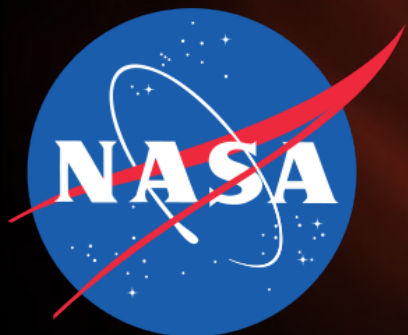


SiPM-based Technologies for Solar and Heliospheric Science

Georgia de Nolfo
NASA Goddard Space Flight Center
Greenbelt, Maryland, U.S.A



SiPM Workshop
Cern, Switzerland
April 23-25, 2022



Goddard
SPACE FLIGHT CENTER

SOlar Neutron TRACking (SONTRAC) Team

NASA Goddard Space Flight Center

Dr. Georgia de Nolfo/PI

Dr. Alessandro Bruno

Matt Daehn

Jeffrey J. DuMonthier

Grant Mitchell

George Suarez

Teresa Tatoli

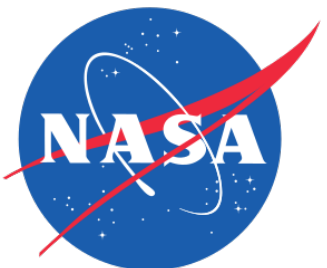
Liam Williams

University of New Hampshire

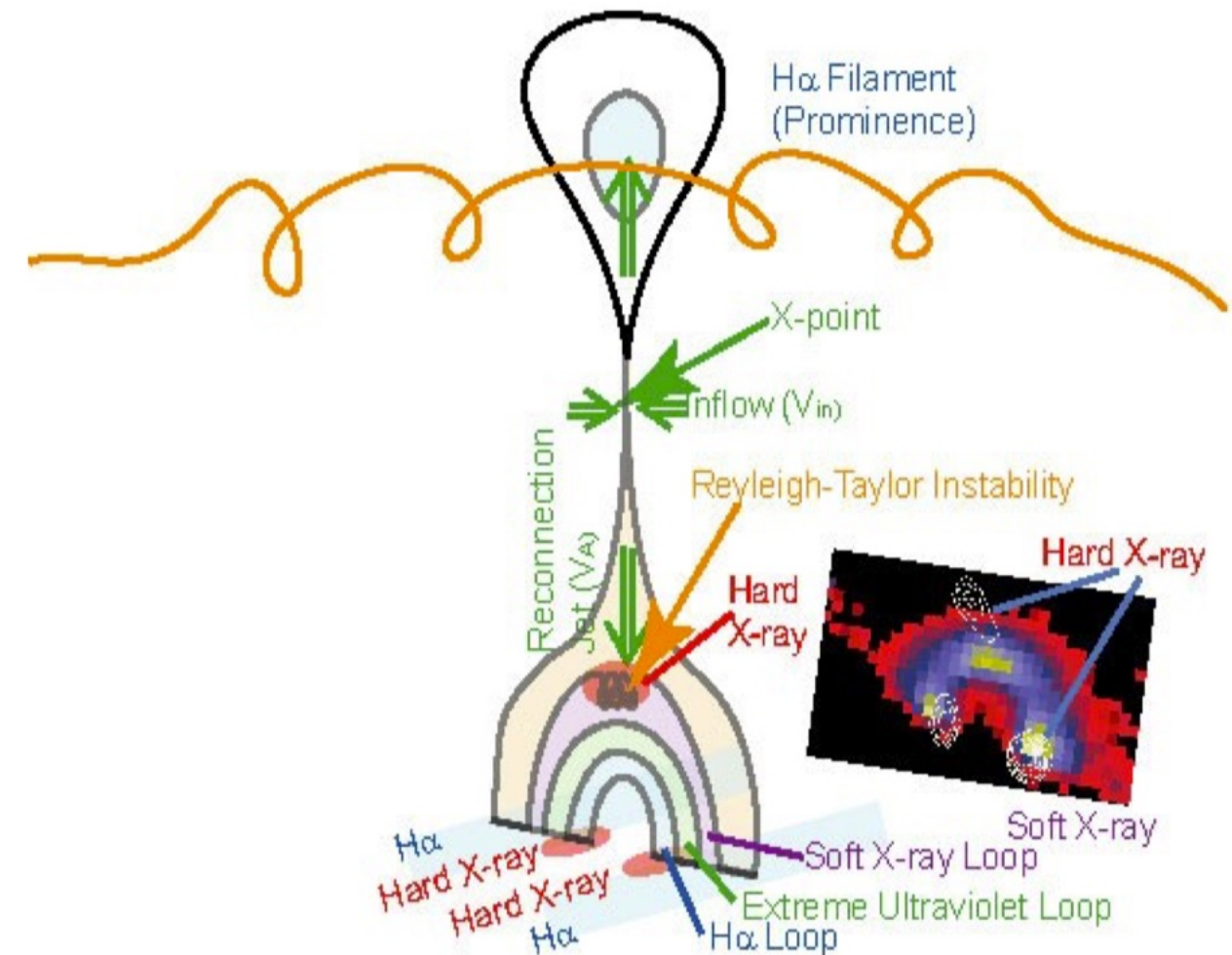
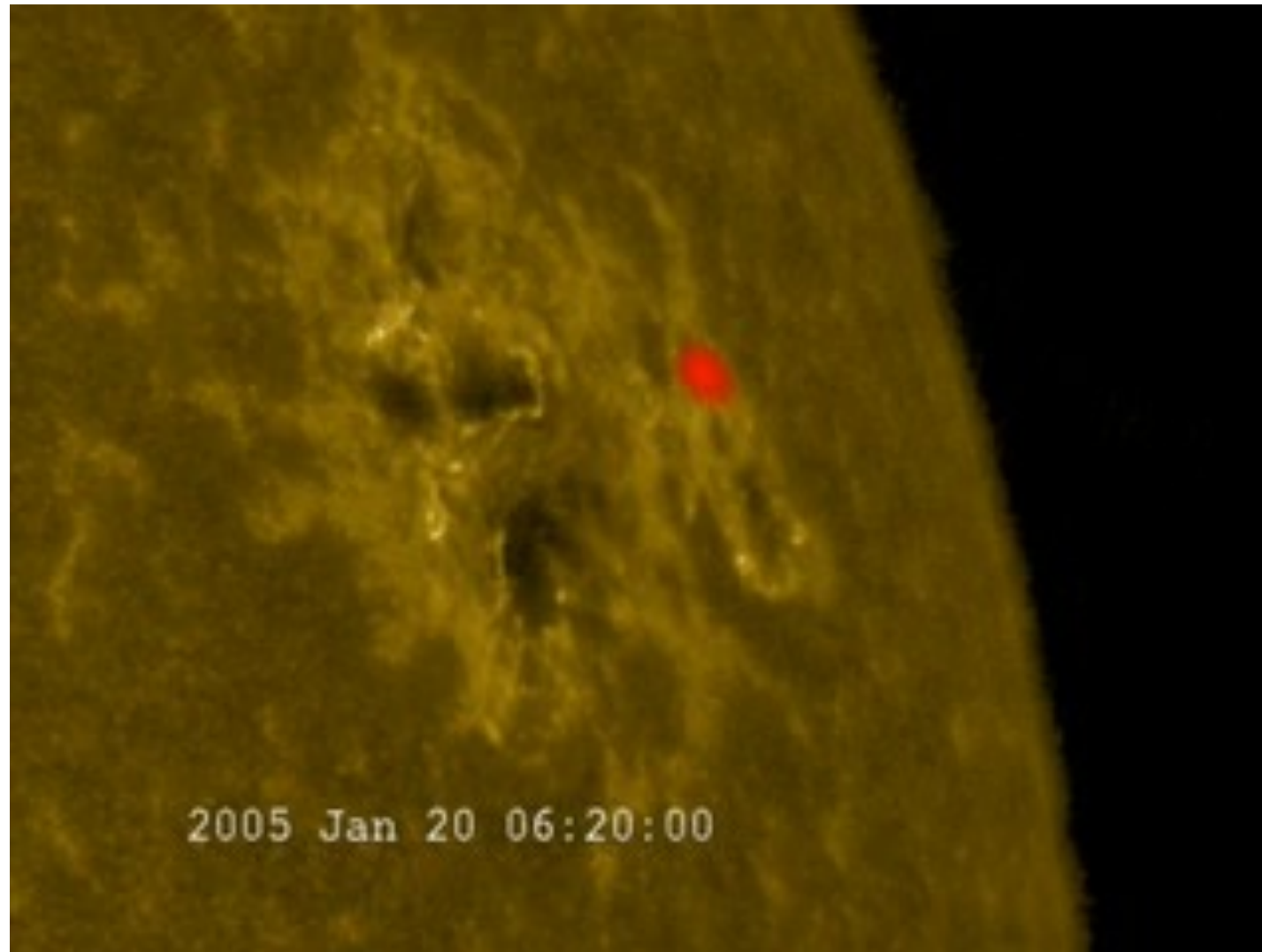
Jason Legere

Dr. Richard Messner

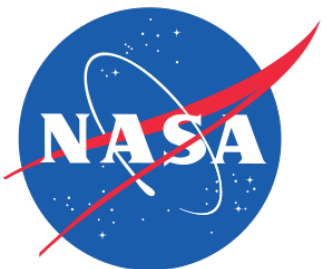
Dr. James Ryan



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

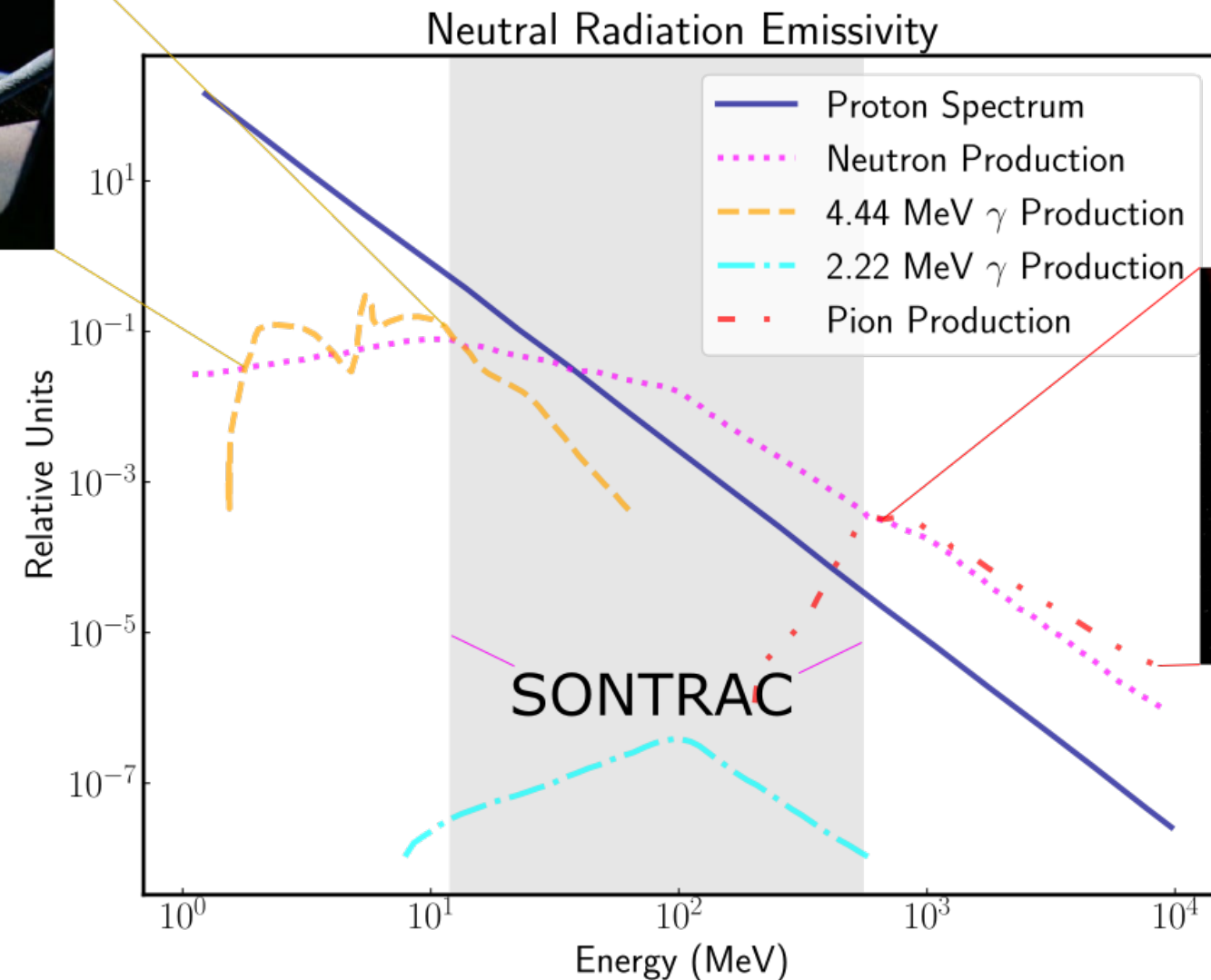


Science Motivation : Energy Range of Interest

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



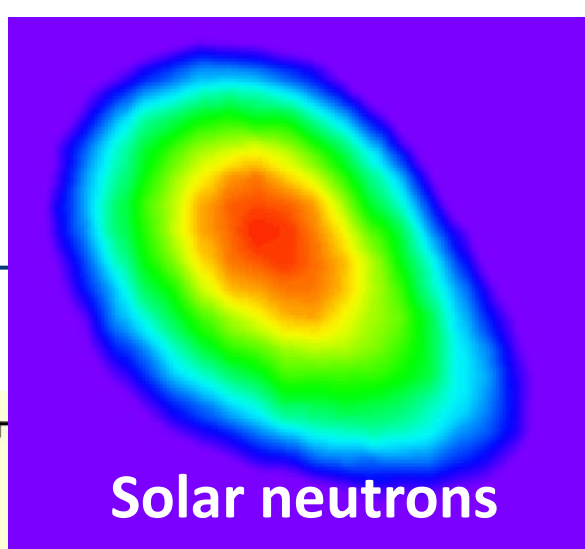
- From 20-40 MeV use γ -ray line emission
- > 300 MeV use π^0 emission (70 MeV)
- From ~ 50 -300 MeV need neutrons



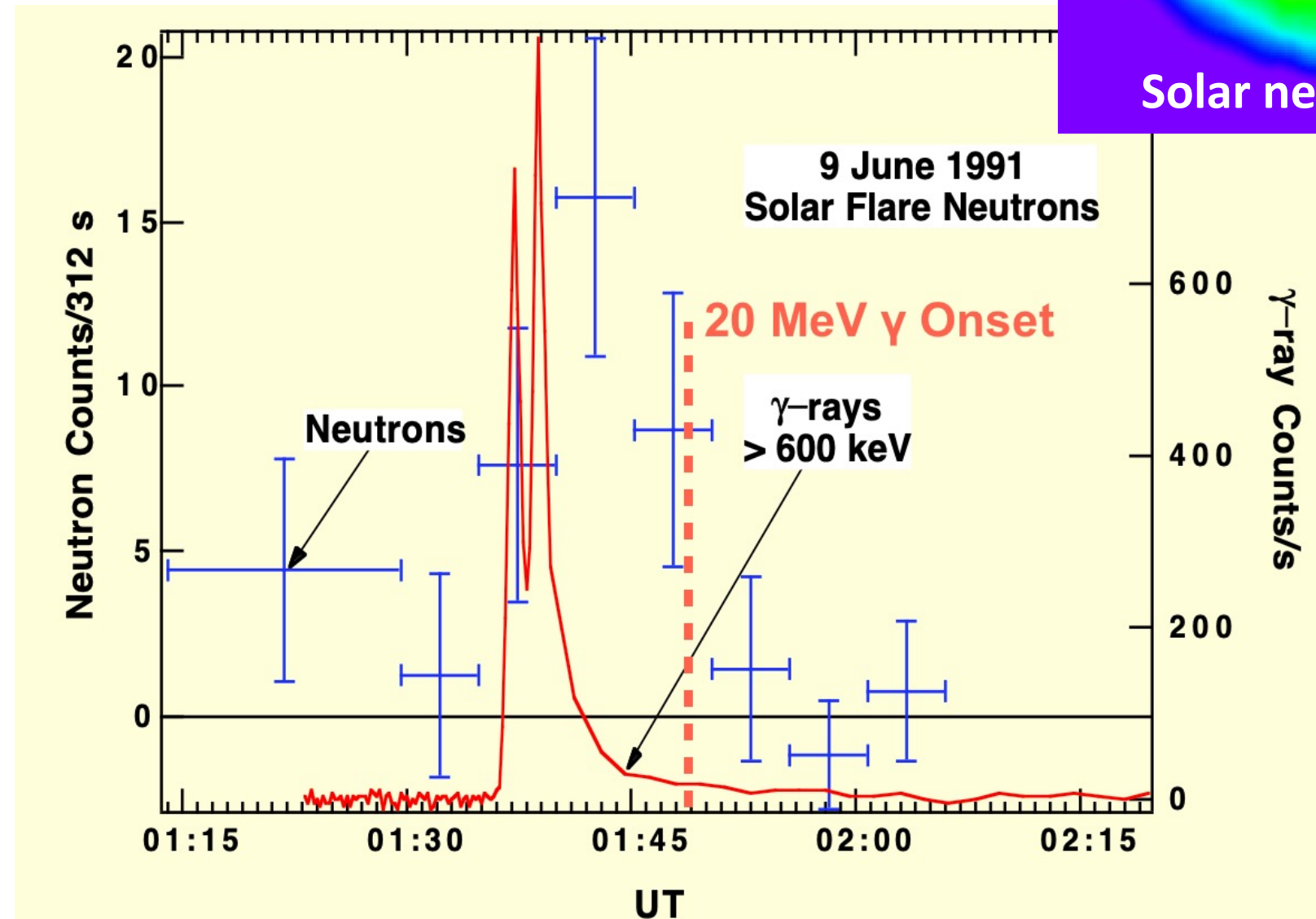
* So neutrons bridge a critical gap

Science Motivation : Solar Neutrons

- * If you can sample the entire proton spectrum you can witness spectral evolution
- * Only ~dozen solar neutron events observed from the Sun and most do not measure the neutron energy directly

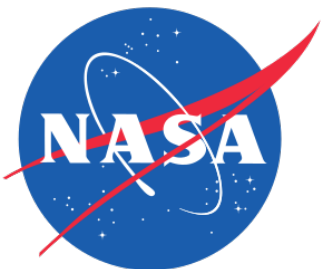


COMPTEL Observations



Broad band emission profile for the 1991 June 11 flare.

→ Watch spectral evolution unfold



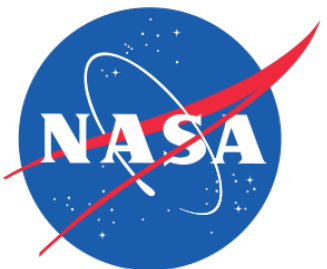
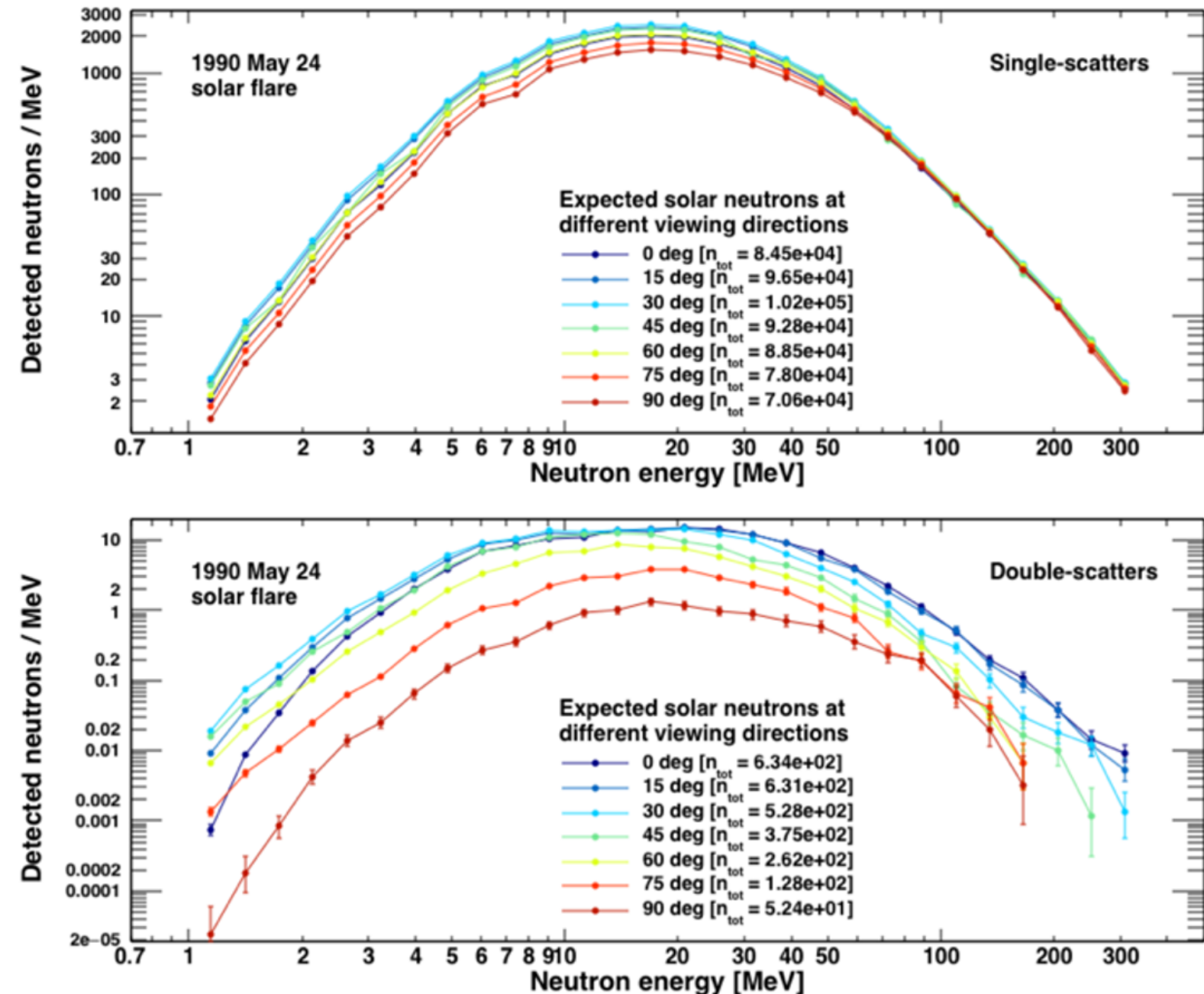
Potential Platforms for Solar Neutrons

- * Inner heliospheric SmallSAT (e.g., best close to the Sun due to neutron decay $\sim 15\text{min}$)

- * Neutrons $> 20\text{ MeV}$ reach 1 AU allowing detection with sufficient effective area

- * Solar observatory on the lunar surface ideal

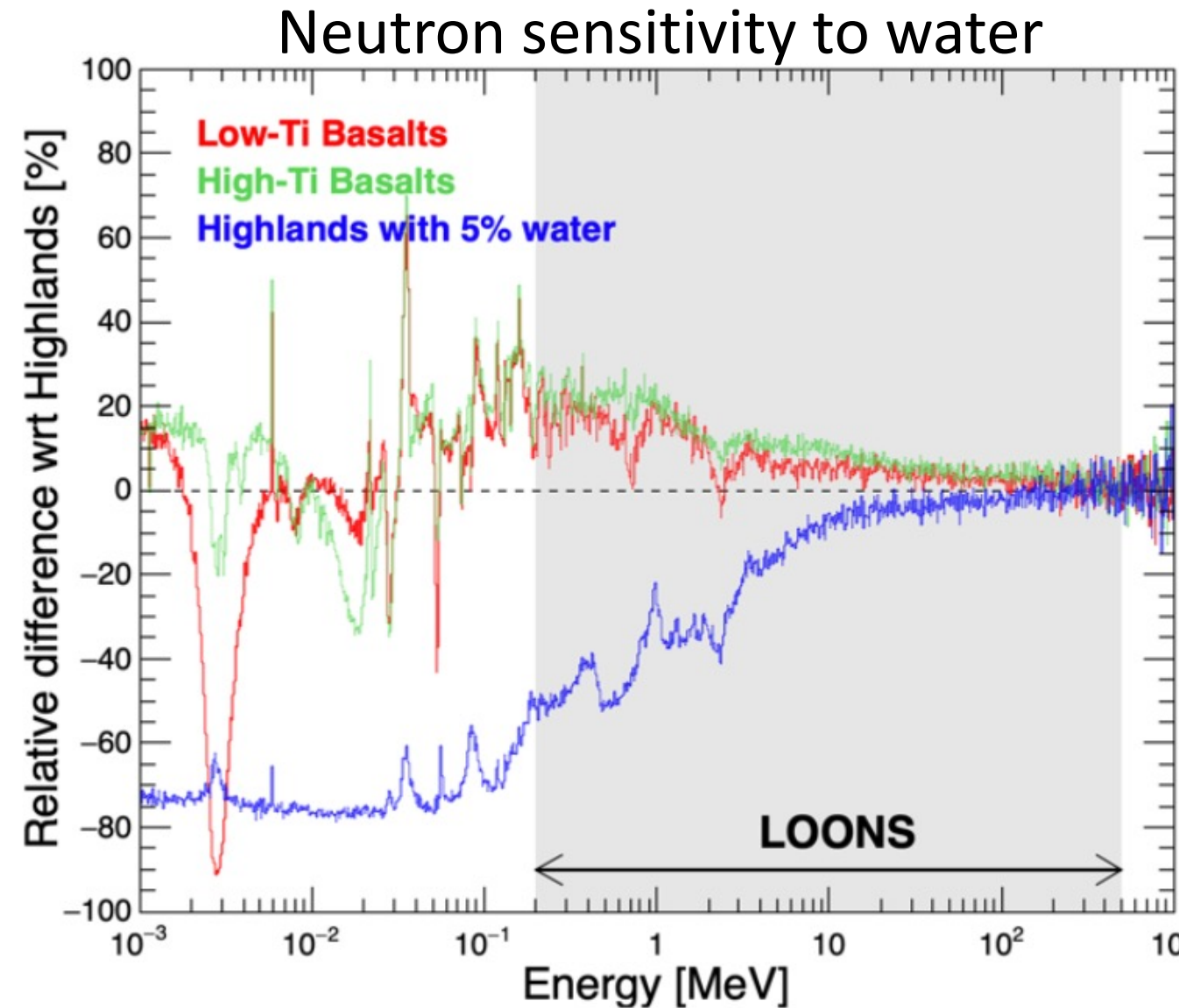
Detect ample solar neutrons from lunar surface



Potential Platforms for Solar Neutrons

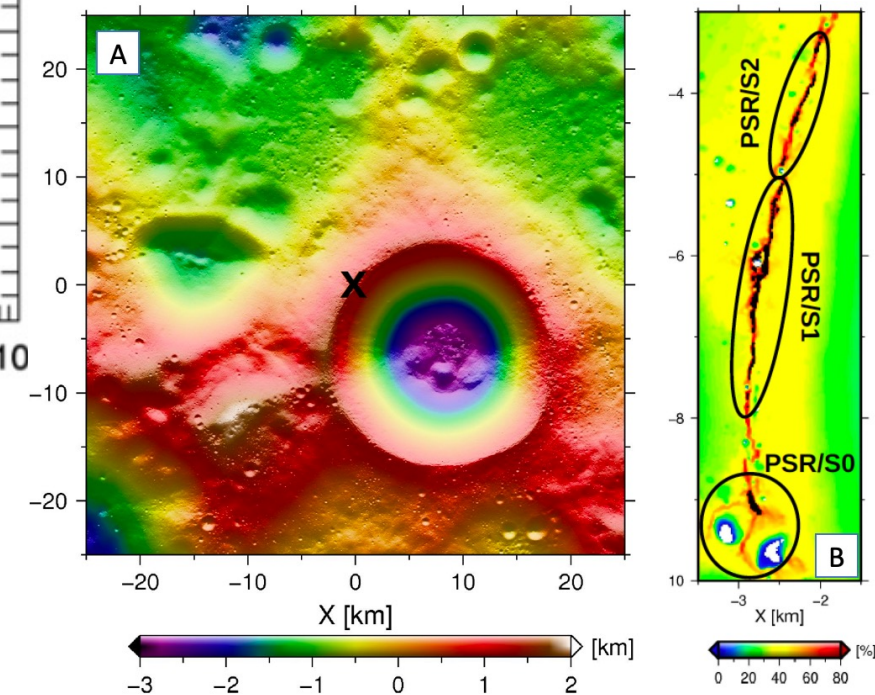
* Neutrons are a dangerous component of lunar (& planetary) radiation environments (~20% total radiation dose; Zhang et al. 2020; Heilbronn et al. 2015)

* Secondary (albedo) neutron intensity sensitive to surface composition

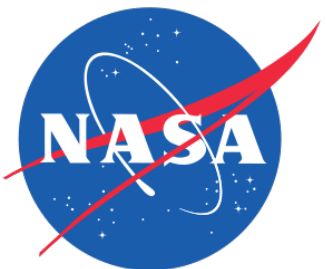


→ Can be utilized to detect water ice in permanently shadowed regions on the lunar surface

PSRs in lunar south pole



Gläser et al. 2018



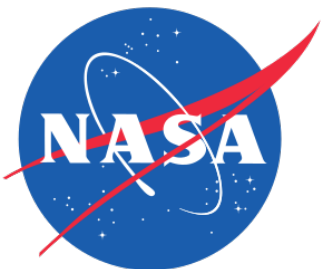
Relevance & Impact

Improved knowledge of atmospheric neutrons themselves, including spatial and temporal variations, are valuable:

- 1) neutron-induced single event upsets in avionics systems are a concern
- 2) avionics and astronauts (Fast neutrons are abundant at commercial or military aircraft altitudes and the spectrum is hard in this range)
- 3) important sources of background for NASA Heliophysics and Astrophysics γ -ray missions in LEO

A CubeSat-sized neutron spectrometer could serve as a redundant radiation monitor, issuing red or yellow alerts in the case of intense ground level enhancement events.

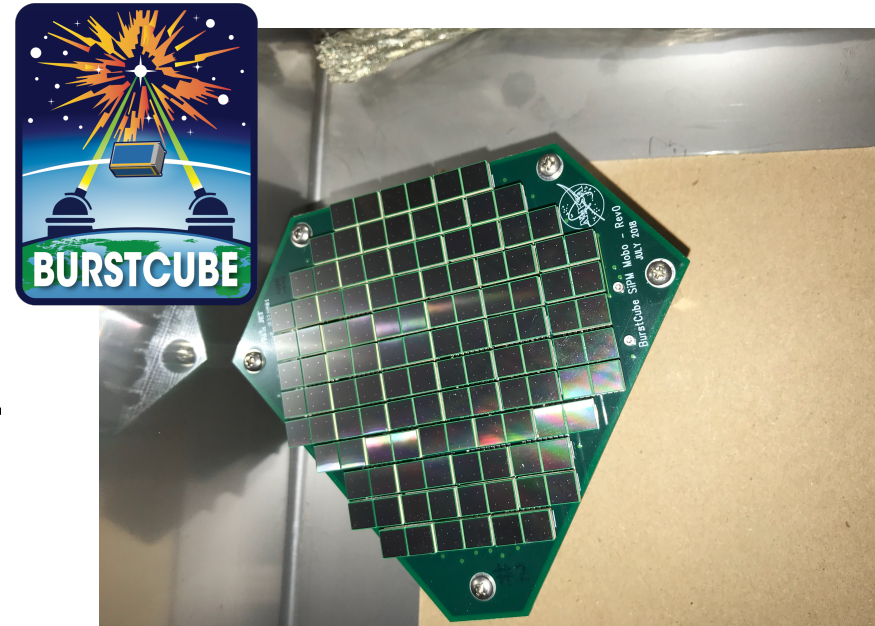
Need to be able to detect and image fast neutrons between ~20-150 MeV



Enabling Technology

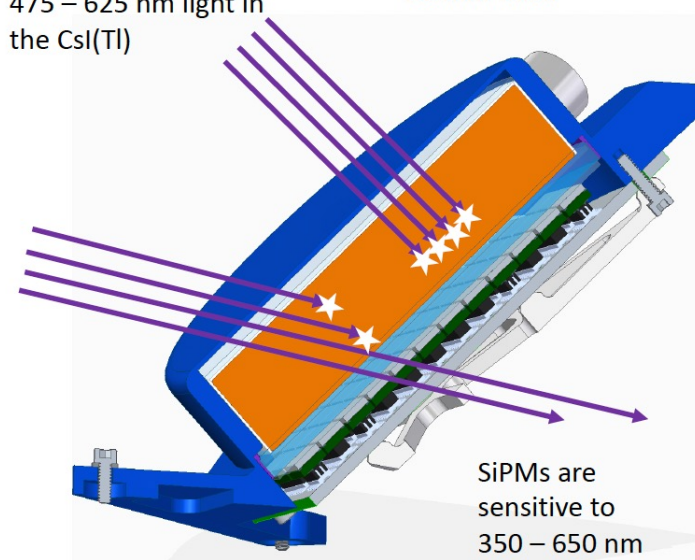
Need to be able to detect and image fast neutrons between ~20-150 MeV

- Silicon Photomultipliers transform accessibility of neutron/gamma-ray instrumentation for smallSAT opportunities
- High-gain, compact, robust, low-power, easy to scale to variety of form factors



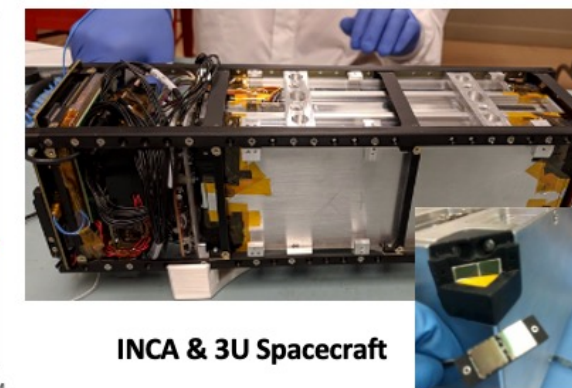
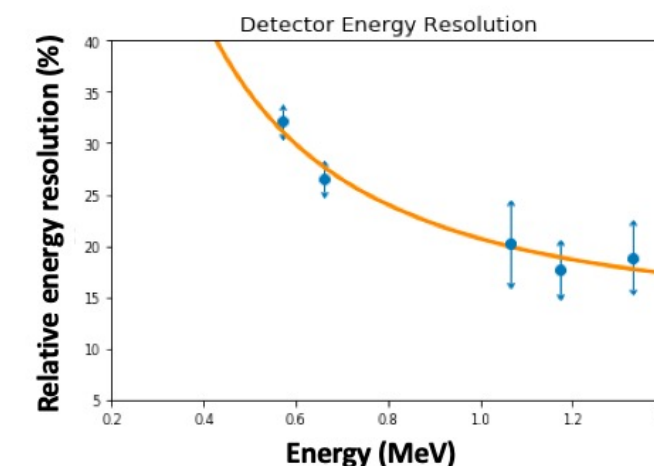
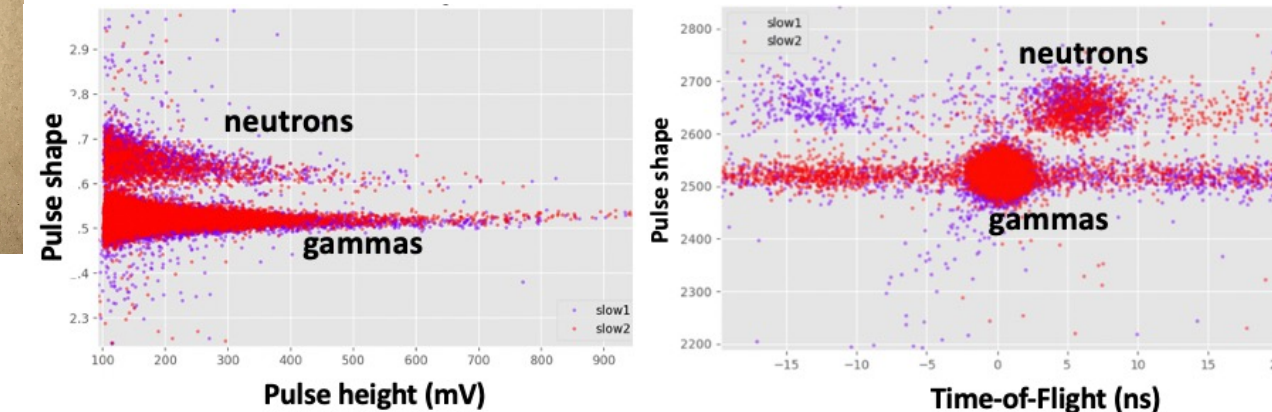
Gamma-rays produce
475 – 625 nm light in
the CsI(Tl)

90 mm diameter
20 mm thick

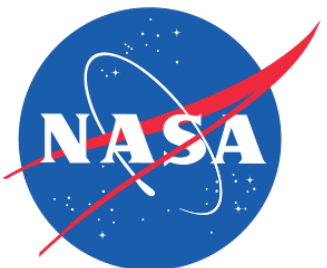


SiPMs are
sensitive to
350 – 650 nm

Ionospheric Neutron
Content Analyzer (INCA)
Failed ASTRA launch in 2021

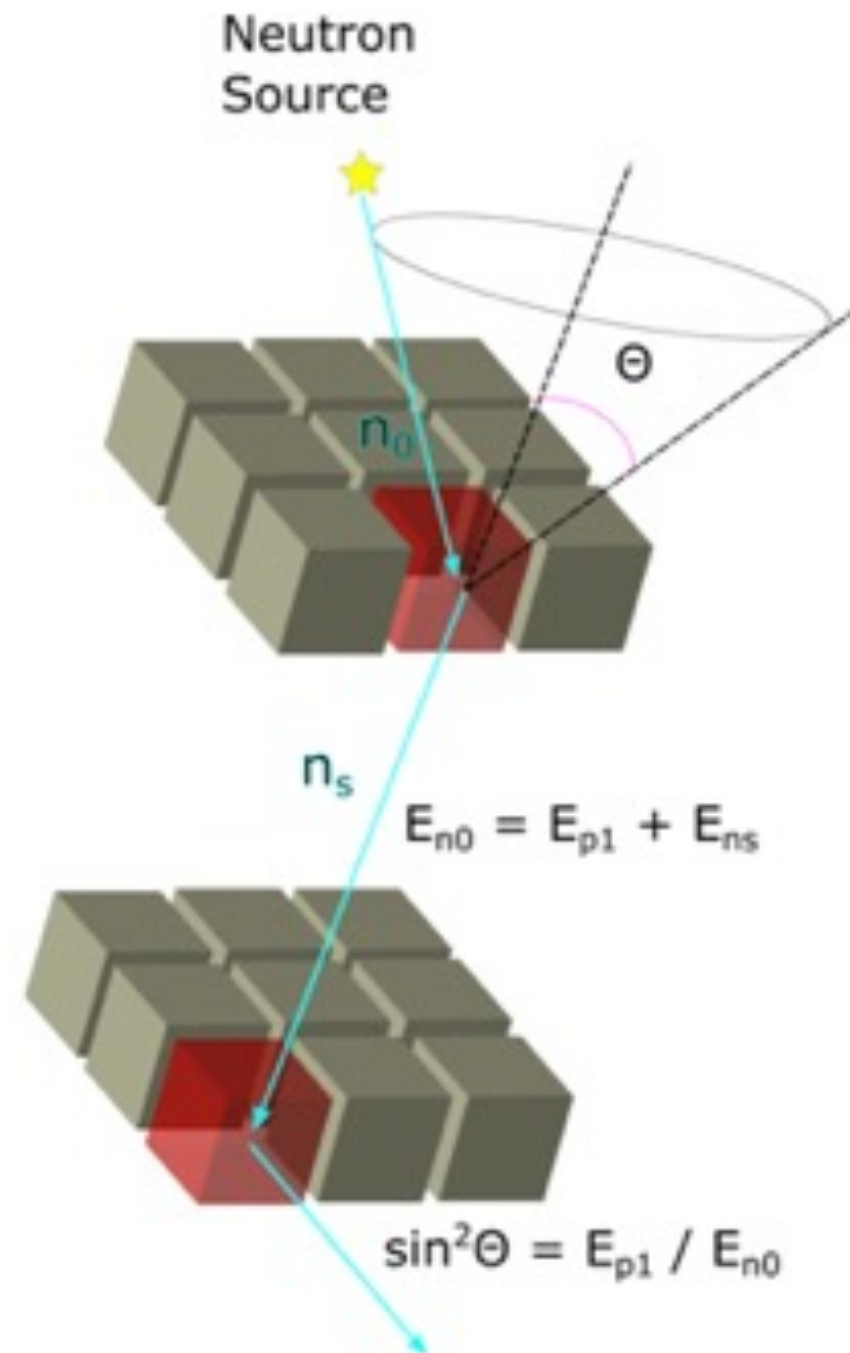


INCA & 3U Spacecraft

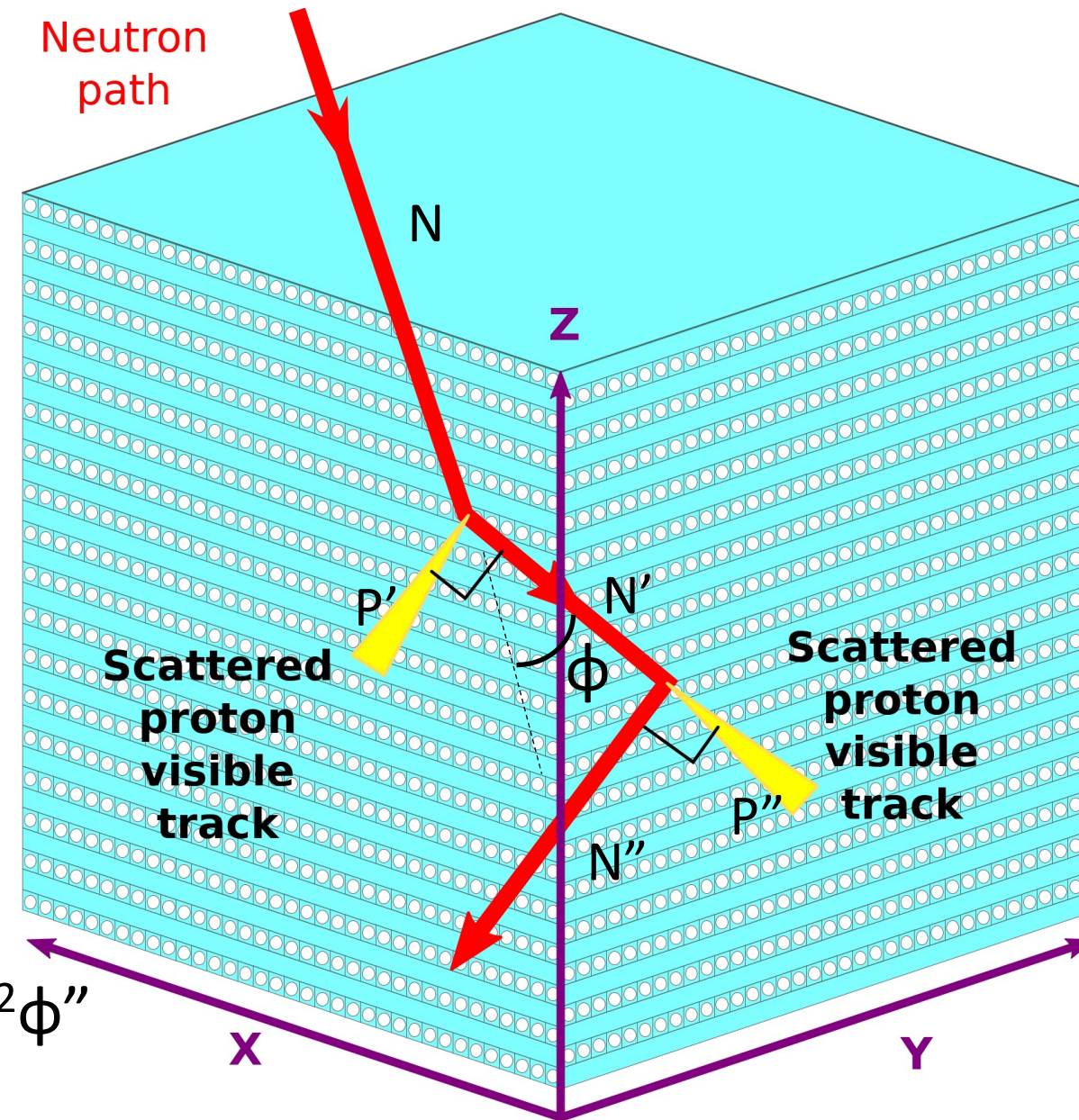


Modern Neutron Spectrometers

Traditional Double Scatter



Solar Neutron Tracking (SONTRAC) Concept



$$E_{N'} = E_{p'} / \cos^2\phi$$

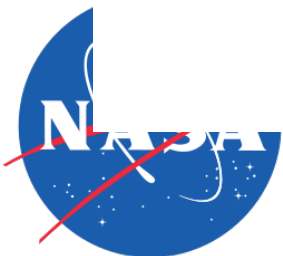
$$E_N = E_{p'} + E_{N'}$$

$$P_N = P_{p'} + P_{N'}$$

*Energy determined from pulse height & Bragg peak

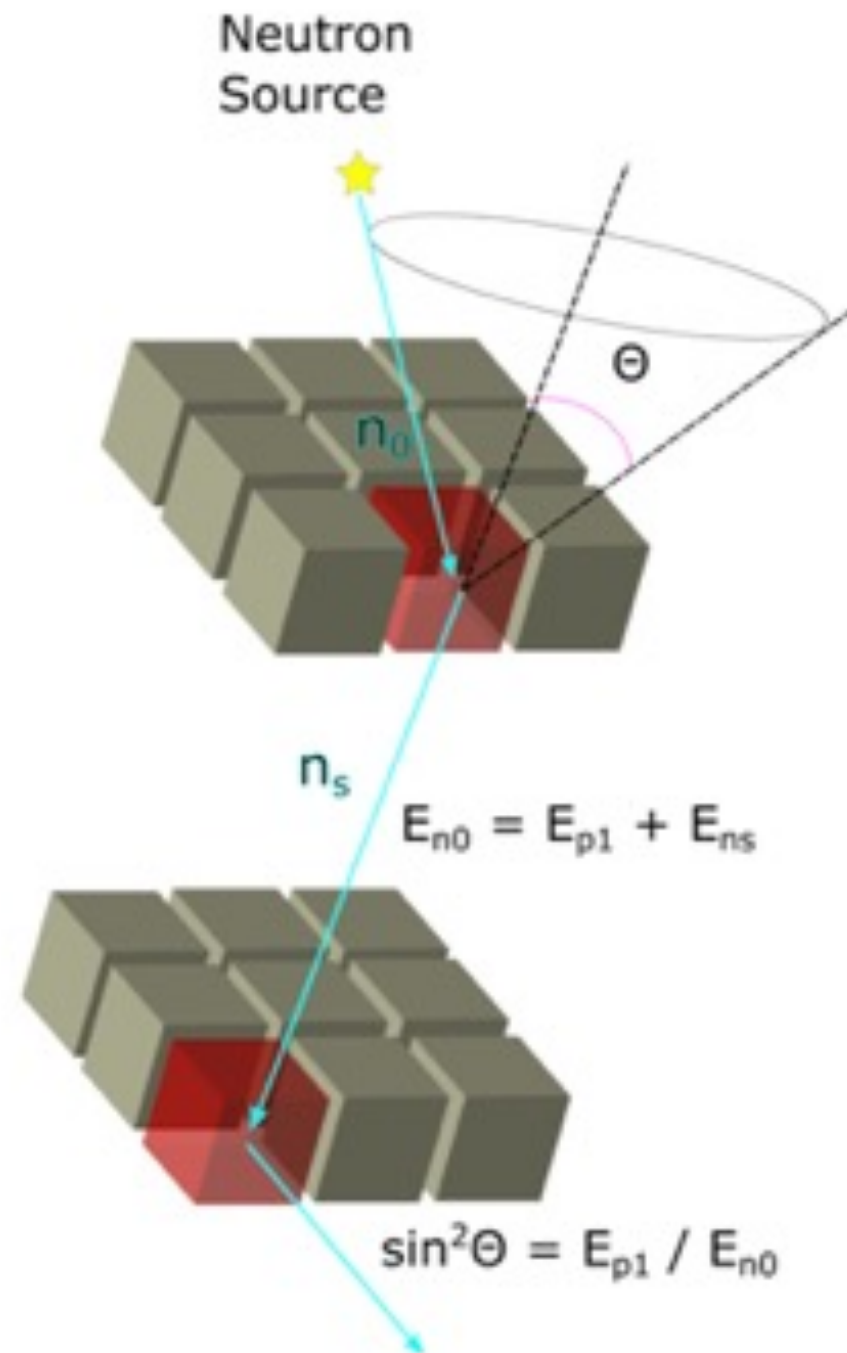
*Angular resolution determined by pitch of fibers

*Good angular resolution translates to lower background

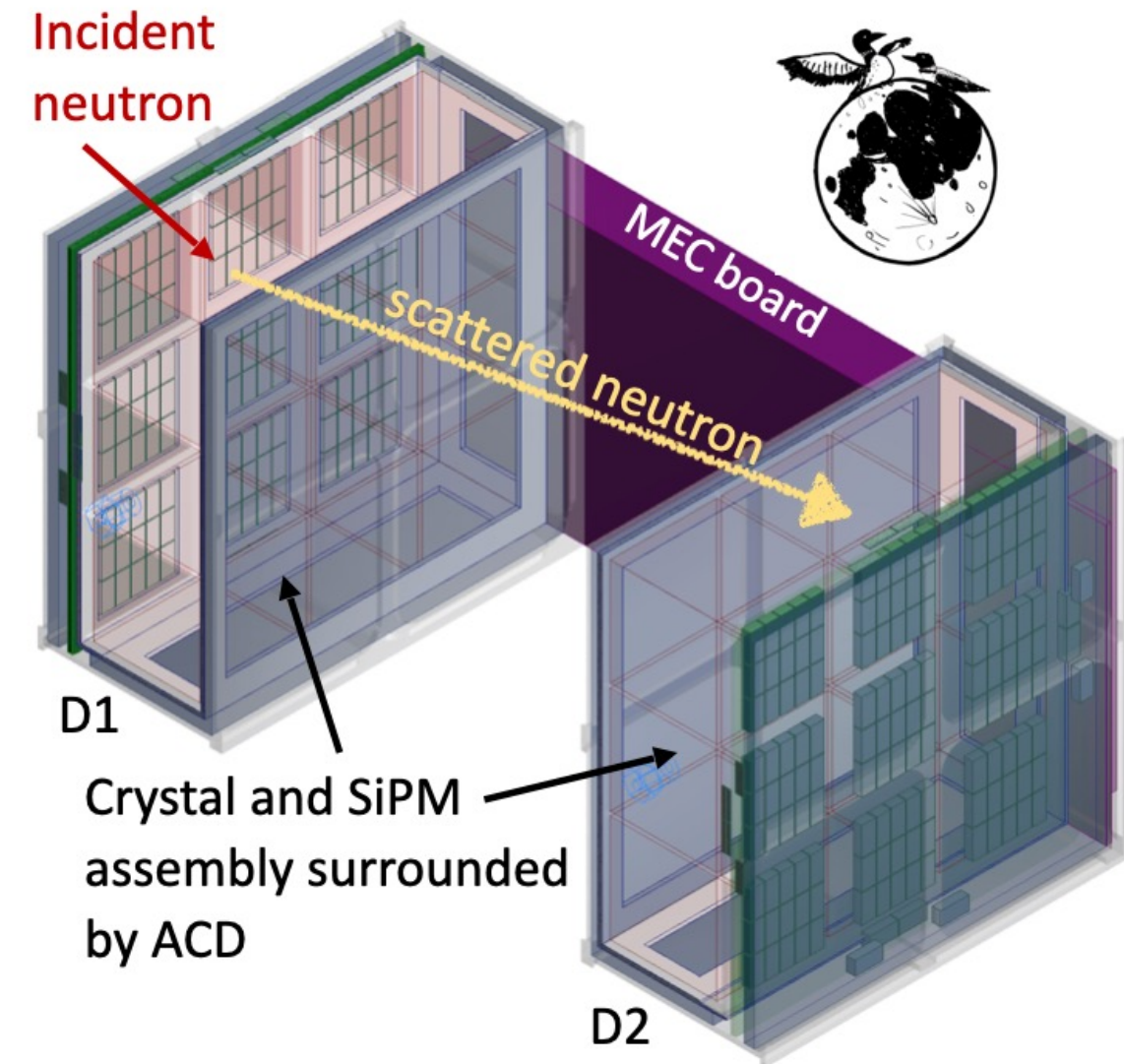


Lunar Outpost Neutron Spectrometer (LOONS)

Traditional Double Scatter



Solar Neutron Tracking (SONTRAC) Concept



$$E_{N'} = E_{p'} / \cos^2\phi''$$

$$E_N = E_{p'} + E_{N'}$$

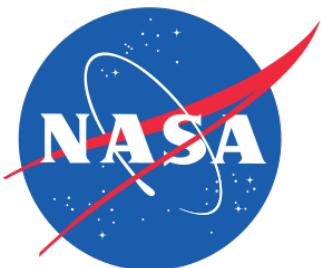
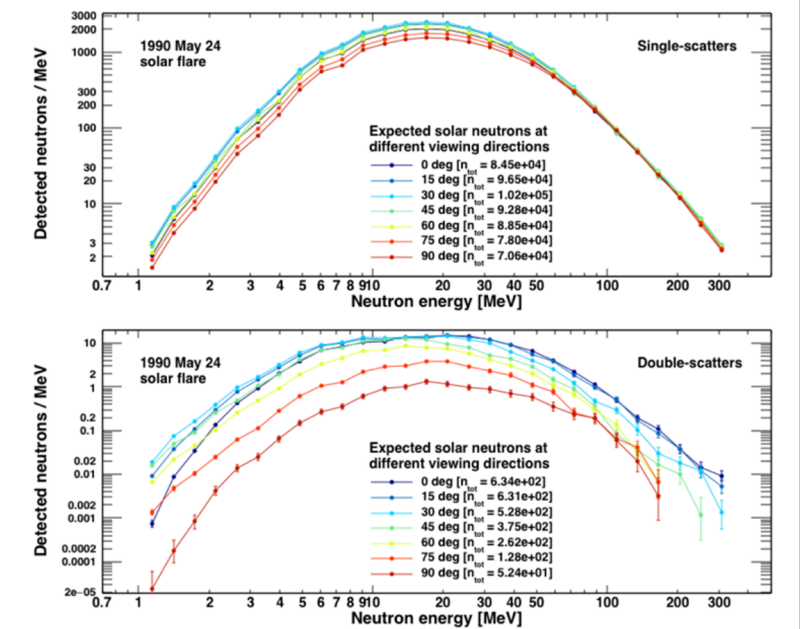
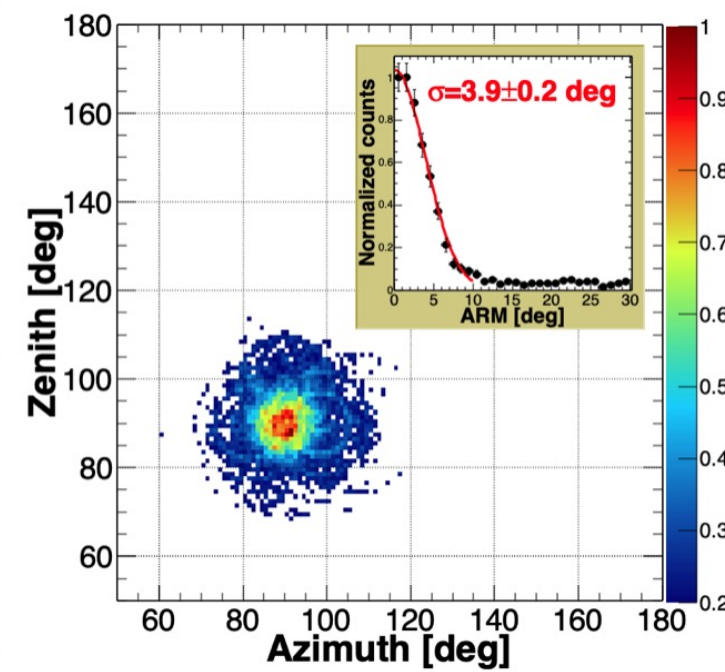
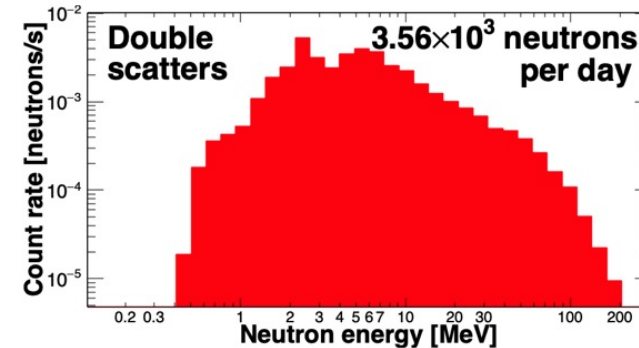
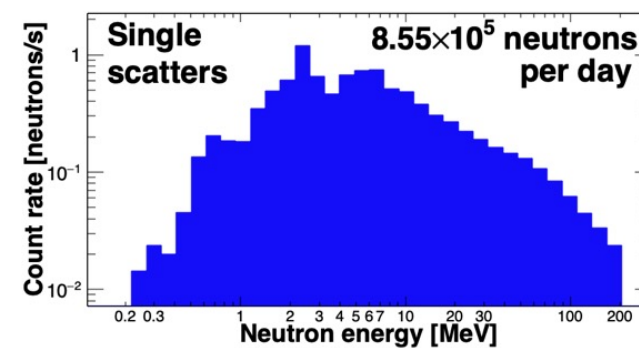
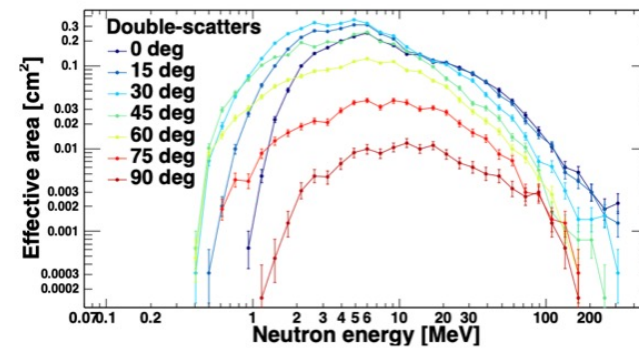
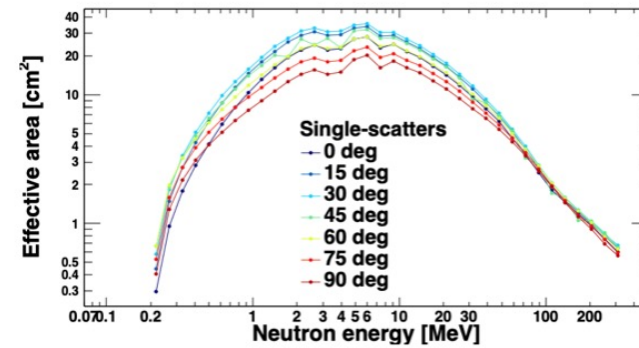
$$P_N = P_{p'} + P_{N'}$$

*Energy determined from pulse height & Bragg peak

*Angular resolution determined by pitch of fibers

*Good angular resolution translates to lower background

LOONS Performance



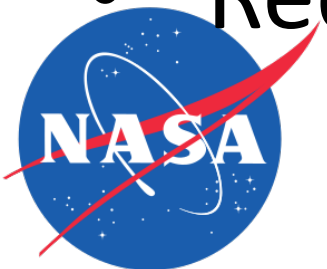
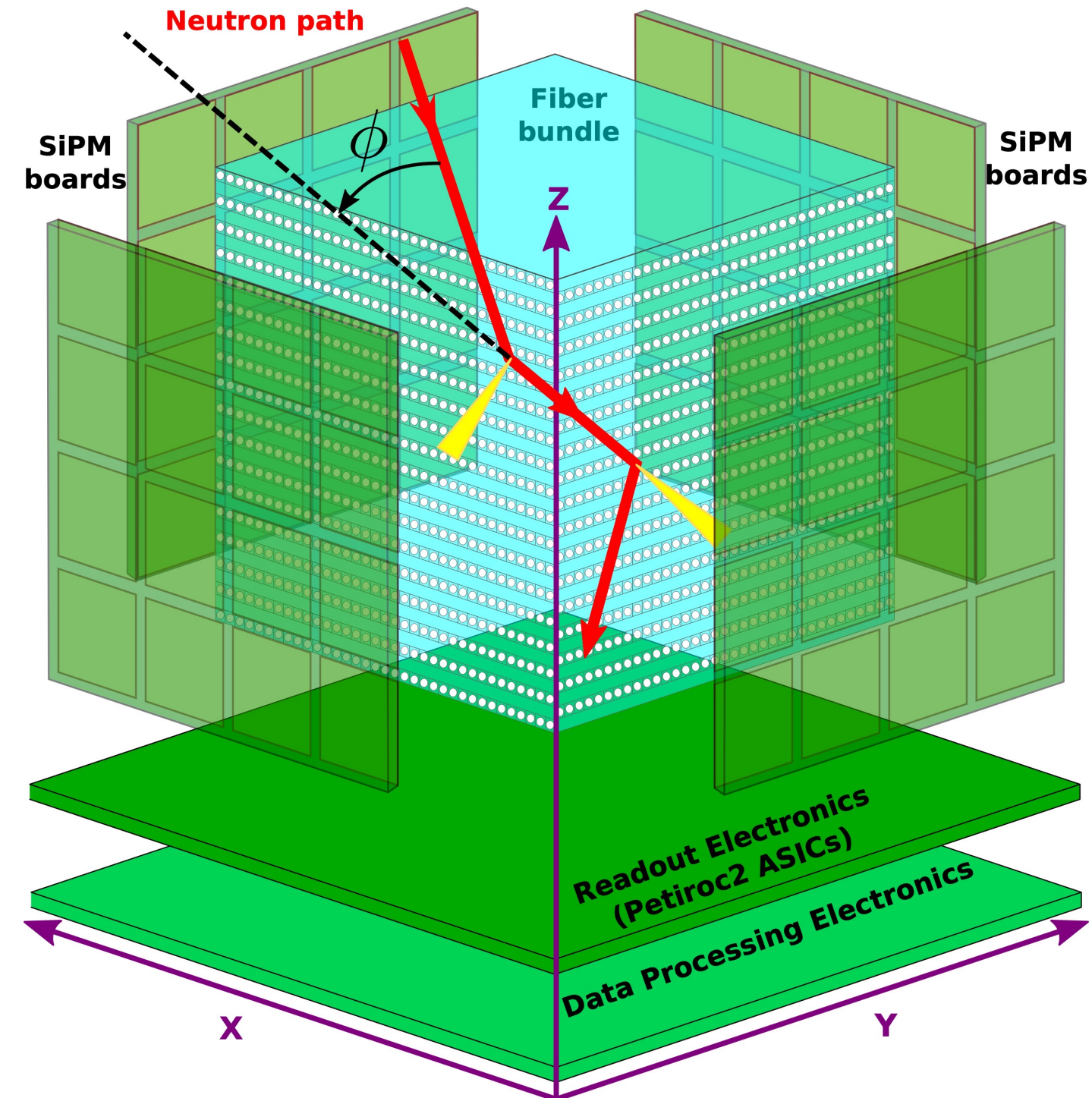
SONTRAC 3D Neutron Spectrometer

SONTRAC Original Concept:

- 5 cm cube with 300 μ m orthogonally stacked plastic scintillating fibers
- Read by PMT/taper/intensifier/CCD camera (Ryan et al. 1999)

Next-Generation SONTRAC:

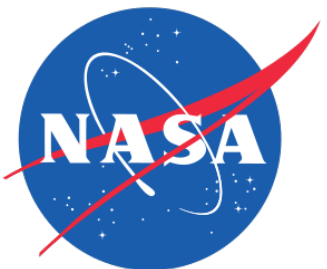
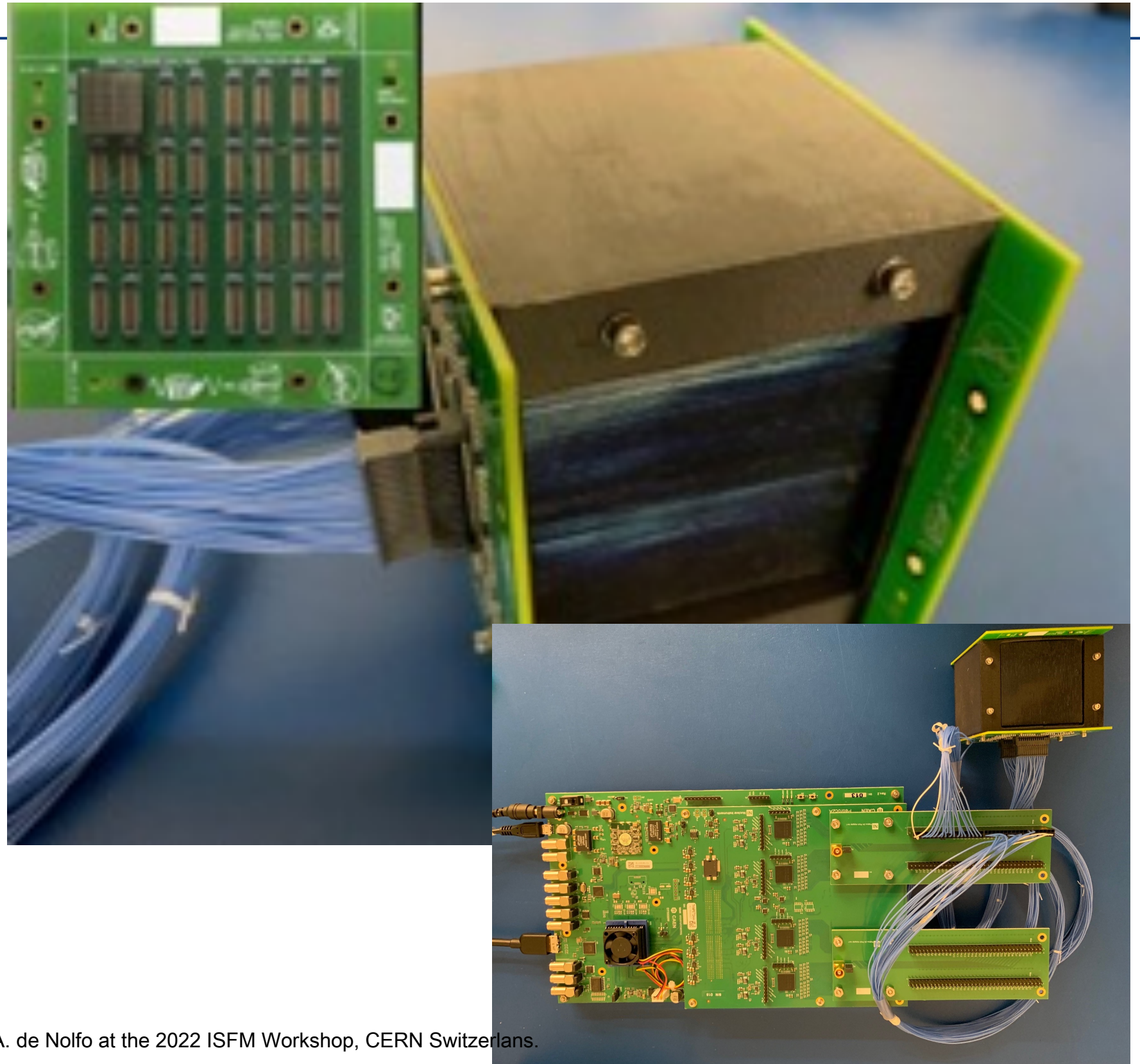
- 5 cm cube with $\sim$ 1-mm orthogonally stacked plastic scintillating fibers
- **Readout with arrays of SiPMs** : fast rise time (several ns), PDE $\sim$ 40%, gain $\sim 10^{5-6}$
- Requires at least 2 planes of 2D readout



Status of SONTRAC Prototype

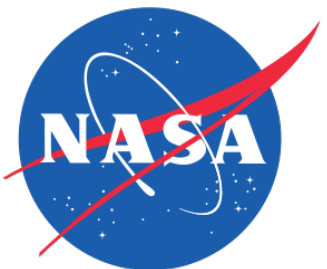
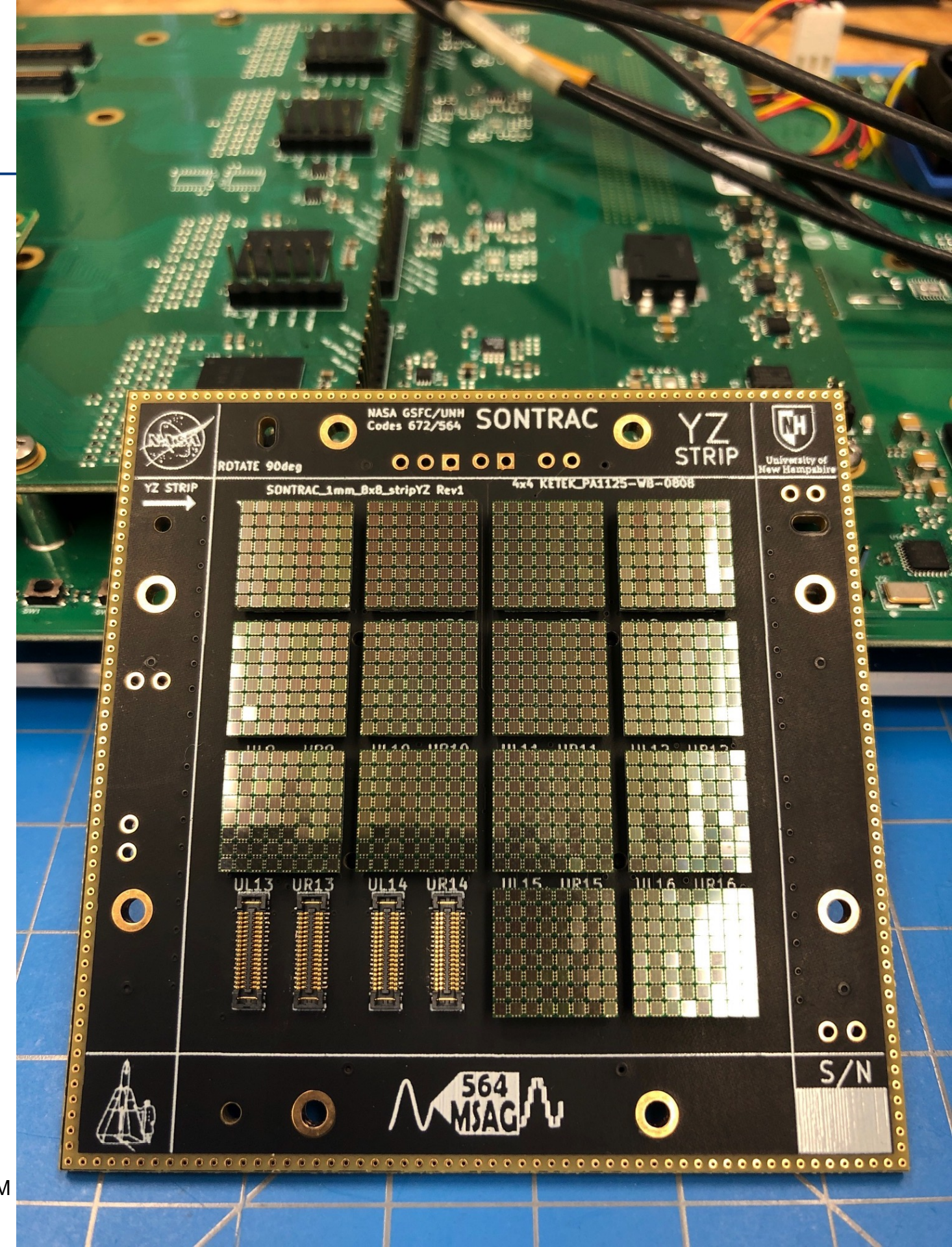
Science Model 1:

- 300 μm pitch orthogonally stacked fibers (Saint Gobain BF-12 fibers)
- Viewed by 1.36-mm pitch arrays of SiPMs
- Signal Processing: CAEN DT5550W with Petiroc@ASICs (32-channel)



SiPM readout

- Purchased off-the-shelf 8x8 1-mm SiPMs from KETEK
- Will begin to test Hamamatsu 16x16 SiPMs
- Also investigating smaller pitch SiPMs ($\sim 500\text{ }\mu\text{m}$) from Fondazione Bruno Kessler & Hamamatsu

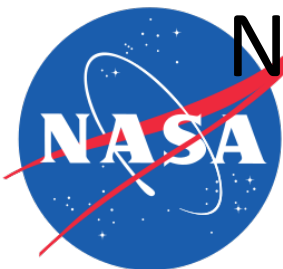
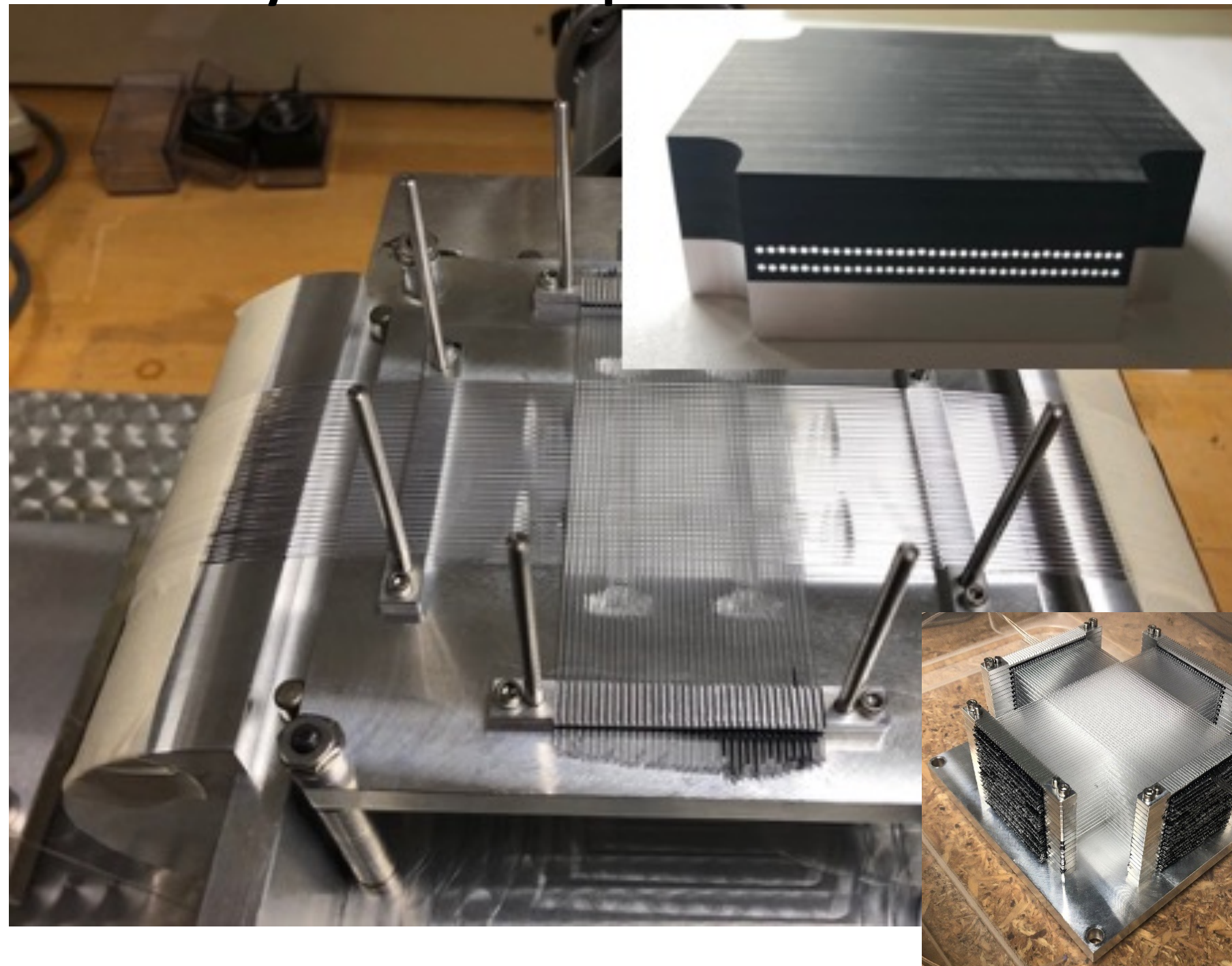


SONTRAC Science Model 2

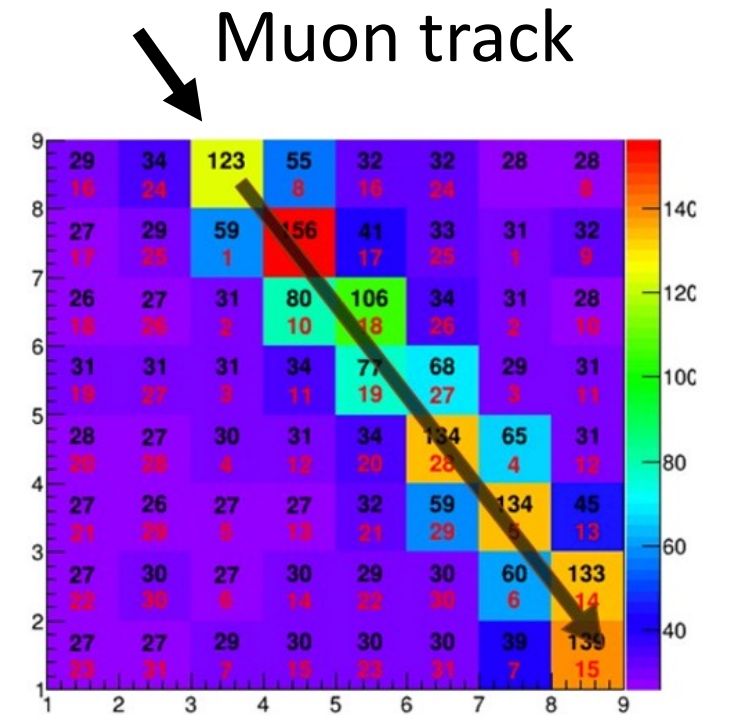
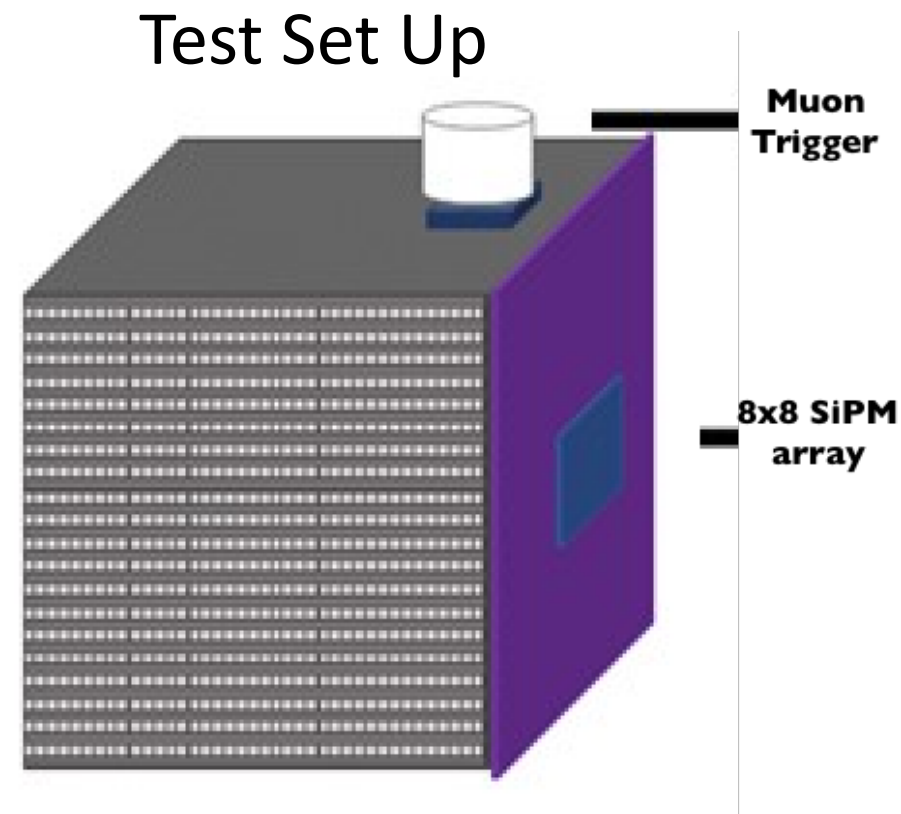
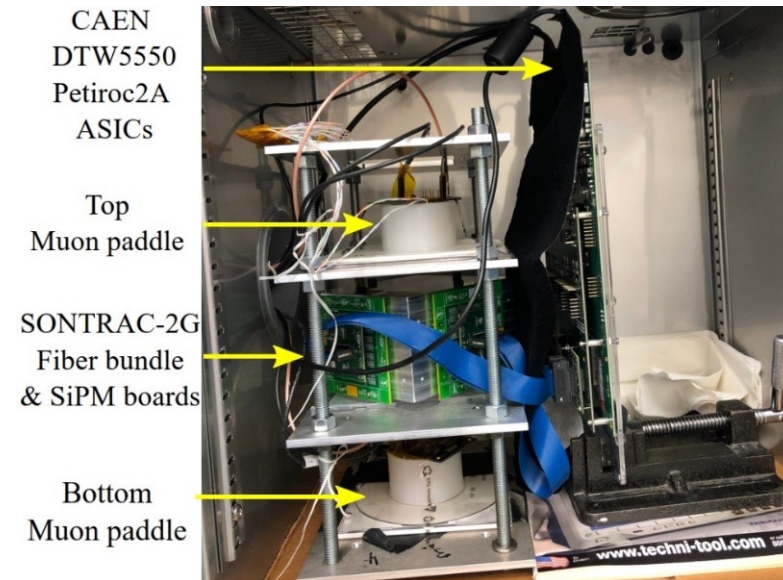
Fabricating New Bundle:

- 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 of SM-2 planned (Jun. 2020 @ Crocker National Lab's cyclotron)

University of New Hampshire Bundle Fabrication



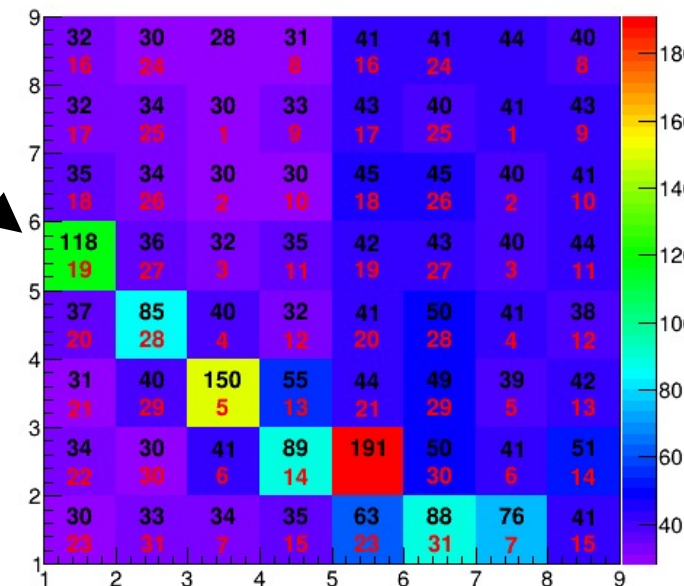
SONTRAC SM-1 Performance : Muon Tracks



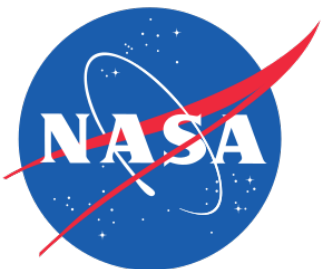
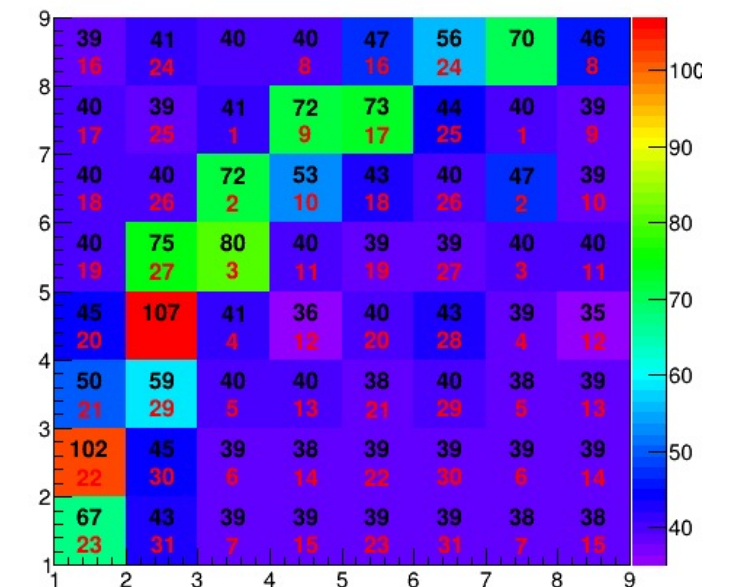
Ground-level muon tests:

- Employ small muon detector in coincidence
 - Observe muon tracks
- sensitivity to minimum ionizing particles.

39590-39600

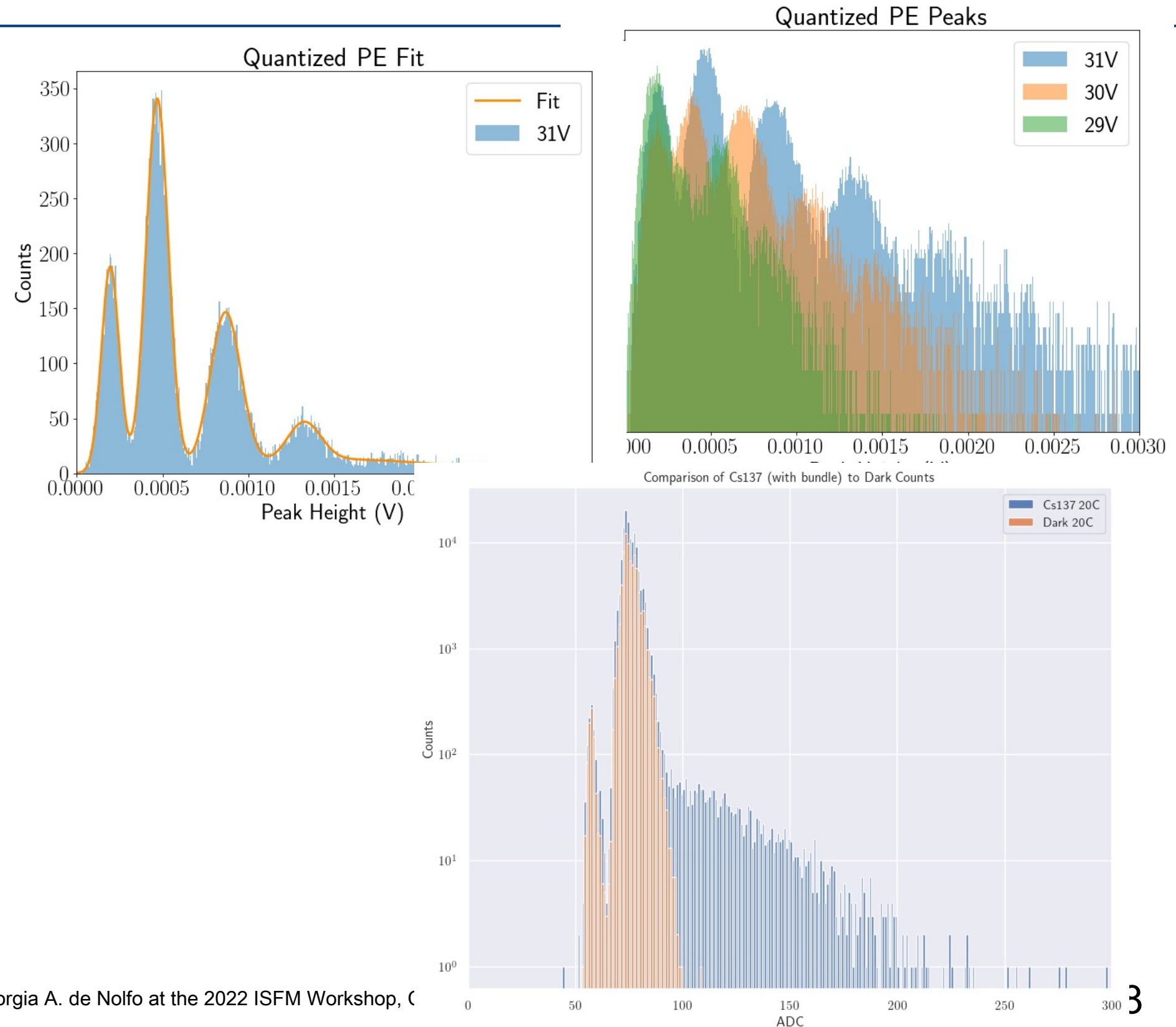


28150-28160

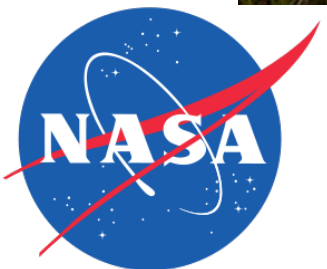
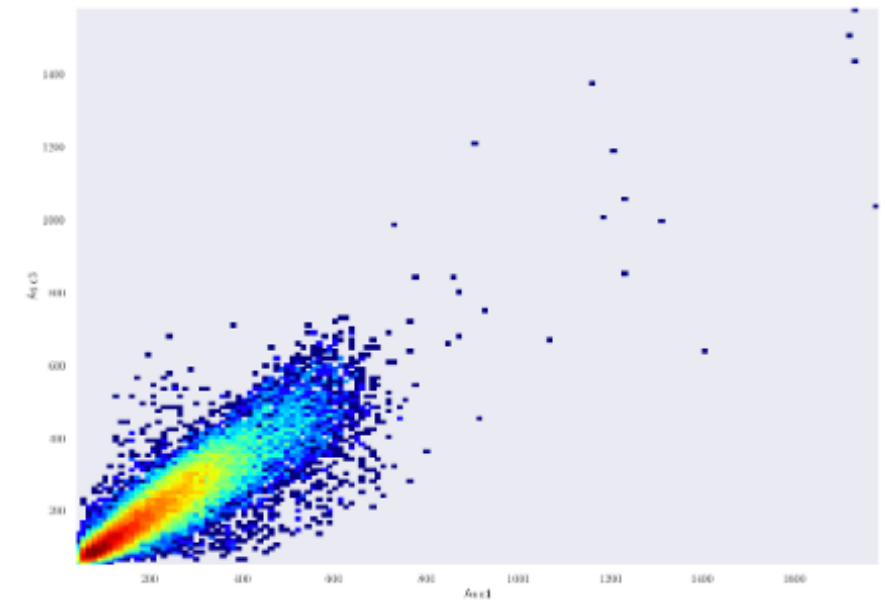
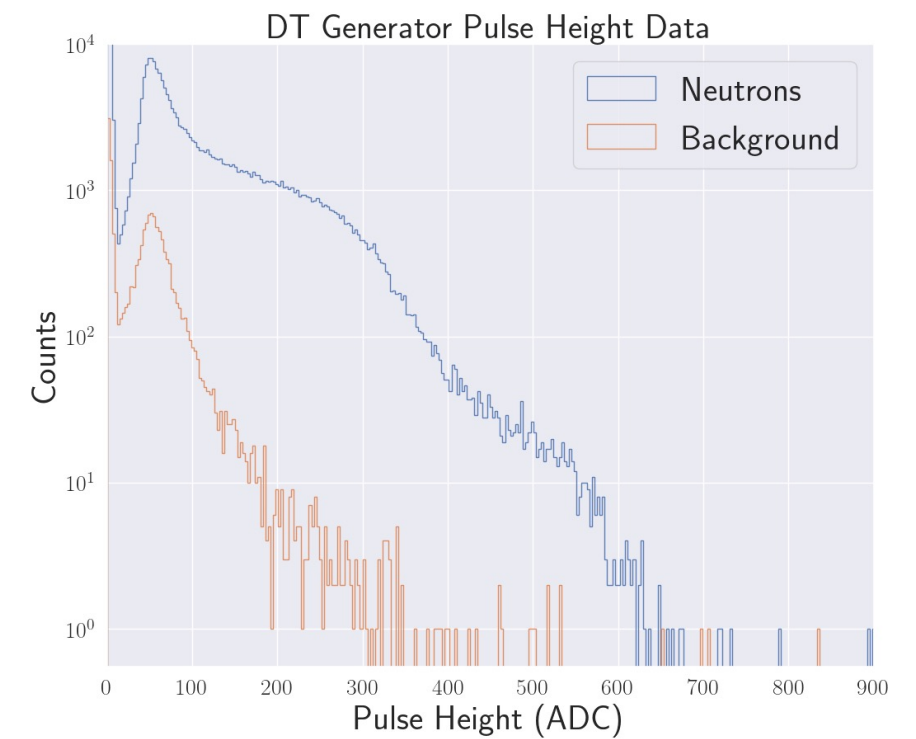
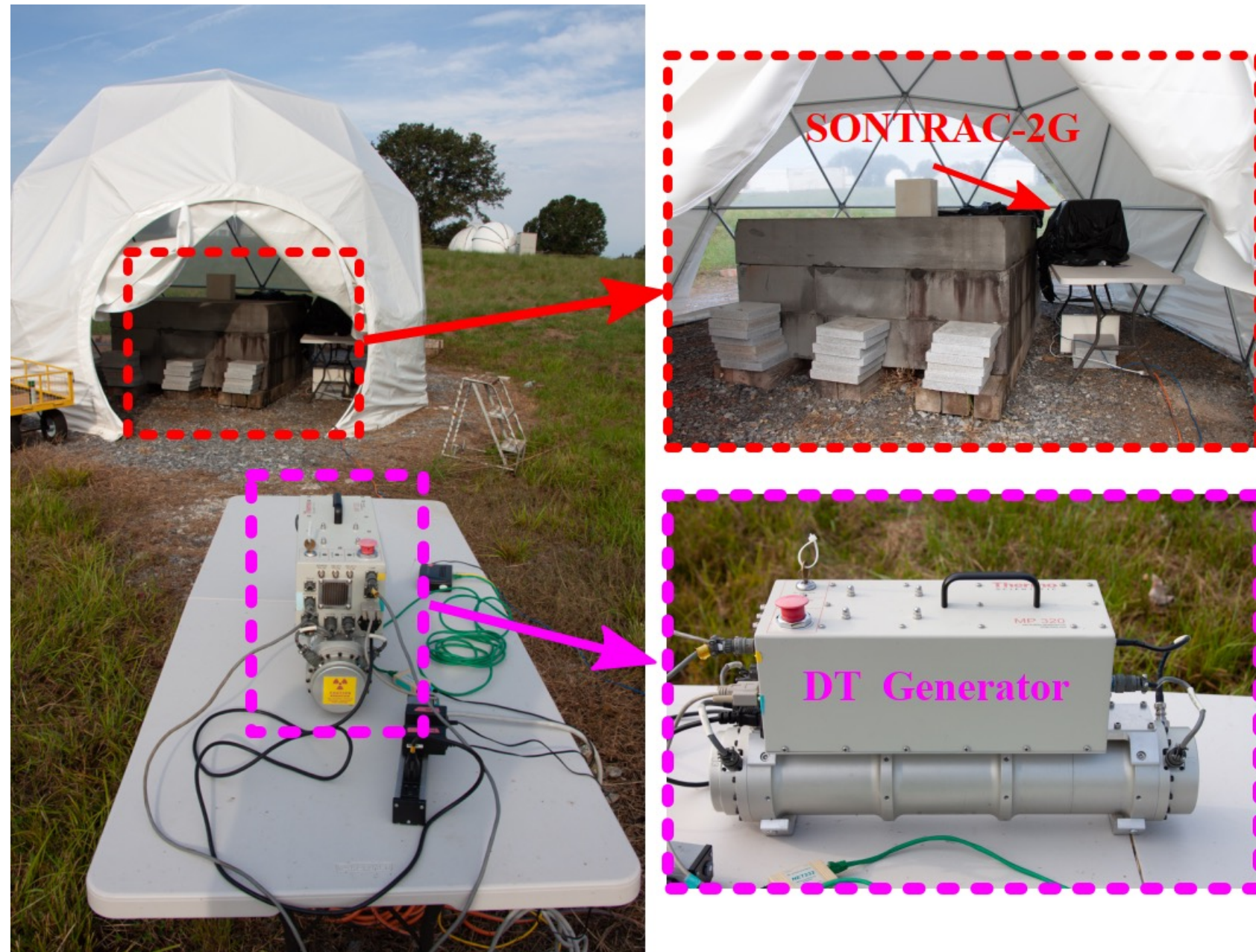


SONTRAC SM-1 Performance : Energy Threshold

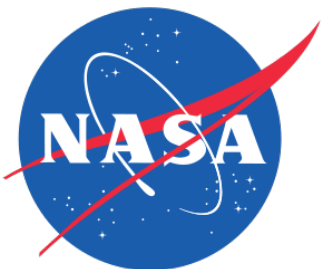
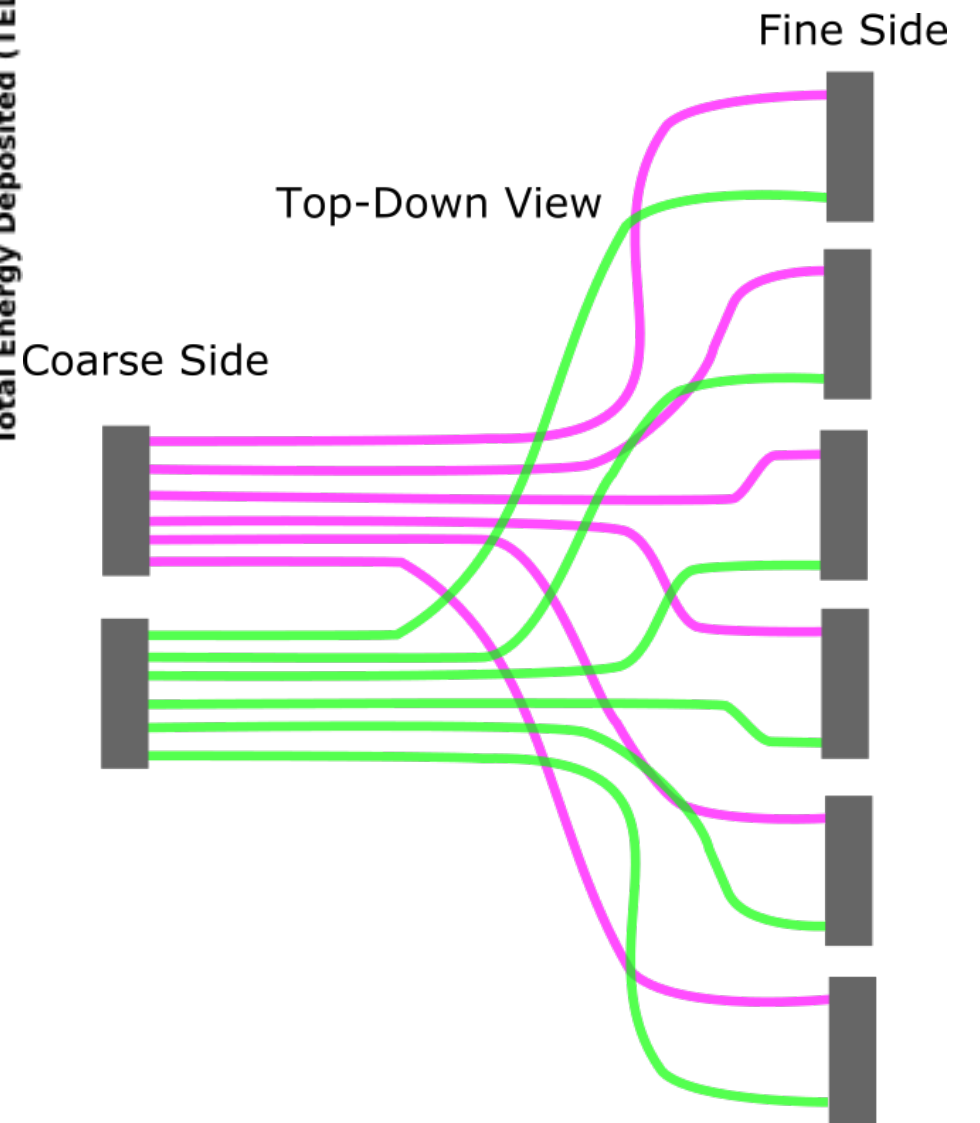
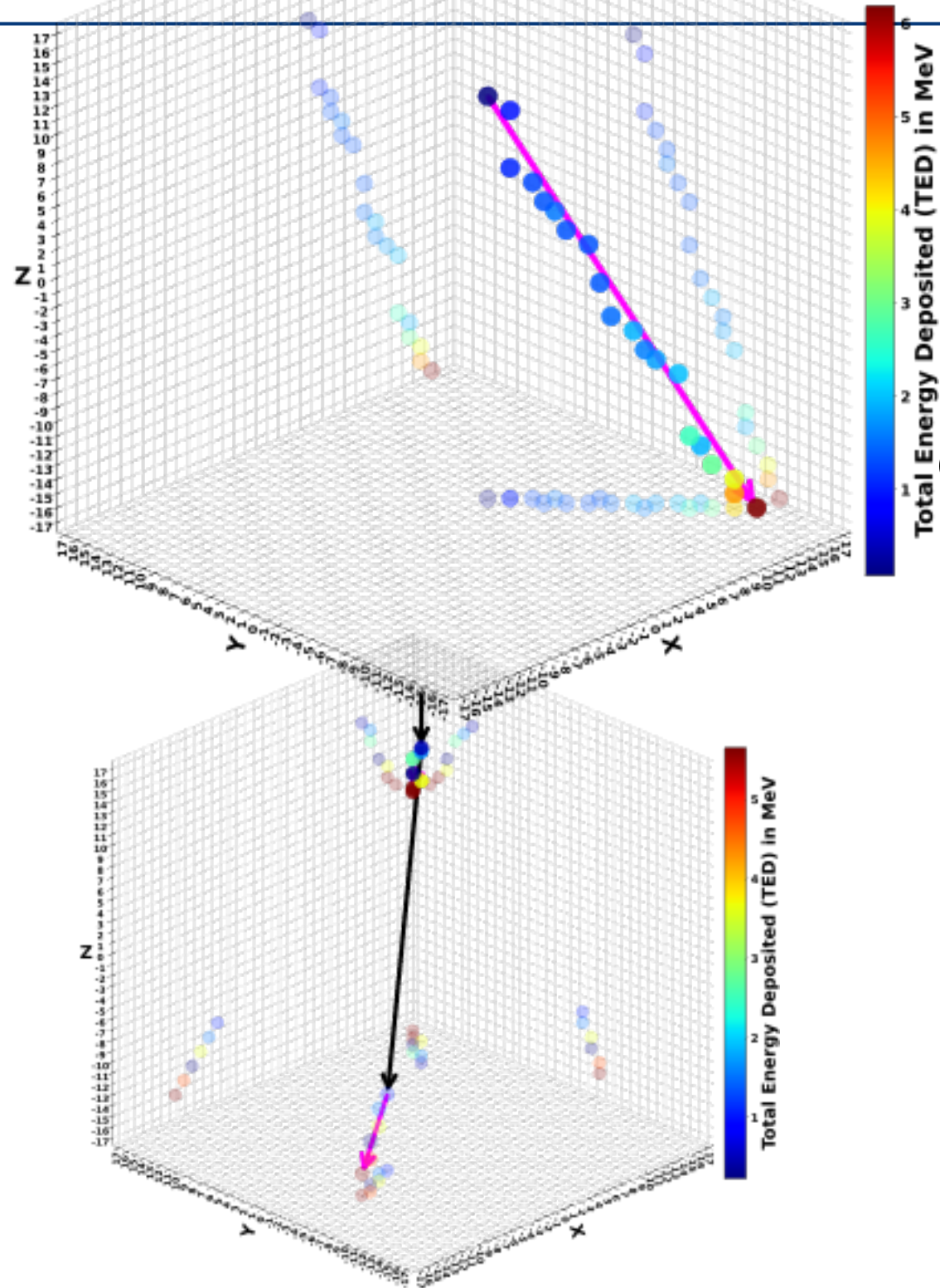
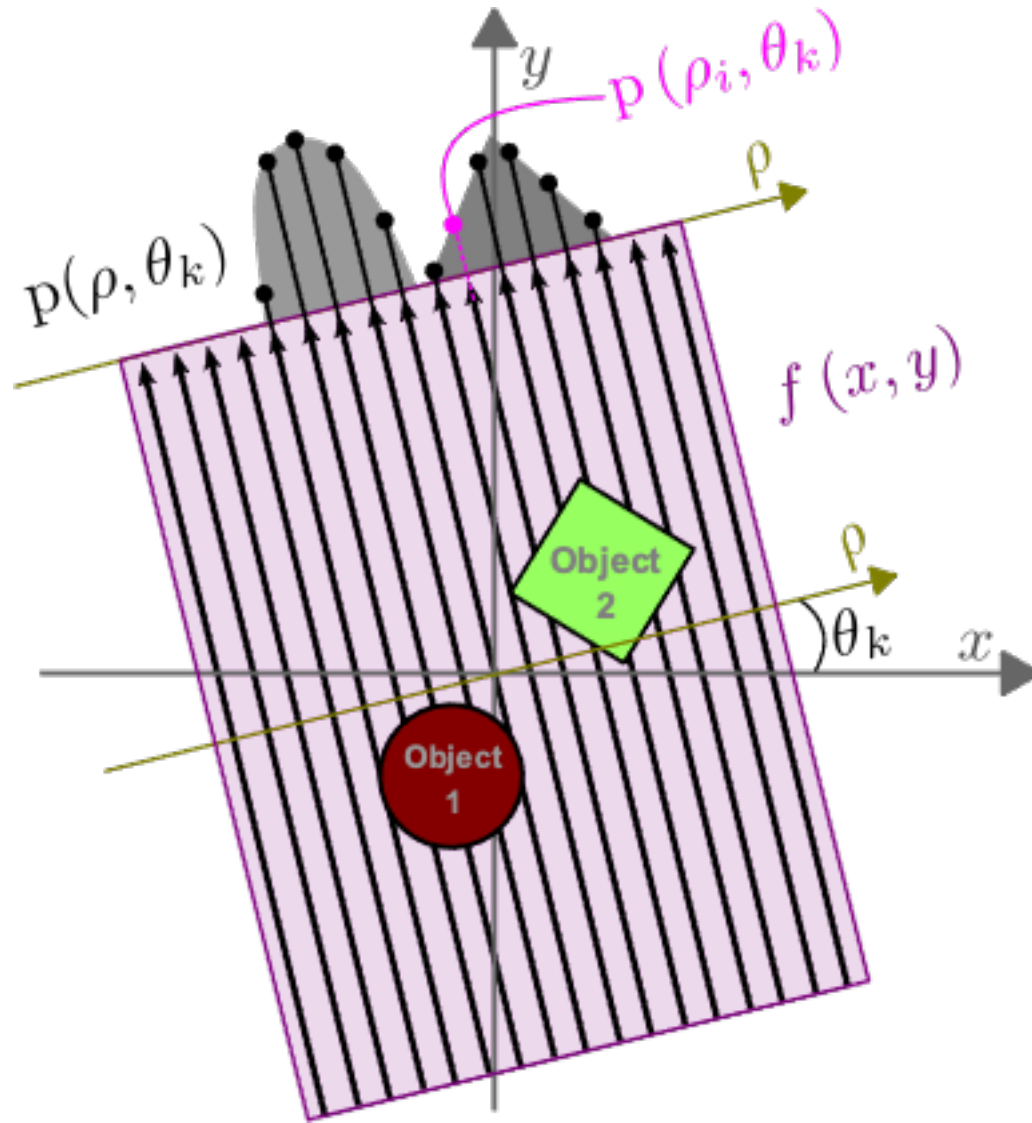
- Examine single 1-mm SiPM response to muons & radioactive γ -sources
- Six 300- μm fibers are viewed by one individual SiPM, although muons and scattered electrons typically pass through 1-2 fibers
- Average energy deposited $\sim$ 300 μm fiber $\Rightarrow$ **$\sim 180 \text{ keVpe}$ threshold**



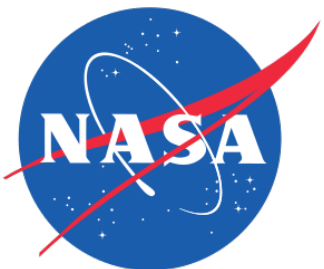
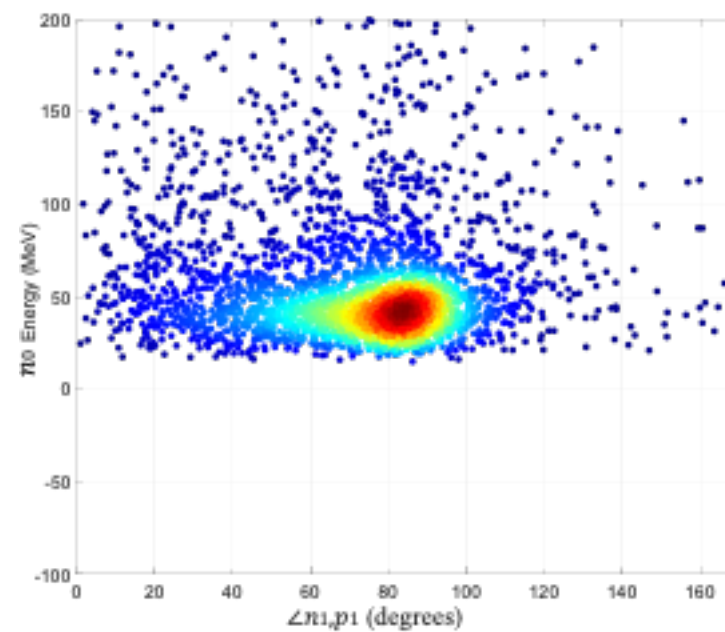
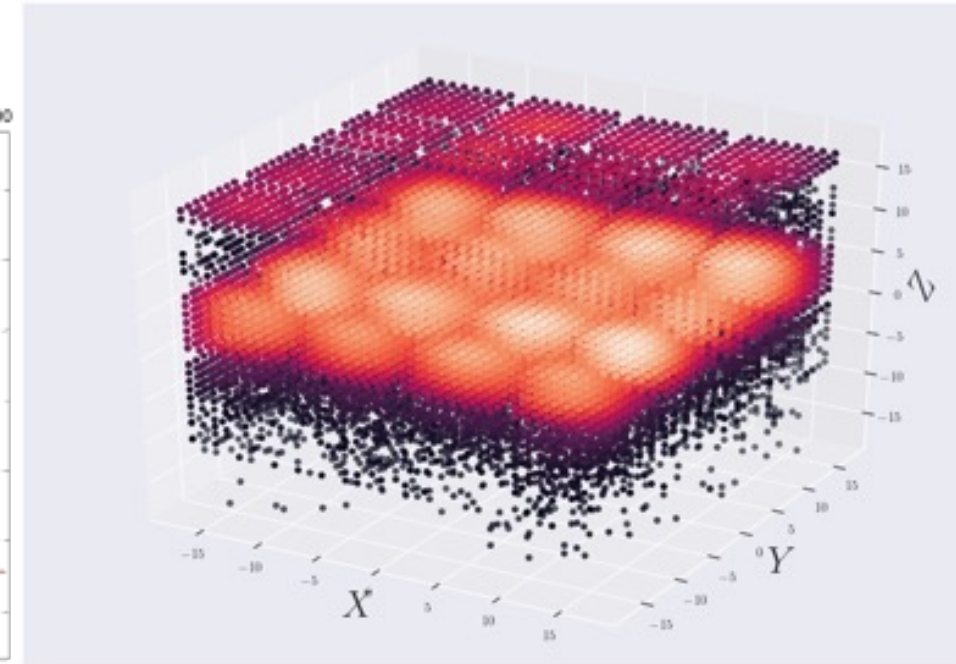
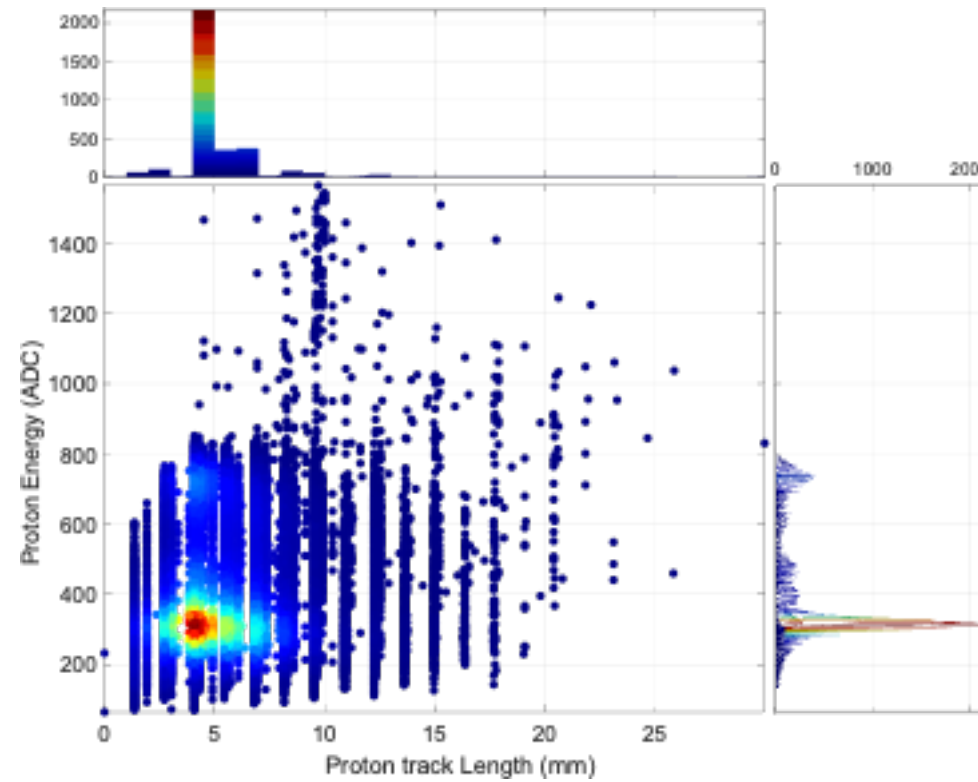
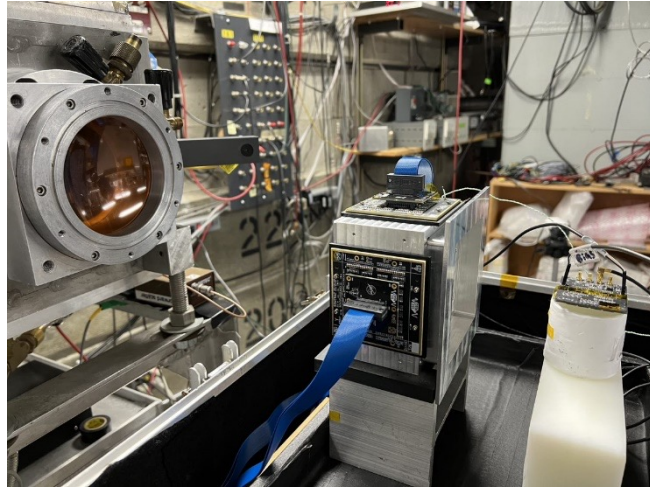
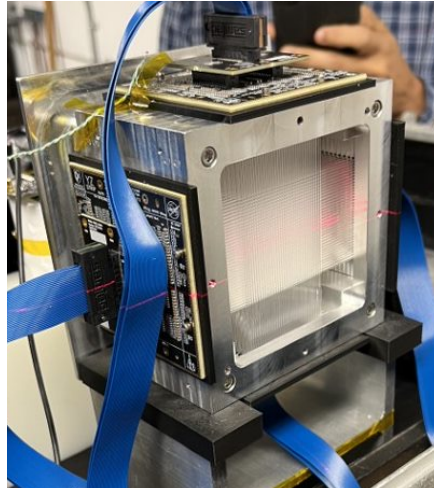
DT Generator Tests



SONTRAC Readout



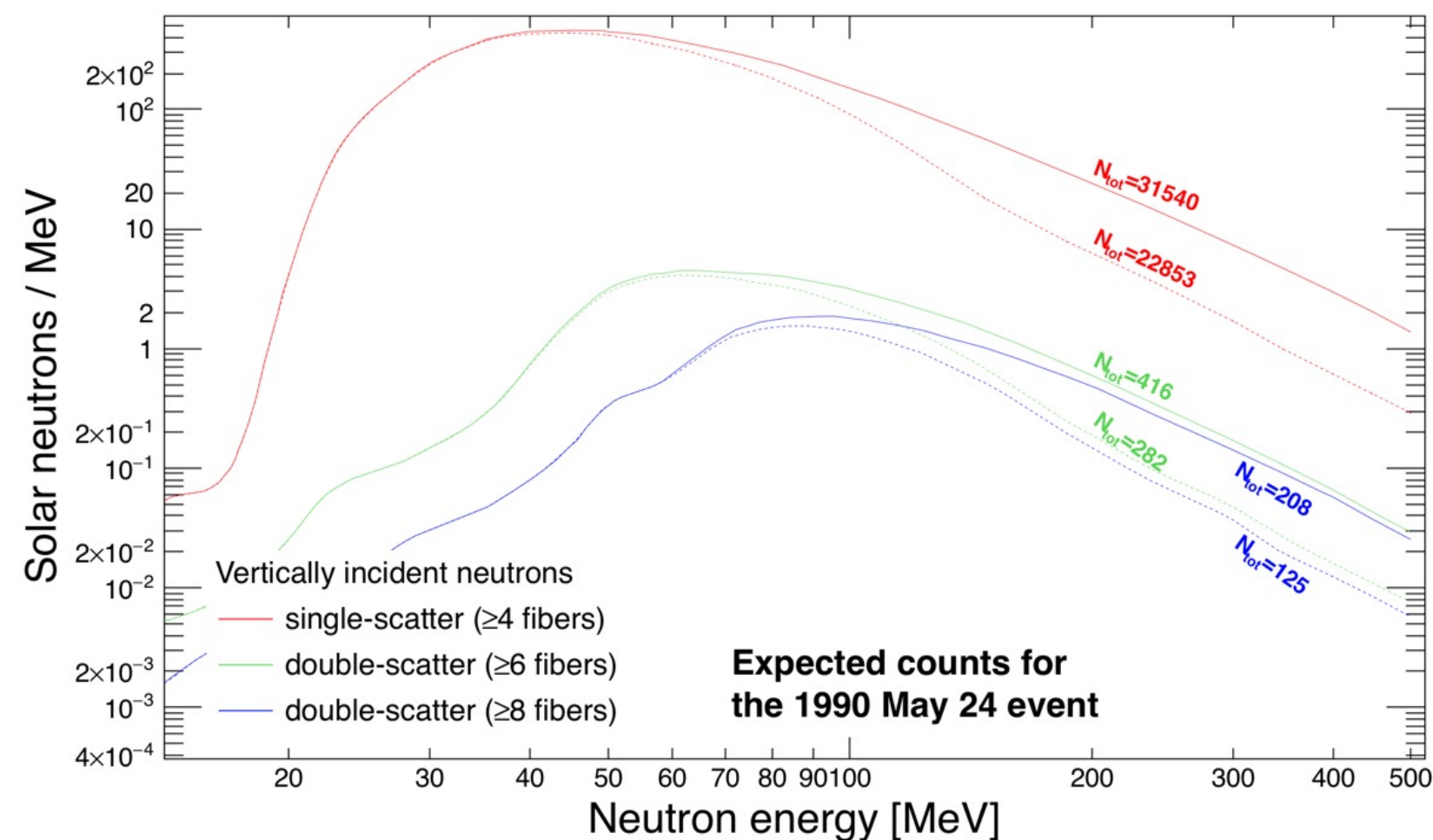
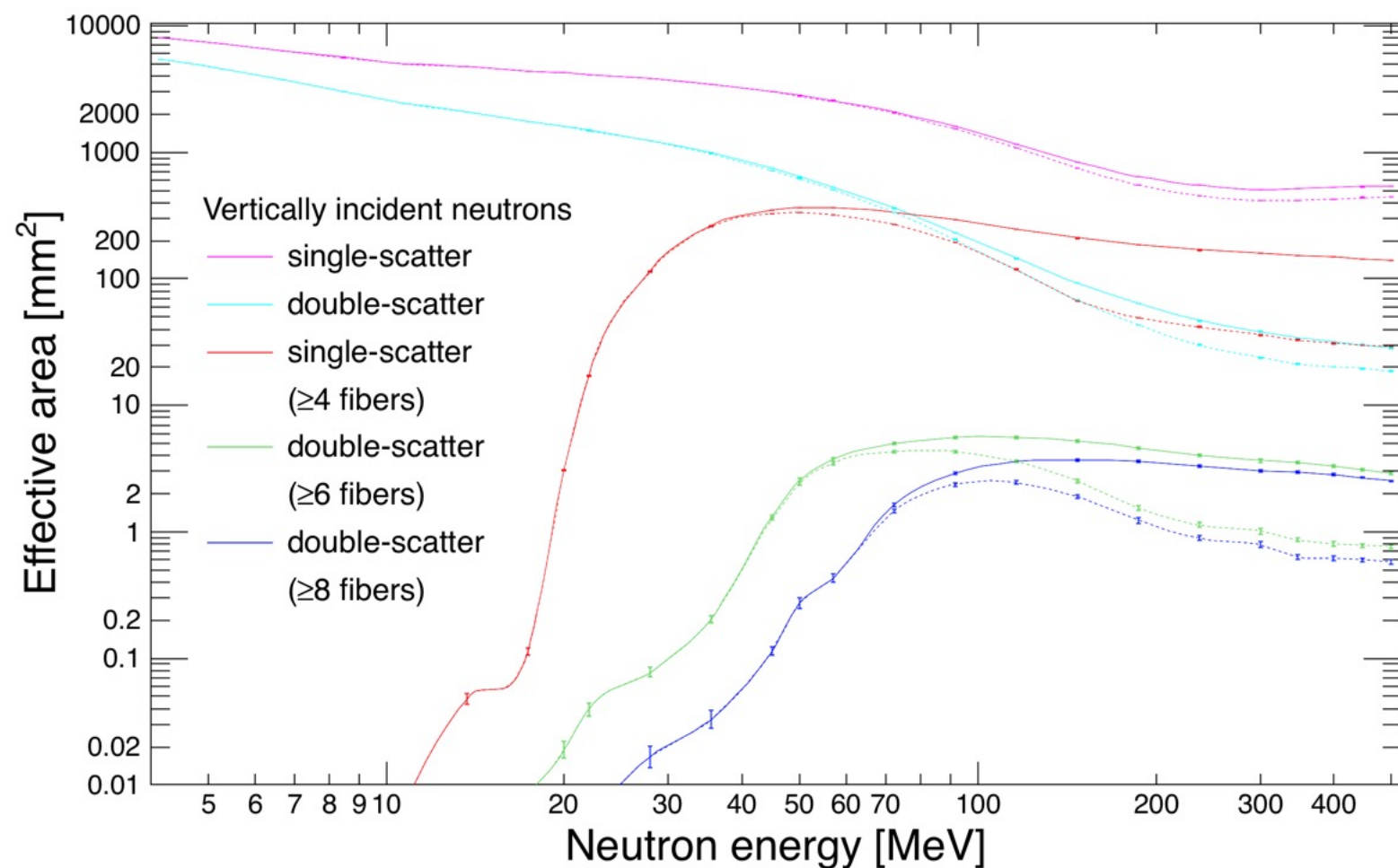
BEAM results



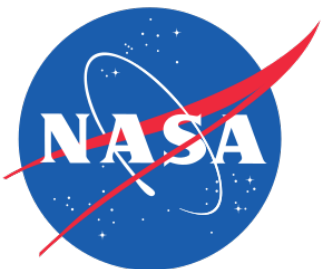
To be presented by Georgia A. de Nolfo at the 2022 ISFM Workshop, CERN Switzerland.

Expanded SONTRAC for a CubeSAT Platform

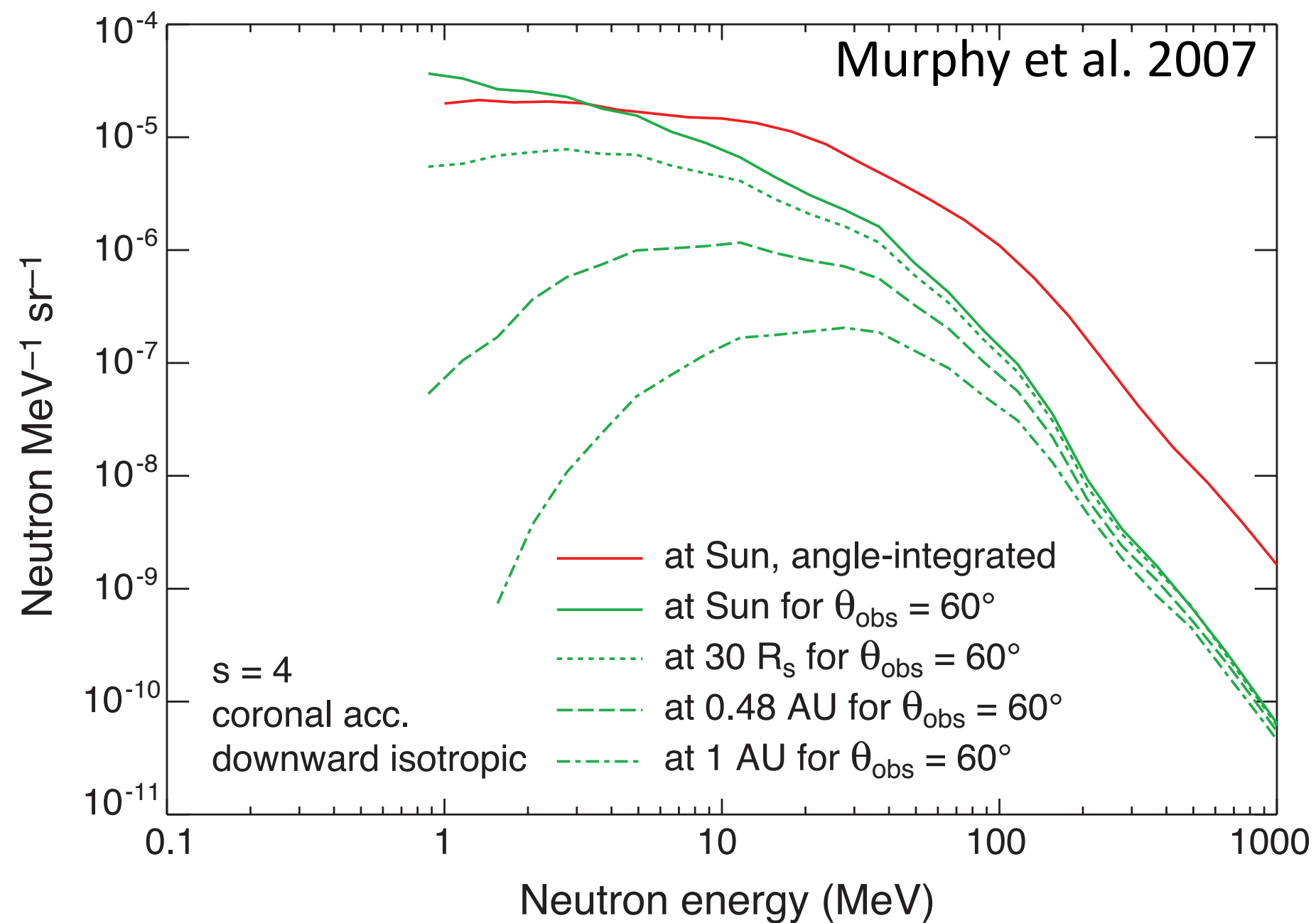
Geant4 Simulations for 10-cm³ SONTRAC



Possible to tile together for even larger effective area

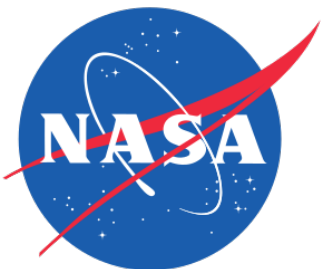


Inner Heliospheric CubeSAT

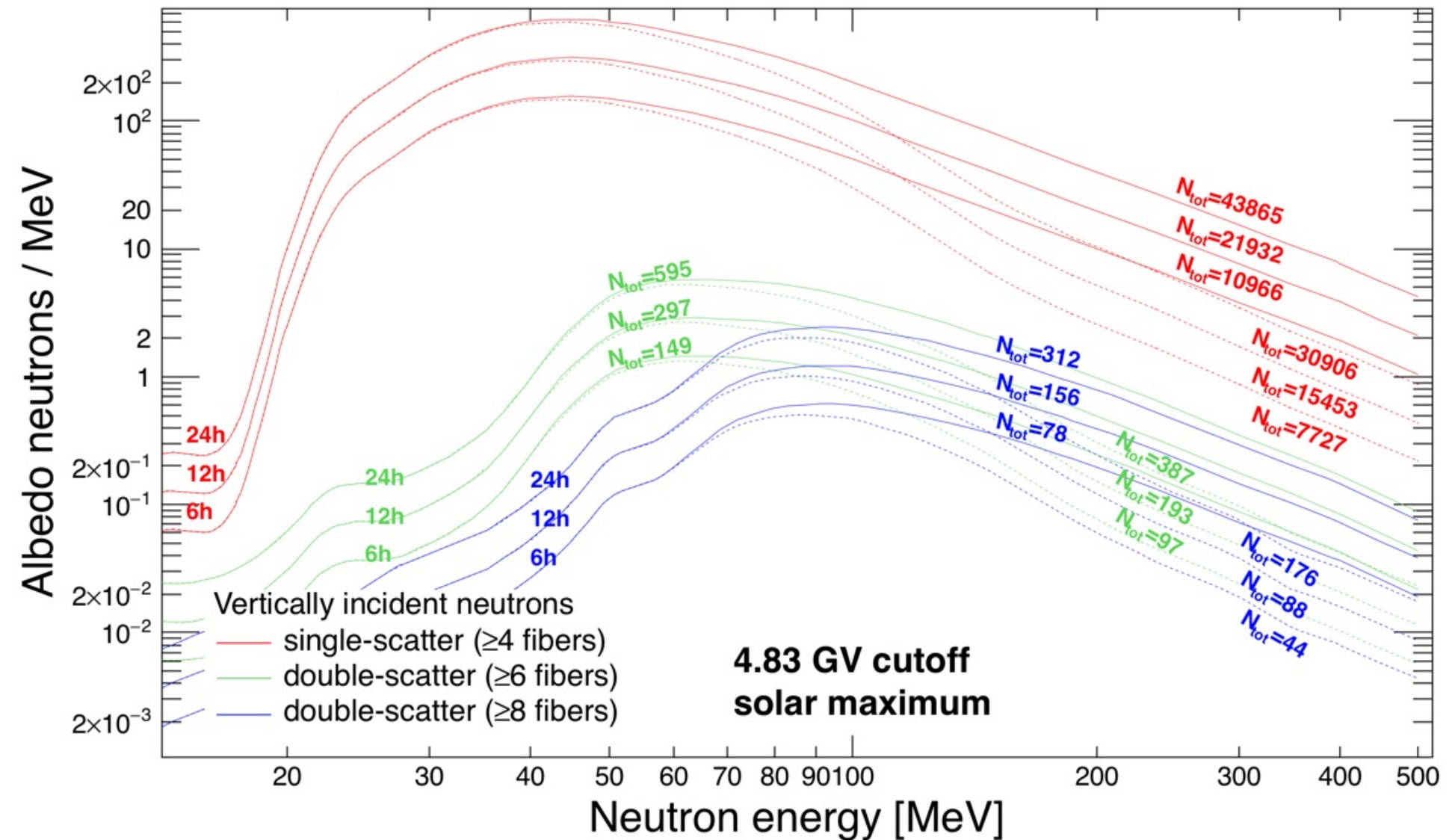
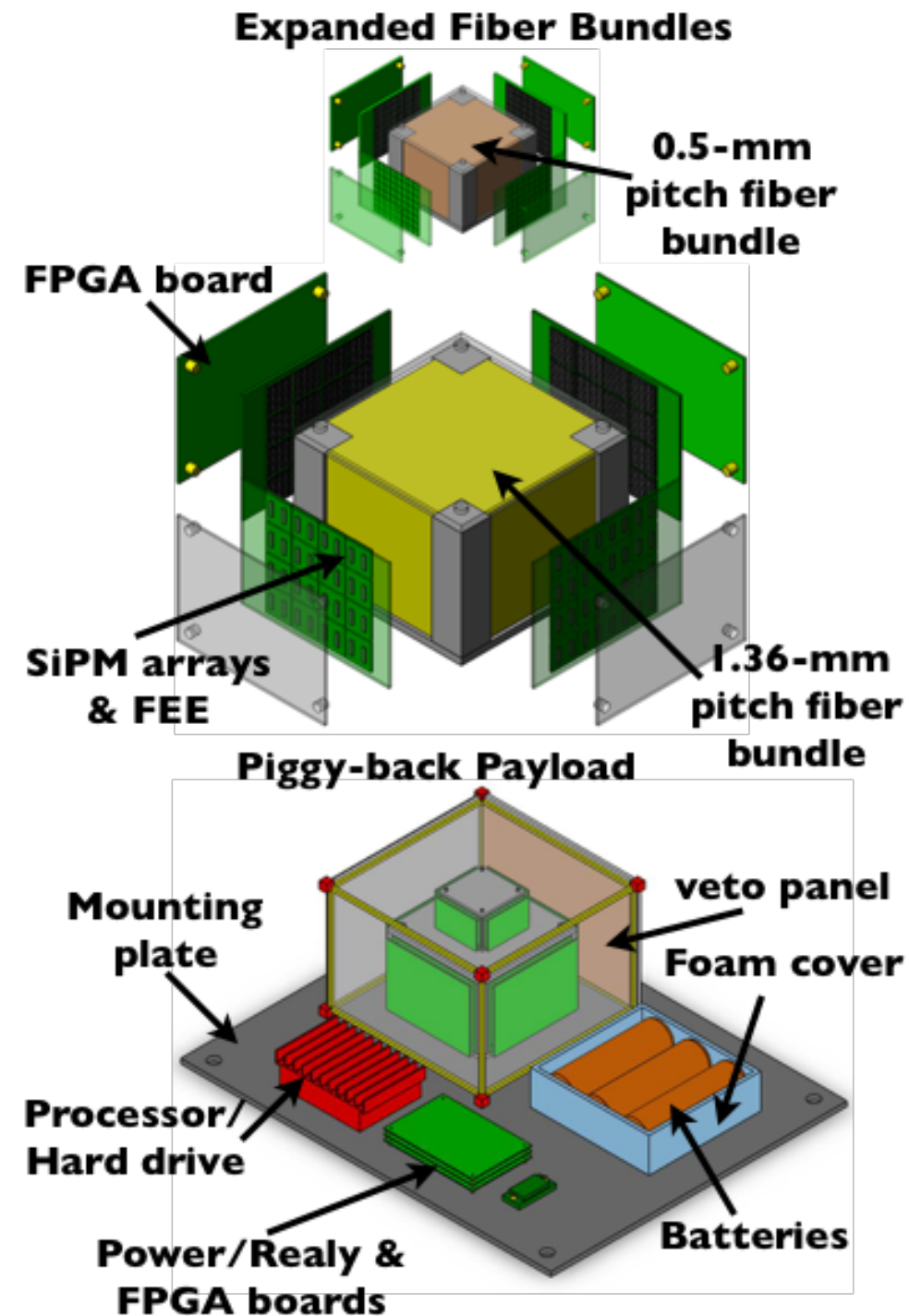


* Considerable benefit by getting closer to the Sun

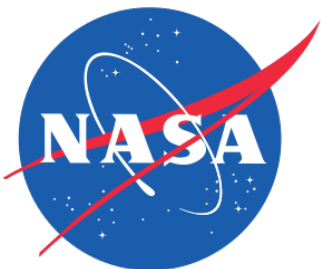
* Neutron half life $\sim 15 \text{ min}$



Raising the TRL for SONTRAC : High-Altitude Balloon Flight



proposal pending



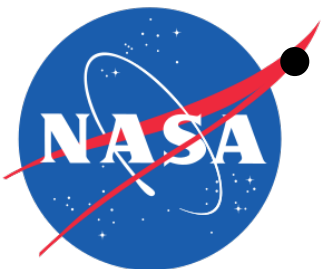
Summary/Future Work

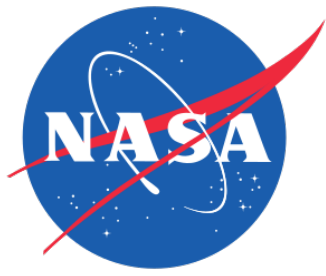
- Demonstrates sensitivity to minimum ionizing particles with good energy threshold
- Beam test November 2021
 - examine energy and angular resolution (SM-1 was promising with 10% energy res. ; 5° @ 50 MeV)
- Compare to Geant4 simulations & optimize design

Future work

- Investigate new readout, smaller pitch SiPM arrays ($\sim 500\mu\text{m}$), optimized design

Beam test in spring 2023





Q&A

Acronyms

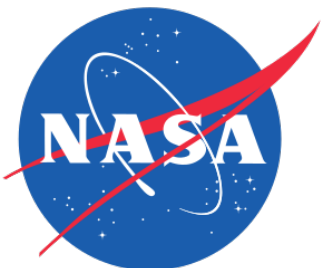
ASIC – Application Specific Integrated Circuit

FPGA – Field Programmable Gate Array

PCB – Printed circuit board

SiPM – Silicon Photomultiplier

SONTRAC – SOLar Neutron TRACking



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

