

Large-area Si(Li) Detectors for X-ray Spectrometry and Particle Tracking

Kerstin Perez 

Workshop on Techniques and Detectors
for Heavy-ion Charge-State Identification
in High-acceptance Spectrometers

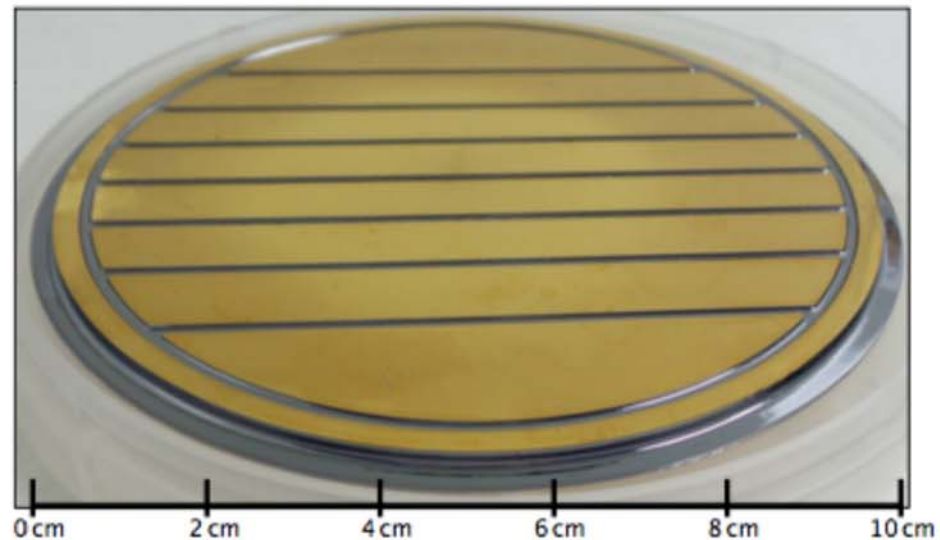
2020/12/17



High-performance, low-cost Si detectors



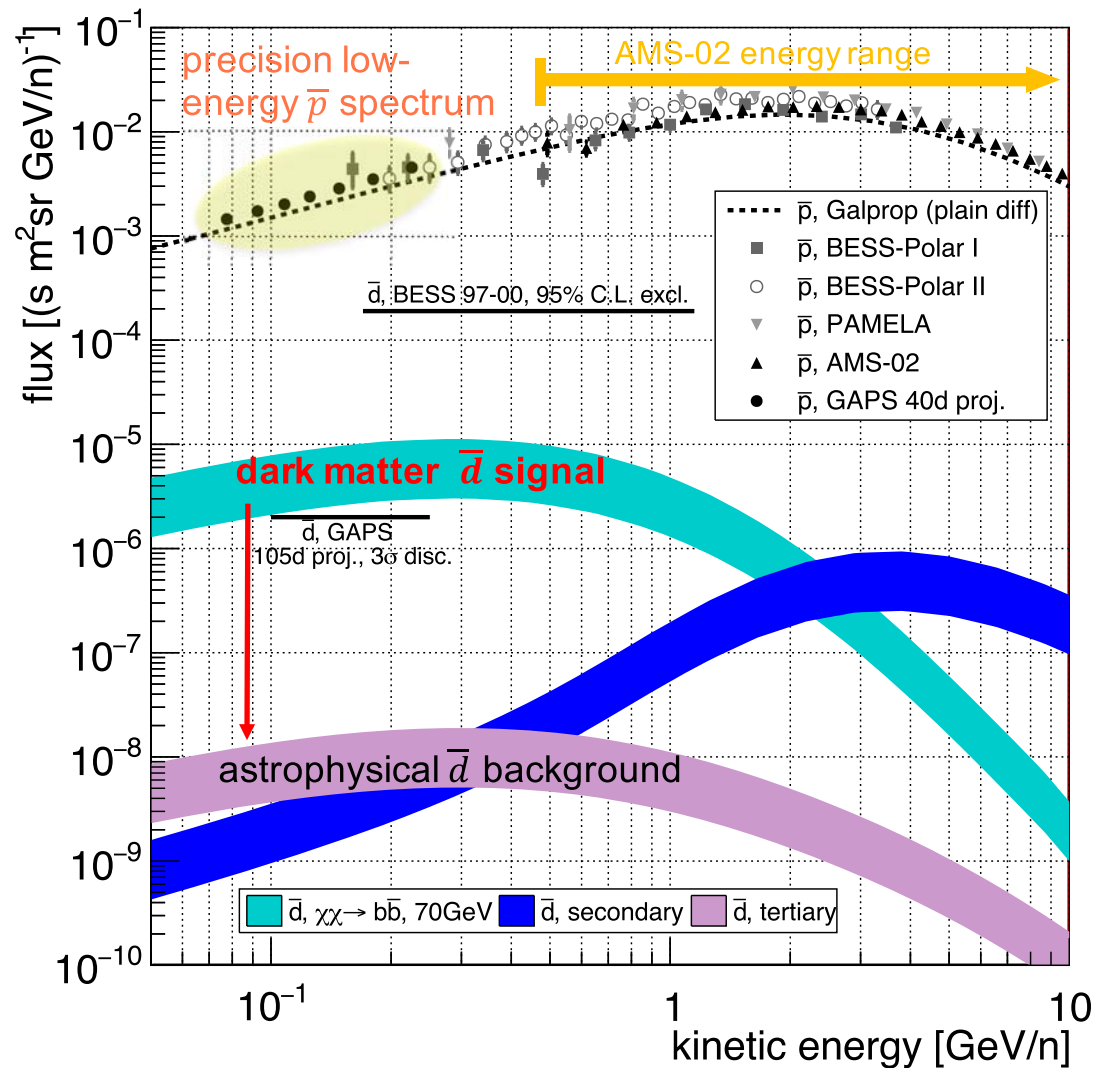
- Large area (10 cm diameter)
- Thick active depth (2.3 mm)
- < 4 keV energy resolution
- High temperature (-35 °C)
- Low cost (~\$500 materials)
- Low power (250 V bias)
- High fabrication yield (~90%)
- > 1000 detectors for GAPS!



Si(Li) Detector = Lithium Drifted Silicon Detector

- *Lithium-drifted Si* detectors for The General Antiparticle Spectrometer (GAPS)
- Why Si(Li)?
- How to build a Si(Li) detector
- Onwards! Resuming in-house R&D

GAPS: New physics in cosmic antideuteron



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

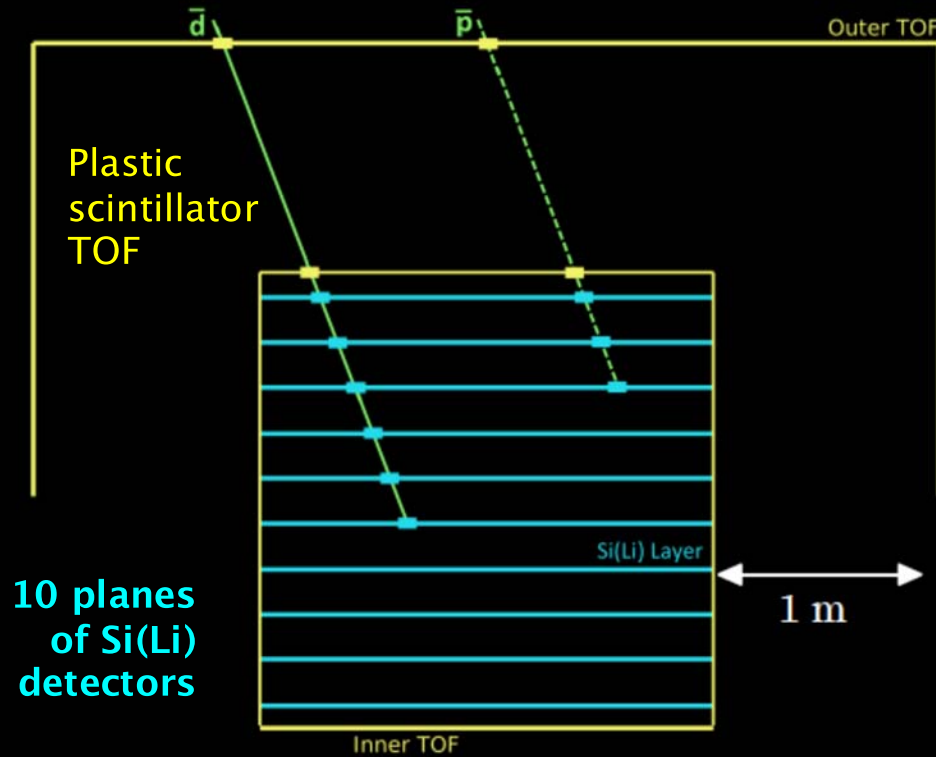
A generic ***new physics*** signature with *essentially zero* conventional astrophysical background

+ precision antiproton spectrum in unexplored low-energy range

+ unprecedented sensitivity to antihelium

First Antarctic balloon flight late 2022

Novel detection of low-energy cosmic antinuclei



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

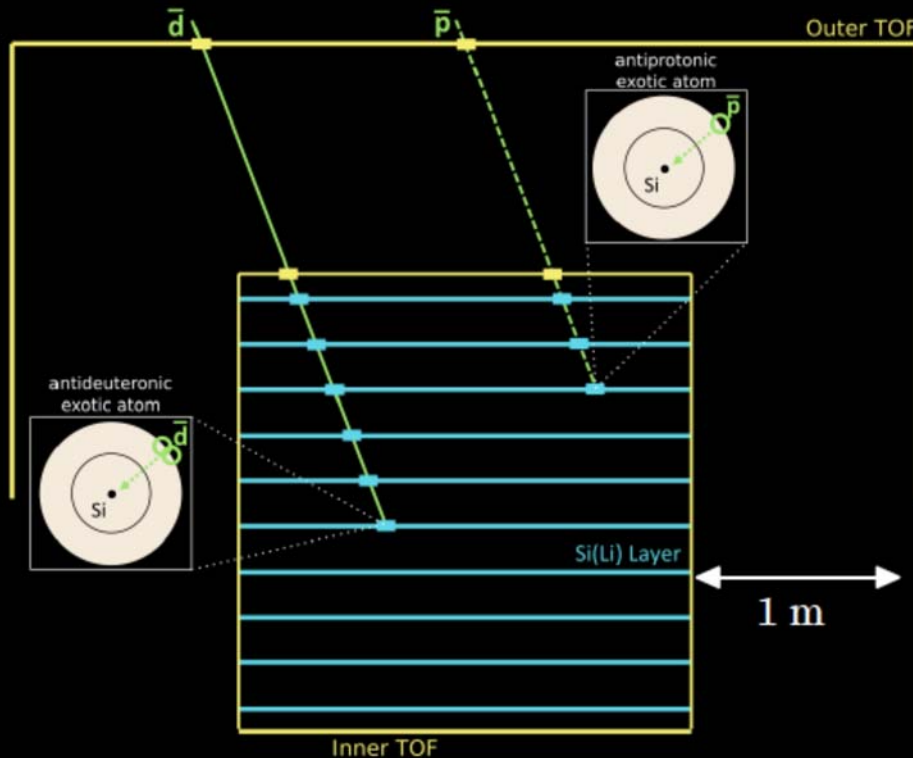
Si(Li) tracker acts as:

- ***target*** to slow and capture an incoming antiparticle

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

Illustration credit:
A. Lowell (UCSD)

Novel detection of low-energy cosmic antinuclei



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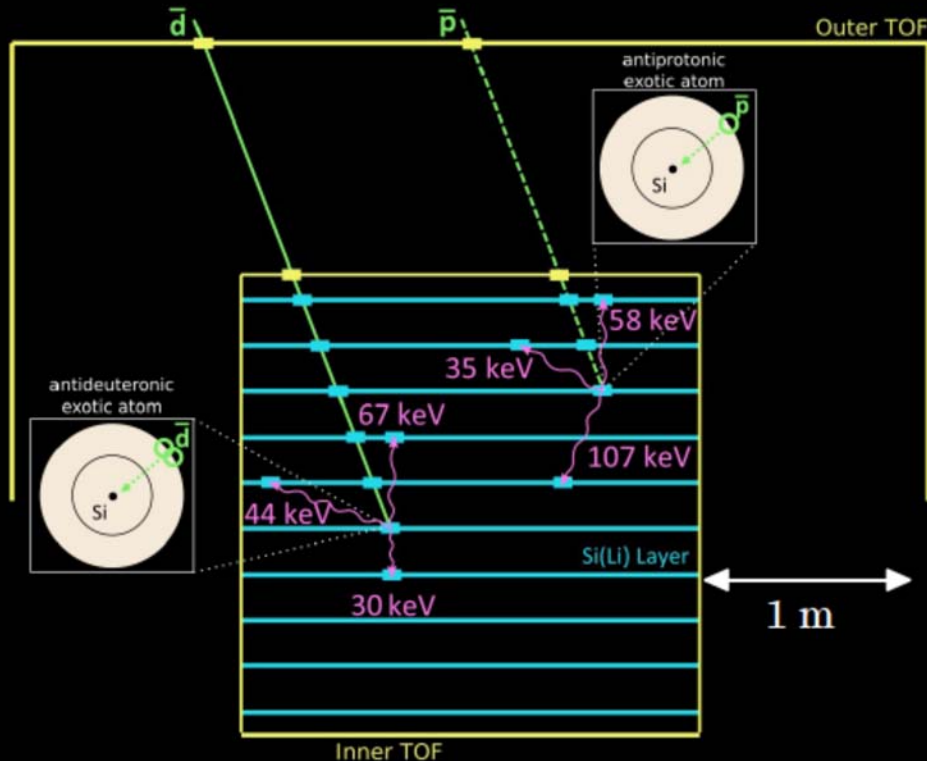
Si(Li) tracker acts as:

- **target** to slow and capture an incoming antiparticle into an **exotic atom**

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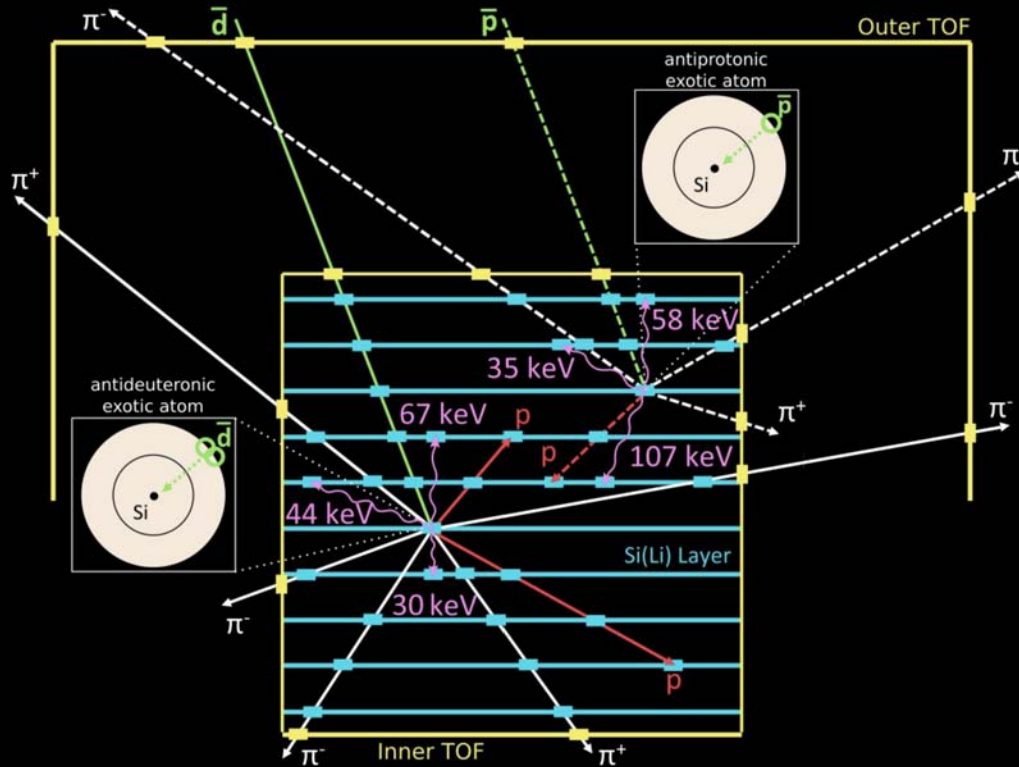
Si(Li) tracker acts as:

- **target** to slow and capture an incoming antiparticle into an exotic atom
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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

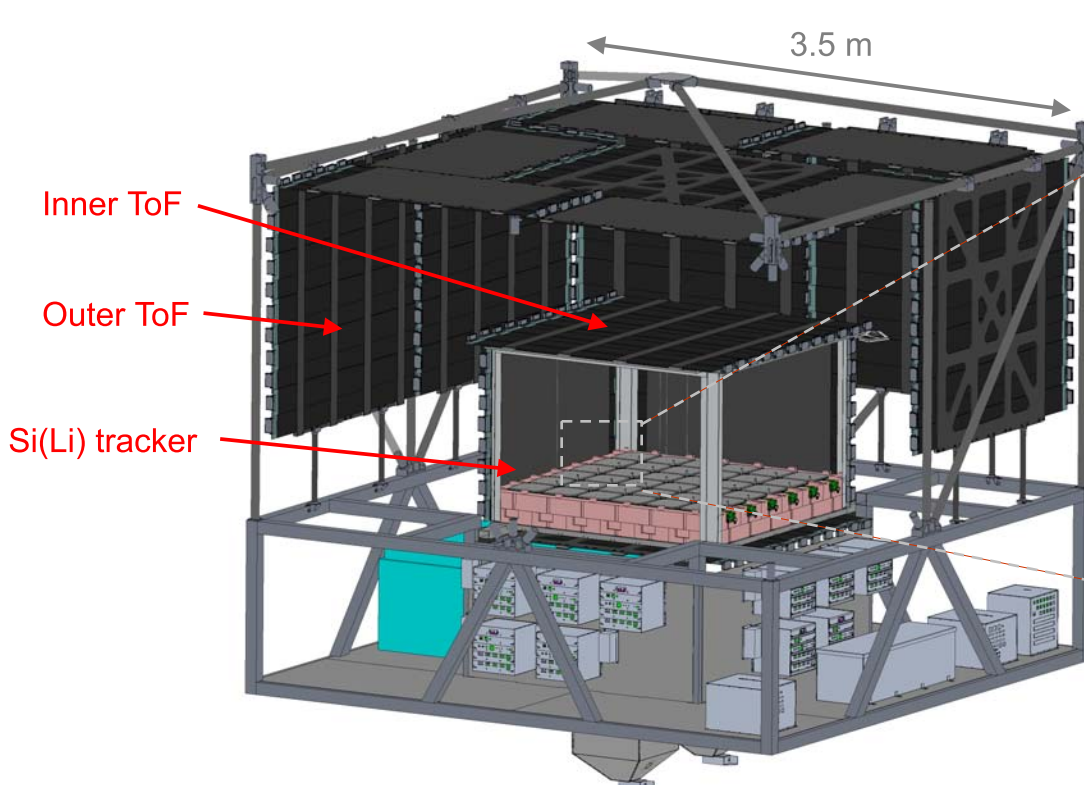
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Si(Li) detectors are key to GAPS science goals

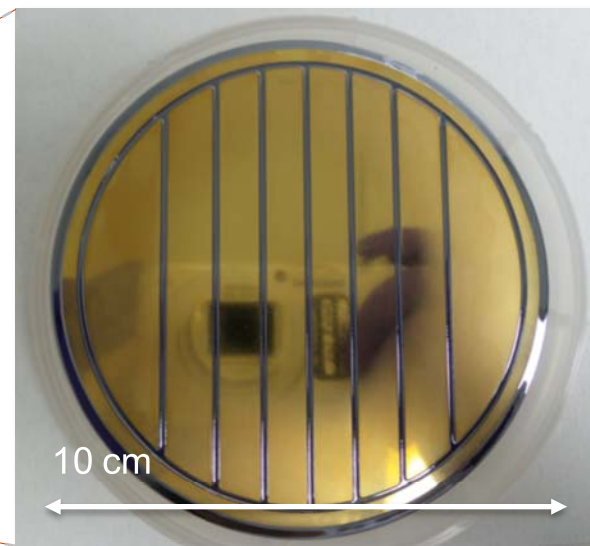


Plastic scintillator TOF

- high-speed trigger and veto (< 400 ps timing reso)



1440 Si(Li) detectors



Si(Li) tracker

1. X-ray identification
2. dE/dx
3. stopping depth
4. particle multiplicity, vertex reconstruction
5. **$>10 \text{ m}^2$ of active area**

On a balloon!



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

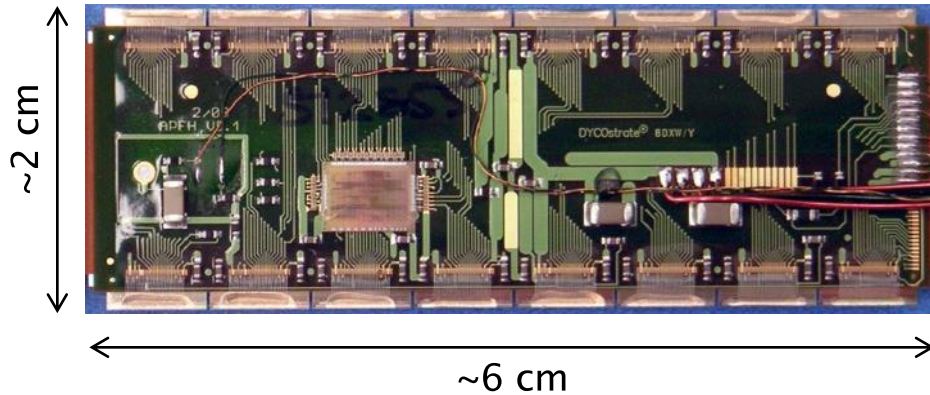
Key challenges:

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

Why Si(Li) Detectors?



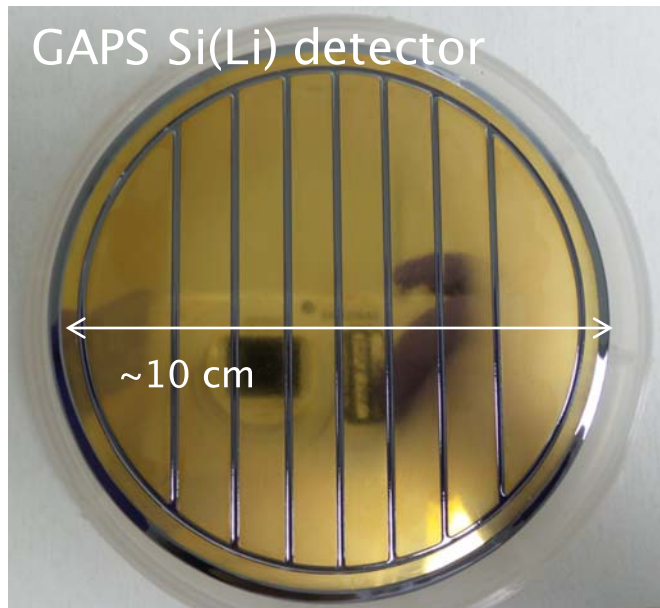
ATLAS Si pixel module



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

Delivers ***spatial resolution*** 10 μm in r- ϕ ,
115 μm in z (or r)

GAPS Si(Li) detector

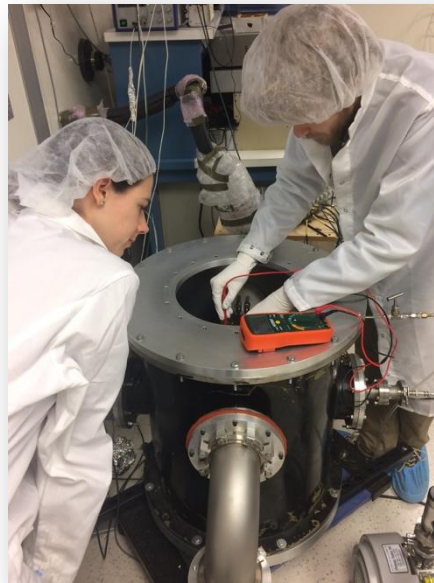


- 8 channels per detector
- ~2.5 cm wide strip
- 2.5 mm thick
- ✓ ***tracking efficiency*** sufficient to distinguish X-rays, annihilation products, incident cosmic rays
- ✓ ***stopping power*** to capture d up to 0.25 GeV/n
- ✓ ***energy resolution*** < 4 keV at to distinguish X-rays from different antiparticles
- ✓ ***active area*** totaling ~**10 m²**

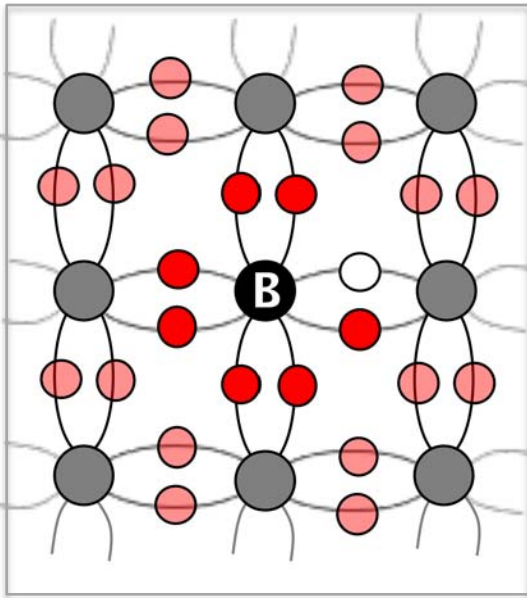
GAPS Si(Li) Development Team



**Massachusetts
Institute of
Technology**

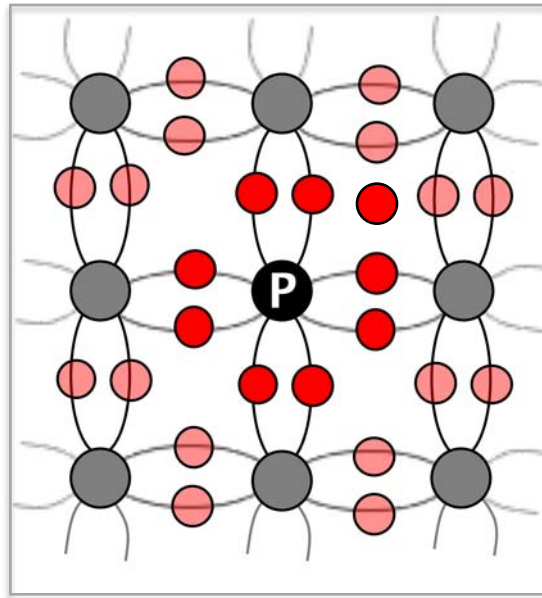


Doped materials used to make detectors



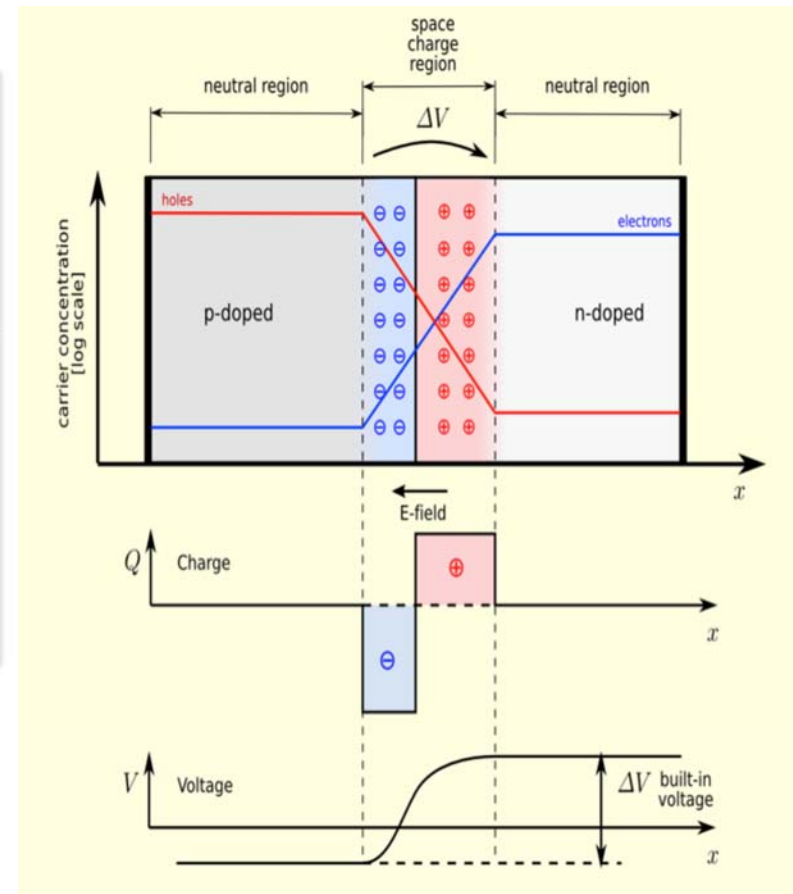
P-type doping:
Free positive hole
Fixed negative ion

An *acceptor* impurity



N-type doping:
Free electron
Fixed positive ion

A *donor* impurity



Lithium-drifted Si detector fabrication



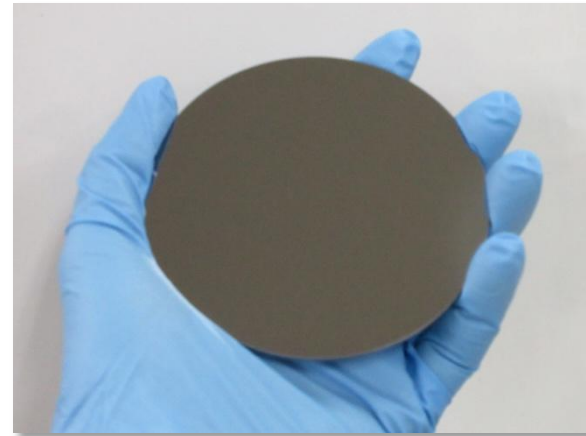
Lithium ions compensate impurities in boron-doped Si, creating
extended charge-free regions

Lithium-drifted Si detector fabrication

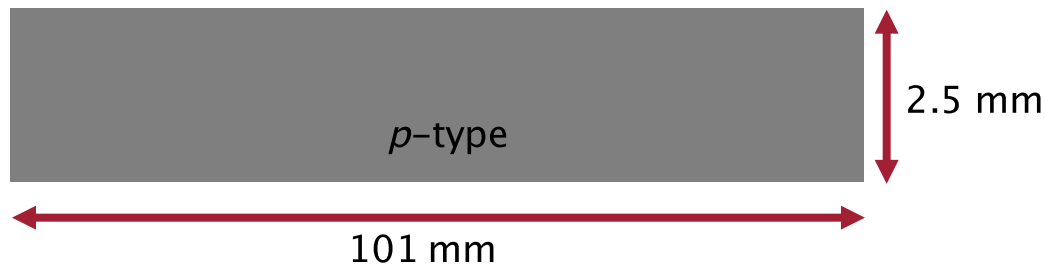


1. B-doped, *p*-type substrate wafers
2. Evaporate and diffuse Li for *n*⁺-layer
3. Form top-hat structure to control drift
4. Evaporate Ni + Au electrodes
5. Drift Li through wafer
6. Form guard ring + strips
7. Apply polyimide passivation

High quality, inexpensive boron-doped silicon substrate developed for GAPS by SUMCO Corporation



➤ \$400 per wafer vs several \$1000



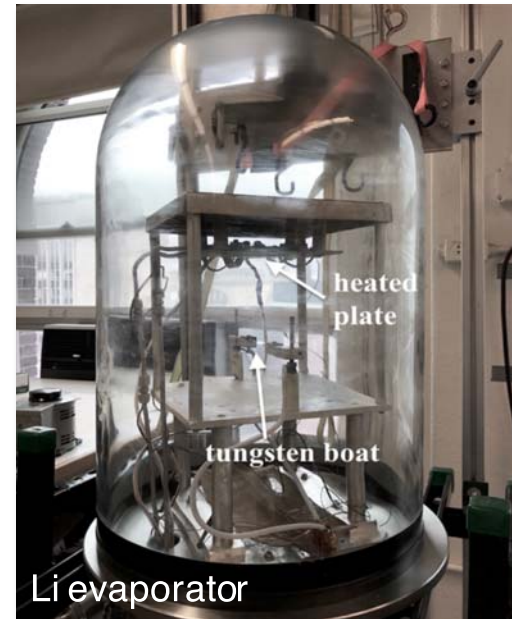
Crystal orientation	(1-1-1) ±1°
Bulk ingot lifetime	> 400 μs
Resistivity	800-2000 Ω-cm
O impurity	< 2 × 10 ¹⁶ atoms cm ⁻³
C impurity	< 2 × 10 ¹⁶ atoms cm ⁻³

Perez+ NIM A (2018)
arXiv:1807.07912

Kozai+ NIM A (2019)
arXiv:1906.05577

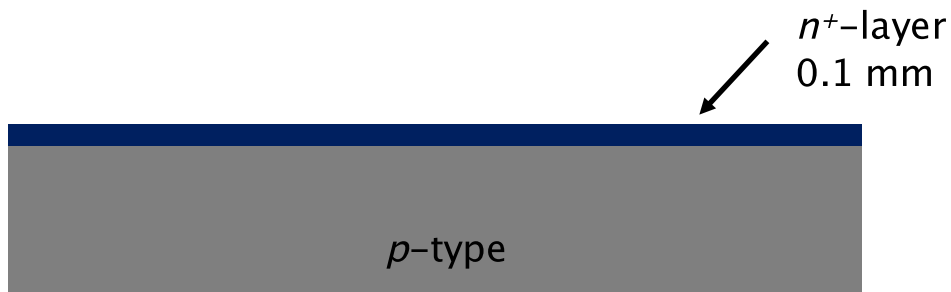
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Prototype in-house evaporation facility

1. Li easily ionized in Si, donates electrons
→ n -type layer
2. High mobility in Si
→ mobile positive Li ion



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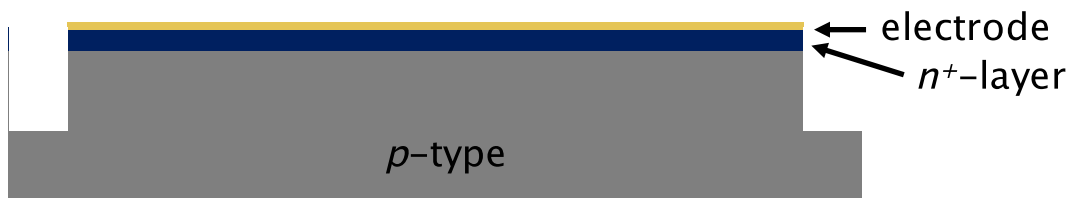


Prototype
fabrication
facility

Ultrasonic
impact grinder



Commercial thermal
evaporator for Au/Ni



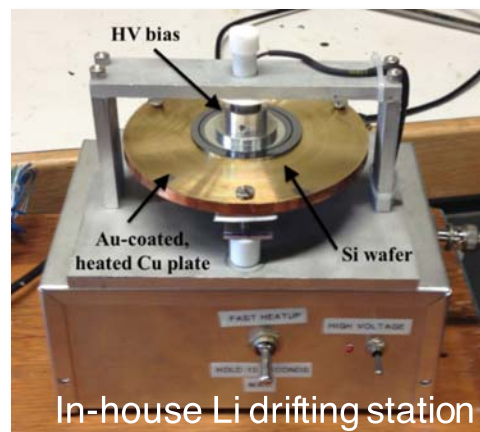
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Mobile Li^+ ions
compensate impurities in B-doped Si,
creating extended charge-free regions



2.3 mm drift:

- 100°C
- 600 V bias
- ~4 days

In-house Li drifting station

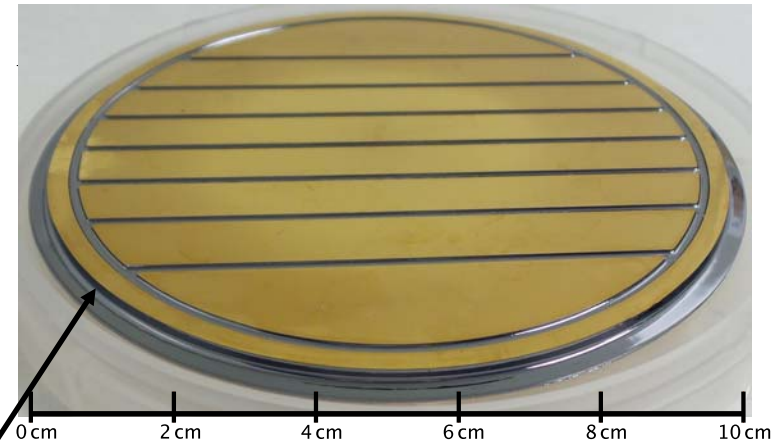
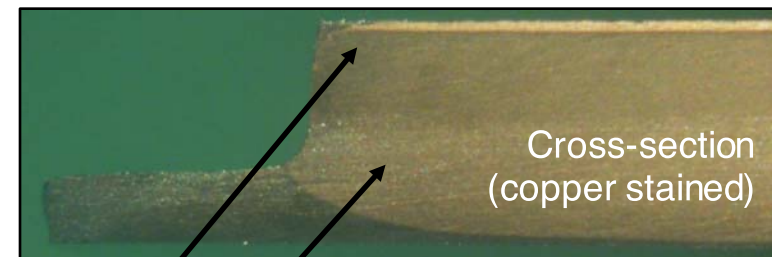
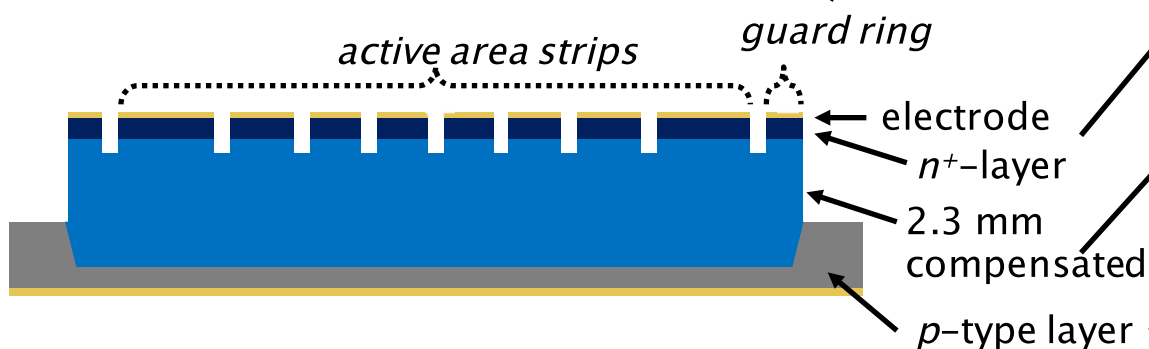


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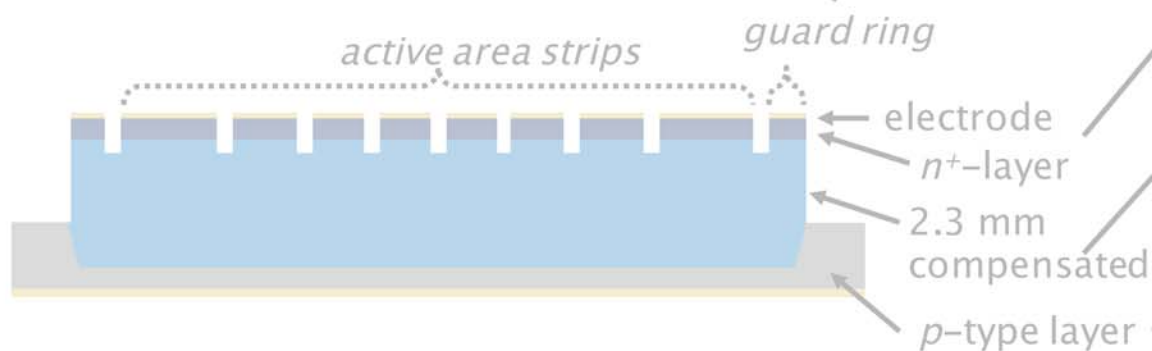


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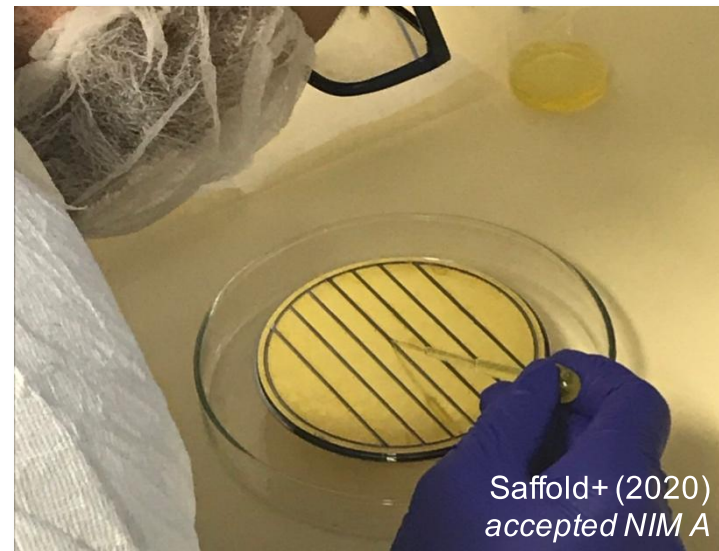


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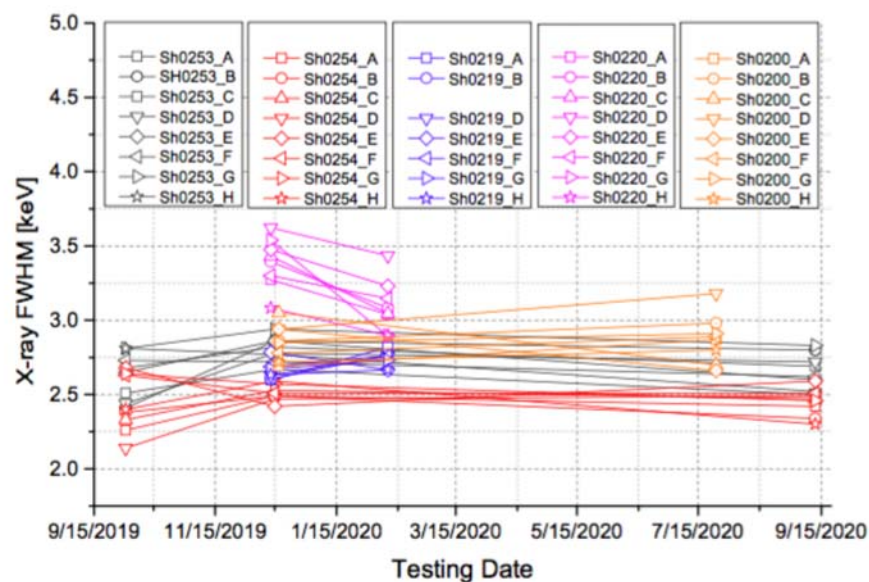
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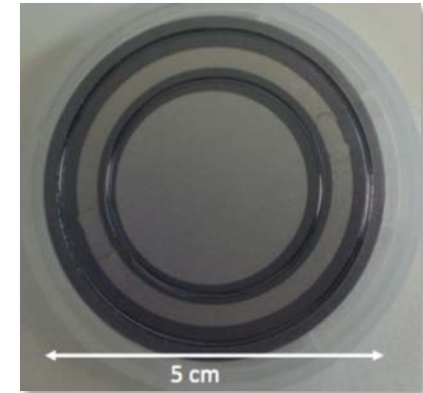
Silane + thermally-cured polyimide protects Si surfaces from humidity and other environmental conditions



Rapid, successful development of flight detectors



In-house prototype Si(Li) detectors:
5-cm diameter, 1-1.75 mm thick



Rapid, successful development of flight detectors



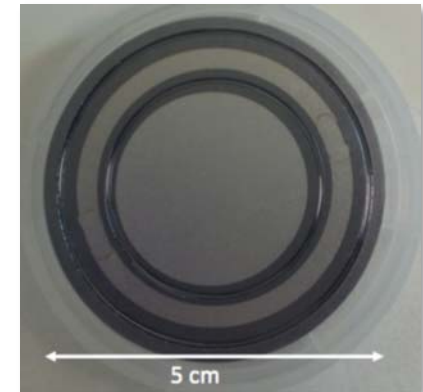
In-house prototype Si(Li) detectors:
5-cm diameter, 1-1.75 mm thick



Partnered with **Shimadzu Corp.**,
a commercial producer of Si(Li)
detectors with >40 yrs experience



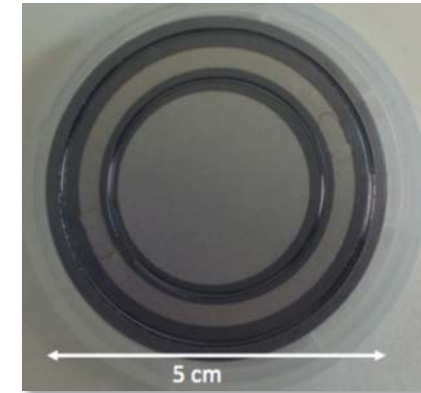
- Small diameter < 1 cm
- Low operation temperature (Liquid nitrogen temperature)



Rapid, successful development of flight detectors



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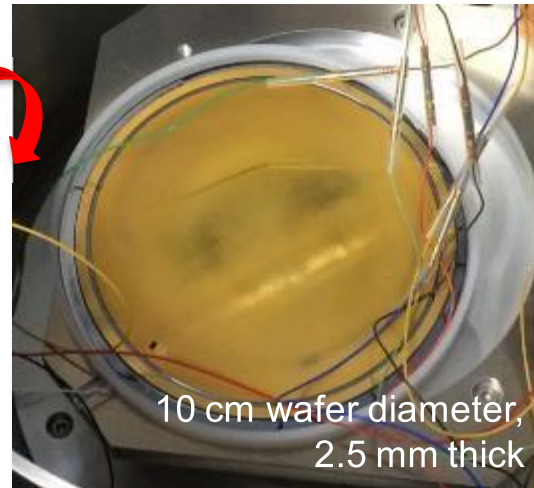


Commercial
products:
~10 mm
diameter
~3 mm thick



5 cm diameter,
2.5 mm thick

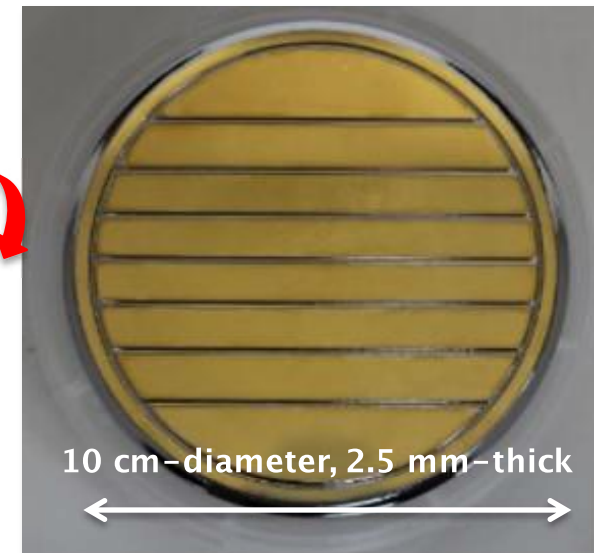
2015



10 cm wafer diameter,
2.5 mm thick

2016

**Flight production completed:
2018-2020**



10 cm-diameter, 2.5 mm-thick

Suppressing leakage current:

(1) Guard ring geometry and surface preparation



“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)

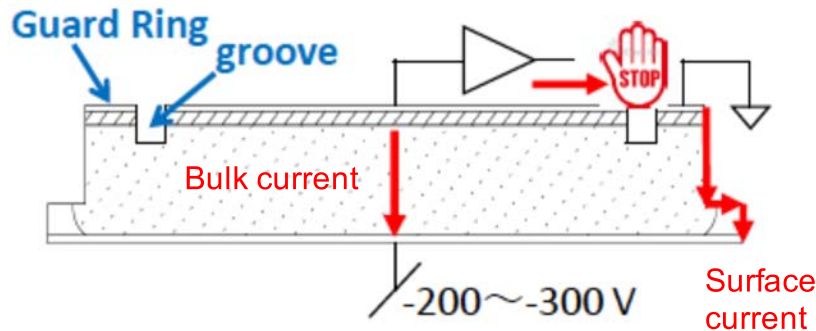
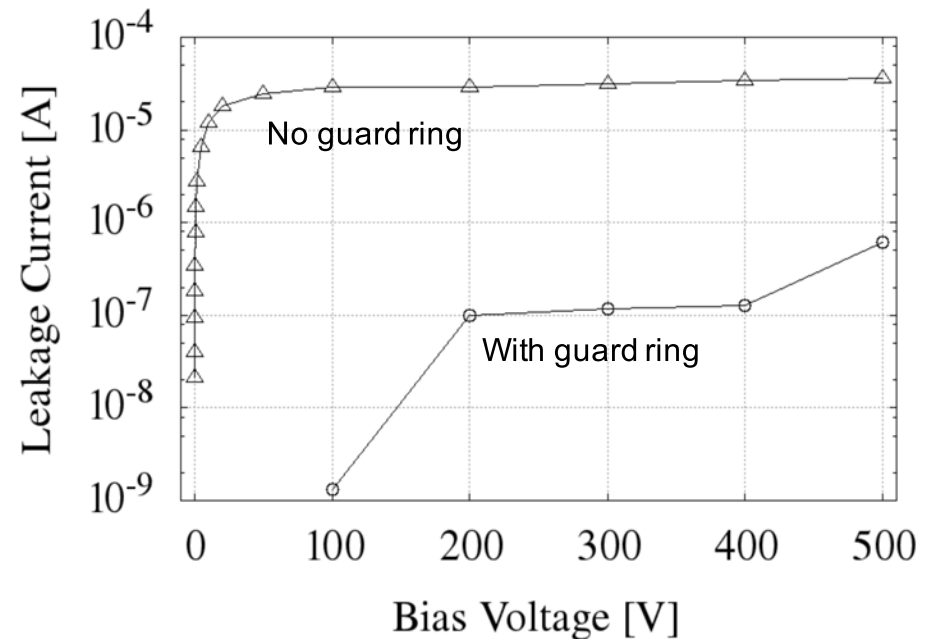
Suppressing leakage current:

(1) Guard ring geometry and surface preparation



Guard ring structure prevents surface leakage current from entering readout circuit

e.g. Goulding NIM 12 249-262 (1962)



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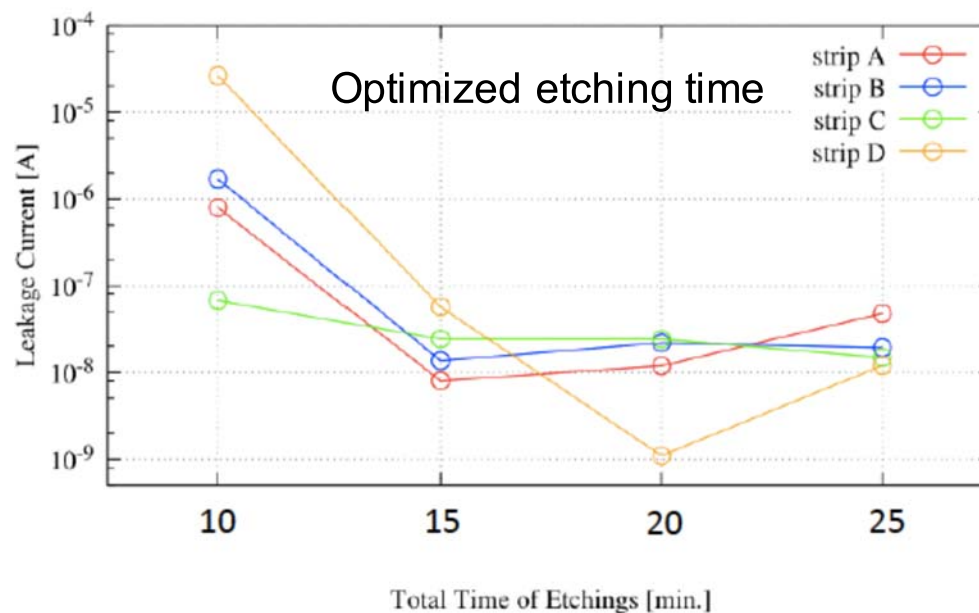
(1) Guard ring geometry and surface preparation



Chemical etching of grooves:

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

→ **Proper groove surface treatment** ensures electrical isolation of detector regions, in particular the guard ring



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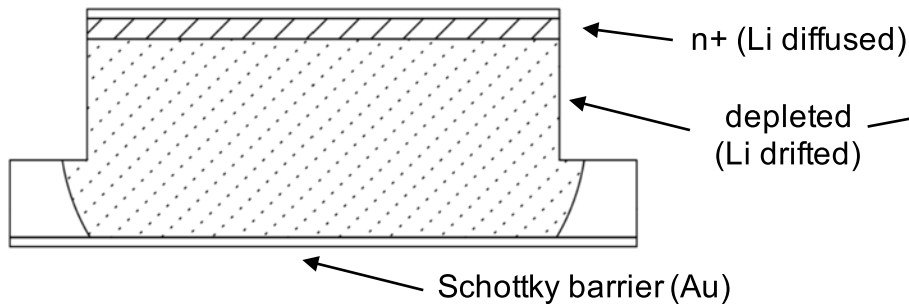
Suppressing leakage current:

(2) Optimized drifting process



Typical Si(Li):

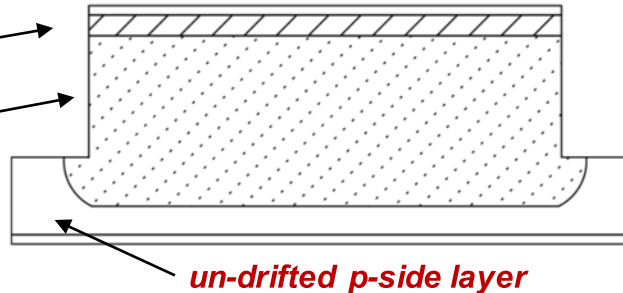
Au p-side contact prevents charge injection into intrinsic detector region



Shimadzu development:

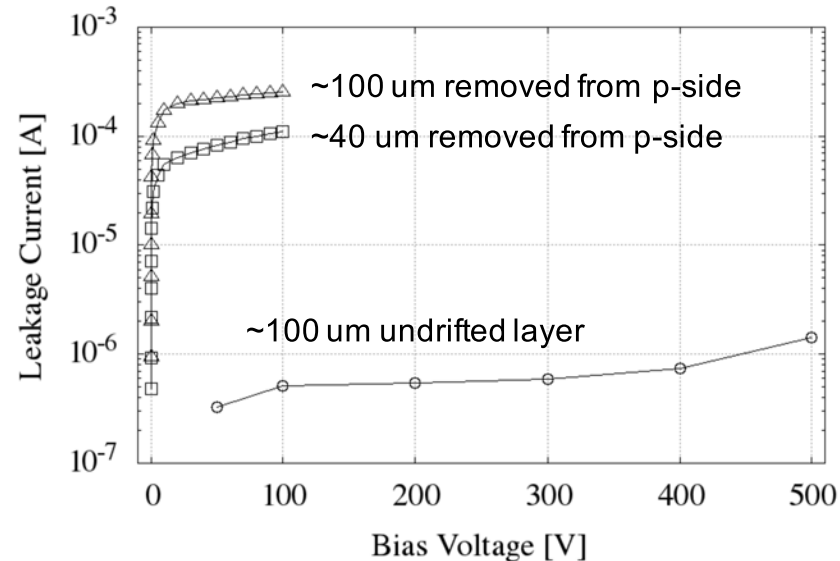


Un-drifted p-side layer suppresses leakage current

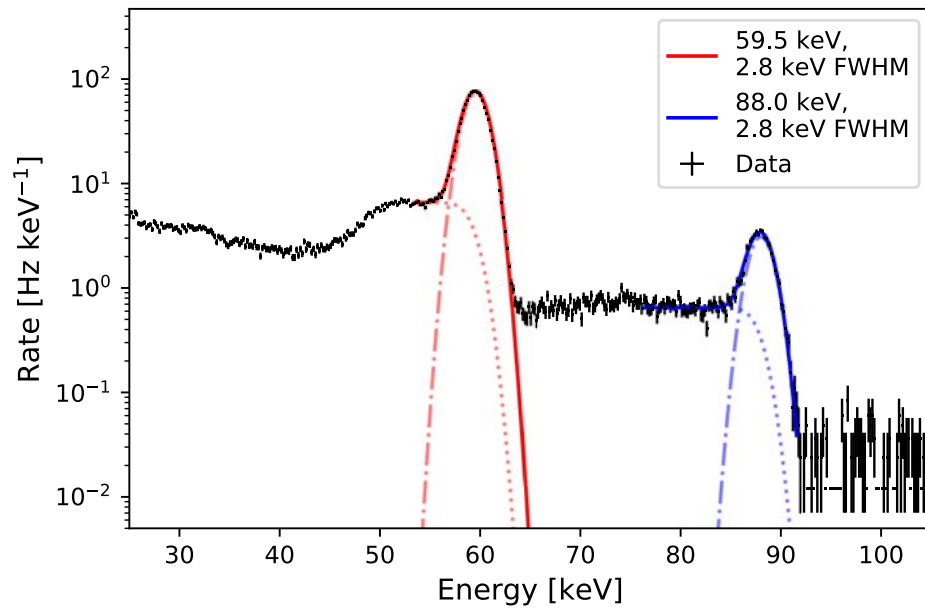


Un-drifted p-side layer suppresses leakage current

- GAPS Si(Li) only for X-rays >20 keV
 - No need for thin p-side “window” in conventional Si(Li)
- Un-drifted layer does not affect anti-nuclei identification

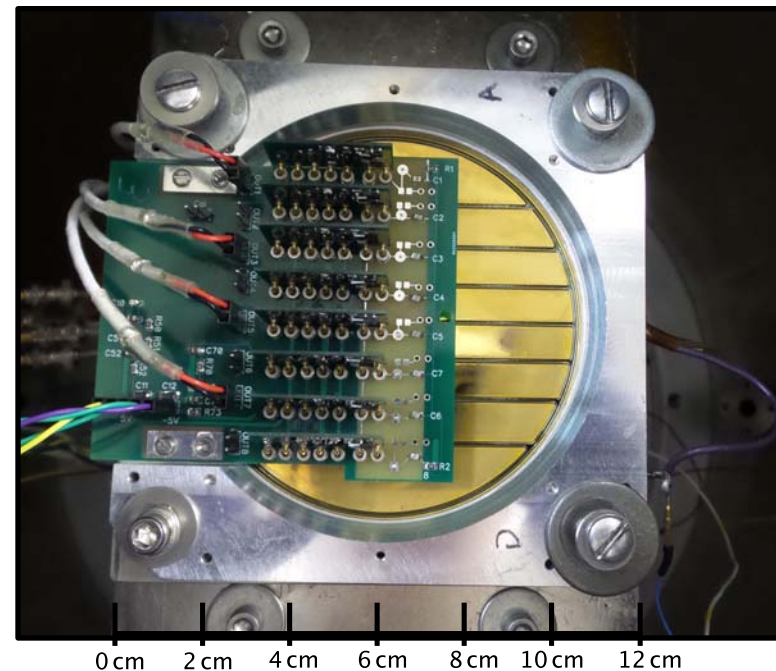


Achieved < 3 keV energy resolution at -41 C!



< 3 keV FWHM energy resolution at -41°C for 59.5 and 88.0 keV lines of ^{241}Am and ^{109}Cd

Measurement with custom discrete-component preamplifier + shaping electronics, and flowing N_2 cooling

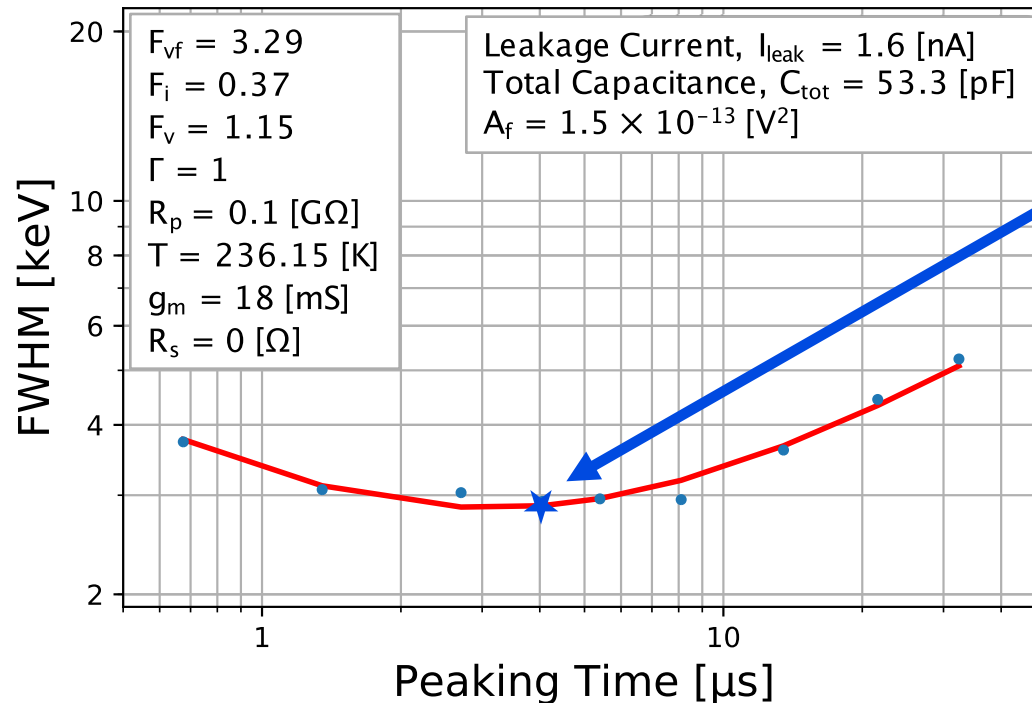


Rogers+ JINST (2019)
[arXiv:1906.00054](https://arxiv.org/abs/1906.00054)

Energy resolution meets model predictions



Noise model combines detector, readout, and pulse shaping to model energy resolution varying peaking time τ



2.8 keV FWHM at
4 μ s peaking time
(-37°C)

Detector dominated

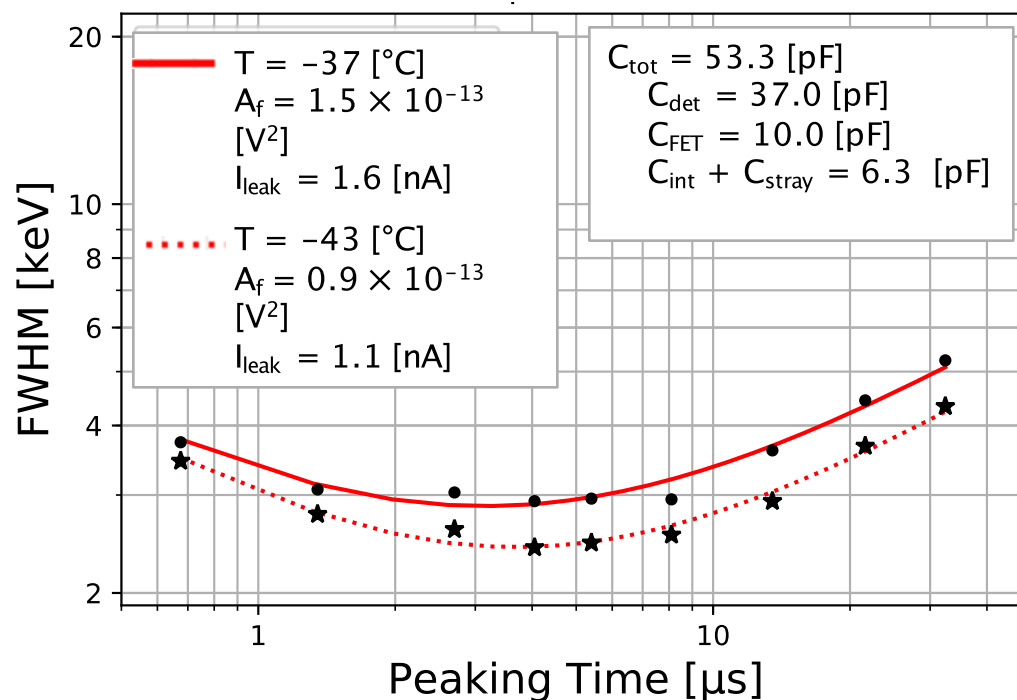
$$ENC^2 = \left(2qI_{leak} + \frac{4kT}{R_p} \right) \tau F_i + 4kT \left(R_s + \frac{\Gamma}{g_m} \right) \frac{C_{tot}^2}{\tau} F_v + A_f C_{tot}^2 F_{vf},$$

e.g. Goulding, NIM 100
(1972) 493-504; Radeka,
BNL (1974)

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Energy resolution meets model predictions

Noise model combines detector, readout, and pulse shaping to model energy resolution varying peaking time τ and temperature



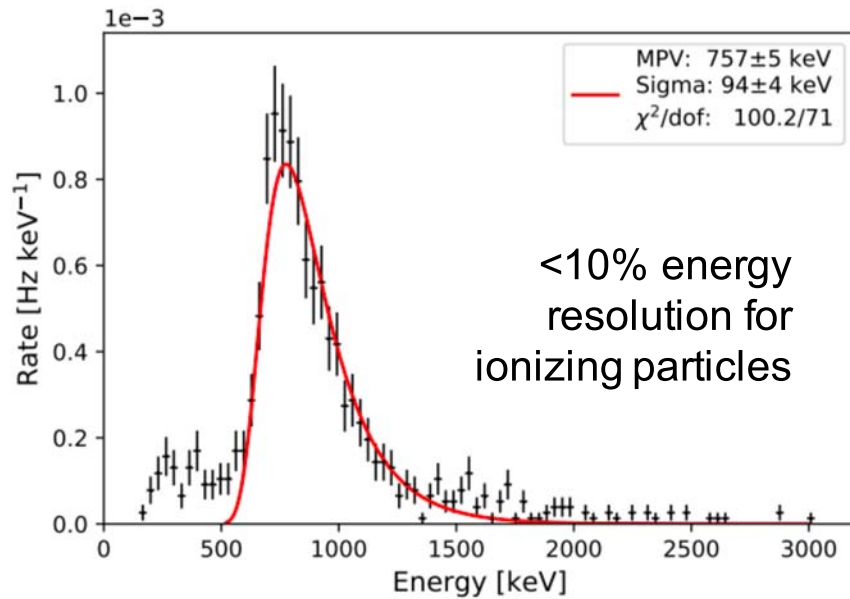
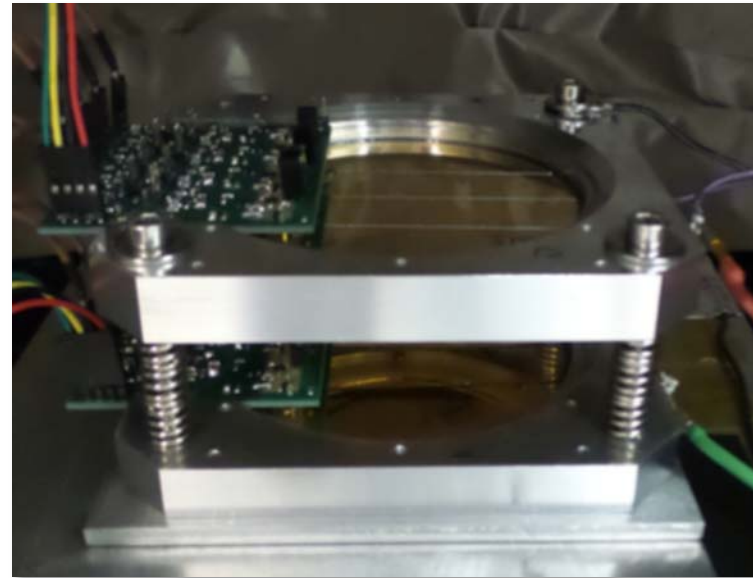
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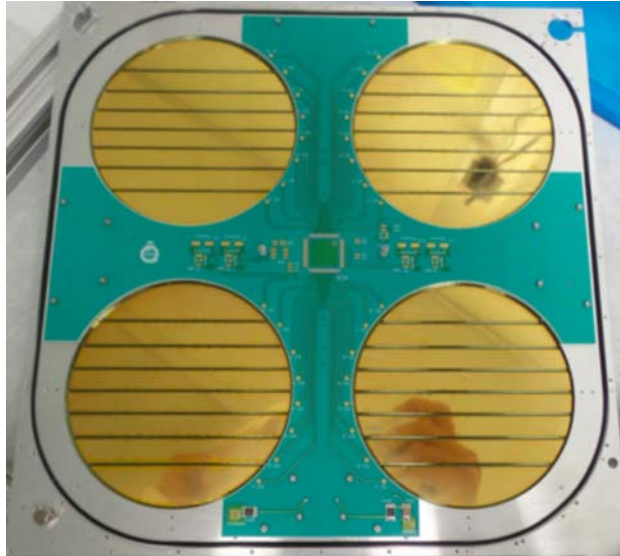
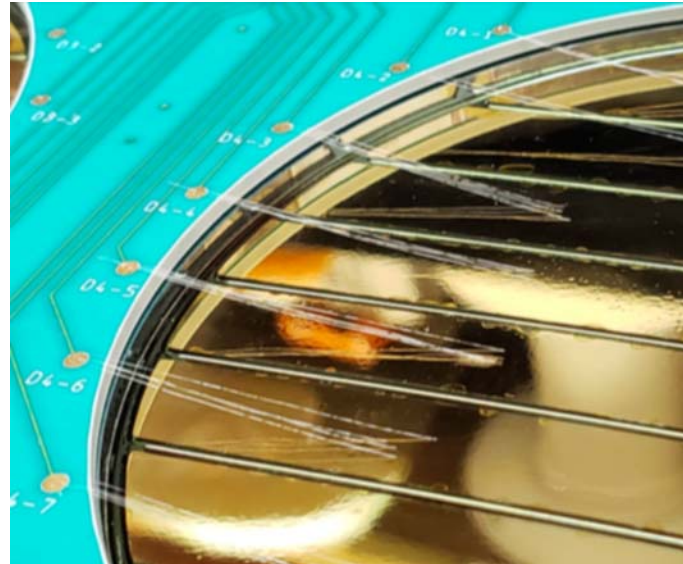
Tracking: Cosmic muon spectrum



Flight readout electronics designed to deliver < 10% energy resolution for energy deposits 1-100 MeV

Rogers+ JINST (2019)
[arXiv:1906.00054](https://arxiv.org/abs/1906.00054)

Large-scale calibration ongoing at MIT



4-detector modules
with custom ASIC

To date:

- ✓ 1102 detectors received
- ✓ ~500 detectors passivated
- ✓ ~100 detectors calibrated



Back to the future: in-house fabrication



Improving Si(Li) design is key to boosting GAPS' sensitivity for future flights:

- Increasing active area and segmentation improves signal/background discrimination
- ***Need to build-out tracker with more detectors for future flights***

Returning to in-house fabrication necessary:

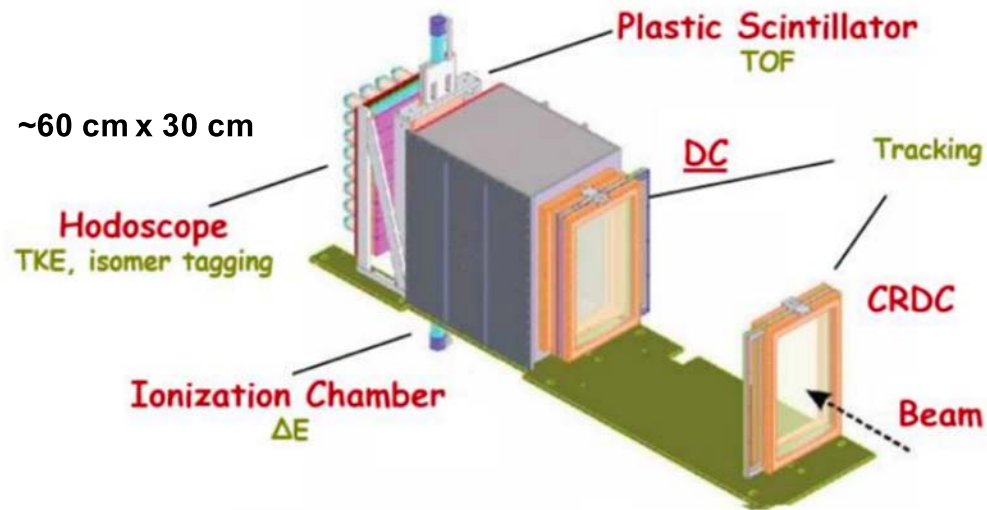
- separate development from commercial interests and profit
- dramatically reduce costs
- facilitate custom/hybrid instrument designs

R&D program resuming now!

Custom detectors enable broader applications

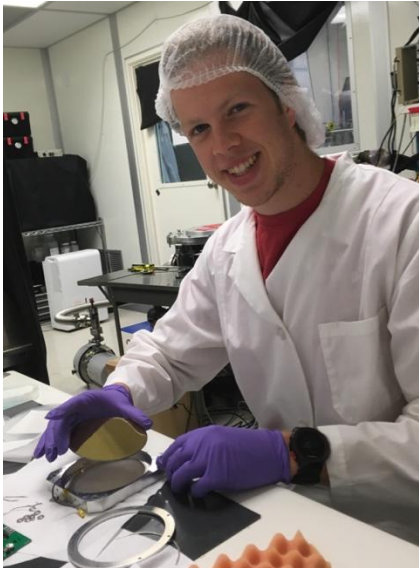
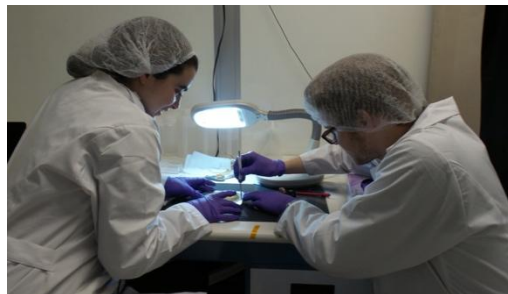
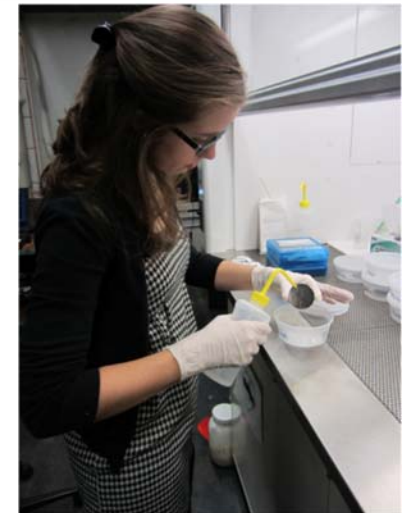


Facility for Rare Isotope Beams (FRIB) is nuclear physics new flagship facility (2022)



- Isotope beam is scattered off of a target, and the resulting exotic nucleus is measured
- Stacks of thick Si(Li) detectors could replace hodoscope calorimeter
- Cost-effective, improved total energy measurement

Back to the future: in-house fabrication



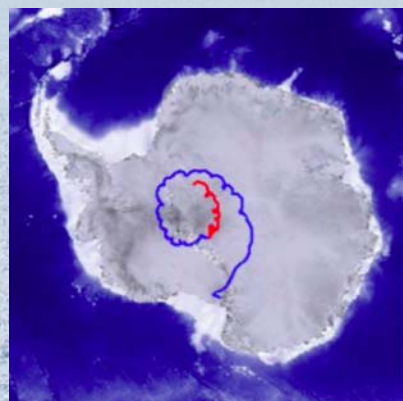
Initial Antarctic flight in late 2022!



- Large-area Si(Li) detectors developed to meet the unique temperature, power, cost constraints of the GAPS Antarctic balloon experiment
- Demonstrated **<4 keV X-ray energy resolution** at relatively high temperature of **-35 to -45 C**, production yield ~90%
- **Return to R&D will allow improvements, custom designs for broader applications**

**First GAPS
flight late 2022**

Long-duration
balloon flight
(~30 days)

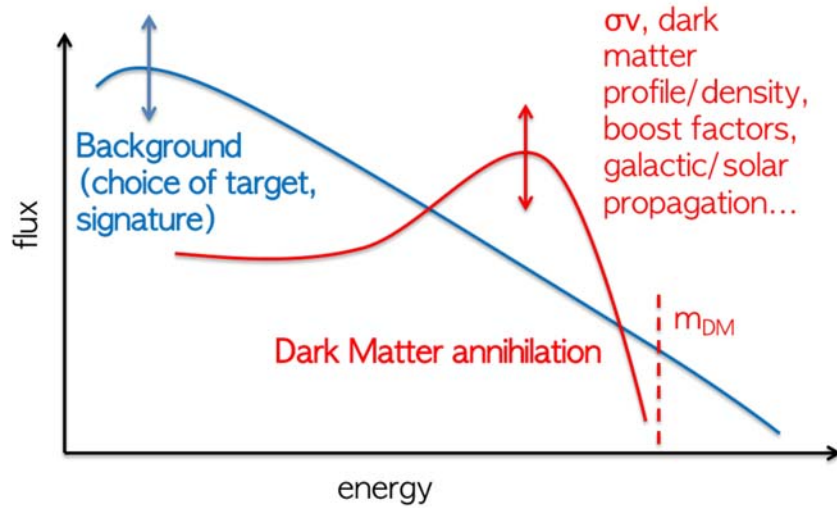


Stay tuned!

Backup



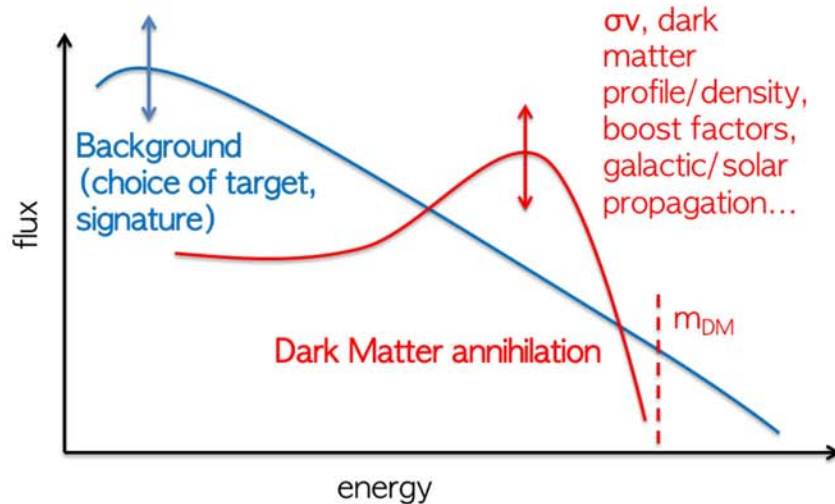
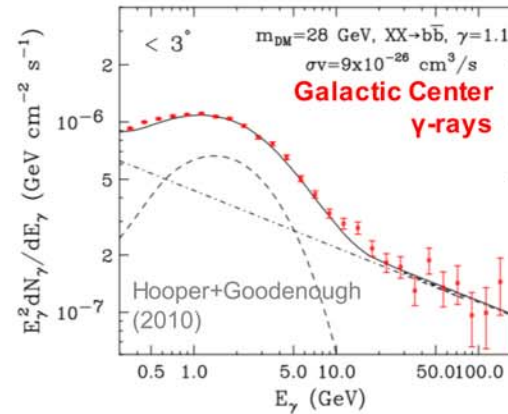
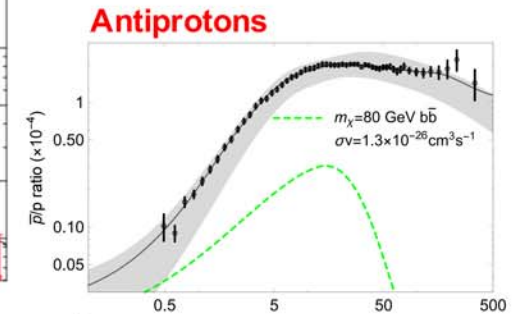
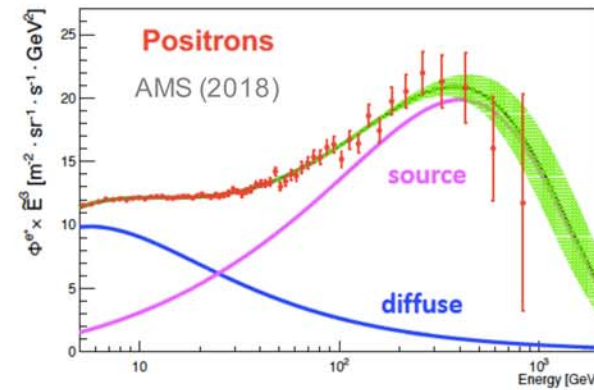
The challenge of astroparticle searches...



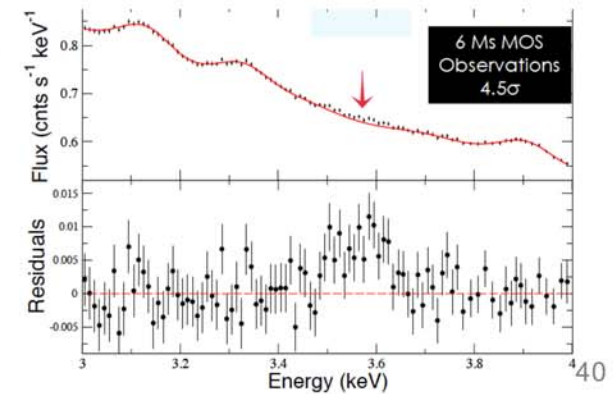
The challenge of astroparticle searches...



Cuoco+(2016), Cui+(2016),
Cui+ (2018), A. Cuoco+ (2019),
Cholis+ (2019)



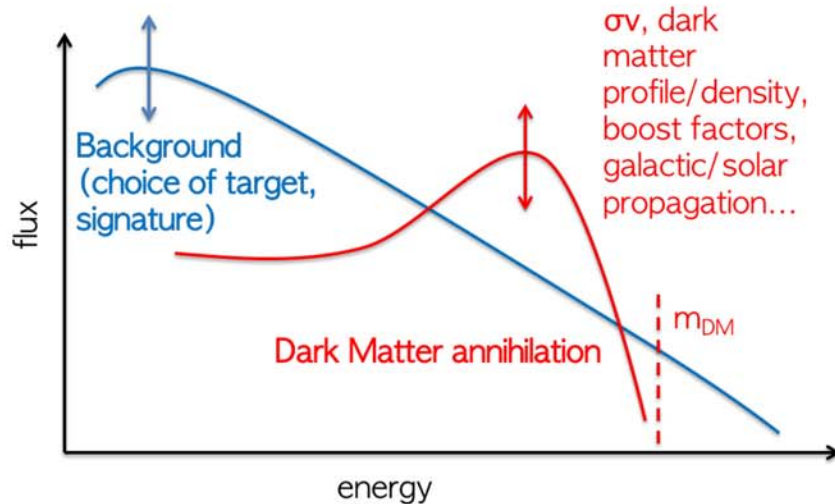
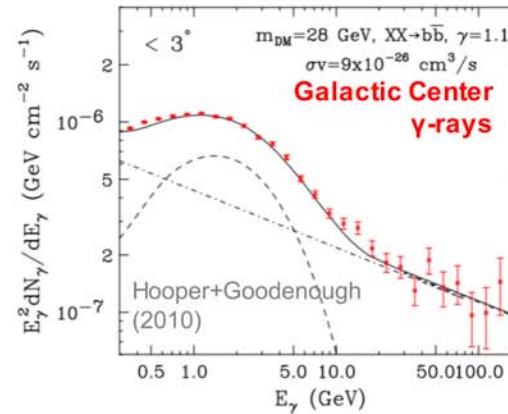
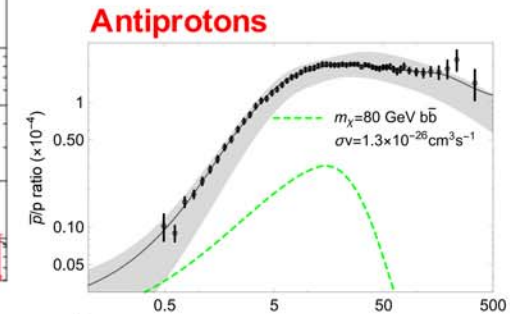
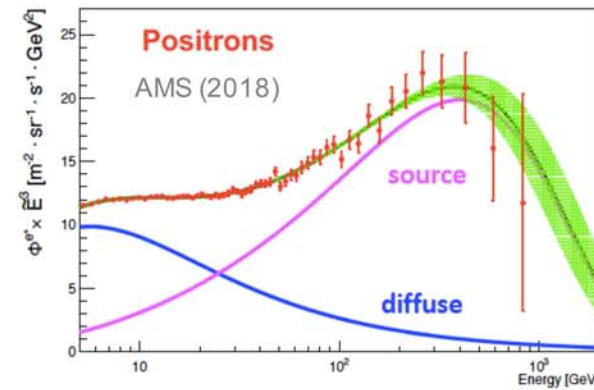
**X-rays:
3.5 keV**
 Bulbul+ (2014)



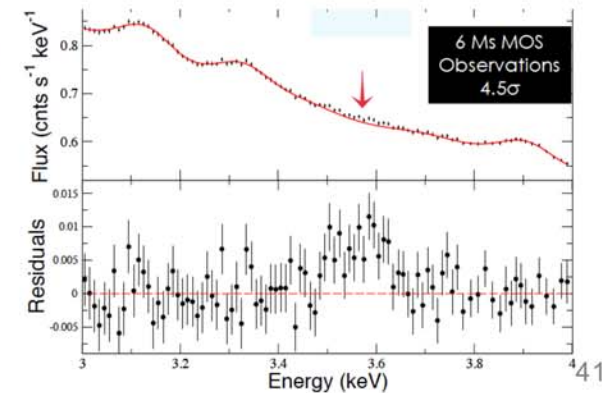
The challenge of astroparticle searches...



Cuoco+(2016), Cui+(2016),
Cui+ (2018), A. Cuoco+ (2019),
Cholis+ (2019)



**X-rays:
3.5 keV**
 Bulbul+ (2014)



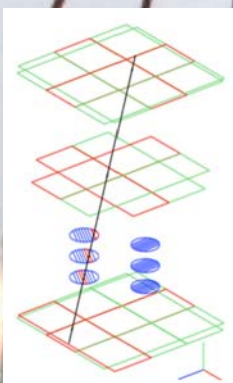
1. Cosmic signatures are full of surprises!
2. Surprises are difficult to interpret due to large/uncertain astrophysical backgrounds
3. Need cross-correlation with different signatures

Prototype flight (pGAPS)

Taiki, Japan
2012



6 TOF planes
+ 6 Si(Li)
detectors



100% of flight goals met!

- ✓ verify stable, low-noise Si(Li) operation at ambient flight pressure
- ✓ validate the cooling system and thermal model
- ✓ measure the background levels to validate simulation codes

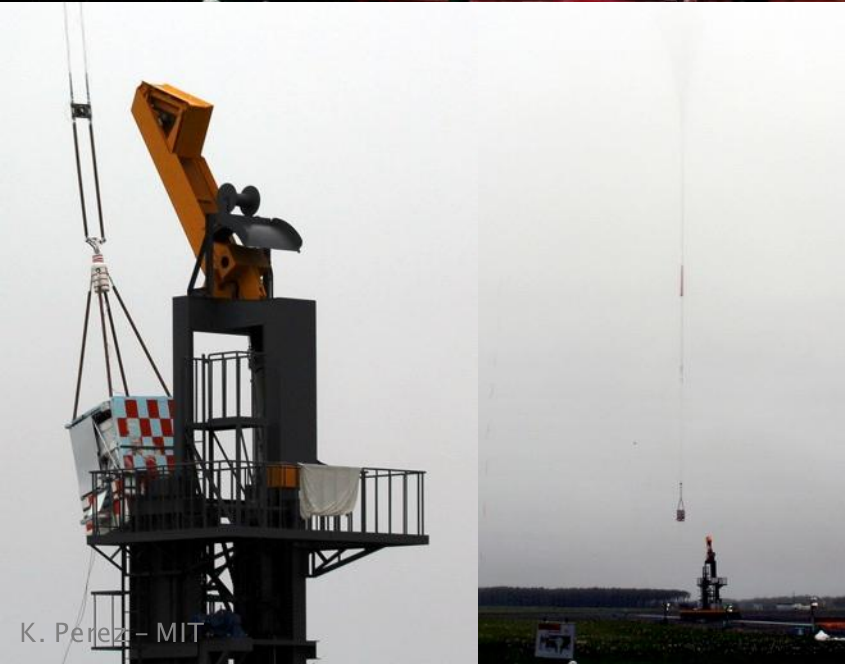
Mognet et al., Nucl. Instrum.
Meth. A735 (2014) 24
von Doetinchem et al.,
Astropart. Phys. 54 (2014) 93

Liftoff!
4:55 am



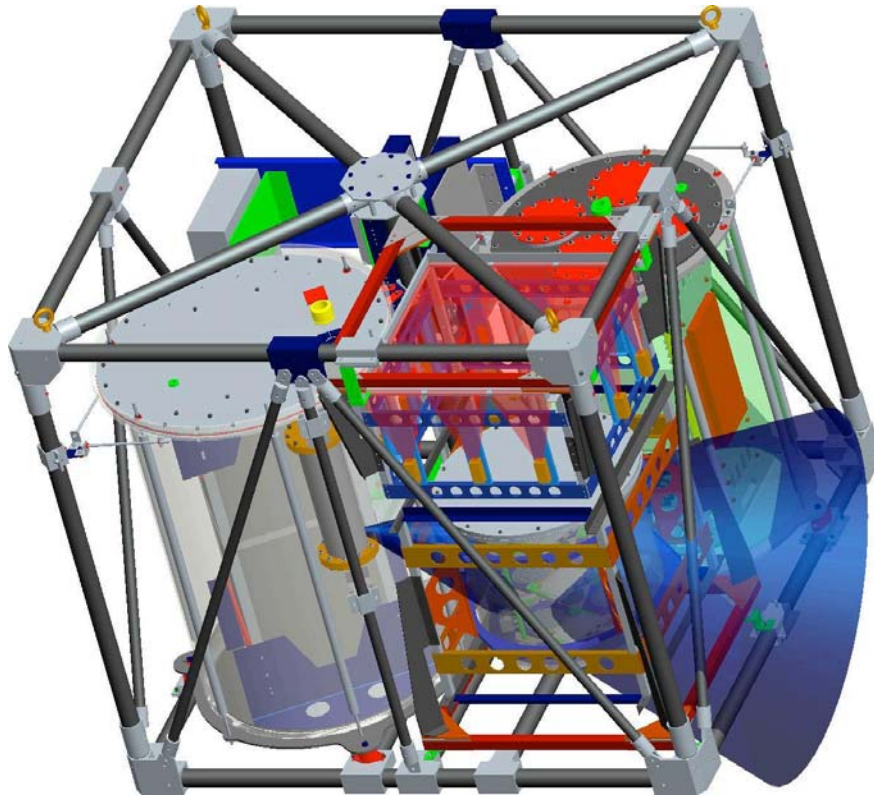
Float altitude = ~ 33 km
10:22 am

2012:06:03 10:22:14

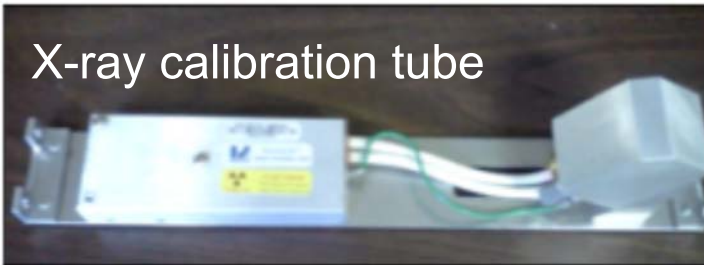
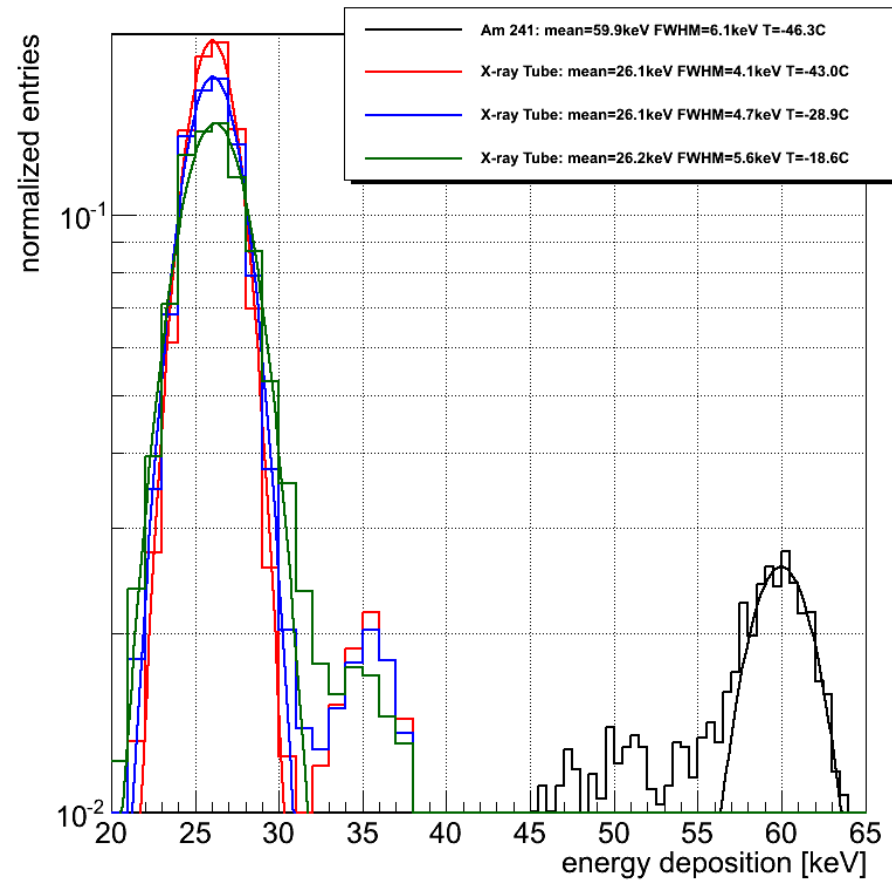


Recovery
11:45 am

pGAPS Detector Results

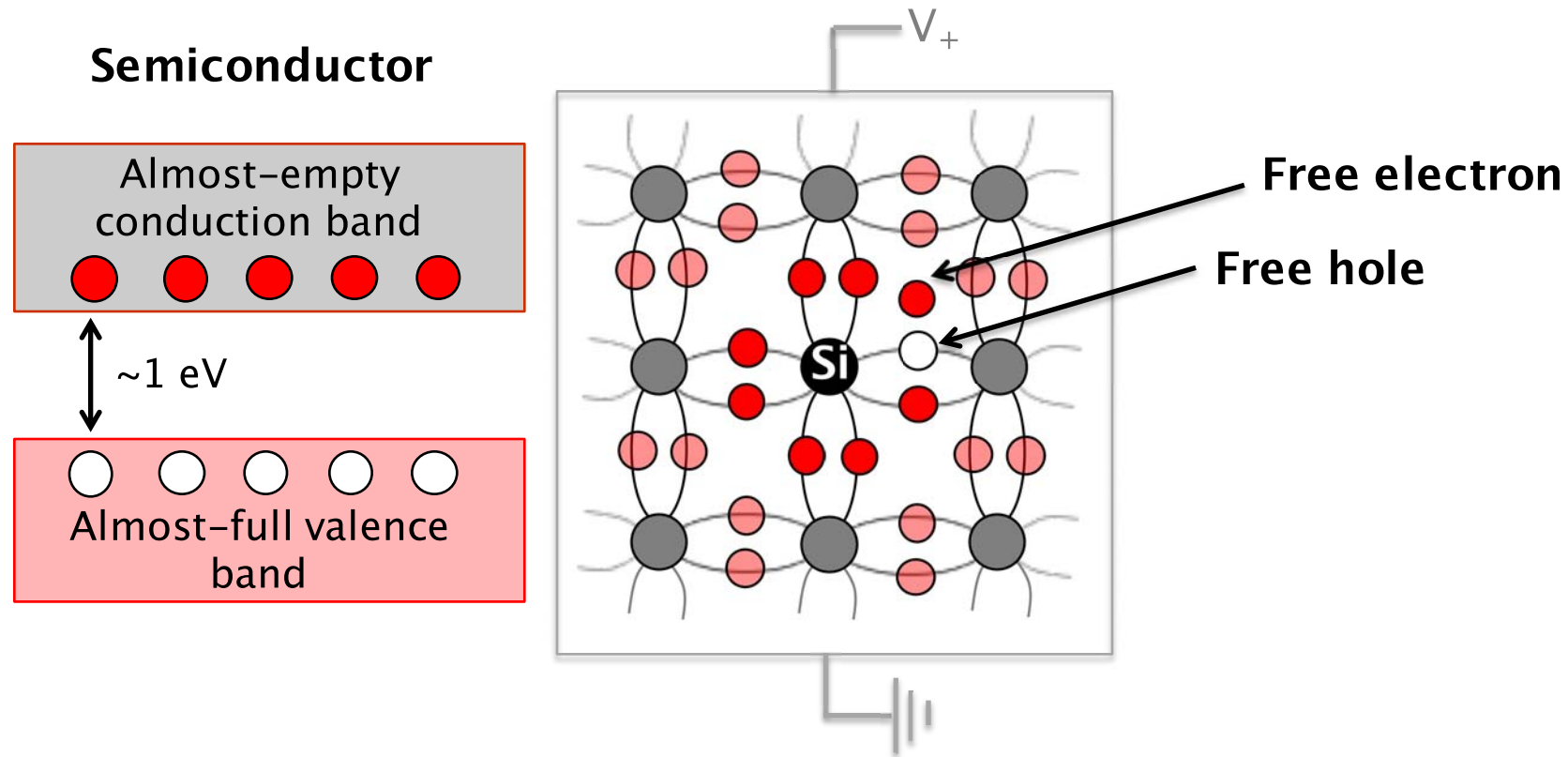


X-ray calibration tube

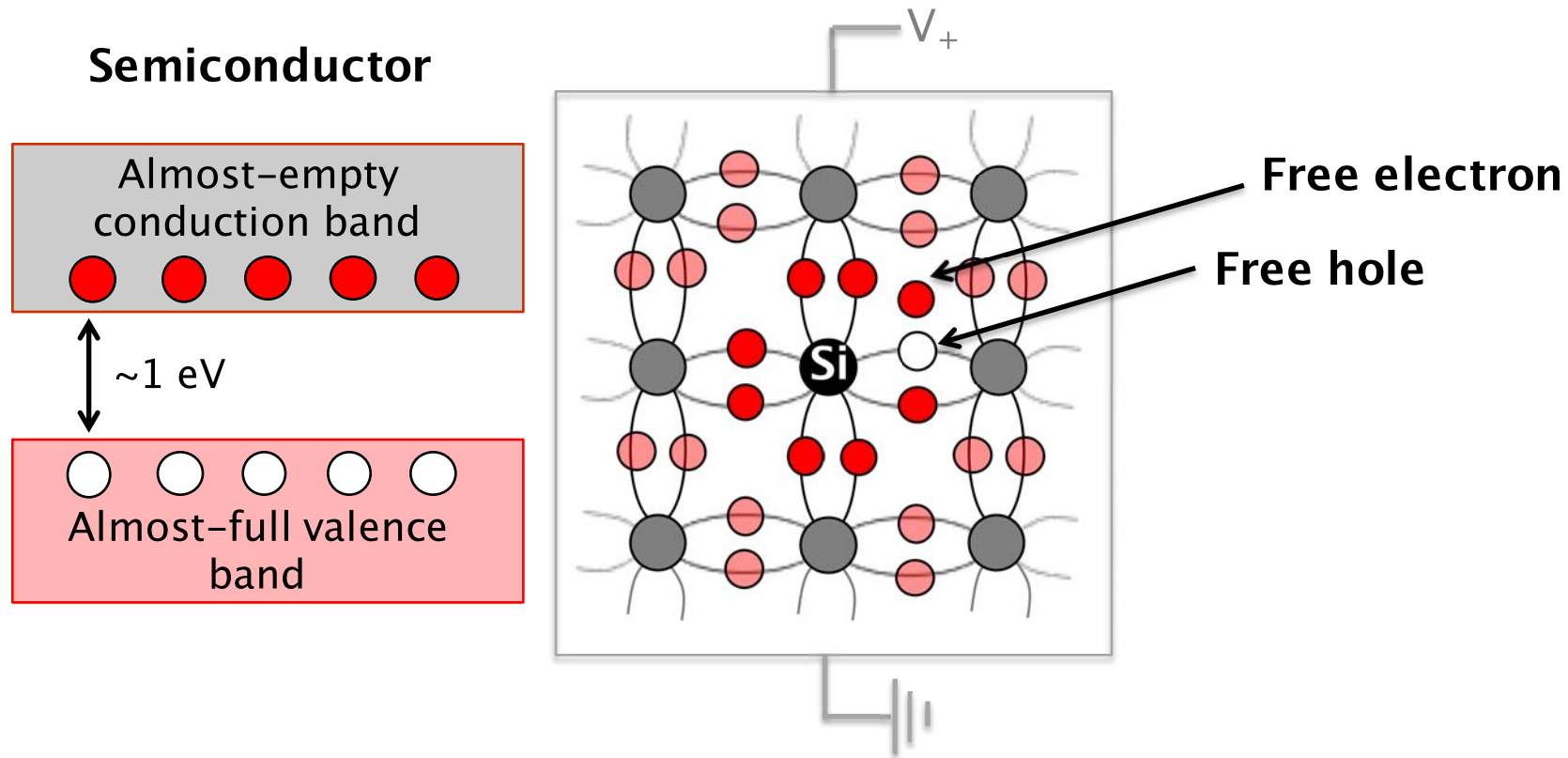


Si(Li) resolution consistent with temperature-dependent predictions

Semiconducting detector basics



Semiconducting detector basics

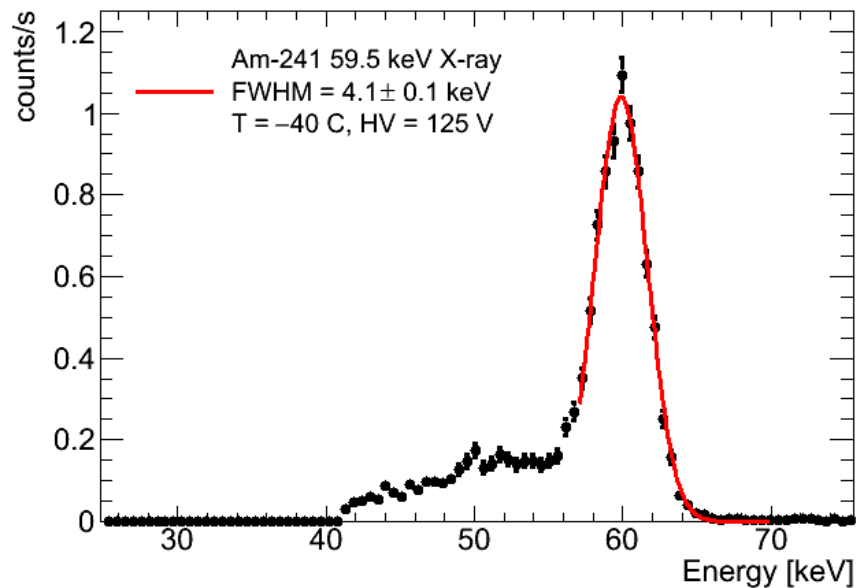


The **leakage current**, or current that flows in absence of ionizing radiation, too high even for high-resistivity Si

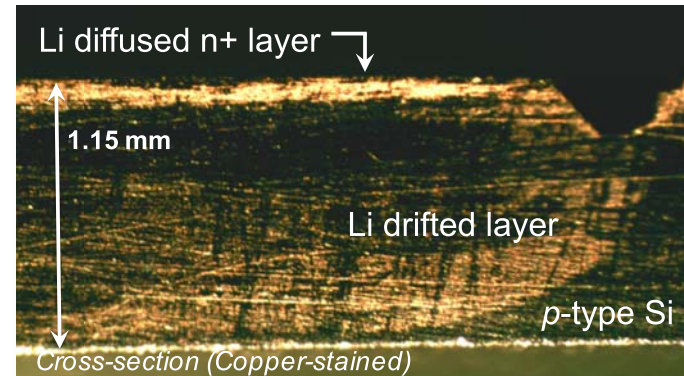
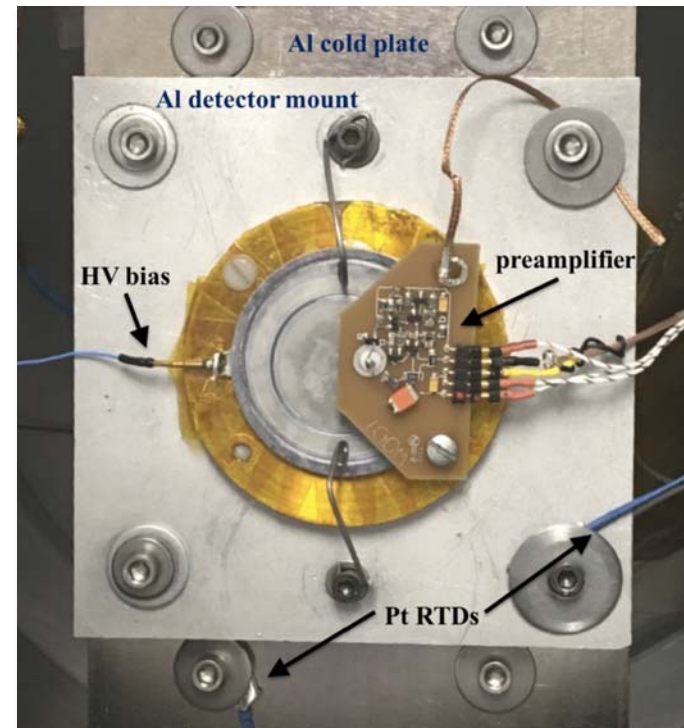
Validated low-cost technique with prototype Si(Li)



- Prototype Si(Li) detectors:
5-cm diameter, 1-1.75 mm thick
- ✓ **Low-cost** fabrication scheme developed to achieve required 4 keV energy resolution at relatively high operating temperature of -40 C
- ✓ Total cost ~few hundred dollars in materials



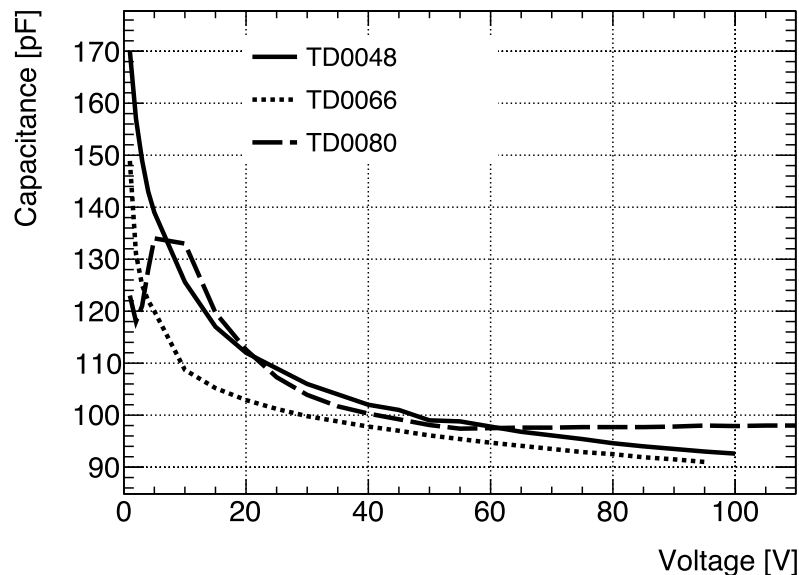
Perez et al. NIM A905 12-21 (2018)



Prototype Si(Li): key diagnostics

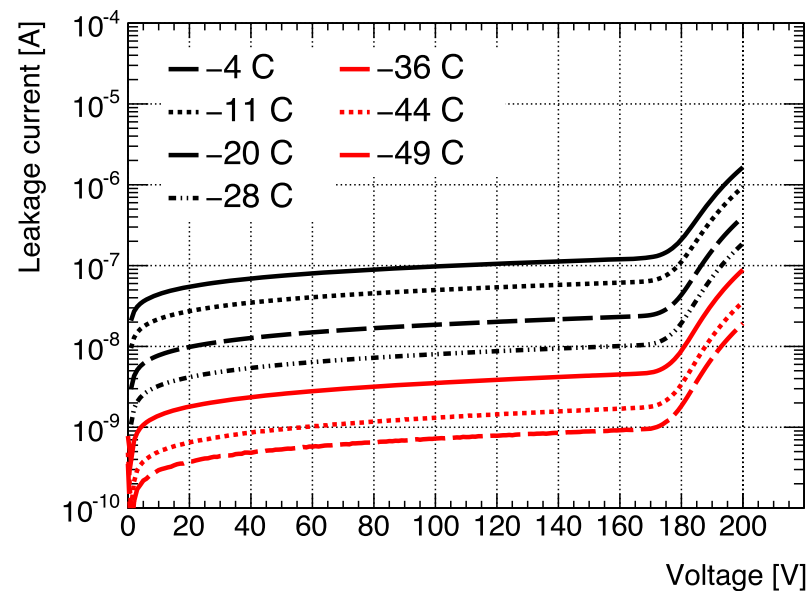


- Capacitance scales with intrinsic region width, and is used to determine the proper operating bias



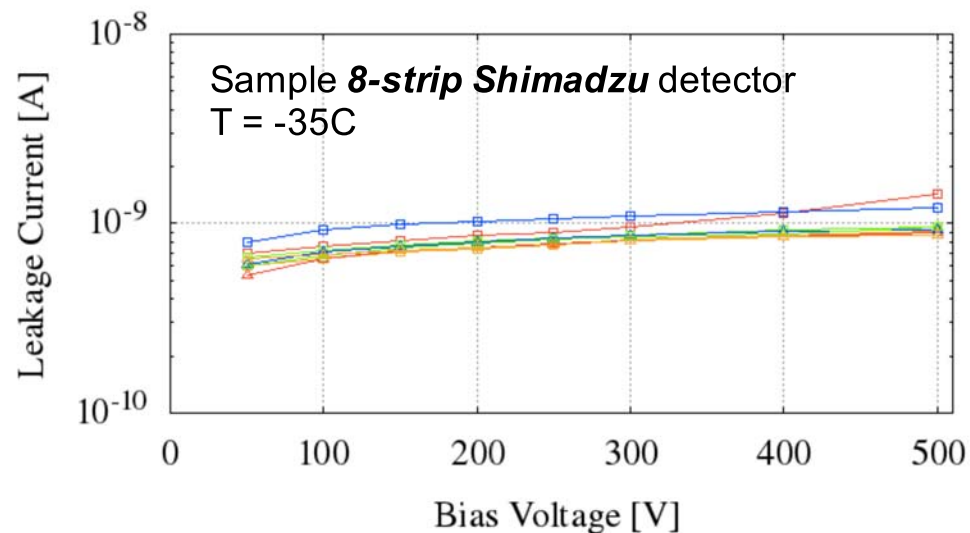
- ✓ Well-functioning detector (TD0048) is >90% depleted by ~1000 V/cm (150V bias for these 1.5 mm detectors)

- Leakage current is main contributor to energy resolution
- For bulk-current dominated, decreases with temperature as $I \sim \exp\{-E_g/2kT\}$

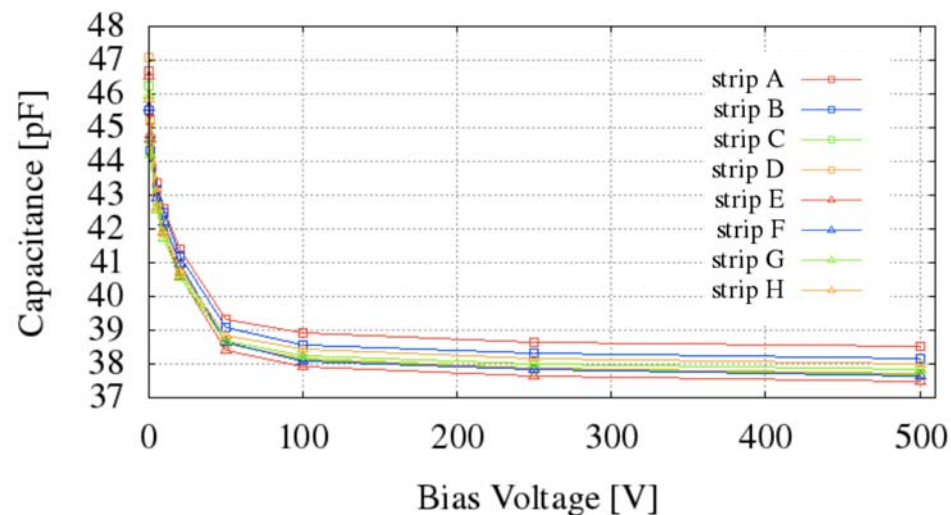


- ✓ Achieve $< 0.5 \text{ nA/cm}^2$, necessary for required energy resolution performance
- ✓ Scales with temperature as expected

Basic 8-strip performance meets requirements



- ✓ Uniform characteristics across all strips
- ✓ Leakage is far below the 0.5 nA/cm² requirement to provide <4 keV (FWHM) energy resolution

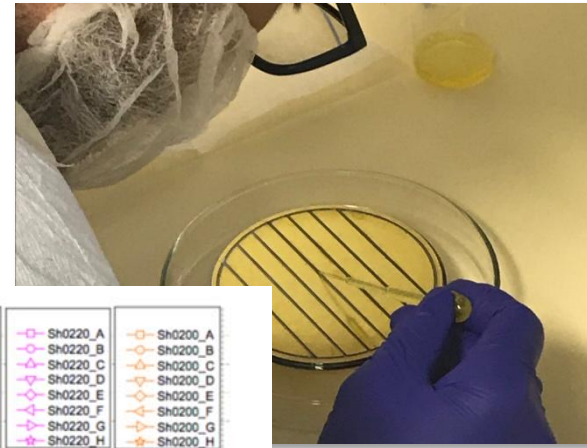


- ✓ Capacitance indicates detector is fully depleted by our operating bias of 250 V
- ✓ Depletion corresponds to ~95% of detector thickness

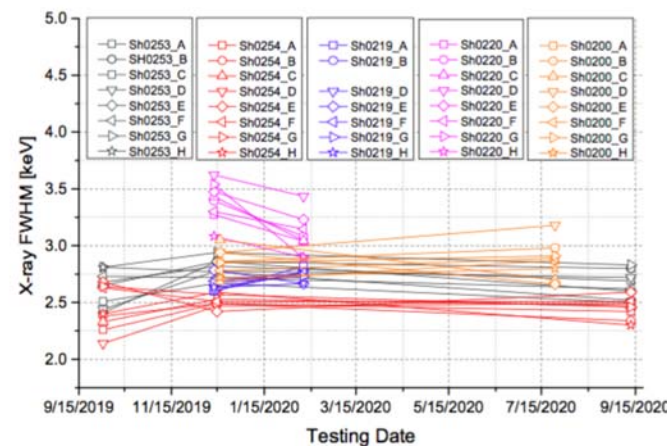
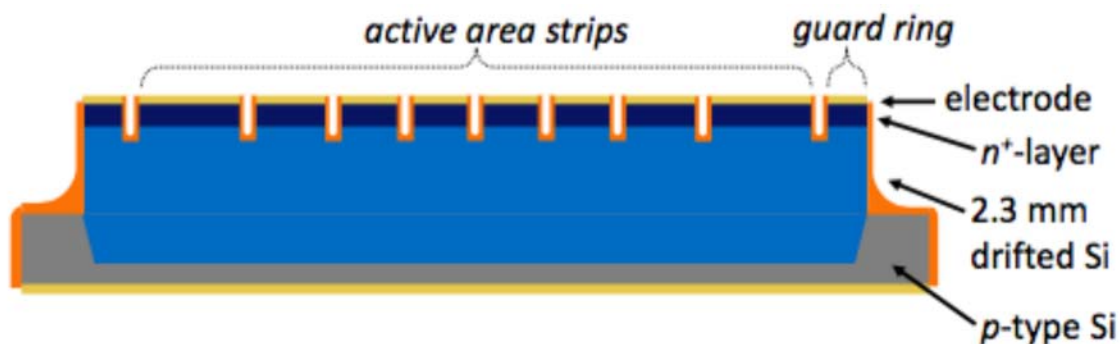
M. Kozai et al. Proc. IEEE (2018)

Lithium-drifted Si detector fabrication

1. B-doped, p -type substrate wafers
2. Evaporate and diffuse Li for n^+ -layer
3. Form top-hat structure to control drift
4. Evaporate Ni + Au electrodes
5. Drift Li through wafer
6. Form guard ring + strips
7. Apply polyimide passivation



Saffold+ (2020)
accepted NIM A



Silane + thermally-cured polyimide protects Si surfaces from humidity and other environmental conditions.