# Development of novel low-cost, large-area Si(Li) detectors

**Kerstin Perez**

Columbia University

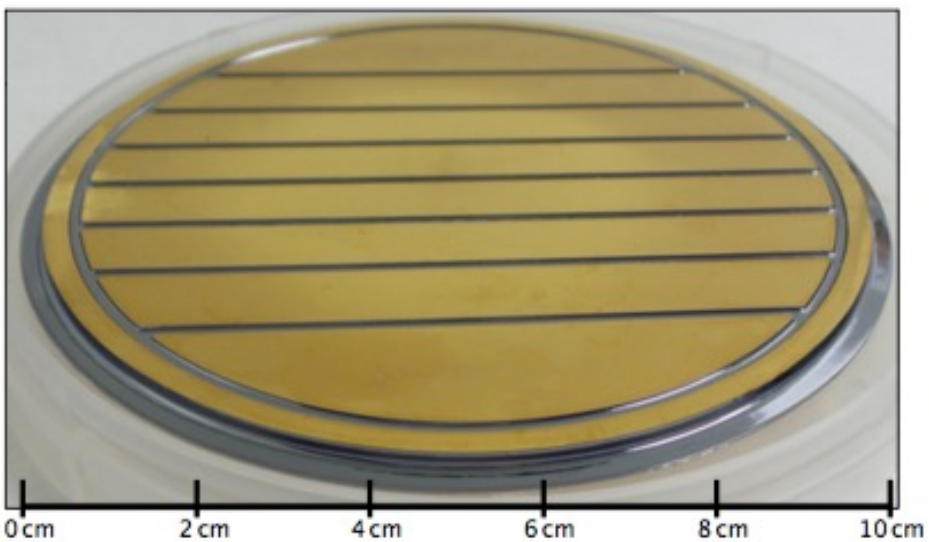
MIT

APS DPF Early Career Instrumentation Award

2022/07/24

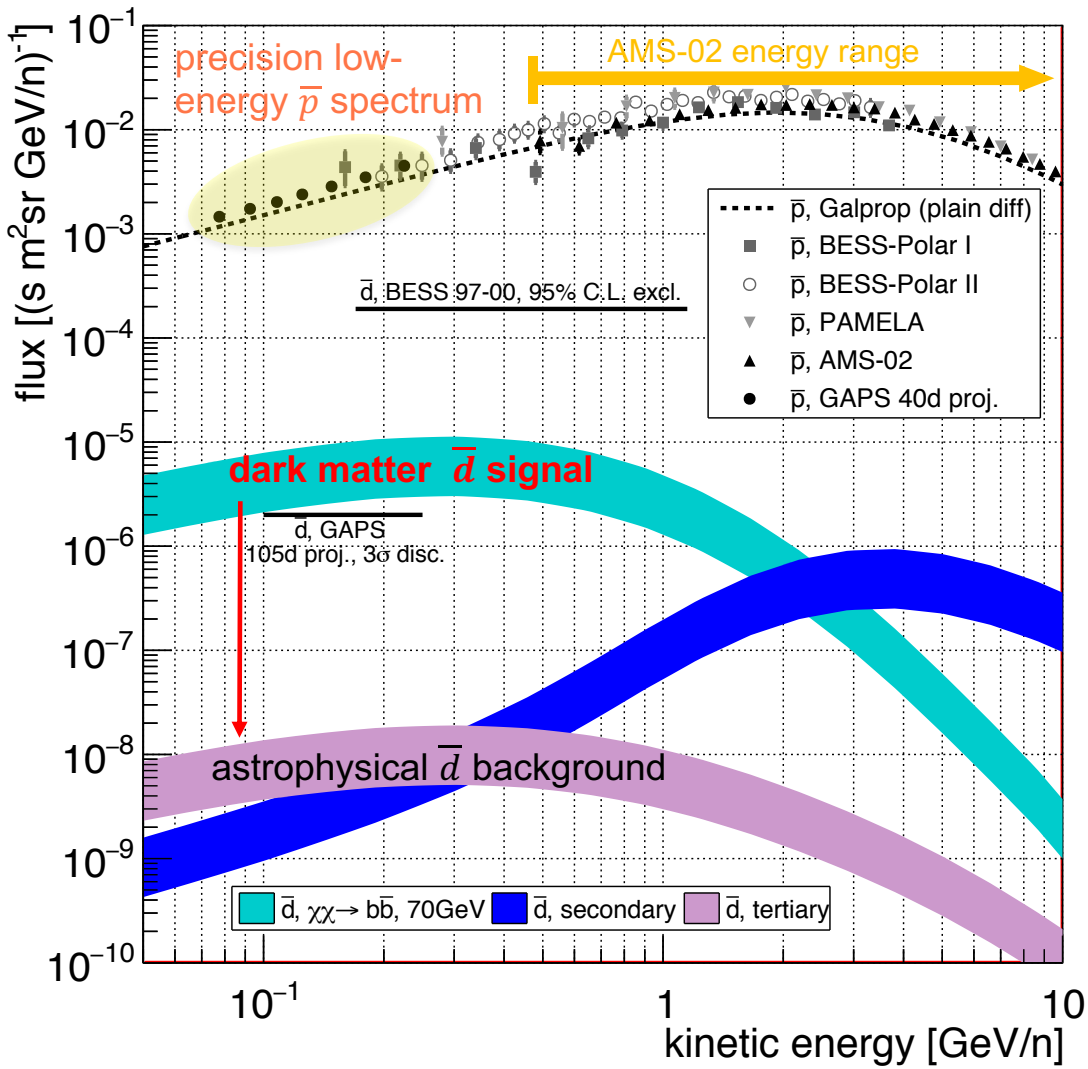
# High-performance, low-cost Si detectors

- Large area (10 cm diameter)
- Thick (2.5 mm)
- < 4 keV energy resolution
- High temperature (-35 C)
- Low power (250 V bias)
- Low cost (~$500 materials)
- High fabrication yield (~90%)
- >1000 detectors for GAPS




Si(Li) Detector = Lithium Drifted Silicon Detector

# GAPS: New physics in cosmic **antideuterons**




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

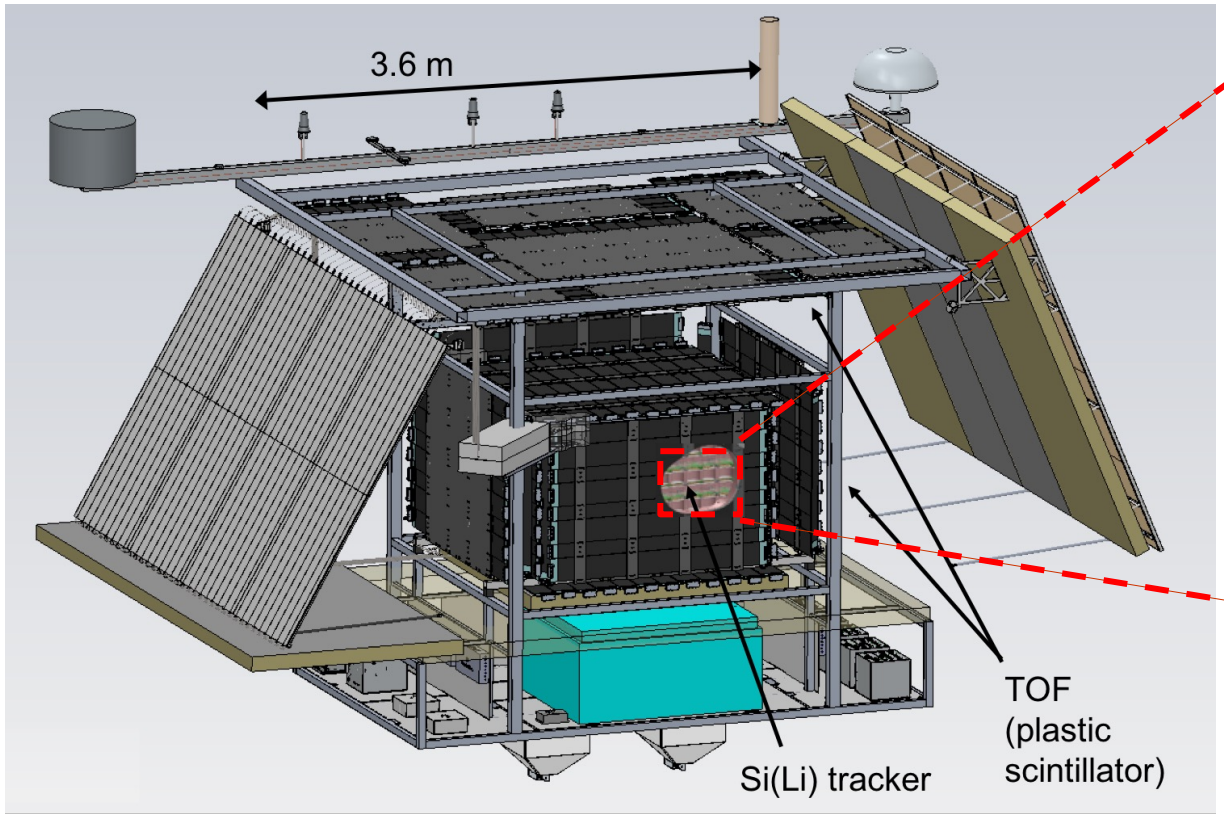
+ precision **antiproton** spectrum in unexplored low-energy range

+ unprecedented sensitivity to **antihelium**

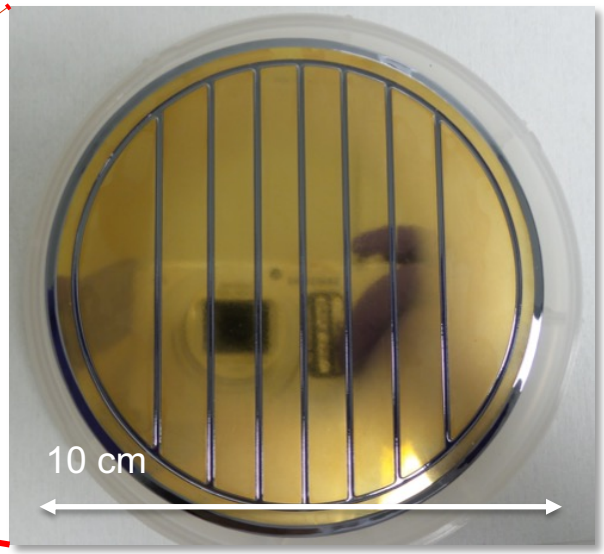
**First Antarctic balloon flight late 2023**

von Doetinchem, Perez, et al. (arXiv:2002.04163 , JCAP 2020)

# Si(Li) detectors are key to GAPS science goals




>1000 Si(Li) detectors



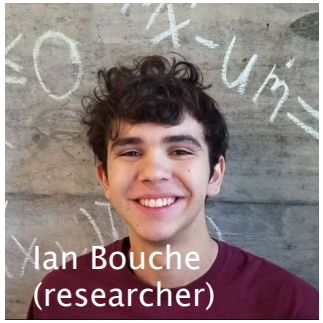

*Available for faculty!*



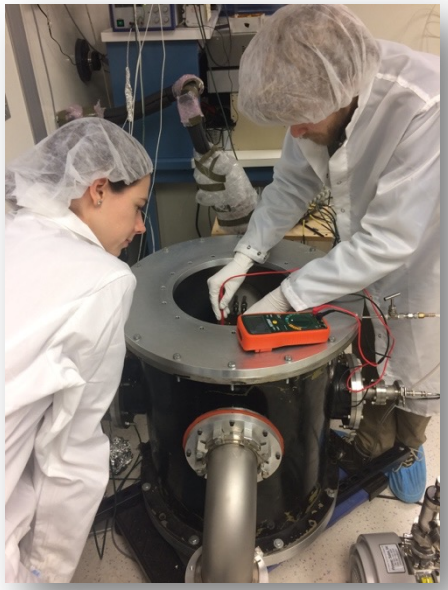
*Available for postdoc!*



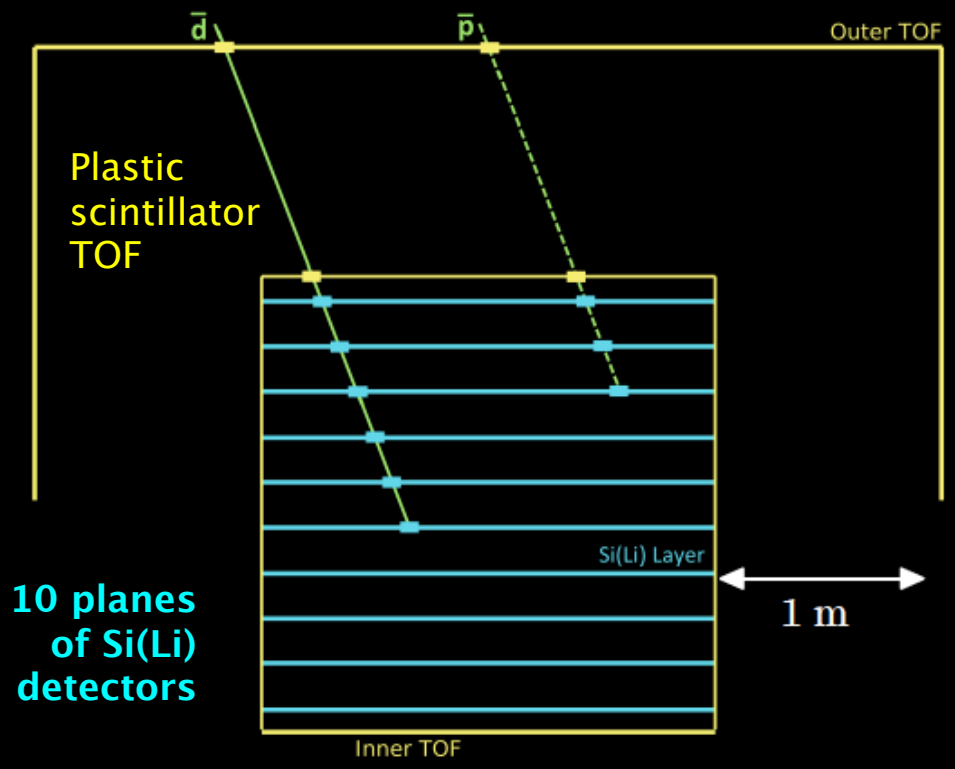
The MIT Si(Li) crew



# The GAPS Si(Li) Team



# 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

Extoic atom technique verified at KEK: Aramaki+ Astropart.Phys. 49, 52-62 (2013)
GAPS sensitivity to antideuterons: Aramaki+ Astropart.Phys. 74, 6 (2016)
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Illustration credit: A. Lowell (UCSD)

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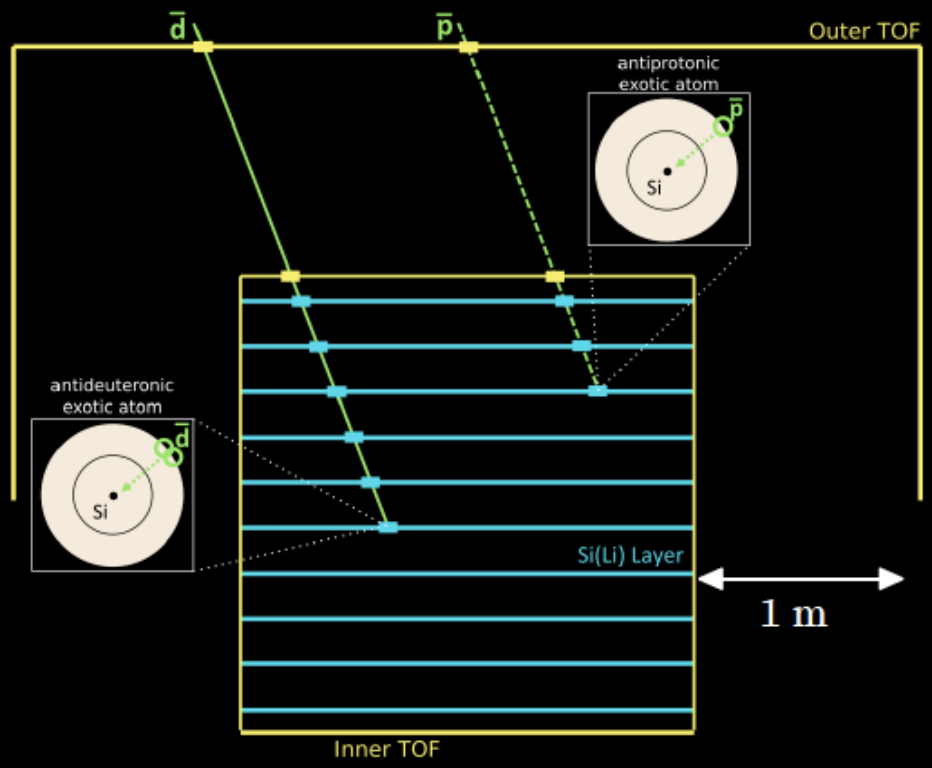


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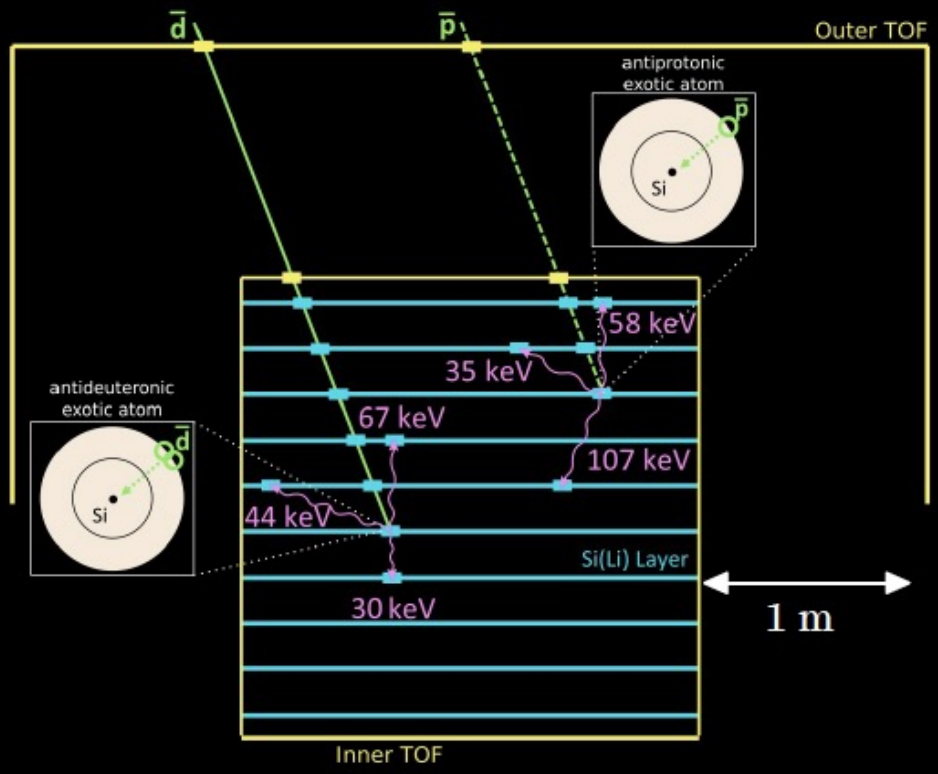


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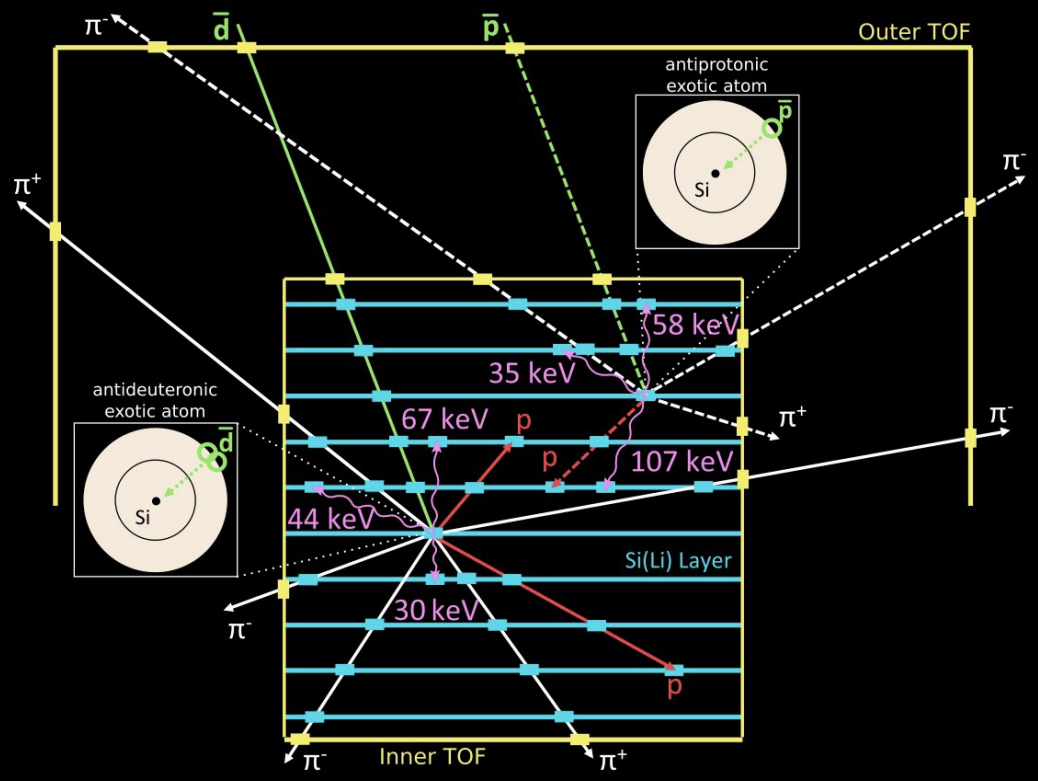


Time-of-flight system measures velocity and dE/dx

***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

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# On a balloon!

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

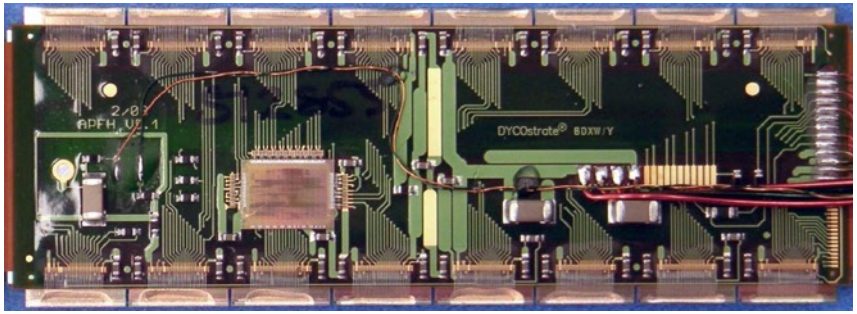
Key challenges:

- **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

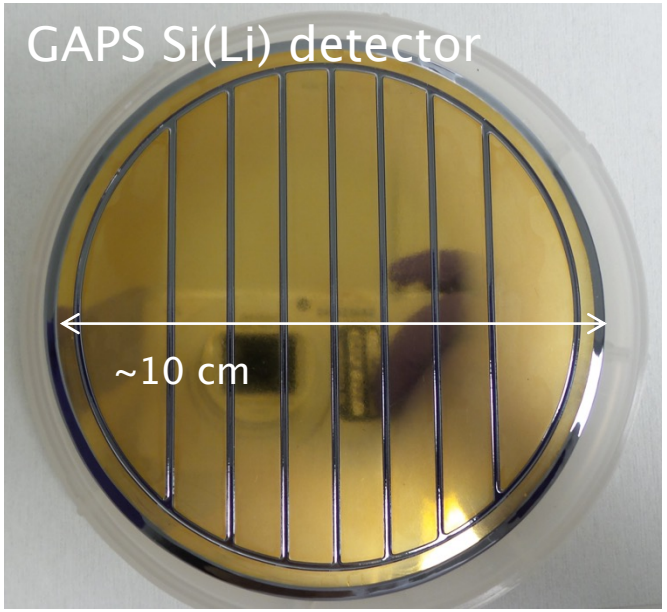
# Why Si(Li) Detectors?

ATLAS Si pixel module




- ~46k channels
- ~50 x 400 μm pixel size
- 250 μm thick

✓ ***spatial resolution*** ~10–100 μm




- 8 channels per detector
- ~2.5 cm wide strip
- 2.5 mm thick

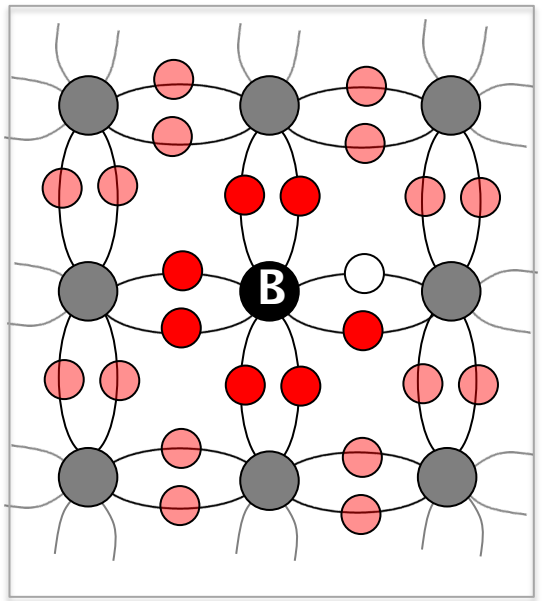
✓ ***tracking efficiency*** in low-multiplicity events

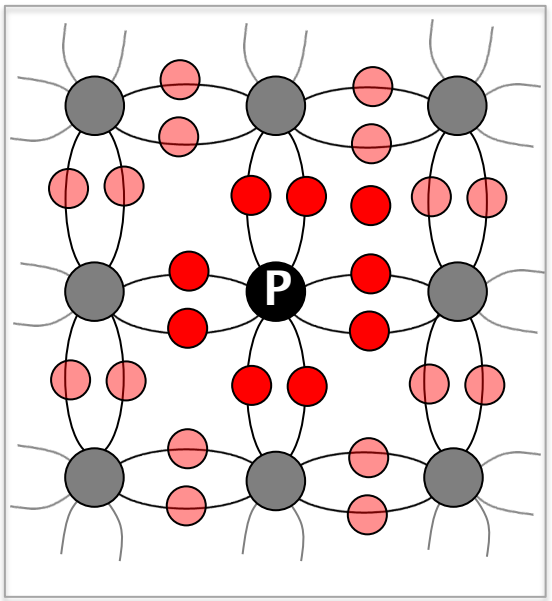
✓ ***stopping power*** up to 0.25 GeV/n

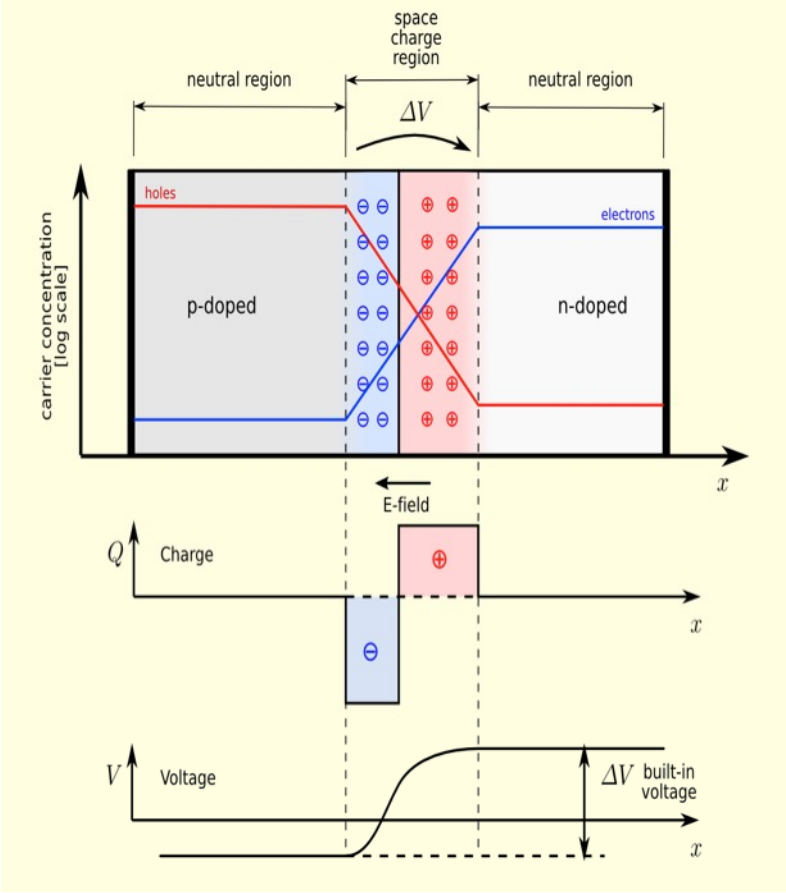
✓ ***energy resolution*** < 4 keV to distinguish X-rays

✓ ***active area*** totaling ***~10 m²***

# Doped materials used to make detectors




**P-type doping:**
Free positive hole
(Fixed negative ion)

**N-type doping:**
Free electron
(Fixed positive ion)

Image credit: Wikipedia commons

# Lithium-*drifted* detector fabrication

See e.g. F.S. Goulding
"Semiiconducting Detectors for
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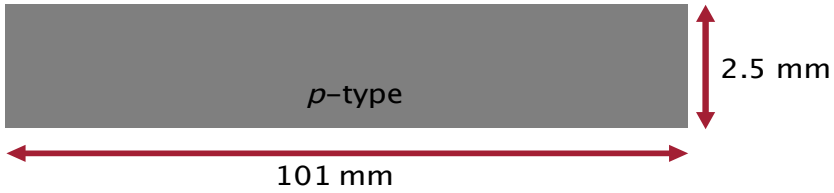
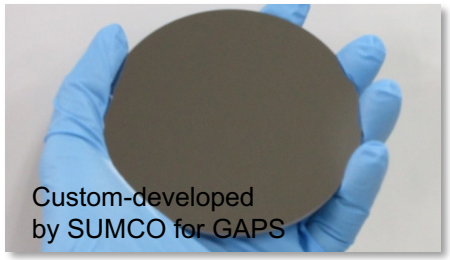



**Step 1:**
**Boron-doped Si**

*free hole,*
*fixed negative ion*



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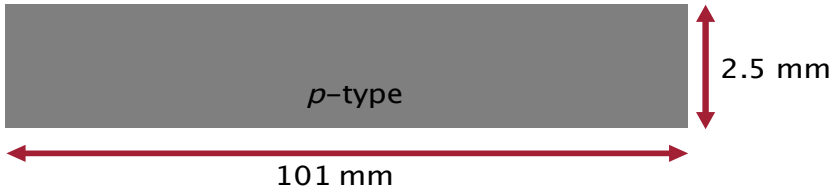


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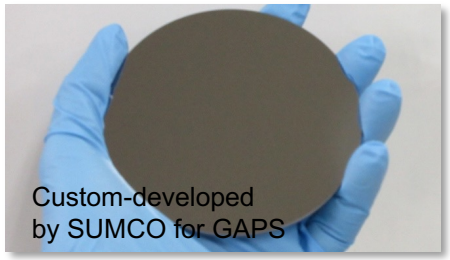


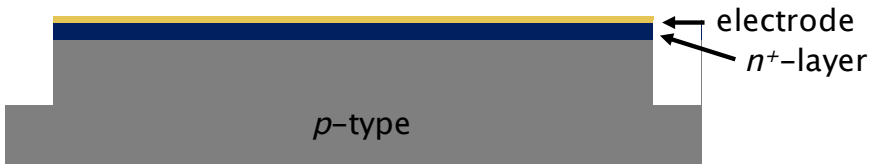


**Step 2:**
**Evaporate and diffuse Li**

Li easily ionized in Si
→ *free electron* (*n-type layer*)
High mobility in Si
→ *mobile positive Li ion*

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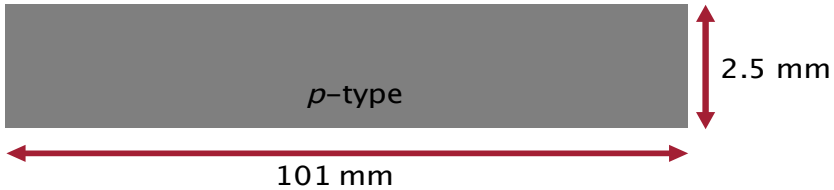


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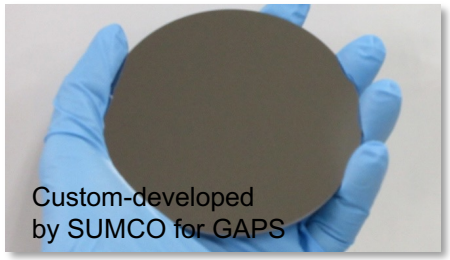


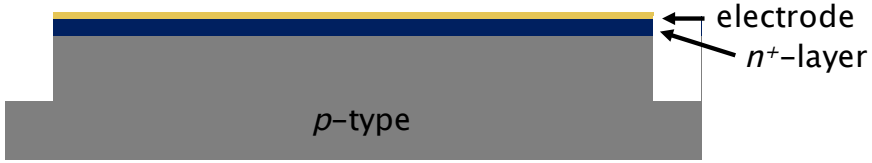


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**Step 3: Drift!**

- 100°C
- 600 V bias
- ~4 days

*Mobile Li+ ions compensate impurities in B-doped Si, creating extended charge-free regions*

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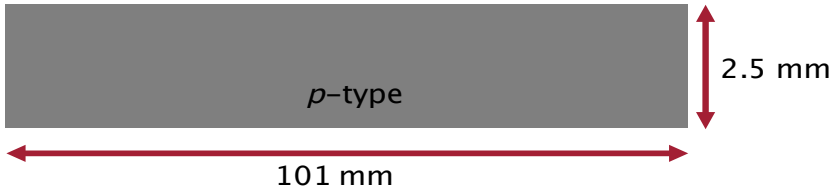


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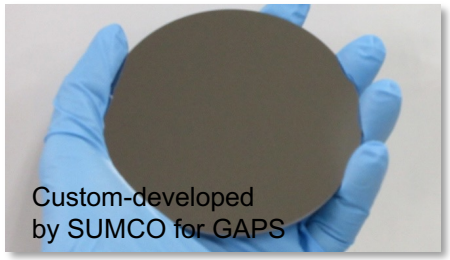


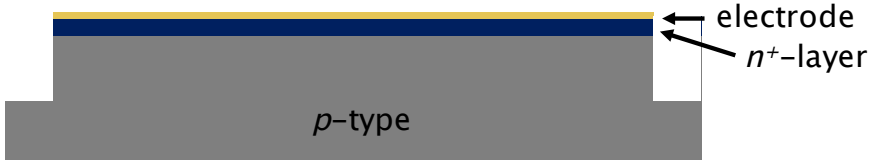


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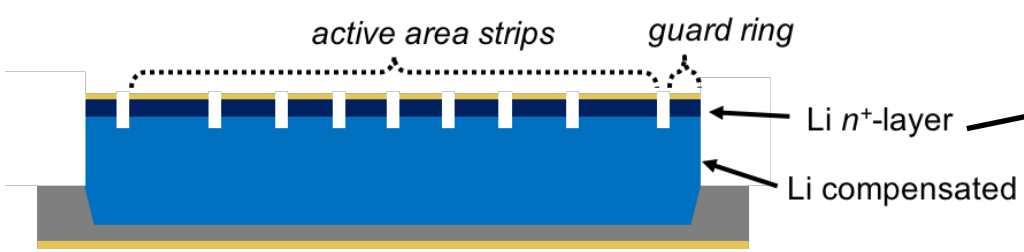
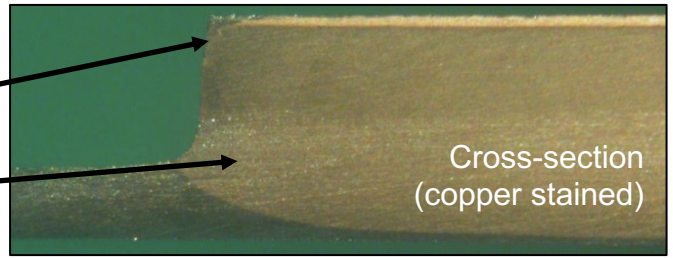
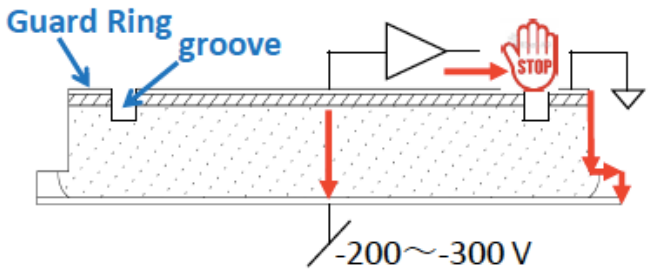


*"It would be no exaggeration to say that the least understood and most time-consuming aspect of semiconductor devices is the behavior of the region where a junction intersects the surface of the crystal." – F.S. Goulding (1963)*

**(1) Guard ring** structure prevents surface leakage current from entering readout circuit e.g. Goulding NIM 12 249-262 (1962)

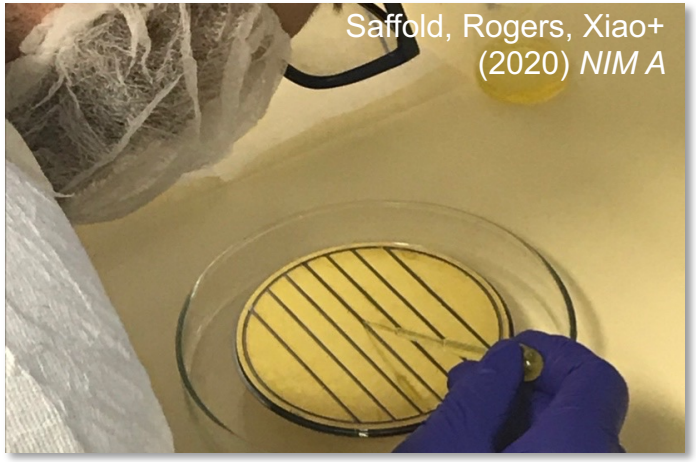



**(2) Chemical etching of grooves**

- Removes surface impurities
- Smooths surface
- Sets proper surface state (lightly *n*-type)

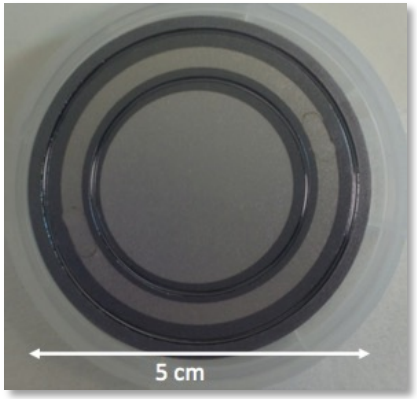
Kozai, Fuke, Yamada, Perez+ NIMA (2019)

**(3) Novel passivation** necessary to preserve surface state, protect from environmental degradation



# 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)

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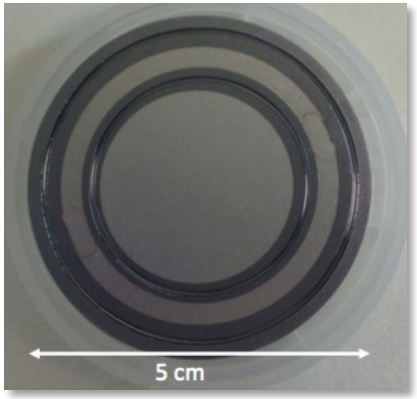
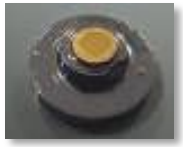



Perez+ NIM A905 12-21 (2018)

SHIMADZU
Excellence in Science



- Small diameter < 1 cm
- Low operation temperature (Liquid nitrogen temperature)

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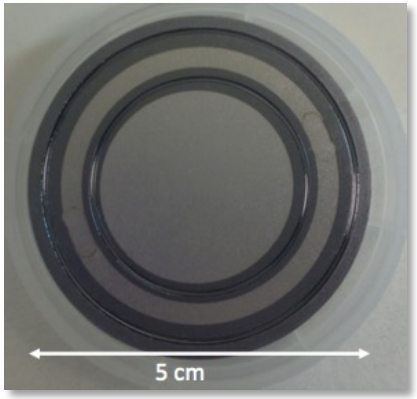
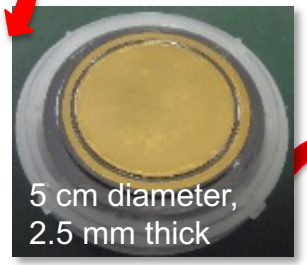


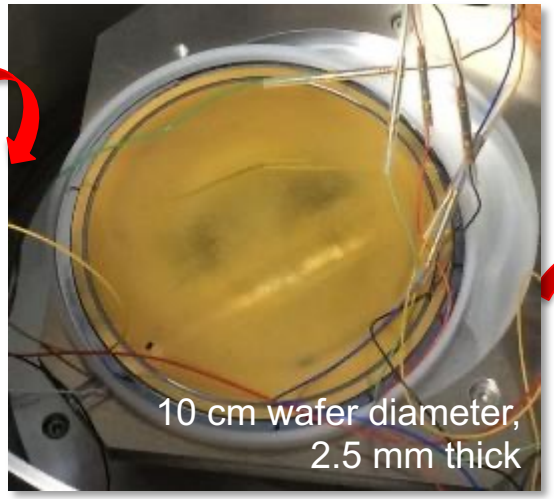

Perez+ NIM A905 12-21 (2018)

SHIMADZU
Excellence in Science

Commercial products:
~10 mm diameter
~3 mm thick

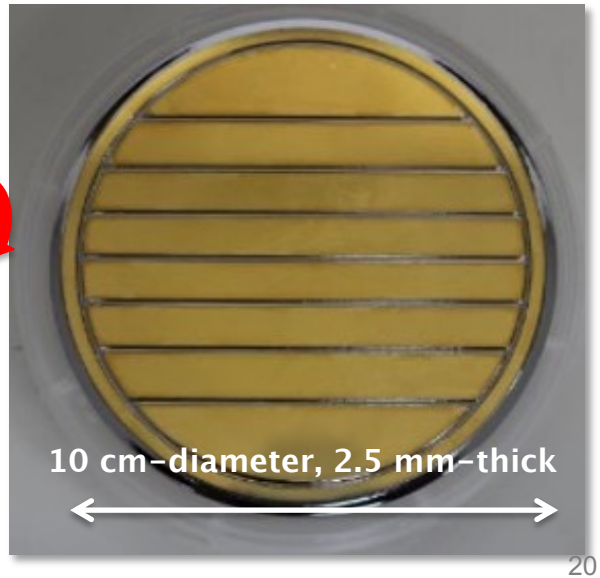



**2015**




**2016**

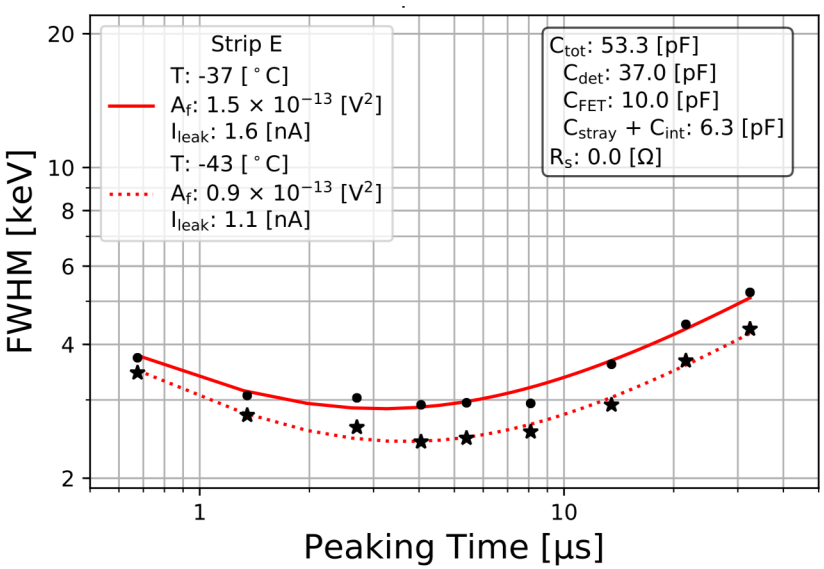
**Flight production completed!**
**2018-2020**

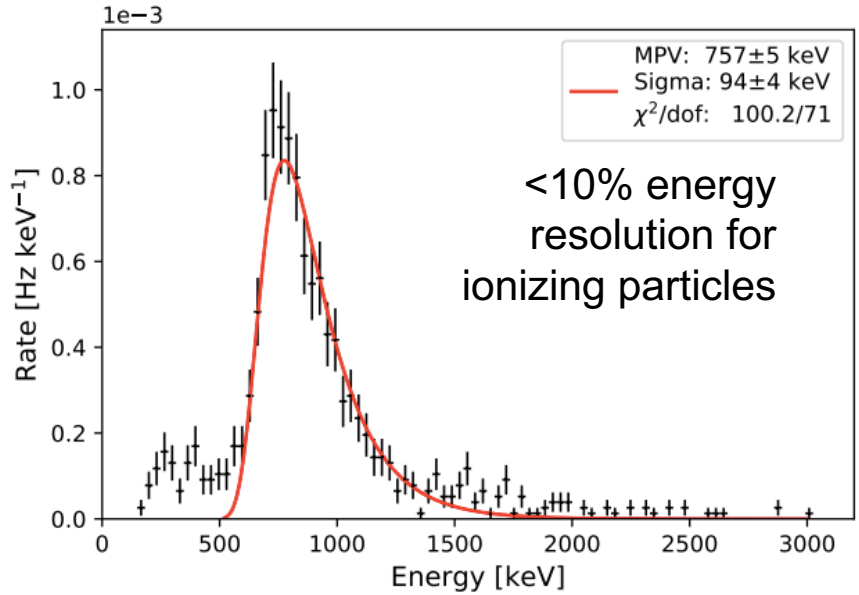



*Future applications:*
*Si(Li) for use in heavy nuclei ID at NSCL/FRIB*

Kozai, Fuke, Yamada, Perez+ NIM (2019)
Saffold, Rogers, Xiao+ NIM (2020)

# Achieved < 3 keV energy resolution at -40 C!



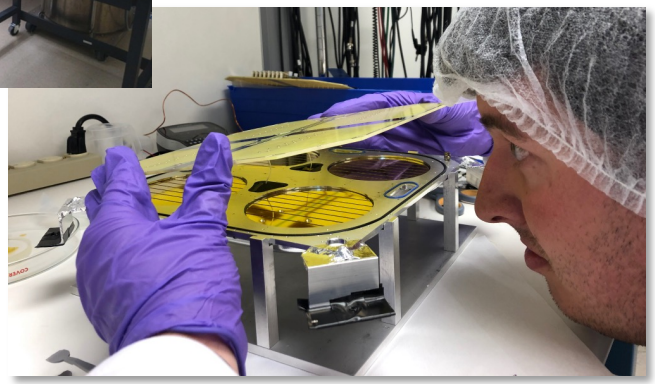

↑ Noise model allows to predict resolution in-flight, with new generations of readout, varying temperature

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

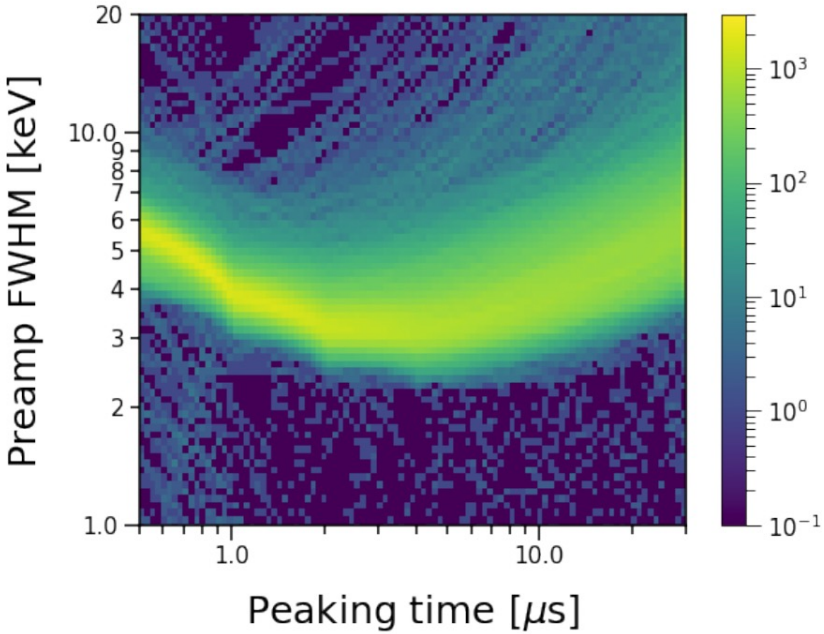
Rogers, Xiao, Perez, et al. Proc. IEE NSS (2019).

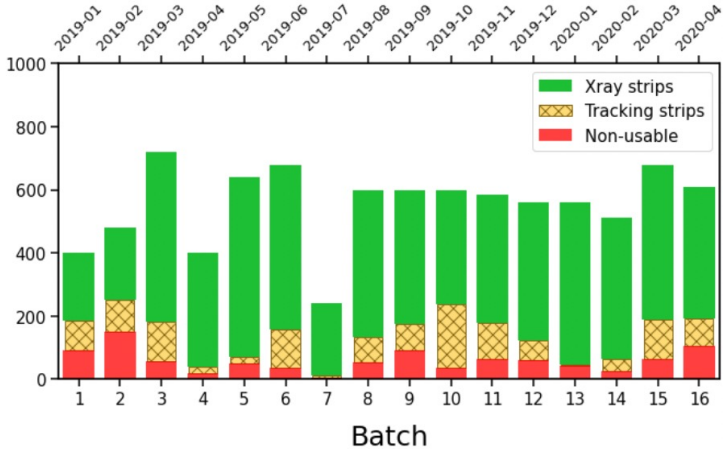
# *Completed!* Characterization of >1000 detectors


Duplicate, parallel facility at UHawaii



M. Xiao, Stoessel, Roach, Gerrity+ (2022) in prep.



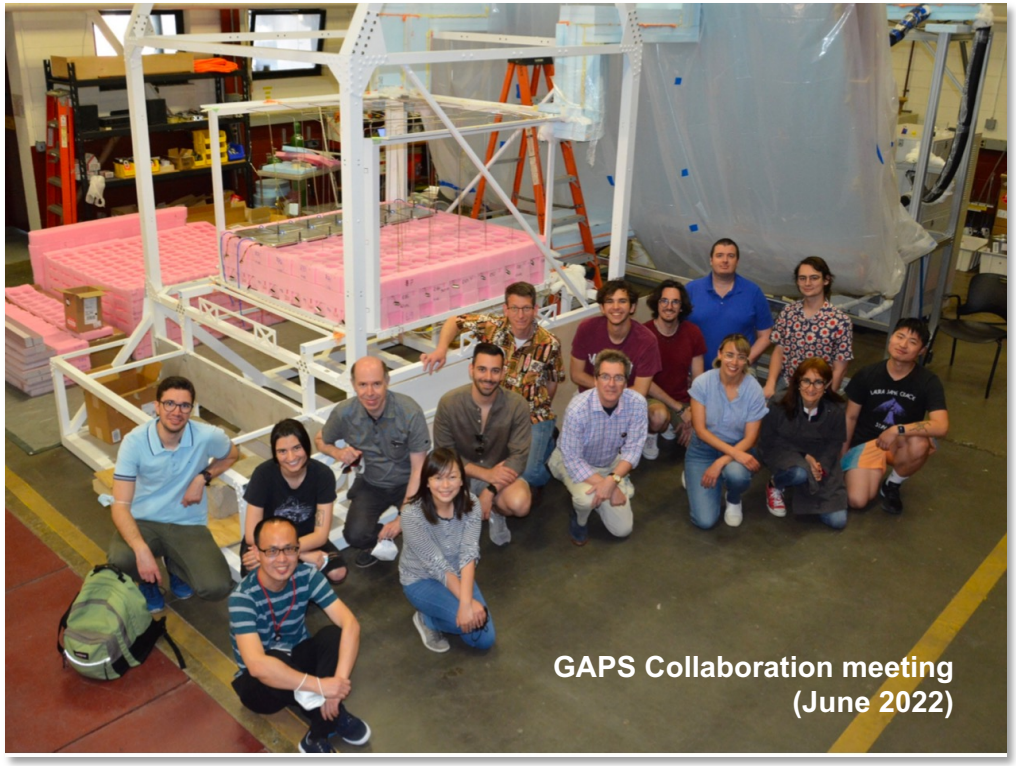



# Initial Antarctic GAPS flight in late 2023!

- Large-area Si(Li) detectors developed to meet the unique temperature, power, cost constraints of the GAPS Antarctic balloon experiment

- Experiment integration well underway!

- **Return to R&D will allow improvements, custom designs for broader applications**




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

# *Back to the future*: in-house fabrication