Gamma-Ray and Anti-Matter Survey

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Jonathon Sensenig (Columbia University)

on behalf of the GRAMS Collaboration

JAXA

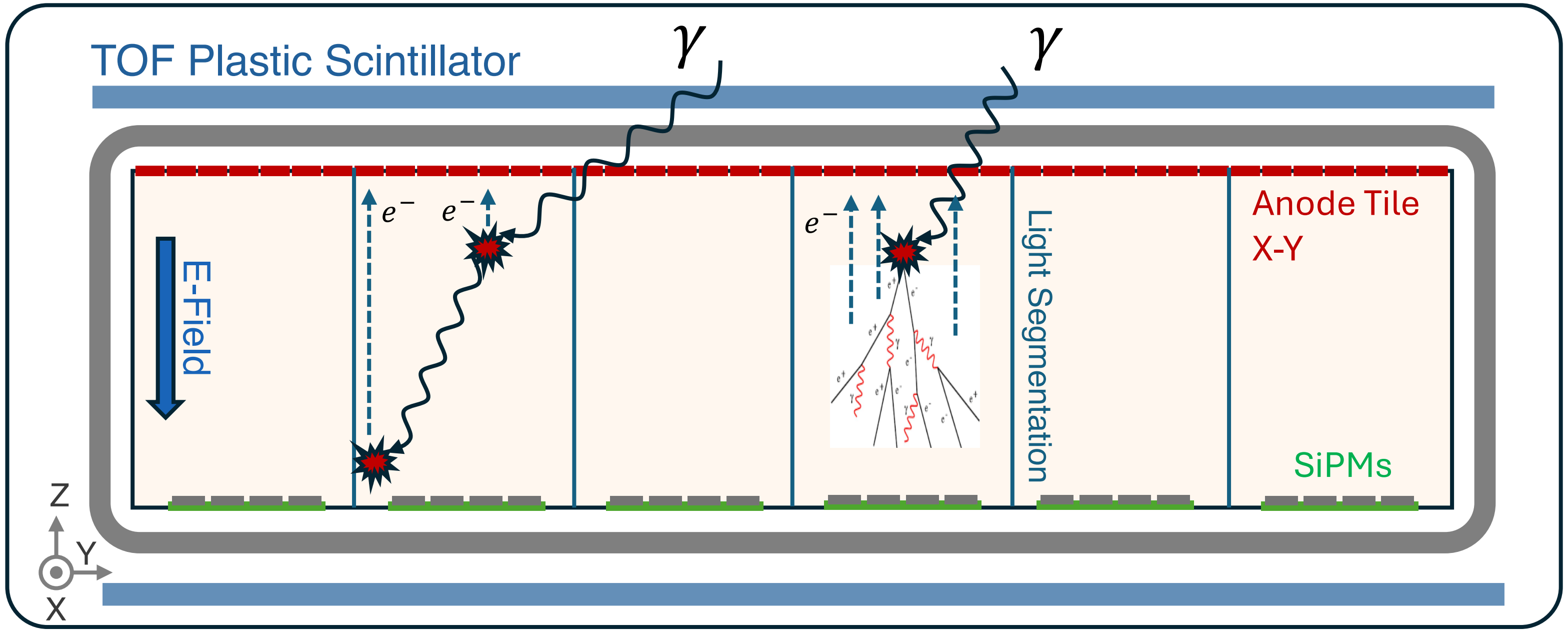
NEVIS LABORATORIES
COLUMBIA UNIVERSITY

NASA

Gamma-Ray & Anti-Matter Survey (GRAMS)

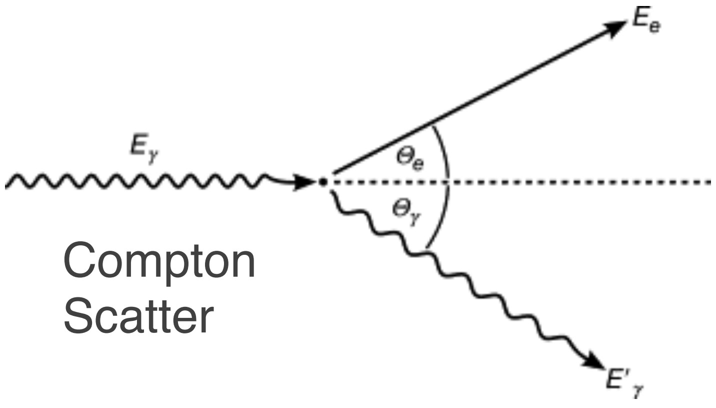
- Gamma rays: Probing gamma rays in the MeV-gap.
- Antimatter: Indirect searches for dark matter via cosmic antinuclei.
- First Liquid Argon Time Projection Chamber (LArTPC) Compton-camera, proposed to operate in space.
- Engineering, demonstrator and science balloon flights, followed by satellite mission.
- Funded for a prototype balloon flight.

GRAMS LArTPC Detector

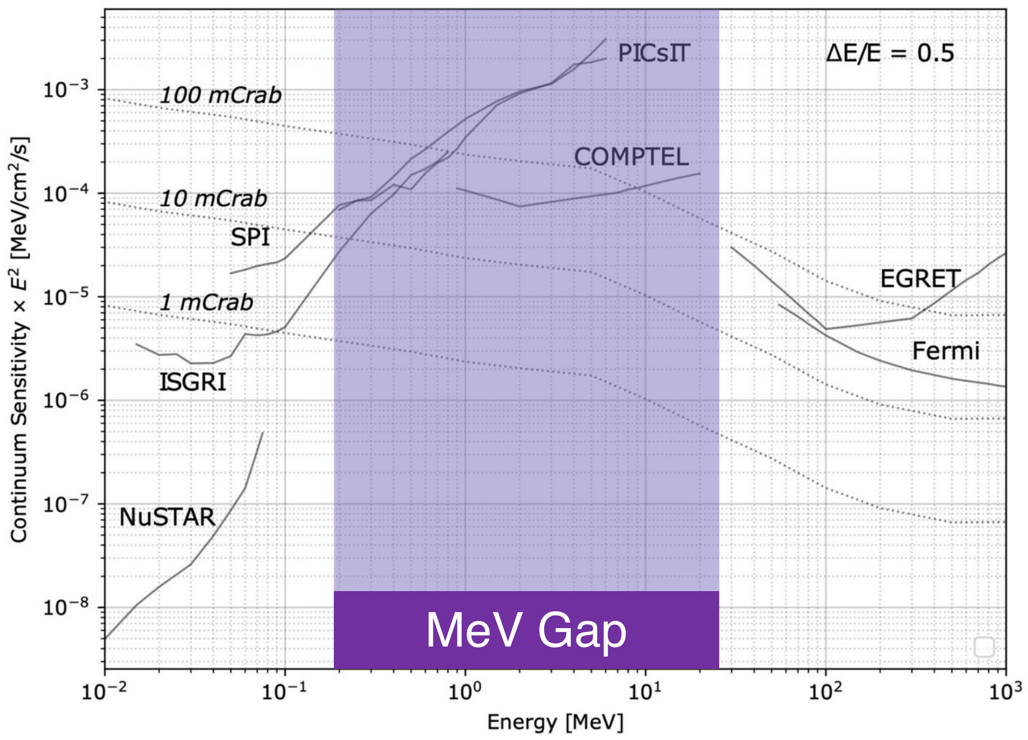


Gamma-ray Survey Motivation

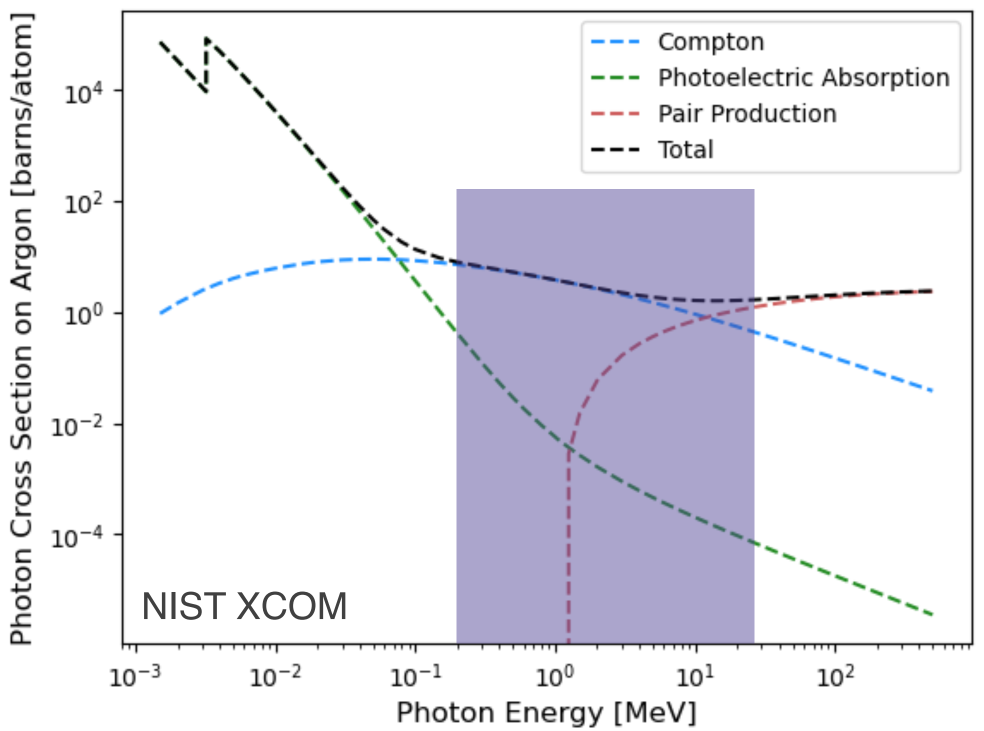
- Gamma-ray MeV region is under-explored relative to lower/higher energy regions.
- MeV region dominated by Compton scattering of gamma ray.



Current & Past Missions

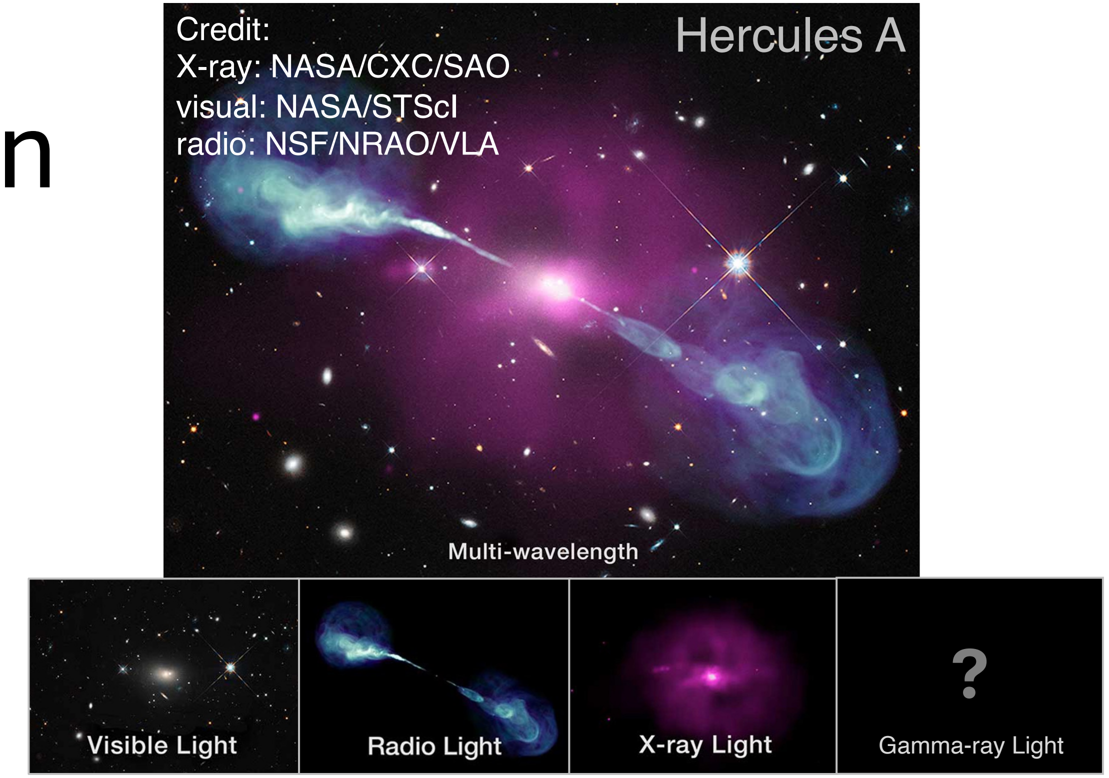


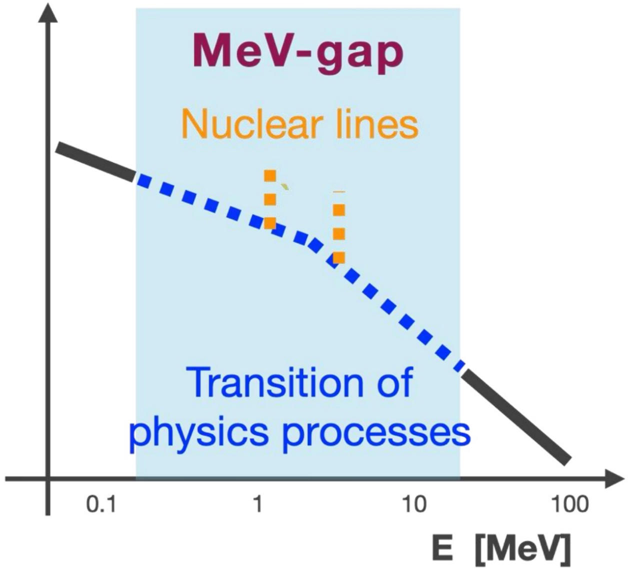
Photon Cross Section on Argon

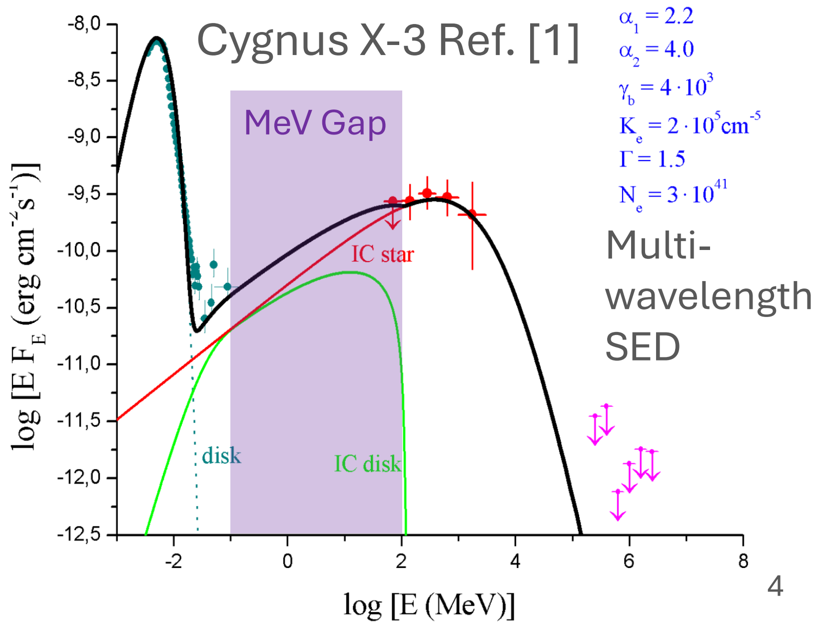


Gamma-ray Survey Motivation

- Multi-wavelength astronomy.
- Multi-messenger astronomy,
  - MeV γ & GWs
  - MeV γ & high-energy ν
  - NS/BH mergers, GRBs, SNe, AGNs
- Nuclear transition lines & nucleosynthesis,
  - r-process of kilonovae, magnetar flares.
  - Galactic center, classic novae, SNe, etc.
  - 511-keV line, $e^- \, e^+$ annihilation excess.
- Particle accelerator spectral features,
  - Thermal to non-thermal transitions.
  - Pion bump signature of hadronic accelerators
  - Magnetic properties and energetics.

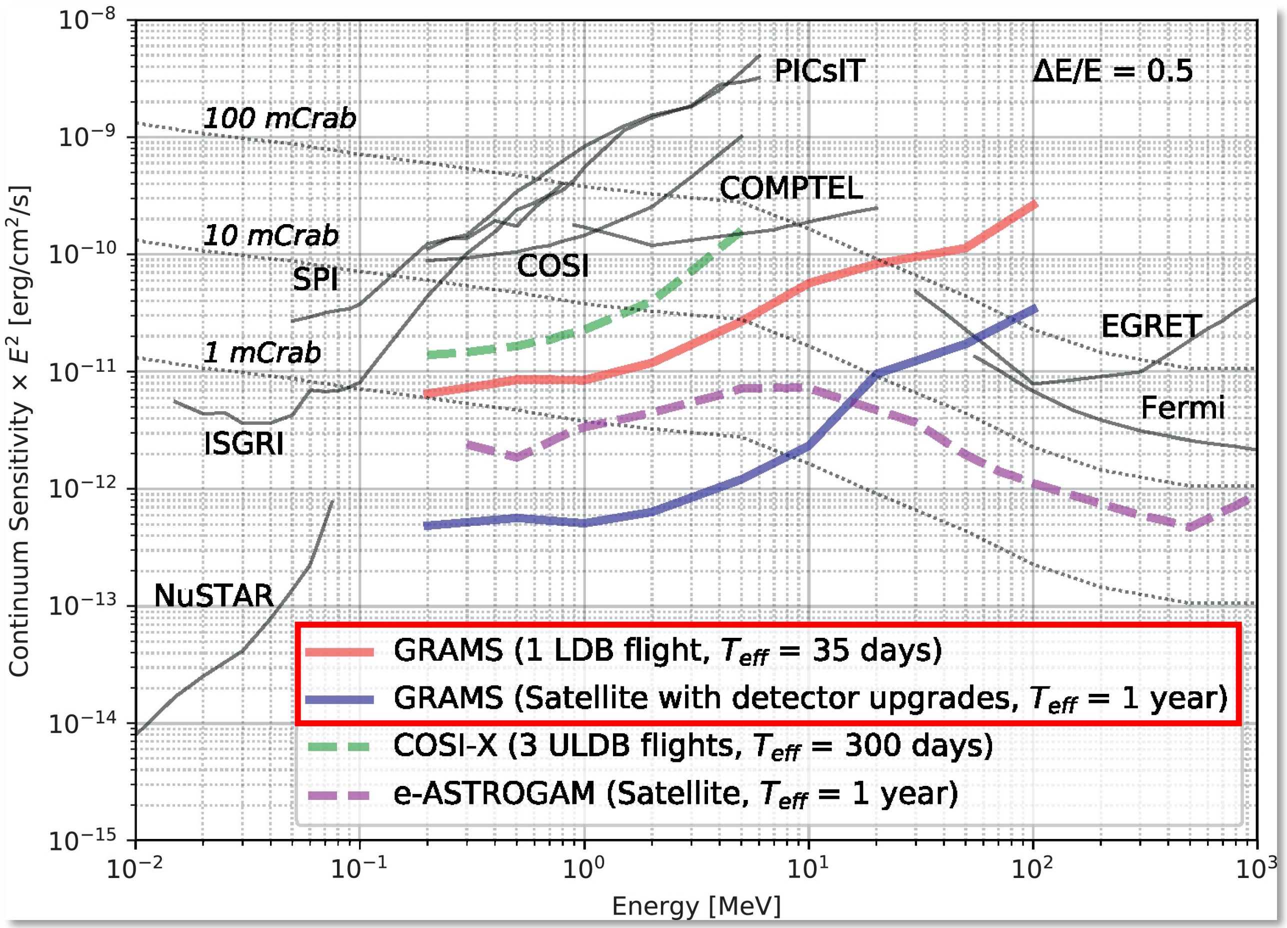






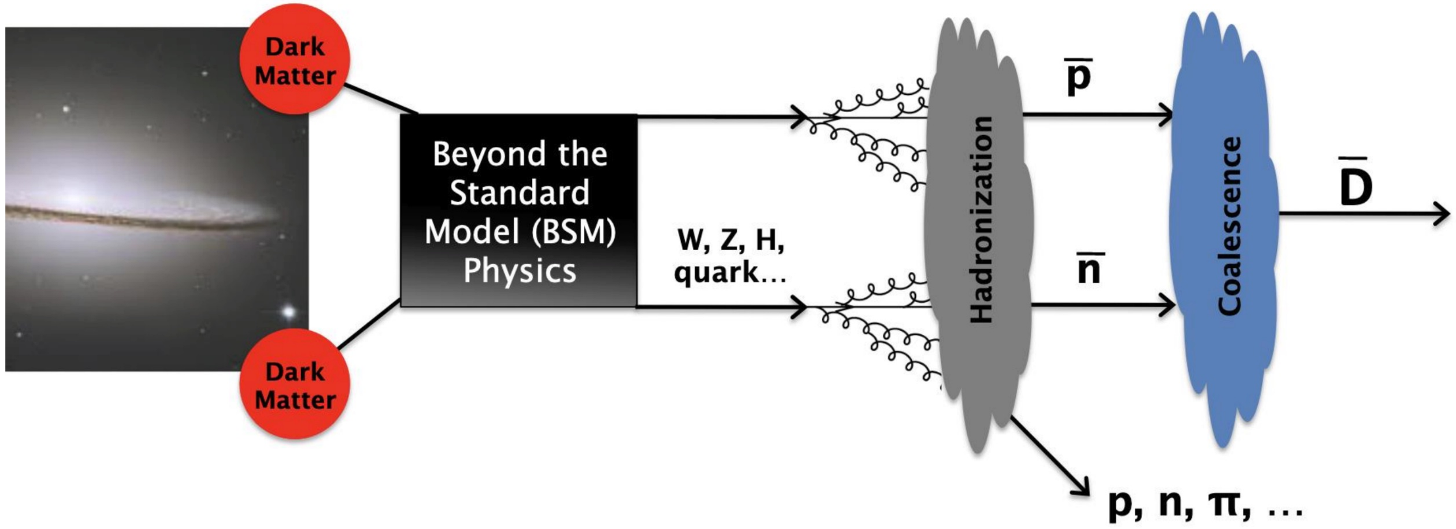
Gamma-ray Sensitivity

- Order of magnitude sensitivity improvement over COMPTEL, even with 35d long-duration balloon flight,
  - Using $1.4 \times 1.4 \times 0.2$ m^3 TPC.
- Additional order of magnitude sensitivity increase for satellite mission.

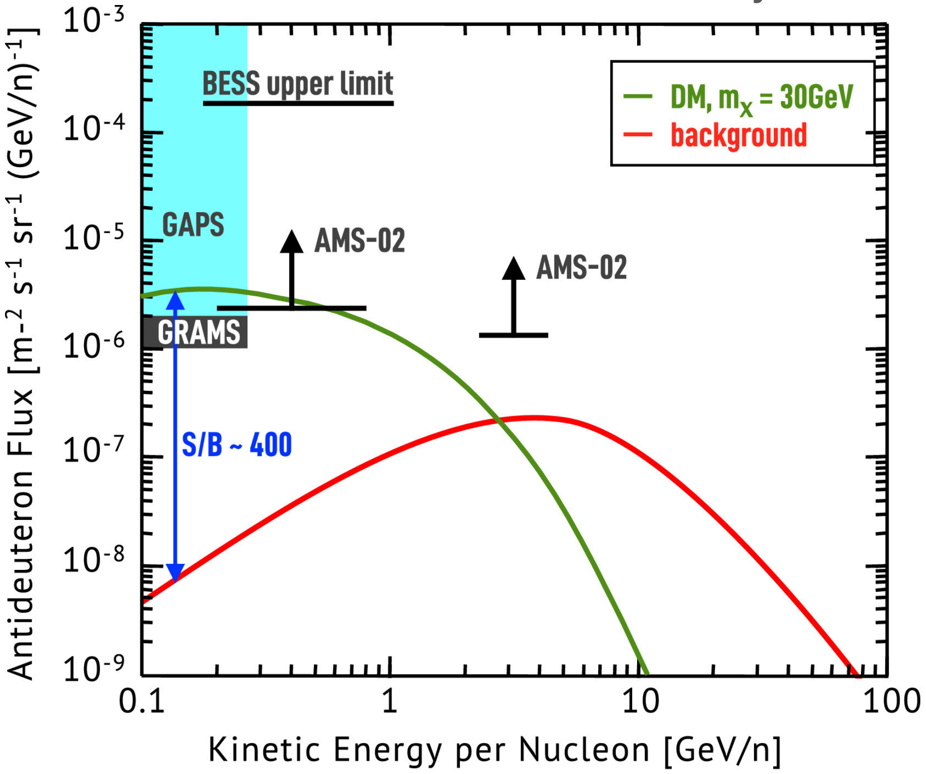


Antimatter Search Motivation

- Indirect search for dark matter annihilation via antinuclei.
    - Antinuclei: $\bar{p}$, $\bar{d}$, $\overline{He}$
- Search for excess in antinuclei spectrum.

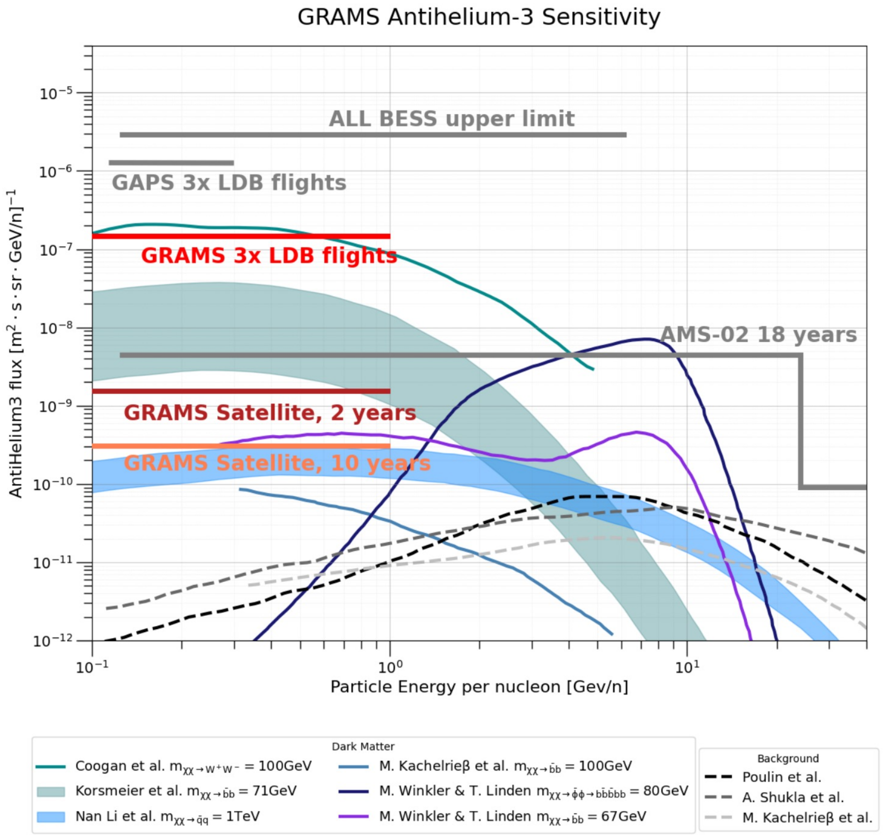


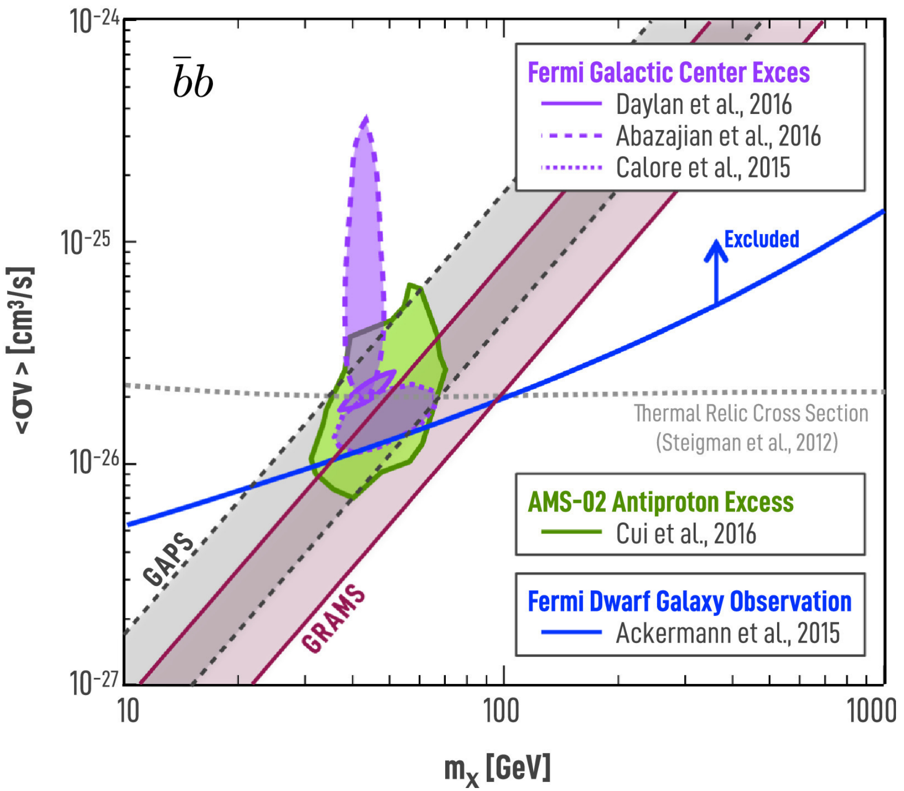
Antideuteron Sensitivity



Antimatter Sensitivity

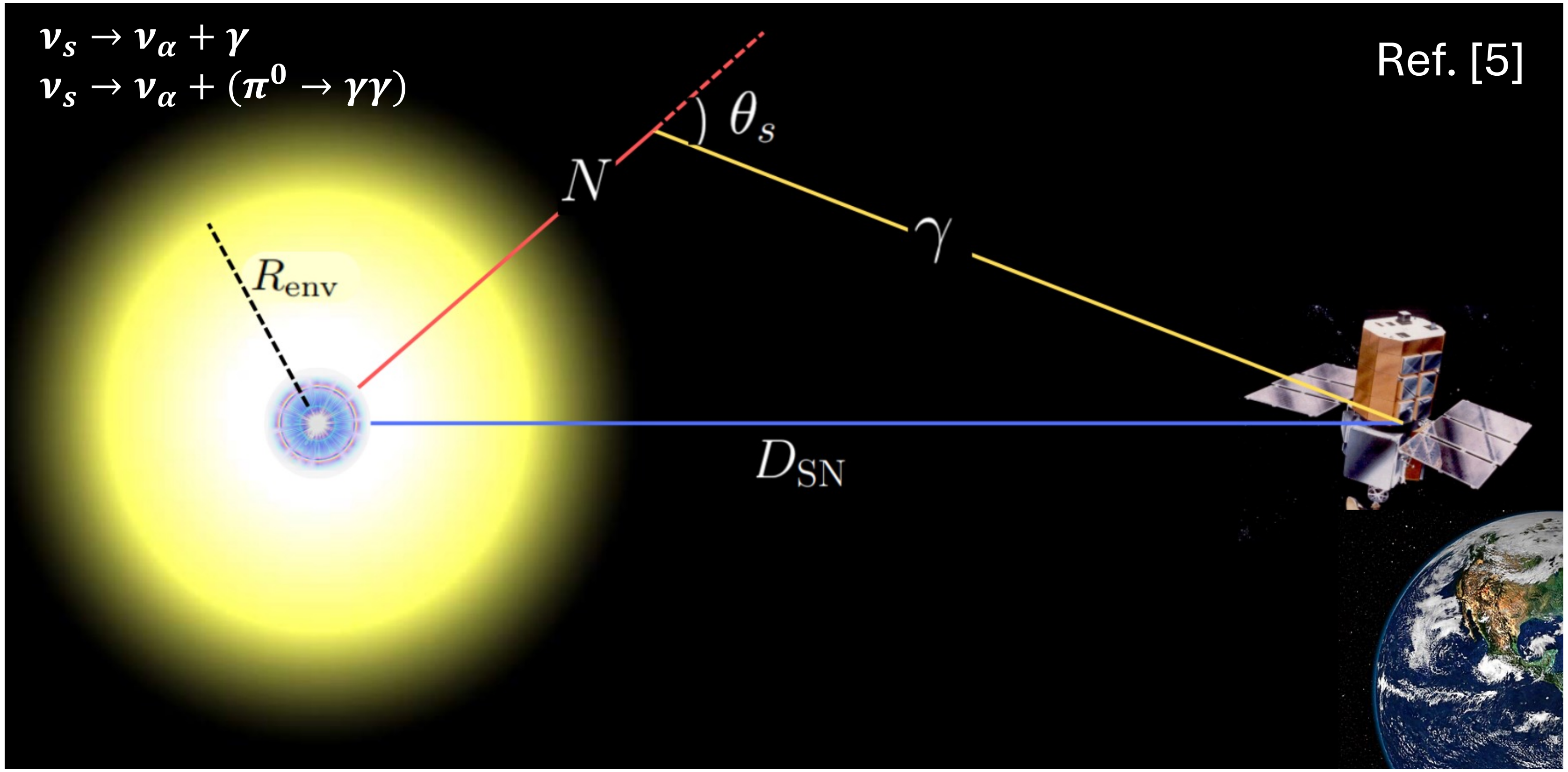
- Class-leading sensitivity to antinuclei.
  - Set strong limits on dark matter annihilation → antinuclei cross section.
- Verify antiproton excesses observed in AMS-02 [3] and Fermi [4].



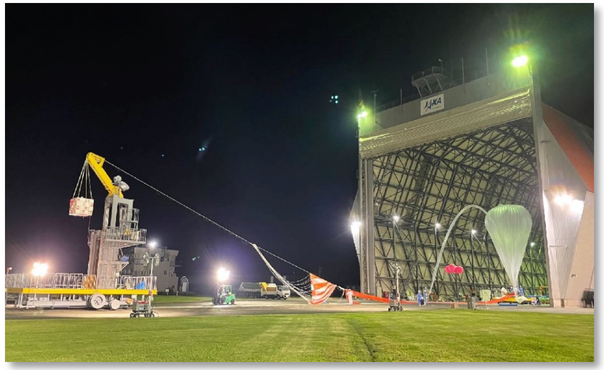


Fundamental Particle Physics

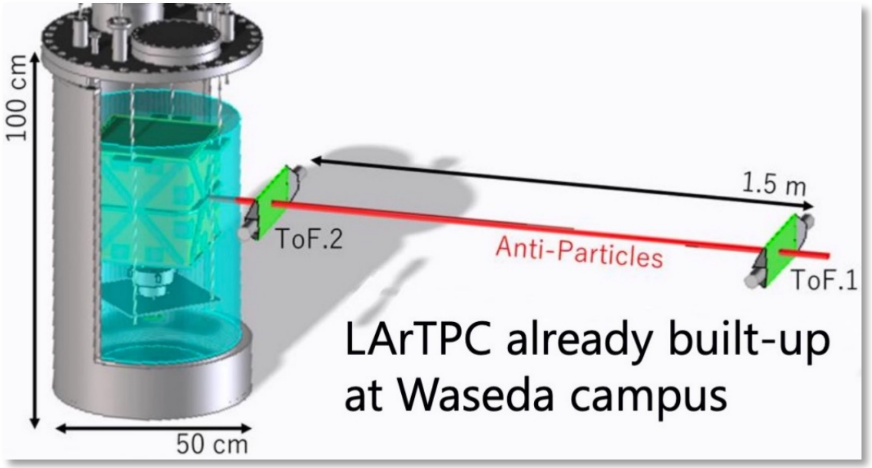
- GRAMS will also have the capability to probe fundamental particle physics.
- **Example:** If a nearby SNB occurs, set limits on sterile neutrino parameter space by searching for excess gamma rays from radiatively decaying sterile neutrinos, produced in SN core [5].

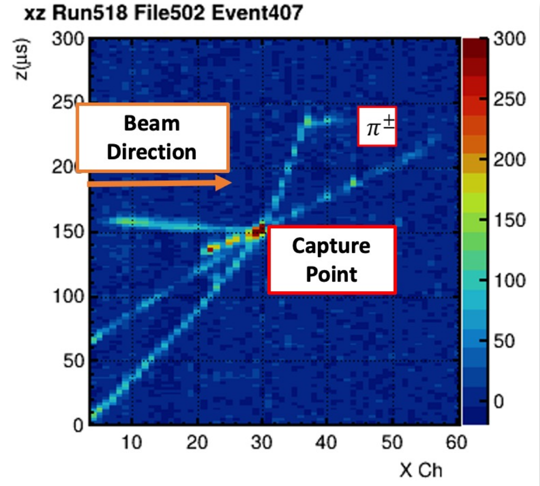


Schedule

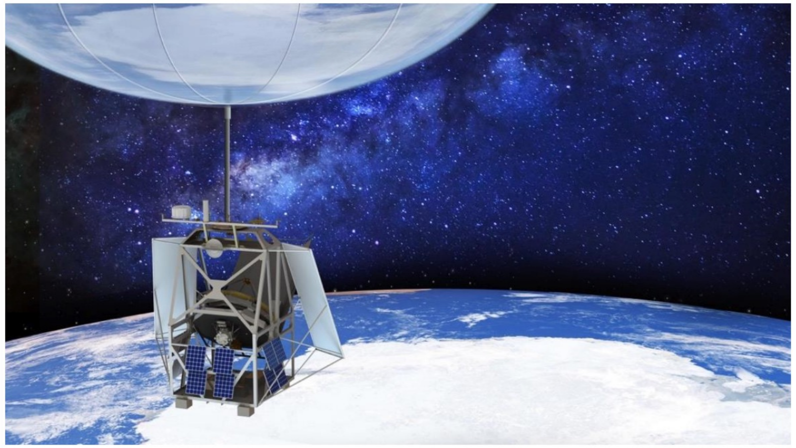


eGRAMS Flight
LArTPC Demonstrator





J-PARC $\overline{p}$ Beam Test



NASA LDB mission with payload of similar size to GRAMS (Image credit: NASA/JPL-Caltech)

Long Duration Balloon Science Flights

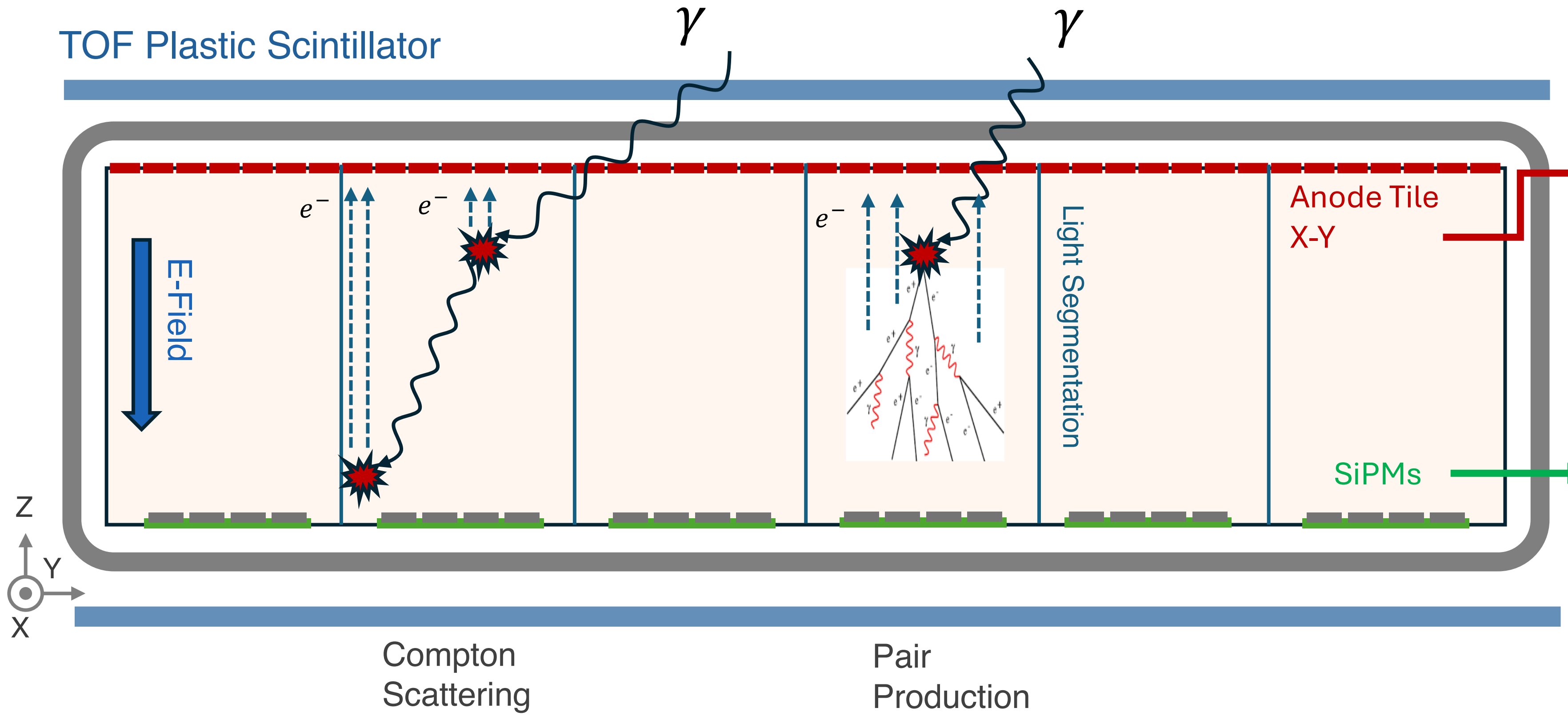
8-16hr Balloon
Demonstrator Flight

Satellite Mission

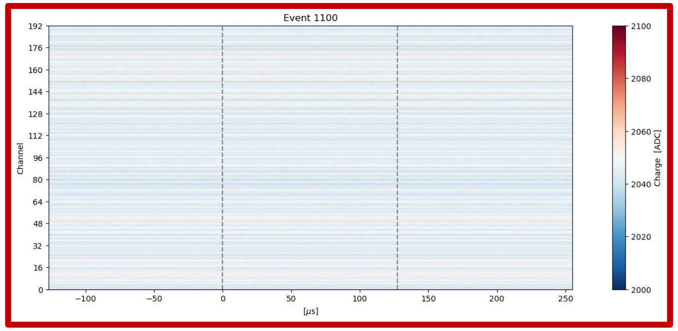
2023 → 2024 → 2025 → 2026 → Late 2020s → 2030s

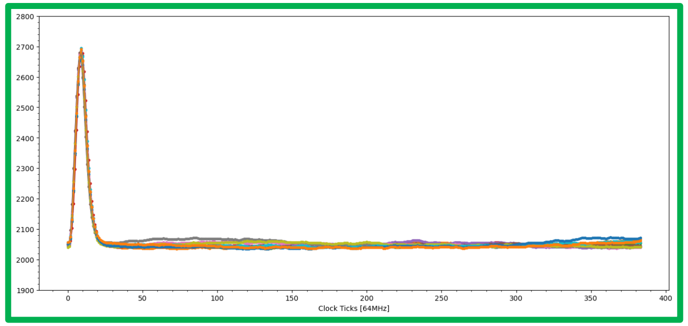
* Schedule subject to change

Gamma-ray Detection



Example Ionization Charge Readout (baselines only)

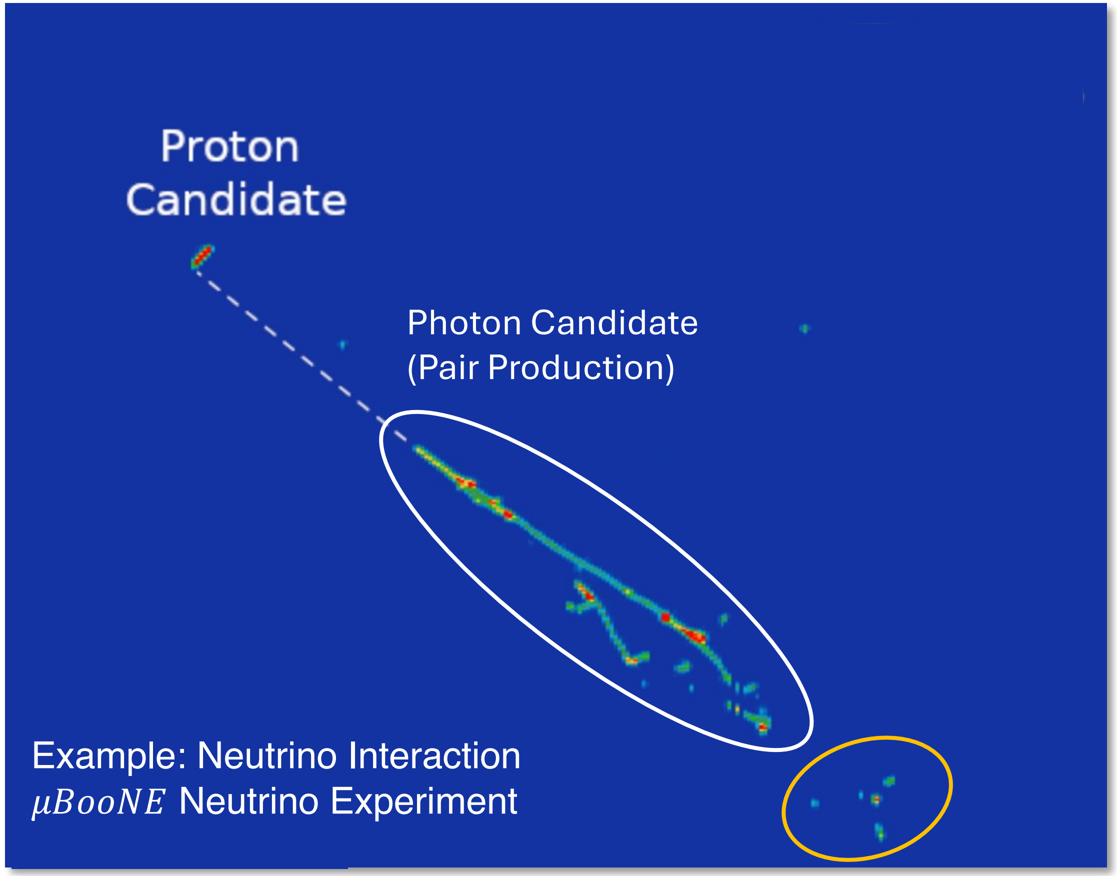


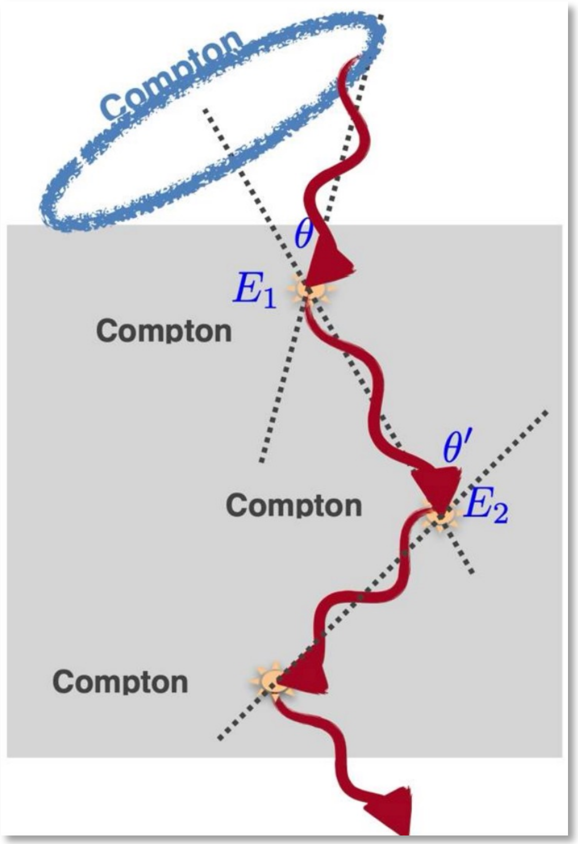


SiPM Signals

- GRAMS uses a Liquid Argon Time Projection Chamber (LArTPC).
- Mature LArTPC detector technology, used widely in neutrino and underground dark matter experiments.
- Scalable, low dead space and cost effective.

Gamma-ray Detection

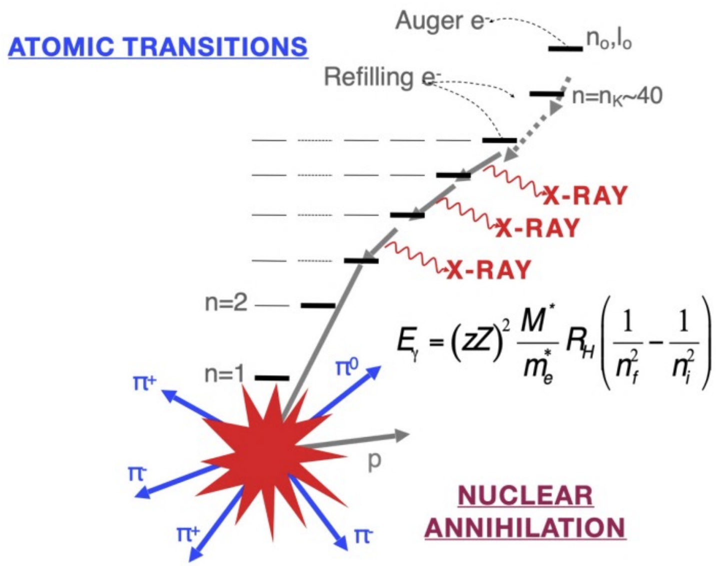


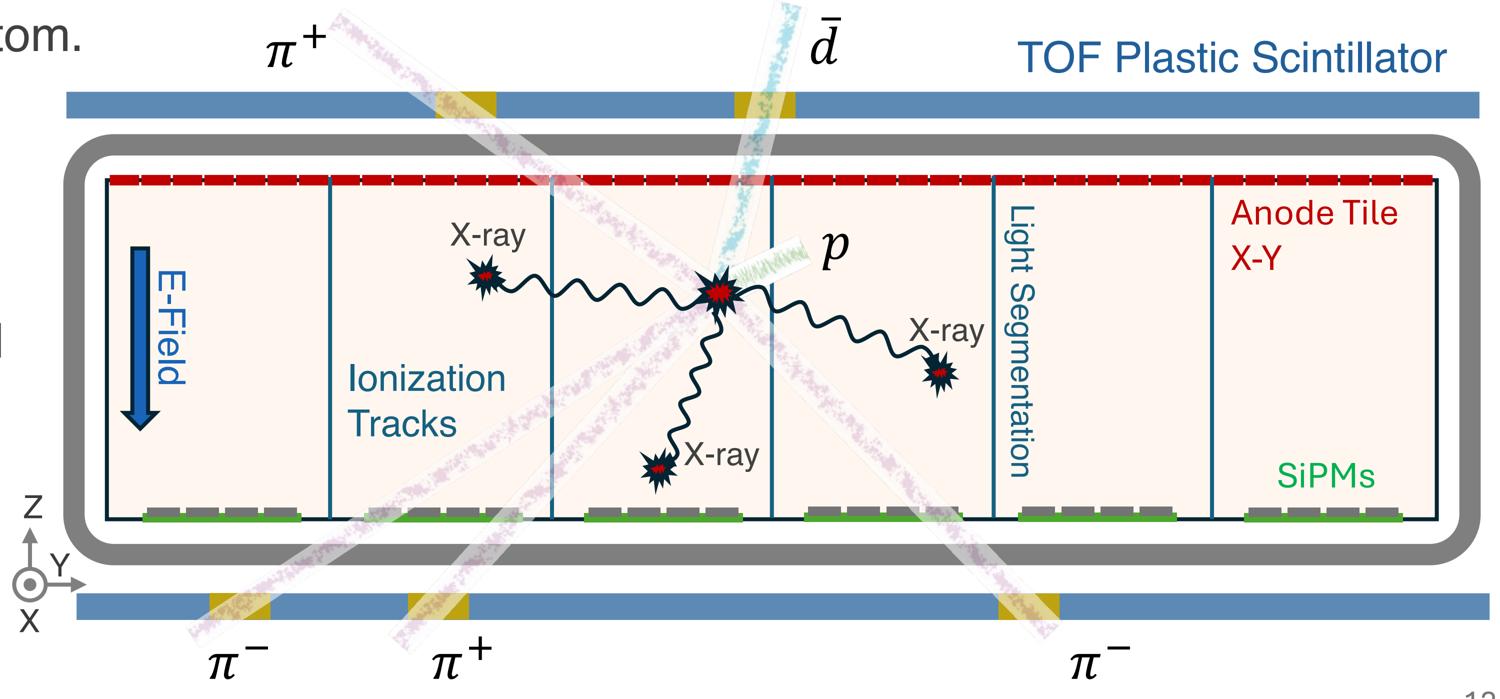


- Compton scatters dominate in MeV region but includes pair-production.
- LArTPC detector suited for multiple gamma-ray interaction processes.
- Multiple Compton scatters give direction and energy of original gamma ray.

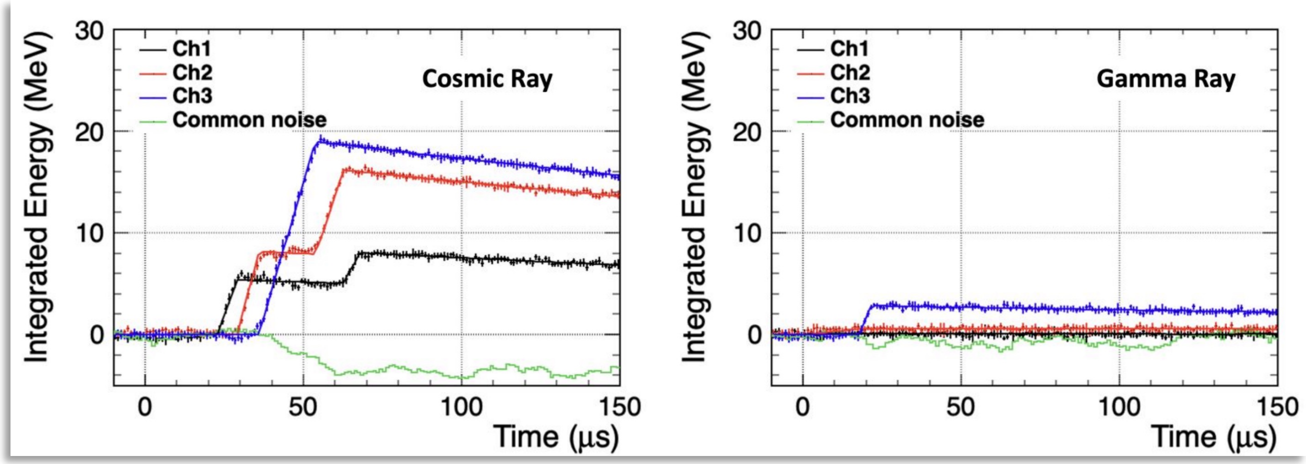
Antimatter Detection

- Antimatter detection using TOF and TPC.
- Low background interaction signature:
  - TOF system tags and measures velocity.
  - Stopping antiparticles form exotic Ar atom.
  - Atom de-excitation produces X-ray signature.
  - Nuclear annihilation produces charged particle signature.

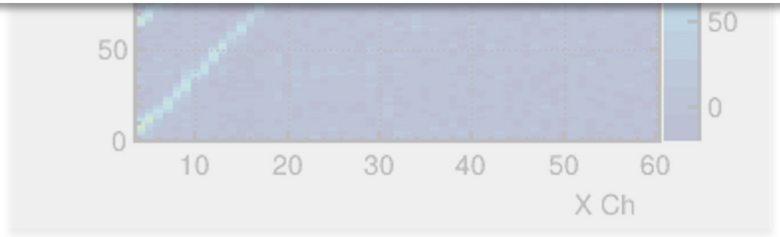




eGRAMS Flight & Beam Test

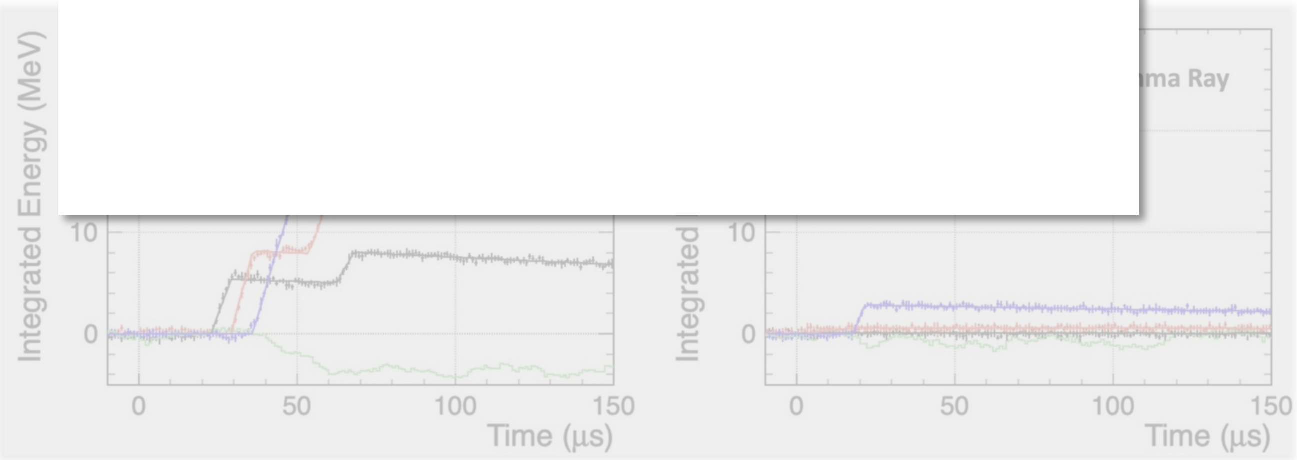


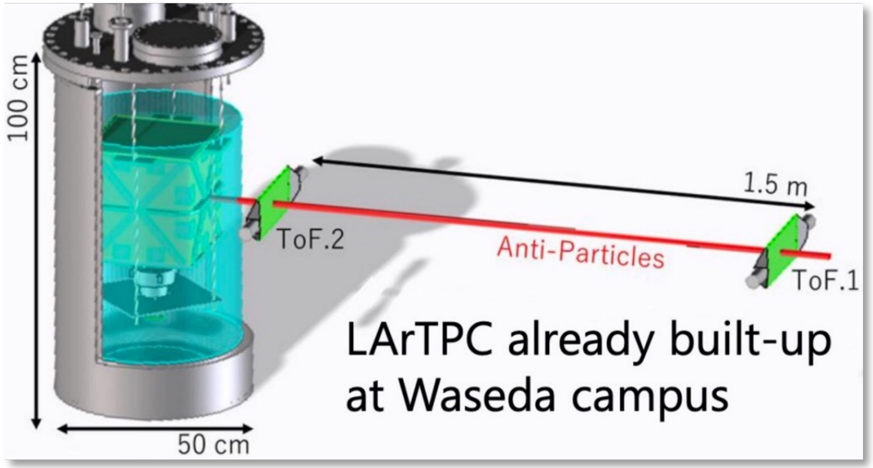
- Engineering flight at JAXA Taiki Aerospace Research Field 2023 [6].
- Demonstration of safe high-purity LArTPC operation, on a balloon flight.
- TPC $10\times10\times10$ cm^3
  - 3 charge & 1 SiPM channel.
- 0.5M events collected including gamma-ray and cosmic-ray candidates.

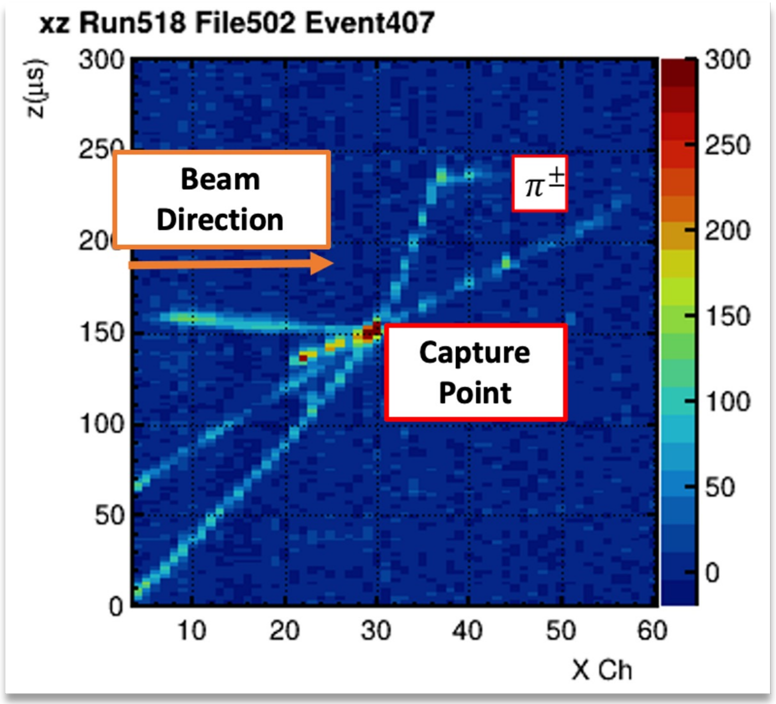


eGRAMS Flight & Beam Test

- Beam test at J-PARC Hadron Hall, Feb. 2025.
- Validate Waseda University $30\times30\times30$ cm^3 LArTPC.
- Beam of $\bar{p}$ to validate antimatter detection.

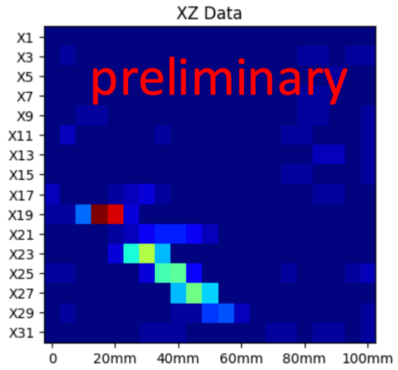


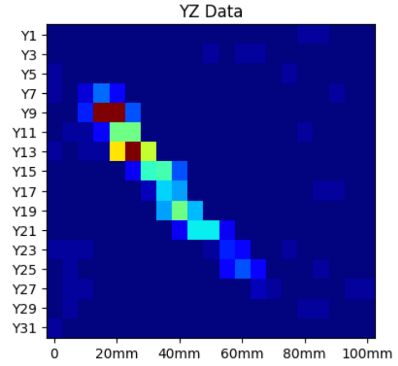


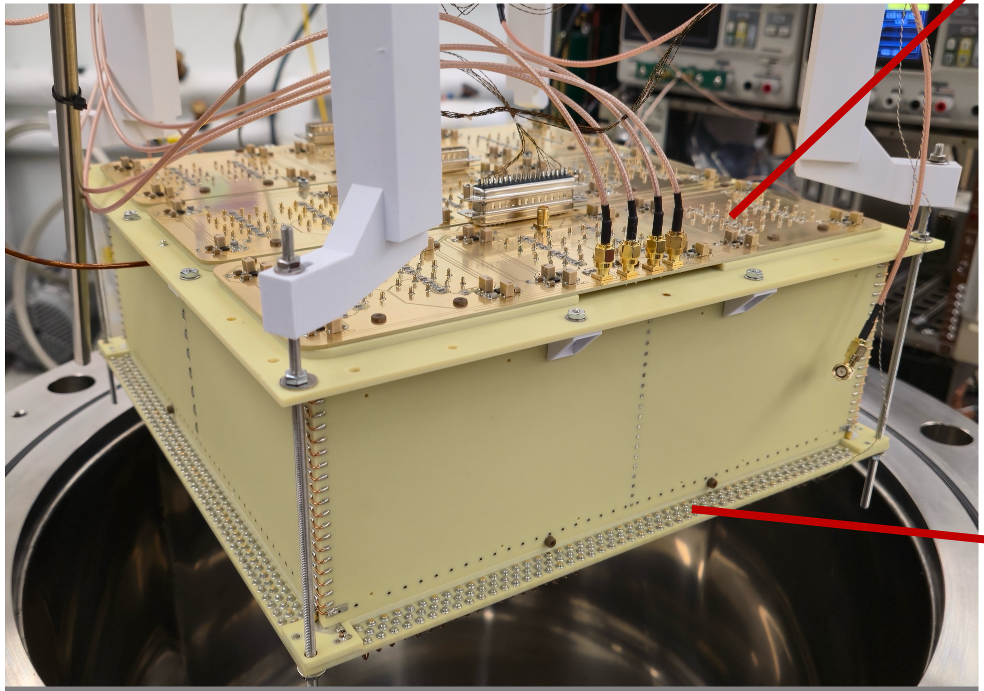


Prototype GRAMS (pGRAMS) Detector

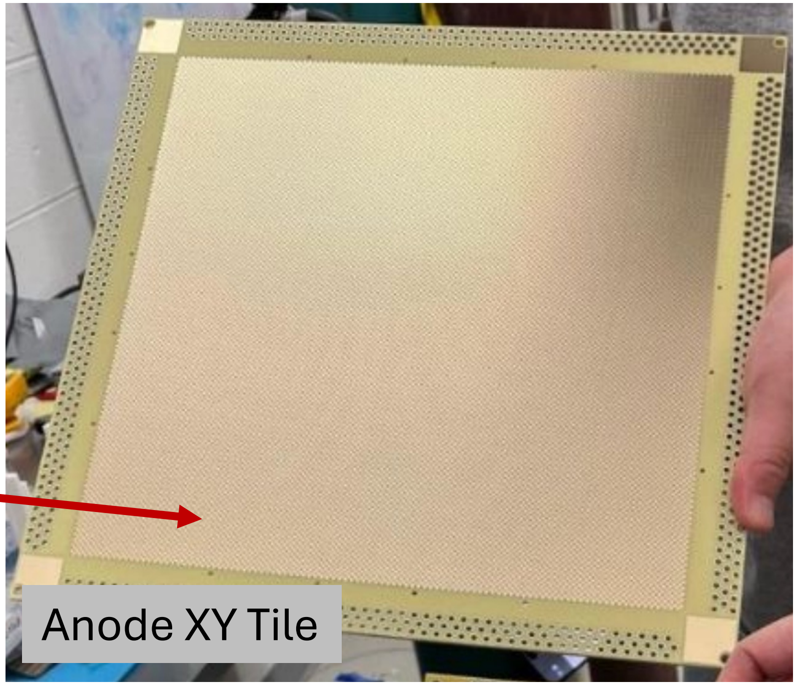
- Demonstrator balloon flight funded by NASA, with spring 2026 launch date.
- Mission goals: Demonstrate detector performance on balloon flight,
  - Charged particle tracking.
  - Compton scatter detection and reconstruction.
- Mini-GRAMS TPC dimensions $30 \times 30 \times 20$ cm^3.





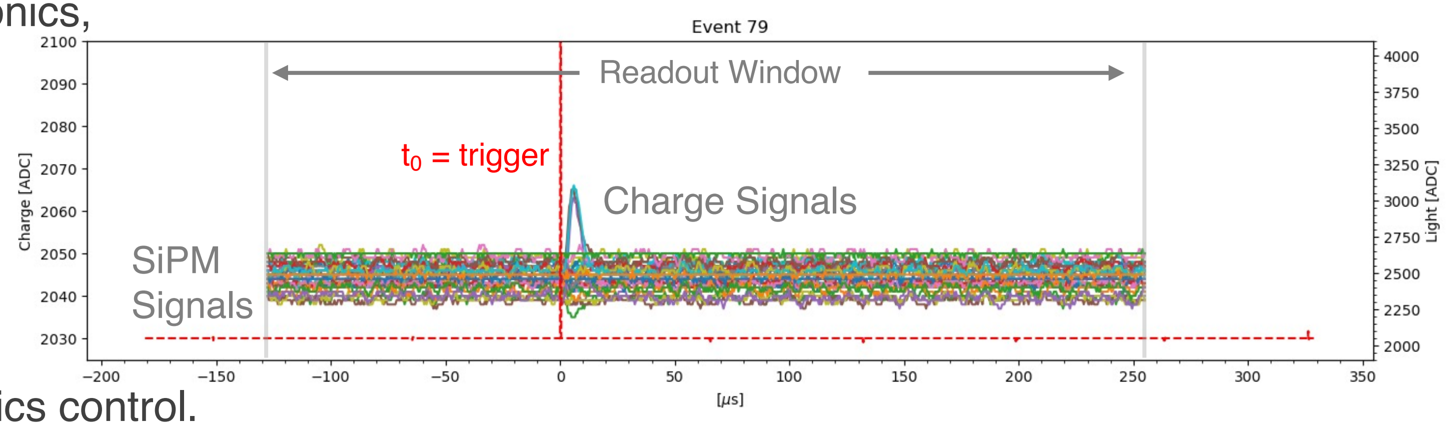


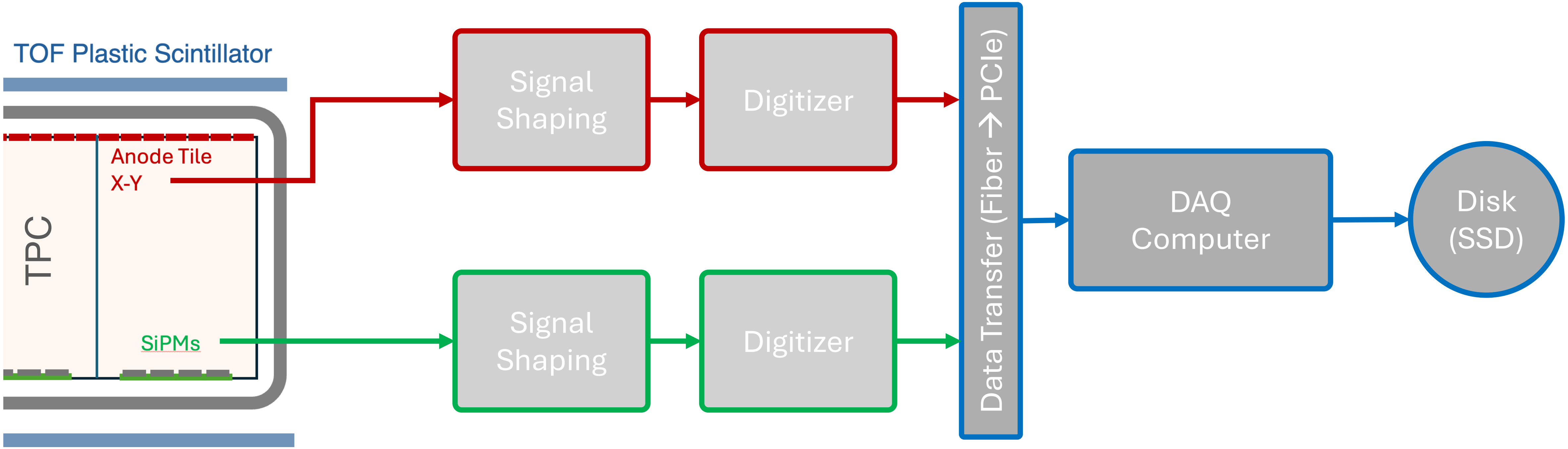
Northeastern University: Aramaki Lab



pGRAMS Readout Electronics: Columbia U.

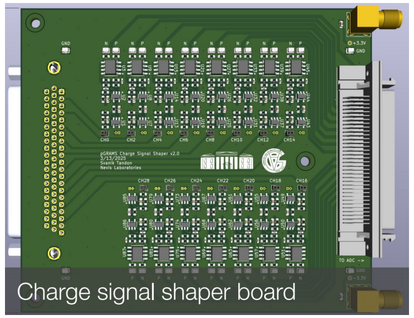
- Columbia team delivering TPC & SiPM readout electronics,
    - Analog signal shaping for SiPM and TPC signals.
    - Digitization of SiPM and TPC signals.
    - Trigger (data selection)
- Computer and software for data acquisition & electronics control.

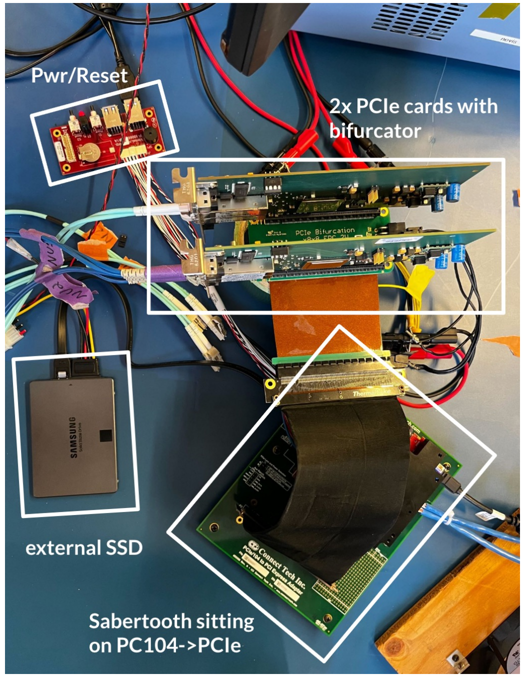


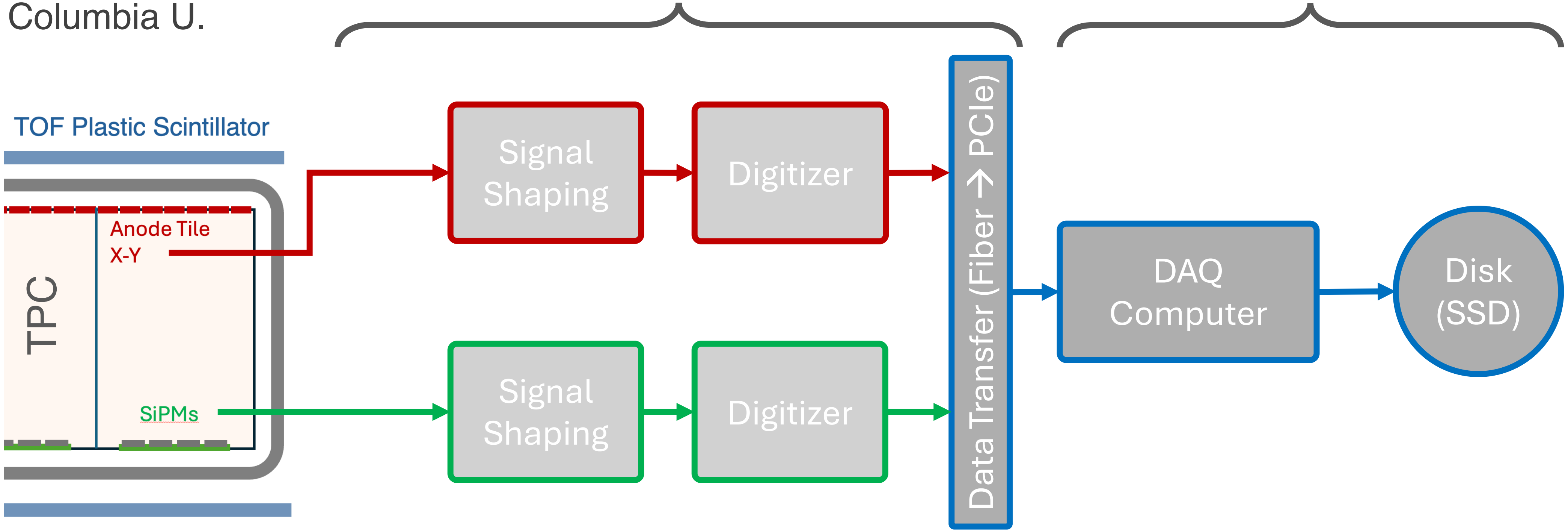


pGRAMS Readout Electronics: Columbia U.

- Custom electronics designed at Columbia U. for signal shaping, digitization and data transfer.
- COTs computer & disk with software from Columbia U.


Charge signal shaper board





Summary

- The GRAMS experiment will survey the historically under-explored MeV-gap gamma rays and indirectly search for dark matter by measuring antimatter fluxes.
- Successful engineering flight completed in 2023 and antimatter detection demonstration, with $\bar{p}$ beam, in Feb. 2025.
- A demonstrator flight (pGRAMS) is scheduled for Spring 2026.
- Significant improvement of MeV gamma-ray sensitivity, up to 2 orders of magnitude, relative to COMPTEL data.
- More stringent bounds on dark matter models using very low background antinuclei measurements and searches.

Thank You!

USA

- Barnard College
- Columbia University
- Howard University
- NASA GSFC
- Northeastern University
- Oak Ridge National Lab
- UCB/SSL
- University of Chicago
- UT Arlington
- Washington University

International

- Hiroshima University
- Tokyo University of Science
- Kanagawa University
- Nagoya University
- National Defense Medical College
- Osaka University
- Universität Würzburg
- RIKEN - Rikkyo University
- University of Tokyo
- JAXA
- Yokohama National University
- Waseda University

References

[1] Piano, G. et al. (2012). The AGILE monitoring of Cygnus X-3: transient gamma-ray emission and spectral constraints. *Astronomy & Astrophysics, 545, A110.*

[2] Zeng, J., et. al (2025). Antihelium-3 sensitivity for the GRAMS experiment. *Astroparticle Physics, 173, 103152.*

[3] M.Y. Cui, Q. Yuan, Y.L.S. Tsai, Y.Z. Fan, A possible dark matter annihilation signal in the ams-02 antiproton data, arXiv:1610.03840v1 (2016).

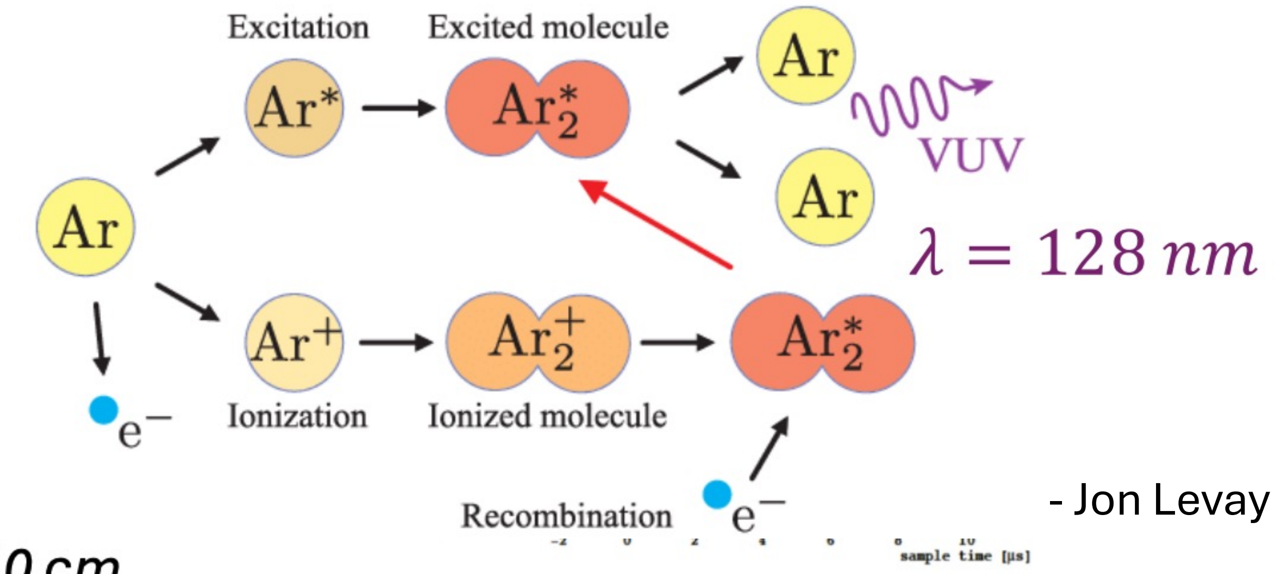
[4] M. Ackermann, M. Ajello, A. Albert, W. Atwood, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, R. Bellazzini, E. Bissaldi, *et al.* The fermi galactic center gev excess and implications for dark matter Astrophys. J., 840 (2017), p. 43

[5] Garv Chauhan, R. Andrew Gustafson, & Ian M. Shoemaker. (2025). Supernova Gamma-Ray Constraints from Heavy Sterile Neutrino Decays.

[6] Nakajima,et al. (2024). First Operation of a Liquid Argon Time Projection Chamber (LArTPC) in the Stratosphere as an Engineering Gamma-Ray and AntiMatter Survey (GRAMS) Balloon Flight (eGRAMS). *Progress of Theoretical and Experimental Physics, 2024(12).*

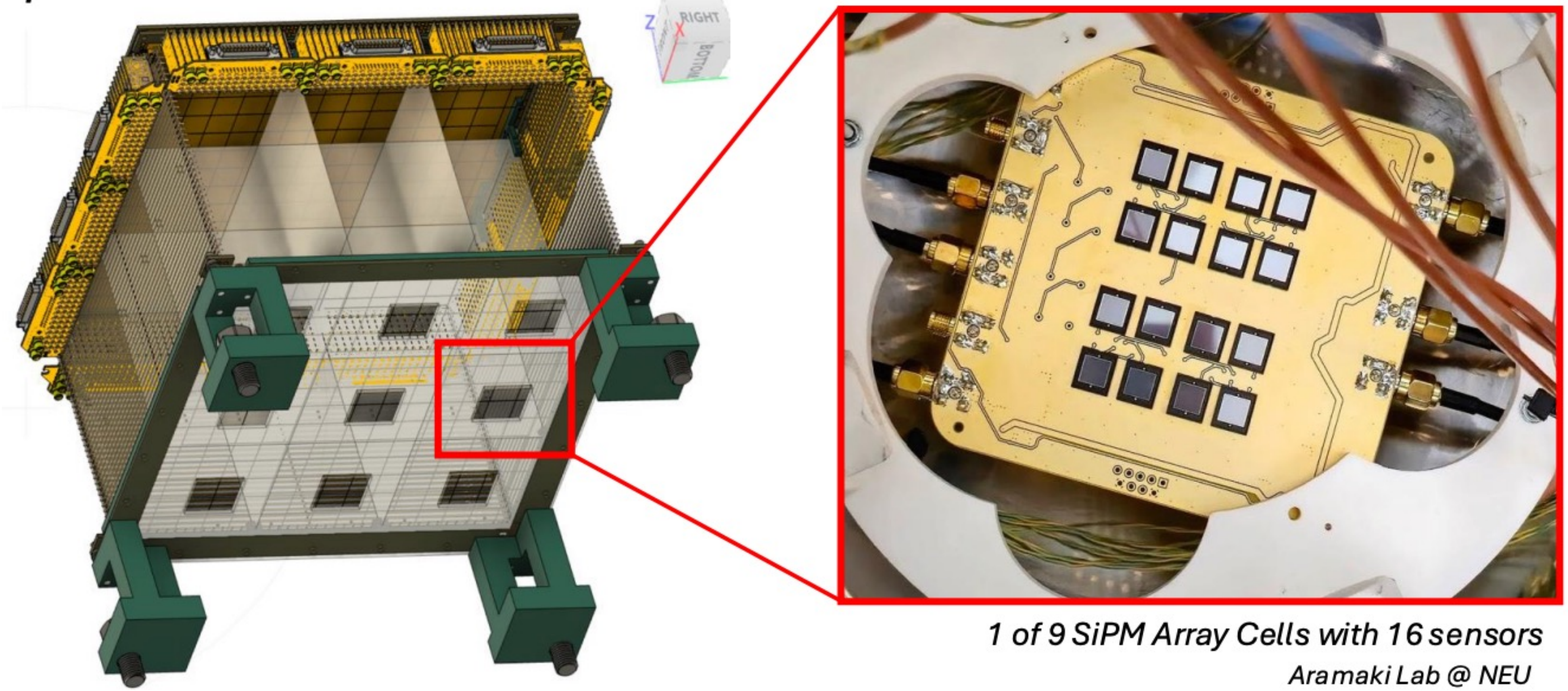
Backup Slides

Backup: Scintillation Light



- Jon Levay

pGRAMS detector: 30x30x10 cm

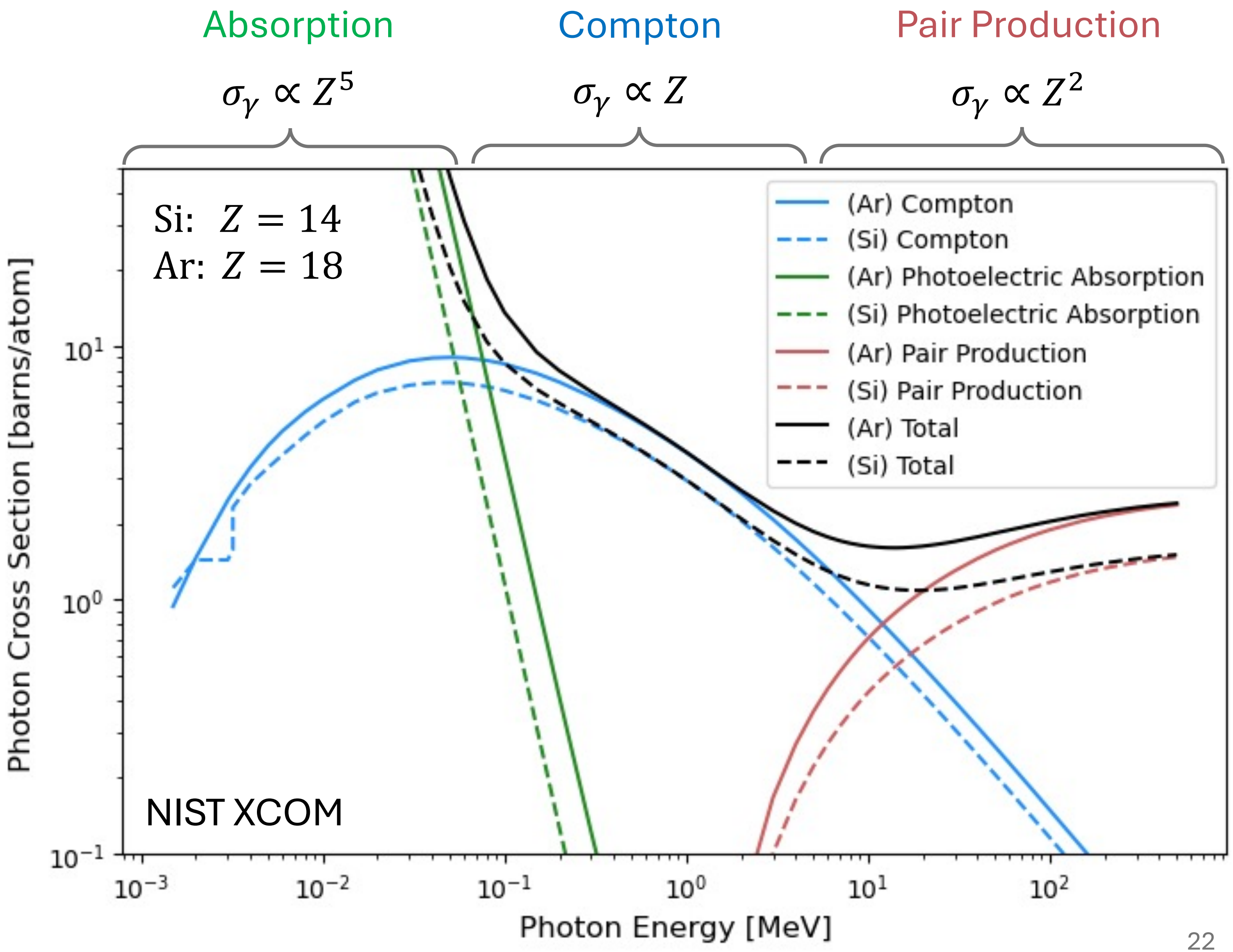


1 of 9 SiPM Array Cells with 16 sensors

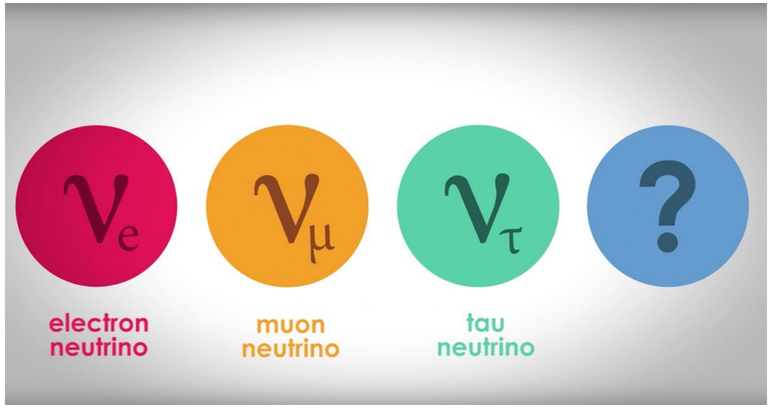
Aramaki Lab @ NEU

Backup:
Liquid **A**rgon **T**ime **P**rojection **C**hamber
Why LArTPC?

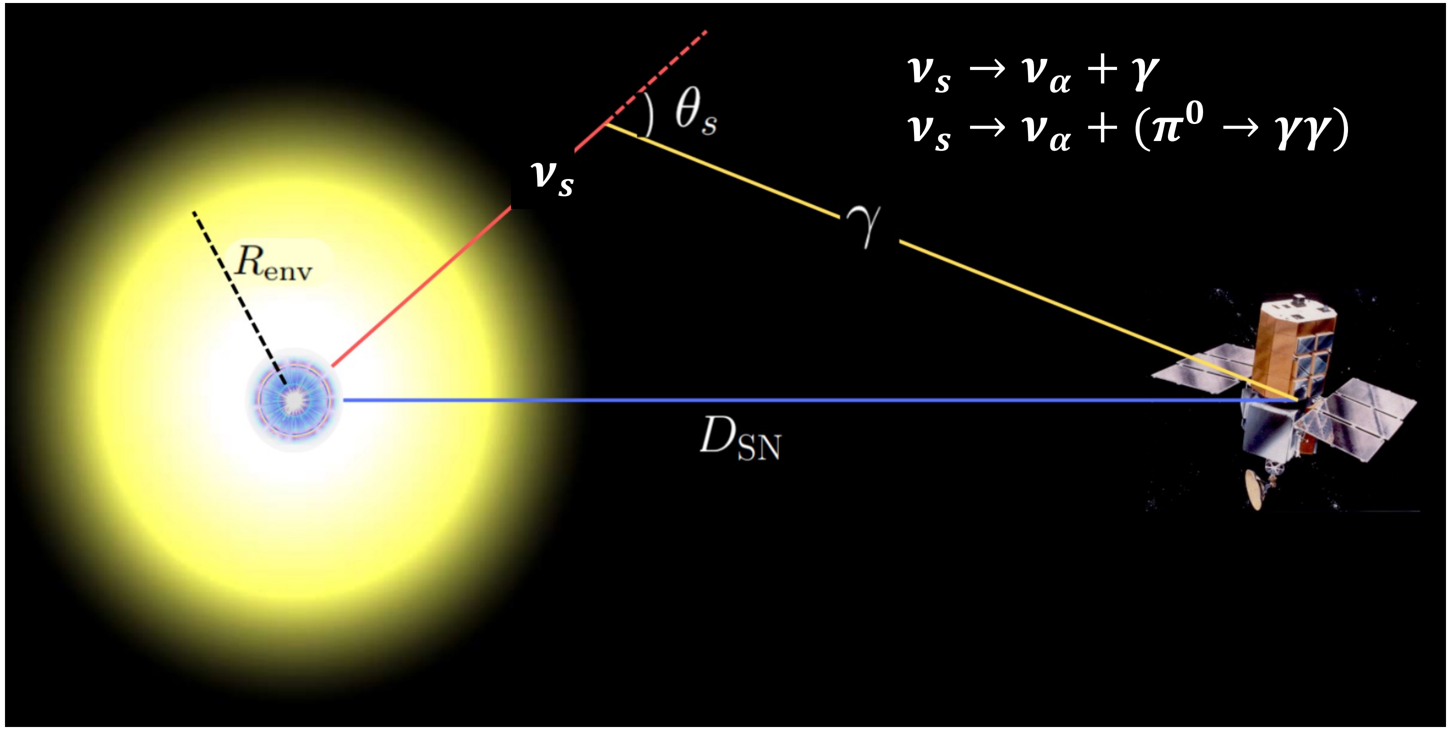
- LArTPC combines tracking with energy measurement.
- Argon is relatively high Z and cheap.
- Scalable with almost no dead volume.
- Since drift does not require channels, #ch. ∝ area (not volume).
    - Lower cost
    - Lower power
- Almost no dead volume, readout is at edges of volume.



Backup: Sterile Neutrinos



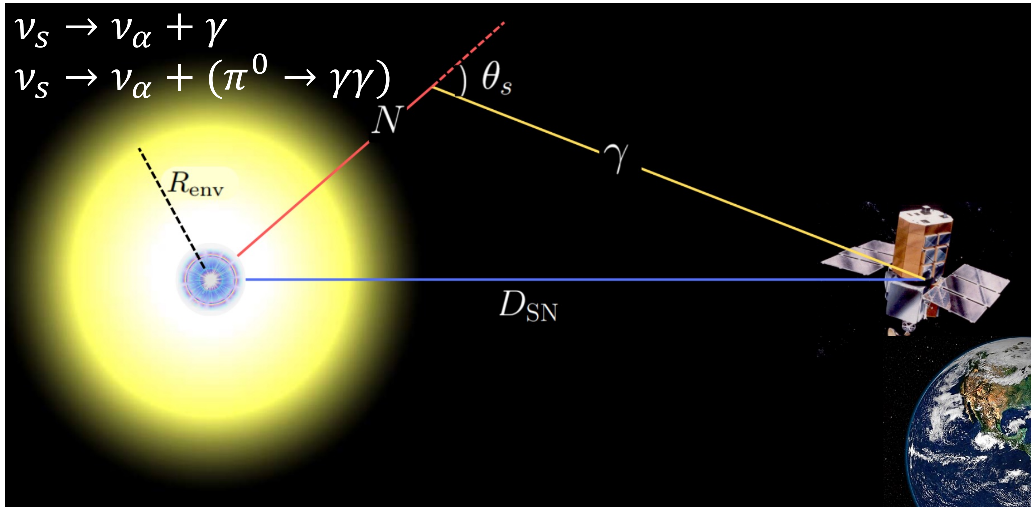
- Three known flavors of neutrinos.
- Heavy sterile neutrino hypothesized could help explain neutrino mass and dark matter.
- "Sterile" as it very weakly interacts with normal matter.
- High density of supernova cores could produce large number of sterile neutrinos.
- If a nearby supernova, could potentially see gamma rays if the sterile neutrinos radiatively decay.
- Complementary to terrestrial searches for sterile neutrinos.



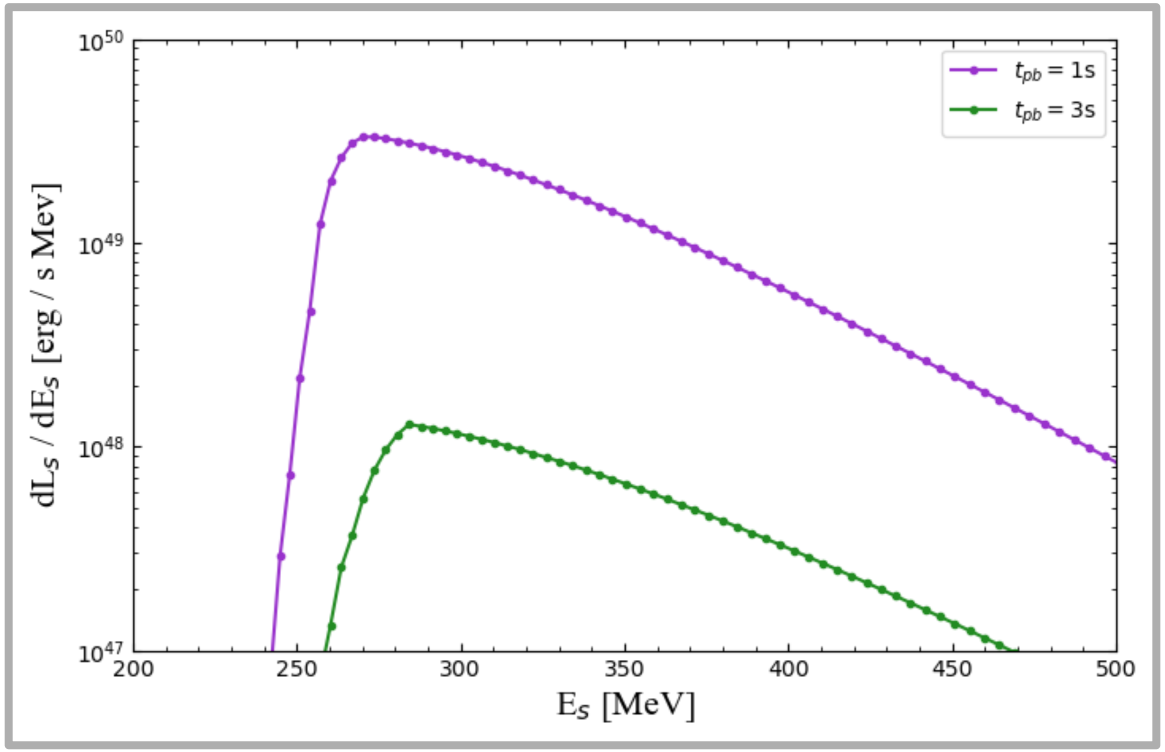
Garv Chauhan, R. Andrew Gustafson, & Ian M. Shoemaker. (2025). Supernova Gamma-Ray Constraints from Heavy Sterile Neutrino Decays.

Backup: Gamma-ray Survey Motivation

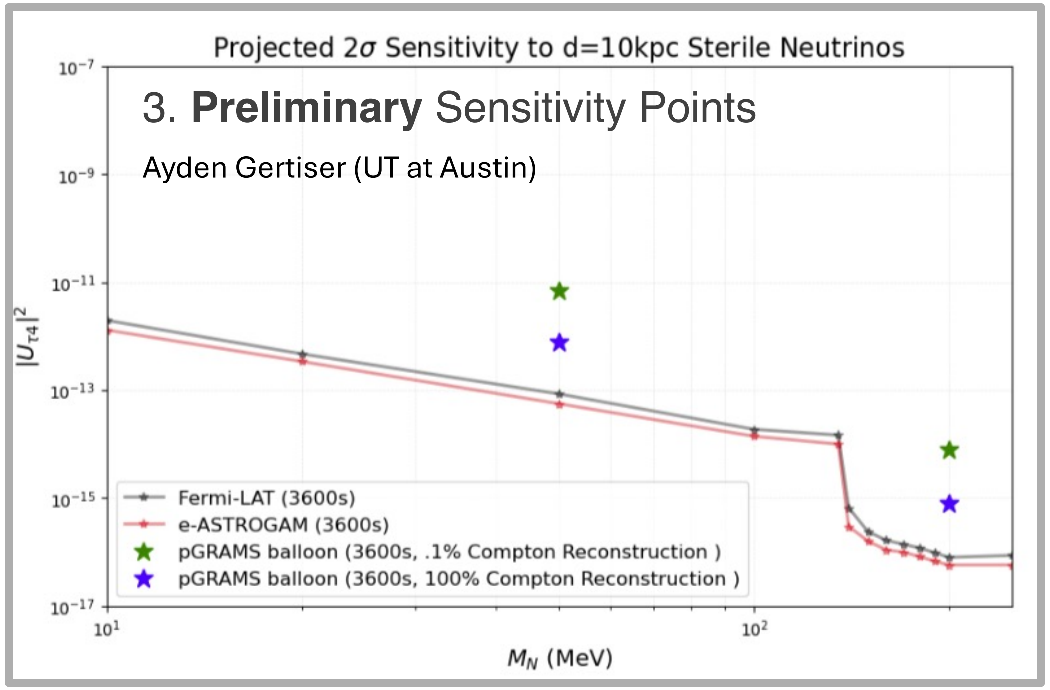
- Model predictions of sterile neutrino flux and subsequent decay rate to gamma-ray from paper: [arXiv: 2503.13607](arXiv:2503.13607).
  - *Supernova Gamma-Ray Constraints from Heavy Sterile Neutrino Decays* (Garv Chauhan, R. Andrew Gustafson, Ian M. Shoemaker)



Sterile ν Production from SN



Gamma-ray Survey Motivation



1. Use calculated expected gamma-ray flux from SNB sterile ν decays.
2. Gamma-ray flux input into (p)GRAMS detector simulation.
    - Time and energy profile from SNB sterile ν decays (points in $M_s, |\mathcal{U}_{x4}|^2$).
    - Expected γ-ray background flux EGB and atmospheric (balloon flight)
3. Calculate (p)GRAMS sensitivity to decay gamma rays.

2. Gamma rays from sterile ν radiative decays & backgrounds