Title: In Search of Cosmic Antinuclei from Dark Matter with the GAPS Experiment

Speakers: Kerstin Perez

Collection/Series: Particle Physics

Subject: Particle Physics

Date: October 15, 2024 - 1:00 PM

URL: https://pirsa.org/24100115

Abstract:

Dark matter particle interactions could imprint characteristic signals in cosmic-ray and multi-wavelength observations of the sky. The central challenge is to distinguish these signatures from similar spectra produced by standard astrophysical processes, such as the life and death of stars and the interactions of cosmic rays with interstellar material. The GAPS Antarctic balloon payload, en route for its initial flight in December 2024, is the first experiment optimized specifically for low-energy cosmic antideuterons, an essentially background-free signature of dark matter, as well as antiprotons in an unprecedented low-energy region and leading sensitivity to cosmic anithelium. In this talk, I will detail the novel GAPS detection technique, its flight instrument, and the potential impact of these measurements in the coming years.

In Search of Cosmic Antinuclei from Dark Matter with the GAPS Experiment

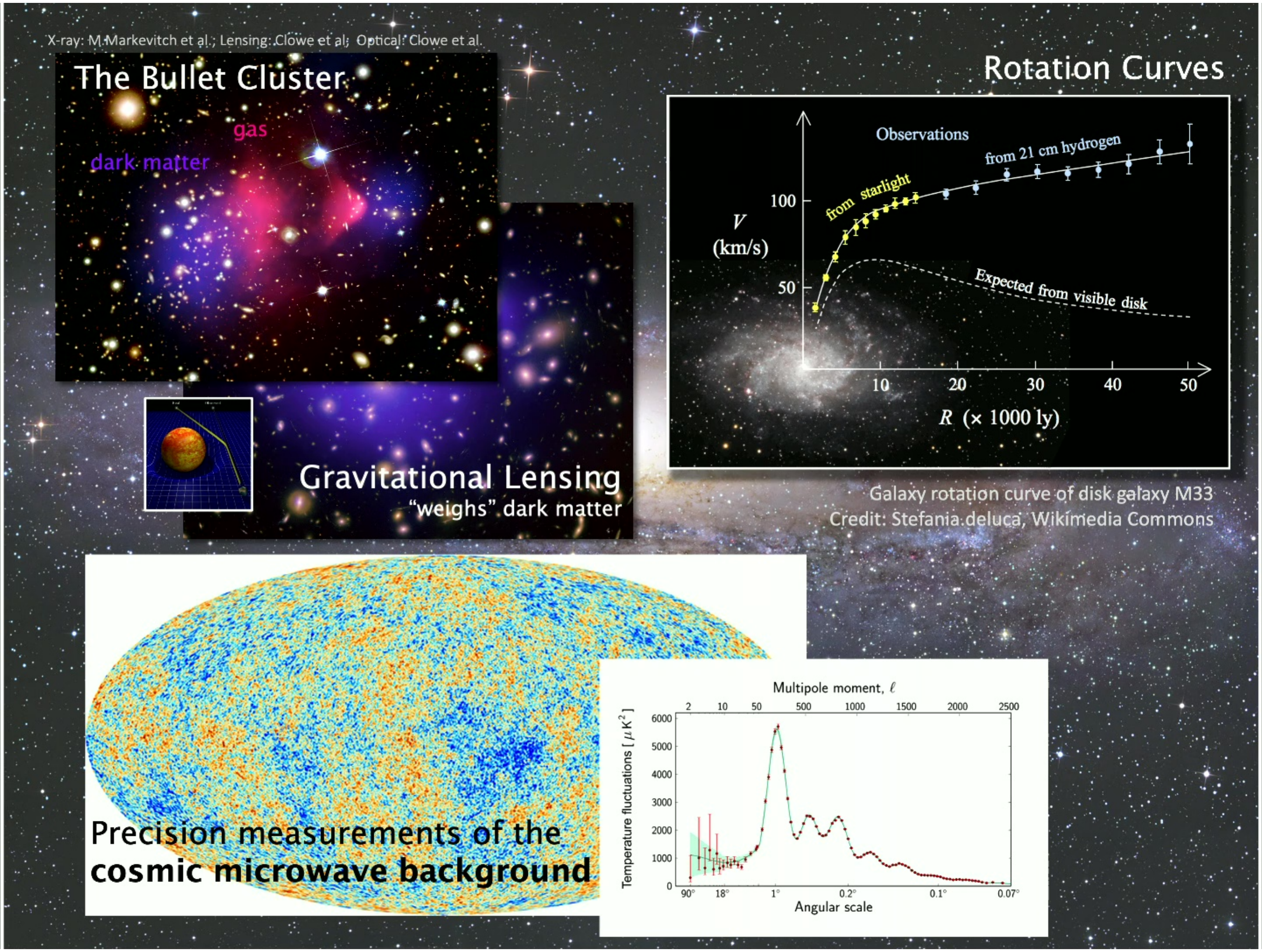
Kerstin Perez

Columbia University

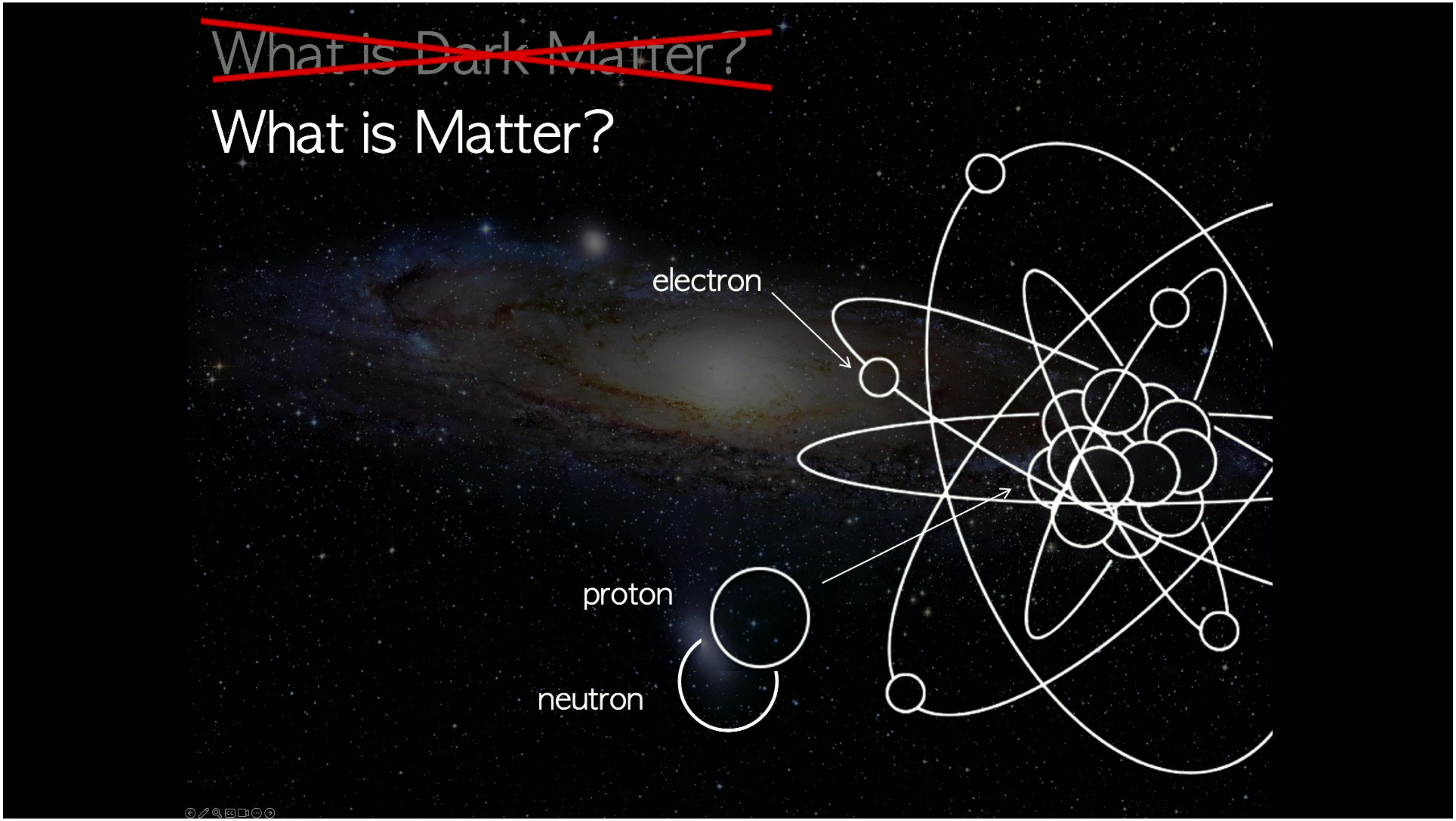
Perimeter Institute Seminar

October 15, 2024

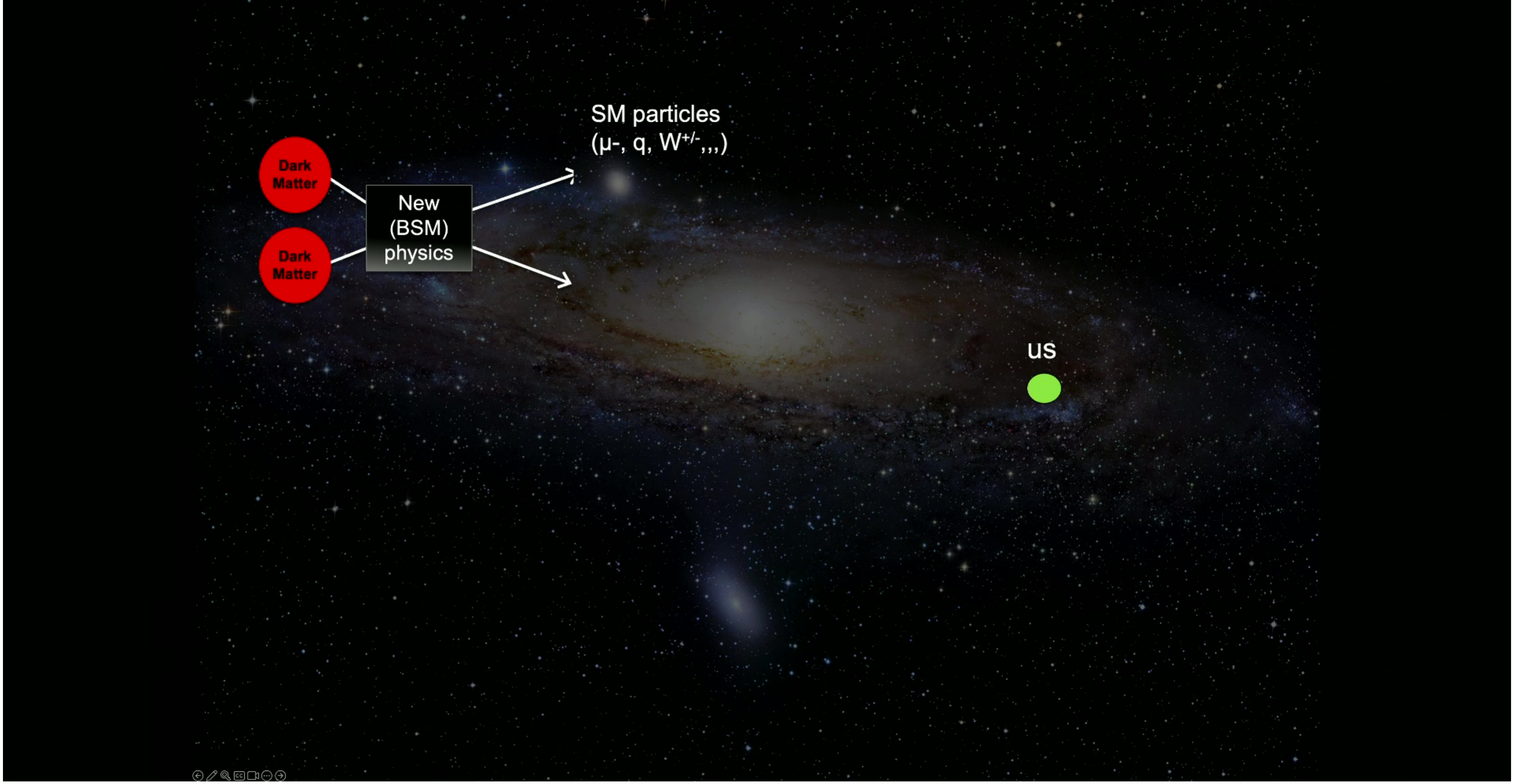
*** Photo from 33 km up in the air!**
Prototype GAPS balloon flight, June 2012

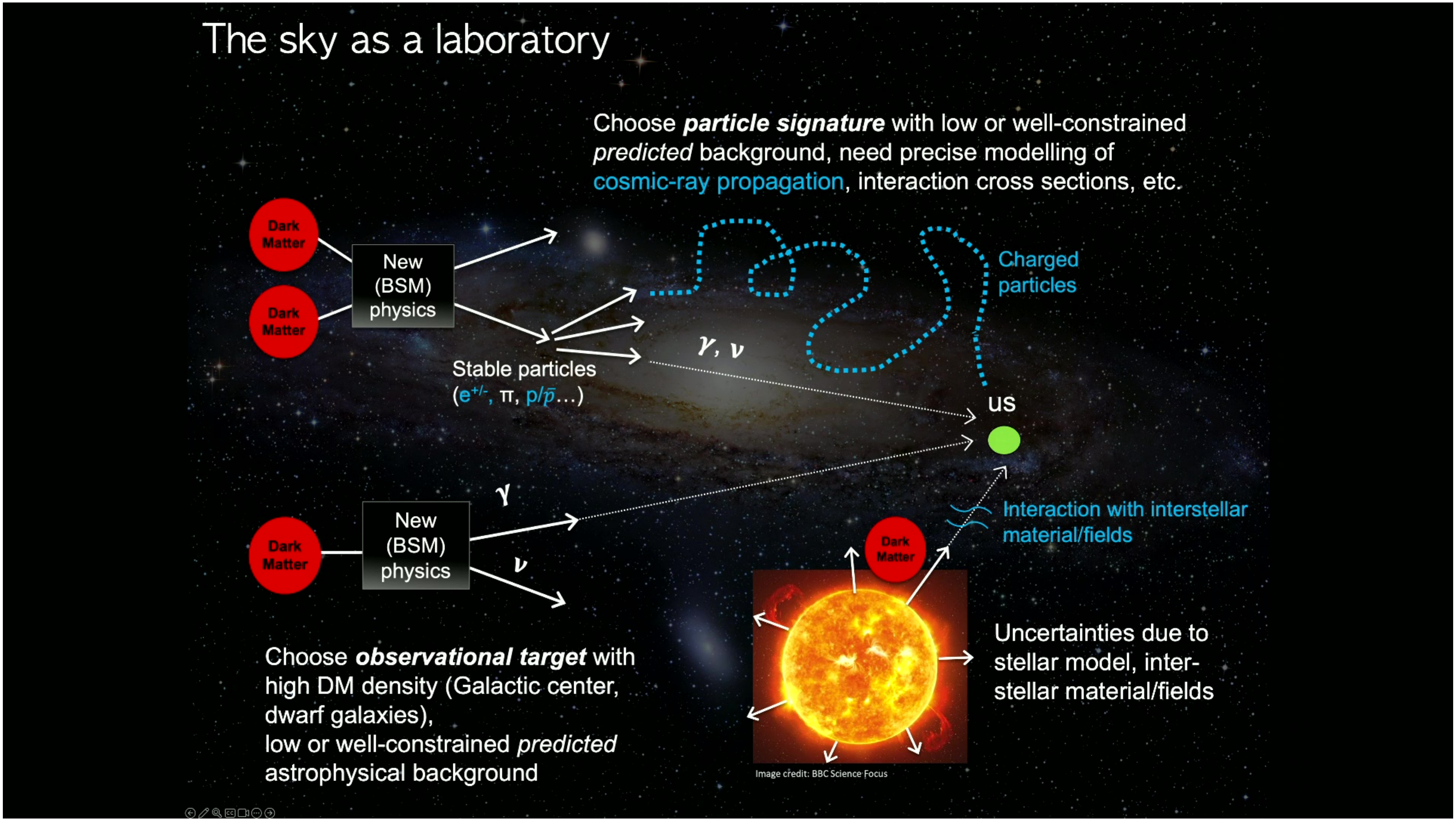


X-ray: M.Markevitch et al.; Lensing: Clowe et al; Optical: Clowe et al.
The Bullet Cluster
gas
dark matter
Gravitational Lensing
"weighs" dark matter
Rotation Curves
Observations
from 21 cm hydrogen
from starlight
V (km/s)
Expected from visible disk
R (× 1000 ly)
Galaxy rotation curve of disk galaxy M33
Credit: Stefania.deluca, Wikimedia Commons
Precision measurements of the
cosmic microwave background
Multipole moment, ℓ
Temperature fluctuations [μK²]
Angular scale


What is Dark Matter?
What is Matter?
electron
proton
neutron

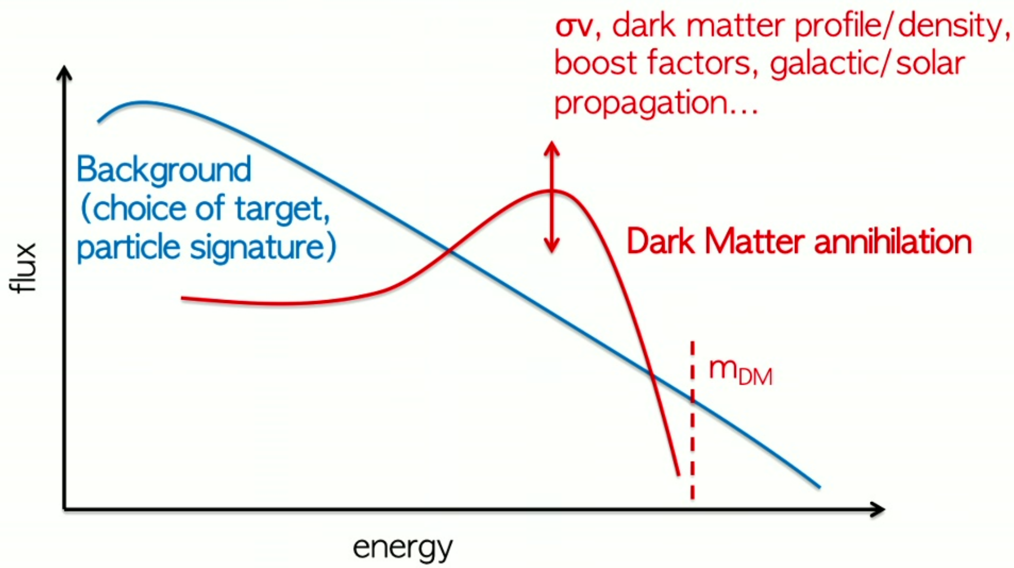
The sky as a laboratory




The sky as a laboratory
Choose particle signature with low or well-constrained predicted background, need precise modelling of cosmic-ray propagation, interaction cross sections, etc.
Dark Matter
Dark Matter
New (BSM) physics
Charged particles
γ, ν
Stable particles
(e+/-, π, p/p̄…)
us
γ
Dark Matter
New (BSM) physics
ν
Interaction with interstellar material/fields
Dark Matter
Uncertainties due to stellar model, inter-stellar material/fields
Choose observational target with high DM density (Galactic center, dwarf galaxies),
low or well-constrained predicted astrophysical background
Image credit: BBC Science Focus

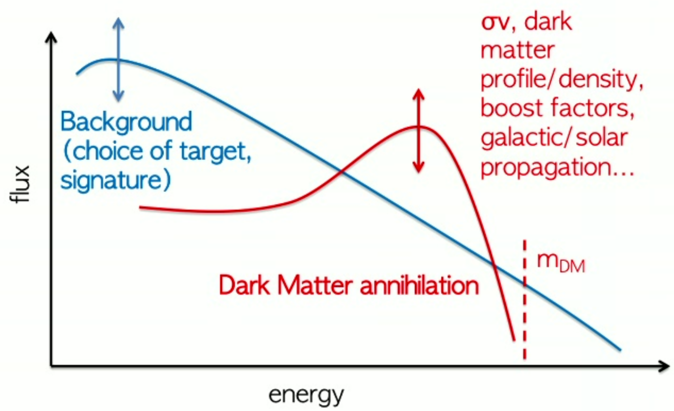
The ~~challenge~~ *FUN* of astroparticle searches!

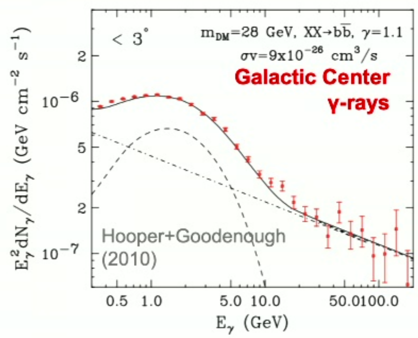
Common challenge = minimize/constrain astrophysical background, maximize predicted dark matter signal

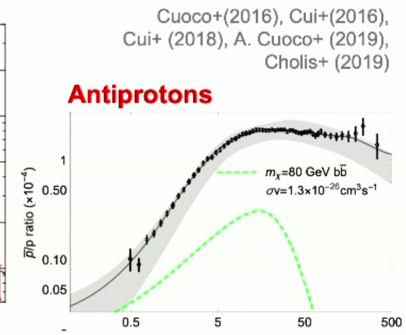


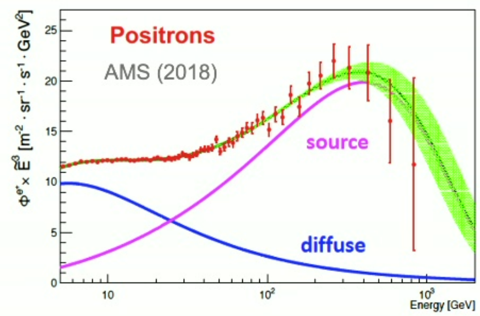
No matter what, measuring something new about the universe!

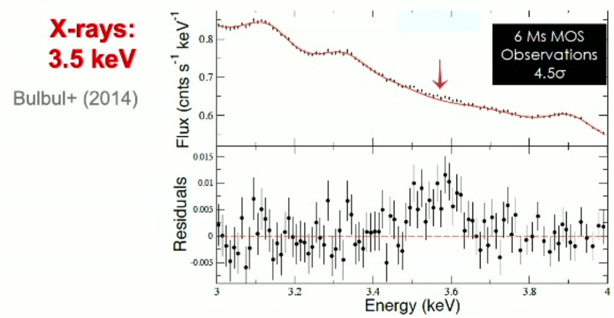
The ~~challenge~~ *FUN* of astroparticle searches!









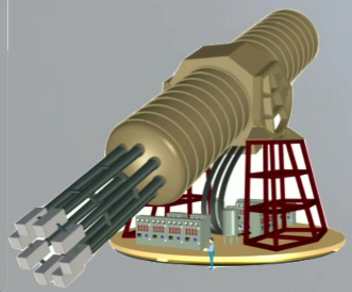


1. **Measuring something new about the universe!**
2. Surprises are difficult to interpret due to large/uncertain astrophysical backgrounds
3. Need cross-correlation with different signatures

Astroparticle Searches for Dark Matter

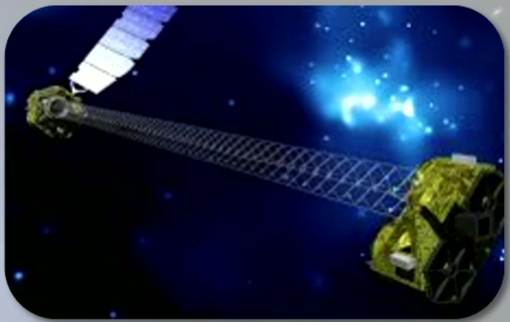
GAPS

Novel detectors for rare cosmic antinuclei searches



IAXO

X-ray optics for solar axion dark matter



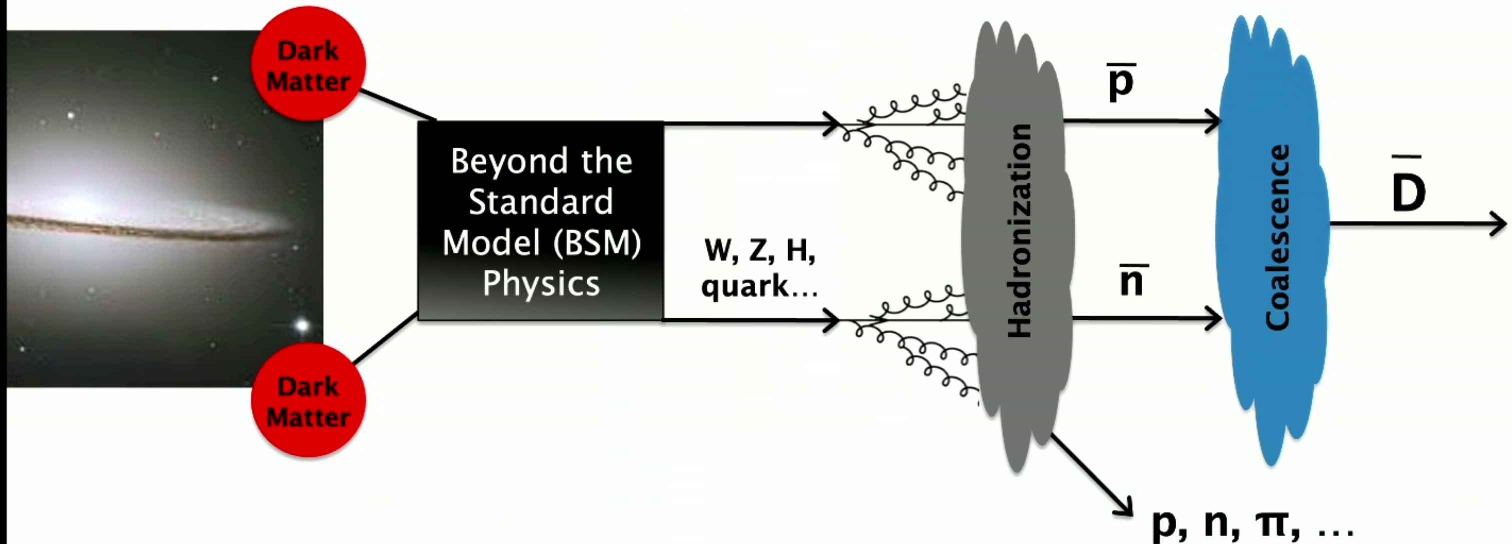
NuSTAR

Leading sensitivity to light dark matter *and* stellar backgrounds to new physics

Outline

- Antiproton, **Antideuteron**, and Antihelium signatures of Dark Matter
- The General Antiparticle Spectrometer (GAPS)
  - Exotic atom detection technique
  - On the road with GAPS…
- Onwards: Towards our late-2024 launch!

Antideuterons from Dark Matter



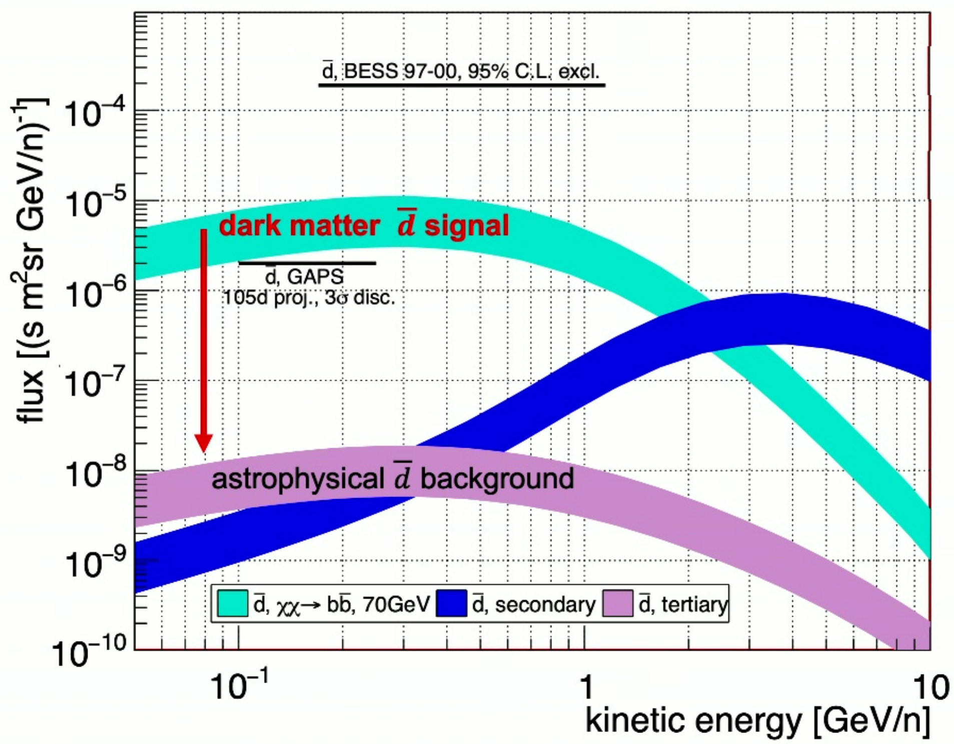
Dark matter particles annihilate…

…create jets of Standard Model particles…

…some of which can make an antideuteron…

GAPS: New physics in cosmic antideuterons

A generic ***new physics*** signature with *essentially zero* conventional astrophysical background

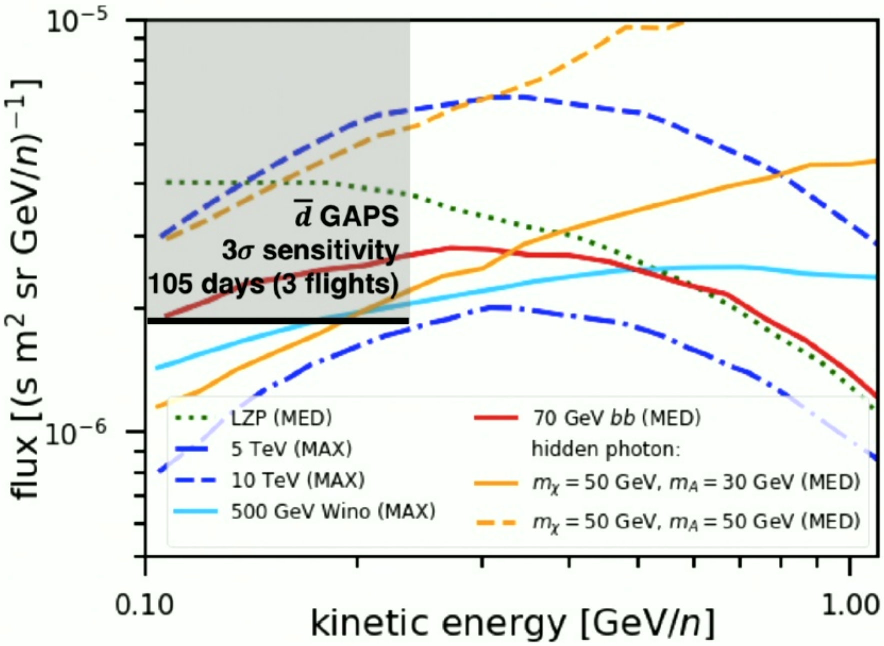


- GAPS first experiment optimized specifically for low-energy antinuclei signatures
- **First Antarctic balloon flight late 2024**

Review of Cosmic Antinuclei Searches for Dark Matter:
von Doetinchem, Perez+ JCAP (2020)

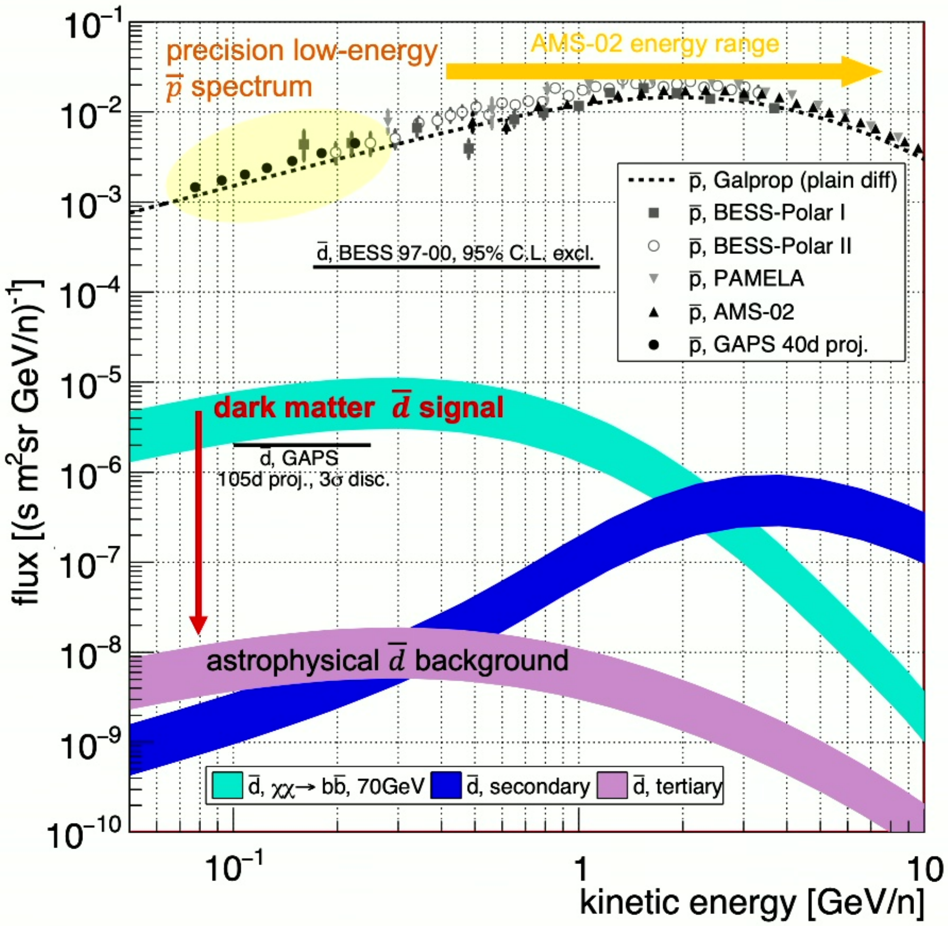
Complementary sensitivity to viable DM signatures

Korsmeier+ 1711.08465 (2018), Cui+ 1006.0983 (2010), Braeuninger+ 0904.1165 (2009), Hryczuk 1401.6212 (2014), Randall+ 1910.14669 (2020)



- Sensitive to ~10s of GeV mass dark matter models, ***as invoked to explain gamma-ray and antiproton observations***
- Sensitive to heavy dark matter models, ***as invoked to explain positron observations***
- Unique sensitivity to ***hidden sector models***

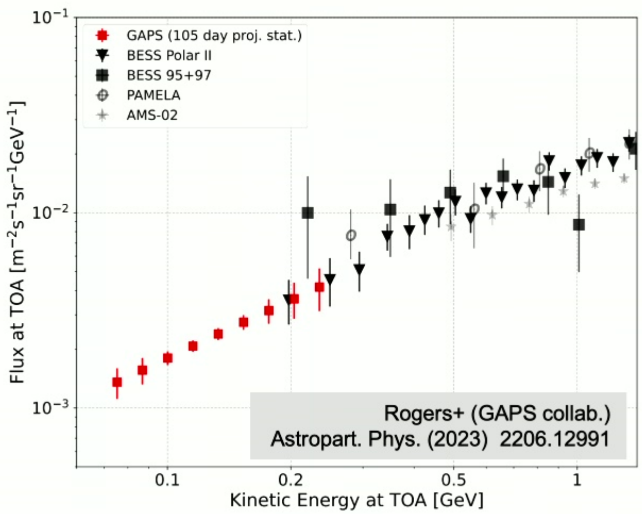
GAPS: New physics in cosmic antideueterons & antiprotons

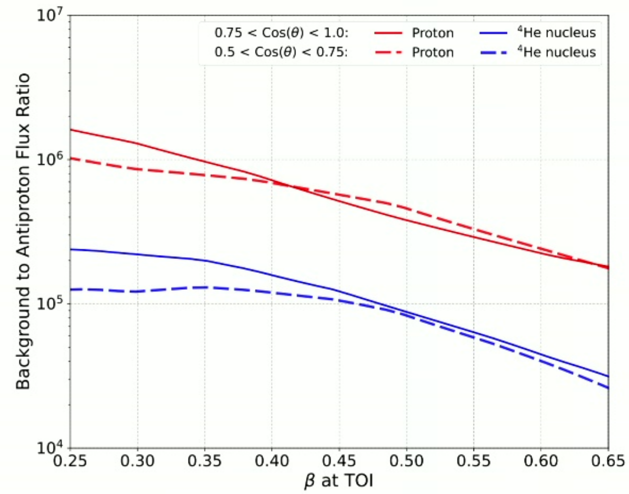


- **precision antiproton spectrum in unexplored low-energy range!**
- sensitive to light dark matter, local PBH, systematic uncertainties for heavier antinuclei searches

Rogers+ (GAPS collab.)
Astropart. Phys. (2023) 2206.12991

Precision low-energy antiproton spectrum





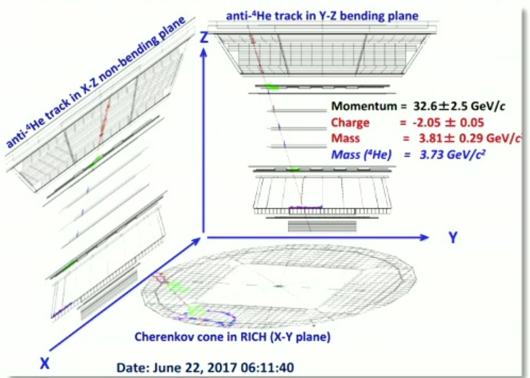
- GAPS will detect ~500 cosmic antiprotons per flight
- Sensitive to light dark matter, primordial black holes, and cosmic ray propagation
- Validate identification technique for rare heavy antinuclei signatures
- Separate study of events with cos(θ) < 0.5 validates atmospheric modelling

New physics in cosmic antihelium?

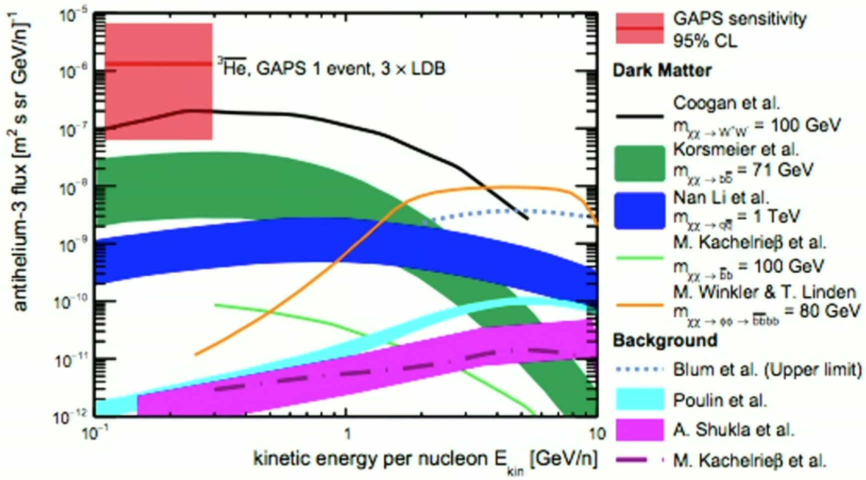
- **pre-2016: “**New work on anit-He signatures is promising, but outside the scope of current experiments” – me, repeatedly

- **2016-2023:** “we have observed eight events…with Z = -2. All eight events are in the helium mass region.”
  – Prof. Samuel Ting (2018 La Palma, AMS overview)

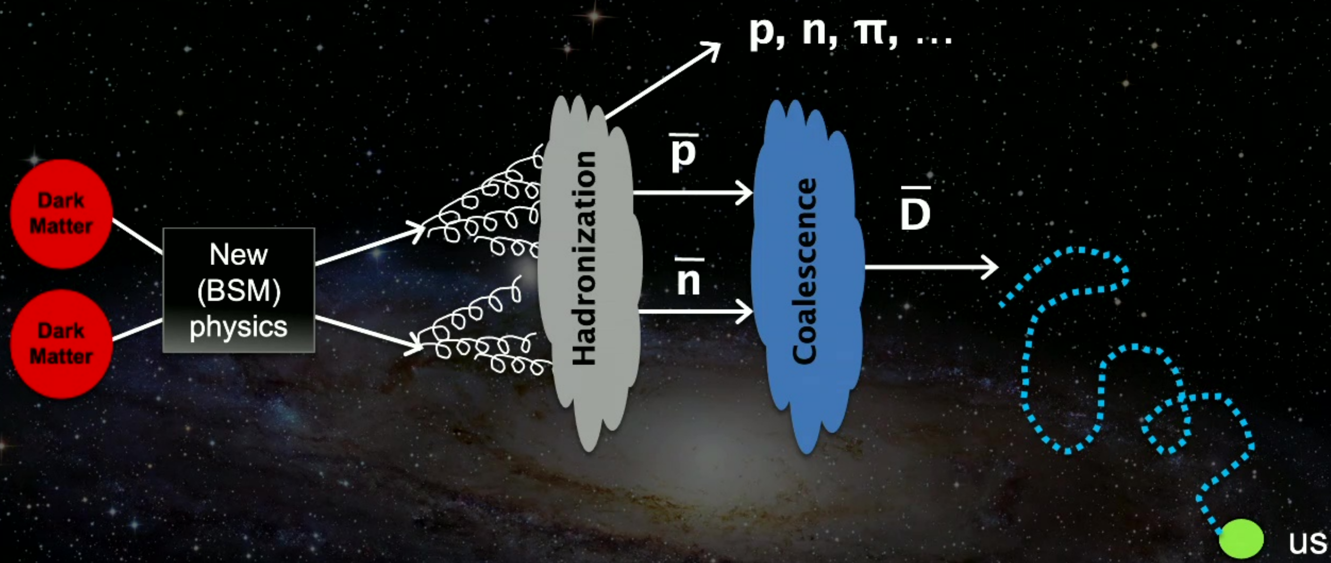
AMS Candidate Anti-He4 event (p = 32.6 GeV/c)



Saffold+ (GAPS collab.) Astropart. Phys. (2021) 2012.05834



- GAPS only experiment capable of confirming signal
- Orthogonal detection technique
- Uniquely low-background energy range



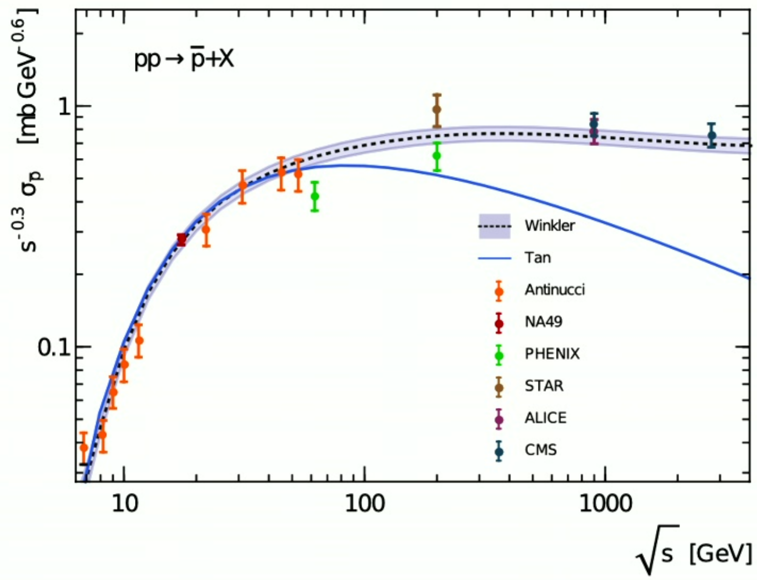
Challenges for comparing antinuclei results with other methods:

1. Antiproton production cross sections
2. Antinuclei formation
3. Propagation in the Galactic disk and Solar field

* Pretend this is our Galaxy
~~Andromeda Galaxy, Hubble telescope~~

Antiproton production

Winkler+ arXiv:1610.03071 (2017)



← At high energies, AMS-02 antiproton spectrum showed excess over predictions

New parameterization at √s > 100 GeV from PHENIX, STAR, CMS, ALICE (along with updated B/C ratio) relieved this tension

↑ At √s < 20 GeV, NA61/SHINE has provided new cross section measurements

- Uncertainties remain ~10-20% at AMS-02 energies
- Larger uncertainties at lower energies, for p+N processes
- Future measurements at lower energies of p+N processes (e.g. LHCb) could improve

Antinculei Formation: Coalescence Model

Coalescence: $\bar{n}$ and $\bar{p}$, merge when relative momentum < $\mathbf{p_0}$ (Yield ~ p_0^3)

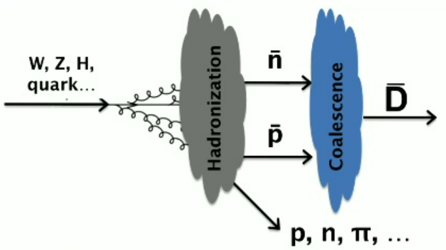
To determine p_0:

- MC generator with antideuteron "afterburner" accounts for correlations due to production channel or center-of-mass energy
- All depends on choice of **hadronization** model (and antiproton cross sections)
- Then tune this to experimental data

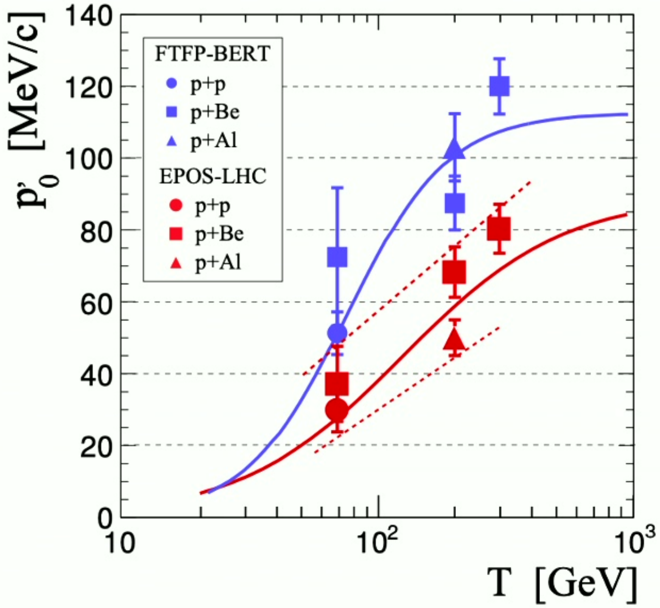
Current status: a dominant uncertainty of ~10x on low-E antideuteron production

Prospects for improvement (soon!): measurements at NA61/SHINE, COMPASS, LHCb, ALICE

See also: freeze-out from a quark-gluon plasma aka "**statistical thermal model**", e.g. Floris 1408.6403 (2014), Bellini+Kalweit 1807.05894 (2019)



D.-M. Gomez-Coral+ PRD (2018) 1806.09303



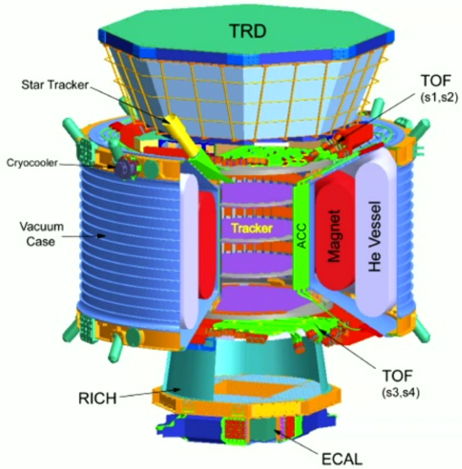
Outline

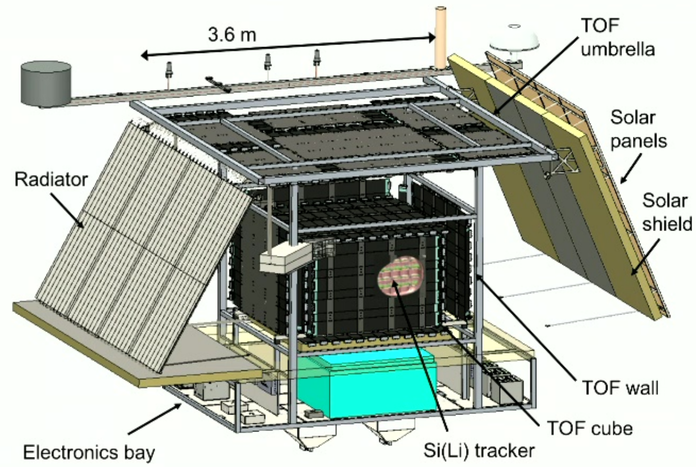
- Antiproton, **Antideuteron**, and Antihelium signatures of Dark Matter
- The General Antiparticle Spectrometer (GAPS)
  - Exotic atom detection technique
  - On the road with GAPS…
- Onwards: Towards our late-2024 launch!

GAPS Collaboration:
~50 members, prominent leadership from postdocs, grad students!

AMS and the GAPS Antarctic balloon instrument

Rare event search and first-time measurement!
Need multiple experiments with complementary experimental systematics

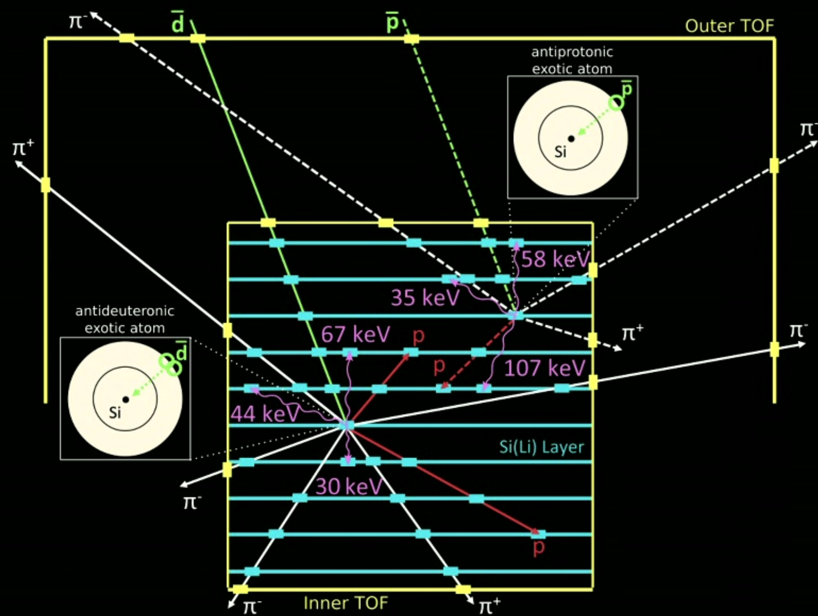




- AMS-02 has been in operation on the ISS since May 2011
- Magnetic spectrometer, combines signals from array of sub-detectors
- Advantages: high statistics spectra, comparison over solar cycle

- GAPS scheduled for initial Antarctic balloon flight late 2022
- Novel antiparticle detection method using exotic atom capture and decay
- Advantages: large acceptance, optimized for low-energy antiparticles

Novel detection of low-energy cosmic antinuclei



Time-of-flight system measures velocity and dE/dx

Si(Li) tracker acts as:

- ***target*** to slow and capture an incoming antiparticle into an exotic atom
- ***X-ray spectrometer*** to measure the decay X-rays
- ***particle tracker*** to measure the resulting dE/dX, stopping depth, and annihilation products

Extoic atom technique verified at KEK: Aramaki+ Astropart.Phys. 49, 52-62 (2013)
GAPS sensitivity to antideuterons: Aramaki+ Astropart.Phys. 74, 6 (2016)
GAPS sensitivity to antiprotons: Aramaki+ Astropart.Phys. 59, 12-17 (2014)

Illustration credit:
A. Lowell (UCSD)

On a balloon!

GAPS' balloon nature constrains power, weight, size, temperature...

Key challenges:

- **High operating temperature**: -35 to -45C
- **Power limited** by long-duration flight
- **Large area**, but low leakage current
- *Need to develop* ***low-cost, high-yield fabrication process***

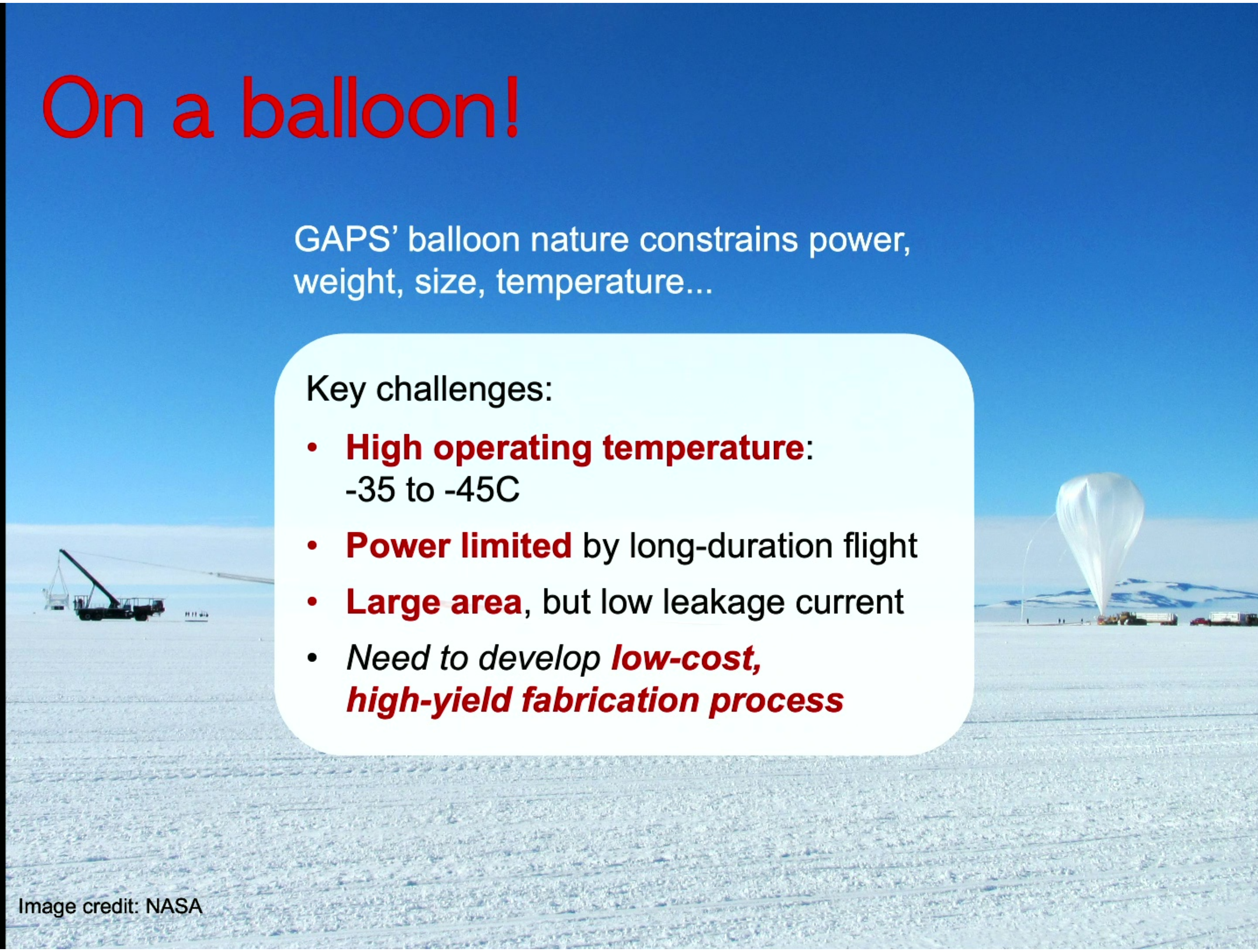
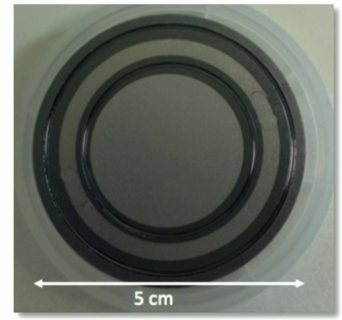


Image credit: NASA

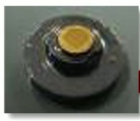
Rapid, successful development of flight detectors

In-house prototype Si(Li) detectors:
5-cm diameter, 1-1.75 mm thick
Total cost ~few hundred dollars in materials

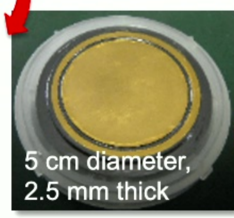


Perez+ NIM A905 12-21 (2018)

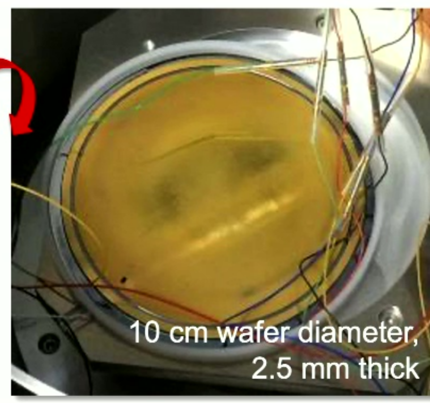
SHIMADZU
Excellence in Science



Commercial products:
~10 mm diameter
~3 mm thick



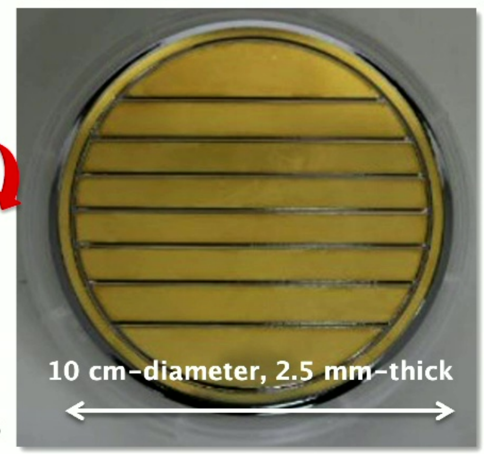
2015



2016

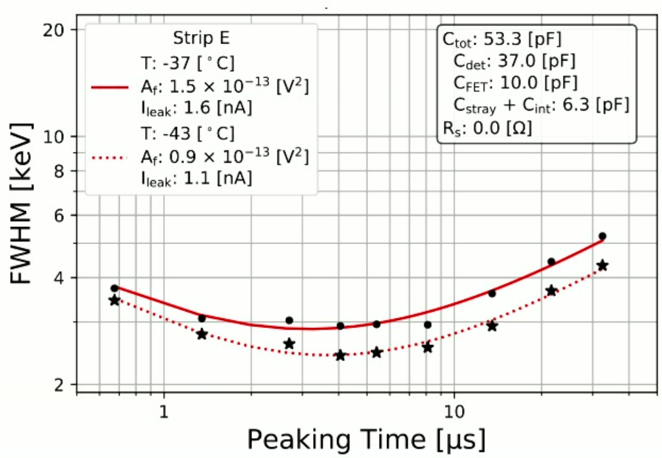
Kozai, Fuke, Yamada, Perez+ NIM (2019)

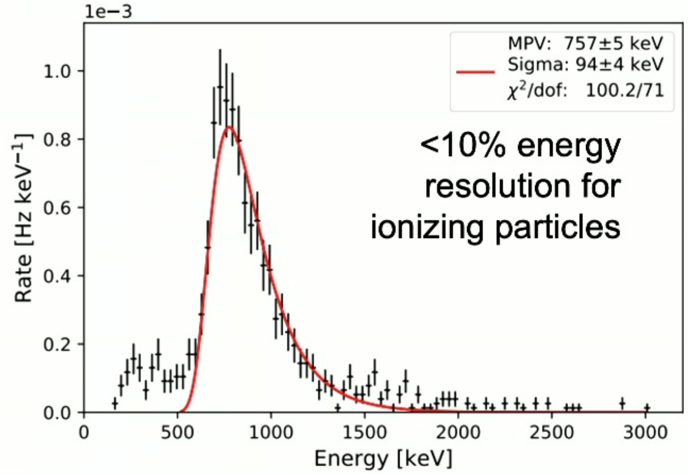
Flight production completed!
2018-2020



Future applications:
Si(Li) for use in heavy nuclei ID
at NSCL/FRIB

Achieved < 3 keV energy resolution at -40 C!





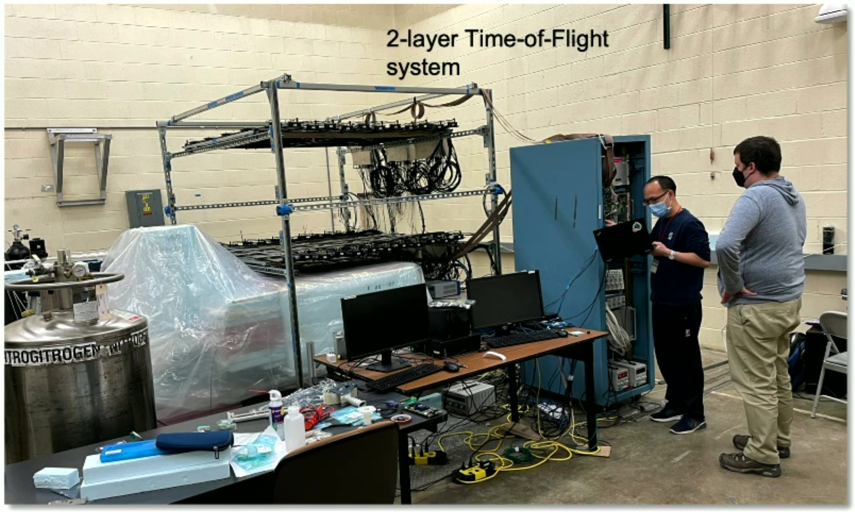
<10% energy resolution for ionizing particles

↑ Noise model allows to predict resolution in-flight, with new generations of readout, varying temperature

Rogers, Xiao, Perez, et al. JINST 14, 10 (2019)

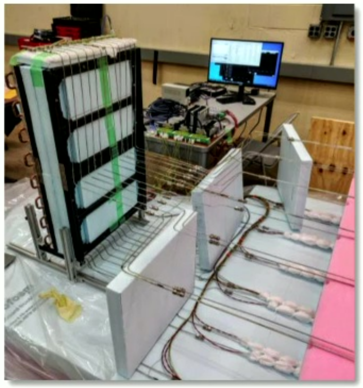
Rogers, Xiao, Perez, et al. Proc. IEE NSS (2019).

Completed! The GAPS Functional Prototype



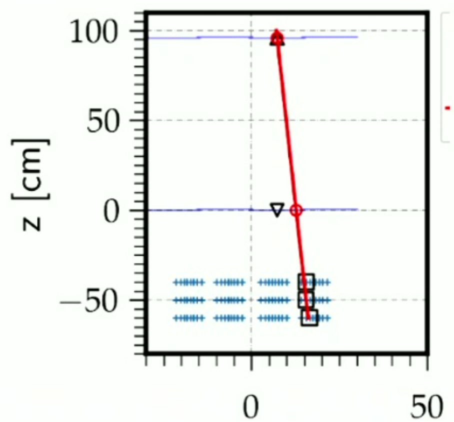
- Validates key system interfaces
- Reconstruction of cosmic muon tracks:
  verification of trigger, event building, and track reconstruction algorithms.

GAPS System tests (Xiao+ *in prep.)*

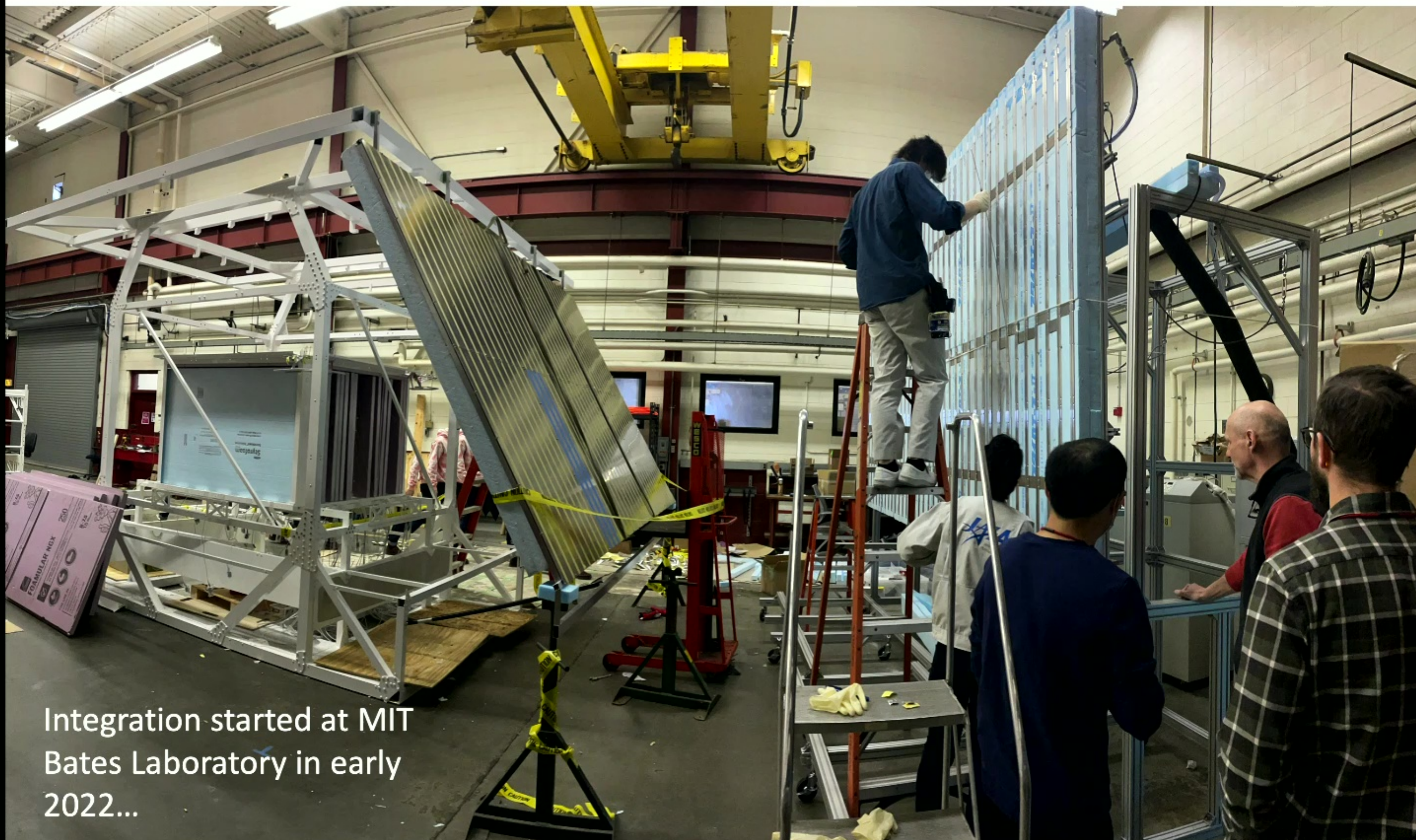


← Oscillating heat pipe thermal system

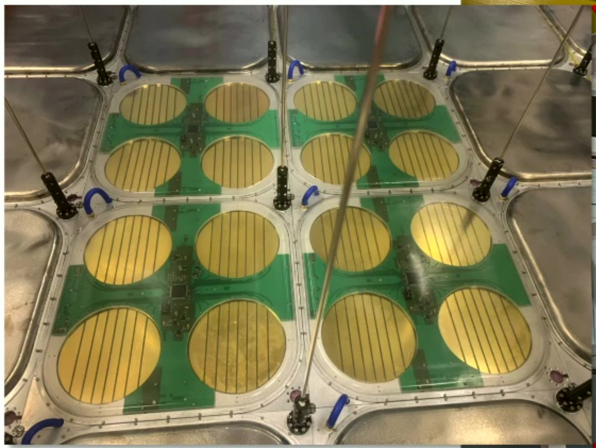
3-layer Si(Li) tracker



Completed! Oscillating heat pipe (OHP) thermal system



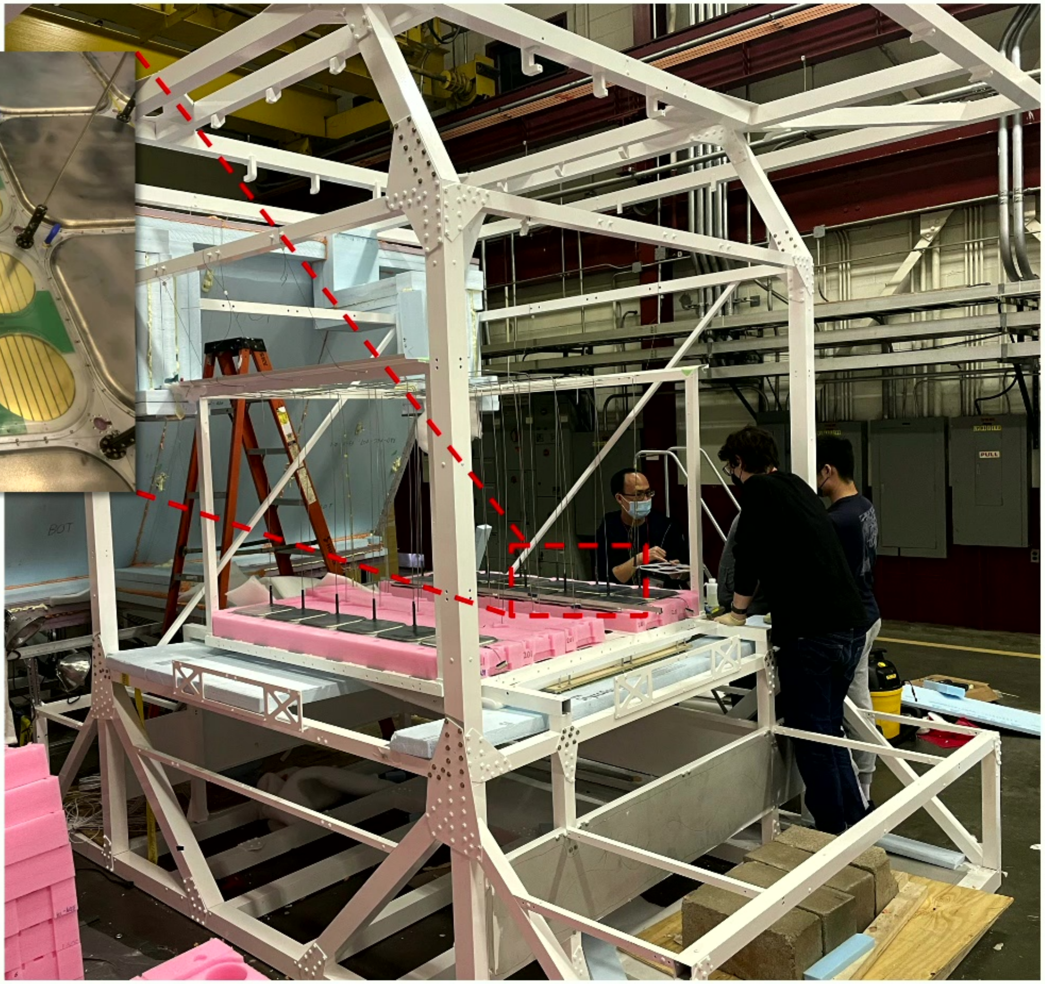
Completed! Si(Li) tracker



32-channel SLIDER ASIC

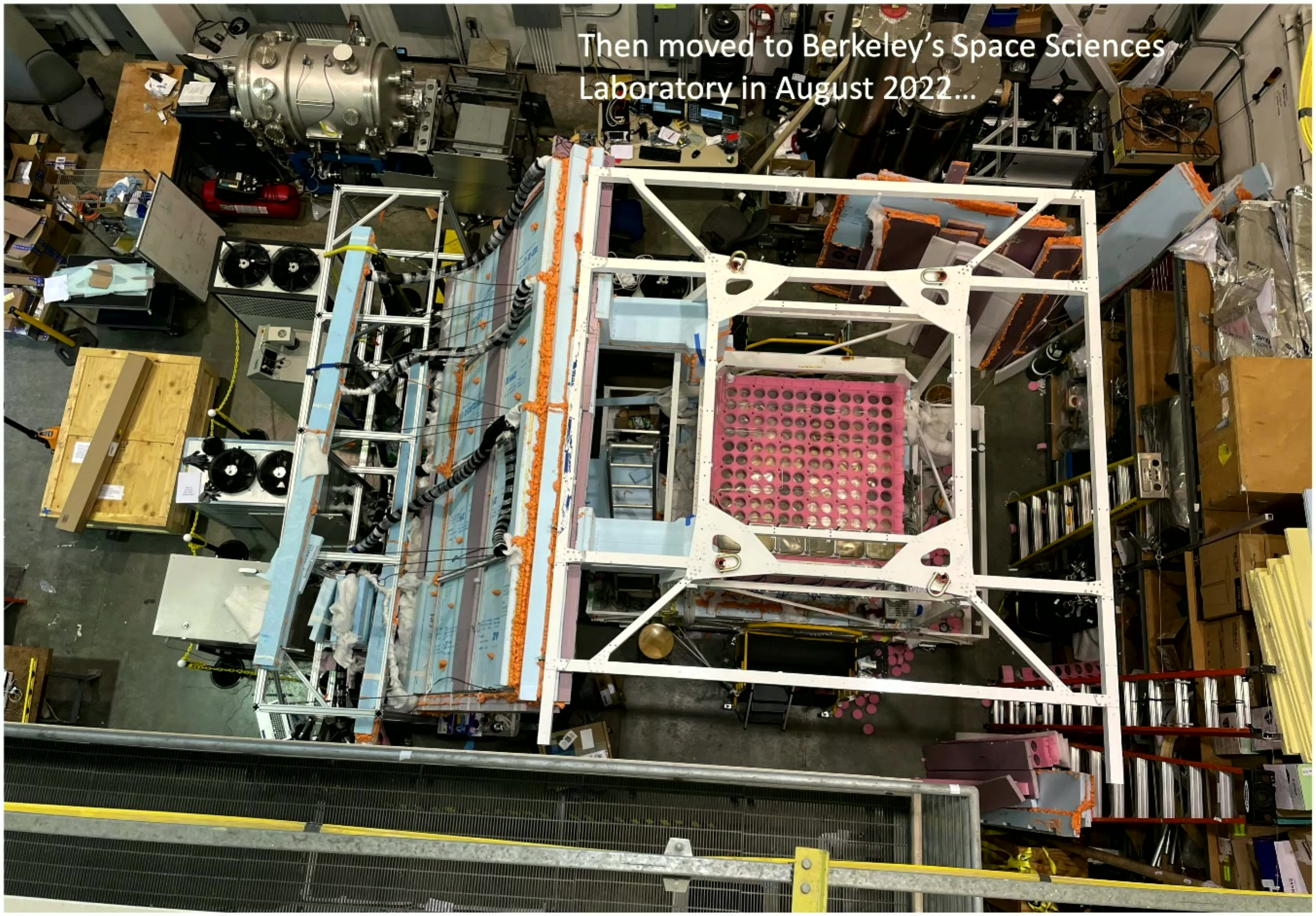
- *1 keV resolution in 10-100 keV*
- *<10% resolution up to 100 MeV*

Tracker integrated with thermal system, layer-by-layer…

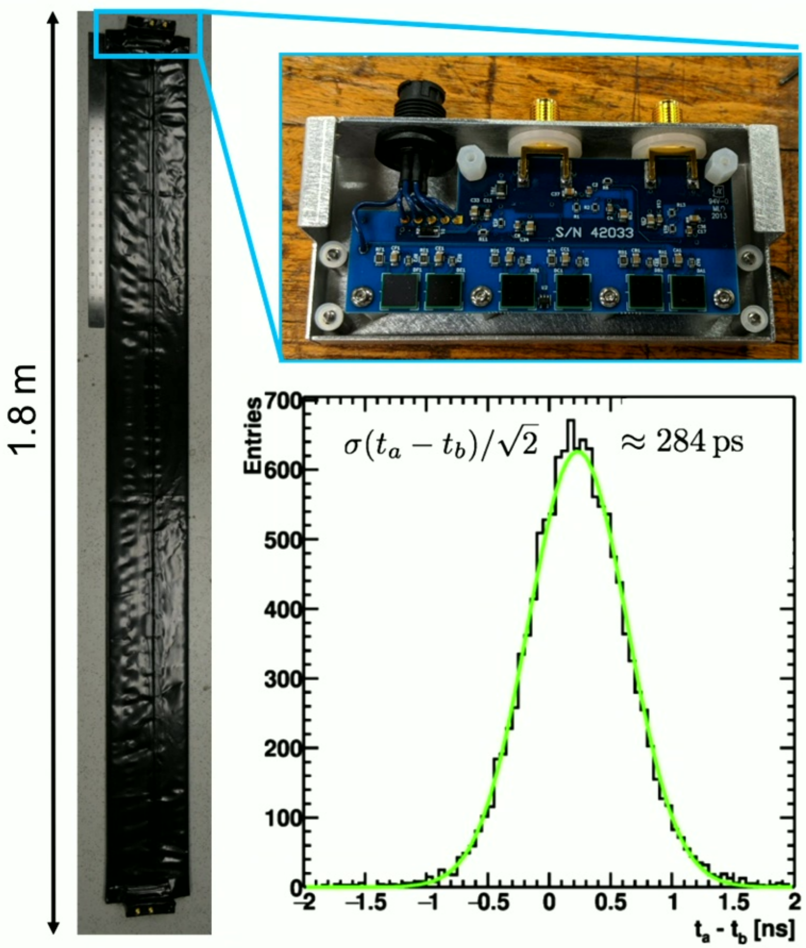


On the road with the GAPS instrument…

Completed! Full Payload Integration



Time-of-flight system: precision timing and trigger

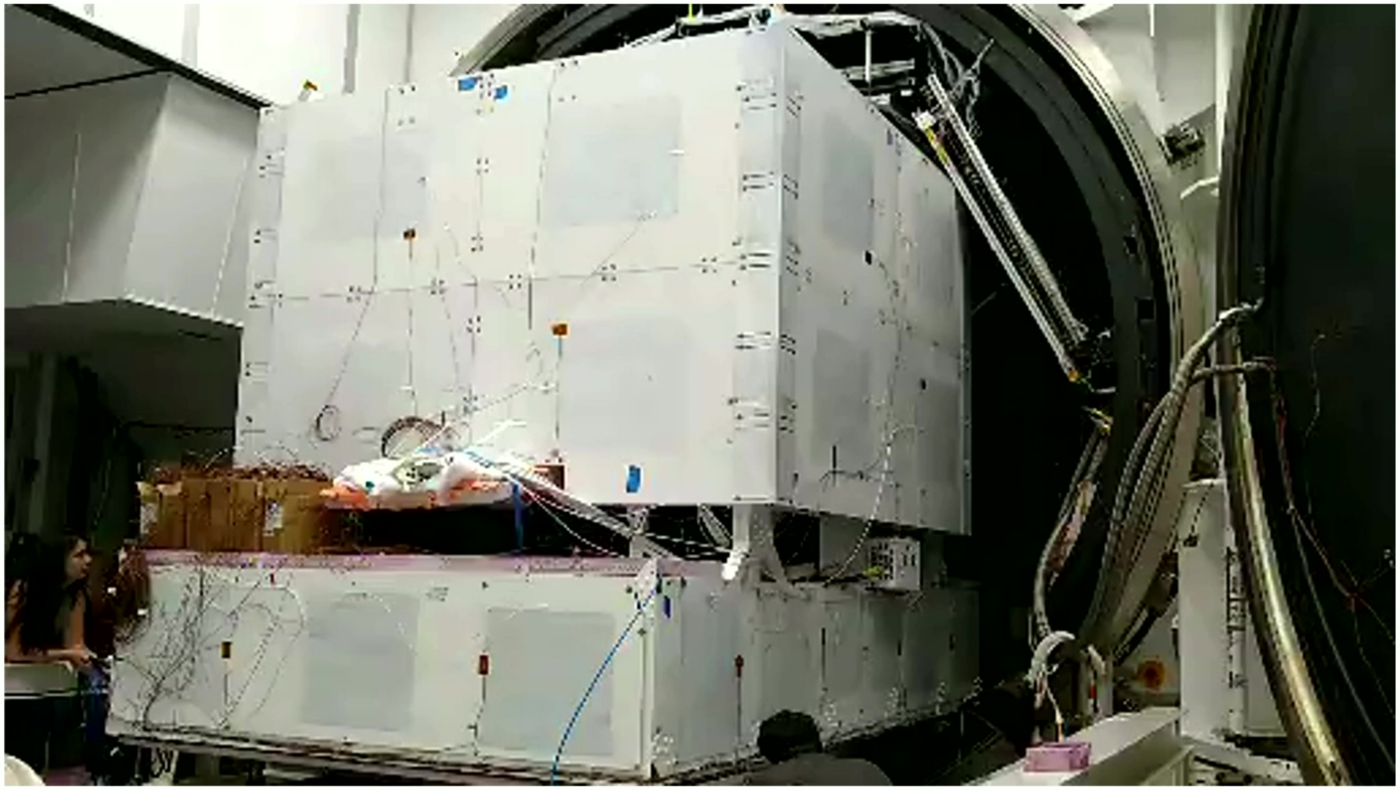


- Plastic scintillator TOF provides precision timing, trigger, dE/dx, >99% hermetic coverage
- Velocity (beta) measurement is basis of GAPS energy scale
- Custom power, readout, and trigger electronics developed
- 25 m^2 of instrumented scintillator!

Bird et al., Proc. ICRC (2019)
Quinn et al., Proc. ICRC (2019)
Quinn et al., Proc. ICRC (2021)
Feldman et al., Proc. ICRC (2023)

On the road with the GAPS instrument…

Completed! Environmental testing



On the road with the GAPS instrument…

On the road with the GAPS instrument…

GAPS arrives at Nevis Laboratory…
…via 2x 53’ flat-bed trucks

Completed! Instrument checkout at NASA/CSBF

Completed! Instrument checkout at NASA/CSBF