Indirect dark matter searches

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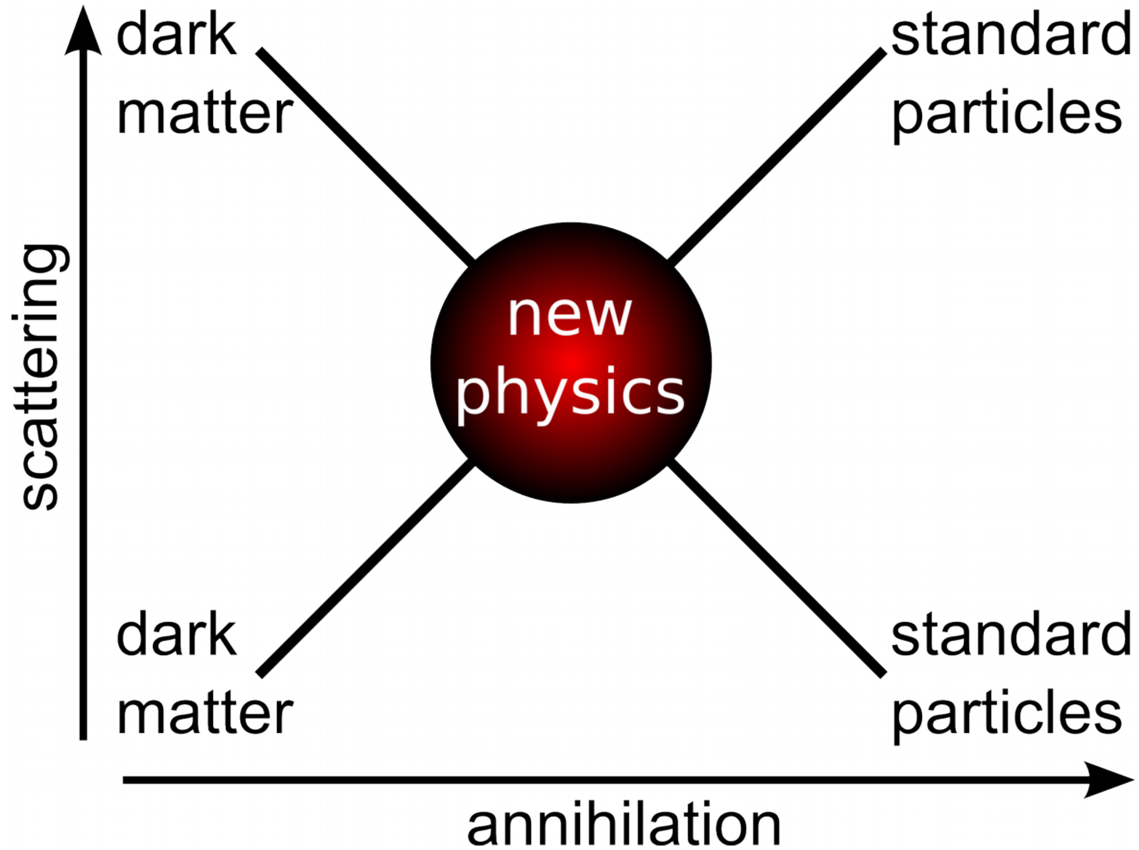
How is dark matter interacting?

→ Cirelli



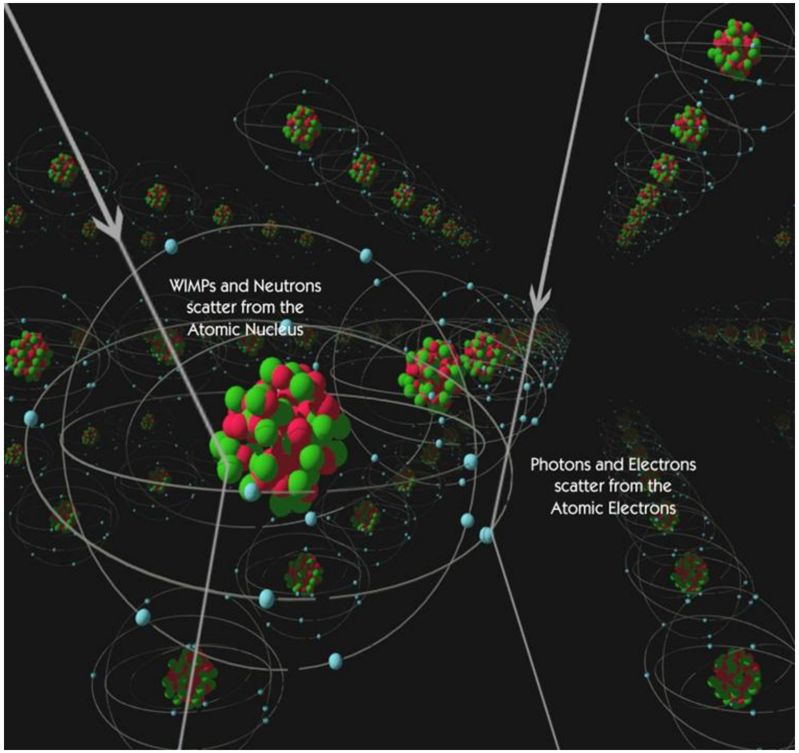
- **natural assumption:** dark matter was in thermal equilibrium in the early universe expansion led to dark matter freeze-out
- **WIMP miracle:** weak-scale particles are ideal candidates (~10-1000GeV) to reproduce observed relic dark matter density

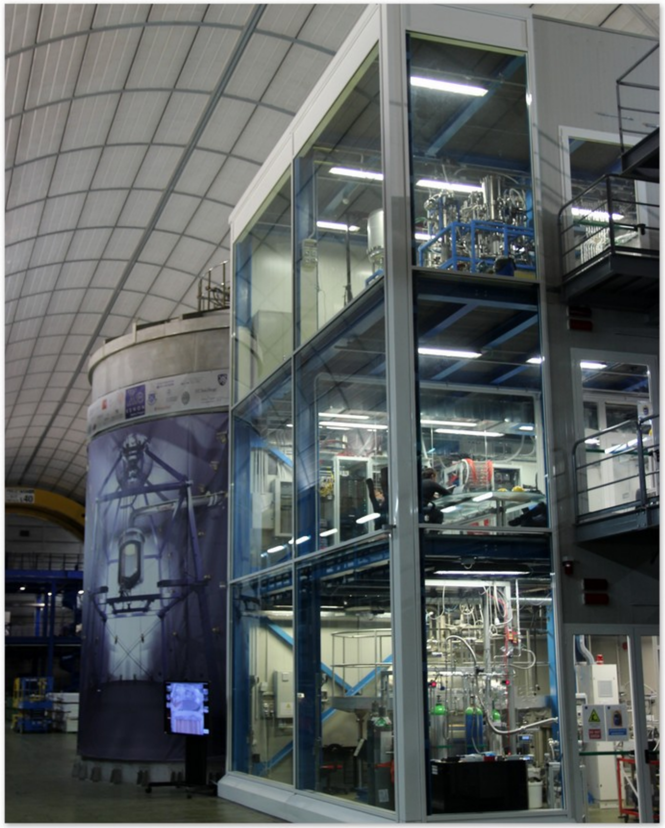
→ **dark matter must(?) be able to interact with standard model particles**

- we entered the era of discovery
- data analyses are starting to make claims
- but so far inconclusive
- general strategy: use search channel where dark matter signal is larger than astrophysical flux!

Complementarity approach:
direct, indirect, and collider experiments

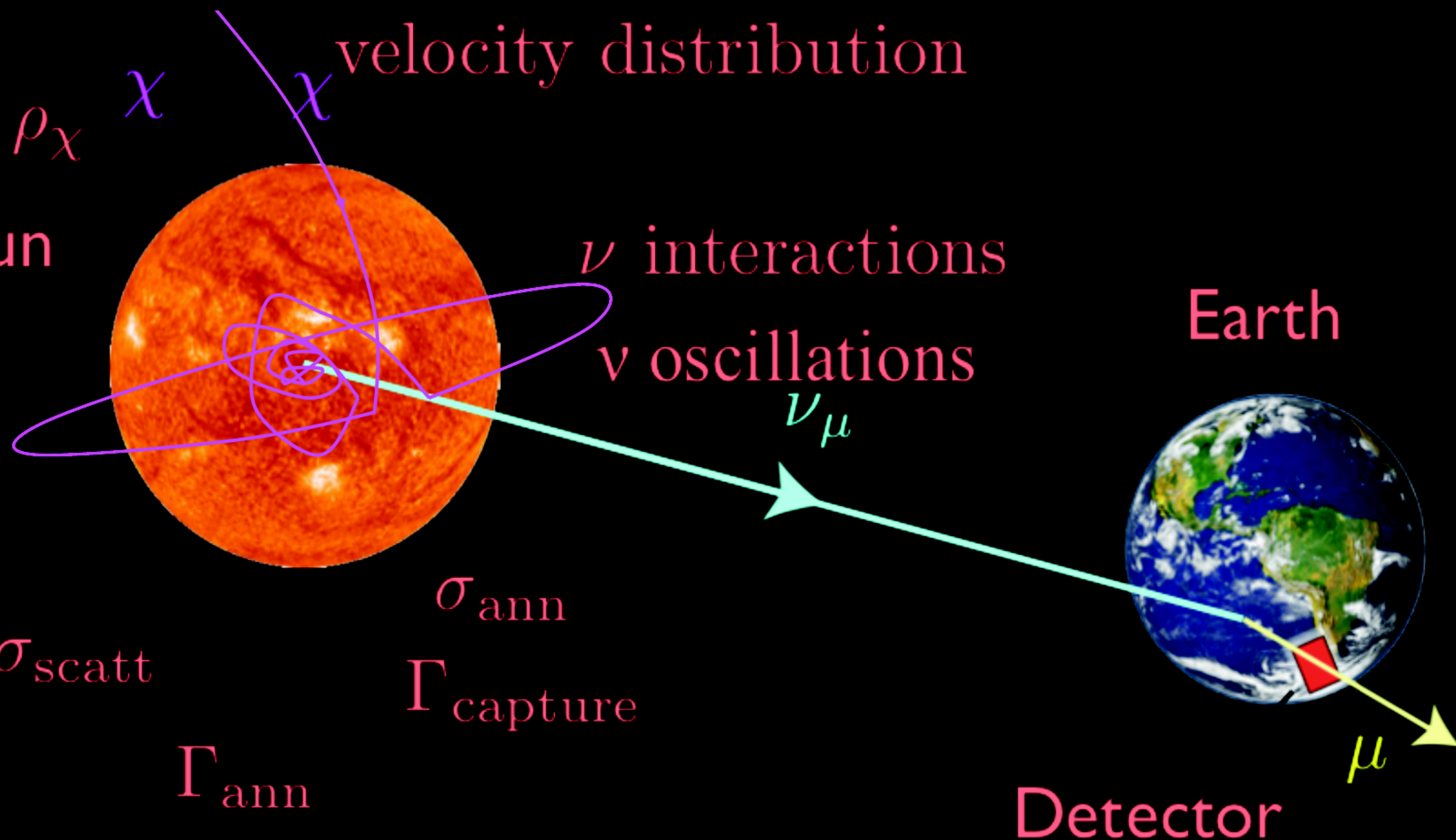
Direct dark matter searches (scattering)





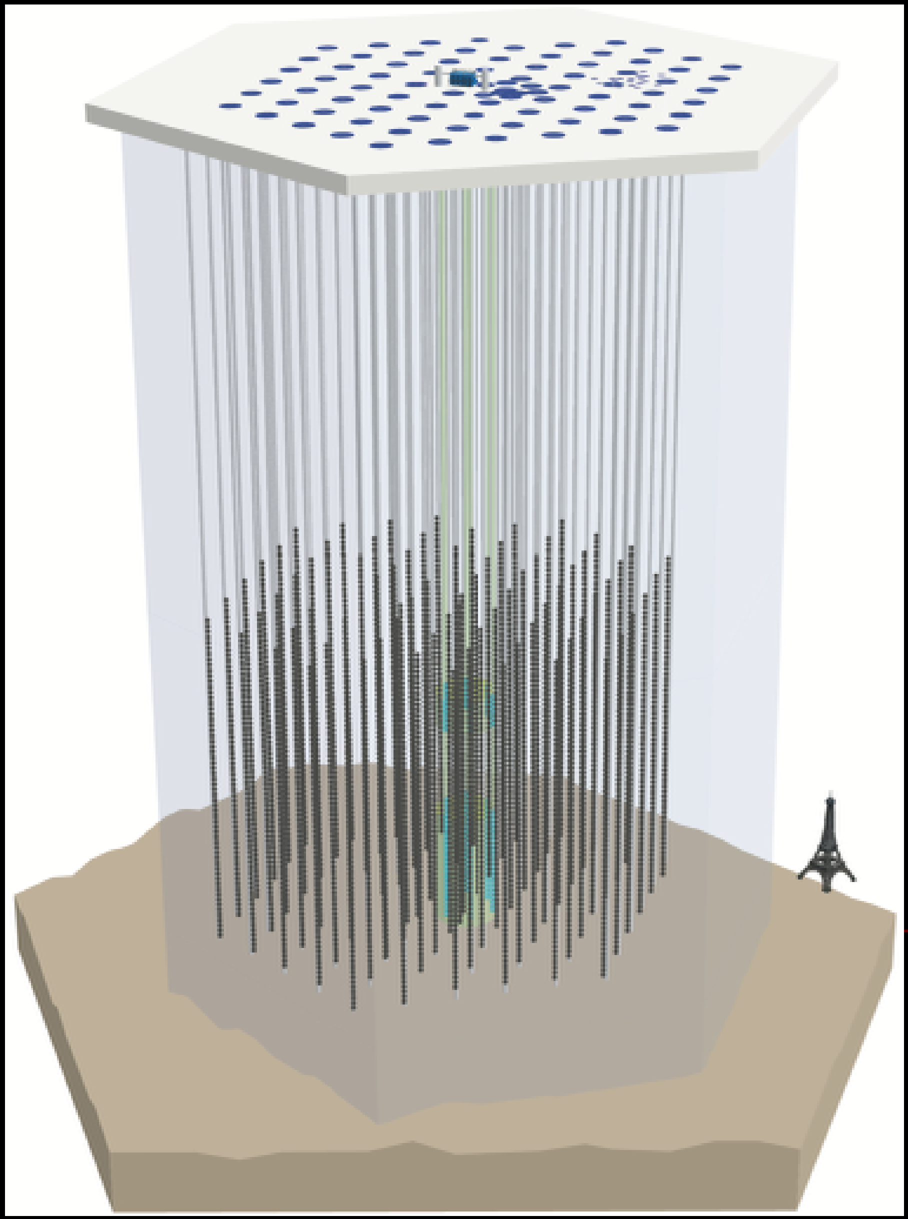
- **direct dark matter search:** measure cross-section via nuclear recoil
- typically large, heavy and very pure target materials in deep mines (~10 operating experiments)
- experiments start to reach in theoretically preferred parameter space
- **experiments disagree →** some experiments claim discovery,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

Neutrino production from dark matter in the Sun

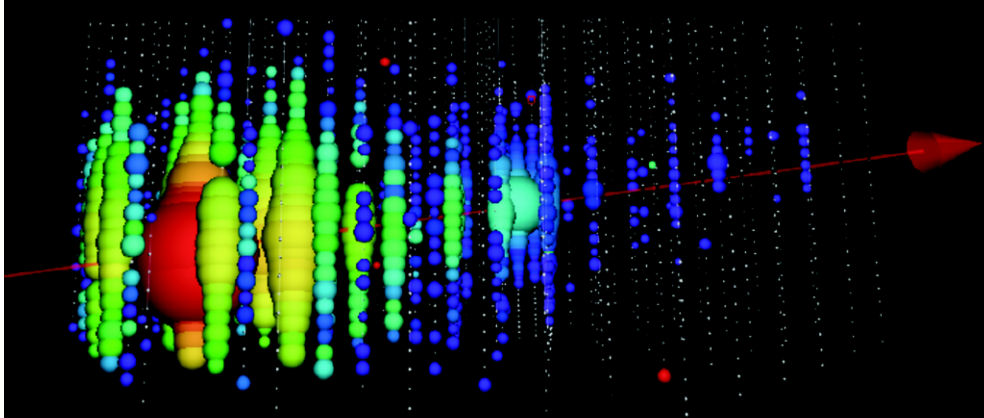


mainly probes the scattering cross section of DM off of nuclei

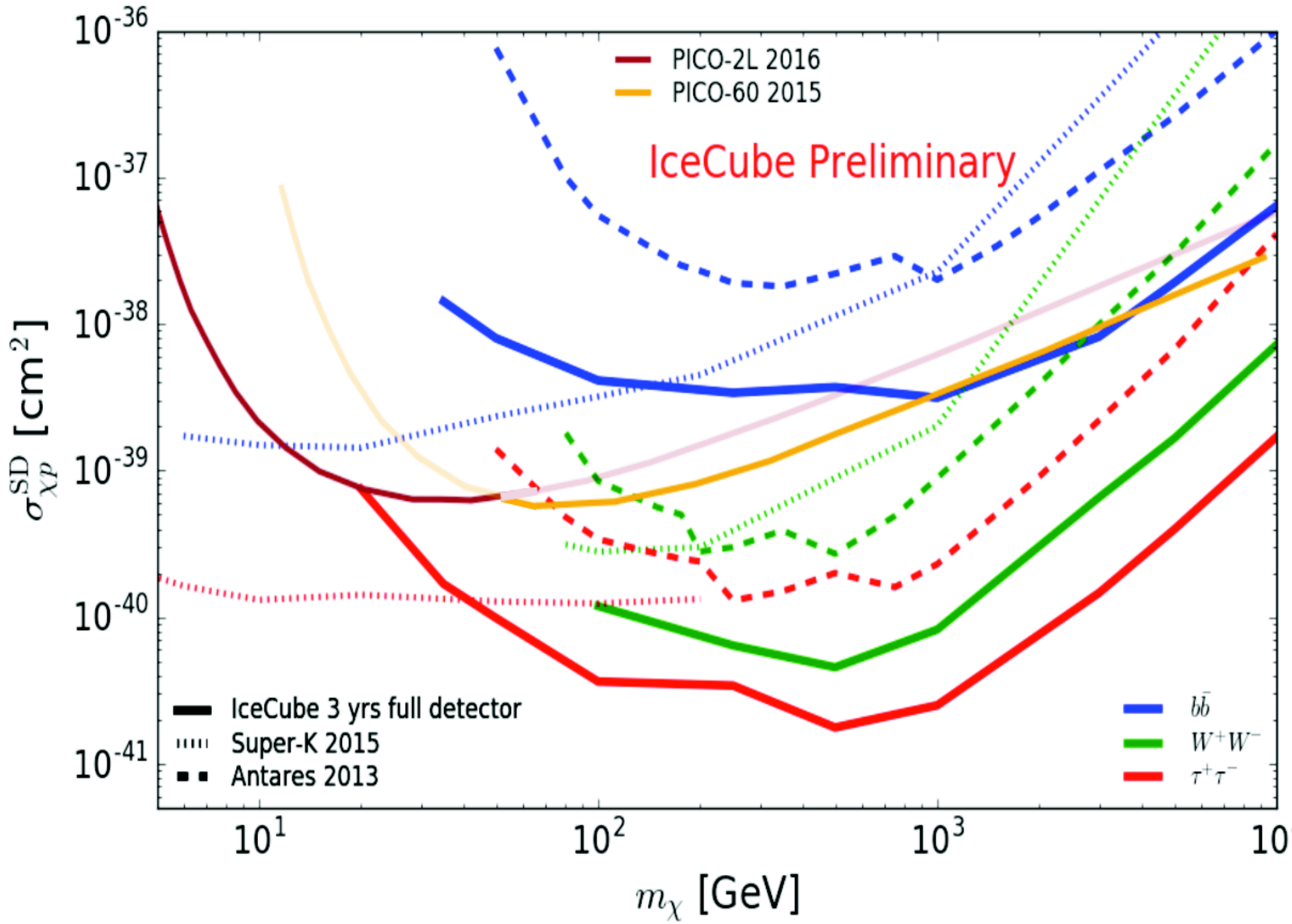
IceCube



- located at the South Pole
- $1km^3$ instrumented volume and 1.5-2.5km deep
- 5160 Optical modules
- Cherenkov light by charged particles
- neutrinos detectable > 100GeV



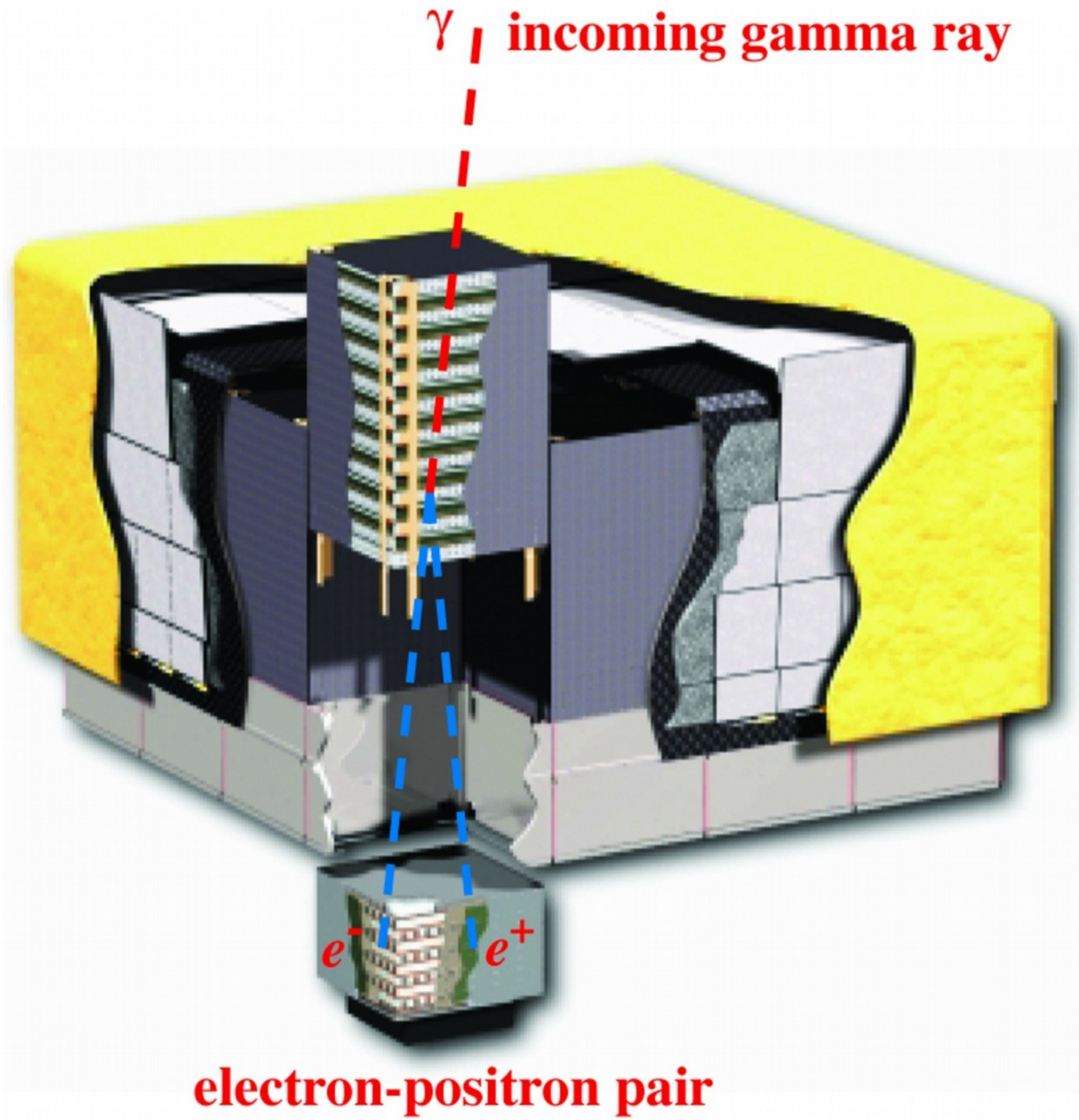
Dark matter limits



- search for an excess of events from the direction of the Sun
- observed events consistent with background only expectations
- search for neutrino access also compatible with background

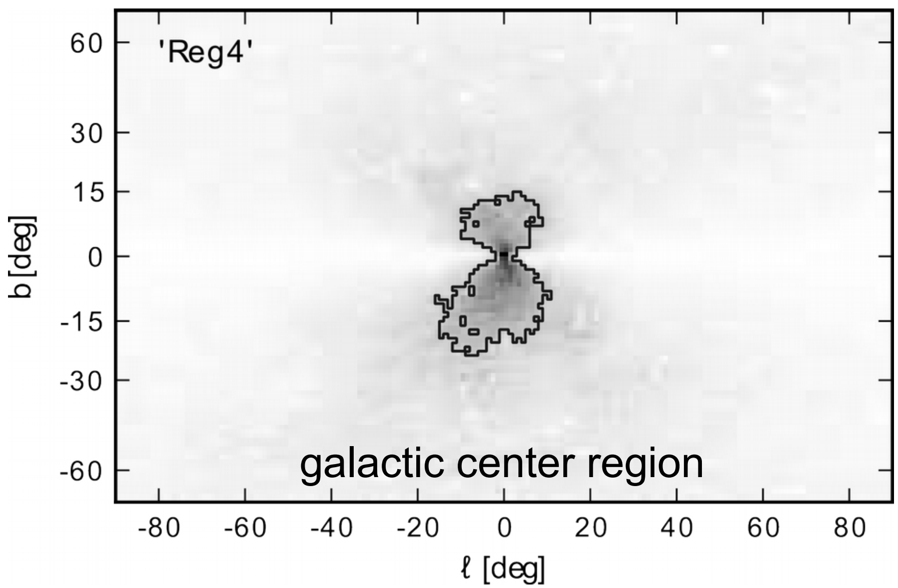
γ-rays: Fermi

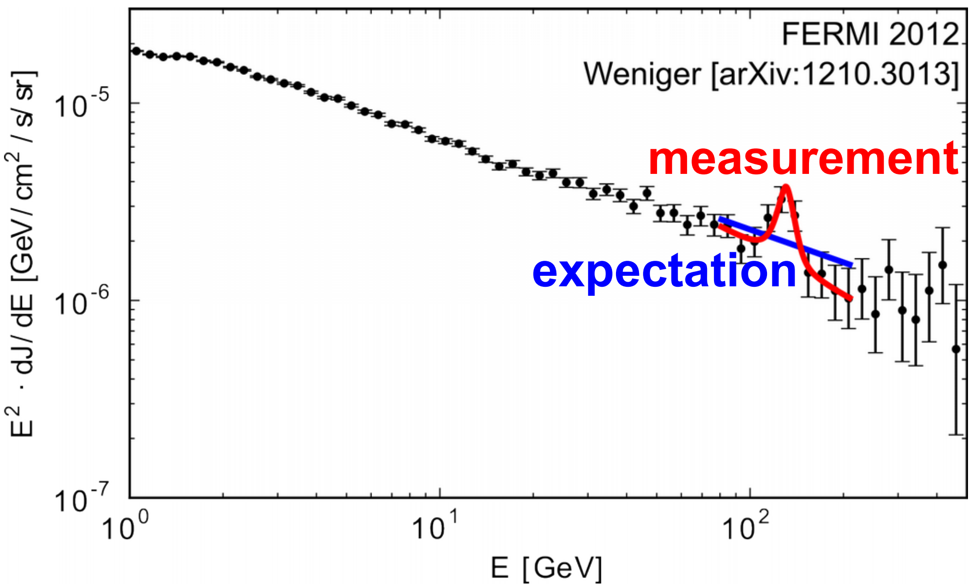
→ Aharonian, Latronico



- in space since 2008
- identify gamma-rays by conversion to e^+-e^- pairs
- electromagnetic showers in ECAL ($8.6X_0$)
- positrons by deflection in geomagnetic field
- gamma-rays, electrons, positrons

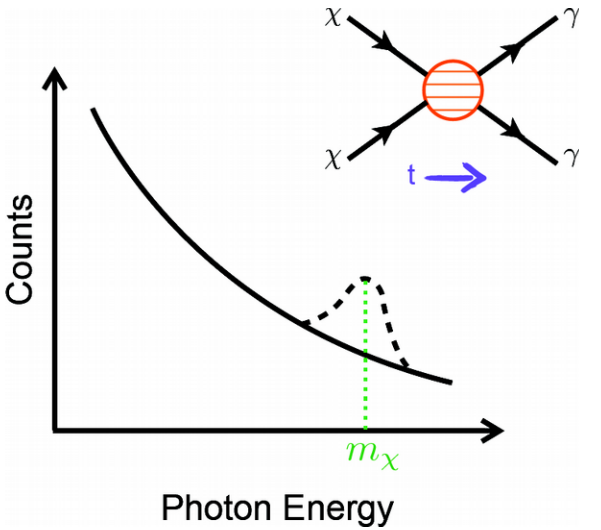
Photon line from the Galactic center?



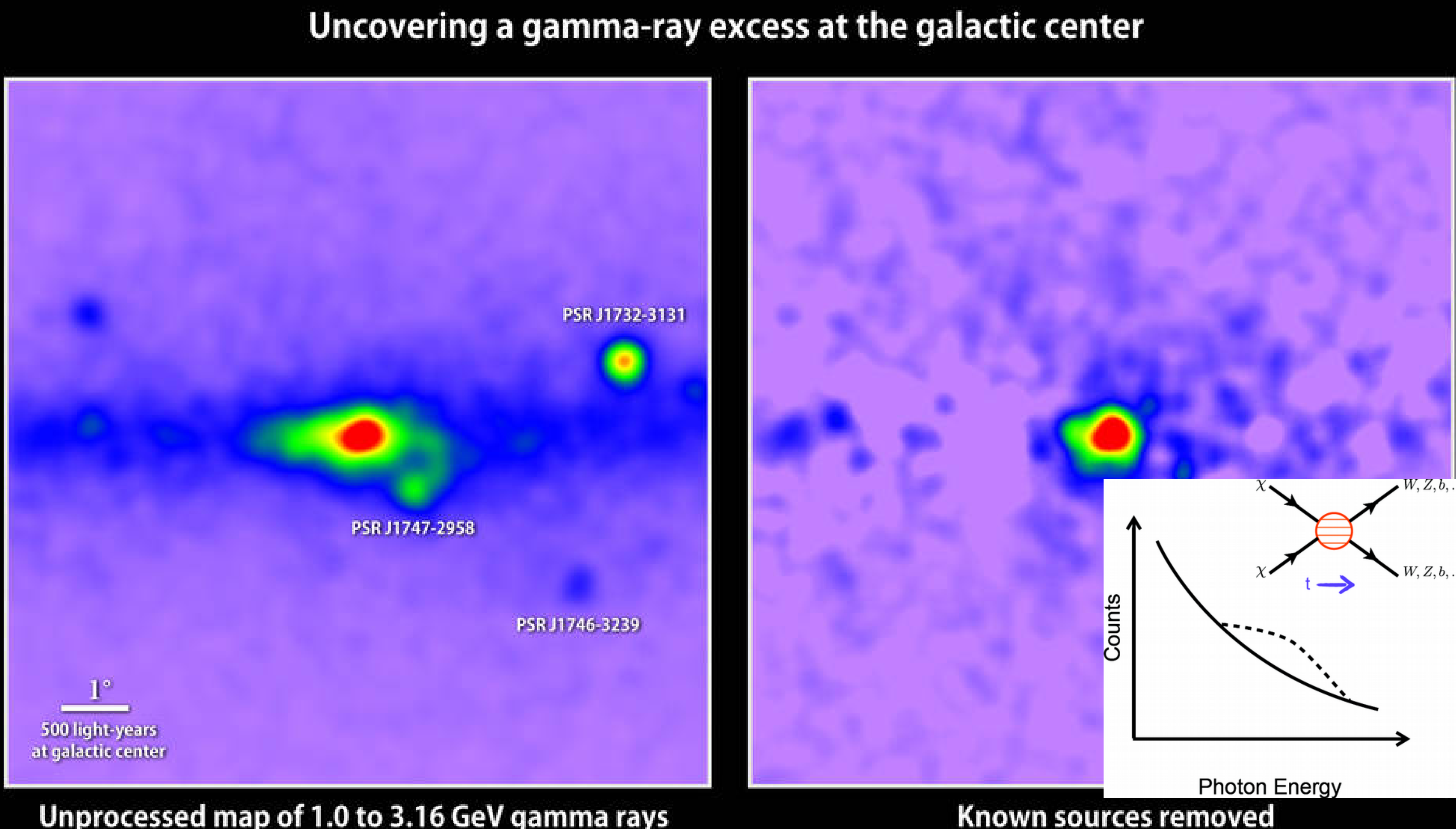


- Fermi in 2012 [JCAP 1208 (2012) 007]
  → **smoking gun signature for dark matter annihilation?**

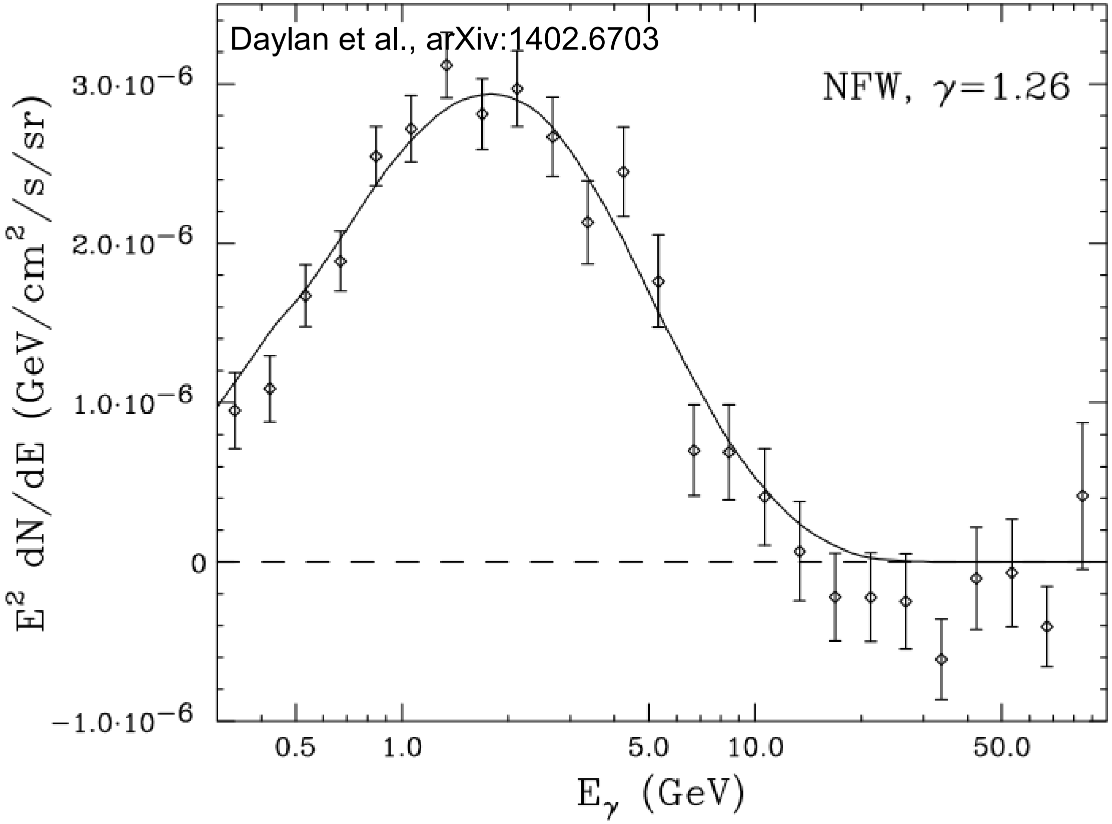
- **caused big excitement:** more than 100 papers citing this discovery
  → but it was eventually identified to be a statistical upward fluctuation



Diffuse Galactic γ-ray excess?



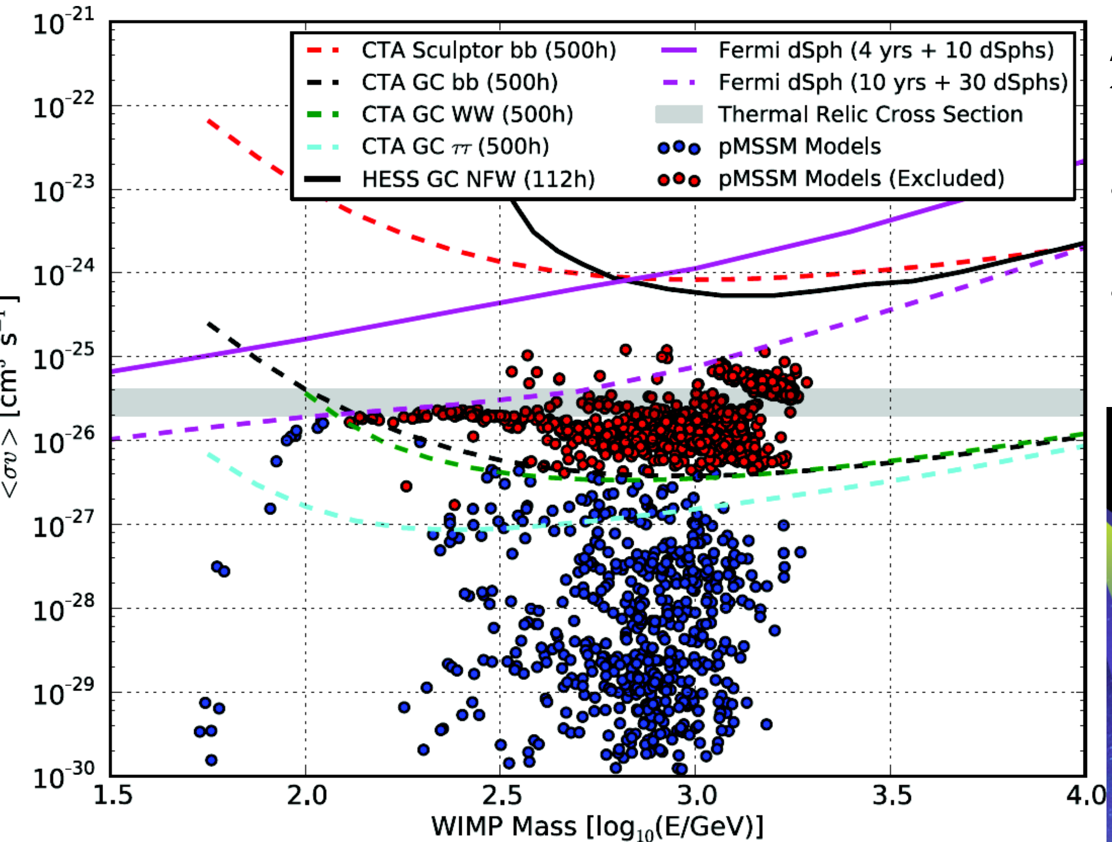
Diffuse Galactic γ-ray excess?



- gamma-ray excess at the galactic center → ~30GeV dark matter particle?
- signal in low-energy antiprotons?
- understanding of astrophysical background is a big challenge

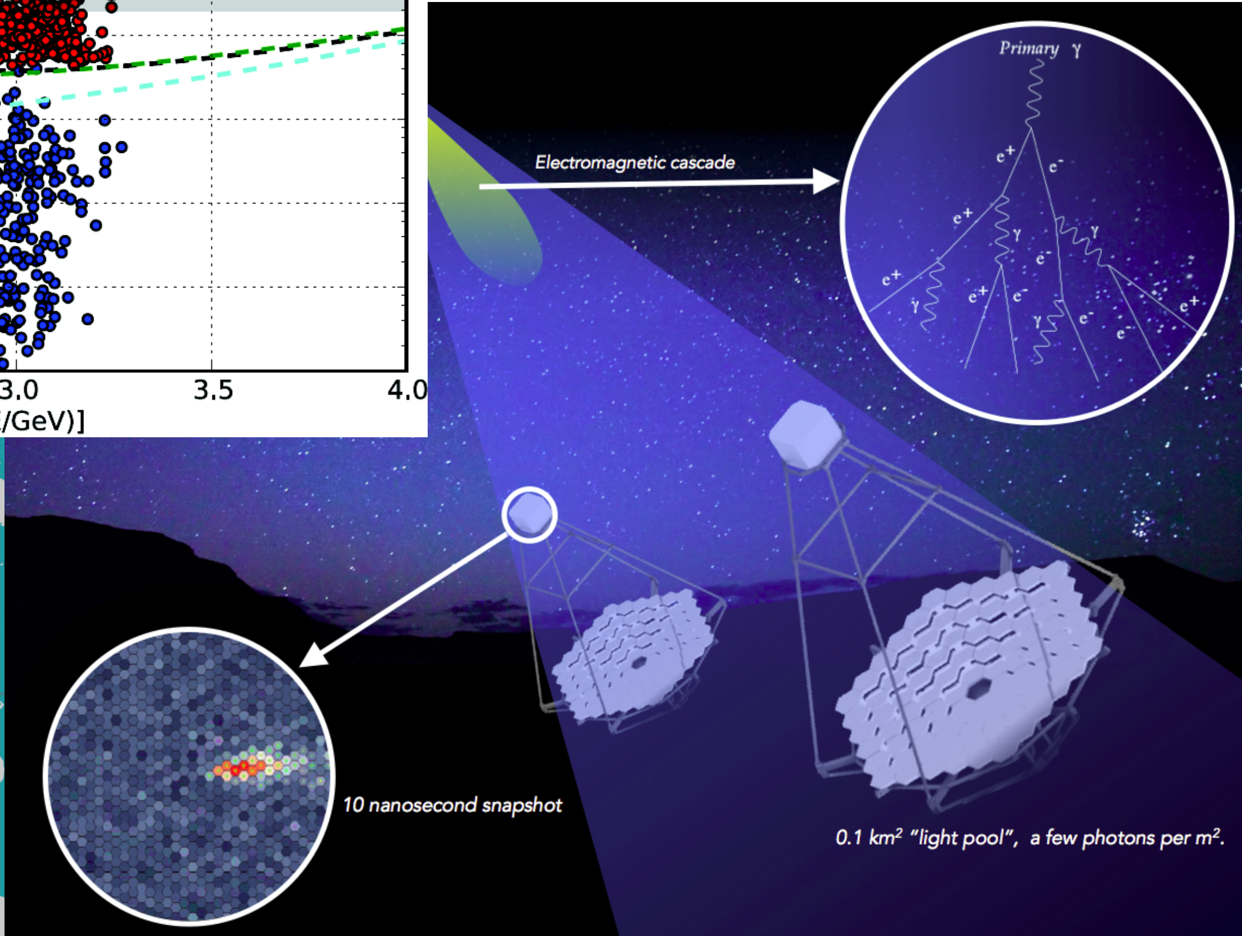
Cherenkov Telescope Array

→ Ragan

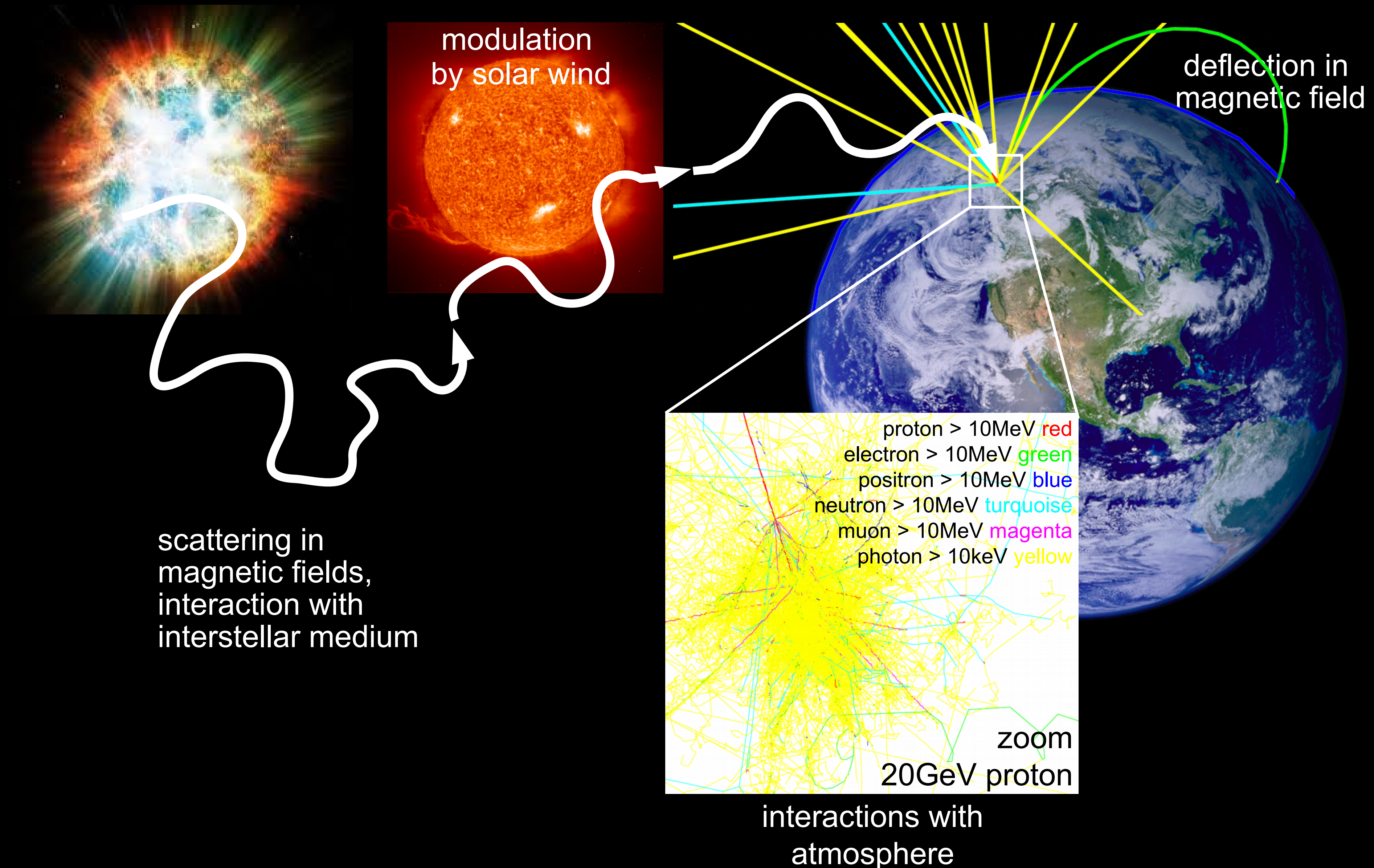


Array of telescope detecting Cherenkov radiation of γ-rays entering the atmosphere:

- 100GeV-10 TeV: 40 Medium-Sized Telescopes (MSTs), 8 Large-Sized Telescopes (LSTs)
- <100 GeV, >10TeV: 70 Small-Sized Telescopes (SSTs)



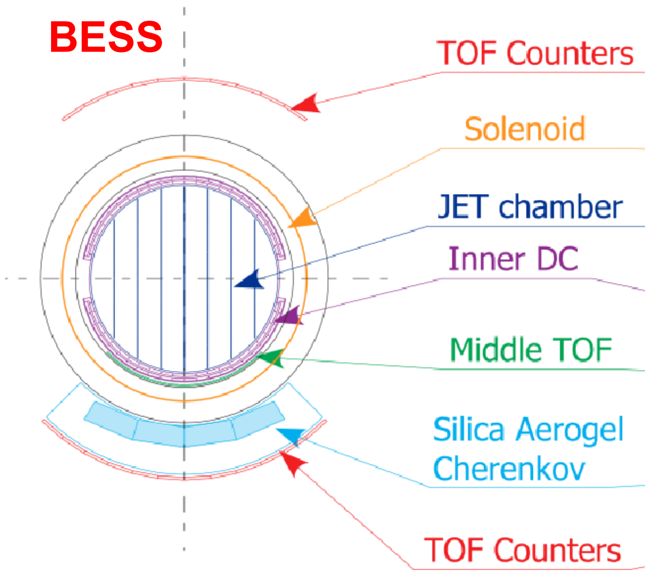
Charged cosmic rays as messengers



Charged cosmic-ray experiments

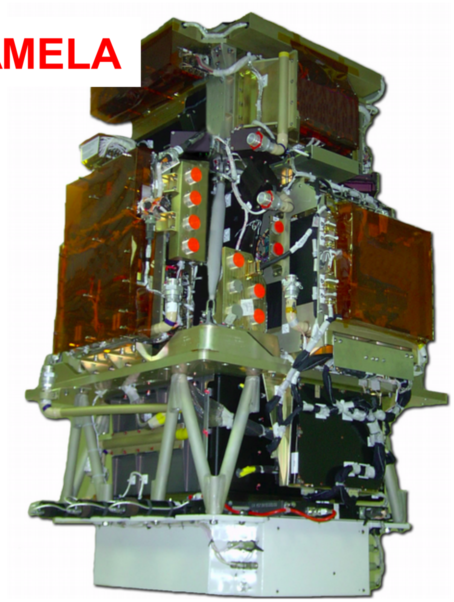
→ Vannuccini

BESS



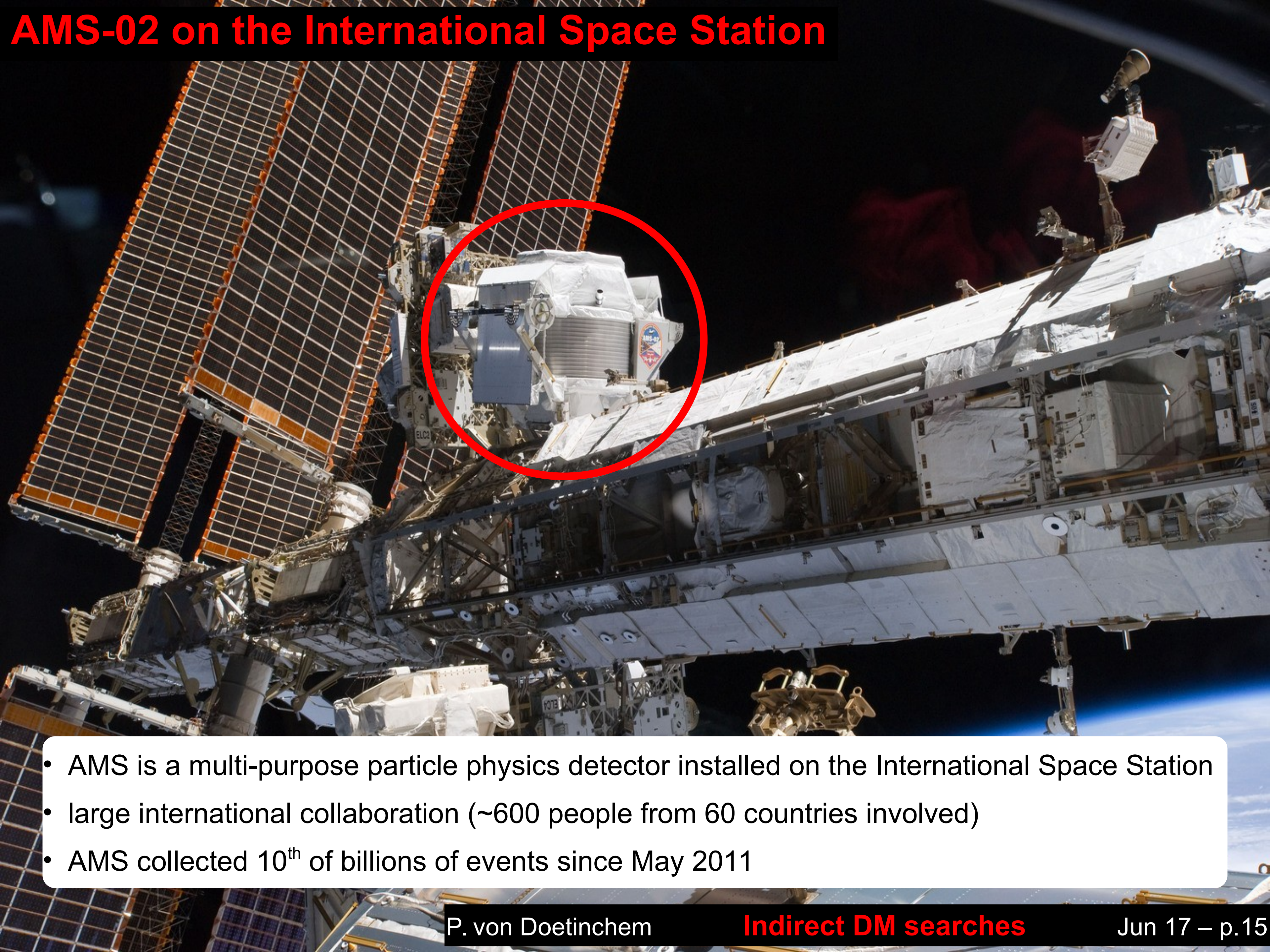
- magnetic-rigidity spectrometer:
  - superconducting solenoidal magnet
  - drift-chamber tracking system
  - time of flight
  - Cherenkov counter
- balloon flights from Canada and Antarctica from 1993-2008
- antiprotons, antideuterons, antihelium

PAMELA



- magnetic spectrometer in space since 2006-2015
- particle identification with several typical particle physics sub-detectors
- relatively small acceptance (21.5cm^{2}sr)
- electrons, positrons, antiprotons

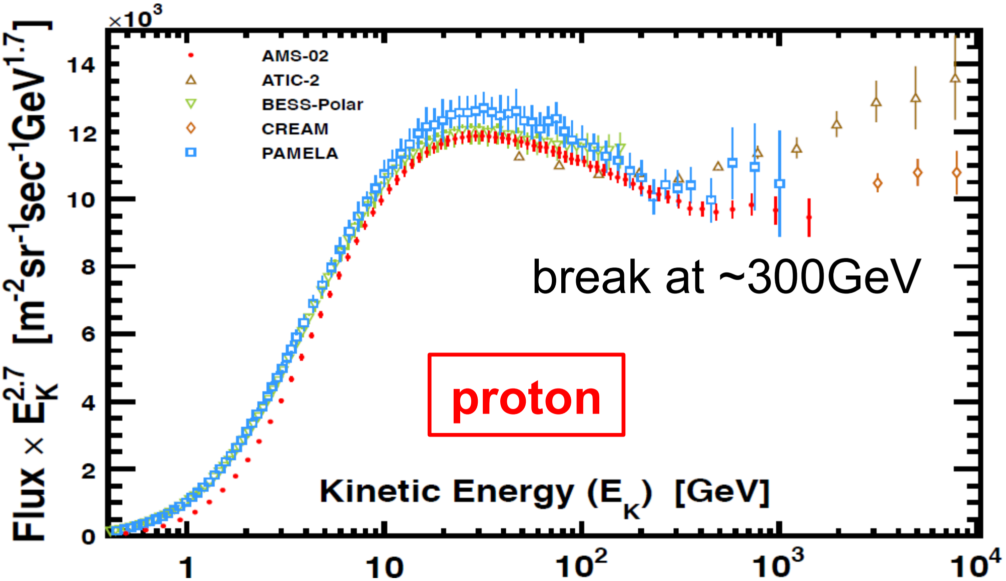
AMS-02 on the International Space Station

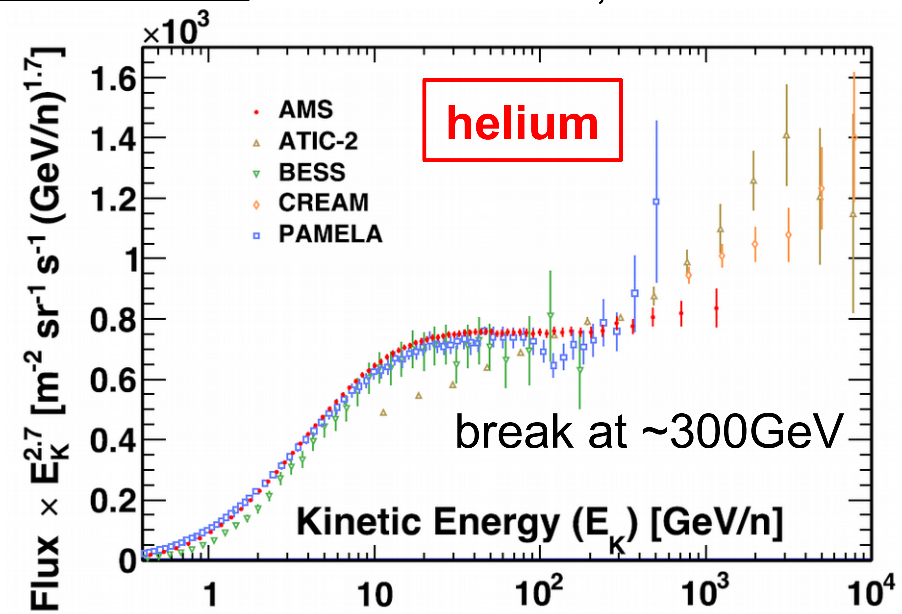


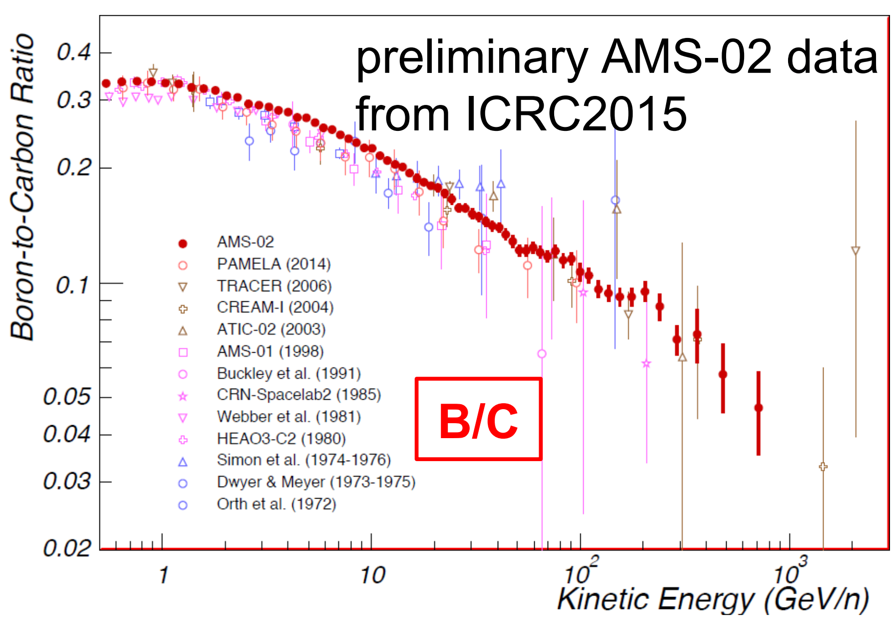
- AMS is a multi-purpose particle physics detector installed on the International Space Station
- large international collaboration (~600 people from 60 countries involved)
- AMS collected 10th of billions of events since May 2011

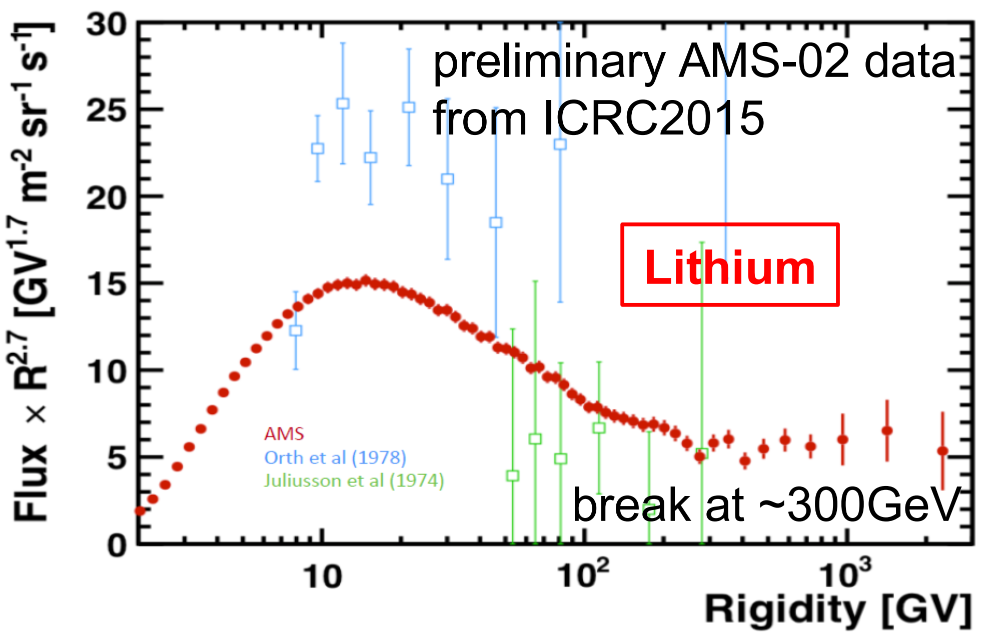
Highly abundant cosmic rays

→ Blasi, Maestro

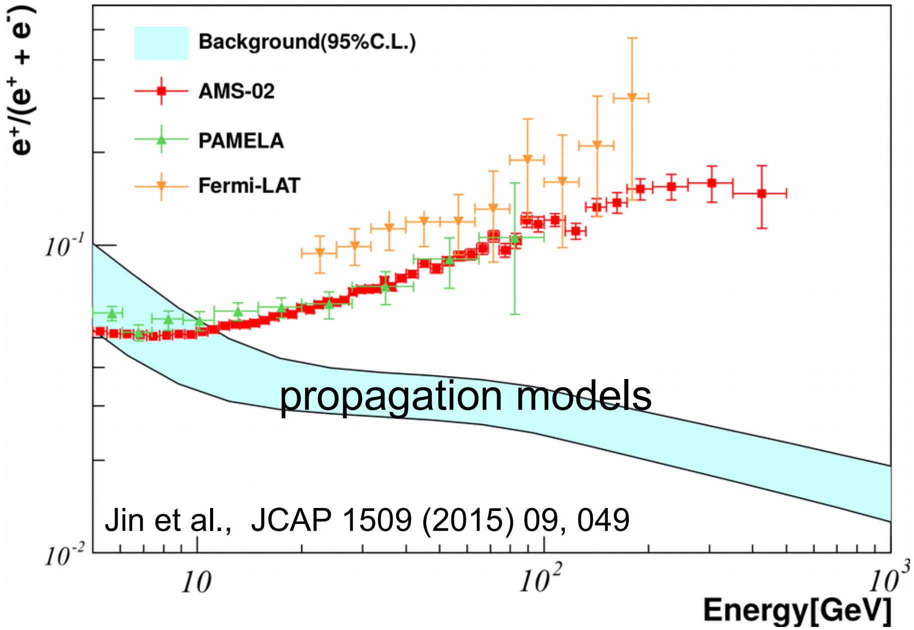


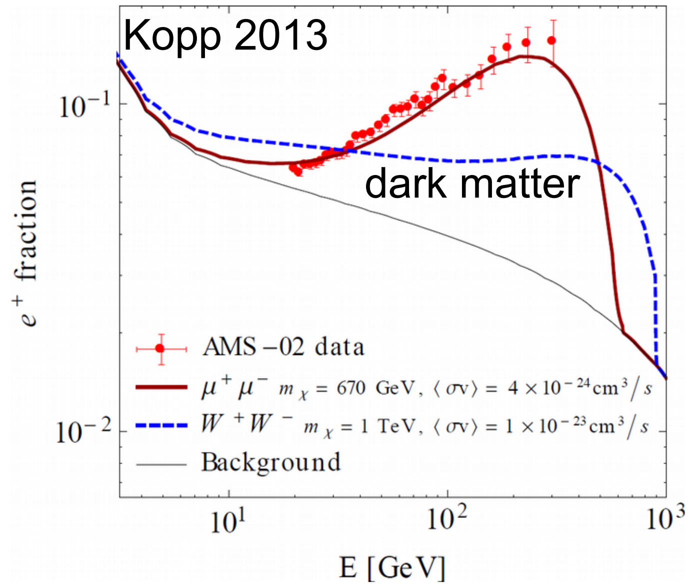




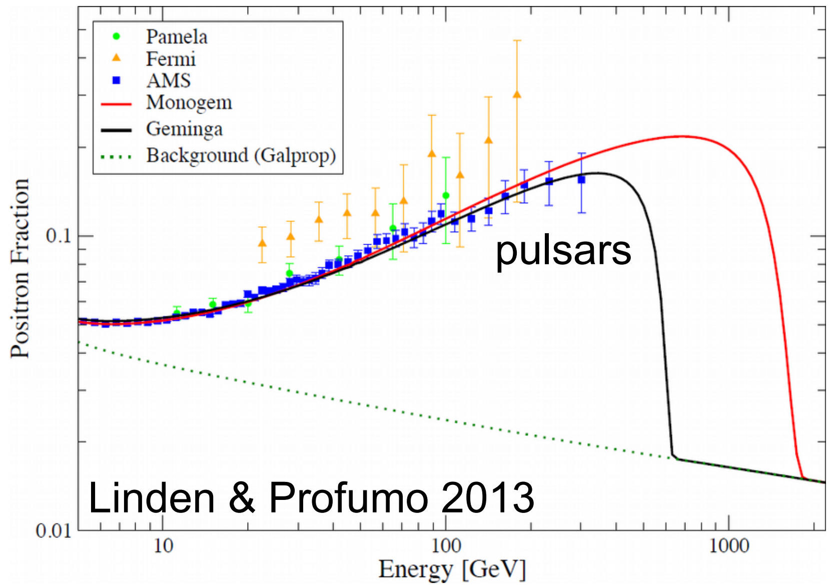


Dark matter signal in positrons?

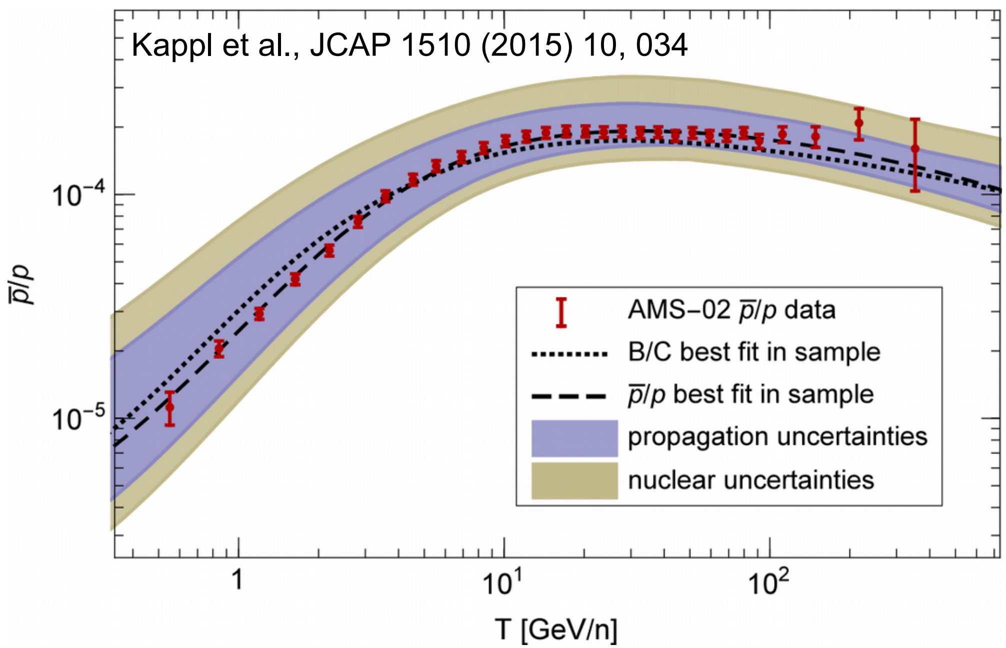


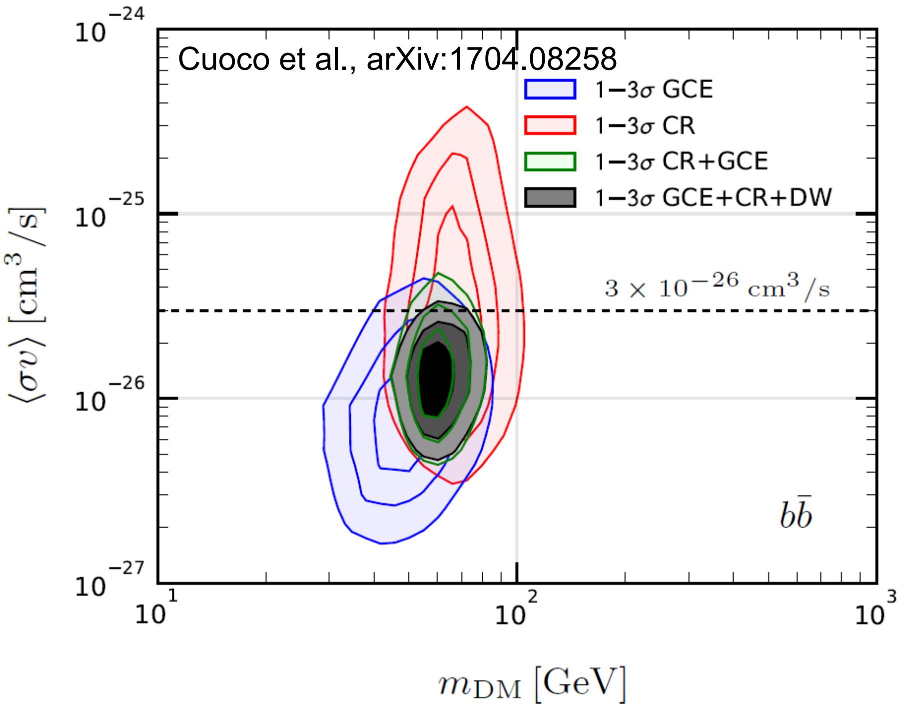


- dark matter models are severely constrained:
  - large cross sections
  - leptophilic?
- explained by nearby pulsars producing electrons and positrons?
  - anisotropy should be smaller than AMS-02 limit, but still measurable with ACTs
- different acceleration mechanisms
- important to see how the positron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



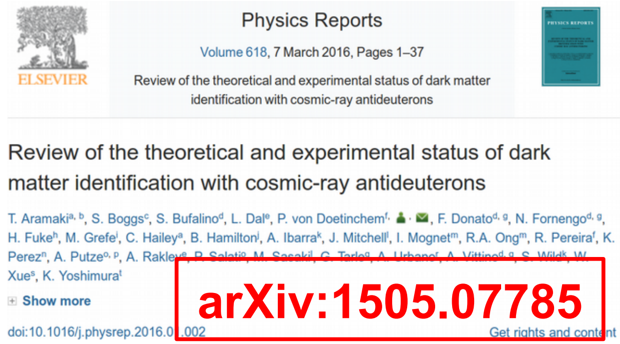
Antiprotons





- 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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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

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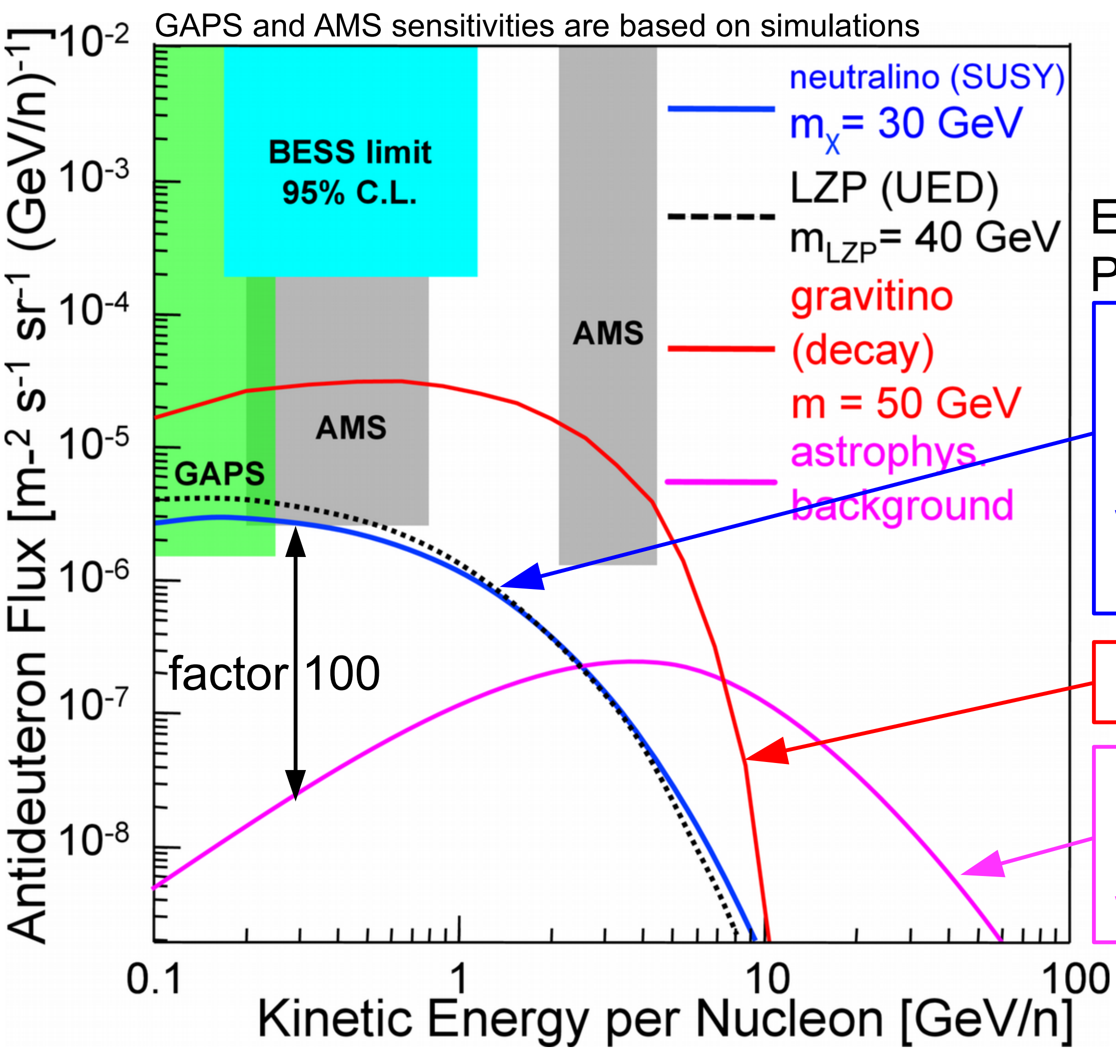


Examples for beyond-standard-model Physics (compatible with $\bar{p}$):

Neutralino:
SUSY lightest supersymmetric particle, decay into $b\bar{b}$, compatible with signal from Galactic Center measured by Fermi

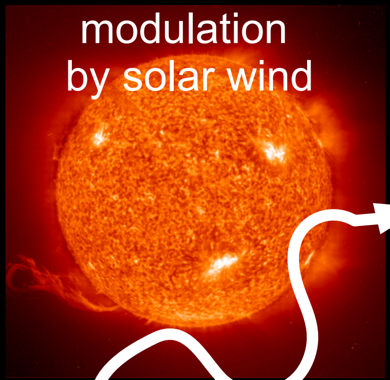
late decays of unstable gravitinos

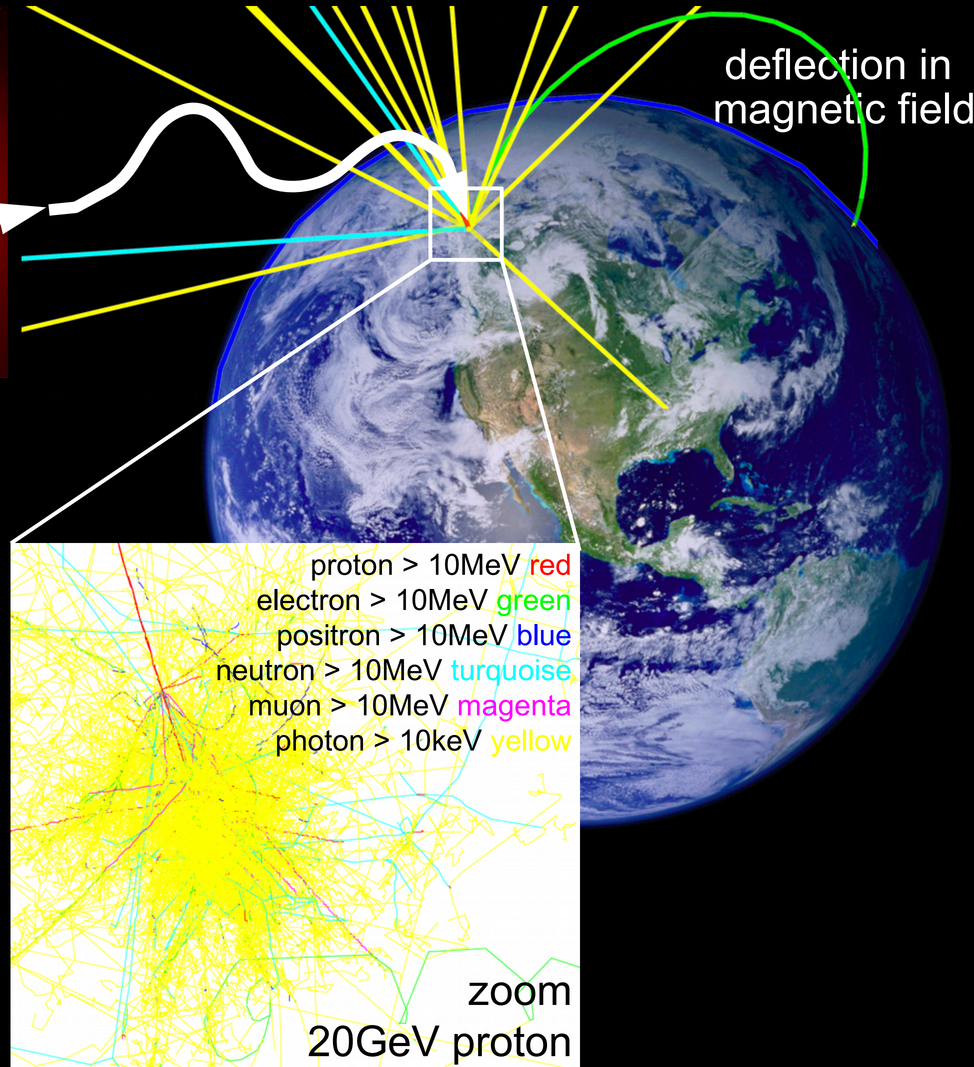
astrophysical background:
collisions of protons and antiprotons with interstellar medium

+ models with heavy dark matter

Antideuterons are the most important unexplored indirect detection technique!

Uncertainties

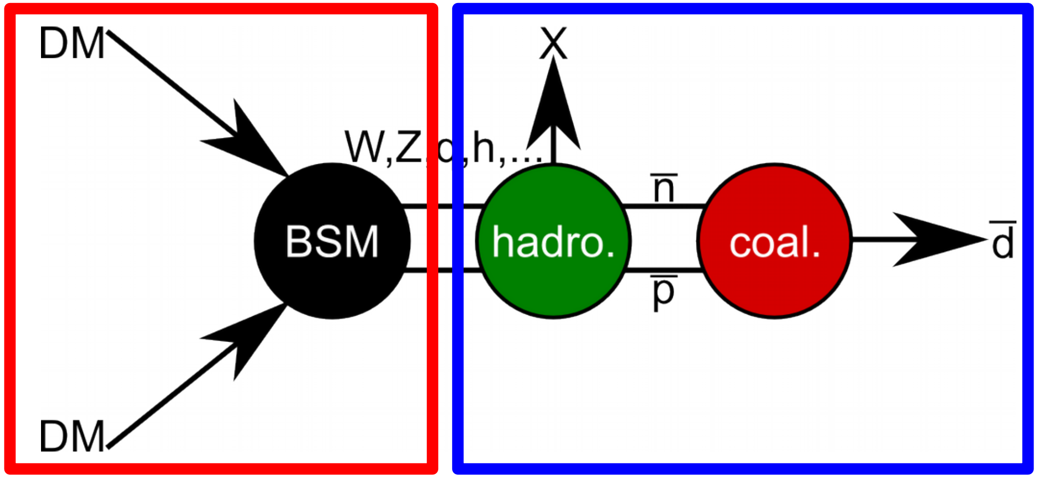




interactions with
atmosphere

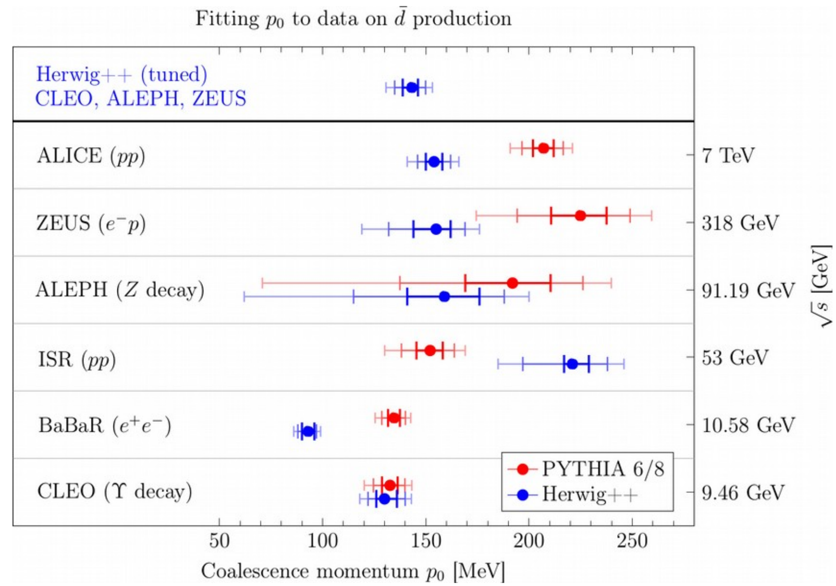
- dark matter annihilation or decay
- dark matter clumping
- **antideuteron production**
- **Galactic propagation**
- **solar modulation**
- **geomagnetic deflection**
- atmospheric interactions
- **interactions in detector**

Antideuteron formation



dark matter

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



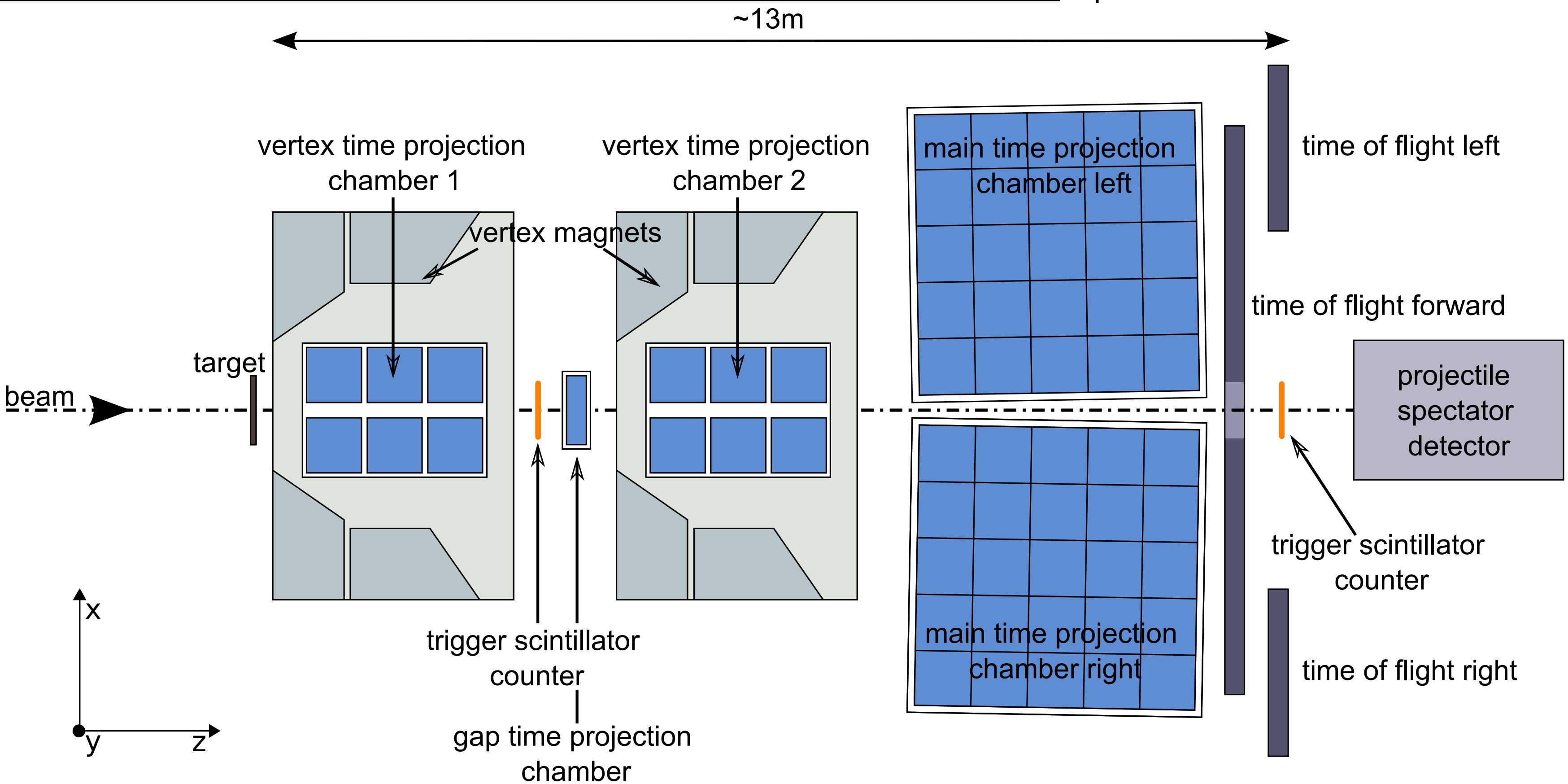
- $\bar{d}$ can be formed by an $\bar{p}$-$\bar{n}$ pair if coalescence momentum p_0 is small

$$\frac{\mathrm{d}N_{\bar{d}}}{\mathrm{d}T_{\bar{d}}} = \frac{p_0^3}{6} \frac{m_{\bar{d}}}{m_{\bar{n}} m_{\bar{p}}} \frac{1}{\sqrt{T_{\bar{d}}^2 + 2 m_{\bar{d}} T_{\bar{d}}}} \frac{\mathrm{d}N_{\bar{n}}}{\mathrm{d}T_{\bar{n}}} \frac{\mathrm{d}N_{\bar{p}}}{\mathrm{d}T_{\bar{p}}}$$

- **important differences for different experiments and MC generators exist → more data will help**

NA61/SHINE at CERN

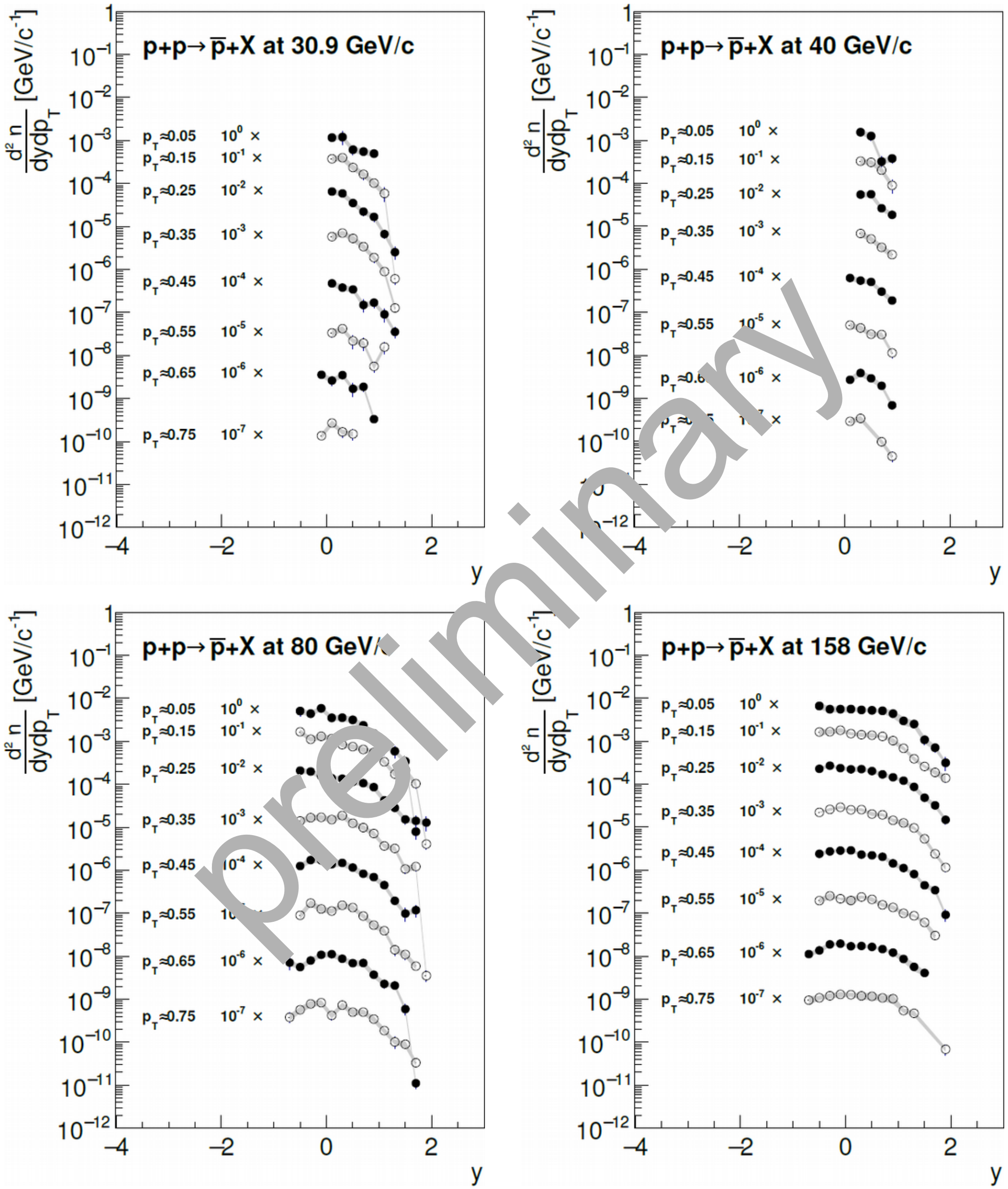
SPS **H**eavy **I**on and **N**eutrino **E**xperiment
pre-decessor: NA49

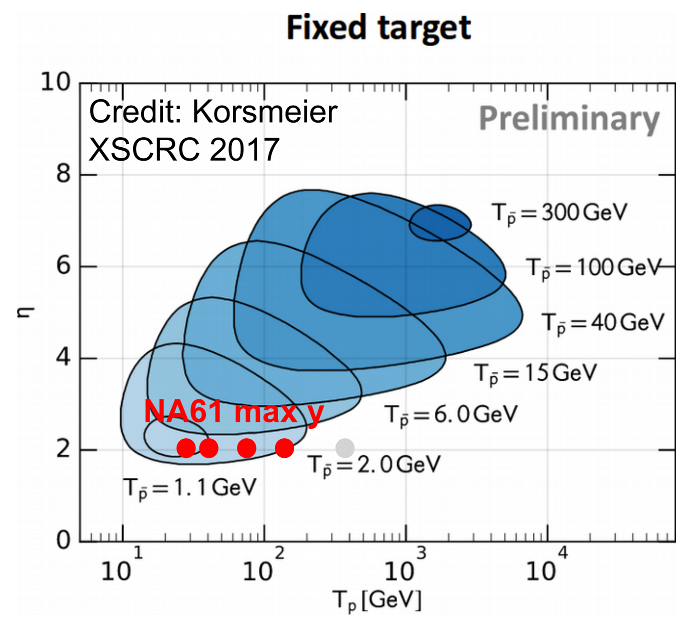


- multi-purpose, fixed-target experiment at the CERN SPS (NA61/SHINE facility paper: JINST 9 (2014) P06005)
  - precise measurements of properties of produced particles: q, m, p
- cosmic-ray antideuteron production happens between 40 and 400GeV
  - SPS energies from 9 to 400GeV are ideal
- data under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

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

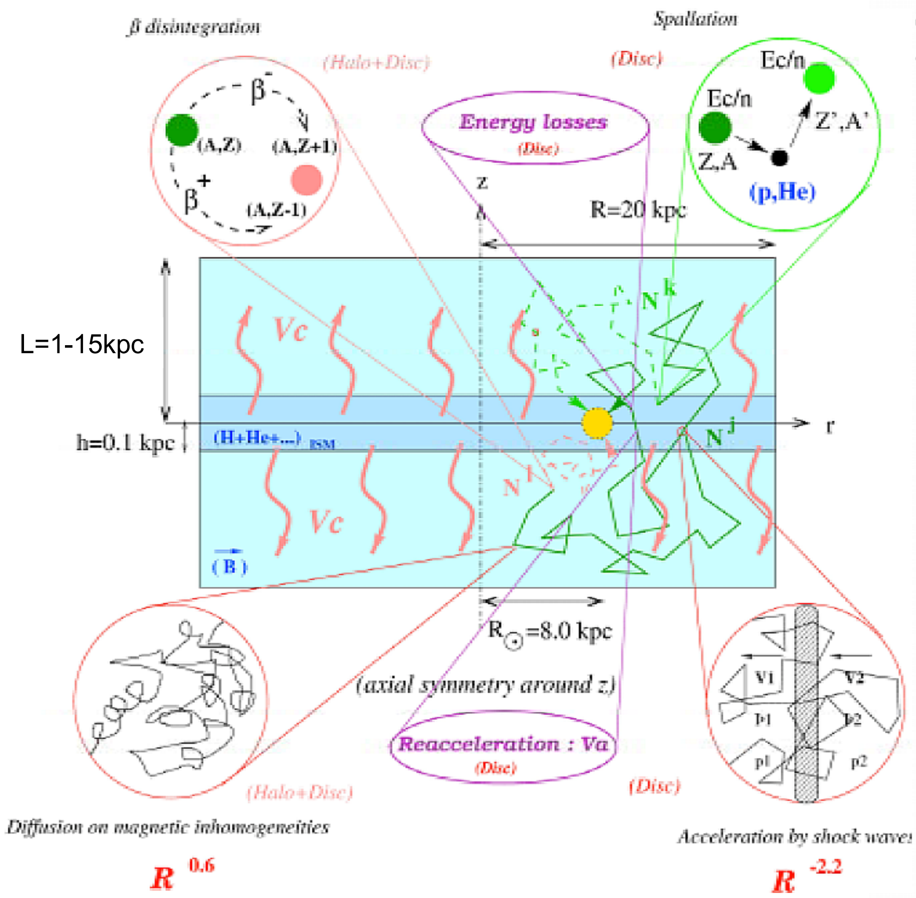
Antiprotons as function of rapidity

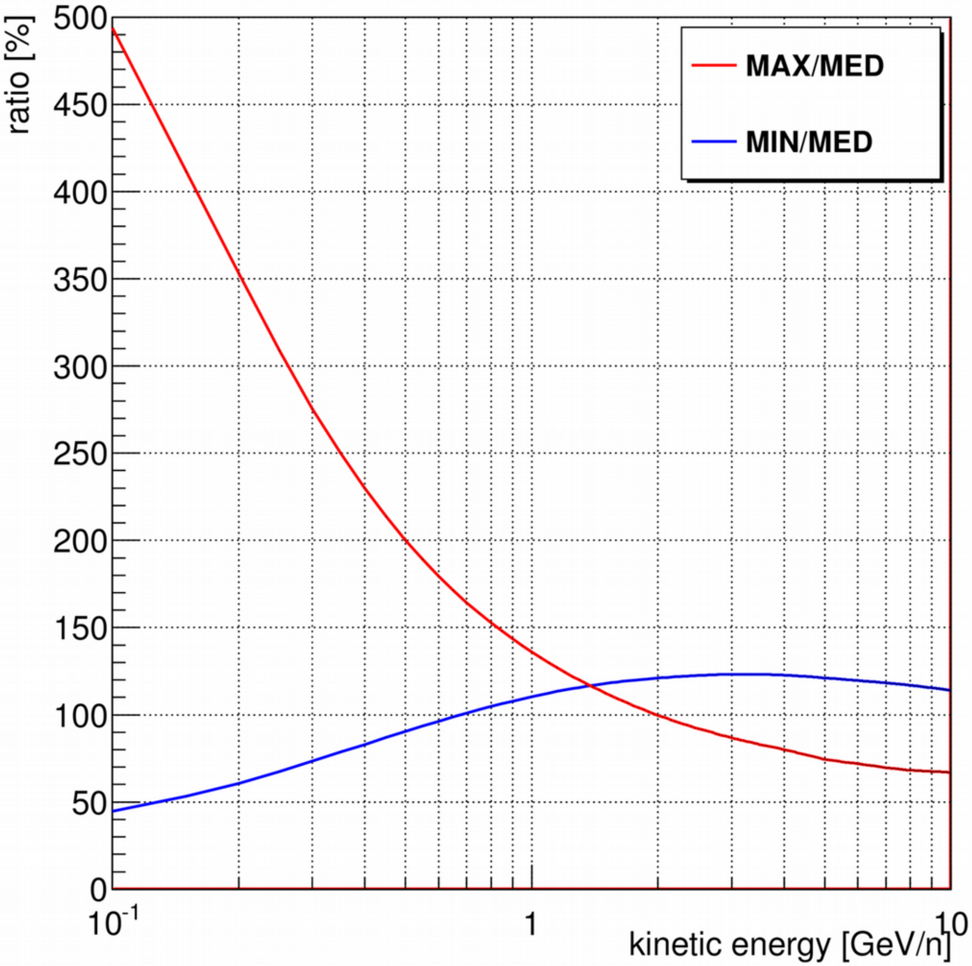




Propagation uncertainty

→ Blasi

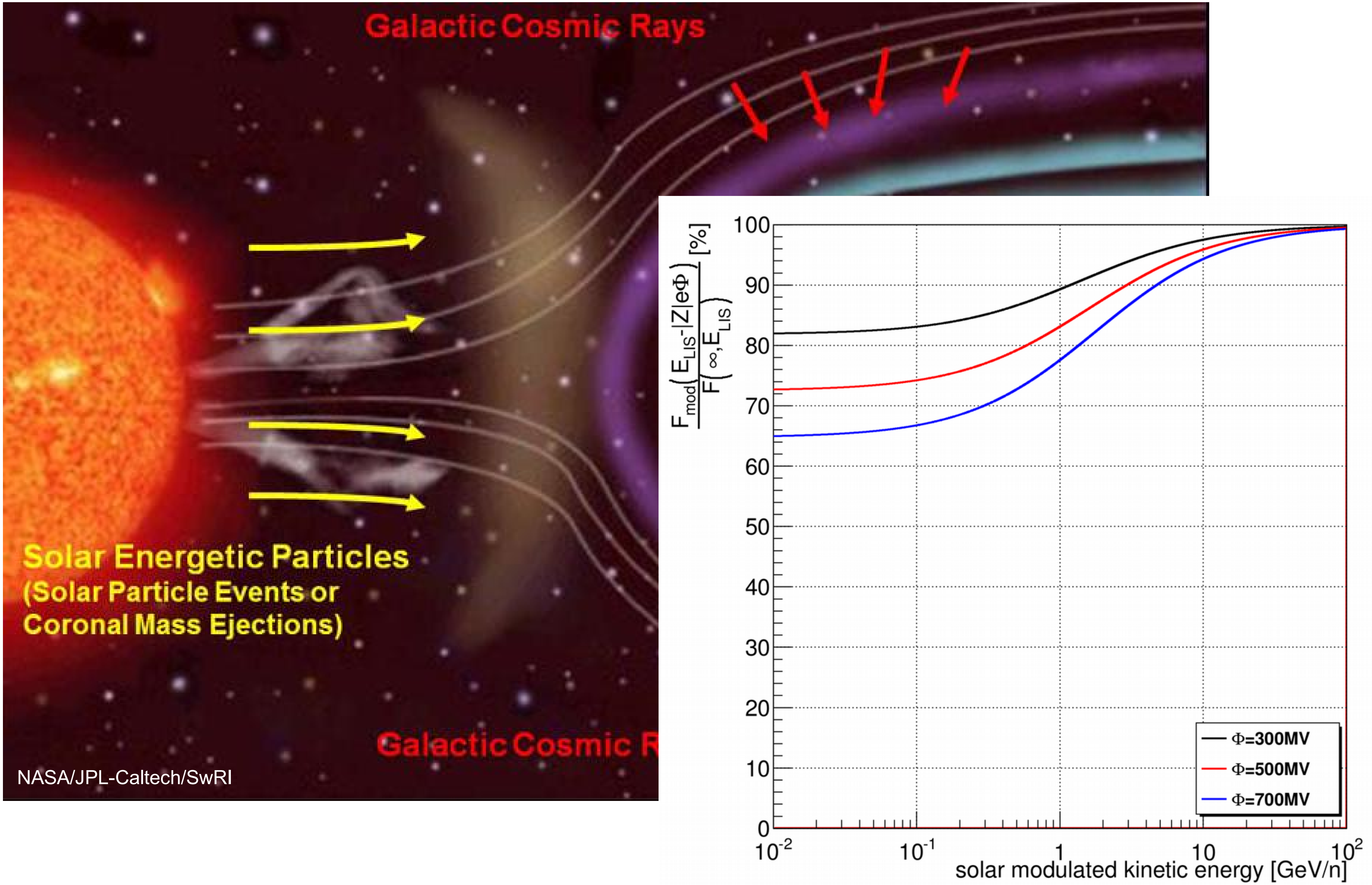




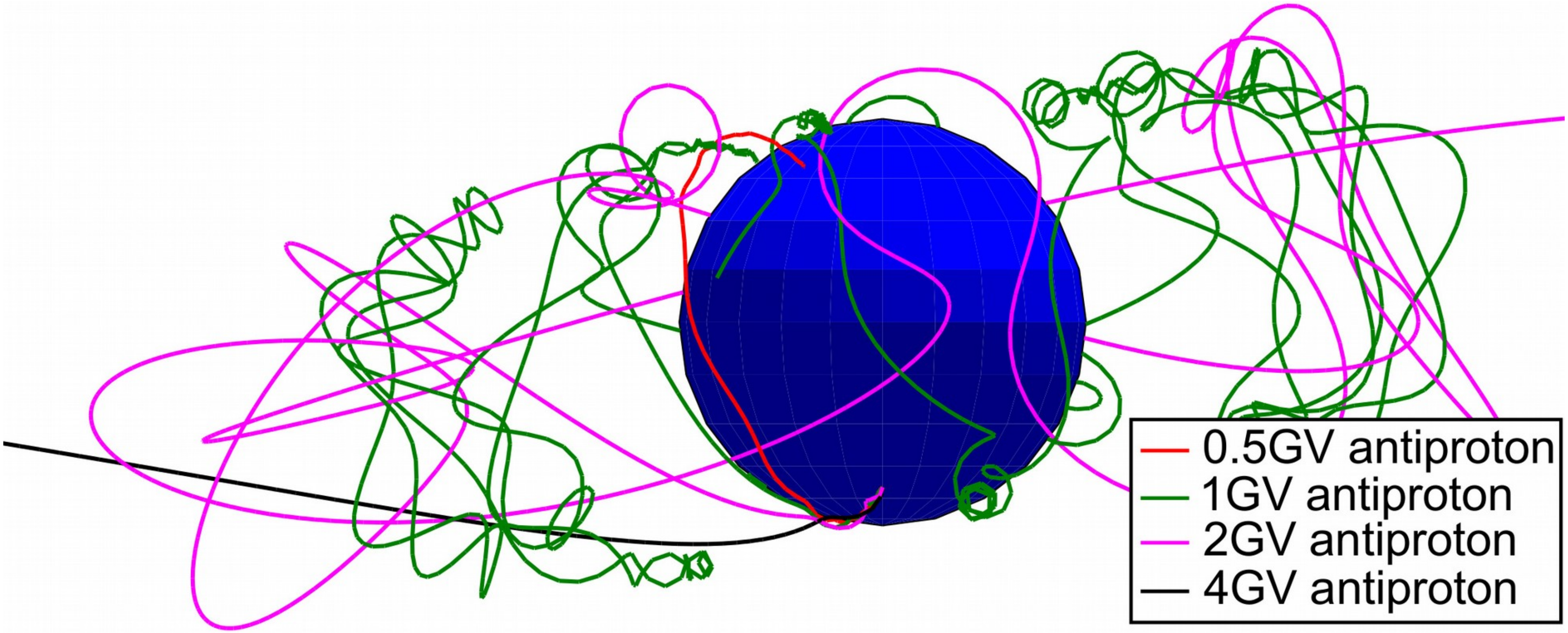
- propagation is the strongest uncertaintiy source for primary antideuterons: **halo size for diffusion calculation poorly constrained**
- more data on various nuclear species are needed for better constraint (→ Be10/Be9 ratio)

Solar modulation

→ Potgieter



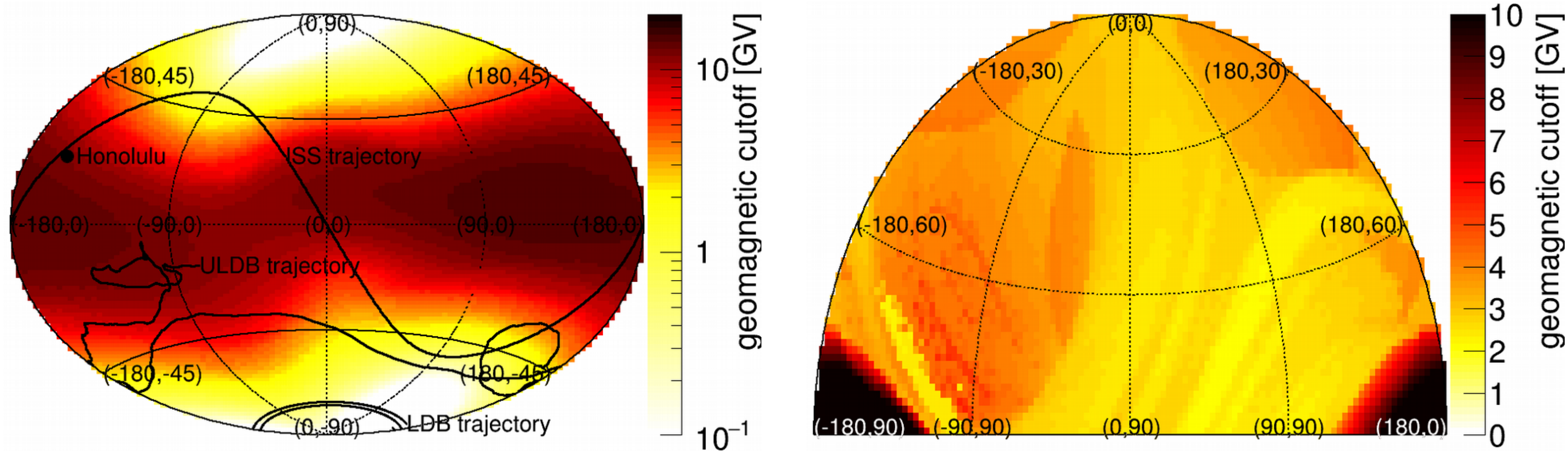
Geomagnetic cutoff



- reverse computation of antiproton trajectories starting at the same location in the same direction for different rigidities (R=p/q)

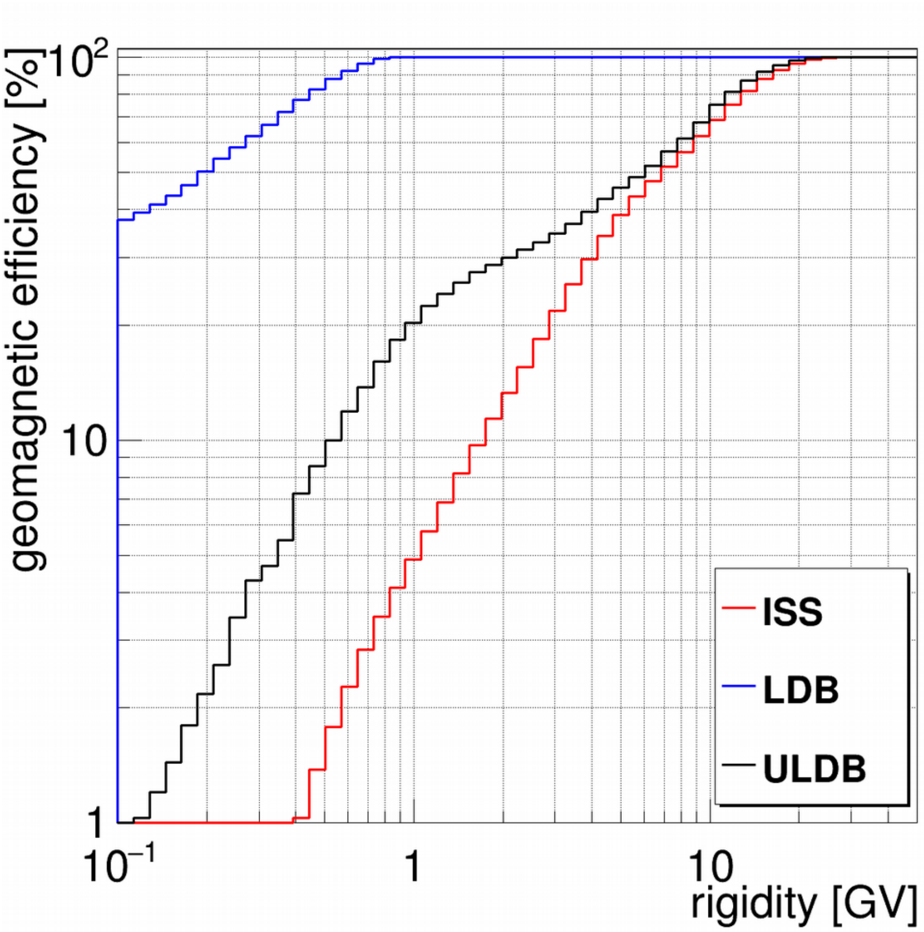
- magnetic environment changes with solar activity
  → trajectories drastically change and influences the cutoff values

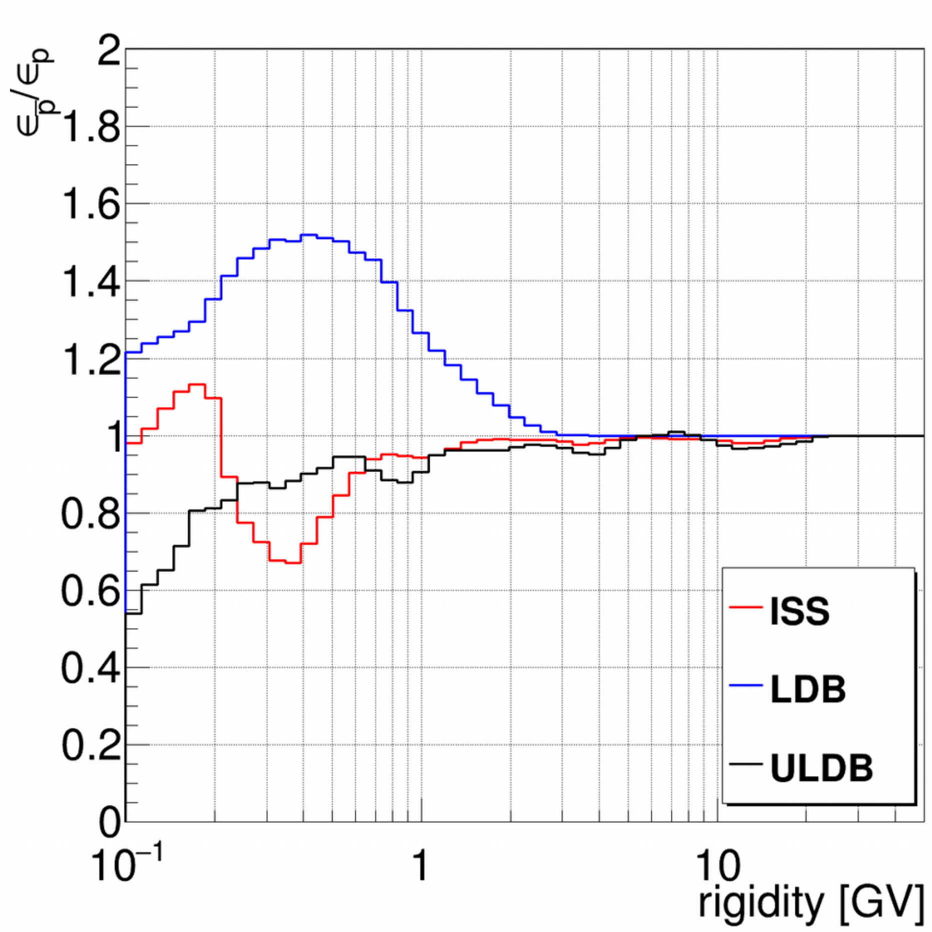
Geomagnetic cutoffs



- cutoff varies as the function of direction
- very important for rare-event searches at low energies

Average cutoff





- average geomagnetic cutoff efficiency depends on flight location
- antiprotons and protons behave differently for low rigidities

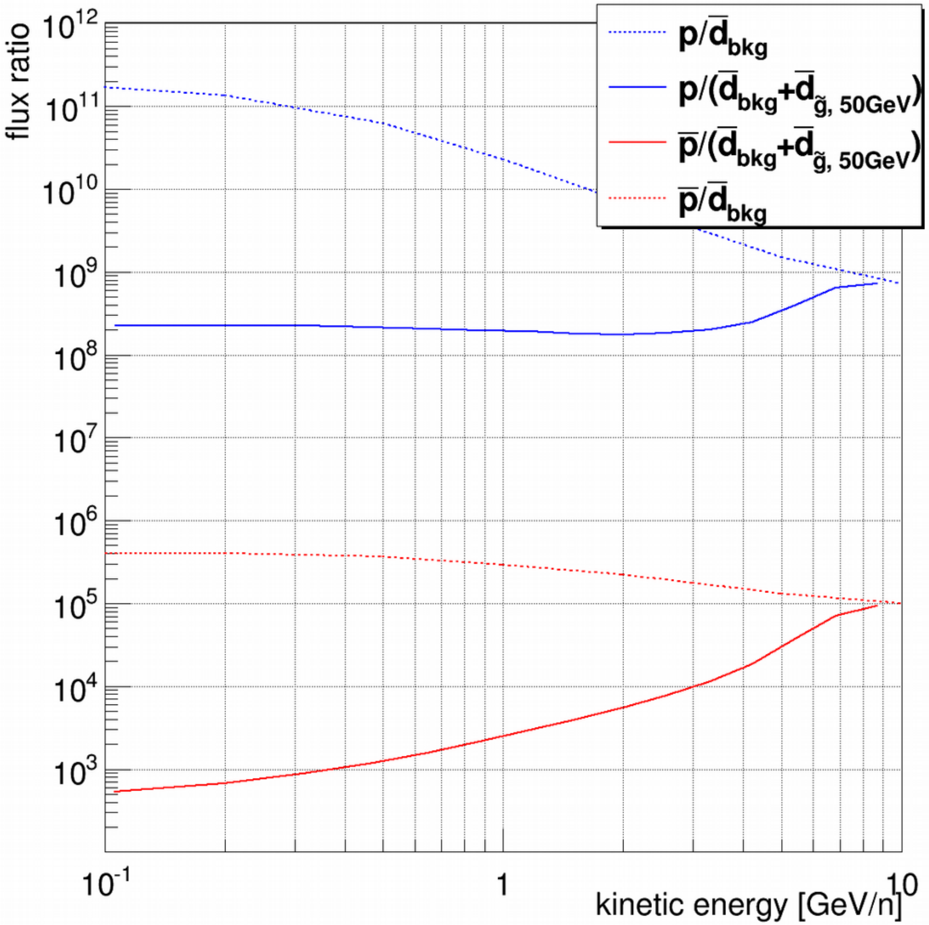
Identification challenge

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

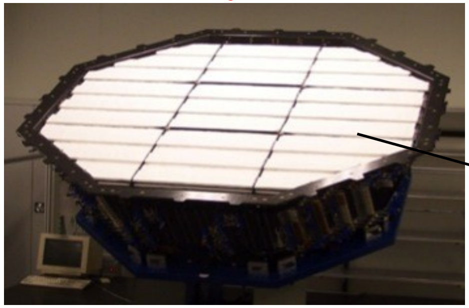
Antideuteron measurement with balloon and space experiments require:

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

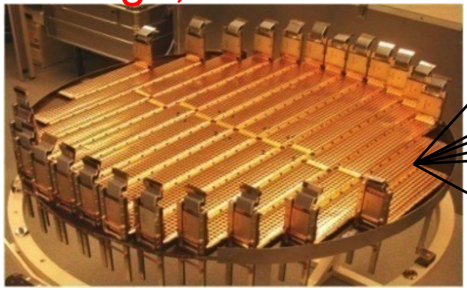


AMS-02 sub-detectors

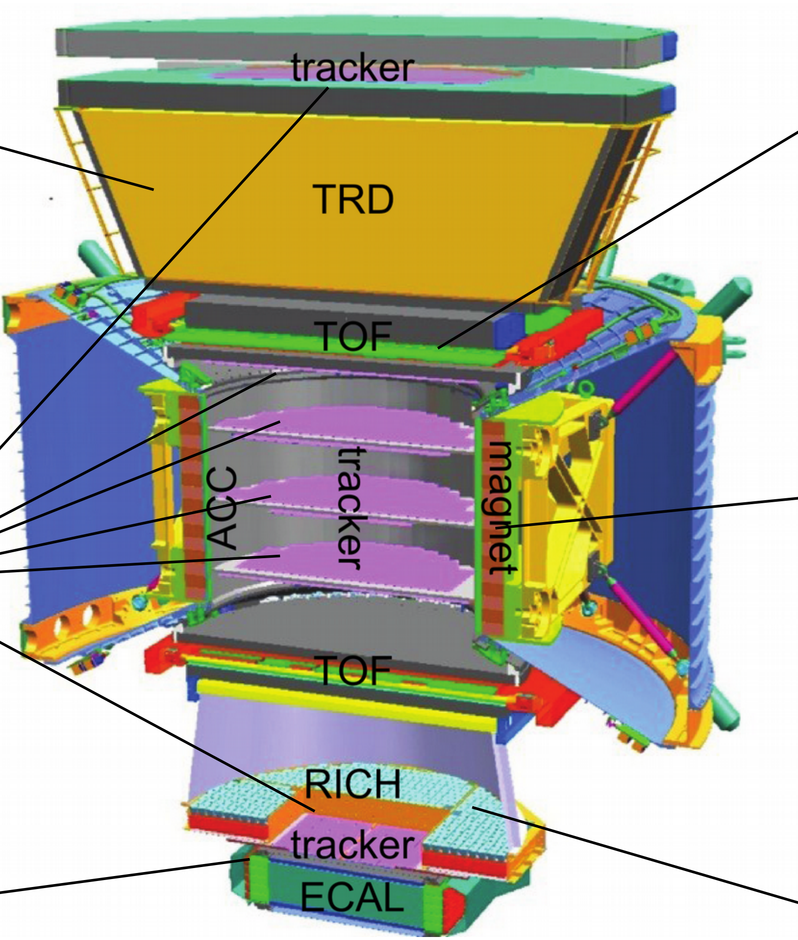
TRD
identify e+,e-



Silicon tracker
charge, momentum

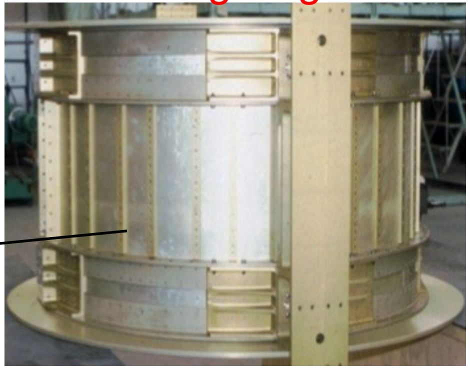


ECAL
energy of e+, e-, γ

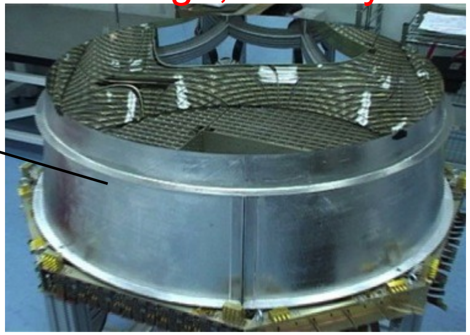


TOF
charge, velocity

magnet
charge sign

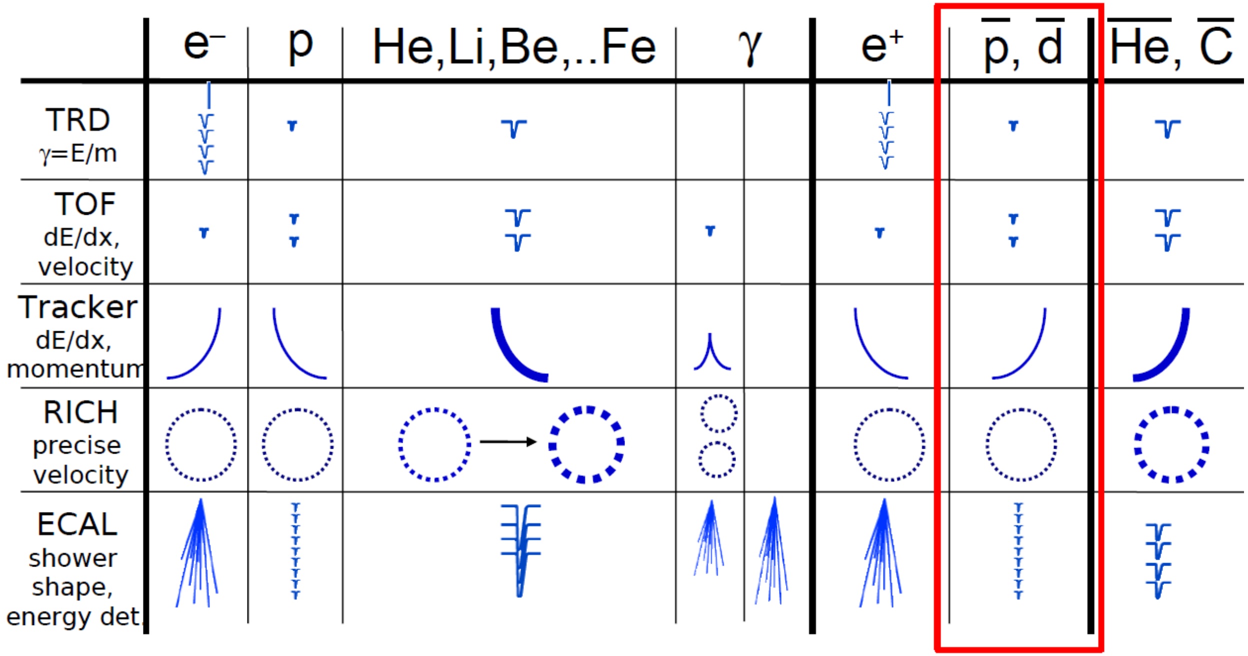


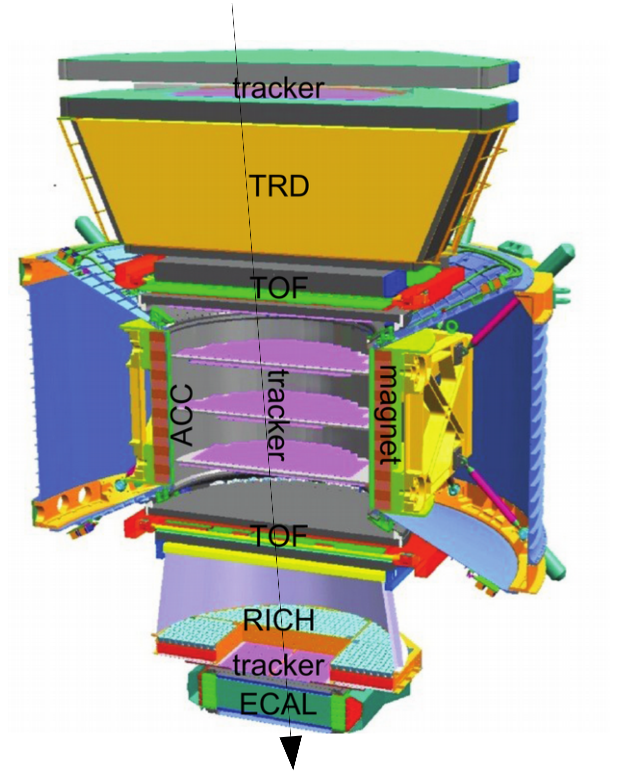
RICH
charge, velocity



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

AMS-02 antideuteron analysis



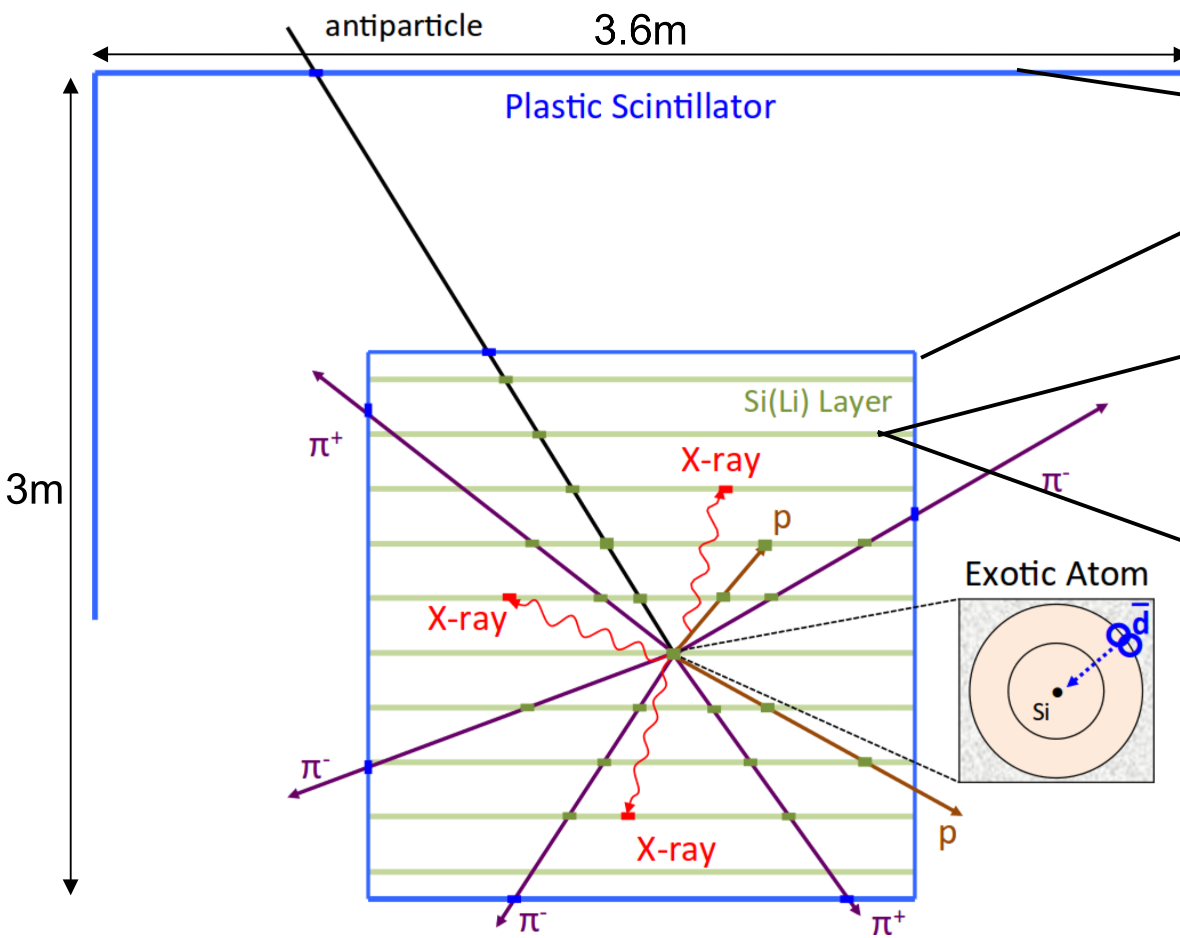


- **antideuteron identification:**
  - –momentum measured in the form of rigidity
  - –charge from TOF, TRD, tracker
  - –lower velocities: **T**ime **O**f **F**light scintillator system
  - –higher velocities: **R**ing **I**mage **Ch**erenkov detector

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

- **self-calibrated analysis:**
  - –calibrate antideuteron analysis with deuterons and antiprotons (simulations and data)
  - –geomagnetic cut-off location is challenging: study low-energy protons and electrons to calibrate geomagnetic and solar effects

The GAPS experiment

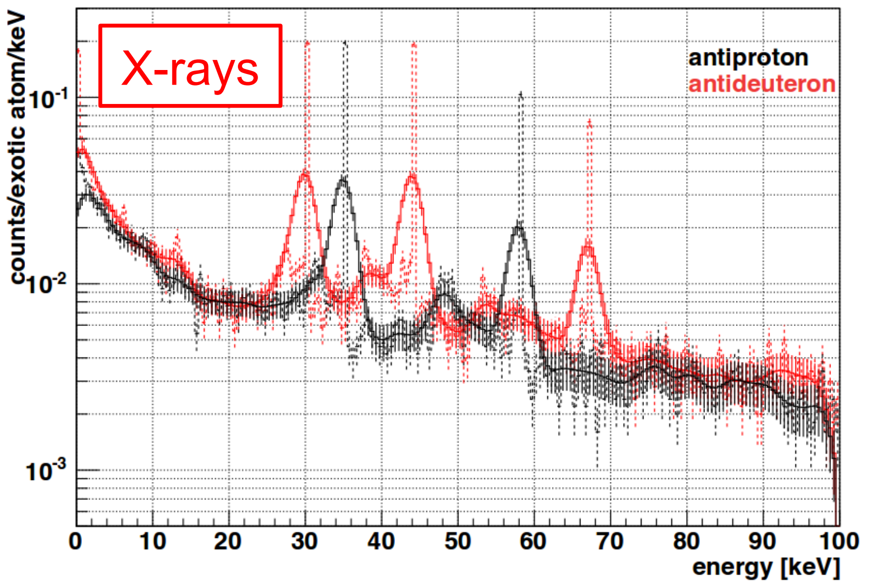


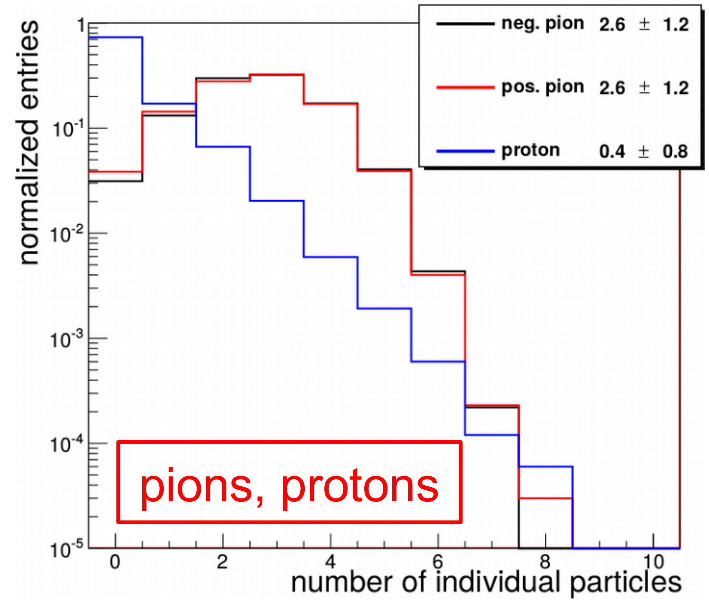
weight: 1700kg
power: 1.4kW (Si(Li) 600W, TOF 400W)

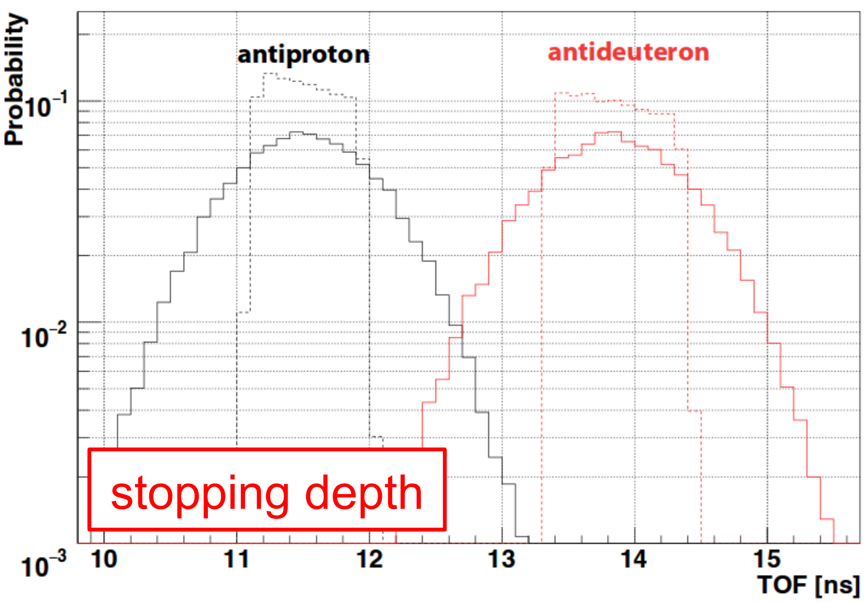
- the **G**eneral **A**nti**P**article **S**pectrometer is specifically designed for low-energy antideuterons and antiprotons
- Long Duration Balloon flights from Antarctica
- identification by stopping and creation of exotic atoms tested in KEK testbeam measurements: Astropart. Phys. 49, 52 (2013)
-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

GAPS sensitivity

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



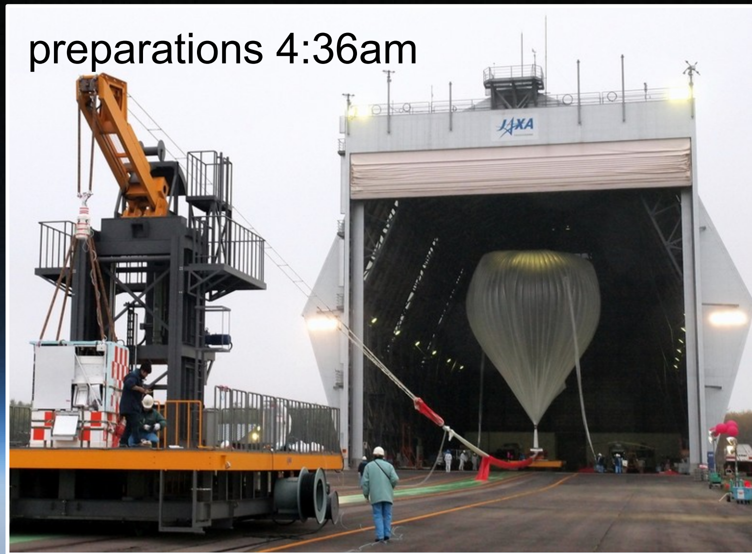




Background rejection:

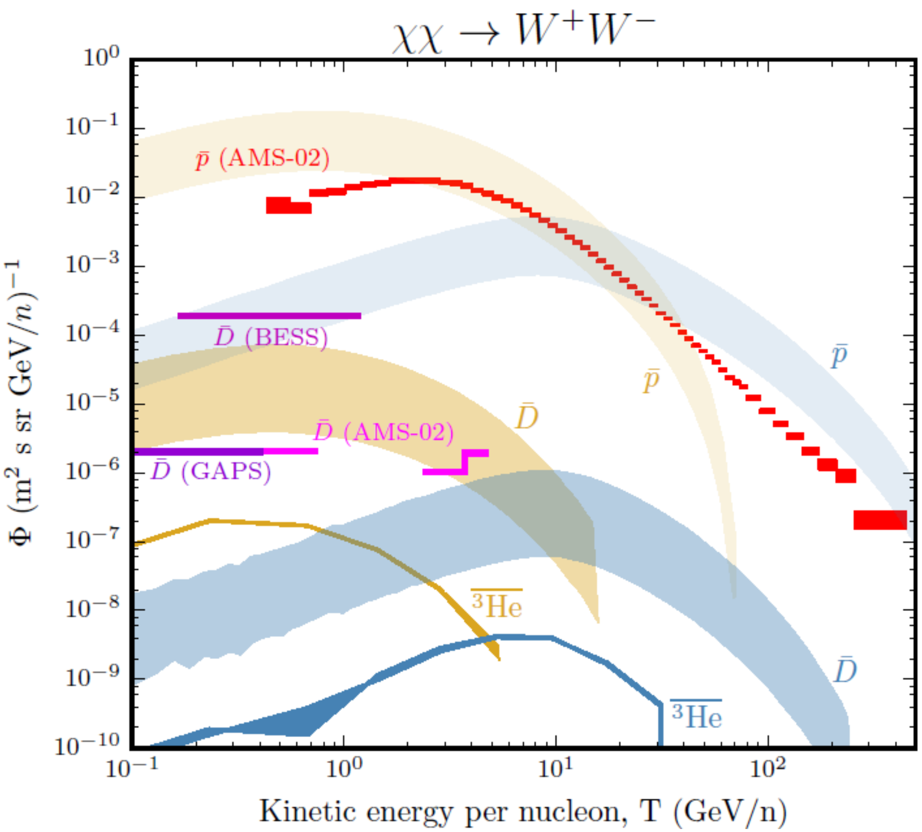
- stopping protons don't have enough energy to produce pions and cannot form exotic atoms (pos. charge)
- deexcitation X-rays have characteristic energies
- number of annihilation pions and protons
- stopping depth in detector

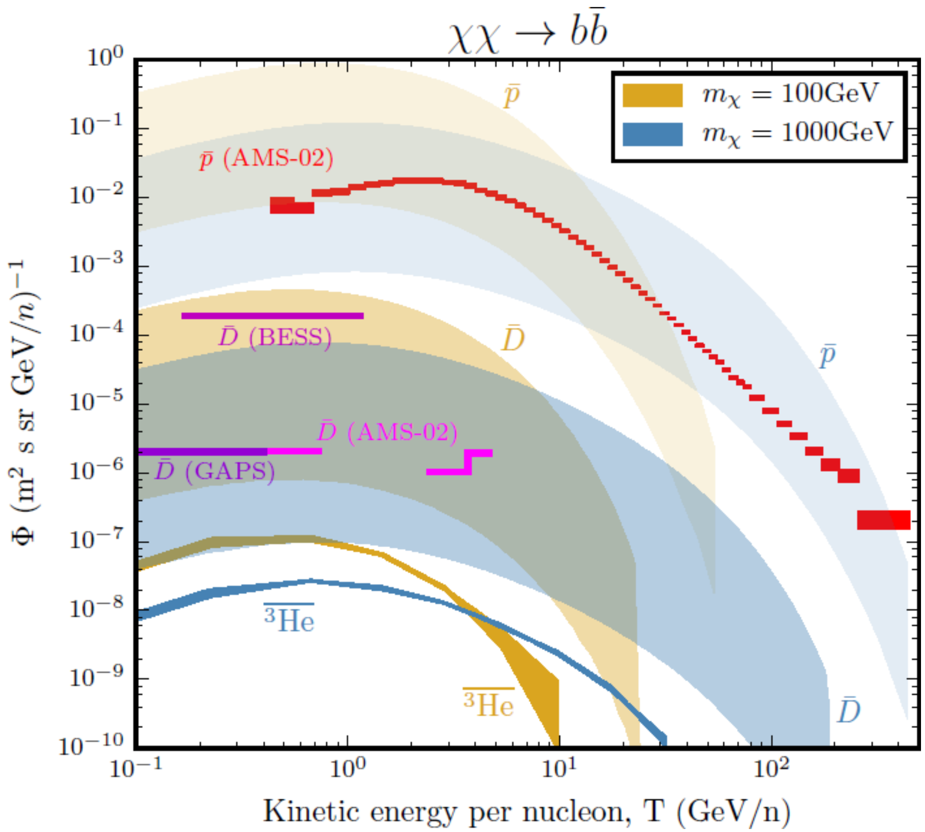
pGAPS flight: June 3rd 2012 from Taiki, Japan



Next up: antihelium?

Coogan, Profumo, arXiv:1705.09664





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

Conclusion

- First of all: this overview is not complete
  → more models are under test, more experiments exist
- cosmic-ray data are used to probe a lot of different theories for dark matter and other unidentified sources
- unexplained features exist and a consistent solution for all different species is needed
- astrophysical secondary background is a key challenge
- production cross sections have to measured with higher precision
- **multiple experiments for cross-checks are important in any rare event search**