Cosmic-ray Antinuclei as Messengers of New Physics: Status and Outlook for the New Decade*

Physics Colloquium October 2020

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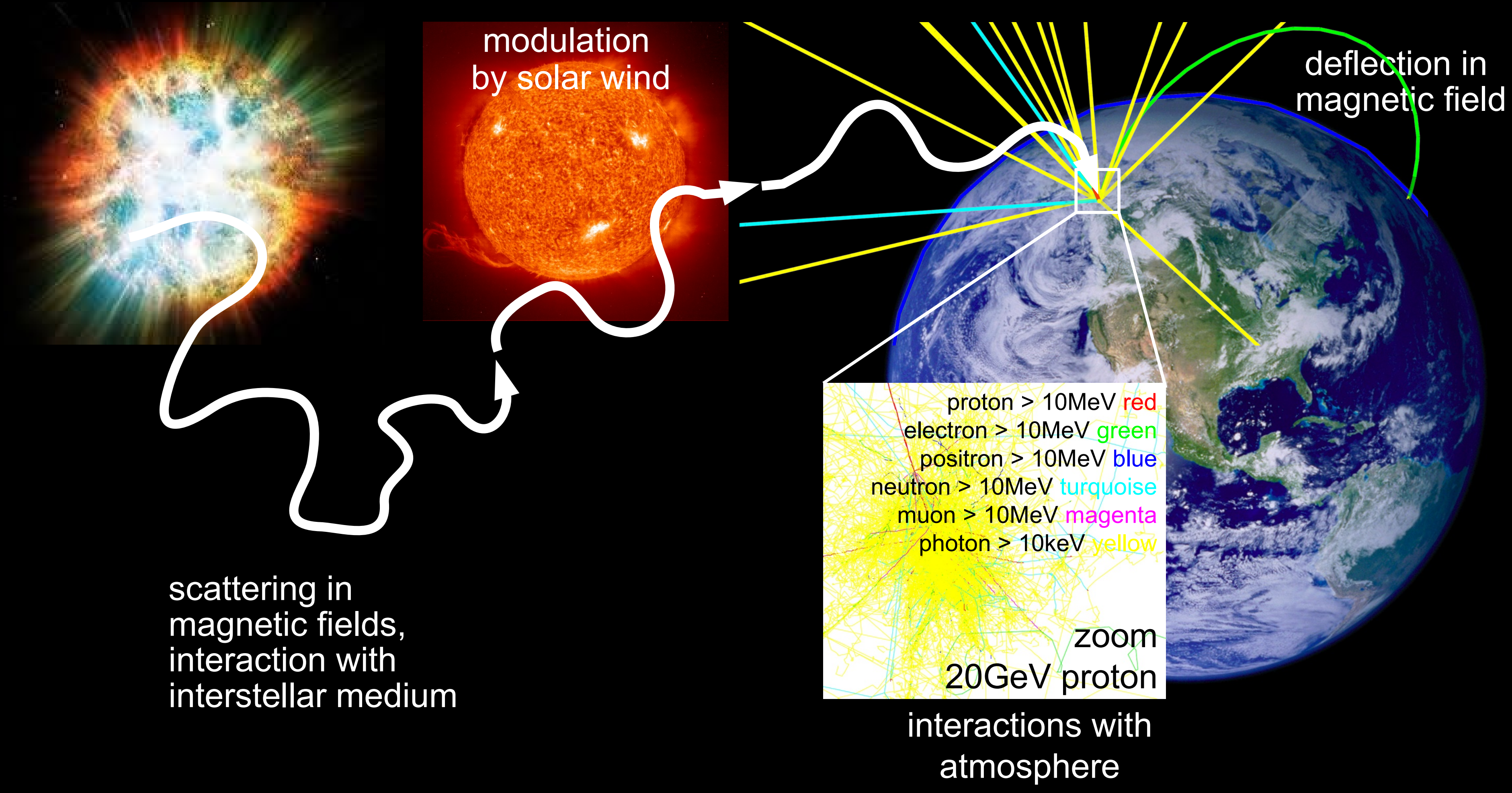
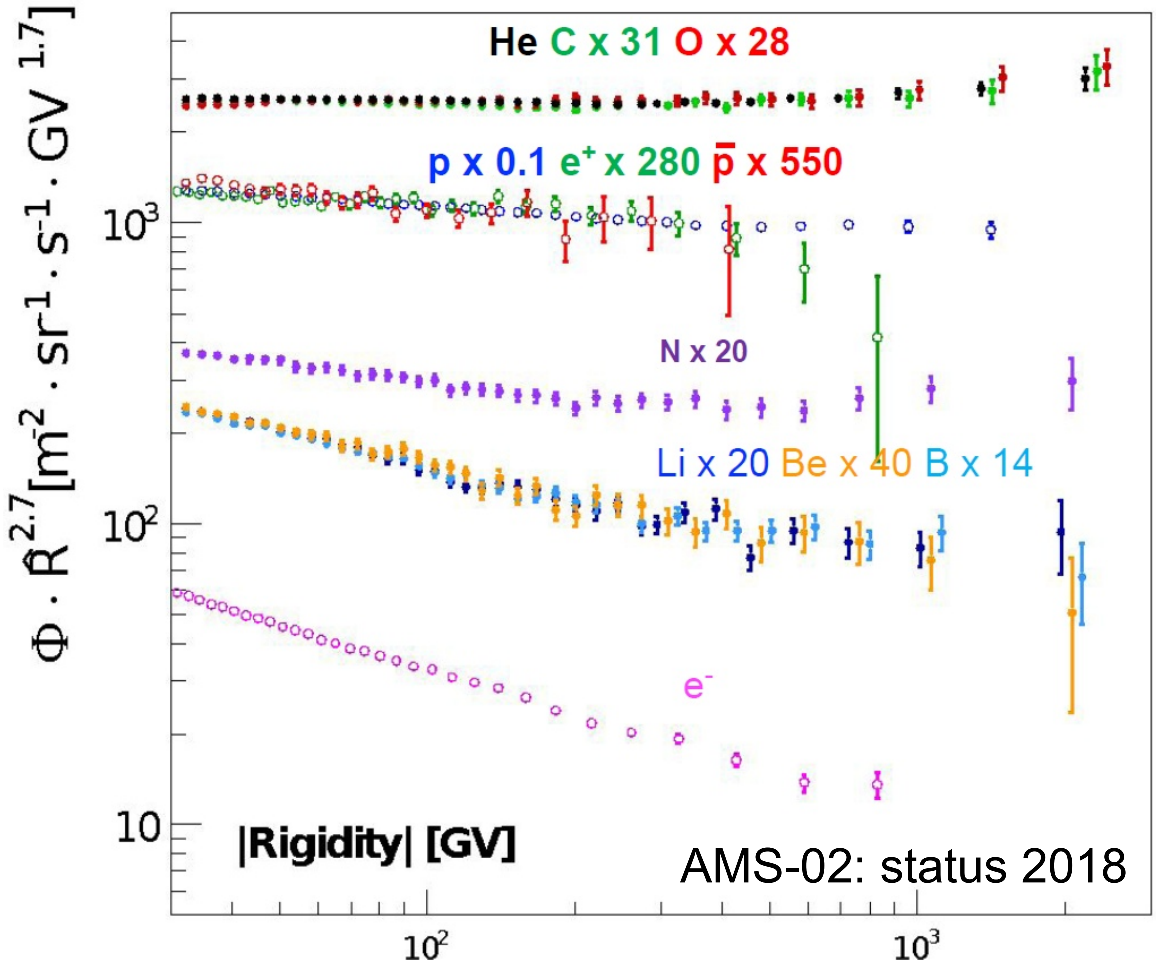
*JCAP08 035 (2020), arXiv:2002.04163

Cosmic rays as messengers



Snapshot of cosmic-ray status



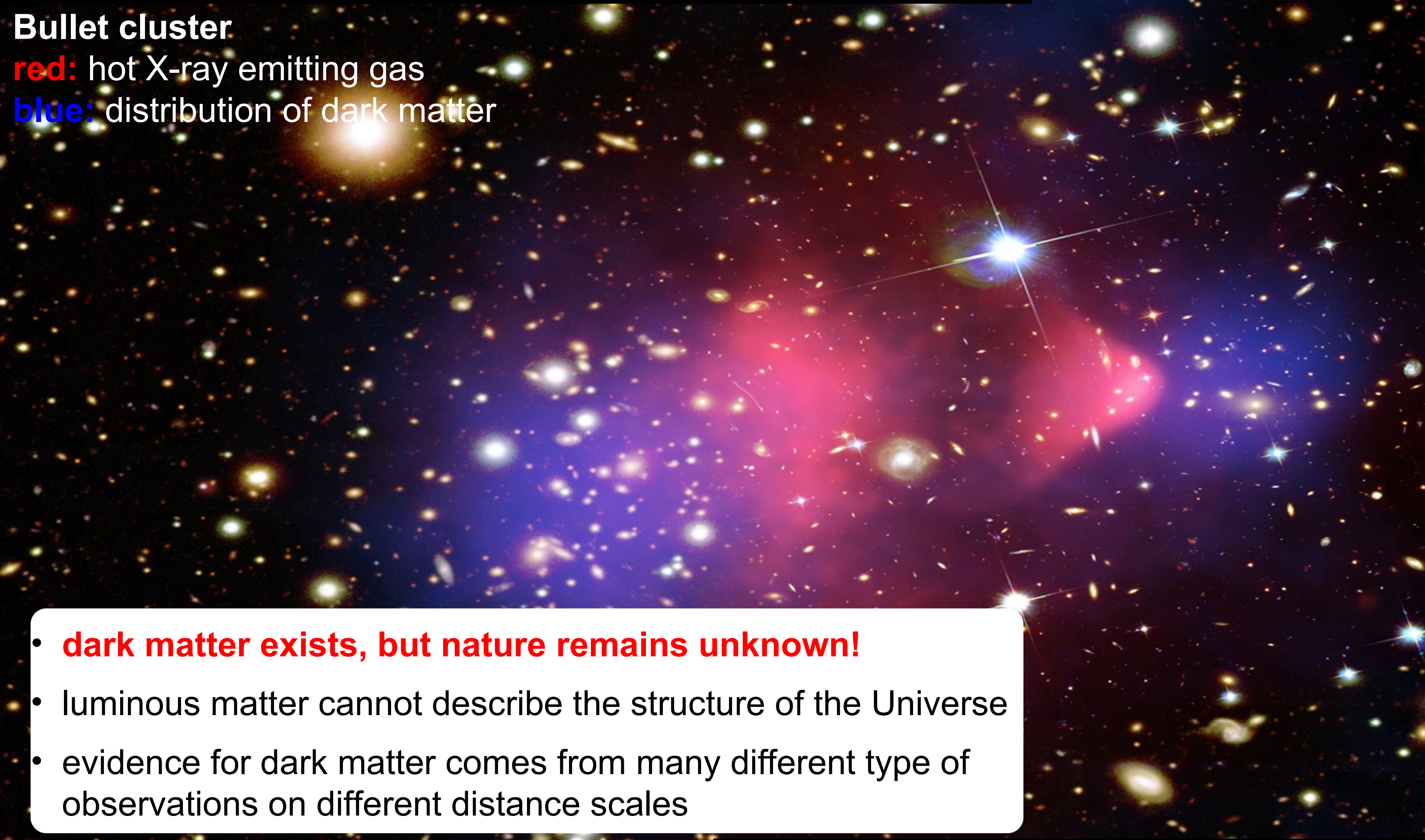
- **AMS-02 started new precision era of direct cosmic-ray measurements**
- Lots of interesting new findings for cosmic-ray physics concerning sources, acceleration, transport, interstellar medium
- Also available: helium isotopes, Neon, Magnesium, and Silicon
- Focus of this talk: **antinuclei**

Cosmic-ray antinuclei searches

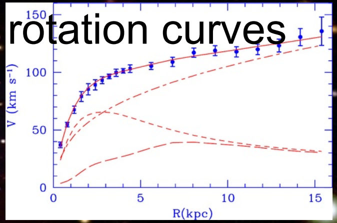
- This talk reviews some key results of the: **2nd Cosmic-ray Antideuteron Workshop** (UCLA, March 27-29, 2019, 45 participants) https://indico.phys.hawaii.edu/e/dbar19

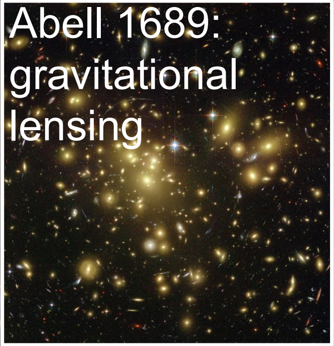
- Measurement of cosmic-ray antinuclei (antiproton, antideuteron, antihelium) is an exciting way to search for new physical phenomena:
  - potential primary sources of antinuclei
  - uncertainties of production and propagation in our Galaxy
  - experimental cosmic-ray search updates
  - path forward

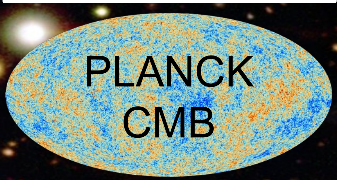
Existence of dark matter



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

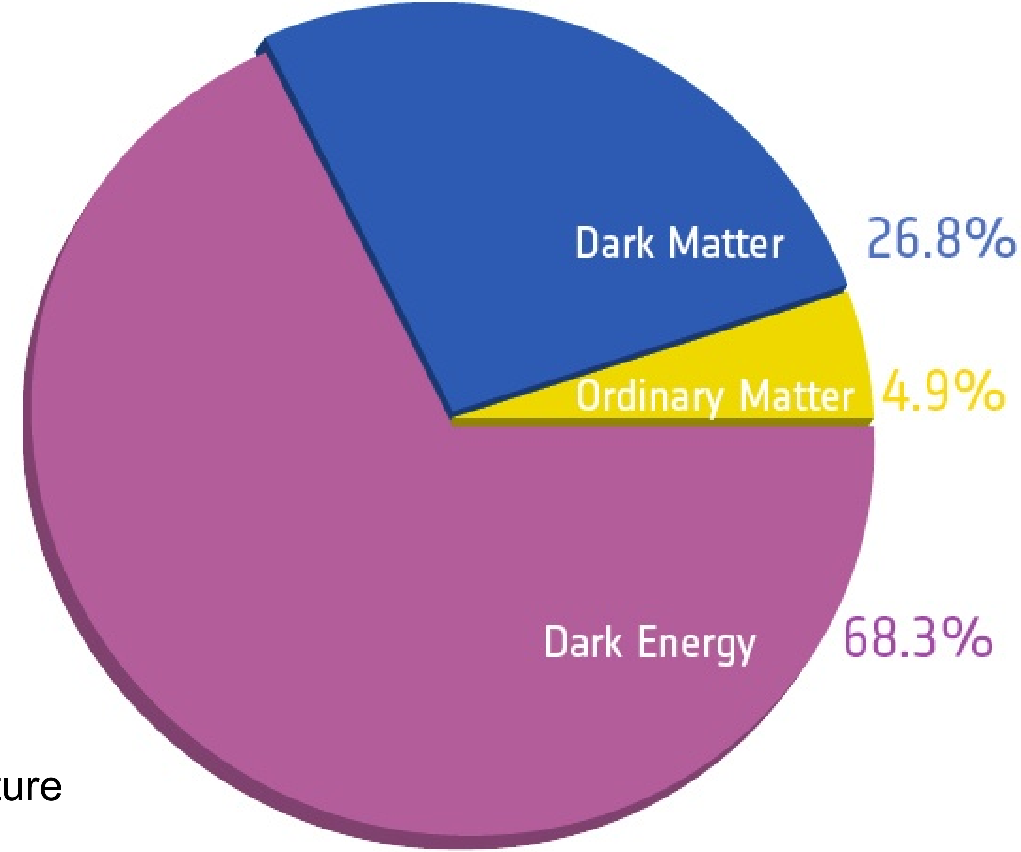






- **dark matter exists, but nature remains unknown!**
- luminous matter cannot describe the structure of the Universe
- evidence for dark matter comes from many different type of observations on different distance scales

Why do we need something new?

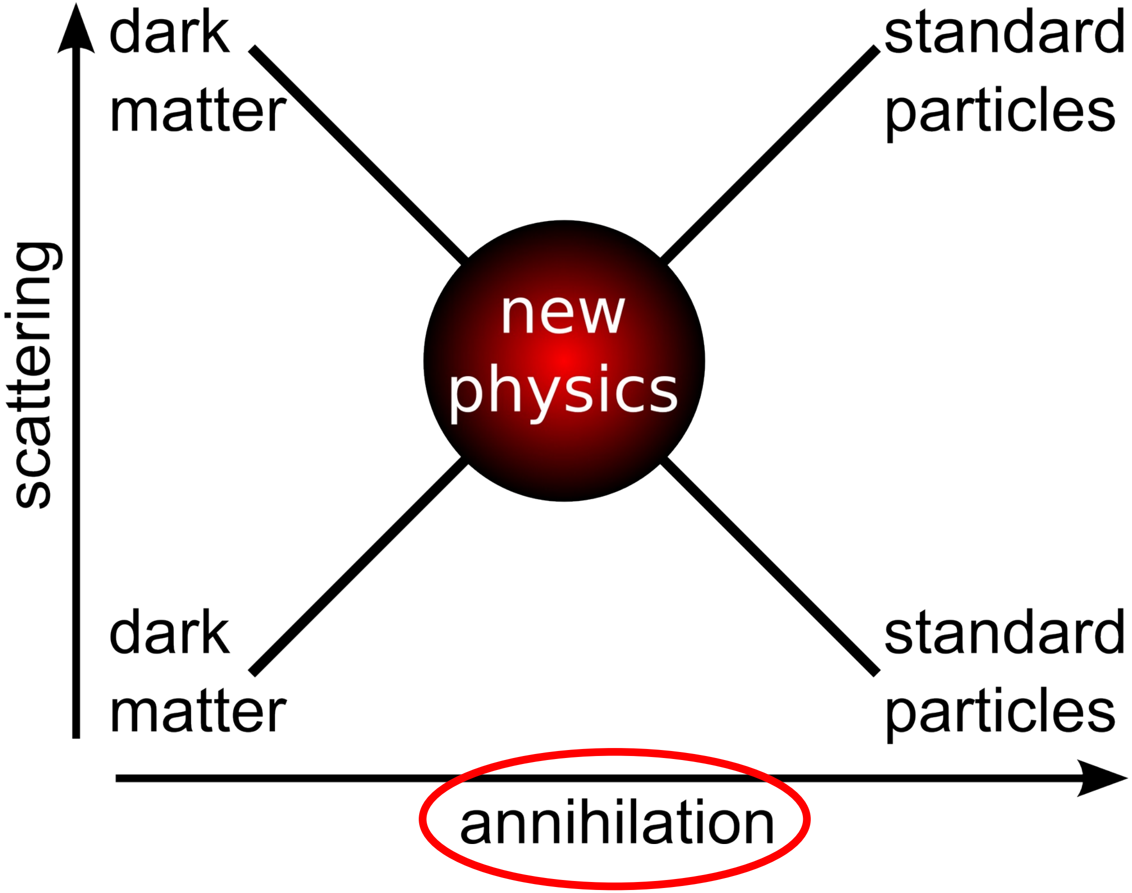


- dark matter is so far only gravitationally visible and must be a **new non-baryonic type of particle**
  - neutral
  - with relatively high mass to explain the structure formation of the universe
  - with only very weak interactions with standard particles (if at all)
- **discovering the nature of dark matter is one of the most striking problems in physics**

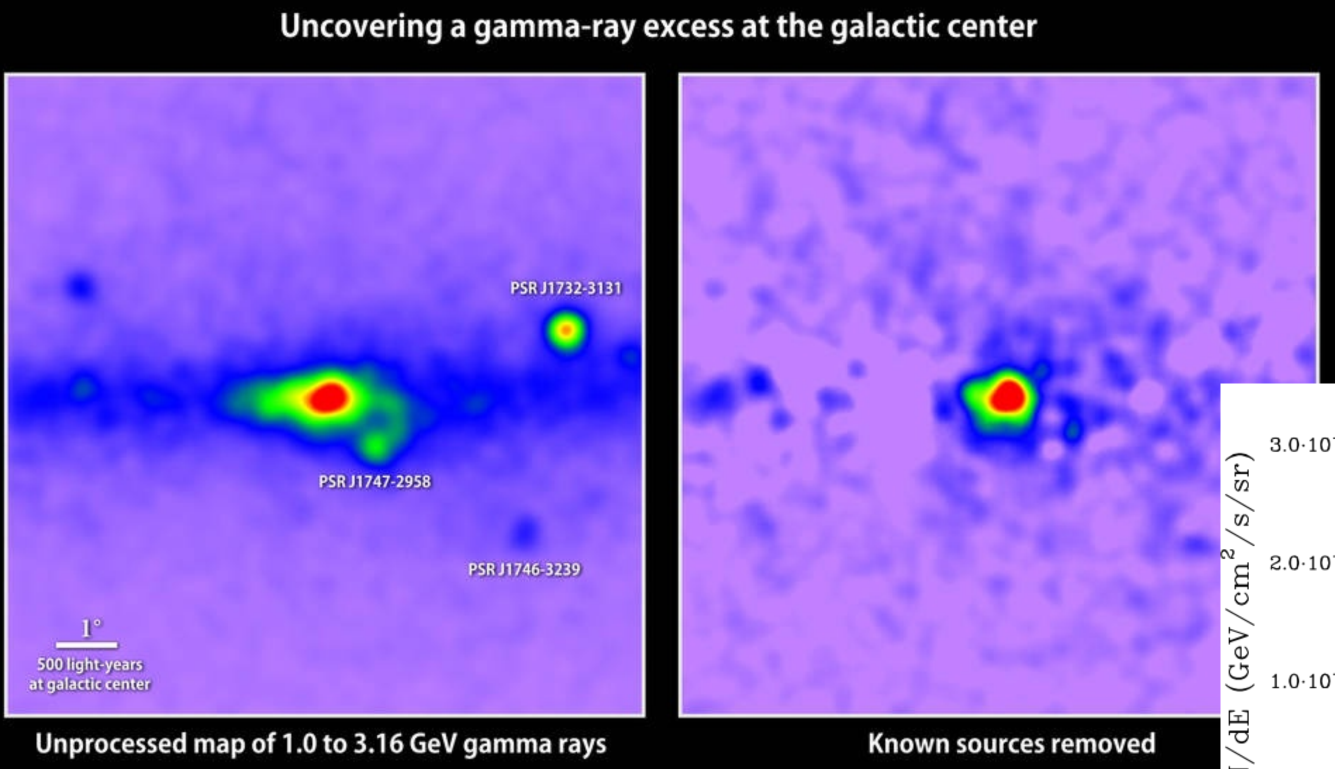
How is dark matter interacting?

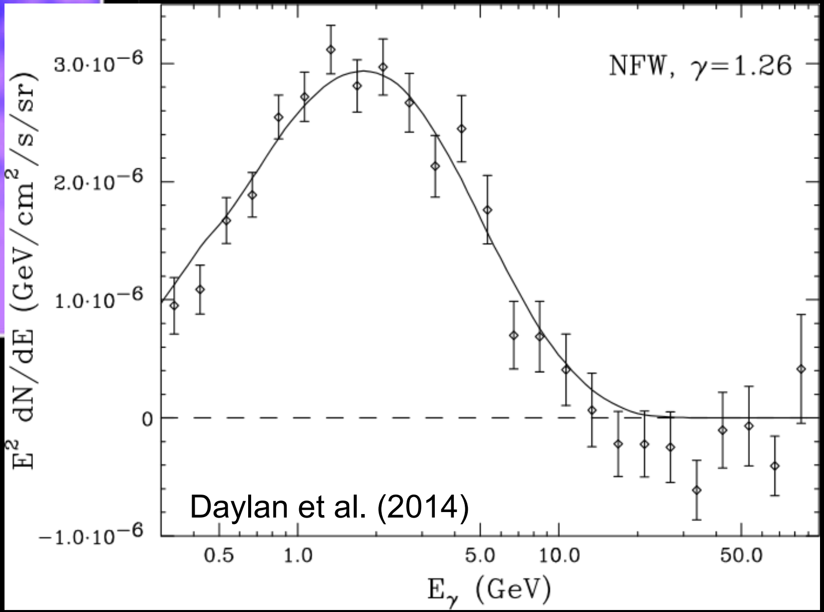
- **natural assumption:** dark matter was in thermal equilibrium in the early universe expansion led to dark matter freeze-out
- **WIMP miracle (?):** weak-scale particles are ideal candidates (~100-1000GeV) to reproduce observed relic dark matter density

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



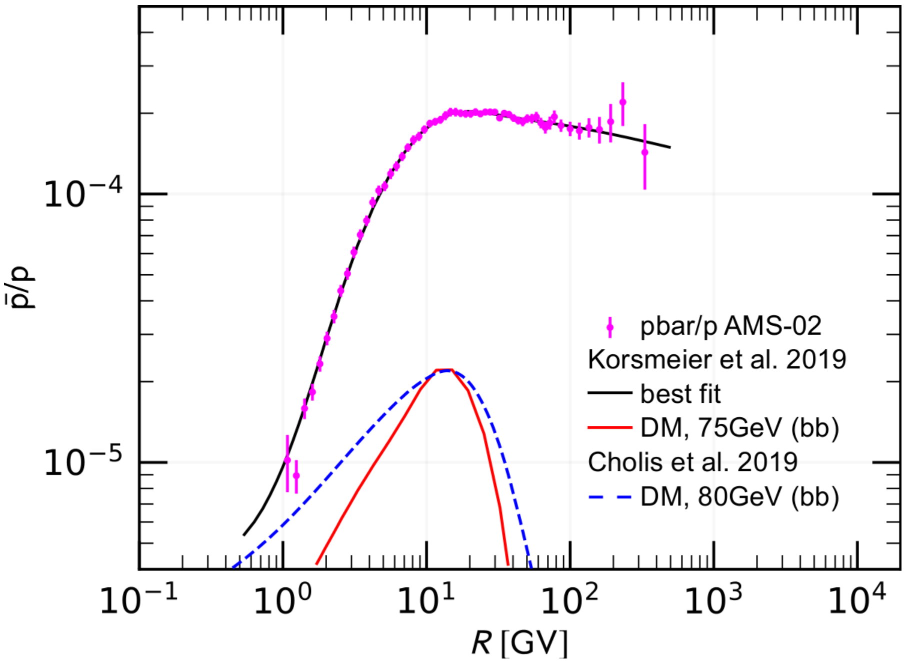
Diffuse Galactic γ-ray excess?

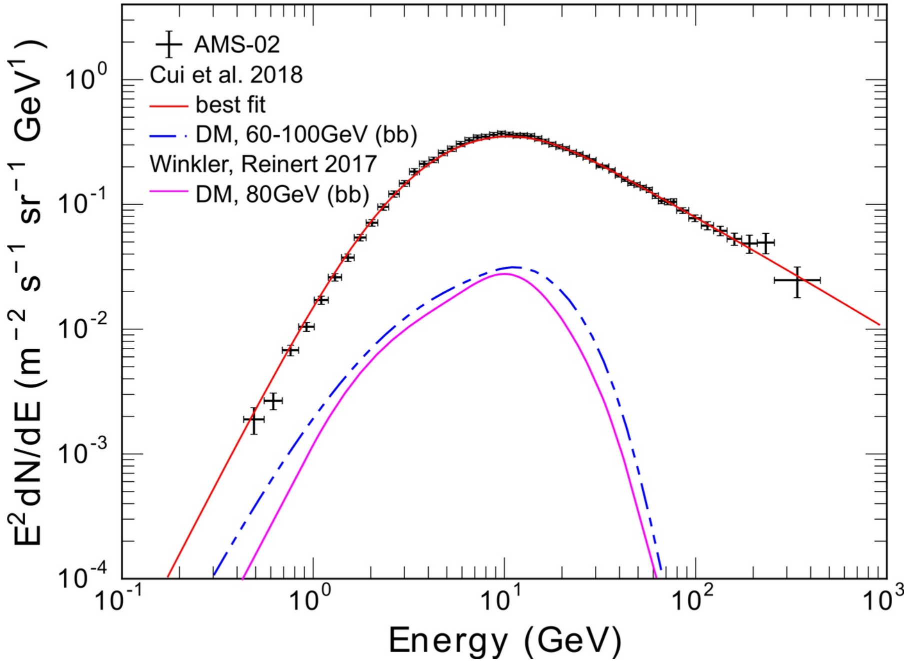




- gamma-ray excess at the galactic center → ~30GeV dark matter particle?
- unresolved millisecond pulsars?
- from pion production in molecular clouds
- tension with dwarf galaxies
- understanding of astrophysical background is a big challenge

Low-energy antiproton excess

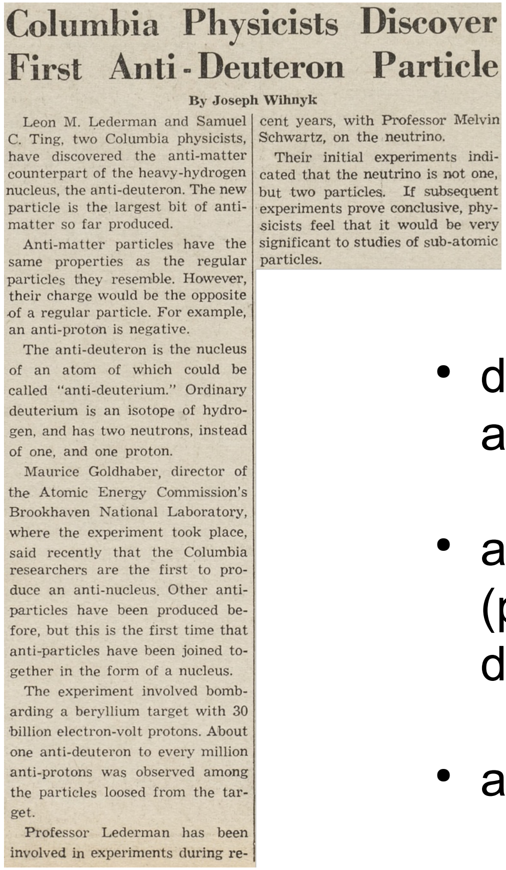




- A small $\bar{p}$ excess in AMS-02 data above secondary background predictions at R~10 GV was found in various studies → significance level unclear
- This excess is in agreement with explaining the γ-ray excess at the Galactic Center with a signal from dark matter annihilation
- **discussion is inconclusive → better constraints on cosmic-ray propagation and astrophysical production needed**

Antideuteron discovery


COLUMBIA DAILY SPECTATOR
FOUNDED 1877
Vol. CIX—No. 85 NEW YORK, N.Y., THURSDAY, MARCH 11, 1965 401 FIVE CENTS


Columbia Physicists Discover First Anti-Deuteron Particle

By Joseph Wihnyk

Leon M. Lederman and Samuel C. Ting, two Columbia physicists, have discovered the anti-matter counterpart of the heavy-hydrogen nucleus, the anti-deuteron. The new particle is the largest bit of anti-matter so far produced.

Anti-matter particles have the same properties as the regular particles they resemble. However, their charge would be the opposite of a regular particle. For example, an anti-proton is negative.

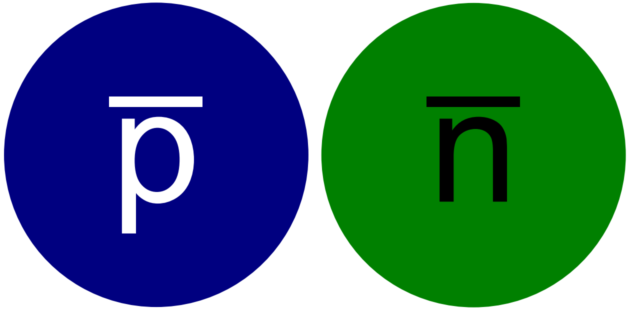
The anti-deuteron is the nucleus of an atom of which could be called "anti-deuterium." Ordinary deuterium is an isotope of hydrogen, and has two neutrons, instead of one, and one proton.

Maurice Goldhaber, director of the Atomic Energy Commission's Brookhaven National Laboratory, where the experiment took place, said recently that the Columbia researchers are the first to produce an anti-nucleus. Other anti-particles have been produced before, but this is the first time that anti-particles have been joined together in the form of a nucleus.

The experiment involved bombarding a beryllium target with 30 billion electron-volt protons. About one anti-deuteron to every million anti-protons was observed among the particles loosed from the target.

Professor Lederman has been involved in experiments during recent years, with Professor Melvin Schwartz, on the neutrino.

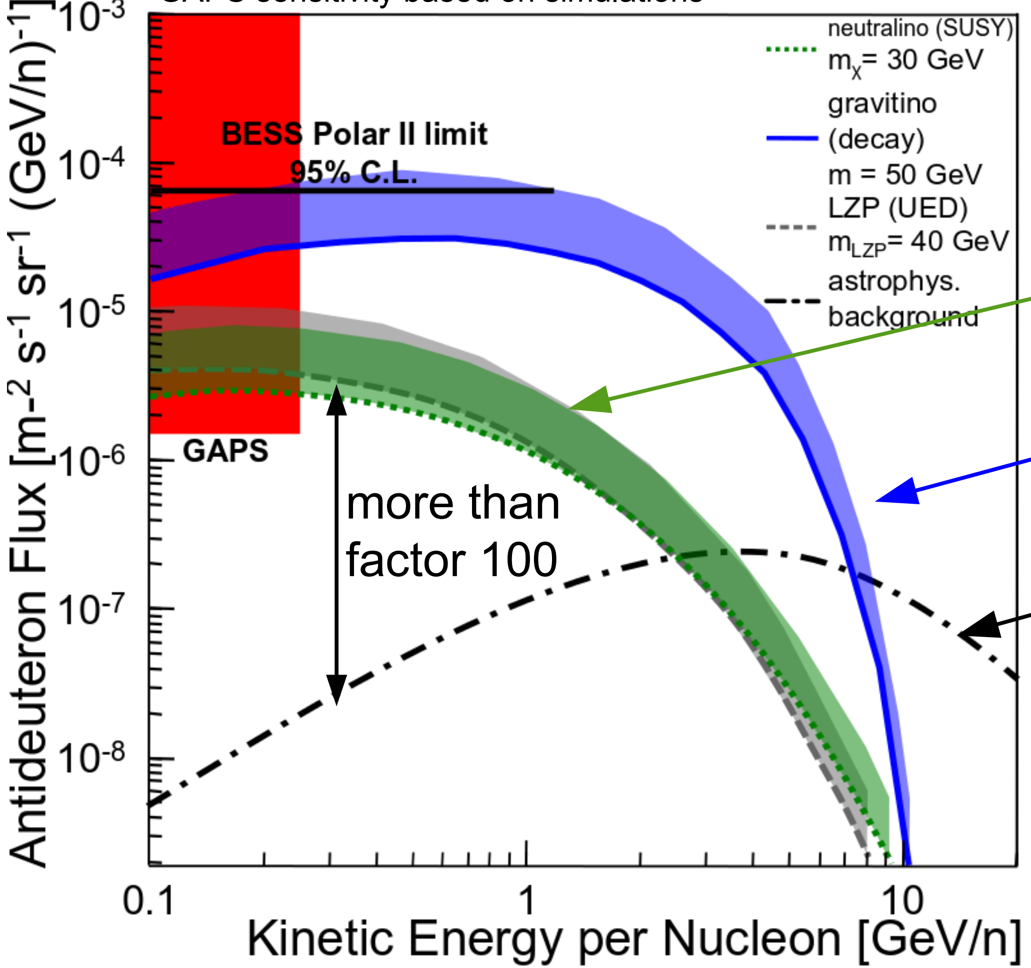
Their initial experiments indicated that the neutrino is not one, but two particles. If subsequent experiments prove conclusive, physicists feel that it would be very significant to studies of sub-atomic particles.



- deuterons are the nuclei of heavy water and antideuterons are the corresponding antimatter (Z=-1,m=1876MeV, s=1)
- antideuterons were discovered in 1965 at Brookhaven (p+Be) and CERN and were the first bound antimatter ever discovered
- antideuterons have not been detected in cosmic rays

Antideuterons as a probe of dark matter

GAPS sensitivity based on simulations



Examples for beyond-standard-model Physics (compatible with $\overline{p}$):

Neutralino:
SUSY lightest supersymmetric particle, decay into $b\overline{b}$
[Baer & Profumo, JCAP 0512, 008 (2005), Donato et al., Phys. Rev. D78, 043506 (2008)]

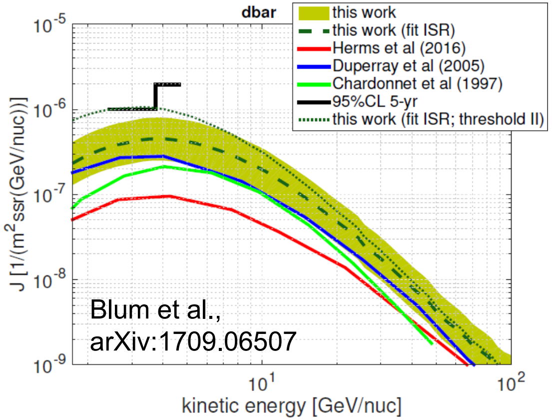
late decays of unstable gravitinos
[Dal & Raklev, Phys. Rev D89, 103504 (2014)]

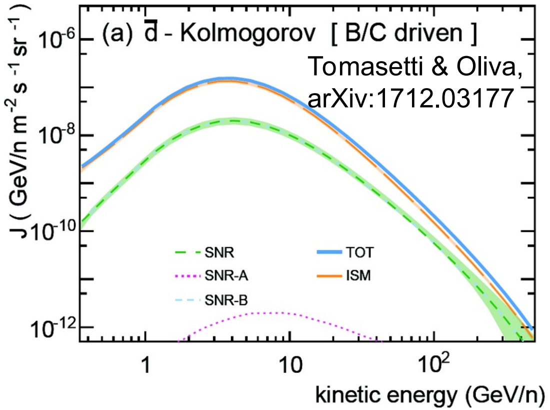
astrophysical background:
collisions of protons and antiprotons with interstellar medium
[Ibarra & Wild, Phys. Rev. D88, 023014 (2013)]

Antideuterons are an important unexplored indirect detection technique!

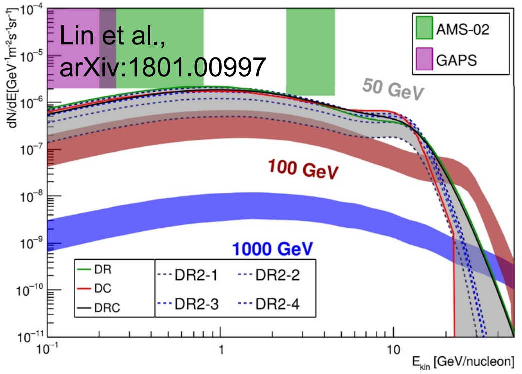
More antideuteron models

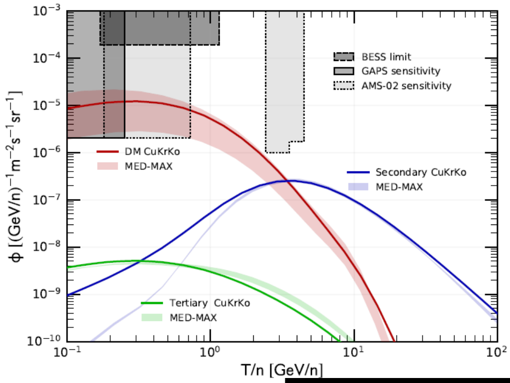
Astrophysical background only:



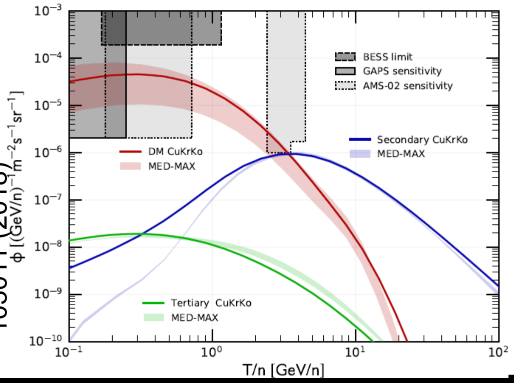


Dark matter annihilation:



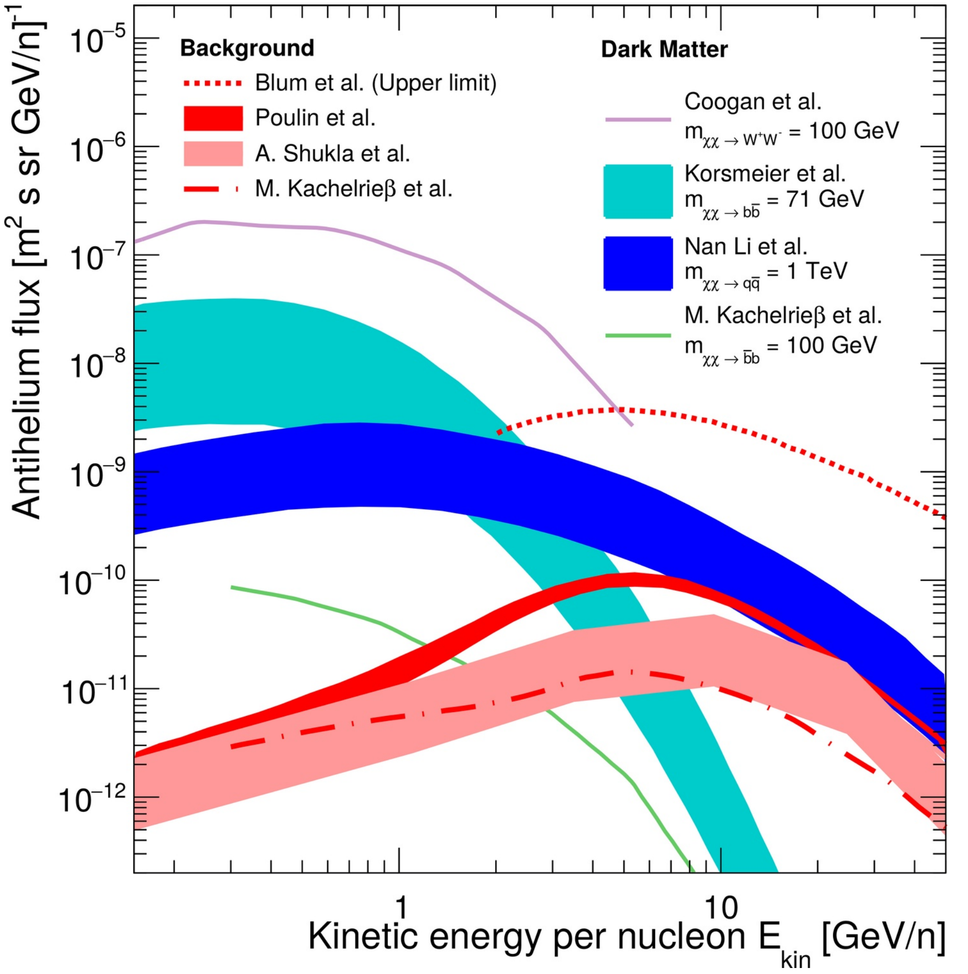


Korsmeier et al., Phys. Rev. D 97, 103011 (2018)



Cosmic-ray antihelium

- AMS-02 reported that **several $\overline{\text{He}}$ candidate events have been observed**
  → interpretations are actively ongoing
- Antiproton and antihelium both constrain antideuterons
  → no explanation of antihelium should overproduce antiprotons and antideuterons
- **Possible antihelium candidate explanations include:**
  - Secondary astrophysical background
  - Dark matter annihilation or decay
  - Nearby antistar: at distance of ~1pc
- **Search for antinuclei with independent experimental techniques is critical**

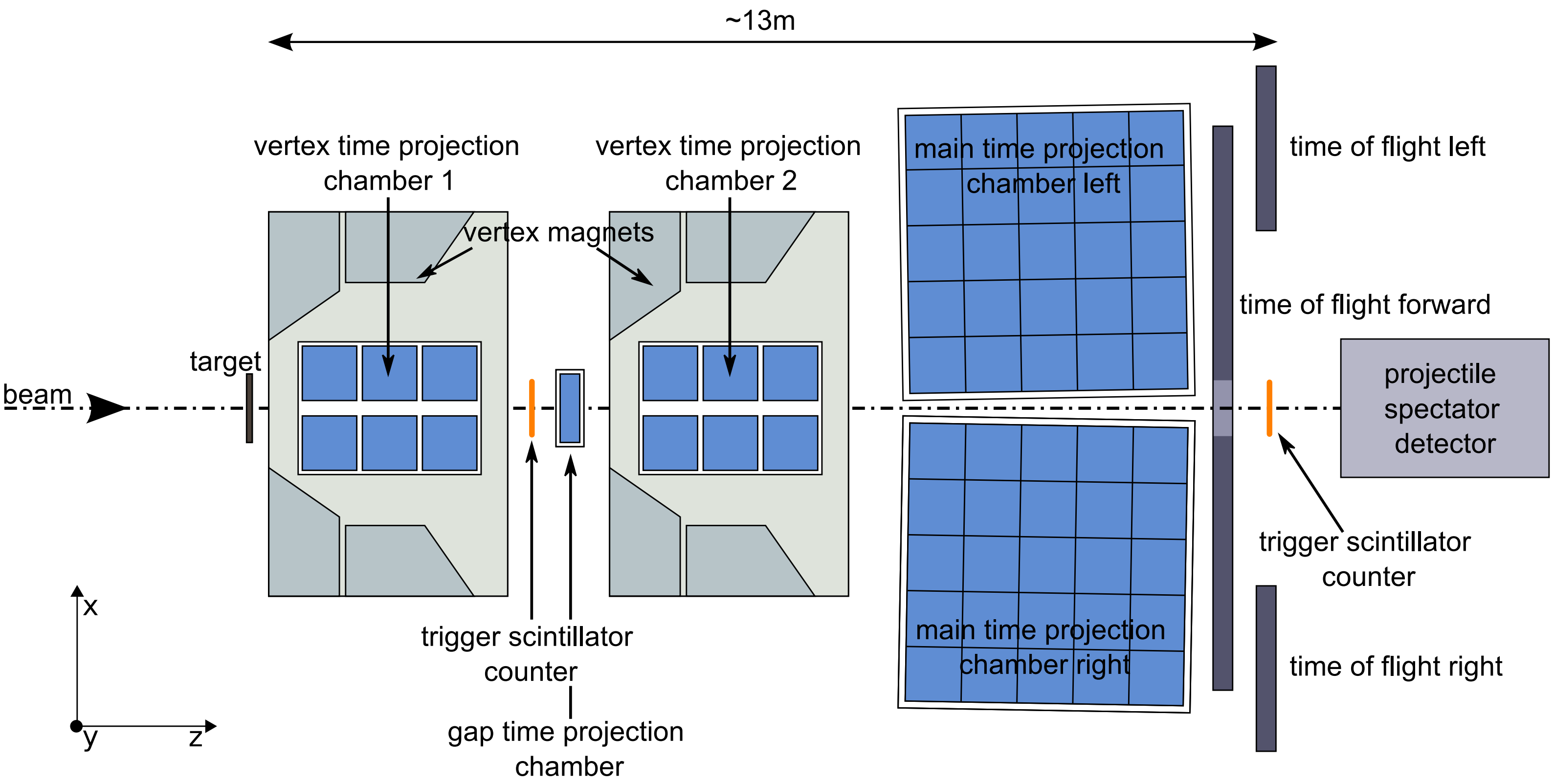


Uncertainties

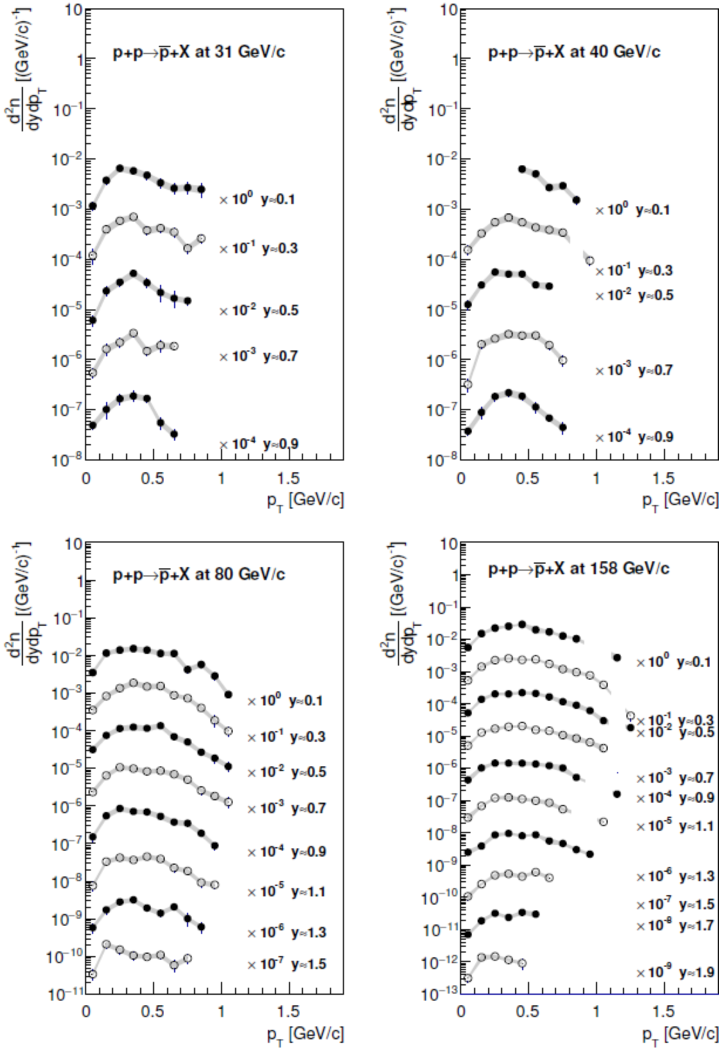
- **Cosmic-ray propagation**:
  - Important constraint for antinuclei flux from dark matter annihilations is the Galactic halo size, which directly scales the observable flux
  - Fits of cosmic-ray nuclei data are very important to constrain cosmic-ray propagation models (e.g., Li/C, Li/O, Be/C, Be/O, B/C, B/O)
- **Antinuclei formation** process breaks the degeneracy of antinuclei with antiprotons
  - Coalescence: $\bar{d}$ can be formed by an $\bar{p}$-$\bar{n}$ pair if relative momentum is small compared to coalescence momentum p_0
  - Thermal model: Antinuclei directly formed at hadronization stage
- **Measurements of relevant primary cosmic ray and interstellar medium cross sections are important**

NA61/SHINE at CERN

- multi-purpose, fixed-target experiment at the CERN SPS
- Most relevant momentum range for cosmic rays: 40-400GeV/c matches nicely SPS energies
- data under discussion from the NA61/SHINE strong interactions program:
  - p+LH data taken at 13, 20, 31, 40, 80, 158, 400GeV/c



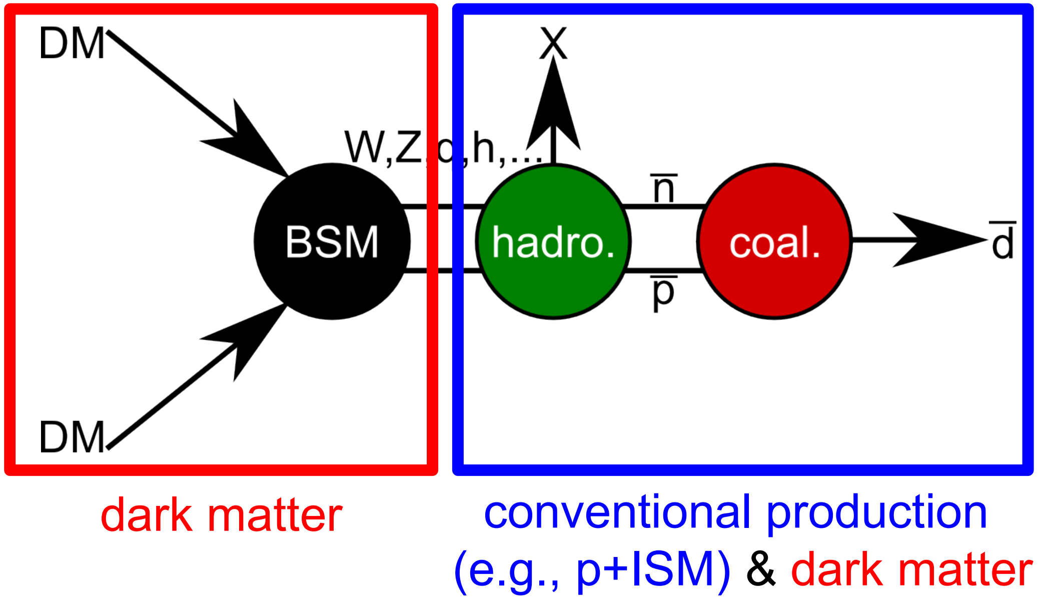
Antiproton yields

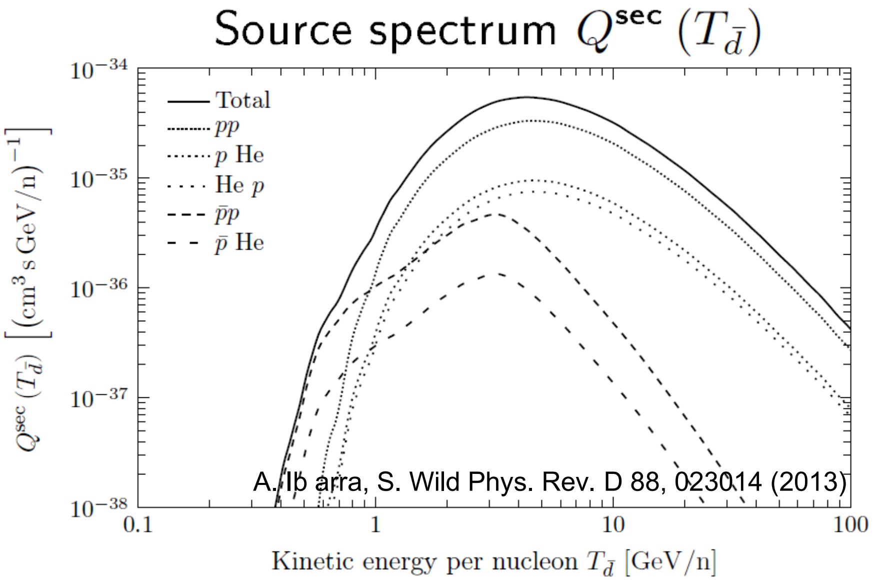


Eur. Phys. J. C77 10, 671 (2017)

- results based on 2009 p-p runs
- 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
- analysis for large 158GeV/c and 400GeV/c p-p data sets ongoing (UH CRA: A. Shukla)

(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

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

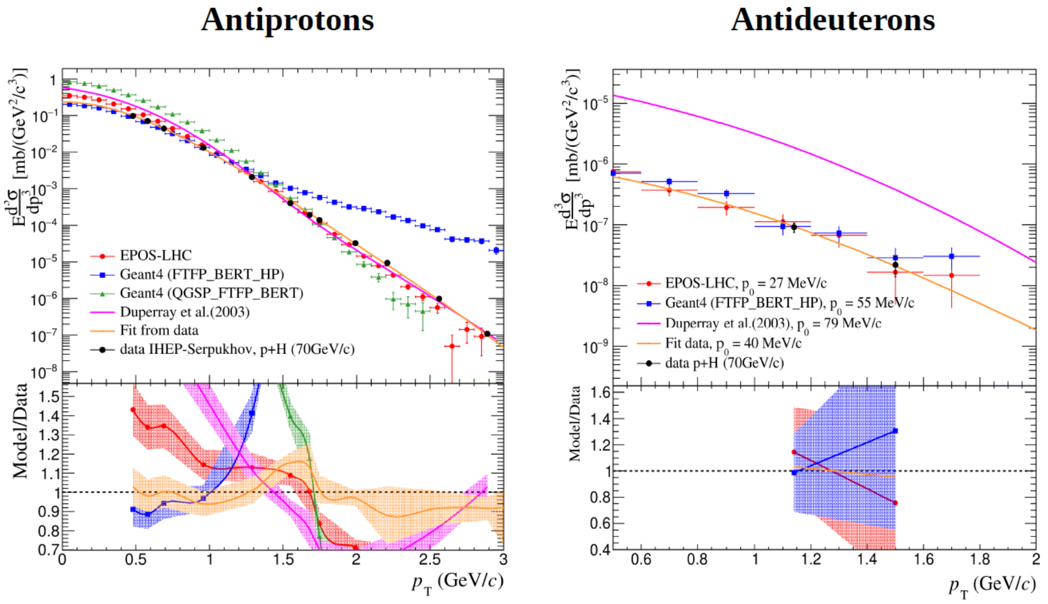
- use an event-by-event coalescence approach with hadronic generators

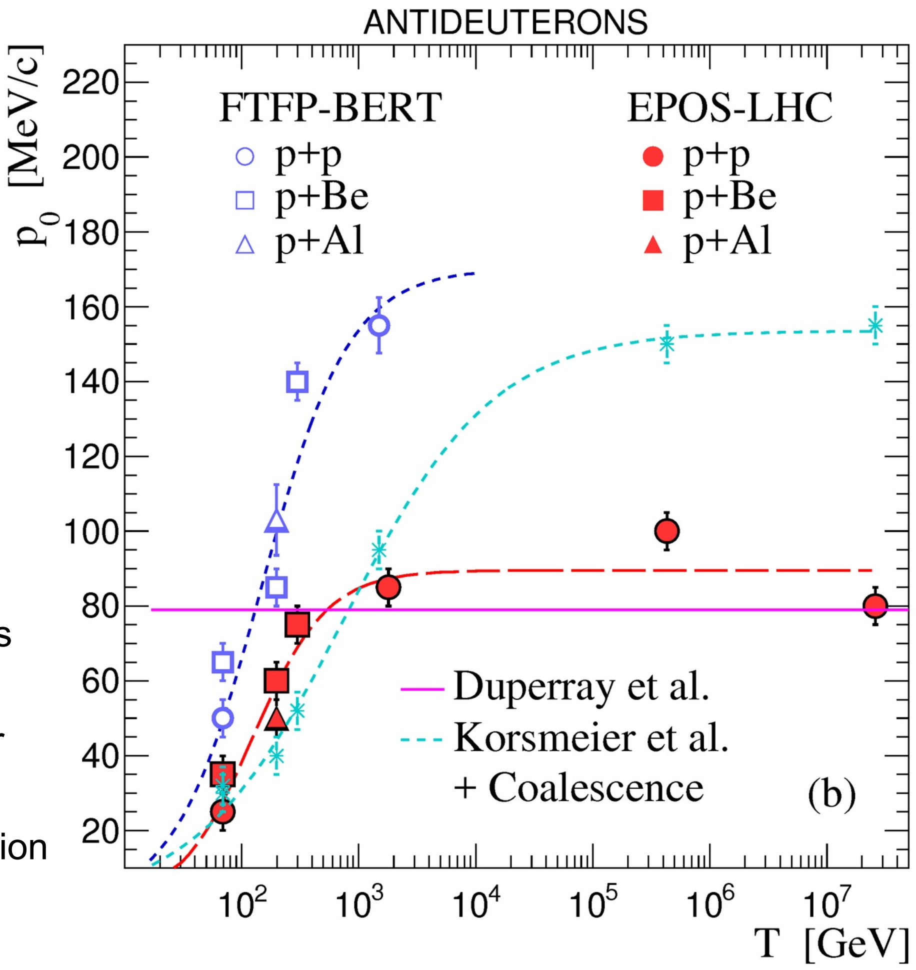
Issues of the coalescence model

- **phase space** for ion production depends on the available energy in the formation interaction
- highly sensitive to **two-particle correlations** between the participating (anti)nucleons
- (anti)neutron spectra are very challenging to access, potential asymmetries should be evaluated
- hadronic generators failing to describe (anti)proton and (anti)neutron spectra automatically result in a shift of p_0
- **spin** is not considered
- generators not really tuned for antiparticle production
  → use dedicated antiproton, deuteron, and antideuteron data

Coalescence modelling

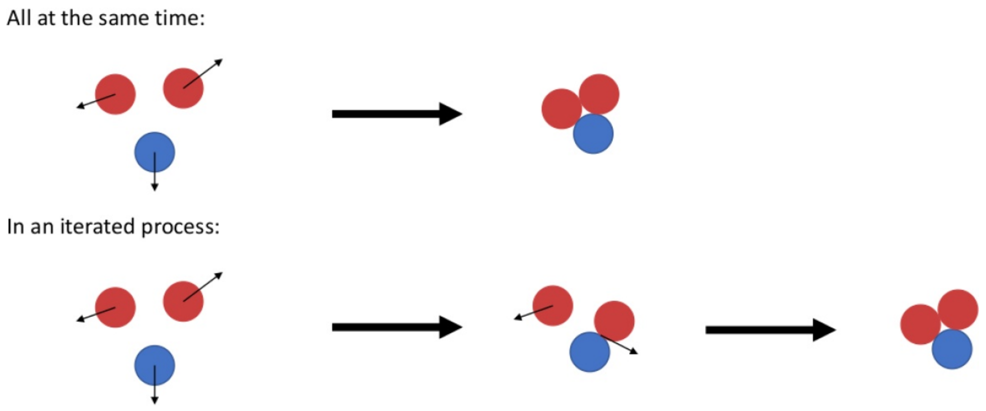
D. Gomez-Coral et al. 2018



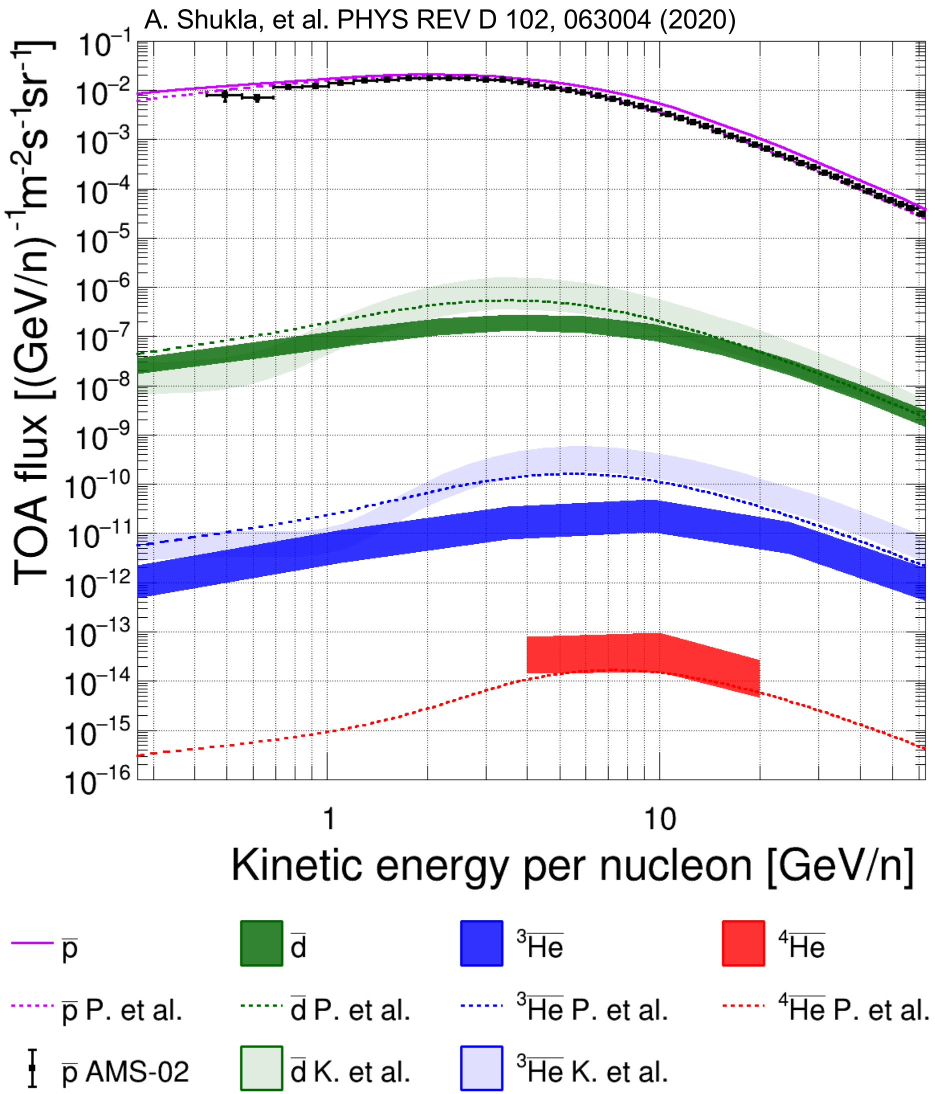


- find p_0 for each data set where antiproton and antideuteron results exist
- p_0 show strong energy depedence in the range most important for cosmic rays
- Other models exist: thermal model, quantum-mechanical description
- **more high statistics data needed to constrain antinuclei formation models**

Antihelium coalescence

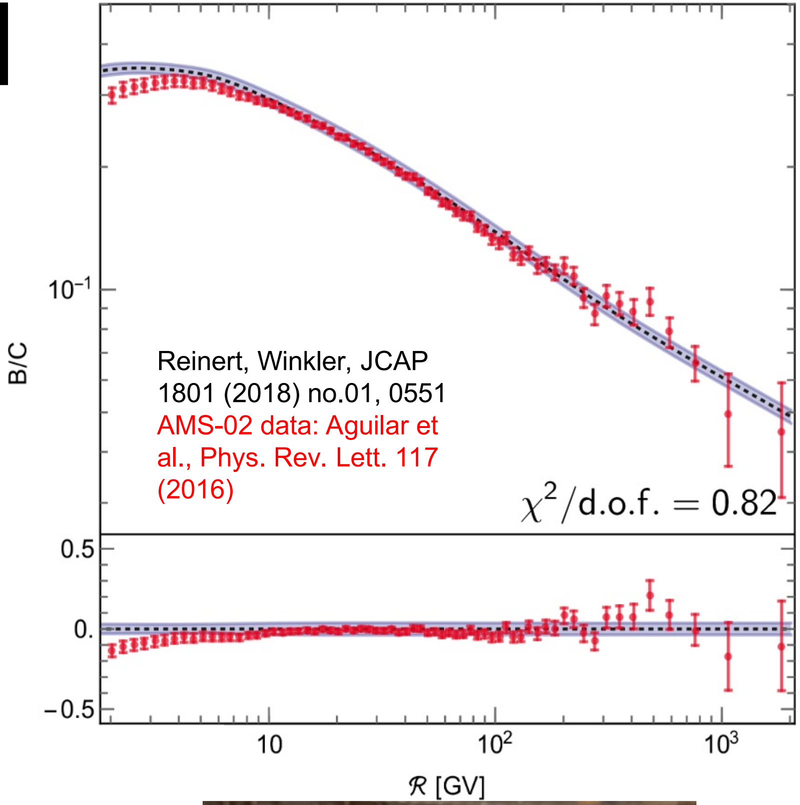


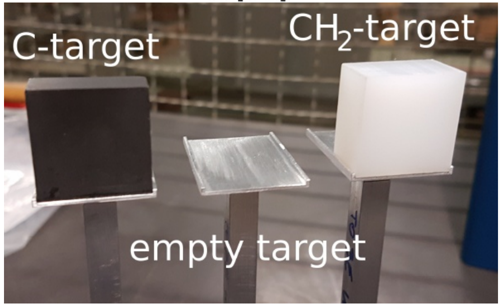
- expanded modified MC coalescence model to merging multiple antinucleons from p-p interactions
  → requires quite a bit of computing power (~**5,000 years** so far, every additional antinucleon is about a factor of 1,000 suppressed → thanks UH HPC, OSG)
- use the p_0 behavior from antideuterons
- Very good agreement with ALICE antihelium-3 data (p-p at $\sqrt{s}$=7TeV)



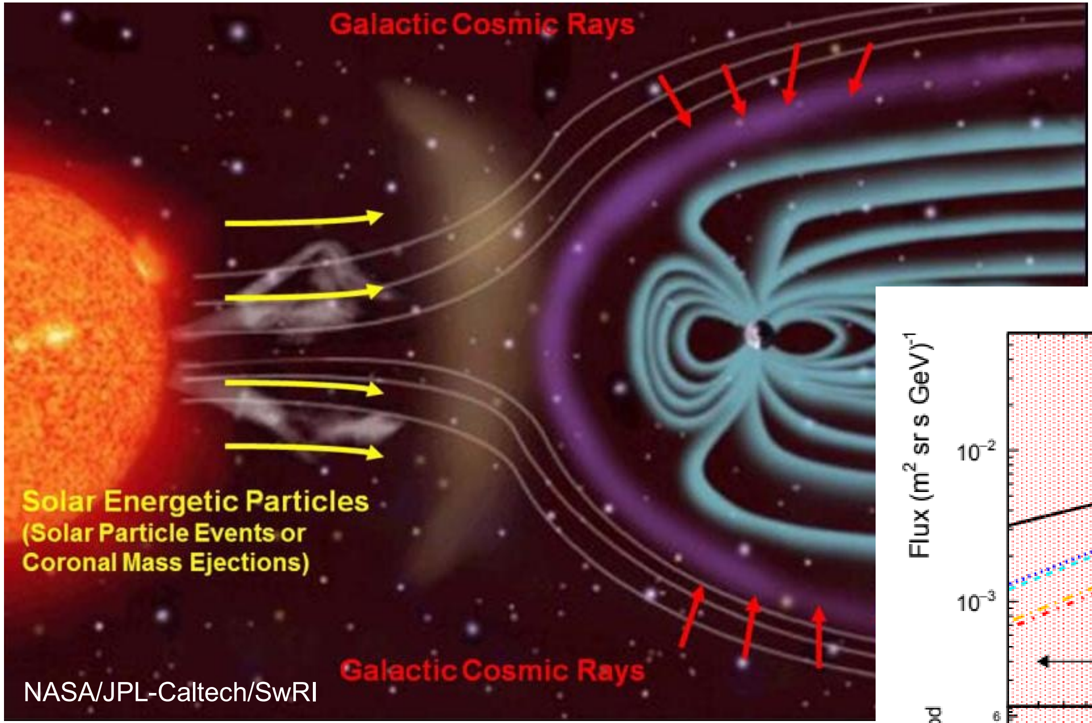
Propagation uncertainties

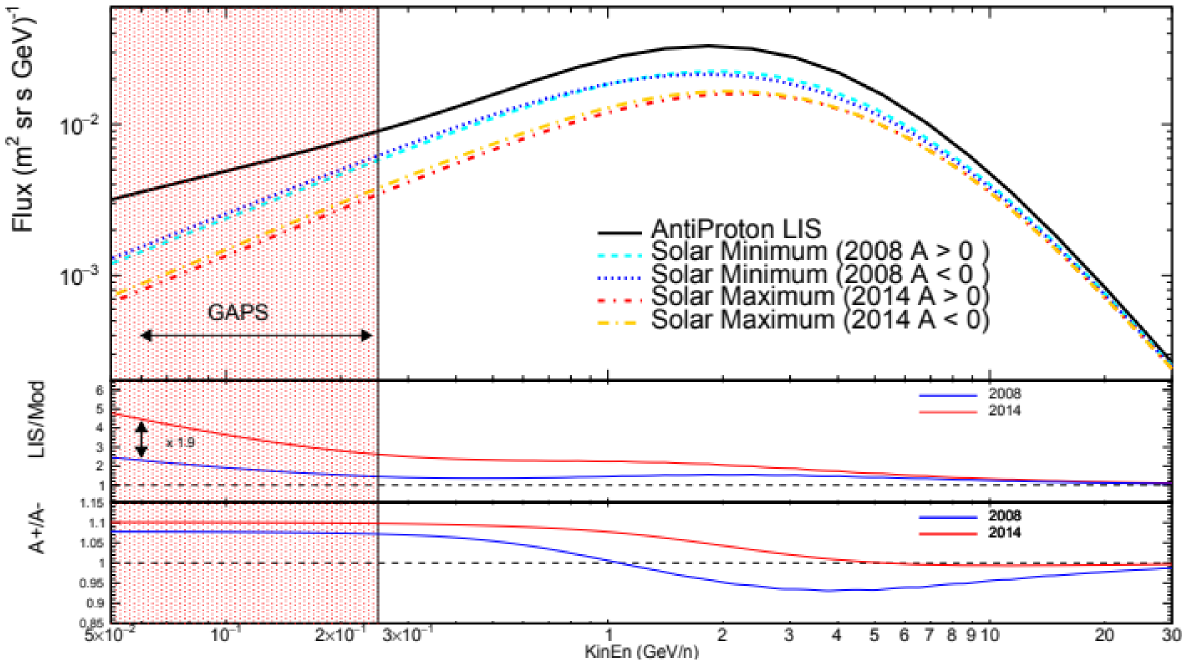
- An important constraint for antinuclei flux from dark matter annihilations is the Galactic halo size, which directly scales the observable flux
- amount of particle production in the Galaxy depends on the integrated traversed matter density → ratio of secondary-to-primary cosmic rays, e.g., Boron/Carbon or Deuteron/Helium
- Need to know fragmentation cross sections from laboratory measurements→ **limitation:** cross sections are currently only known on the 10-20% level
- NA61/SHINE pilot run for C-p cross section in Dec 2018 (3 days) (Subtract C-C from C-CH_2 to get C-H)





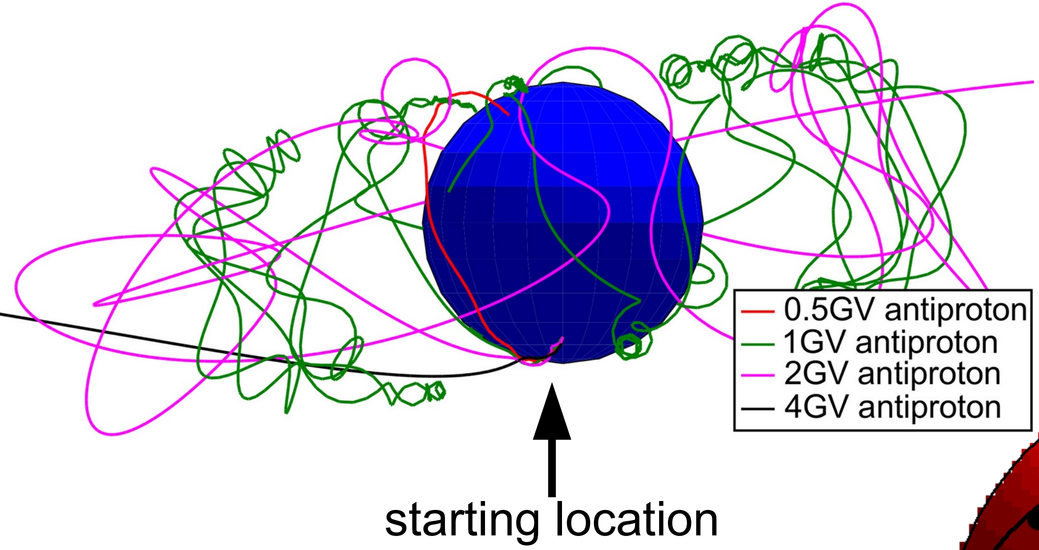
Solar modulation

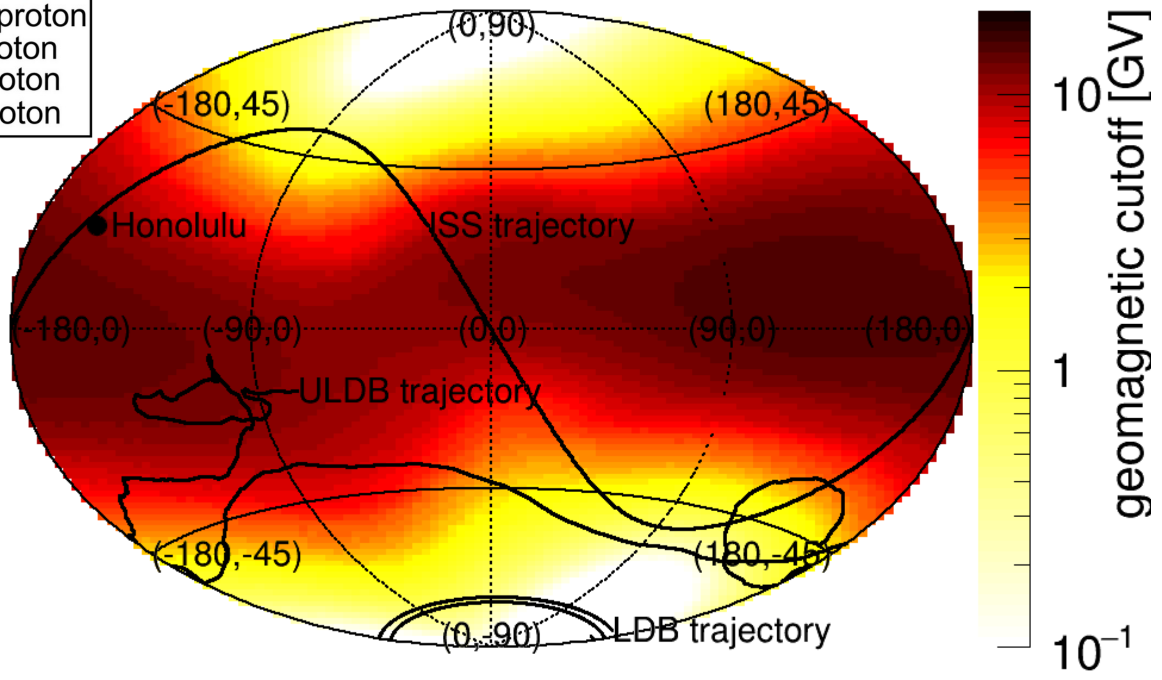




Geomagnetic Effects

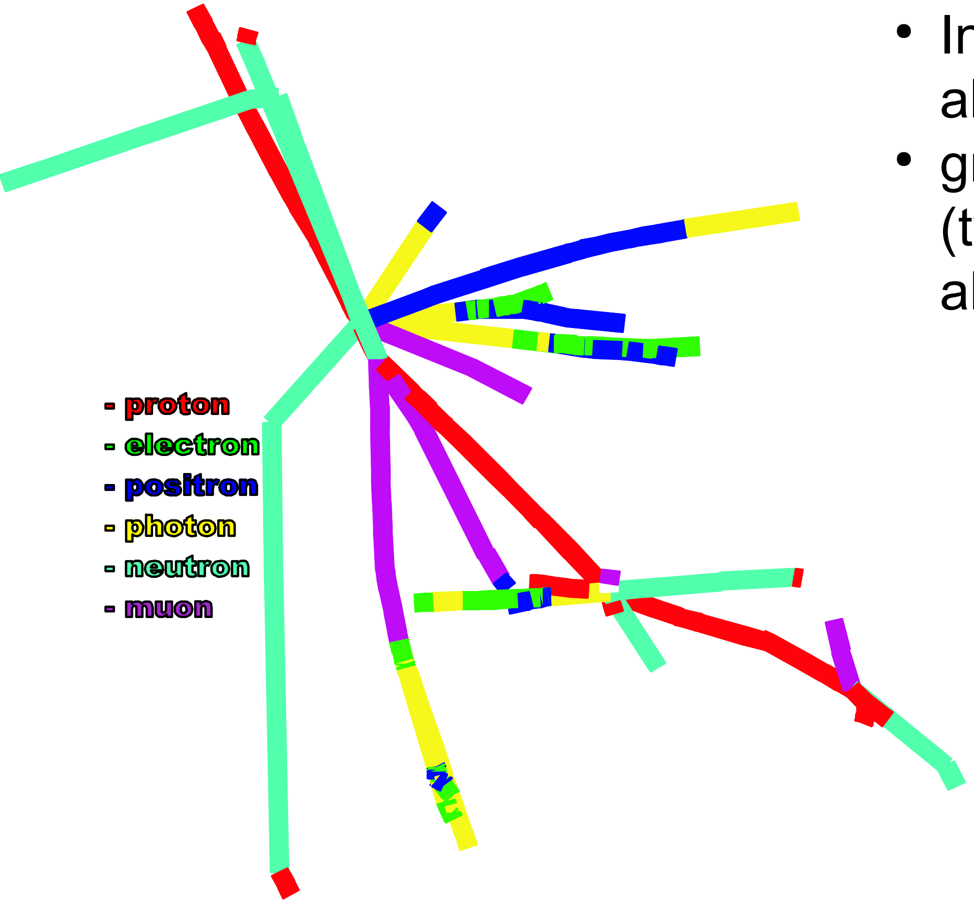
PvD, Yamashiro, PoS(ICRC2017)151 (2017)



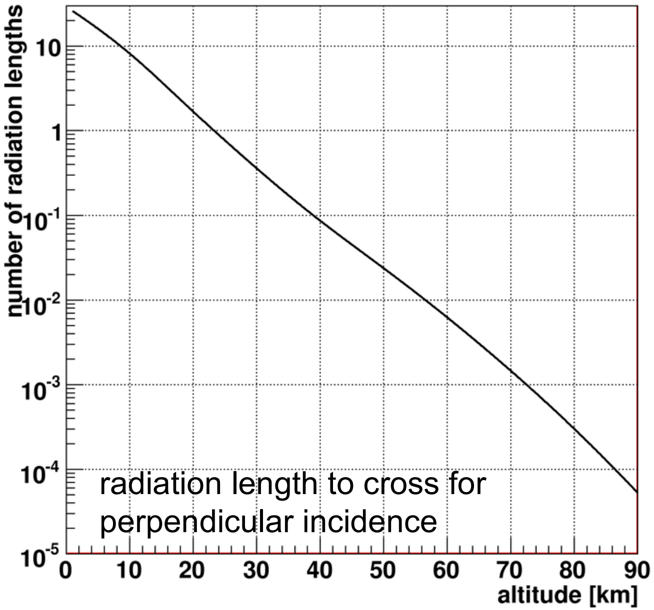


- Charged low-energy particles can be strongly adeflected by the magnetosphere
- reverse computation of cosmic-ray trajectories to investigate which particles can make it through to the detector

Atmospheric interaction



- Interactions of cosmic rays with the atmosphere alter the detectable flux
- grammage of matter in front of 37km: ~6g/cm^2 (typical balloon altitude, cosmic ray traverse about 6-10g/cm^2 in the Galaxy)



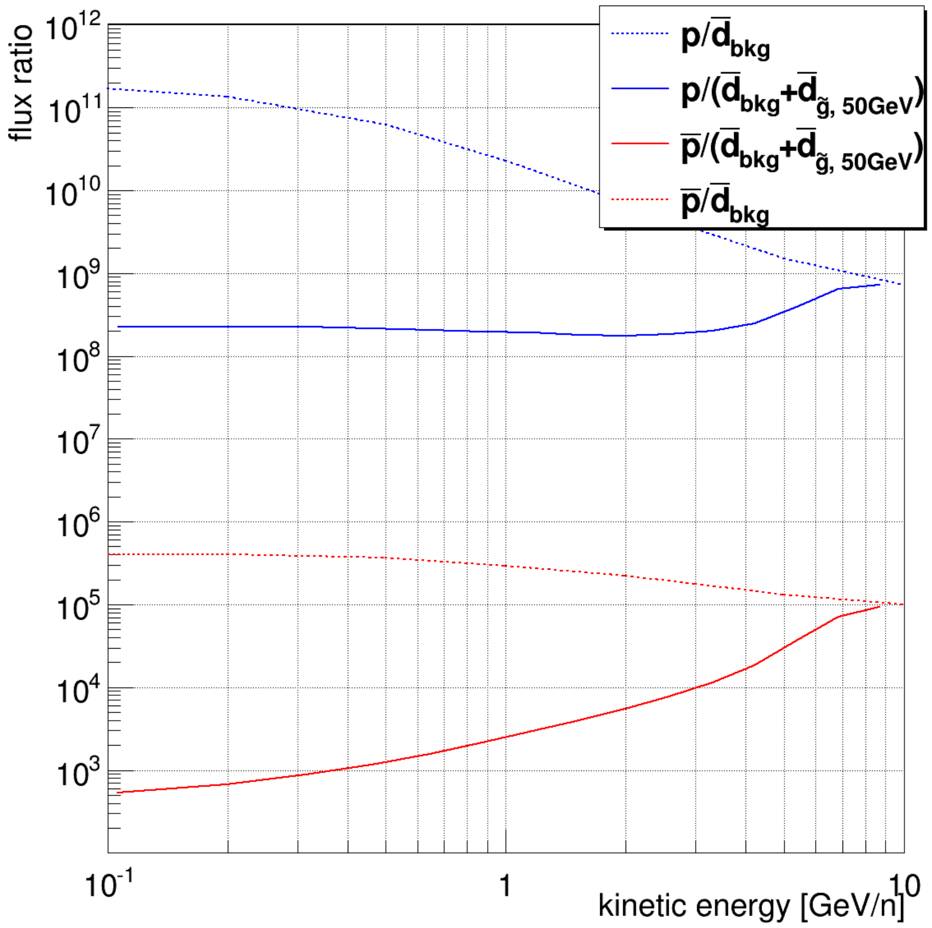
Identification challenge

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:

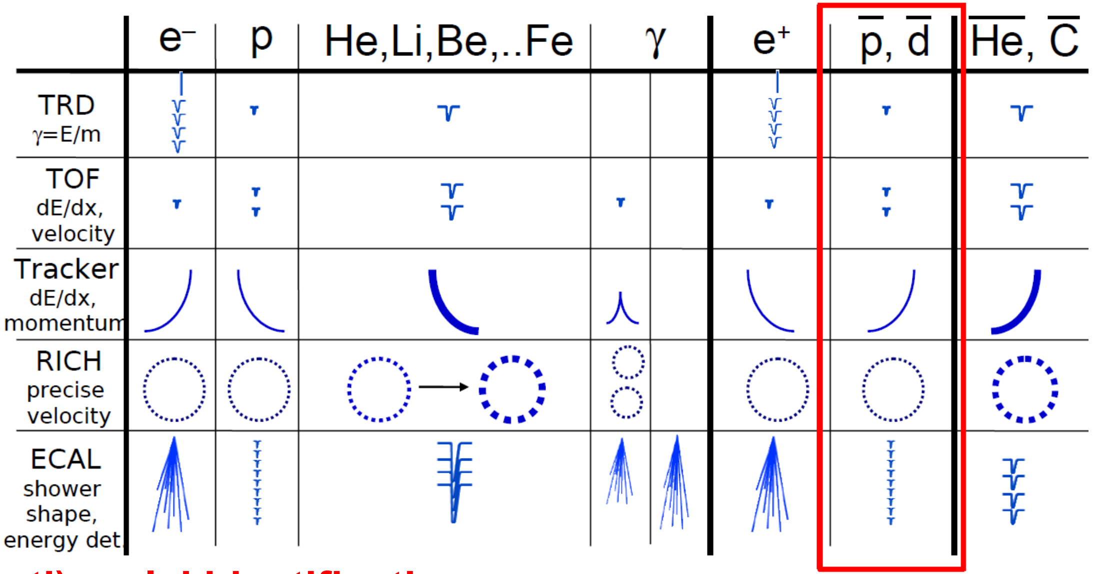
- **strong background suppression**
- **long flight time and large acceptance**

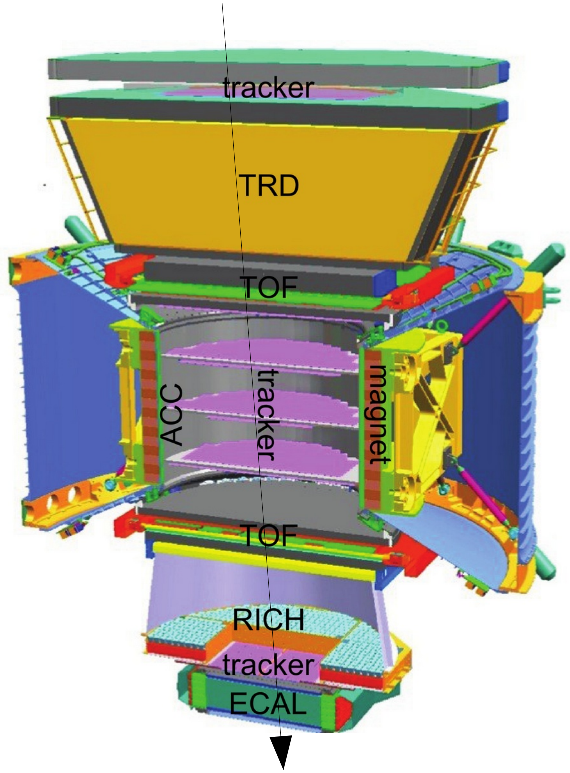


AMS-02 on the International Space Station

- 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 more than100 billion of events since May 2011

AMS-02 antinuclei analyses

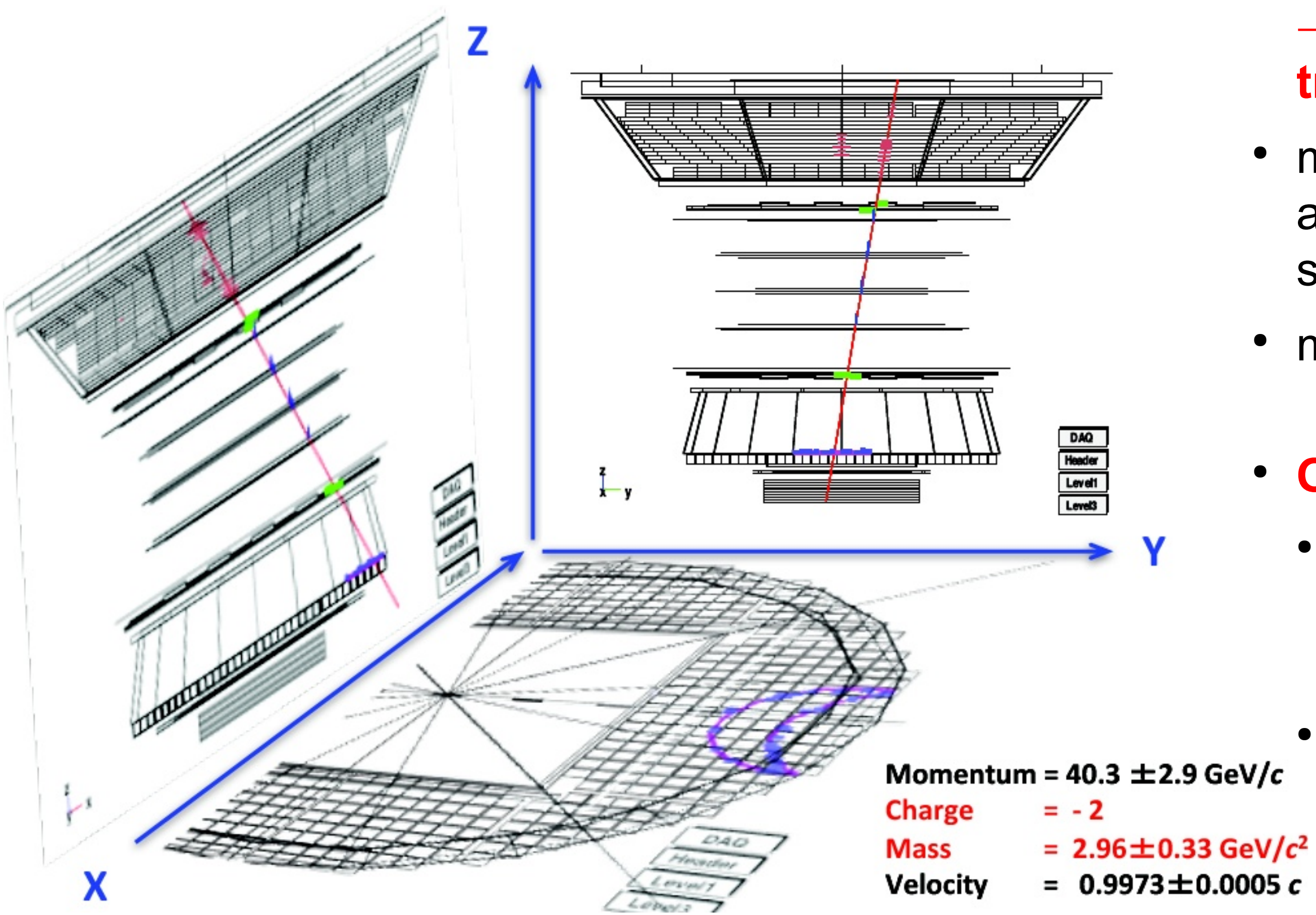




- **(anti)nuclei identification:**
  - momentum measured in the form of rigidity
  - charge from TOF, TRD, tracker
  - lower velocities: **T**ime **O**f **F**light scintillator system
  - higher velocities: **R**ing **I**mage **Ch**erenkov detector
- **self-calibrated analysis:**
  - calibrate antinuclei analyses with deuterons, helium, and antiprotons

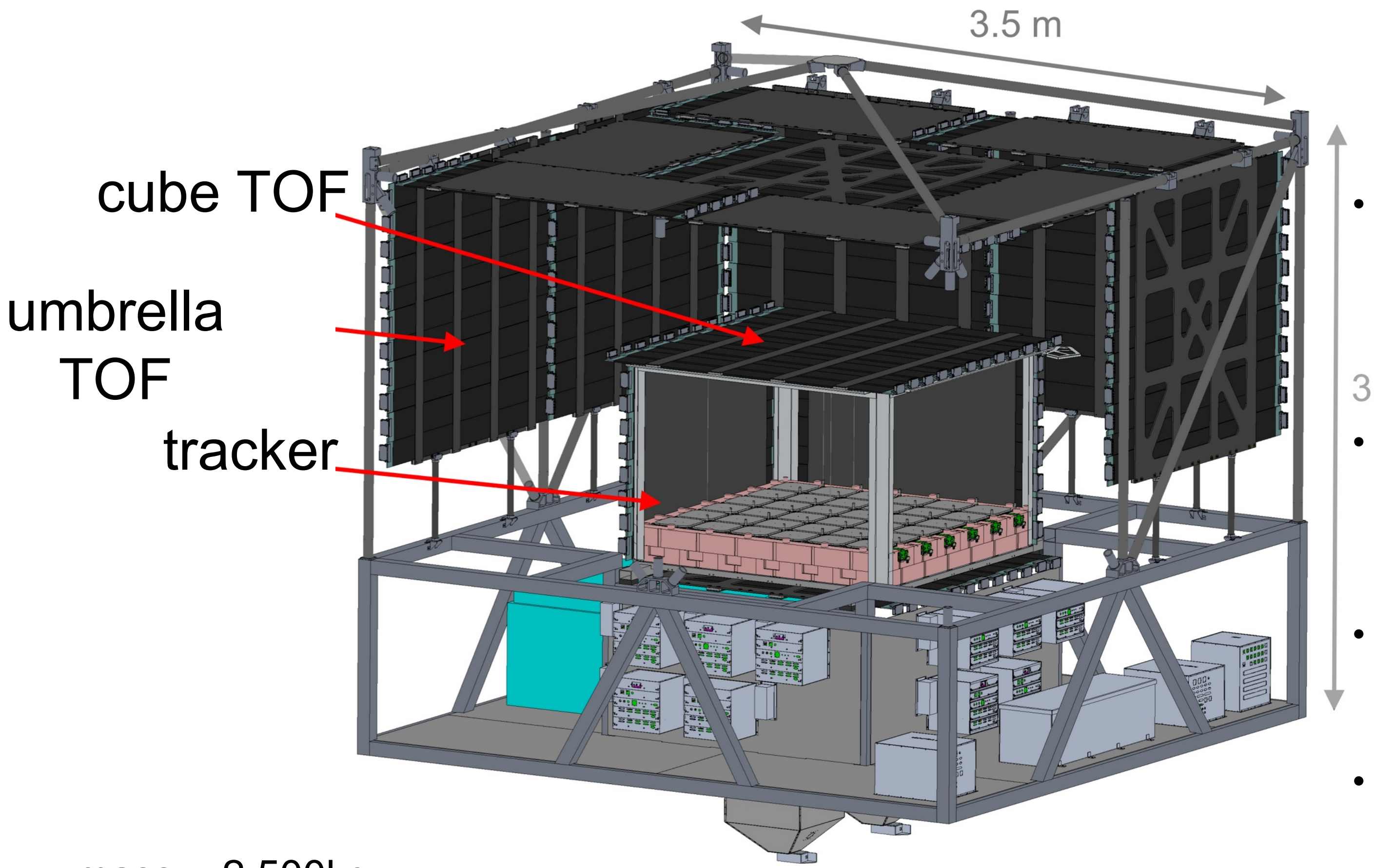
$$m = R \cdot Z \sqrt{\frac{1}{\beta^2} - 1}$$

Antihelium candidates by AMS-02



- antihelium-3 and antihelium-4 candidates have been identified **→ would be a very transformative finding**
- massive background simulations are carried out to evaluate significance
- more data are needed
- **Ongoing in the UH CRA group:**
  - Low-energy antiproton, antideuteron (D. Gomez), anthelium (J. Negrete) analysis
  - Low-energy deuteron analysis (D. Gomez)

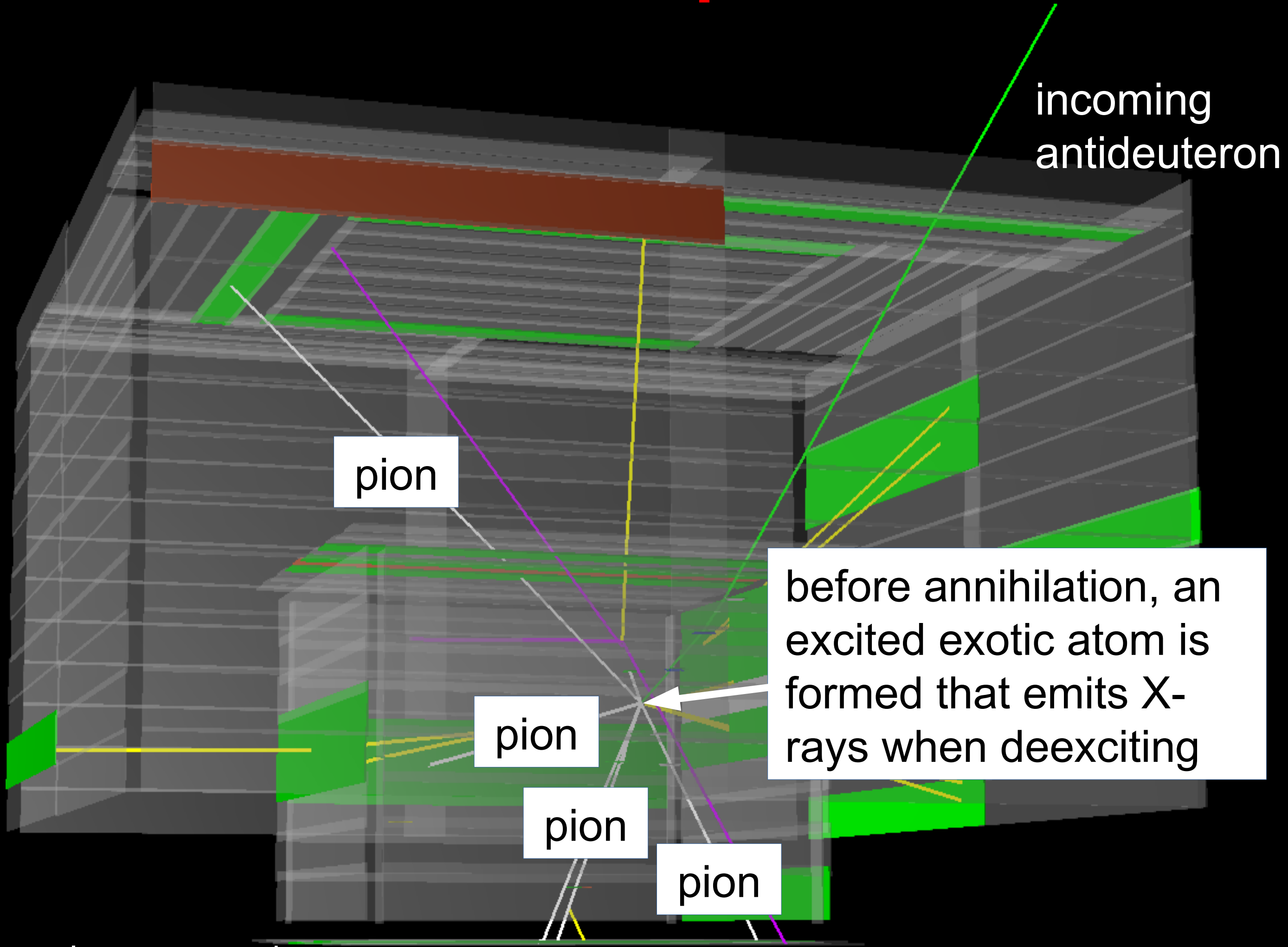
The GAPS experiment



- The **G**eneral **A**nti**P**article **S**pectrometer is the first experiment dedicated and optimized for low-energy cosmic-ray antinuclei search
- GAPS has the ability to detect DM for a wide variety of models or to put strong constraints
- requirements: long flight time, large acceptance, large identification power
- **GAPS is under construction**
  → first Long Duration Balloon flight from Antarctica in late 2022

mass: ~2,500kg
power: 1.5kW

GAPS Technique

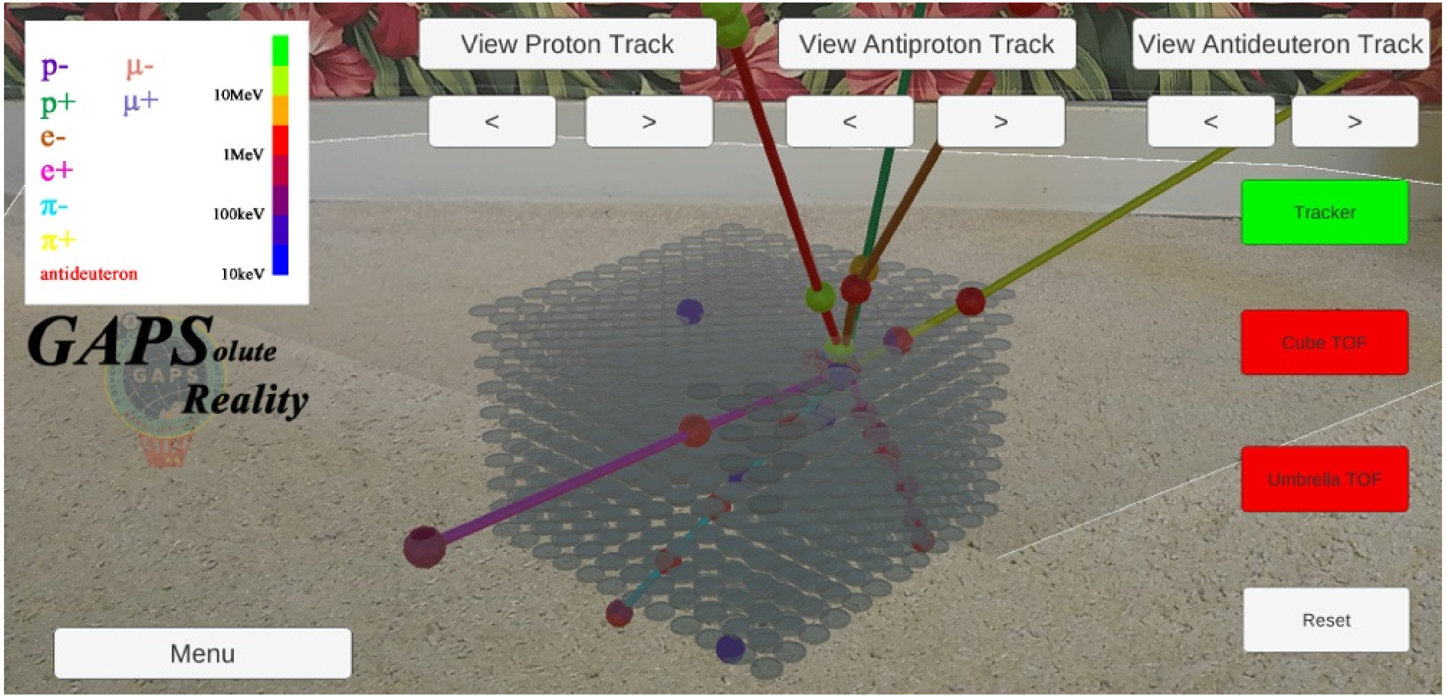


Color scale corresponds to deposited energy

- antiparticle slows down and stops in material
- large chance for creation of an excited exotic atom (E_{kin}~E_{I})
- deexcitation:
  - fast ionization of bound electrons (Auger) → complete depletion of bound electrons
  - Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via characteristic X-ray transitions depending on antiparticle mass
- Nuclear annihilation with characteristic number of annihilation products

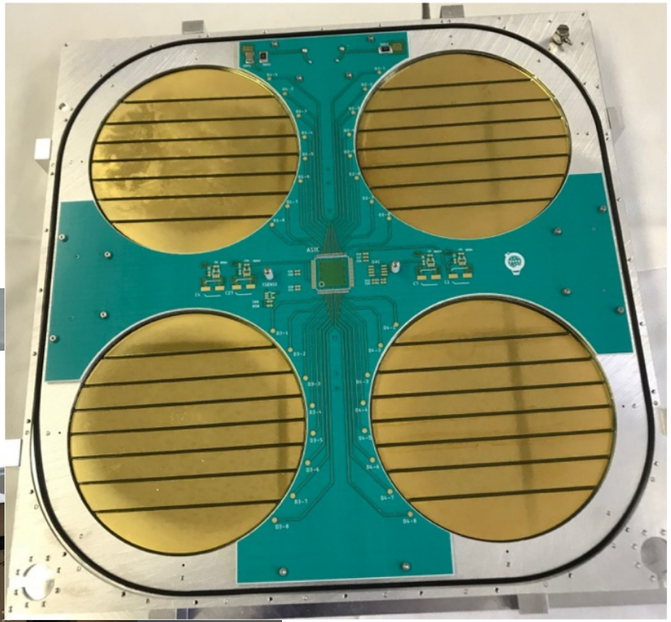
GAPS augmented reality app

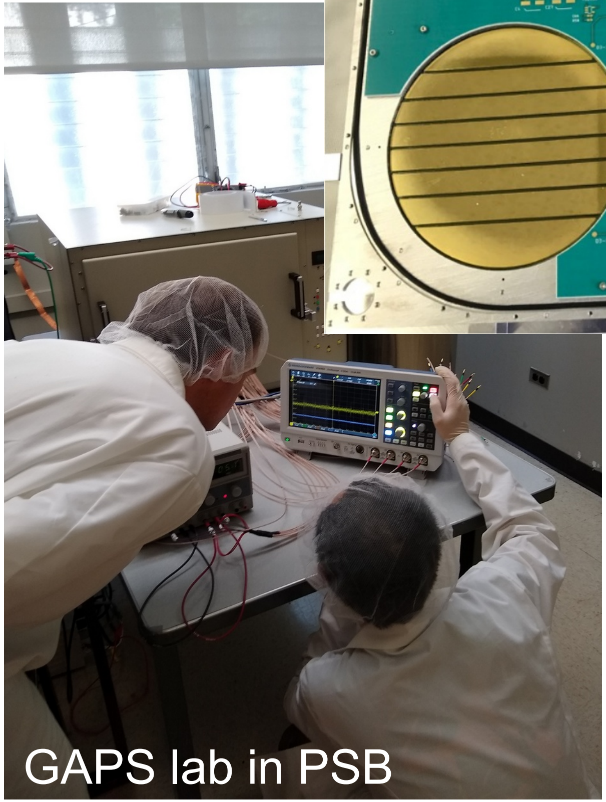
- Undergrad L. Fujioka developed AR app for Android with UROP funding: https://www.phys.hawaii.edu/~philipvd/pvd_research_gapsapp.html



Tracker

- Tracker acts as target and tracking device
- GAPS will use 1,440 4” Si(Li) detectors, 2.5mm thickness, demonstrated <4keV energy resolution
- Operation at relatively high temp of -35C to -45C, cooling system will use novel OHP approach
- Fabrication scheme developed at Columbia U and MIT, produced by private company Shimadzu, Japan
- **Fabrication completed, calibration and flight qualification is ongoing (50% of the modules are calibrated at UH by A. Stoessl, C. Gerrity)**
- Publications:
  - Perez et al., NIM A 905, 12 (2018)
  - Kozai et al., NIM A 947, 162695 (2019)
  - Rogers et al., JINST 14, P10009 (2019)





GAPS lab in PSB

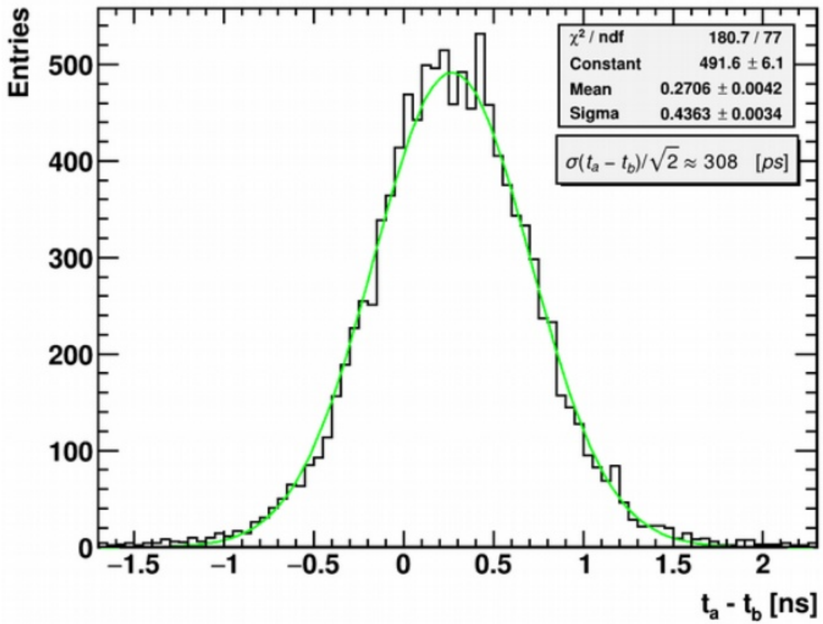
Time-of-Flight

- Tasks:
  - main trigger system, critical to reduce data rate to manageable level (~500Hz)
  - velocity measurement

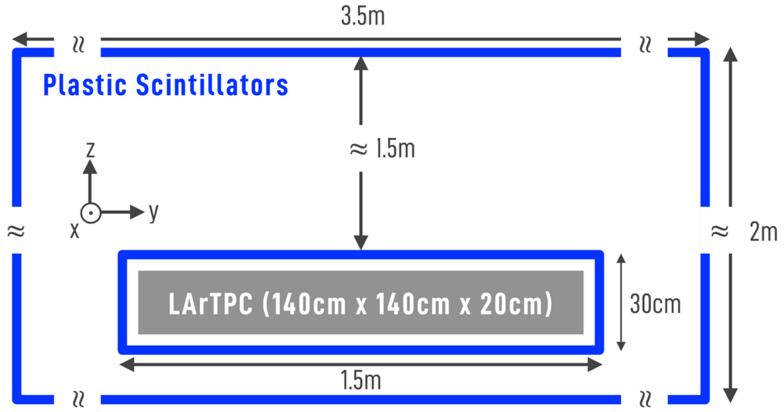
- Plastic scintillator: Eljen EJ-200: 160-180cm long, 0.6 cm thick

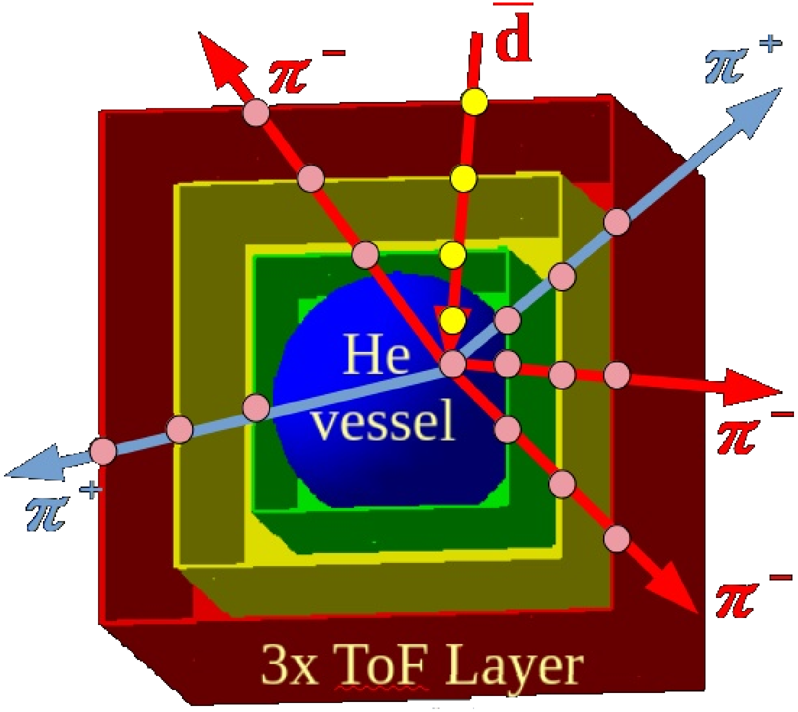
- SiPM: Hamamatsu S13360-6050VE

- fast sampling with DRS4 ASIC: ~300ps timing resolution end-to-end/√2 timing has been demonstrated in the lab



Future Beyond AMS-02 and GAPS



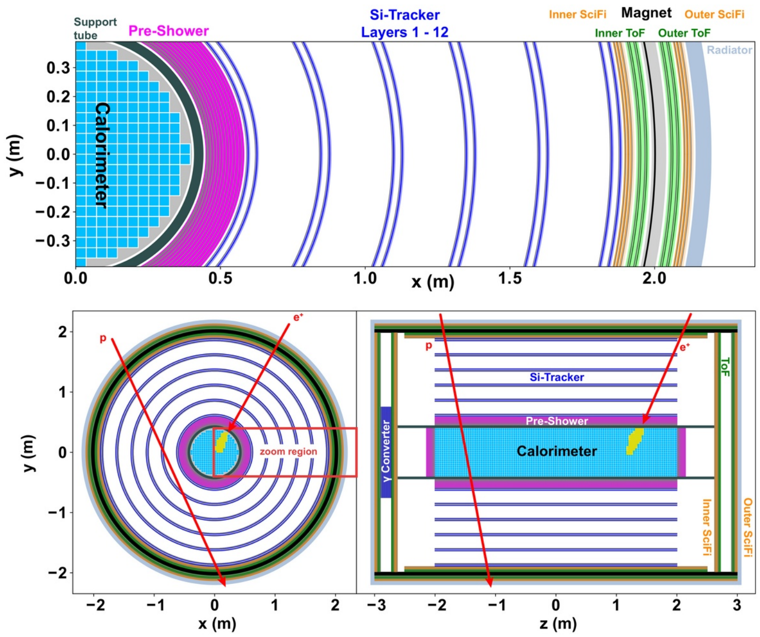


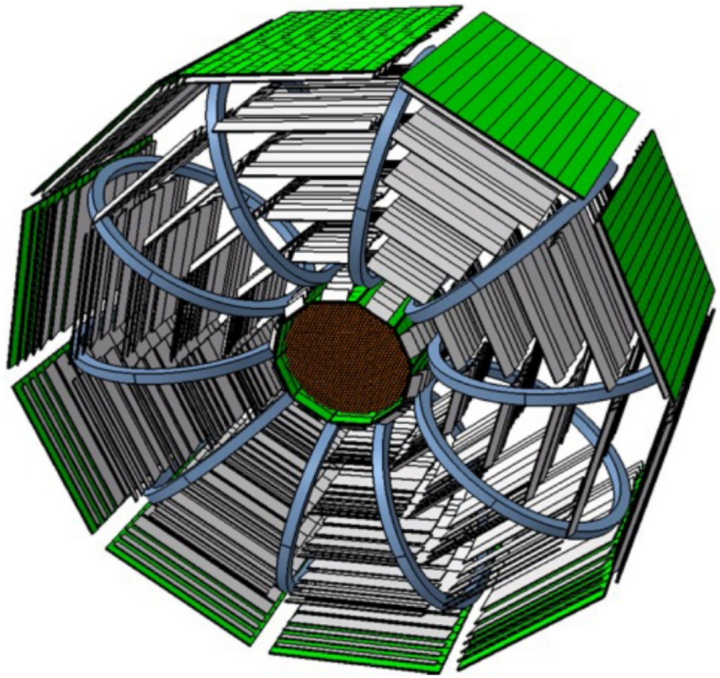
- The balloon experiment GRAMS is designed to simultaneously target both astrophysical gamma-rays with MeV energies and antimatter signatures (like GAPS, using the atomic atom signature)
- consists of a liquid-argon time projection chamber (LArTPC) surrounded by plastic scintillators
- Astropart. Phys. 114, 107 (2020)

- AntiDeuteron Helium Detector (ADHD) (balloon or space) makes use of delayed annihilation of antinuclei in helium

  → larger delay of the annihilation signature is expected for antideuteron capture in helium than for antiproton capture
- J. Phys. Conf. Ser. 1548 1, 012035 (2020)

Future Beyond AMS-02 and GAPS





- AMS-100 a space-based platform (10-year oepration at Sun-Earth Lagrange Point 2) using a thin, large-volume, high-temperature superconducting solenoid magnet
- large geometrical acceptance of 100 m^2sr will measure the antideuteron spectrum, test heavier cosmic antimatter ($Z \leq -2$).
- NIM A 944 162561 (2019)

- ALADino: large accpetance, superconducting magnet
- Operation at Langrange Point 2

  Nuclear antimatter up to 1000 GV, dark matter at the multi TeV/c^2, composition of CR in the multi 10 TV

Conclusion & Outlook

- Cosmic-ray antinuclei are important means to the study new physics
- All antinuclei species need to be explained together
- Uncertainties need to be reduced:
  - Antideuteron and antihelium formation are not well understood
  - Cross section measurements need to be conducted on for the interpretation
- AMS-02 continues collecting data
- GAPS will have first flight in two years
- The UH CRA group is always looking for interested (under)grad students


July 2019, A. Datta left and J. Negrete joined