Overview and status of cosmic ray antideuteron searches

TeVPA / IDM Amsterdam, June 2014

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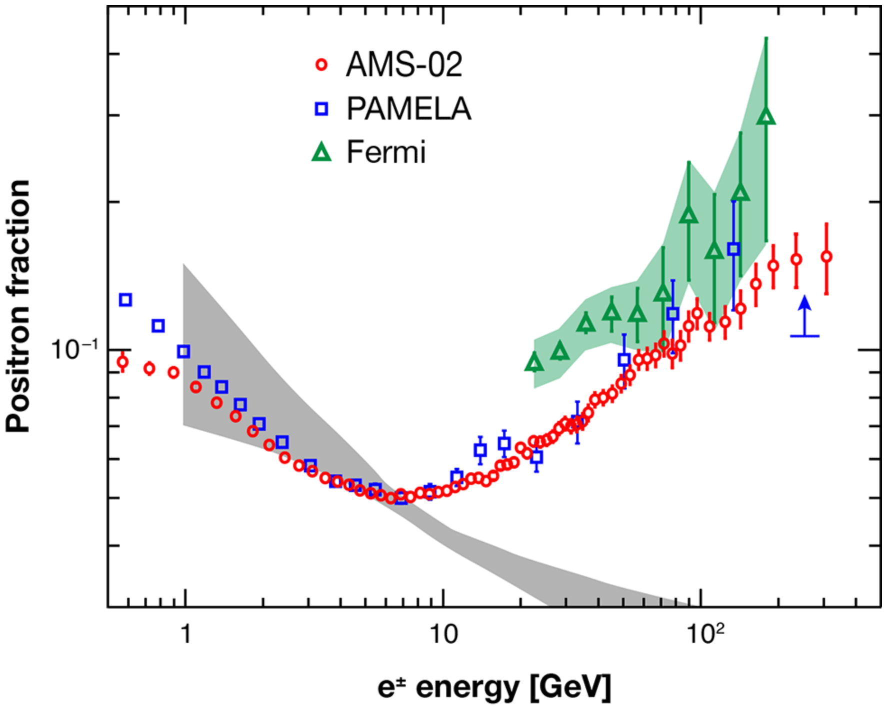
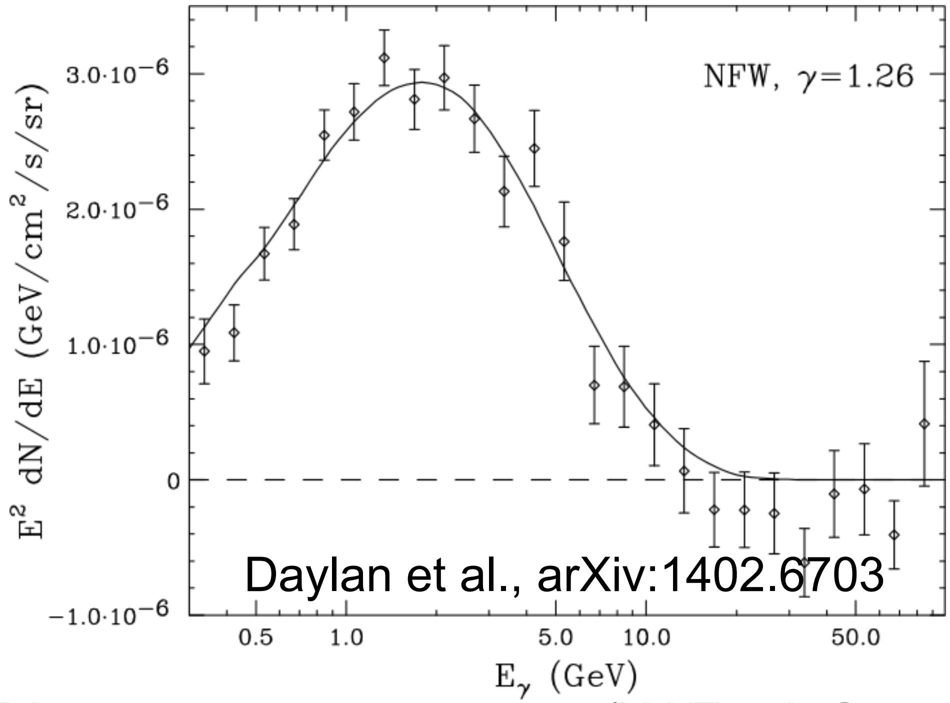
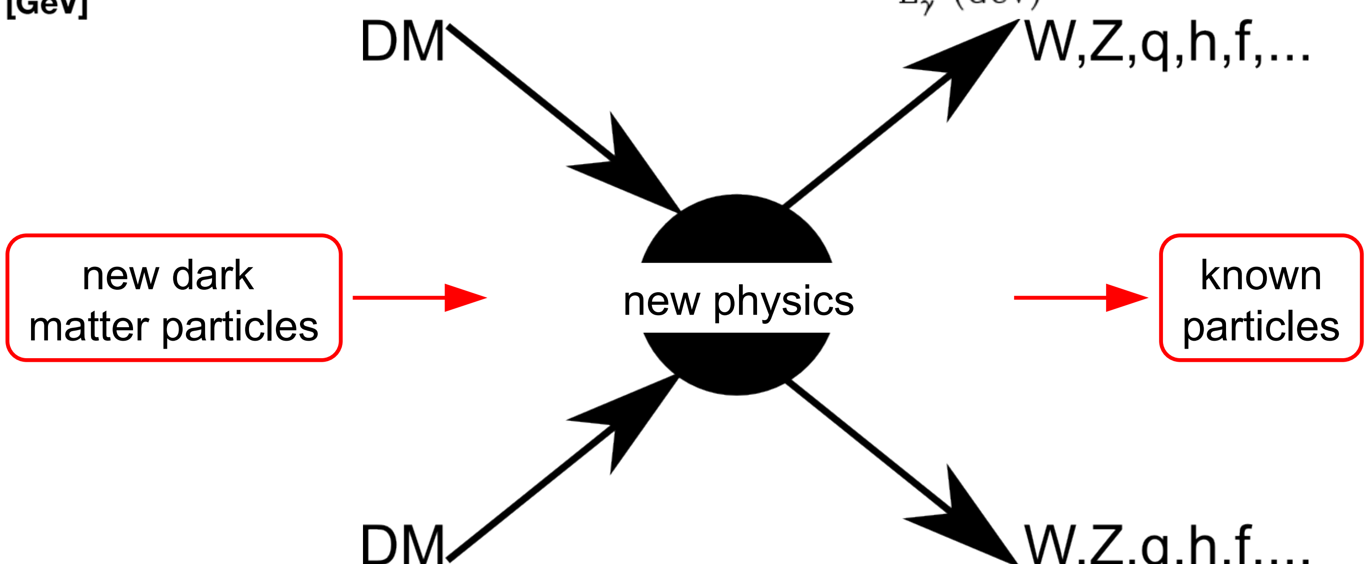
d̄14
1st cosmic ray antideuteron workshop
June 5 and 6 at UCLA
ABAZAJIAN, Kevork - ARAMAKI, Tsuguo - BINDI, Veronica - BOEZIO, Mirko
BOUDAUD, Mathieu – BUFALINO, Stefania - CARLSON, Eric - CLINE, David - DAL, Lars
VON DOETINCHEM, Philip - DONATO, Fiorenza - PEREIRA, Rui - FORNENGO, Nicolao
GREFE, Michael - HAMILTON, Brian - HOFFMAN, Julia - KAPLINGHAT, Manoj
MERTSCH, Philipp - MOGNET, Isaac - ONG, Rene - OSTAPCHENKO, Sergey
PEREZ, Kerstin - PUTZE, Antje - SALATI, Pierre - SASAKI, Makoto - TARLÉ, Gregory
WILD, Sebastian - WRIGHT, Dennis - ZWEERINK, Jeffrey

Dark matter signal in cosmic rays?

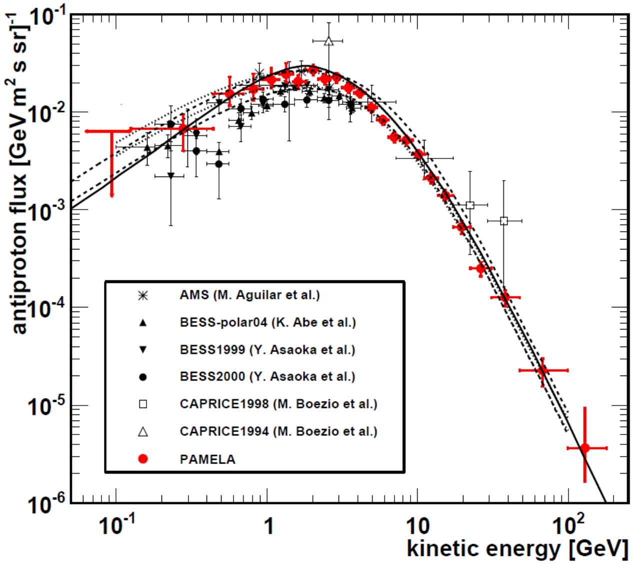


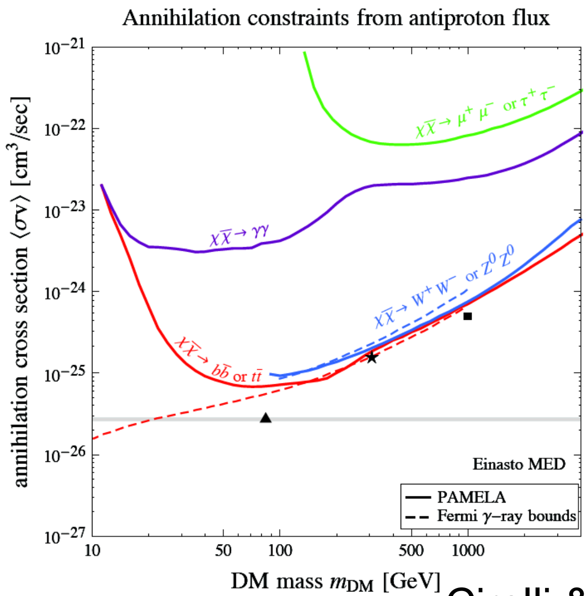


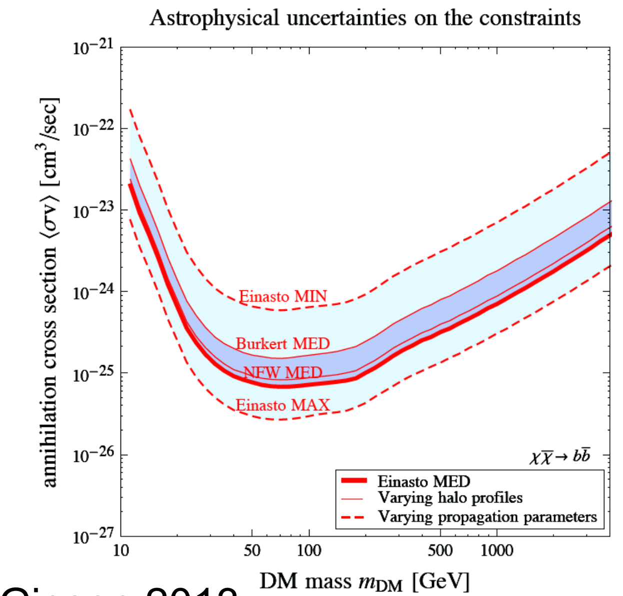
- unexplained features in positrons
- proposed theories:
  - astrophysical origin → pulsars
  - SNR acceleration
  - **dark matter self-annihilation**
- Gamma-ray excess at the galactic center → 30GeV dark matter particle?



Antiprotons



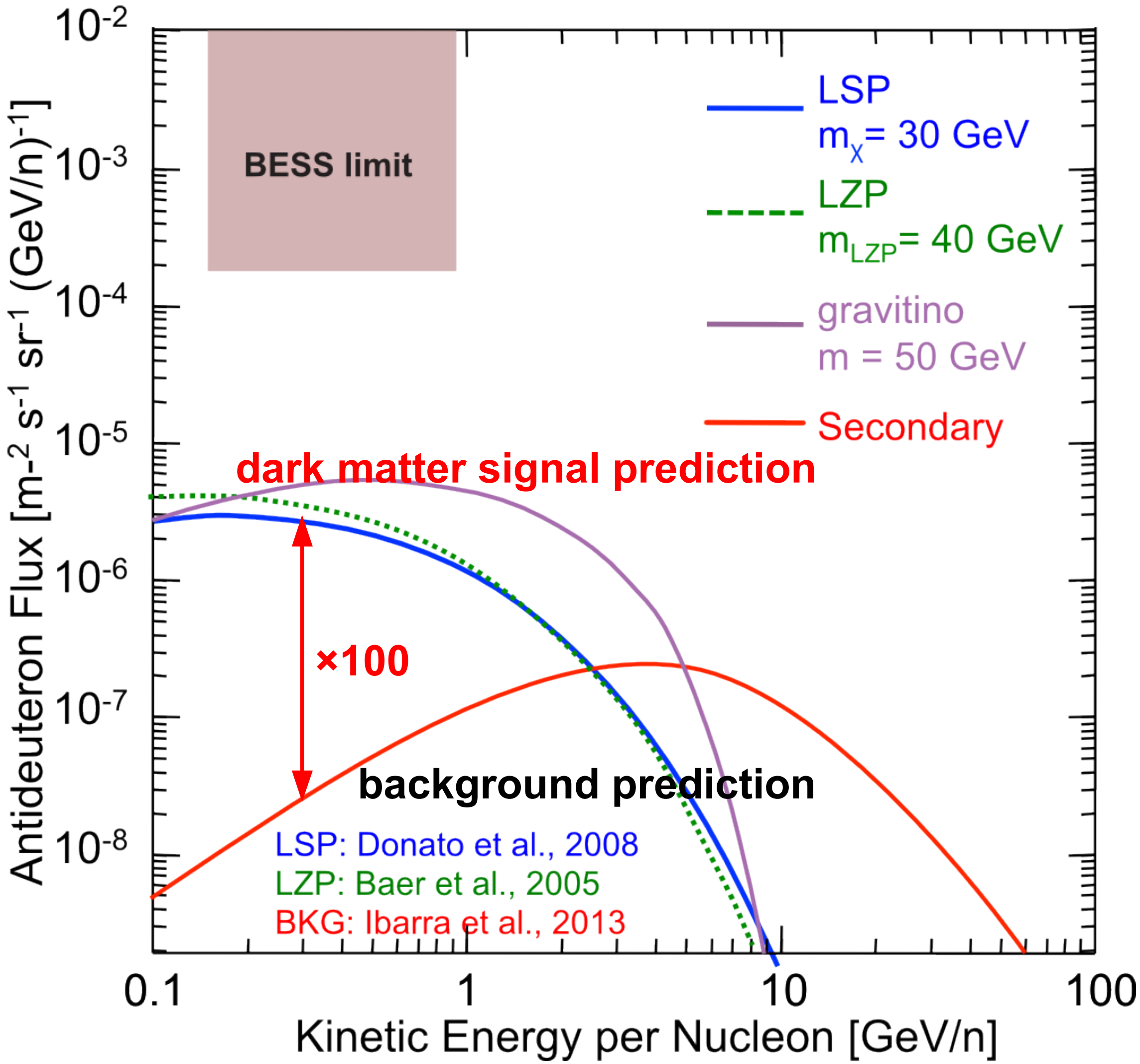




Cirelli & Giesen 2013

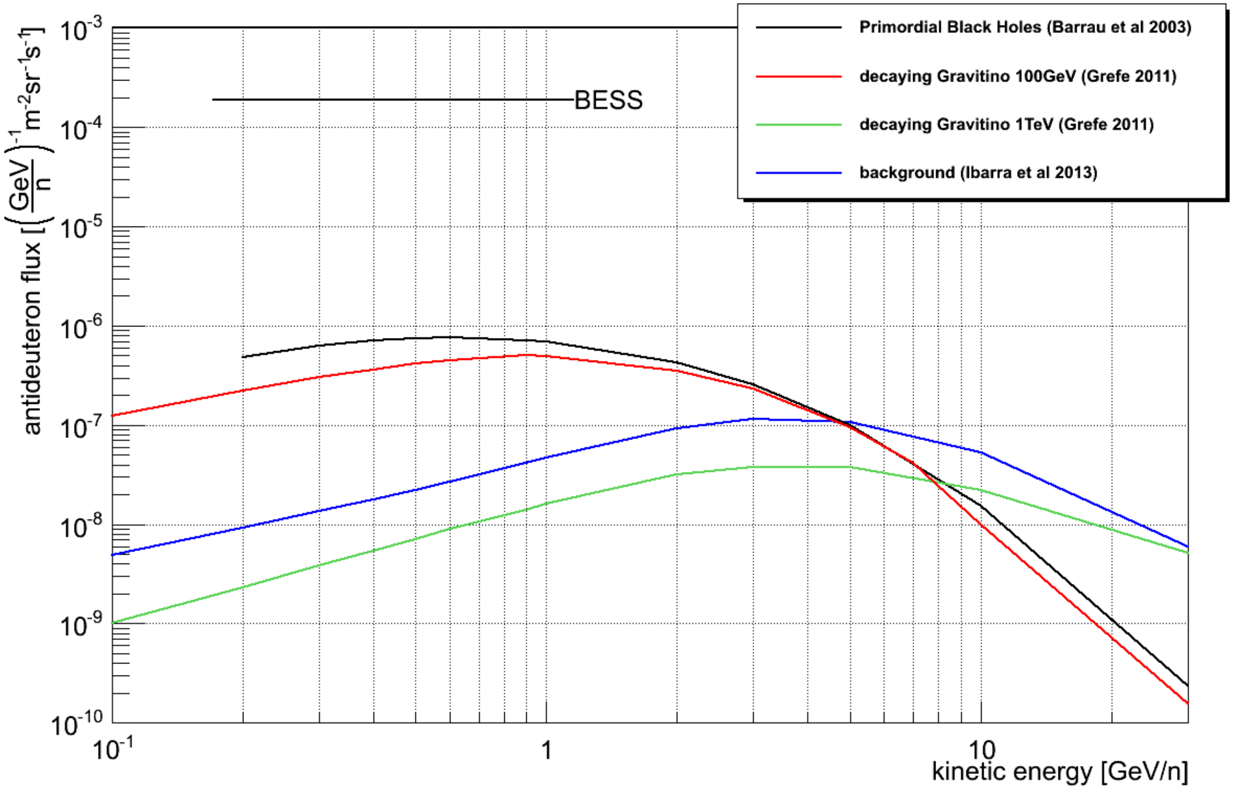
- PAMELA/BESS constraints on annihilating/decaying dark matter are strong
- constraining DM properties in case of a measured excess is complicated as astrophysical background and different channels shapes are very similar

Antideuterons



- **antideuterons are the most important unexplored indirect detection technique**
- **prediction:** antideuterons from dark matter annihilations up to ~100 times more abundant than from conventional cosmic rays

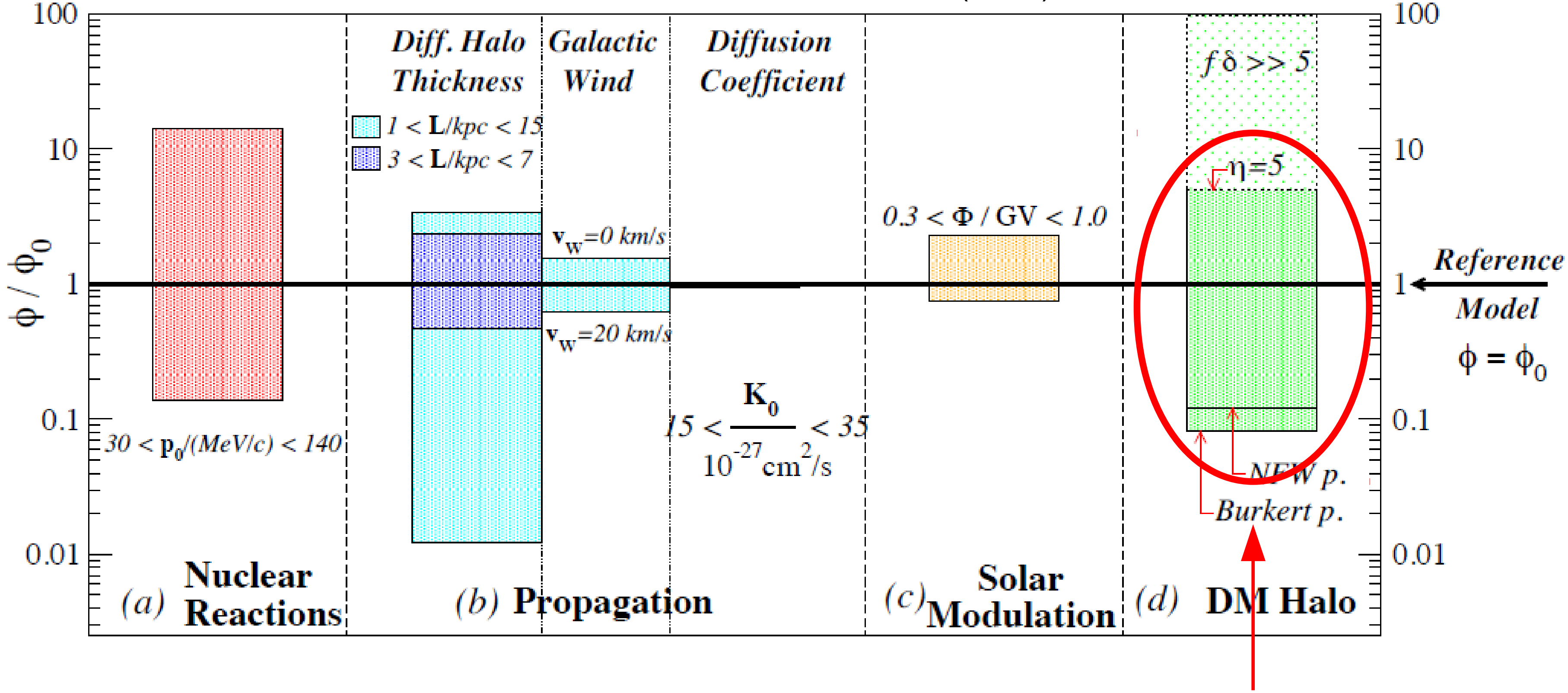
Primordial black holes and gravitinos



- **primary black holes:**
  - very small black holes could have formed in the early universe due to, e.g., initial density inhomogeneities
  - might evaporate antideuterons and **maybe the only chance to detect primordial black holes**
- **cosmological gravitino problem:**
  - hypothetical mediator of gravity: graviton → superpartner gravitino
  - late decays of unstable gravitinos to standard particles would produce antideuterons

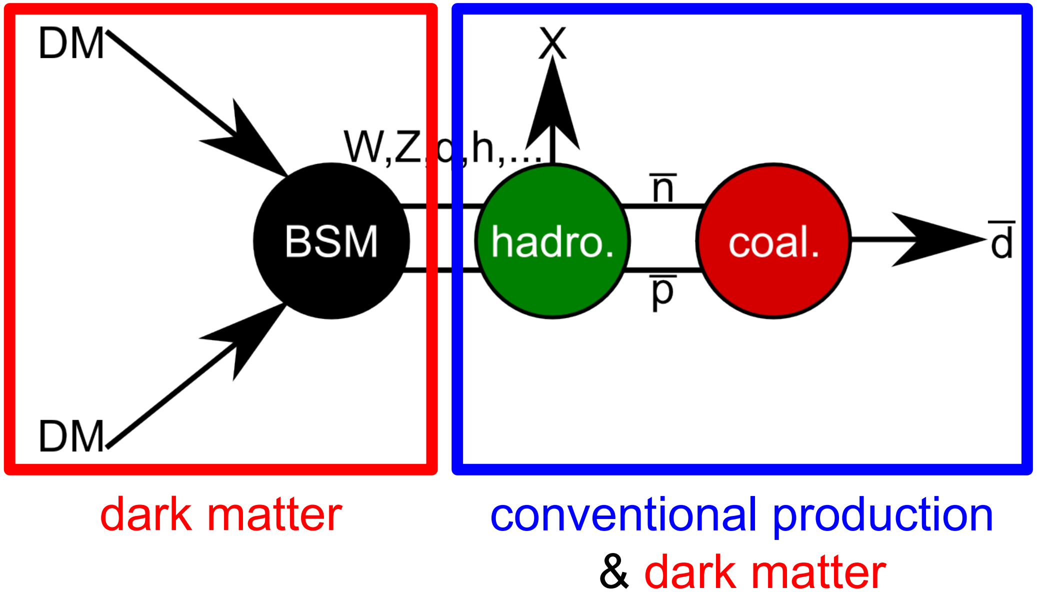
Uncertainties

H. Baer & S. Profumo, JCAP 12 (2005) 8



Boost factor shouldn't be higher than 2-3
→ remaining talk is conservative and
assumes no boost

Antideuteron formation



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

$$\gamma \frac{d^3 N_{\bar{d}}}{d\vec{p}^3_{\bar{d}}} = \frac{4\pi}{3} p_0^3 \left(\gamma \frac{d^3 N_p}{d\vec{p}^3_p} \right)^2 ; \qquad \frac{d^3 N_i}{d\vec{p}^3_i} = \frac{1}{\sigma_R} \frac{d^3 \sigma_i}{d\vec{p}^3_i} .$$

- major conventional production mechanisms of cosmic rays with ISM protons at rest:
  - $p+p \rightarrow \bar{d}+X$ (threshold 17GeV)
  - $\bar{p}+p \rightarrow \bar{d}+X$ (threshold 7GeV)
    → important even though antiproton flux is small

- coalescence momentum plays crucial role for cosmic-ray yield

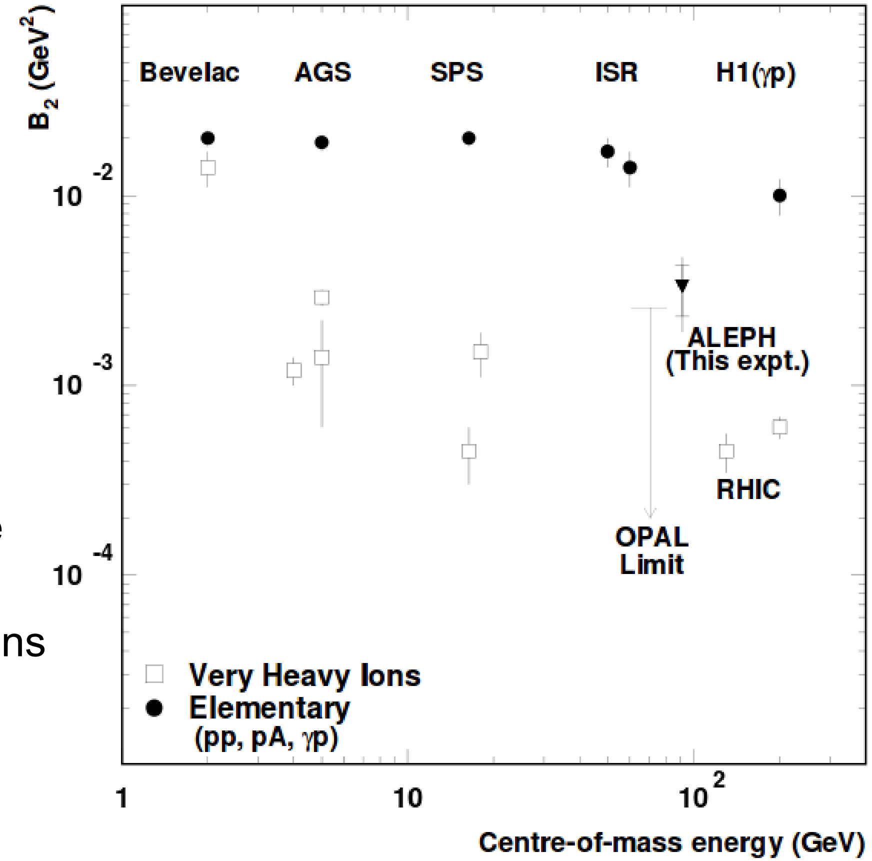
Coalescence uncertainty

$$E_A \frac{d^3 N_A}{d^3 P} = B_A \left(E_p \frac{d^3 N_p}{d^3 p} \right)^Z \left(E_n \frac{d^3 N_n}{d^3 p} \right)^{A-Z}$$

$$B_A = \left(\frac{4\pi}{3} p_0^3 \right)^{(A-1)} \frac{m_A}{m_p^A}.$$

- Simple factorization model seems to be to simple and one choice of B_2 cannot describe all experiments at all energies
- Improvement during the last years using tools like Pythia and Herwig for hadronization:
  - produce antiprotons and antineutrons
  - respect jet structure
  - antiproton and antineutron have to be close in space and momentum space
- What is best value?
  Z resonance (100GeV DM)?
  ϒ resonance (10GeV DM)?
- Coalescence does not affect antiproton/proton ratio → break degeneracy of antiproton and antideuteron

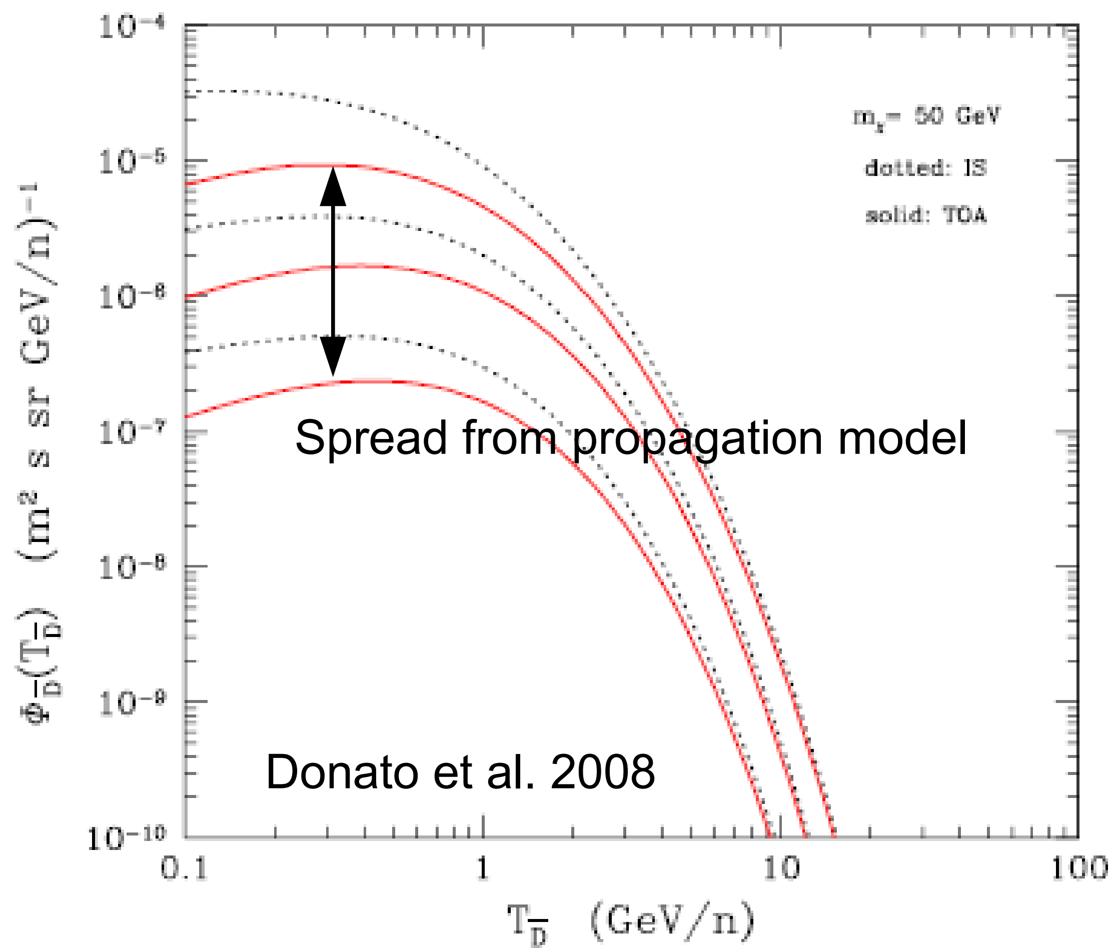
Phys. Lett. B 639 (3–4) 192 (2006)



Experiment	Process	Pythia 6	Pythia 8	Herwig++
ALEPH	e^+e^-	–	192	159
CLEO	e^+e^-	–	133	145
ZEUS	ep	236	–	150
CERN ISR	pp	–	152	221
ALICE	pp	230	–	154

Table from Lars Dal

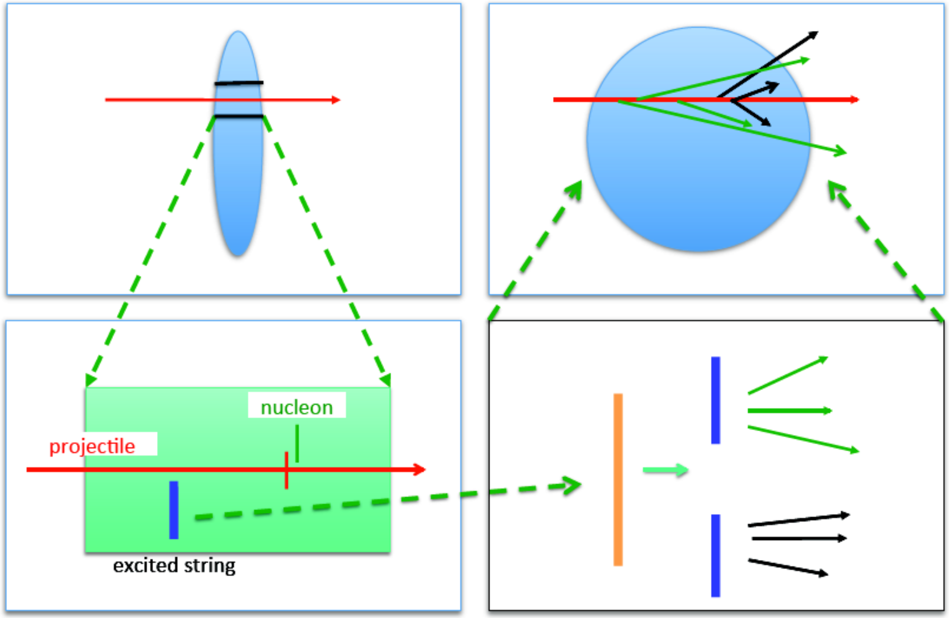
Propagation uncertainty

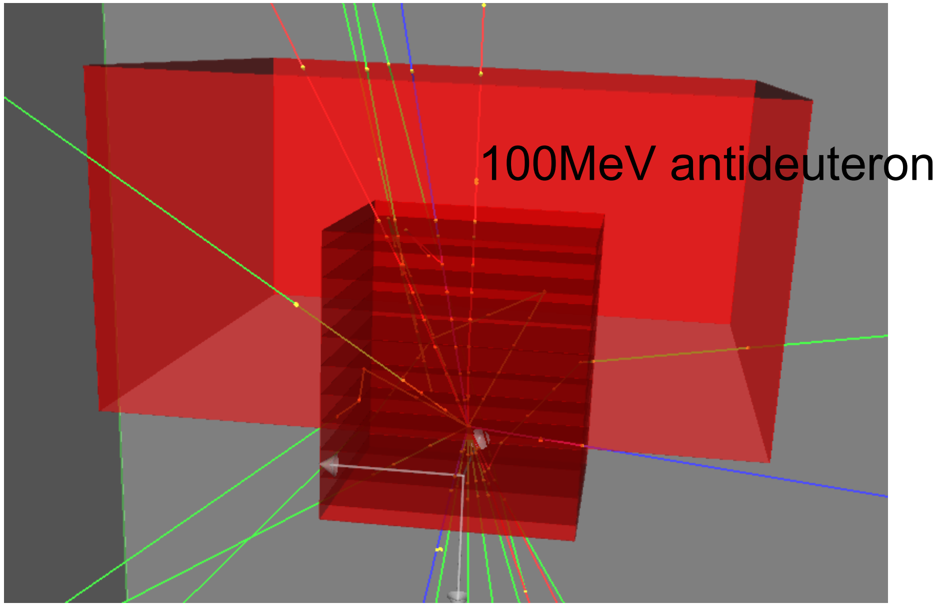


- Propagation is the strongest uncertaintiy source for primary antideuterons: **halo size for diffusion calculation poorly constrained**
- More data on various nuclear speces are needed (and hope that they do not need more complicated modeling for interpretation!)

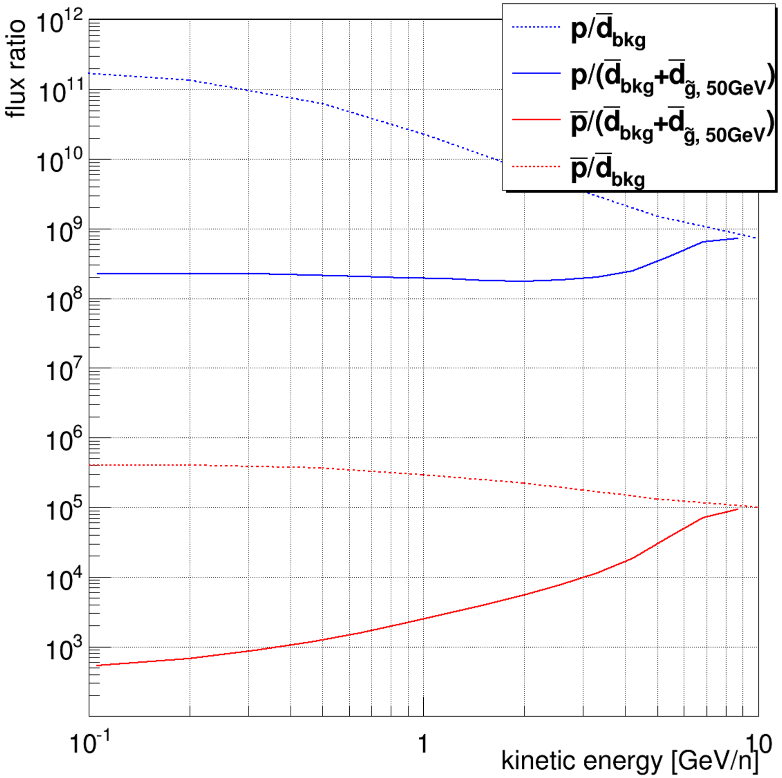
GEANT4 - Fritiof model for $\bar{d}$ simulation

- new in GEANT4: antideuteron simulations
- FTF model was extended to handle nucleus-nucleus interaction down to 0 GeV
- now the best model for antiprotons, antineutrons, antideuterons
  also for stopped antiprotons and slow antineutrons:
  - very little data for validation available
  - needed: antideuteron formation

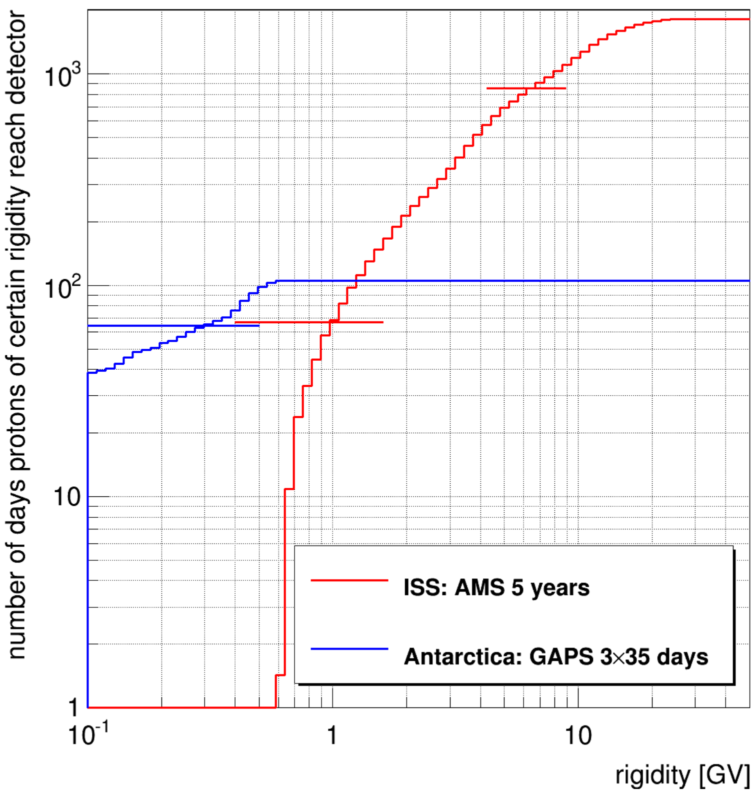




Observational challenges



flux ratios

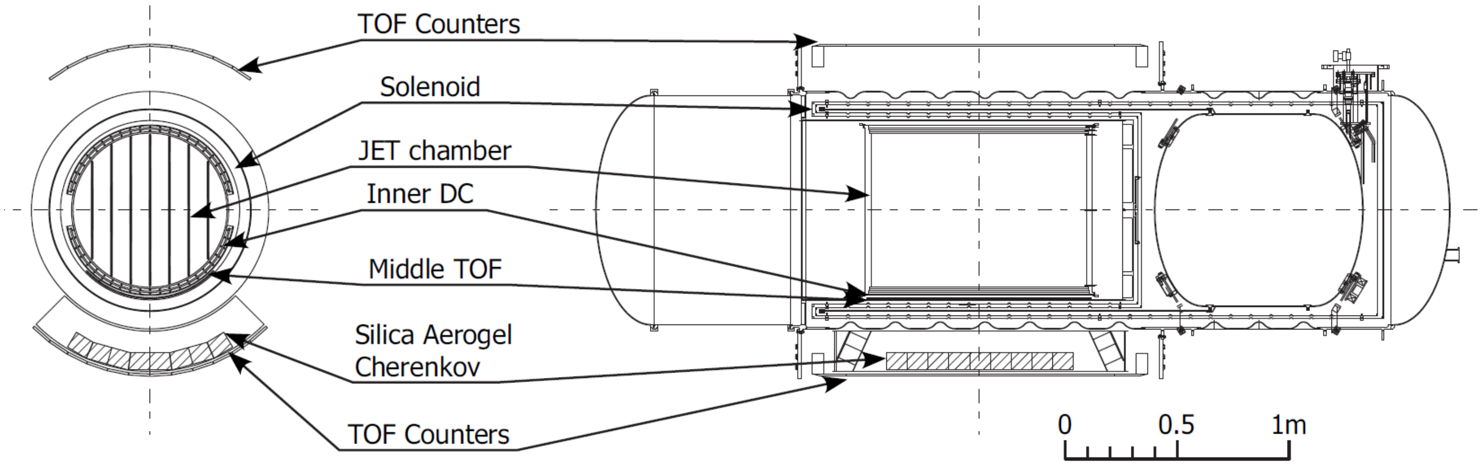


geomagnetic cut-off

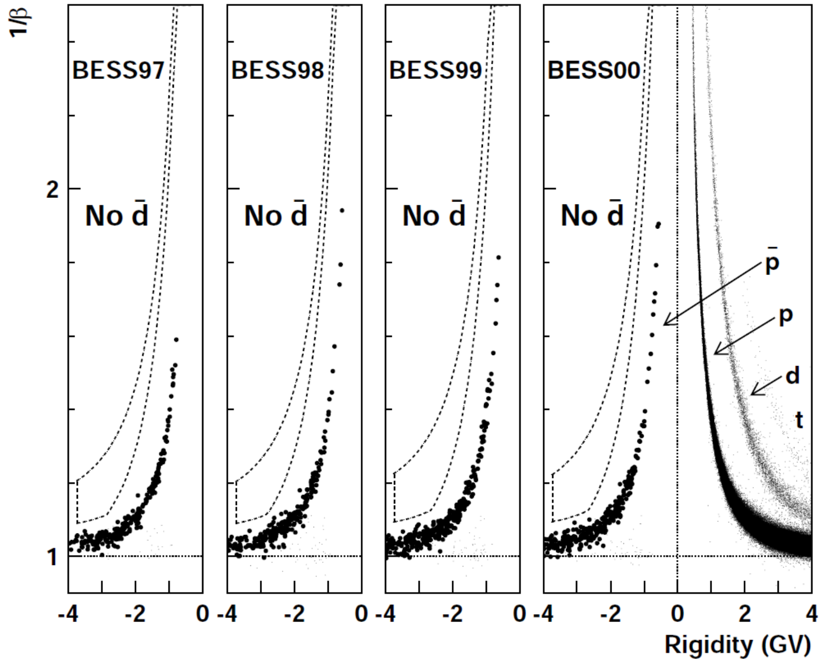
antideuteron measurement with balloon and space experiments requires:

- **strong background suppression**
- **long flight time and large acceptance**
- **geomagnetic location of experiment**

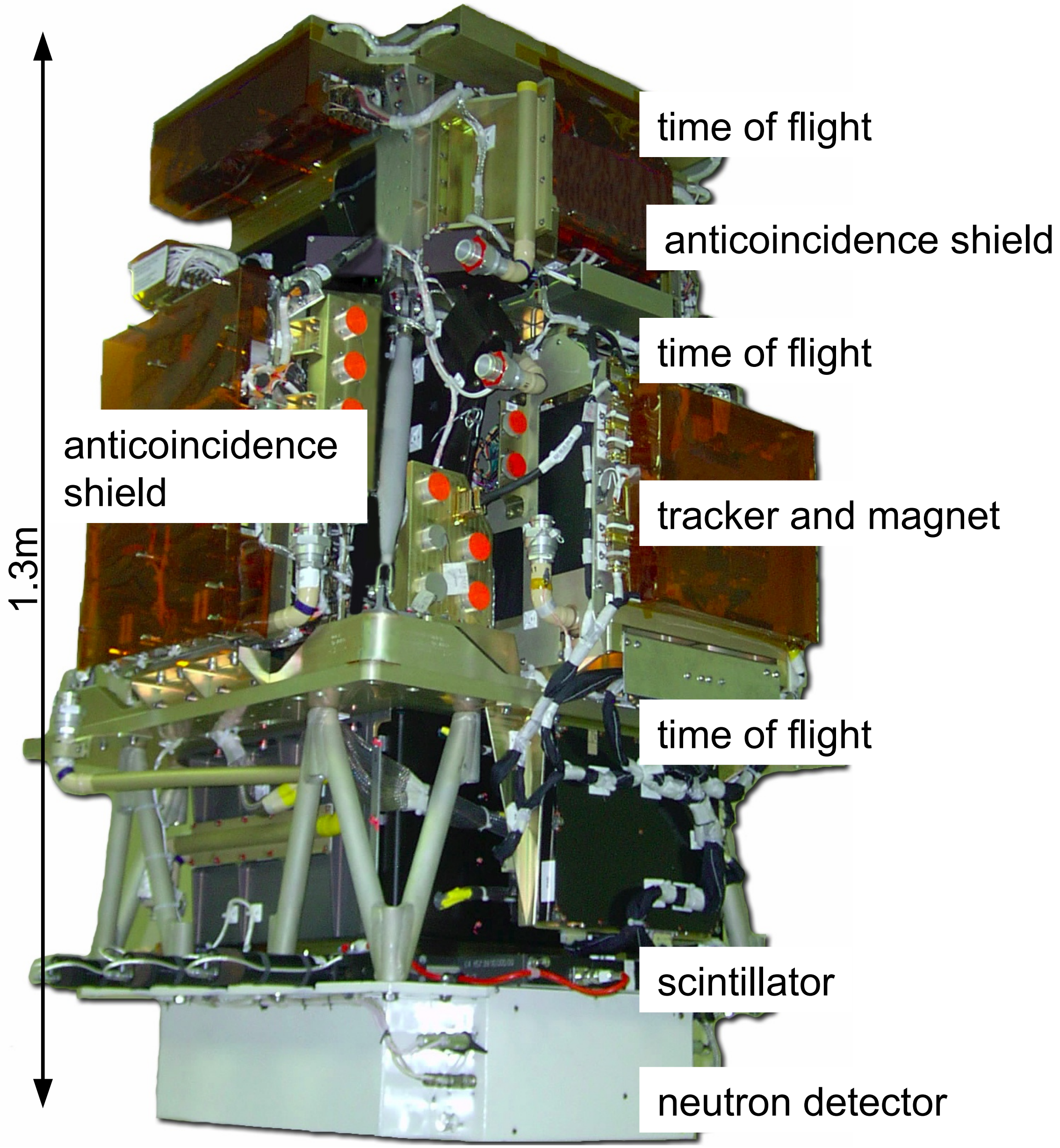
Balloon-borne: BESS



- magnetic-rigidity spectrometer:
  - superconducting solenoidal magnet
  - drift-chamber tracking system
  - time of flight
  - Cherenkov counter
- balloon flights in Canada and at Antarctica
- **antideuteron results:**
  kinetic energy range: 0.17-1.15 GeV/n
  limit $1.9\times10^{-4}(m^2 s\ sr\ GeV/n)^{-1}$ @ 95% C.L.
- improved results from BESS polar coming soon (down to 10^{-5}?)

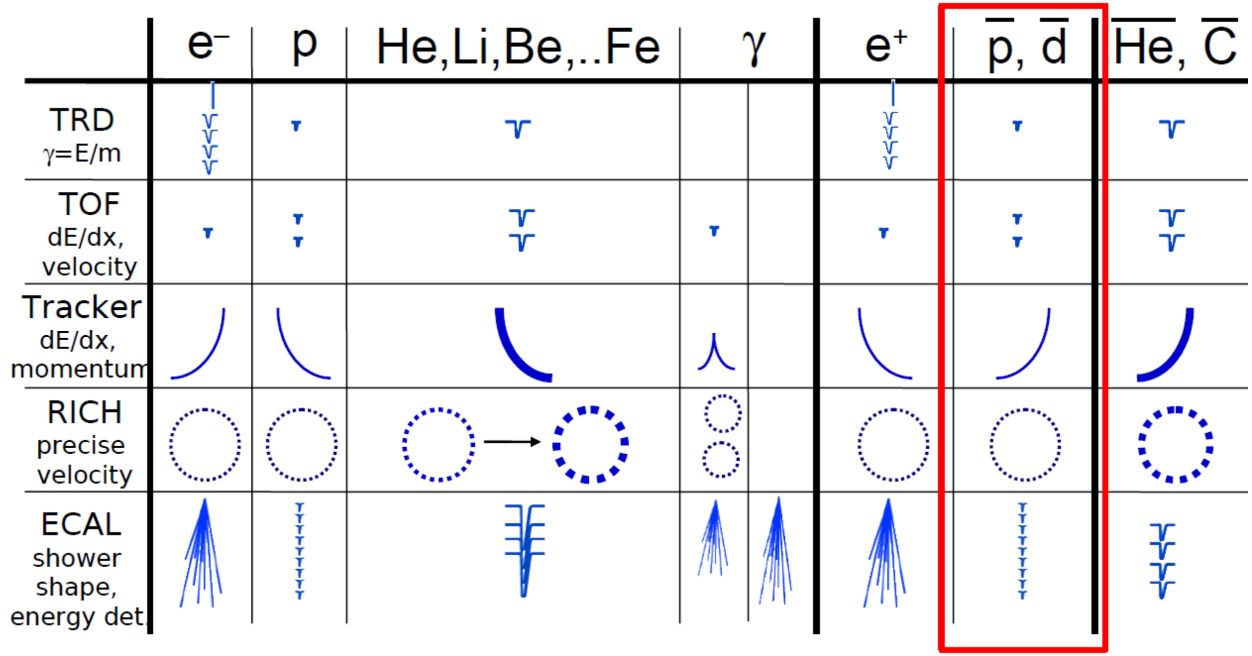


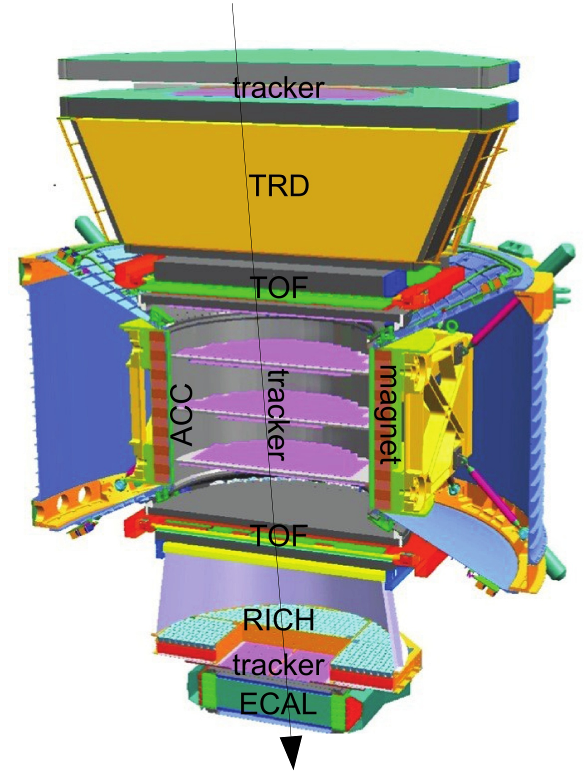
Space-based: PAMELA



- magnetic spectrometer in space since 2006
- particle identification with several typical particle physics sub-detectors
- relatively small acceptance (21.5cm^{2}sr)
- so far only indirect antideuteron limits derived from antiprotons [Kadastik et al. Phys. Lett. B, 683(4–5), 248 (2010]

AMS antideuteron analysis





- **antideuteron identification:**
  - 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

Some possible contaminants for antideuteron region

Protons: right charge, wrong sign, wrong mass by factor 2, but extremely abundant

Deuterons: right charge, wrong sign, right mass, very abundant - dangerous especially if upgoing

Antiprotons: potentially one of the most difficult to deal with - same charge sign as antideuterons, also hadronic, several orders of magnitude more abundant

Electrons: most abundant CR component with negative charge, but non-hadronic and with very different mass

Positrons: same as electrons but less abundant and with wrong charge sign - if electrons are handled positrons will also be solved

Helium-4: extremely abundant, same mass/charge ratio, but wrong sign; frequently fragments into deuterons in AMS-02 - dangerous if upgoing (the He ion itself or its fragments)

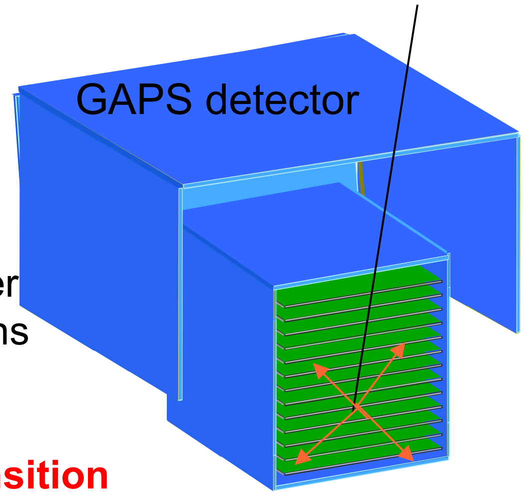
Novel approach for antideuteron identification

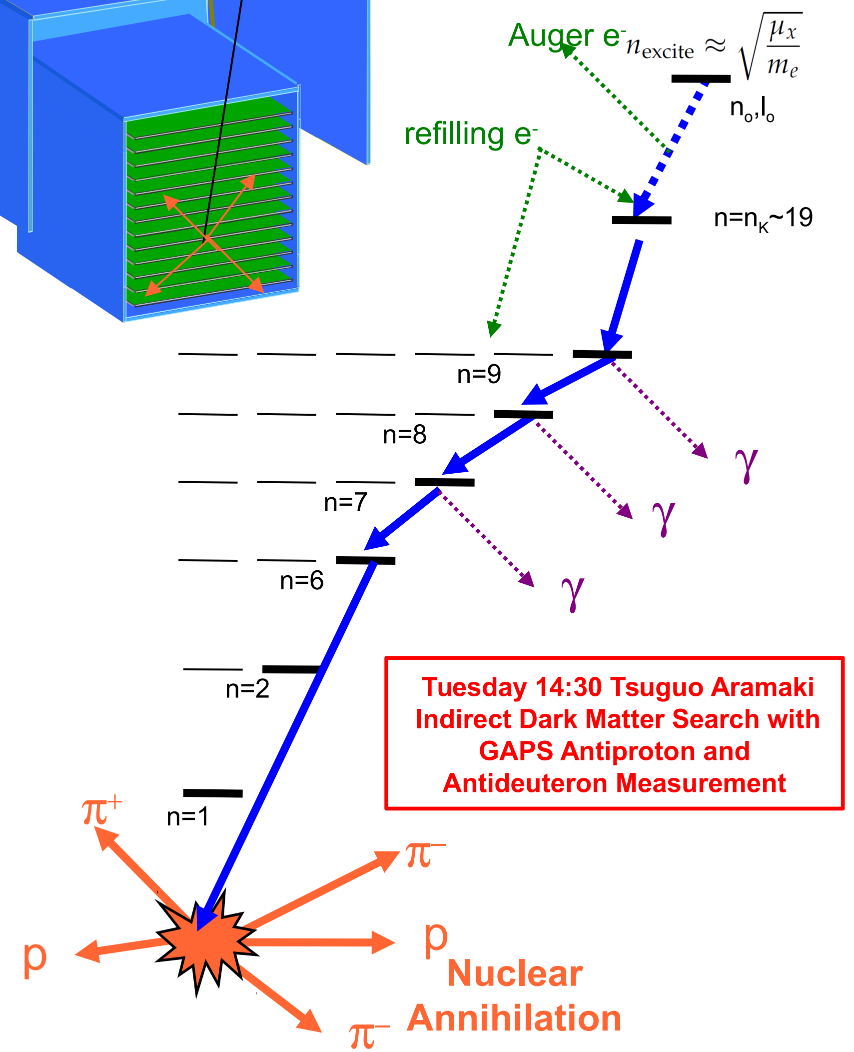
- antideuteron slows down and stops in material
- large chance for creation of an excited exotic atom (E_{kin}~E_I)
- Deexcitation [ns]:
  - fast ionisation of bound electrons (Auger) → complete depletion of bound electrons
  - Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via **characteristic X-ray transition**

$$\Delta E = 13.6\,eV \cdot (z_x Z_N)^2 \cdot \frac{\mu_x}{\mu_H} \cdot \left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

$$\mu_x = \frac{m_x \cdot m_N}{m_x + m_N} \quad \wedge \quad \mu_e = \frac{m_e \cdot m_N}{m_e + m_N}$$

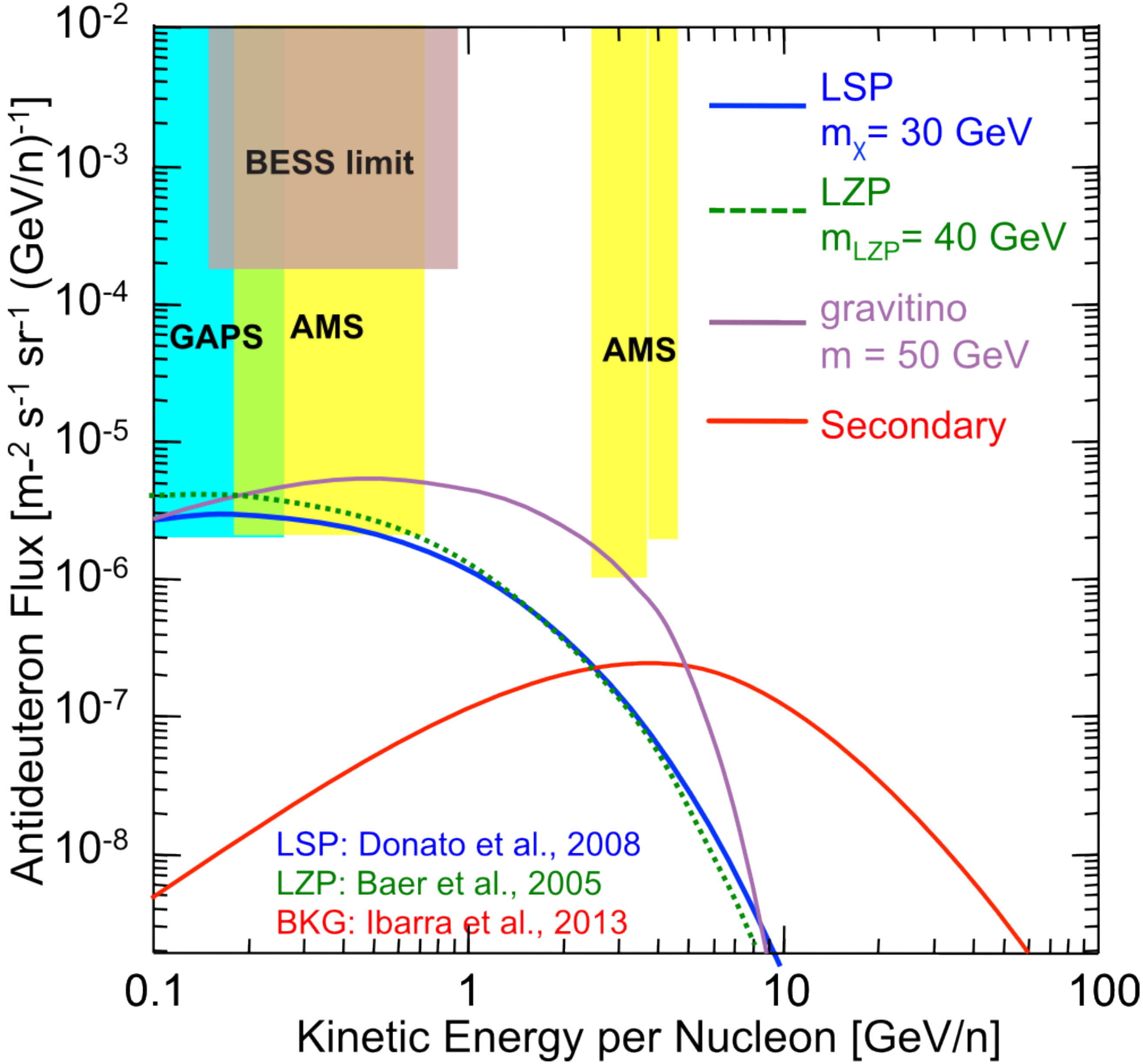
- nucleus-antideuteron annihilation: **pions and protons**
- KEK testbeam measurements → exotic physics well understood
  [Aramaki et al. Astropart. Phys. 49, 52 (2013)]
- Prototype 2012 worked very well
  [PvD et al., Astropart. Phys. 54, 93 (2014),
  I.Mognet et al. Nucl. Instr. Meth. A 735, 24 (2014)]
- Planned first science flight: 2018/19



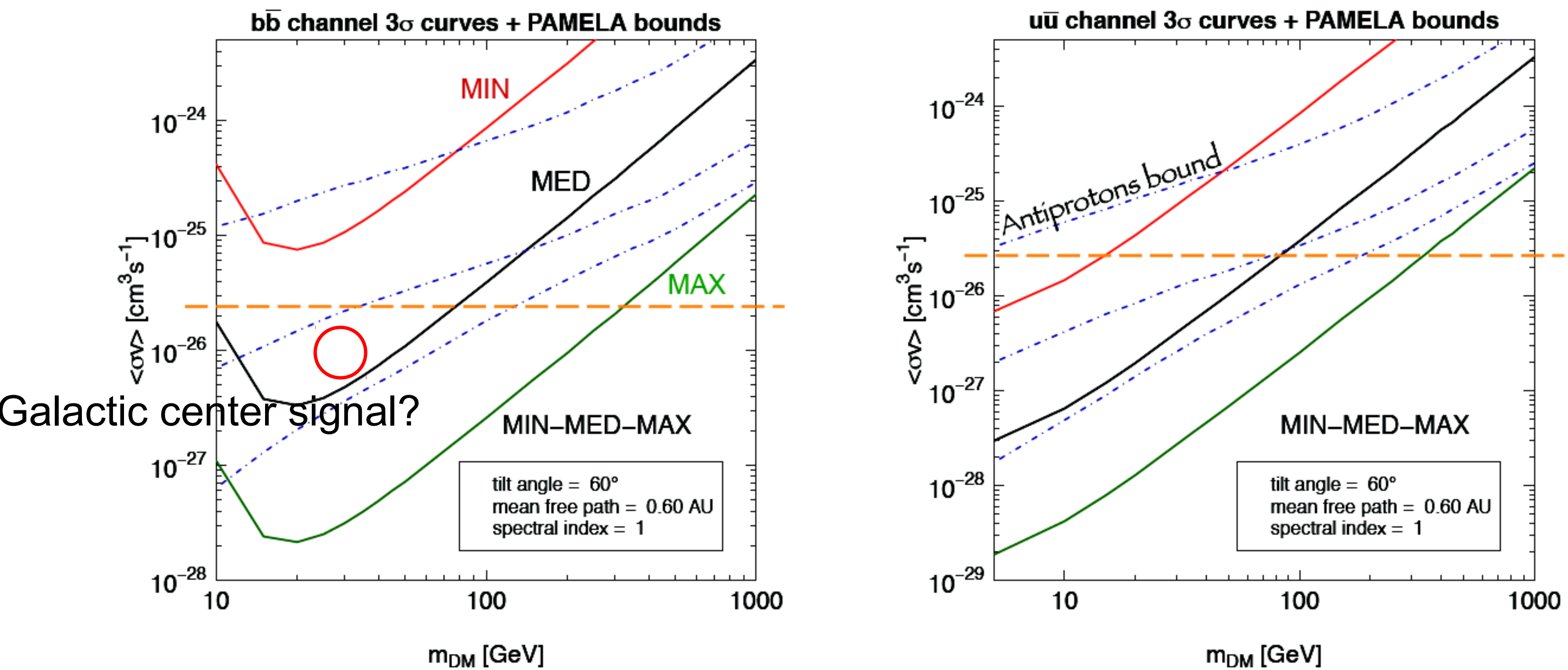


Tuesday 14:30 Tsuguo Aramaki Indirect Dark Matter Search with GAPS Antiproton and Antideuteron Measurement

Antideuteron sensitivity



Reach for the GAPS experiment



Fornengo, Maccione, Vittino, JCAP 1309 (2013) 031

- important sensitivity from low to high dark matter masses
- Independent probe of direct dark matter searches

Conclusion

- measurement of antideuterons is a promising way for indirect dark matter search
- AMS on the ISS is currently the best instrument for the study of antideuterons
- future GAPS is specifically designed for low-energetic antideuterons
- more exchange between theory and experiments:
  start a bigger community effort
- What experimental data are needed?
  What would we need from the collider community?