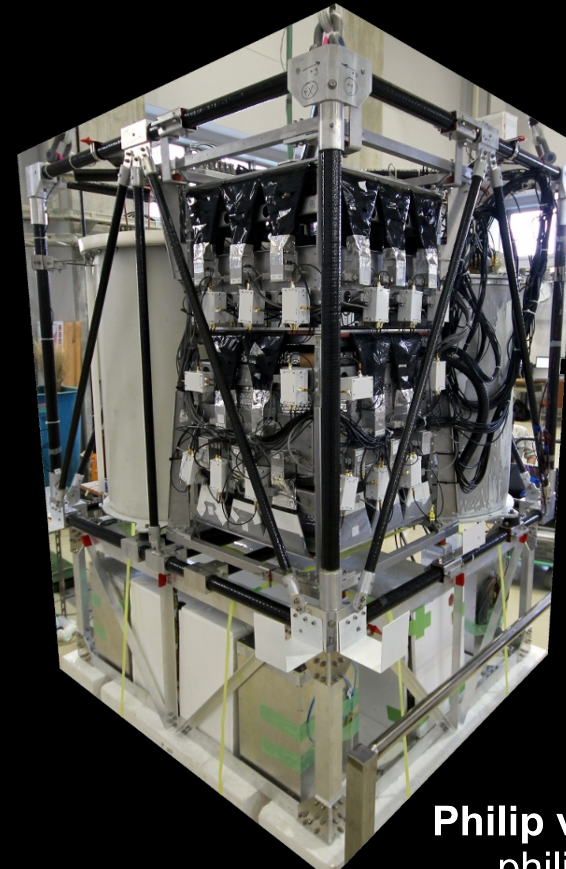
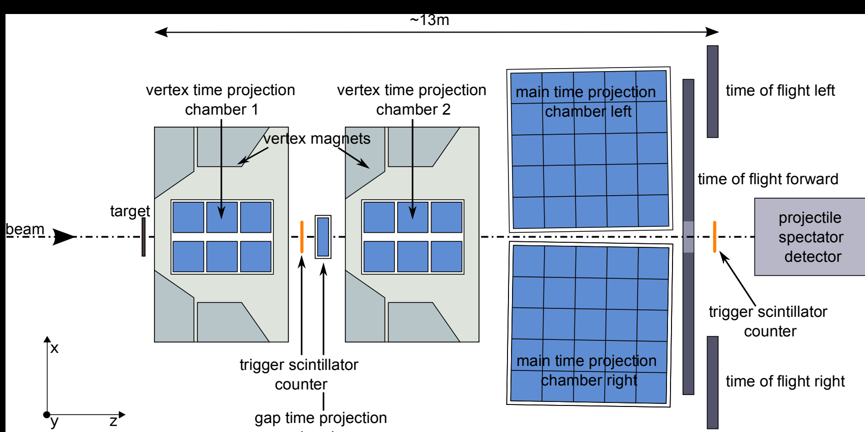
Cosmic-ray antideuteron searches





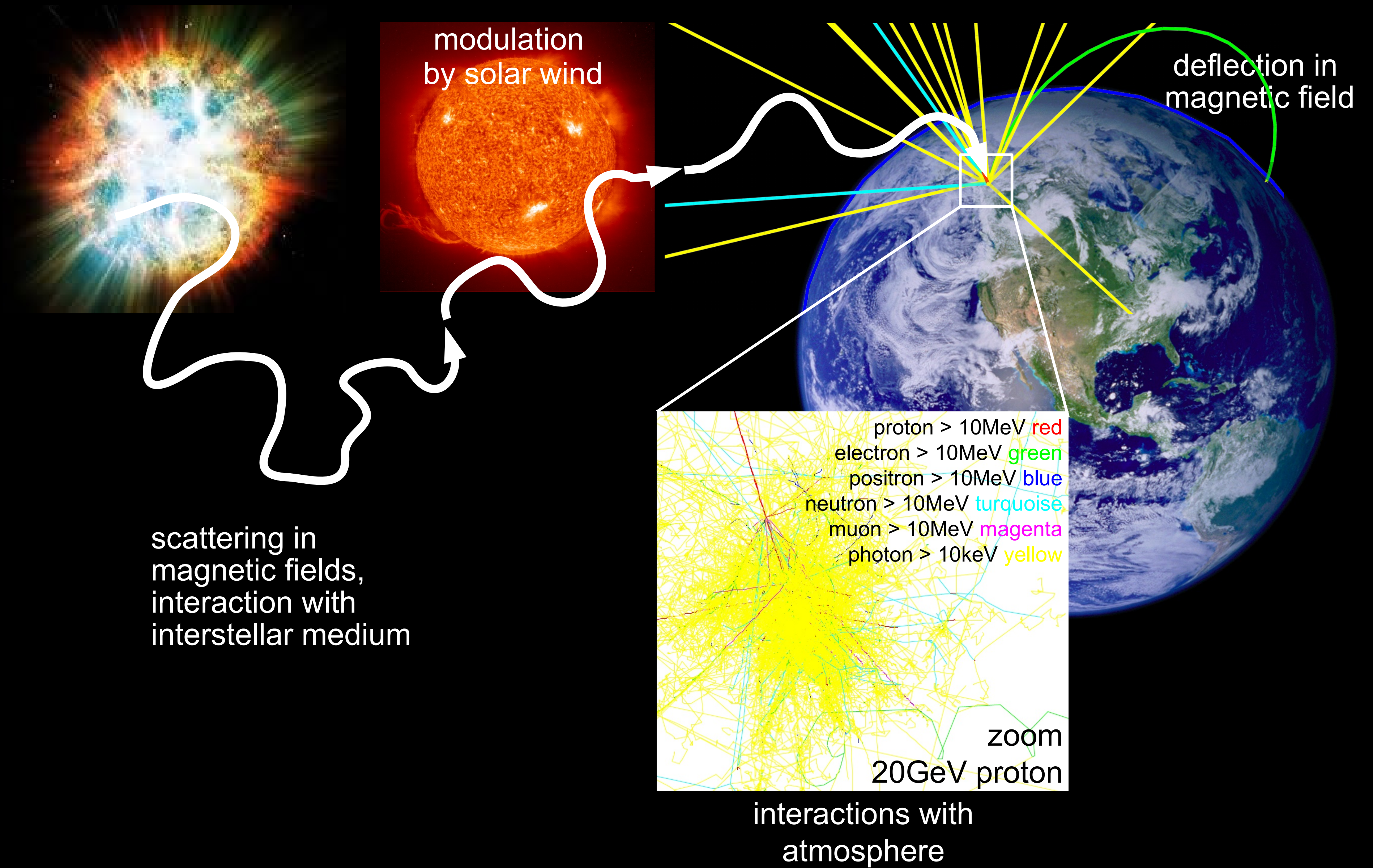
UNAM
Mexico City
November 2015

Philip von Doetinchem
philipvd@hawaii.edu
Department of Physics & Astronomy
University of Hawai'i at Mānoa

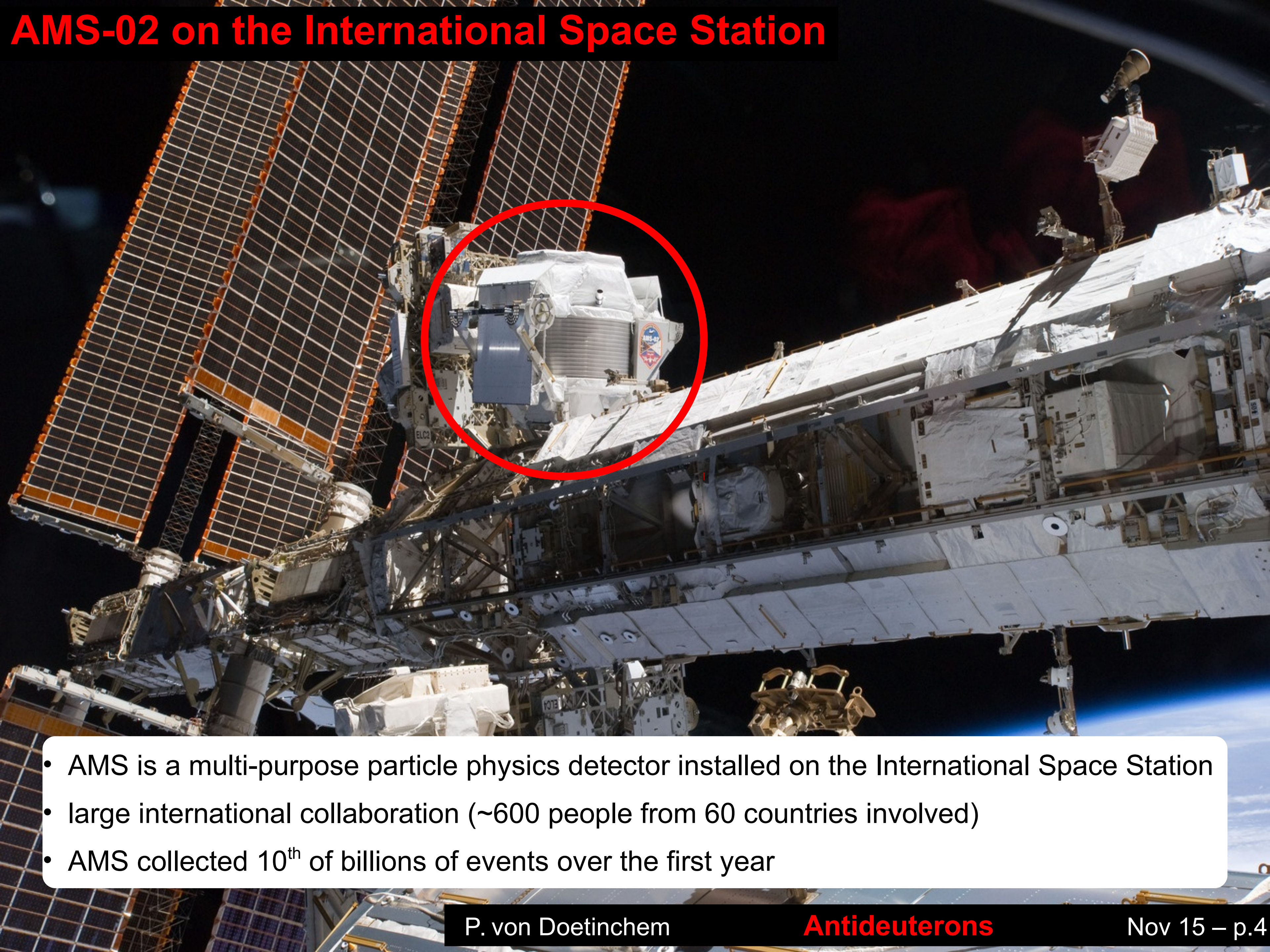
http://www.phys.hawaii.edu/~philipvd
www.antideuteron.com


Diamond Head
Waikiki
Physics Department

Cosmic rays as messenger

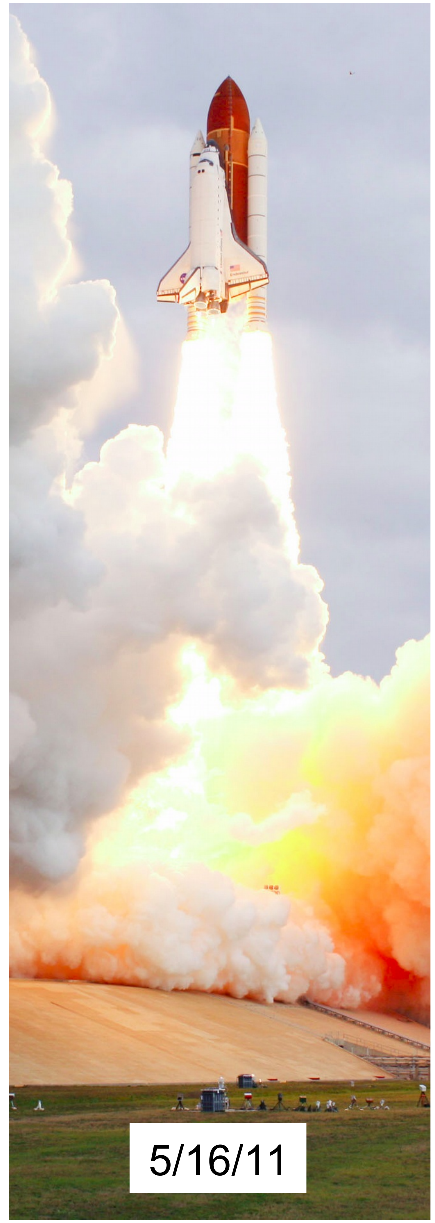


AMS-02 on the International Space Station



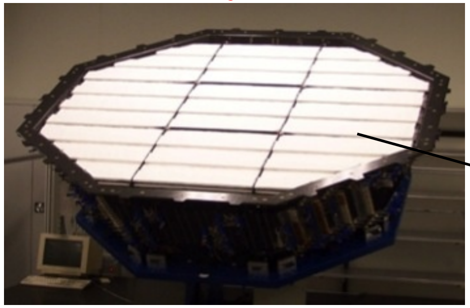
- AMS is a multi-purpose particle physics detector installed on the International Space Station
- large international collaboration (~600 people from 60 countries involved)
- AMS collected 10^{th} of billions of events over the first year

Launch STS-134

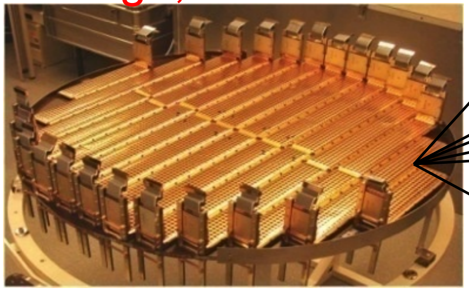


AMS sub-detectors

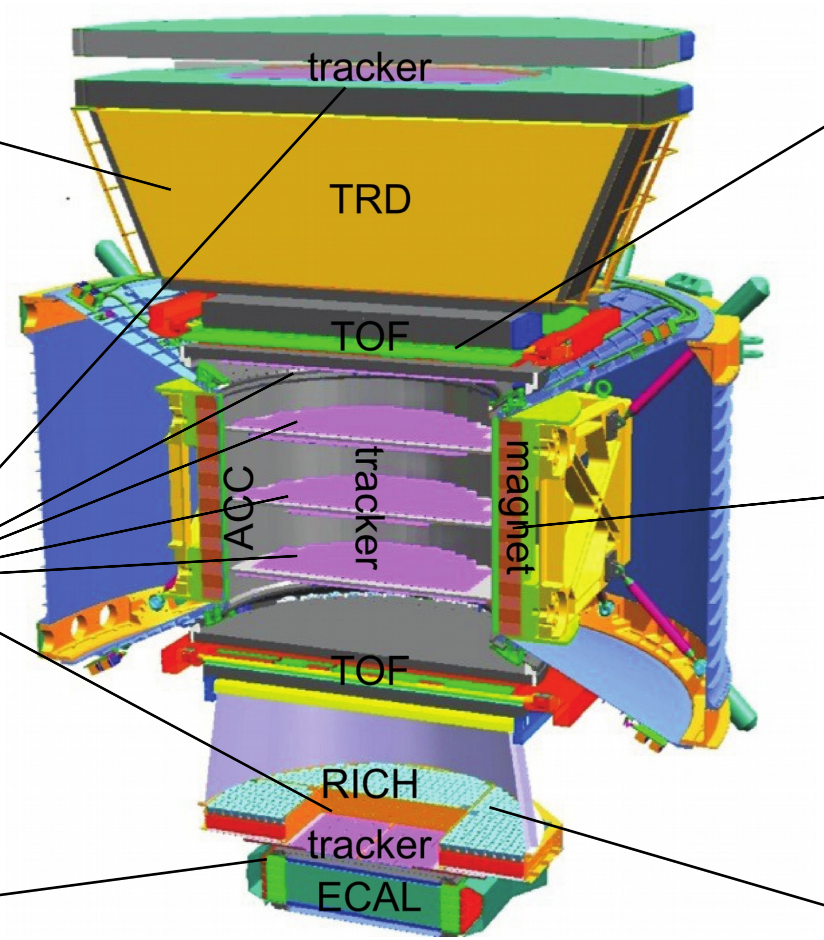
TRD
identify e+,e-



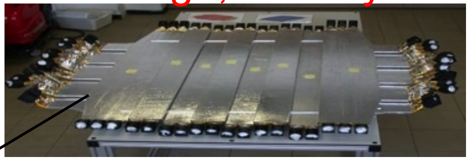
Silicon tracker
charge, momentum



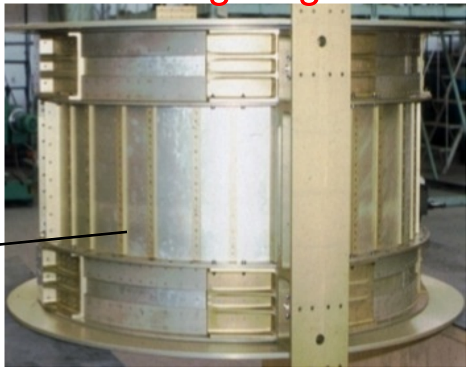
ECAL
energy of e+, e-, γ



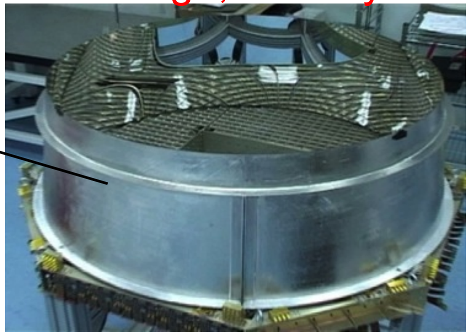
TOF
charge, velocity



magnet
charge sign

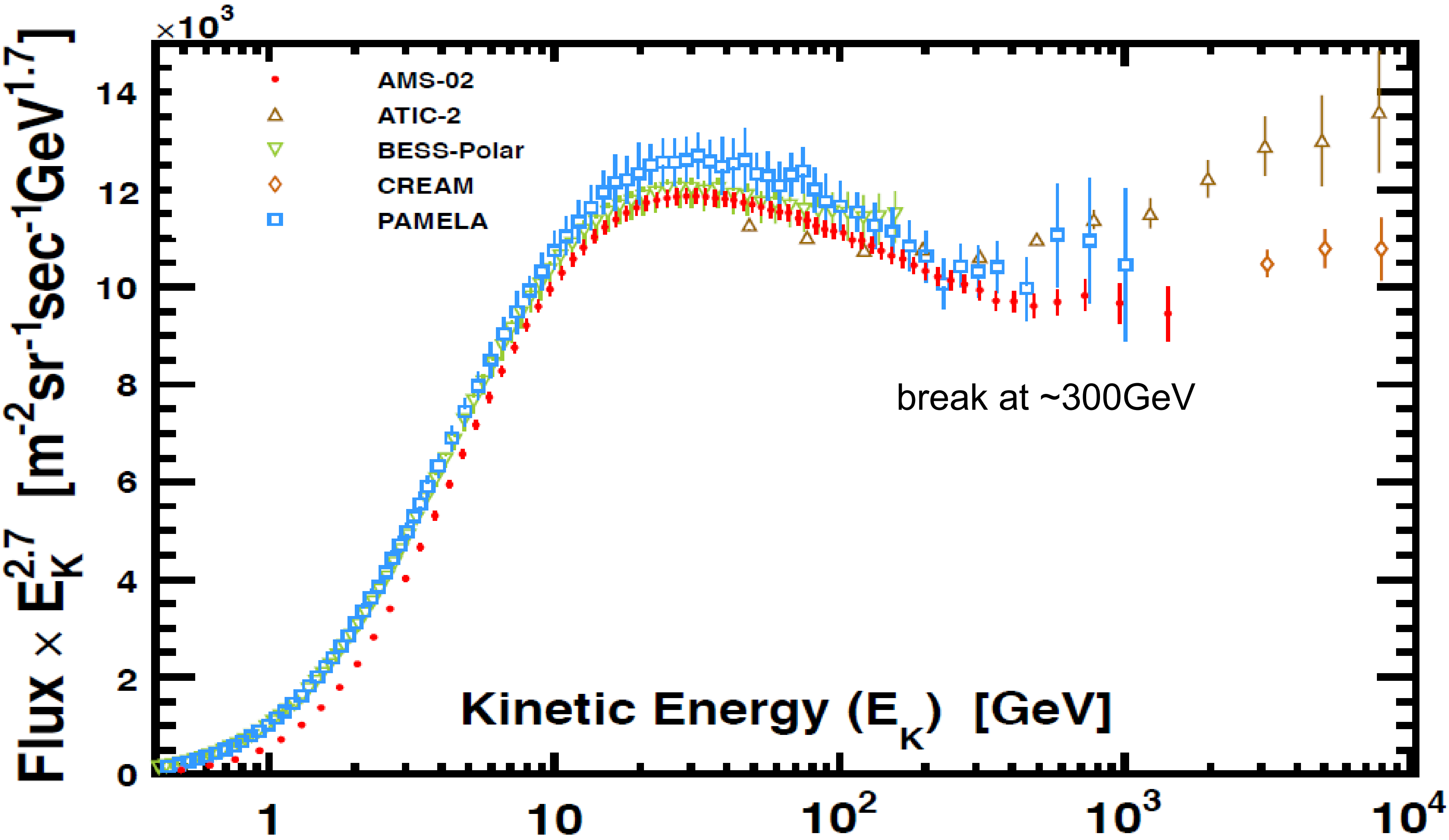


RICH
charge, velocity



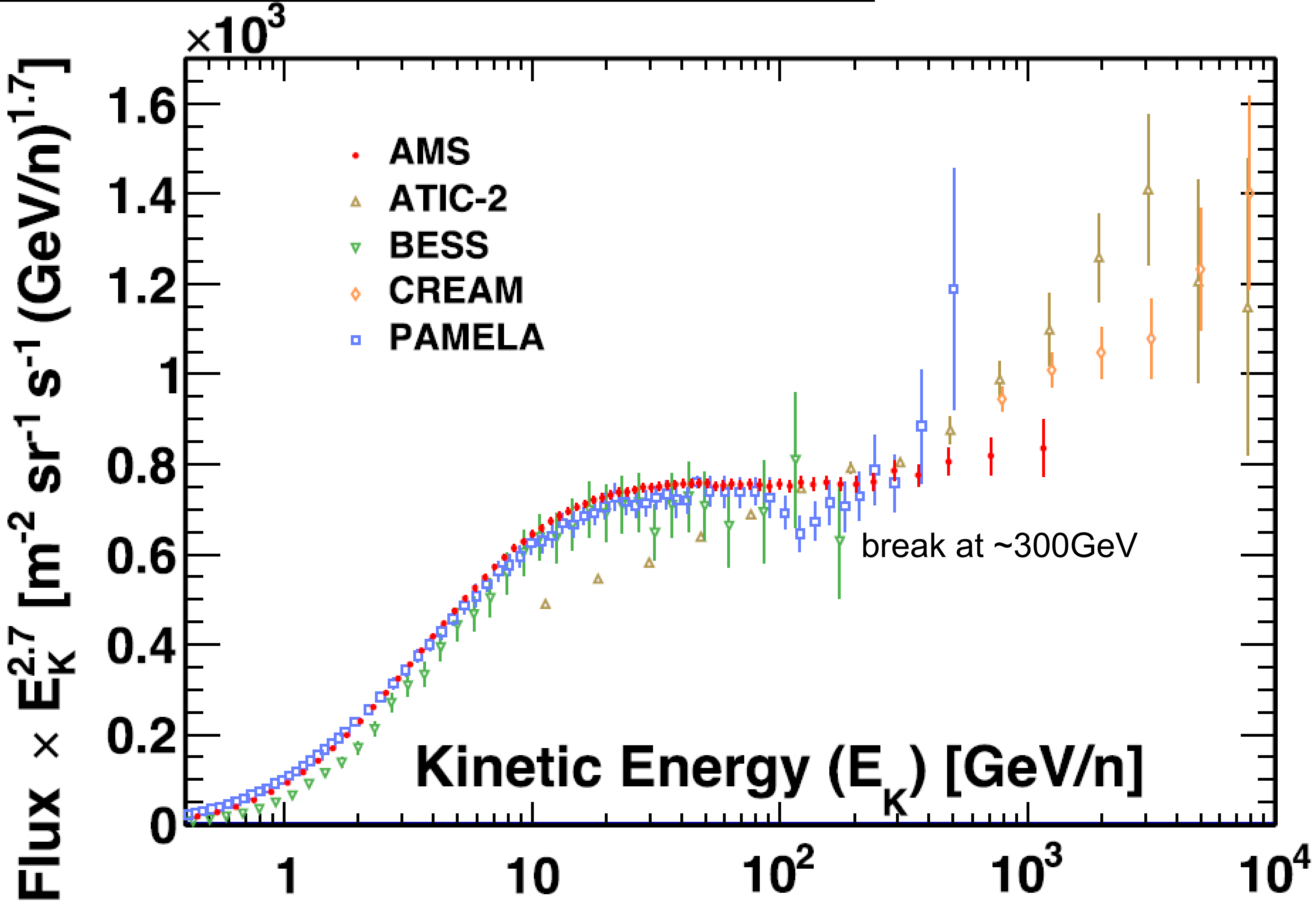
Charge and momentum/energy are measured independently by the tracker, RICH, TOF and ECAL

Protons



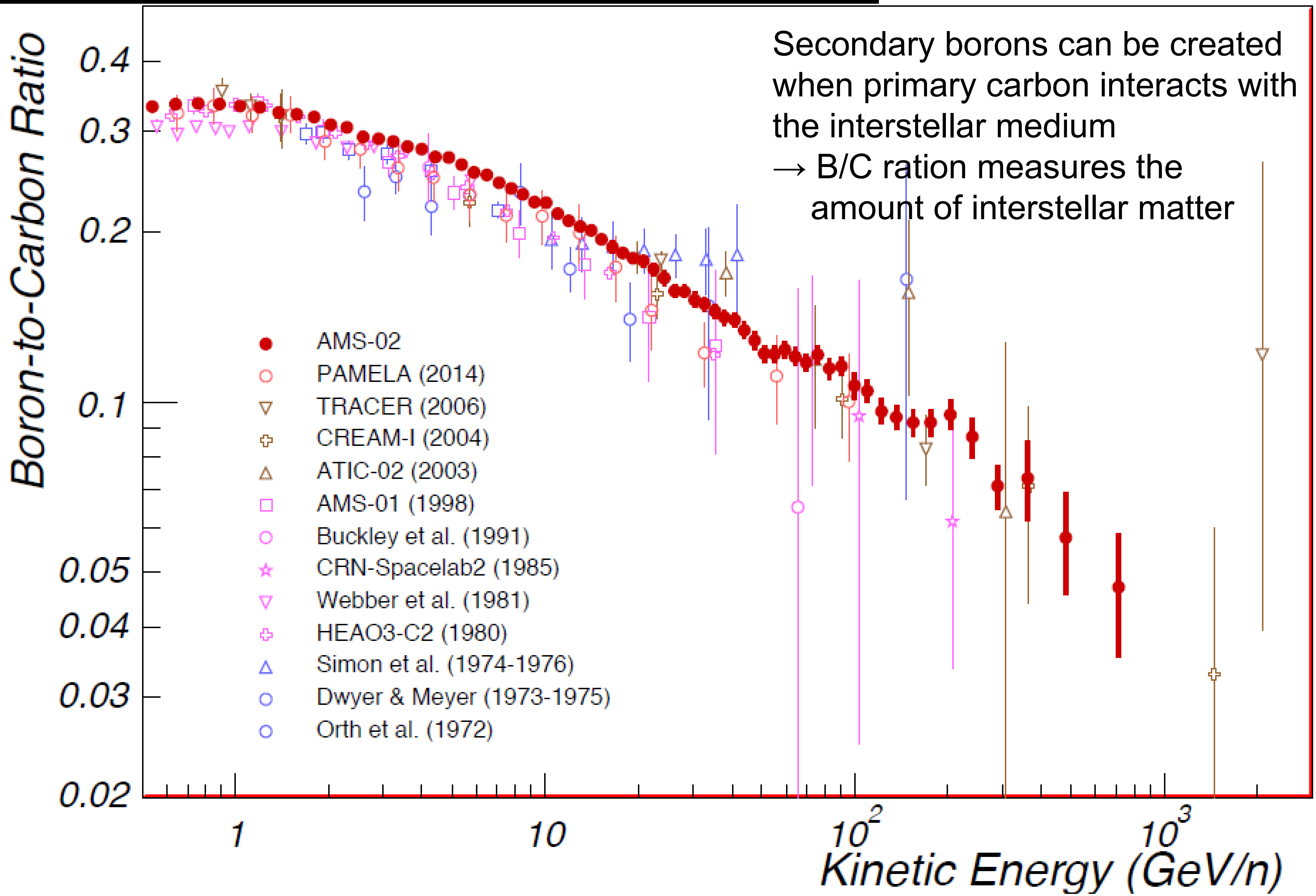
×10³
Flux × $E_K^{2.7}$ [$m^{-2}sr^{-1}sec^{-1}GeV^{1.7}$]
AMS-02
ATIC-2
BESS-Polar
CREAM
PAMELA
break at ~300GeV
Kinetic Energy (E_K) [GeV]
0
2
4
6
8
10
12
14
1
10
10^2
10^3
10^4

Helium



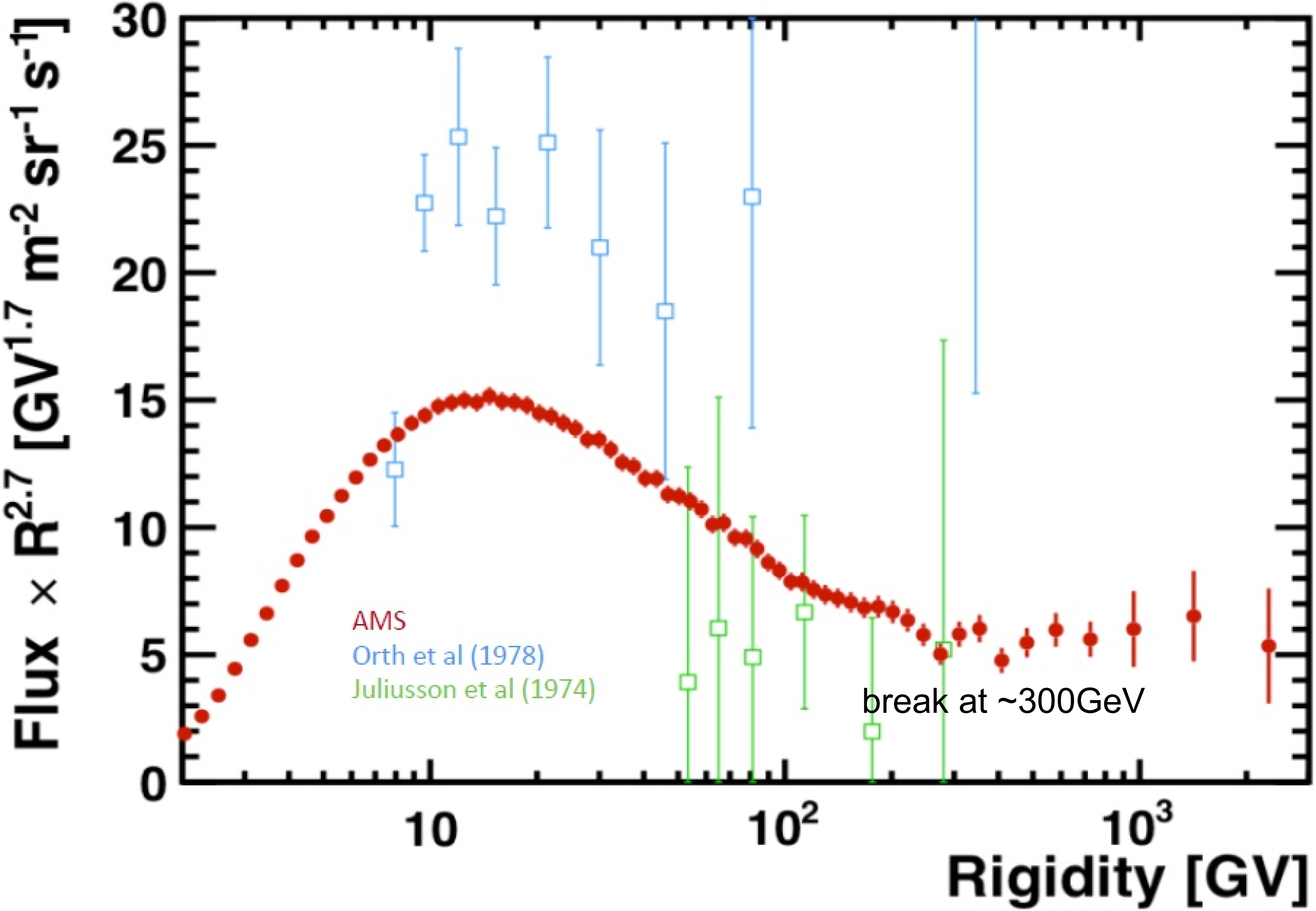
×10^3
Flux × E_K^2.7 [m^-2 sr^-1 s^-1 (GeV/n)^1.7]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
AMS
ATIC-2
BESS
CREAM
PAMELA
break at ~300GeV
Kinetic Energy (E_K) [GeV/n]
1
10
10^2
10^3
10^4

Boron-to-carbon



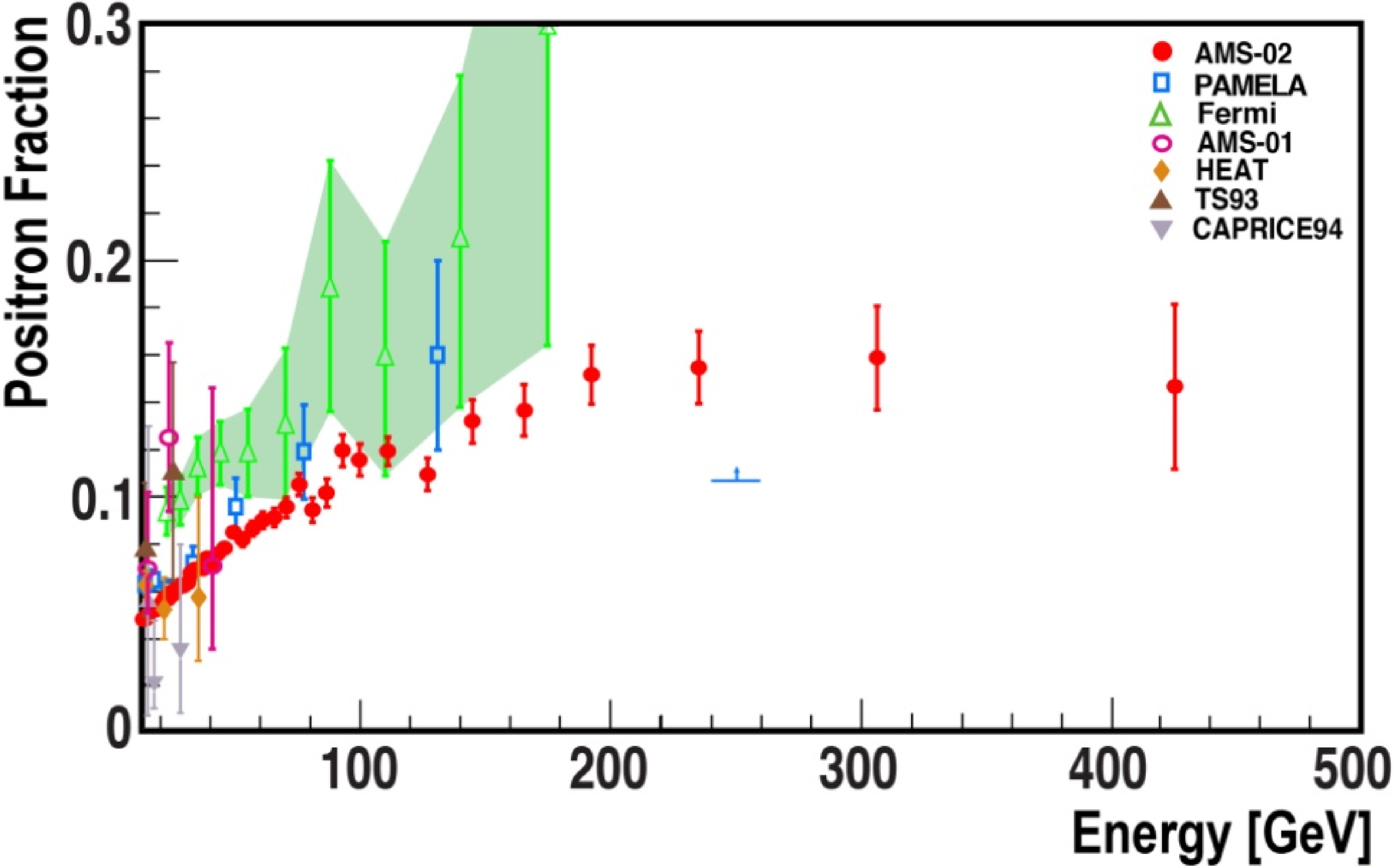
Secondary borons can be created when primary carbon interacts with the interstellar medium
→ B/C ration measures the amount of interstellar matter

Lithium

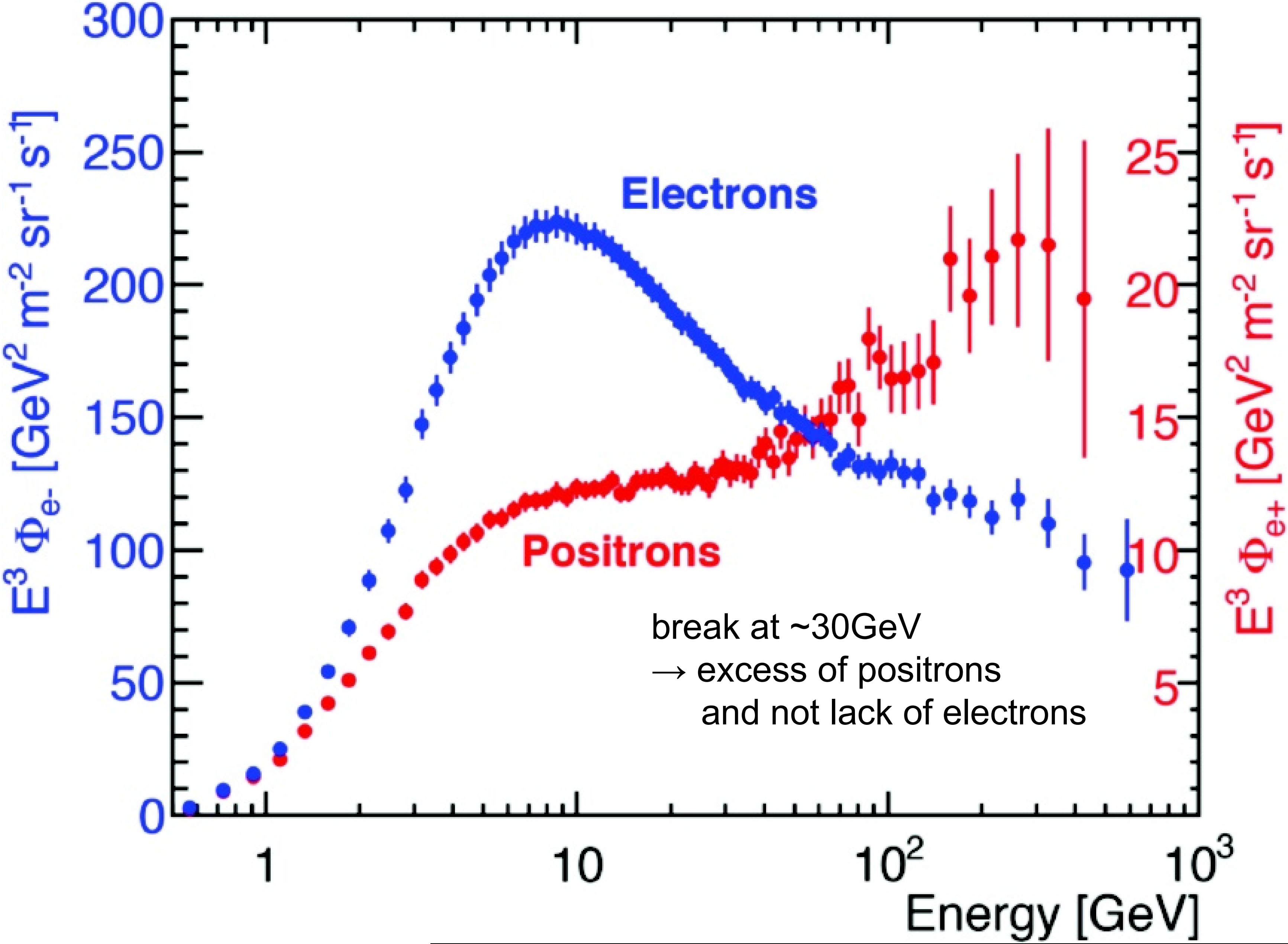


Flux × R^2.7 [GV^1.7 m^-2 sr^-1 s^-1]
30
25
20
15
10
5
0
10
10^2
10^3
Rigidity [GV]
AMS
Orth et al (1978)
Juliusson et al (1974)
break at ~300GeV

Positron fraction

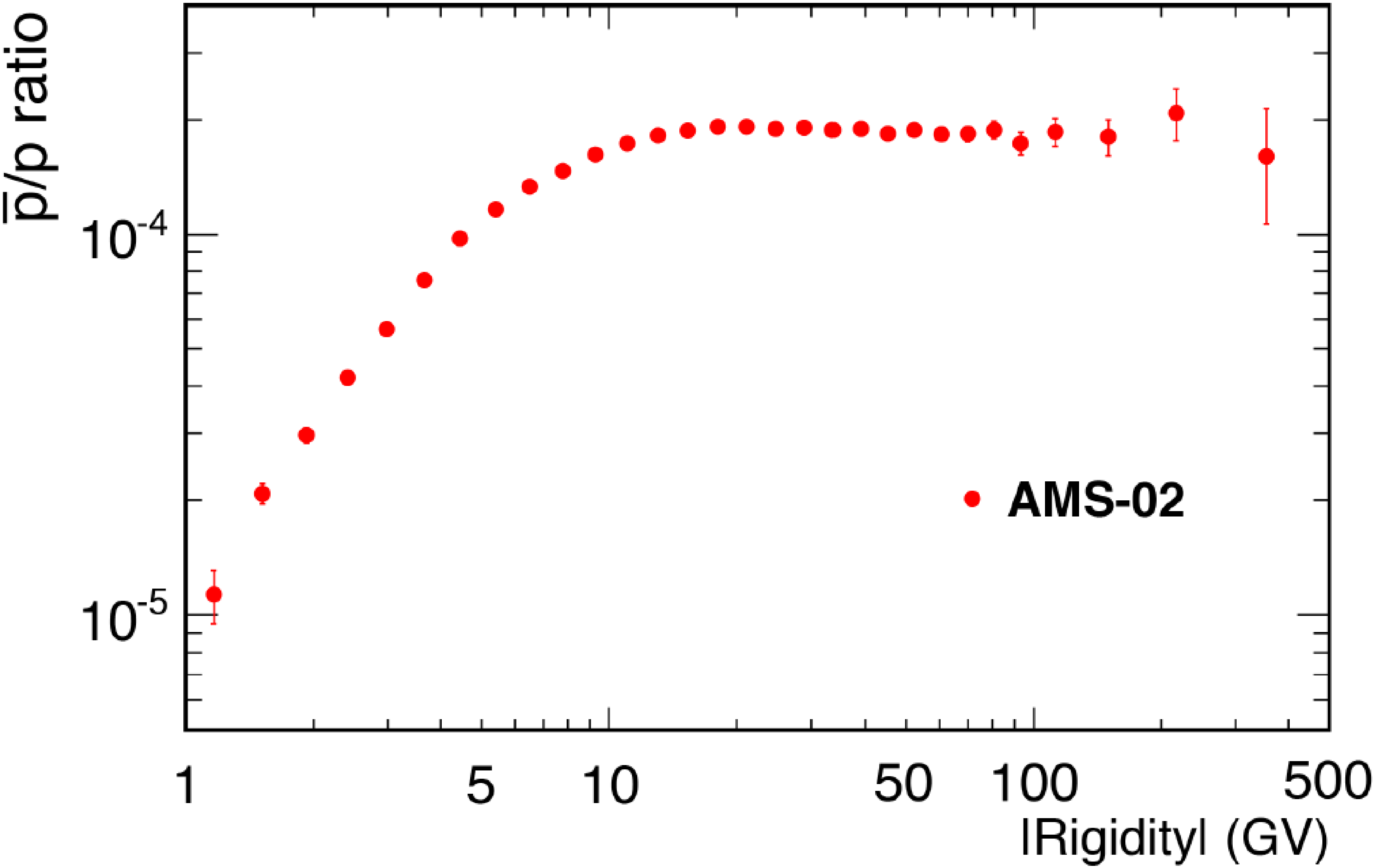


Electron and positron flux

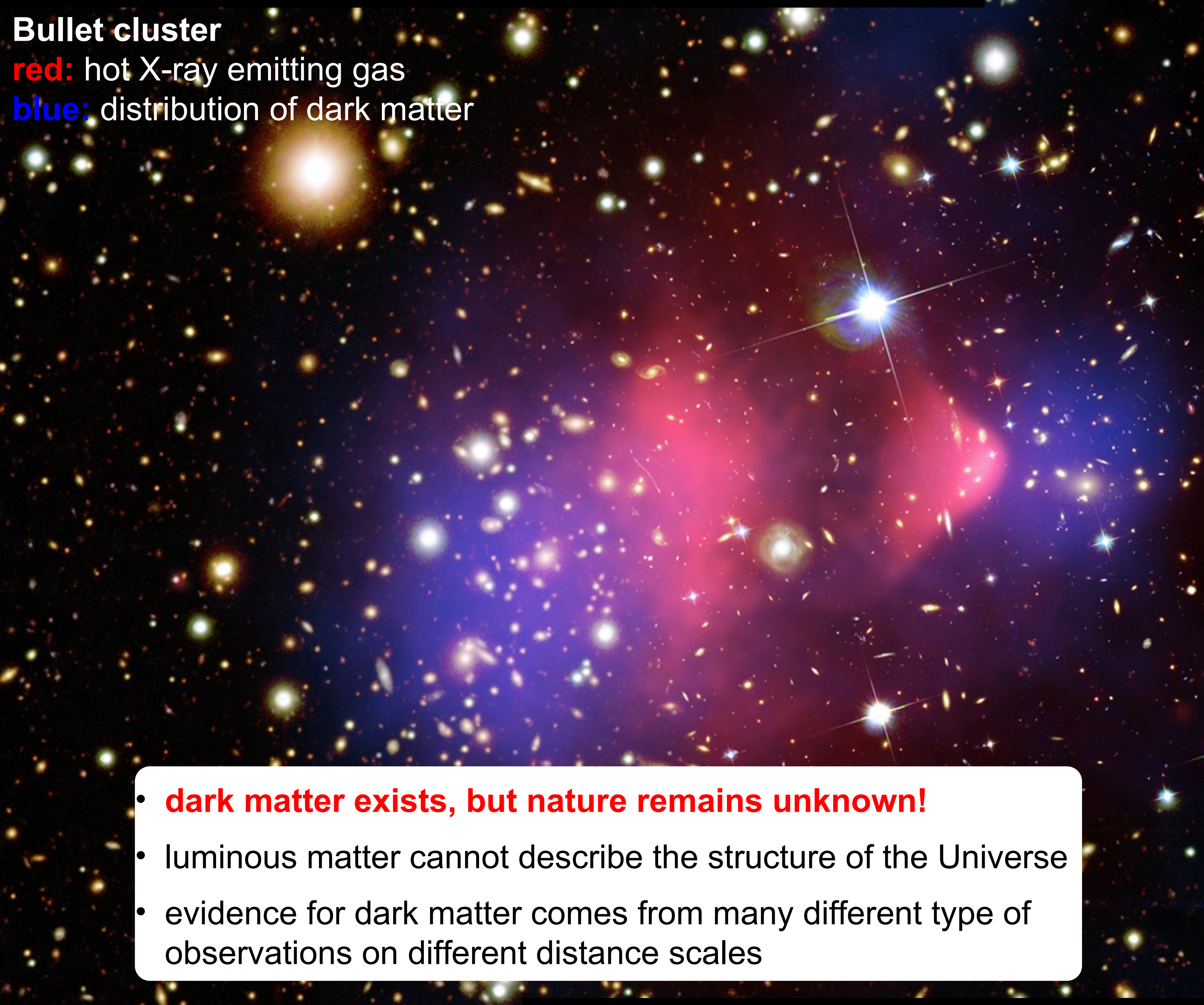


break at ~30GeV
→ excess of positrons
and not lack of electrons

Antiprotons



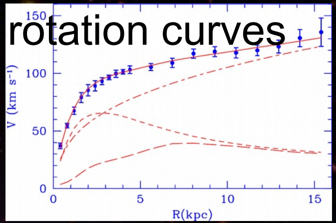
Existence of dark matter

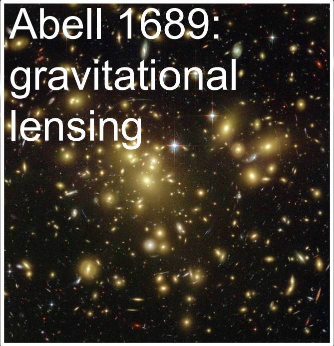


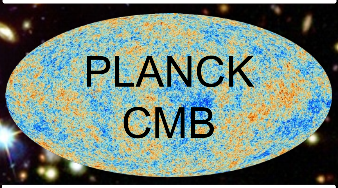
Bullet cluster

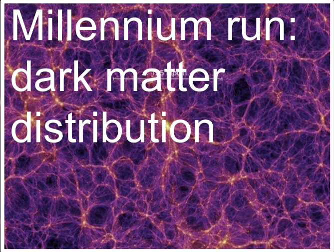
red: hot X-ray emitting gas

blue: distribution of dark matter



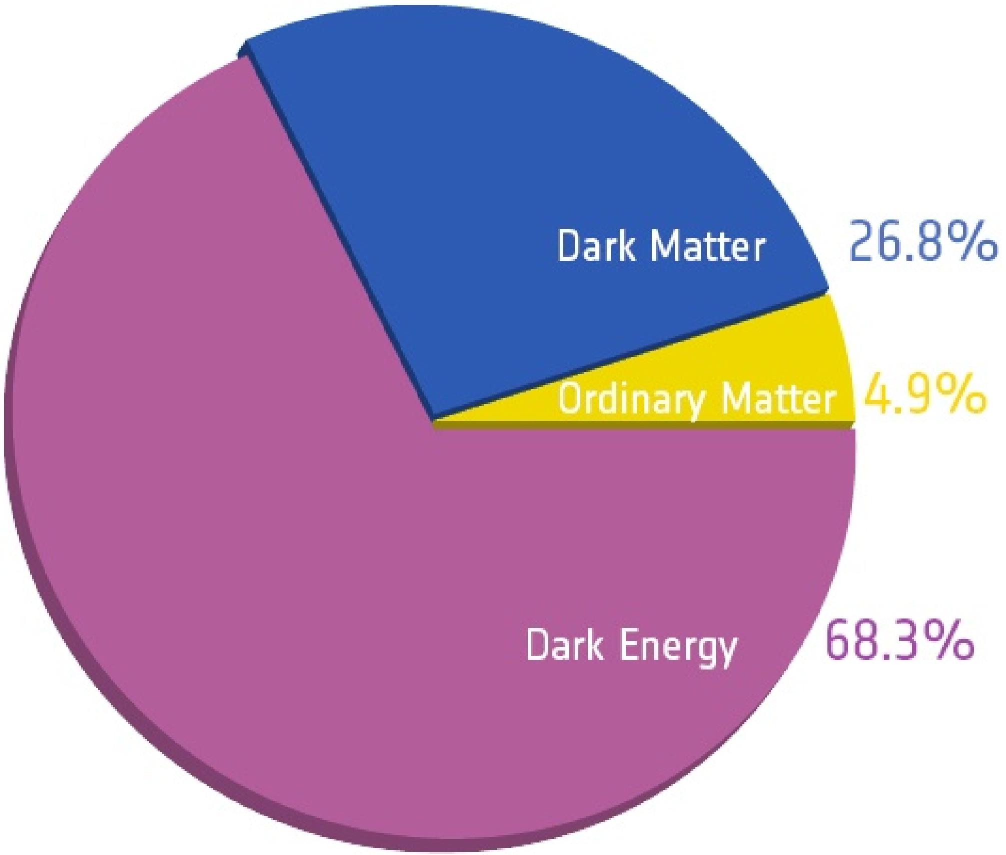






- **dark matter exists, but nature remains unknown!**
- luminous matter cannot describe the structure of the Universe
- evidence for dark matter comes from many different type of observations on different distance scales

Why do we need something new?



- dark matter is so far only gravitationally visible and must be a **new non-baryonic type of particle**
  - neutral
  - with relatively high mass to explain the structure formation of the universe
  - with only very weak interactions with standard particles (if at all)

→ most popular: **W**eakly **I**nteracting **M**assive **P**articles

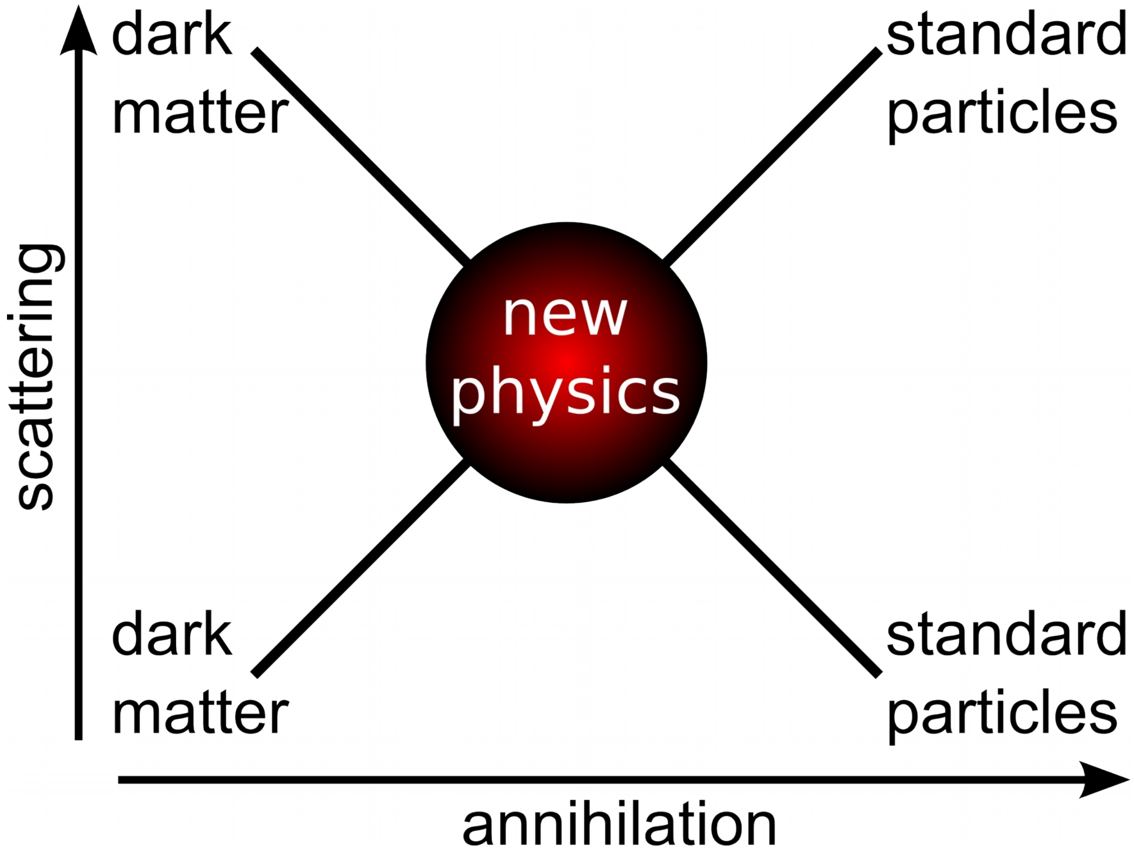
- **discovering the nature of dark matter is one of the most striking problems in physics**

General challenge

particle physics × astrophysics = signal

- solving the dark matter problem means therefore disentangling particle physics and astrophysics
- beyond standard model particle physics need to provide stable dark matter candidates
- astrophysics:
  - dark matter distribution: substructures, density, velocity distribution

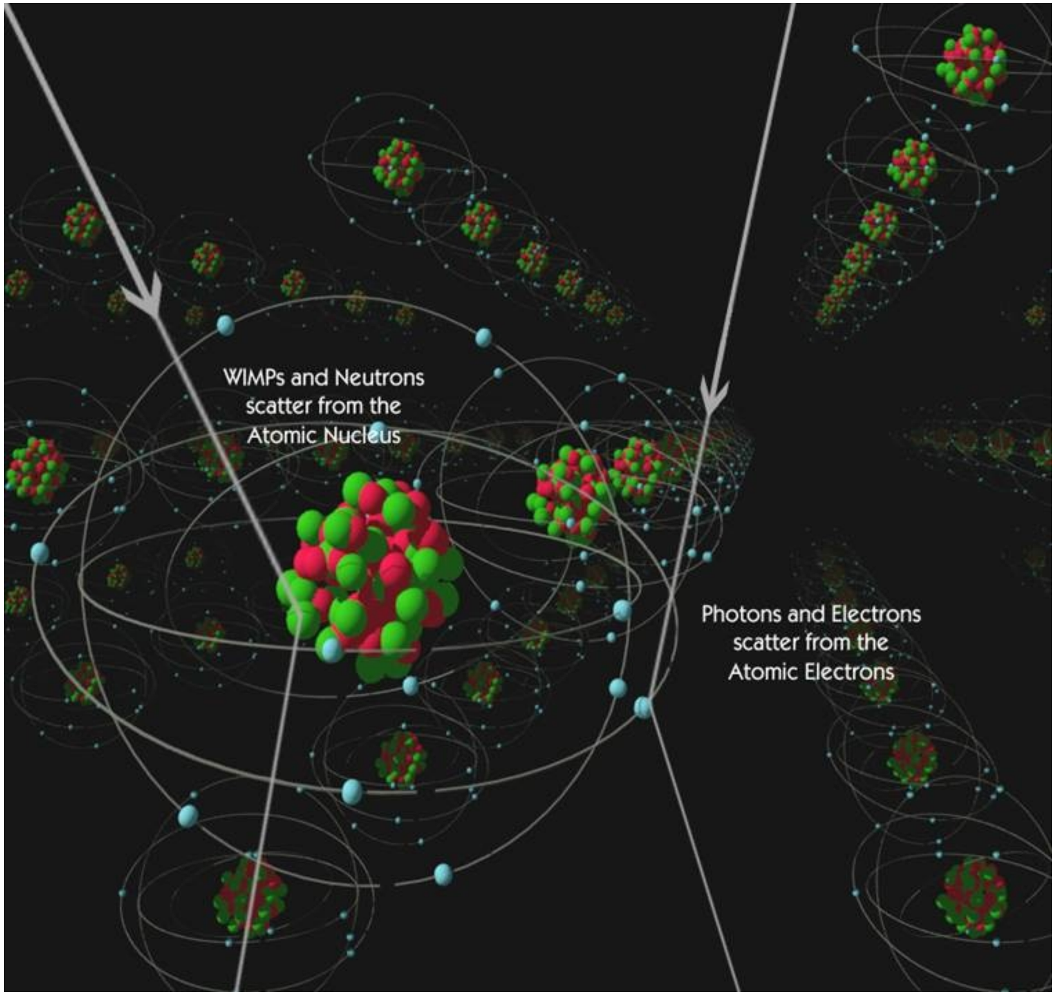
How is dark matter interacting?



- **natural assumption:** dark matter was in thermal equilibrium in the early universe expansion led to dark matter freeze-out
- **WIMP miracle:** weak-scale particles are ideal candidates (~100-1000GeV) to reproduce observed relic dark matter density

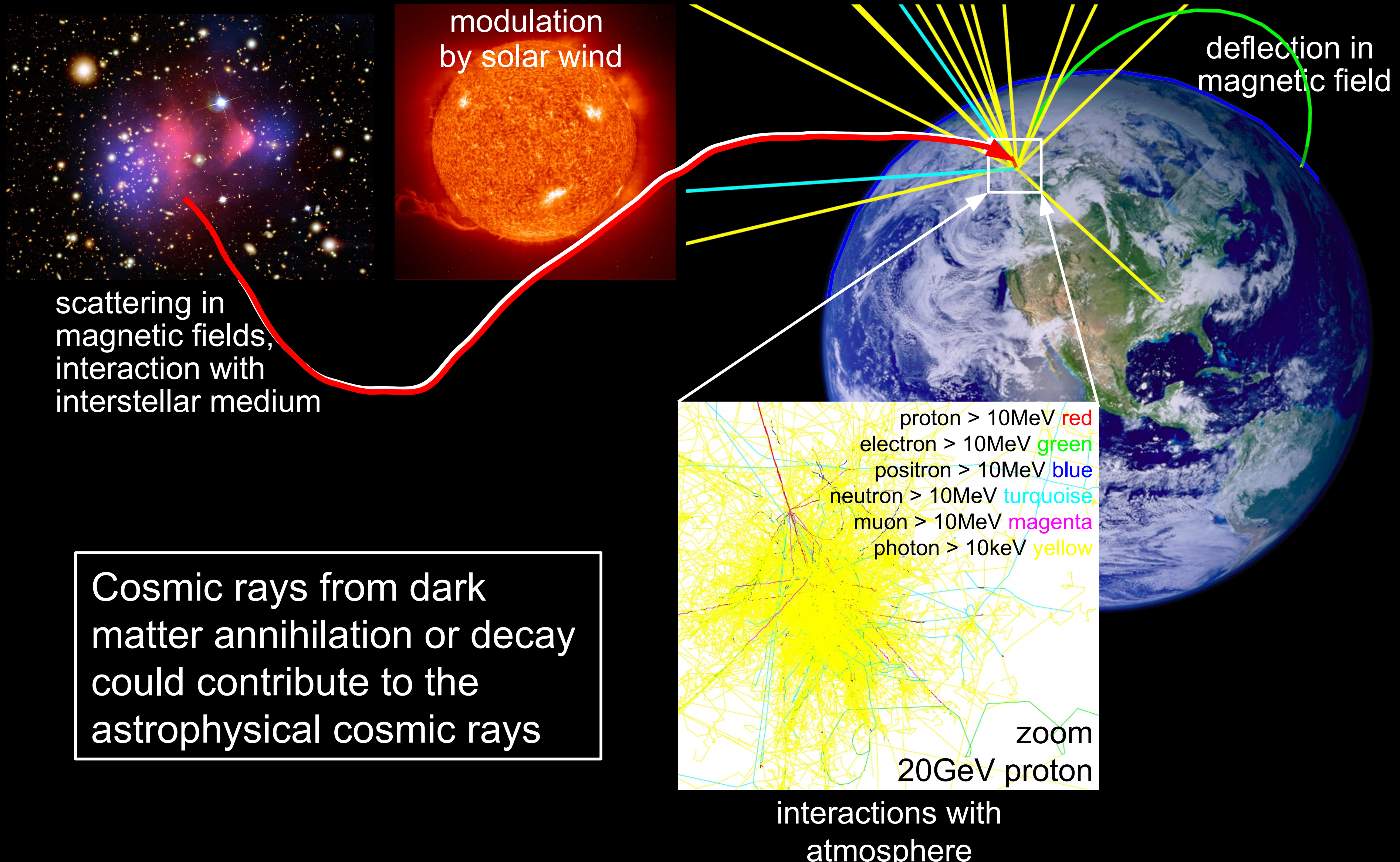
→ dark matter must(?) be able to interact with standard model particles

Direct dark matter searches (scattering)



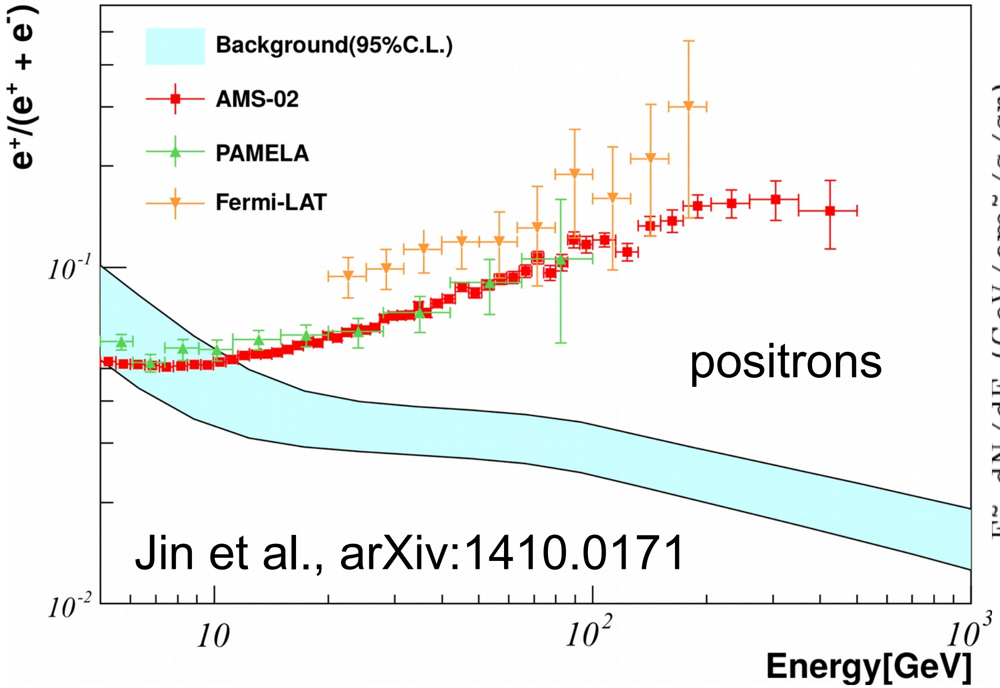
- **direct dark matter search:** measure cross-section via nuclear recoil
- typically large, heavy and very pure target materials in deep mines (~10 operating experiments)
- experiments start to reach in theoretically preferred parameter space
- **experiments disagree →** some experiments claim discovery, some set exclusion limits

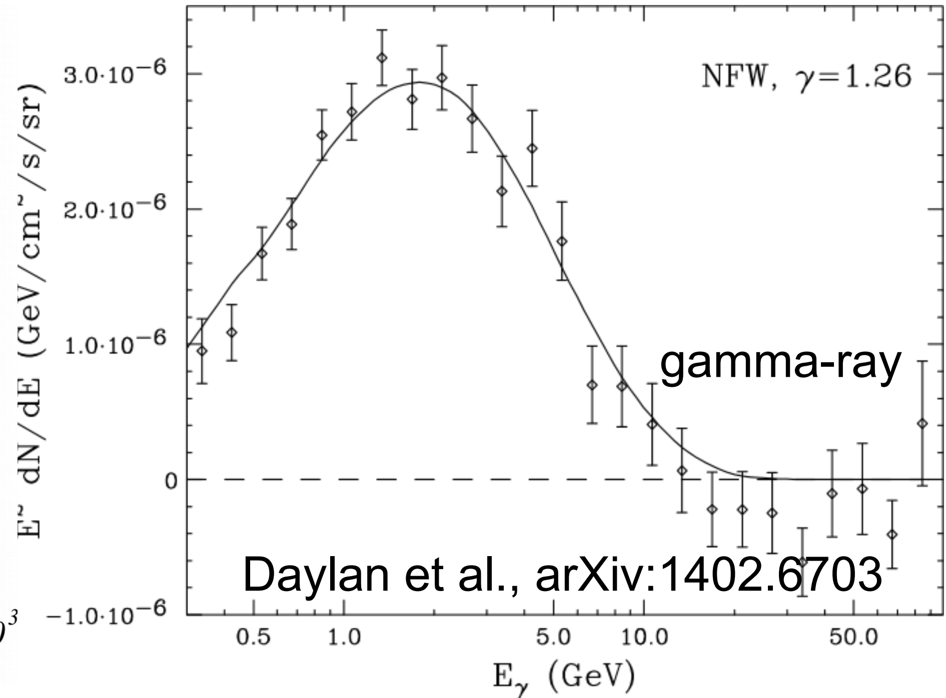
Cosmic rays as messenger for dark matter?



Cosmic rays from dark matter annihilation or decay could contribute to the astrophysical cosmic rays

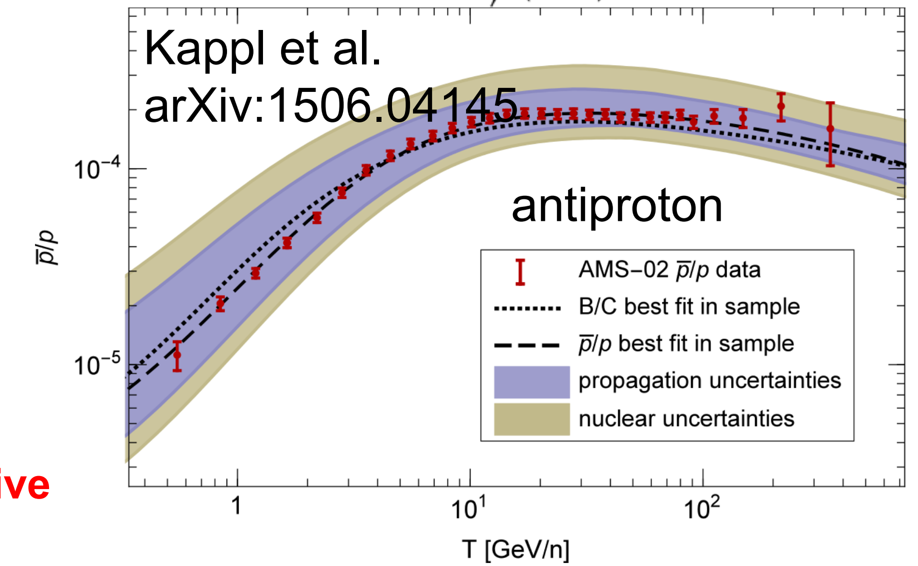
Dark matter signal in cosmic rays?





- unexplained features in positrons
- proposed theories:
  - astrophysical origin → pulsars
  - SNR acceleration
  - **dark matter self-annihilation**
- gamma-ray excess at the galactic center → 30GeV dark matter particle?

- **No (?) excess for antiprotons → inconclusive**

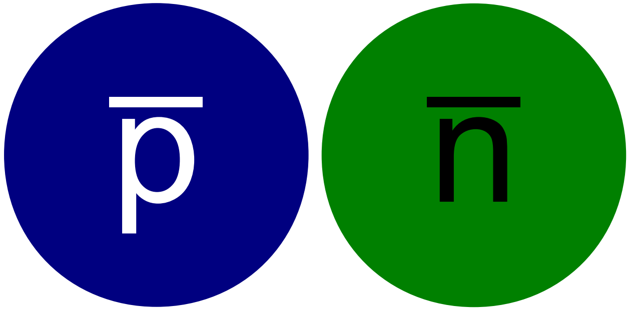


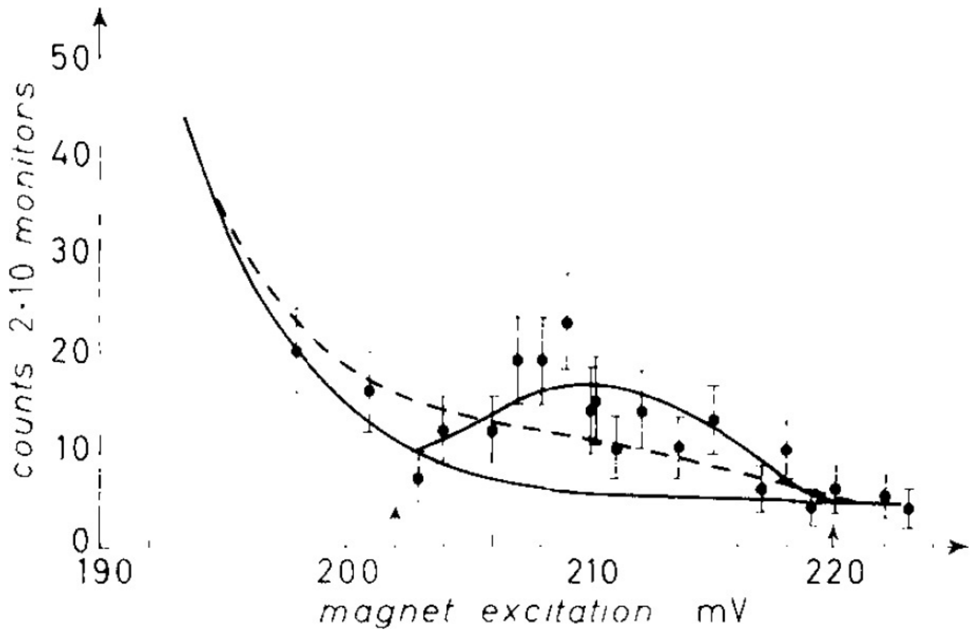
Review of the theoretical and experimental status of dark matter identification with cosmic-ray antideuterons

under review at Physics Reports: arXiv:1505.07785

T. Aramaki[a,b], S. Boggs[c], S. Bufalino[d], L. Dal[e], P. von Doetinchem[f,*], F. Donato[d,g], N. Fornengo[d,g], H. Fuke[h], M. Grefe[i], C. Hailey[a], B. Hamilton[j], A. Ibarra[k], J. Mitchell[l], I. Mognet[m], R.A. Ong[m], R. Pereira[f], K. Perez[n], A. Putze[o,p], A. Raklev[e], P. Salati[o], M. Sasaki[l], G. Tarle[q], A. Urbano[r], A. Vittino[d,g], S. Wild[k], W. Xue[s], K. Yoshimura[t]

Antideuterons

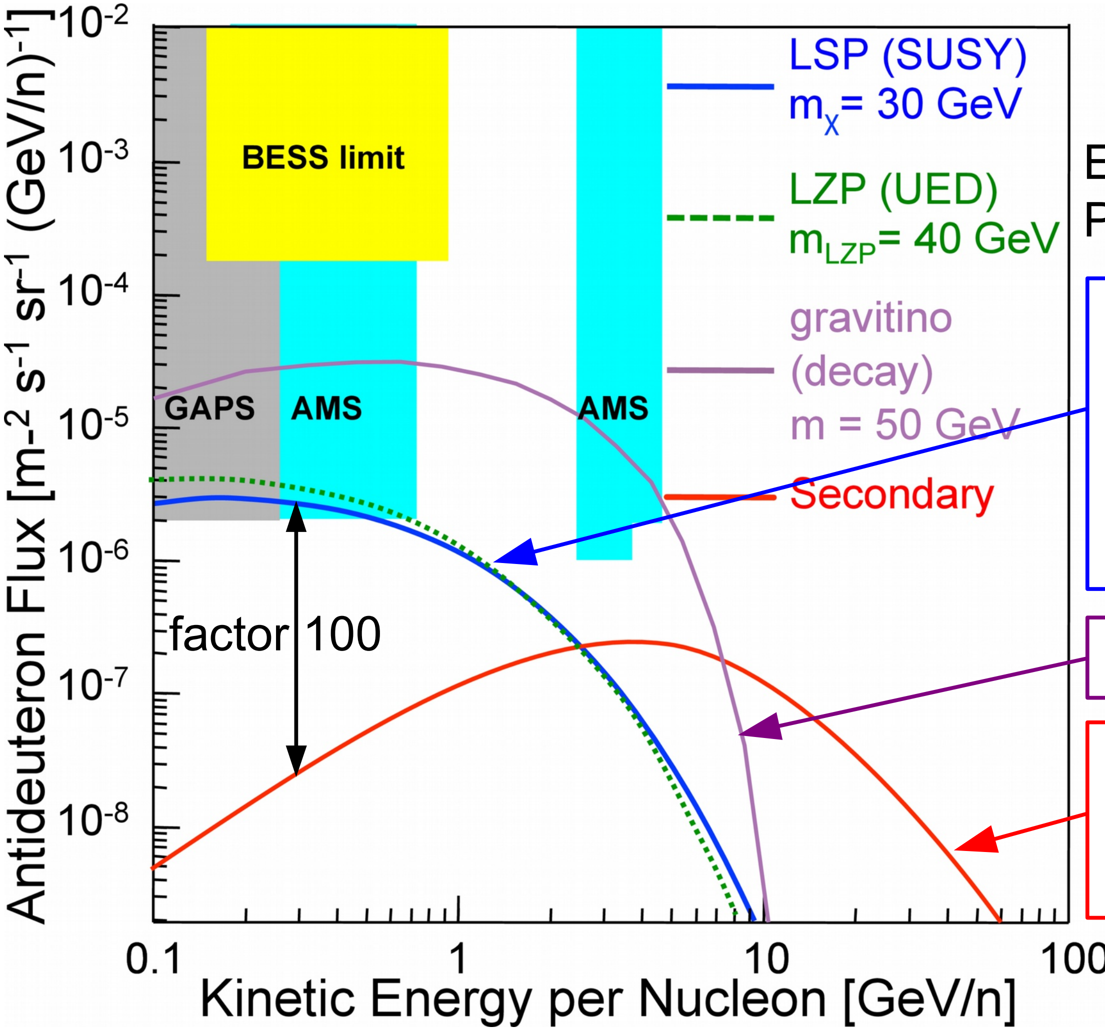




- deuterons are the nuclei of heavy water and antideuterons are the corresponding antimatter (q=-1,m=1876MeV, s=1)
- antideuterons were discovered in 1965 at CERN and Brookhaven and were the **first real antimatter ever discovered**
- seen since then at, e.g., LEP, Tevatron, LHC collider experiments

- **have never been discovered in cosmic rays**
  (next antinucleus in line after the antiproton and before antihelium)

Status of cosmic ray antideuterons



Examples for beyond-standard-model Physics:

Neutralino:
SUSY lightest supersymmetric particle, decay into $b\bar{b}$, compatible with signal from Galactic Center measured by Fermi

late decays of unstable gravitinos

astrophysical background:
collisions of protons and antiprotons with interstellar medium

Antideuterons are the most important unexplored indirect detection technique!

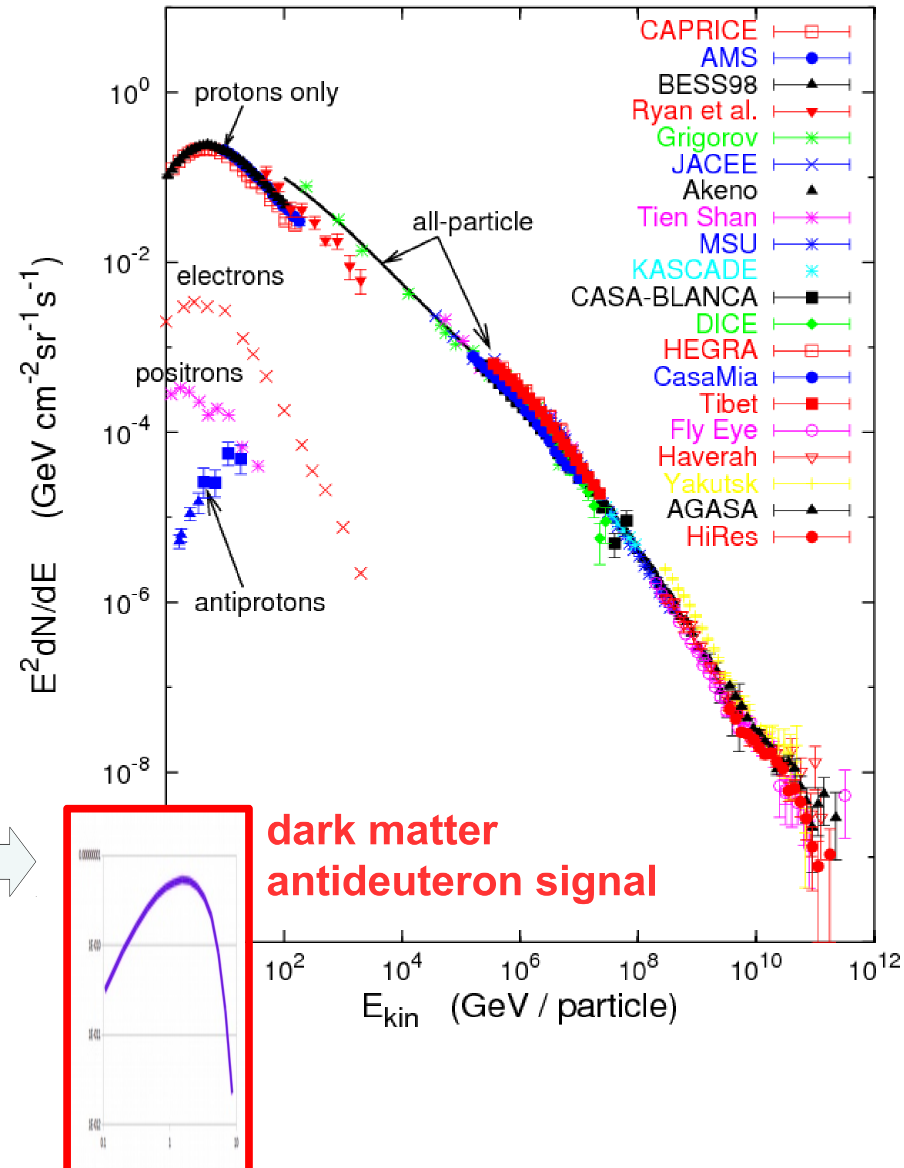
Identification challenge

Required rejections for antideuteron detection:

- **protons**: > 10^8 - 10^{10}
- **He-4**: > 10^7 - 10^9
- **electrons**: > 10^6 - 10^8
- **positrons**: > 10^5 - 10^7
- **antiprotons**: > 10^4 - 10^6

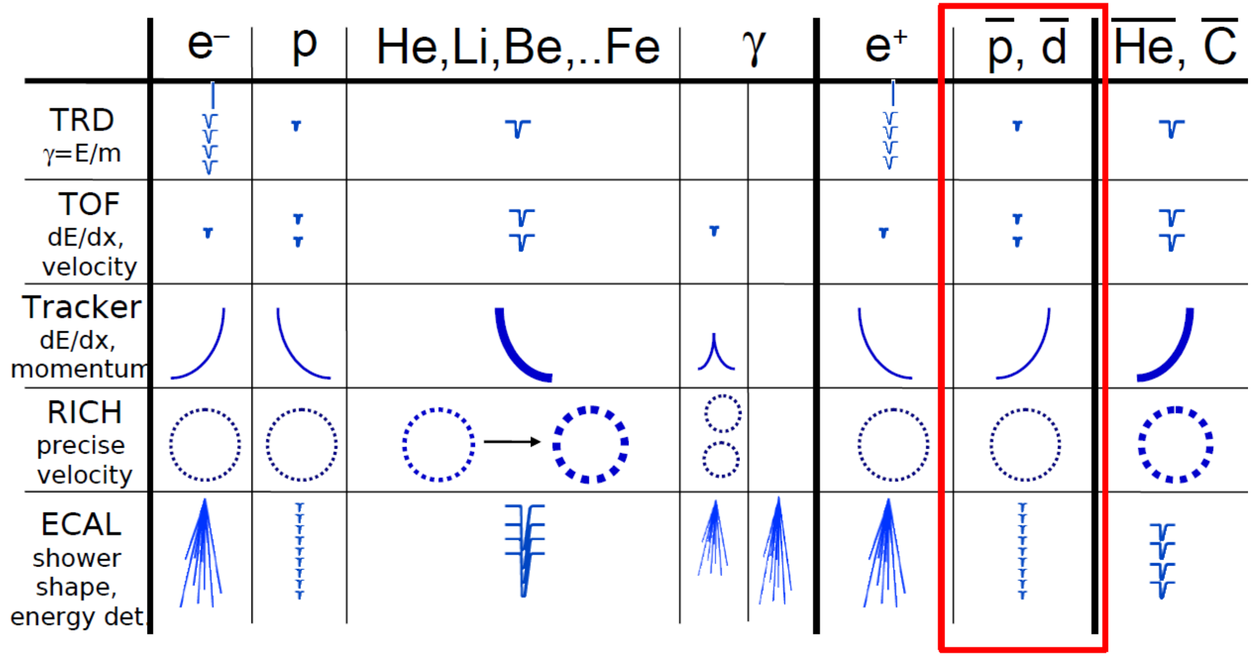
Antideuteron measurement with balloon and
space experiments require:

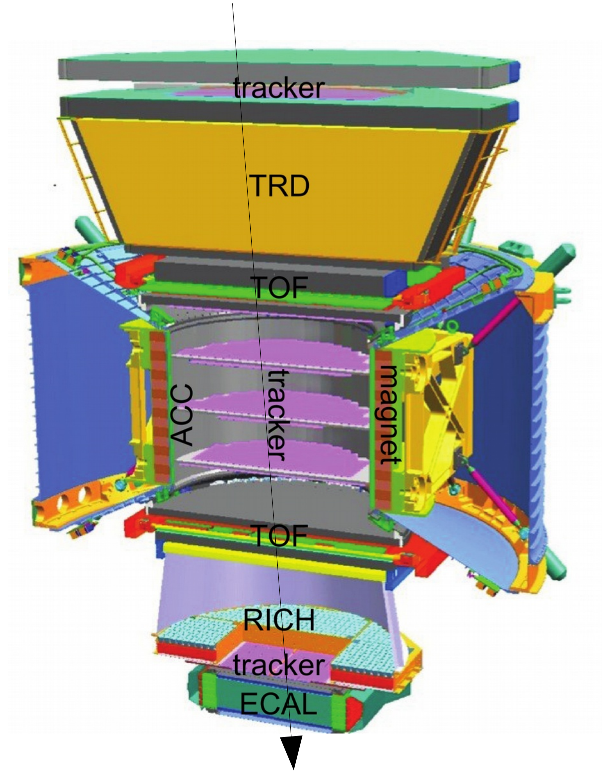
- **strong background suppression**
- **long flight time and large acceptance**



dark matter antideuteron signal

AMS antideuteron analysis



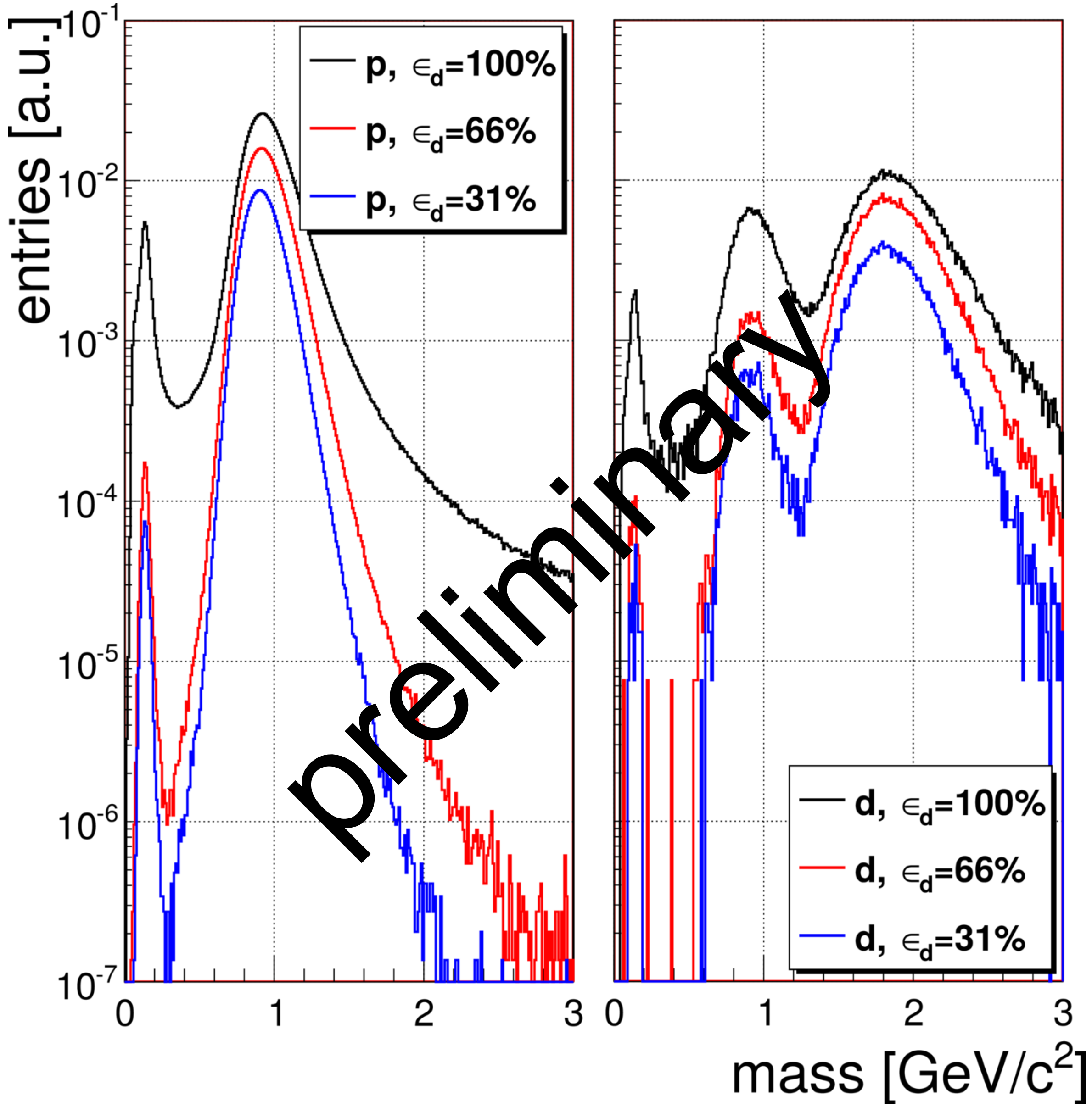


- **antideuteron identification:**
  - –momentum measured in the form of rigidity
  - –charge from TOF, TRD, tracker
  - –lower velocities: **T**ime **O**f **F**light scintillator system
  - –higher velocities: **R**ing **I**mage **Ch**erenkov detector

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

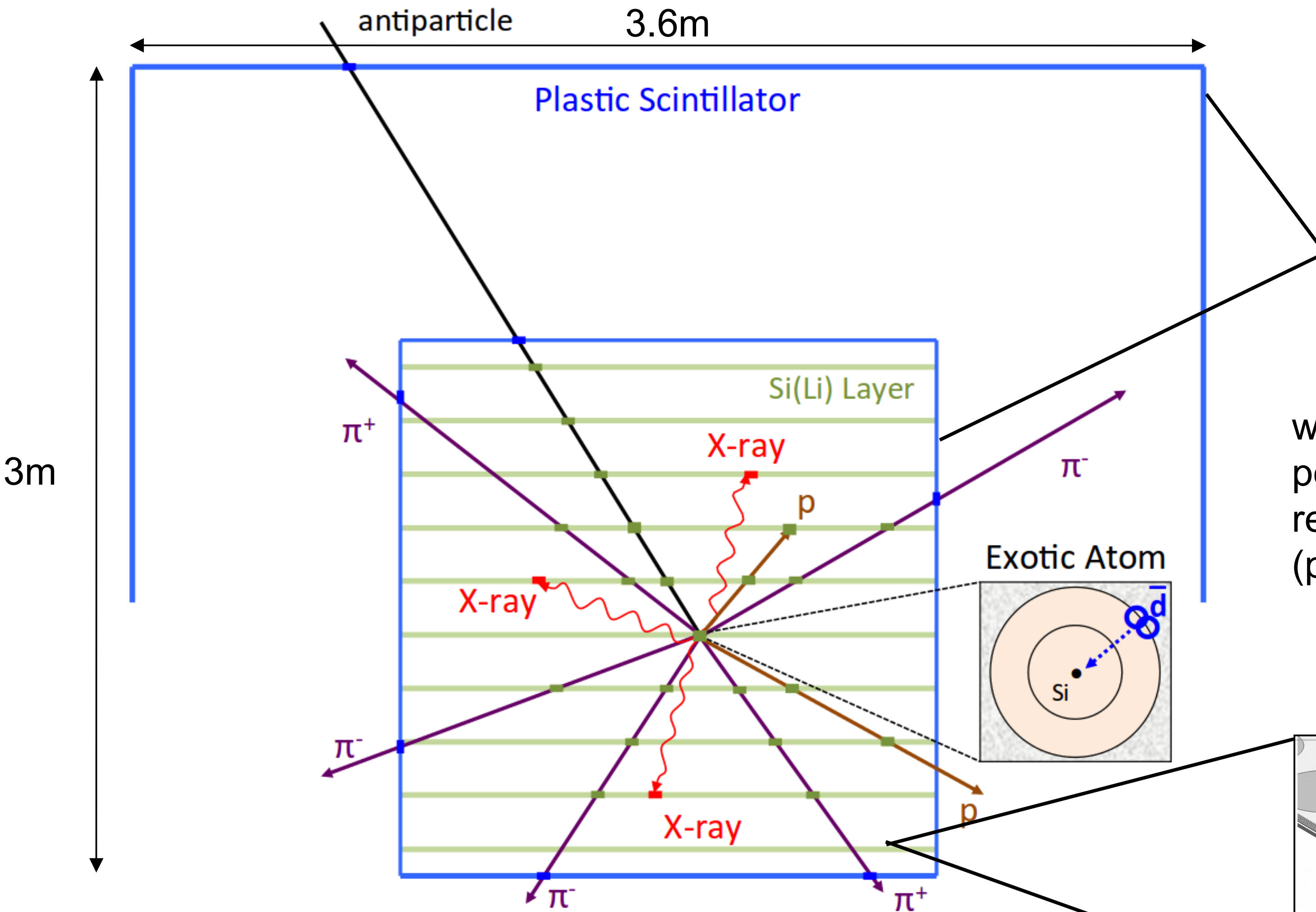
- **self-calibrated analysis:**
  - –calibrate antideuteron analysis with deuterons and antiprotons (simulations and data)
  - –geomagnetic cut-off location is challenging: study low-energy protons and electrons to calibrate geomagnetic and solar effects

Example for proton and deuteron mass reconstruction

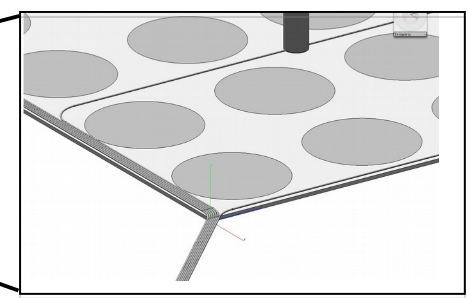


The GAPS experiment

Columbia U, UC Berkeley
UCLA, U Hawaii,
Haverford



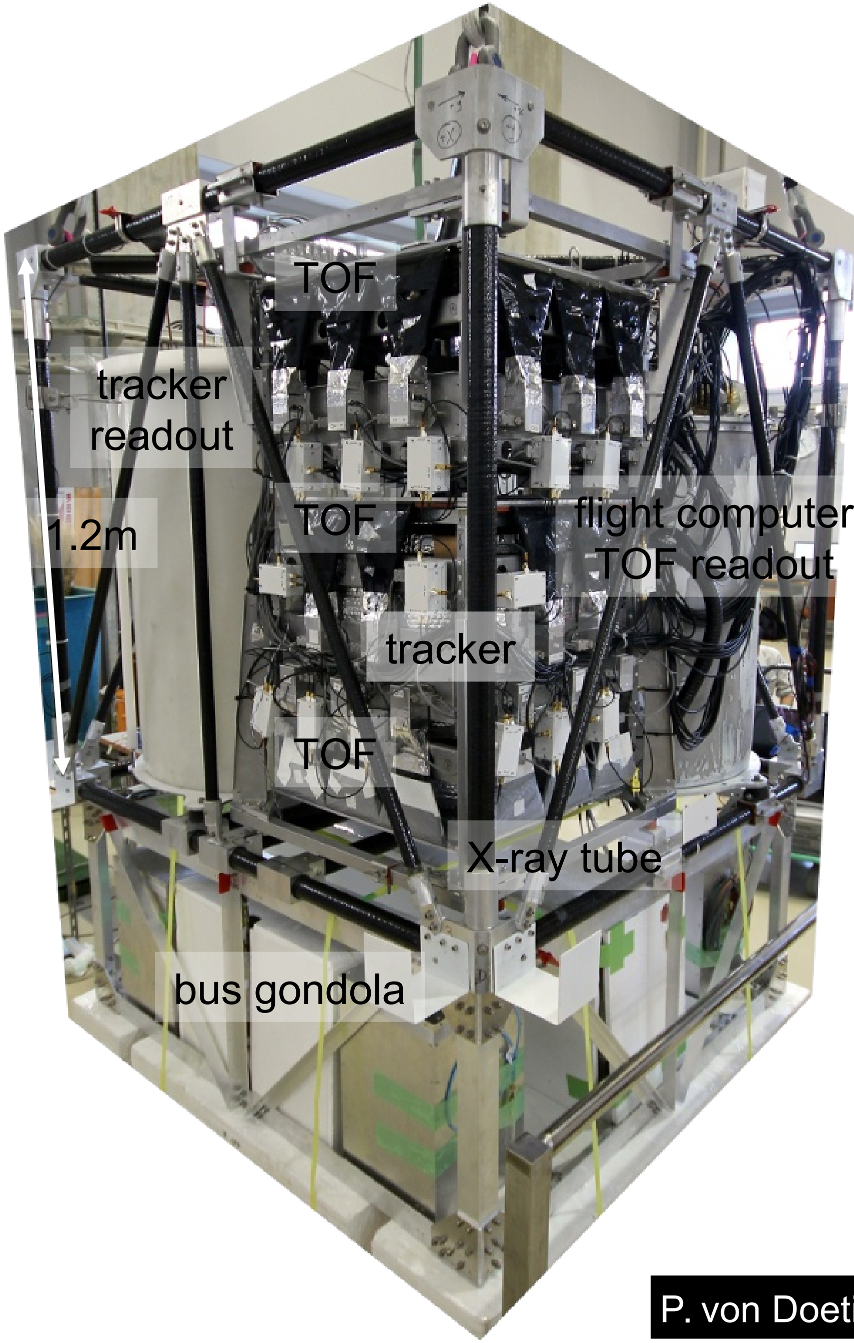
weight: 1700kg
power: 1.4kW
readout: ~100mW/ch
(preamp: ~15mW/ch)



~1400 Si(Li) wafers

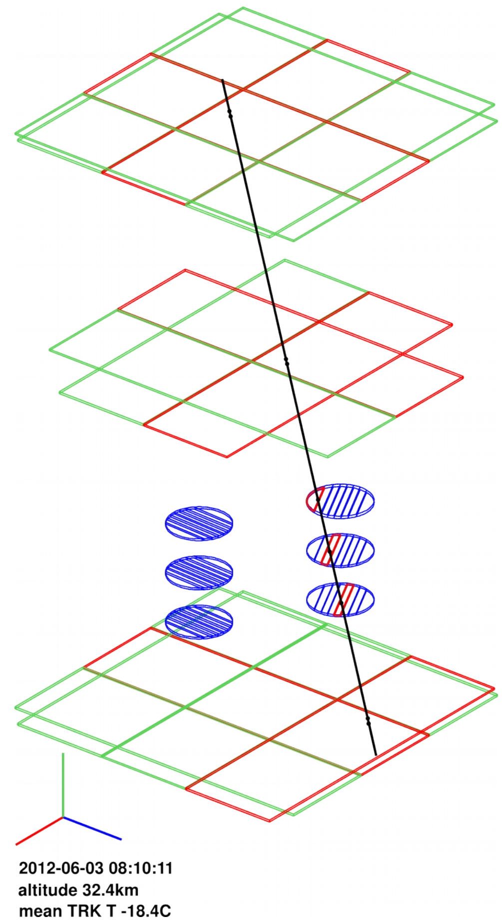
- the **G**eneral **A**nti**P**article **S**pectrometer is especially designed for **low-energy antideuterons and antiprotons**
- identification by stopping and creation of an exotic atom [KEK testbeam measurements → Astropart. Phys. 49, 52 (2013)]
- LDB flights from Antarctica

Prototype GAPS



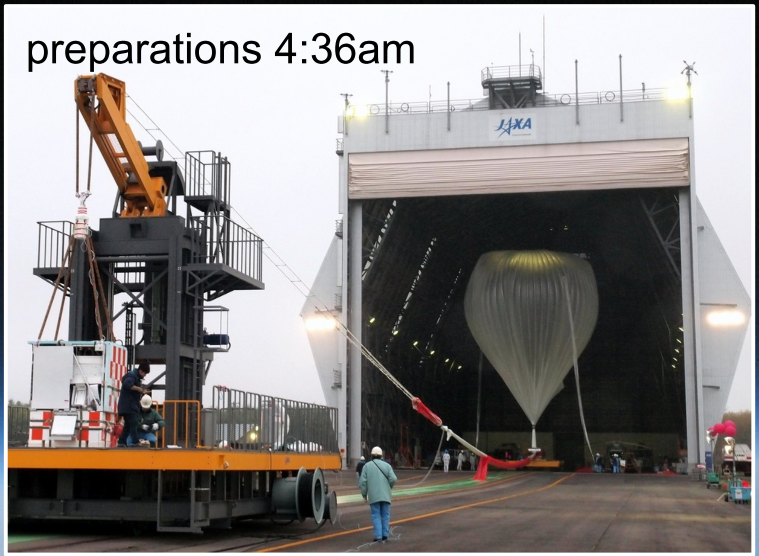
Goals:

- demonstrate stable operation of the detector components during flight
- study Si(Li) cooling approach for thermal model
- measure background levels




GENERAL ANTIPARTICLE SPECTROMETER
GAPS
NASA+JAXA
2012:06:03 02:29:14

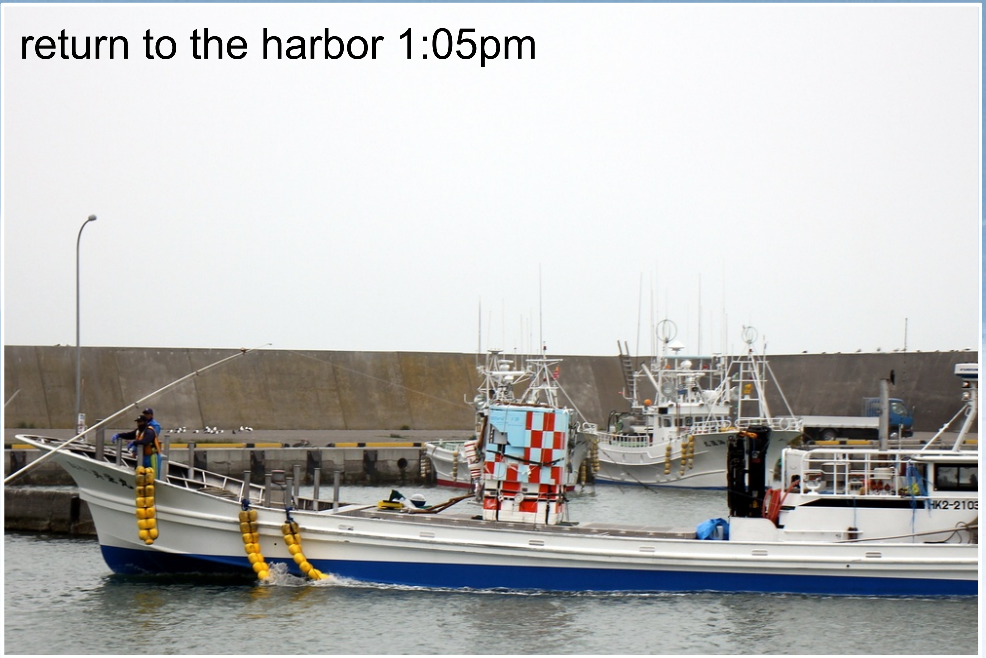
pGAPS flight: June 3rd 2012 from Taiki, Japan



preparations 4:36am

release of balloon

4:55am **take off**

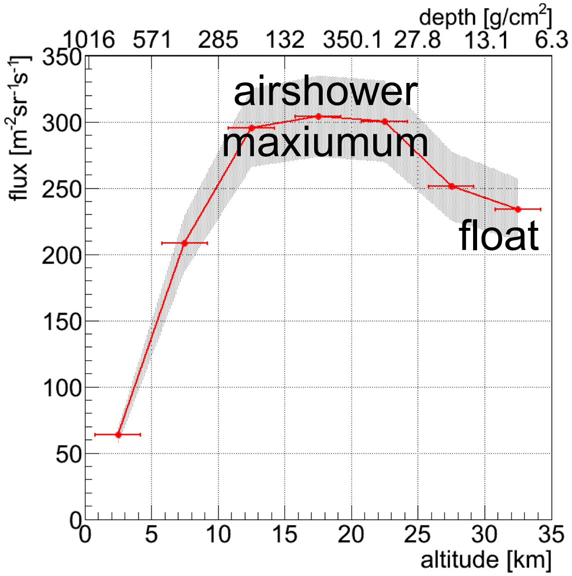


return to the harbor 1:05pm

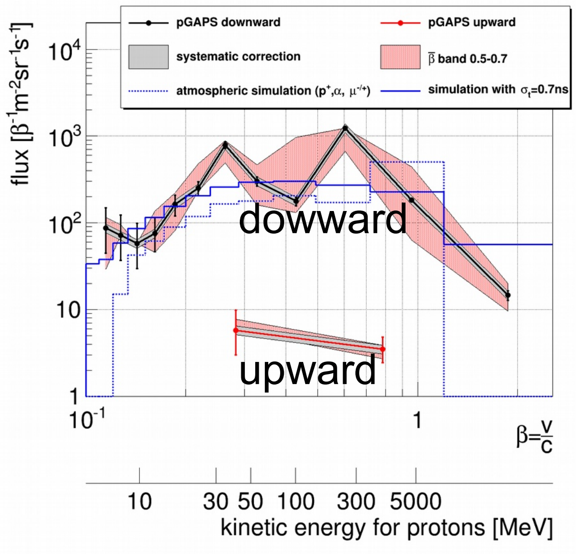
- **well defined TOF trigger and tracker runs**
  - time: 19×13min
  - ~600,000 triggers
- **carry out in-flight calibration of Si(Li) detectors**
  - run X-ray tube
  - time: 13×4min
- **trigger on Si(Li) detectors to study incoherent X-ray background**
  - time: 9×3min

pGAPS flux measurement

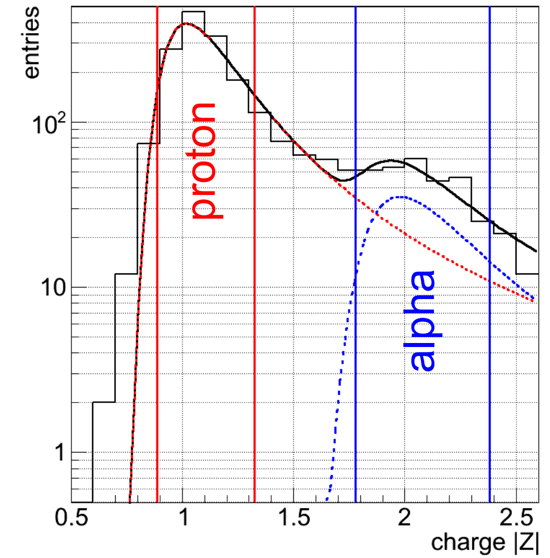
total flux vs. altitude



flux vs. β at 33km



particle composition at 33km

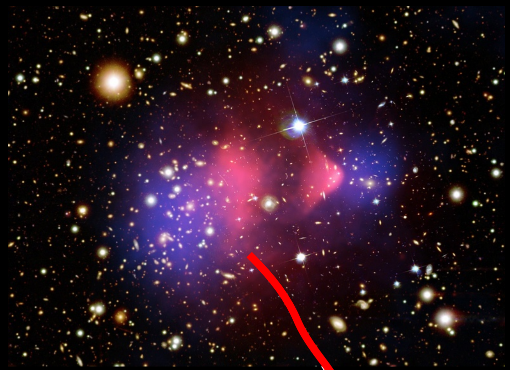


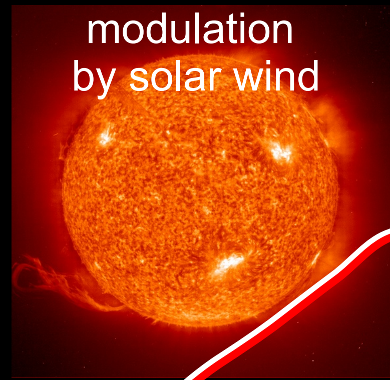
- flux at drift-out "boomerang" altitude (10-15km) is ~30% higher than at float (33km)

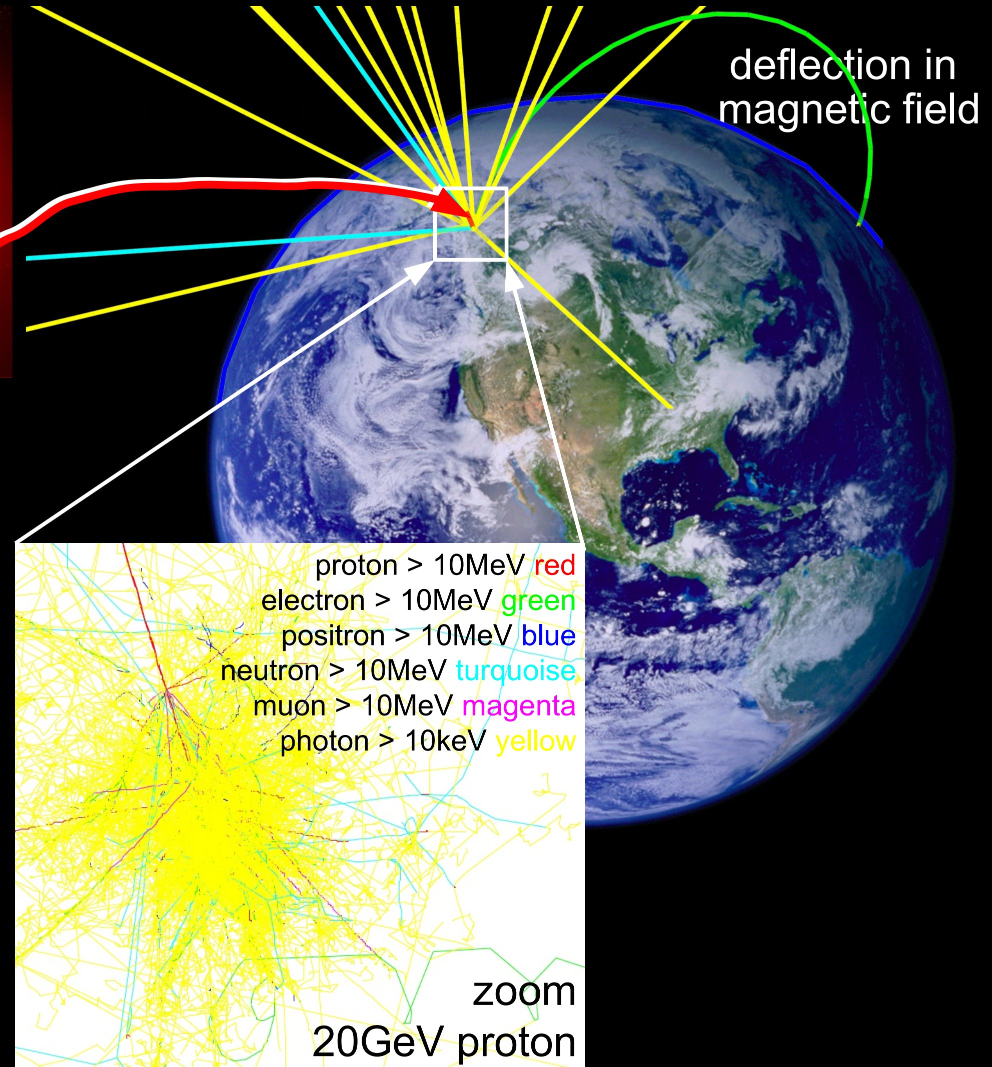
- flux as function of velocity compared to simulations with Geant4+PLANETOCOSMICS (incl. geomagnetic, atmospheric effect)
  - $\beta<0.2$ ($E_{kin,proton}$~20MeV) very good agreement
  - $\beta=0.3-0.5$ ($E_{kin,proton}$~50-150MeV) within systematic errors
  - $\beta>0.7$ ($E_{kin,proton}$~400MeV) good agreement
  - deviations at 0.3 and 0.6 visible → more simulation work at low energies in the future

- α particles constitute about ~10% of the flux at 33km (~9g/cm^2) → in good agreement with BESS data

Uncertainties

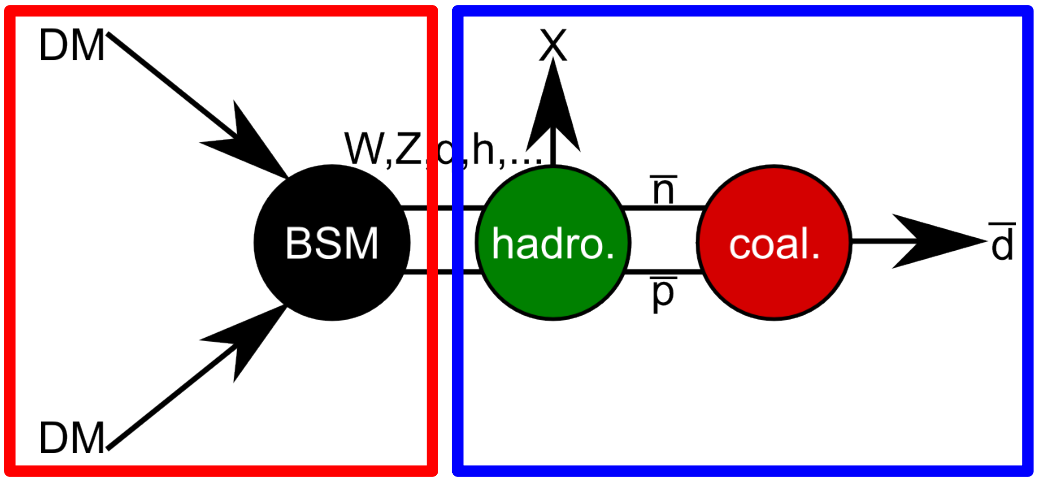






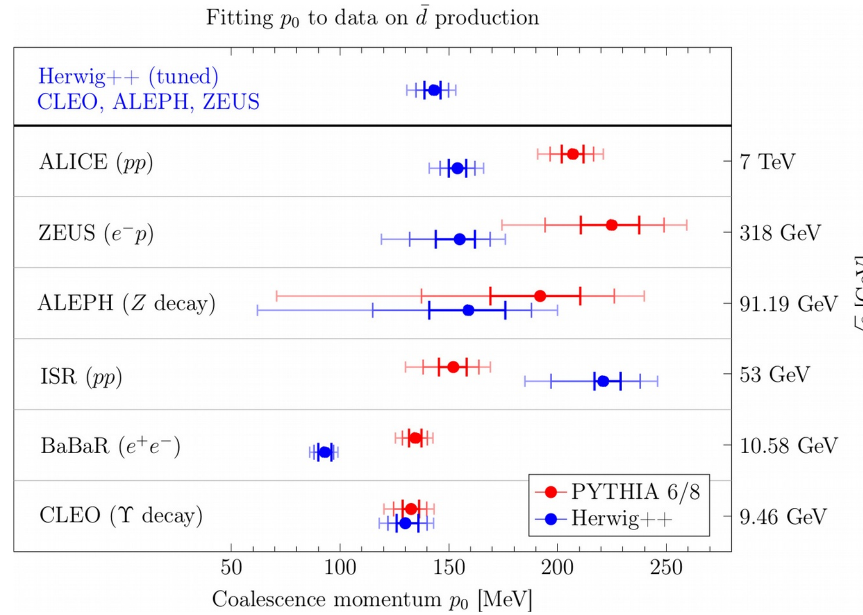
- Dark matter annihilation or decay
- Dark matter clumping
- **Antideuteron production**
- **Galactic propagation**
- **Solar modulation**
- **Geomagnetic deflection**
- Atmospheric interactions
- **Interactions in detector**

Antideuteron formation



dark matter

conventional production
& dark matter

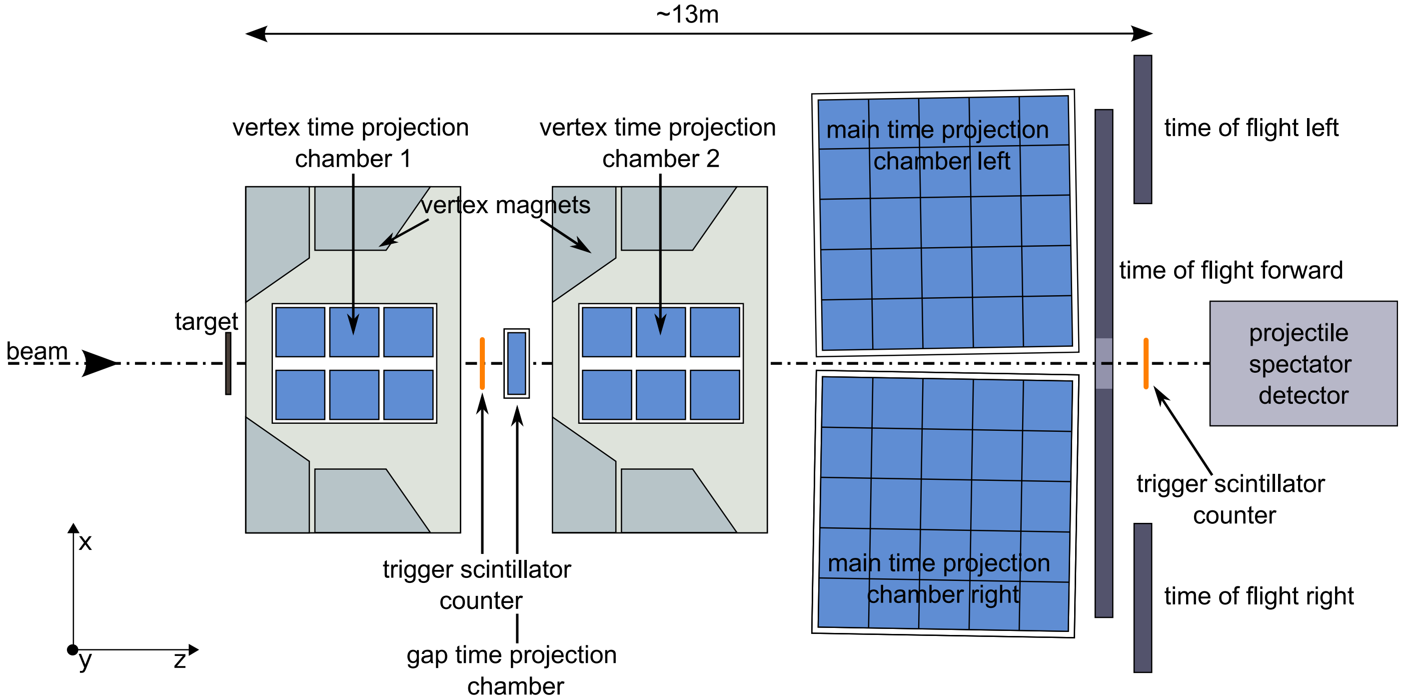


- antideuterons can be formed by an antiproton-antineutron pair if relative momentum is small (coalescence momentum p_0)

$$\frac{\mathrm{d}N_{\bar{d}}}{\mathrm{d}T_{\bar{d}}} = \frac{p_0^3}{6}\,\frac{m_{\bar{d}}}{m_{\bar{n}}m_{\bar{p}}}\,\frac{1}{\sqrt{T_{\bar{d}}^2 + 2m_{\bar{d}}T_{\bar{d}}}}\,\frac{\mathrm{d}N_{\bar{n}}}{\mathrm{d}T_{\bar{n}}}\,\frac{\mathrm{d}N_{\bar{p}}}{\mathrm{d}T_{\bar{p}}}$$

- **important differences for different experiments and MC generators exist → more data would help**

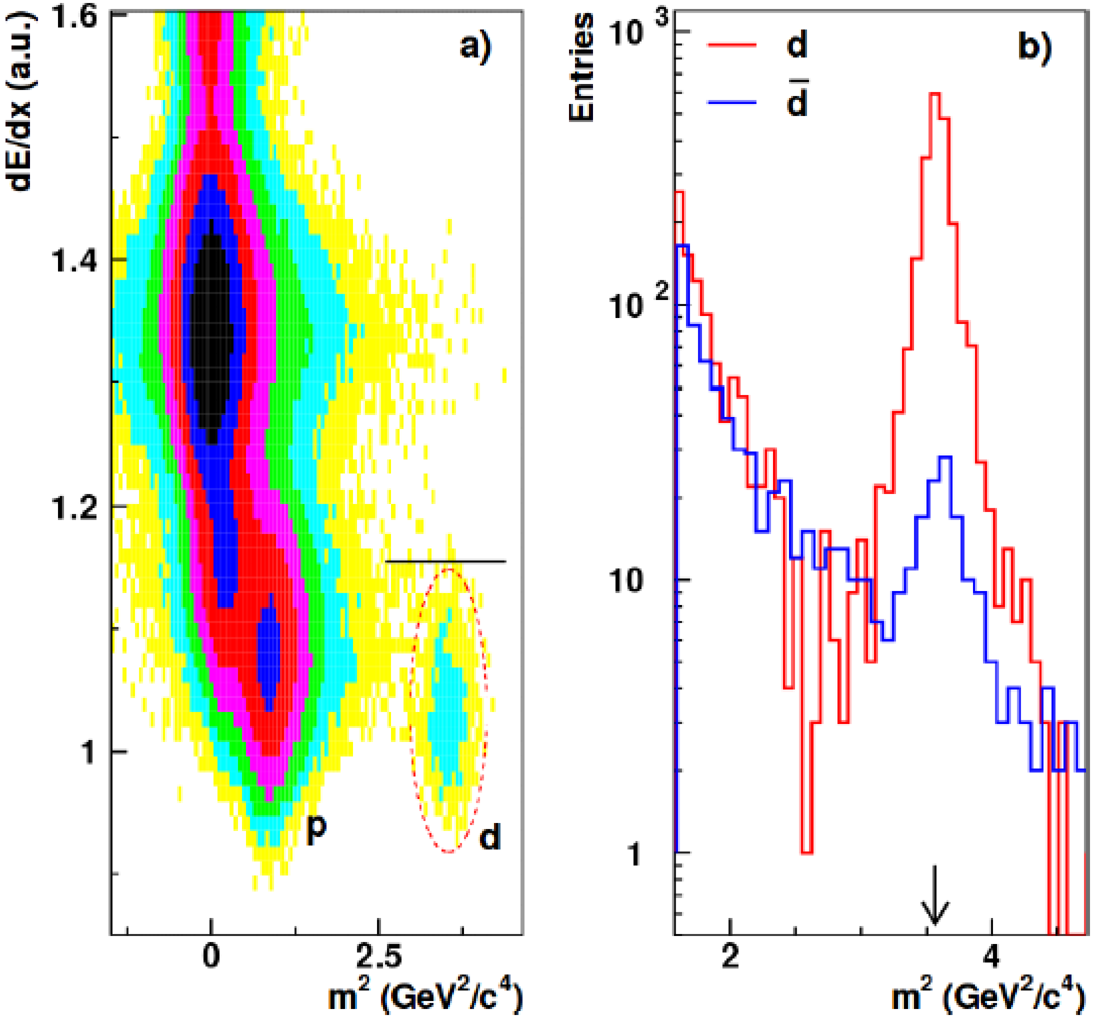
Antideuterons and NA61/SHINE



- Fixed target experiment: main motivation is QCD phase transition, but NA61 also has “customers“ from the UHECR and neutrino community
- Cosmic ray production happens between 40 and 400 GeV
  → SPS energies from 9 to 400 GeV are ideal
- proton-proton interactions with incident momentum between 13 and 158 GeV/c were already recorded in 2011
- 350GeV *p*-*p* run next spring

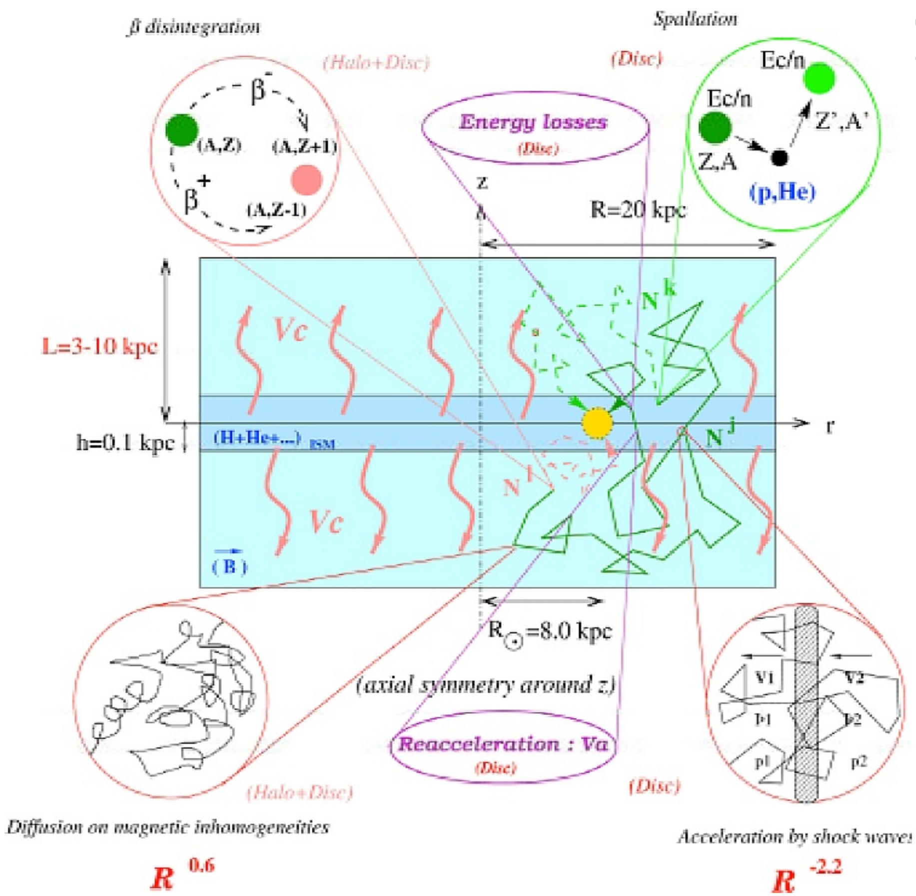
NA49 antideuterons

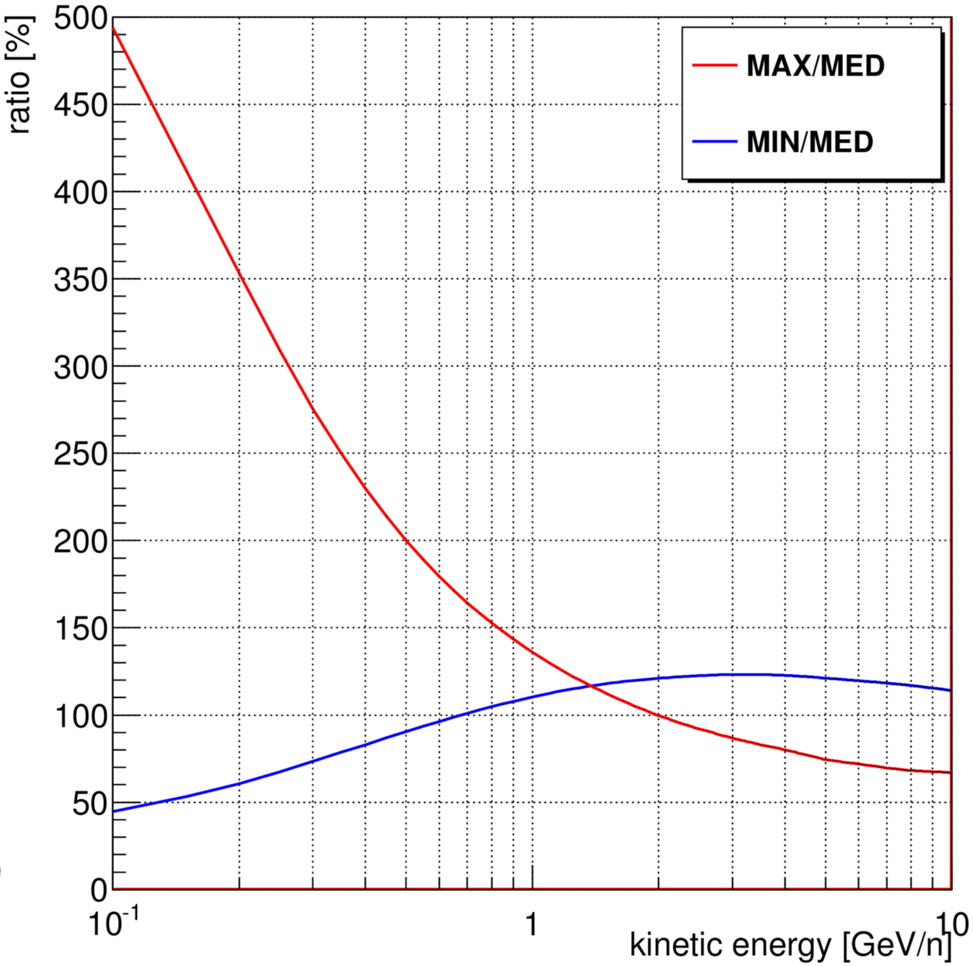
- NA49 is pre-decessor experiment
- NA49 lead-lead data were already analyzed for antideuterons
- important cross-check for the MC generators: measurement of the yield of antiprotons with the same data



T. Anticic et al., Phys. Rev. C 85, 044913 (2012)

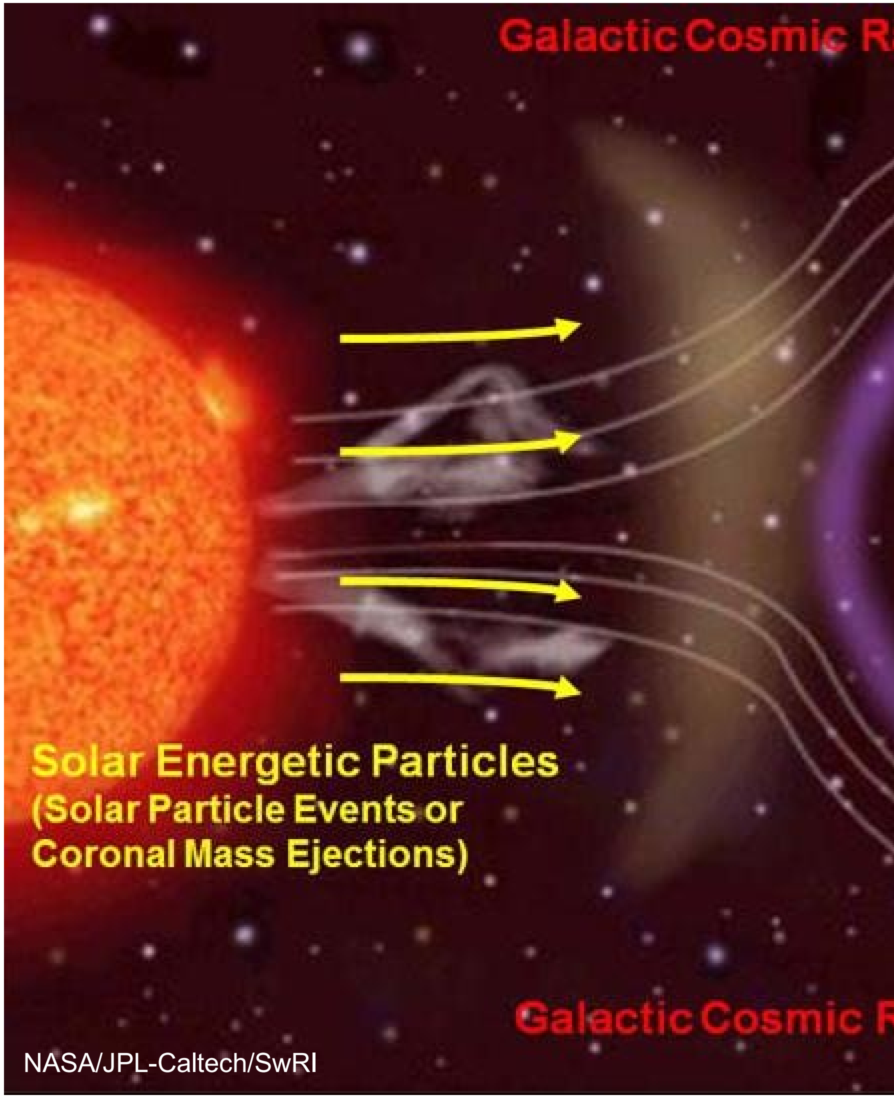
Propagation uncertainty

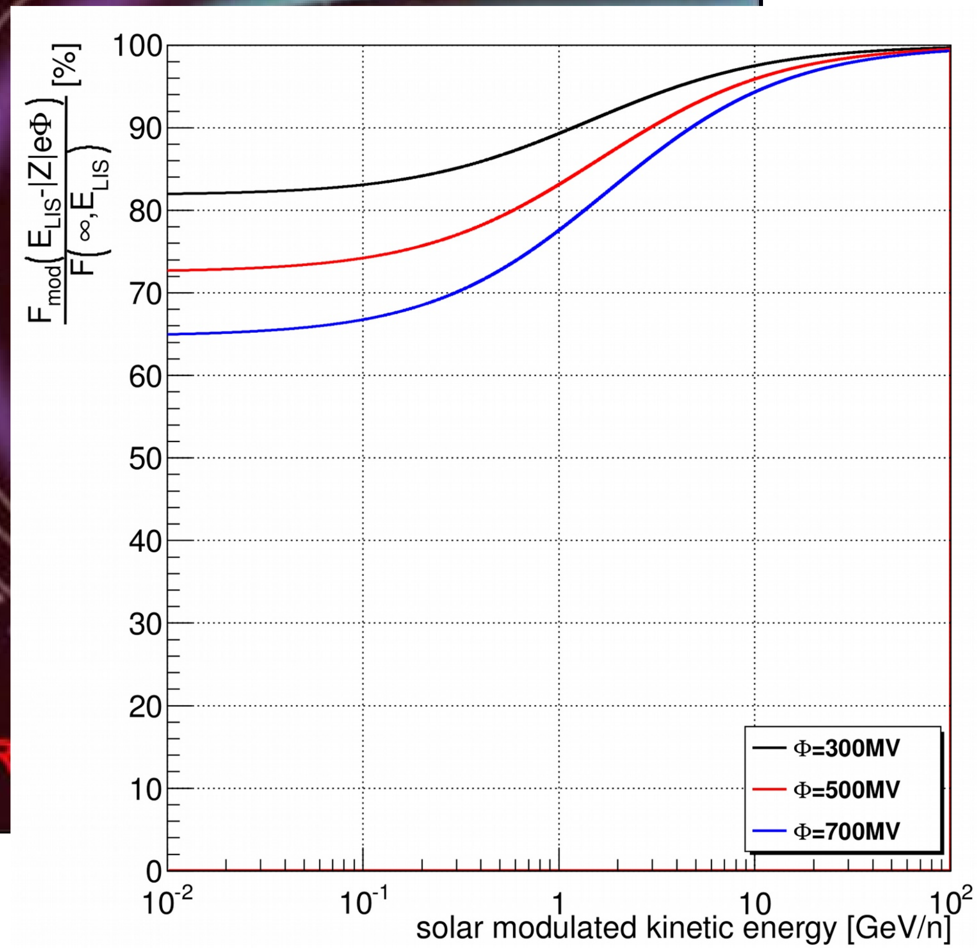




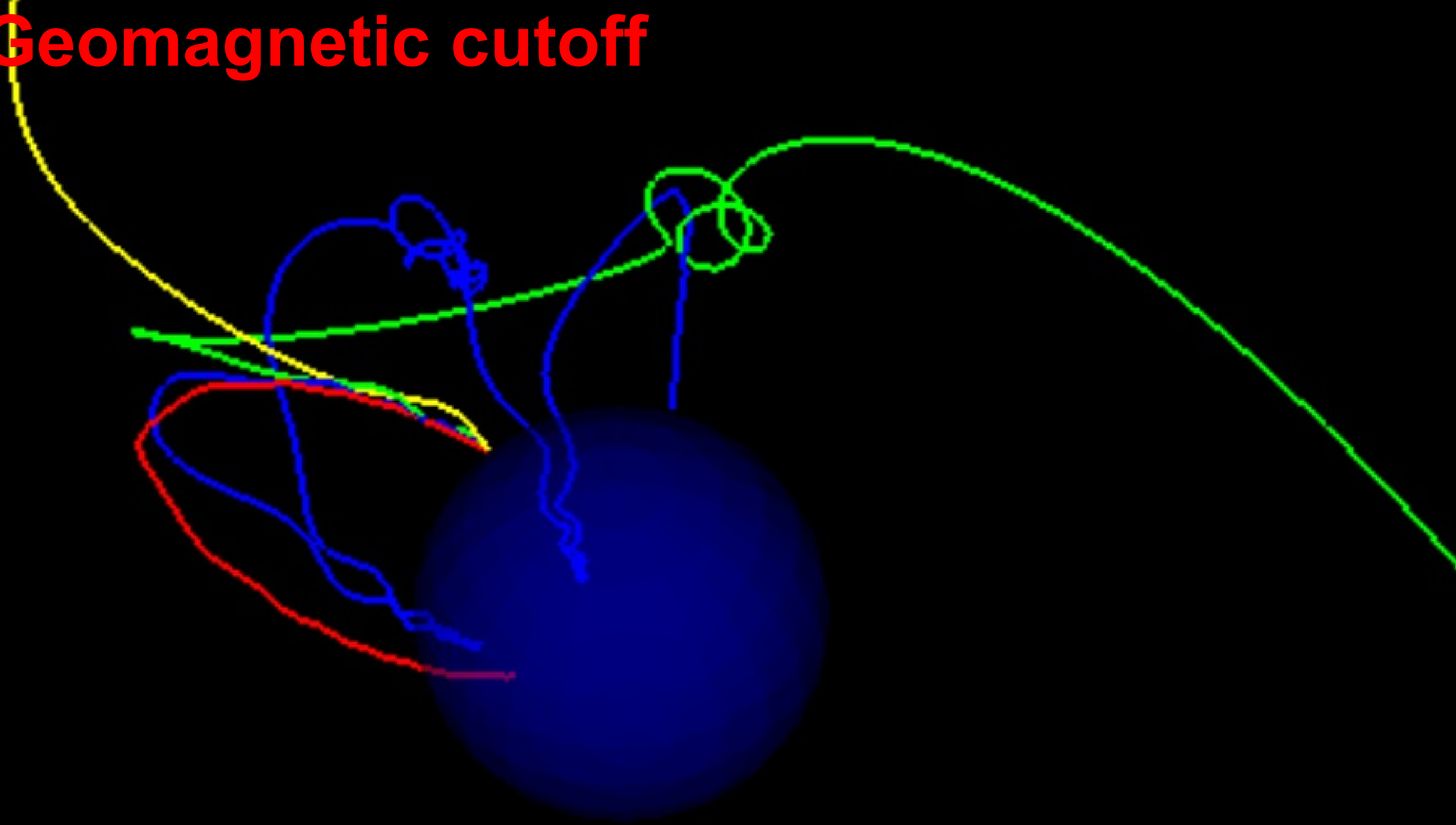
- Propagation is the strongest uncertaintiy source for primary antideuterons: **halo size for diffusion calculation poorly constrained**
- More data on various nuclear speces are needed for better constraints

Solar modulation



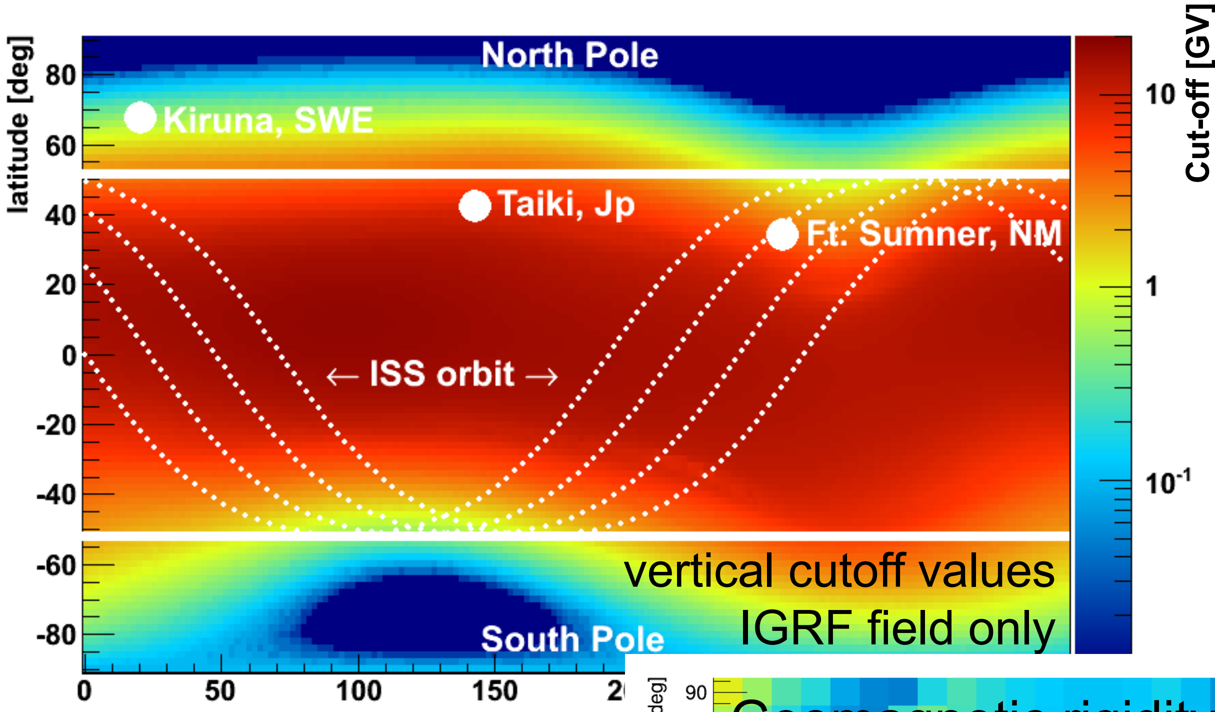


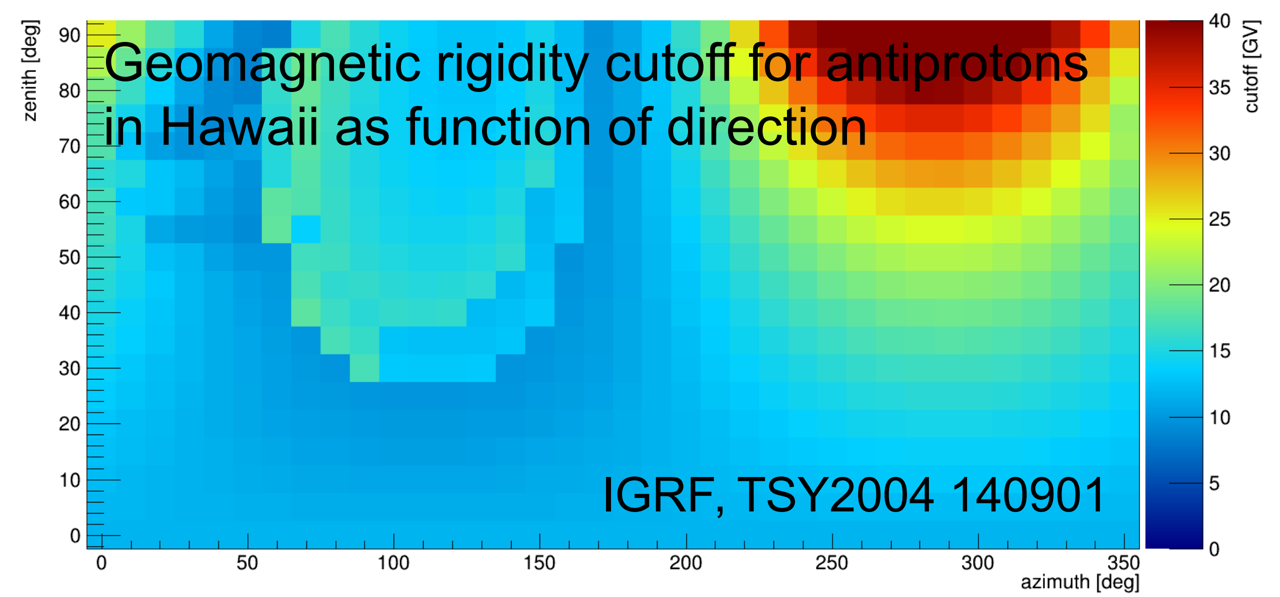
Geomagnetic cutoff



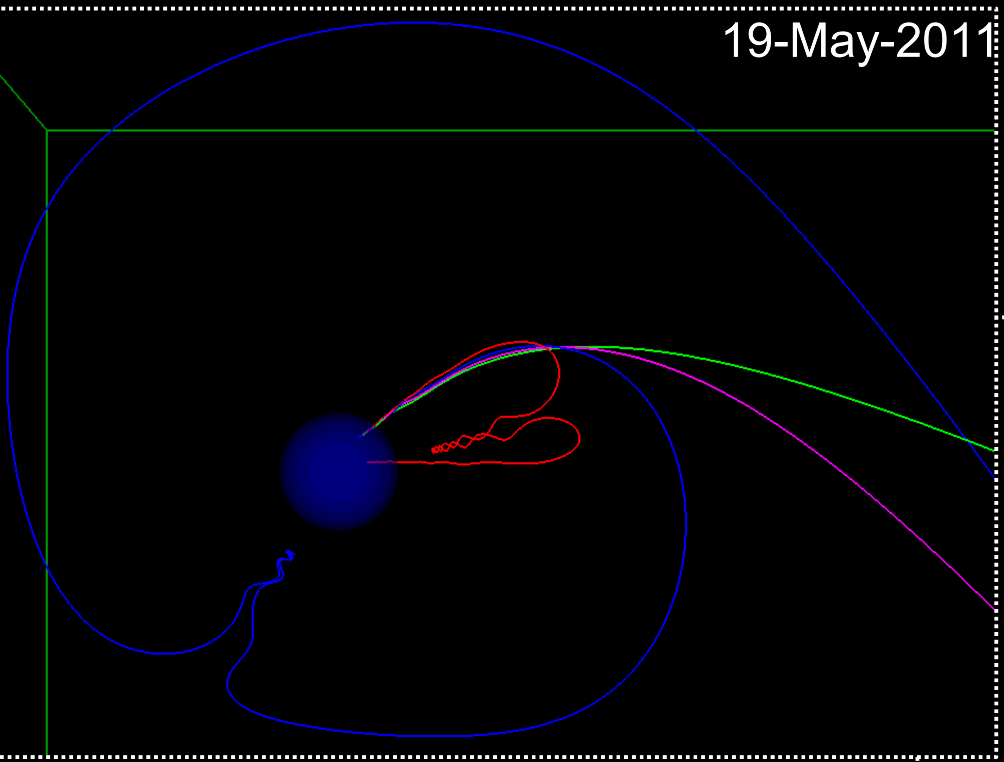
Proton backtracing in geomagnetic field
0.5GV
1.0GV
2.0GV
4.0GV

Geomagnetic cutoff

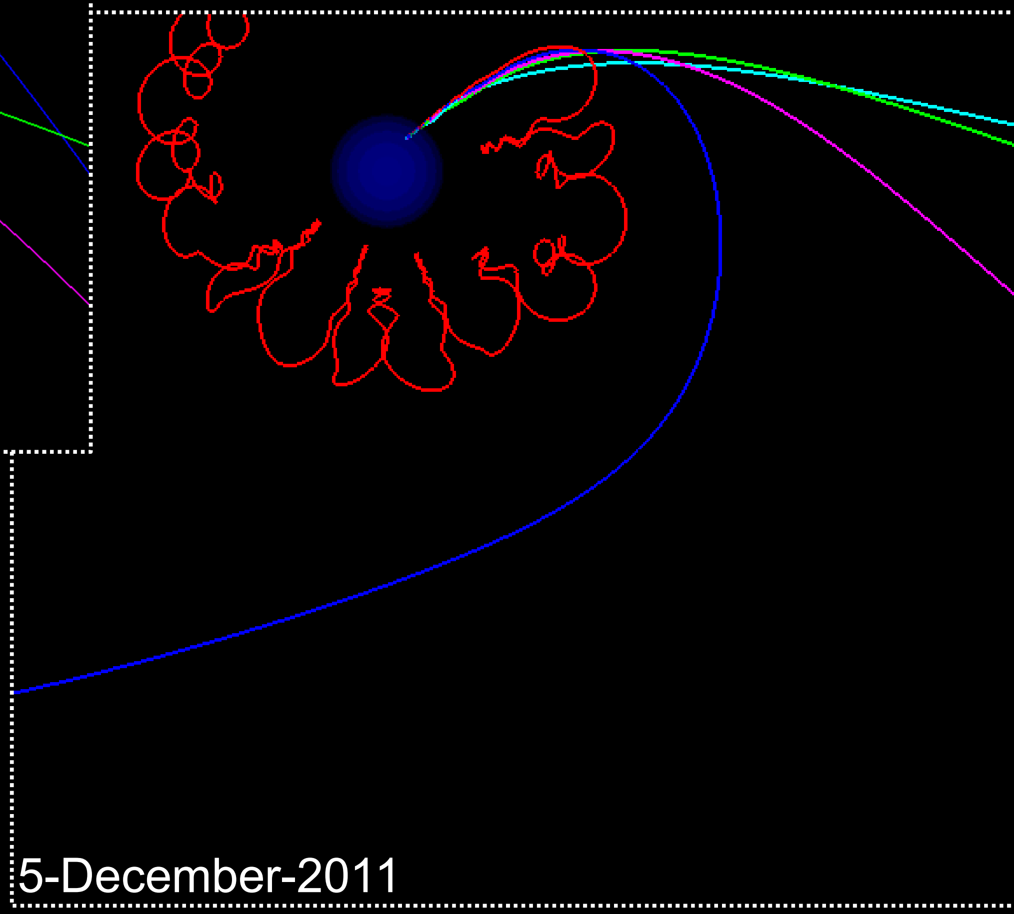




Time dependence of cutoff: events



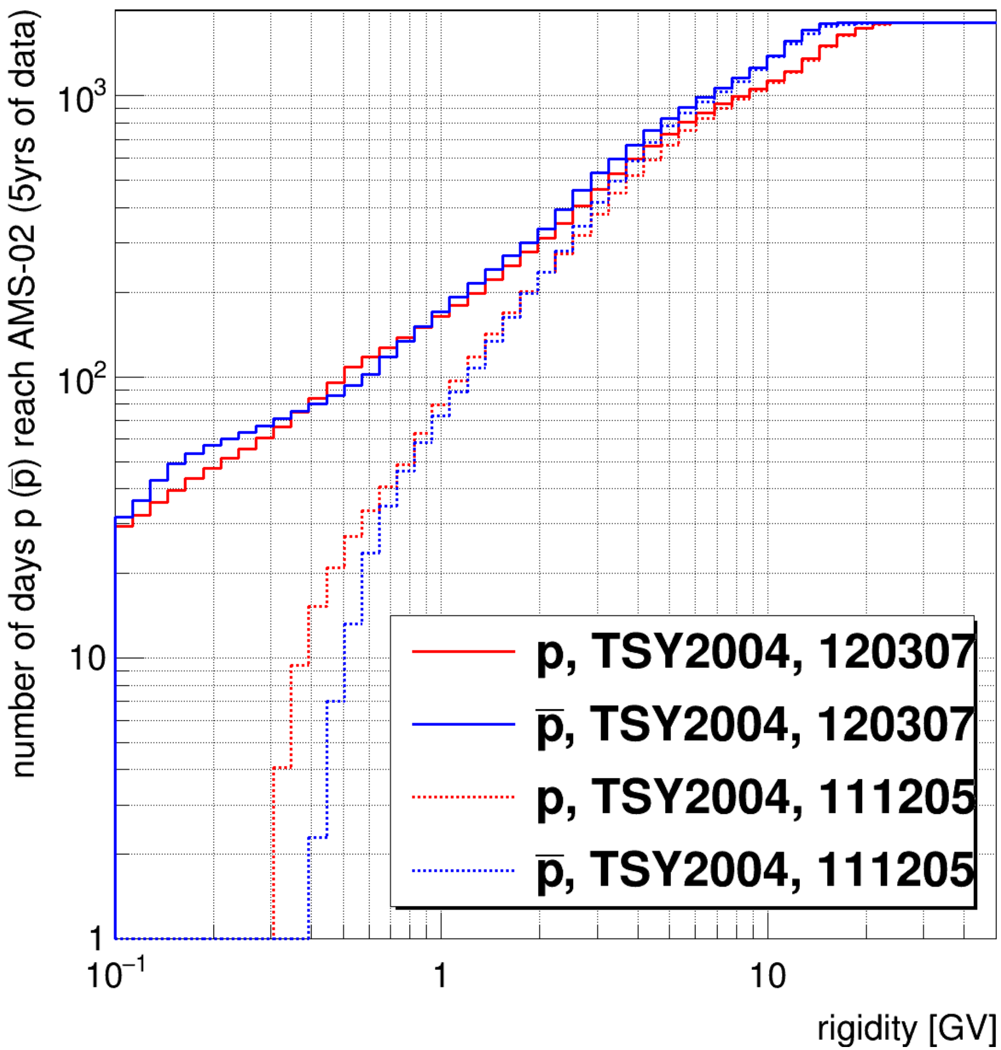
Red: 0.5GV
Blue: 1.0GV
Magenta: 1.5GV
Green: 2.0GV
Cyan: 2.5GV

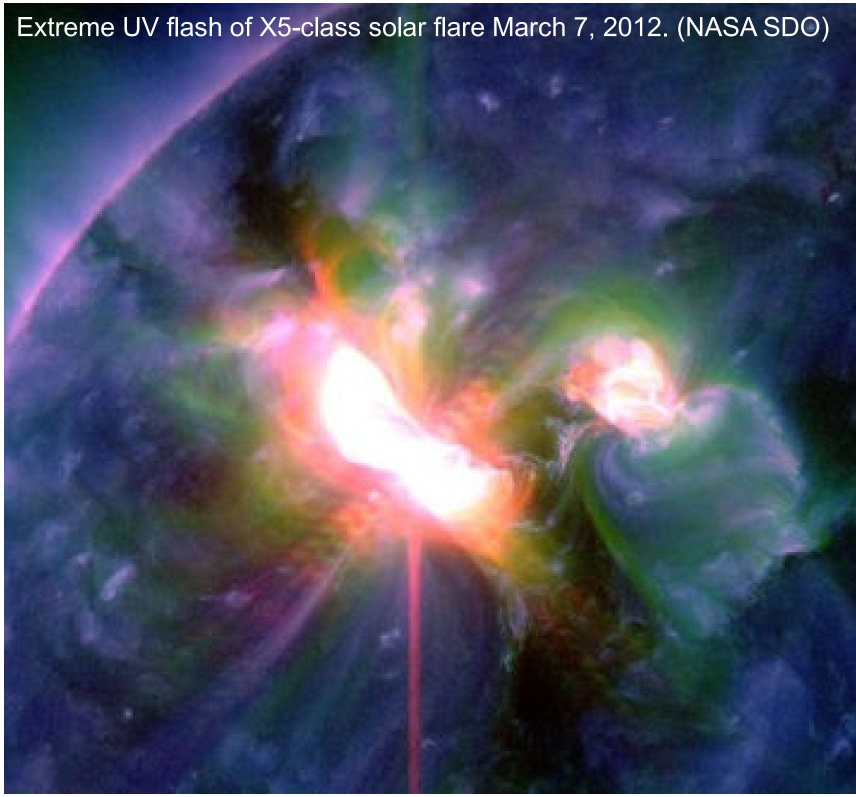


Reverse computation of antiproton trajectories starting at the same location in the same direction for two different times

→ magnetic environment change changes the trajectories drastically and influences the cutoff values

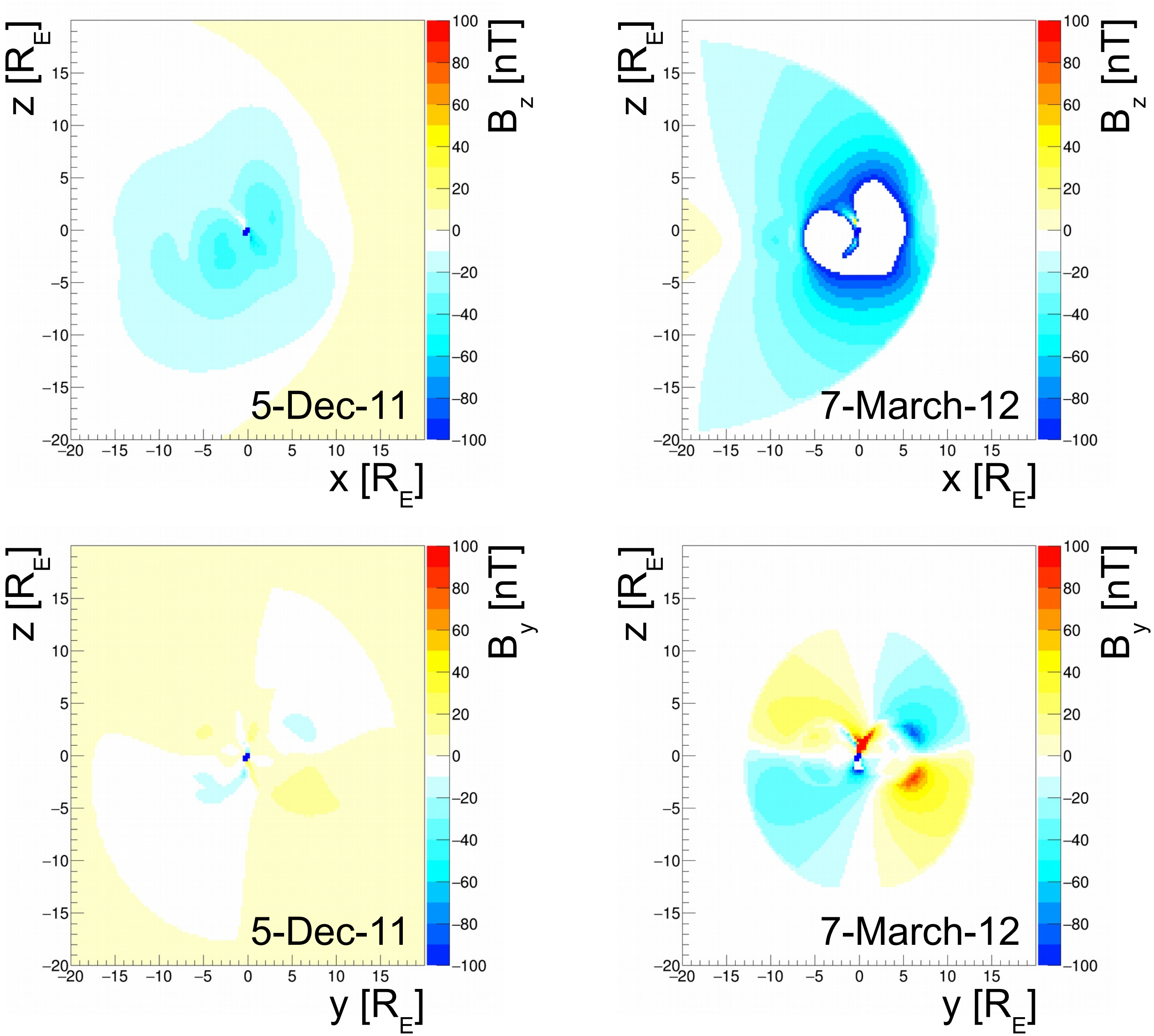
Solar flare event: 7-March-2012





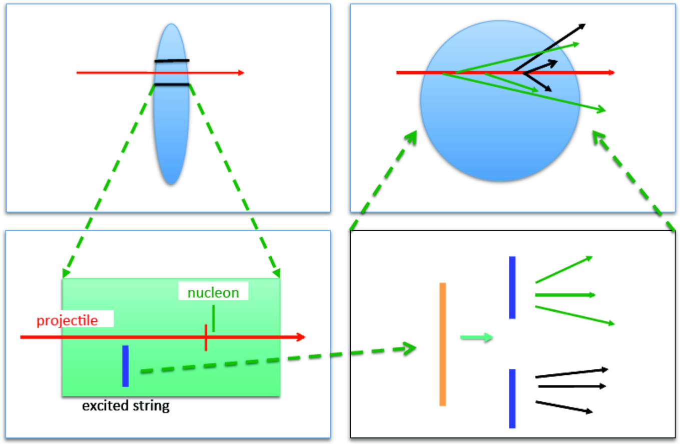
Significant decrease of geomagnetic cutoff

Magnetic field changes

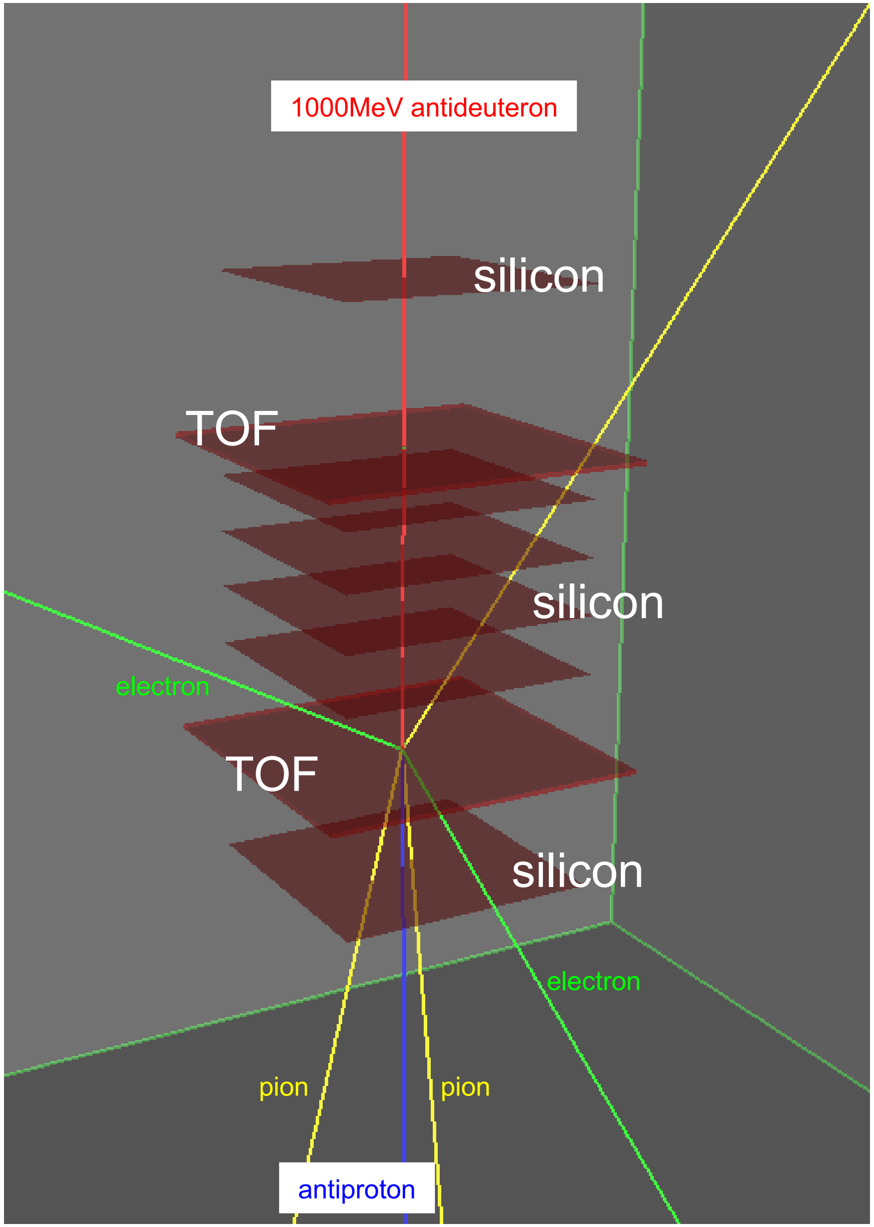


Geant4 - Model for $\bar{d}$ simulation

- recent implementation in Geant4: antideuteron simulations
- FTF model (diffractive string excitation with momentum transfer) was extended to handle nucleus-nucleus interaction down to 0GeV
- best model for antiprotons, antineutrons, antideuterons:
  - very little data for validation available
  - needed:
    - antideuteron formation
    - exotic model for antiproton and antideuteron (GAPS)

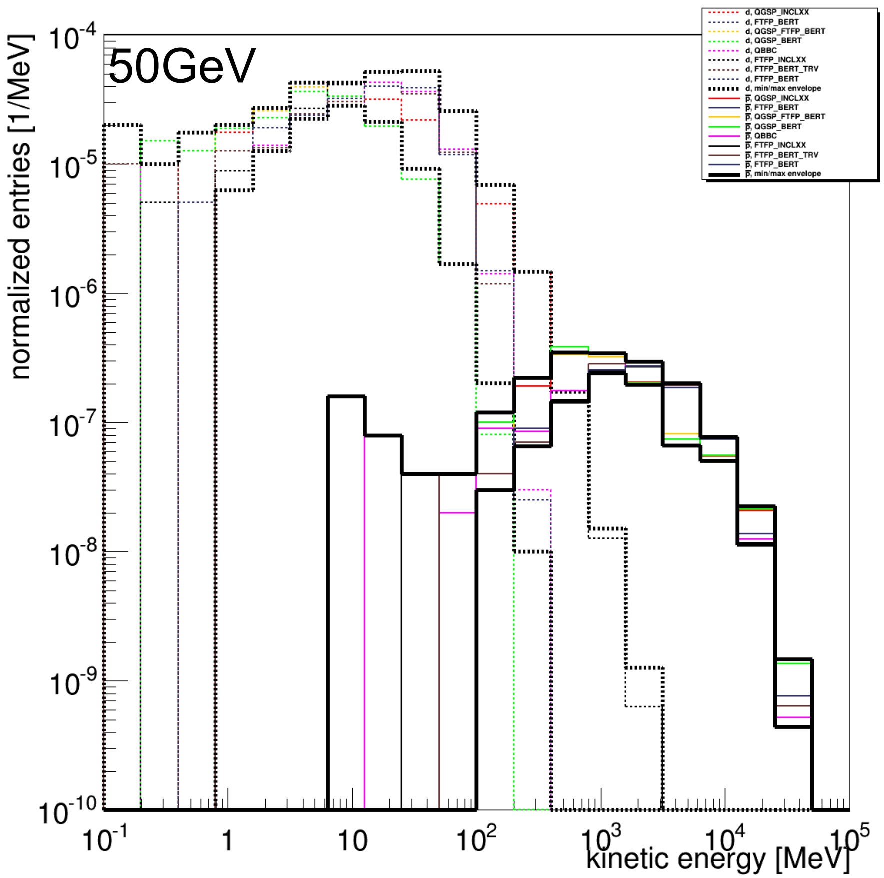


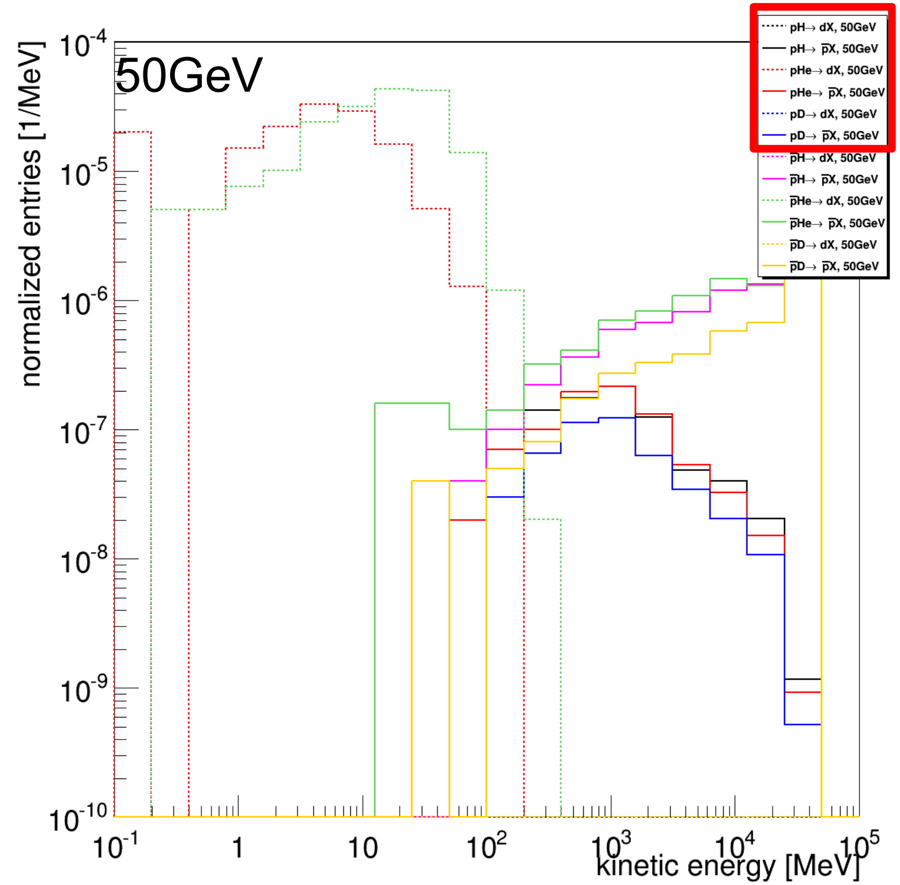
Galoyan, Uzhinsky arXiv:1208.3614



Geant4 studies

Test G4 for p+H, p+He, p+D
for $\bar{p}$, D production with data

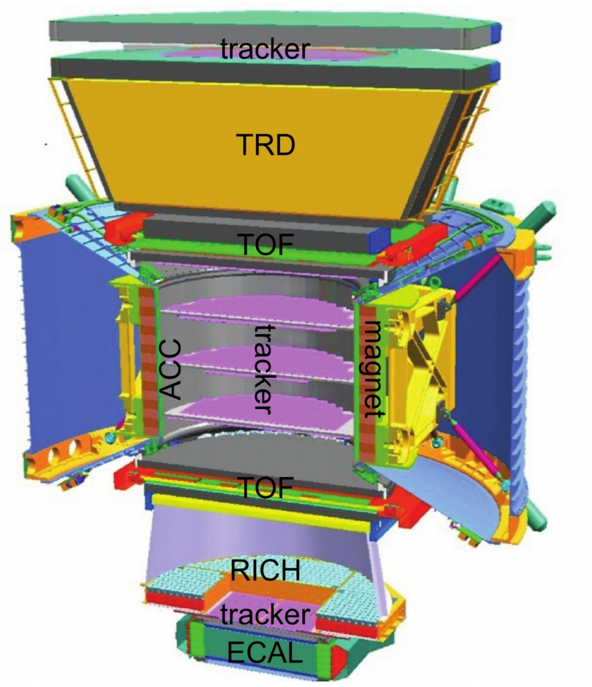


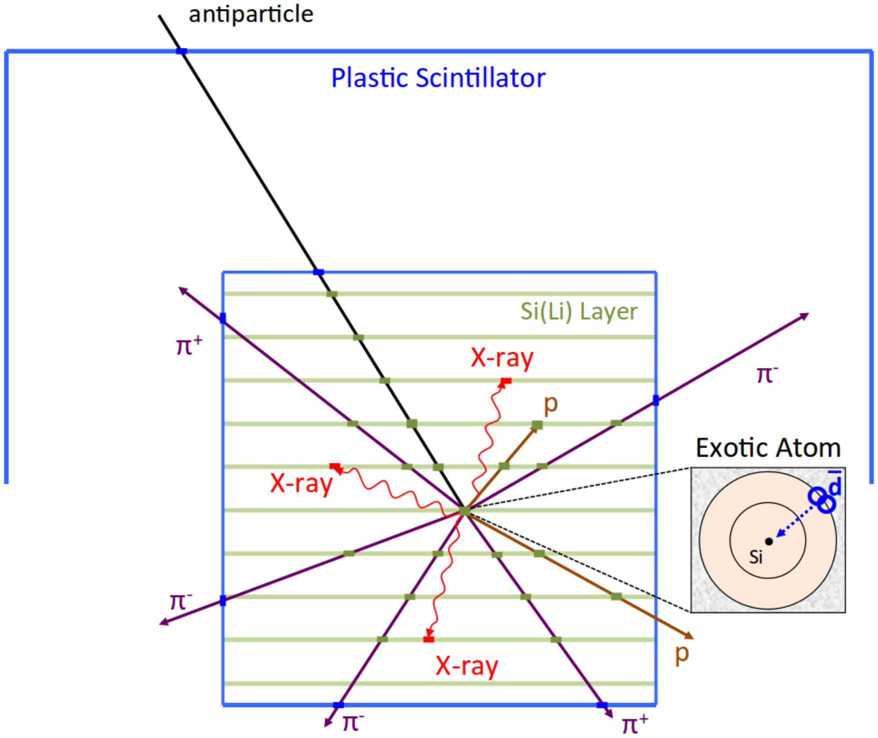


- test of Geant4 physics for *p*-He production “as is“ for different models
- average yield for 8g/cm² of helium (→ if all the traversed matter in ISM for cosmic rays would be helium)

- yields for 5g/cm² of different materials in QGSP_FTF_BERT
- no deuteron coalescence, only break-up implemented

AMS-02 and GAPS comparison





- ISS orbit is not ideal for low-energy cosmic rays, geomagnetic correction for GAPS is 10× smaller
- GAPS and AMS use different detection techniques: mandatory for a reliable confirmation of results to reduce systematic effects
- GAPS (100 days of LDB) and AMS (5yrs) deliver similar sensitivities in the signal region

Conclusion & Outlook

- Measurement of antideuterons is a promising way for indirect dark matter search
- AMS-02 and GAPS have for the first time sensitivity to antideuterons from dark matter annhihilation or decay
- Extended models and improved simulation tools needed
- Measurements with NA61/SHINE will improve understanding of antideuteron production and modeling