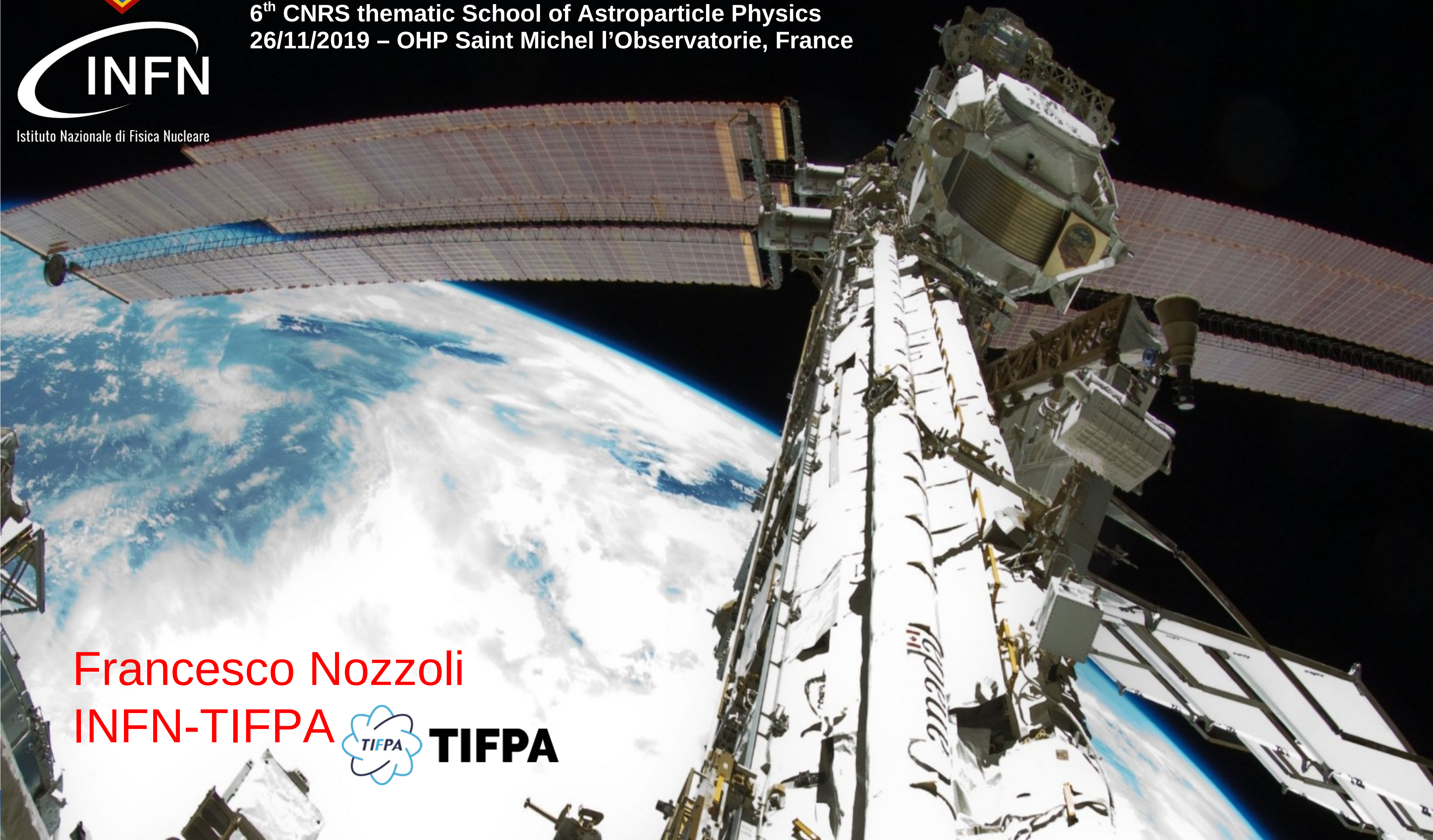
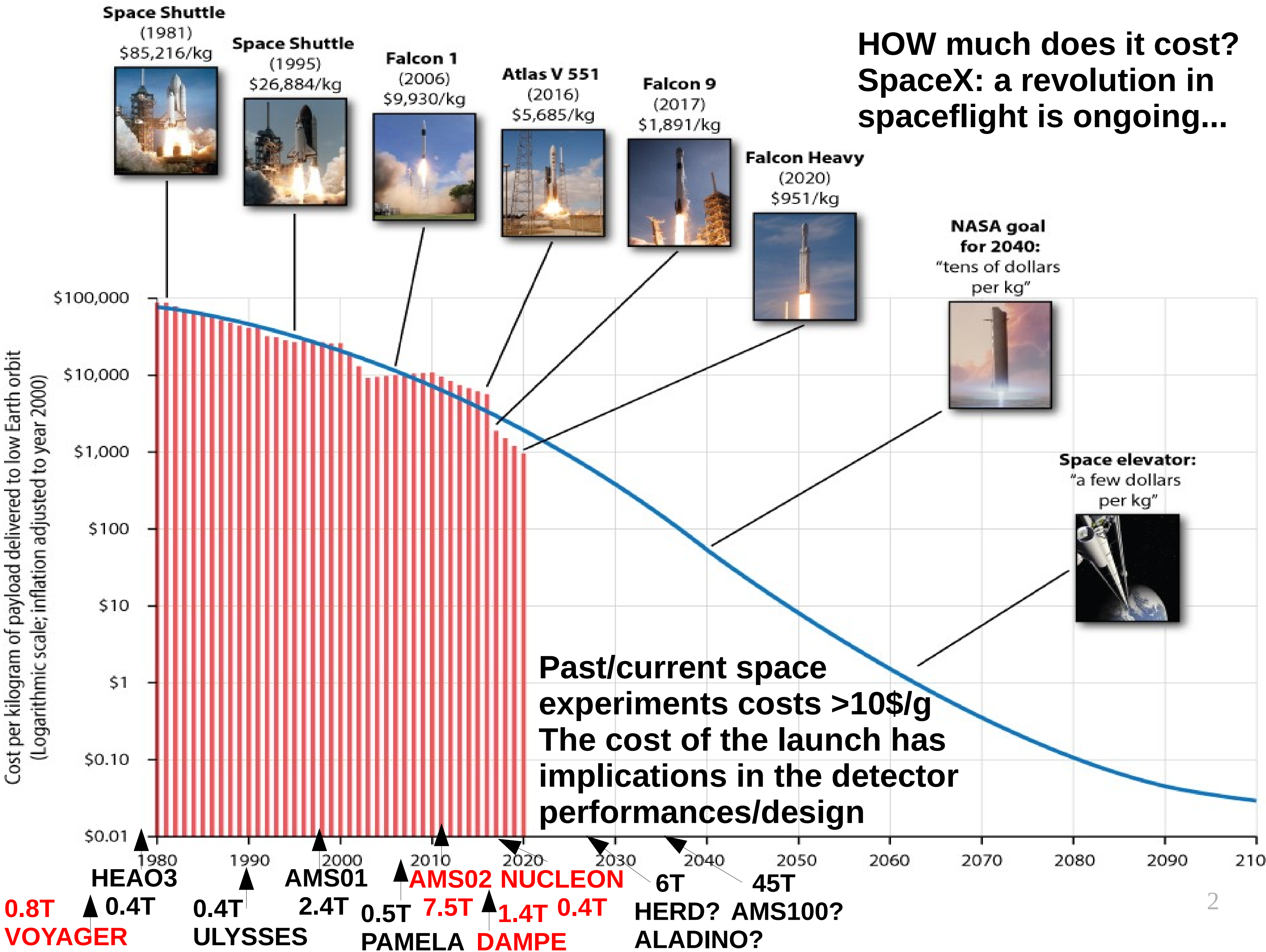
Detection of high-energy particles from the Universe: basic concepts, methods, and challenges

6th CNRS thematic School of Astroparticle Physics
26/11/2019 – OHP Saint Michel l'Observatorie, France



Francesco Nozzoli
INFN-TIFPA

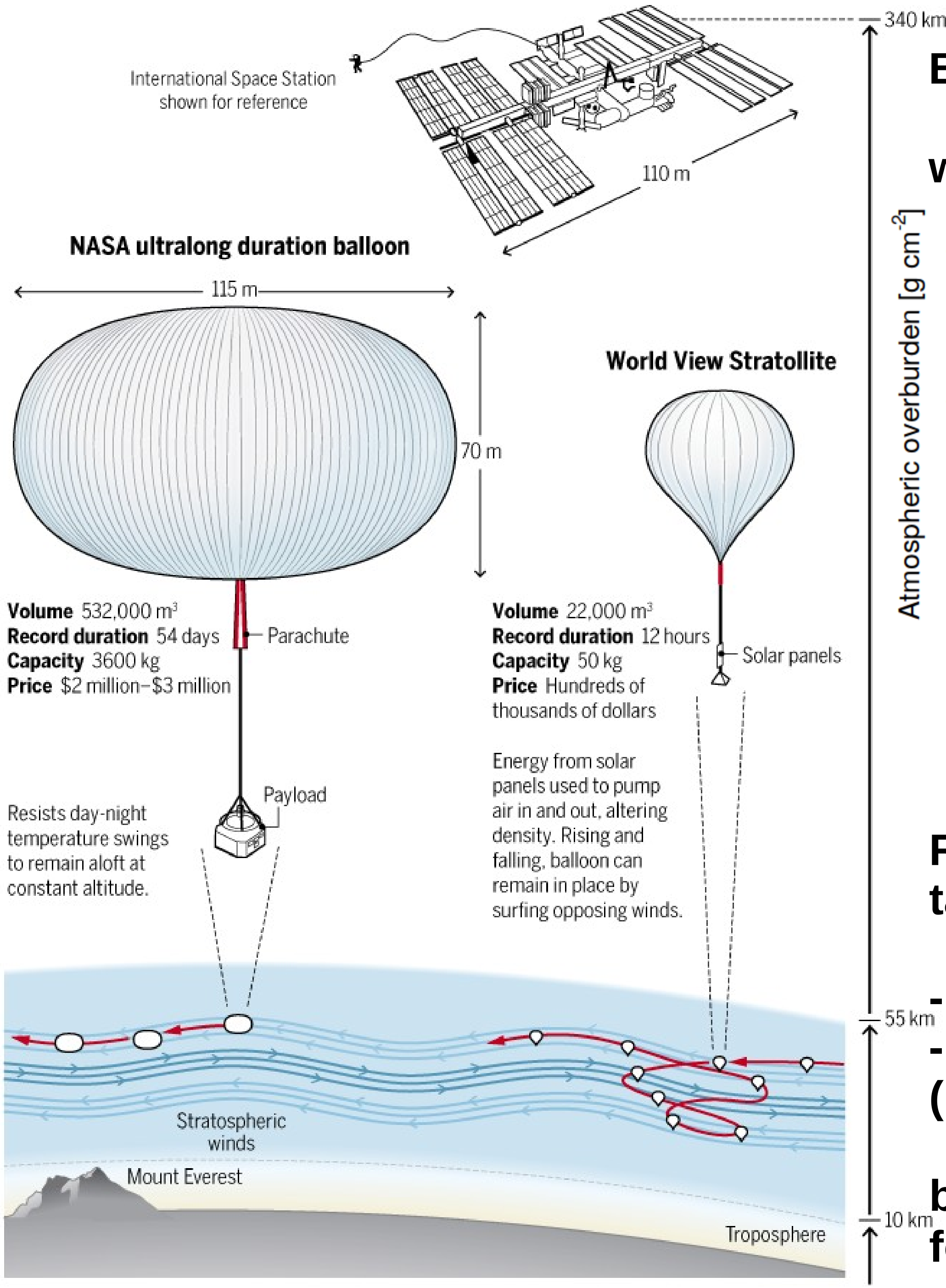
HOW much does it cost? SpaceX: a revolution in spaceflight is ongoing...

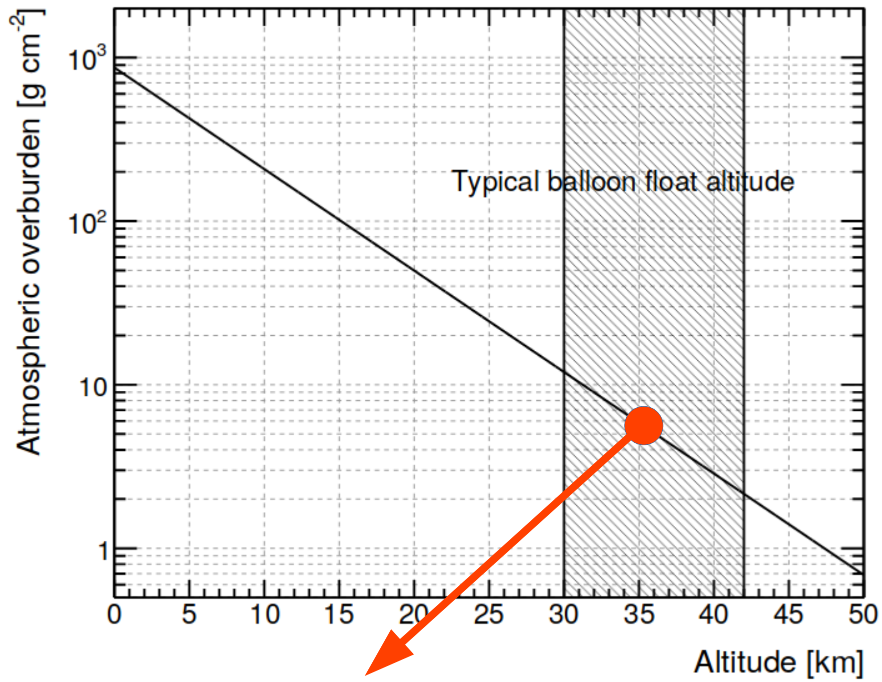


Past/current space experiments costs >10$/g
The cost of the launch has implications in the detector performances/design

Balloons? Not really cheaper now …

was an option for past experiments

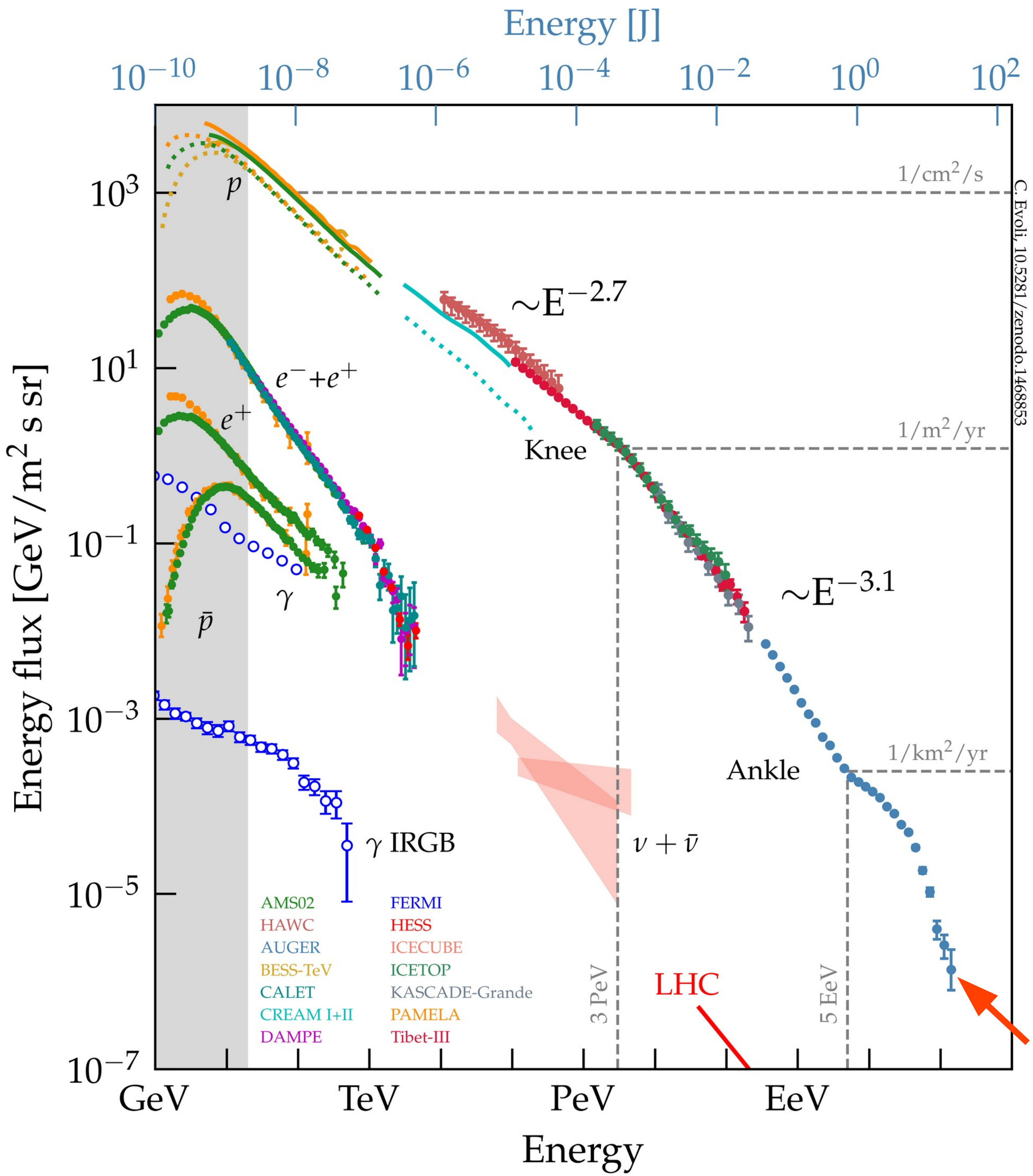




Residual atmosphere is a passive target: the same of 5 cm of plastic

- **Fragmentation effects**
- **Production of secondary particles (problem for antimatter search)**

by comparison Galaxy grammage for CR typ. path lenght is ~2 g/cm^2



88 % of protons

10 % of He

<1% of heavy nuclei

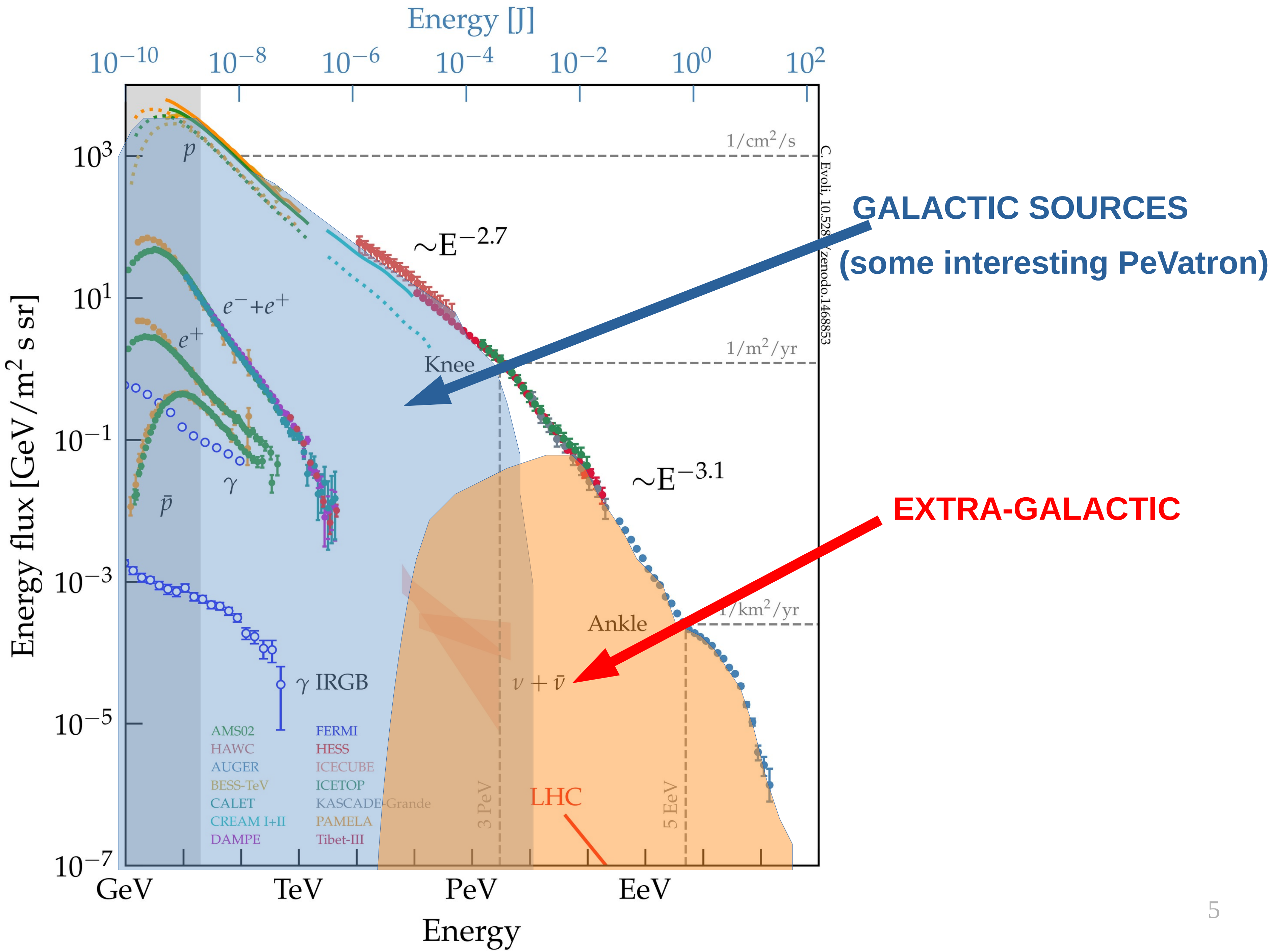
1% of electrons

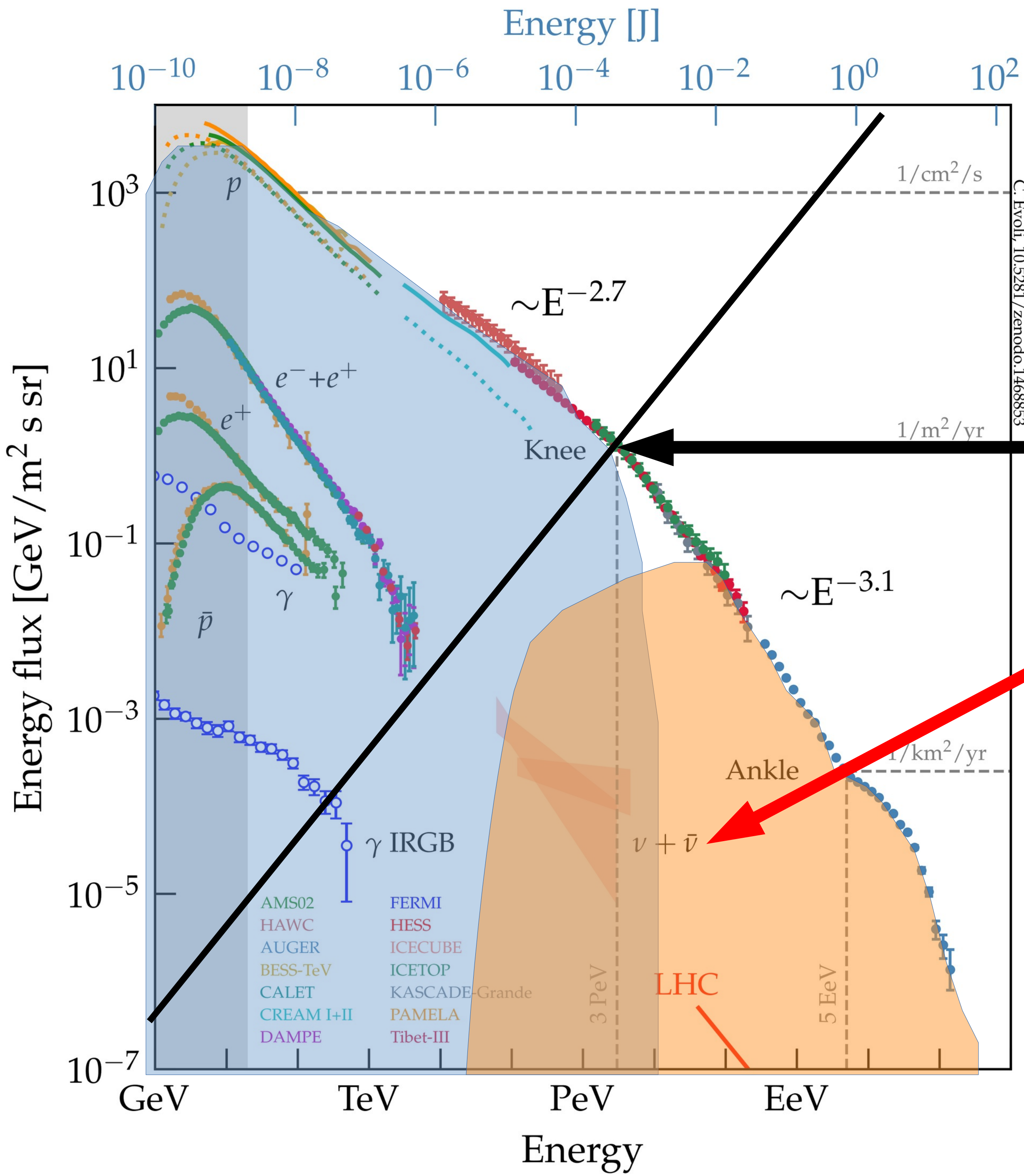
rare components

$\bar{p}/p \sim 10^{-4}$

$e^+/e^- \sim 10^{-1}$

your kinetic energy during a quiet walking (3km/h) … but the momentum of just a single eyelash hair ...


Energy [J]
10^−10
10^−8
10^−6
10^−4
10^−2
10^0
10^2
1/cm²/s
1/m²/yr
1/km²/yr
C. Evoli, 10.5281/zenodo.1468853
p
~E^−2.7
e^− + e^+
e^+
γ
p̄
Knee
~E^−3.1
Ankle
ν + ν̄
γ IRGB
AMS02
HAWC
AUGER
BESS-TeV
CALET
CREAM I+II
DAMPE
FERMI
HESS
ICECUBE
ICETOP
KASCADE-Grande
PAMELA
Tibet-III
3 PeV
5 EeV
LHC
Energy flux [GeV/m² s sr]
10^3
10^1
10^−1
10^−3
10^−5
10^−7
GeV
TeV
PeV
EeV
Energy
GALACTIC SOURCES
(some interesting PeVatron)
EXTRA-GALACTIC



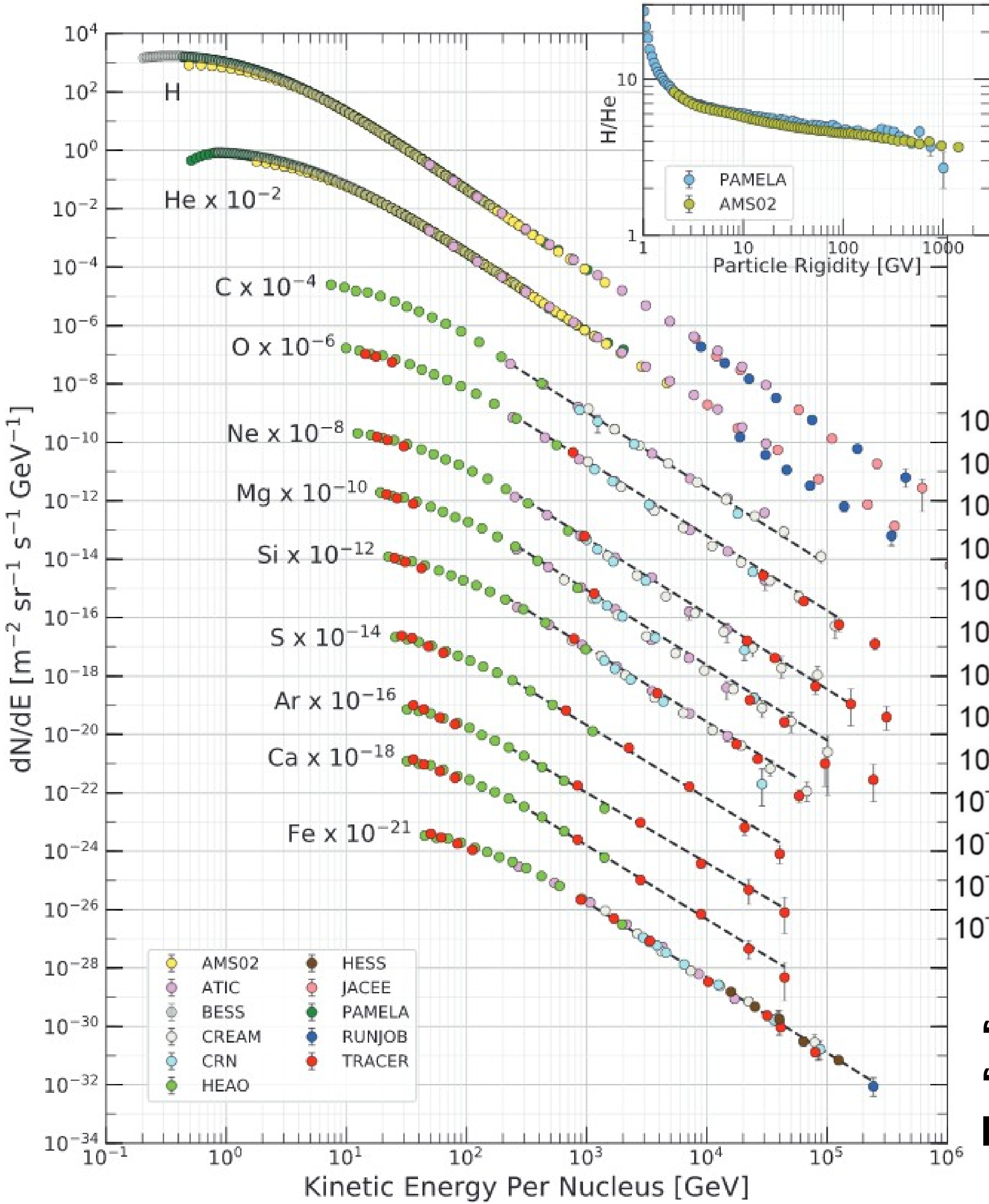
GALACTIC SOURCES

Direct measurement of cosmic rays with a detector in space are feasible above this line (m^2 acceptance x year)

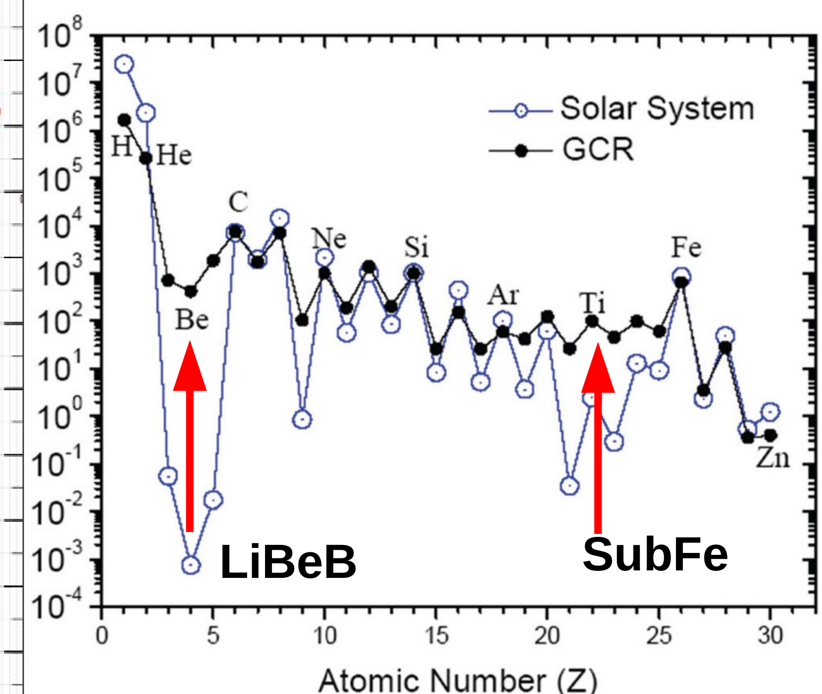
EXTRA-GALACTIC

Indirect measurements (next lectures …)

Cosmic Ray composition:

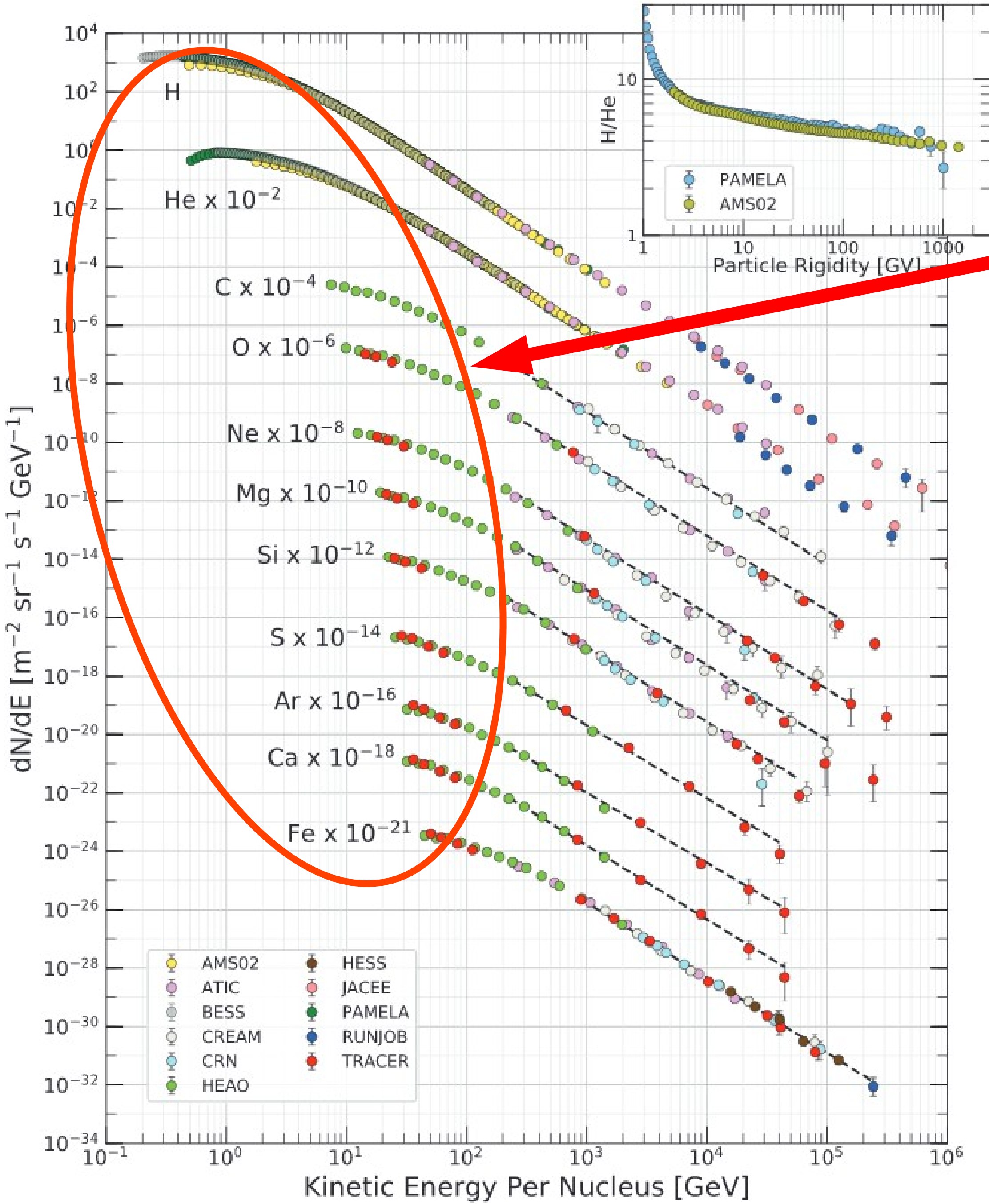


NUCLEI composition:
- particle charge
- particle "Energy"



"High" abundances of "secondary nuclei" Production by Fragmentation

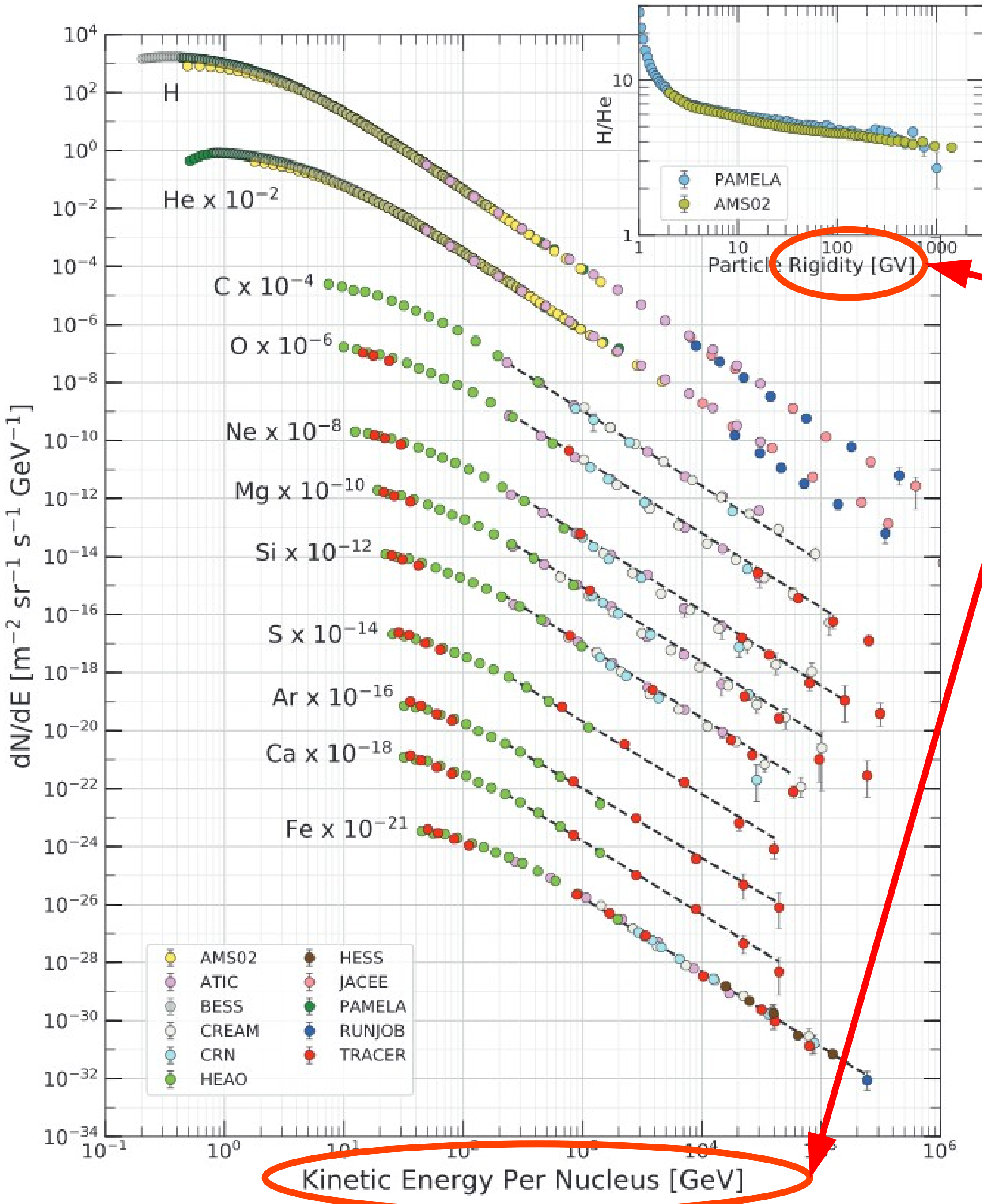
Cosmic Ray composition:



NUCLEI composition:

- **particle charge**
- **particle "Energy"**

Cosmic Ray composition:



NUCLEI composition:
- particle charge
- particle "Energy"

which "Energy"?

Kinetic Energy: calorimeters (ATIC, JACEE, RUNJOB)

E/nucleon: TRD, Cherenkov (CRN-Spacelab, HEAO, HESS, CREAM, TRACER, HESS)

Rigidity (P/Z): Spectrometers (AMS02, Pamela, Bess)

Energy vs Energy/nucleon vs Rigidity: Measurement + Physics

RIGIDITY: GV (Giga-Volt)

MEASUREMENT: P/Z is the quantity related to the trajectory in magnetic field
(easily converted to Momentum knowing the particle charge Z)

PHYSICS:
Different particles with same rigidity follow the same trajectory in magnetic fields
(in the Galaxy, in the Heliosphere, in the Earth magnetic field, in the detector field)
Main effects of propagation in the magnetic field (and the main time dependent solar modulation effects) would cancel out in <Flux Ratio> vs <Rigidity>

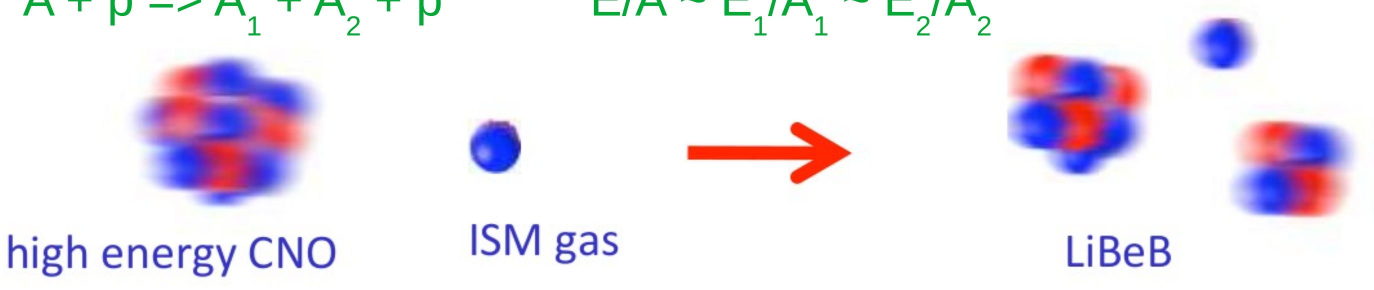
- -

Energy/nucleon: GeV/n (usually average isotopic composition is assumed)

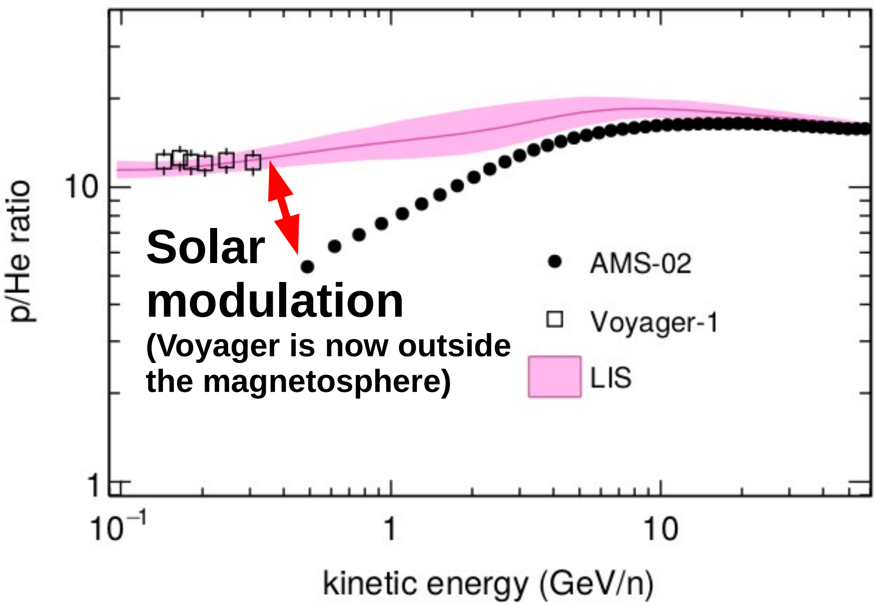
MEASUREMENT: is a quantity related to velocity (ToF, RICH, TRD)
(they measure GeV/M and cannot be converted to Energy if mass is unknown)

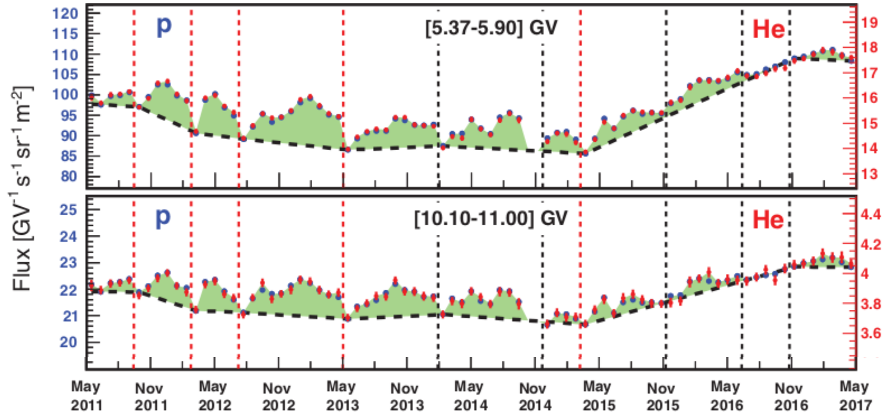
PHYSICS:
Fragmentation of nuclei roughly conserve E/n in spallation processes
(when a relativistic CR nuclei during propagation interacts on a proton of ISM)

$A + p \Rightarrow A_1 + A_2 + p$ $\qquad E/A \sim E_1/A_1 \sim E_2/A_2$

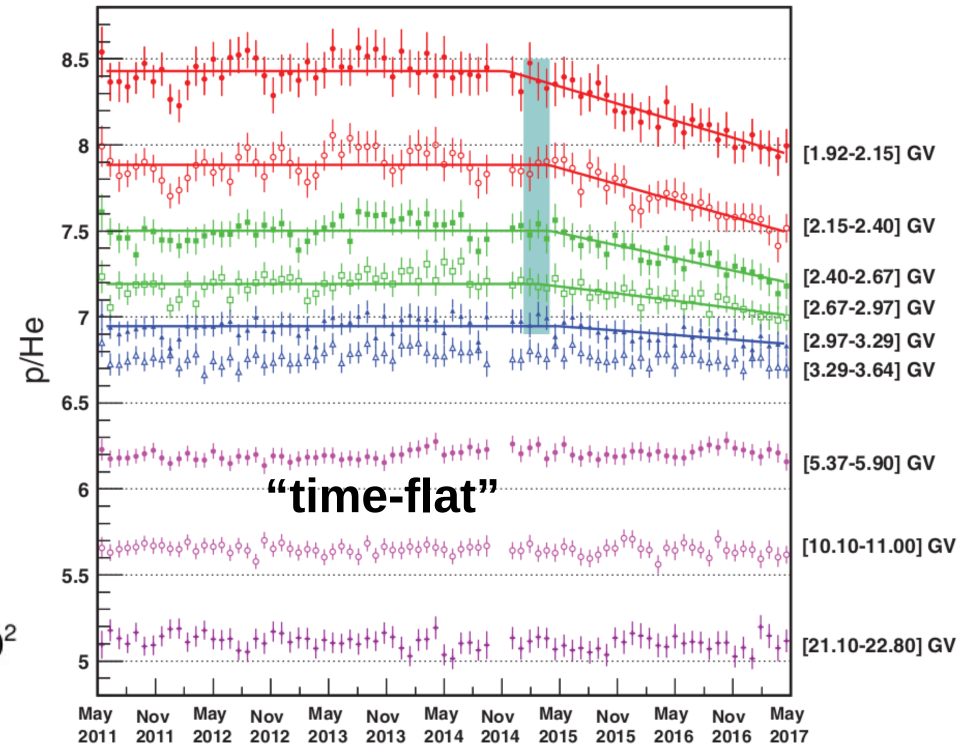


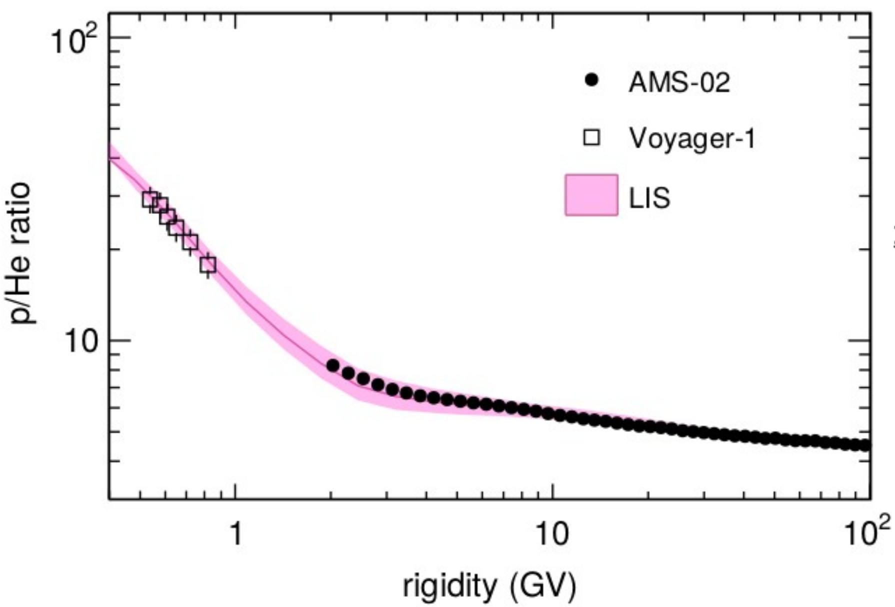
Flux ratio vs Rigidity: solar modulation





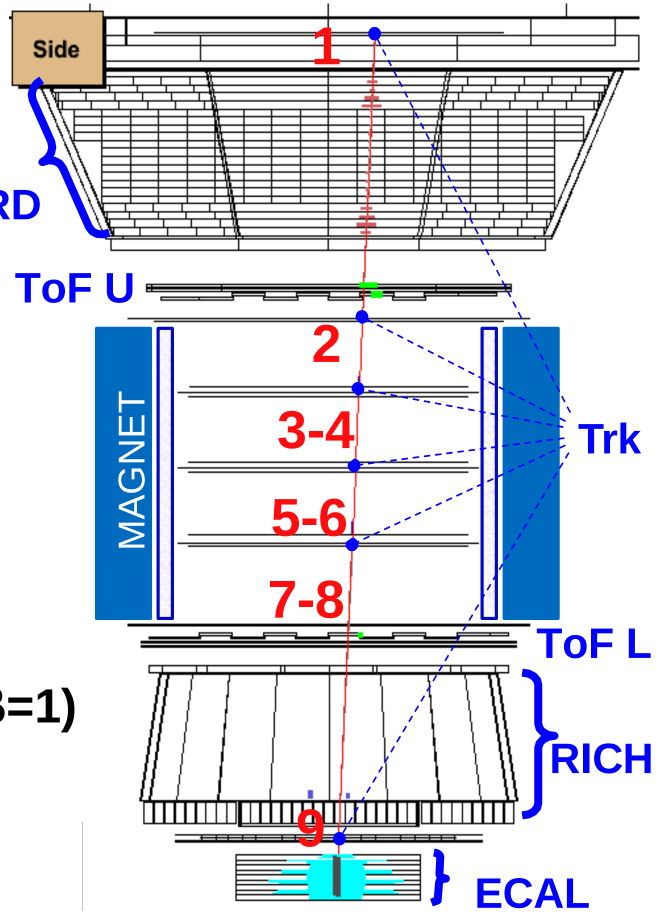
Flux ratio vs R





Particle identification - a summary:

AMS02: 7.5 Tons – 5x4x3m
B=0.15T in space since 2011
able to identify few antinuclei
over 150G events (0.5m^2 sr)
is shown for PID examples



- **Absolute value of charge: VERY SIMPLE**

- **Particle Mass: easy for E<M, very difficult for E>>M**
(typically evaluated by "velocity" vs Energy)

- **Particle Velocity: "easy" at few % (but saturation to β=1)**
(TRD measuring γ = E/M to avoid saturation for E>>M)

- **Particle direction: VERY SIMPLE**

- **Particle Momentum: hard to do better than few %, very difficult for P>TV**

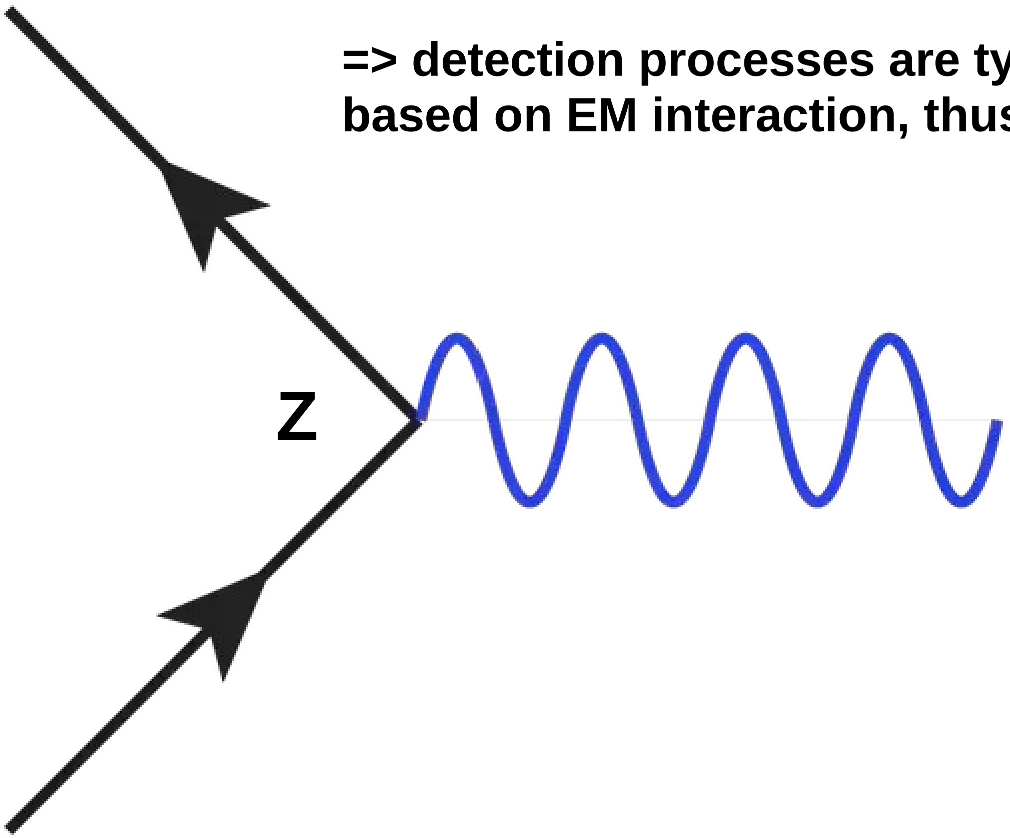
- **Charge sign: (up to now) impossible for R>TV**

- **Particle Energy: feasible down to few %, but large systematics for E>>TeV**

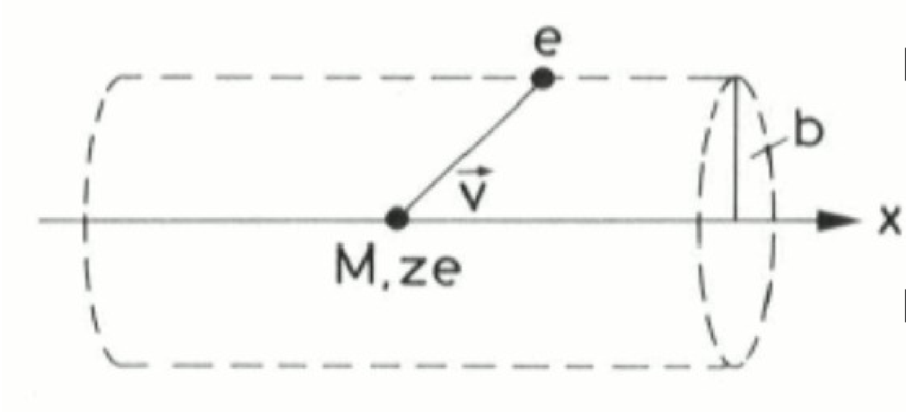
The “easy” measurement: particle CHARGE

Vertices of electromagnetic interactions are proportional to particle charge z

=> detection processes are typically based on EM interaction, thus prop to z^2



Energy loss: Bohr classical evaluation



Momentum transferred to an electron:

Gauss th. $\Phi_E = \frac{Q}{\epsilon_0}$

$$\Delta P = \int F\, dt = \int eE_{\perp} \frac{dx}{v} = \frac{ze^2}{2\pi \epsilon_0 b v}$$

Energy loss in dV = 2πb db dx : $n_e = \rho N_A Z/A$

$$-dE = \frac{(\Delta P)^2}{2 m_e} n_e dV = \frac{1}{(4\pi\epsilon_0)^2} \frac{4\pi z^2 e^4}{m_e v^2} n_e \frac{db}{b} dx$$

b_{min}: head on collision (v_e = 2 v) $\Delta E_{max} = 2\gamma^2 m_e v^2$ $\quad b_{min} = \frac{1}{4\pi\epsilon_0} \frac{ze^2}{\gamma m_e v^2}$

b_{max}: This approach assumes electrons "at rest" that is Tcollision << Trevolution

Tcollision ≈ b/(γv) and Trevolution ≈ 1/ν => b_{max} ≈ γv/ν (then integrate over b)

Bohr formula:

$$-\frac{dE}{dx} = \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \frac{4\pi N_A}{m_e} \frac{z^2}{v^2} \rho \frac{Z}{A} \ln\left(\frac{\gamma^2 m_e v^3}{z e^2 \bar{\nu}}\right)$$

Full quantum mechanical: Bethe-Block

$$-\frac{dE}{\rho dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

projectile

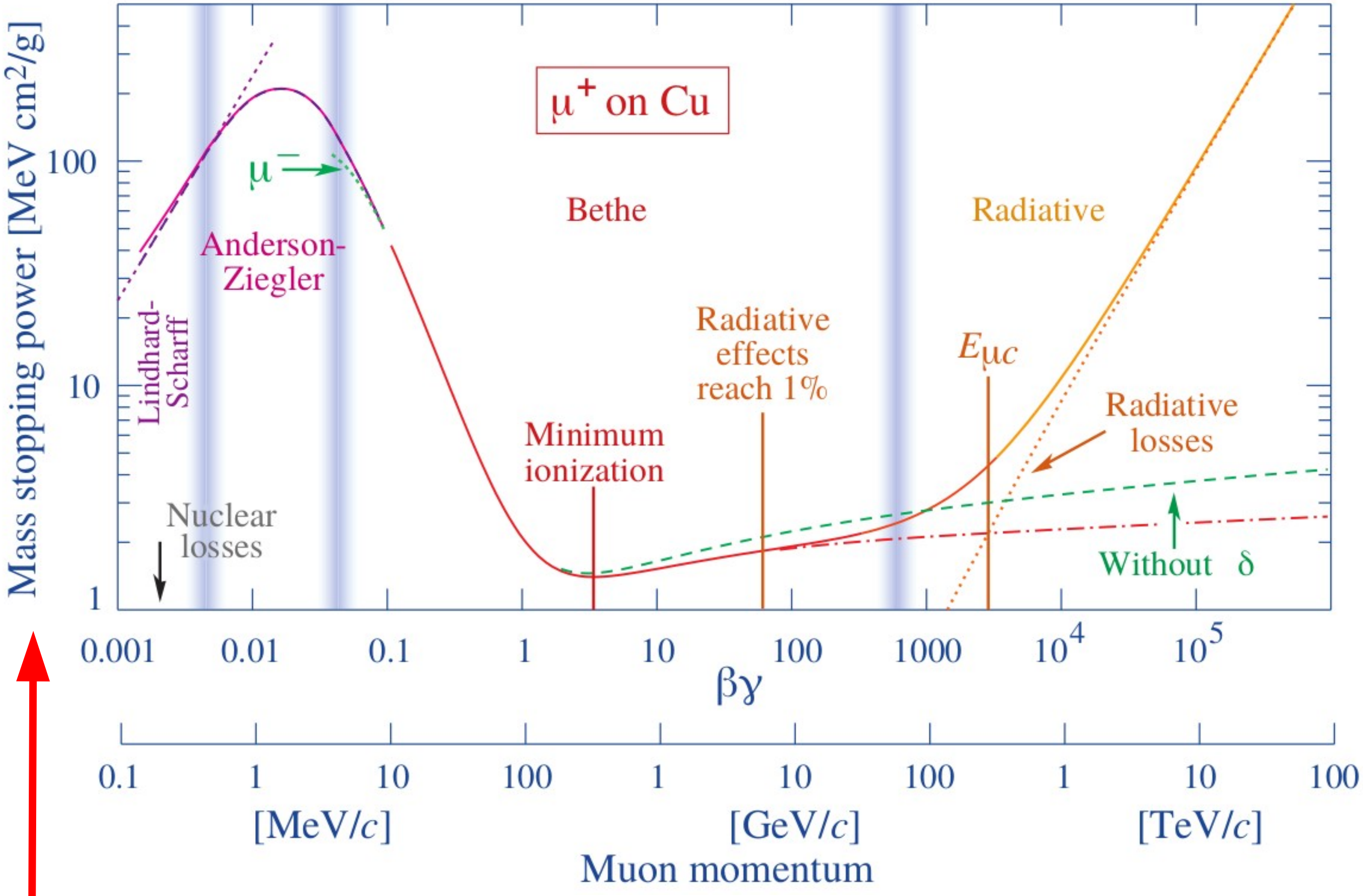
Target material

relativistic rise (E>>M)

"minor" corrections

Z/A quite similar in all materials main material effect from density

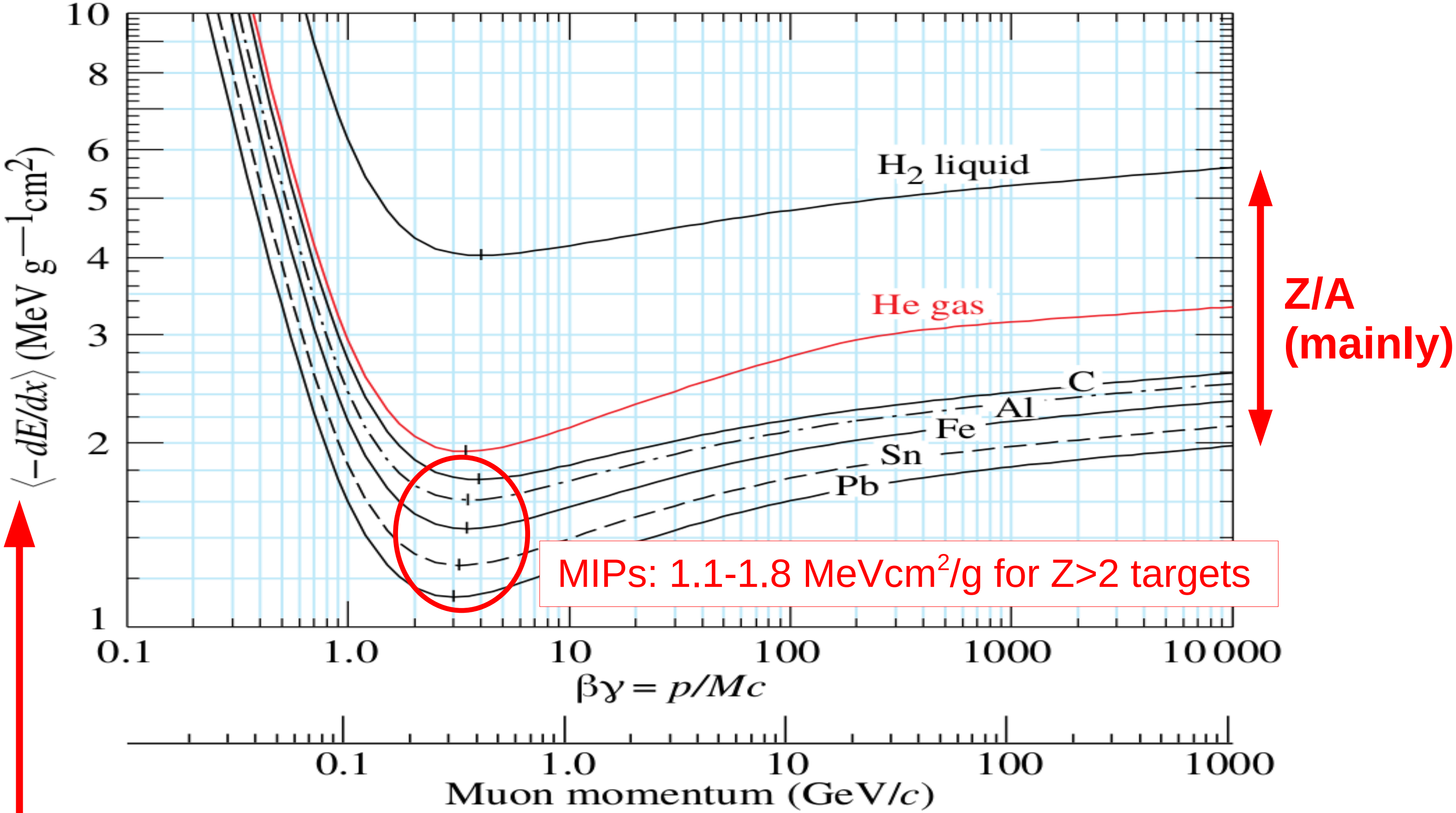
Energy loss: Bethe Block – in different materials



$$-\frac{dE}{\rho\, dx} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

The main effect of target material (due to the density) can be factorized out.

Energy loss: Bethe Block – in different materials

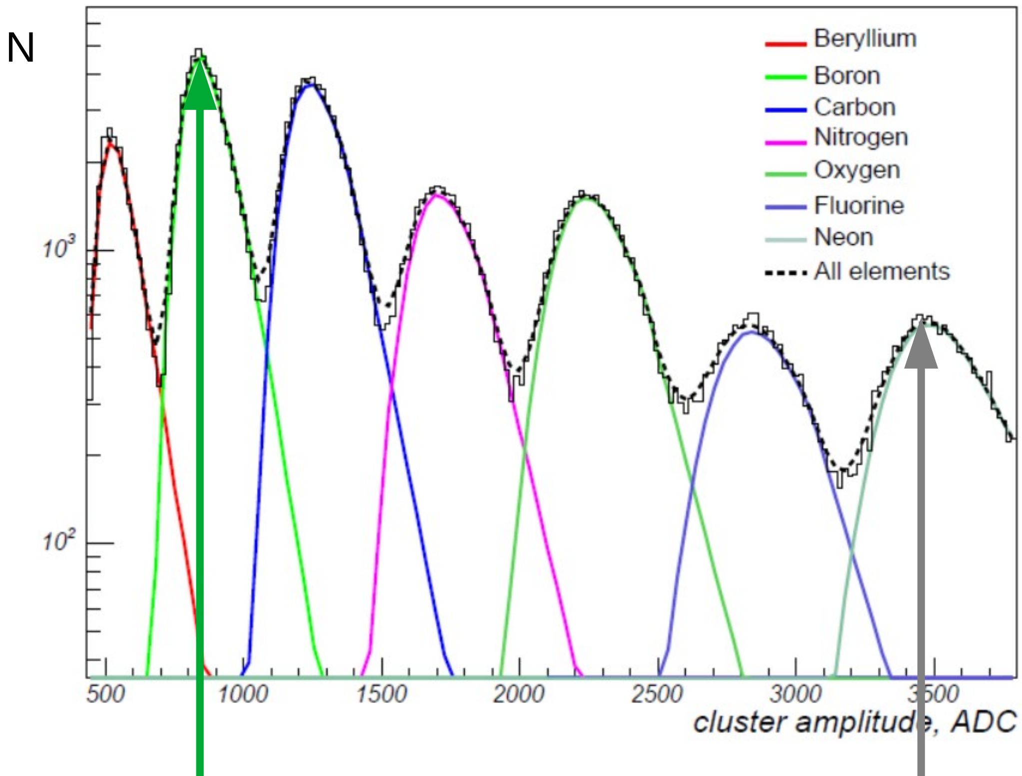


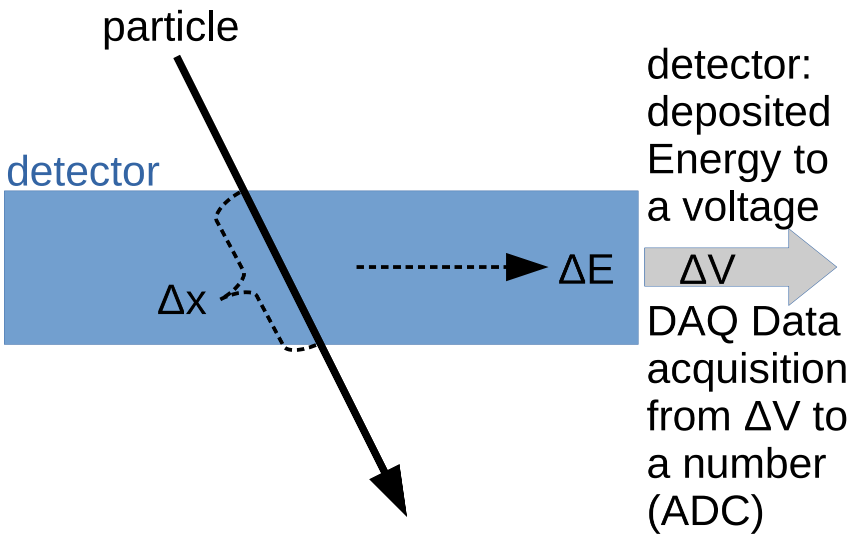
$$-\frac{dE}{\rho\, dx} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

The main effect of target material (due to the density) can be factorized out.

MIPs (Minimum Ionizing Particles) are “calibration sources” for detectors.

Energy loss: Bethe Block - the Charge measurement





(Analog to Digital Converter)
(from the voltage to a number)

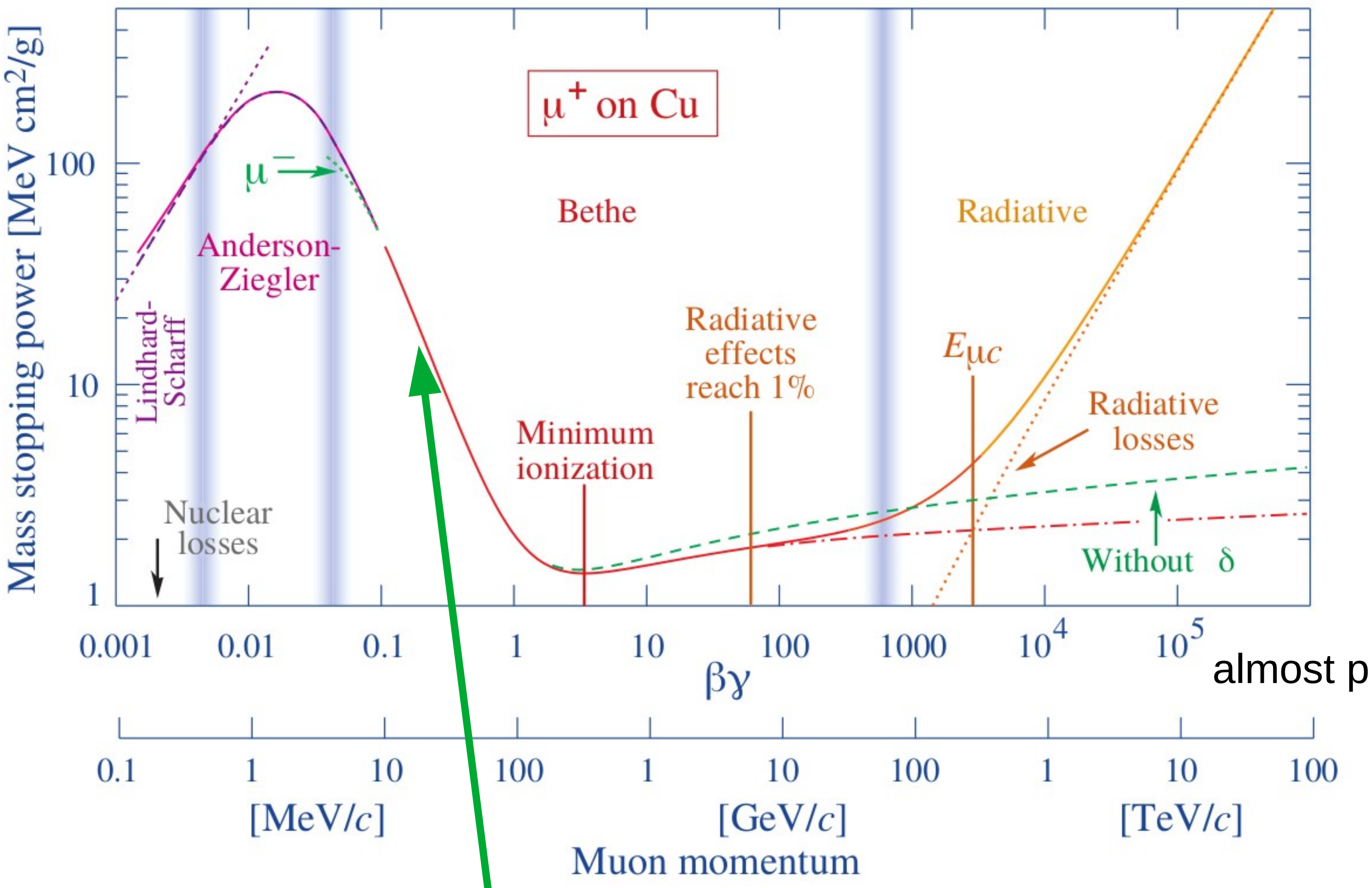
Boron z=5
Signal amplitude: 860 ADC channels

Neon z=5**x2**=10
Signal amplitude: 860**x4** = 3440 ADC channels

$$-\frac{dE}{\rho\, dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

to measure dE/dx also some tracking to measure dx is necessary…
(and to get a good charge measurement also some value for velocity is needed)

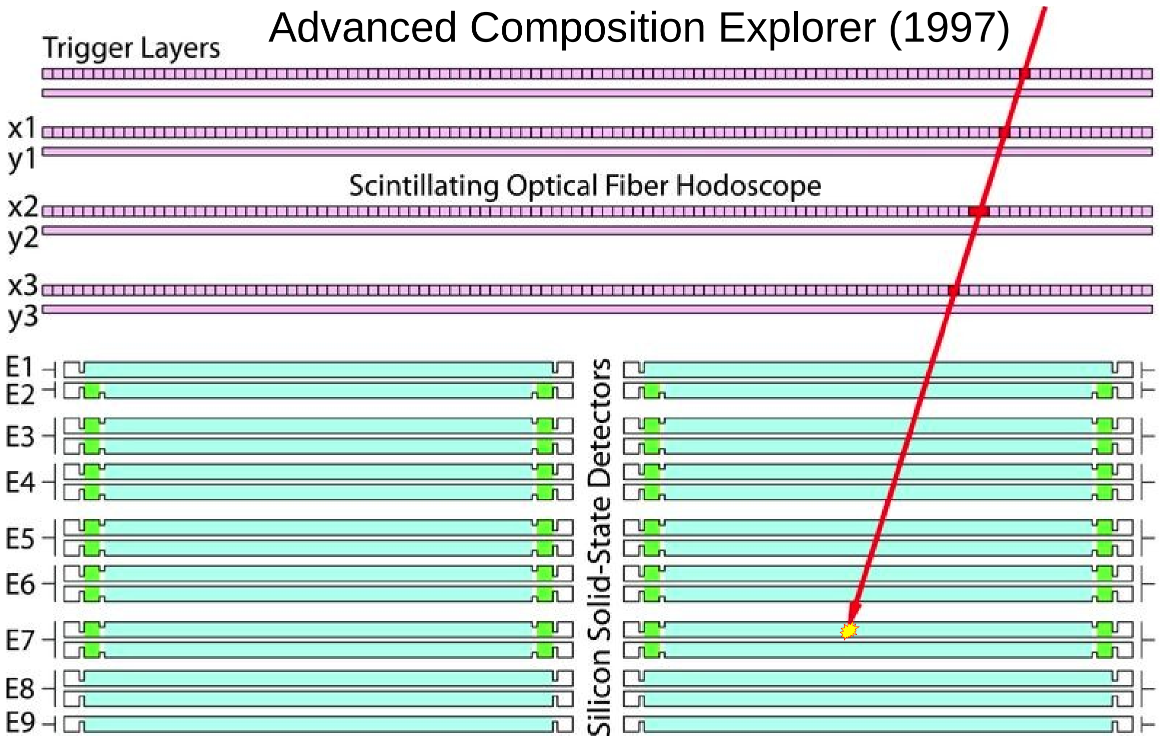
Energy loss: Bethe Block - the Velocity measurement

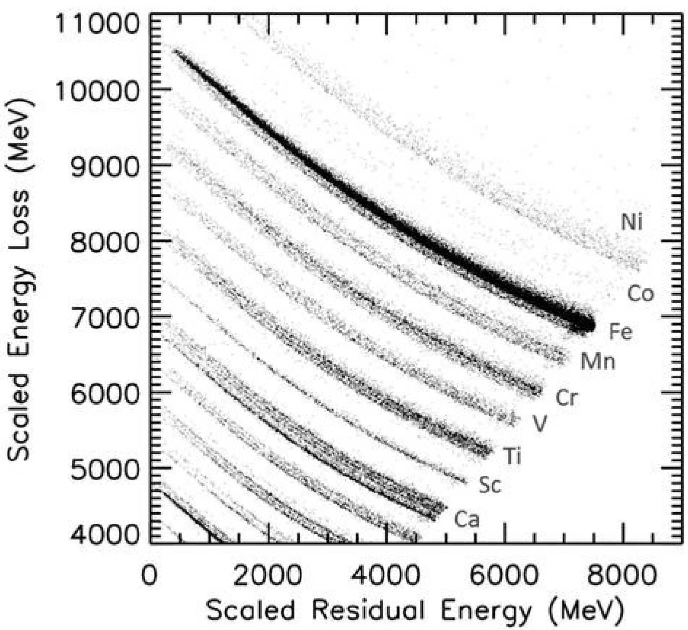


$$-\frac{dE}{\rho\, dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

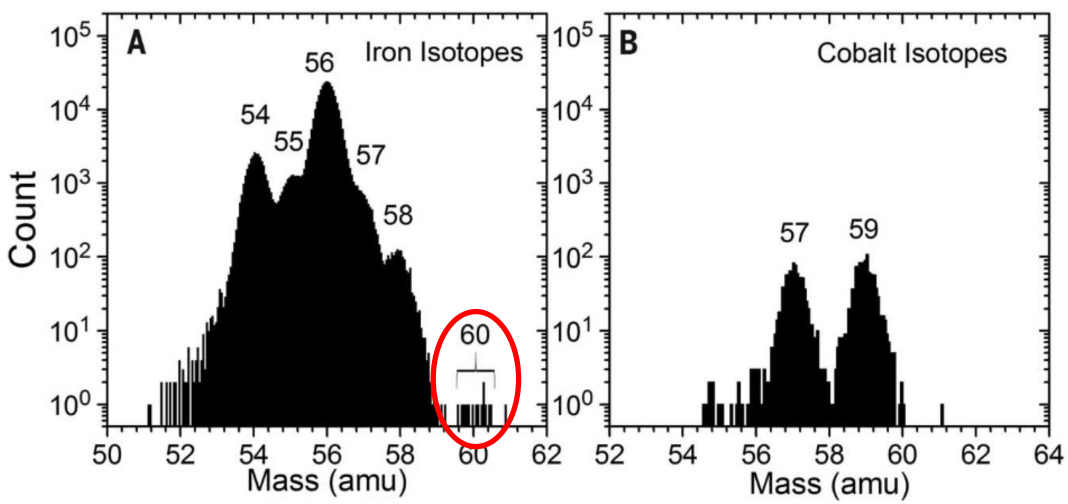
If charge is known, the energy loss allows a reasonable velocity measurement for γ<1
(possible but hard to exploit the relativistic rise for γ measurement)
On the other hand correction for this effect is required for precise charge measurements.

Simple spectrometers ΔE/E (mass for sub-MIPs particles):



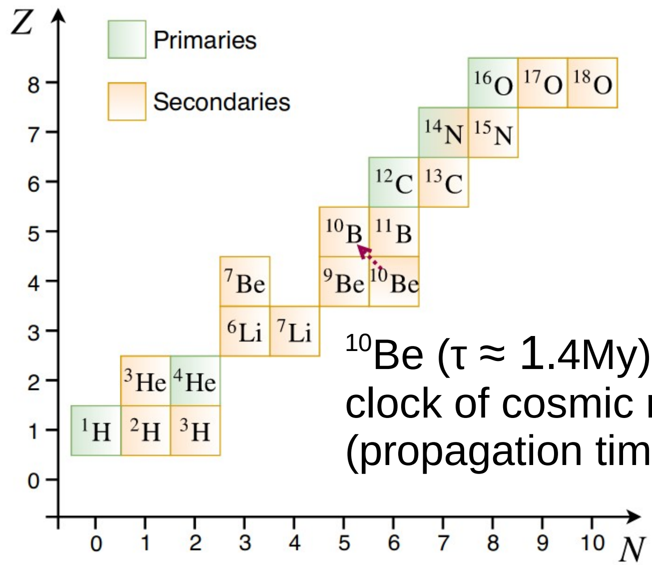


ACE-CRIS evidence for ^{60}Fe ($\tau \approx 2.6$My)
200<E<500 MeV/n
=> PRODUCED BY A NEARBY SN



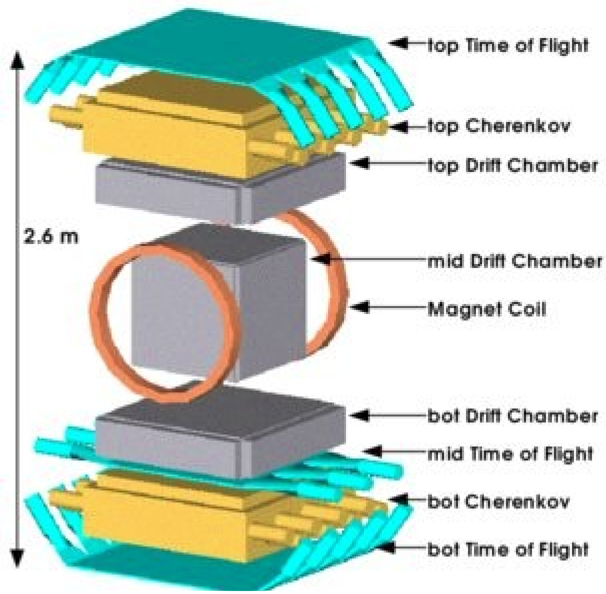
mass above MIPs? (directly measured) Velocity vs Momentum

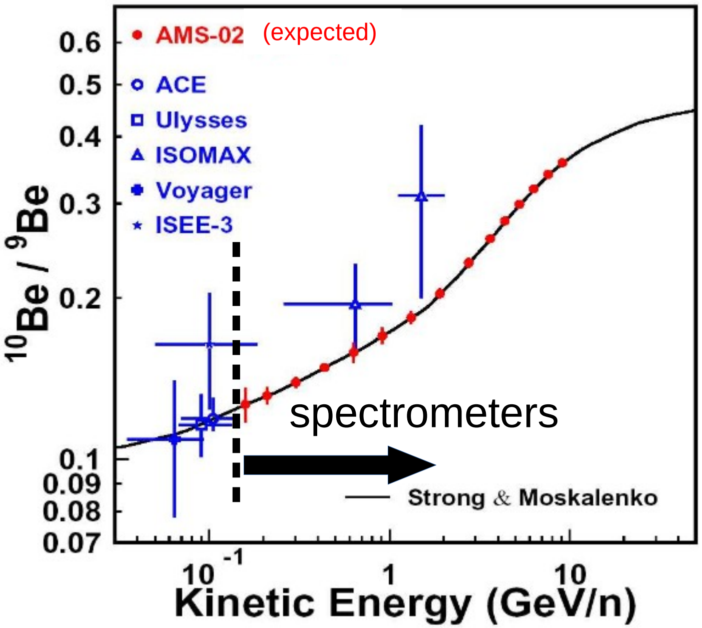
Isotopes in light cosmic rays:



^{10}Be (τ ≈ 1.4My) is the clock of cosmic rays (propagation times)

ISOMAX: Balloon (1998)





$$M = \frac{RZ}{\gamma\beta} \Rightarrow \frac{\Delta M}{M} = \sqrt{\left(\frac{\Delta R}{R}\right)^2 + \left(\gamma^2 \frac{\Delta\beta}{\beta}\right)^2}$$

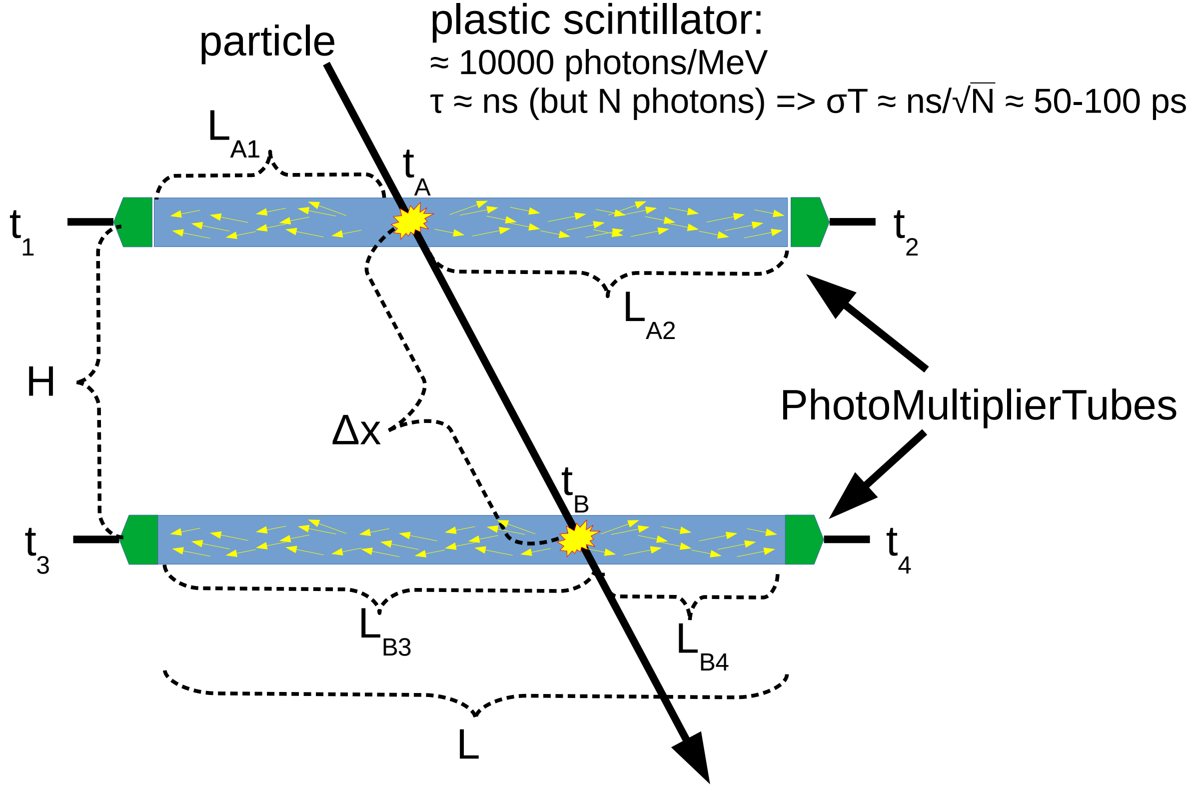
DETECTOR COMPLEXITY INCREASES

Velocity direct measurement:
Time of Flight
Cherenkov Detector

Momentum measurement: (R = P/z)
Magnet + tracker

Velocity measurement using Time Of Flight

plastic scintillator:
≈ 10000 photons/MeV
$\tau \approx$ ns (but N photons) => $\sigma T \approx \text{ns}/\sqrt{N} \approx$ 50-100 ps



c = 30cm/ns (speed of light)
n ≈ 1.6 (plastic scint. refr. index)

$t_1 = t_A + L_{A1} n/c$

$t_2 = t_A + L_{A2} n/c$

$t_A = (t_1 + t_2)/2 + L\, n/(2c)$

$t_B = (t_3 + t_4)/2 + L\, n/(2c)$

$\text{ToF} = t_B - t_A = (t_3 + t_4 - t_1 - t_2)/2$

$\beta = \Delta x / (\text{ToF}\ c)$

some tracking is required

Velocity resolution:
$\Delta\beta/\beta \approx \Delta\text{ToF}/\text{ToF} \approx 100\ \text{ps}\ c/H$
H=1m => $\Delta\beta/\beta \approx 3\%$
Energy up to ≈ GeV/n

Position resolution (along the bar)
from time difference ≈ few cm

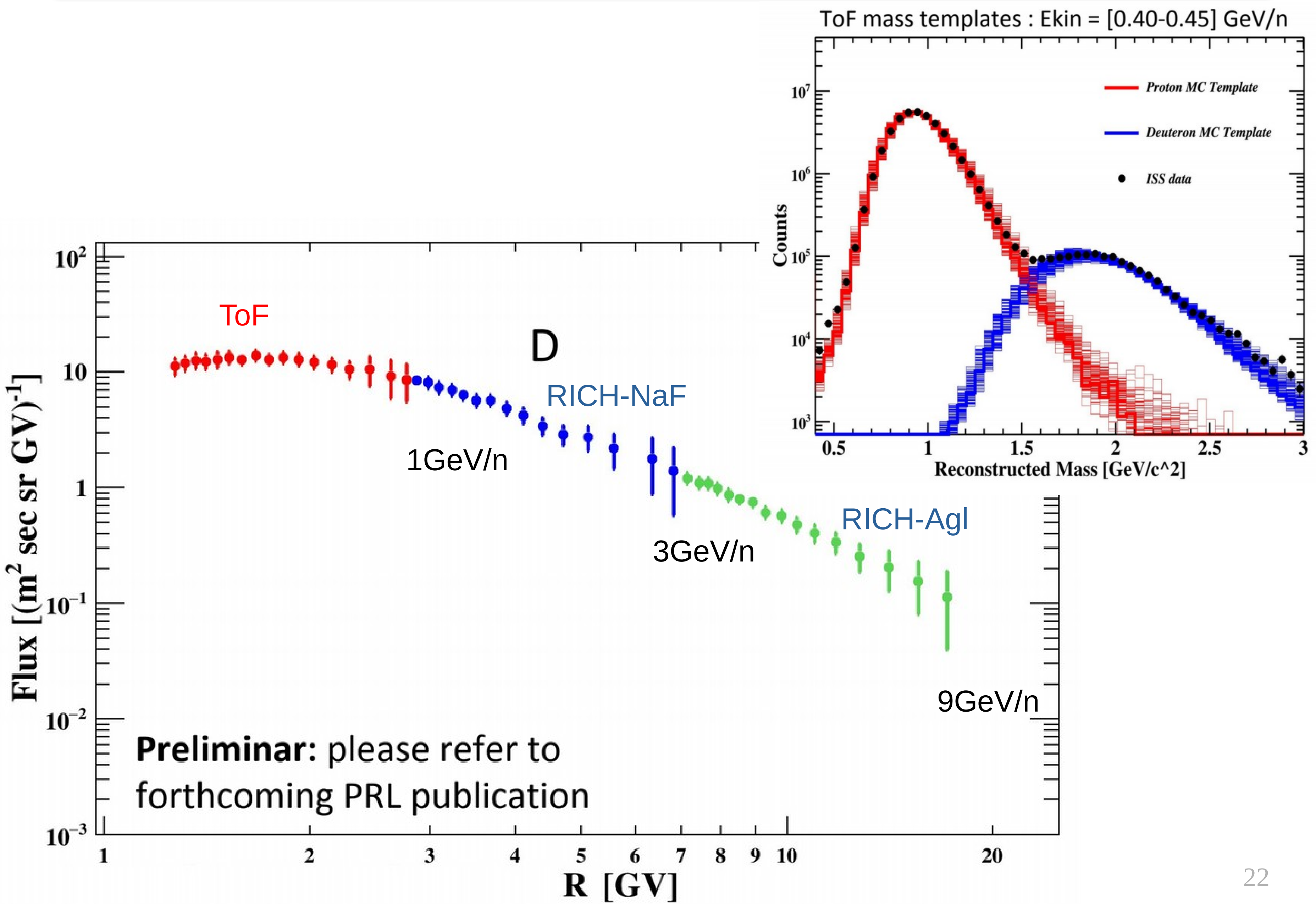
Some "self tracking" capability:

$t_2 - t_1 = (L_{A2} - L_{A1}) n/c = \Delta L_A n/c$

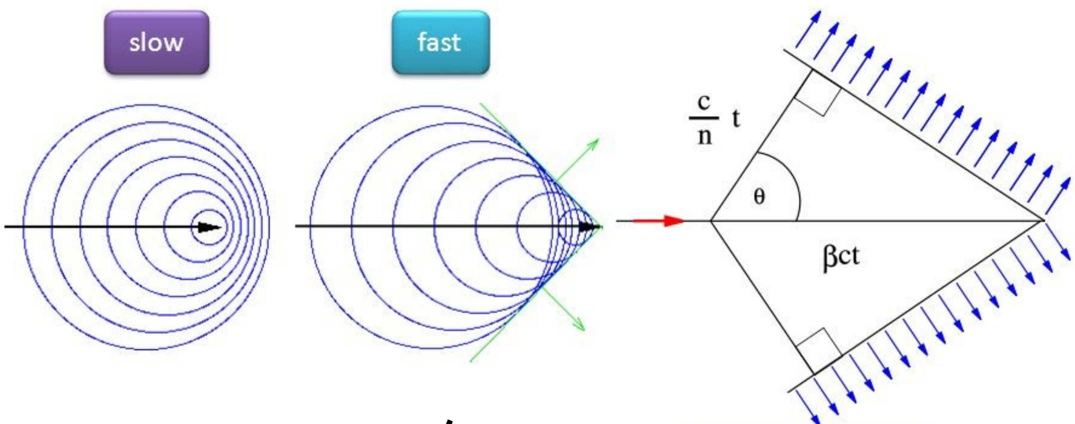
$t_4 - t_3 = (L_{B4} - L_{B3}) n/c = \Delta L_B n/c$

$(\Delta x)^2 = H^2 + (\Delta L_A - \Delta L_B)^2/4$

Example: AMS02 - Deuteron flux



Velocity measurement using Cherenkov Ring Imaging

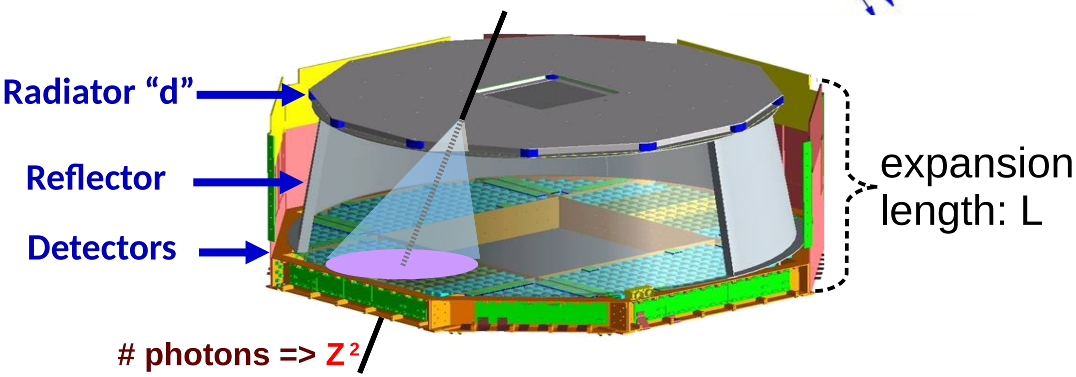


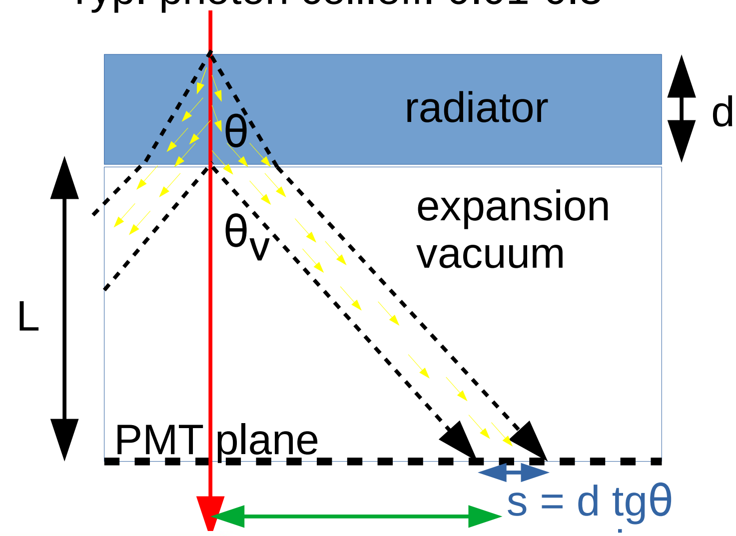
Basic equations:
1) cosθ = 1/(nβ) [Cherenkov]
2) n sinθ = sinθ_V [Snell]

3) $N_{ph} \simeq \epsilon d\, 2\pi\alpha Z^2 \sin^2\theta \frac{\lambda_2-\lambda_1}{\lambda_2\lambda_1}$

$N_{ph} \simeq \epsilon d K Z^2 \sin^2\theta$

Typically K 500-1000 photons/cm:
Typ. photon coll.eff. 0.01-0.3

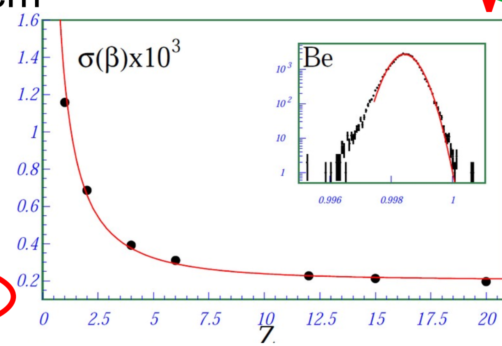




Example of AMS02 RICH: L = 45cm
AeroGel n = 1.05 β_{min} = 0.95 sinθ ≈ 0.3 d=2.5cm
NaF: n = 1.33 β_{min} = 0.75 sinθ ≈ 0.65 d=0.5cm

$$\sigma_\beta = \sigma_r \frac{d\beta}{dr} = \frac{s}{\sqrt{12(N_{ph}-2)}} \frac{d\beta}{dr} \sim \frac{d}{L}\frac{\beta}{n}\frac{\sin^2\theta}{\sqrt{12(N_{ph}-2)}}$$

AMS02:$\langle N_{ph}\rangle \approx 3 x z^2$; $\frac{\sigma_\beta}{\beta} \sim \frac{1.2 x 10^{-3}}{z} \Rightarrow 10\,GeV/n$



$\bar{r} = \frac{d}{2} tg\,\theta + L\, tg\,\theta_v$

some tracking helps a lot to find the ring center

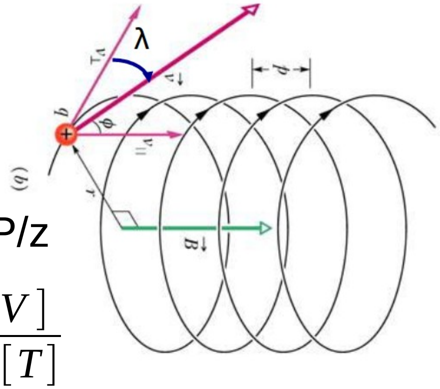
Momentum measurement: magnetic spectrometers

Lorentz force

$$\frac{d\mathbf{P}}{dt} = z e\, \mathbf{v} \times \mathbf{B}$$

Helix trajectory: R=P/z

$$\rho = \frac{P_\perp}{zeB} \Rightarrow \rho[m] = \frac{R[GV]}{0.3\,B[T]}$$



Rigidity resolution:

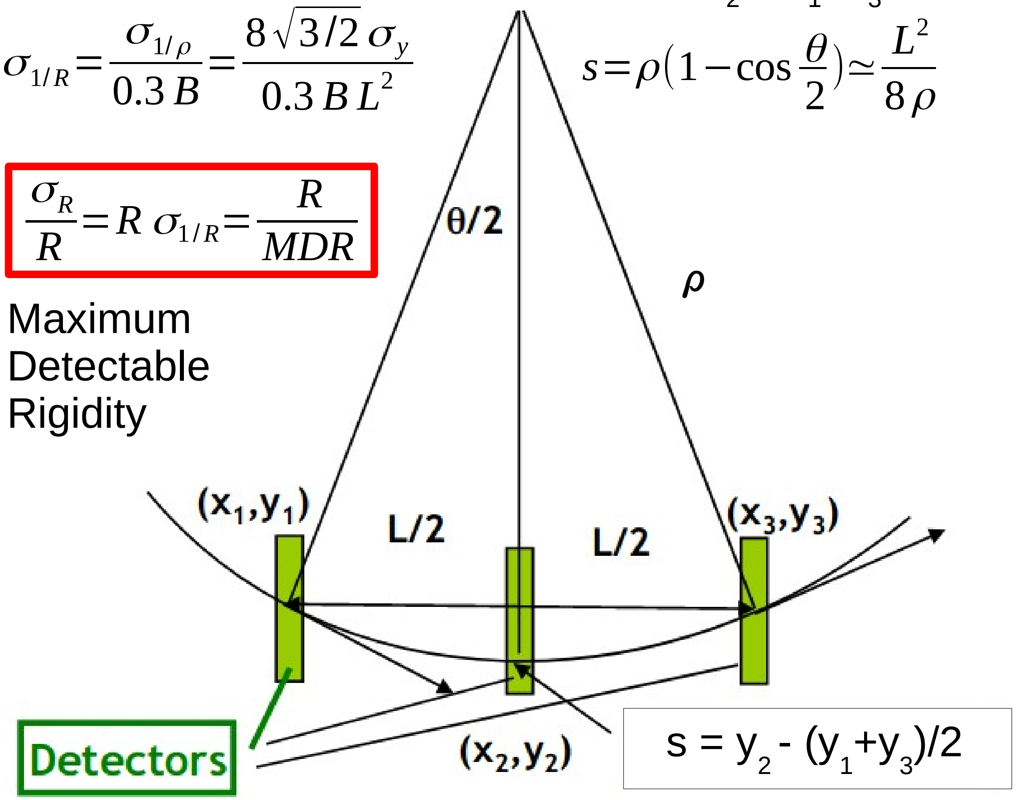
$$\sigma_{1/R} = \frac{\sigma_{1/\rho}}{0.3\,B} = \frac{8\sqrt{3/2}\,\sigma_y}{0.3\,B\,L^2}$$

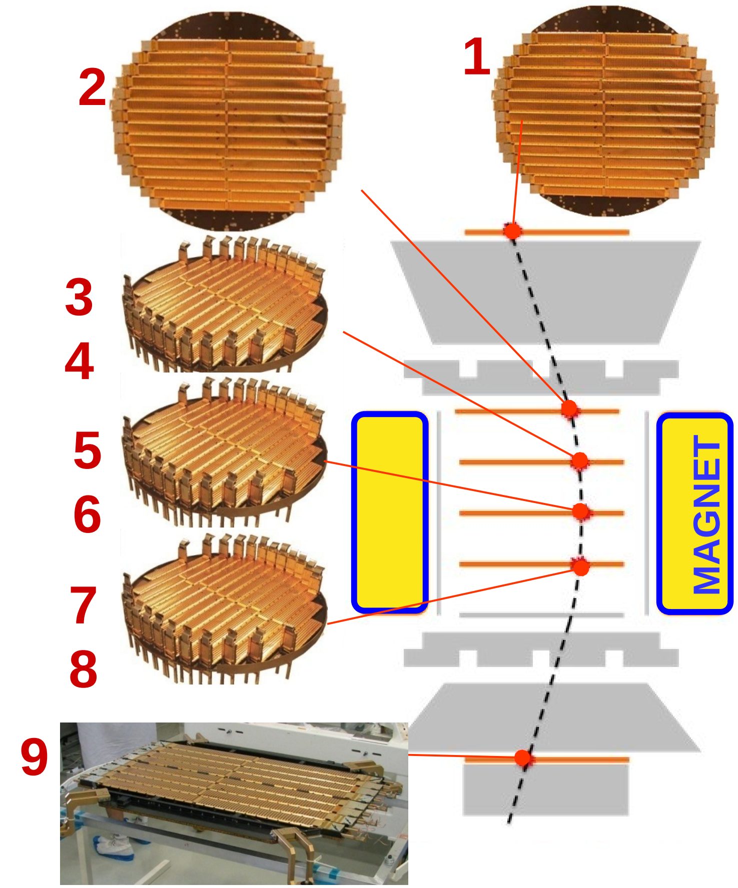
$$\frac{\sigma_R}{R} = R\,\sigma_{1/R} = \frac{R}{MDR}$$

Maximum Detectable Rigidity

Sagitta: $y_2 - (y_1+y_3)/2$

$$s = \rho\left(1-\cos\frac{\theta}{2}\right) \simeq \frac{L^2}{8\rho}$$





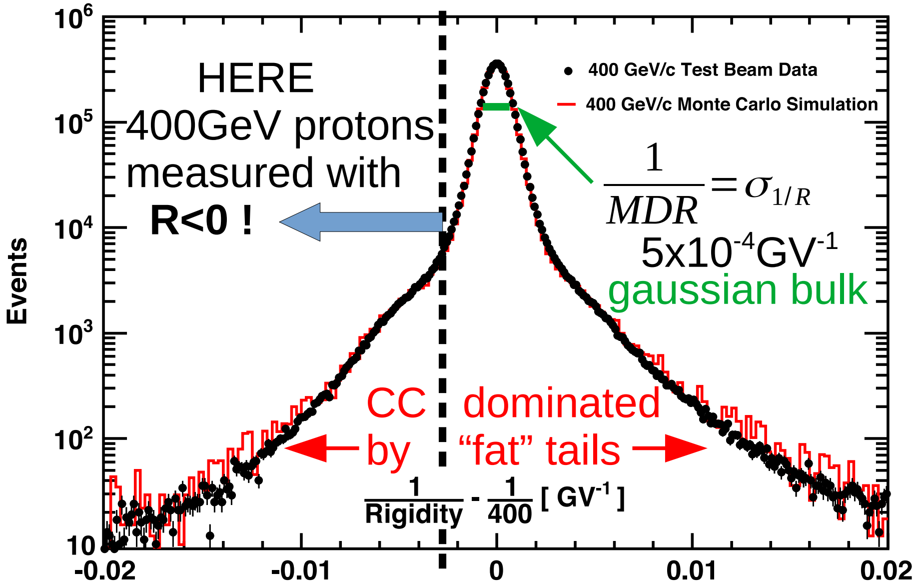
For a Tracker with N>>3 layers:

$$\frac{1}{MDR} = \sigma_{1/R} \simeq \sqrt{\frac{720}{N+4}}\,\frac{\sigma_y}{0.3\,B\,L^2}$$

AMS02: z=1 σ_y=10um $MDR_{(z=1)}$ = 2 TV

z=2 σ_y = 5um (larger S/N)

Momentum measurement: charge sign identification

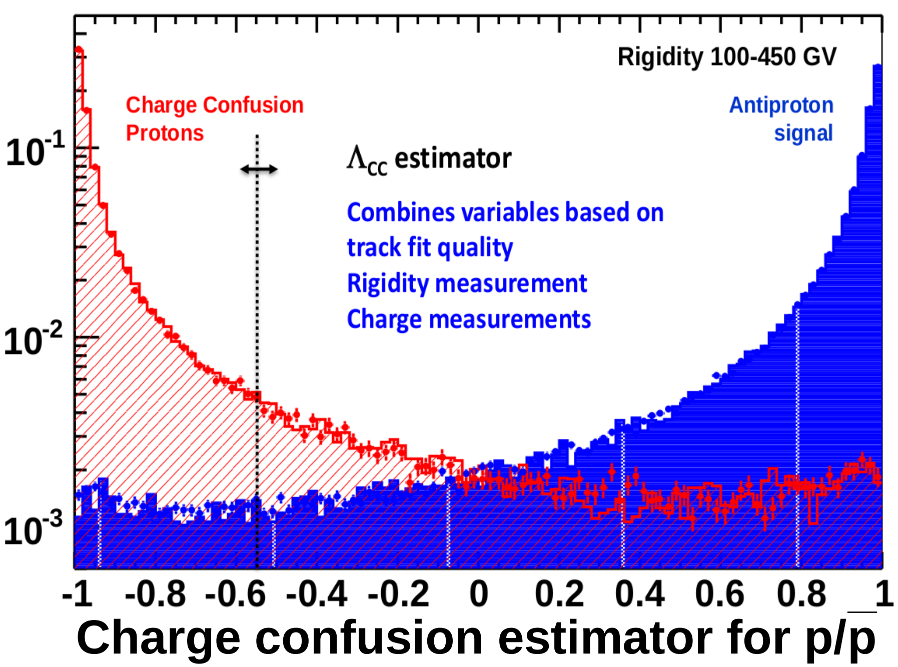


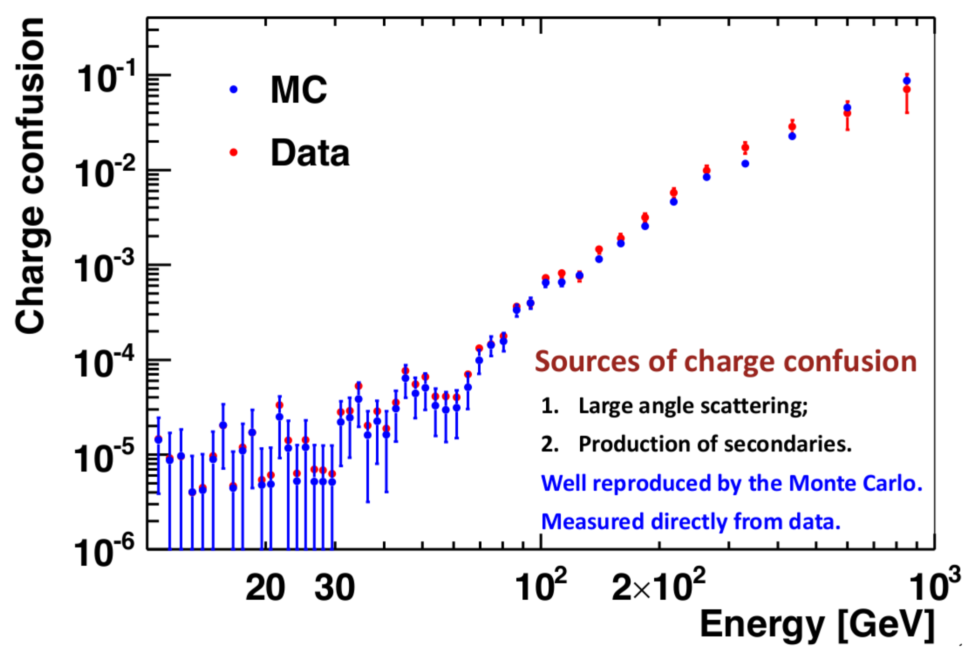
Tracker MDR = 2 TV for Z=1 particles

Charge confusion = probability of wrong charge sign measurement

<1% up to 300 GeV
<10% up to TeV

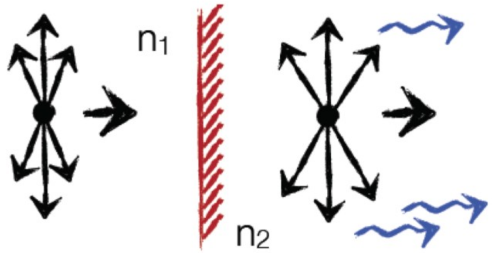
Reduction/identification by MC based multivariate analysis.





Measurement of E/M - TRD detector

Particle crossing an interface.



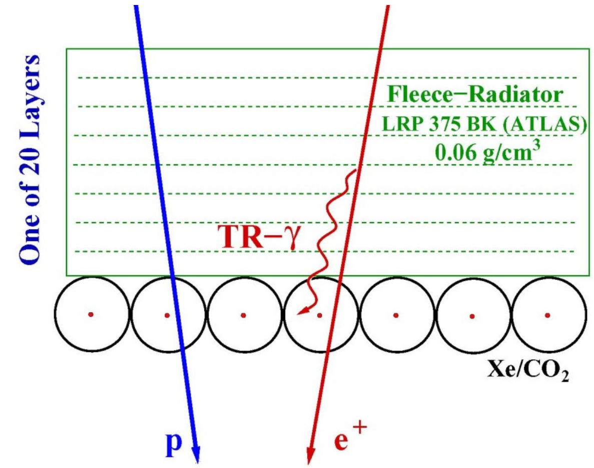
Radiated energy/crossing:

$$W = \frac{1}{3}\alpha\hbar\omega_p\gamma \qquad E_\gamma^{max} \simeq \gamma\hbar\omega_p$$

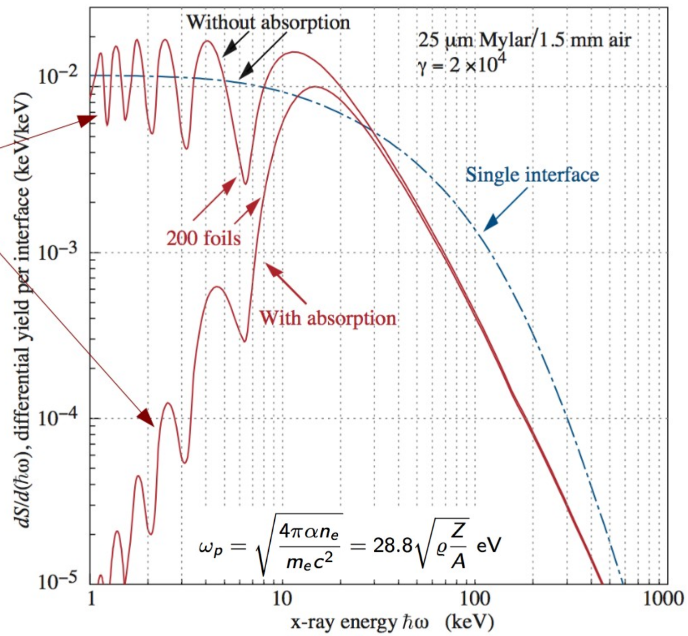
#radiated photons/crossing:

$$N \sim \frac{W}{\hbar\omega} \sim \alpha = \frac{1}{137}$$

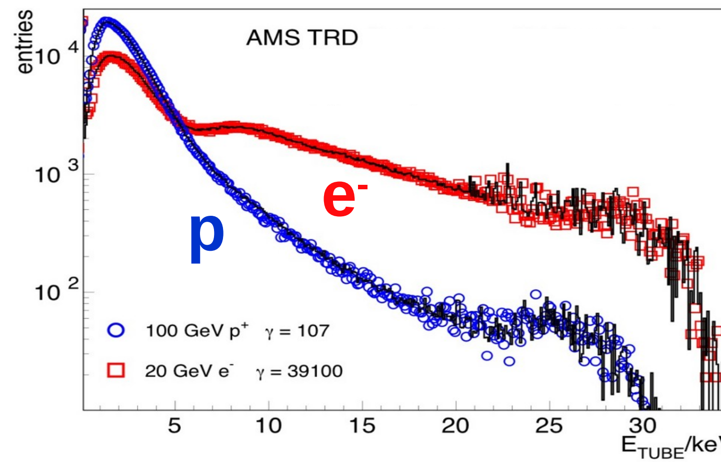
Needs a lot of interfaces!



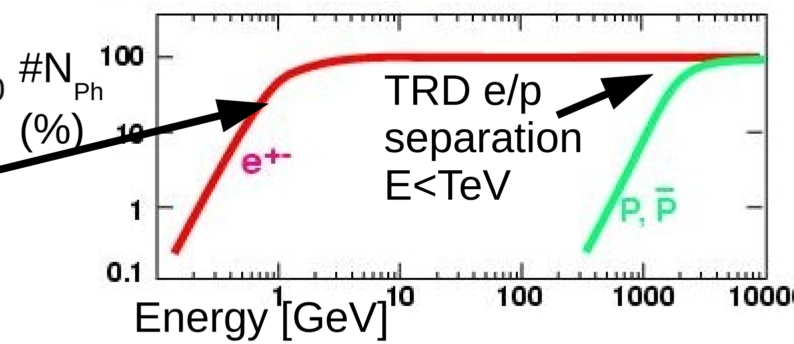
Oscillations are due to interference between successive boundaries



X-ray photon energy spectra for a radiator consisting of 200 25 μm thick foils of Mylar and for a single surface



Saturation of number of TRD photons $\gamma > \gamma_{sat} \sim 2000$



Not easy to perform isotopic separation…

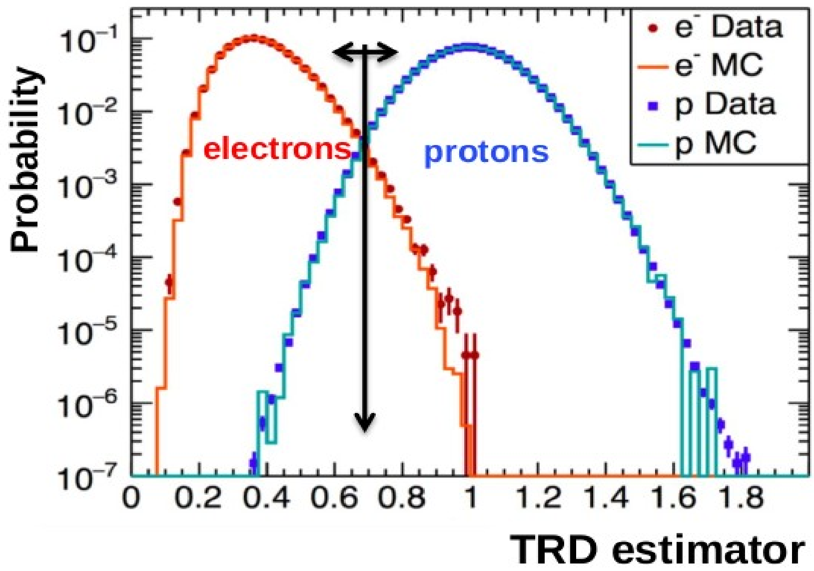
Usually Likelihood technique adopted to do PID

TRD based Mass measurement at high energy:

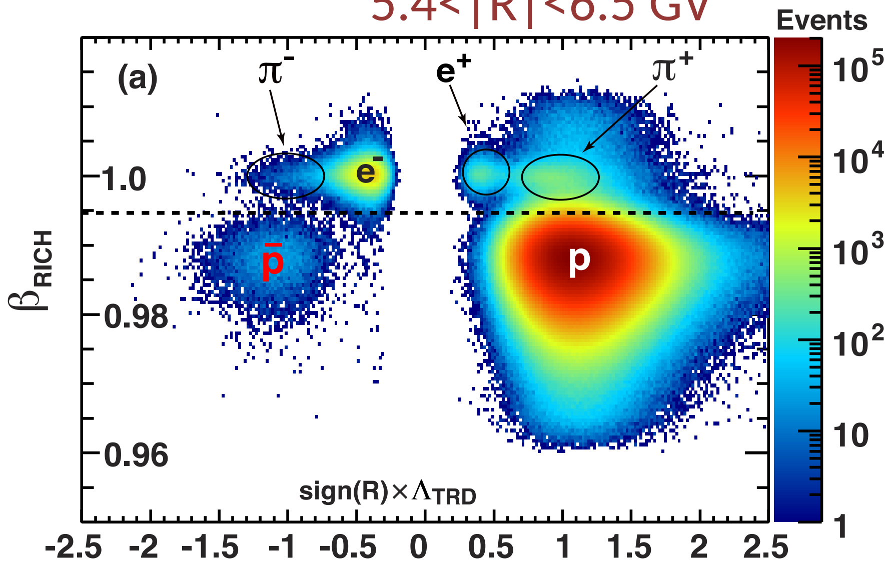
N = 20 layers

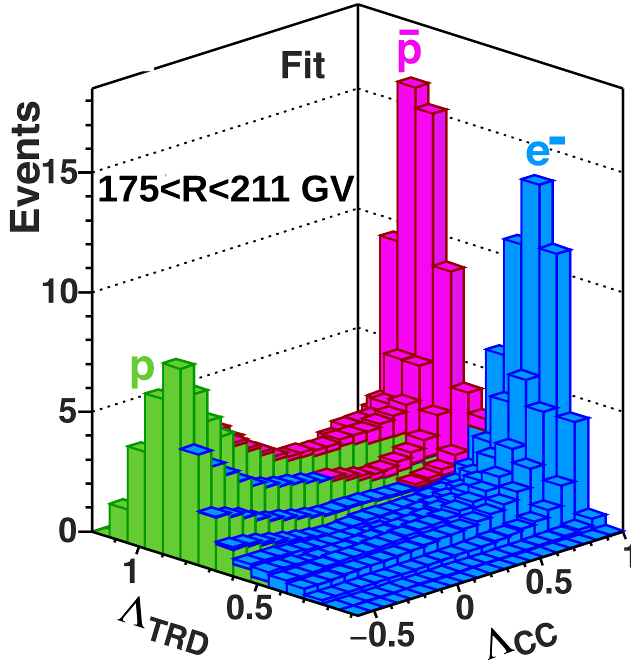
$$P_p = \sqrt[n]{\prod_i^n P_p^{(i)}(A)} \qquad P_e = \sqrt[n]{\prod_i^n P_e^{(i)}(A)}$$

TRD estimator = $-\ln(P_e/(P_e+P_p))$



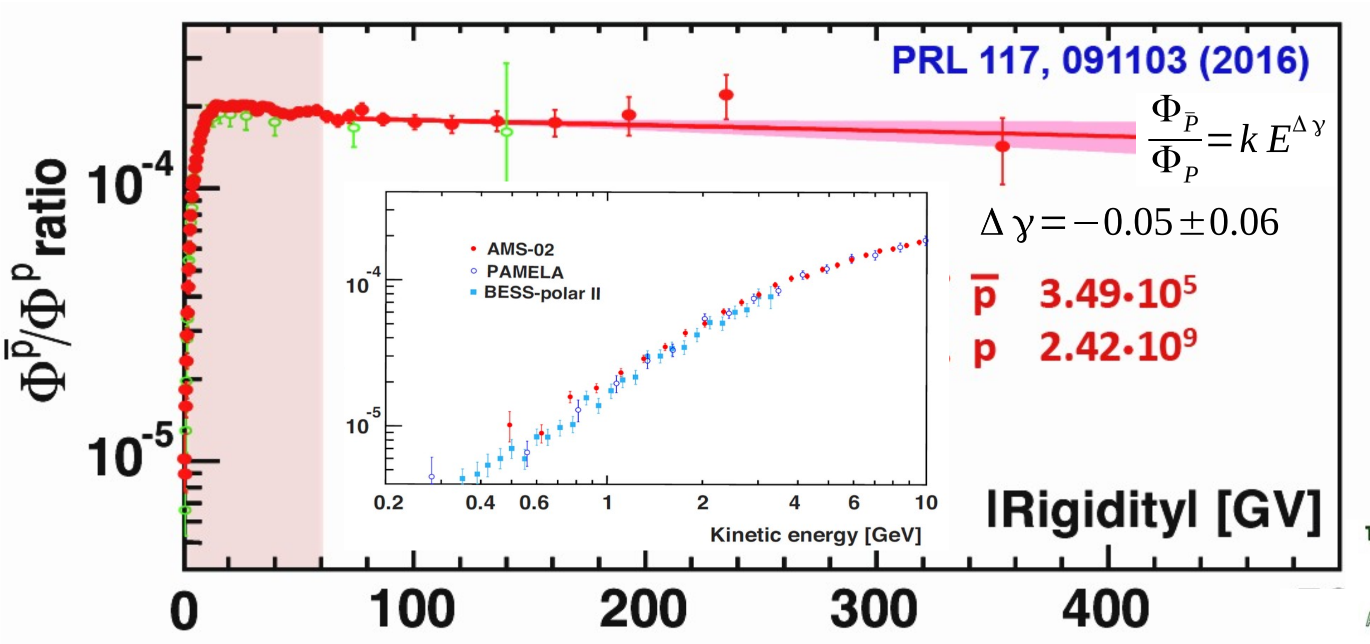
5.4<|R|<6.5 GV





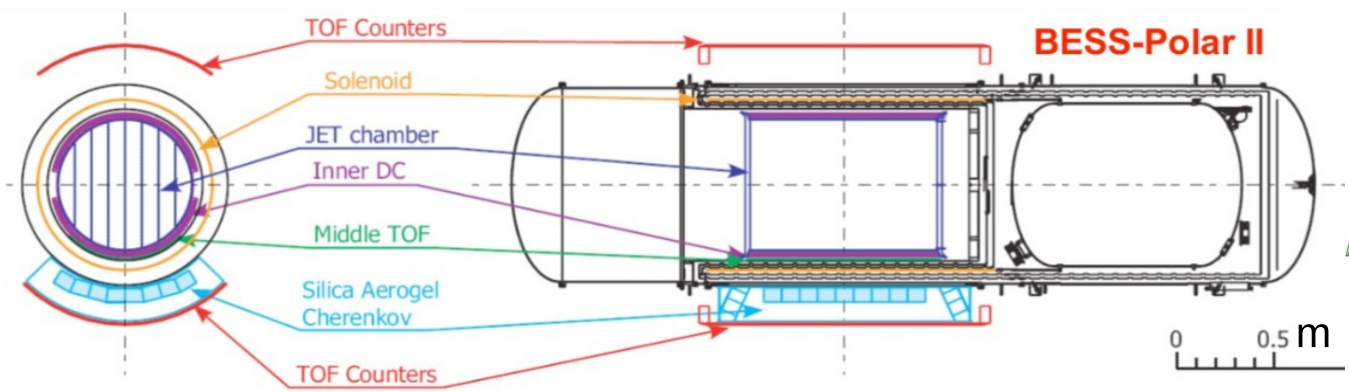
<= TRD: Mass separation for E>>M

Antiprotons in cosmic rays



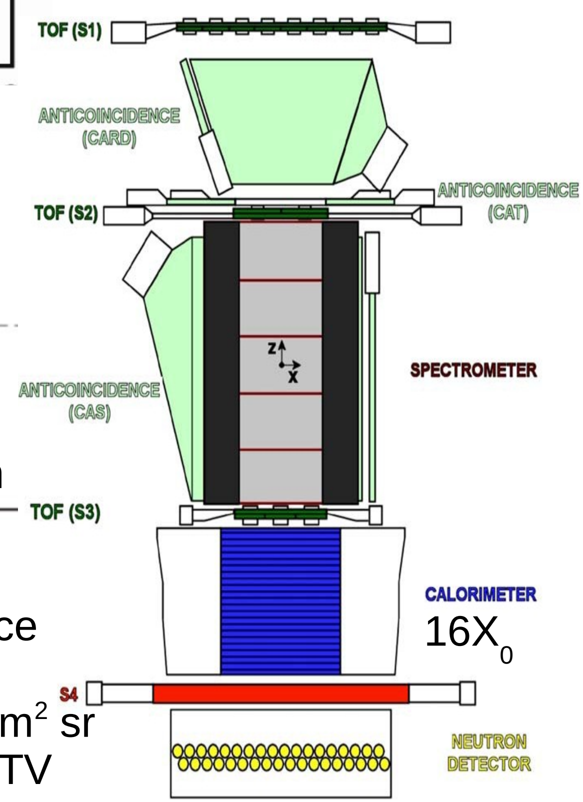
Flat antiproton ratio.

“exotic” sources? Background model still uncertain (next slides...)



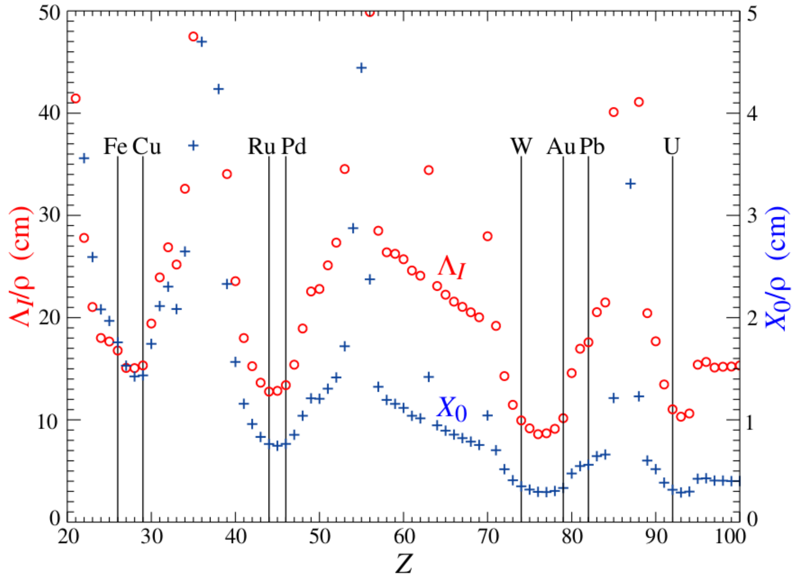
BESS-Polar II (2008-2010)
Balloon: ≈ 30gg 4.7x10⁹ events
Acceptance: 3000 cm² sr 1500kg
1T superconducting magnet
drift chambers => MDR = 270 GV

PAMELA



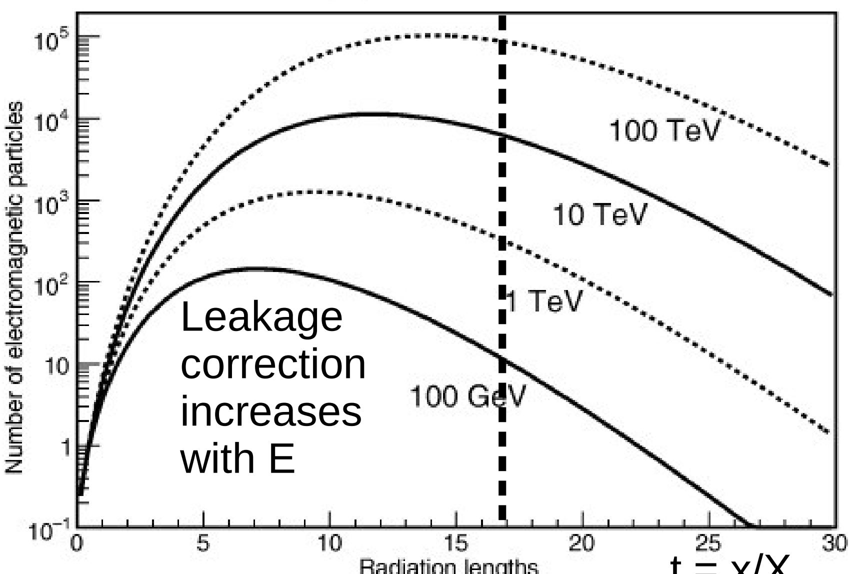
PAMELA:
(2006-2016) in space
1.3m x 460kg
Acceptance: 21.5 cm² sr
0.43T => MDR = 1 TV

the Mass "of the detector": Calorimetry



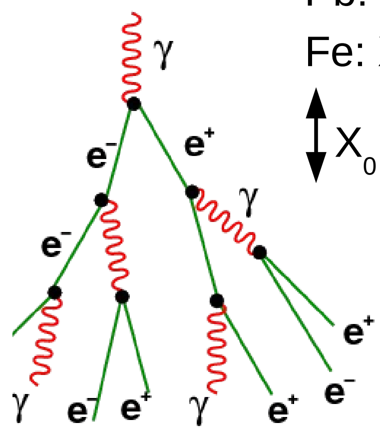
$$\frac{dE}{dt} = E_0\, b\, \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

$$t_{max} = \ln\left(\frac{E}{E_c}\right) \pm 0.5$$



$t = x/X_0$

em cascade

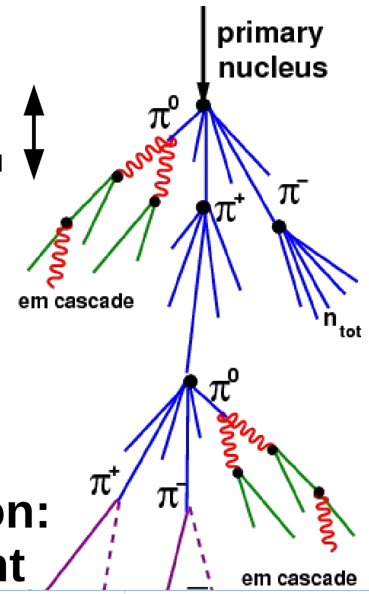


Pb: $X_0 = 0.03\, \Lambda_I$

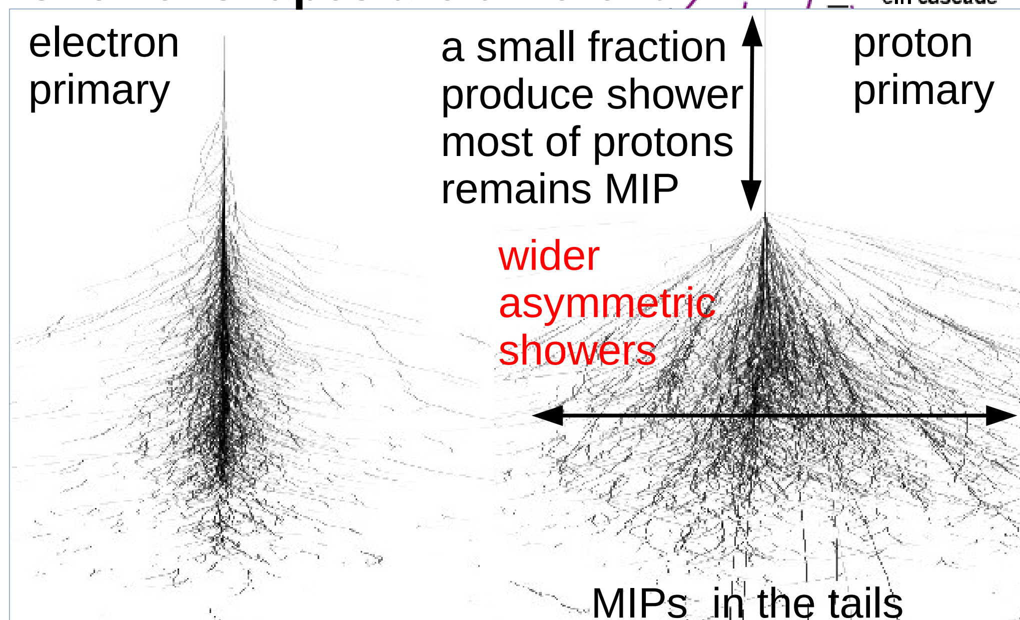
Fe: $X_0 = 0.1\, \Lambda_I$

$X_0 \ll \Lambda_I$

hadronic cascade

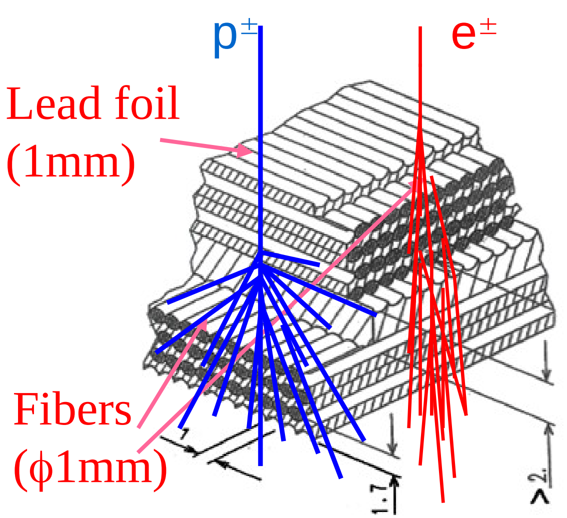


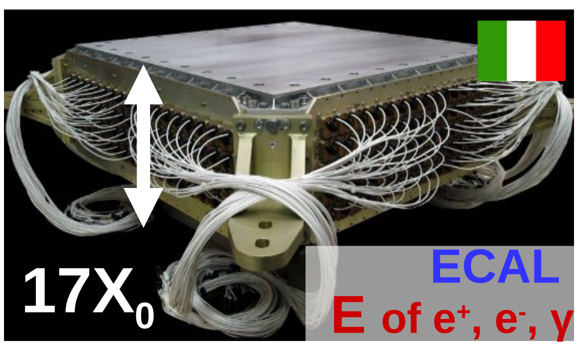
ECAL classifier e/p rejection: shower shapes are different



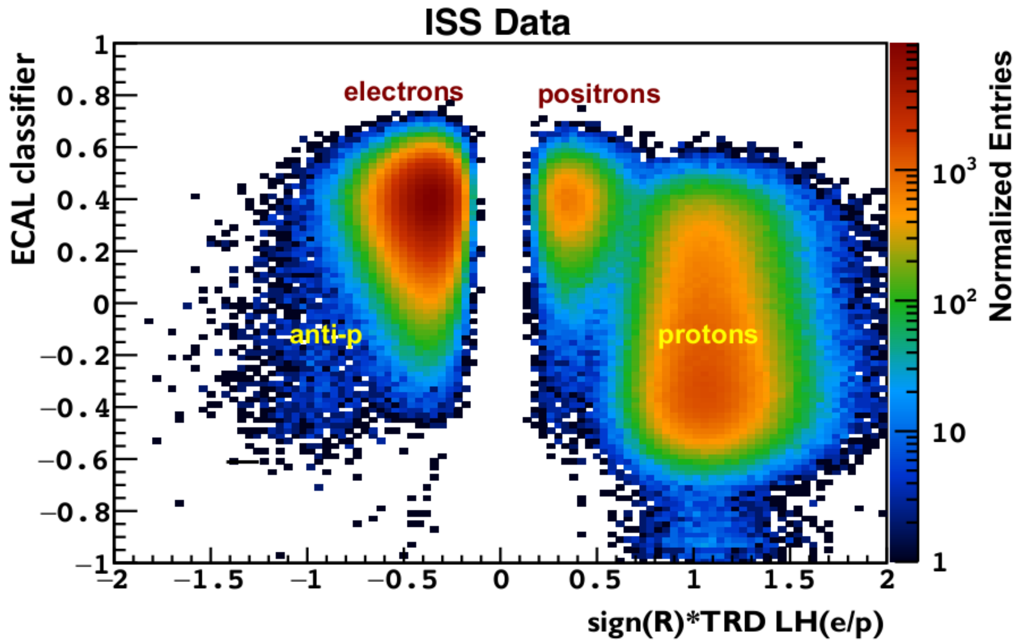
AMS02-ECAL: redundancy matters

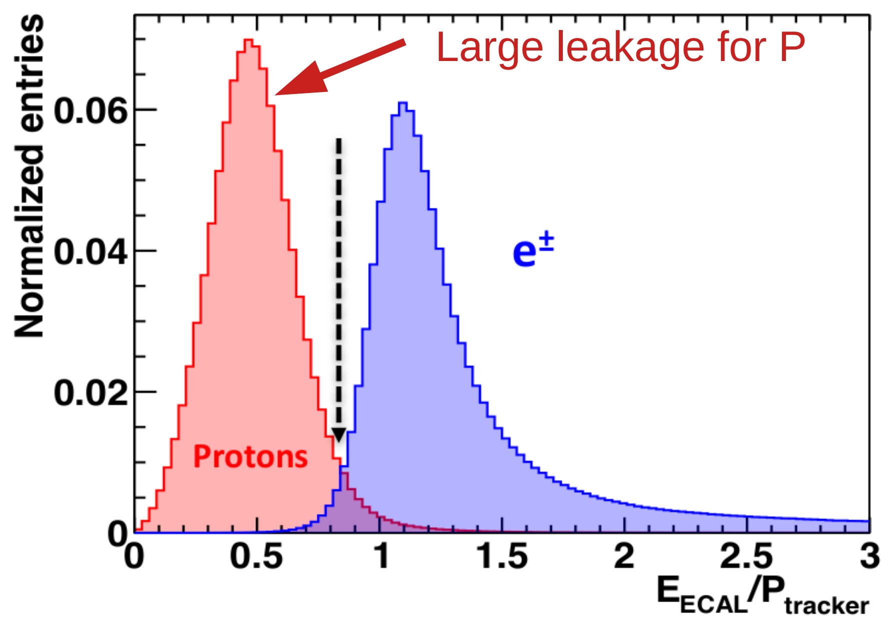
50,000 fibers, ϕ = 1 mm
Inside 600 kg of lead



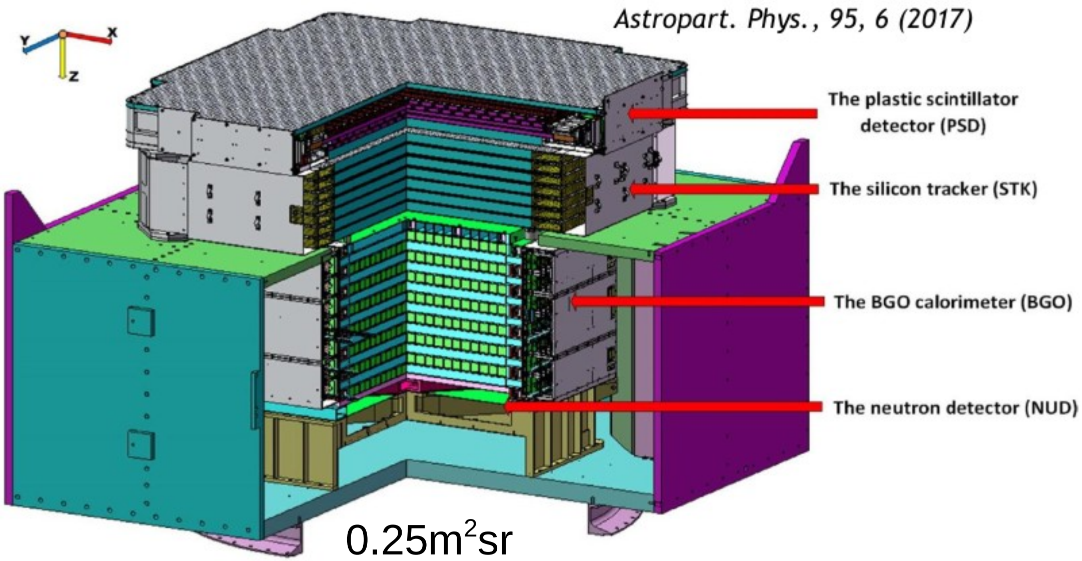


ECAL energy resolution ~2% at HE
ECAL energy absolute scale tested during test beams on ground + E/R
MIP ionization used to cross-calibrate the energy scale in flight



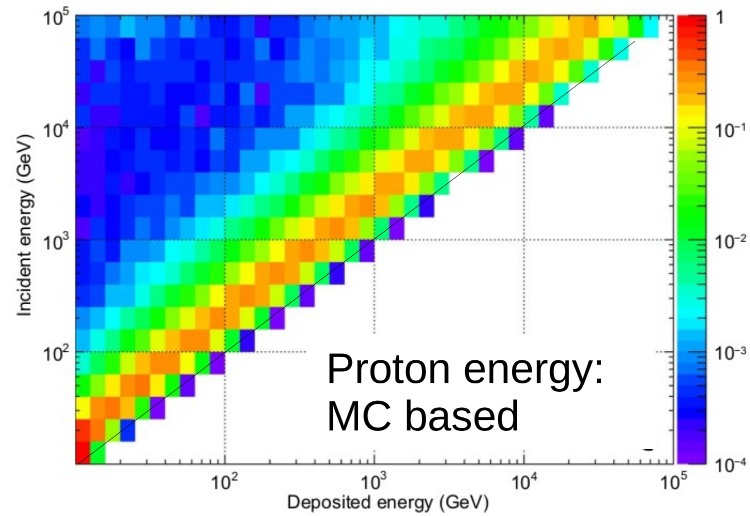


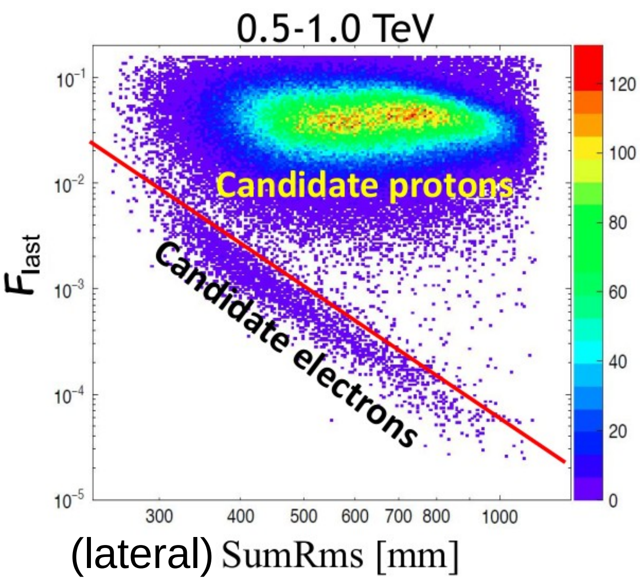
DAMPE: 31 X_0 (1.6 Λ_I) size matters

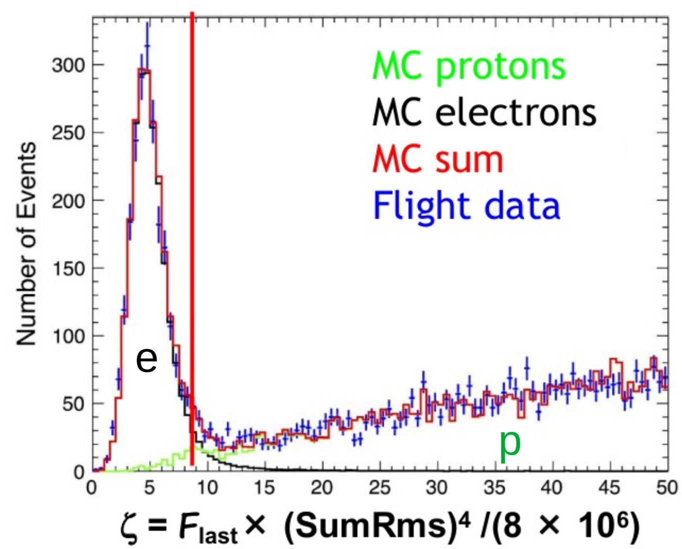


0.25m²sr

Electron: Test Beam up to 243 GeV
MC extrapolated to 5 TeV
Proton: Test Beam up to 400 GeV
MC extrapolated to 100 TeV





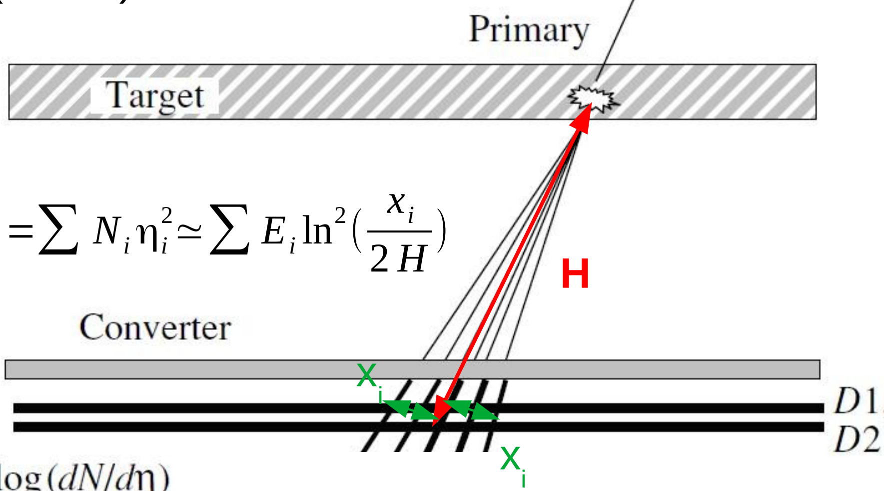


Proton Energy resolution:
100 GeV => 10 TeV
25% => 35%

No redundancy of Energy scale :(

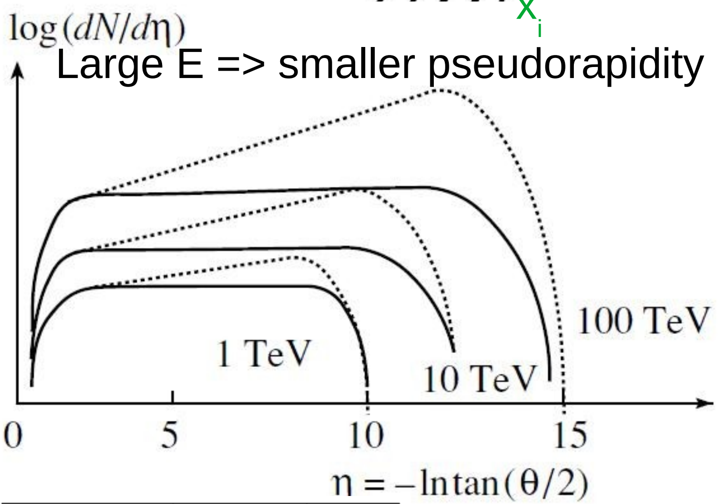
NUCLEON: size does not matter … if you have a clever idea (and a good MC)

Kinematic Lightweight Energy Method (KLEM)



$$S = \sum N_i \eta_i^2 \simeq \sum E_i \ln^2\left(\frac{x_i}{2H}\right)$$

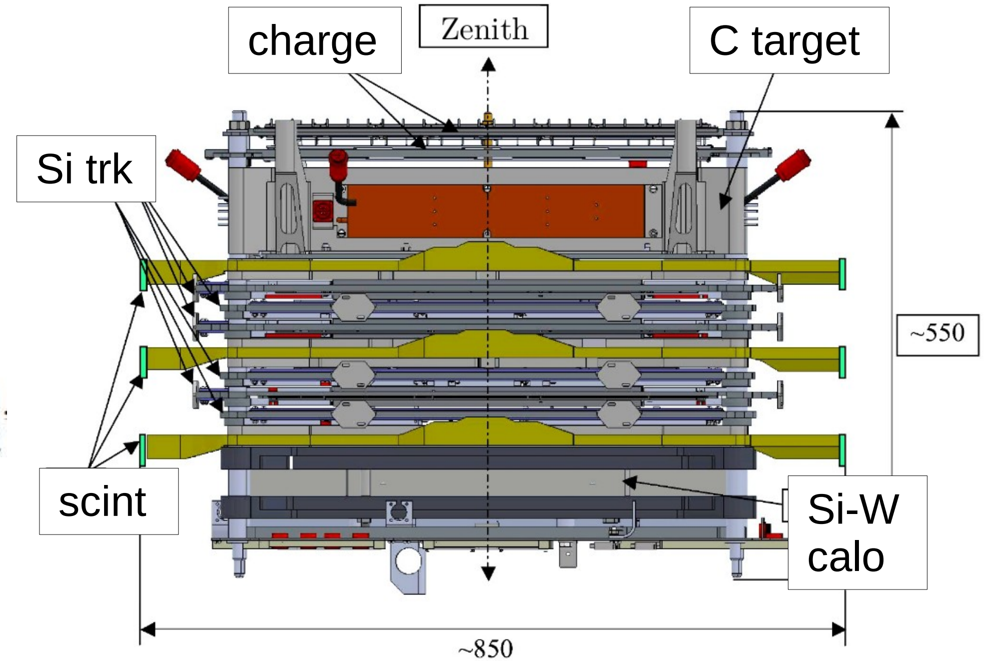
Large E => smaller pseudorapidity

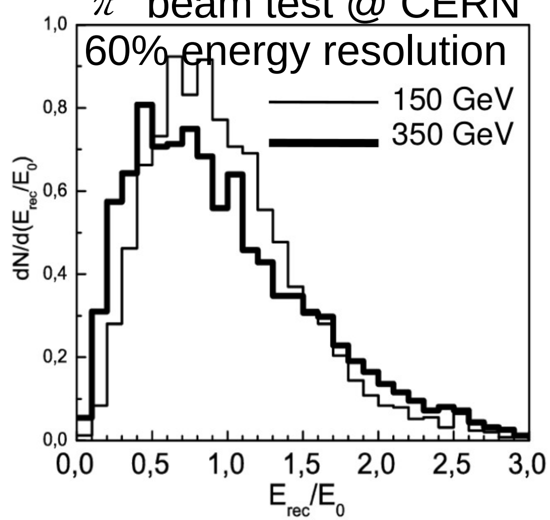


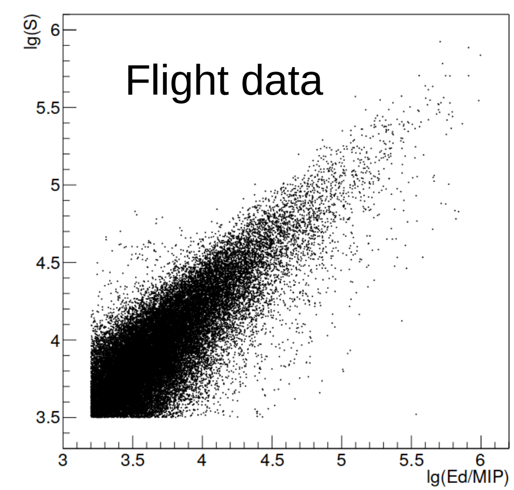
Projectile	a, GeV	b
p	1651	1.36
He	2556	1.27
C	3514	1.18
S	4163	1.14
Fe	4362	1.12

$$E_{primary} \simeq aS^b$$

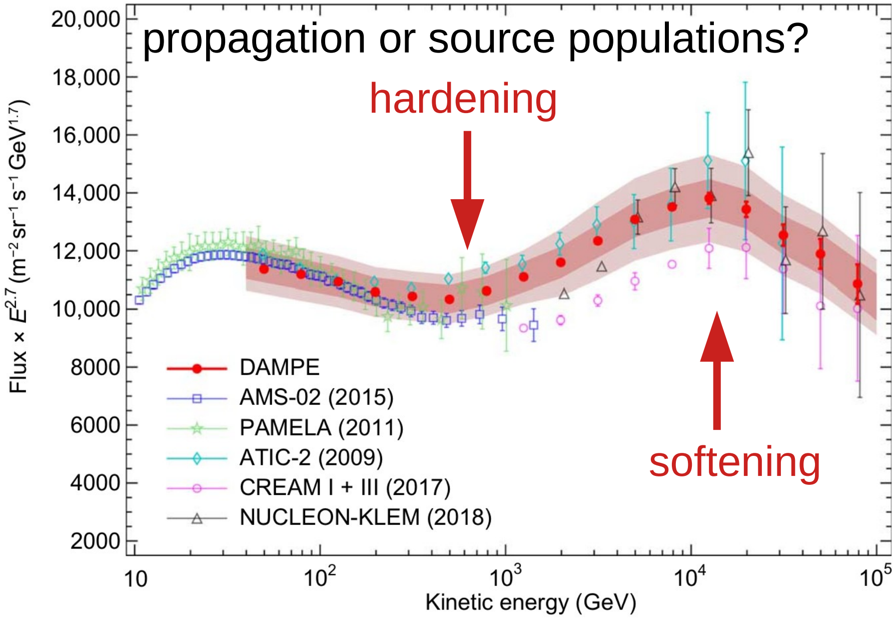
Thin Calorimeter 12 X_0 350kg 0.2m^{2}sr (2017)

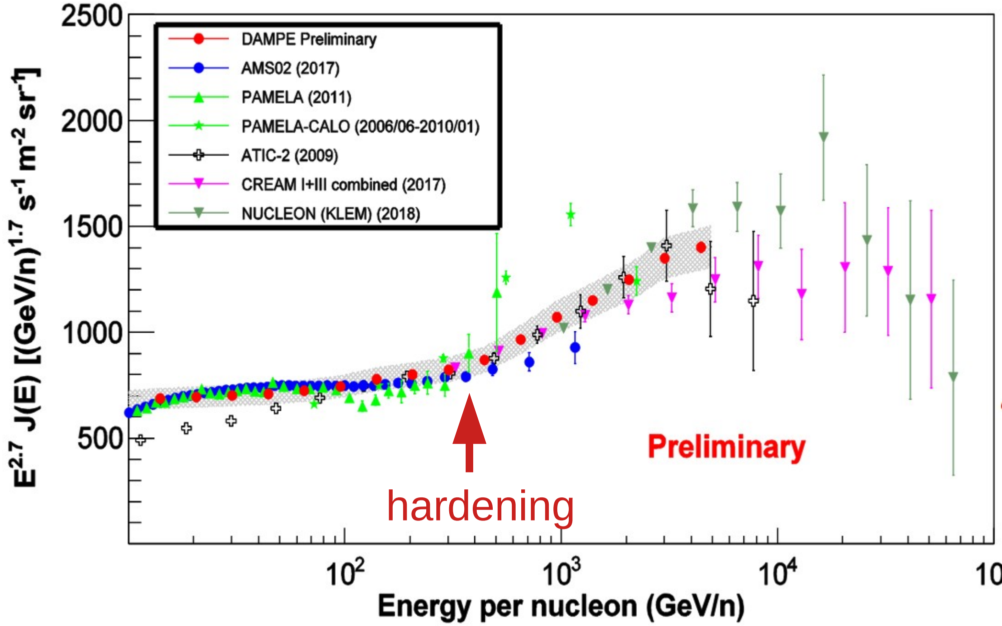


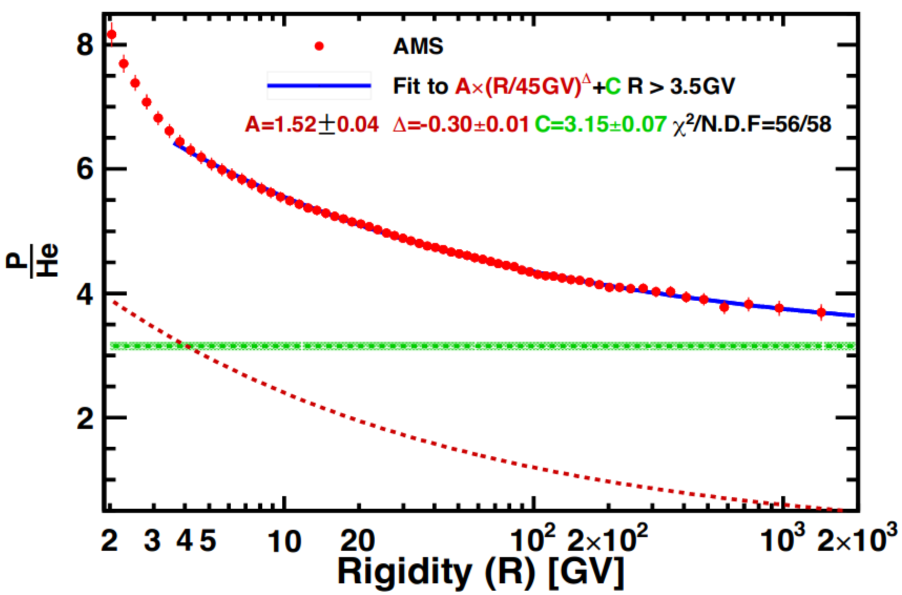


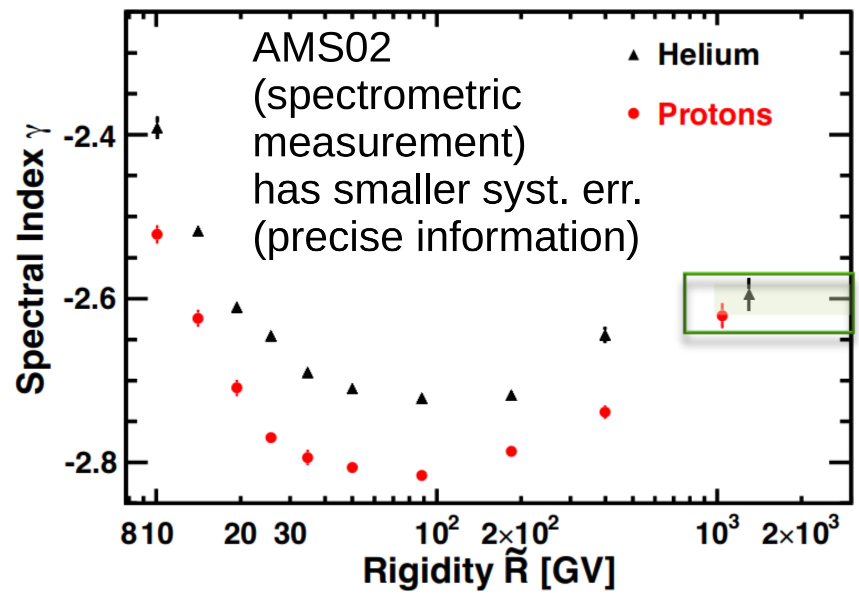


P & He spectrum









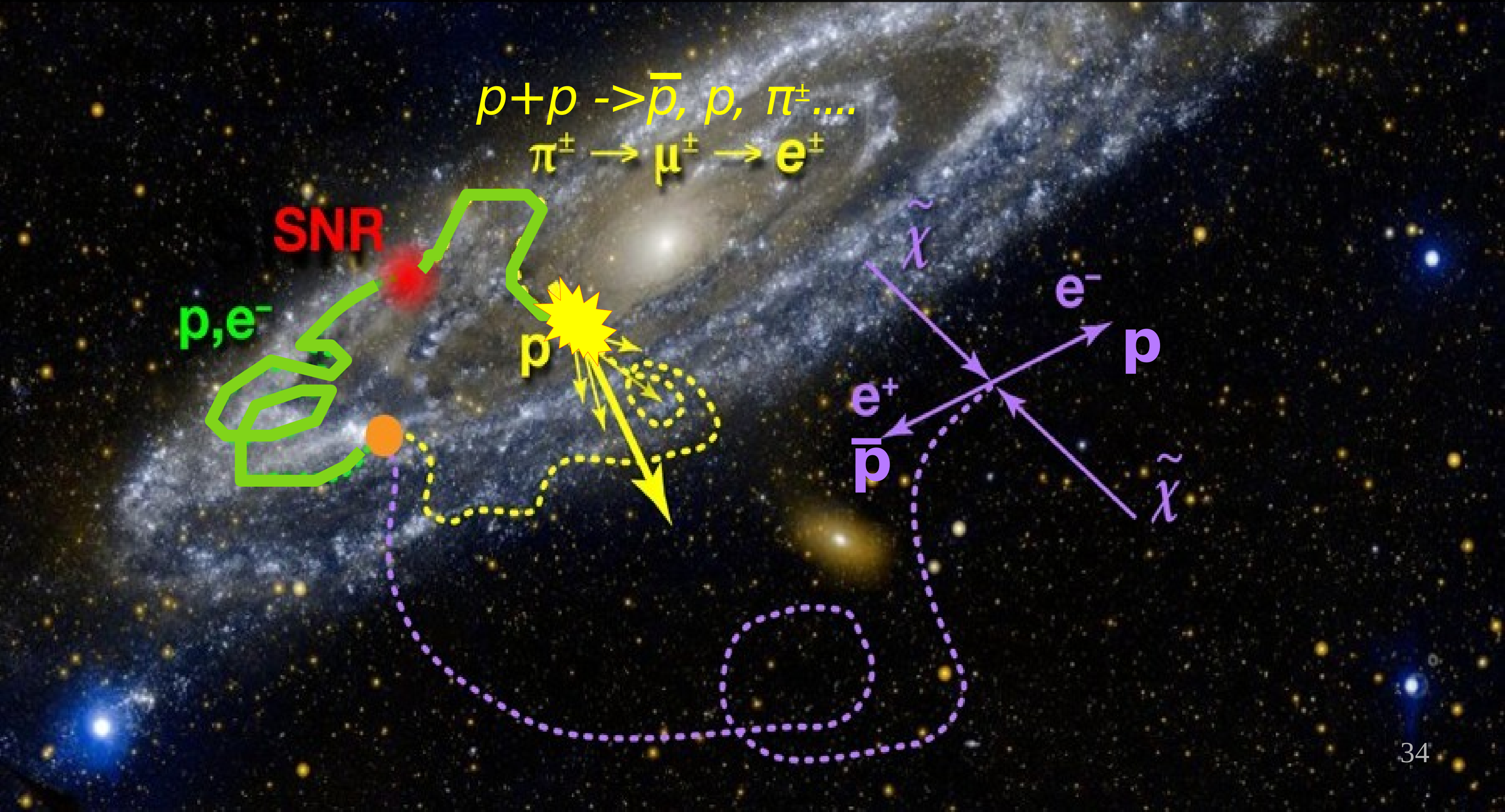
Cosmic Rays & DARK MATTER

e^- and p are produced and accelerated from SNR

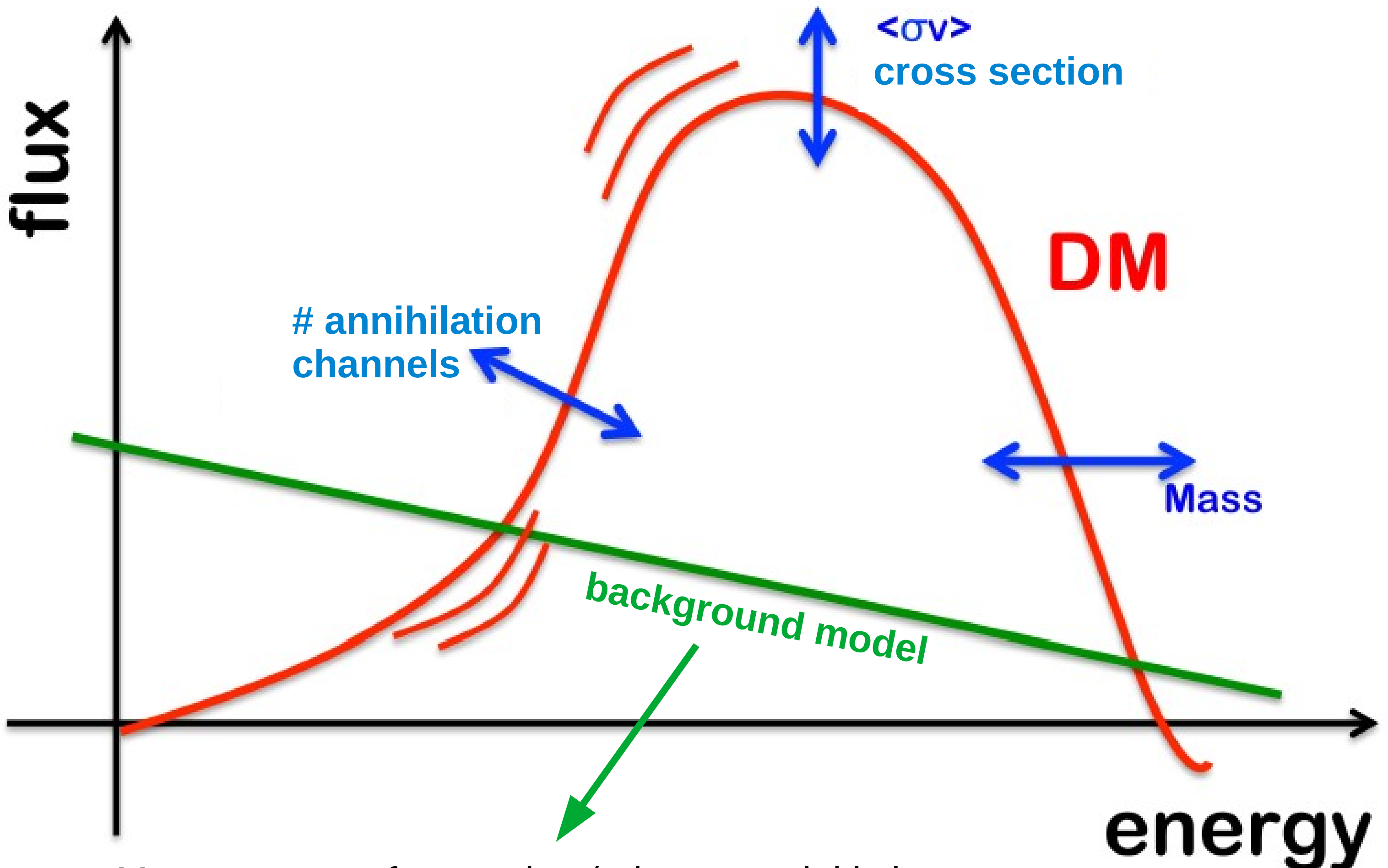
Collision of "ordinary" Cosmic Rays produce secondary e^+, e^-, $\bar{p}$

Among many possible mechanisms:

Collisions of Dark Matter will produce additional e^+, e^- , $\bar{p}$

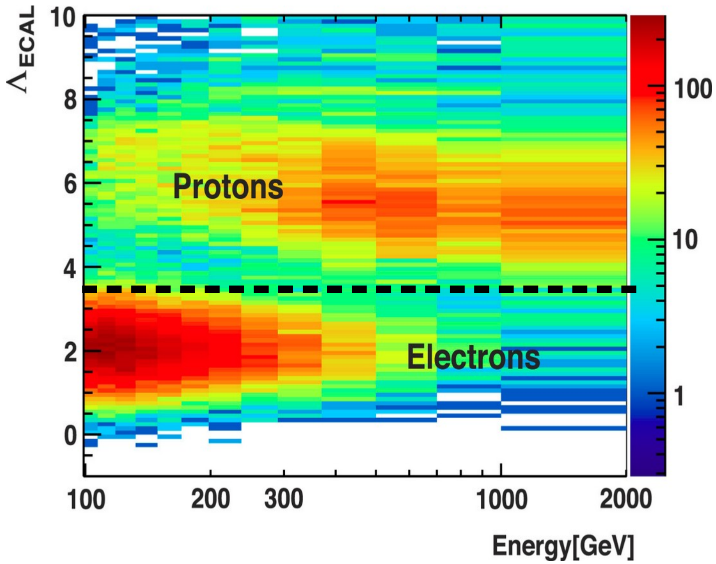


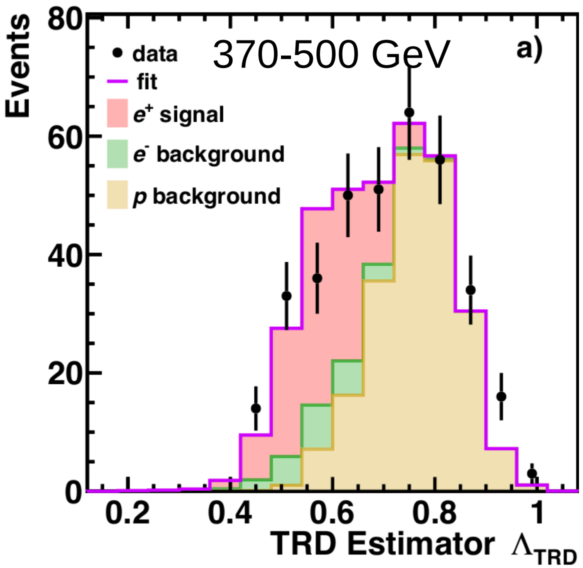
Dark Matter => antimatter exotic source

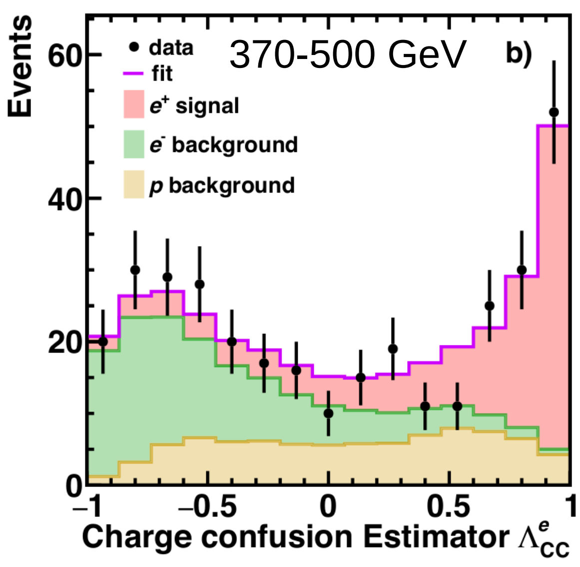


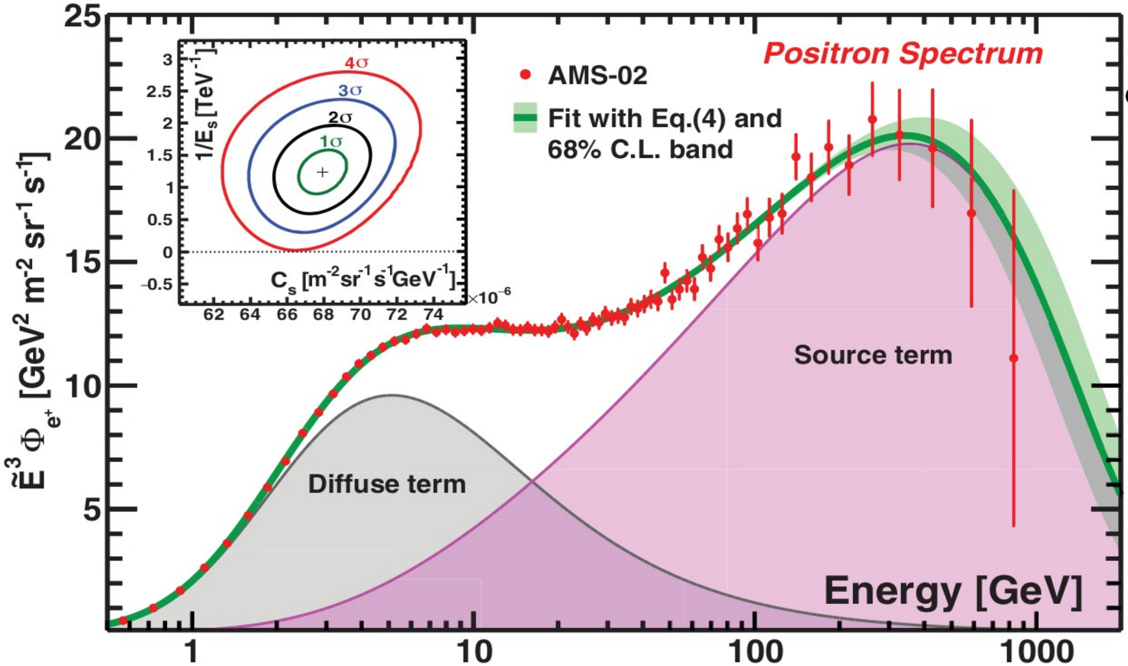
Measurement of secondary/primary nuclei is important to define effects of propagation/interaction in ISM.
This allows a precise evaluation of the antimatter background.

AMS02 Positrons







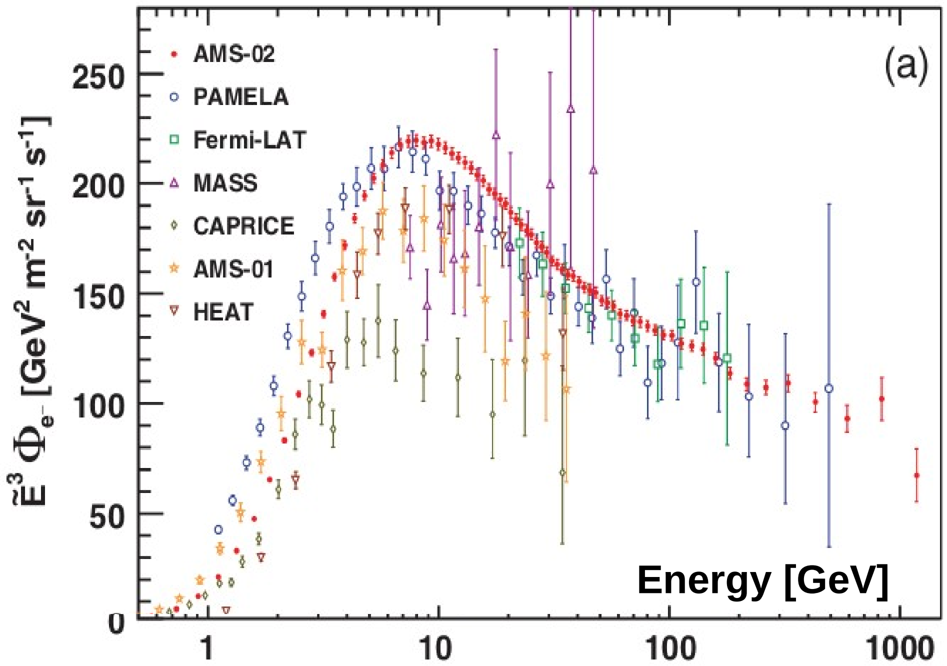


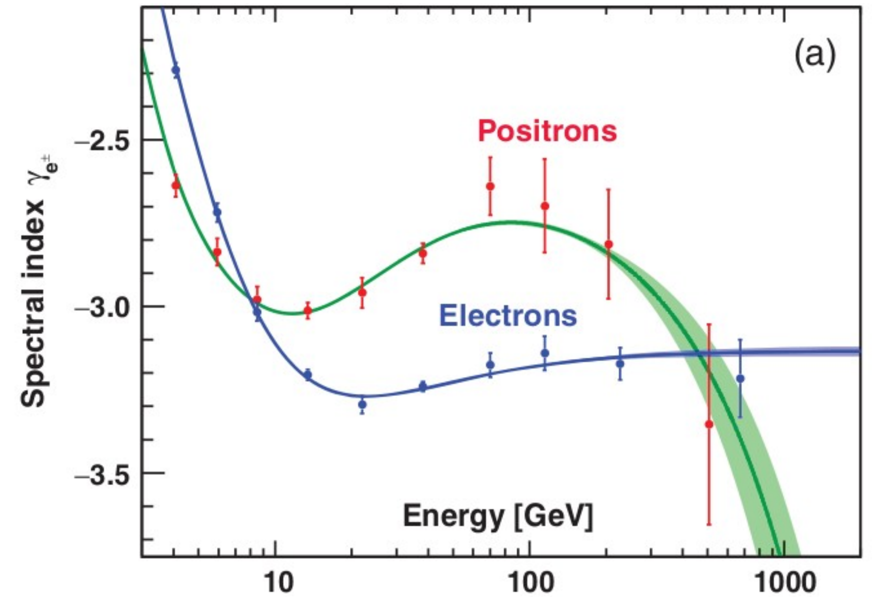
$$\Phi_{e+}(E) = \frac{E^2}{\hat{E}^2}\left[C_{e+}\hat{E}^{\gamma_{e+}} + C_S\hat{E}^{\gamma_S}\exp(-\hat{E}/E_S)\right]$$

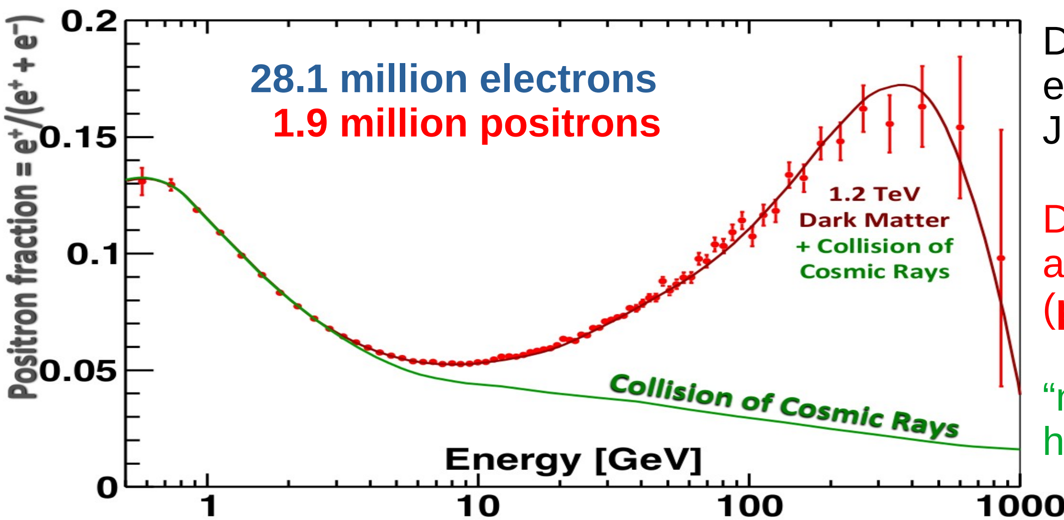
MINIMAL MODEL:
- **quantitative** information about the Positron source
- **minimal assumptions** on the underlying physics

Evidence for a cutoff energy:
E_s = 810 GeV @ 99.99% (4 σ)

AMS02 Electrons & Positron fraction





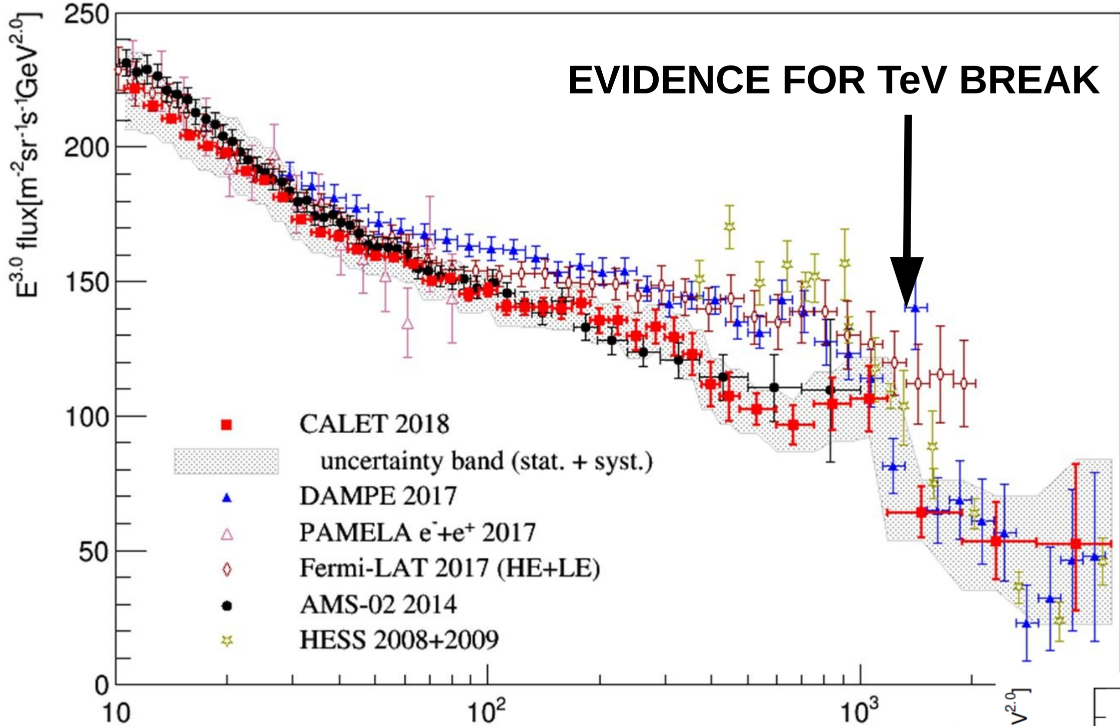


Detailed information on the positron source e.g. “excess” is compatible with Dark Matter J. Kopp, Phys. Rev. D 88, 076013 (2013).

Dark Matter is just an “intriguing” example, also nearby astrophysical positron sources (**pulsar**) could account for the excess…

“next point” (1-1.5 TeV, AMS02@2026) will help to solve degeneracy ...

Electrons + Positrons



Some tension in results:
DAMPE compatible with Fermi-LAT
CALET compatible with AMS02
All of them within 2.5 σ considering syst. uncertainties in calorim. E scale

HESS
(indirect detection see next lecture)

CALET (2015)

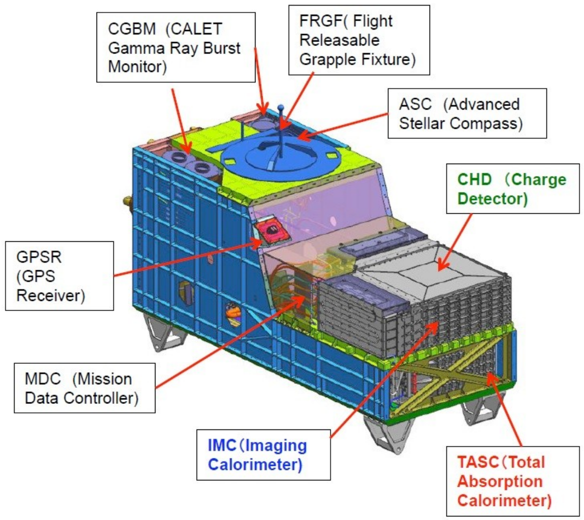
SciFi
41064 fibers 40.6 kg

MA-PMT
642 PMTs

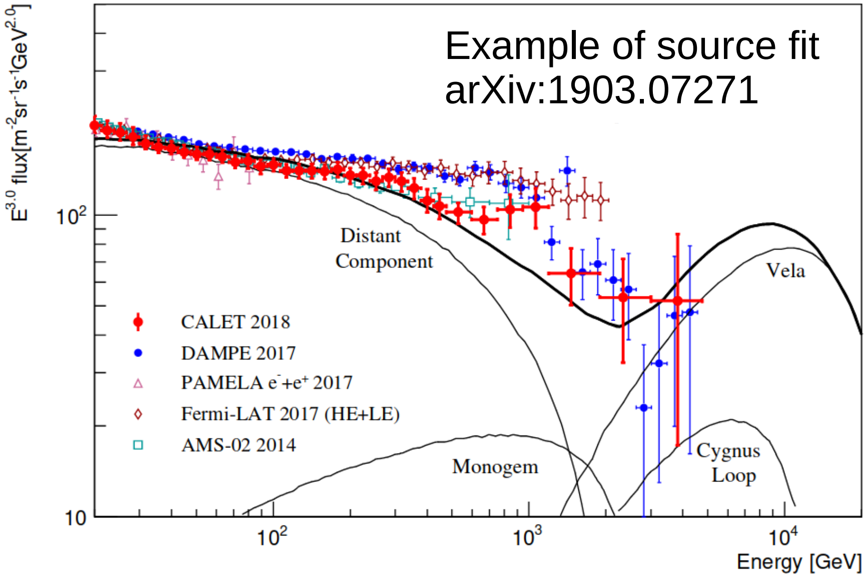
Lead 1024 mm x 1024 mm
4 r.l. = { 0.1 r.l. x 10, 0.2 r.l. x 5, 1 r.l. x 2 } 266.6 kg

BGO 25 mm x 25 mm x 350 mm
784 logs 1222.8 kg
32 r.l. 1.6 m.f.p

Detector Total Weight 1530 kg
(+15% Support => 1760 kg)

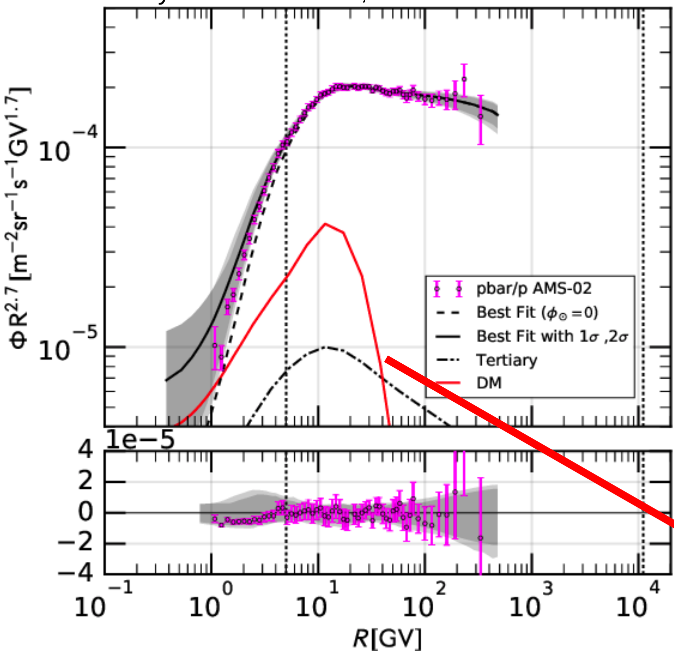


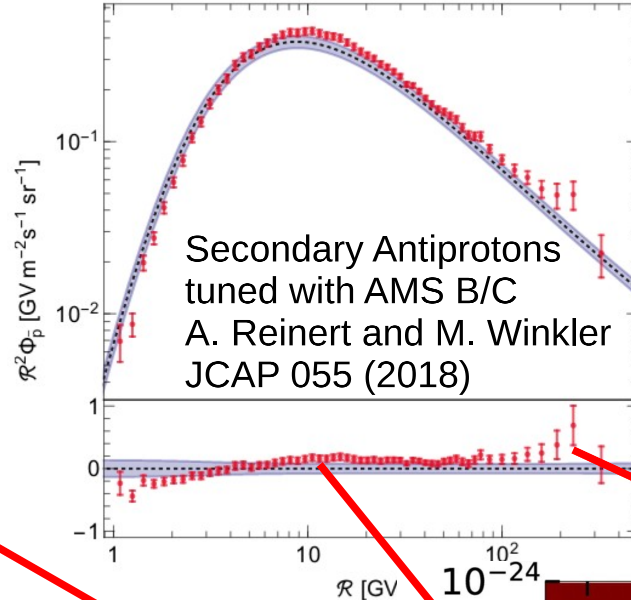
Example of source fit
arXiv:1903.07271



Some excess in Antiprotons?

Phys. Rev. Lett. 118, 191102





AMS02@2026

Can just add a new point up to 550-600 GeV

Charge confusion is dominated by gaussian “spillover” (MDR bulk)

“A Robust Excess in the Cosmic-Ray Antiproton Spectrum” Phys. Rev. D 99, 103026 (2019)

“AMS-02 antiprotons are consistent with a secondary astrophysical origin” arXiv:1906.07119

There is room for DM but…

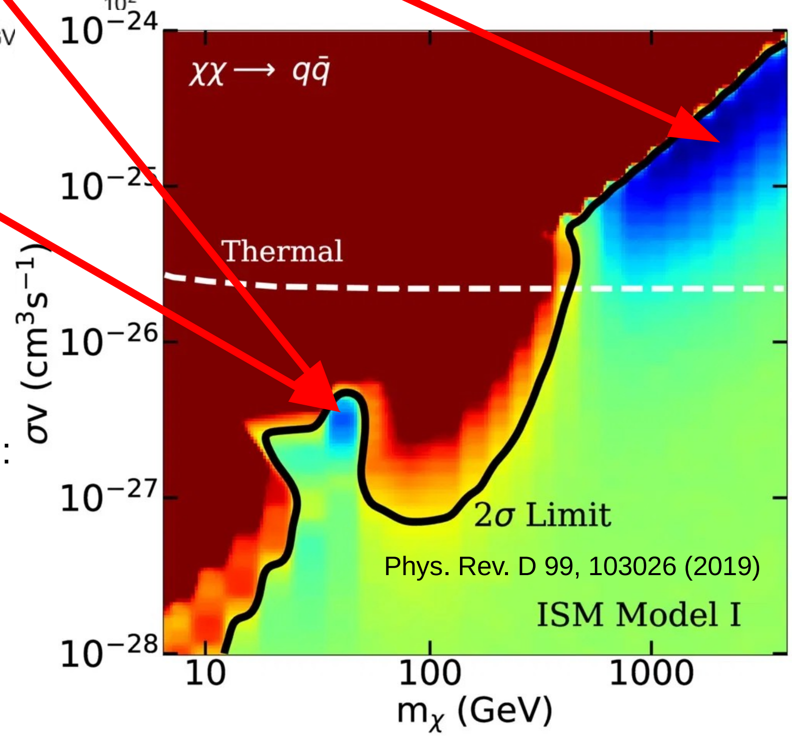
It is necessary to decrease uncertainty in the background model:

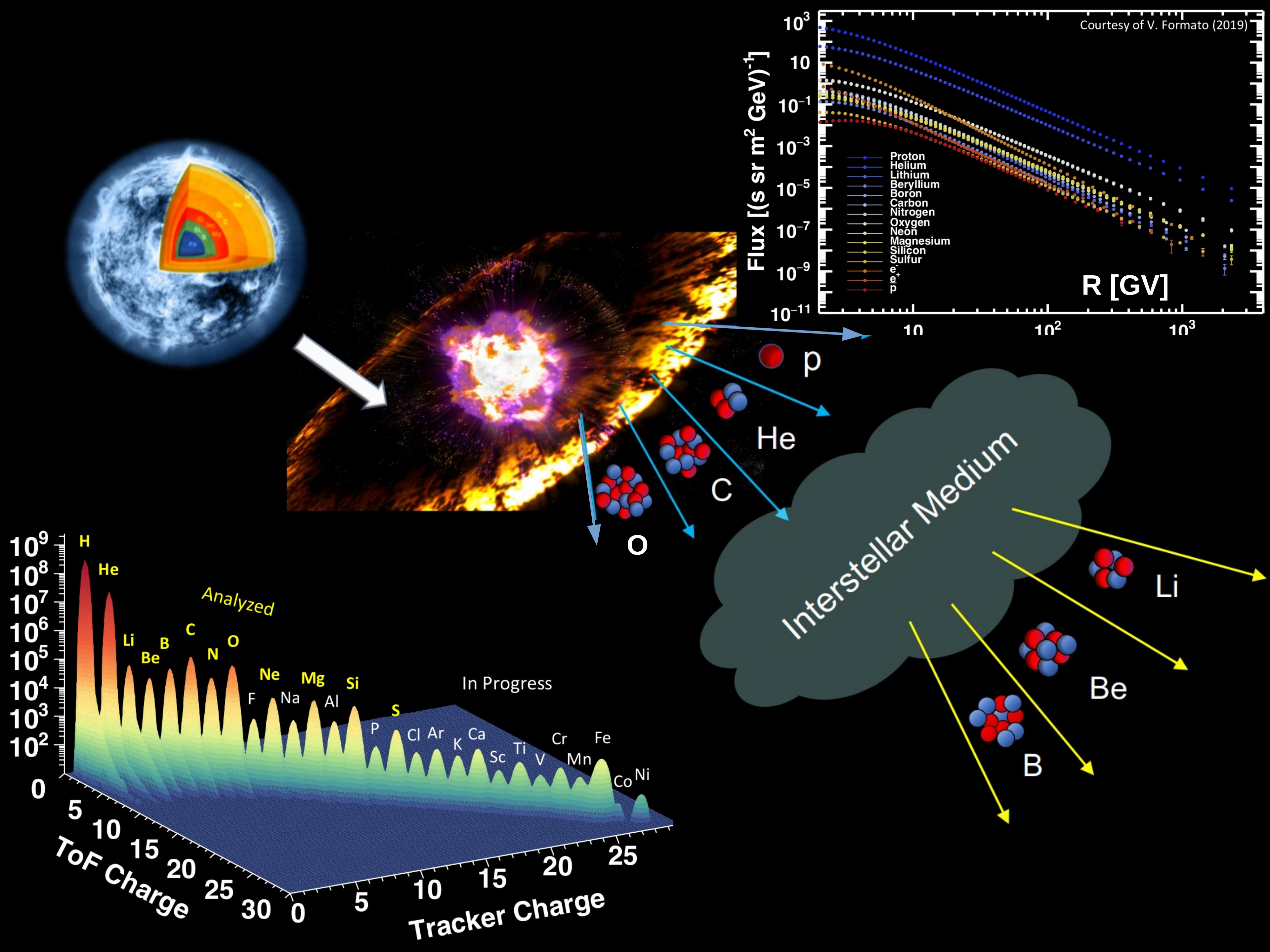
-cross sections knowledge (new measurements in lab)

-propagation models (**flux of other secondary cosmic rays**)

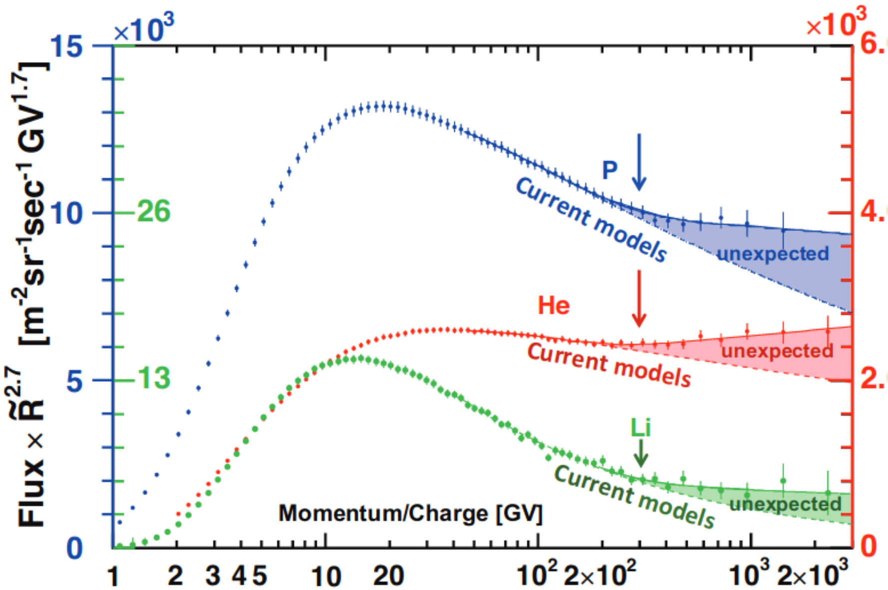
-solar modulation models (low energy time dependence)

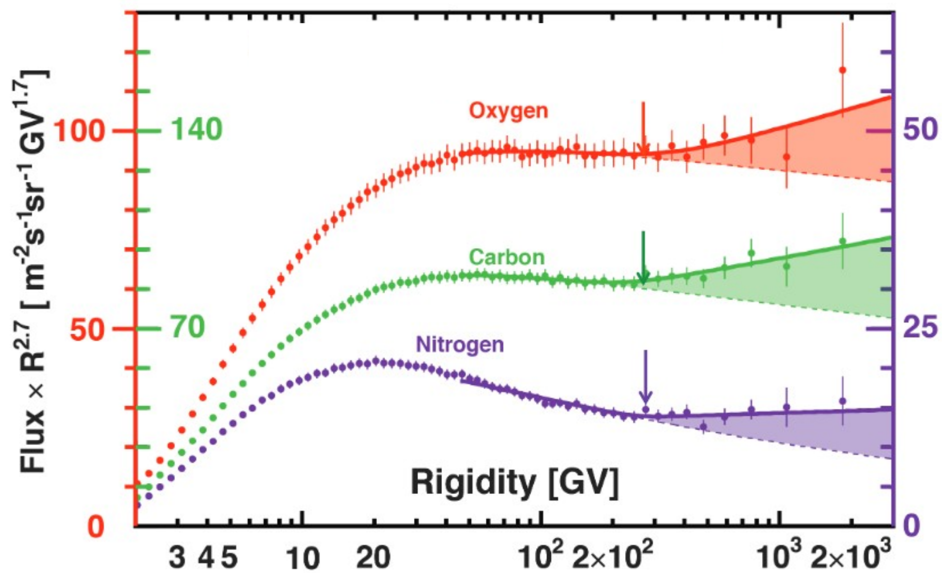
=> expected signal in low energy antideuteron?

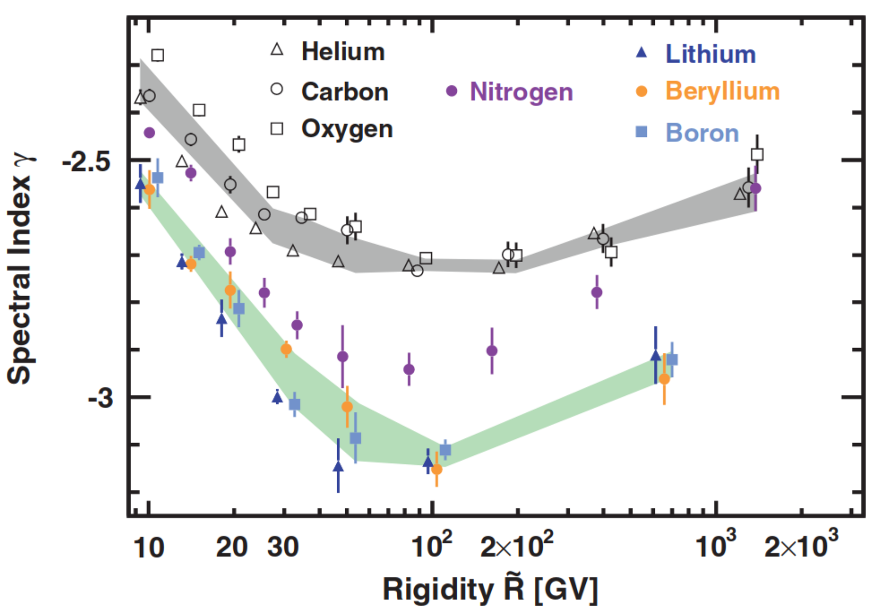



Courtesy of V. Formato (2019)
Flux [(s sr m² GeV)⁻¹]
R [GV]
Proton
Helium
Lithium
Beryllium
Boron
Carbon
Nitrogen
Oxygen
Neon
Magnesium
Silicon
Sulfur
p
He
C
O
Interstellar Medium
Li
Be
B
Analyzed
In Progress
H He Li Be B C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni
ToF Charge
Tracker Charge

AMS: primary & secondary break







AMS02 accuracy & new evidence:

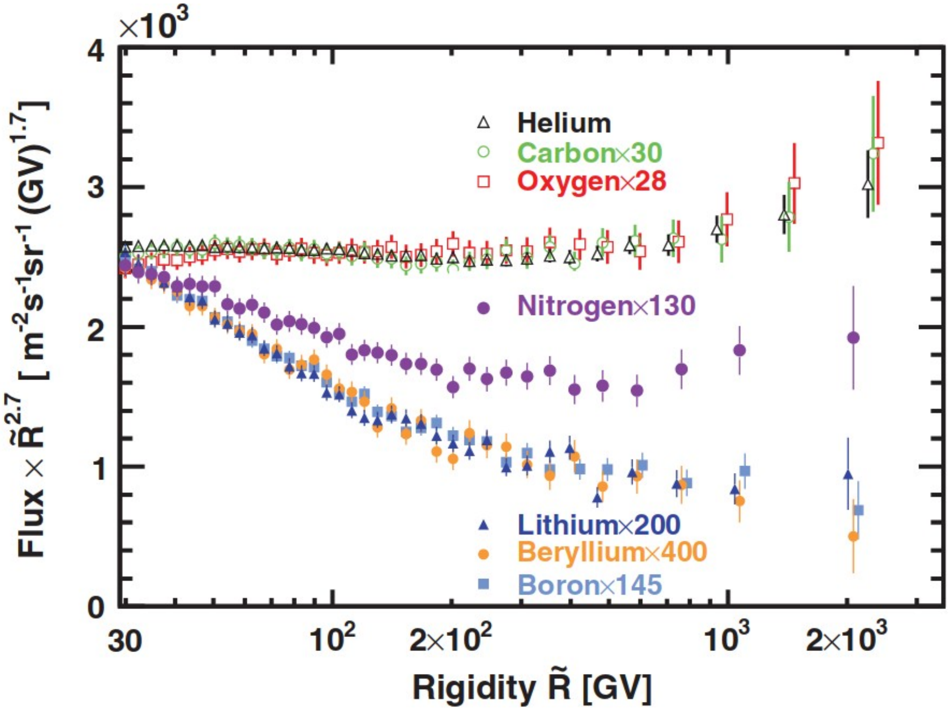
-Both show hardening above 200 GV

-Primary => common behavior

-Secondary => common behavior

-Nitrogen is a mixture

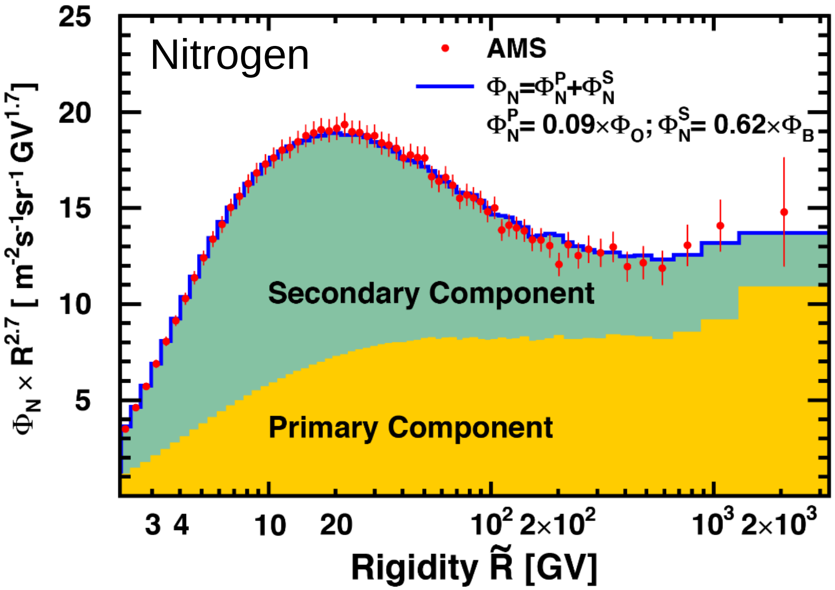
AMS: NITROGEN



Primary => common behavior

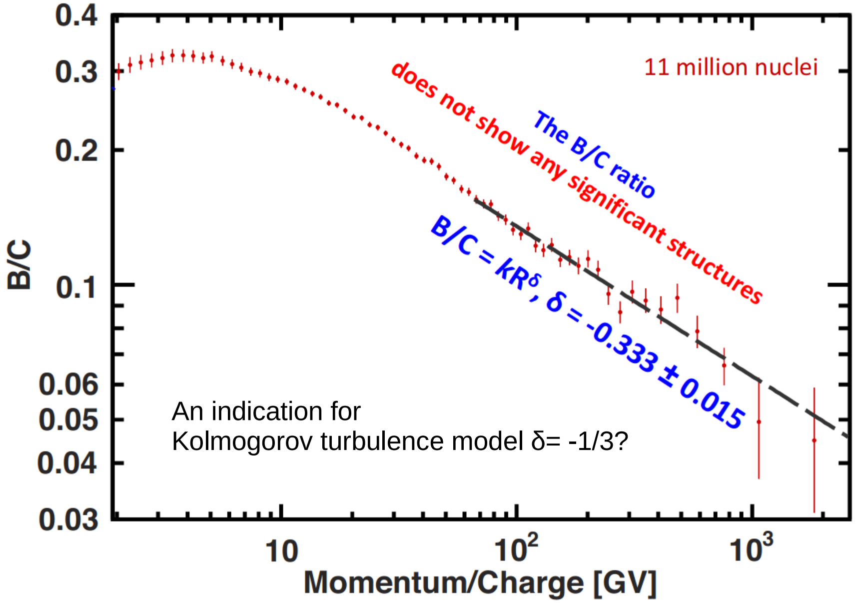
Primary + Secondary MIXTURE

Secondary => common behavior



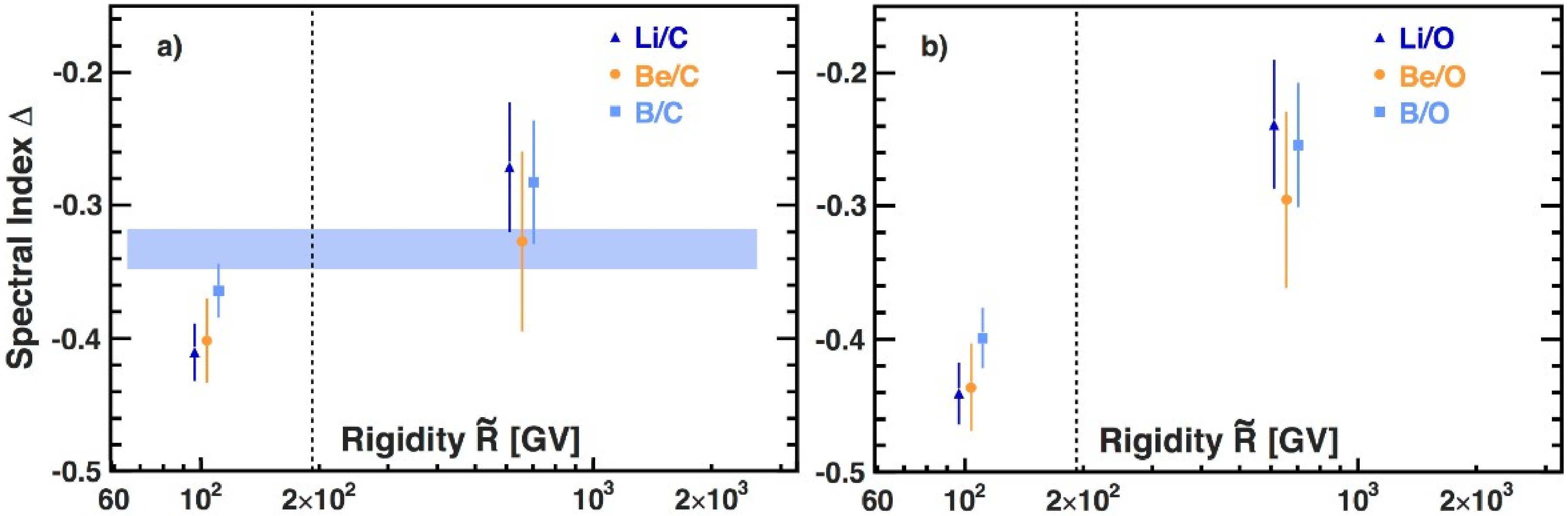
In the Solar System:	In the Cosmic Rays:
N/O = 0.14 ± 0.05	N/O = 0.090 ± 0.002 (primary component)
C/O = 0.46 ± 0.09	C/O = 0.91 ± 0.02

AMS: secondary/primary



If the hardening in CRs is related to the **injected spectra at their source**, then similar hardening is expected both for secondary and primary cosmic rays.

If the hardening is related to **propagation** properties in the Galaxy then a stronger hardening is expected for the secondary with respect to the primary cosmic rays.

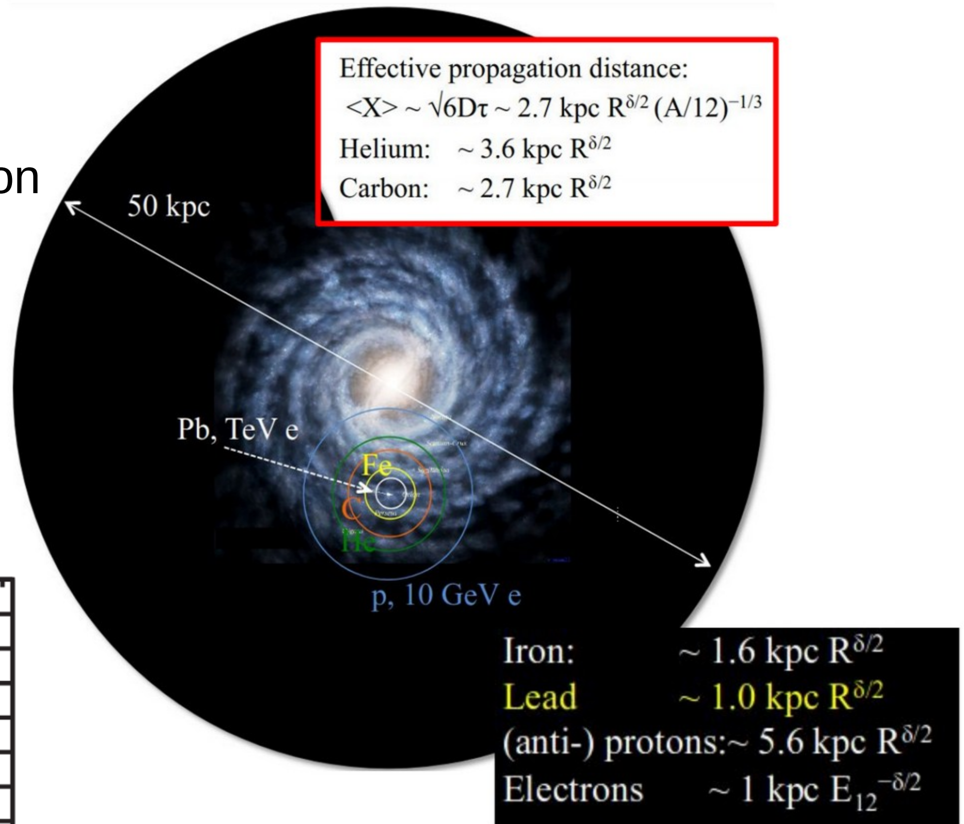


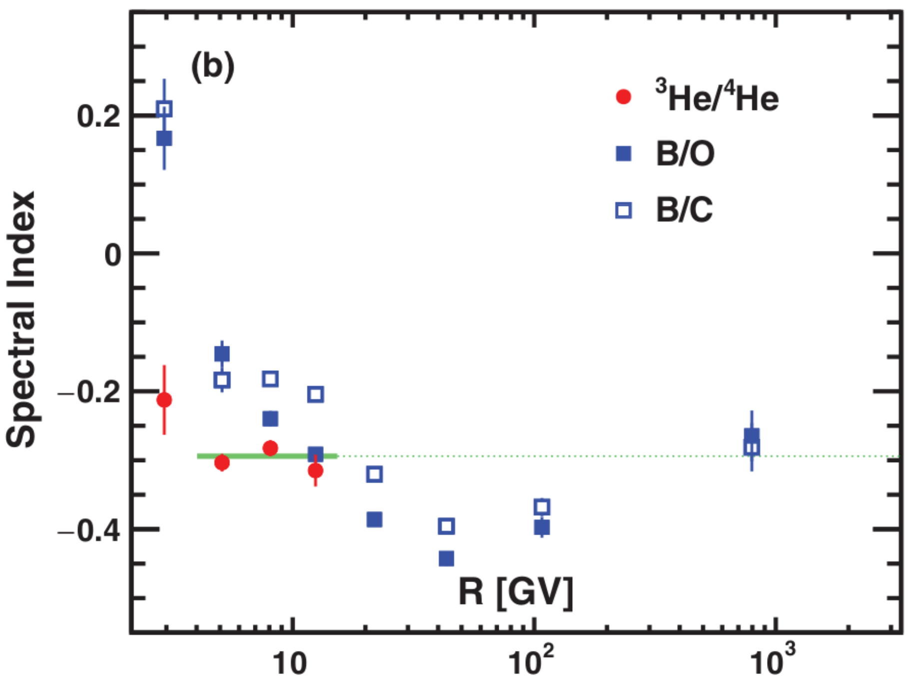
An hardening of 0.13±0.03 at 200 GV is observed combining the six secondary/primary ratios
This observation favors the flux hardening as an universal propagation effect

AMS: secondary/primary & distance

Probing Non-Homogeneous Diffusion:

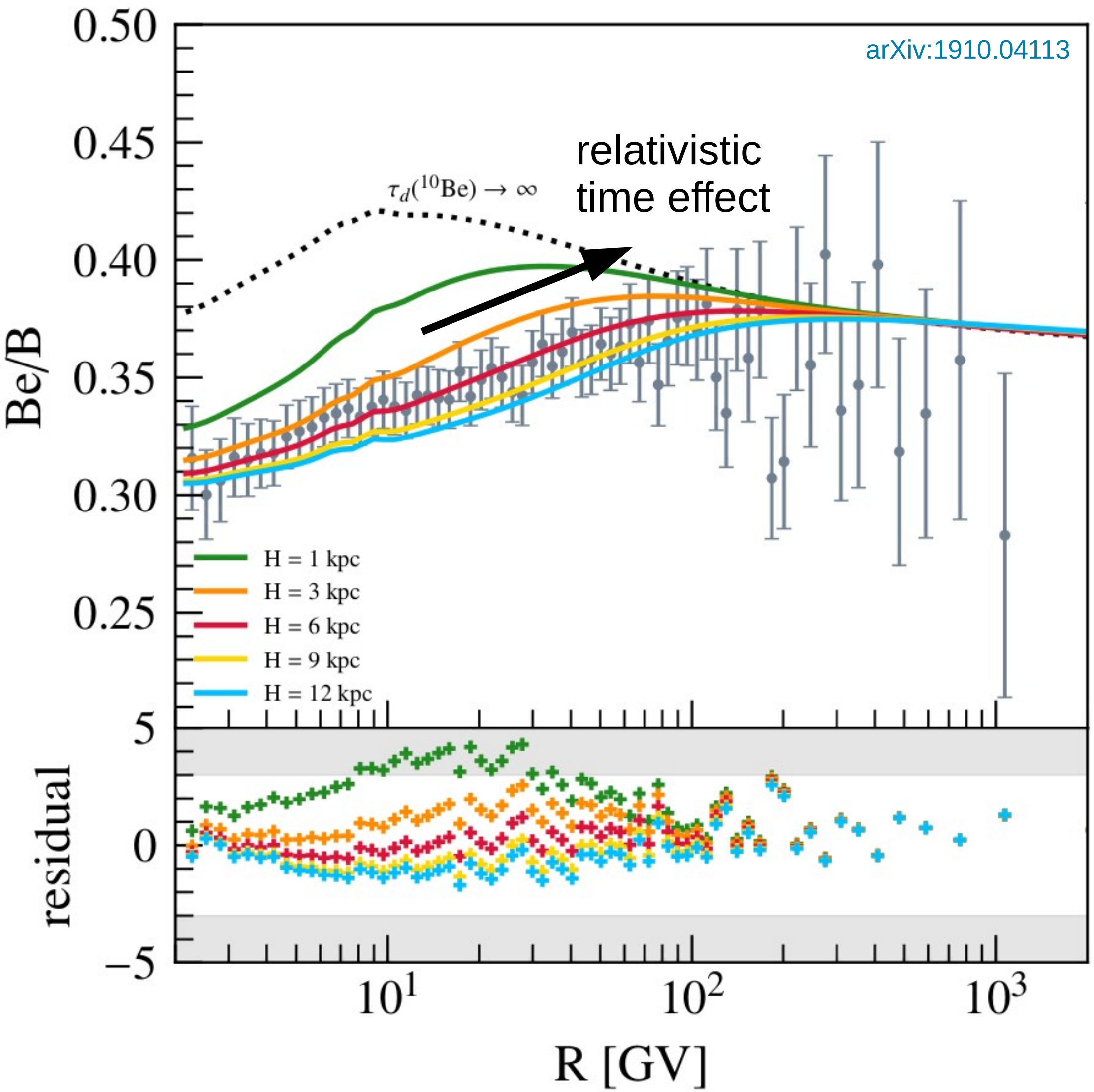
- B/C is a probe for only “local” propagation
- p,D and $\bar{p}$ come from much further
- light secondary like D, ^{3}He investigate better the $\bar{p}$ secondary production



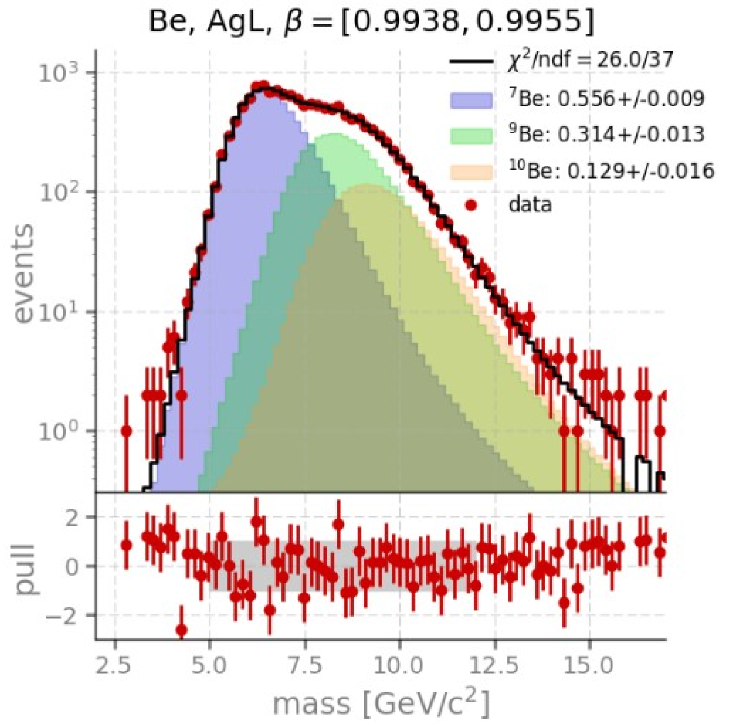


Spectral index for ^{3}He/^{4}He is the same obtained for B/C and B/O at high R. May indicate the effect of a different diffusion coefficient in non local regions

AMS: Be/B clock

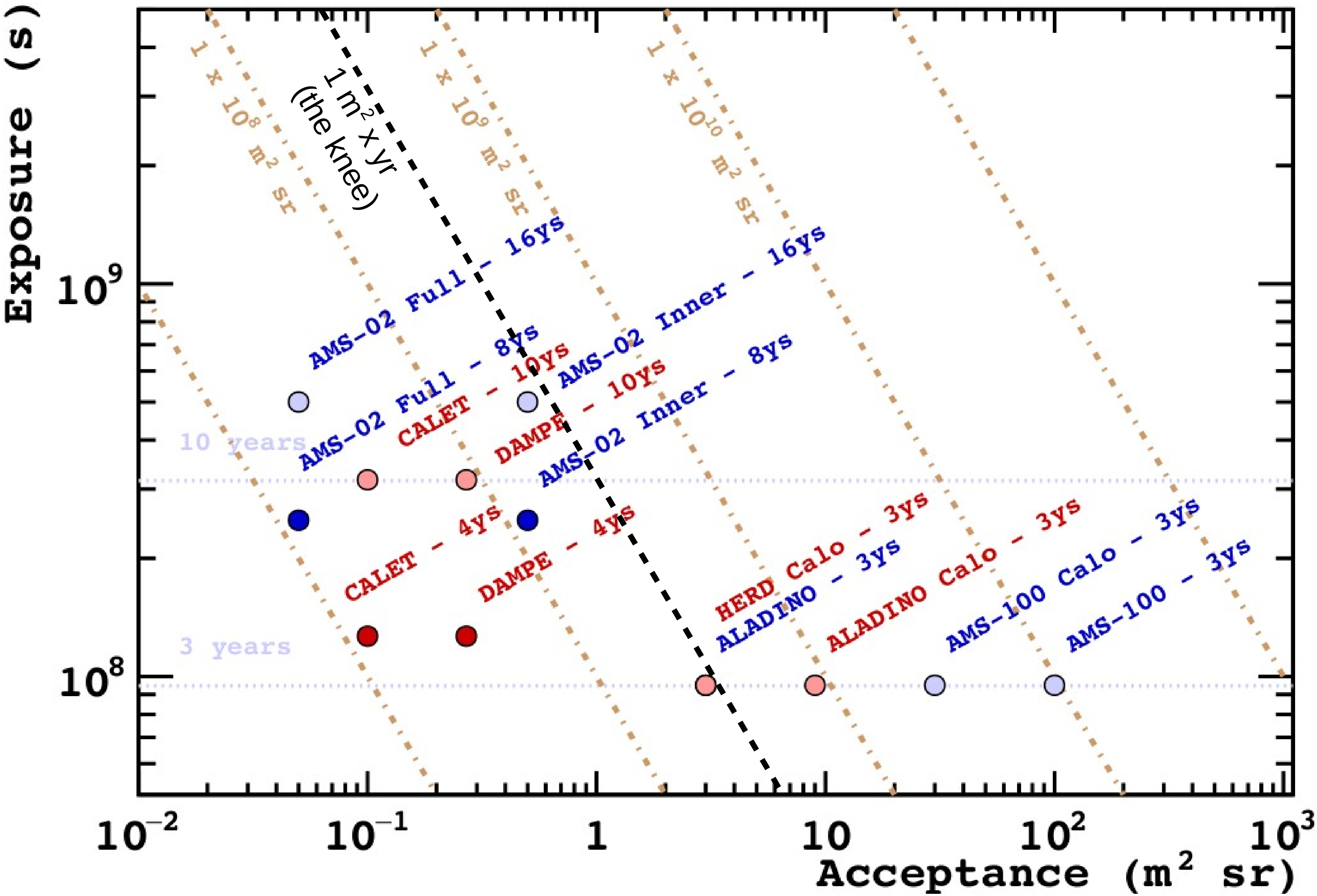


^{10}Be (τ ≈ 1.4My) => ^{10}B + e$^-$ + $\bar{\nu}$
sensitive to residence time of CR in the Galaxy => halo size H.

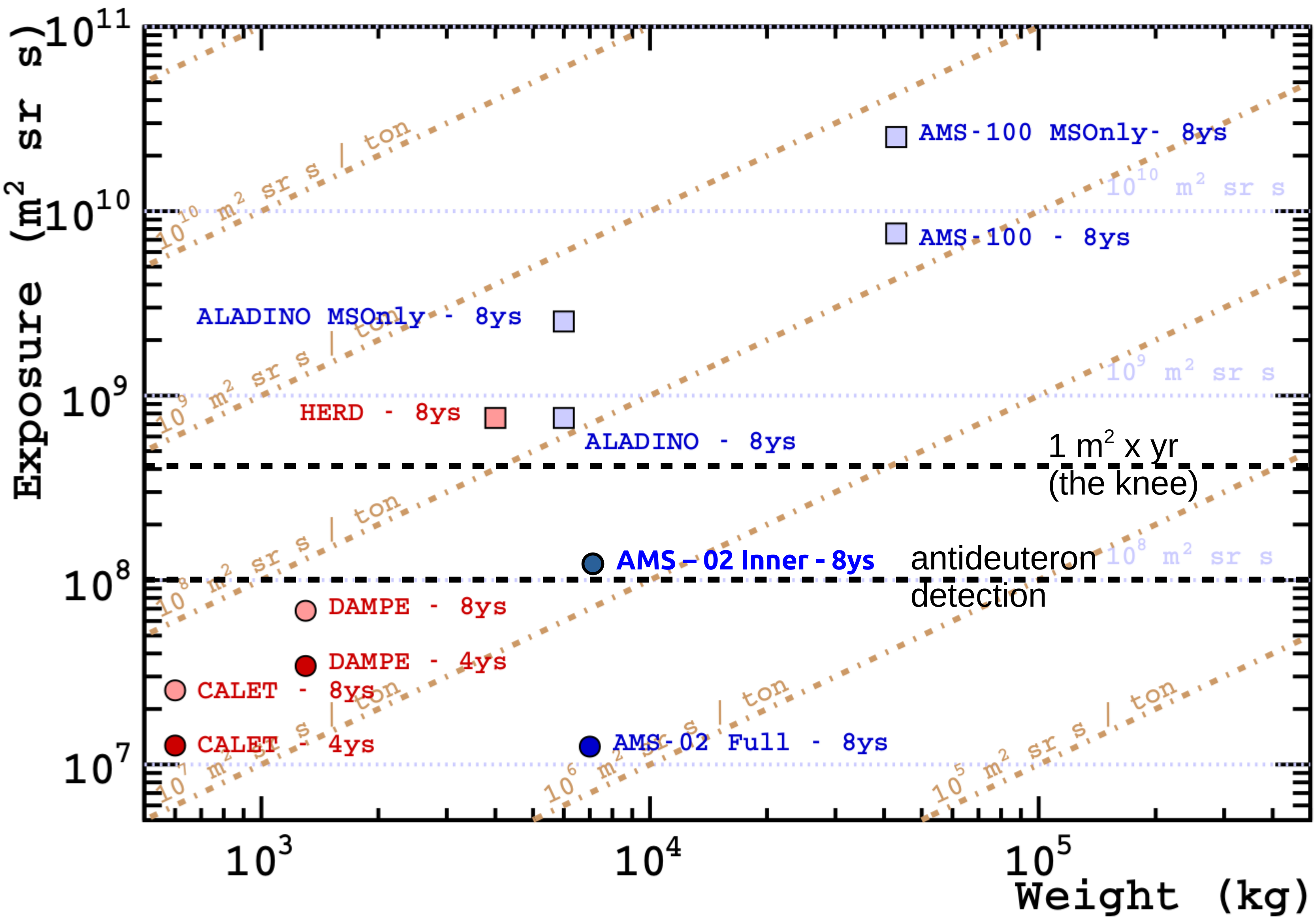


Hard to get direct measurement of ^{10}Be content at "high energy", but Be/B is sensitive to ^{10}Be fraction.

Current - future experiments

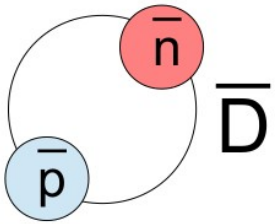


Current - future experiments

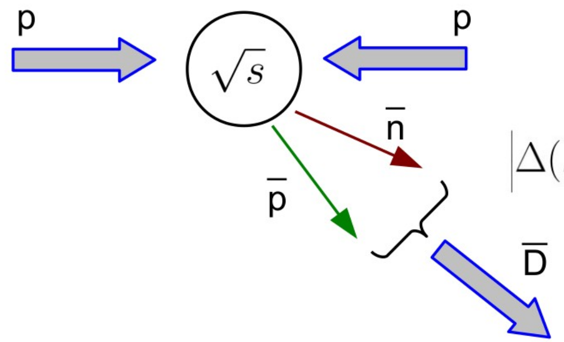


… and …
anti-nuclei?

anti-D coalescence production



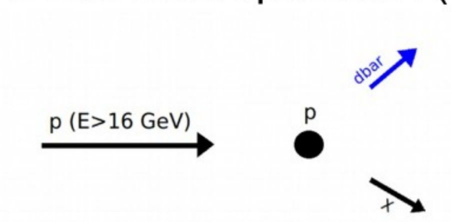
M = 1875.6 MeV
Z = -1
A = -2
ΔE = 2.2 MeV



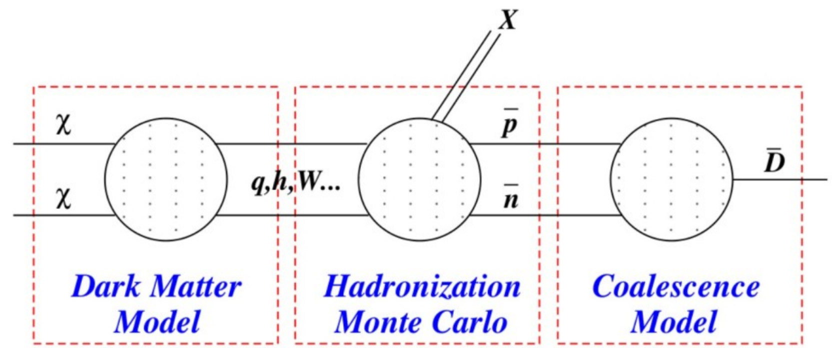
$$\left|\Delta(\vec{k})\right| = \vec{k}_{\bar{p}} - \vec{k}_{\bar{n}} < p_0$$

p_0 ~ 180 MeV

$\bar{D}$ flux from spallation (background, B)



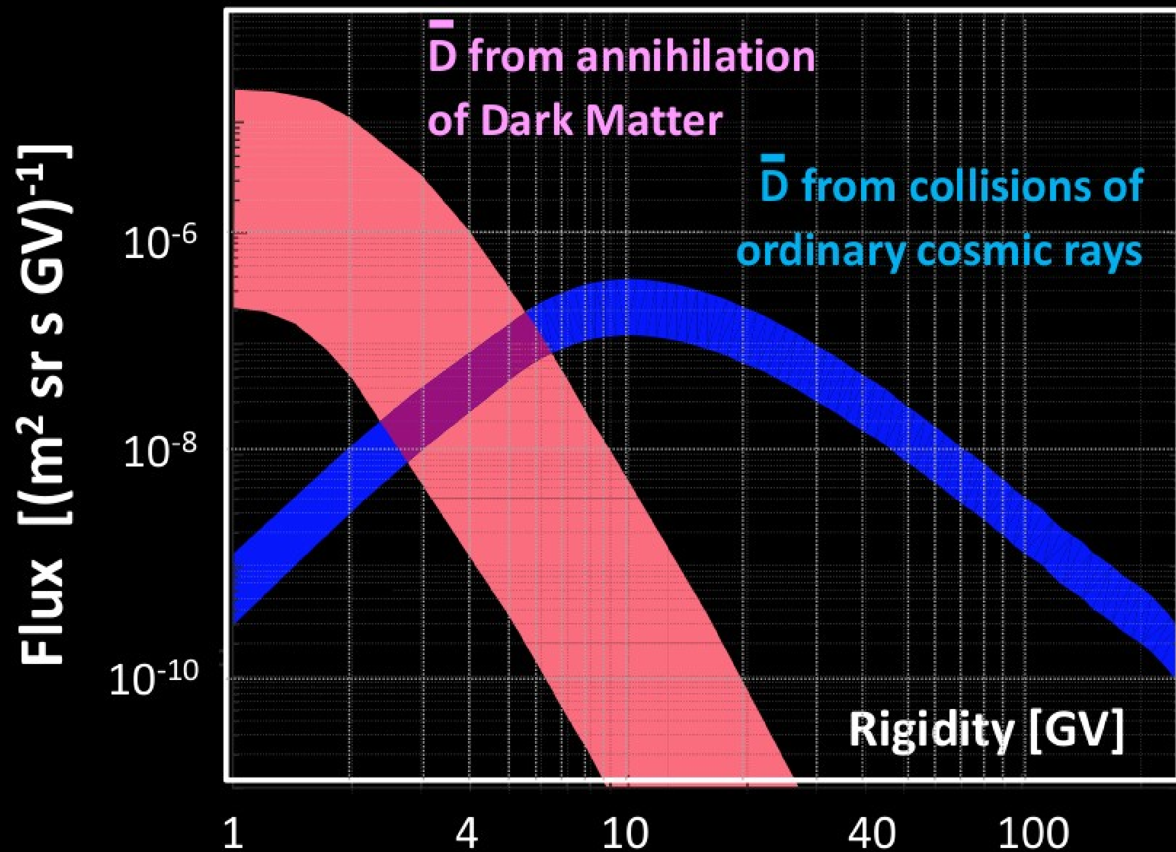
$\bar{D}$ flux suppressed from
→ Boosted RF
→ Steeply falling CR p flux



-Coalescence is a very rare process.
-Low energy, secondary (bkg) anti-D suppressed by: threshold (16 GeV) + boost.
-Jet structure (correlation of $\bar{p}$,$\bar{n}$) enhance anti-D production at low energy (i.e. from DM annihilation).

Anti Deuterons in Cosmic rays

Anti Deuterons have been proposed as an almost background free channel for Dark Matter indirect detection



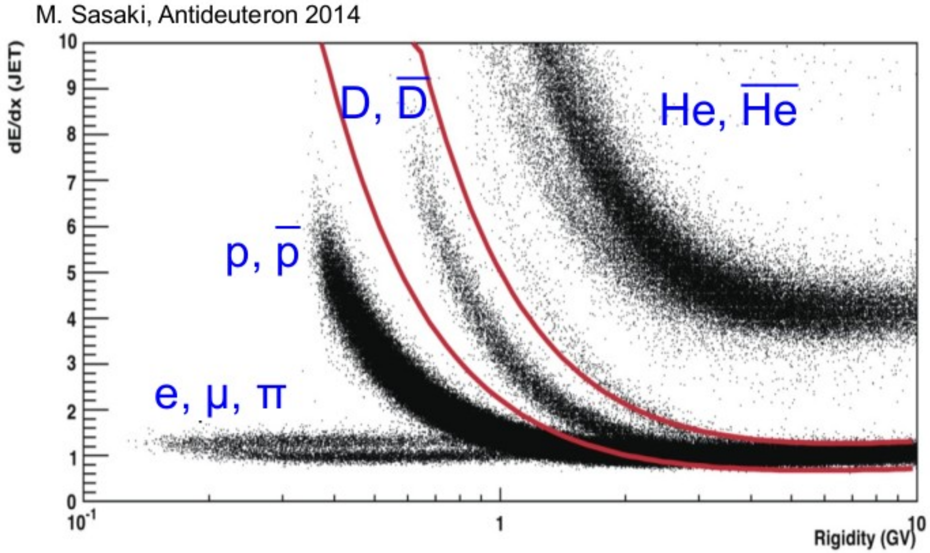
Dark Matter model:
F. Donato et al., Phys. Rev. D, 62 (2000) 043003

Collisions of CR model
K. Blum et al., Phys. Rev. D 96 (2017) 103021)

The Anti Deuterons Flux is $< 10^{-4}$ of the Antiproton Flux.

Additional background rejection needed

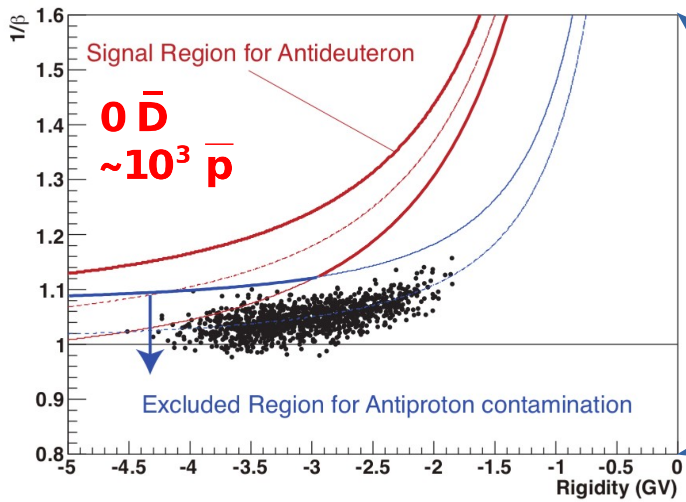
BESS-Polar II : we are still waiting for an “official” limit

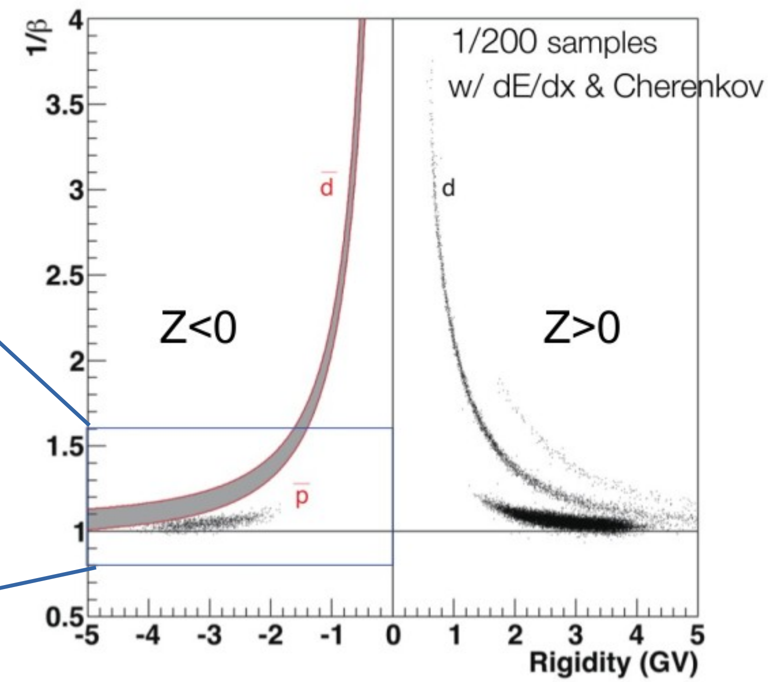


- Typical approach: MASS SELECTION

$$m = \frac{p}{Z}\frac{\sqrt{1-\beta^2}}{\beta}$$

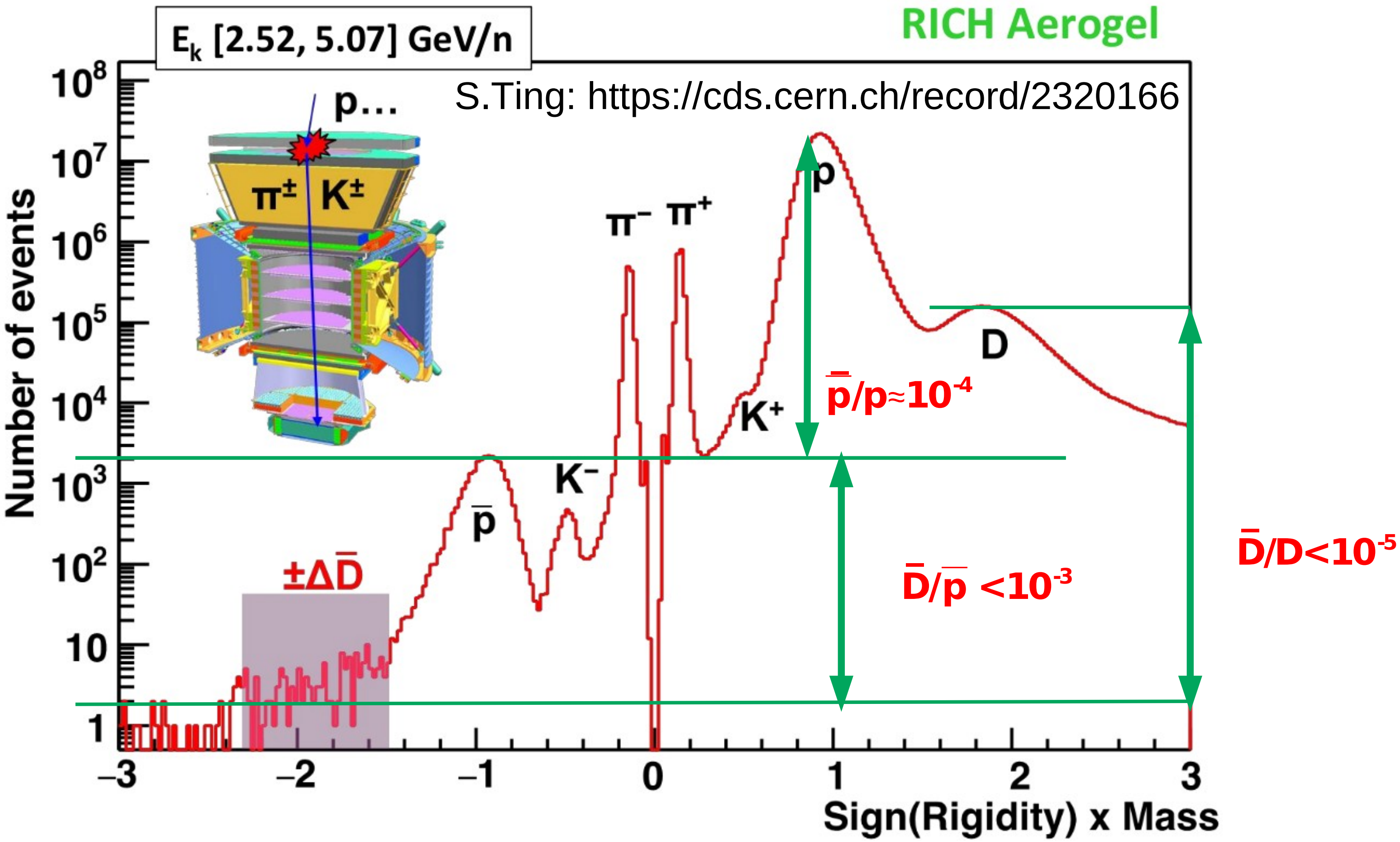
- dE/dX sampled in many subdetectors and used to select the signal window





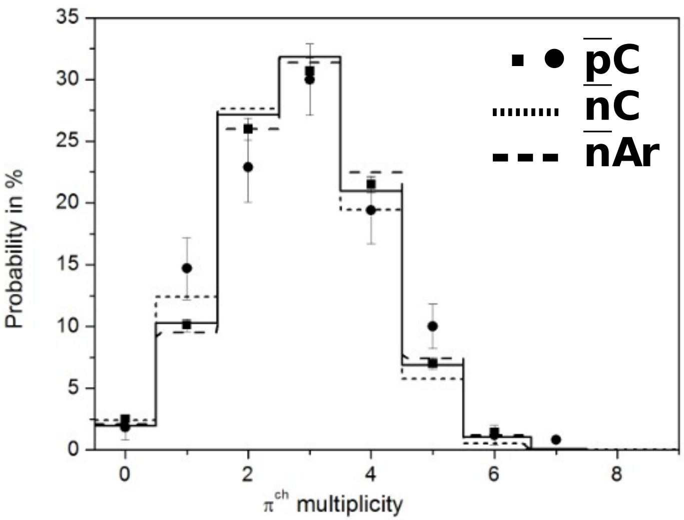
a coming-soon improvement in sensitivity: AMS-02

Status of AMS02 anti-D search: **already exceed the sensitivity of BESS**

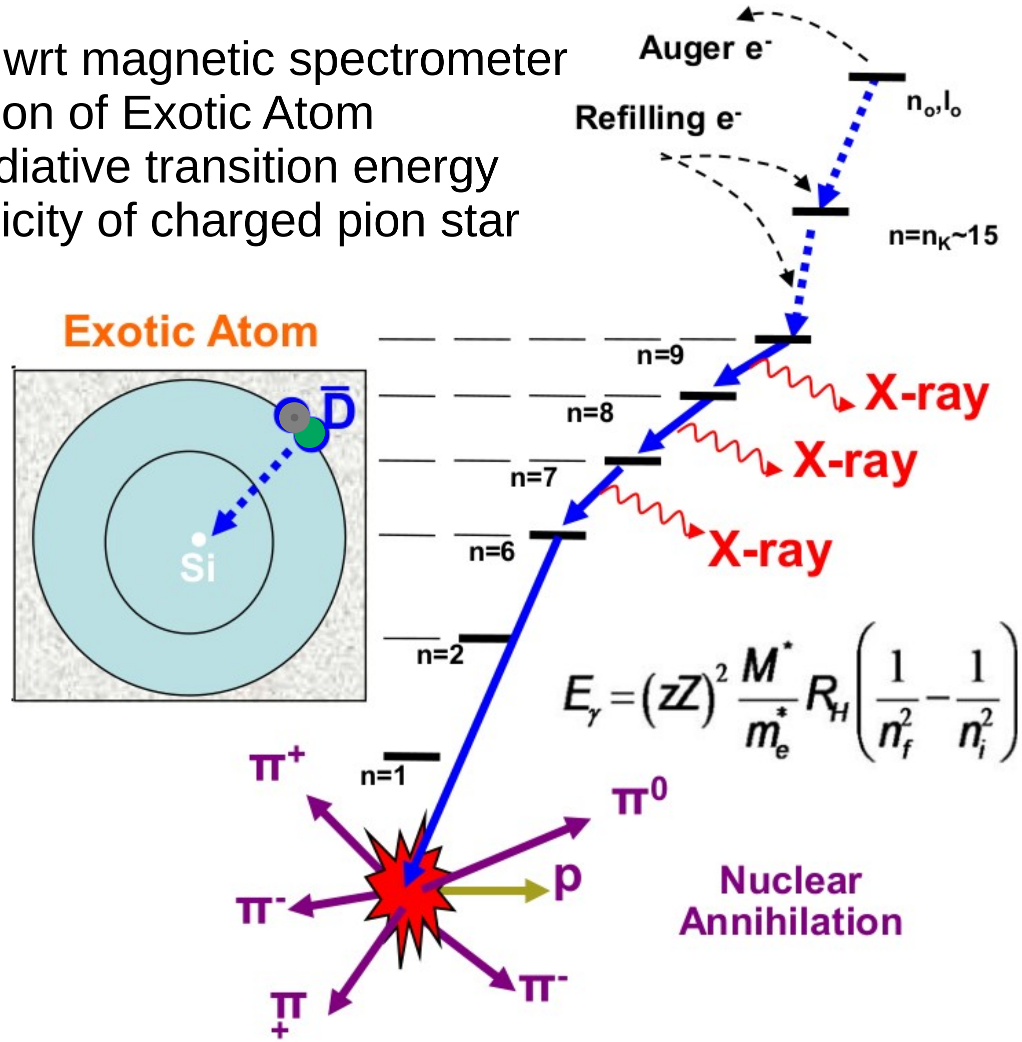


Atomic-transitions:
additional signatures for low energy anti-D

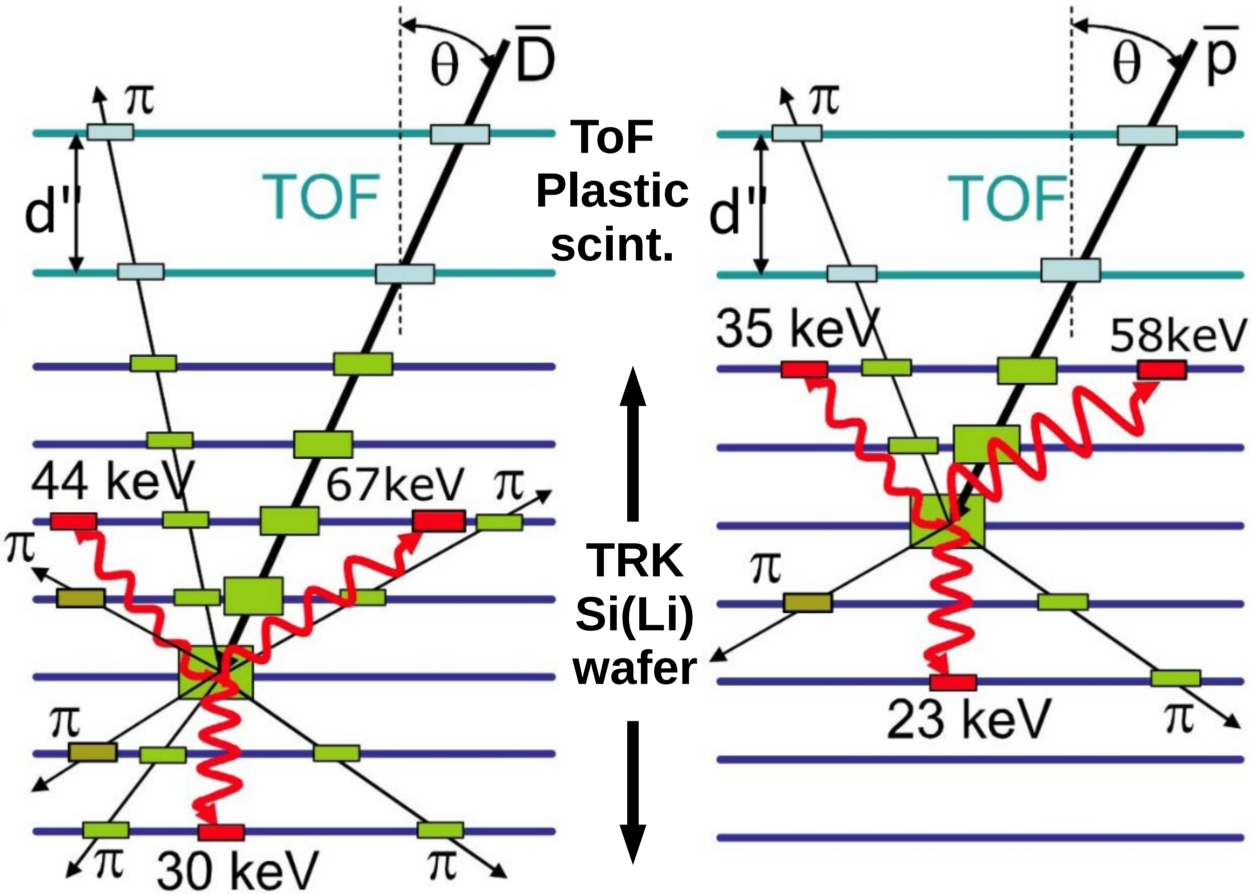
For low energy additional signature wrt magnetic spectrometer
- Charge sign is detected by formation of Exotic Atom
- anti-D recognized by distinctive radiative transition energy
- anti-D recognized by larger multiplicity of charged pion star



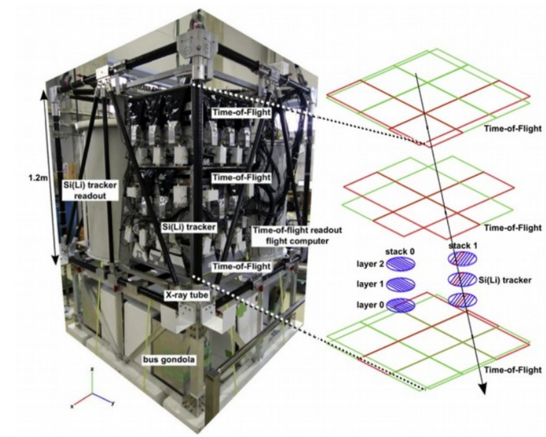
3 pions ($\bar{p}$) vs 6 pions (anti-D)



planned: GAPS (General Anti Particle Spectrometer)



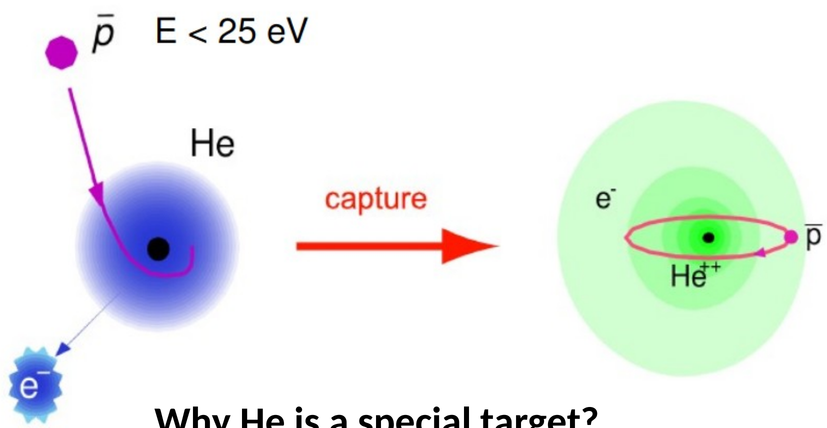
2004/2005 KEK Beam Test
2012 pGAPS flight (6h)



2021 GAPS planned
for a long flight (35d)
36 km -- 5g/cm^2
1700 kg 1.4 kW
Acceptance ~1.8 m^{2}sr
Ek: 0.1-0.25 GeV/n

Combination of time-of-flight + depth-sensing, X-ray, and π detection yield rejection > 10^6

a “new” signature: He metastable states



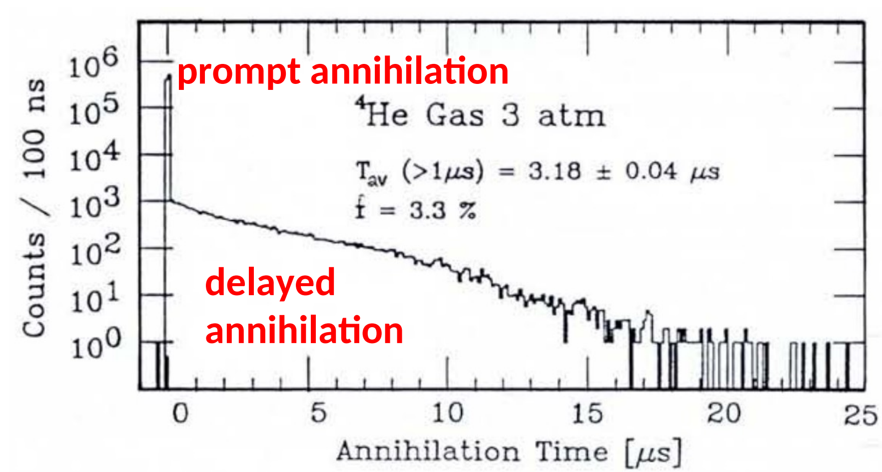
Why He is a special target?

1) the Auger decay is suppressed as well due to large level spacing of the remaining electron (~25 eV) compared to the small (~2 eV) n→n-1 level spacing of $\bar{p}$
=> metastability is unexpected and excluded for Z>3 atoms
(metastability for Li^+ target? → still not confirmed by expt.)

2) the remaining electron in $\bar{p}$He suppresses the collisional Stark effect (the main de-excitation channel for $p\bar{p}$ system)

$$(p\,\bar{p})_{nl} + H \Rightarrow (p\,\bar{p})_{nl'} + H$$

-In matter lifetime of stopped $\bar{p}$ is ~ps
-In liquid/gas He delayed annihilation: few μs (~3% of the $\bar{p}$)(discovered @ KEK in 1991)
The electron is on 1s ground state, while the $\bar{p}$ (or also π^-,k^-,$\bar{d}$) occupies a **large n** level (~38 for $\bar{p}$)
(~same bounding energy of the ejected e-)
Theory: Phys. Lett. 9 (1964) 65 PRL 23 (1969) 63

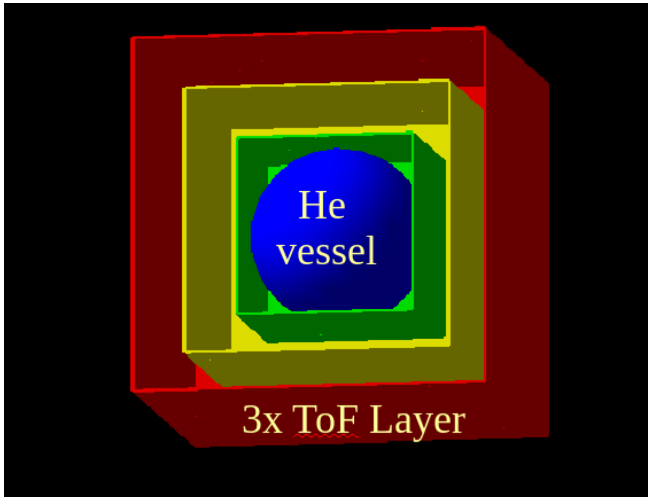


a signature for Z=-1 antimatter capture in He is a ~μs delayed energy release (in ~3% of cases)

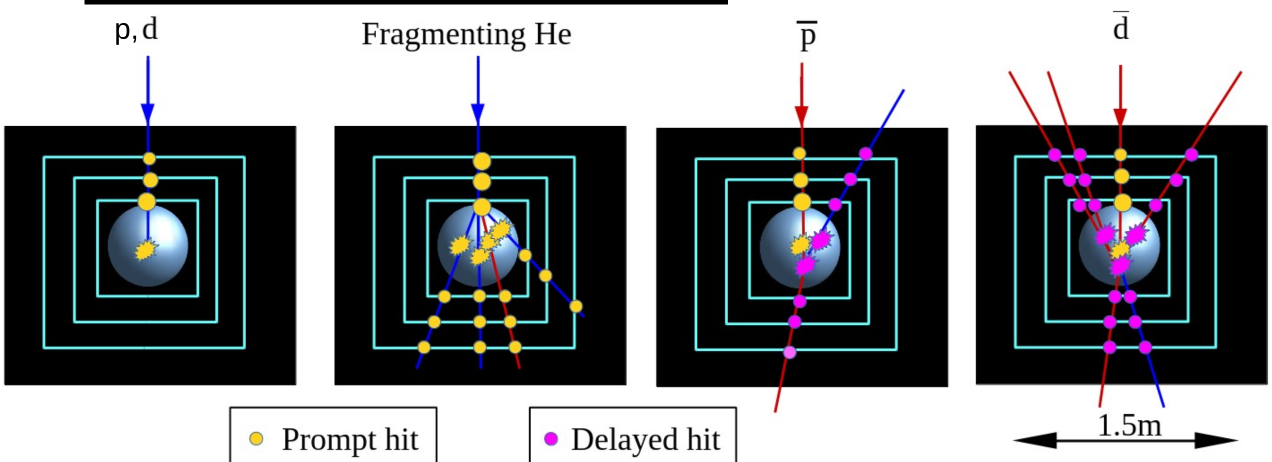
Not really new: similar effect already proven, and used, by the ASACUSA experiment

Anti Deuteron He Detector (ADHD)

Concept: HeCalorimeter (scintillator)
3xTime of Flight (compact) layers

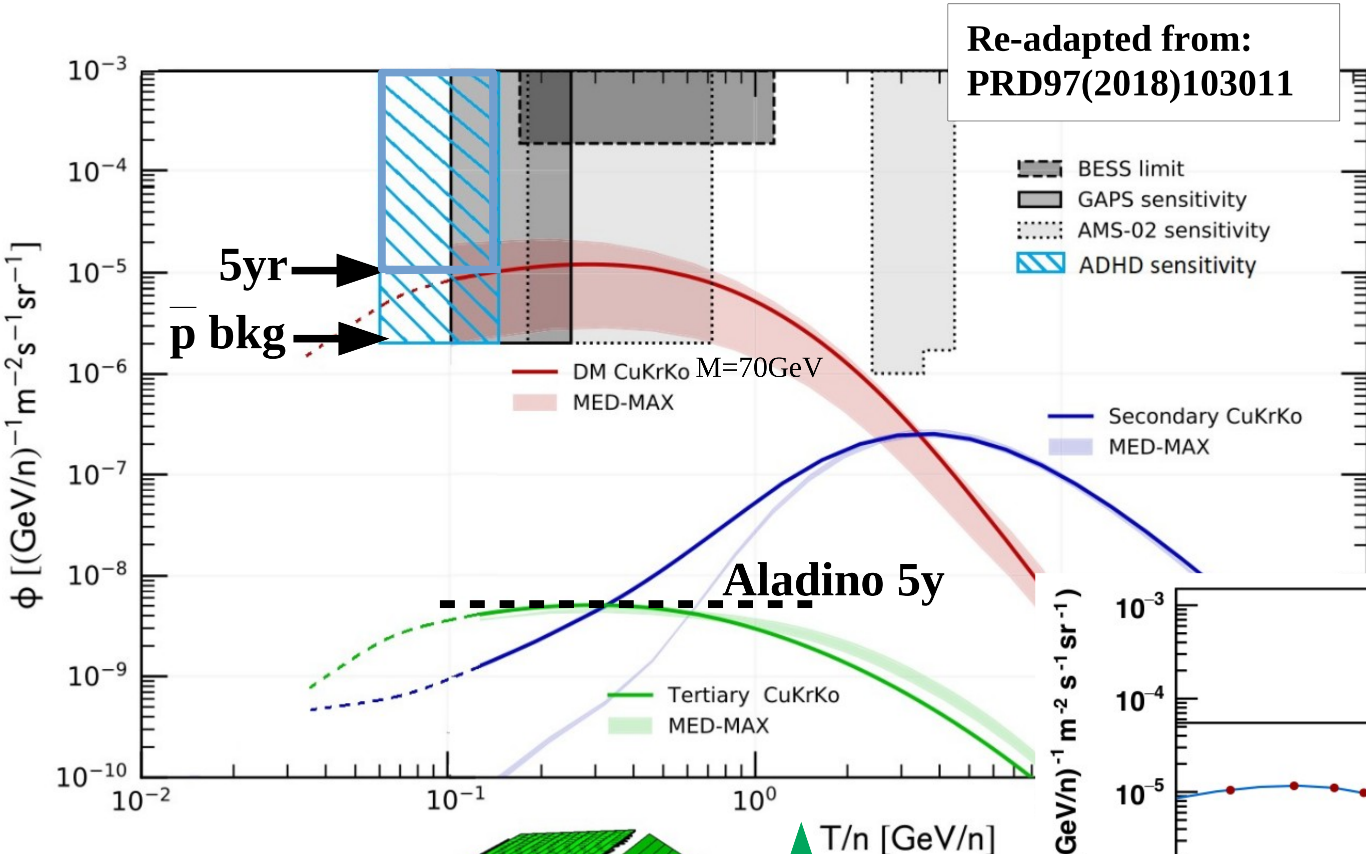


Status: preliminary Geant4 simulation
Detector size: External ToF L = 1.5m;
Vessel R=45cm Thick=3cm “thermoplastic”
He pressure 400bar (typ. He bottle 130bar)
(“commercially” feasible space qualified)
Detector mass: He = 20 kg Vessel = 100kg
ToF = 110 kg (4mm scintillator thickness)
Kinetic energy range: 0.06-0.15 GeV/n
(threshold due to energy loss in vessel/ToF)
... a small & light detector ...



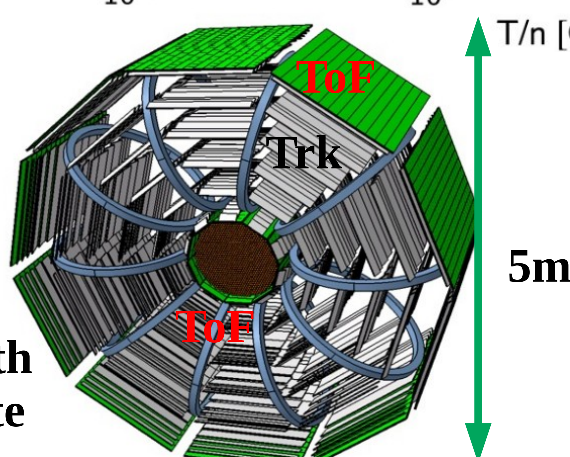
Particle identification by:
1) timing of tracks
2) dE/dx on ToF
3) Beta ToF
4) Prompt HeCal Energy
5) Delayed HeCal Energy
6) event topology

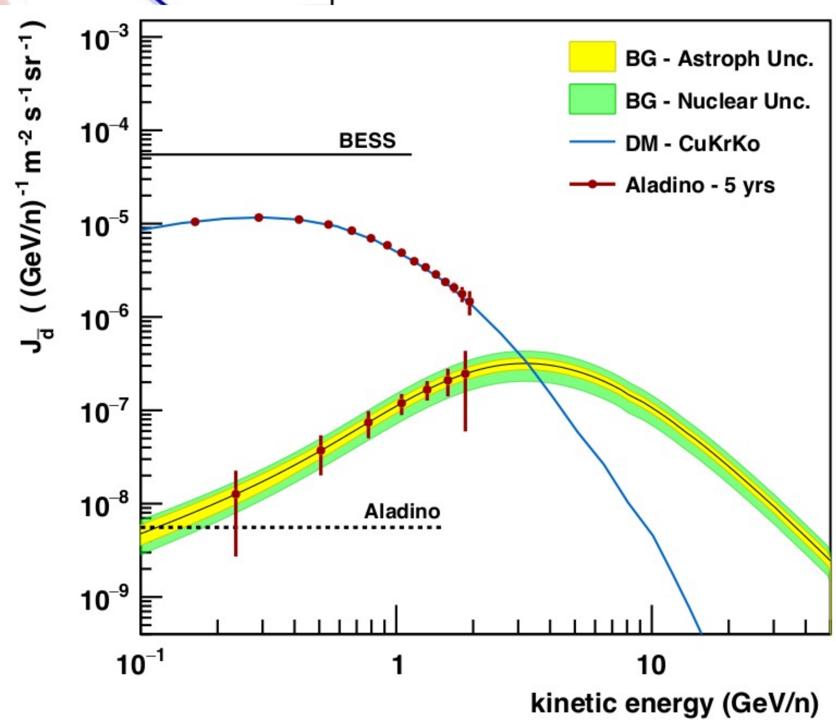
planned sensitivity



AMS02-GAPS-ADHD: different techniques, similar sensitivity, complementary Ek/n

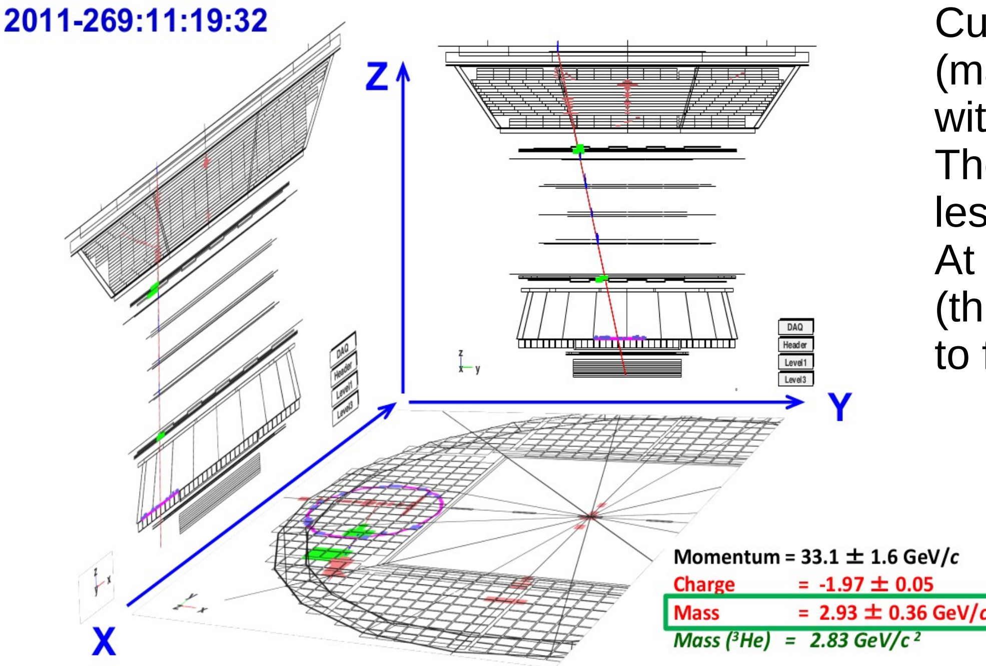
Join of all the signatures in a future/ ultimate Antideuteron detector?



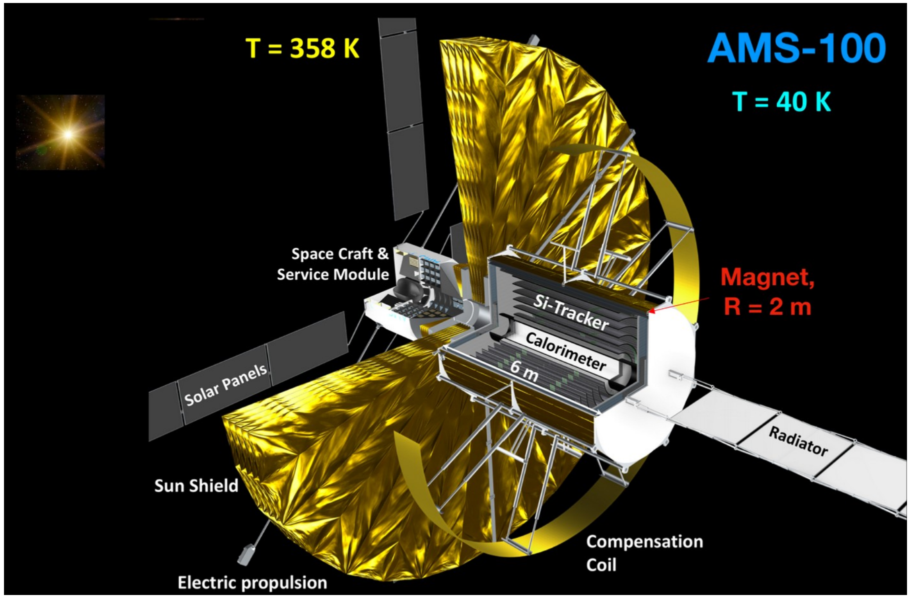


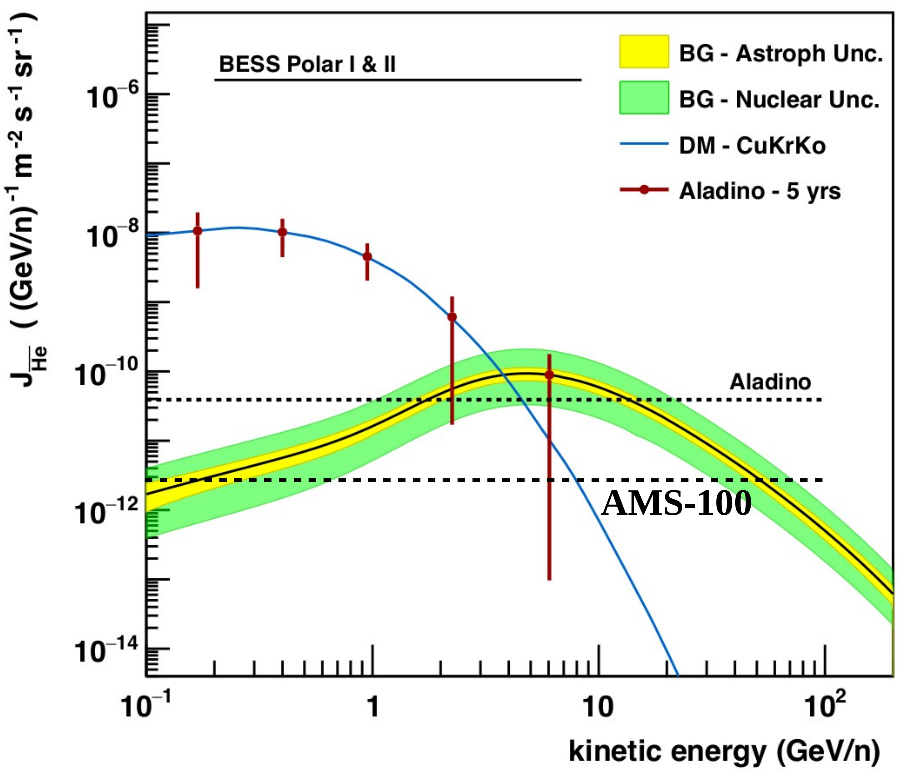
Aladino: detector technology almost ready (how to deal with huge trigger rate in L2?)

anti-He?



Currently, AMS observed 8 anti-helium candidates (mass region from 0-10 GeV) rigidity <50 GV with respect to a sample of 700 million He events. The rate in AMS of antihelium candidates is less than 1 in 100 million helium. At this extremely low rate, more data (through the lifetime of the ISS) is required to further check the origin of these events.





Bibliography – some useful links

-Cosmic ray database:
https://lpsc.in2p3.fr/cosmic-rays-db/ (France, user friendly)
https://tools.ssdc.asi.it/CosmicRays/ (Italy, only published data tables)

-Particle Data Book (a lot of review on particle,cosmology, ecc… very very useful):
https://journals.aps.org/prd/pdf/10.1103/PhysRevD.98.030001

-Link to homepages of many Cosmic rays experiments:
https://www.mpi-hd.mpg.de/hfm/CosmicRay/CosmicRaySites.html

-AMS02 webpage:
https://ams02.space/

-ADHD webpage:
https://www.tifpa.infn.it/projects/adhd/

-Aladino proposal:
https://www.cosmos.esa.int/documents/1866264/3219248/BattistonR_ALADINO_PROPOSAL_20190805_v1.pdf

-AMS100 proposal:
https://www.cosmos.esa.int/documents/1866264/3219248/SchaelS_AMS100_Voyage2050.pdf
arXiv:1907.04168v1