The GAPS Experiment

Probing Unique Dark Matter Parameter Space With Low Energy Cosmic Ray Antinuclei

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for the GAPS collaboration

ICHEP 2020

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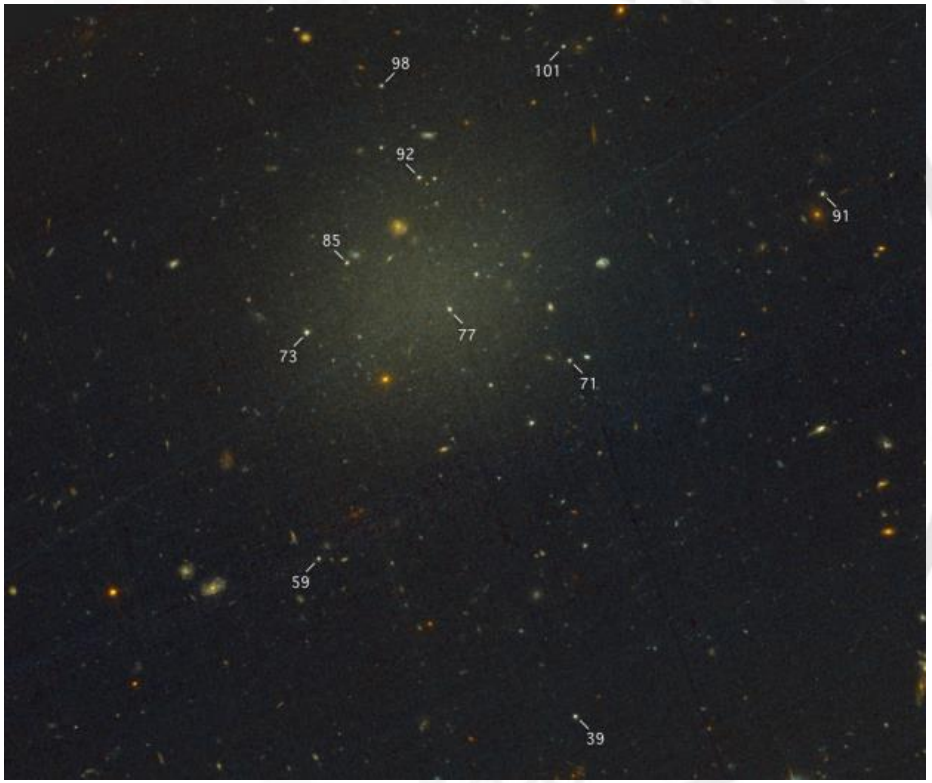
UCLA
PHYSICS & ASTRONOMY

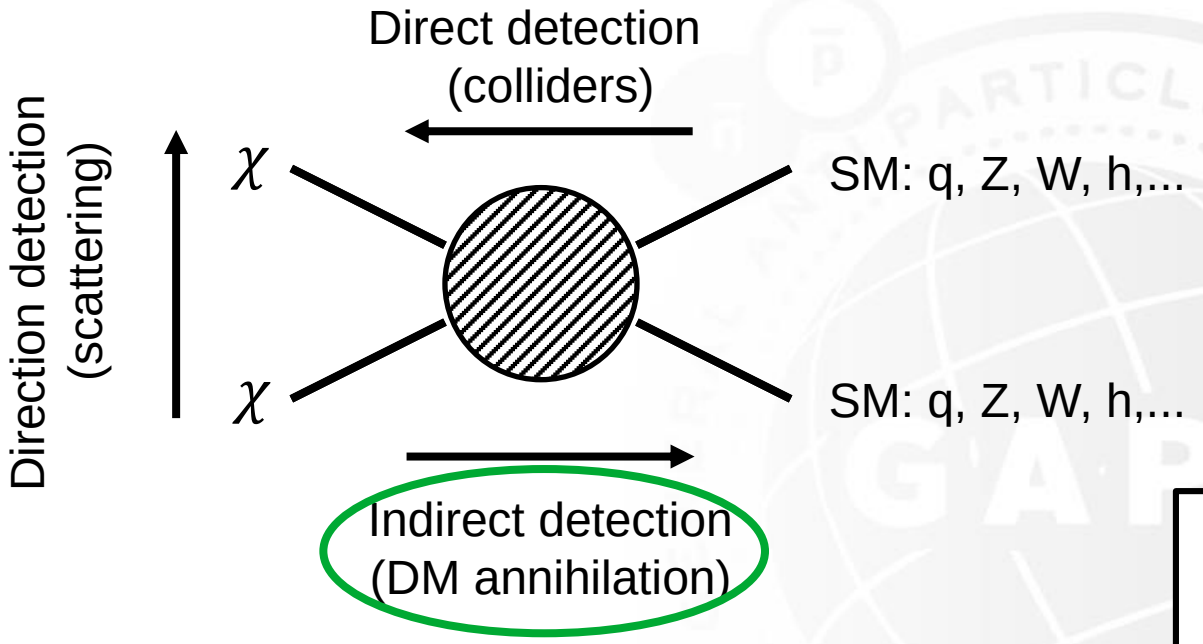
Dark matter: motivation

- Existence of DM largely accepted (astrophys. observations, especially cosmological probes)
  - Sensitive to gravitational effects
- Particle properties poorly understood
  - WIMPs well motivated
- Can look for clues in cosmic ray antimatter fluxes
  - SM astrophysical processes nominal background
  - Excess flux of certain species result from DM pair annihilation



[1803.10237]

Indirect dark matter detection



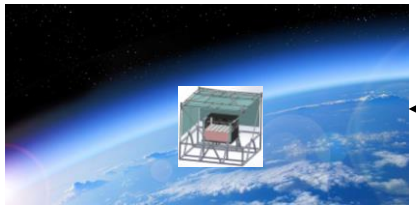
q→n n p p
(Hadronization)

p n→D
(Coalescence)

(Propagation)

(Solar modulation)

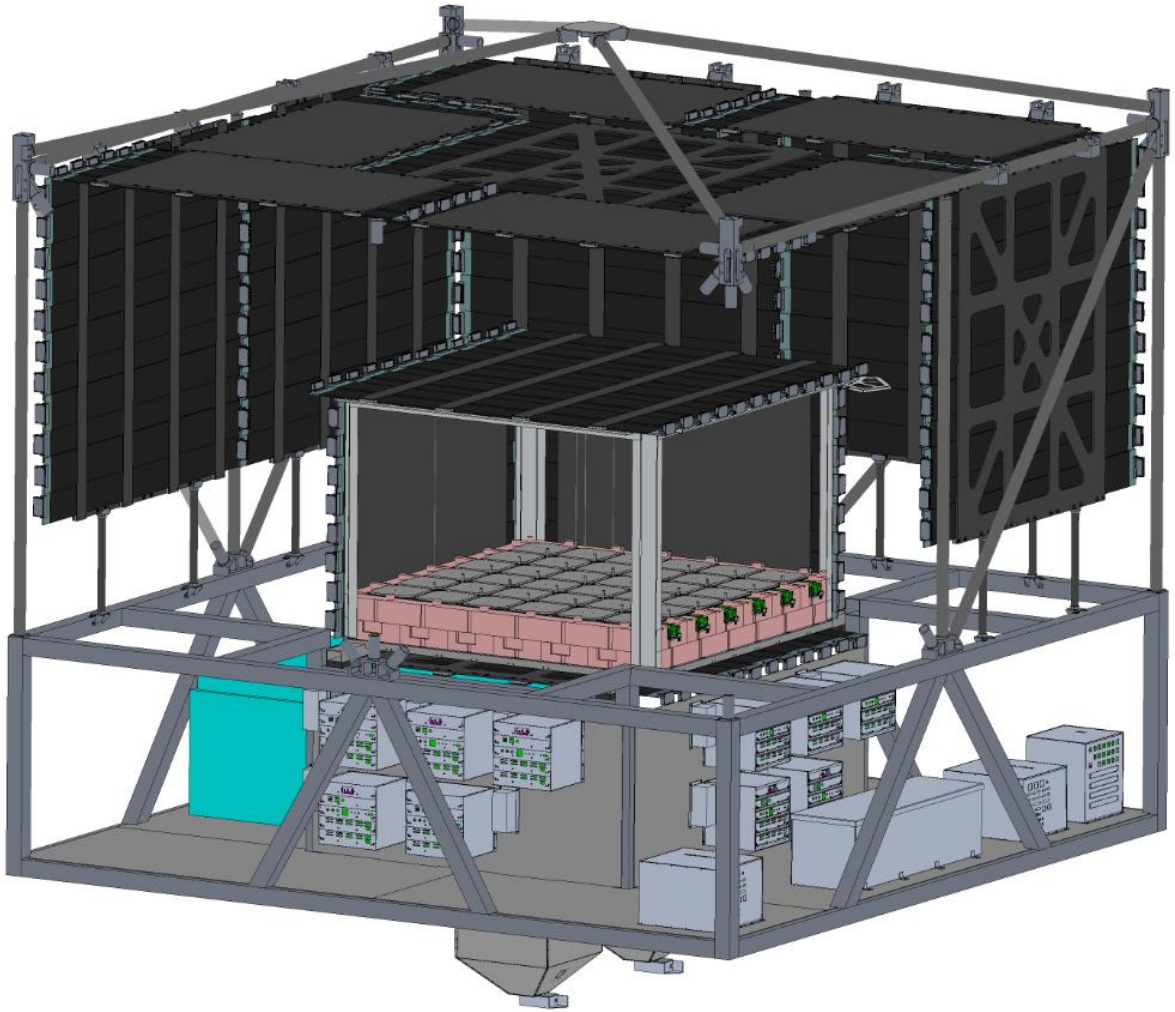
Long duration
balloon flight
McMurdo Station,
Antarctica



Observation
~ 40 km
~ 4 g cm^{-2}

Indirect dark matter detection: GAPS

- GAPS is a balloon payload
- LDB (~30 days) flight
- ~1,200 kg instrument mass
- 1.2 kW power budget
- ~40 km altitude (4 g cm^{-2})



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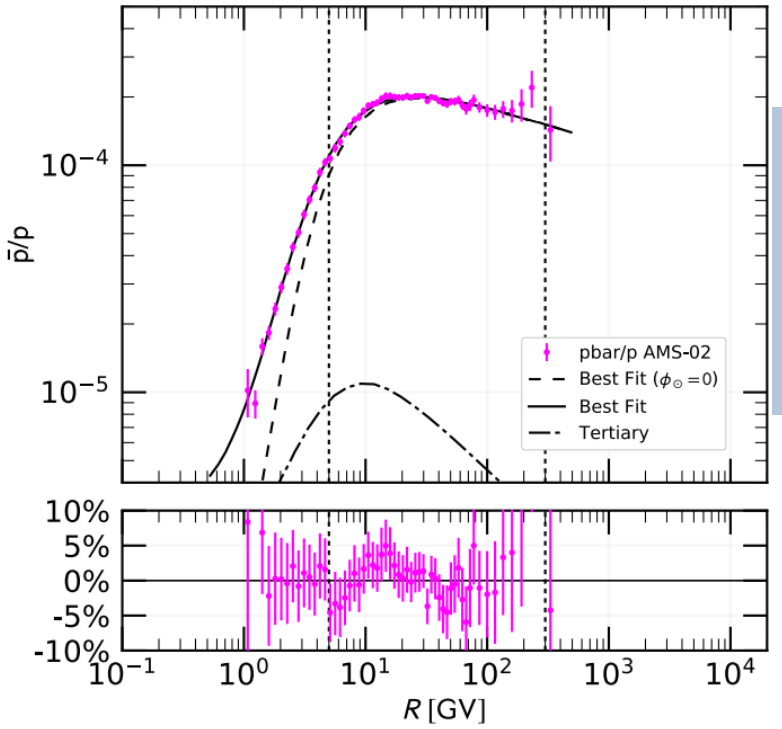
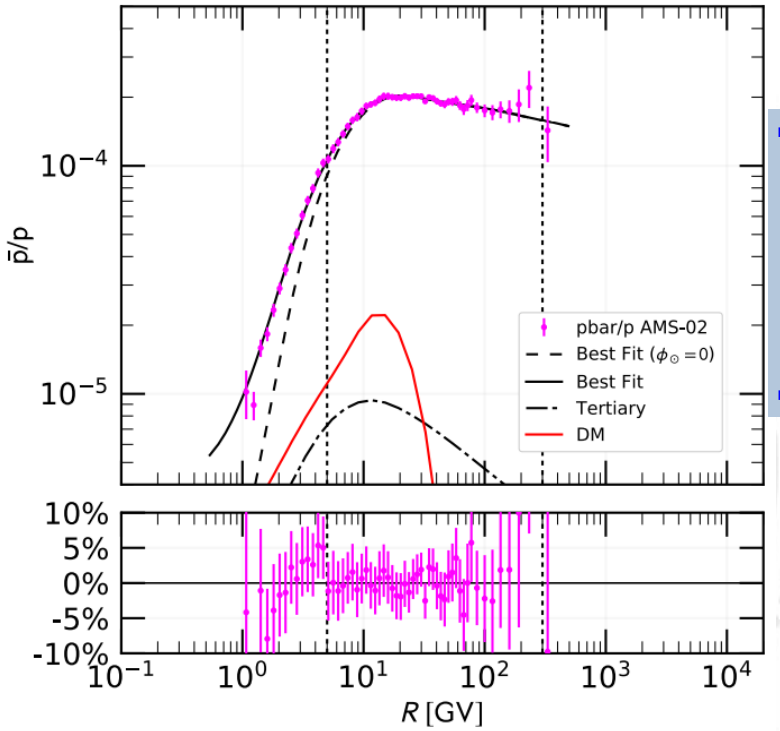
Current challenges



[1903.01472]

- Traditional >1 GeV $\bar{p}$ spectrometer measurements extremely precise, but interpretation of results very complicated [1906.07119]
- Positron excess also difficult to disentangle from astrophysical sources [PhysRevLett.122.041102,1402.0321,1501.01618,1702.08436]

Current challenges



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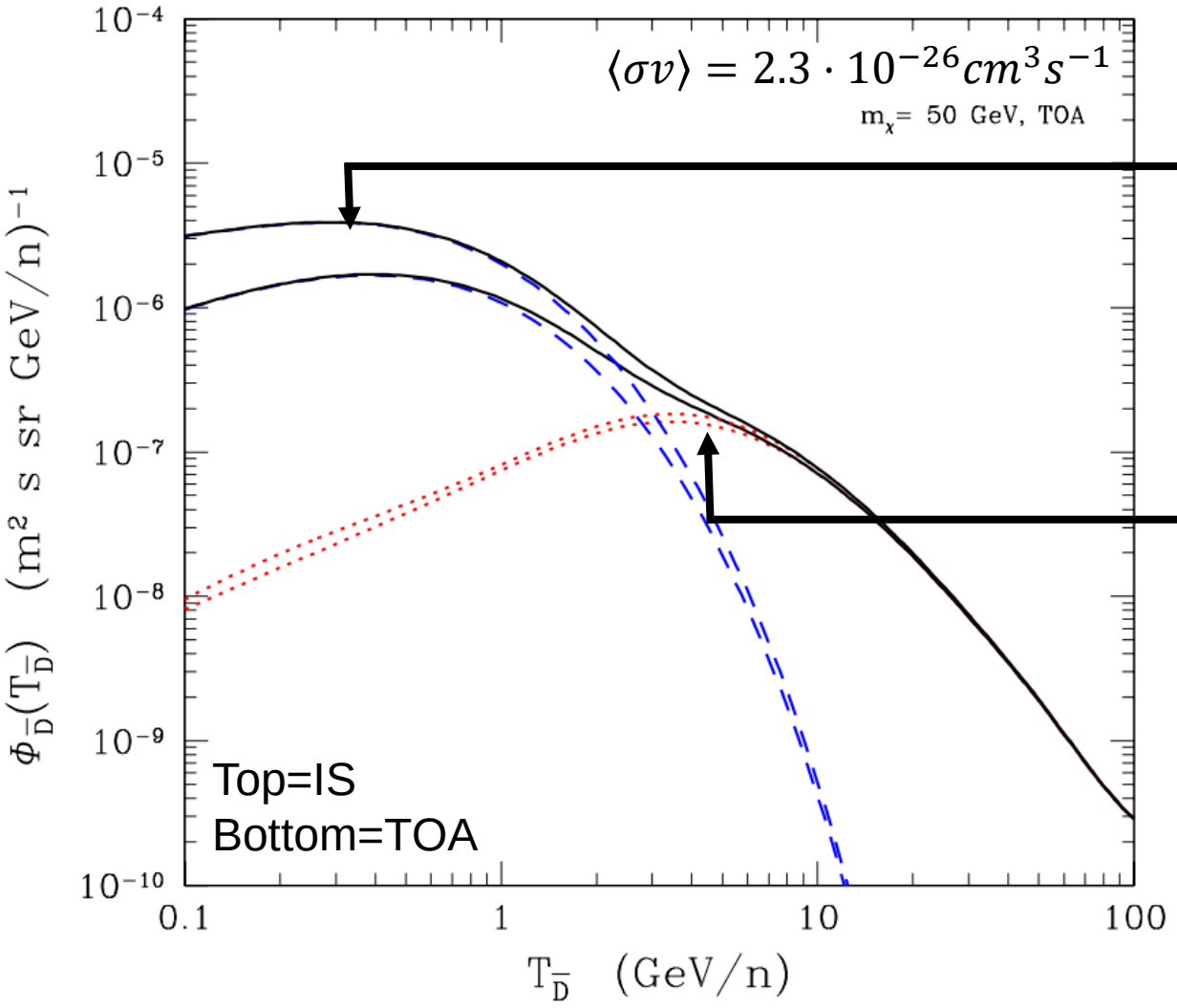
A cleaner regime: low energy anti-nuclei



[0803.2640]

"Primary" DM flux

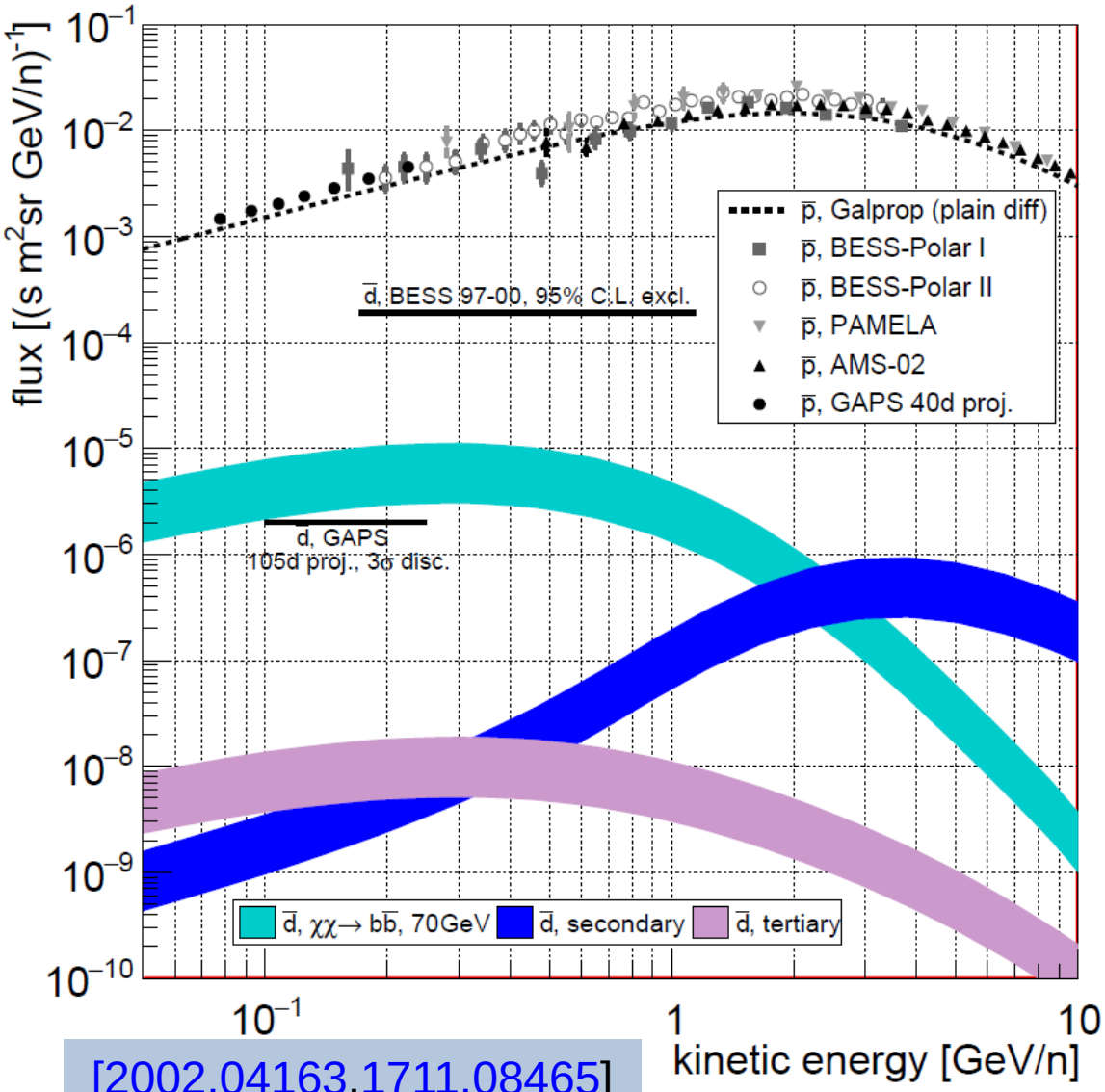
"Secondary" CR bkg flux

Dominant: p+H→ $\bar{D}$ + …

Moderate: p+He→ $\bar{D}$ + …

Other: He+H→ $\bar{D}$ + …
He+He→ $\bar{D}$ + ...
$\bar{p}$ +H→ $\bar{D}$ + ...
$\bar{p}$ +He→ $\bar{D}$ + ...

DM models probed: low mass



[2002.04163,1711.08465]

Additional models

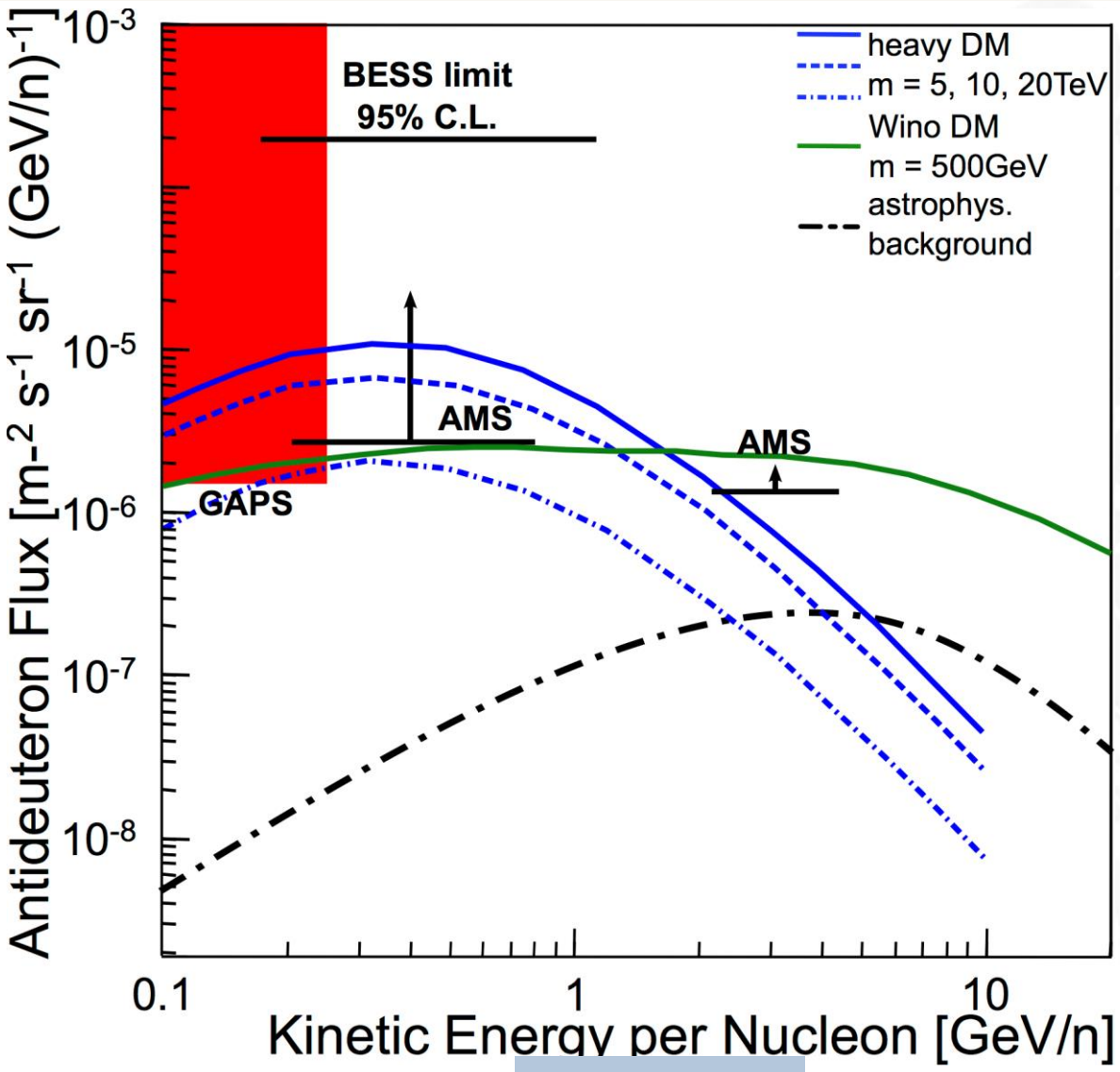
30 GeV neutralino: $\chi\bar{\chi} \rightarrow b\bar{b}$

50 GeV gravitino: $\tilde{G} \rightarrow u_i d_j d_k^c, d_j u_i d_k^c$

40 GeV LZP (UED): $\chi \rightarrow gg$

[1505.07785]

DM models probed: high mass



[1505.07785]

$\chi\bar{\chi} \rightarrow b\bar{b}$

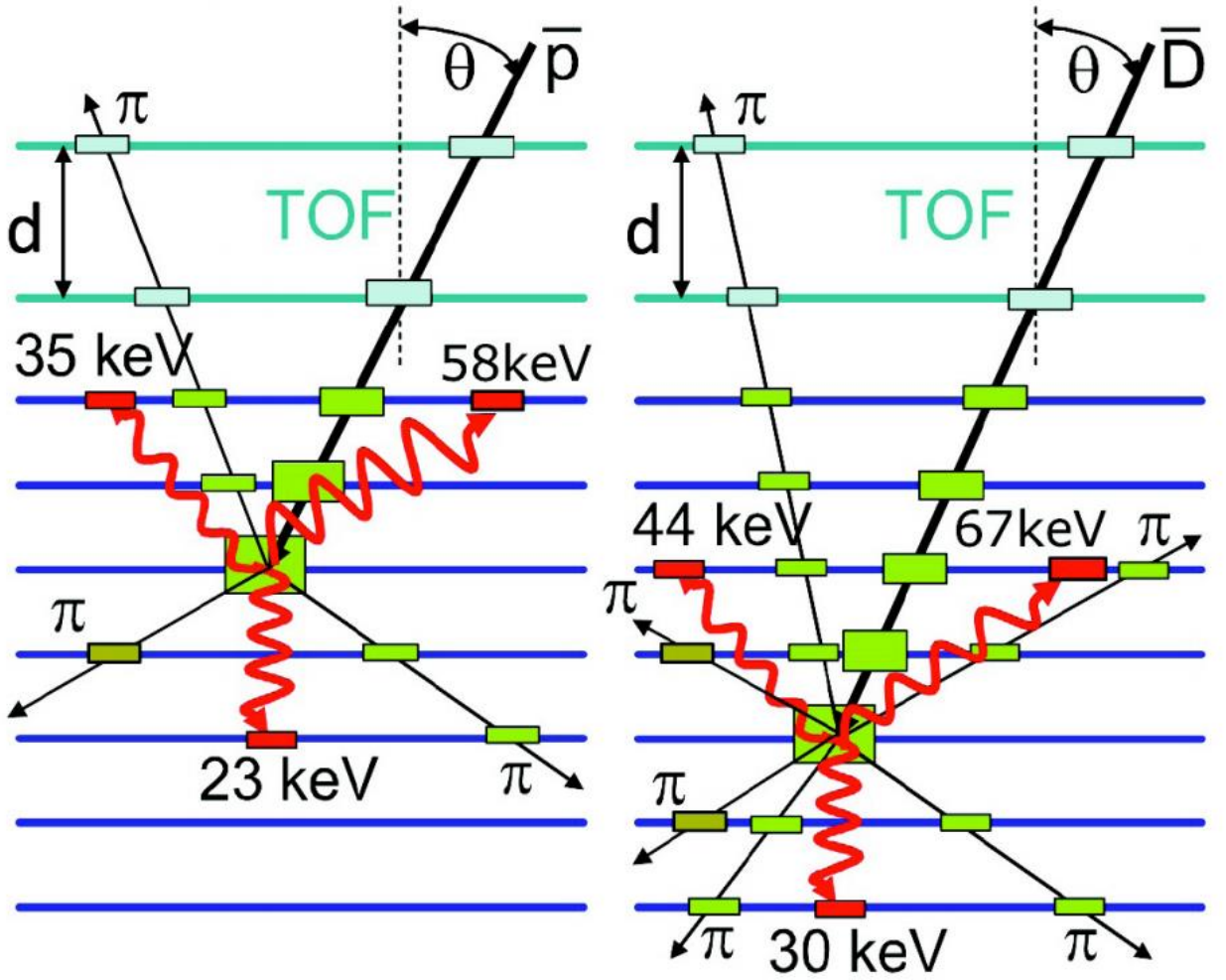
$\chi\bar{\chi} \rightarrow W^{+}W^{-}$

$p + p \rightarrow p + p + p + n + \bar{D}$

* Not an exhaustive list!
See review: [1505.07785]

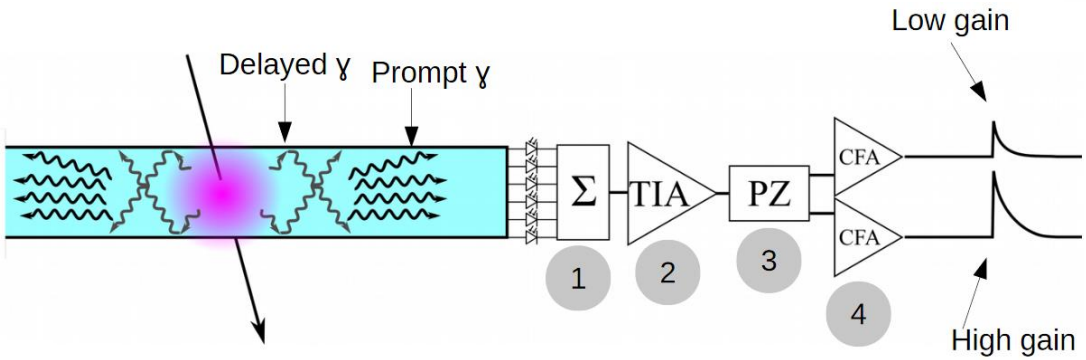
GAPS detection technique

- Tandem time of flight and silicon tracker
- No heavy magnet
  - More active material and larger acceptance
  - Increased sensitivity
- TOF trigger using hit patterns and timing
- Exotic atom spectrometry

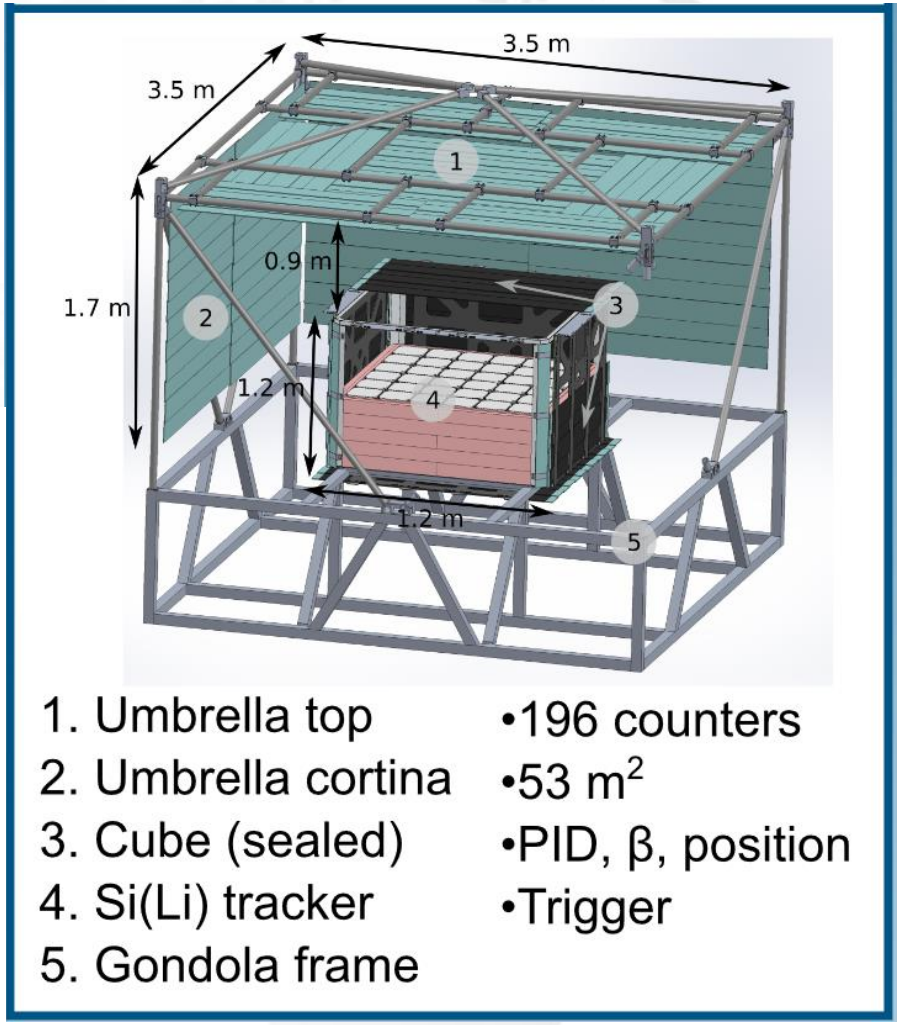


Time of flight

- Two-layer design led by UCLA: canopy umbrella + hermetic cube
- Interleaved plastic scintillator (Eljen EJ-200) planks
- Lightweight carbon fiber mounting framework
- SiPM detectors: high gain timing, low gain trigger
- DRS4 waveform sampling (custom DAQ board)



1. Analog sum stage
2. Transimpedance amplifier stage
3. Pole zero cancellation
4. Current feedback amplifier stage

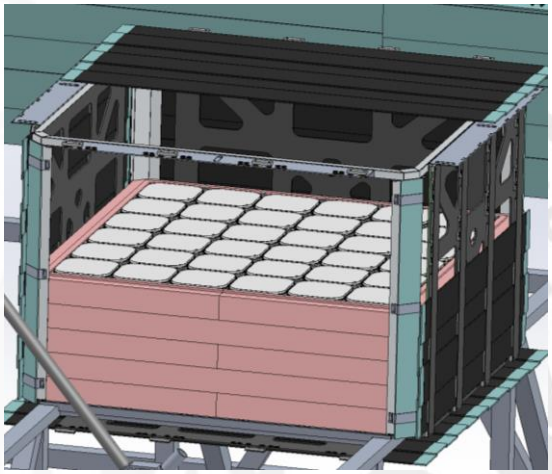


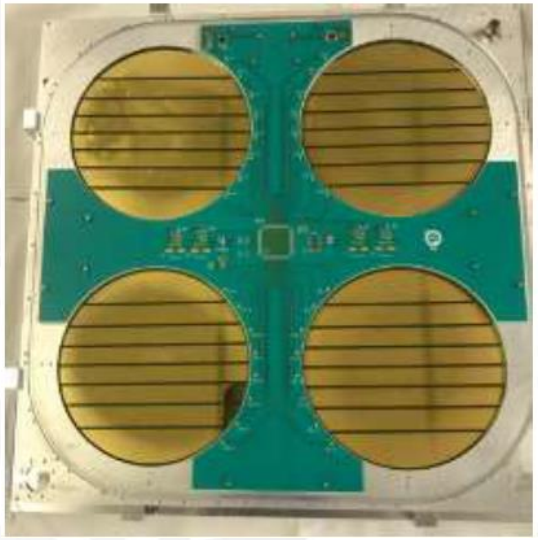
1. Umbrella top
2. Umbrella cortina
3. Cube (sealed)
4. Si(Li) tracker
5. Gondola frame

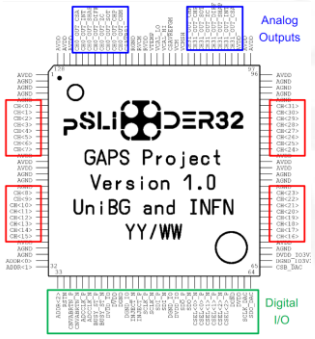
- 196 counters
- 53 m^2
- PID, β, position
- Trigger

Tracker

- Large area lithium-drifted Si detectors. Development pioneered by Columbia, MIT, ISAS/JAXA
  - [1807.07912,1906.05577,1906.00054]
  - Mass production partnership with Shimadzu Corp.
- 10 cm wafers segmented into 8 strips
- Four detectors per module, 36 modules per layer, 10 layers
- 4 keV achieved at -40 °C
- Custom ASIC readout developed by INFN/ASI
  - [IEEE NSS/MIC: N-28-04]
  - Optimized for high dynamic range, low power, high density

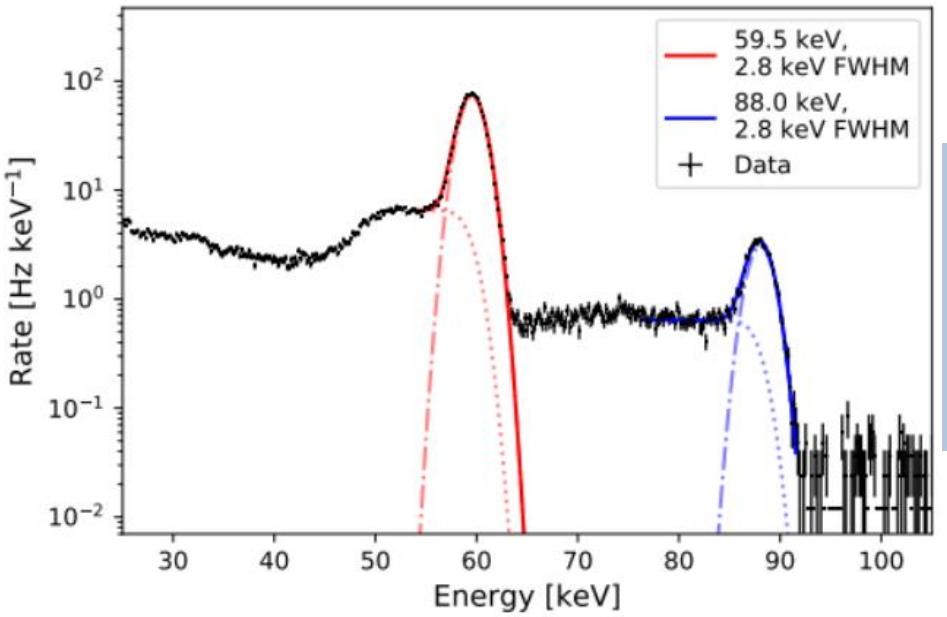




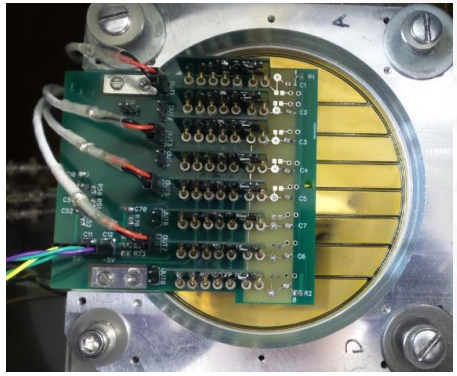


Tracker: performance and calibration

- Procurement of detectors ongoing
  - 821 received
  - 393 passivated
  - 58 calibrated
- High throughput, automated test systems with X-ray sources and temperature control
  - CU (NYC)
  - MIT (Cambridge)
  - UHM (Honolulu)



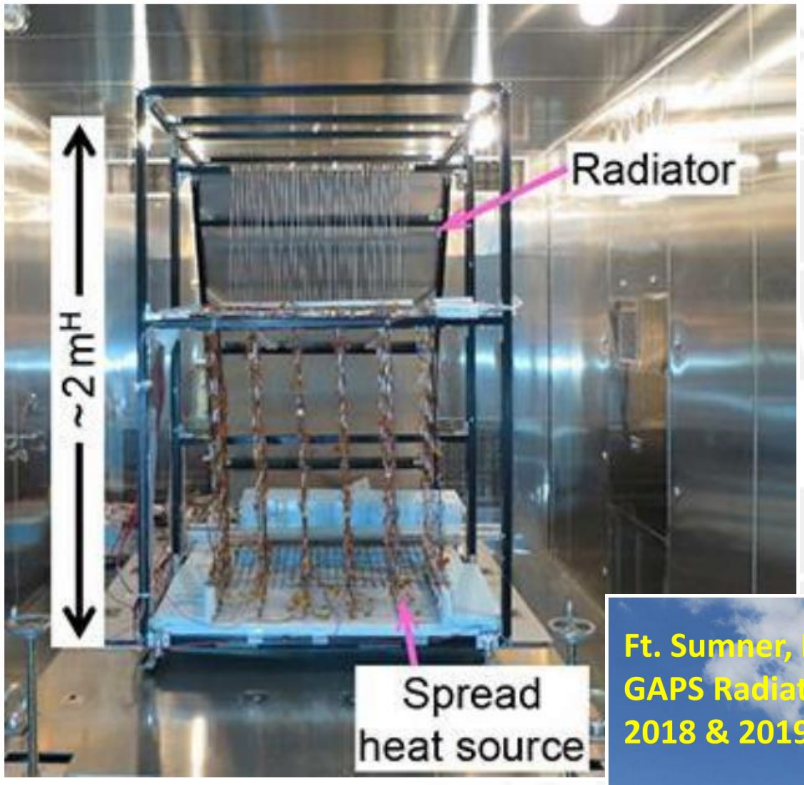
[1906.00054]

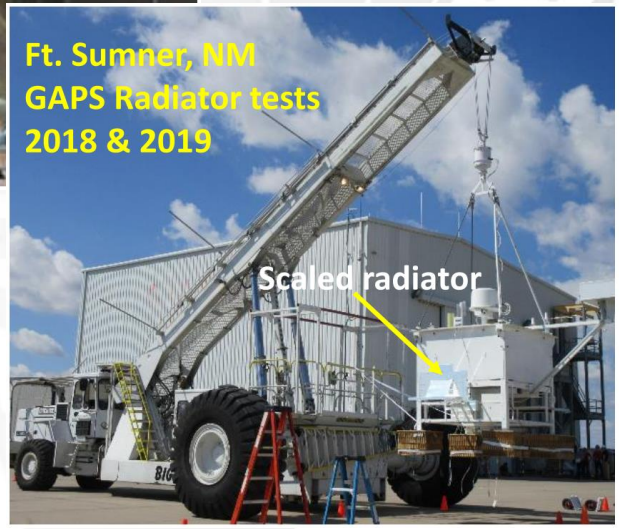


Novel thermal system

- Design led by ISAS/JAXA
- Oscillating heat pipe design optimized for low mass/power and very low temperatures
- Thermal modeling suggests excellent performance
- Successful scaled down prototype piggy-backed at Ft. Sumner Sep. 23, 2019

Engineering model





[10.1142/S2251171717400062]

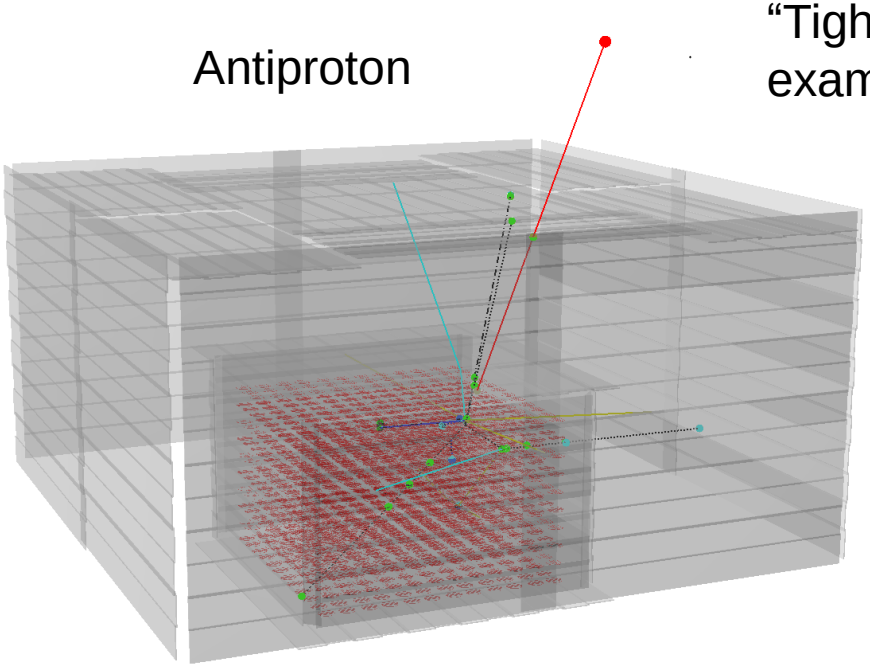
[10.1016/j.applthermaleng.2018.05.116]

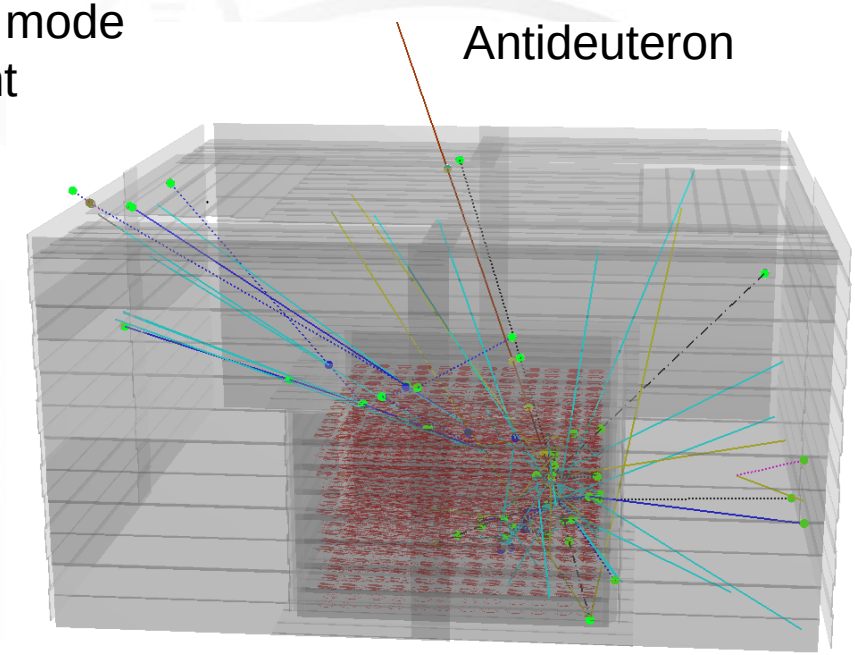
Simulation and reconstruction

Antiproton

"Tight" trigger mode example event

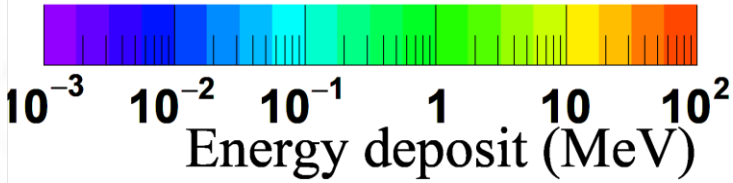
Antideuteron





p $\bar{p}$ $\bar{D}$ e^-, e^+ π^-, π^+, π^0

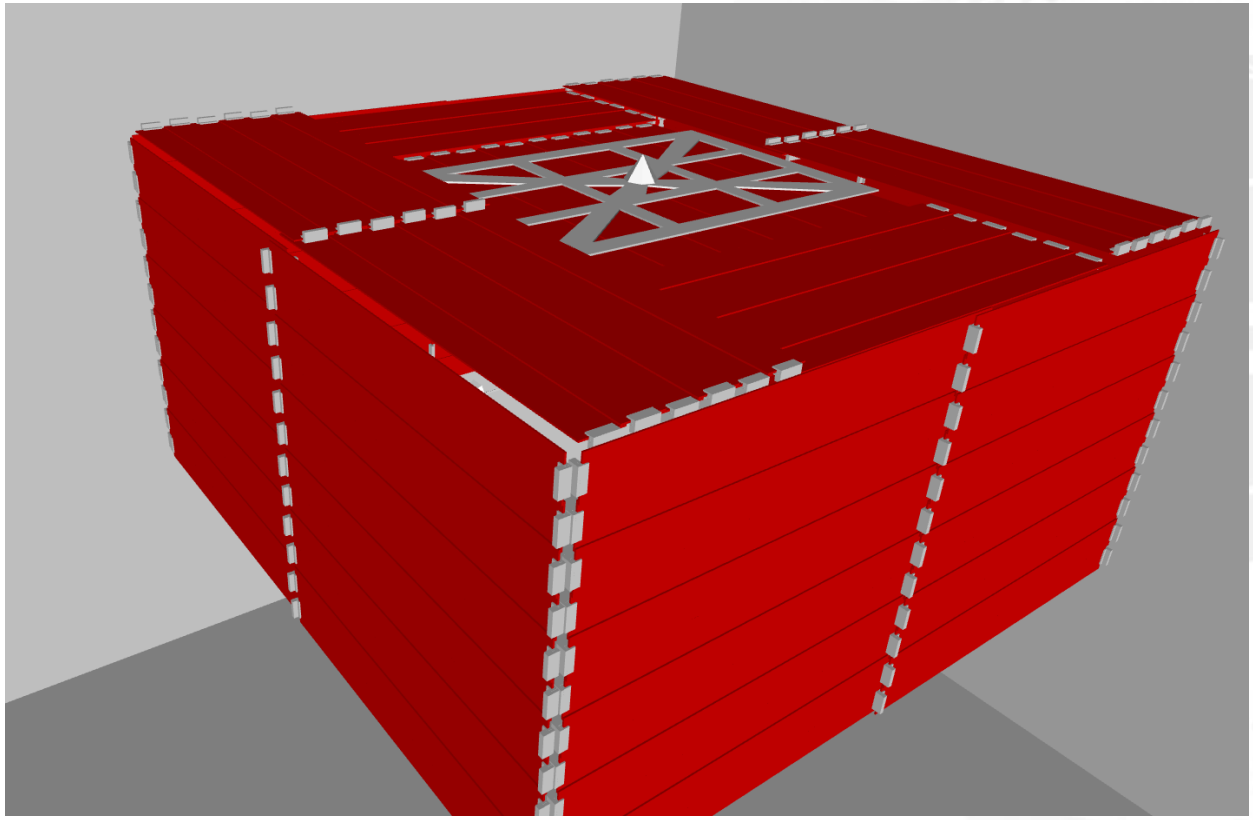
photons μ^-, μ^+ others



- G4 framework
  - Full implementation of active *and* passive material
  - FTFP for annihilation physics, X-ray de-excitation afterburner

Simulation and reconstruction

TOF passive detail



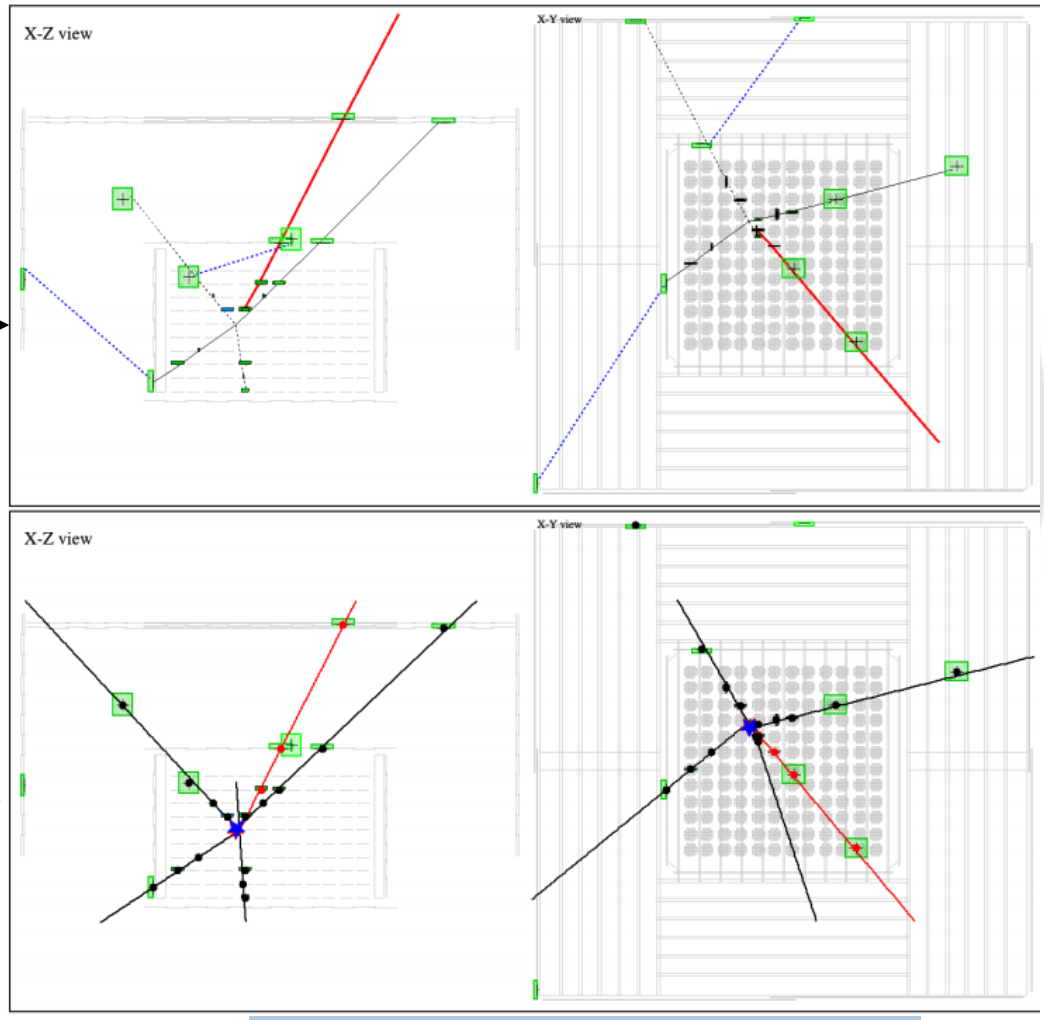
- G4 framework
  - Full implementation of active *and* passive material
  - FTFP for annihilation physics, X-ray de-excitation afterburner

Simulation and reconstruction

- Iterative, adaptive, multistep vertex finding
- ~8 cm resolution (68% containment)
- Δβ/β~4% using 400 ps timing resolution

MC →

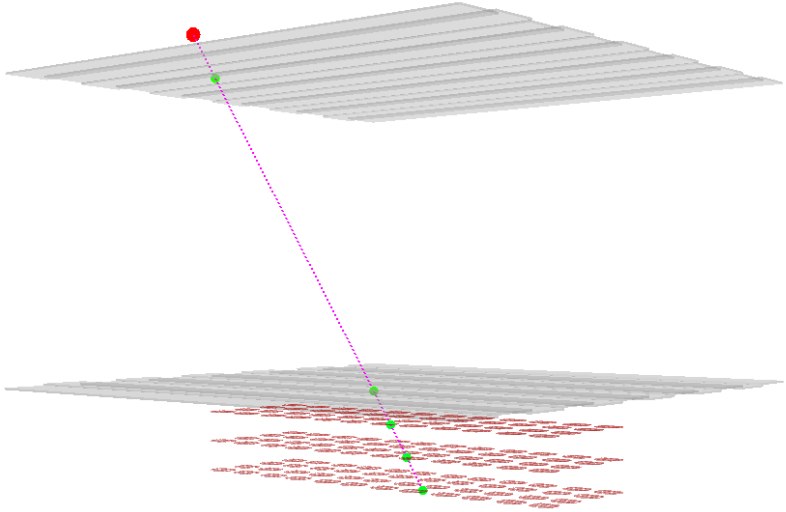
Reco →



[R. Munini ICRC2019(358-535)]

Summary & conclusion

- GAPS will be the most sensitive low kinetic energy $\overline{\mathrm{D}}$ instrument operating in the upcoming decade.
- Null $\overline{\mathrm{D}}$ result places strong limits on range of dark matter models.
- GAPS will detect ~1500 $\bar{\mathrm{p}}$ per LDB flight in a new kinetic energy regime.
  - Critical for estimating $\overline{D}$ background
  - Validation of exotic atom technique
- GAPS will be sensitive to $^{3}\overline{\mathrm{He}}$



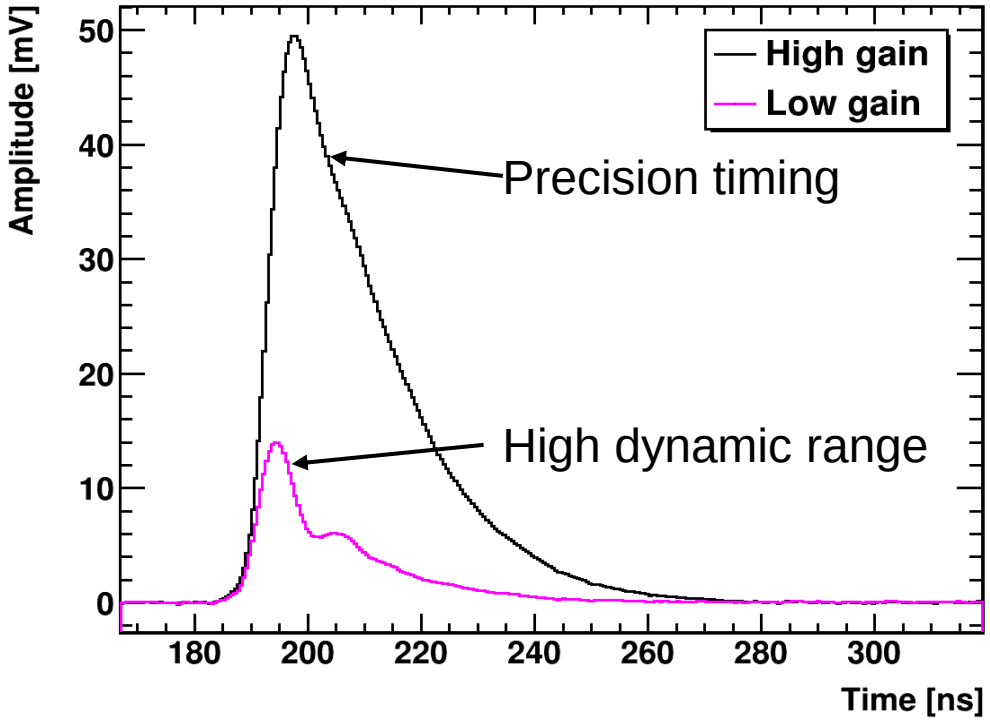
- Mini-integration dry run
- Test read-out chain, trigger system
- Collect X-ray/muon data
- Spring 2021(?)

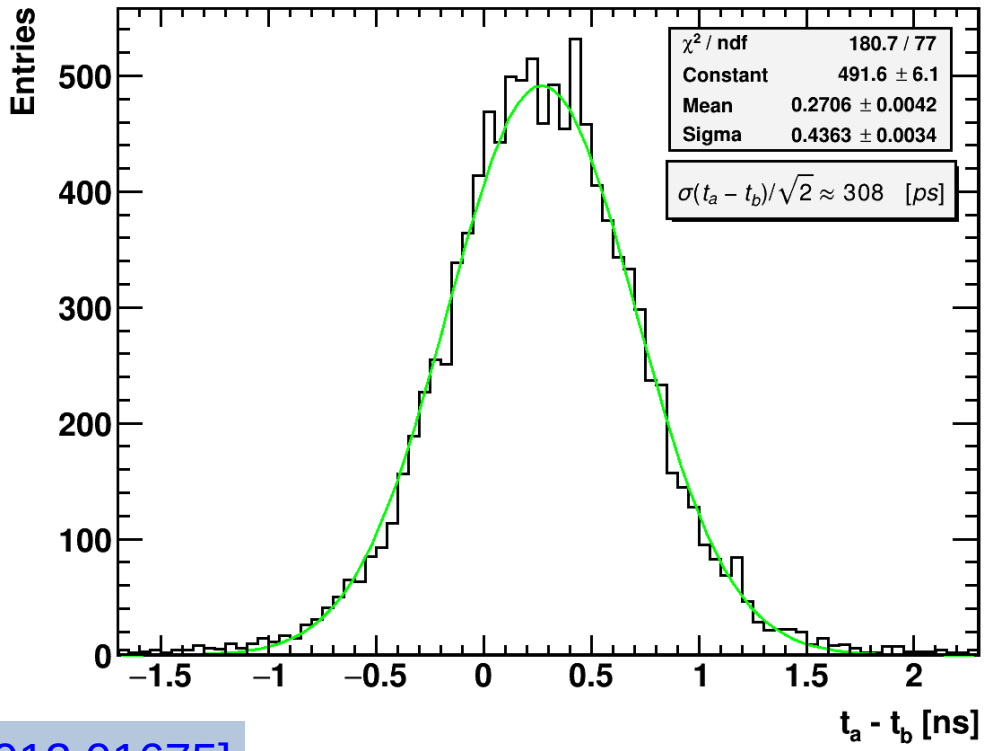
Thank you for your attention!

Visit us at: https://gaps1.astro.ucla.edu/gaps

BACKUP

Time of flight: performance





[1912.01675]

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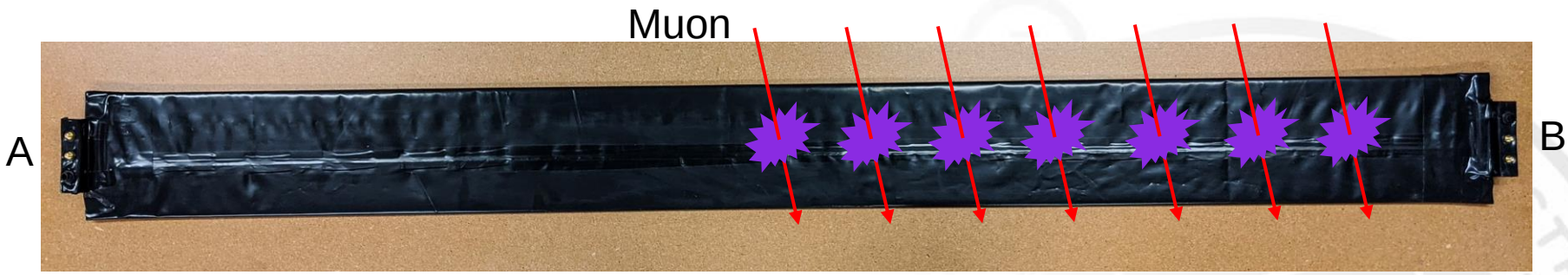
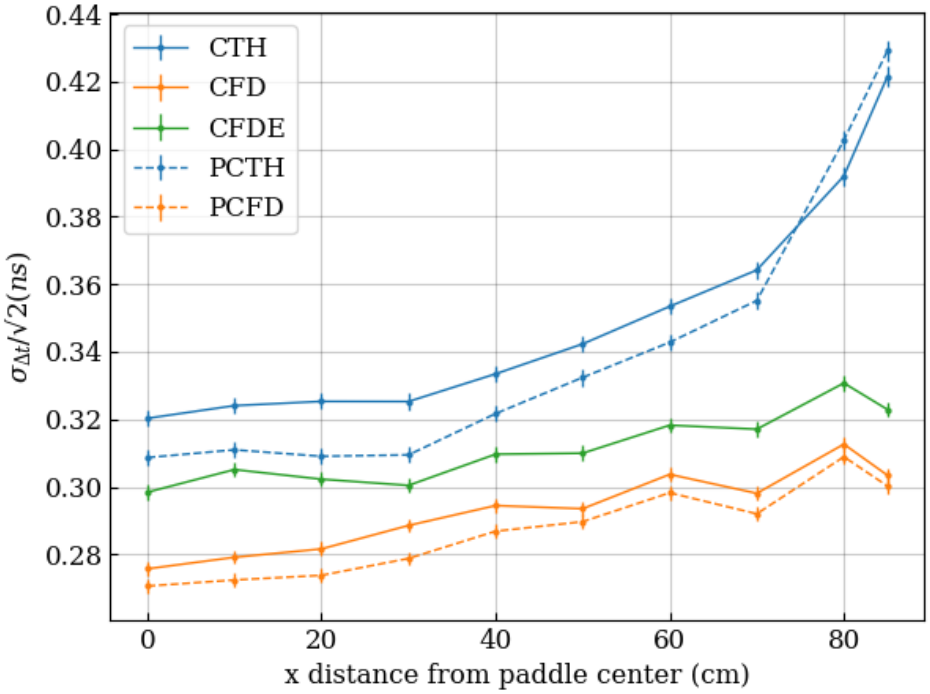
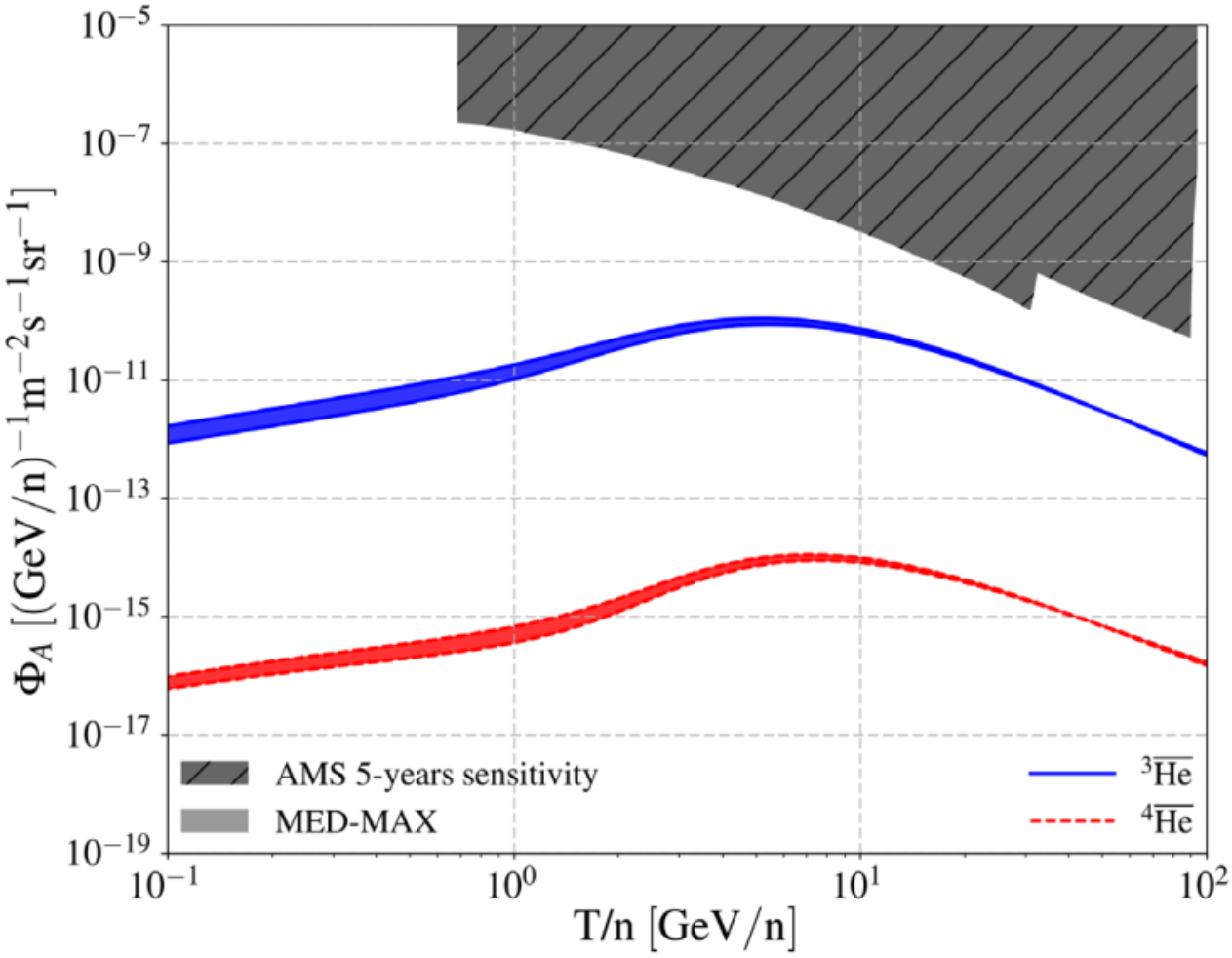
Time of flight: performance





$\overline{\mathrm{He}}$

- Growing interest in anti-helium
- $\overline{\mathrm{D}}$ signal should correspond to AMS-02 $\overline{\mathrm{He}}$ “hints”
- Detection would be **seismic**.
- AMS-02 $\overline{\mathrm{He}}$ “hints” make no sense vis a vis zero D events.
- p, D and He must be understood simultaneously. Fluxes follow a hierarchical relation, suppression of ~$10^{-3.5}$ for each species



V. Poulin et al., Phys. Rev. D 99, 023016

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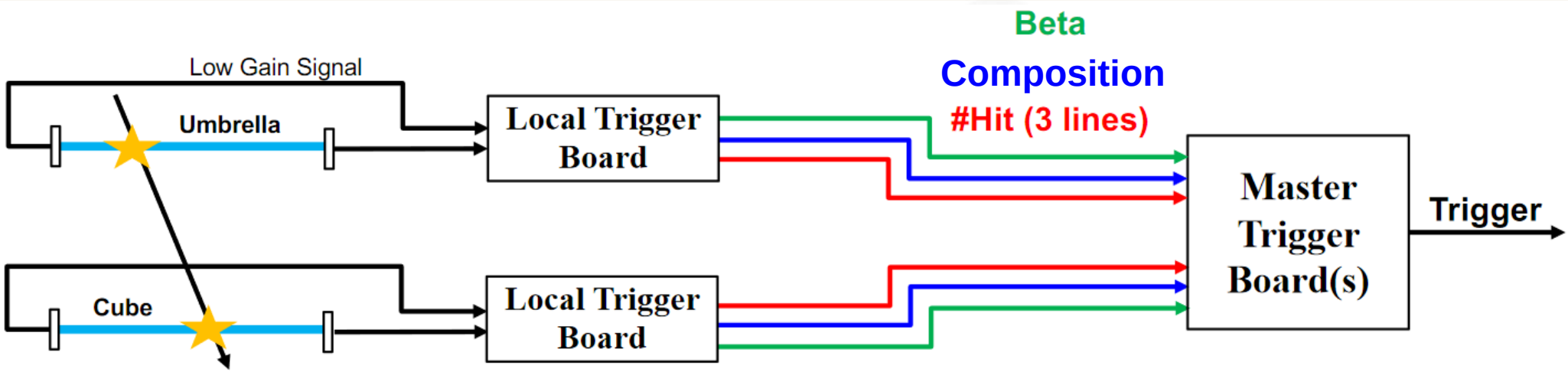
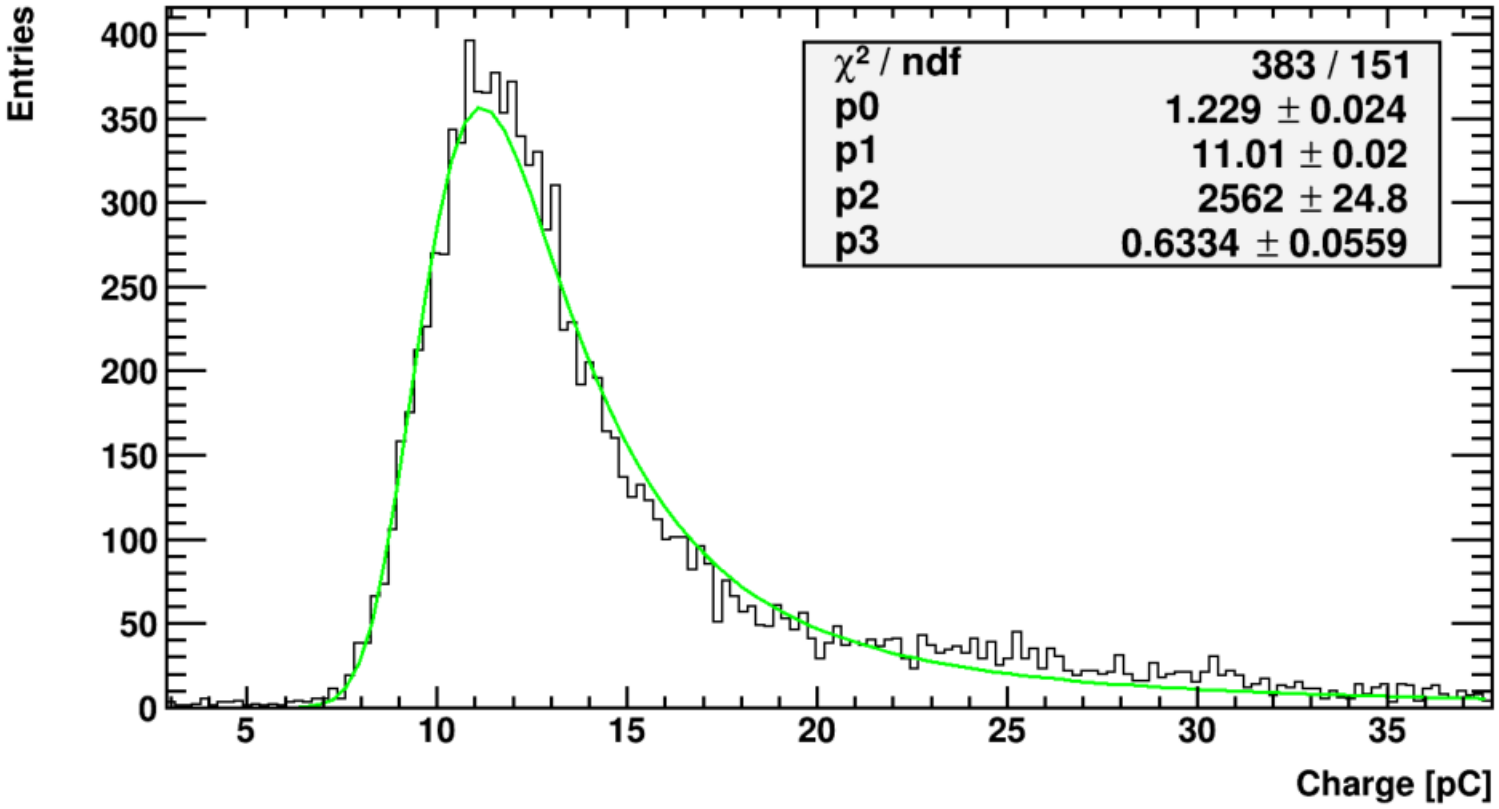
Trigger concept



Trigger Scheme	Min # of Paddles Hit			Energy Deposited (MIP)		Time Umbrella -> Cube [ns]	Primary Angle Cut (Effective)
	Total	Umbrella	Cube	Beta	Charge		
Loose	8	3	3	> 2.5	< 30	0-40	57°
Tight	10	4	4	> 2.5	< 30	0-40	57°

p.e. per MIP

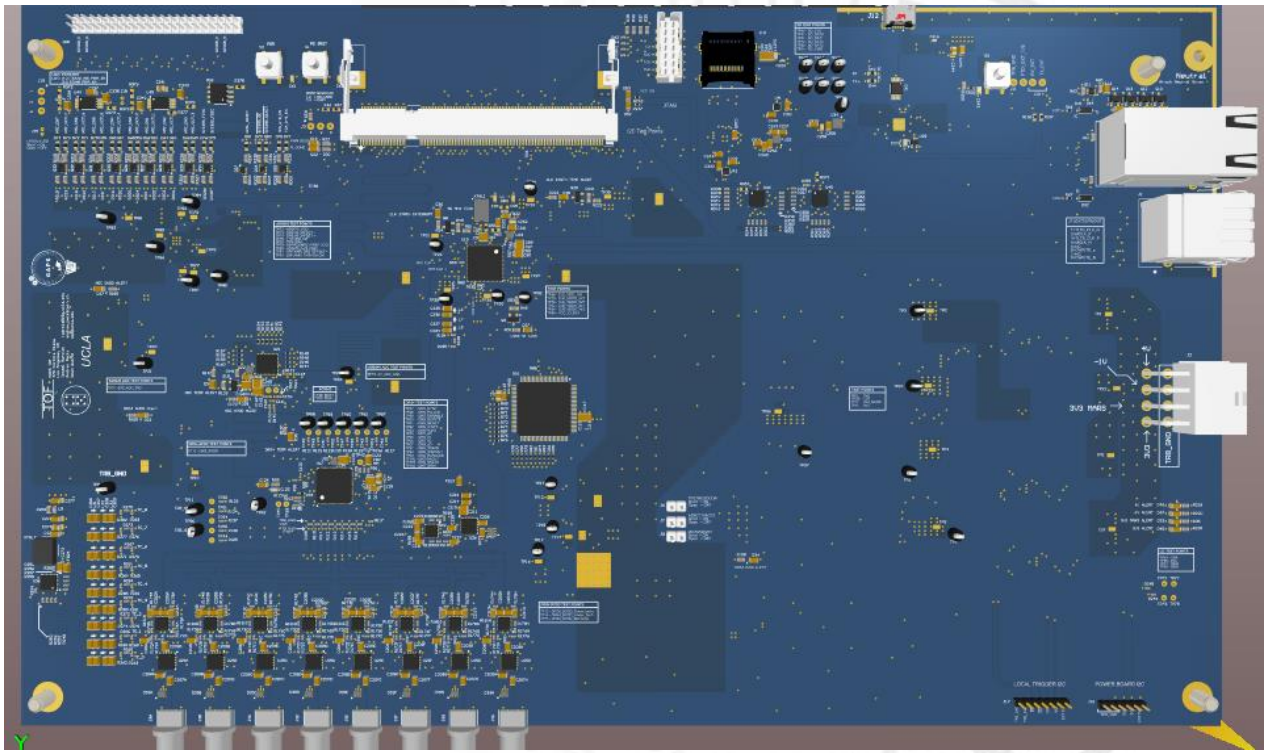
- Can now calculate number of photons measured for typical MIP event
- MPV for Q_{int} found from Gaussian*Landau
- MPV = 11 pC



68 p.e. per MIP, pretty good!

Time of flight system: DAQ hardware

- Waveforms for every trigger
- Fast timing/complete event tomography: useful for distinguishing multiple hits in a counter.
- SCA (DRS4) for digitization
  - Dense
  - Low power
  - Fast: 2 GS/s (up to 1024 samples)
  - All chips synchronized to global clock
- Off the shelf SOM
- First use of technology in balloon campaign

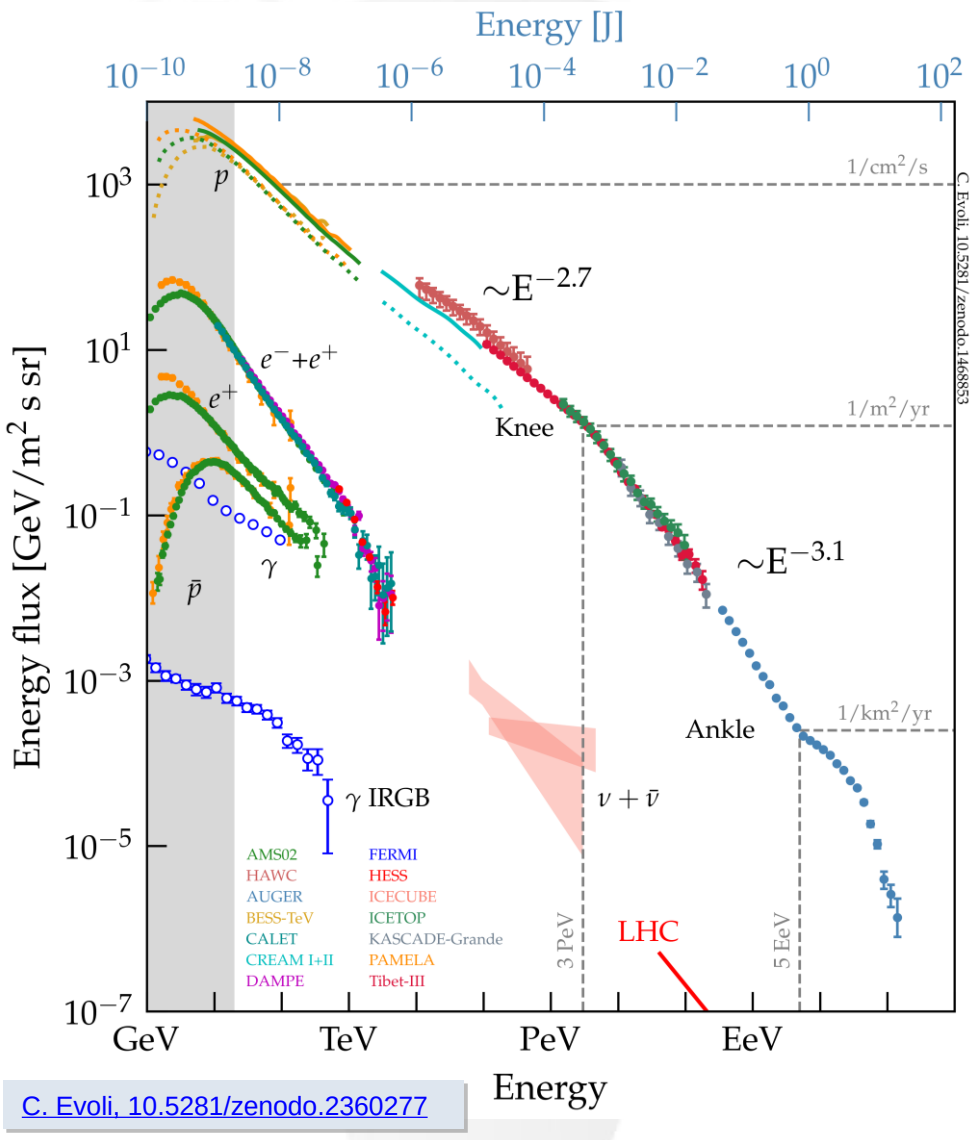


UCLA V2.3 readout board

Indirect DM: cosmic ray antimatter

$\chi + \chi \rightarrow S.M.$ $\chi \rightarrow S.M.$

- Antimatter excess compared to astrophysical processes.
- Primary channels: $\bar{p}$, e^+, $\bar{D}$, $\overline{He}$
- $\frac{\partial}{\partial t}\frac{dn}{dE}(E,\vec{x},t) = \vec{\nabla}\cdot\left[D(E,\vec{x})\vec{\nabla}\frac{dn}{dE}(E,\vec{x},t)\right] + \frac{\partial}{\partial E}\left[\frac{dE}{dt}(E)\frac{dn}{dE}(E,\vec{x},t)\right] + Q(E,\vec{x},t)$
- Many parameters, but constraints from flux ratios
- Difficulties: diffusion model simplifications/propagation, source term uncertainties



C. Evoli, 10.5281/zenodo.2360277

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