Neutron Detection

And thoughts on why neutrons are interesting and hard to deal with

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Talk plan:

- Why are we (greater we) interested in neutrons?
- Some obvious things about neutrons
- Nuclear reactions
- Classes of detectors
- Metrology
- Fast neutrons
- How this ties into meeting

My hope is to build toward *high-efficiency fast neutron spectrometry*, as this is likely rather relevant to the topic at hand

Disclaimer: There are an astonishing number of ways to detect neutrons
Can't do a full treatment, just a survey… ignoring long counters, bubble chambers (a possible candidate), solid state, etc…

A few well known things about neutrons:

They are neutral:

- there is no direct ionization in a material, thus no continuous deposition of energy
- long interaction lengths
- don't care much about electric and magnetic fields, not simple to manipulate

They interact via the nuclear force:

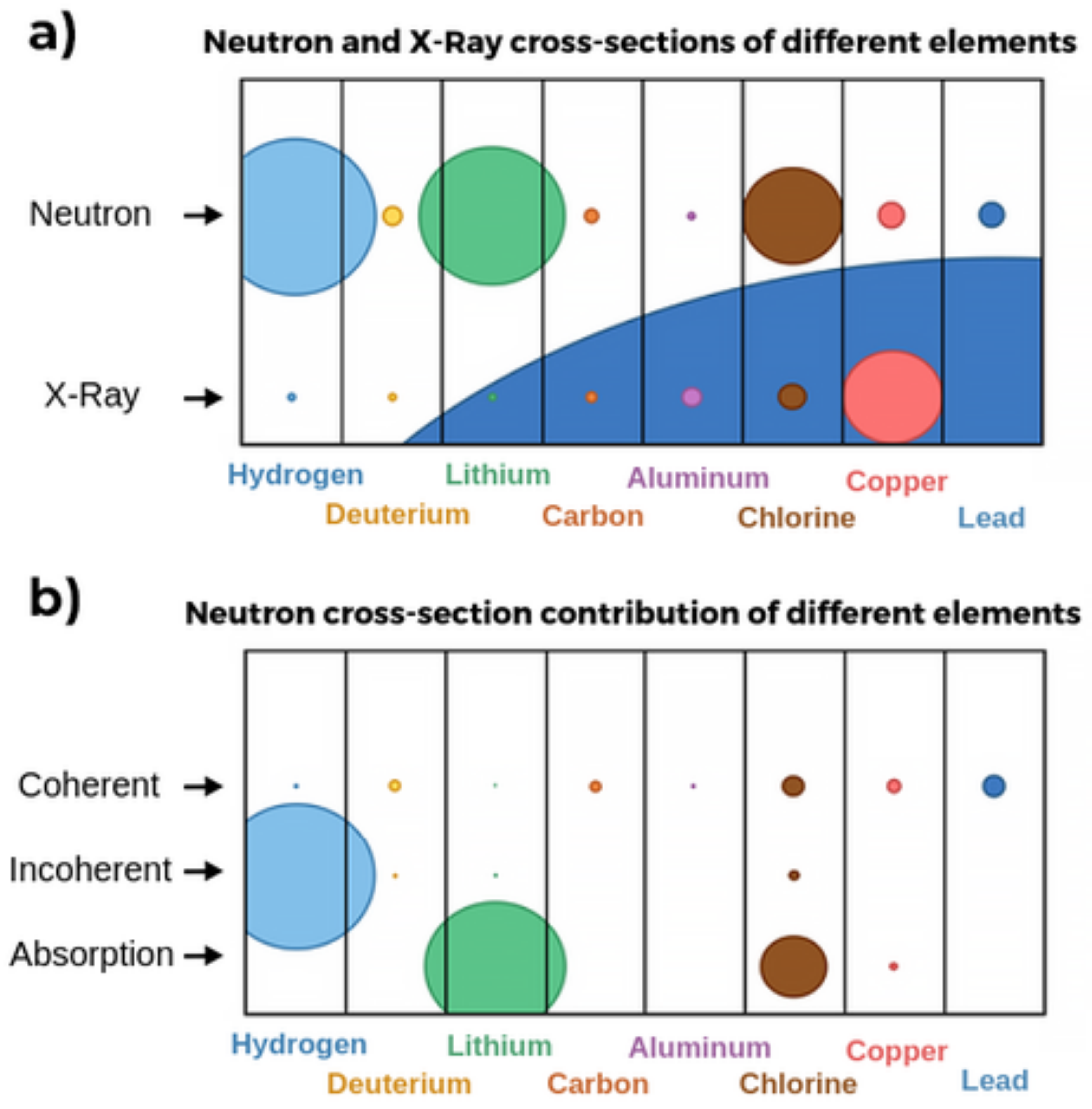
- interaction depends on nuclear structure
- Scattering and absorption trend differently
- Very very strong isotope and energy dependence

They are 'heavy'

- recoil energies can be significant kinematically

They interact via the weak force

- isotopes with too many neutrons reach stability by emitting detectable radiation (usually)



https://theory.labster.com/neutron_cross-section/

Why do neutrons matter?

Thermal (and cold): < 0.025 eV, > Angstrom wavelengths

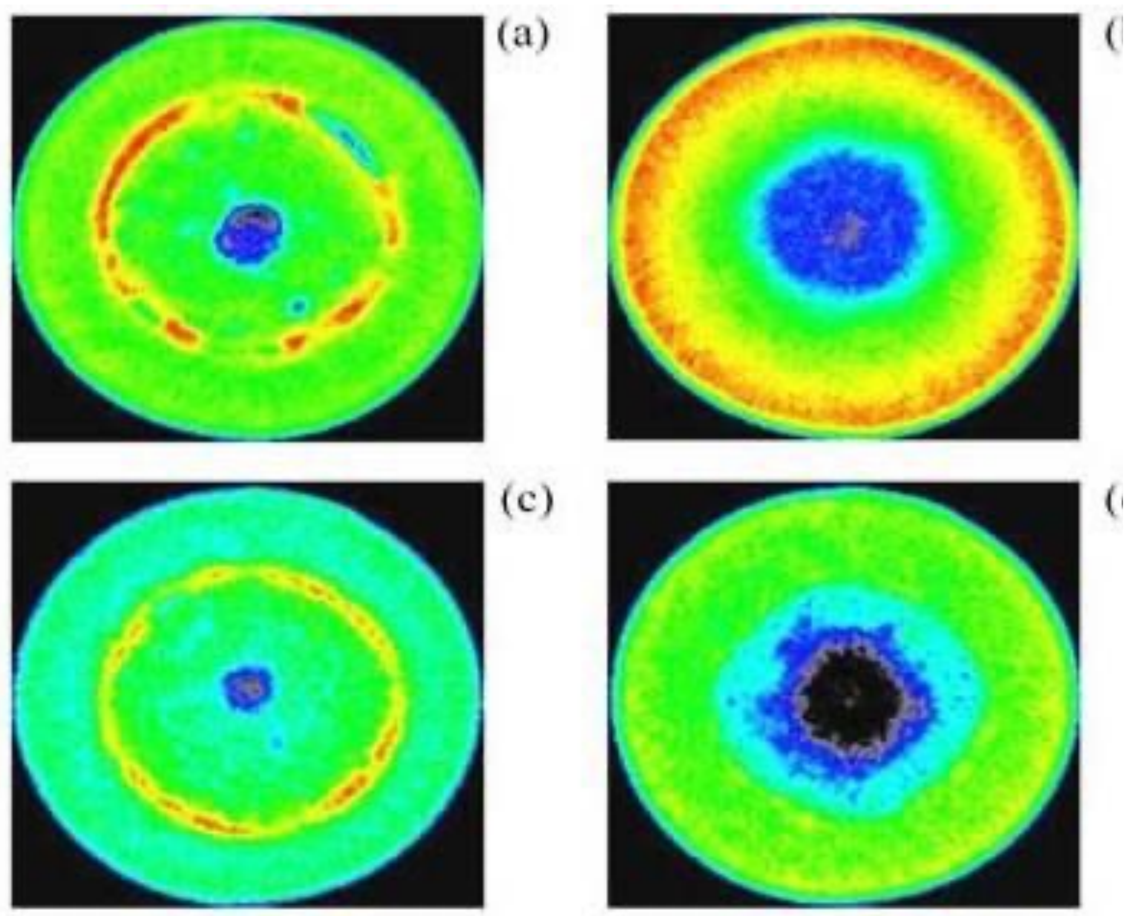
- Reactors
- Dosimetry in neutron facilities
- Penetrating w/ wavelengths similar to lattice spacing in materials - fantastic for studies of condensed matter, imaging
- Variation in cross section can be a wonderful tool
- Cold neutrons are easy to manipulate and offer many precision tests of the Standard Model

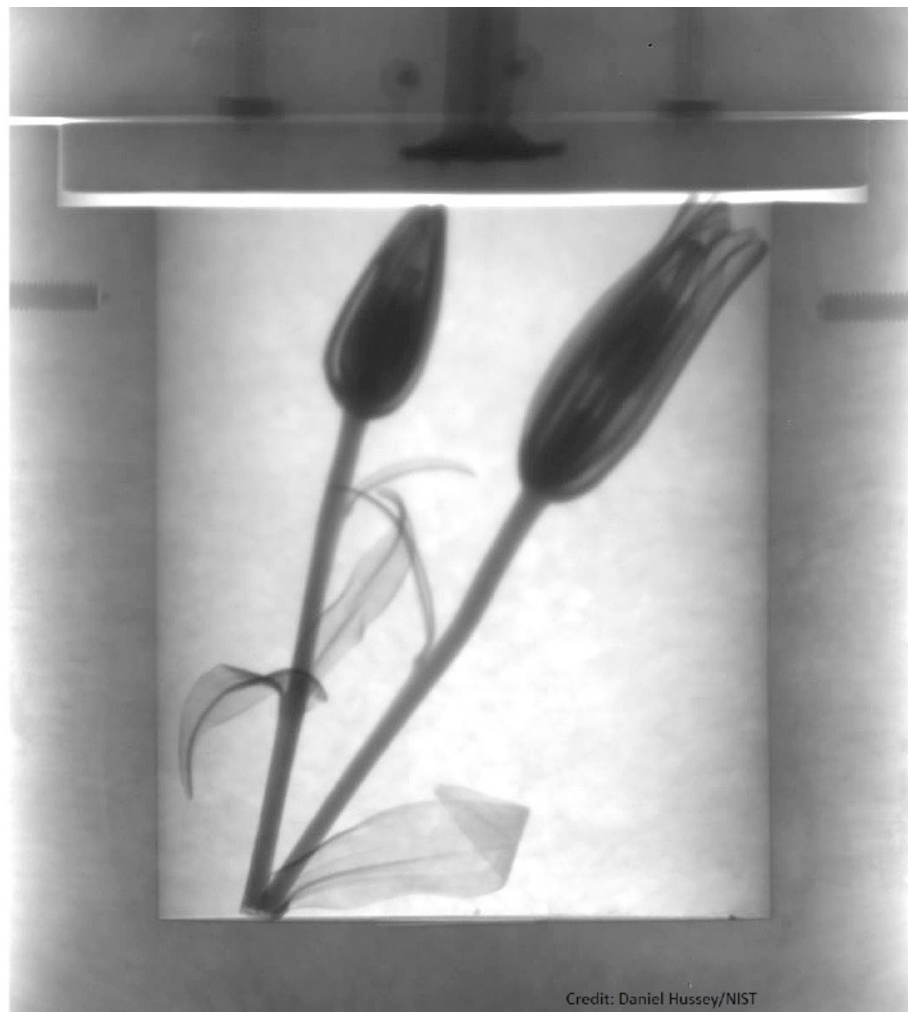
Epithermal: 0.025–0.4 eV

- Penetrating in region w/ many resonances, less material damage
- Activation studies, transmutation

Fast: > 1 MeV

- Reactors again…
- Penetrating material studies (e.g. oil wells, concrete aging)
- Material damage studies, lattice dislocations
- Dosimetry (50% of high-altitude dose is from fast neutrons)





$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\mathrm{CKM}}(\epsilon_i)$$

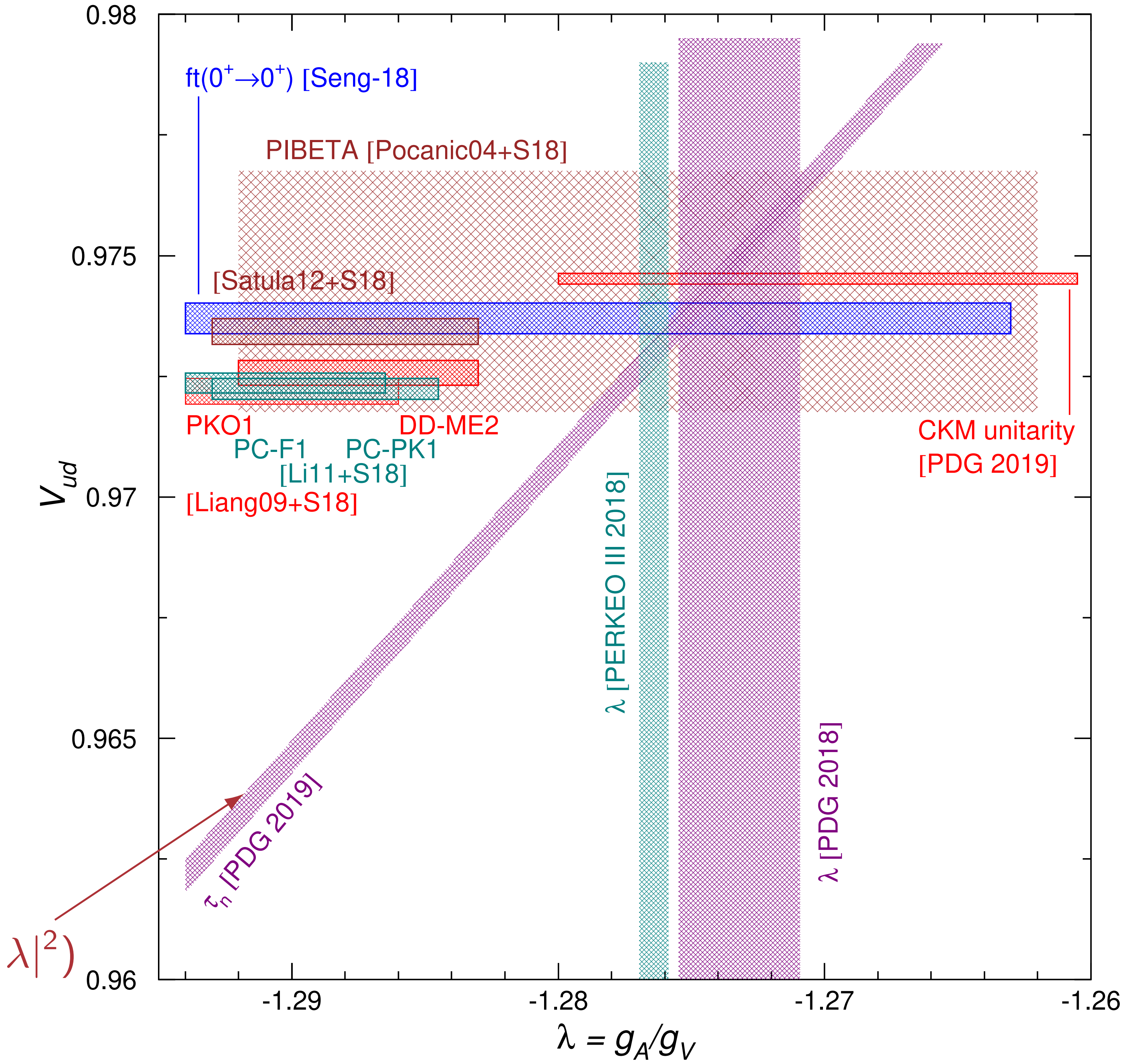
Until recently, CKM unitarity appeared valid:

A 2018 dispersion rel. analysis of Δ_R^V, universal radiative correction to superallowed β decay, has led to a dramatic downward shift in V_{ud}:

[Seng et al., arXiv: 1807.10197/PRL **121** (2018) 241804, 1812.033352, 1812.04229]

(theoretical work continues)

$\tau_n^{-1} \propto |V_{ud}|^2 |g_V|^2 (1 + 3|\lambda|^2)$



From Počanić (2019)

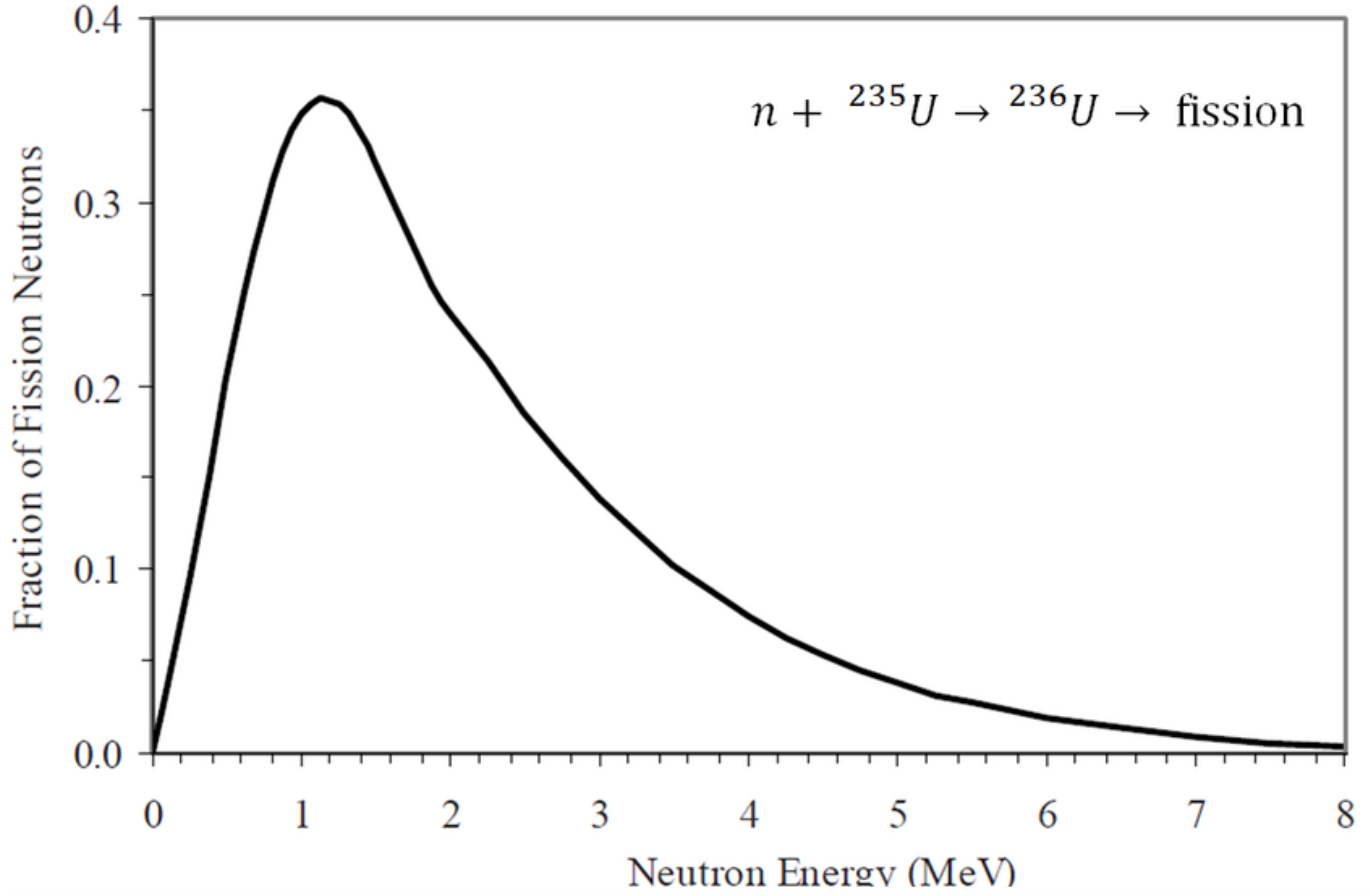
Neutrons from fission

All isotopes yield similar spectra

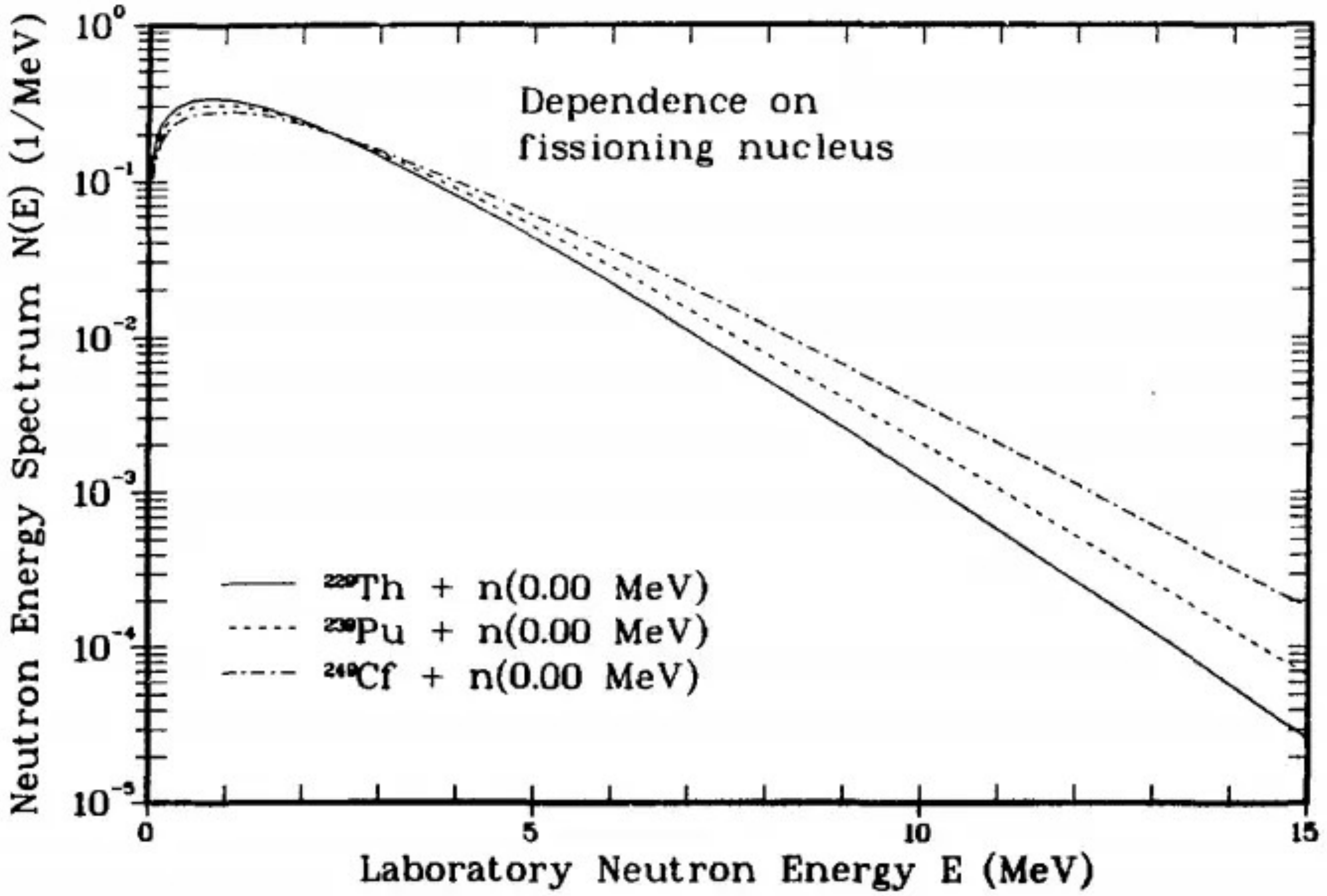
- 2-3 neutrons per fission
- Nearly all neutrons between 0.1 and 10 MeV
- Most probable energy is around ~1 MeV

In the natural environment the dominant fissioning isotope is ^{238}U (^{235}U has a natural abundance of ~0.7%) - amount varies widely but is very roughly a few ppm.

Fission is usually dominated by other sources of neutrons in the 'nature'.



https://www.researchgate.net/figure/Neutron-energy-spectrum-for-thermal-fission-of-235-U-Image-from-11_fig8_359467502



https://www.nuclear-power.com/nuclear-power/reactor-physics/atomic-nuclear-physics/fundamental-particles/neutron/fission-neutron/

Cosmogenic neutrons

High energy:

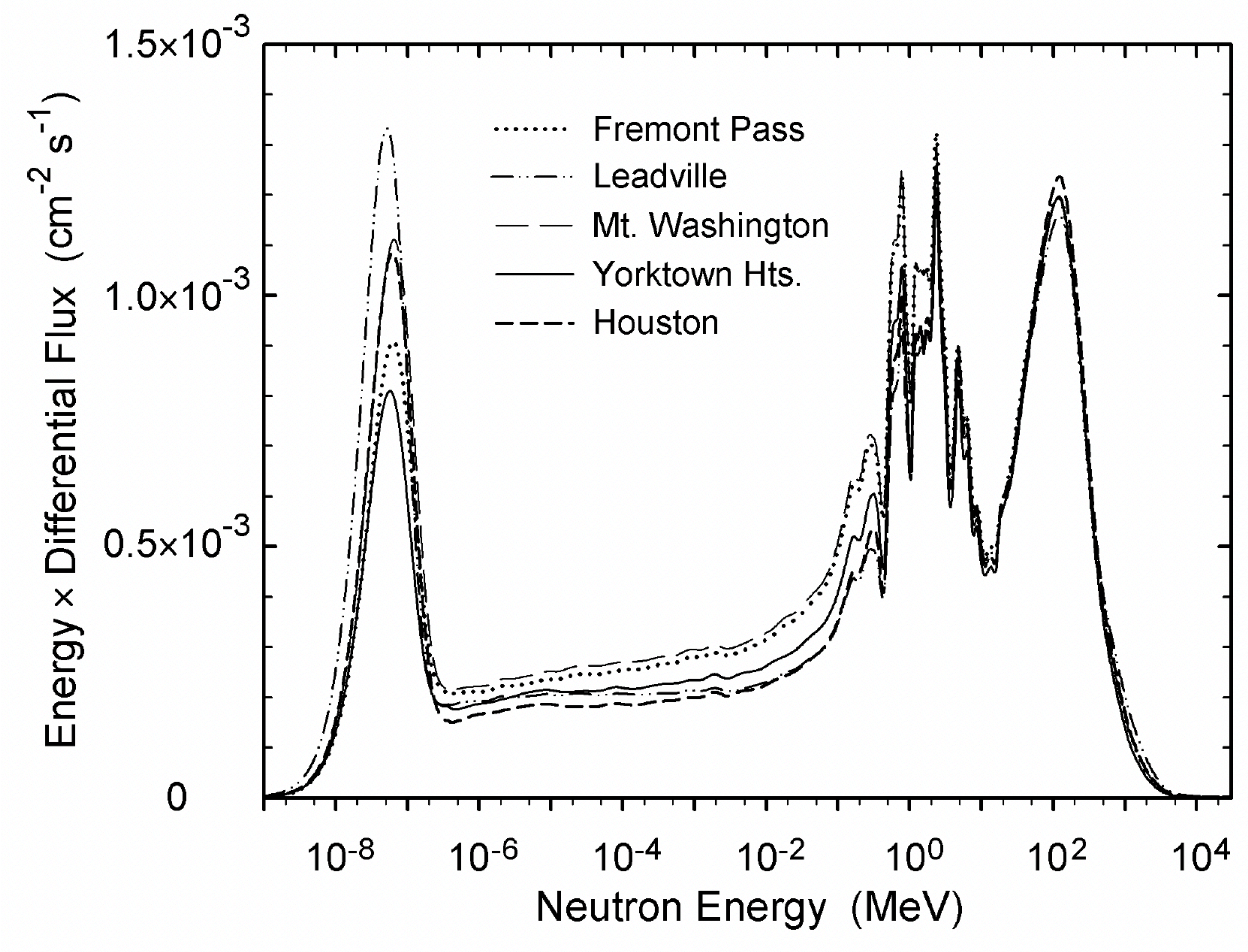
- High energy cosmic rays fragment nuclei (nitrogen and oxygen) and yield 'direct' ≤ GeV neutrons

Evaporation peak:

- High energy proton and muon collisions excite nuclei in the atmosphere. De-excitation of the nucleus occurs by statistical evaporation of light particles - predominantly neutrons

Thermal peak:

- Fast neutrons from the higher portion of the spectrum thermalize in the ground (to a lesser extent in the atmosphere)
- Peak amplitude is thus *highly* dependent on environmental conditions.



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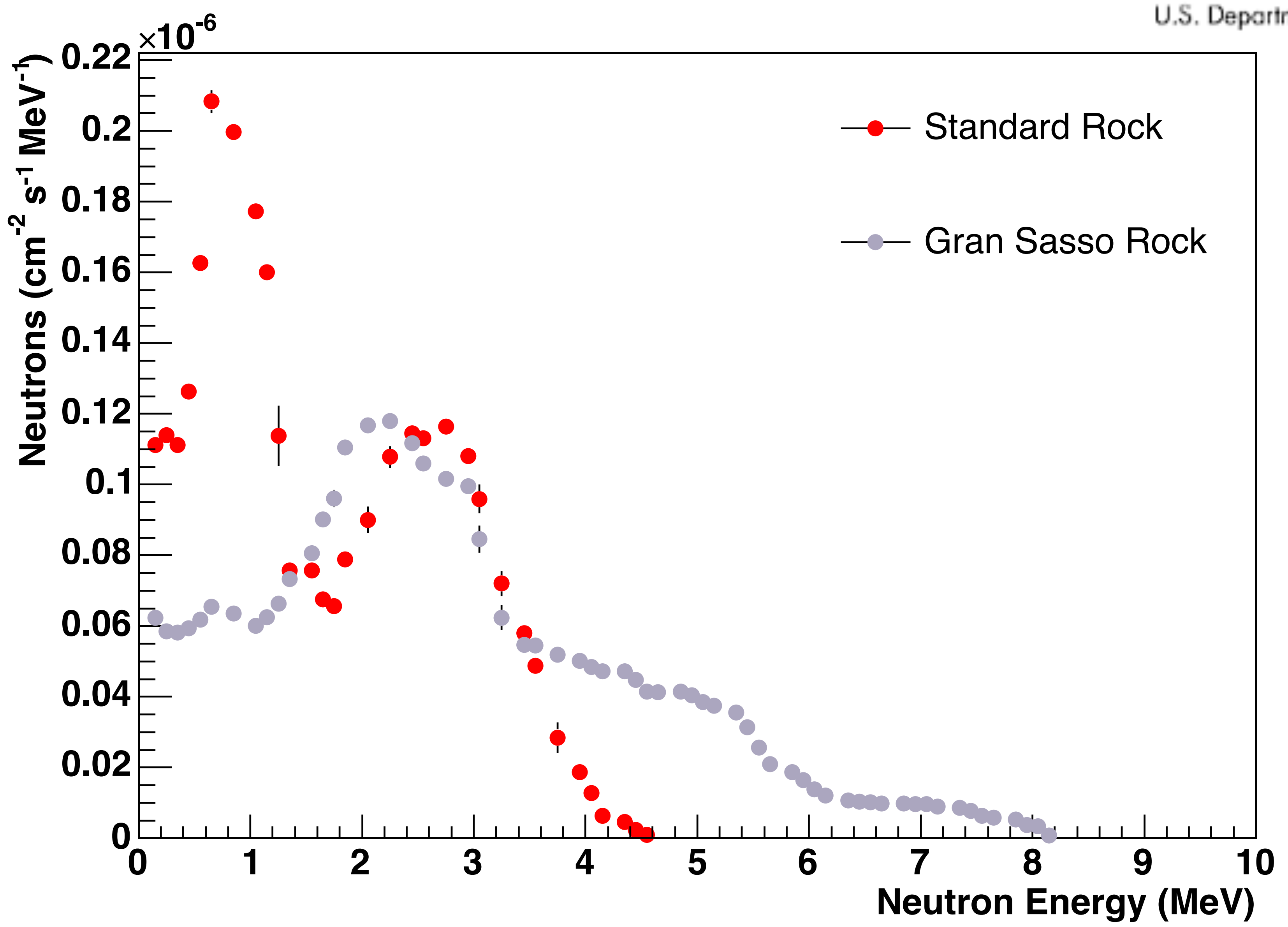
Other nuclear reactions

(α,n):

- Fission decay chains (^{238}U and ^{232}Th and consist of 6 and 8 alpha-decays, respectively)
- Energetic alphas give (α,n) reactions on light nuclei
- Typically higher than muon induced neutrons at deep underground sites, but softer spectrum
- Because they depend on makeup of rock, specialized computer codes used to predict spectra



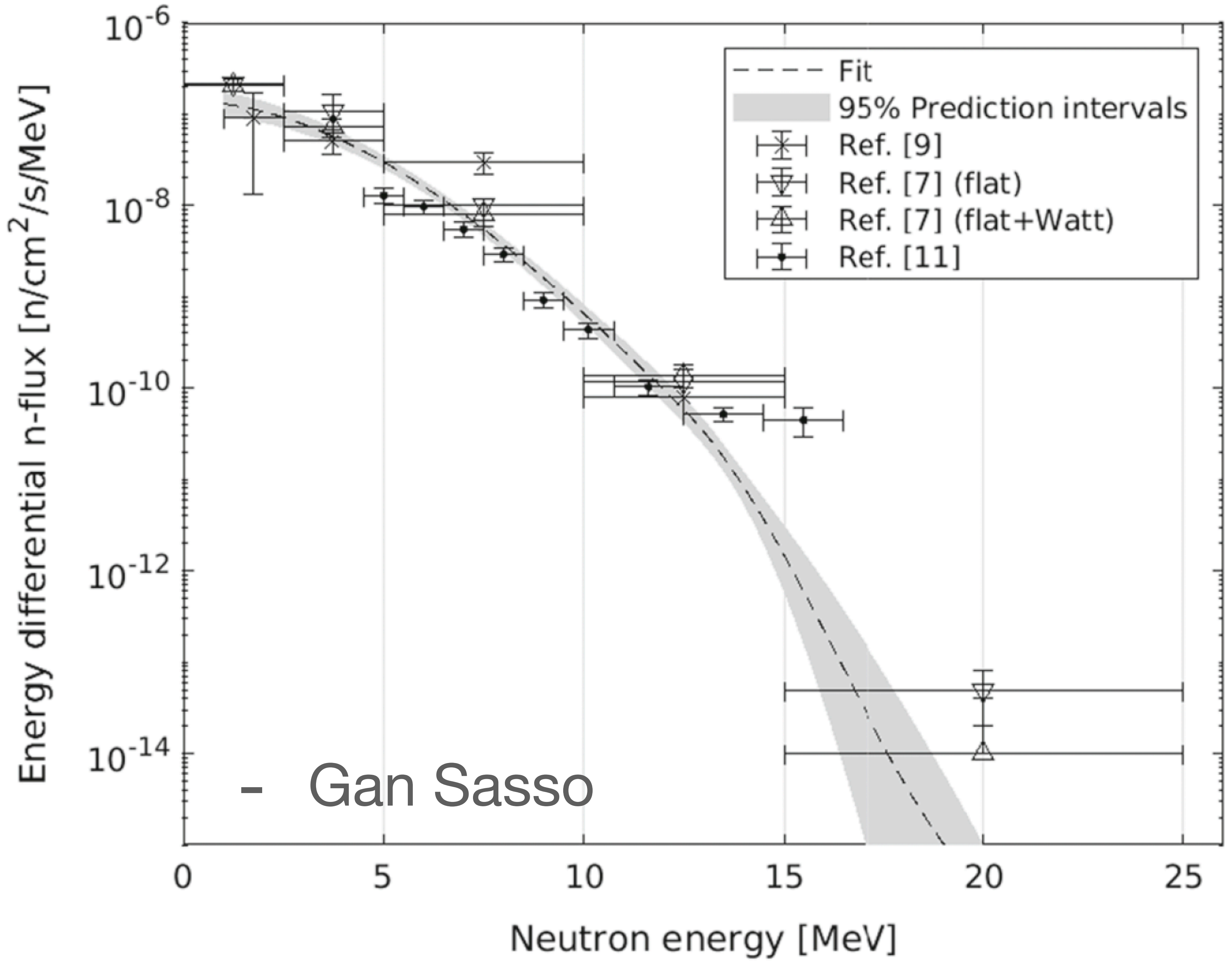
Mei and Hime, Phys.Rev.D73:053004,2006

Accelerator systems:

- Light beams (protons, deuterons, alphas) on a variety of targets used to produce high intensity (spallation) or mono-energetic (nuclear reaction) neutron beams.
- p+T, p+D, p+7Li, etc… up to 20 MeV

Reactors:

- Obviously controlled fission in a reactor can be used to create very high ~10^{15} cm^{-2} neutron fields.
- Moderated to produce high flux thermal and cold beams



https://doi.org/10.1140/epjc/s10052-023-11522-x

https://doi.org/10.1016/j.nima.2020.164095

Interaction length and time scales

Neutron cross sections are in some sense ‘small’.

- Absorption cross sections for isotopes like H and O are ~10s mb (100 times smaller than capture)
- Traveling at ~2000 m/s, thermal neutrons can propagate large distances before capturing (~10% scattering per meter in air)
- If you don’t want to deal with thermal neutrons you better have a hermetic shield (e.g. boron rubber)
- Fast neutrons can penetrate at meter scale in solids, among other things this means interactions are distributed in the bulk
- Thermalization occurs in μs and capture (solids) occurs ~100μs scales
- Fast neutron detectors need to be large to have high efficiency (especially at 100 MeV and above)

Applications:

- Thermal neutron return from materials tells you about water content, isotopic makeup
- Long rang monitoring of reactors
- Nuclear security

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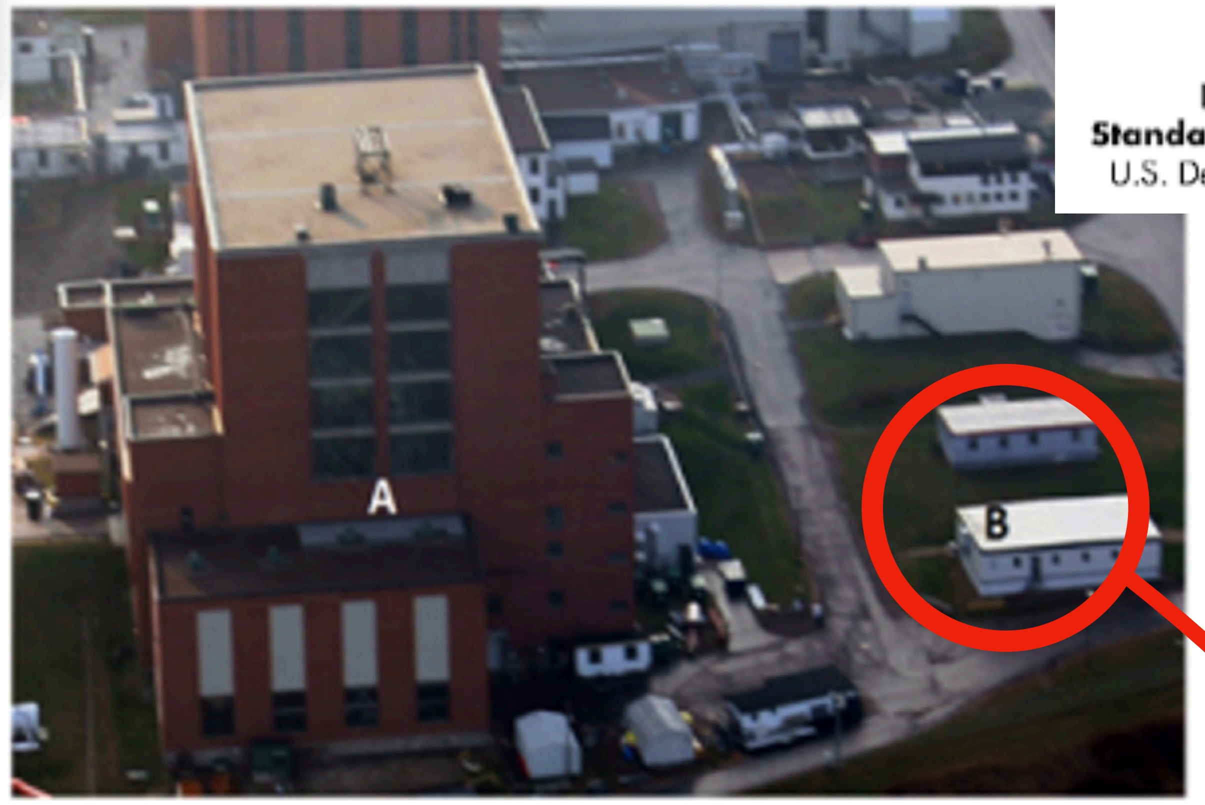
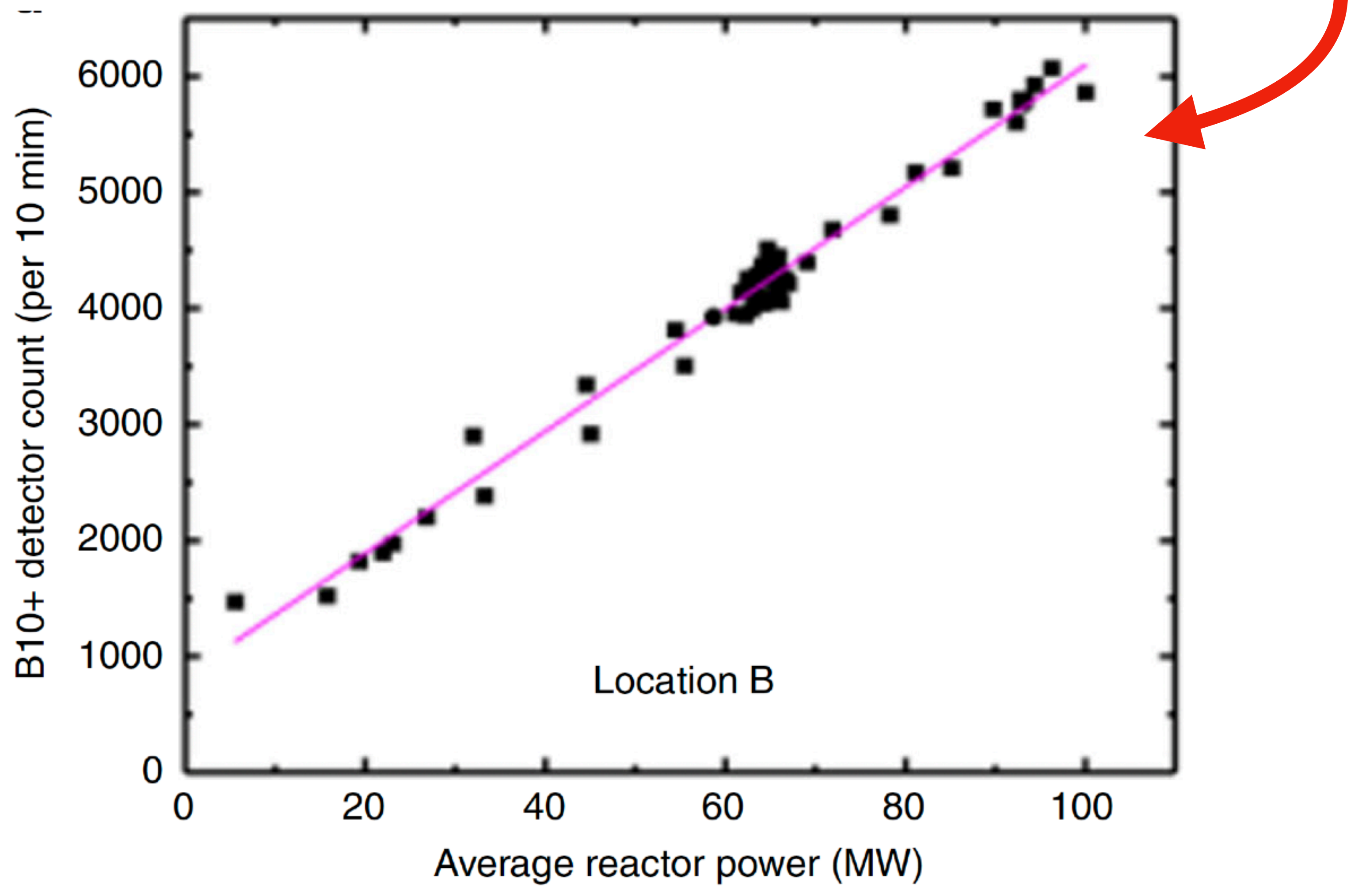
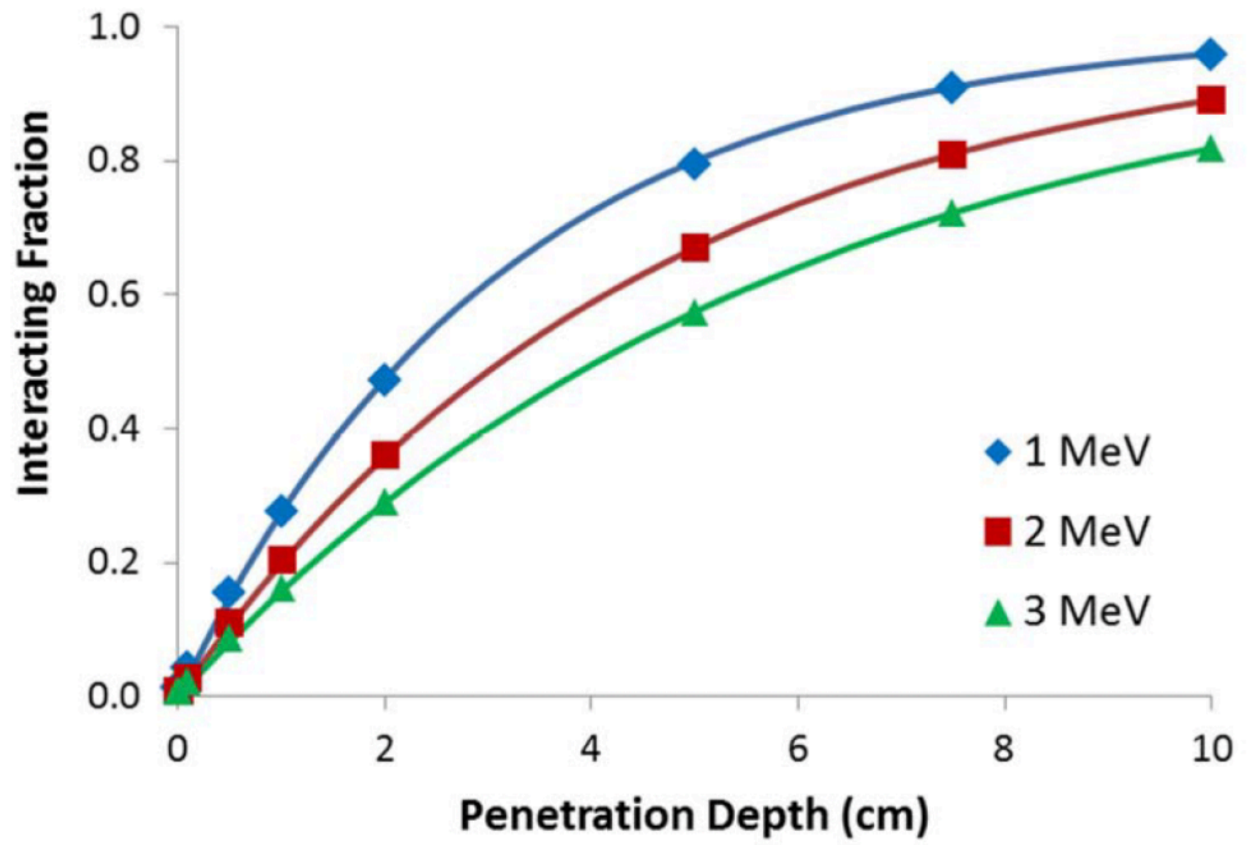


https://doi.org/10.1038/s41467-019-09967-4





Cross sections vary wildly by isotope and energy

- several orders of magnitude difference between large and small cross sections
- several orders of magnitude between cross sections at thermal and 'fast' energies

At thermal energies and below vary as 1/v

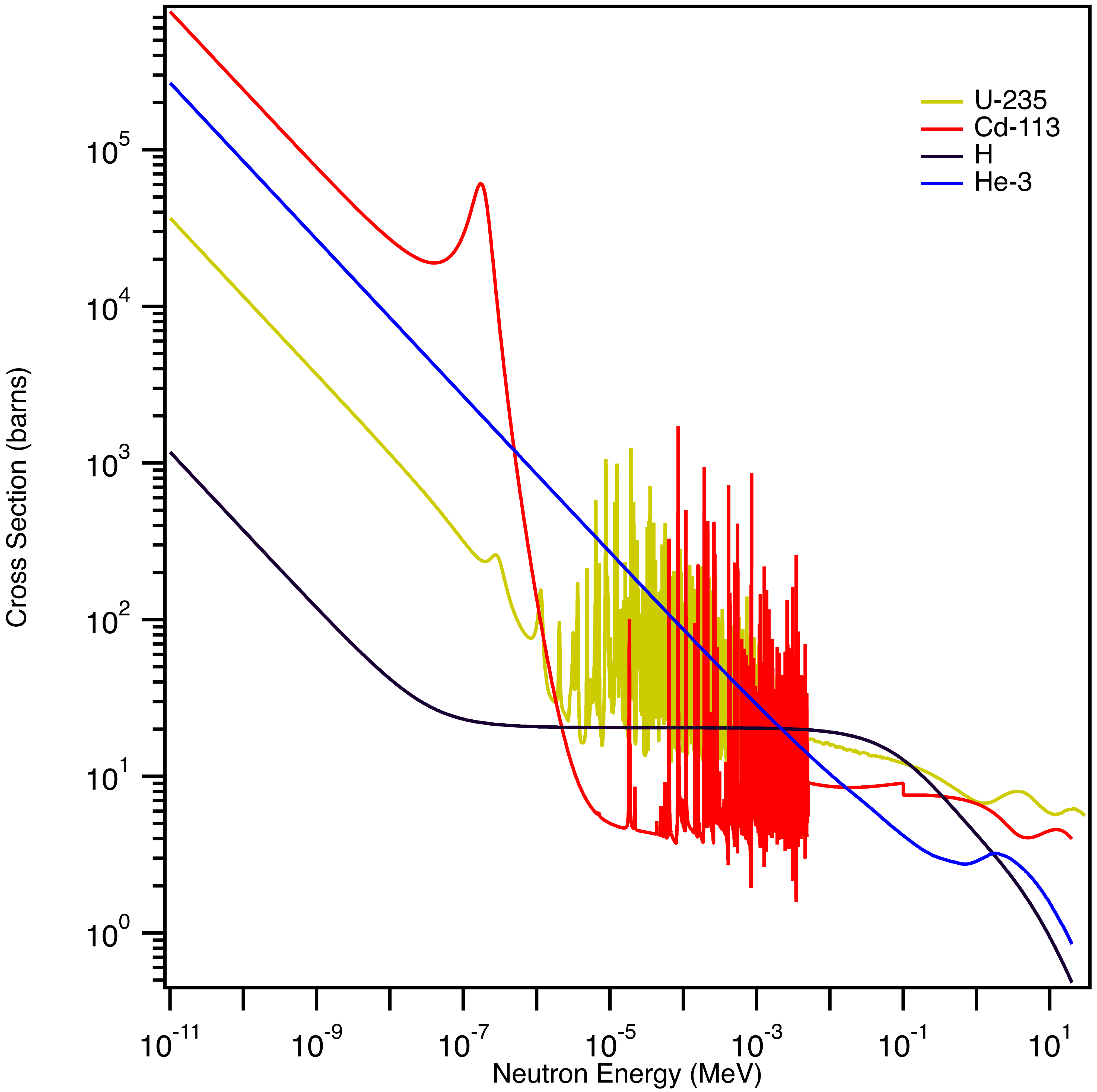
- absorption depends on time spent near the nucleus

Nuclear structure leads to resonances

- Cross sections have important and complicated structures

Many isotopes have fairly sharp changes in cross section.

- cutoffs can be useful in determining spectral information even with counts-only information.



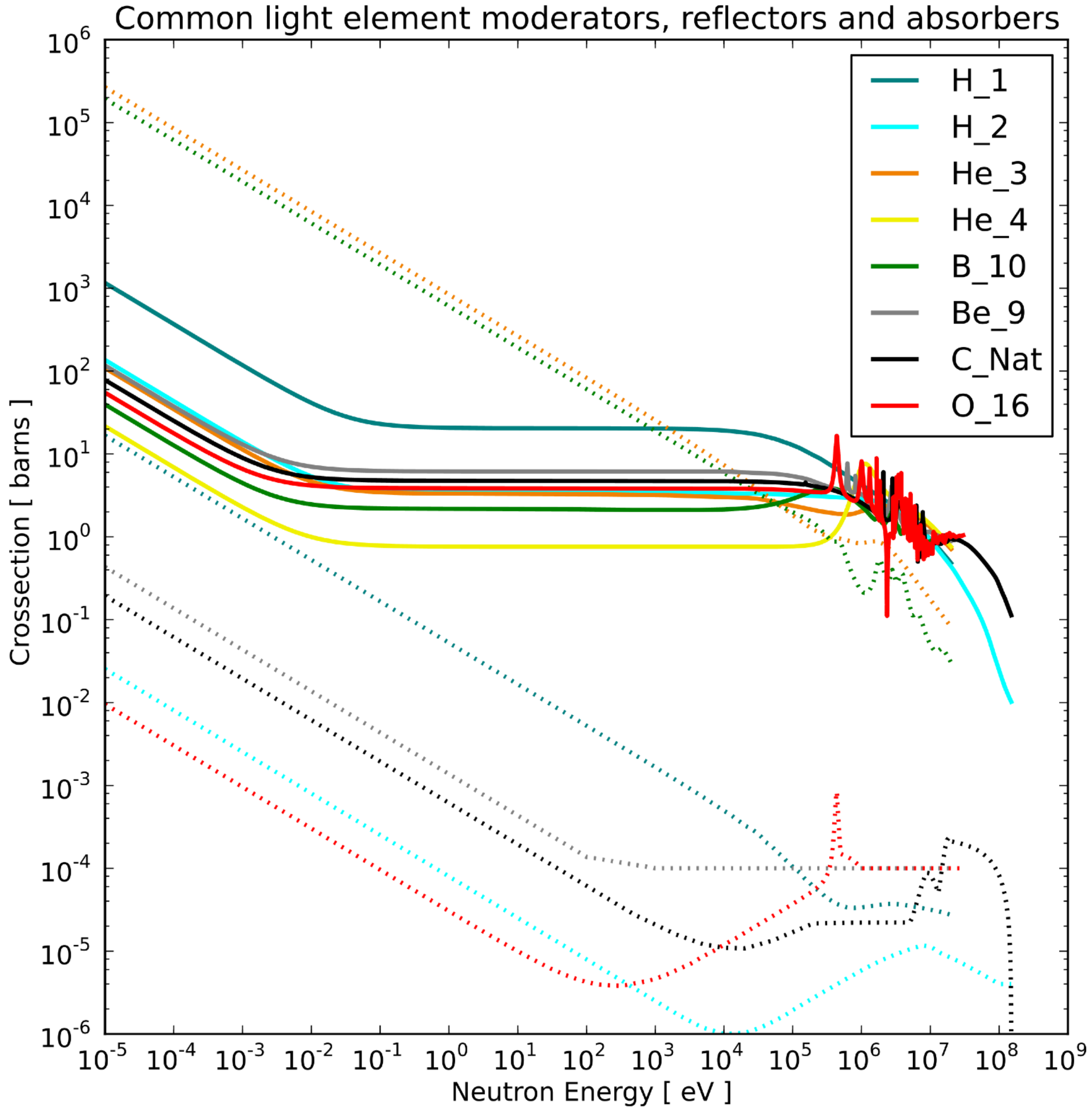
https://www.nndc.bnl.gov/endf/

Many/most elements have large differences between absorption and scattering cross sections

- Useful for moderating fast neutrons to lower energies where other isotopes have large cross sections.

In light moderators neutrons loose significant energy per scatter (H ~ x2)

- Fast neutrons rapidly loose energy on scales of ~10 cm
- ‘good’ moderator materials: water, polyethylene
- One of the best moderators is ^{2}H because it moderates but *doesn’t* capture



Scattering solid, absorption dotted

Detecting neutrons

Prompt capture reactions:

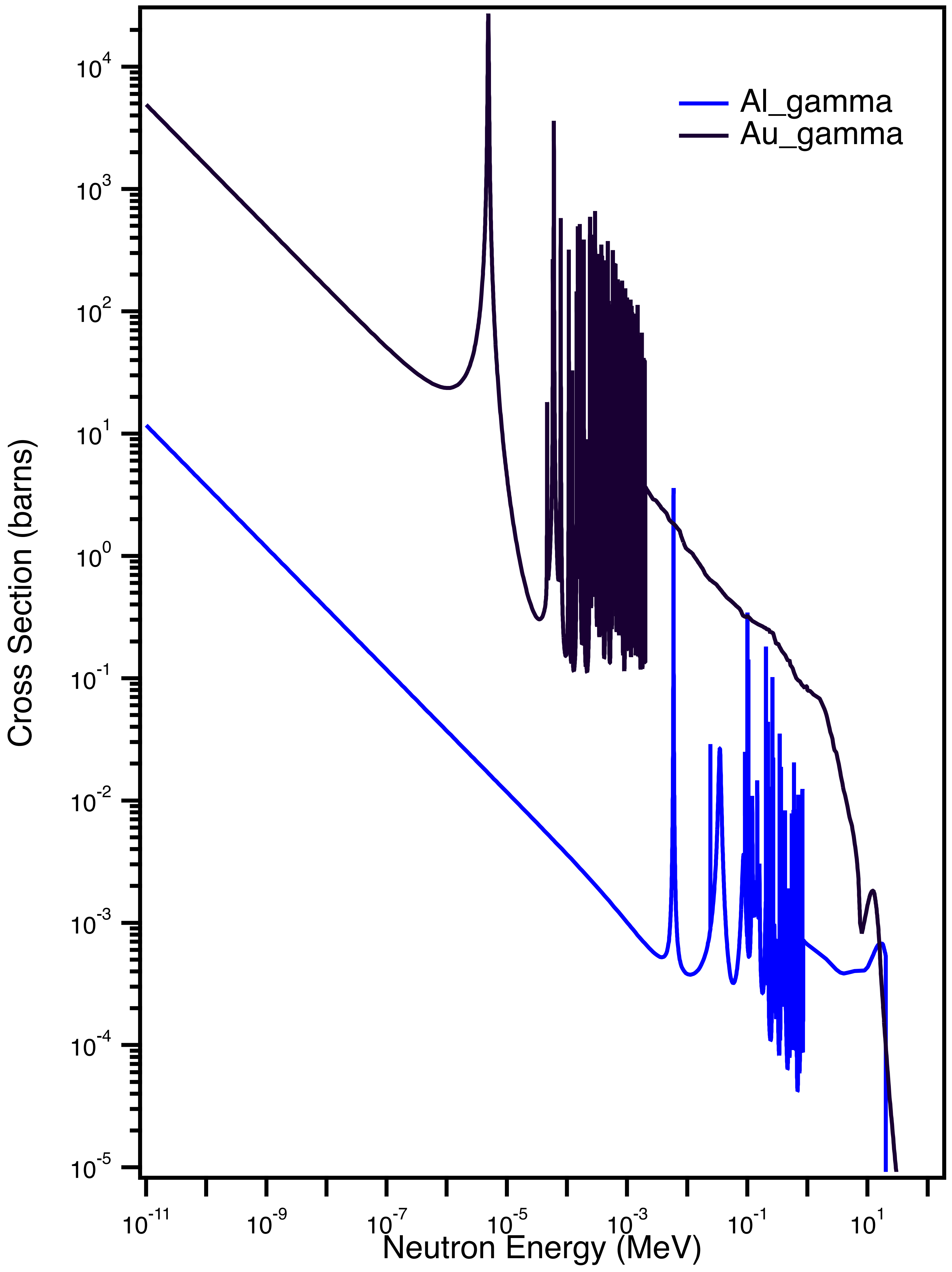
- Utilize absorbing isotope with large (e.g kilo barns) capture cross sections.
- Detection depends on energetic ionizing products
- e.g. $^{3}He(n,p)$, $^{6}Li(n,t)$, $^{10}B(n,\alpha)$, and uranium fission

Absorption (activation) reactions:

- radiative capture, spallation reactions, etc…
- Many materials (e.g., indium, gold, rhodium, iron ($^{56}Fe(n,p)^{56}Mn$), aluminum ($^{27}Al(n,\alpha)^{24}Na$),niobium ($^{93}Nb(n,2n)^{92m}Nb$), & silicon ($^{28}Si(n,p)$ ^{28}Al)) capture neutrons in narrow resonances, multiple samples allows reconstruction of of incident spectrum
- Activation also useful for forensics and material characterization

Elastic scattering reactions:

- Elastic reactions transfer energy to target which is then detected (e.g scintillation)
- Highest energy transfer is to light nuclei, so often hydrogenous targets



Neutron detection and metrology

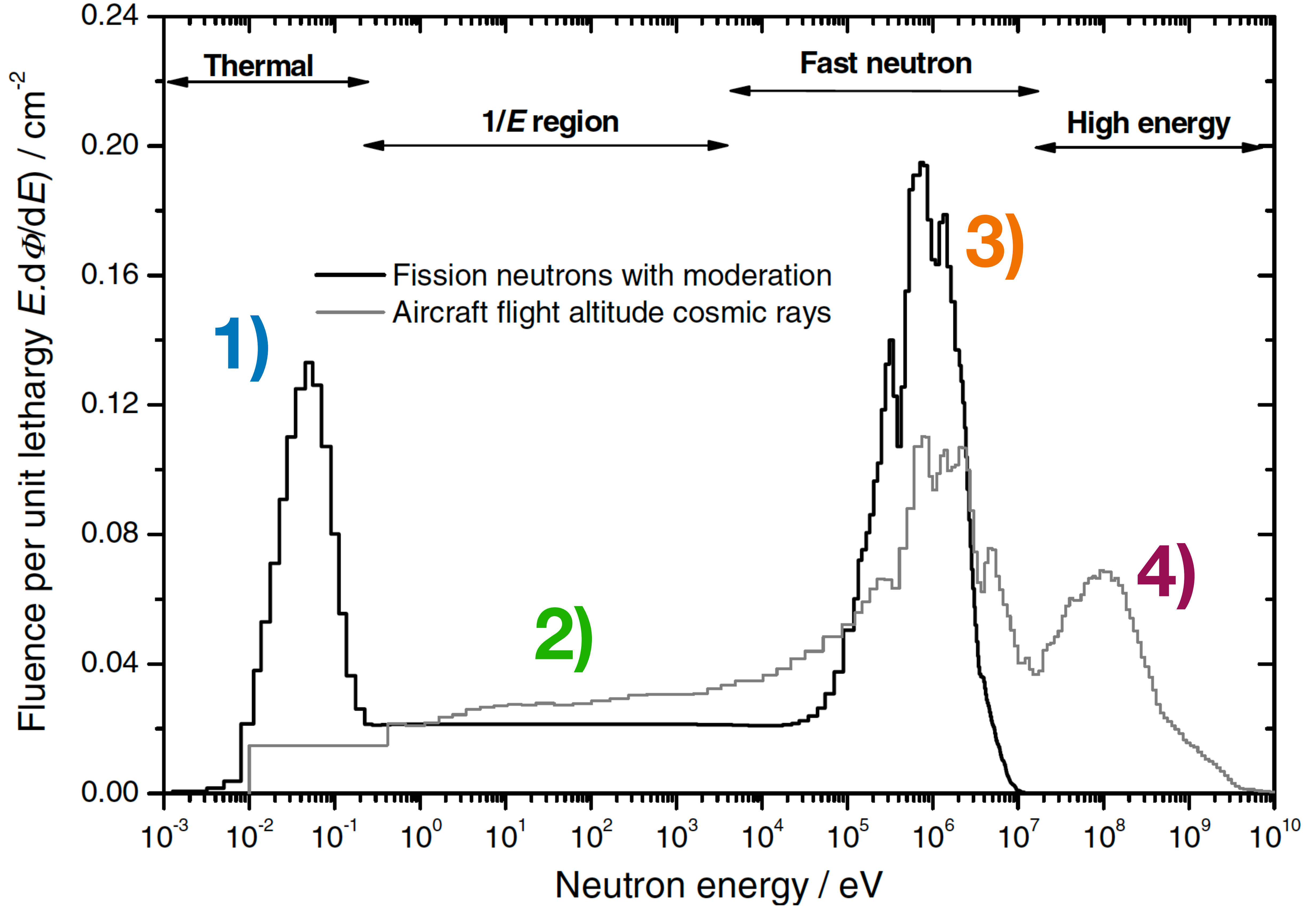
Four ranges of energy with different metrology needs and techniques

1) Thermal neutrons: easy to detect
But lose direction and energy information

2) 1/E region: challenging and specialized

3) Fast neutron: cross sections small, interaction distances large (1-10 cm)
Maintain some direction information

4) Highest energies: interaction lengths are large relative to typical detectors, so again, energy information is a challenge



Gas counters

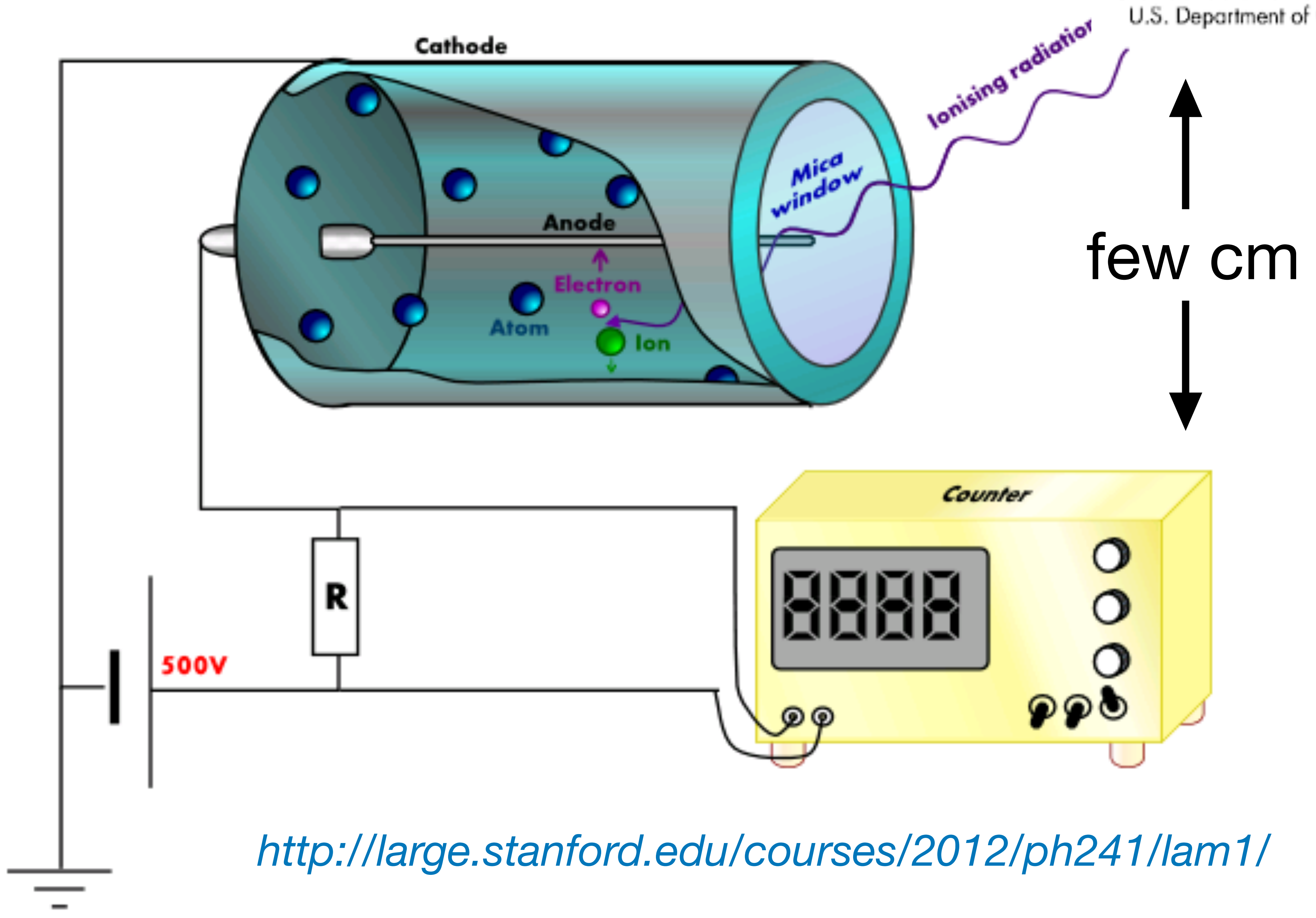
- Most common method for detecting thermal neutrons

How they work:

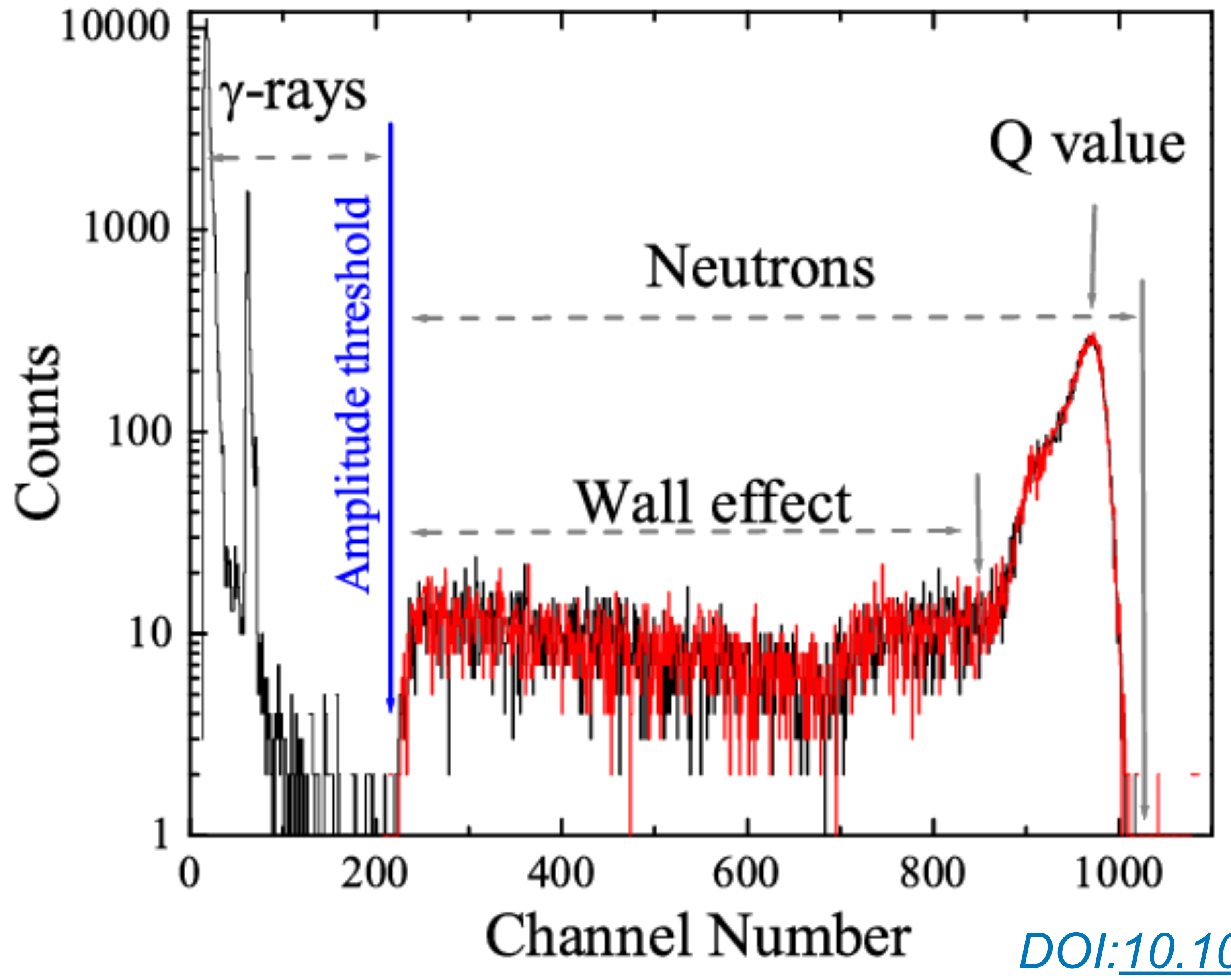
- gas-filled tube with a high voltage applied across the anode and cathode.
- Thermal neutrons capture (e.g. on ^3He) producing ionizing products (e.g a proton and triton)
- Ionization + voltage collection of charge (proportional to energy w/ appropriate voltage)

Performance:

- Very robust and transportable
- Various gasses usable, e.g. ^3He and BF_3 (toxic 😞)
- Generally insensitive to gammas
- Counting detector only
- Rather hard to calibrate absolutely due to complicated geometric effects (several percent at best)



http://large.stanford.edu/courses/2012/ph241/lam1/



DOI:10.1063/1.4909595

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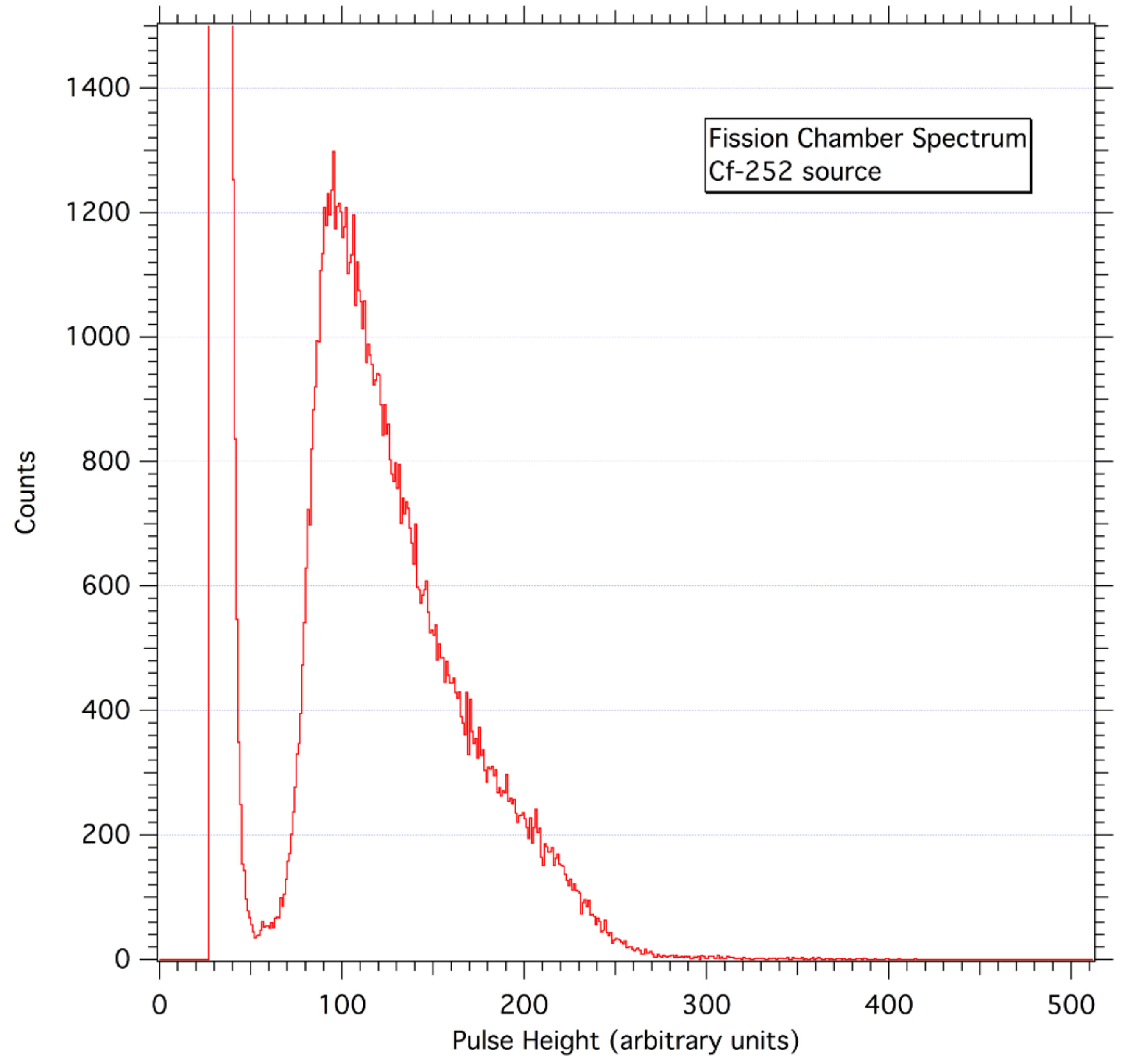
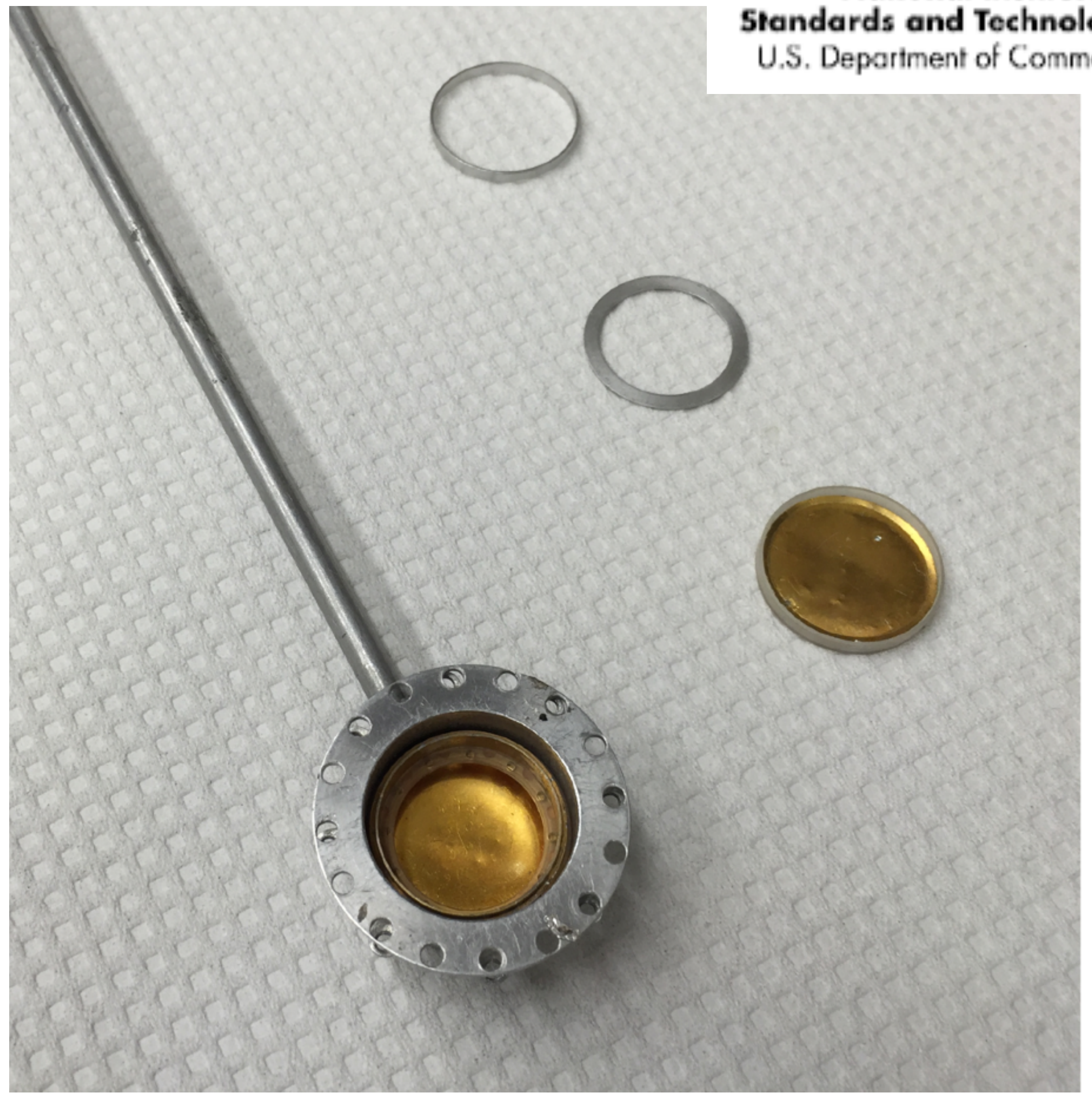
Fission Chambers:

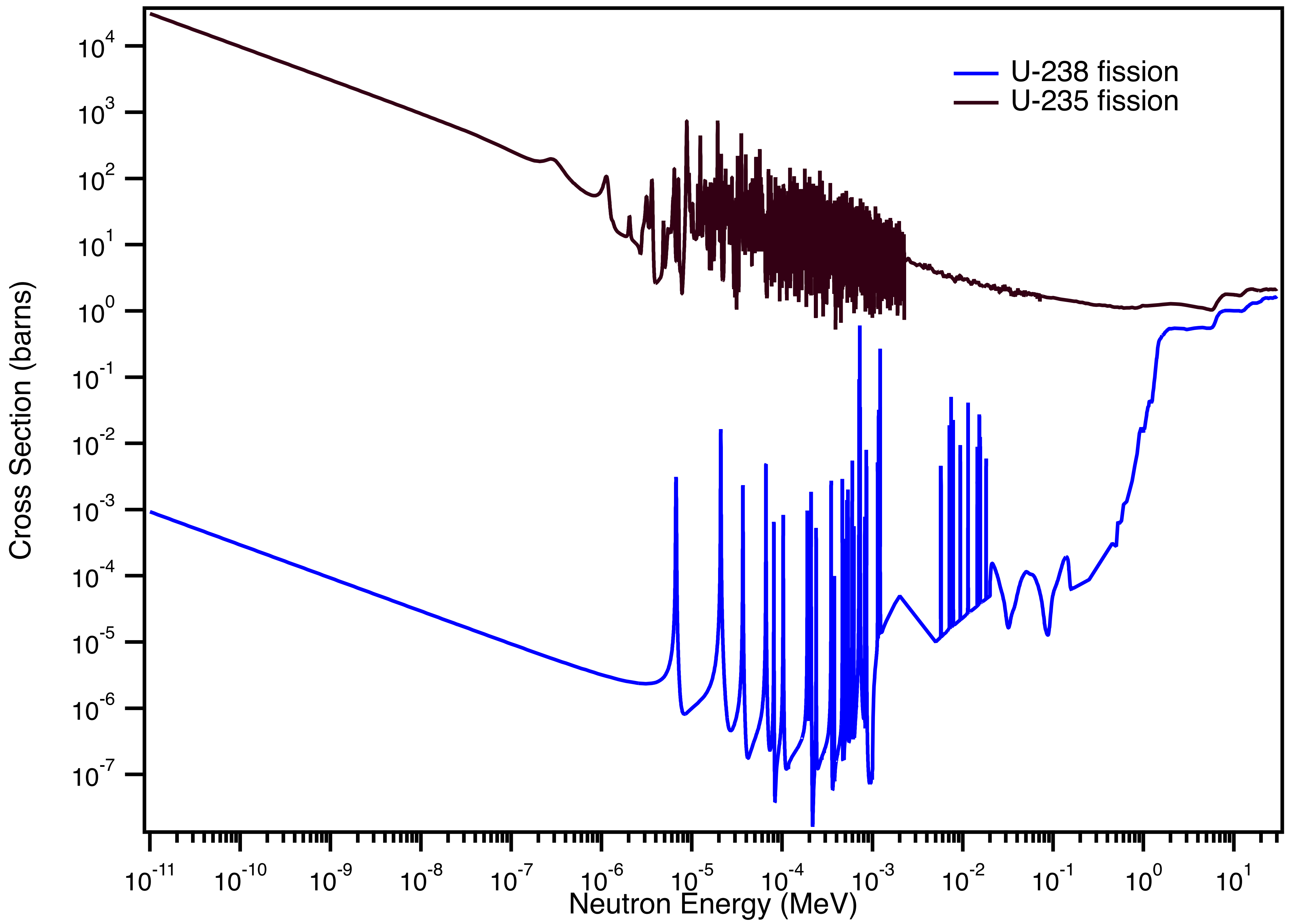
- Similar in function to a gas counter but with a fission isotope target
- Straightforward counting detector:

$$\Gamma = N\sigma\Phi$$

- Large signal from fission fragments, well-separated from noise and alphas
- Largely gamma insensitive
- Wide range of available masses gives wide range of sensitivity
- Variety of isotopes for thermal or fast detection
- Systematic uncertainties are tractable ≲ 1-2%
- Calibrations traceable through internationally accepted standards
- Physically robust and very stable







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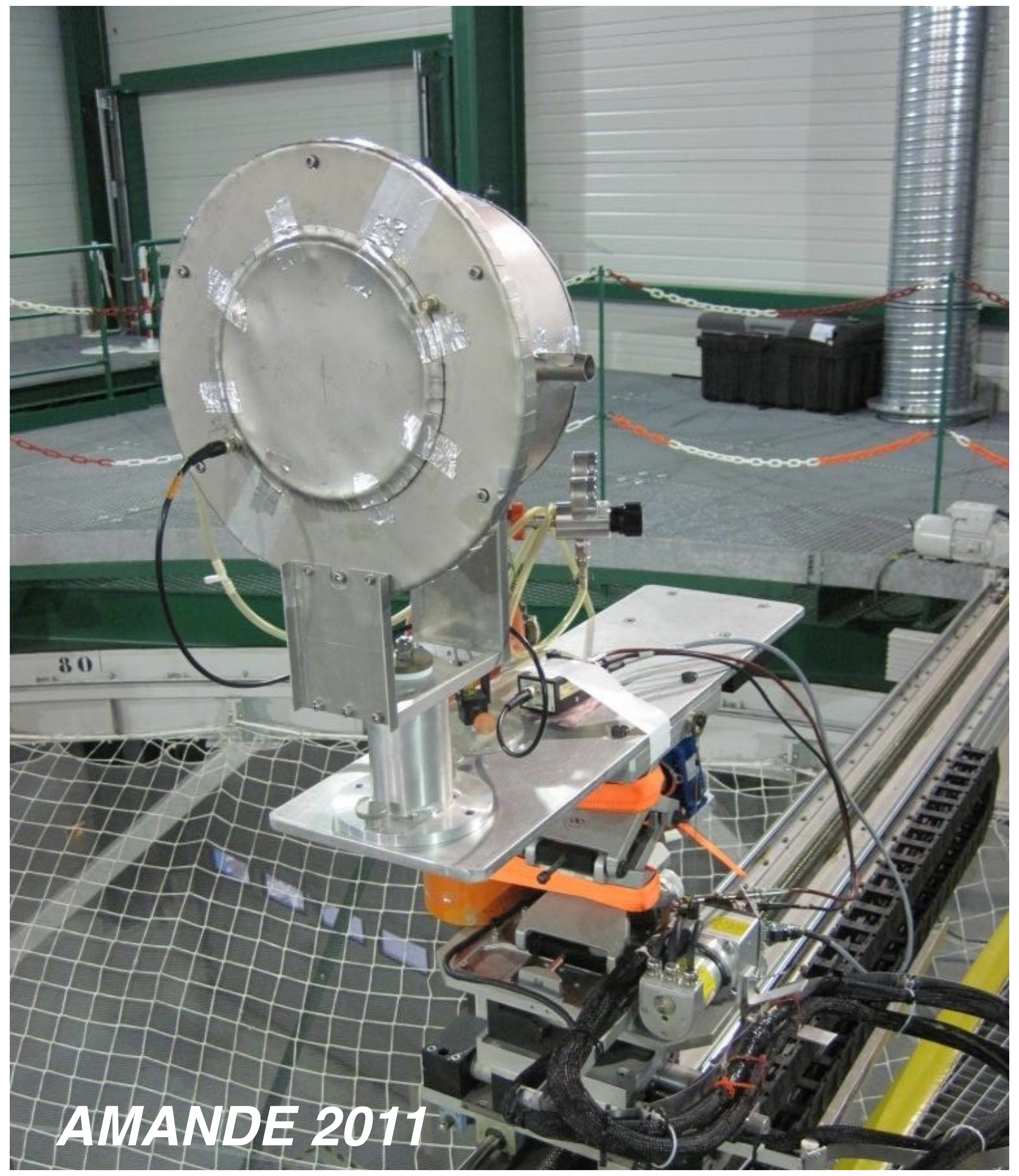
Fission Chambers (continued):

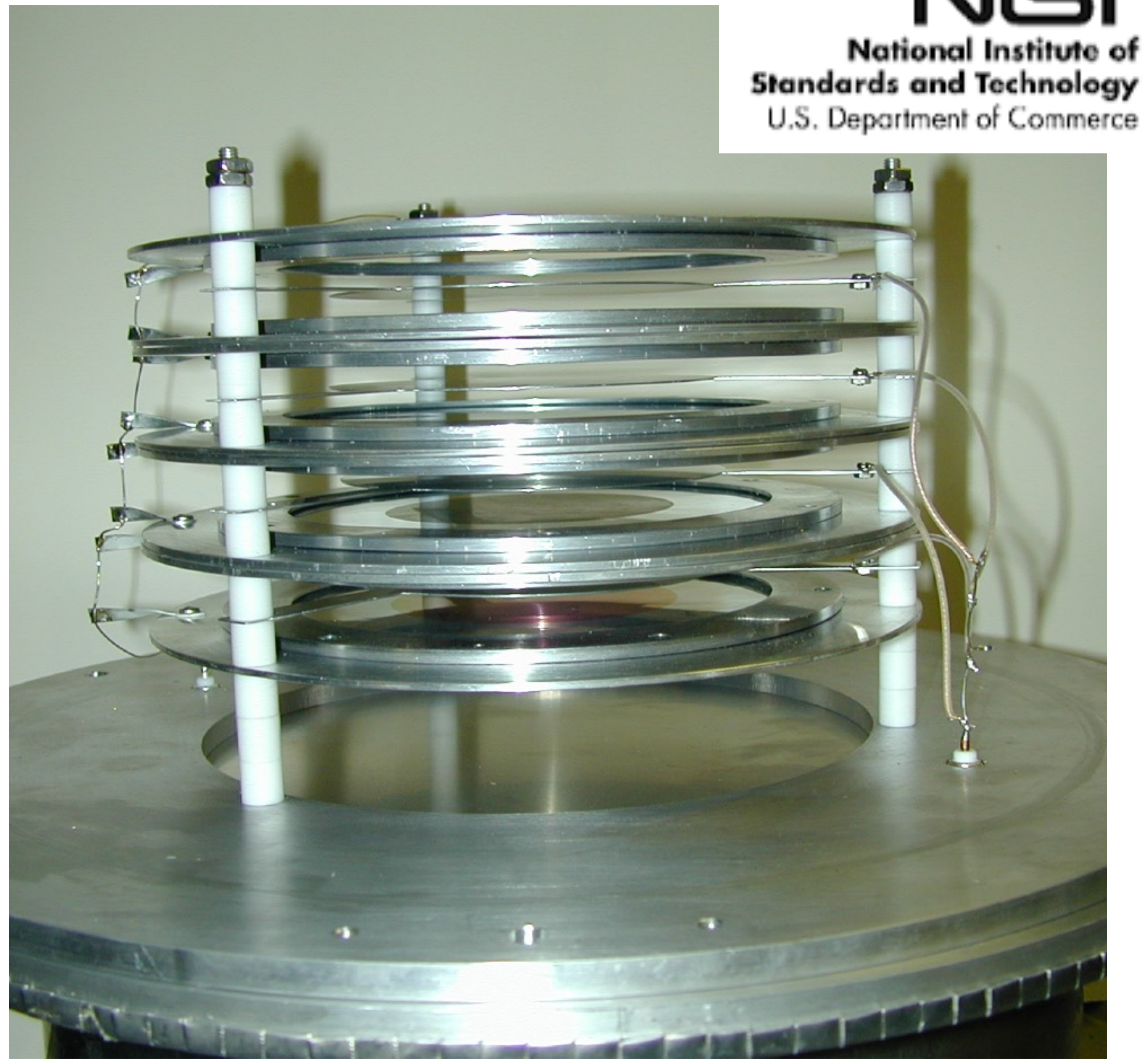
A special feature of fission chambers: absolute calibration

- Dual (multi) deposit chambers allow precise inter comparison between deposits (e.g. NIST has ~500 different deposits)
- Gravimetric mass spec or alpha counting techniques allow absolute determination of number of target atoms (ref deposit)
- Response is then determined by knowledge of cross section
- Such a calibration is not easy/impossible to achieve with other detector types
- Verified through international inter-comparisons.

Applications:

- Establish standard reactor thermal neutron fields
- Measure thermal and cold neutron beam fluence rates
- Fast neutron fluence (Cf-252, 2.5 MeV, 14 MeV)
- Neutron dosimetry
- High-dose, mixed neutron/gamma fields (e.g., fuel rods)
- Detector calibration





Metrologia **51** (2014), *Tech. Suppl. Series* 06009

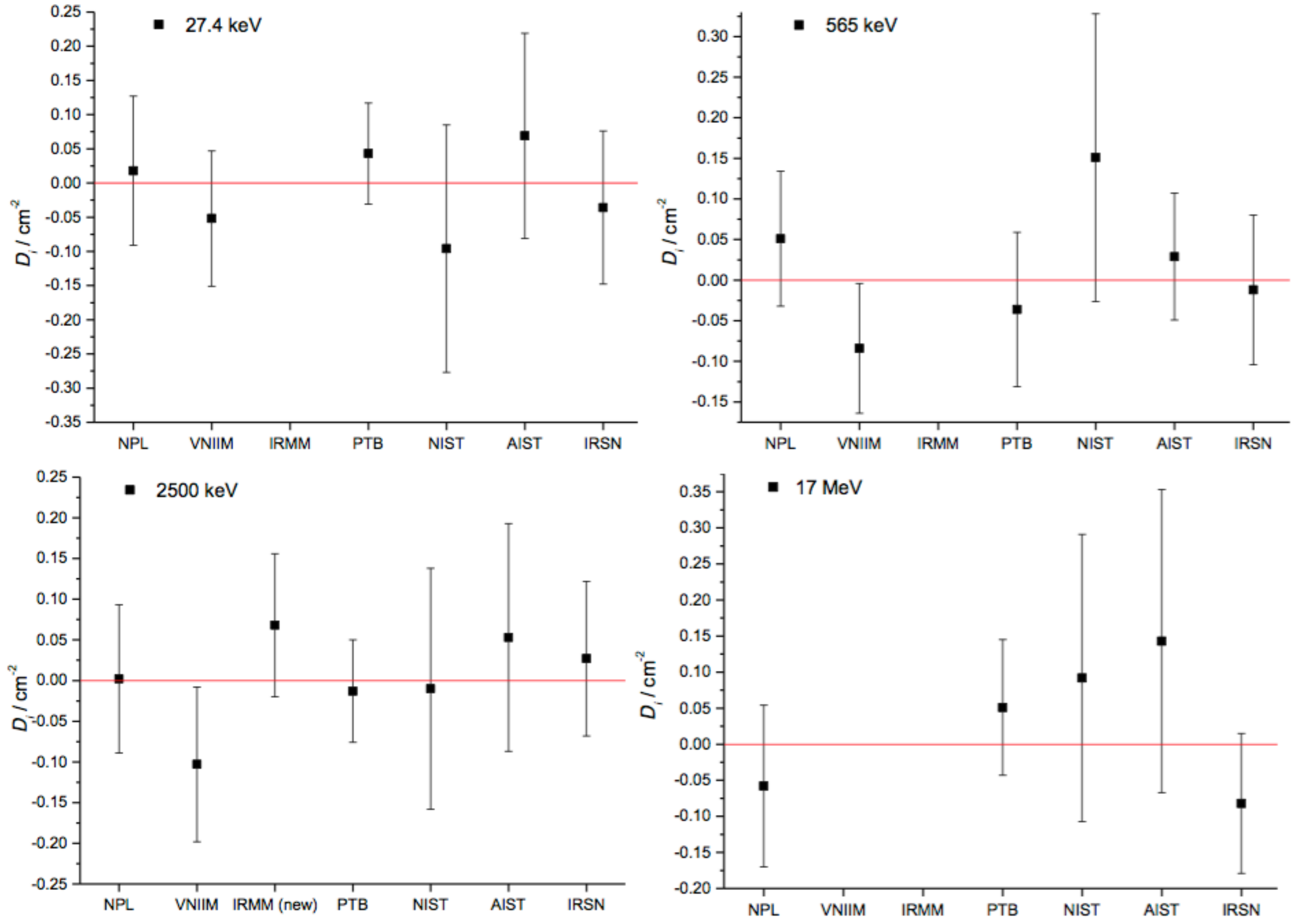
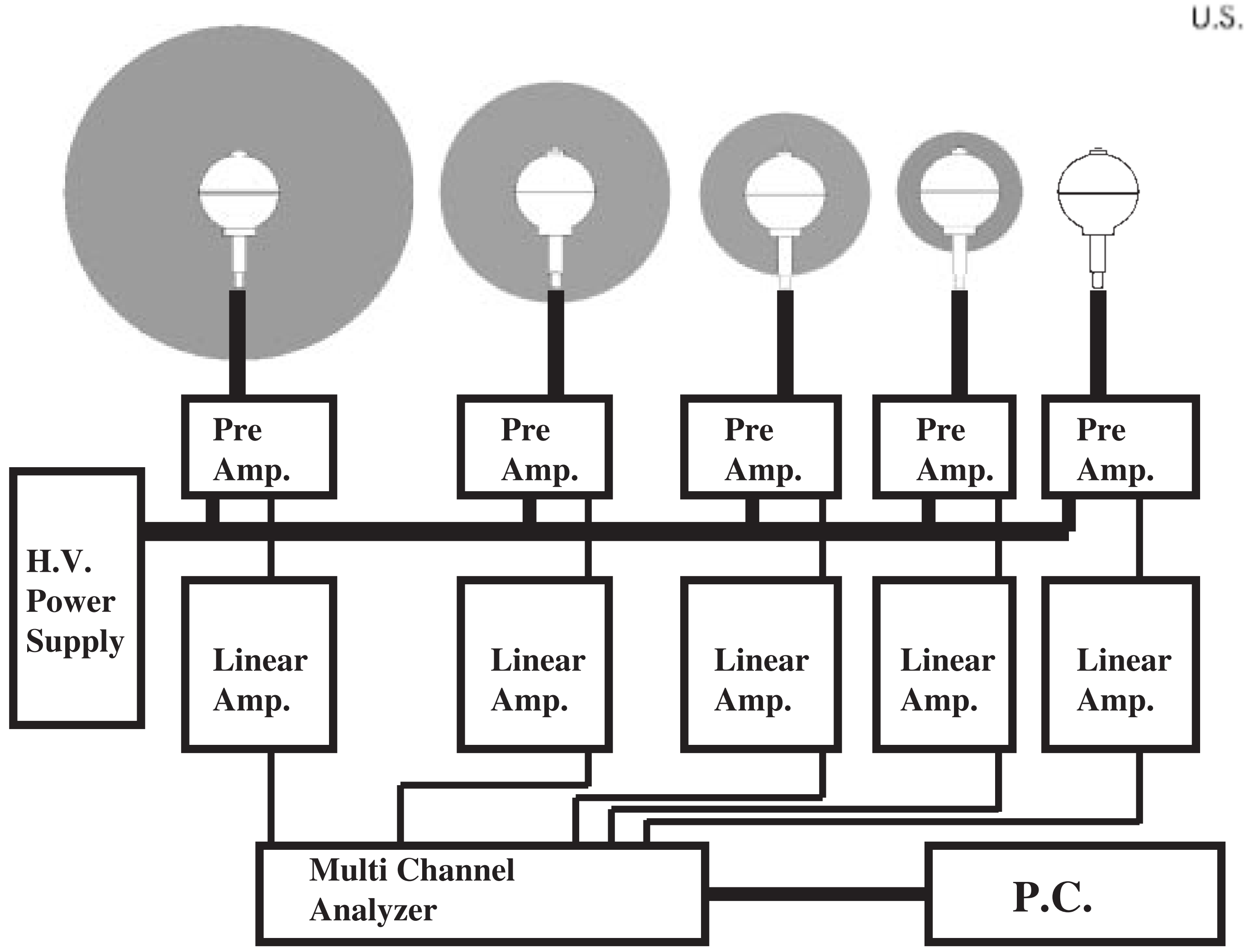


Figure 6.1. Degree of equivalence (DoE) defined as the deviation of the result reported by the laboratory from the KCRV and the expanded uncertainty

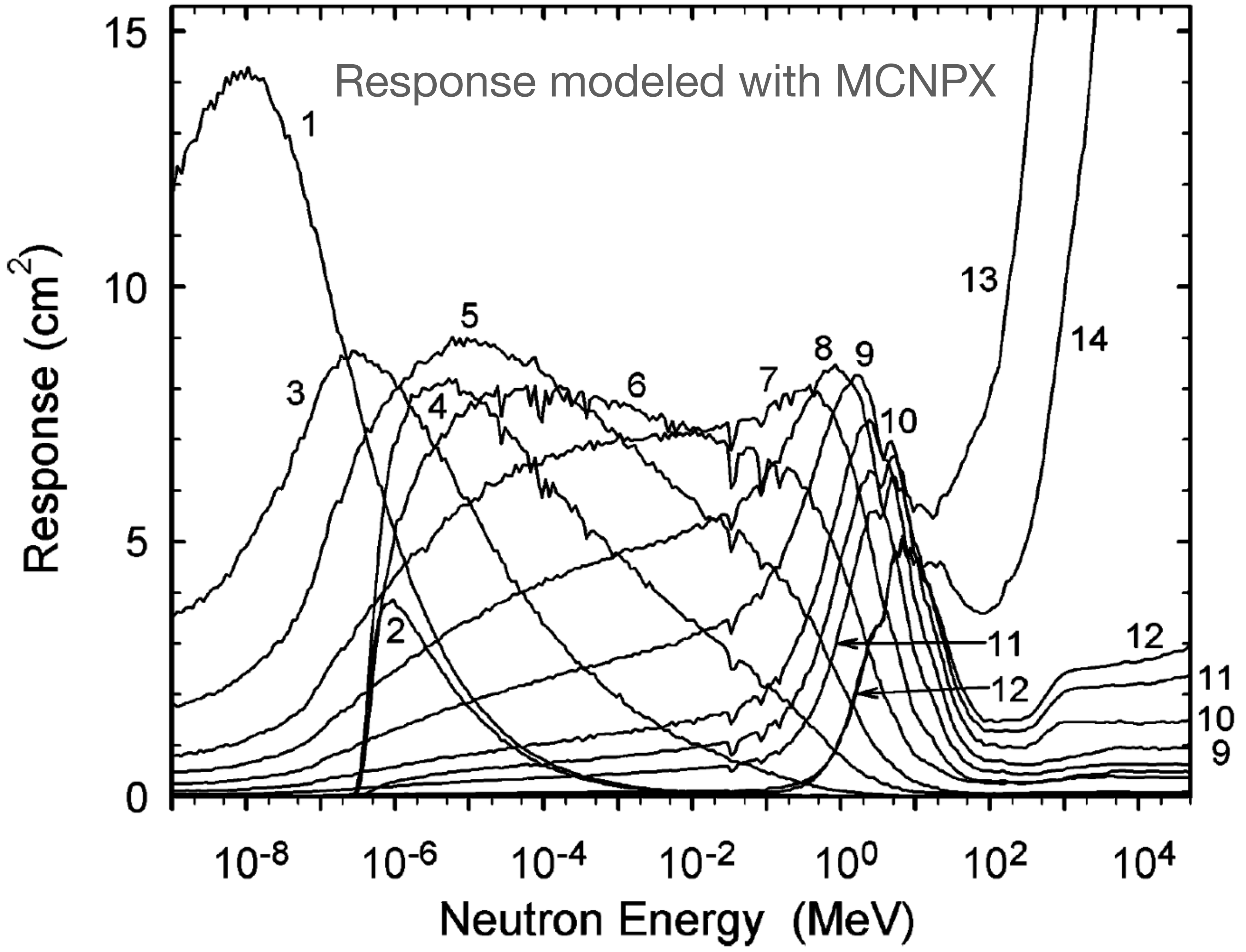
Bonner sphere arrays

- A large number of thermal neutron detectors covered with different amounts of moderator or absorber material
- e.g. Cd, polyethylene, lead
- Neutron response varies by incident energy
- Complex response modeled in Monte Carlo



Performance:

- Robust and transportable
- No direct energy information
- Requires complex unfolding often usually with a prior (and the attendant noise/systematics)
- Low efficiency - esp. at high E (>100 MeV)



Depending on application, e.g. cosmogenic surface spectrum, Bonner ball arrays have produced the best spectrum measurements available.

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Scintillation neutron detectors

- Many technologies: liquid organic scintillators, crystals, plastics, glass, and scintillation fibers
- work somewhat motivated by the cost and scarcity of ^{3}He

Neutron-sensitive scintillating glass fiber detectors

- Incorporate ^{6}Li and Ce^{3+} into the glass bulk composition
- Energy transfer to Ce^{3+} ions results in the emission of photons - read out by e.g. PMT
- Rugged fast, high efficiency, flexible geometry

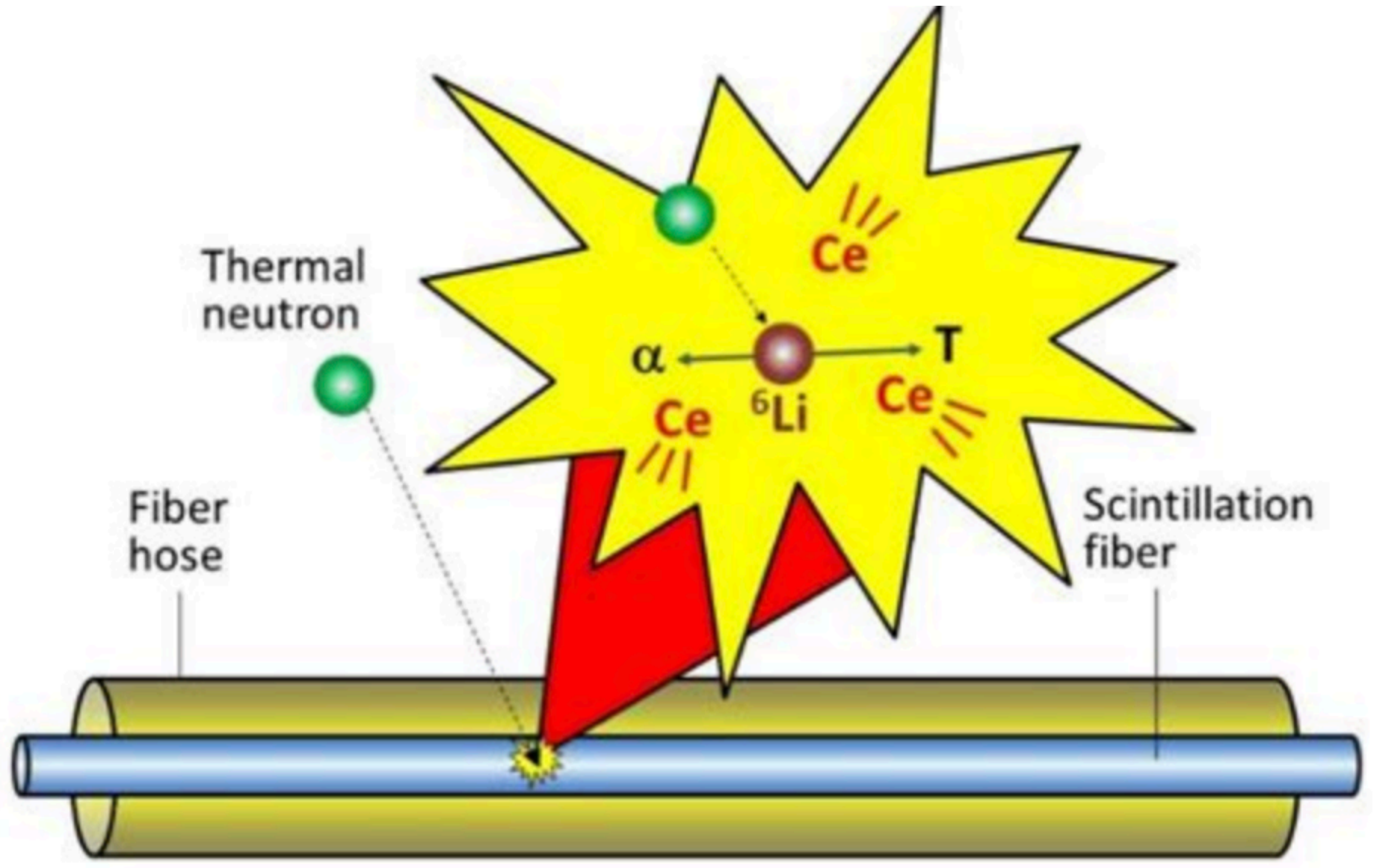
Inorganic and organic scintillator crystals:

- Many many possibilities e.g. ^{6}Li doped CsI, LiF/ZnS:Ag, NaIF, $LiCaAlF_6$, anthracene, stilbene, etc..
- Generally inorganic get doped with a neutron absorber
- Inorganics used for fast neutron detection due to hydrogen content
- High detection efficiencies, neutron - gamma discrimination
- Sometimes robust, easy to use, often expensive and/or hard to grow
- anisotropic response

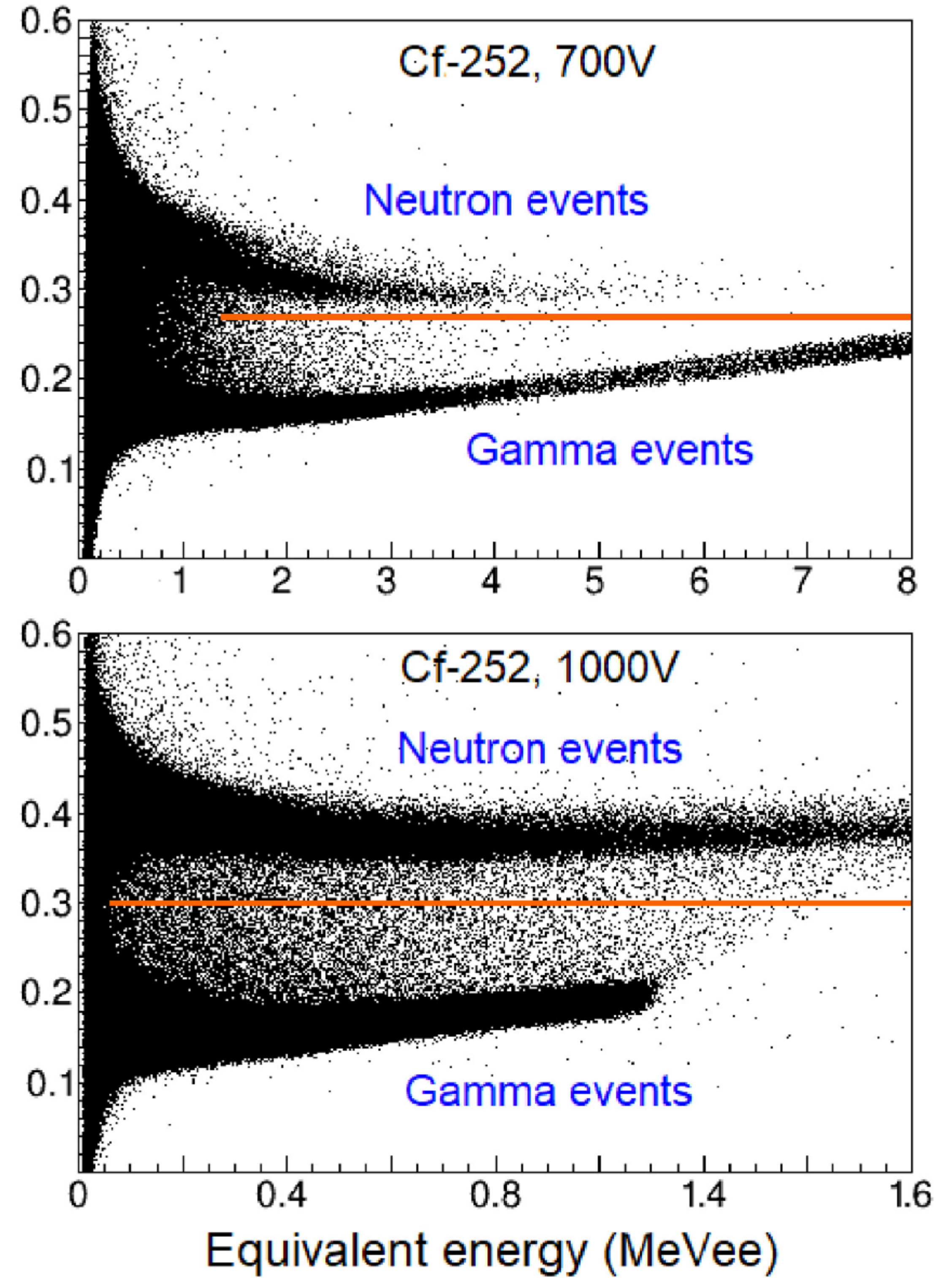
https://doi.org/10.3390/cryst9090480

Complicated heterogeneous materials:

- Many explorations of mixtures of scintillating materials and methods of optical transport have been explored.
- Mostly aimed at gamma/neutron discrimination



DOI:10.1016/B978-0-12-819725-7.00087-8



https://doi.org/10.1016/j.net.2022.10.041

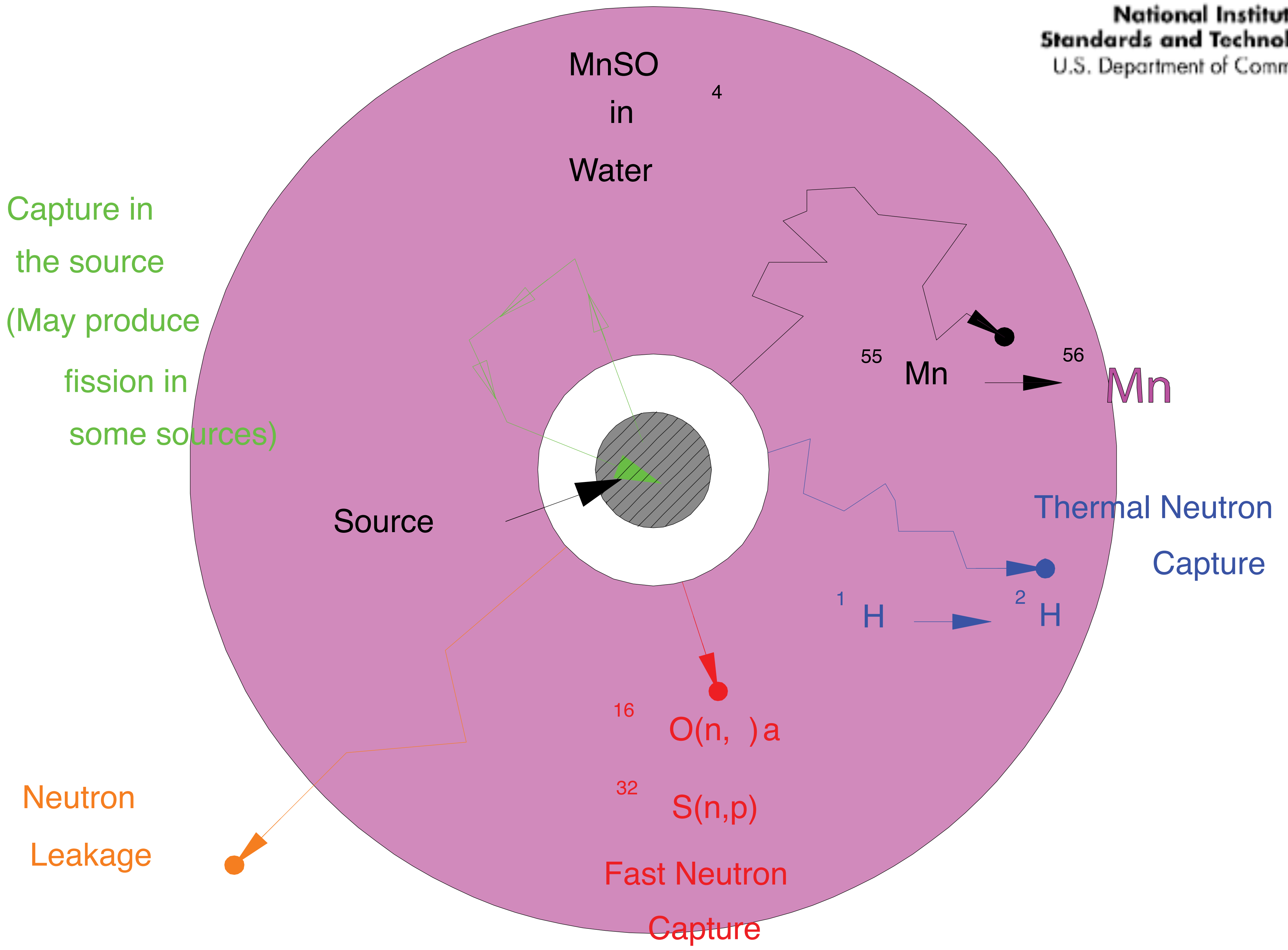
Determination of neutron source strength

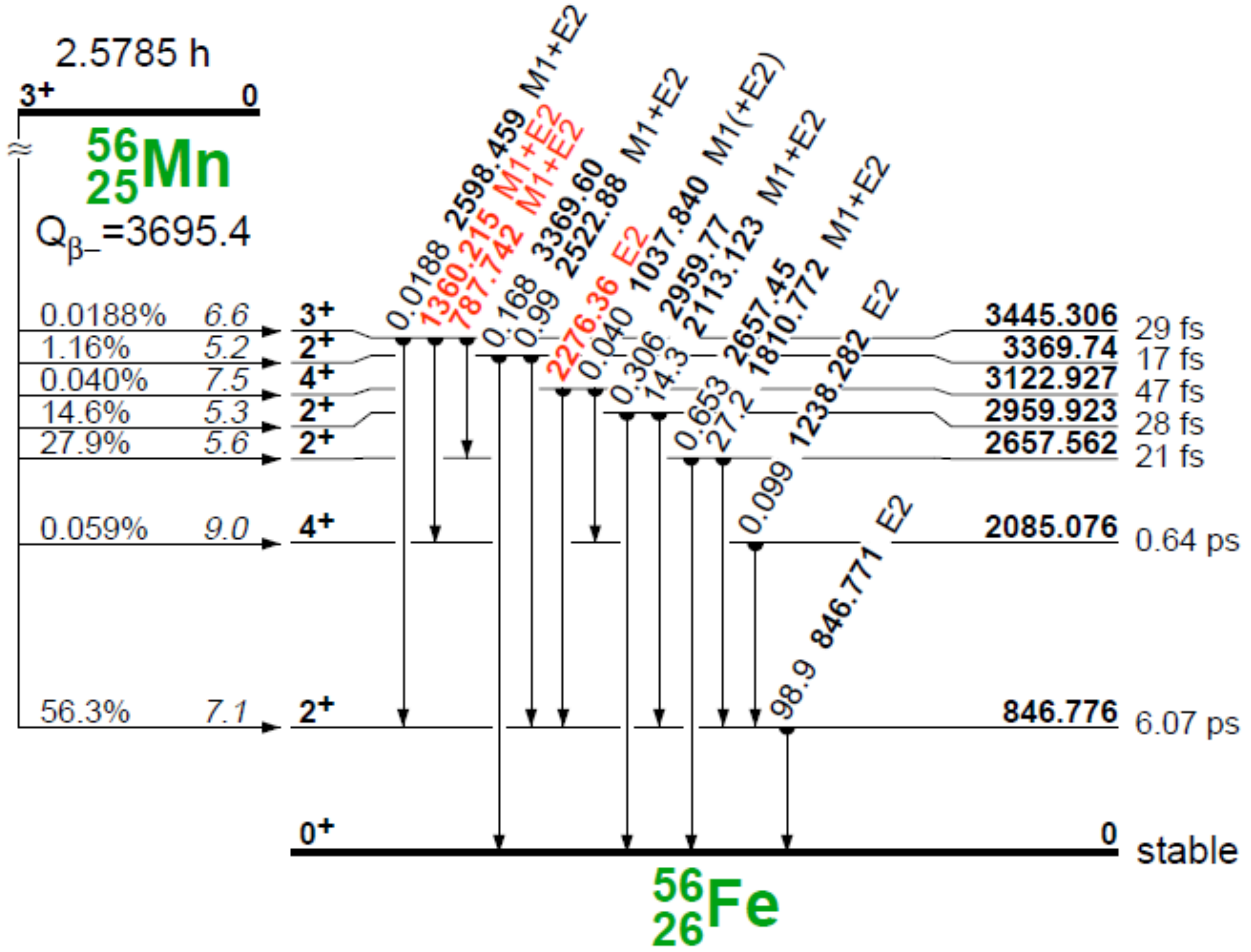
Manganese bath:

- Internationally, the workhorse method for traceable determinations of neutron source strength
- Capable of <1% precision for activities ≥ 10^5
- Traceability through CCRI(III) comparisons.

How it works:

- Meter scale bath of manganese sulfate
- Source placed in middle of bath (e.g. ^{252}Cf)
- All neutrons thermalize and ~50% capture on ^{55}Mn; very few escape
- ^{56}Mn decays to ^{56}Fe mostly w/ emission of an 846 keV gamma and a half-life of 2.6 hours
- Solution can reach saturation at reasonable activities and timescales





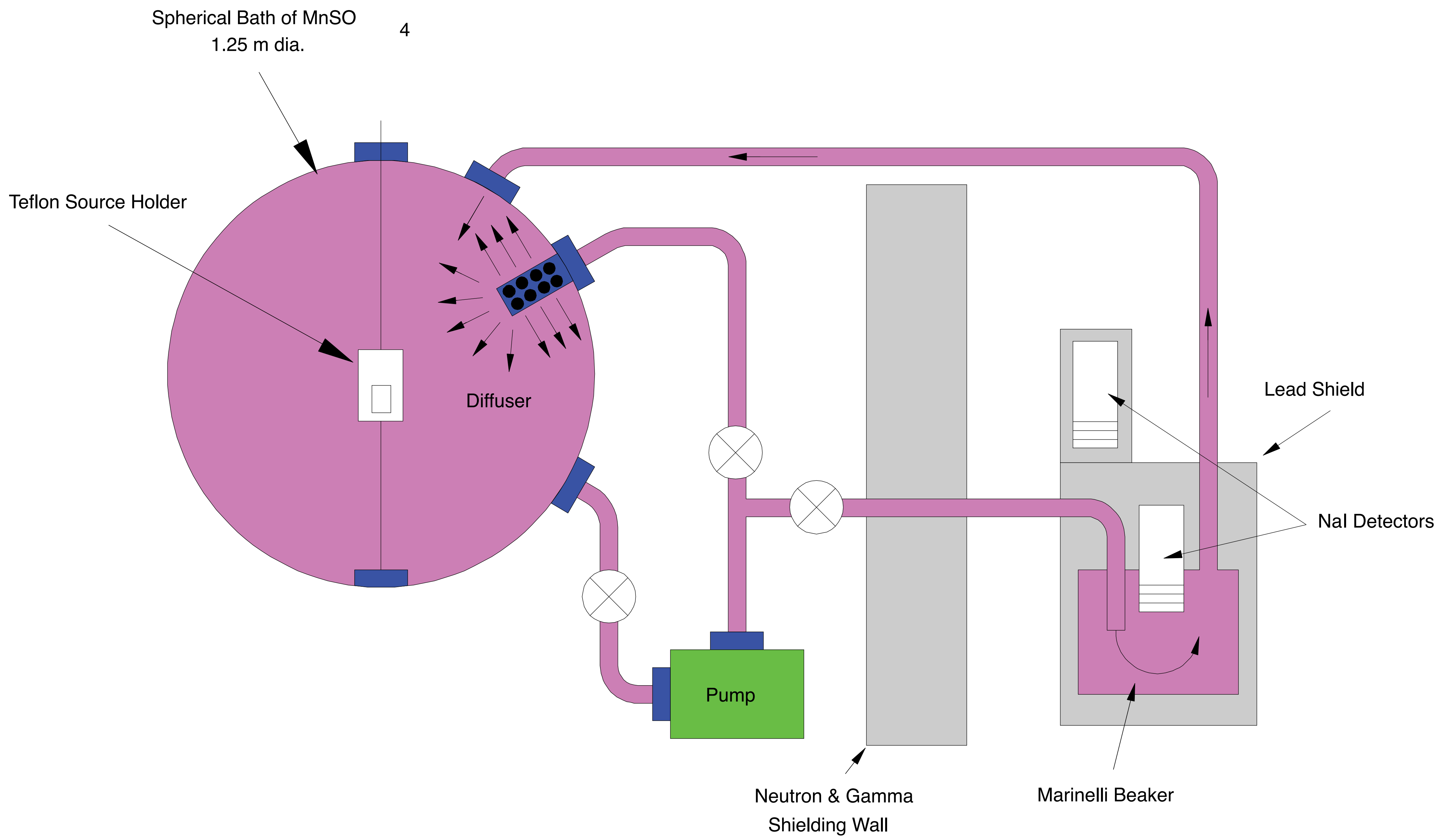
Determination of neutron source strength

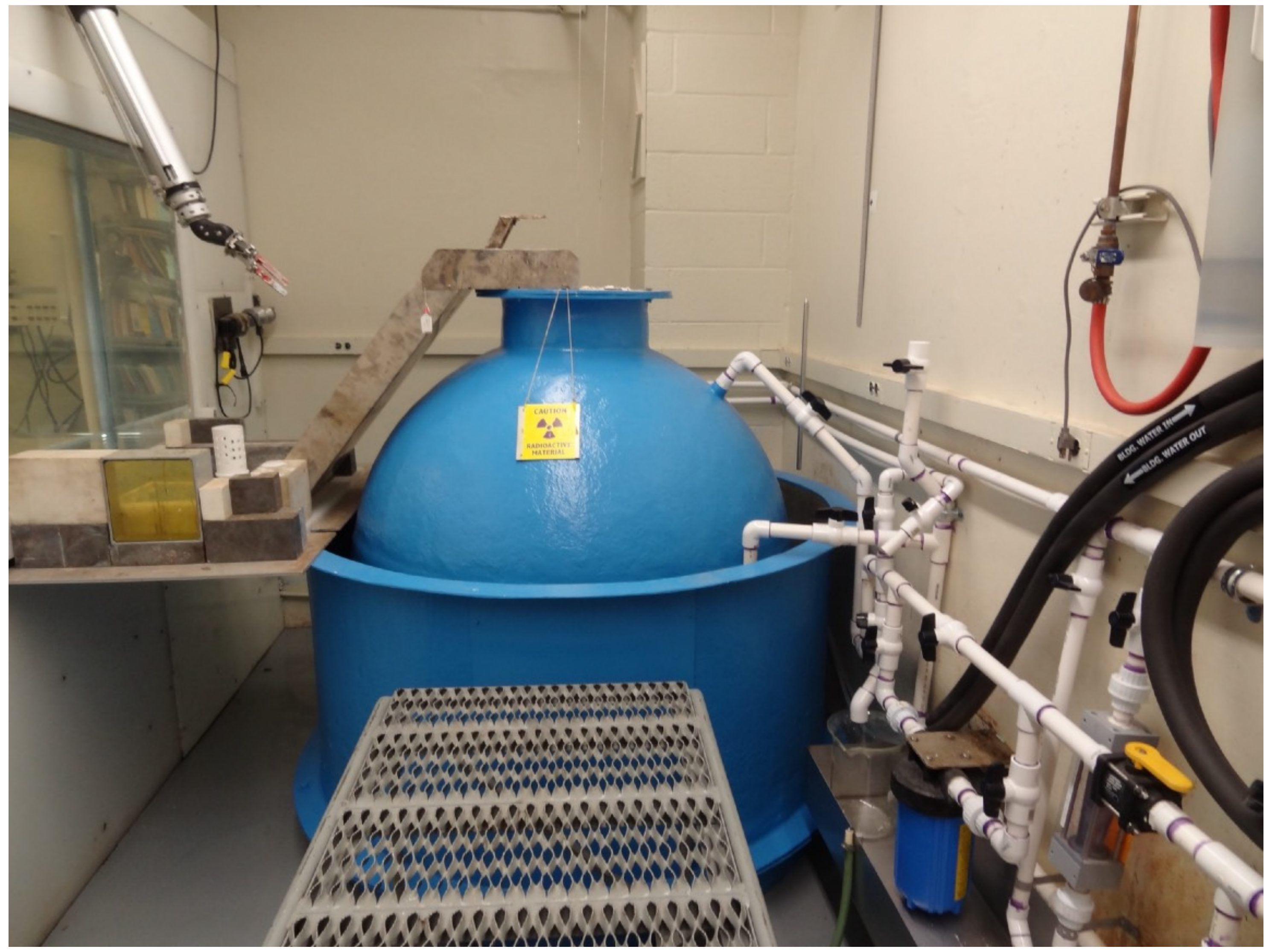
How it works continued:

- Activated solution is pumped to a pair of remote detectors (e.g. NaI) and continuously counted.
- Various methods used to determine the efficiency from using a standard source artifact to gravimetric spiking with activated solution

Calibrated sources used to:

- Create standard neutron fields (absolute) for detector or dosimeter calibration
- Neutron fields for activation or radiation damage studies. E.g. calibrated neutron induced defect studies
- *In situ* calibration sources for spectrometers, etc…
- Lower limit on activity reduces utility for some purposes, e.g. dark matter/neutrino detectors





Focusing on fast neutrons

Underground science

- Increasing number of experiments requiring ultra low background environment (dark matter, double beta decay, solar neutrino,...) where fast neutrons can mimic experimental signals
- Fast neutron backgrounds are not well characterized either on the surface or underground (cosmic-induced neutrons, fission, & α-n)
- Measurements and simulations are not always consistent.

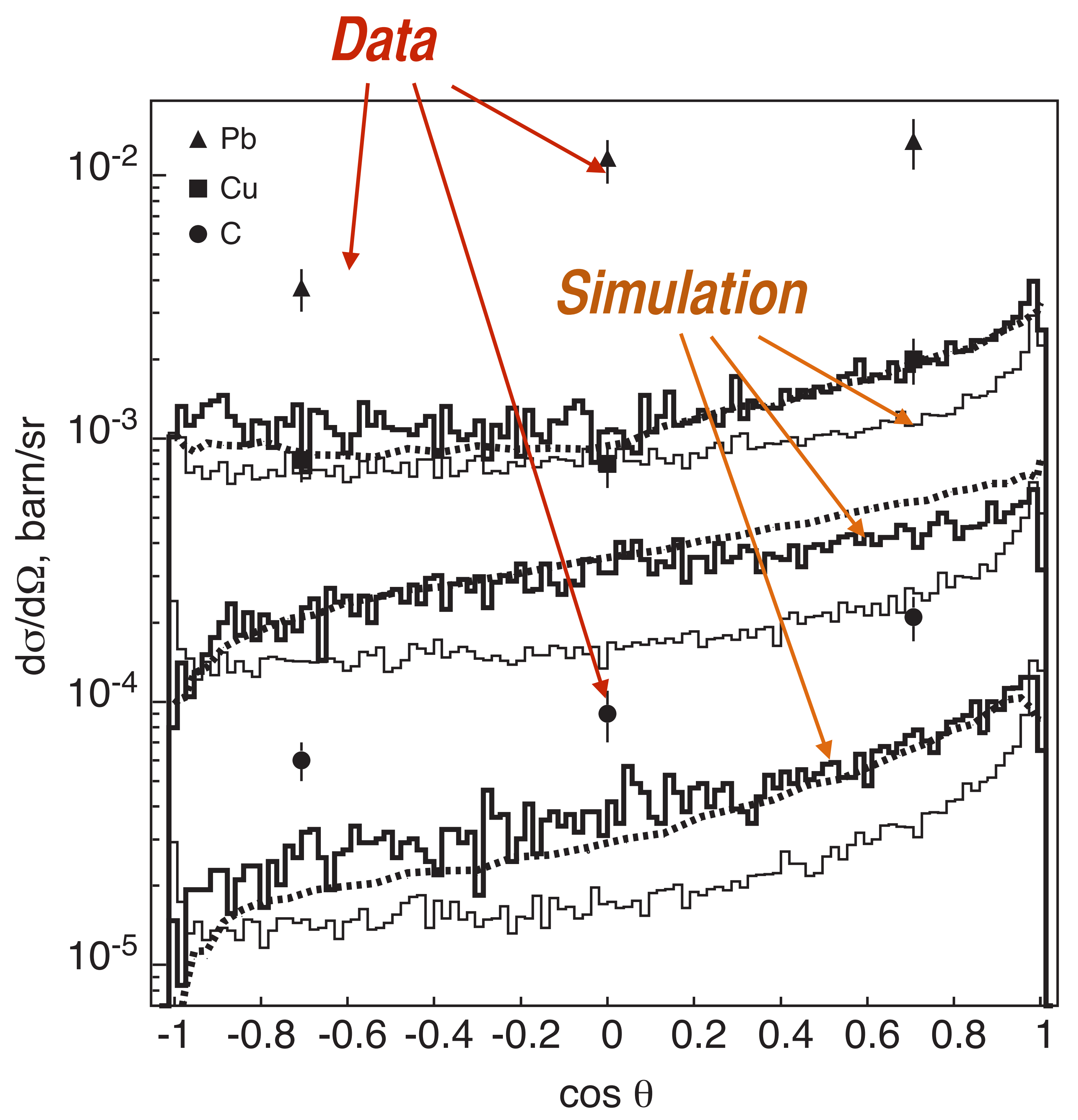


Fig. 7. Differential cross-section of neutron production by 190 GeV muons for a 10 MeV threshold in neutron energy. The data points represent the results of the NA55 experiment. The thin-line histogram shows the GEANT4 simulation considering muon–nucleus interaction only; the thick histogram includes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

Araújo, et. al. NIM A, 2005

National needs

- Detection of low-levels of neutrons from fissile material
- Use in active and passive interrogation technologies

Health physics and dosimetry

- Dosimetry of fast neutrons above several MeV is poorly understood - Ion therapy up to 400 MeV
- Increased exposure from 14 MeV generators and medium and high energy accelerator facilities

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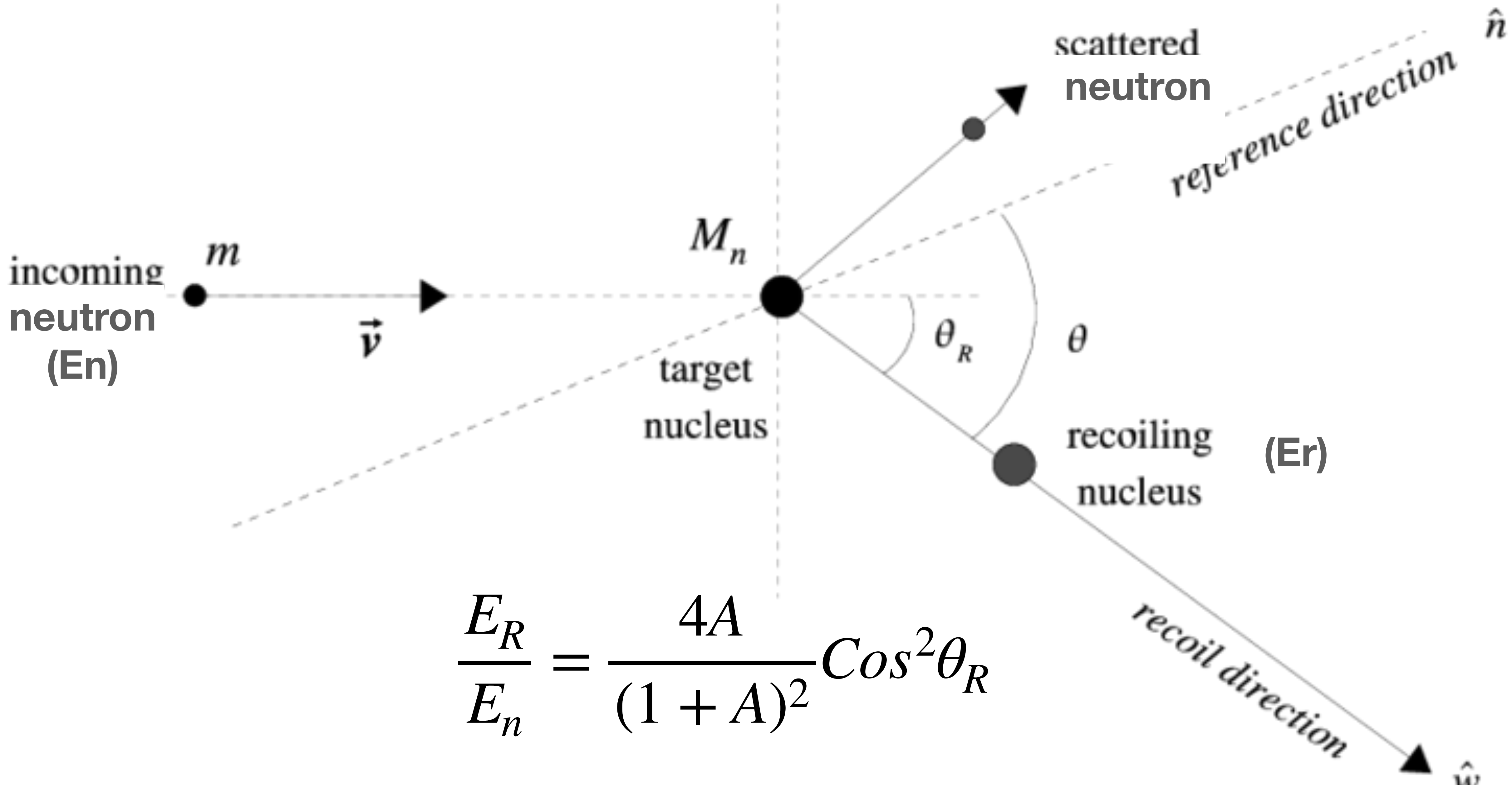
High efficiency fast neutron detection

Recoil detectors

- Recoil energy and cross section go down with target mass
- Motivates using hydrogenous materials



$$\frac{E_R}{E_n} = \frac{4A}{(1+A)^2} Cos^2\theta_R$$

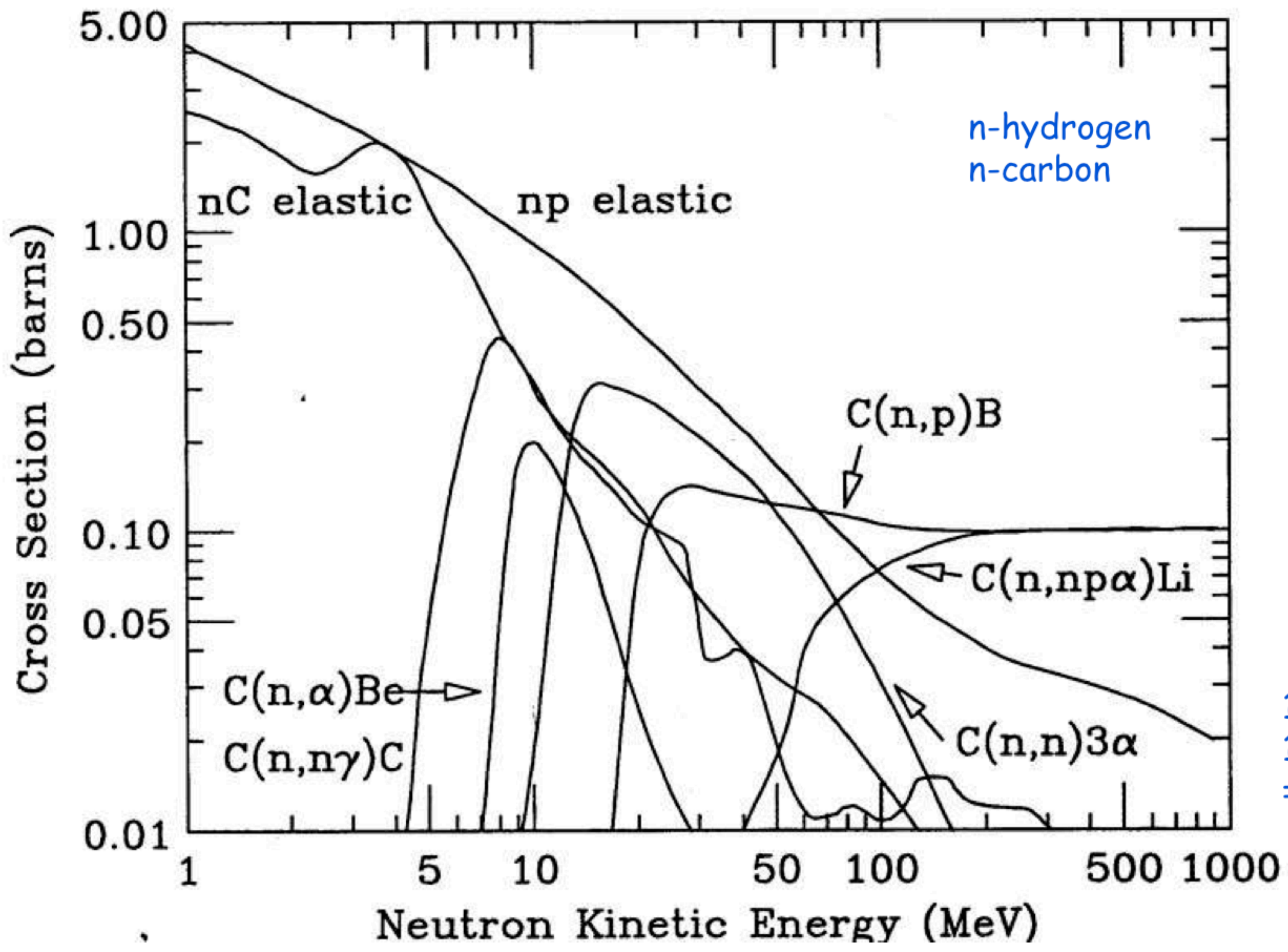
Tgt	A	$4A/(1+A)^2$
^1H	1	1
^2H	2	8/9=0.889
^4He	4	16/25=0.64
^{12}C	12	48/169=0.284

Concept:

- Build a large mass of organic material that provides some way of detecting deposited energy
- Liquid or plastic scintillators, composite materials

Challenges:

- Competing cross sections at high energy
- Large mass = high sensitivity to non-neutrons
  - Background rejection critical
- Detector response



1b= 10^{-24}cm^2 =100fm^2

V. Udo Schröder, 2011

A brief aside on material interactions:

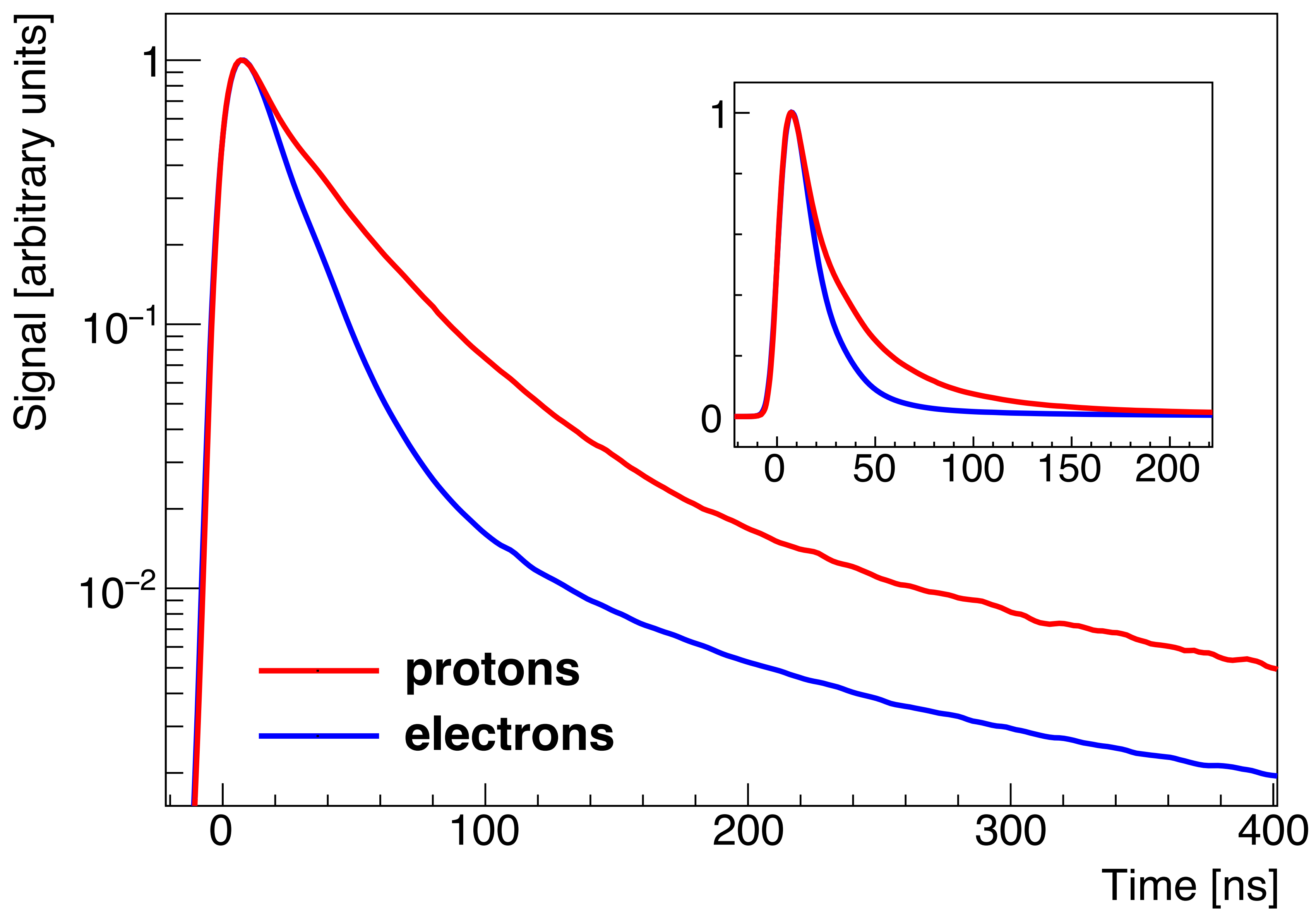
- Energy deposition, dE/dx, is different for different particle types, $\propto 1/v^2$ n
- Generally, signal production is 'slow' and competes with other ways of dissipating energy

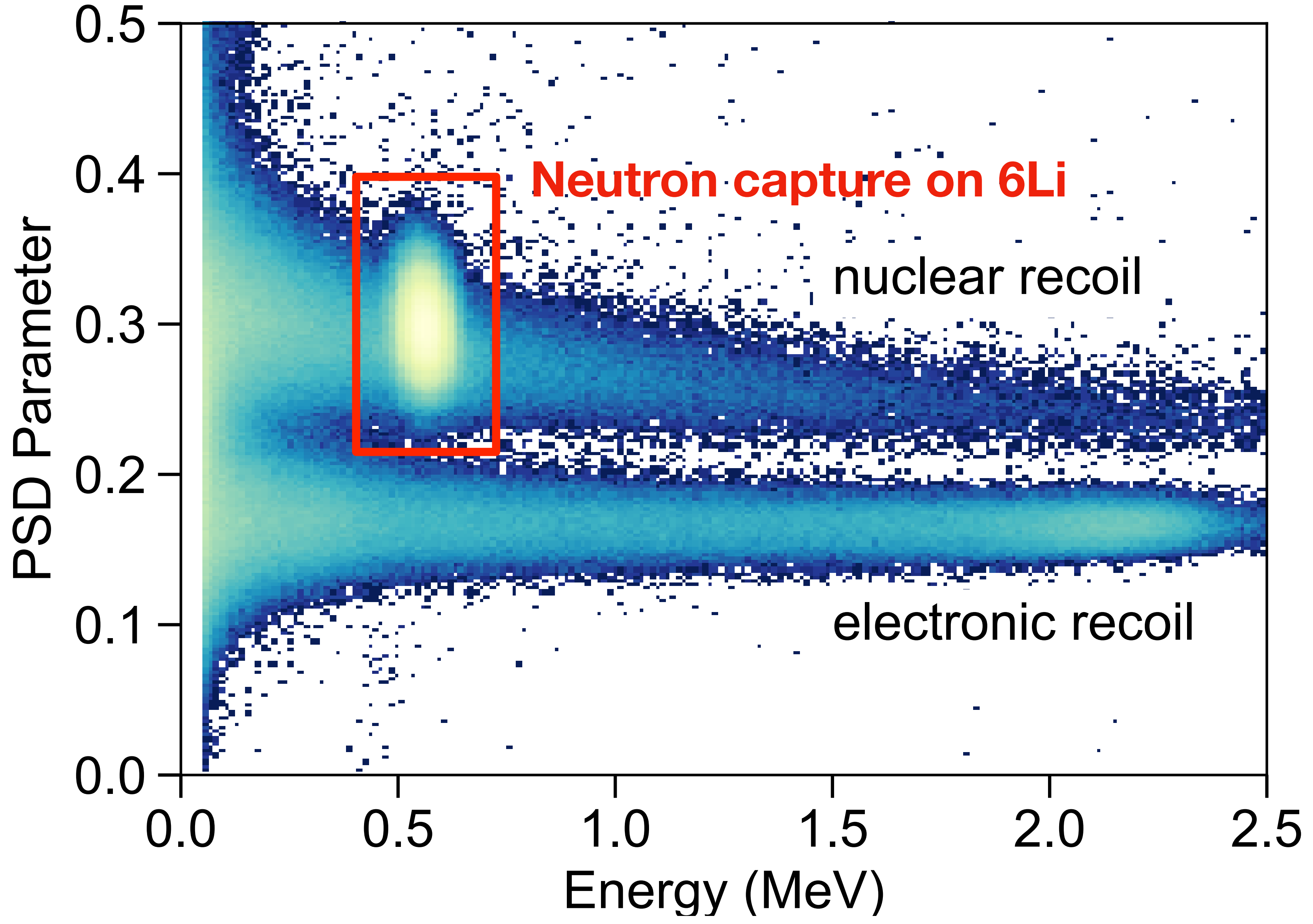
Pulse shape discrimination

- Ionization density and thus molecular excitation of triplet and singlet states thus depends on particle type,
- Singlet and triplet molecular states have different decay times
- Very powerful way to distinguish particle type

Quenching and non-linearity

- Density dependent excitation annihilation
- Excitons interacting with and getting neutralized by free electrons and ions in track
- Since density is dependent on particle type and energy, available signal becomes non=linear in energy.





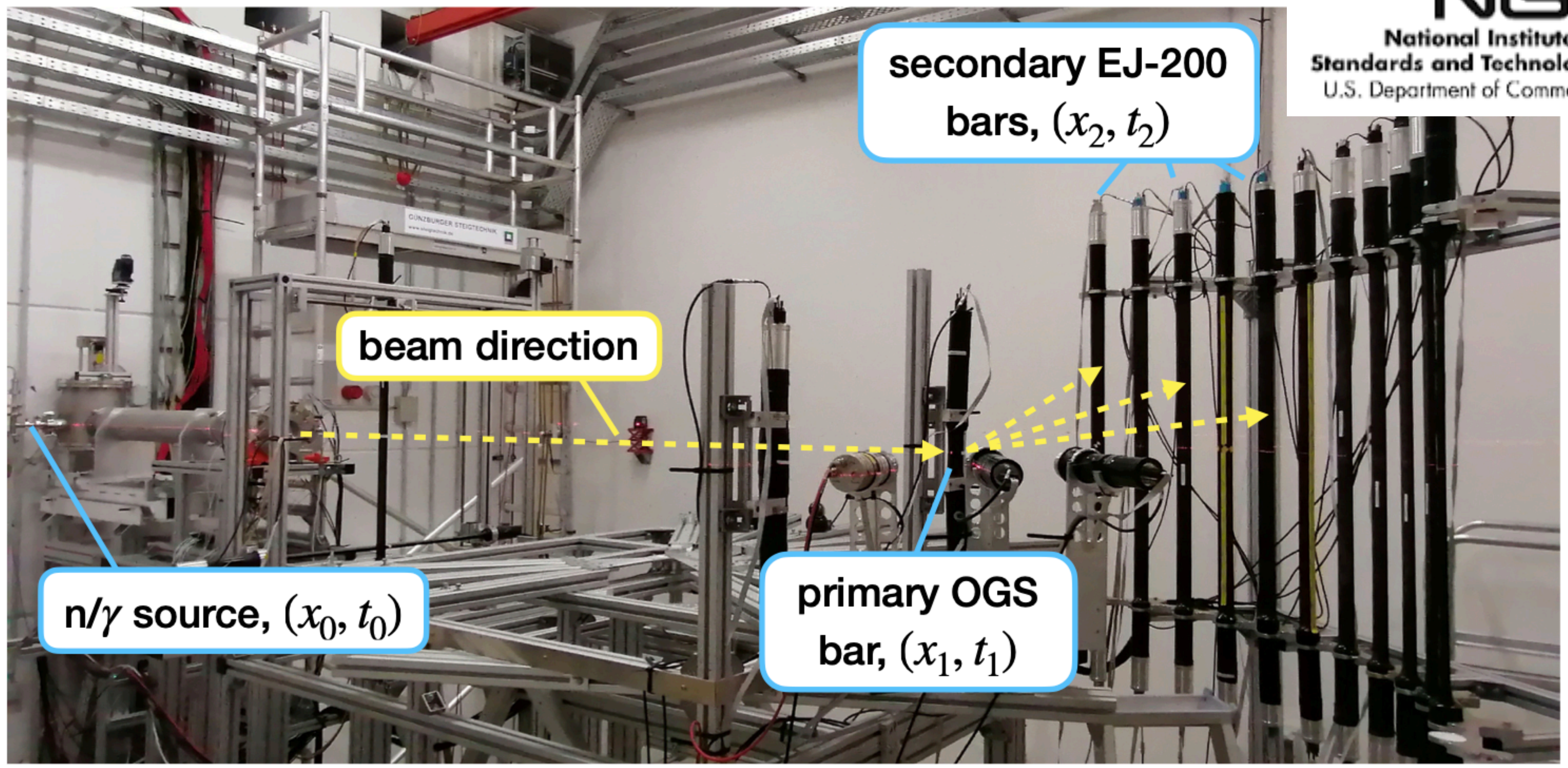
Nuclear Instruments and Methods in Physics Research A 570 (2007) 72–83

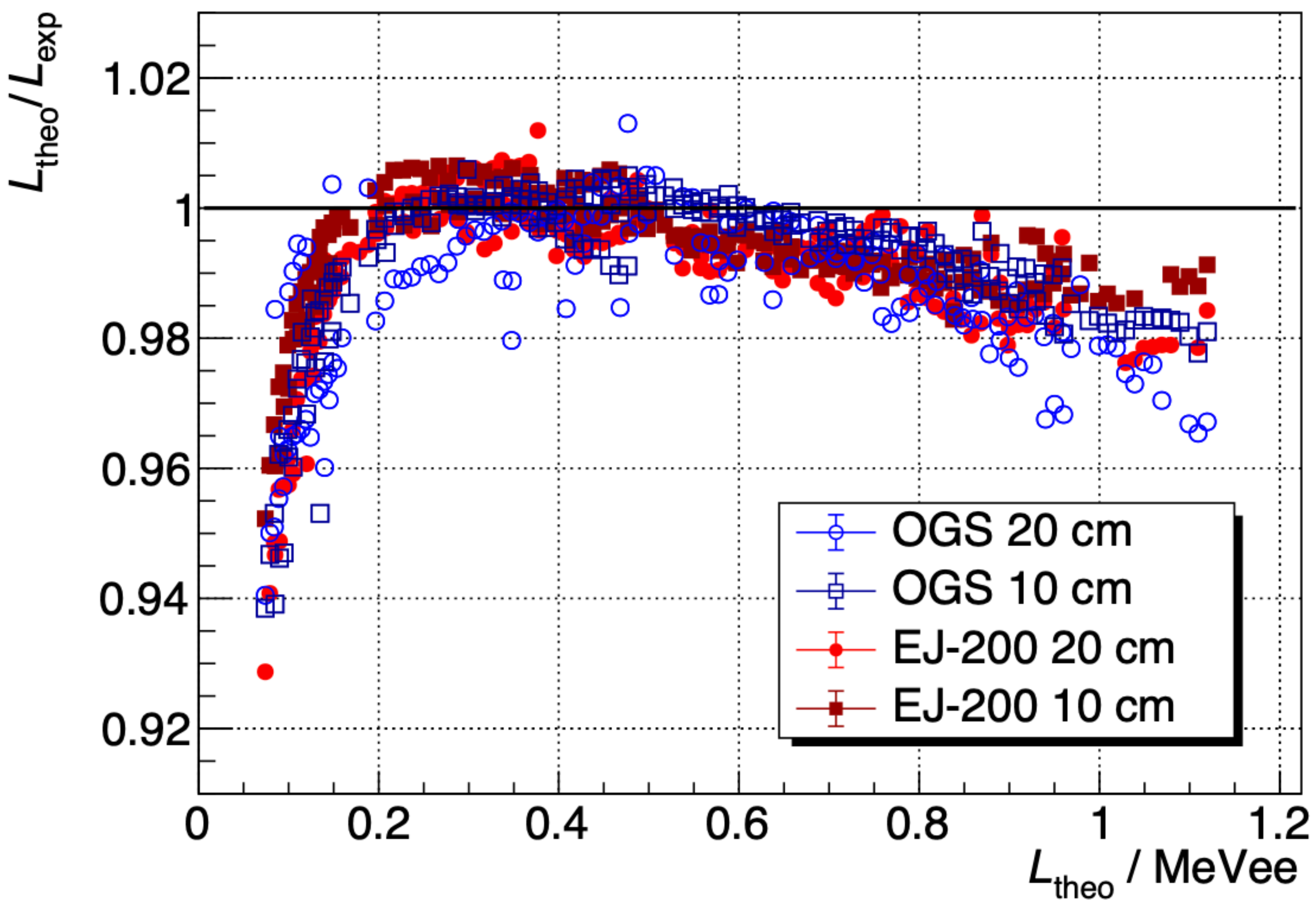
Determining scintillator neutron response

- Various methods, e.g. TOF with tagged ^{252}Cf source, accelerator based neutron beams.

Example of <u>ELBE - Center for High-Power Radiation Sources</u>:

- Electron beam emitted by a superconducting electron LINAC is used to produce a white neutron spectrum in a liquid-lead neutron radiator
- Energy ranges from below 100 keV to above 10 MeV with a variable repetition rate
- TOF give neutron energy, scattering angle provides recoil energy transfer
- e.g. Organic glass scintillators compared to EJ-200





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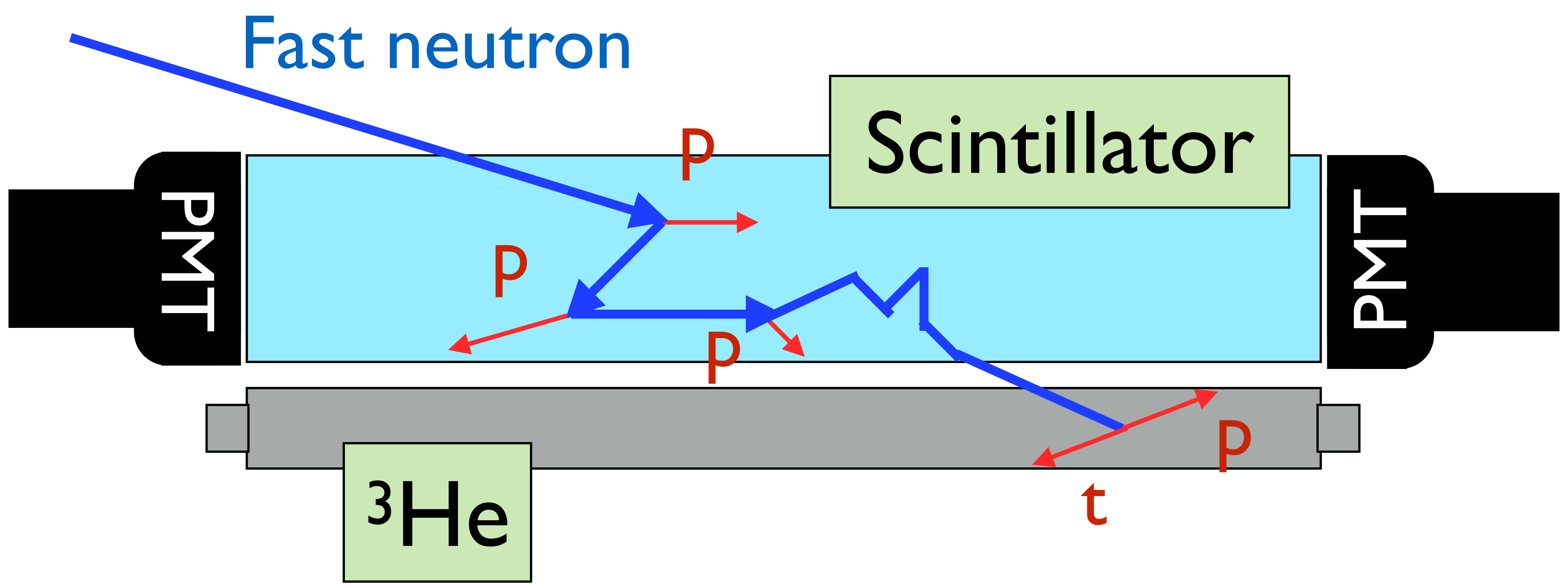
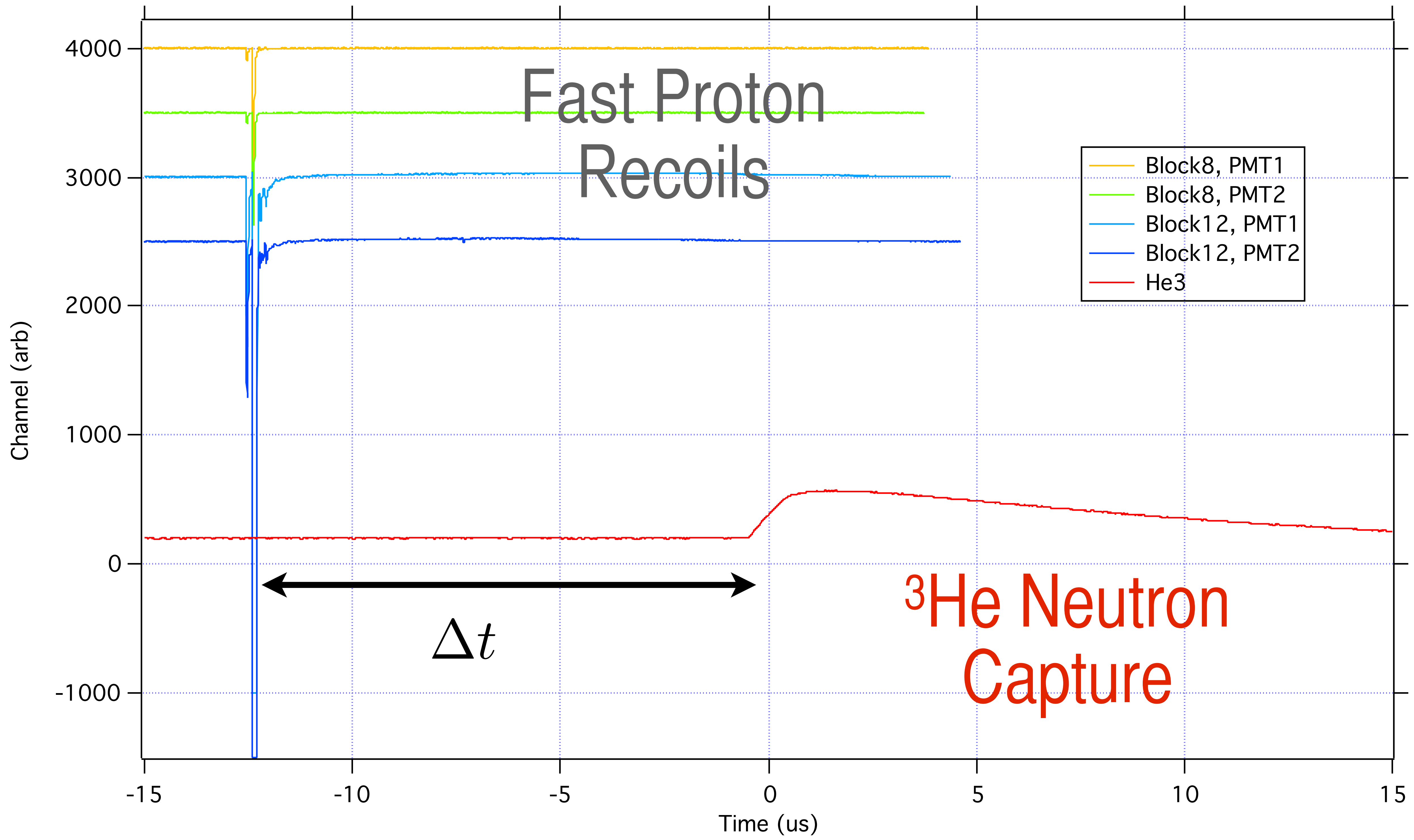
Capture Gating (FaNS example)

- Trigger on ^{3}He neutron capture
- *(very high gamma rejection)*
- Digitize all scintillator events within some window (~10s μs)
- Requiring a coincidence implies full energy deposition (approximately)
- Directly measures incident energy (minimal reconstruction)





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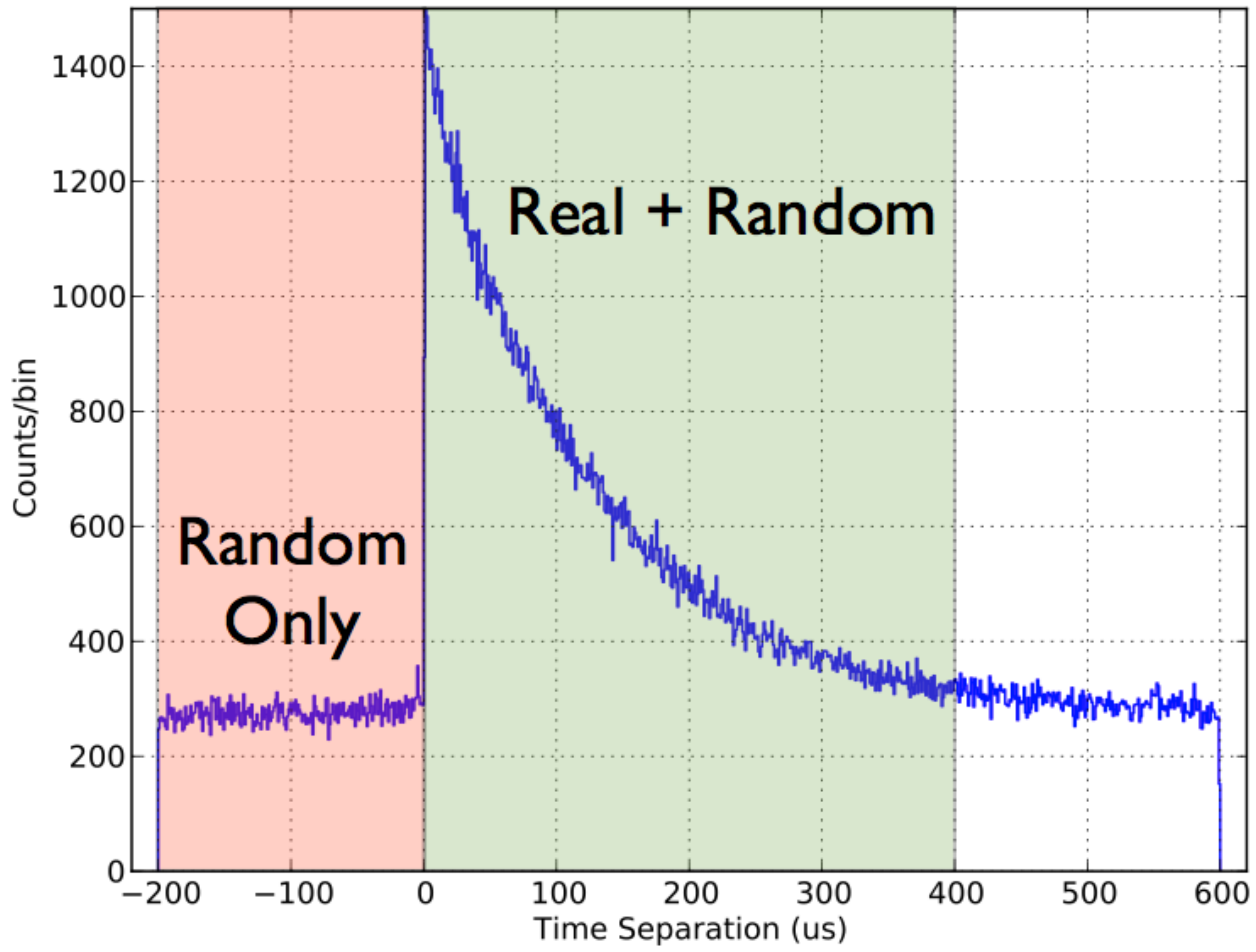


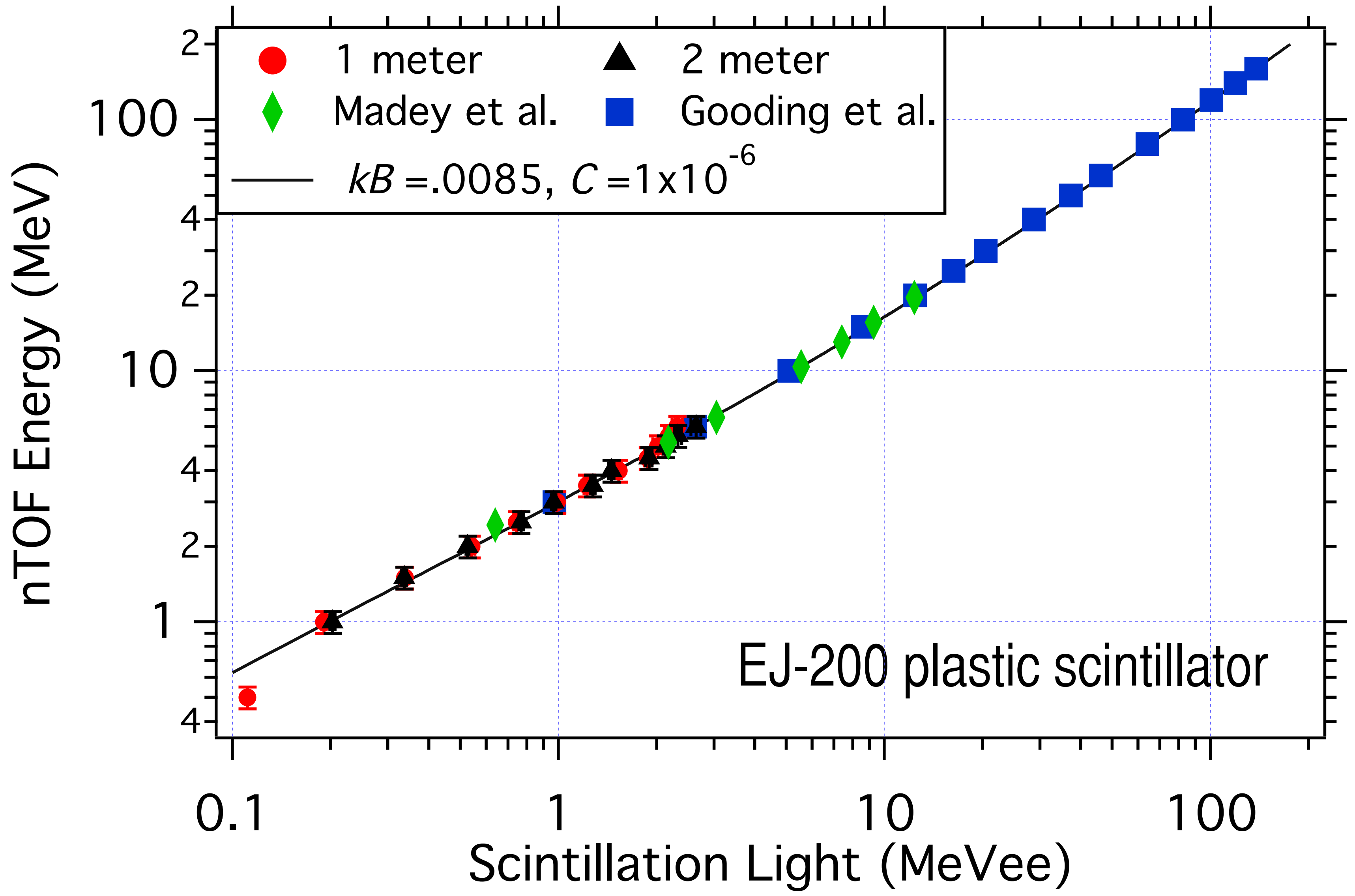
Reverse ordered events used to subtract background

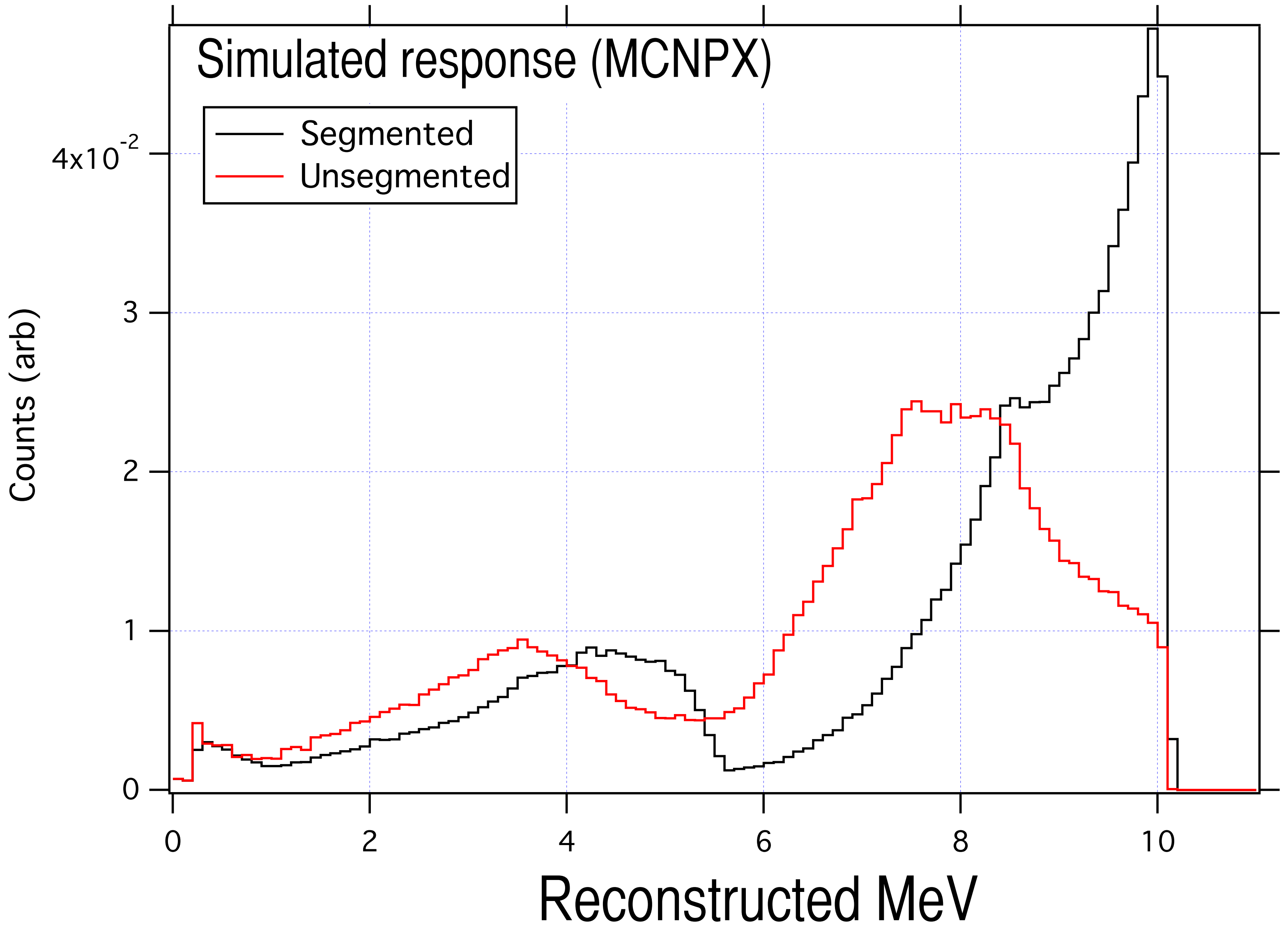
Time scale dominated by neutron capture time
(can be shortened e.g. by integrating capture agent into material)

Data and plot from T. Langford

Detector segmentation

- As noted: many materials (esp. plastic scintillator) have a response to charged particles that is nonlinear
- Optimized segmentation leads to better energy resolution
- Can be characterized using neutron TOF or tagged ^{252}C sources
- Energy reconstruction is improved by treating each recoil separately, determining energy and summing
- Segment size is a trade-off between cost (channels) and matching neutron mean free path





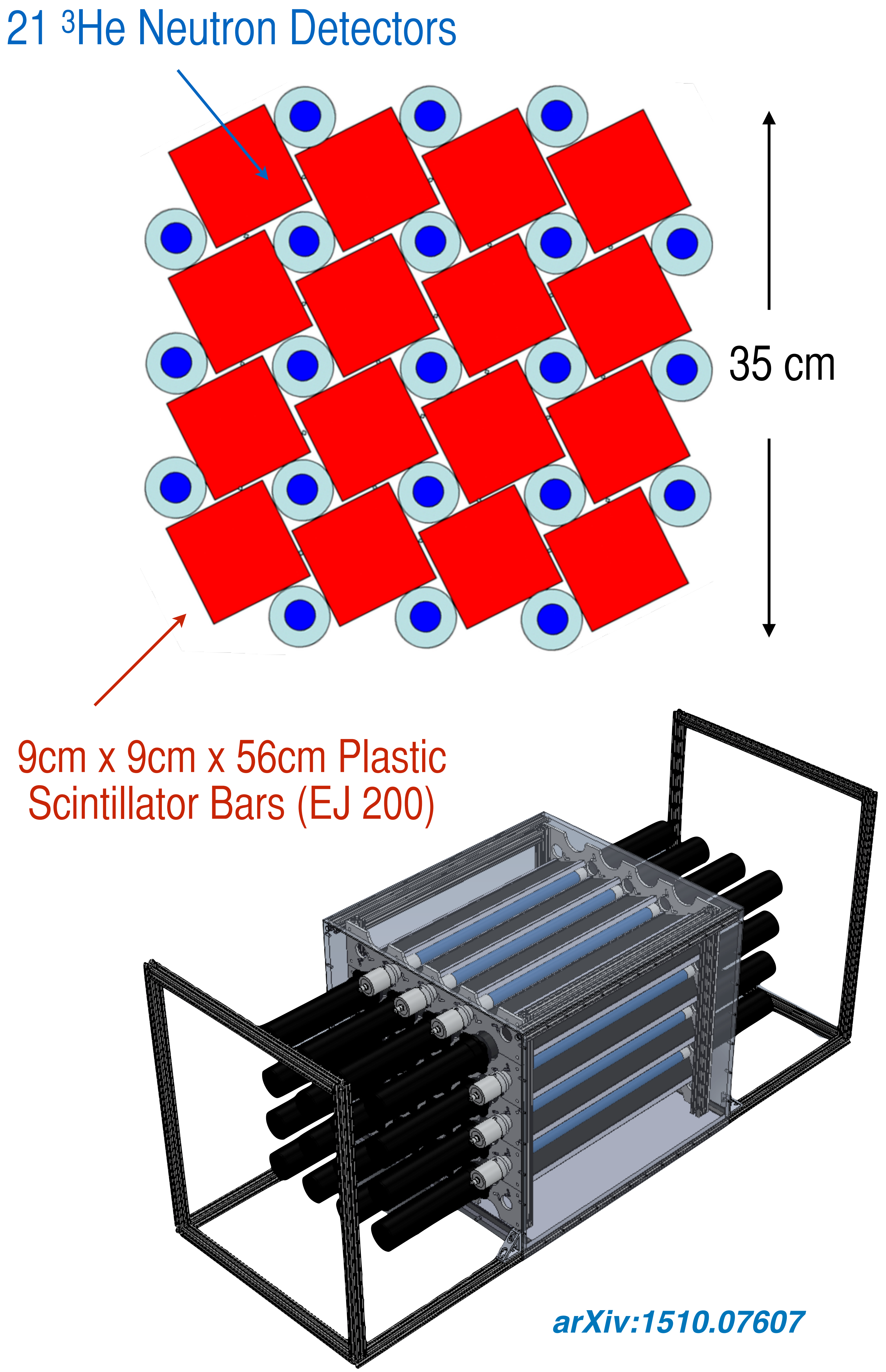
FaNS-2

NIST collaboration with University of Maryland:

- 72 liters effective volume
- 56 channel DAQ - CAEN 250 Ms/s
- PMTs with excellent linearity and characterization

Performance:

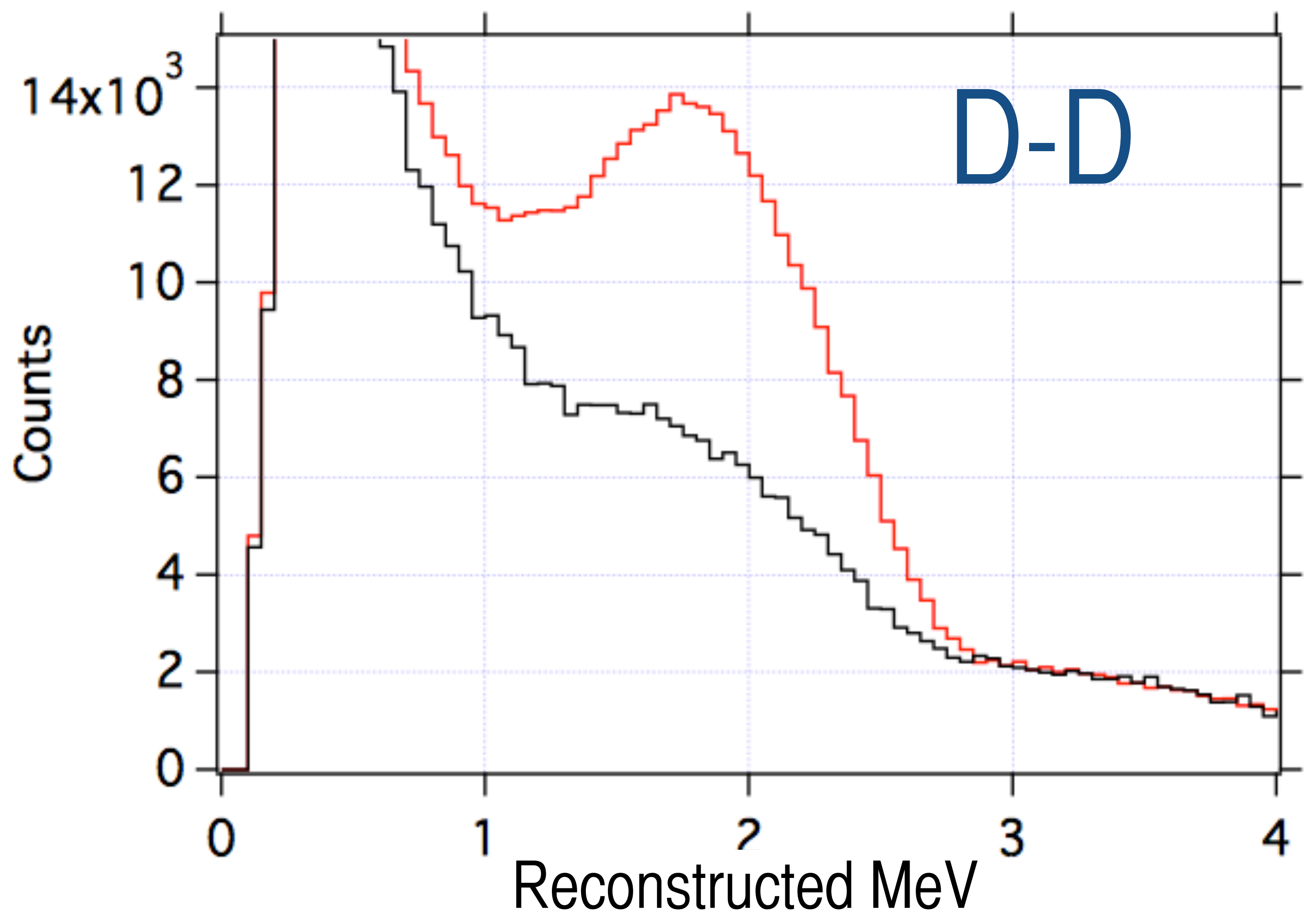
- Order of magnitude higher sensitivity compared to earlier versions
- Characterized w/ various sources in a low-backscatter facility at NIST
- Average efficiency 1-10 MeV (^{252}Cf) is 3.6 ± 0.15%
- Scale sets ‘effective’ sensitivity range of 1 MeV - 1 GeV

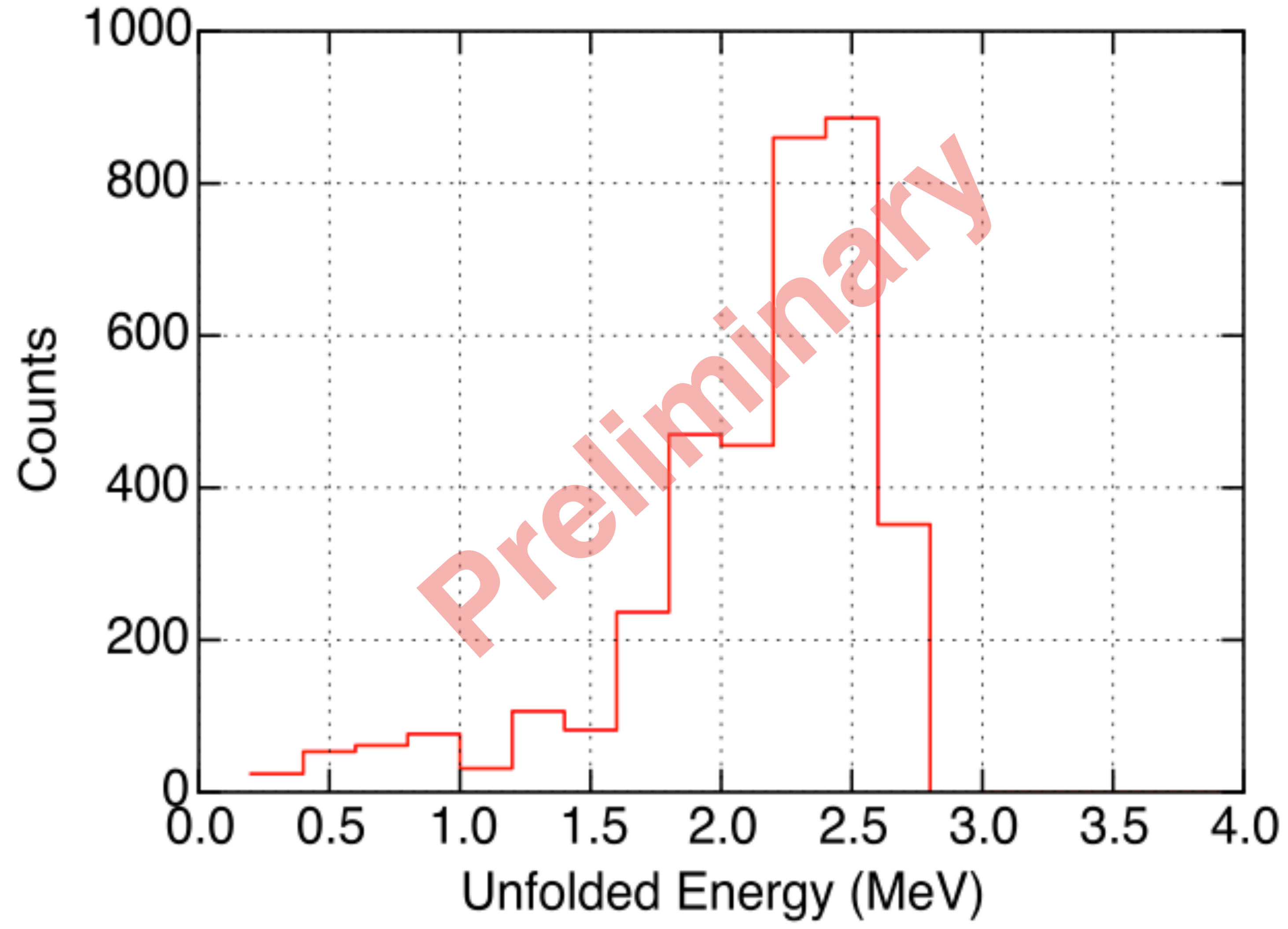


arXiv:1510.07607

Demonstration of segmentation:

- Illuminate detector with neutron generators
  - D-T at 14 MeV $D + T \rightarrow \, ^4He + n \; (14.1 \; MeV)$
  - D-D at 2.5 MeV $D + D \rightarrow \, ^3He + n \; (2.5 \; MeV)$
- Low backscatter room (low mass walls)
- Use MCNP to generate a response matrix and then Single Value Decomposition to deconvolve the spectrum
- Response is good:
  - 'raw' ~ 1 MeV at 2 MeV
  - deconvolved ~ 0.5 MeV at 2 MeV
  - Roughly 2 MeV at 14 MeV





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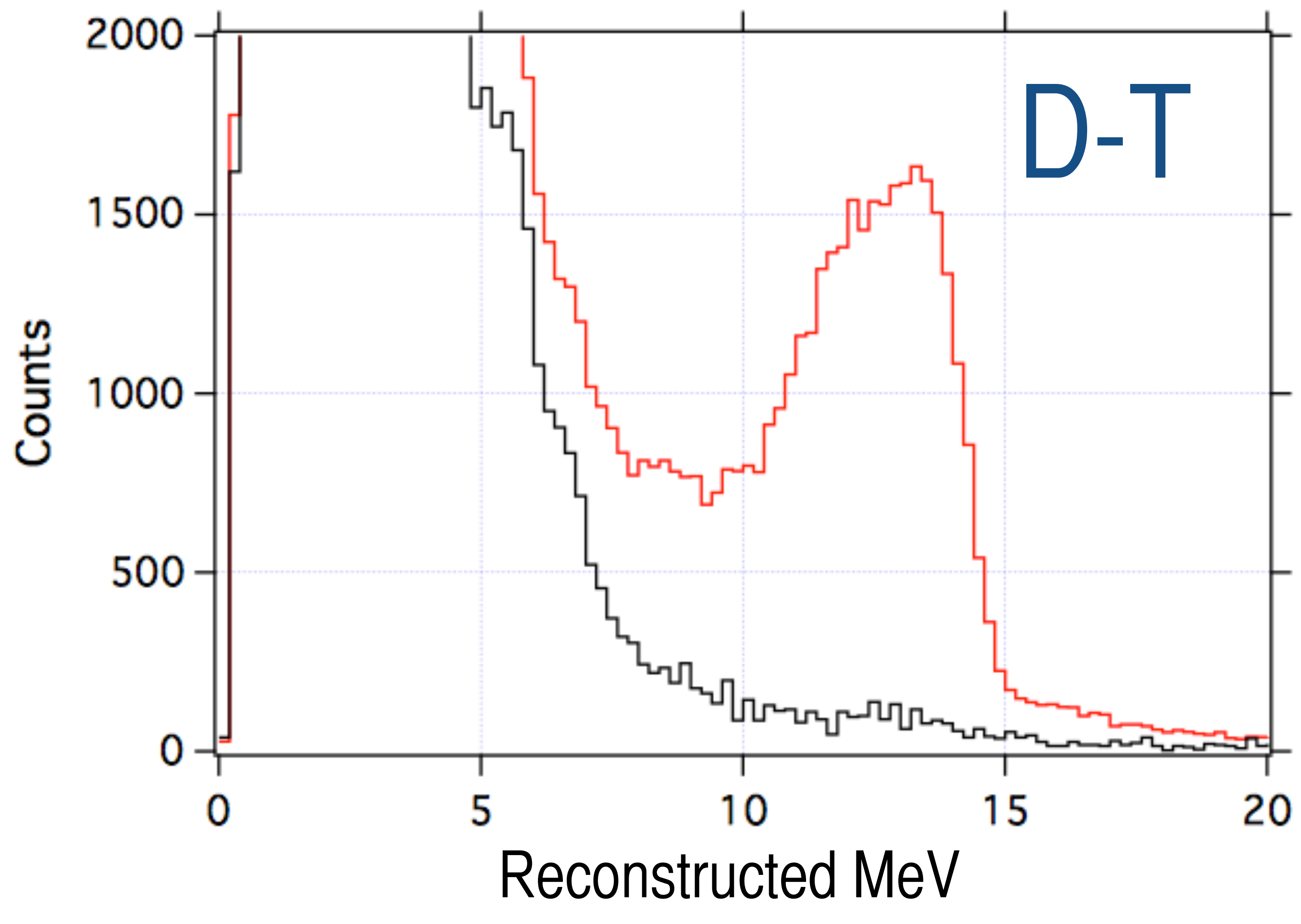
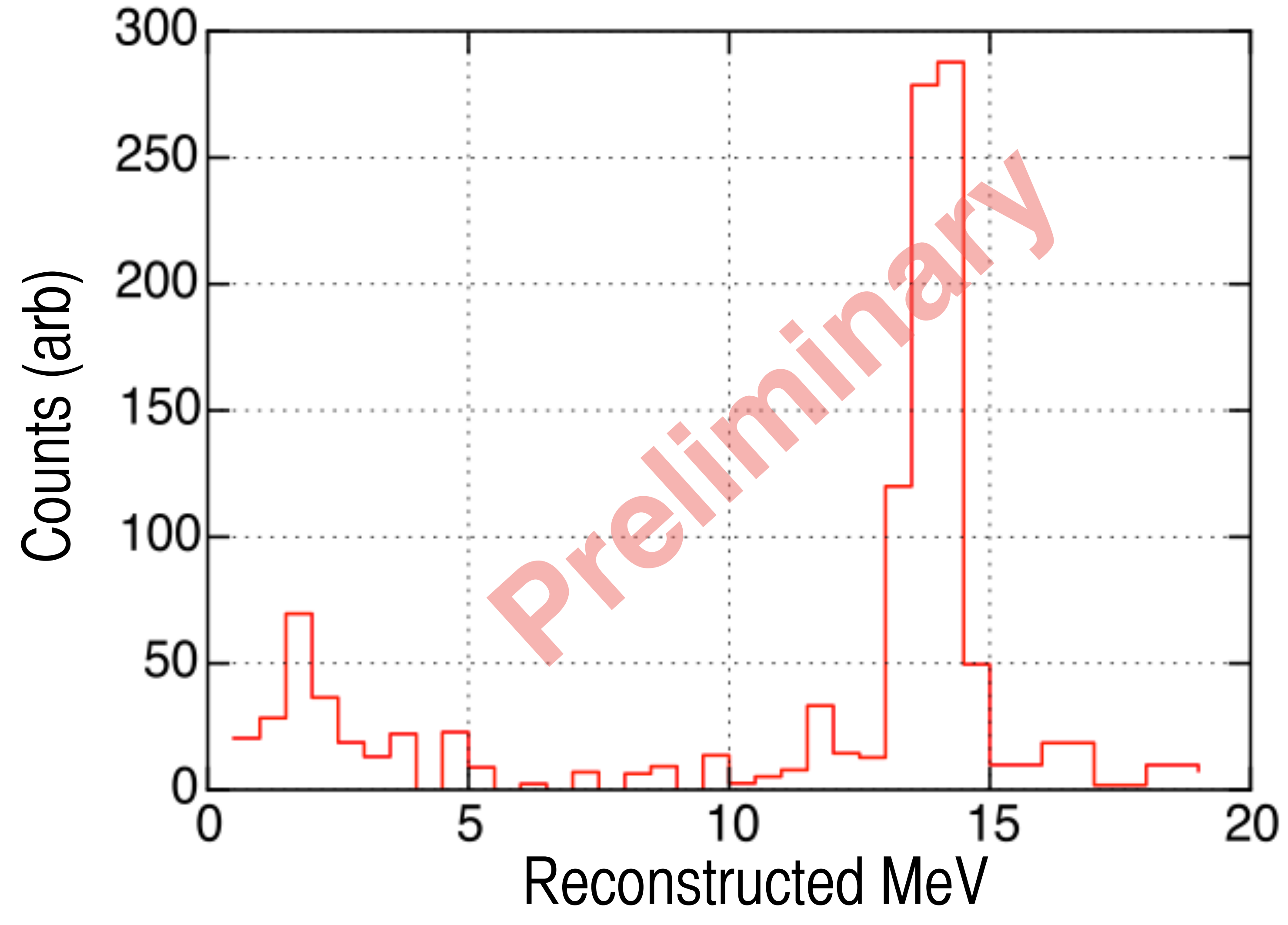
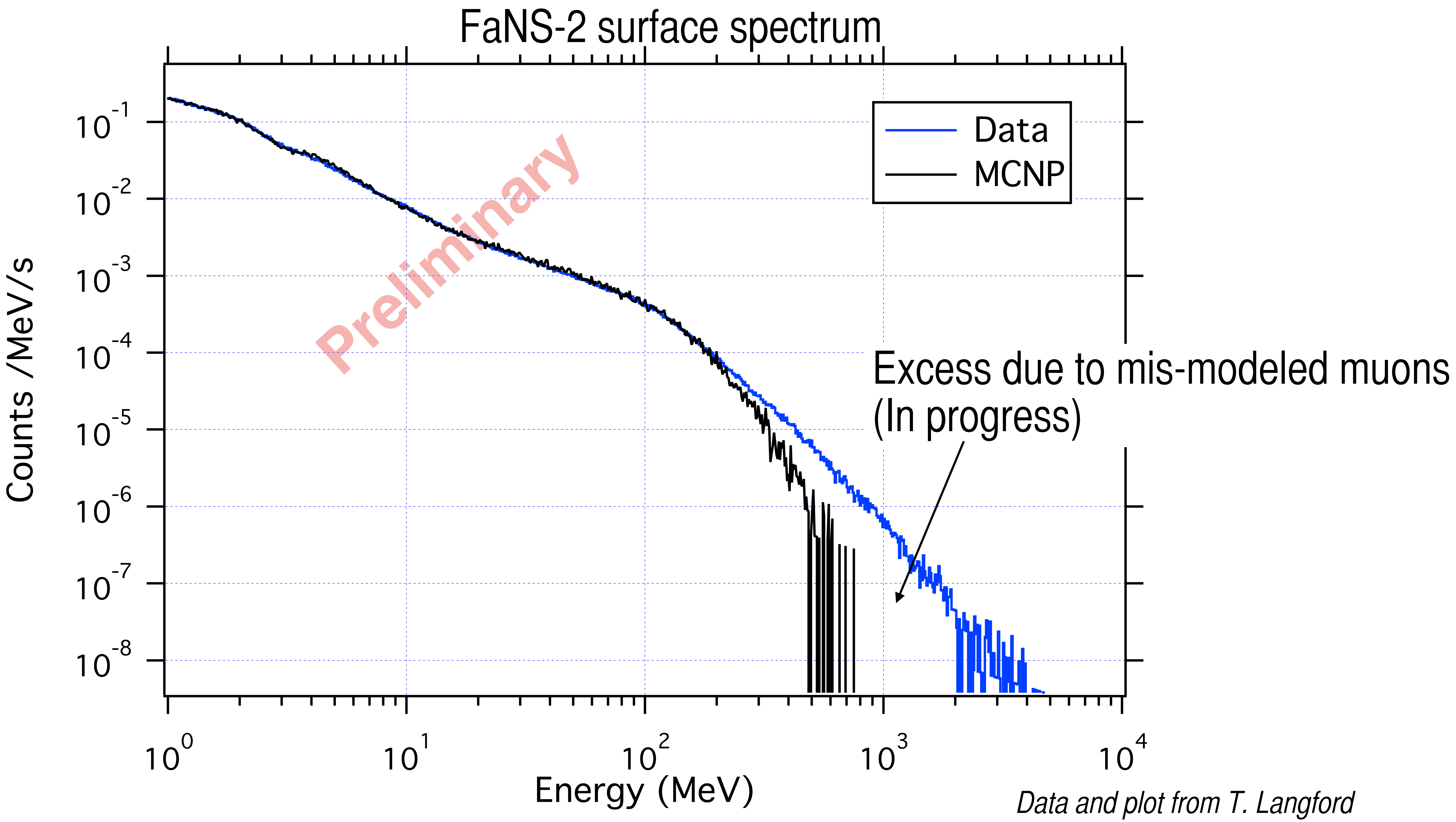




Cosmogenic fast neutrons (w/ structure in spectrum)



Data and plot from T. Langford

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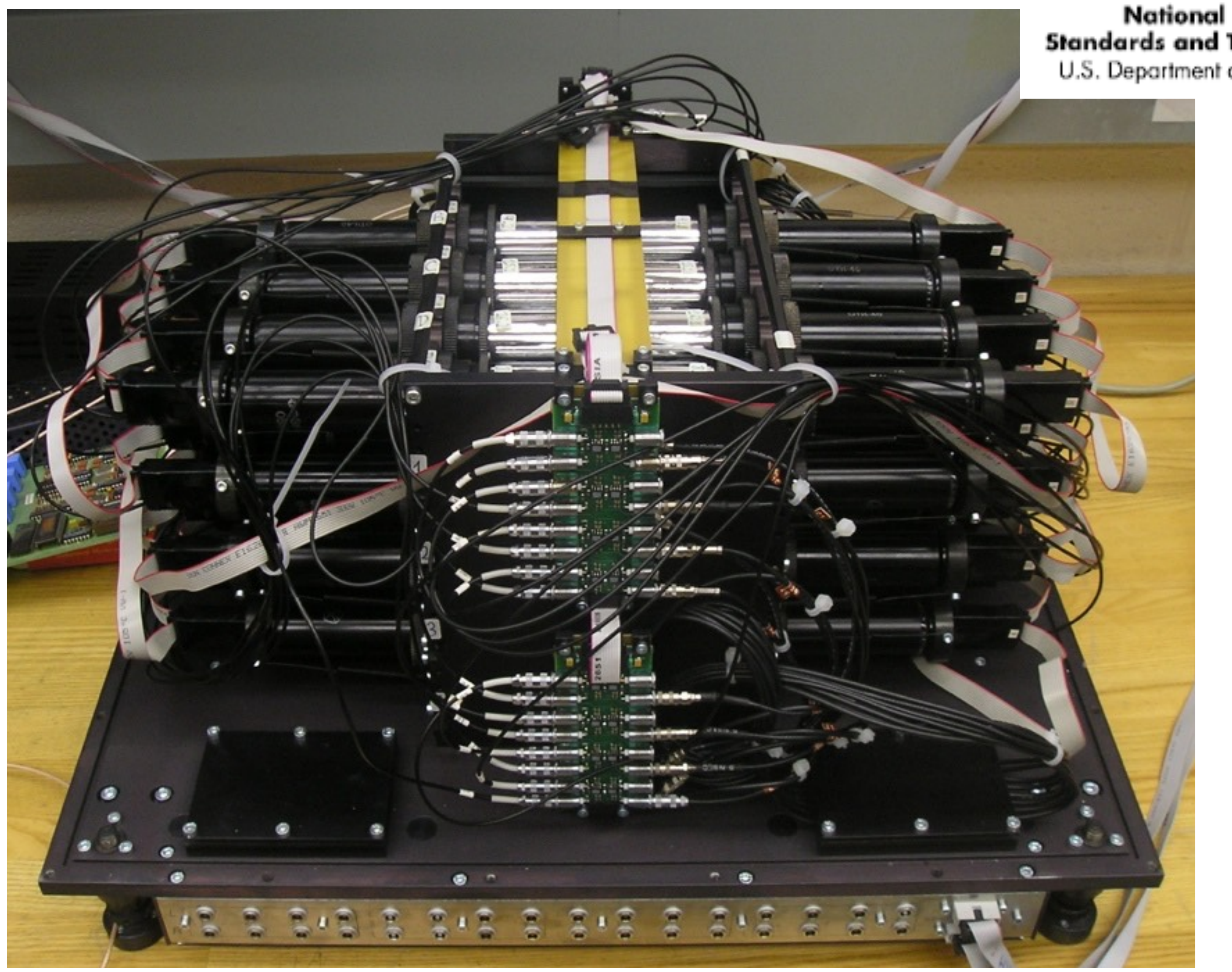
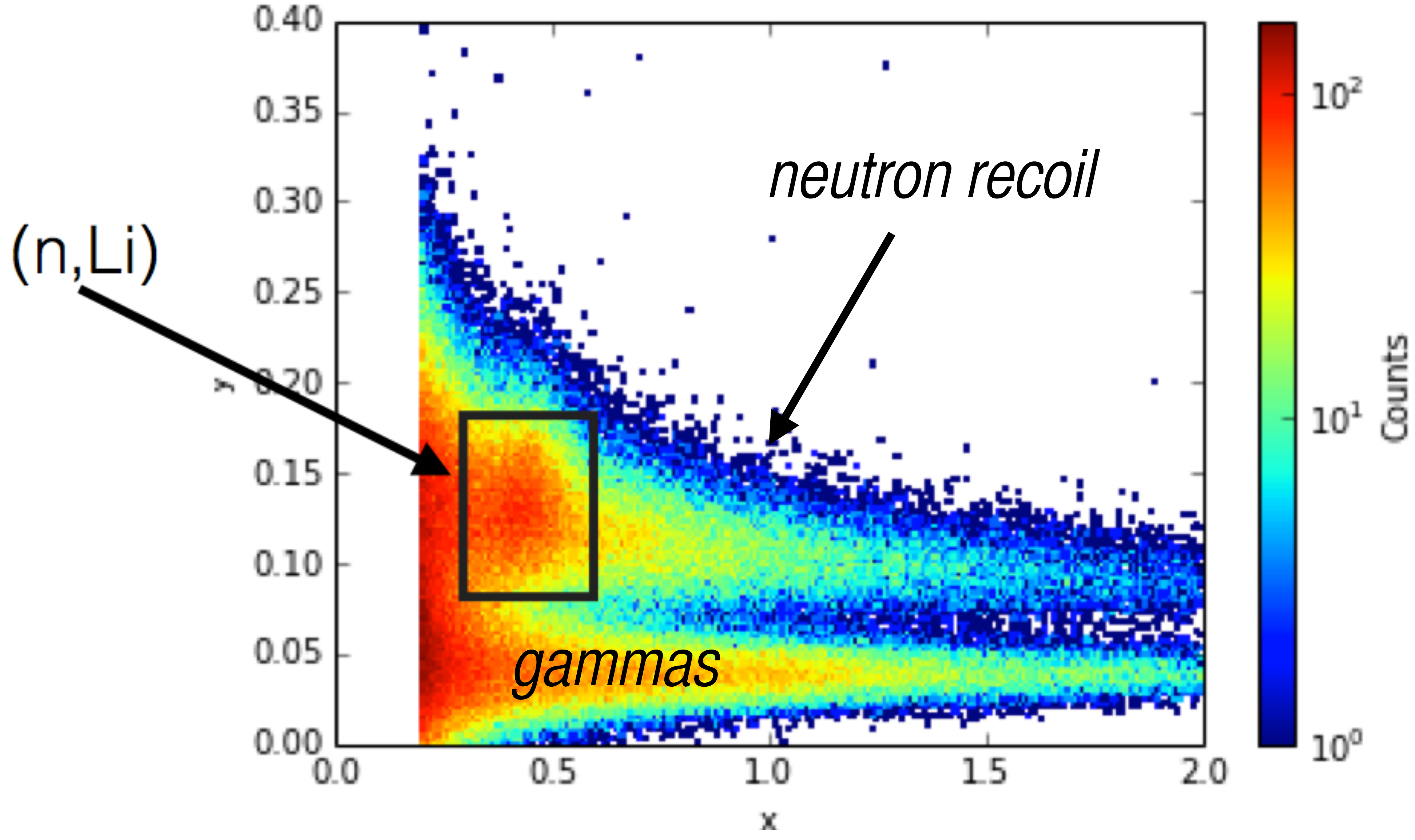
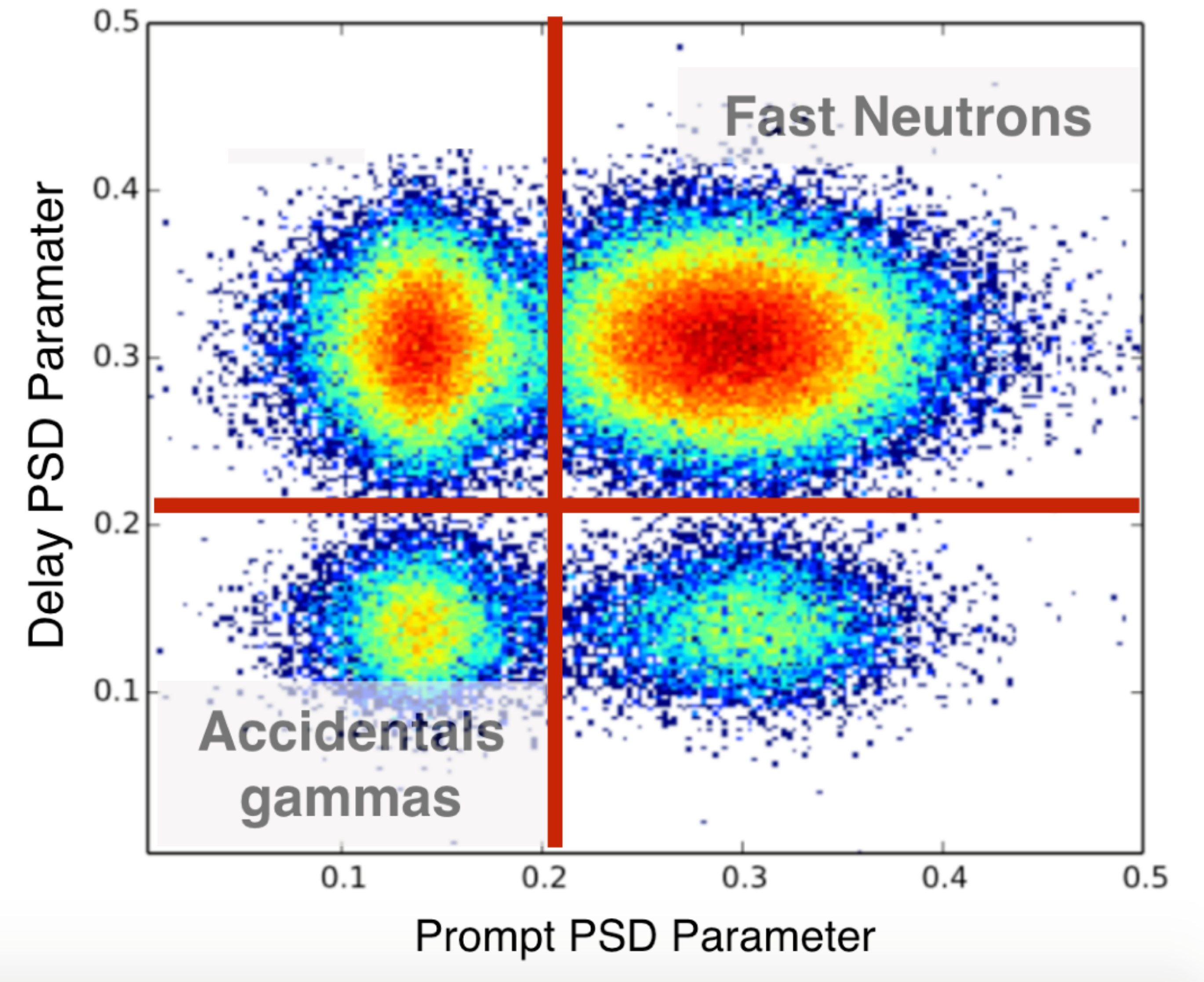
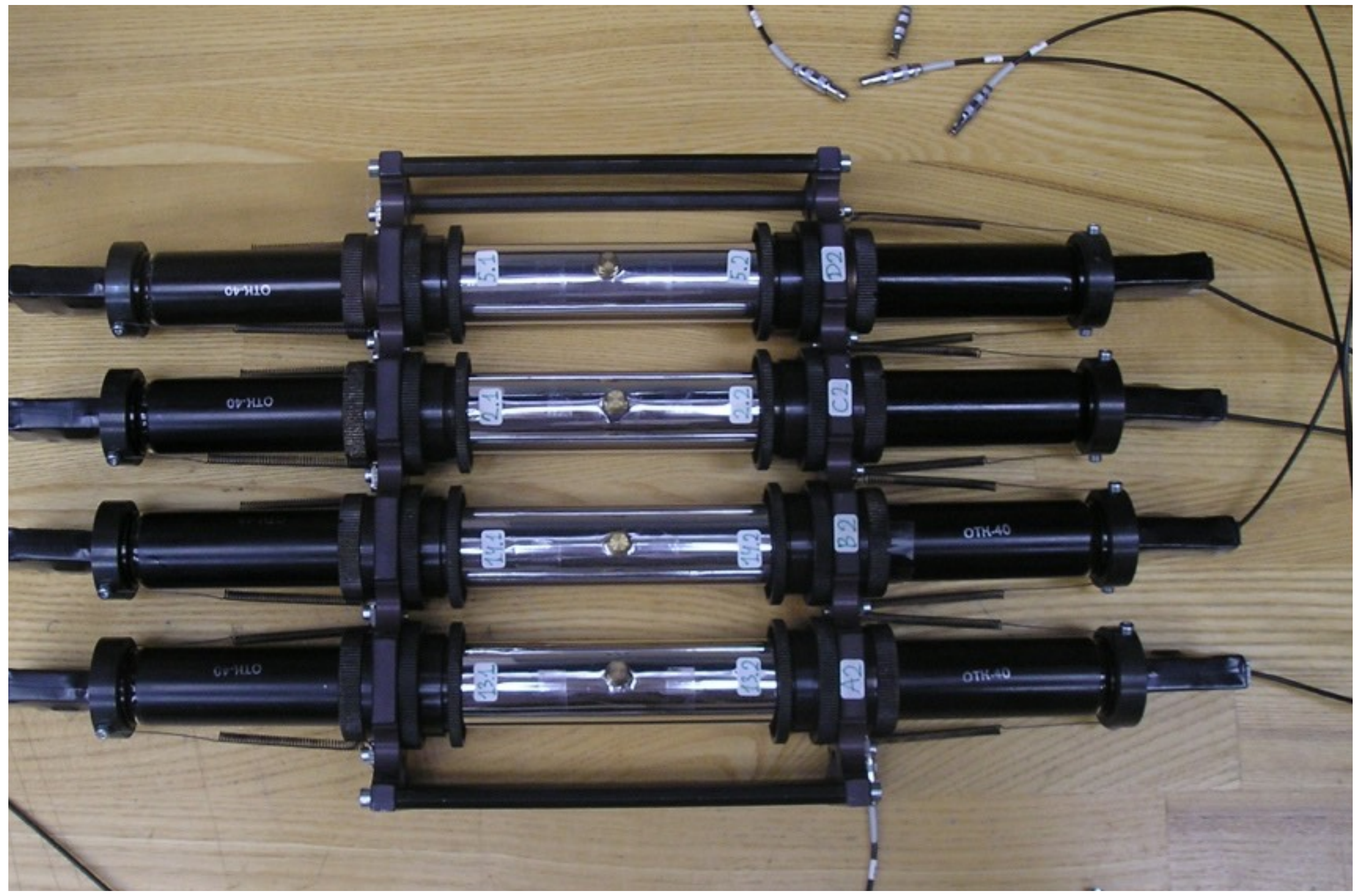
Incorporating PSD

- Array of 16 quartz LS-filled tubes (0.4% ^{6}Li-doped PSD capable UltimaGold AB)
- Dimensions optimized for ~ MeV scale neutrons - maximum energy resolution
- Combining capture gating w/ PSD offers much improved background rejection
- Highly transportable

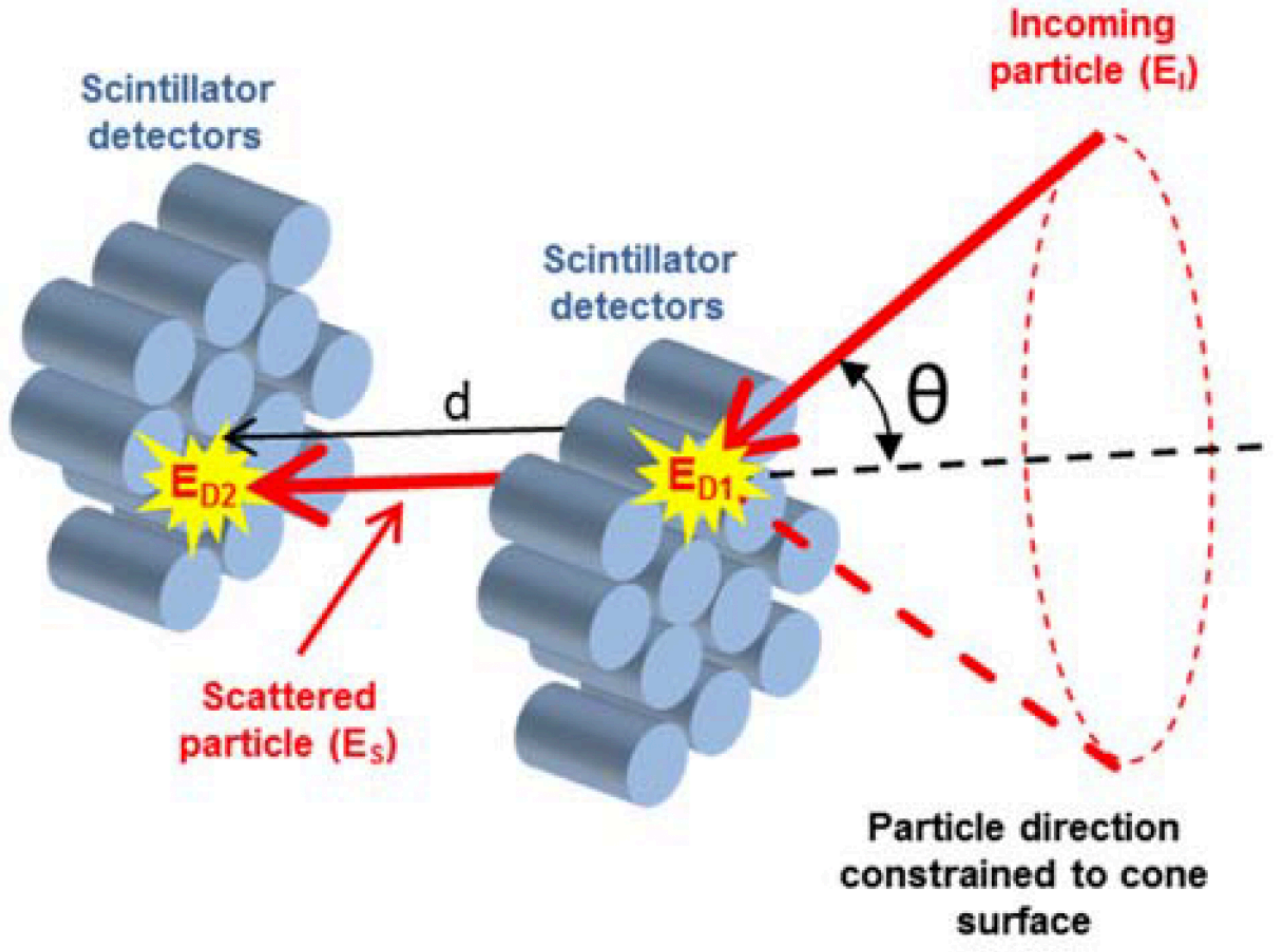






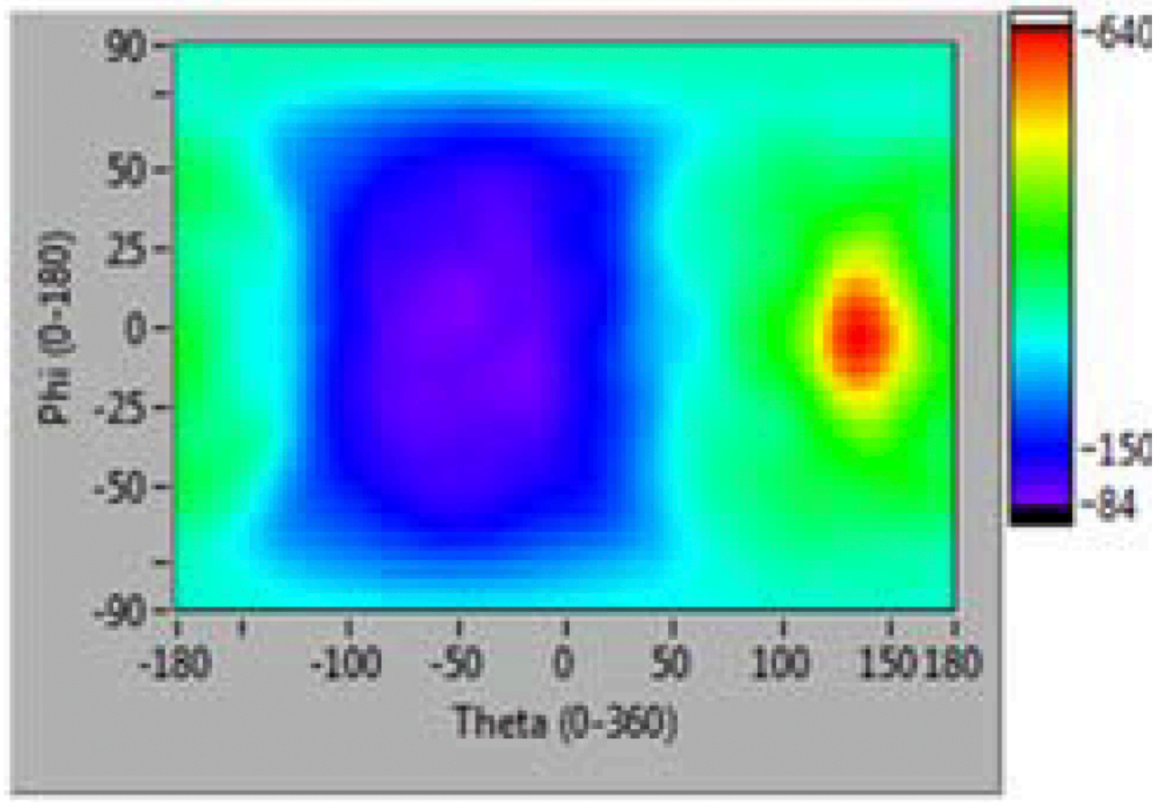


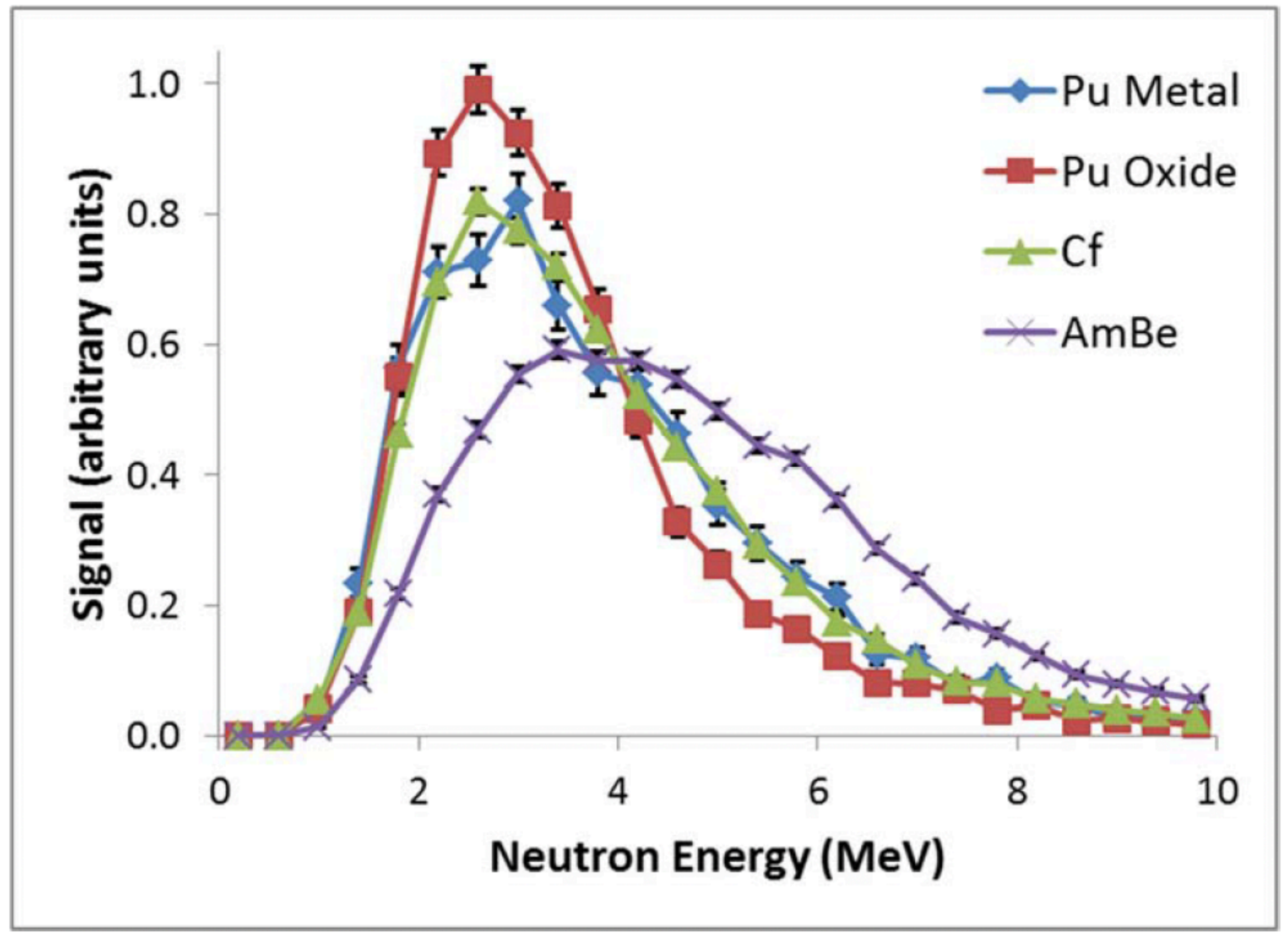
Neutron scatter camera



Event by event directionality

- Scatter-camera imaging of fast neutrons utilizes the kinematics of elastic scattering to reconstruct the incident energy and direction of neutrons that interact twice in a detector system
- E1, E2, and TOF give total energy and incoming cone of angles
- Design tradeoffs familiar; reject gammas (PSD), single scatter per segment (many segments) etc…
- Direction and energy can allow localization and identification of source
- Negative is the obvious low efficiency





Review of Scientific Instruments 87, 083307 (2016)

Recoil track detectors

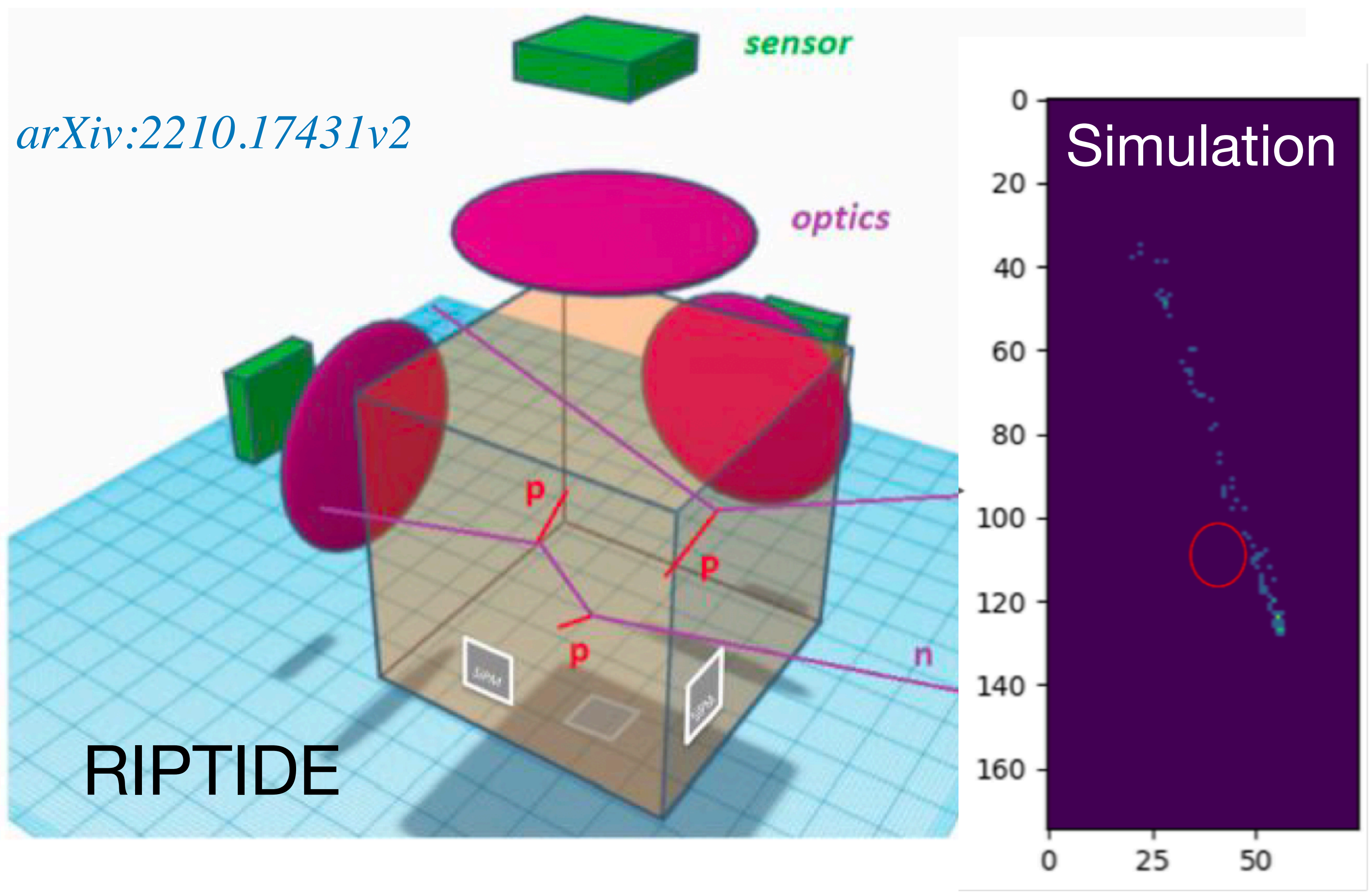
- Image the recoiling nucleus = direction information!

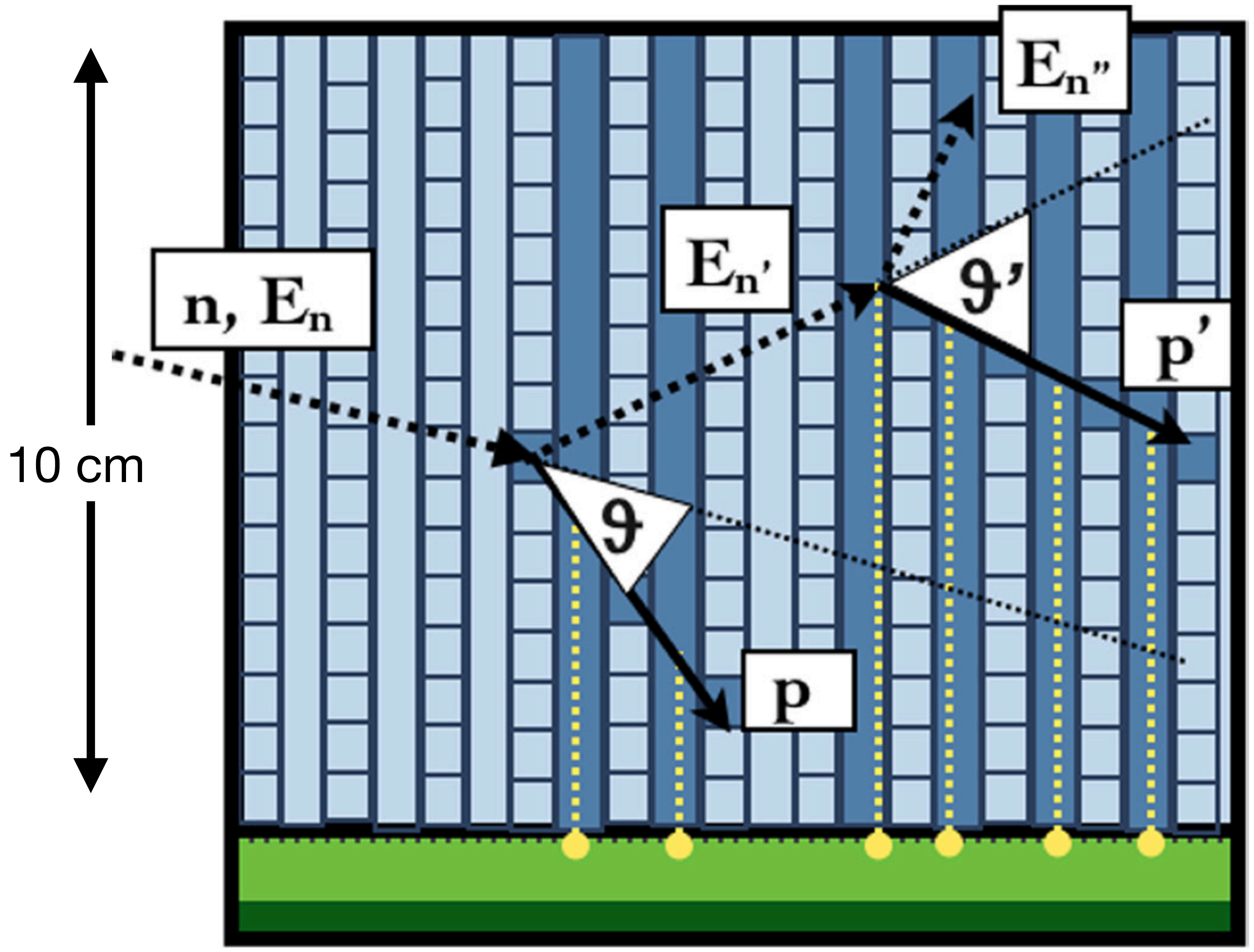
Challenge:

- Complex to implement
- Not a lot of signal to work with
- Efficiency

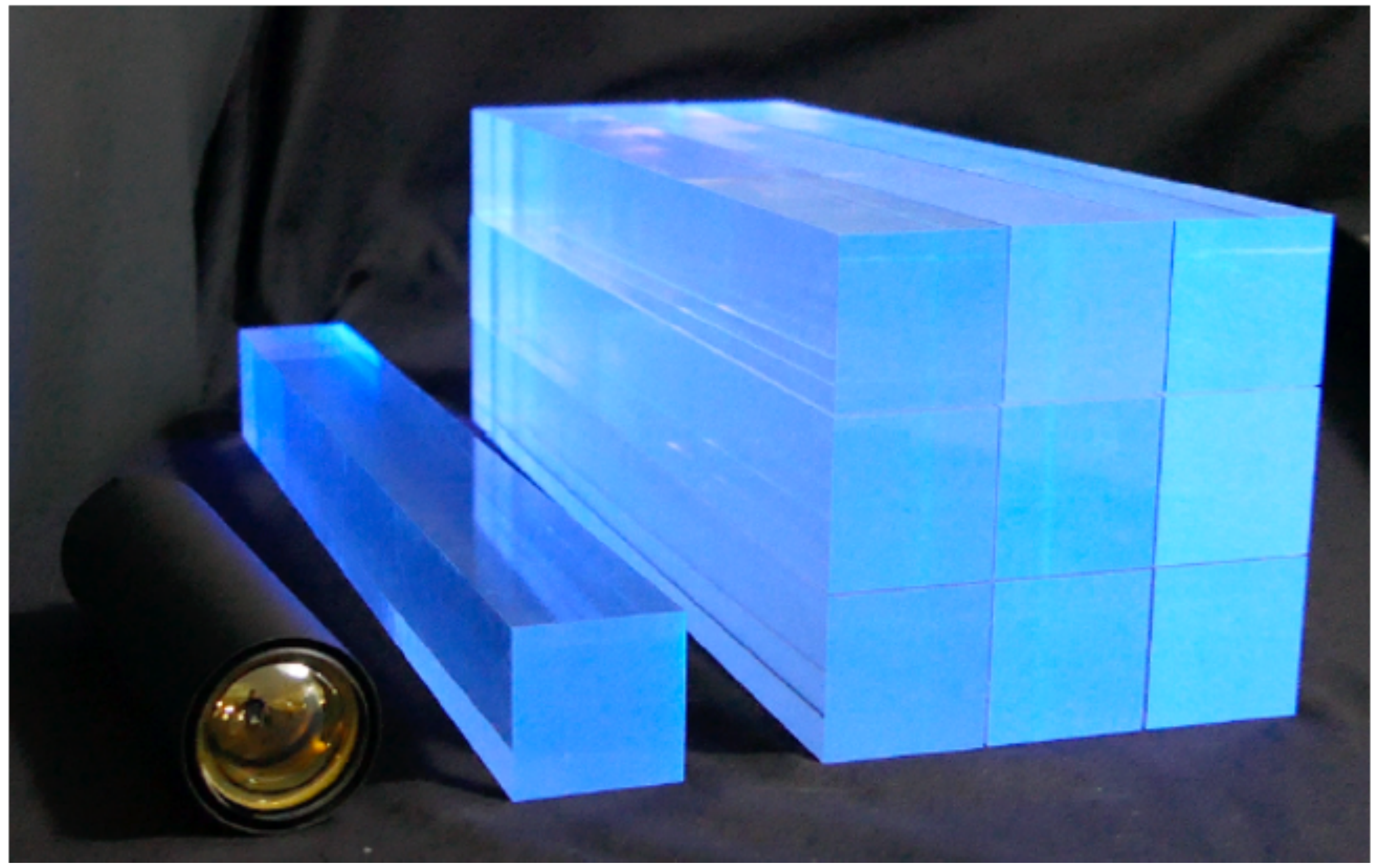
Concepts exsit:

- RIPTIDE (CMOS sensors w/ optics) around plastic
  - Bragg peak gives direction, track length gives recoil energy
- MONDO (250 μm layers of scintillating fibers)
- detector capable of tracking the fast and ultrafast neutrons produced in PT treatment
- Primary challenge is photons/recoil
- CMOS single particle tracking (with possible amplification)
- Efficiency 😞





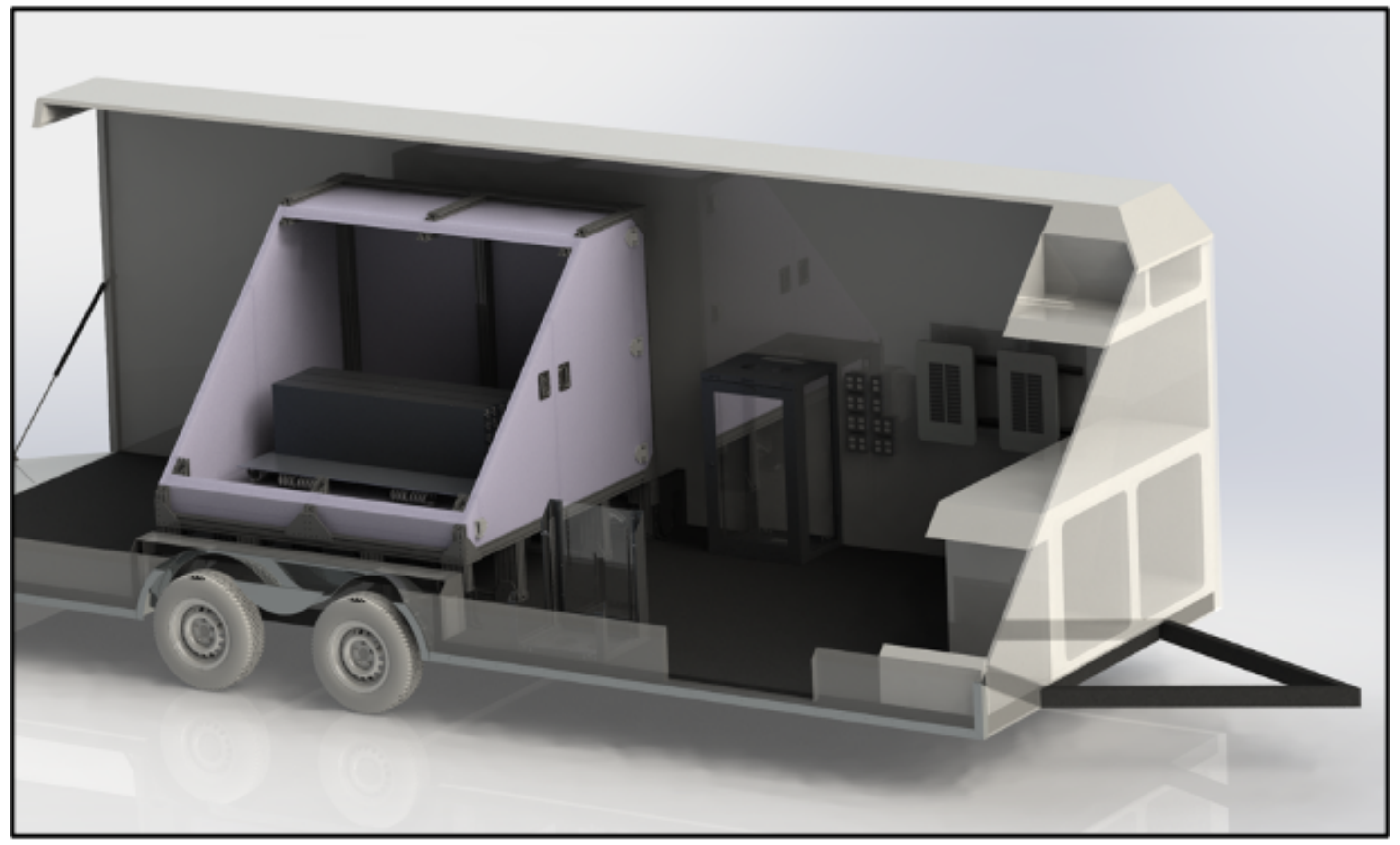
Bar size: 55mm x 55mm x 500mm

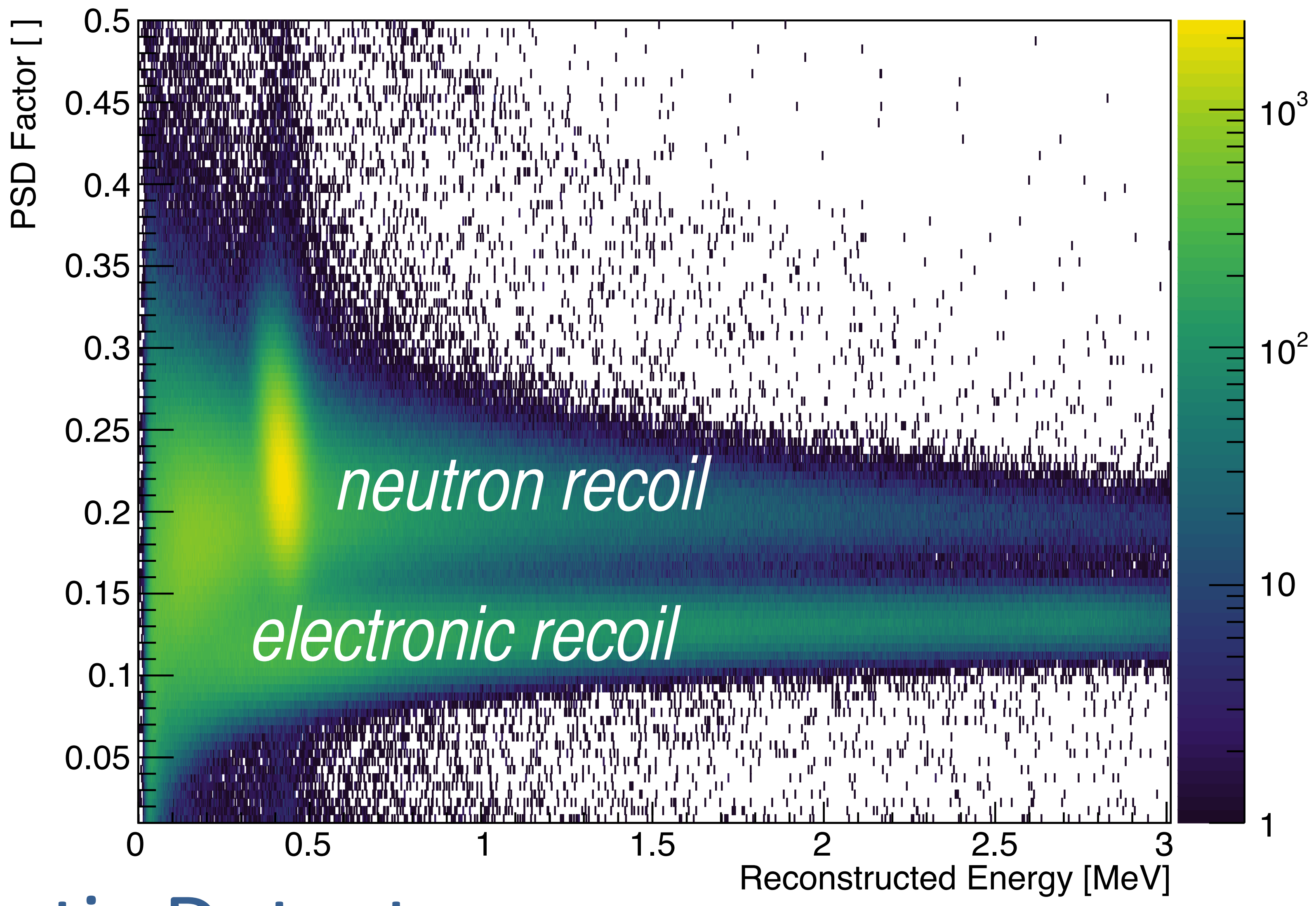


Nucl. Inst. And Meth. A V668, P88, (2012))

Future directions in fast neutron detection

- Meter-scale ^{6}Li doped PSD plastics developed by LLNL & Eljen
- Detection performance comparable to good ^{6}Li-doped liquid scintillators
- PSD performance in long bars suitable for neutron capture ID and fast neutron recoil detection
- Robust transportable solid detectors for fast neutron spectroscopy at site





ROADSTR Prototype ^{6}Li PSD Plastic Detector

Detailed description of ROADSTR was presented as a SNOWMASS 21 Letter of Interest - https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF9_NF7_ROADSTR_Mobile_Antineutrino-184.pdf

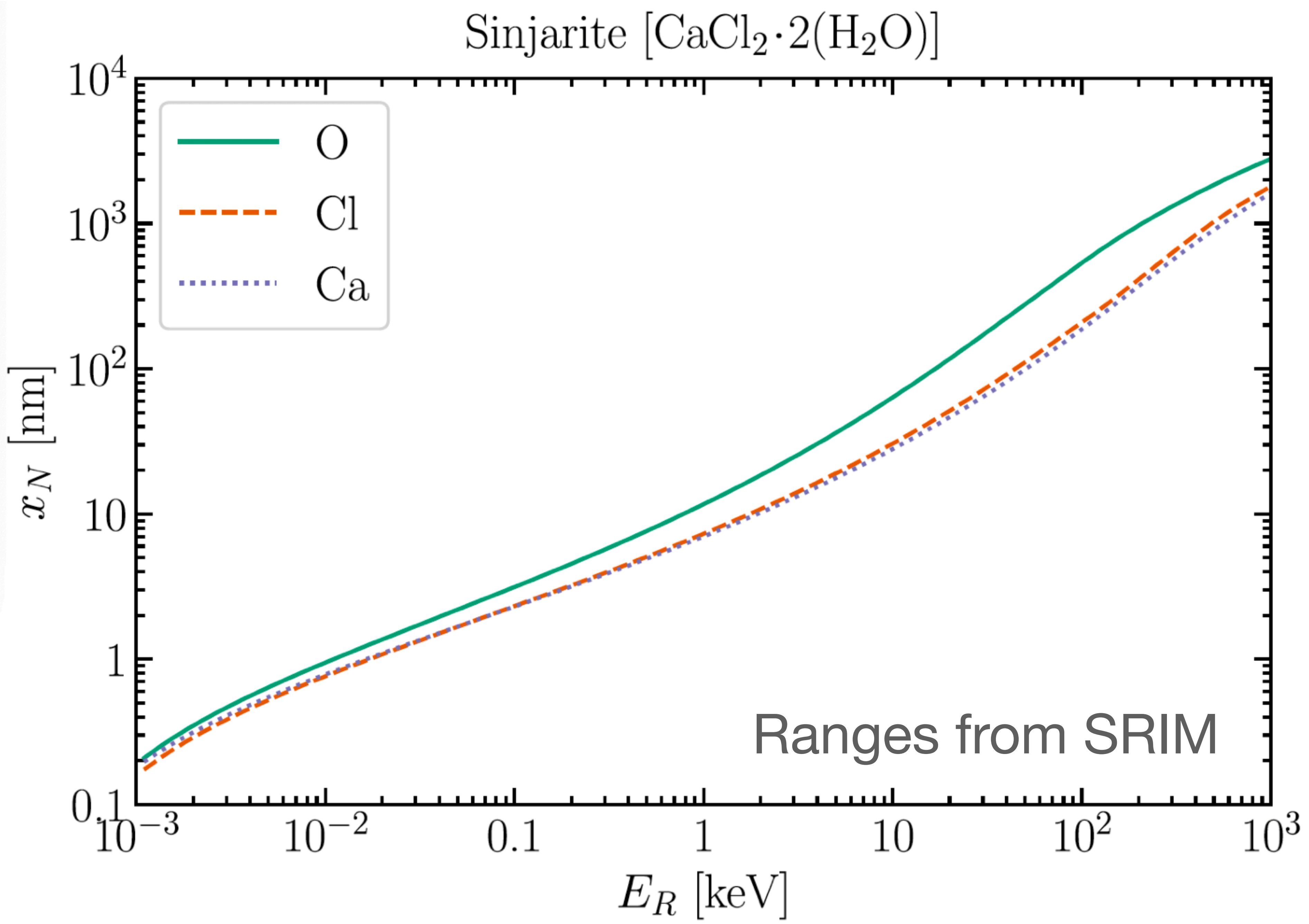
Neutron recoils in minerals

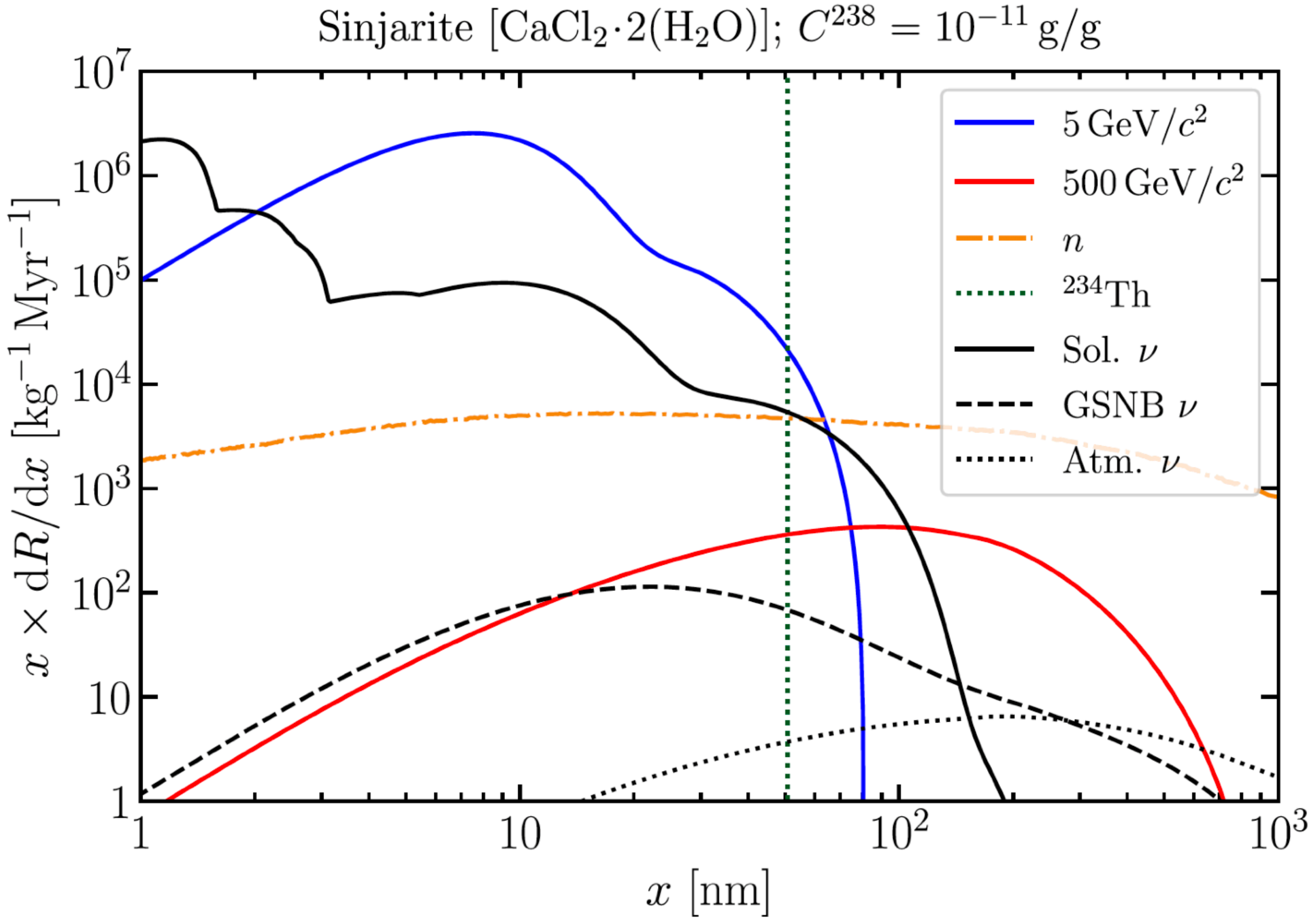
Just like a WIMP or neutrino, neutrons cause recoils:

- Track length (up to μm) depends on recoil energy & primary knockout atom
- This range can be different that signals of interest (e.g. atmospheric neutrinos)
- Shape of signal depends on the model of the incident particle, allowing statistical discrimination - not event by event.
- At depth, neutrons primarily come from (α,n) and directly from ^{238}U fission
- Neutrons of 1-10 MeV scatter multiple times (but not densely clustered in location) yielding a 'flat' spectrum of track lengths.

Minerals with a low ^{238}U content critical to background reduction.

Similarly, precise characterization of neutron induced tracks is key.





Physics of the Dark Universe, Vol 41, 2023, 101245

Conclusions

- Neutron metrology is a rather mature field with many many tools available.
- Despite this, precision neutron measurements present challenges due to the nature of the neutron
  - Length scales of interactions
  - Cross section that are big enough the matter but small enough to allow penetration
  - Single neutrons interact over a ‘large’ area
- In the context of paleo detectors:
  - Characterizing potential neutron backgrounds may be critical for many use cases
  - Metrological studies of neutron induced tracks
- Advances in high-efficiency fast neutron spectrometers offer new capabilities that could prove essential.
- Don’t ignore neutron metrology

Thanks!

Backup slides

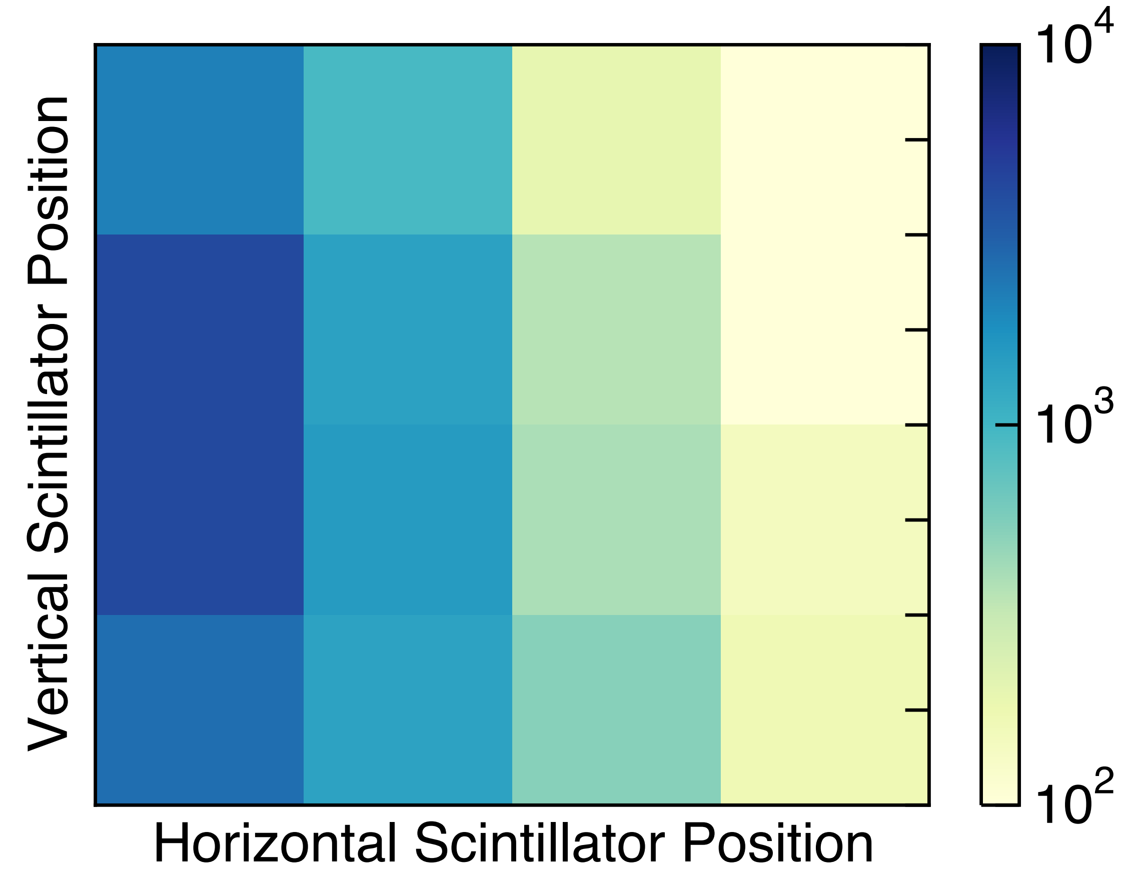
National Institute of Standards and Technology
U.S. Department of Commerce

Source detection and calibration

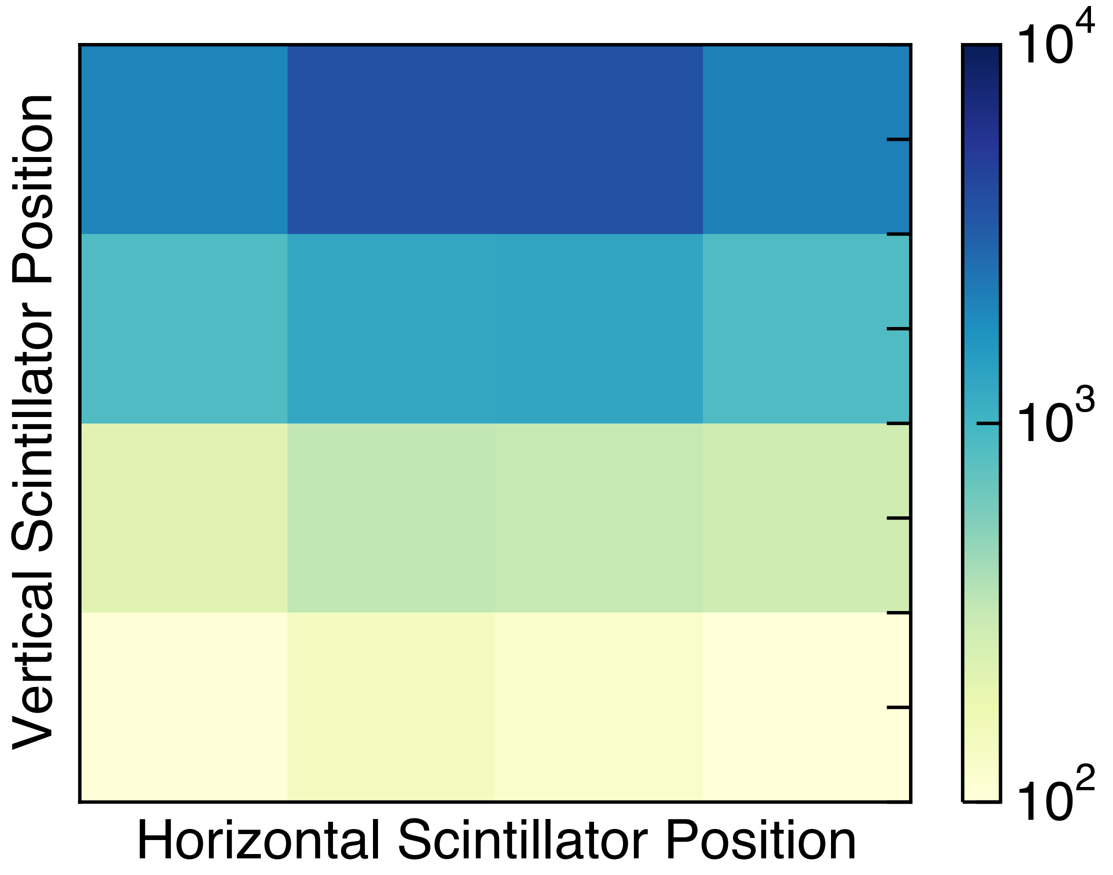
- ^{252}Cf source runs at 50 cm show good *statistical* directionality

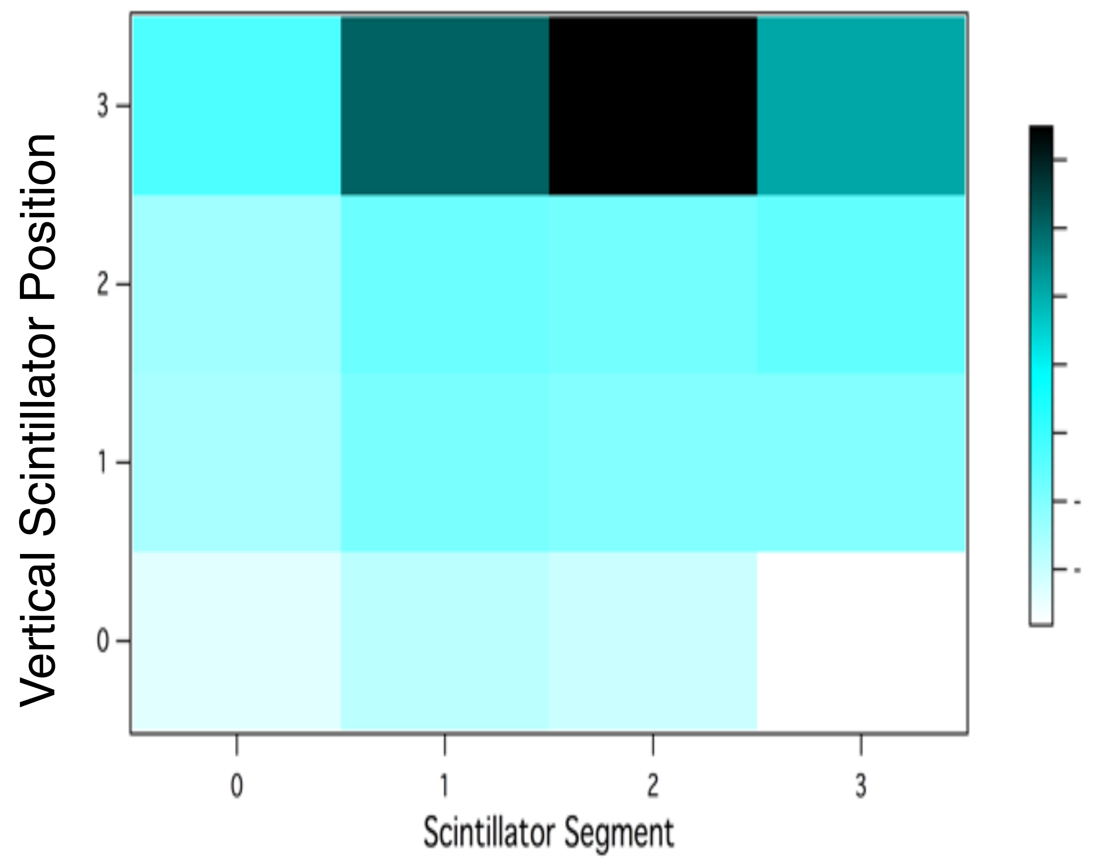
  (simply attenuation)
- 221 µg ^{240}Pu at 1 cm (0.23 s^{-1}) gives 5 sigma detection after one day
- Implies 5 sigma detection of 100 g at 10 m in 15 min
- Well-understood high-efficiency detector can in principle be used for source calibration, i.e. remove central tube and replace w/ source
- Fills gap in source strength calibration relevant to dark matter searches, i.e. 100 Bq activities

^{252}Cf source

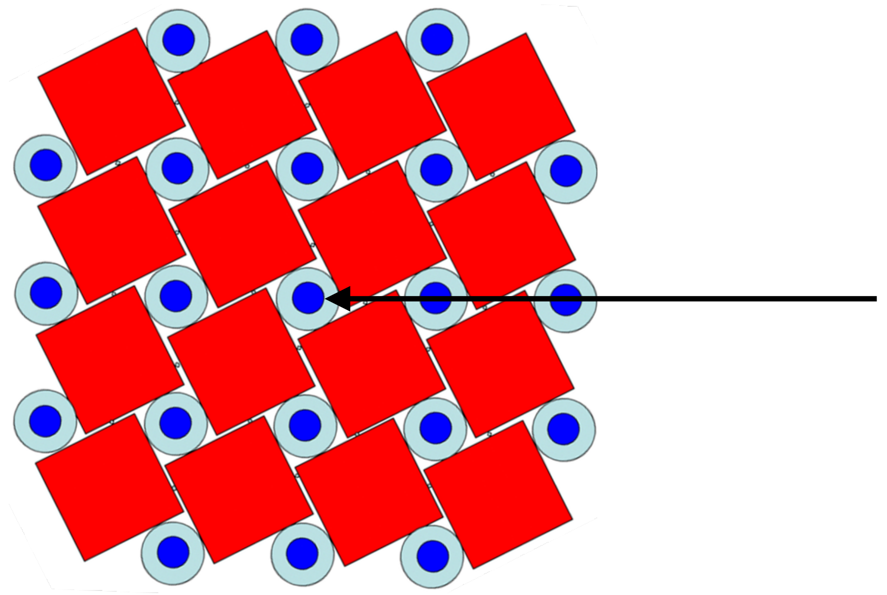


^{252}Cf source





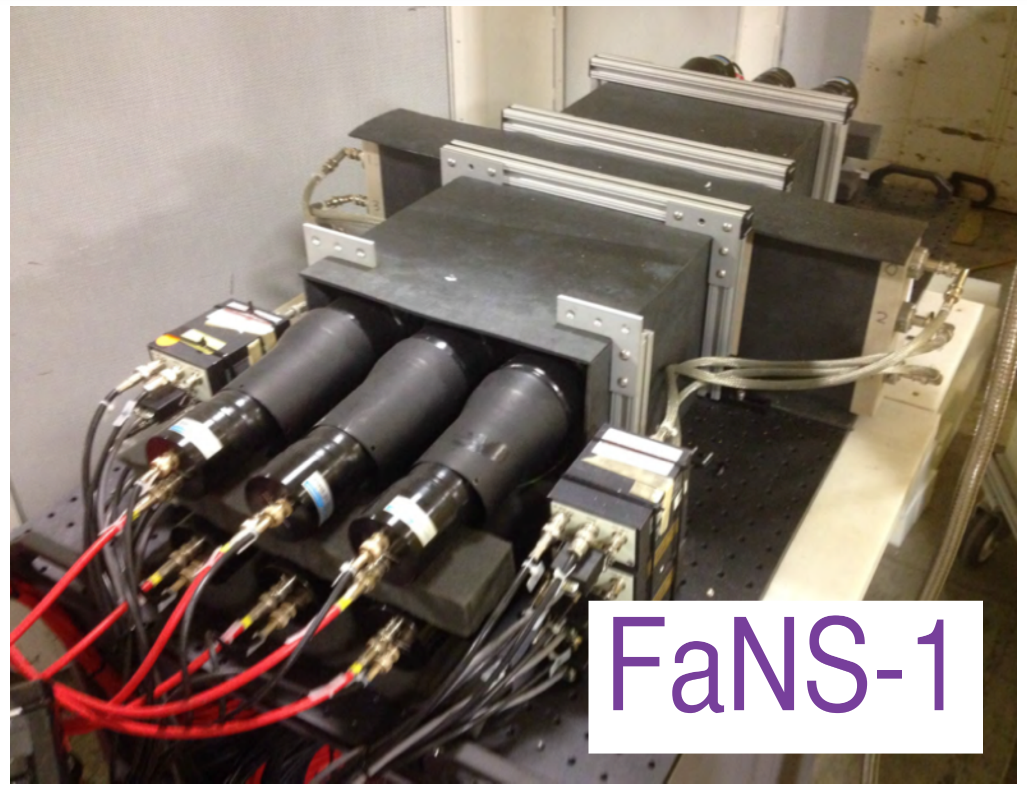
- ^{240}Pu detection

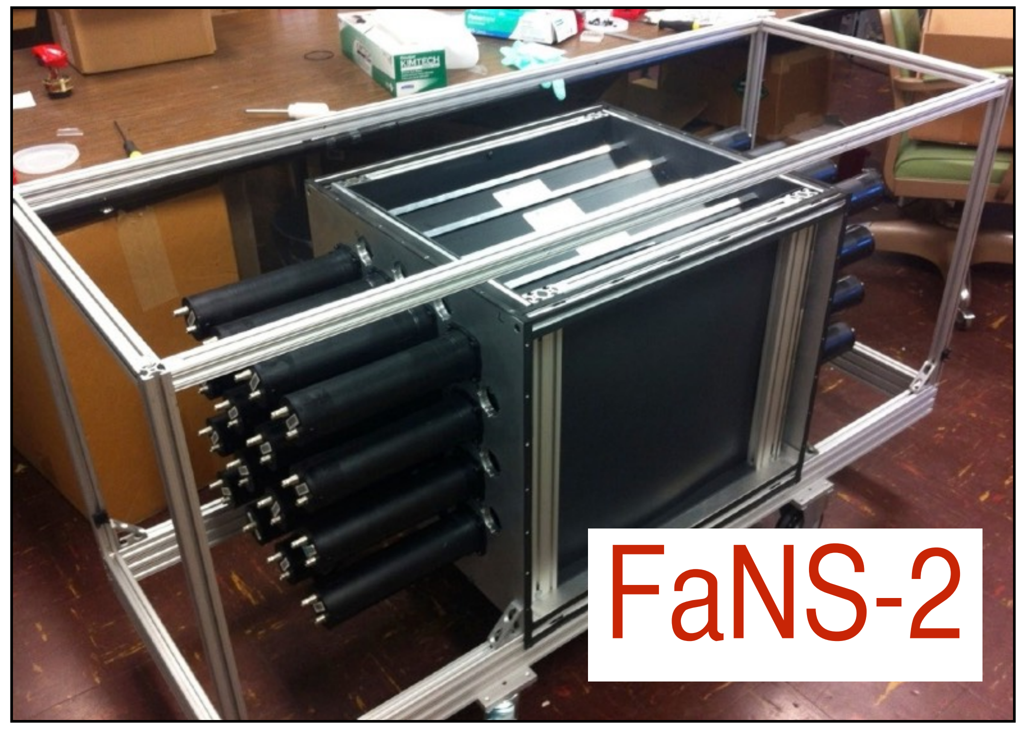


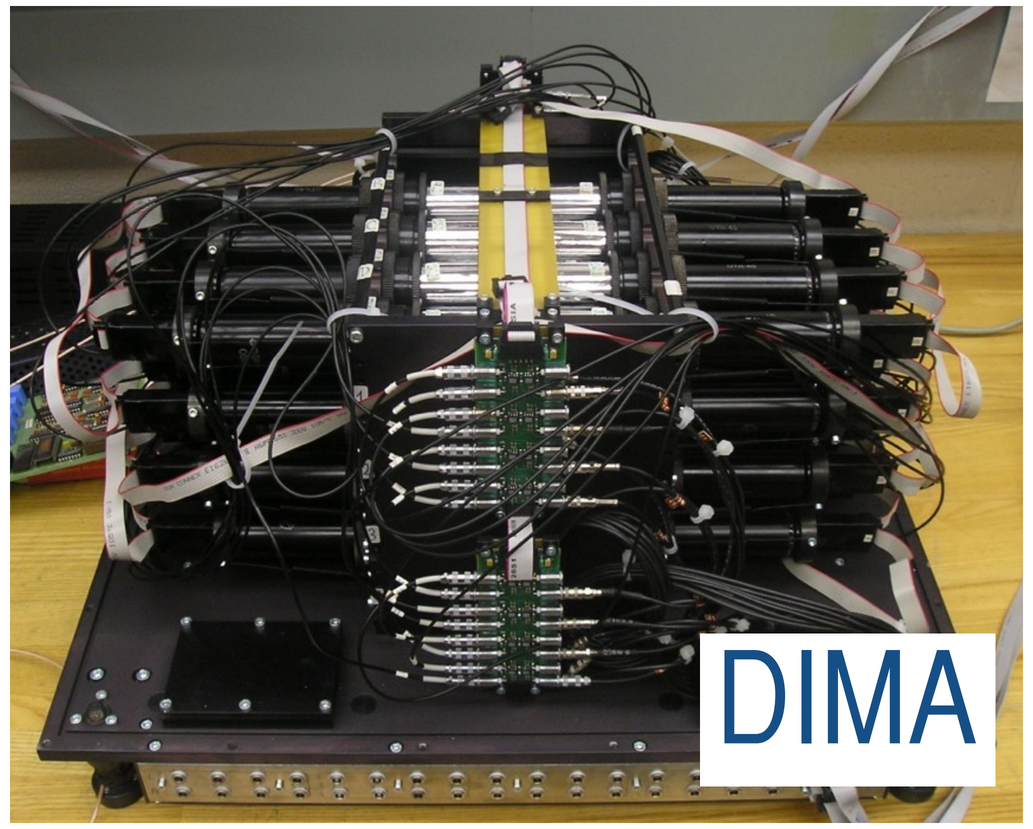
Remove central segment to make accurate measurements of low-activity (> 1 s^{-1}) sources.

Current NIST detector suite

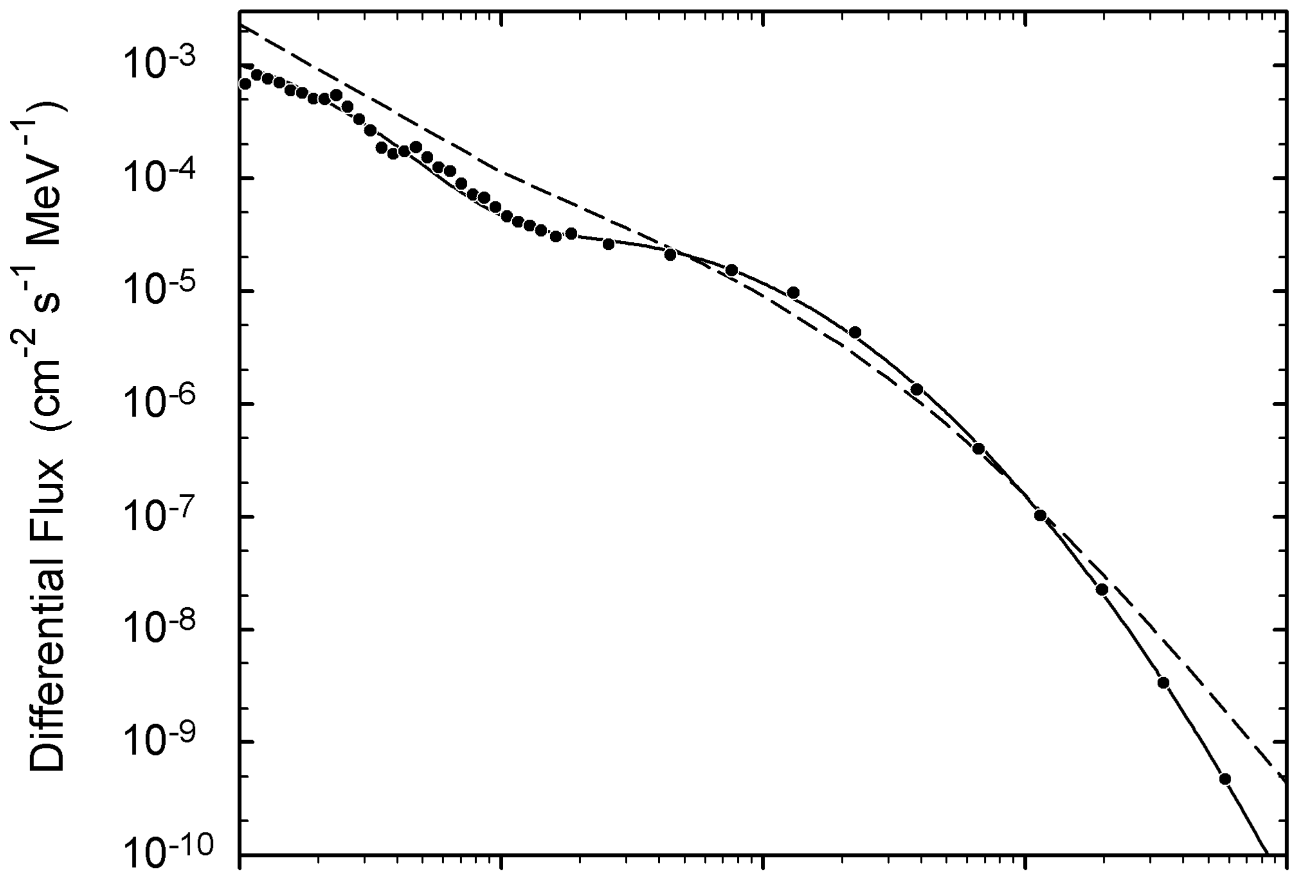
- Arrays of hydrogenous scintillator segments and with appropriate high-fidelity neutron capture technique
    - *- Plastic for FaNS-1 and 2, 6Li-doped liquid for DIMA*
    - *- 3He tubes for FaNS-1 and 2, 6Li for DIMA*
    - *- Segmented to improve energy reconstruction*
- Use Capture-gated Spectroscopy for particle identification and energy information
- Calibrated at NIST with Cf-252, DD, and DT neutrons
- FaNS-1: Rapidly deployable for multiple site background characterization
- FaNS-2: Detector optimized for low rates and high energies
- DIMA: Liquid demonstrator; optimized for energy resolution at 1-10MeV





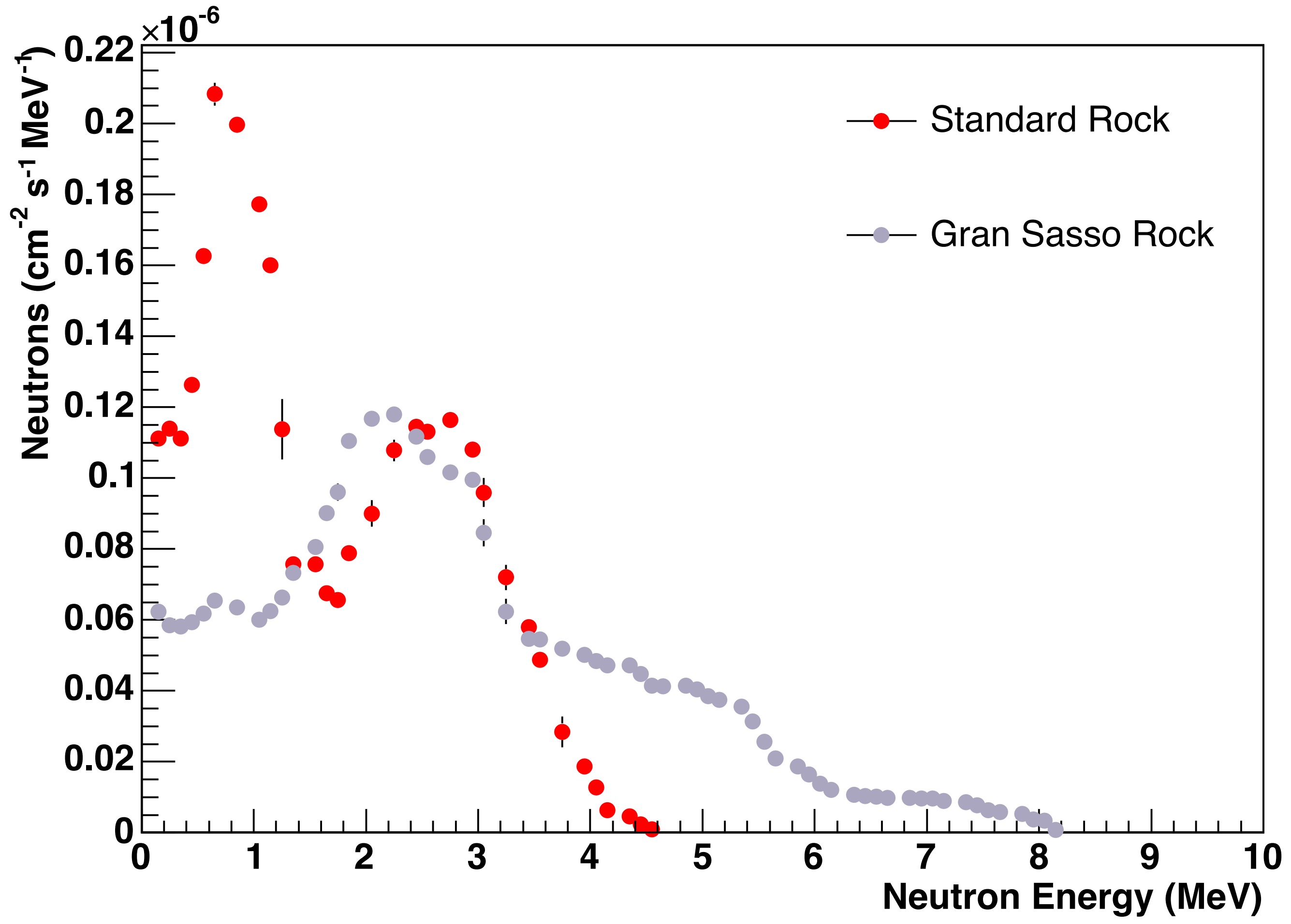


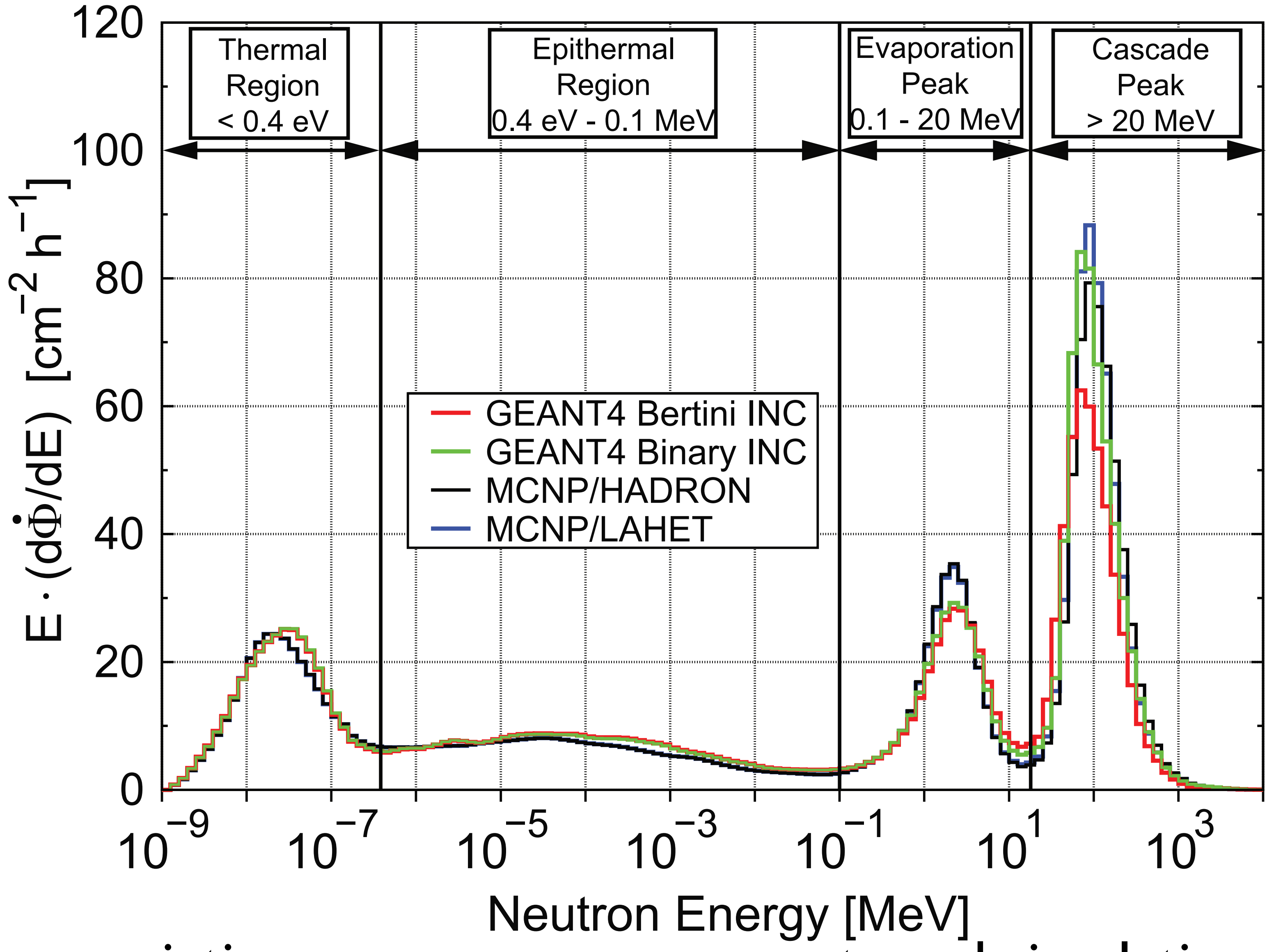
Environmental fast neutrons



high energy neutrons are created in cosmic ray air showers

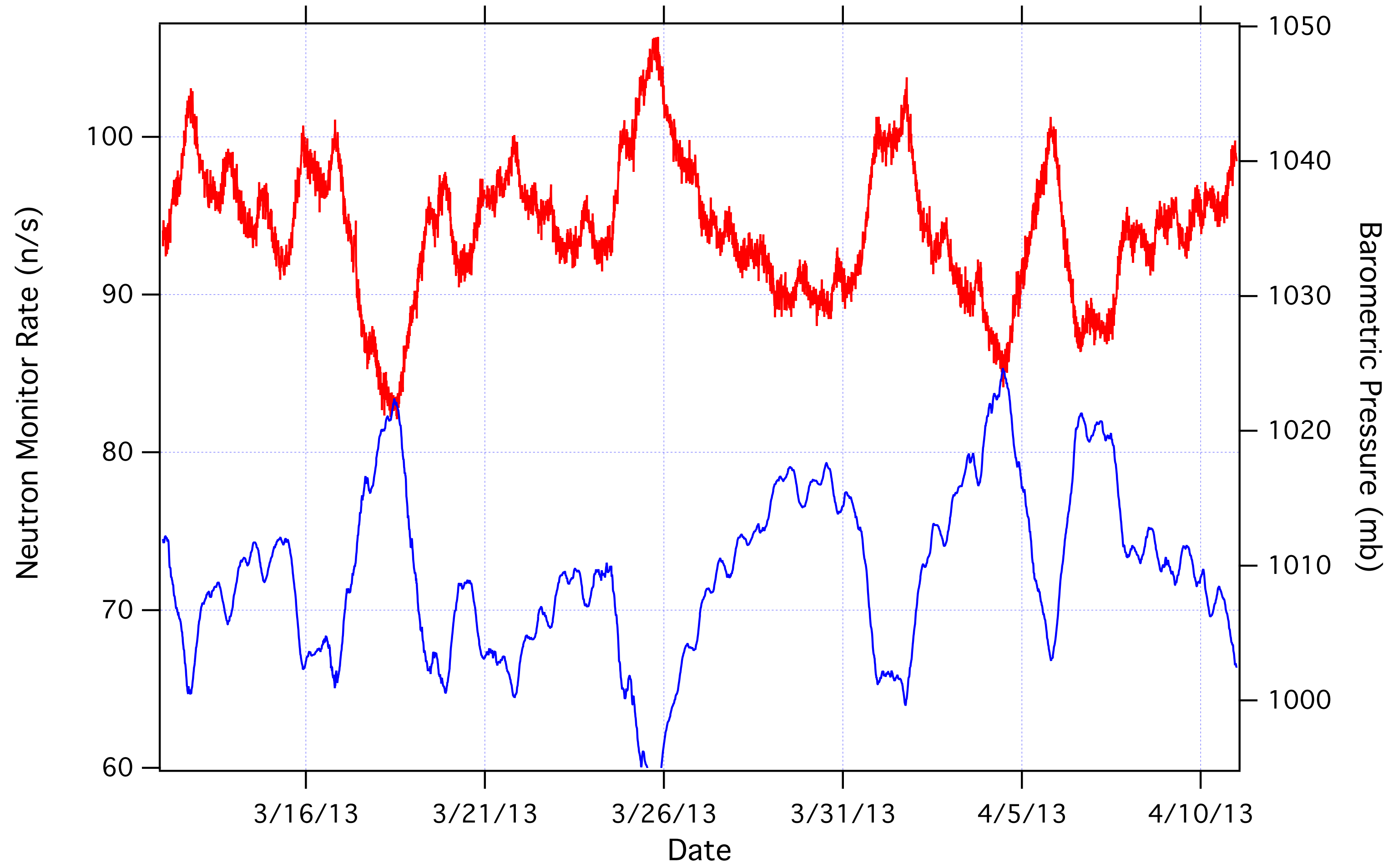
1 MeV - GeV: Muon-induced neutrons (depth dependent)





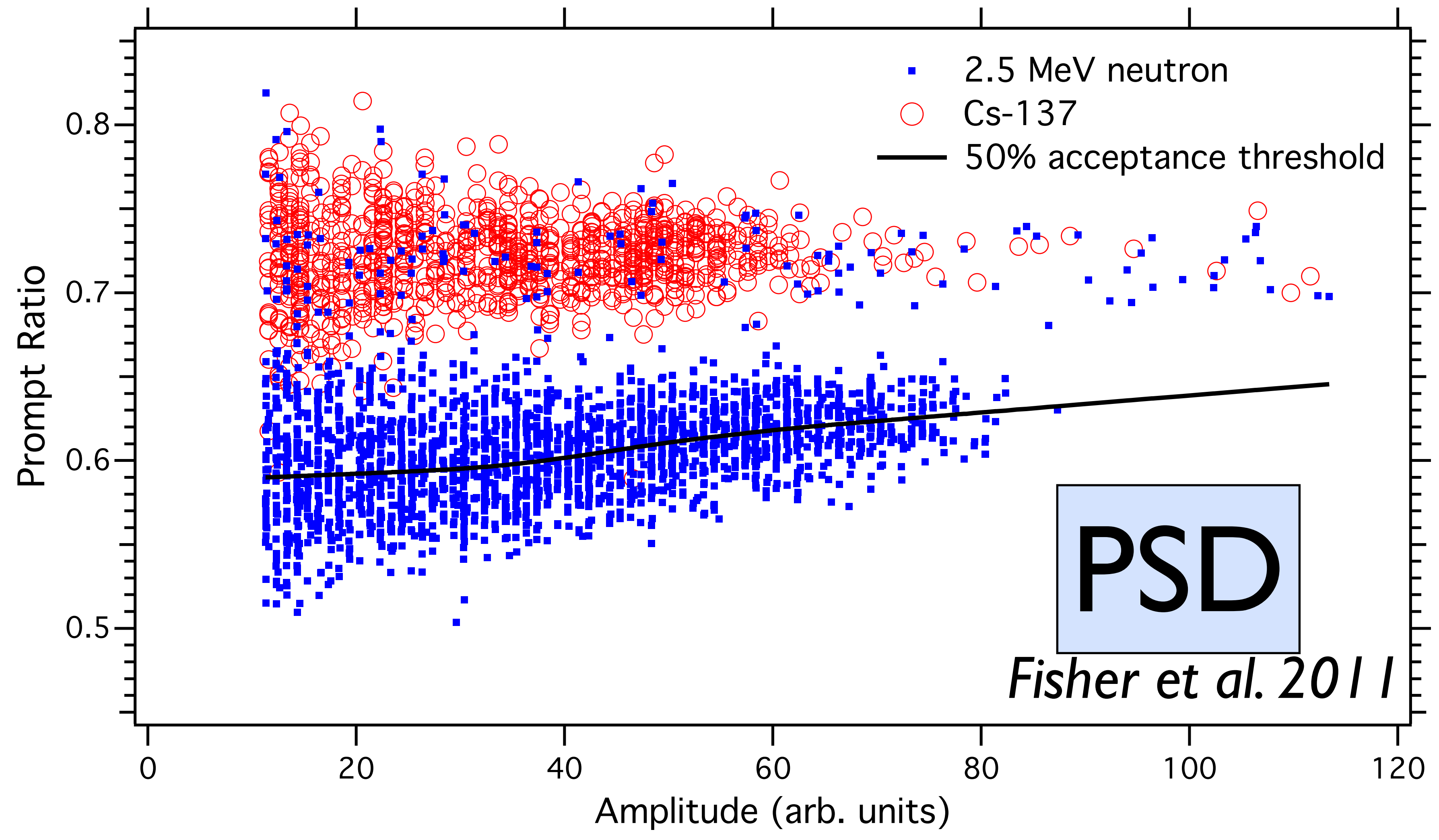
Large variations among measurements and simulations

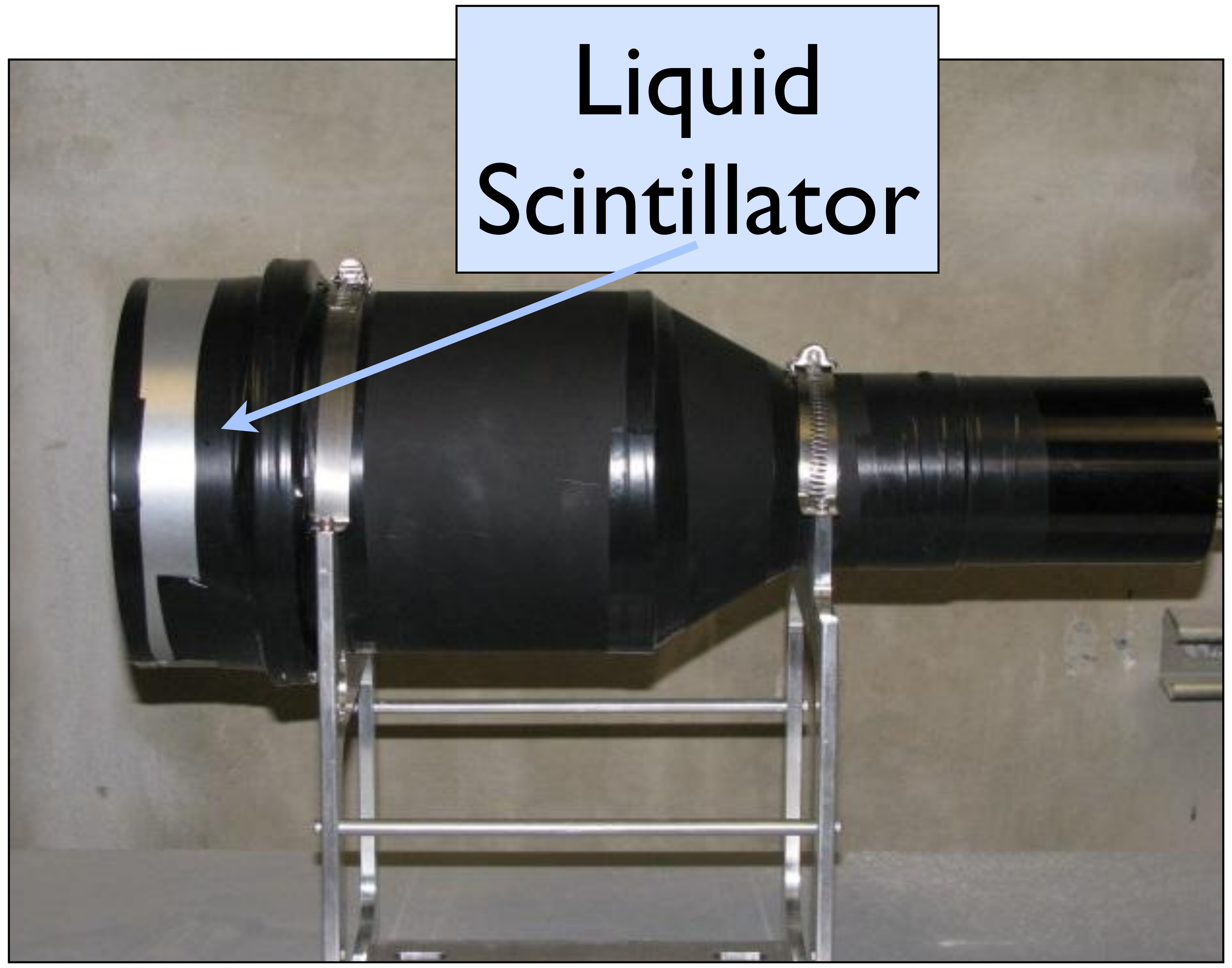
1-10MeV: Natural radioactivity from surround material, mainly (alpha,n) (location dependent)

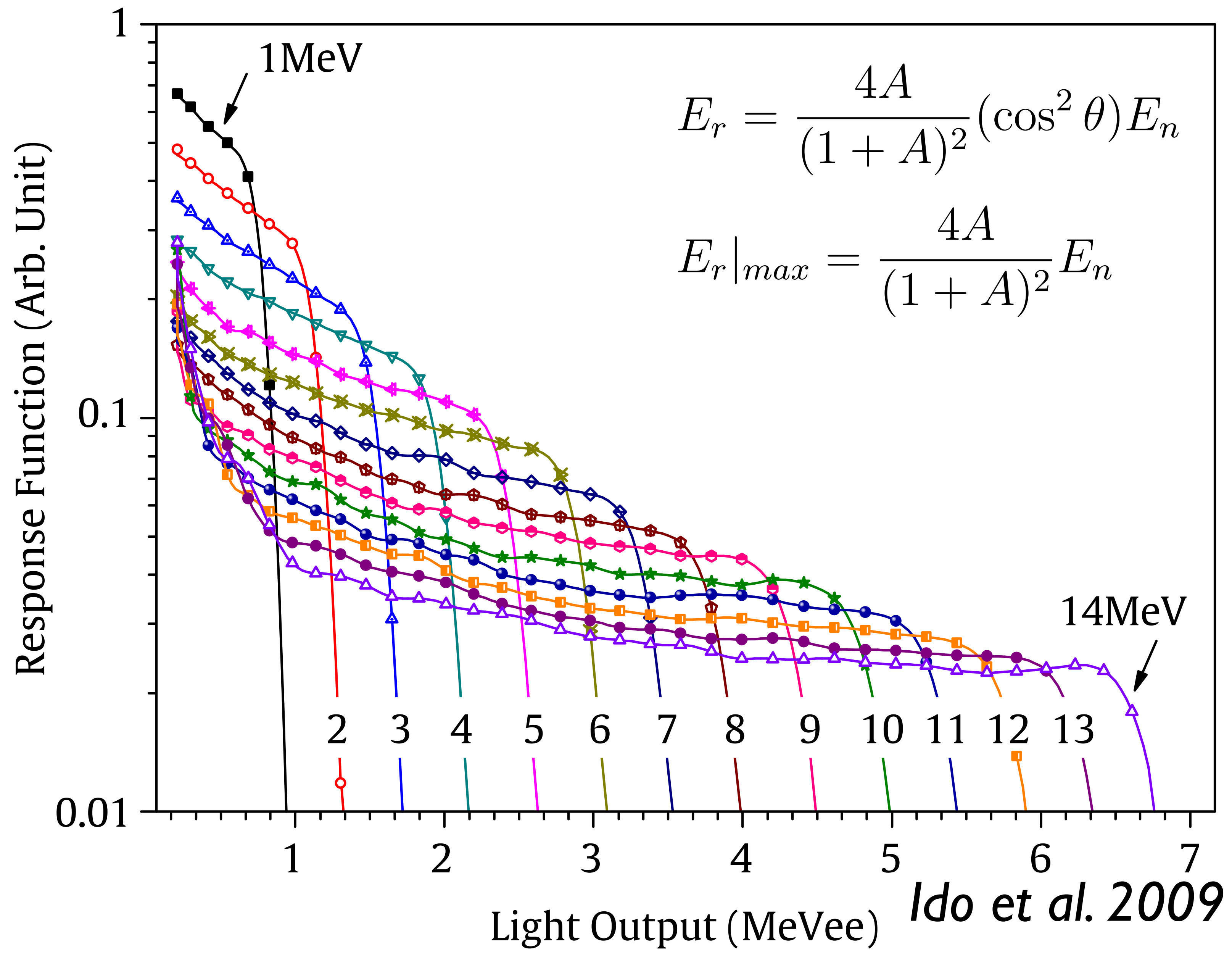


Large fluctuations with local environment and conditions

LS Proton Recoil Detectors

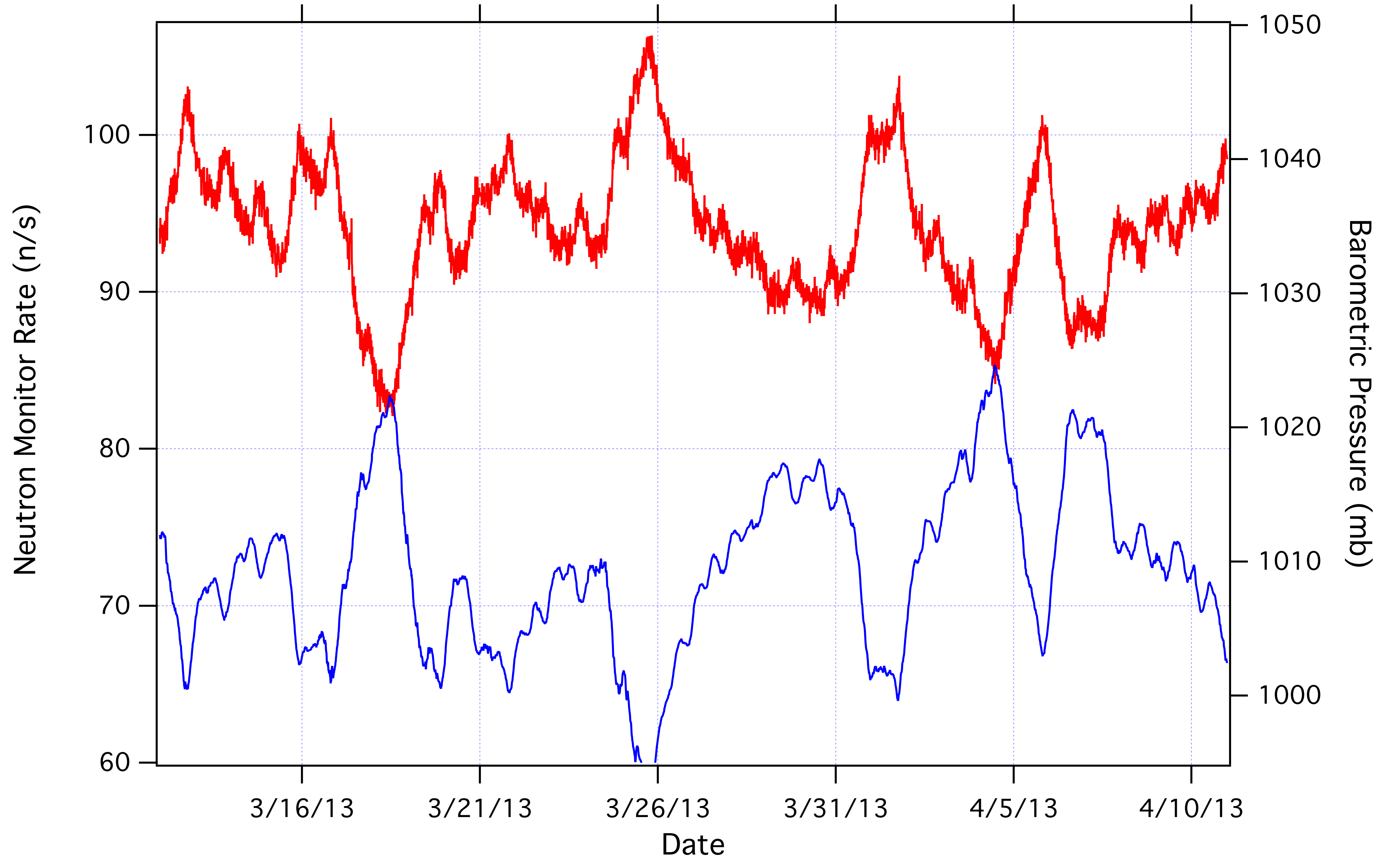




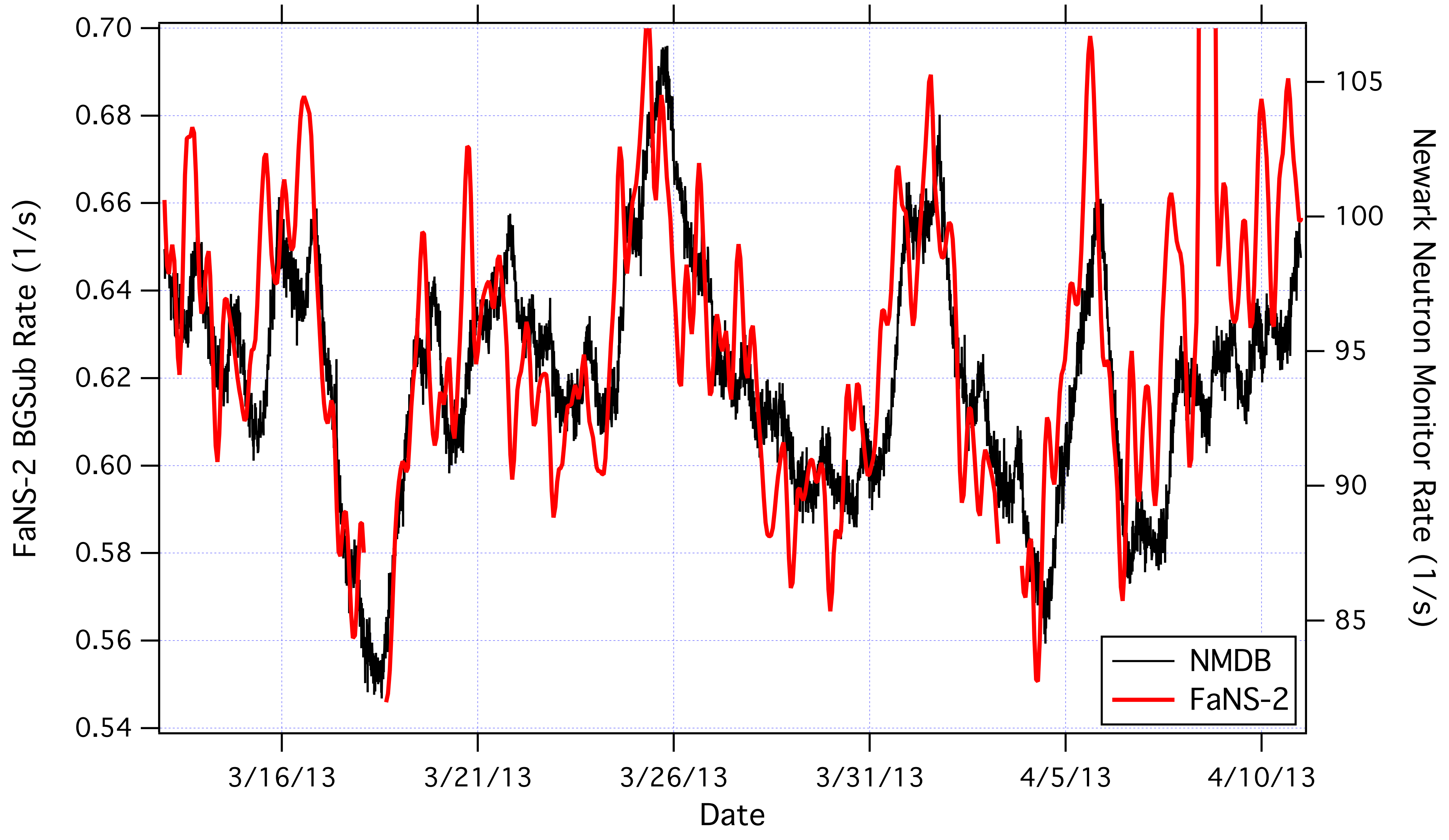


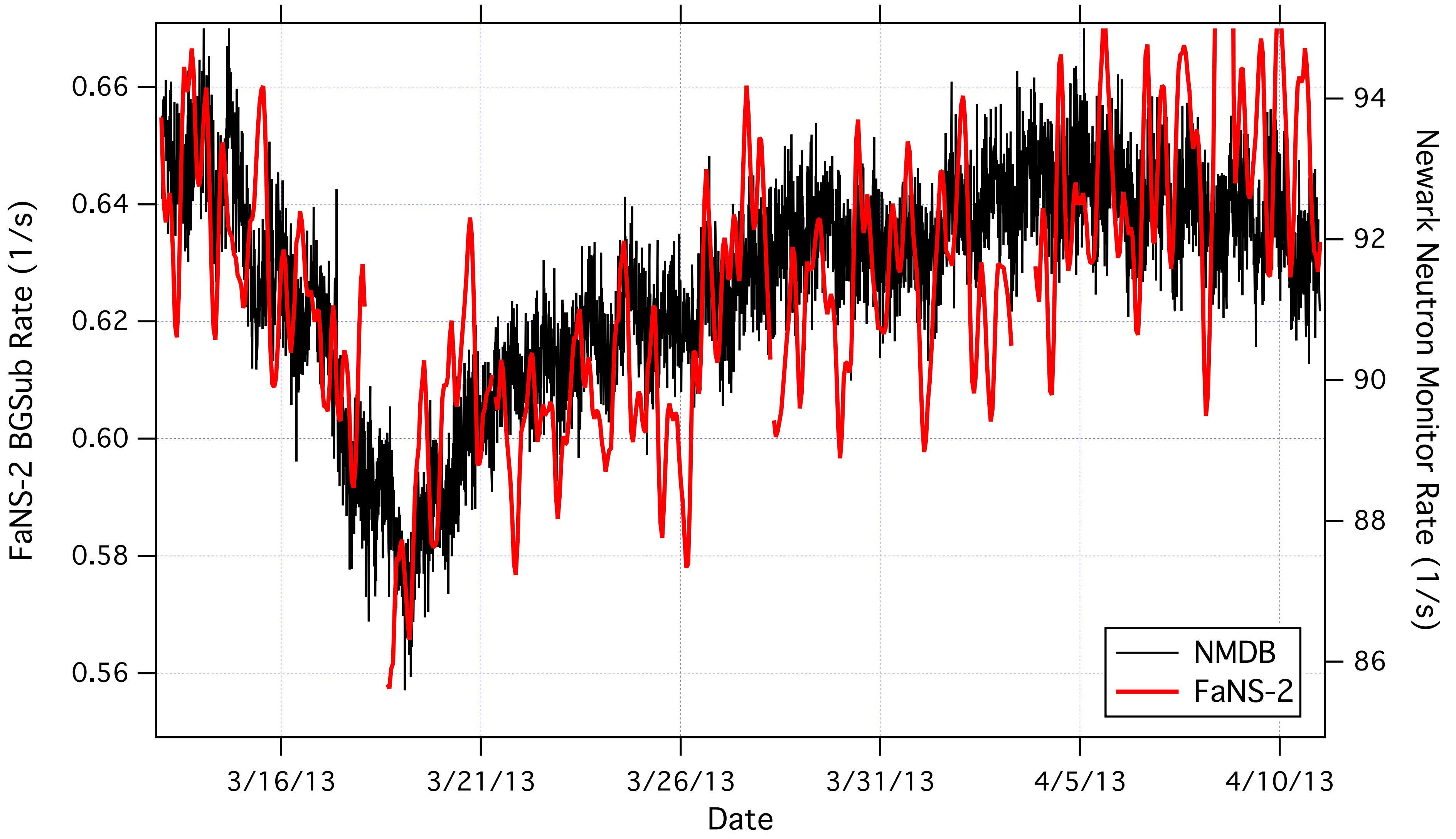
- N-P scattering to detect deposited energy
- Use pulse shape to separate gammas from neutrons *~100x reduction*
- *All neutron interactions detected, mostly partial-energy depositions*

Barometric Variation



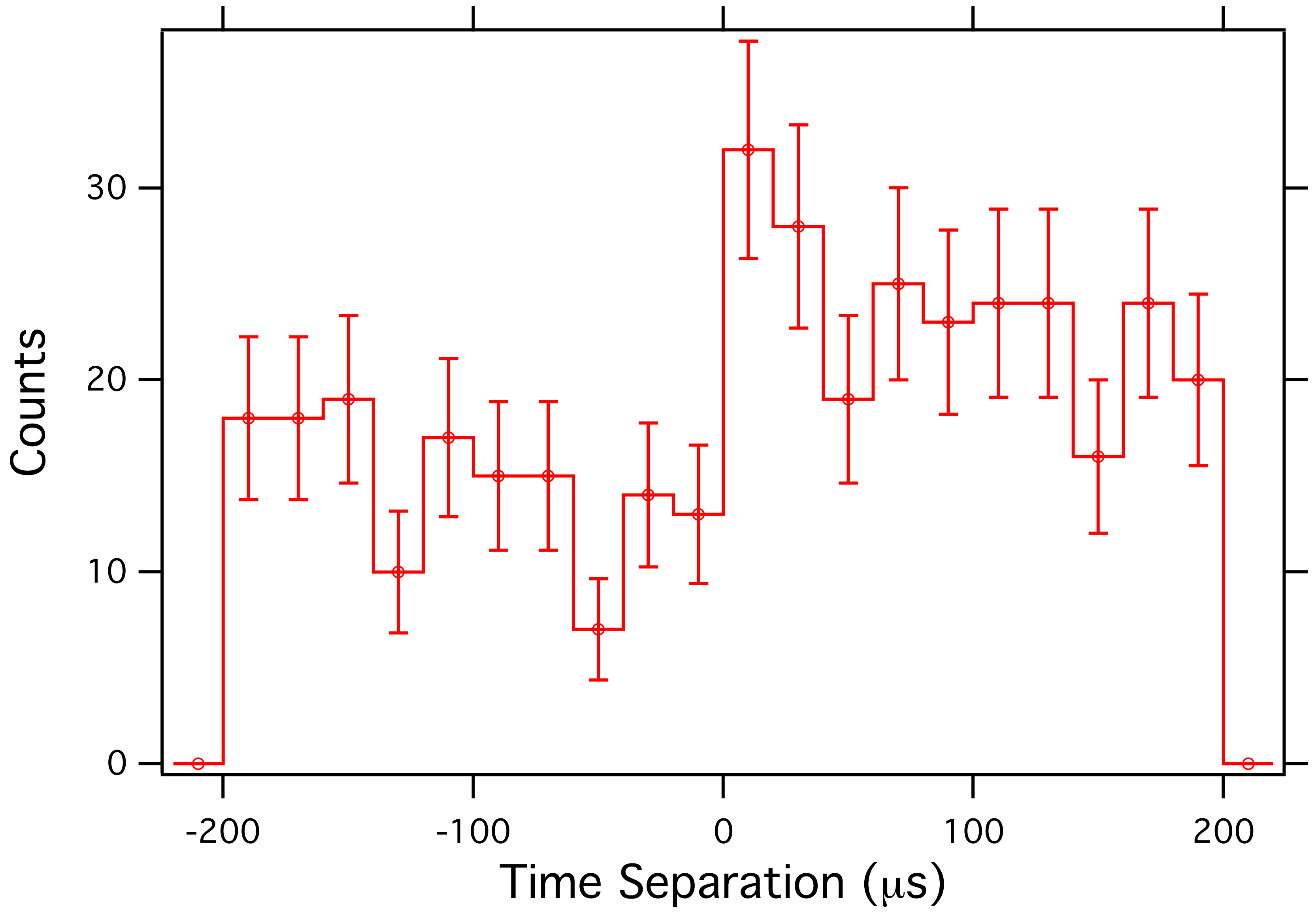
- Neutron monitoring stations to study solar activity are spread across the globe
- Data freely available!
- Can compare pressure corrected and uncorrected event rates

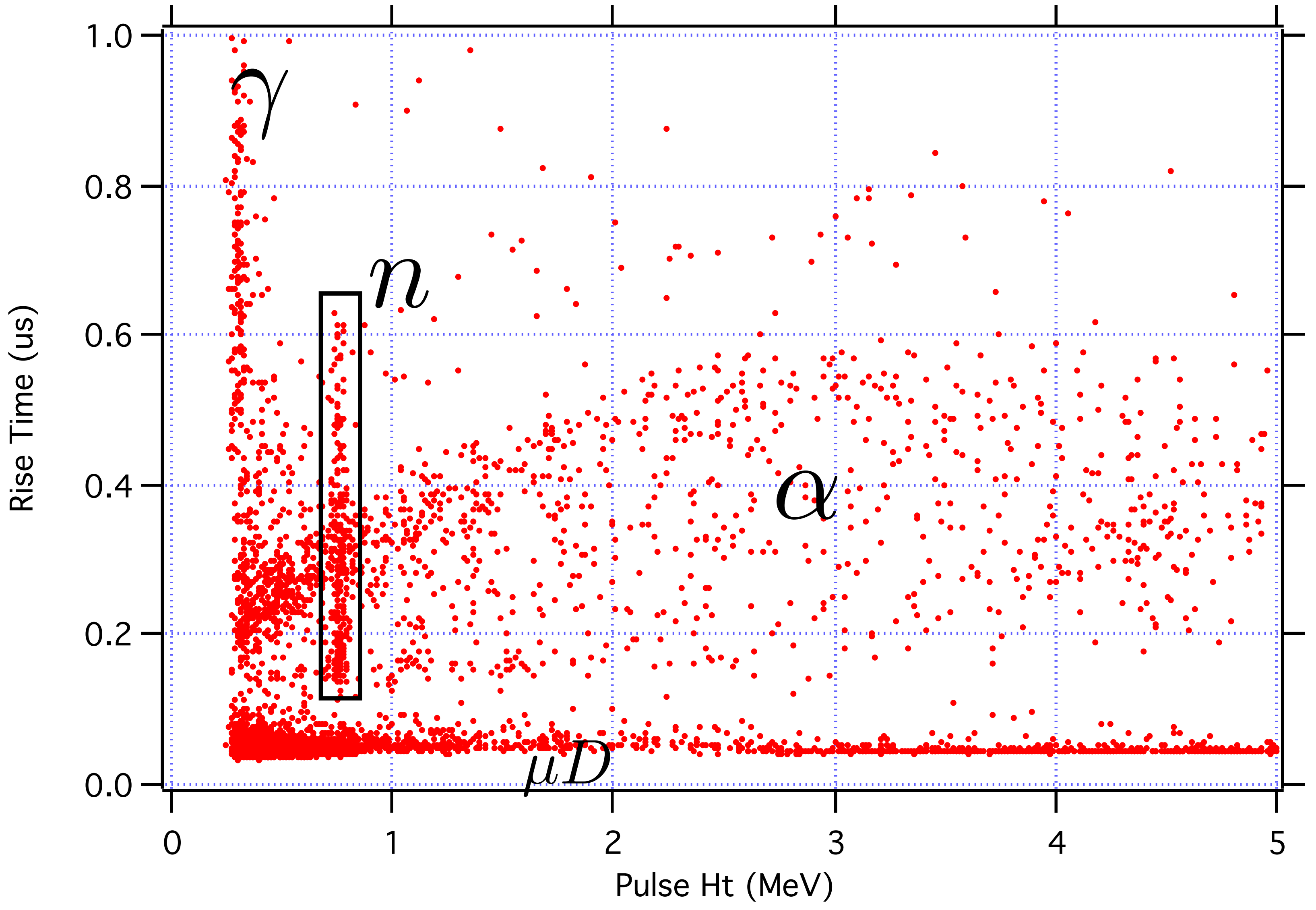




http://www.nmdb.eu/

FaNS-1 at KURF - 1450 mwe





- 3.74x10⁶ s dataset
- 1.67x10⁵ He-3 triggers
- 384 counts pass all cuts
- *89 remain after BG subtraction*