Antinuclei in cosmic rays

DSU - Annecy
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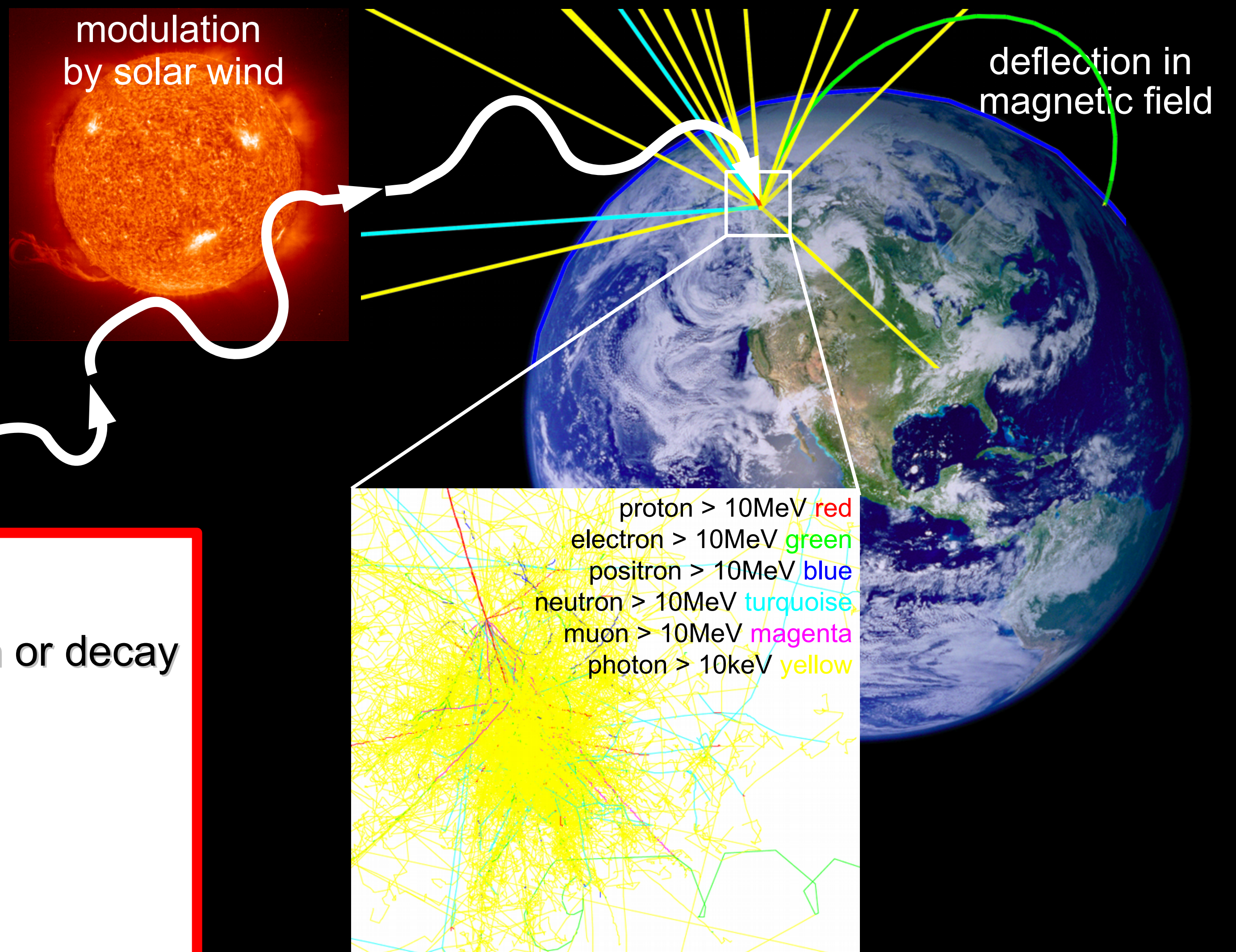
Cosmic rays as dark matter messengers

DM annihilation
or decay



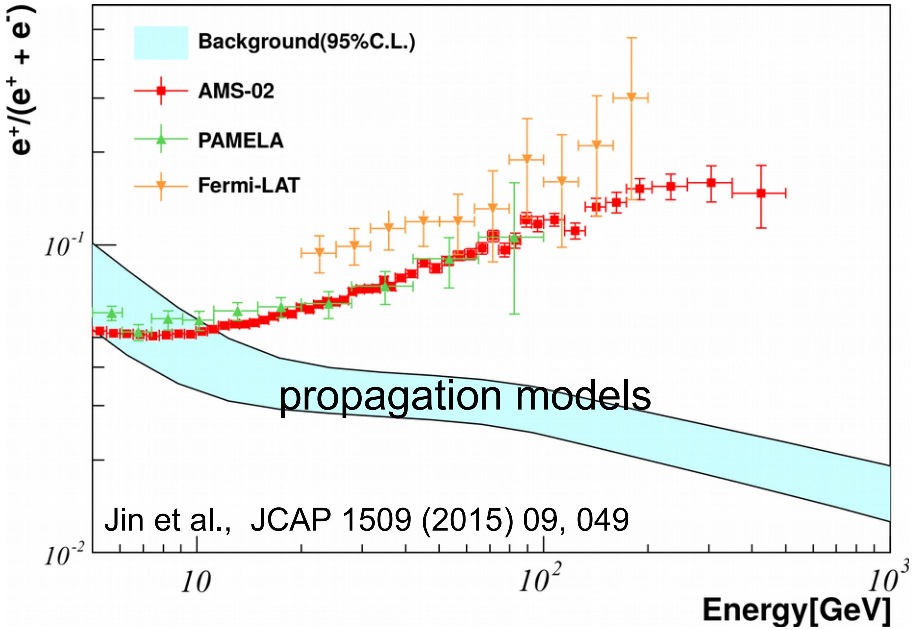
interactions with
atmosphere

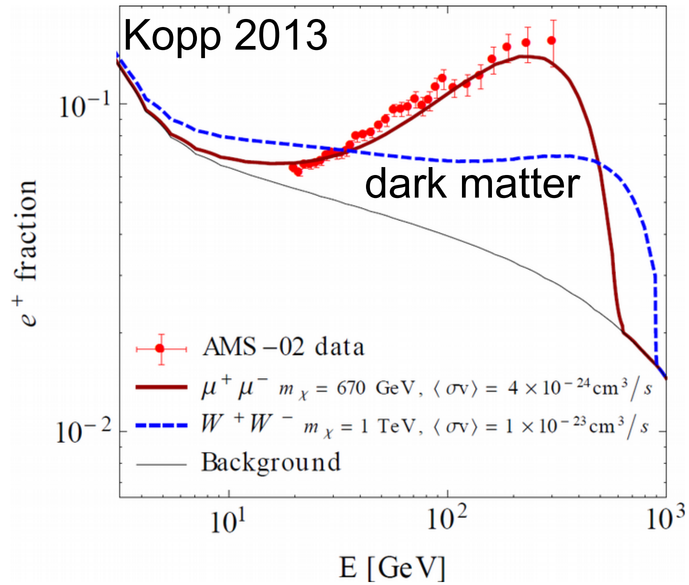
Uncertainties:

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

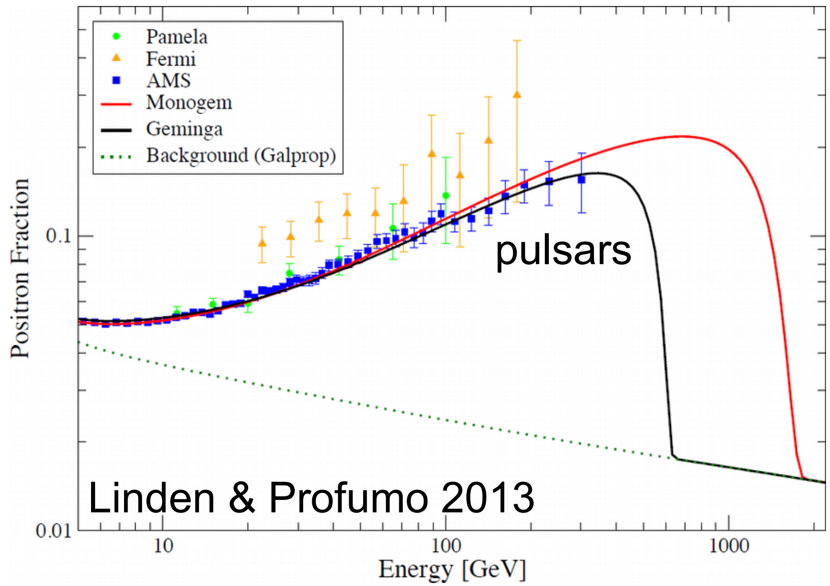
+ astrophysical background

Dark matter signal in positrons?

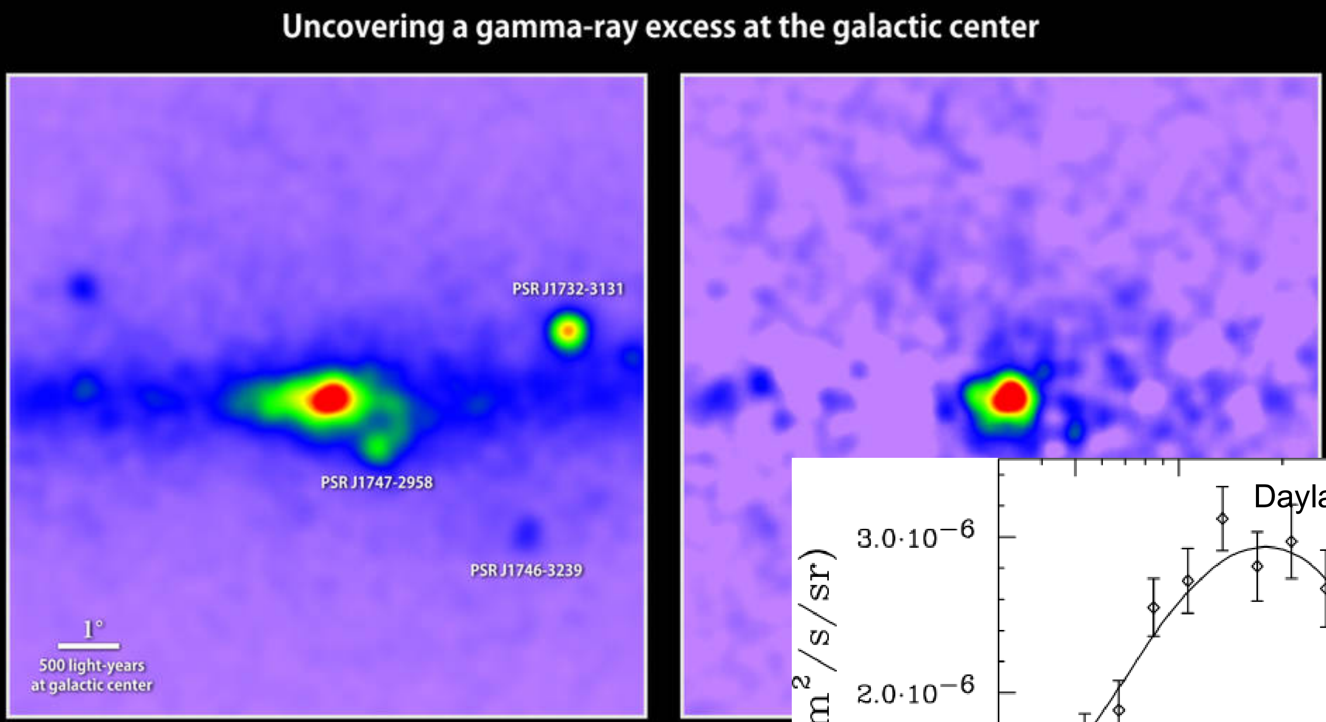




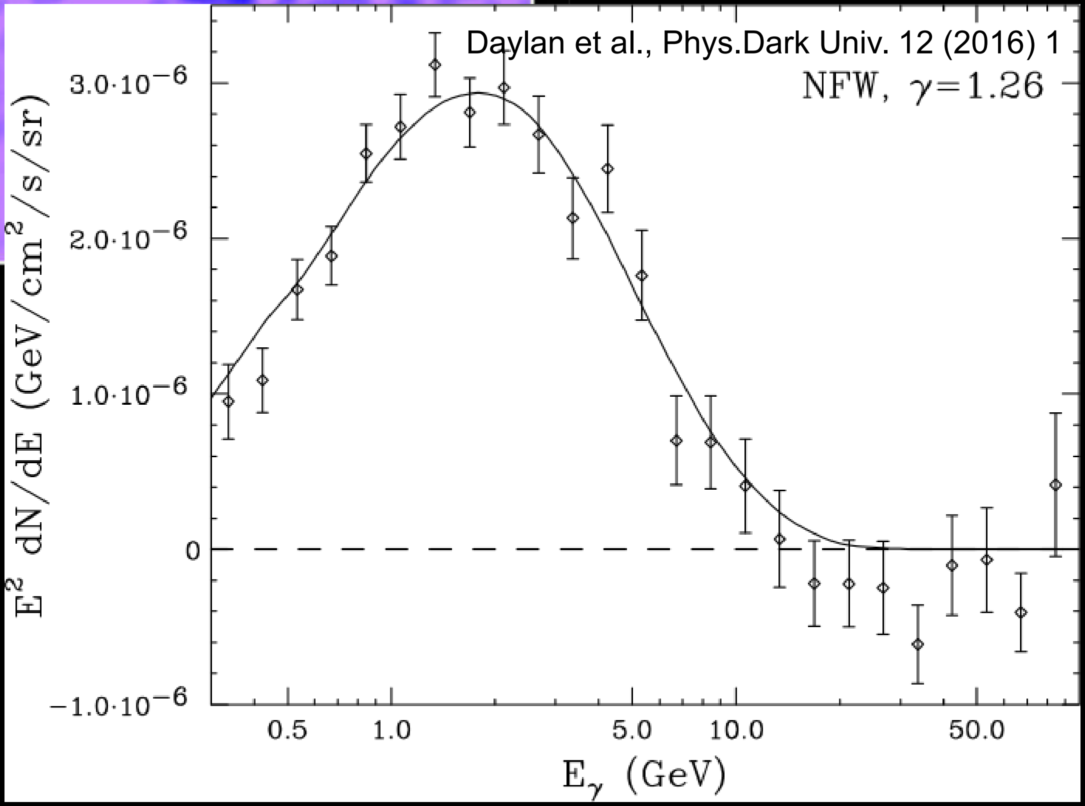
- dark matter models are severely constrained:
  - large cross sections
- explained by nearby pulsars producing electrons and positrons?
  - anisotropy should be smaller than AMS-02 limit, but still measurable with ACTs
  - HAWC excludes some local pulsars as source of anomalous positron fraction
- different acceleration mechanisms



Diffuse Galactic γ-ray excess

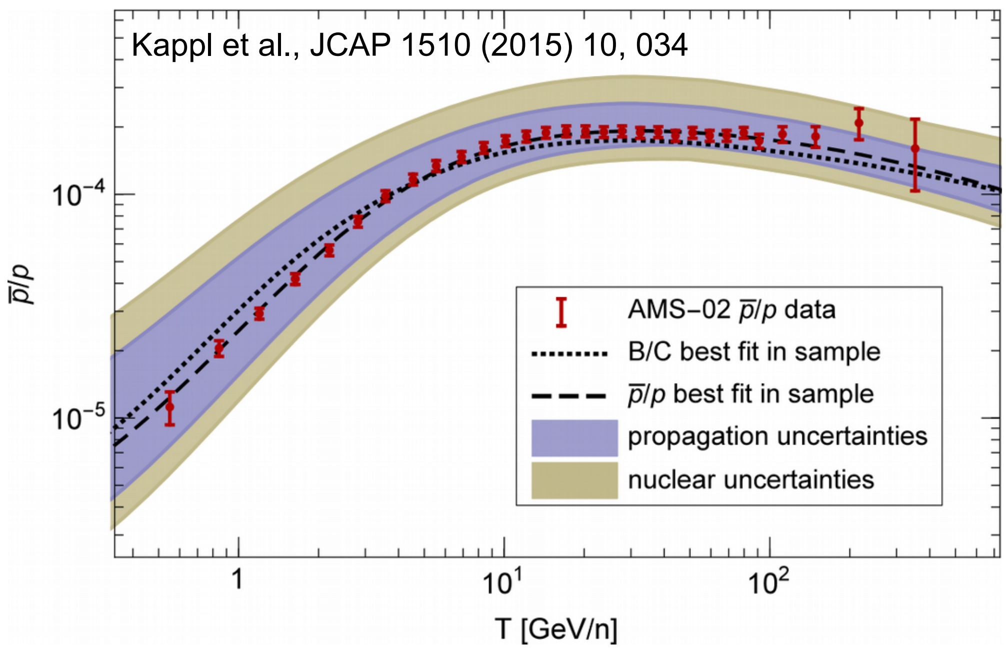


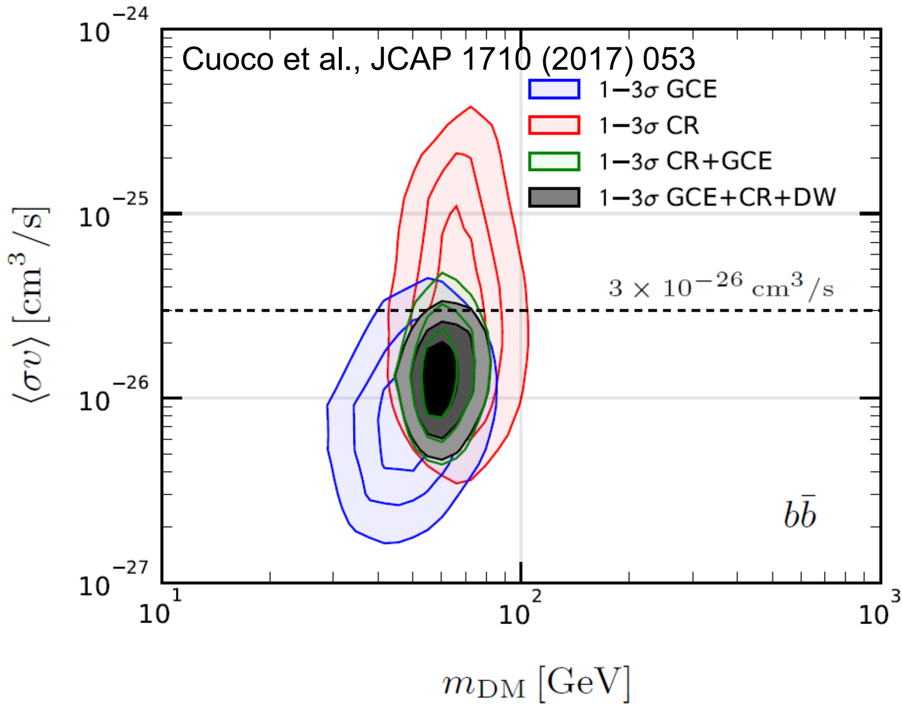
Unprocessed map of 1.0 to 3.16 GeV gamma rays



- 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

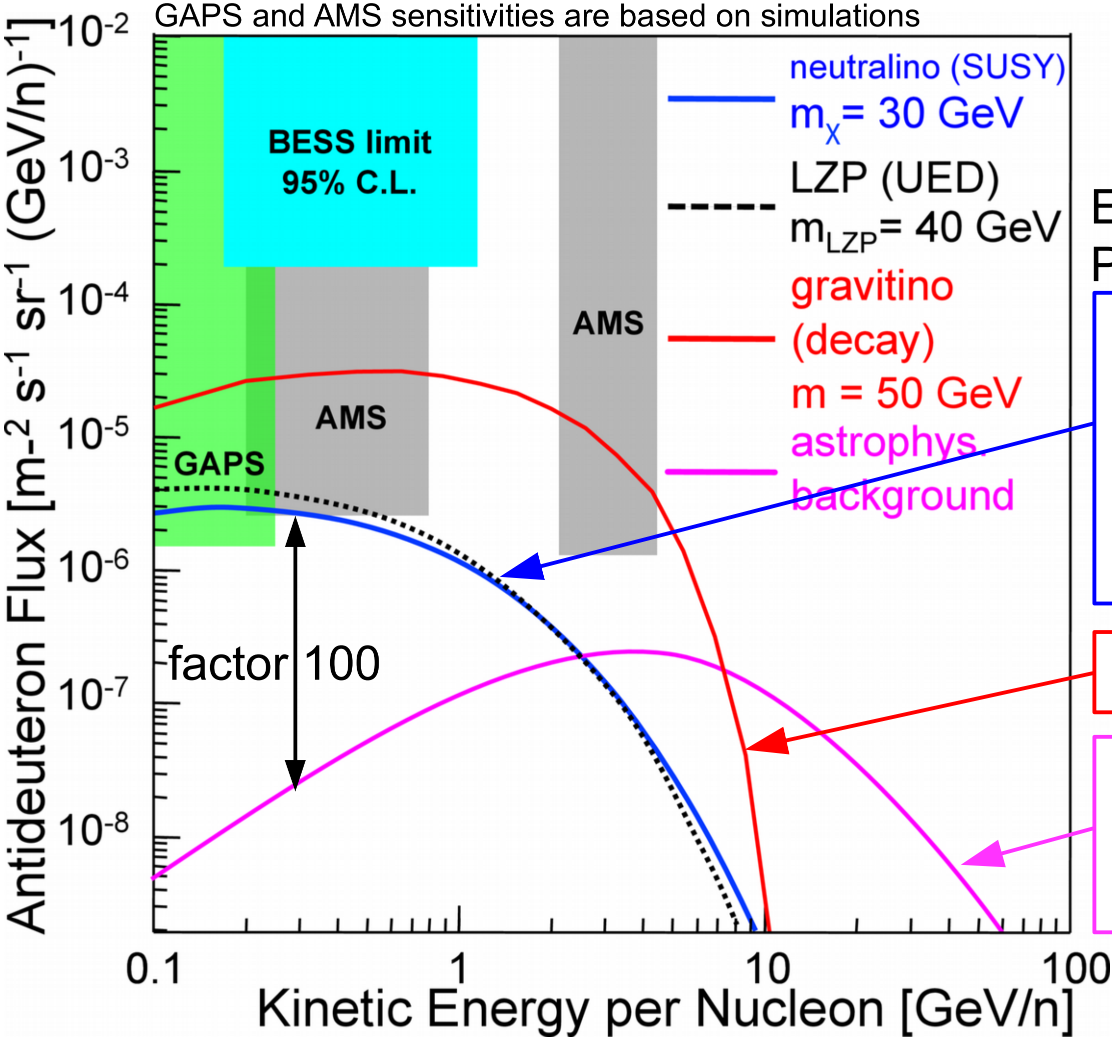
Antiprotons





- 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



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

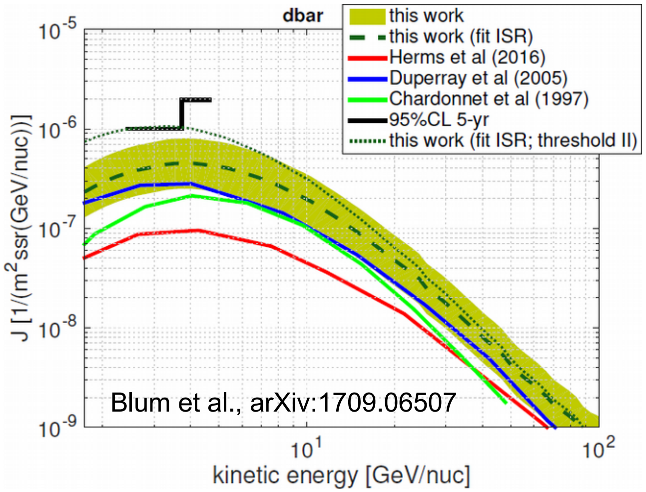
late decays of unstable gravitinos

astrophysical background:
collisions of protons and antiprotons with interstellar medium

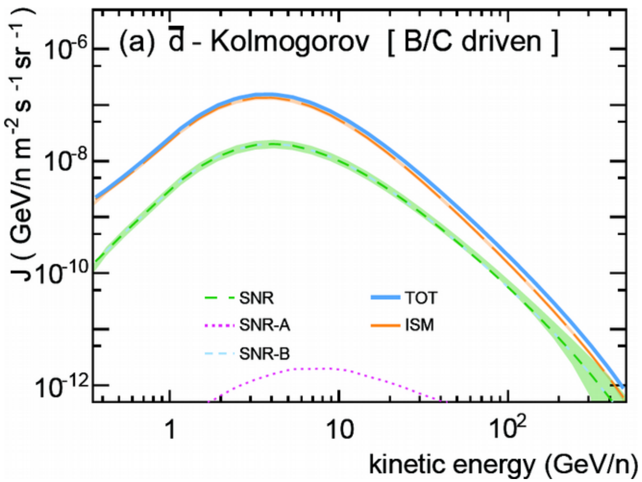
Antideuterons are the most important unexplored indirect detection technique!

More antideuteron models

Astrophysical background only:

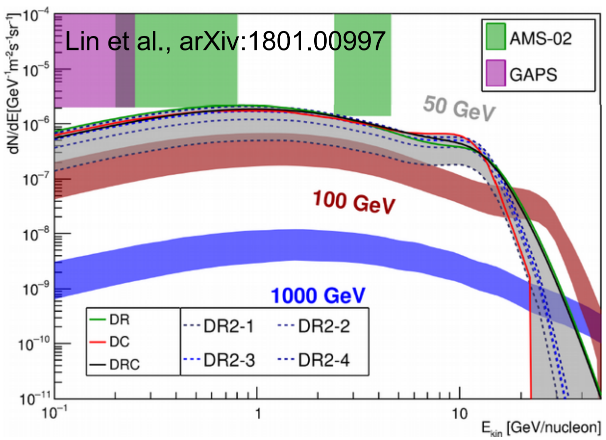


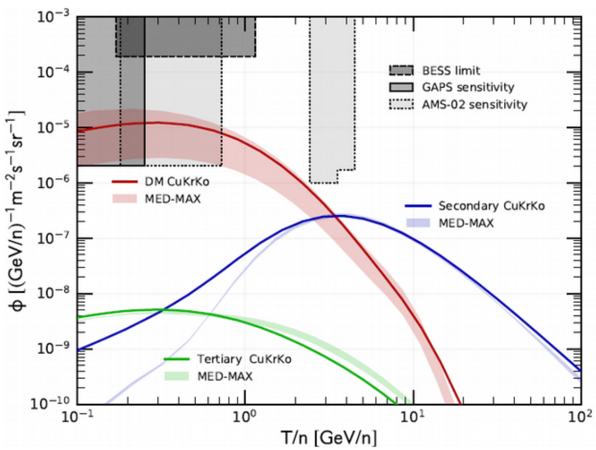
Tomasetti & Oliva, arXiv:1712.03177



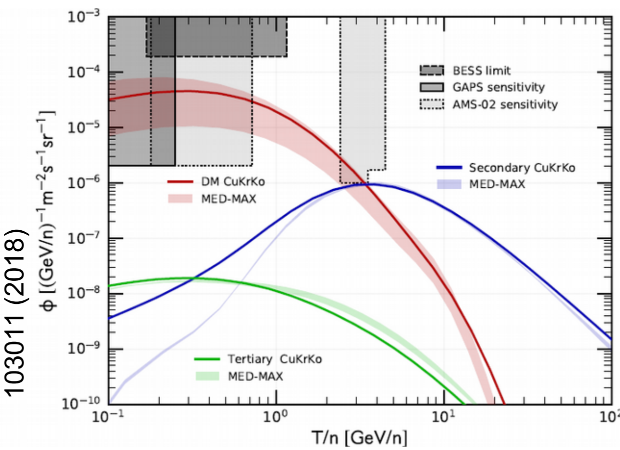
- antideuterons and antiprotons have to be explained simultanously
- evaluate propagation effects
- nuclear modeling

Dark matter annihilation:

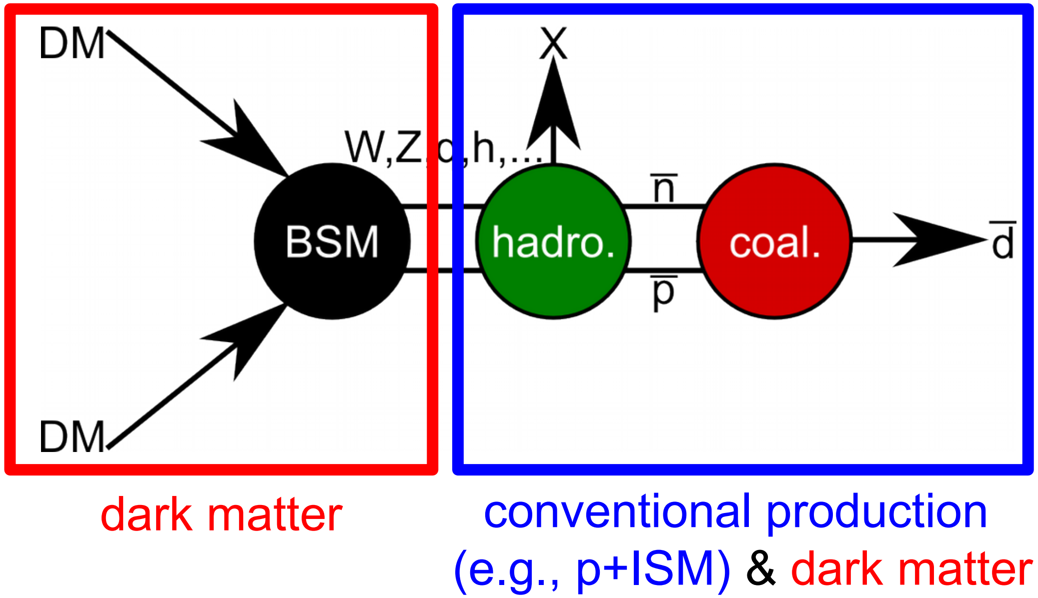


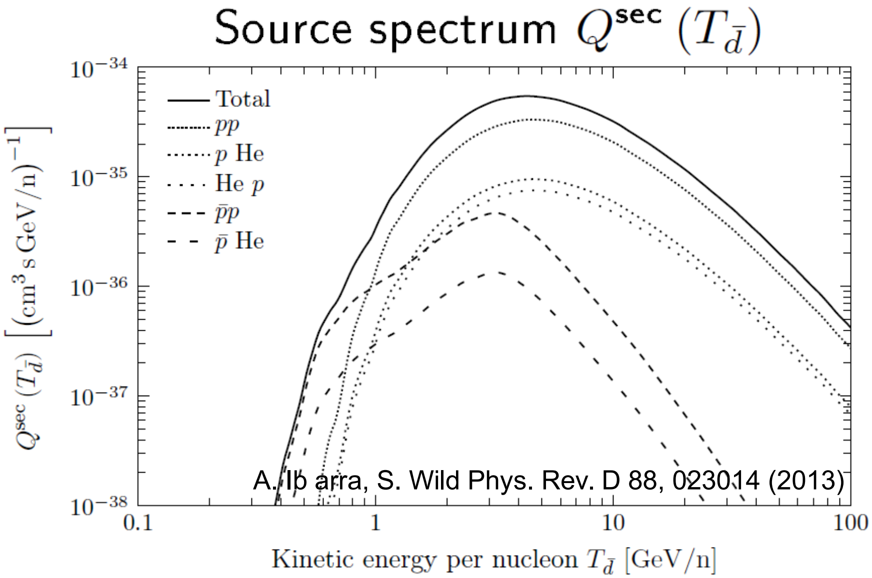


Korsmeier et al., Phys. Rev. D 97, 103011 (2018)



(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

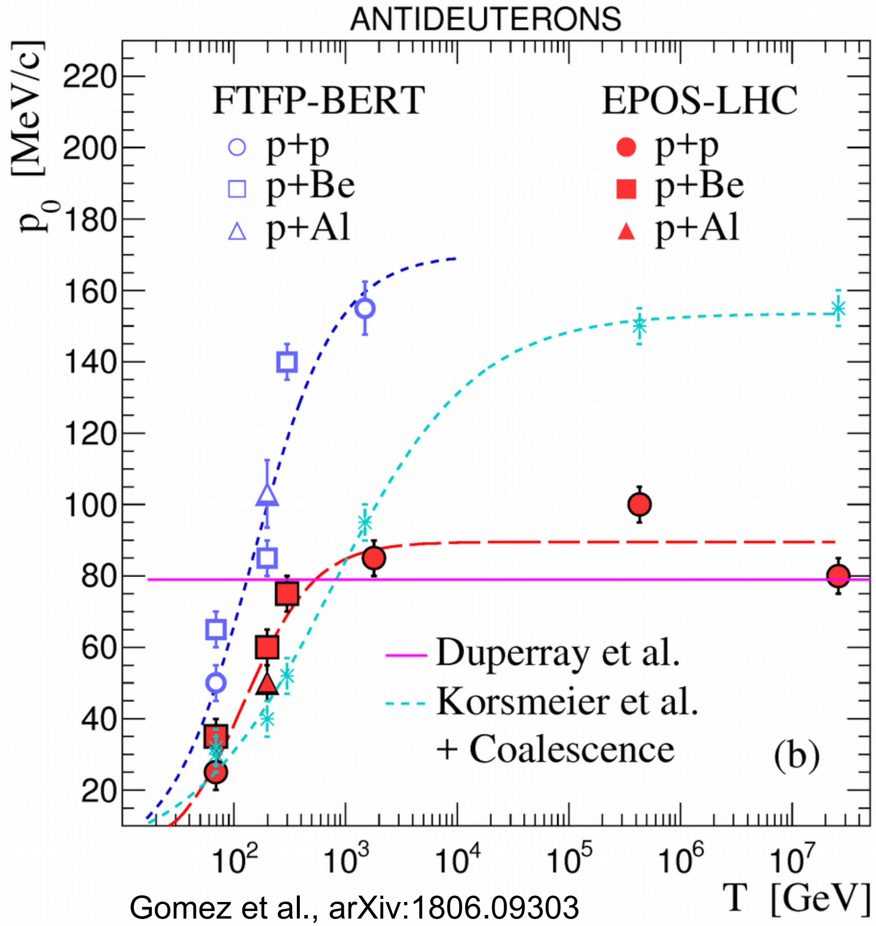
$$\gamma_d \frac{d^3 N_d}{dp_d^3} = \frac{4\pi}{3} p_0^3 \left(\gamma_p \frac{d^3 N_p}{dp_p^3} \right) \left(\gamma_n \frac{d^3 N_n}{dp_n^3} \right)$$

- 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

- coalescence uncertainties are about **a factor of 10** on the flux
- coalescence is highly sensitive to two-particle correlations between the participating (anti)nucleons (non-pertubative regime)
- 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
  → add "afterburner"

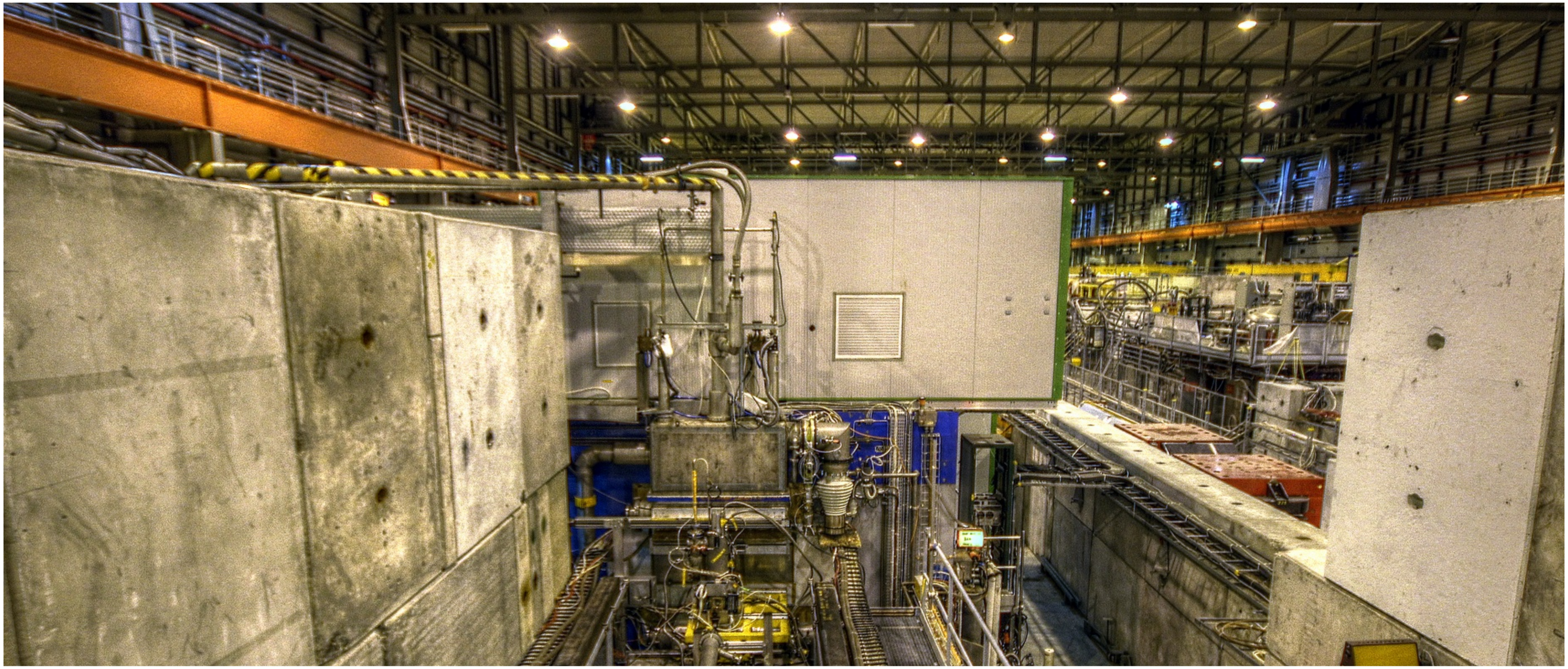


Gomez et al., arXiv:1806.09303

- compared simulation results to available data sets (p+p, p+A) → best-fit coalescence momentum per data set
- **more high statistics data needed to constrain (anti)deuteron coalescence model**

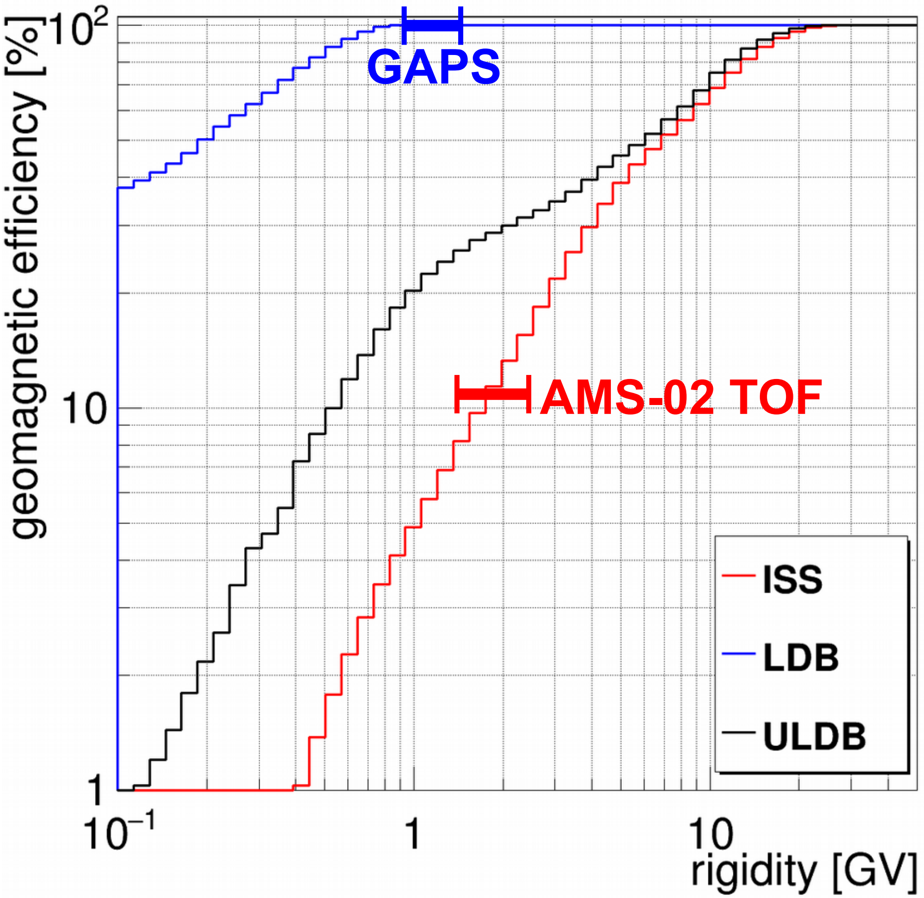
NA61/SHINE experiment at SPS, CERN

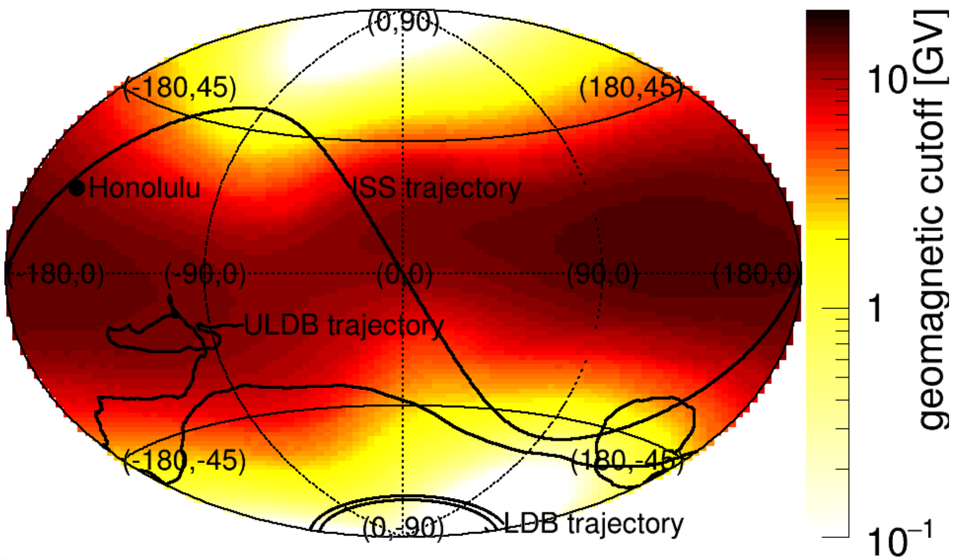
SPS **H**eavy **I**on and **N**eutrino **E**xperiment
pre-decessor: NA49



- 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)
- (anti)deuteron analysis is ongoing

Geomagnetic efficiency





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

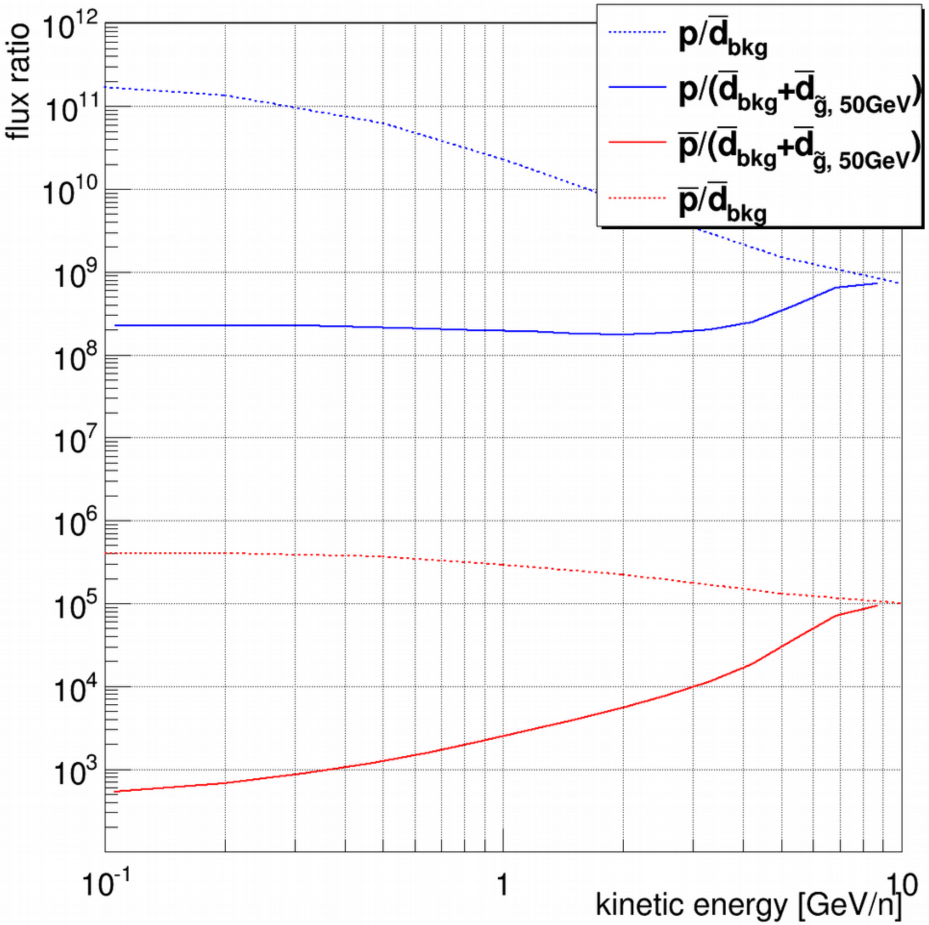
Identification challenge

Required rejections for antideuteron detection:

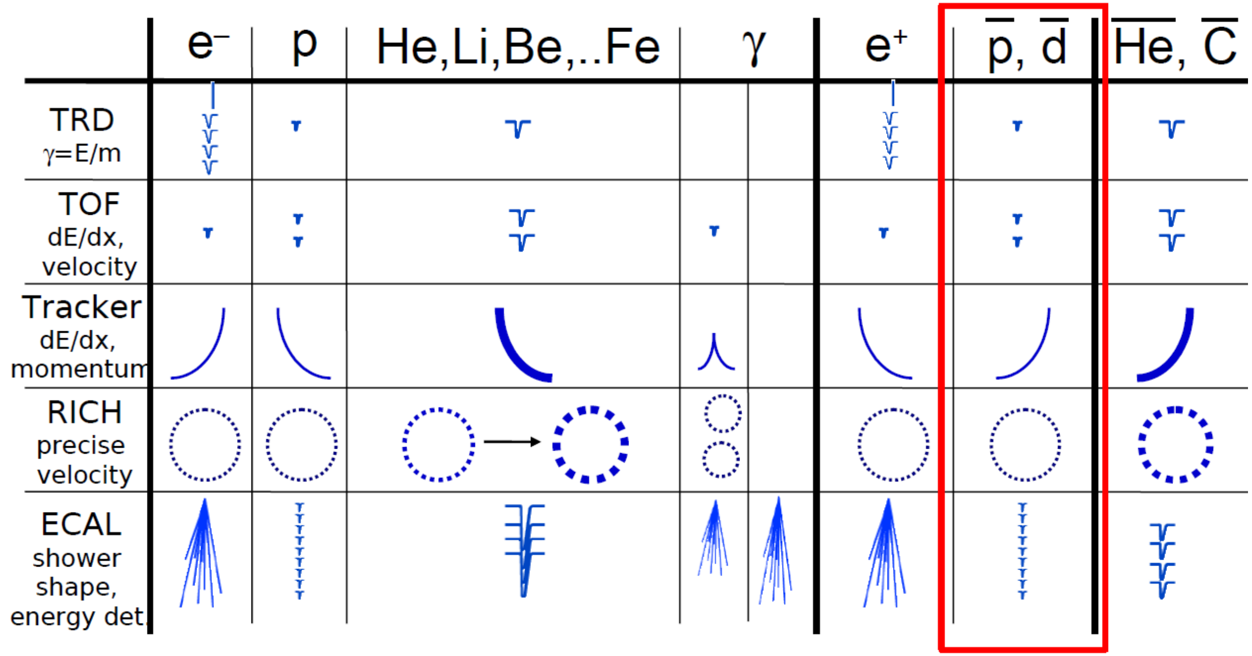
- **protons**: > 10^8 - 10^{10}
- **He-4**: > 10^7 - 10^9
- **electrons**: > 10^6 - 10^8
- **positrons**: > 10^5 - 10^7
- **antiprotons**: > 10^4 - 10^6

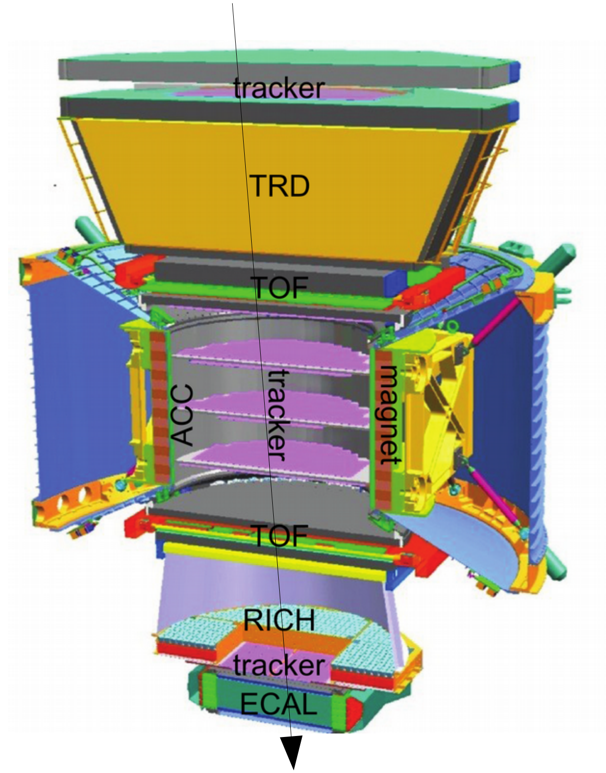
Antideuteron measurement with balloon and space experiments require:

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



AMS-02 antideuteron analysis





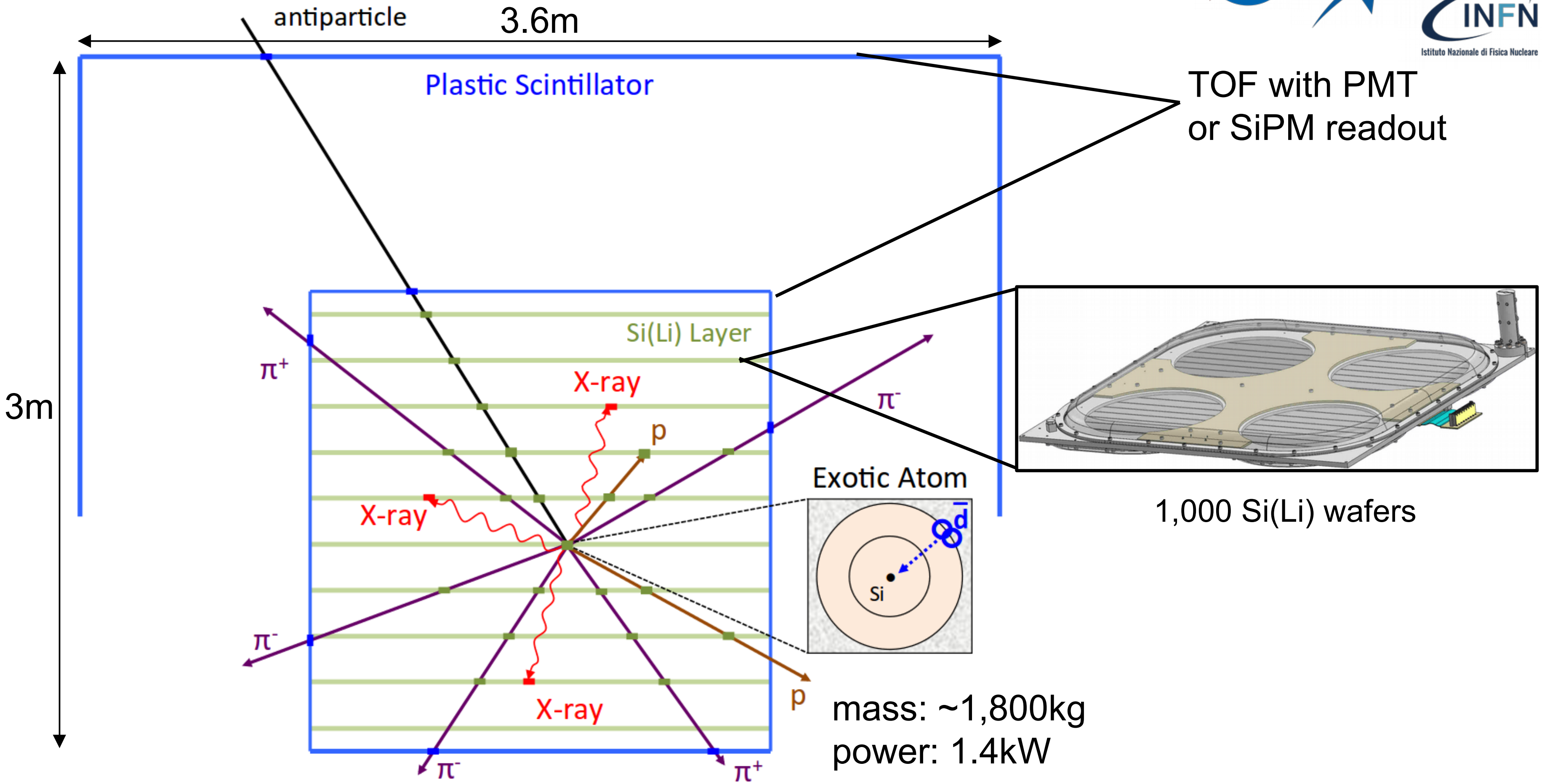
- **antideuteron identification:**
  - momentum measured in the form of rigidity
  - charge from TOF, TRD, tracker
  - lower velocities: **T**ime **O**f **F**light scintillator system
  - higher velocities: **R**ing **I**mage **Ch**erenkov detector

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

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

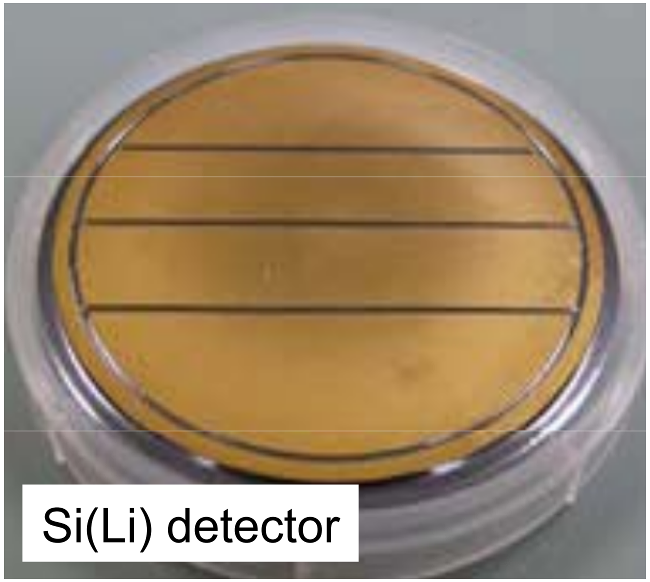
The GAPS experiment

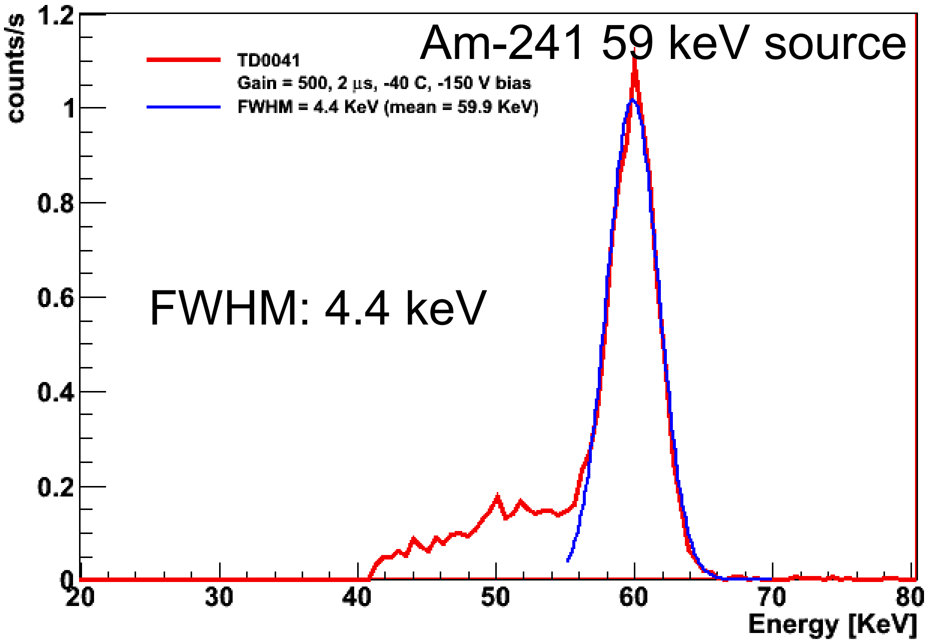
Columbia U, UCSD
UCLA, UCB,
U Hawaii, MIT



- 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, JSPS, INFN since 2017 → first flight 2020**

GAPS detector production

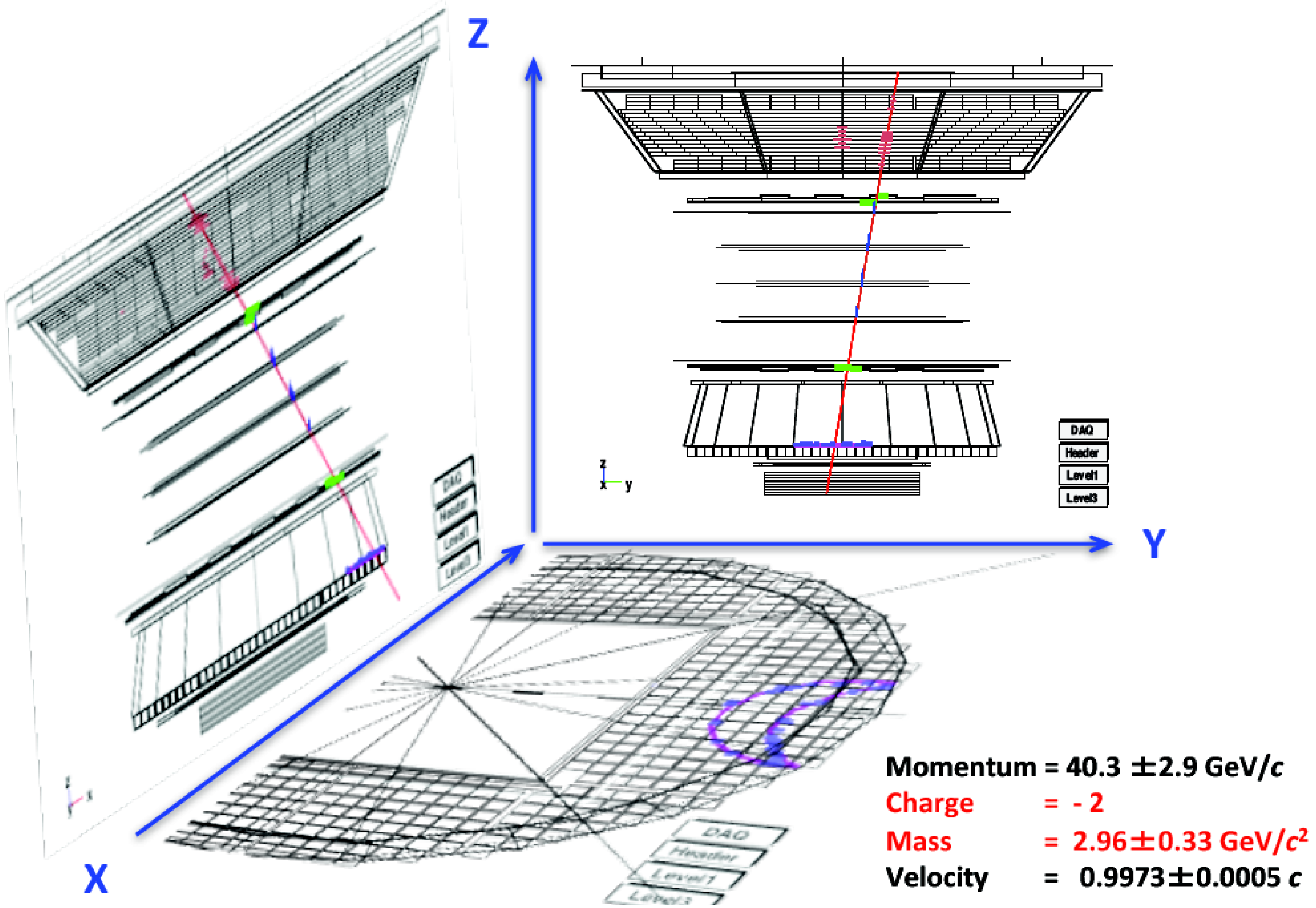




- GAPS will use ~1,000 4” Si(Li) detectors, 2.5mm thick
- fabrication scheme developed at Columbia U, produced by private company Shimadzu, Japan
- confirmed performance with cosmic rays (MIPs) and Am-241 source (X-rays)

- TOF testing and development ongoing

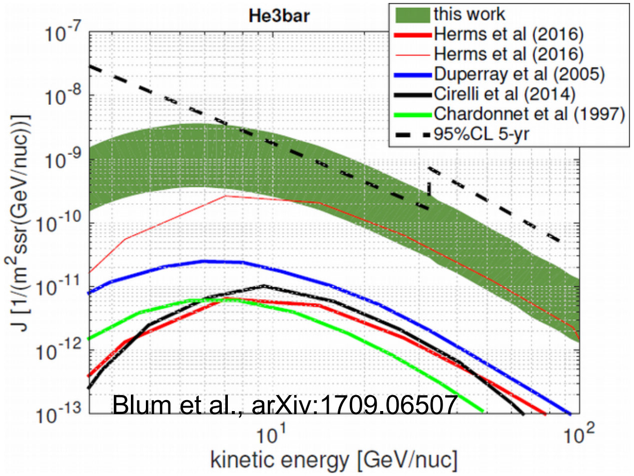
Antihelium candidates by AMS-02



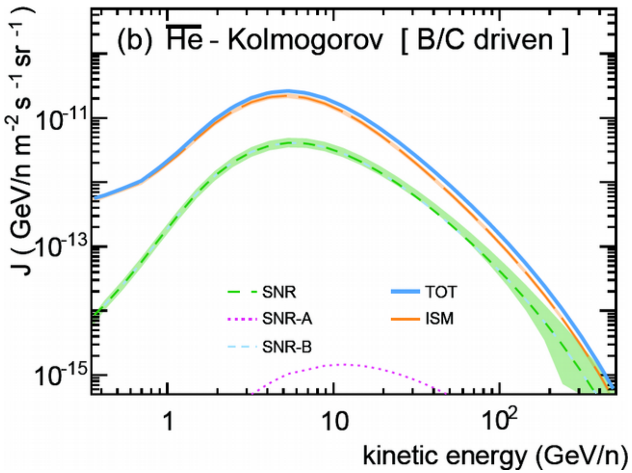
- antihelium-3 and antihelium-4 candidates have been identified
- massive background simulations are carried out to evaluate significance
- more data are needed

Antihelium models

Astrophysical background only:

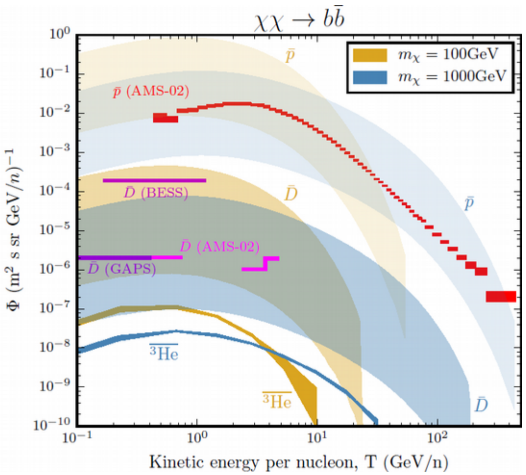


Tomasetti & Oliva, arXiv:1712.03177

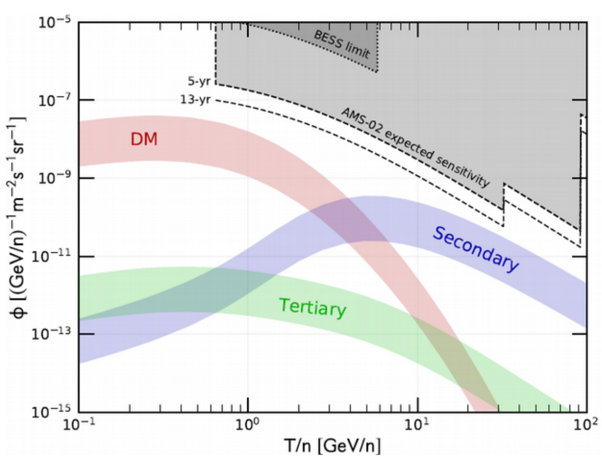


- antideuterons, antiprotons, antihelium have to be explained simultanously
- nuclear modeling

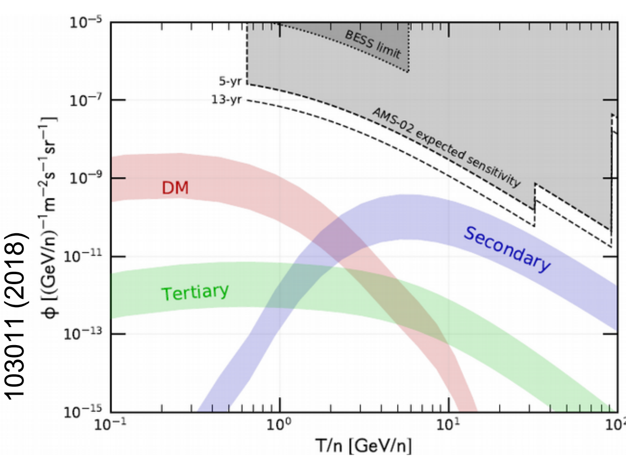
Dark matter annihilation:



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



Korsmeier et al., Phys. Rev. D 97, 103011 (2018)



Conclusion & Outlook

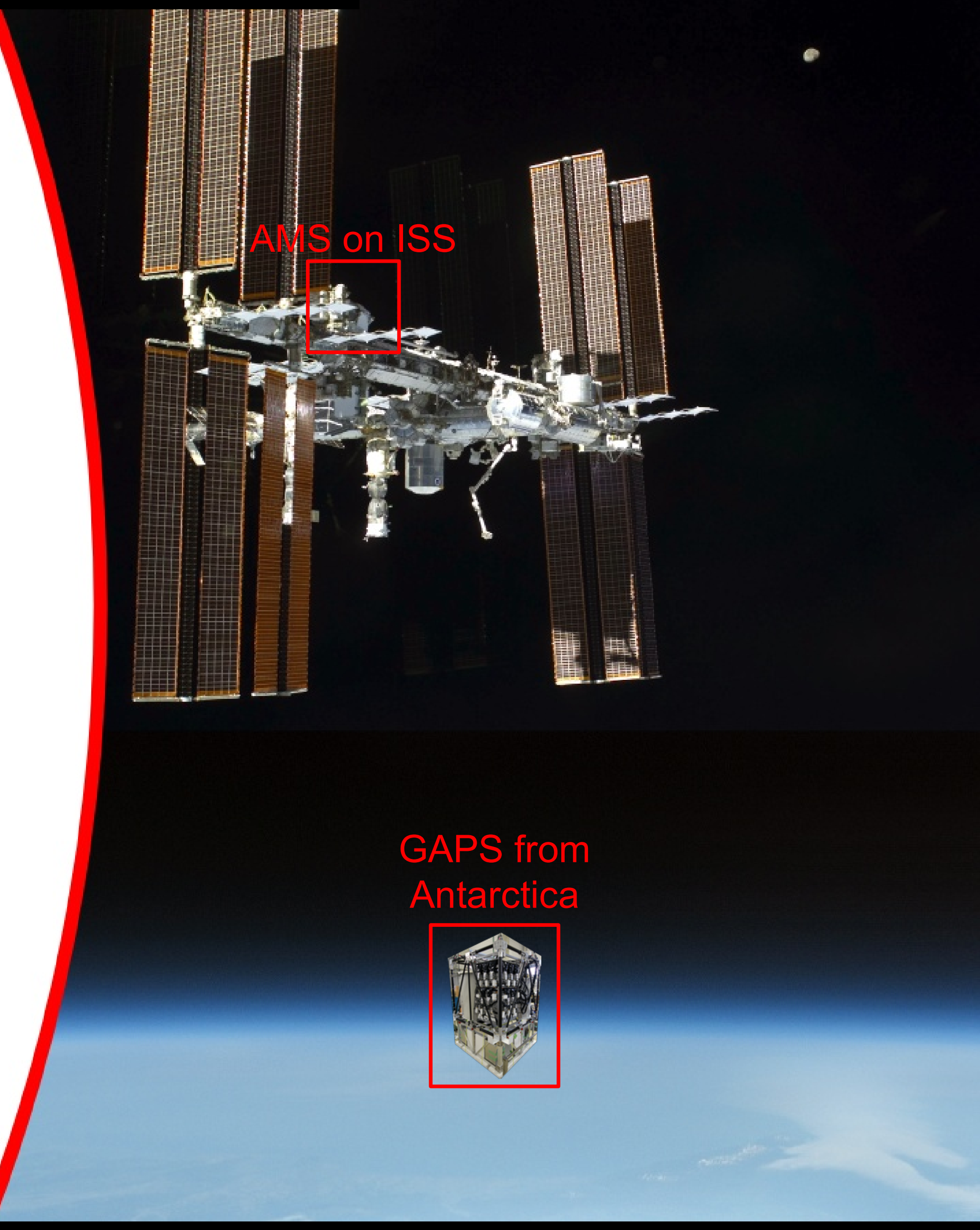
- antideuteron searches are experimentally challenging
  → **multiple experiments for cross-checks are important**

- AMS-02 antideuteron and antihelium analyses are ongoing

- GAPS is under development
  → **first flight in late 2020**

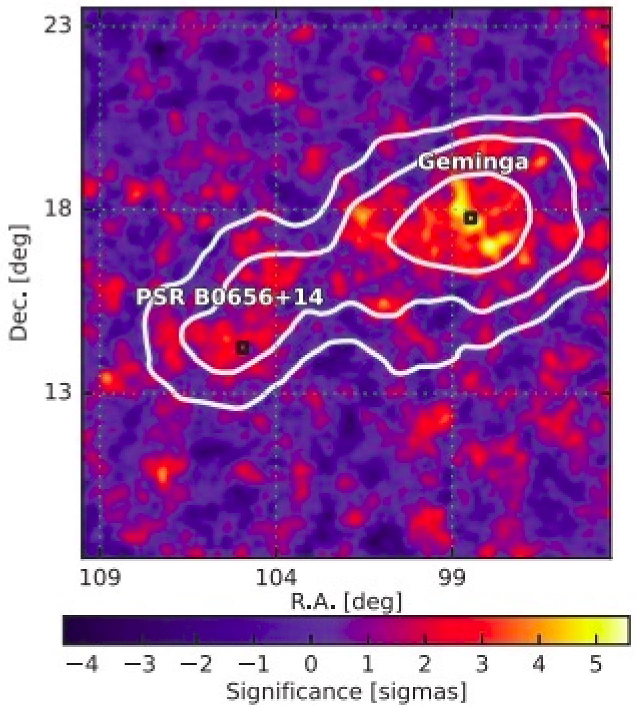
- measurements with NA61/SHINE will improve understanding of antideuteron production and modeling

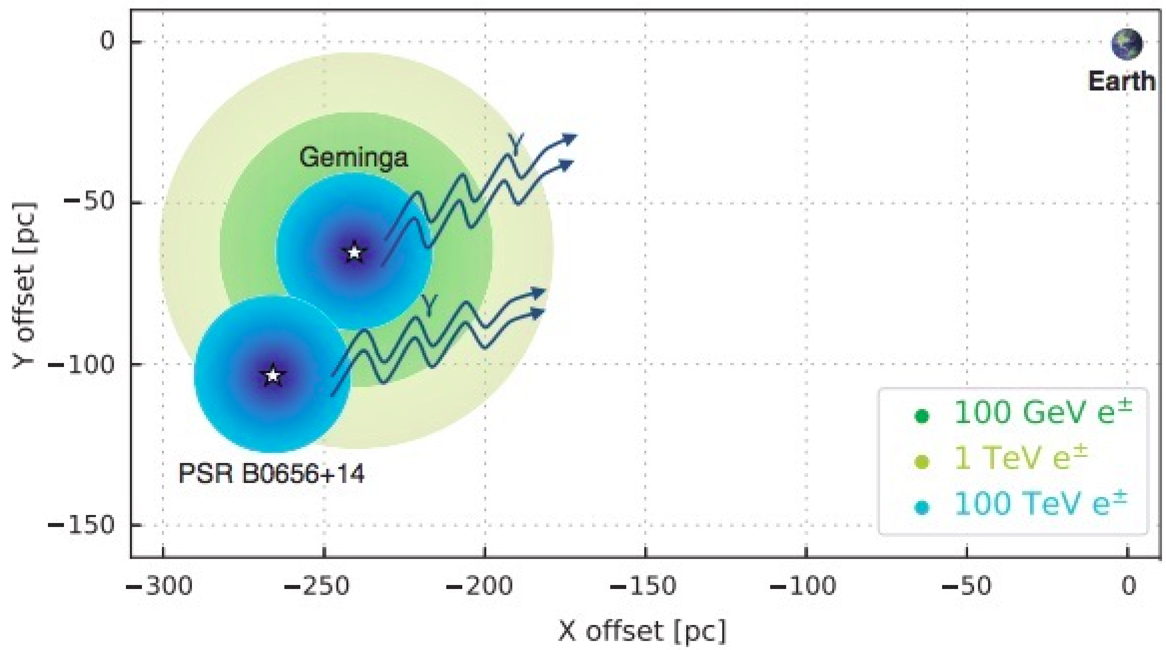
- measurement of antideuterons is a promising way for indirect dark matter search



Positrons from pulsars?

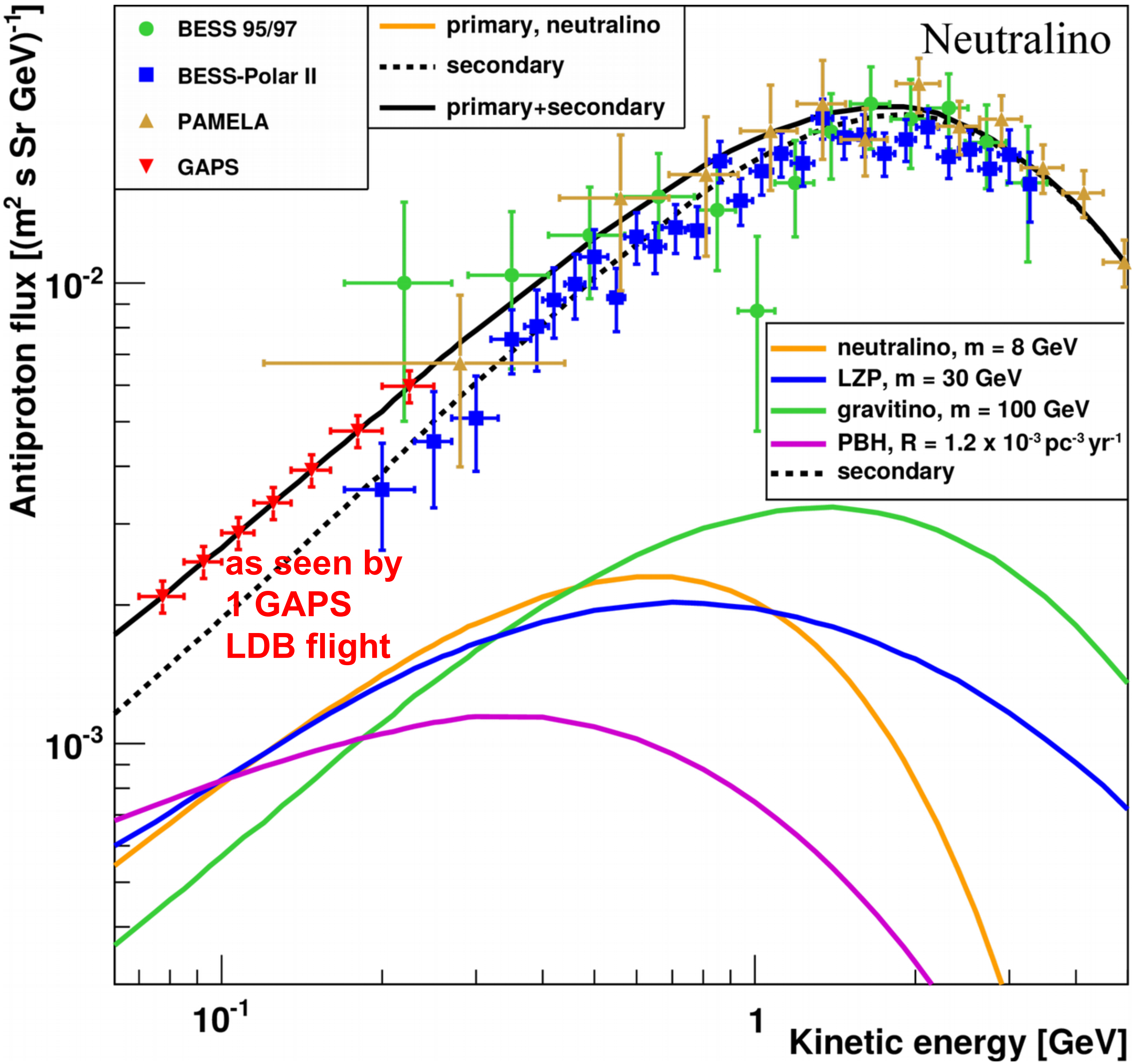
HAWC collaboration, Science 358 (6365), 911 (2017)





- 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.

GAPS low-energy antiproton



Predicted primary antiproton fluxes from:

- Neutralinos
- LZP
- Gravitinos
- primordial black holes