SiPM-based Technologies for Solar and Heliospheric Science

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Neutron/γ-ray Instrument Development Team

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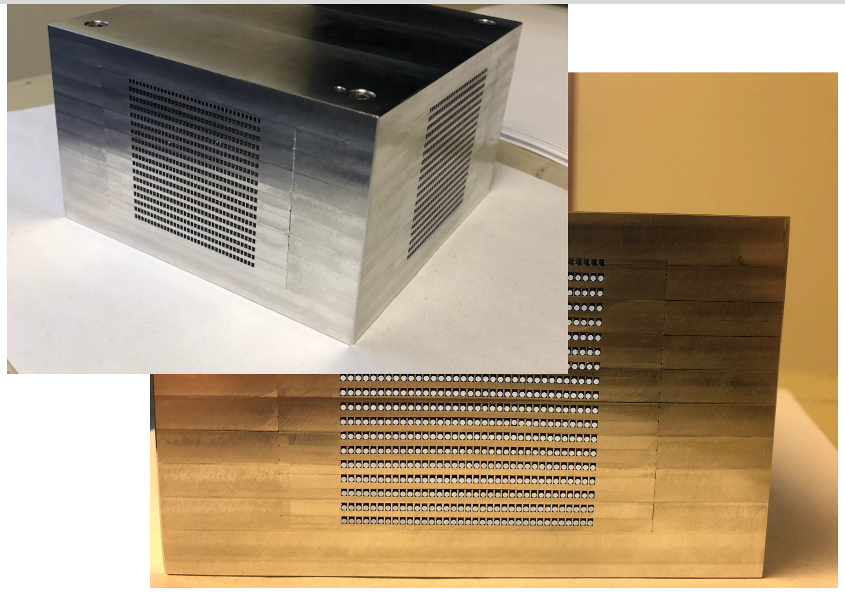
Enabling Technology: SiPMs

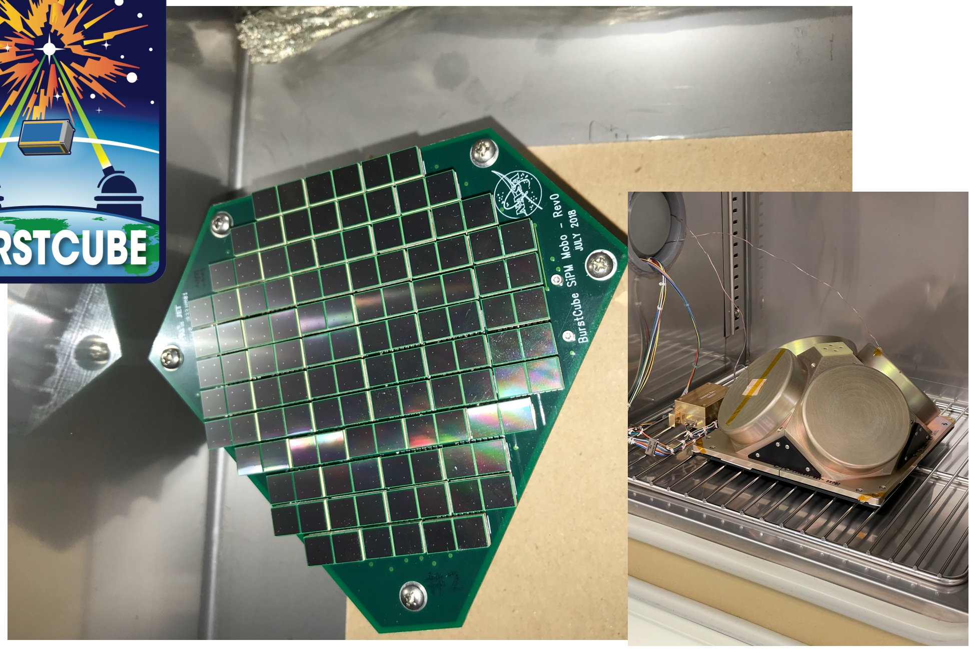
- Develop neutron/γ-ray instruments which continue to rely on scintillators as most efficient material for radiation detection
- Advantages of SiPMs : compact, high-gain & rugged → SiPMs transform accessibility for space applications.
- SiPMs are also sensitive to low light levels and easy to scale to variety of form factors
- Fabricated in-house carrier boards to enable scalable array configurations.
- Concern for radiation tolerance

Detect γ-rays and neutrons for heliospheric/astrophysics applications

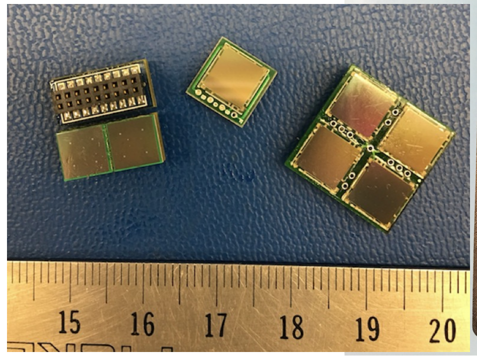
Solar Neutron TRACking (SONTRAC)

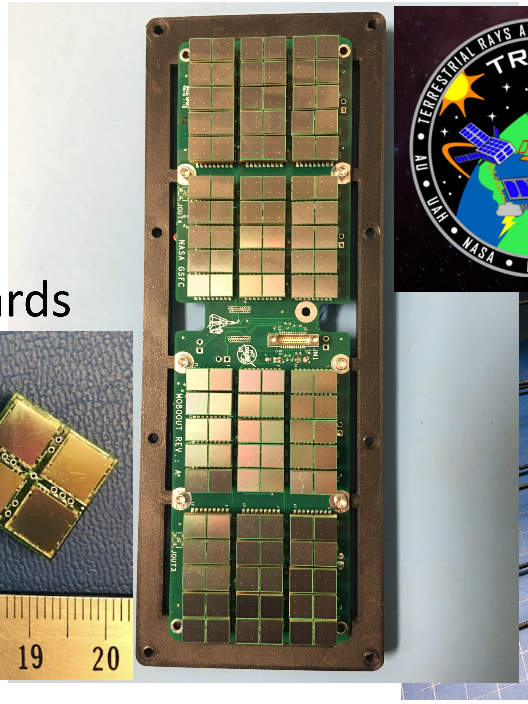


BURSTCUBE

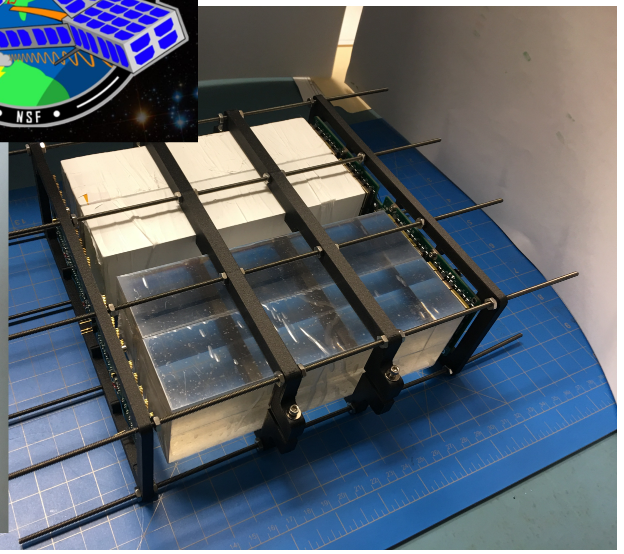


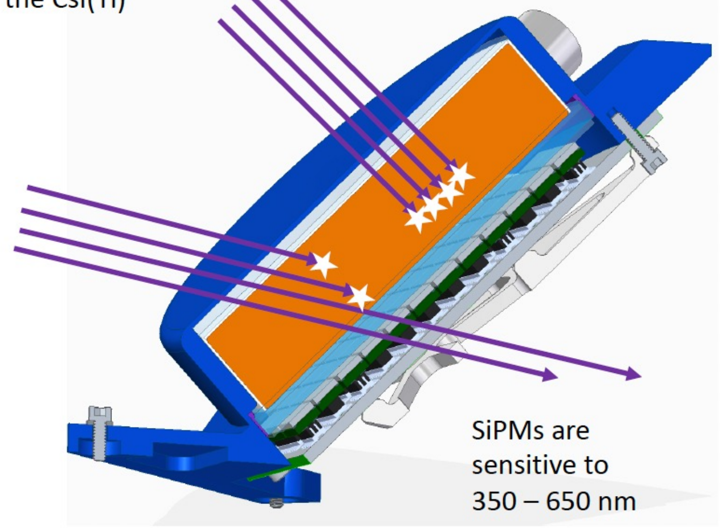
carrier boards



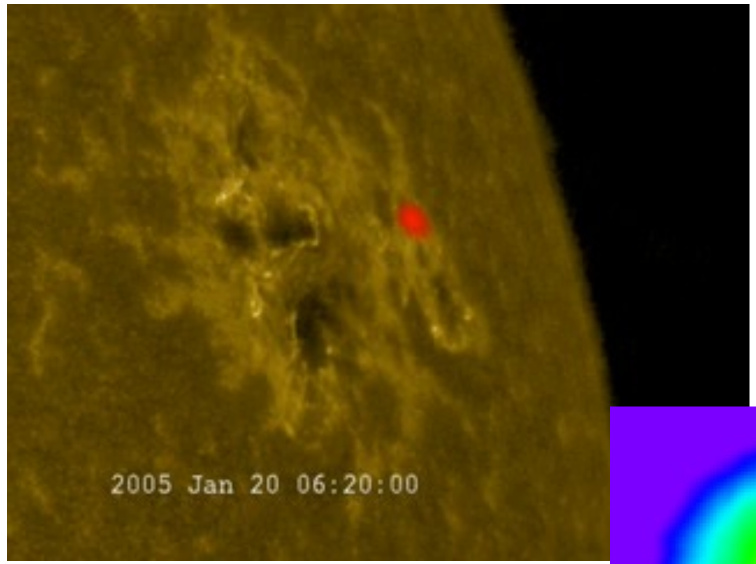


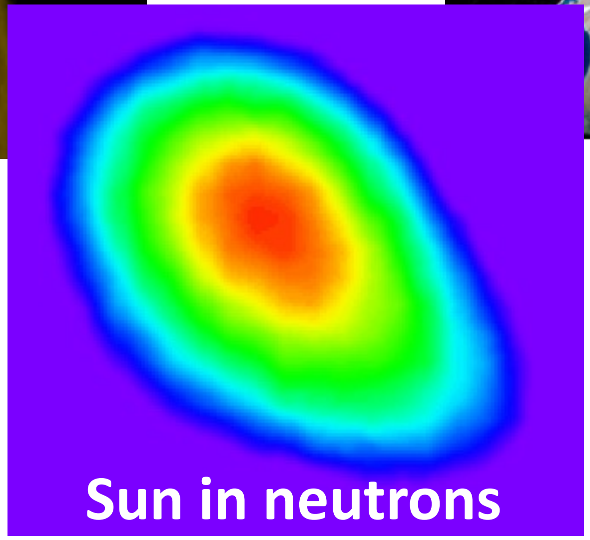
TRYAD



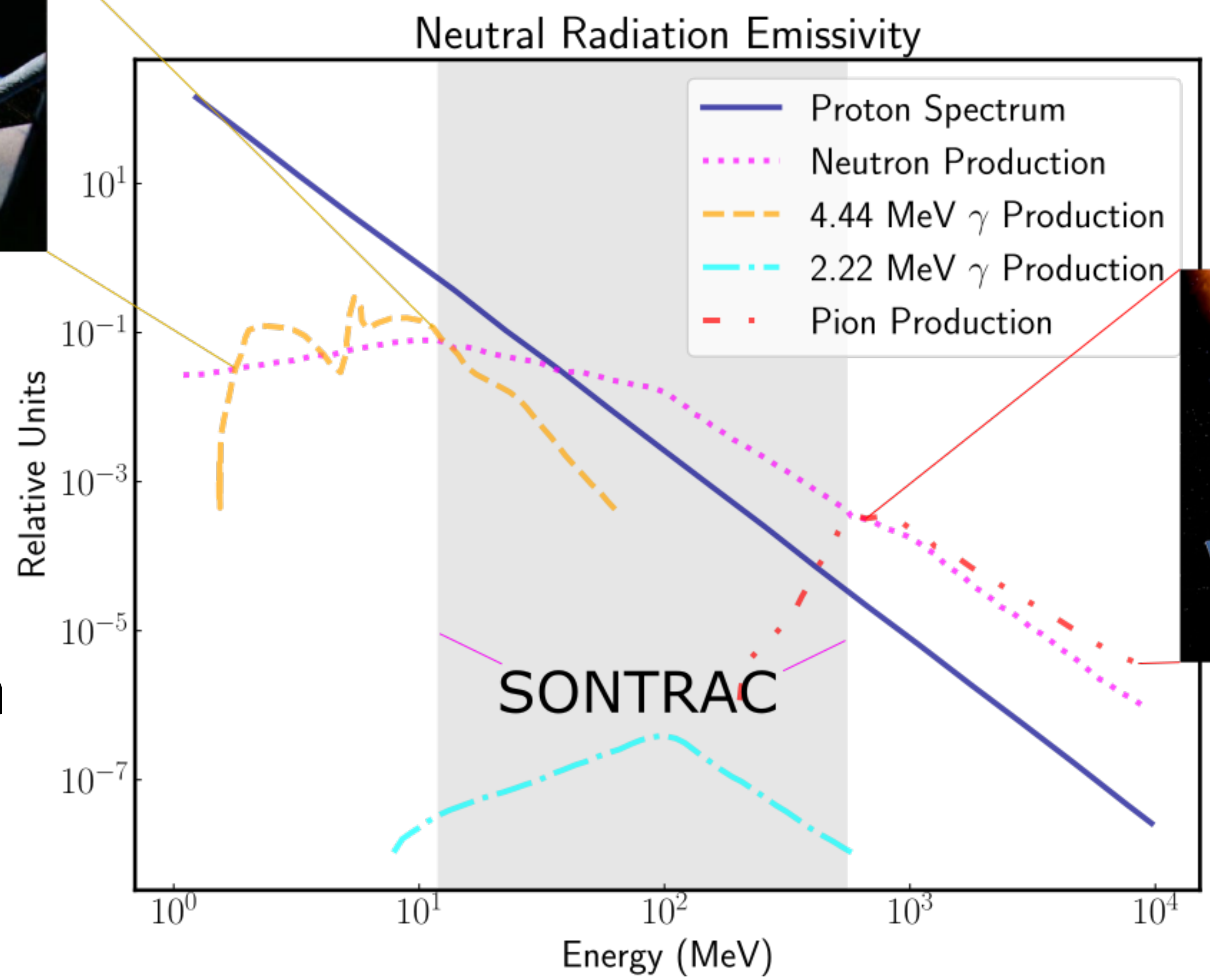


Science Motivation : Solar Neutrons





Require gamma-ray & neutron observations to sample the entire energy range of the interacting protons at the Sun.



- From 20-40 MeV use γ-ray line emission
- > 300 MeV use π^0 emission (70 MeV)
- From ~50-300 MeV need neutrons

* Neutrons bridge a critical gap

Science Motivation: Lunar Neutrons

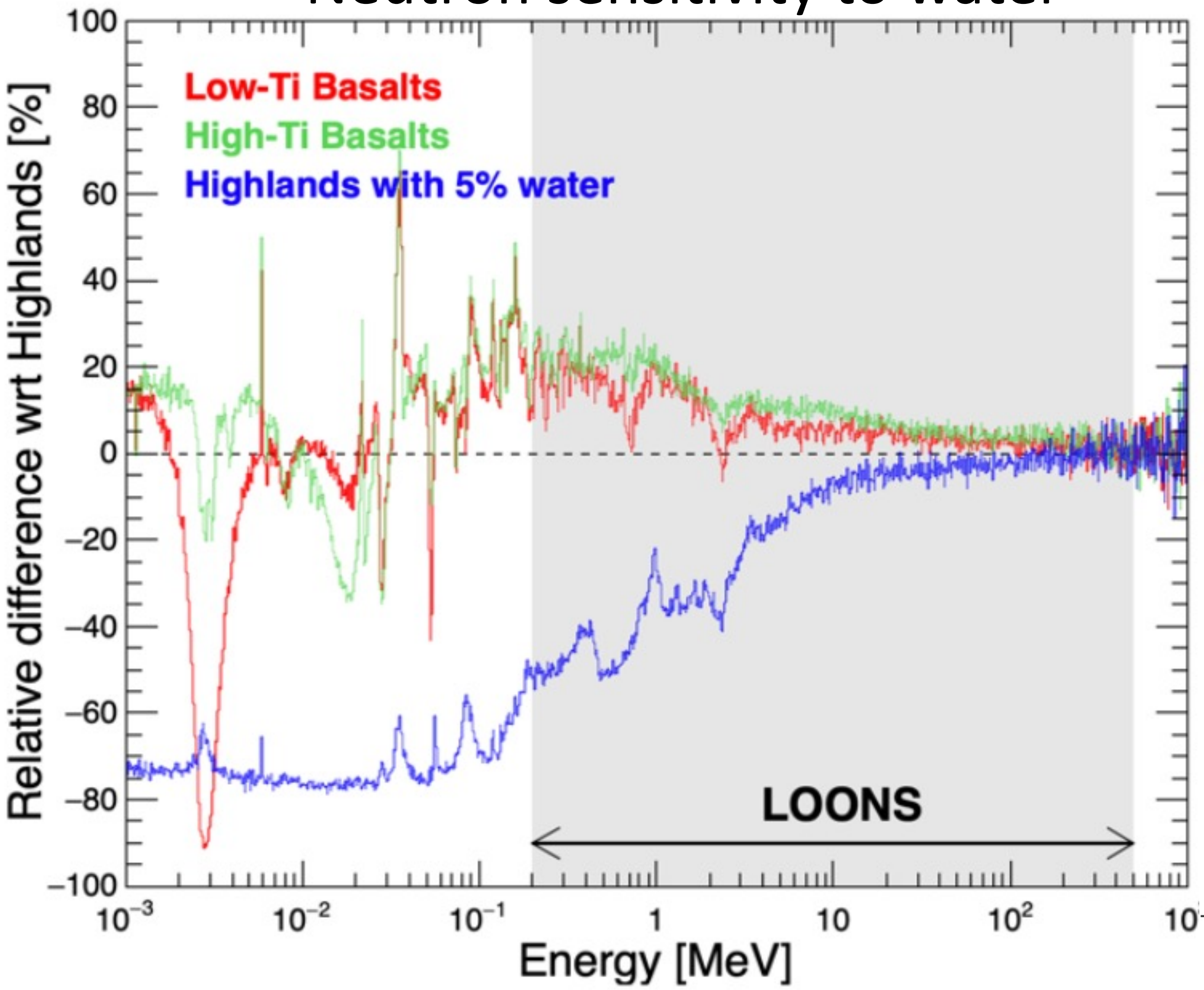
* Lunar surface solar observatory

Moon is a prolific producer of neutrons:

(1) Neutrons are a dangerous component of lunar (& planetary) radiation environments (~20% total radiation dose; Zhang et al. 2020; Heilbronn et al. 2015)

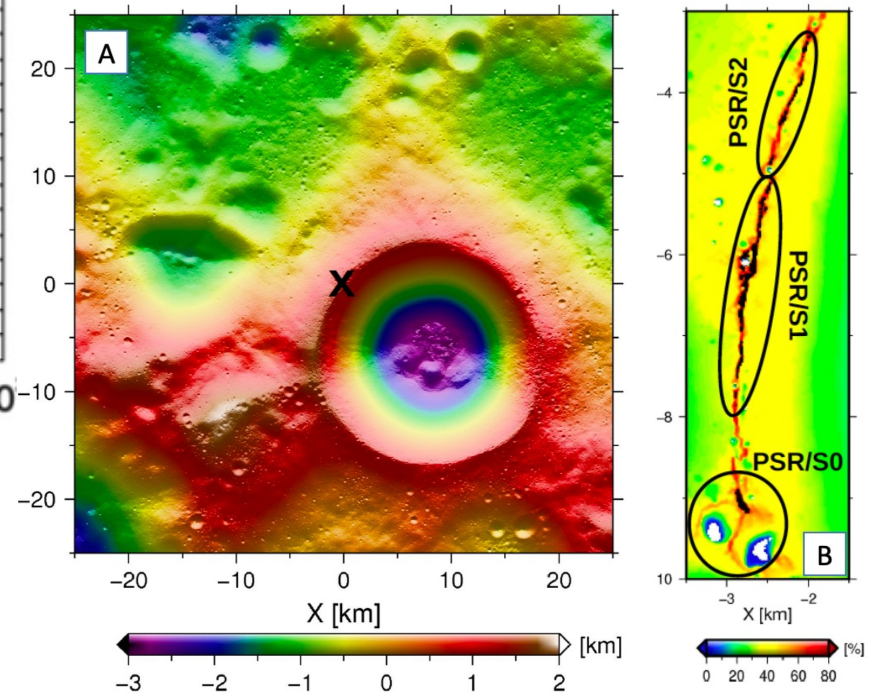
(2) Secondary (albedo) neutron and γ-ray intensity is sensitive to surface composition

Neutron sensitivity to water



Can be utilized to detect water ice in permanently shadowed regions on the lunar surface

PSRs in lunar south pole

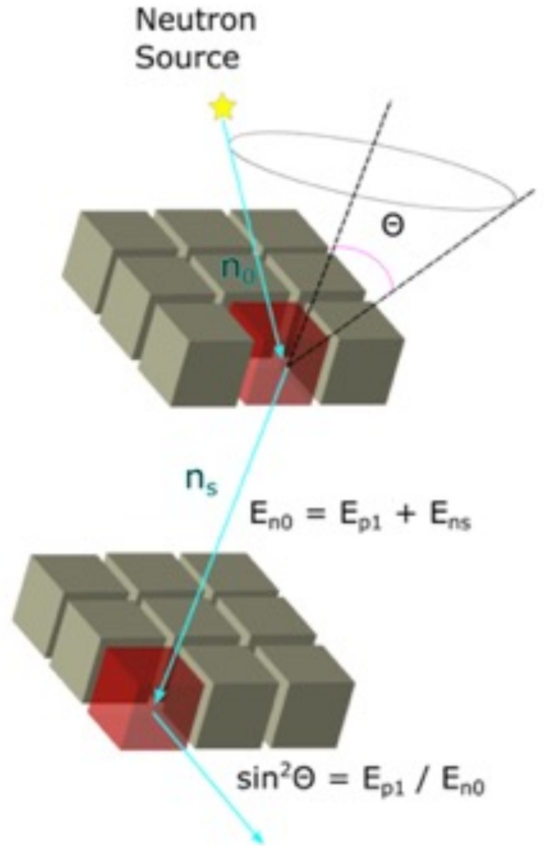


Gläser et al. 2018

→ Neutron spectrometers fill a unique combination of scientific and programmatic needs

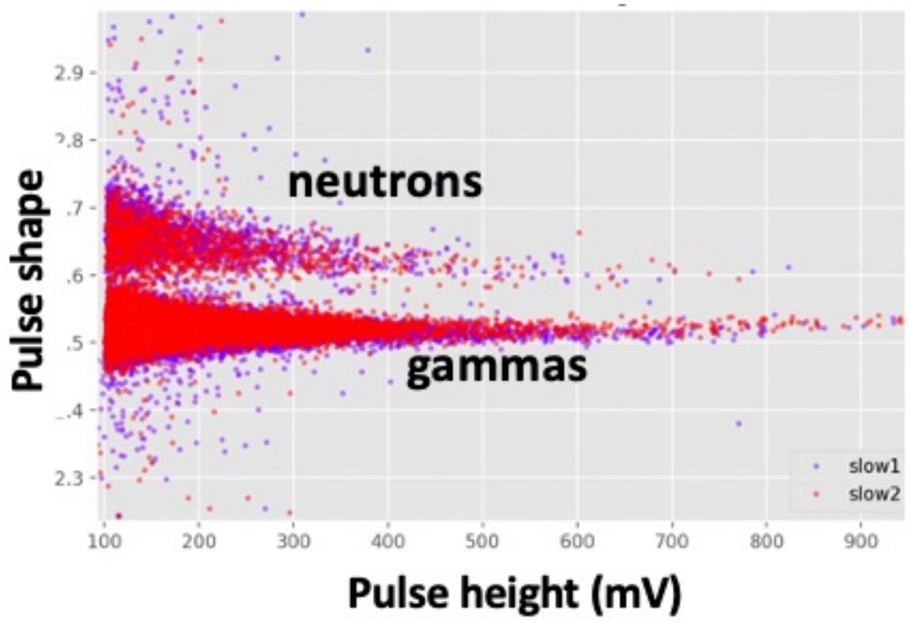
Double Scatter Neutron Spectrometers

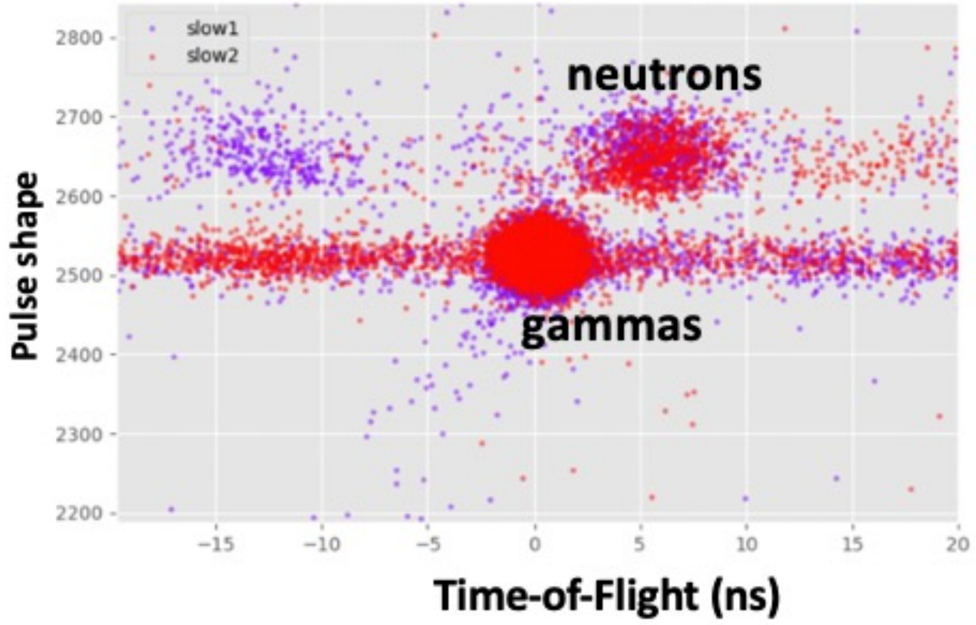
Traditional Double Scatter

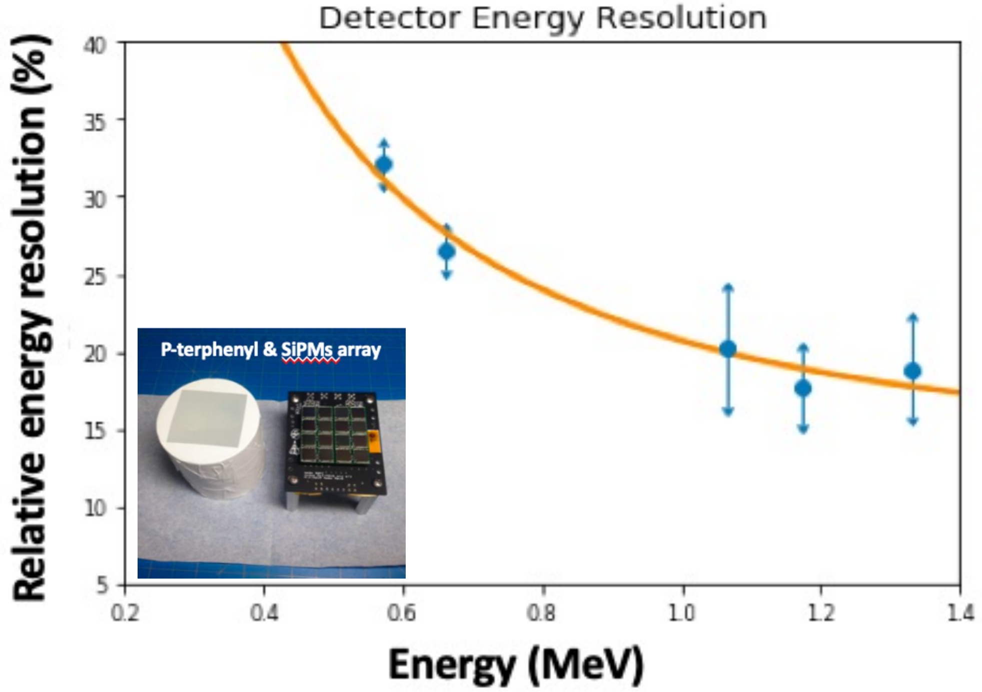


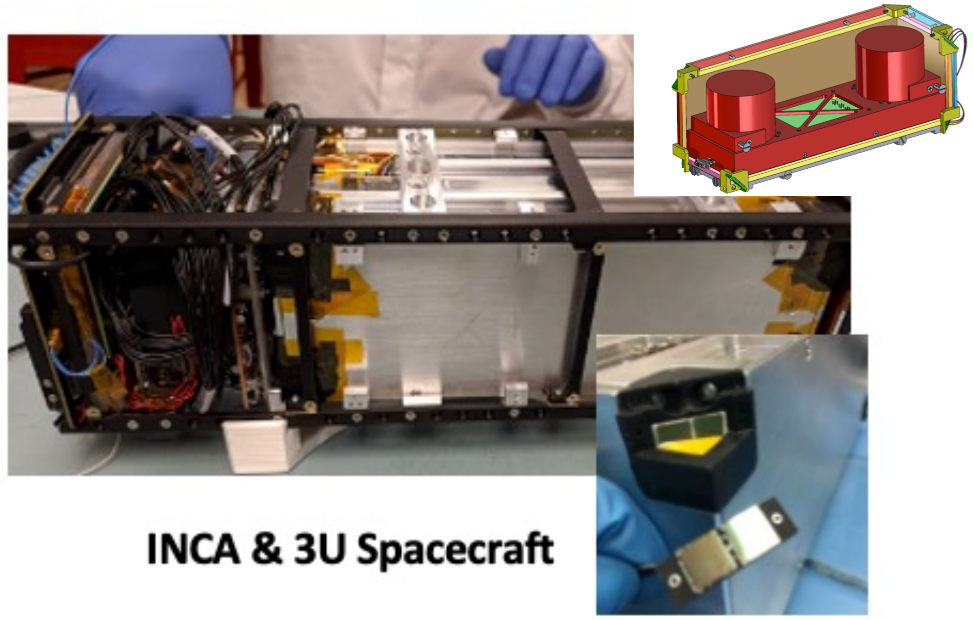
Ionospheric Neutron Content Analyzer (INCA)

Failed ASTRA launch in 2021









INCA & 3U Spacecraft

Driving factors for SiPMs

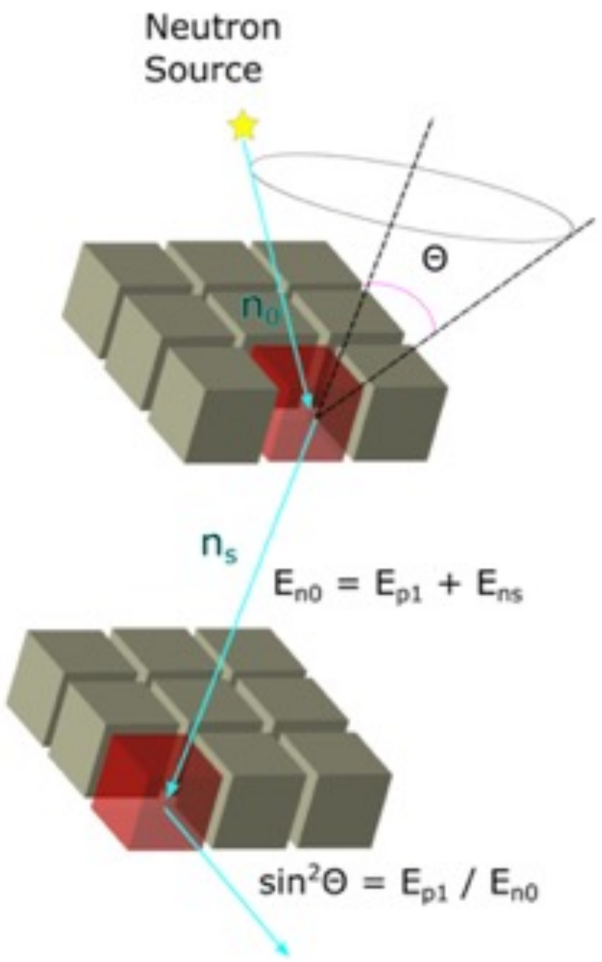
*Fast (need < 1 ns timing resolution)

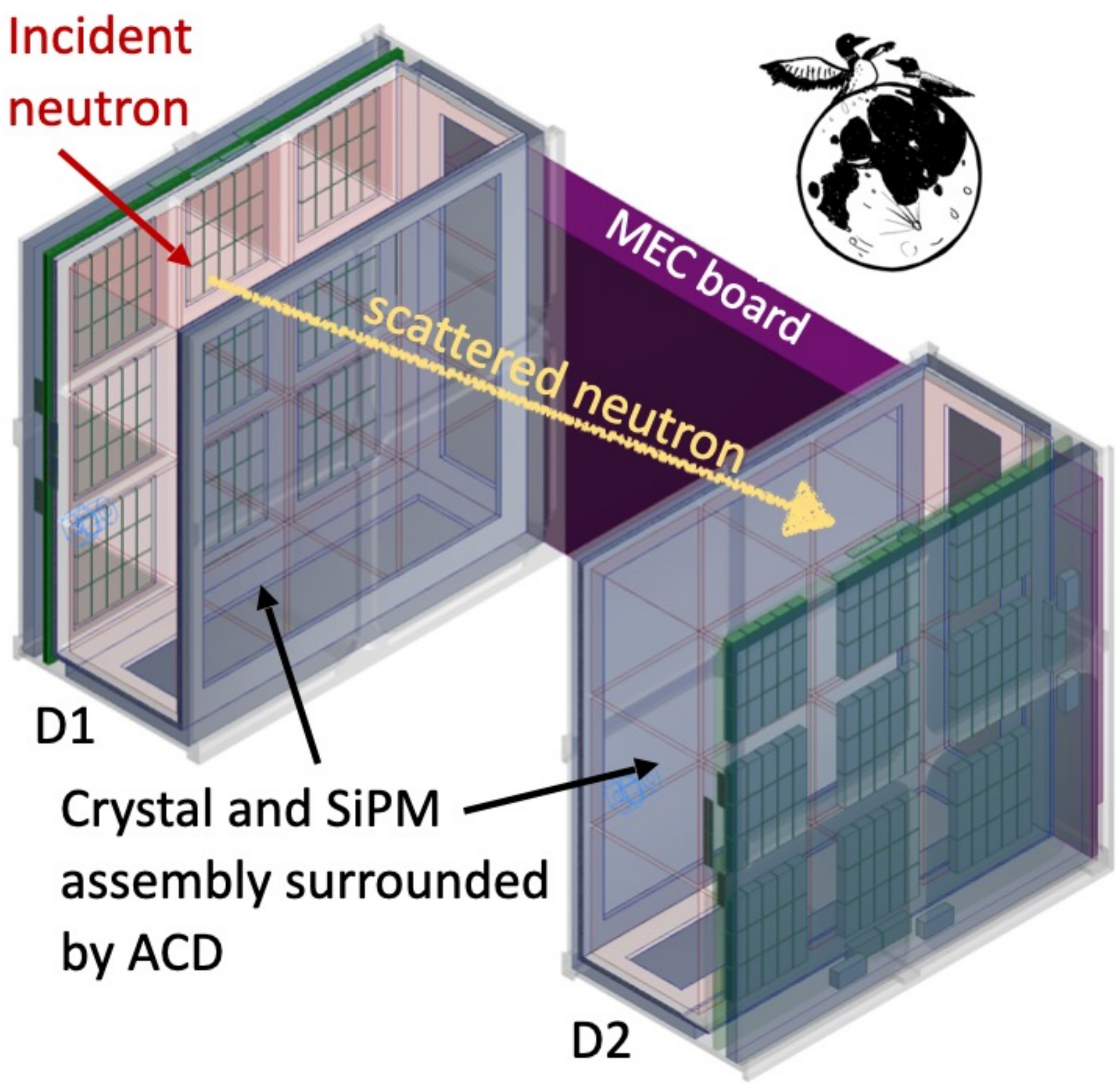
*Low noise/high gain to reduce threshold energy

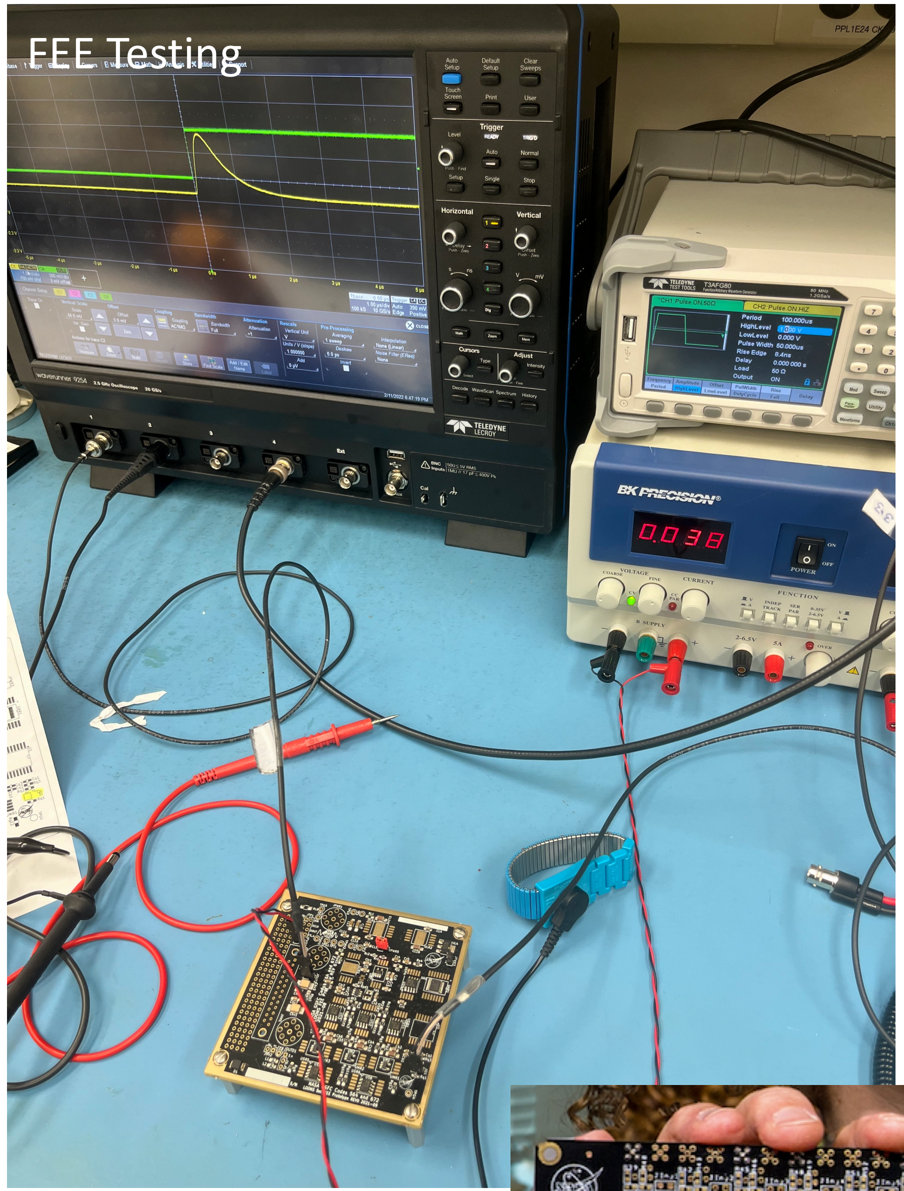
*Pulse shape discrimination

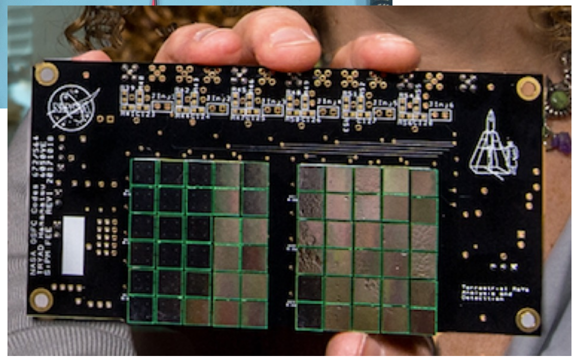
*Signal digitization with DRS4 waveform capture ASIC : Switched Capacitor Array (~140 mW)

Lunar OutpOst Neutron Spectrometer (LOONS)





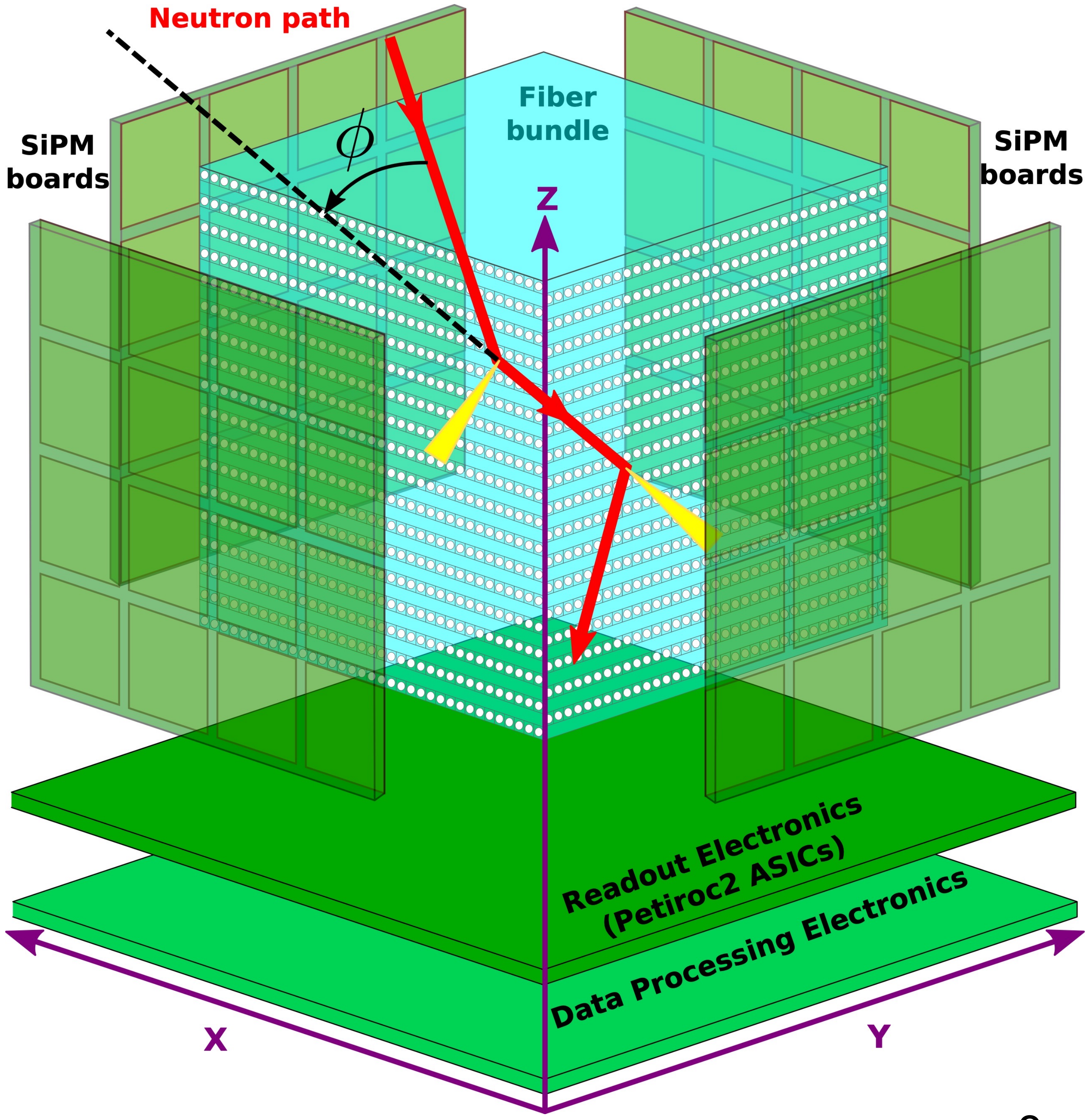




*3x3 arrays of p-terphenyl crystals (with pulse shape discrimination)
*Arrays of 30 6-mm SiPMs view each crystal
(Hamamatsu S13360-6050; S14160HS)
*Signal digitization with DRS4

Solar Neutron TRACking (SONTRAC)

- Significantly expand segmentation → orthogonally stacked scintillating fibers readout by similarly pitched SiPMs
- Interacting neutrons → recoil proton track
- Track reconstruction requires a minimum of two 2D projections



Based on original "proton tracking" concept of 300µm orthogonally stacked plastic scintillating fibers readout by PMT/taper/intensifier/CCD camera (Ryan et al. 1999)

Solar Neutron TRACking (SONTRAC)

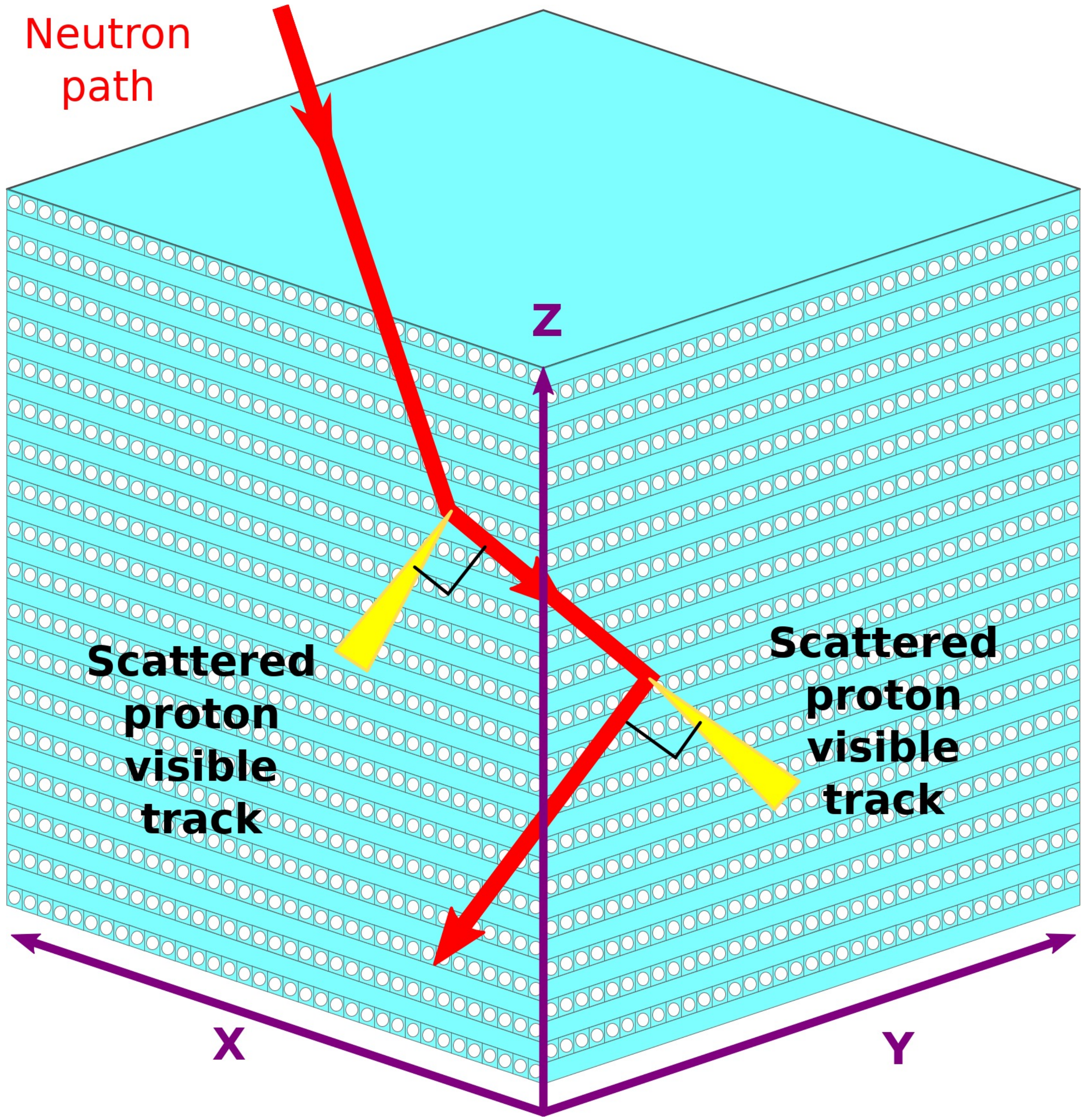
From the neutron kinematics, we can reconstruct the incident neutron energy & direction uniquely.

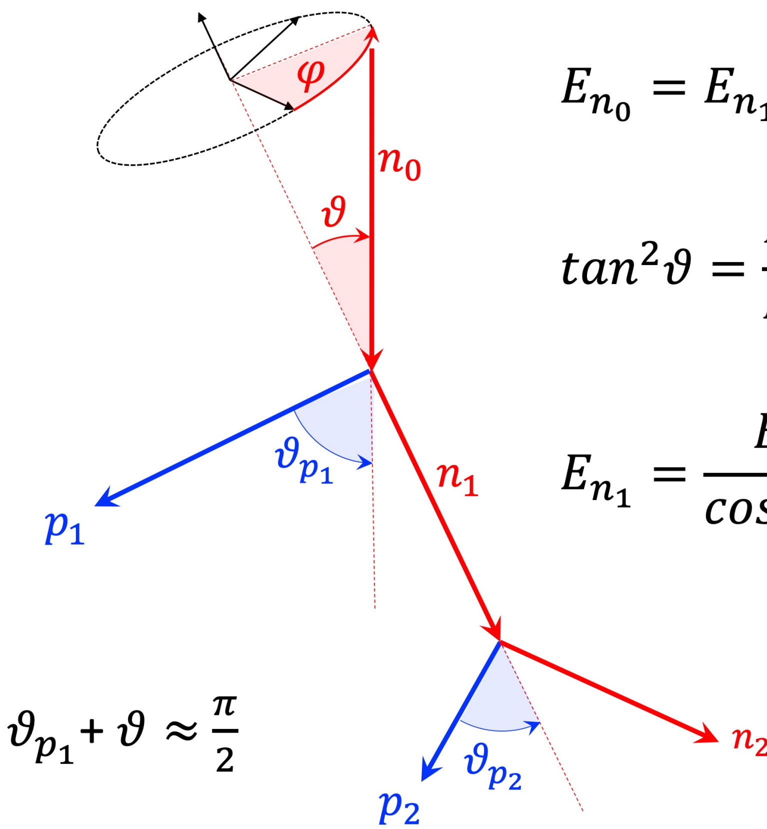
*Energy determined from pulse height & Bragg peak

*Angular resolution determined by pitch of fibers

*Good angular resolution translates to lower background

Proton tracking with finer segmentation



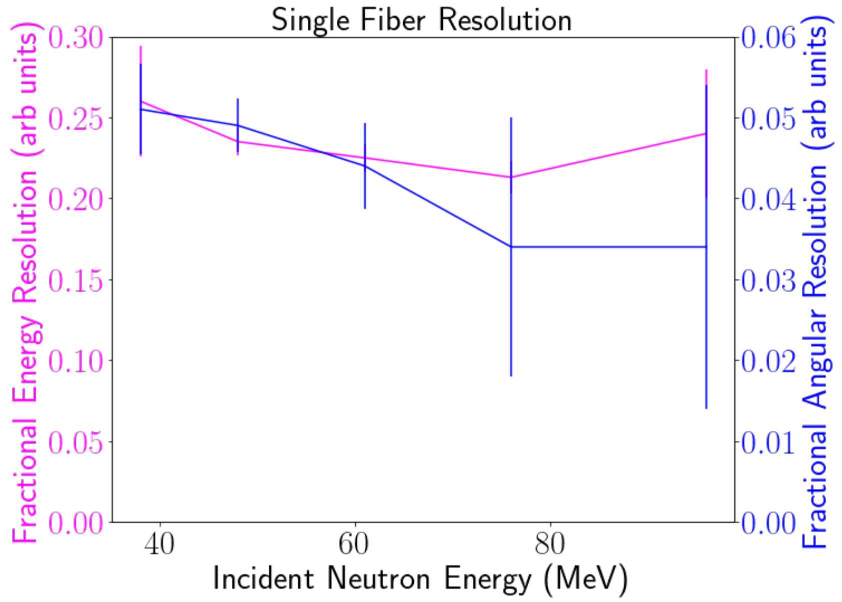


$$E_{n_0} = E_{n_1} + E_{p_1}$$

$$tan^2\vartheta = \frac{E_{p_1}}{E_{n_1}}$$

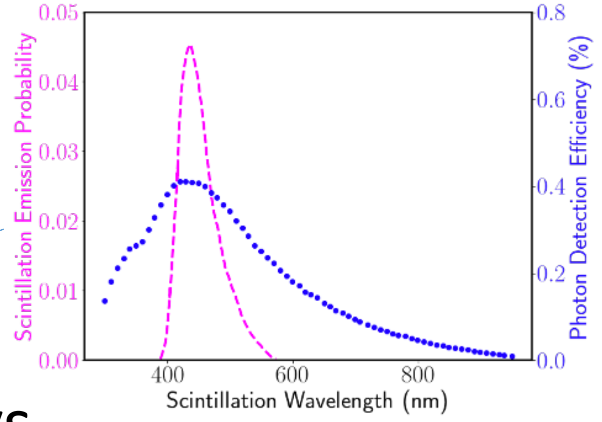
$$E_{n_1} = \frac{E_{p_2}}{cos^2\vartheta_{p_2}}$$

$$\vartheta_{p_1} + \vartheta \approx \frac{\pi}{2}$$



SONTRAC Prototype

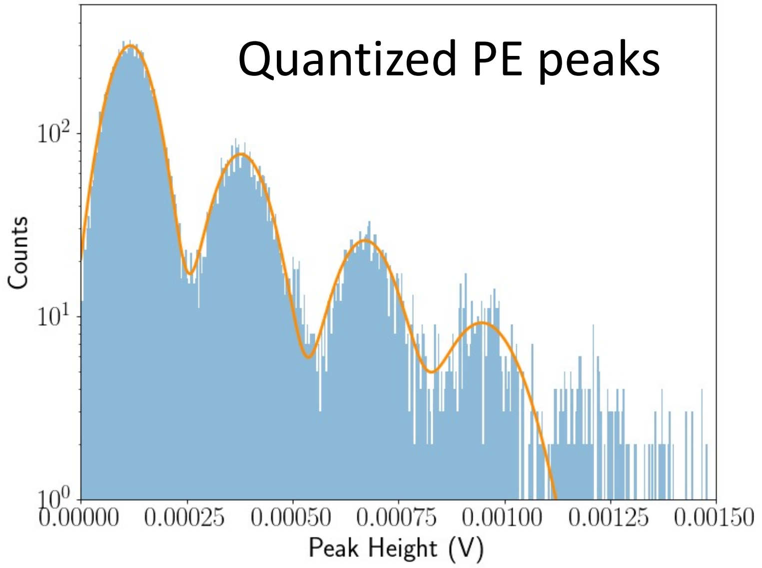
Scintillating Fiber Bundle: 5-cm bundle with 1.36 mm pitch orthogonally stacked fibers (Saint Gobain BFC-12 fibers)

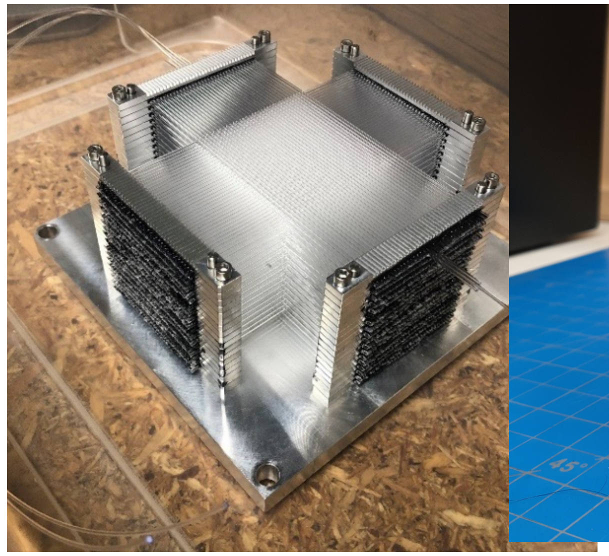


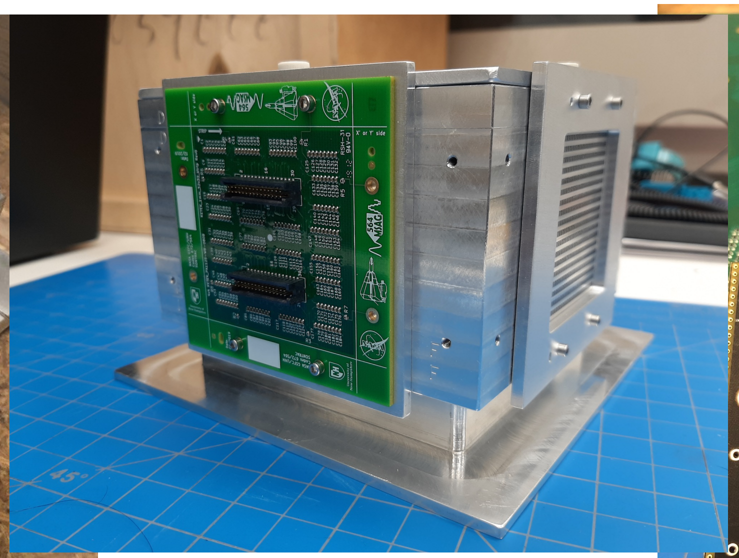
Viewed by 1.36-mm pitch arrays of 8x8 1-mm SiPMs from KETEK (now Broadcom) with fast rise time (several ns), PDE ~ 40%, gain~$10^{5\text{-}6}$

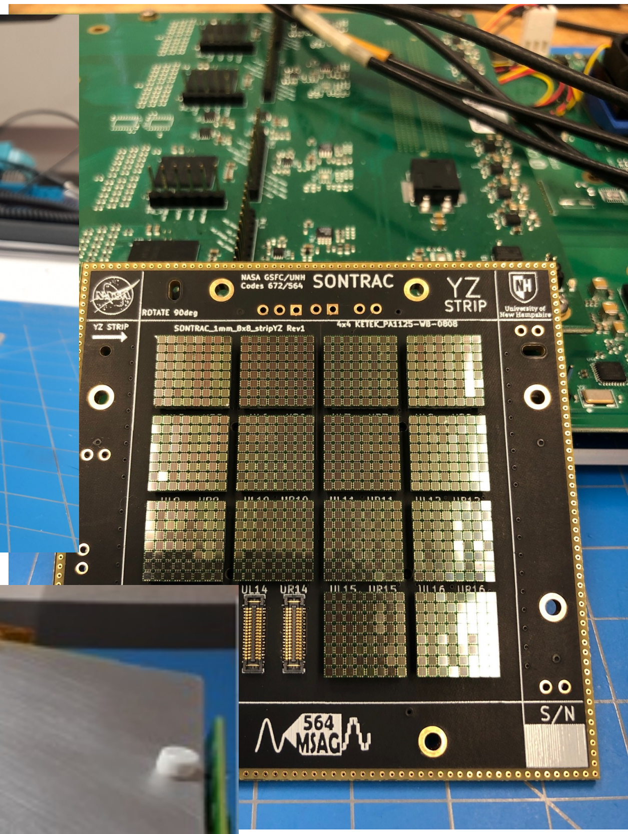
SiPM requirements:

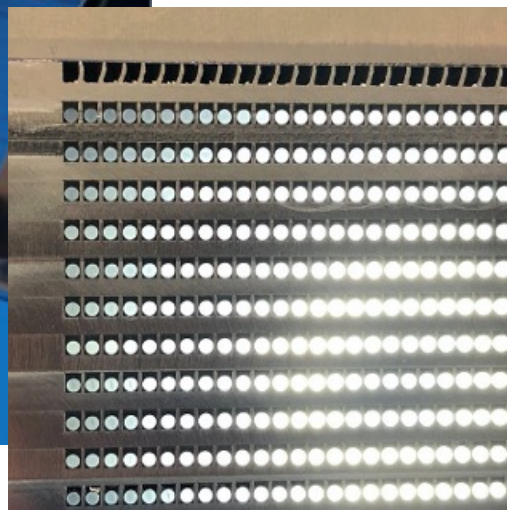
- Arrays with prescribed pitch
- Sensitive to single PEs



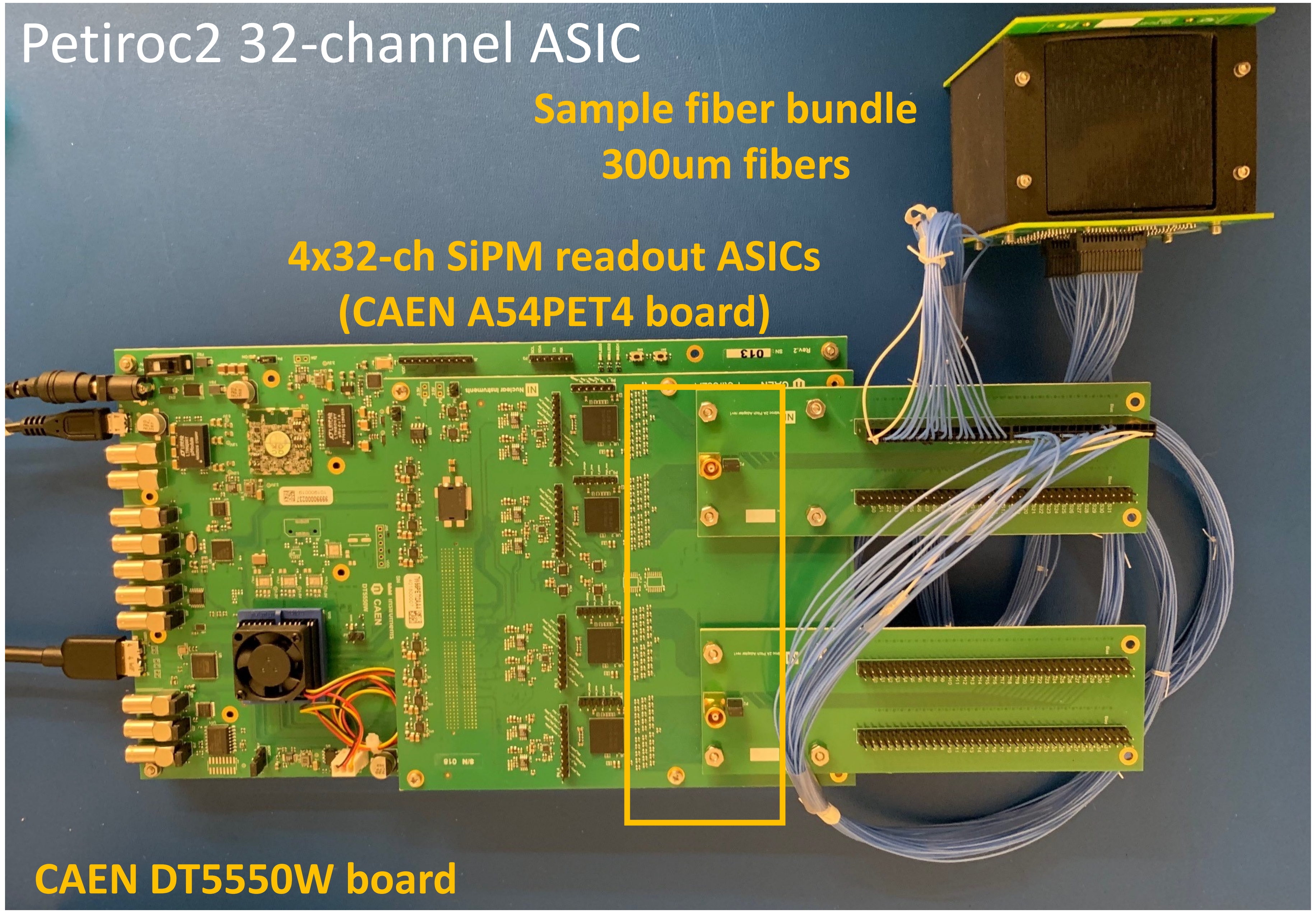




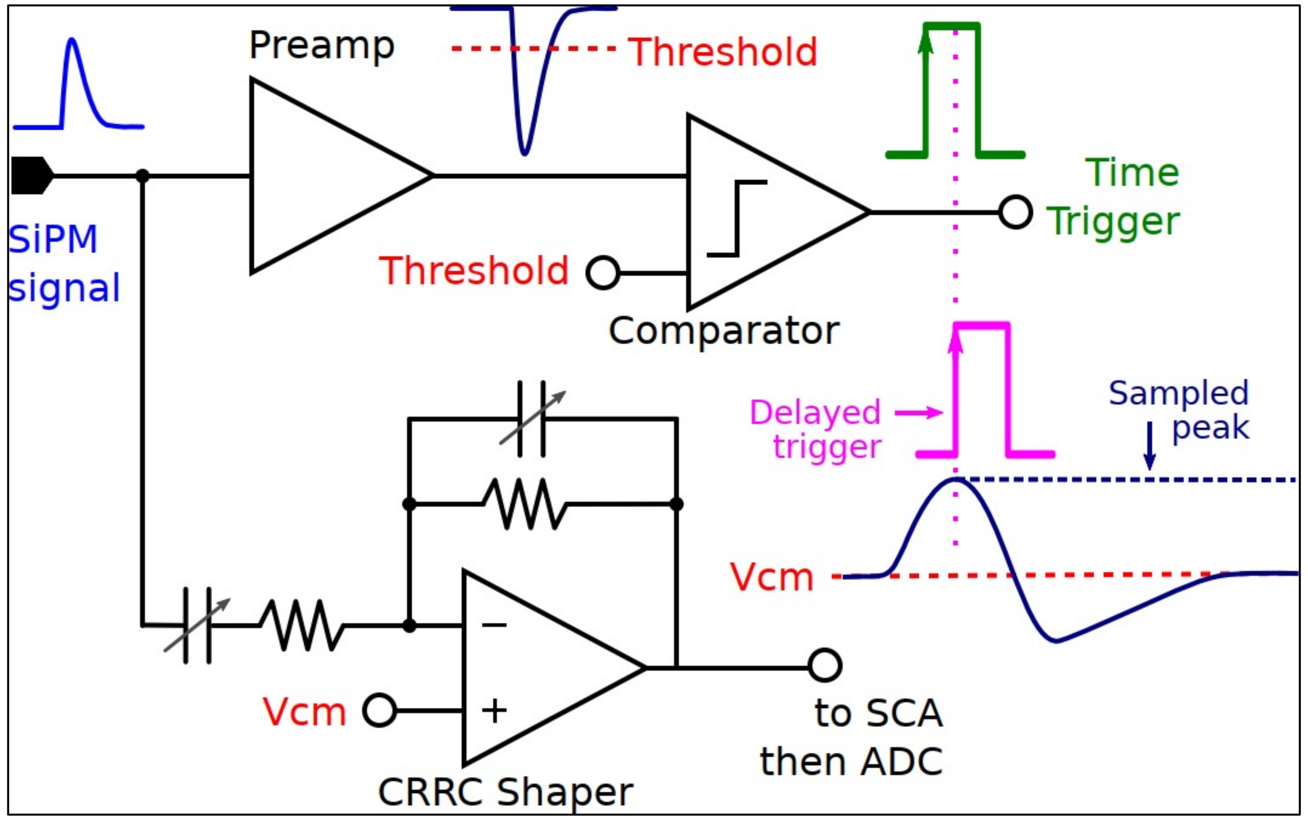




SONTRAC – Readout CAEN DT5550W/Petiroc2 ASICs



Signal processing with commercial 32-ch CAEN Petiroc 2A



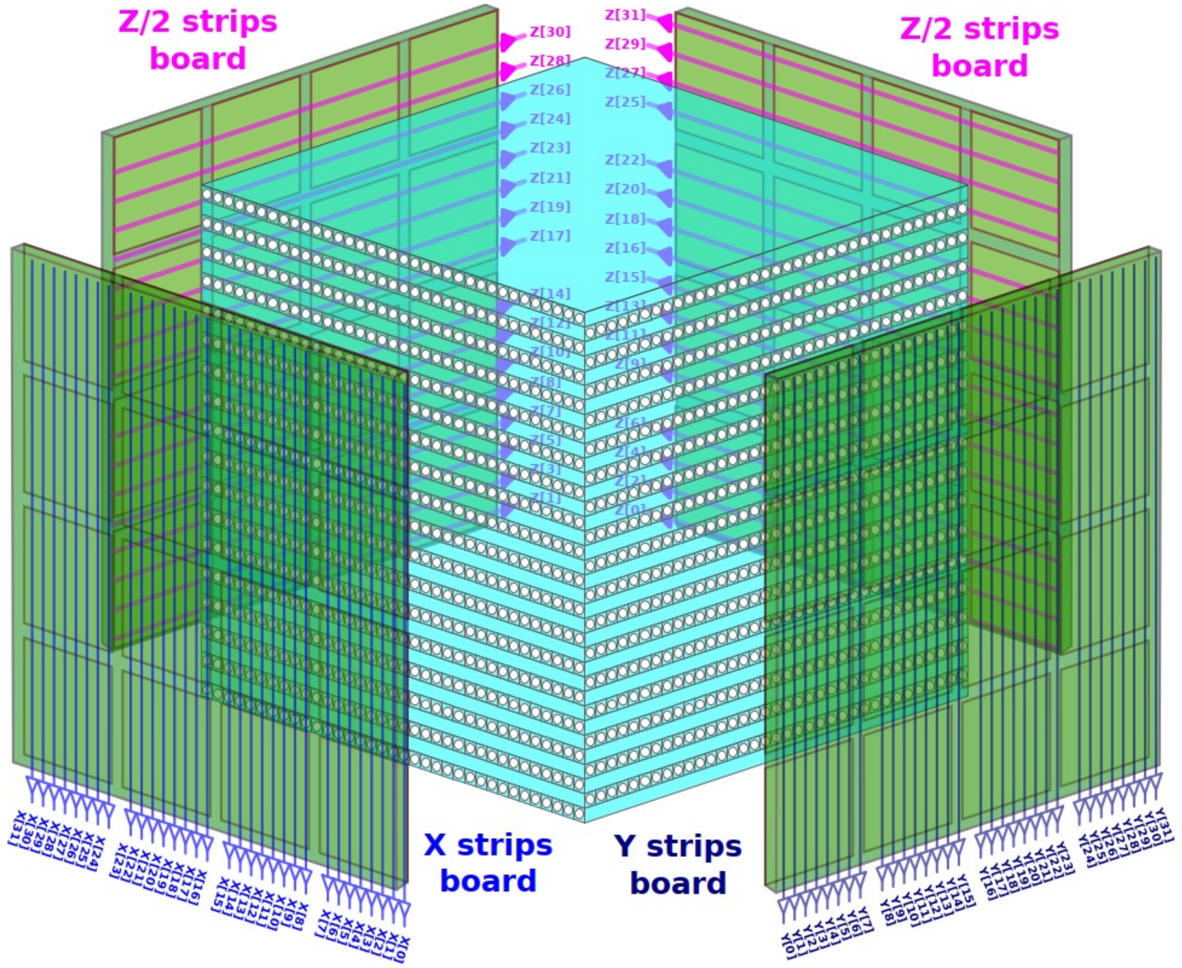
6mW/ch, dynamic range: 480 pC ~ 3000 pe

Petiroc2 offers both timing & pulse height measurements. Currently using the DT5550W (4 ASICs) but working to develop our own digital processing board to house the ASICs directly.

SONTRAC Readout

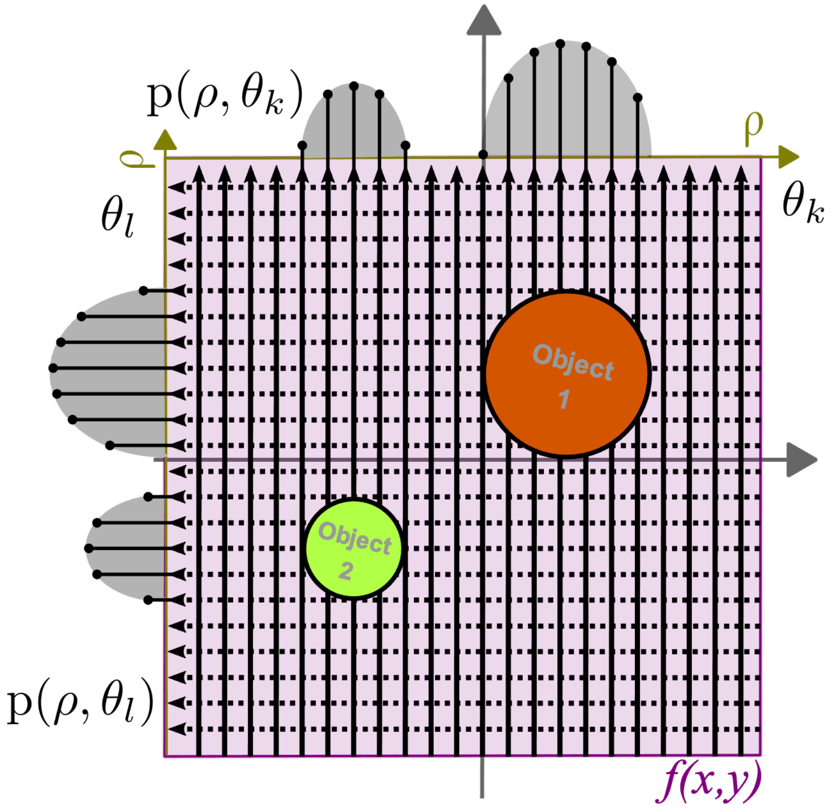
- Readout is a challenge!
  32x32x2 = 2048 channels!
- Gain considerable data compression by summing SiPMs along a strip
- Provides there (or 4) 1D projections → 3D recoil proton track
  reducing the channel # from 32x32x2 to 32x4
- Reconstruction based on limited Computed Tomography

Strip readout (1D projections)



Sum horizontal and vertical strips
Proton tracks are encoded in strips

Computed Tomography: filtered back projection



SONTRAC Performance : Ground-level Muon Tracks

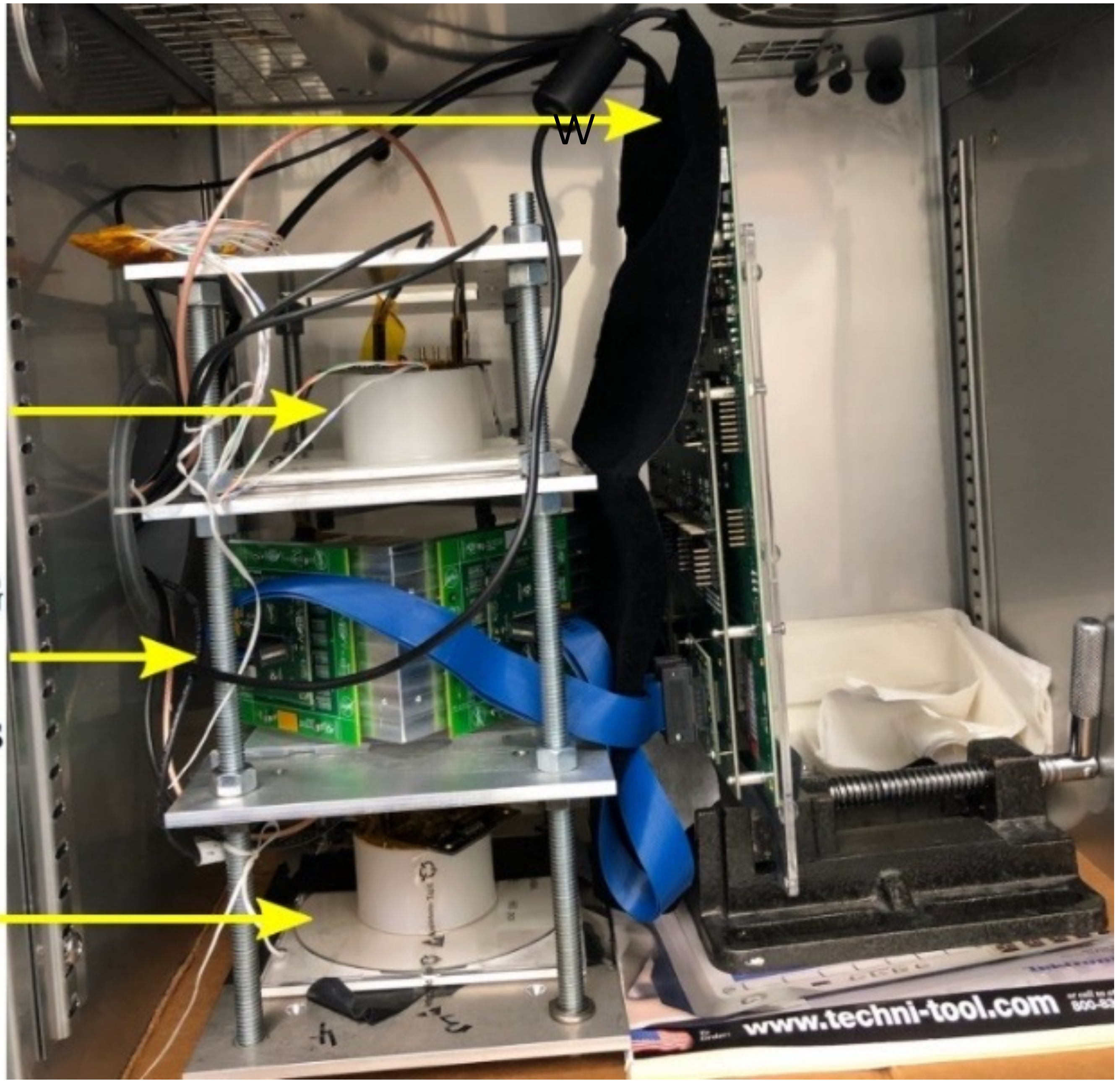
Test Set Up Inside Temperature Chamber

CAEN DTW5550 Petiroc2A ASICs

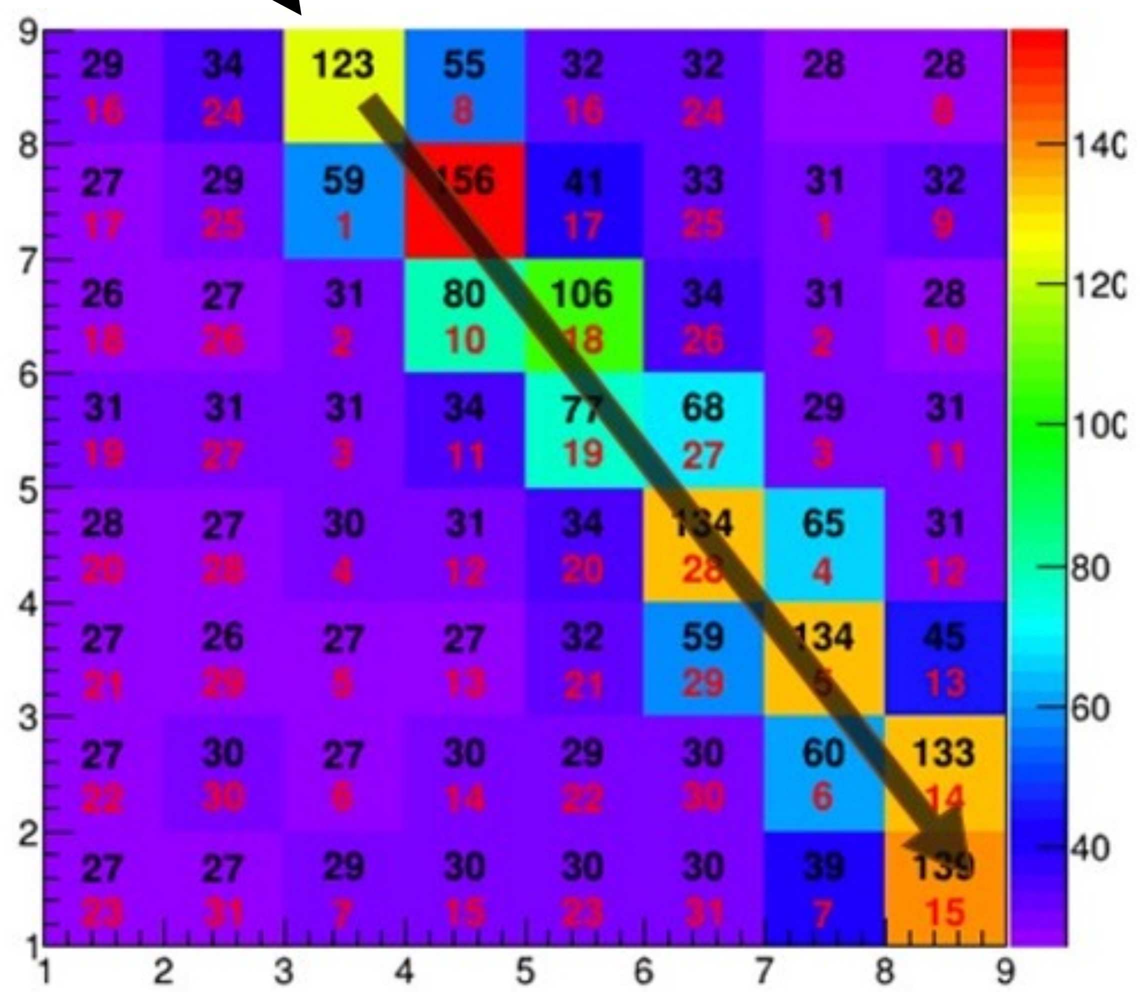
Top Muon paddle

SONTRAC-2G Fiber bundle & SiPM boards

Bottom Muon paddle

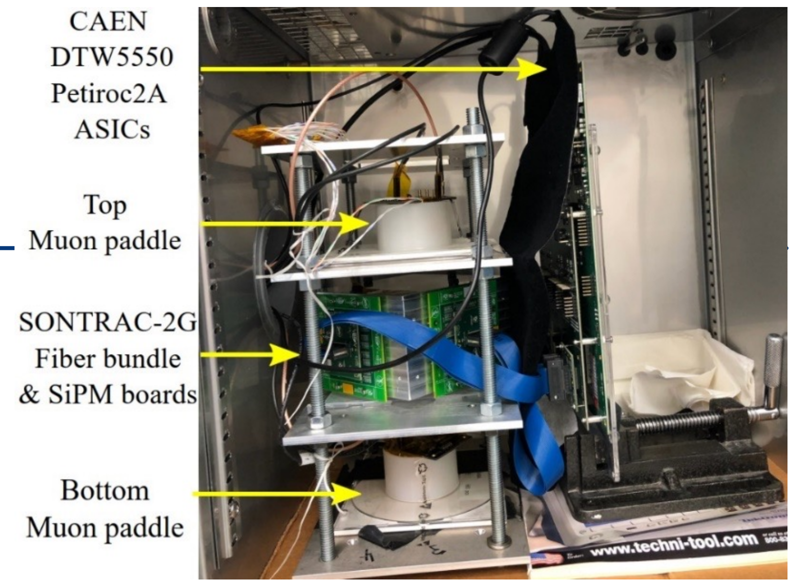


Muon tracks

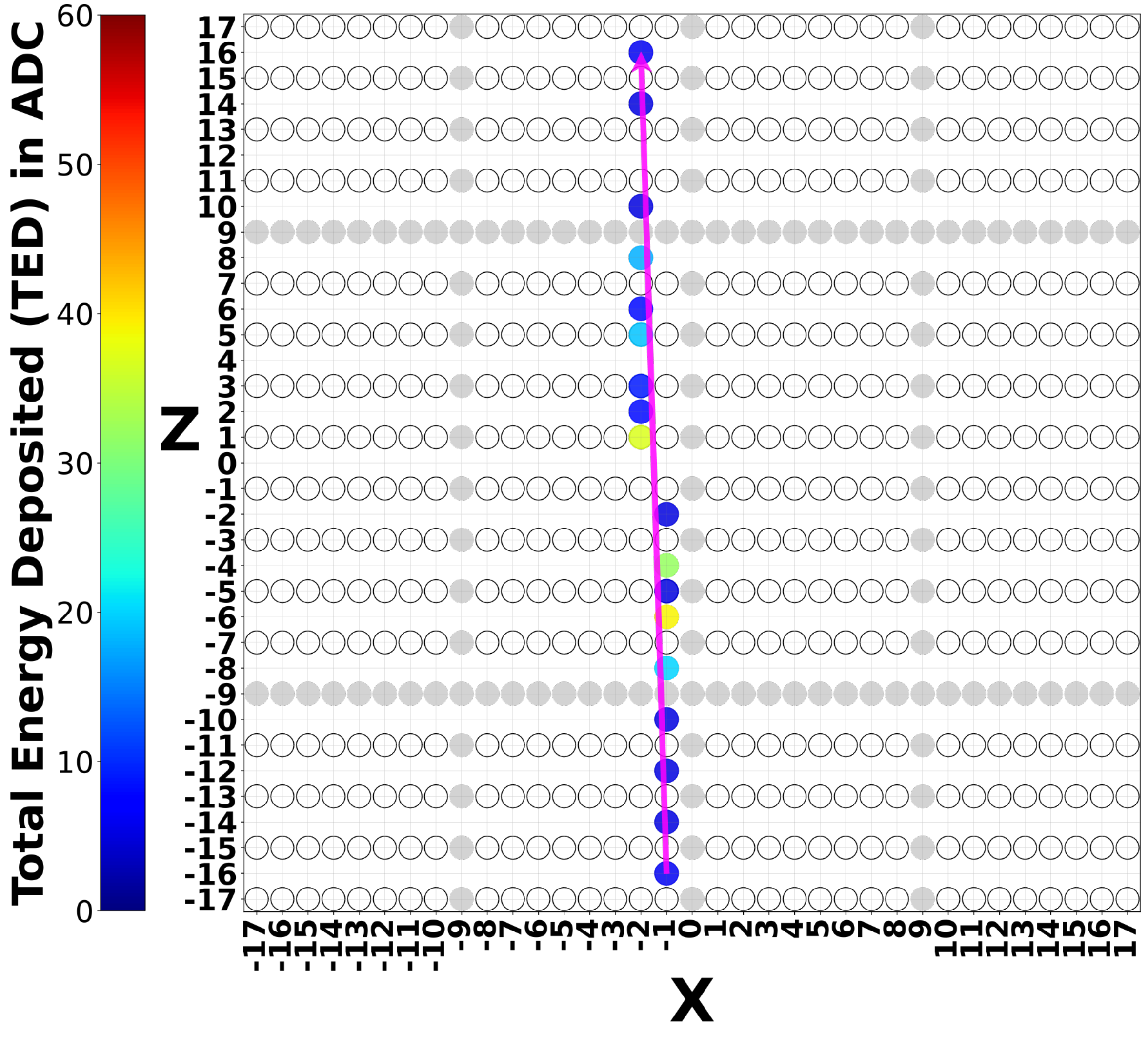


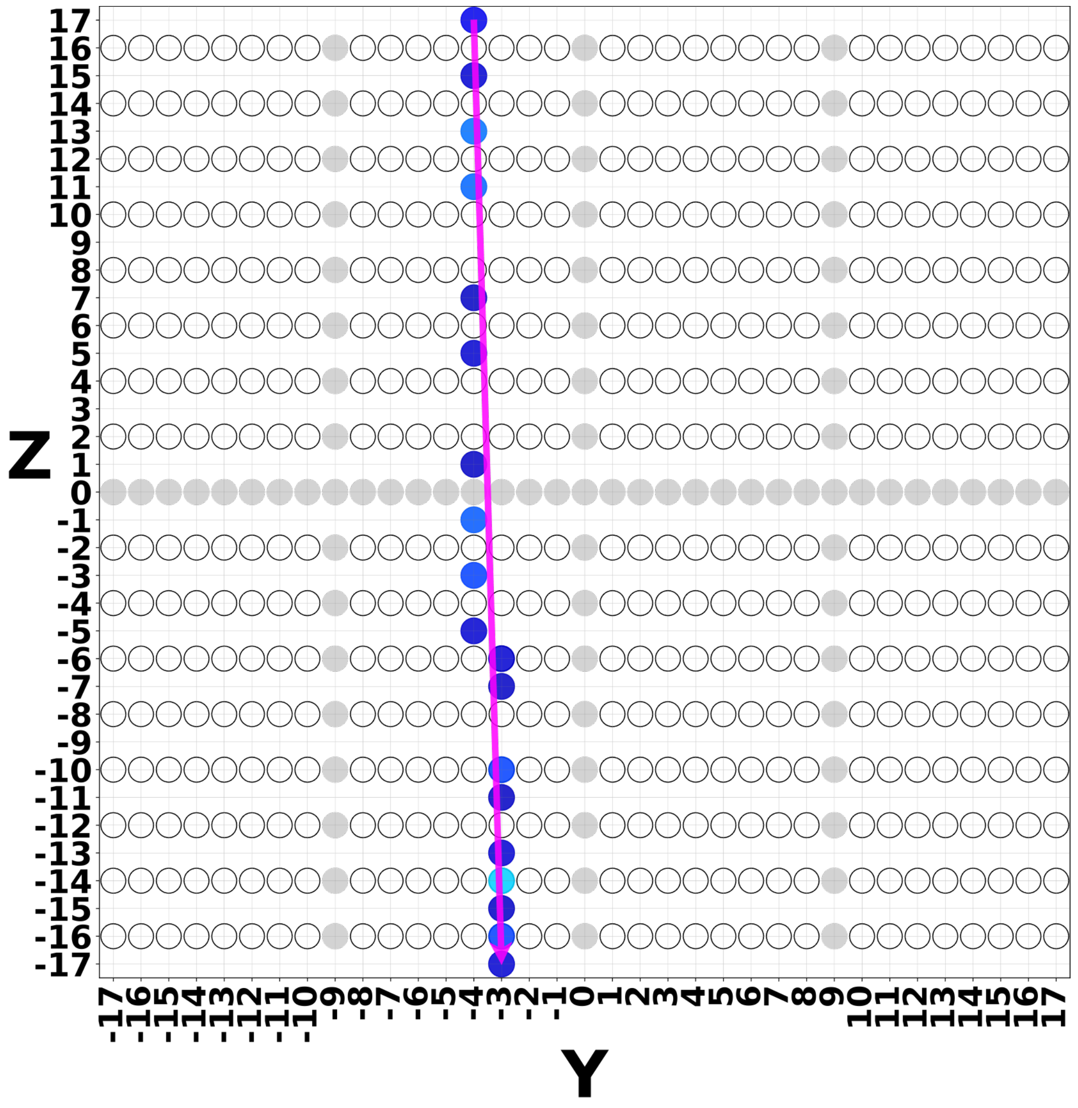
⇒ Demonstrate sensitivity to minimum ionizing particles !

Reconstructed Muon Tracks

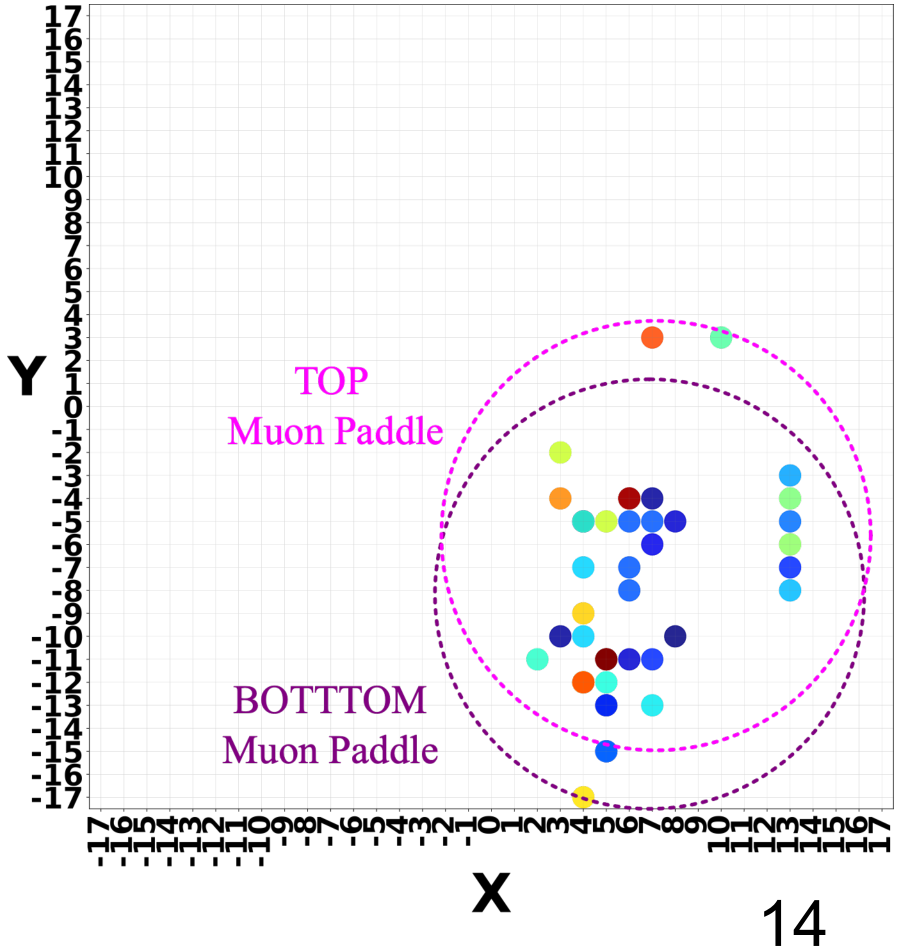


Reconstructed Muon Tracks





Tracks projected to fiber bundle top

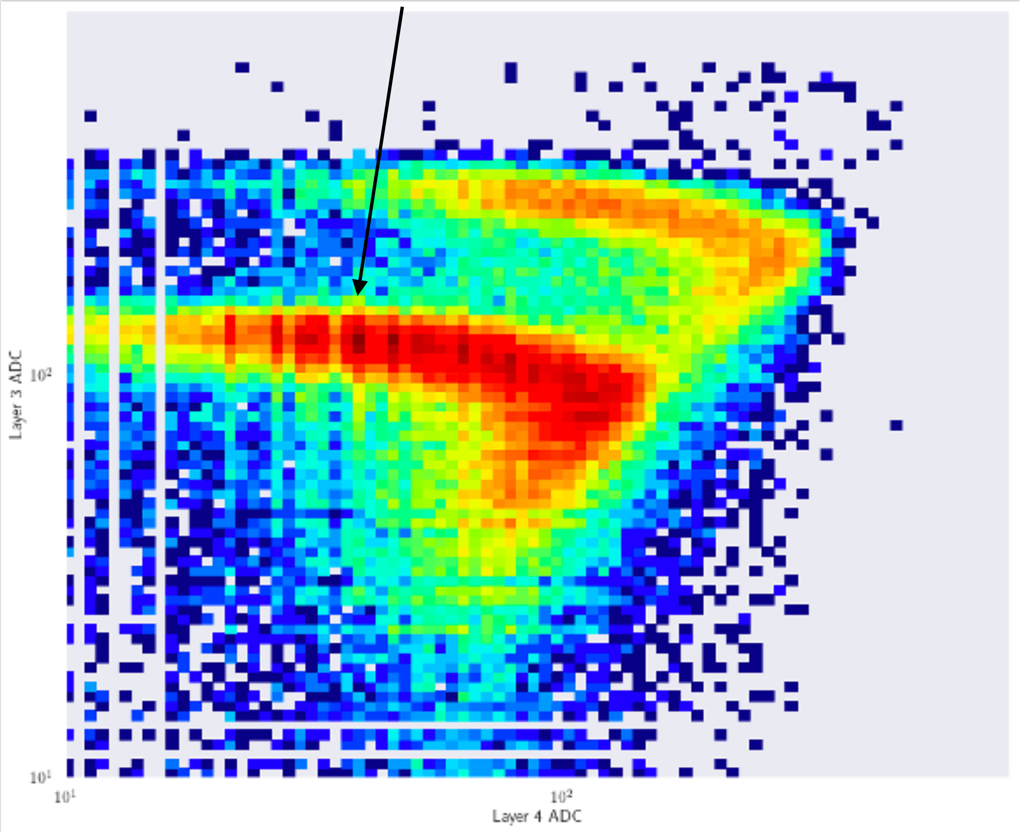


Crocker National Lab : UC Davis

- 76” isochronous cyclotron with proton energy up to 68 MeV
- Thin (1.3 mm) ^{7}Li target convert protons to neutrons (60% by $^{7}Li(p,n)^{7}Be$)
- 1pA ~ $1x10^{5}$ protons/cm^{2}s

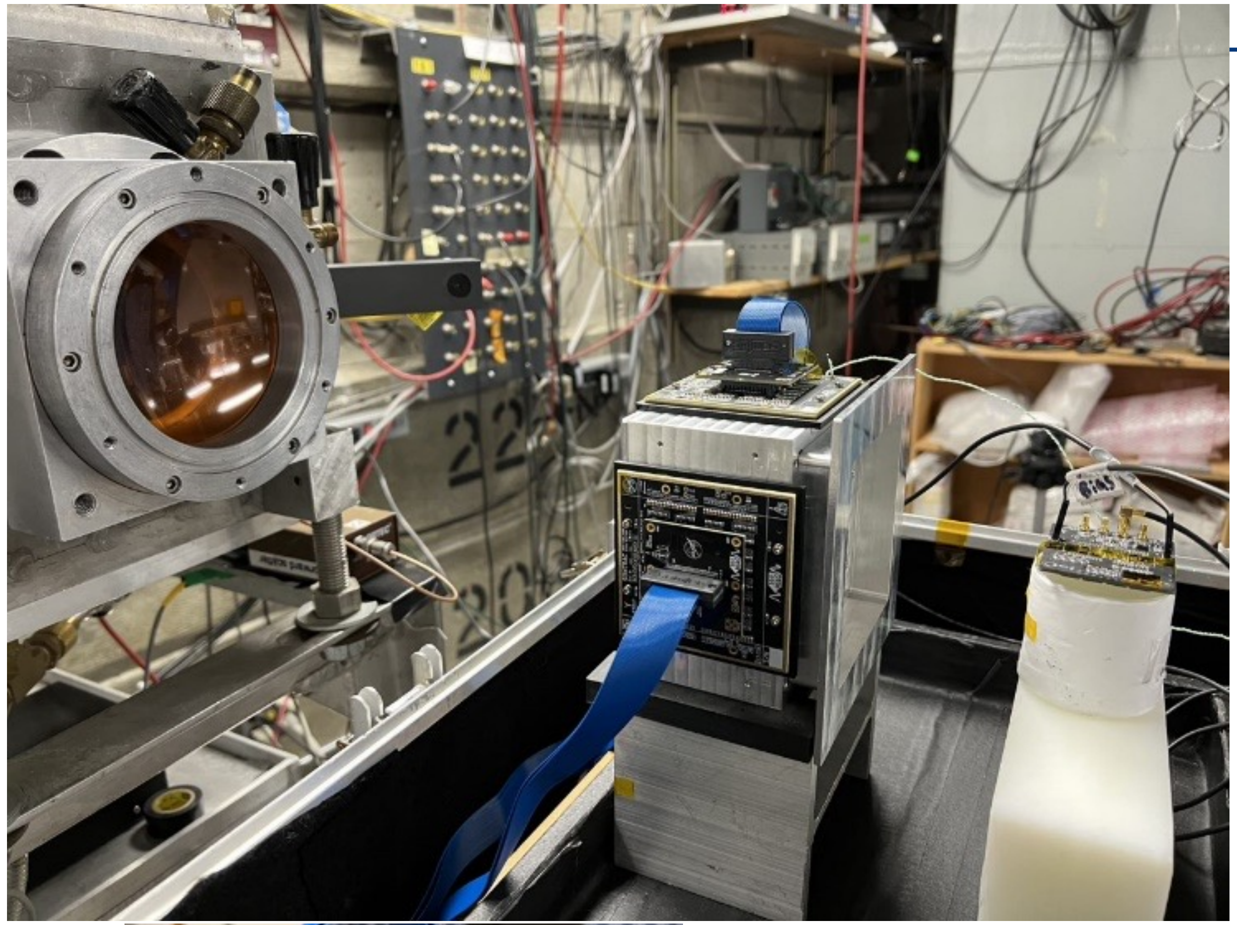
Proton Energy (MeV)	Beam Current (pA)
19.45	0.0625
33.8	0.0625
66.4	0.125

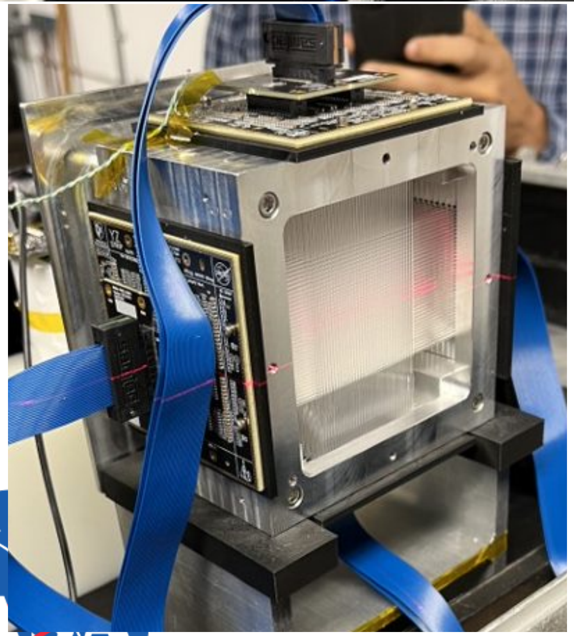
dEdx ~ mz^{2}/E

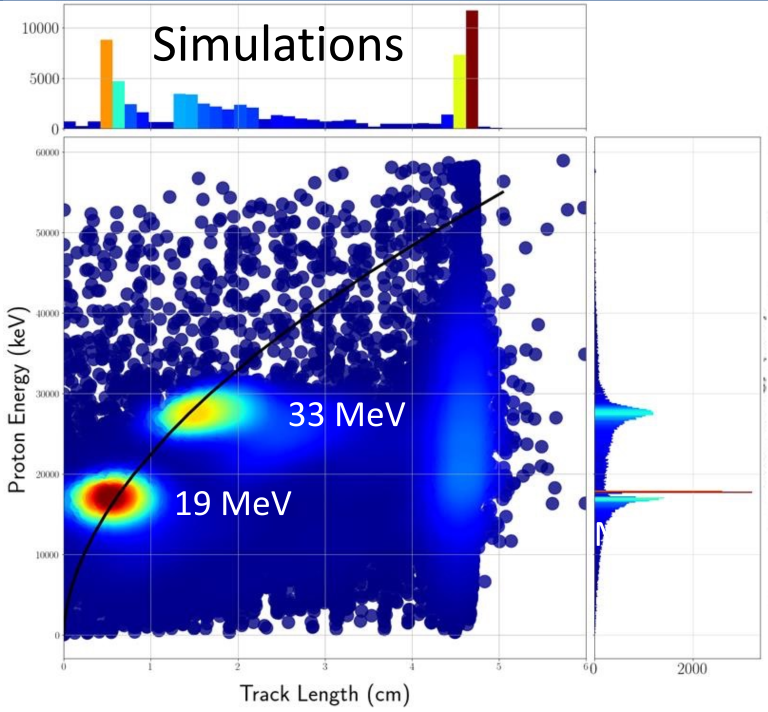


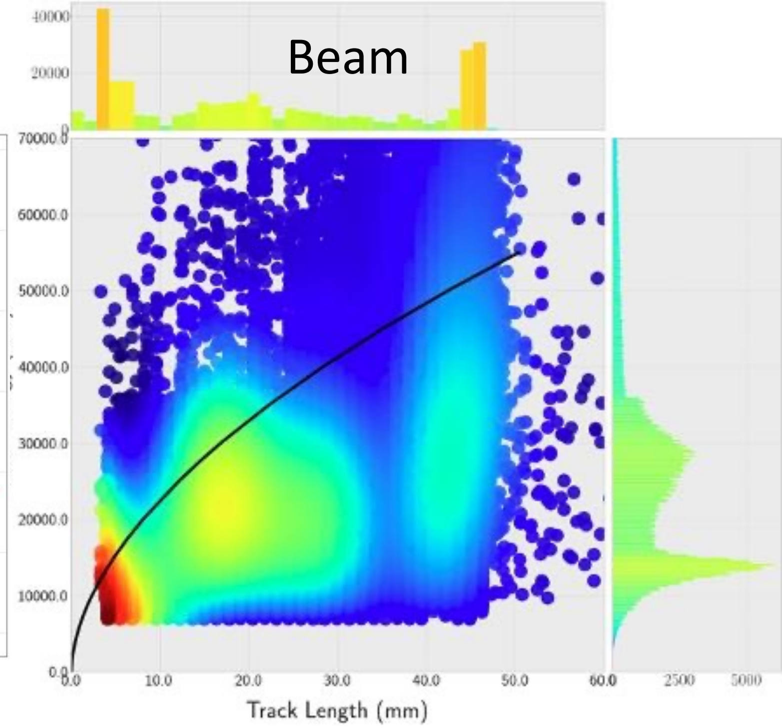
dEdx vs. residual energy for 19 MeV

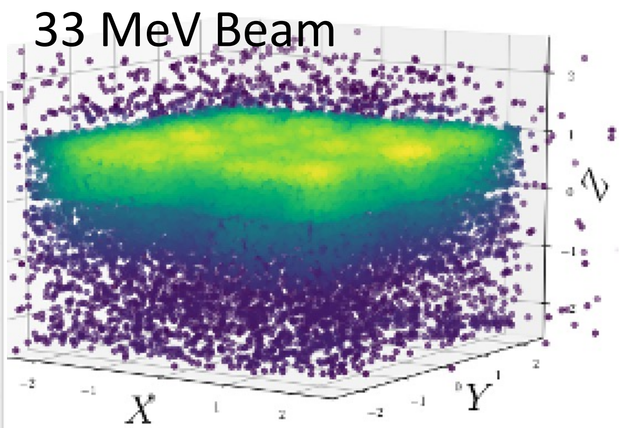
Proton Beam Test: Crocker National Lab Cyclotron

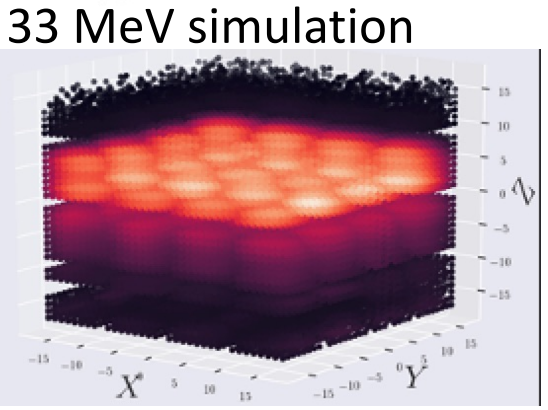


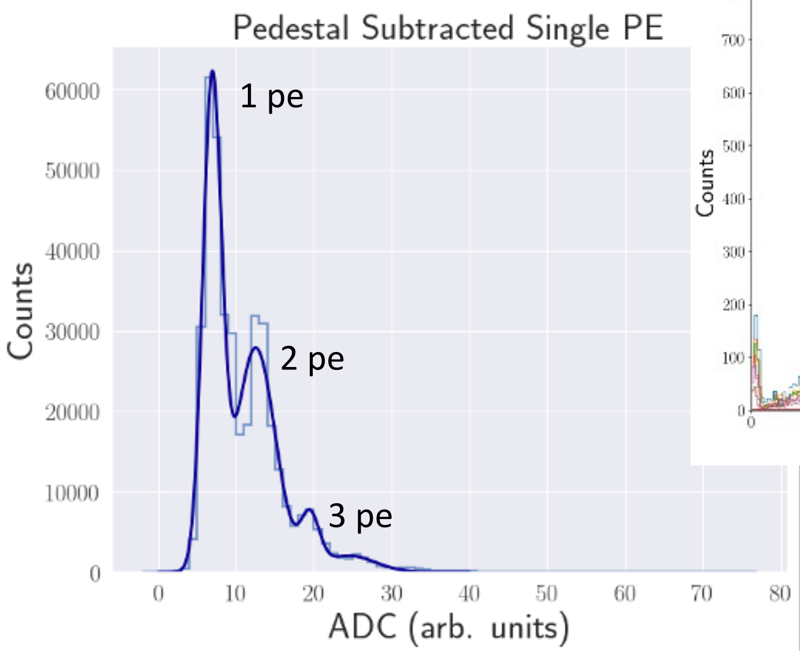


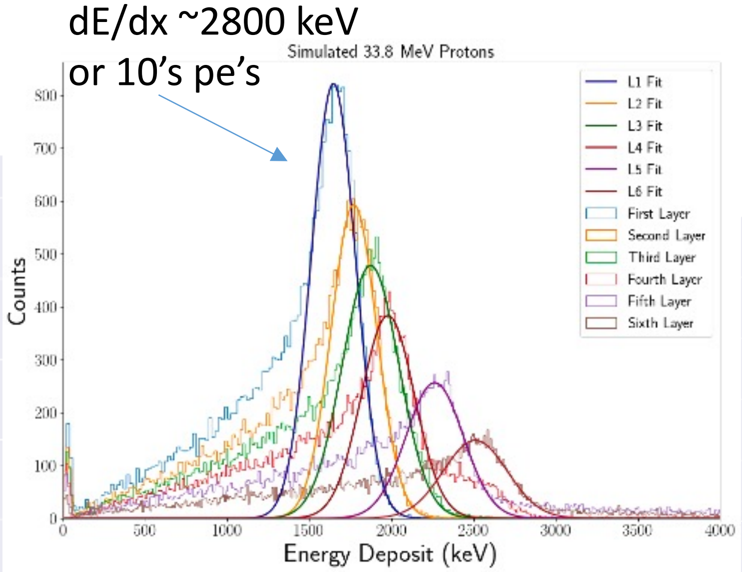


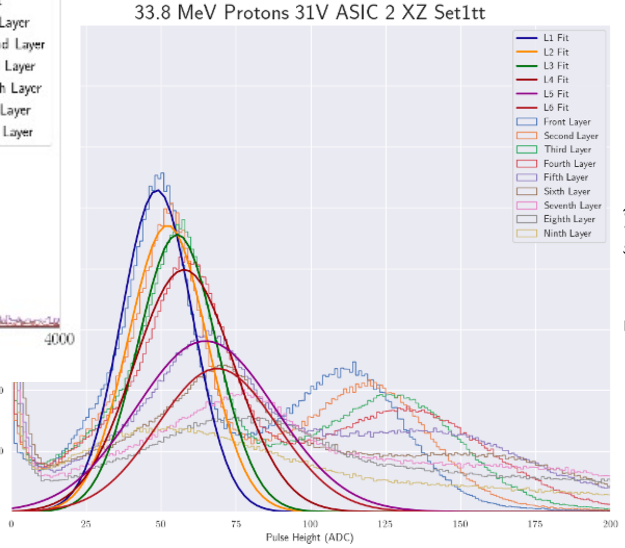


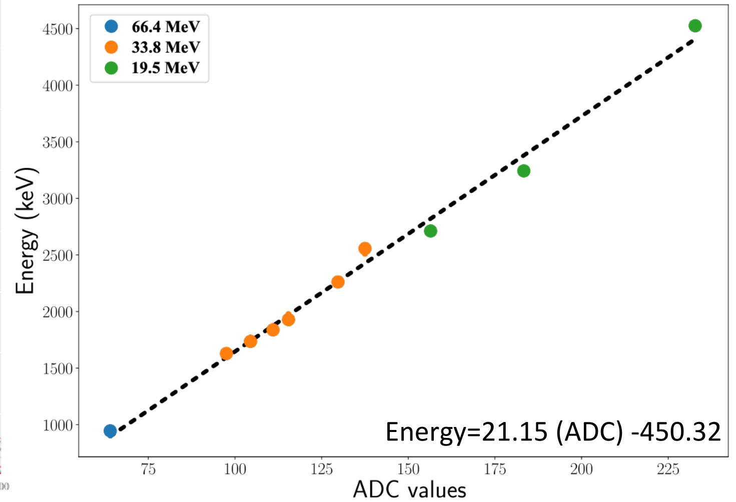




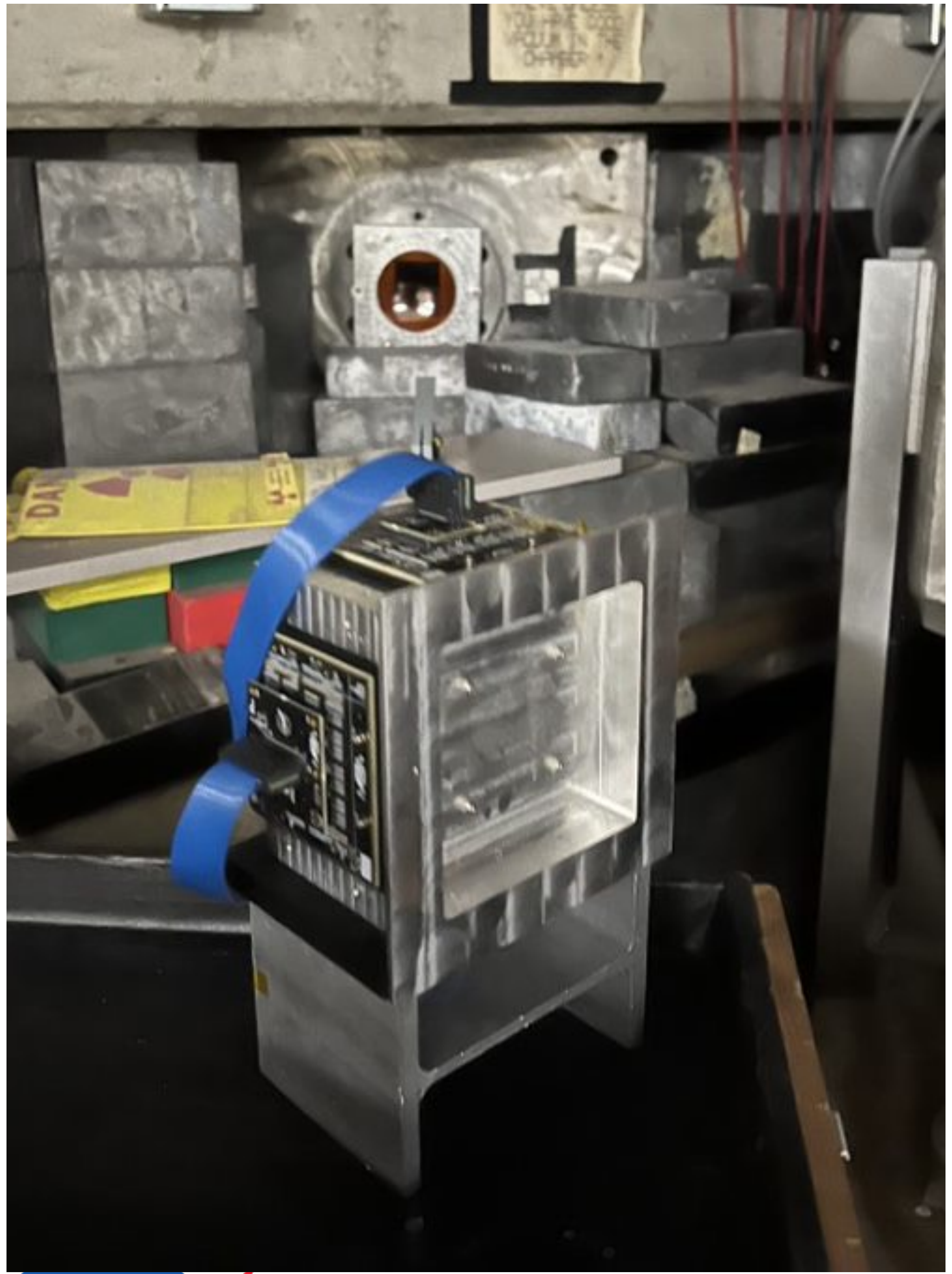






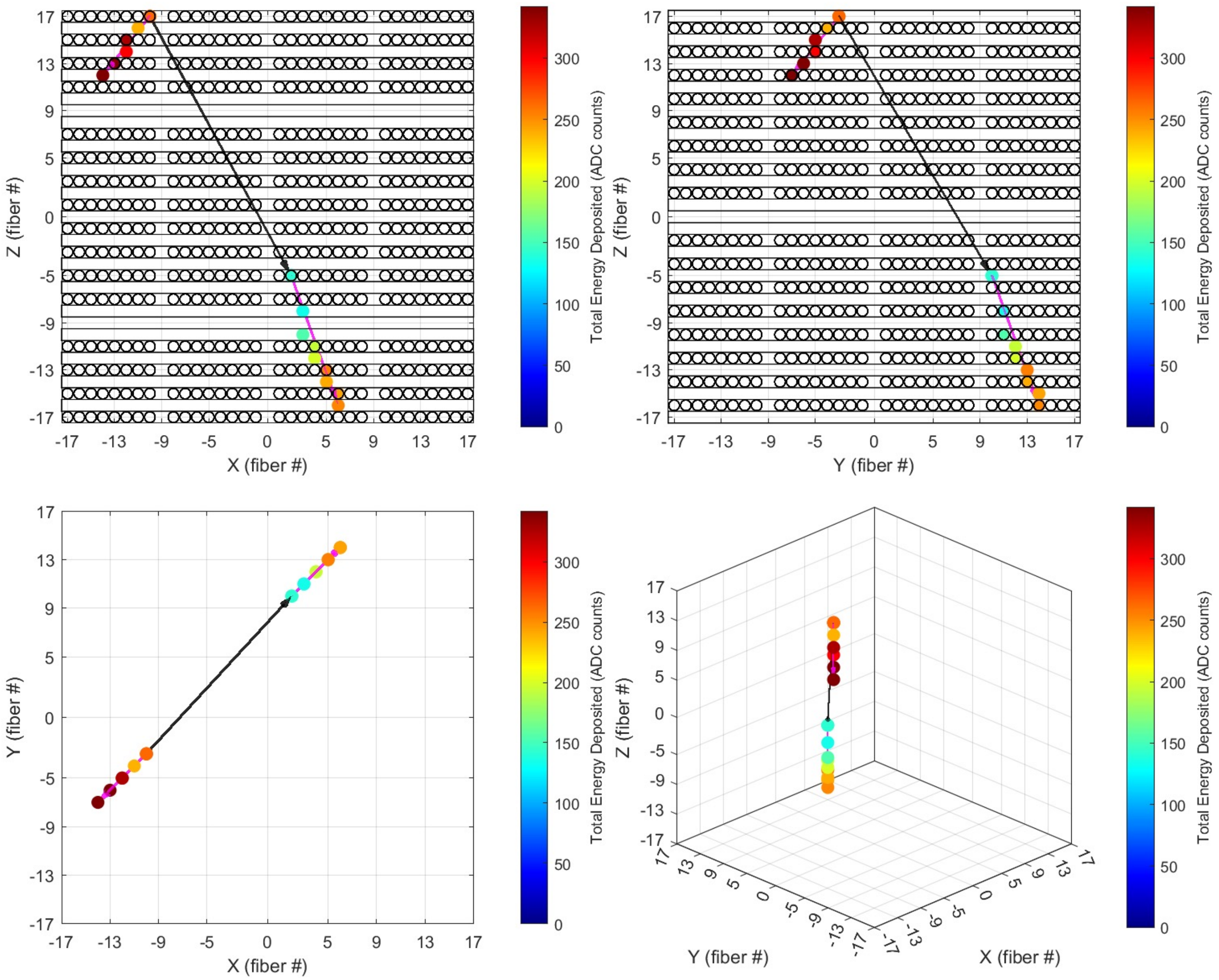


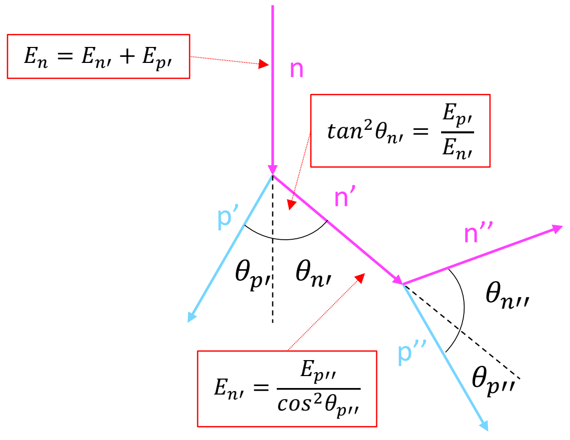
Neutron Beam Test: Crocker National Lab

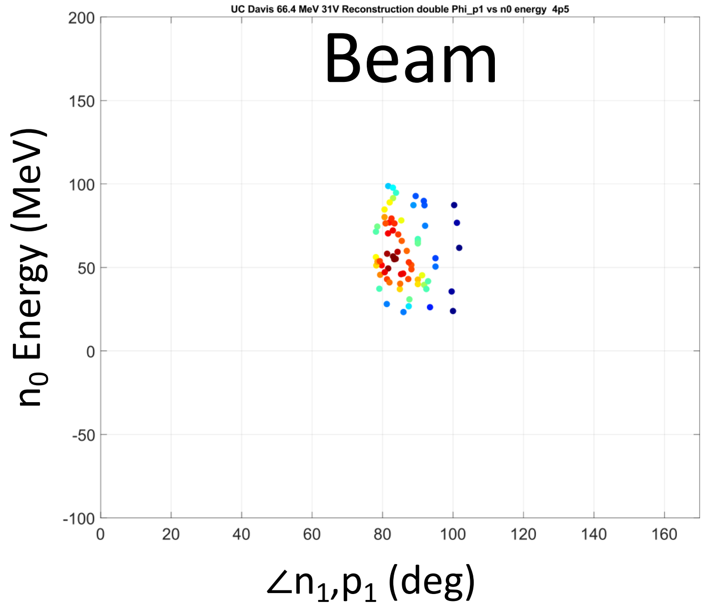


67 & 35 MeV neutrons

Reconstructed Recoil Proton tracks

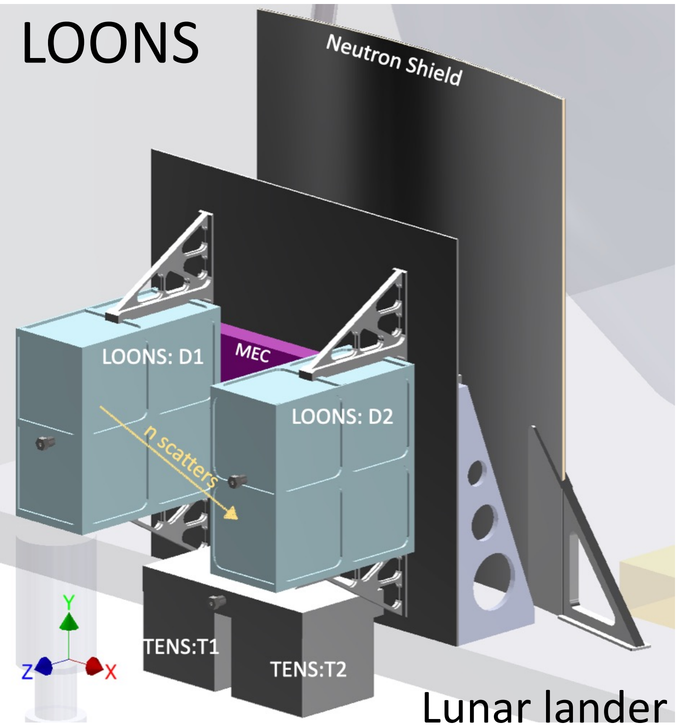




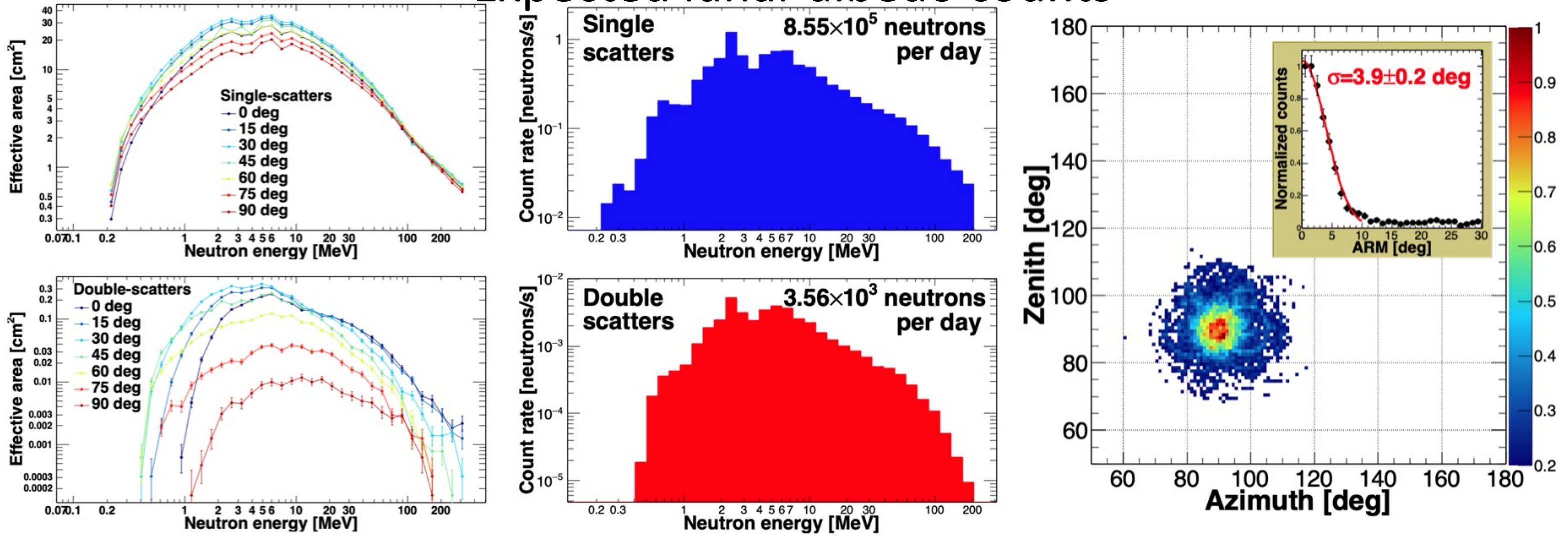


Platforms for SONTRAC

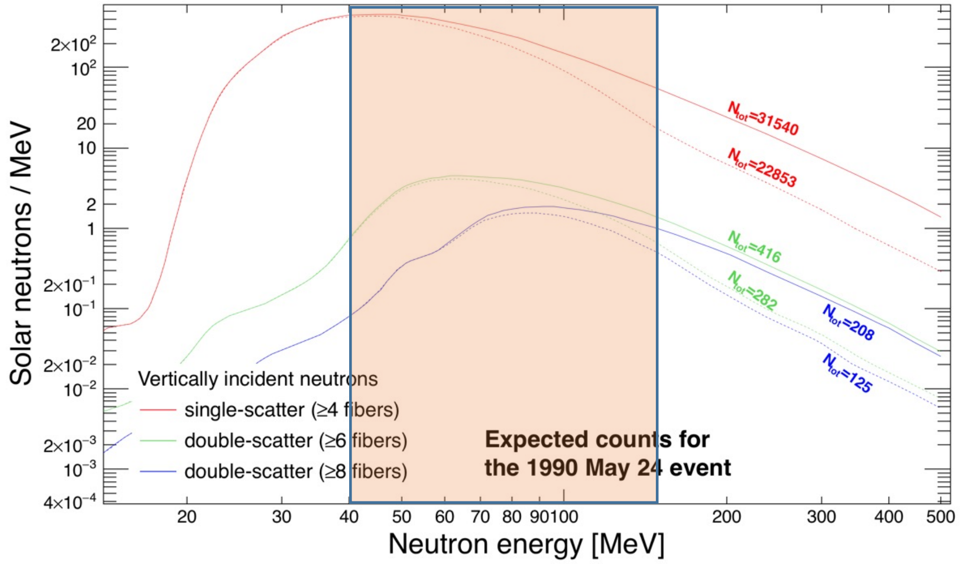
Target Lunar Lander or inner-heliospheric SmallSAT



Expected lunar albedo counts

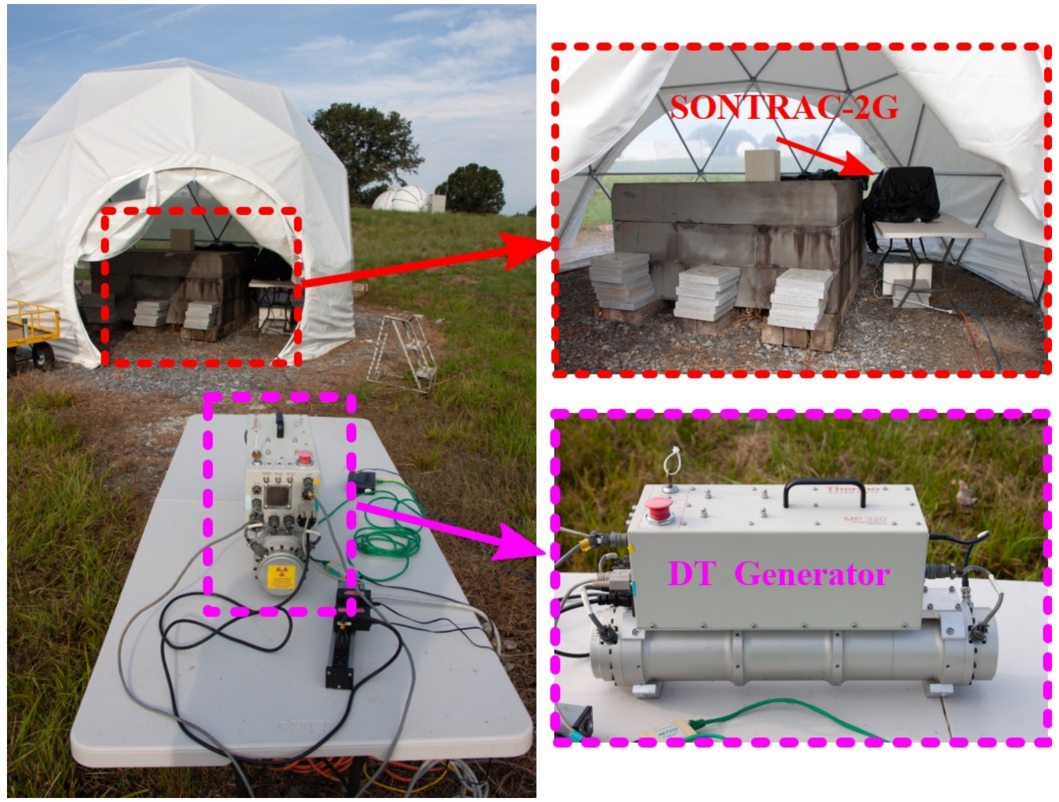


10-cm^3 SONTRAC @ 1 AU



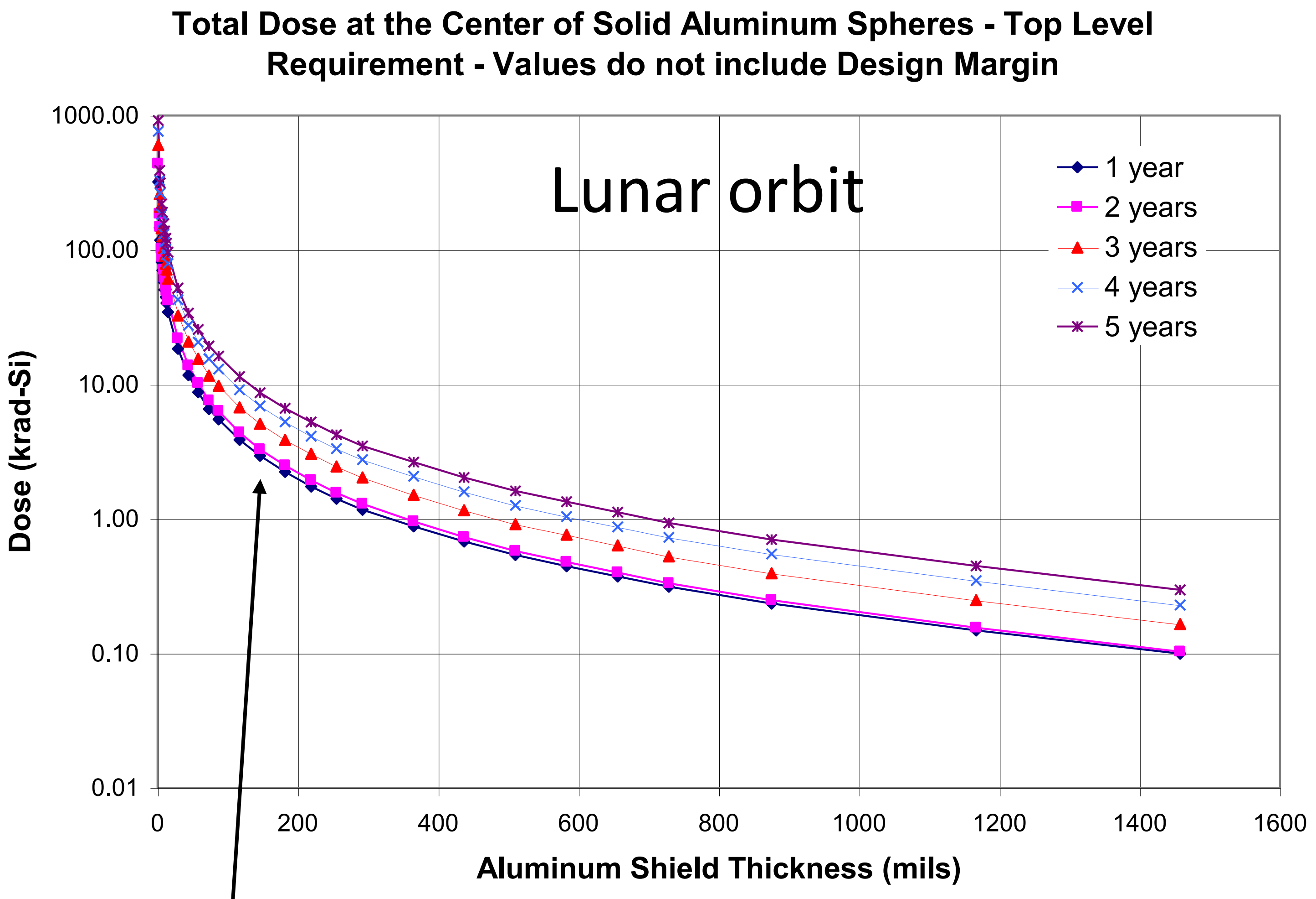
Expected neutron count rate for the 1990 May 24 solar event ⇒ 100s of double scatter neutrons.

DT Generator : $^2H,^3H$ fusion → 14 MeV neutron
Maximum rate 10^8 n/s in 4π

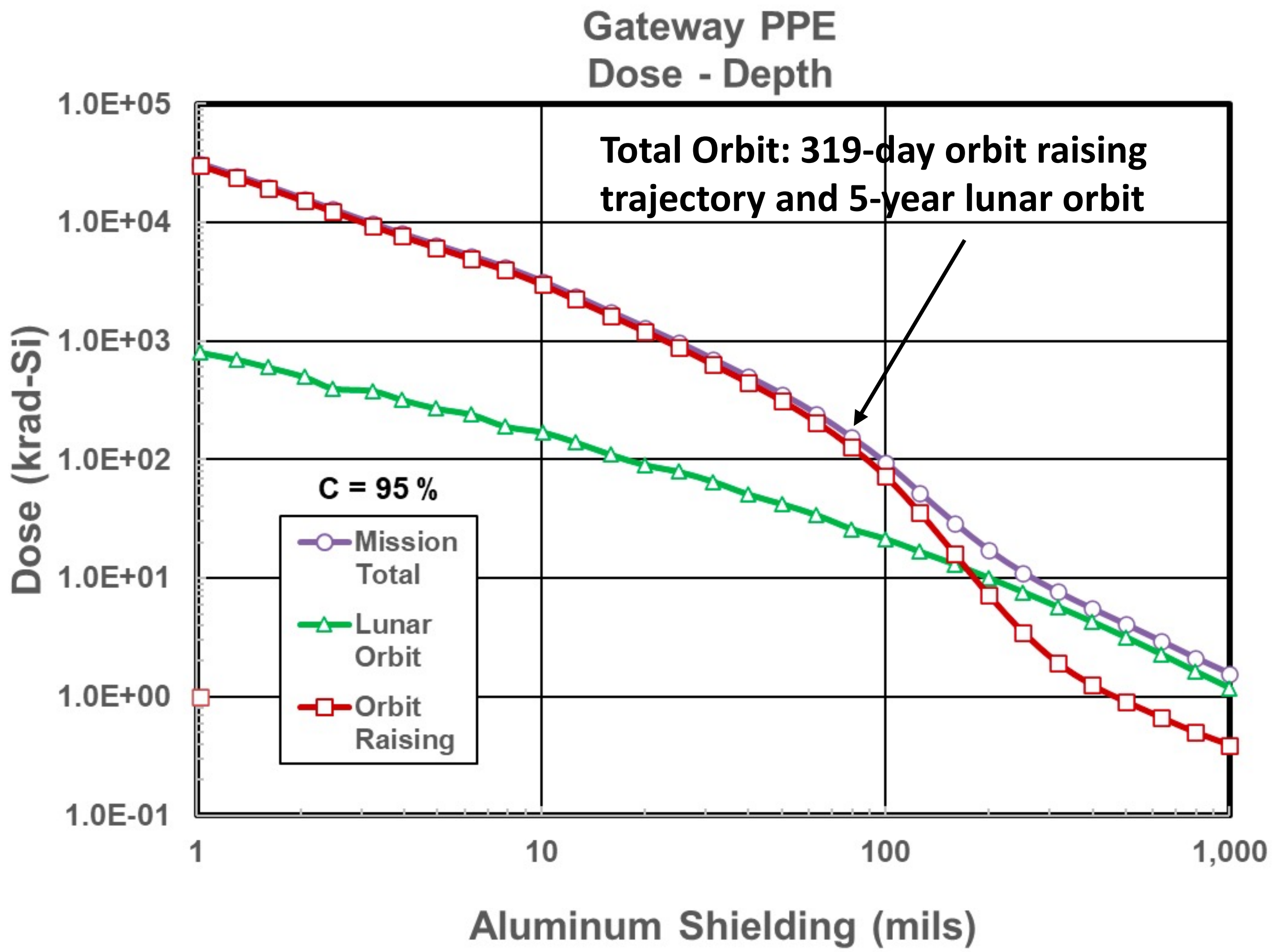


Possible to tile together for even larger effective area

Expected Lunar Surface Dose



100 mils → 3 krad requirement



Majority of dose driven by raising orbit to the Moon ; target 100 mils Al shielding w/ confidence level of 90/95% ⇒ ~3krad requirement for parts

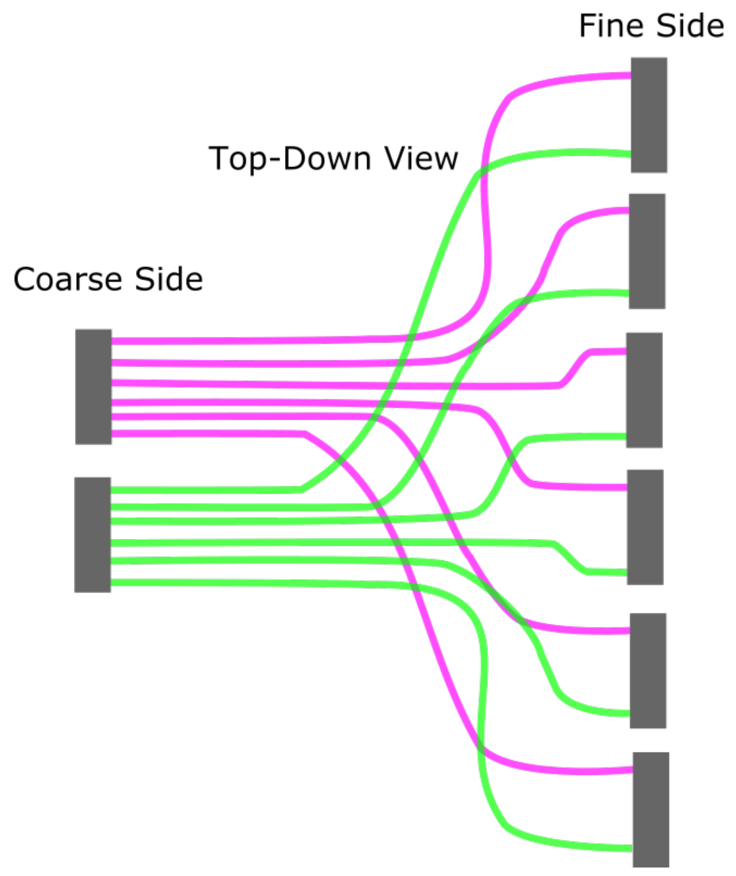
Lunar surface Total Dose ~10's rad (Si)/year
Neutral Dose ~ 2-3 rad (Si)/year
So, < 10^9 p(n)/cm^2 in one year
~300 µA/cm^2 (Mitchell et al. 2021)

Summary/Future Work

- SiPM technology combined with modern scintillators dramatically improve space applications (both γ and neutron spectroscopy)
- Two instrument developments for neutrons:
  - LOONS is ideal for lunar lander opportunities as a radiation monitor and solar observatory.
  - SONTRAC Beam test successful; many lessons learned
- Designing next-generation prototype with improved readout; stacked “ribbons” of scintillator; separation between layers to improve angular resolution

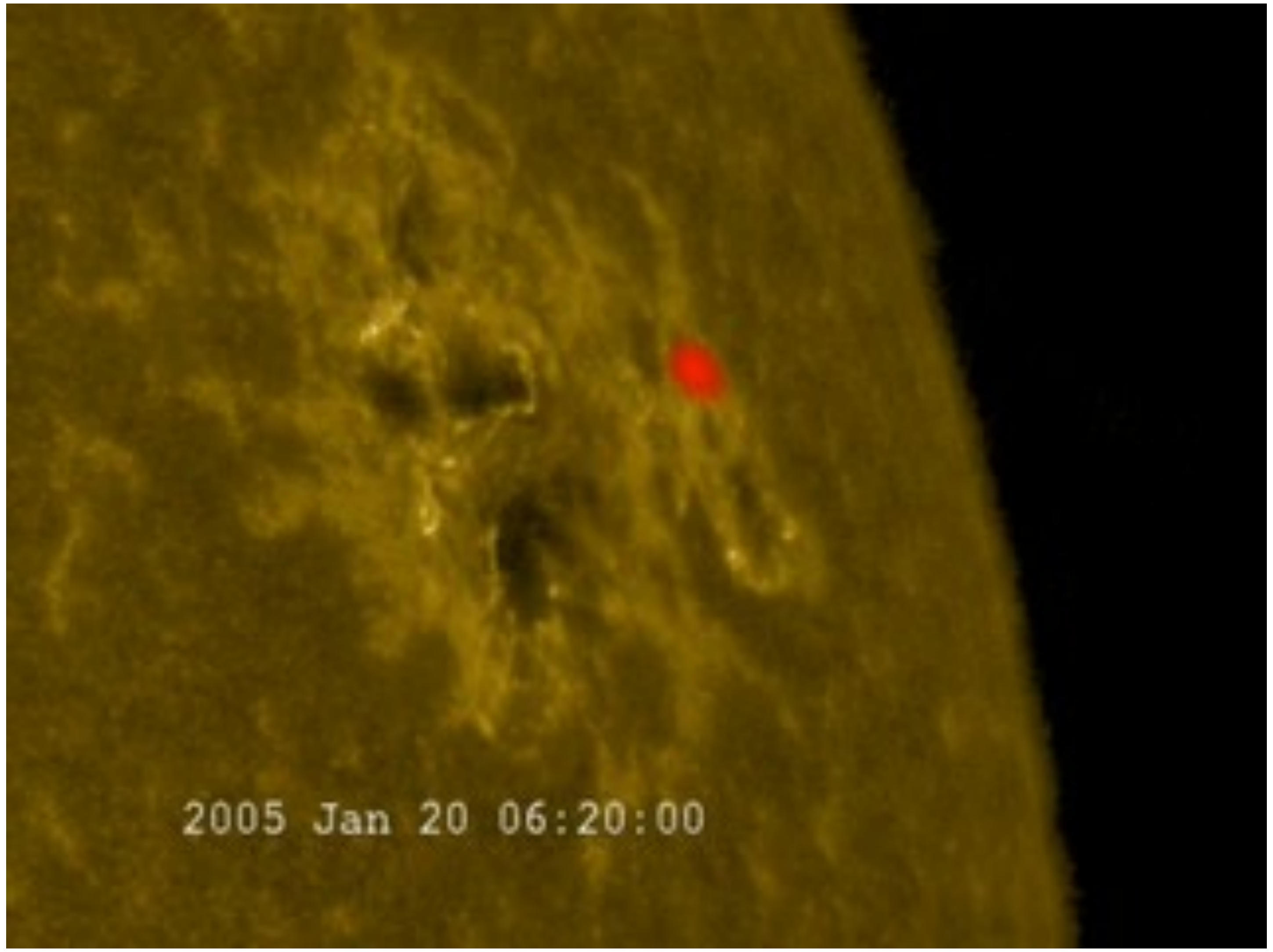
→ Will need custom SiPM arrays

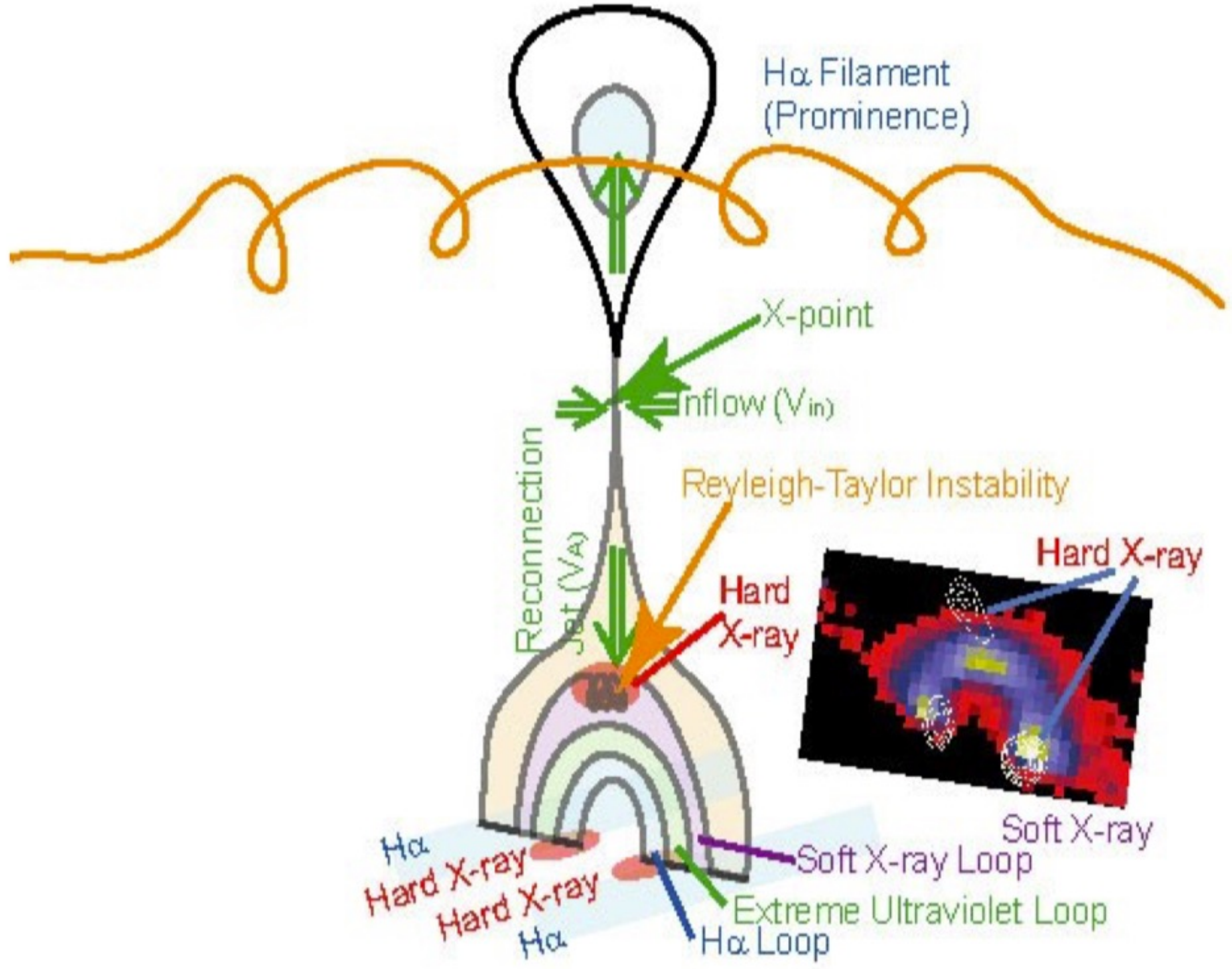
- Concern for DCR increase for SONTRAC (better SiPM model?, lower temperatures?)
- Next-generation SONTRAC will be tested at CNL in summer 2023



Q&A

Science Motivation : Particle Acceleration in Flares





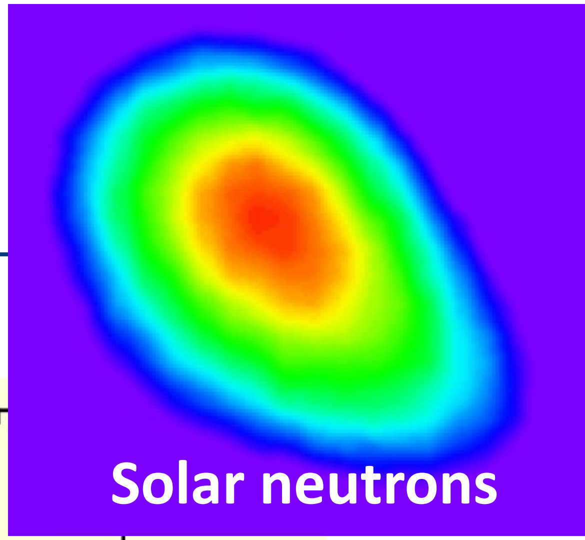
Magnetic fields associated with sunspots undergo dramatic realignment (or reconnection), the accompanying energy release is known as a solar flare, releasing a host of *secondary particles* observable at 1 AU

Science Motivation : Solar Neutrons

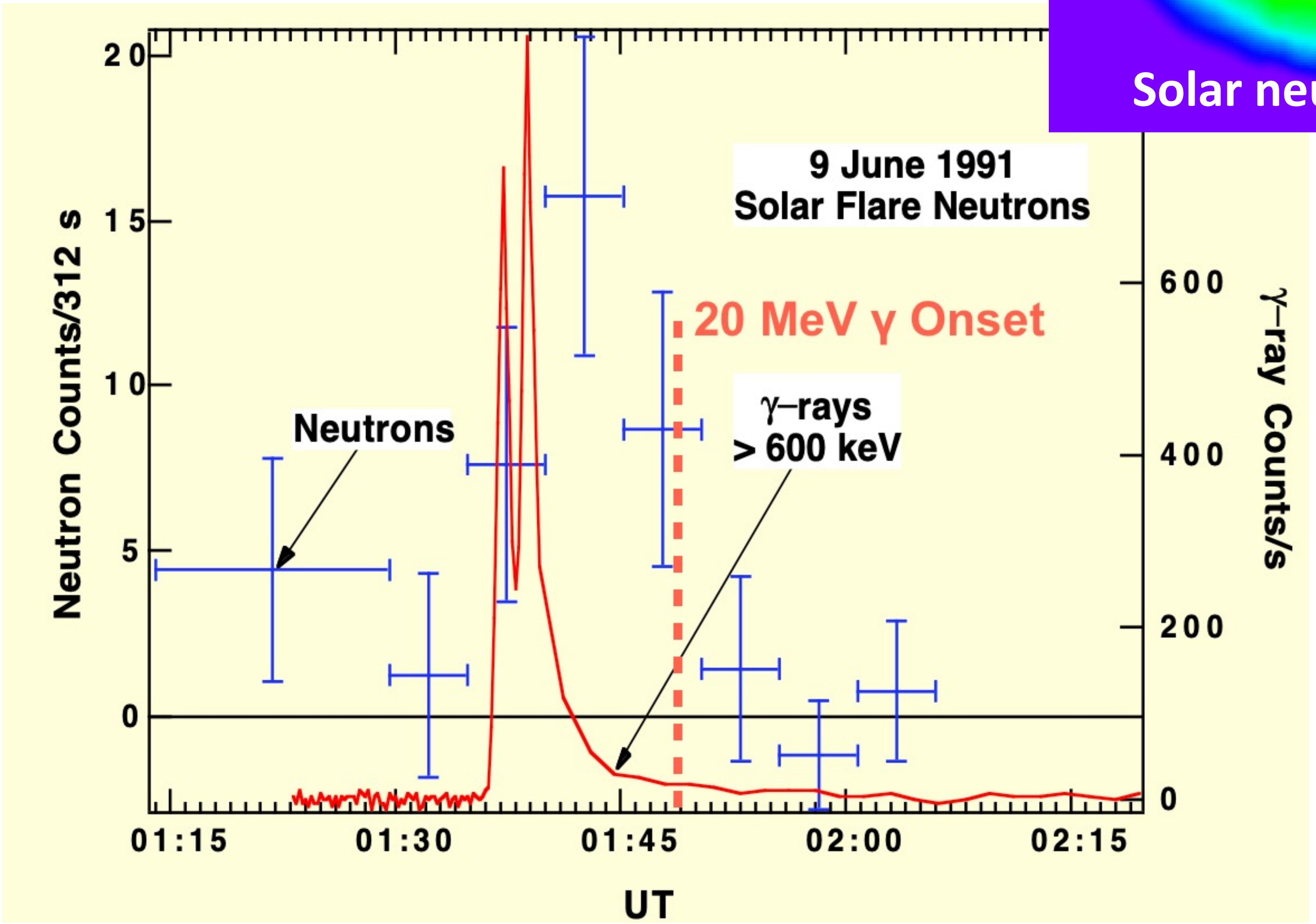
* We can witness the spectral evolution of the solar flare by sampling the entire interacting ion spectrum

* Neutrons also probe heavy ion content

* Only ~dozen solar neutron events observed from the Sun and most do not measure the neutron energy directly



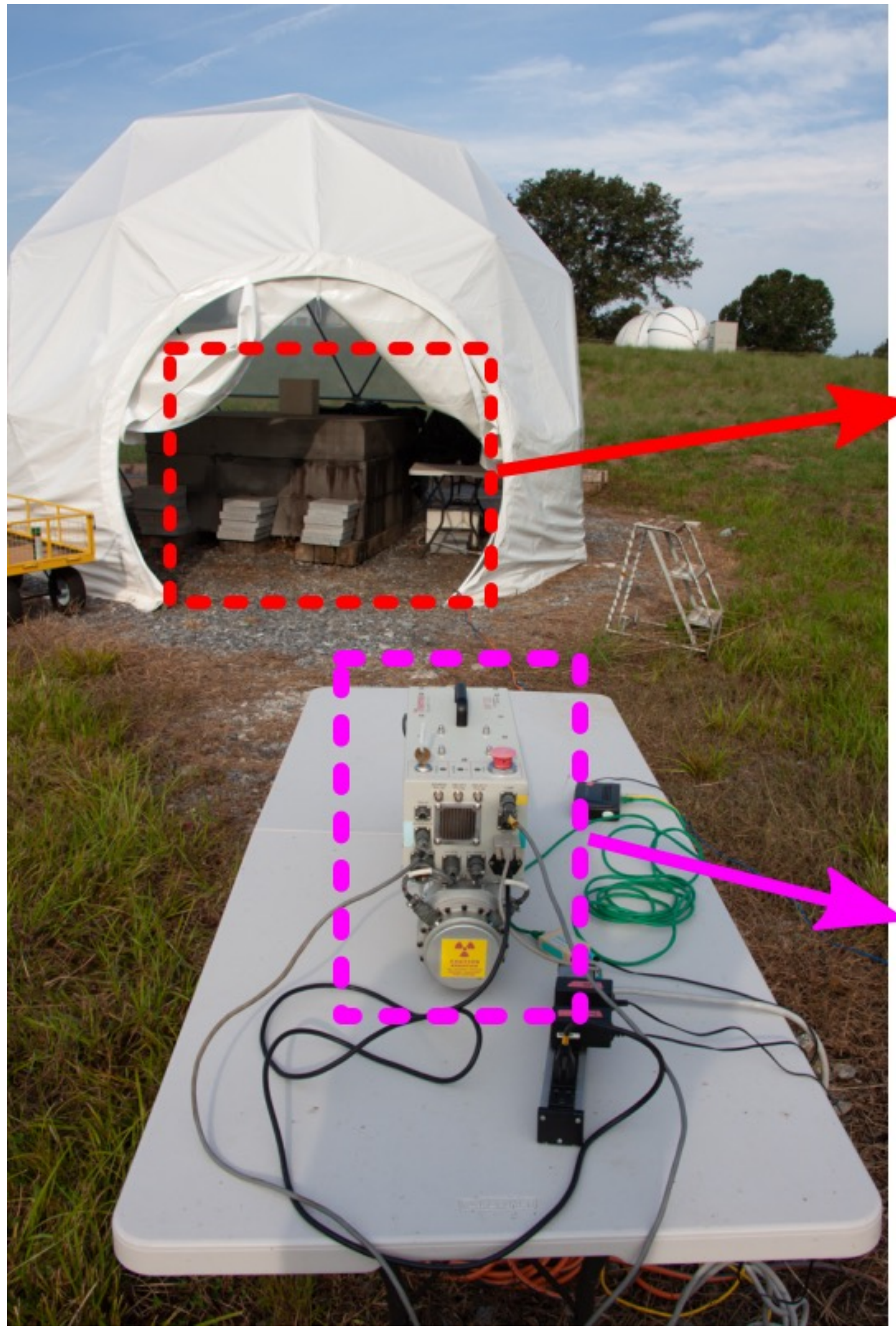
COMPTEL Observations

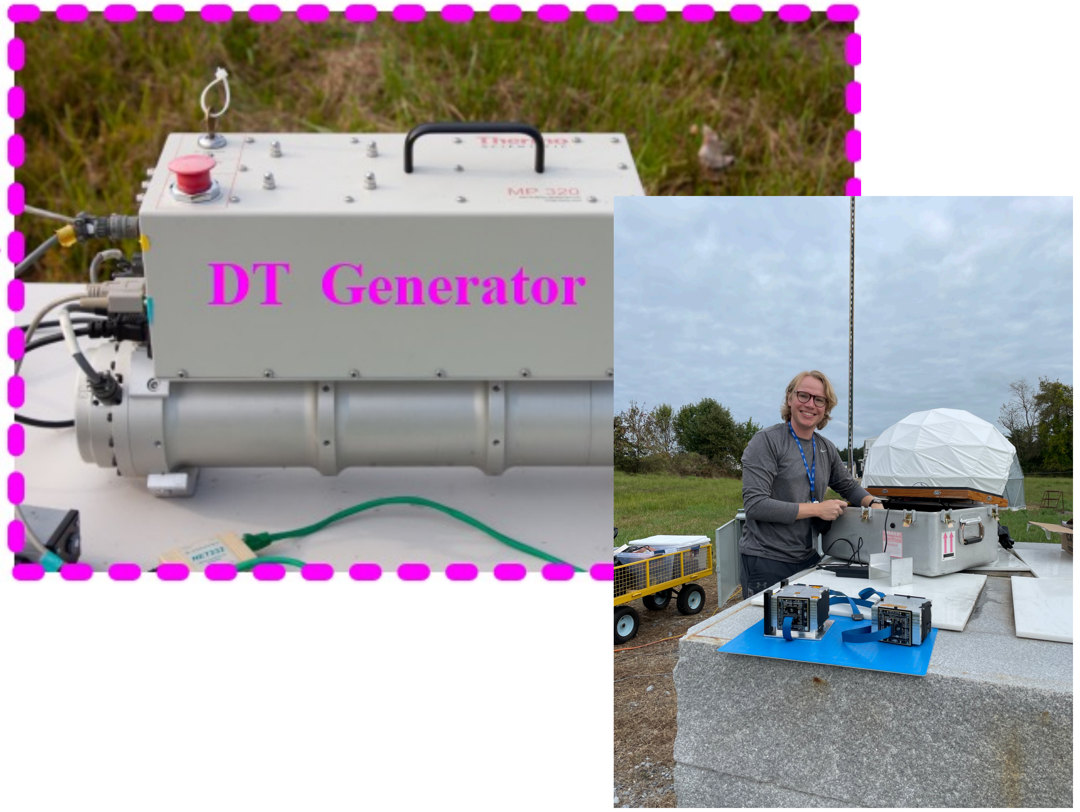


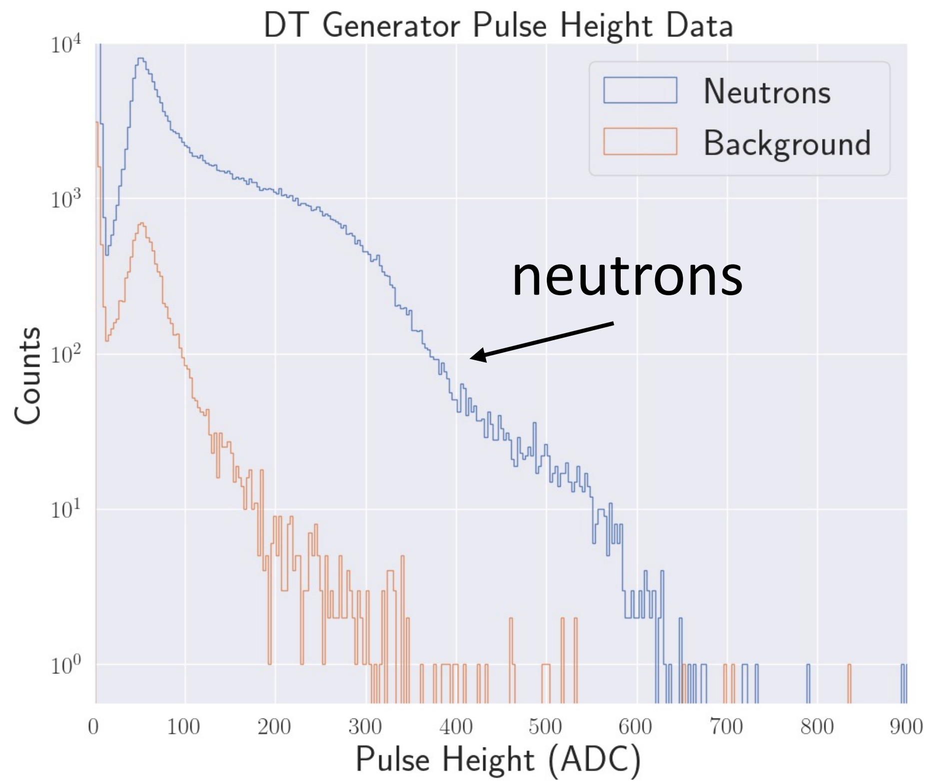
Broad band emission profile for the 1991 June 11 flare.

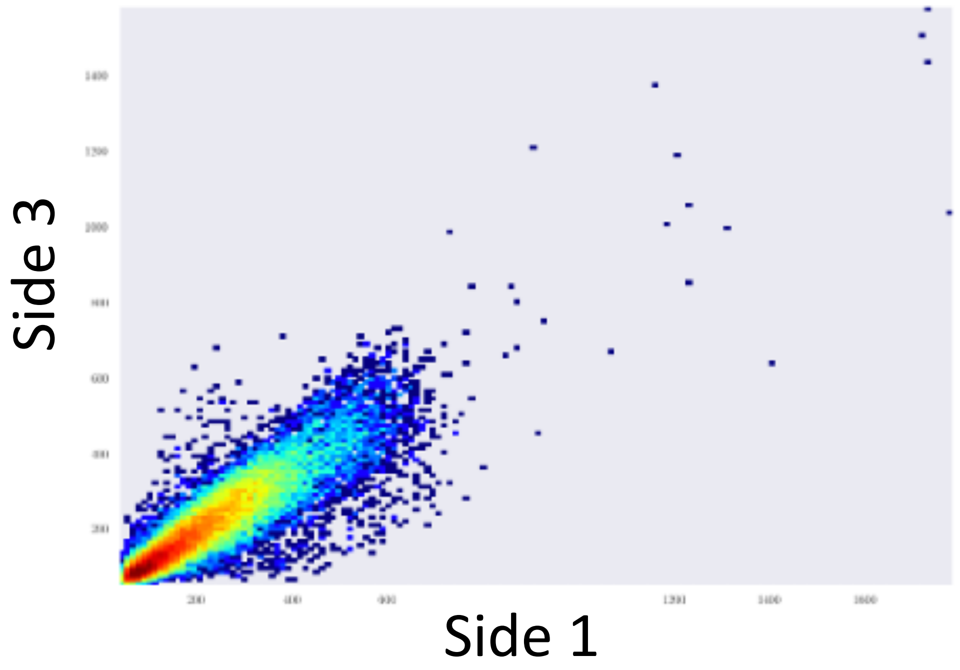
→ Watch spectral evolution unfold

DT Generator Tests (14 MeV neutrons)









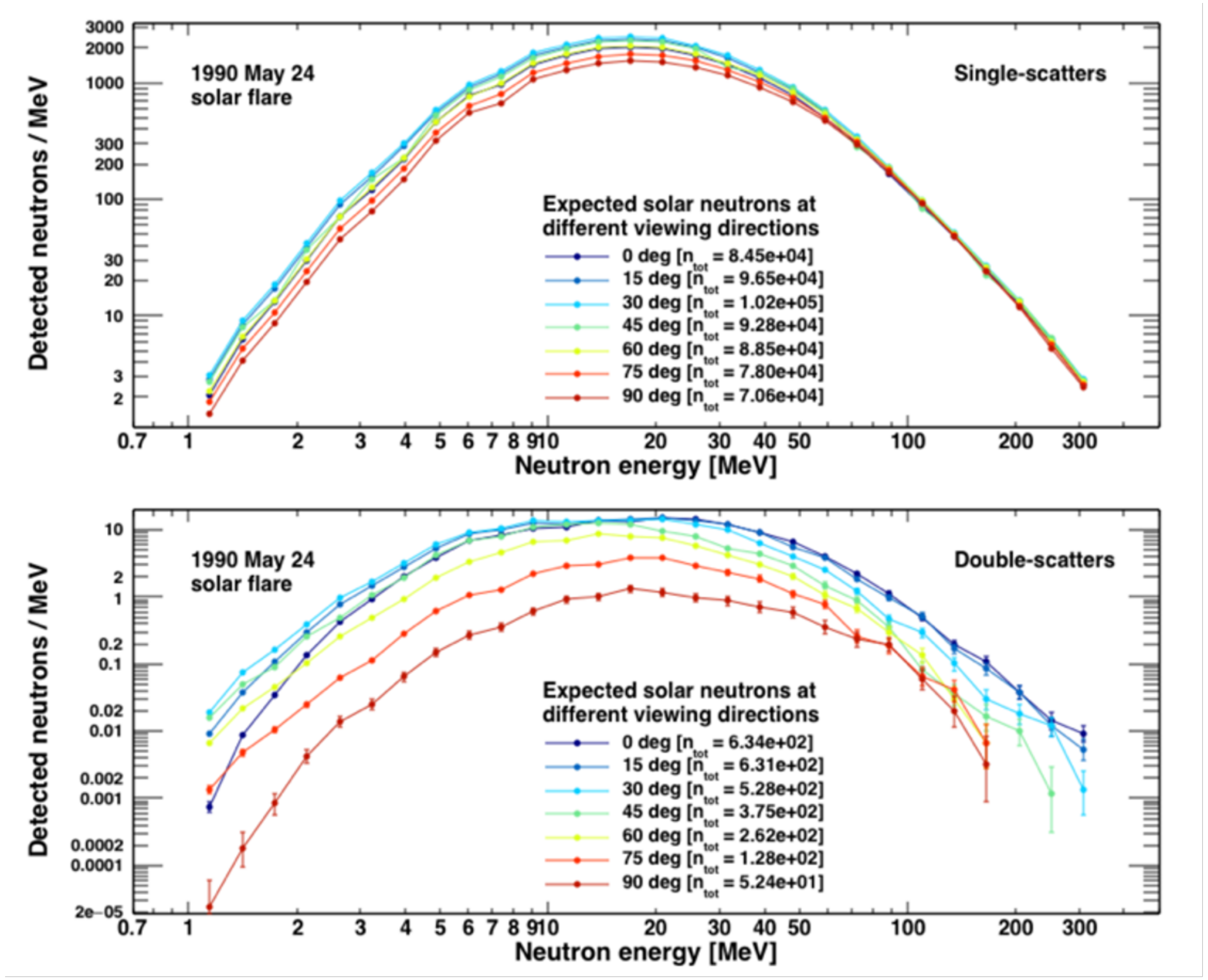
Solar Neutrons with LOONS

* Inner heliospheric SmallSAT (e.g., best close to the Sun due to neutron decay ~15min)

* Neutrons > 20 MeV reach 1 AU allowing detection with sufficient effective area

* Solar observatory on the lunar surface ideal

Detect ample solar neutrons from lunar surface

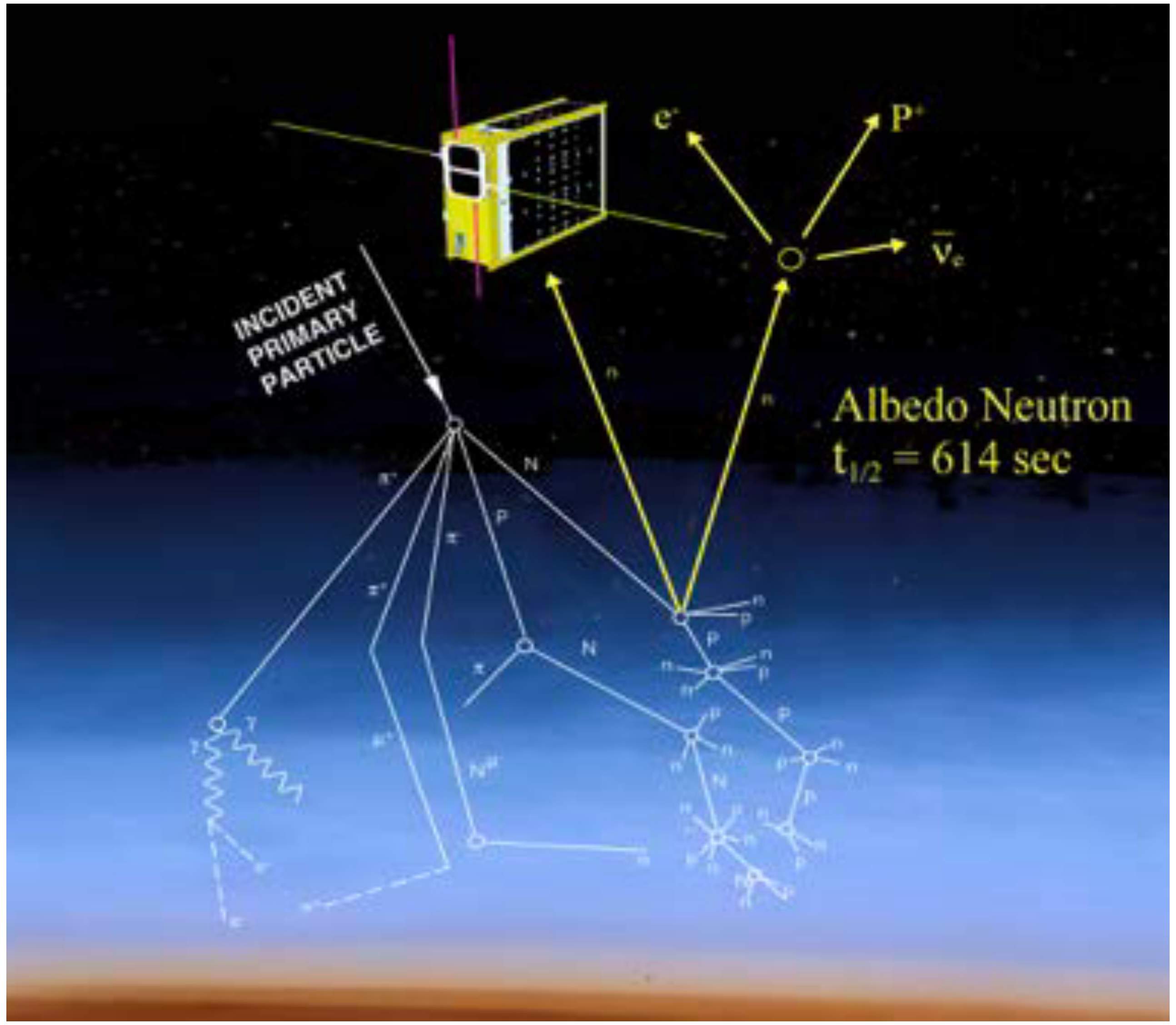


Science Motivation : Albedo Neutrons

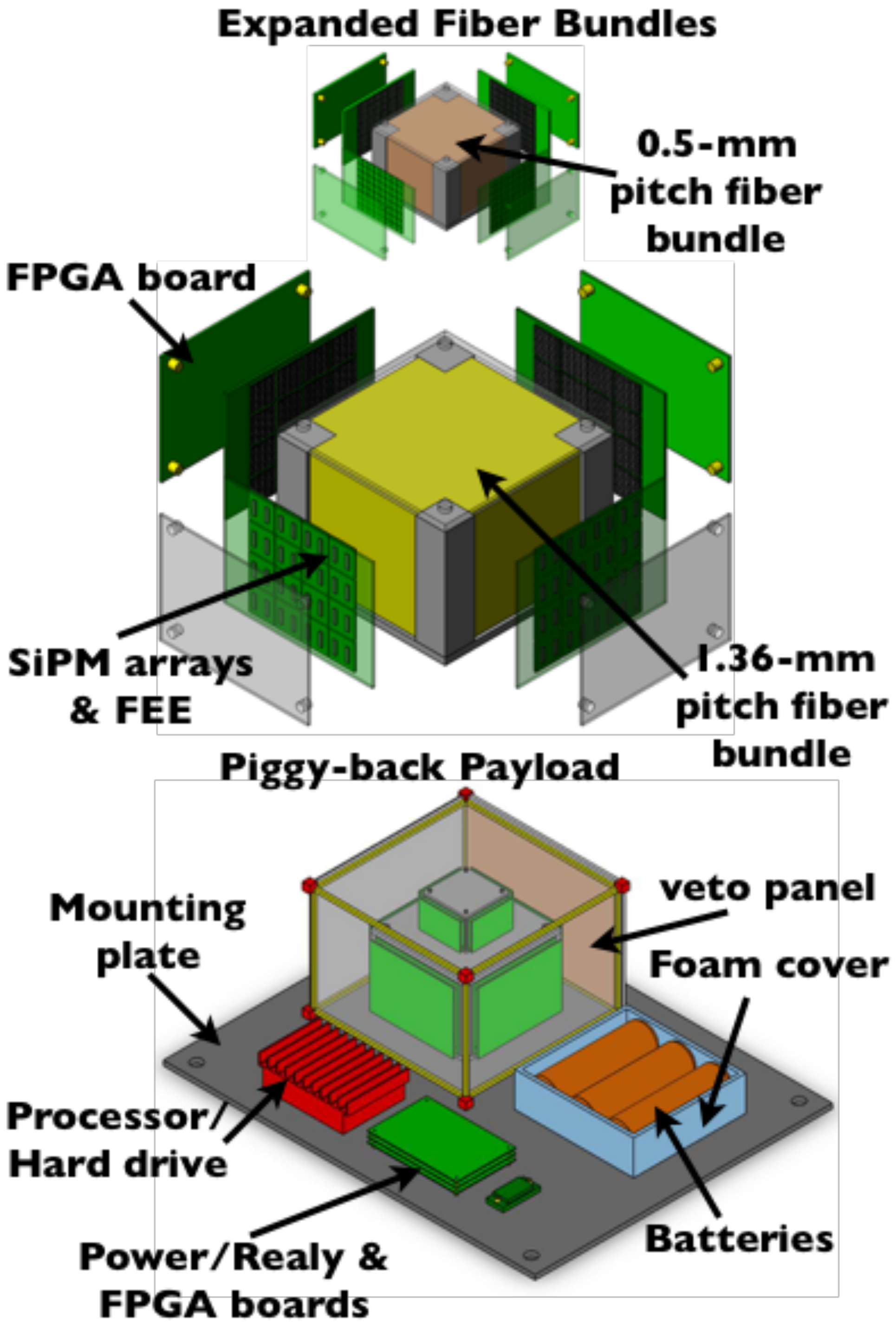
*Cosmic Ray Albedo Neutron Decay (CRAND):

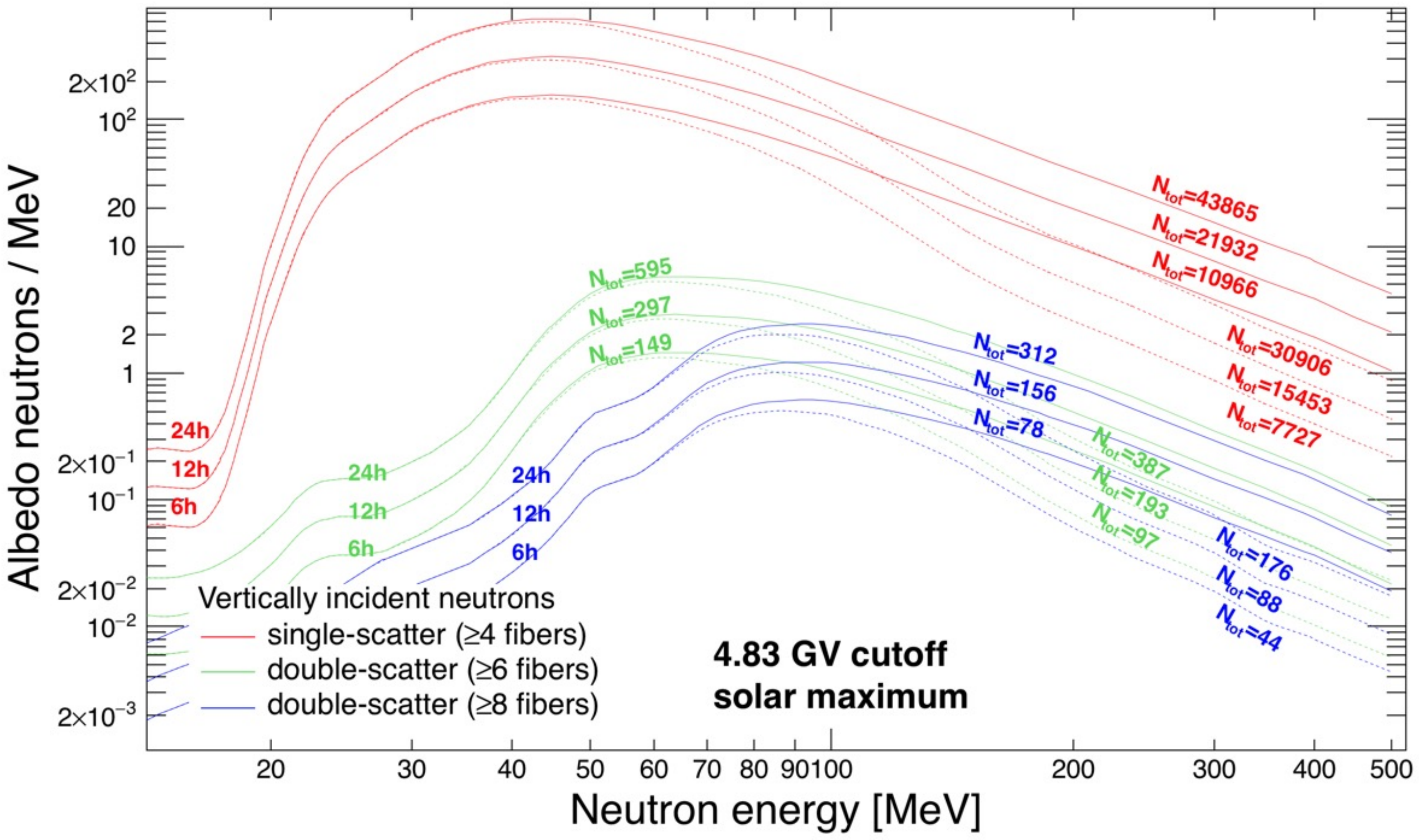
Dominant source of geomagnetically trapped protons above 10s of MeV in the inner Van Allen belt is the decay of albedo neutrons from interactions of galactic cosmic rays in the Earth's atmosphere

*Also detected in magnetospheres of other planets, i.e., Jupiter & Saturn



Raising the TRL for SONTRAC : High-Altitude Balloon Flight

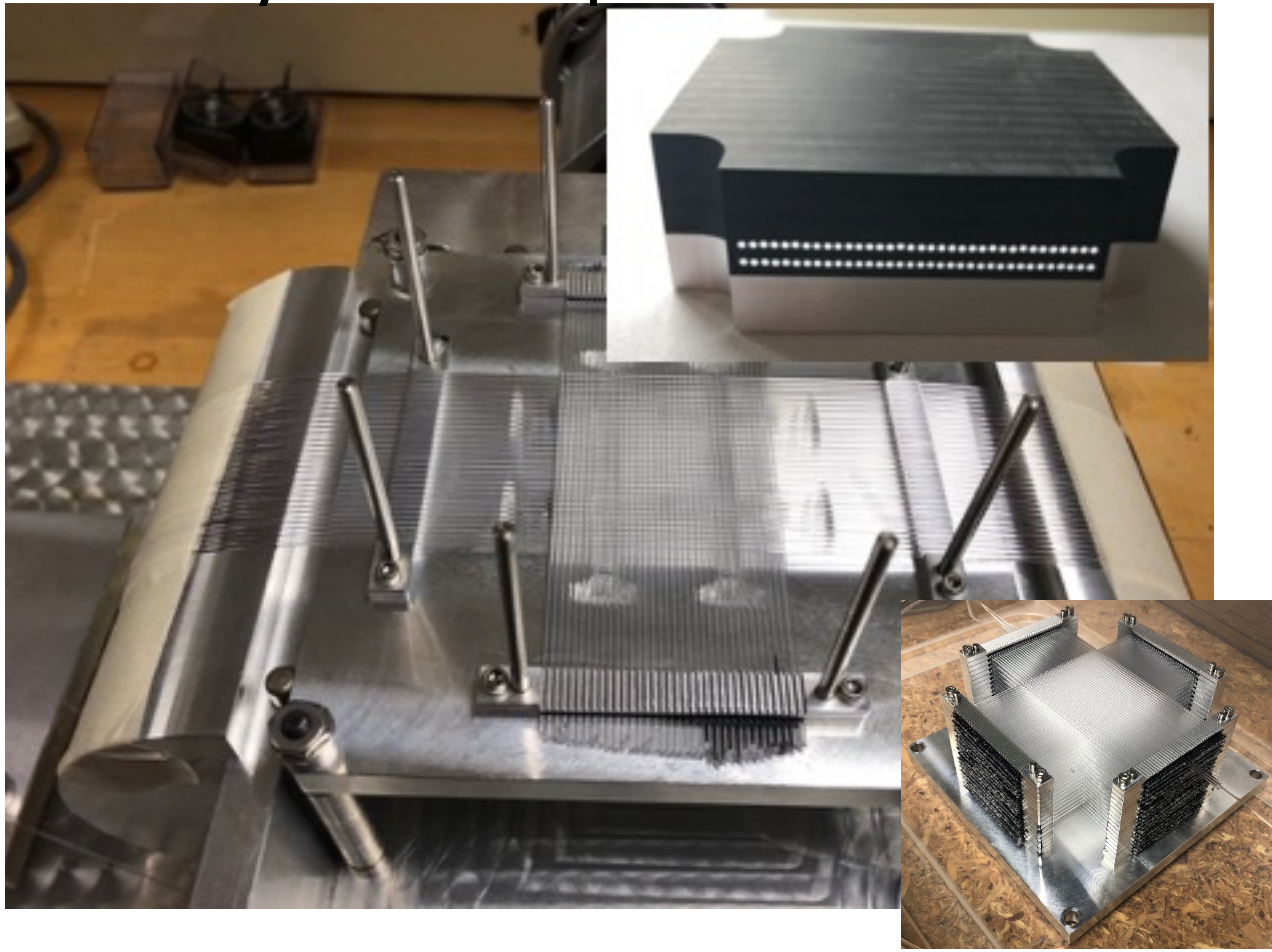




proposal pending

SONTRAC Science Model 2

University of New Hampshire Bundle Fabrication



Fabricating New Bundle:

- Orthogonally stacked bundle with 1.36-mm pitch
- Matches the pitch of the Ketek SiPM arrays
- Signal Processing: CAEN DT5550W with Petiroc@ ASICs
- Configure for strip-readout (see Suarez et al. this IEEE)
- Accelerator Beam Test (Nov. 2021 @ Crocker National Lab's cyclotron)