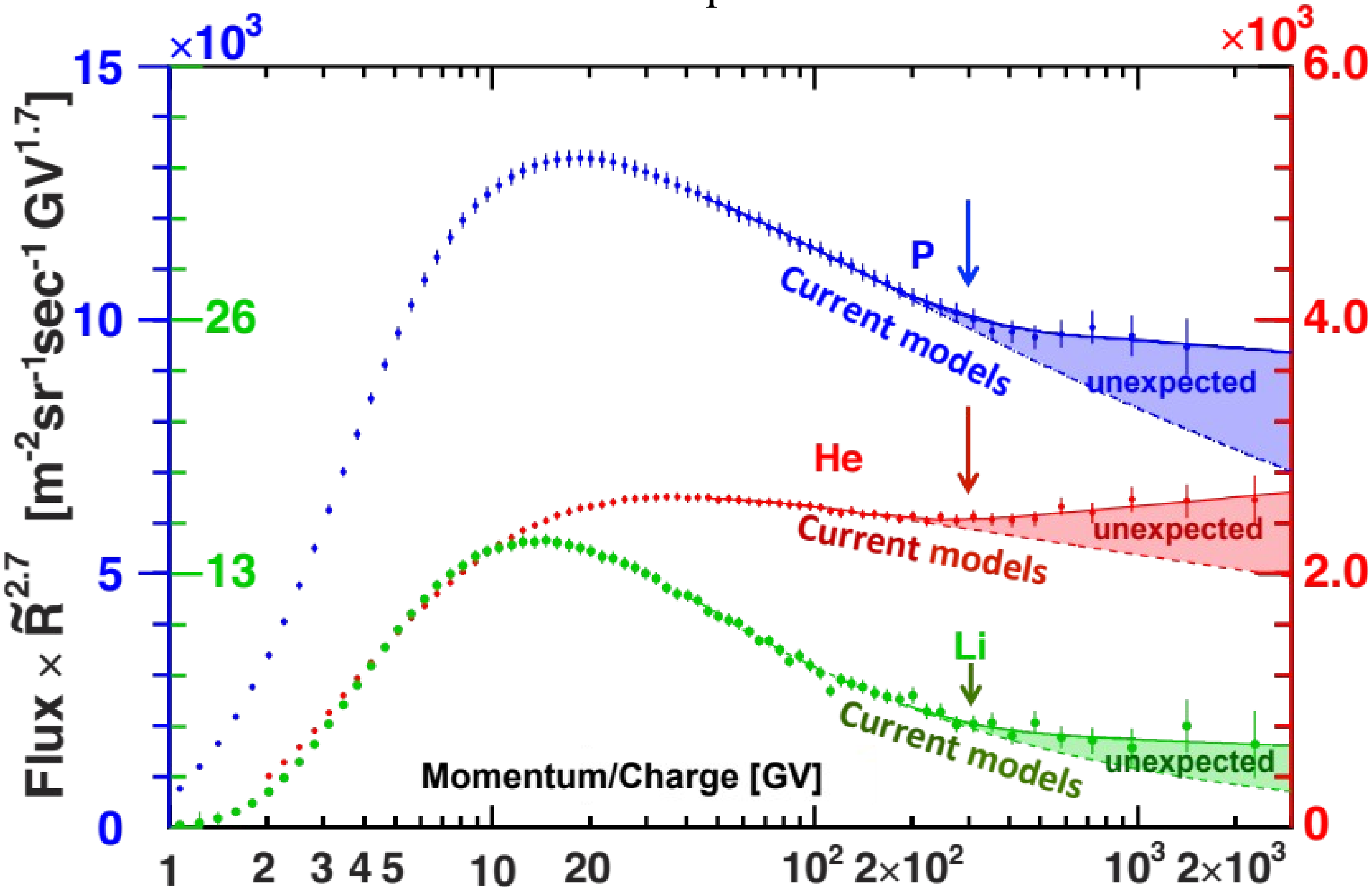
- Contribution from local SNRs/pulsars?
  → e.g., Delahaye et al., A&A 524, A51 (2010)

- 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)]

# Unexpected results: breaks

→ Spectral break at ~300 GV

→ Different slope H and He




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

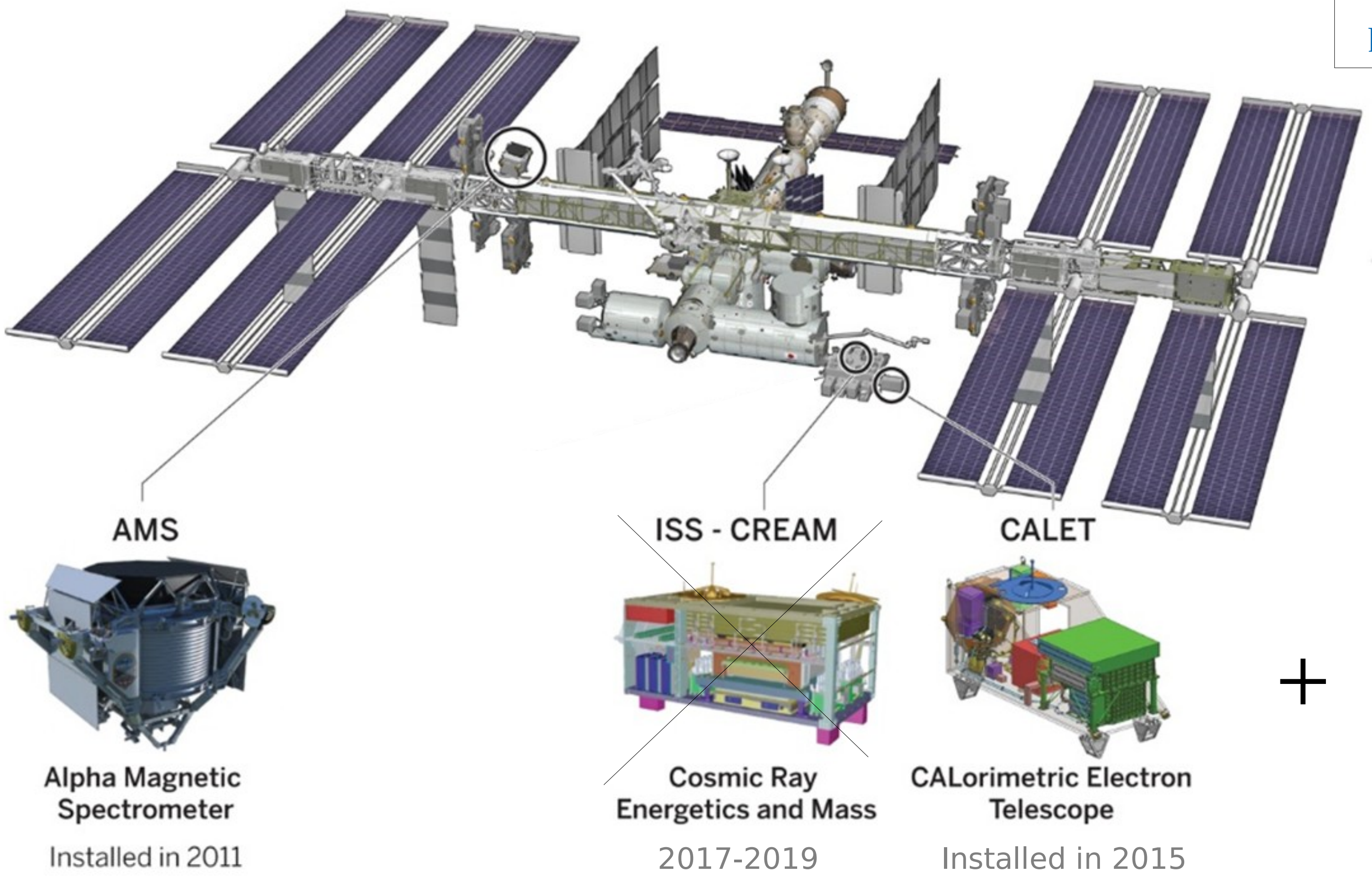
Aguilar *et al.*,
PRL 120, 021101 (2018)

→ most likely transport (not source spectrum)
[coupling CR/B/gas via MHD]

# Conclusions

→ Wealth of new GCR data...

*For more on CR data and useful links*
https://lpsc.in2p3.fr/crdb




+

**DAMPE satellite**

Launched in 2015

… triggered many theoretical studies and debates

*N.B.: by 2024, LAPP or LPSC teams no longer involved in charged CR experiments*