Charged cosmic rays and Dark Matter

New Directions in Nuclear/Particle Astrophysics and Cosmology
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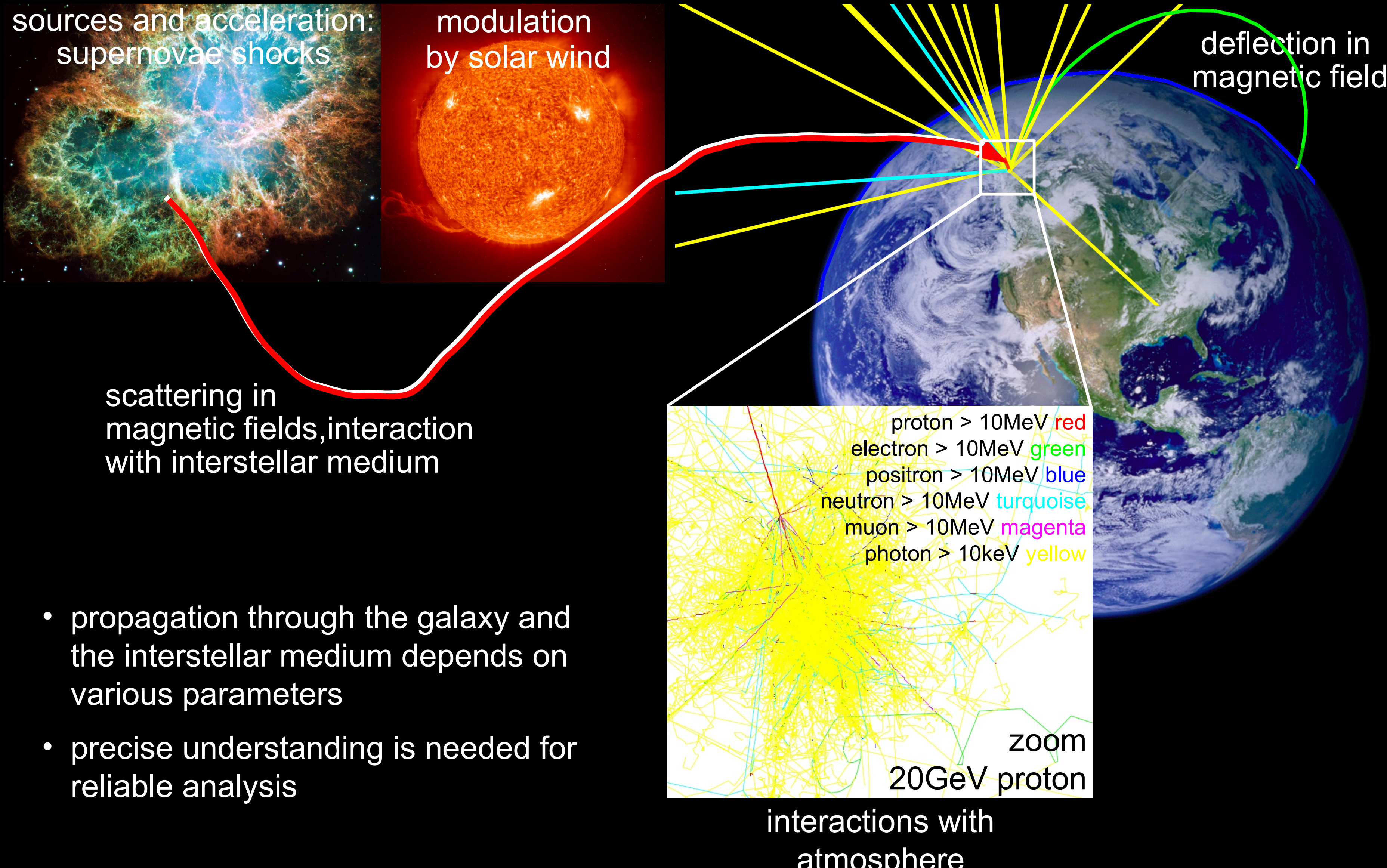
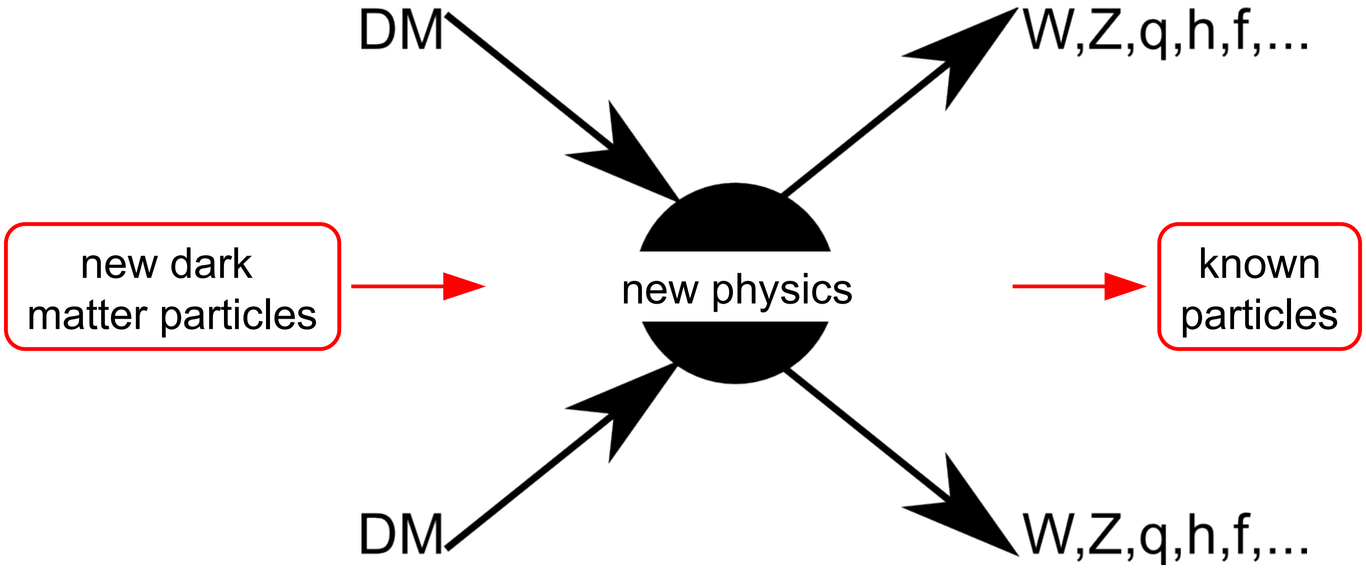
Cosmic rays as messengers



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

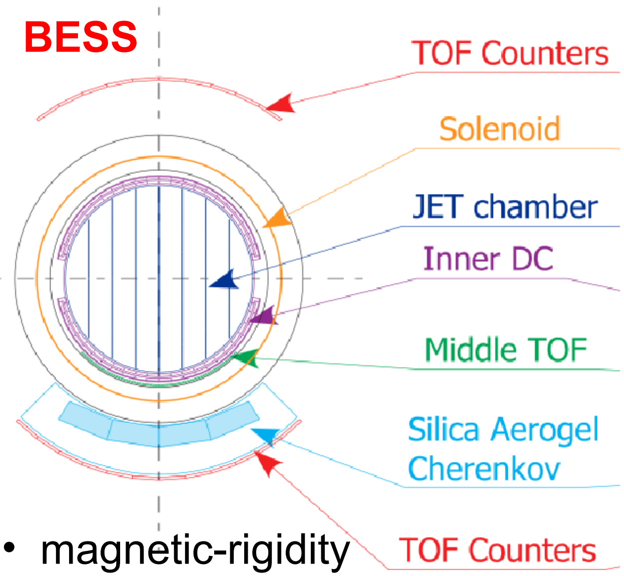
Indirect Dark Matter searches (annihilation)



- **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:
  - **charged particles:** electrons, positron, antiprotons, antideuterons
  - photons, neutrinos

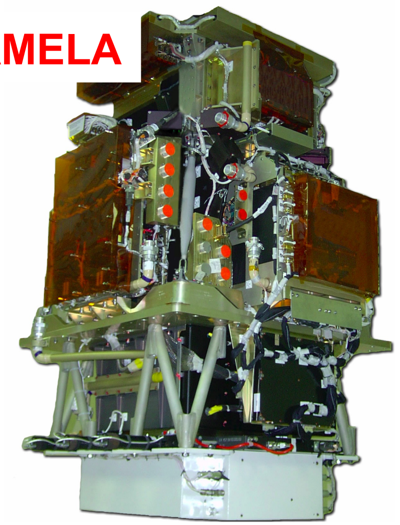
Experiments

BESS



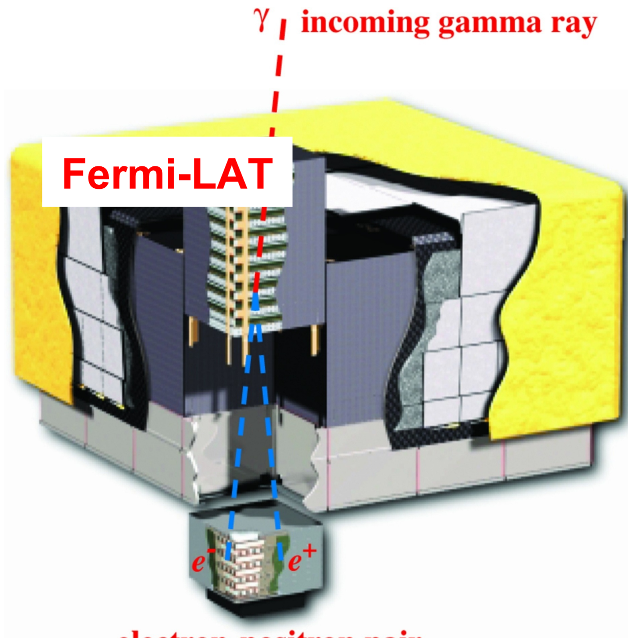
- magnetic-rigidity spectrometer:
  - superconducting solenoidal magnet
  - drift-chamber tracking system
  - time of flight
  - Cherenkov counter
- balloon flights from Canada and Antarctica from 1993-2008
- antiprotons, antideuterons, antihelium

PAMELA



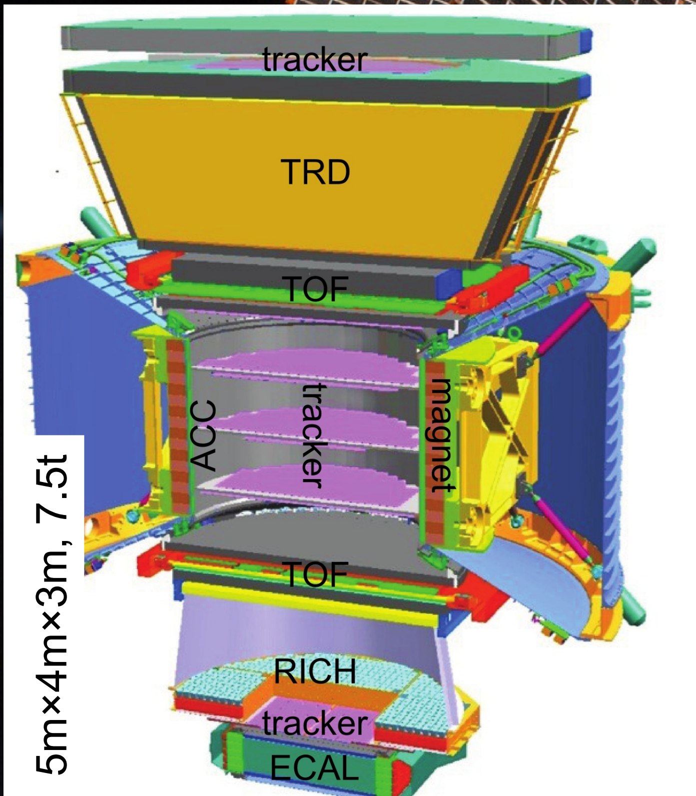
- magnetic spectrometer in space since 2006
- particle identification with several typical particle physics sub-detectors
- relatively small acceptance ($21.5 cm^2 sr$)
- electrons, positrons, antiprotons

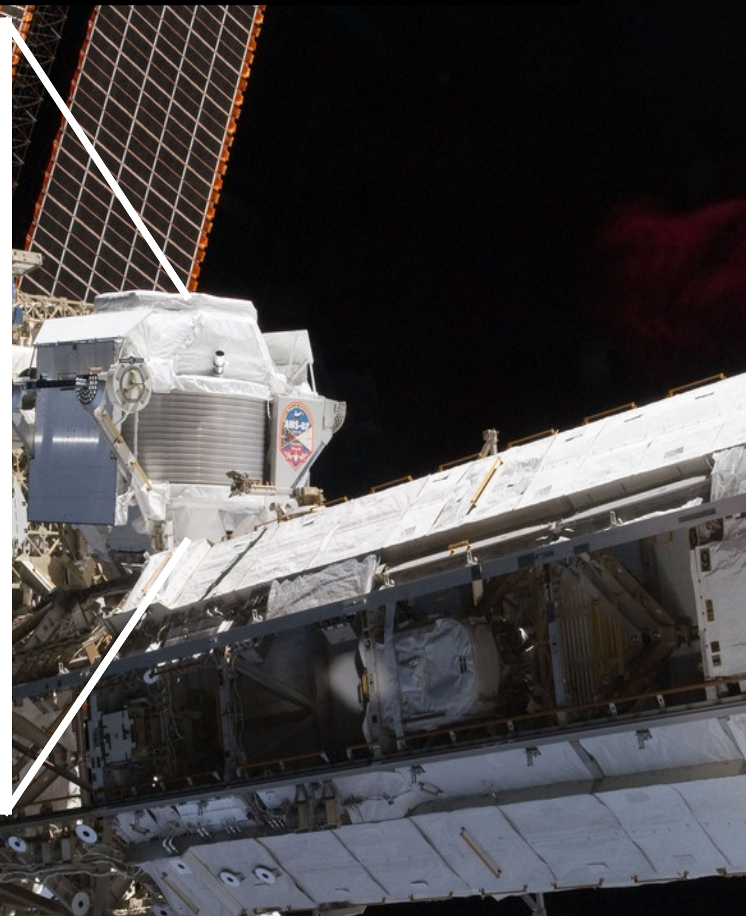
Fermi-LAT



- 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

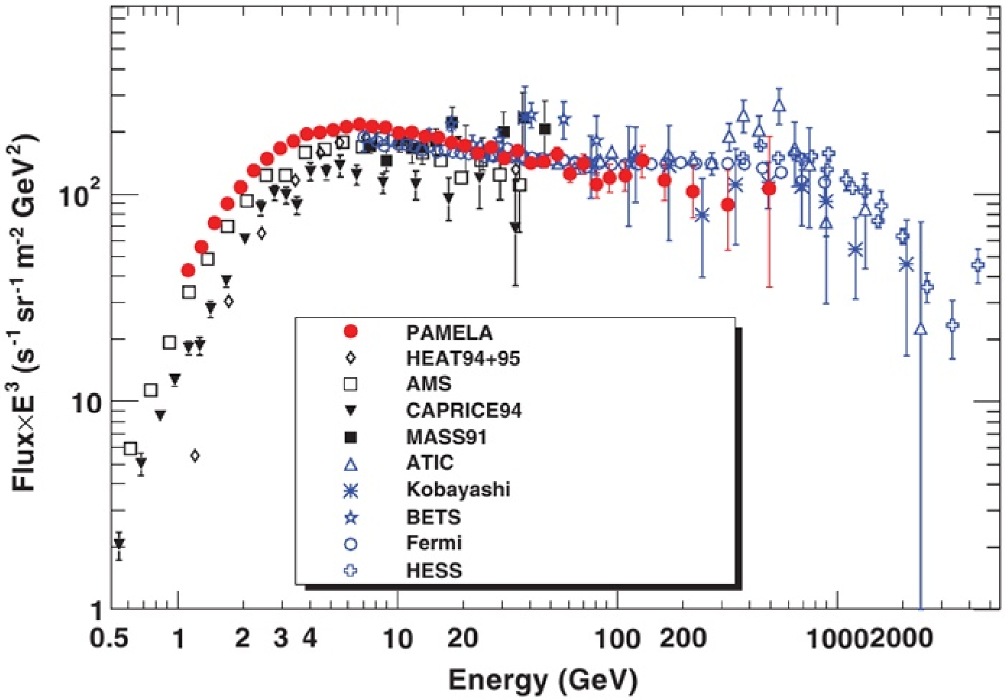
AMS-02 on the ISS

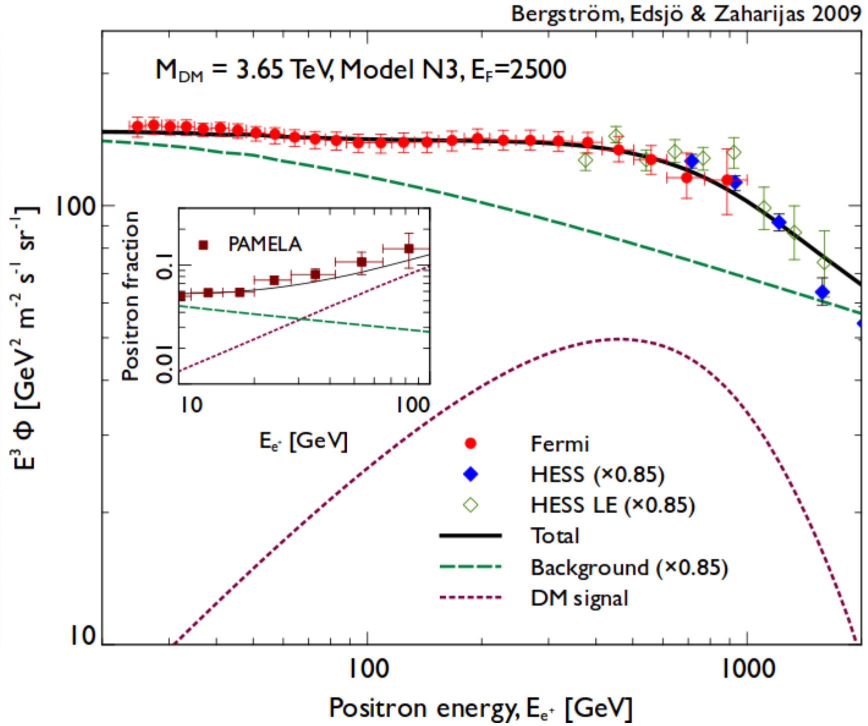




- AMS is installed on the International Space Station
- six sub-detectors provide partially redundant information for particle identification and strong permanent magnet
- AMS collected more than 25 billions of events

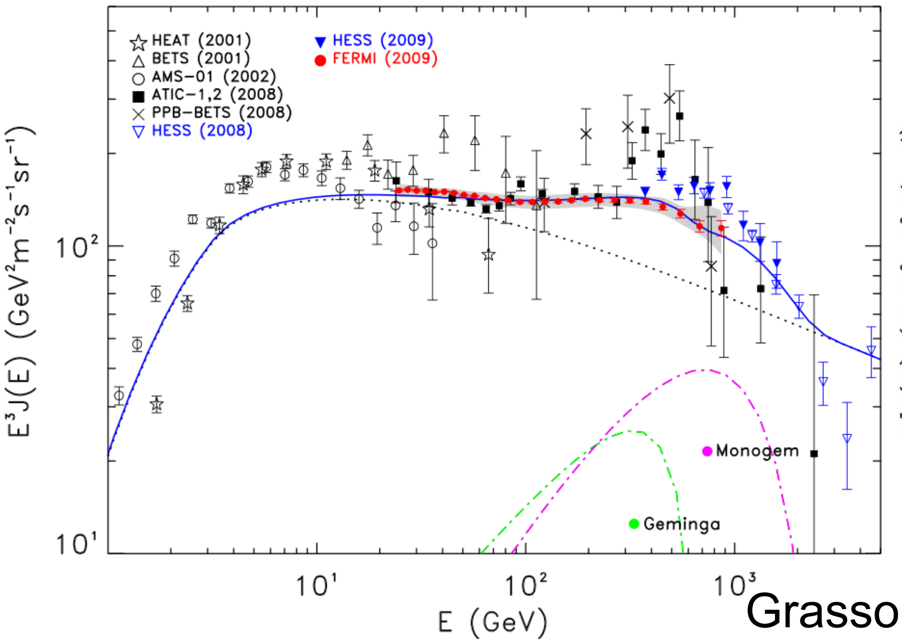
Electrons: Dark Matter

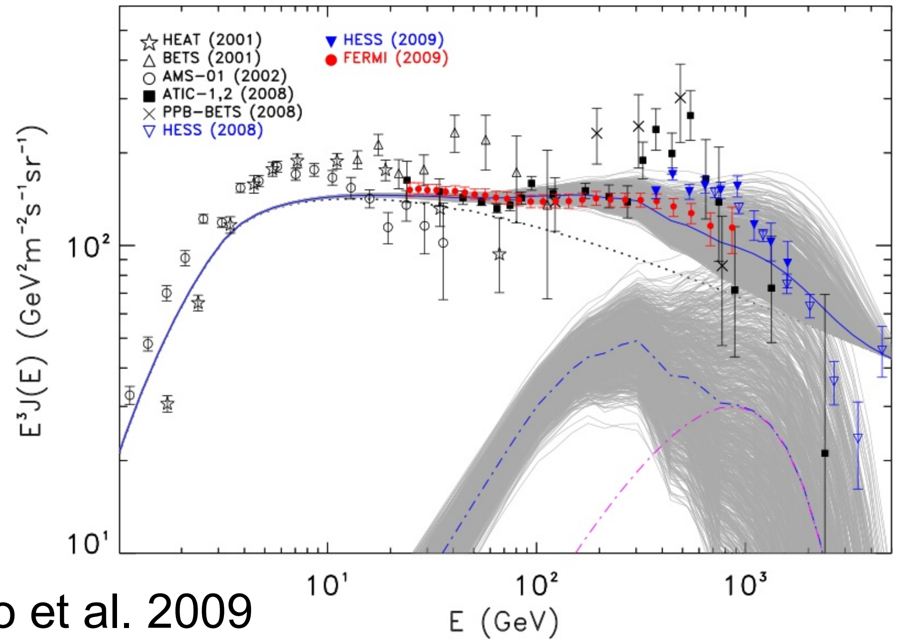




- Fermi, ATIC, HESS measurements caused big excitement in spring 2009
- more than 600 papers discuss results
- Dark Matter is a possible explanation
- interesting energy region: 100s of GeV - TeV
- enhancement factors are needed

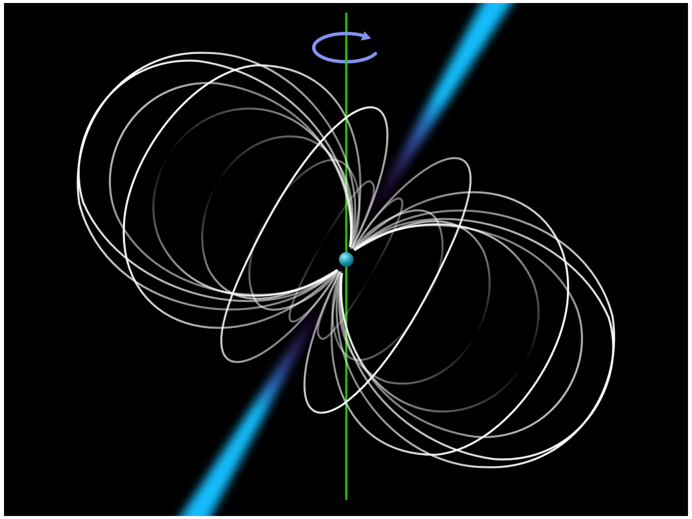
Electrons: pulsars



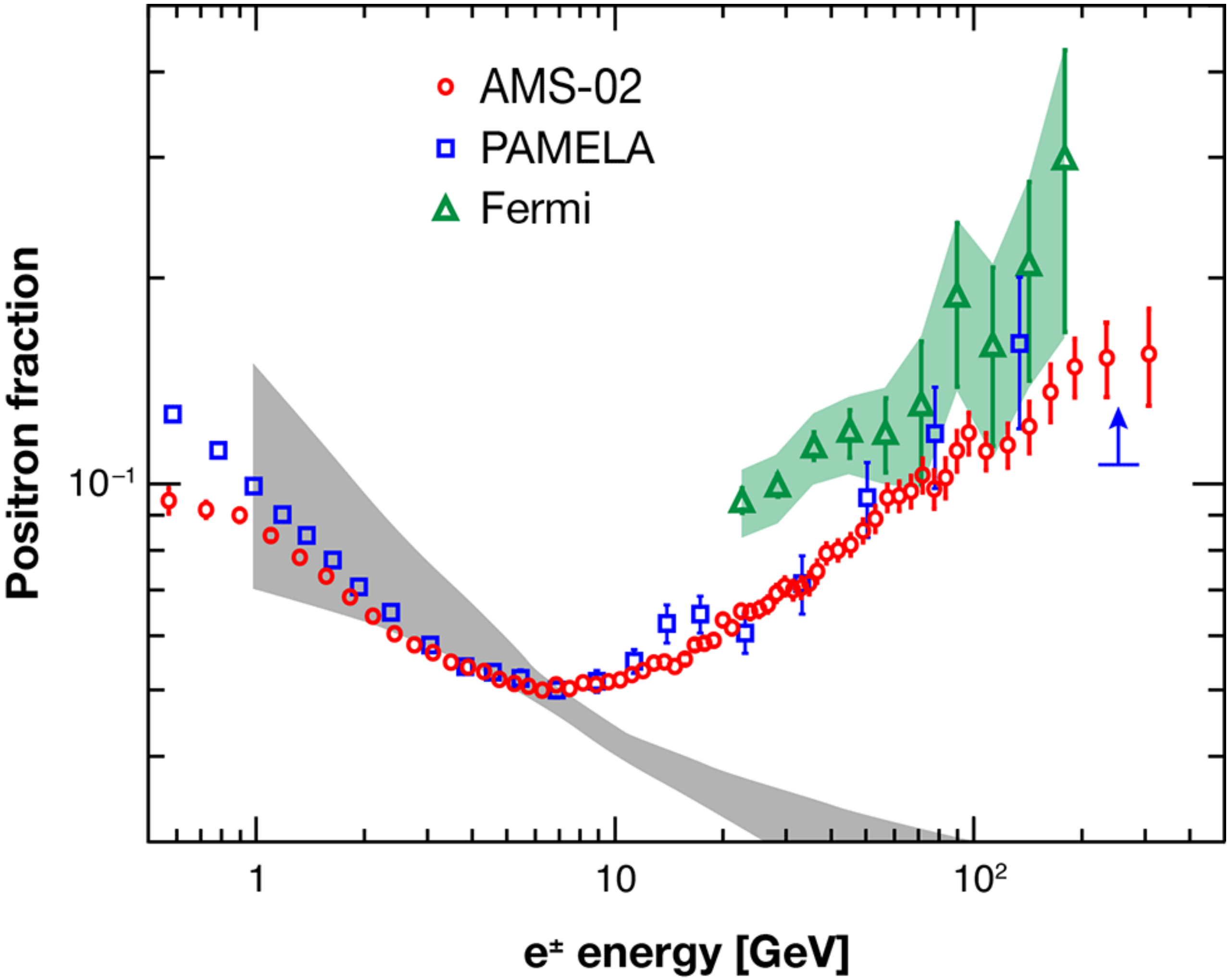


Grasso et al. 2009

- γ-ray pulsars can produce **electron and positrons via pair production** in the magnetosphere
- **positrons and electrons can be accelerated** in PWN or SNR shocks
- individual close-by pulsars or overlap of multiple pulsars
- anisotropy in signal should be visible
- more data with better statistics and lower systematics will come from AMS-02, CALET, HESS (and CTA)

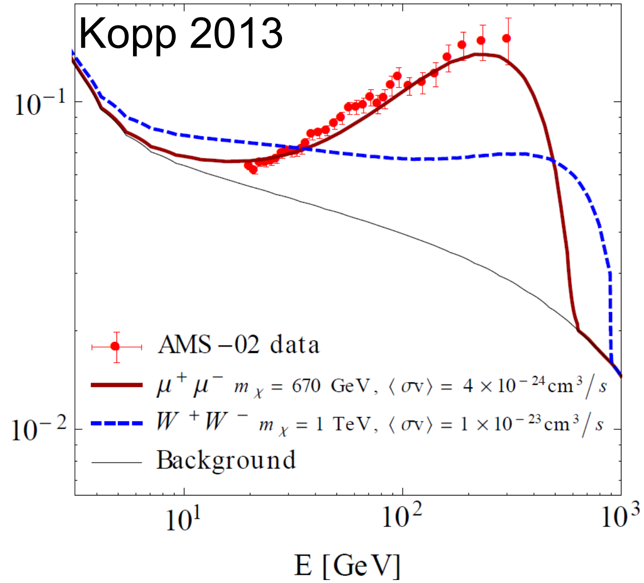


Positron status

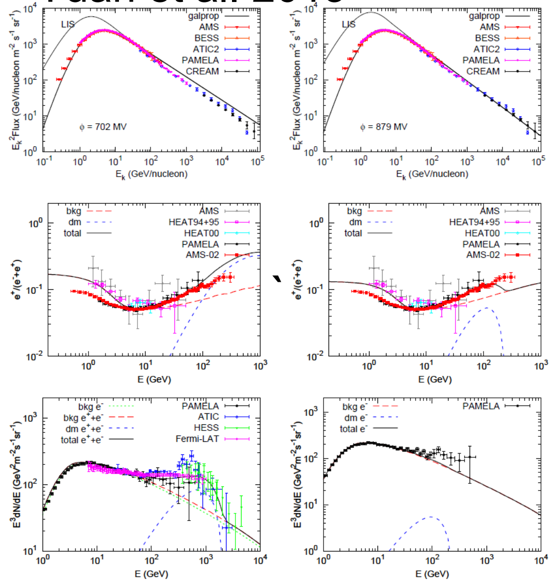


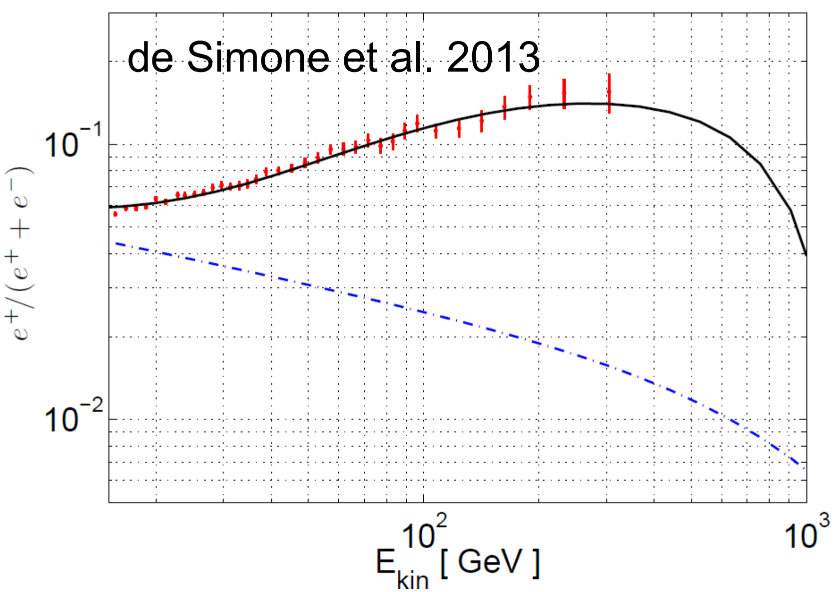
- AMS-02 positron results were presented April 3, 2013
- increase is confirmed with high statistics
- positron fraction is consistent with isotropy
- already many papers on the arXiv discussing AMS-02 results

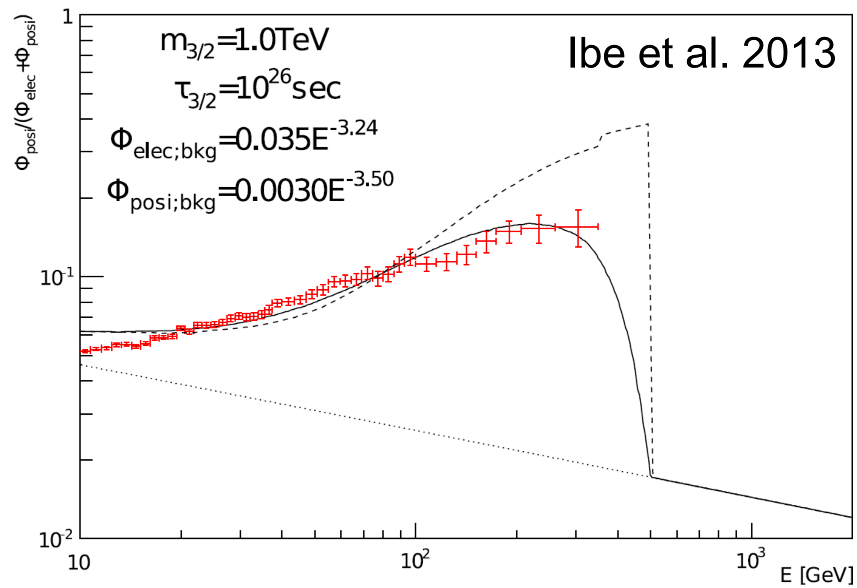
Positrons: Dark Matter



Yuan et al. 2013

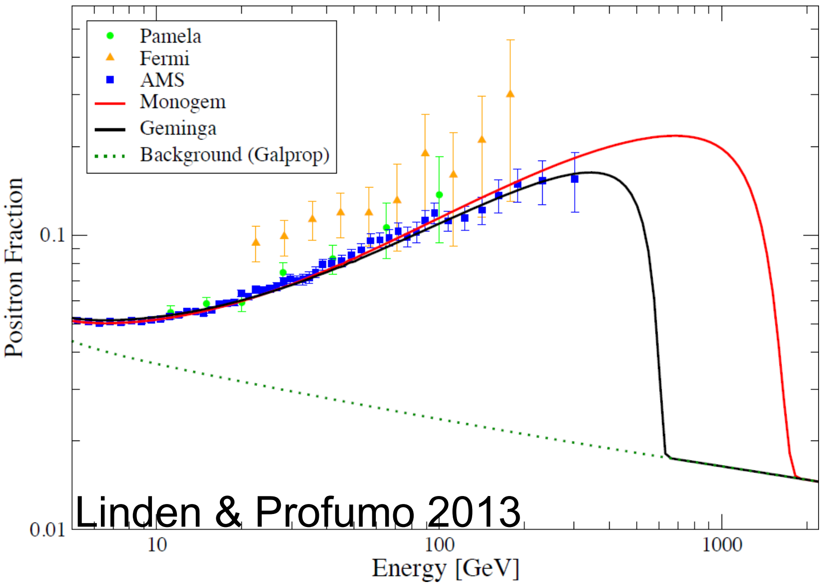


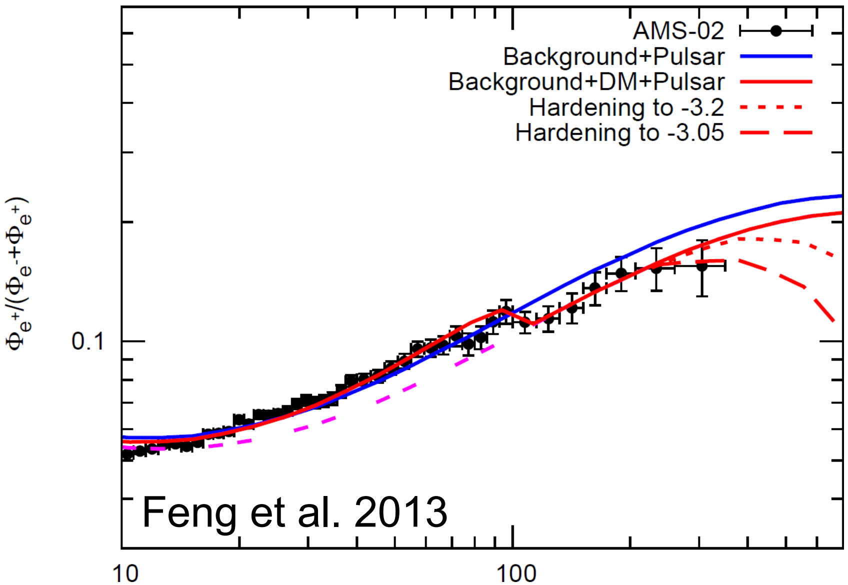




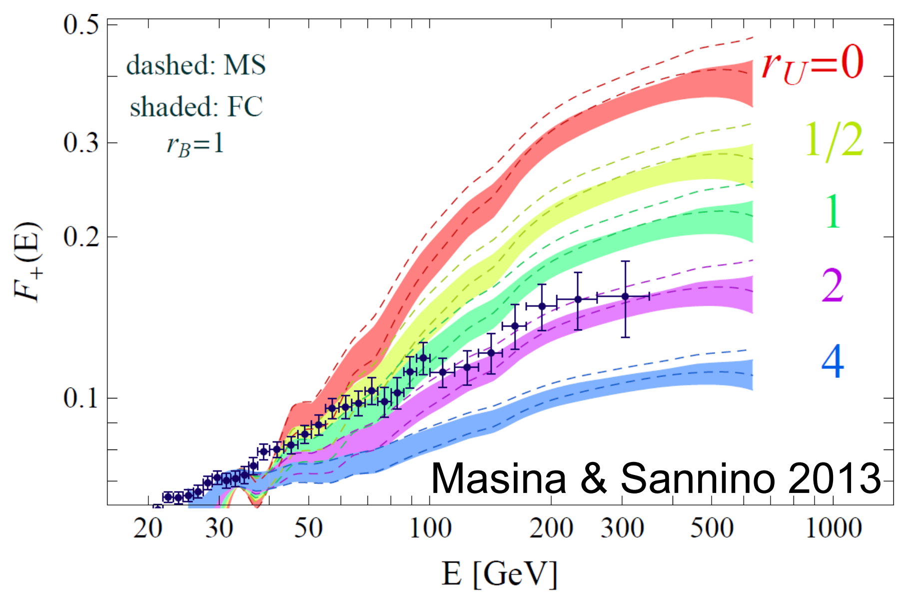
- Dark Matter models are severely constrained:
  - large cross sections
  - boost factors too large?
  - leptophilic?
- degeneracy in annihilation channels
- R-parity violating SUSY models
- decaying gravitino Dark Matter
- combined analysis of different CR channels important: γ-rays, antiprotons

Positrons continued



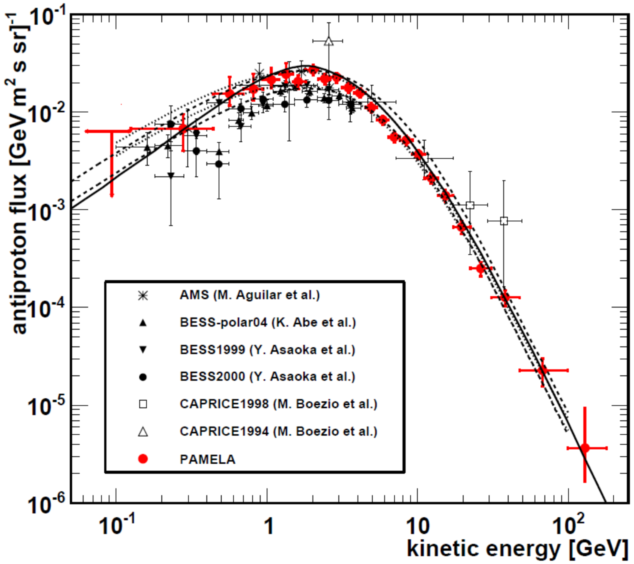


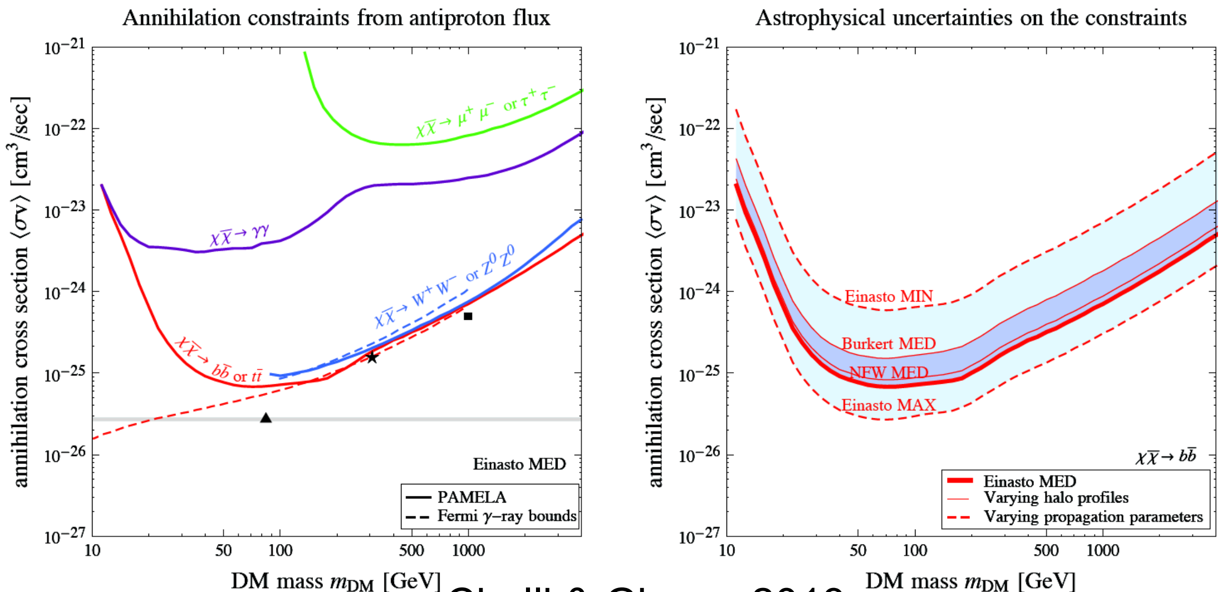
- AMS-02 can be explained by simple nearby pulsar
- anisotropy should be smaller than AMS-02 limit, but still measurable with ACTs
- important to see where and if the positron fraction continues



- pulsar **AND** Dark Matter?
- spectral hardening of electron component?
- charge asymmetric e^--e^+ source? electrons favored?

Antiprotons: Dark Matter





Cirelli & Giesen 2013

- PAMELA constraints on annihilating/decaying Dark Matter are strong
- astrophysical uncertainties: different halo/propagation parameter choices span two orders of magnitude
- AMS-02 has potential to improve limits by a factor of ~10 and test thermal relic cross section
- constraining DM properties in case of a measured excess is complicated as astrophysical background and different channels shapes are very similar

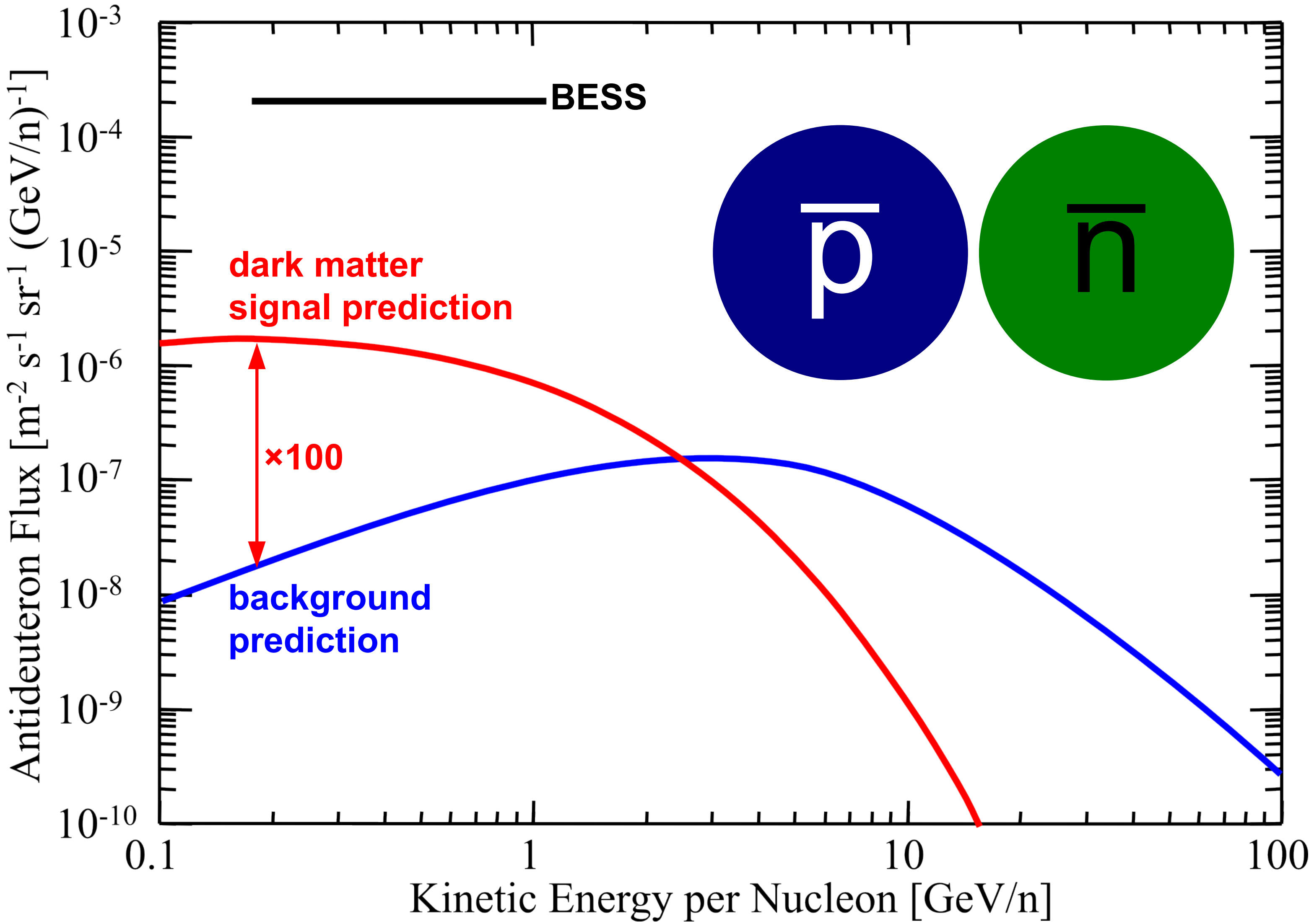
- **it is really exciting during the last years (but so far inconclusive)**
  - 2008: positron fraction from PAMELA
  - 2009: electron fluxes: Fermi, ATIC, HESS
    antiprotons from PAMELA
  - 2011: positron fraction from Fermi
  - 2012: 130GeV line from Fermi
  - 2013: positron fraction from AMS-02

- **DM explanation needs boosts and suppress antiprotons?**
- **electron/positron production by pulsars efficient enough?**
- **astrophysical background/propagation needs to be more constrained → AMS-02**

- **strategy: look for new channels with better dark matter to background prediction!**

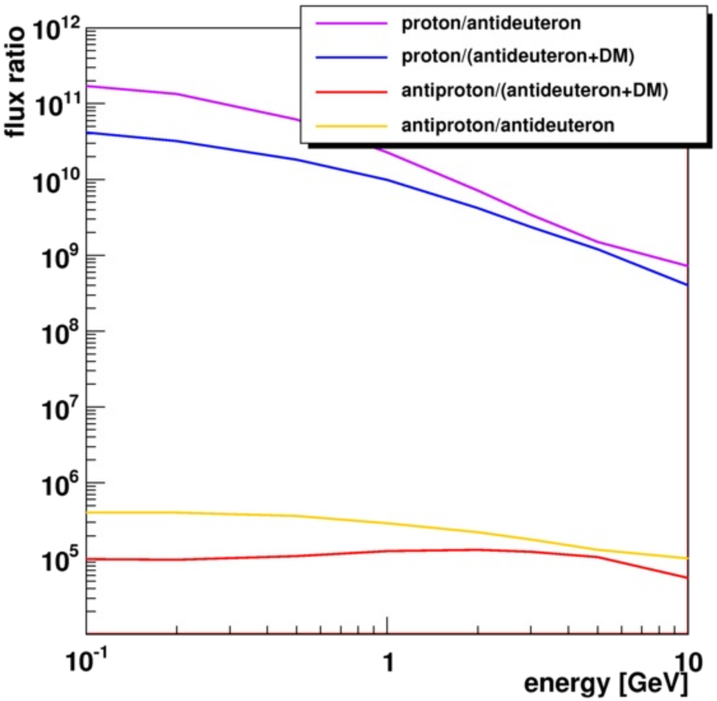
Complementarity approach: direct, indirect, and collider experiments

Antideuterons and Dark Matter

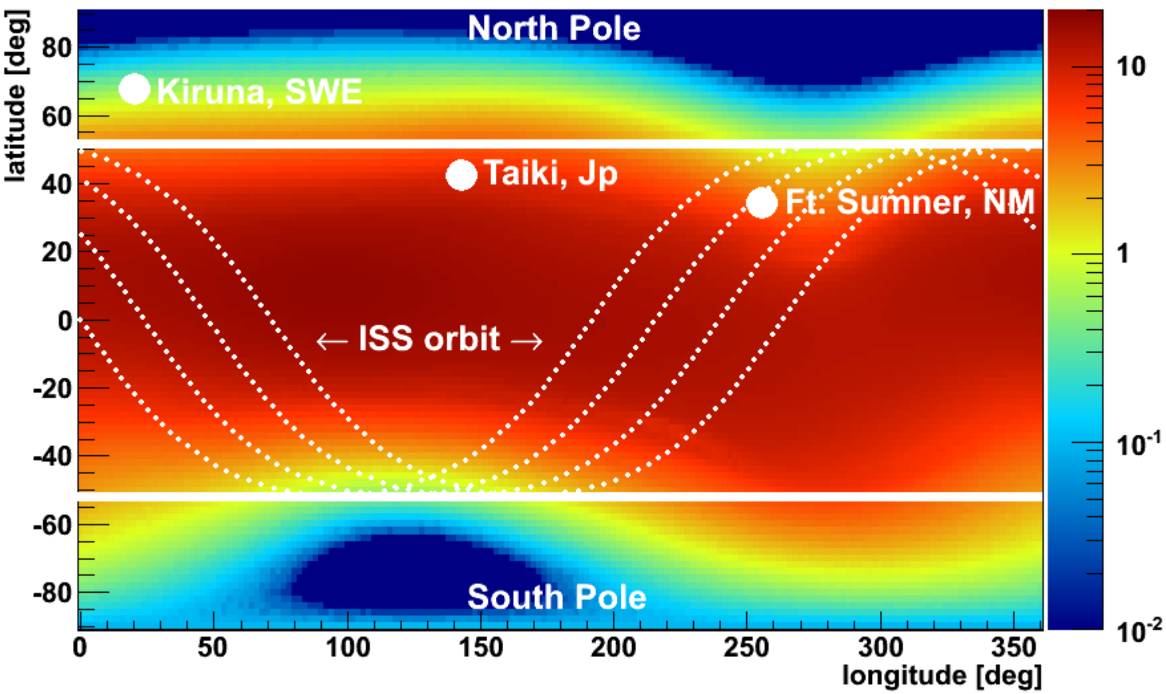


- **antideuterons are the most important unexplored indirect detection technique**
- **prediction:** antideuterons from Dark Matter annihilations up to 100 times more abundant than from conventional cosmic rays

Observational challenges



flux ratios

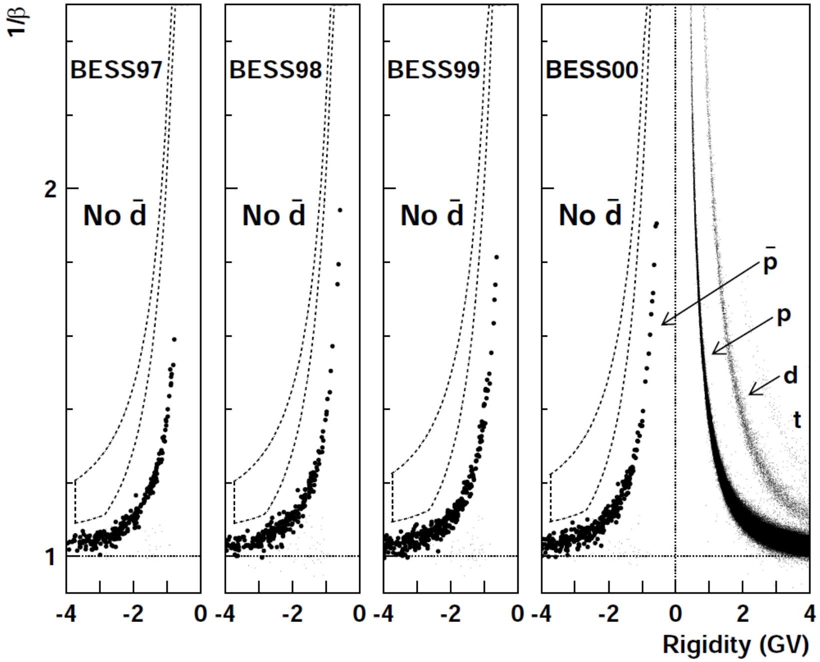


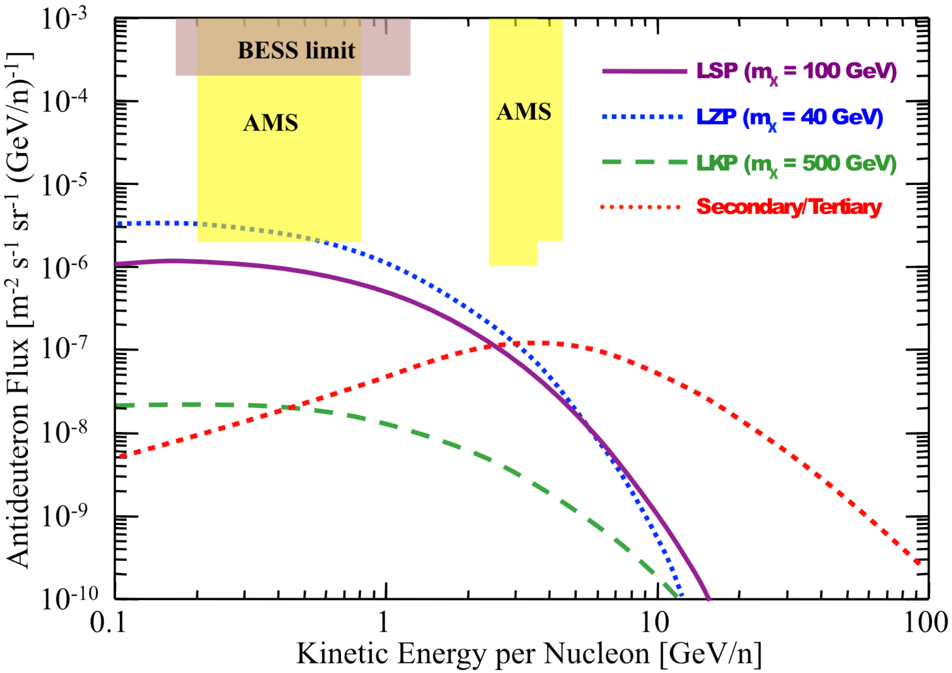
geomagnetic cut-off

antideuteron measurement with balloon and space experiments requires:

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

Antideuterons with BESS and AMS





- **BESS antideuteron results:**
  limit of 1.9×10^{-4}(m^{2}s sr GeV/n)$^{-1}$ @ 95% C.L. for 0.17-1.15 GeV/n
- improved results from BESS polar II coming soon (~factor 3 better)

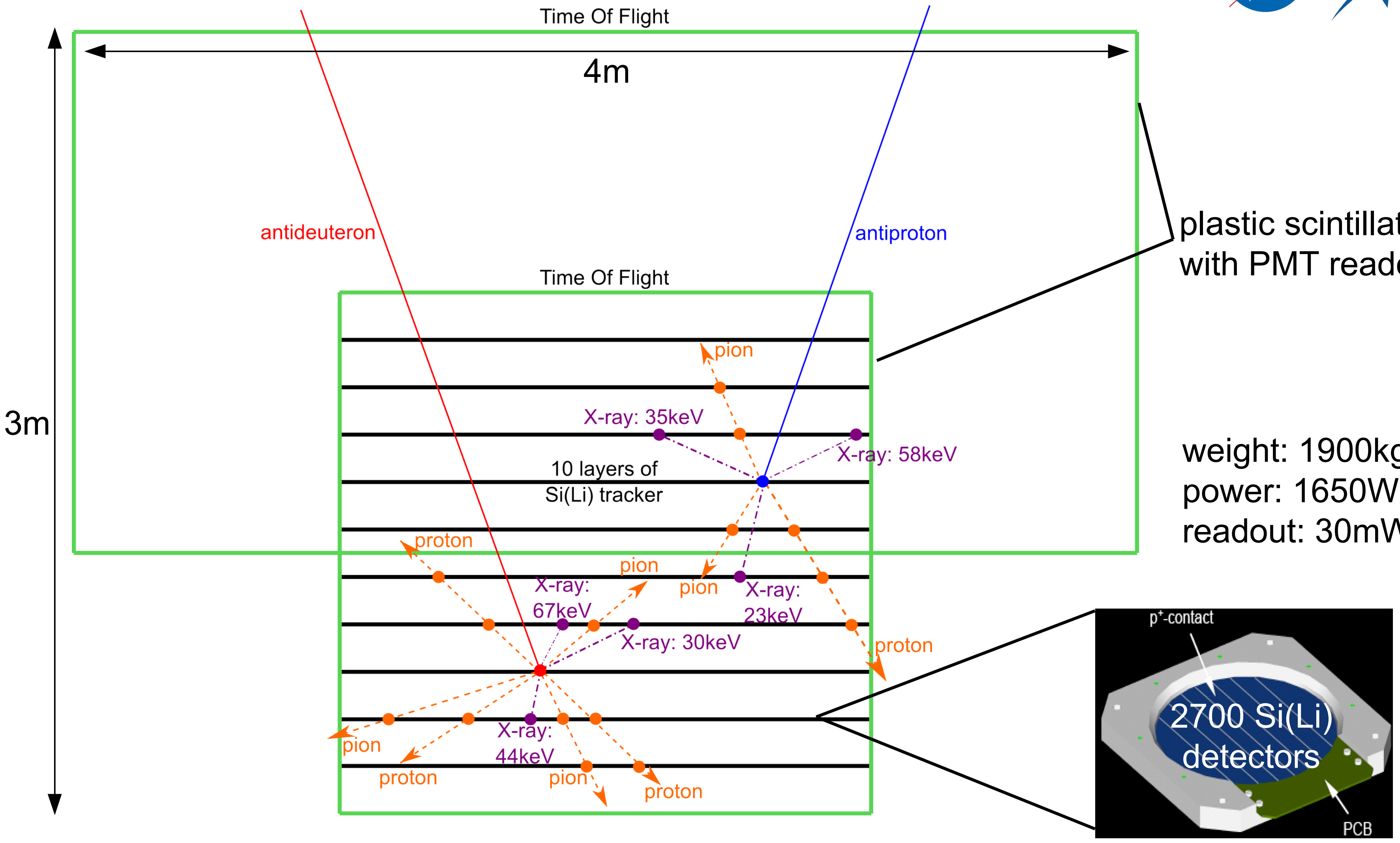
- PAMELA is too small to reach meaningful sensitivity

- AMS is the best running experiment to go after antideuterons
- analysis challenges: ISS → geomagnetic cut-off, multiple scattering

- different detection techniques are very important for rare event searches

The GAPS experiment

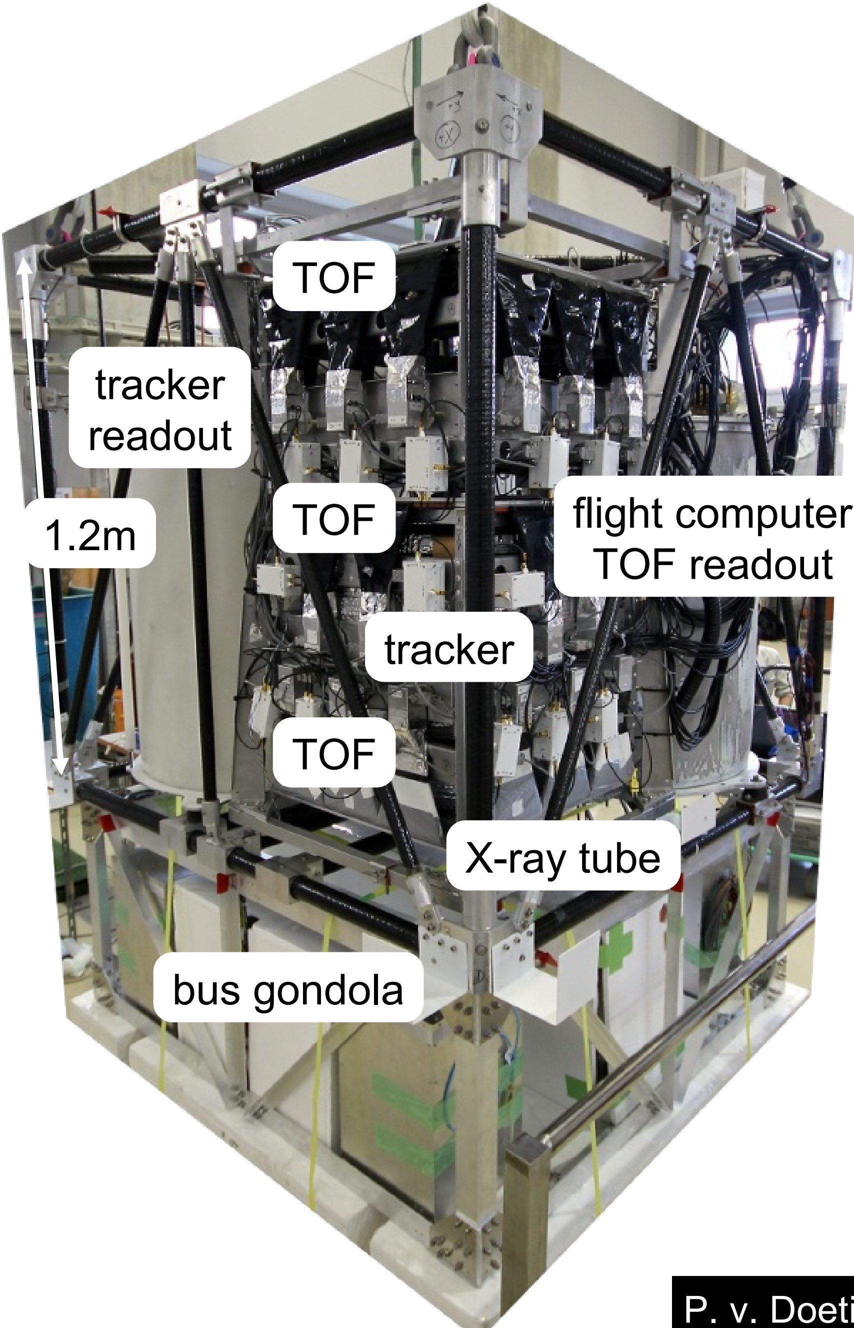
Columbia U, UC Berkeley
UCLA, U Hawaii



weight: 1900kg
power: 1650W
readout: 30mW/ch

- 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 [arXiv:1303.3871]
- long duration balloon flights from Antarctica starting from 2017

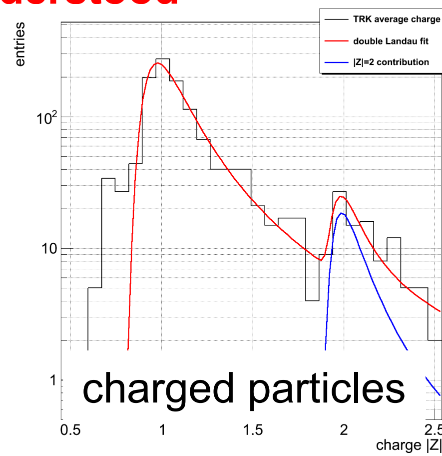
GAPS development

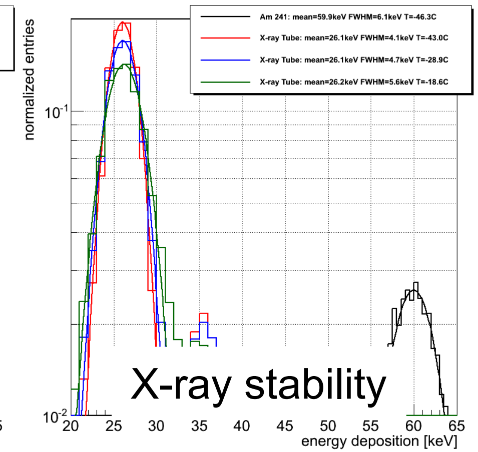


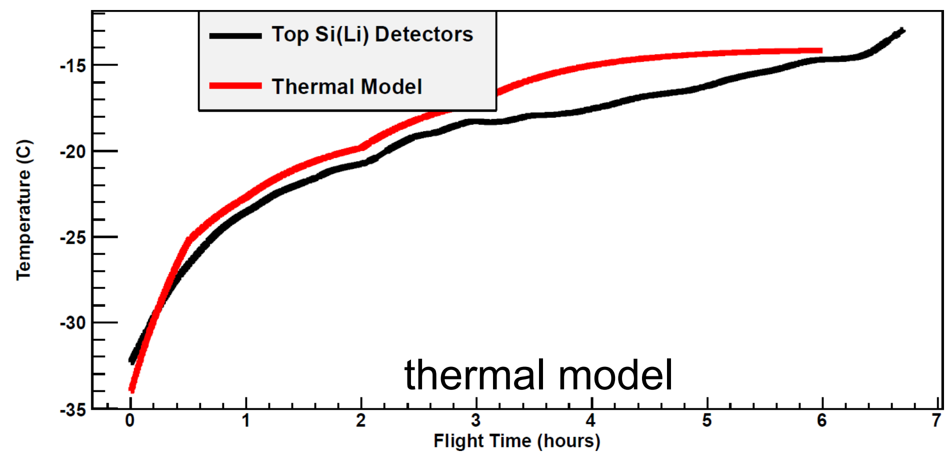
Prototype flight from Japan in 2012 [arXiv:1303.1615]

- demonstrated stable operation of the detector components during flight
- measured background levels
- verified Si(Li) cooling approach for thermal model

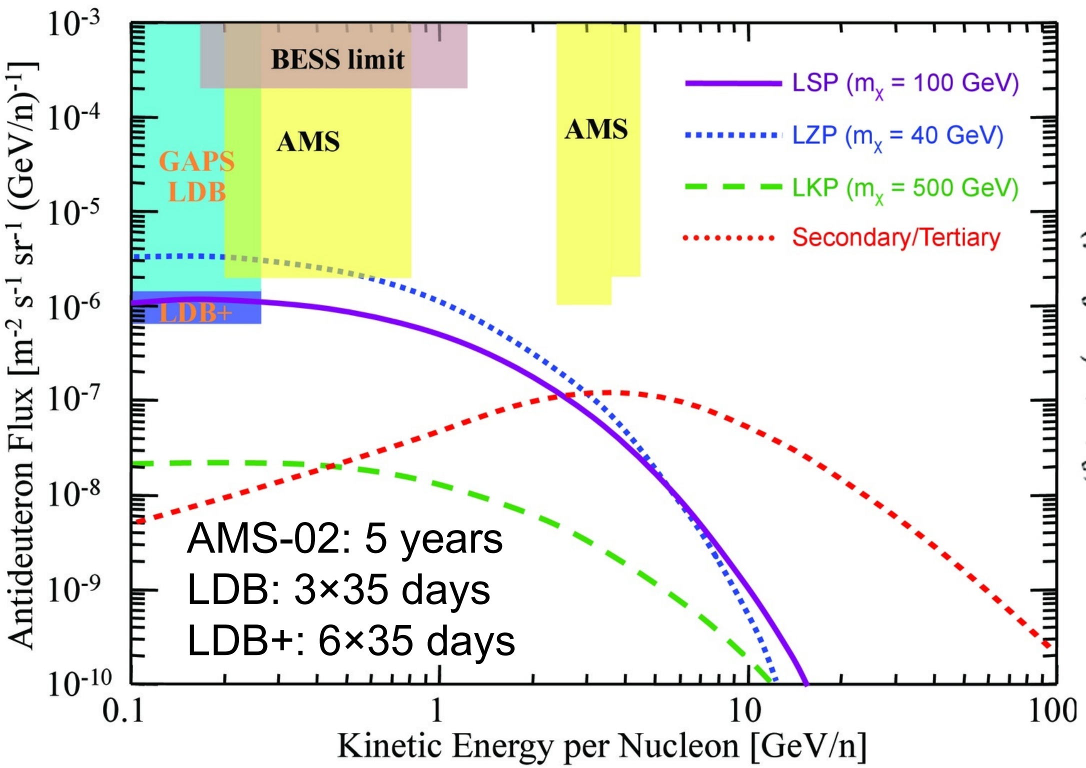
In-house Si(Li) detector fabrication at Columbia well understood

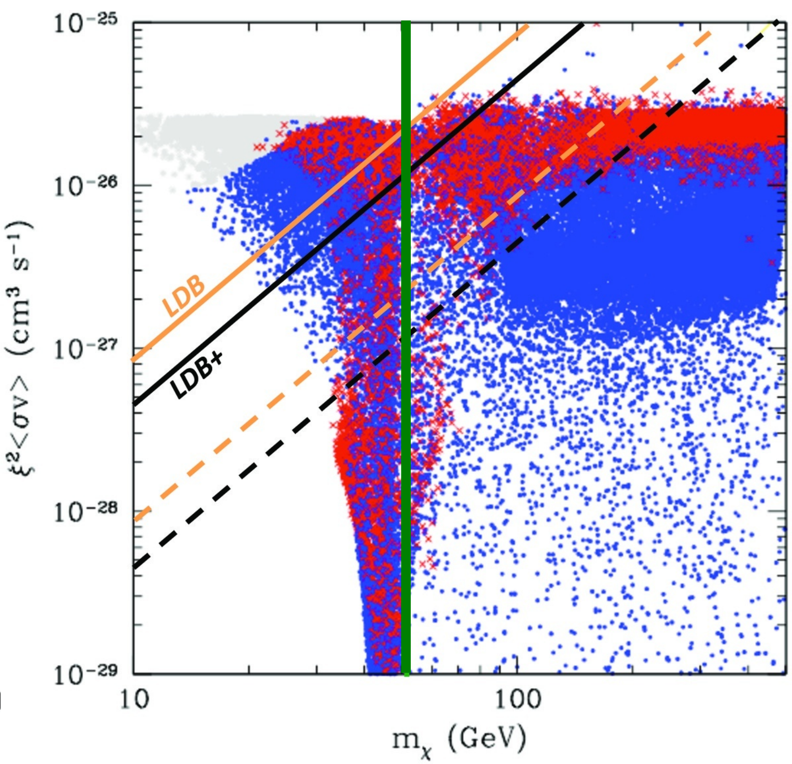






Antideuteron sensitivity





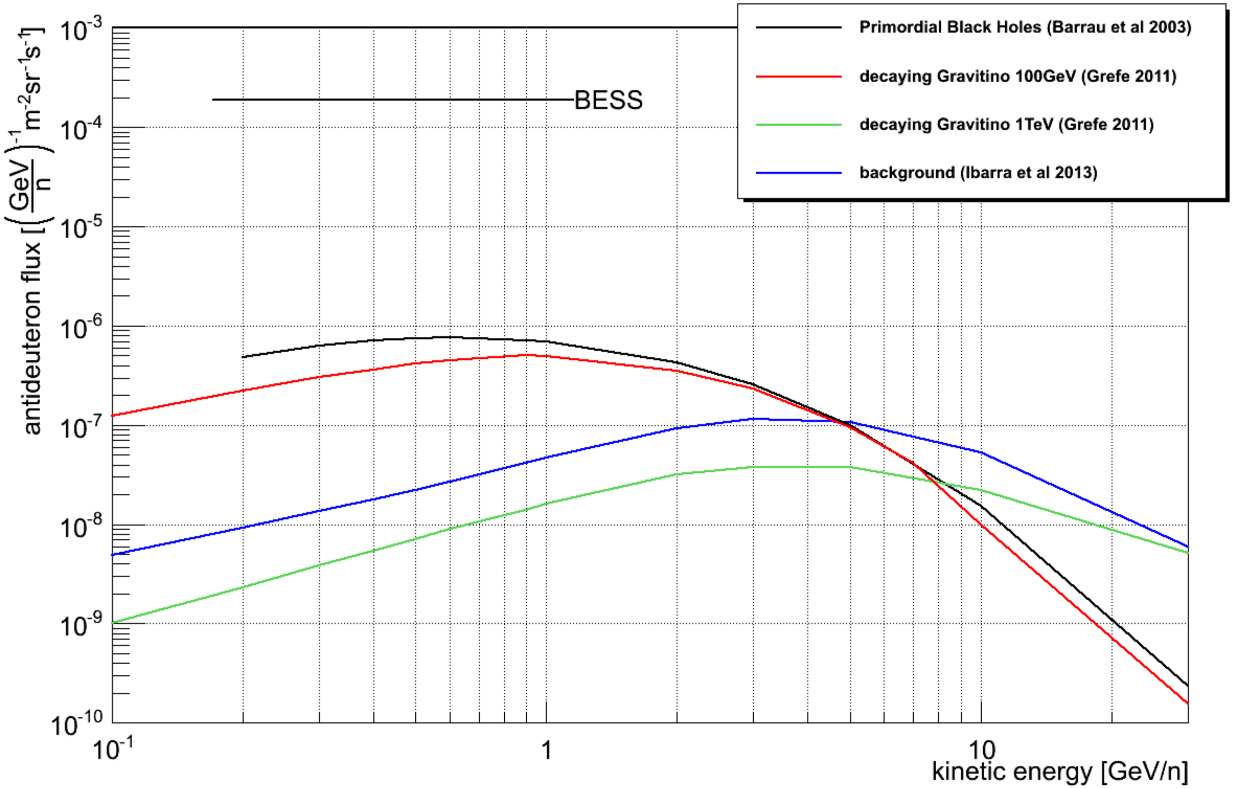
- GAPS is very effective to search for light WIMPS
- rare event searches always require independent confirmation
  - **if AMS detects $\bar{d}$: confirmation is needed**
  - **if no detection: GAPS goes deeper**
- building GAPS right now is important for timely comparison

Conclusion

- charged 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
- AMS-02 will push the field with its long-term and high precision measurements and will strongly constrain cosmic-ray propagation models
- other experiments will come online: CALET, hopefully CTA

- antideuterons are the most unexplored channel for indirect Dark Matter search and meaningful sensitivity will be reached within the next five years
- GAPS is specifically designed for low-energetic antideuterons
- **it is the right time to start building GAPS to compare to AMS and direct searches**

Primordial black holes and gravitinos



- **primordial 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**
- **cosmological gravitino problem:**
  - graviton → superpartner gravitino
  - late decays of unstable gravitinos to standard particles would produce antideuterons