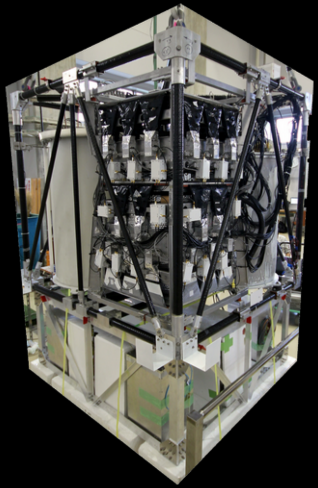
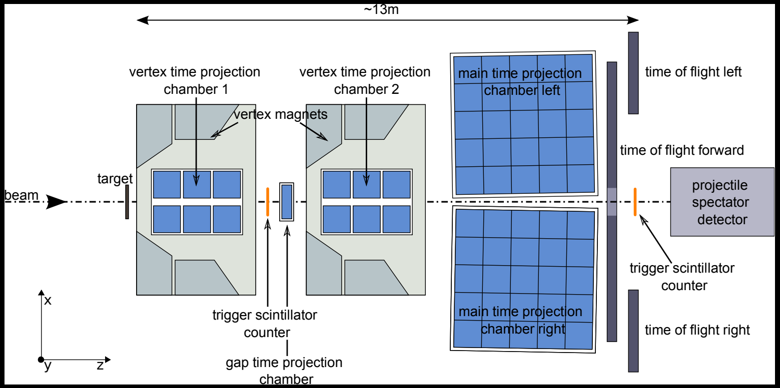
Dark matter identification with cosmic-ray antideuterons





FAU Erlangen-Nürnberg
October 2017

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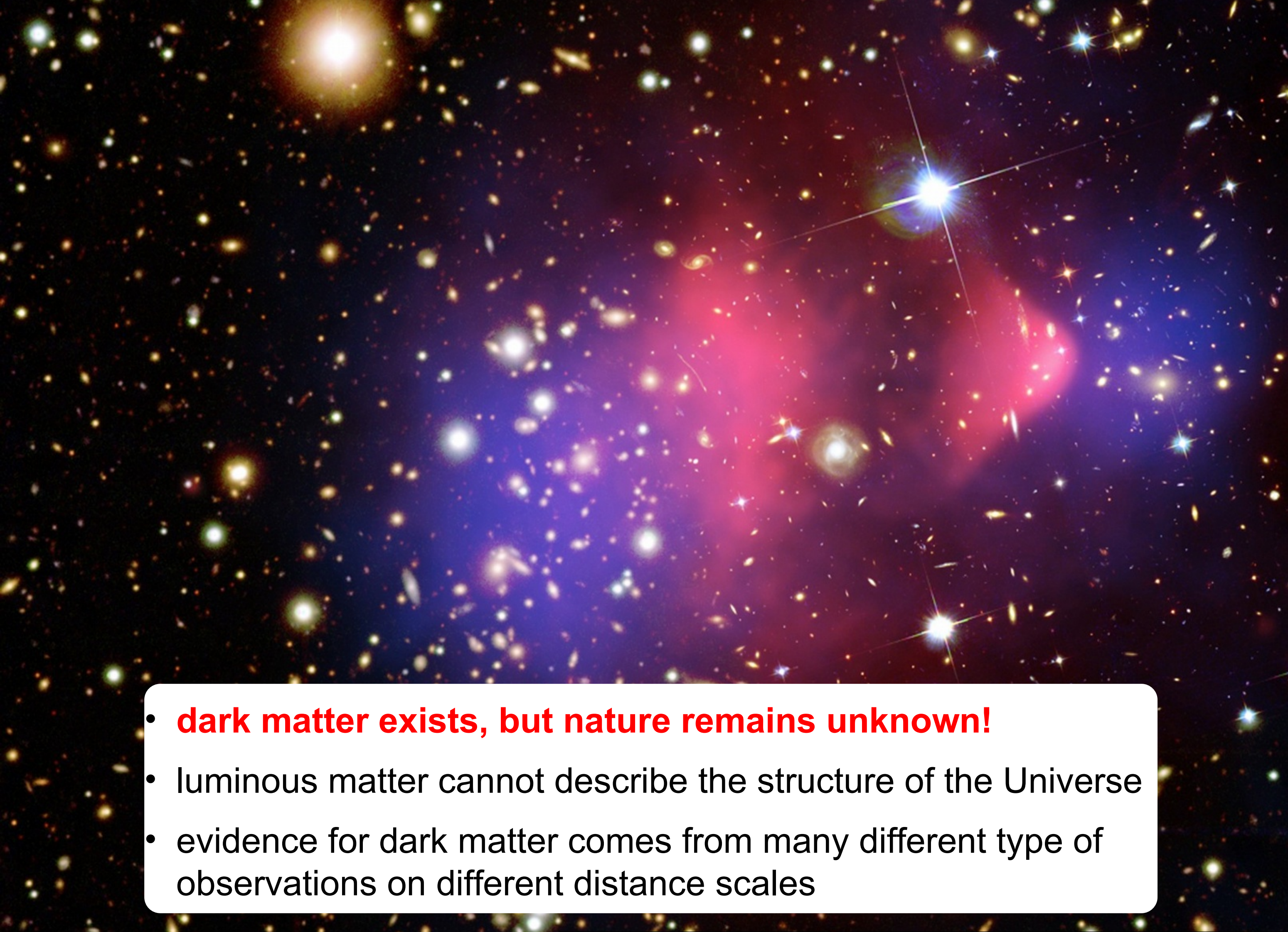
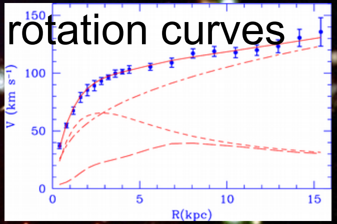
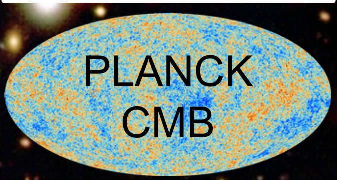
Existence of dark matter

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



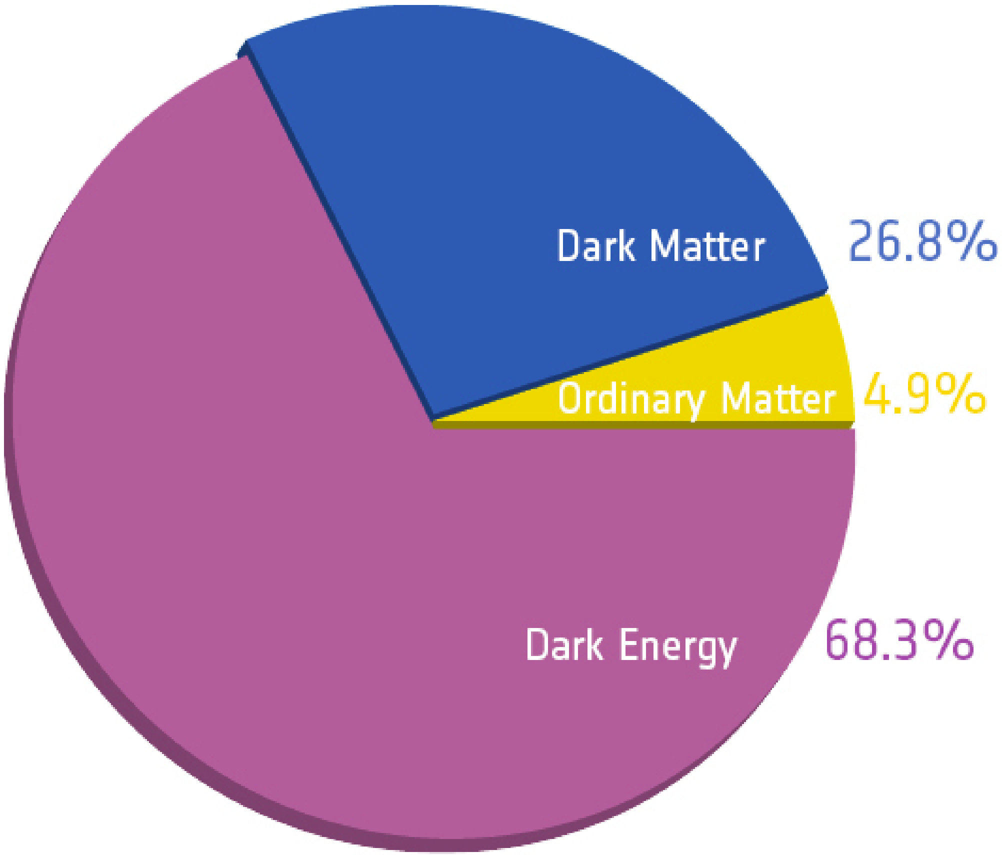
rotation curves


Abell 1689: gravitational lensing

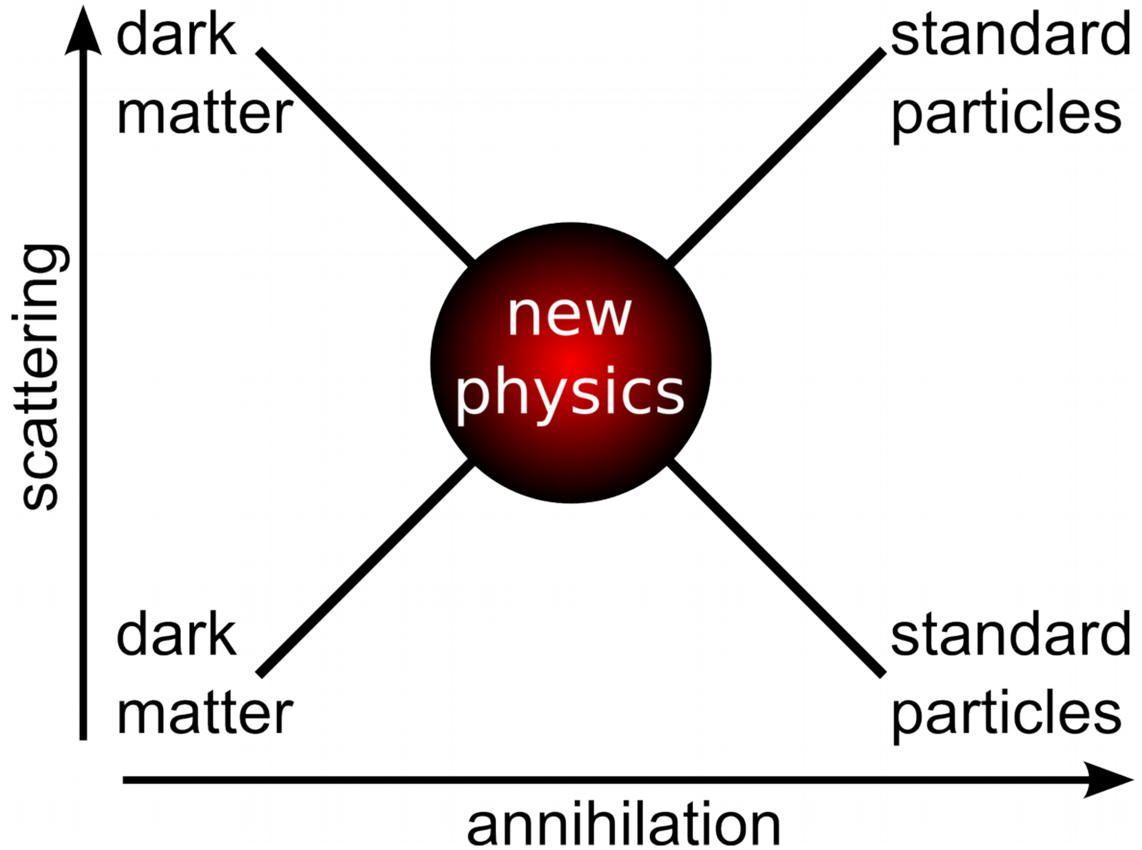
- **dark matter exists, but nature remains unknown!**
- luminous matter cannot describe the structure of the Universe
- evidence for dark matter comes from many different type of observations on different distance scales

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**

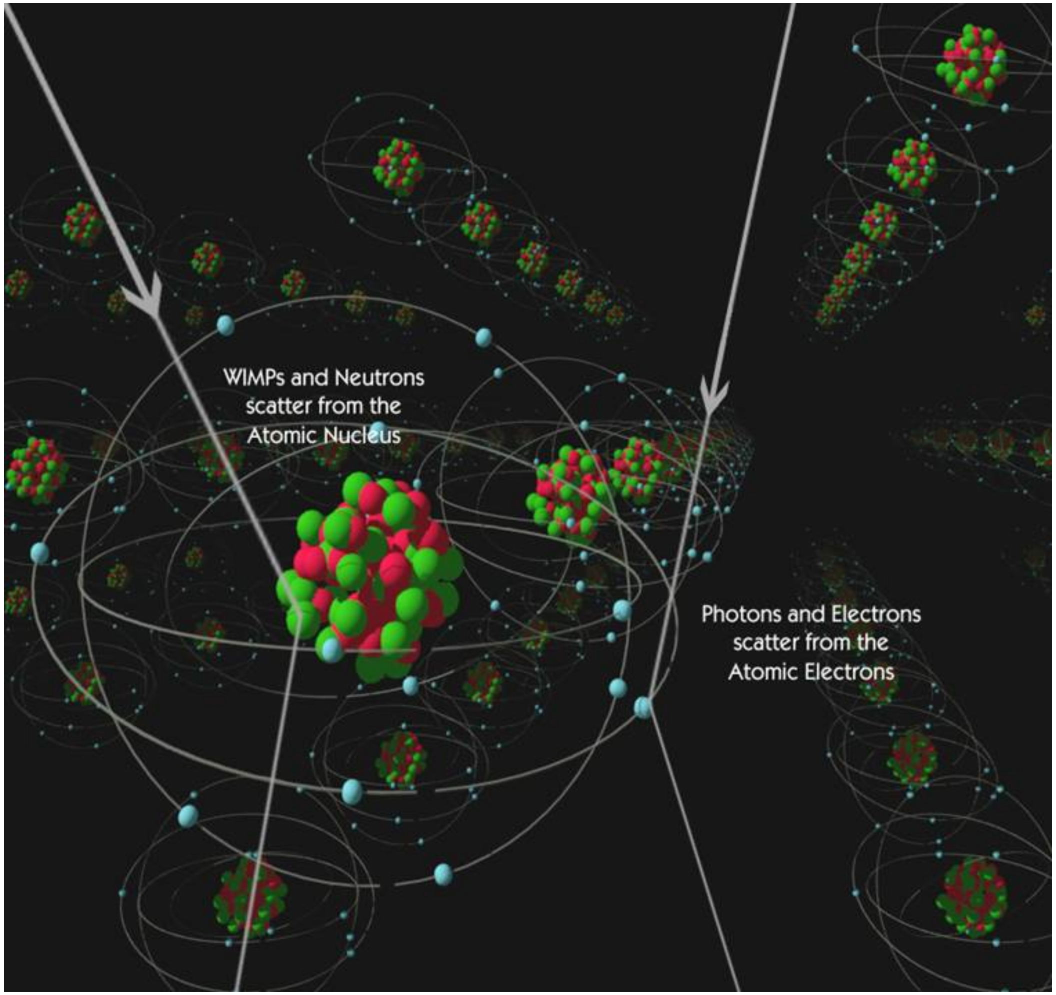
How is dark matter interacting?



- **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

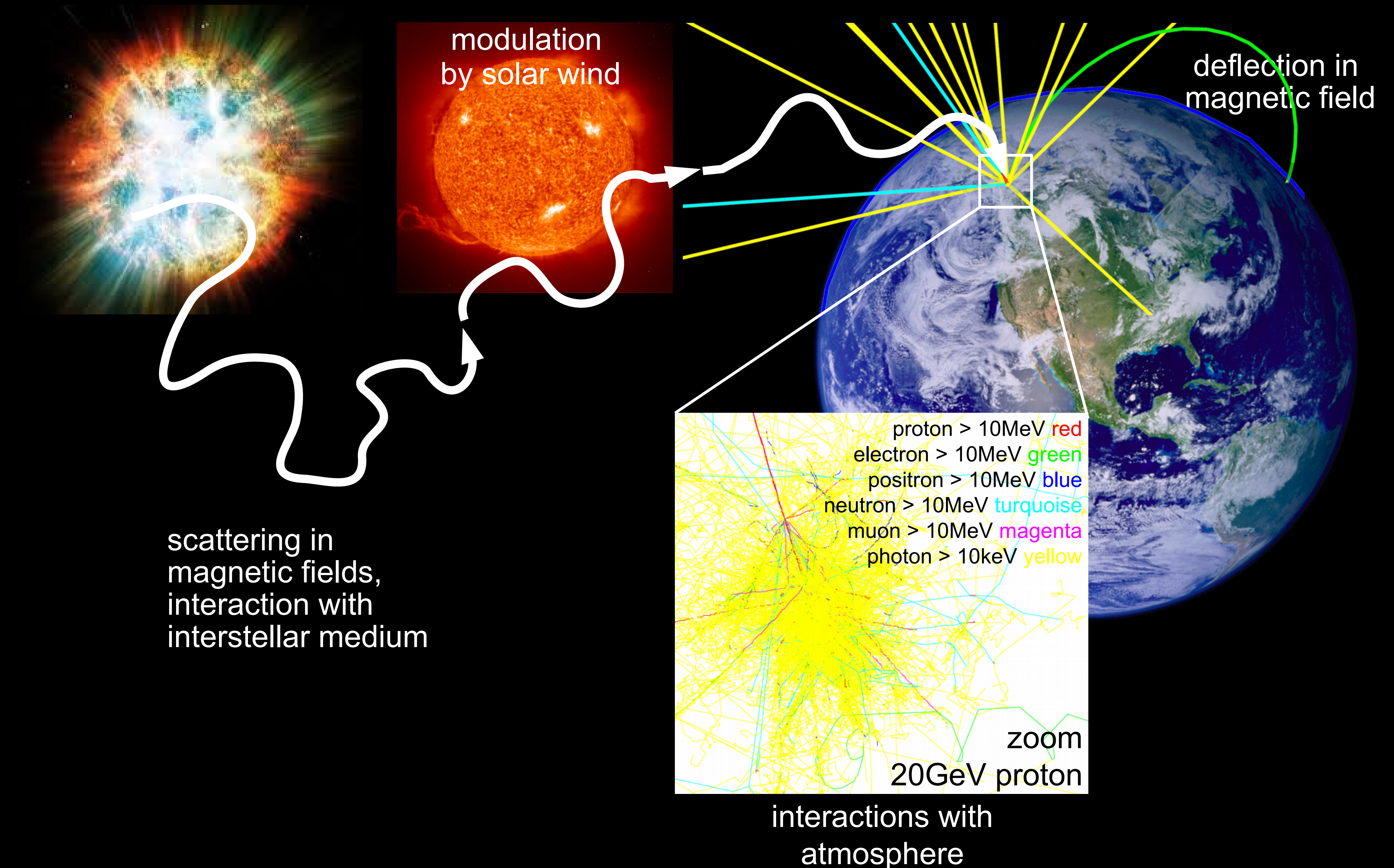
→ dark matter must(?) be able to interact with standard model particles

Direct dark matter searches (scattering)



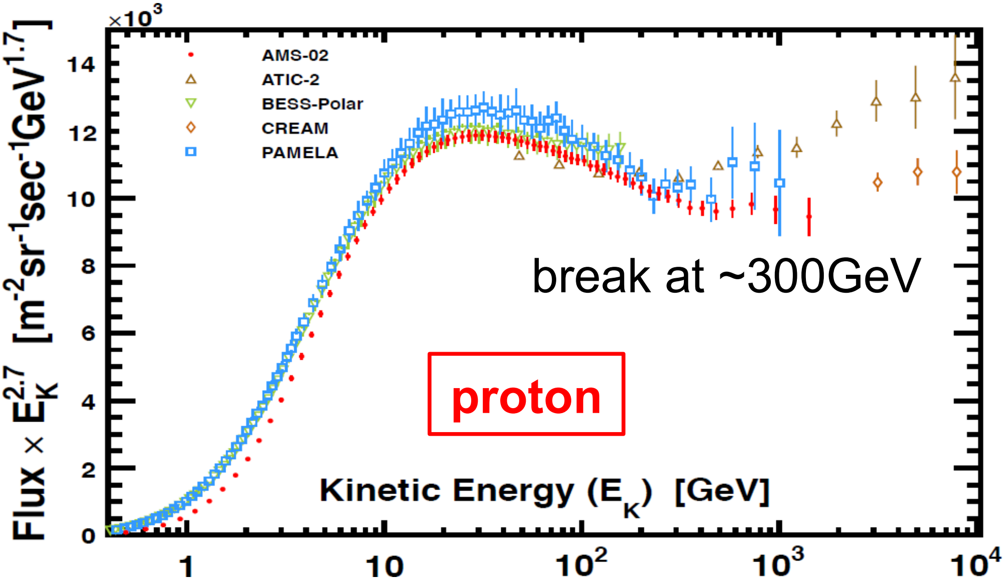
- **direct dark matter search:** measure cross-section via nuclear recoil
- typically large, heavy and very pure target materials in deep mines (~10 operating experiments)
- experiments start probing theoretically preferred parameter space
- **very challenging experiments →** some experiments claim discovery,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

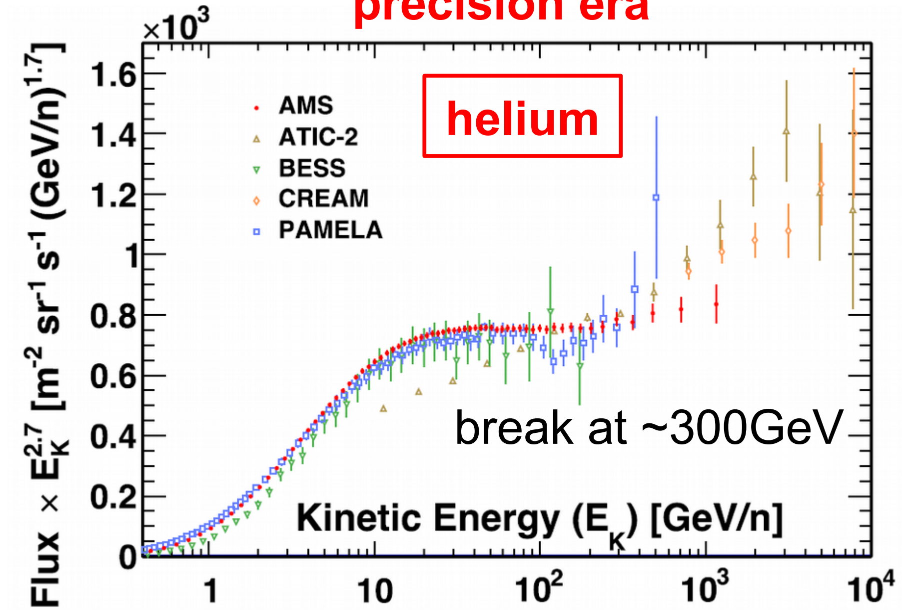
Cosmic rays as messengers

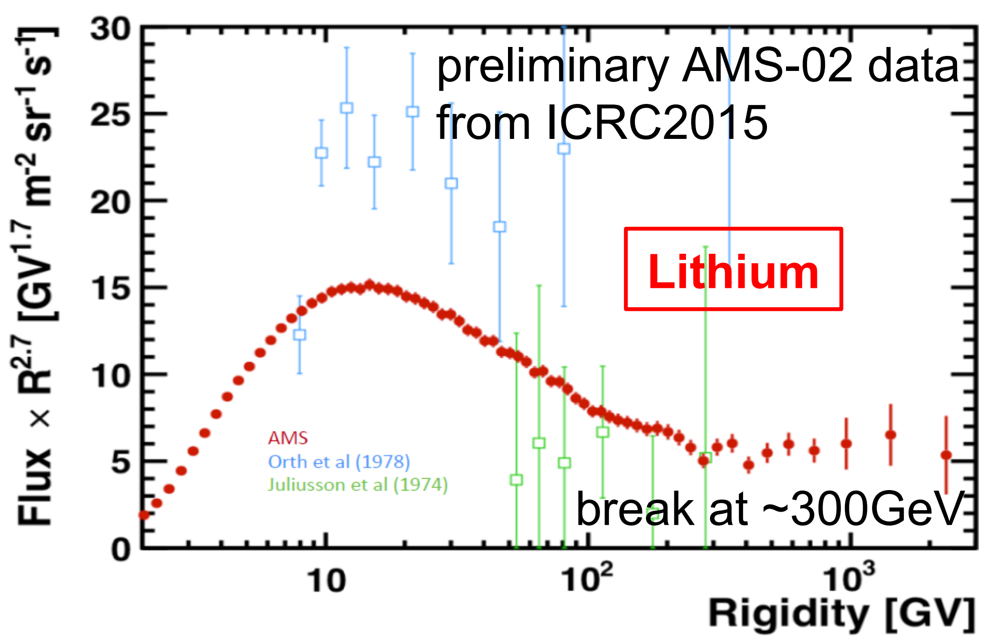


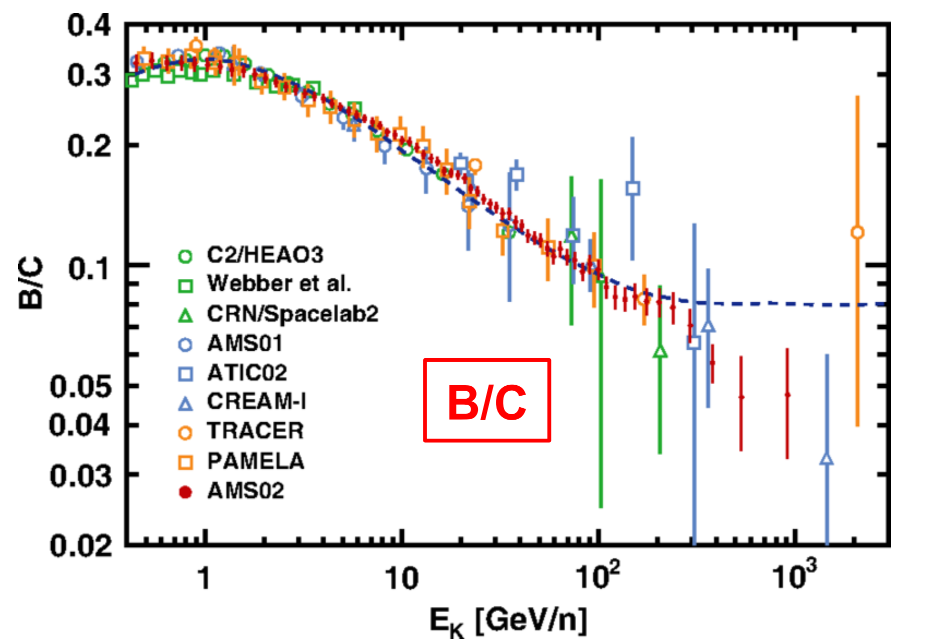
Snapshot of cosmic-ray status

AMS-02 started new precision era

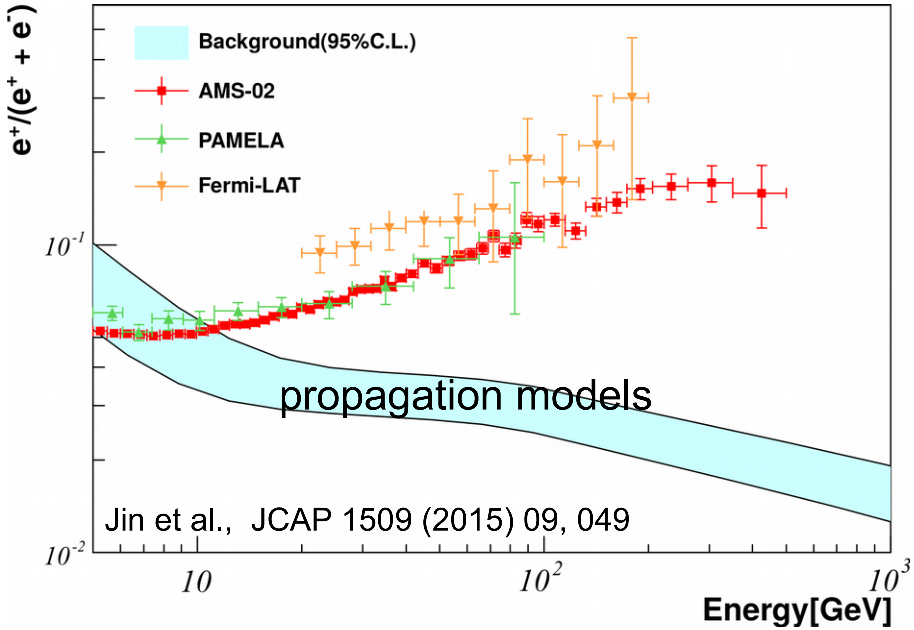


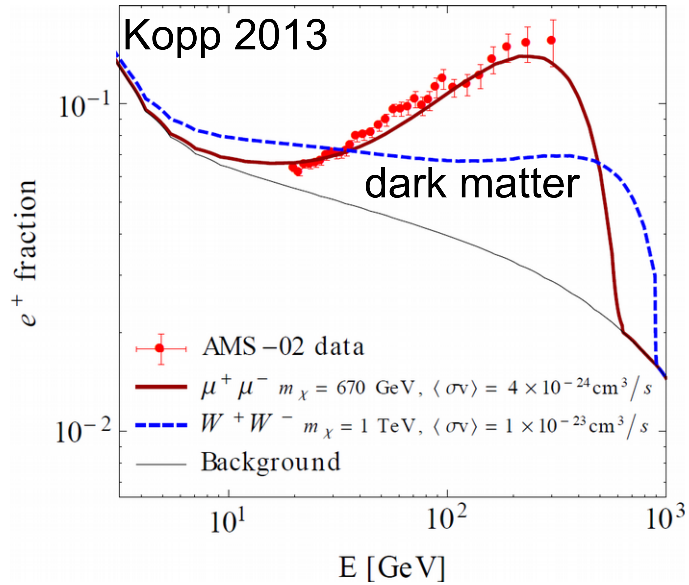




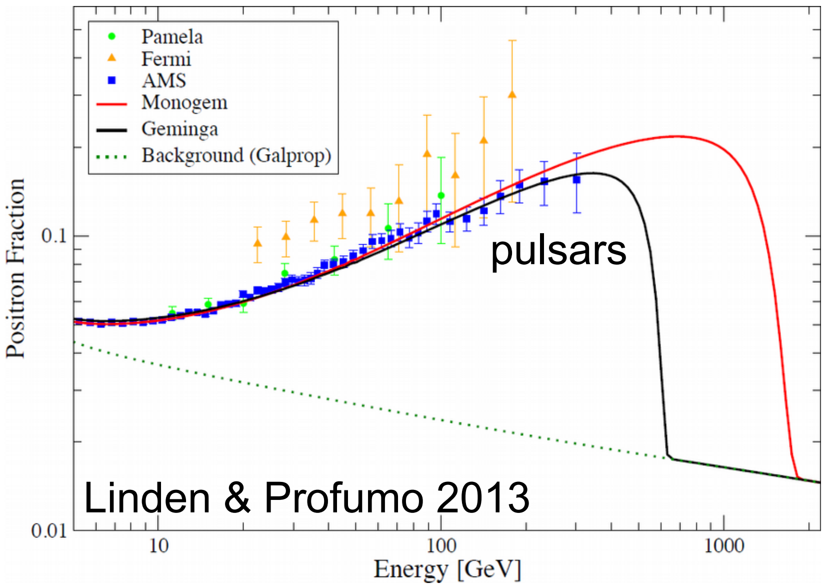


Dark matter signal in positrons?

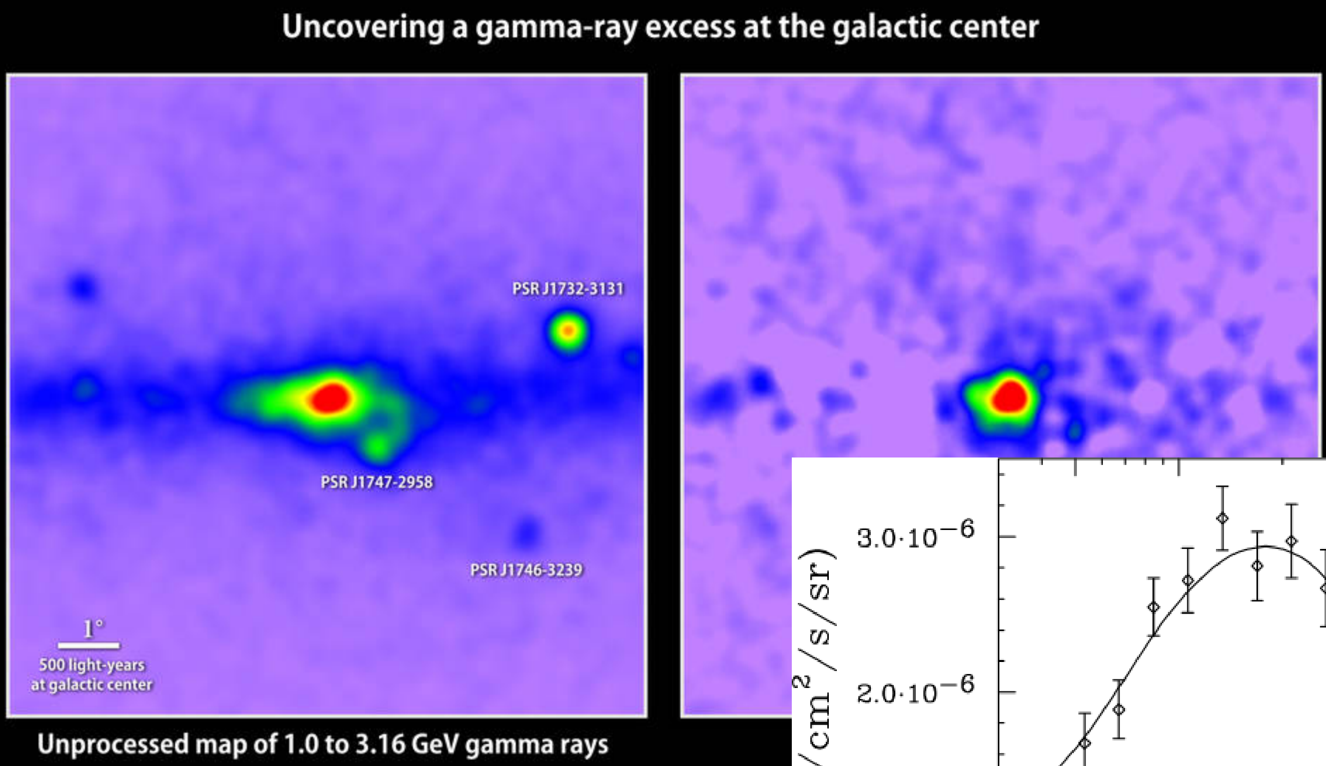




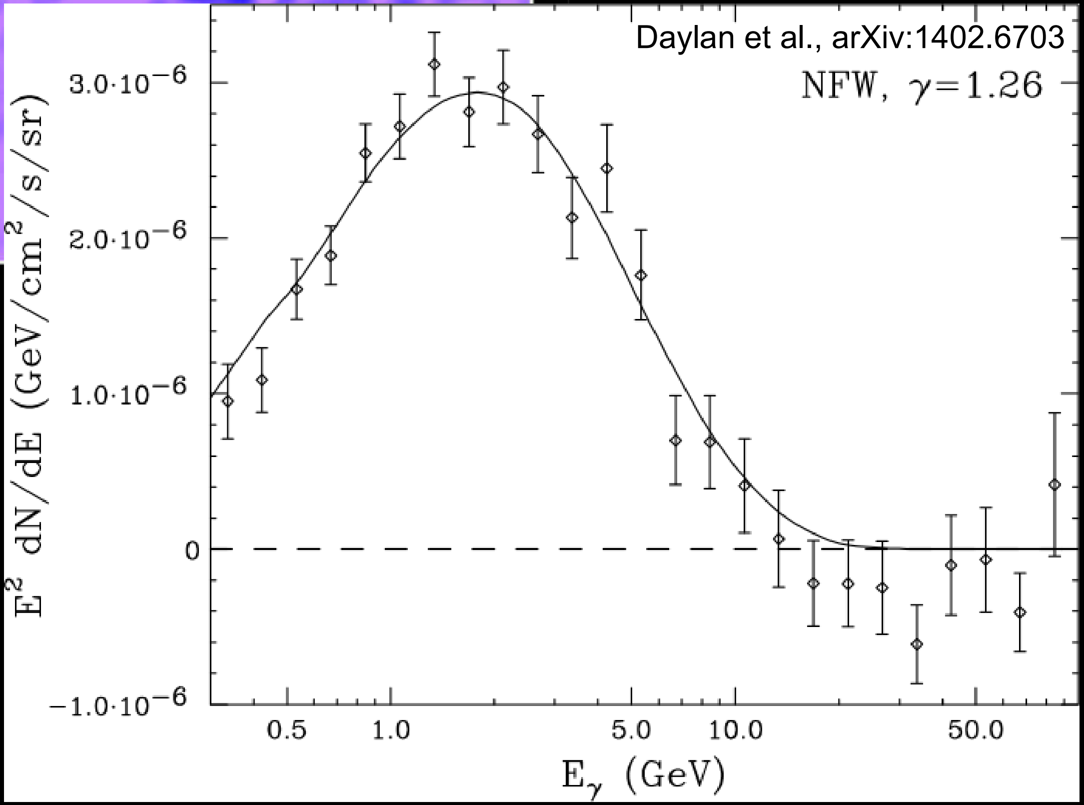
- dark matter models are severely constrained:
  - large cross sections
  - leptophilic?
- explained by nearby pulsars producing electrons and positrons?
  - anisotropy should be smaller than AMS-02 limit, but still measurable with ACTs
- different acceleration mechanisms
- important to see how the positron fraction continues



Diffuse Galactic γ-ray excess?

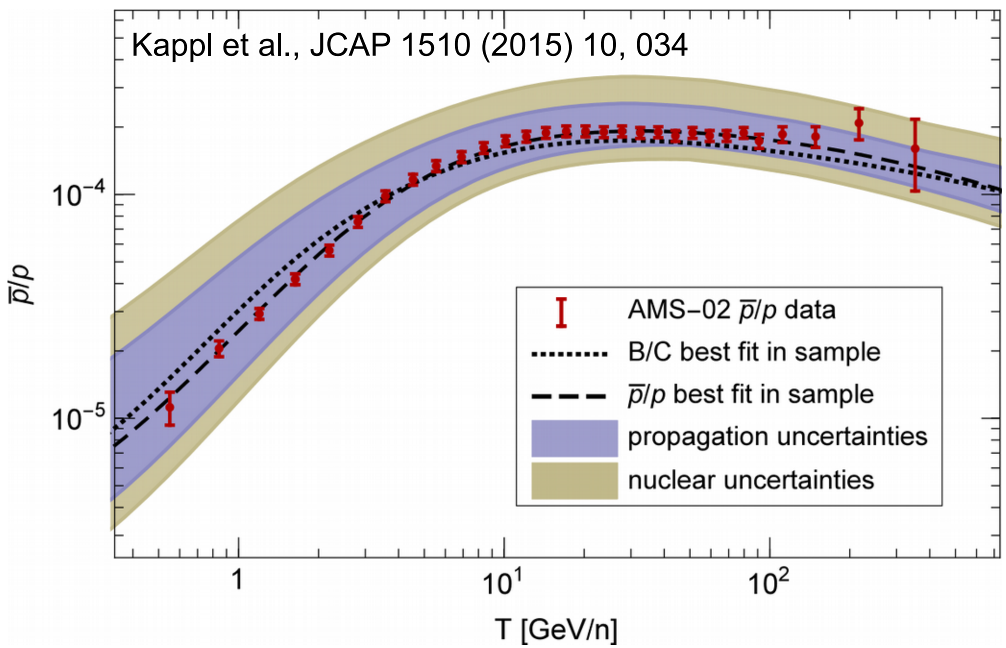


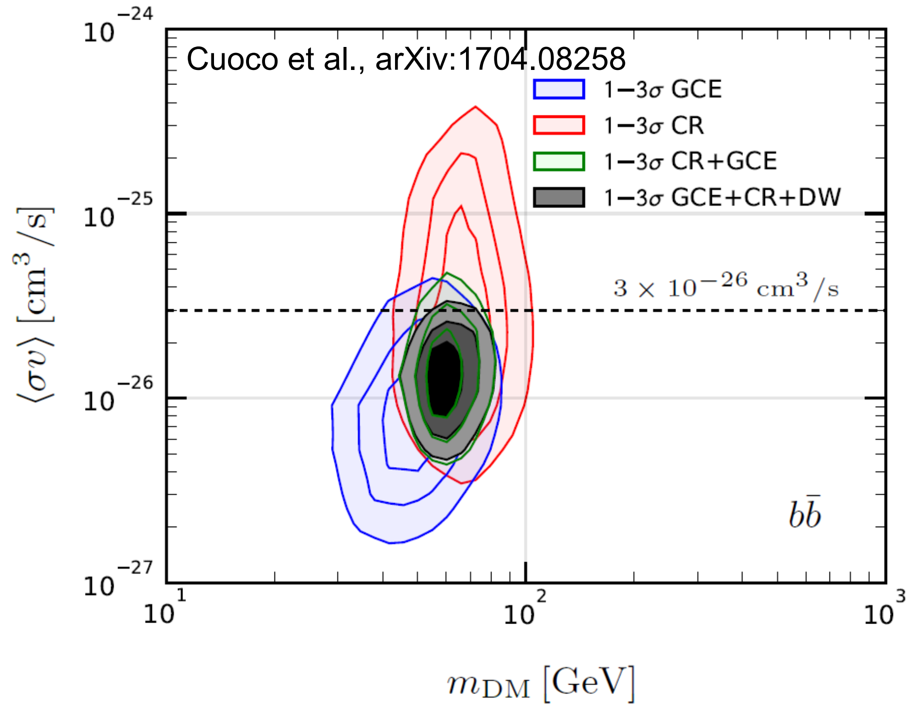
Unprocessed map of 1.0 to 3.16 GeV gamma rays



- gamma-ray excess at the galactic center → ~30GeV dark matter particle?
- unresolved millisecond pulsars?
- from pion production in molecular clouds
- tension with dwarf galaxies
- understanding of astrophysical background is a big challenge

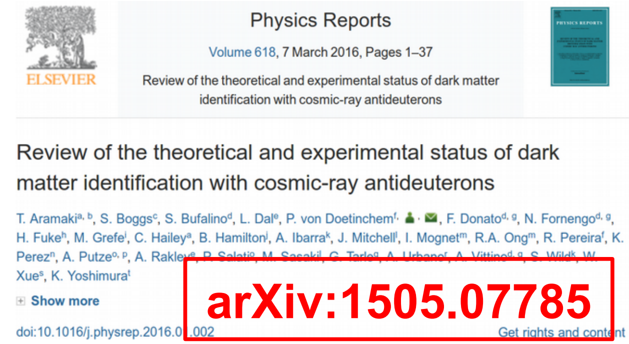
Antiprotons





- latest AMS-02 antiproton results are also very actively interpreted
- discussion is inconclusive if an additional component is needed or not
- better constraints on cosmic-ray propagation and astrophysical production are needed

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

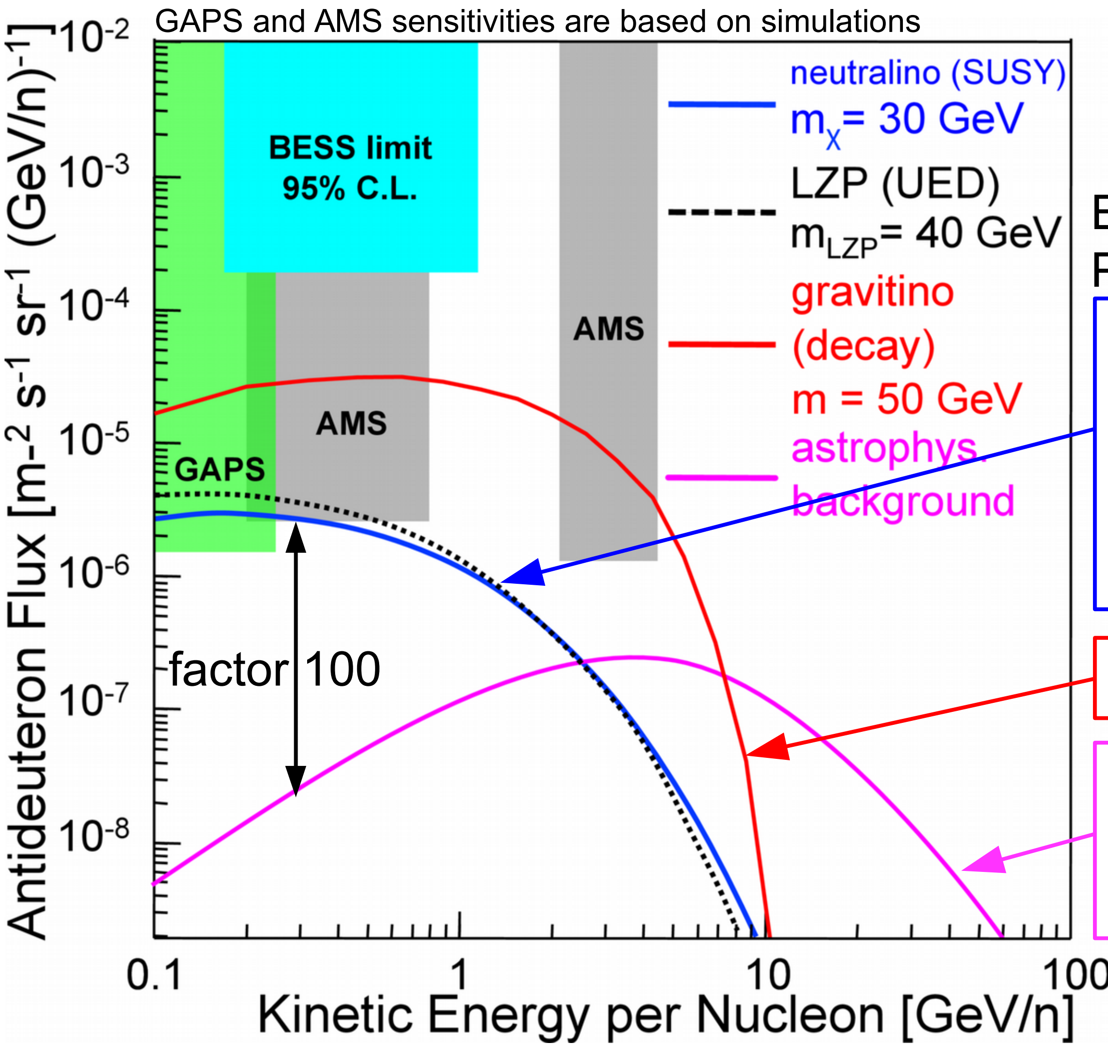
Review of the theoretical and experimental status of dark matter identification with cosmic-ray antideuterons

T. Aramaki, S. Boggs, S. Bufalino, L. Dal, P. von Doetinchem, F. Donato, N. Fornengo, H. Fuke, M. Grefe, C. Hailey, B. Hamilton, A. Ibarra, J. Mitchell, I. Mognet, R.A. Ong, R. Pereira, K. Perez, A. Putze, A. Raklev, ... Xue, K. Yoshimura

Show more

doi:10.1016/j.physrep.2016.0...002

arXiv:1505.07785



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

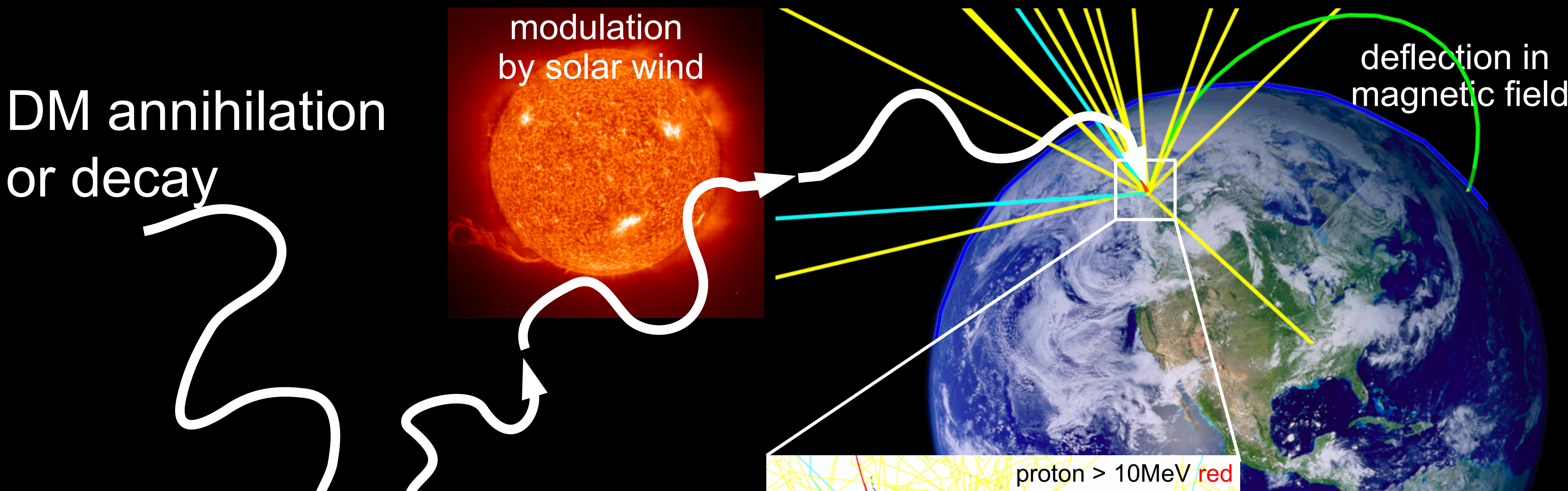
\+ models with heavy dark matter

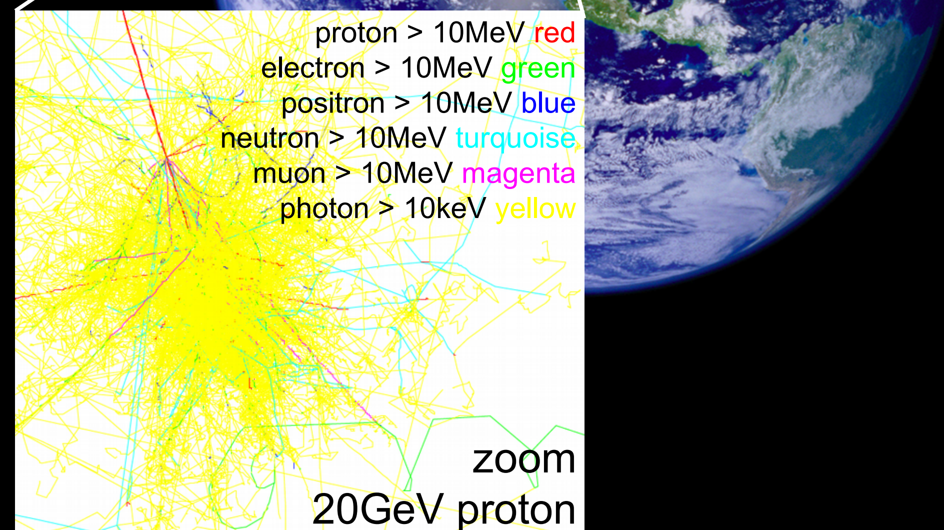
Antideuterons are the most important unexplored indirect detection technique!

Antideuterons are exciting

- They have never been discovered in cosmic rays (artificially produced since the 60s)
- The anti-side for cosmic rays is very unknown (only positron and antiproton known)
- Our situation is comparable to the mid 70s before the first detection of a handful of antiprotons in 1979
- Antideuteron detection could be a very strong hint for new physics (astrophysical background very low)

Uncertainties

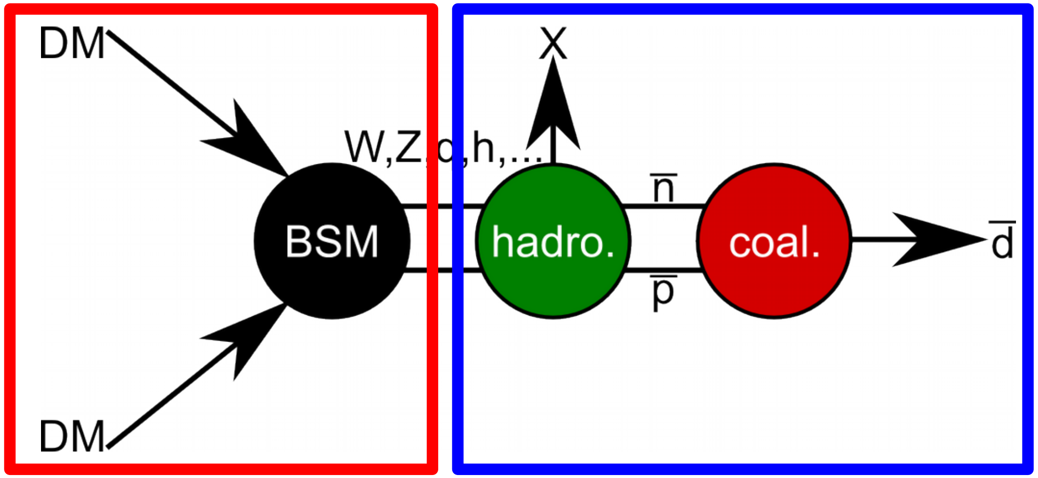




interactions with
atmosphere

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

(Anti)deuteron formation



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

$$\gamma_d \frac{d^3 N_d}{dp_d^3} = \frac{4\pi}{3} p_0^3 \left(\gamma_p \frac{d^3 N_p}{dp_p^3} \right) \left(\gamma_n \frac{d^3 N_n}{dp_n^3} \right)$$

- use an event-by-event coalescence approach with hadronic generators

Schwarzschild &Zupancic, Physical Review 129, 854 (1963)
Ibarra & Wild, Physical Review D88 020314 (2013)
Aramaki et al., Physics Reports 618, 1 (2016)

Issues of the coalescence model

- phase space for ion production depends on the available energy in the formation interaction

- coalescence is highly sensitive to two-particle correlations between the participating (anti)nucleons
  → no a-priori reason to expect two-particle correlations from one generator to be more reliable than from another

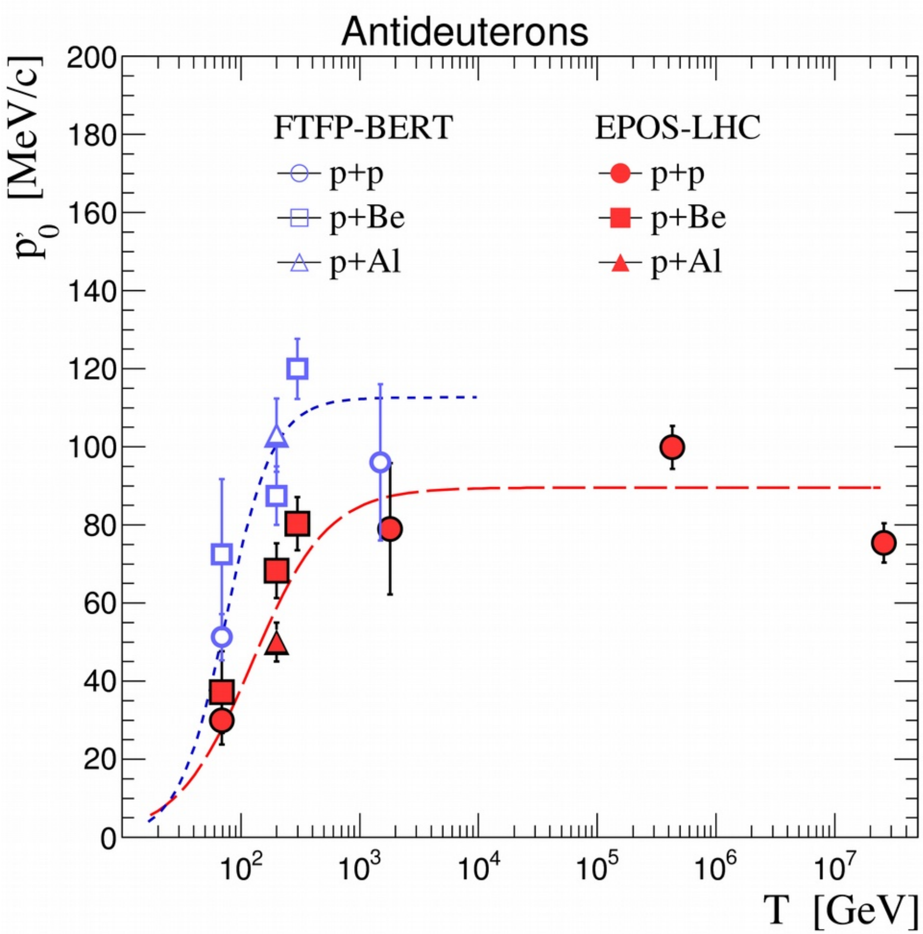
- spatial separation
  → antinucleons originating from weakly decaying particles with macroscopic decay lengths are produced too far from the primary interaction vertex

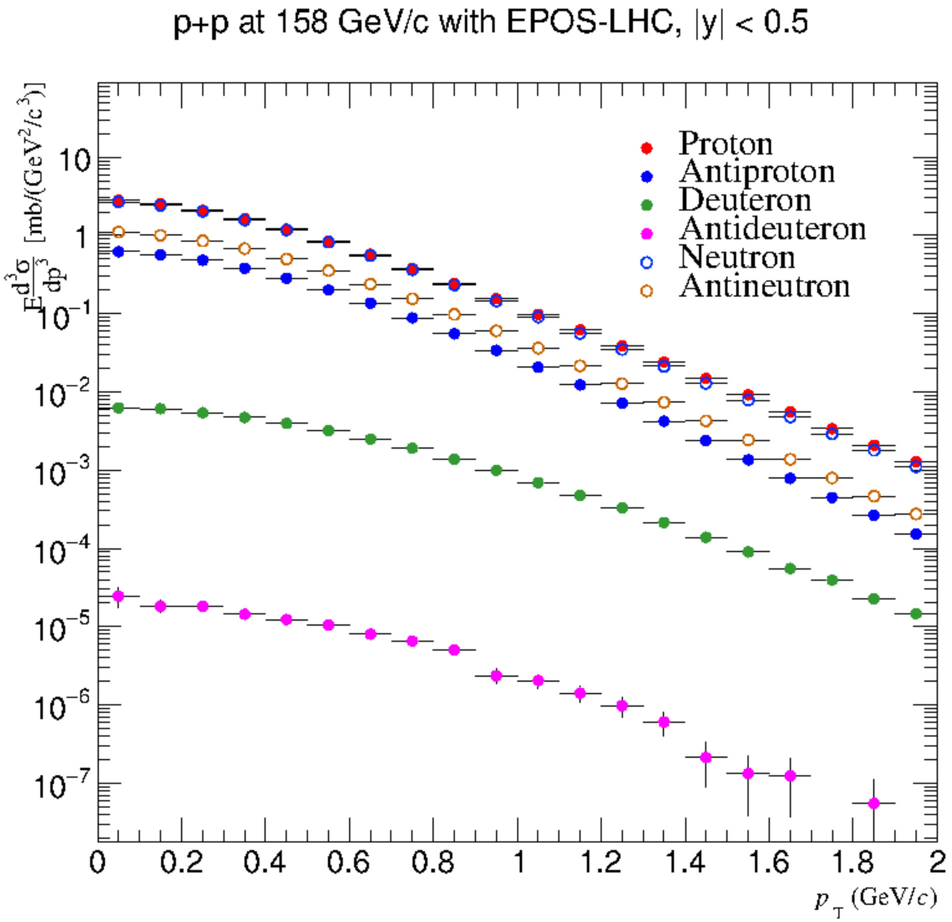
- generators not really tuned for antiparticle production
  → tune with antiproton, deuteron, and antideuteron data
  → test antiproton spectra first, antineutron data are hard to come by

- hadronic generators do not include coalescence formation

Modified antideuteron coalescence

Together with Gomez, Menchaca (UNAM)

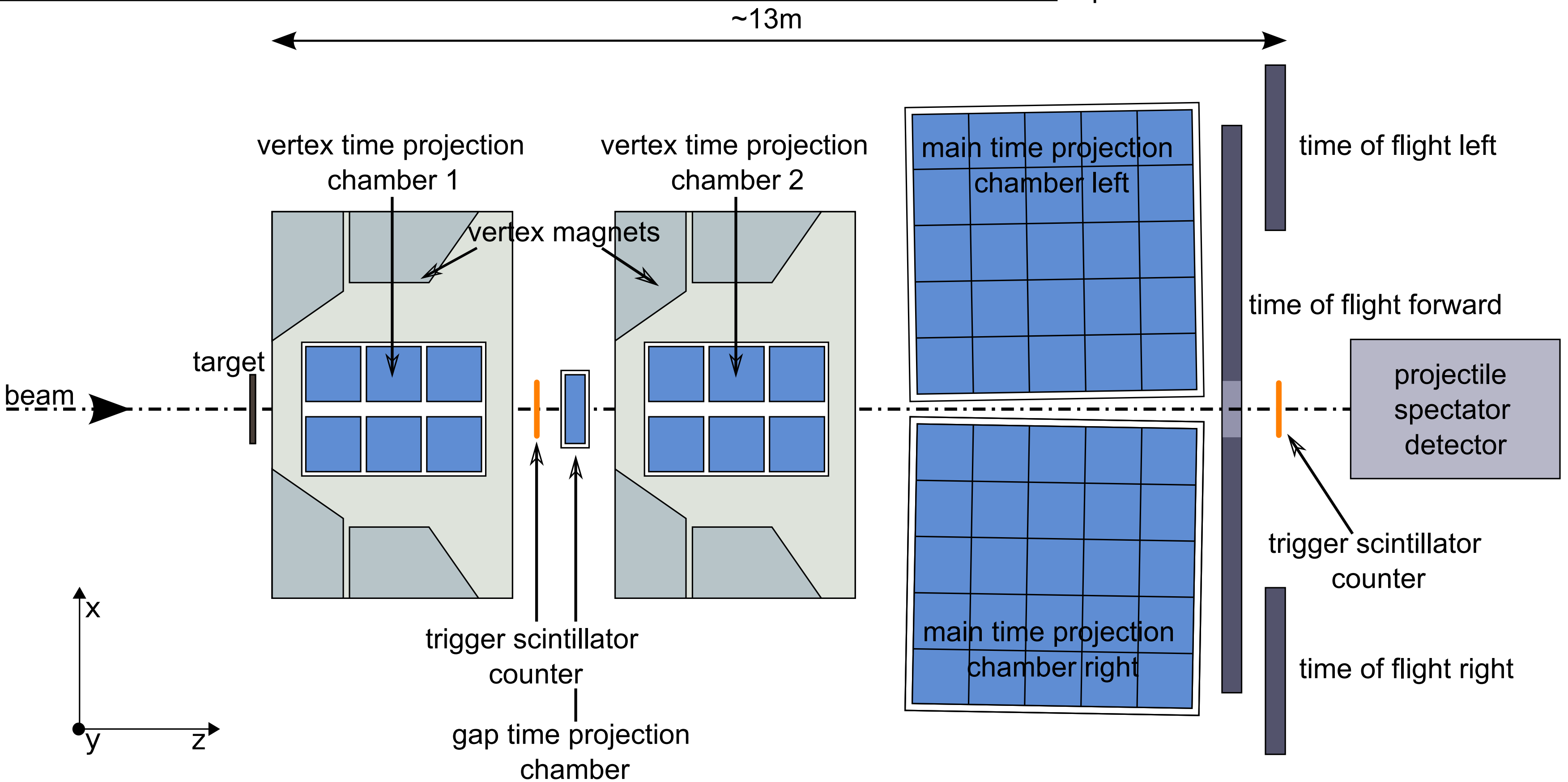




- coalescence afterburner added to EPOS-LHC, Geant4
- more data needed to constrain (anti)deuteron coalescence model

NA61/SHINE at CERN

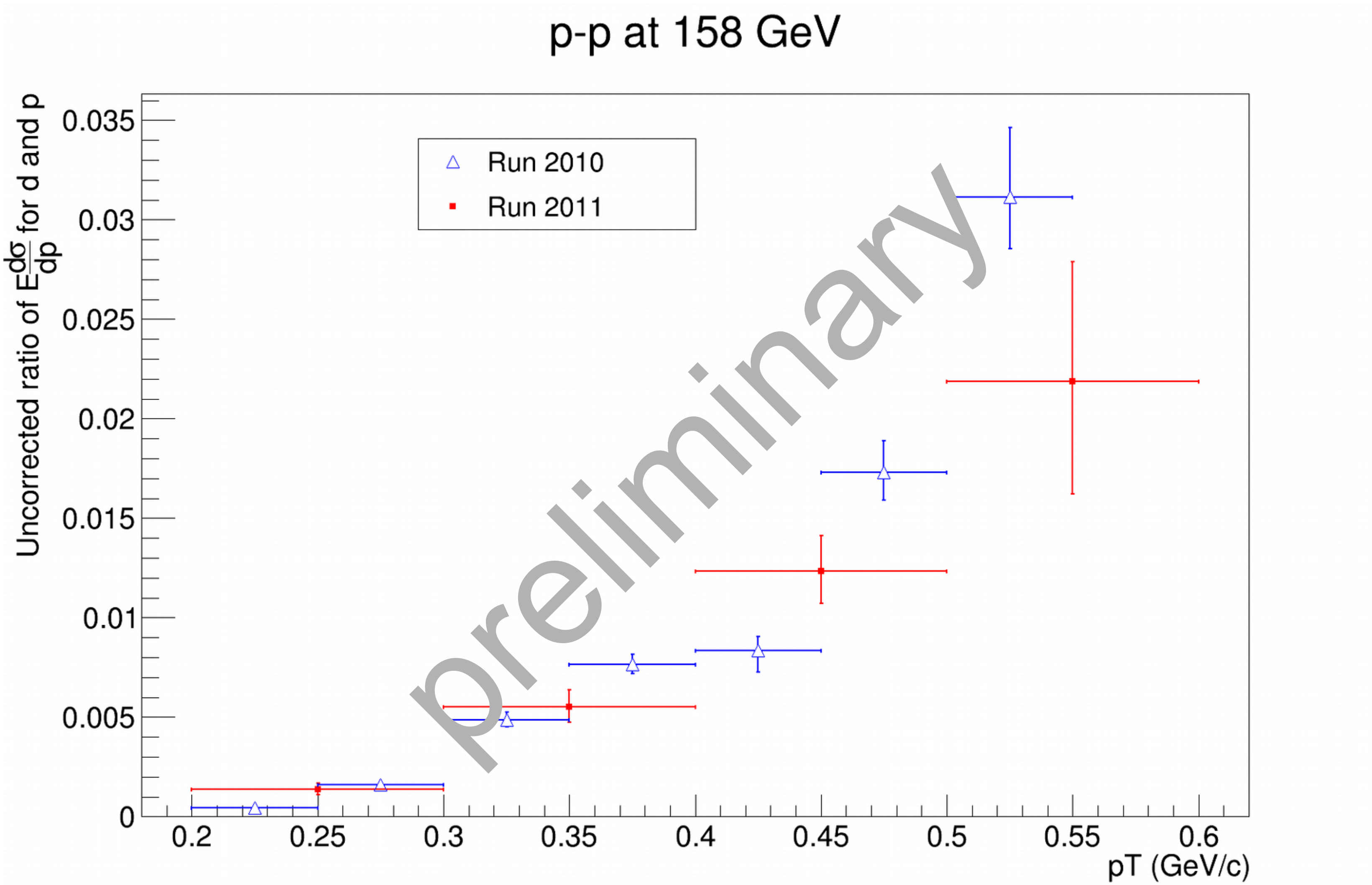
SPS **H**eavy **I**on and **N**eutrino **E**xperiment
pre-decessor: NA49



- multi-purpose, fixed-target experiment at the CERN SPS (NA61/SHINE facility paper: JINST 9 (2014) P06005)
  - precise measurements of properties of produced particles: q, m, p
- cosmic-ray antideuteron production happens between 40 and 400GeV
  - SPS energies from 9 to 400GeV are ideal
- data under discussion from the NA61/SHINE strong interactions program:
  - p+LH data taken at 13, 20, 31, 40, 80,158GeV/c + 400GeV/c (2016)

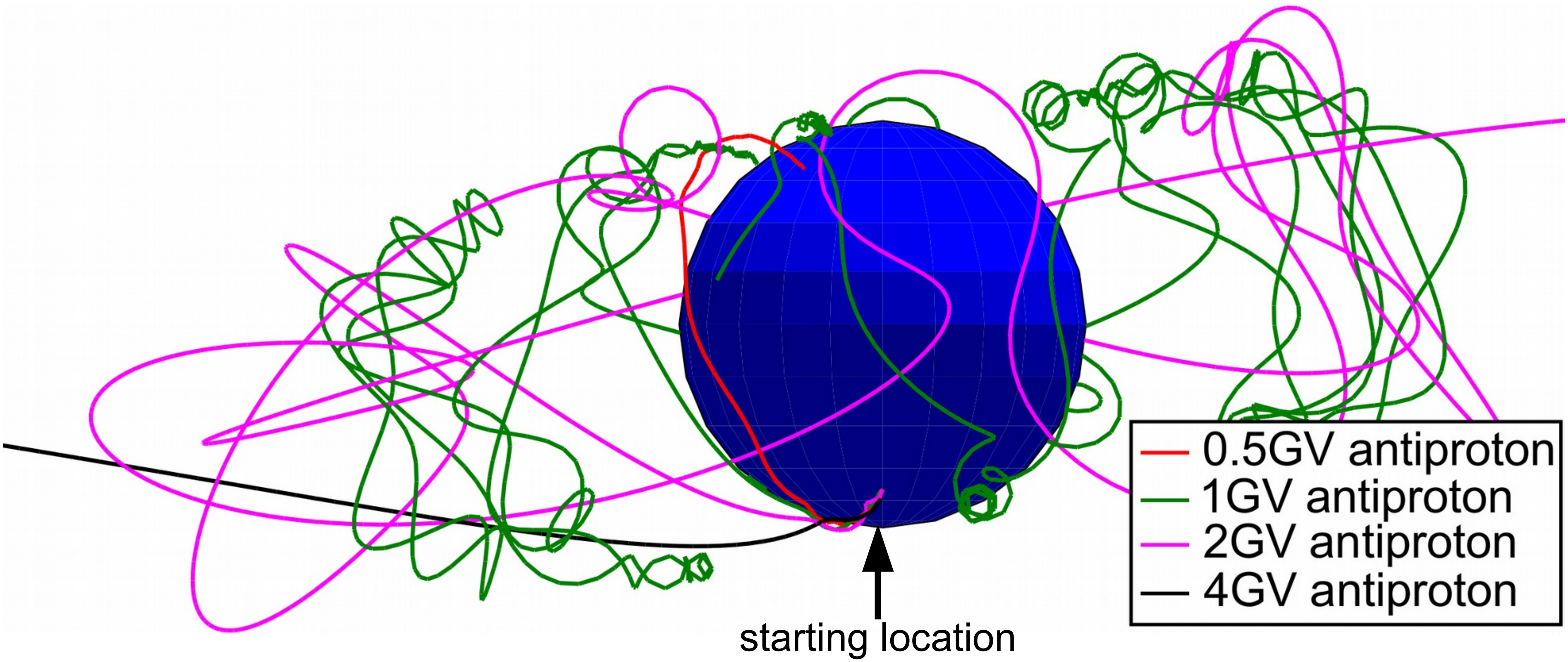
- high momentum resolution: $\sigma(p)/p^2 \approx 10^{-4}(\mathrm{GeV}/c)^{-1}$ (at full B=9Tm)
- ToF walls resolution:
  - ToF-L/R: $\sigma(t) \approx 60$ps
  - ToF-F: $\sigma(t) \approx 120$ ps
- Good particle identification:
  - $\sigma(dE/dx)/\langle dE/dx\rangle \approx 0.04$
  - $\sigma(minv) \approx 5$ MeV
- high detector efficiency: > 95%
- event rate: 70Hz

d/p ratio



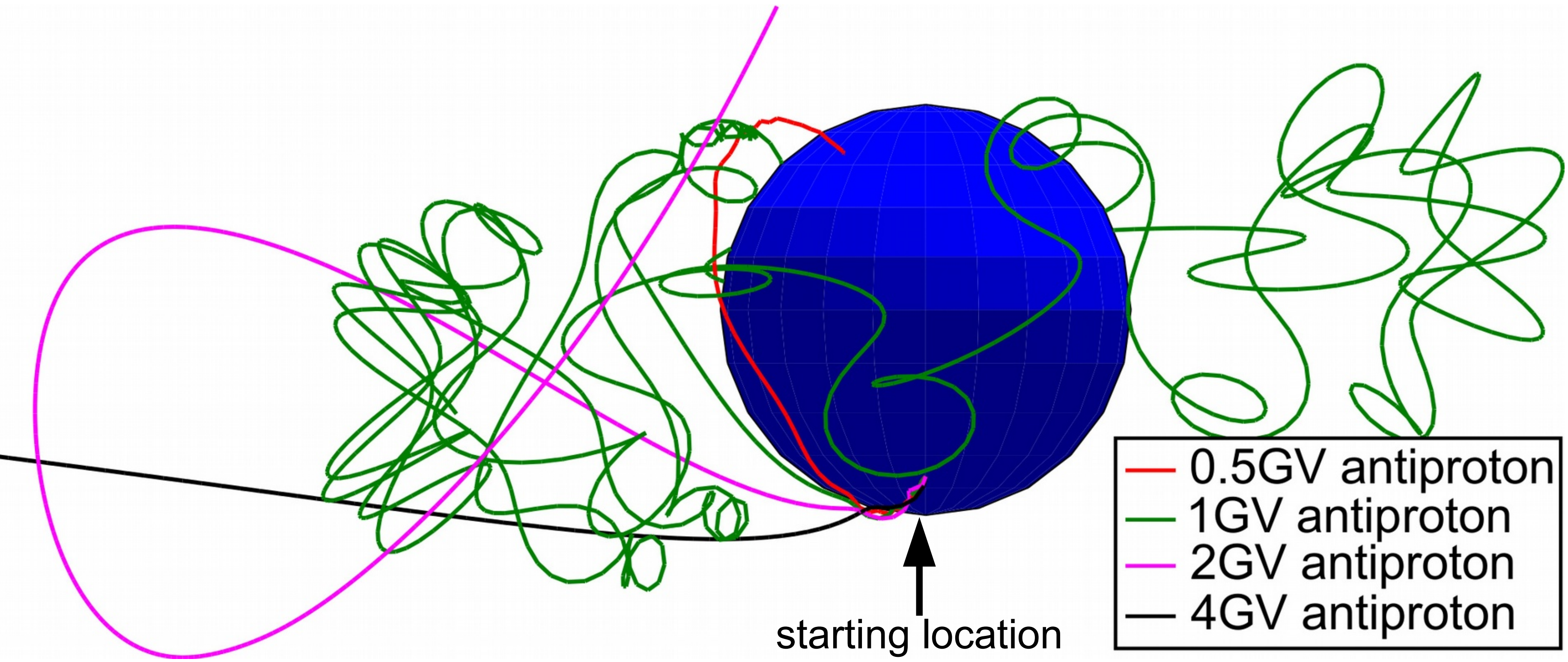
- Goal: tune hadronic generators

Geomagnetic cutoff – 5/19/11



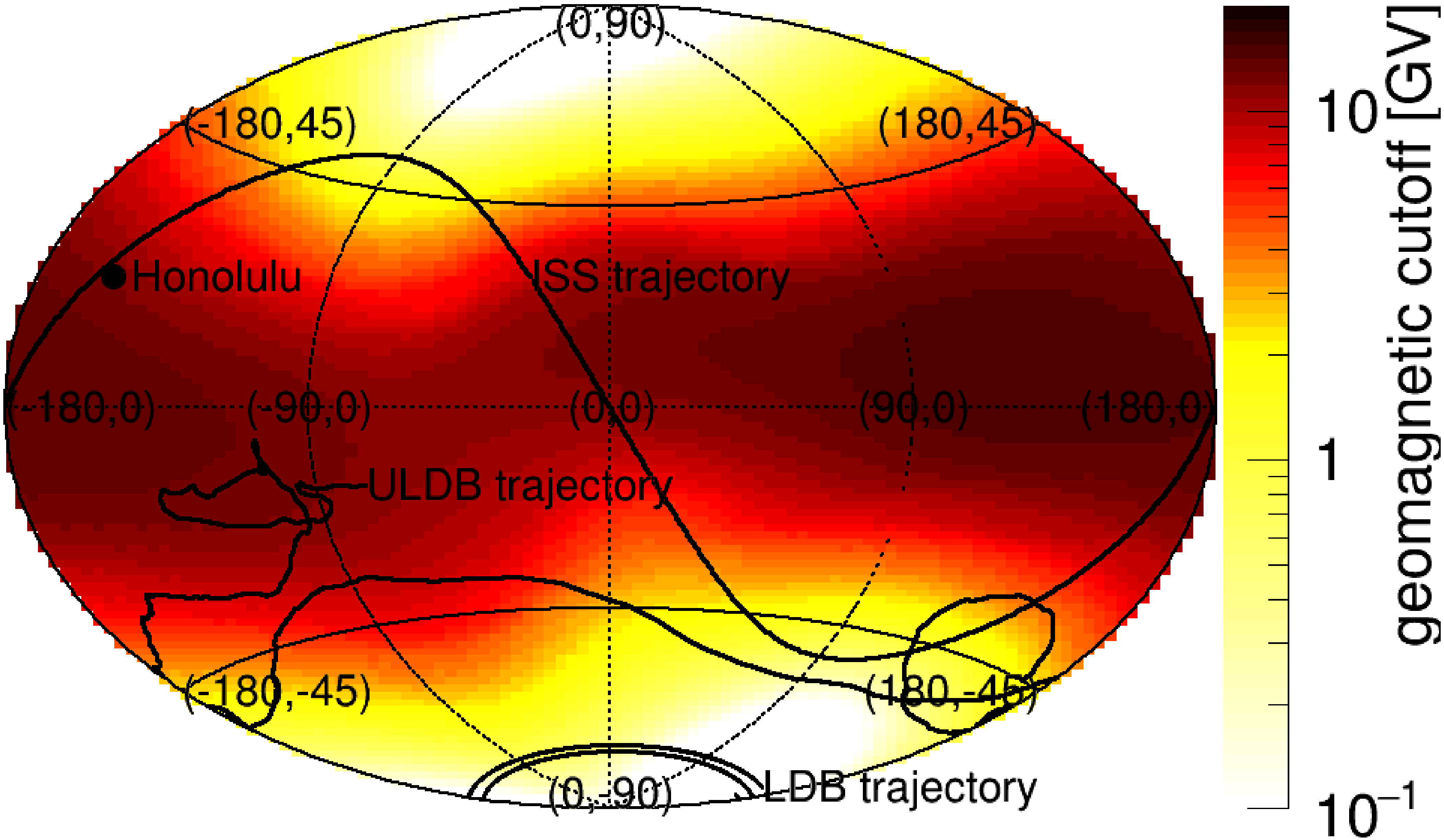
- reverse computation of antiproton trajectories starting at the same location with different rigidities

Geomagnetic cutoff – 3/7/12



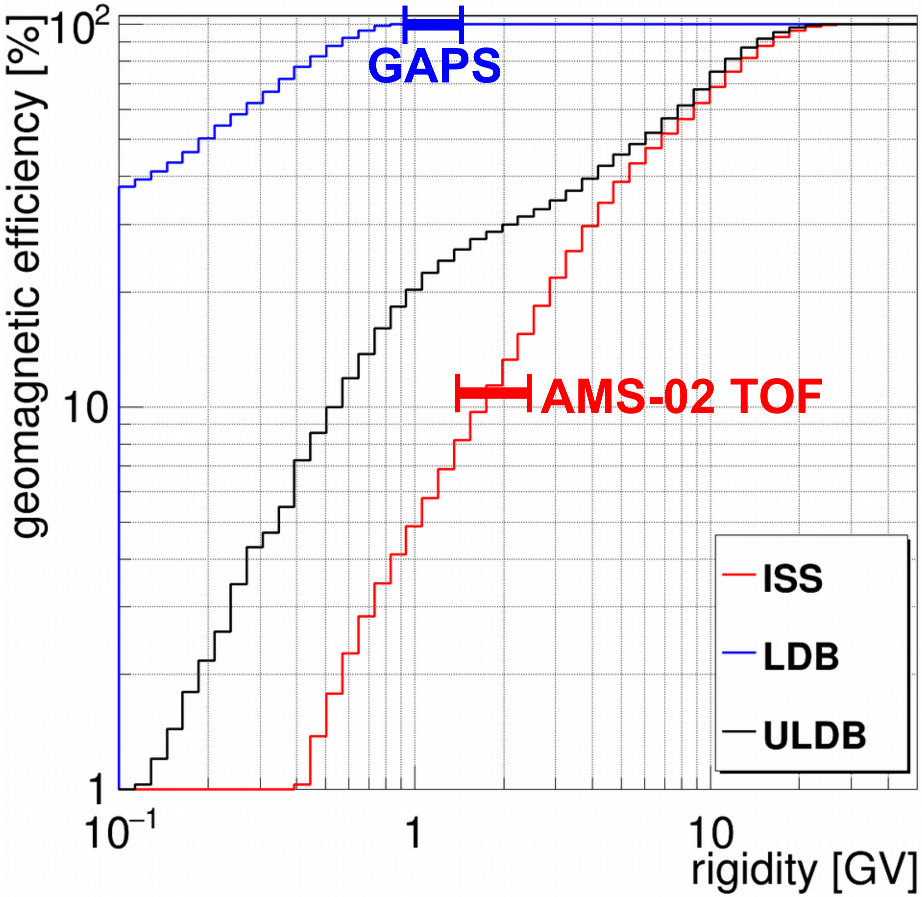
- reverse computation of antiproton trajectories starting at the same location with different rigidities
- change in magnetic environment changes the trajectories drastically
  → changes geomagnetic cutoff values

Geomagnetic cutoff map – 5/19/11



- geomagnetic cutoff for antiprotons averaged over an isotropic incoming particle distribution

Cutoff comparison of different trajectories



- average geomagnetic cutoff efficiency depends on flight location (LDB = antarctic trajectory, ULDB = COSI flight from Wanaka, New Zealand)

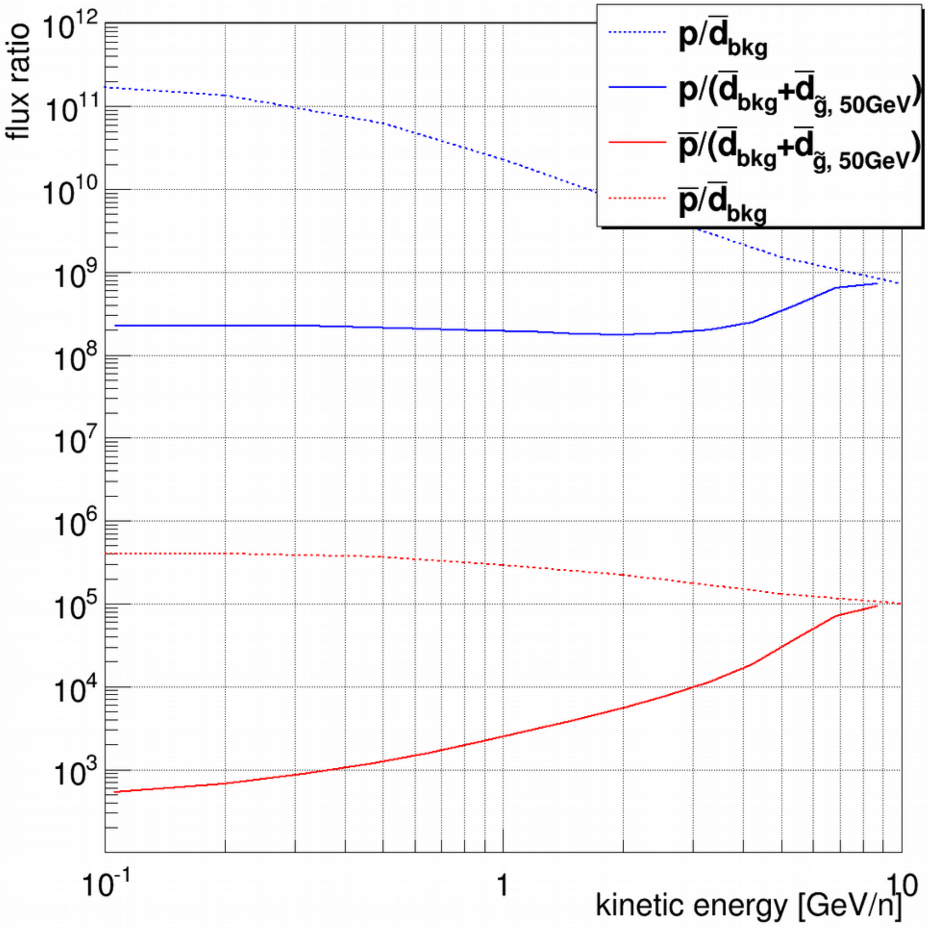
Identification challenge

Required rejections for antideuteron detection:

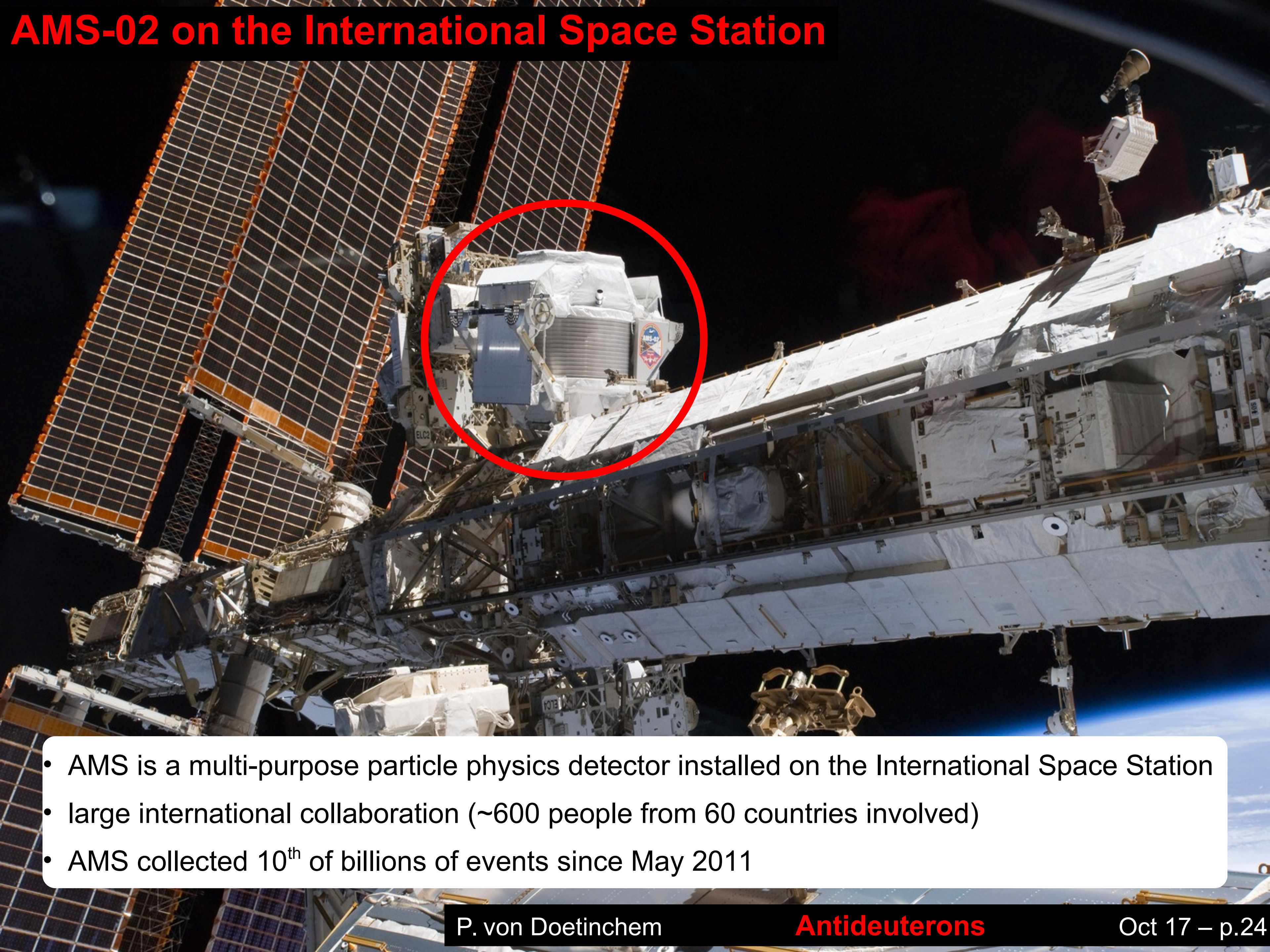
- **protons**: > 10^8 - 10^{10}
- **He-4**: > 10^7 - 10^9
- **electrons**: > 10^6 - 10^8
- **positrons**: > 10^5 - 10^7
- **antiprotons**: > 10^4 - 10^6

Antideuteron measurement with balloon and space experiments require:

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

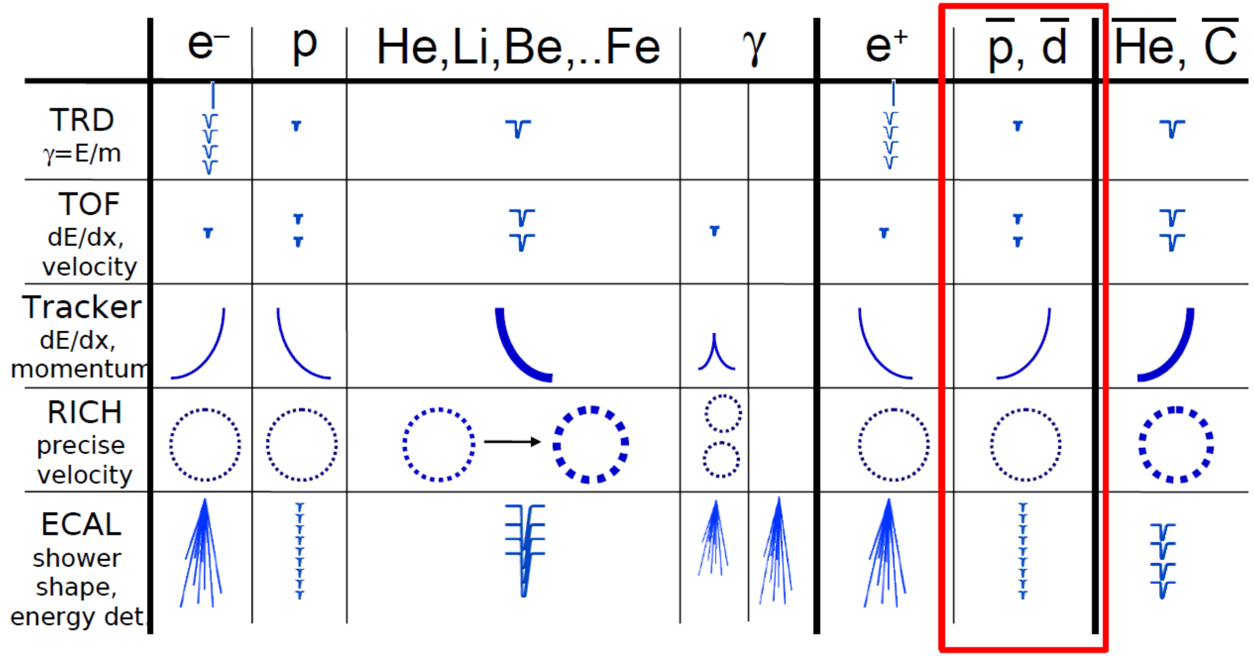


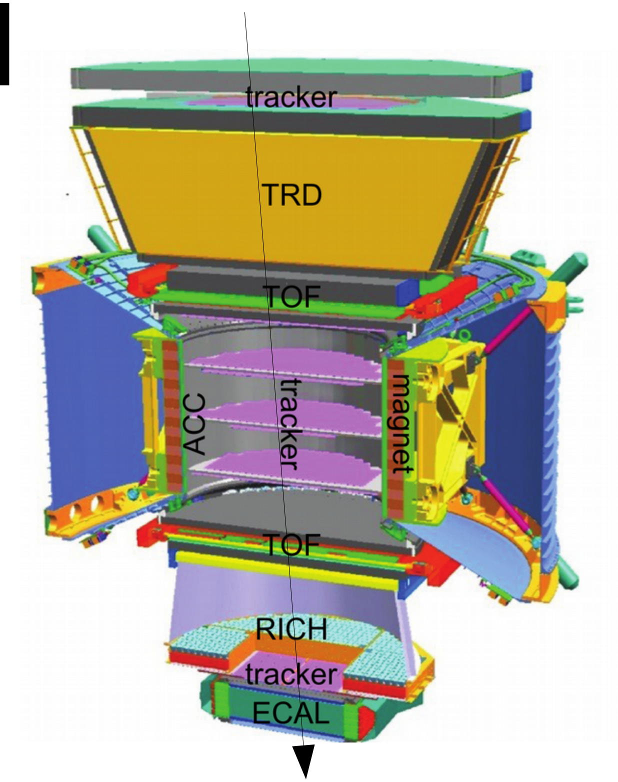
AMS-02 on the International Space Station



- 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-02 antideuteron analysis





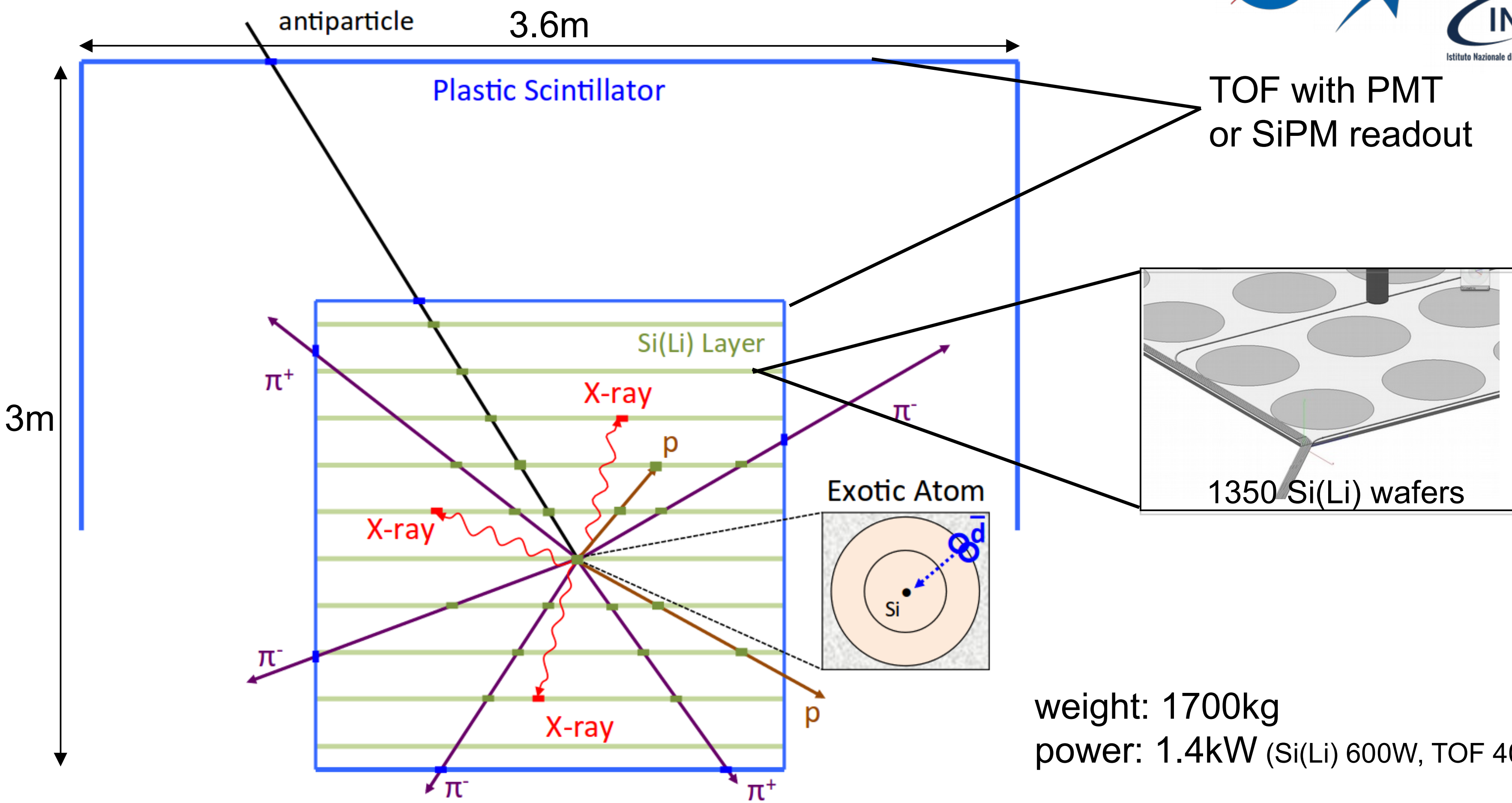
- **antideuteron identification:**
  - momentum measured in the form of rigidity
  - charge from TOF, TRD, tracker
  - lower velocities: **T**ime **O**f **F**light scintillator system
  - higher velocities: **R**ing **I**mage **Ch**erenkov detector

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

- **self-calibrated analysis:**
  - calibrate antideuteron analysis with deuterons and antiprotons (simulations and data)
  - $\boxed{\text{\textbf{analysis is ongoing}}}$

The GAPS experiment

Columbia U, UCSD
UCLA, U Hawaii,
MIT

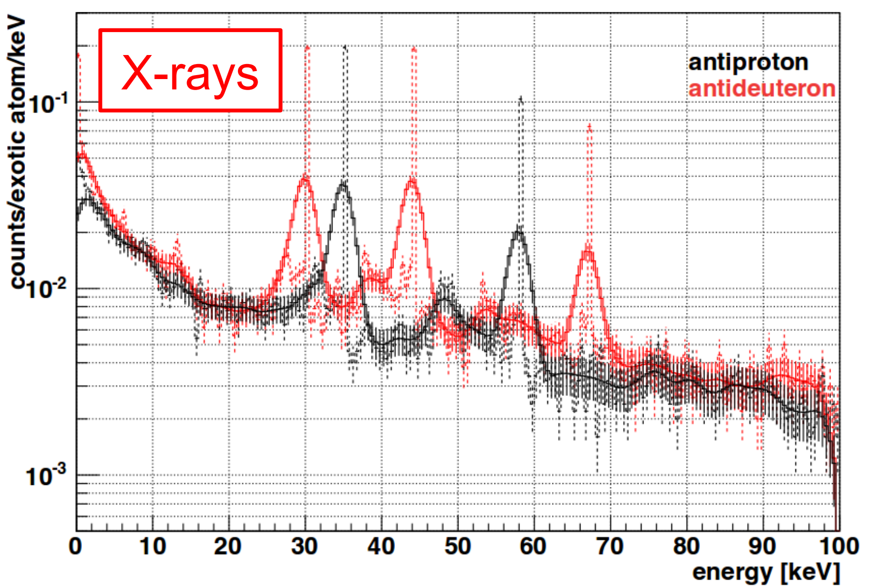


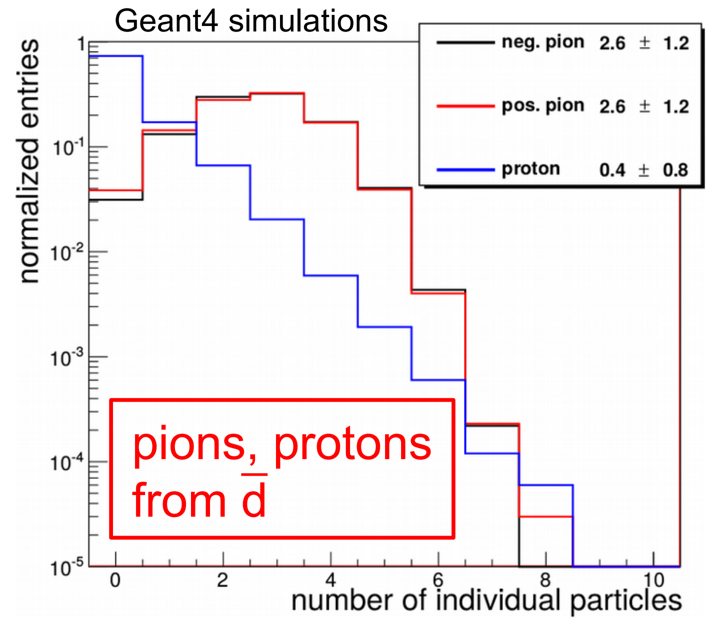
weight: 1700kg
power: 1.4kW (Si(Li) 600W, TOF 400W)

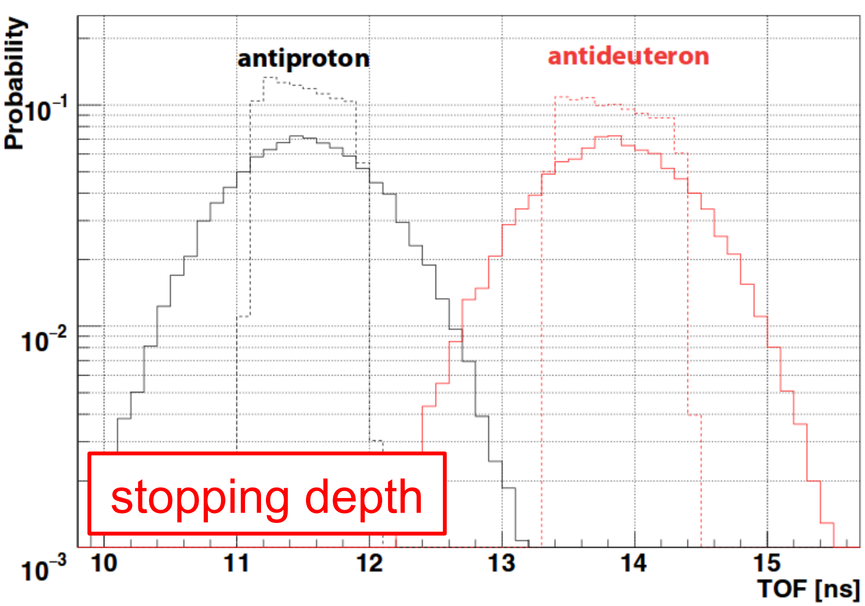
- the **G**eneral **A**nti**P**article **S**pectrometer is specifically designed for low-energy antideuterons and antiprotons
- Long Duration Balloon flights from Antarctica
- identification by stopping and creation of exotic atoms tested in KEK testbeam measurements: Astropart. Phys. 49, 52 (2013)
- **GAPS has been approved by NASA & JAXA → first flight 2020**

GAPS sensitivity

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



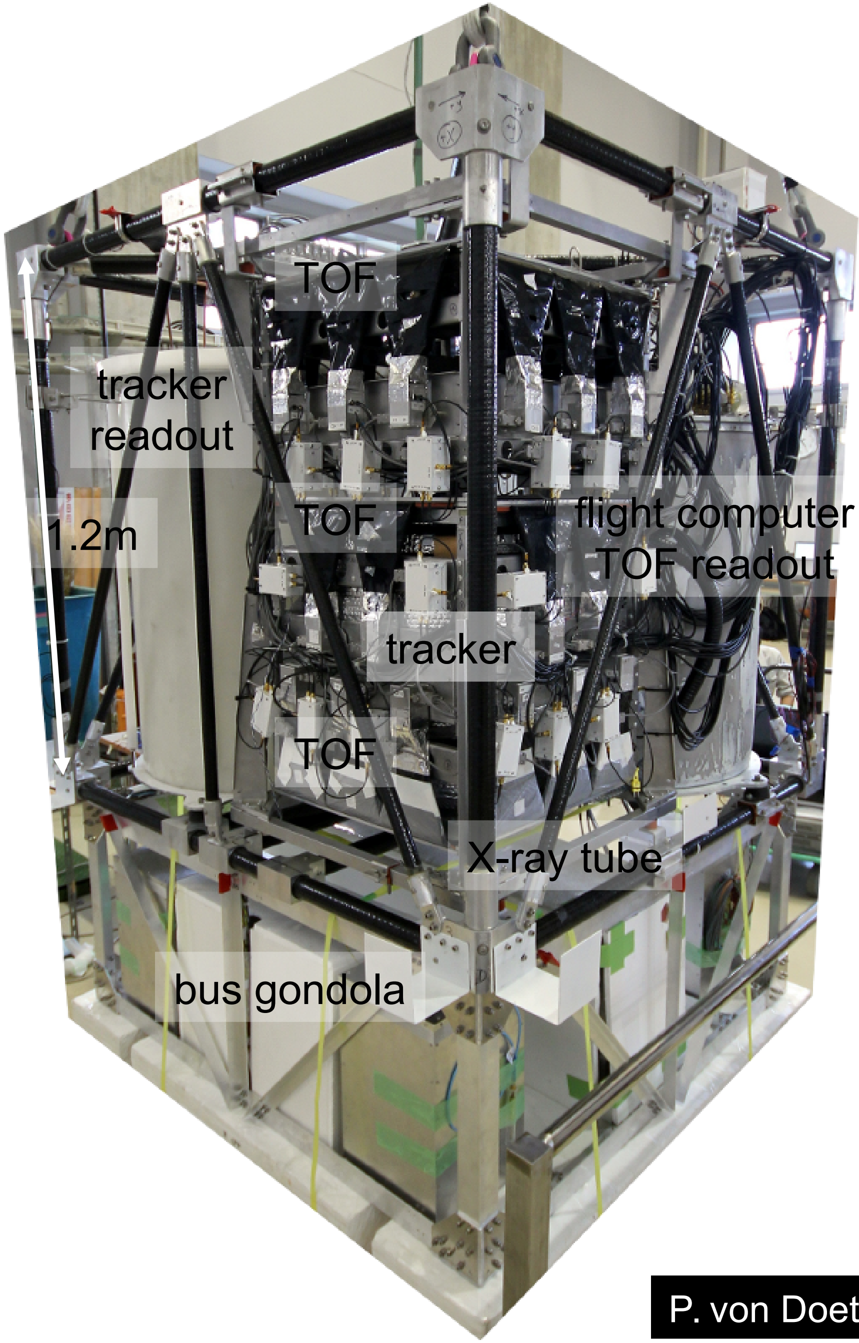




Background rejection:

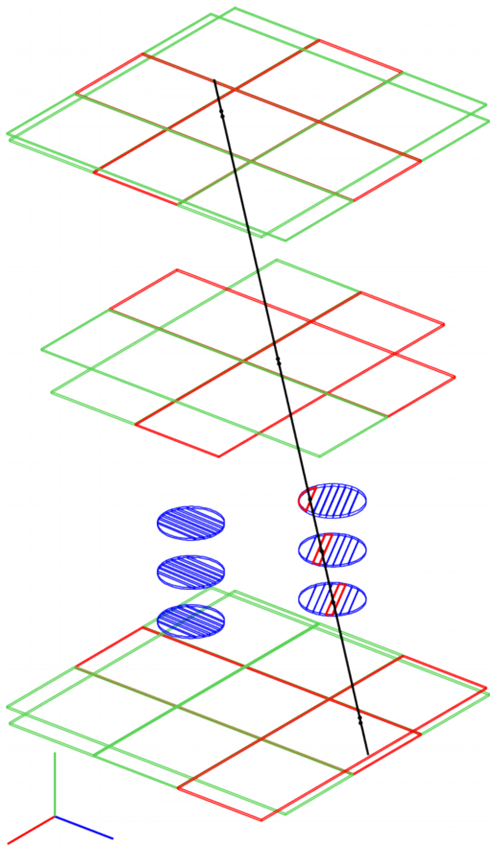
- stopping protons don't have enough energy to produce pions and cannot form exotic atoms (pos. charge)
- deexcitation X-rays have characteristic energies
- number of annihilation pions and protons
- stopping depth in detector

Prototype GAPS



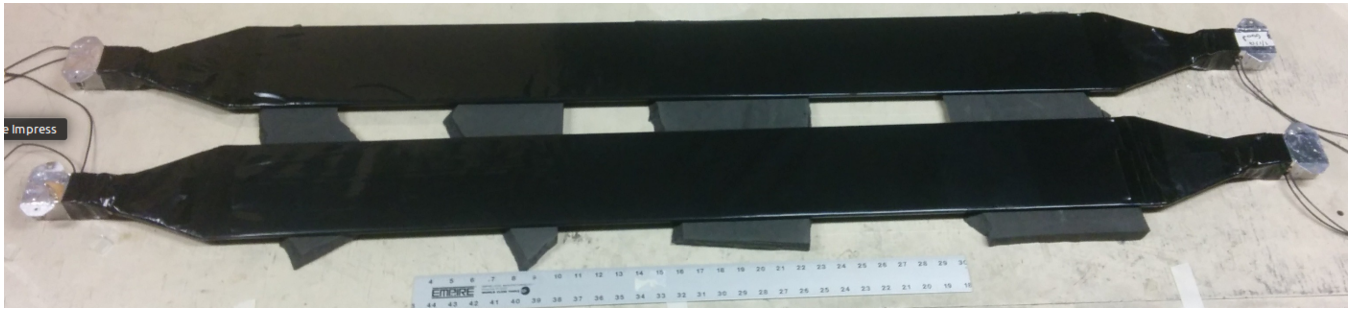
Goals:

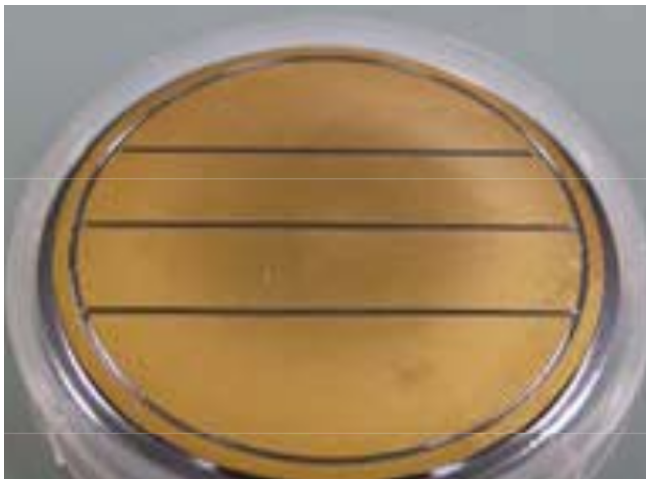
- demonstrate stable operation of the detector components during flight
- study Si(Li) cooling approach for thermal model
- measure background levels



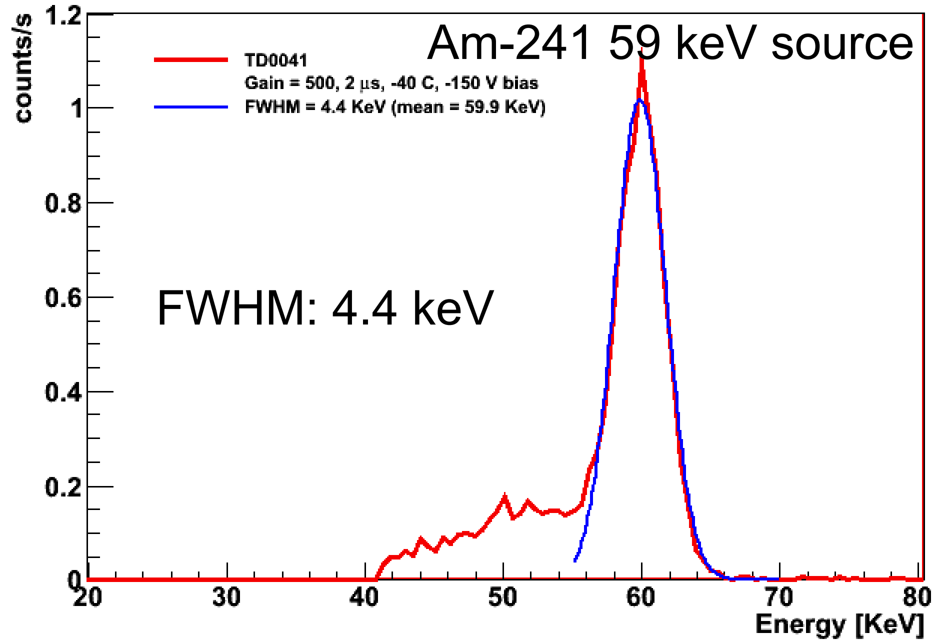

GENERAL ANTIPARTICLE SPECTROMETER
GAPS
NASA•JAXA
2012:06:03 02:28:16

Detector production





Shimadzu detector

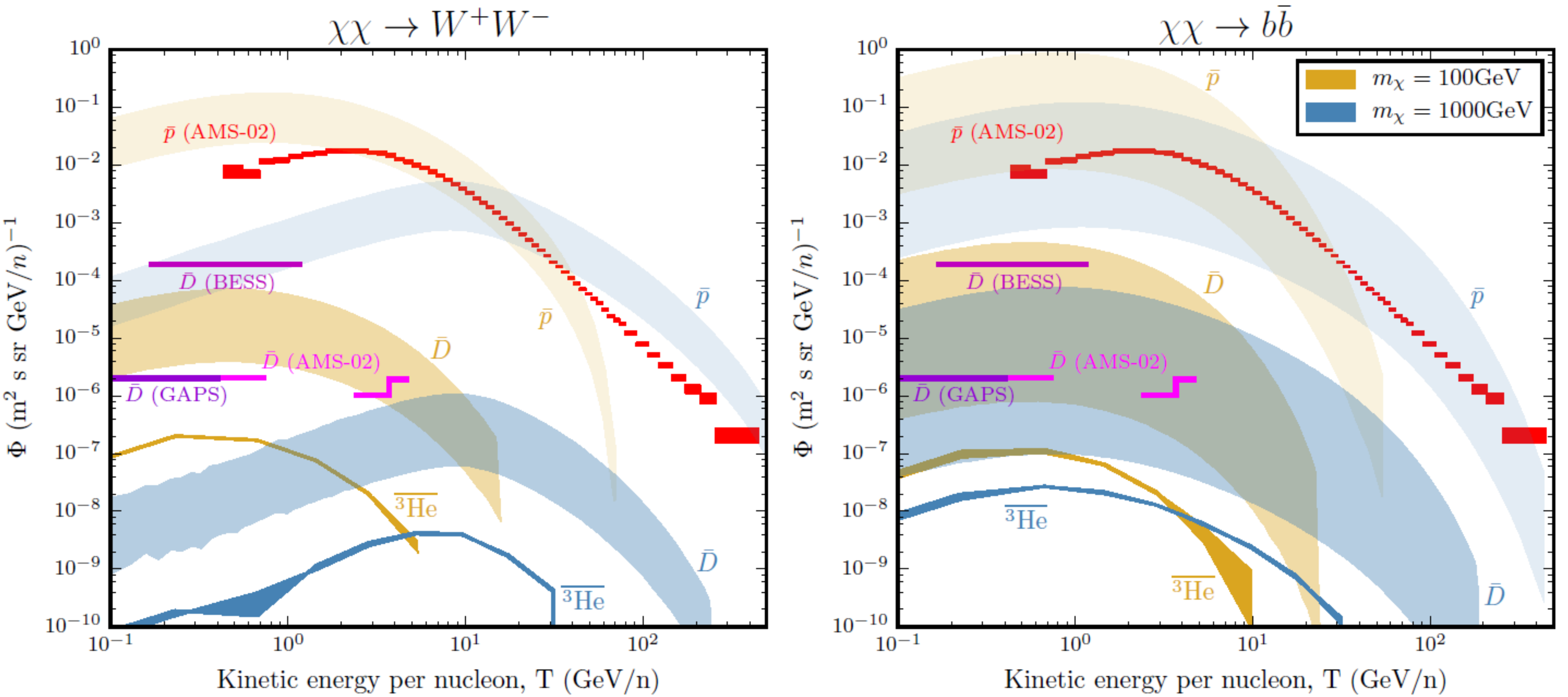


- GAPS will use ~1350 4” Si(Li) detectors, 2.5mm thick
- fabrication scheme developed at Columbia U, produced by private company Shimadzu, Japan
- confirmed performance with cosmic rays (MIPs) and Am-241 source (X-rays)

- TOF testing and development ongoing → decision between PMTs and SiPms

Next up: antihelium?

Coogan, Profumo, arXiv:1705.09664

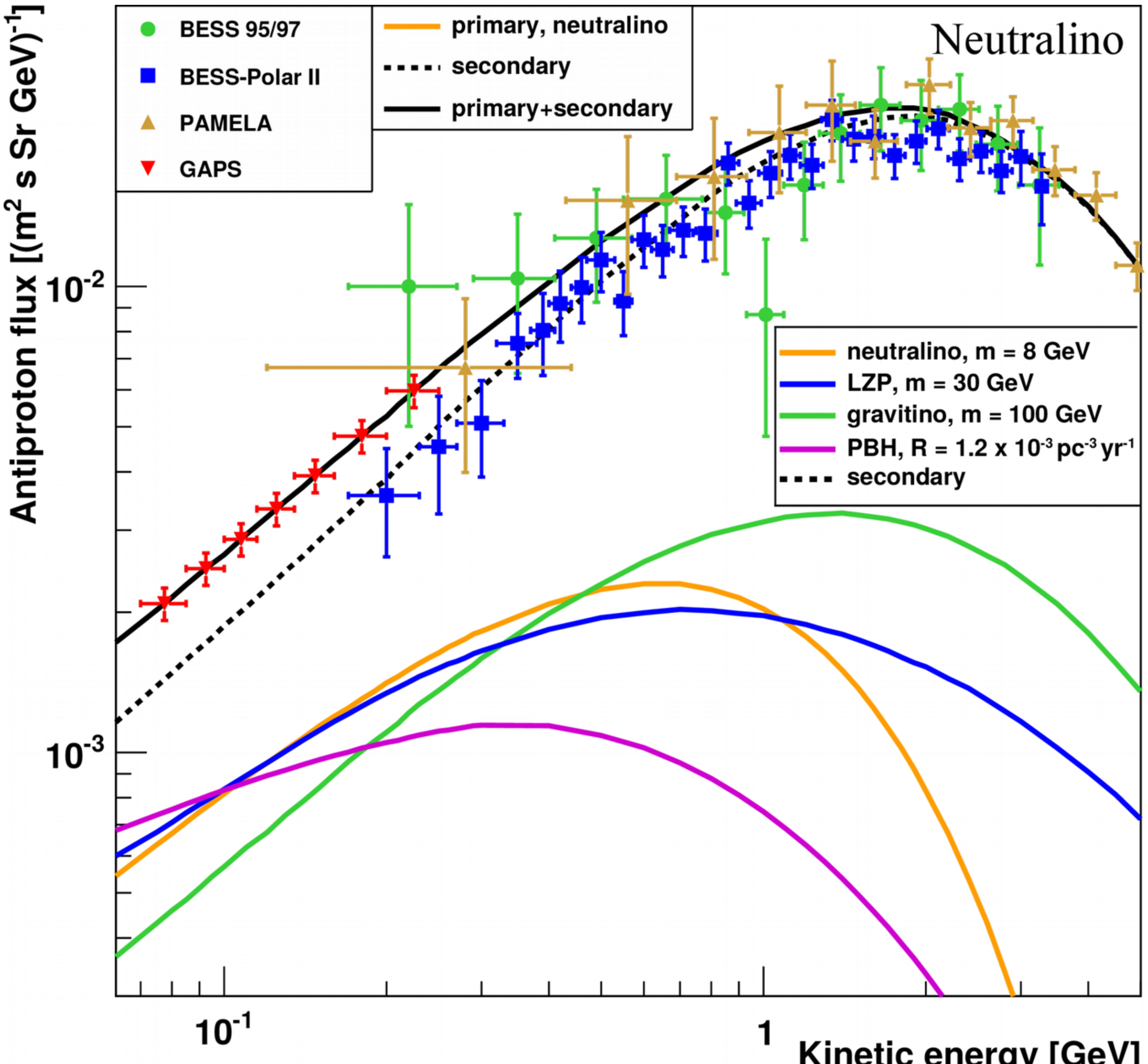


- AMS-02 announced antihelium candidates
- needs more data over the next years to make a statistically sound statement
- has important implications for antiprotons and antideuterons
  → all three channels have to be explained at the same time
  → nuclear formation is a key issue

Conclusion & Outlook

- 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**
- measurements with NA61/SHINE will improve understanding of antideuteron production and modeling
- measurement of antideuterons is a promising way for indirect dark matter search

GAPS low-energy antiproton



Predicted primary antiproton fluxes from:

- Neutralinos
- LZP
- Gravitinos
- primordial black holesPBHs, along with neutralino signals

as seen by 1 GAPS LDB flight