GAPS: a new cosmic ray antimatter experiment

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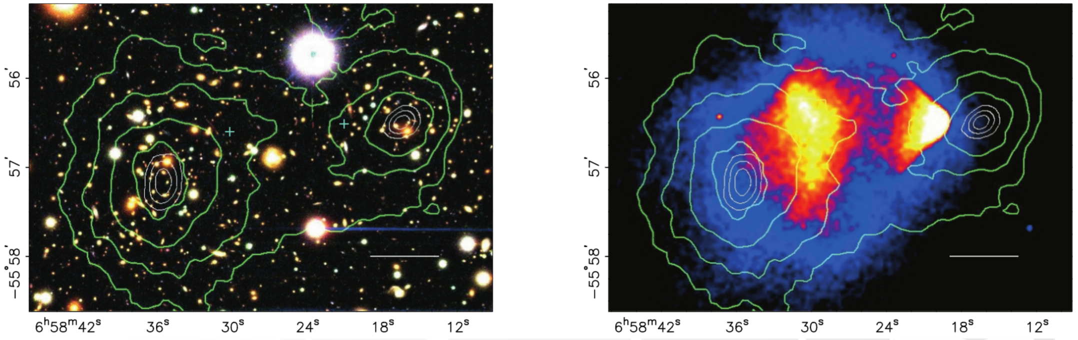
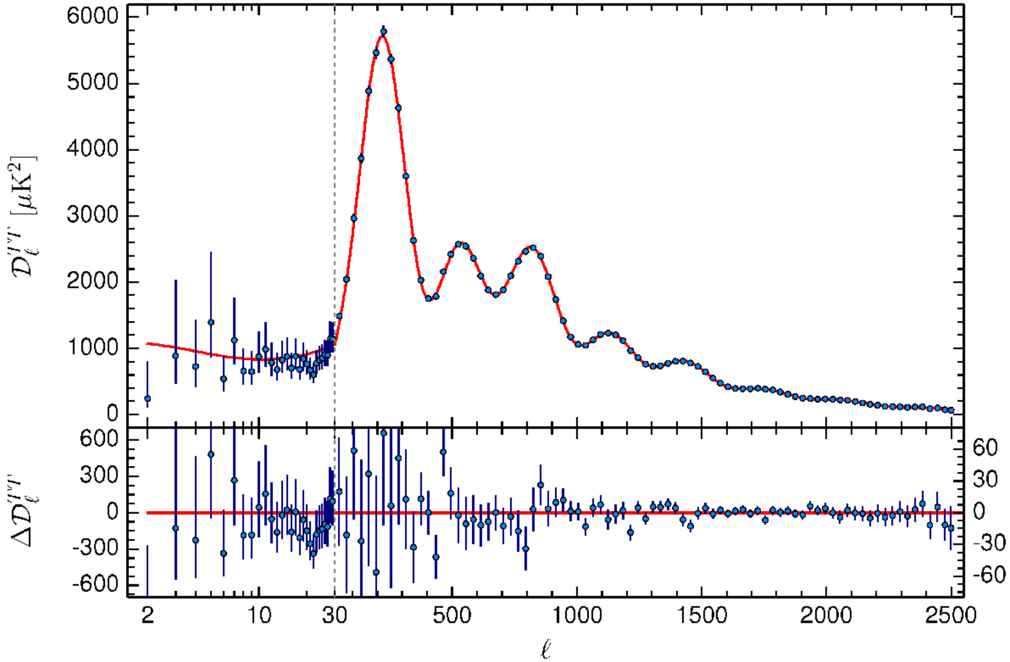
UCLA
PHYSICS & ASTRONOMY

Dark Matter: historical/contemporary evidence

- Canonical calculation of virialized cluster, Newtonian gravity (a la Zwicky)
- Flat rotation curves (Rubin & Kent 1970)
- X-ray halos and mis-aligned mass density contours: Bullet cluster
- BAO $\Omega_\chi h^2 = 0.1198 \pm 0.0015$ from Planck
- Simple GR+stat mech+particle physics (BBN) gives: $\Omega_b h^2 = 0.0205 \pm 0.0018$ (O'Meara et al. 2001), agrees with Planck
- Baryon density only about 5% of overall critical density
- Strong limits set by Planck on neutrino contribution to matter density, no more than 2%

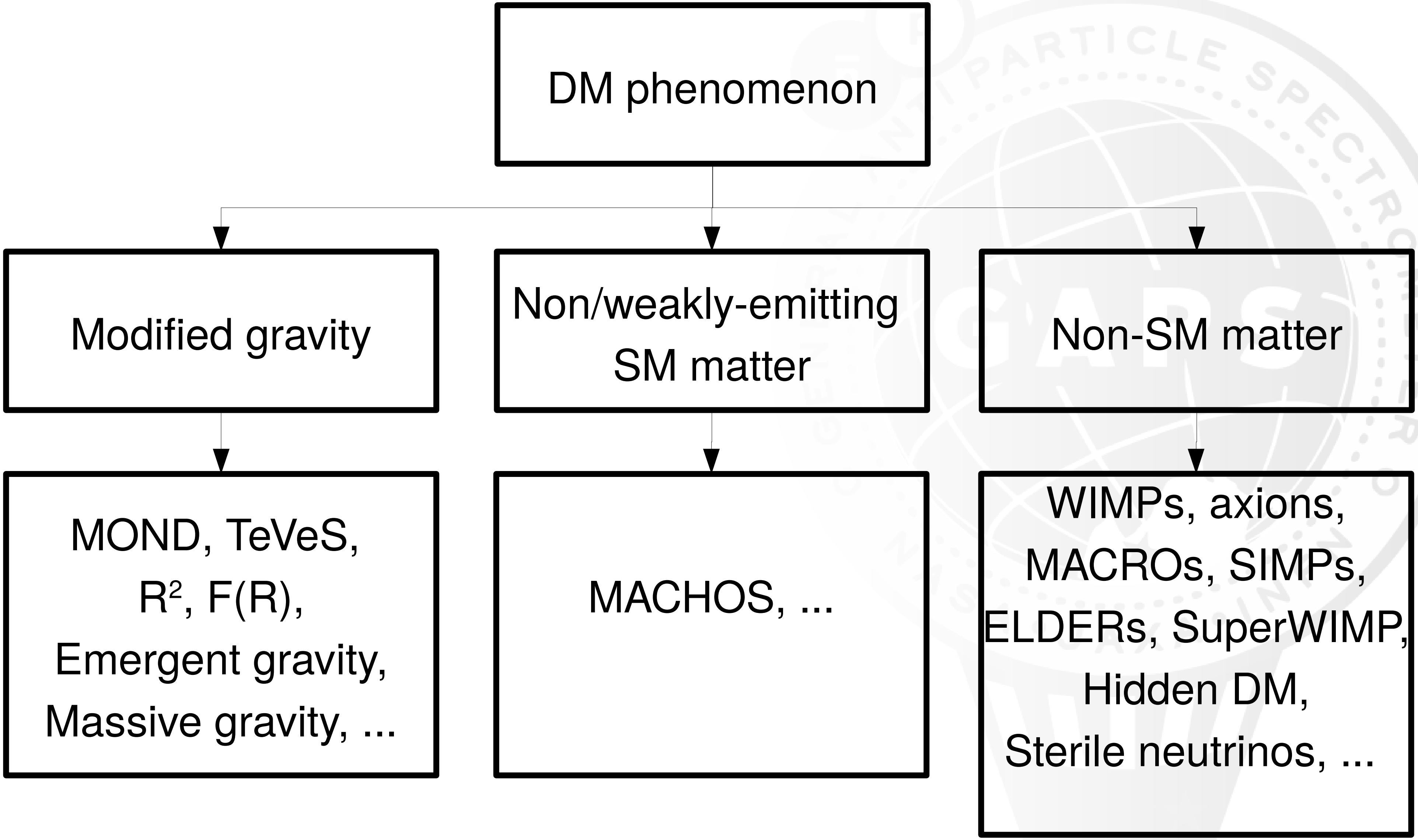


Clowe et al. (2006)



Planck collab. (2016)

Proposed explanations



DM phenomenon

Modified gravity

Non/weakly-emitting SM matter

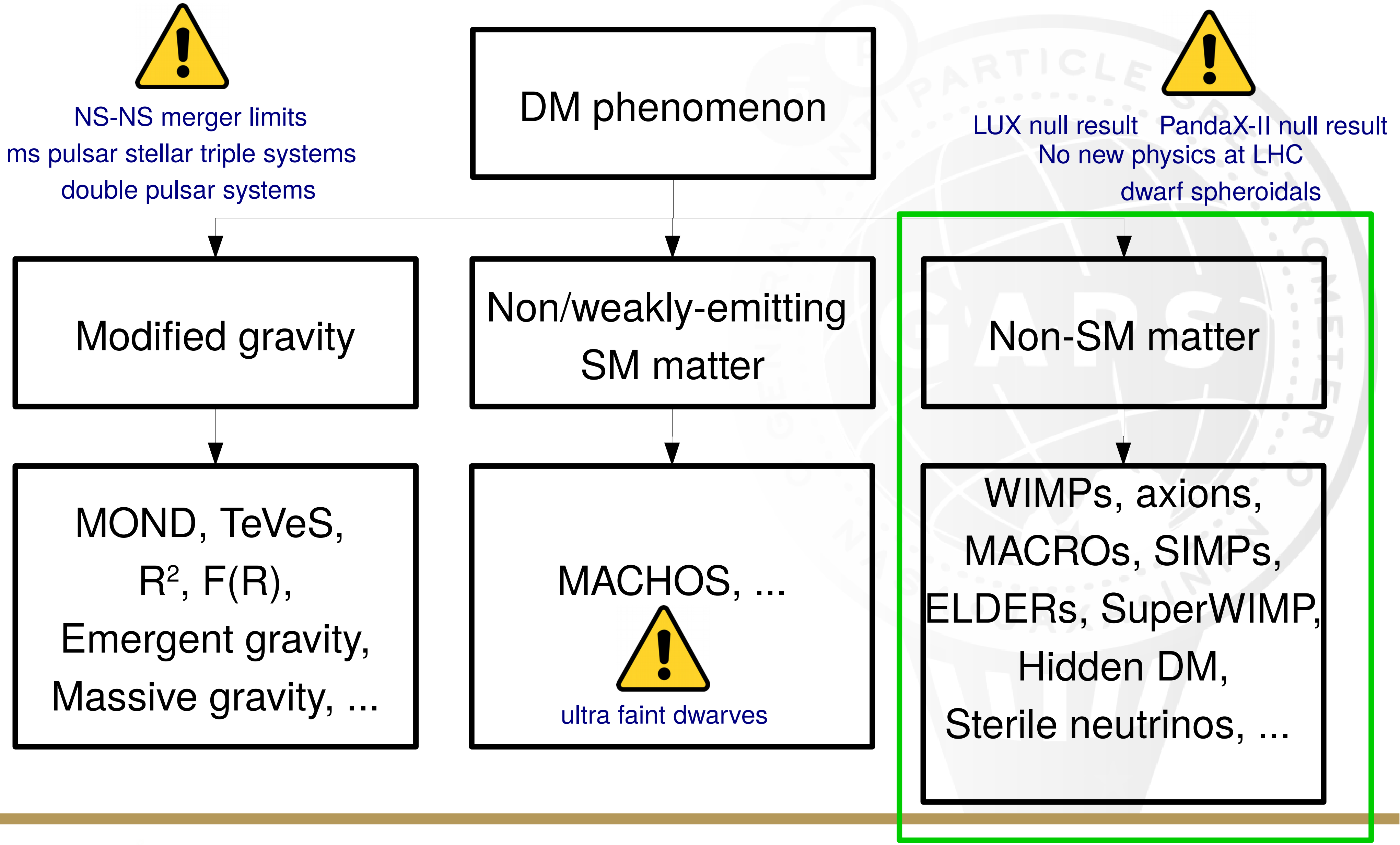
Non-SM matter

MOND, TeVeS, R^2, F(R), Emergent gravity, Massive gravity, ...

MACHOS, ...

WIMPs, axions, MACROs, SIMPs, ELDERs, SuperWIMP, Hidden DM, Sterile neutrinos, ...

Proposed explanations



DM phenomenon

NS-NS merger limits
ms pulsar stellar triple systems
double pulsar systems

LUX null result PandaX-II null result
No new physics at LHC
dwarf spheroidals

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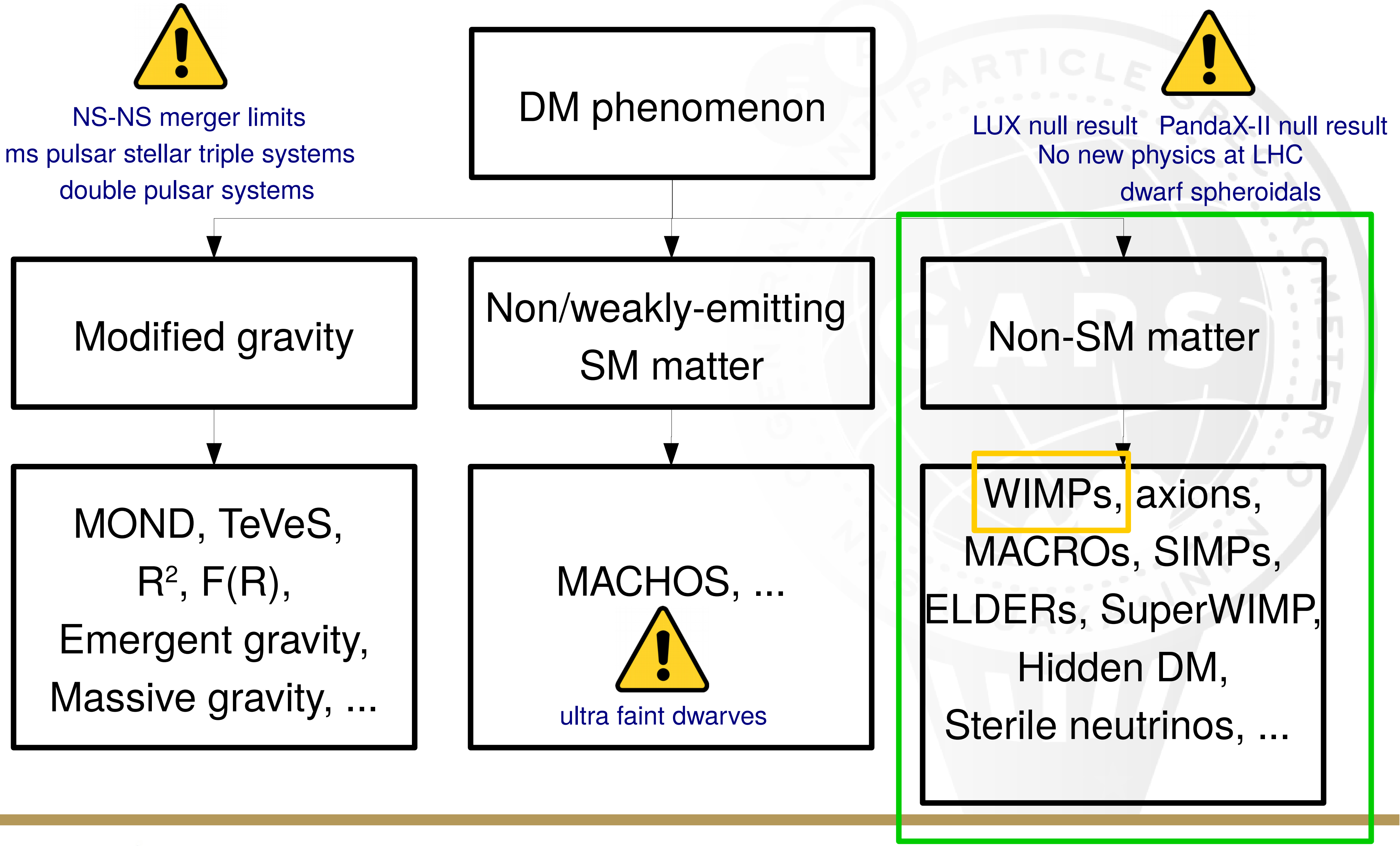

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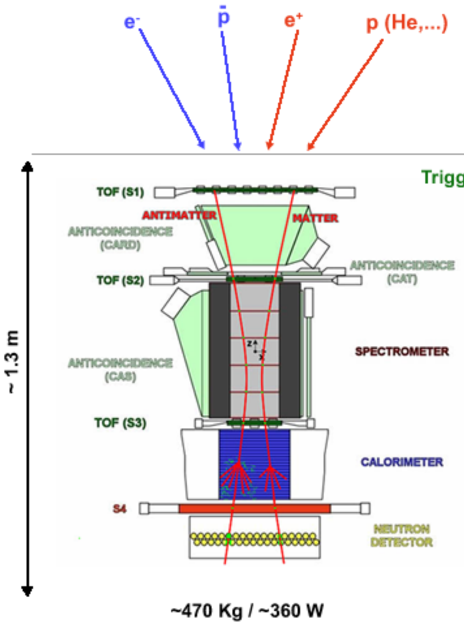
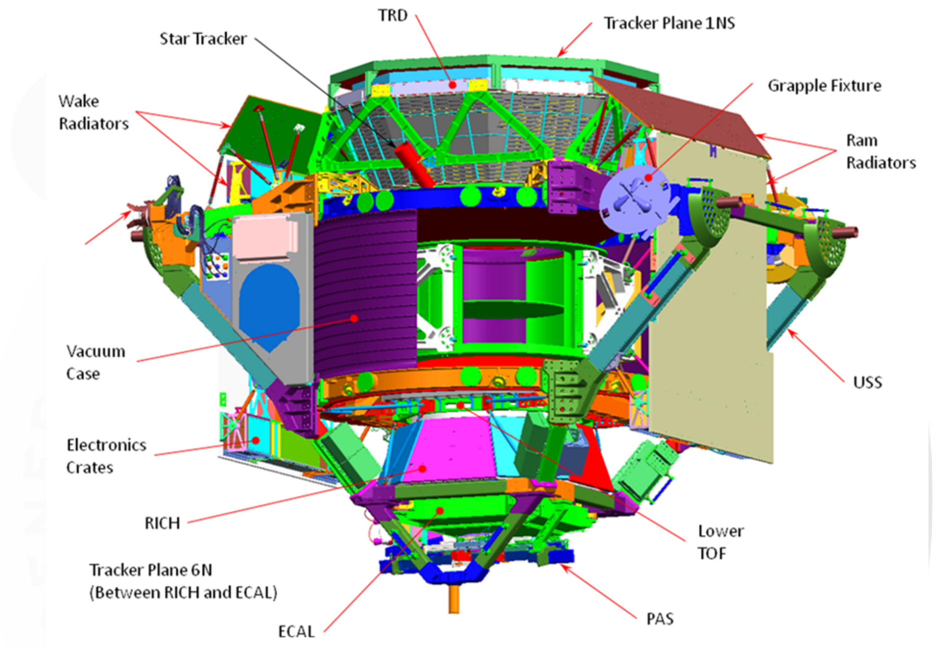
Testing the (WIMP) theories: *in*direct detection

- Look at standard model fragments from pair annihilation or decay
- Produced for free in the galaxy
- Kinematics of primaries arriving in upper atmosphere, low earth orbit



http://pamela.roma2.infn.it/index.php

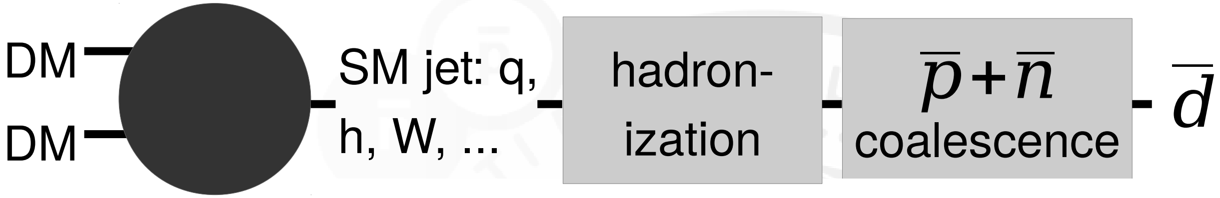


http://www.ams02.org/what-is-ams/tecnology/

https://asd.gsfc.nasa.gov/bess/BESS.html

Cosmic-rays from DM: anti-deuteron fluxes

- Annihilation/decay
- Source term:
- Fusion from simple coalescence as before
- Propagation to Earth using standard methods. Variety of models possible: MIN, MED, MAX
- Difference due mostly to variations in galactic scale height
- Tension between MIN and variety of measurements see e.g. Giesen et al. 2015



DM

DM

SM jet: q, h, W, ...

hadron-ization

$\overline{p}+\overline{n}$ coalescence

$\overline{d}$

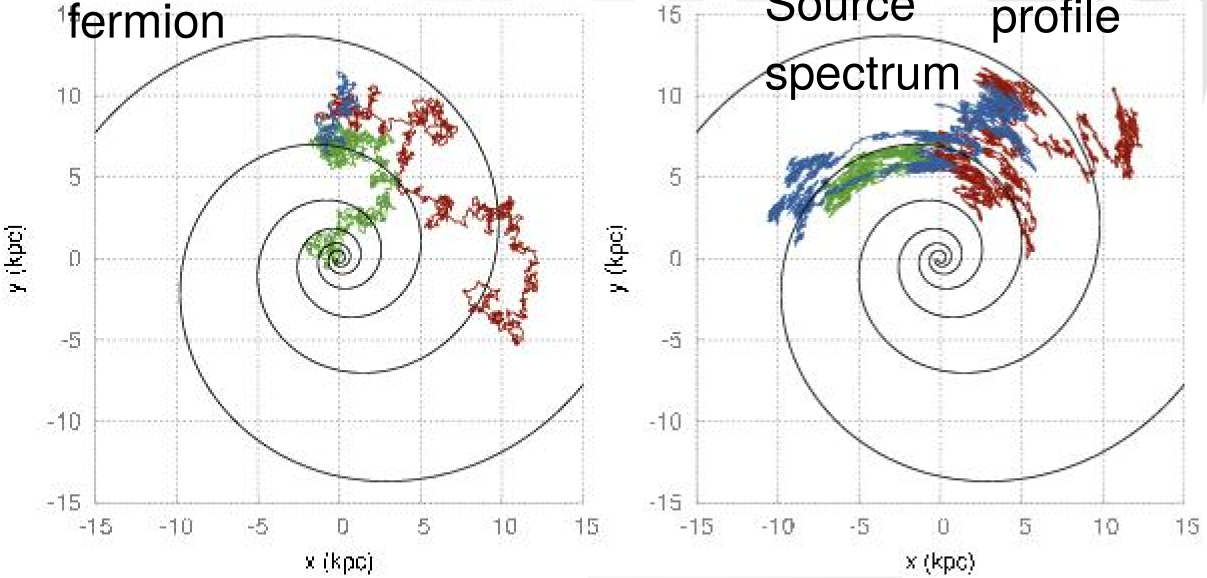
$$q_{\bar{d}}^{\rm prim}(r,z,E) = \eta\, \xi^2 \langle \sigma_{\rm ann} v \rangle_0 \frac{dN_{\bar{d}}}{dE_{\bar{d}}} \left(\frac{\rho_{\rm DM}(r,z)}{m_\chi} \right)^2$$

½ or ¼ type of fermion

$2.3\text{x}10^{-26}$ cm^3 s^{-1}

Source spectrum

Halo profile



F. Effenberger, et al., A&A 547, A120 (2012)

Cosmic ray anti-matter: astrophysical background

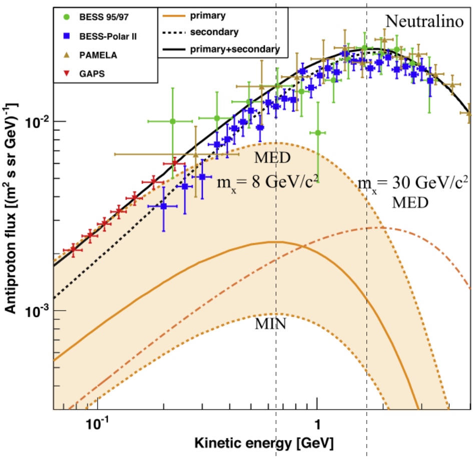
- Typical spallation process:
- Turns on ~ 7 GeV
- “natural” $\overline{p}/p$ peak KE separated from DM KE peak due to annihilation, decay, ..

$$p+p \rightarrow p+p+\overline{p}+p$$

CR primary

ISM H^+

Anti-nucleon, KE~E_{thresh}



- Astrophysical vs DM peak for $\overline{d}/d$ has *better* separation!
- Turns on ~17 GeV
- **Astrophysical population: no additional scattering/energy loss. Simply break up!**

$$p+p \rightarrow p+p+\overline{p}+p+\overline{n}+n$$

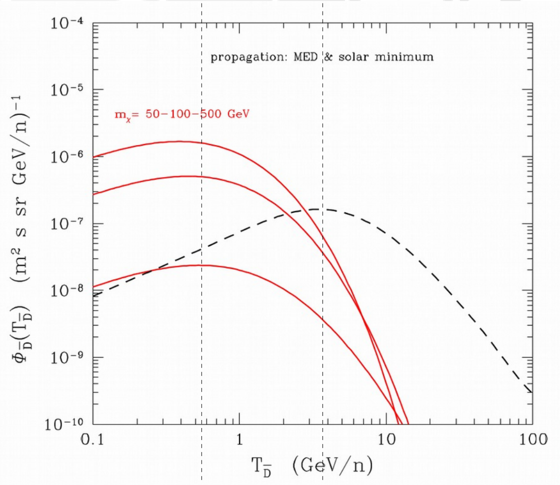
CR primary

ISM H^+

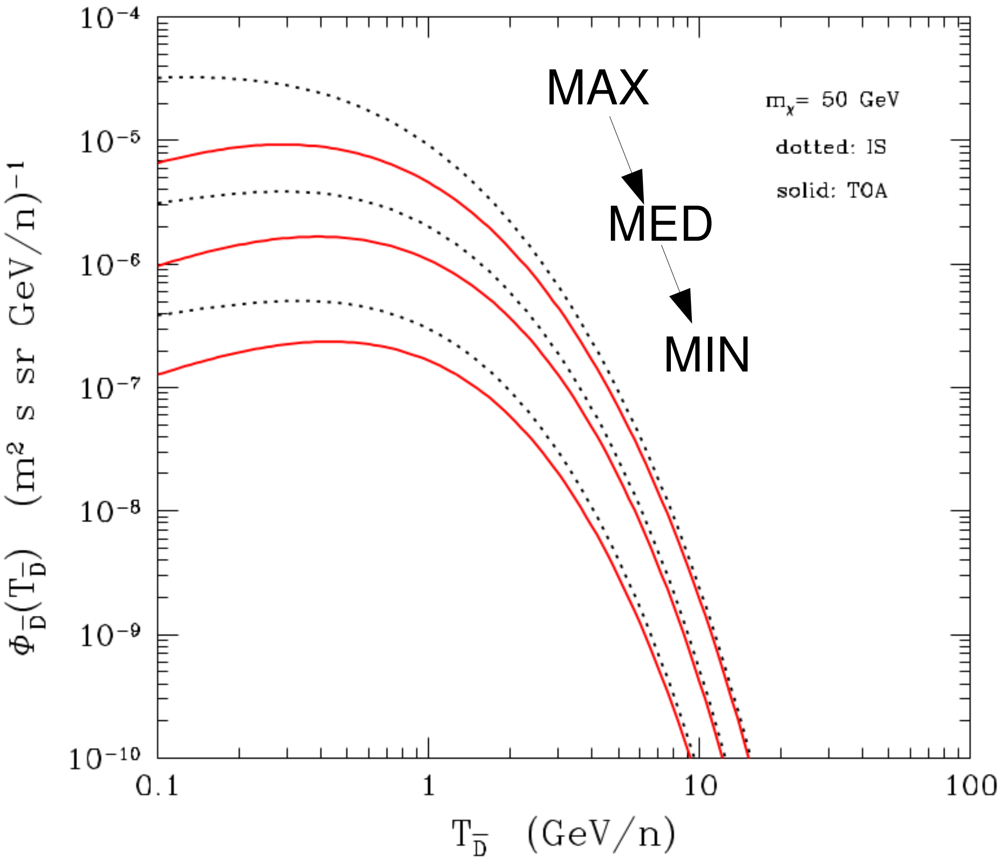
$\overline{d}$ from fusion

Coalescence described in

10.1103/PhysRevD.71.08301



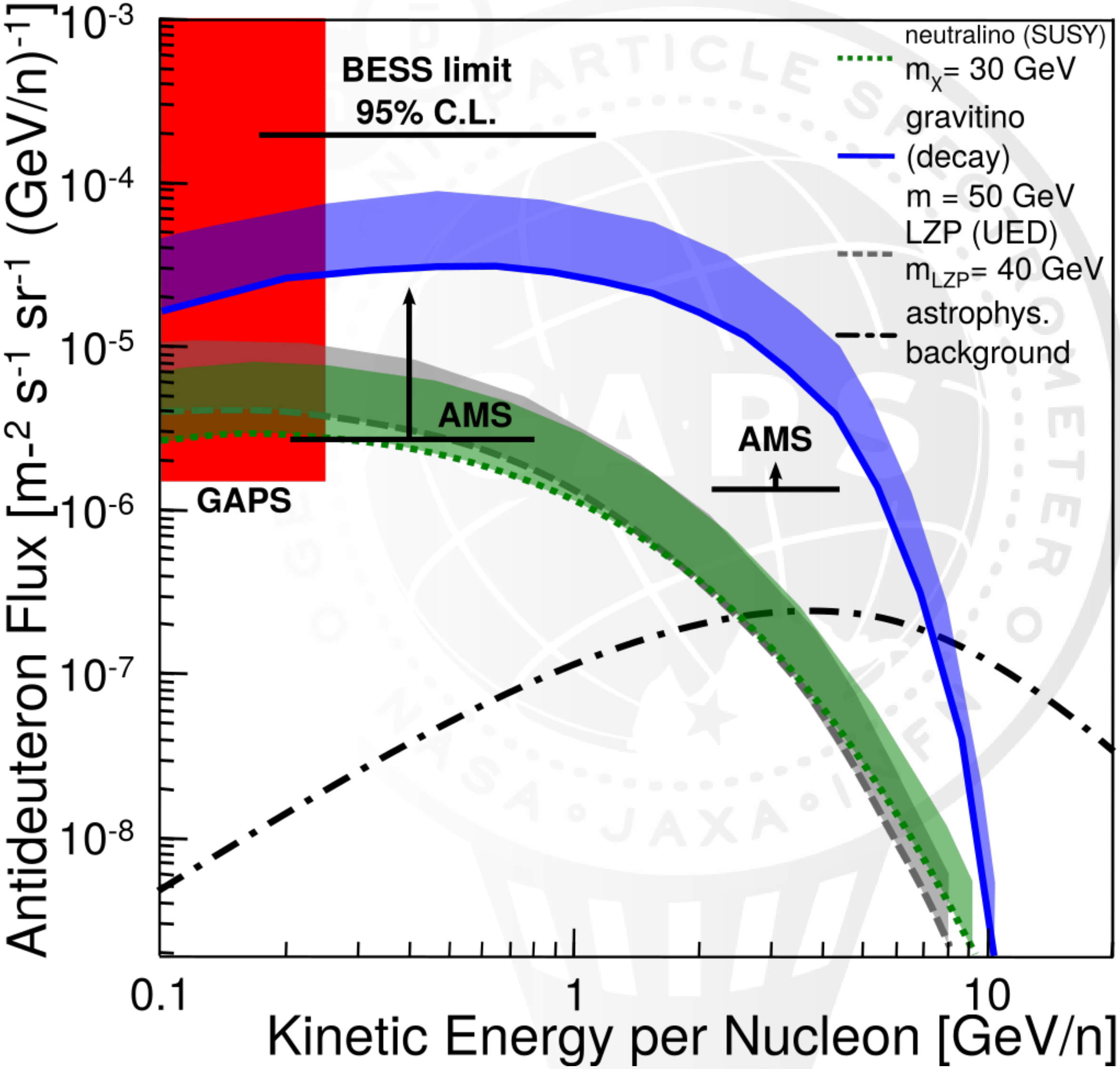
DM Anti-deuteron fluxes, top of atmosphere



F. Donato, N. Fornengo, and D. Maurin. Phys. Rev. D 78, 043506

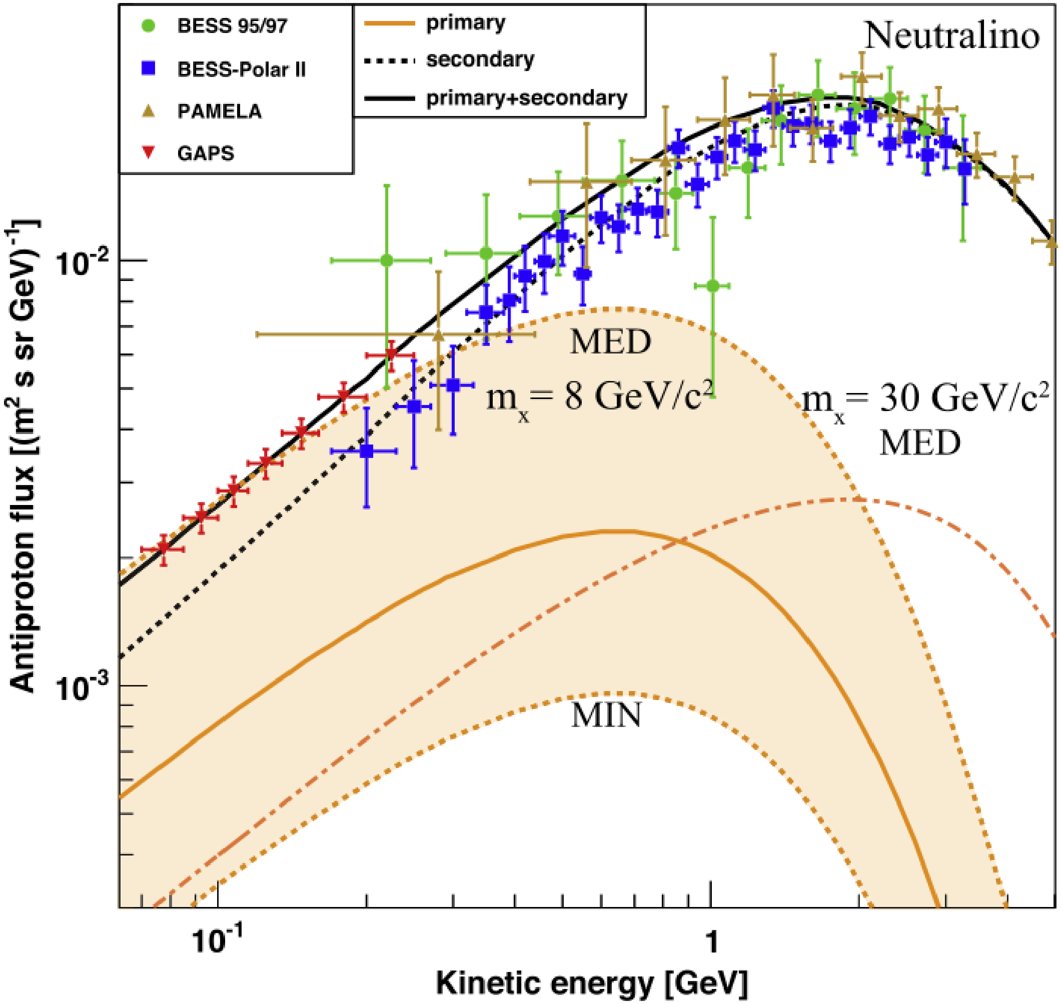
GAPS sensitivity: $\overline{d}$

- Low mass WIMPs (MED prop.)
- Lightest Kaluza-Klein particle universal extra-dimensions
- SuperWIMP gravitinos
- **Given the secondary flux estimate, a detection of a handful of anti-deuterons is significant**



GAPS sensitivity: $\overline{p}$

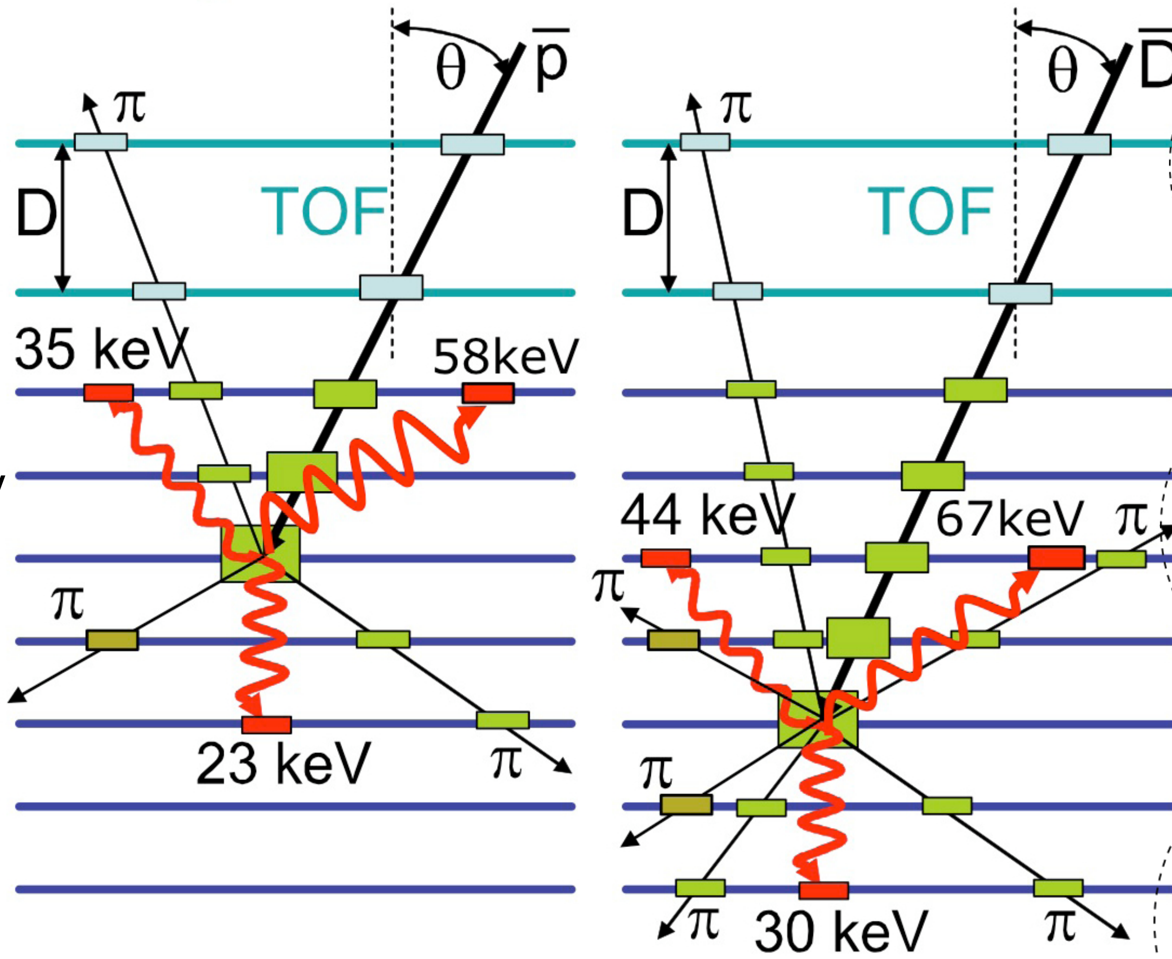
- Overlap with complementary searches
- Extends spectrum to lower energies
- SuperWIMP
- Sensitive to other models, see T. Aramaki's paper for more details

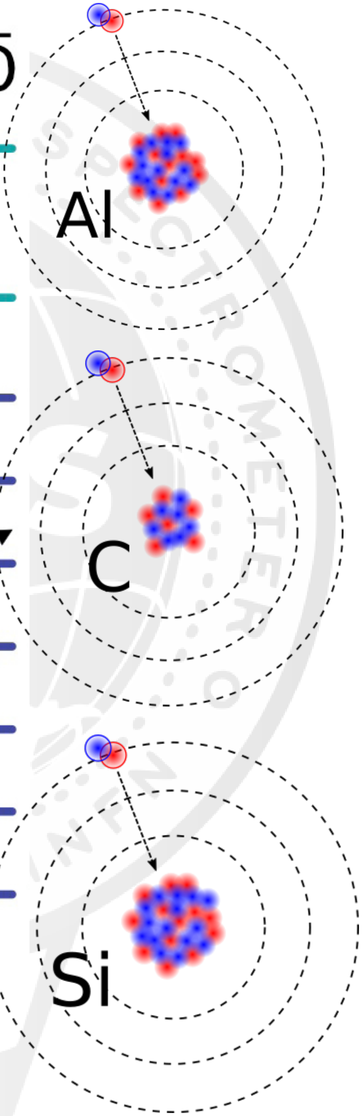


T. Aramaki et al., Astroparticle Physics, Volume 59, 2014, Pages 12-17

Detection technique

- TOF using plastic scintillator: β, dE/dx
- Exotic atom formation
- De-excitation produces characteristic x-rays
- Si(Li) tracker concept provides powerful x-ray discrimination
- Annihilation event produces pions, protons
- Combination of TOF and Si(Li) should provide excellent reconstruction capability





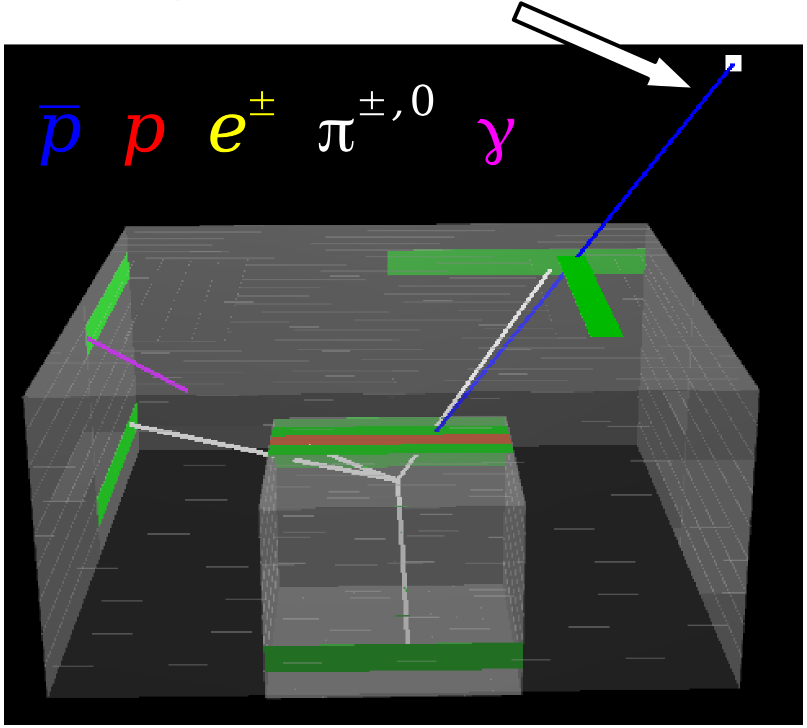
T. Aramaki et al., Astroparticle Physics, Volume 74, 2016, Pages 6-13

$$E_x=(zZ)^2\frac{\widetilde{M}}{\widetilde{m}_e}R_H\left(\frac{1}{n_f^2}-\frac{1}{n_i^2}\right)$$

Example simulated events

ANTI-PROTON

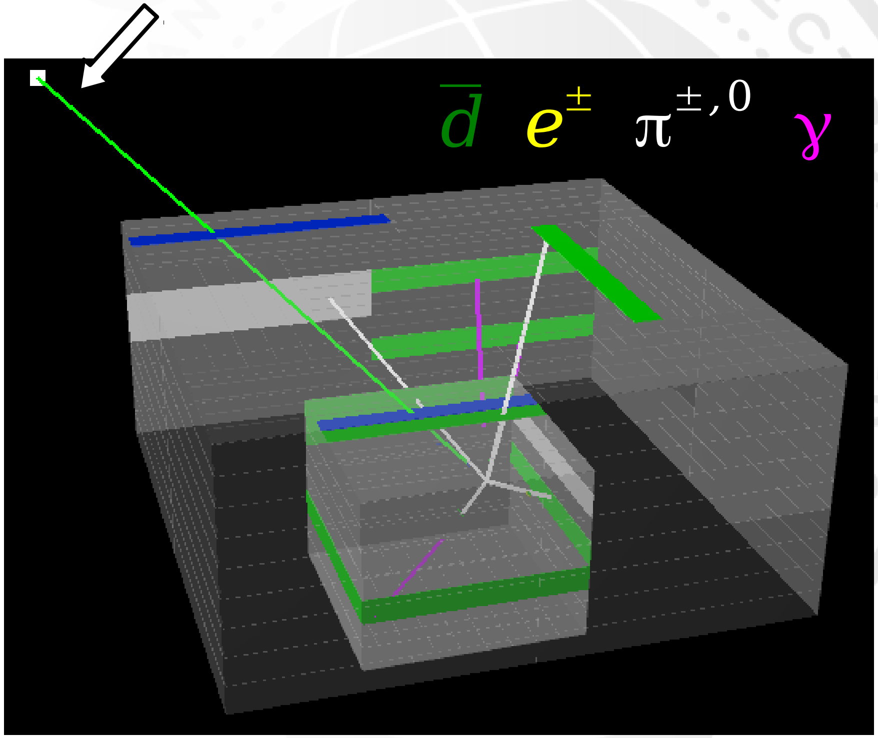
$Primary:\beta=0.388, KE=79.9\,MeV$



TOF HIT=10, Si(Li) HIT=6

ANTI-DEUTERON

$Primary:\beta=0.334, KE=114.4\,MeV$

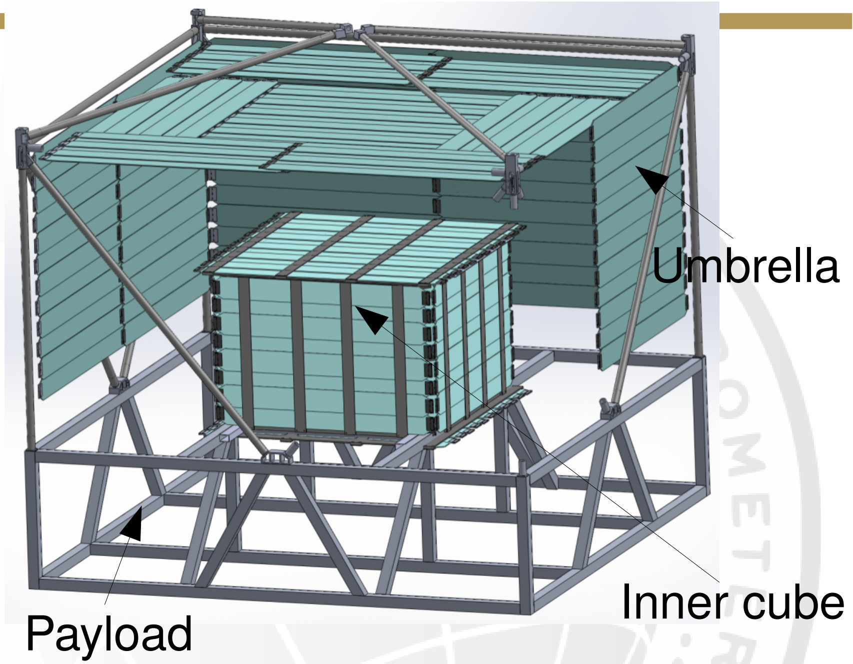


TOF HIT=14, Si(Li) HIT=11

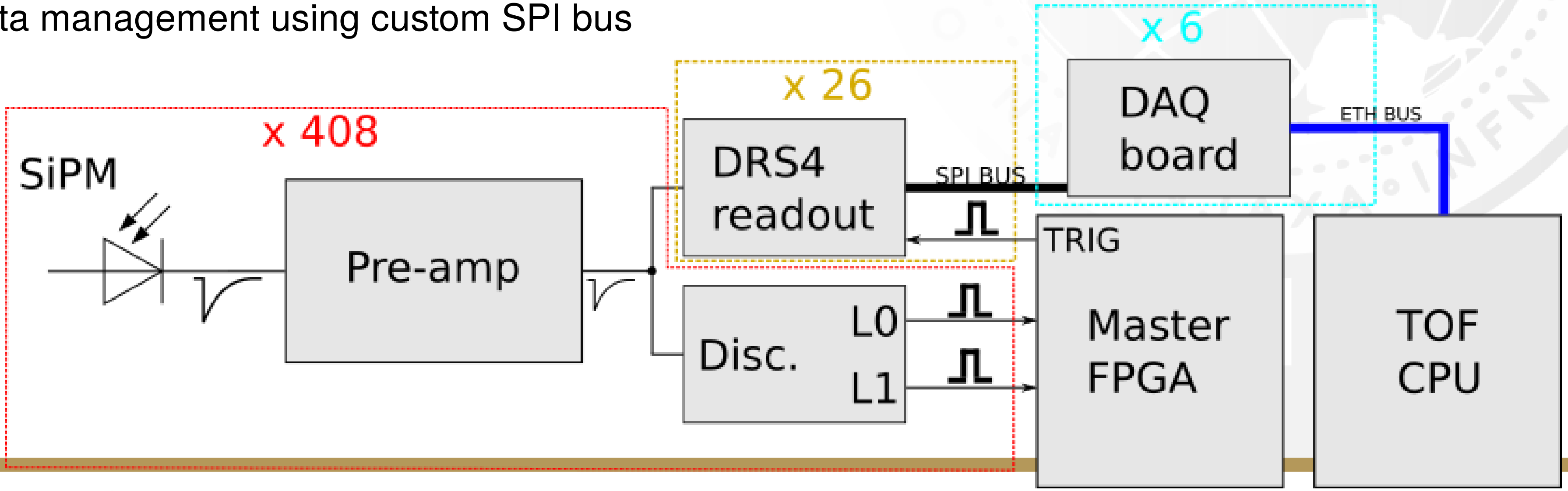
Energy deposited: 🟩🟦🟪

1 10 100 MeV

Instrument design: time of flight

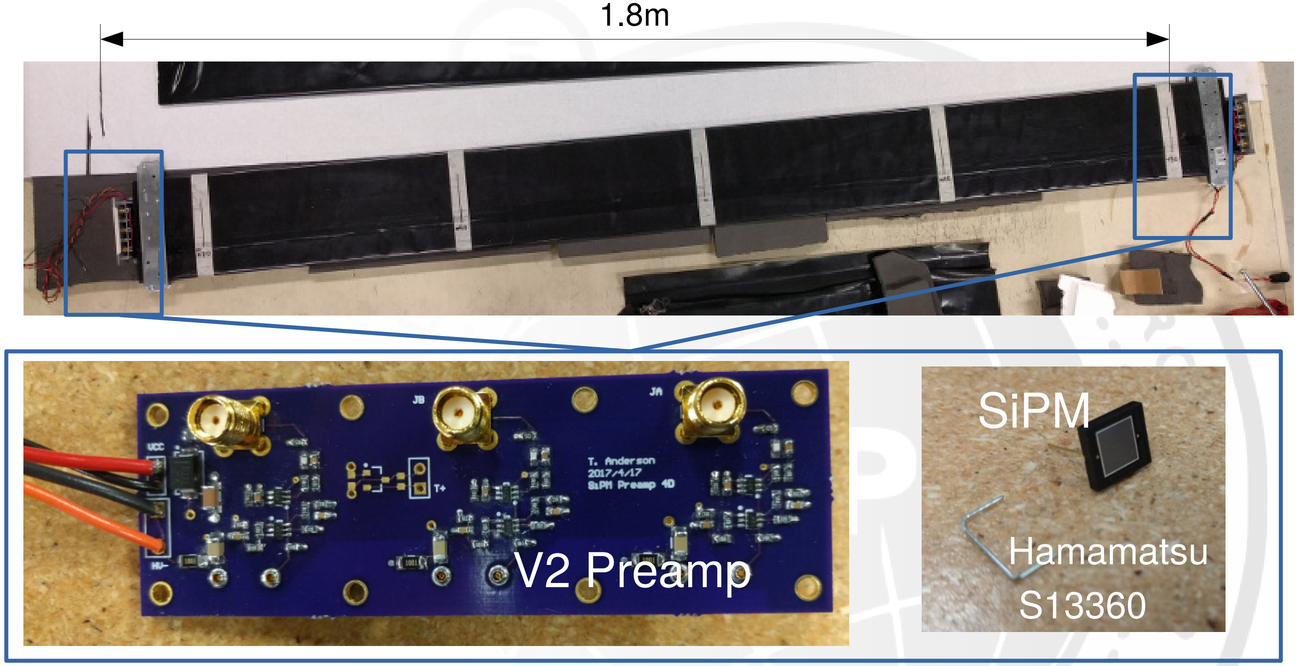


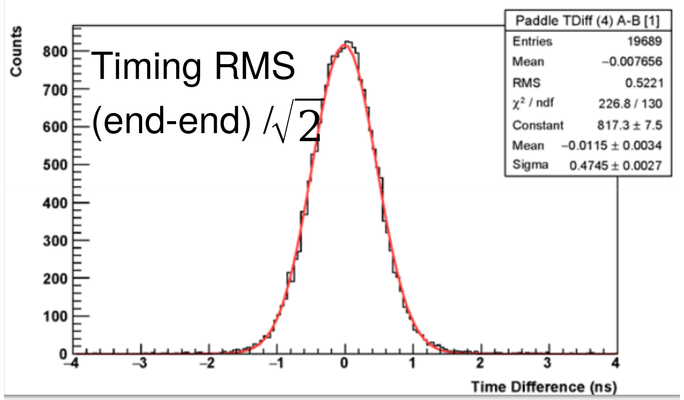
- 202 PVT paddles: umbrella with hermetic cube
- State of the art carbon fiber mechanical support structure
- Detailed study of PMT vs. SiPM.
- SiPM low-light detectors: low mass, low HV, no B-field issues
- Resistively loaded voltage pre-amp
- Read out using low power, fast and channel dense DRS4 chip
- Data management using custom SPI bus

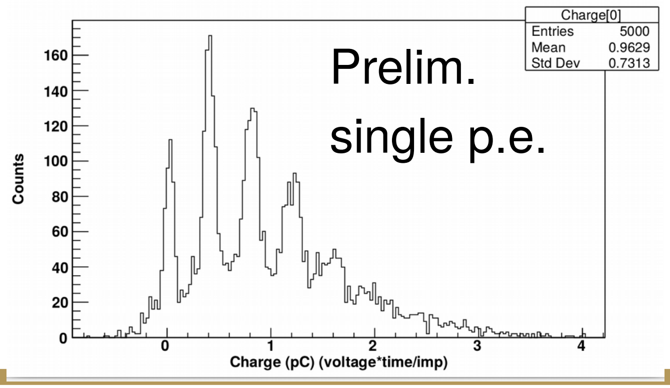


Instrument design: time of flight

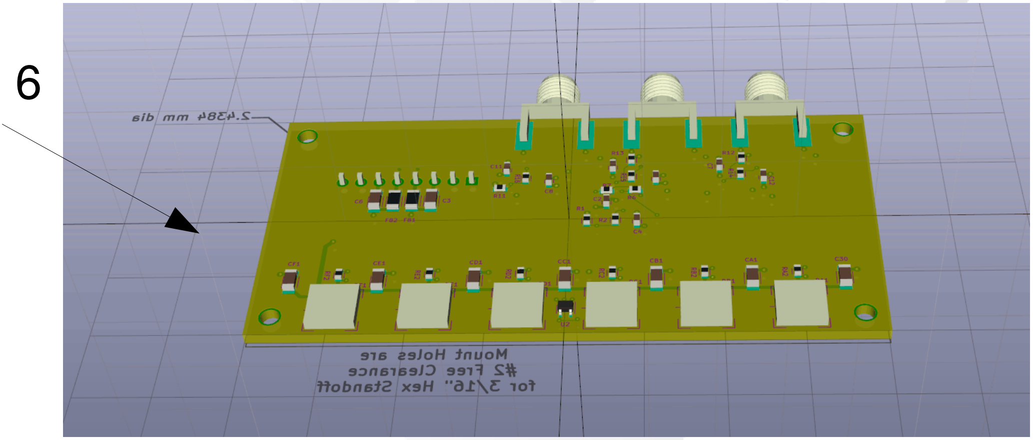
- TOF requirement: ~500 ps resolution
- ~350 ps achieved with DRS4 eval board in lab
- 0.4-36 MIP dynamic range (0-2200 p.e.)




Timing RMS (end-end) $/\sqrt{2}$

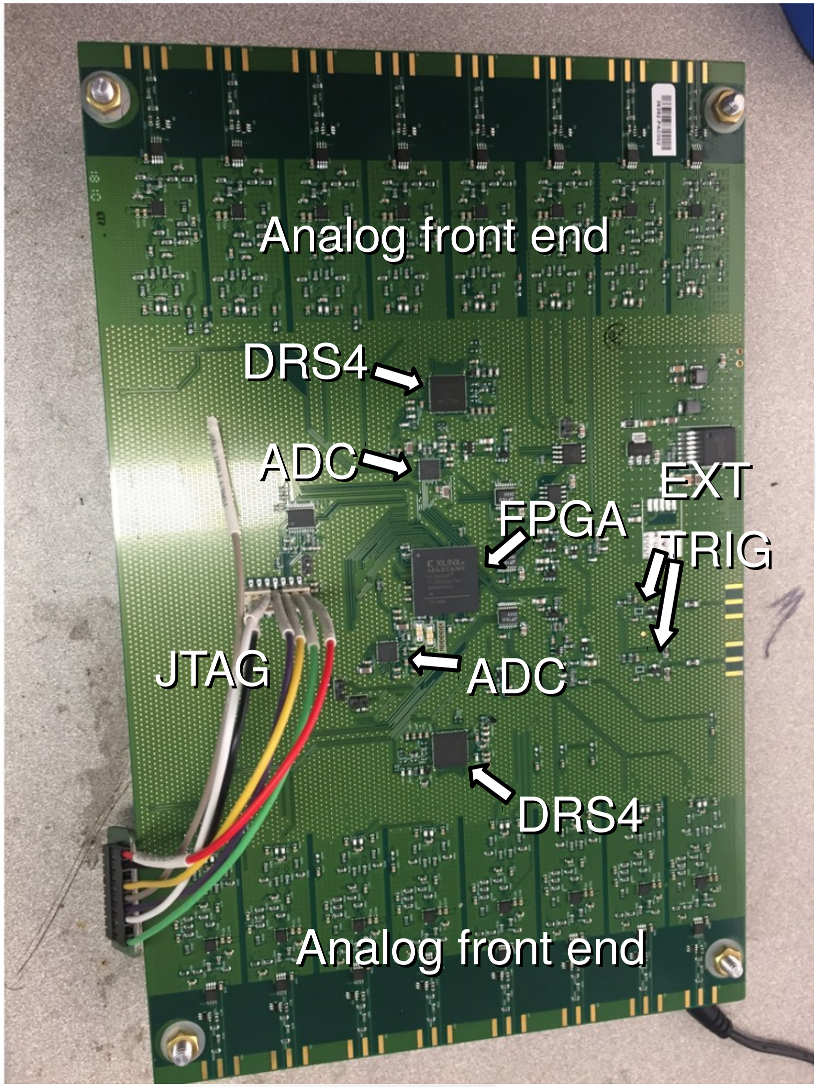

Prelim. single p.e.

V3 preamp upgraded to 6 SiPMs!



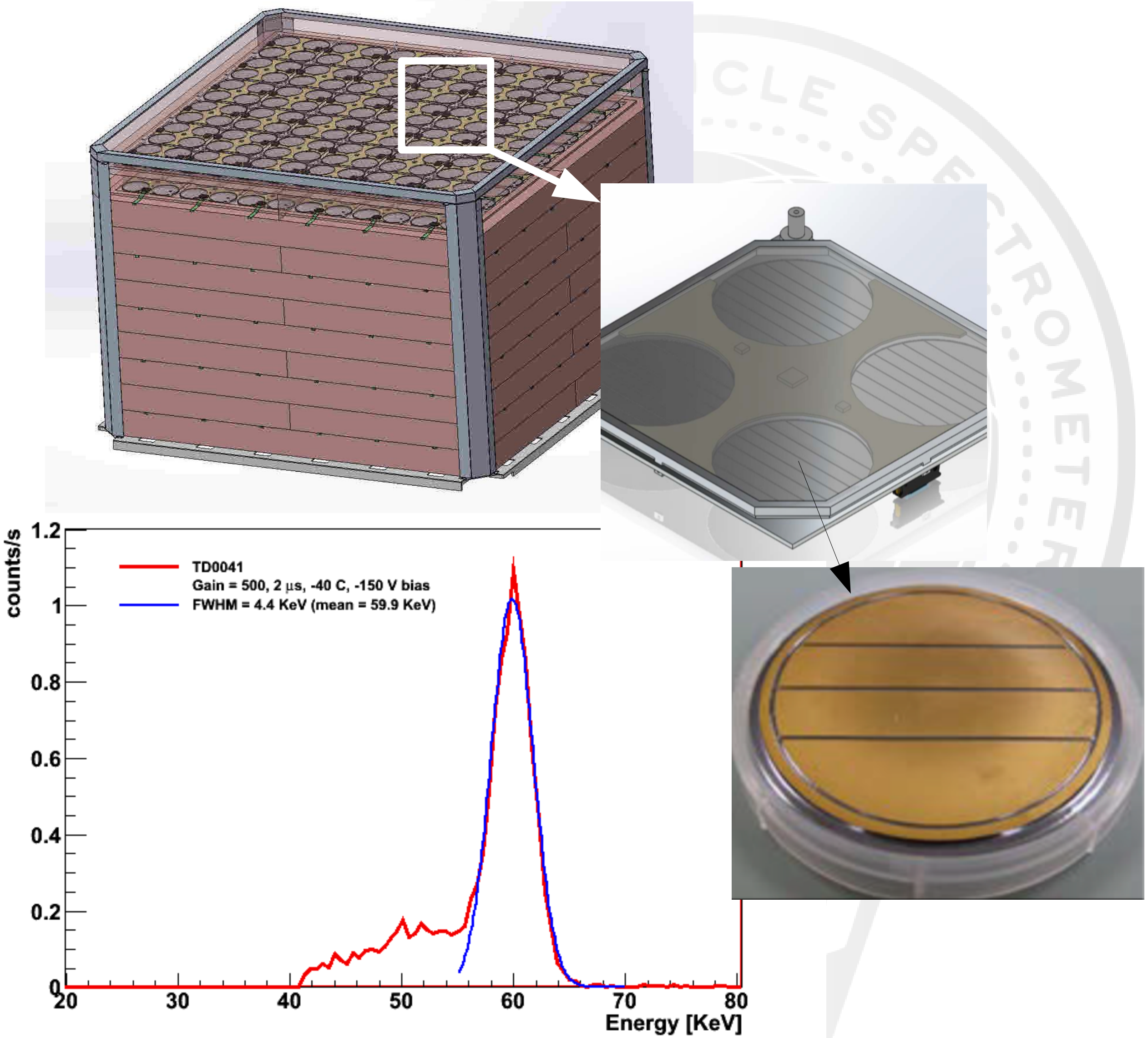
Instrument design: time of flight

- 8 paddles per read out board
- 16 input channels
- Up to 2 digital input triggers
- SPI bus for fast communications and data throughput
- 27 read out boards for TOF system (umbrella + cube)
- v1.0.0-beta assembled, testing + debugging underway



Instrument design: silicon tracker

- Lithium drifted silicon Si(Li)
- 4 keV energy resolution and 100 ns timing requirements
- 10 layers, 4” dia. & 2.5mm thick wafer
- Original fabrication technique pioneered at Columbia U. Tech transfer to private company
- Several commercially produced (Shimadzu corp.) detectors delivered. Measurements ongoing at MIT



Instrument design: silicon tracker

- Integral pre-amp
- 16 channel ASICs
- 11,520 total channels for 10 layers
- Bias: ~300V
- -40 C operating temp
- SPI communications for speed
- FPGA based digital back-end

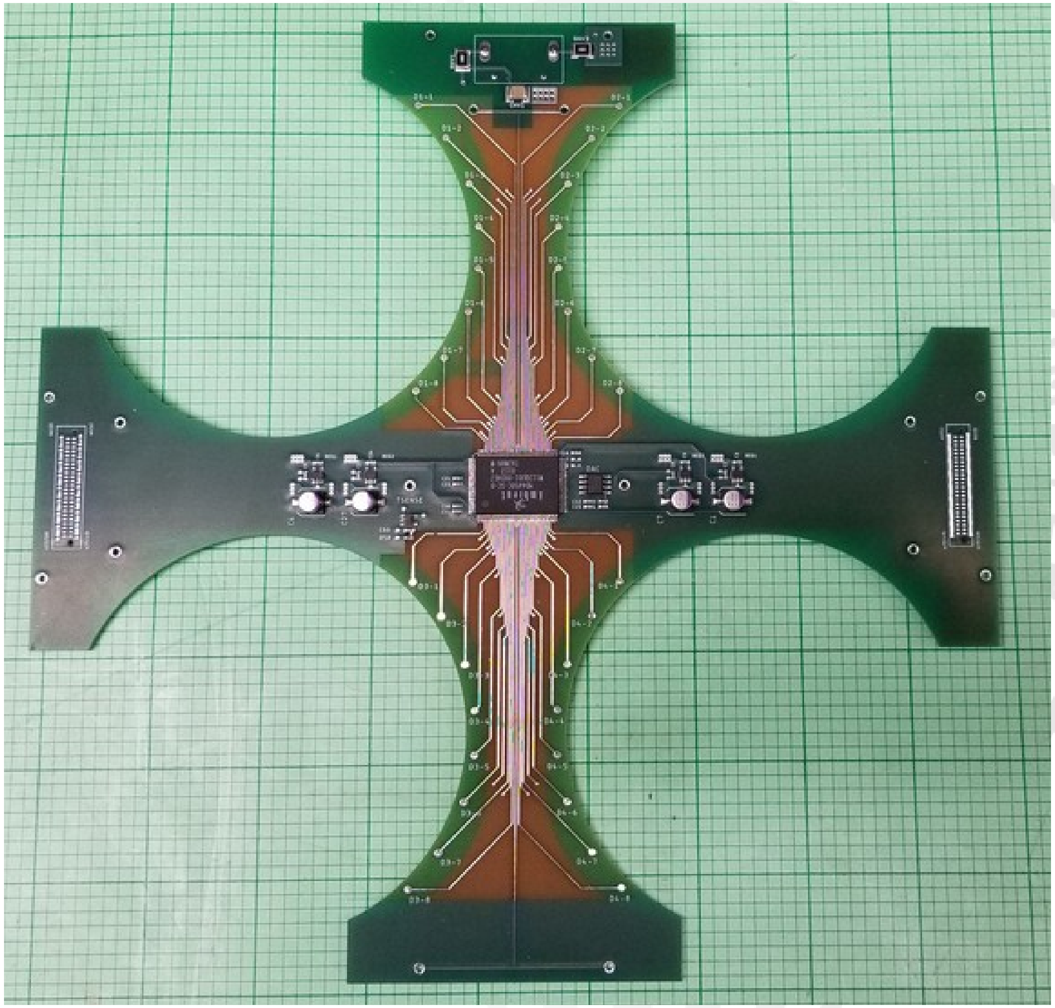
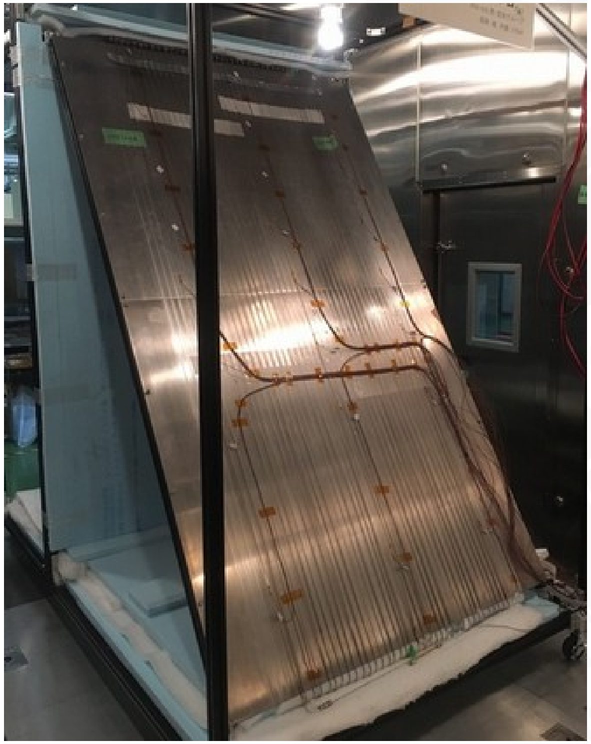
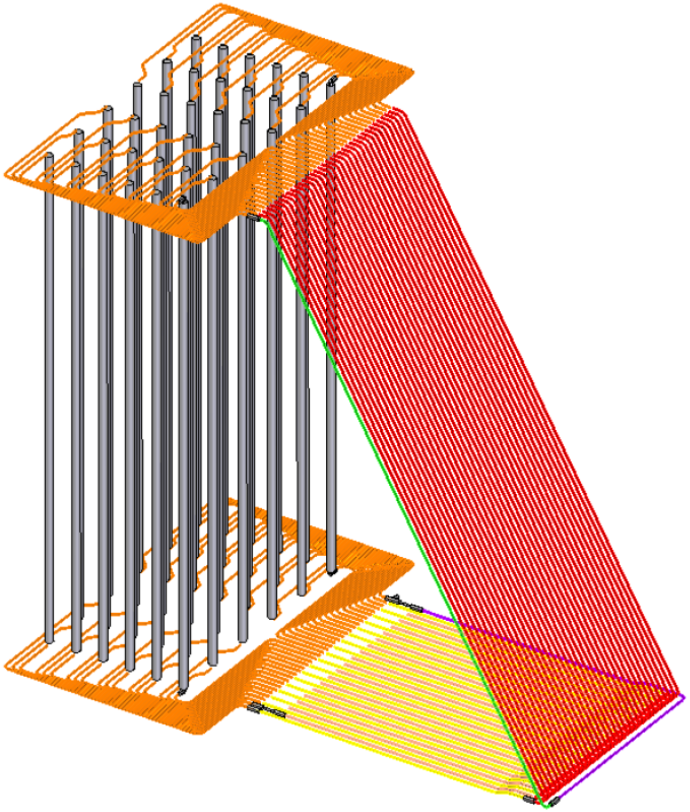


Image credit: L. Fabris

Instrument design: silicon tracker

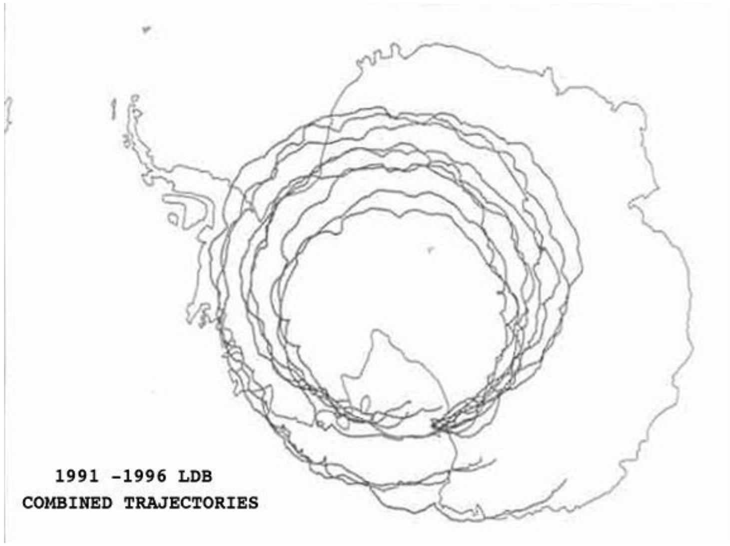
- Cooled using oscillating heat pipe (OHP) system
- Phase change in capillary tube
- Easy to design and build, low cost
- Does not require active pumping





Long duration (35 d) balloon flight

- Early 2021 launch (solar minimum)
- ~1700kg payload
- ~1400W power budget
- 36km altitude, 5 gm cm^{-2} overburden



The GAPS collaboration

Columbia University

Massachusetts Institute of Technology

UCLA

University of Hawaiʻi Mānoa

UC San Diego

SLAC

Oak Ridge National Laboratory

INFN Istituto Nazionale di Fisica Nucleare

Funding agencies (started 2017)

NASA

JAXA Japan Aerospace Exploration Agency

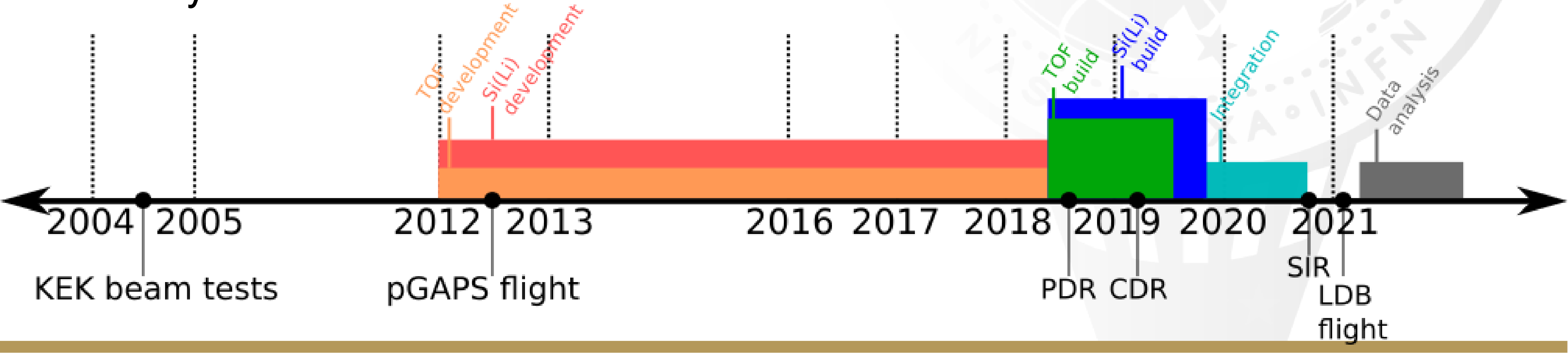
科研費 KAKENHI

Heising-Simons Foundation

NSF

Summary + Time-line

- Anti-deuteron cosmic rays interesting for astrophysics, in addition to DM probe
- GAPS designed for anti-protons and anti-deuterons
- Independent detection technique that can complement AMS02, BESS, PAMELA
- Extend anti-proton energy spectrum to unexplored regime
- Viability of design demonstrated in successful pGAPS flight
- TOF and Si(Li) development nearing completion, measurements and testing recently started



Backup: Exotic atom

- Energy of atomic X-ray unique to the exotic atom, allows discrimination of dbar vs. pbar
- Predicted in 1940s, cascade models developed since then
- Generalized, extend-able cascade model developed for GAPS
- Free parameters optimized with beam tests using Al, S, Cl, Br targets at KEK in 2005
- For comprehensive description see: Aramaki et al. 2013

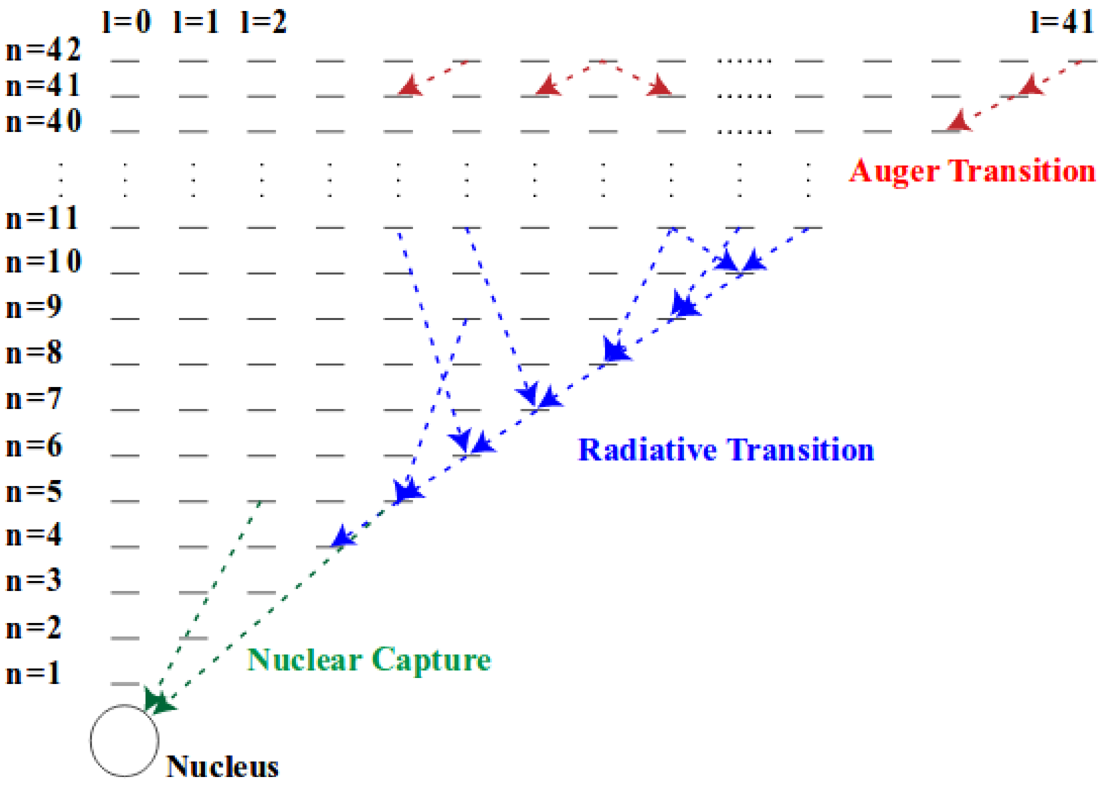
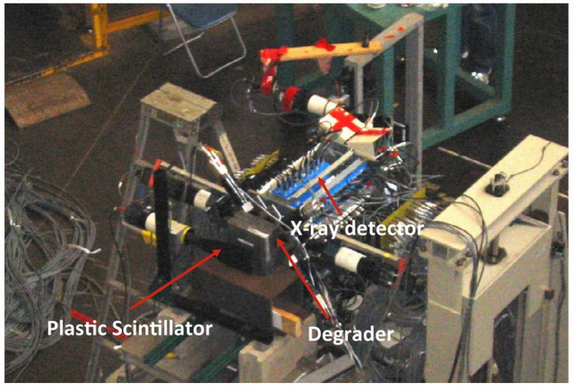
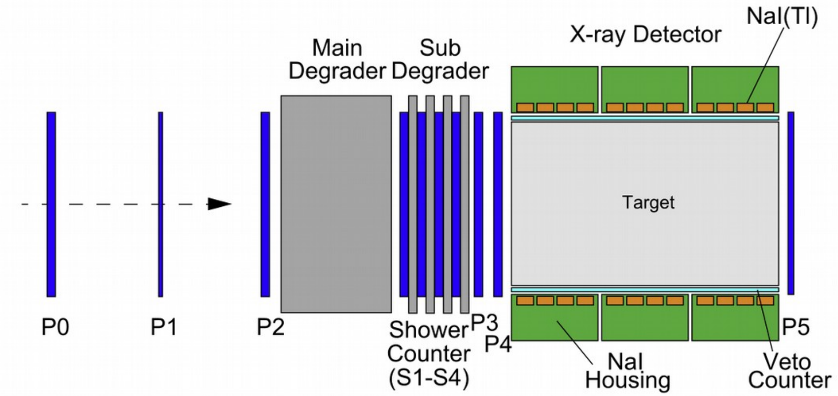


Image credit: Aramaki et al. 2013

Backup: KEK beam tests

- GAPS cascade model validated with data
- Extrapolate X-ray yield of pbar or dbar exotic atom formed by any material (active or structural) of GAPS detector
- dbar/pbar yield for Si target estimated at ~80%
- See Aramaki et al. 2013 for more details





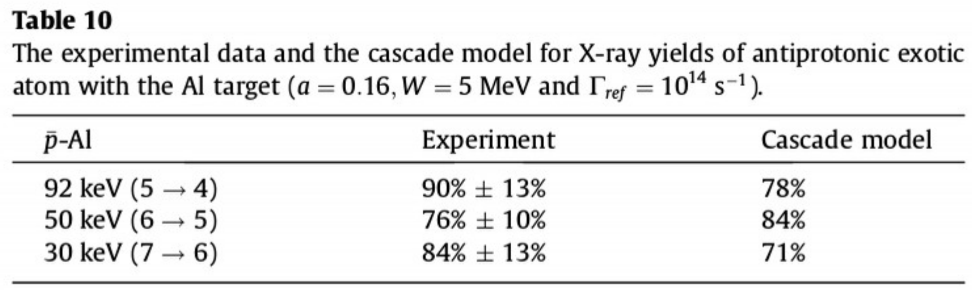


Table 10
The experimental data and the cascade model for X-ray yields of antiprotonic exotic atom with the Al target ($a = 0.16, W = 5$ MeV and $\Gamma_{ref} = 10^{14}$ s^{-1}).

$\bar{p}$-Al	Experiment	Cascade model
92 keV (5 → 4)	90% ± 13%	78%
50 keV (6 → 5)	76% ± 10%	84%
30 keV (7 → 6)	84% ± 13%	71%

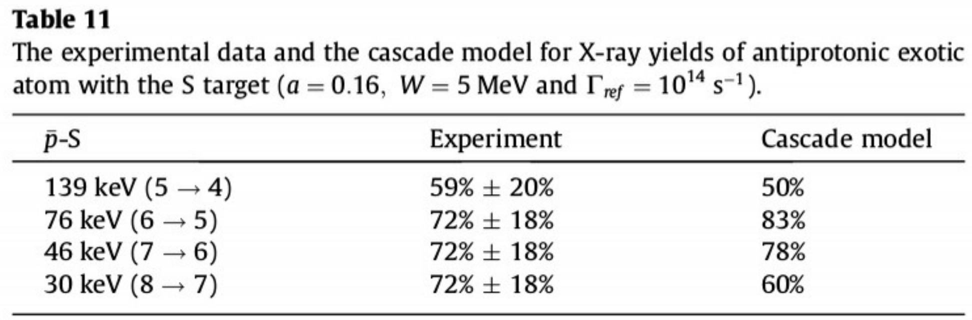


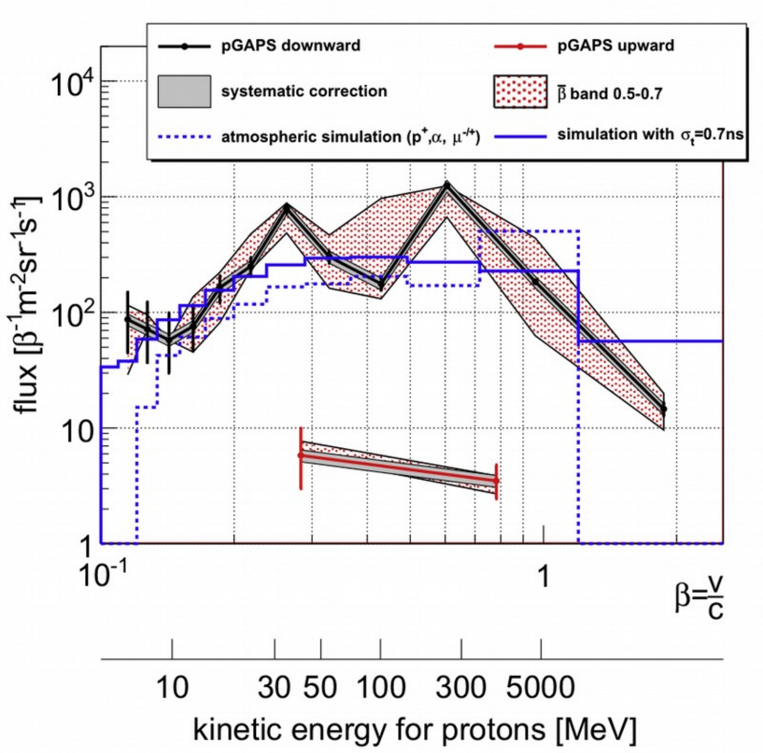
Table 11
The experimental data and the cascade model for X-ray yields of antiprotonic exotic atom with the S target ($a = 0.16,\ W = 5$ MeV and $\Gamma_{ref} = 10^{14}$ s^{-1}).

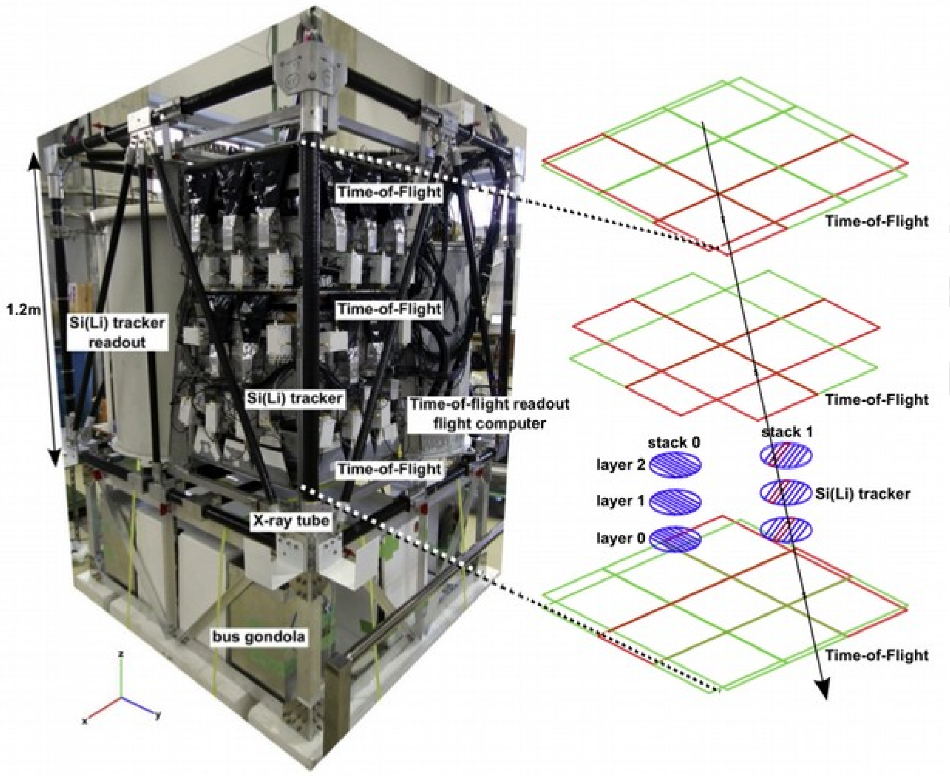
$\bar{p}$-S	Experiment	Cascade model
139 keV (5 → 4)	59% ± 20%	50%
76 keV (6 → 5)	72% ± 18%	83%
46 keV (7 → 6)	72% ± 18%	78%
30 keV (8 → 7)	72% ± 18%	60%

Image credits: Aramaki et al. 2013

Backup: pGAPS

- Prototype successfully flow in June 2012
- Si(Li) modules and TOF worked reliably, thermal model verified
- X-ray fluxes measured
- For comprehensive description see: von Doetinchem et al. 2014





Backup: Coalescence process

- (Anti)Nucleons close in phase space can form (anti)nuclei
- Coalescence momentum of 79 MeV
- Detailed description available in Donato et al. 2008

$$B_2 \equiv \sigma^{\mathrm{R}}_{\mathrm{inel}} \cdot E_{\bar{d}} \frac{d^3\sigma^{\mathrm{R}}_{\bar{d}}}{d\vec{k}_{\bar{d}}} \cdot \left(E_{\bar{\mathrm{p}}} \frac{d\sigma^{\mathrm{R}}_{\bar{\mathrm{p}}}}{d\vec{k}_{\bar{\mathrm{p}}}} \right)^{-2} ,$$

$$p_0 = \left(\frac{1}{B_2} \cdot \frac{m_{\bar{d}}}{m^2_{\bar{p}}} \cdot \frac{4\pi}{3} \right)^{-1/3} .$$

Equations 8, 9 from Donato et al. 2008