Space-based searches: MMs and other HIPs

Yi Jia, IHEP

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NFMMS2026, IHEP

Magnetic charge and highly ionizing particles

- Dirac magnetic charge

$$g = n g_{\mathrm{D}}, \qquad g_{\mathrm{D}} = \frac{\hbar c}{2e} \approx 68.5e$$

Dirac, Proc. R. Soc. A 133 (1931) 60

Gaussian units, using e as the elementary electric charge

- Highly ionizing particle (HIP)

Several proposed particles can produce high ionization

Candidate	Charge / signal
Magnetic monopole (MM) / dyon	Magnetic charge g / both q and g
Strangelet / nuclearite	Anomalous mass-to-charge / bulk energy deposition
Charged Q-ball	Model-dependent charge

Patrizii & Spurio, Annu. Rev. Nucl. Part. Sci. 65 (2015) 279

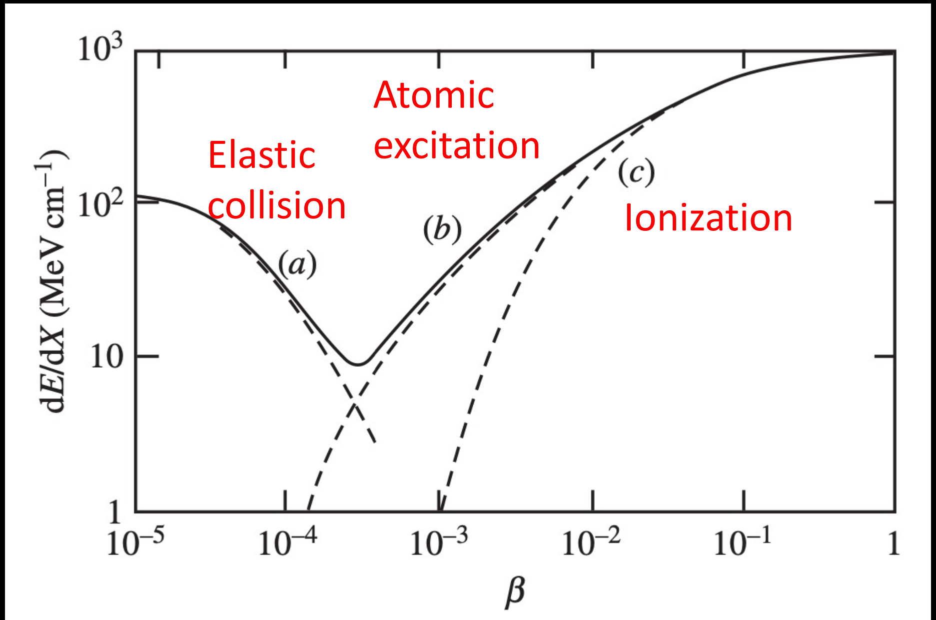
Detection Technique

- Energy Loss
  - Ionization (β>0.05): for a particle with electric charge ze, $\mathrm{dE/dx} \propto z^2$. For a particle with magnetic charge ng_D, z is replaced by $ng_D/\mathrm{e}\beta$:

$$\mathrm{dE}/dx \propto (ng_D/\mathrm{e}\beta)^2 \text{ or } \mathrm{dE}/dx \propto (68.5n\beta)^2$$

Relativistic monopole with charge g_D ionize ~4700 more than minimum ionizing particles (MIP)

  - Atomic excitation (10^{-3}<β<0.01)
  - Elastic collision (β< 10^{-4})



Liquid hydrogen at one Dirac charge
G. Giacomelli – Riv. Nuovo Cim. 7 No. 12 1984
Reproduced in MoEDAL 2014 Fig. 8
arXiv 1405.7662

- Induction: search for the induction of a persistent current within a superconducting loop, mostly deployed in searches for magnetic monopoles bound in matter, such as lunar rocks, meteorites.

- Cherenkov light: relativistic monopole by neutrino telescope

Accessible region for detectors on earth

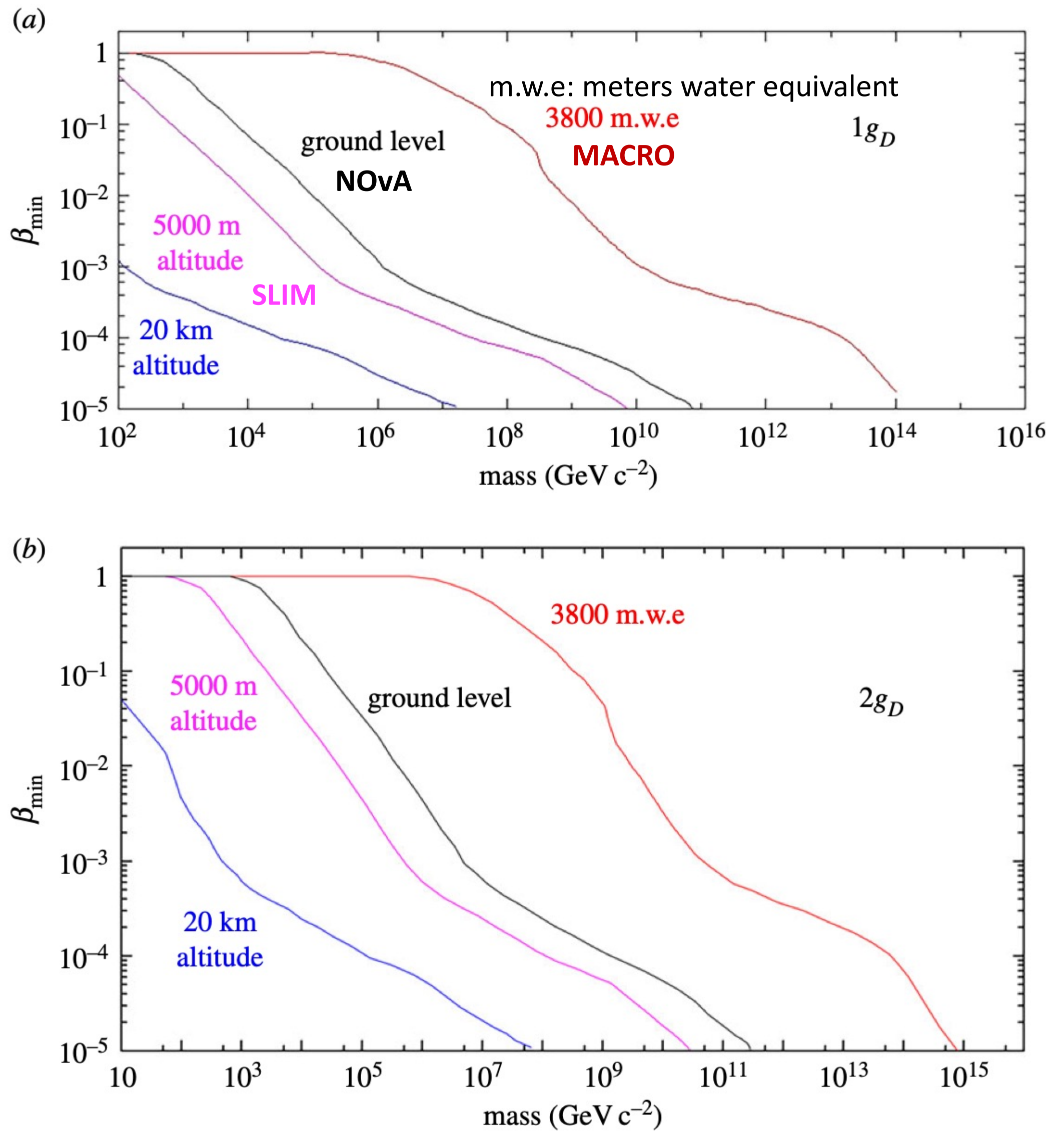
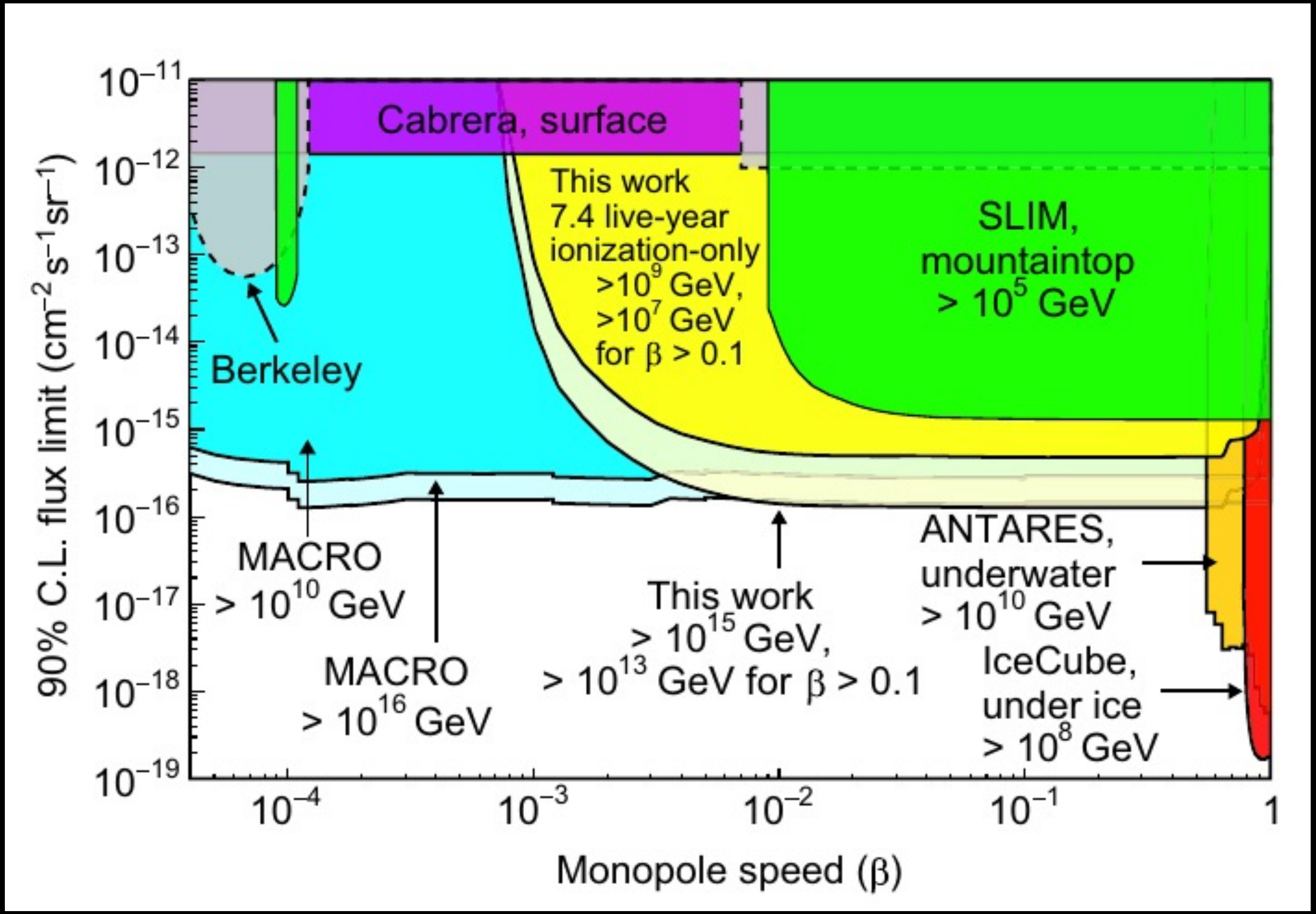


Figure 5. Accessible regions in the (mass, β) plane for downgoing monopoles with magnetic charge (*a*) $1g_D$ and (*b*) $2g_D$ for a detector at 20 km altitude, at 5230 m altitude, at ground level, and at 3800 m.w.e. (like the MACRO detector at the Gran Sasso underground laboratory). (Online version in colour.)

Experiments on earth can only measure magnetic monopoles above a minimum mass

Review Article:
L. Patrizii, Z. Sahnoun, and V. Togo, Phil. Trans. R. Soc. A 377, 20180328 (2019)

Ground-based monopole limits



NOvA ionization search, Phys. Rev. D 113 (2026) 112014, Fig. 9

- MACRO and NOvA

MACRO underground; NOvA near the surface. NOvA uses both timing and ionization.

- SLIM

High-altitude nuclear track detectors with less atmospheric shielding.

- IceCube and ANTARES

Large ice and water detectors search for relativistic monopoles.

IceCube, PRL 128 (2022) 051101
ANTARES, JHEAp 50 (2026) 100500

Space-based searches can probe particles that cannot penetrate the atmosphere or rock overburden.

Space-based search methods

- **Direct detection in space and balloon flights**

  Passive track detectors: Skylab
  Balloon search: HECRO-81
  Magnetic spectrometers: PAMELA, AMS

- **Optical searches from orbit**

  Optical searches for atmospheric nuclearite tracks
  TUS and Mini-EUSO

- **Searches using extraterrestrial material**

  Returned lunar samples and meteorites
  Induction, mass spectrometry and lunar seismology

- **Future space searches**

  SQM-ISS and POEMMA

Space-based search methods

- **Direct detection in space and balloon flights**
- Optical searches from orbit
- Searches using extraterrestrial material
- Future space searches

Nuclearite search with Skylab

Skylab in orbit. NASA.

- Track detector exposure

Lexan track detectors, 253-day exposure.

- Nuclearite flux limit

$$\Phi \lesssim 3 \times 10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

90% CL, galactic-speed nuclearite model

For $\beta \approx 10^{-3}$, sensitive to nuclearite masses down to $\sim 10^{7}$ GeV/c^2.

Price, Phys. Rev. D 38 (1988) 3813, Fig. 1 (Skylab curve)
Reinterpretation of Shirk & Price, ApJ 220 (1978) 719

HECRO-81: balloon strangelet candidates

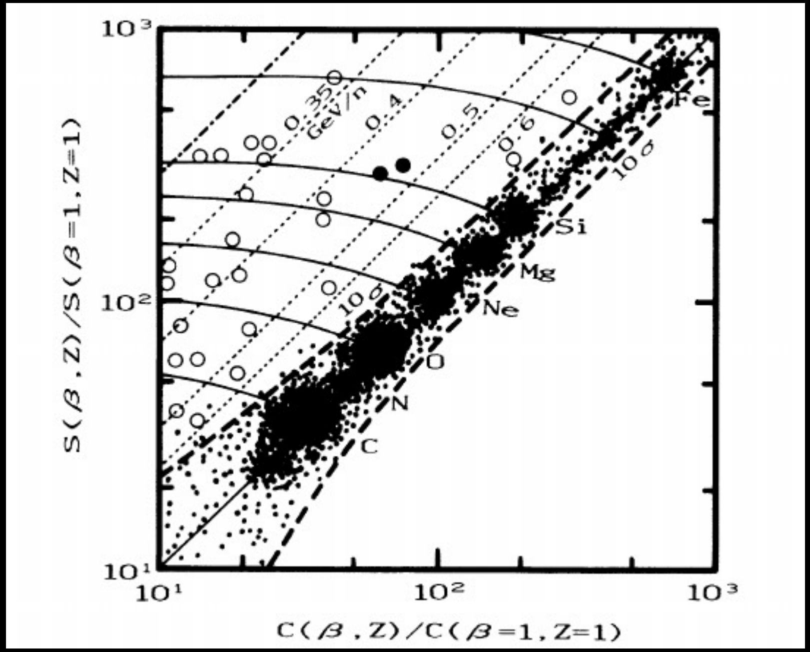
VOLUME 65, NUMBER 17 PHYSICAL REVIEW LETTERS 22 OCTOBER 1990

Is There Strange-Quark Matter in Galactic Cosmic Rays?

Takeshi Saito, Yoshikazu Hatano, and Yutaka Fukada
Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo, Japan

Hiroshi Oda
Department of Physics, Kobe University, Kobe, Japan
(Received 19 March 1990)

In the analysis of background events from a counter-technique experiment to study cosmic-ray nuclei above 8-GV rigidity, two events were observed which are consistent with the assumption of $Z \sim 14$, $A \sim 350$, and 450 MeV/nucleon and which cannot be accounted for by more conventional background. Such events may be explained by the hypothesis of strange-quark matter (SQM). It is concluded that the existence of SQM has not been excluded by experiment at a flux level of $\sim 6 \times 10^{-9}$ cm^{-2}s^{-1}sr^{-1}.



Cherenkov output vs scintillator output
Filled circles: the two candidate events

- 1981 balloon flight

  28 hours above Sanriku, Japan.
  Cherenkov and scintillation counters, with proportional counters for tracking.

- Two anomalous events

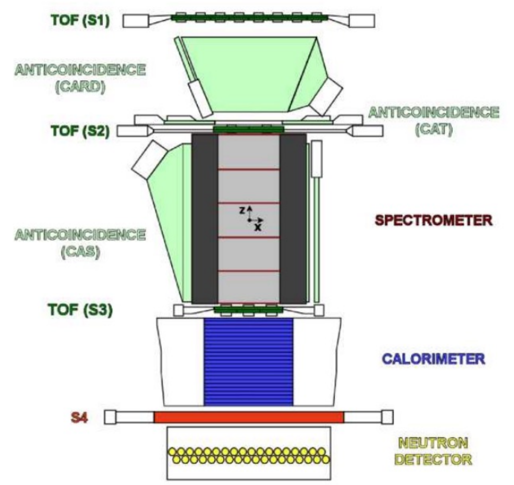
  Charge near 14 and energy near 450 MeV per nucleon. Ordinary silicon at this speed could not pass the local geomagnetic cutoff.

- Mass inferred from the cutoff

  Estimated mass number near 370, assuming a cosmic-ray rigidity spectrum. The candidates remain unconfirmed.

Strangelet search with PAMELA

- PAMELA detector



Picozza et al., Astropart. Phys. 27 (2007) 296–315, Fig. 4

A satellite-borne magnetic spectrometer.
The tracker measures rigidity, the TOF measures velocity, and ionization determines charge.

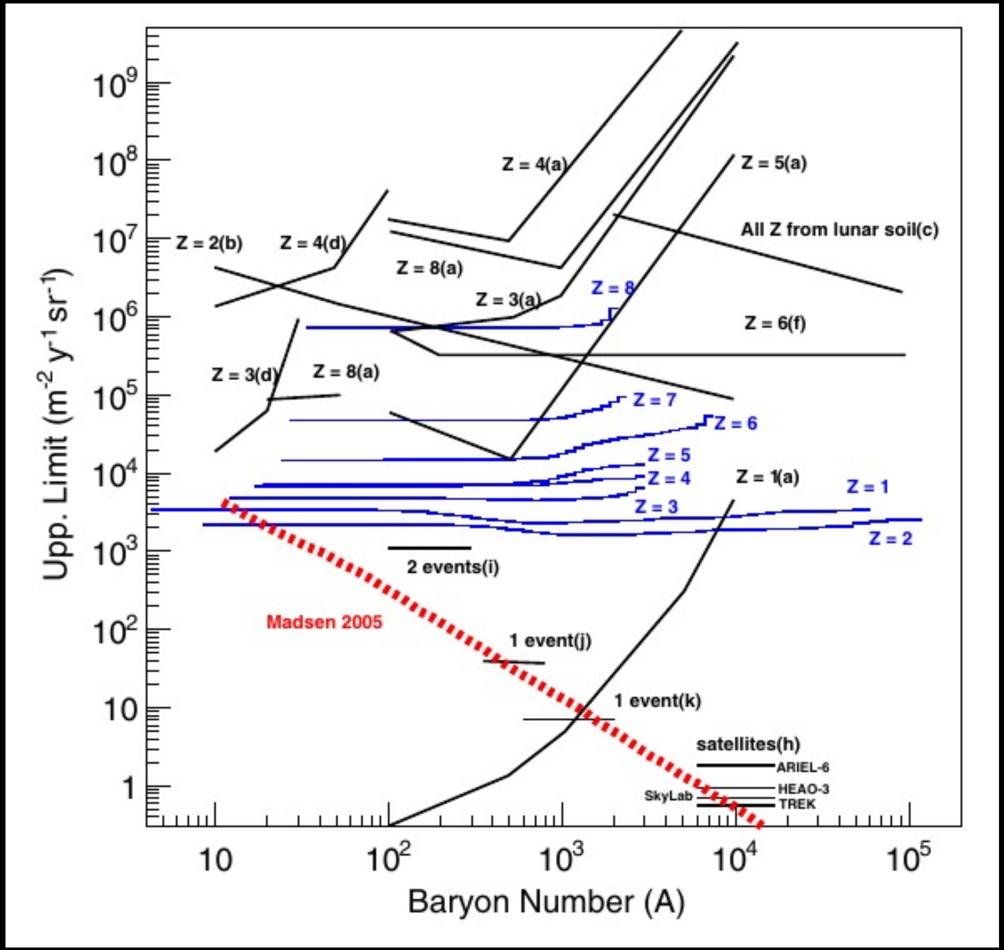
- Data from 2006–2009

Search for anomalously large mass-to-charge ratio using rigidity, velocity and ionization.

PAMELA, Phys. Rev. Lett. 115 (2015) 111101

- No strangelet candidates

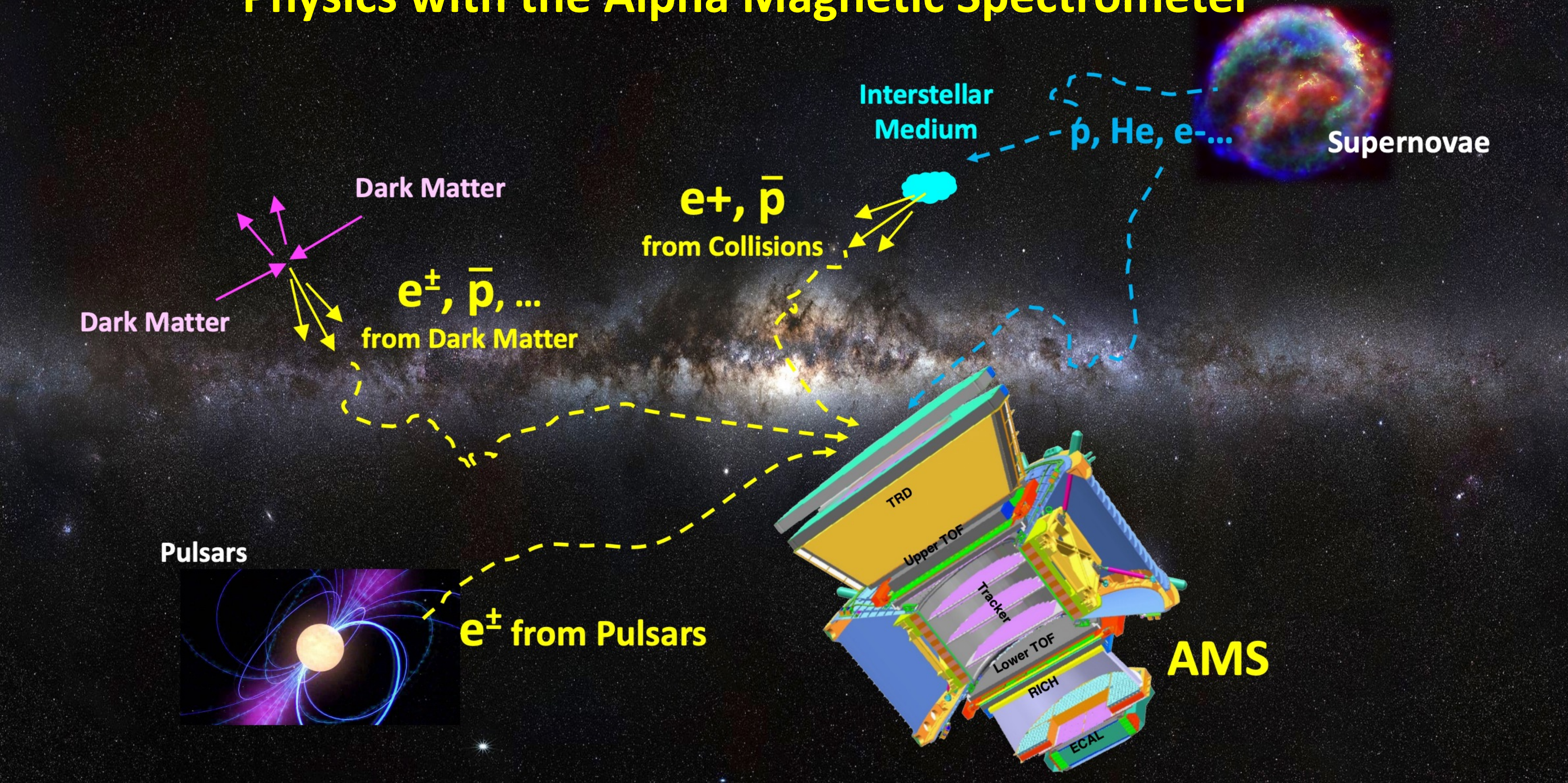
Flux limits are given for each charge, assuming a strangelet velocity distribution.



PAMELA, Phys. Rev. Lett. 115 (2015) 111101, Fig. 3

Blue: PAMELA. Black: earlier searches.
Red dotted: model prediction.

Physics with the Alpha Magnetic Spectrometer

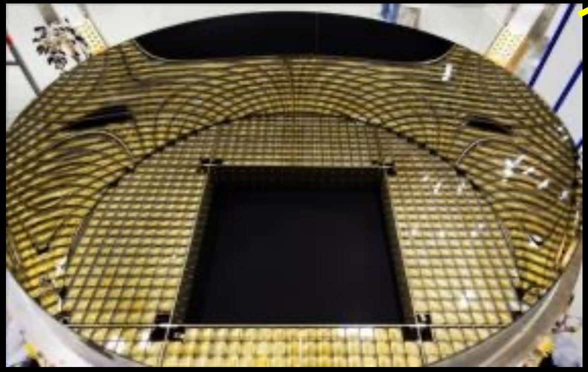


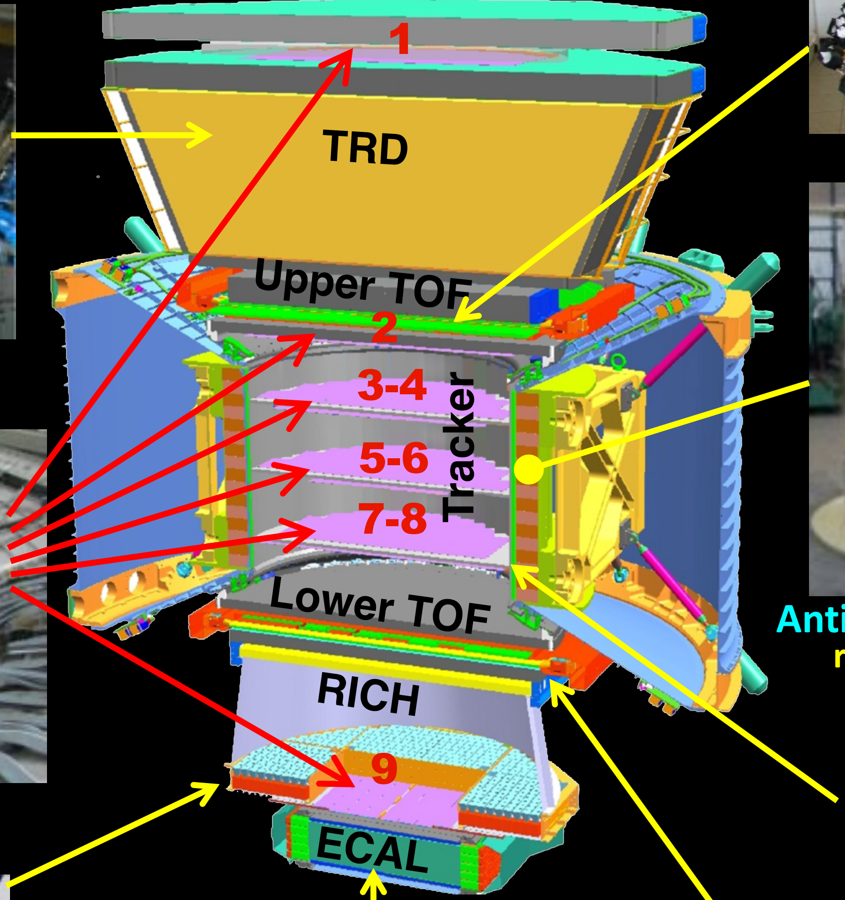
AMS is a space version of a precision detector used in accelerators

Transition Radiation Detector (TRD)
identify e^+, e^-

Silicon Tracker
measure Z, P

Ring Imaging Cerenkov (RICH)
measure Z, E





Electromagnetic Calorimeter (ECAL)
measure E of e^+, e^-

Upper TOF measure Z, E

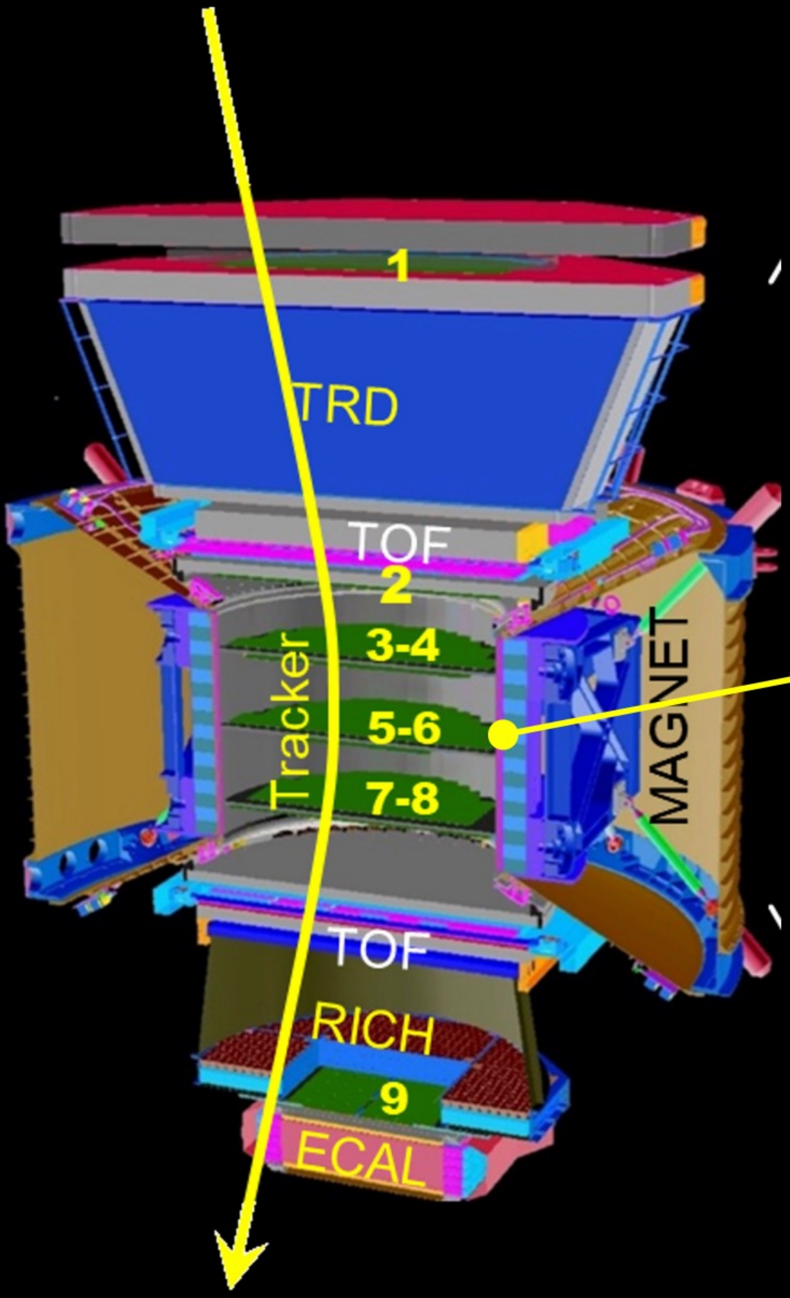
Magnet identify ±Z, P

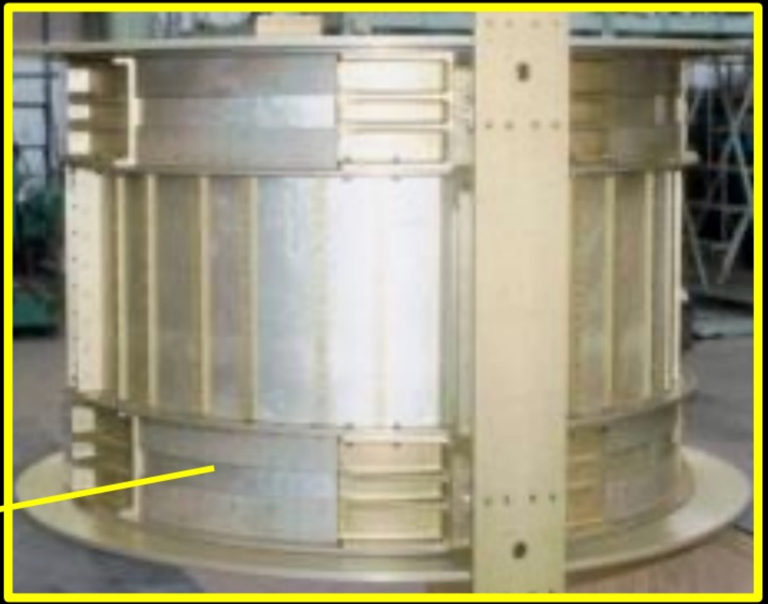
Anticoincidence Counters (ACC)
reject particles from the side

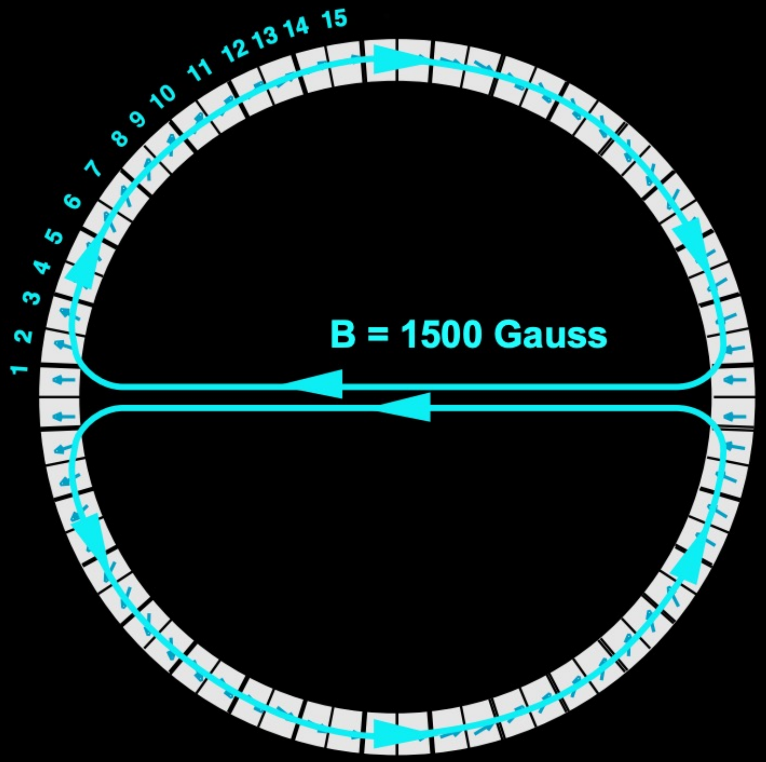
Lower TOF measure Z, E

The Magnet

Identify ±Z, P





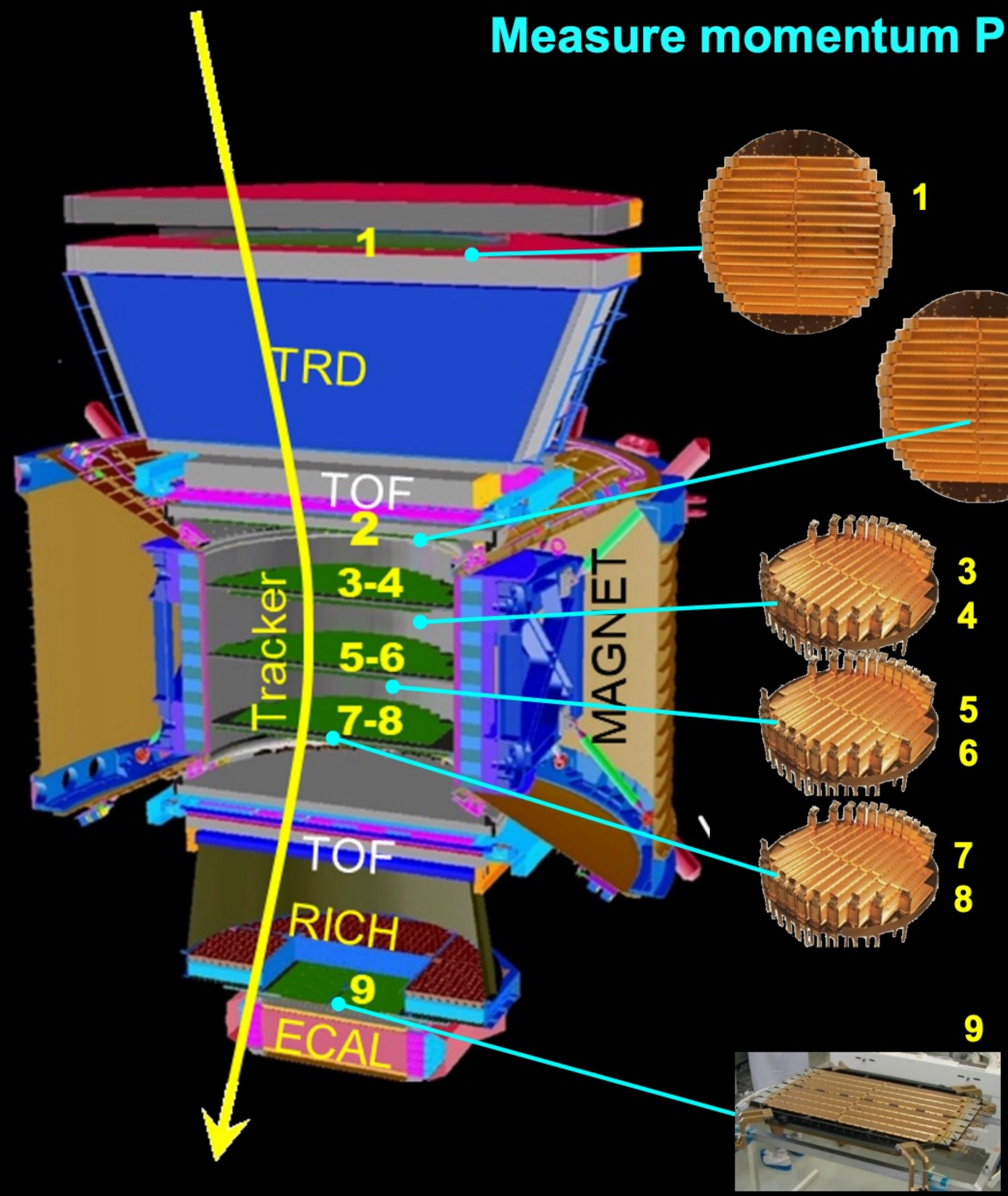


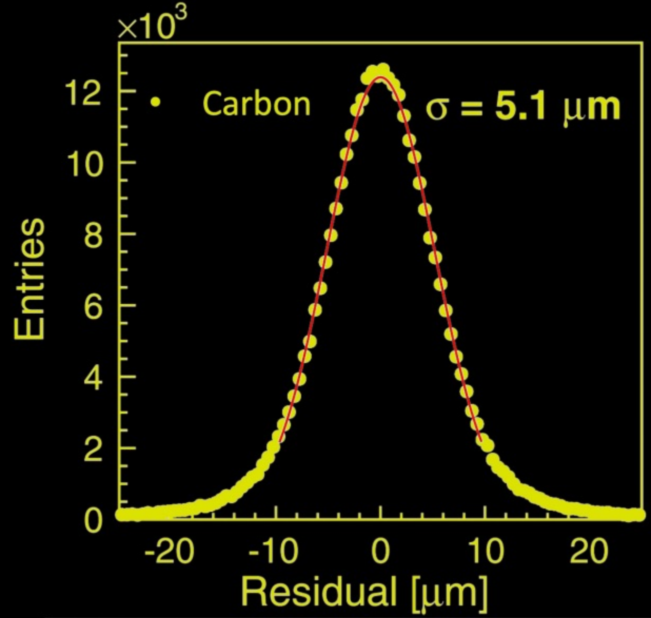
Low energy $e^{\pm}$ produced in TRD are swept away by the magnet and do not enter into ECAL:

Independent rejection of TRD and ECAL: e^{+}/p separation : > 10^{6}

Silicon Tracker

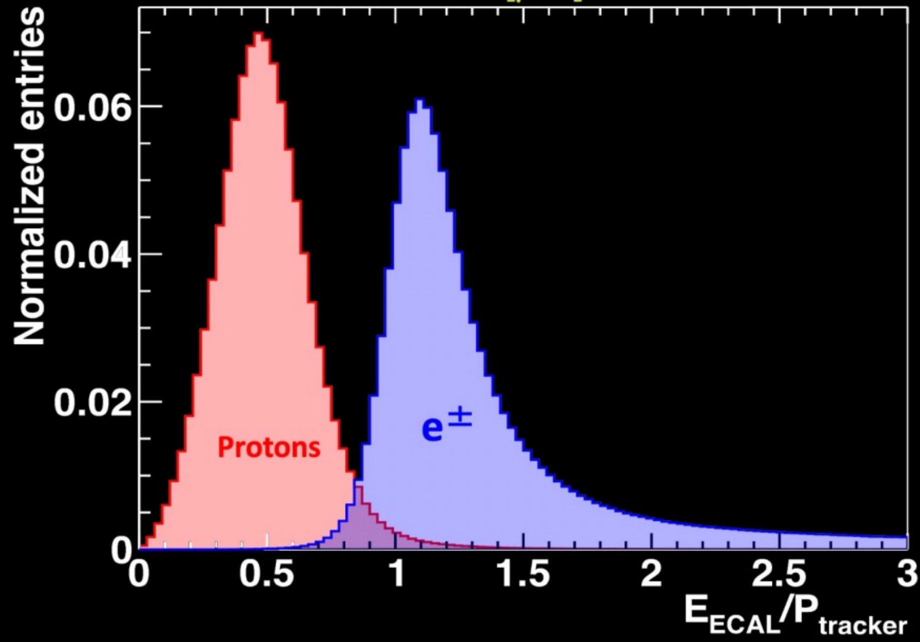
Measure momentum P and nuclear charge Z, Rigidity: P/Z





Spatial resolution: 5-10 μm in bending plane.

Maximum Detectable Rigidity:
~2TV for protons,
~3.7 TV for heavy nuclei

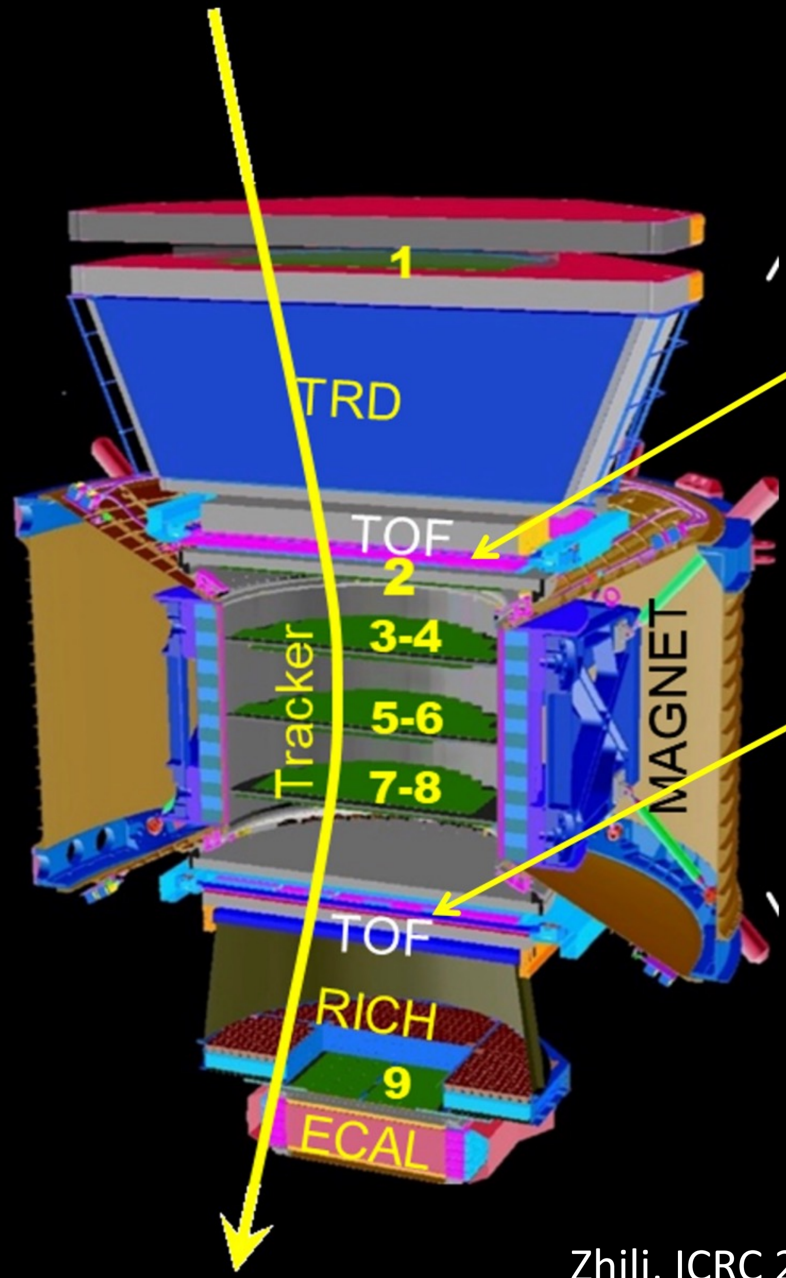


Independent Momentum and Energy measurement.
For electron and positron require: E=P

Zhili, ICRC 2025

Time of Flight (TOF)

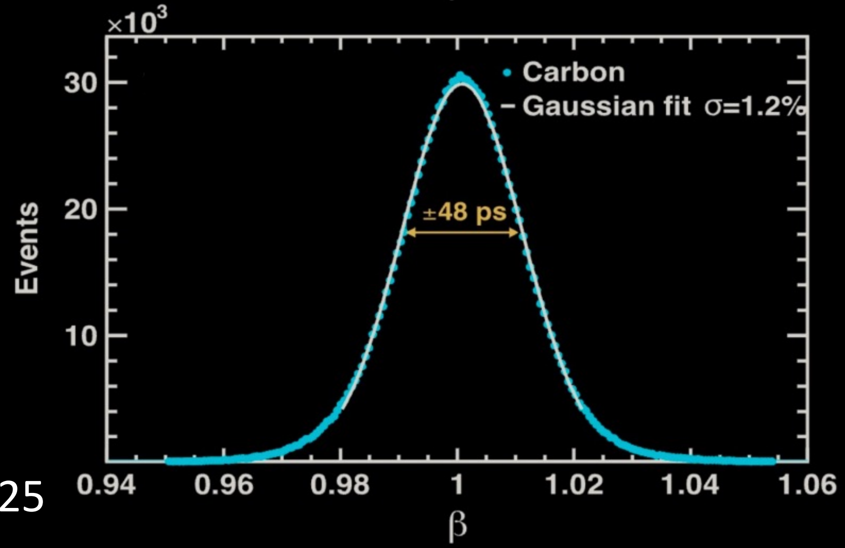
Measure velocity β , charge Z

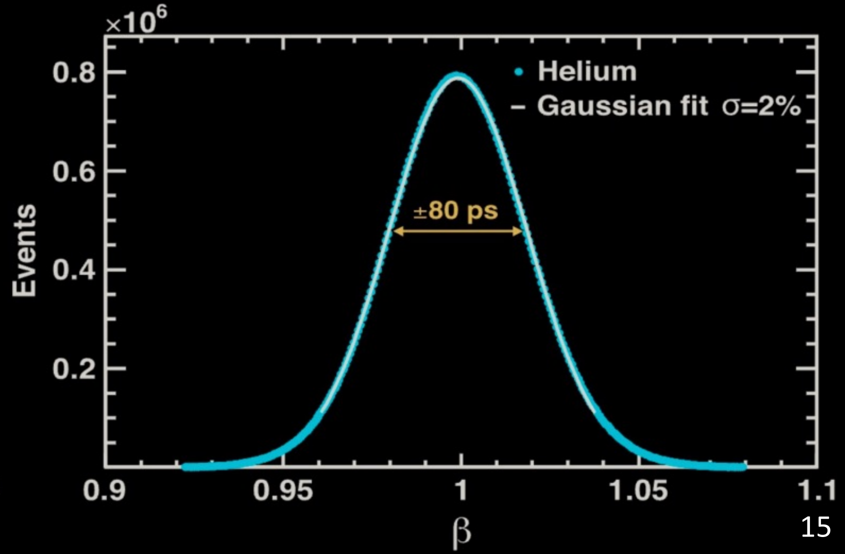


Measures velocity, charge, direction, and trigger.

Time resolution:
~50-160 ps

Velocity resolution:
1% (Z>6) to 4% (Z=1)





Zhili, ICRC 2025

Possible detection in AMS

- Velocity

AMS Collaboration, Phys. Rep. 894 (2021) 1–116, Sec. 1.8, p. 22

In AMS, signals from the 300,000 data acquisition channels are only digitized in response to a two-level trigger (fast trigger and level-1 trigger) which detects that a cosmic ray of interest may have passed through the detector. The fast trigger is formed from the logical OR of three inputs:

1. for all cosmic rays: the coincidence within 240 ns of signals in any three of the four TOF planes each with a pulse height greater than 0.5 times that deposited by a $Z = 1$ minimum-ionizing particle (MIP);
2. for electrons, positrons and photons: an energy deposition in the ECAL consistent with an electromagnetic particle of energy greater than 1 GeV;
3. for slow particles: the coincidence within 640 ns of signals from four TOF planes each with a pulse height greater than 3.5 times a MIP.

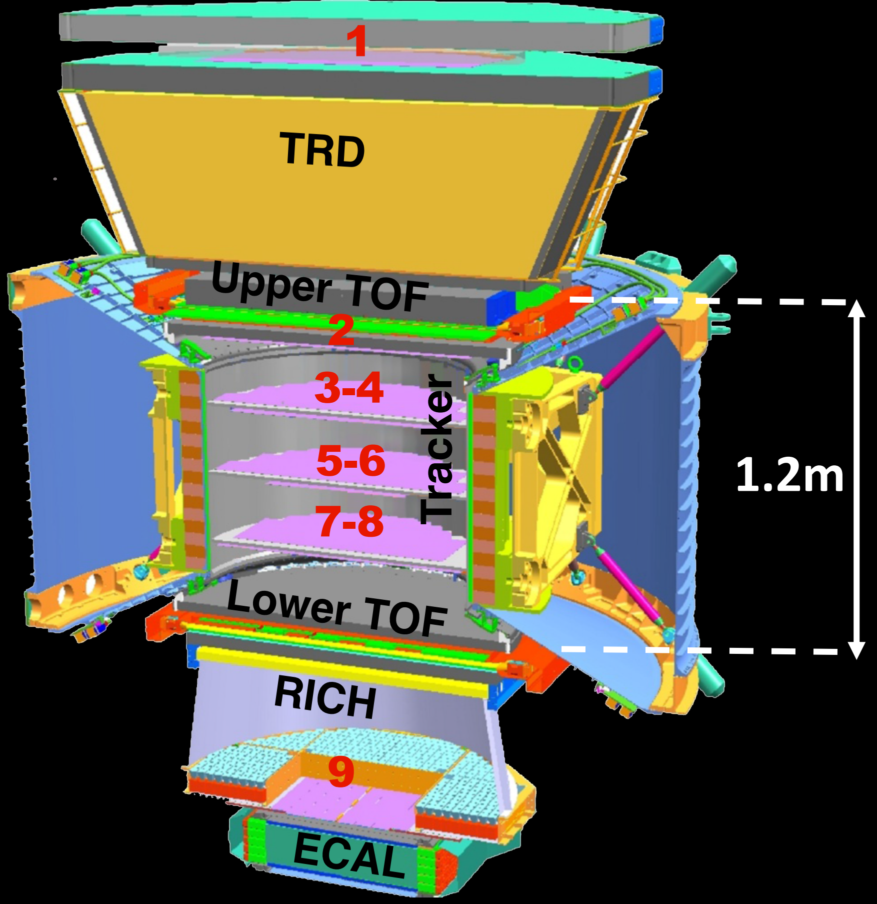
  - Distance between upper and lower TOF is ~1.2m. 640ns allows measurements of $\frac{1.2m}{640ns} = 0.006c$

- Energy Loss: Large energy deposition compared to MIP

- Trajectories: magnetic monopole will be accelerated along the magnetic field, namely x direction. If particles only carry magnetic charge and do not carry electric charge, it will not be bended in y direction.

Lorentz forces $\vec{F_e} = Ze\left(\vec{E} + \frac{1}{c}\vec{v_e}\times\vec{B}\right)$, $\vec{F_g} = ng_D\left(\vec{B} - \frac{1}{c}\vec{v_m}\times\vec{E}\right)$

AMS Trigger for Slow Particles

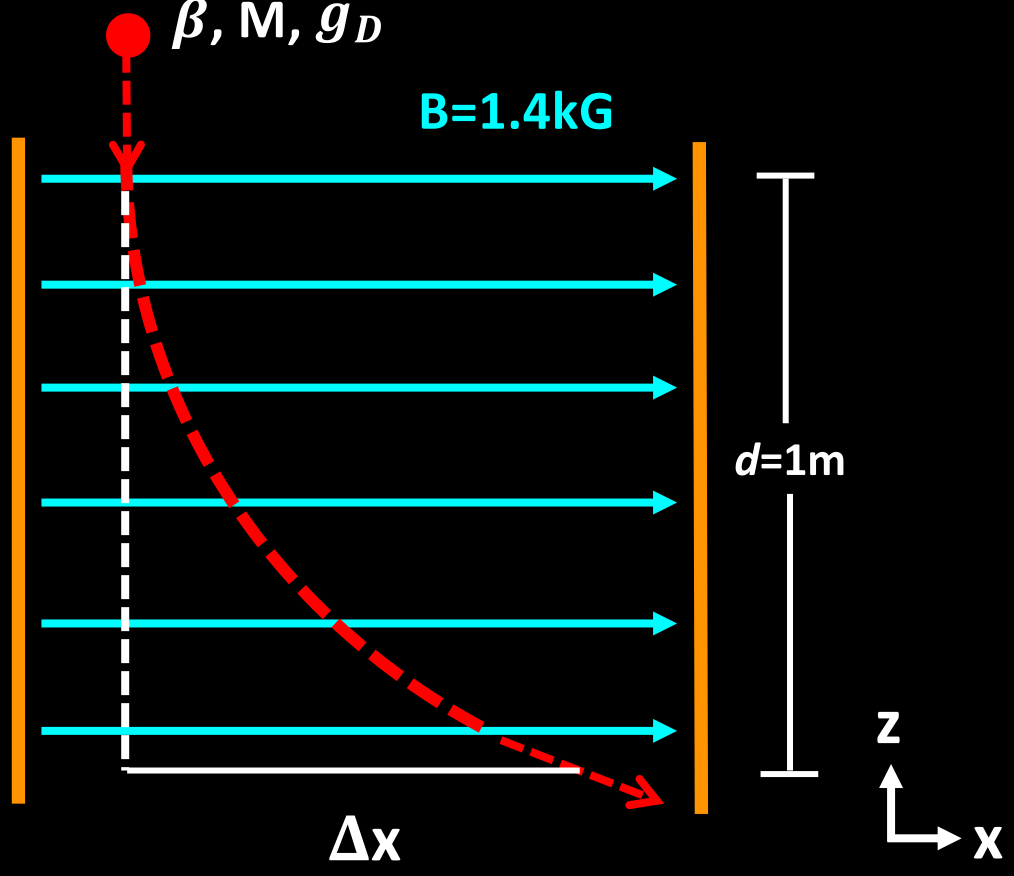


Special trigger for slow particle: the coincidence within **640ns** of signals from four TOF planes each with a pulse height greater than 3.5 times a minimum ionizing particle.

Distance between upper and lower TOF is ~1.2m.

This allows velocity measurements above $\frac{1.2m}{640ns} = 0.006c$

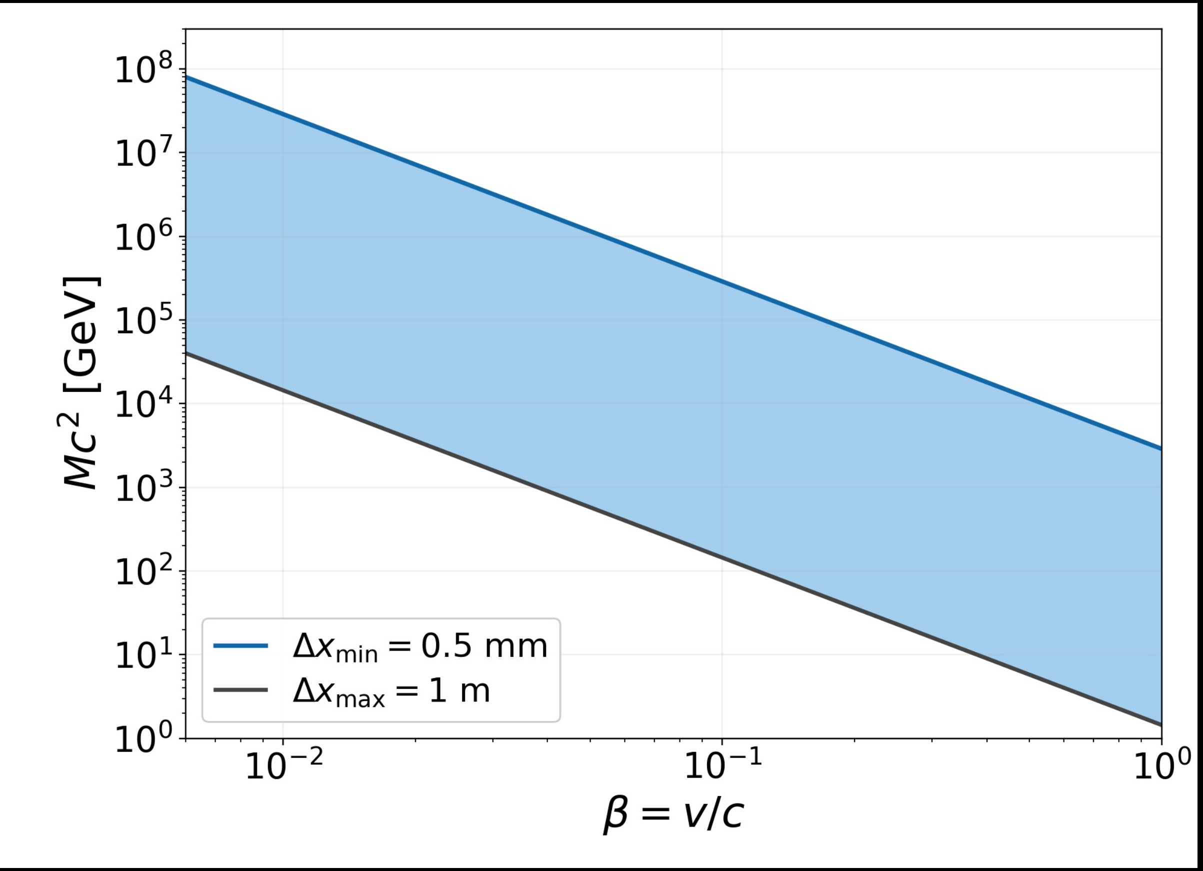
Magnetic Monopole Measurement with AMS



$$\Delta x \approx \frac{1}{2}at^2 = \frac{1}{2}\frac{F}{M}\left(\frac{d}{\beta}\right)^2 = \frac{1}{2}\frac{Bg}{M}\left(\frac{d}{\beta}\right)^2$$

$$\Delta x[m] \approx \frac{1.44}{M[GeV]\beta^2}$$ for g_D =68.5e

Very rough estimate



Assuming 0.5 mm as a conservative precision estimate

Strangelets search with the AMS

- No strangelet candidates

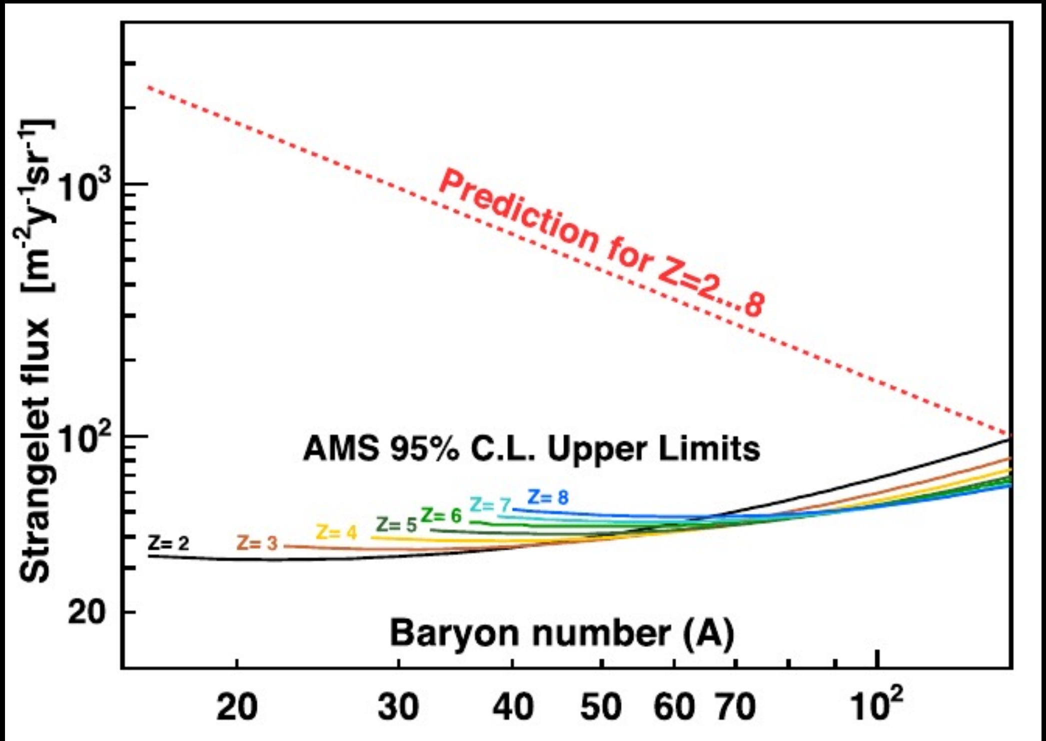
  No events with $\frac{Z}{A} < 0.1$ in the selected sample.

- 95% confidence-level upper limits

  Acceptance is simulated for each charge. The assumed rigidity spectrum follows primary cosmic rays.

- Comparison with the model

  The model prediction lies above the AMS limits in the plotted range.



AMS Collaboration, Phys. Rep. 894 (2021), Sec. 14, Fig. 105

Strangelet identification uses anomalous mass-to-charge ratio, not dE/dx alone.

Space-based search methods

- Direct detection in space and balloon flights
- **Optical searches from orbit**
- Searches using extraterrestrial material
- Future space searches

Optical searches for nuclearites

- **Hypothetical strange quark matter**

  Macroscopic nuggets may deposit energy as they cross the atmosphere.

- **Energy deposited along the path**

$$\frac{dE}{dx} \approx \sigma \, \rho \, v^2 .$$

σ: effective collision cross-section
ρ: atmospheric mass density
v: nuclearite speed relative to the atmosphere

  The cross-section is set by the nugget size or its surrounding electron cloud.

  De Rújula & Glashow, Nature 312 (1984) 734

- **Light from the heated atmosphere**

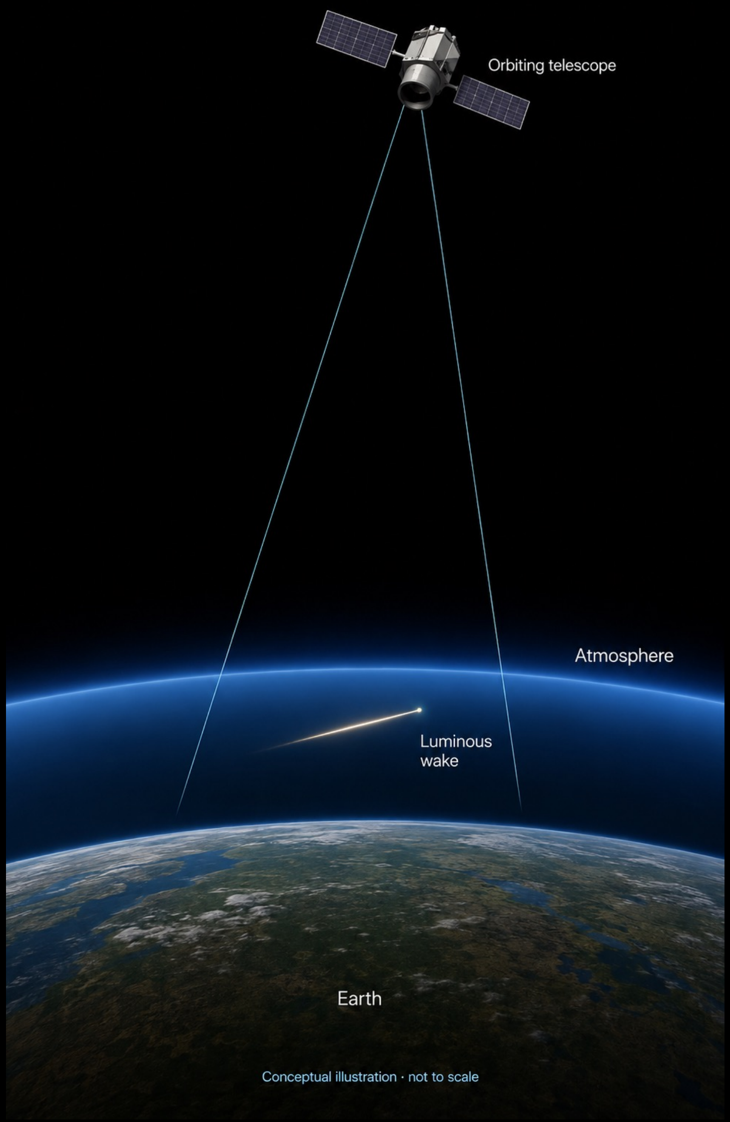
  A luminous wake may be visible from orbit. Its brightness depends on the light yield.

  De Rújula & Glashow, Nature 312 (1984) 734

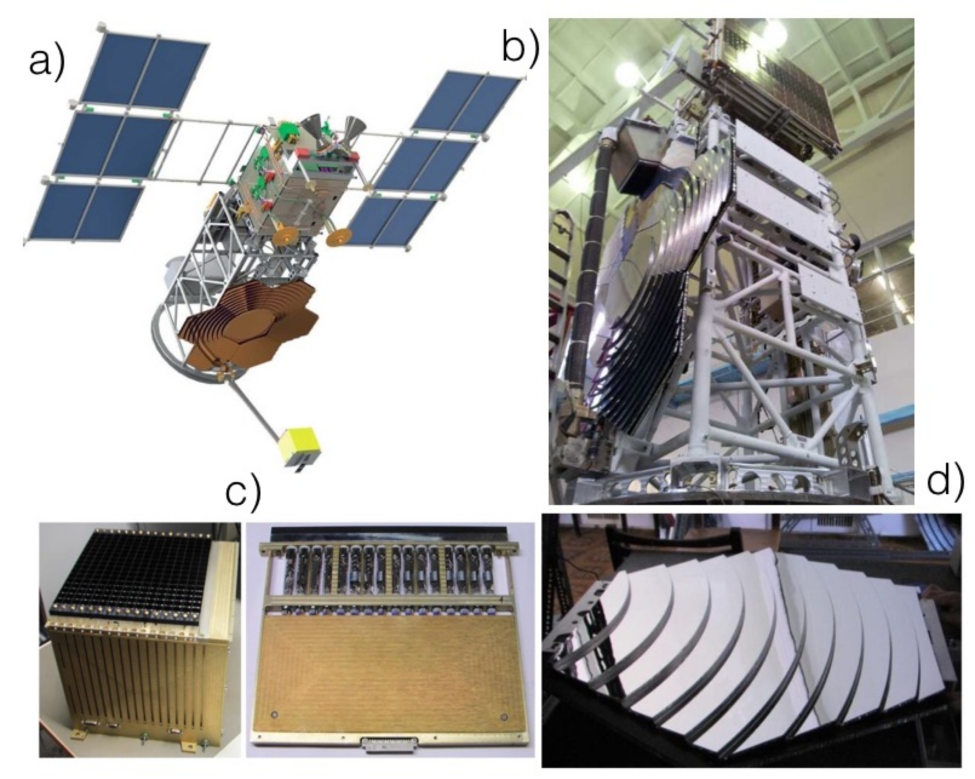
- **Separating signals from meteors**

  Identify tracks using apparent speed, light profile and altitude.

  Meteor-track analysis: Barghini et al., A&A 687 (2024) A304



TUS on the Lomonosov satellite



TUS: spacecraft, photomultipliers and reflector

Barghini et al., Adv. Space Res. 70 (2022) 2734, Fig. 1

- An orbital UV telescope

  Tracking Ultraviolet Setup (TUS).
  Observed from May 2016 to November 2017
  in a roughly 500 km orbit.

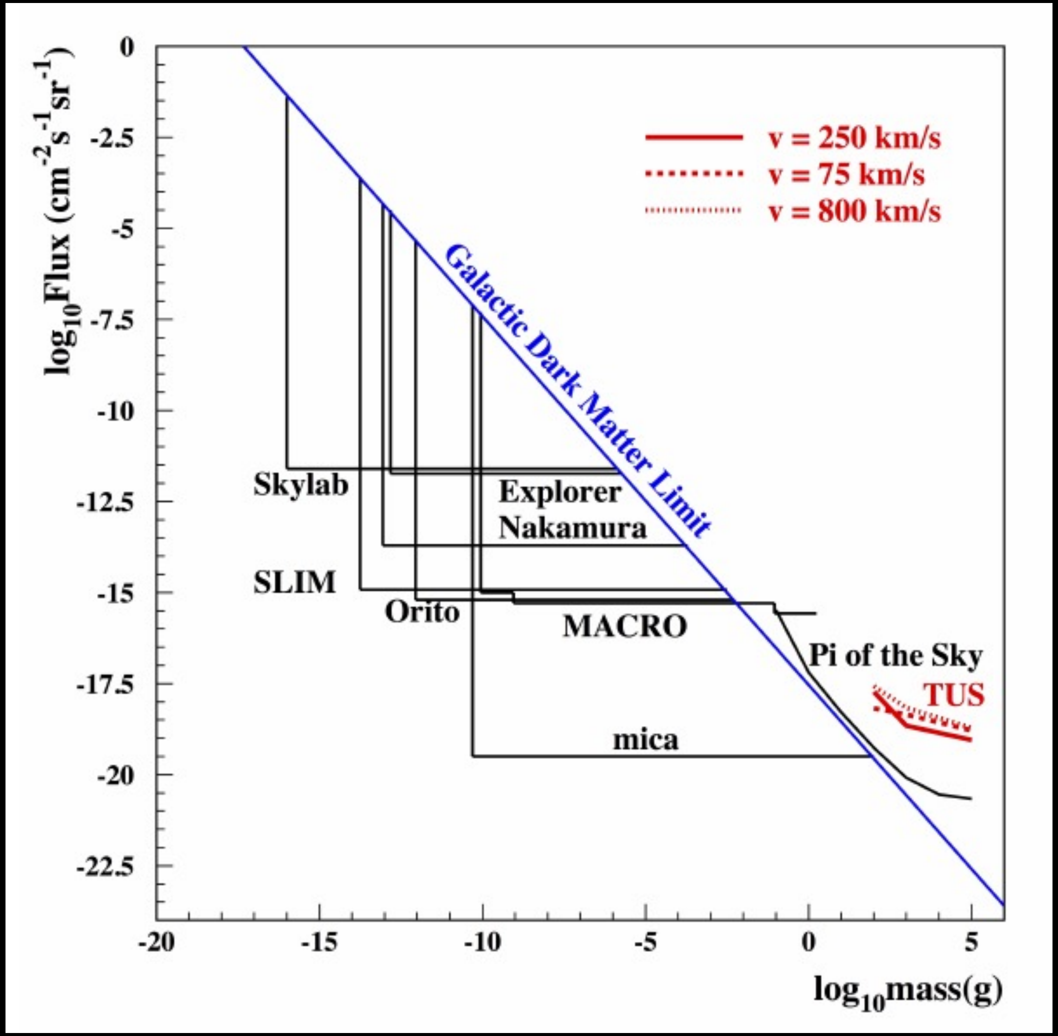
- Main goal: ultra-high-energy cosmic rays

  Test orbital detection of UV fluorescence
  from ultra-high-energy cosmic-ray air showers.
  A Fresnel reflector and 256 photomultipliers
  view an area of about 80 km by 80 km.

- Meteor observation mode

  Samples every 6.6 ms to record moving lights.
  A nuclearite crossing the atmosphere could
  produce a luminous track in this mode.

Nuclearite search with TUS



Red curves: TUS limits at 75, 250 and 800 km/s

Barghini et al., Adv. Space Res. 70 (2022) 2734, Fig. 17

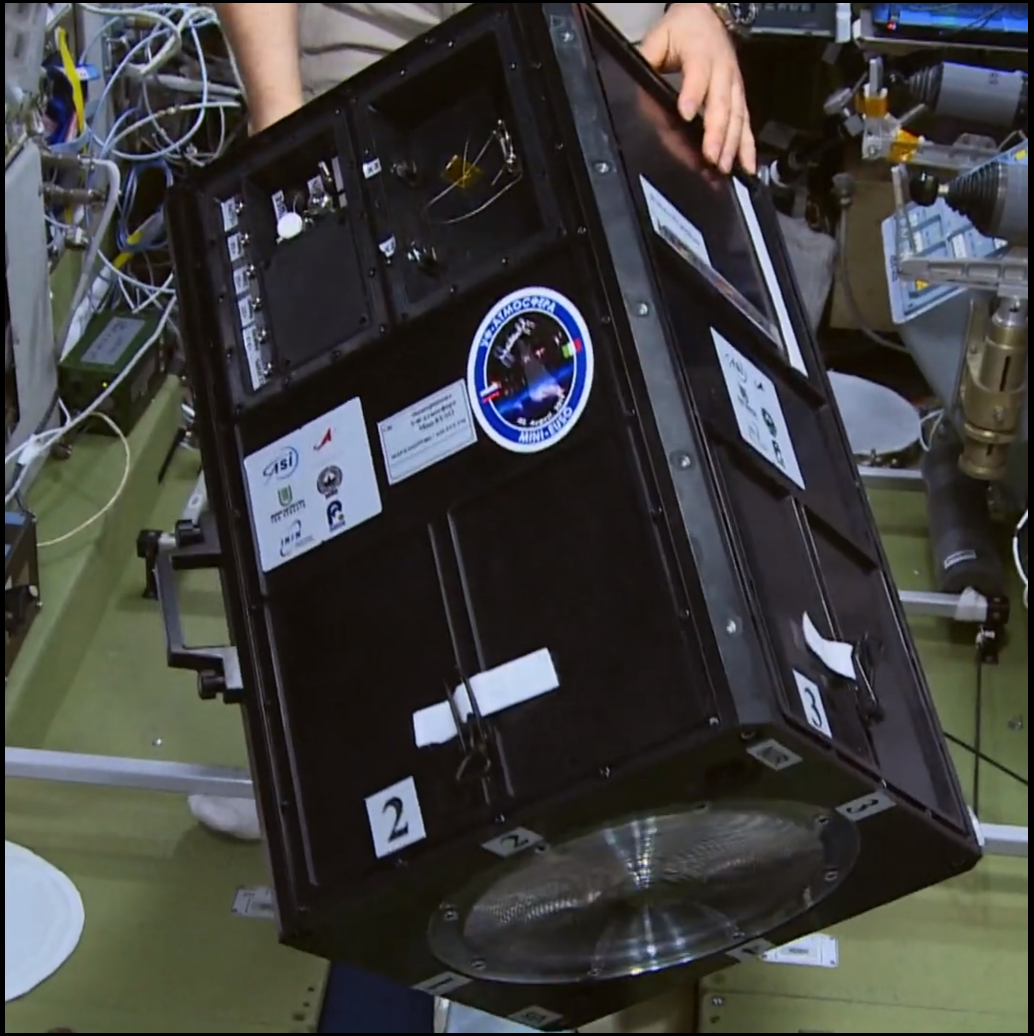
- Low optical background

  Dark night-side regions reduce optical background.
  TUS used moonless ocean data far from coasts.
  Estimated observing time: 47.4 hours.

- No surviving nuclearite candidates

  The speed selection leaves 76 events.
  Visual inspection finds no moving light spot consistent with the simulated nuclearites.
  The search sets preliminary flux limits.

Mini-EUSO on the International Space Station



Mini-EUSO in Zvezda, before window installation

Bacholle et al., ApJS 253 (2021) 36, Fig. 2

- Data taking since 2019

Views Earth through a UV-transparent window in Zvezda, the Russian service module of the ISS. Typically two ~12-hour sessions per month.

Barghini et al., A&A 687 (2024) A304

- A compact UV camera

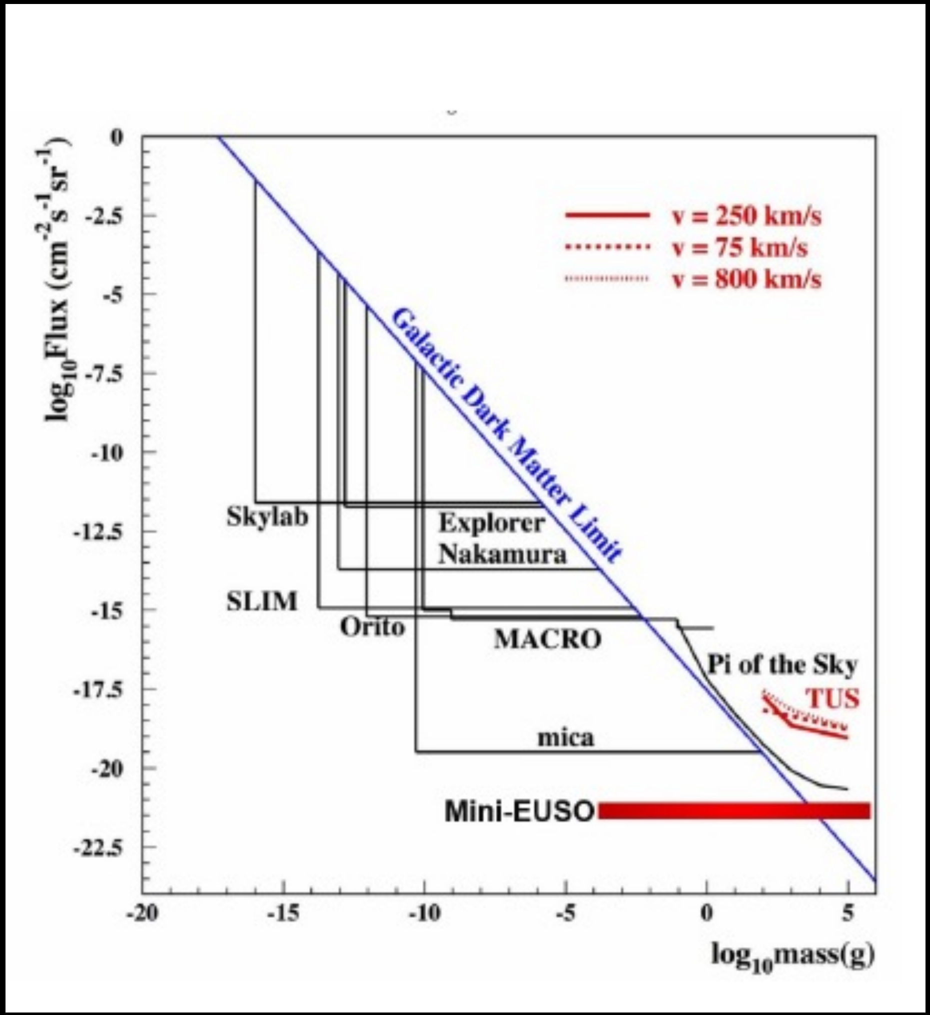
Two 25 cm Fresnel lenses and 2,304 pixels. It records light at 290–430 nm over a 44° field of view.

- Five-year mission summary

More than 150 observing sessions, about 750 hours of data in total. Images are recorded every 40.96 ms.

Battisti, PoS(ICRC2025)183; arXiv:2601.11458

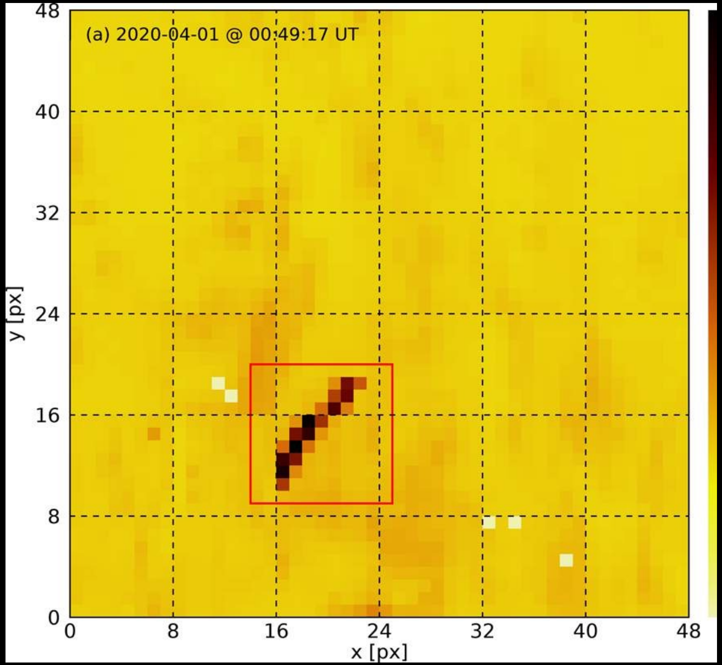
Nuclearite search with Mini-EUSO



Projection: 3 years, 3–4 twelve-hour sessions/month
≈1,300–1,700 h, assuming a nuclearite light model.
Casolino et al., PoS(ICRC2023)1410, Fig. 3

- Fast luminous tracks

A nuclearite could leave a luminous wake.
Use track speed and light profiles
to distinguish it from ordinary meteors.



Observed meteor: background to the nuclearite search
Barghini et al., A&A 687 (2024) A304, Fig. 1a

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- **Searches using extraterrestrial material**
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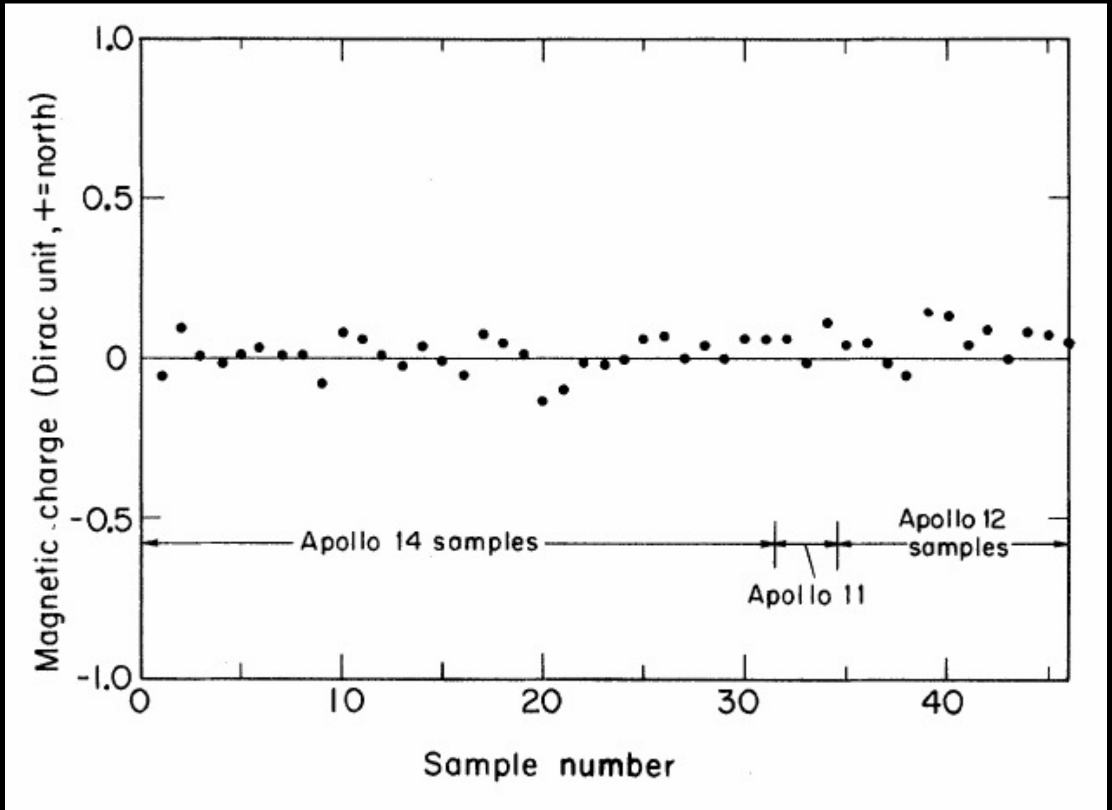
Trapped monopoles in Apollo samples



Magnetic charge measured in individual lunar samples

Ross et al., Phys. Rev. D 8 (1973) 698, Fig. 2

- Lunar samples as natural collectors

  Monopoles could stop and remain trapped in lunar material. The searches examined about 19.8 kg from Apollo 11, 12 and 14.

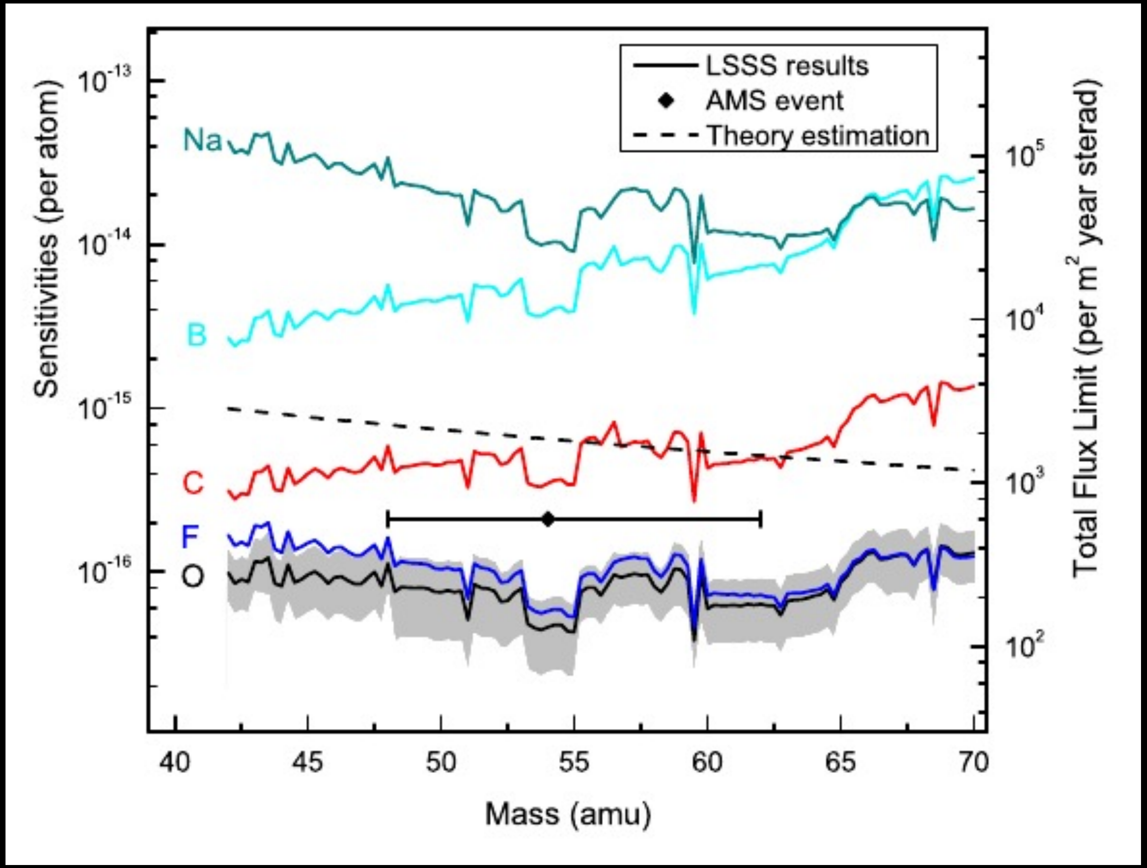
- Magnetic-charge measurement

  Samples pass through a superconducting loop. A trapped monopole produces a persistent current change, measured with a SQUID.

- No magnetic charge detected

  The combined search gives a 95% CL limit on isolated monopoles in lunar material: $C_m < 1.7 \times 10^{-4}$ monopoles/g.

Strangelet search in Apollo lunar soil



Han et al., PRL 103 (2009) 092302, Fig. 3

- 15 g of Apollo 11 soil

  Sample 10084 served as a natural collector. The Yale tandem accelerator searched for unusually massive nuclei in this material.

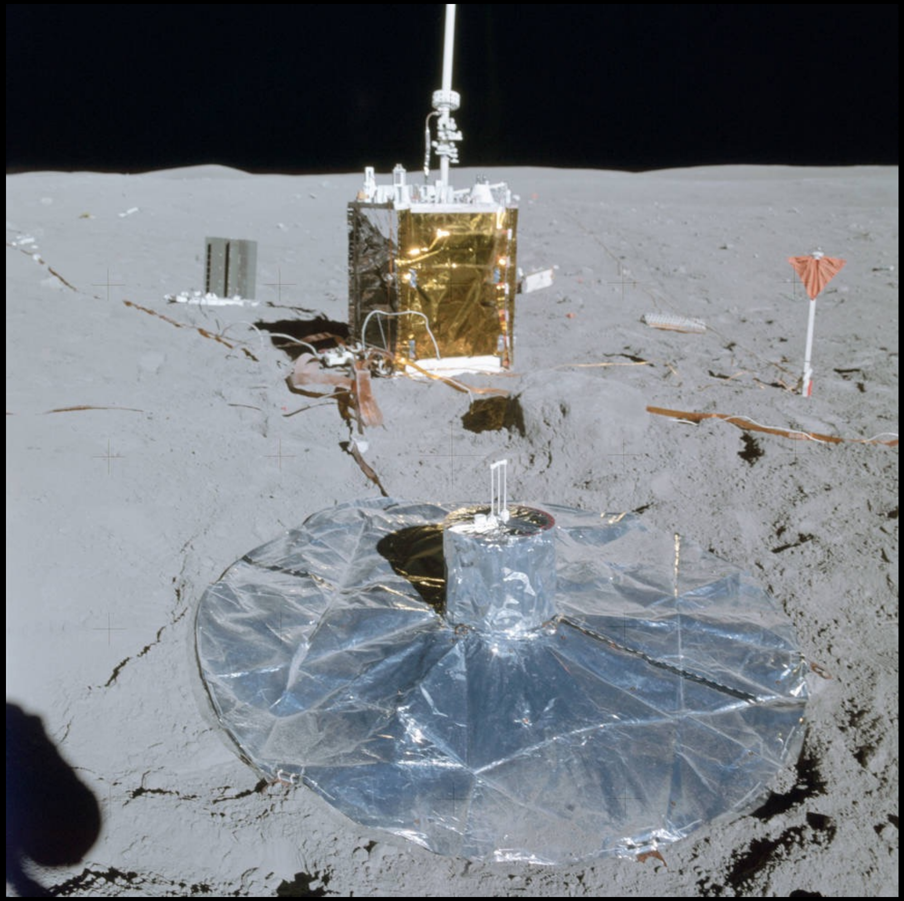
- Accelerator mass spectrometry

  Magnets select ions by mass and charge. A gold foil and silicon detectors distinguish penetrating strangelets from ordinary nuclei.

- No strangelet candidates

  The search covered masses of 42–70 u for boron, carbon, oxygen, fluorine and sodium. The strongest concentration limit is obtained for strange oxygen (Z = 8).

Lunar seismic searches for massive nuclearites



Apollo 16 seismic experiment

NASA, AS16-113-18347

- A track through the Moon

A massive nuclearite could deposit energy along its path and launch seismic waves. A network of stations could record the transit.

- A different signal from an impact

Arrival times at several stations can test a moving source inside the Moon, rather than a single source at the surface.

- Constraints from Apollo seismic data

Assuming that 5% of the deposited energy produces seismic waves, Apollo data constrain 10–1,000 kg nuclearites to contribute less than about 10% of the local dark matter density.

Herrin et al., Phys. Rev. D 73 (2006) 043511, Sec. III.

Trapped monopoles in meteorites

Meteorite collection in Antarctica

NASA / ANSMET

- Extraterrestrial material on Earth

  Meteorites may retain monopoles captured before reaching Earth. The 1995 search included 112 kg of meteorites.

- A superconducting coil and SQUID

  Samples pass through a 15 cm bore.
  A superconducting quantum interference device reads the persistent-current change.

- No monopoles in the sample survey

  Jeon and Longo tested 331 kg in total, including meteorites and terrestrial materials.

Jeon & Longo, PRL 75 (1995) 1443; erratum 76 (1996) 159

Space-based search methods

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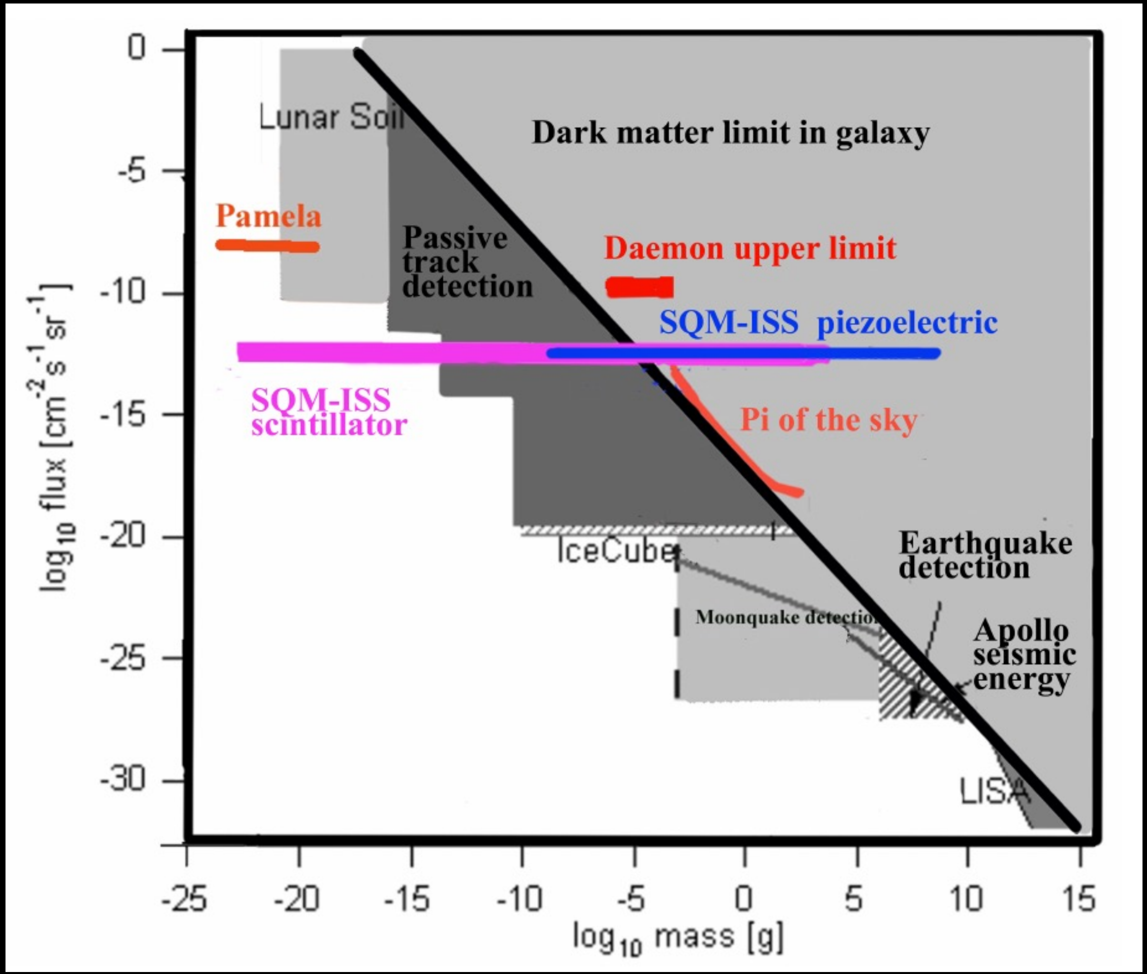
SQM-ISS: search for slow, massive particles

Projected sensitivity: 3 years



Bianchi et al., Sensors 24 (2024) 5090, Fig. 2

SQM projection; Q-ball response depends on the model.

Open Access Article

Search for Strange Quark Matter and Nuclearites on Board the International Space Station (SQM-ISS): A Future Detector to Search for Massive, Non-Relativistic Objects in Space

Sensors 24 (2024) 5090

- Scintillators and piezoelectric sensors

Scintillators record ionization and timing.
Piezoelectric sensors record vibrations.
Other potential targets include Q-balls.

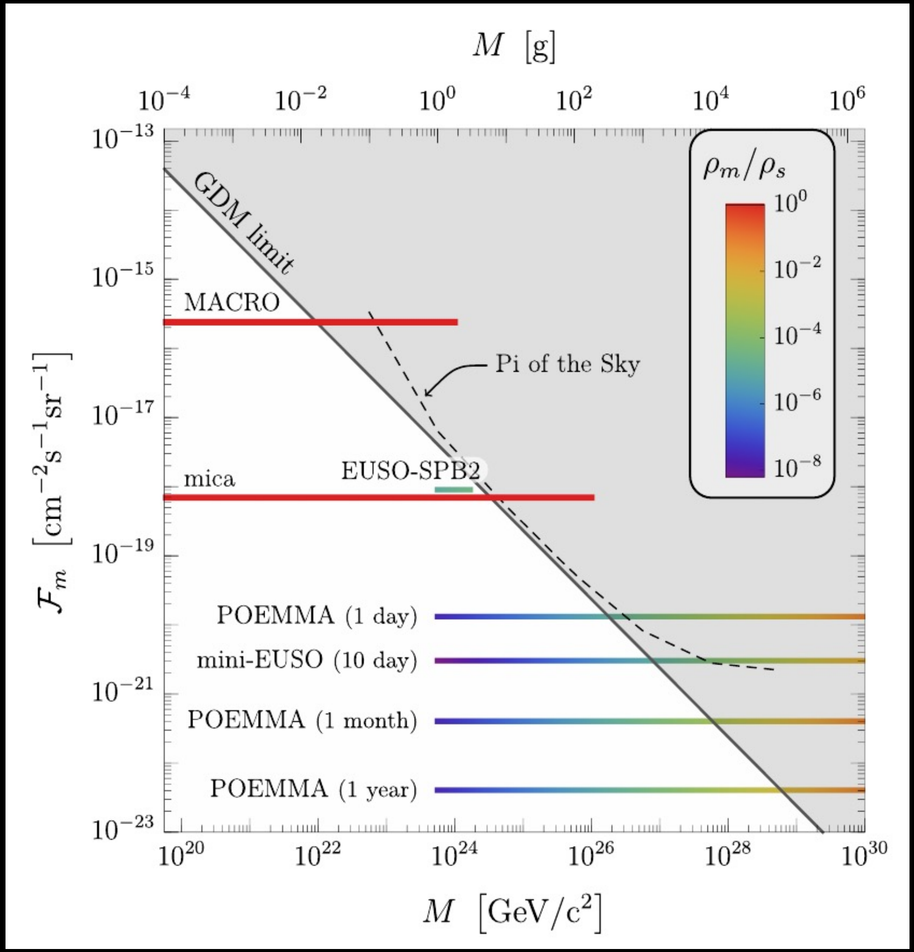
- Proposed to ESA in 2022

INFN Roma Tor Vergata-led team.
Marco Casolino (lead),
Laura Marcelli (deputy).

INFN, SQM-ISS proposal announcement (2023)

POEMMA: optical searches for nuclearites

Projected 90% C.L. flux limits



Effective exposure: 1 day, 1 month or 1 year.
At 20% duty cycle, 1 year of data takes 5 calendar years.
Olinto et al., JCAP 06 (2021) 007, Fig. 24 (right)

- A two-satellite mission concept

  Probe of Extreme Multi-Messenger Astrophysics (POEMMA). Two orbiting telescopes view the atmosphere.

- Main science goals

  Identify the sources of ultra-high-energy cosmic rays and observe cosmic neutrinos from space.

- Additional search: nuclearites

  The mission study includes optical searches for massive quark nuggets. Track speed and direction help distinguish them from meteors.

Conclusions and outlook

- Monopole searches above the atmosphere

  Less material above the detector can admit monopoles that would stop before reaching a ground-based experiment.

- Strangelet and nuclearite searches

  AMS and PAMELA search for strangelets in cosmic rays.
  TUS and Mini-EUSO search for atmospheric light.

- Searches in returned samples

  Apollo samples and meteorites allow laboratory searches for trapped monopoles and strangelets.

- Future detectors

  SQM-ISS combines scintillation and mechanical signals.
  POEMMA includes optical searches for nuclearites.