Hunt for dark matter using cosmic-ray antideuterons

UHM Physics Department Colloquium
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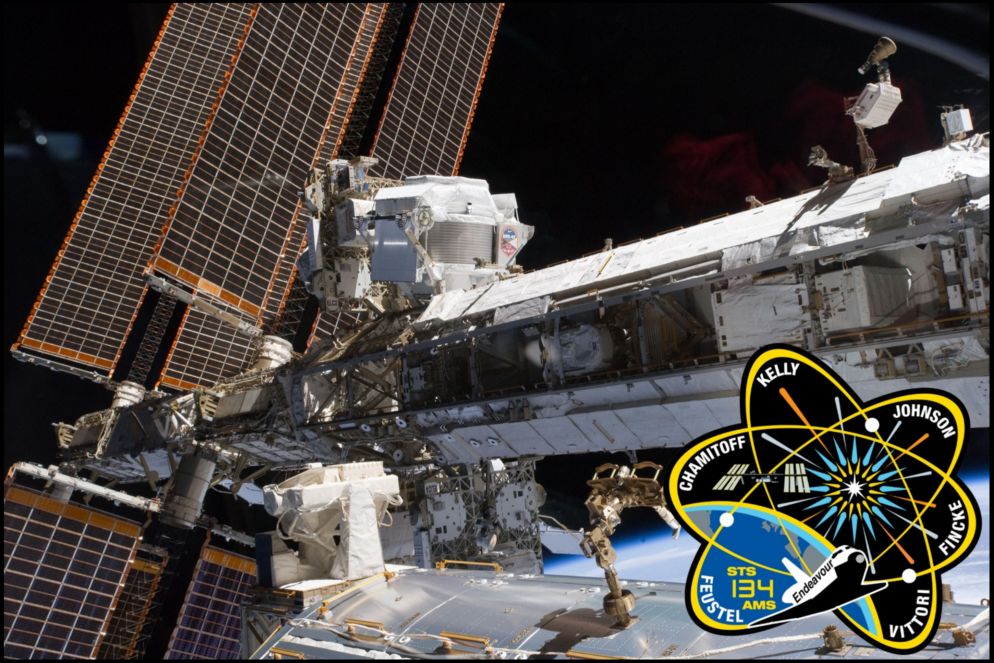
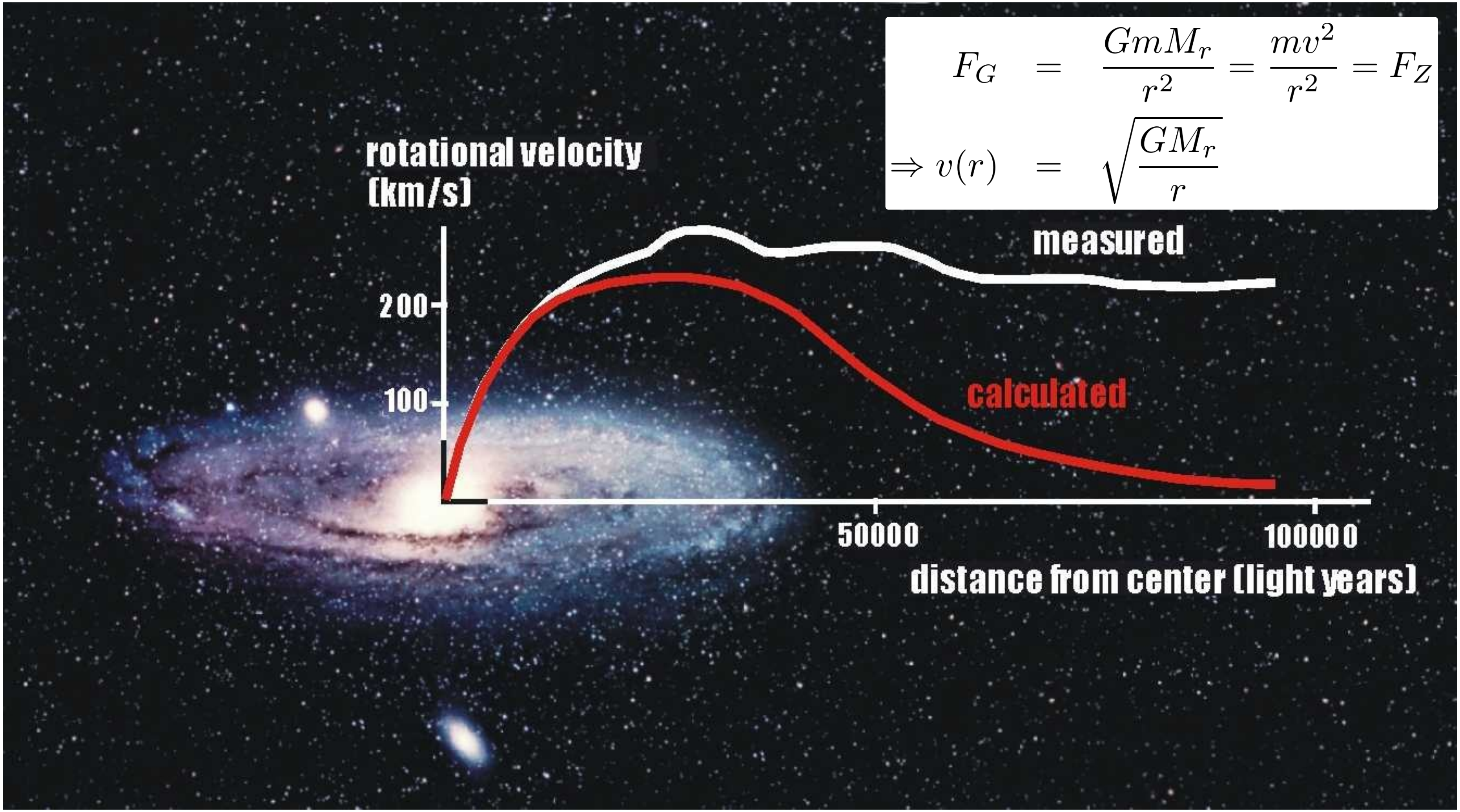


Key questions throughout my talk

- How do we know that dark matter exist?
- How to study the nature of dark matter?
- Why are cosmic-ray antideuterons exciting?
- What is the current experimental status?

Existence of dark matter



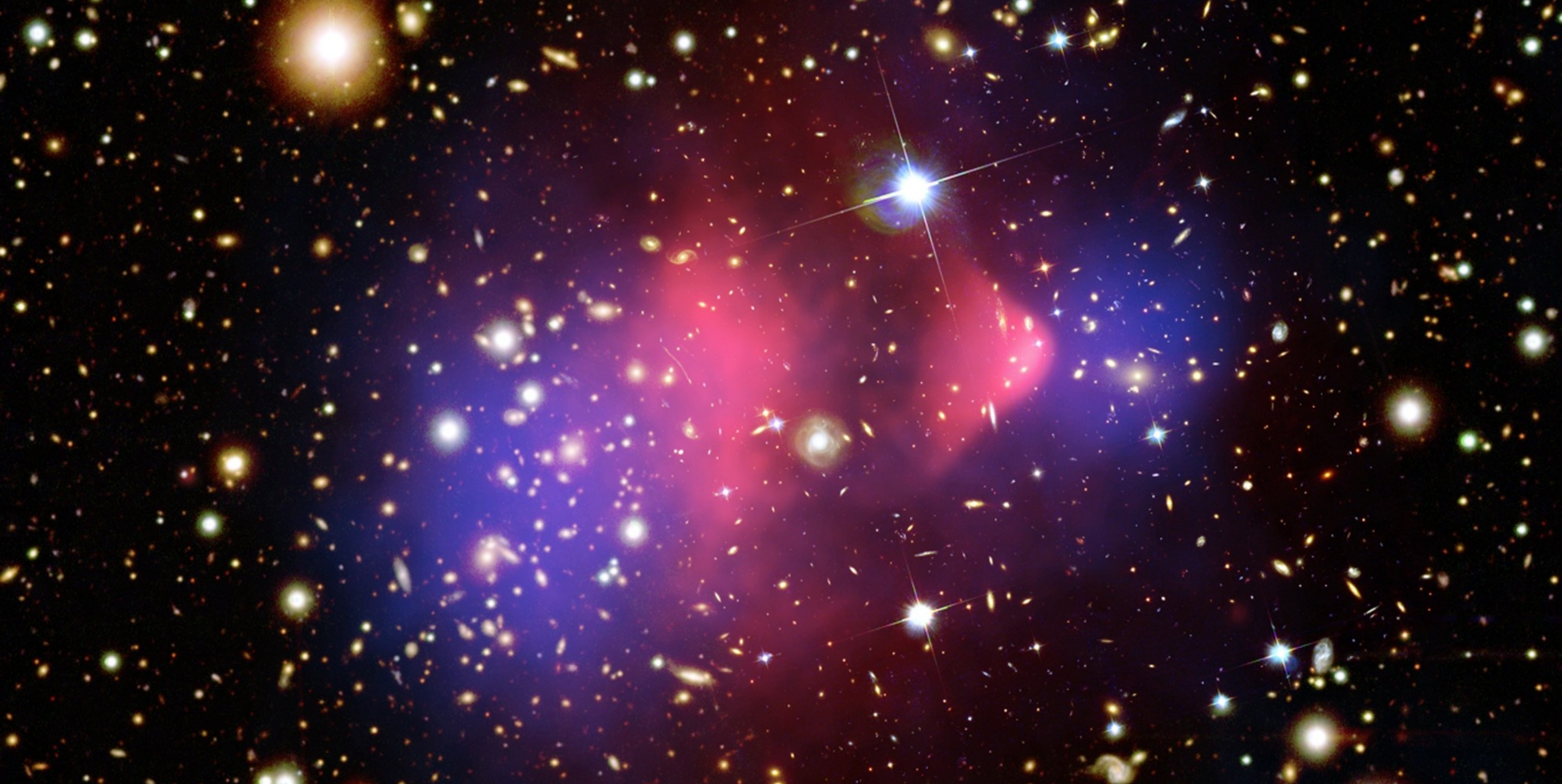
$$F_G = \frac{GmM_r}{r^2} = \frac{mv^2}{r^2} = F_Z$$

$$\Rightarrow v(r) = \sqrt{\frac{GM_r}{r}}$$

- velocity distributions of galaxies need mass extending along the disk

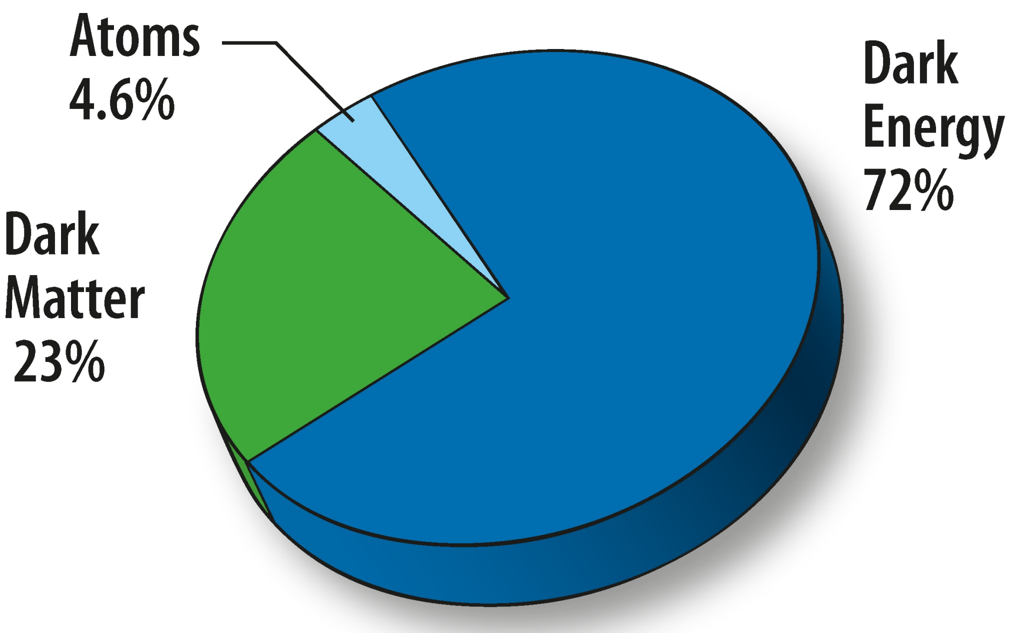
Existence of dark matter

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



- **dark matter exists!**
- evidence for dark matter comes from many different type of observations on different 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)

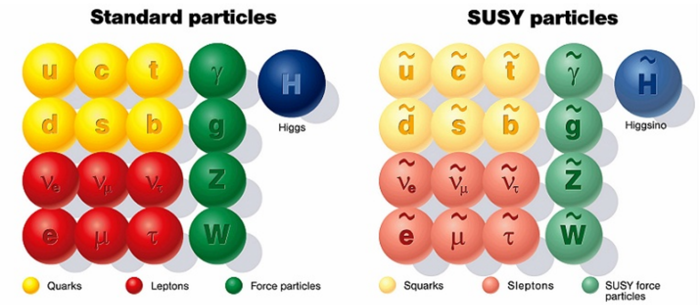
→ most popular: **W**eakly **I**nteracting **M**assive **P**articles

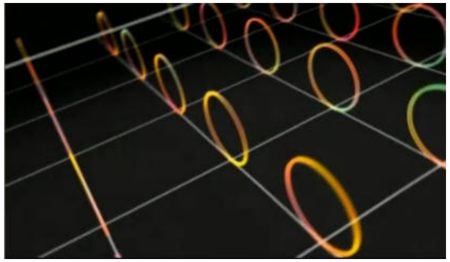
- **discovering the nature of dark matter is one of the most striking problems in physics**

General challenge

particle physics × astrophysics = signal

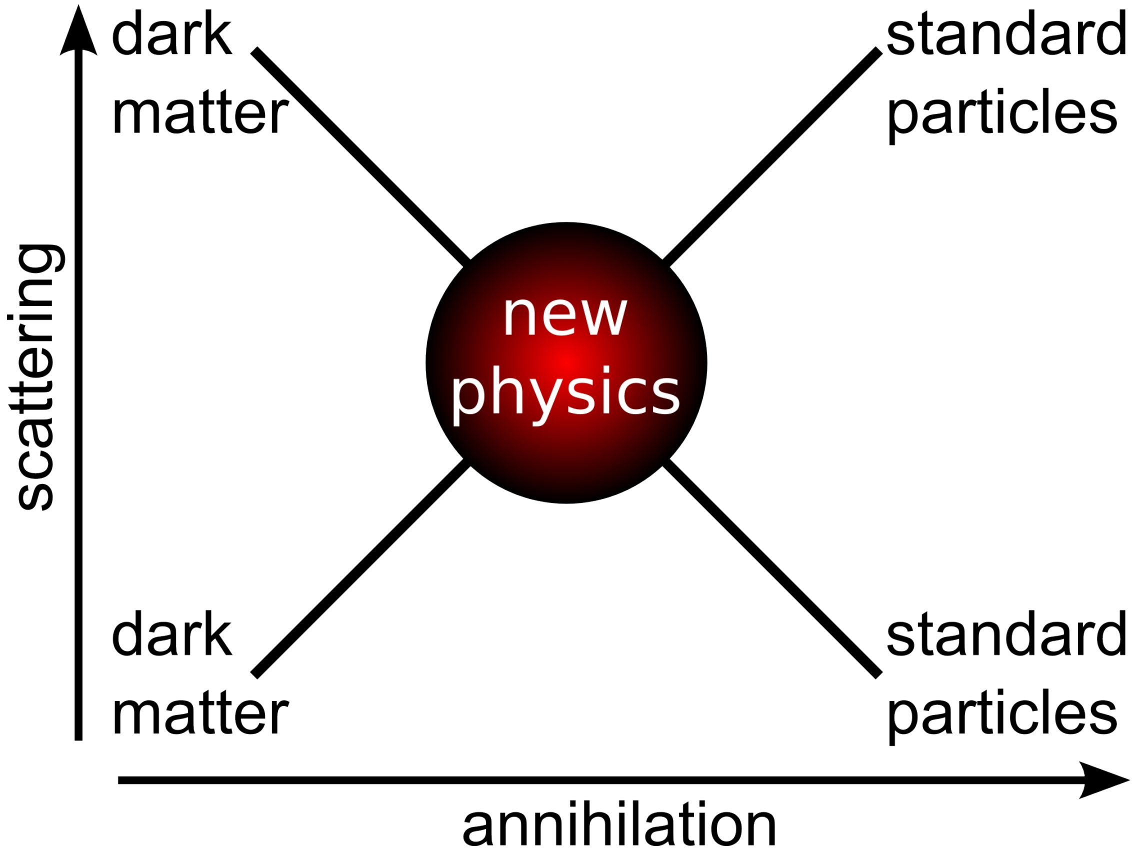
- solving the dark matter problem means therefore disentangling particle physics and astrophysics
- beyond standard model particle physics need to provide stable dark matter candidates, e.g.:
  - Supersymmetry:
    fermions (bosons) have a bosonic (fermionic) superpartner
    dark matter candidate: neutralino (majorana fermion)
  - Kaluza-Klein extra dimensions:
    extra dimensions seen as extra mass
    dark matter candidate: 1^{st} excitation of photon (boson)
  - solve also problems like electroweak symmetry breaking along the way





- astrophysics:
  - dark matter distribution: substructures, density, velocity distribution

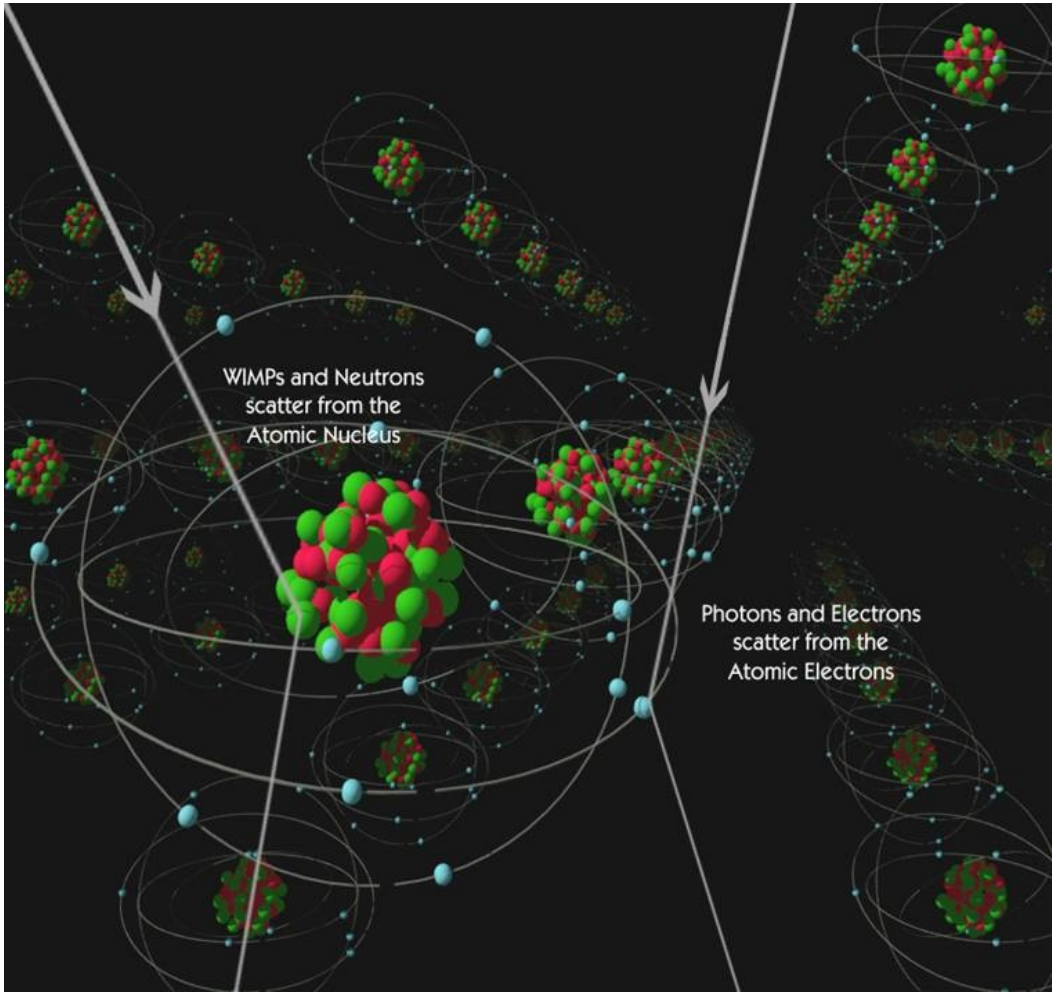
How is dark matter interacting?



- **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

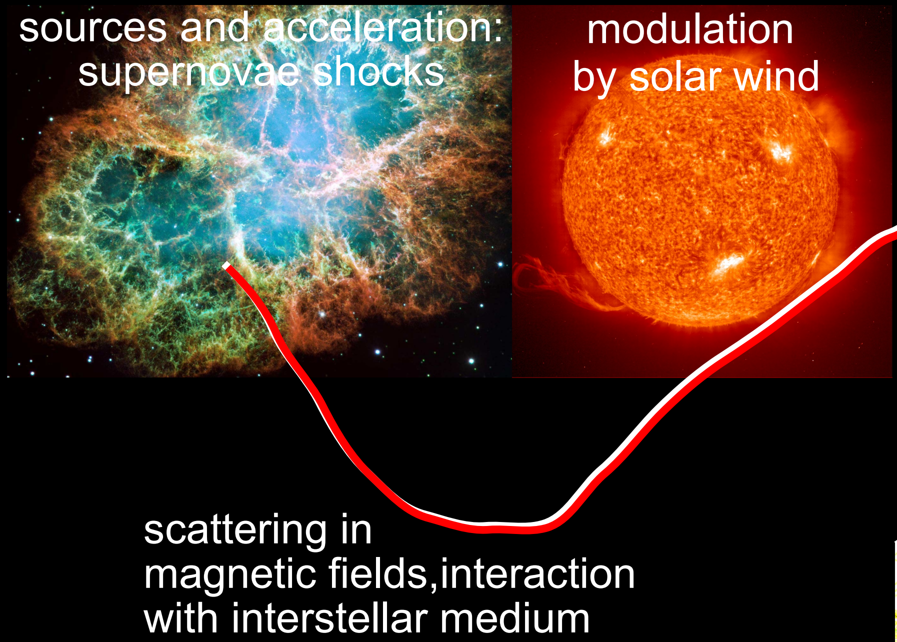
→ **dark matter must be able to interact with standard model particles**

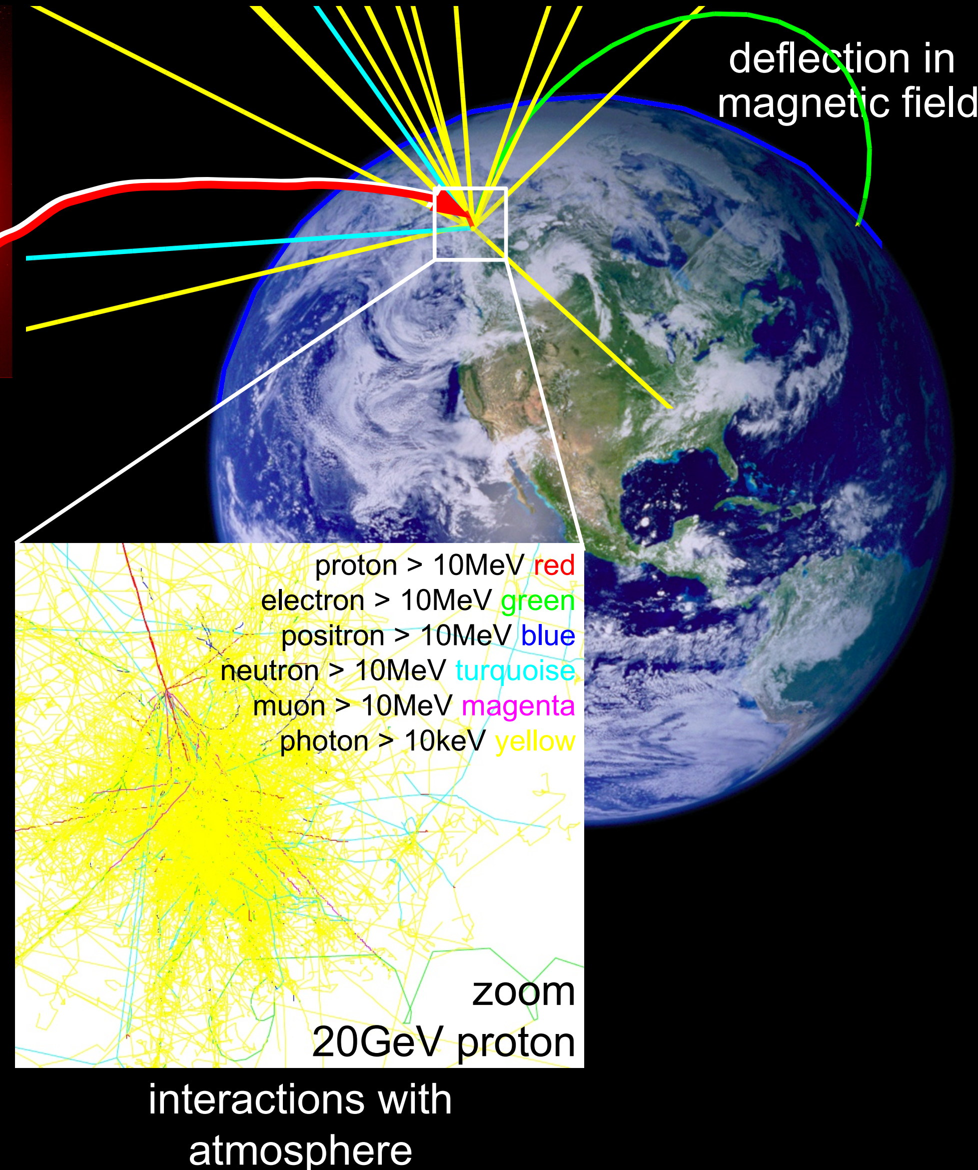
Direct dark matter searches (scattering)



- **direct dark matter search:** measure cross-section via nuclear recoil
- typically large, heavy and very pure target materials in deep mines (~20 operating experiments)
- experiments start to reach in theoretically preferred parameter space
- **experiments disagree →** some experiments claim discovery, some set exclusion limits

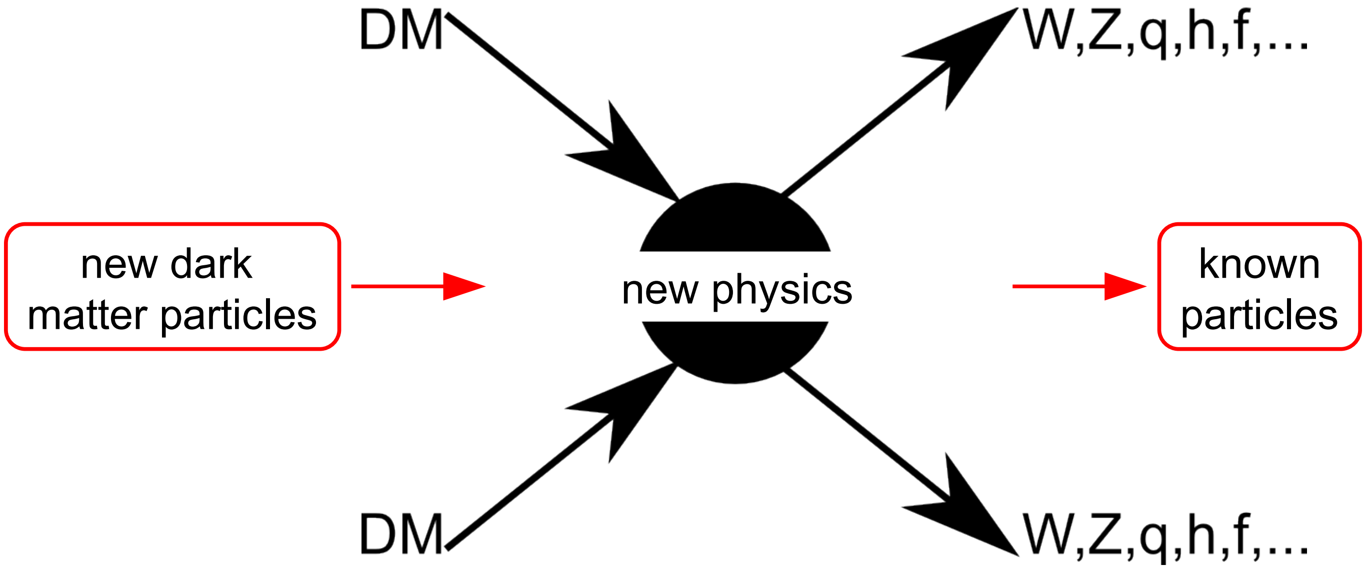
Cosmic rays as messengers





- propagation through the galaxy and the interstellar medium depends on various parameters
- precise understanding is needed for reliable analysis

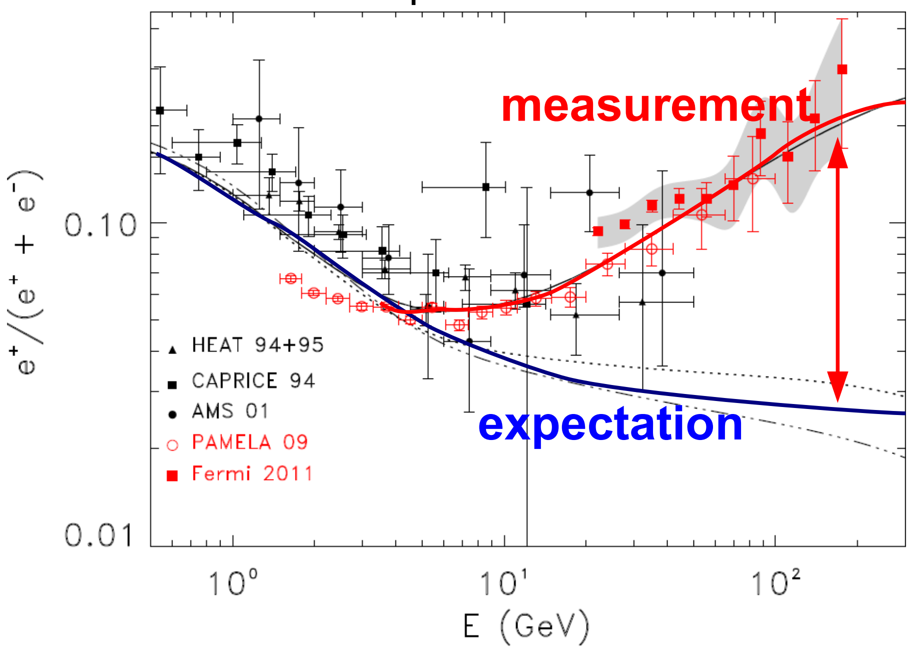
Indirect dark matter searches (annihilation)



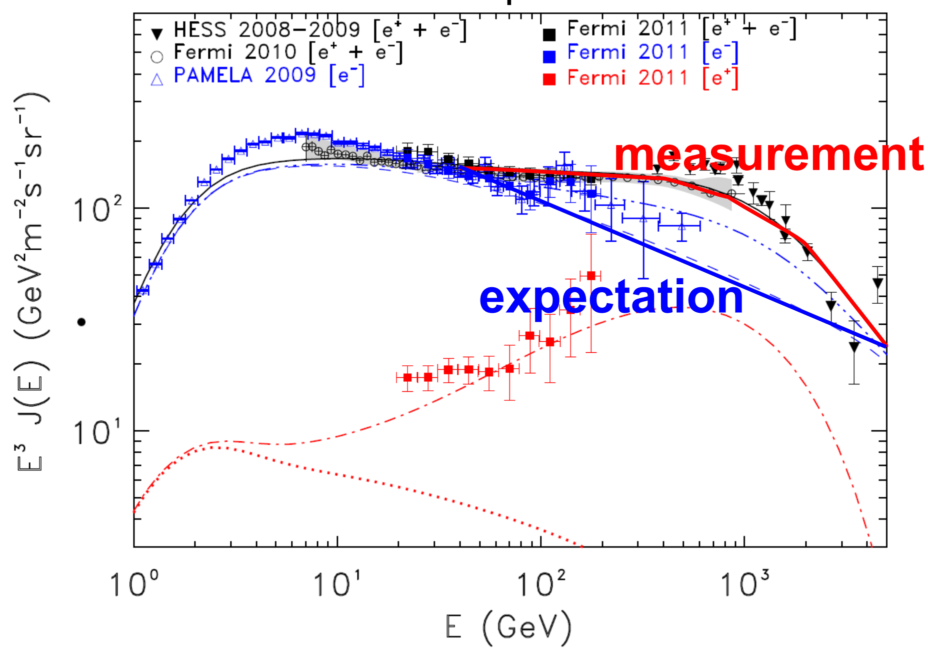
- **assumption:** cosmic-rays from dark matter annihilation follow different kinematics than conventional production
- peak/bump/shoulder on top of conventional spectrum expected
- use search channel without strong conventional production: positrons, photons, antiprotons, electrons, neutrinos, ...

Possible dark matter signals?

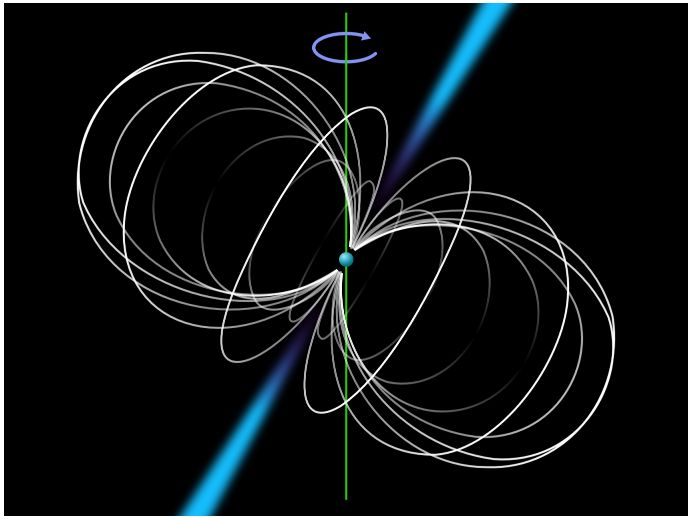
positrons



electron+positron flux



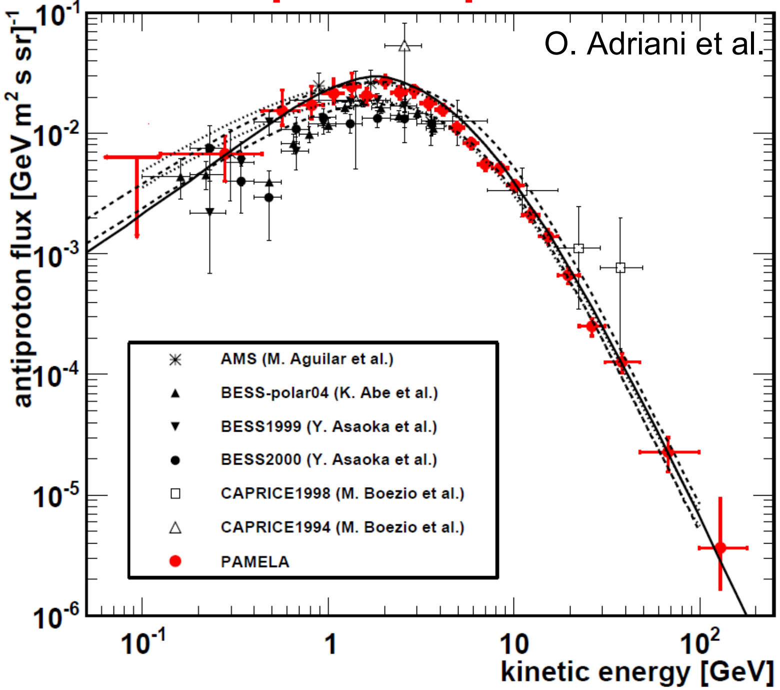
- unexplained features in positron and electron spectra
- proposed theories, e.g.:
  - **dark matter self-annihilation**
  - additional astrophysical sources, like γ-ray pulsars pair producing electrons and positrons?



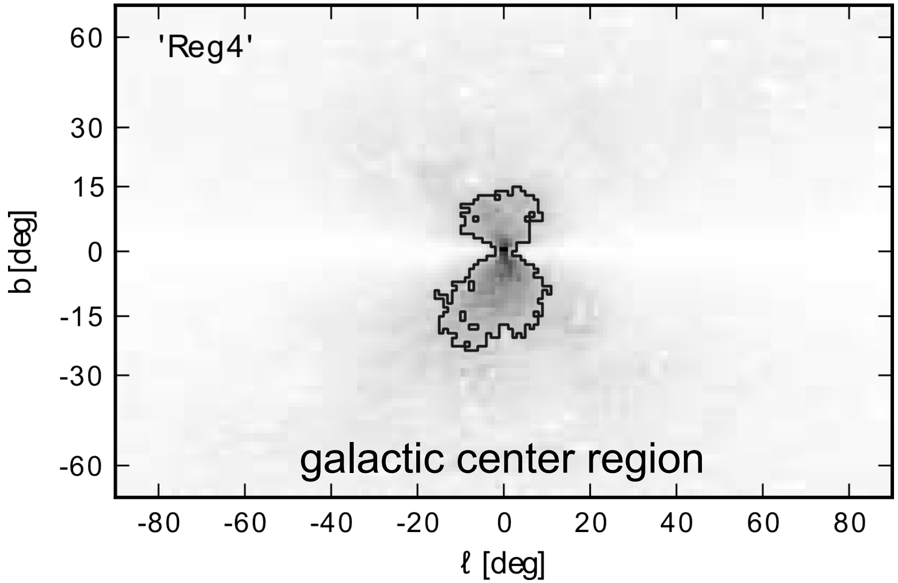
What makes the interpretation difficult?

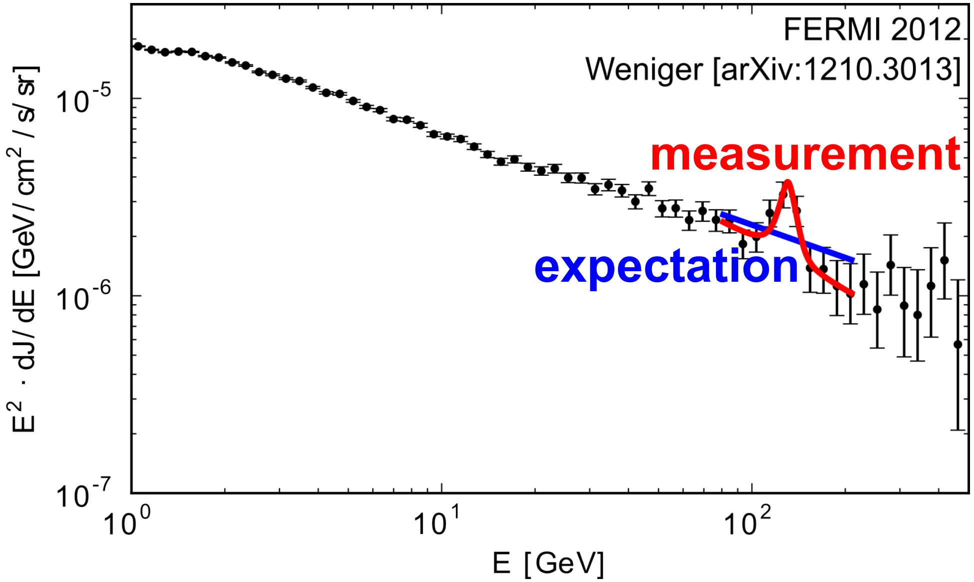
- **drawbacks exist:**
  - observed deviations are relatively small
  - dark matter signals need boost
  - antiprotons can be explained without additional contribution
  - are pulsars able to produce enough electrons and positrons?
- **further questions:**
  - are experimental effects well understood (background rejections need to be very high)?
  - are cosmic-ray propagation models good enough?

antiproton spectrum



New: photons from the galactic center





- new FERMI analysis from Ch. Weniger published in April 2012 [arXiv:1204.2797]
- **smoking gun signature for dark matter annihilation?**

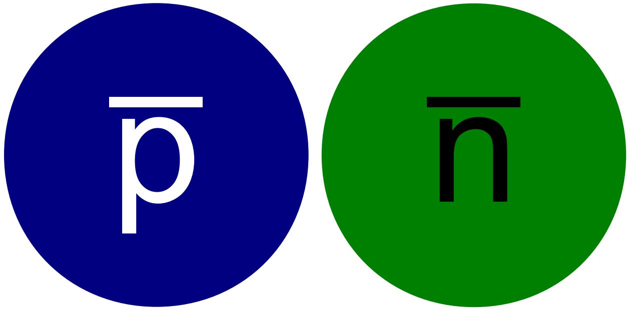
- **caused big excitement:** ~100 papers citing this discovery trying to explain what is going on
  - dark matter annihilation line from pair annihilation (DM particle mass 130GeV)
  - is it even two lines? [Rajaraman et al. arXiv:1205.4723]
  - cold ultrarelativistic pulsar winds [Aharonian et al. arXiv:1207.0458]
  - experimental effects, 130GeV line from Earth's albedo [Su et al. arXiv:1206.1616]

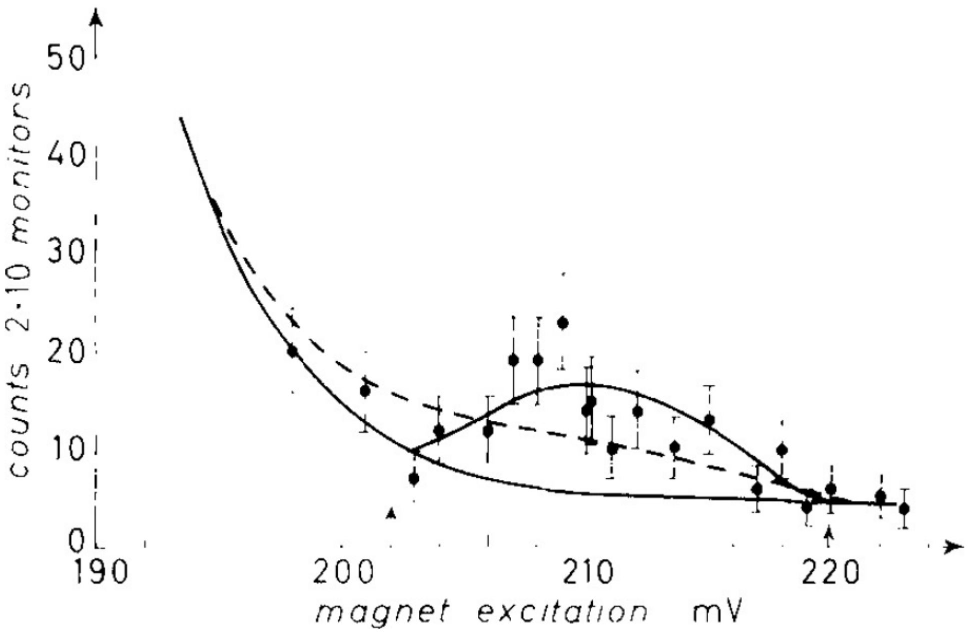
- **needs independent confirmation and higher statistics**
  - new FERMI data set from the galactic center
  - HESS telescope should be able to see lines
  - similar signal from spheroidal galaxies (high fraction of dark matter) expected

- **we entered the era of discovery**
- **data analysis is starting to make claims**
- **but so far inconclusive**
- **strategy: use search channel where additional dark matter contribution is much larger than astrophysical flux!**

[Search will always be a synergy between direct, indirect, and collider experiments]

Antideuterons

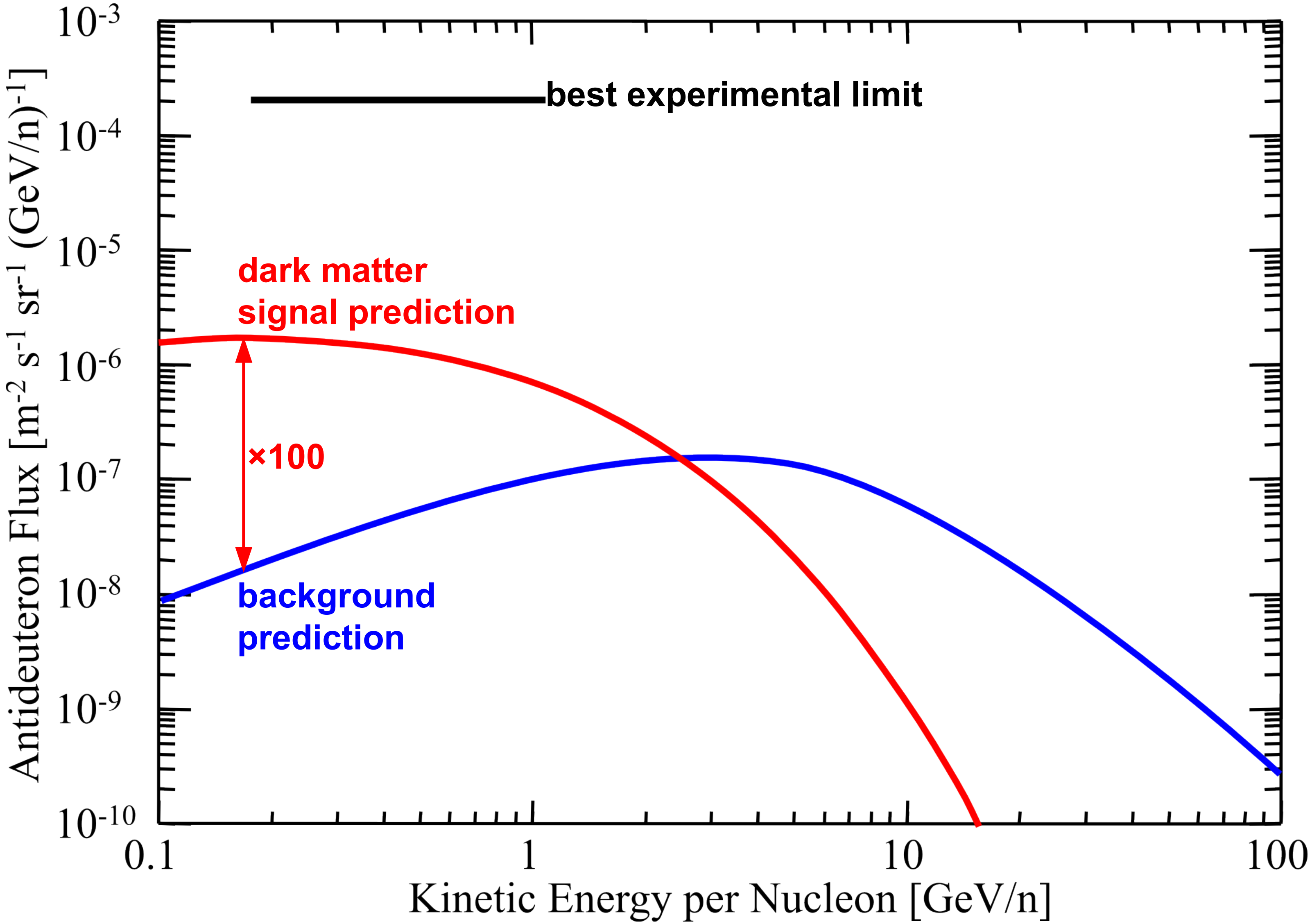




- deuterons are the nuclei of heavy water and antideuterons are the corresponding antimatter (q=-1,m=1876MeV, s=1)
- antideuterons were discovered in 1965 at CERN and Brookhaven and were the **first real antimatter ever discovered**
- seen since then at, e.g., LEP, Tevatron, LHC collider experiments

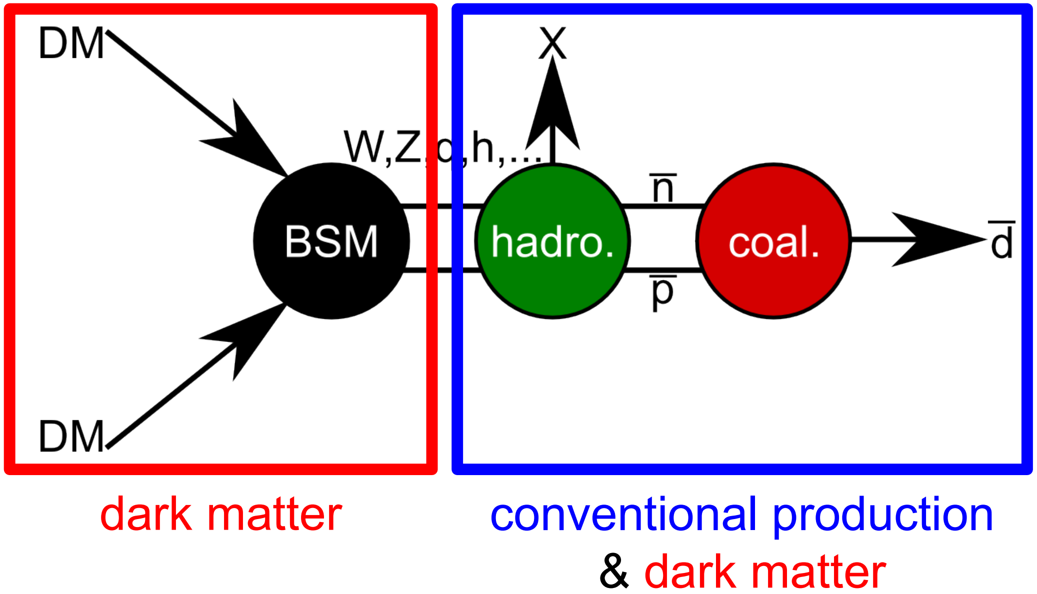
- **have never been discovered in cosmic rays**
  (next antinucleus in line after the antiproton and before antihelium)

Antideuterons and dark matter



- **prediction:** antideuterons from dark matter annihilations up to 100 times more abundant than from conventional cosmic rays

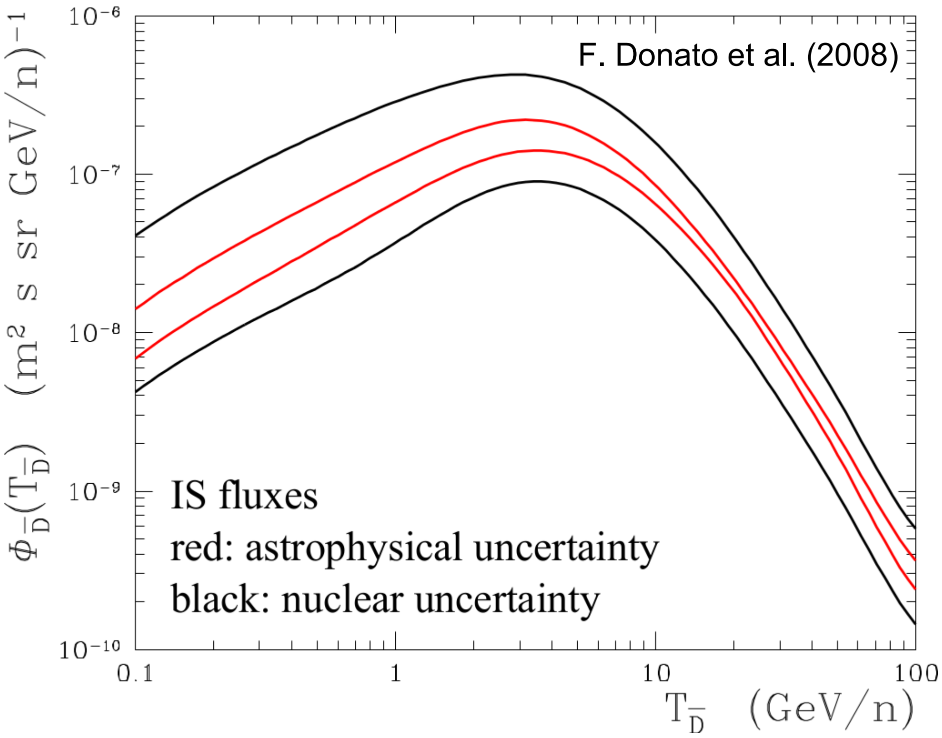
Antideuteron physics

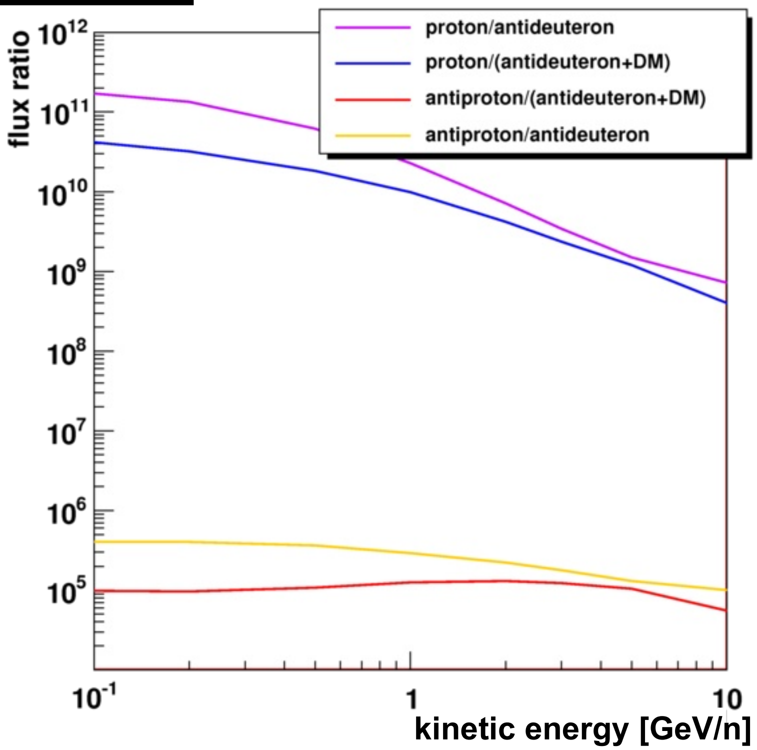


- antideuterons can be formed by an antiproton-antineutron pair if relative momentum is small (coalescence momentum p_0)
- major conventional production mechanisms of cosmic rays with ISM protons at rest:
  - $p+p \rightarrow \bar{d}+X$ (threshold 17GeV)
  - $\bar{p}+p \rightarrow \bar{d}+X$ (threshold 7GeV) → important even though antiproton flux is small

- coalescence momentum plays crucial role for cosmic-ray yield, but literature discusses p_0 from 80MeV to 240MeV depending on exact process
- understanding of antideuteron physics is essential for interpretation
  → antideuteron search has to be a synergy with collider experiments

Antideuteron measurement



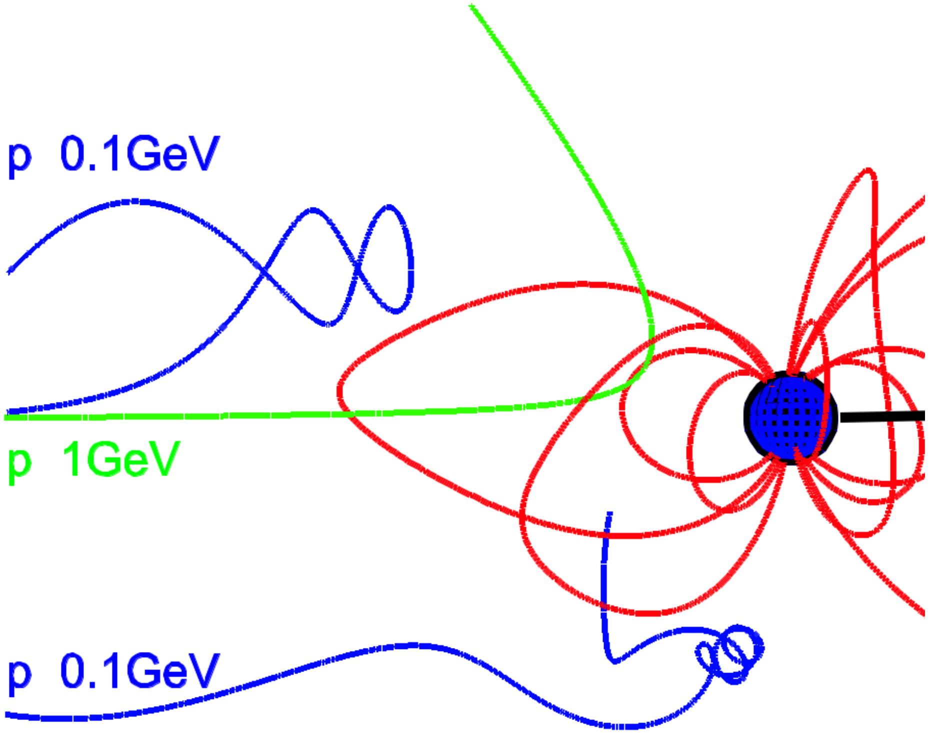


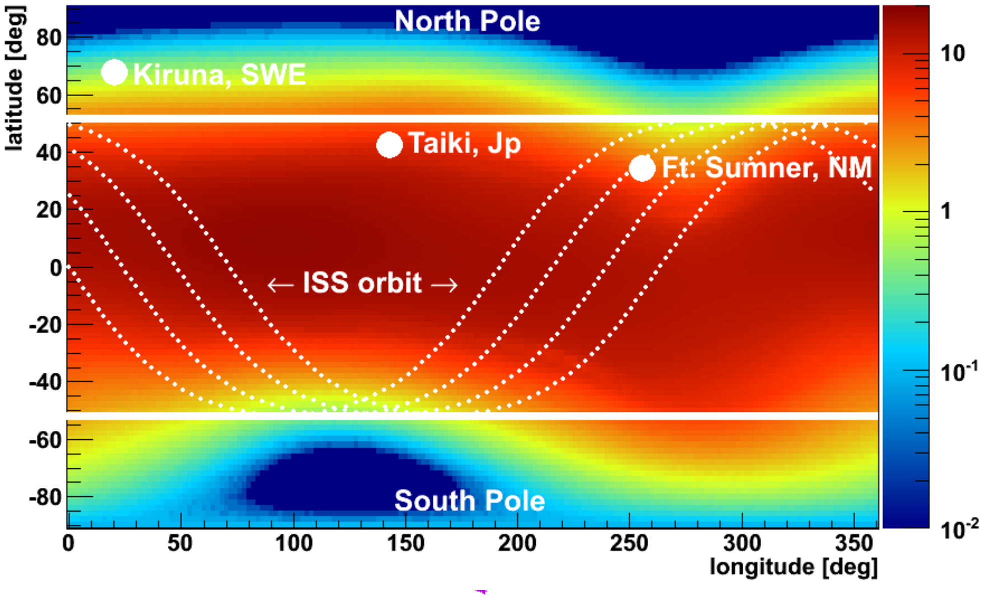
- **conventional antideuterons**
  - p-ISM production in galactic disk
  - dominant uncertainty from production cross-section
- **dark matter antideuterons:**
  - dark matter concentrated in halo
  - dominant uncertainty from propagation

antideuteron measurement with balloon and space experiments requires:

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

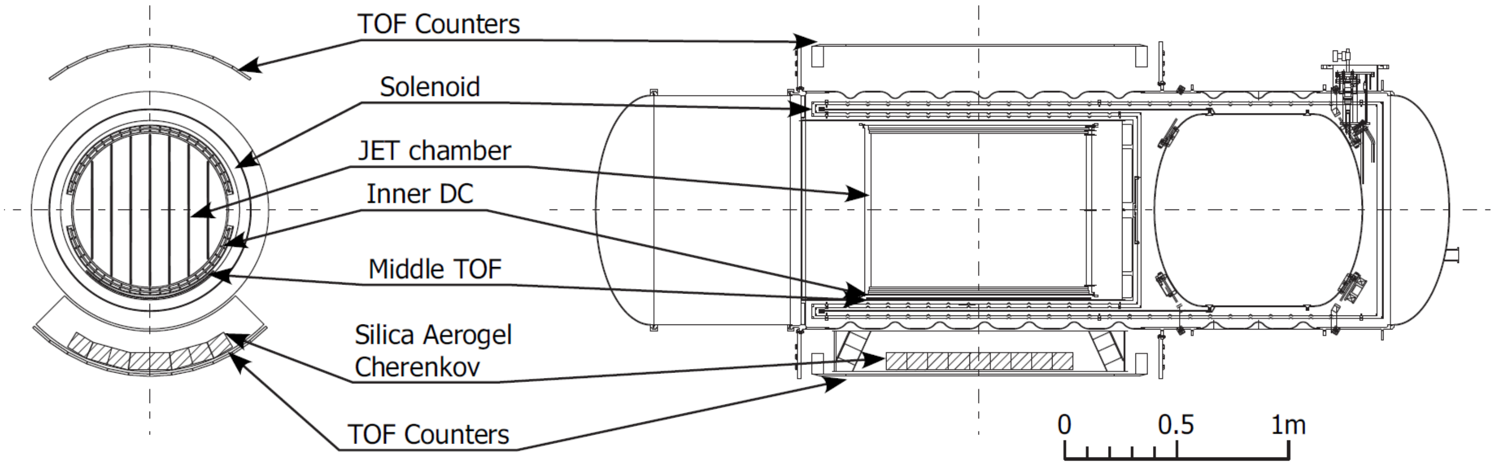
Geomagnetic shielding



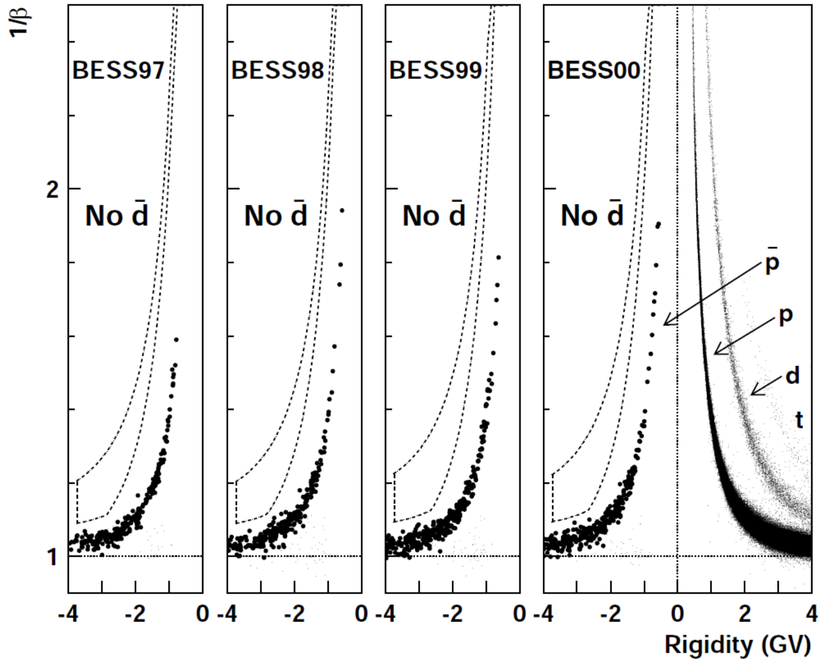


- geomagnetic field shields especially low-energy charged particles
- effect depends on the position

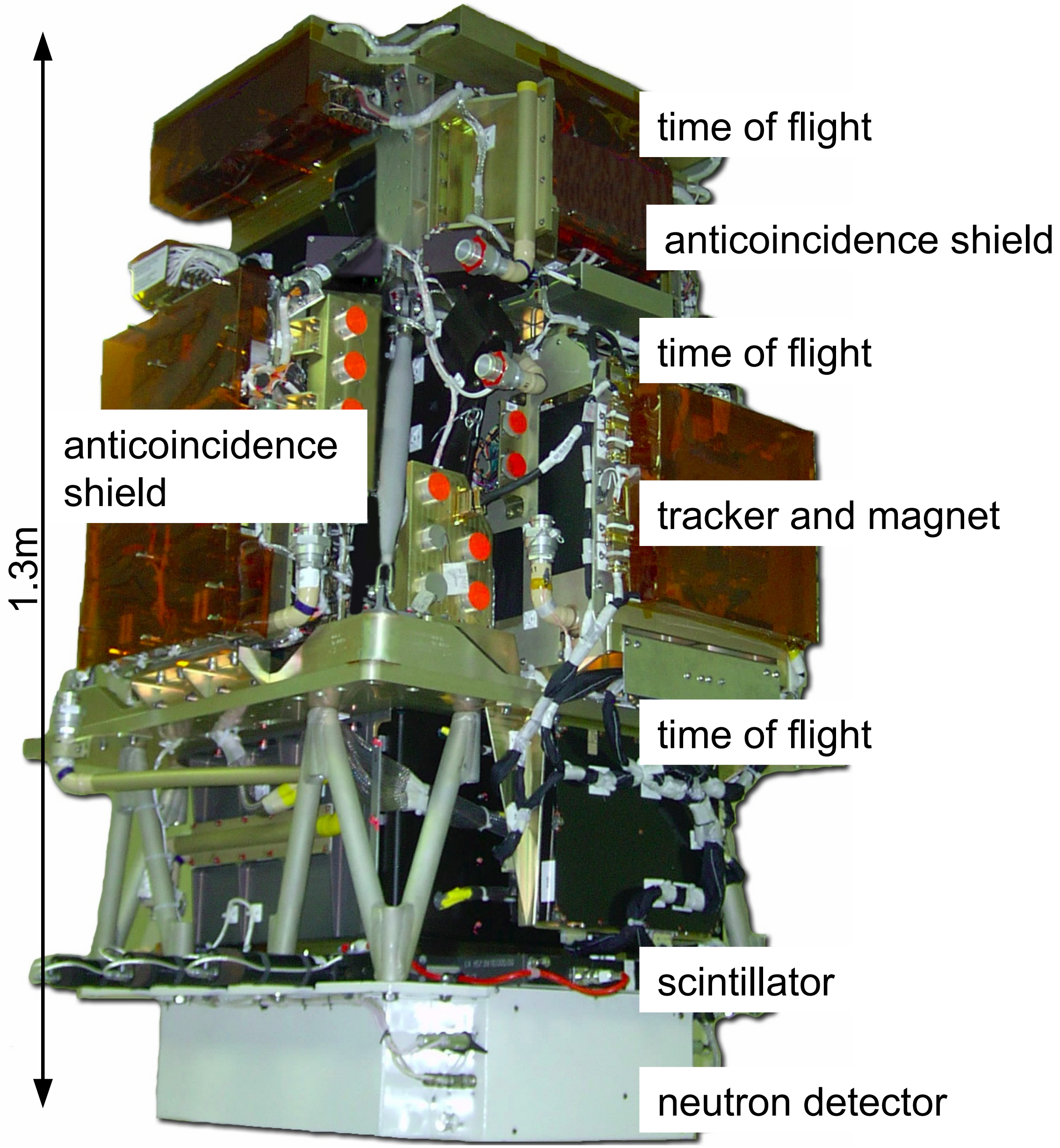
Balloon-borne: BESS



- magnetic-rigidity spectrometer:
  - superconducting solenoidal magnet
  - drift-chamber tracking system
  - time of flight
  - Cerenkov counter
- balloon flights in Canada and at Antarctica
- **antideuteron results:**
  kinetic energy range: 0.17-1.15 GeV/n
  limit $1.9\times10^{-4}(m^2 s\ sr\ GeV/n)^{-1}$ @ 95% C.L.

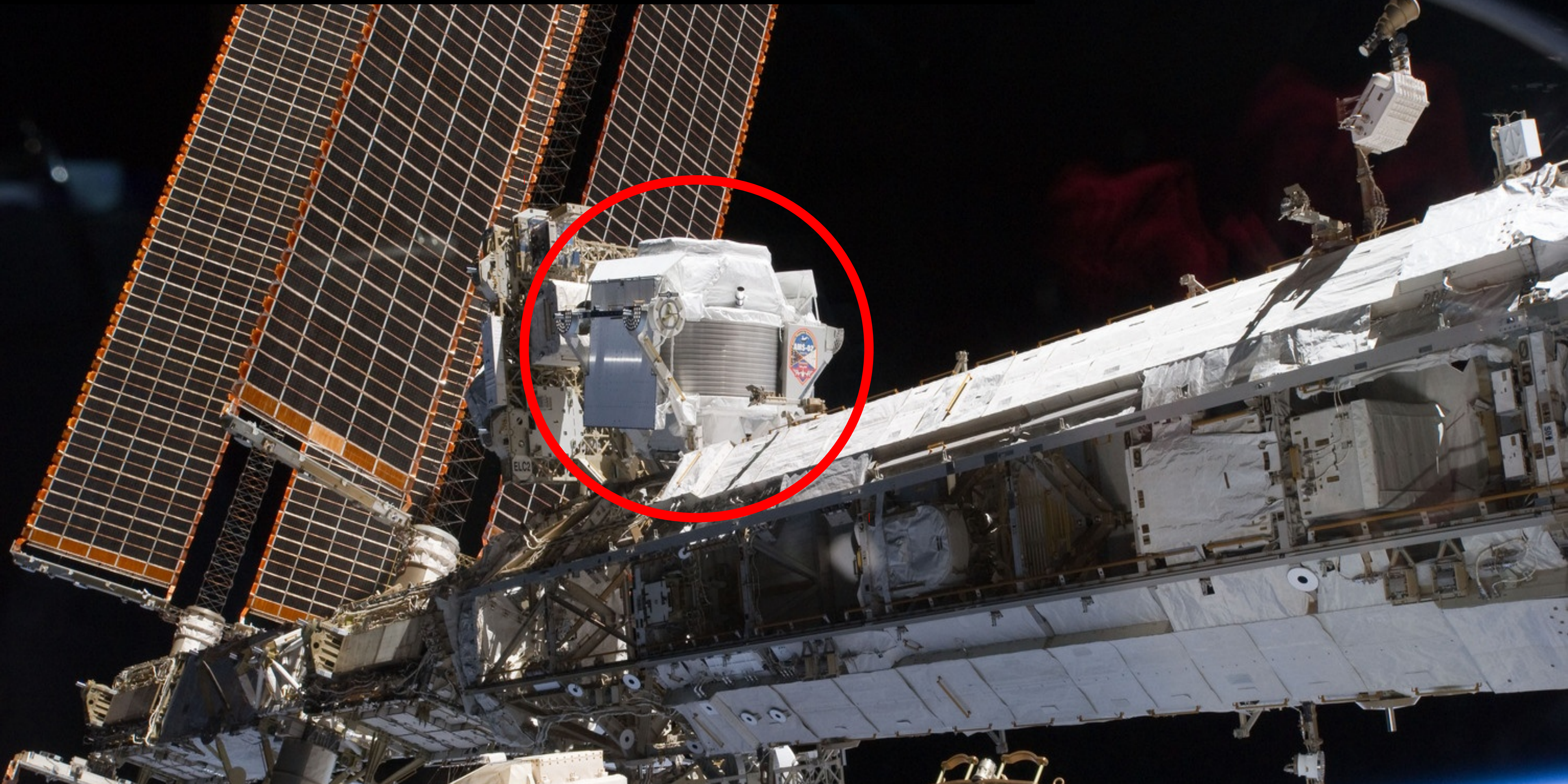


Space-based: PAMELA



- magnetic spectrometer in space since 2006
- particle identification with several typical particle physics sub-detectors
- relatively small acceptance ($21.5 cm^2 sr$)
- so far only indirect antideuteron limits derived from antiprotons [Phys. Lett. B, 683(4–5), 248 (2010)]
- background rejection not strong enough for antideuterons?

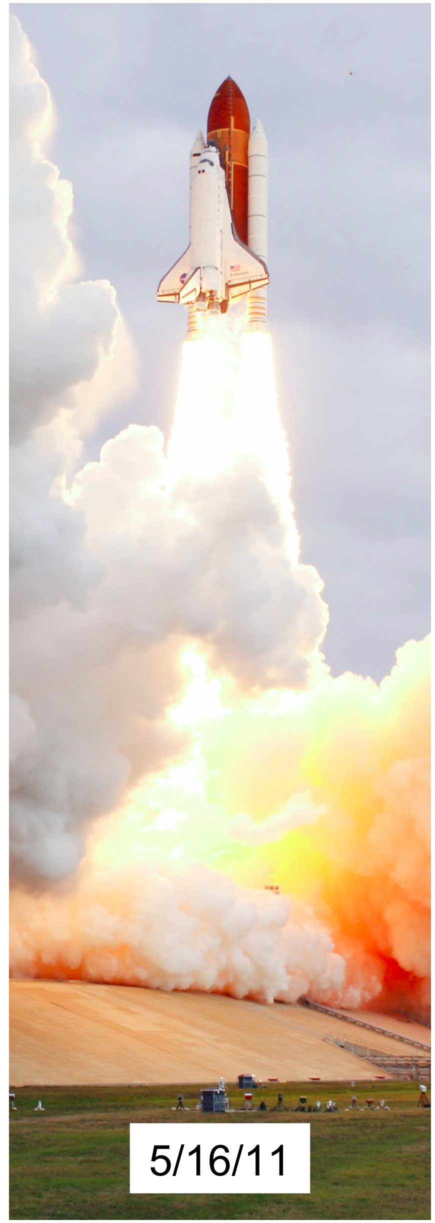
AMS on the International Space Station



- 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 billions of events over the first year
- first physics data coming soon

Launch STS-134

on the launc
4



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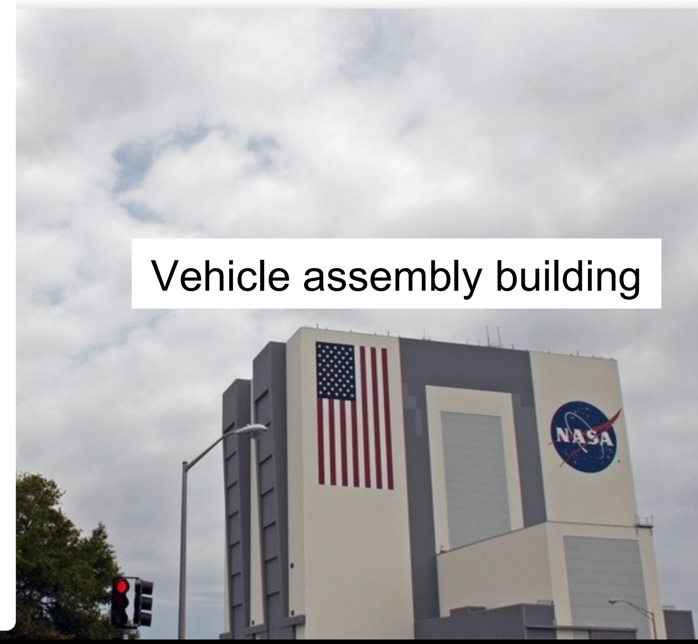
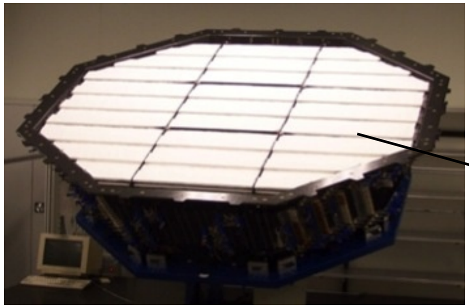


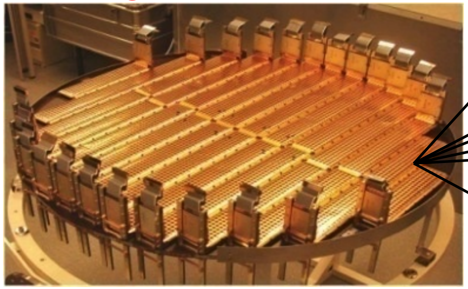
Vehicle assembly building

AMS sub-detectors

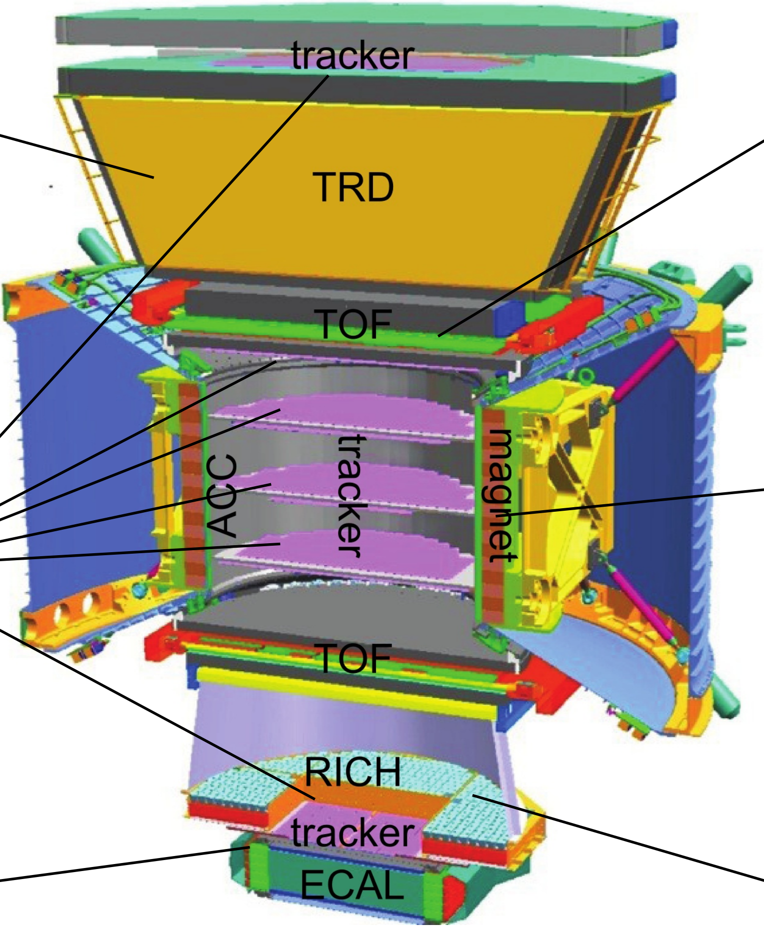
TRD
identify e+,e-



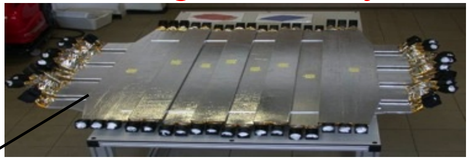
Silicon tracker
charge, momentum



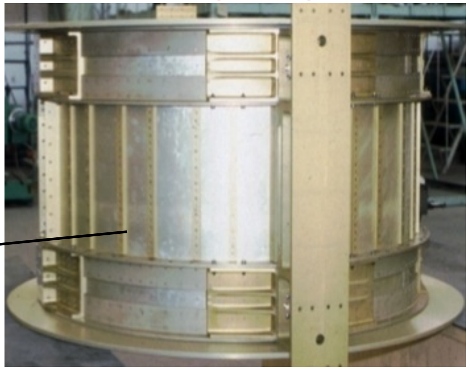
ECAL
energy of e+, e-, γ



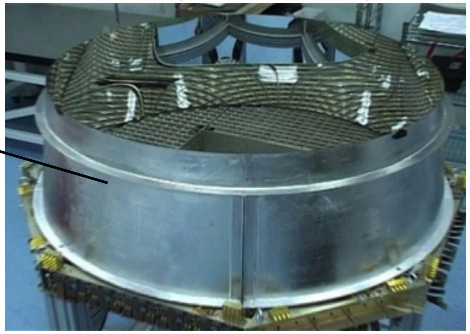
TOF
charge, velocity



magnet
charge sign

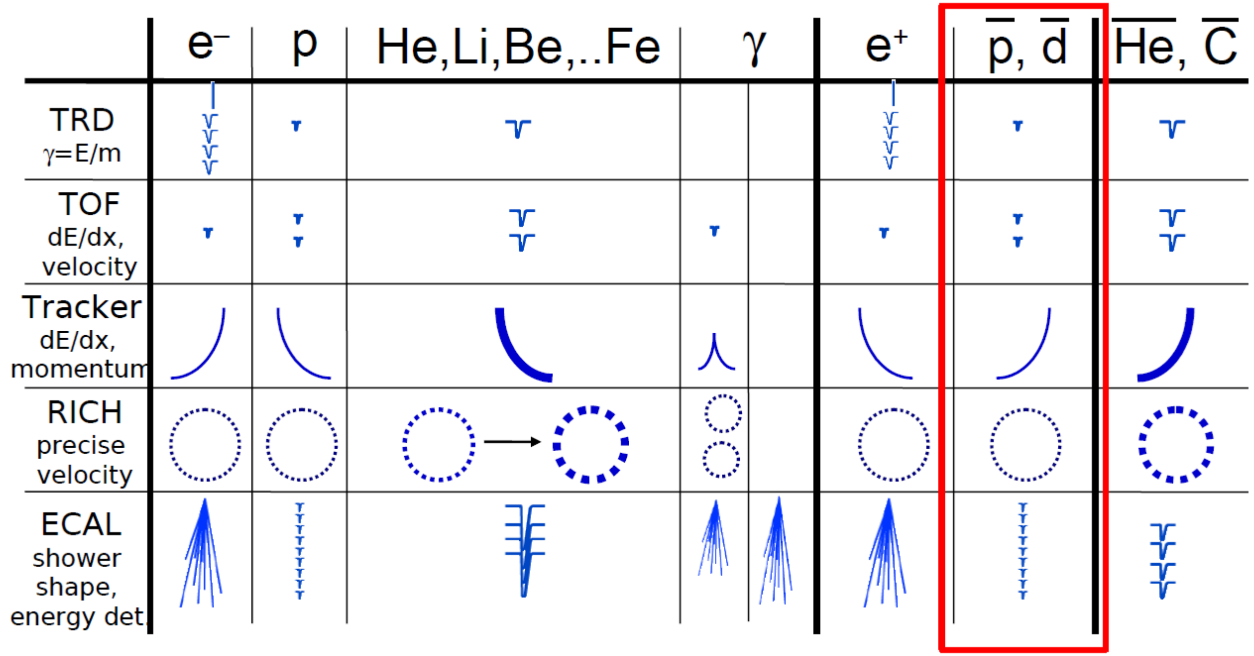


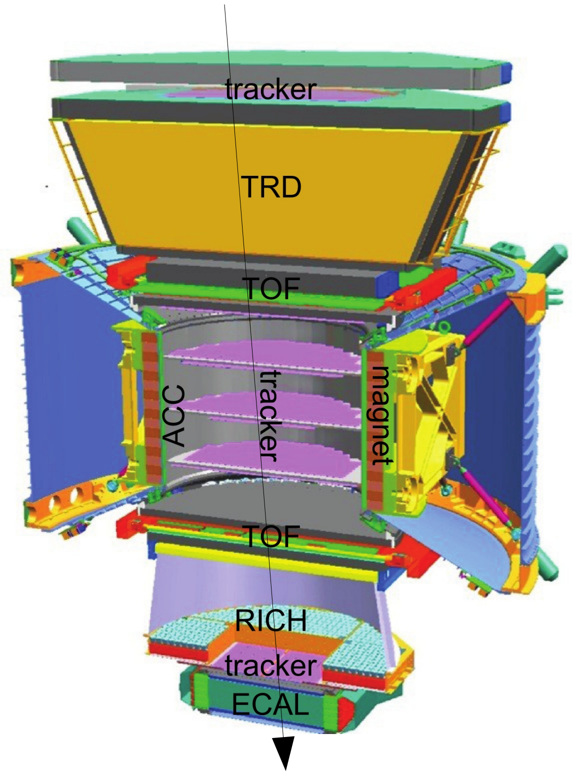
RICH
charge, velocity



Charge and momentum/energy are measured independently by the tracker, RICH, TOF and ECAL

AMS antideuteron analysis

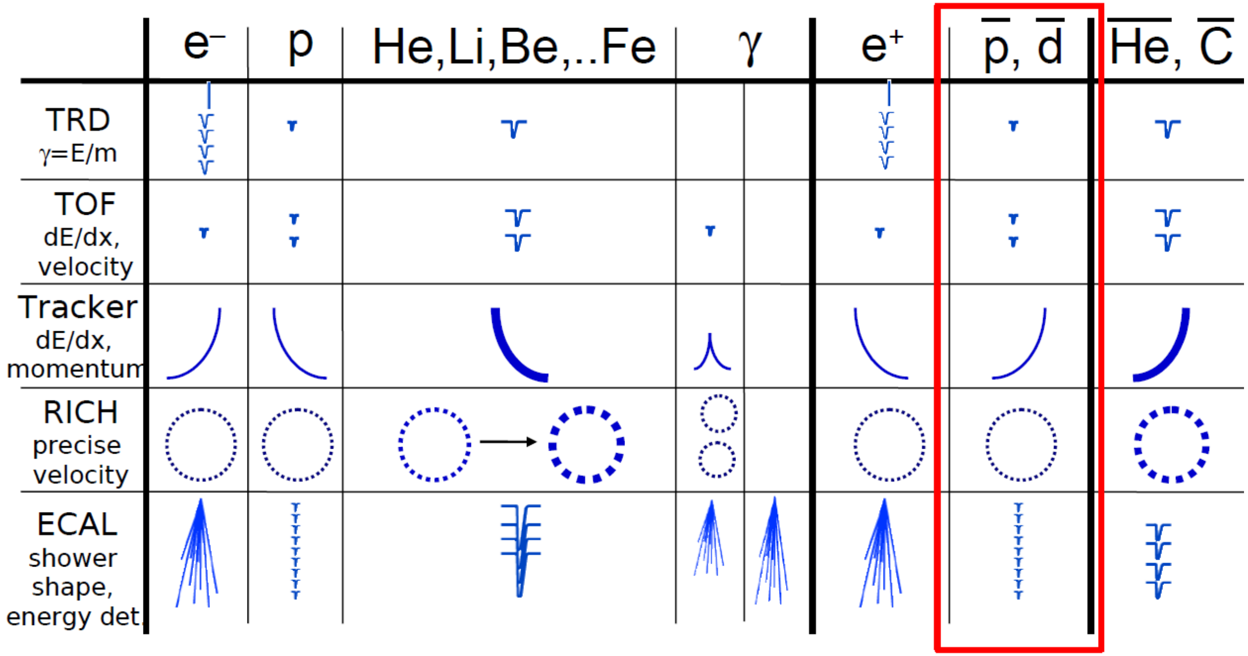


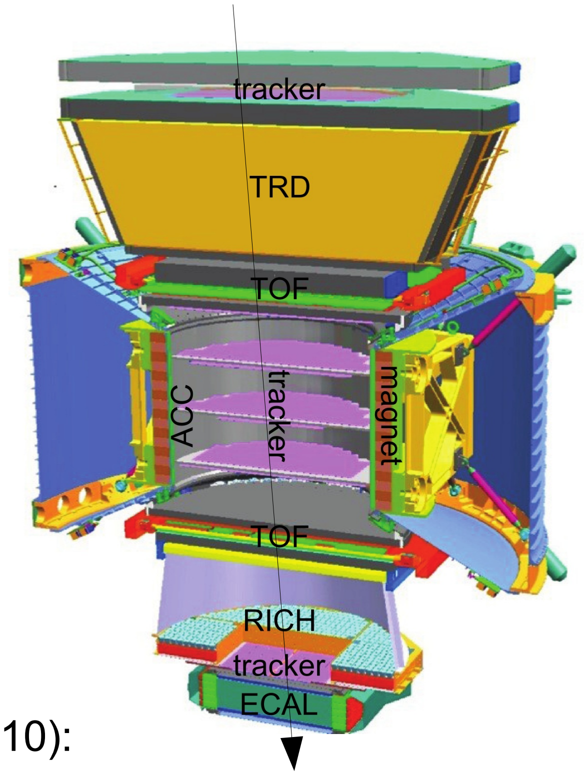


- **antideuteron identification:**
  - particle velocity:
    - lower velocities: **T**ime **O**f **F**light scintillator system
    - higher velocities: **R**ing **I**mage **Ch**erenkov detector
  - proton background: charge sign and momentum: tracker/magnetic field
  - electron background: reject electrons with TRD and ECAL
  - most complicated background: antiprotons

$$m = p\sqrt{\frac{1}{\beta^2} - 1}$$

AMS antideuteron analysis





- study change to **permanent magnet** and new tracker layout (2010): longer lifetime, but more multiple scattering
- **self-calibrated analysis:**
  - calibrate antideuteron analysis with deuterons and antiprotons (simulations and data)
  - study low-energy protons and electrons to predict geomagnetic and solar effects

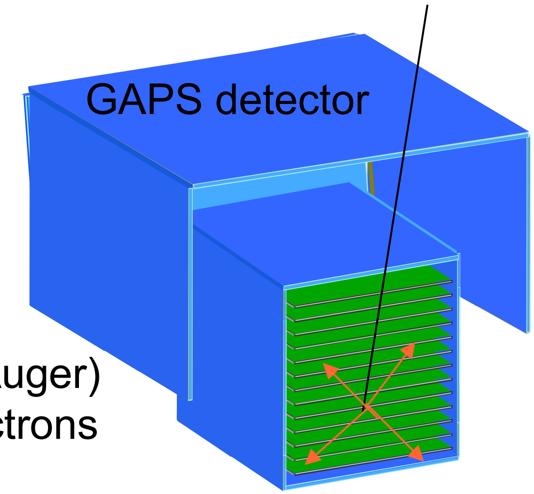
Novel approach for antideuteron identification

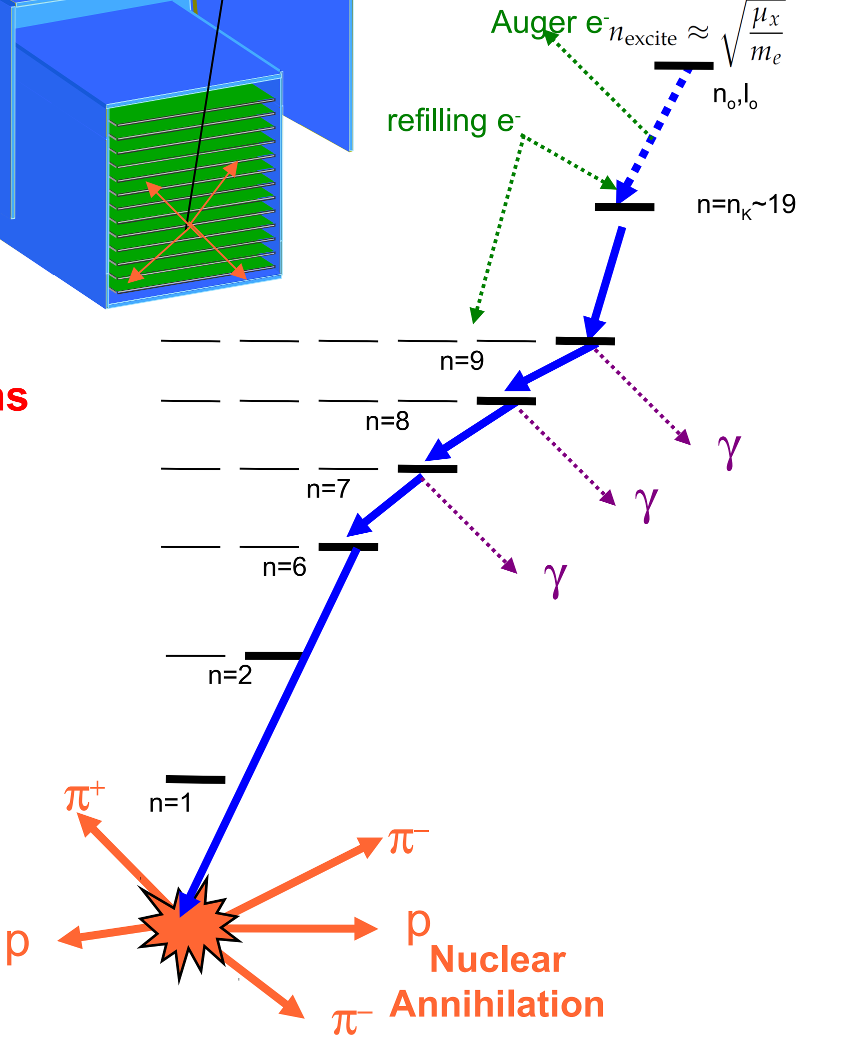
- antideuteron slows down and stops in material
- large chance for creation of an excited exotic atom ($E_{kin} \sim E_I$)
- deexcitation:
  - fast ionisation of bound electrons (Auger) → complete depletion of bound electrons
  - Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via **characteristic X-ray transitions**

$$\Delta E = 13.6\,eV \cdot (z_x Z_N)^2 \cdot \frac{\mu_x}{\mu_H} \cdot \left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

$$\mu_x = \frac{m_x \cdot m_N}{m_x + m_N} \quad \wedge \quad \mu_e = \frac{m_e \cdot m_N}{m_e + m_N}$$

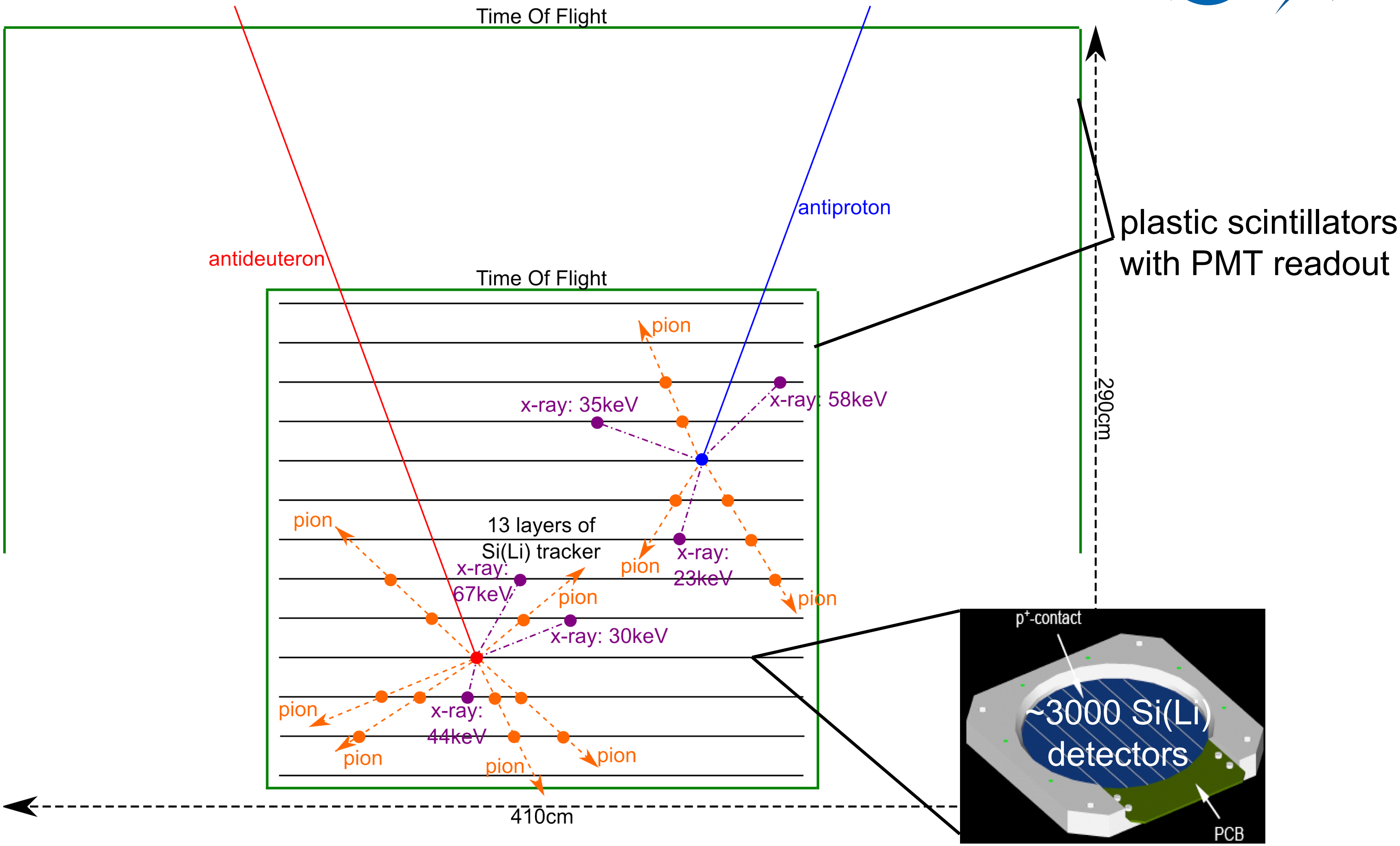
- nucleus-antideuteron annihilation: **pions and protons**





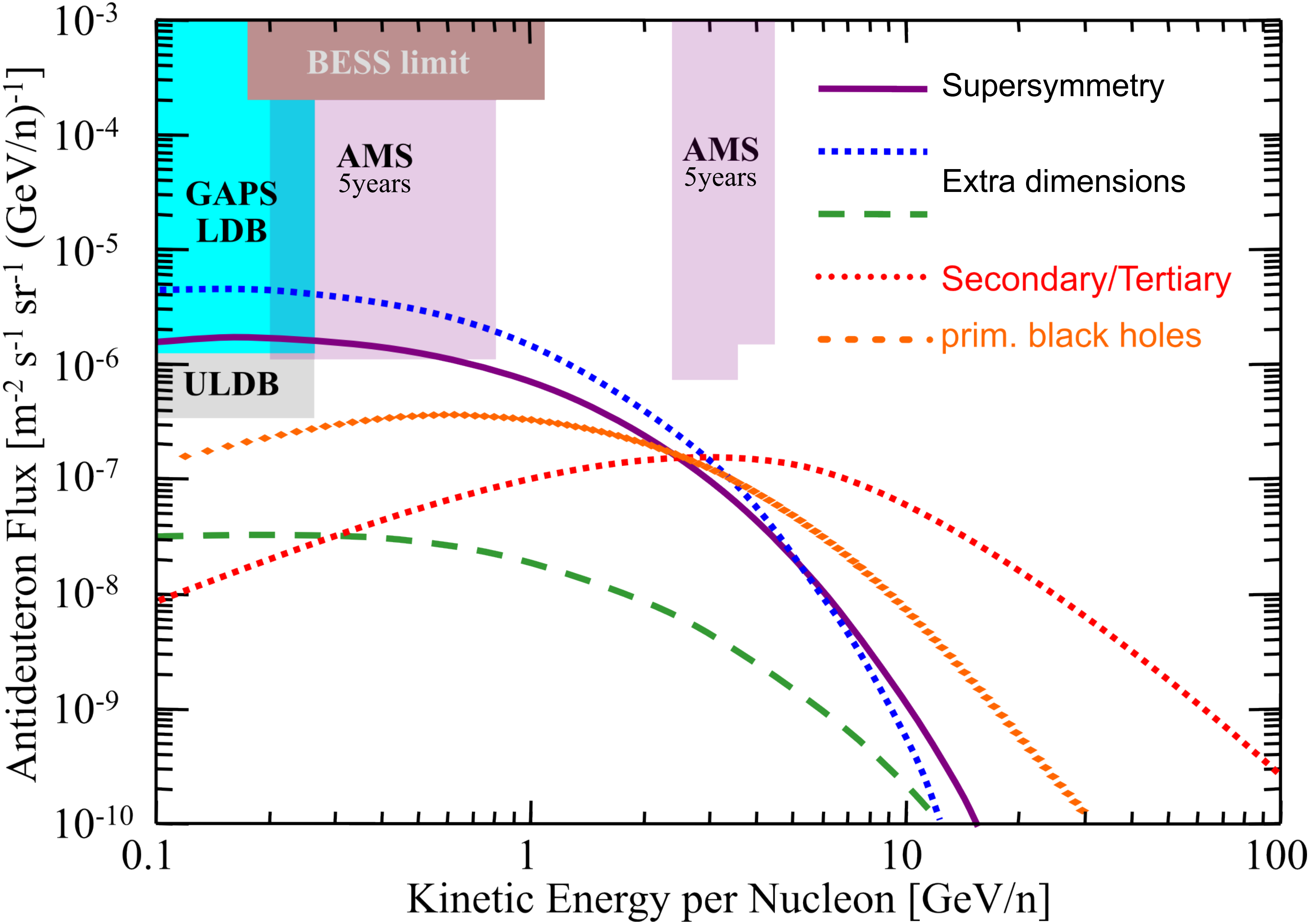
The GAPS experiment

Columbia University,
UC Berkeley, UCLA

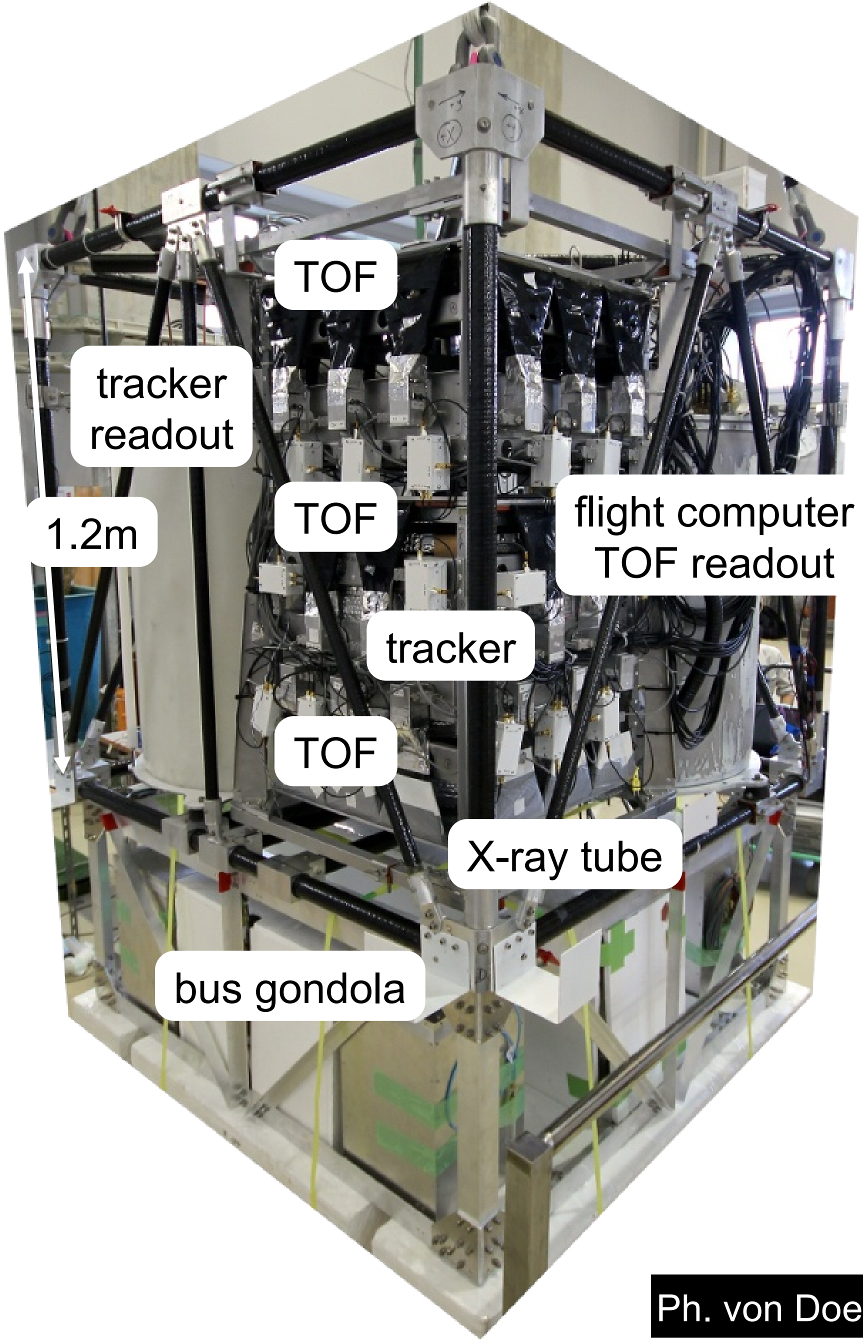


- the **G**eneral **A**nti**P**article **S**pectrometer is especially designed for **low-energy antideuterons**
- identification by stopping them in the tracker and creating an exotic atom
- (ultra) long duration balloon flights from Antarctica starting from 2017

Antideuteron sensitivity

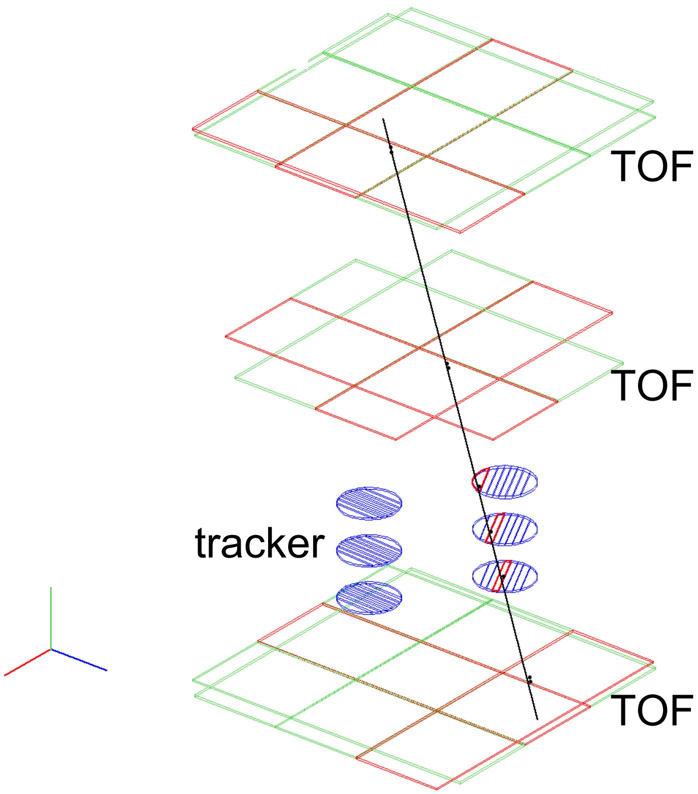


Prototype GAPS

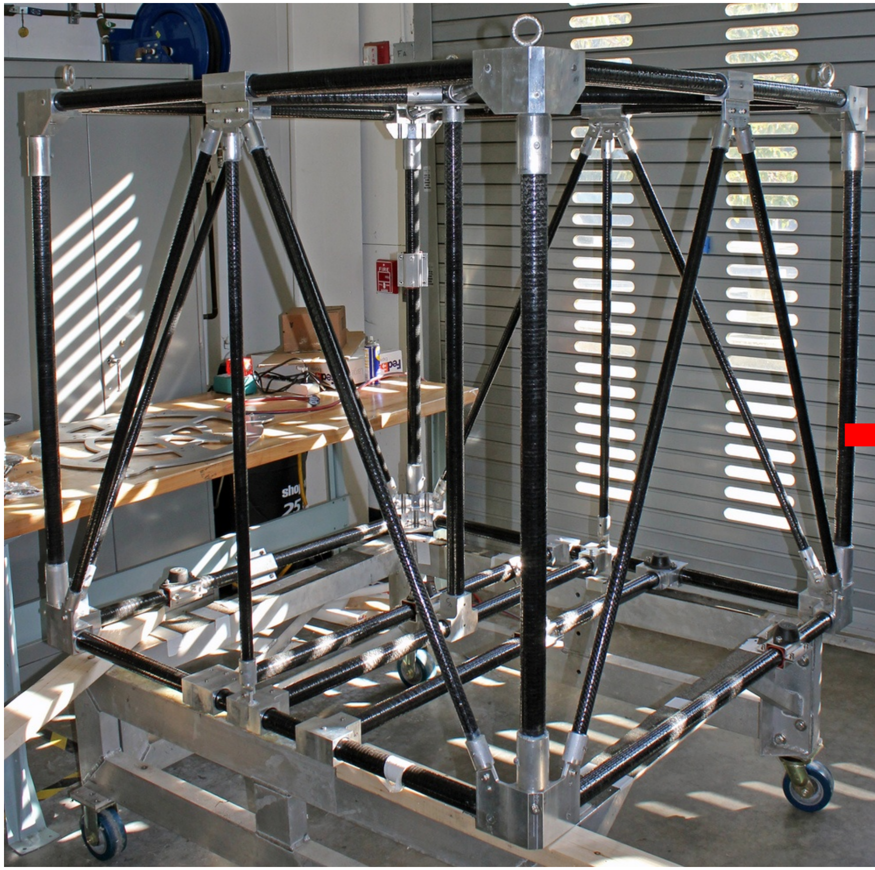


Goals:

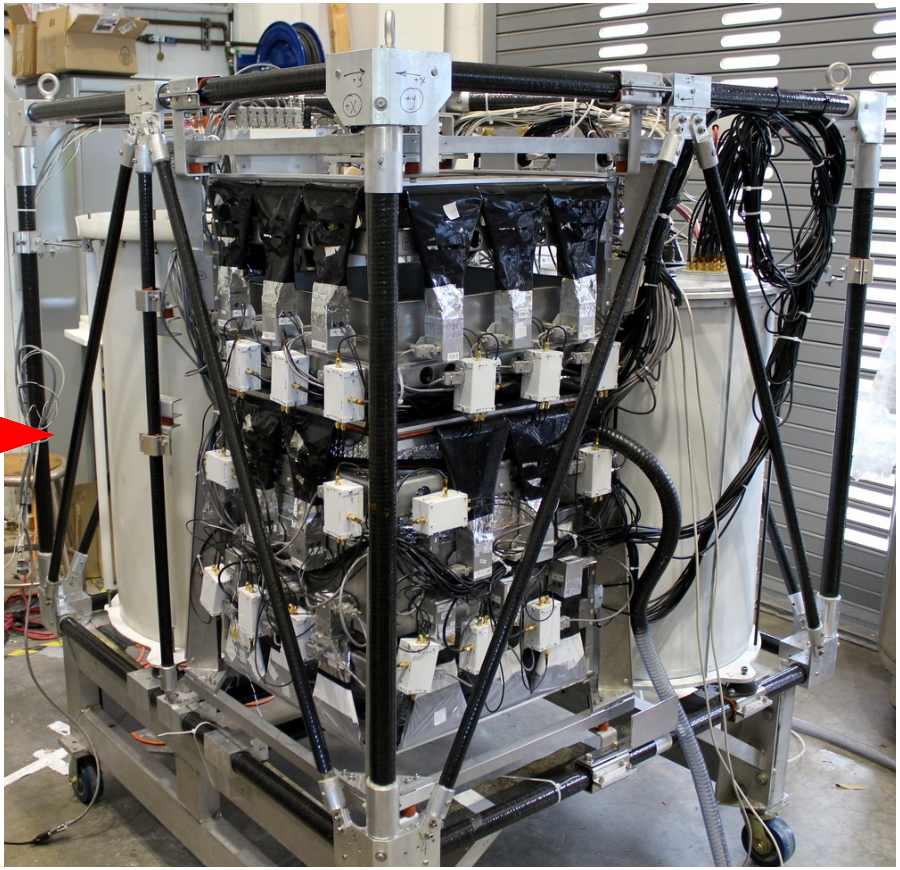
- demonstrate stable operation of the detector components during flight
- study Si(Li) cooling approach for thermal model
- measure background levels



Integration in Berkeley

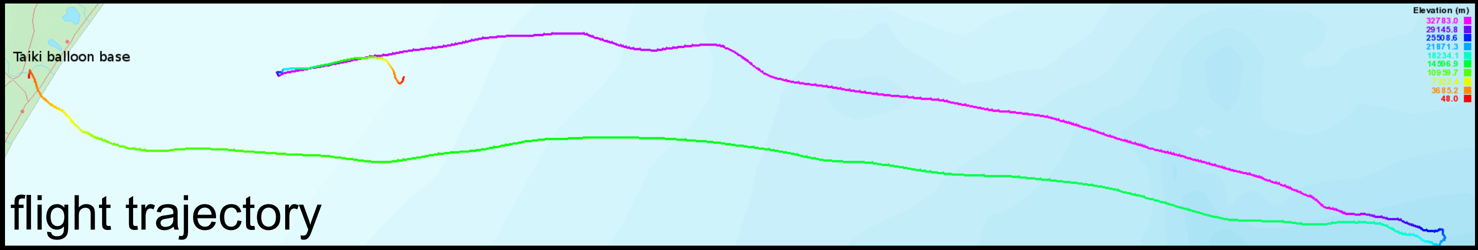


June 2011



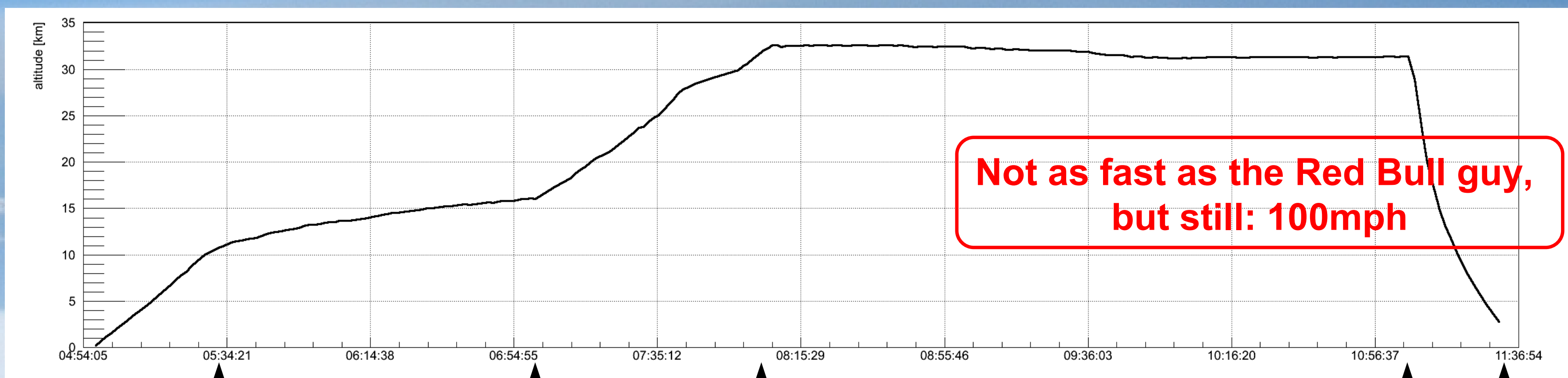
April 2012

- solving all mechanical and electronics issues
- debugging, extensive test runs, and calibration



Successful prototype flight!

Altitude profile



reached boomerang altitude (10-15km)

drop more ballast

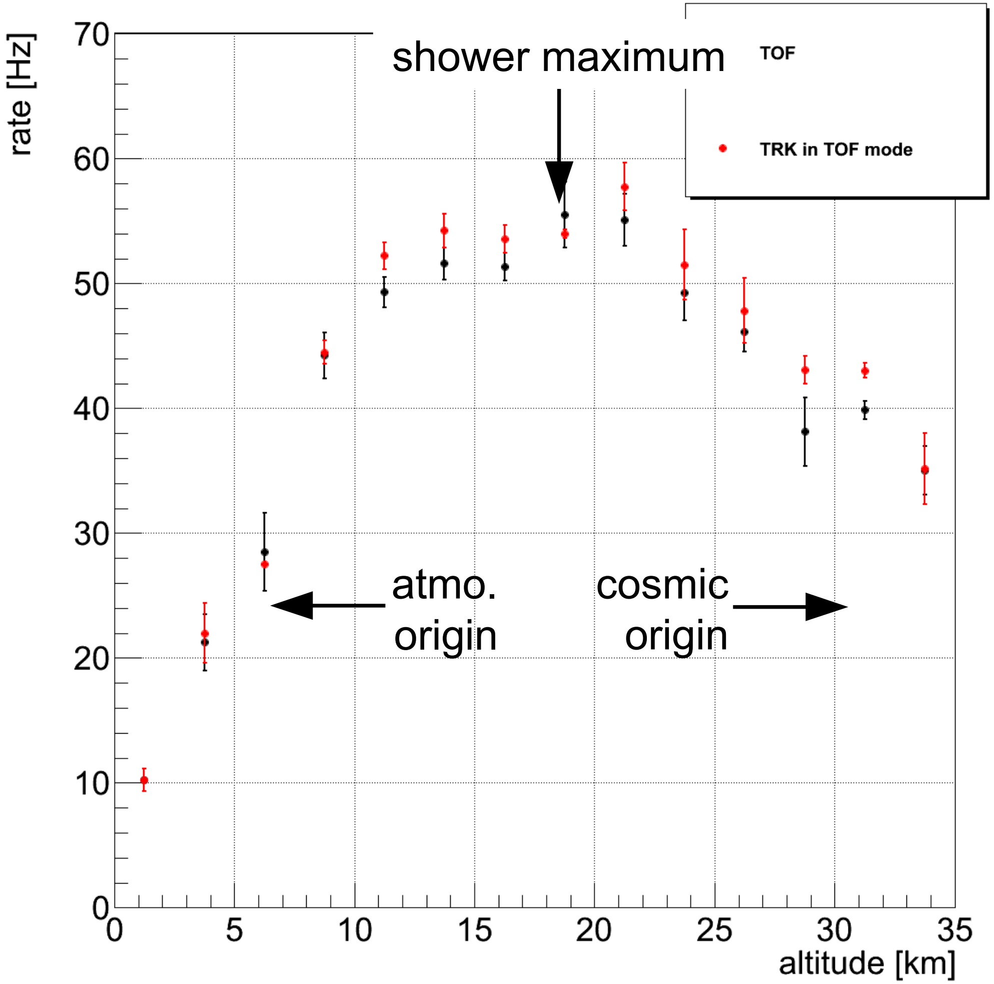
reached 33km float altitude

perfect flight
3h at float

cut balloon

splash down in Pacific

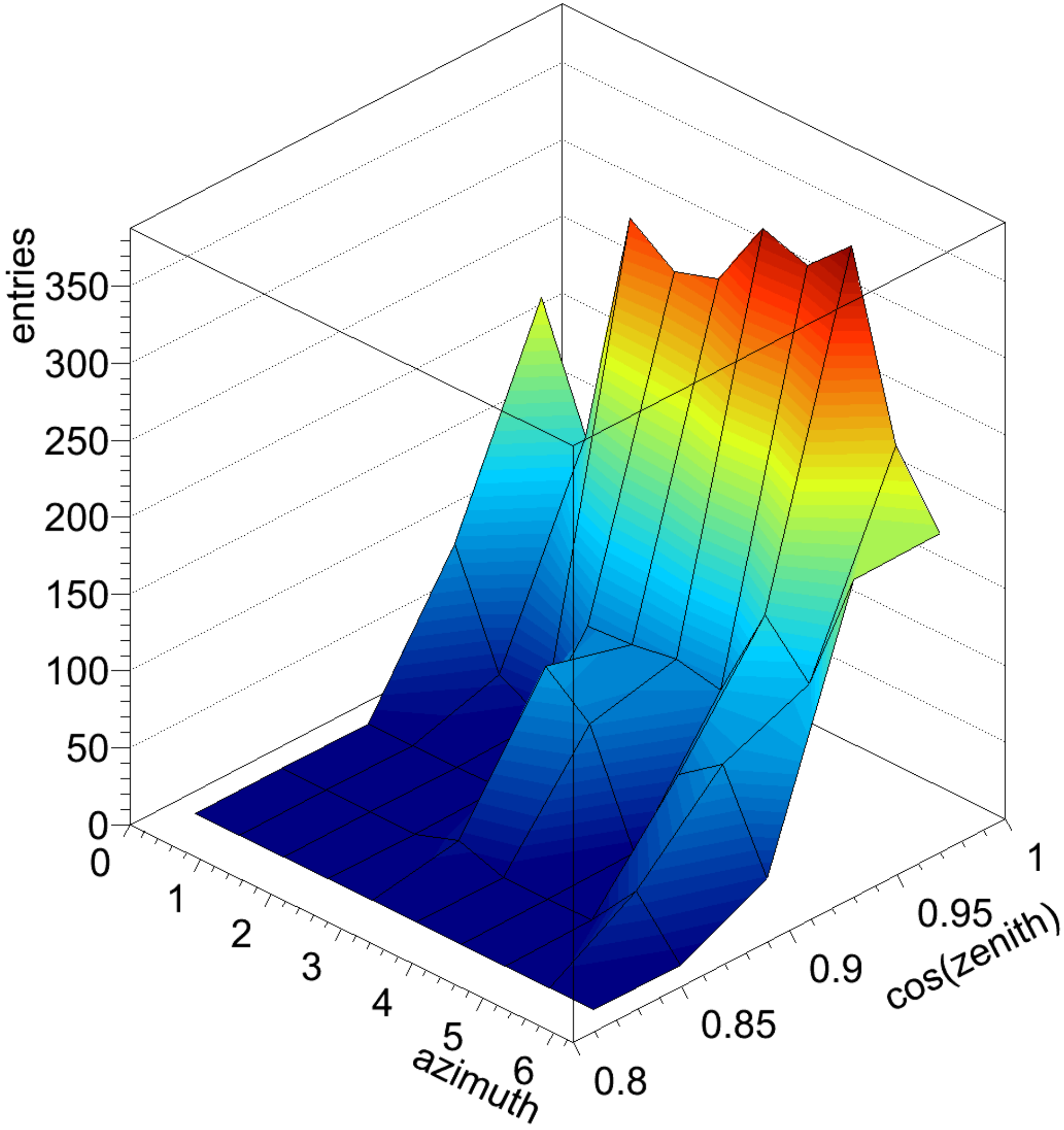
Data taking modes



raw TOF trigger rates

- **trigger on coincidences of TOF paddles to find charged particle tracks**
  - time: 244min
  - ~1Million triggers
- **carry out in-flight calibration of Si(Li) detectors**
  - run X-ray tube
  - time: 50min
- **trigger on Si(Li) detectors to study incoherent X-ray background**
  - time: 29min

pGAPS analysis status

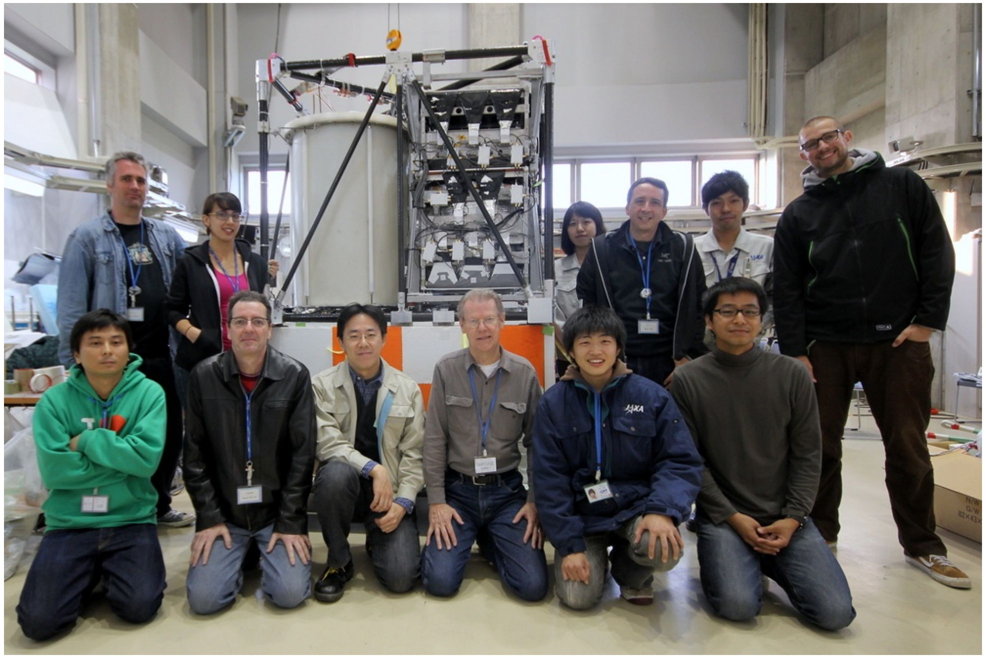


- counts need to be corrected for
  - angular acceptance
  - efficiency
  - livetime
- TOF timing analysis

→ flux as function of velocity β

Timeline for GAPS

- **2000** first idea
- **2004/05** KEK beamtests with antiprotons
- **2006-08** design work
- **2008-12** technical validation
- **2009-12** prototype flight from Japan
- **2013-2017** detailed design and construction
- **2017** first science flight from Antarctica



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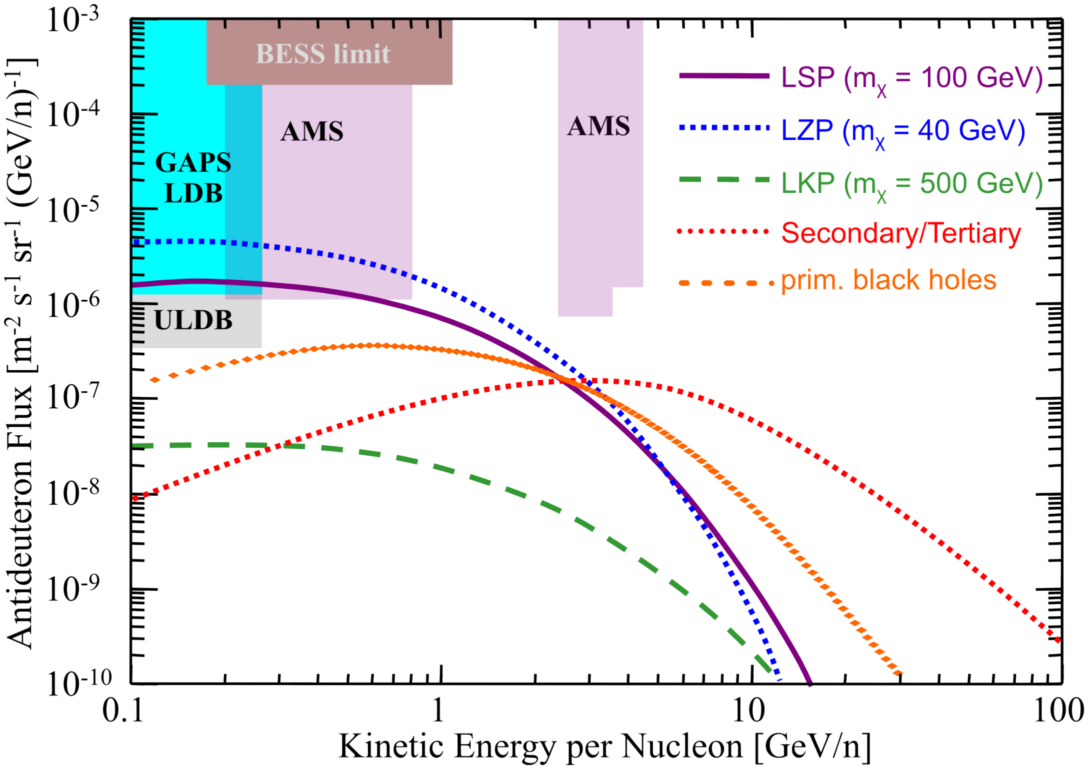
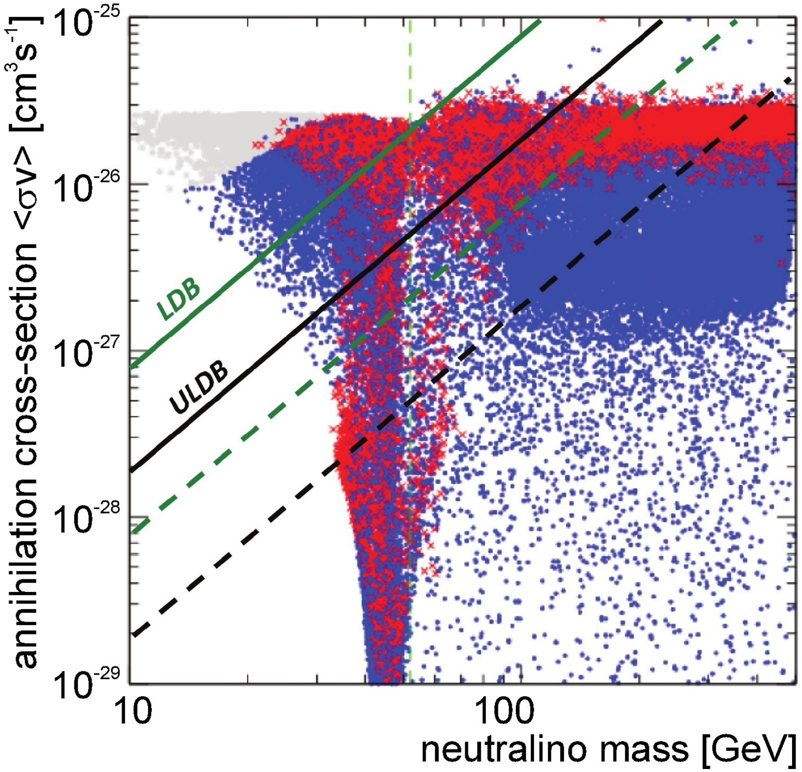
Future outlook: combine AMS and GAPS

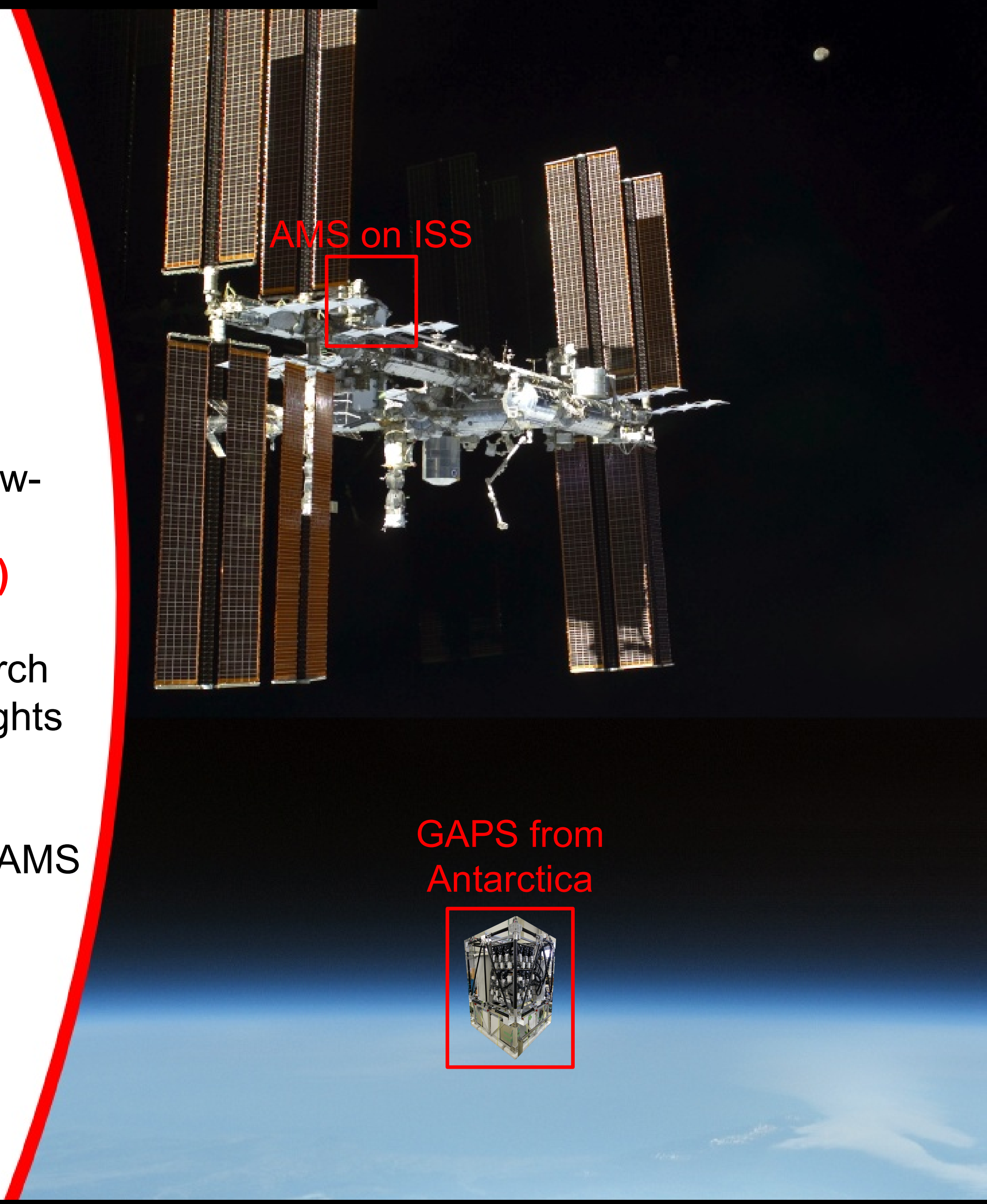




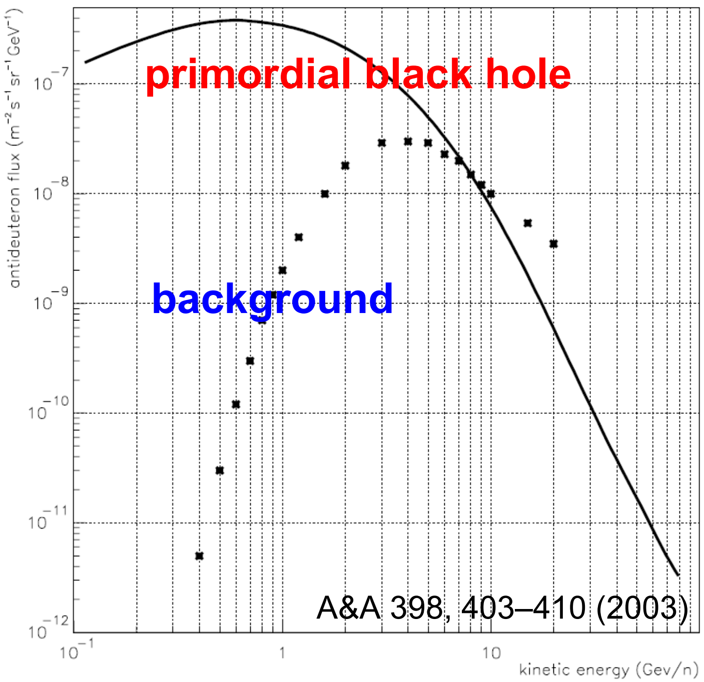
- **combination of two independent experiments with different techniques**
  - e.g., use antiprotons as cross-check
  - rare event searches always require independent confirmation
- **ideal case:** AMS measures antideuterons also in high velocity range, break in spectrum?

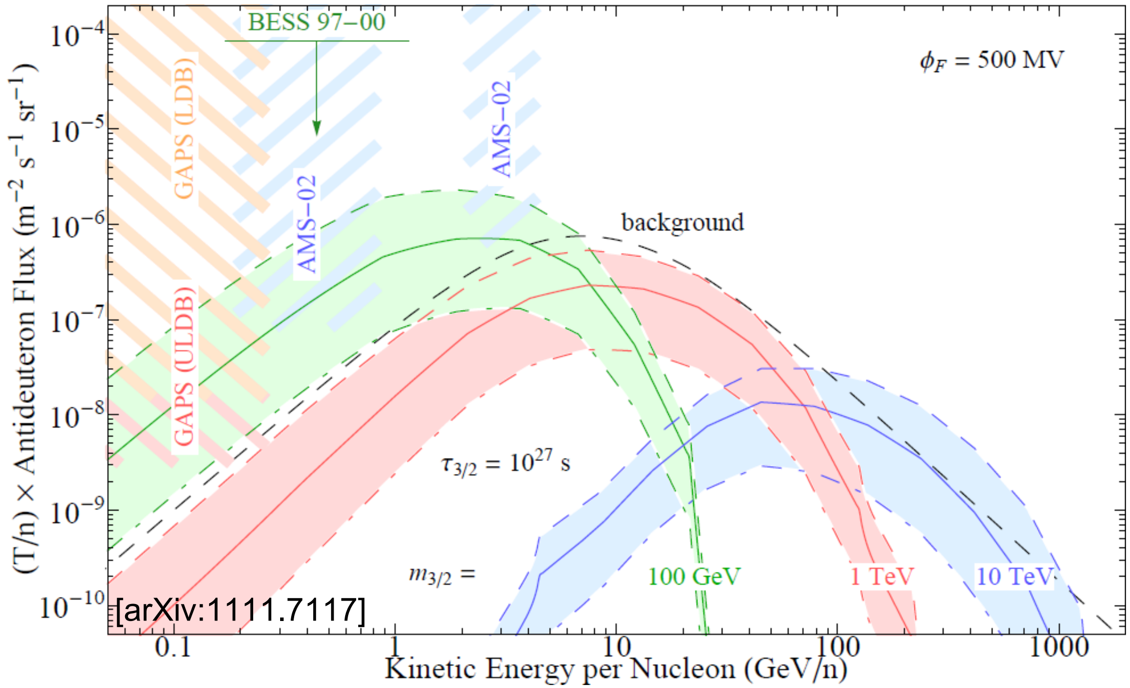
Conclusion

- measurement of antideuterons is a promising way for indirect dark matter search
- AMS on the ISS is currently the best instrument for the study of antideuterons
- future GAPS is specifically designed for low-energetic antideuterons
  (all goals for prototype GAPS were met)
- **timeline:** 5 year of AMS antideuteron search compatible with 3 long duration balloon flights of GAPS (starting ~2017)
- **necessary:** independent cross checks of AMS and GAPS results
- **hopefully create similar excitement like the FERMI photon results did!**



Even more exotic sources producing antideuterons?





- **primary black holes:**
  - very small black holes could have formed in the early universe due to, e.g., initial density inhomogeneities
  - might evaporate antideuterons and **maybe the only chance to detect primordial black holes**
- **baryon asymmetry/cosmological gravitino problem:**
  - hypothetical mediator of gravity: graviton → superpartner gravitino
  - late decays of unstable gravitinos to standard particles would produce antideuterons

Extension to antihelium searches

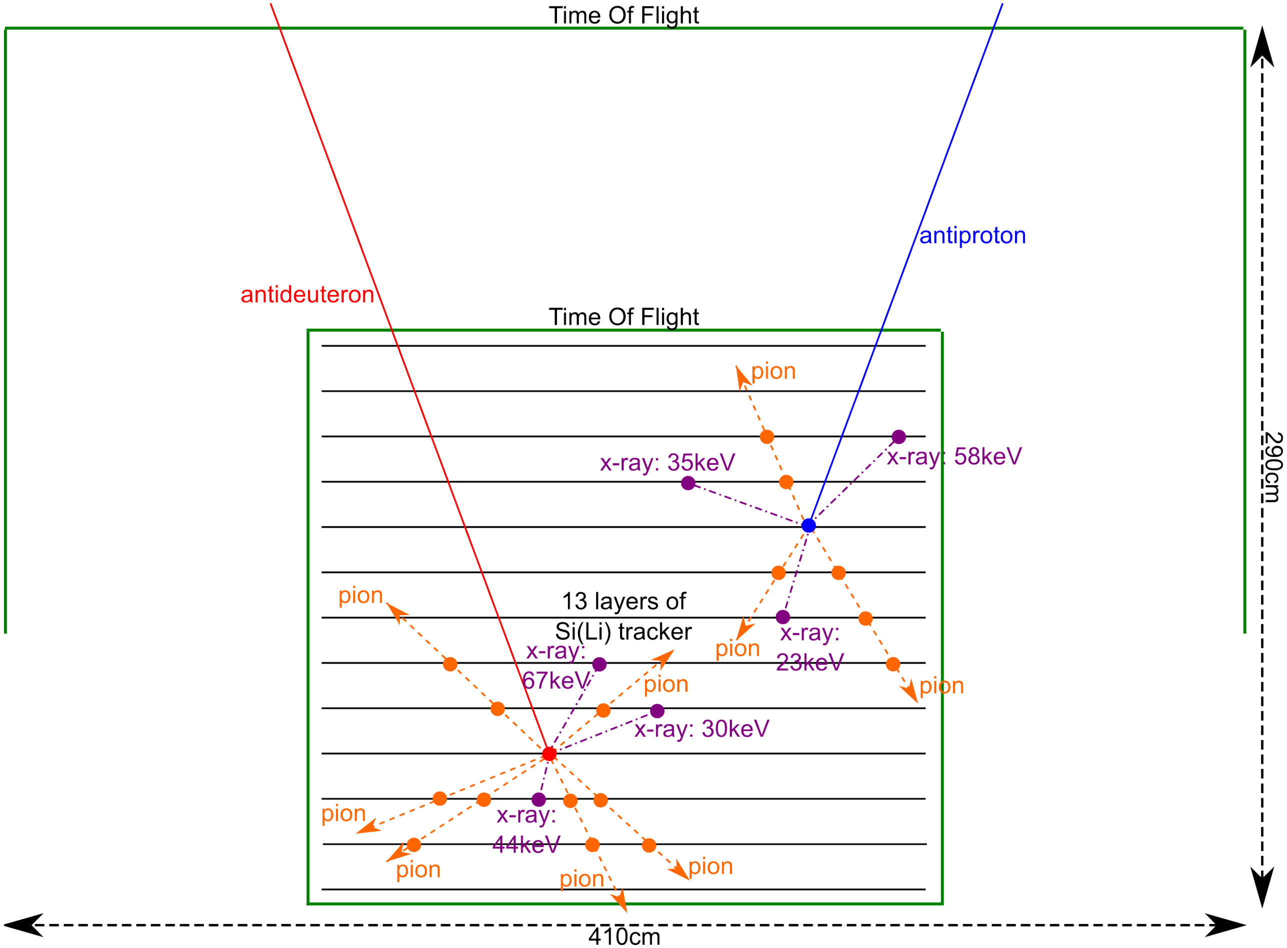
baryon asymmetry in the universe:

- dynamically: large CP violation is needed
- separation of matter and antimatter in the early universe

antihelium is a natural extension of the antideuteron search:

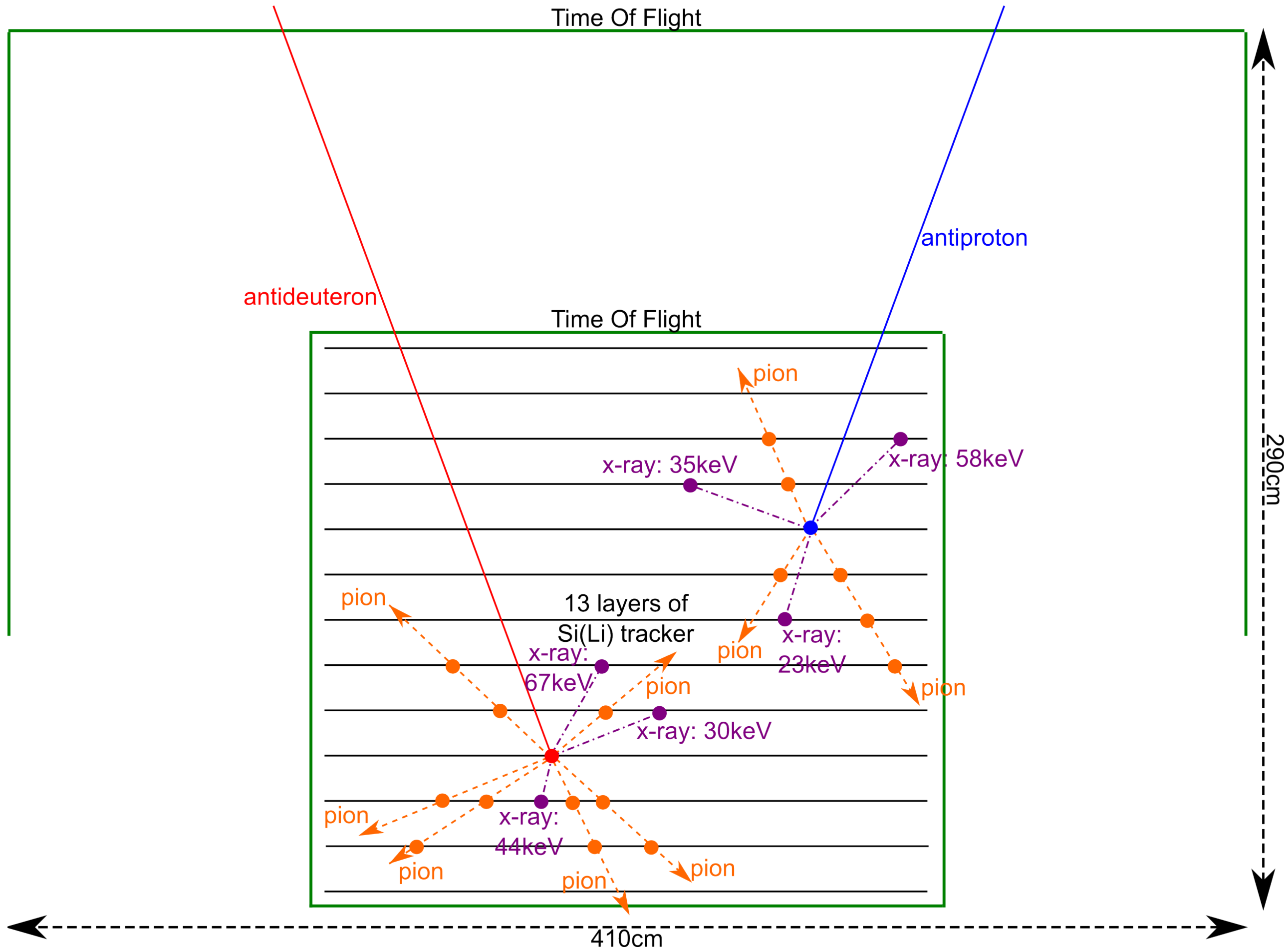
- bound on antihelium gives constraint for the distance between galaxies and antigalaxies
- because antihelium production in p-ISM interactions in the matter universe is extremely small

GAPS antideuteron analysis



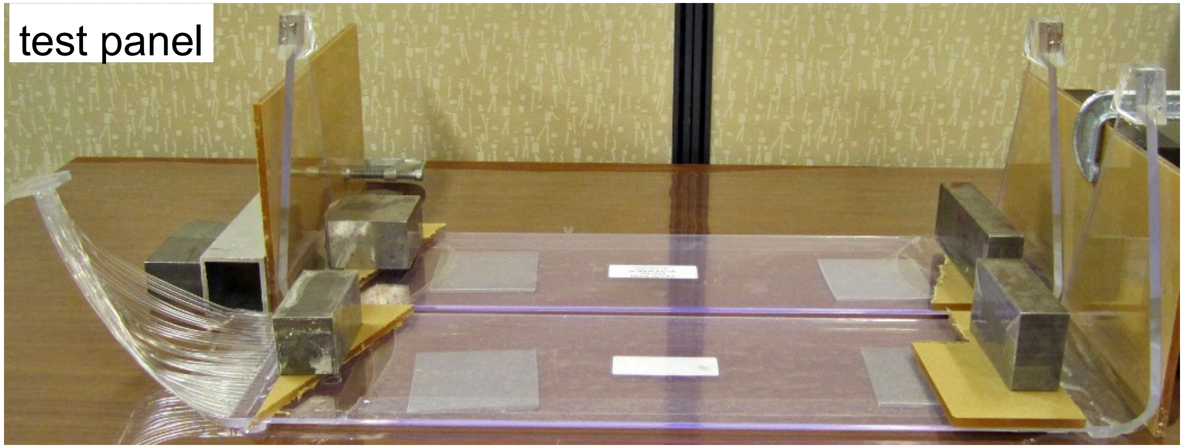
- **GAPS needs a very reliable particle identification:**
  - TOF velocity and tracks
  - charge |Z|
  - depth in tracker
  - X-rays from deexcitation
  - pions and protons from annihilation

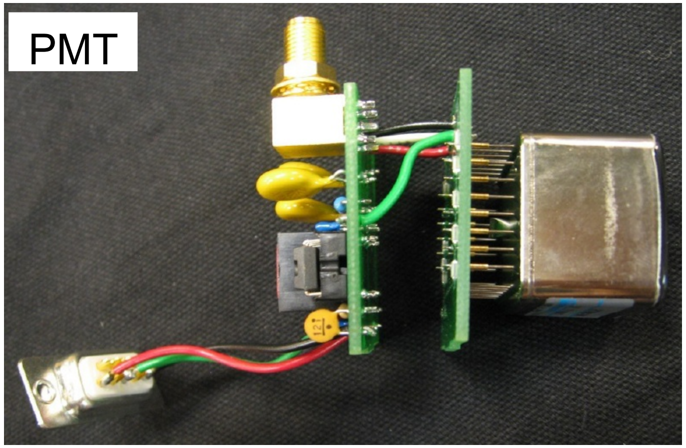
GAPS antideuteron analysis



- **main source of background: antiprotons** (only differ in mass)
- other important backgrounds:
  - coincidences from cosmic and atmospheric X-ray flux
  - coincidences of X-rays produced in interactions of charged particles with the detector
  - atmospheric antideuterons

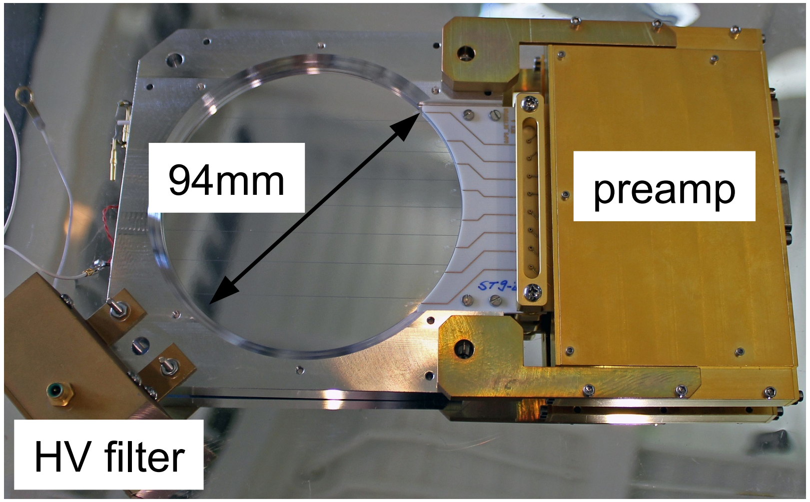
Time of flight



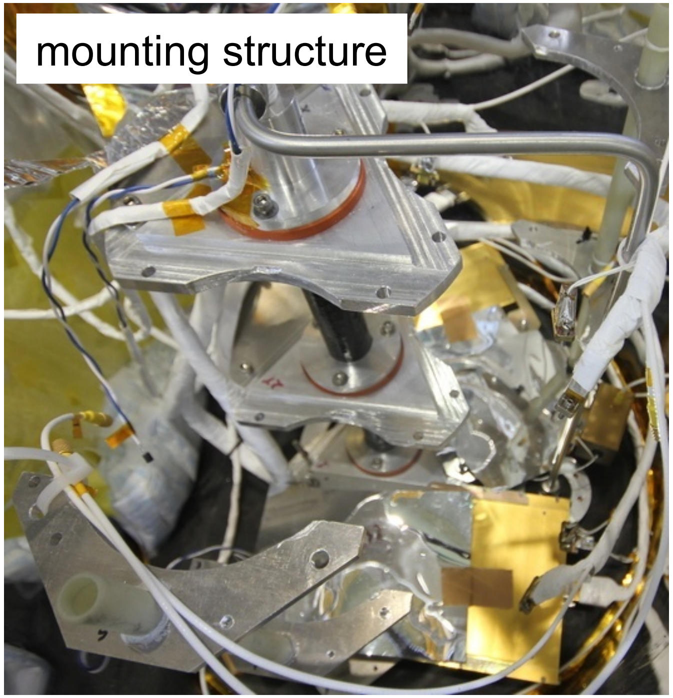


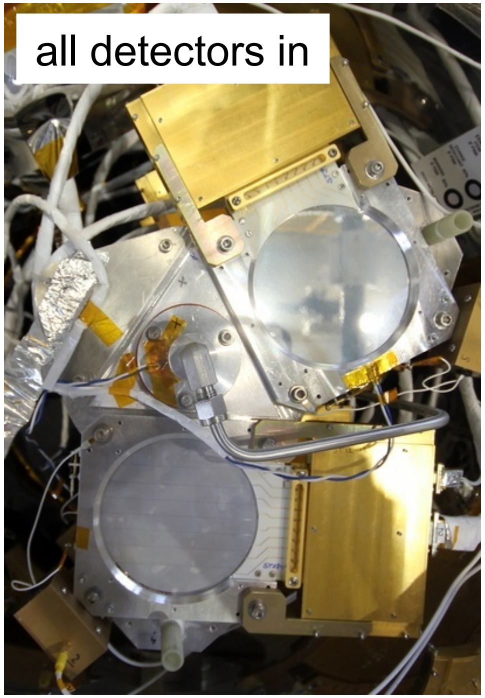
- **tasks:**
  - charged particle trigger
  - velocity measurement
  - tracking
- **design:**
  - 3 planes of TOF
    outer planes consists of 3×3, middle plane 2×2 crossed paddles
    1 paddle has 2 PMTs = **16 paddles and 32 PMTs**
  - 3mm scintillator from Saint-Gobain (BC-408)
  - Hamamatsu R-7600 PMT
- **properties:**
  - timing resolution: **500ps**
  - charge resolution: **0.35e**
  - angular resolution: **8°**

Si(Li) tracker

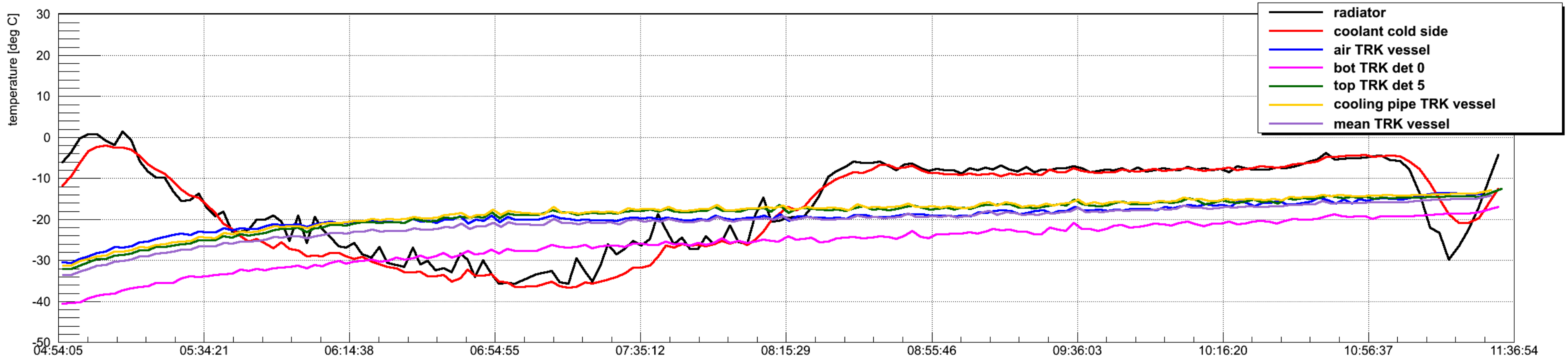


- 6 detectors
  2 stacks with 3 layers
- 4mm/2.5mm thick, 8 strips
- N+: Lithium contact
  P+: Boron implanted (strips)
- operation at ambient pressure during flight (8mbar)
- closed-loop fluid pumping system (Fluorinert)



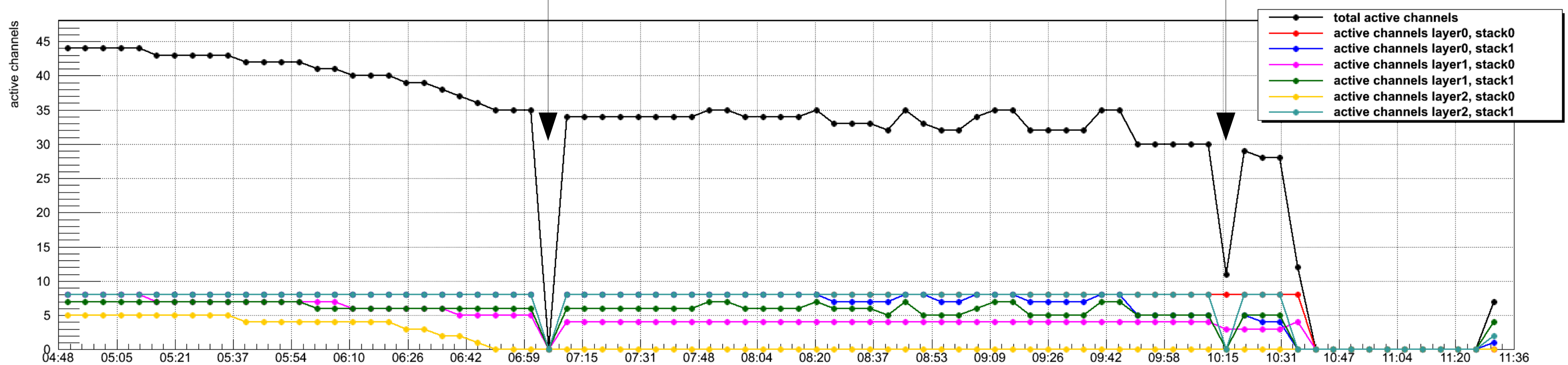


Tracker operation



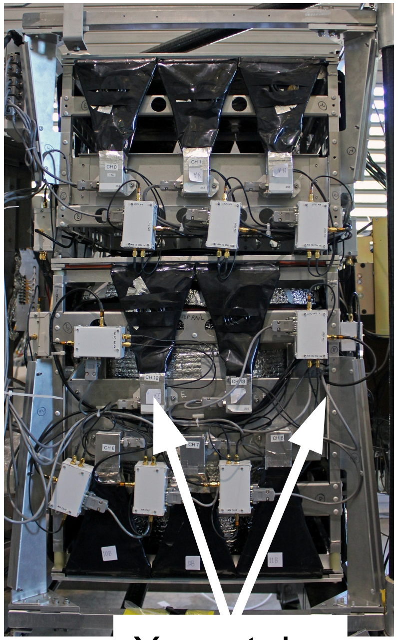
flight computer reboot

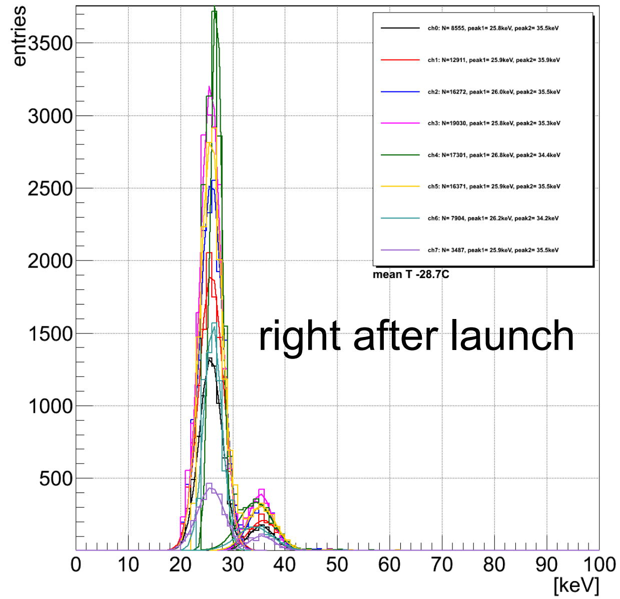
tracker electronics reset

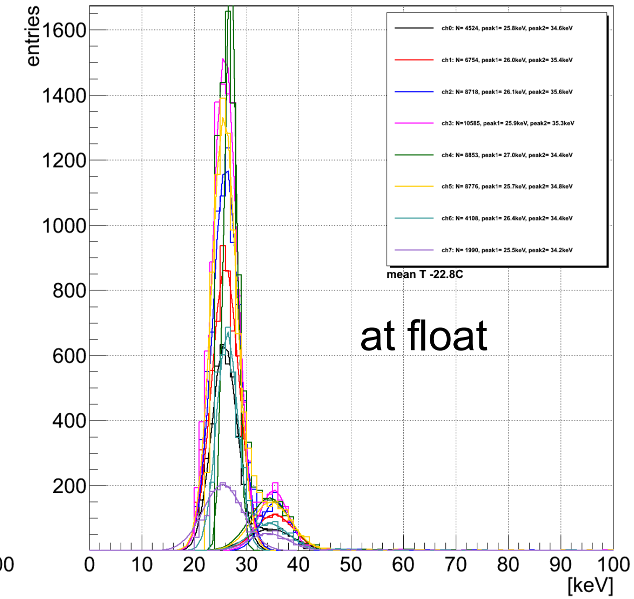


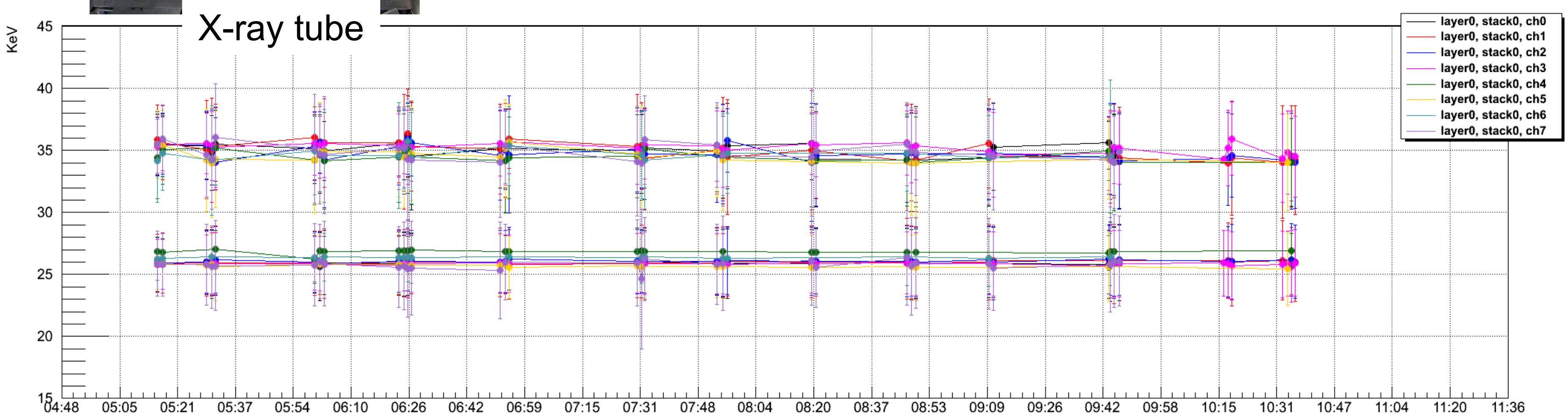
- tracker worked reliably even at rather high temperatures by the end of the flight

In-flight X-ray tube calibration



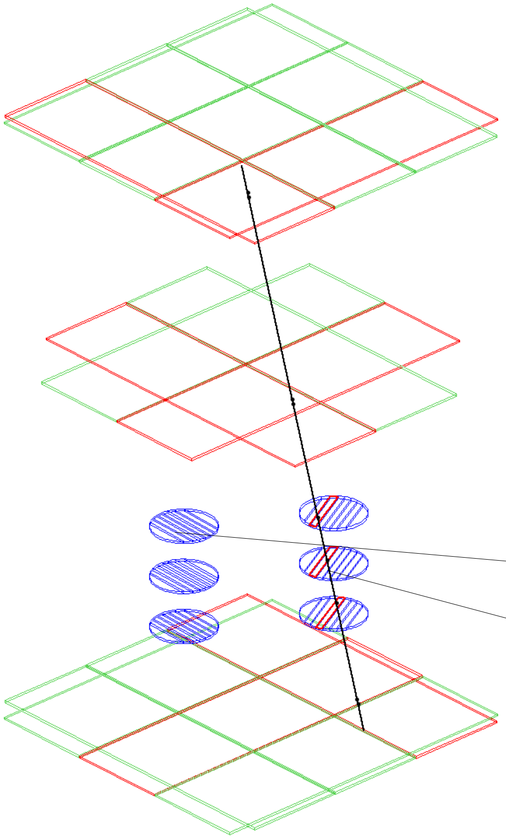




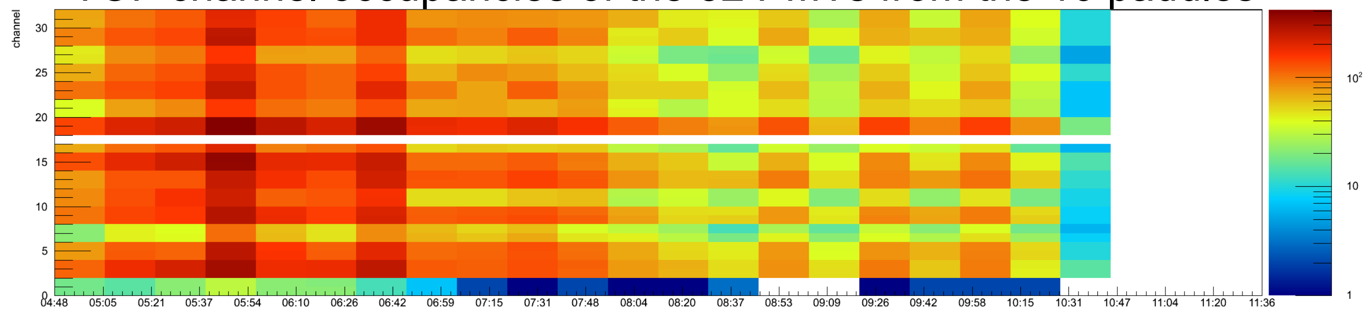


- position and width appear to be stable over time even with a relatively warm detector by the end of the flight

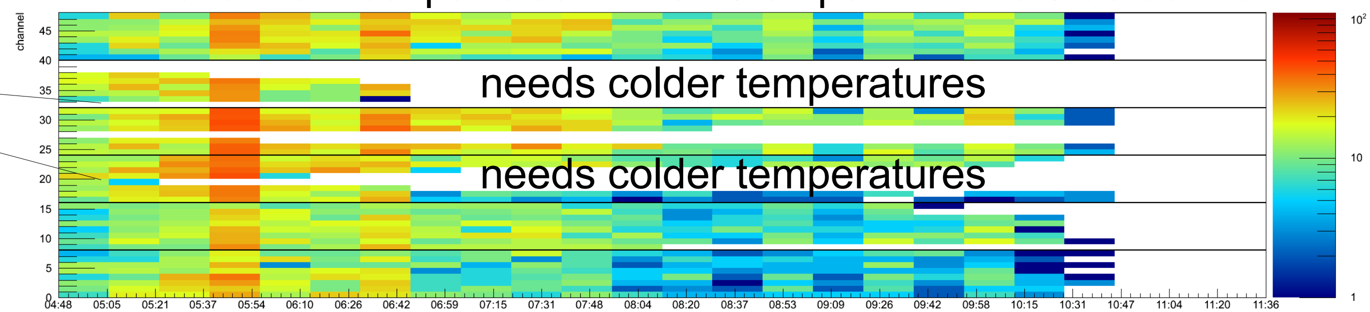
Clean track analysis



TOF channel occupancies of the 32 PMTs from the 16 paddles



TRK channel occupancies of the 48 strips from the 6 detectors



Clean events: 6 TOF layers with only one paddle fired
at least 2 TRK detectors with only one strip fired in low gain channel