The UMD/NIST Fast Neutron Spectrometers

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Outline

- Fast neutrons for low-background science
  - At sea-level
  - Underground
- Previous detection techniques
- *Capture gated spectroscopy*
- The FaNS detectors
  - FaNS-1: The proof-of-principle
  - FaNS-2: The purpose-built detector
- Outlook for FaNS

Fast Neutrons for Low-Background Physics

Fast Neutrons for Low Background Science

- Fast neutrons play a particularly problematic role in low background experiments
- Deeply penetrating, and difficult to shield
- Surface → Activation of shielding and detector materials
    - *Backgrounds for experiments that must run sea-level*
- Underground → FNs are indistinguishable from WIMP dark matter interactions
- *Important to know the fast neutron spectra in both environments for experiment design and background rejection*

Sea-level Cosmogenic Neutrons

- Very high energy neutrons are created in cosmic ray air showers
- Low background materials are required for many experiments, especially (Ge, Pb, Cu)
- Determination of material activation requires precision knowledge of neutron flux and spectrum
- Large variations among measurements and simulations
- Large fluctuations with local environment and conditions

Gordon et al. (2004)
FN Spectrum with 14 Bonner Spheres

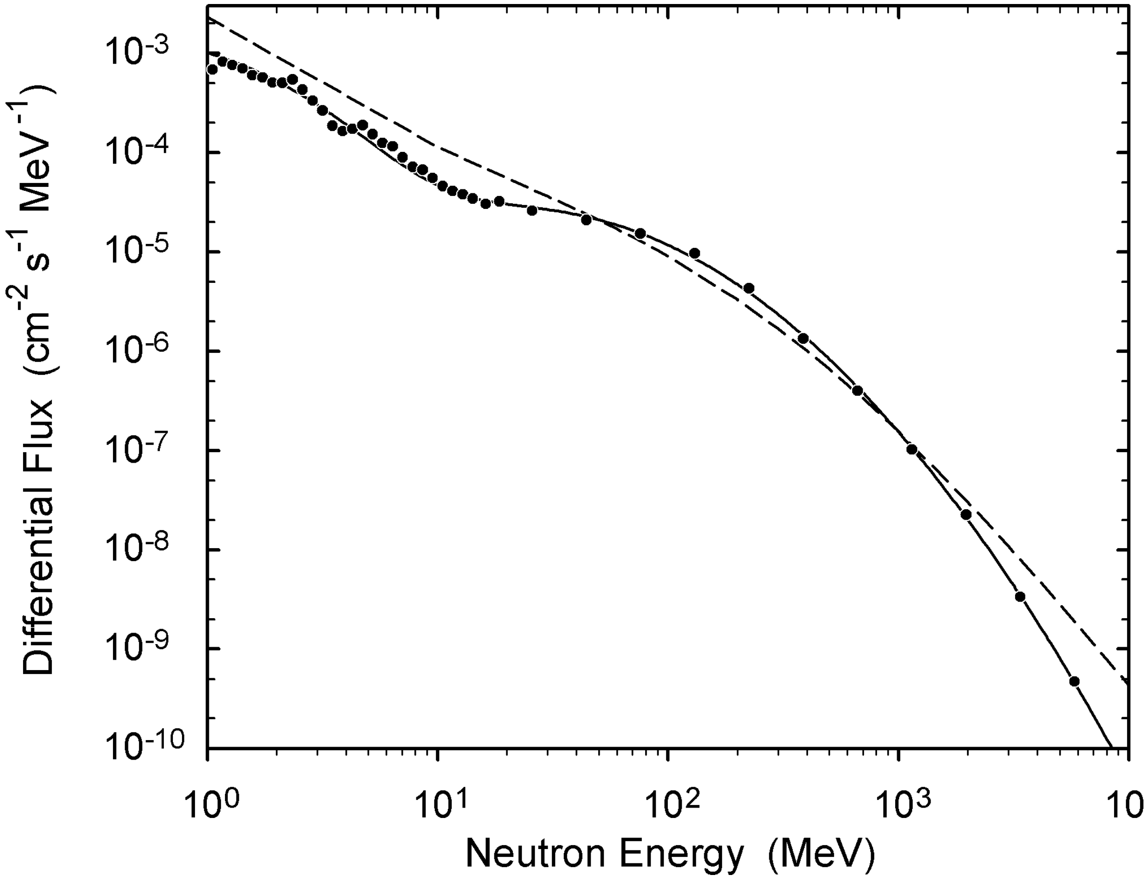

Fig. 8. Differential flux, $d\phi/dE, (\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{MeV}^{-1})$ of cosmic-ray induced neutrons as a function of neutron energy. The data points are our reference spectrum from the measurements, the solid curve is our analytic model, and the dashed curve is the JEDEC model [38].

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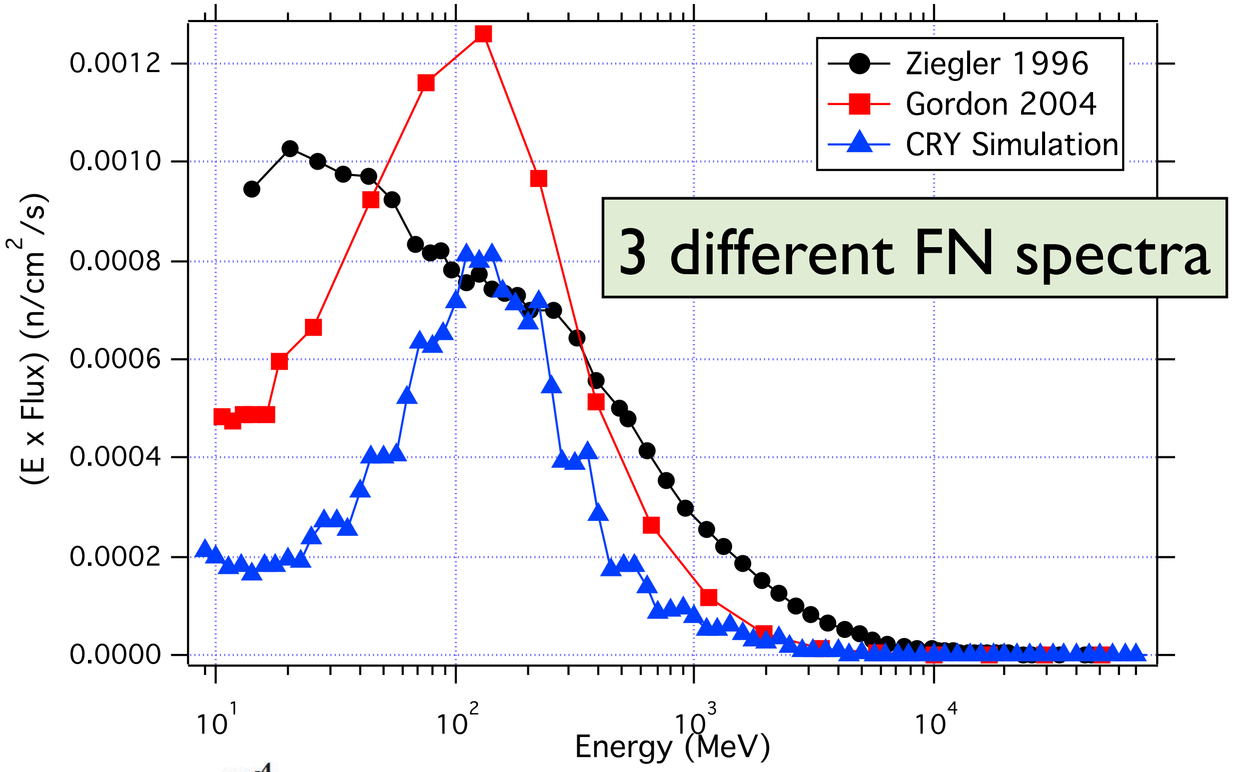
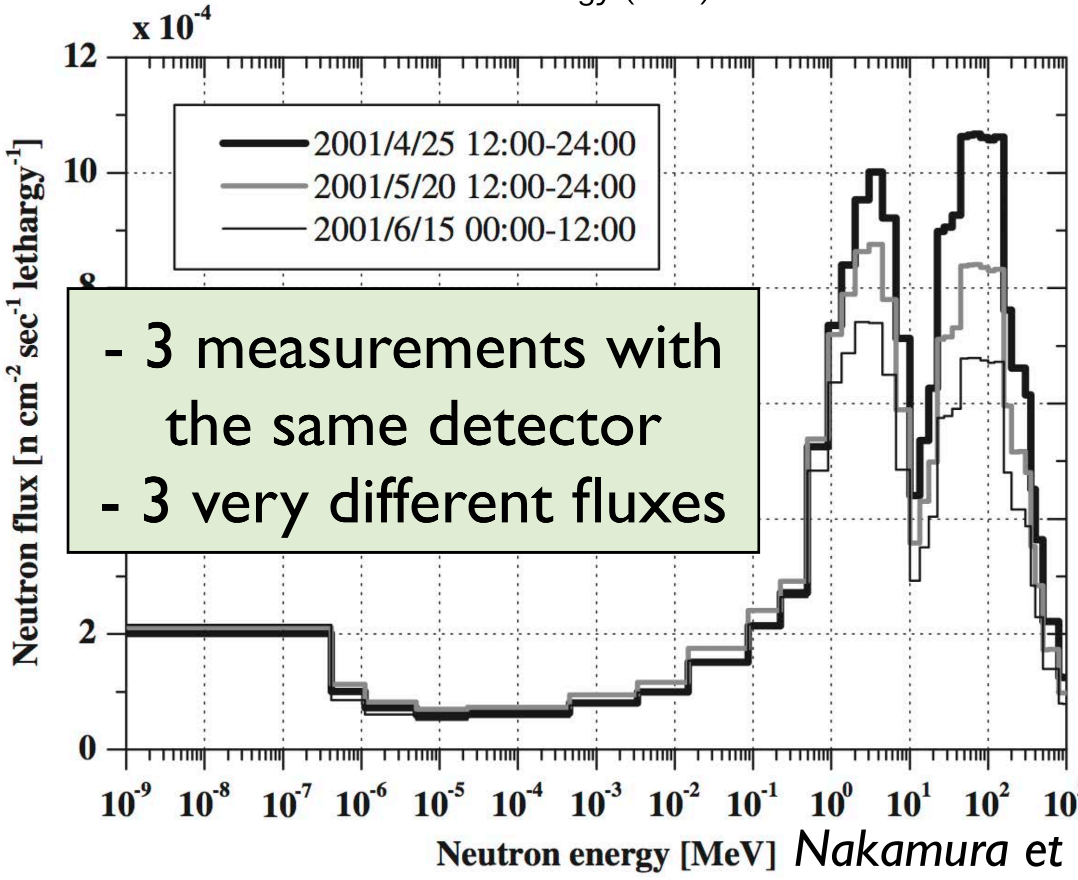


3 different FN spectra

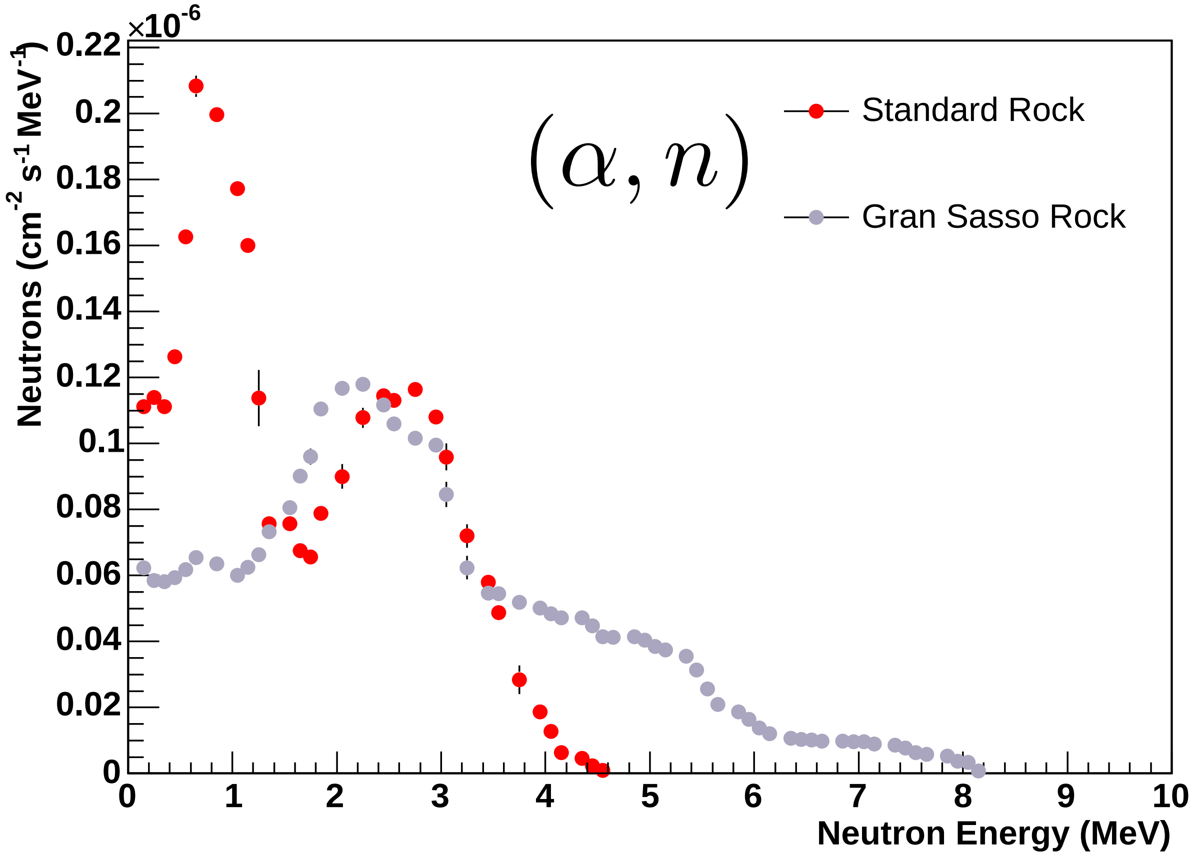


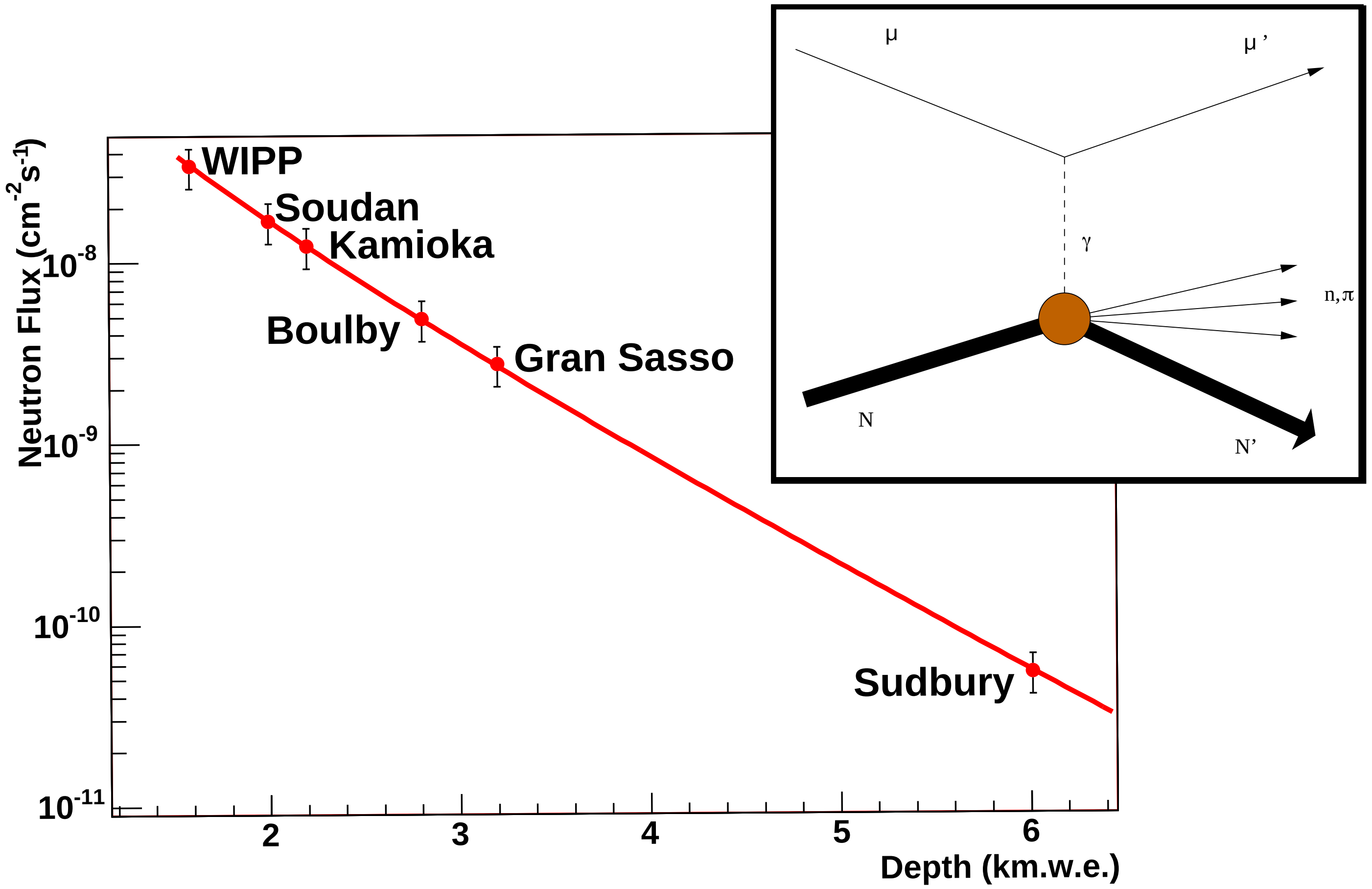
- 3 measurements with the same detector
- 3 very different fluxes

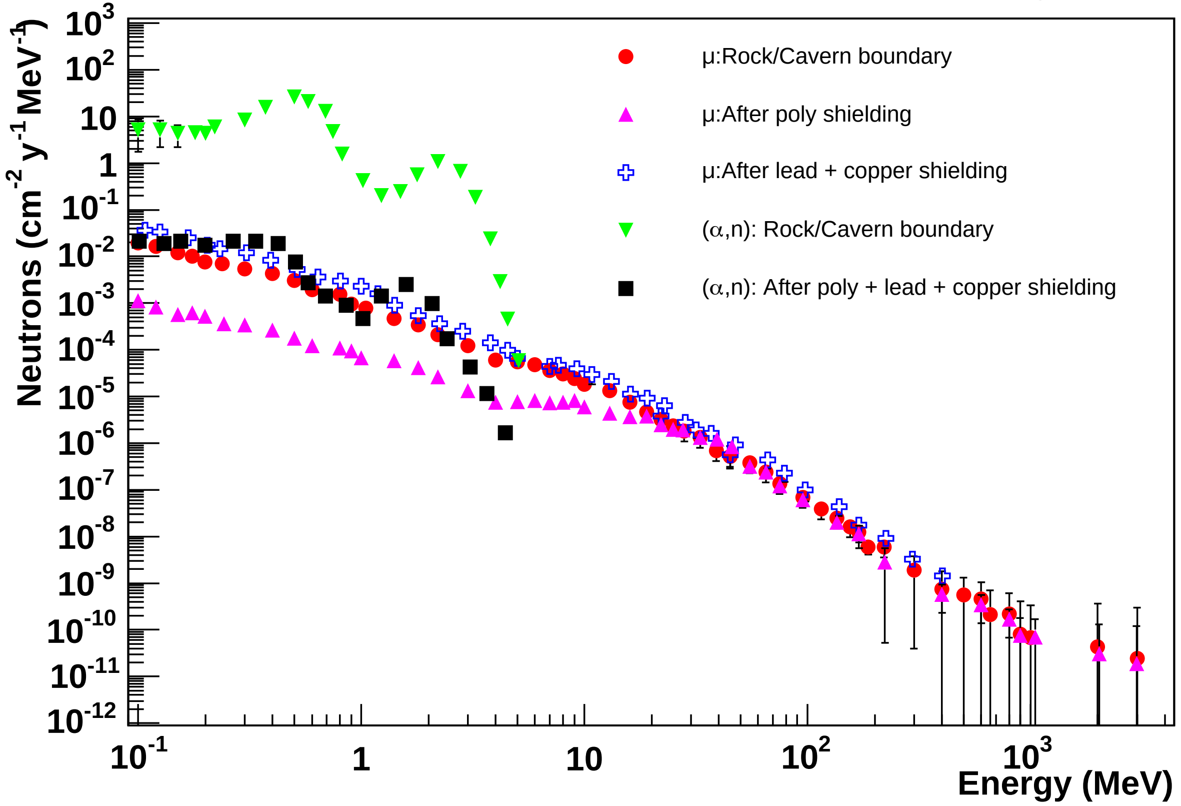
Nakamura et al. 2005

Underground Neutrons

- 1-10MeV: Natural radioactivity from surround material, mainly (alpha,n) (location dependent)
- 1 MeV - GeV: Muon-induced spallation neutrons (depth dependent)
- *Addition of shielding materials (like Pb) can enhance the production of muon-induced neutrons*







Plots from Mei and Hime 2006

Neutron Production

Simulation vs Data

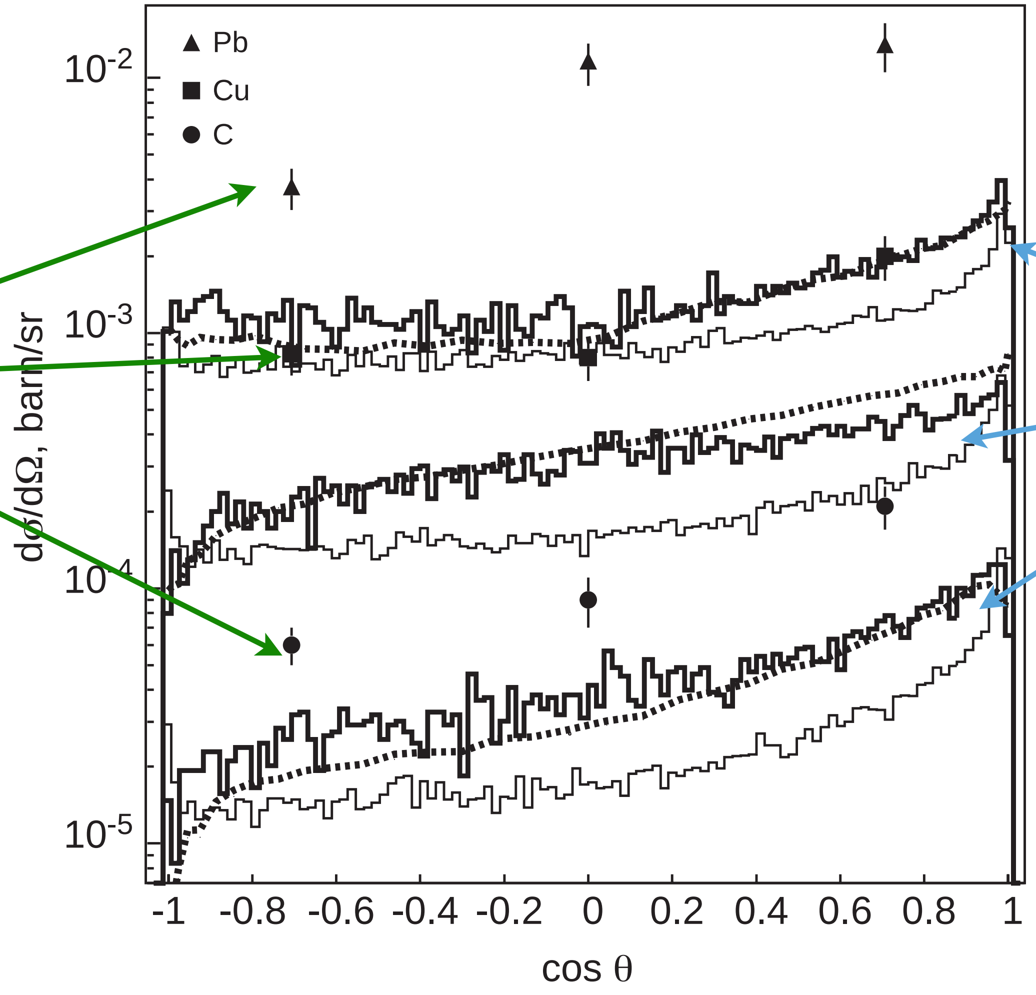
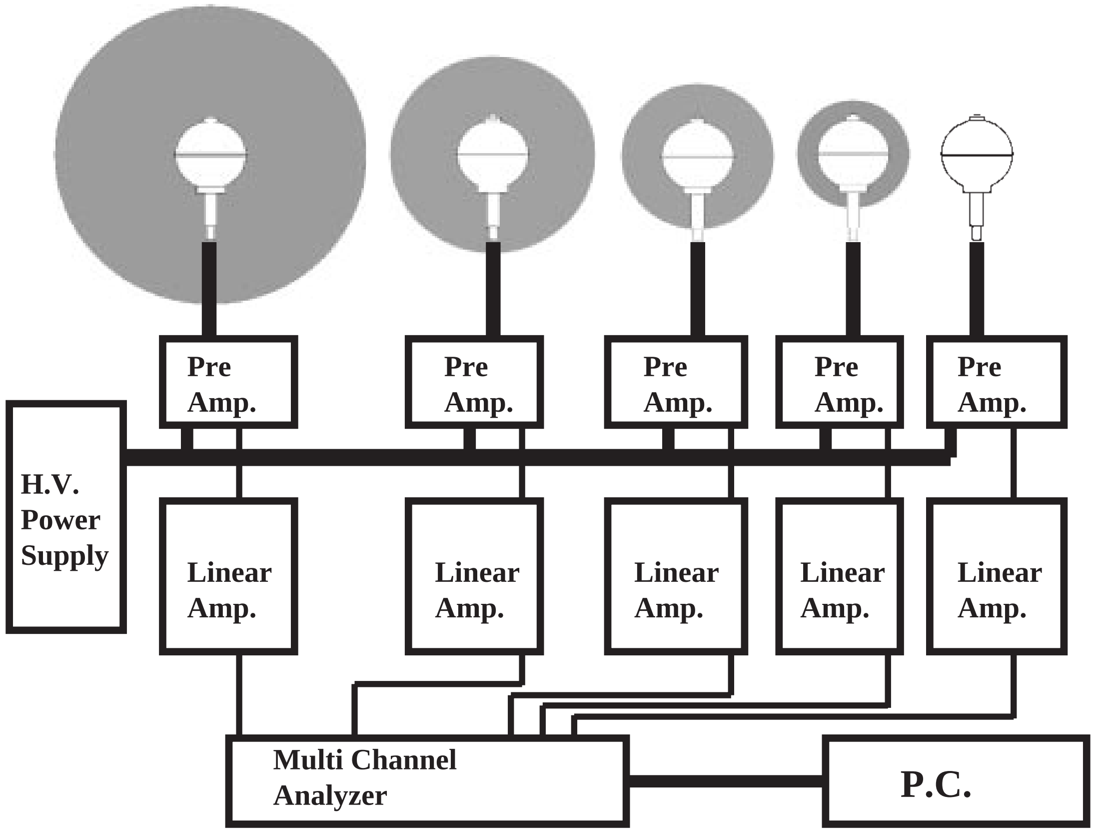


Fig. 7. Differential cross-section of neutron production by 190 GeV muons for a 10 MeV threshold in neutron energy. The data points represent the results of the NA55 experiment. The thin-line histogram shows the GEANT4 simulation considering muon–nucleus interaction only; the thick histogram includes all physics processes. The dashed line represents the FLUKA results for the latter case. *Araújo, et. al. NIM A, 2005*

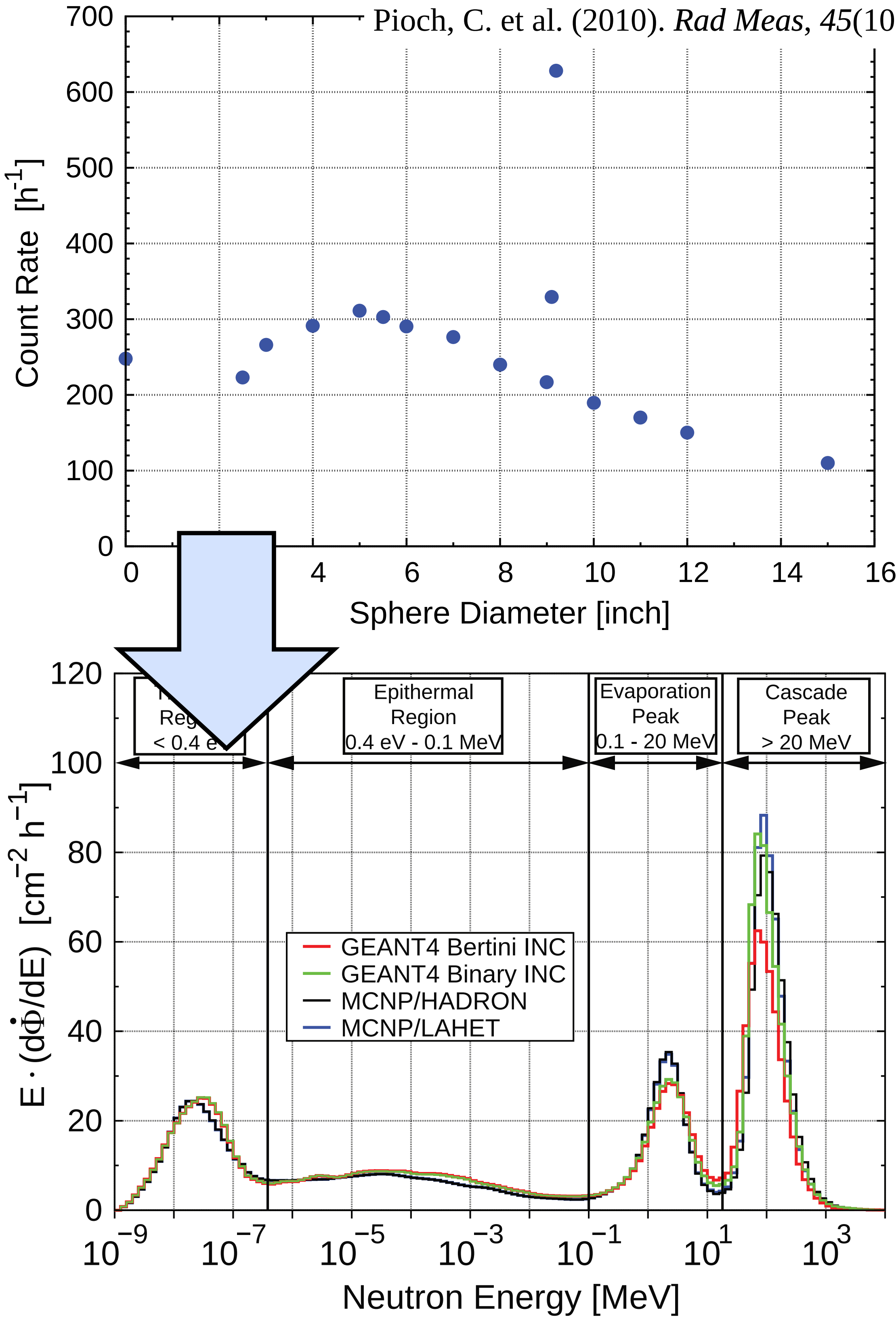
n-production is severely underestimated

Previous Detection Techniques

Bonner Sphere Arrays



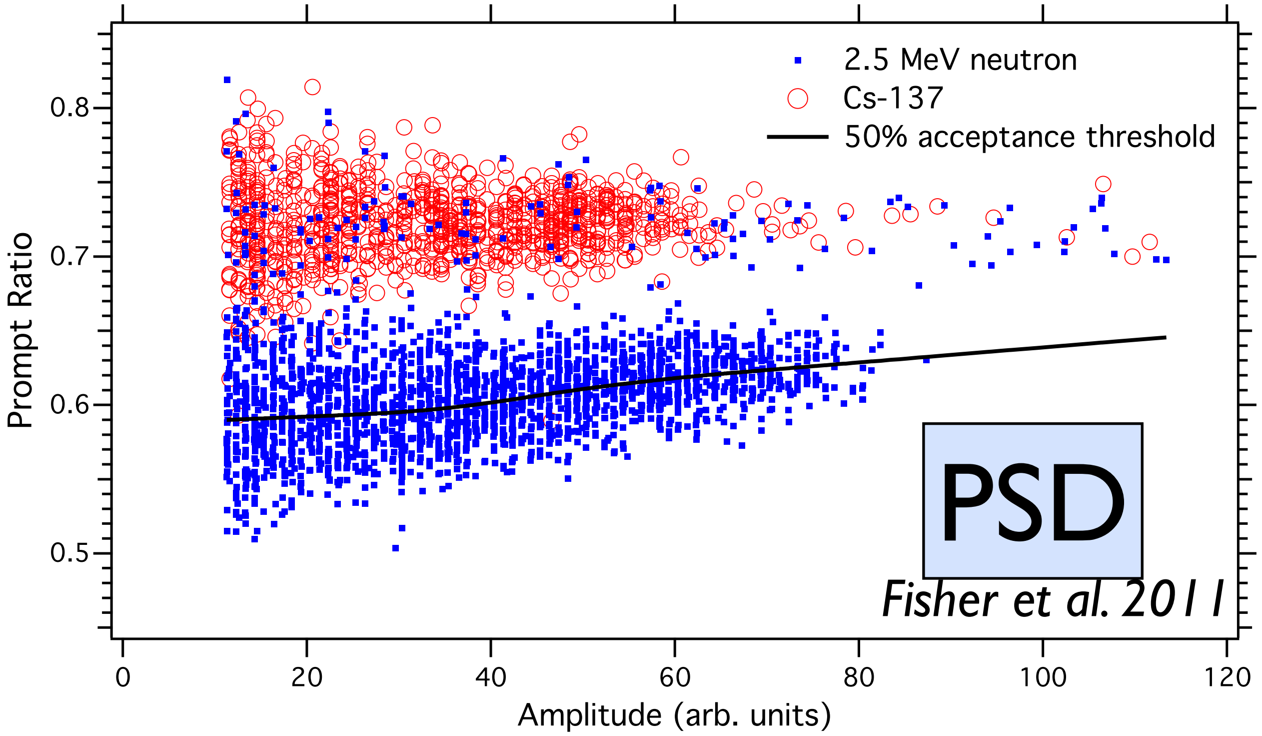
KOWATARI, M. et al. (2005). *J. of Nuc. Sci. and Tech.*, *42*(6), 495–502.



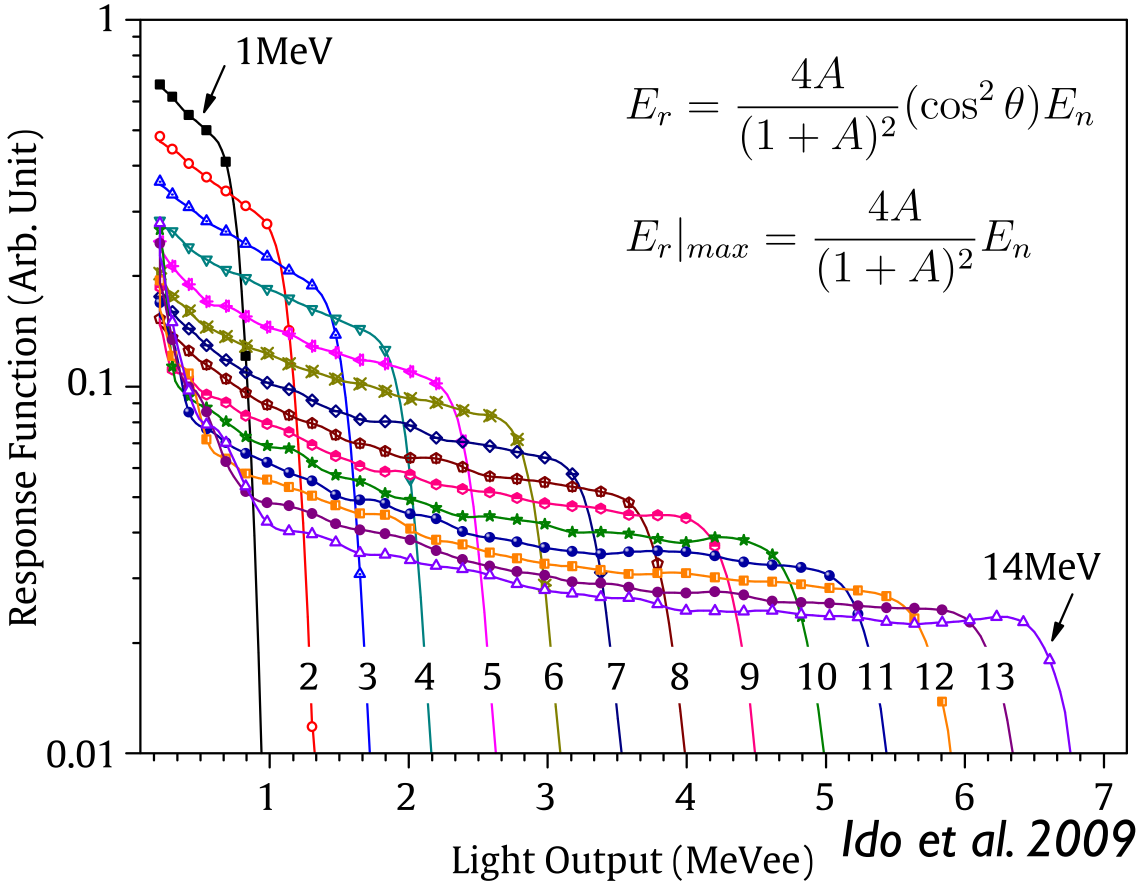
Pioch, C. et al. (2010). *Rad Meas*, *45*(10), 1263–1267

- Passively moderated ^{3}He counters
- Deployed in arrays of ~10 detectors with different diameters
- Convert count rates into spectrum
  - Relies on response functions
- *No direct energy observation*

LS Proton Recoil Detectors



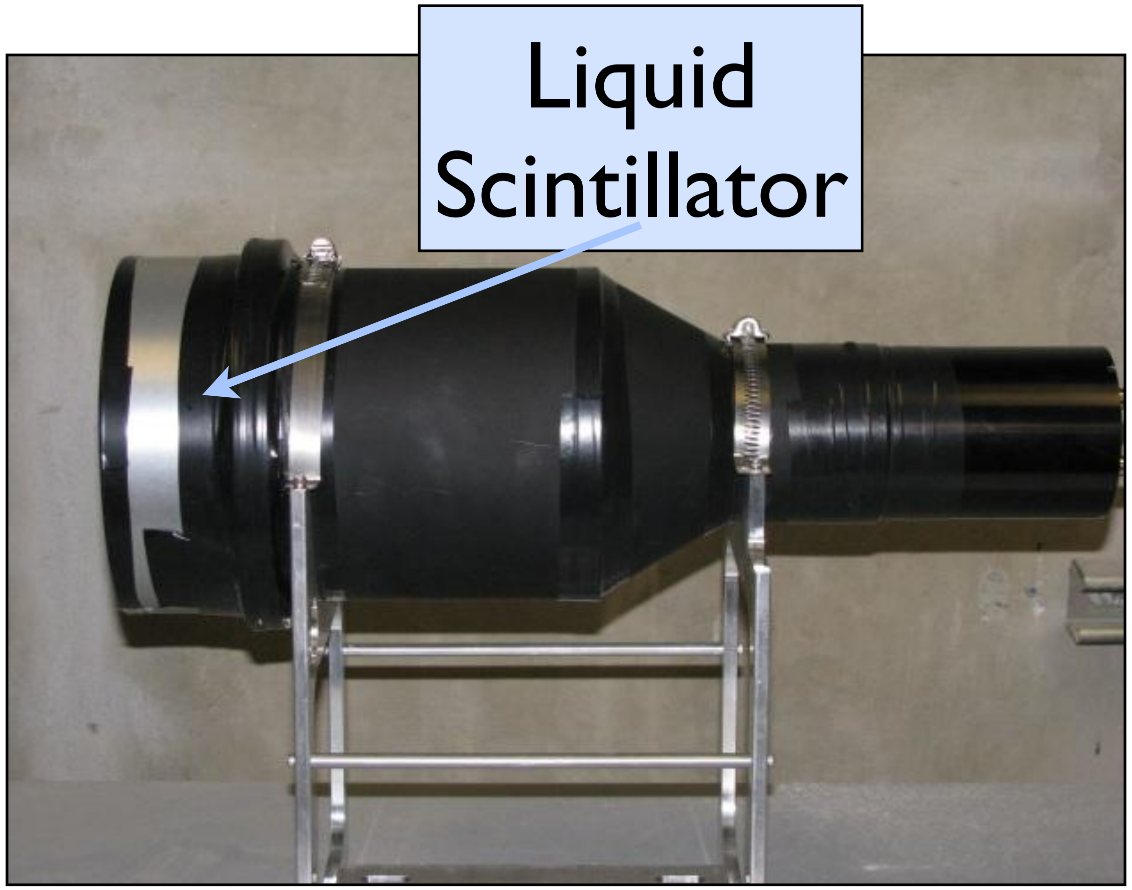
Fisher et al. 2011



$$E_r = \frac{4A}{(1+A)^2}(\cos^2\theta)E_n$$

$$E_r|_{max} = \frac{4A}{(1+A)^2}E_n$$

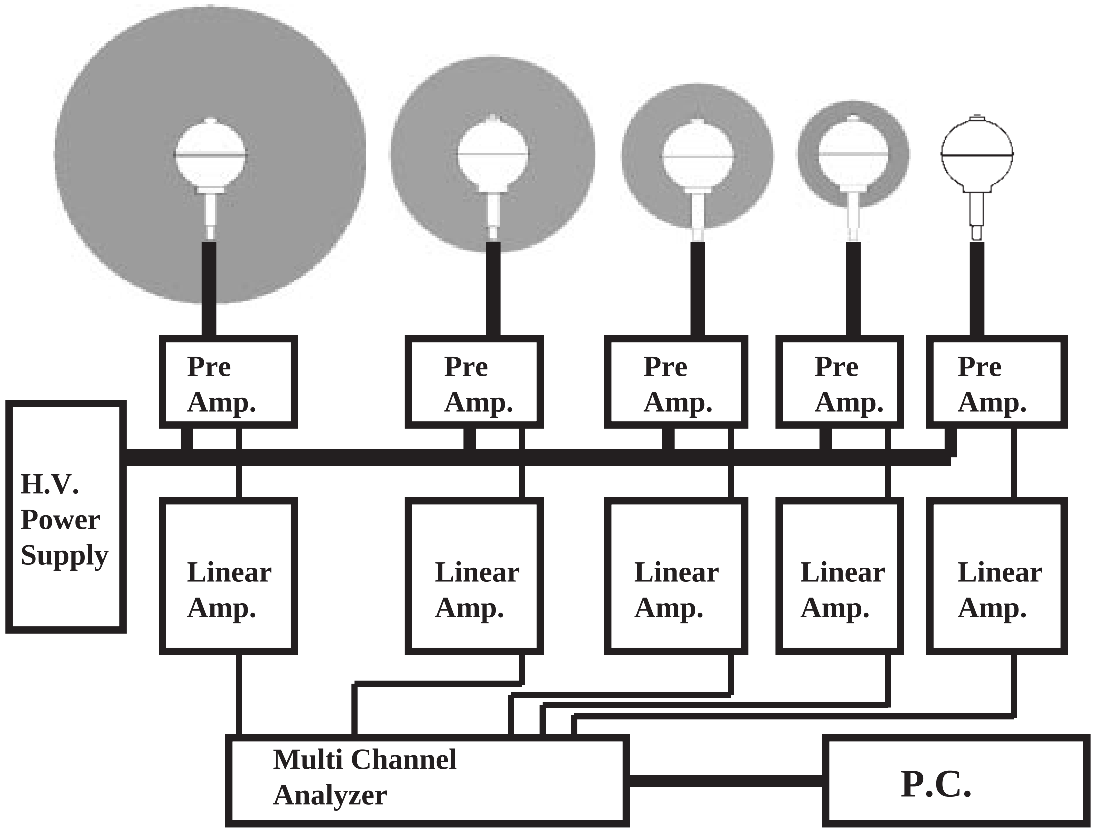
Ido et al. 2009



- N-P scattering to detect deposited energy
- Use pulse shape to separate gammas from neutrons
- *All neutron interactions detected, mostly partial-energy depositions*

Bonner Spheres

LS Proton Recoil



Vs

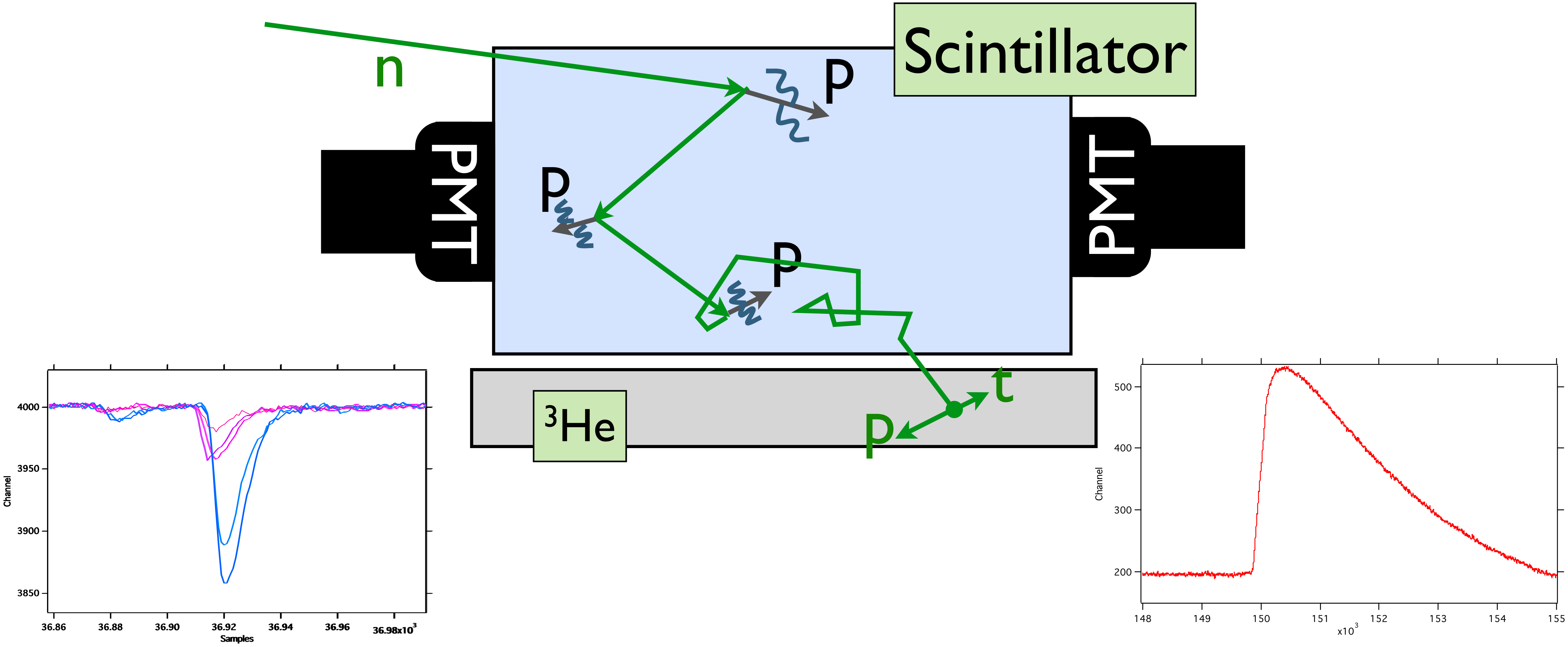
- Only measure thermal neutron capture
- Very difficult to calibrate response functions
- *No direct energy observation*

- Detect energy from every interaction
- PID from pulse shape
- *Most events are partial energy deposition, bad for spectroscopy*

Capture Gated Spectroscopy

Combine features from BS and PR detectors:

1. Demand capture
   - *Full energy deposition*
2. Directly measure deposited energy



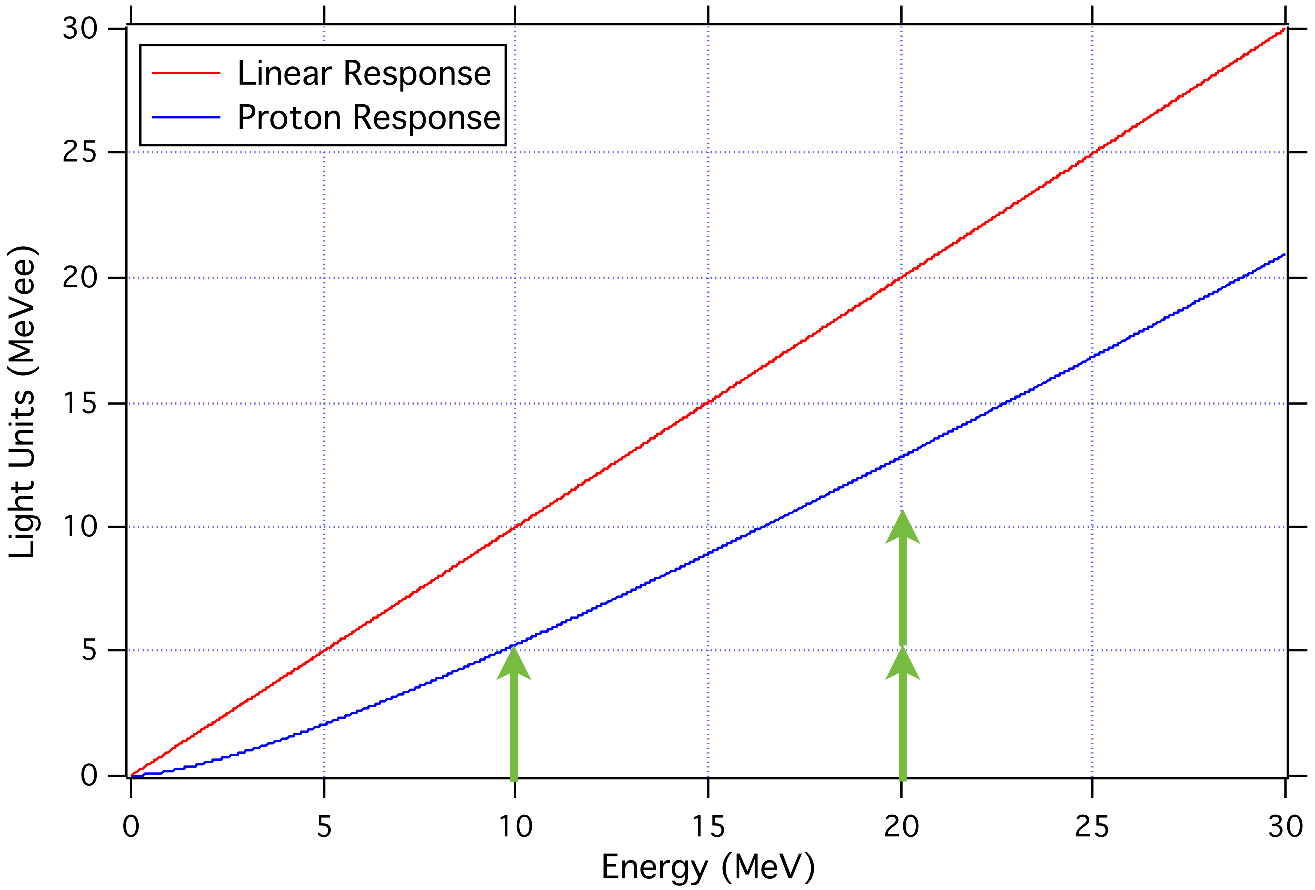
The FaNS Detectors

The FaNS Detectors

- Arrays of plastic scintillator segments and ^{3}He proportional counters
  - Segmentation improved energy reconstruction
- *Use Capture-gated Spectroscopy for particle identification and energy information*
- Calibrated at NIST with Cf-252, DD, and DT neutrons
- FaNS-1: Rapidly deployed as proof-of-principle
- FaNS-2: Full fledged detector

Energy Resolution Through Segmentation

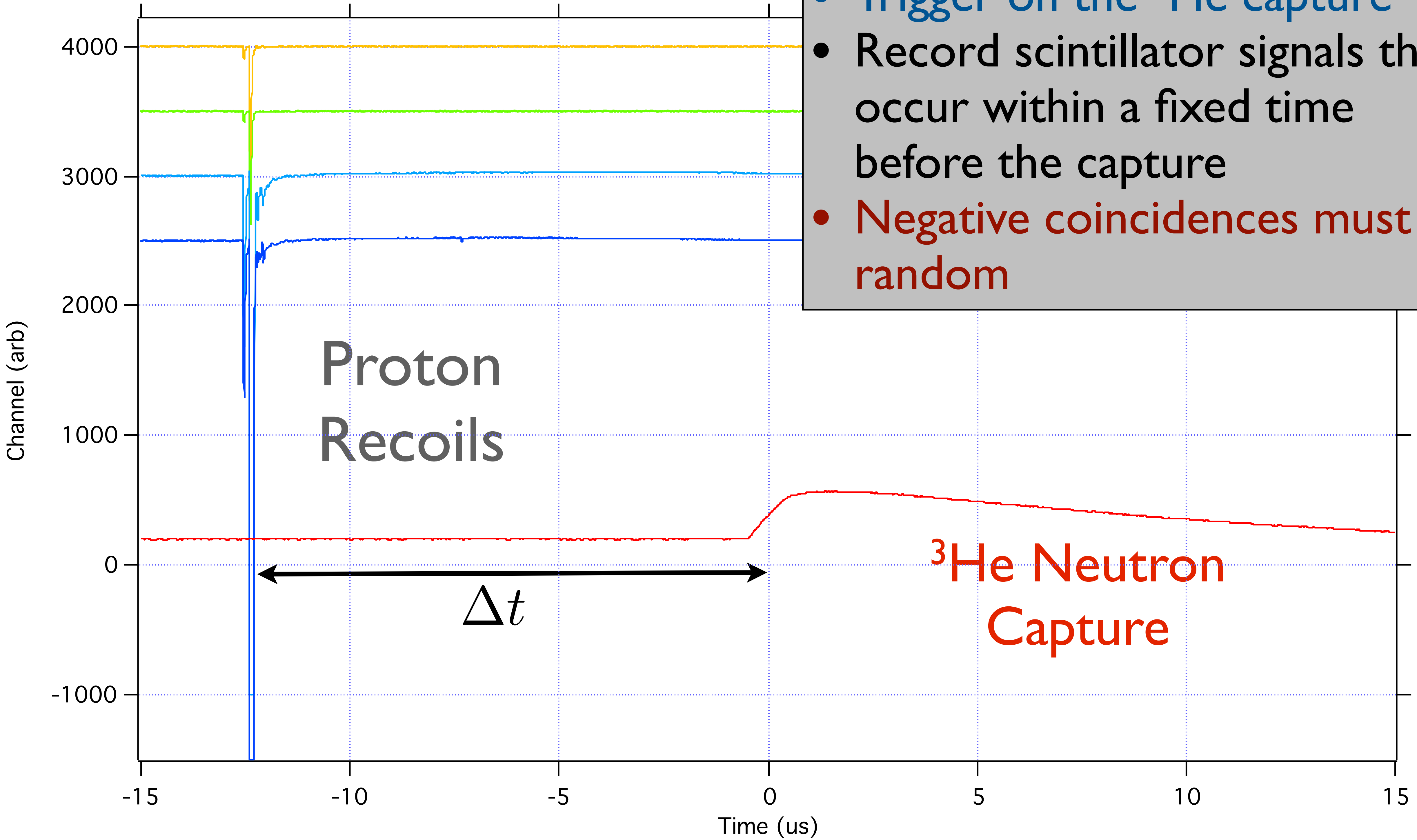
- Plastic scintillator has a non-linear light response to heavy charged particles
- To achieve better energy resolution, we segment the detector to reconstruct each scatter separately
- Segment size is chosen to match the mean free path of target neutrons



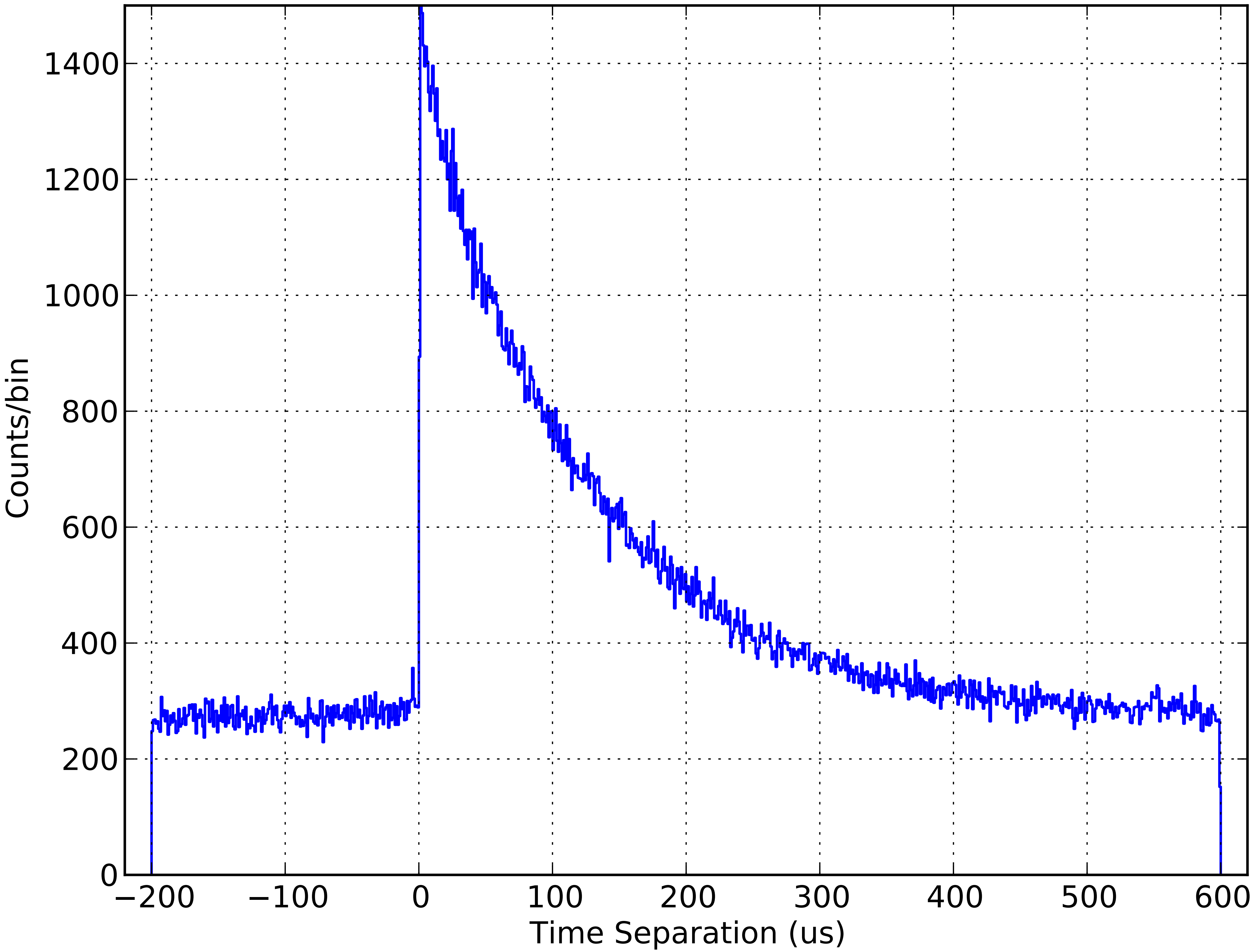
We want to detect each scatter separately, convert light into energy, and then sum

CGS with FaNS

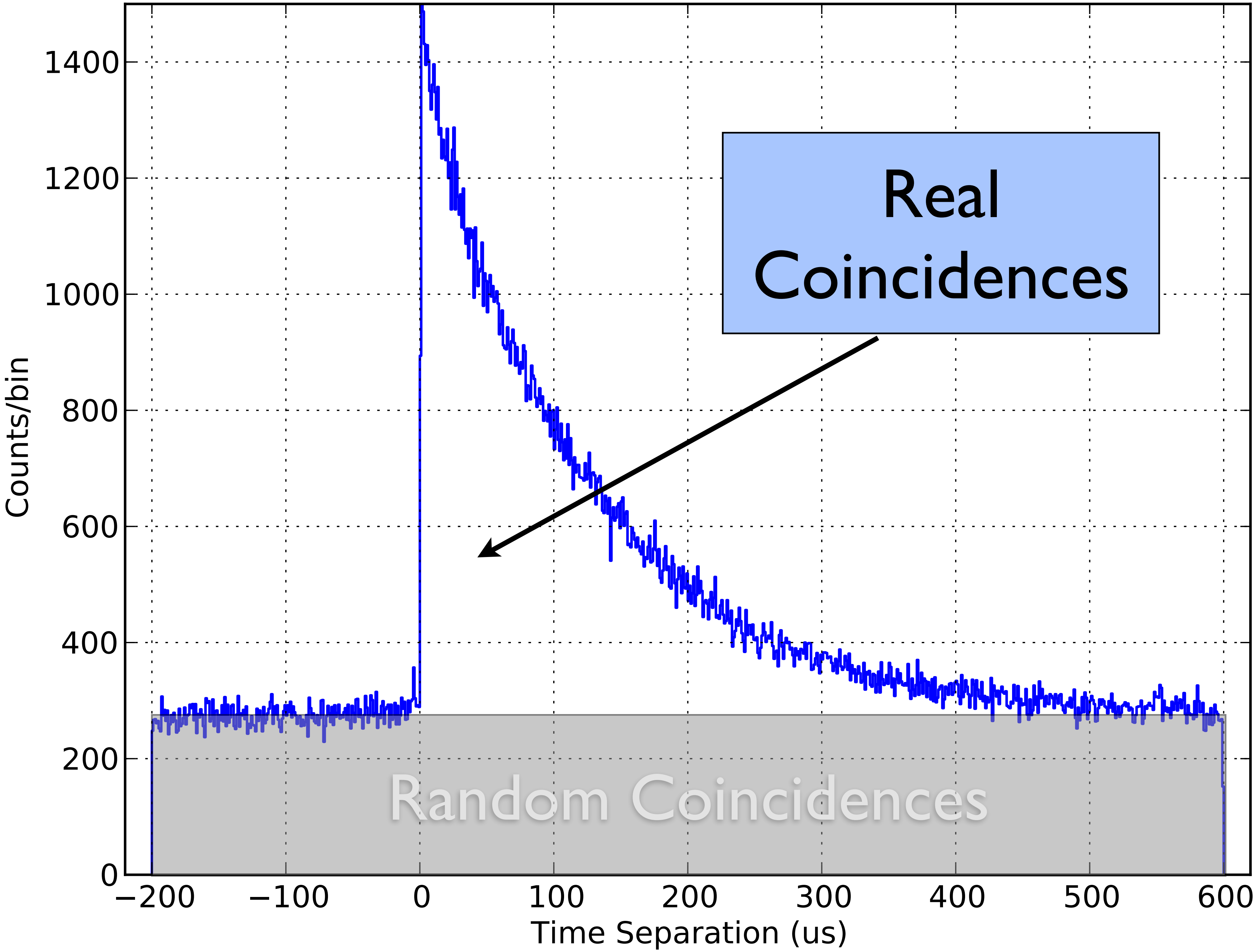
- Trigger on the ^{3}He capture
- Record scintillator signals that occur within a fixed time before the capture
- Negative coincidences must be random



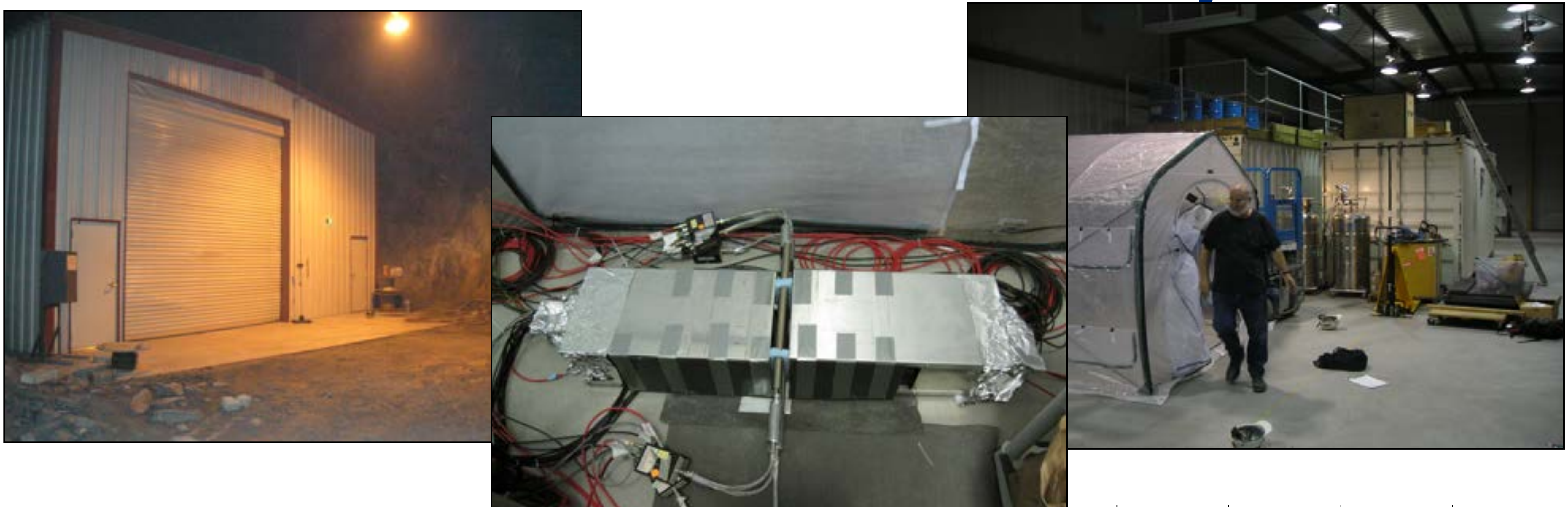
Time Separation Spectrum



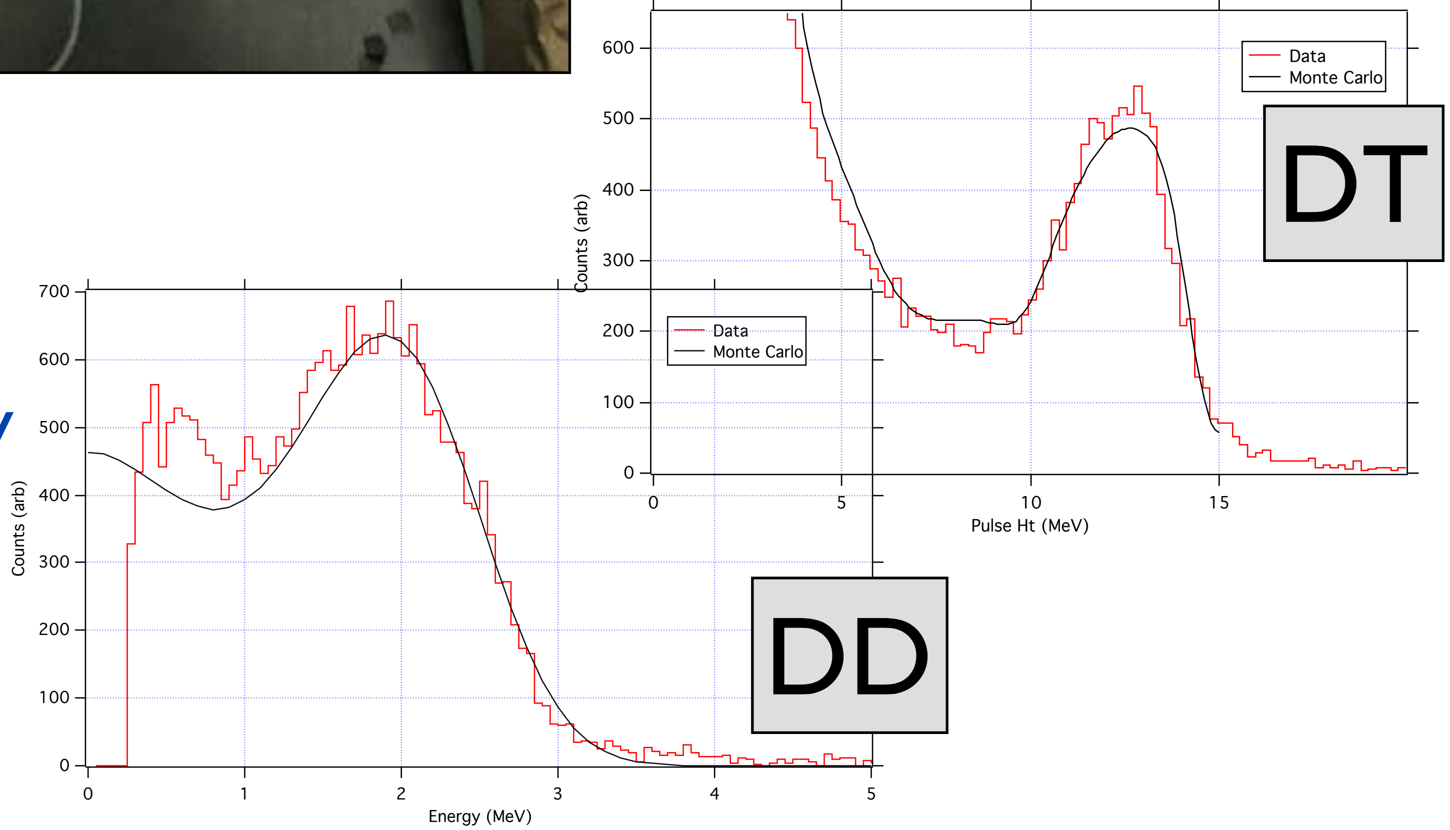
Time Separation Spectrum



FaNS-1 Summary

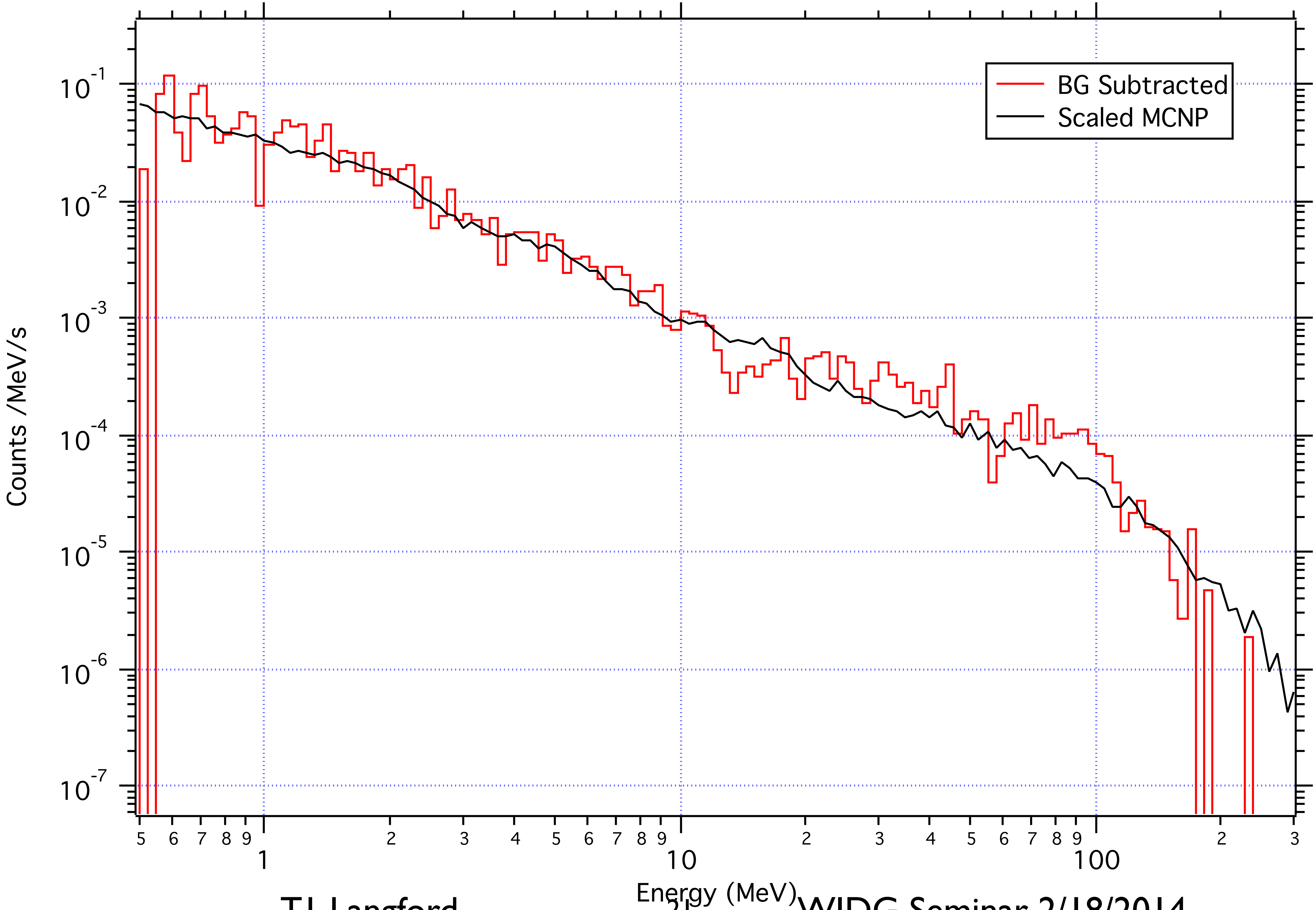


- 18liters of PS in six segments
- Six He-3 proportional counters
- Calibrated at NIST
- *Measured surface spectrum to 150MeV*
- Installed at Kimballton Lab
- Measured the neutron spectrum and flux at KURF

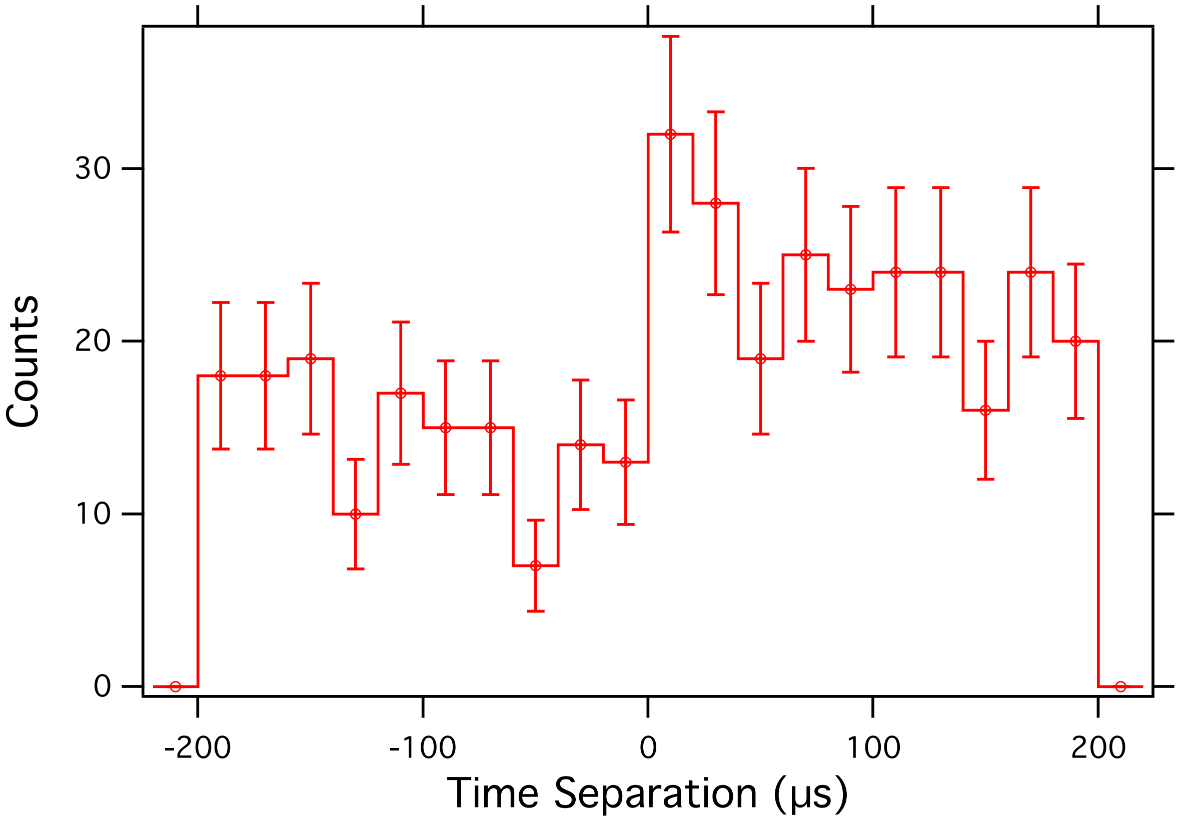


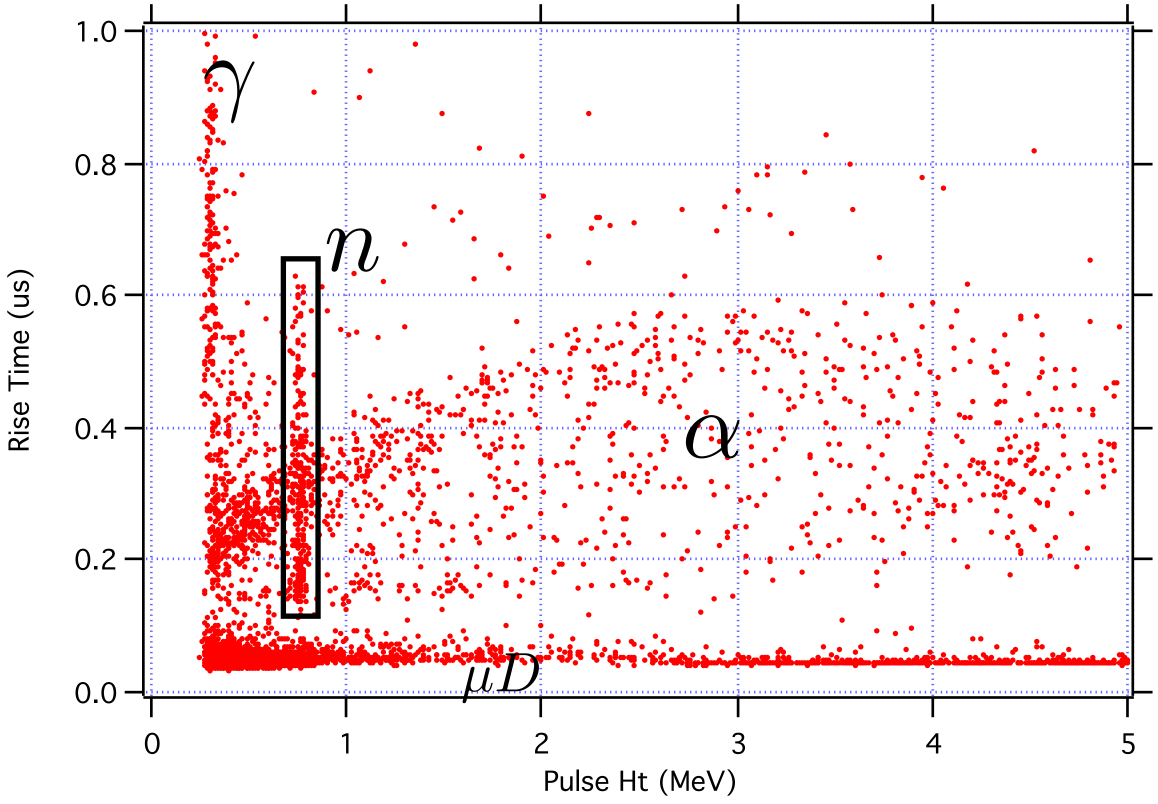
FaNS-1 Surface Neutrons

$$\Phi(E_n > 1\ MeV) = (4.0 \pm 1.0) \times 10^{-3} n/cm^2/s$$

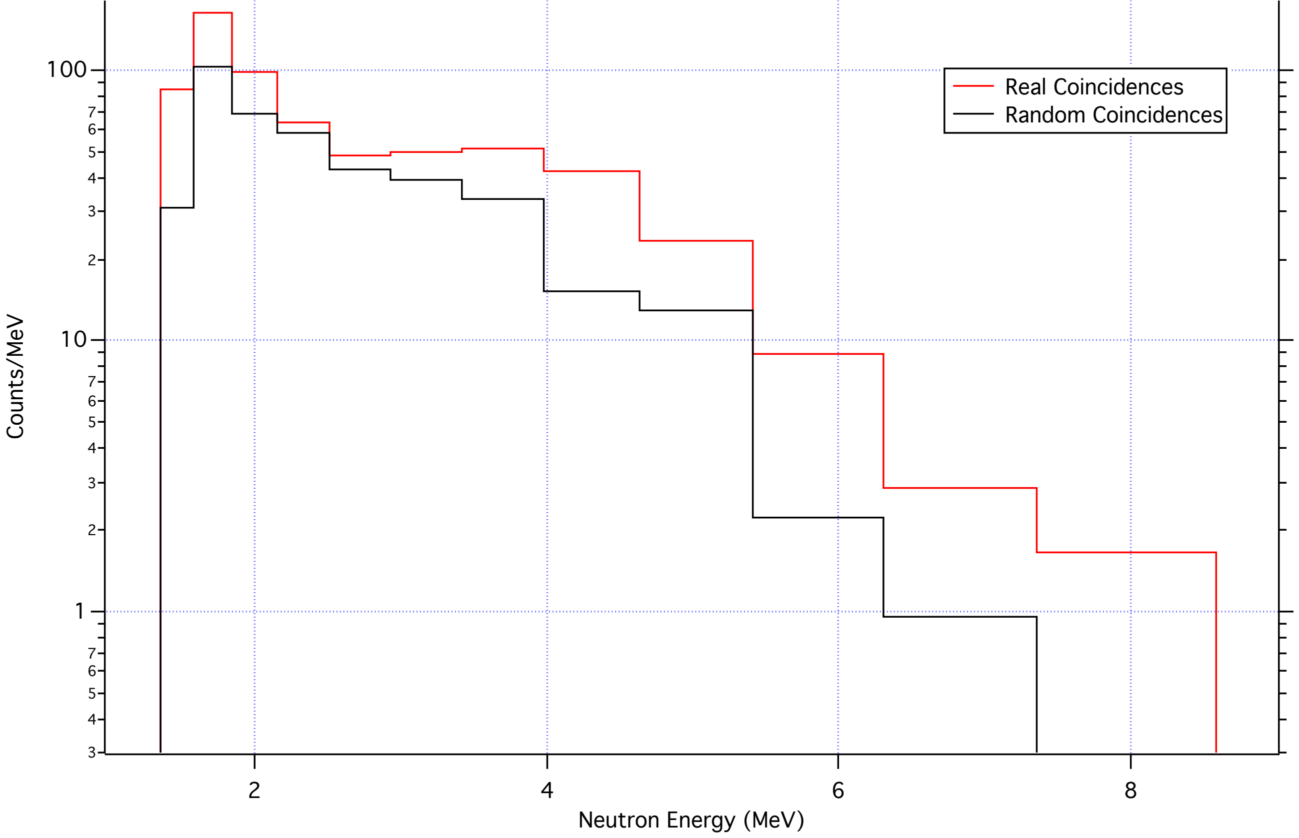


FaNS-1 at KURF - 1450 mwe



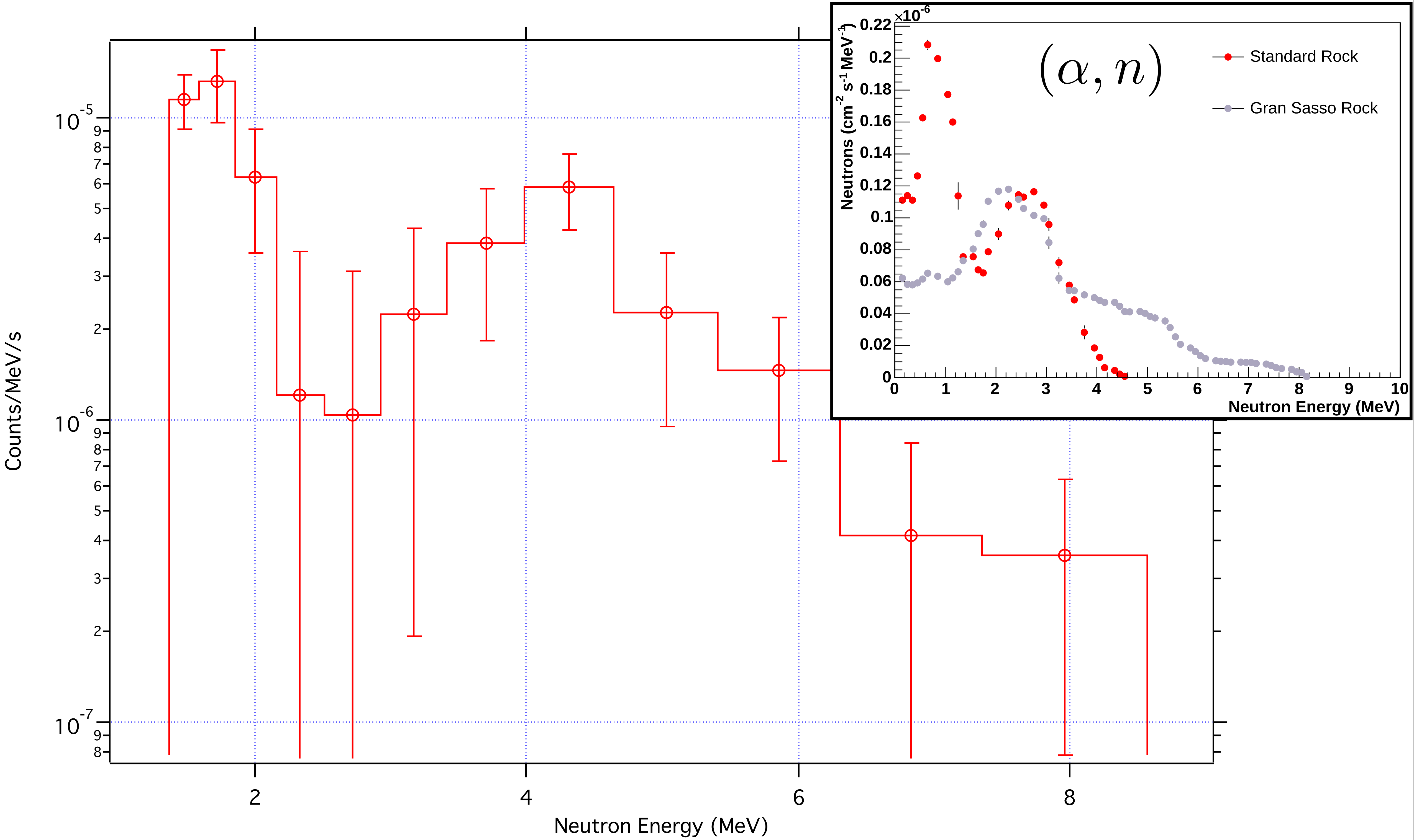


- $3.74\text{x}10^6$ s dataset
- $1.67\text{x}10^5$ He-3 triggers
- 384 counts pass all cuts
- *89 remain after BG subtraction*



FaNS-1 at KURF - 1450mwe

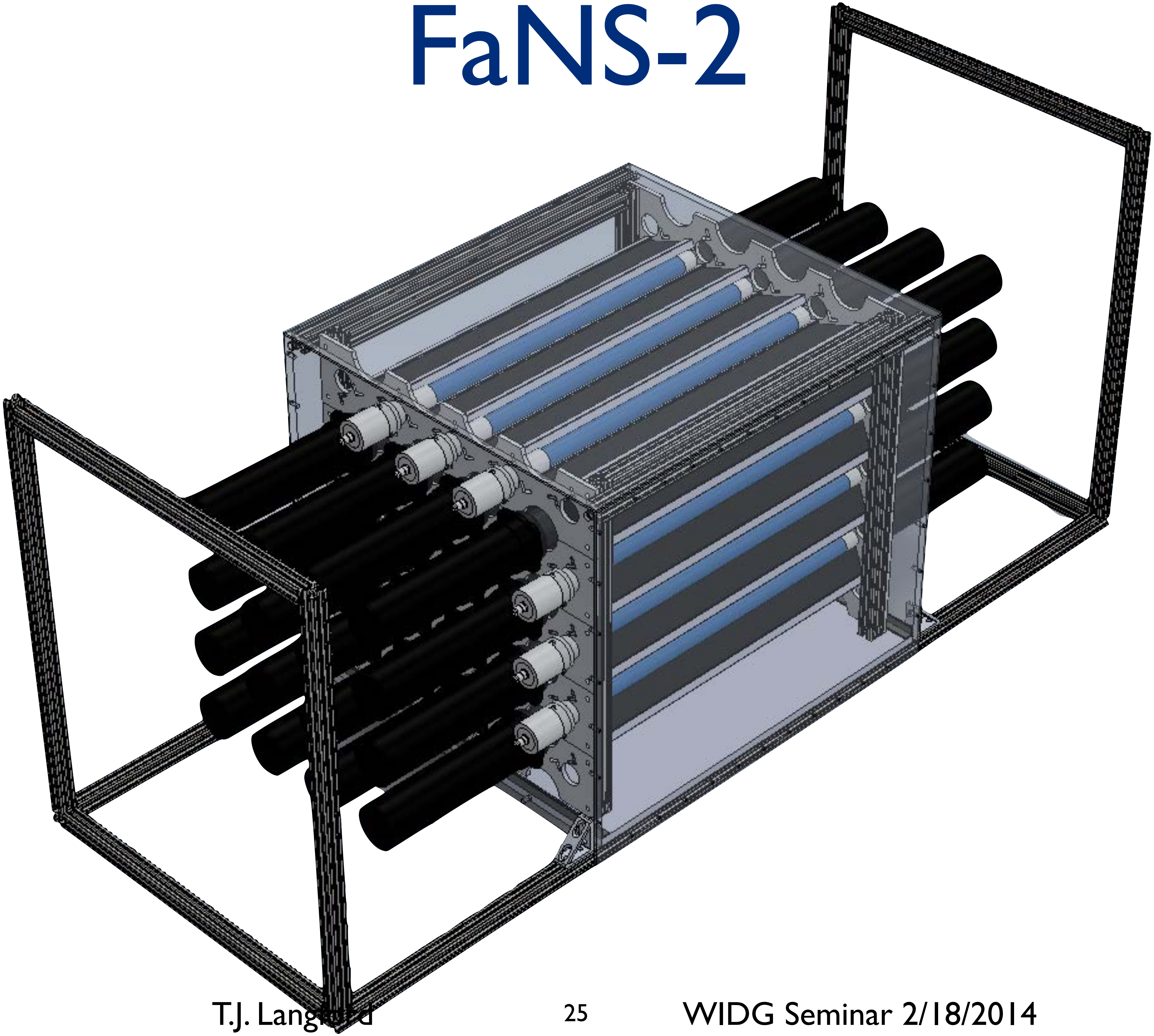
$$\Phi(E_n > 1.4\ \mathrm{MeV}) = (1.6 \pm 0.4) \times 10^{-6}\ \mathrm{n/cm^2/s}$$



FaNS-1 Conclusions

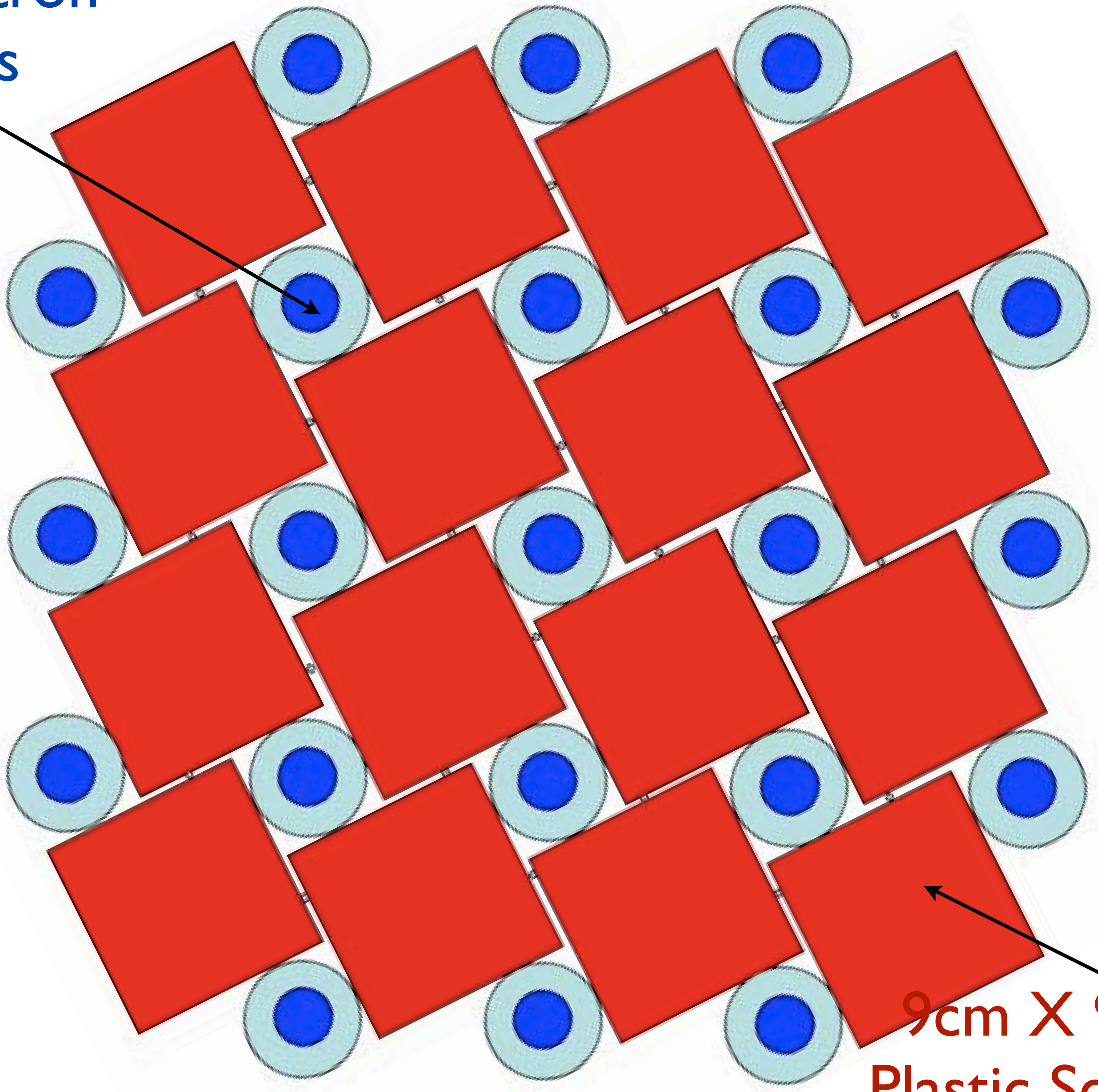
- Demonstrates the power of CGS
  - *Detect peaks rather than edges*
- Measured the surface fast neutron spectrum and flux from 1 to 150 MeV
- Deployed FaNS-1 at KURF, where an (alpha, n)-like spectrum and flux were successfully measured
- Influenced design of FaNS-2
  - Focus on muon-induced neutrons ($E_n > 10$ MeV)
  - *Operate at a shallow location to measure flux and spectrum*

FaNS-2



FaNS-2

FaNS-2



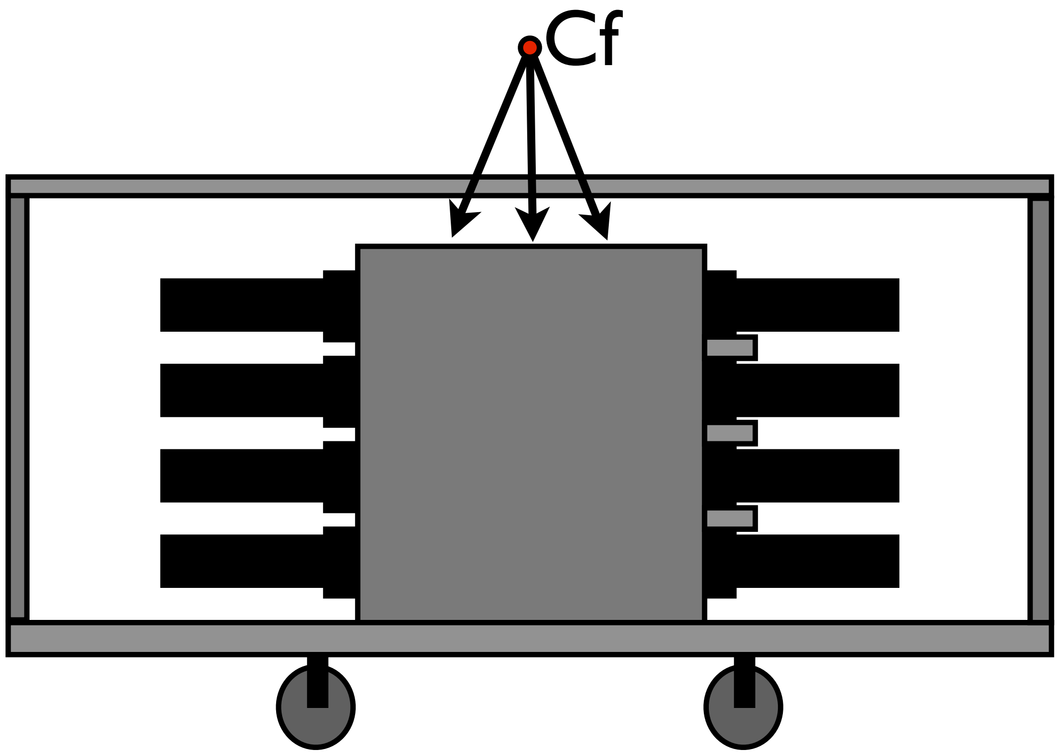
21 ^{3}He Neutron Detectors

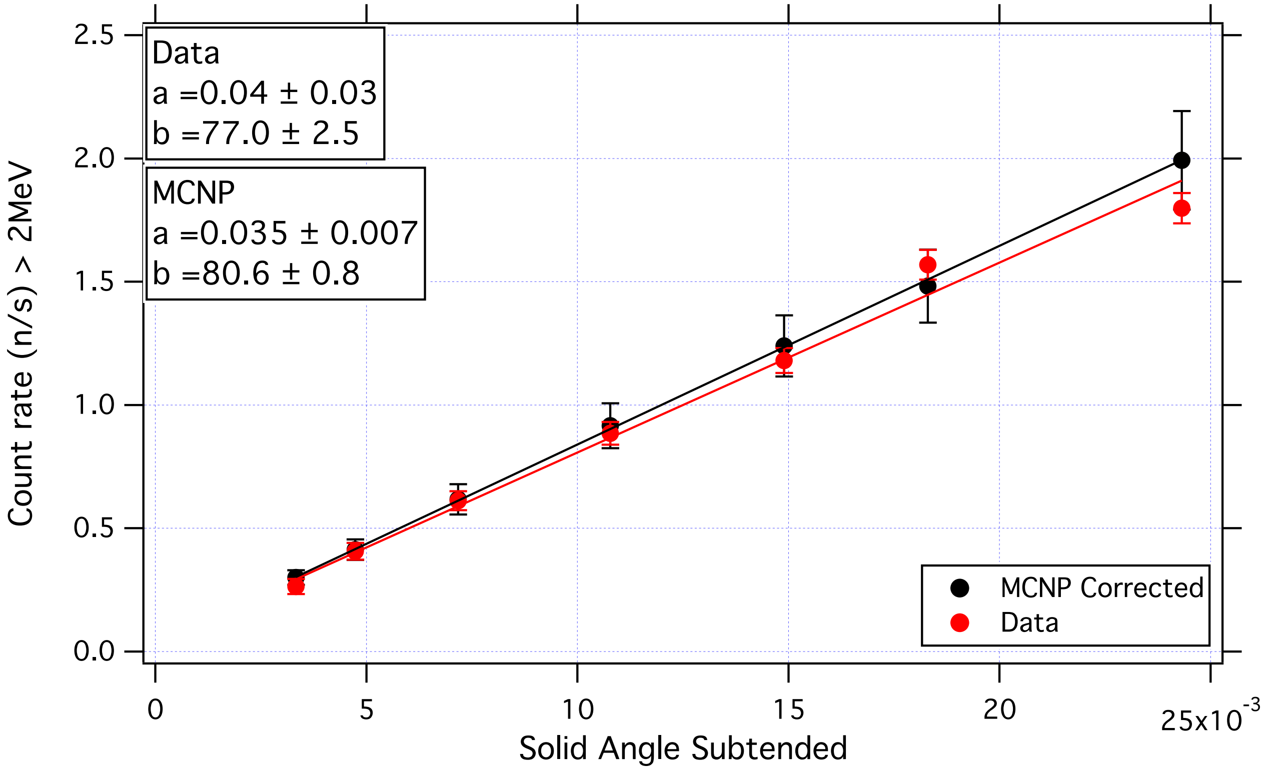
9cm X 9cm X 56cm Plastic Scintillator Bars

FaNS-2

- The “Purpose-built” Detector
- Improvement over FaNS-1 in almost every way:
  - Volume: 15 liters → 72 liters
  - DAQ: twice as fast, 8ch → 56ch
  - PMTs: better linearity and characterization
- Built at UMD, commissioned at NIST in December 2012
- FaNS-2 was operated in a low scatter room measuring source and ambient neutrons
  - Reduce backscattering neutrons compared to FaNS-1
  - *Effectively no shielding of ambient neutrons from cosmic rays*

Cf-252 Source Calibration

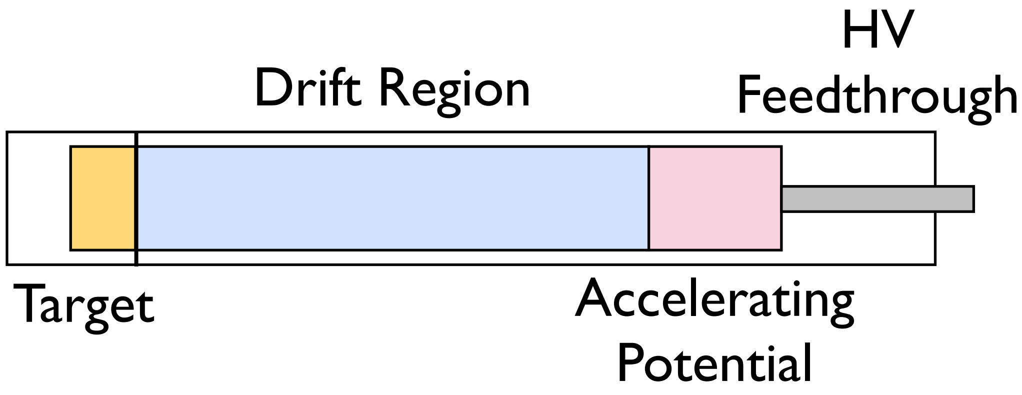


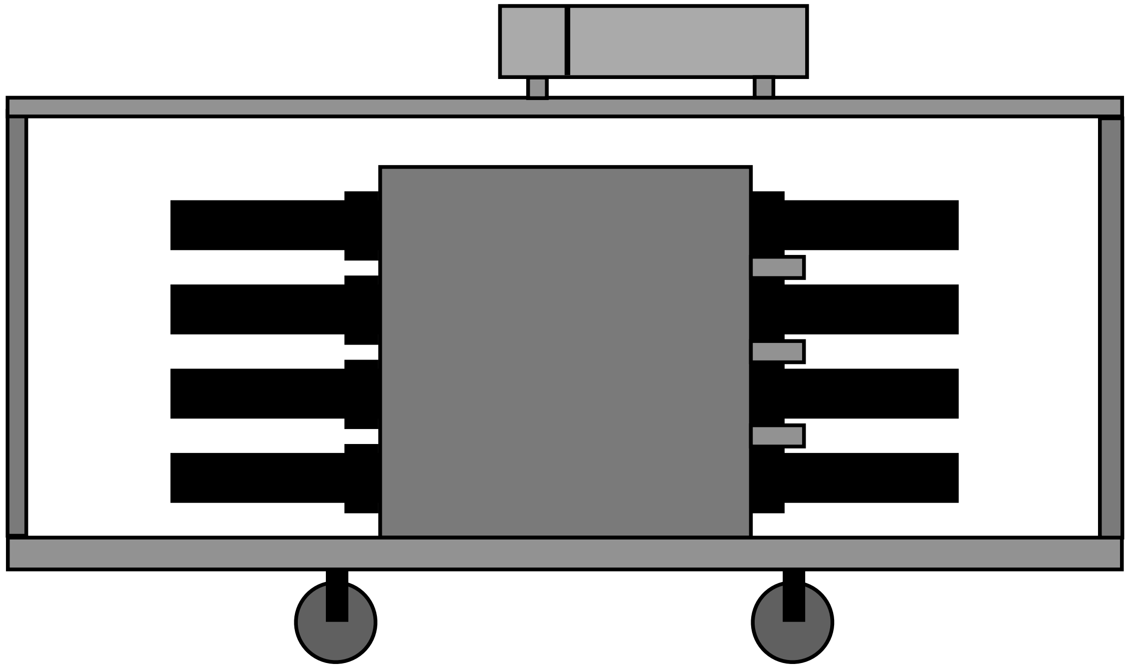


- Seven different source positions were measured - (85 cm - 238 cm above FaNS-2) and two runs without the source
- Each position was modeled in MCNP, and the same cuts were applied to data and simulation
- The slope of the fit-line is extracted for the efficiency

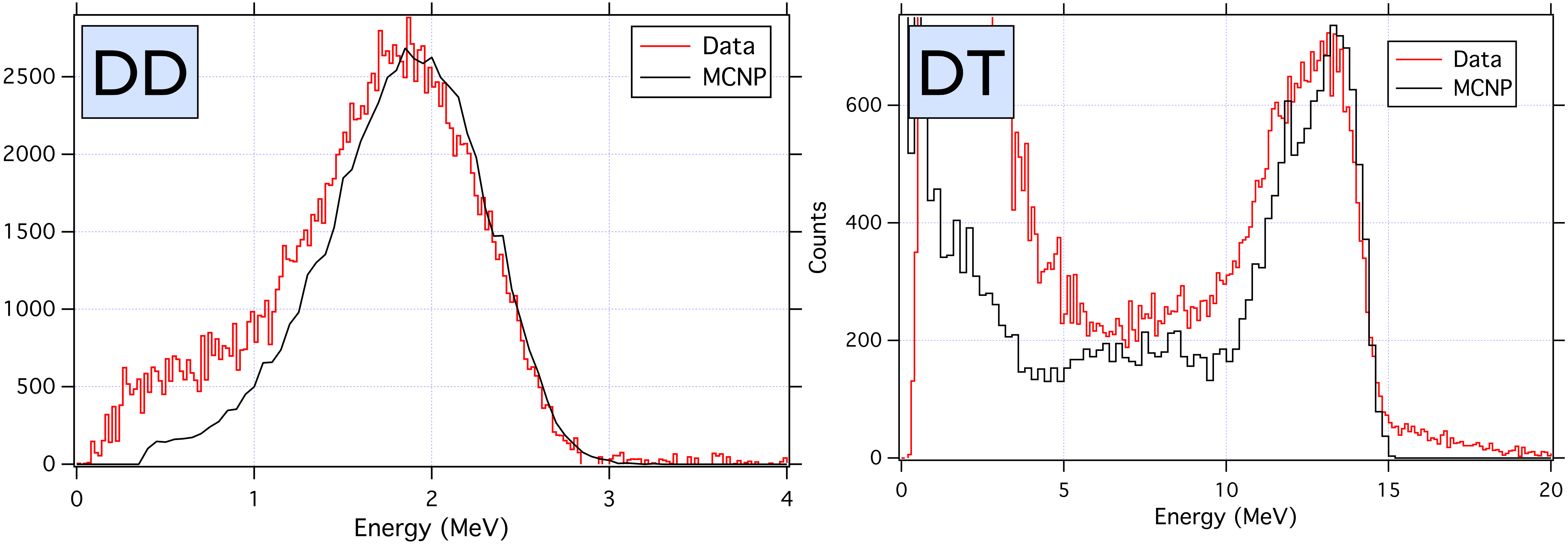
$$\epsilon = \frac{slope}{source\ activity} = (3.6 \pm 0.15)\%$$

Neutron Generator Data

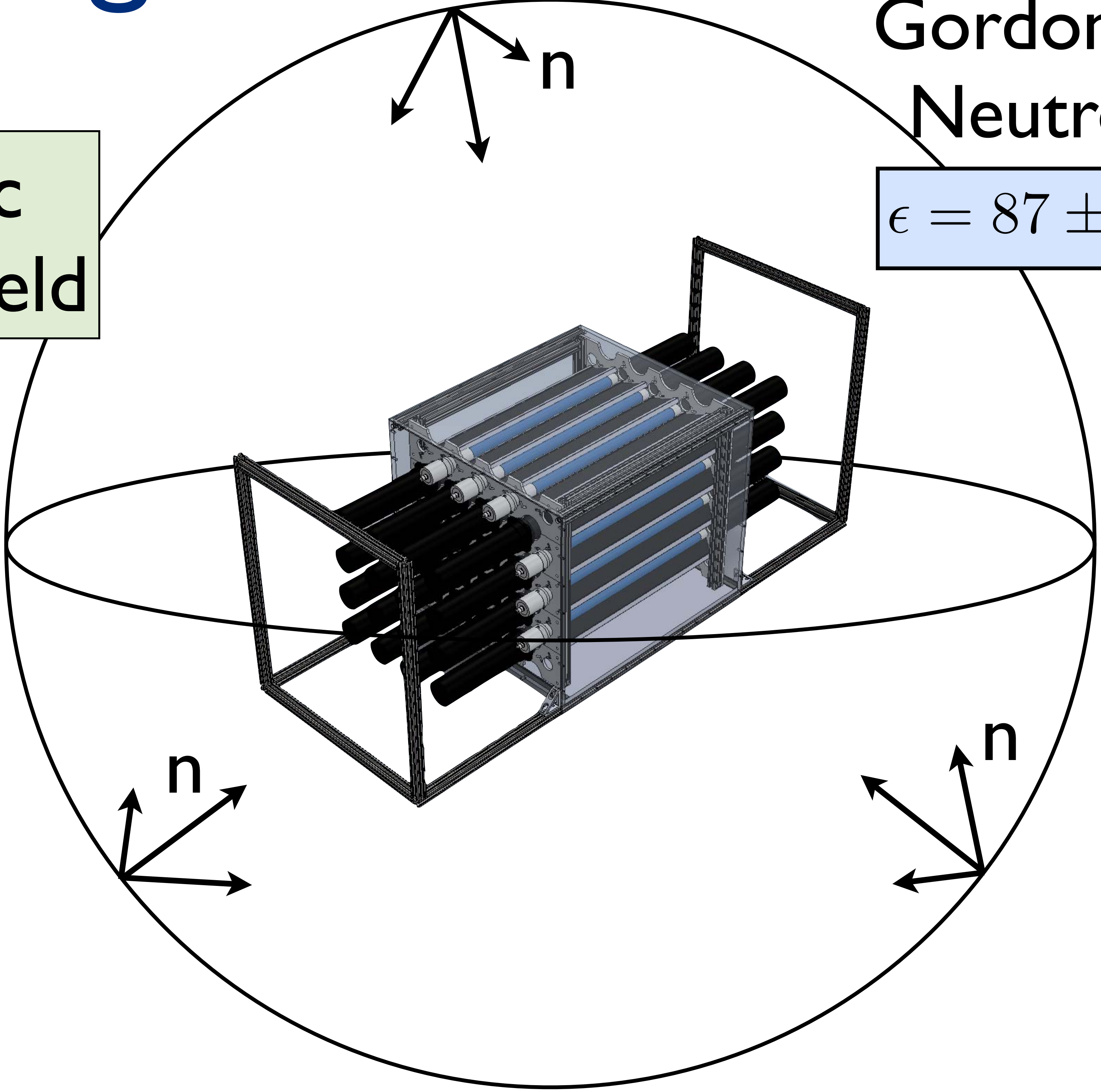




$$D + D \rightarrow {}^{3}He + n\ (2.5\ MeV)$$
$$D + T \rightarrow {}^{4}He + n\ (14.1\ MeV)$$



Cosmogenic Neutrons at NIST



Isotropic neutron field

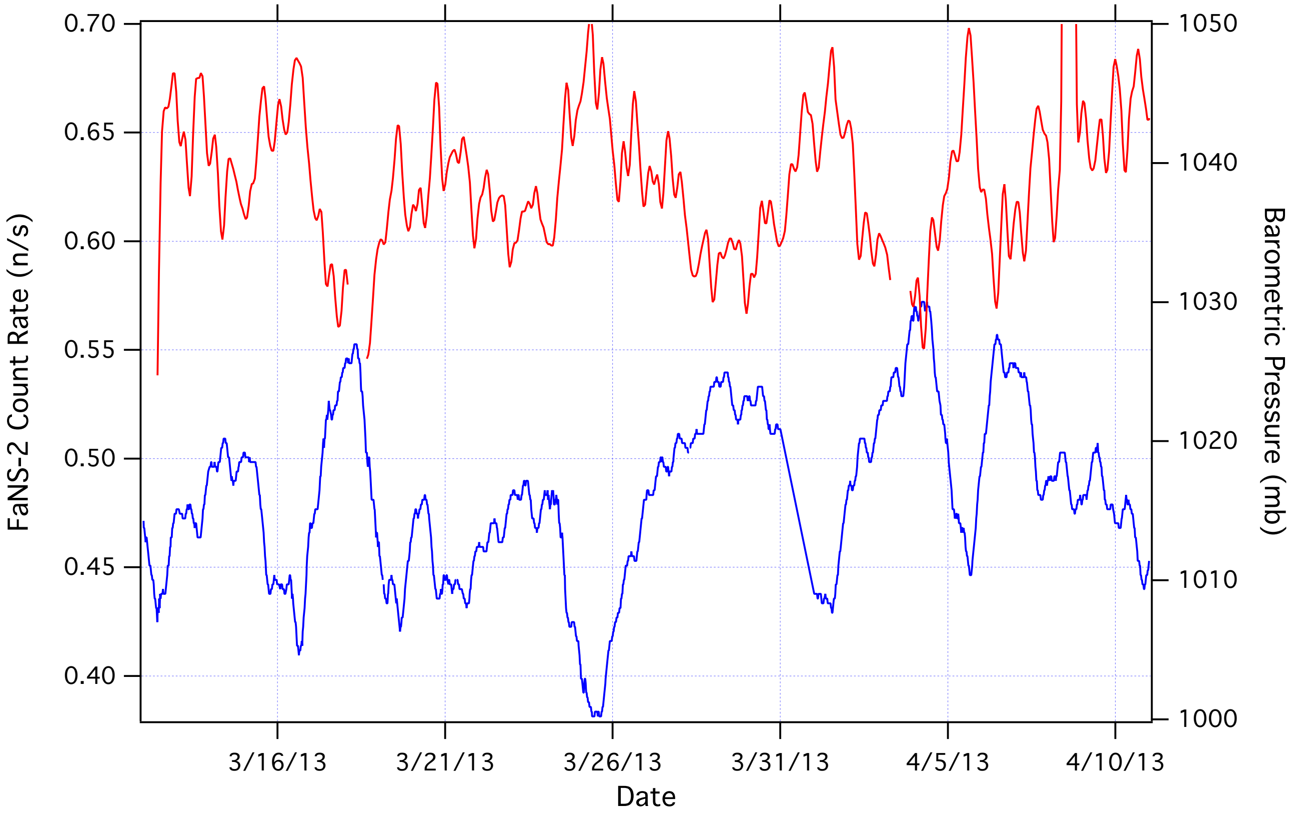
Gordon et al. Surface Neutron Spectrum

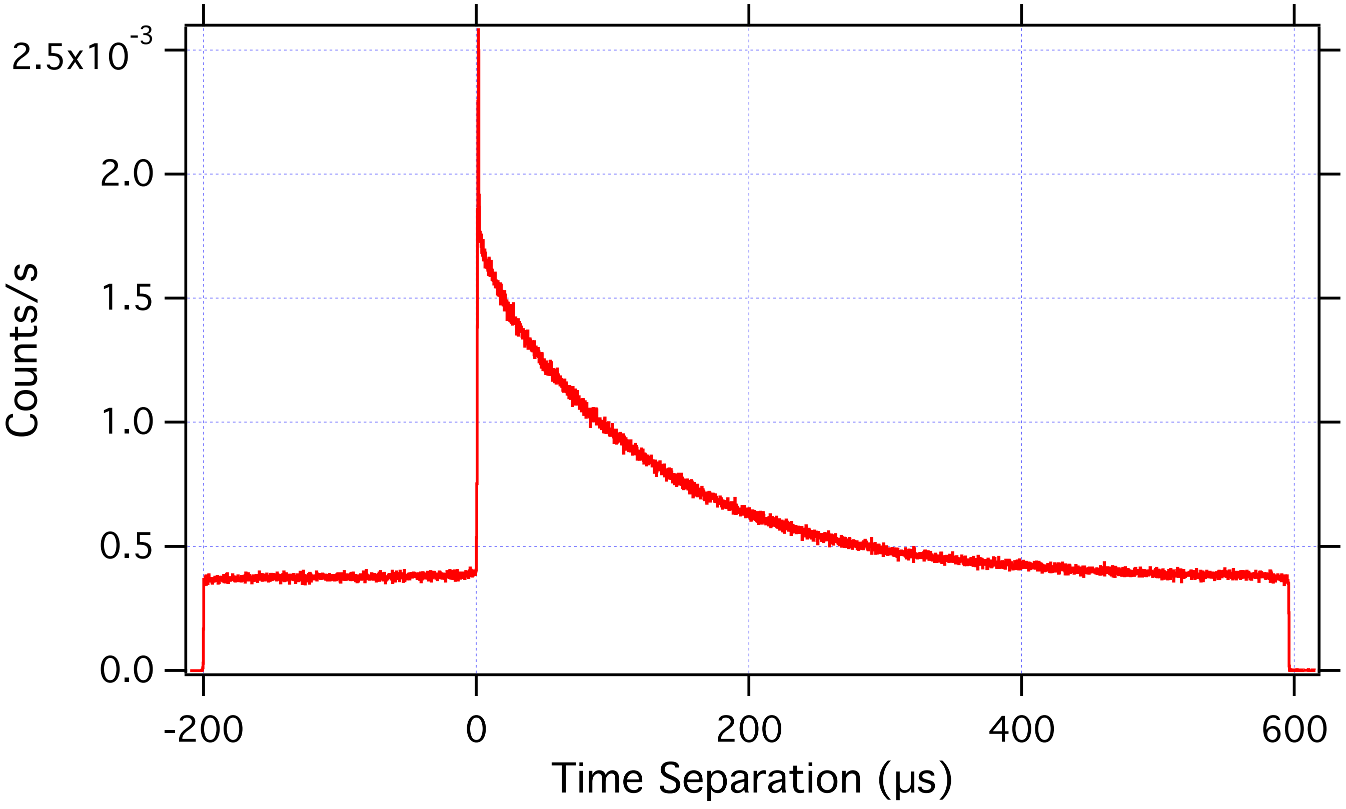
$\epsilon = 87 \pm 13\ n/(fluence)$

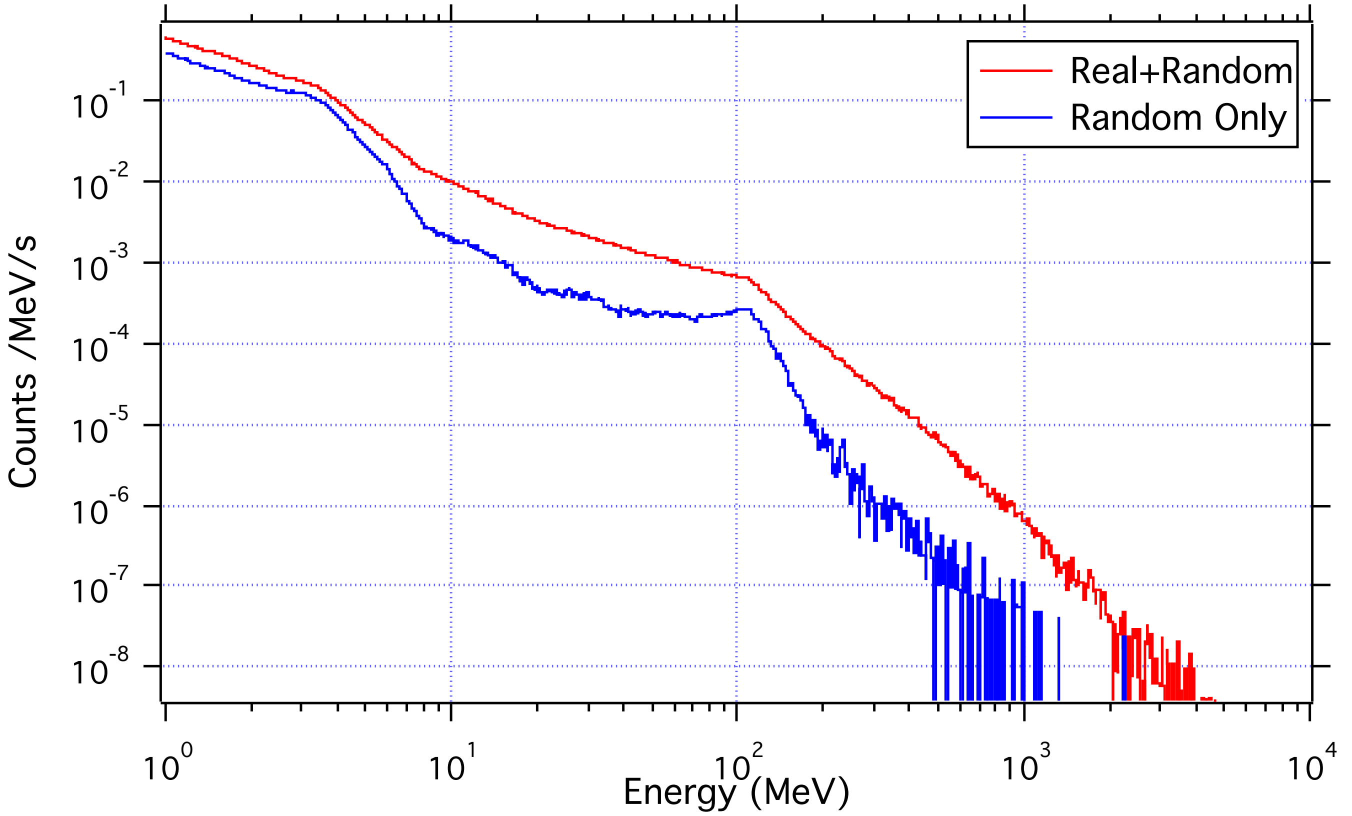
- Determine the response of FaNS-2 to an assumed cosmogenic neutron spectrum
- *Use the response to convert measured neutrons into incident flux*

Cosmogenic Neutrons at NIST

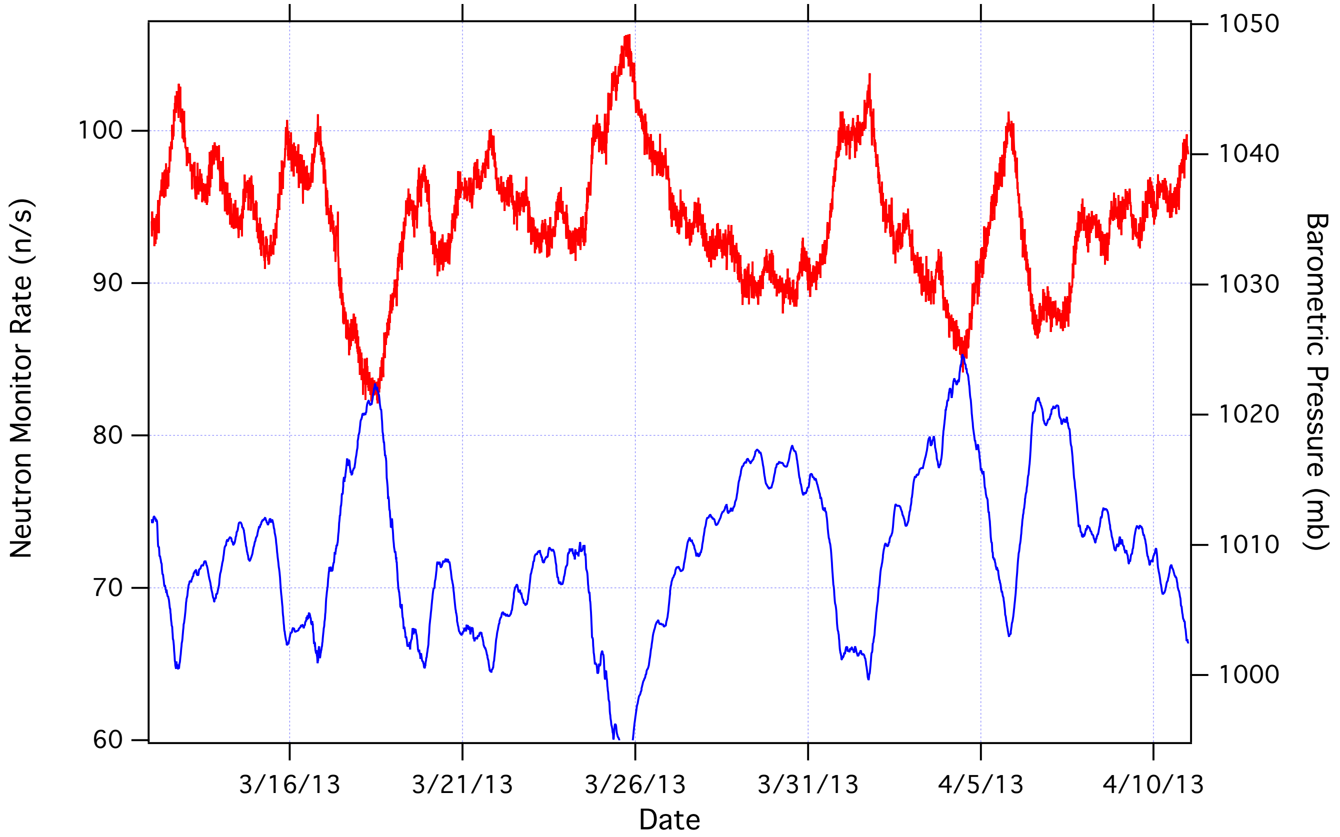
- Operated periodically over the course of 6 months
- 4×10^{6} triggers were collected
- Post BG subtraction, 1.7×10^{6} events remain



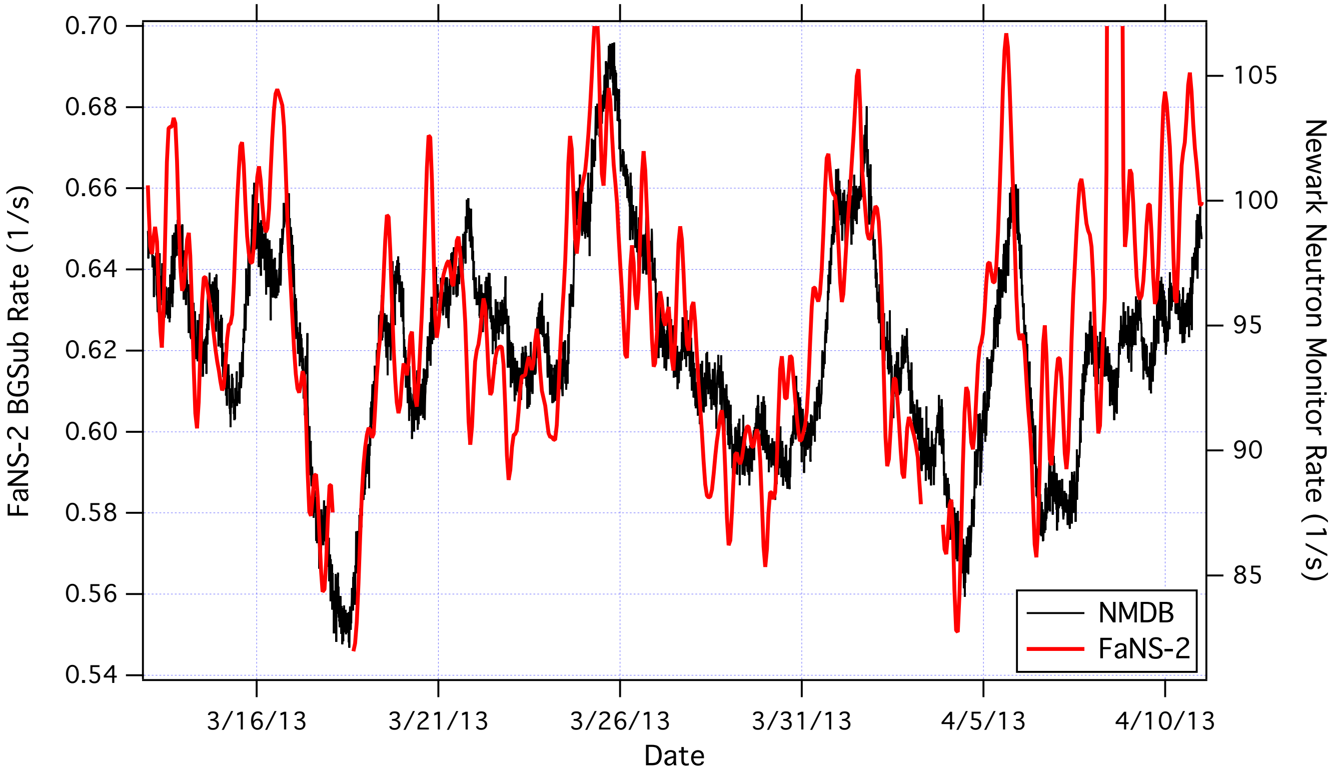


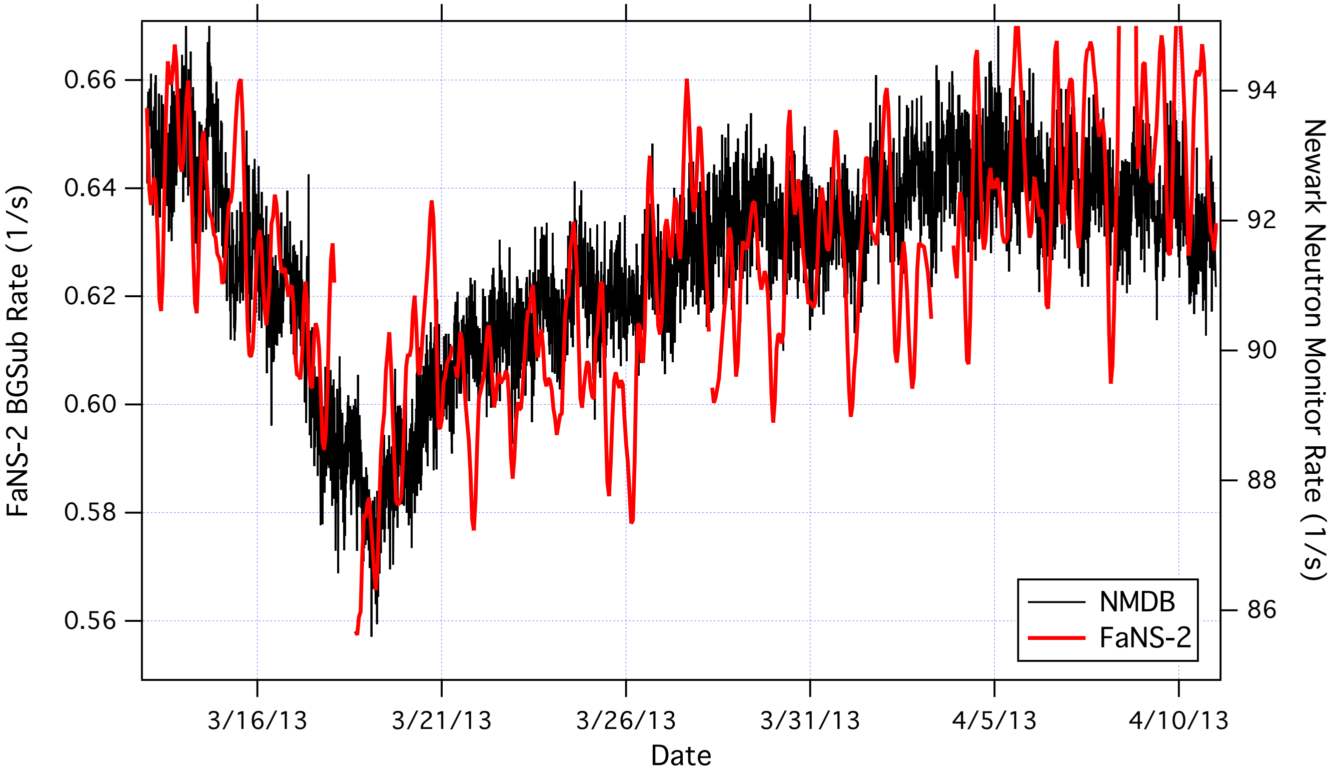


Barometric Variation



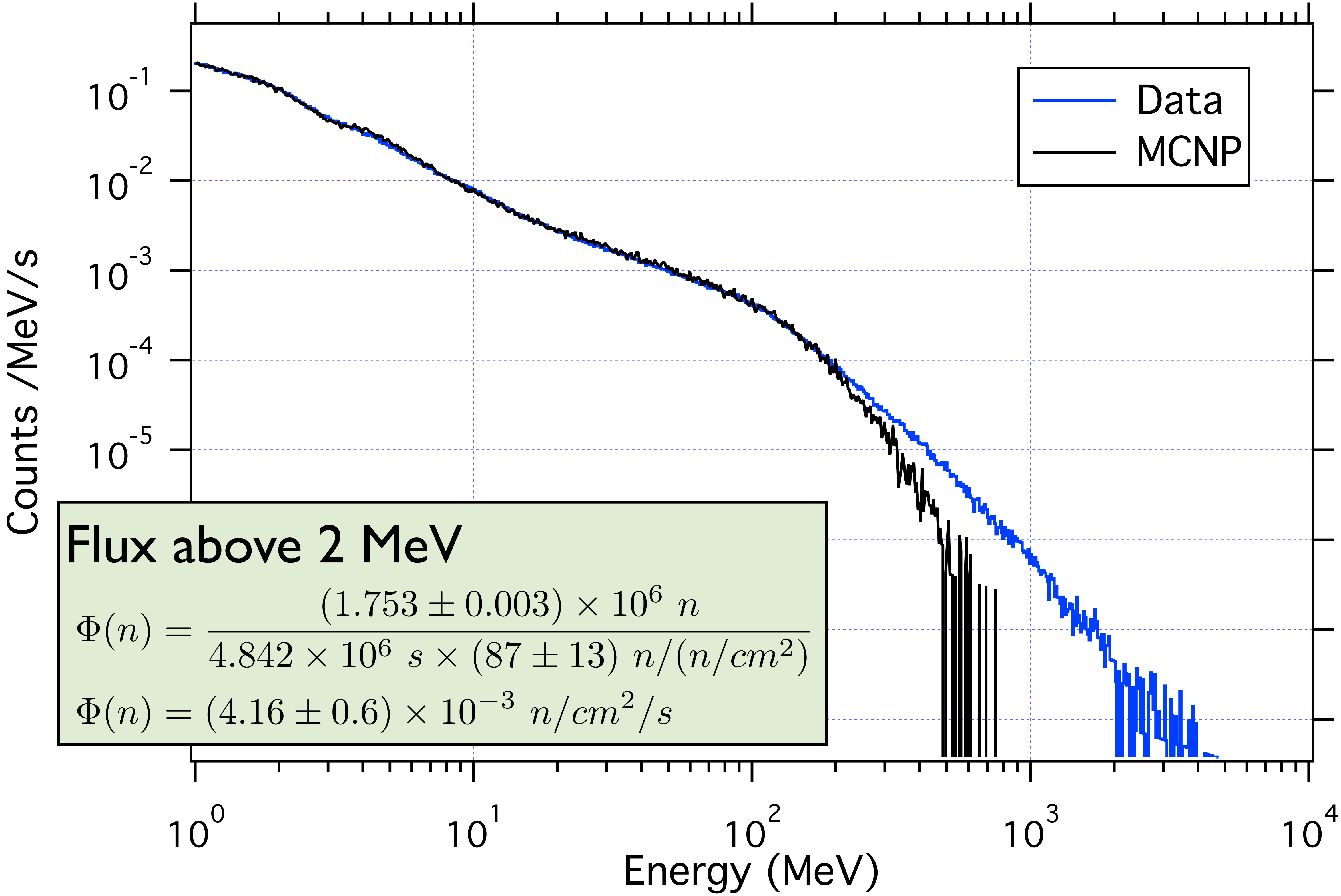
- Neutron monitoring stations to study solar activity are spread across the globe
- Data freely available!
- Can compare pressure corrected and uncorrected event rates





http://www.nmdb.eu/

Cosmogenic Neutrons at NIST

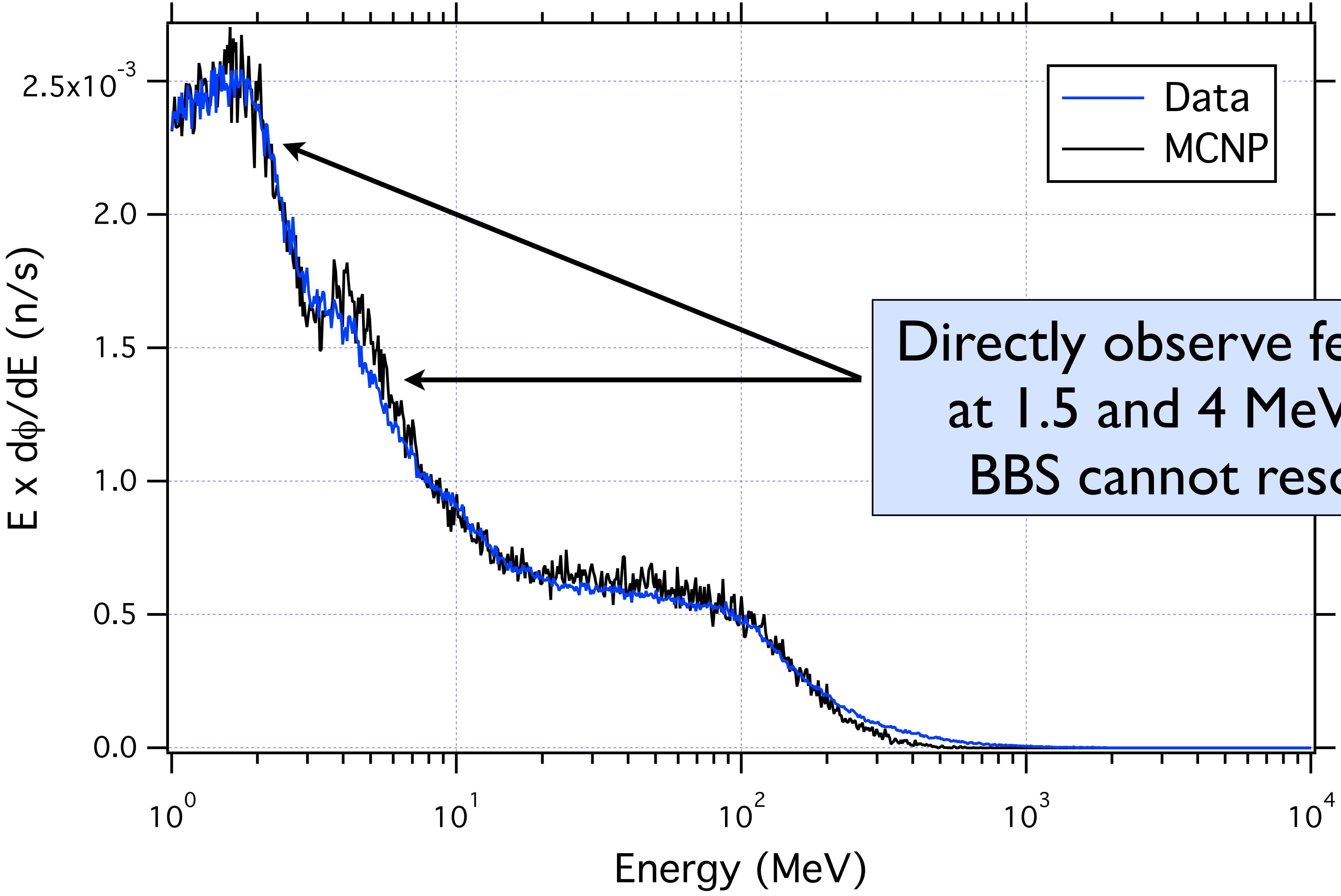


Flux above 2 MeV

$$\Phi(n) = \frac{(1.753 \pm 0.003) \times 10^6 \ n}{4.842 \times 10^6 \ s \times (87 \pm 13) \ n/(n/cm^2)}$$

$$\Phi(n) = (4.16 \pm 0.6) \times 10^{-3} \ n/cm^2/s$$

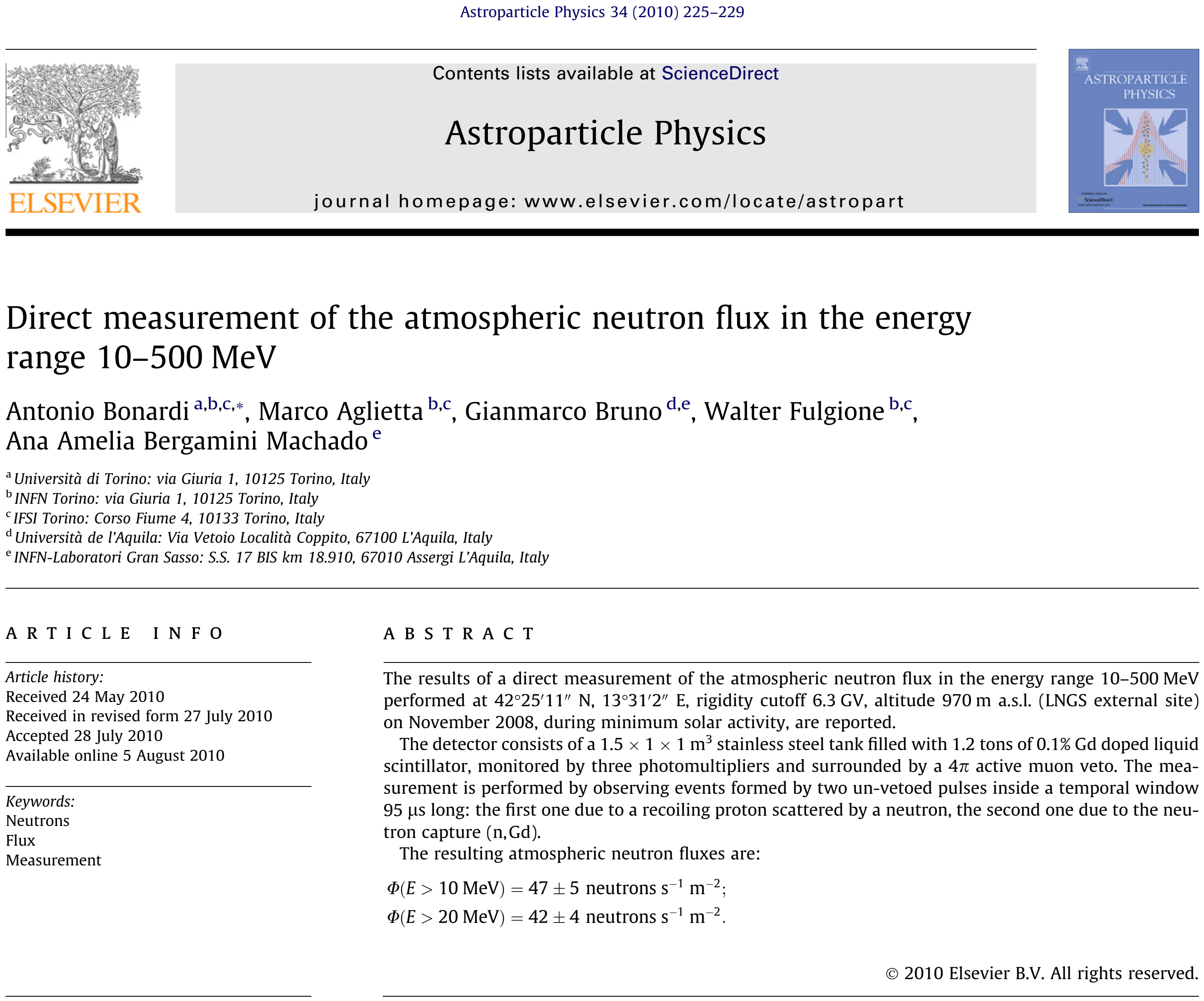
Cosmogenic Neutrons at NIST



Directly observe features at 1.5 and 4 MeV that BBS cannot resolve

CGS Measurement at LNGS

- 1.2 m^3 liquid scintillator doped with Gd, operated for 5 days
- Collected ~6×10^3 neutron events
- Measured flux above two thresholds (10 and 20 MeV) with 10% uncertainties



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Direct measurement of the atmospheric neutron flux in the energy range 10–500 MeV

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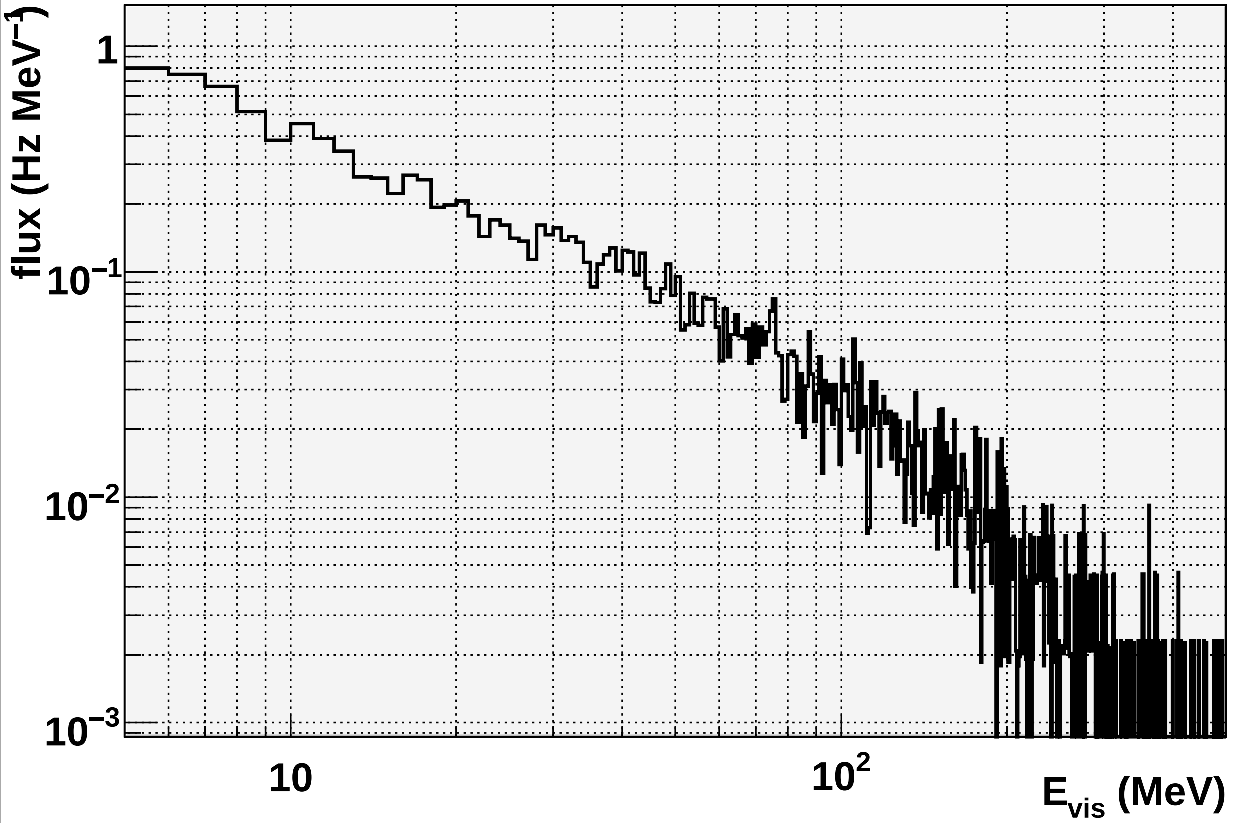
ABSTRACT

The results of a direct measurement of the atmospheric neutron flux in the energy range 10–500 MeV performed at 42°25′11″ N, 13°31′2″ E, rigidity cutoff 6.3 GV, altitude 970 m a.s.l. (LNGS external site) on November 2008, during minimum solar activity, are reported.

The detector consists of a $1.5 \times 1 \times 1$ m^3 stainless steel tank filled with 1.2 tons of 0.1% Gd doped liquid scintillator, monitored by three photomultipliers and surrounded by a 4π active muon veto. The measurement is performed by observing events formed by two un-vetoed pulses inside a temporal window 95 μs long: the first one due to a recoiling proton scattered by a neutron, the second one due to the neutron capture (n,Gd).

The resulting atmospheric neutron fluxes are:

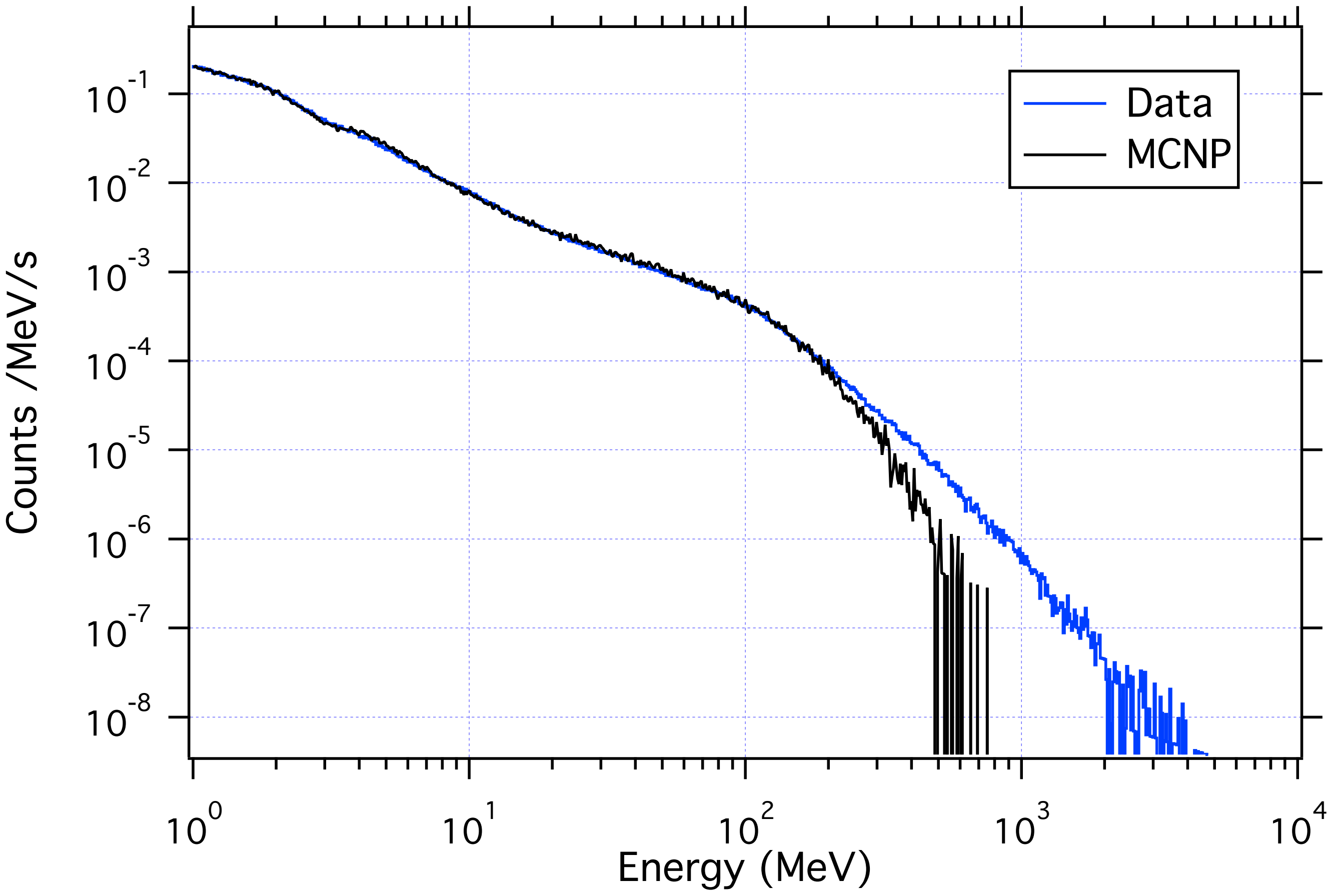
$$\Phi(E > 10\ \text{MeV}) = 47 \pm 5\ \text{neutrons s}^{-1}\ \text{m}^{-2};$$
$$\Phi(E > 20\ \text{MeV}) = 42 \pm 4\ \text{neutrons s}^{-1}\ \text{m}^{-2}.$$

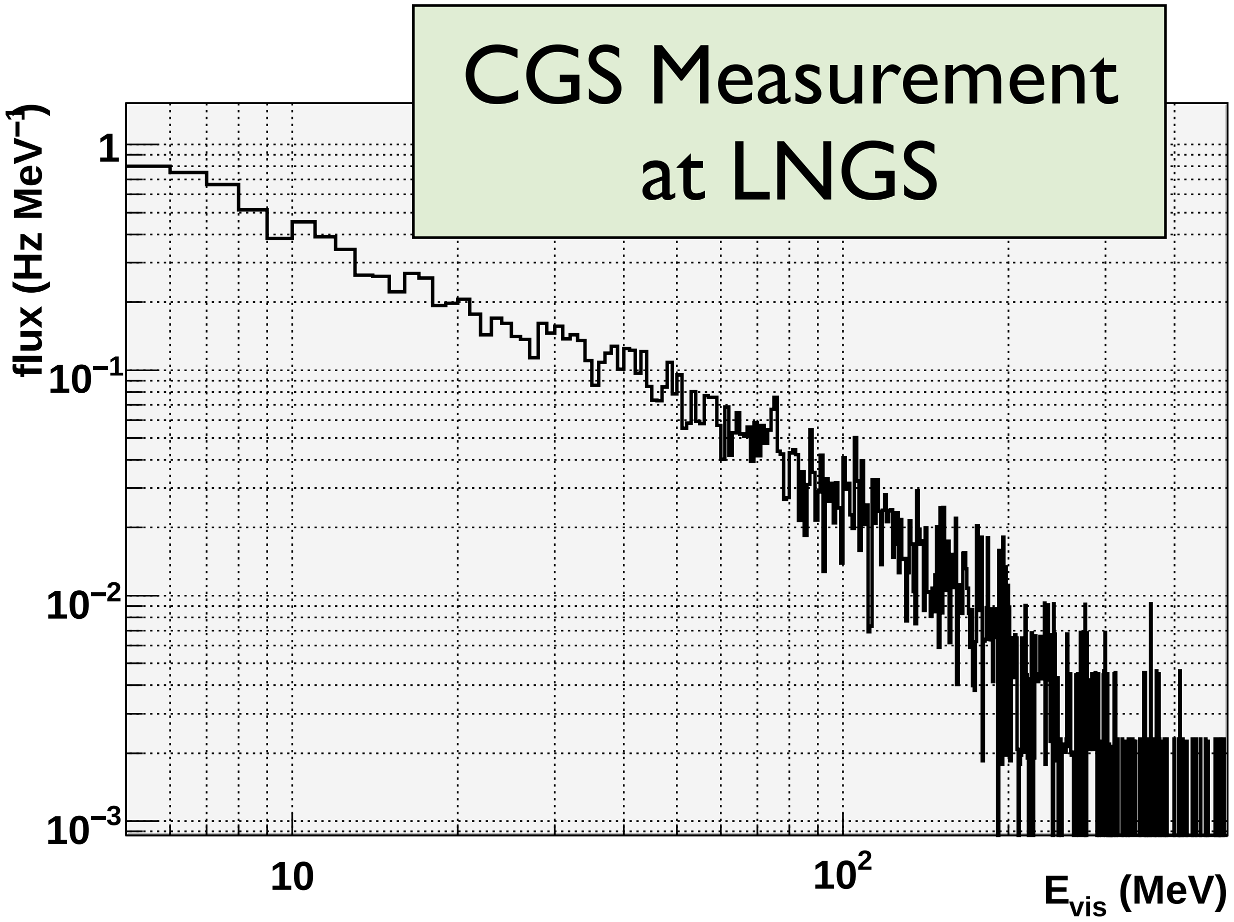


Conversion based on altitude, Geomag. cut-off, and solar activity to estimate location dependence of measurements

Gordon et al. 2004

NIST vs Gran Sasso National Lab





CGS Measurement at LNGS

Bonardi et al. Astroparticle Phys 34 (2010) 225–229

To compare between LNGS and NIST, a conversion factor (x1.64) based on location, and solar cycle has been applied

Table 7.14: A comparison between the LNGS and FaNS-2 measurements of the neutron flux above 10 MeV and 20 MeV.

Energy Range	LNGS Flux n/cm^2/s	Corrected LNGS n/cm^2/s	FaNS-2 Flux n/cm^2/s
$E_n > 10$ MeV	$(4.7 \pm 0.5) \times 10^{-3}$	$(2.9 \pm 0.3) \times 10^{-3}$	$(3.05 \pm 0.4) \times 10^{-3}$
$E_n > 20$ MeV	$(4.2 \pm 0.4) \times 10^{-3}$	$(2.6 \pm 0.3) \times 10^{-3}$	$(2.75 \pm 0.4) \times 10^{-3}$

FaNS Outlook

- Both FaNS-1 and FaNS-2 are operating at NIST
  - FaNS-1 is characterizing fast neutron backgrounds at reactors for PROSPECT, a new neutrino oscillation experiment that will operate at sea-level
  - FaNS-2 is measuring the muon-induced neutron spectrum at a depth of 20 m.w.e.
  - Work is underway to better understand the deviation between data and MCNP for $E_n > 200$ MeV
- The FaNS program has definitively demonstrated the benefit of CGS for neutron detection
- *The FaNS detectors are improving NIST's functionality for precision neutron spectroscopy*

Conclusions

- The surface and underground fast neutron backgrounds pose serious threats to the feasibility of current and future low-background experiments
- Current detection techniques lack the ability to fully characterize the spectrum and flux of these backgrounds
- Two novel detectors based on Capture Gated spectroscopy have been developed and calibrated by the UMD/NIST collaboration
- FaNS-1 successfully performed a measurement of the surface fast neutron spectrum before being deployed at KURF
- FaNS-1 characterized the fast neutron background at KURF demonstrating that the spectrum is (alpha,n)-like
- *FaNS-2 greatly improved on the measurement of the surface fast neutron spectrum, and made a definitive measurement of the flux*