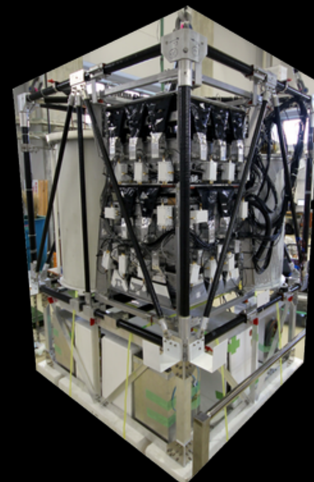
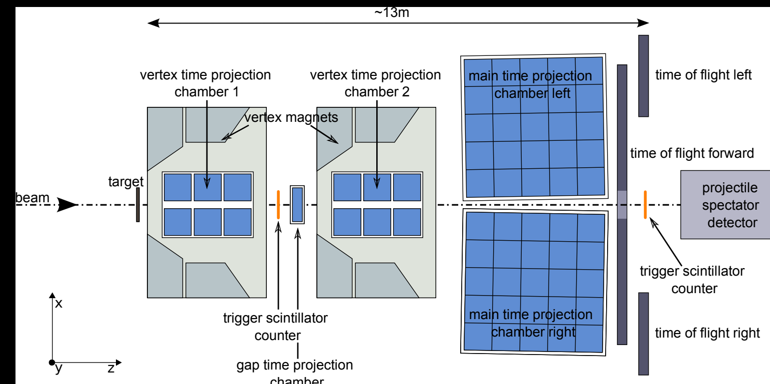
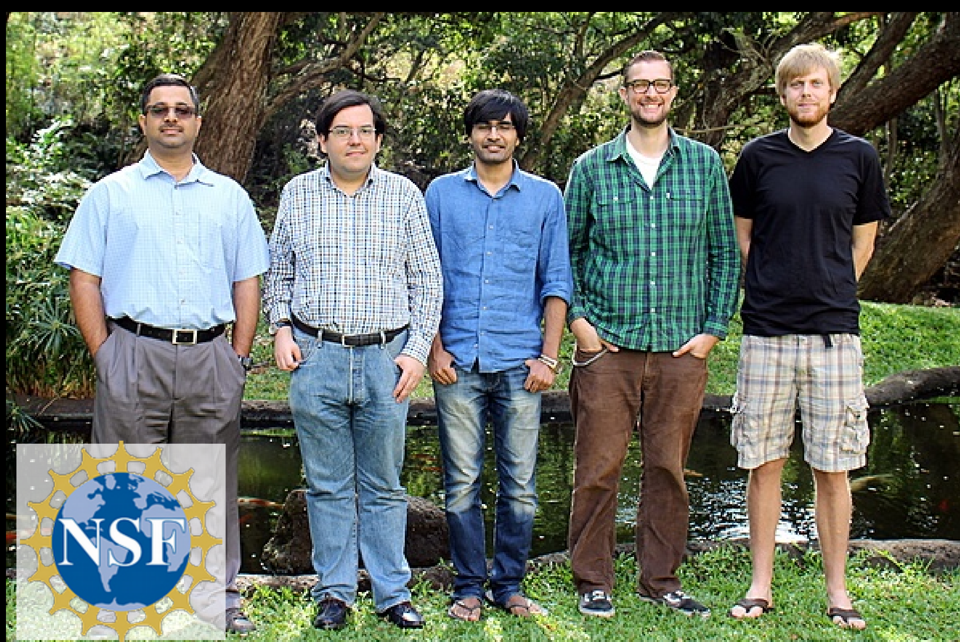
Cosmic-ray antideuteron searches







Ruhr-Universität Bochum
July 2016

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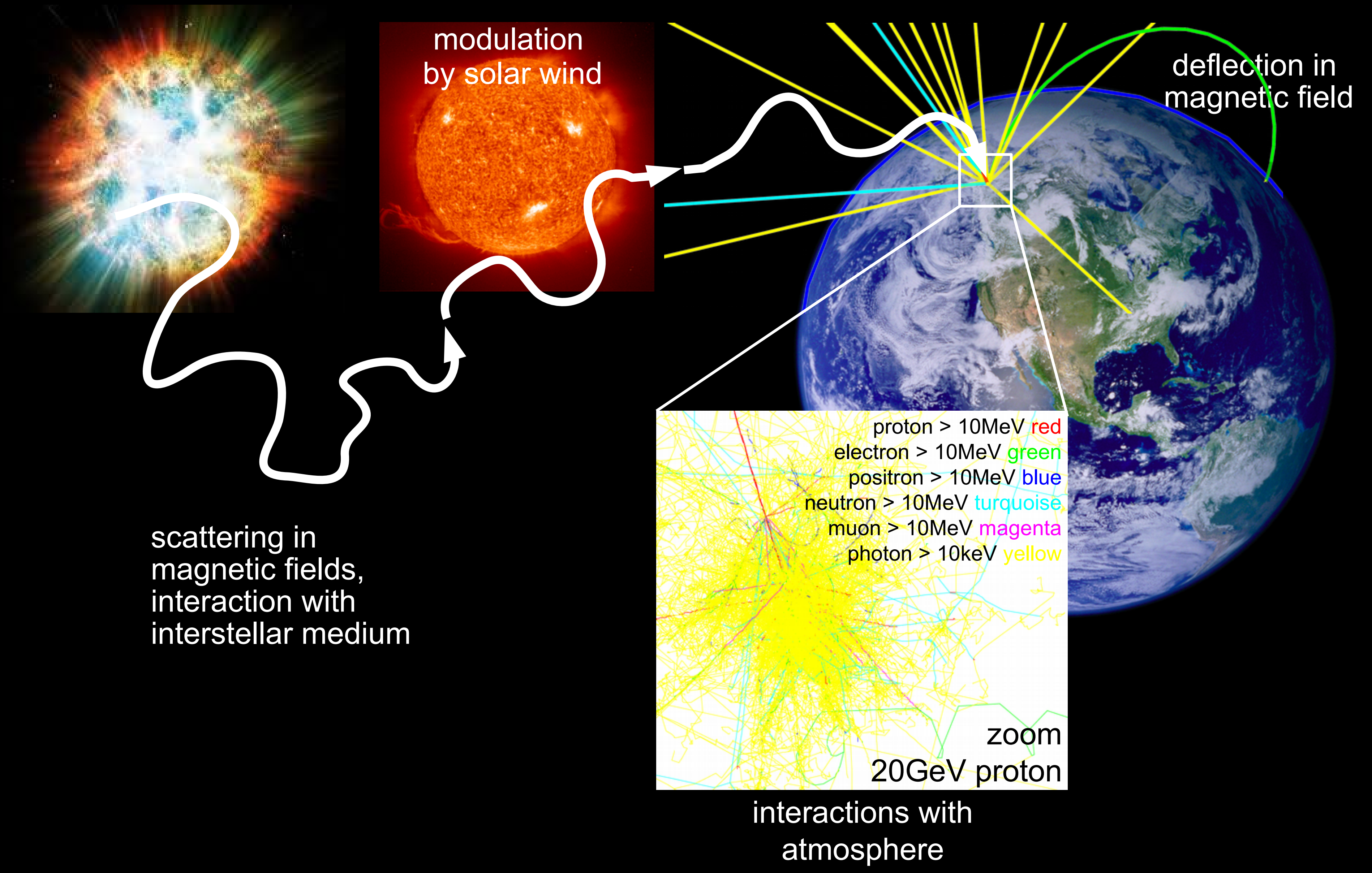
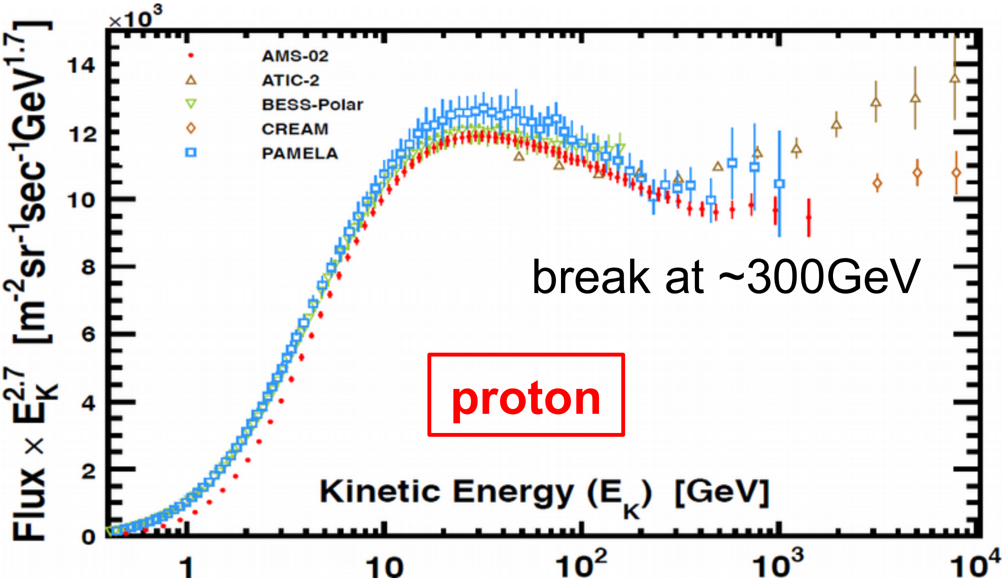
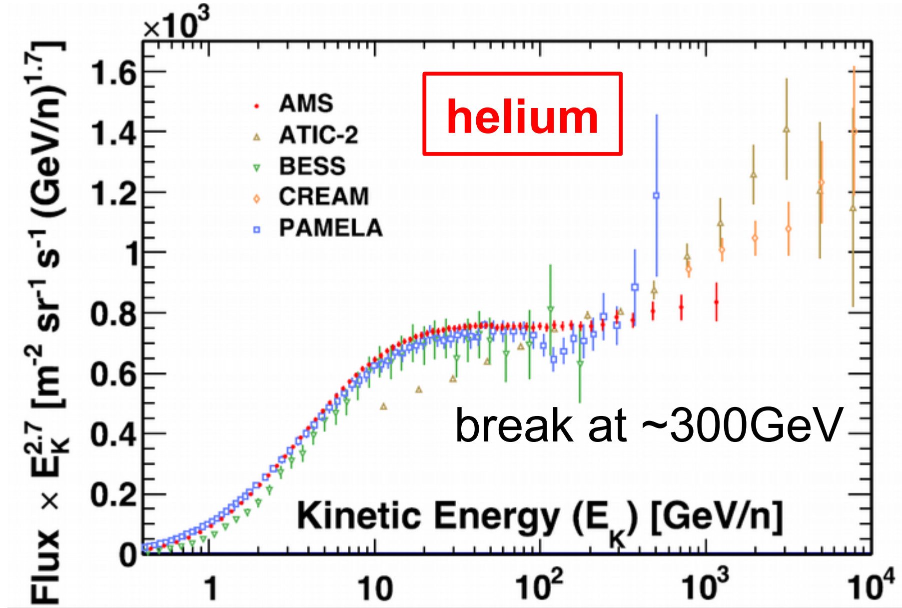
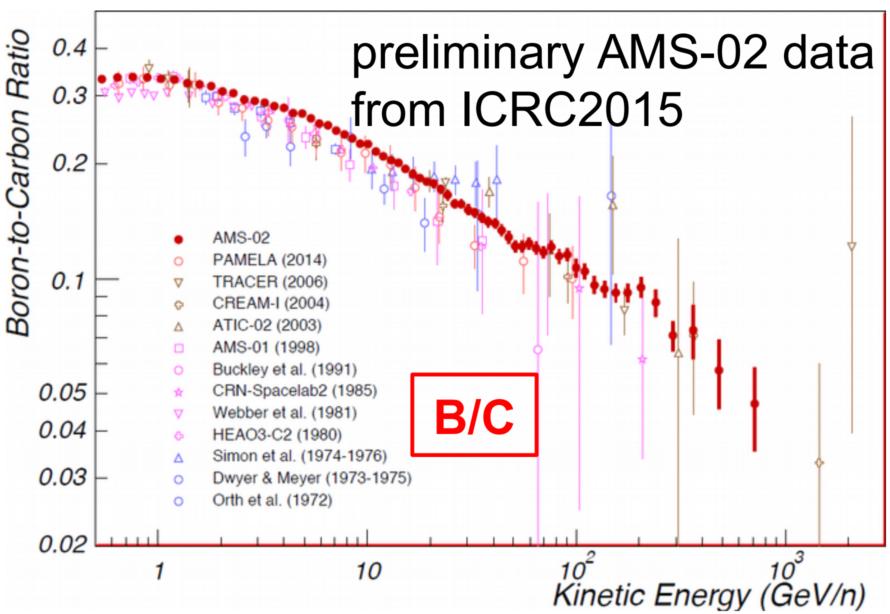
Cosmic rays as messengers

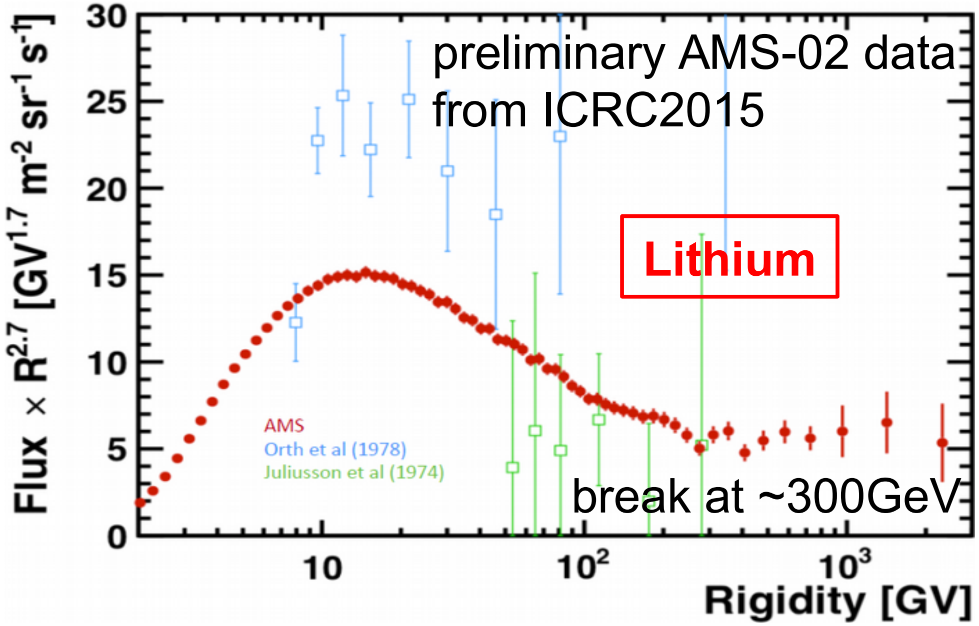


Cosmic rays 2016



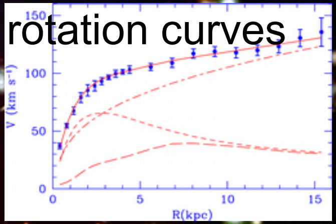


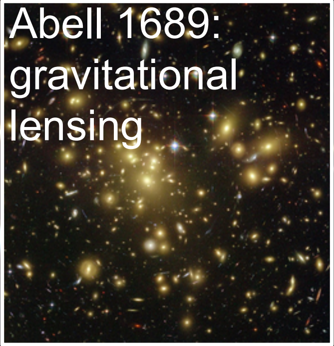


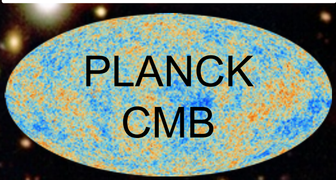


Existence of dark matter

Bullet cluster
red: hot X-ray emitting gas
blue: distribution of dark matter

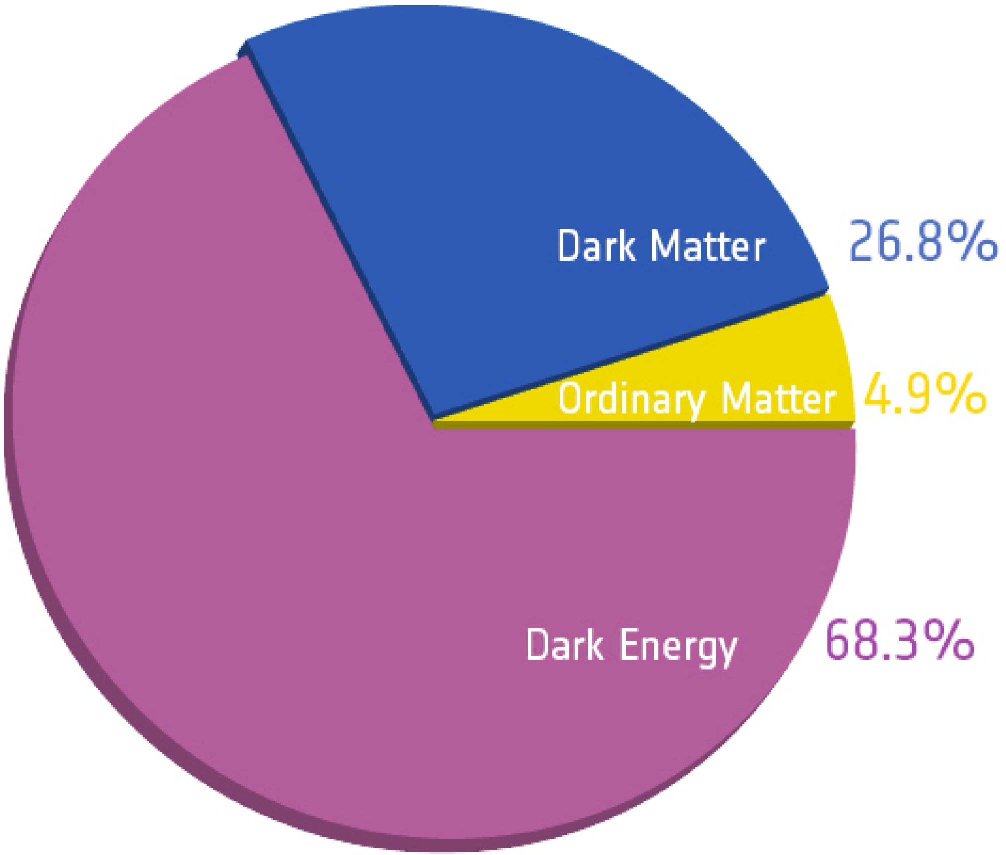






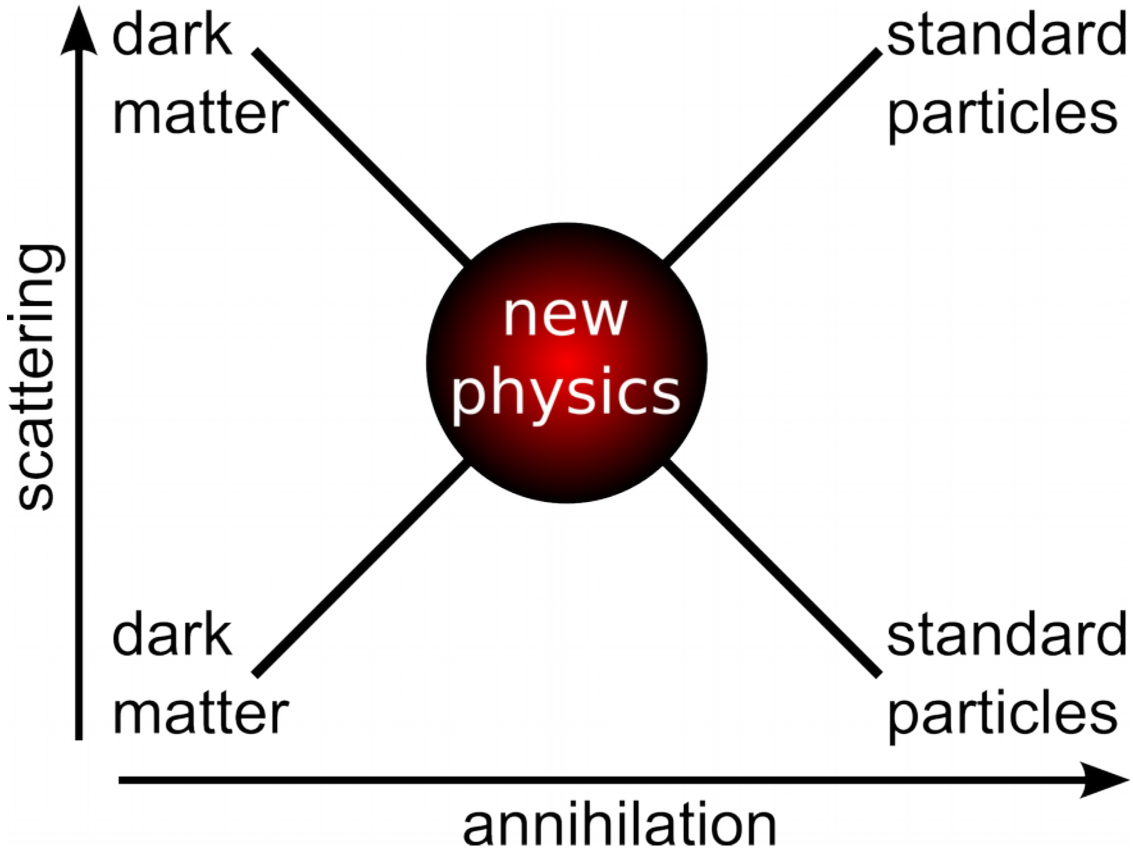
- **dark matter exists, but nature remains unknown!**
- luminous matter cannot describe the structure of the Universe
- evidence for dark matter comes from many different type of observations on different distance scales

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

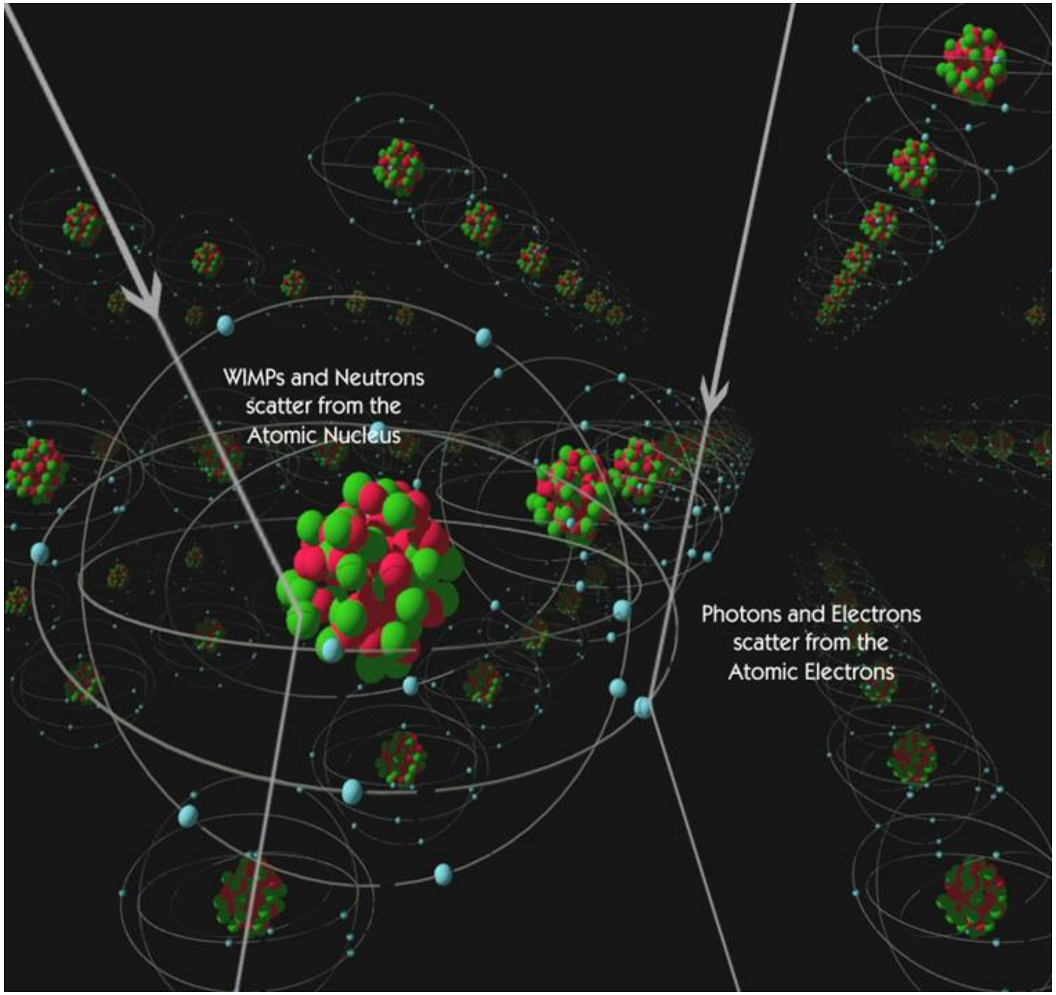
How is dark matter interacting?



- **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

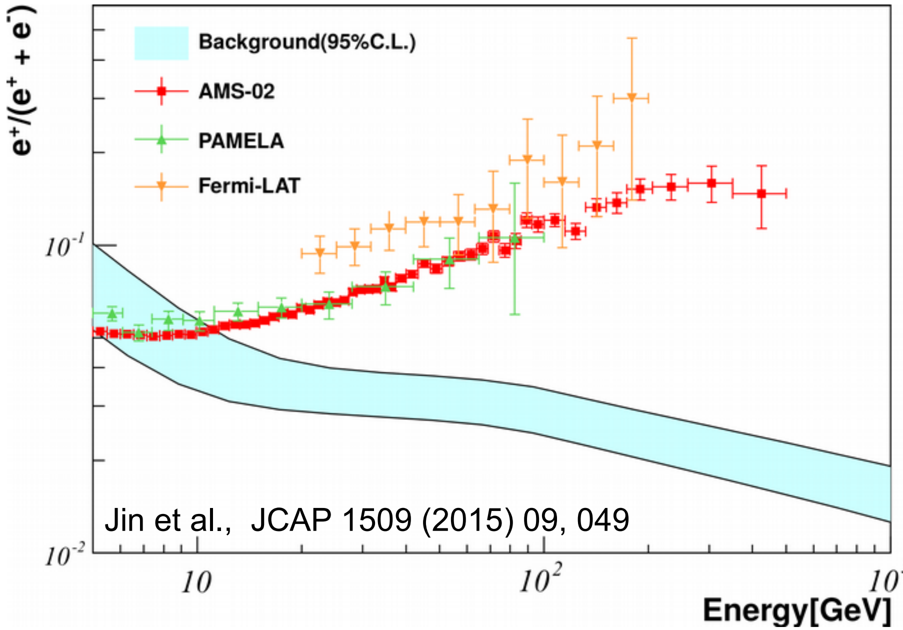
→ dark matter must(?) be able to interact with standard model particles

Direct dark matter searches (scattering)

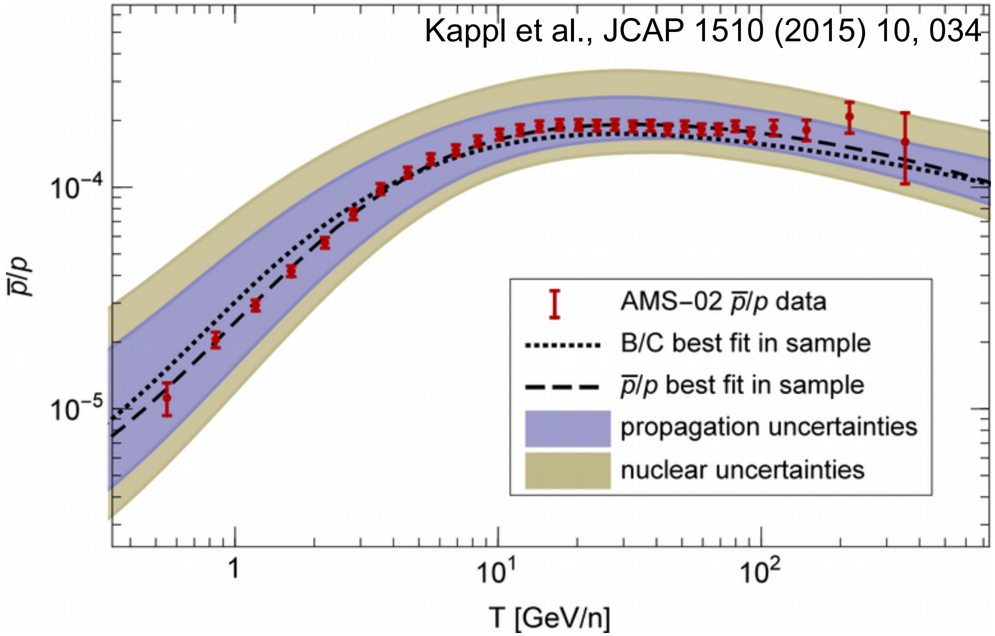


- **direct dark matter search:** measure cross-section via nuclear recoil
- typically large, heavy and very pure target materials in deep mines (~10 operating experiments)
- experiments start to reach in theoretically preferred parameter space
- **experiments disagree →** some experiments claim discovery,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

Dark matter signal in cosmic rays?



positrons

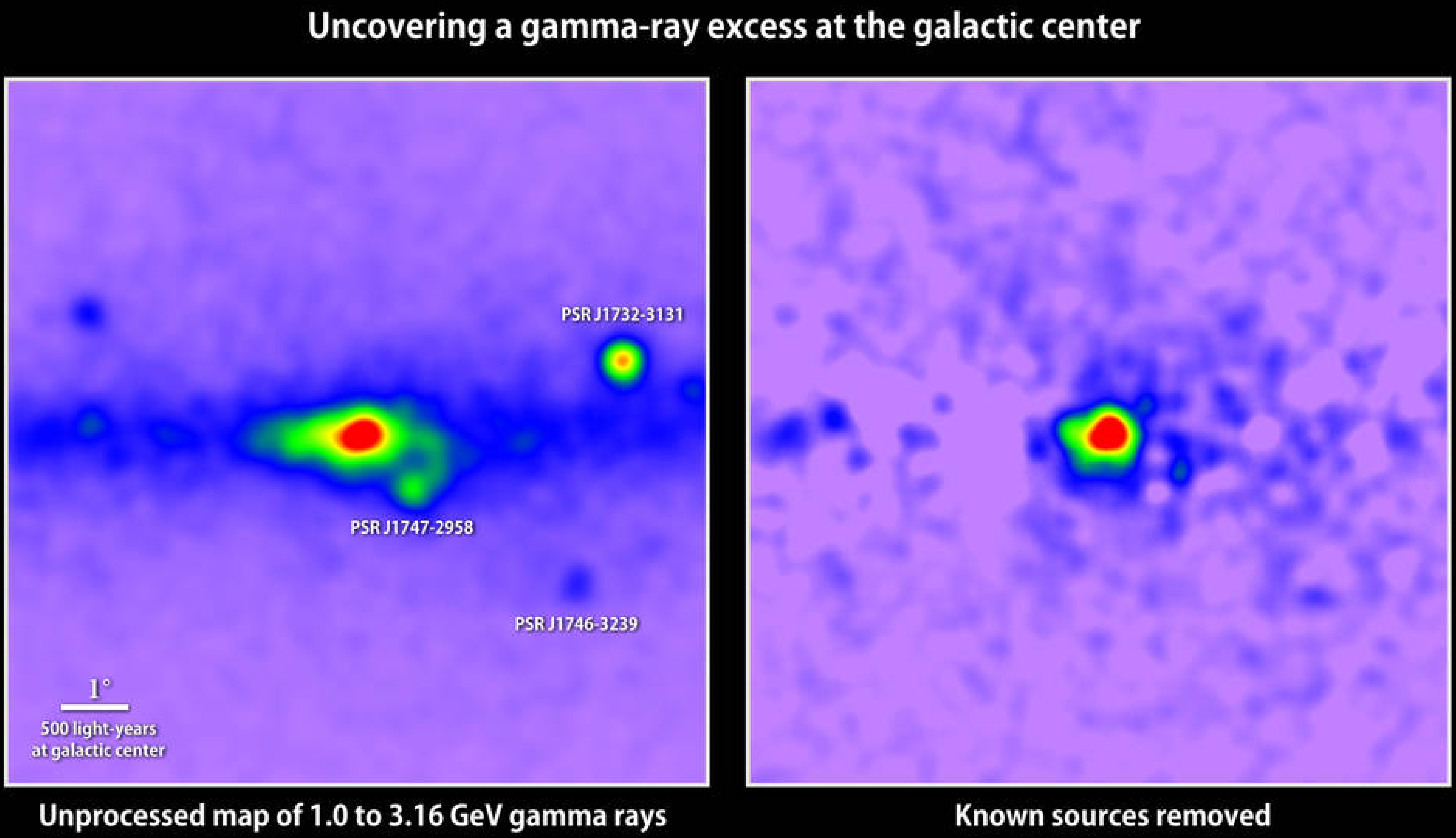


antiproton

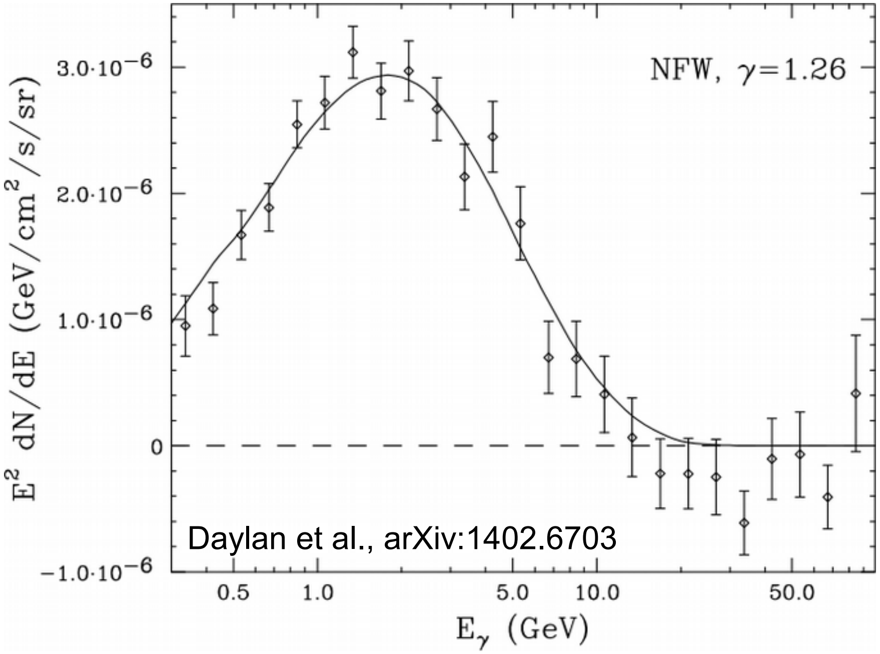
Cosmic rays from dark matter annihilation or decay could contribute to the astrophysical cosmic rays

- unexplained features in positrons
- proposed theories:
  - astrophysical origin → pulsars
  - SNR acceleration
  - **dark matter annihilation**
- **no (?) excess for antiprotons → inconclusive**

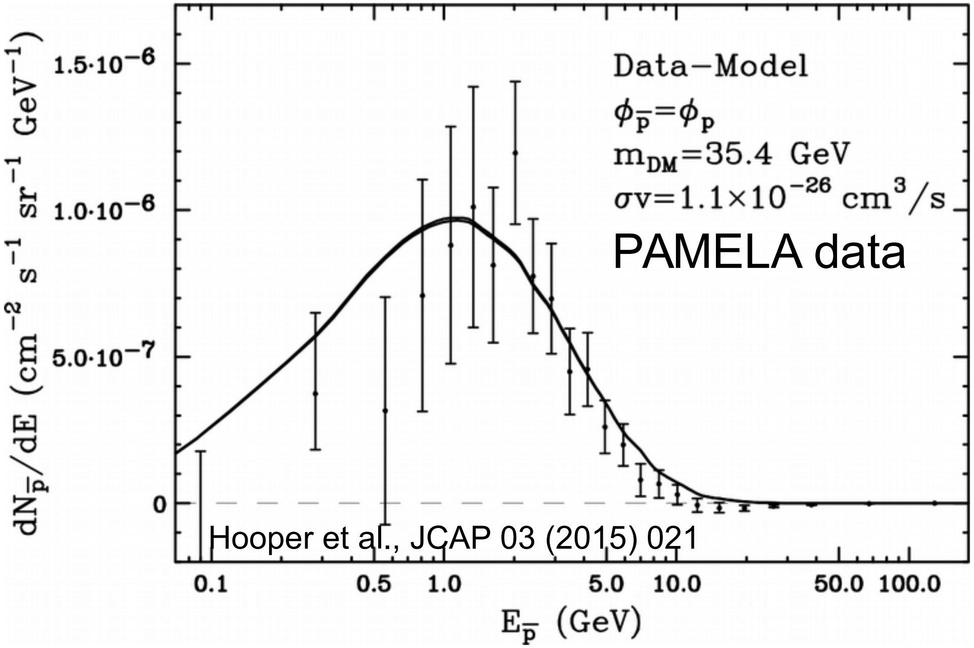
Galactic gamma-ray excess



Galactic gamma-ray excess



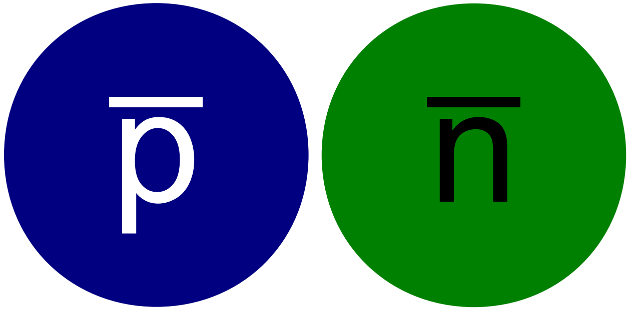
gamma-ray

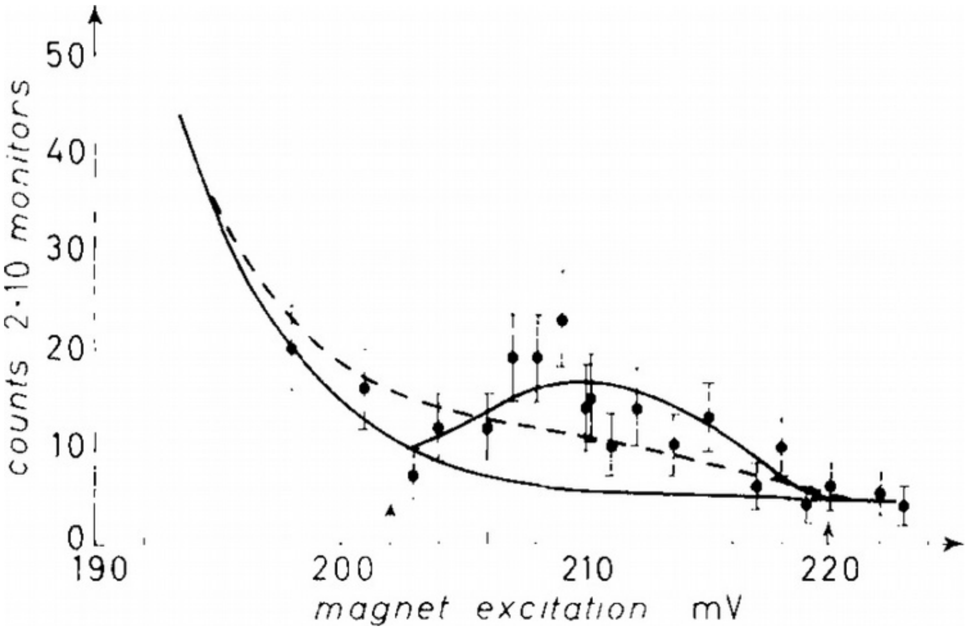


antiproton

- gamma-ray excess at the galactic center → ~30GeV dark matter particle?
- signal in low-energy antiprotons?
- understanding of astrophysical background is a big challenge

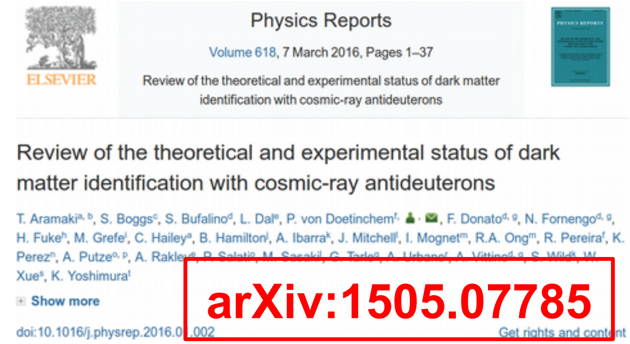
Antideuterons





- 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 (bound) 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


Physics Reports
Volume 618, 7 March 2016, Pages 1–37
Review of the theoretical and experimental status of dark matter identification with cosmic-ray antideuterons

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

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. Rakley[q], … W. Xue[s], K. Yoshimura[t]

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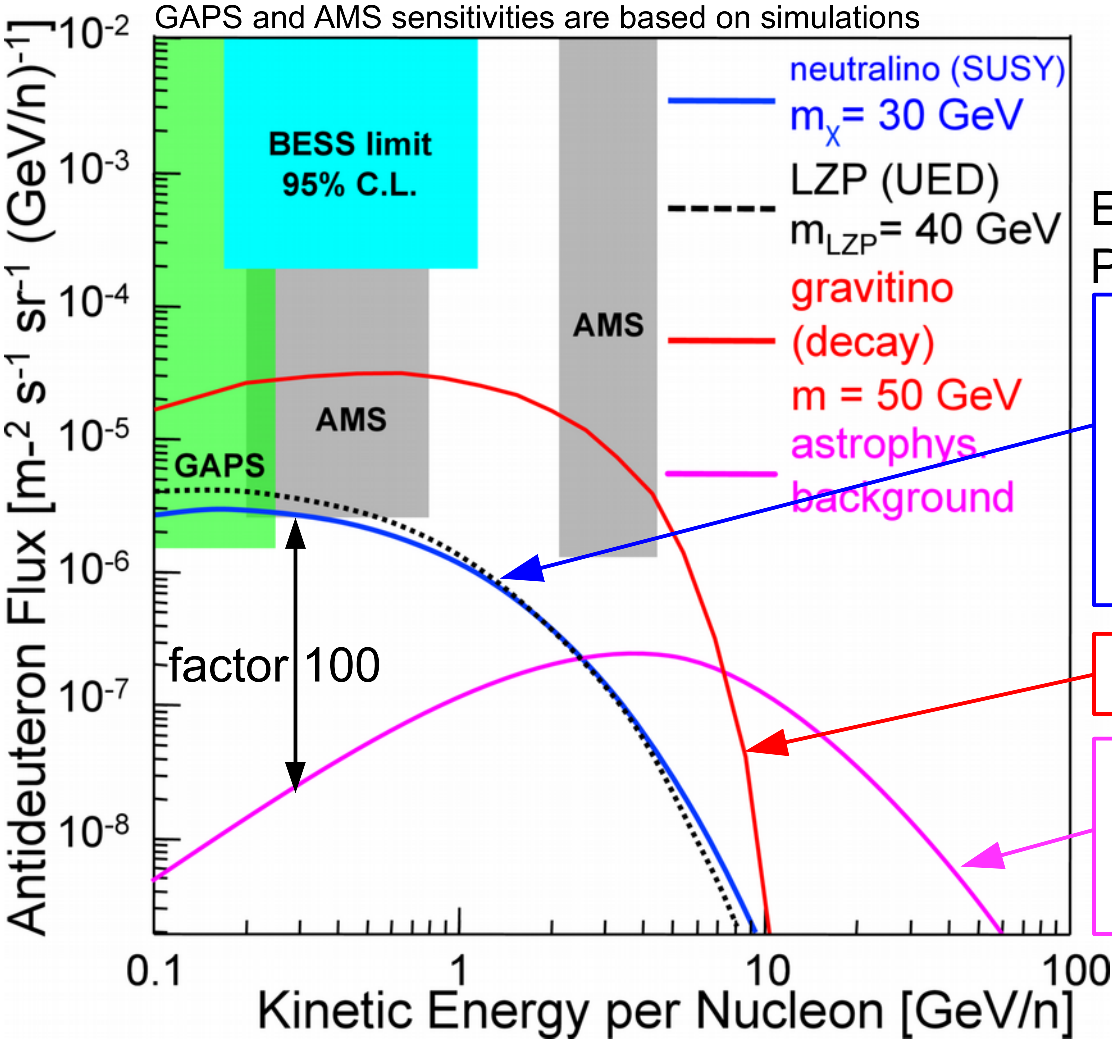


Examples for beyond-standard-model Physics (compatible with $\bar{p}$):

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

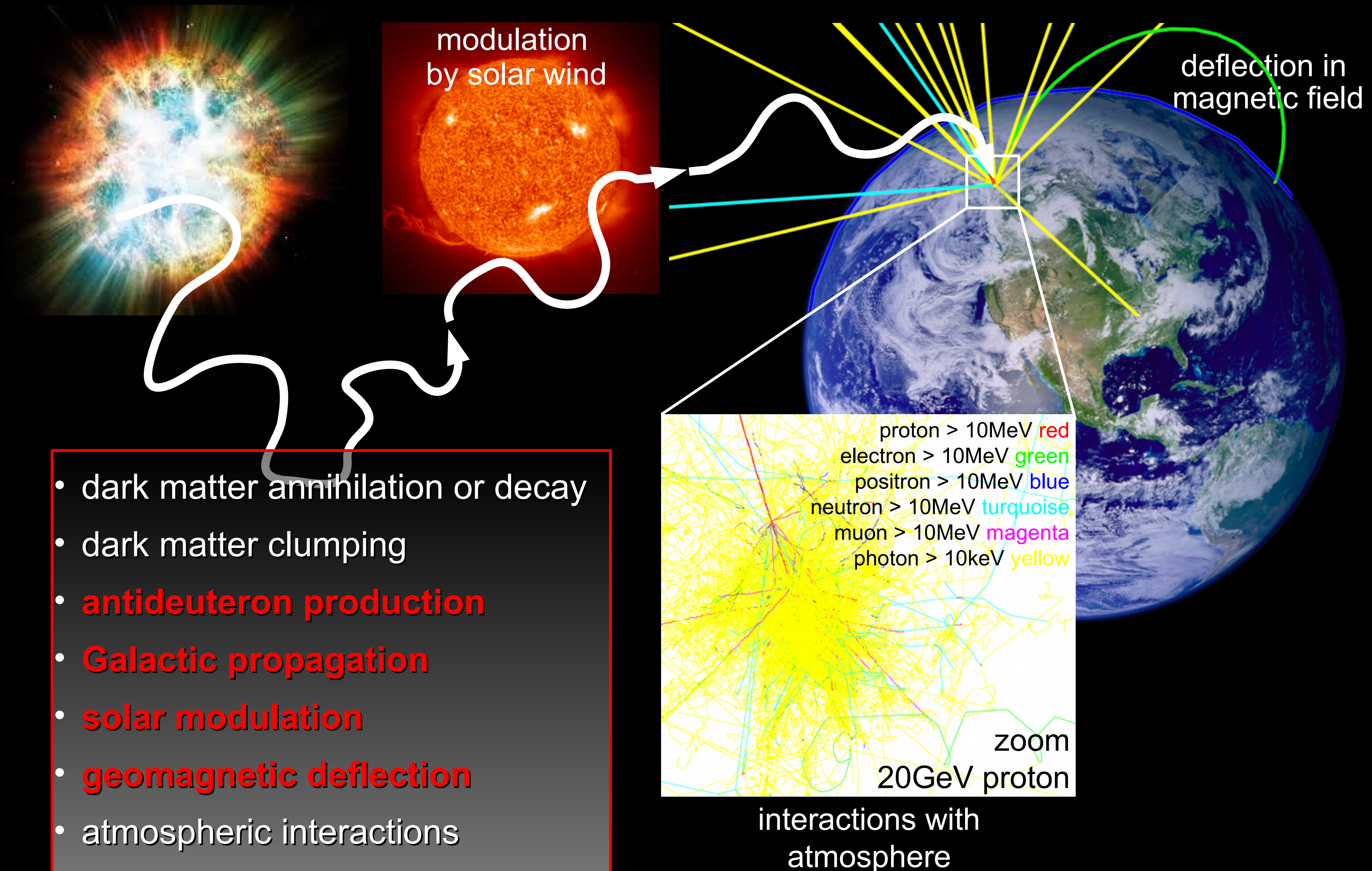
late decays of unstable gravitinos

astrophysical background:
collisions of protons and antiprotons with interstellar medium

+ models with heavy dark matter

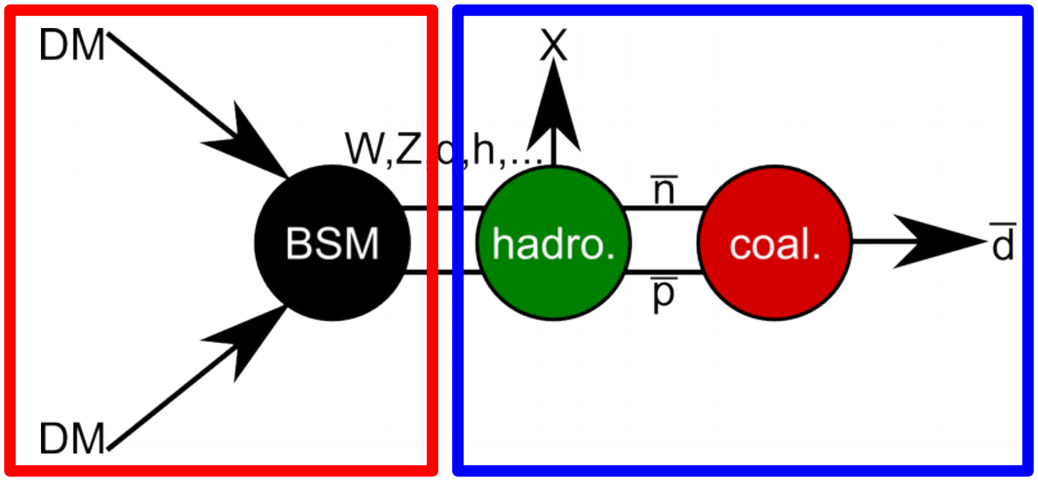
Antideuterons are the most important unexplored indirect detection technique!

Uncertainties



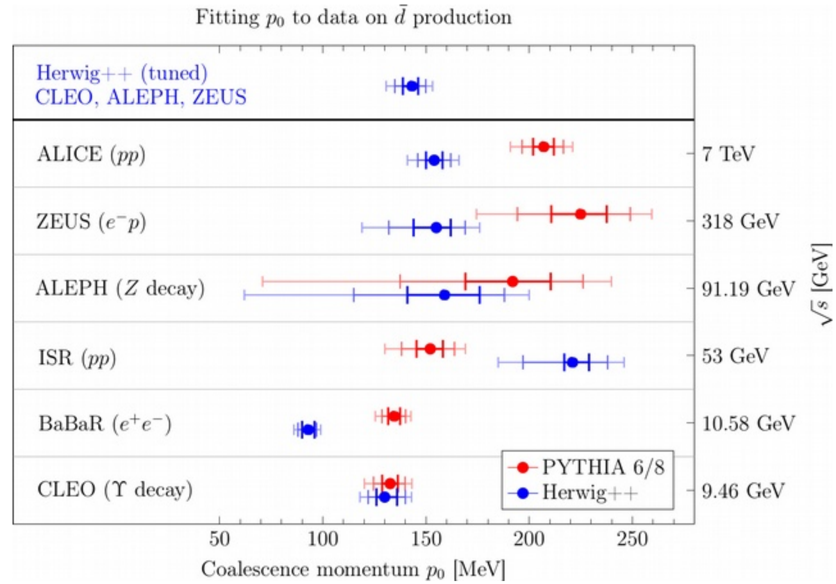
- dark matter annihilation or decay
- dark matter clumping
- **antideuteron production**
- **Galactic propagation**
- **solar modulation**
- **geomagnetic deflection**
- atmospheric interactions
- **interactions in detector**

Antideuteron formation



dark matter

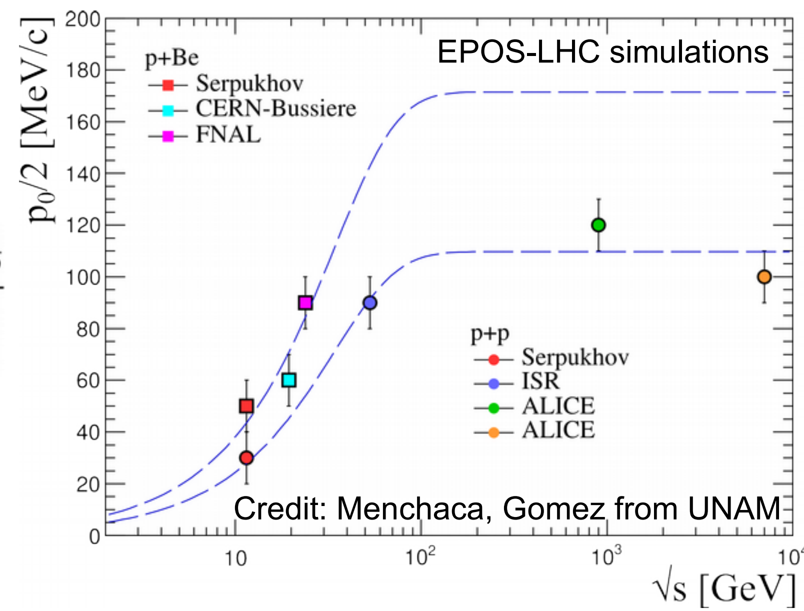
conventional production (e.g., p+ISM) & dark matter



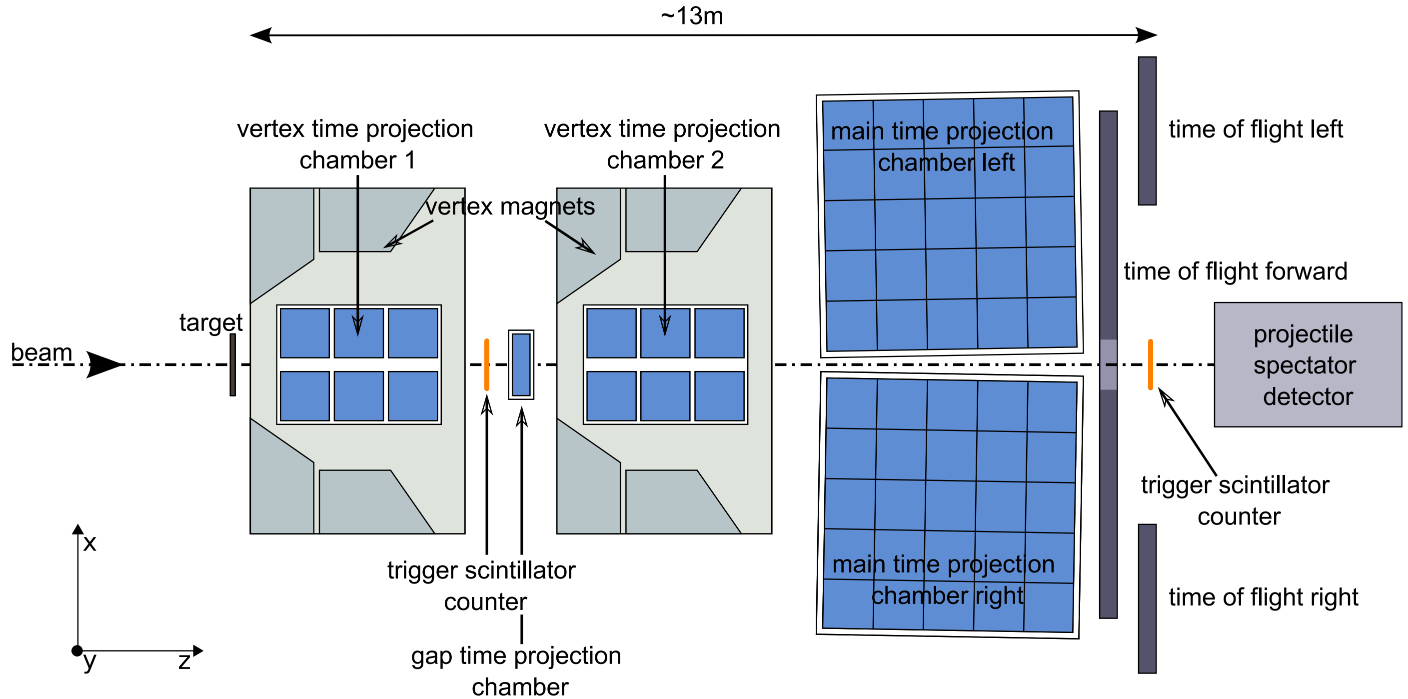
- $\bar{d}$ can be formed by an $\bar{p}$-$\bar{n}$ pair if coalescence momentum p_0 is small

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

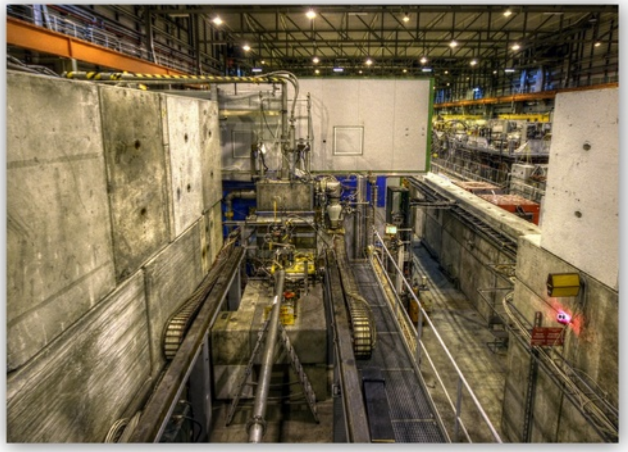
- **important differences for different experiments and MC generators exist → more data would help**

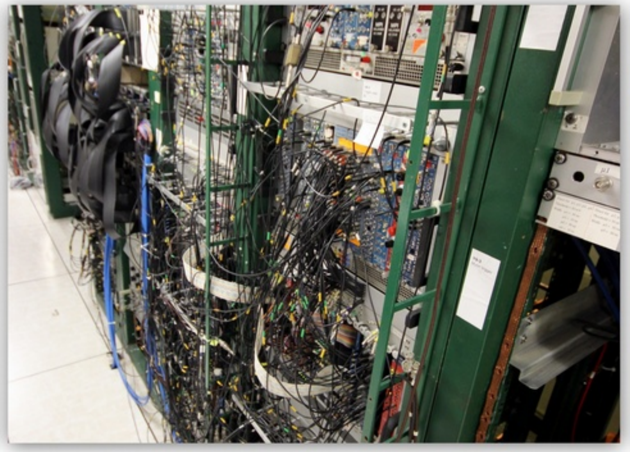


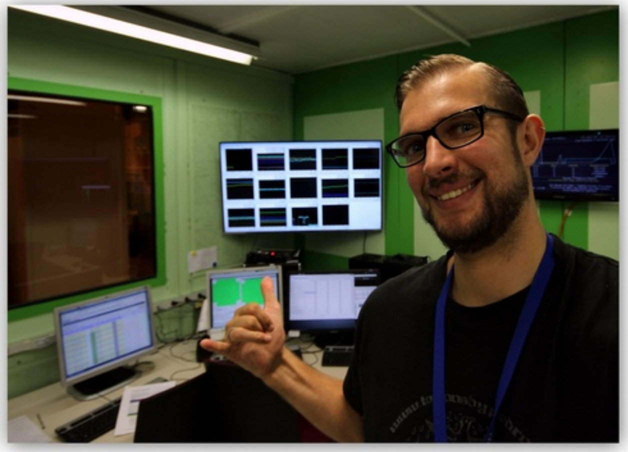
(Anti)deuterons and NA61/SHINE



- cosmic ray production happens between 40 and 400 GeV → SPS energies from 9 to 400 GeV are ideal
- we are working on (anti)deuteron and antiproton analysis

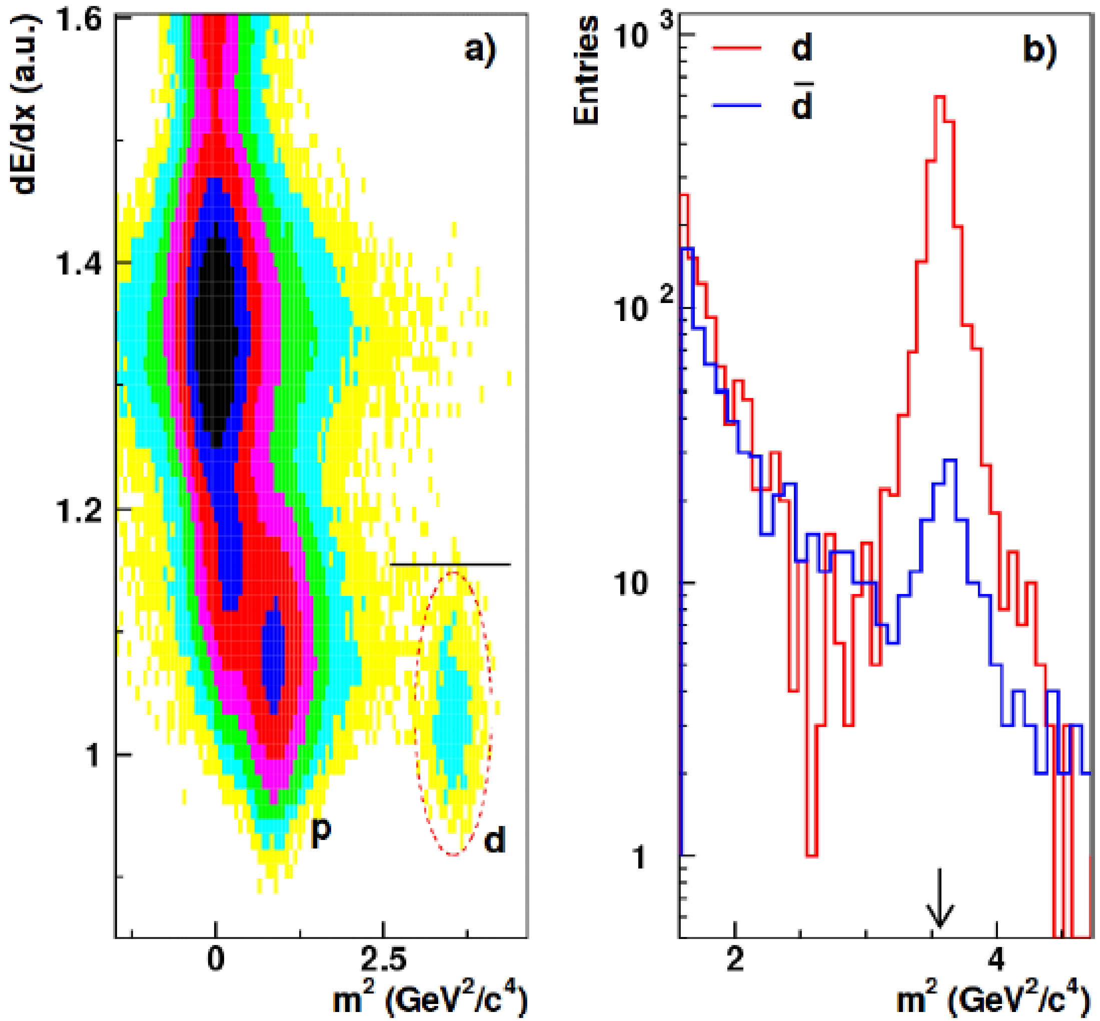






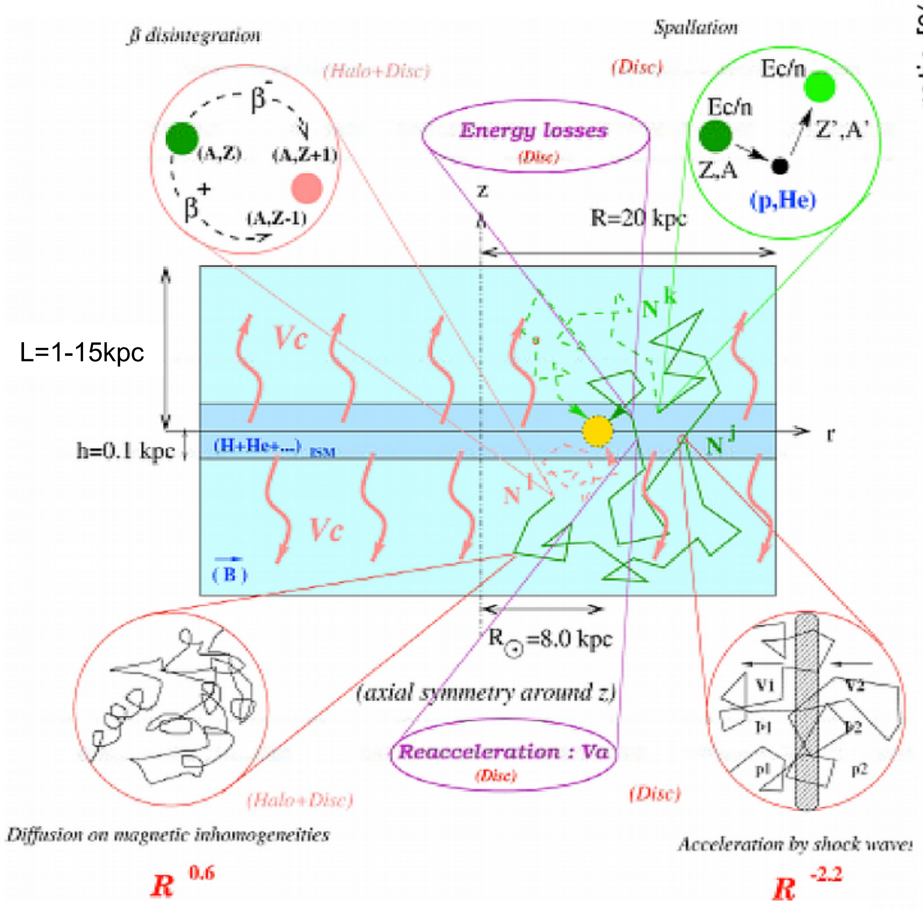
NA49 antideuterons

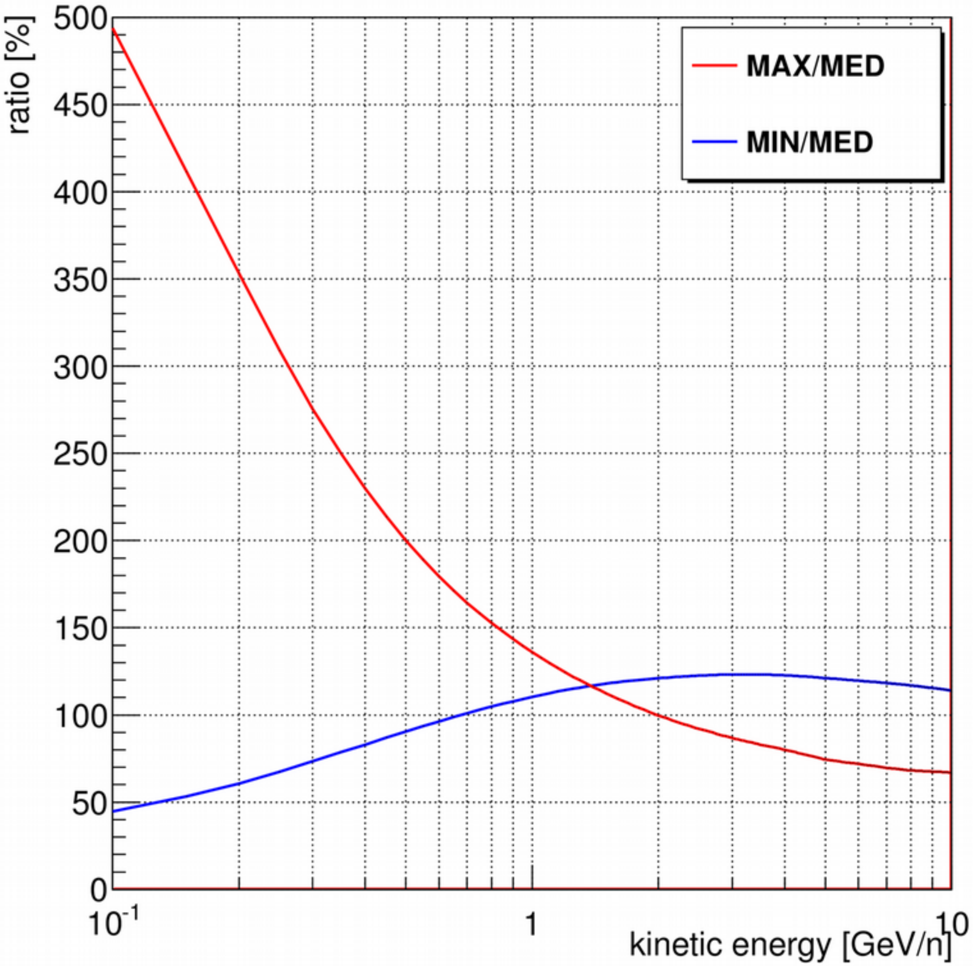
- NA49 is pre-decessor experiment
- NA49 lead-lead data were already analyzed for antideuterons
- important cross-check for the MC generators: measurement of the yield of antiprotons with the same data



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

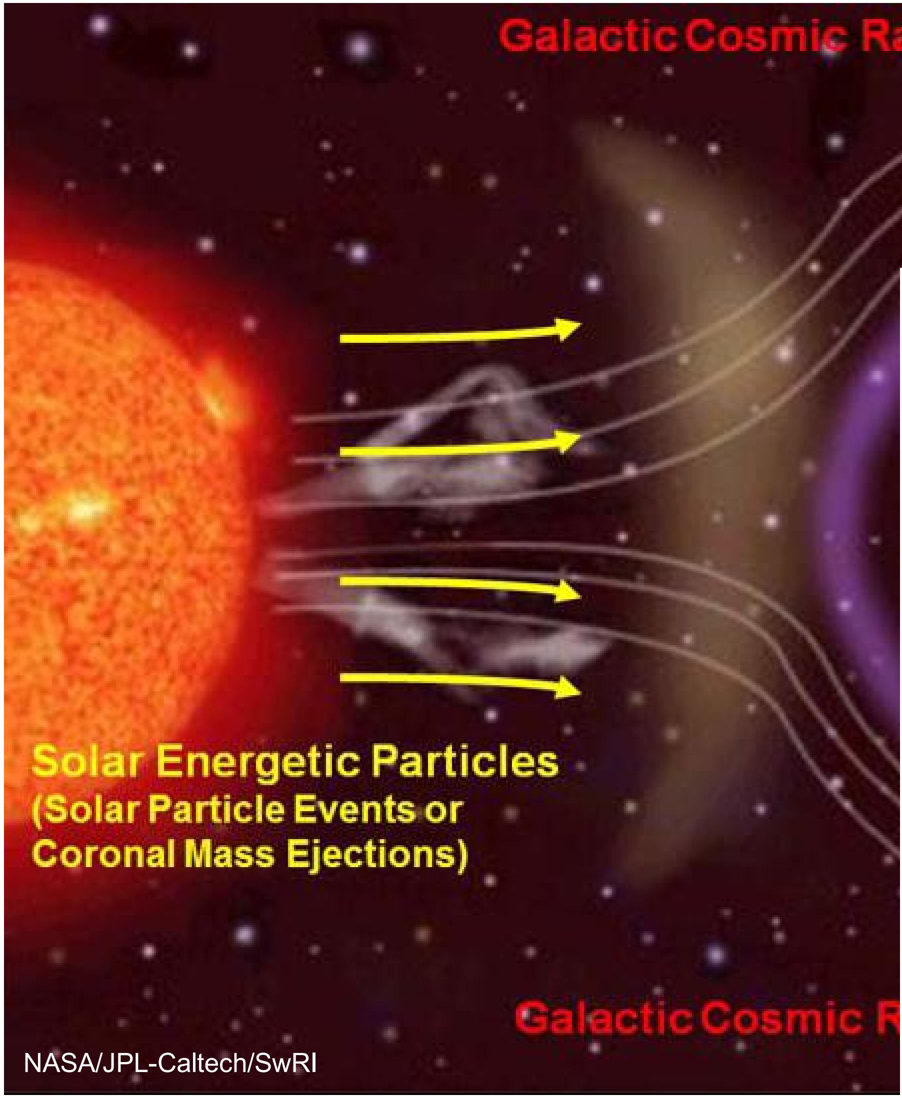
Propagation uncertainty

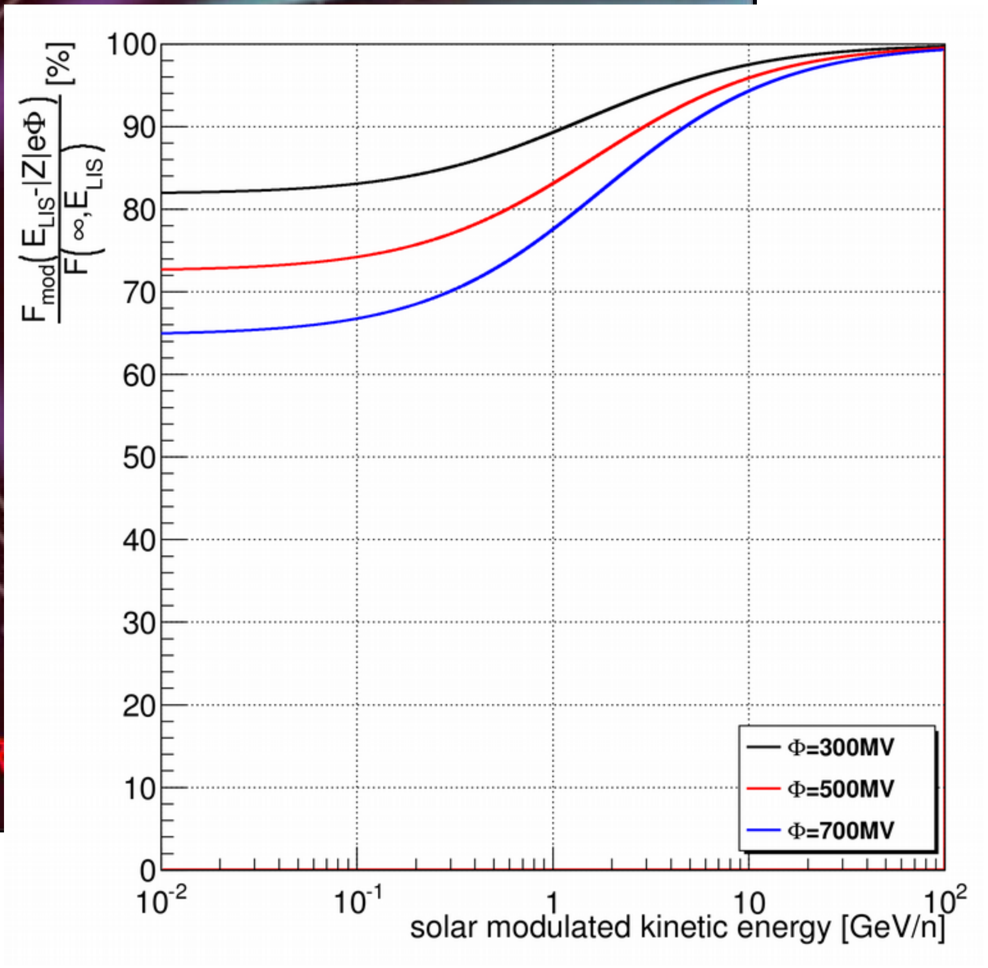




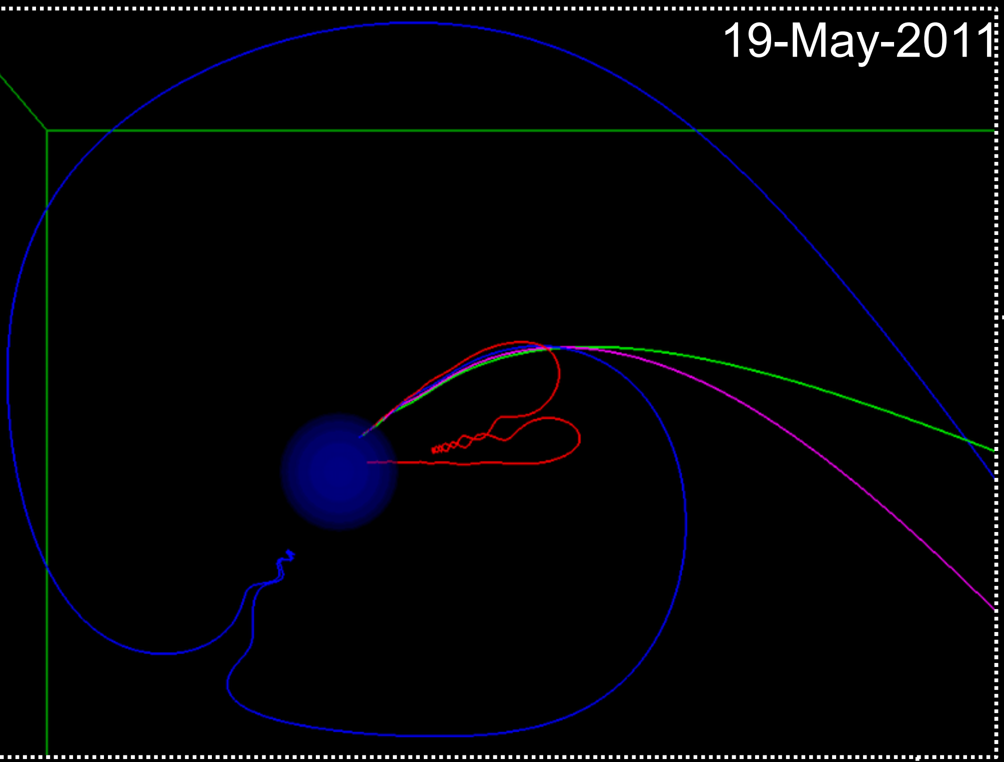
- propagation is the strongest uncertaintiy source for primary antideuterons:
  halo size for diffusion calculation poorly constrained
- more data on various nuclear speces are needed for better constraints

Solar modulation

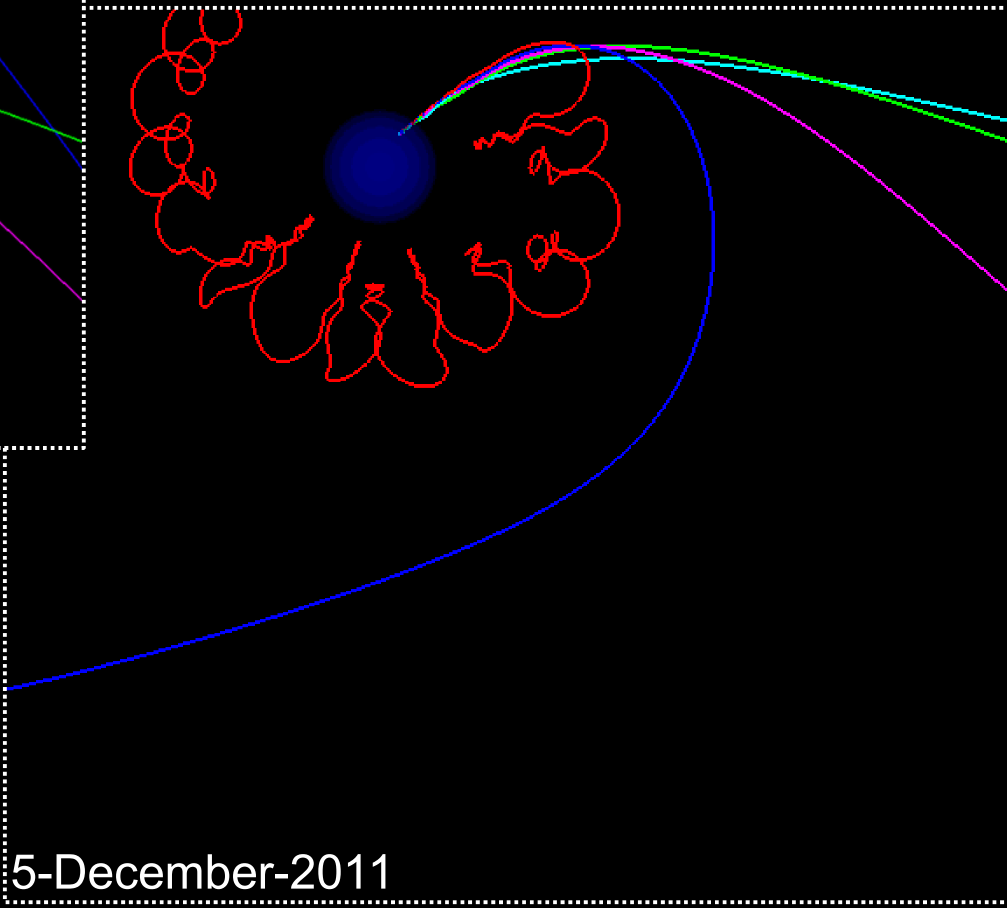




Geomagnetic cutoff



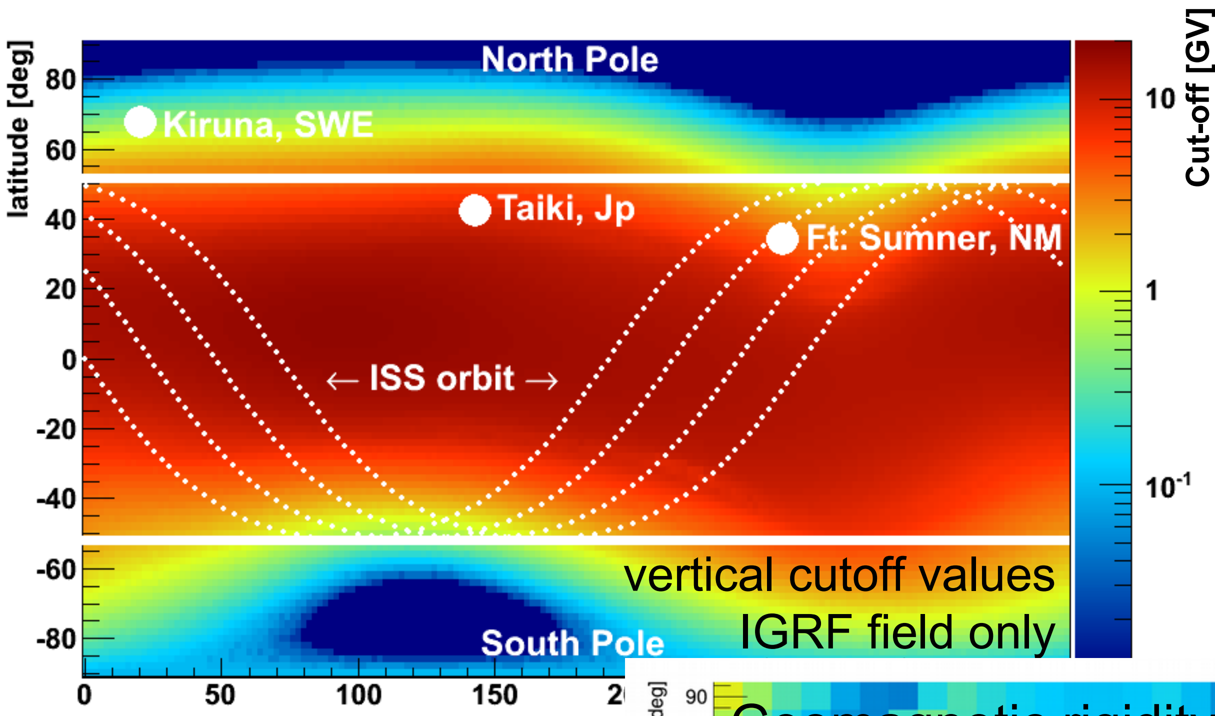
Red: 0.5GV
Blue: 1.0GV
Magenta: 1.5GV
Green: 2.0GV
Cyan: 2.5GV

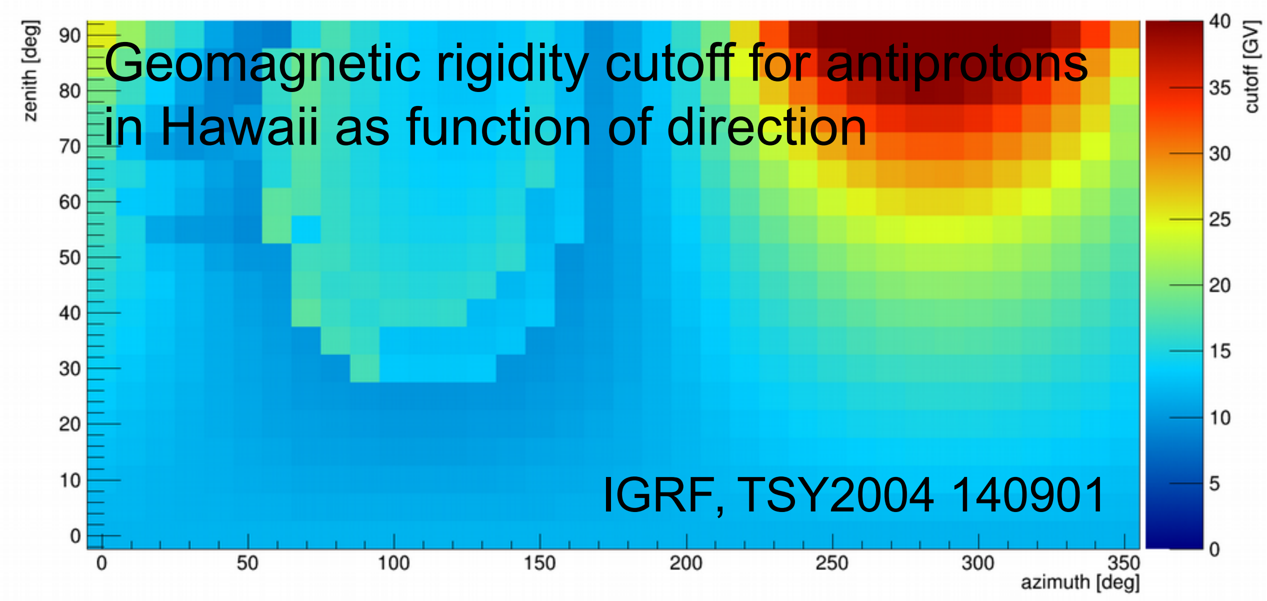


Reverse computation of antiproton trajectories starting at the same location in the same direction for two different times

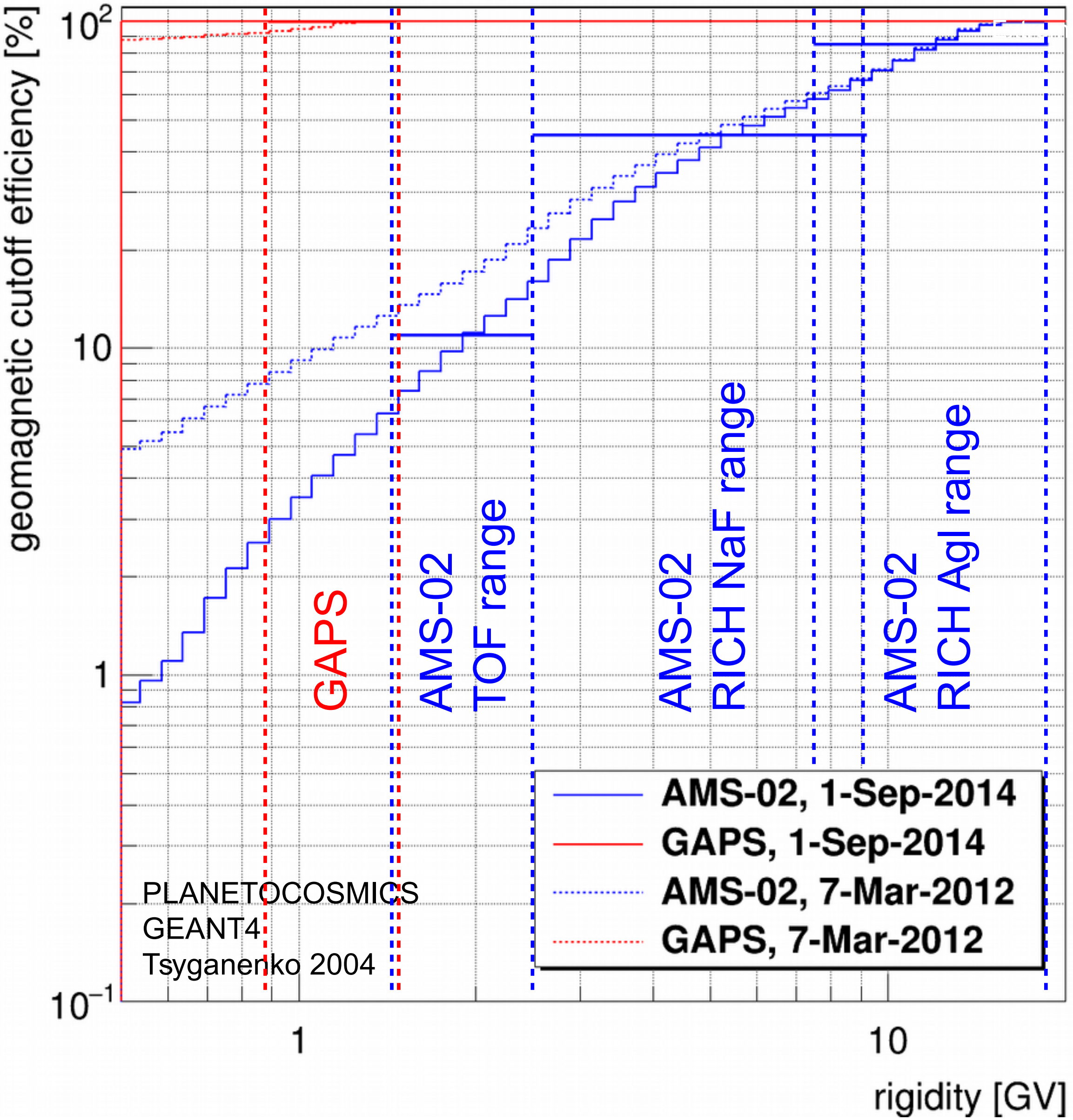
→ magnetic environment change changes the trajectories drastically and influences the cutoff values

Geomagnetic cutoff



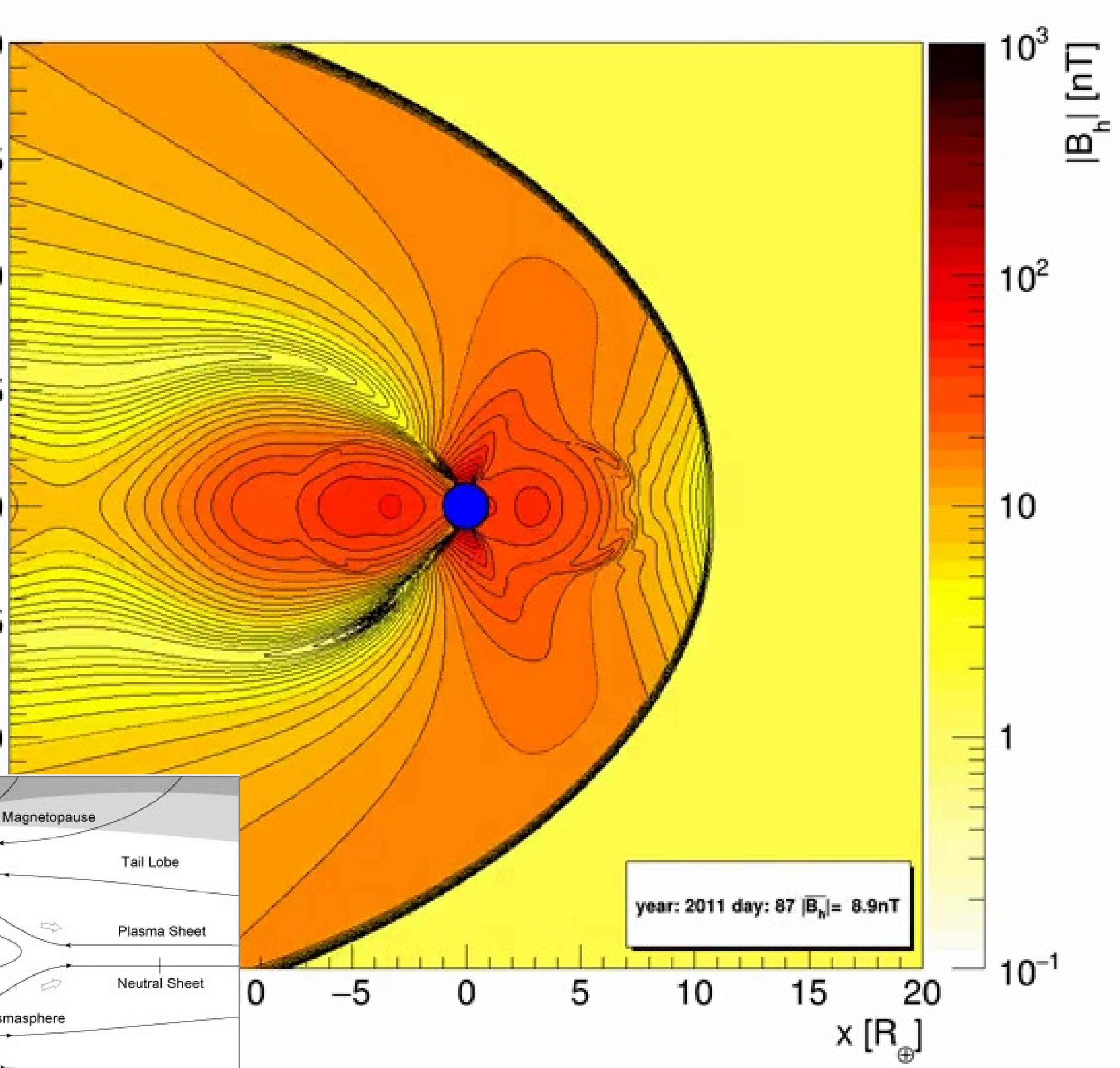


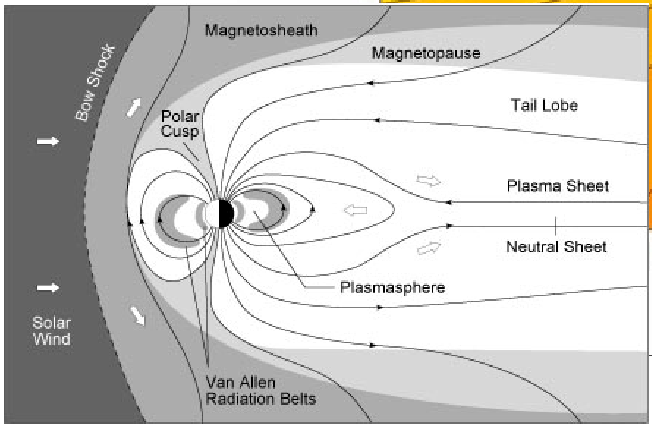
Geomagnetic cutoff for AMS-02 and GAPS



- geomagnetic environment is influenced by solar activity
- AMS-02 is installed on the ISS (latitude ±52°)
  → understanding of geomagnetic environment crucial for low energies
- GAPS is planned to fly from Antarctica (~-80°)
  → geomagnetic corrections are minimal

Magnetic field changes since 2011





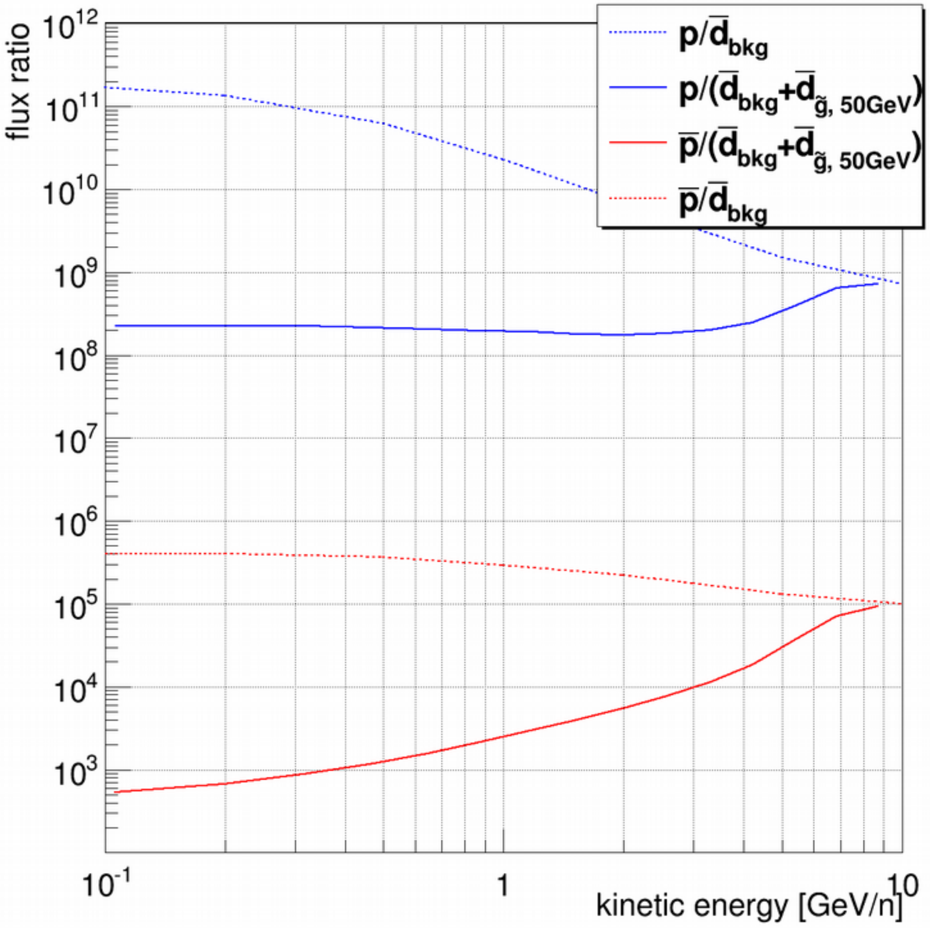
Identification challenge

Required rejections for antideuteron detection:

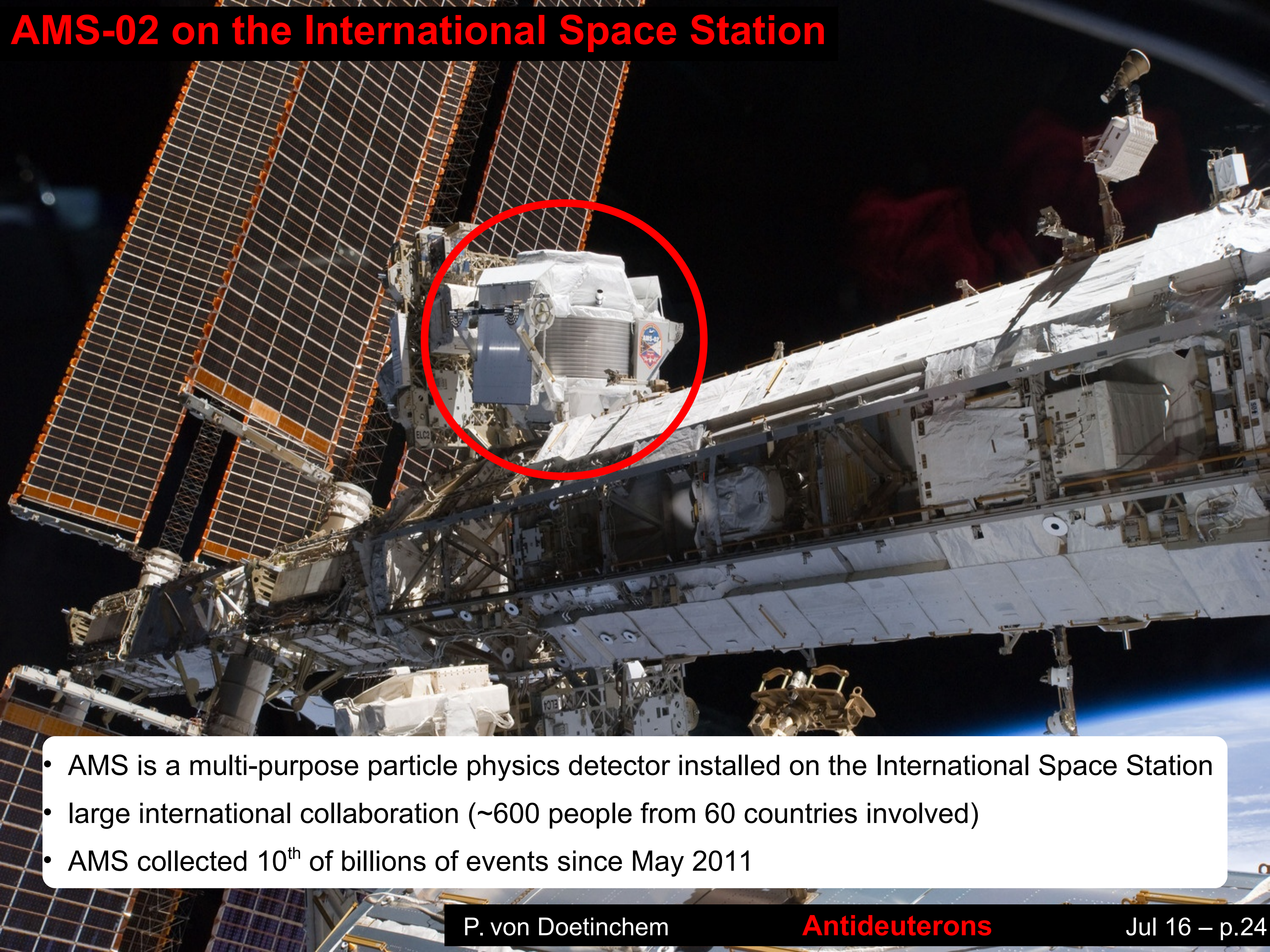
- **protons**: > 10^8 - 10^{10}
- **He-4**: > 10^7 - 10^9
- **electrons**: > 10^6 - 10^8
- **positrons**: > 10^5 - 10^7
- **antiprotons**: > 10^4 - 10^6

Antideuteron measurement with balloon and space experiments require:

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



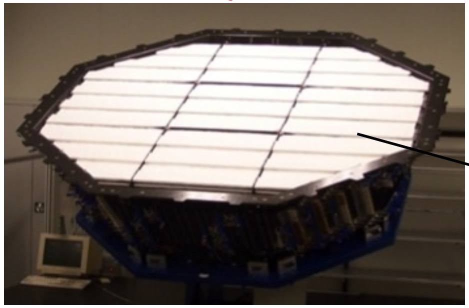
AMS-02 on the International Space Station



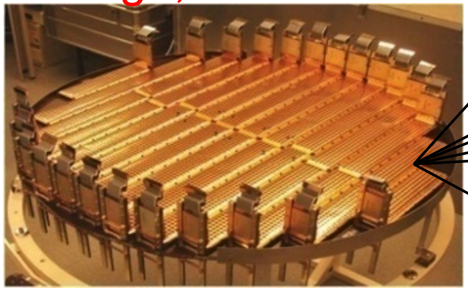
- AMS is a multi-purpose particle physics detector installed on the International Space Station
- large international collaboration (~600 people from 60 countries involved)
- AMS collected 10^{th} of billions of events since May 2011

AMS sub-detectors

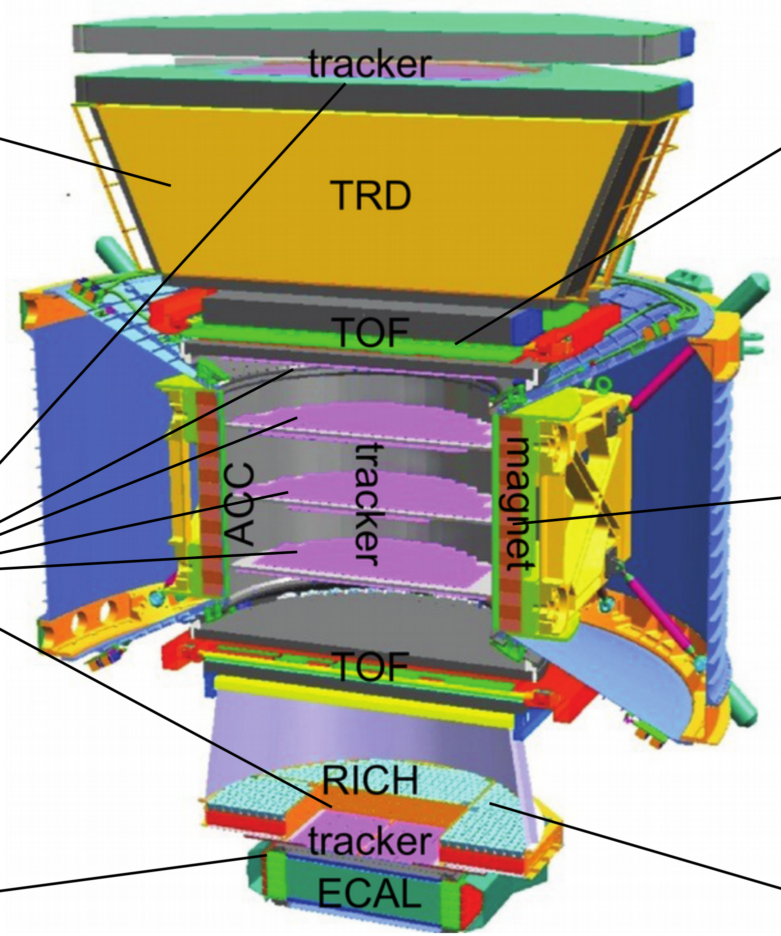
TRD
identify e+,e-



Silicon tracker
charge, momentum

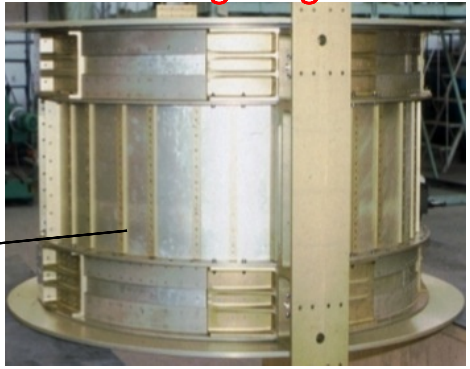


ECAL
energy of e+, e-, γ

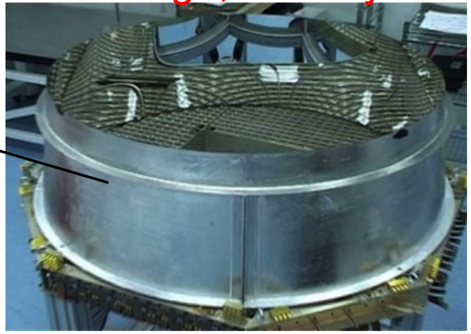


TOF
charge, velocity

magnet
charge sign

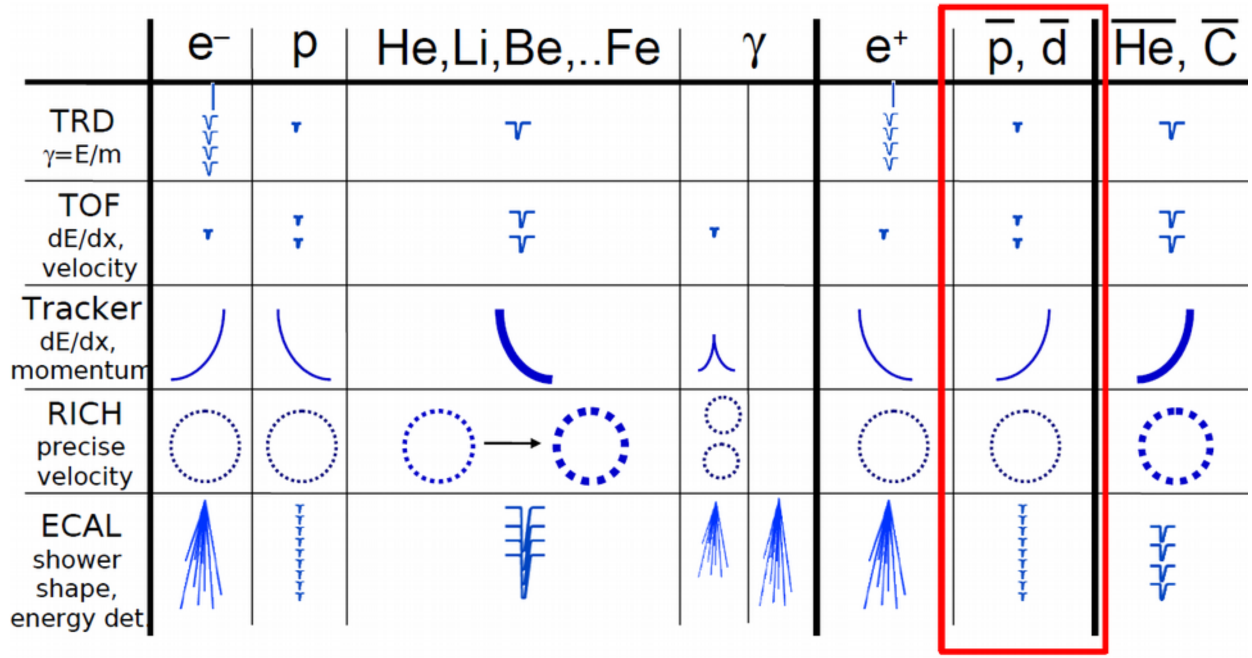


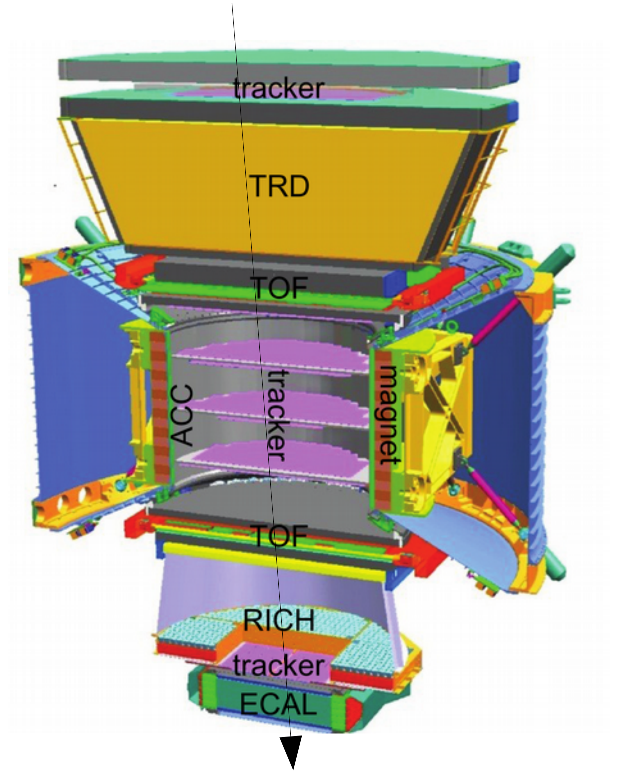
RICH
charge, velocity



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

AMS antideuteron analysis



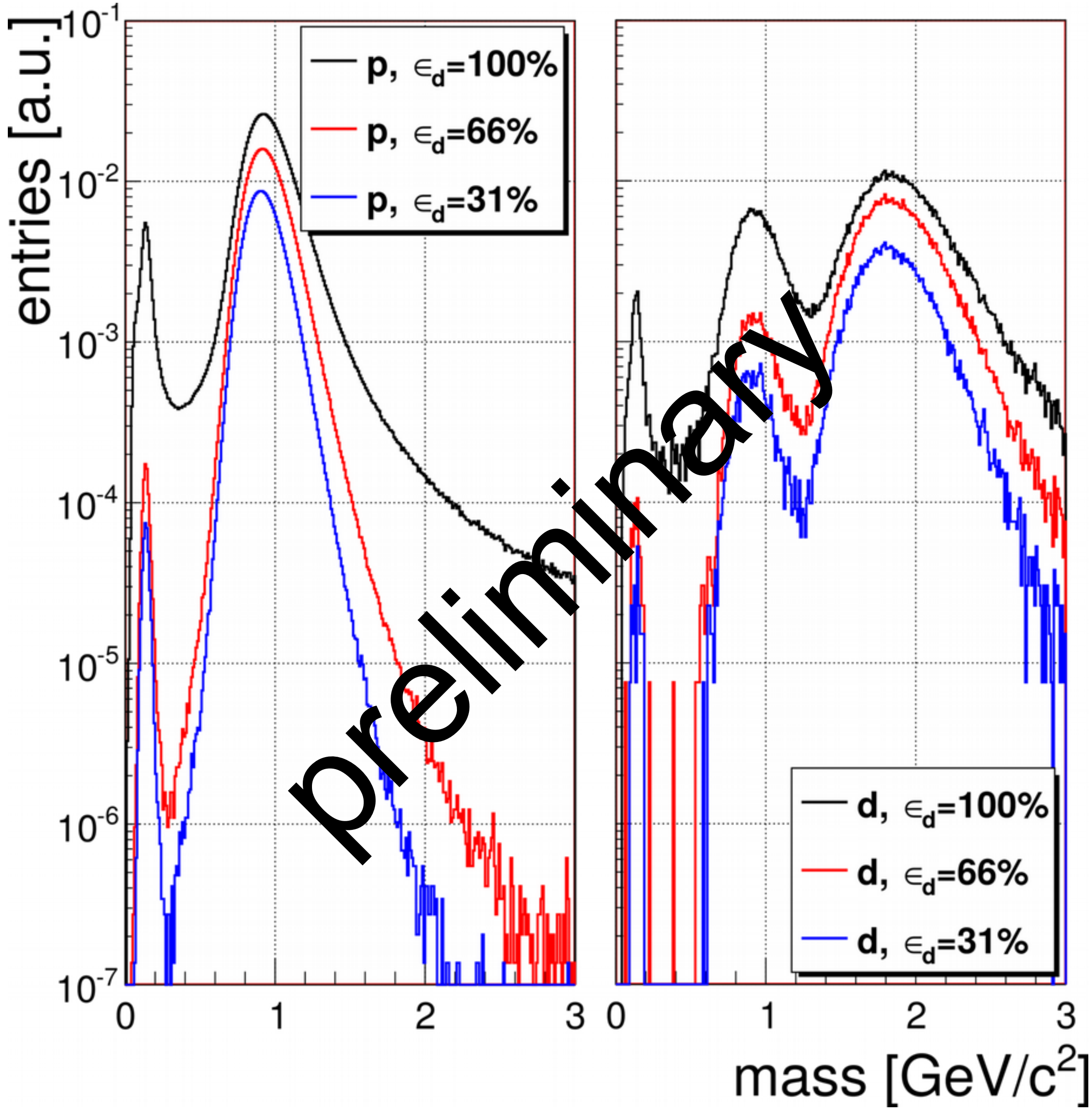


- **antideuteron identification:**
  - –momentum measured in the form of rigidity
  - –charge from TOF, TRD, tracker
  - –lower velocities: **T**ime **O**f **F**light scintillator system
  - –higher velocities: **R**ing **I**mage **Ch**erenkov detector

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

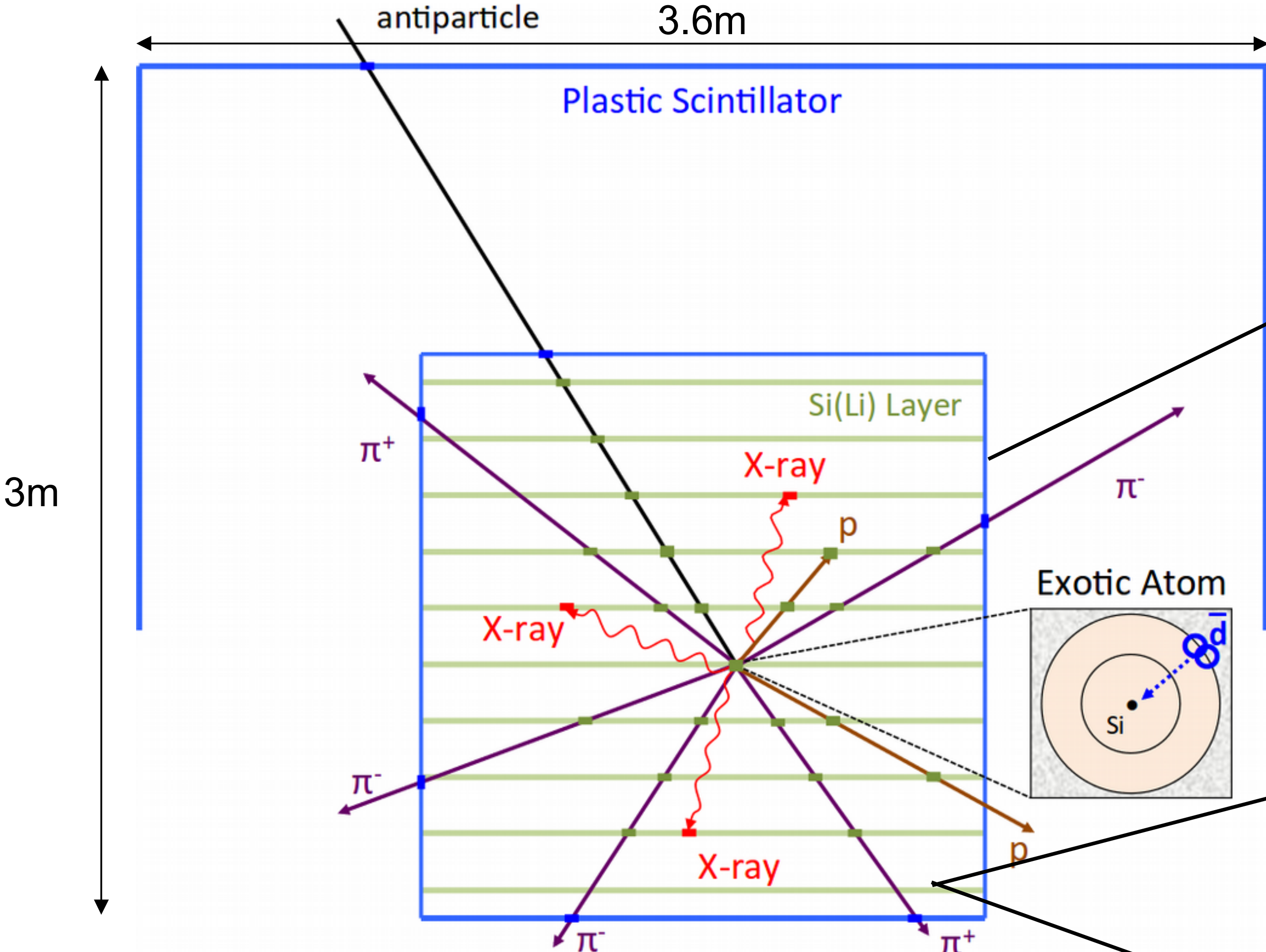
- **self-calibrated analysis:**
  - –calibrate antideuteron analysis with deuterons and antiprotons (simulations and data)
  - –geomagnetic cut-off location is challenging: study low-energy protons and electrons to calibrate geomagnetic and solar effects

Example for proton and deuteron mass reconstruction



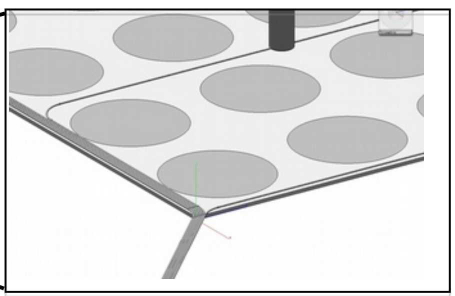
The GAPS experiment

Columbia U, UC Berkeley
UCLA, U Hawaii,
Haverford



plastic scintillators with PMT readout

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

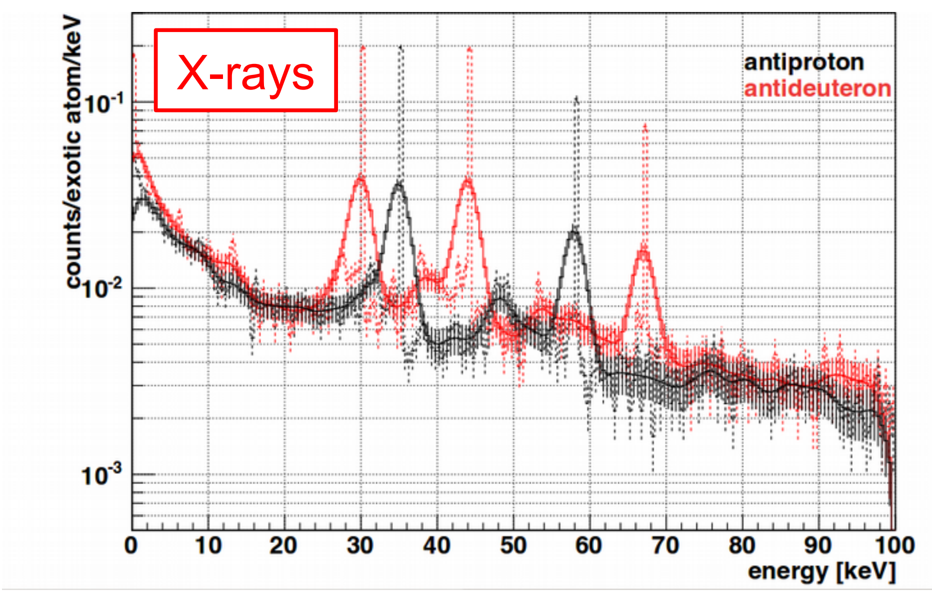


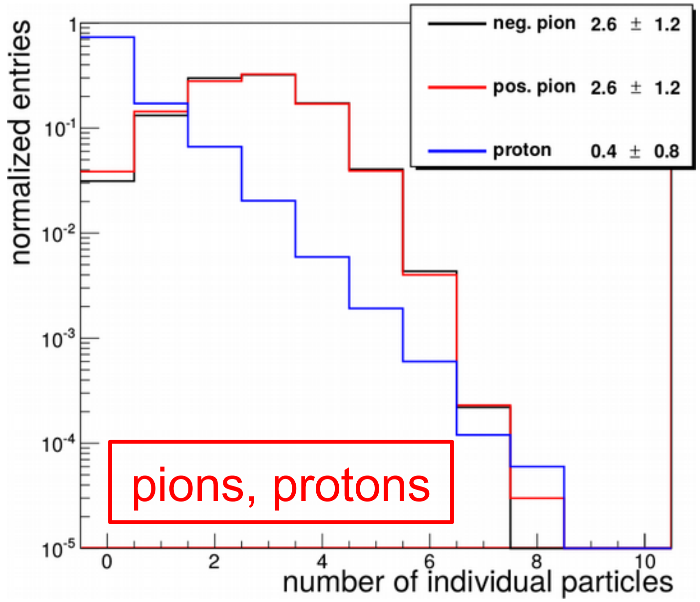
~1400 Si(Li) wafers

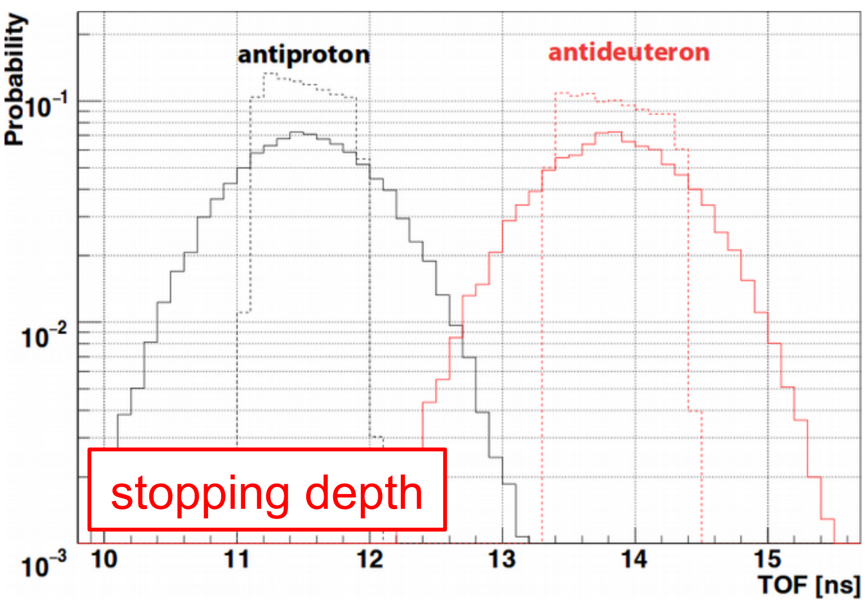
- the **G**eneral **A**nti**P**article **S**pectrometer is especially designed for **low-energy antideuterons and antiprotons**
- identification by stopping and creation of an exotic atom [KEK testbeam measurements → Astropart. Phys. 49, 52 (2013)]
- LDB flights from Antarctica

GAPS sensitivity

Aramaki et al., Astropart. Phys. 74, 6 (2016)



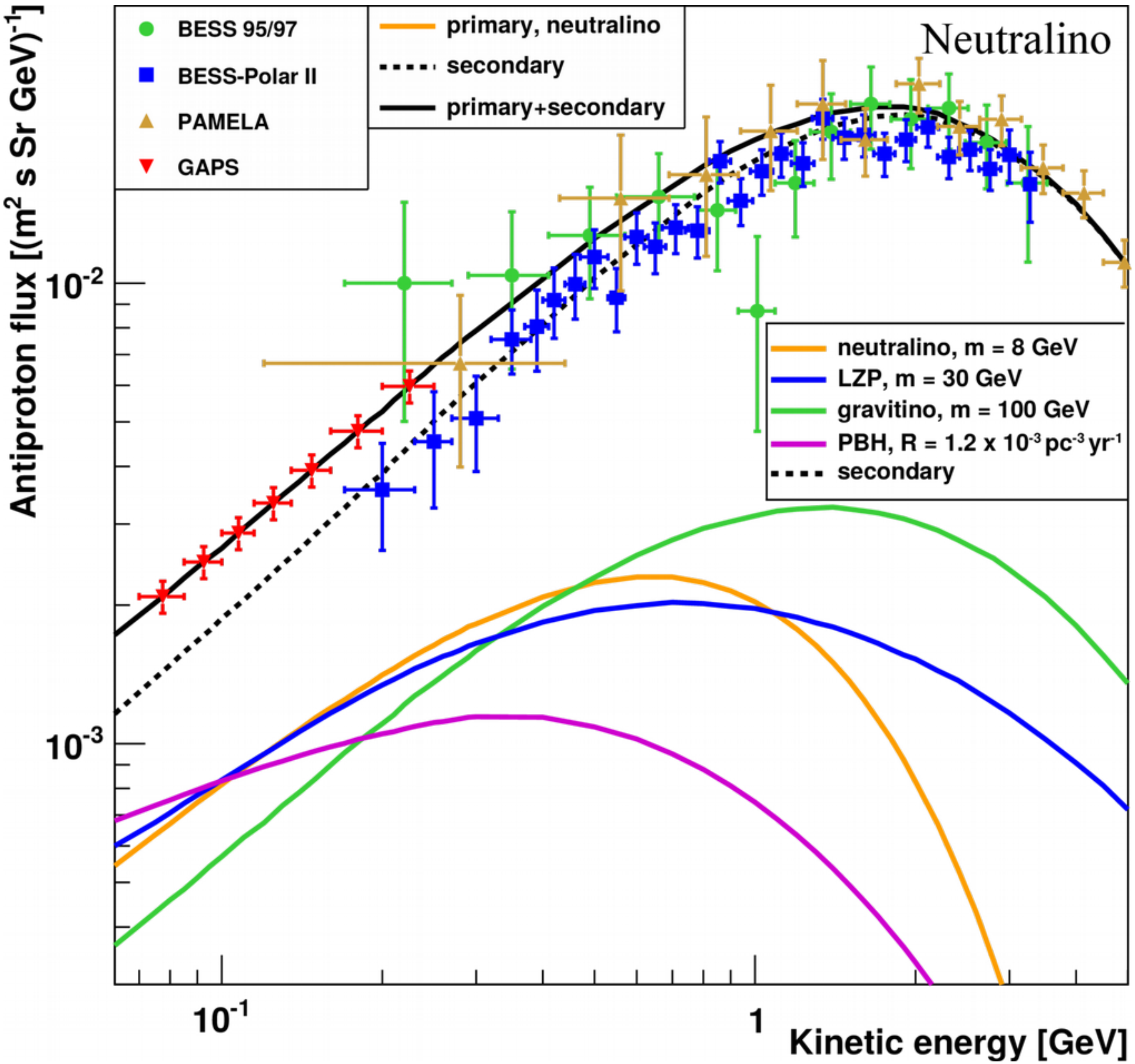




Background rejection:

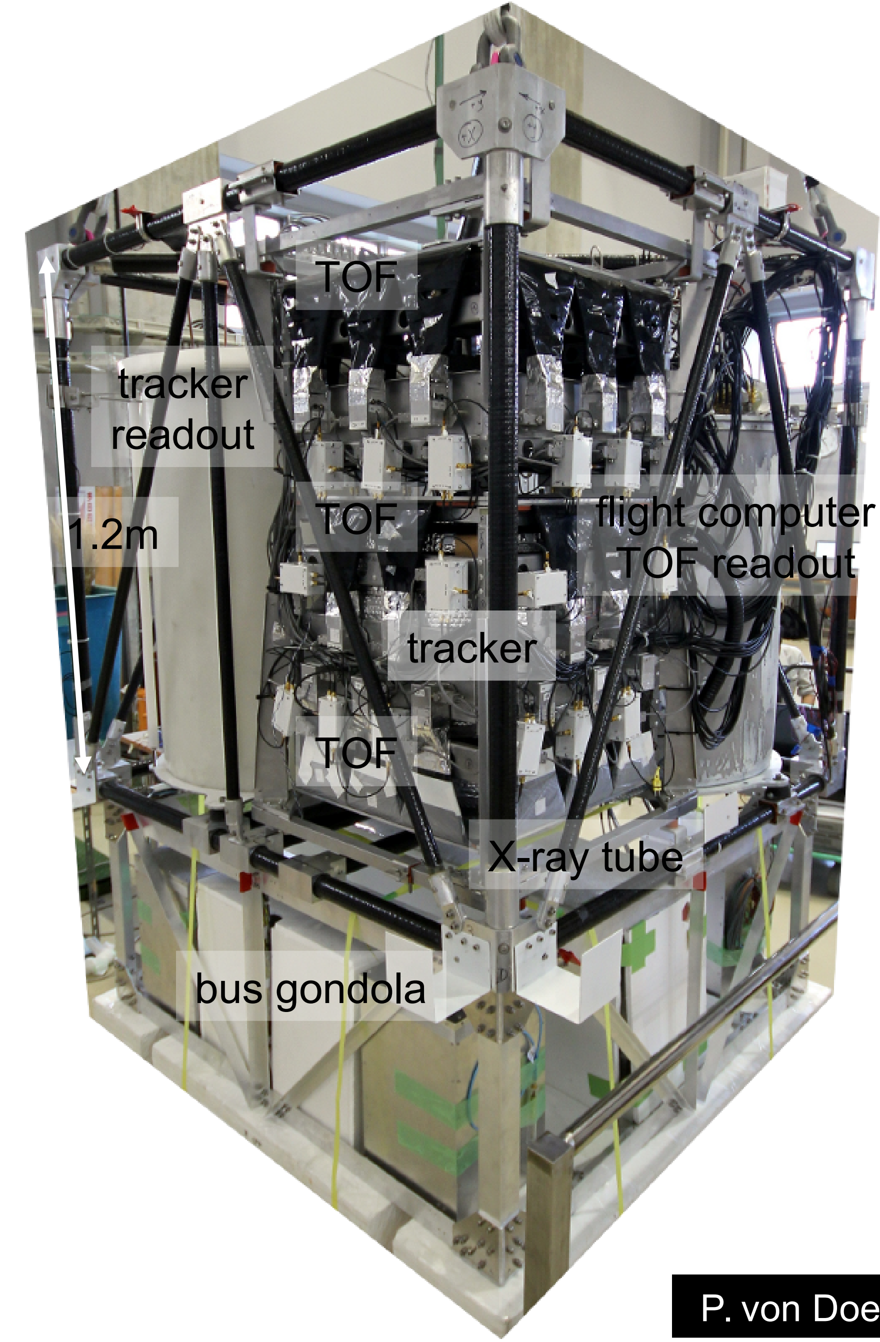
- stopping protons don't have enough energy to produce pions and cannot form exotic atoms (pos. charge)
- deexcitation X-rays have characteristic energies
- number of annihilation pions and protons
- stopping depth in detector

GAPS antiproton



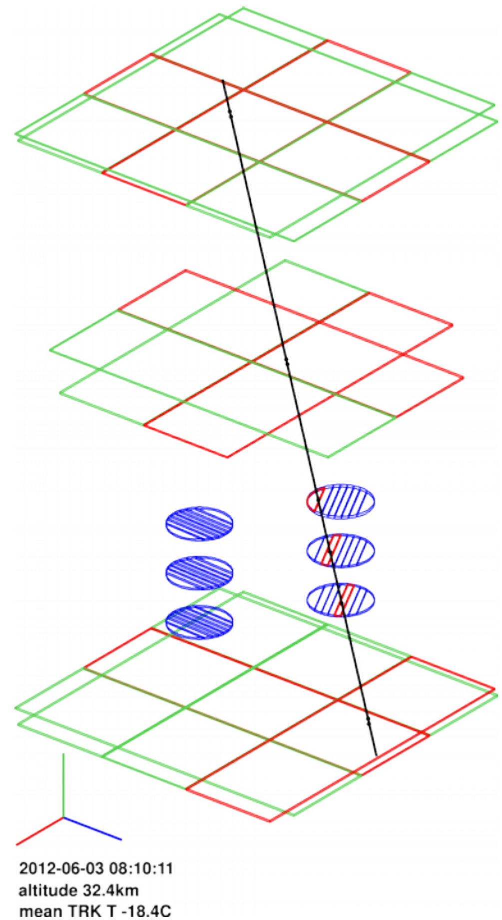
Predicted primary antiproton fluxes at TOA from neutralinos, LZPs, gravitinos, or PBHs, along with neutralino signals as seen by 1 GAPS LDB flight

Prototype GAPS



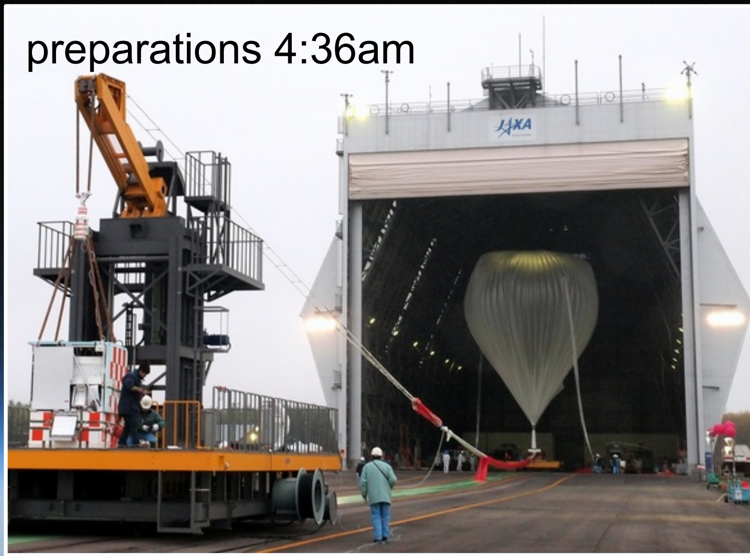
Goals:

- 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 02:28:16

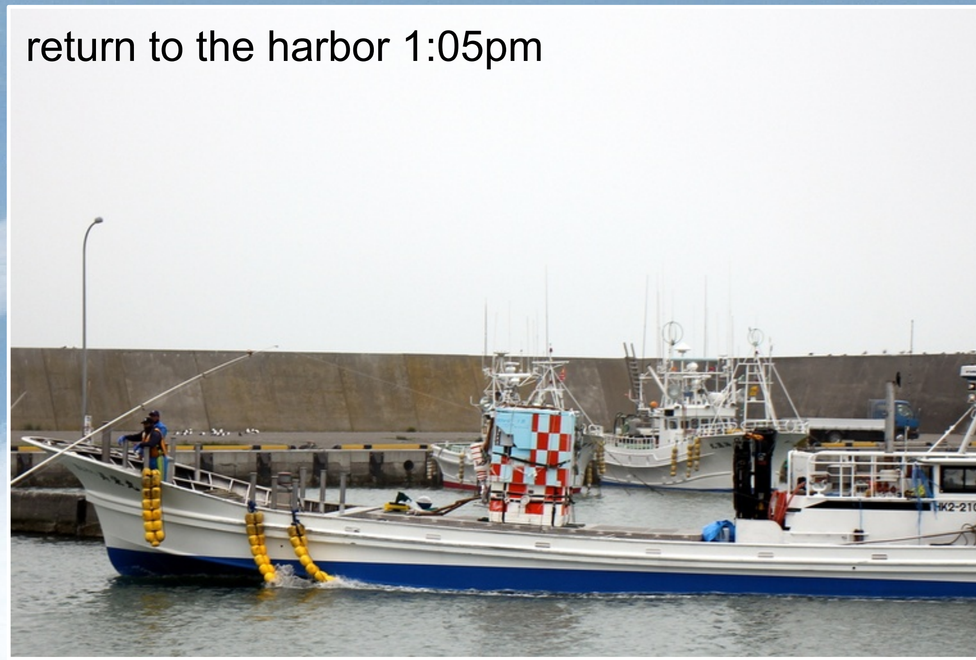
pGAPS flight: June 3rd 2012 from Taiki, Japan



preparations 4:36am


release of balloon

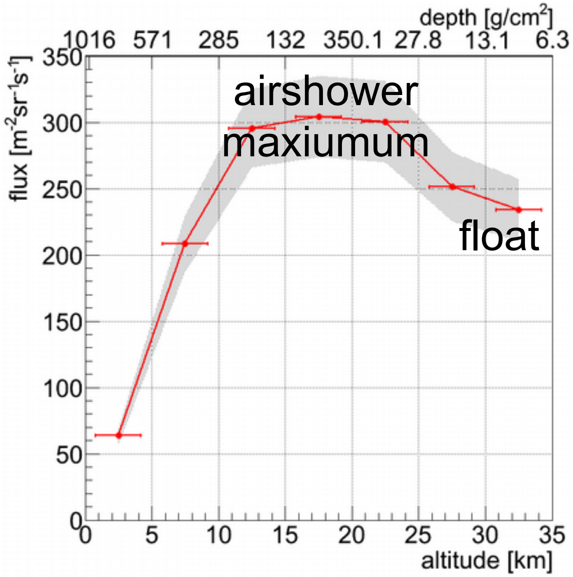

4:55am
take off


return to the harbor 1:05pm

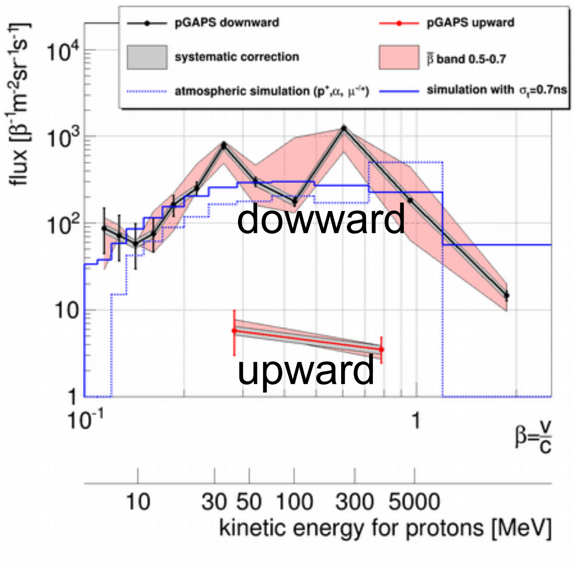
- **well defined TOF trigger and tracker runs**
  - time: 19×13min
  - ~600,000 triggers
- **carry out in-flight calibration of Si(Li) detectors**
  - run X-ray tube
  - time: 13×4min
- **trigger on Si(Li) detectors to study incoherent X-ray background**
  - time: 9×3min

pGAPS flux measurement

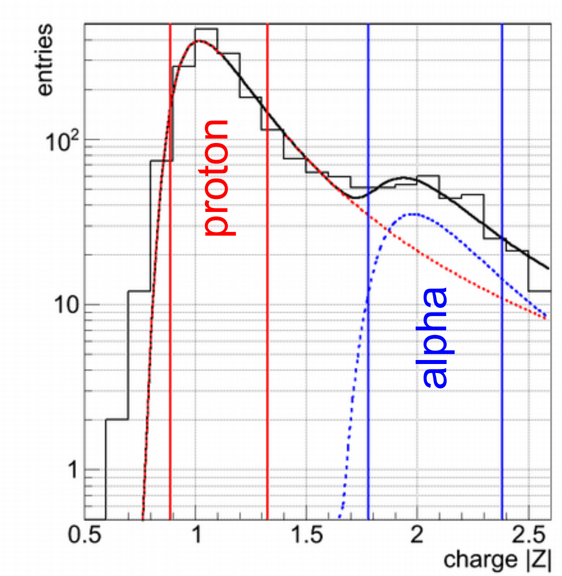
total flux vs. altitude



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)
  - β<0.2 ($E_{kin,proton}$~20MeV) very good agreement
  - β=0.3-0.5 ($E_{kin,proton}$~50-150MeV) within systematic errors
  - β>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/cm²) → in good agreement with BESS data

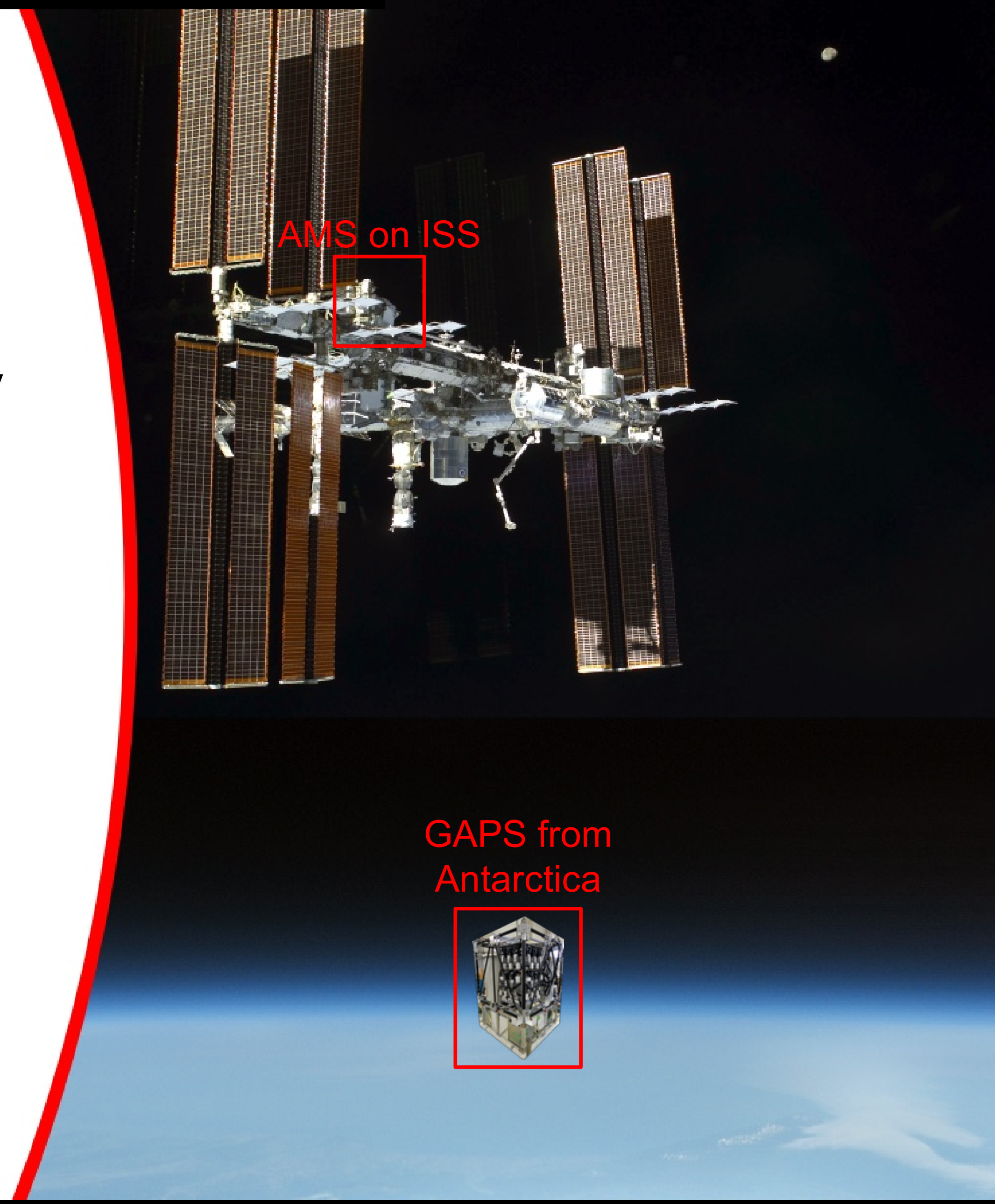
Path forward

- antideuteron searches are experimentally challenging
  → **multiple experiments for cross-checks are important**

- AMS-02 and GAPS have very different event signatures **AND** very different backgrounds
  → **very good for independent confirmation**

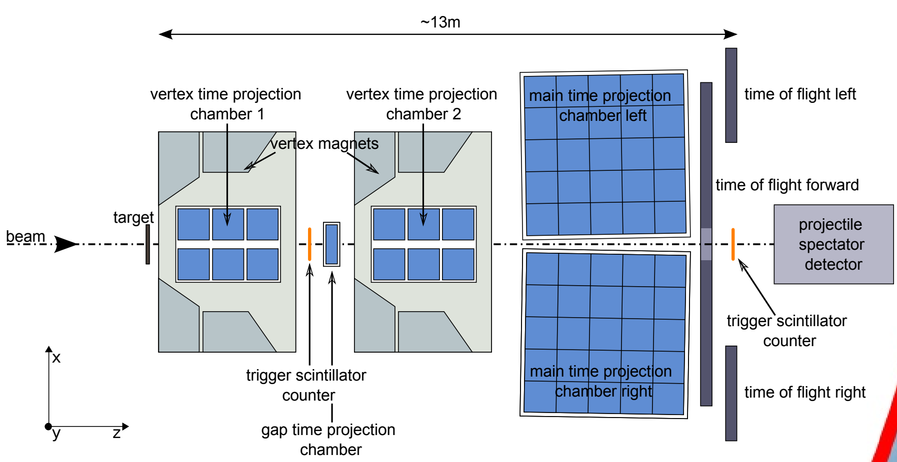
- two independent flight trajectories
  - AMS-02 has a factor of 10 geomagnetic cutoff correction
  - GAPS analysis has nearly no geomagnetic correction

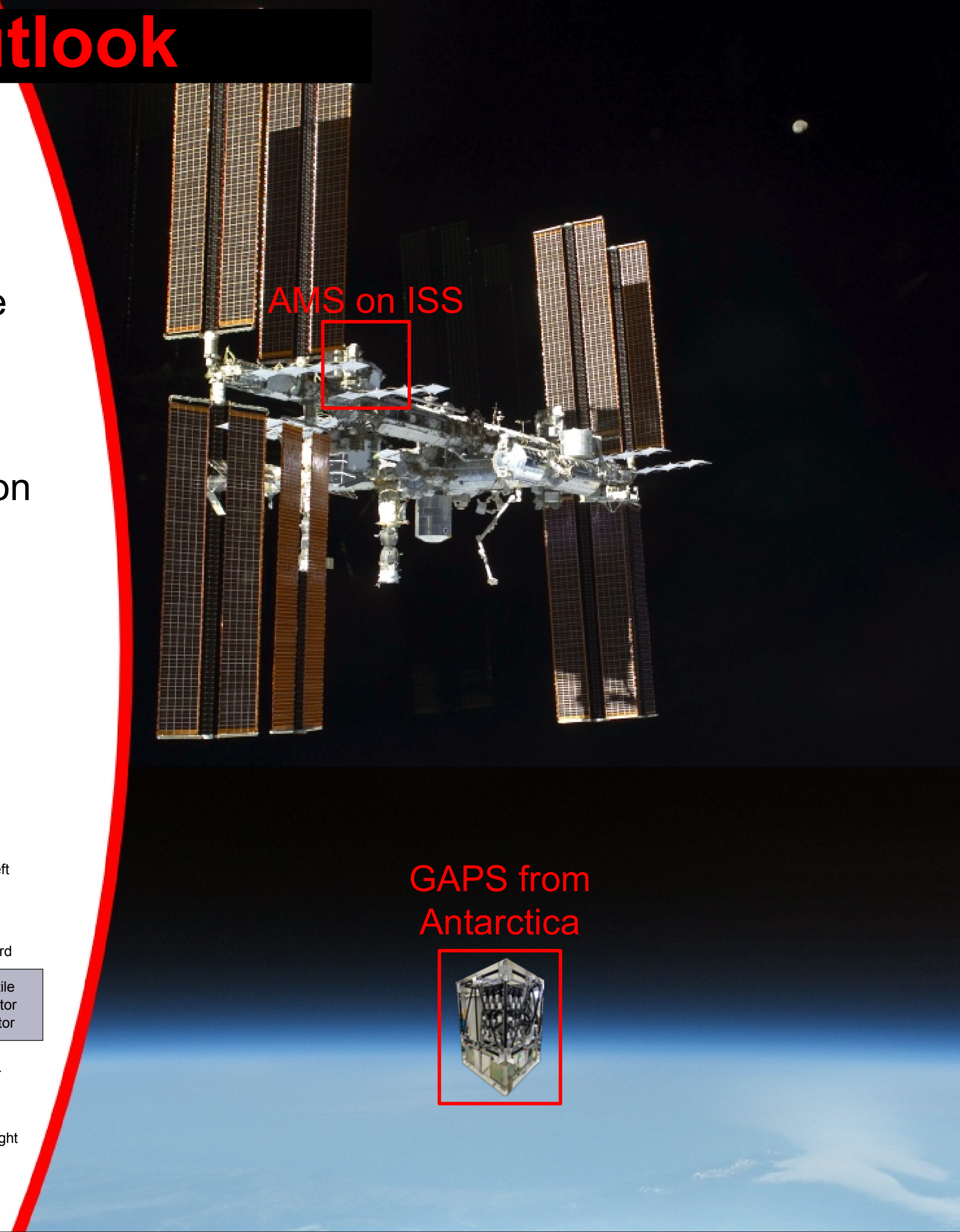
- **low-energy antiproton flux measurement will be the most important cross-check between AMS-02 and GAPS**



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





Dark matter interactions

Berlin, Hooper, McDermott: Phys. Rev. D 89, 115022 (2014)

Model Number	*DM*	*Mediator*	*Interactions*	Elastic Scattering	Near Future Reach? Direct	LHC
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	ϕ^2, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B^\dagger_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
7	Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
7	Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

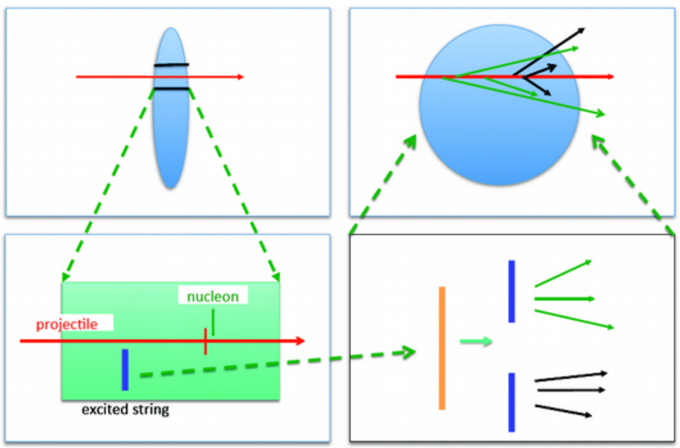
TABLE V. A summary of the simplified models identified in our study as capable of generating the observed gamma-ray excess without violating the constraints from colliders or direct detection experiments. In the last two columns, we indicate whether the model in question will be within the reach of near future direct detection experiments (LUX, XENON1T) or of the LHC. Models with an entry of "Never" predict an elastic scattering cross section with nuclei that is below the irreducible background known as the "neutrino floor". The "Model Number" given in the first column provides the key for the model points shown in Fig. 9.

Depends on

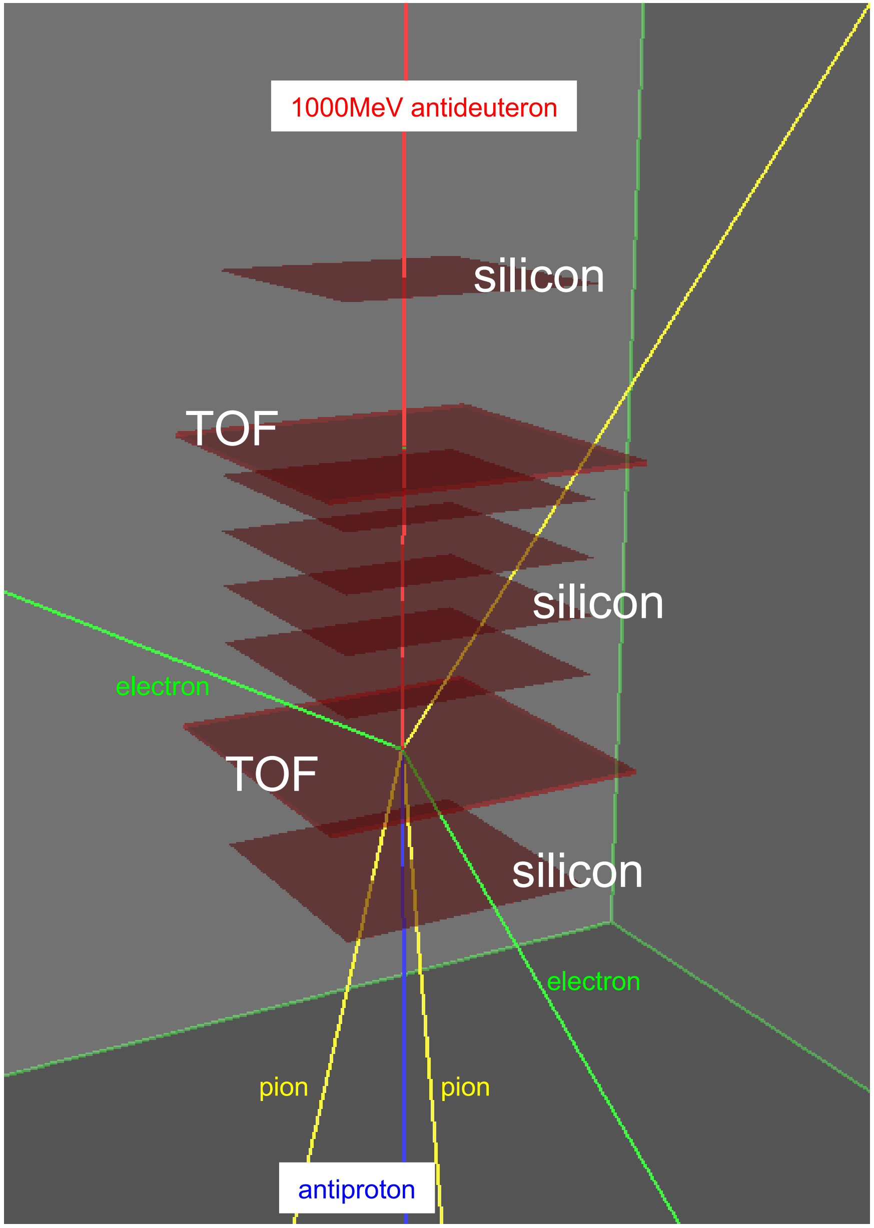
- type of DM: scalar, fermion, vector
- type of coupling: scalar (1), pseudoscalar (γ^5), vector (γ^μ), axial ($\gamma^\mu\gamma^5$)

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)

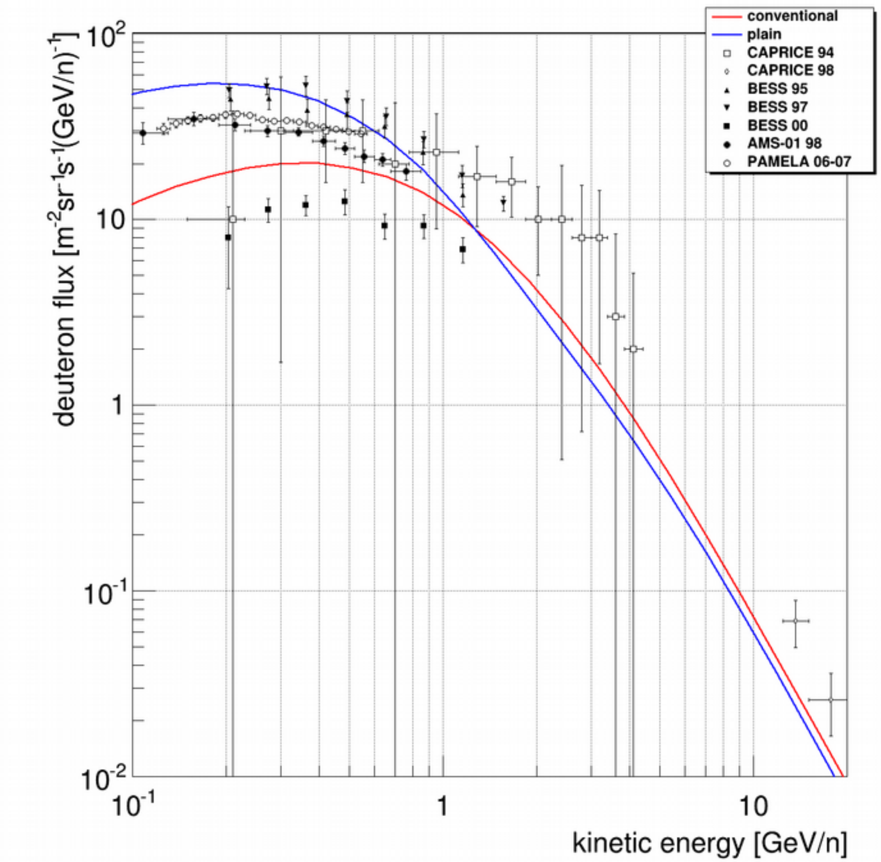


Galoyan, Uzhinsky arXiv:1208.3614

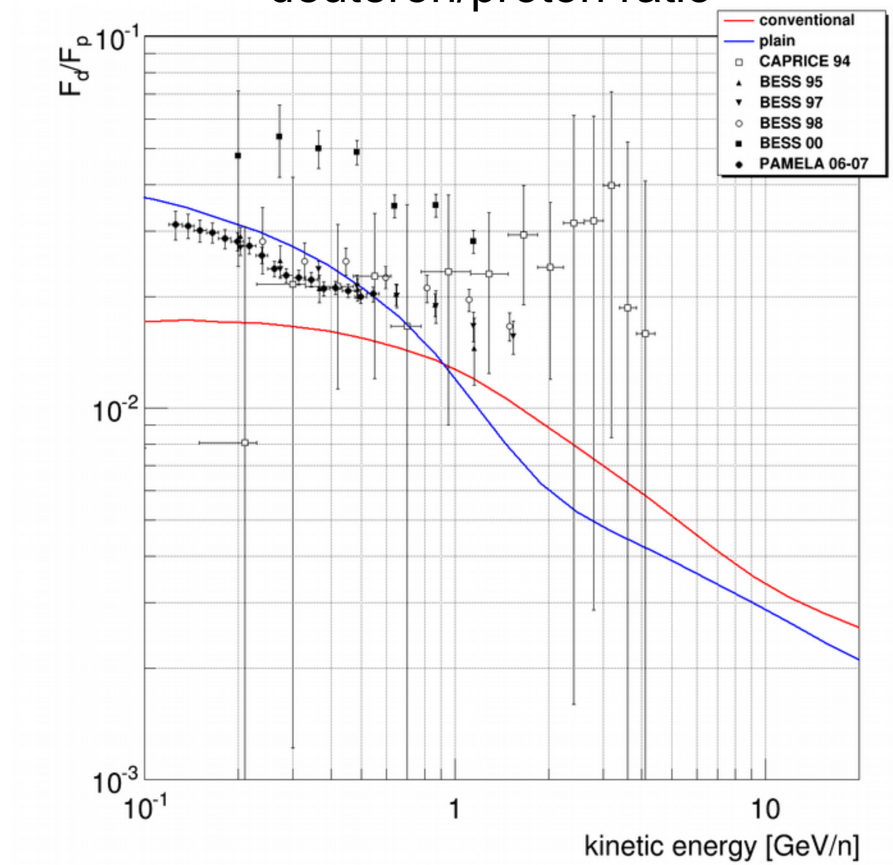


Deuterons are interesting, too

deuteron flux



deuteron/proton ratio



- available deuteron measurements have mostly large error bars
- RICH energy range (~1-9GeV/n) will be important to constrain propagation models
- d/p, d/He-4, d/He-3 ratios are very important to understand cosmic-ray propagation