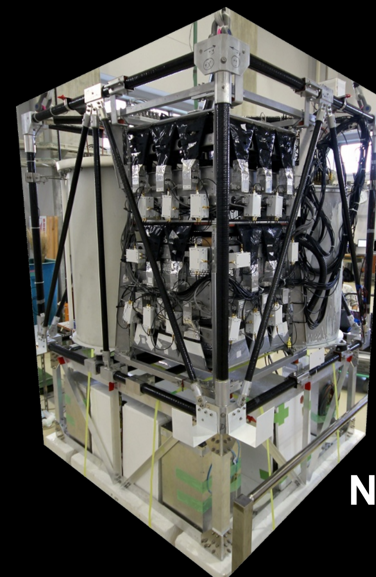
Cosmic ray antideuteron searches and NA61/SHINE



NA61/SHINE & NA49 meeting
January 2015

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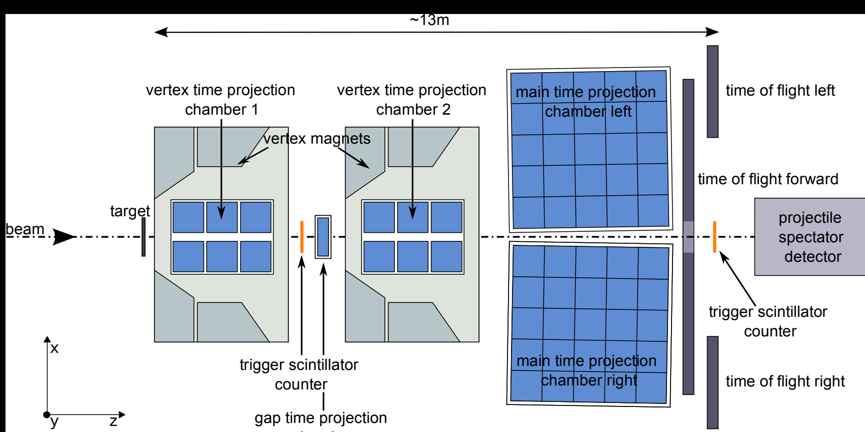
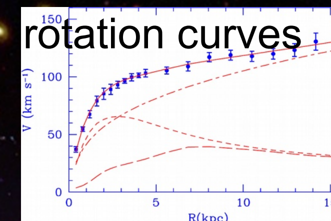


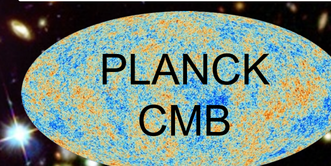
http://www.phys.hawaii.edu/~philipvd
www.antideuteron.com


Diamond Head
Waikiki
Physics Department

Existence of dark matter

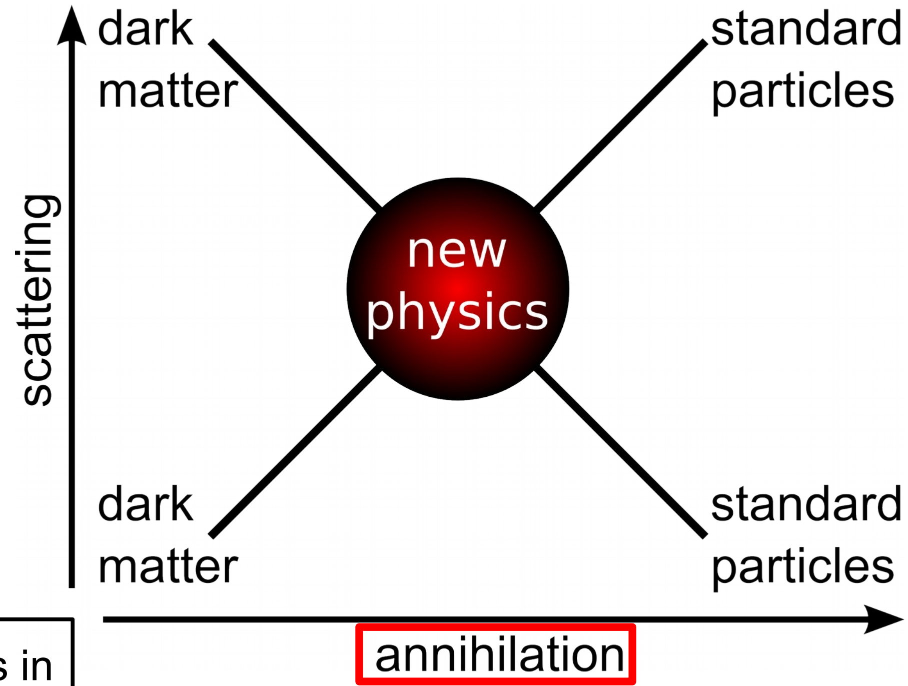
Bullet cluster
red: hot X-ray emitting gas
blue: distribution of dark matter





- **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

How is dark matter interacting?



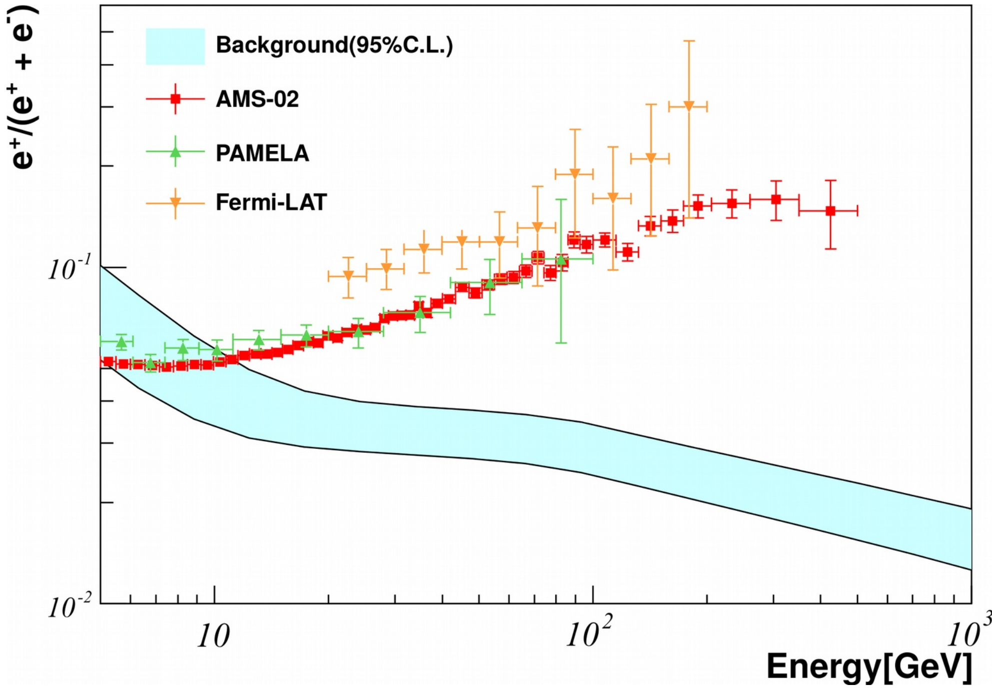
- **direct dark matter search**
  - heavy, very pure target materials in deep mines
  - experiments start to reach preferred parameter space
  - **experiments disagree**

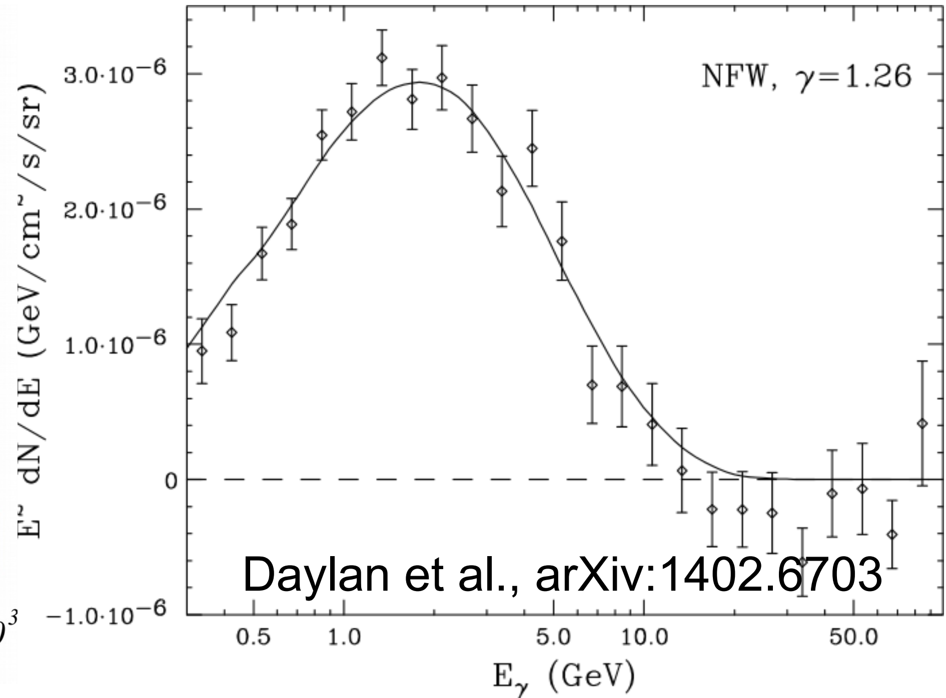
- **natural assumption:** dark matter was in thermal equilibrium in the early universe expansion led to dark matter freeze-out
- **WIMP miracle:** weak-scale particles are ideal candidates (~100-1000GeV) to reproduce observed relic dark matter density

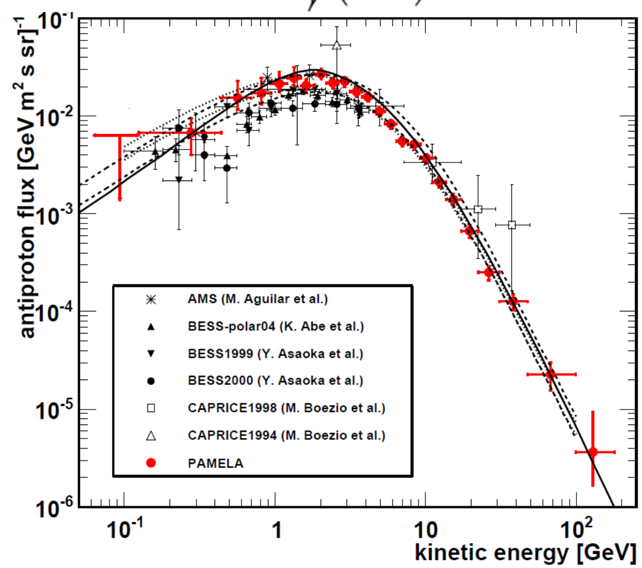
→ dark matter must be able to interact with standard model particles

- **assumption:** cosmic-rays from dark matter annihilation follow different kinematics than conventional production
- peak/bump/shoulder on top of conventional spectrum expected
- use search channel without strong conventional production: positrons, photons, antiprotons, electrons, neutrinos, ...

Dark matter signal in cosmic rays?





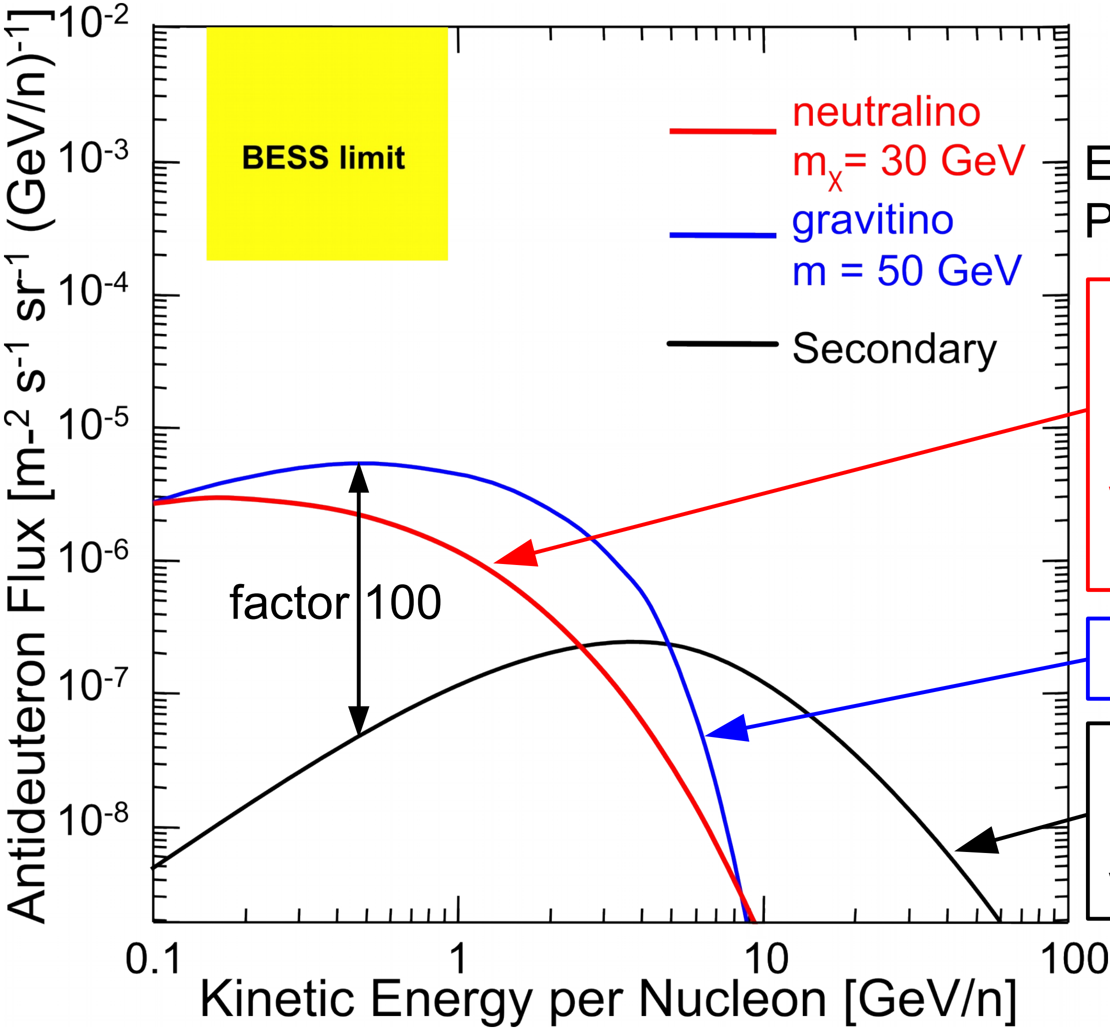


- unexplained features in positrons
- proposed theories:
  - astrophysical origin → pulsars
  - SNR acceleration
  - **dark matter self-annihilation**
- gamma-ray excess at the galactic center → 30GeV dark matter particle?

- **no excess for antiprotons → used to constrain dark matter models**


d14
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

Status of cosmic ray antideuterons



Examples for beyond-standard-model Physics:

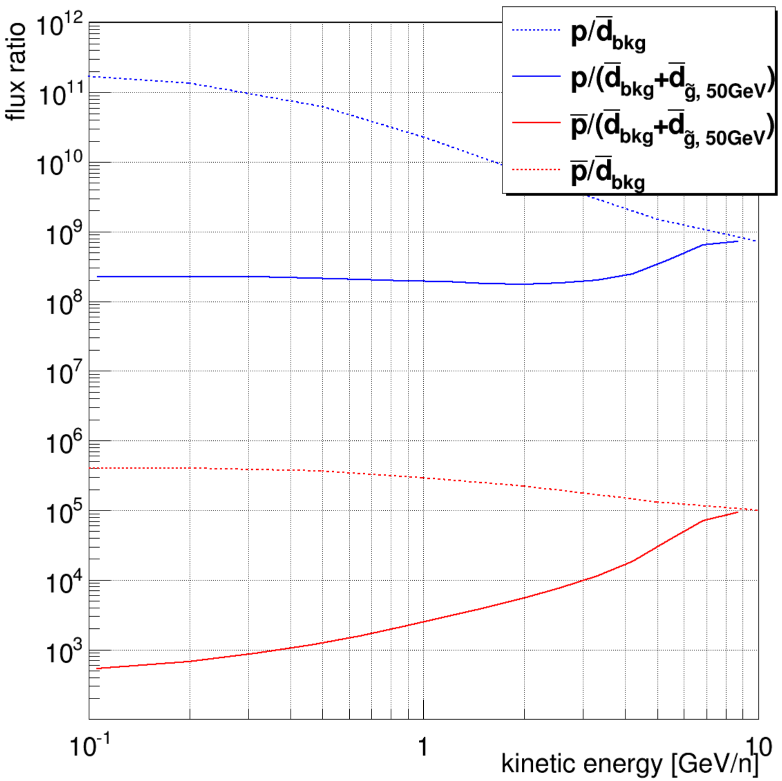
Neutralino: SUSY lightest supersymmetric particle, decay into $b\bar{b}$, compatible with new signal from galactic center measured by Fermi

late decays of unstable gravitinos

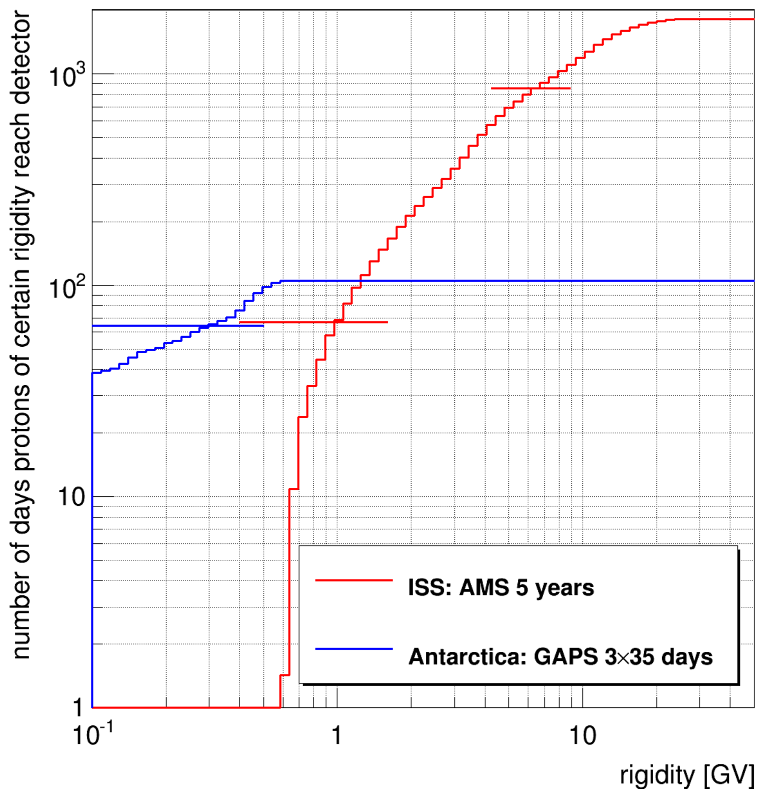
astrophysical background: collisions of protons and antiprotons with interstellar medium

Antideuterons are the most important unexplored indirect detection technique!

Observational challenges



flux ratios

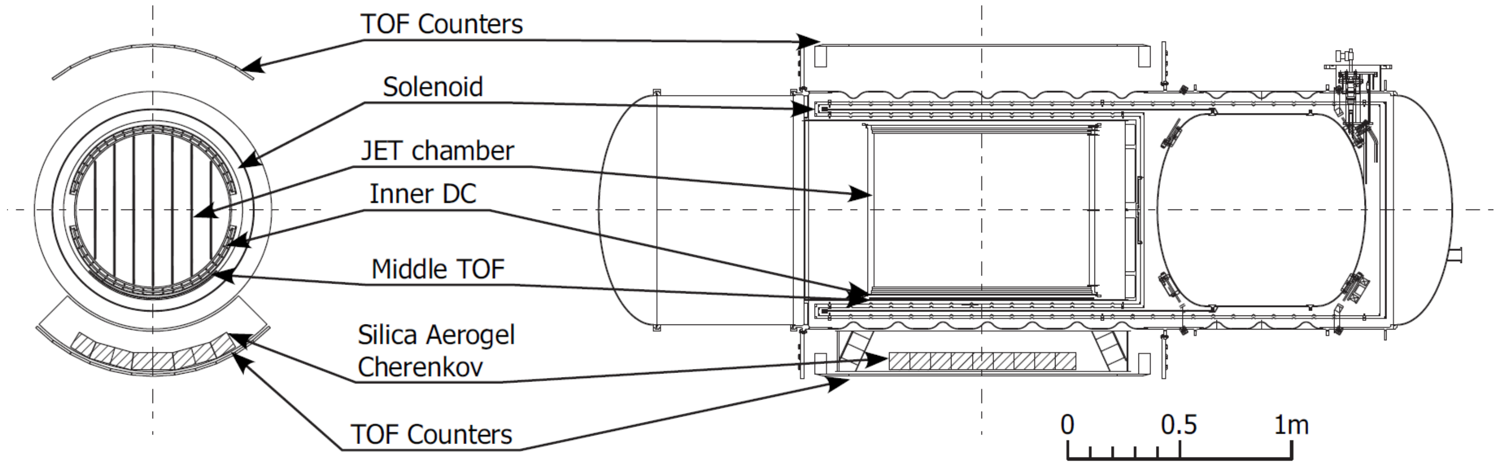


geomagnetic cut-off

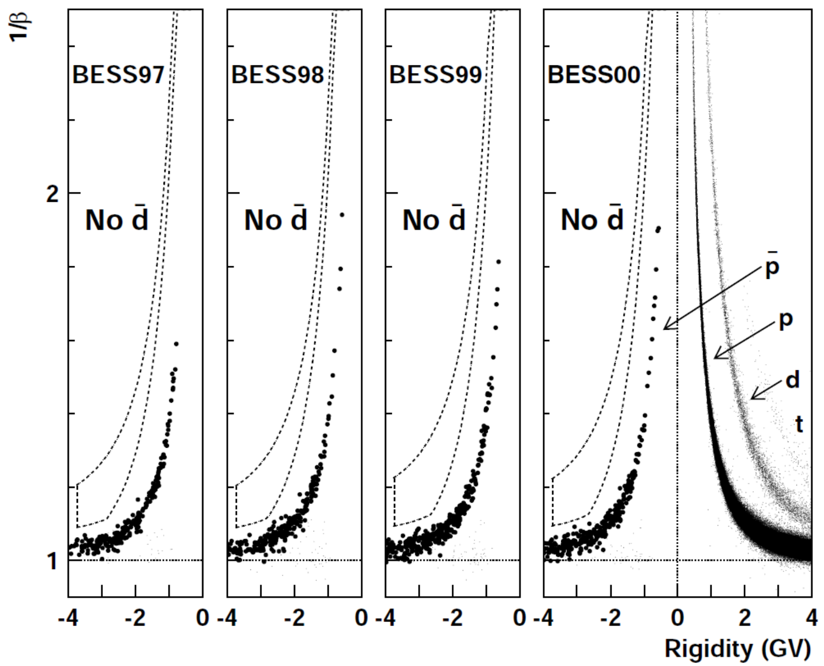
antideuteron measurement with balloon and space experiments requires:

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

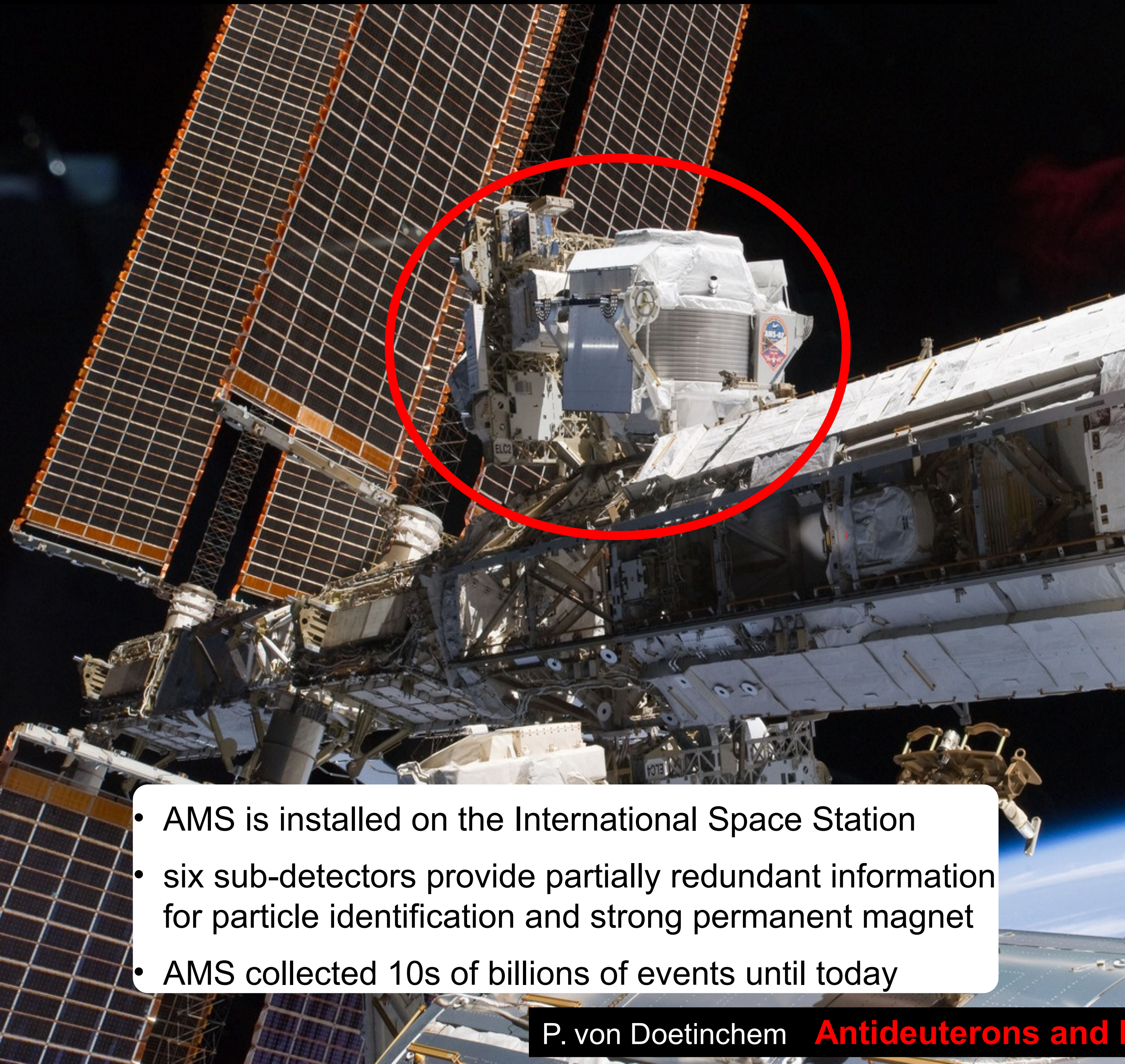
Best antideuteron limit: BESS



- 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 1.9×10^{-4}(m^2s sr GeV/n)$^{-1}$ @ 95% C.L.

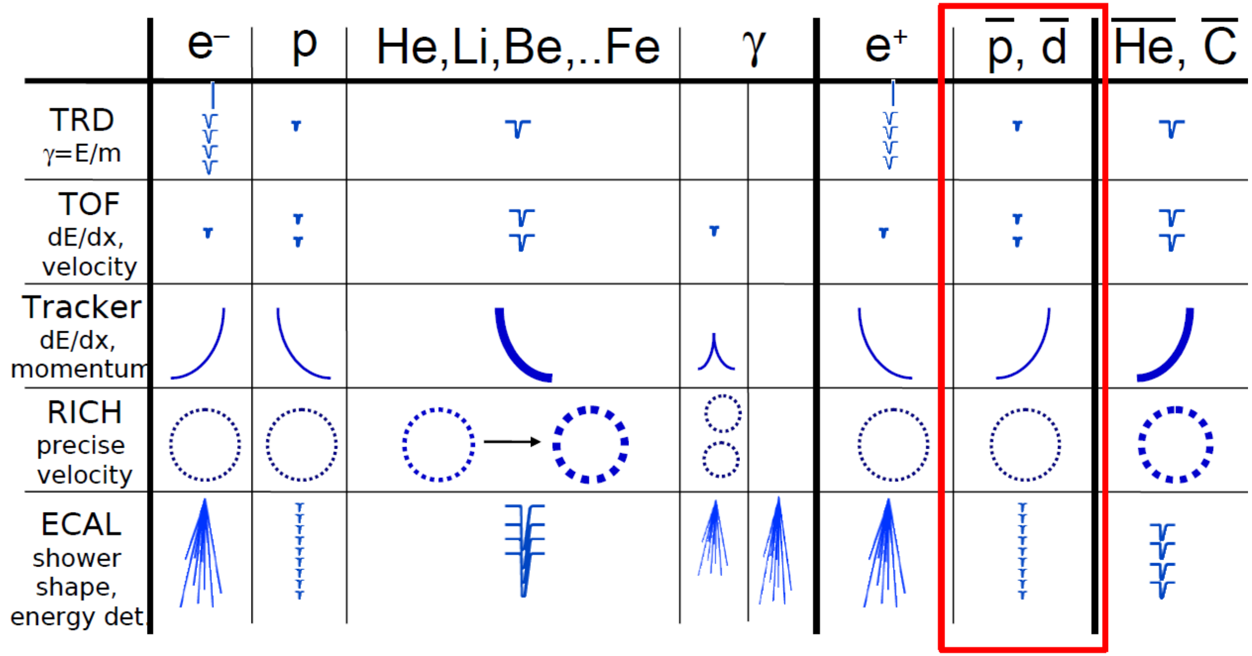


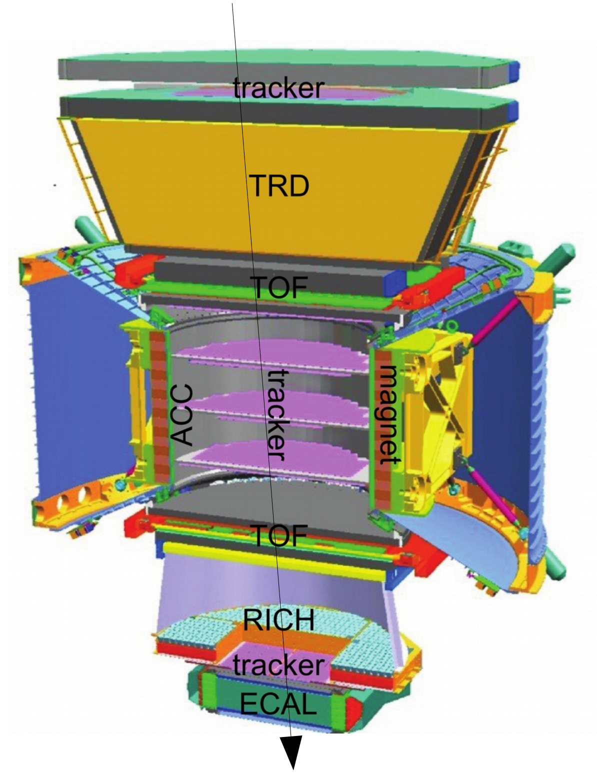
AMS on the International Space Station



- AMS is installed on the International Space Station
- six sub-detectors provide partially redundant information for particle identification and strong permanent magnet
- AMS collected 10s of billions of events until today

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

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

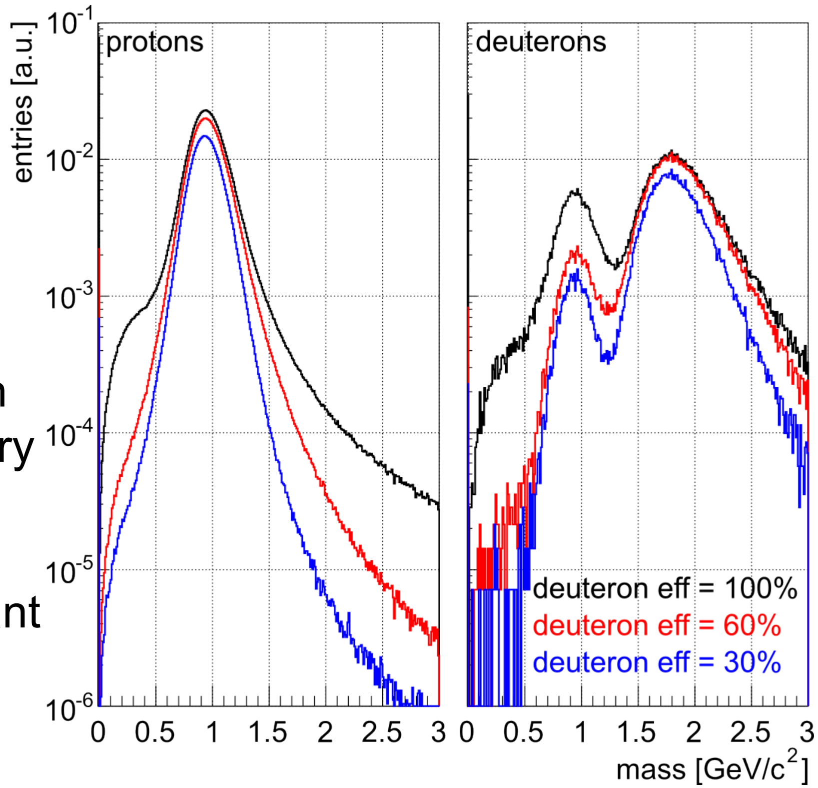
- **self-calibrated analysis:**
  - –calibrate antideuteron analysis with deuterons and antiprotons (simulations and data)
  - –geomagnetic cut-off location is challenging: study low-energy protons and electrons to calibrate geomagnetic and solar effects

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



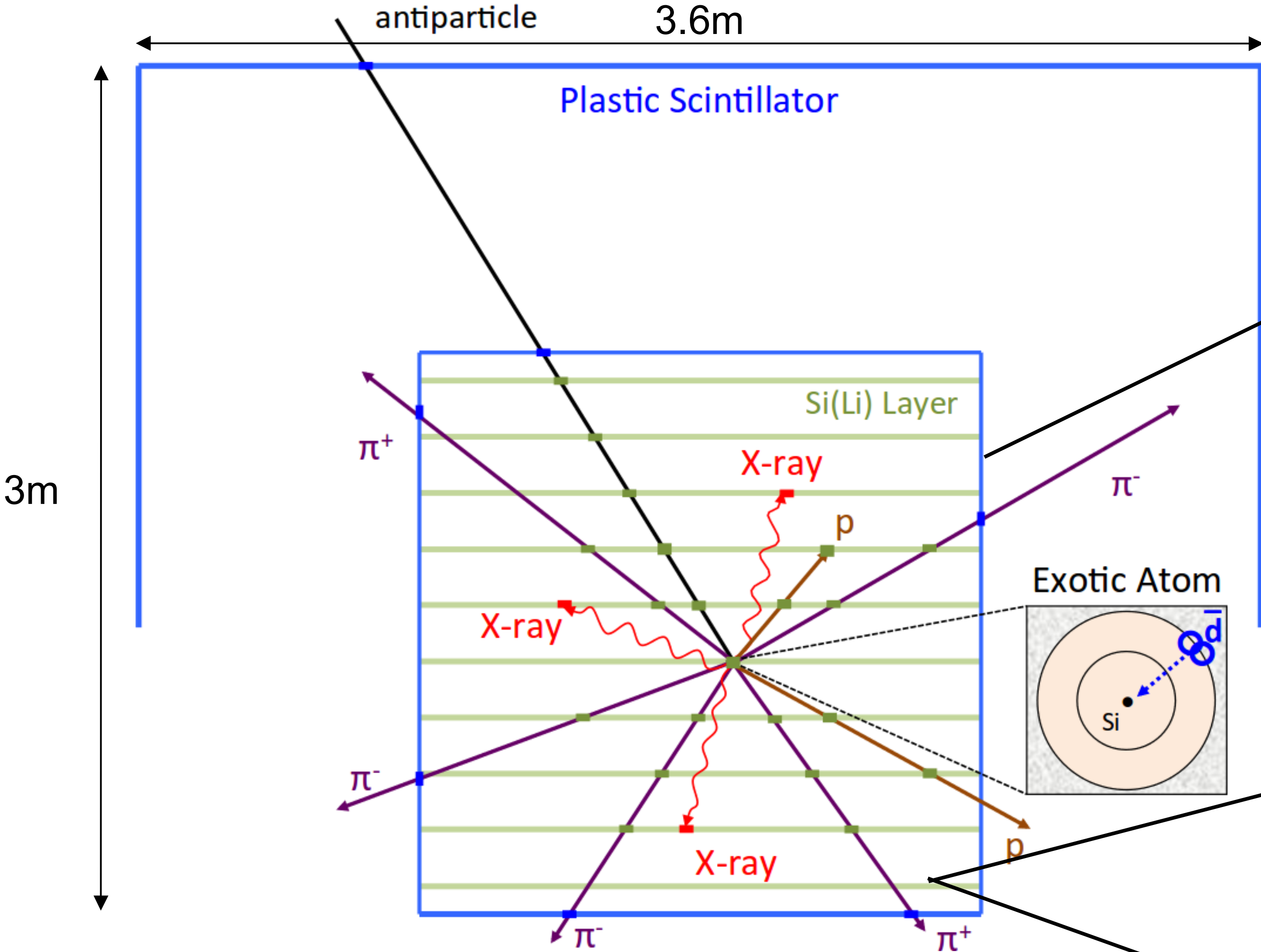
Electrons: most abundant CR component with negative charge, but non-hadronic and with very different mass

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 (~40% AMS top to ECAL top) - dangerous if upgoing (the He ion itself or its fragments)

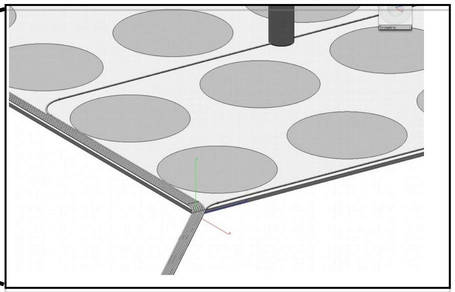
The GAPS experiment

Columbia U, UC Berkeley
UCLA, U Hawaii,
Haverford



plastic scintillators
with PMT readout

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

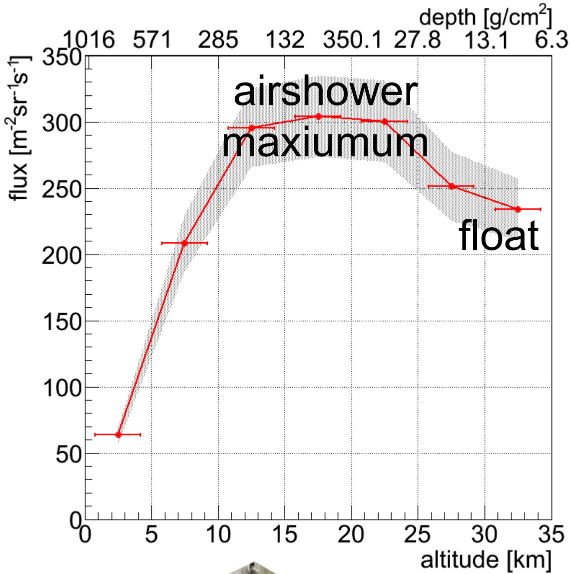


~1400 Si(Li) wafers

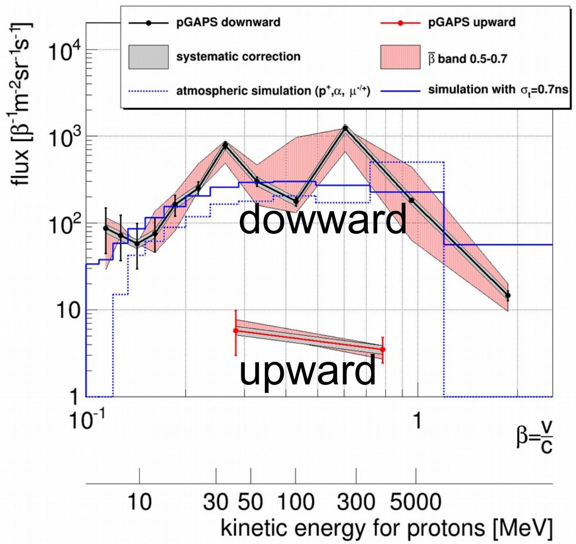
- the **G**eneral **A**nti**P**article **S**pectrometer is especially designed for **low-energy antideuterons and antiprotons**
- identification by stopping and creation of an exotic atom [KEK testbeam measurements → Astropart. Phys. 49, 52 (2013)]
- LDB flights from Antarctica

Prototype GAPS

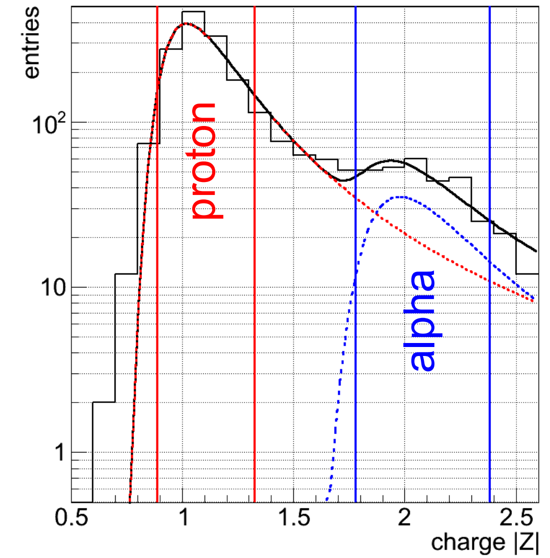
total flux vs. altitude

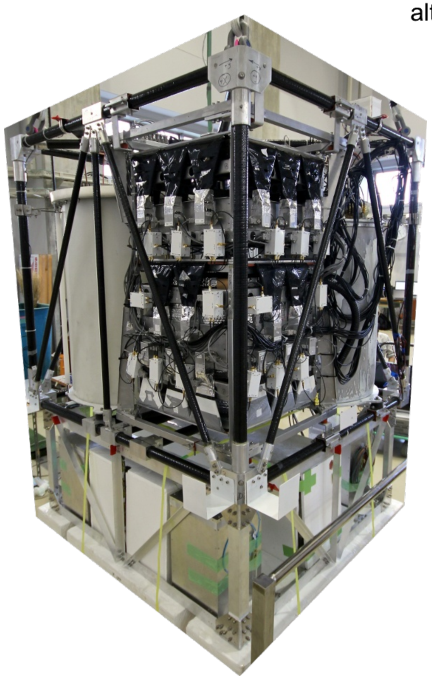


flux vs. β at 33km



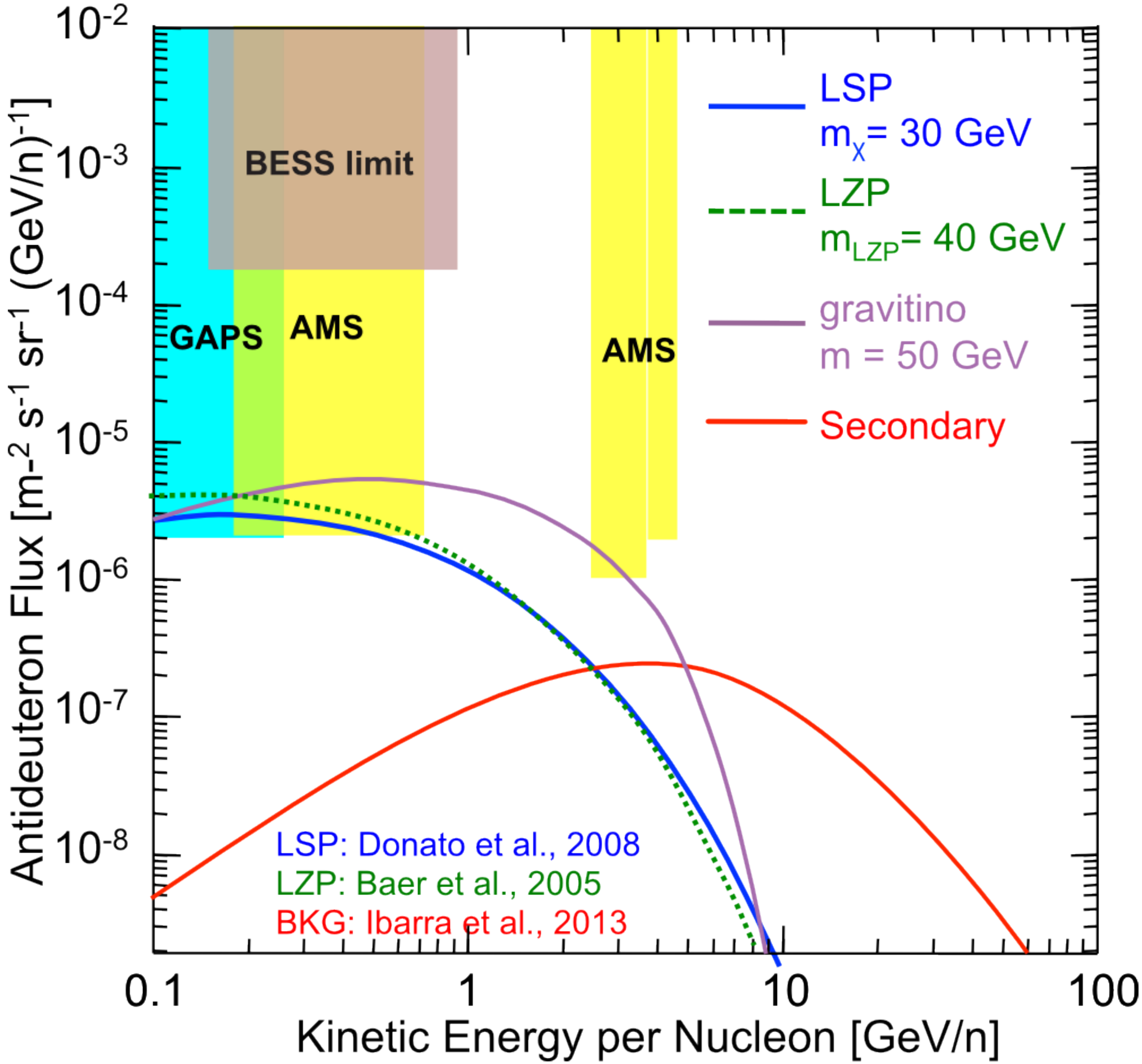
particle composition at 33km



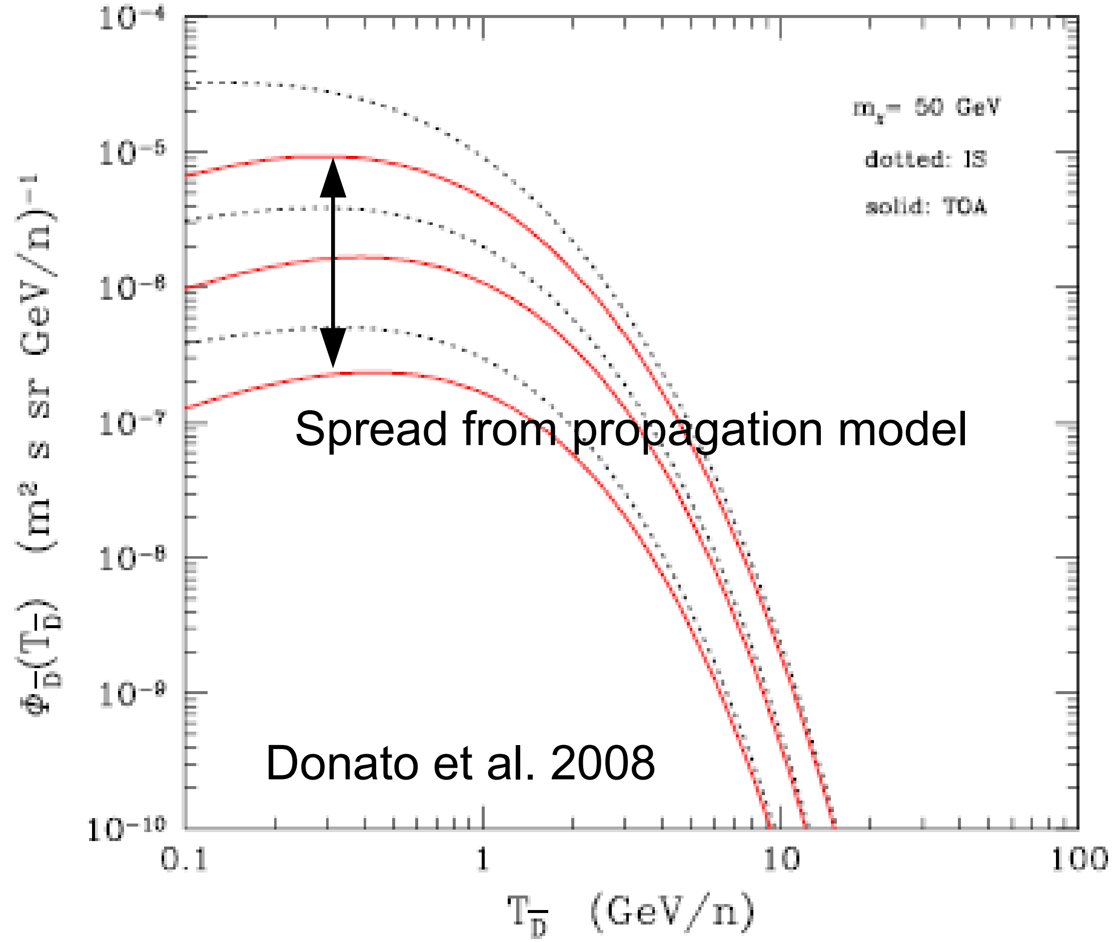


- successful flight of small prototype GAPS from Japan in June 2012
- demonstrated stable operation of the detector components during flight
- studied Si(Li) cooling approach for thermal model
- flux measurements:
  - flux at drift-out “boomerang” altitude (10-15km) is ~30% higher than at float (33km)
  - flux as function of velocity compared to simulations with Geant4+PLANETOCOSMICS (incl. geomagnetic, atmospheric effect)
  - α particles constitute about ~10% of the flux at 33km (~9g/cm^2) → in good agreement with BESS data

Antideuteron sensitivity



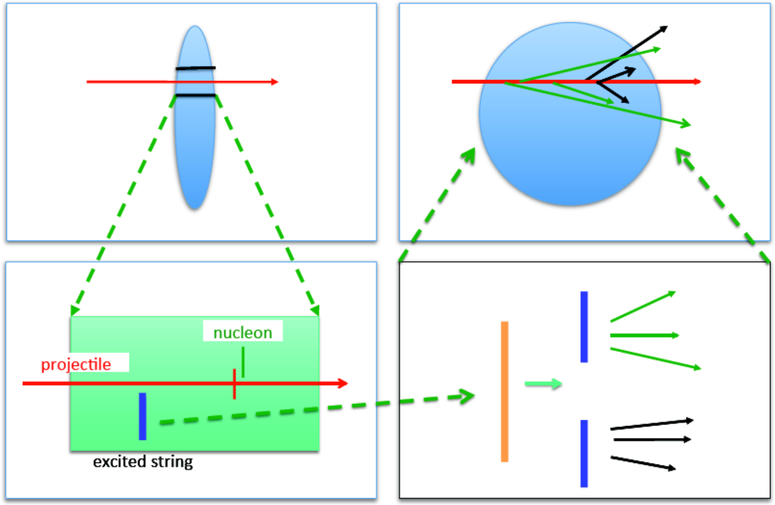
Propagation uncertainty

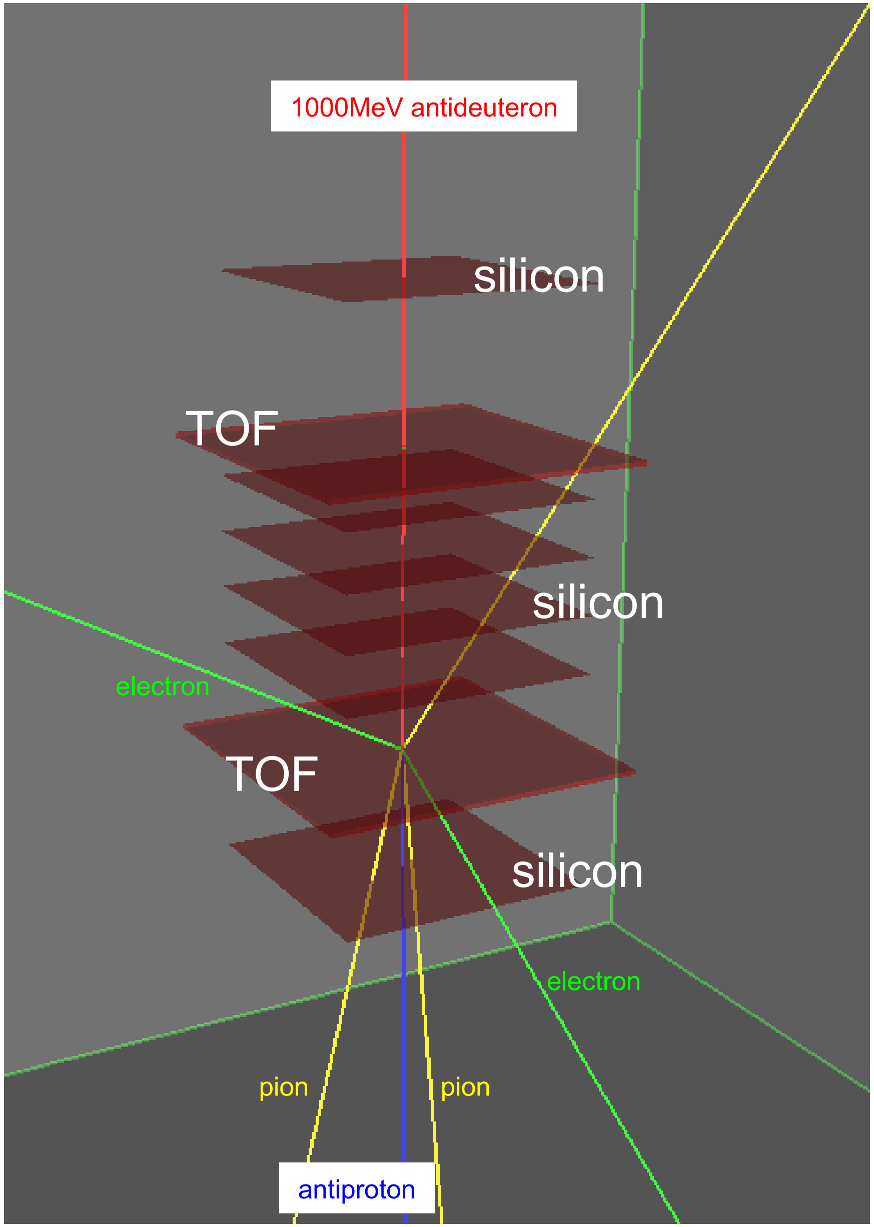


- Propagation is the strongest uncertaintiy source for primary antideuterons: **halo size for diffusion calculation poorly constrained**
- More data on various nuclear species are needed

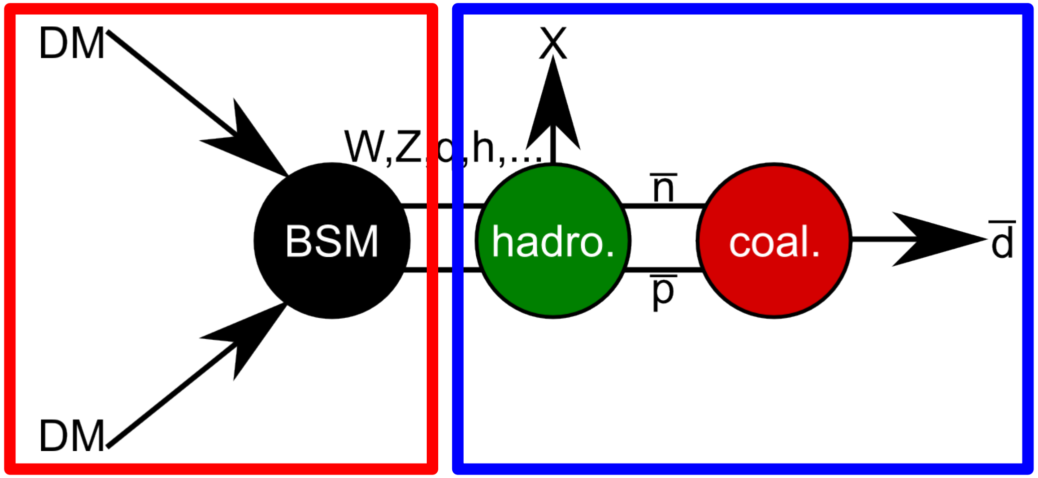
Geant4 - Model for $\bar{d}$ simulation

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



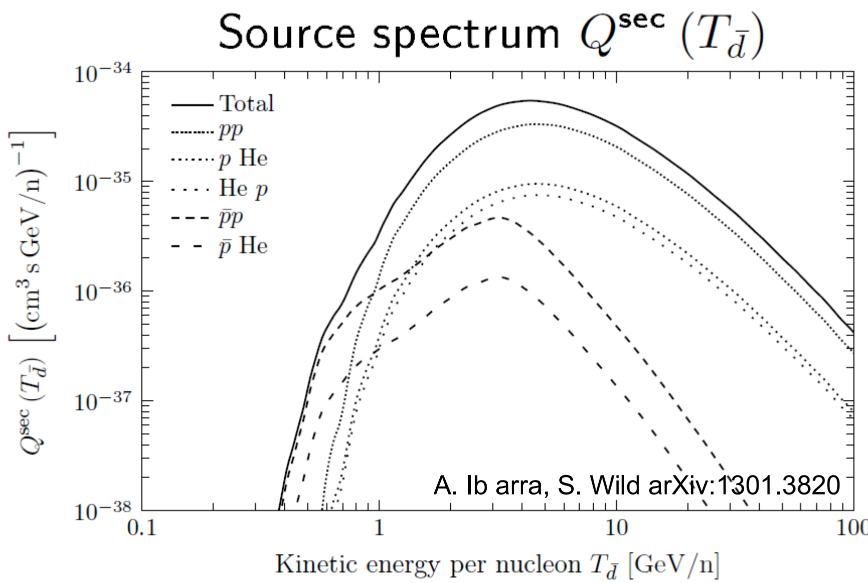


Antideuteron formation



dark matter

conventional production & dark matter



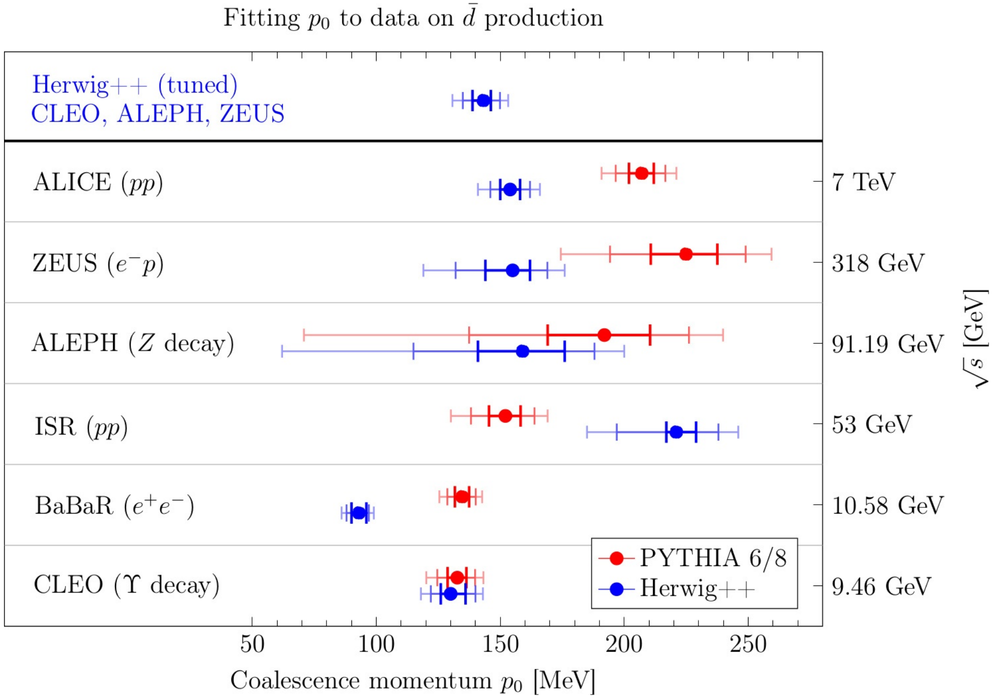
- antideuterons can be formed by an antiproton-antineutron pair if relative momentum is small (coalescence momentum p_0)

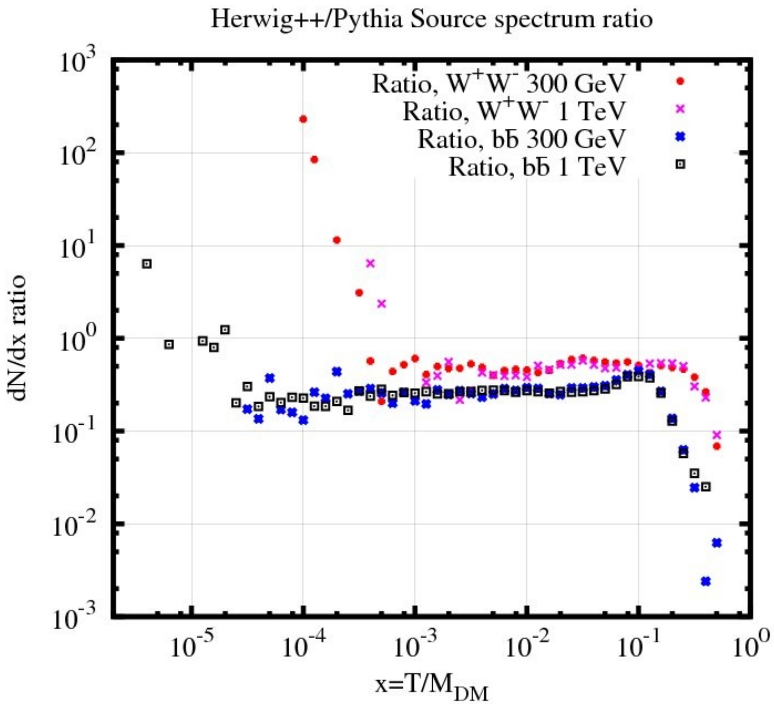
$$E_{\bar{d}} \frac{d^3 N_{\bar{d}}}{d^3 k_{\bar{d}}} = p_0^3 \cdot \frac{1}{8} \cdot \frac{4\pi}{3} \cdot E_{\bar{p}} \frac{d^3 N_{\bar{p}}}{d^3 k_{\bar{p}}} \cdot E_{\bar{n}} \frac{d^3 N_{\bar{n}}}{d^3 k_{\bar{n}}}$$

- 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)

    → threshold is much lower → antiprotons are important

Coalescence uncertainty





- 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) or Υ resonance (10GeV DM)?
- Coalescence does not affect antiproton/proton ratio → break degeneracy of antiproton and antideuteron

How to improve?

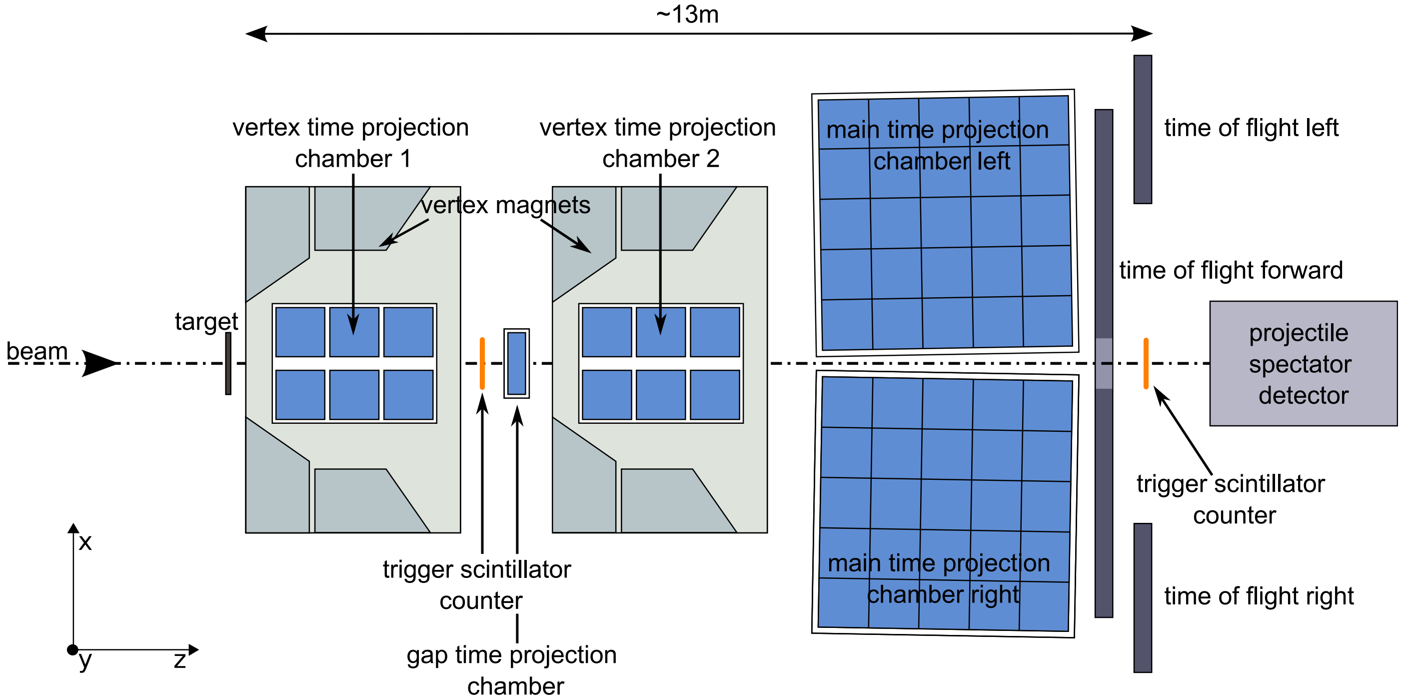
(1) Antideuteron production depends on the exact underlying process and the available center of mass energy:

- Cosmic ray antideuteron production is most likely dominated by the production relatively close to the threshold (anti-correlation due to phase space considerations of antiprotons and antineutrons important)
- Different values of p_0 for different dark matter masses and different contributing background processes might be the right approach

(2) Monte Carlo generators are not reliable enough.

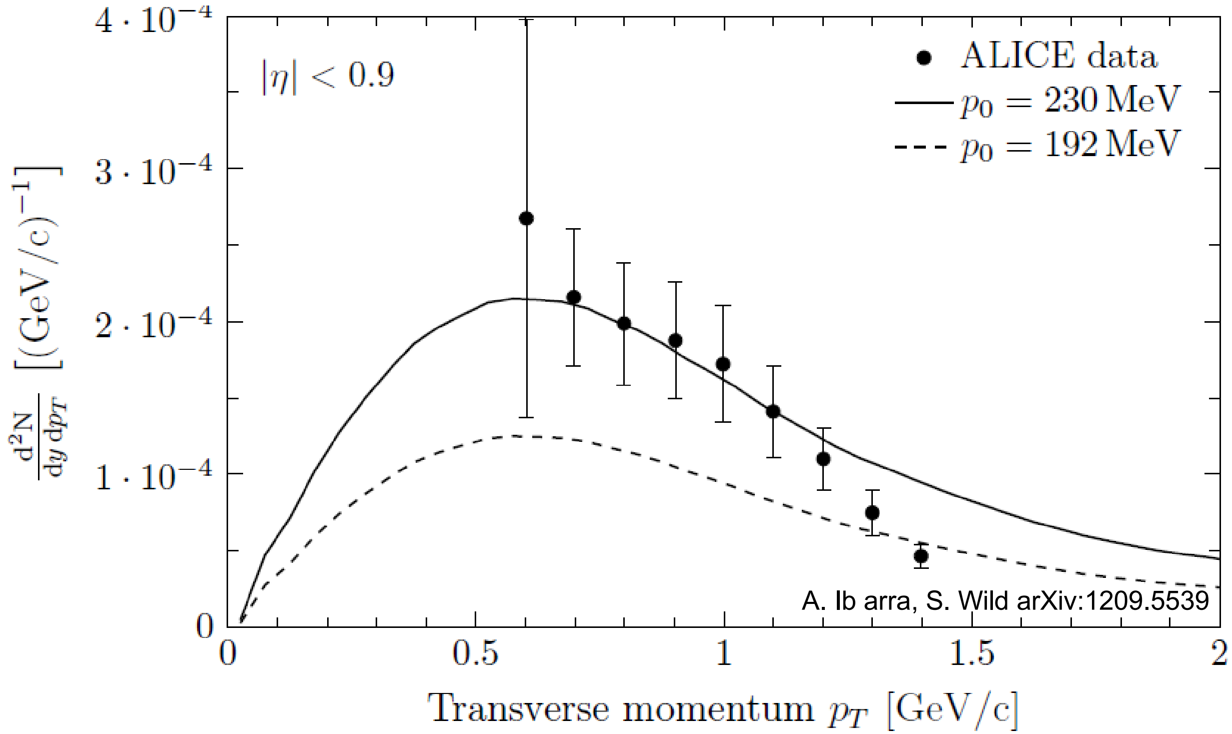
Event-by-event coalescence model approach has to be validated against more data to reduce the production uncertainty for the cosmic ray antideuteron interpretation

Antideuterons and NA61/SHINE



- Low-energy cosmic ray antideuteron background flux (< 1 GeV/n) is dominated by products of proton interactions with interstellar medium hydrogen at somewhat higher kinetic energies (~2-5 GeV/n)
- Cosmic ray production happens between 40 and 400 GeV/c
  → SPS energies from 9 to 400 GeV/c are ideal
- Proton-proton interactions with incident momentum between 13 and 158 GeV/c were already recorded in 2011

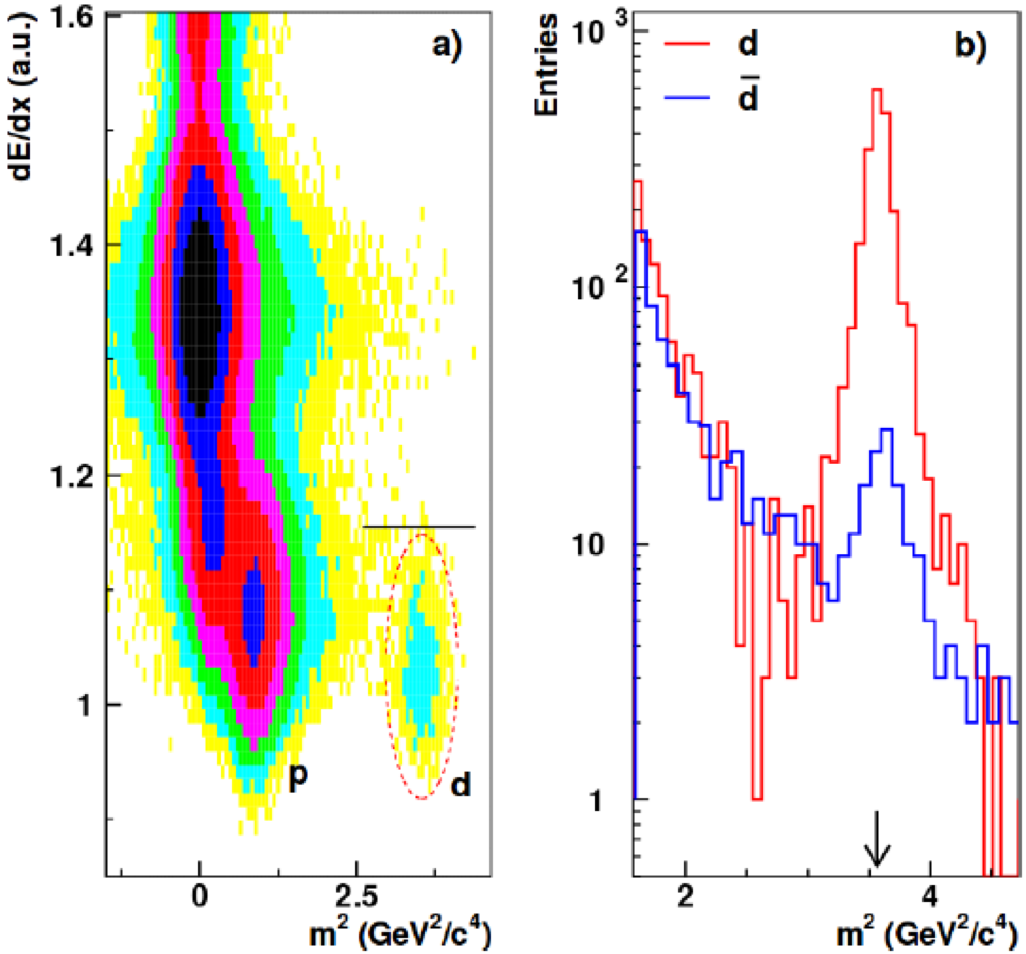
Antideuterons and NA61/SHINE



- Study (anti)deuteron production as a function of rapidity and transverse momentum
- measurement of deuteron yield at different energies will answer question if coalescence is really energy dependent or an effect of MC generators
- important cross-check for the MC generators: measurement of the yield of antiprotons with the same data

NA49 antideuterons

- NA49 lead-lead data were already analyzed for antideuterons
- Theoretically not clear how to apply the event-by-event coalescence model to proton-nucleus or nucleus-nucleus collisions

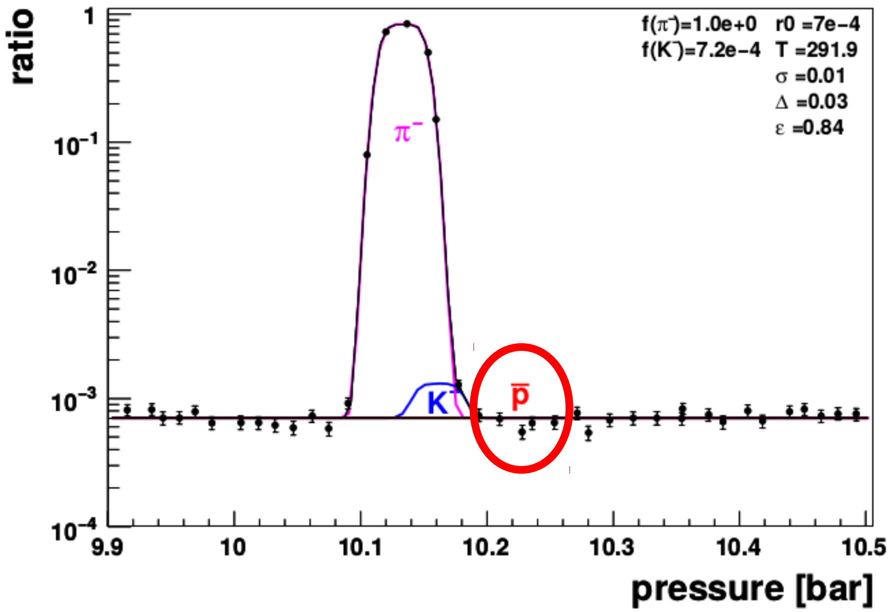


T. Anticic et al., Phys. Rev. C 85, 044913 (2012)

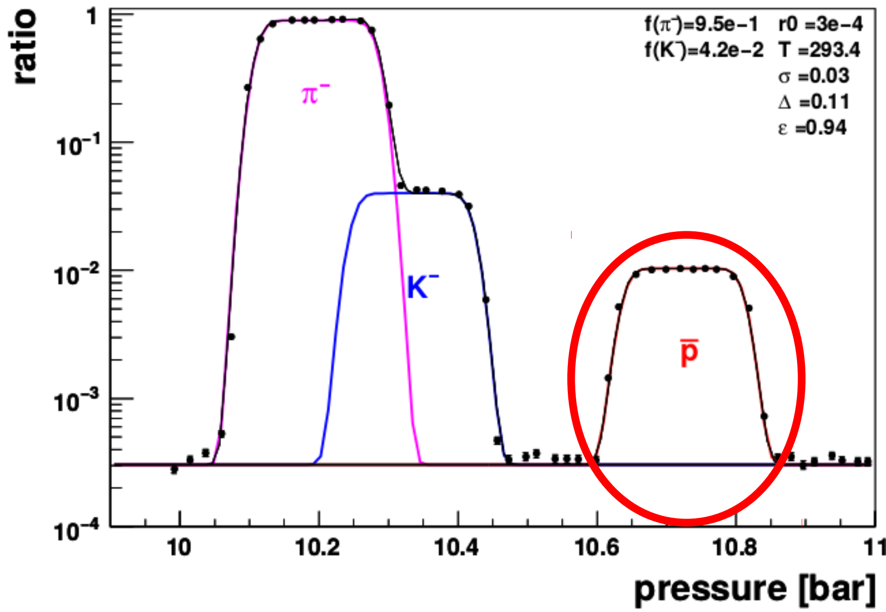
CEDAR scans from 2009

350 GeV/c: **158 GeV/c:**

Incident antiprotons?



from 9756, diaphragm: 0.319 mm, p=10.137 bar



from 9805, diaphragm: 0.958 mm, p=10.2 bar

Postdoc position in Hawaii

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Antideuteron Physics - NA61/SHINE data analysis

Hawaii U. - Postdoc

Field of Interest: astro-ph, hep-ex, nucl-ex
Experiment: CERN-NA-061
Deadline: 2015-02-01
Region: North America

Job description:
Duties and Responsibilities
The research goal is to improve the understanding of antideuteron physics by measuring (anti)deuteron and antiproton production cross-sections with the fixed target experiment NA61/SHINE for the purpose of reducing the uncertainties of cosmic ray antideuteron searches. The successful candidate will participate in NA61/SHINE data taking, experiment calibration, data analysis, and interpretation and will have the opportunity to regularly spend time at CERN. The group is also working on the antideuteron analysis with the ISS-based AMS-02 experiment and the development of the balloon-borne antideuteron experiment GAPS.

Minimum Qualifications
Applicants must hold a doctoral degree, preferentially in (astro)particle physics. Experience with data analysis and software development is expected.

Other Conditions
The initial term of this position is for one year. Renewal subject to satisfactory performance and availability of funds.

To Apply
Send application (cover letter, curriculum vitae, list of publications, and contact information of at least two references) to philipvd@hawaii.edu. Please specify in the subject of the email: Postdoctoral fellow in NA61/SHINE data analysis.

Inquiries
Dr. Philip von Doetinchem
Assistant Professor
e-mail: philipvd@hawaii.edu
www.phys.hawaii.edu/~philipvd
www.antideuteron.com

Contact: Philip von Doetinchem
Email: philipvd@hawaii.edu
More Information: http://workatuh.hawaii.edu/Jobs/NAdvert/20409/3024182/1/postdate/desc
Letters of Reference should be sent to: philipvd@hawaii.edu

Conclusion & Outlook

- 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
- Measurements with NA61/SHINE will improve understanding of antideuteron production and modeling