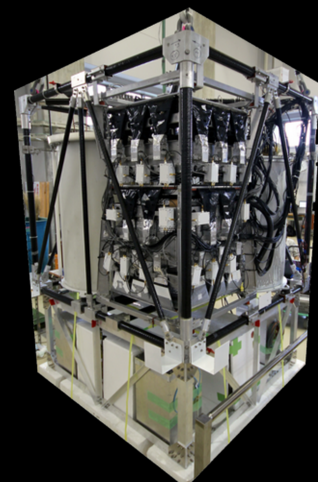
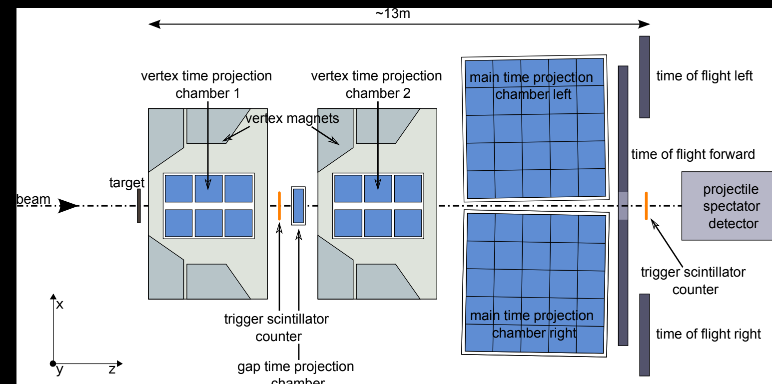
Cosmic-ray antideuterons: a new probe for dark matter identification





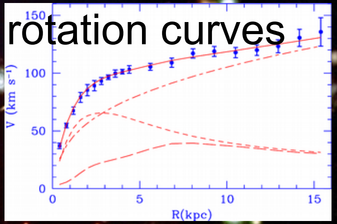
UC Berkeley – Space Science Lab
February 2018

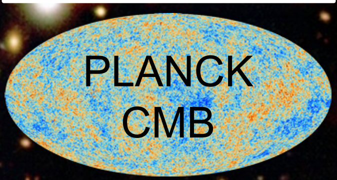
Philip von Doetinchem

philipvd@hawaii.edu
Department of Physics & Astronomy
University of Hawai'i at Mānoa
http://www.phys.hawaii.edu/~philipvd

Evidence for dark matter

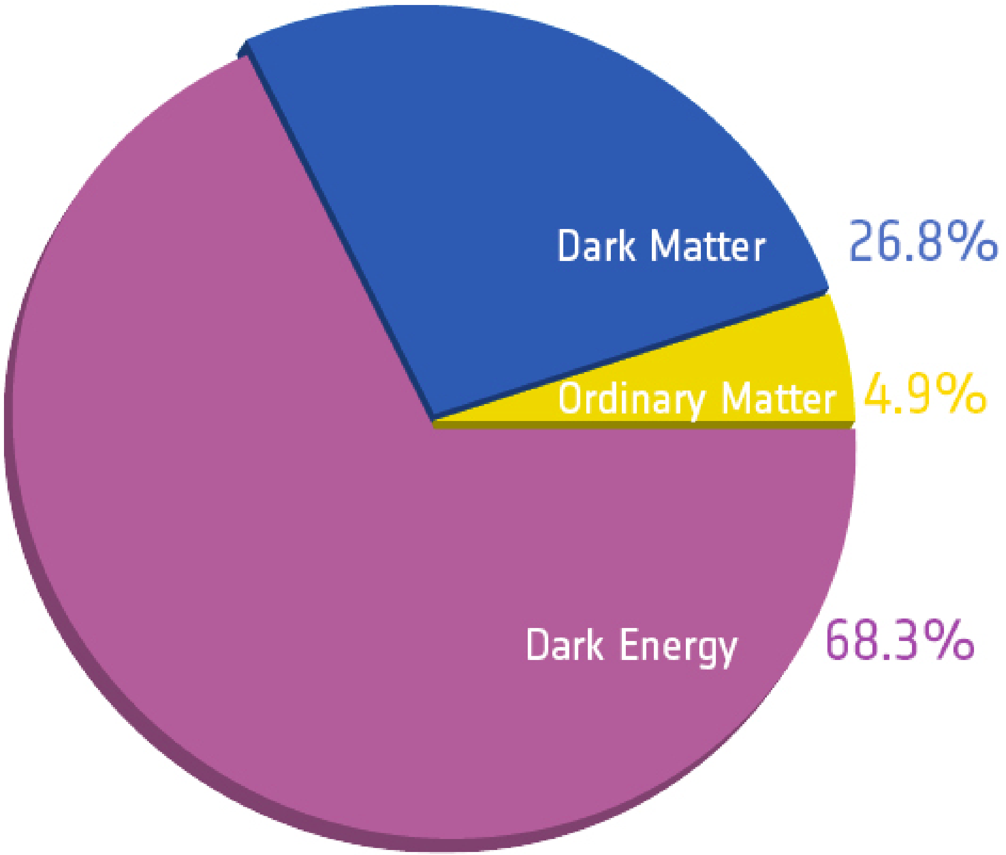
Bullet cluster
red: hot X-ray emitting gas
blue: distribution of dark matter





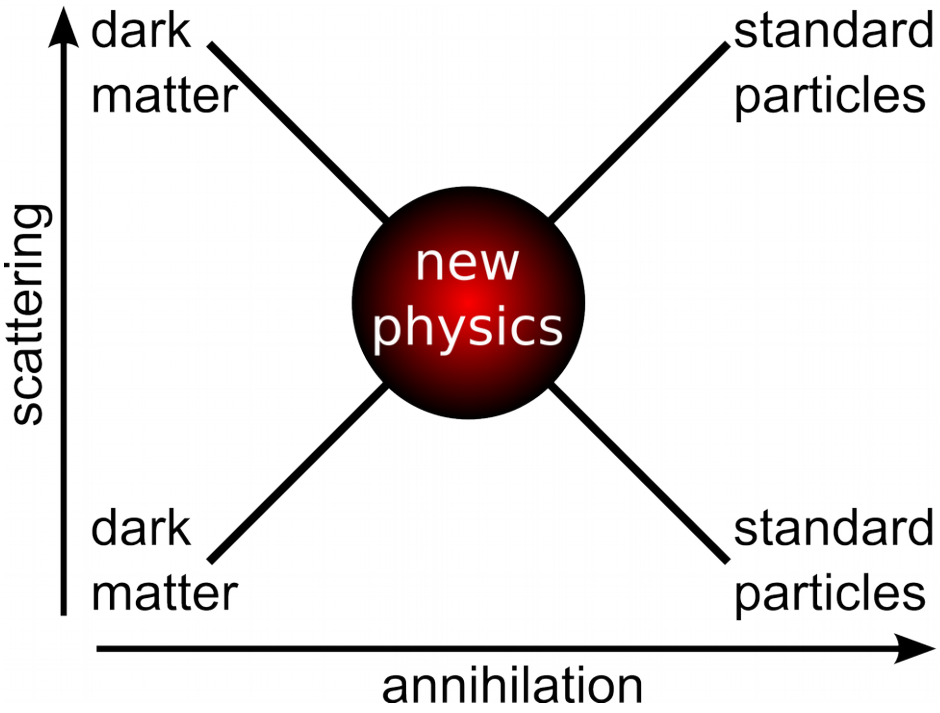
- **dark matter exists, but nature remains unknown!**
- luminous matter cannot describe the structure of the Universe
- evidence for dark matter comes from many different type of observations on different distance scales

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**

Dark matter identification challenge

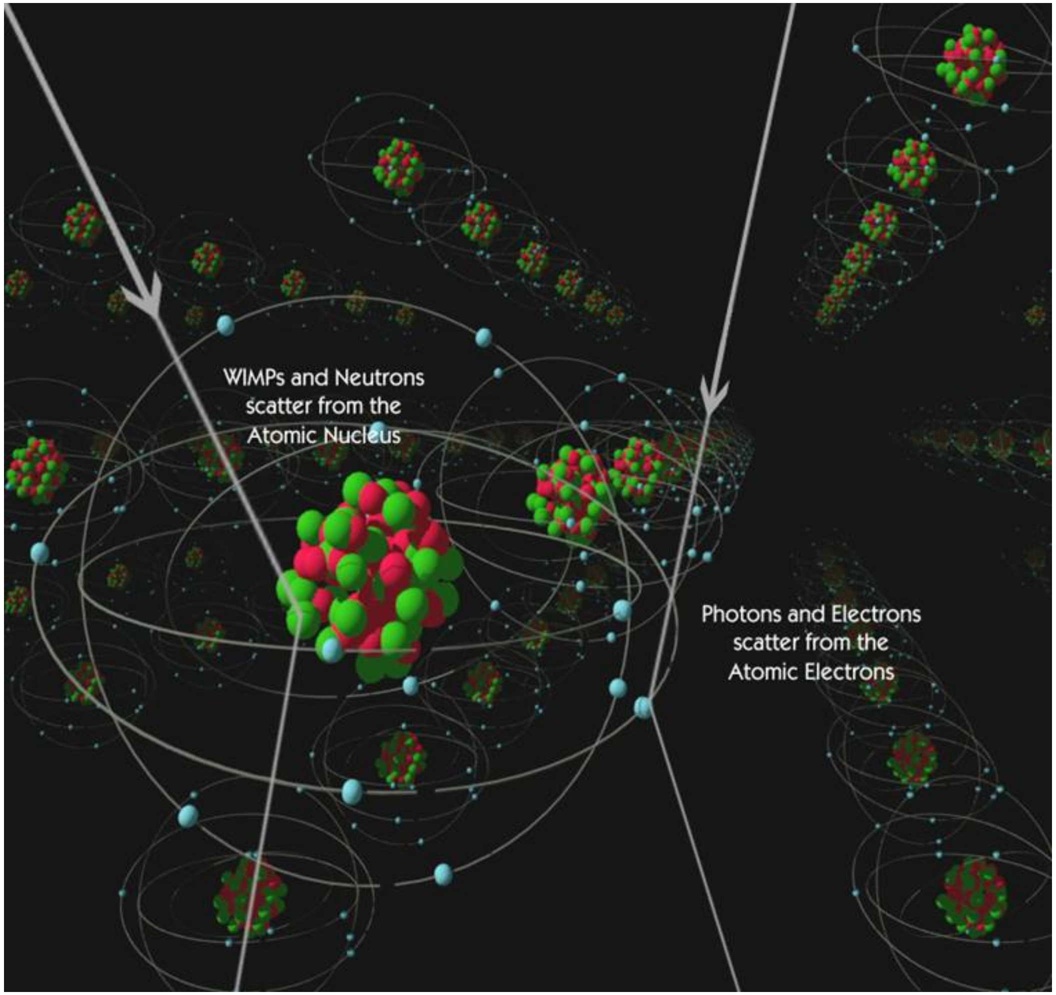


- **natural assumption:** dark matter was in thermal equilibrium in the early universe expansion led to dark matter freeze-out
  → **dark matter must(?) be able to interact with standard model particles**

particle physics × astrophysics = signal

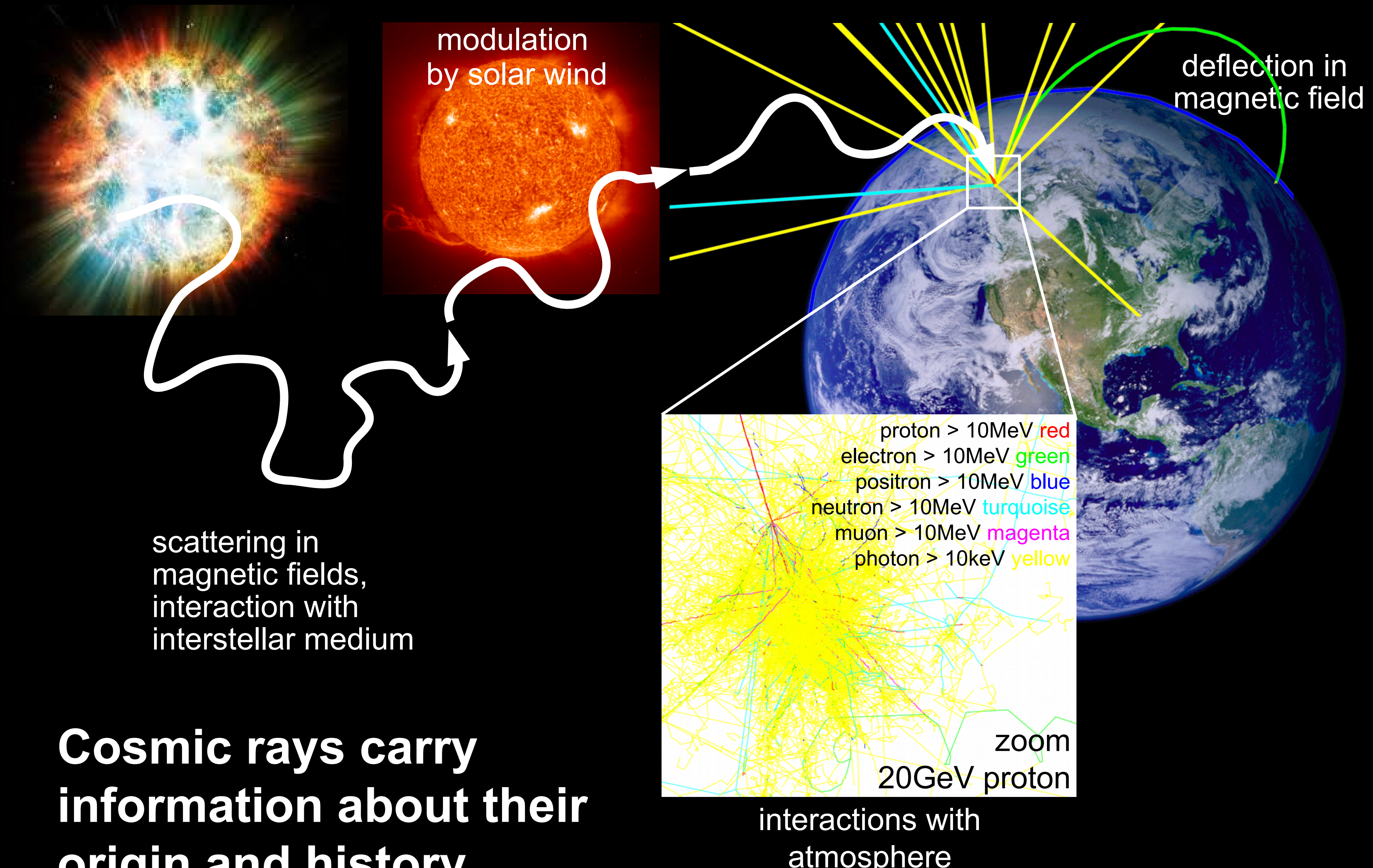
- solving the dark matter problem means therefore disentangling particle physics and astrophysics
- beyond standard model particle physics need to provide stable dark matter candidates
- Astrophysics: dark matter distribution: substructures, density, velocity distribution

Direct dark matter searches (scattering)



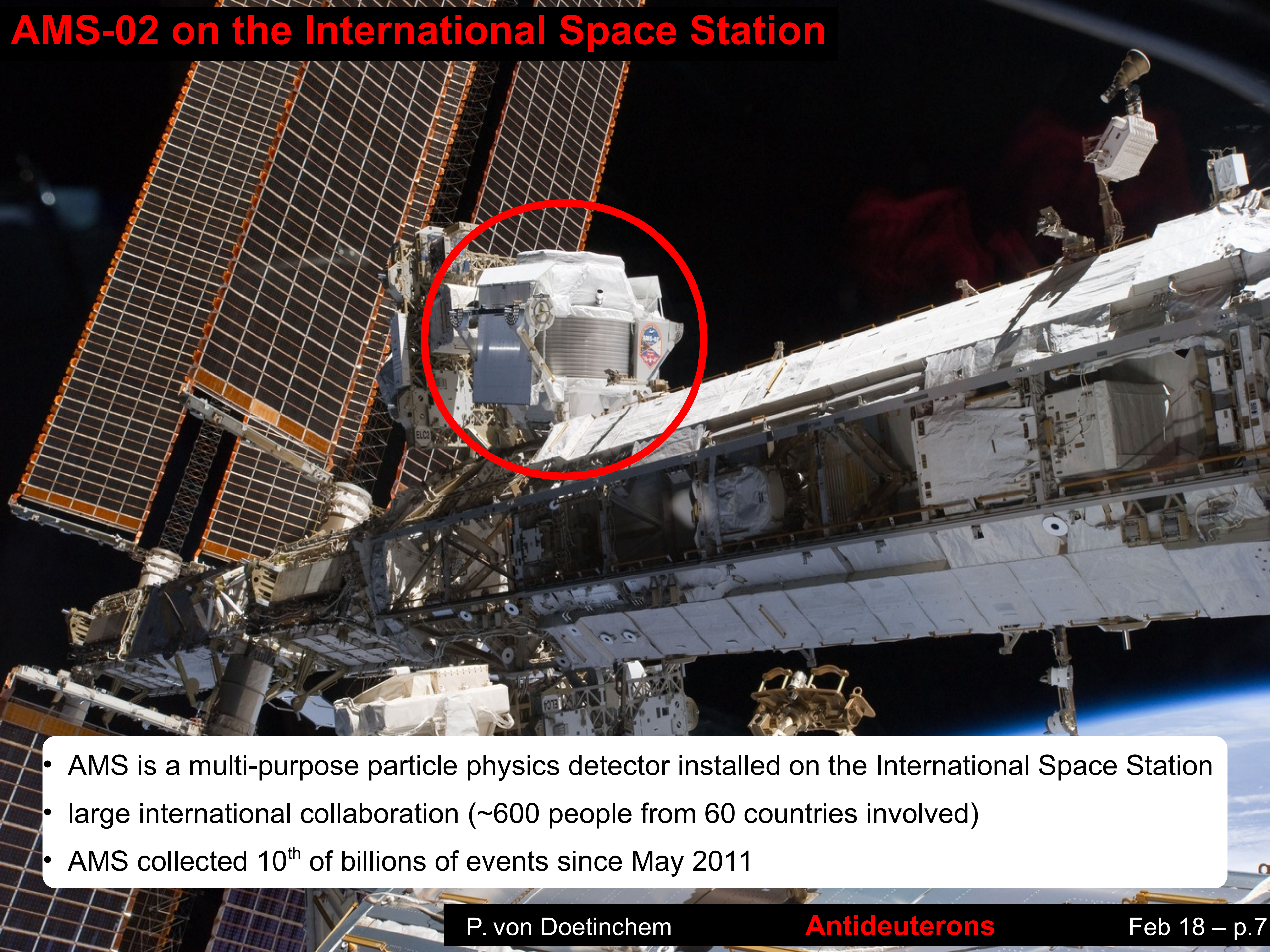
- **direct dark matter search:** measure cross-section via nuclear recoil
- typically large, heavy and very pure target materials in deep mines $\rightarrow$ CDMS, LUX, DEAP/CLEAN, XENON, PANDA XMASS, PICO, LZ, etc.
- experiments start probing theoretically preferred parameter space
- **very challenging experiments**

Charged cosmic rays as messengers



Cosmic rays carry information about their origin and history

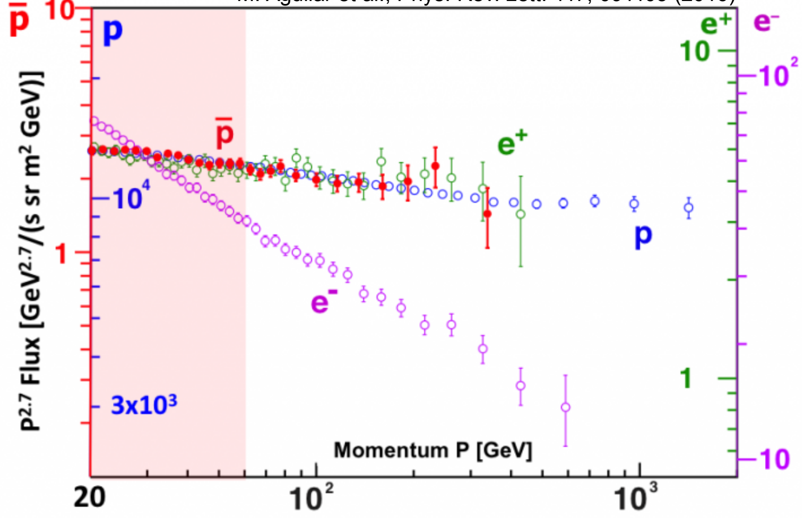
AMS-02 on the International Space Station

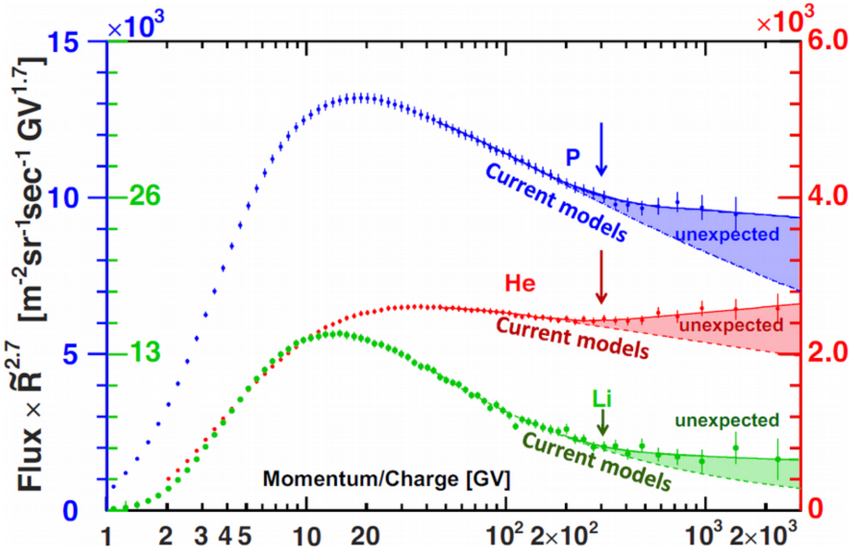


- AMS is a multi-purpose particle physics detector installed on the International Space Station
- large international collaboration (~600 people from 60 countries involved)
- AMS collected 10^{th} of billions of events since May 2011

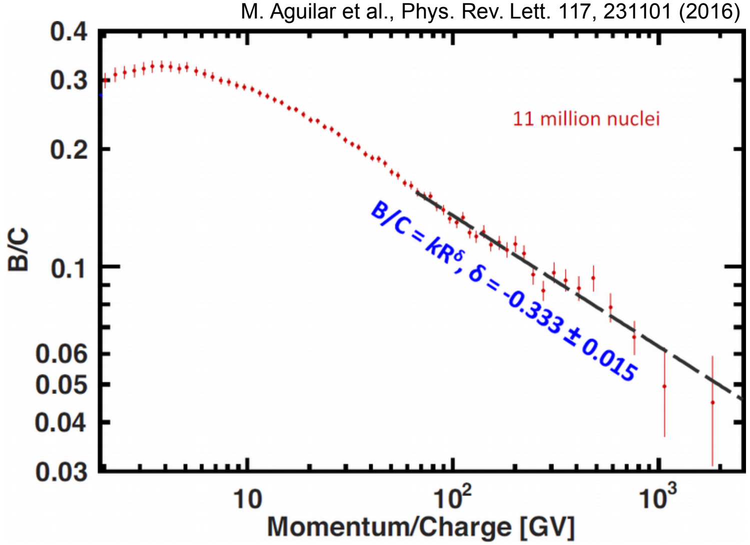
AMS-02 cosmic ray status (selected)

M. Aguilar et al., Phys. Rev. Lett. 117, 091103 (2016)





M. Aguilar et al., Phys. Rev. Lett. 117, 231101 (2016)



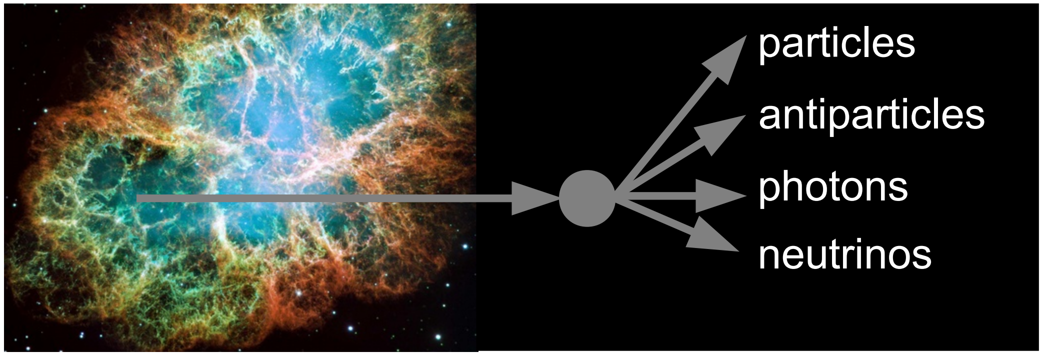
- Spectra of elementary particles e^+, p, $\bar{p}$ have identical energy dependence from 60-500GV. *However, e^- does not.*
  → unknown local e^+ source
- Unexpected breaks in p, He, Li at ~300GV.
- Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM. Above 65 GV, the B/C ratio is well described by a single power law.
- Many more species and ratios are upcoming

→ AMS-02 started new precision era

Indirect dark matter searches (annihilation)

background

conventional cosmic rays

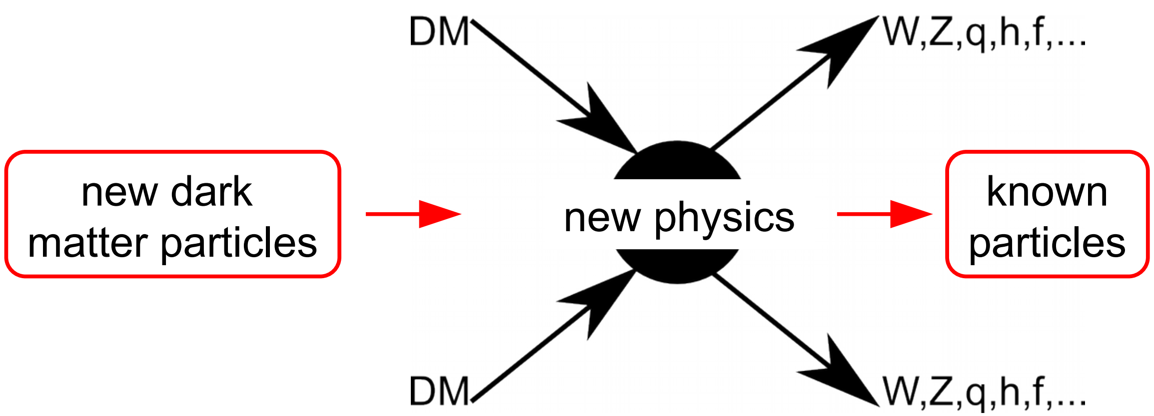


primary cosmic rays from star explosions

interactions with interstellar medium

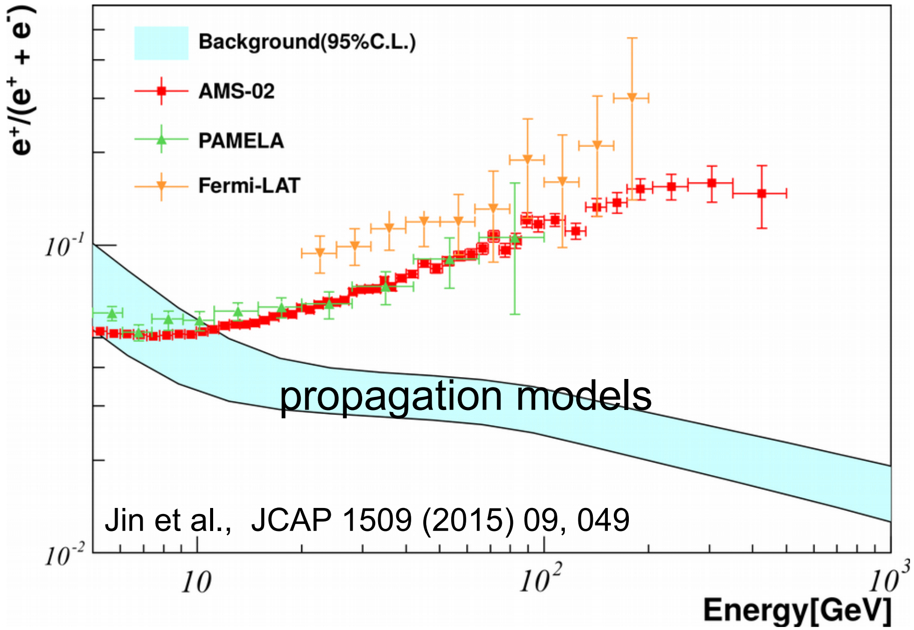
signal

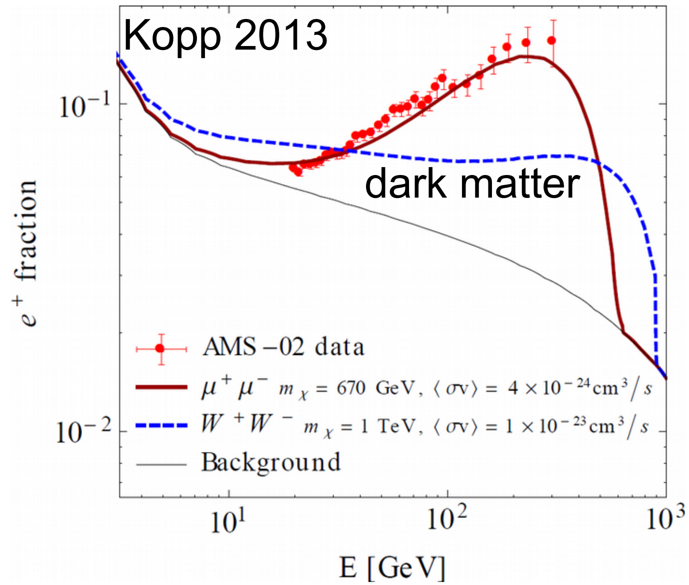
cosmic rays from the annihilation of dark matter

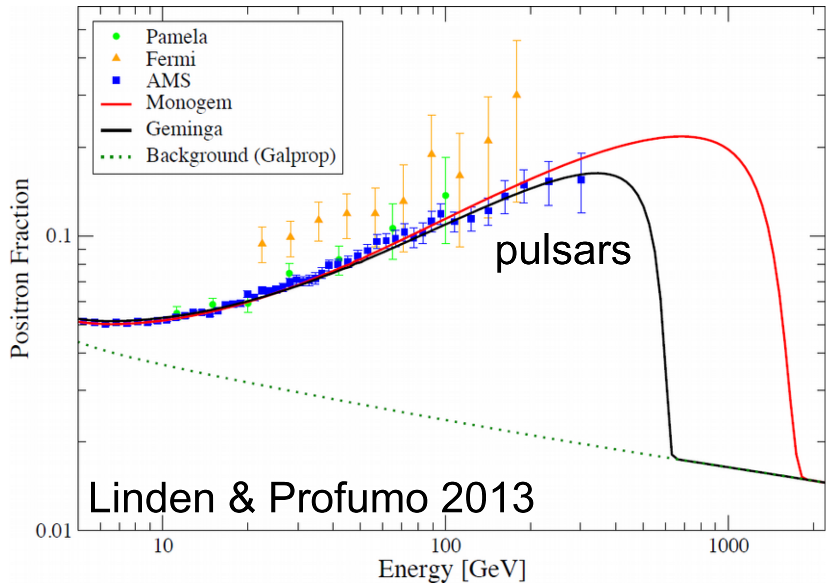


- **assumption:** cosmic-rays from dark matter annihilation follow different kinematics than conventional production
- peak/bump/shoulder on top of conventional spectrum
- use search channel without strong conventional production: e^+, γ, $\bar{p}$, ν

Dark matter signal in positrons?



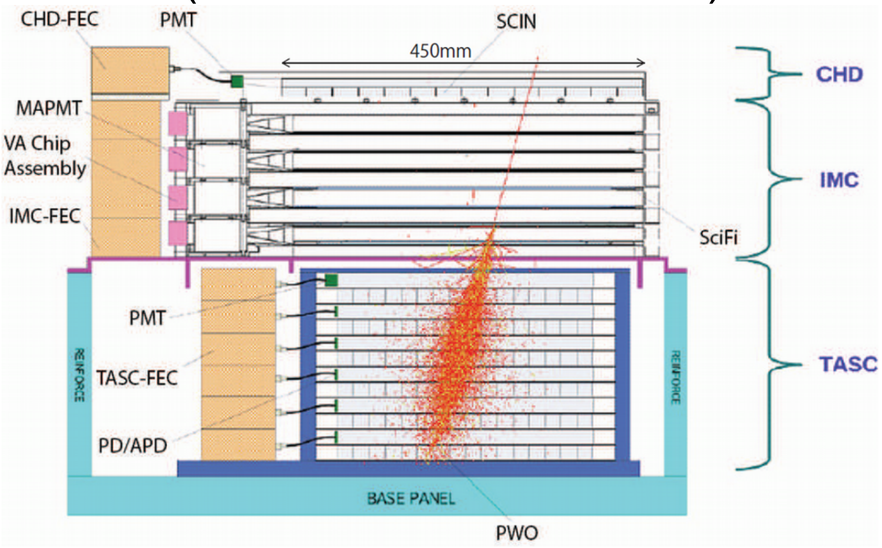


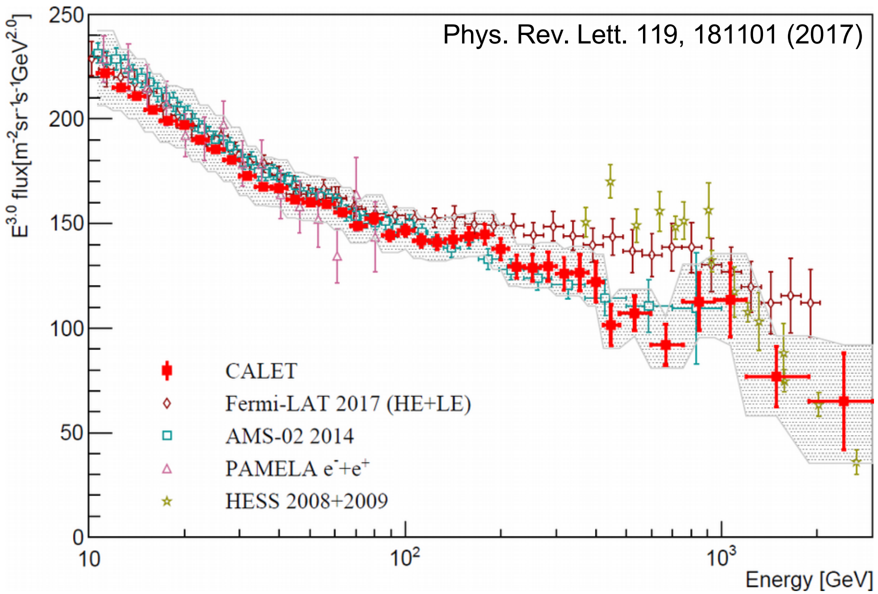


- dark matter models are severely constrained:
  - large cross sections
- explained by nearby pulsars producing electrons and positrons?
  - anisotropy should be smaller than AMS-02 limit, but still measurable with ACTs
- different acceleration mechanisms
- important to see how the positron fraction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

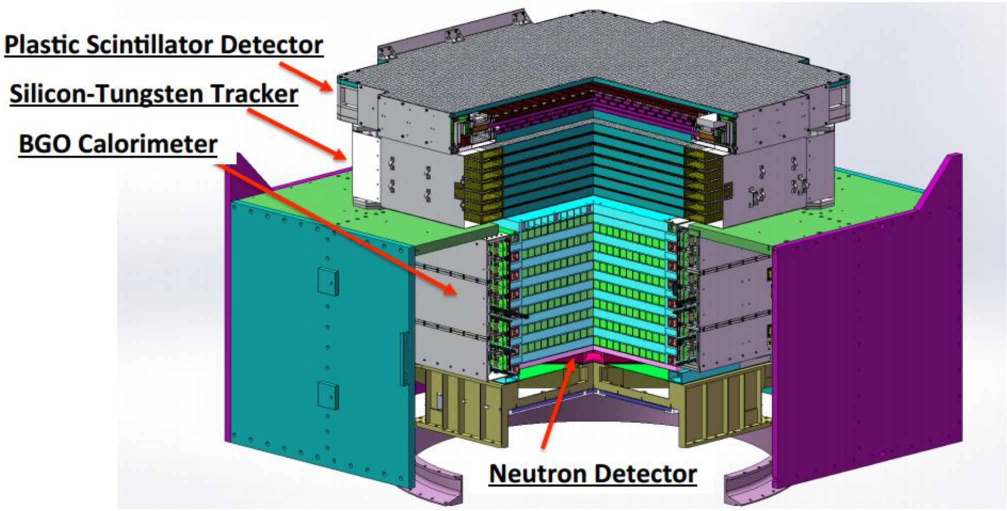
e^-+e^+ fluxes: new CALET, DAMPE results

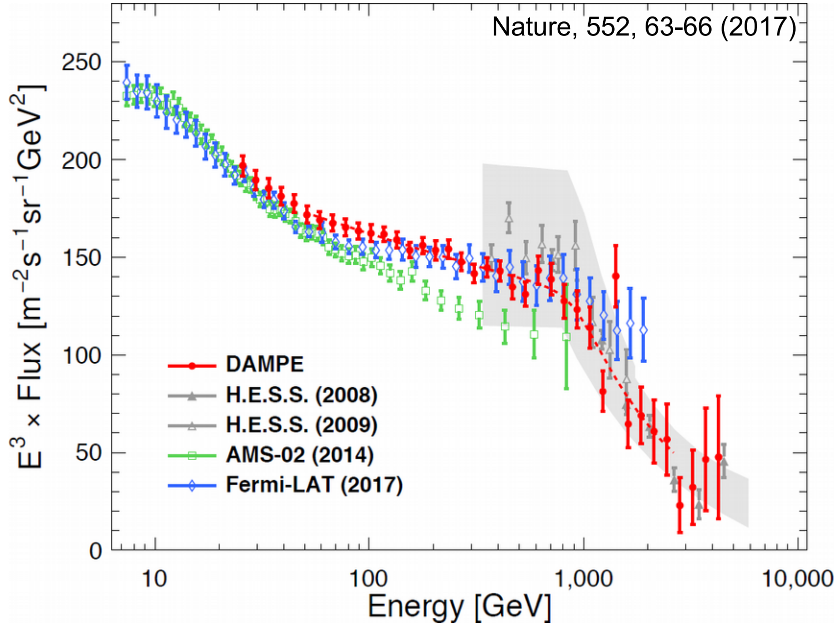
CALET (on the ISS since 8/2015)





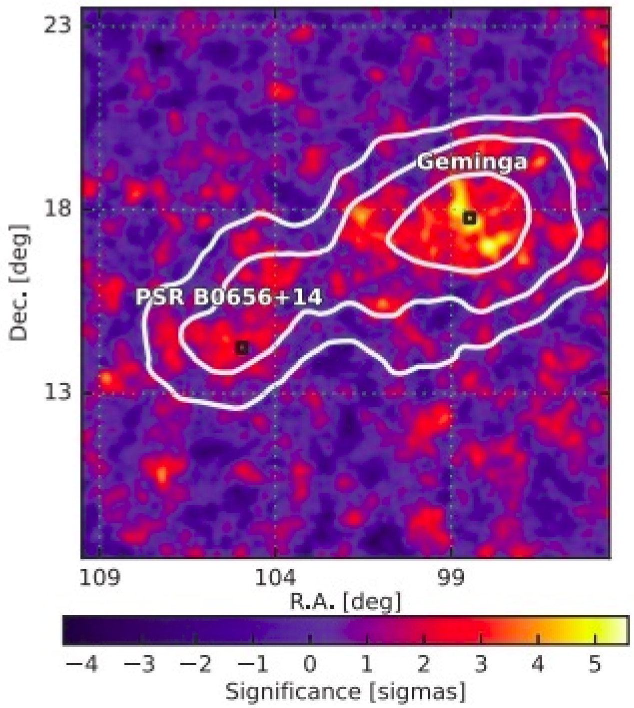
CALET (satellite, in space since 12/2015)

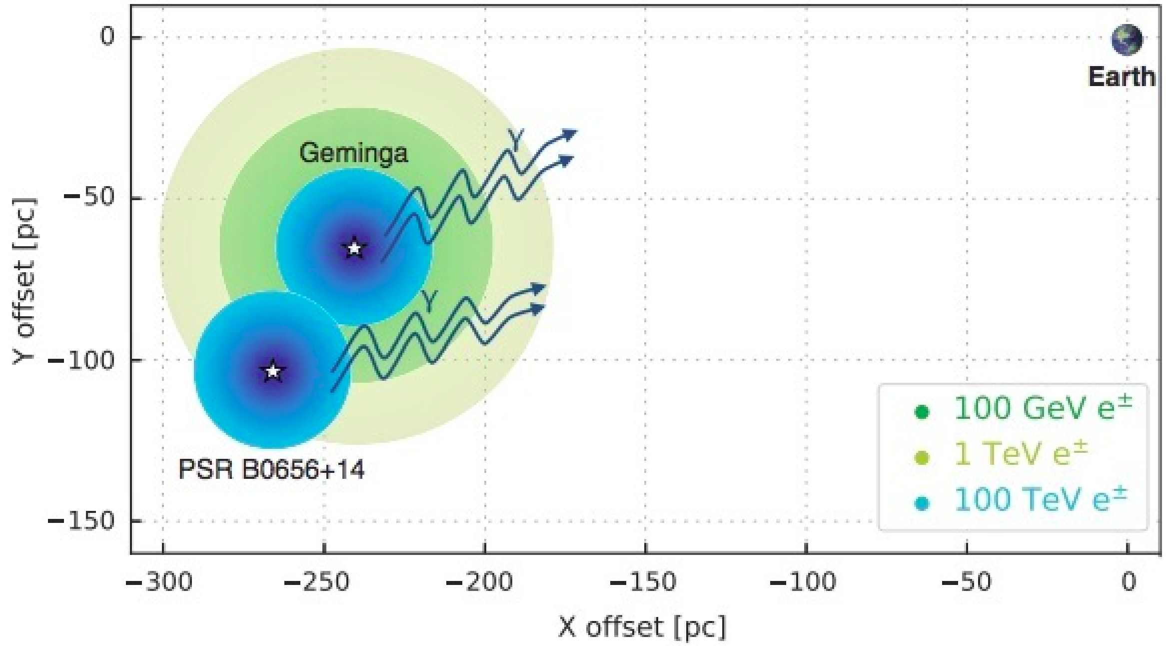




Positrons from pulsars?

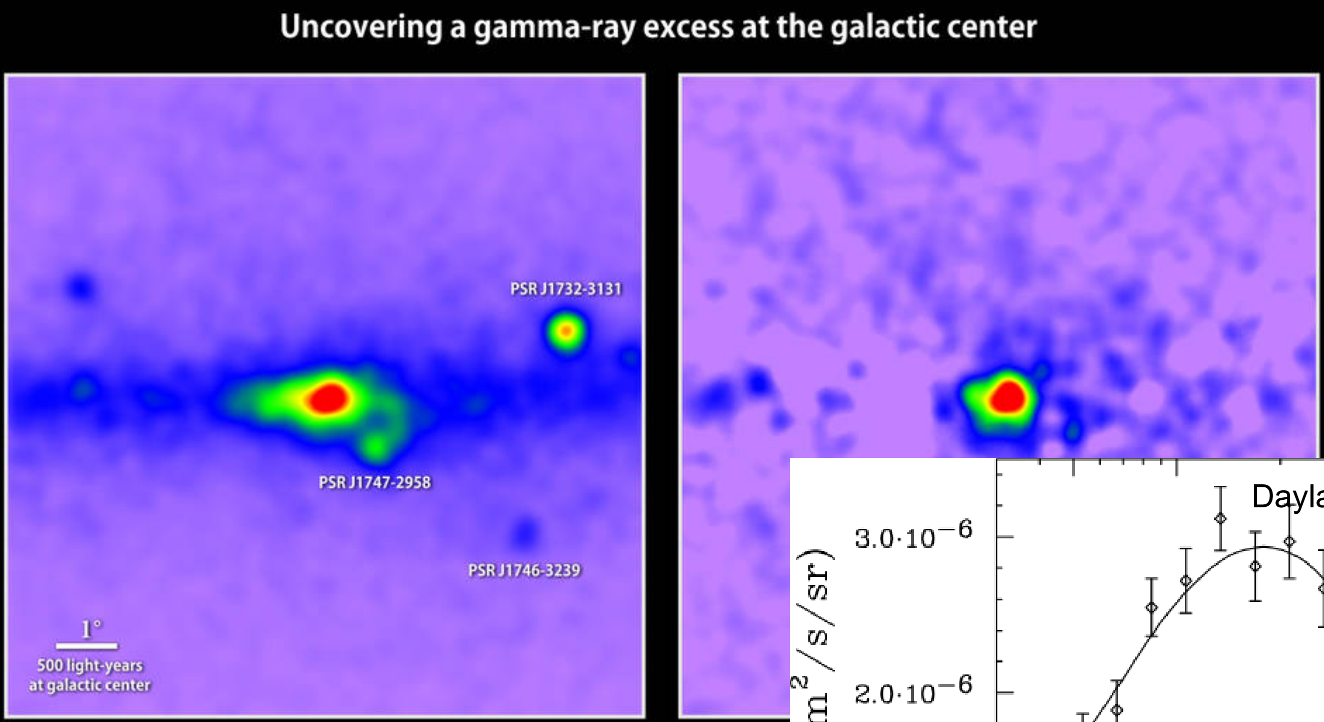
HAWC collaboration, Science 358 (6365), 911 (2017)



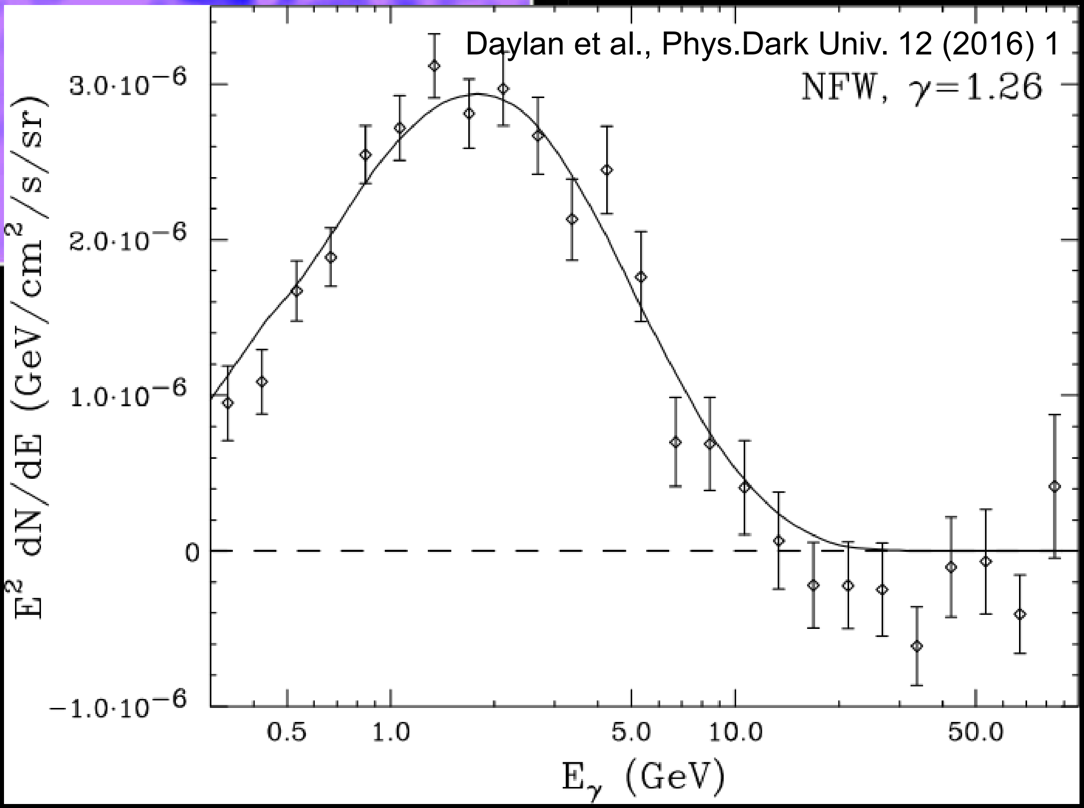


- local pulsars were considered the most probable source for high energy positrons
- observation of local pulsars by HAWC (γ-ray observatory using water Cherenkov method) show that these local pulsars are not bright enough to explain the anomalous positrons observed at Earth
- measurements do not rule out the pulsar hypothesis, they do eliminate two of the most probable local accelerators.

Diffuse Galactic γ-ray excess

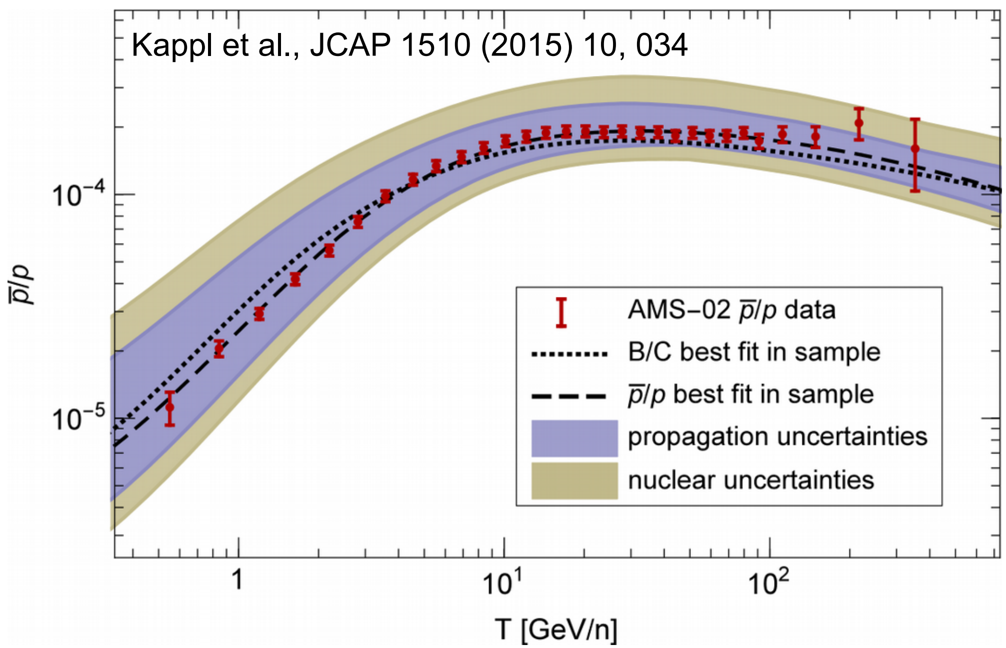


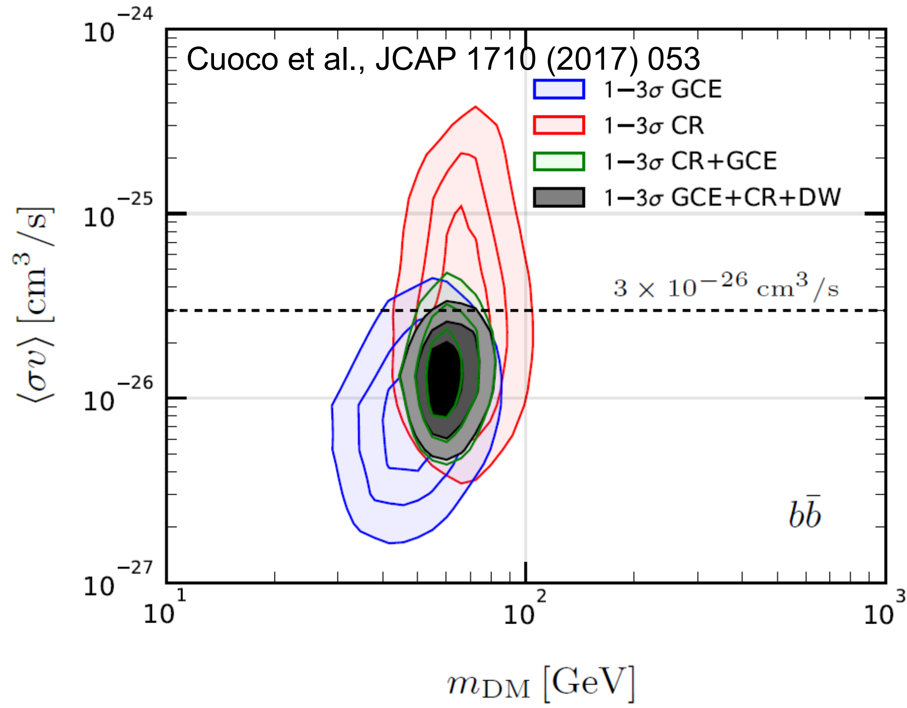
Unprocessed map of 1.0 to 3.16 GeV gamma rays



- 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

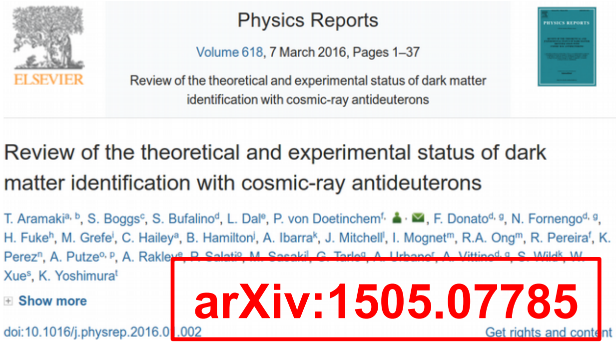
Antiprotons





- 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

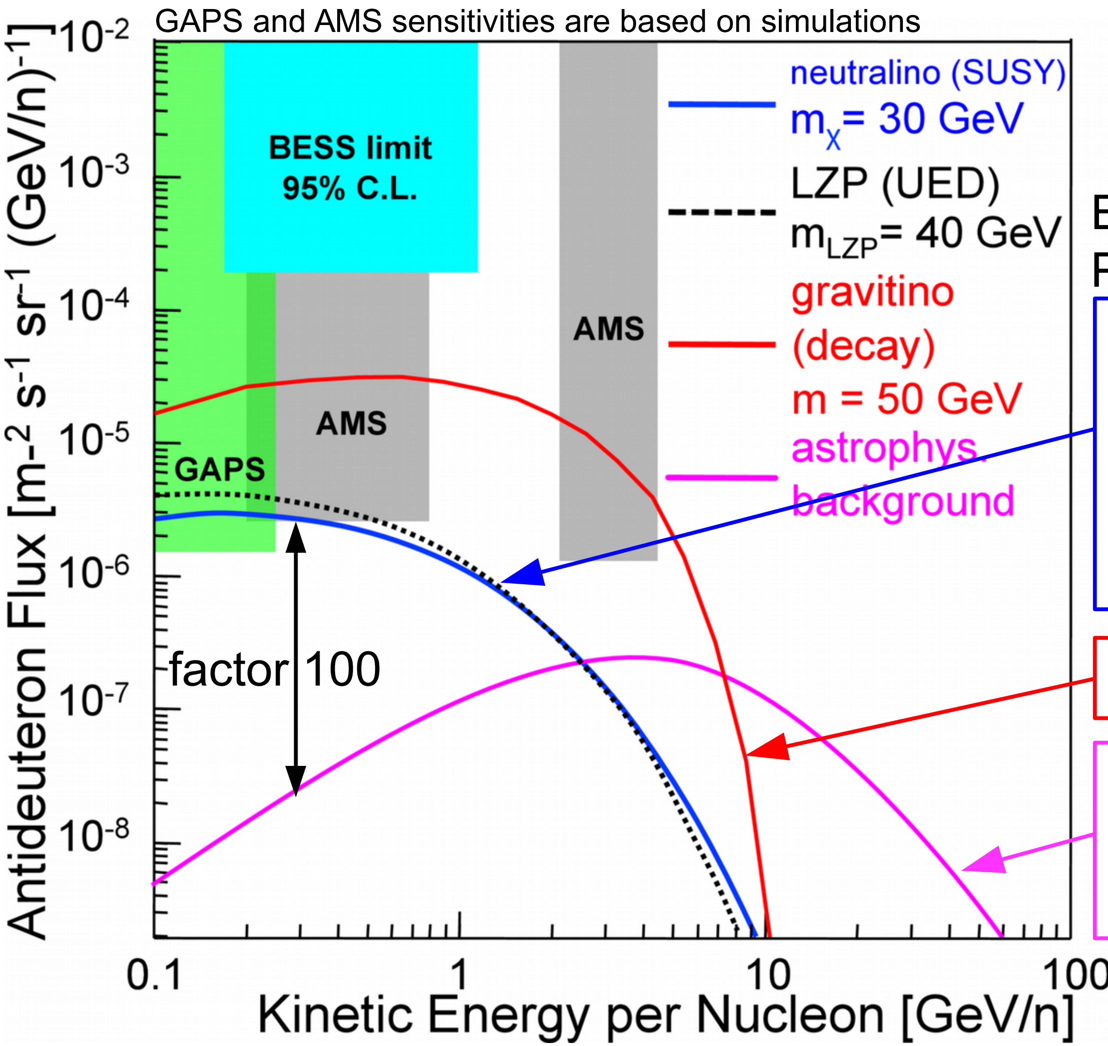
T. Aramaki, S. Boggs, S. Bufalino, L. Dal, P. von Doetinchem, F. Donato, N. Fornengo, H. Fuke, M. Grefe, C. Hailey, B. Hamilton, A. Ibarra, J. Mitchell, I. Mognet, R.A. Ong, R. Pereira, K. Perez, A. Putze, A. Raklev, P. Salati, M. Sasaki, G. Tarle, A. Urbano, A. Vittino, S. Wild, W. Xue, K. Yoshimura

Show more

doi:10.1016/j.physrep.2016.0 .002

Get rights and content

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

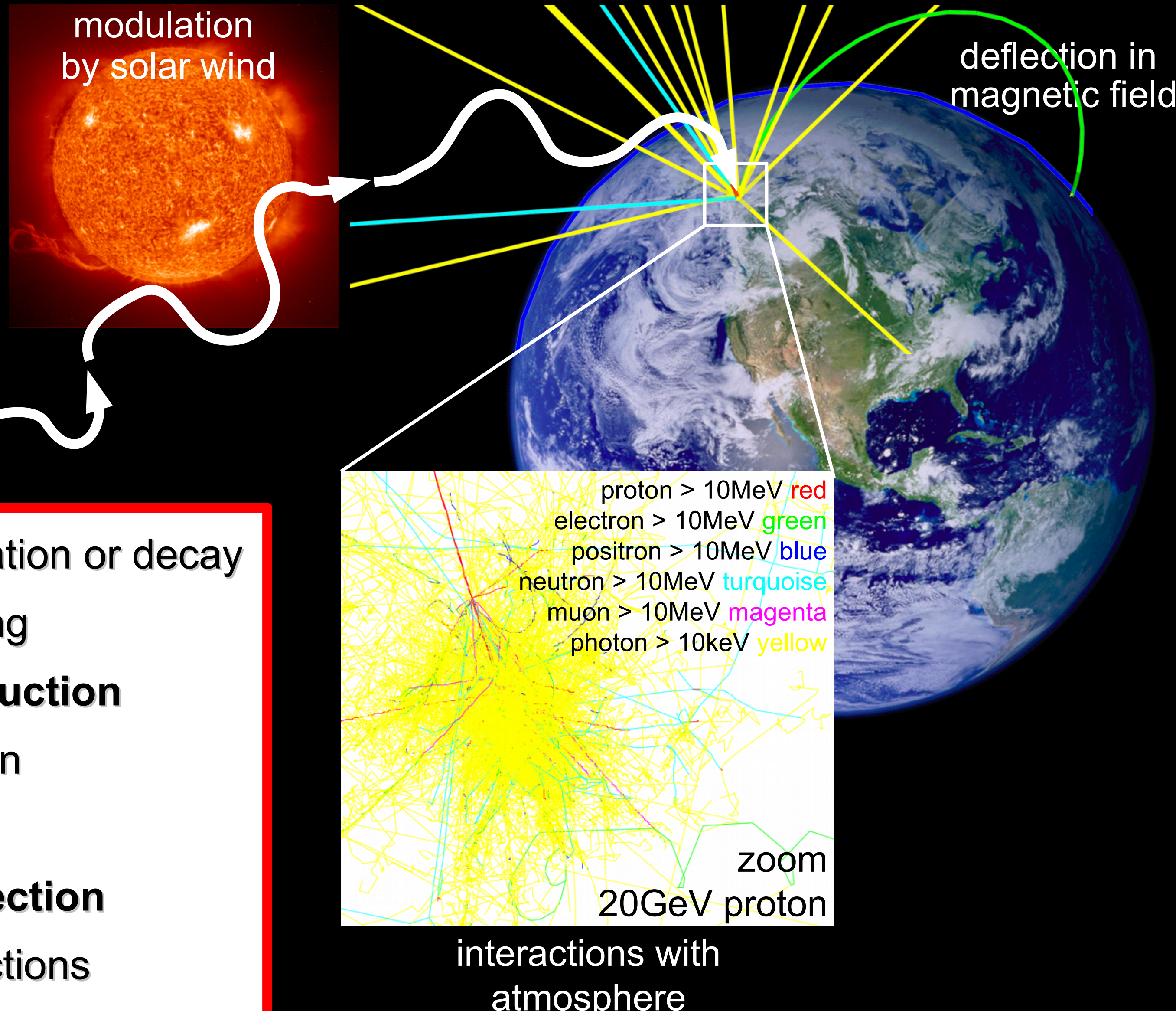
Antideuterons are the most important unexplored indirect detection technique!

Antideuterons are exciting

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

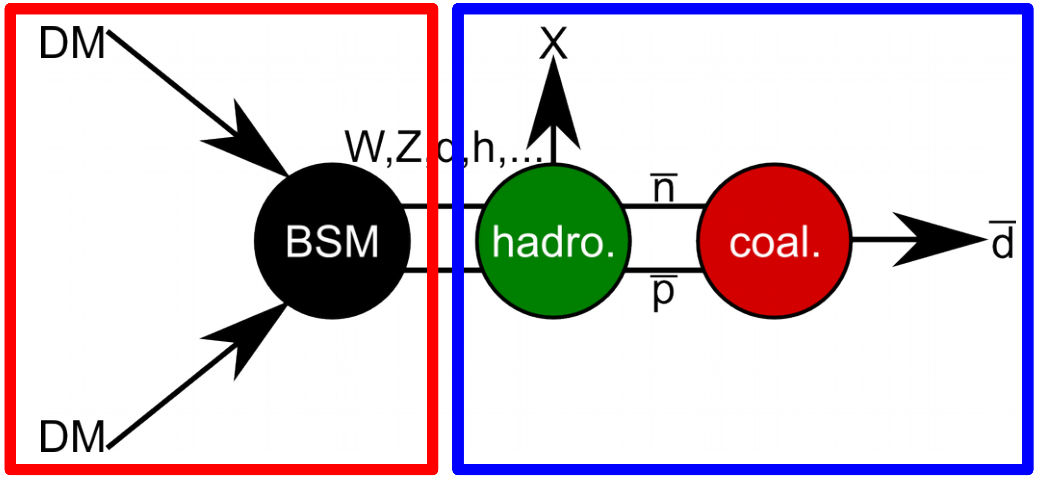
Astrophysical and particle physics challenges

DM annihilation
or decay



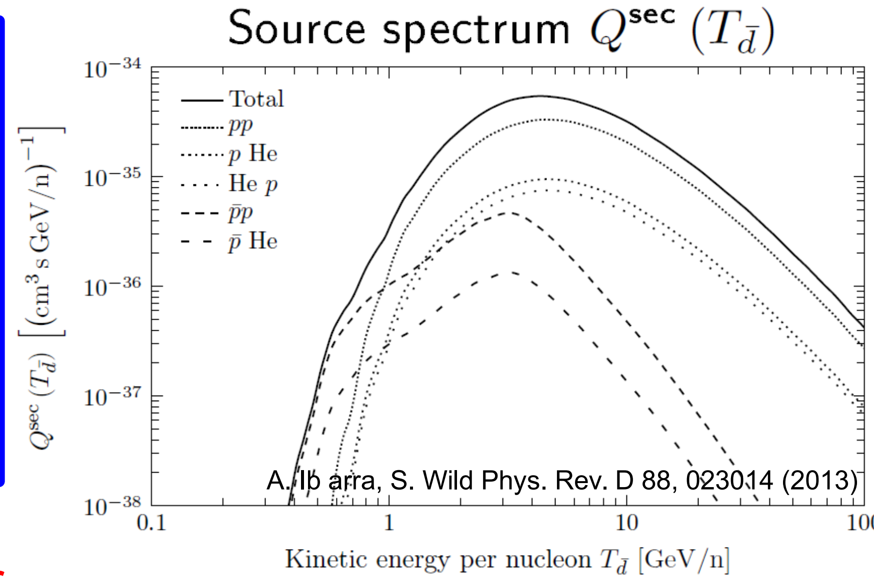
- dark matter annihilation or decay
- dark matter clumping
- **antideuteron production**
- Galactic propagation
- solar modulation
- **geomagnetic deflection**
- atmospheric interactions
- **interactions in detector**

(Anti)deuteron formation



dark matter

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



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

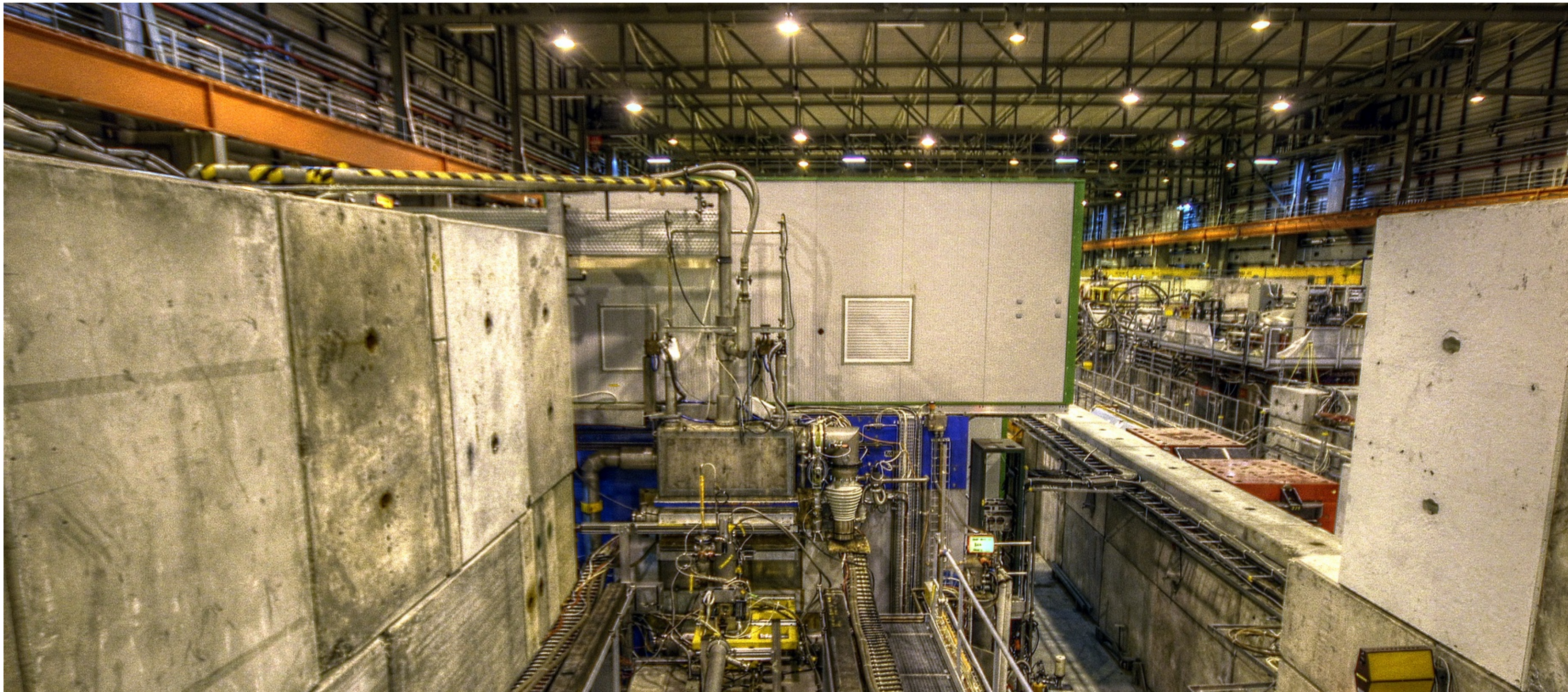
$$\gamma_d \frac{\mathrm{d}^3 N_d}{\mathrm{d}p_d^3} = \frac{4\pi}{3} p_0^3 \left(\gamma_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}p_p^3}\right) \left(\gamma_n \frac{\mathrm{d}^3 N_n}{\mathrm{d}p_n^3}\right)$$

- 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)

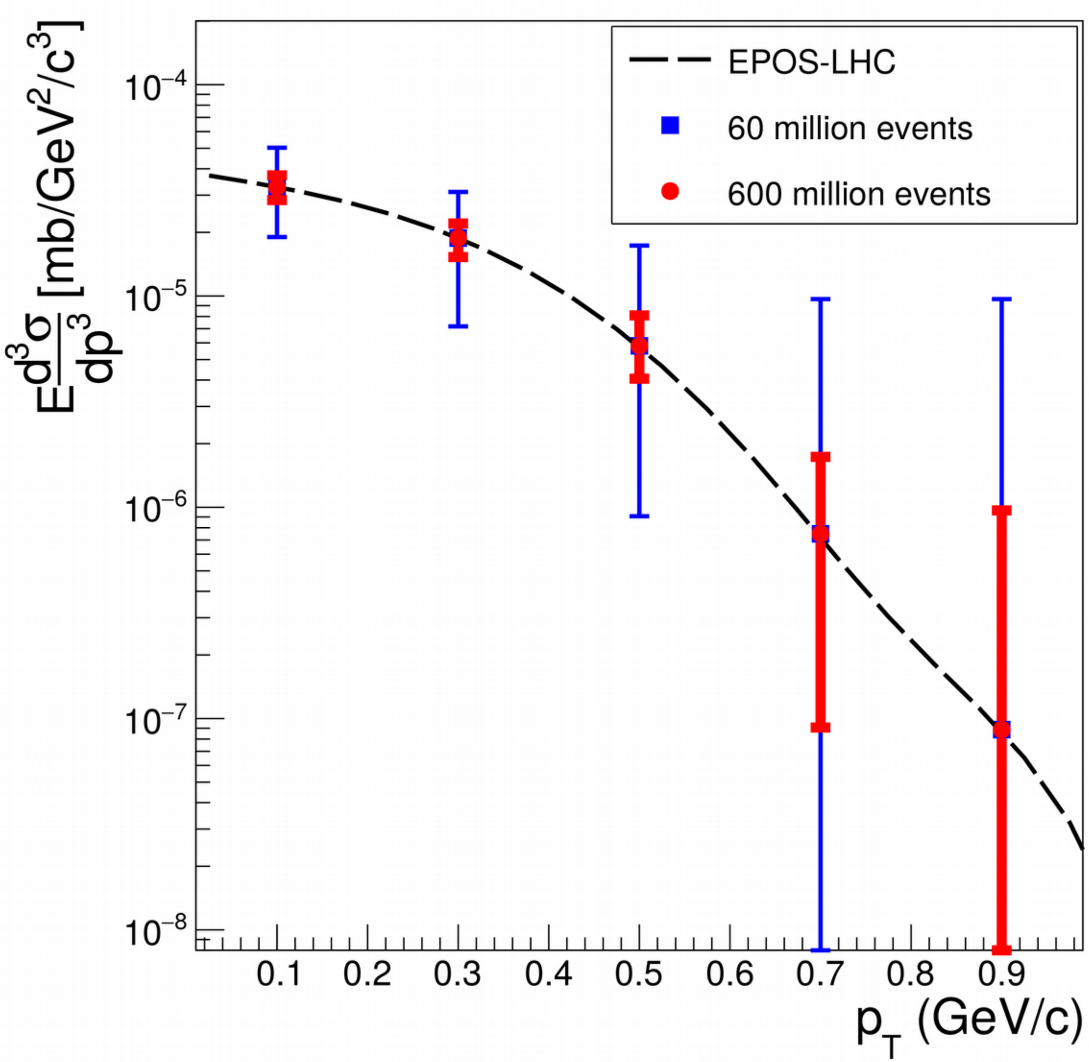
NA61/SHINE experiment at SPS, CERN

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



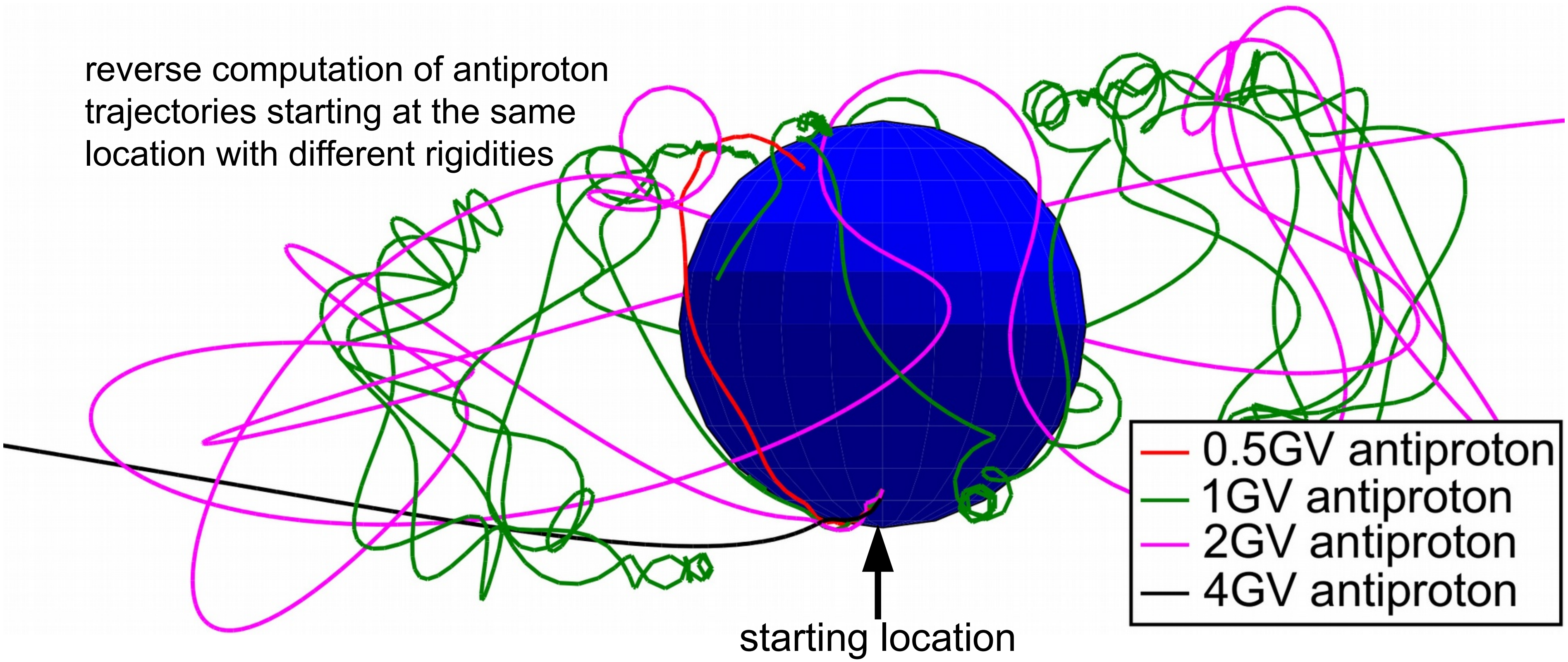
- multi-purpose, fixed-target experiment at the CERN SPS
  (NA61/SHINE facility paper: JINST 9 (2014) P06005)
  - precise measurements of properties of produced particles: q, m, p
- cosmic-ray antideuteron production happens between 40 and 400GeV
  - SPS energies from 9 to 400GeV are ideal
- data under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

Antideuteron prospects with NA61/SHINE



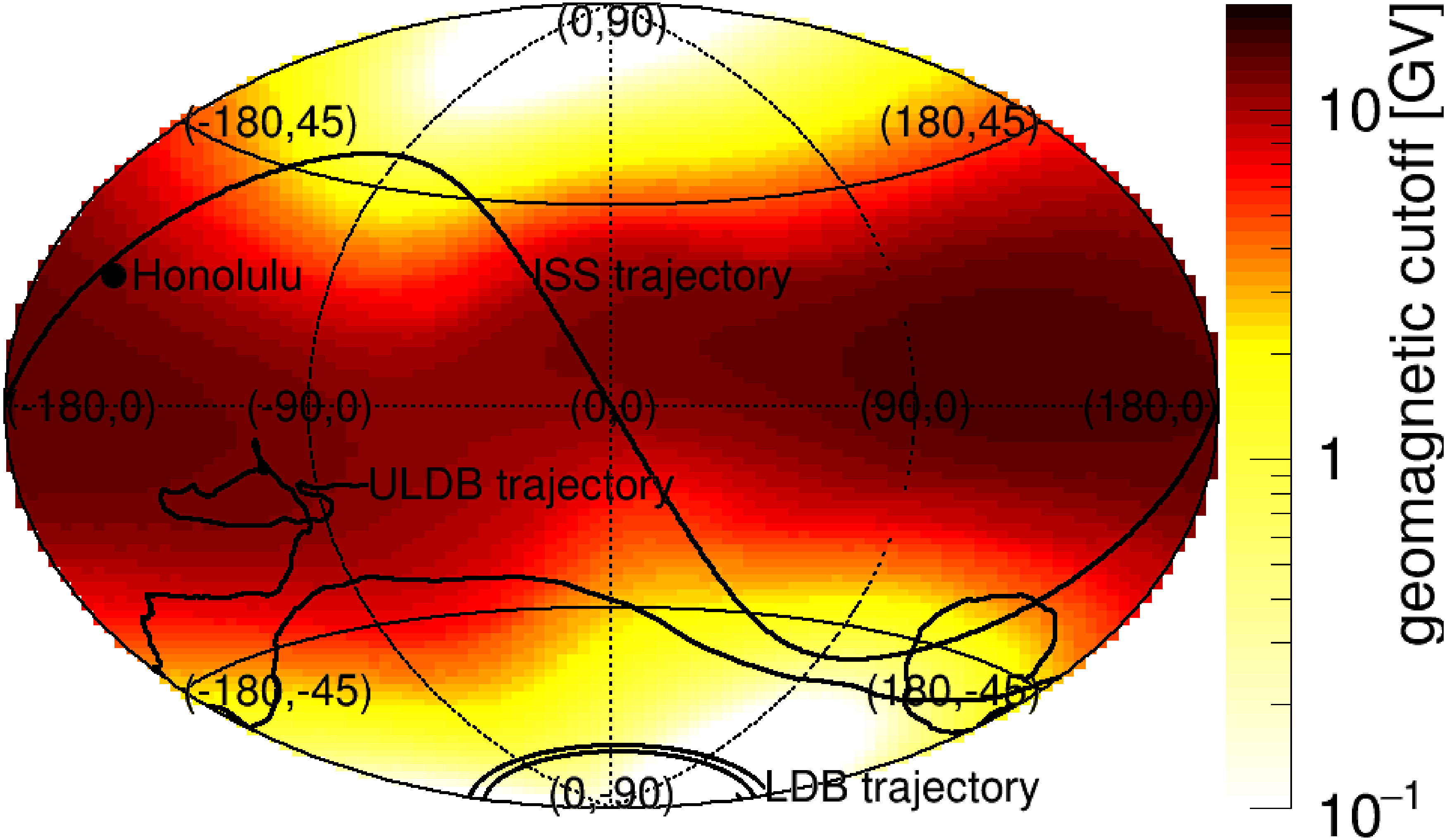
- Planning for data taking after LHC shutdown currently ongoing
  - upgraded detector will push the antideuteron analysis
  - uncertainties on coalescence parameters will be strongly reduced
- NA61/SHINE will also be used for fragmentation measurements
  - improve interpretation of B/C ratio

Geomagnetic cutoff



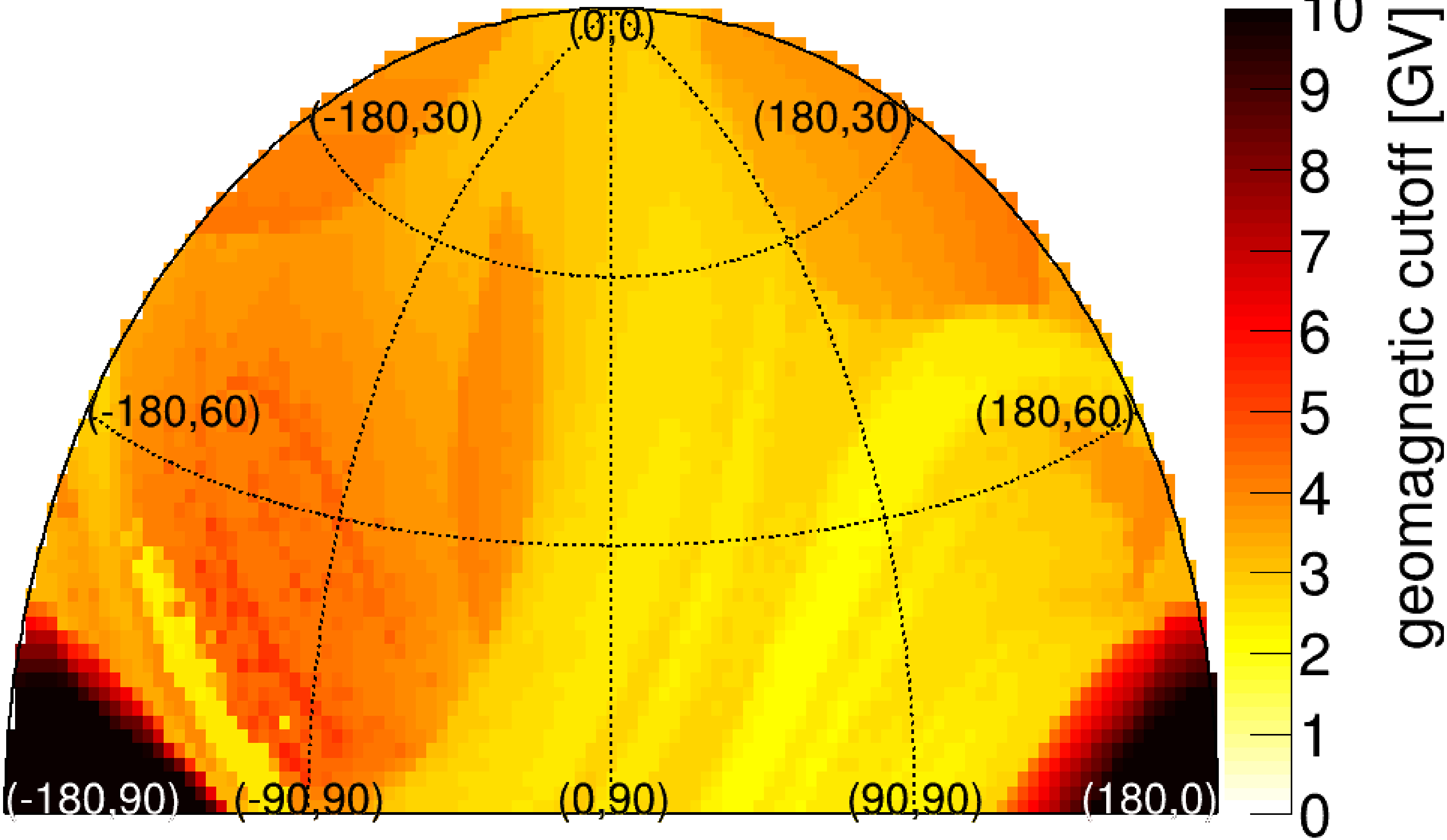
- Earth‘s magnetic field deflects charged particles depending on charge and momentum → not every position on orbit sees the same exposure to cosmic rays

Geomagnetic cutoff map



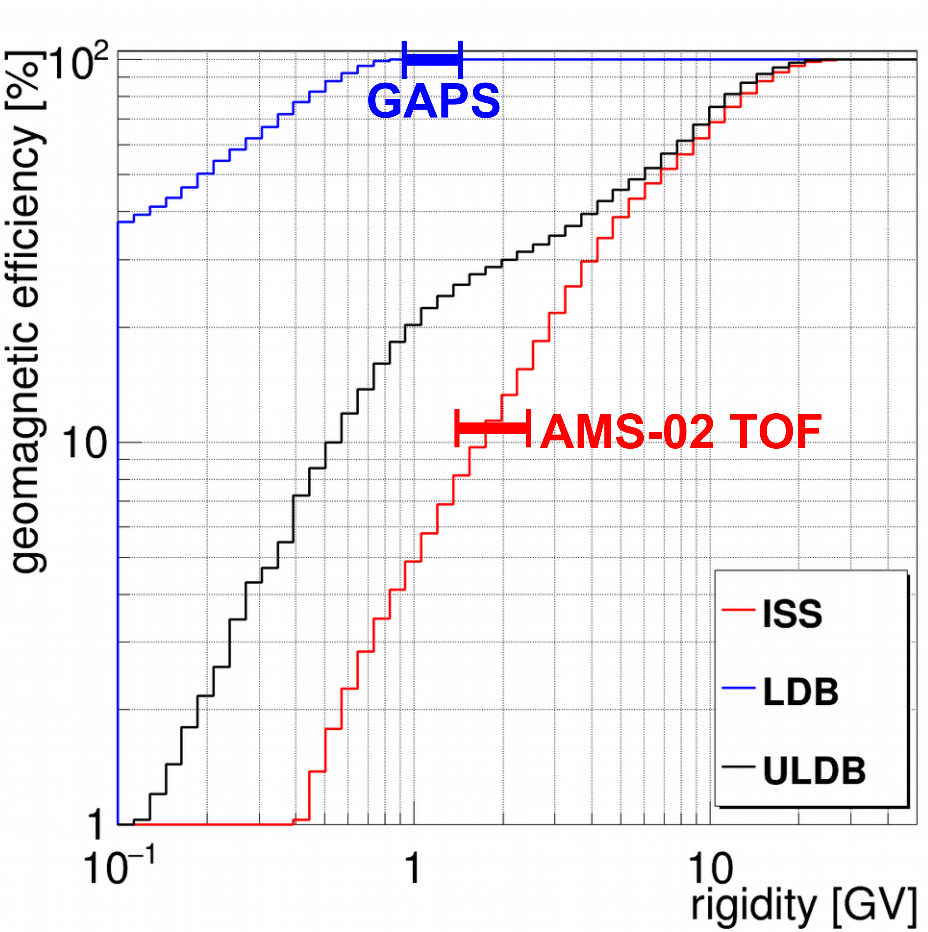
- geomagnetic cutoff for antiprotons averaged over an isotropic incoming particle distribution

Cutoff as function of direction



- cutoff values as a function of direction for 50°S, 0°W
- **depend not only on zenith, but also on azimuth → need to evaluate both**

Geomagnetic efficiency for antiprotons

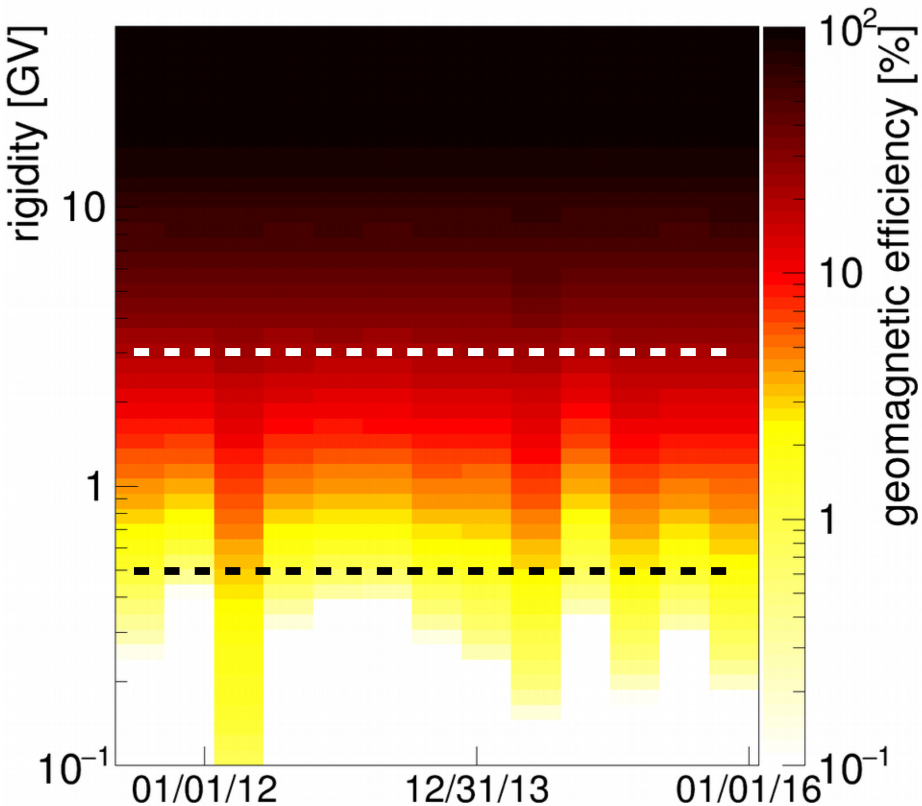


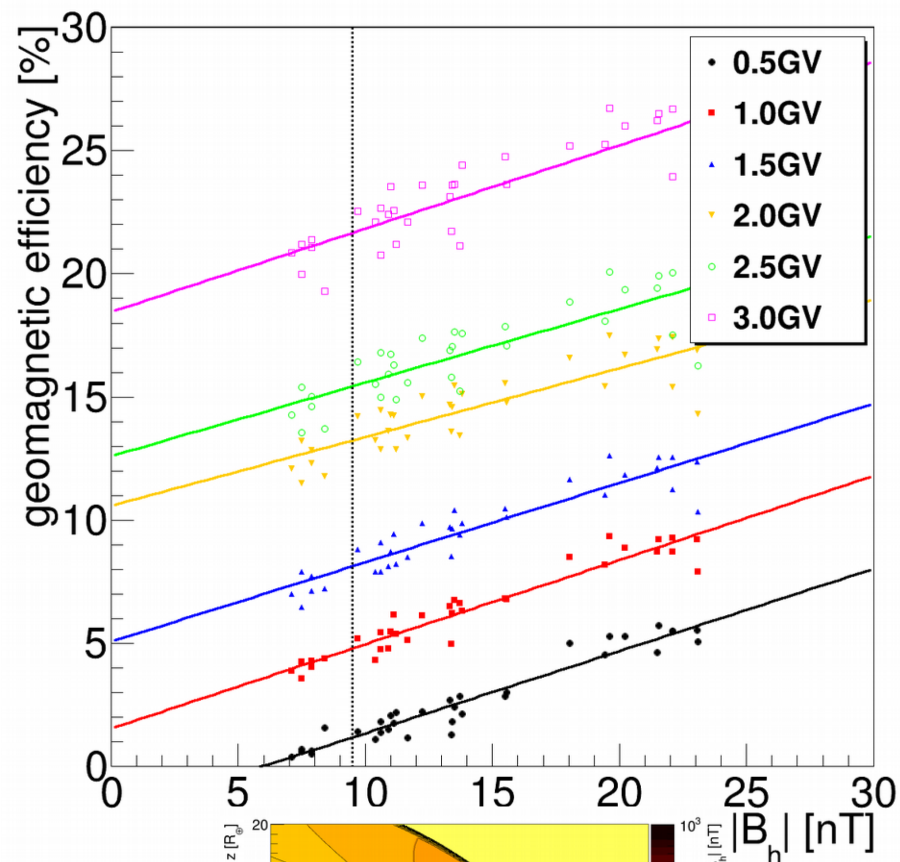
- ISS averaged over calculations from 5/19/11 - 10/6/15 with 100 day steps
- (U)LDB averaged over 5/12/11, 13/1/8, 2/12/14, 12/10/14

- **geomagnetic cutoff efficiency:** ratio of measurement time of particles of cosmic origin within acceptance and total measurement time
- efficiency averaged over flight trajectory
- AMS-02 is installed on the ISS (latitude ±52°)
  → **understanding of geomagnetic environment crucial for low rigidities**
- GAPS is planned to fly from Antarctica (~-80°)
  → **geomagnetic corrections are minimal**

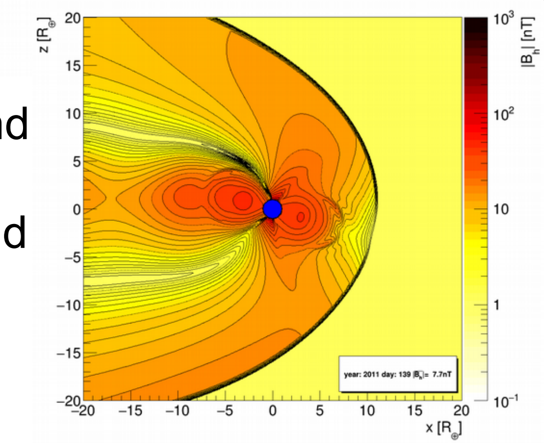
Time dependence for antiprotons

ISS trajectory

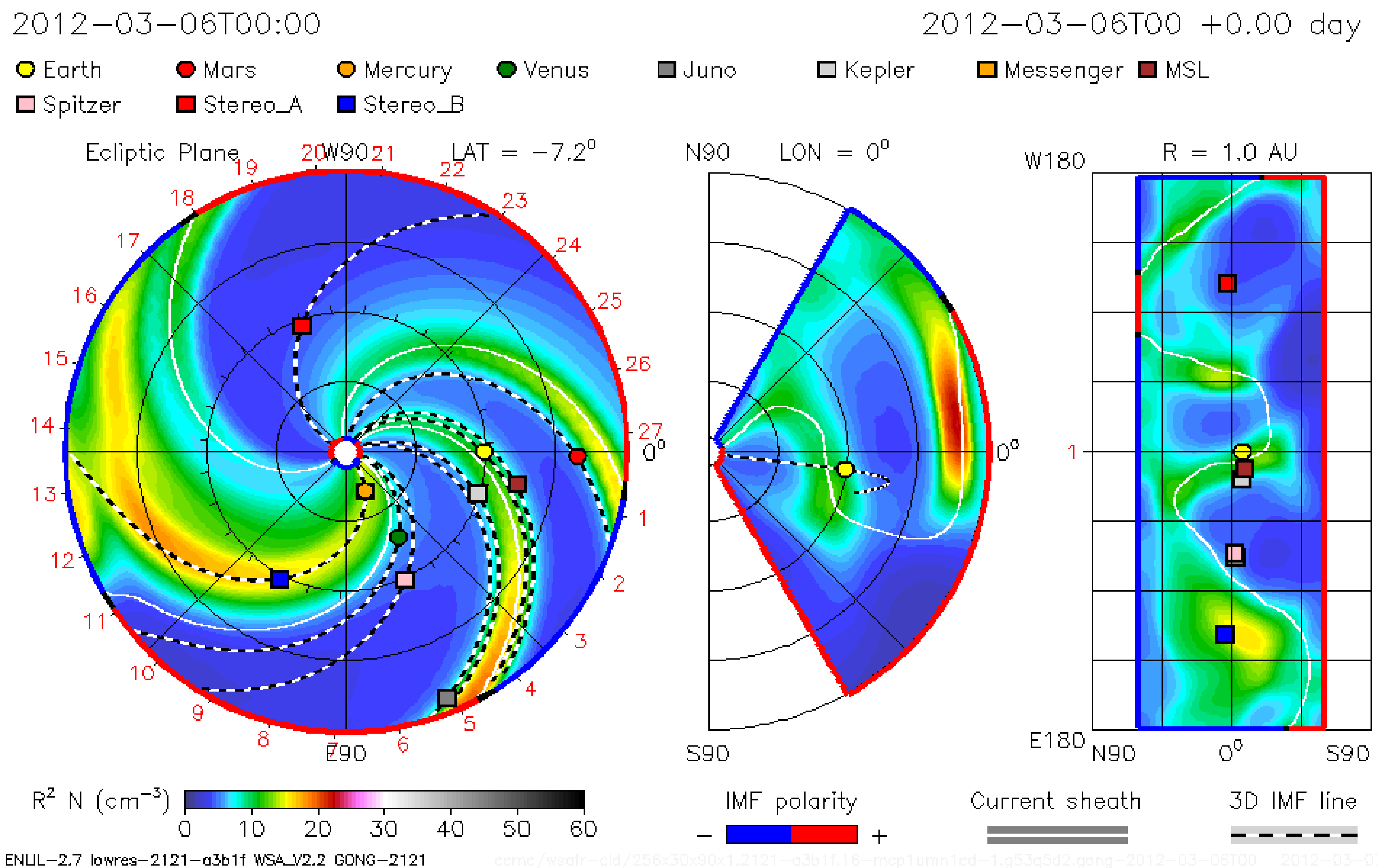




- low-rigidity range exposes strong cutoff efficiency variations as a function of time without an apparent trend
- correlation of mean value of the horizontal magnetic field with geomagnetic efficiencies at different rigidity steps
  → stronger field results in a larger geomagnetic efficiency



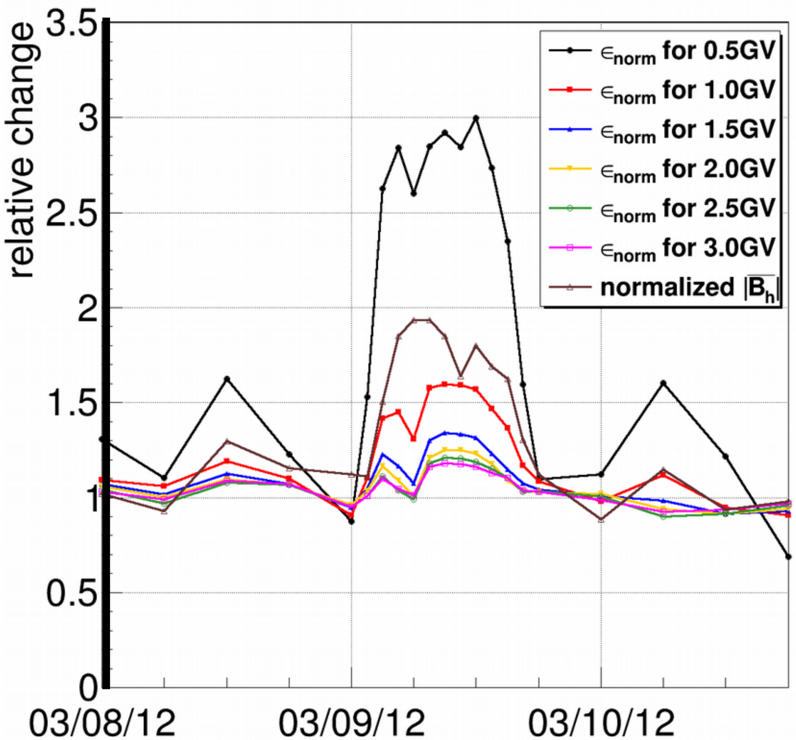
Solar flare and coronal mass ejection

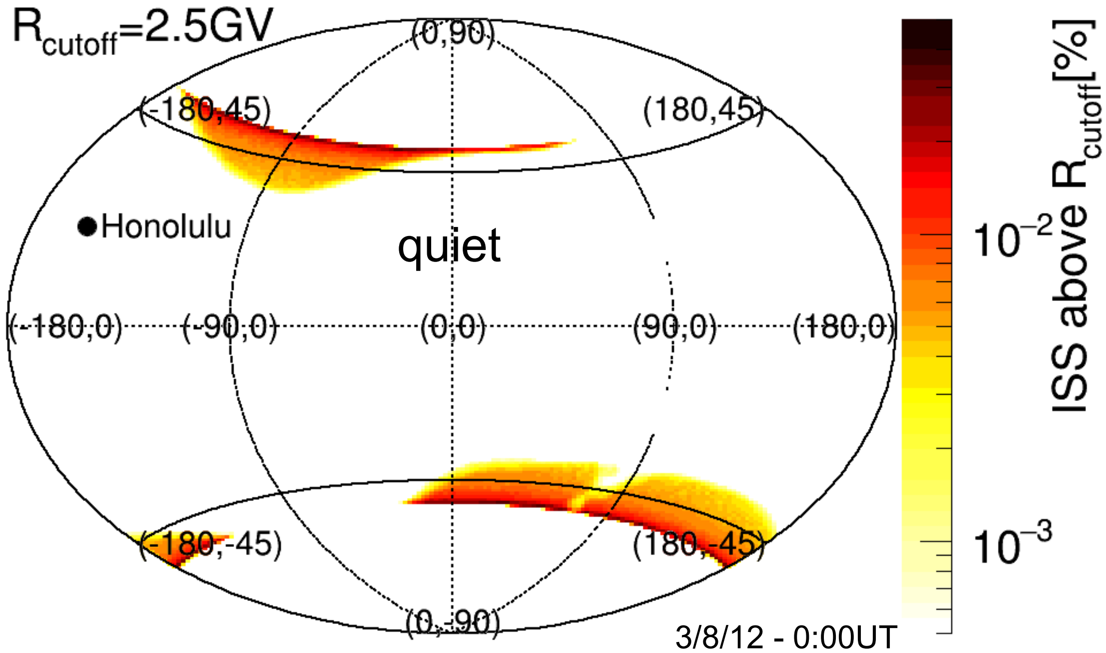


NASA Goddard's Space Weather Lab

Solar X-ray flare event

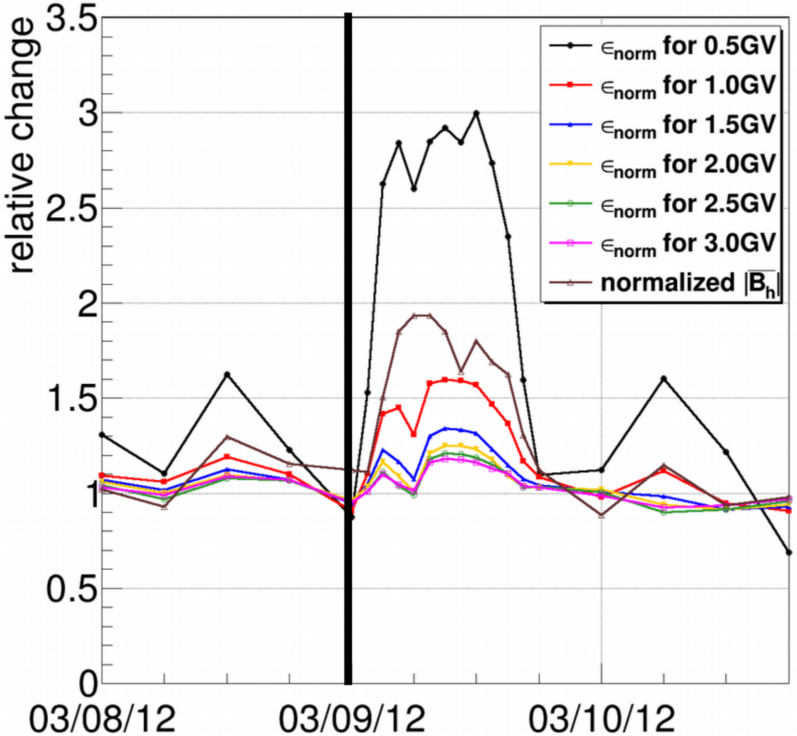
ISS trajectory



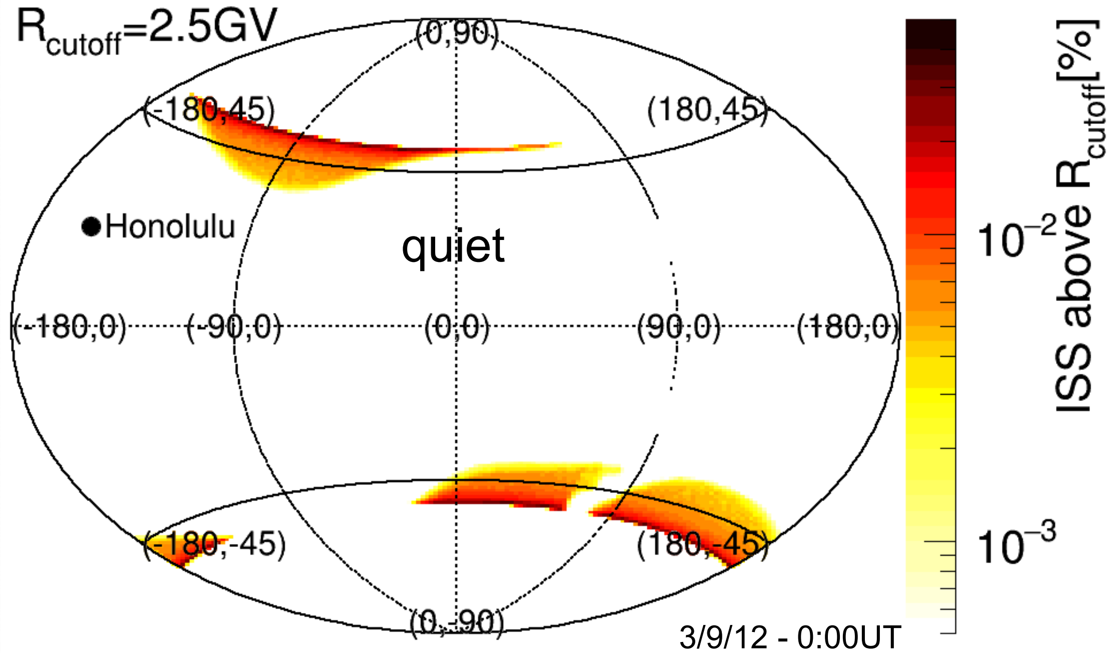


- extreme UV flash of X5-class solar flare March 7, 2012
- **significant increase of geomagnetic cutoff efficiency**
- geomagnetic efficiency is again correlated with $|\overline{B}_H|$
- “windows” in the geomagnetic field open and close quickly

Solar X-ray flare event



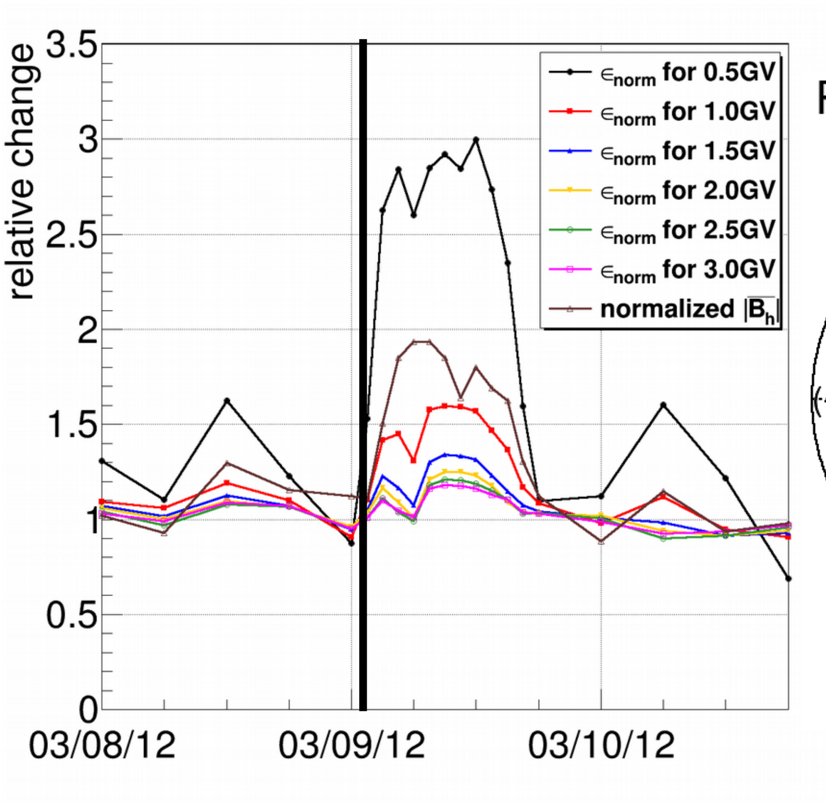
ISS trajectory

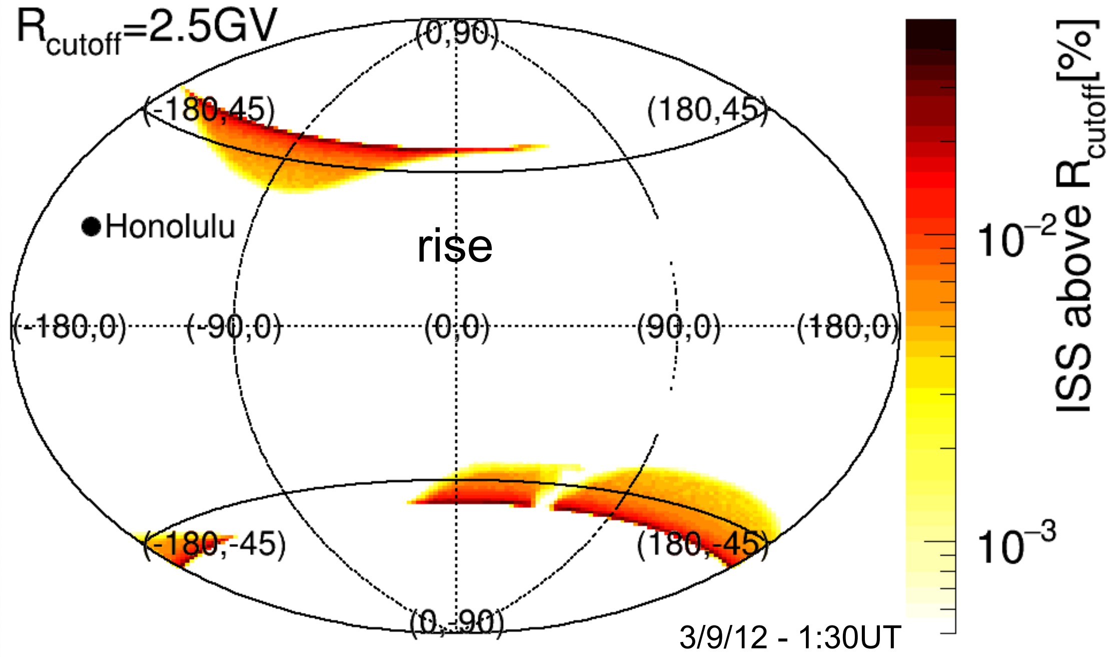


- extreme UV flash of X5-class solar flare March 7, 2012
- **significant increase of geomagnetic cutoff efficiency**
- geomagnetic efficiency is again correlated with $|\overline{B}_H|$
- “windows” in the geomagnetic field open and close quickly

Solar X-ray flare event

ISS trajectory

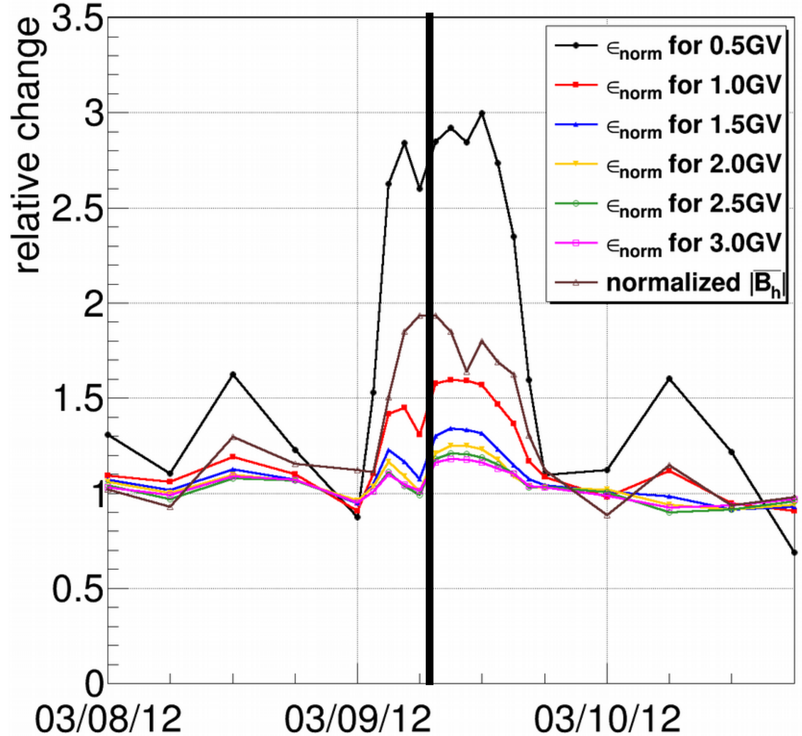


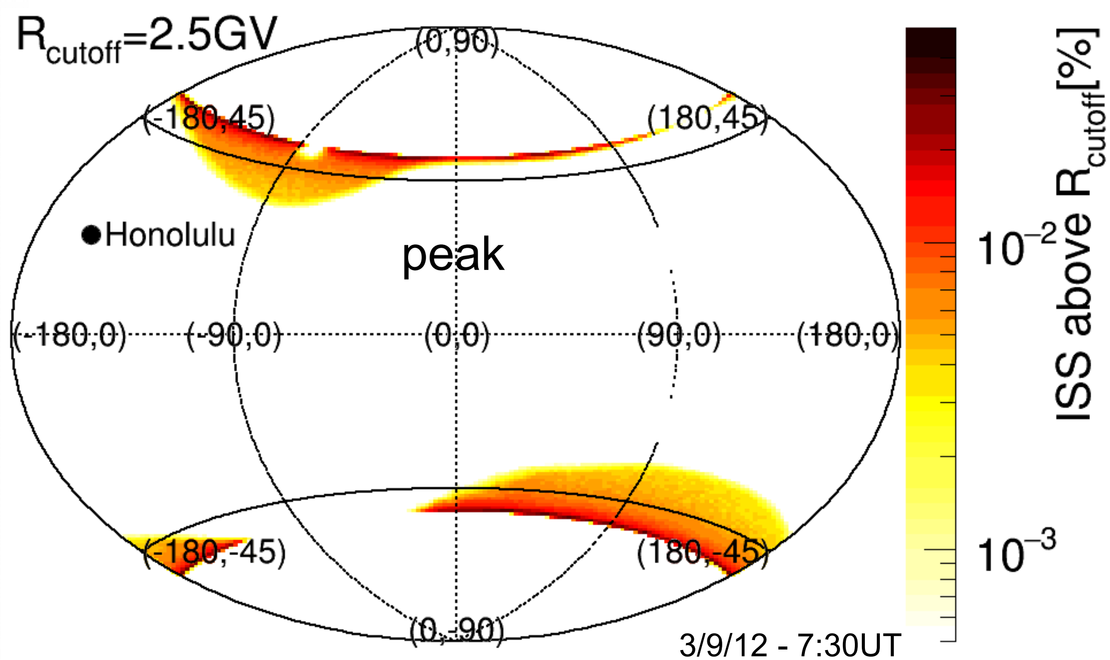


- extreme UV flash of X5-class solar flare March 7, 2012
- **significant increase of geomagnetic cutoff efficiency**
- geomagnetic efficiency is again correlated with $|\overline{B}_H|$
- “windows” in the geomagnetic field open and close quickly

Solar X-ray flare event

ISS trajectory

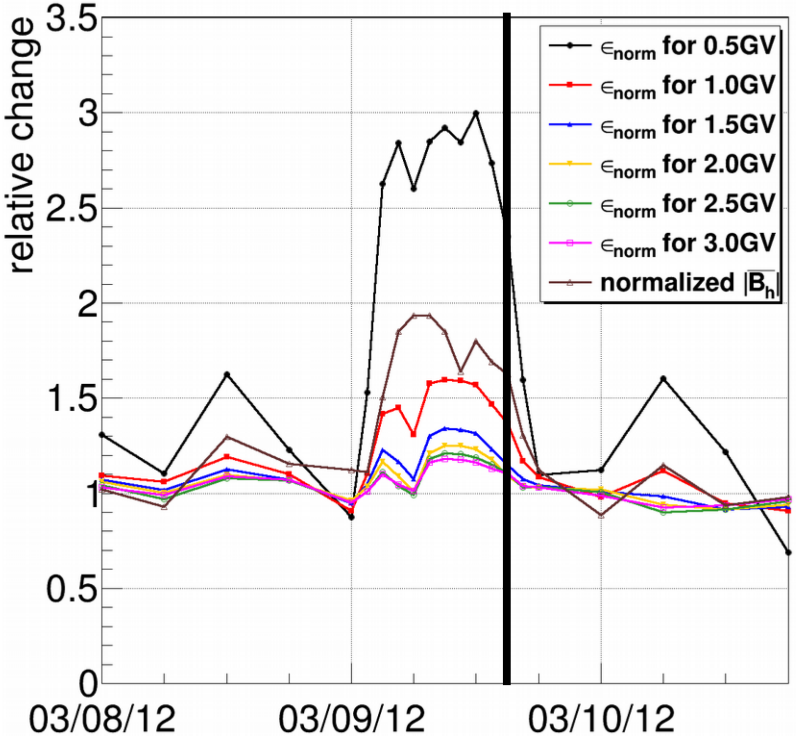


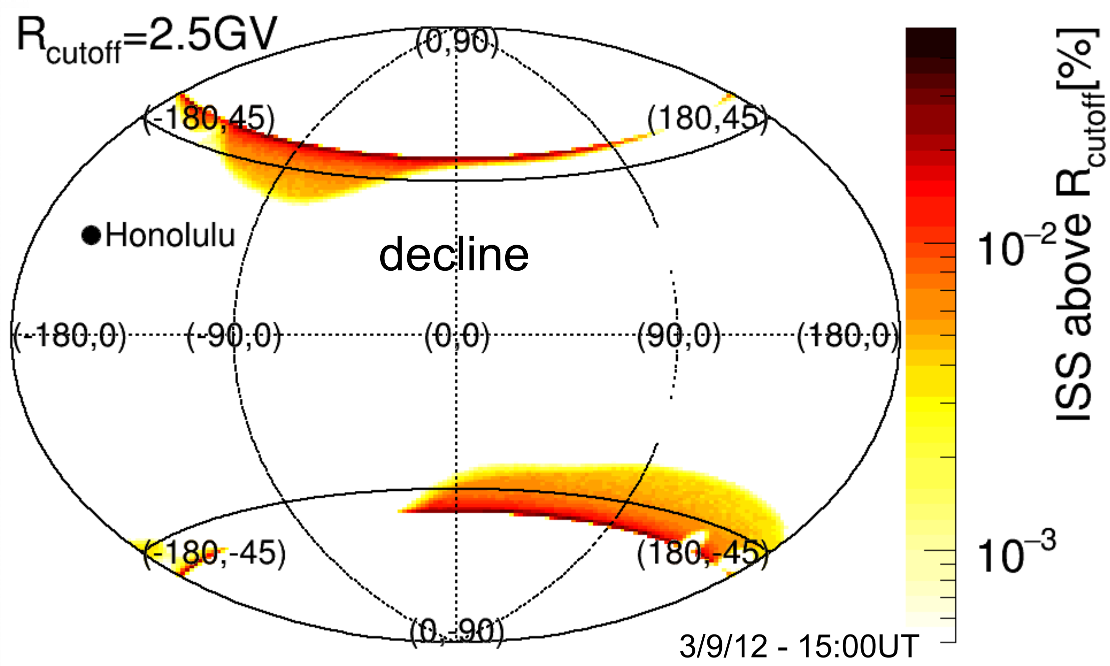


- extreme UV flash of X5-class solar flare March 7, 2012
- **significant increase of geomagnetic cutoff efficiency**
- geomagnetic efficiency is again correlated with $|\overline{B}_H|$
- “windows” in the geomagnetic field open and close quickly

Solar X-ray flare event

ISS trajectory

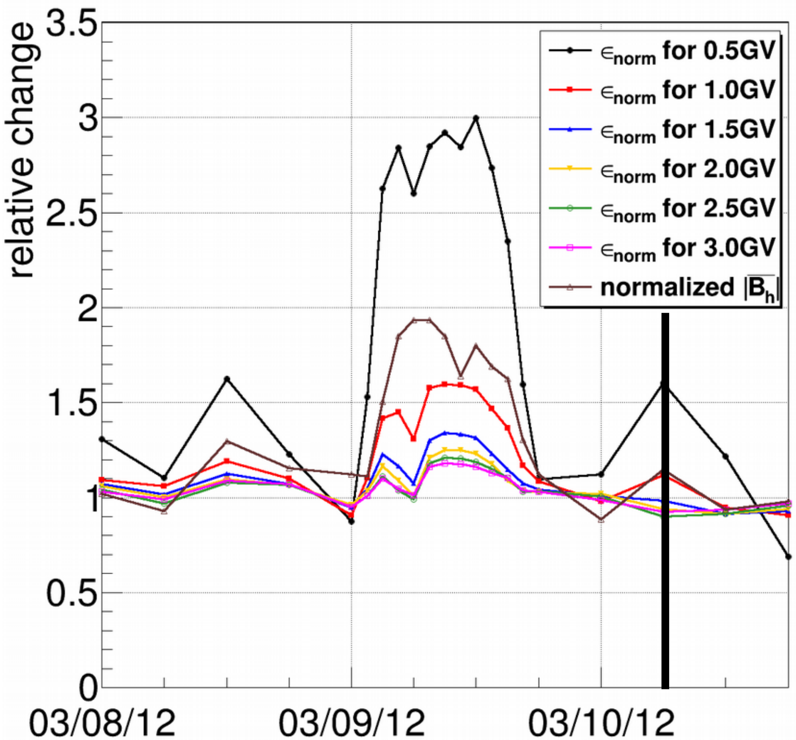


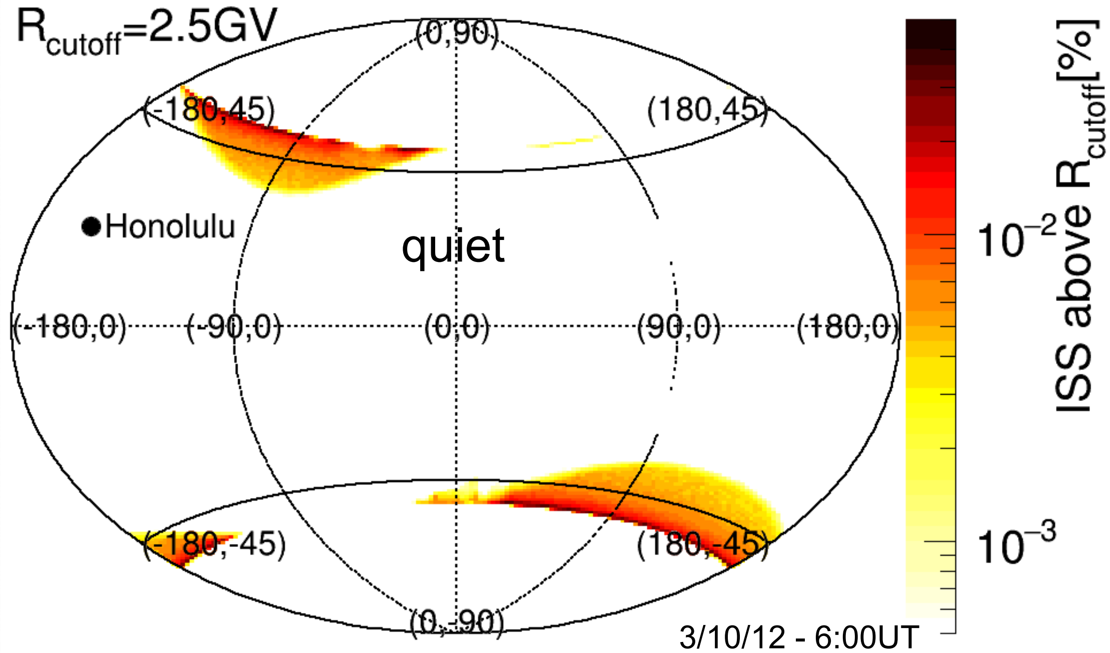


- extreme UV flash of X5-class solar flare March 7, 2012
- **significant increase of geomagnetic cutoff efficiency**
- geomagnetic efficiency is again correlated with $|\overline{B}_H|$
- “windows” in the geomagnetic field open and close quickly

Solar X-ray flare event

ISS trajectory





- extreme UV flash of X5-class solar flare March 7, 2012
- **significant increase of geomagnetic cutoff efficiency**
- geomagnetic efficiency is again correlated with $|\overline{B}_H|$
- “windows” in the geomagnetic field open and close quickly
  → **geomagnetic efficiency increase due to enlarged “allowed” windows**

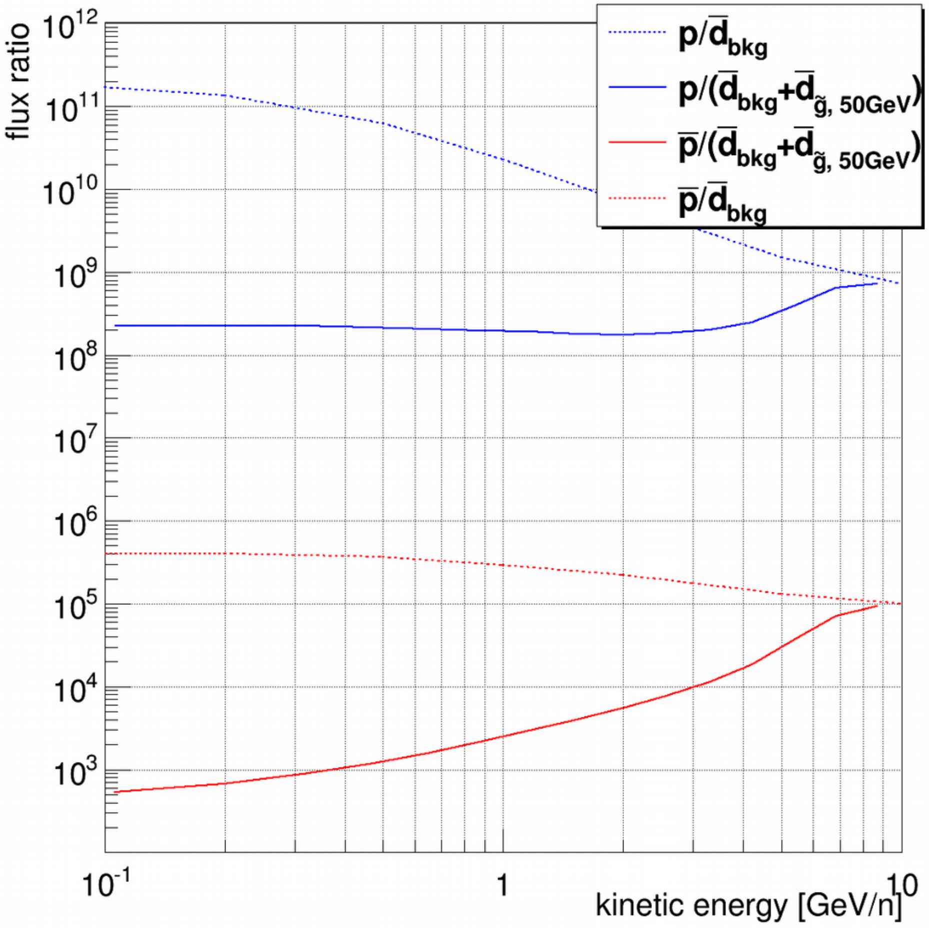
Identification challenge

Required rejections for antideuteron detection:

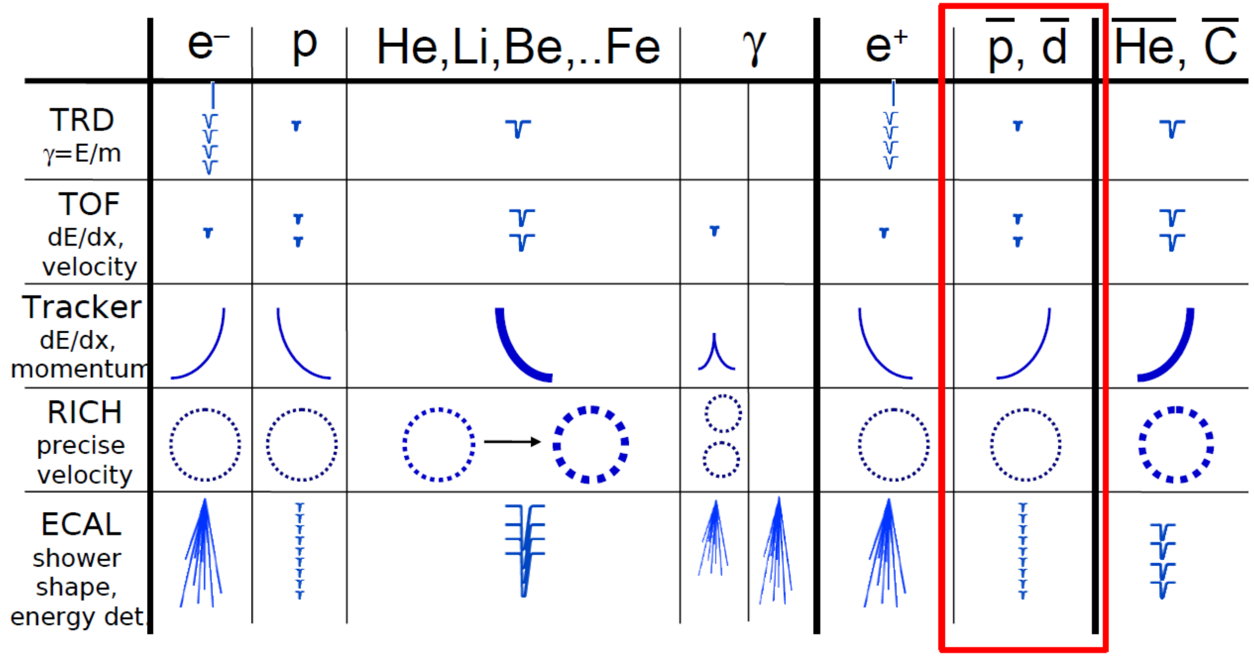
- **protons**: > 10^8 - 10^{10}
- **He-4**: > 10^7 - 10^9
- **electrons**: > 10^6 - 10^8
- **positrons**: > 10^5 - 10^7
- **antiprotons**: > 10^4 - 10^6

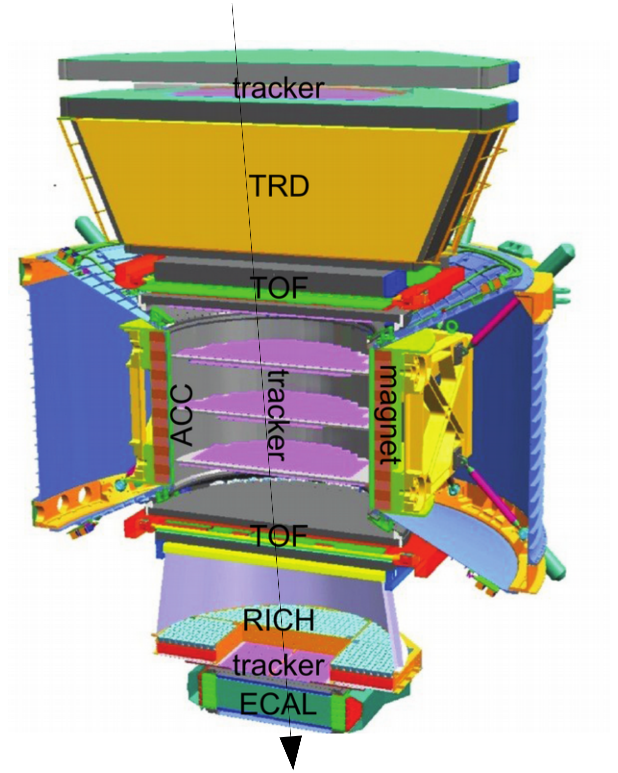
Antideuteron measurement with balloon and space experiments require:

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



AMS-02 antideuteron analysis



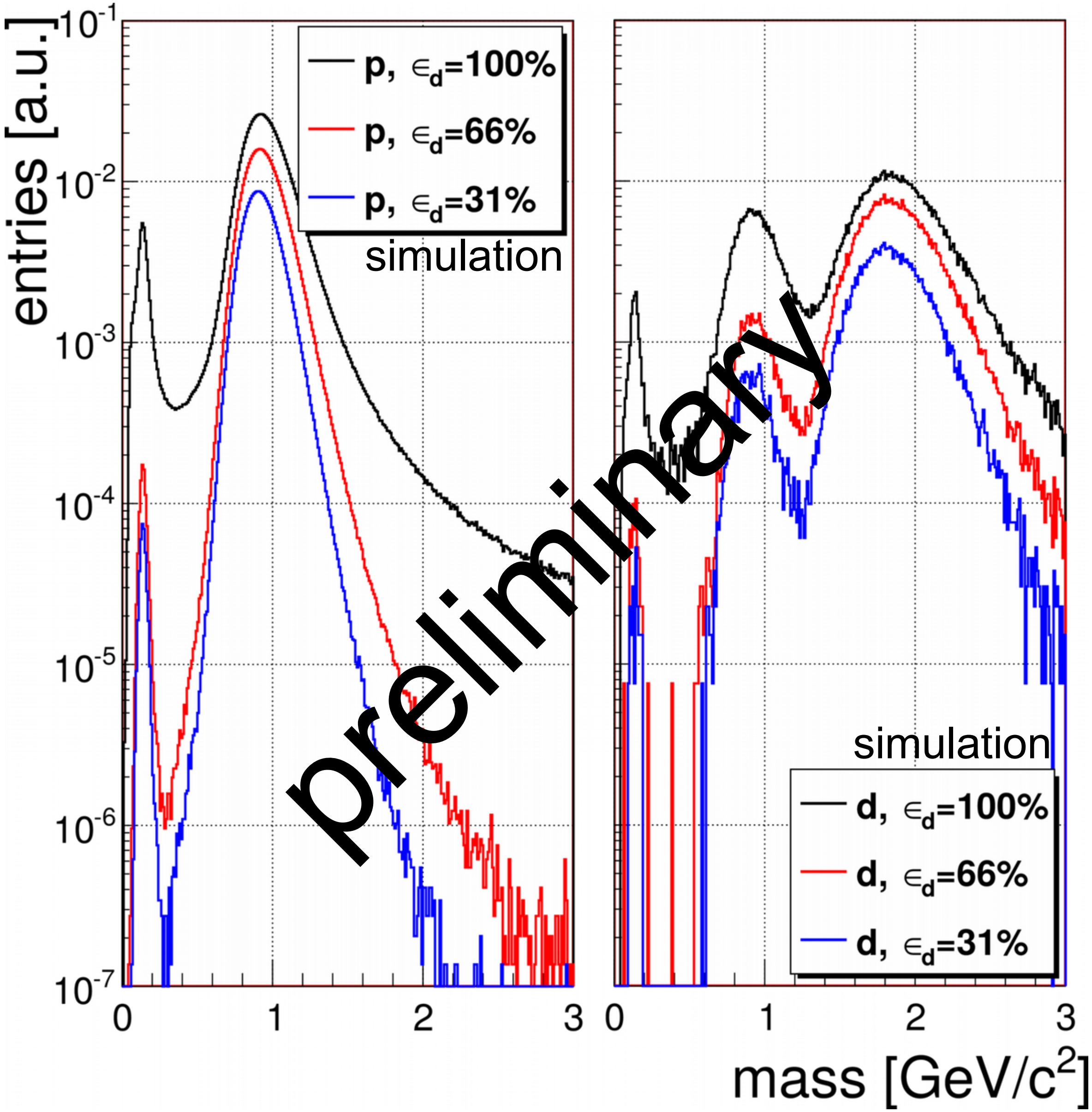


- **antideuteron identification:**
  - momentum measured in the form of rigidity
  - charge from TOF, TRD, tracker
  - lower velocities: **T**ime **O**f **F**light scintillator system
  - higher velocities: **R**ing **I**mage **Ch**erenkov detector

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

- **self-calibrated analysis:**
  - calibrate antideuteron analysis with deuterons and antiprotons (simulations and data)
  - **analysis is ongoing**

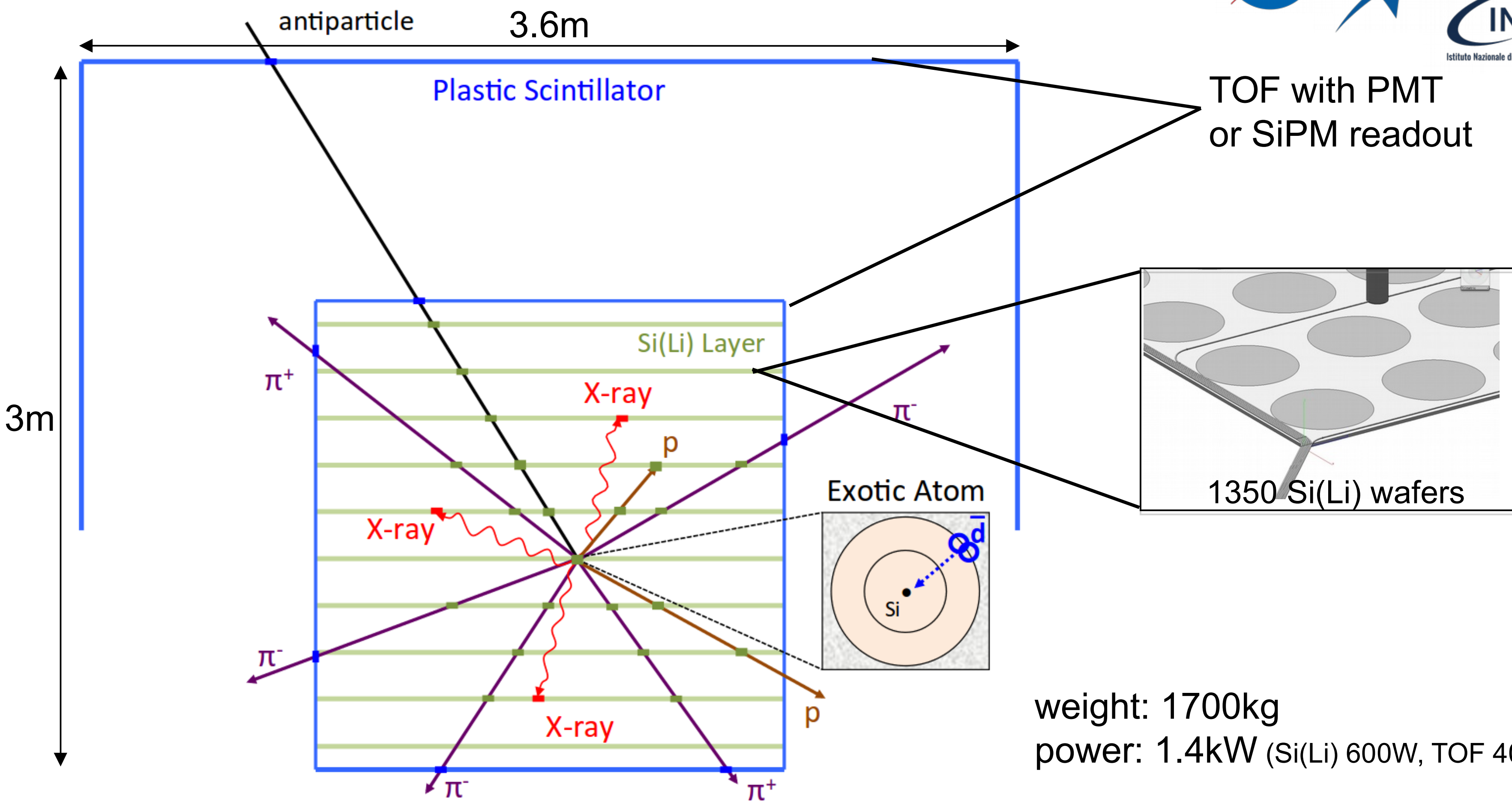
Proton and deuteron mass reconstruction



- low-energy antiproton, deuteron, antideuteron studies are in an advanced stage
- separation of isotopes are among the most challenging analyses for AMS-02

The GAPS experiment

Columbia U, UCSD
UCLA, UCB,
U Hawaii, MIT

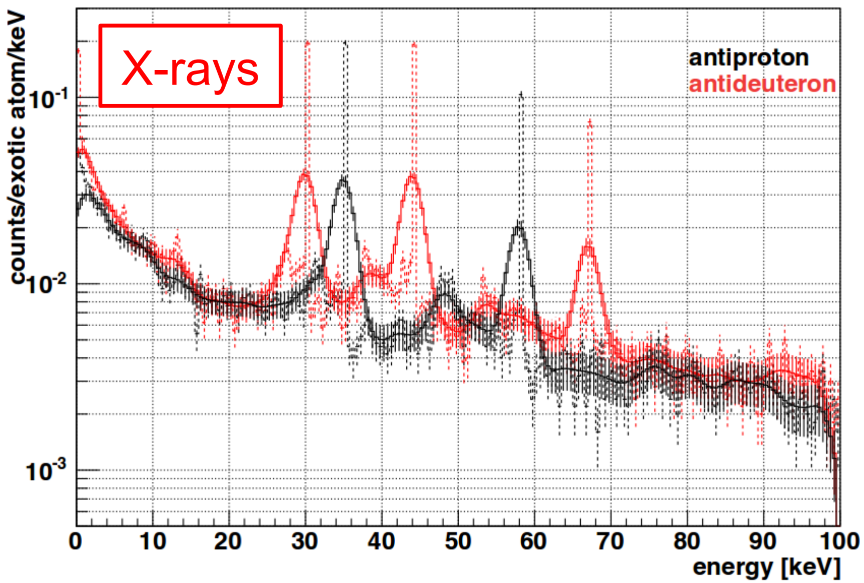


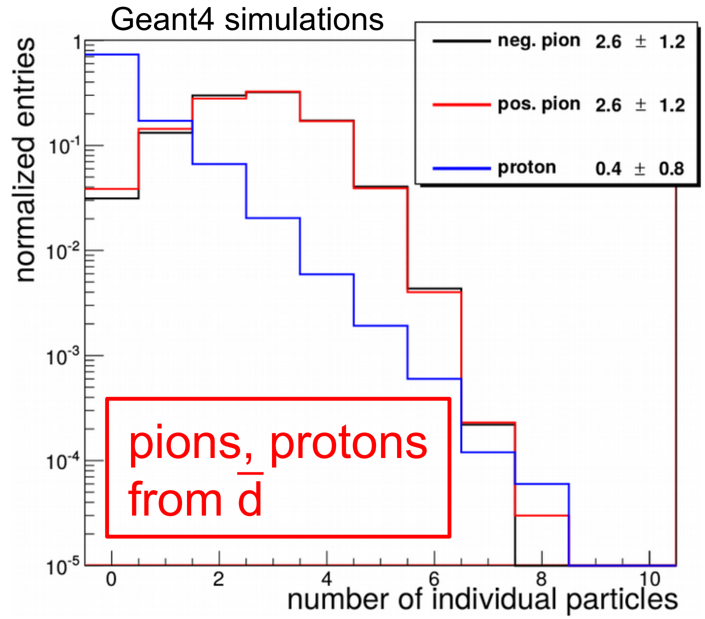
weight: 1700kg
power: 1.4kW (Si(Li) 600W, TOF 400W)

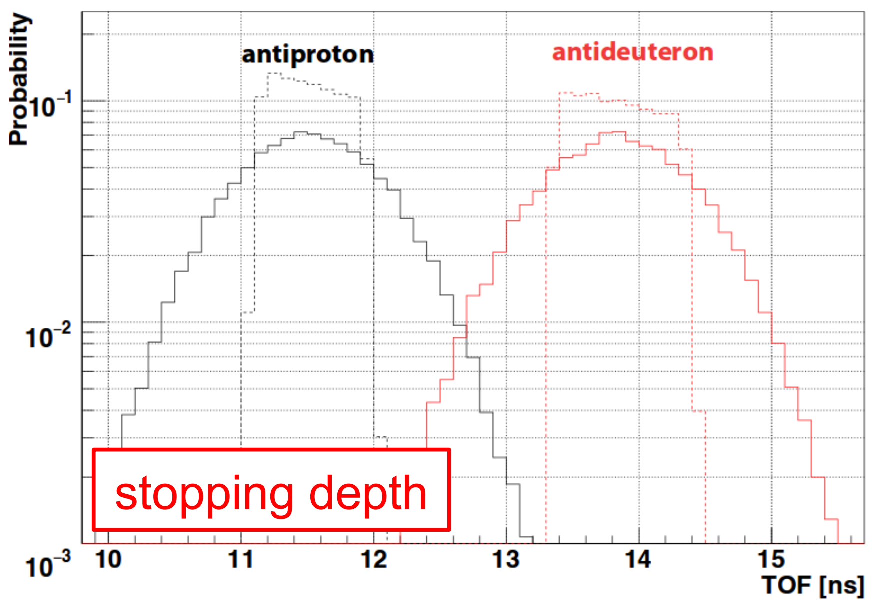
- the **G**eneral **A**nti**P**article **S**pectrometer is specifically designed for low-energy antideuterons and antiprotons
- Long Duration Balloon flights from Antarctica
- **GAPS is funded by NASA, JAXA, INFN since 2017 → first flight 2020**

GAPS sensitivity

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



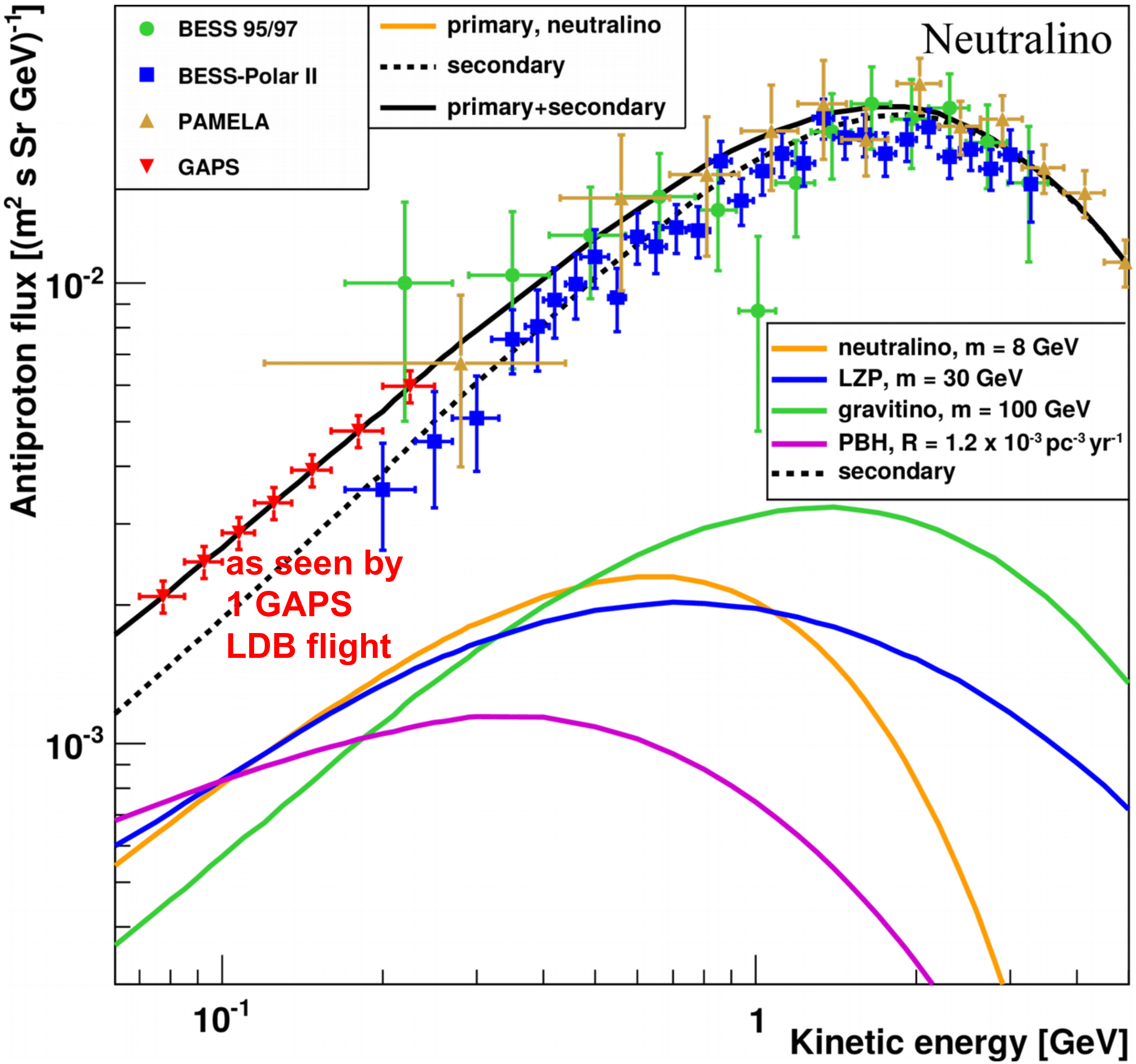




Background rejection:

- 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

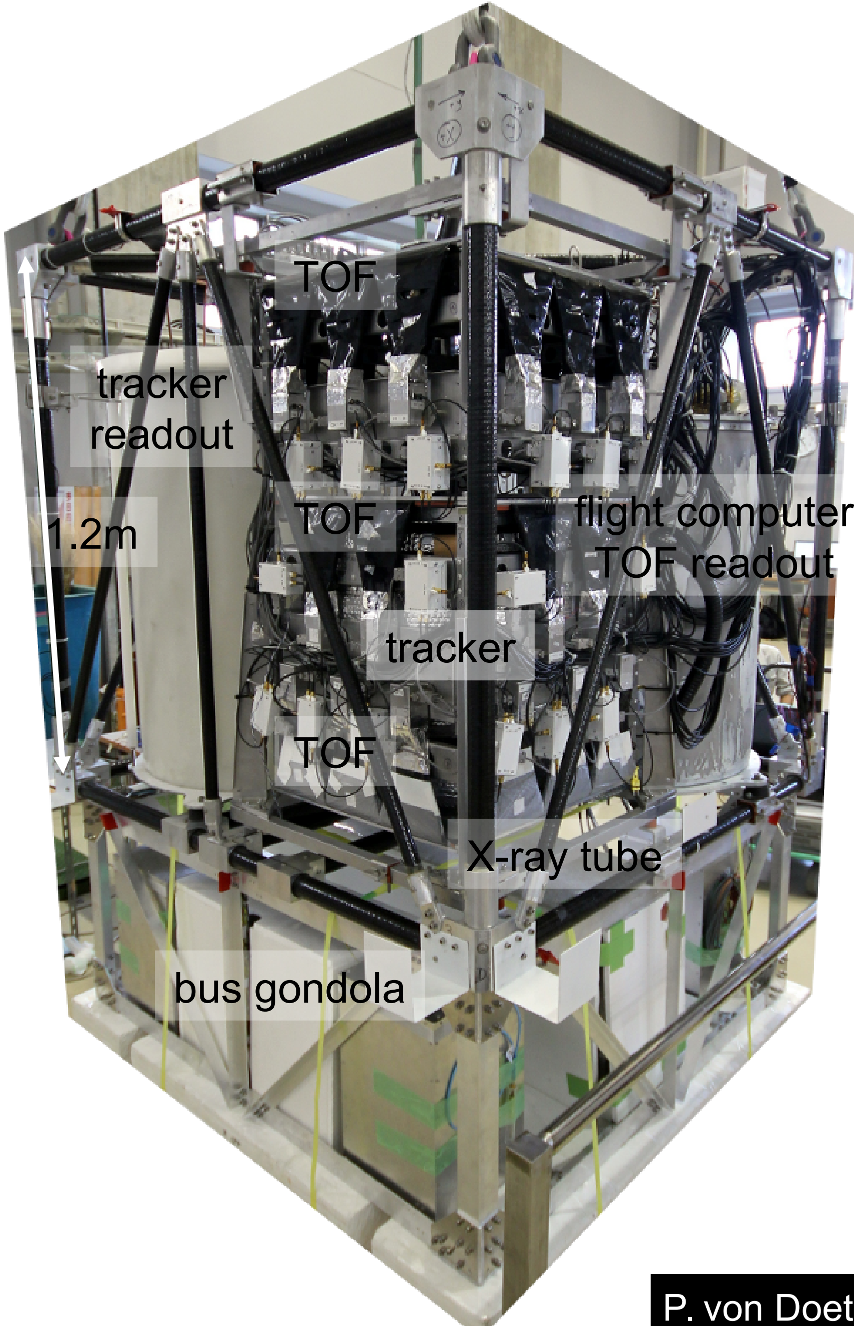
GAPS low-energy antiproton



Predicted primary antiproton fluxes from:

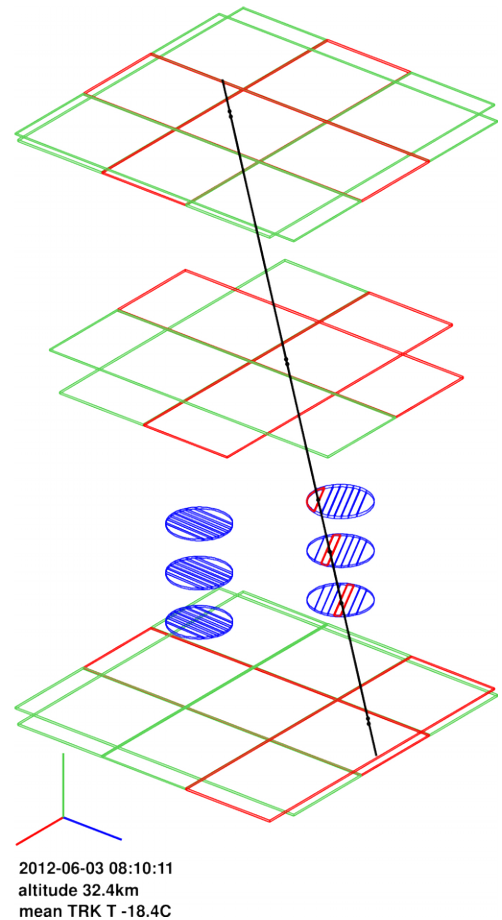
- Neutralinos
- LZP
- Gravitinos
- primordial black holes

Prototype GAPS



Goals:

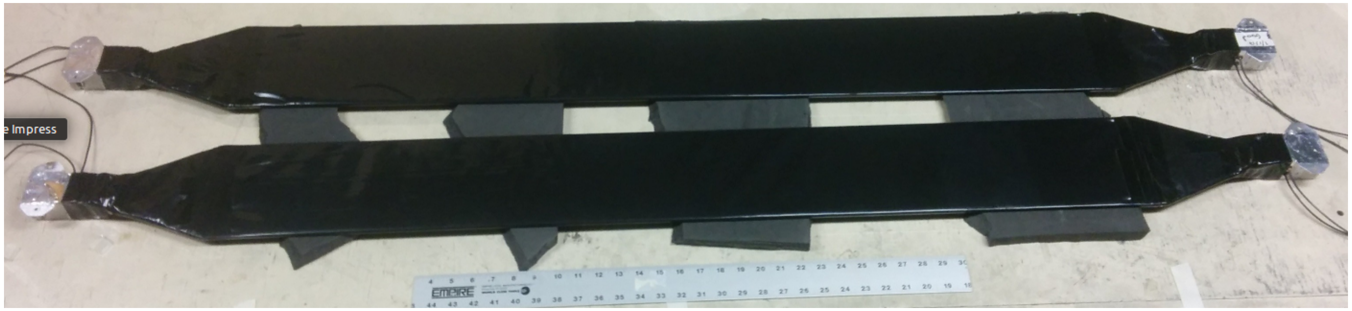
- demonstrate stable operation of the detector components during flight
- study Si(Li) cooling approach for thermal model
- measure background levels

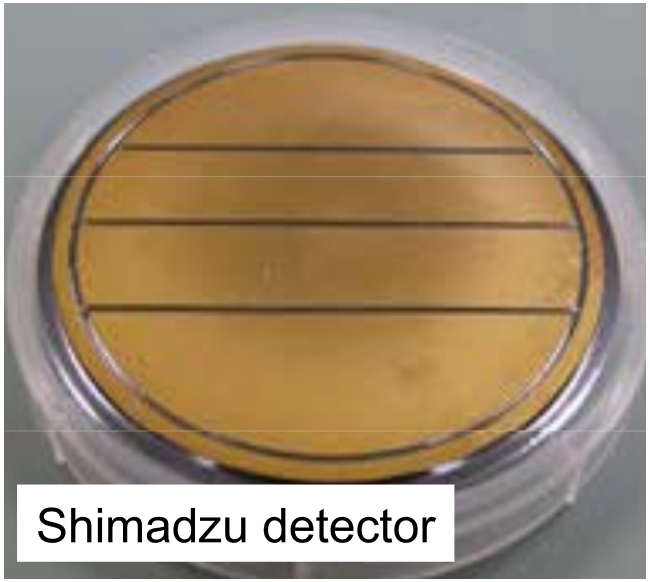


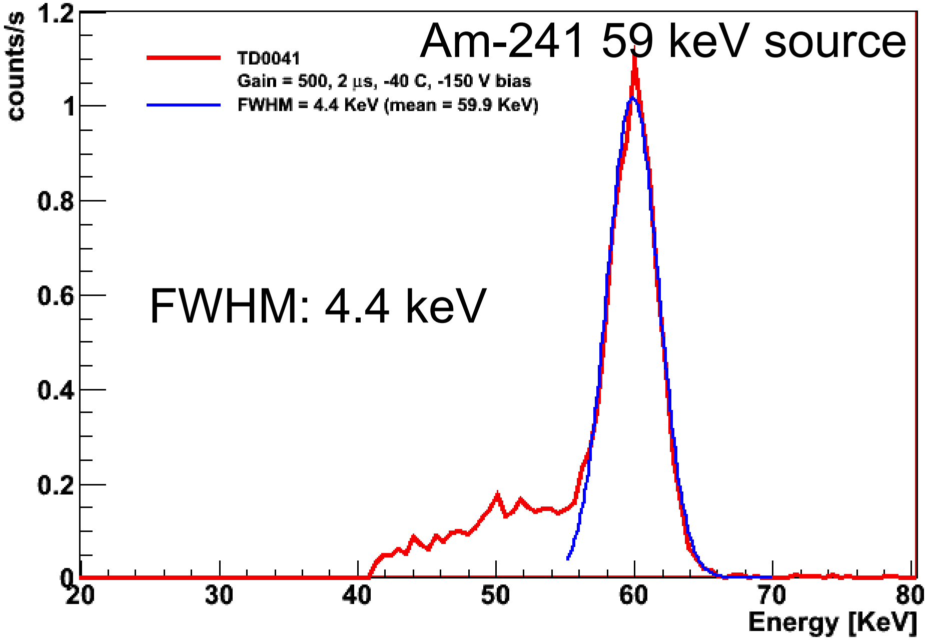
Younger me at SSL after pGAPS integration


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

Detector production







- 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

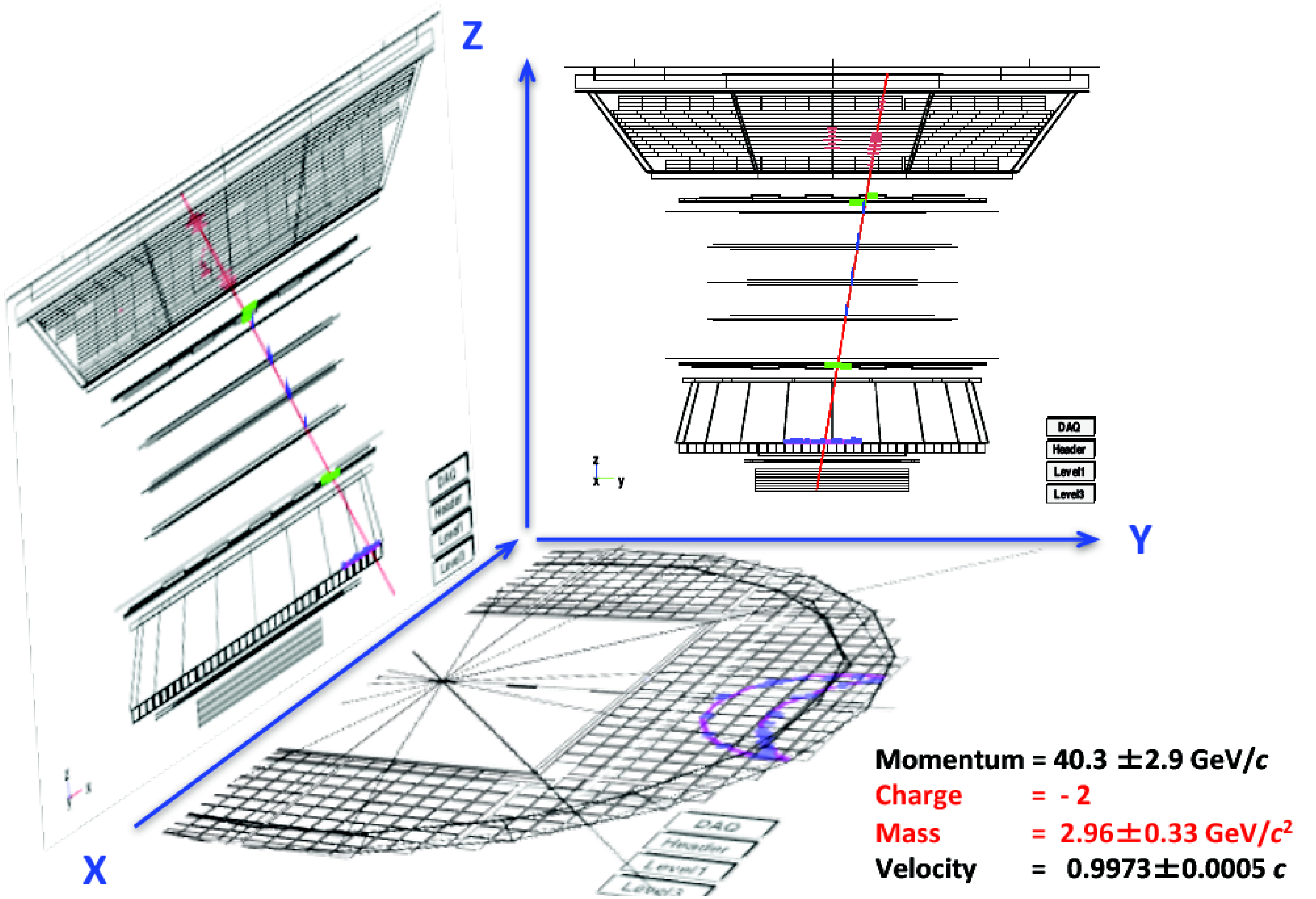
GAPS path forward

- GAPS is specifically designed for low-energetic antideuterons
- all goals for prototype GAPS were met
- currently in finalizing-design phase
  - Technical Interchange Meeting next week here at SSL
- **first GAPS science flight from Antarctica 2020**

GAPS team - Nov 2017

Columbia University, UC Berkeley, Japan Aerospace Exploration Agency, UC Los Angeles, U Hawaii, MIT, INFN

Antihelium-3 candidates by AMS-02



It will take a few more years of detector verification and to collect more data to ascertain the origin of these events.

Conclusion & Outlook

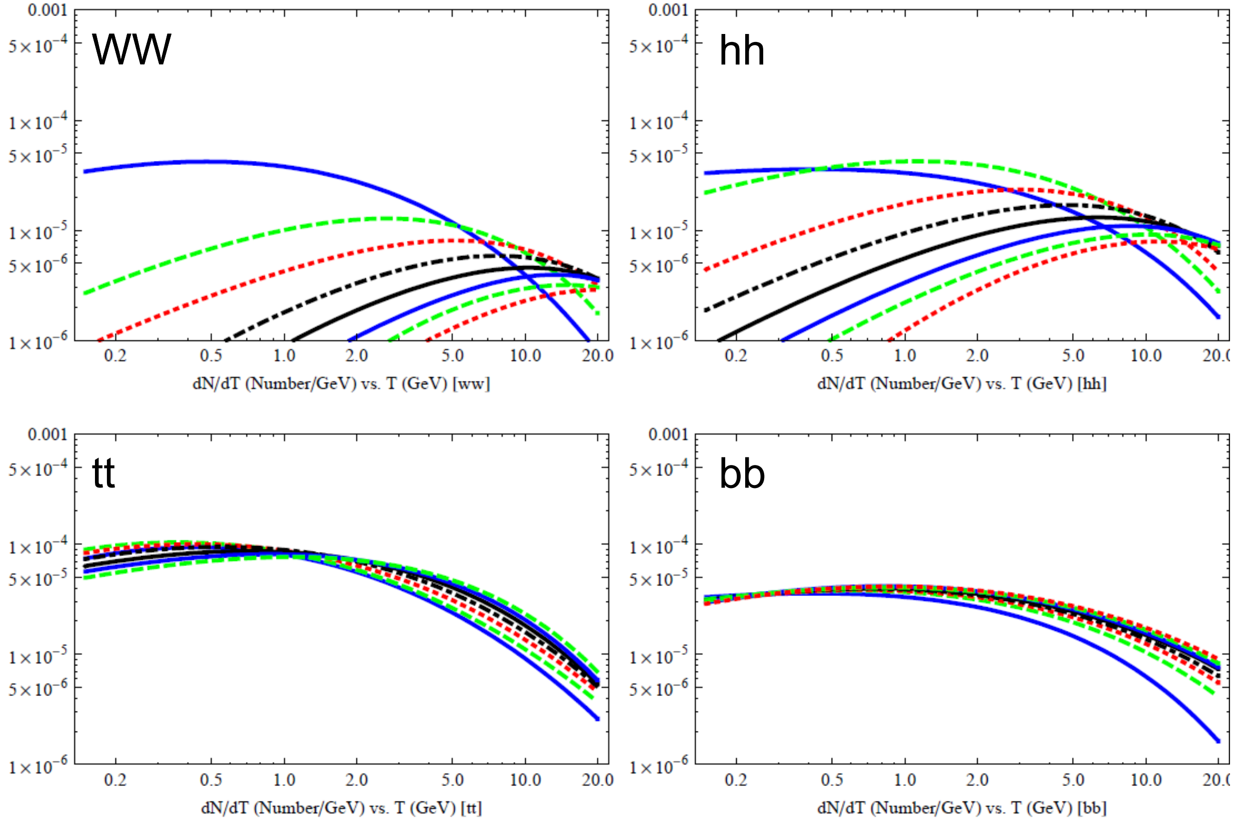
- antideuteron searches are experimentally challenging
  → **multiple experiments for cross-checks are important**

- 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

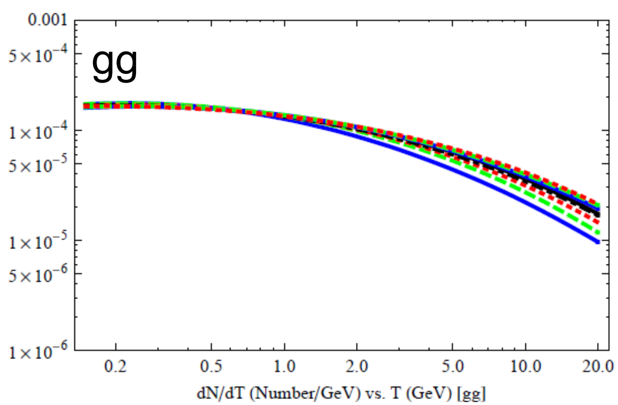
- measurement of antideuterons is a promising way for indirect dark matter search

Antideuteron annihilation channels



m_{DM} =
100 GeV (blue/solid)
200 GeV (green/dashed)
300 GeV (red/dotted)
400 GeV (black/dashed − dotted)
500 GeV (black/solid)
600 GeV (blue/solid)
700 GeV(green/dashed)
800 GeV(red/dotted)

for hh/tt final states:
m_{DM} =
150 GeV (blue/solid)
200 GeV (blue/solid)



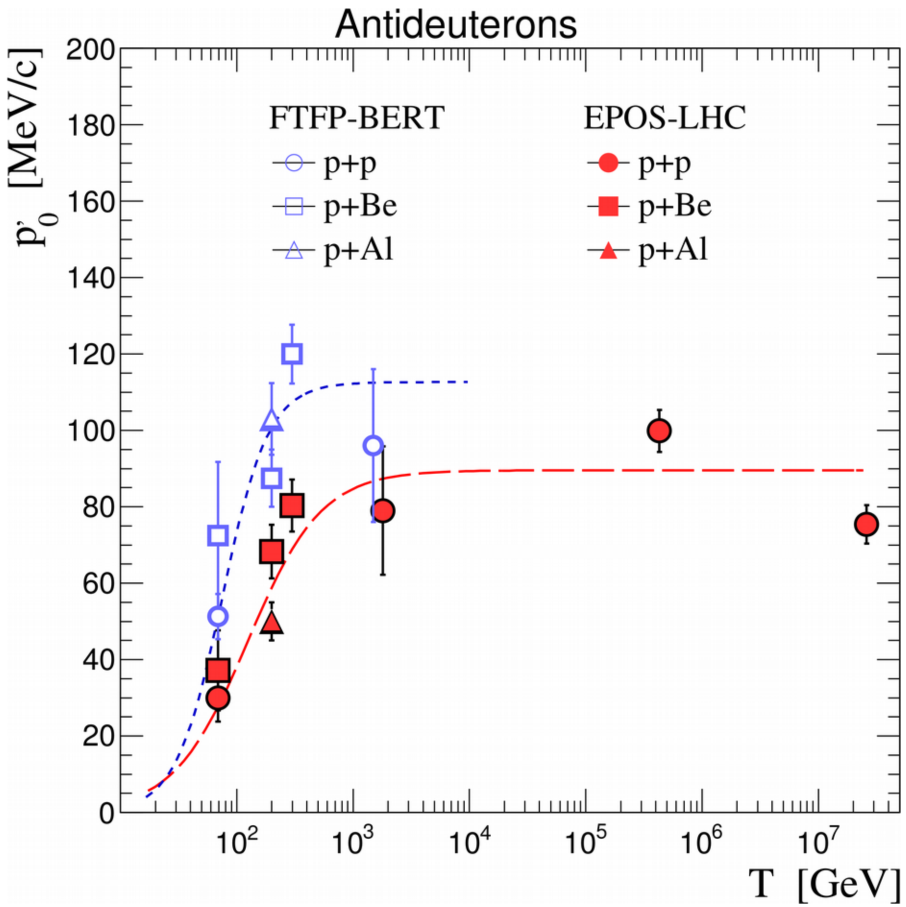
[Cui, Randall, Mason 2010]

- dark matter halo's and Earth's rest frame are roughly the same
  → **dark matter annihilates in Earth's rest frame**

- dark matter mass sets the energy scale for final states
- composition of final states define antideuteron yield
- quarks: hadronization in Earth's frame → **low energies**
  WW, hh, ZZ: boosted frame → **more at higher energies**

Antideuteron coalescence

Together with Gomez, Menchaca (UNAM)

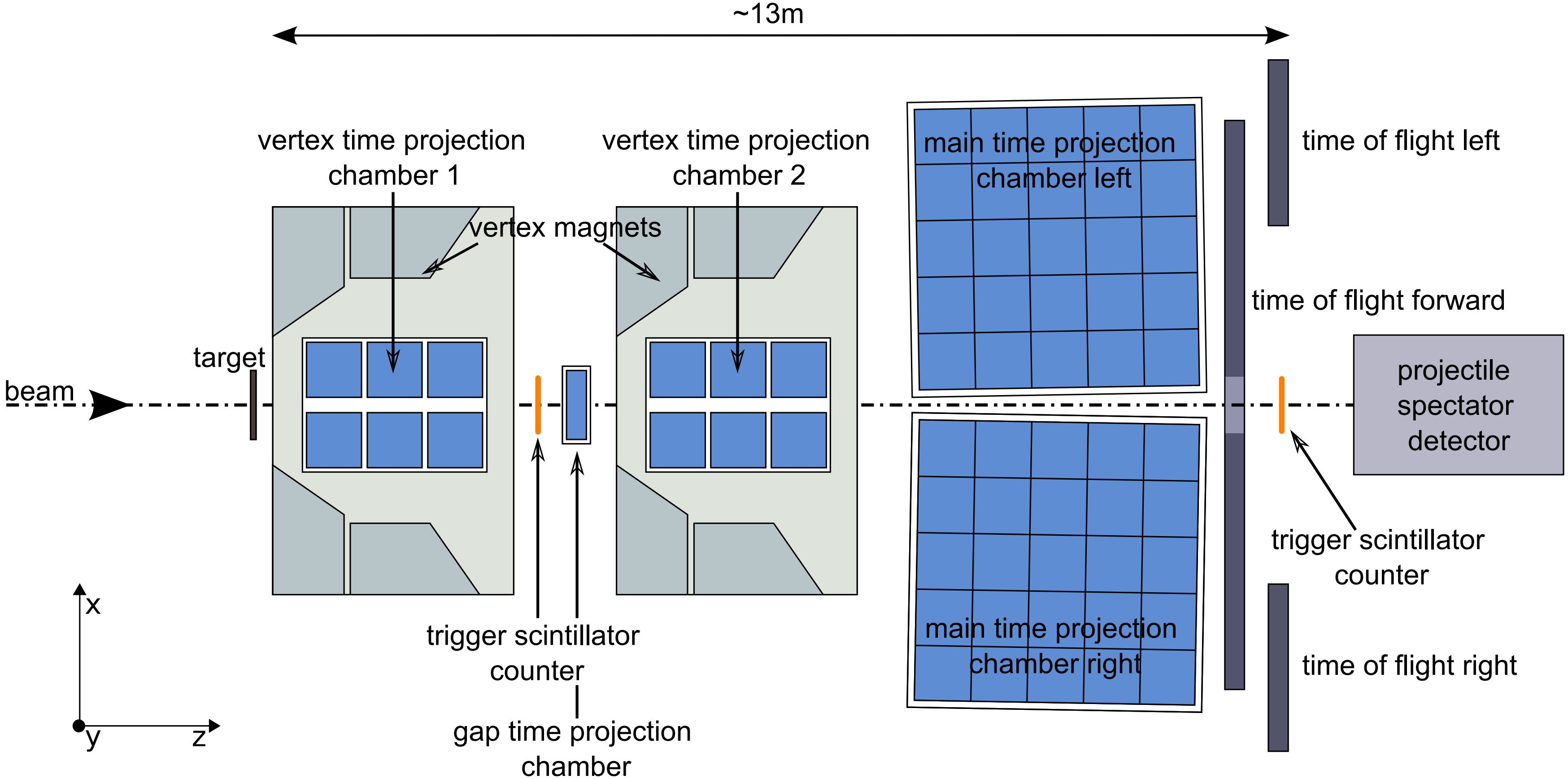


- coalescence afterburner added to EPOS-LHC, Geant4
- compared simulation results to available data sets (p+p, p+A) and estimated the best-fit coalescence momentum per data set (this also included taking into account antiproton yield mismatch)
- more data needed to constrain (anti)deuteron coalescence model
- **Next step:** try to understand how these hadronic studies coul affect dark matter annihilation

Issues of the coalescence model

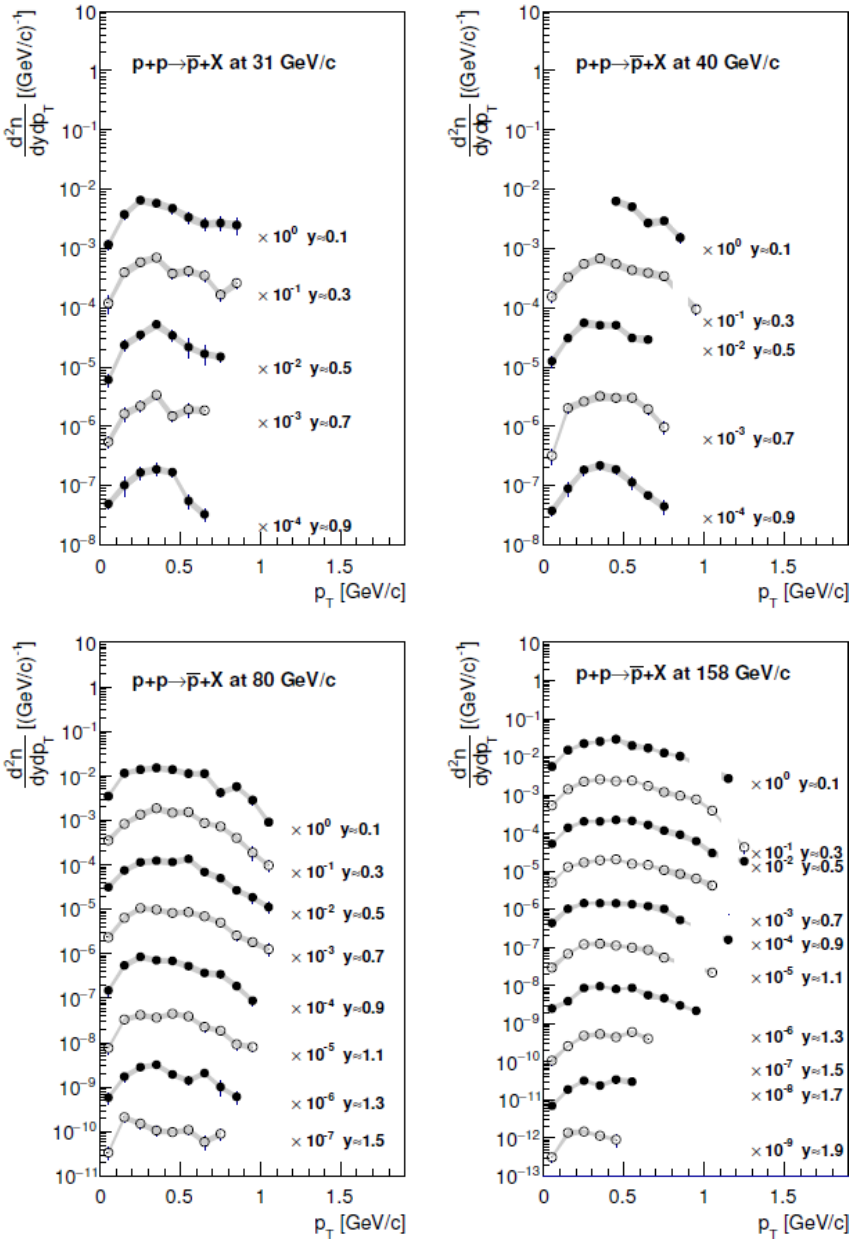
- coalescence uncertainties are about **a factor of 10** on the flux
- phase space for ion production depends on the available energy in the formation interaction
- coalescence is highly sensitive to two-particle correlations between the participating (anti)nucleons
  → no a-priori reason to expect two-particle correlations from one generator to be more reliable than from another
- 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

NA61/SHINE at CERN



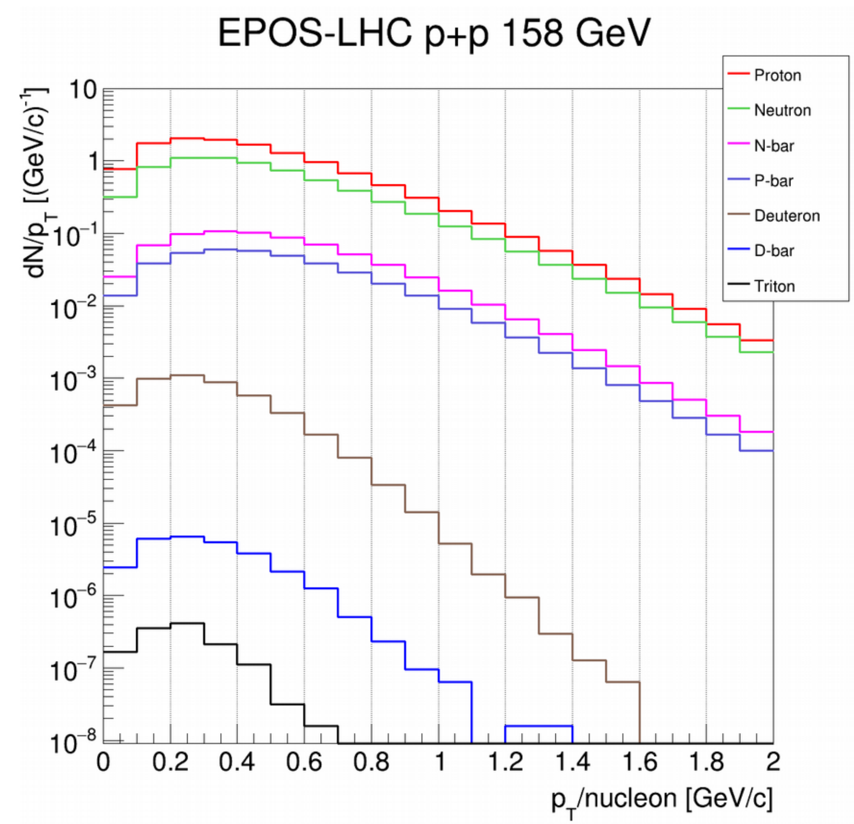
- high momentum resolution: $\sigma(p)/p^2 \approx 10^{-4}(\mathrm{GeV}/c)^{-1}$ (at full B=9Tm)
- ToF walls resolution: ToF-L/R: $\sigma(t) \approx 60$ps, ToF-F: $\sigma(t) \approx 120$ ps
- Good particle identification: $\sigma(dE/dx)/\langle dE/dx \rangle \approx 0.04$, $\sigma(minv) \approx 5$ MeV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

Antiproton yields



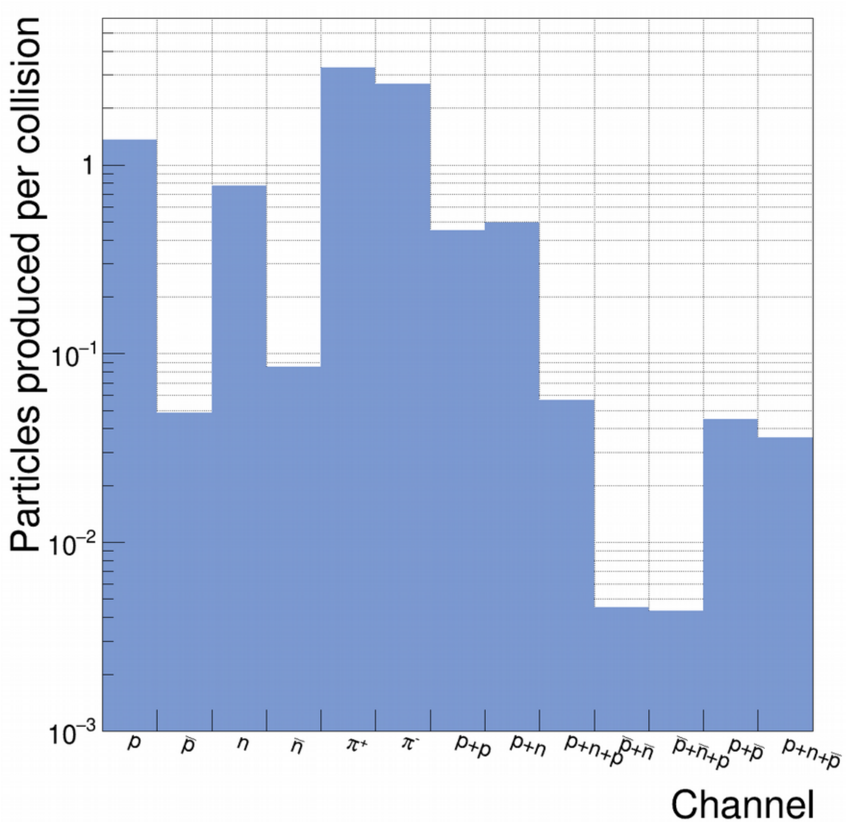
Eur. Phys. J. C77 10, 671 (2017)

- NA61/SHINE results are important to update cosmic-ray antiproton flux interpretation
- Production cross-section of antiprotons needs to be known on percent level to match AMS-02 precision
- Predicted yields for (anti)deuteron and other species (based on new coalescence model):

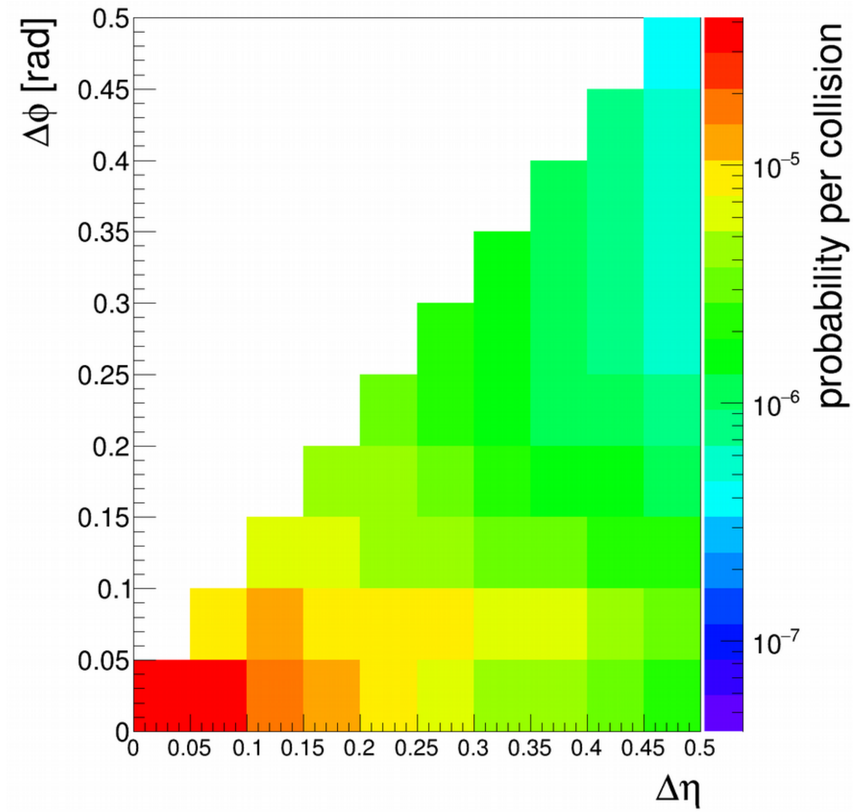


Needed measurements

EPOS-LHC for p-p at 158GeV/c



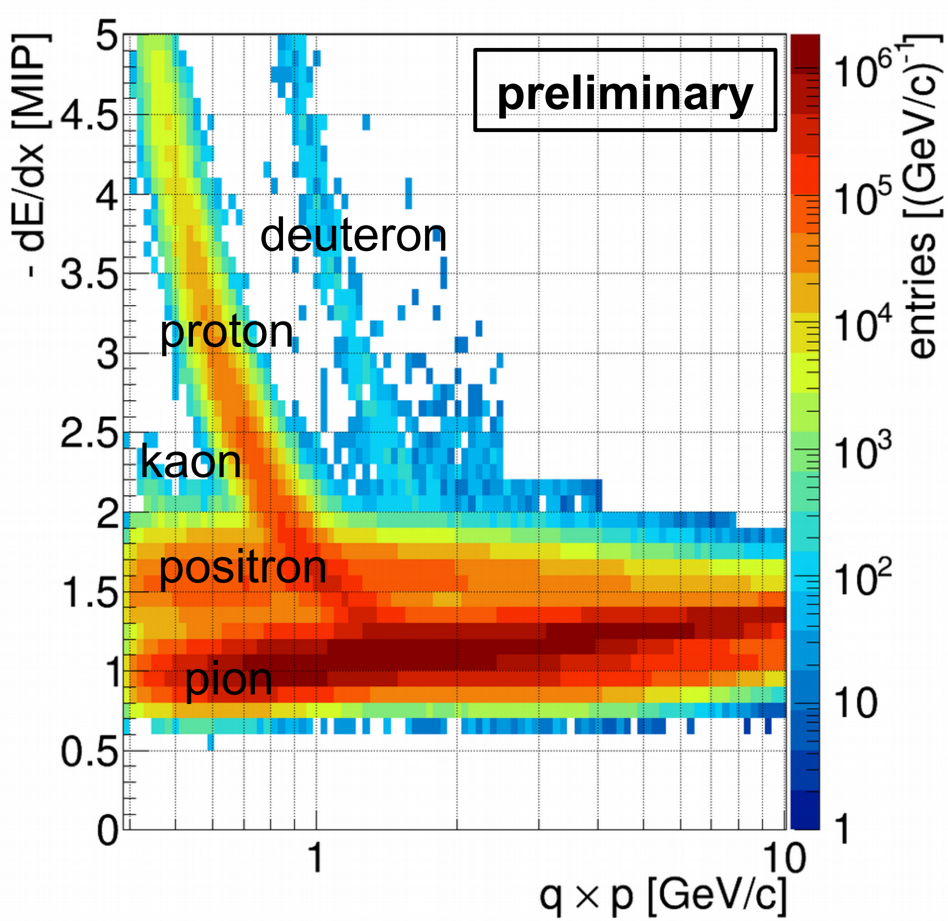
Predicted production of nucleons

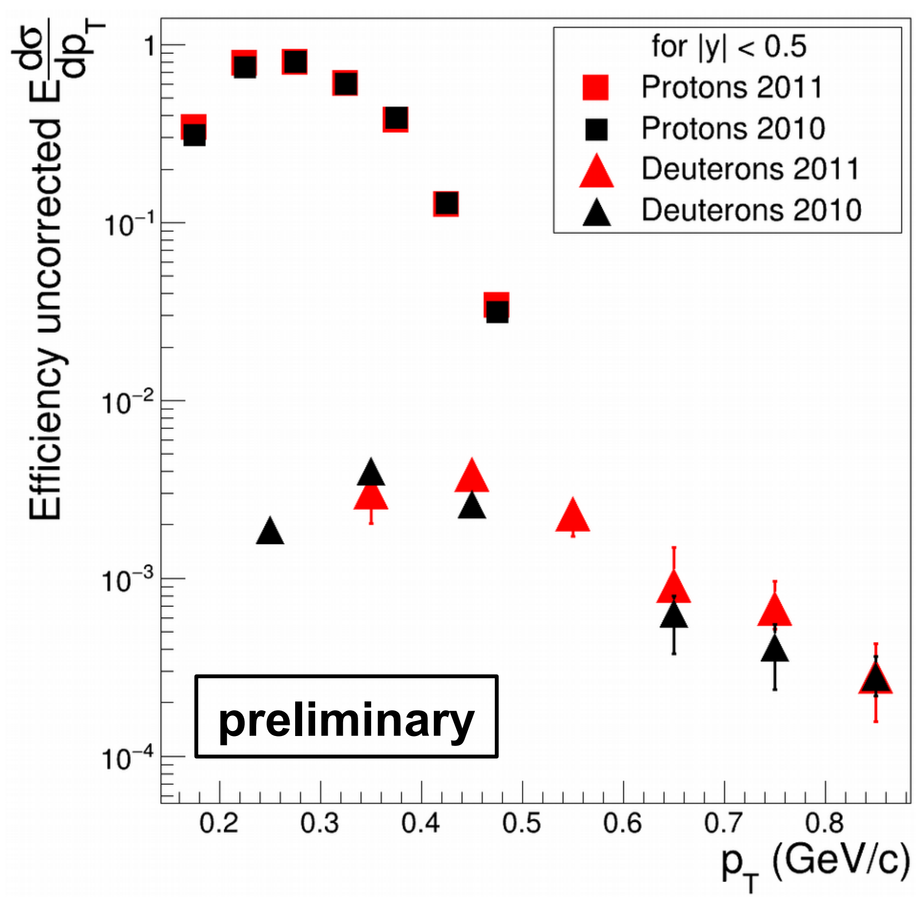


Angular correlation of p-n pairs within a radius of p_0 = 100 MeV

Tune hadronic generators with more information on nucleon correlations

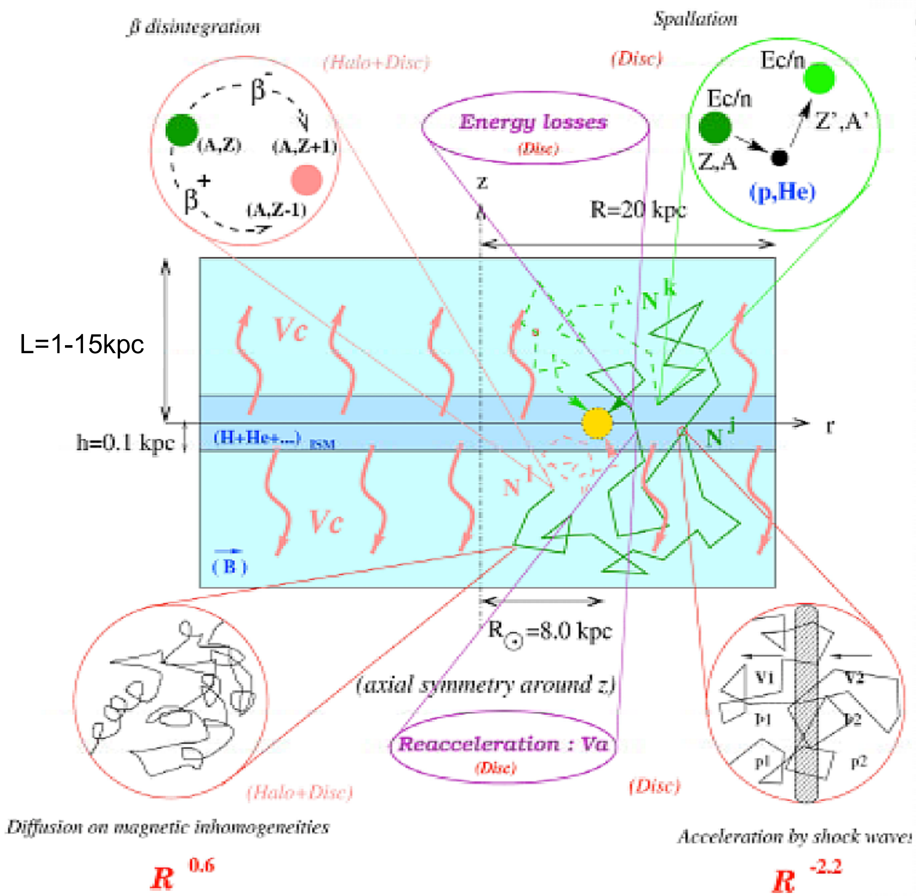
Deuteron analysis for p-p at 158GeV/c

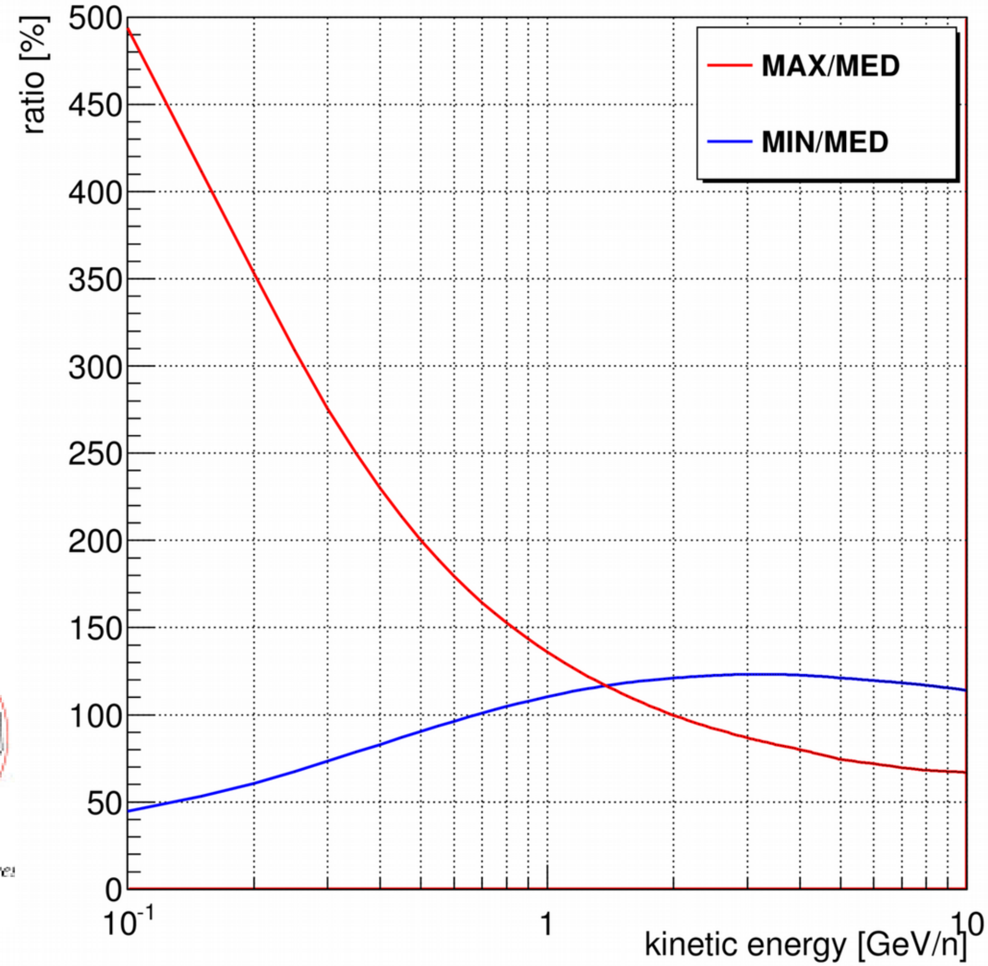




- deuteron analysis is ongoing
- next steps:
  - calculate corrected cross sections
  - study proton-proton correlations
  - conduct antideuteron analysis

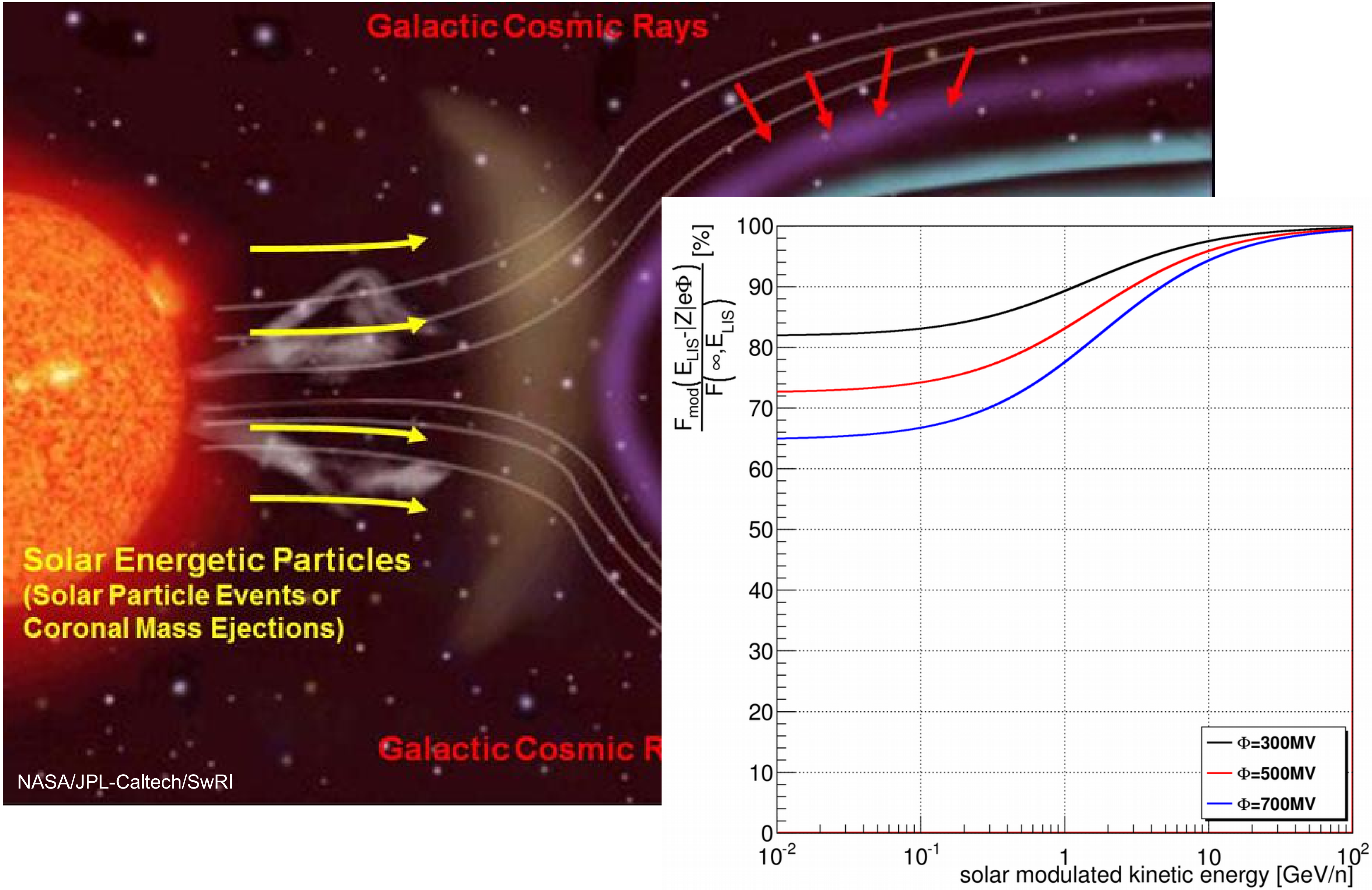
Propagation uncertainty



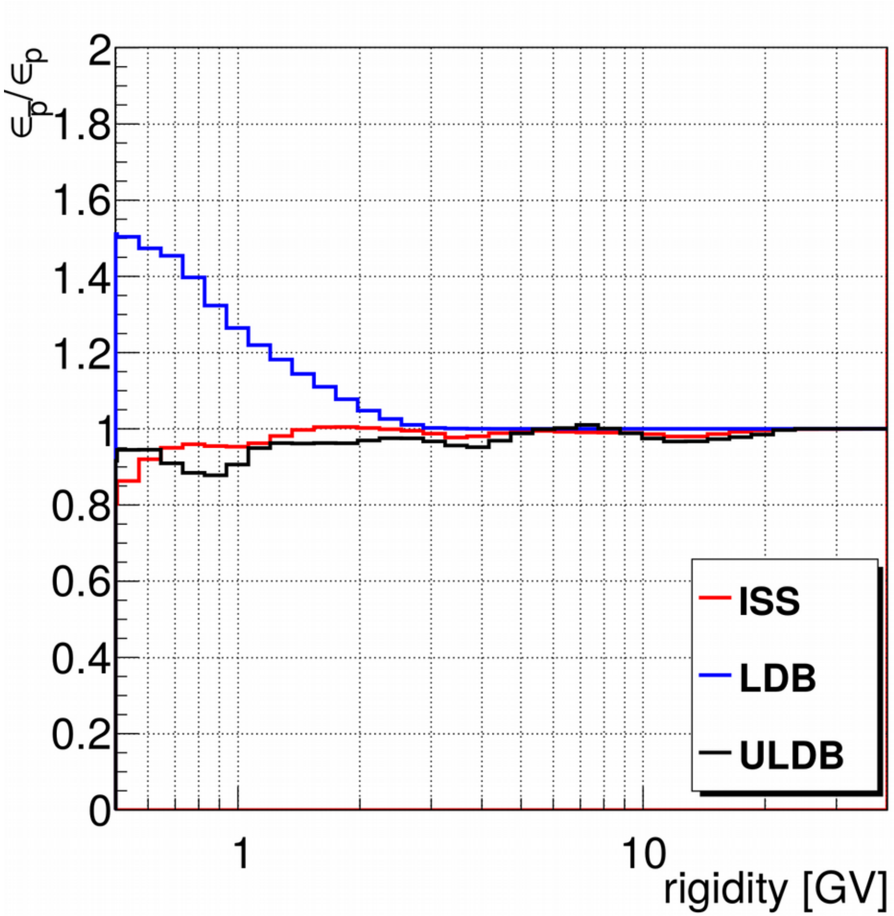


- propagation is a uncertaintiy source for primary antideuterons:
  halo size for diffusion calculation poorly constrained
- more data on various nuclear species are needed, e.g., → Be10/Be9 ratio
- small halo sizes are already disfavored

Solar modulation



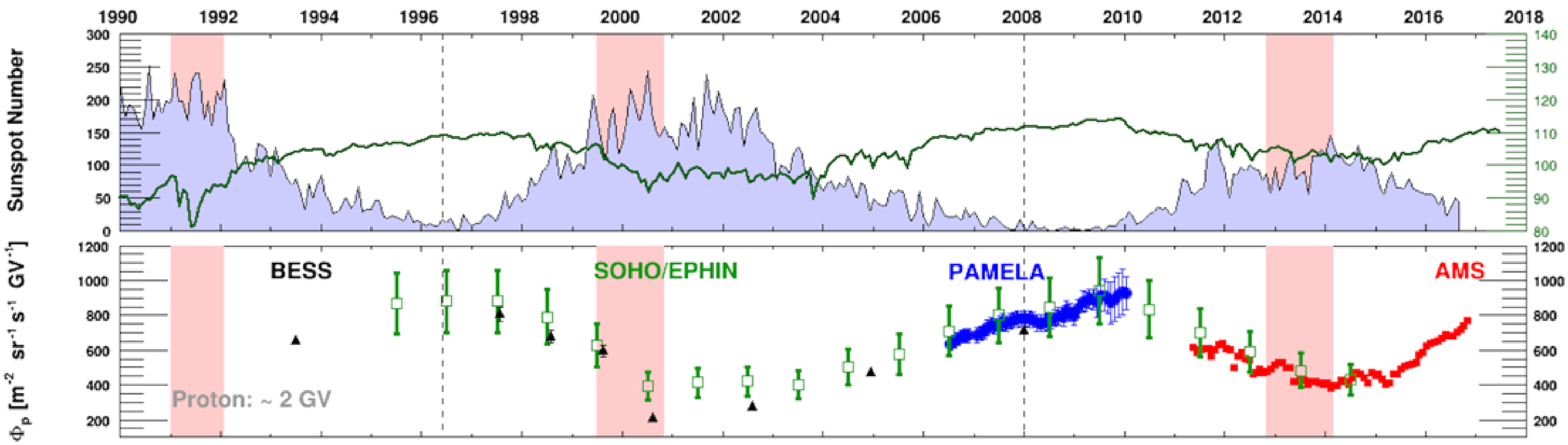
Antiproton-proton comparison



- ratio of antiproton and proton efficiencies for the same trajectories and times
- LDB flights from Antarctica:
  → antiprotons are less suppressed compared to protons
  → better suited for antiproton measurements

- ISS averaged over calculations from 5/19/11 - 10/6/15 with 100 day steps
- (U)LDB averaged over 5/12/11, 13/1/8, 2/12/14, 12/10/14

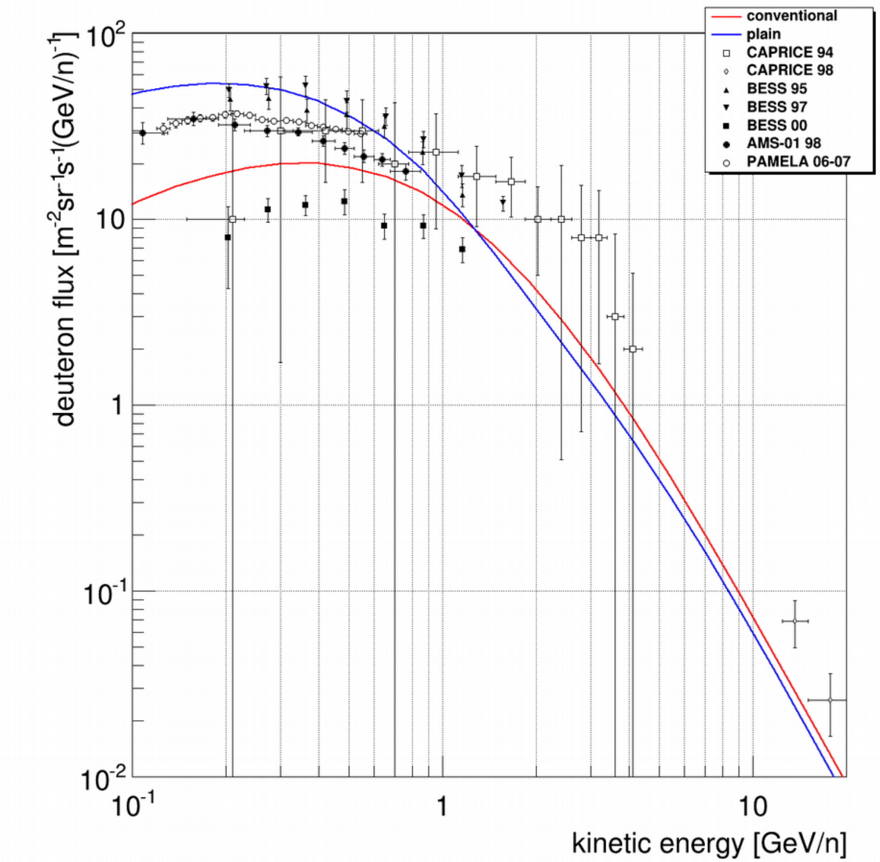
AMS-02 solar results



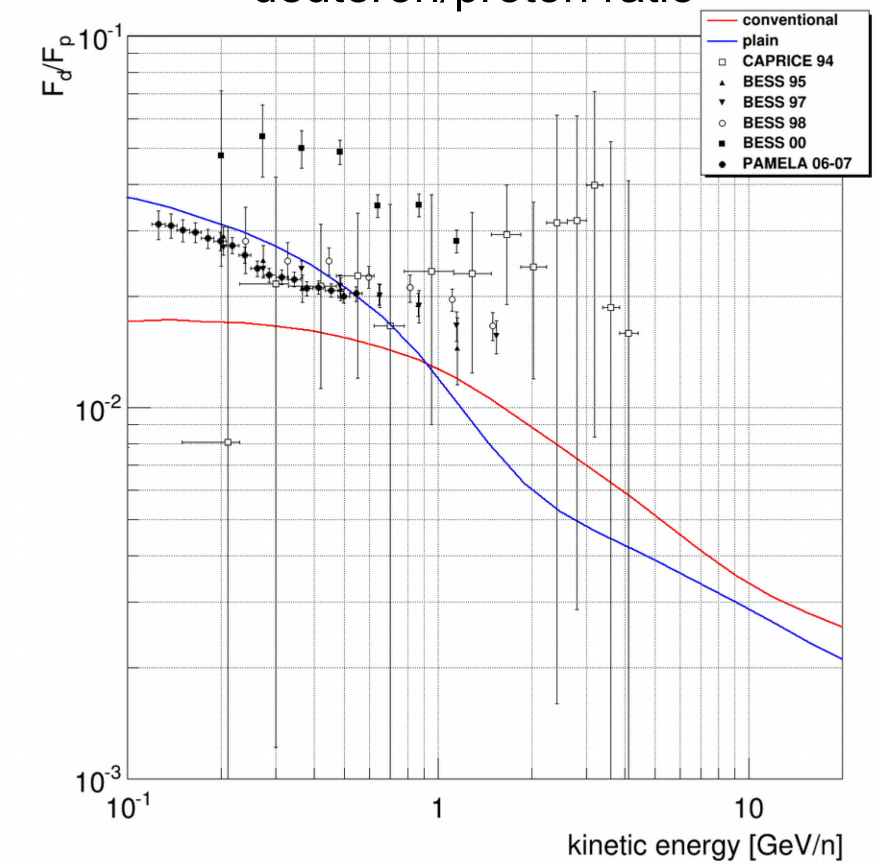
- long-term solar modulation results with PAMELA and AMS-02 in the ~GeV range
- AMS-02 also sees impact of solar flares in temporary changes of cosmic-ray spectra

Deuterons are interesting, too

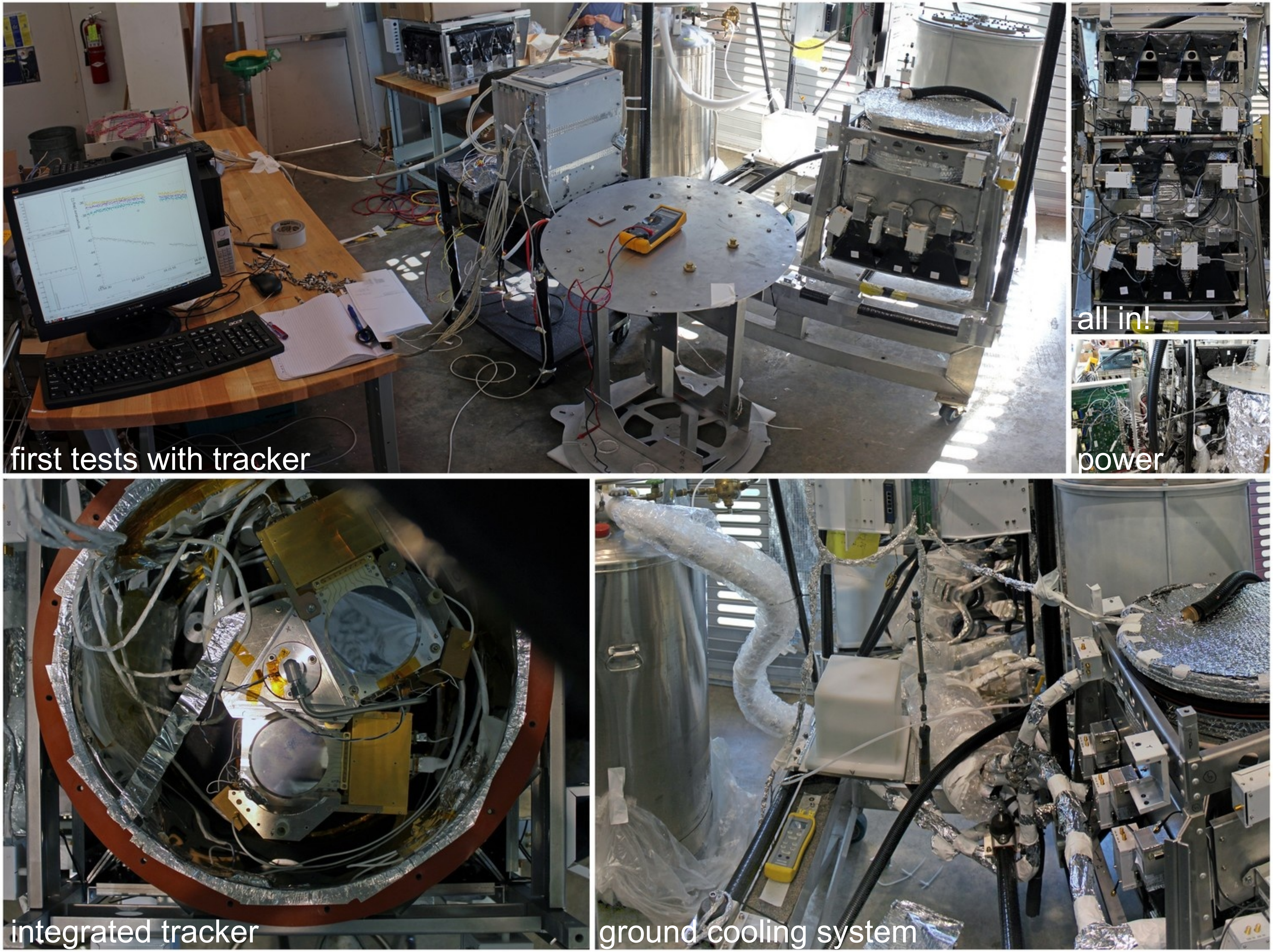
deuteron flux



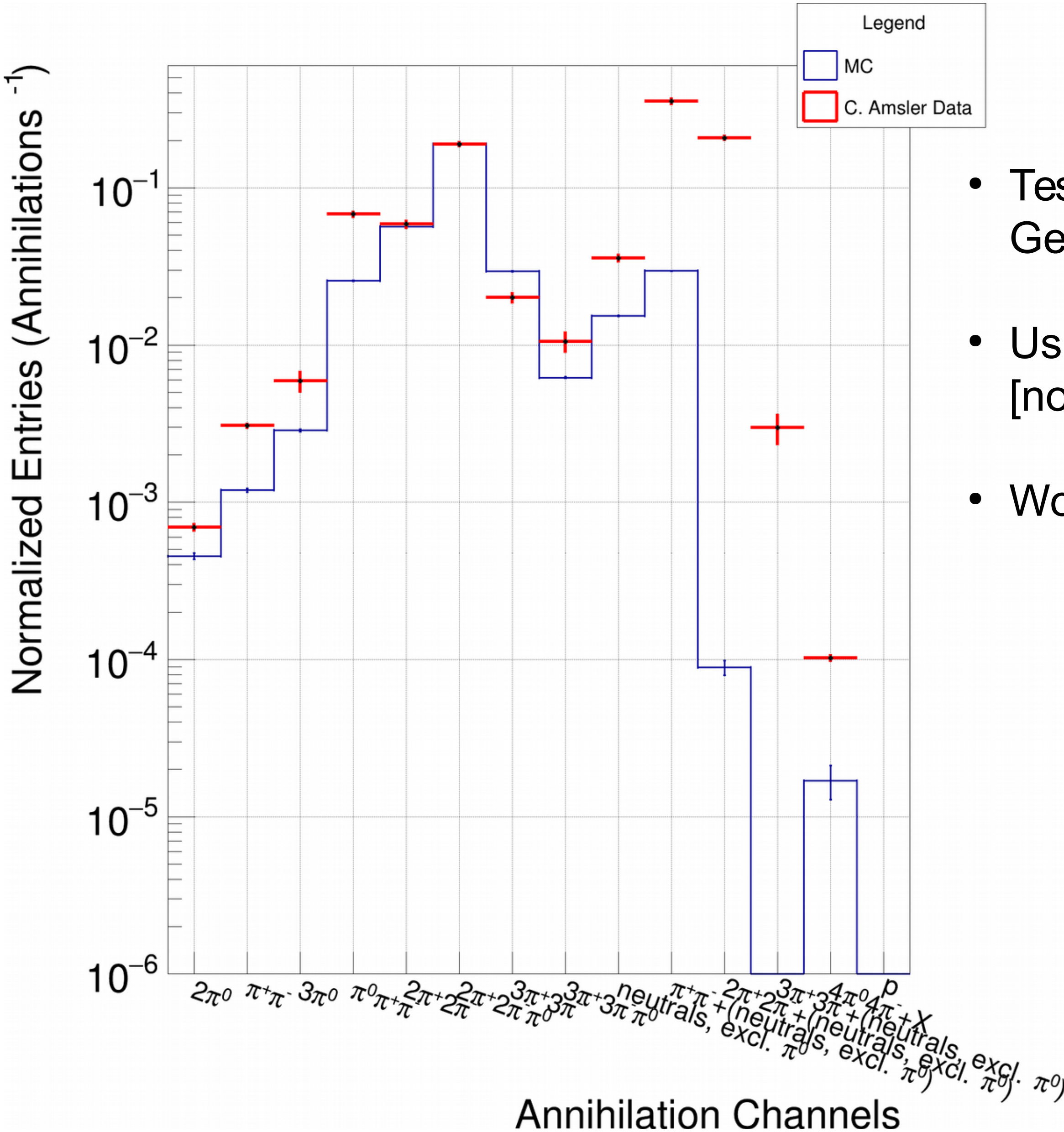
deuteron/proton ratio



- 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

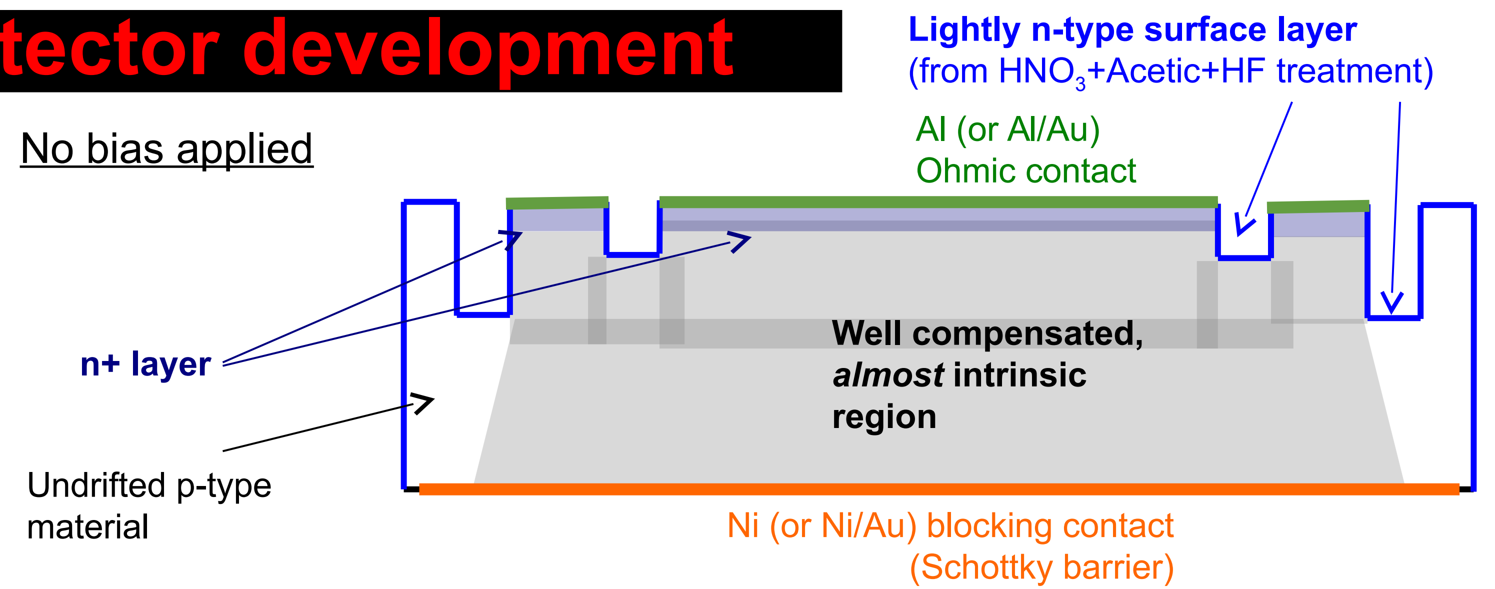

first tests with tracker
all in!
power
integrated tracker
ground cooling system

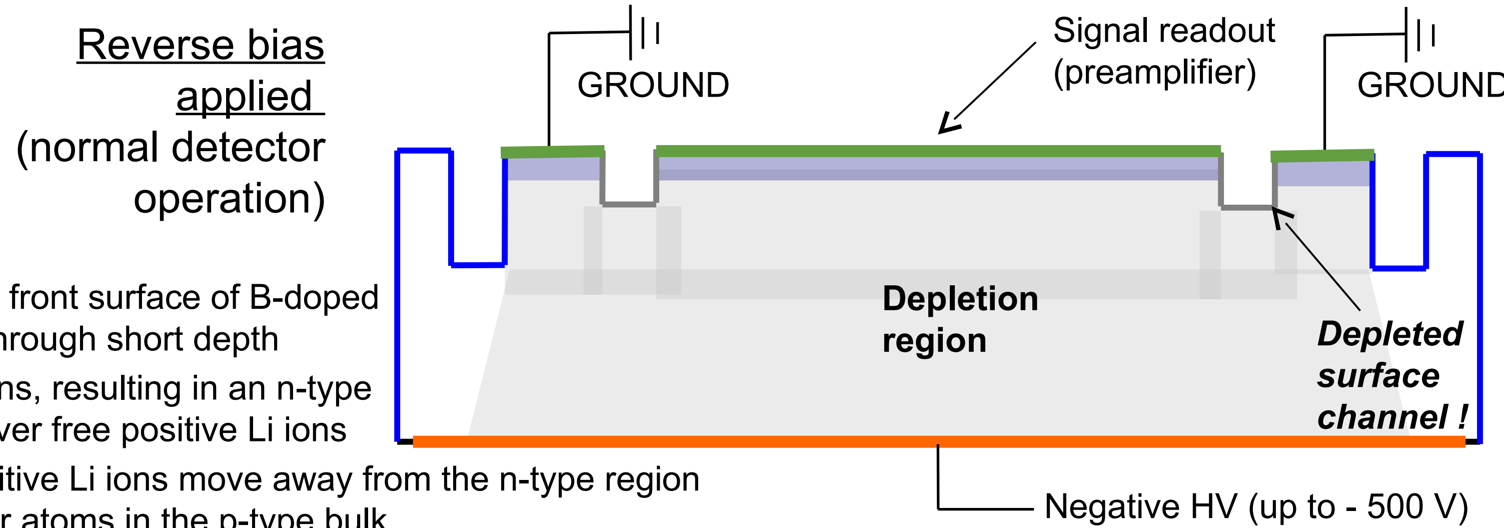
GAPS annihilation physics



- Test of annihilation physics in Geant4 is currently ongoing
- Use antiproton data for validation [no antideuteron beam available]
- Work with Geant4 developers

Si(Li) detector development

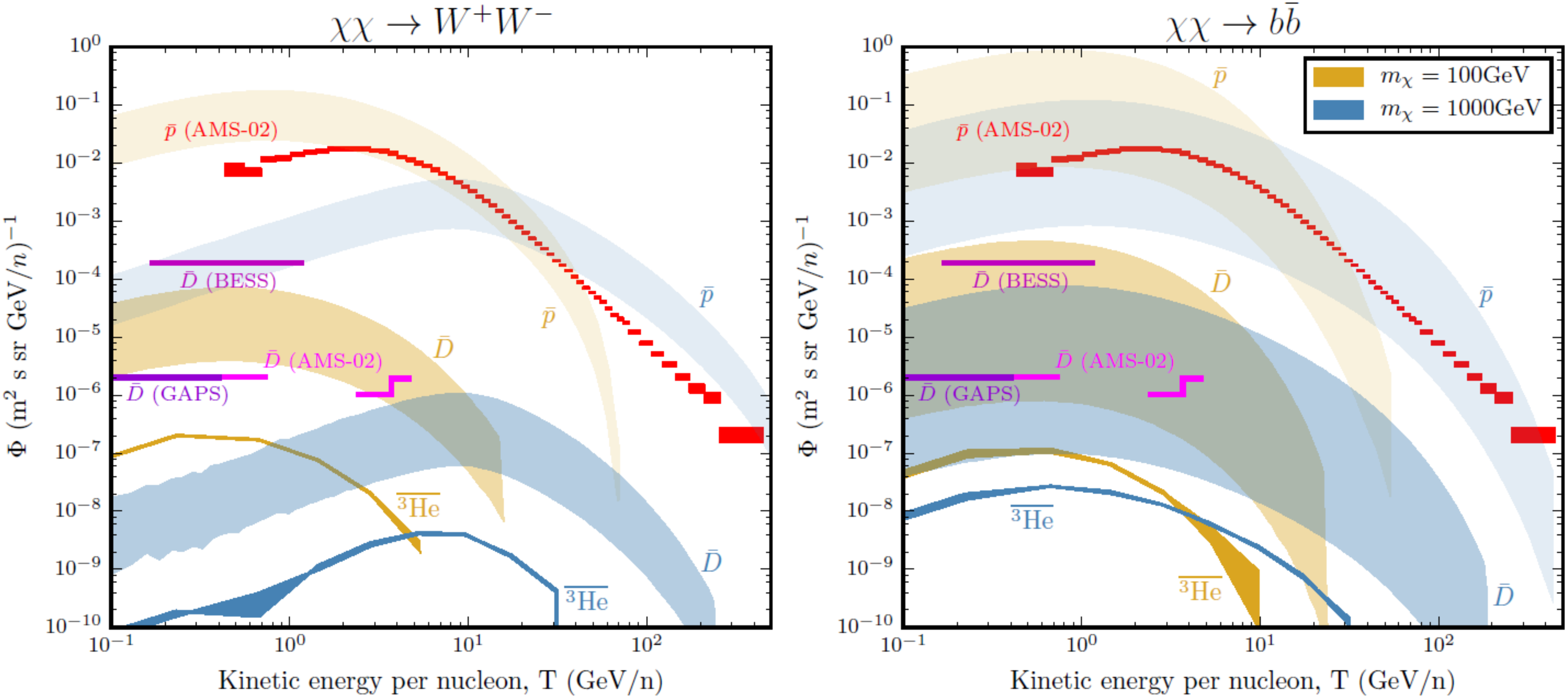




- Lithium is applied to the front surface of B-doped p-type Si and diffused through short depth
- Li atoms donate electrons, resulting in an n-type Si lattice layer and leftover free positive Li ions
- under reverse bias, positive Li ions move away from the n-type region
  → compensate acceptor atoms in the p-type bulk
  → compensate impurities in the Si
- drifting procedure creates a thick compensated region (<1.5 days at 500V and 130C)
- ultrasonic machining on the n+(Li) contact → guard ring structure, reduces leakage current, much better energy resolution
- electrodes are thermal-evaporated ohmic/blocking contacts

Antihelium

Coogan, Profumo, Phys. Rev. D 96, 083020 (2017)



- has important implications for antiprotons and antideuterons
  → all three channels have to be explained at the same time
  → nuclear formation is a key issue

- Caveats:
  - MIN propagation model (disfavored)
  - high annihilation cross section (but still compatible with dwarphs bounds)
  - no antiproton secondaries shown in the figure
  - marginal compatibility for WW