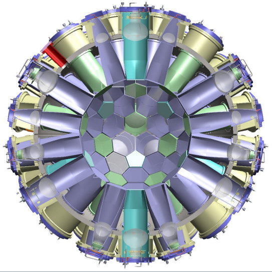
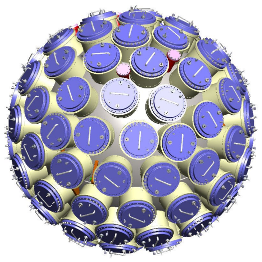
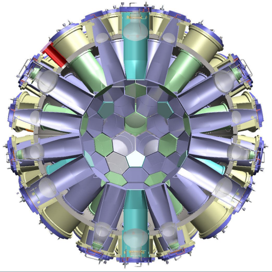


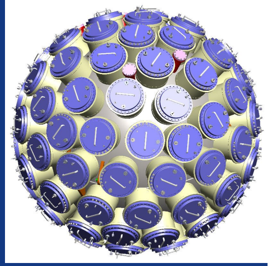


Neutron-Argon Interactions <20 MeV: Verification of 'Neutron HP' in Geant4

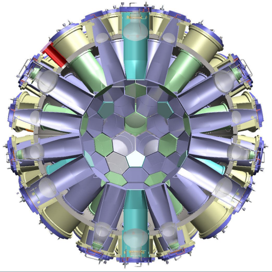
Kimberly J. Palladino
MiniCLEAN Collaboration



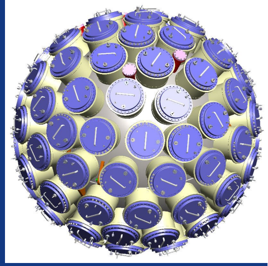
Outline



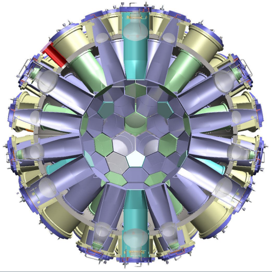
- The RAT Simulation Framework
- Motivation for Neutron Studies for MiniCLEAN
- Pertinent Neutron Physics
- Low Energy Neutrons in Geant4
- Cross-Section Studies



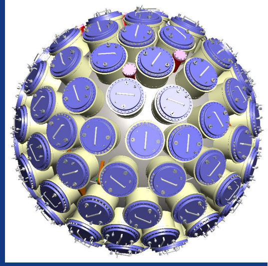
RAT Reactor Analysis Tool



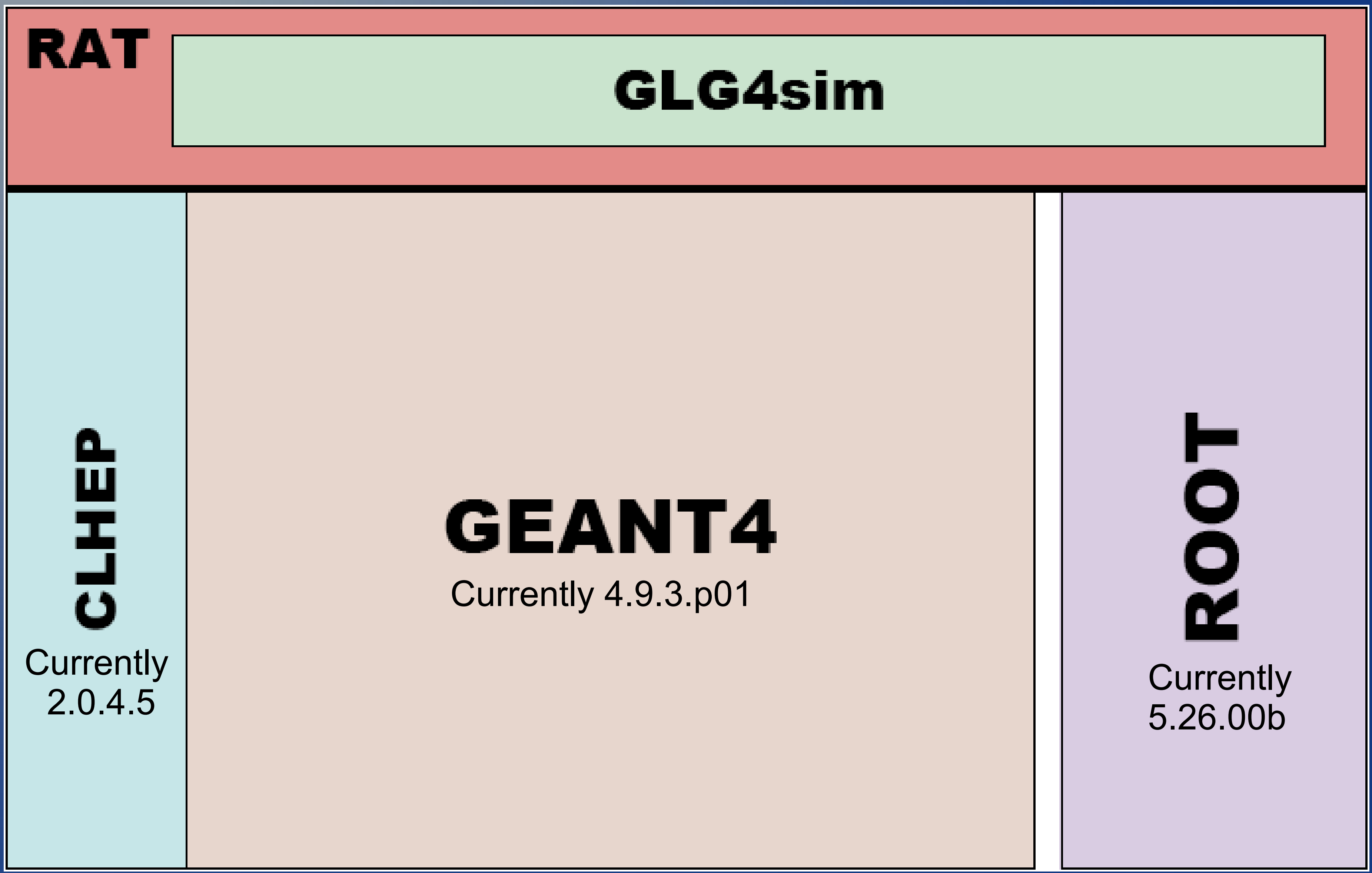
- A collaboration pedigree
  - Started by the Braidwood collaboration
  - Extensively uses GLG4sim from KamLAND
  - Inherits conceptually from SNOMAN
  - Gd physics from Double CHOOZ
  - Some use by SNO, SNO+, DEAP collaborations
  - Extensive use by MiniCLEAN collaboration
- Developers:
  - Stan Seibert (sseibert@hep.upenn.edu), Tim Bolton, Dan Gastler, Josh Klein, Hugh Lippincott, Andy Mastbaum, James Nikkel, Gabriel Orebi Gann, Michael Akashi-Ronquest, Stan Seibert, Stephen Sekula, William Seligman, Chris Tunnell, Matthew Worcester
  - Many (most) DEAP/CLEAN collaboration members

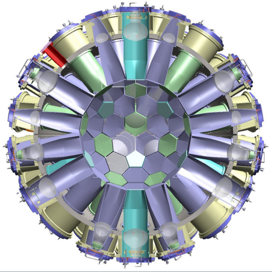


RAT- Components

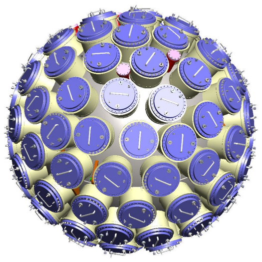


Can all be installed together with no hassle with ratcage





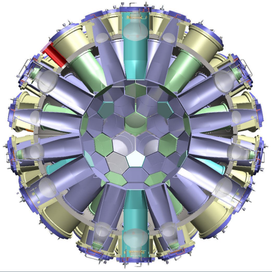
RAT- Operational Concept



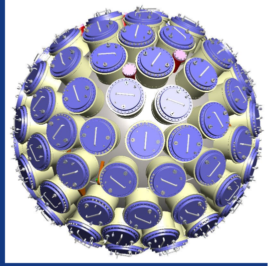
User Input
- RATDB (.ratdb) constants, settings
- Geant4 geometry (.geo)
- RAT macro (.mac) event generators and processors to run
- HEPEvt or ROOT output

RAT processing: Done as an event loop
- Event generators (GLG4sim)
- Event Processors
  - PMT Detection
  - DAQ
  - Trigger
  - Fit
  - Analysis

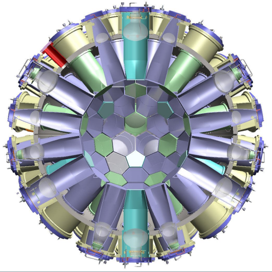
Output
- ROOT files
  - Particle tracking
  - Simulated detector events
  - Analysis values
- Other processor output



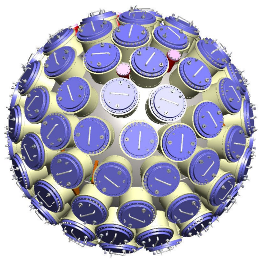
RAT Physics of Interest



- Scintillation
  - Modified version of GLG4sim (not Geant4)
    After each step, determine energy deposited, and using quenching factor determine number of photons produced, drawn from scintillation energy spectrum and time structure, then hands these photons back to Geant4
  - No ionization currently
- Re-emission
  - Area of development: currently have surfaces that absorb from one wavelength and draw from re-emission spectra for new photons, but also possible to absorb and re-emit in a bulk material
- PMTs
  - Follow GLG4Sim for PE production and can include Dark Noise



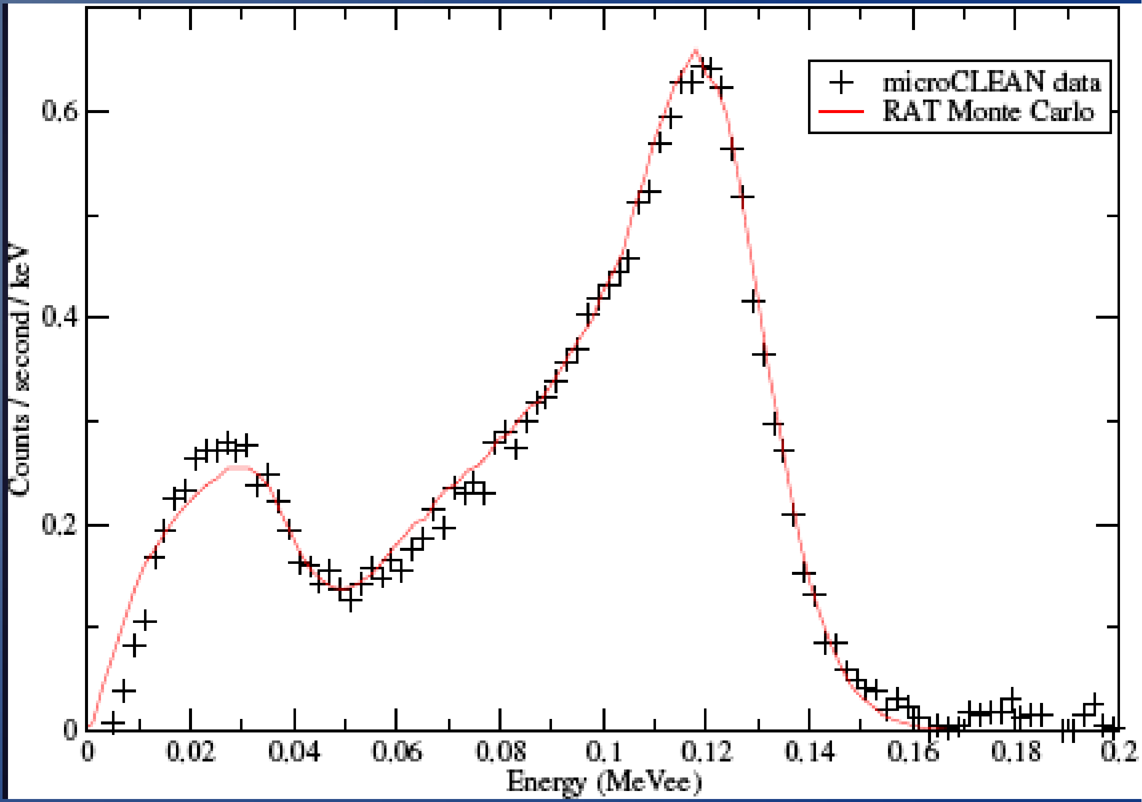
MiniCLEAN and RAT



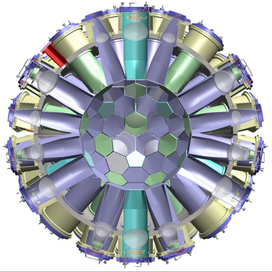
Extensive use at all levels of the experiment

- -Verification of Geant4 physics
- -Engineering design (magnetic compensation, spacing tolerances, etc.)
- -DAQ processing
- -Event reconstruction

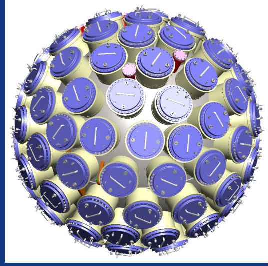
Simulation and data comparisons for MicroCLEAN and DEAP-1

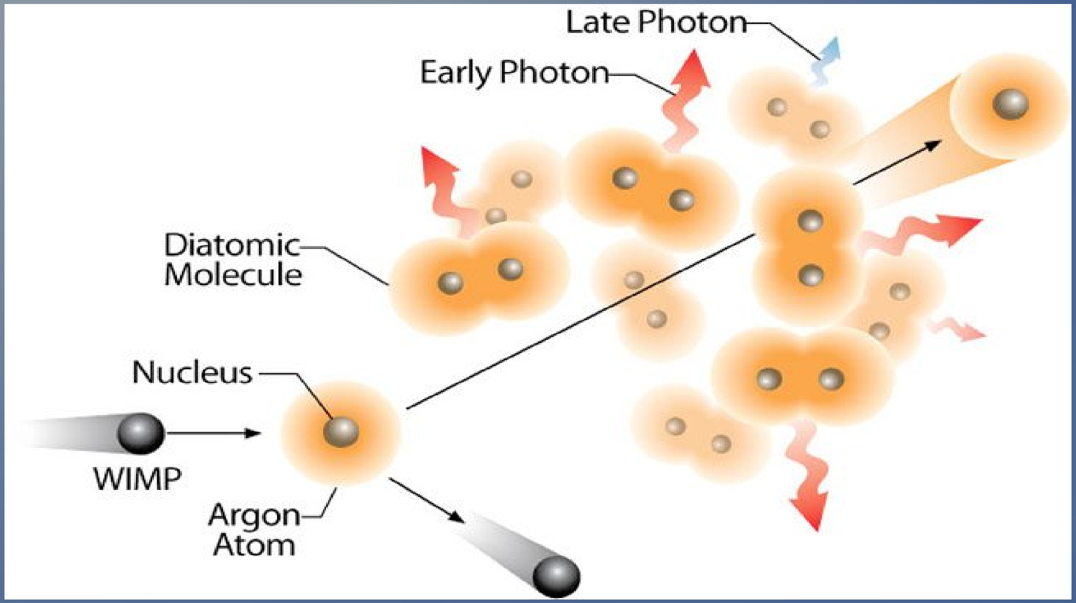


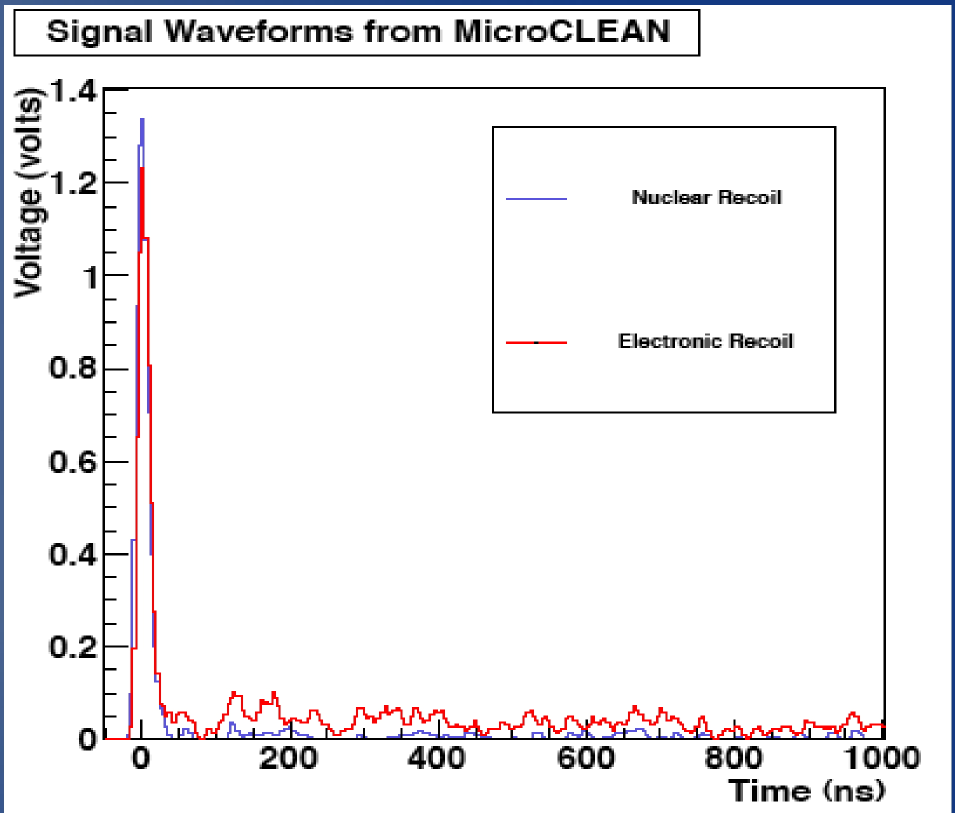
MicroCLEAN comparison of data and simulation Of ^{57}Co gamma rays



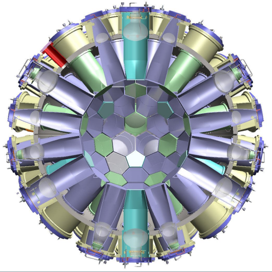
MiniCLEAN & DM Detection



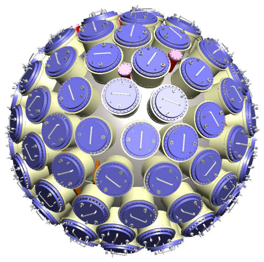


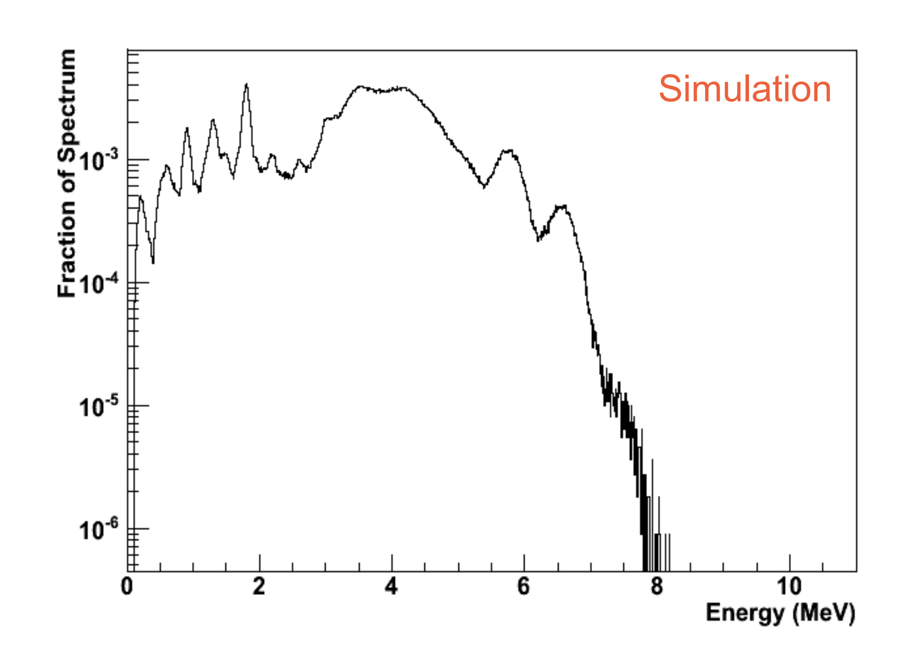


- MiniCLEAN is a single phase liquid argon direct dark matter detector
- Pulse shape discrimination allows separation of electronic recoils and nuclear recoils (will need discrimination to one in 10^{-9} because of ^{39}Ar) -> more late light from electron recoils because they are more likely to result in the longer lived (1.6 us) triplet state than the
- (6 ns) singlet state



Neutron Backgrounds





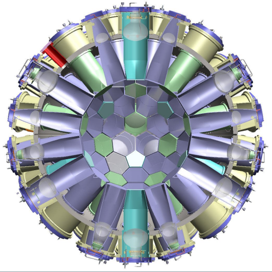
- At SNOLab with >6000 m.w.e., instrumented water shielding can protect from neutrons created by muons penetrating to this depth (10 a day in our veto) that and those from the surrounding material.

- We are left with neutrons from within the detector itself

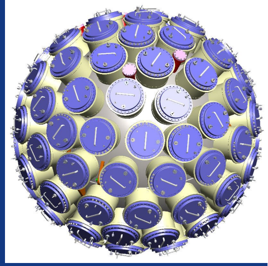
Greatest source of worrisome neutrons for MiniCLEAN are those made in the borosilicate glass of our PMTs.

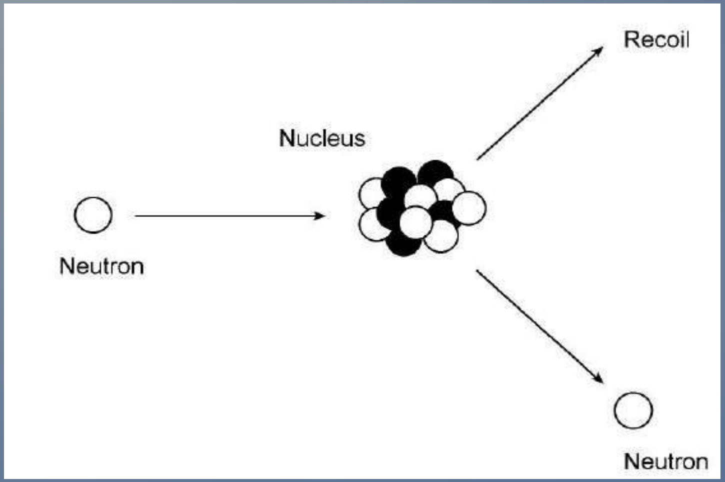
The ^{238}U and ^{232}Th alpha chains are followed in the PMT glass composition to generate the neutron spectrum.

Spectrum from neutronyield.usd.edu
Following the methods of: NIM A 606(2009)651660 (arXiv:0812.4307)
and doi:10.1016/j.astropartphys.2010.04.003 (arXiv:0912.0211)

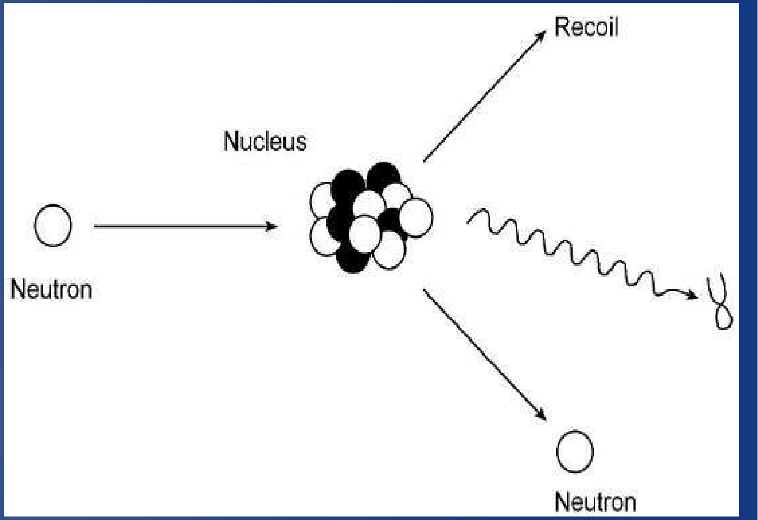


Neutron Scattering

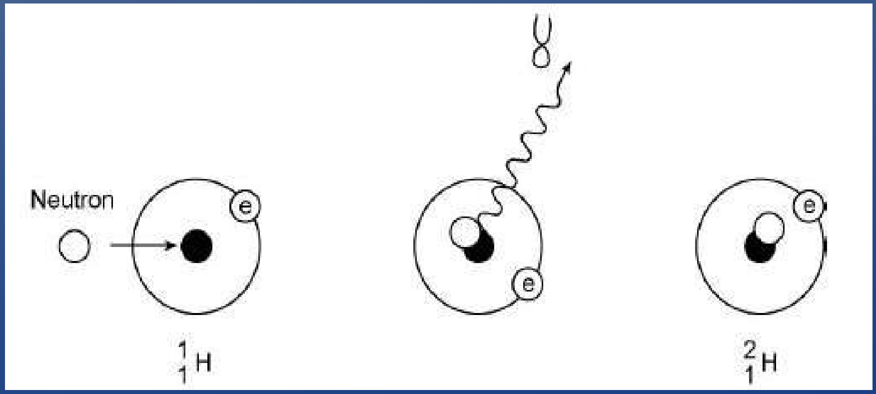




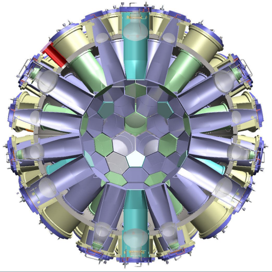
Elastic Scattering: background to a WIMP event
Maximum energy transfer from neutron to argon of 10%
Neutrons below 500 keV cannot produce events above a 50 keVr analysis threshold
Cross section has resonances



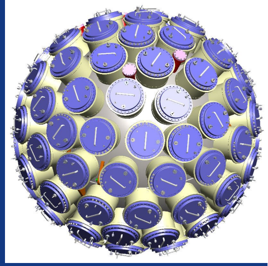
Inelastic Scattering: for our energy region of interest, primarily 1n, gamma in the final state
Thresholds and energy loss set by argon nuclear excited states

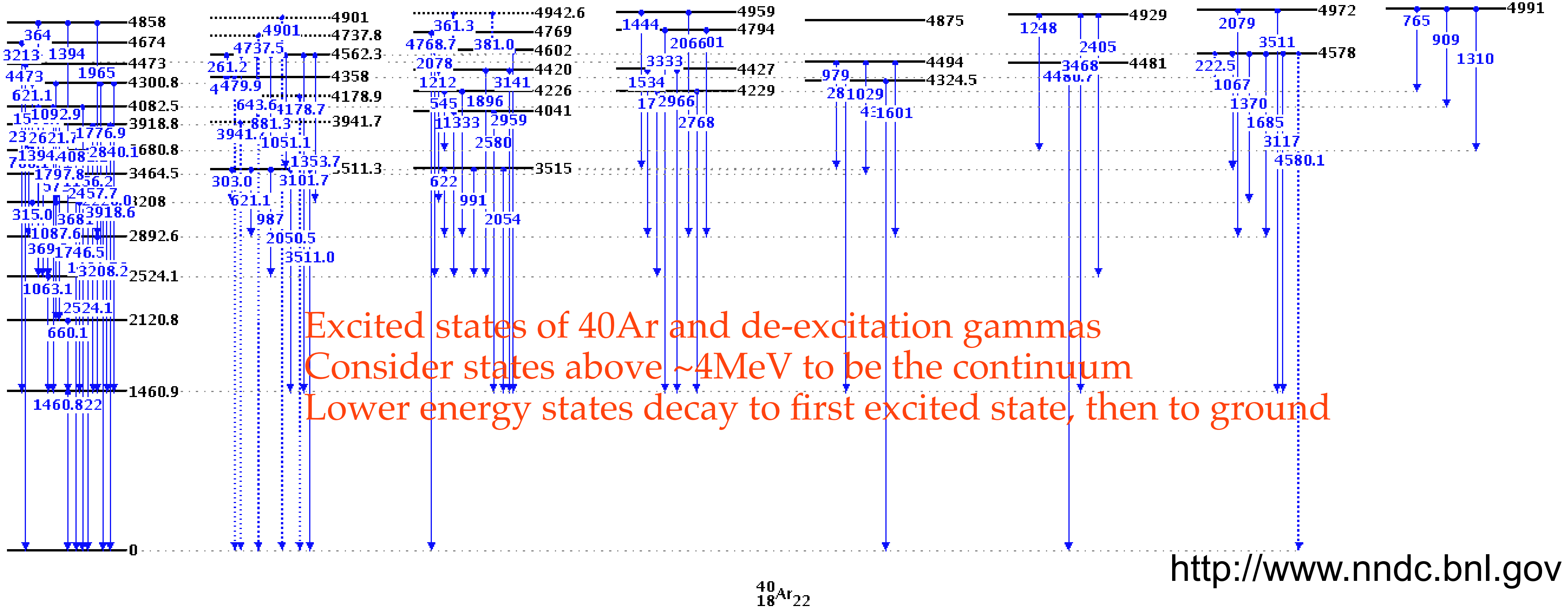


Neutron Capture: Cross section dominates at thermal energies (0.025 eV) also resonances at keV energies
Gamma rays and ^{41}Ar produced
^{41}Ar decays with a half life of 1.8 hrs to ^{41}K, producing a keV electron and 1.3 MeV gamma

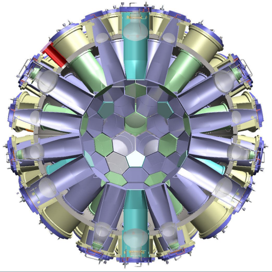


Argon Excited States

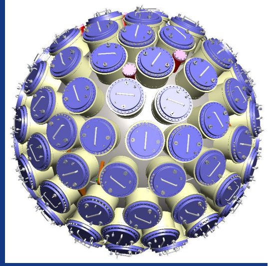




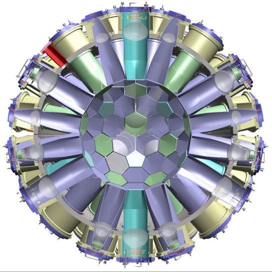
Excited states of 40Ar and de-excitation gammas
Consider states above ~4MeV to be the continuum
Lower energy states decay to first excited state, then to ground



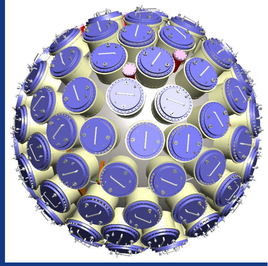
Geant4 and Neutrons



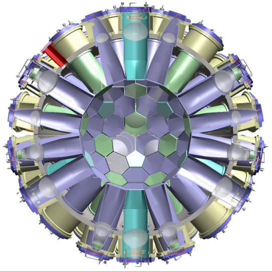
- Look at Geant4's neutron physics
  - Cross-section implementation
- Compare these cross sections to:
  - ENDF/B-VII
  - Measurements
  - Other evaluated databases/simulation packages
- Look individually at Elastic, Inelastic and Capture Processes
- Impact of these processes from the view of a dark matter search



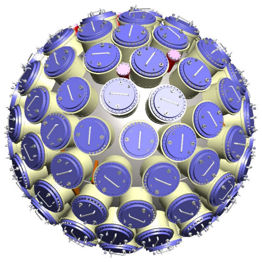
Neutron HP



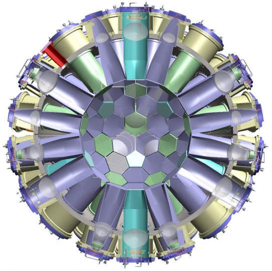
- Geant4 uses the high precision neutron processes <20 MeV
- Uses energy-dependent cross section and final state data from G4NDL3.13 (G4NDL) for Elastic, Inelastic, Capture and Fission (not applicable in Argon)
  - Elastic scatters have cross section information, and final state distribution's Legendre polynomials
  - Inelastic scatters are more complicated
    - Total inelastic cross section
    - Final state cross sections (1n, alpha, proton, 2n, etc.)
    - Cross sections for the different argon nuclear excited states, isotropic emission
    - De-excitation gammas
  - Captures have cross section information



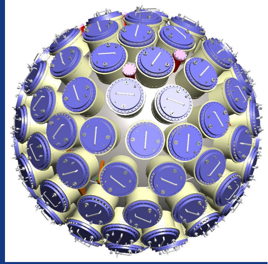
More on Neutron HP

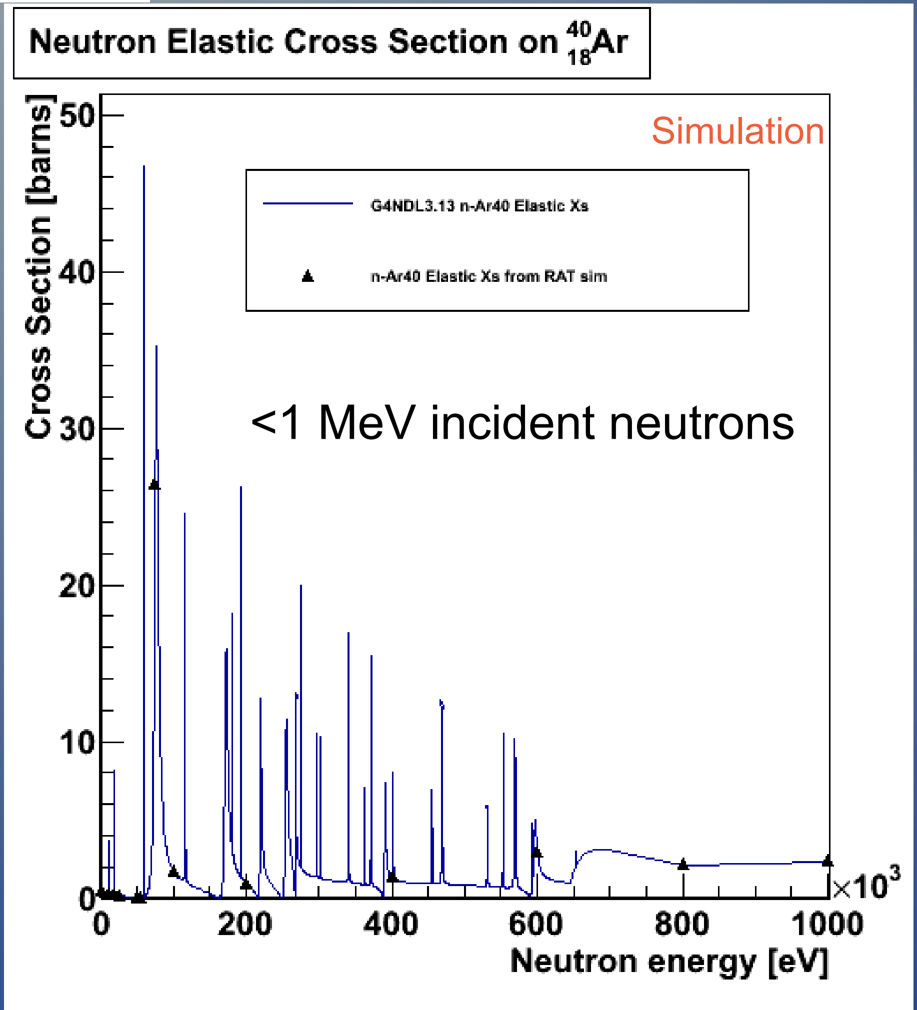


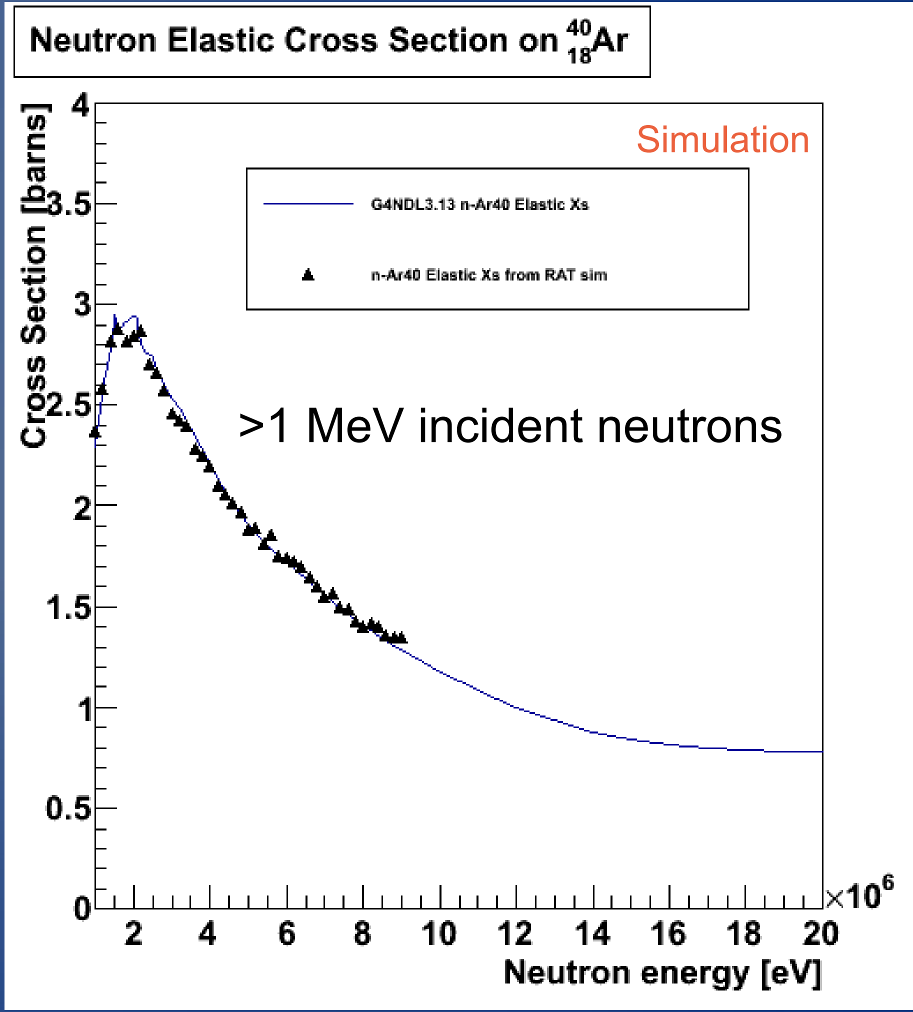
- Using Geant4.9.2 and 4.9.3
  - Cross Sections for ^{40}Ar same back to G4NDL3.9
  - Cross sections come from ENDF/B-VI resonances
- Able to use natural abundances or user-specified
- Are there cross sections for your isotopes in G4NDL?
  - They aren't for Neon!
  - Main argon isotopes are all present
    - ^{40}Ar (.996003), ^{38}Ar(0.000632), ^{36}Ar (0.003365)
- Geant4 Hadronic Physics group adding features, fixing reported bugs



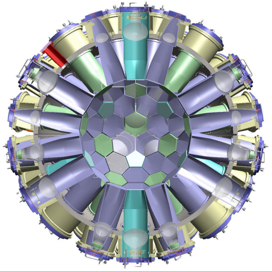
Reproducing G4NDL



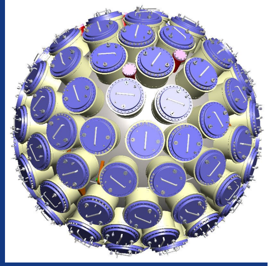


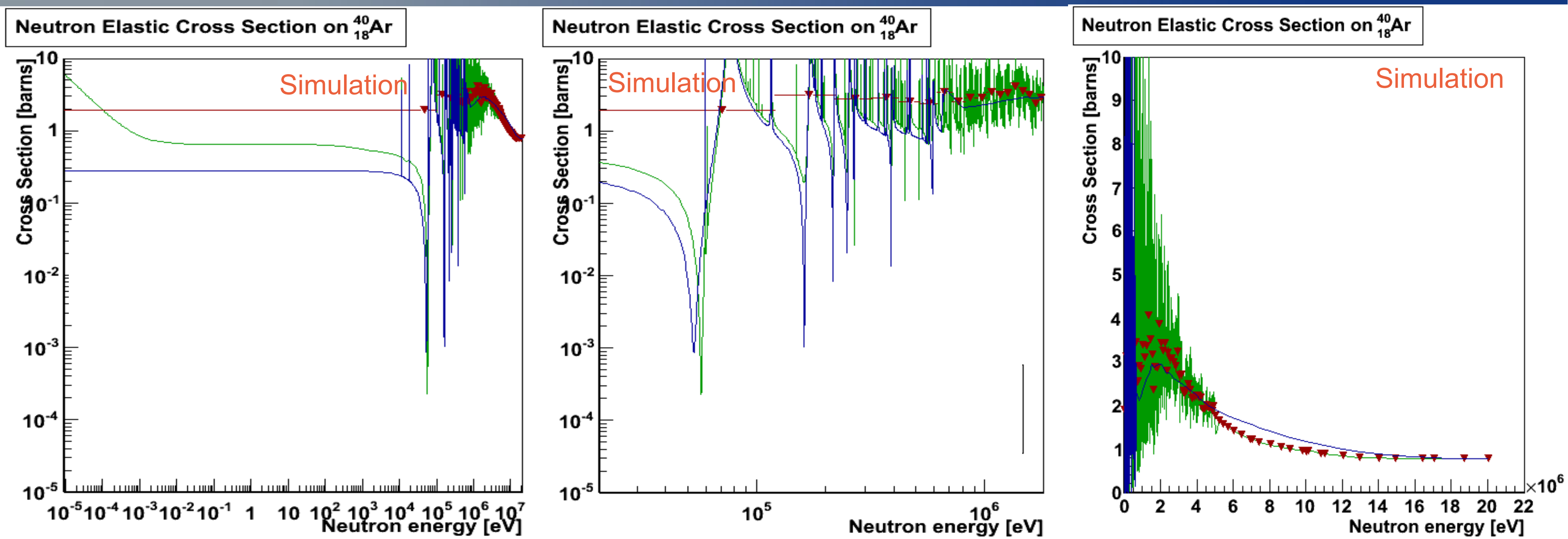


Monoenergetic neutrons shot into liquid natural argon, Inelastic processes turned off
Input cross sections are reproduced.



Comparison with ENDF/B-VII

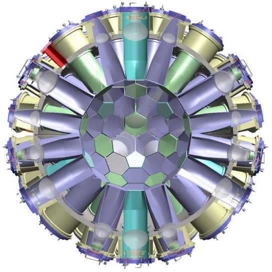




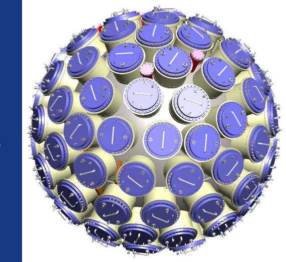
ENDF/B-VII provides cross sections, more resonances than G4NDL

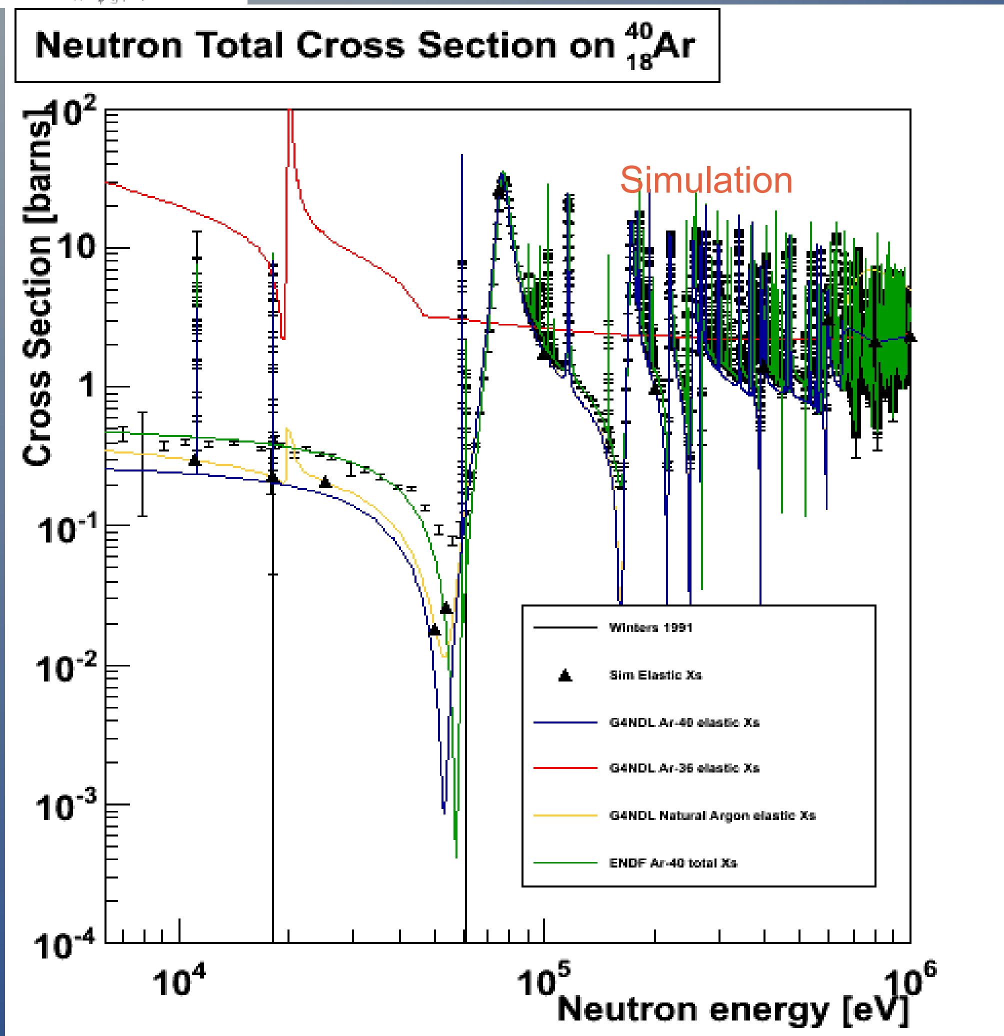
Differences of ~2 at energies < 45 keV
Slight differences at the resonant dip at ~50 keV
Above 1 MeV, 30% effects at peak and on the tail

ENDF/B-VII is in agreement with other datasets: ROSFOND (Russian), JENDL3.3 (Japanese), JENDL4.0, JEFF3.1 (European)



Comparison with Measurements

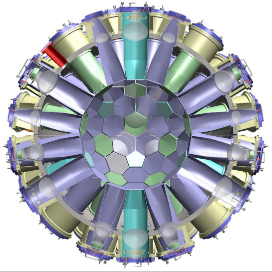




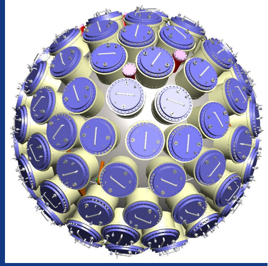
Measurements and simulations have really been done with natural argon, at low energies ^{36}Ar becomes important!

Recall: ^{40}Ar (.996003), ^{36}Ar (0.003365)

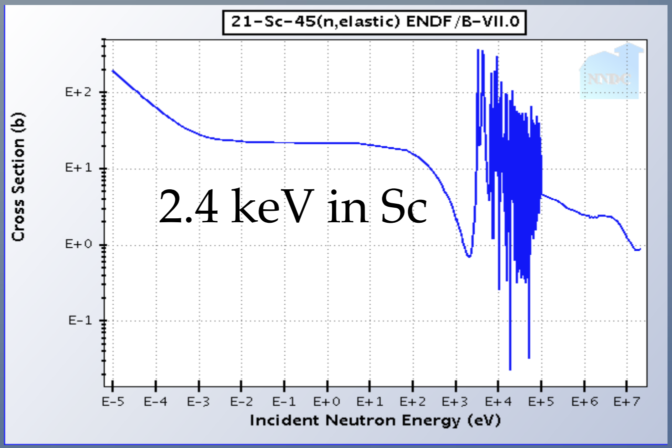
Measurements from Winters et al PRC, 43, 492, 1991
From 7 keV to 50 MeV
ENDF normalized to their data, which is on the NNDC website

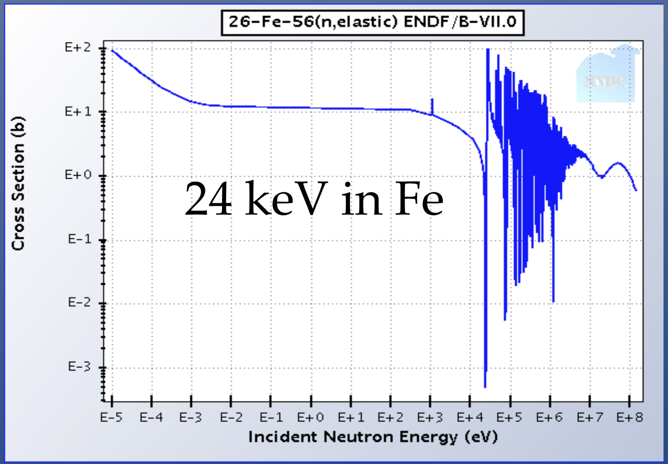


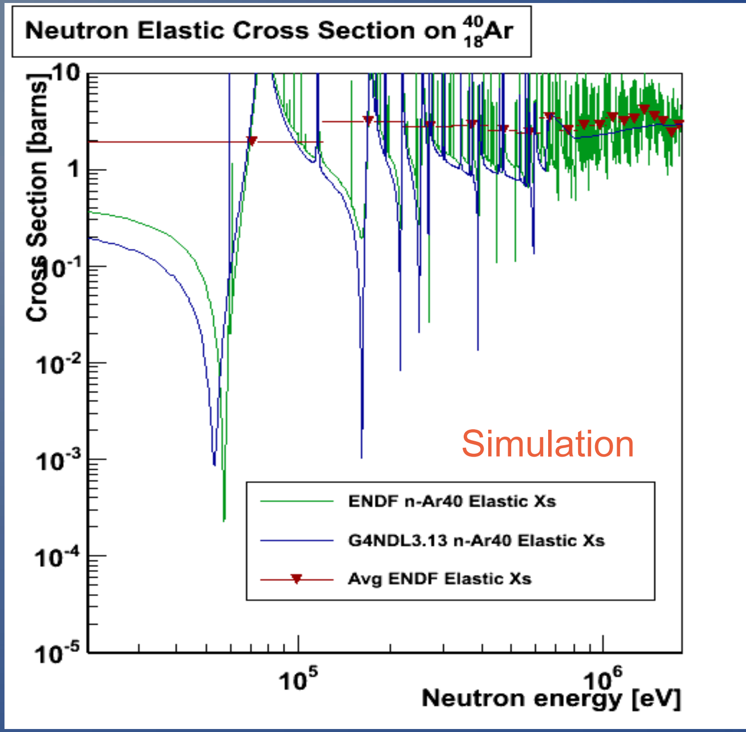
Dip in Elastic Cross Section



Interference between s-wave and hard-sphere scattering gives deep, broad resonant dips in the cross section
Exploited elsewhere to make monoenergetic neutron beams



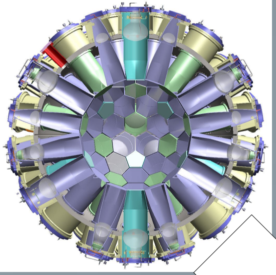




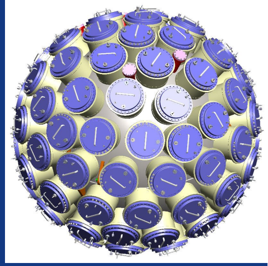
Some uncertainty in depth and position, but Said Mughabghab of BNL, editor of the Atlas of Neutron Resonances, communicates that it is:

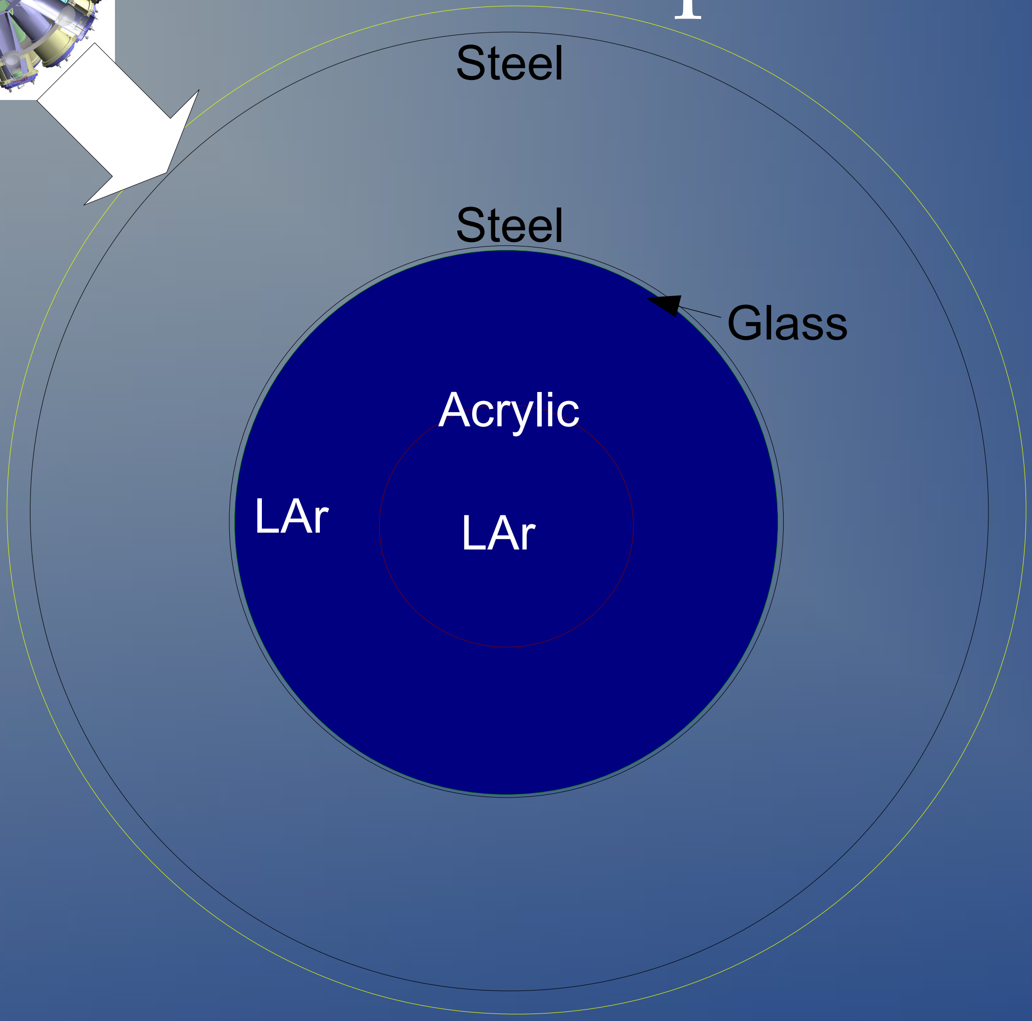
- between 46 and 51 keV
- a minima of 4 mb
- at this energy, an equivalent mean free path of 118 m

Neutrons will not thermalize quickly in liquid Argon



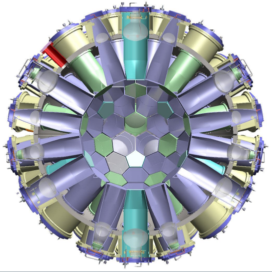
Simple Geometry



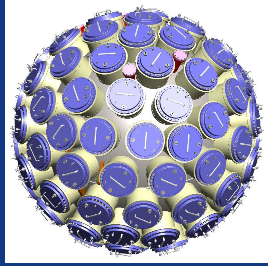


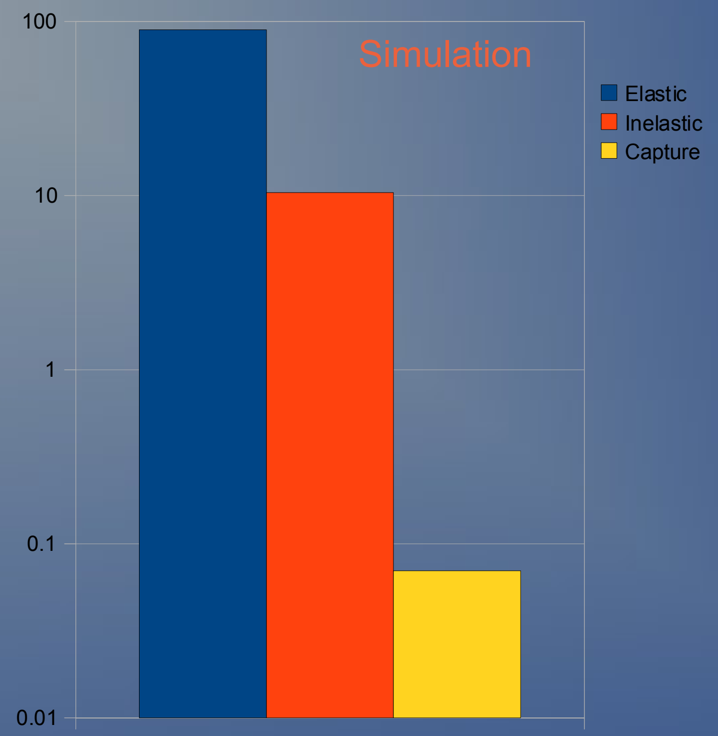
R(world)=1050 mm
R_{inner}(Outer ss)=1000 mm
Thickness:15.679 mm
Mass:1575 kg
R_{inner}(Inner SS)=609.34 mm
Thickness: 27.345 mm
Mass: 1050 kg
R_{inner}(PMT glass)=602.385mm
Thickness: 7 mm
Mass: 72 kg
R_{inner}(buffer LAr)=402.385mm
R_{inner}(acrylic)=400.00mm
Thickness:2.385 mm
Mass:5.5 kg
R<400.00 mm Lar target

Spherical Model, just used for neutron physics studies
60 cm radius of LAr
Neutrons initialized in sphere of glass just outside the argon and are emitted isotropically



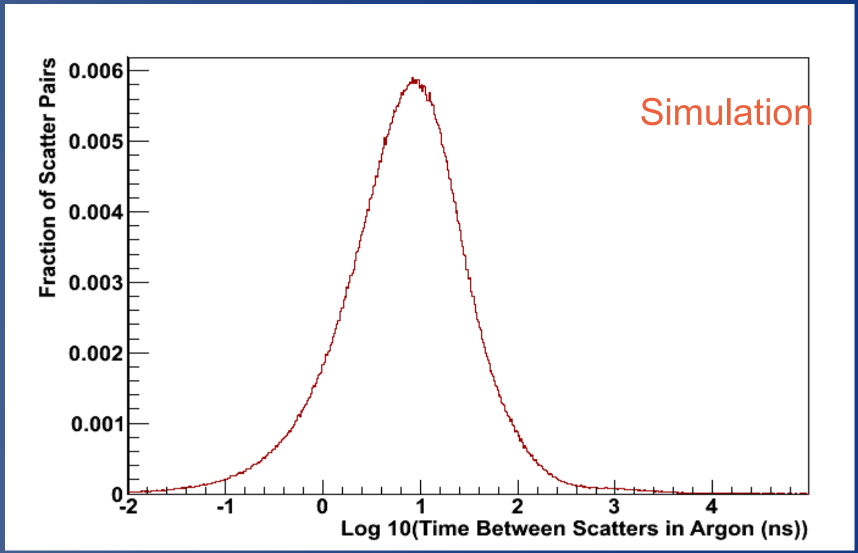
Elastic Scatters: Multiple Scatters



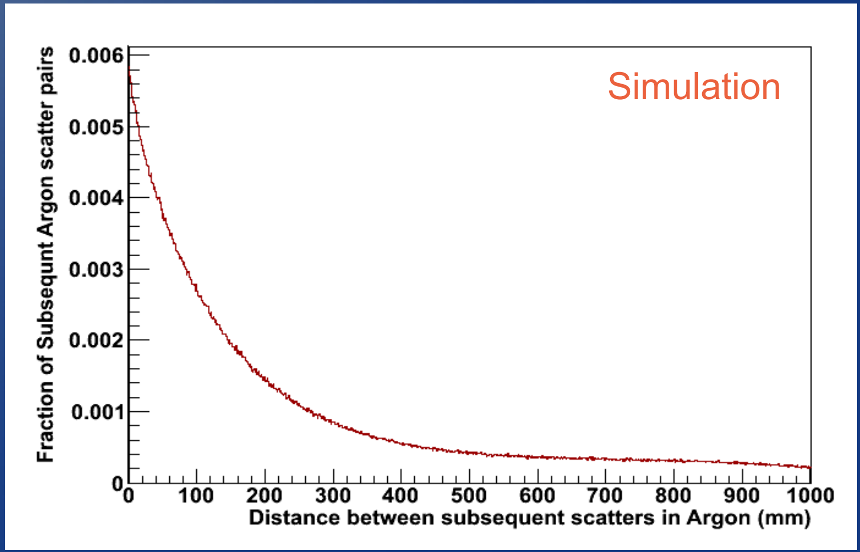


Relative Frequency of Neutron-Argon Interactions

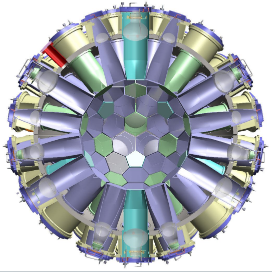
~90% of all neutron scatters in argon are elastic
The mean number of elastic scatters in Argon for a neutron that scatters at least once is 4.72



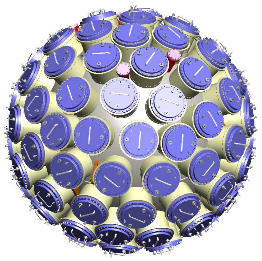
With a mean time of 7 ns between subsequent scatters in argon

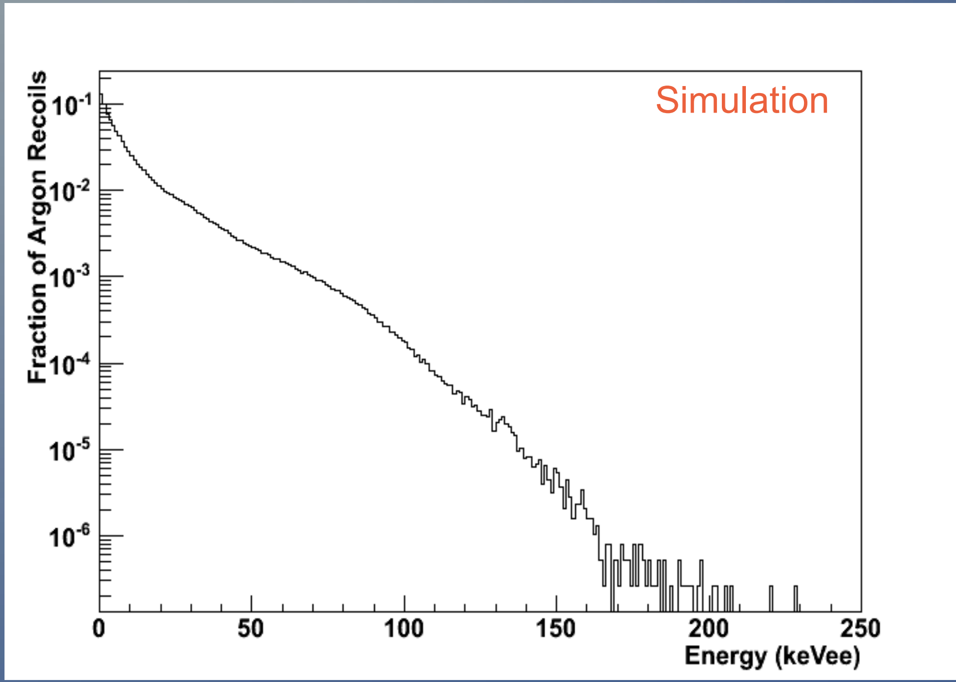


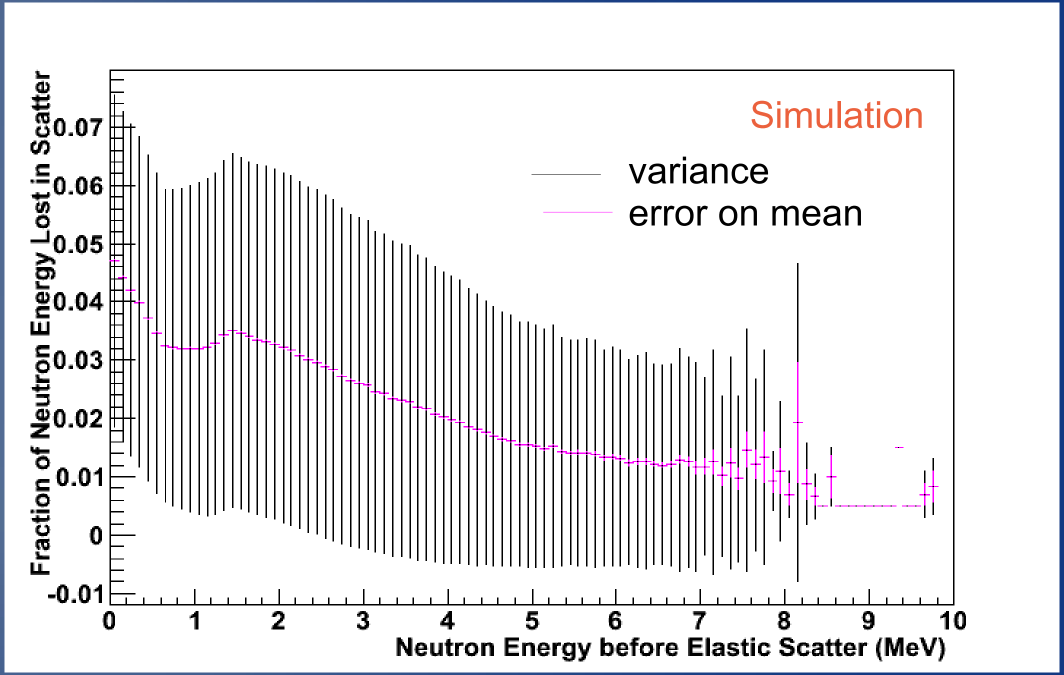
Mean distance between neutron-Argon scatters is 24 cm



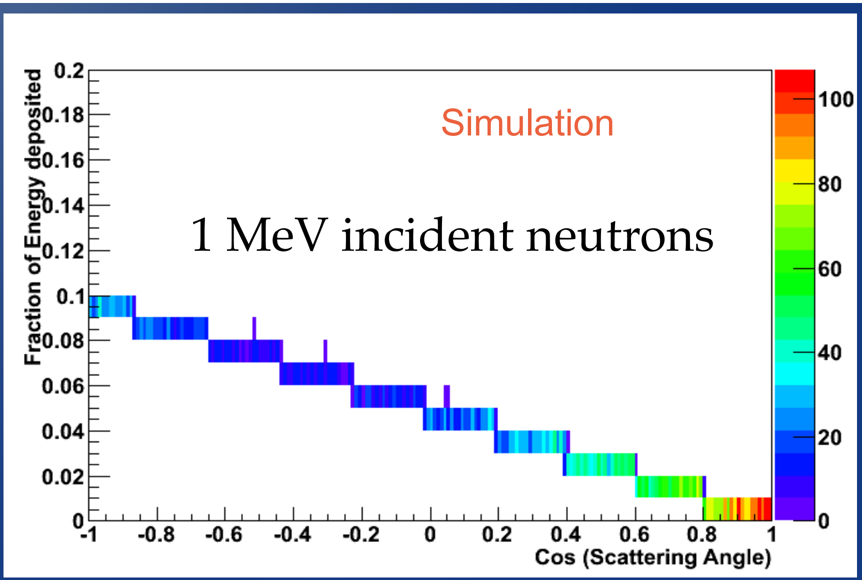
Elastic Scatters: Energy Loss



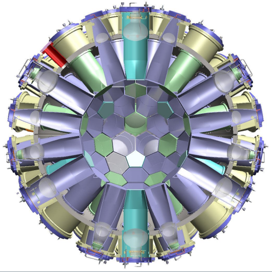




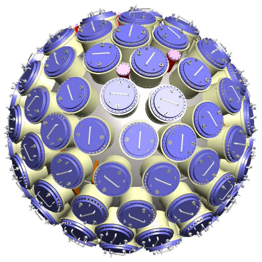
Argon recoils, no radial cuts,
PMT Alpha-n spectrum in Simple Geometry
Quenching factor of 0.25 from
Gastler et. al. arXiv:1004.0373

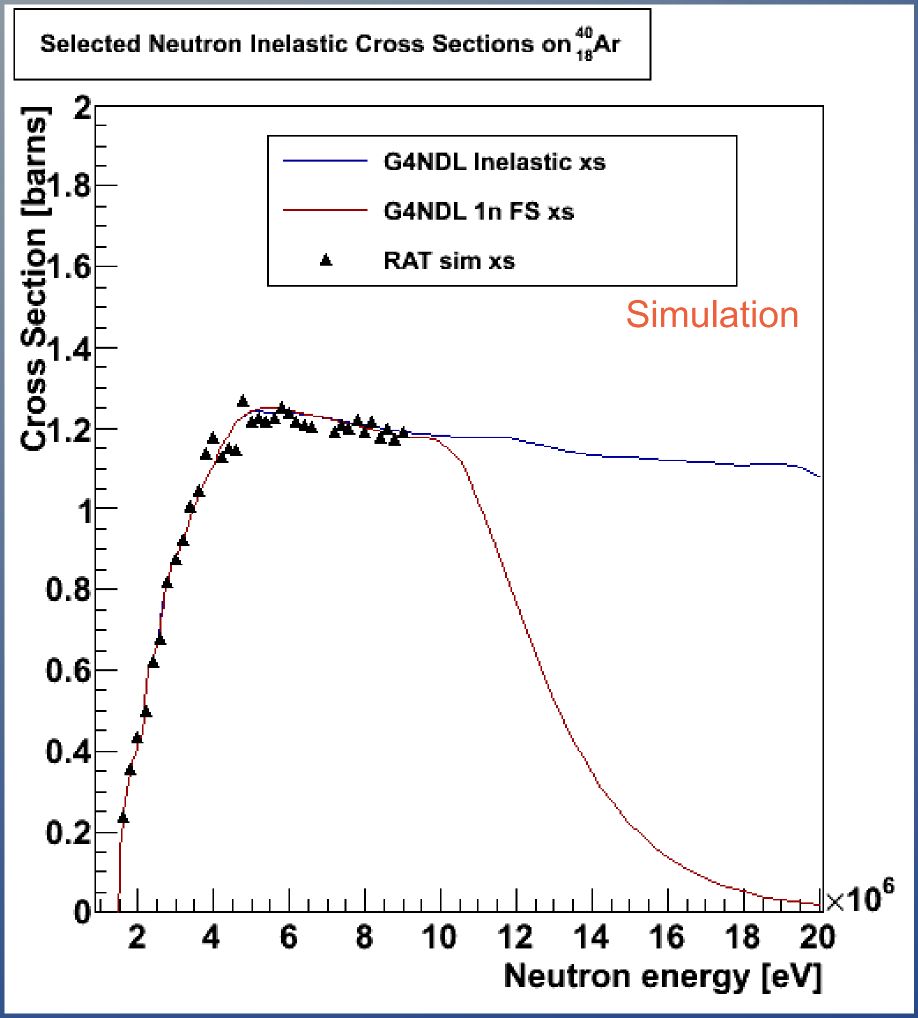


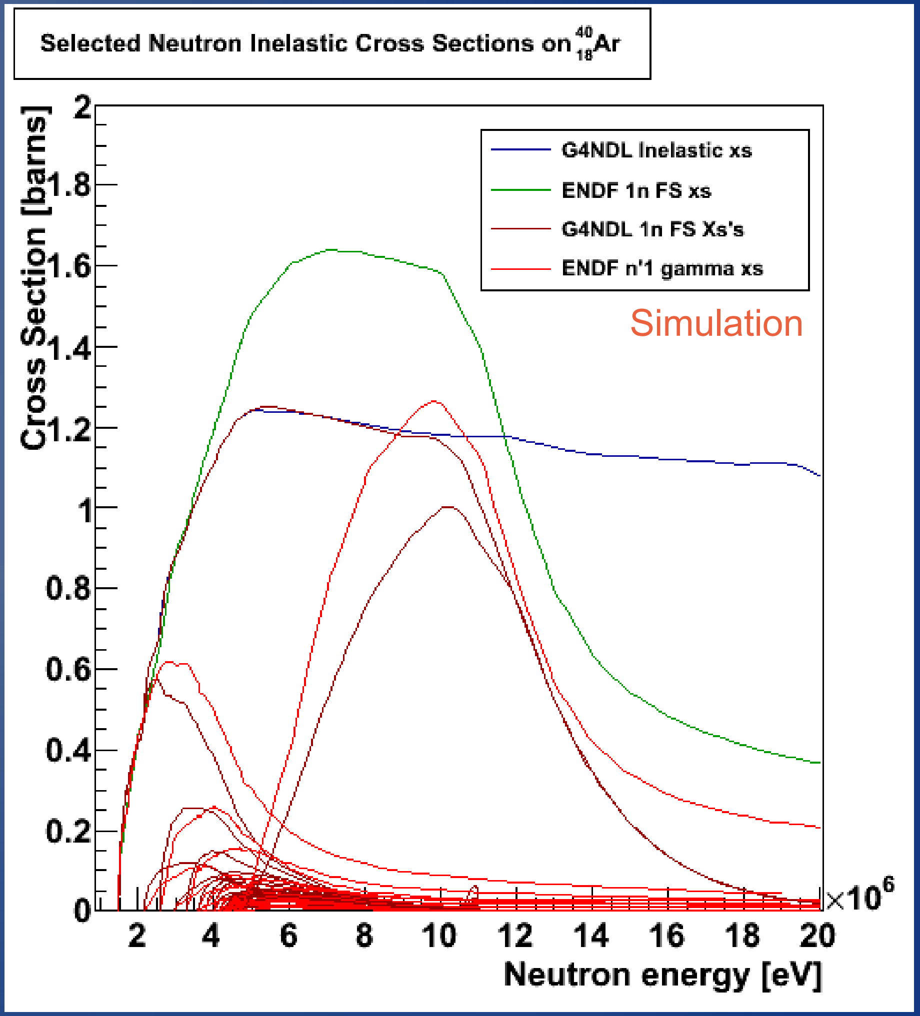
Neutrons may only lose up to 10% of their energy to the argon nuclei,
Average much less: 3.1% at 1 MeV



Inelastic Cross Sections



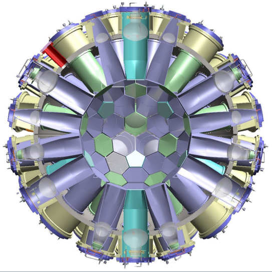




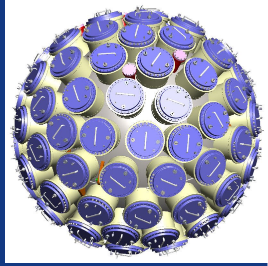
Total Inelastic Cross Section is reproduced

But values are 25% lower than ENDF/B-VII

Fewer independent excited states in G4NDL, missing 1 alpha final state which has a threshhold of 4 MeV, but is an order of magnitude smaller in cross section



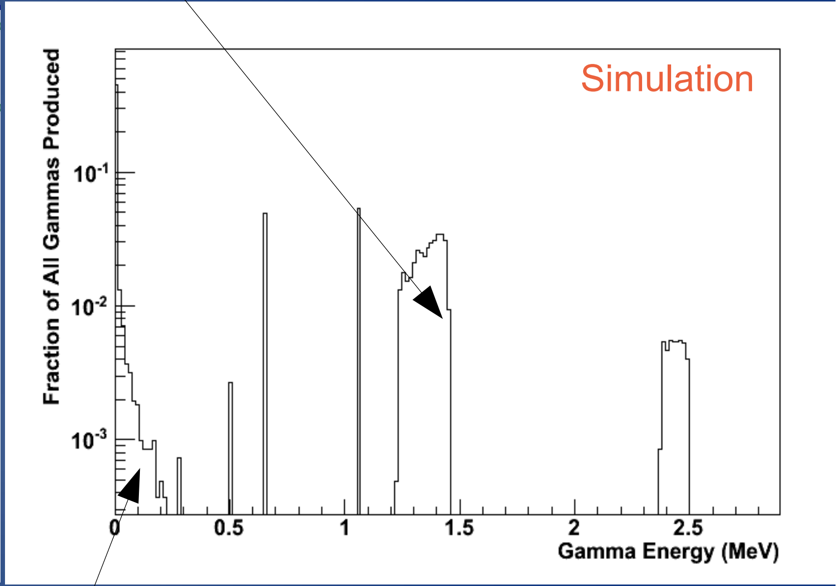
Inelastic Gammas



Peculiar energies of gammas from first excited state:
Not monoenergetic at 1.46 MeV, as expected

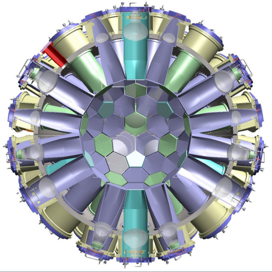
```
****************************************************************************************
* G4Track Information:   Particle = neutron,   Track ID = 4,   Parent ID = 1
****************************************************************************************

Step#     X        Y        Z        KineE    dEStep   StepLeng  TrakLeng   Volume      Process
  0    12 cm  -21.9 cm  -50.2 cm  3.41 MeV    0 eV      0 fm      0 fm   InnerVacuum   initStep
  1   37.8 cm  -18.1 cm  -35.6 cm     0 eV     0 eV   29.9 cm   29.9 cm   InnerVacuum  NeutronInelastic
    :----- List of 2ndaries - #SpawnInStep=  5(Rest= 0,Along= 0,Post= 5), #SpawnTotal=  5 ---------------
    :   37.8 cm  -18.1 cm  -35.6 cm   1.29 MeV   neutron
    :   37.8 cm  -18.1 cm  -35.6 cm   29.9 keV Ar40[0.0]
    :   37.8 cm  -18.1 cm  -35.6 cm   1.44 MeV     gamma
    :   37.8 cm  -18.1 cm  -35.6 cm    660 keV     gamma
    :   37.8 cm  -18.1 cm  -35.6 cm   129 keV      gamma
    :------------------------------------------------------------------- EndOf2ndaries Info ---------------
```

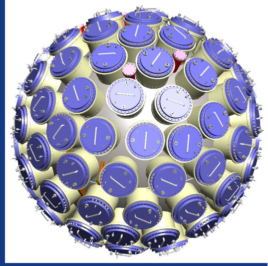


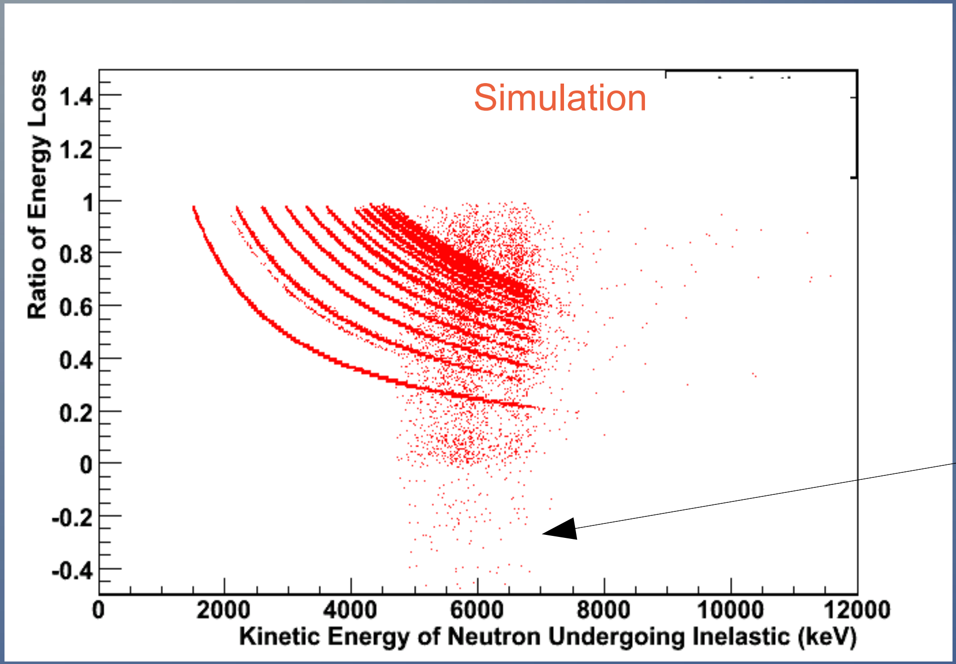
Large numbers of keV gammas, seem to be unphysical
Although we have also considered them to be from electron
Capture: right energy scale, not the right values

Gamma energies produced by 3 MeV neutrons inelastically scattering in liquid argon: first 4 excited states are accessible



Importance of Inelastic Scatters





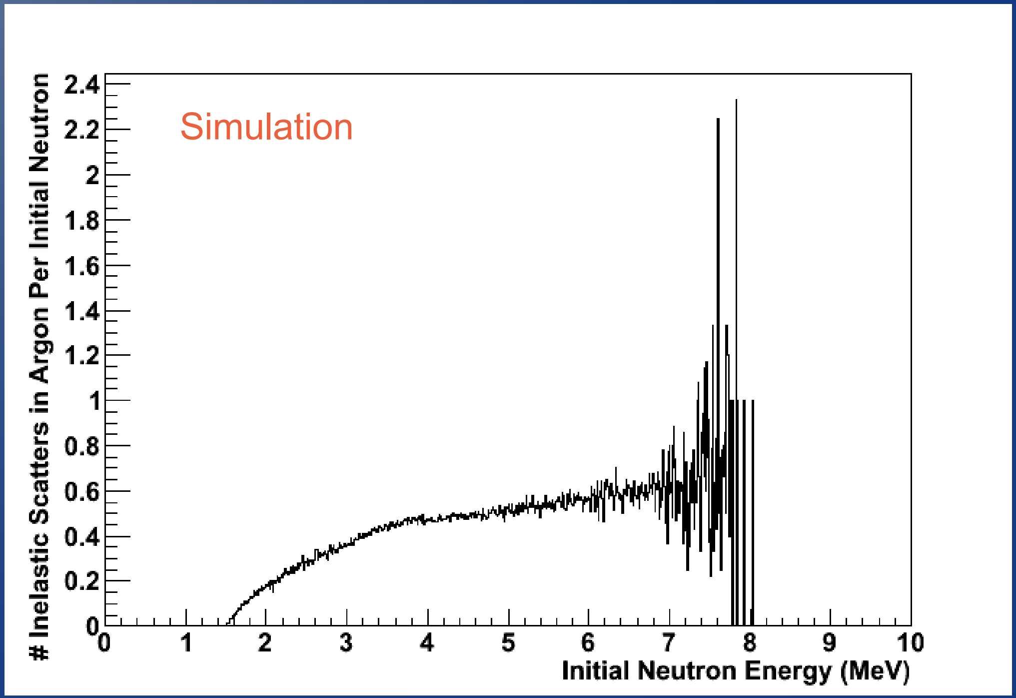
C. Zhang

Simulations with a PMT Alpha-N neutron spectrum in a simplified, spherical MiniCLEAN geometry

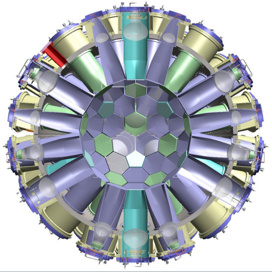
Clear lines when excited states are accessed
Broad when accessing the continuum states

But, energy non-conservation!

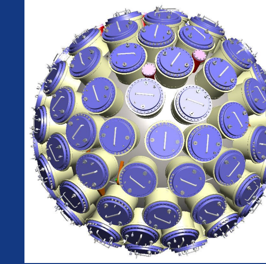
My colleague Chao Zhang has submitted a bug report on this issue:
G4 bug report #1054
http://bugzilla-geant4.kek.jp/show_bug.cgi?id=1054

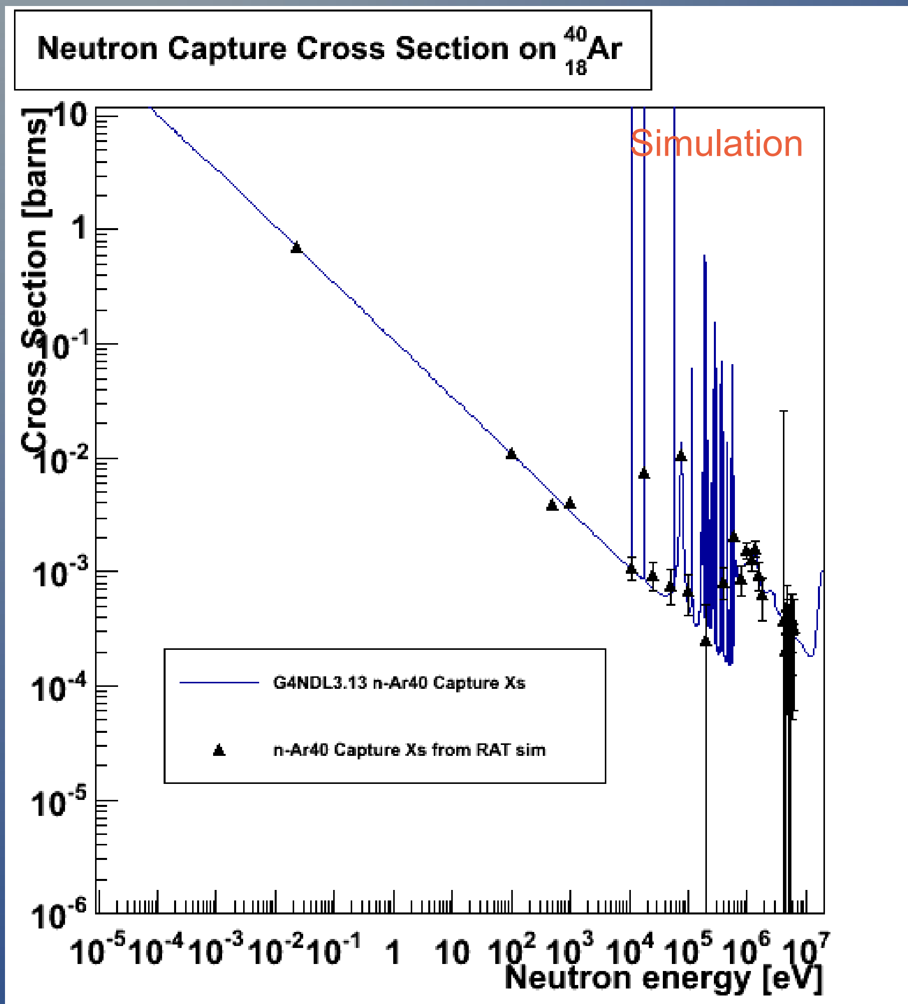


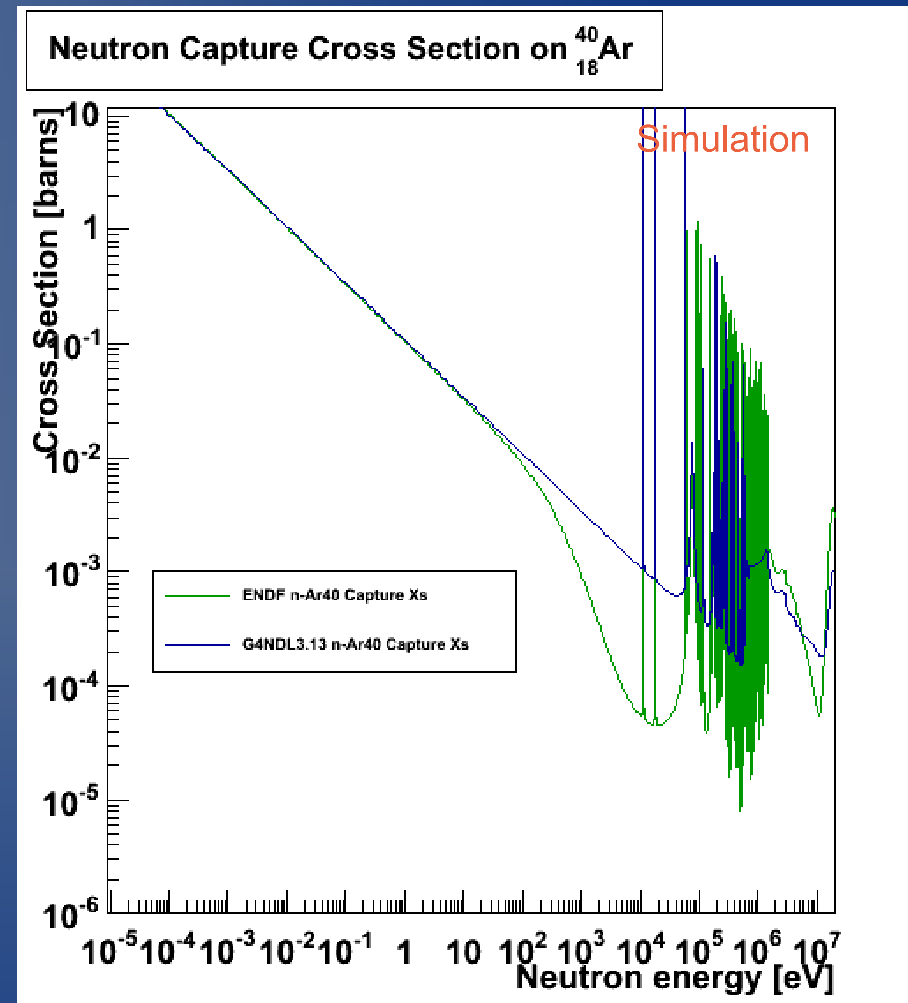
Neutrons starting with 4-7 MeV are likely to inelastically scatter in the liquid argon

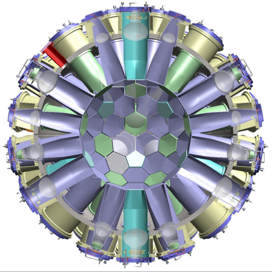


Capture Cross Section

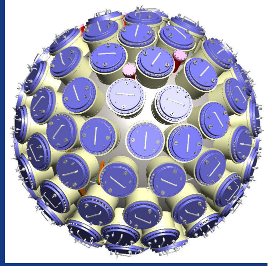








Summary



- RAT is an easy to use and versatile simulation framework
  - Contact Stan Seibert at sseibert@hep.upenn.edu
- For Neutron-Argon interactions <20 MeV, Neutron HP broadly gives results in agreement with the cross-sectional information from ENDF/B-VII
  - But bugs and some differences introduce uncertainties
- Similar checks, including looking at data, nuclear cross-section models, and full simulations in Geant4 are probably necessary at all energy ranges for all important materials

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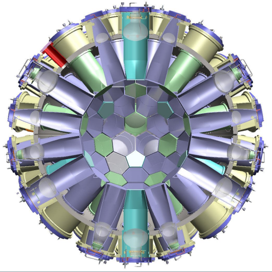
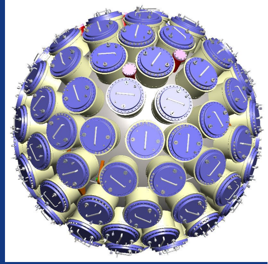
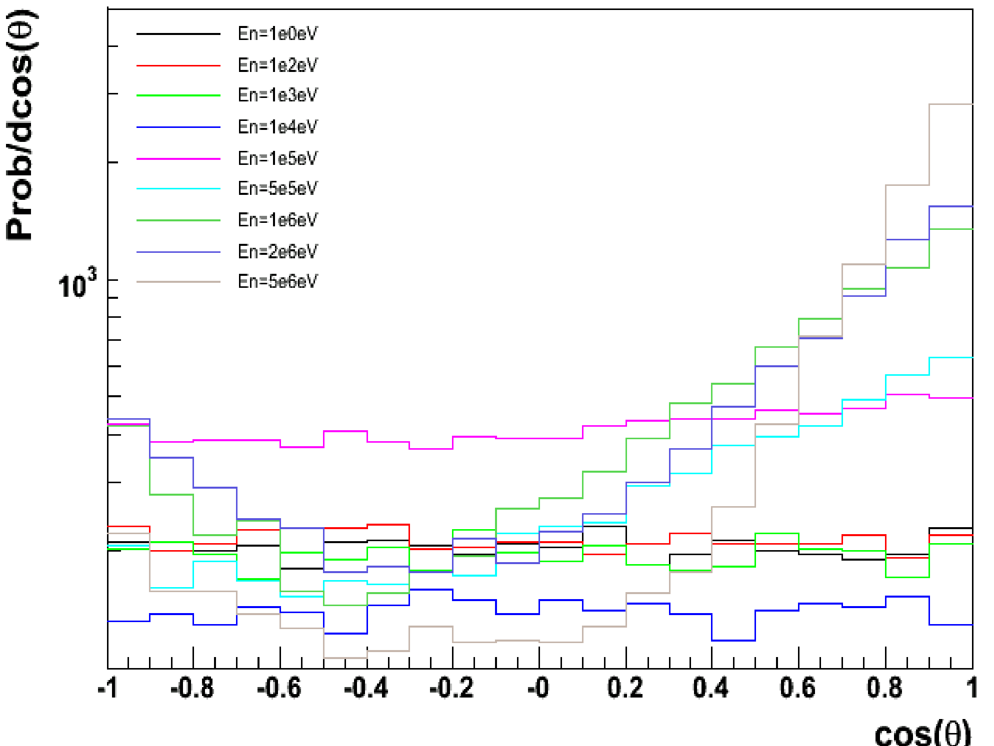
Backup Slides

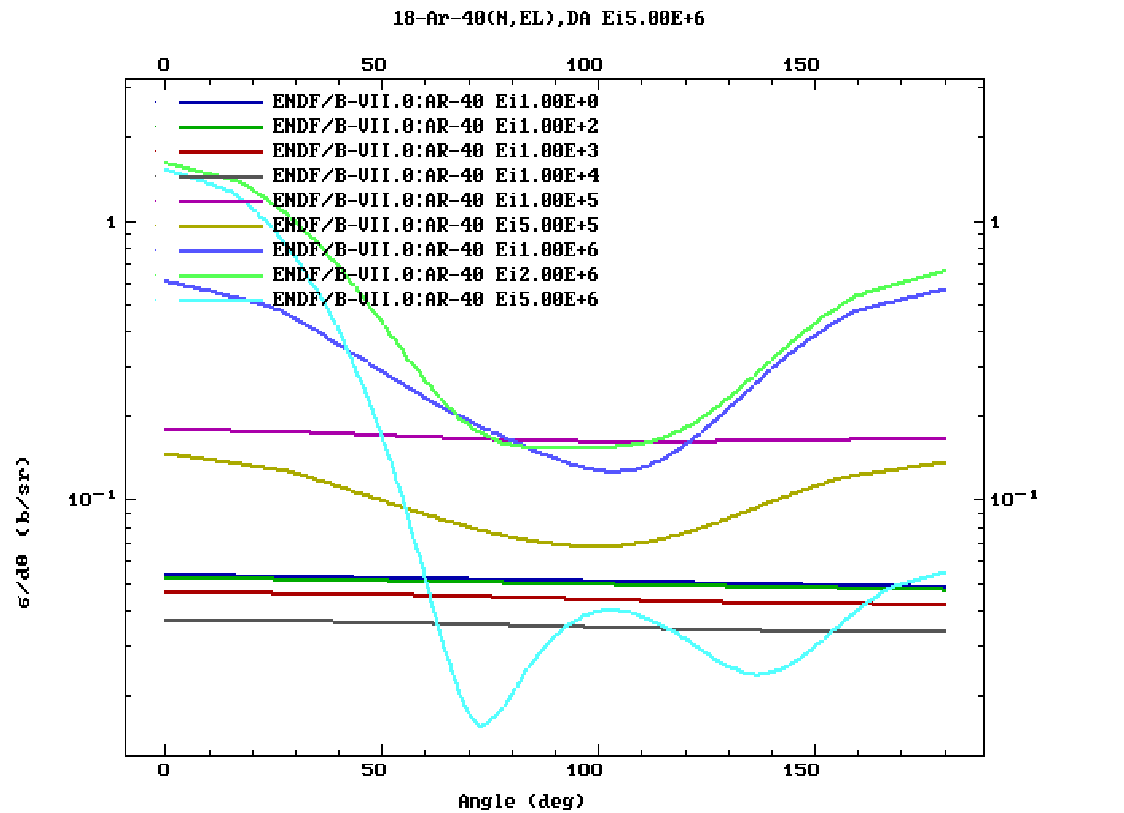


Elastic Angular Distribution



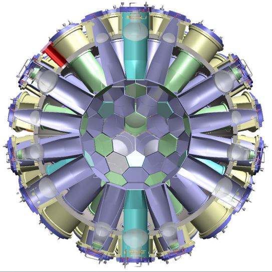
From Chao Zhang



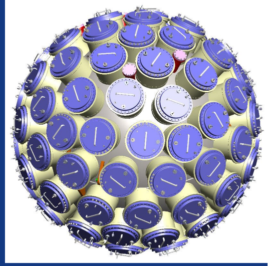


Geant4 simulations of monoenergetic neutrons elastically scattering in Argon
Uniform distribution for low energy neutrons

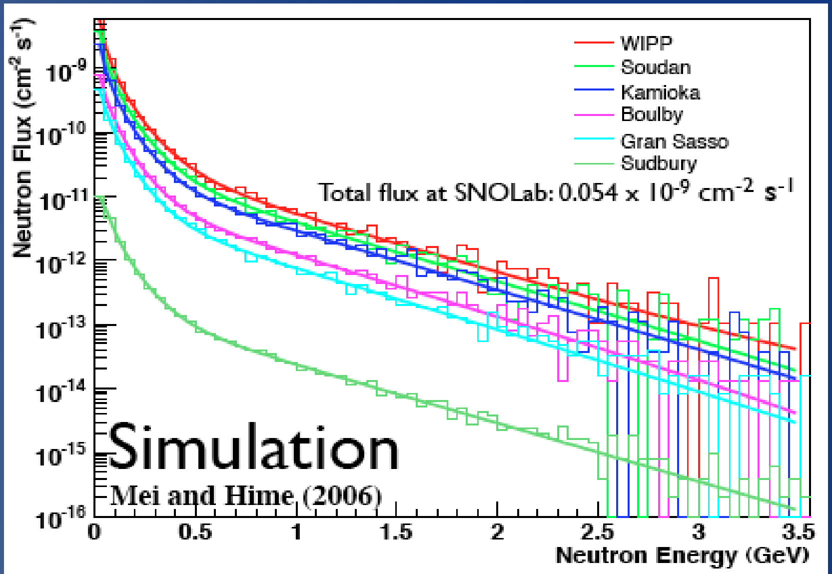
ENDF Differential Cross Section

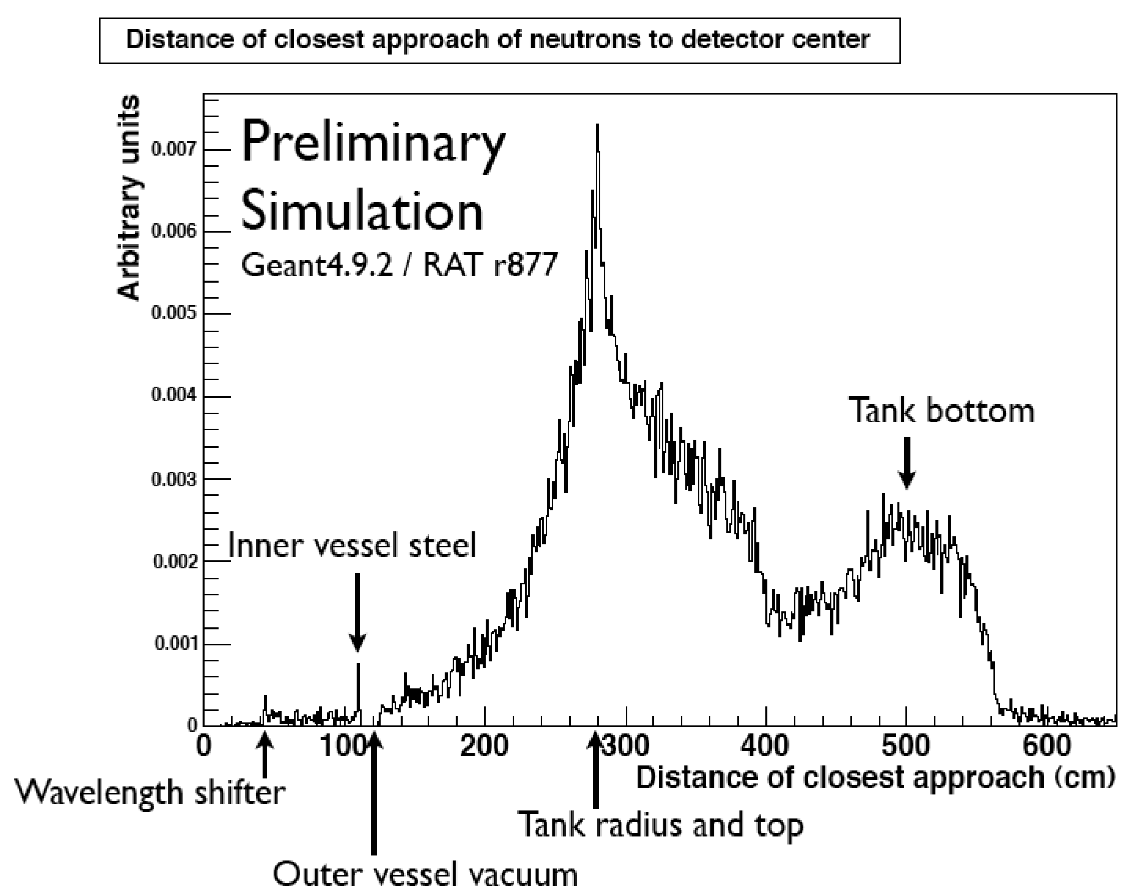


Cosmogenic Neutrons

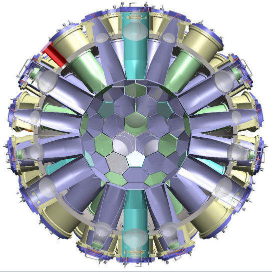


Water tank of 2.8 m radius, 7.9 m height
Shield gammas and neutrons from cavern walls
Tag through-going muons

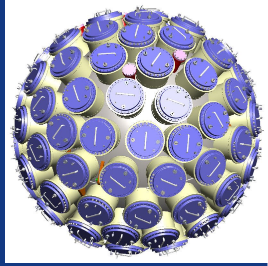




A conservative estimate of muon induced neutrons that originate in the cavern walls with no tagged muon and then create a background signal in the ROI is <0.1 / year



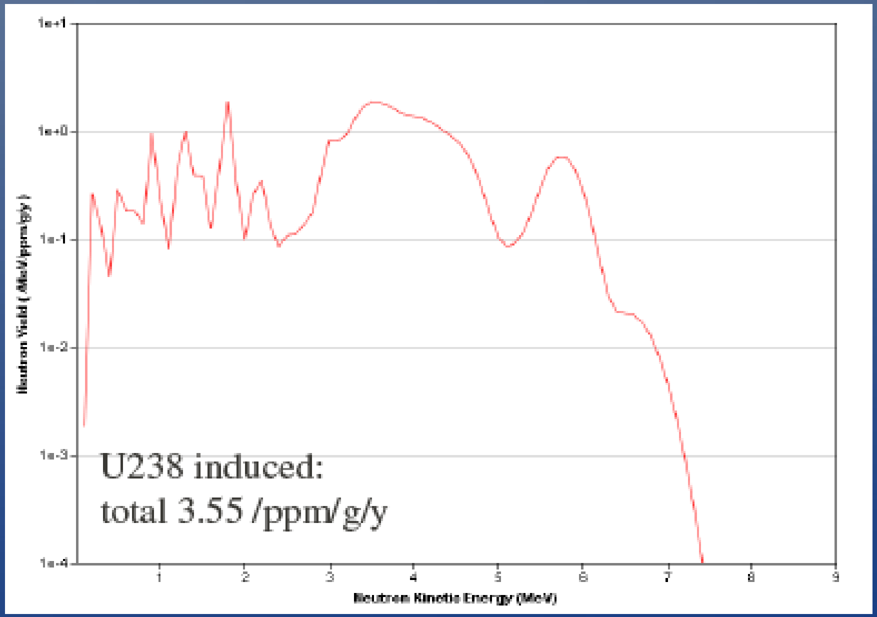
PMT Neutrons

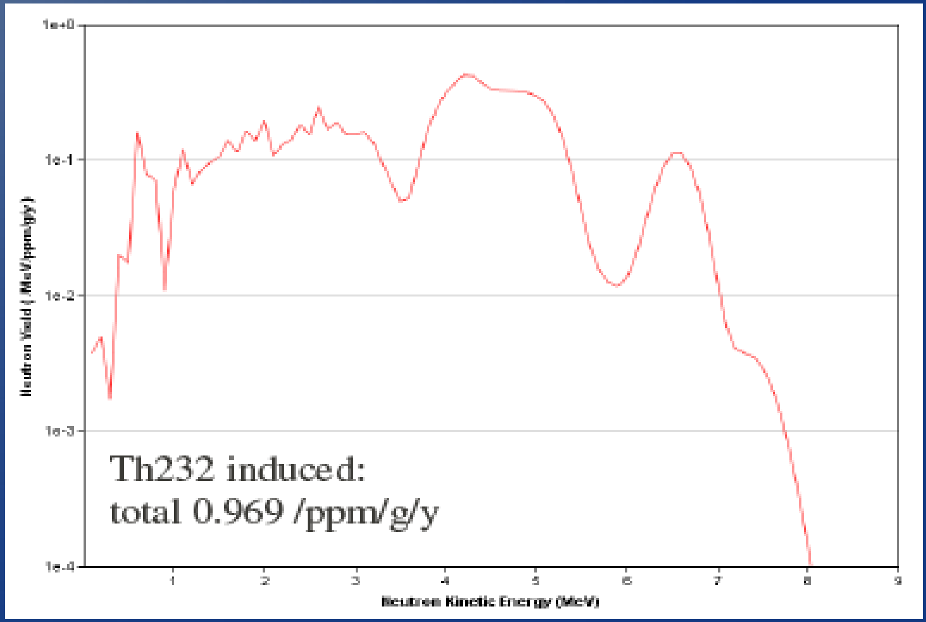


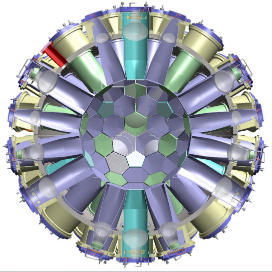
U238 Energy (keV)	U238 Branch Ratio (%)	Th232 Energy (keV)	Th232 Branch Ratio (%)
4198	79	4013	77.9
4151	21	3954	22.1
4775	71.4	5423	71.5
4722	28.6	5340	28.5
4688	76.3	5685	94.9
4621	23.7	5449	5.1
4784	94.4	6288	100
4602	5.6	6778	100
5490	100	8784	64
6002	100	6090	9.8
6902	0.01	6050	26.2
7687	99.99		
5304	100		

http://neutronyield.usd.edu

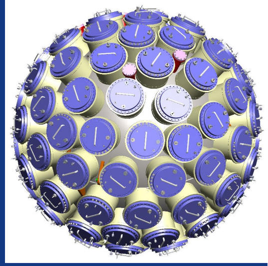
- Decay in secular equilibrium, follow 8 and 6 alphas from ^{238}U and ^{232}Th respectively
- Input glass composition
- Primary contribution to neutrons comes from Boron
- Assay of PMT for radio isotope content:
  - ^{238}U: 0.10287 ppm
  - ^{232}Th: 0.16974 ppm

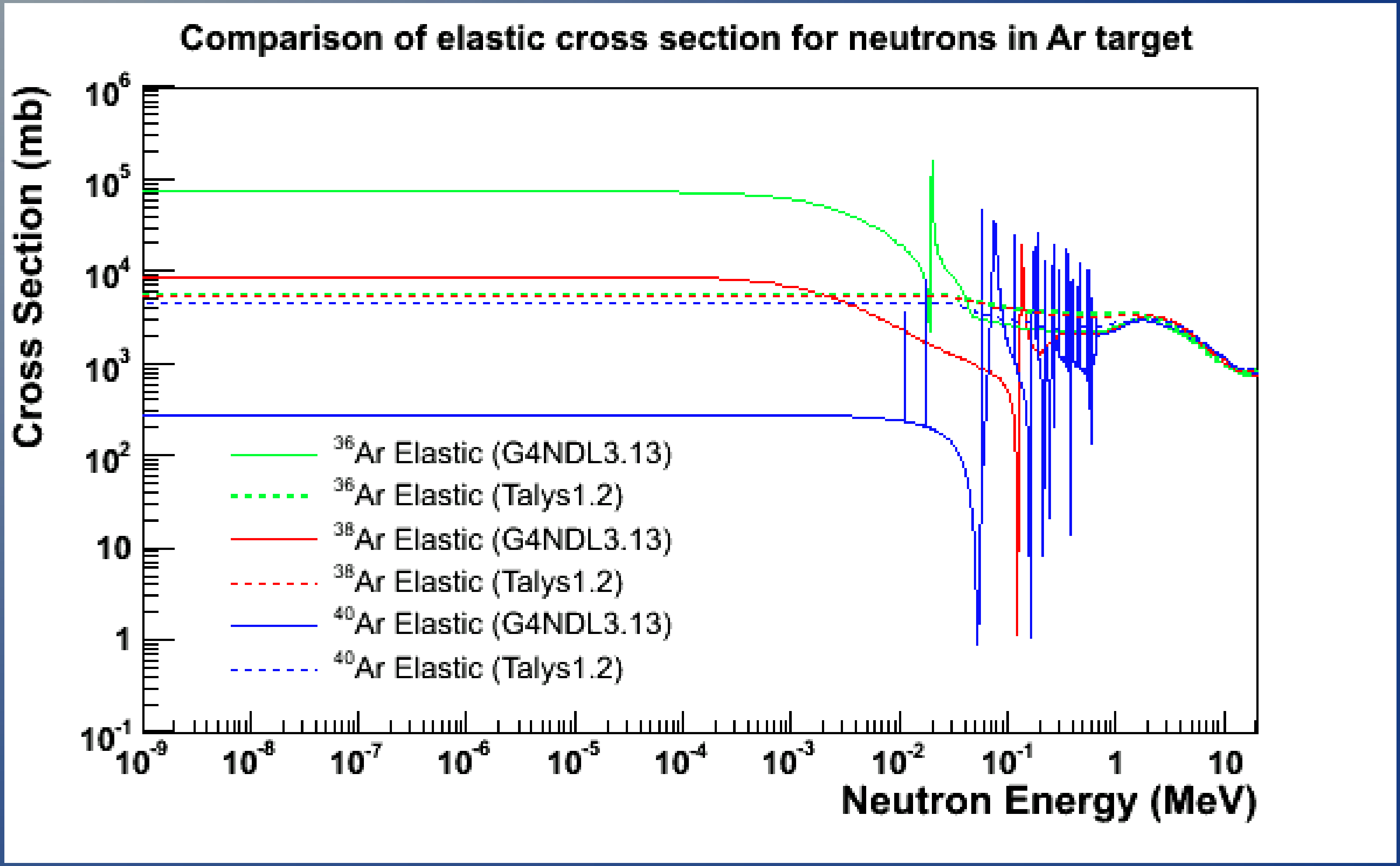






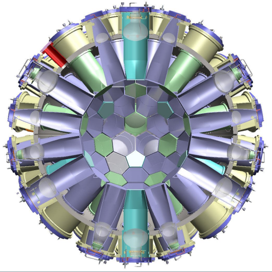
TALYS



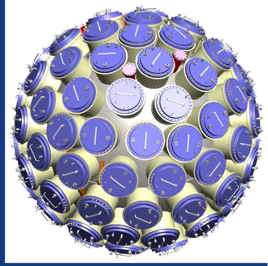


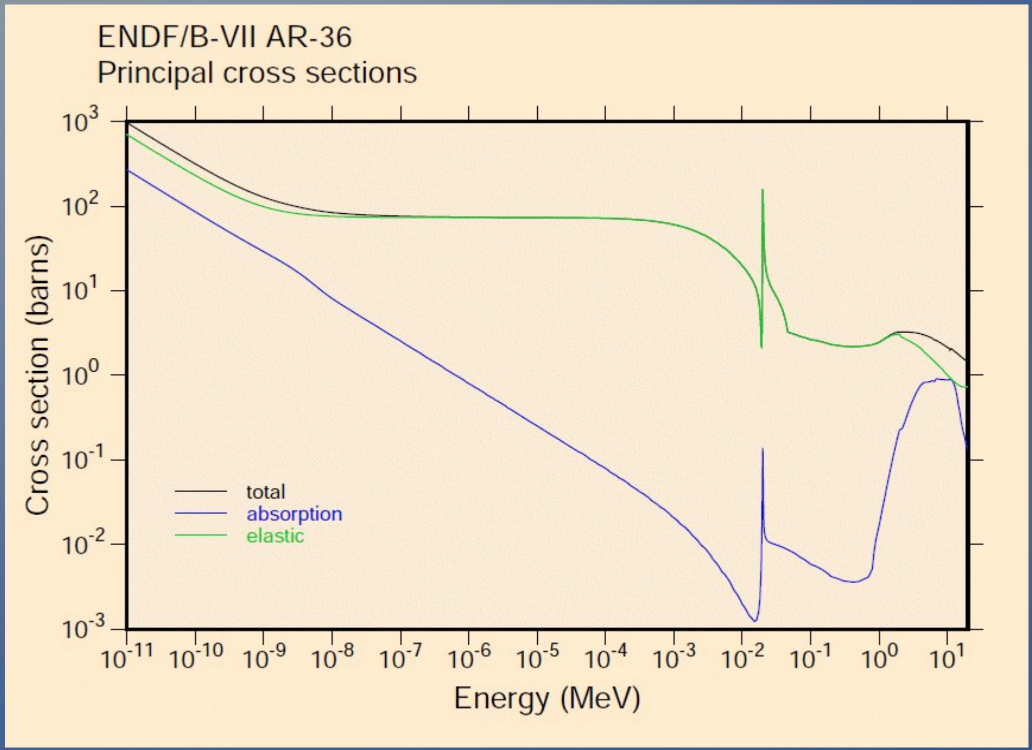
C. Zhang

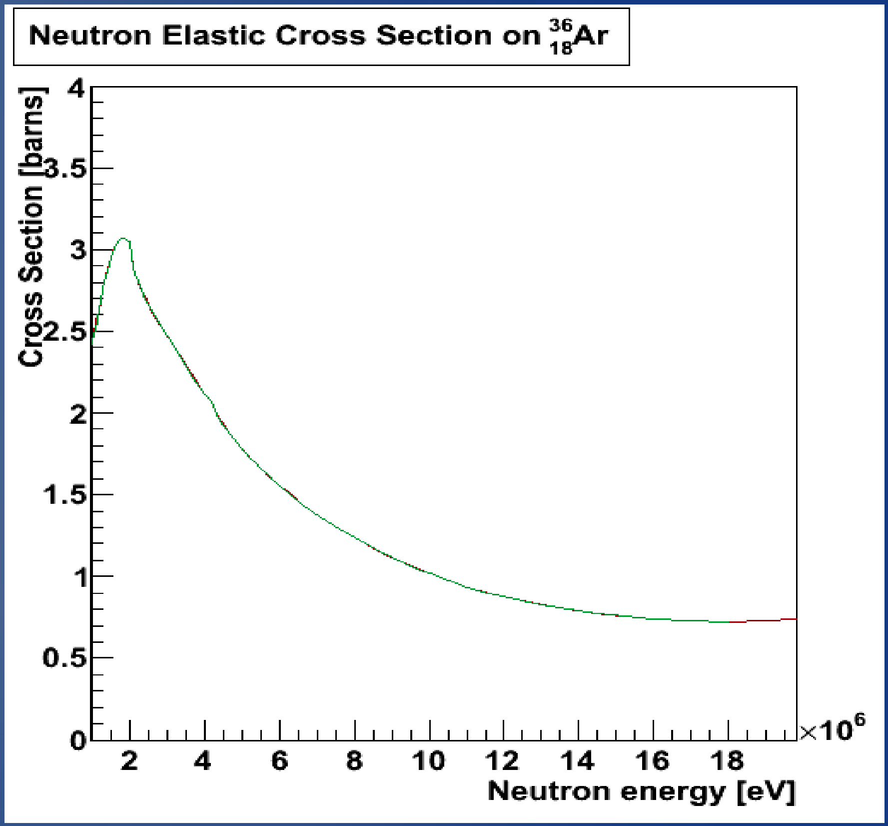
TALYS has no resonances input



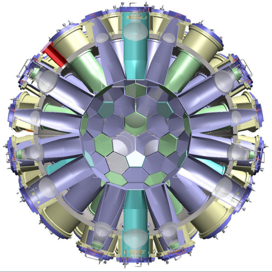
Argon 36



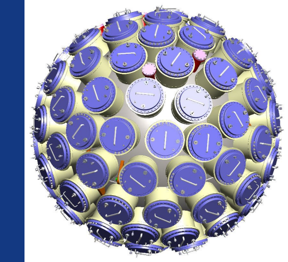


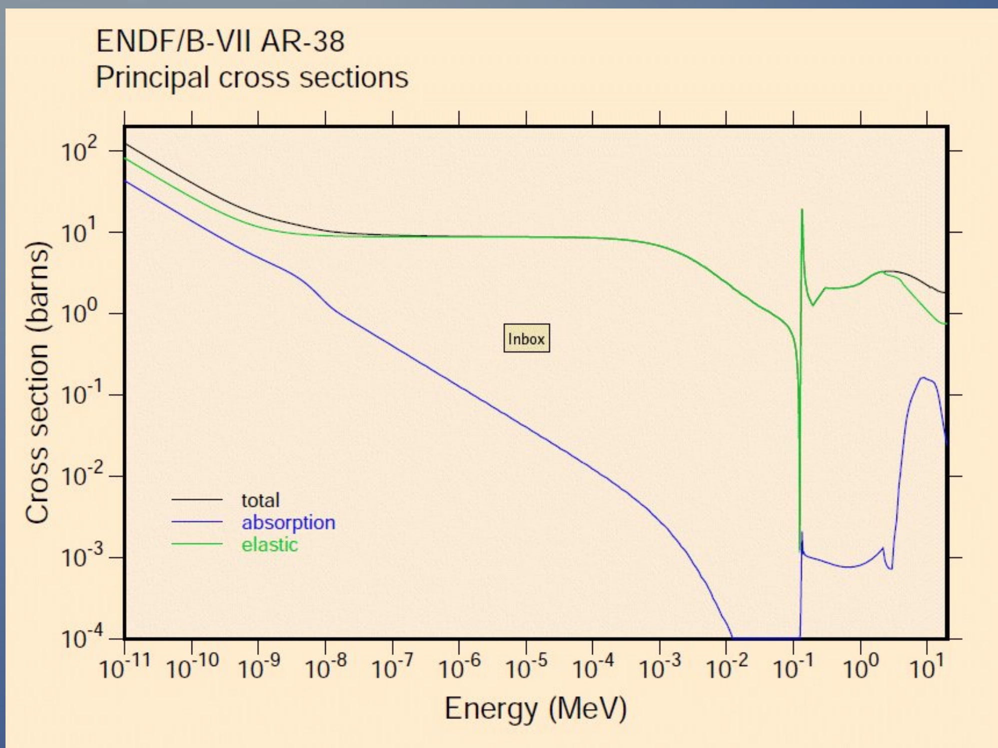


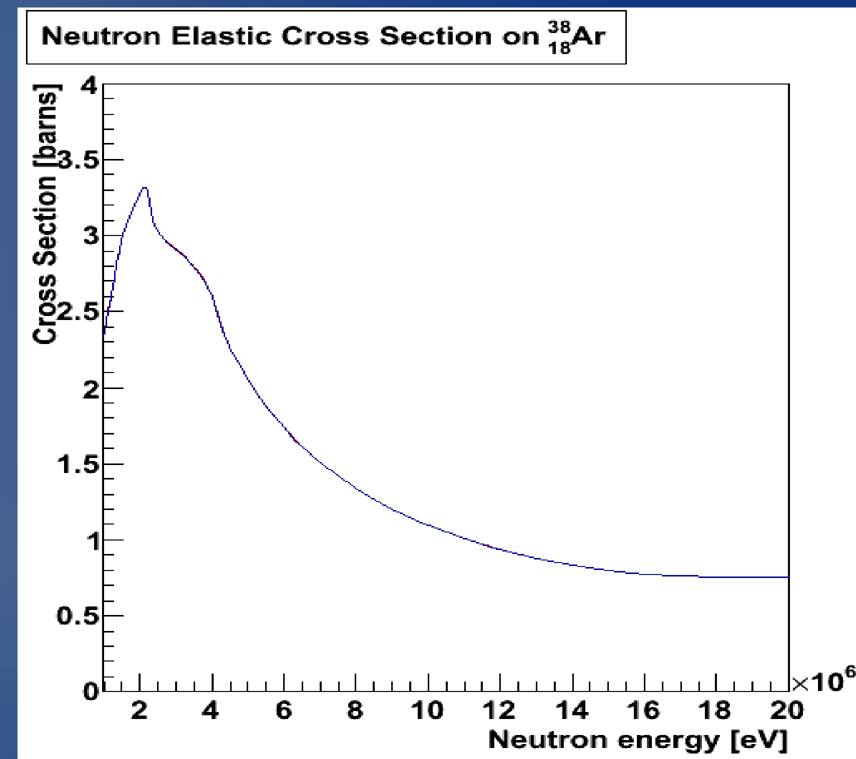
ENDF and G4NDL values are in agreement,
Can't see the other line!



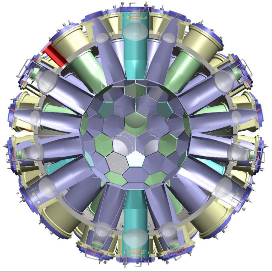
Argon 38



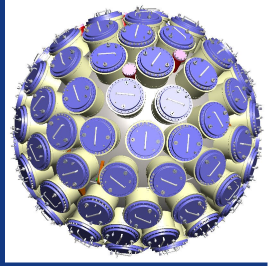


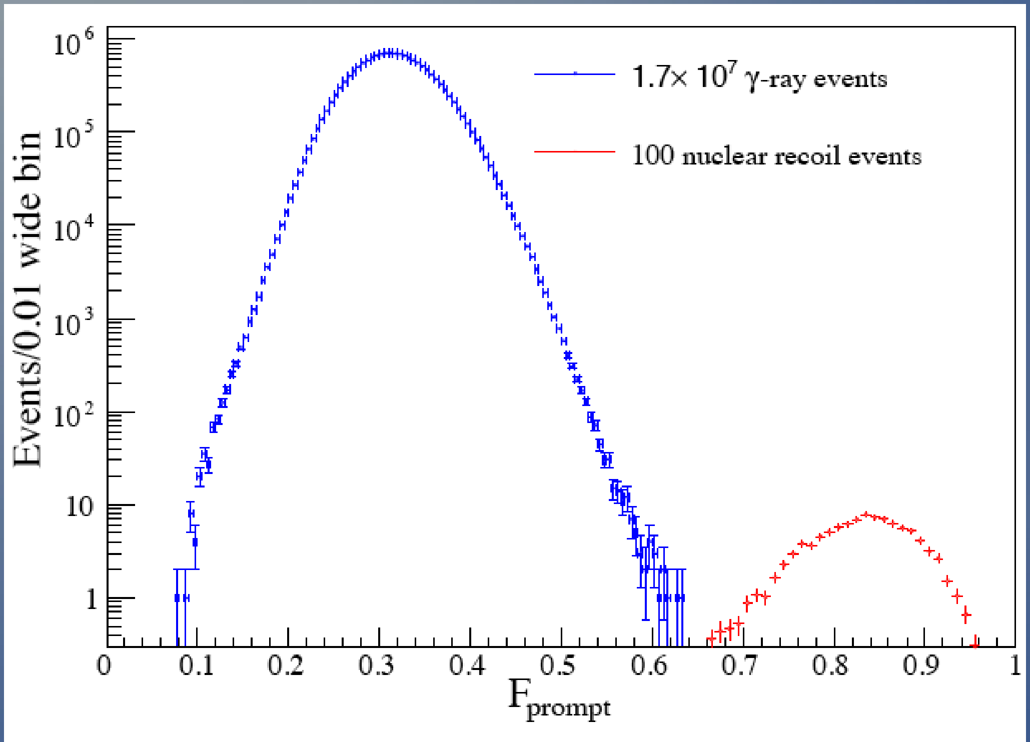


ENDF and G4NDL values are in agreement,
Can't see the other line!

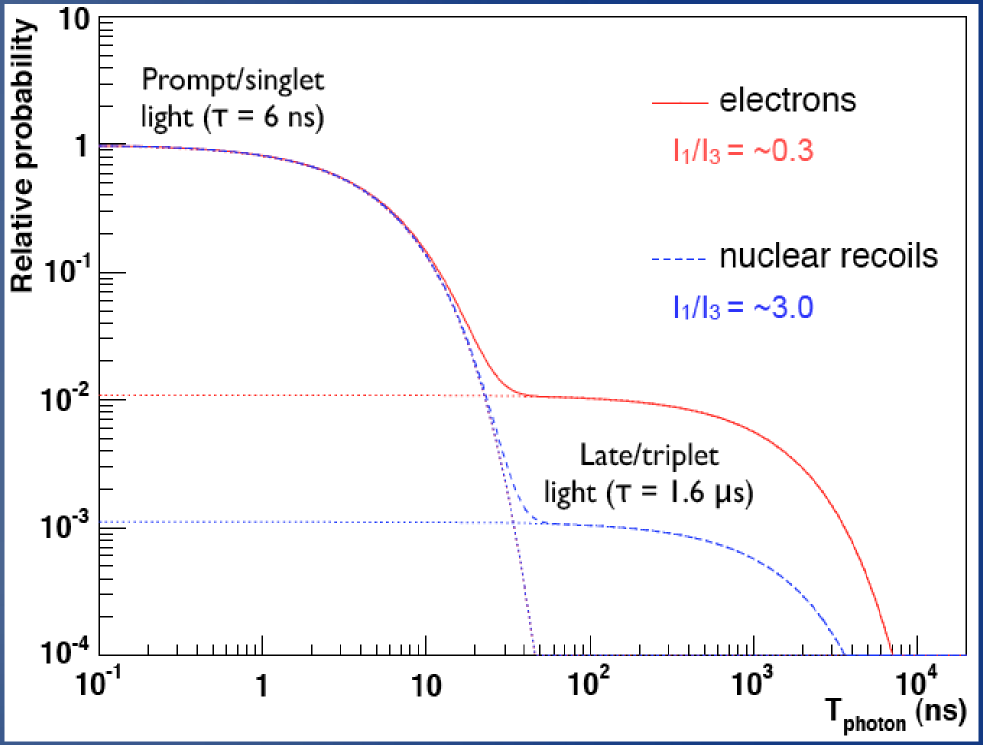


Pulse Shape Discrimination





Boulay et al. arXiv:0904.2930



Boulay and Hime, Astropart. Phys. **25**, 179 (2006)

In LAr, $\tau_{triplet}$ =1.6 us, $\tau_{singlet}$ = 6 ns

F_{prompt} ~ .3 for electron recoils, .8 for nuclear

How well can discrimination work?

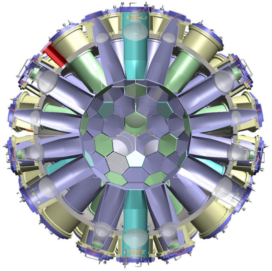
DEAP-1 has demonstrated (stat. Limited)

< 6×10^{-8} 43<E< 86 keV_{ee}

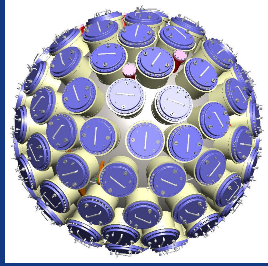
Necessary in LAr because of ^{39}Ar

Also seen $<10^{-3}$ in LNe

Nikkel et al., Astropart. Phys., 29,161 (2008)



Neutron HP Summary



- There are small cross section differences between G4NDL and ENDF/B-VII and a few unexpected features to neutron-Argon interactions in Geant4.
- Although fairly small effects, these introduce uncertainties in the neutron simulations in Geant4 that may affect numbers of expected backgrounds.
- Important features of neutron interactions in argon
  - Inelastic processes are important for neutron energy loss
  - Neutrons will most likely scatter multiple times elastically in the detector
  - 40Ar has a substantial dip in the elastic cross section at ~50 keV, where neutrons have a mean free path of 118 m
- Geant4 neutron physics should be verified for every material!