60th Winter Nuclear and Particle Physics Conference (WNPPC 2023)

Developing The Detector Array For Energy Measurements Of Neutrons (DAEMON)

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TRIUMF

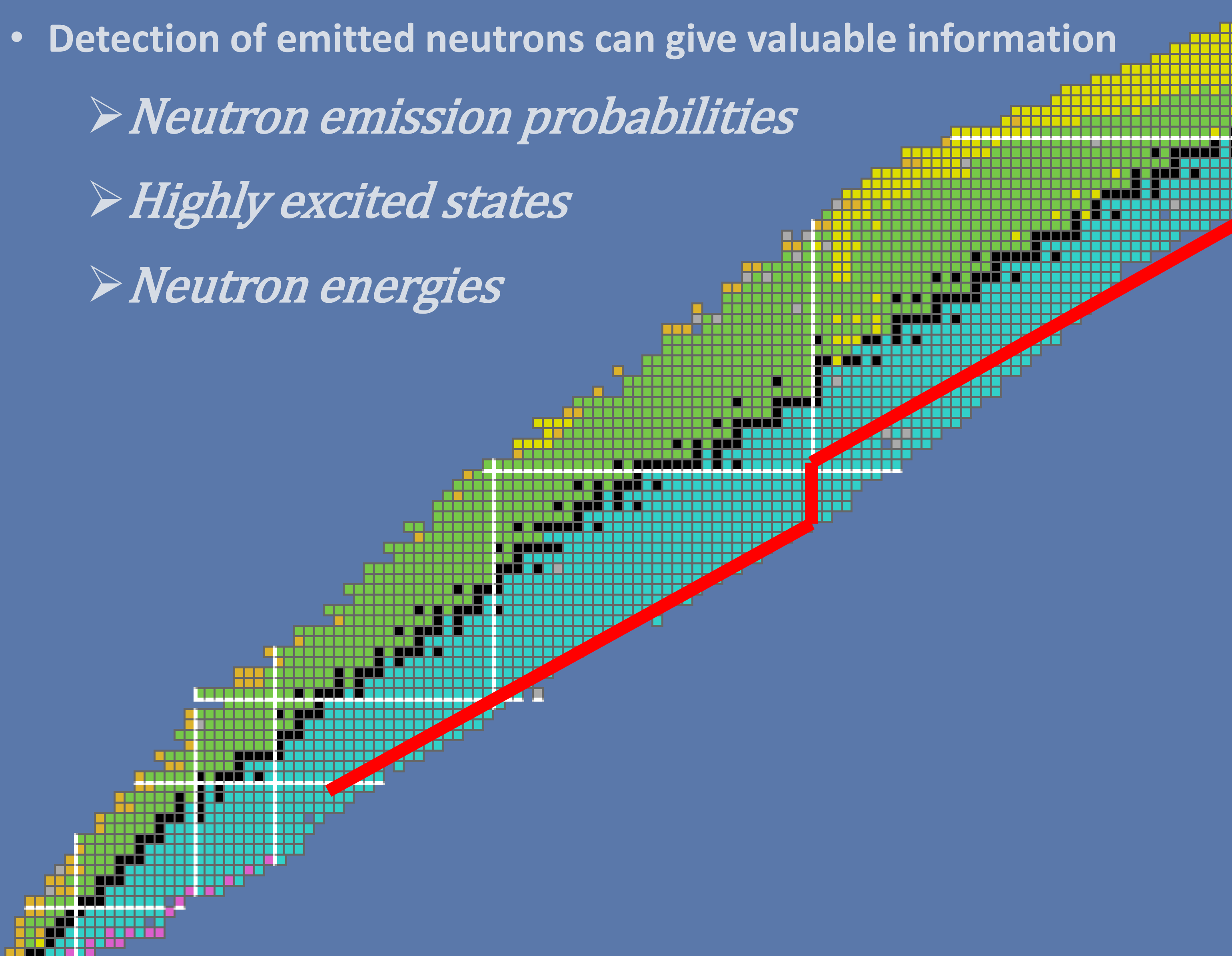
NSERC CRSNG

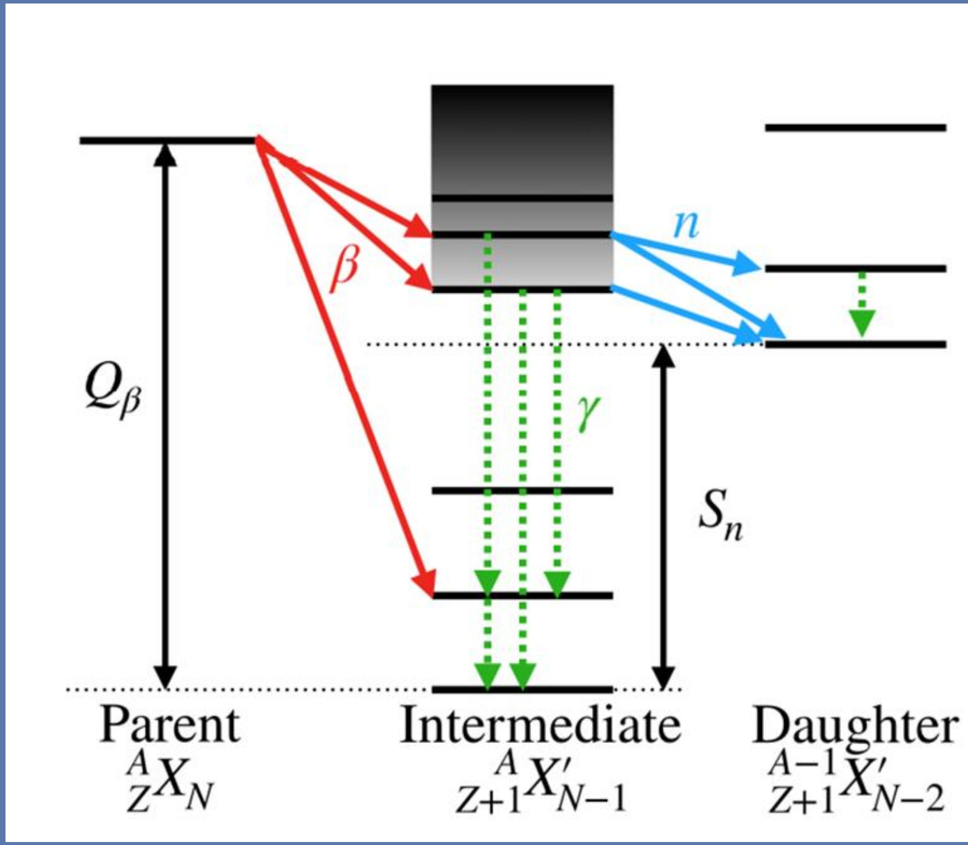
CINP ICPN Canadian Institute of Nuclear Physics
Institut canadien de physique nucléaire

UNIVERSITY of GUELPH

Beta-delayed neutron emission, βn

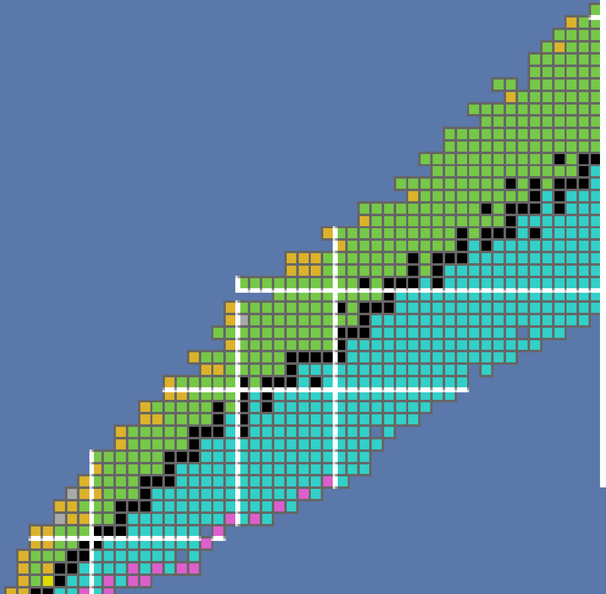
- Can occur directly following β-decay ($n \rightarrow p + e^- + \bar{\nu}$) if $Q_\beta > S_n$
- Detection of emitted neutrons can give valuable information
  - *Neutron emission probabilities*
  - *Highly excited states*
  - *Neutron energies*

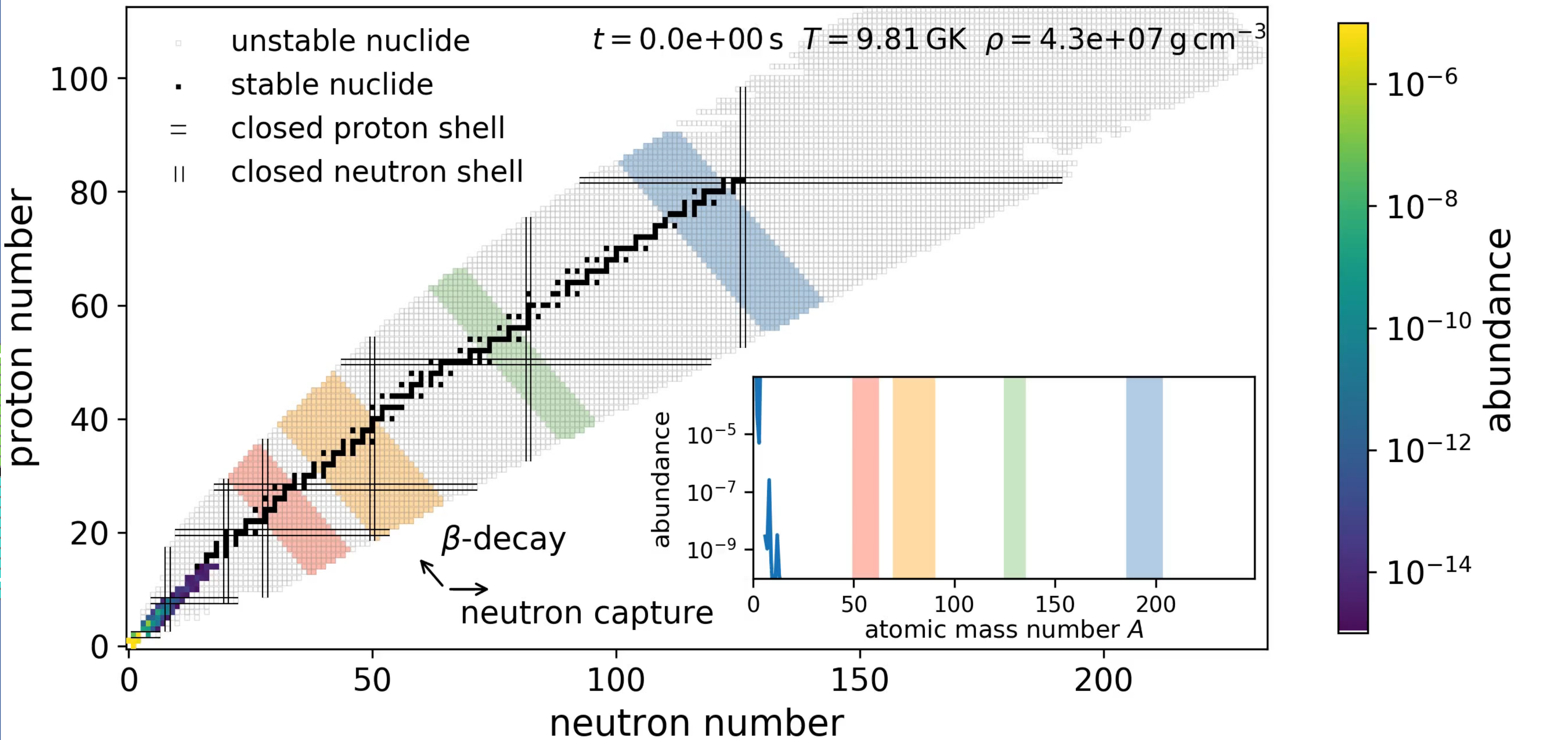




Why study βn emission?

- **Shaping abundance curve for astrophysical r-process**
- **Controlling fission in nuclear reactors**
- **Nuclear structure**





Siegel, D. M. (2022). r-Process nucleosynthesis in gravitational-wave and other explosive astrophysical events. *Nature Reviews Physics*, *4*(5), 306-318.

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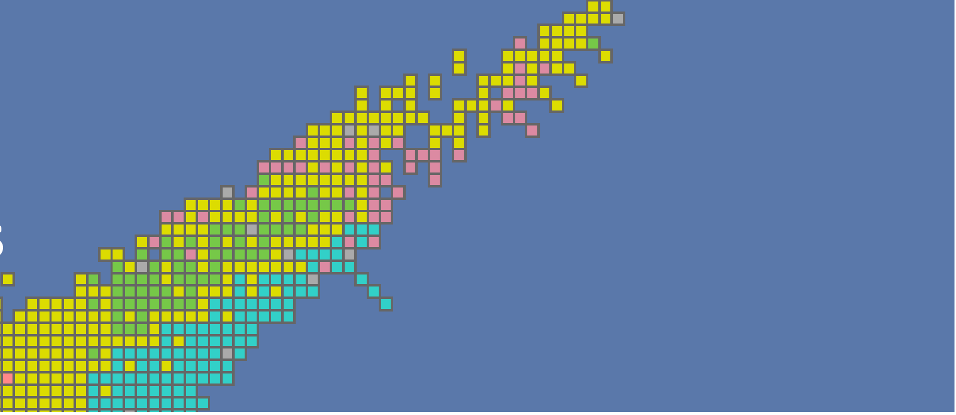

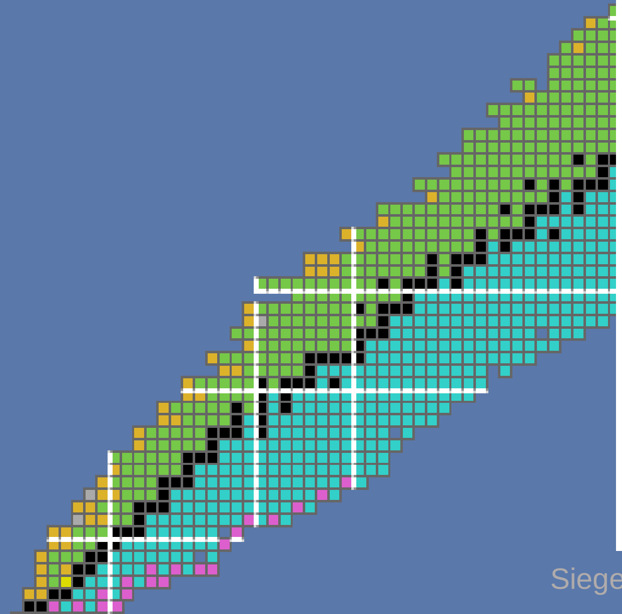

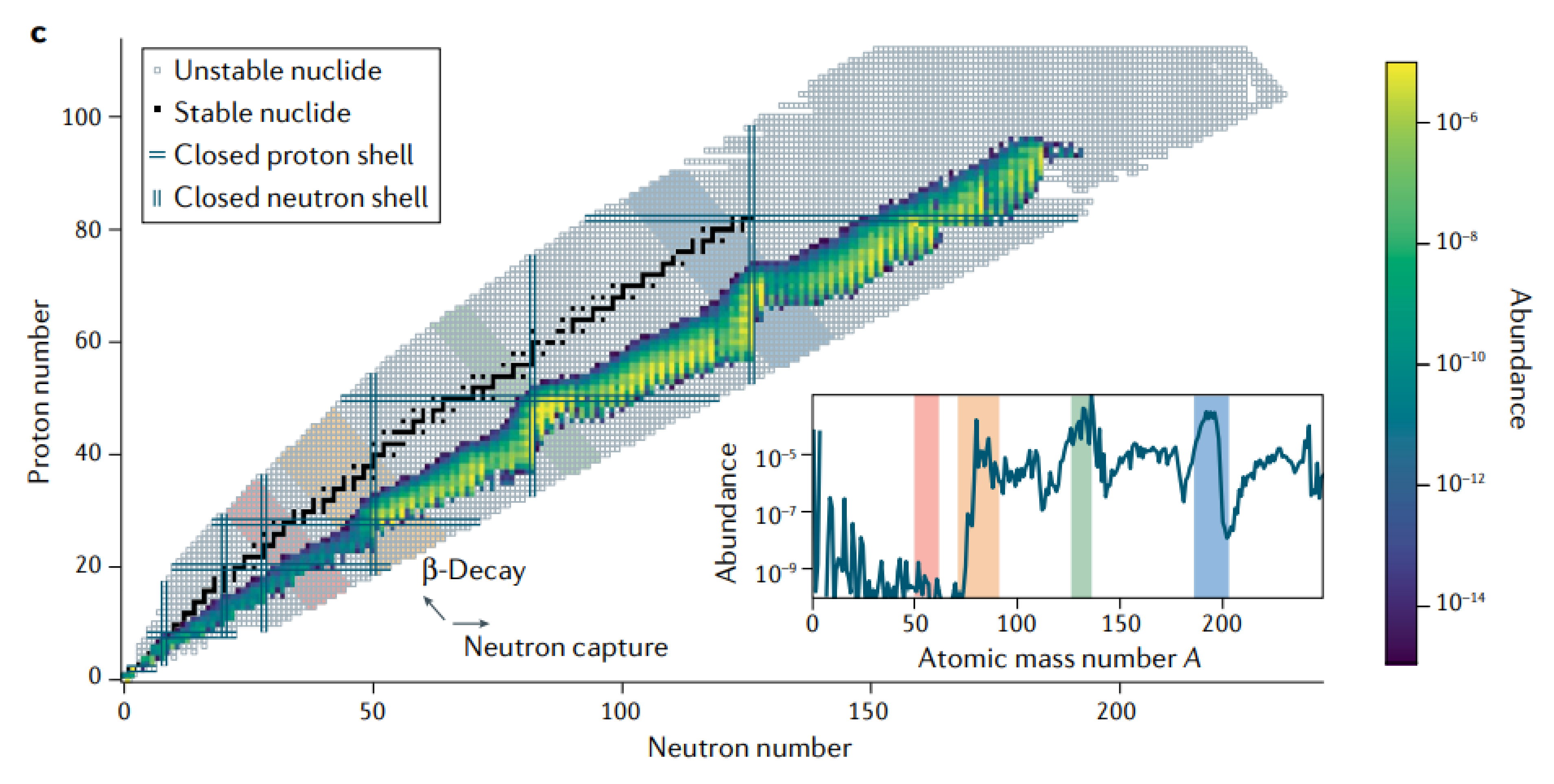

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Time-Of-Flight (TOF) Technique

- Measure neutron energies following $\boldsymbol{\beta n}$ emission

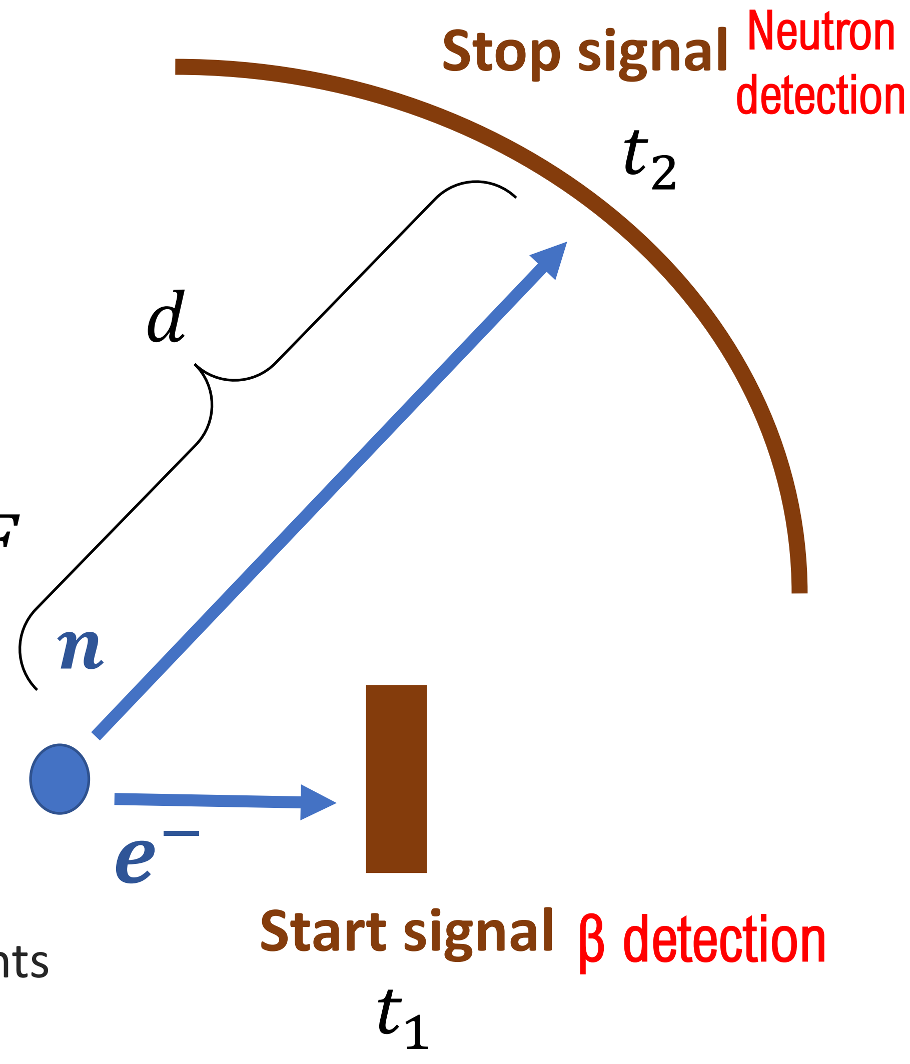
$$E_n = \frac{1}{2}mv^2 = \frac{1}{2}m\frac{d^2}{TOF^2}$$

  - d, known flight path
  - $TOF = t_2 - t_1$, time difference between two detectors

- Energy resolution dependent on flight d and TOF

$$\frac{\delta E_n}{E_n} = 2\sqrt{\left(\frac{\delta t}{TOF}\right)^2 + \left(\frac{\delta d}{d}\right)^2}$$

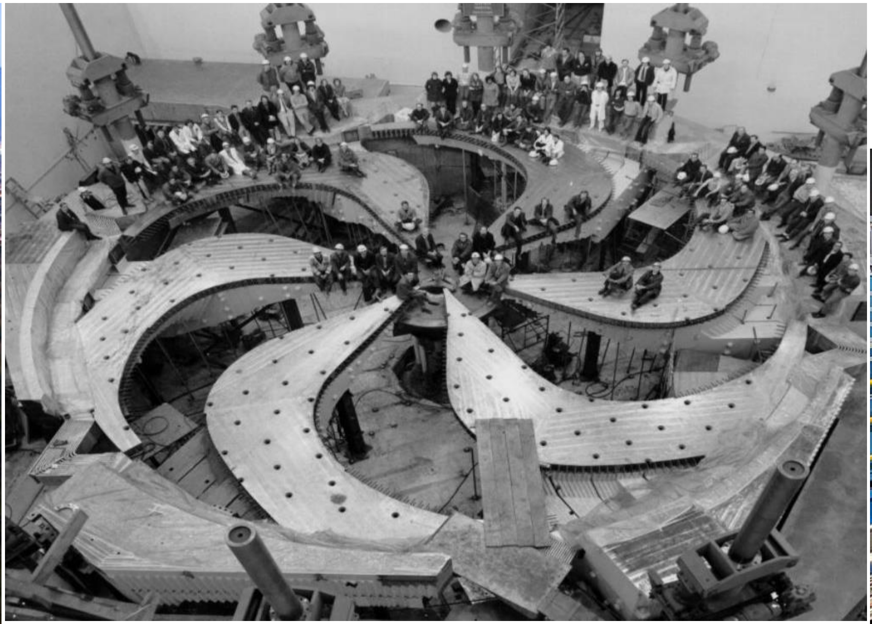
- δd, detector thickness — Reduced by — thin detectors
- δt, time resolution of electronics — Reduced by — Fast components



TRIUMF

Canada's particle accelerator centre
Centre canadien d'accélération des particules

Vancouver, BC



GRIFFIN
Decay Station

Isotope Separator and Accelerator (ISAC) facility

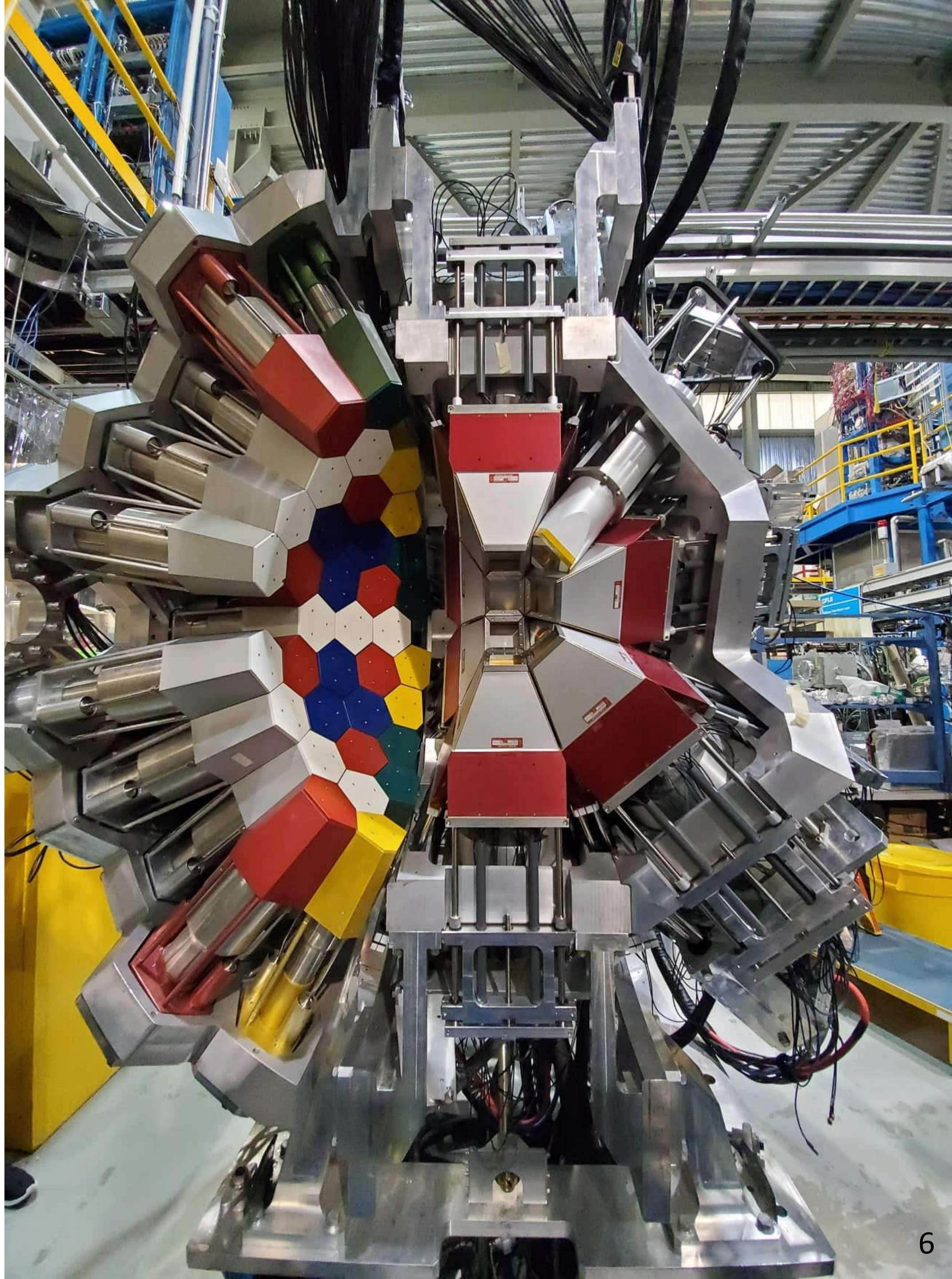
GRIFFIN Decay Station:

- High efficiency γ-ray spectrometer

- Ancillary detectors:
  - **Z**ero **D**egree **S**cintillator (**ZDS**)
  - **D**euterated **S**cintillator **A**rray for **N**eutron **T**agging (**DESCANT**)

- High detection efficiency of neutrons

- Poor resolution for measuring neutron energies (15cm scintillator depth)



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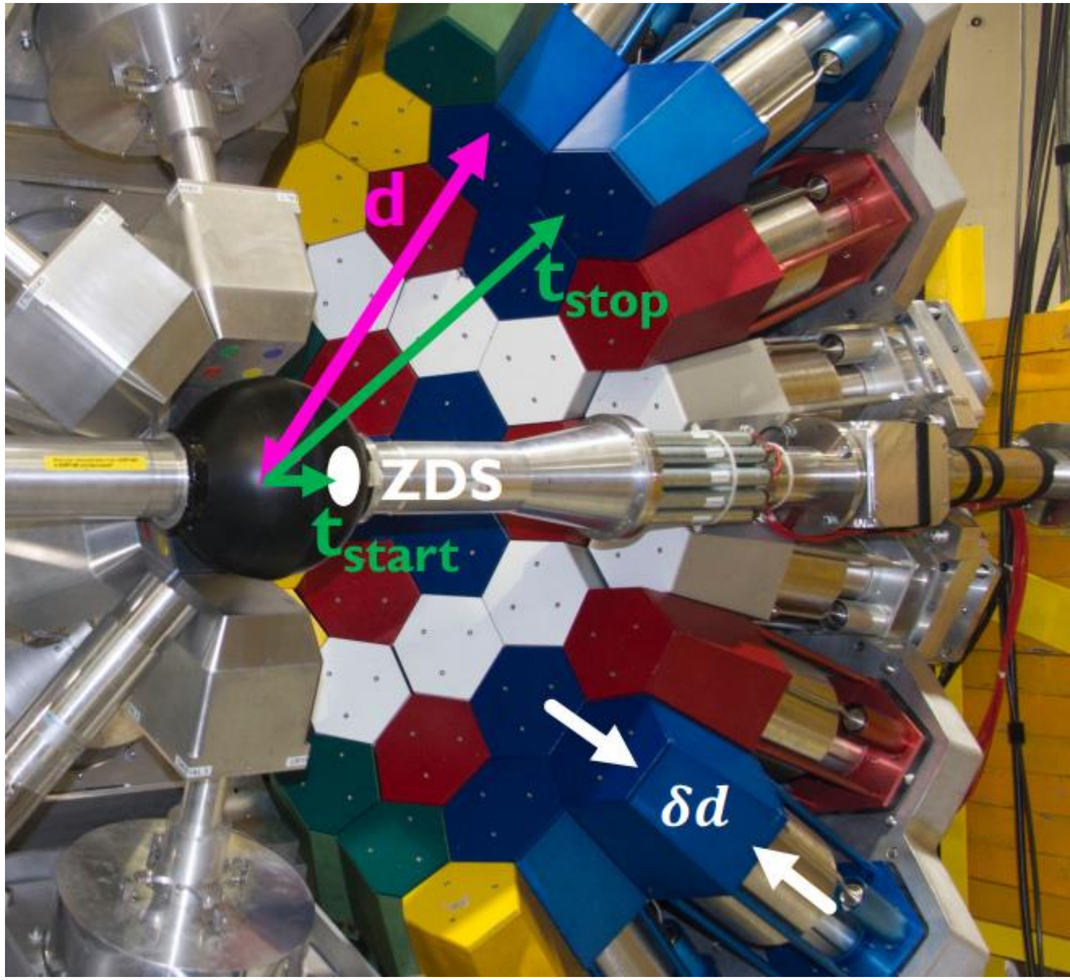
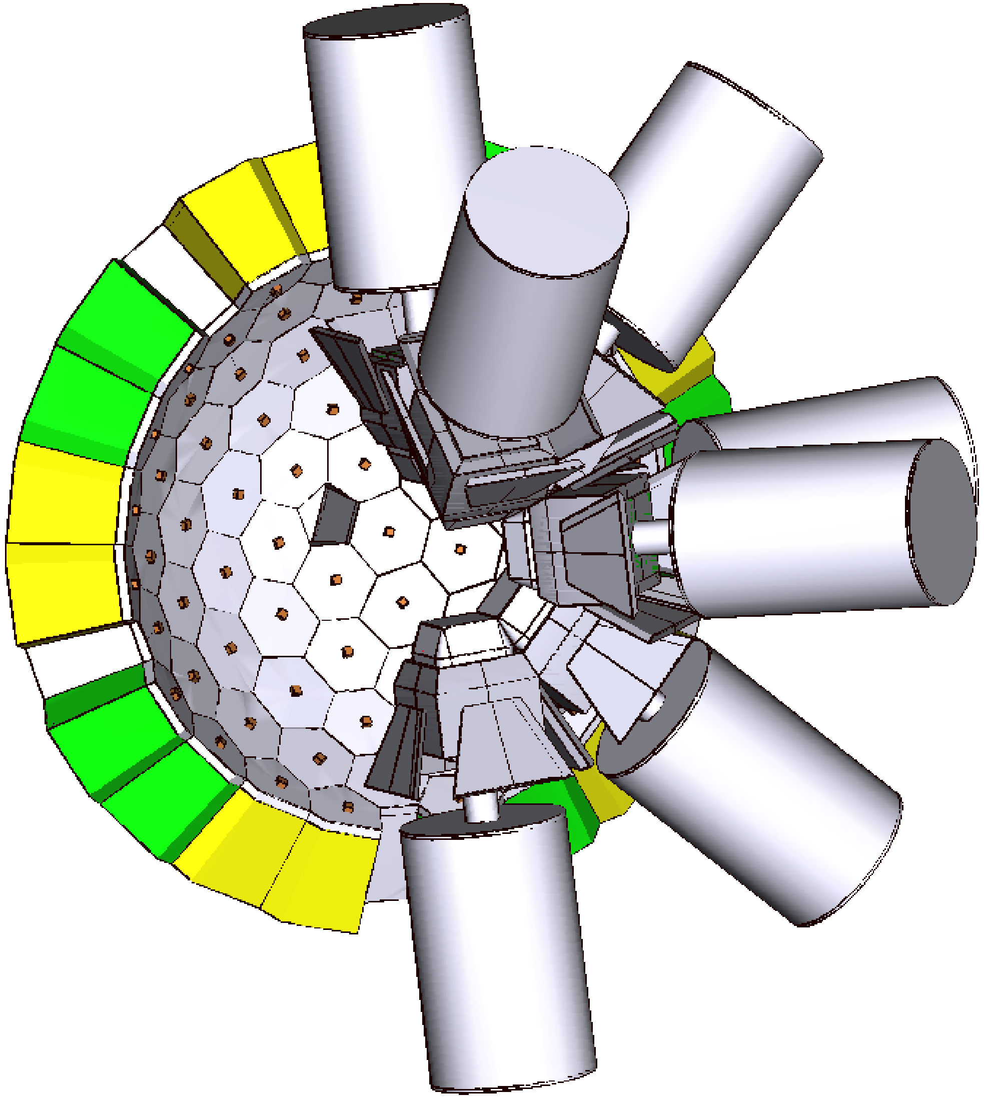
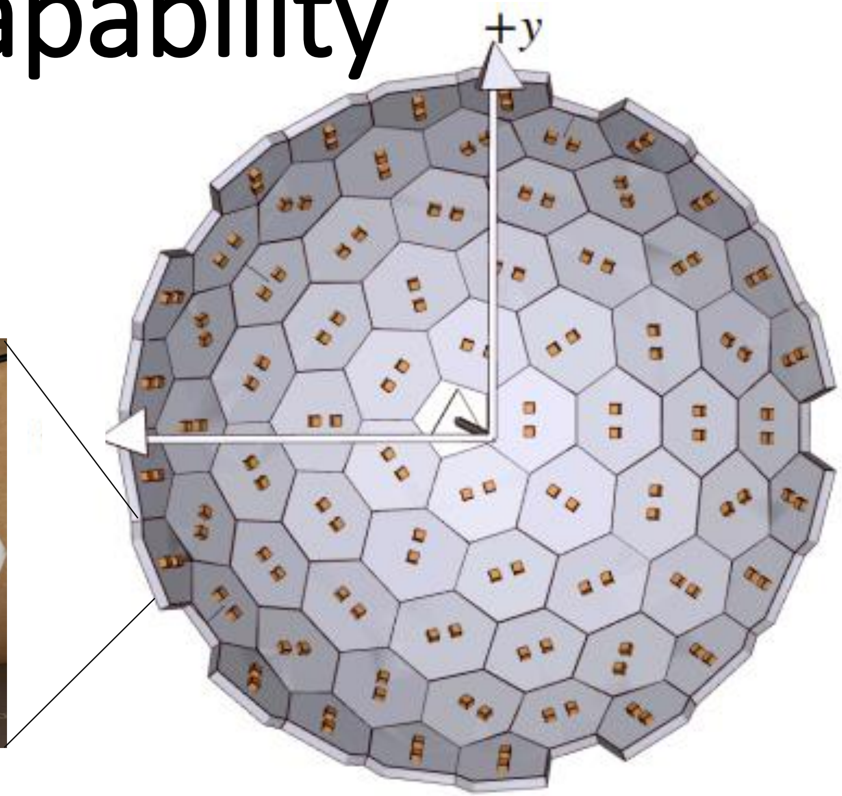


$$\frac{\delta E_n}{E_n} = 2\sqrt{\left(\frac{\delta t}{TOF}\right)^2 + \left(\frac{\delta d}{d}\right)^2}$$

Building a powerful all-in-one capability

for broad investigation of neutron-rich species





DAEMON - Detector Array for Energy Measurement of Neutrons

Improved energy resolution
($\delta d \sim 15\text{cm}$ vs $\delta d \sim 1.5\text{cm}$)

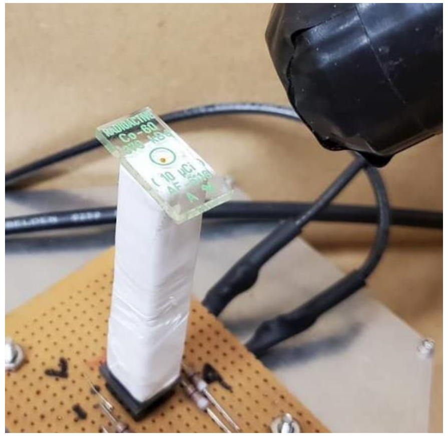
DAEMON Components

PLASTIC SCINTILLATOR

- ✓Well-suited for fast-timing measurements
- ✓Large light attenuation length (380 cm)

Eljen EJ-200 plastic scintillator

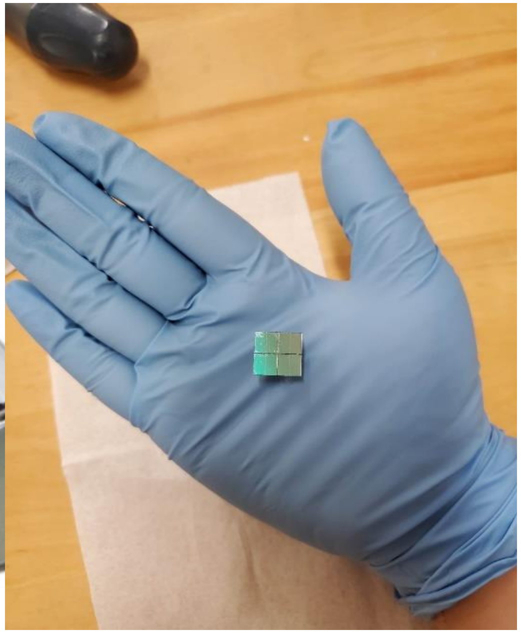
$1cm \times 1cm \times 1cm$



$1cm \times 1cm \times 6cm$

$1.5cm\ thick\ hexagon$

DAEMON Components



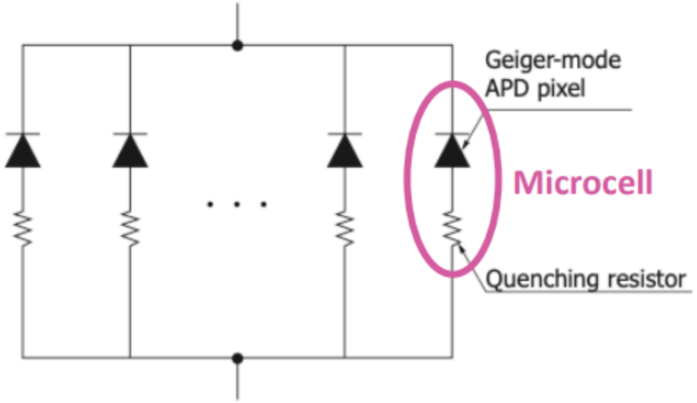
$4mm \times 4mm$ 2x2 array of $6mm \times 6mm$

SCINTILLATION LIGHT COLLECTION

- *Collected light converted to electrical signal and amplified for processing*

Silicon Photomultipliers (SiPM)

- ✓ Alternative to a photomultiplier tube (PMT)
- ✓ Robust, cheaper, less bulky, require relatively small bias voltage (25-50V) compared to PMT that requires 1-2 kV



SensL, 2017

- Dense array of single photon avalanche diodes (SPAD)
- Each microcell operates independently and in Geiger Mode
- Photocurrents from all microcells are summed → instantaneous photon flux

Data Acquisition System (DAQ)

- Analog DAQ → To understand SiPM signals

- Digital DAQ → Customizable parameters

  ➢Generation 1 : **CAEN VX1730 digitizer**

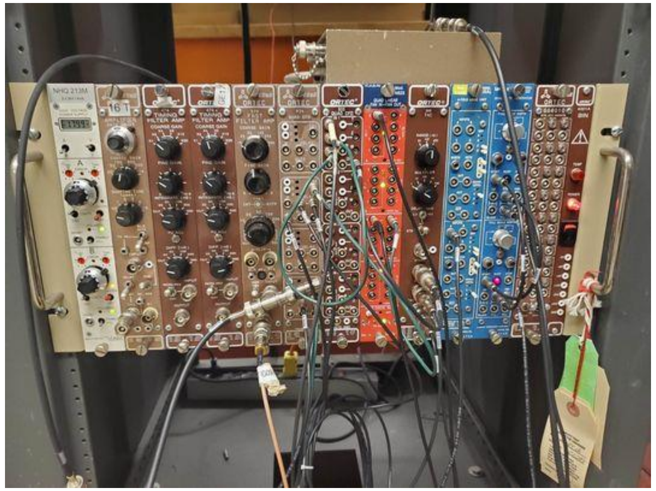
  → Customizable threshold, pulse polarity, has dynamic range and waveform collection option and event selections

  → Each comes with 16 readout channels

  ➢Generation 2: **Application-specific integrated circuit (ASIC)**

  → Currently under investigation

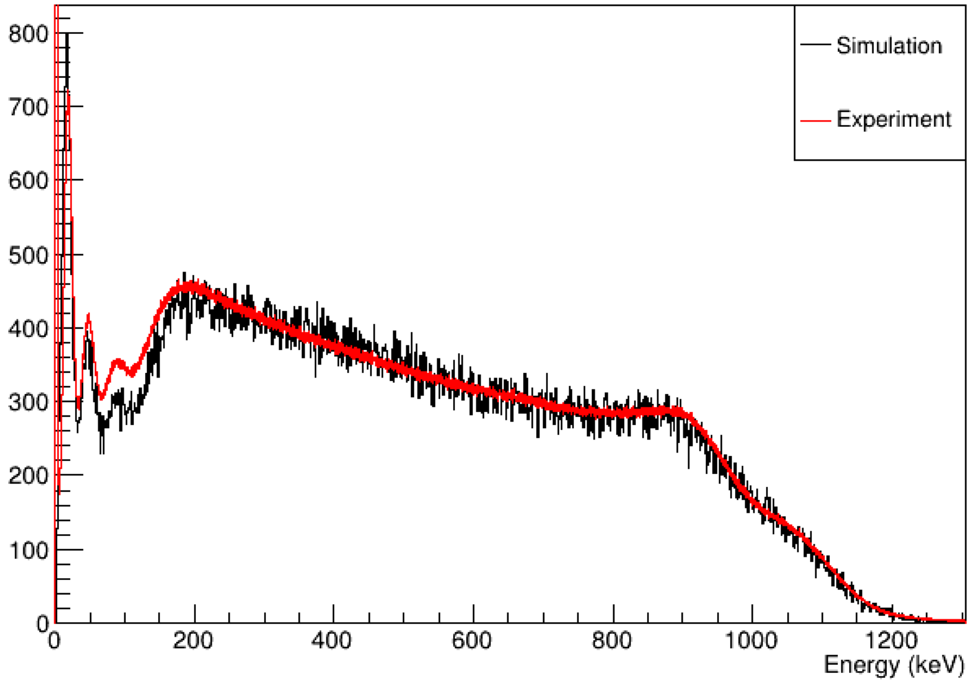
  → Each comes with 64 readout channels

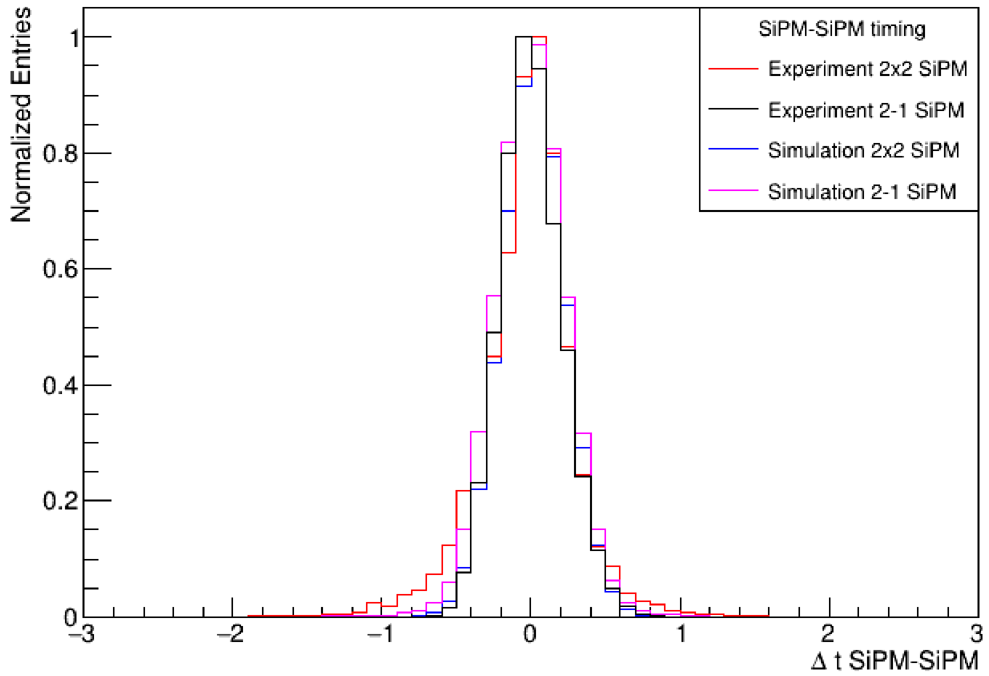


Experimental Comparison

- Simulation [Bidaman, H., PhD dissertation in progress] versus experimental data
    - ➢ Ensure Compton edges align
    - ➢ Anomalies in comparison

- If simulation for a single unit proves successful, we can confidently make simulations of the whole array





CONCLUSION & NEXT STEPS

- First work with SiPM’s as scintillation light collectors by UofG NPG (initial timing resolution measurement as low as 339(4) ps for small scale scintillator-SiPM setup) [Radich, A.J., PhD Dissertation]

- Intensive complementary investigation of experimental and simulations

- On-going & future multi-pixel SiPM and ASIC data acquisition system

- No neutrons were hurt in this work (Unfortunately). Tests with monoenergetic neutron beam

- Introducing powerful capability at TRIUMF-ISAC enabling high-resolution energy measurement of neutrons via TOF, while simultaneously, with DESCANT providing a high efficiency device to tagging on the neutrons (& unsurpassed γ-ray detection efficiency with GRIFFIN)

THANK YOU

University of Guelph

Paul Garrett

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Allison Radich

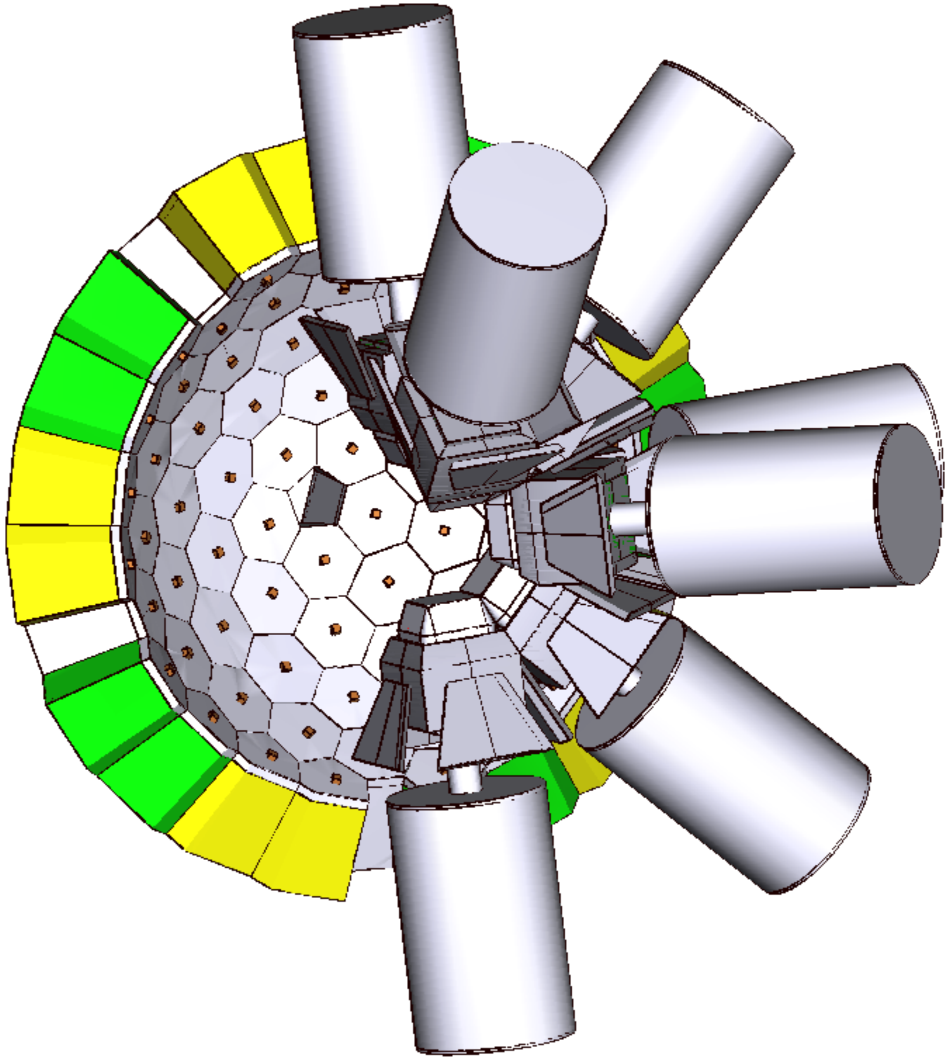
Konstantin Mastakov

Harris Bidaman

TRIUMF

Iris Dillmann

Adam Garnsworthy



BACK-UP SLIDES

Reactor Physics

- **Requires extensive knowledge of decay properties of fission nuclei, which are particularly neutron-rich.**
  - Improved accuracy of delayed neutron yields
  - Energy resolution of neutron spectra

- **Additional neutron induced fission can occur from some neutron-rich fission products undergoing βn emission.**

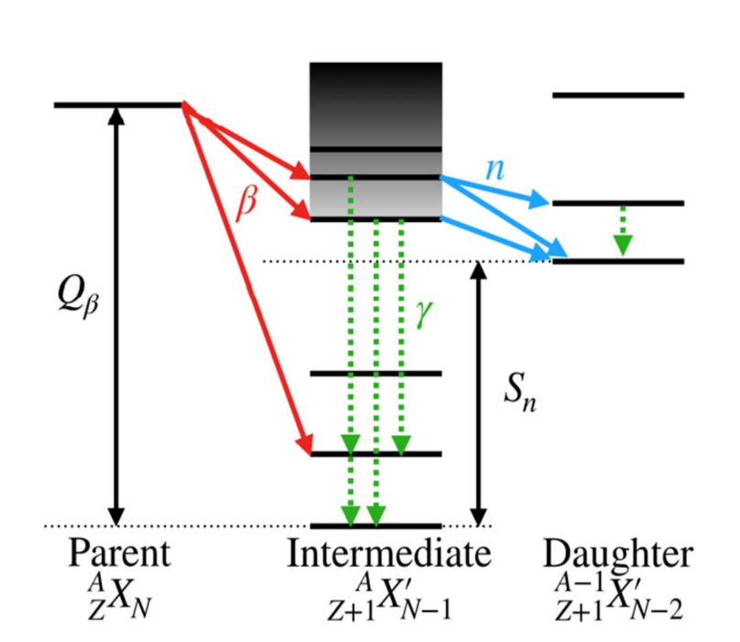
- **Current experimental libraries lack delayed neutron data which are needed for determining decay heat emitted by fission products via β or γ-rays (half-lives, βn abundances & neutron emission probabilities)**

- **Experimental work at RIB facilities is anticipated to provide data on neutron-rich isotopes that can improve reactor calculations leading to improved design, safety & sustainability.**

$\boldsymbol{\beta}$-decay strength function & neutron-rich nuclei

$$T_{1/2}^{-1} = \sum_{E_i \geq Q_\beta}^{E_i \leq Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i)$$

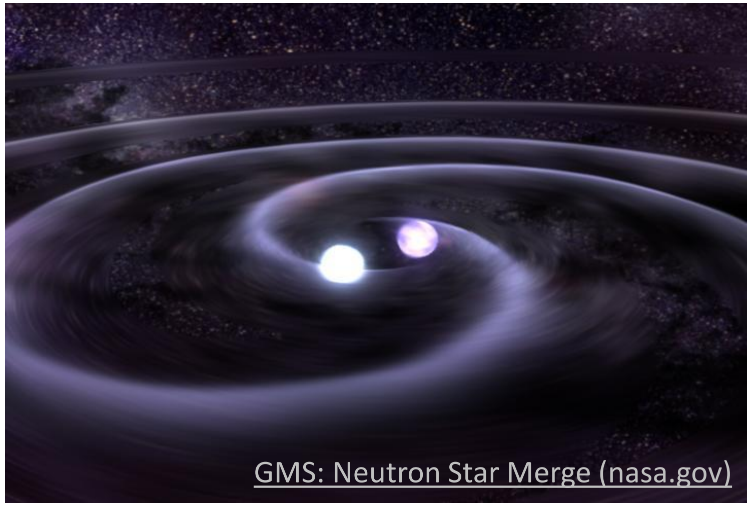
- Gamow-Teller (GT) transitions dominate β strength distribution $S_\beta(E_i)$ for neutron-rich nuclei
- $B(GT)$ within Q_β value has direct influence of β decay half-life
- Theoretical models have high success in $B(GT)$ calculations in limited areas
- Neutron spectroscopy will allow deriving $B(GT)$ for neutron-unbound states
    - Evidence of single-particle states influencing $B(GT)$ (M. Madurga et al. 2016)



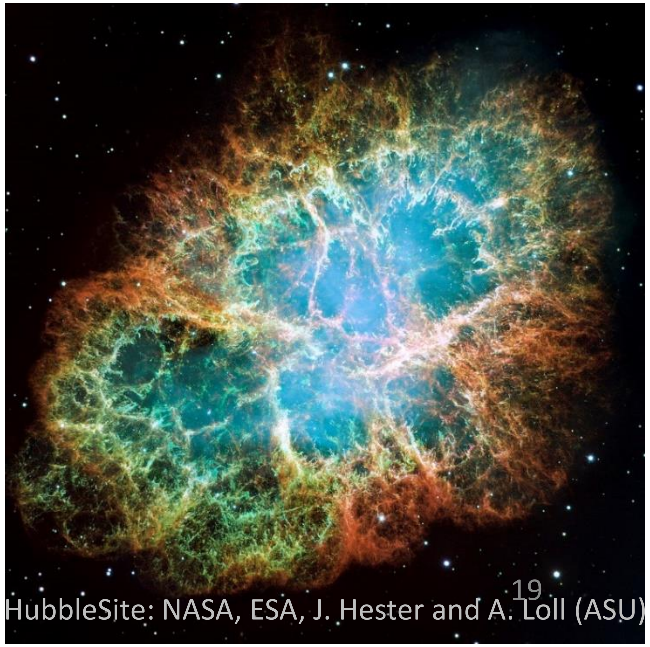
GW170817 – observation of first neutron star merger (2015)

"for decisive contributions to the LIGO detector and the observation of gravitational waves" 2017 Nobel Prize in Physics

Credit: LIGO



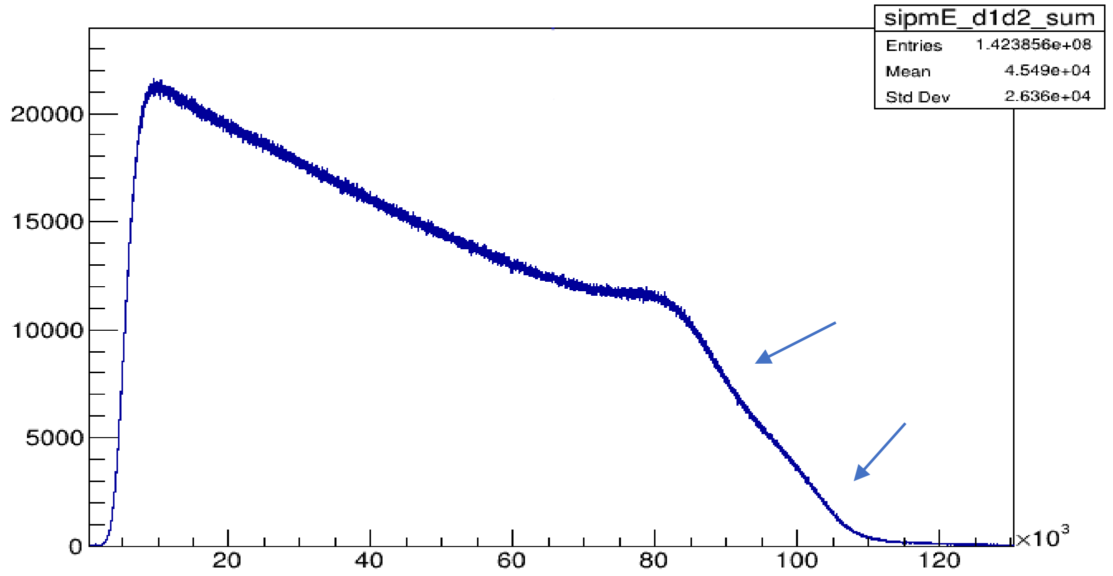
GMS: Neutron Star Merge (nasa.gov)

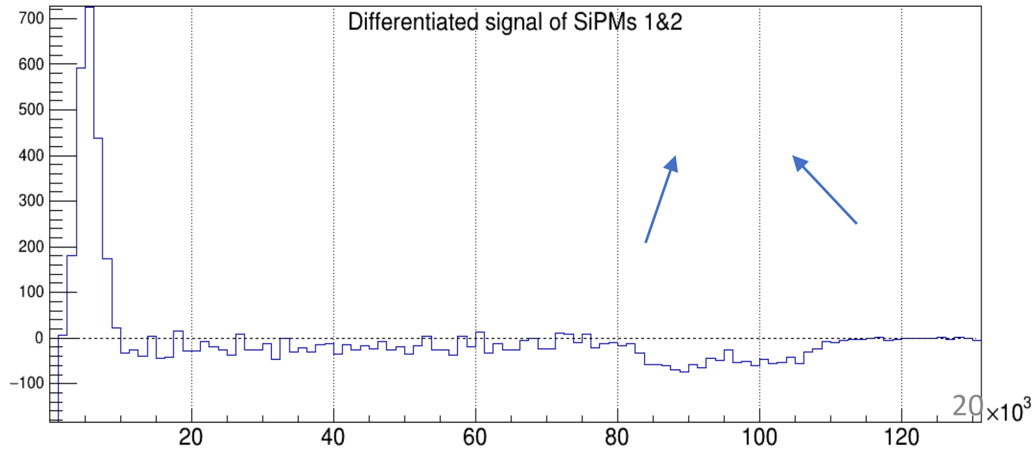


HubbleSite: NASA, ESA, J. Hester and A. Loll (ASU)

DAEMON Experimental Testing

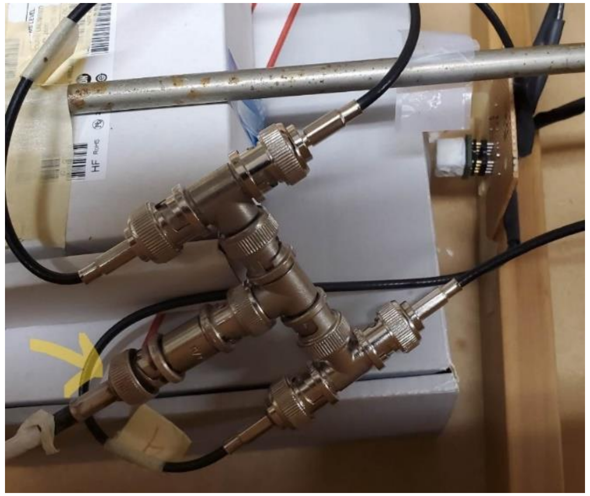
- Single SiPM with analog and digital DAQ (Radich, A.J., Phd Dissertation)
- 2x2 SiPM array
  - ➢ZDS-SiPM Coincidence Timing Resolution
  - ➢SiPM Energy Measures – γ sources
  - ➢**Energy calibration with γ sources**
  - ➢Low energy threshold measurement
  - ➢Summing at software & hardware level



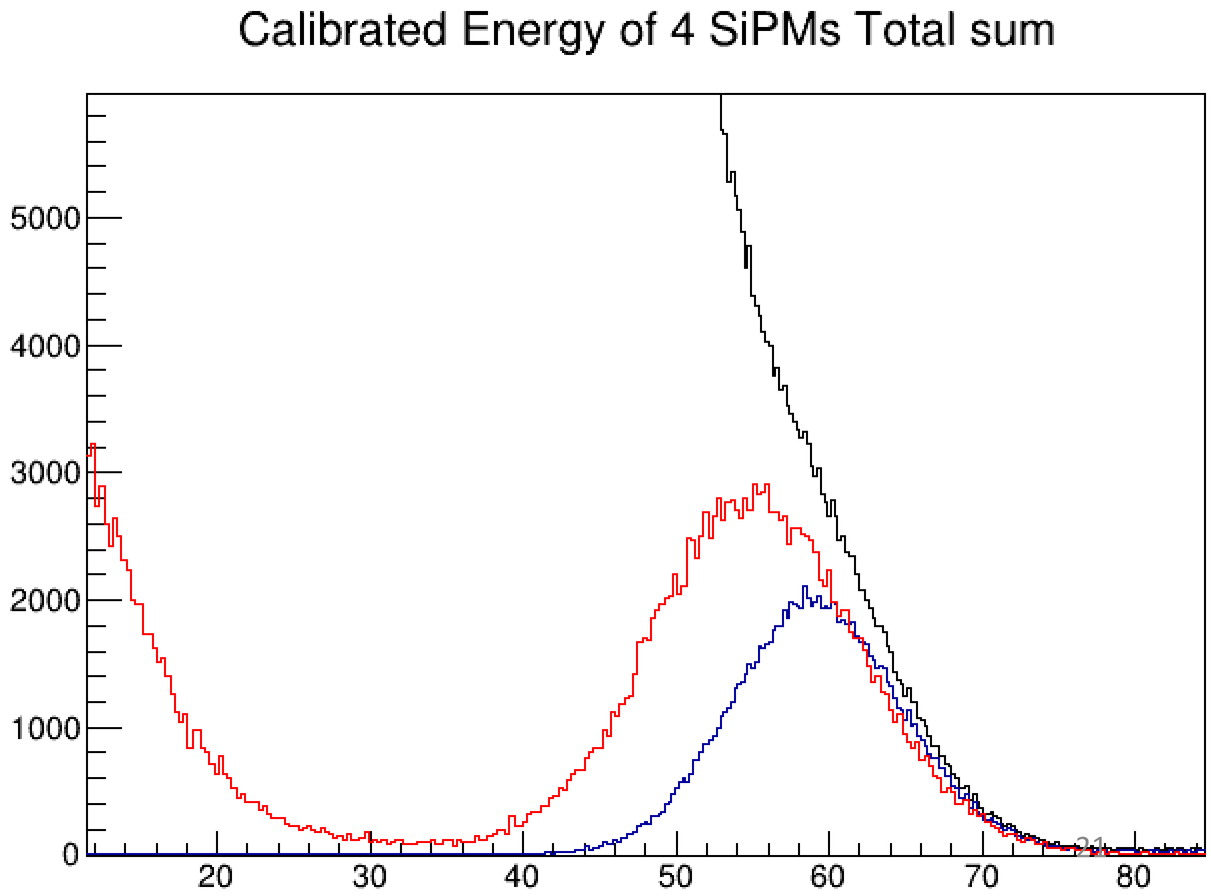


Threshold Tests

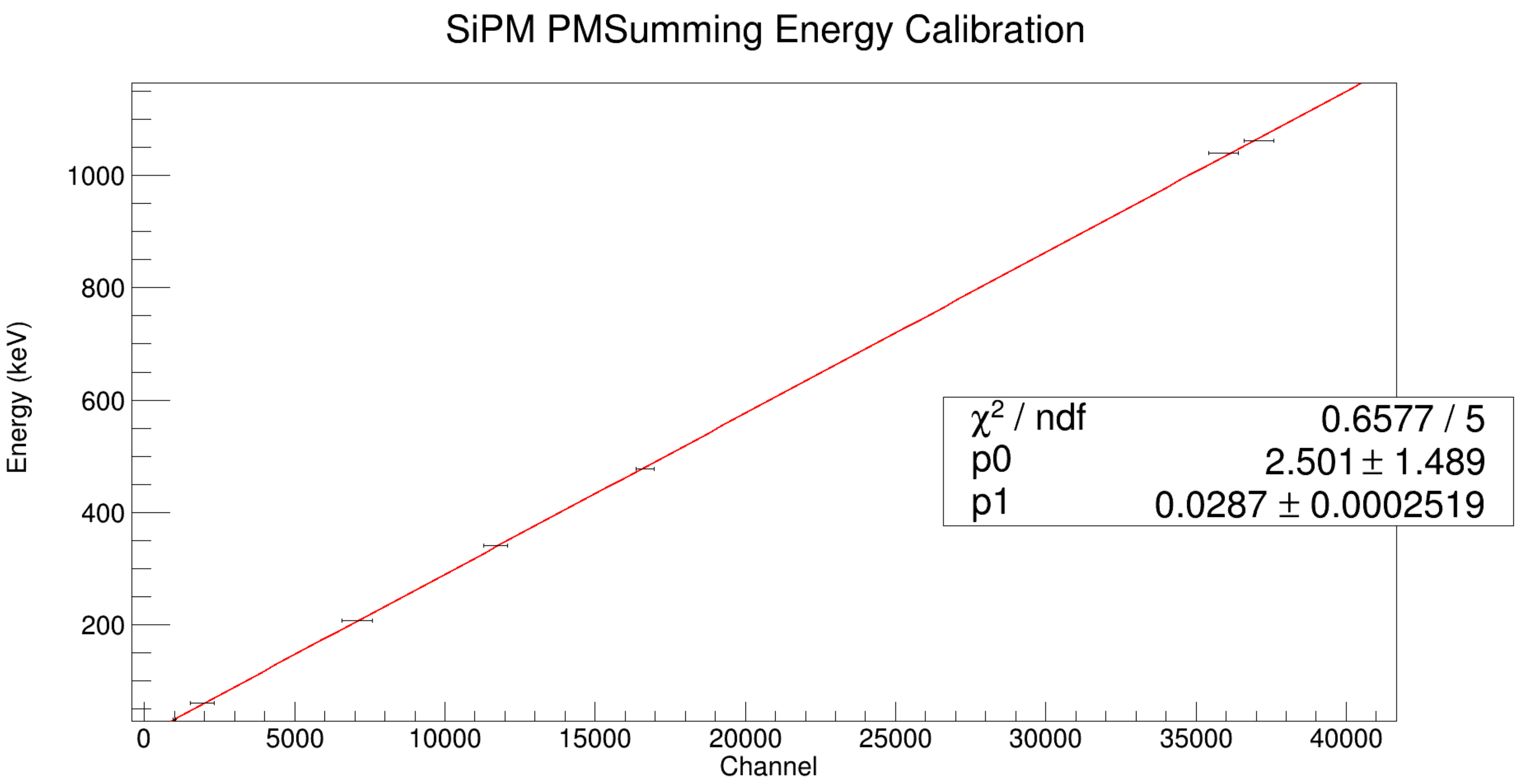
“Poor man’s summing” at hardware level



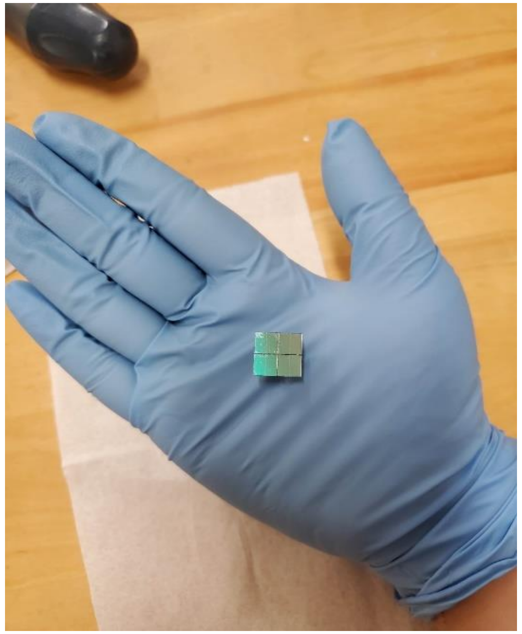
- ➢Reduced noise/event rate allowed to go low threshold settings
- ➢Reduces cost of electronic channels by a factor of 4
- ➢Impedance mismatch – need to test on industrial summing boards



“Poor-man’s summing” Calibration



$4mm \times 4mm$



2x2 array of $6mm \times 6mm$

Gain	$\sim 1 \times 10^6$	$> 1 \times 10^6$
“Efficiency”	~25% QE	~25-50% PDE
Bias voltage	1 – 2 kV	25 - 50 V
Rise time	0.7 ns	0.09 – 0.11 ns

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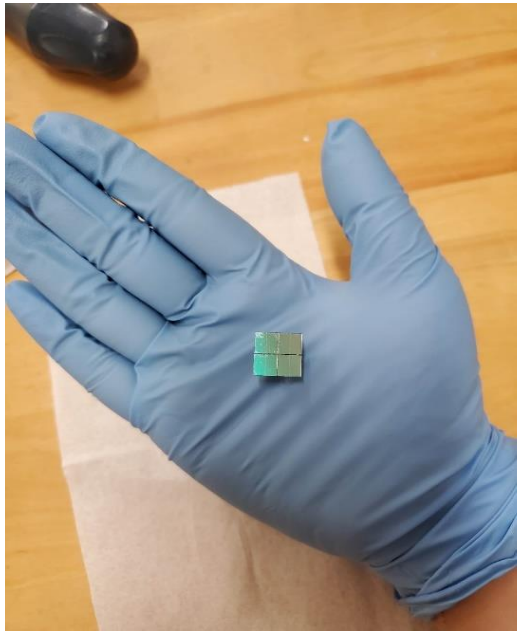

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<u>Detector Array for Energy Measurements of Neutrons (DAEMON)</u>

EJ200 plastic scintillators (various geometries under test)

Has a proven fast time response

Can be machined into complex shapes

+

SiPMs –Silicon Photomultipliers (various arrays under testing)

Compact, inexpensive, requires low bias voltage

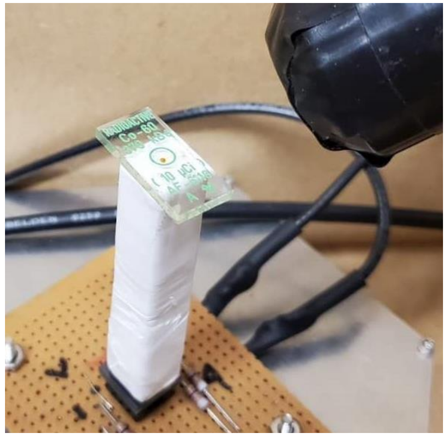
<u>Zero Degree Scintillator (ZDS)</u>

1 mm plastic scintillator (BC422Q)

+

photomultiplier assembly (Hamamatsu H6533)

$\mathbf{1cm \times 1cm \times 1cm}$

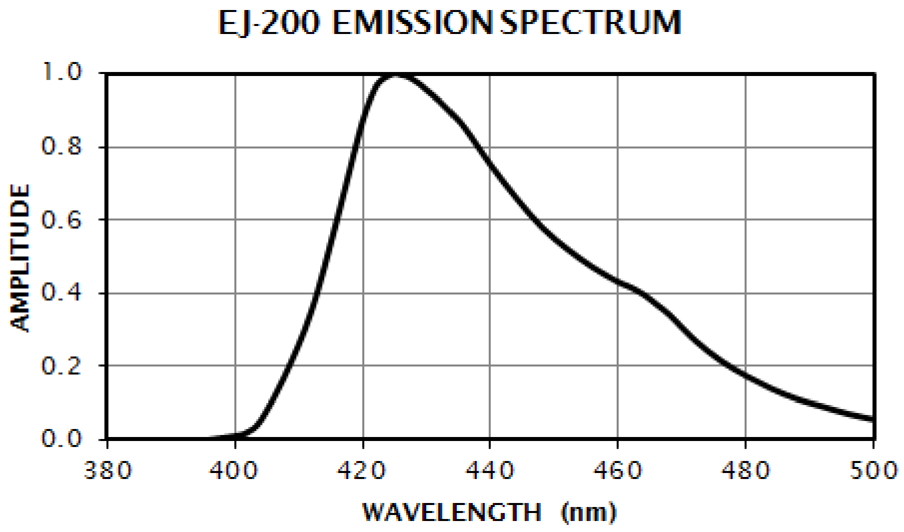


$\mathbf{1cm \times 1cm \times 6cm}$

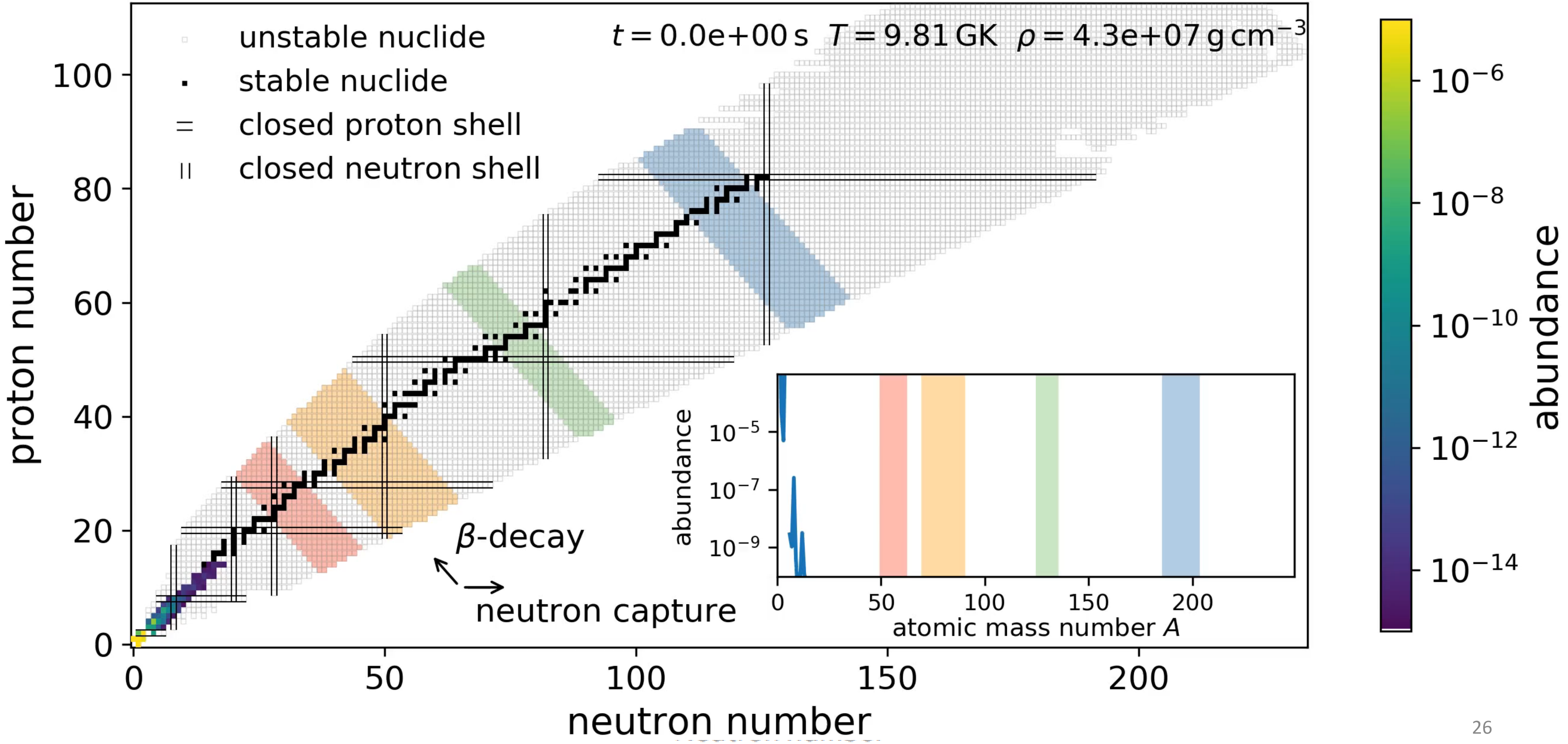
$\mathbf{1.5cm\ thick\ hexagon}$

Eljen EJ-200 plastic scintillator

- Scintillation emission wavelengths in the violet-indigo visible region
- Well-suited for fast-timing measurements
- Sensitive to X-rays, γ rays, charged particles and fast neutrons
- Can be machined to different shapes and sizes
- Large light attenuation length (380 cm)
- For critical operating requirements such as high sensitivity and signal uniformity



Rapid Neutron-Capture Process



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