ISS-RAD Fast Neutron Detector (FND)

ACO On-Orbit Neutron Dose Equivalent and Energy Spectrum Analysis Status

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on behalf of the ISS-RAD science team

esa
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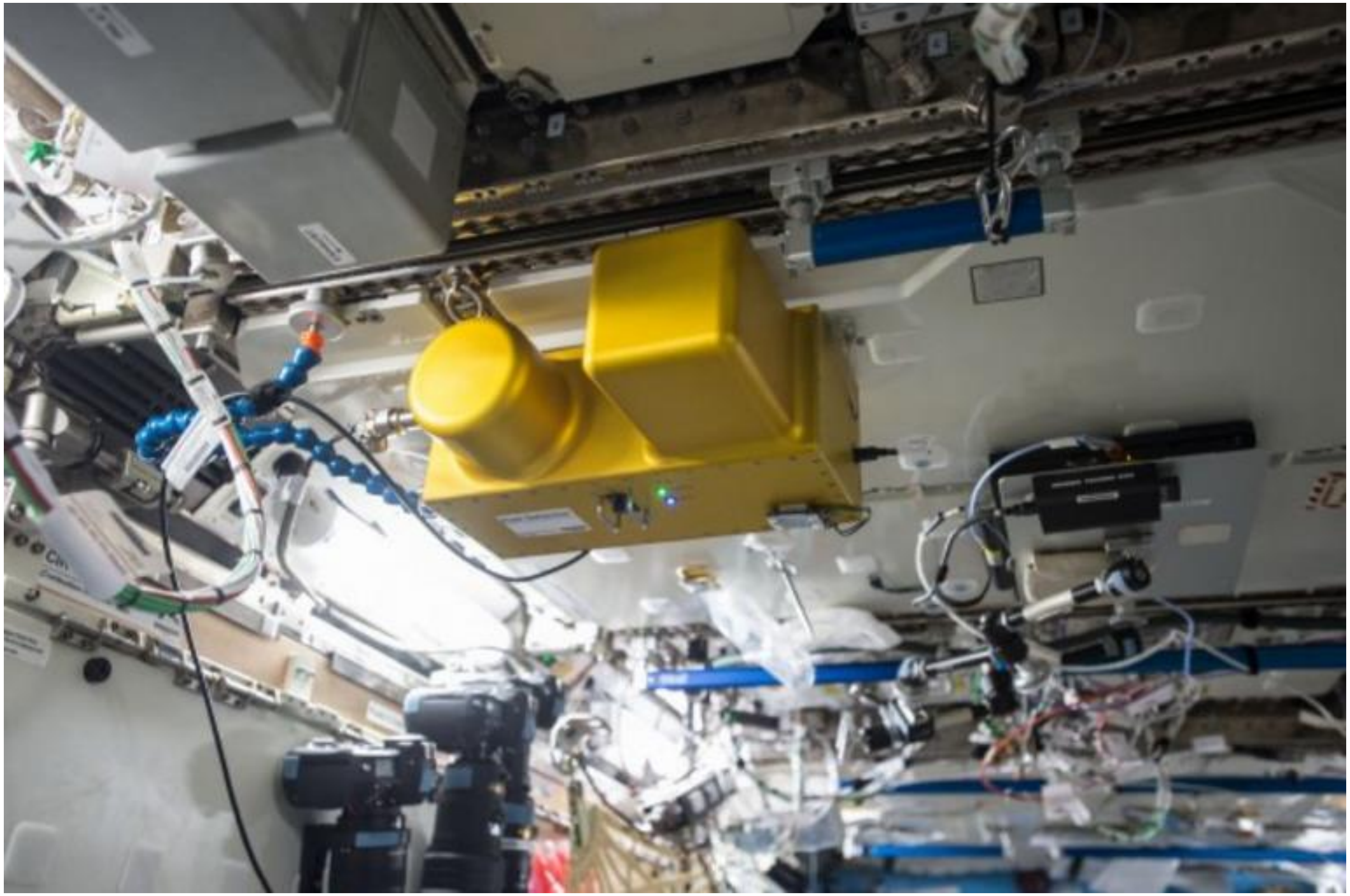
9/7/16

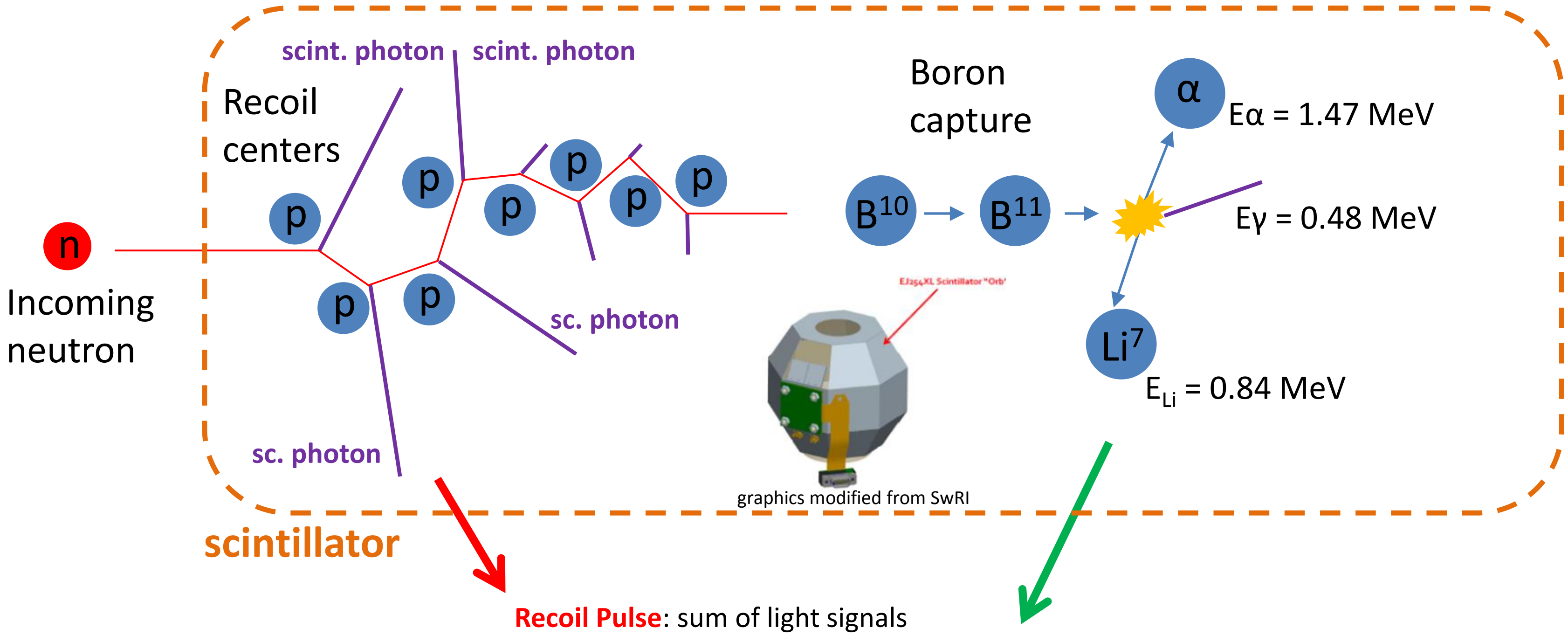
0. ISS-RAD Launch and Deployment

- ISS-RAD Arrived on Orbit!
- Launched in December 2015
- Deployed on ISS on 2/1/2016 in US Lab on Lab1O3, pointing forward



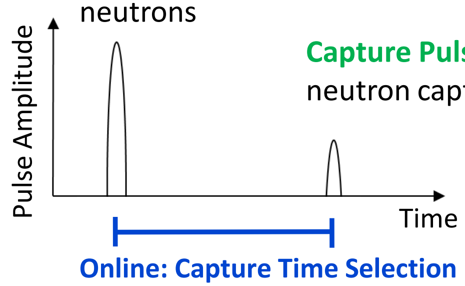
1. Introduction: Detection/Selection Mechanism: Boron-loaded Scintillator

- Neutrons deposit energy in plastic scintillator, some captured by ^{10}B atoms:

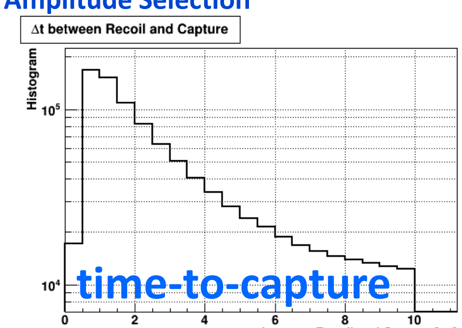


Recoil Pulse: sum of light signals produced during deceleration of neutrons

Capture Pulse: light produced by neutron capture on boron



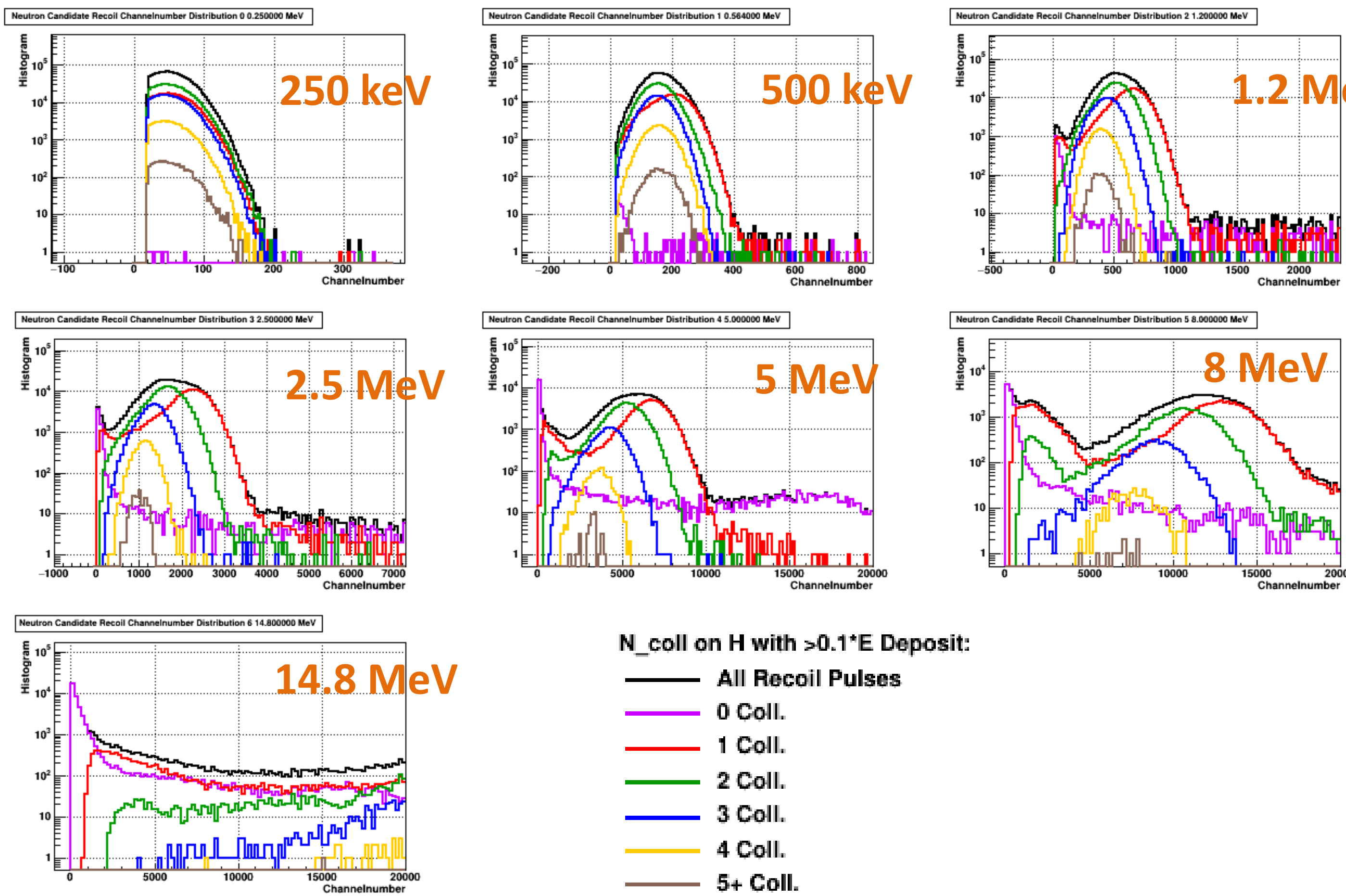
Online: Capture Amplitude Selection



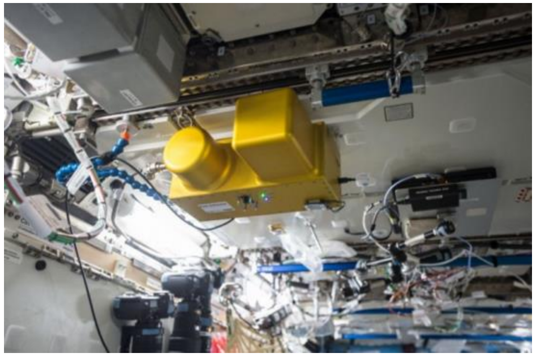
- Measurements of **recoil** and **capture** photon signals and **time-to-capture**:

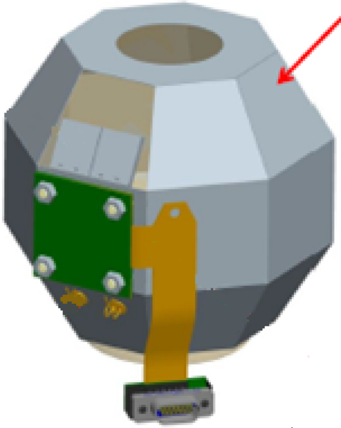
1. Introduction: Scintillation Light Creation/Propagation

- Example: End-to-end FND simulation (MCNP-PoliMi and FND signal processing algorithms) for monoenergetic neutron fields at PTB
- Spectral shape driven by number of high energy deposit neutron collisions off hydrogen
- Due to multiple scattering and scintillation light quenching in scintillator, even monoenergetic neutron create broad distributions in FND recoil spectra.



2. Analysis Methods





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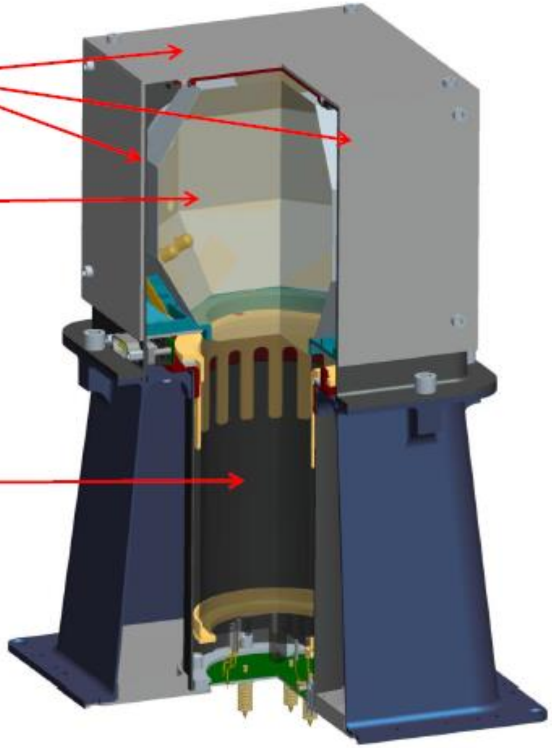
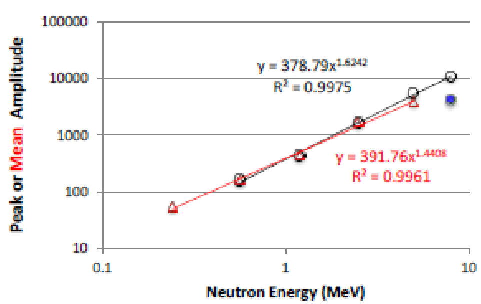


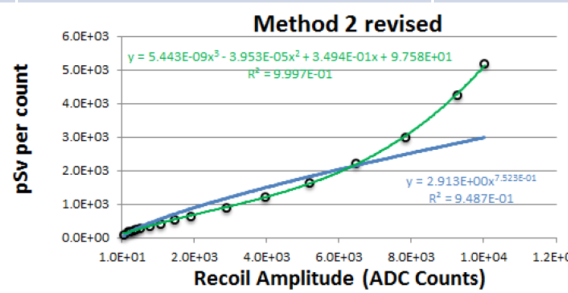
2. Analysis Variants to Extract Dose Equivalent and Neutron Energy Spectrum

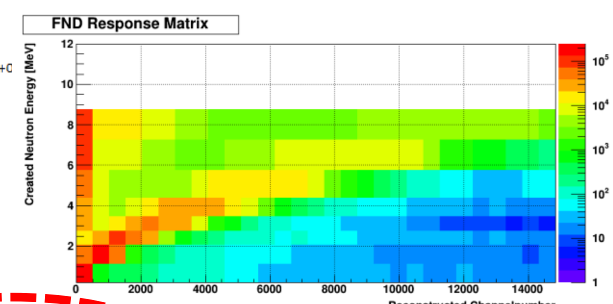
- Different analysis methods depending on computational resource availability
- Dose equivalent (H*(10)) calculated with ICRP 74 conversion factors

Analysis	Computational Complexity	Output	Analysis Methods
a) On-board (CZ)	Simple	Dose equivalent	- Conversion factors for each recoil amplitude bin; for fast on-board processing
b) Ground Light (CZ)	Moderate	Dose equivalent	- Background subtraction - Conversion factors for each recoil amplitude bin
c) Ground Heavy (ML)	Complex	Flux and dose equivalent energy spectra	- Background subtraction - Regularized unfolding into energy spectrum

a) and b)







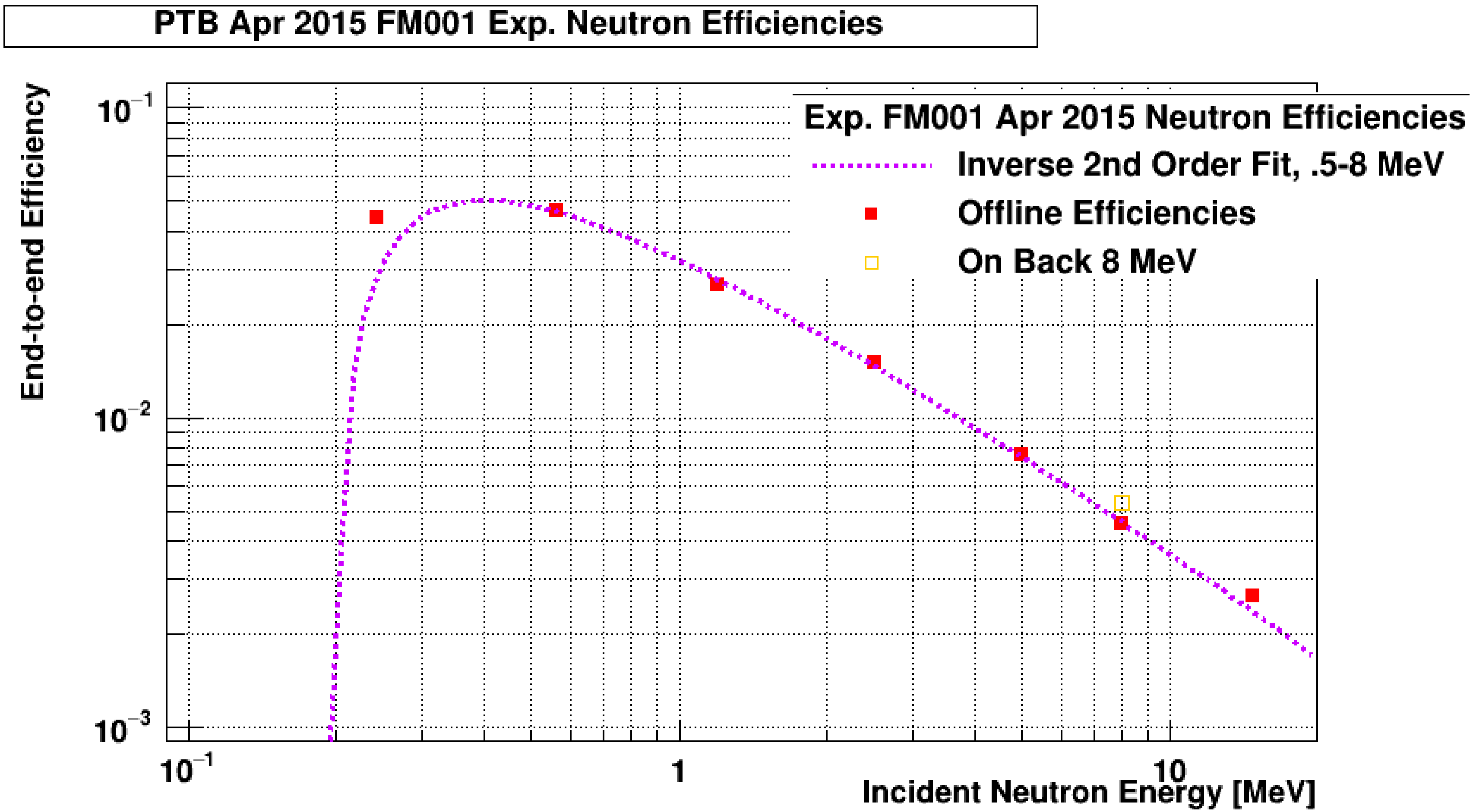
c) $$\hat{A}\, x^{\text{ini}} = b^{\text{ini}},$$

Rescaling and regularization:

$$(\tilde{A}\, w - \tilde{b})^T (\tilde{A}\, w - \tilde{b}) + \tau \cdot (C\, w)^T C\, w = \min$$

Insert: Neutron Efficiencies

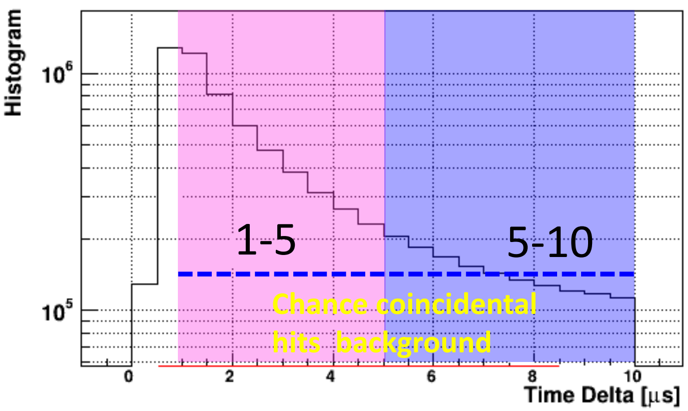
- Use exp efficiencies directly from Apr PTB 2015 data from 0.5 to 8 MeV
- For interpolated energies, use inverse square law fit of 0.5-8 MeV data (Cary Z.)
- Values depending on cuts in background subtraction and recoil/capture spectrum



Insert: Background/Chance Coincidence Subtraction

- Poisson time correlation between recoil and capture pulses for B10 capture event allow to subtract backgrounds (exponential process)
- Oversubtraction ensures all backgrounds subtracted; rejected neutron pairs recovered via efficiency correction
- Performed in both offline analyses

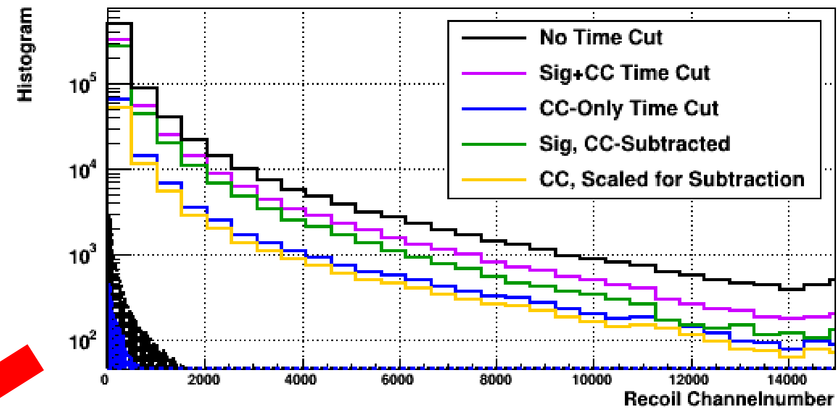
Delta T Capture



Signal + cc

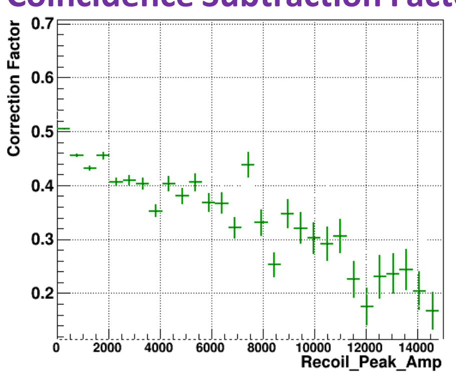
cc

Recoil Channelnumber

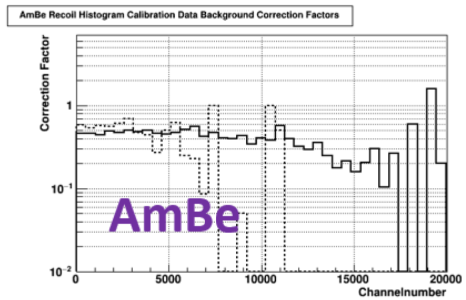


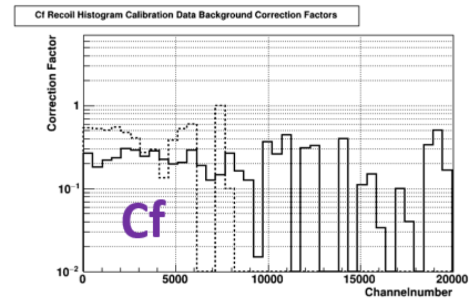
Signal / Total

Chance Coincidence Subtraction Factors

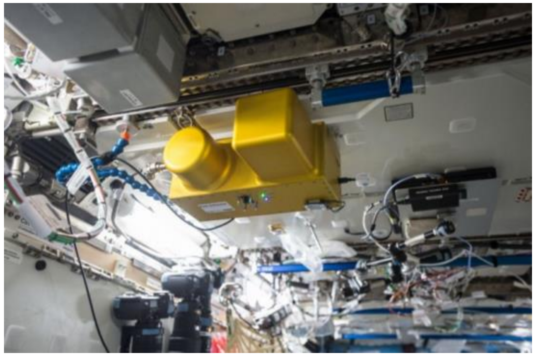


Background fractions for ground test sources:
* AmBe 40-50%
* Cf 80% (50-60% indirect radiation-only)

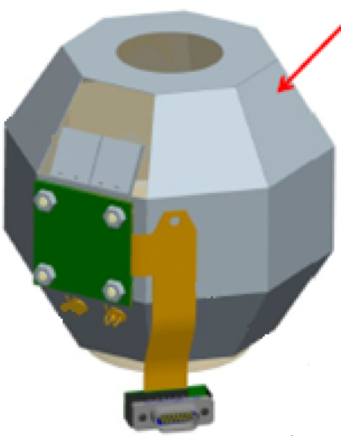




For chance coincidence subtraction of cyclic recoil histograms



3. Ground Verification of Analysis Methods



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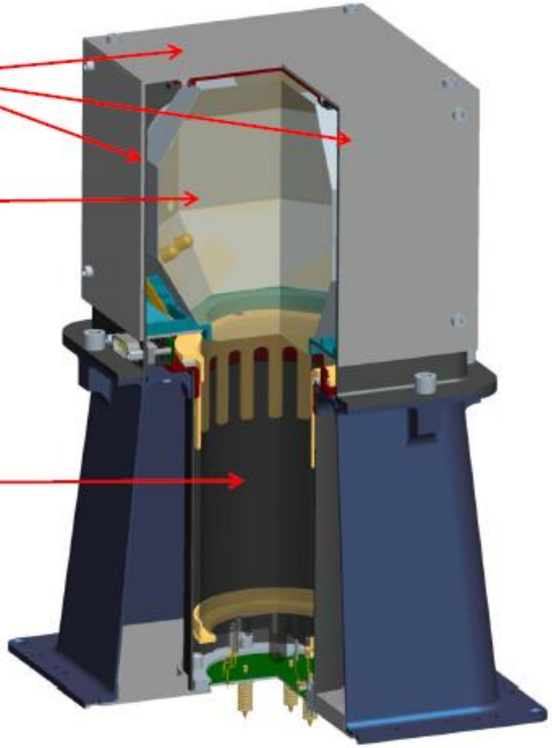
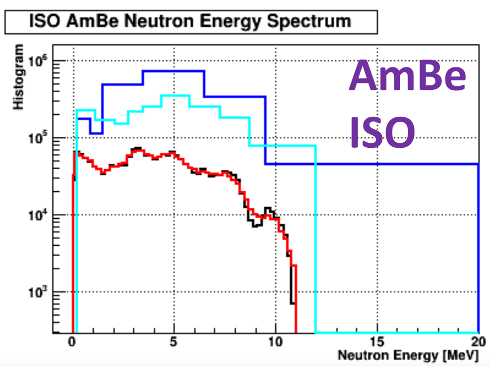
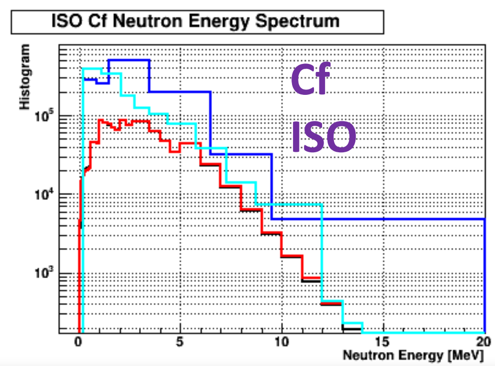


3. Ground Verification- PTB Source Runs

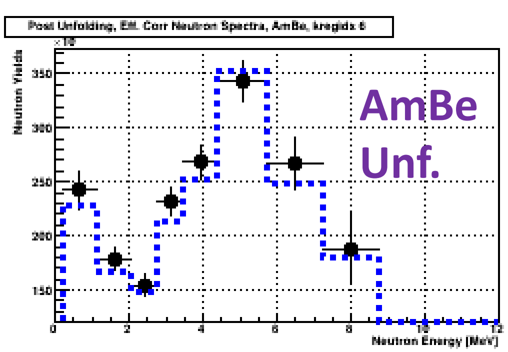
- **AmBe and Cf-254** source runs in **PTB** precision source bunker; corrections for effective depth and FND energy acceptance
- **Dose verifications:**
  * Extract reference dose from PTB normalization for 0.5 to 8 MeV energy range
  * True rate: **0.708** muSv/min AmBe, **0.495** muSv/min Cf (sensitivity to chance coincidences)
  * Online: **0.673** muSv/min AmBe, **1.091** muSv/min Cf
  * Offline light: **0.696** muSv/min Ambe, **0.537** muSv/min Cf
- **Spectral verification** (Offline heavy)
  * Subtraction of PTB room return data to compare to ISO spectra
  * **AmBe**: unfolding results **within 10%** of ISO AmBe in all bins

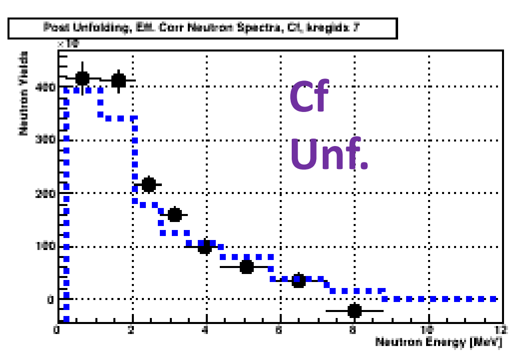


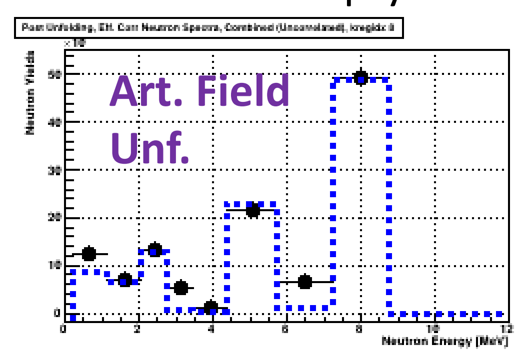


* **Cf**: **within 26%**: possibly due to rapid decrease of spectrum in energy range (factor 30), vs AmBe and Orbital < 3

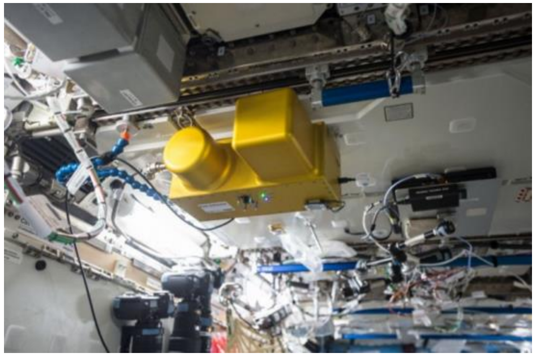
- Test unfold of artificial combination sample of 5 monoenergetic sources within 30% on non-empty bins

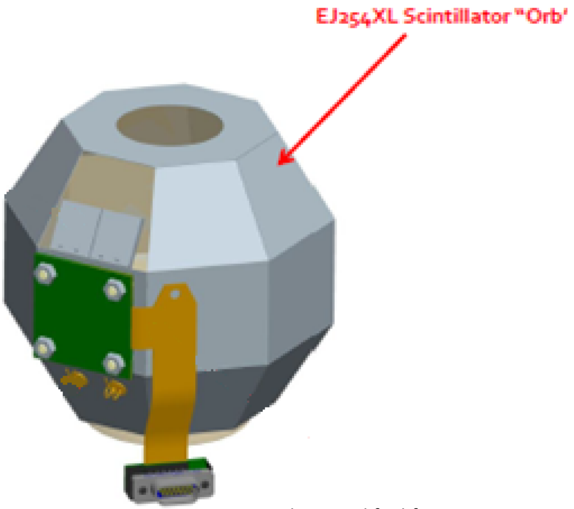






4. Orbital Raw Data





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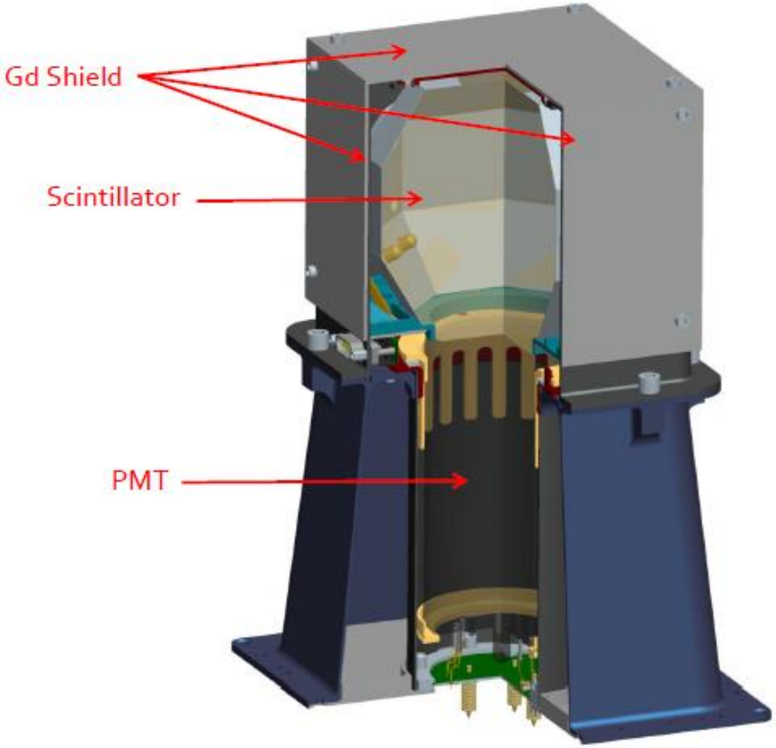
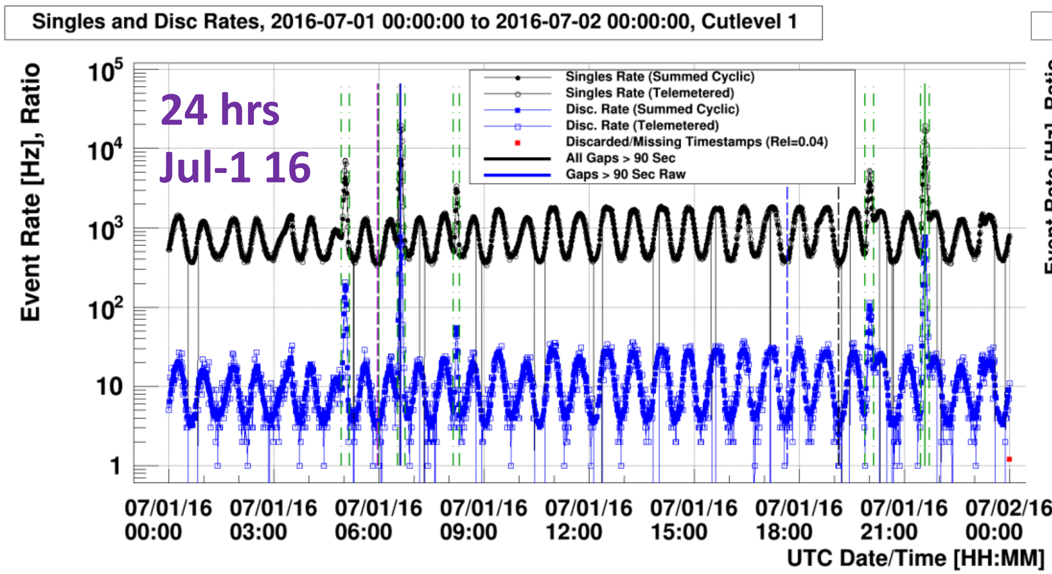
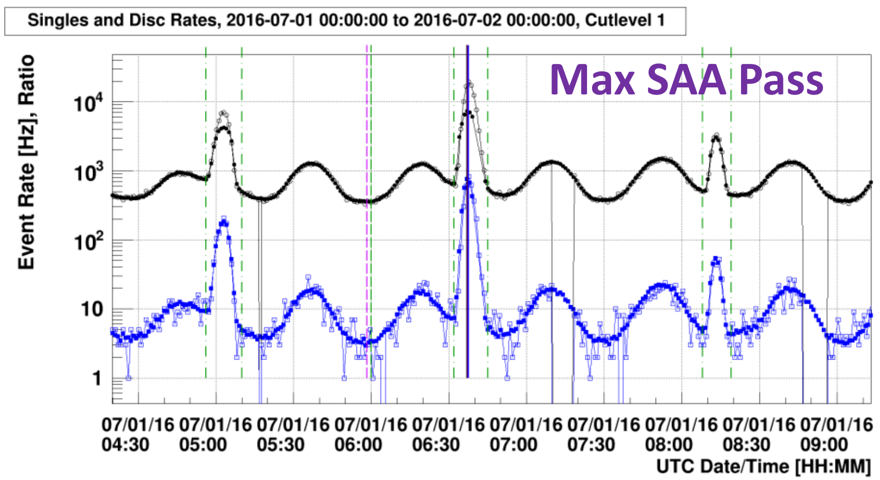
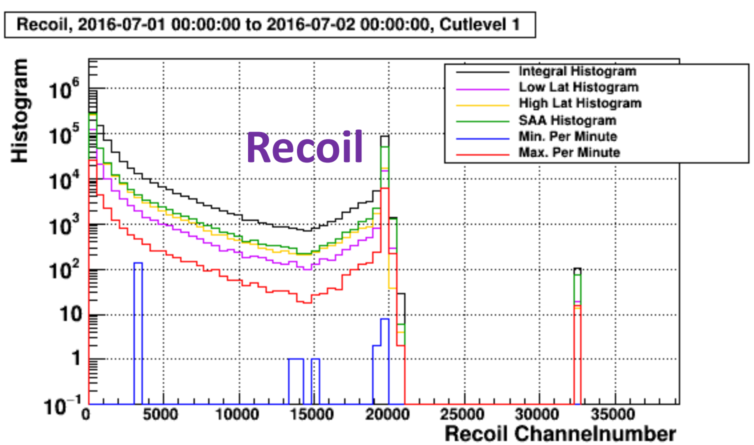


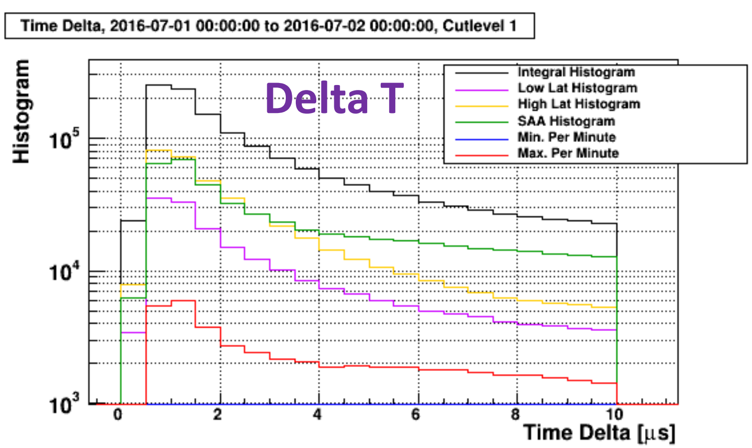
4. Exemplary Raw Orbit Data

- Shown below: 24 hour slice from 7/1/16 with largest SAA pass to date
- Shown are single/raw PMT and pulse-pair-discriminated rates
- Discriminated rate increases by factor 30-40 inside SAA compare to magnetically unshielded areas outside of SAA



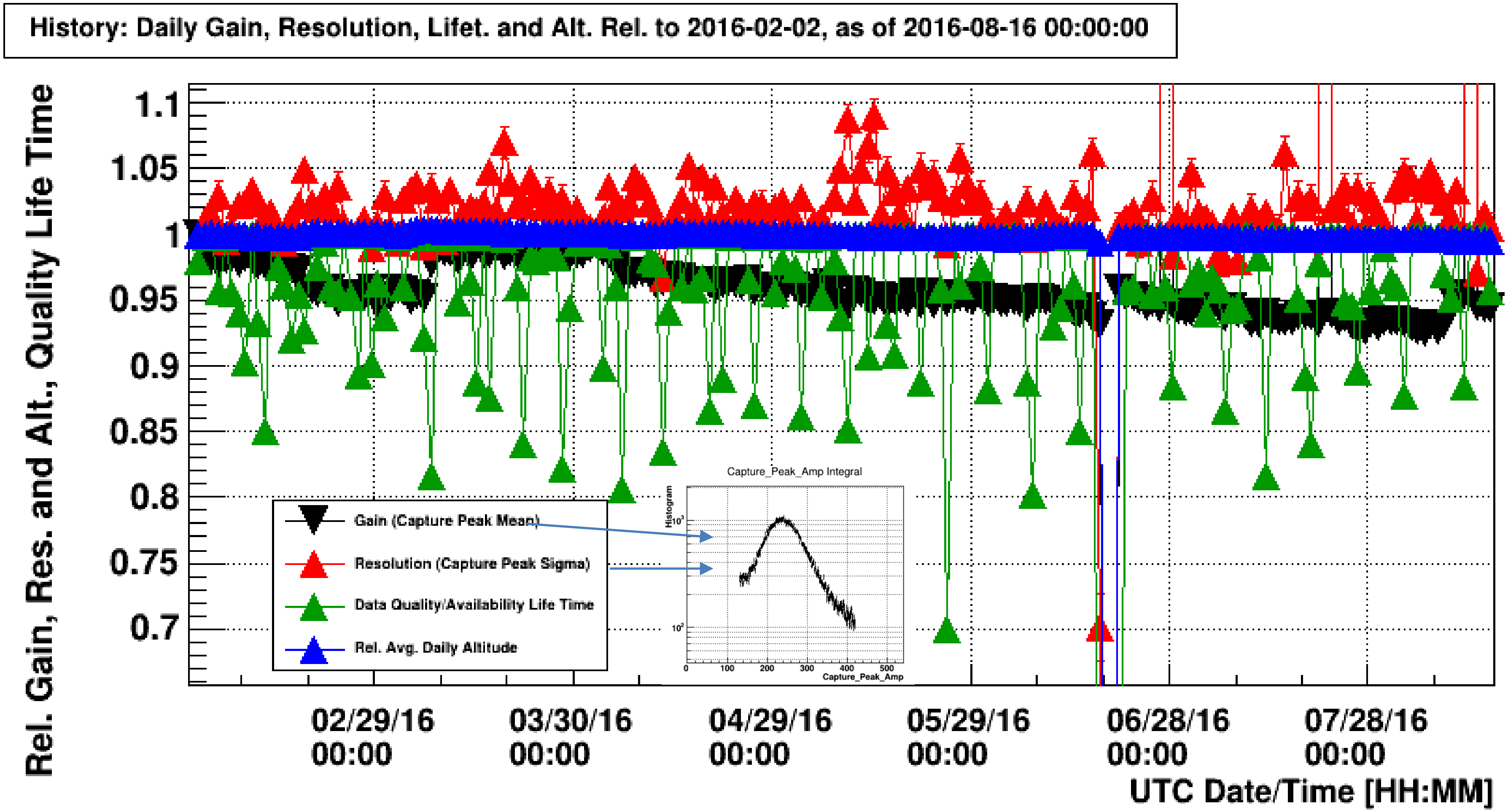




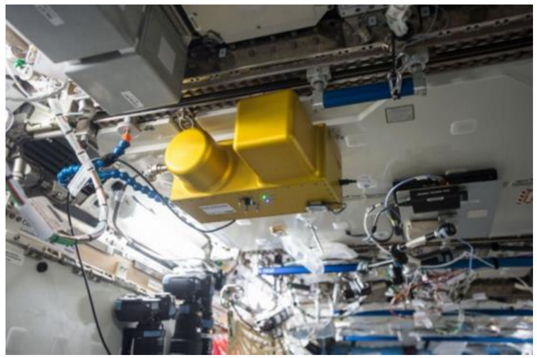


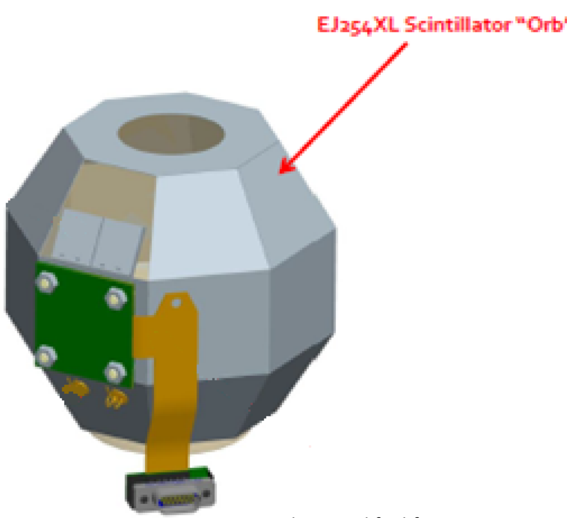
4. Exemplary Raw Orbit Data

- ISS altitude mostly constant/ within 1% since ACO start (411 km)
- Fraction of available data >5% in about 1/3 of ACO period- correction investigations to be performed
- Rework of ground analysis software in ROOT (R. Rios) largely improved data quality and handling



5. ACO Dose and Spectral Analysis, Status





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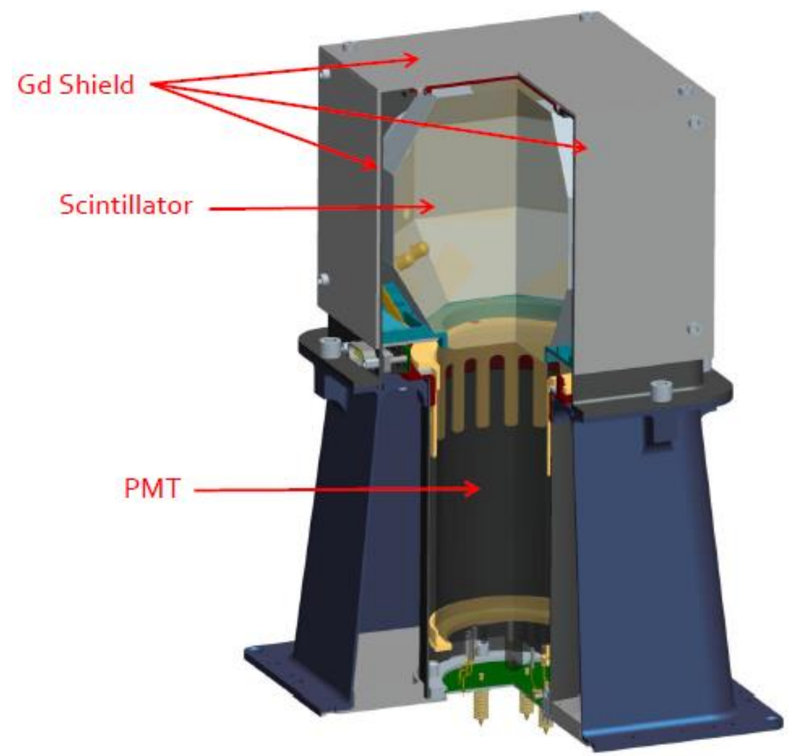
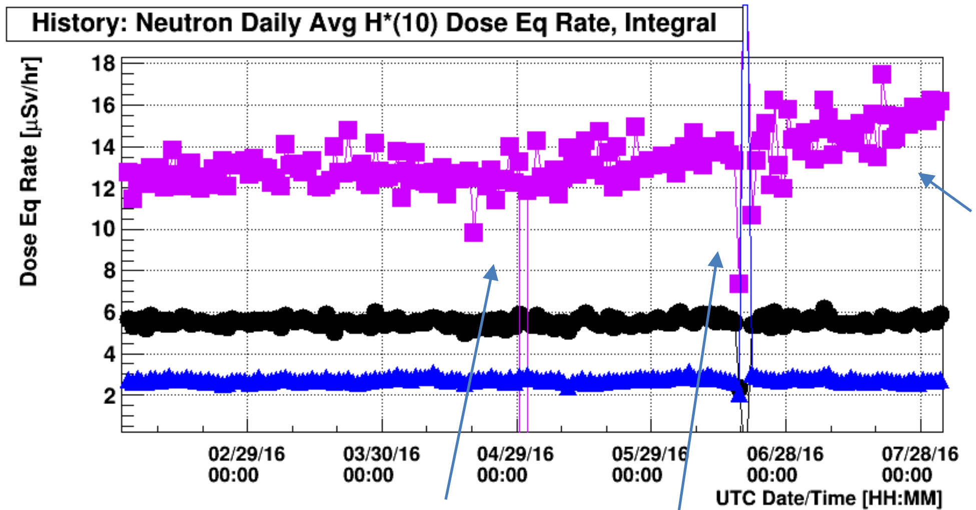
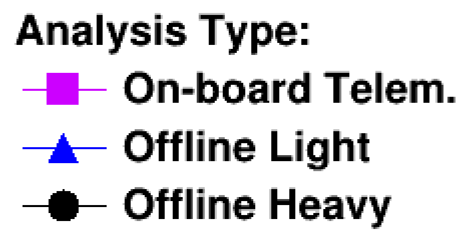


5.1 Dose Equivalent Rate Variation vs. Time

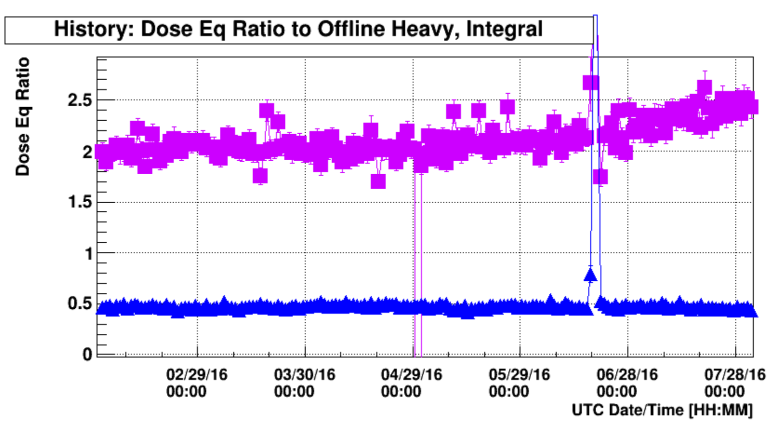
- Analysis Comparison: Online, offline light and offline heavy: H*(10) dose equivalent rates, daily averages
- Current implementations of online algorithm factor of ~2 above offline heavy, offline light ~0.5

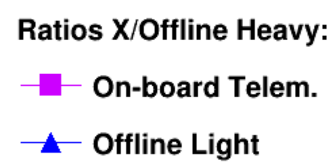


Increase likely due to charged particle environment change (online algorithm does not have background subtraction)



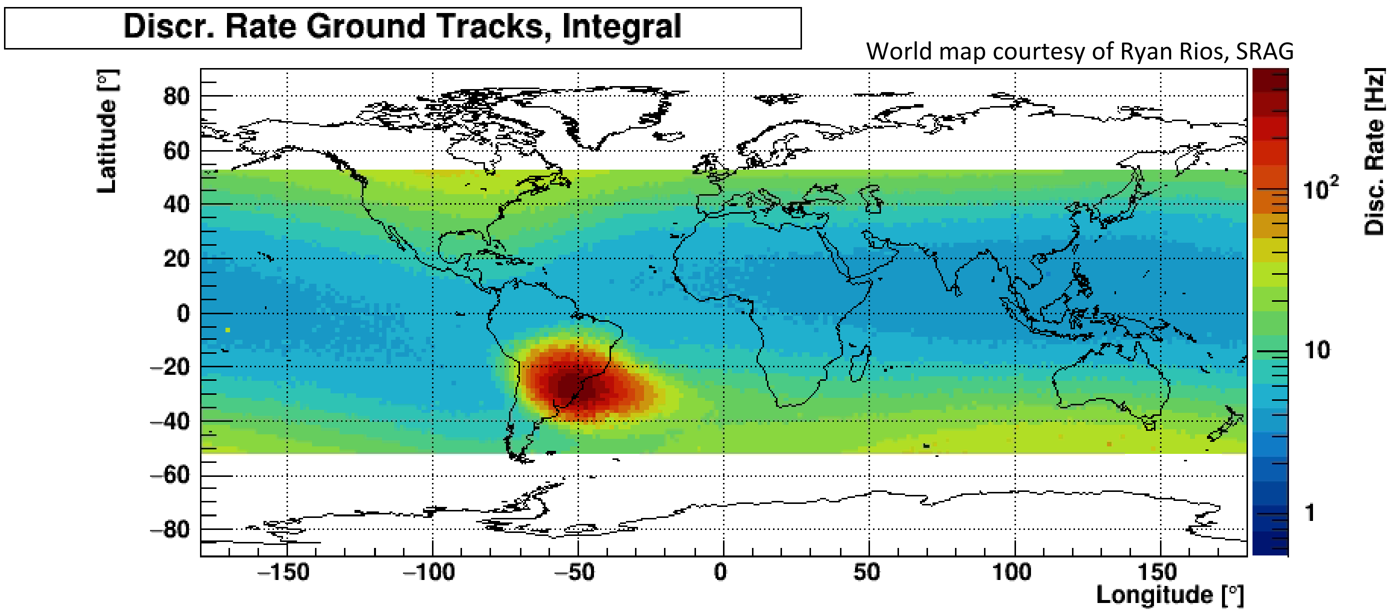
Outages (power/commanding)



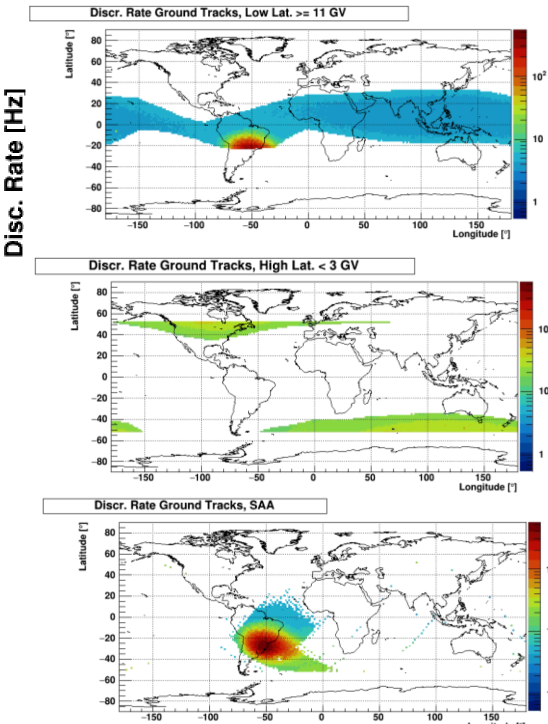


Insert: Longitude/Latitude Binning

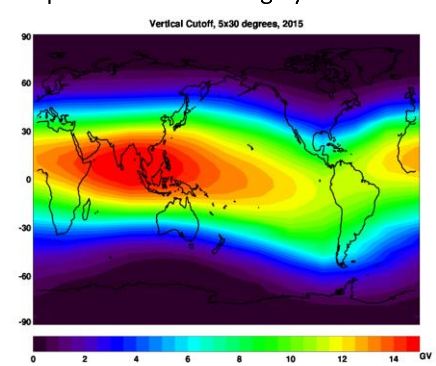
- SAA selection: use cuts: lon in [-90;10); lat < 10 && FND singles rate derivative cut
- To determine rigidity per data point, use 2015 lookup table from NASA LaRC with cuts for sufficient optimize statistics: high lat <3 GV, low lat >=11 GV
- To be cleaned up…



World map courtesy of Ryan Rios, SRAG



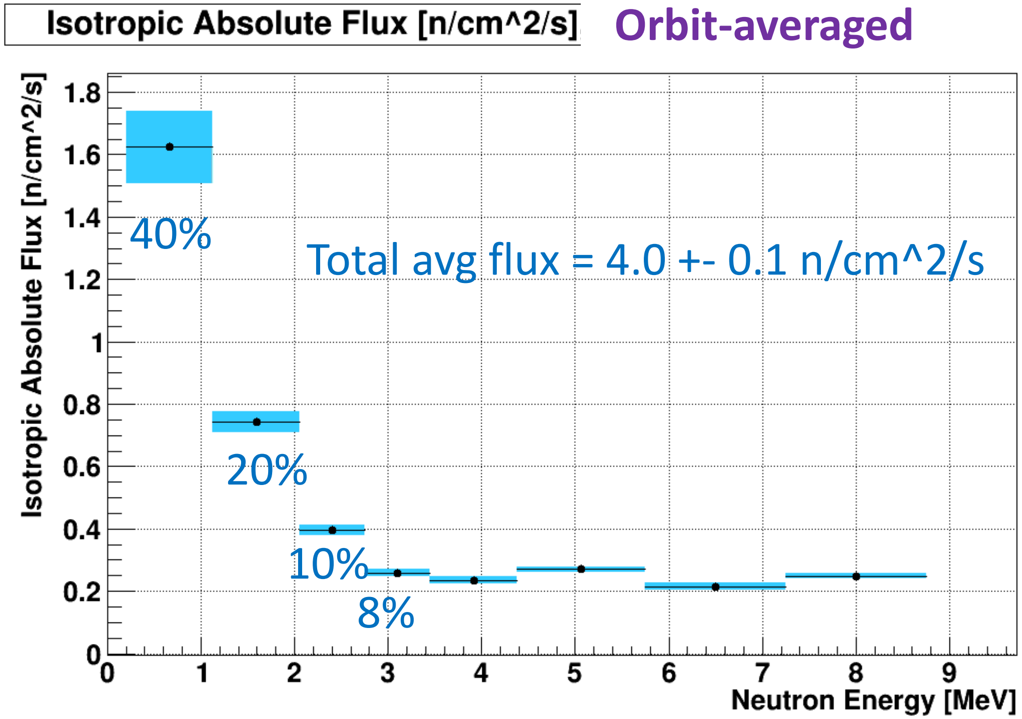
Graphic from NASA Langley Research Center

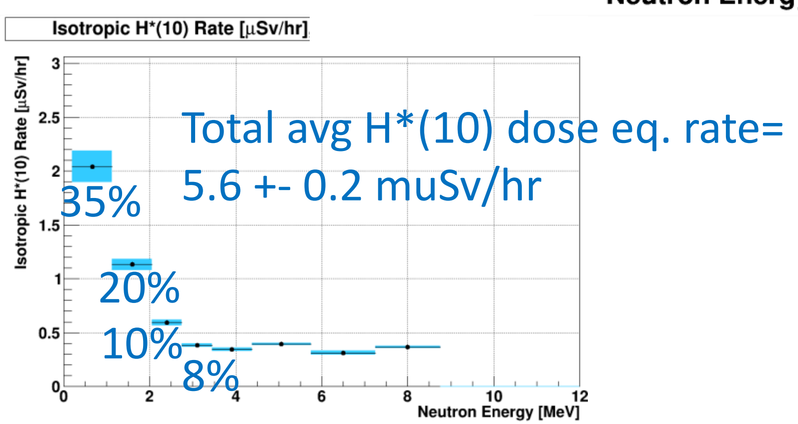


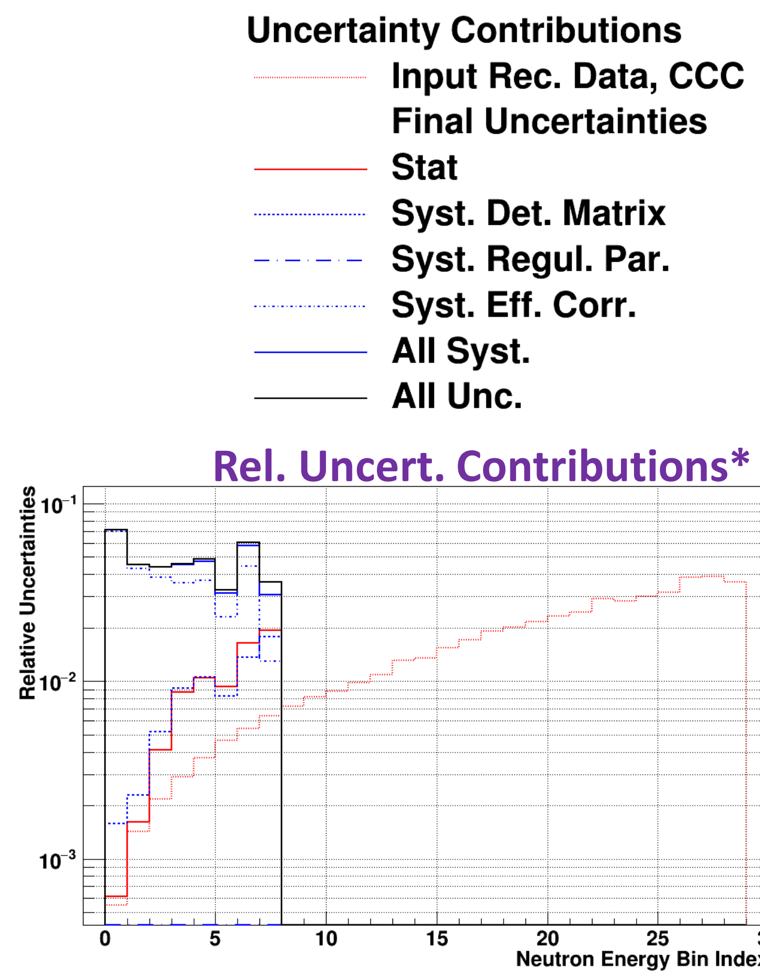
5.2 Energy Spectrum Unfolding Results

- Offline Heavy energy flux spectrum and dose equivalent results in [0.2;0.87) MeV vs time, full ACO period

Orbit-averaged



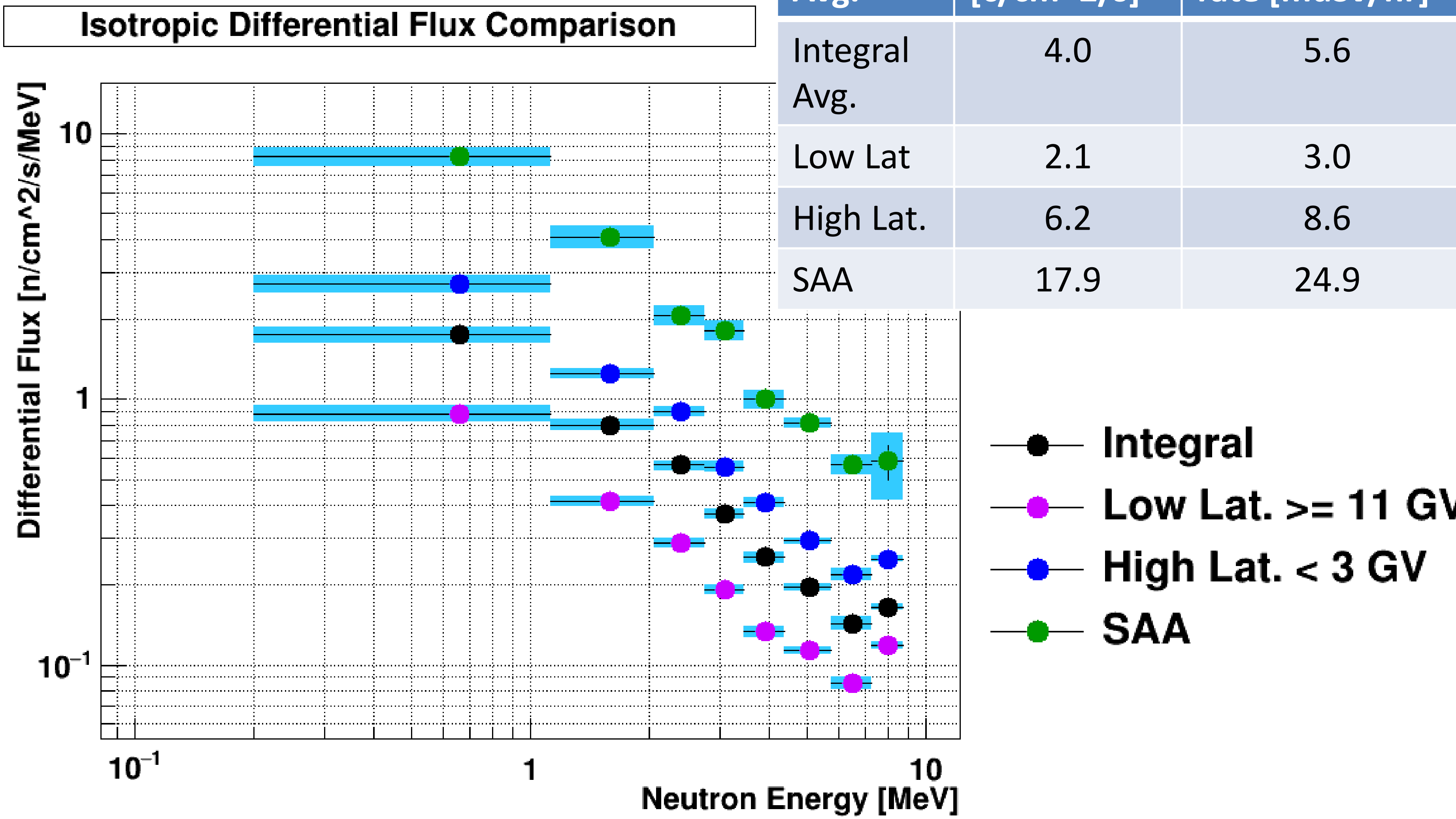




5. Dose Equivalent Results ACO Period Totals/Averages

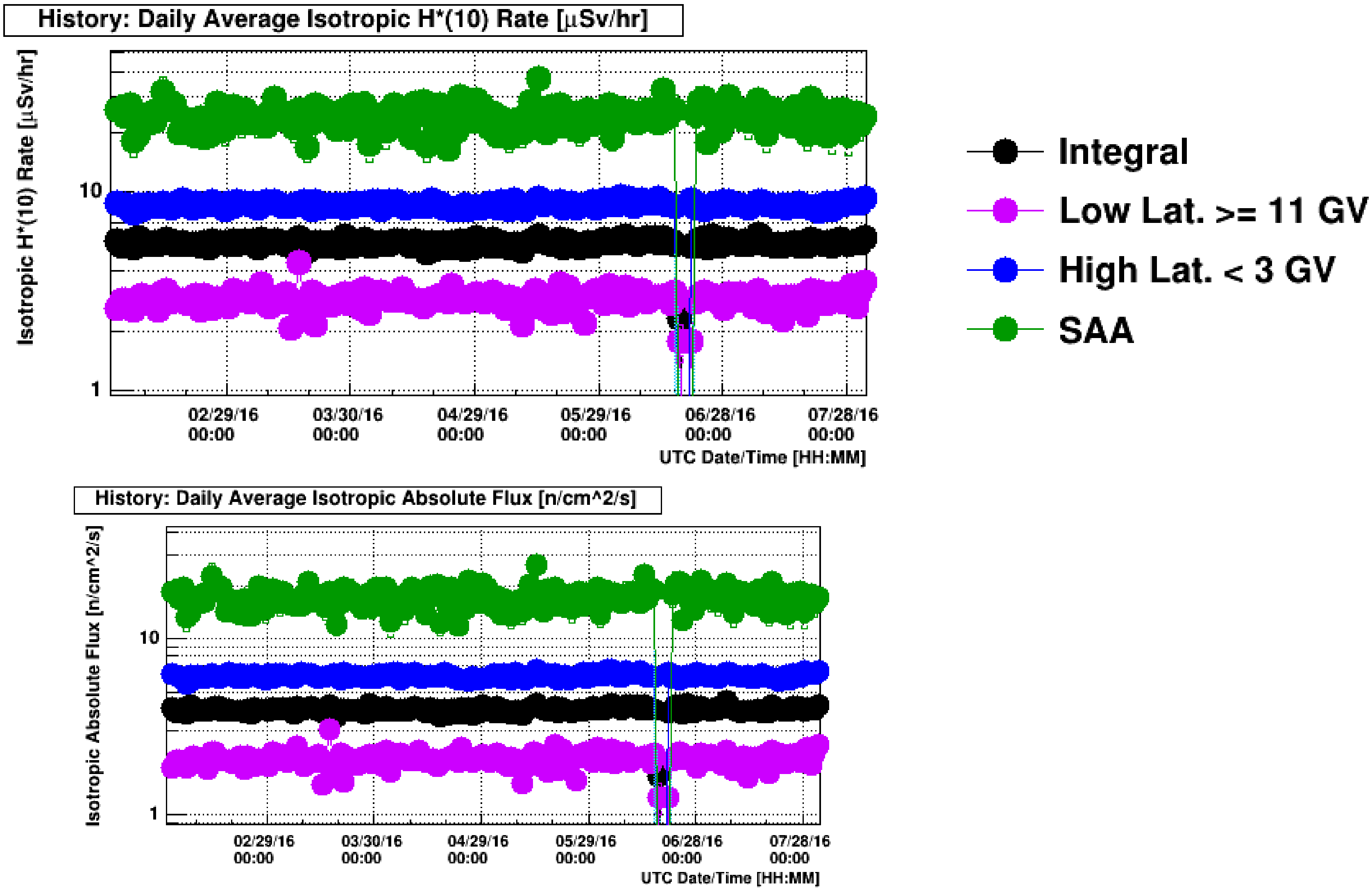
- Offline heavy: Neutron flux energy distributions in [0.2;0.87) MeV

Total Avg.	Flux [c/cm^2/s]	H*(10) dose eq. rate [muSv/hr]
Integral Avg.	4.0	5.6
Low Lat	2.1	3.0
High Lat.	6.2	8.6
SAA	17.9	24.9

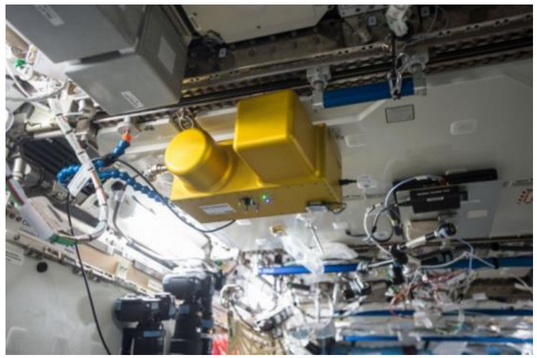


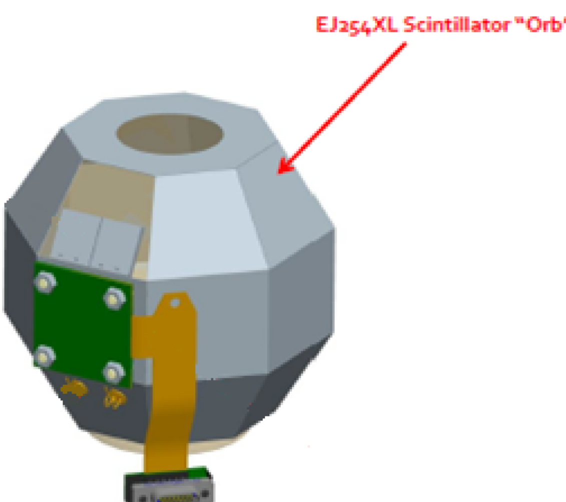
5.2 Energy Spectrum Unfolding Results, Variations vs. Time and Lat/Long Comparison

- Magnetic Shielding/SAA Comparison: Offline Heavy H*(10) dose equivalent rates and flux in [0.2;0.87) MeV, daily averages
- Flat over 6 months



5.3 Comparing ACO to Simulated Data, Status





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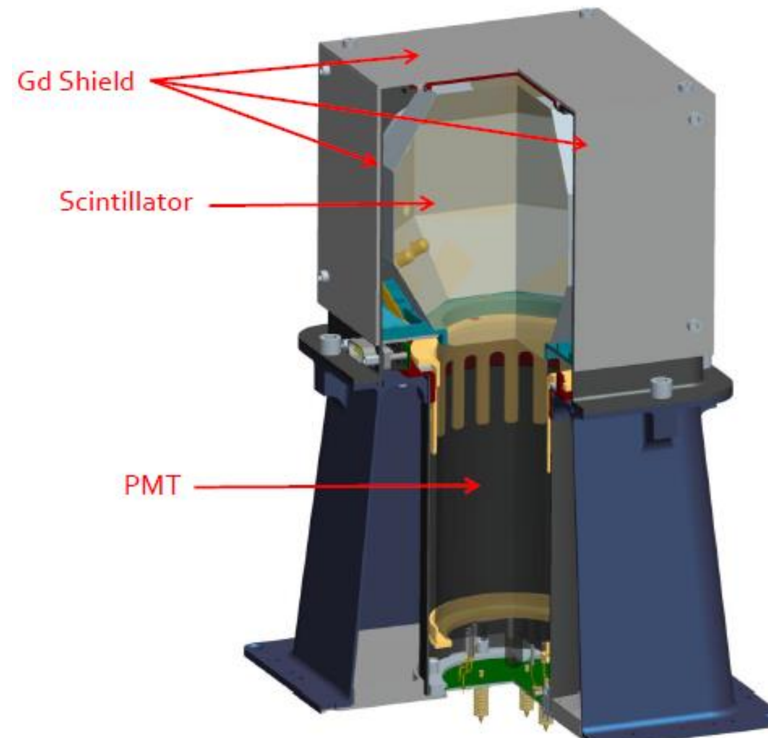
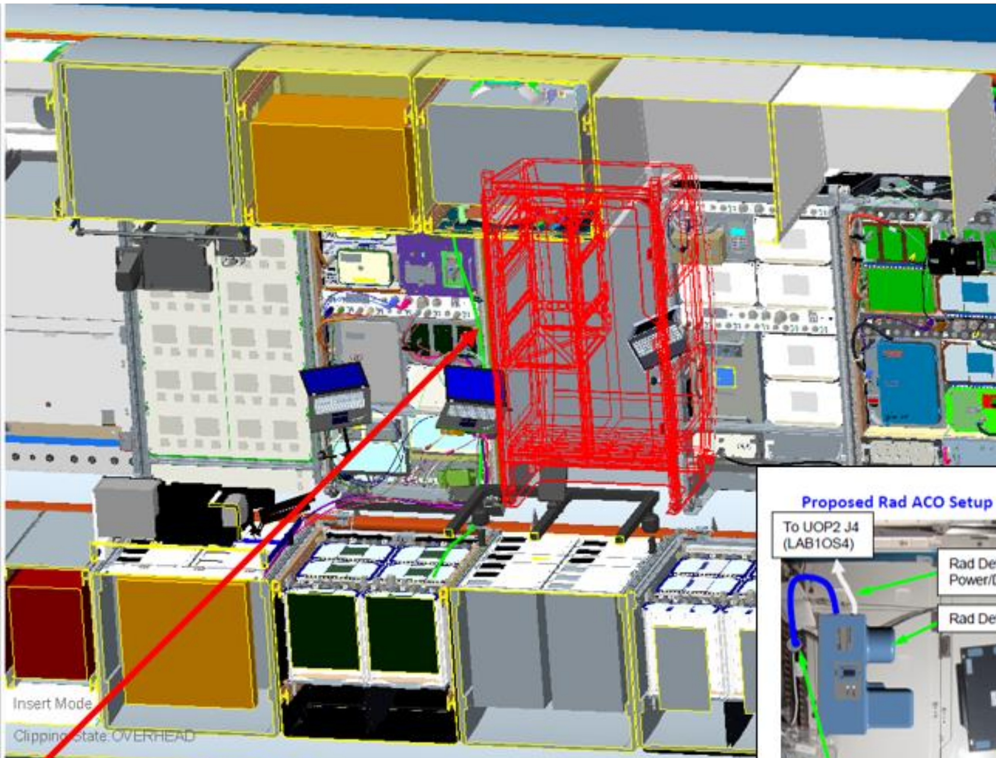
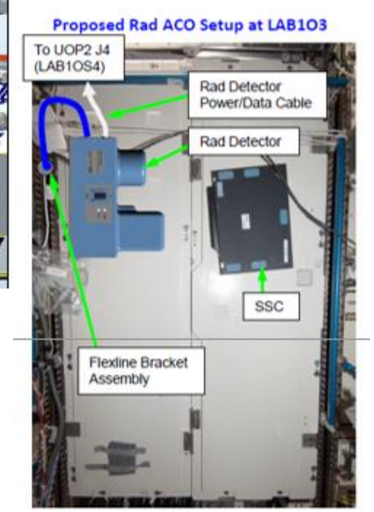


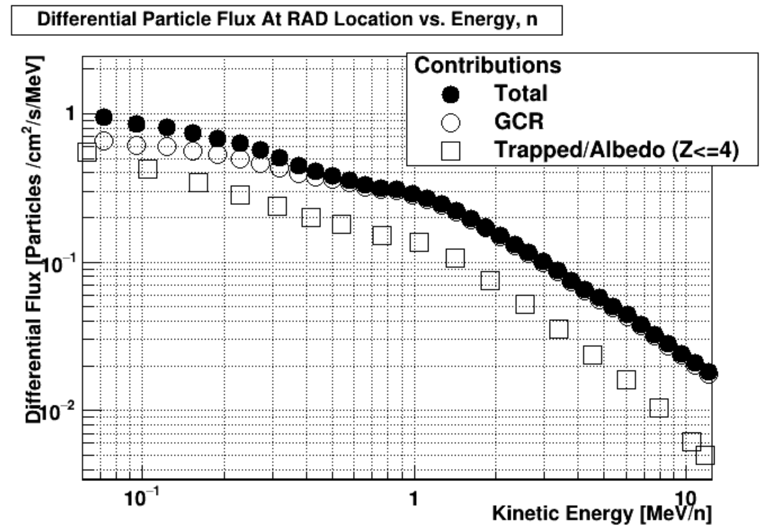
5.3 Spectral Comparison to Simulation

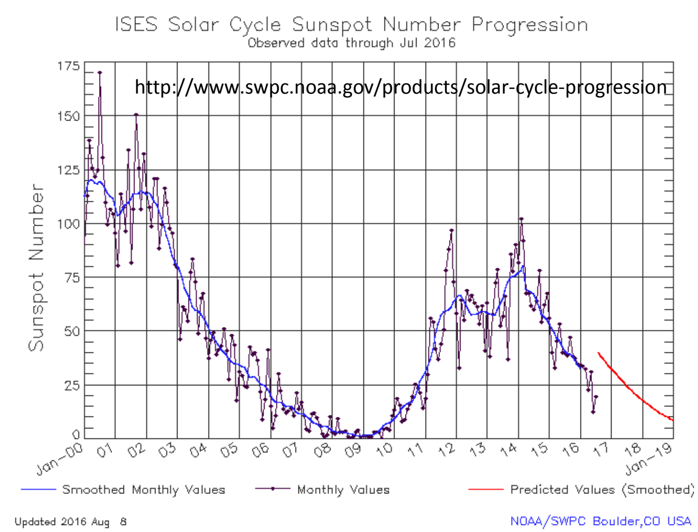
- Comparison to Oltaris (HZETRN-based) simulated data: Simple, forward-only, ray-by-ray simulation
- Ray-trace of material in US lab with latest US lab shield configuration file
- Attempt to match solar conditions: same sunspot number period matched
- Underestimation expected





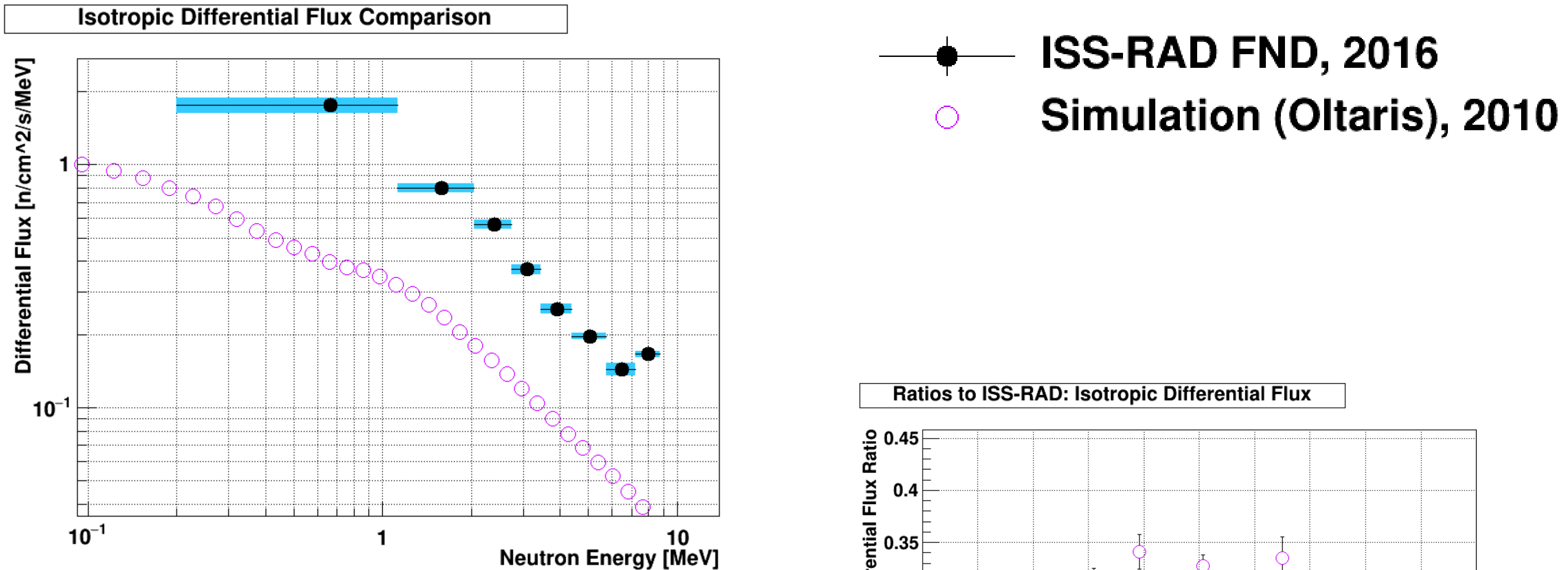
Graphics from NASA Langley Research Center

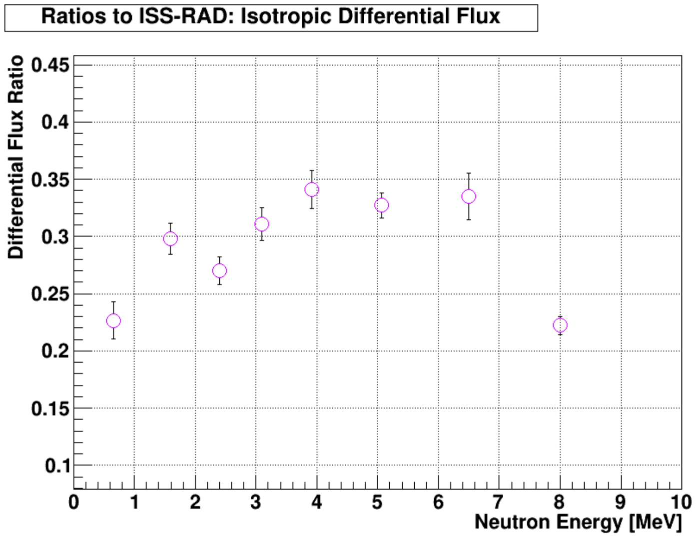




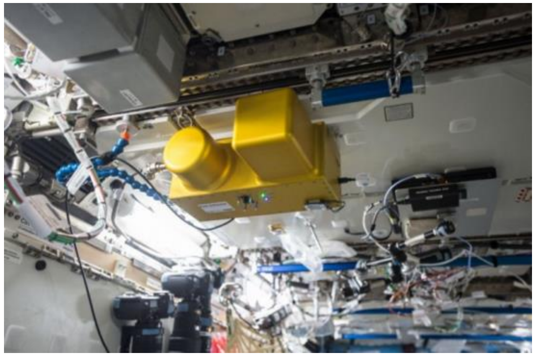
5.3 Spectral Comparison to Simulation

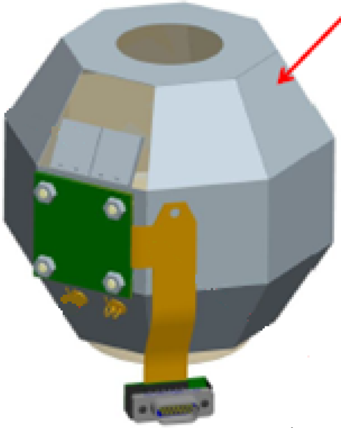
- Spectral comparison to offline heavy: Neutron fluence totals/averages
- Simulation factor 3-4 below unfolded results- simulation fidelity being increased





5.4 Comparing ACO to Other Experimental Measurements, Status





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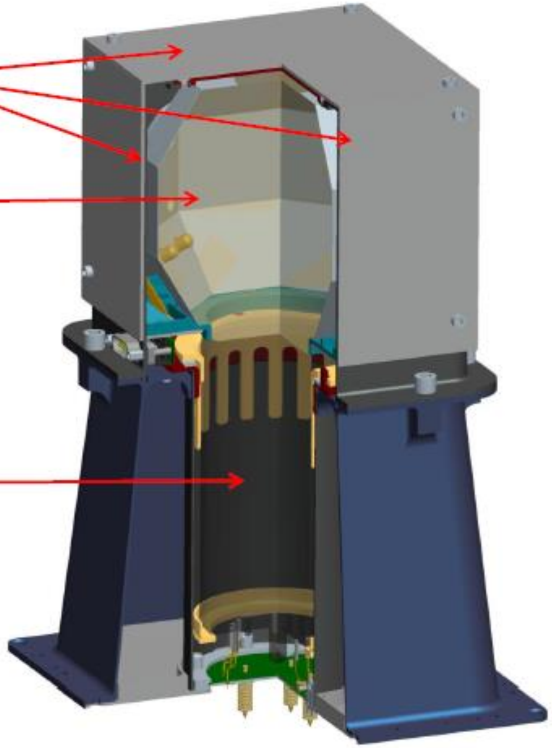
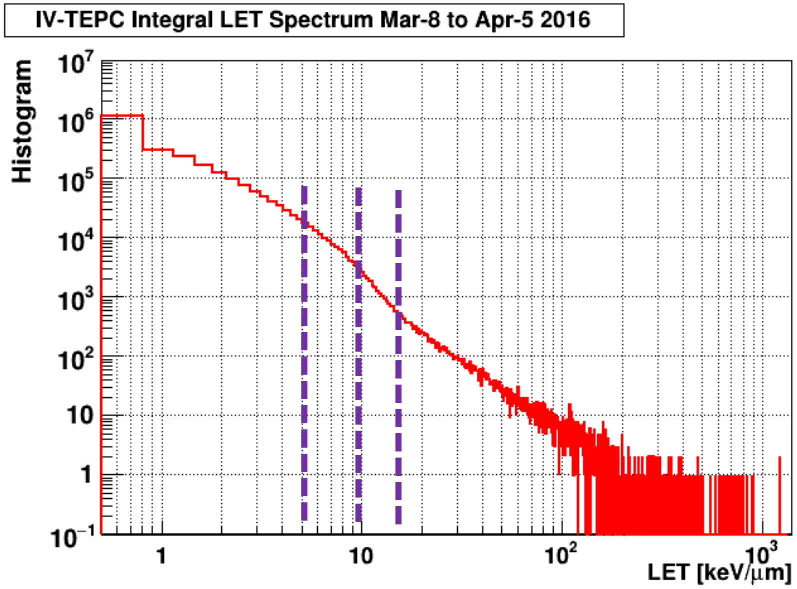


5.4.1 Comparison to Other Neutron Dose Equivalent Measurements

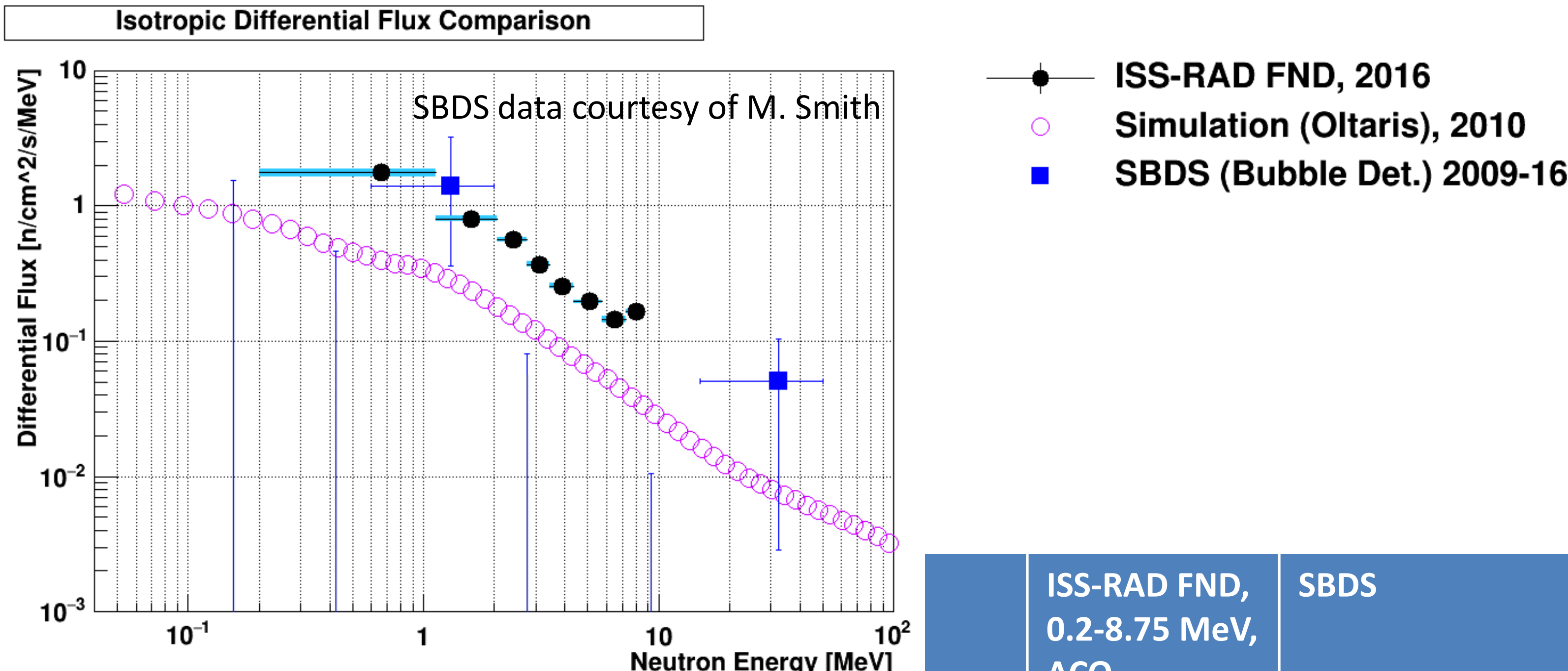
- NASA IV-TEPC:
  * Sensitive to neutrons and heavy ions
  * IV-TEPC located in US Lab from Mar 8 through Apr 5 2016
  * NASA TP-2013-217375 finds Mars surface effective dose from GCR heavy ions **factor 5 larger** than neutron contribution
  * Dose eq calculated for LET > 5, 10, 15 keV/mum (He peak at ~0.8 keV/mum) with ICRP 60 quality factors

	ISS-RAD FND, 0.2-8.75 MeV, ACO	IV-TEPC (LET > X keV/mum)
Dose Equivalent Rate [muSv/day, muSv/hr]	134 +- 4.8*, 5.6 +- 0.2*	506.4, 21.1 (5)
		465.6, 19.4 (10)
		448.8, 18.7 (15)



5.4.2 Comparisons to Prior Spectral Measurements

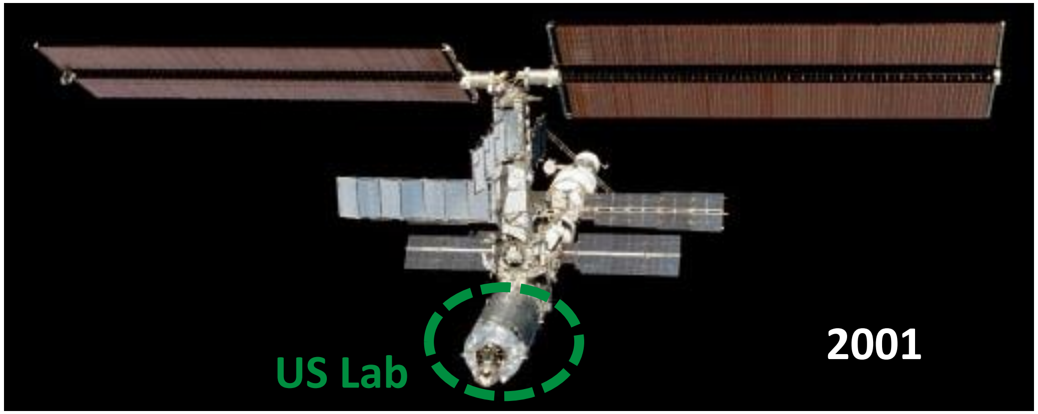
- Bubble detectors, M. Smith et al (US lab data)
- Summed Space Bubble Detector Spectrometer data from ISS-20/21 (Oct 2009) to ISS-45/46 (Jan 2016)
- Dose equivalent difference consistent with different energy acceptance range
- 27% higher than FND data for bin [0.6;2) MeV; uncertainties of other overlapping bins low

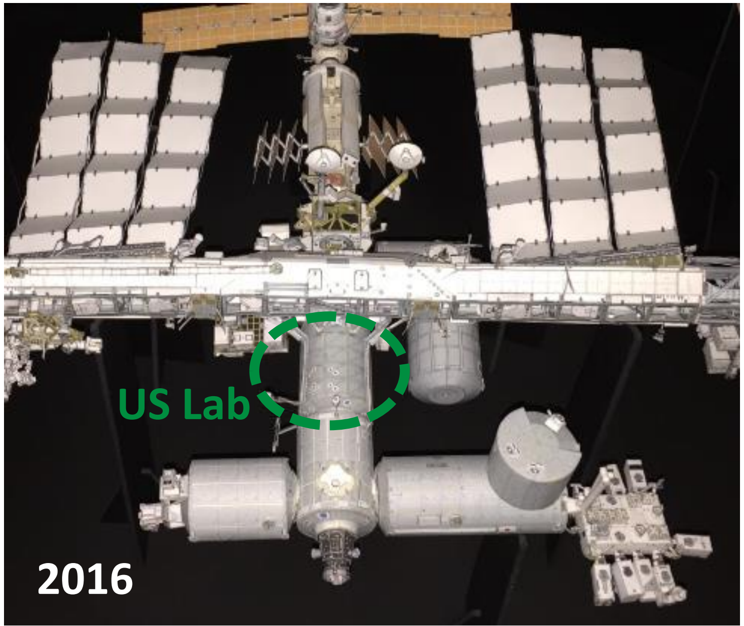


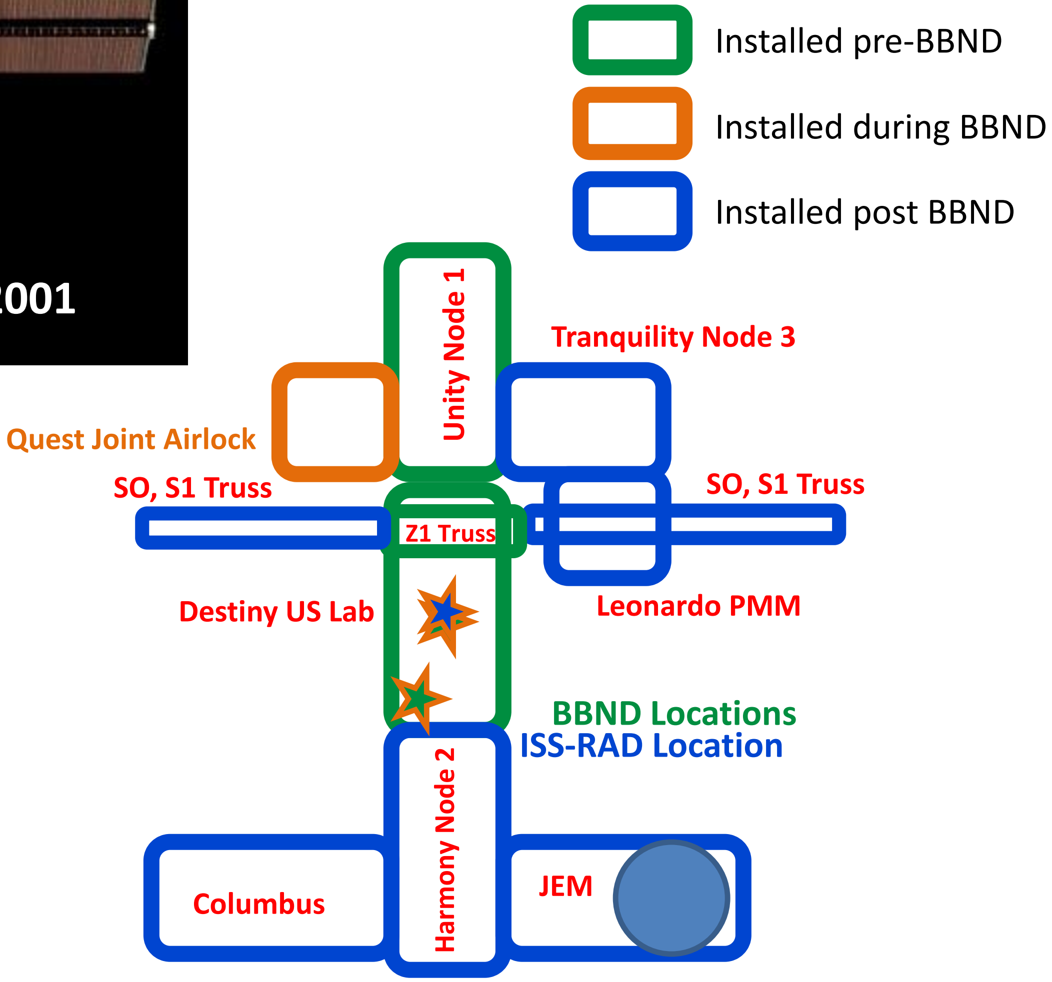
	ISS-RAD FND, 0.2-8.75 MeV, ACO	SBDS
Dose Equivalent Rate [muSv/day, muSv/hr]	134 +- 4.8*, 5.6 +- 0.2*	2016: 152 + 60 – 43, 6.3 + 2.5 - 1.8
		2009-2016 avg.: 149 + 40 - 22, 6.2 + 1.7 - 0.9

5.4.2 Comparisons to Prior Spectral Measurements

- Bonner Ball Neutron Detector (BND): Koshiishi et al (2007), data taken in 2001 in US Lab
- Mass of ISS changed by factor 4+ between 2001 and 2016 (90 to 420 tons)
- Significant increase of mass in vicinity of US Lab (20% effect on neutron flux estimated in Ruymin et al, Rad Meas 43 47ff, 2007)

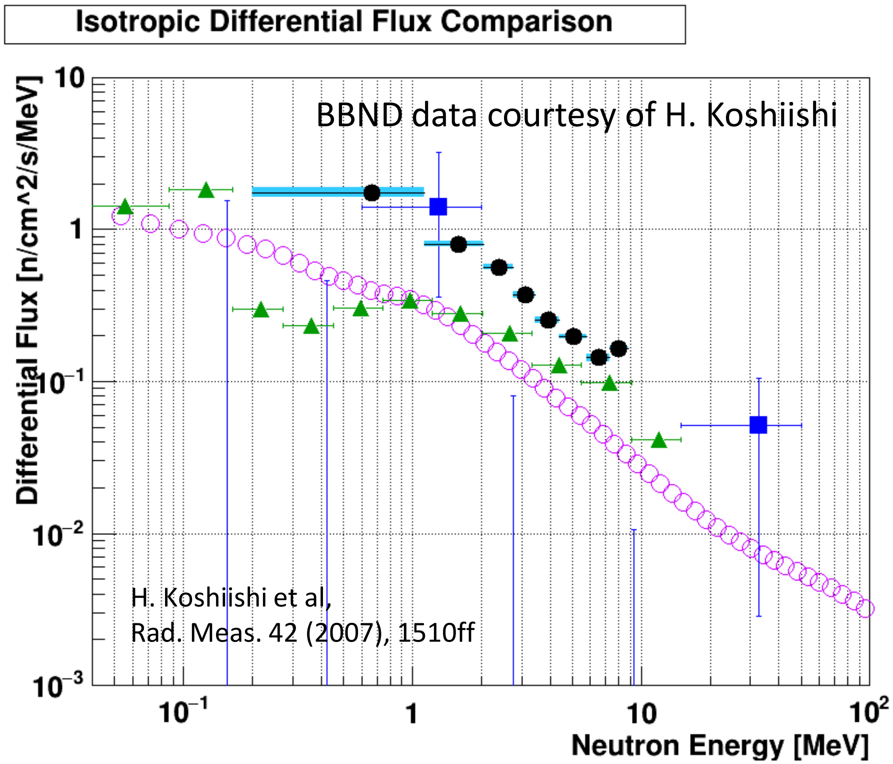


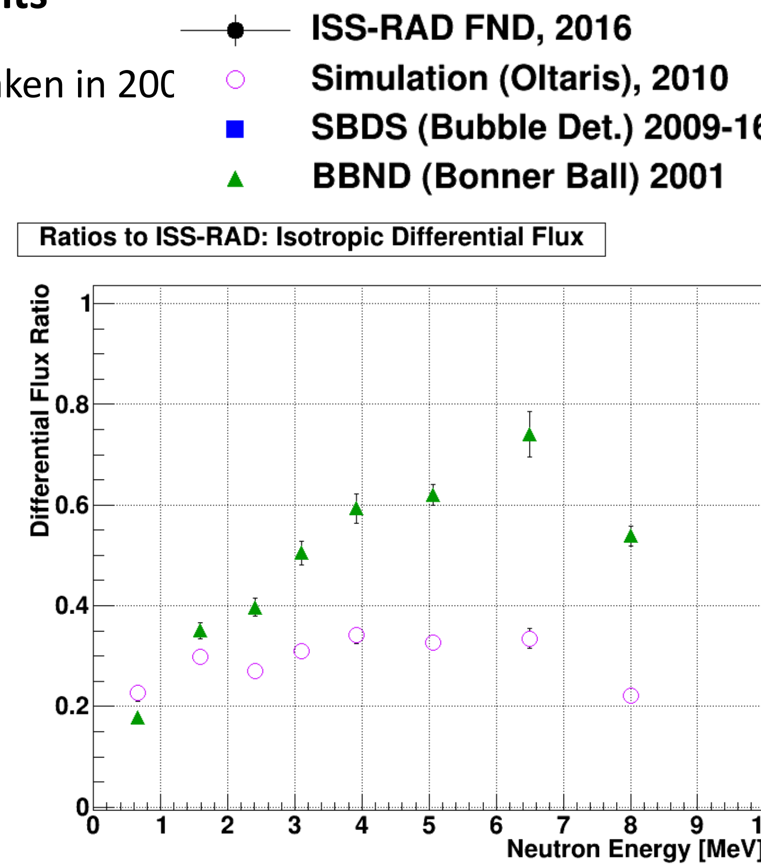




5.4.2 Comparisons to Prior Spectral Measurements

- Bonner ball spheres: H. Koshiishi et al (2007), data taken in 200

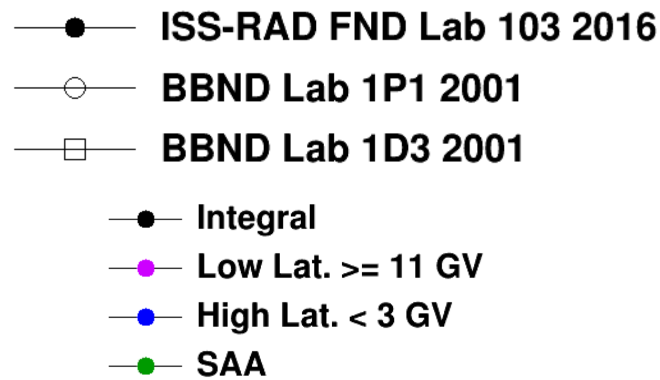


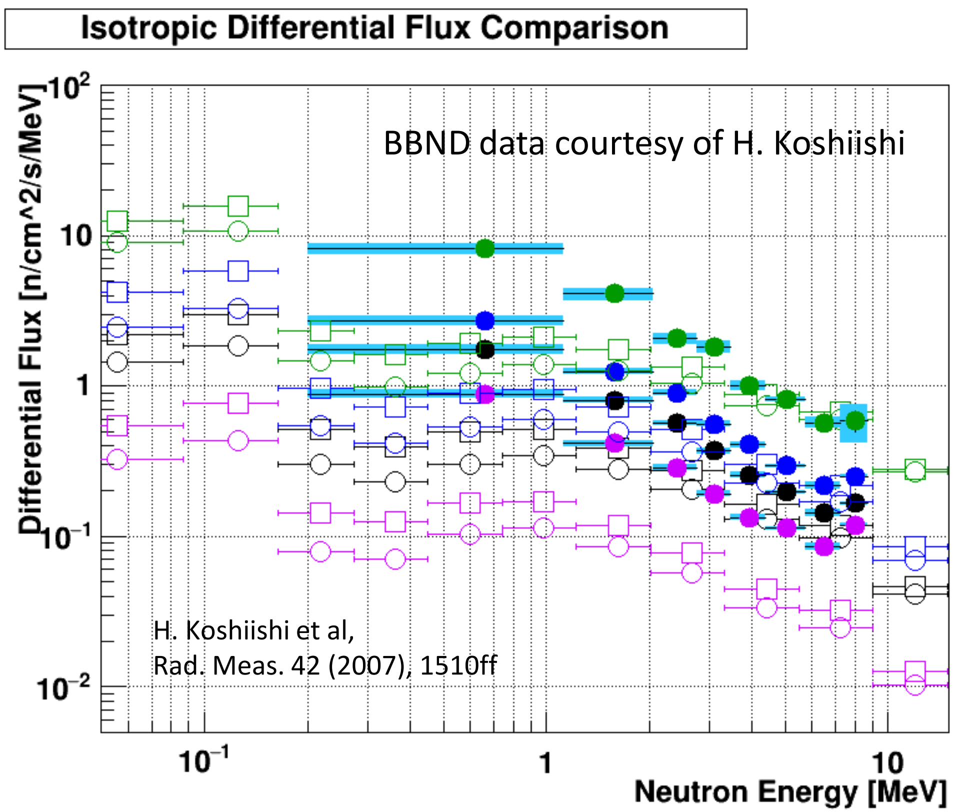


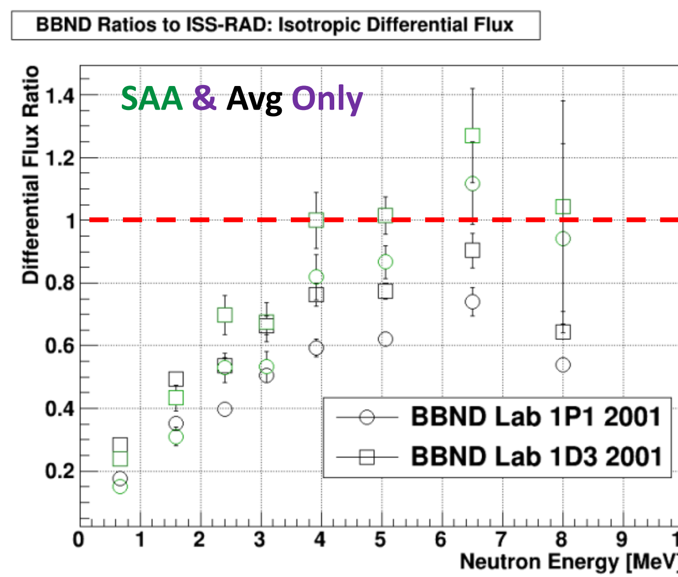
Instrument	ISS-RAD FND, 0.2-8.75 MeV, ACO	SBDS	IV-TEPC (LET > X keV/mum)	Bonner Ball 2001
Dose Equivalent Rate [muSv/day, muSv/hr]	134 +- 4.8*, 5.6 +- 0.2*	2016: 152 + 60 – 43, 6.3 + 2.5 - 1.8	506.4, 21.1 (5)	69.6, 2.9 (LAB1P1)
			465.6, 19.4 (10)	
		2009-2016 avg.: 149 + 40 - 22, 6.2 + 1.7 - 0.9	448.8, 18.7 (15)	88.8, 3.7 (LAB1D3)

5.4.2 Comparisons to Prior Spectral Measurements

- Bonner ball collected time/lat-long resolved data
- High energy SAA close at high energy, orbit-averaged larger discrepancy
- Material difference could account for 20% total flux difference
- BBND relocation: Up to 50% different flux -> significance of local mass environment/distribution
- Further study: Energy-dependent discrepancies potentially due to interplay of different production & scatter cross sections







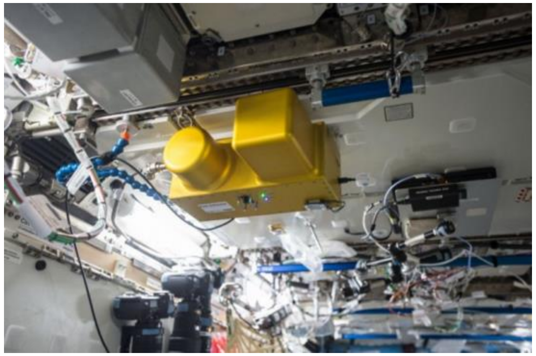
5.5 Comparisons to ISS-RAD CPD Charged Particle Dose Equivalent

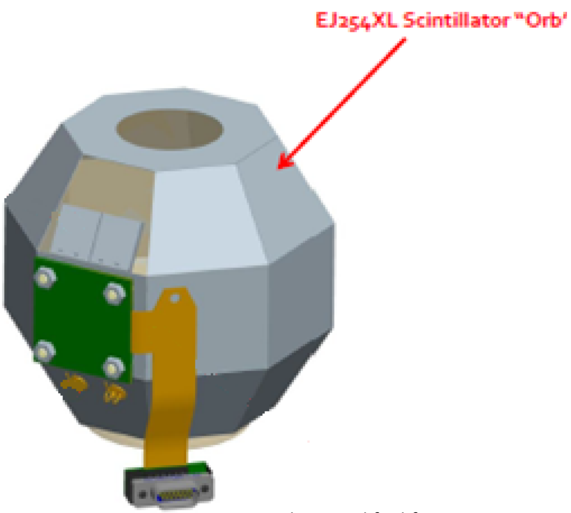
- CPD charged particle dose equivalent with estimated/expected Q factor ~500 muSv/day (see C. Zeitlin's ISS-RAD talk)

- FND energy acceptance possibly accounts for ~50% of total neutron dose equivalent contribution (see L. Heilbronn et al, LSSR 7 90 ff (2015))

-> total neutron dose equivalent ~250 muSv/day, would correspond to 30% of total dose equivalent (Mars surface ~10%)

6. Forward Work





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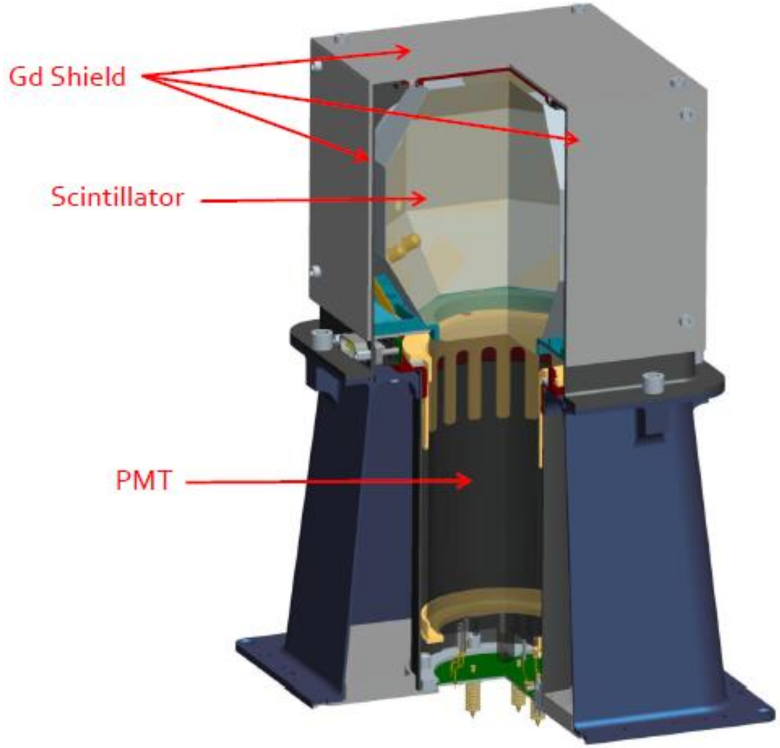
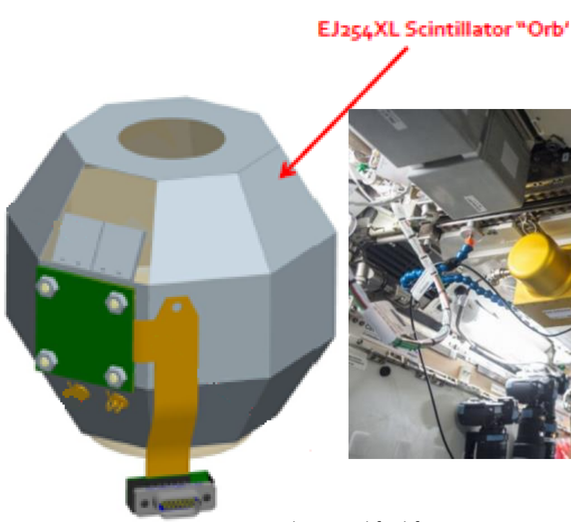


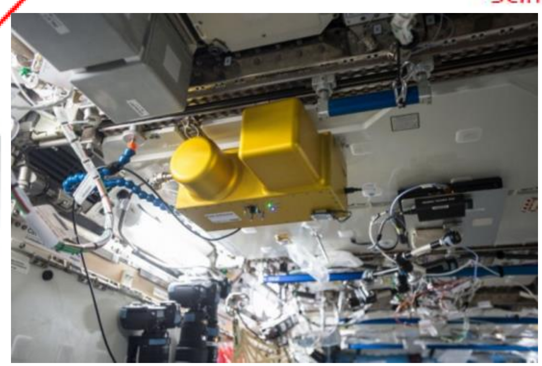
6. Forward Work/Systematic Studies

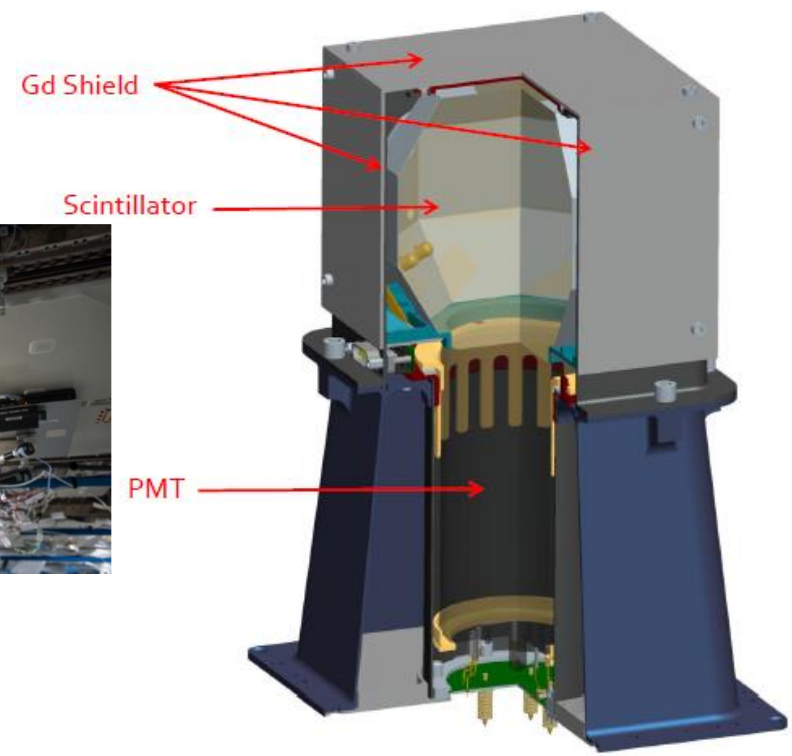
- Accounting for data unavailability (scaling, 2D-interpolation, uncertainty (SAA))
- Estimate sample impurities (protons) from exp data (TRIUMF) and simulation (GEANT)
- Calculate 3D efficiency from ISS-RAD EM experimental data (PTB 2015)
- Calculate full systematic uncertainties from unfolding (boundary effects etc)
- Potential improvement on low energy resolution through software update (pending)

- Call for additional neutron experimental data for ISS!

-> Publish data.







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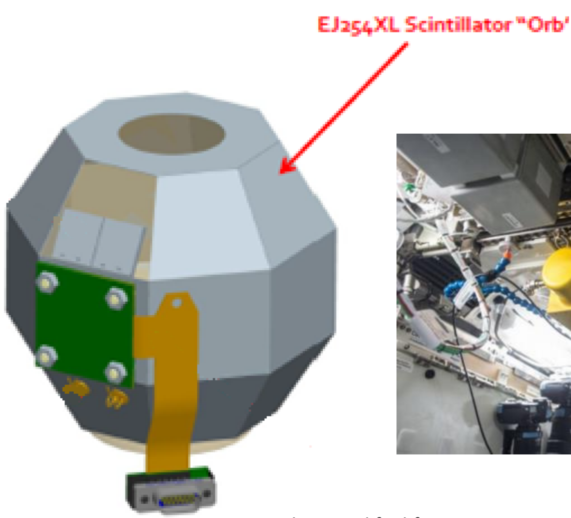
Backup

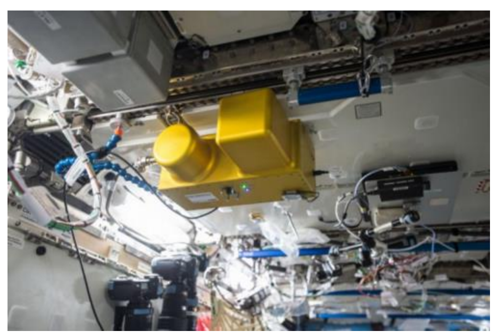
B: Orbital Peculiarities

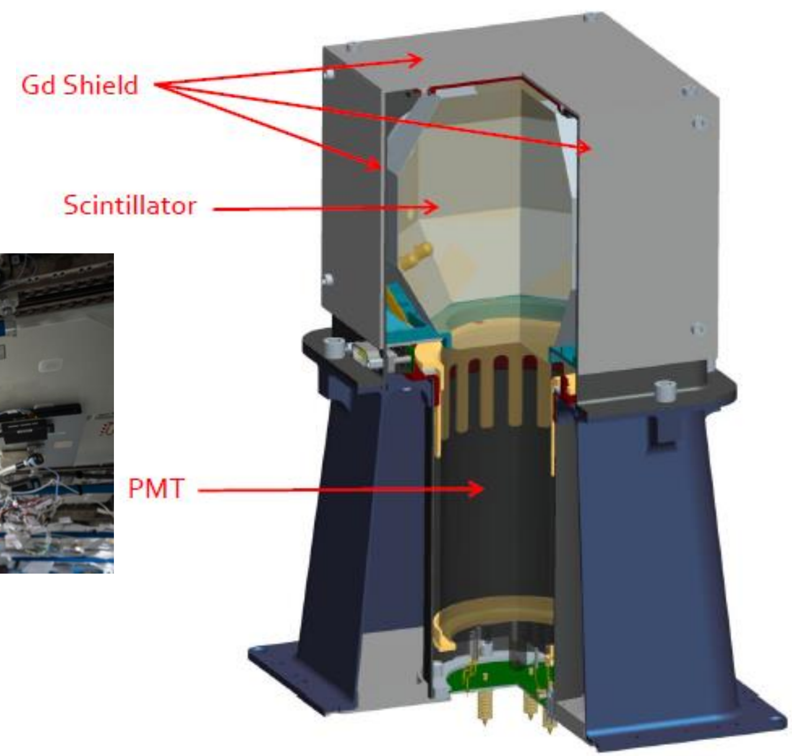
B: Introduction

Outline:

1. Introduction: Basic Interpretation of FND Data
2. Orbital Data Analysis Methods (Online, Offline Light, Offline Heavy)
3. Ground Verification of Analysis Methods
4. Raw Orbital Data
5. ACO Analysis, Status
6. Forward Work







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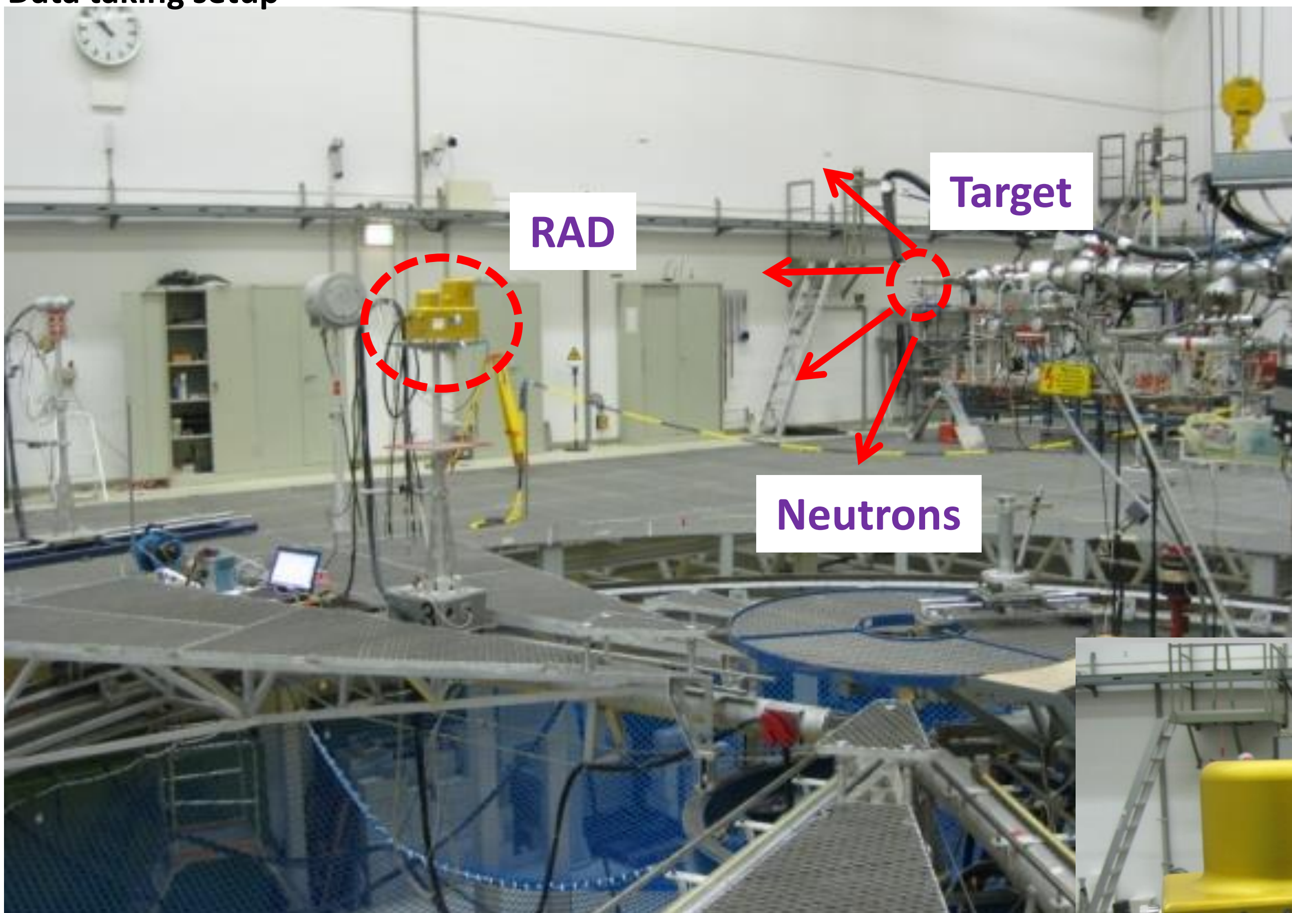
1. Introduction: Response Spectrum Shape

- 'Monoenergetic' neutron calibration ($\Delta E < 5\%$) at PTB, Germany:

Data taking setup

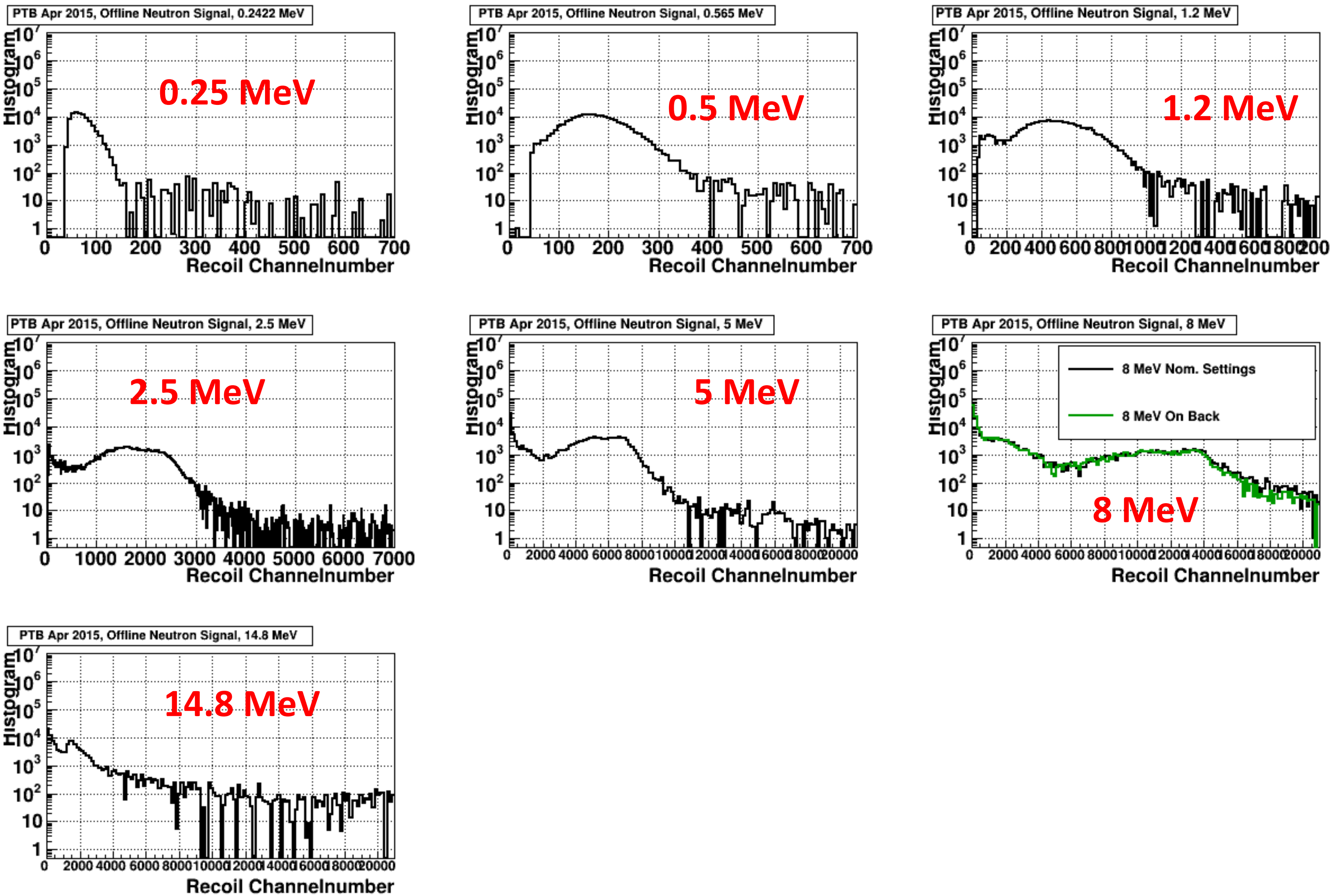


p, d Beamline

FND on beam axis/in forward scattered field at 2.5m from target

1. Introduction: Response Spectrum Shape

- Filtered ADC spectrum in response to monoenergetic neutron fields (after background subtraction):



1. Introduction: Scintillation Light Creation/Propagation: Light Function Formalism

- Shape of response spectra dominated by:

a) Multiple scattering of neutron with scintillator material nuclei: multiple pulses of scintillation light per neutron

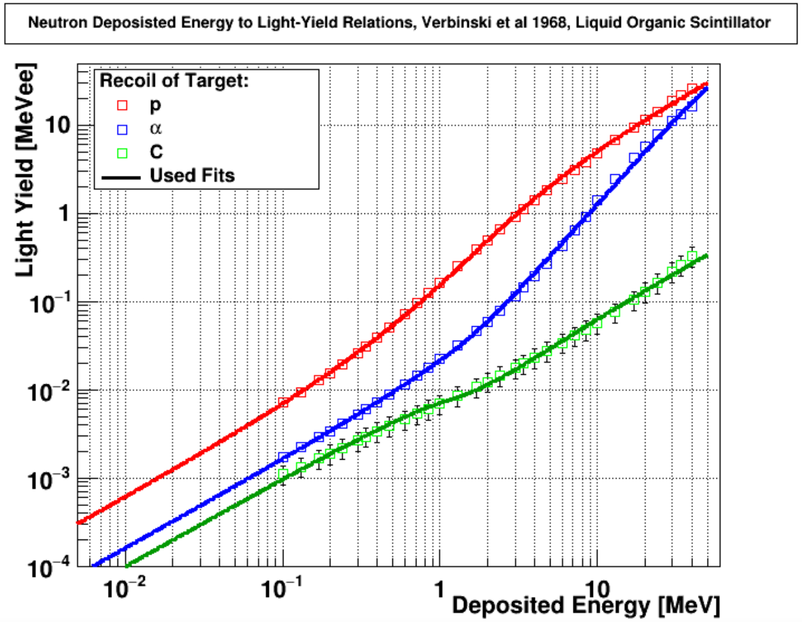
b) Scintillation light quenching (ionization quenching- Birk's law): nonlinear amount of collected scintillation light per interaction depending on energy deposit & scattering target

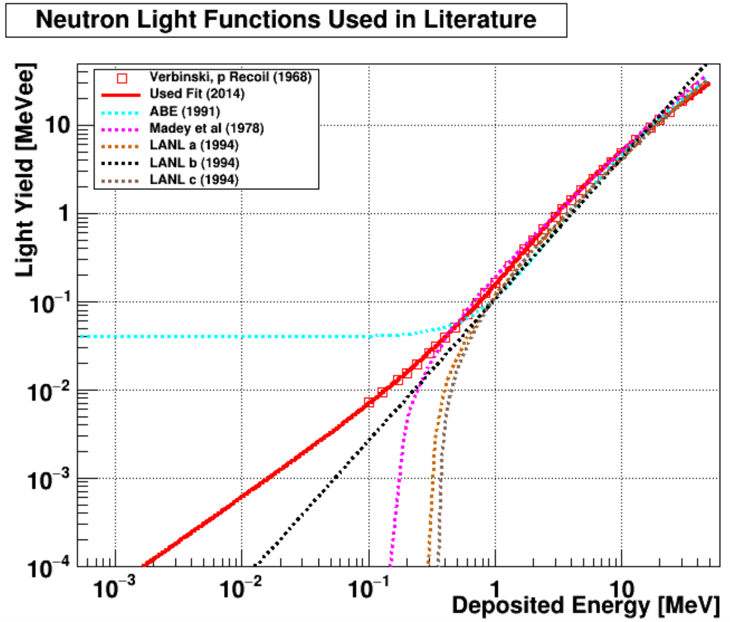
Even monoenergetic neutrons create broad distribution in light deposit/FND recoil spectra.

- Approach describing scintillation light generation in multiple scattering: Light function formalism
- Measurements/parameterization of light functions: Verbinski et al, 1968 (liquid scintillator):

Literature: Neutron recoils on...

V.V. Verbinski et al, NIM 65 (1968) 8 ff

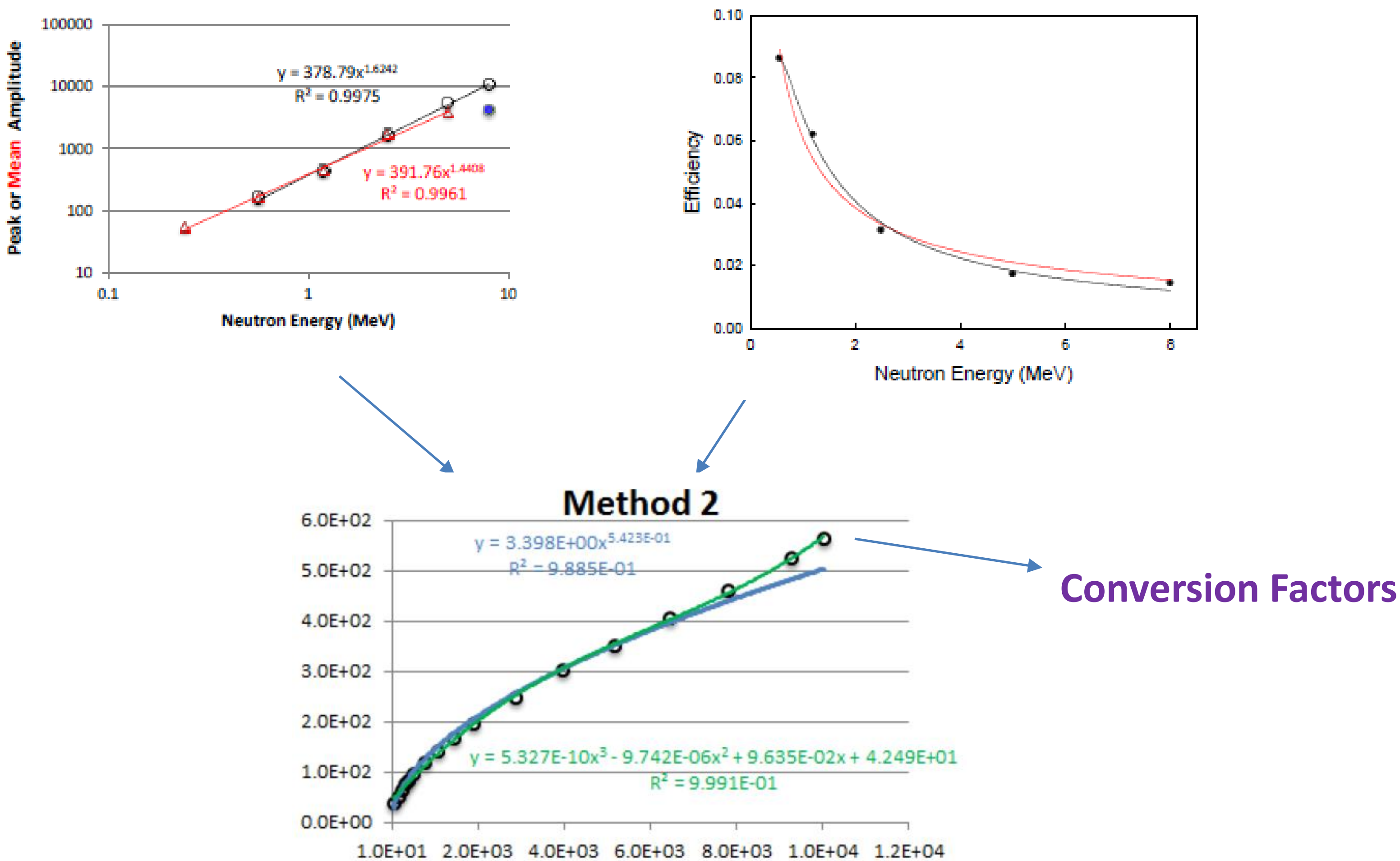




B: Analysis Methods

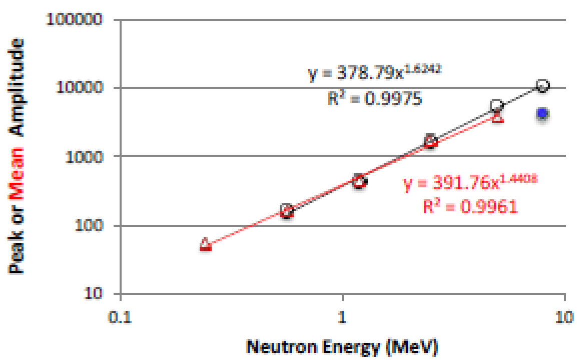
2.a On-Orbit Analysis (Cary Z.)

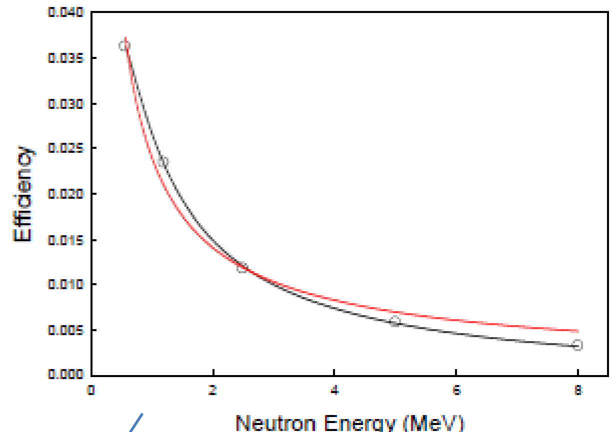
- Conversion factors for each recoil bin amplitude to dose equivalent (H*(10))
- Factors derived from:
  * Fit of PTB recoil spectra means with power law
  * Fit PTB efficiency with inverse second order parameterization
  * Multiply recoil and efficiency fit with ICRP dose conversion factors in each recoil bin

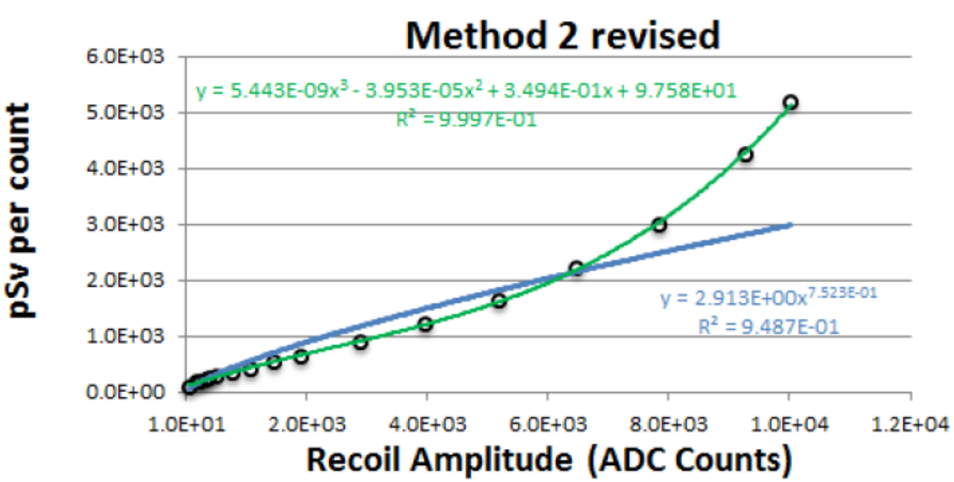


2.b) Offline Light Analysis (Cary Z.)

- Fit of PTB background-subtracted recoil spectra means with power law
- Fit PTB efficiency with inverse second order parameterization
- Multiply recoil and efficiency fit with ICRP dose conversion factors in each recoil bin







2.c) Offline Heavy (Martin L.): Regularized SVD Unfolding

A. Hoecker, V. Kartvelishvili, NIM A372, 469 (1996) [arxiv:hep-ph/9509307]

- Uncertainties on data distributions and response matrix

=> use regularized, singular vertex decomposition-based unfolding algorithm (ROOT: TSVDUnfold)

- **Advantages**:

* correct treatment of uncertainty-equipped input quantities (detector response matrix, input distribution)
* full uncertainty propagation; fast

- **Limitations (found small)**:

* 'strength' of regularization described by free parameter, needs to be determined from characteristics of orbit data, simulation and ground test data (systematic uncertainty)
* dependence on input distribution

general problem formulation:

$$\hat{A}\, x^{\mathrm{ini}} = b^{\mathrm{ini}}, \qquad \sum_{i=1}^{n_b} \left(\sum_{j=1}^{n_x} \hat{A}_{ij} x_j - b_i \right)^2 = \min$$

but: Experimental uncertainties Δb != 0

$$\sum_{i=1}^{n_b} \left(\frac{\sum_{j=1}^{n_x} \hat{A}_{ij} x_j - b_i}{\Delta b_i} \right)^2 = \min \qquad (\hat{A}x - b)^T B^{-1} (\hat{A}x - b) = \min$$

Rescaling and regularization:

$$(\tilde{A}\, w - \tilde{b})^T\, (\tilde{A}\, w - \tilde{b}) + \tau \cdot (C\, w)^T C\, w = \min$$

regularization parameter: chosen from rank of response matrix/problem

-> need response matrix for given recoil channelnumber and chosen neutron energy binning

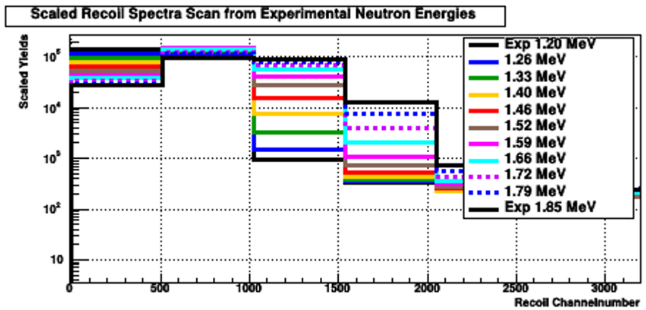
2.c) Unfolding Neutron Energy Binning

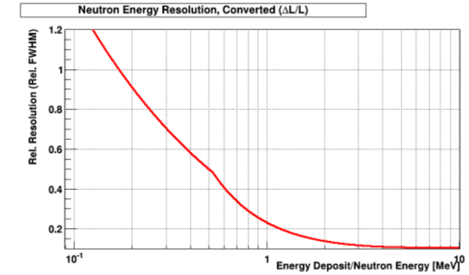
- Neutron energy binning:
  * low and high limits: approach from detector side:
    @ **lower limit: 200 keV** (electronics lower pulse cutoff/arming threshold)
    @ **upper limit: 8.5 MeV** (corresponding pulses start to saturate 12-bit ADC)
  * bin width:
    @ Low energy challenge:
      $ Unfolding requires unique response matrix rows- recoil spectrum of neighboring energy bins should ‘peak’ in different recoil bins
      $ FND orbit data histograms hardcoded to 512 channel width (29 bins)
      $ Light function nonlinearity: first recoil bin contains most of all < 1 MeV neutrons; 1.59 MeV centered in second bin
    @ Unfolding algorithm reacts positively to similar neutron energy bin size
    @ Choose high energy bin widths following detector resolution (from light fct cal.)

Lower Lim	Center	Width
0.2	0.664	0.927
1.127	1.59	0.927
2.054	2.403	0.698
2.752	3.101	0.698
3.45	3.913	0.925
4.375	5	1.375
5.75	6.5	1.5
7.25	8	1.5

recoil binning-driven

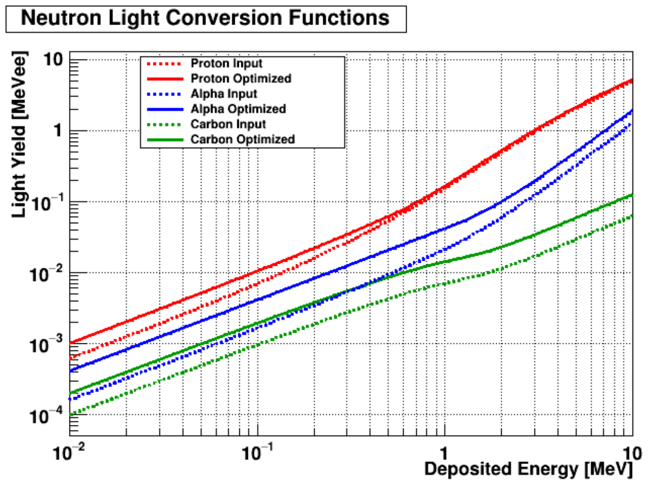
energy resolution-driven

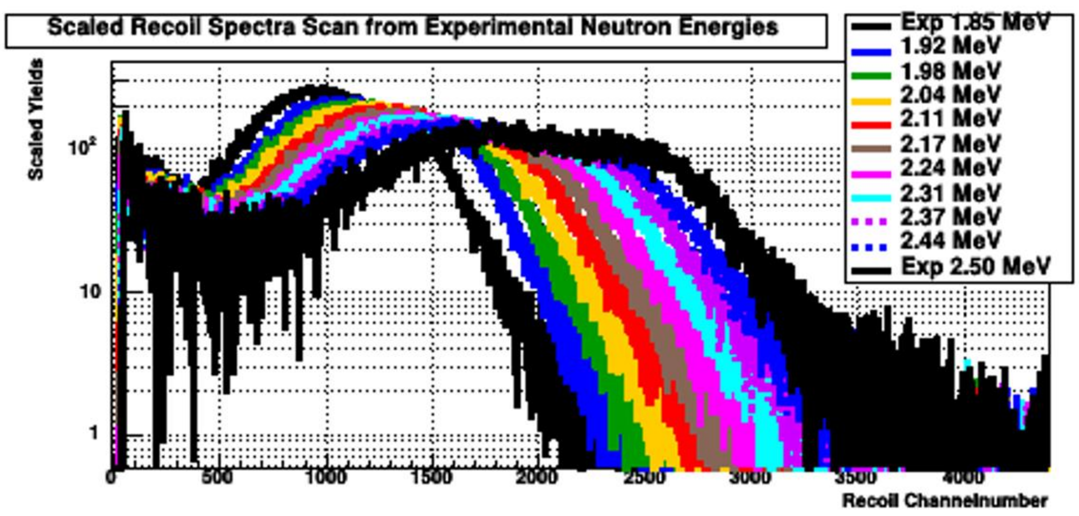




2.c) Response Matrix Assembly

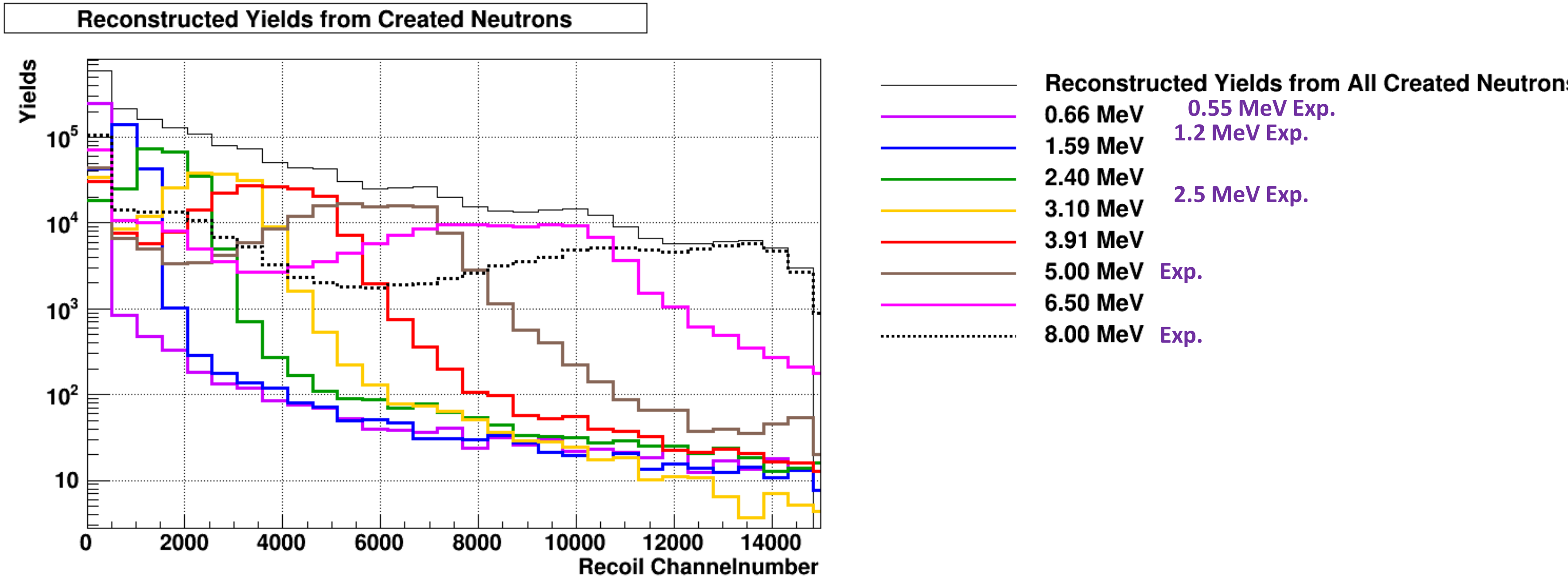
- Unable to reproduce experimental PTB datasets with sufficient accuracy through MCNP-based simulation
- Create response matrix instead by 'scaling' available experimental monoenergetic distributions
- All bin centers straddled by available experimental data; assumption is that spectra change continuously with energy (supported by simulation results): Along MCNP-calibrated light function,
  - a) scale down experimental distribution for **higher energy**
  - b) scale up exp distribution from **lower energy**
  - c) average

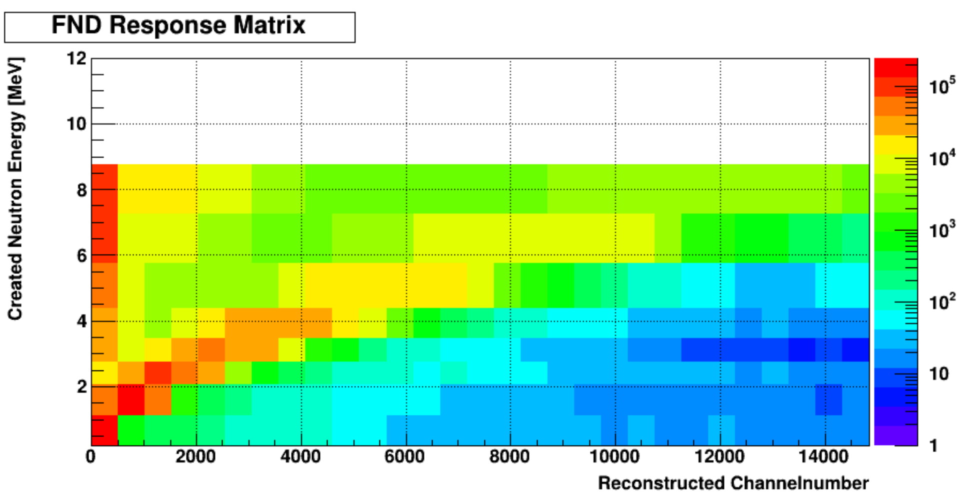


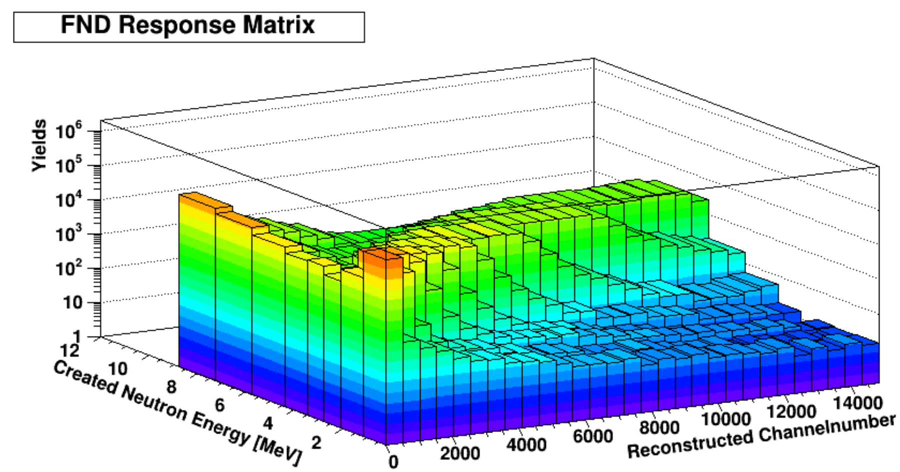


2.c) Response Matrix Assembly

- Response matrix and row slices from scaled experimental distributions



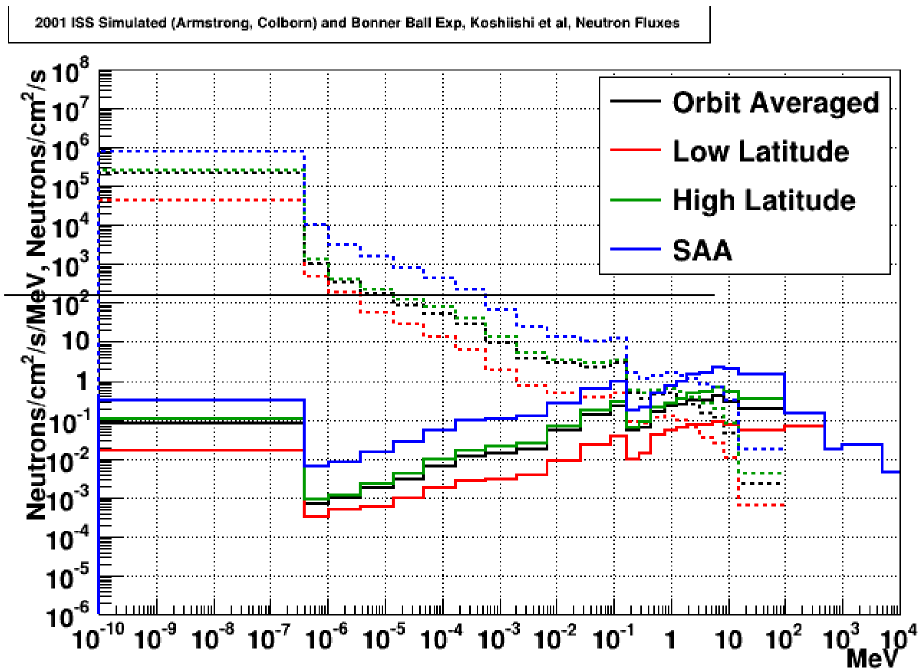




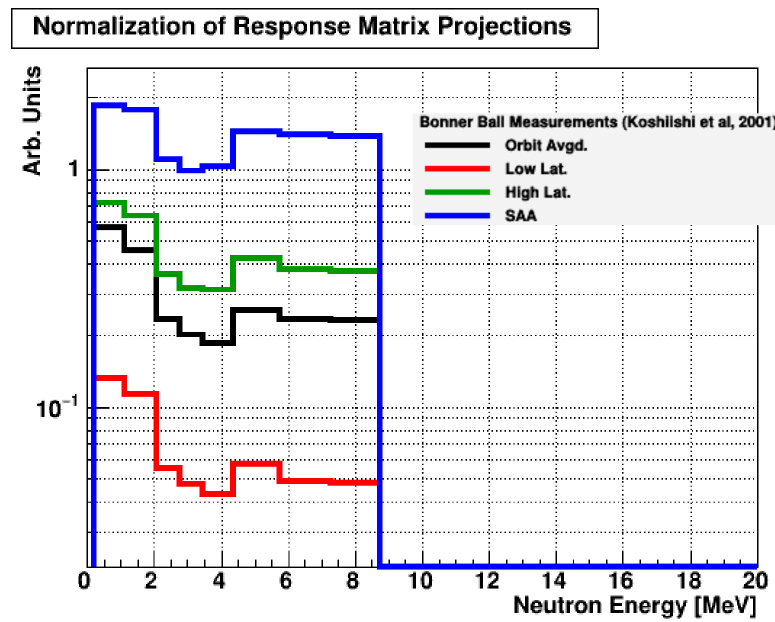
2.c) Response Matrix Assembly

- Can choose 'input spectrum' freely: weighting of columns of response matrix relative to each other
- Choose 'input spectrum' close to expected truth: Koshiishi et al, published 2007 (data from 2001);

H. Koshiishi et al,
Rad. Meas. 42 (2007), 1510ff



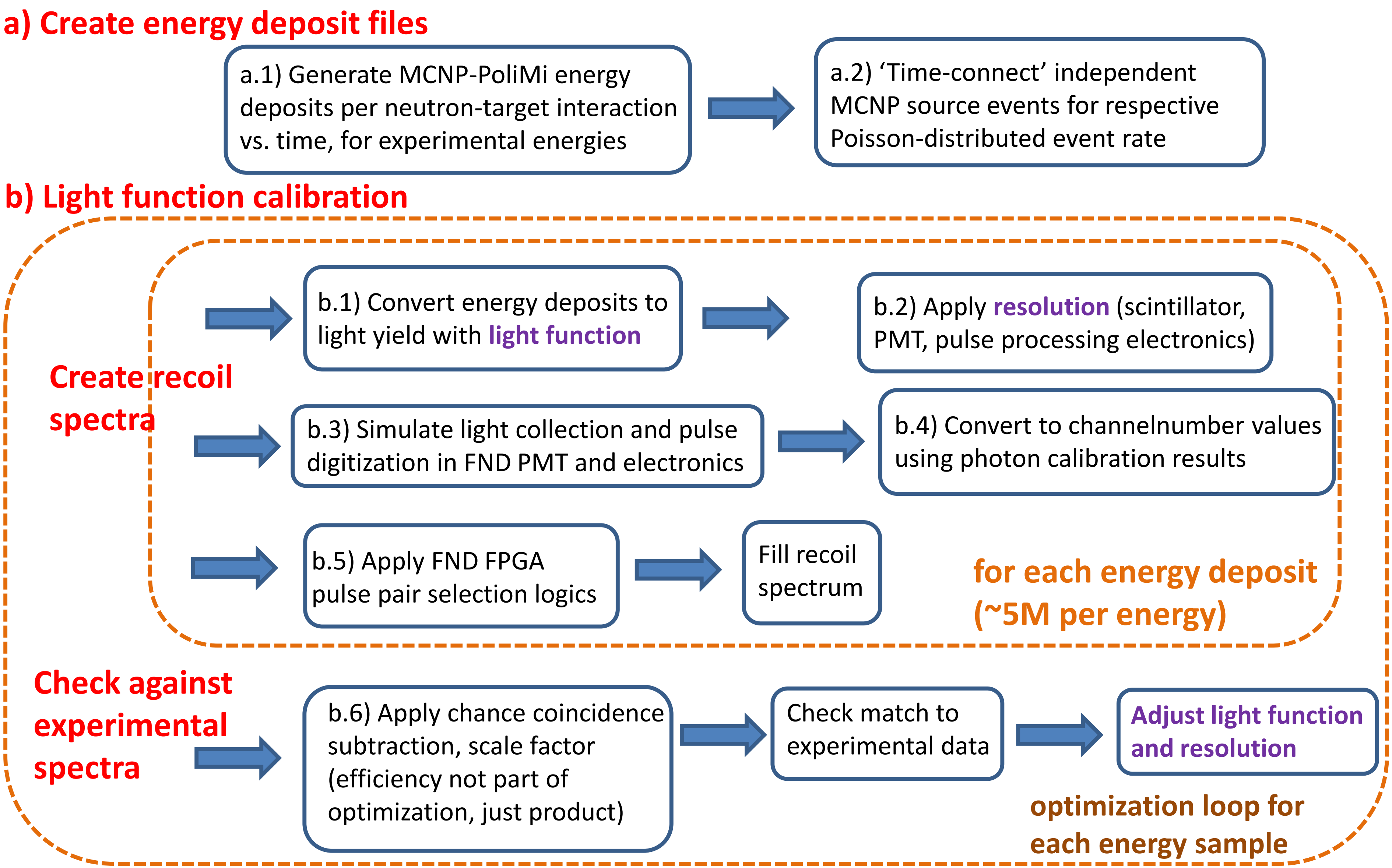
Rebin



B: Light Calibration

2. Light Function Calibration- Flowchart

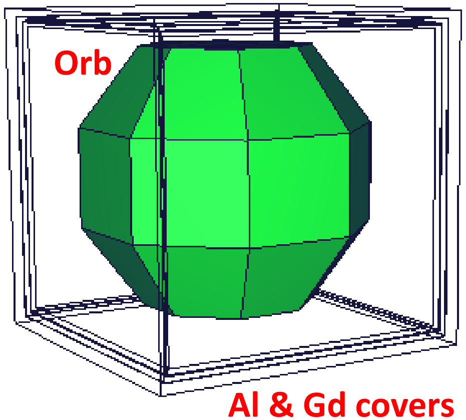
- Goal: Extract continuous light function describing scintillator behavior to freely choose energy binning
- For each experimental monoenergetic data sample, start from first principles:

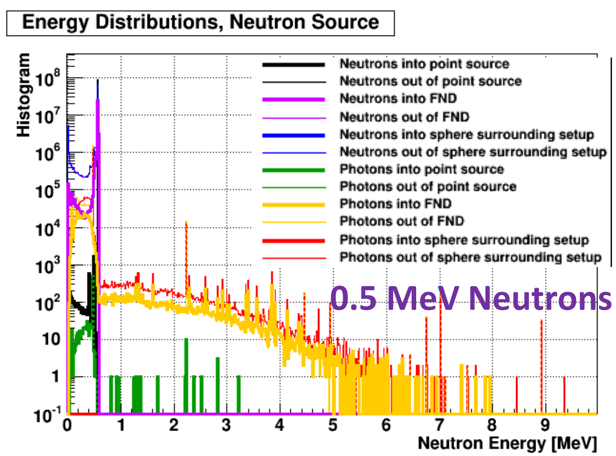


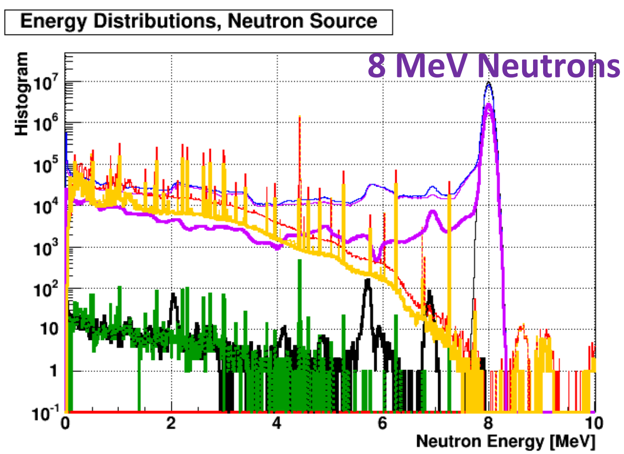
2.a.1 Generation of Neutron Energy Deposits: MCNP-PoliMi

- Use MCNP-**PoliMi** package:
  * MCNP limitations for neutron propagation and fission/inelastic scattering simulation:
    @ only returns total energy deposition of each neutron in target volume for conversion to light
    @ photon and neutron productions in fission/inelastic collision events not correlated in time/energy/multiplicity
  * PoliMi package writes out each interaction of single neutrons and photons
    @ time correlation within each single history, resolution in 100 ps
    => energy-to-light conversion possible on per-interaction-basis
    @ elastic, (n,gamma) and (n,n') interactions accurately modeled/propagated
  * Generations of 1e+08 n per experimental energy in bias cone around FND

Model started by A. Bahadori (SRAG)







2.a.2 ‘Time-connect’ Neutron Energy Deposits from MCNP-PoliMi

- Output of PoliMi: ASCII file containing interactions of neutrons and photons with target material:

	History	Particle Number	Particle Type	Interaction	ZAID	Cell	Energy Deposited [MeV]	Time [Shakes]	X-Coord.	Y-Coord.	Z-Coord.	Weight	Generation Nr	Number of Scatters	Code	Energy Prior to Collision [MeV]
H-scatter	2805	1	1	-99	1001	10	3.589902	8.08	2.05	-1.30	-3.78	1.000E+00	0	0	0	4.958E+00
	2805	1	1	-99	1001	10	1.112997	8.28	0.39	0.26	-1.68	1.000E+00	0	1	0	1.368E+00
	2805	1	1	-99	1001	10	0.003554	8.79	2.27	2.43	0.51	1.000E+00	0	2	0	2.549E-01
	2805	1	1	-99	1001	10	0.181367	8.82	2.39	2.53	0.64	1.000E+00	0	3	0	2.514E-01
	2805	1	1	-99	6000	10	0.004136	8.82	2.39	2.53	0.65	1.000E+00	0	4	0	7.007E-02
	2805	1	1	-99	1001	10	0.043889	9.05	2.41	1.76	0.89	1.000E+00	0	5	0	6.590E-02
B10 Capture!	2805	1	1	0	5010	10	2.789669	24.20	-0.40	2.31	2.63	1.000E+00	0	14	0	1.375E-04
Capture photon	2805	2	2	1	6	10	0.099156	24.22	-1.92	0.93	-2.22	1.000E+00	0	0	801	4.776E-01

- Limitation in PoliMi: no transport of non-neutron/photon decay products of capture/fission reactions -> manually distribute recoil energy among decay products & convert to light

- To create realistic succession of neutron events in scintillator: ‘time-connect’ PoliMi events to experimental flux (30-310 /s/cm^2):

History	Particle Type	Interaction	ZAID	Energy Deposited [MeV]	Absolute Time [μs]
15	1	-99	6000	0.3258	200.9430278347747105272
15	1	-1	6000	1.223006	200.9446278347747067983
15	1	-99	1001	1.19312	200.9471278347747045245
20	1	-1	6000	1.153536	249.6897651601931613641
21	1	-99	6000	2.070328	258.0006369570315882811
35	1	-99	6000	0.027568	372.9355042009522662738
...					
99999932	1	-99	6000	0.009083	943205800.4175952672958
99999958	1	-99	1001	1.209701	943206036.2944241762161
99999988	1	-1	6000	0.332827	943206258.0235788822174
99999988	1	-99	1001	0.772745	943206258.0235788822174
99999997	1	-99	1001	1.429591	943206423.4481251239777

→ ~15 min

2.b.1 Convert Energy Deposit to Light- Function Parameterization

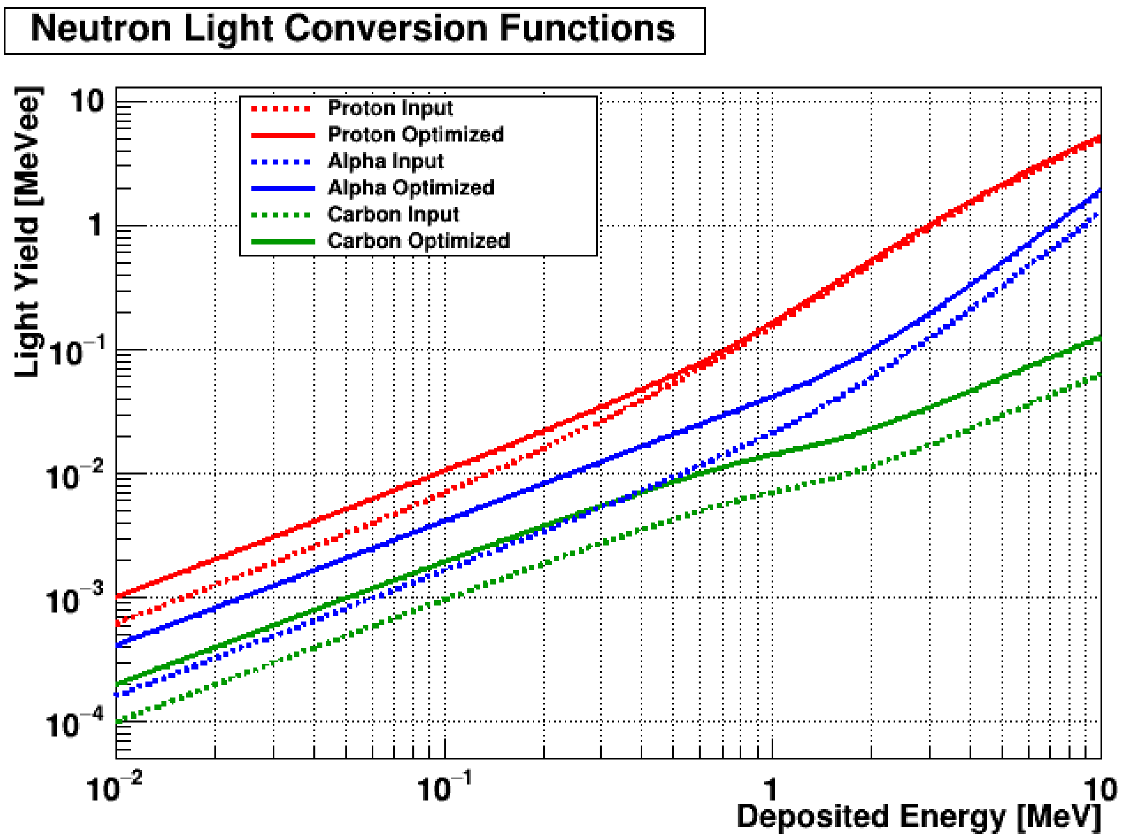
- Fit to Verbinski data parameterized as: 2nd order polynomial at low deposited energy; sqrt(const+E^2) at high energy
- Change 5 parameters to optimize match with experimental data

$$L(x_{ED}) = \begin{cases} a x_{ED} + b x_{ED}^2 & \text{for } x < g \\ c + d\sqrt{e^2 + f^2 x_{ED}^2} & \text{for } x >= g\text{, where} \end{cases}$$

$$a = \frac{d f^2 g}{\sqrt{e^2 + f^2 g^2}} - 2bg$$

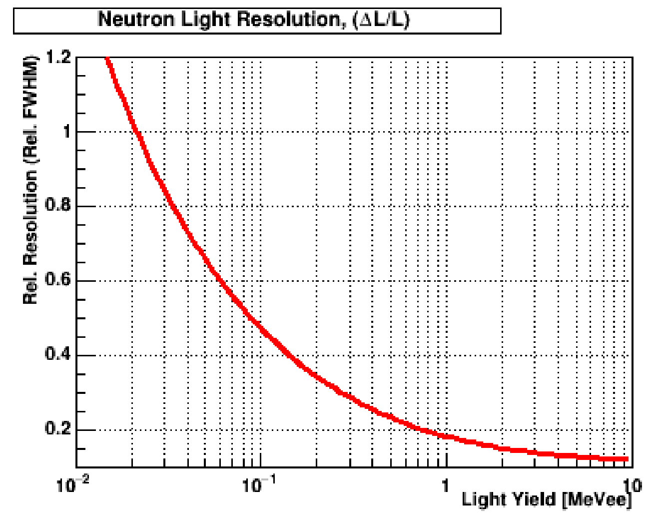
$$c = ag + bg^2 - d\sqrt{e^2 + f^2 g^2}$$

Continuity requirements for 1st and 2nd derivative



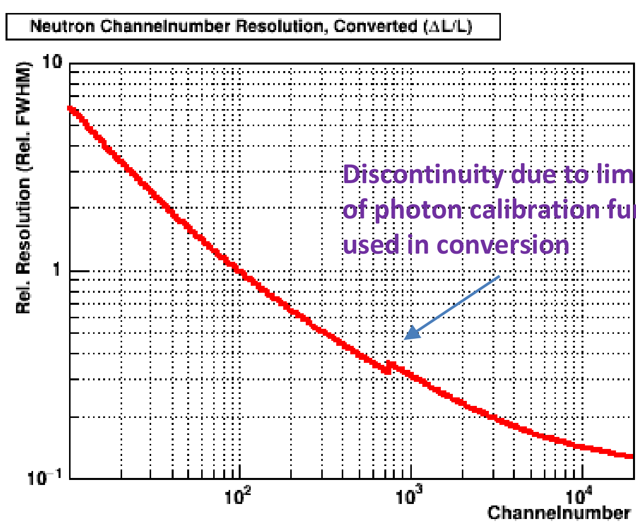
2.b.2 Apply Resolution- Implementation

- Single-point implementation of all experimental resolution contributions:
  * light production/quenching/reflections in plastic,
  * light coupling scintillator to PMT
  * PMT photon detection
  * electronic noise (PMT/amplifier) etc
- Optimize 3 parameters to match experimental data

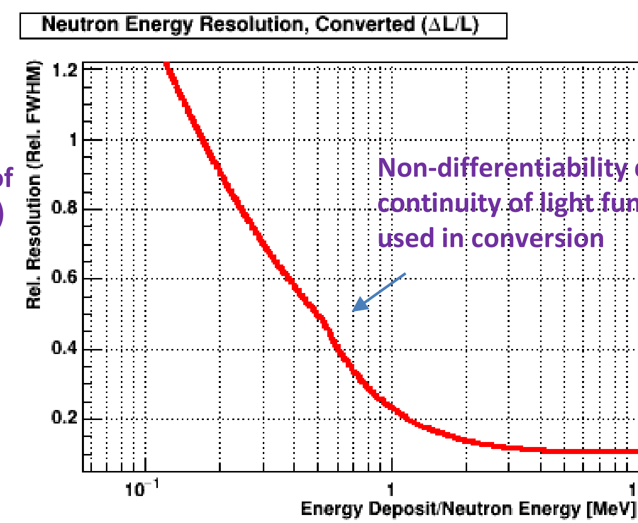


ΔL / L (rel. FWHM):

$$\frac{\Delta L}{L} = \left(\alpha^2 + \frac{\beta^2}{L} + \frac{\gamma^2}{L^2}\right)^{1/2}$$



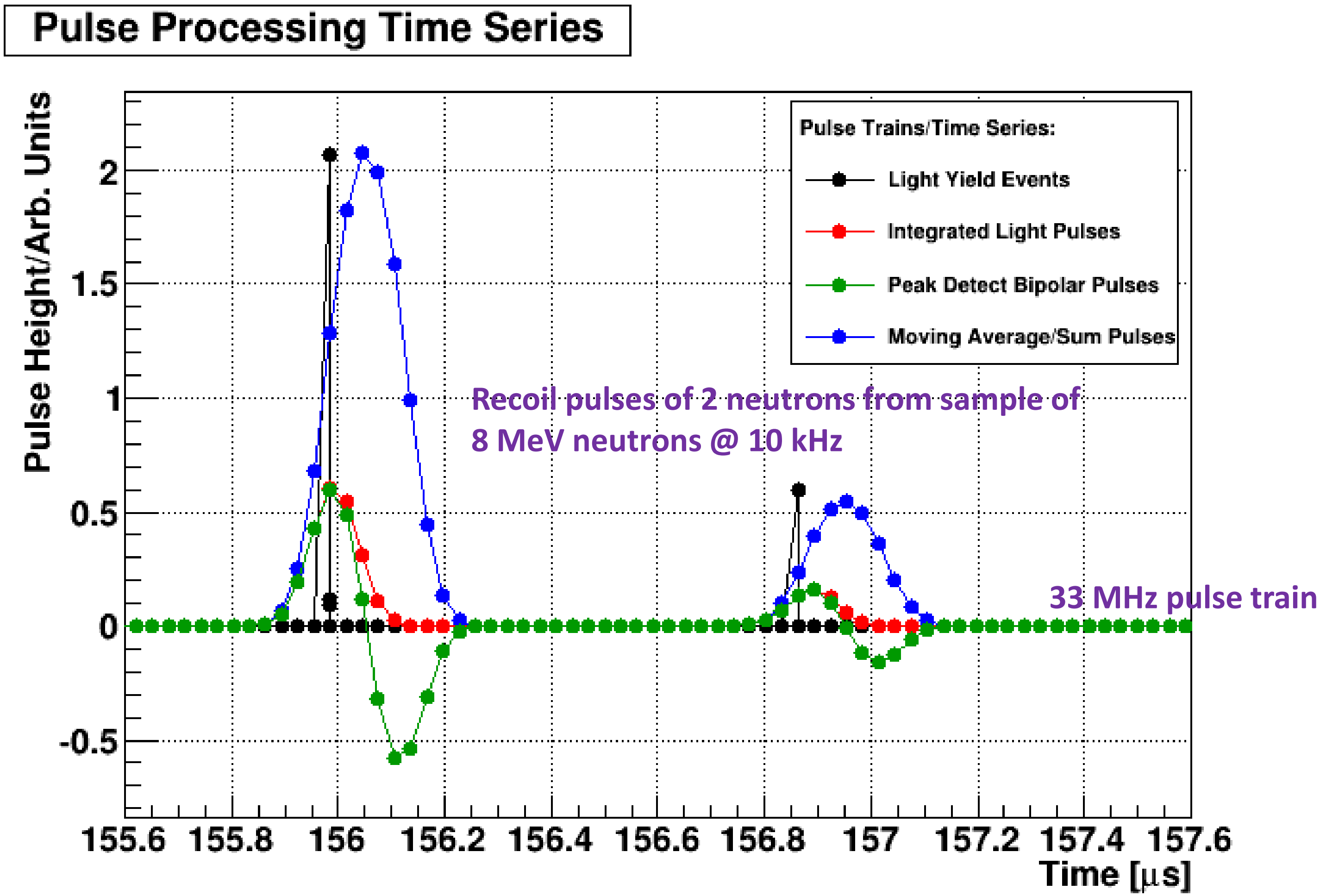
Discontinuity due to limited continuity of of photon calibration function (1st order) used in conversion



Non-differentiability due to limited continuity of light function (2nd order) used in conversion

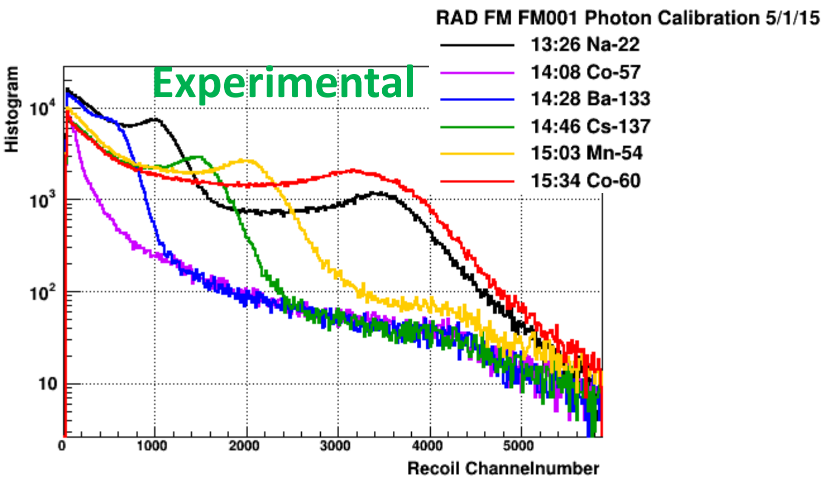
2.b.3 Light Collection/Pulse Digitization (see Michael V.'s talk)

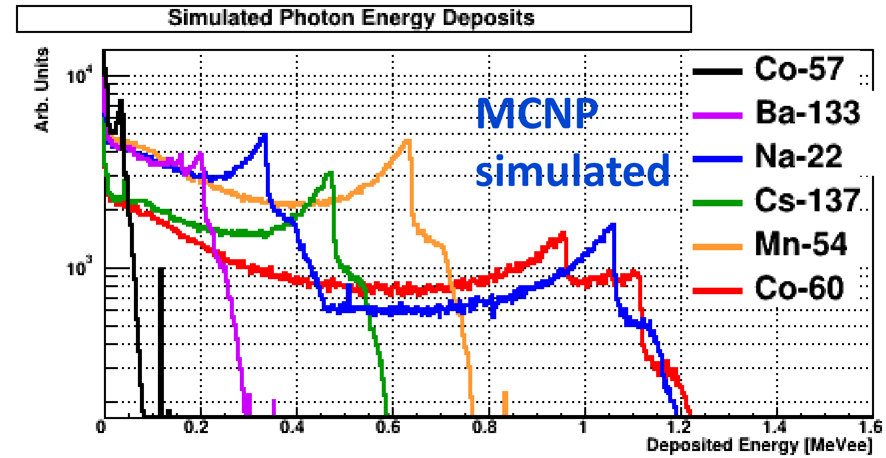
- Convert light yields to corresponding **electronics signal pulses** via Gaussian function sampled by 33 MHz clock; area normalized to light yield
- Two filters create **bipolar signals** for peak detection and '**moving average (sum)**' for signal height
- Time width of Gaussian chosen to match experimental signal processing pulse width (full width ~390 ns)



2.b.4 Light to Channelnumber Conversion: Photon Calibration

- Inputs: experimental photon source and MCNP-simulated energy deposit spectra
- Perform global fit of conversion function parameters: create channelnumber spectra from generated deposited energy spectra





experimental

$$N_{\mathrm{Exp.\,Gamma}}(x_{CHN}) = N_{\mathrm{Exp.\,Bg}}(x_{CHN}) + \int R(x_{CHN}, x_{ED})\, N_{\mathrm{Sim.\,MC}}(x_{ED})\, dx_{ED}$$

$$R(x_{CHN}, x_{ED}) = e^{-\frac{(ED(x_{CHN}) - x_{ED})^2}{2\sigma^2}}$$

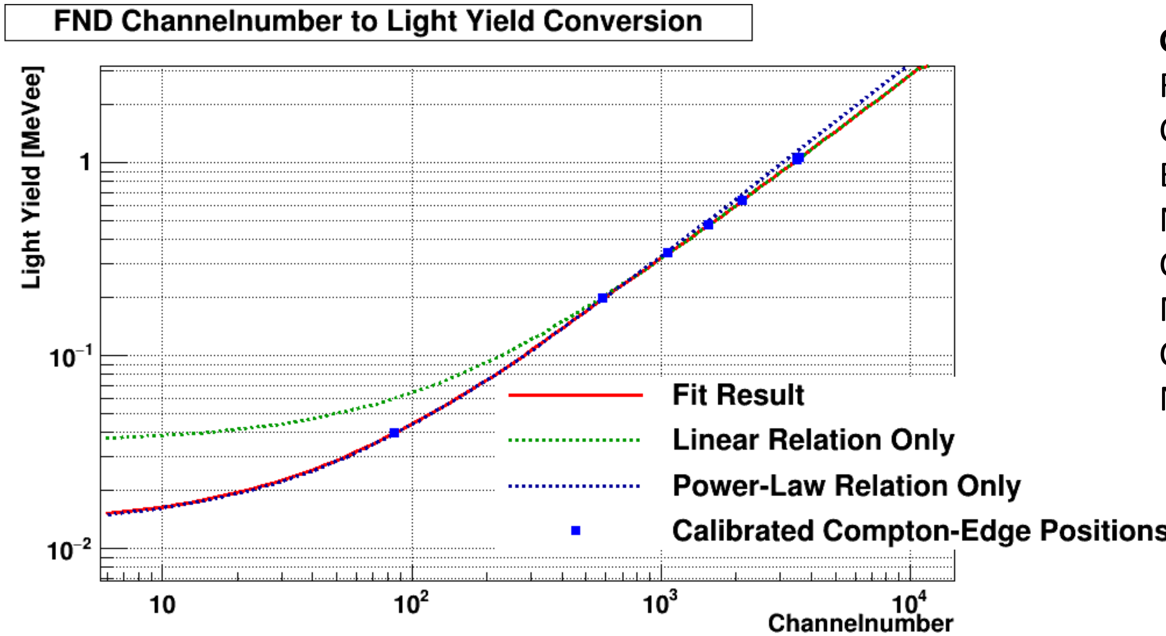
Channelnumber-to-light yield conversion:

$$ED(x_{CHN}) = \begin{cases} a + b x_{CHN}^{c} & \text{for x < e} \\ d + b x_{CHN} & \text{for x >= e, where } d = a + be^{c} - be \end{cases}$$

Continuity requirement

2.b.4 Light to Channelnumber Conversion: Photon Calibration

- Result: Low light yield region prefers nonlinear (power law) shape (also seen in other literature):



Global red. chisq. = 695 / 490 = 1.42

Red. chisq. for single plots:

Co-57: 27/31 = 0.86

Ba-133: 63 / 35 = 1.80

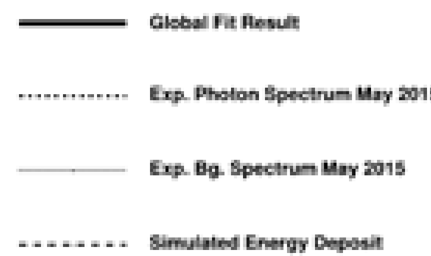
Na-22 a): 53 / 32 = 1.67

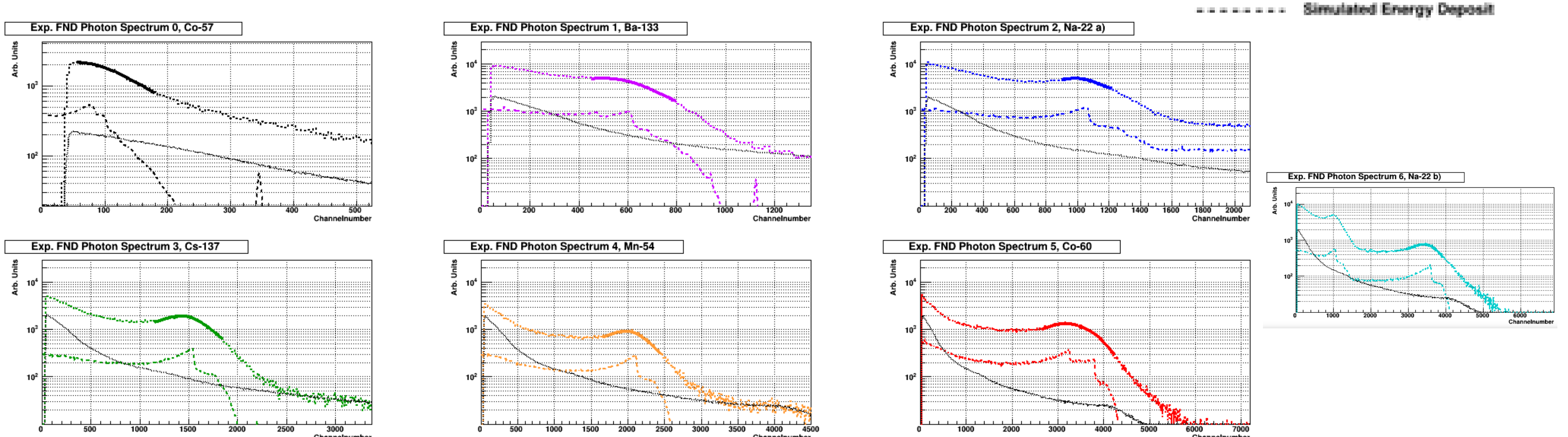
Cs-137: 108 / 70 = 1.54

Mn-54: 69 / 80 = 0.86

Co-60: 211 / 160 = 1.32

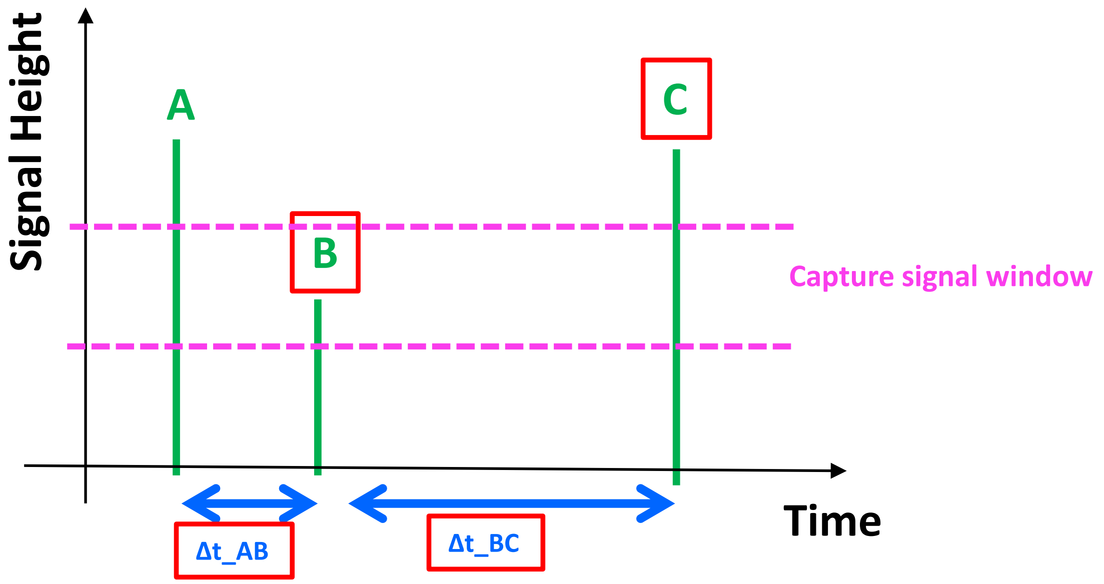
Na-22 b): 164 / 100 = 1.64





2.b.5 FND Pulse Pair Selection (see Michael V.'s talk)

- Apply same selection as FND FPGA
- Algorithm considers three latest detected pulse amplitudes (moving averages) and time intervals between them (zero crossing of bipolar signal)



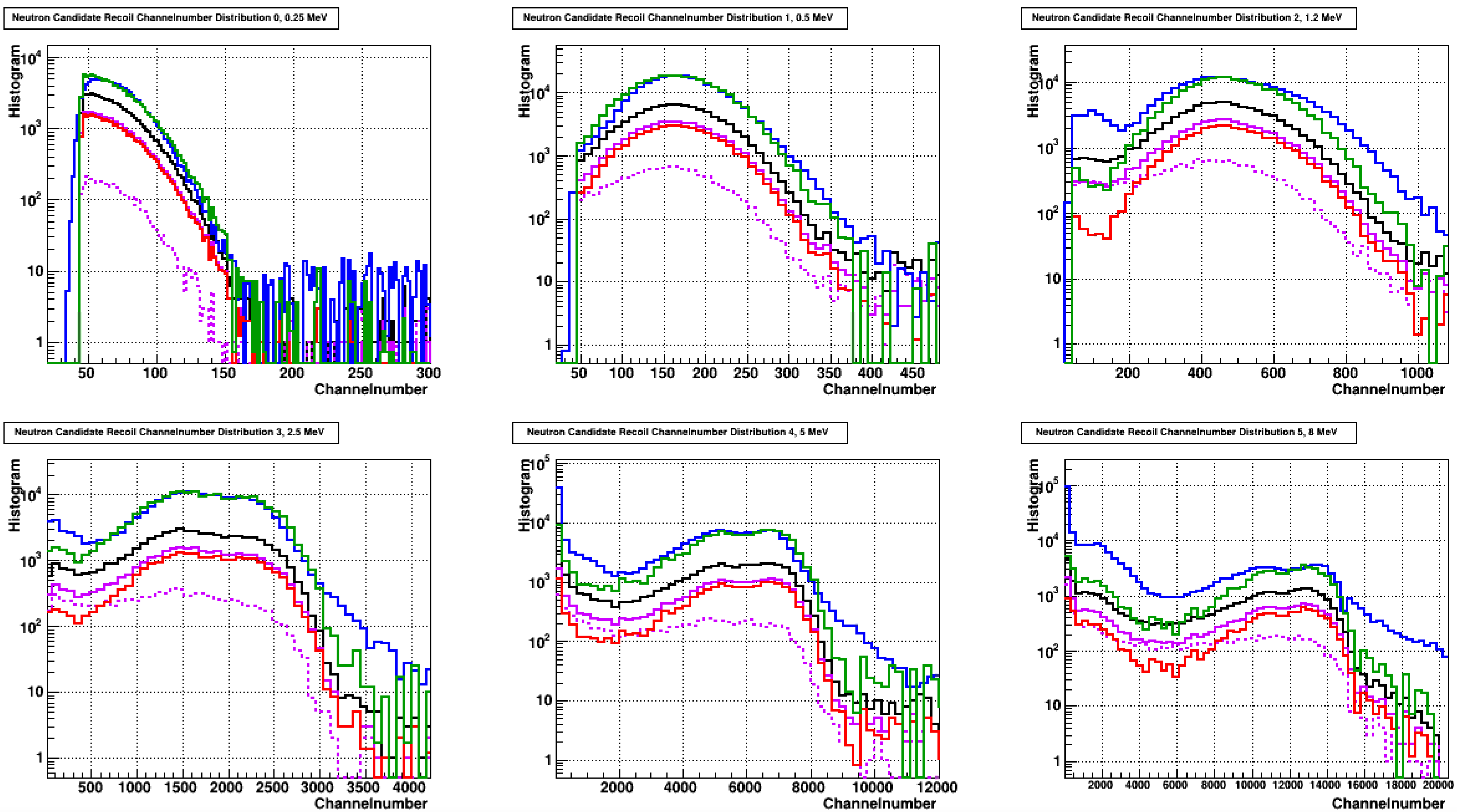
- **Pulse selection logics**: accept A, B as pulse pair:

I) SH_B in capture signal window &&
II) Δt_AB in capture time window &&
III) Δ t_AB < Δ t_BC ||
(SH_C outside of capture signal window || Δ t_BC outside of capture time window)

2. Preliminary Calibration Results- Recoil Spectra Match

- Deviations for low channelnumbers at mid to high energies- further analysis to be done to identify missing process/incorrect treatment of neutron interactions; resolution to be adjusted as well

Simulated Selected Recoil Pulses
Sim. Sel. Recoil Pulses, $\Delta t_{Capt.}$ in [1;5) μs
Sim. Sel. Recoil Pulses, $\Delta t_{Capt.}$ in [5;10) μs
Sim. Final Background-Subtracted
Sim. Fit Result to Exp.
Exp. PTB 15, Bg.-Sub.

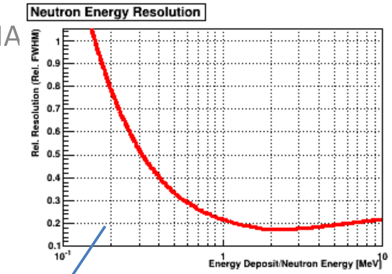


B: Isotropic Source Term Correction

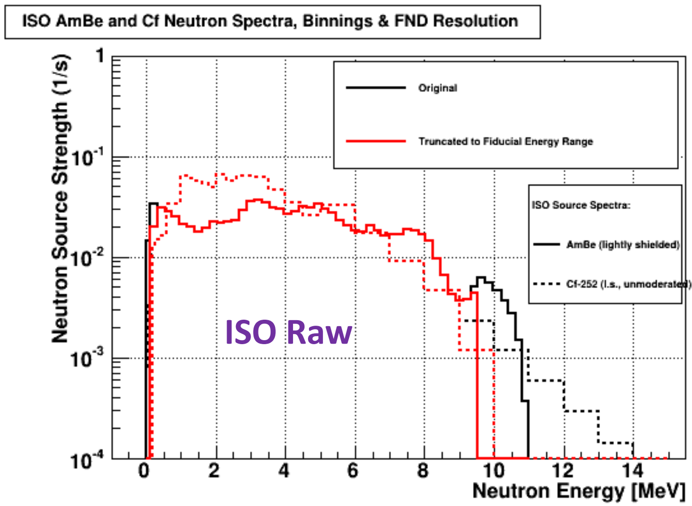
B: Offline Light Spectrum Extraction Study

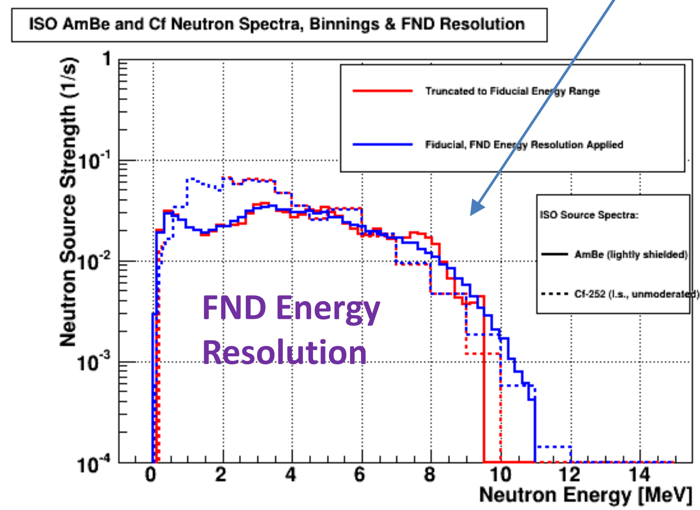
M. Leitgab, NA

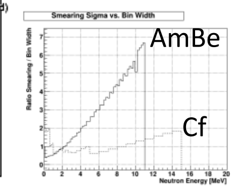
2c) Direct Mapping/Conversion Spectral Match Test

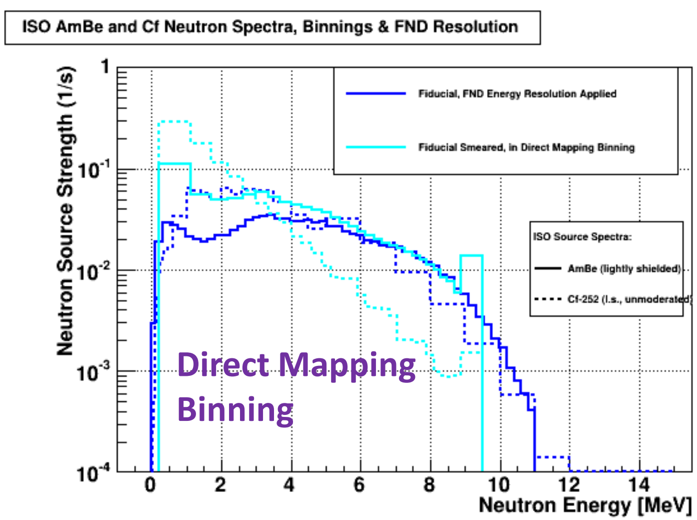


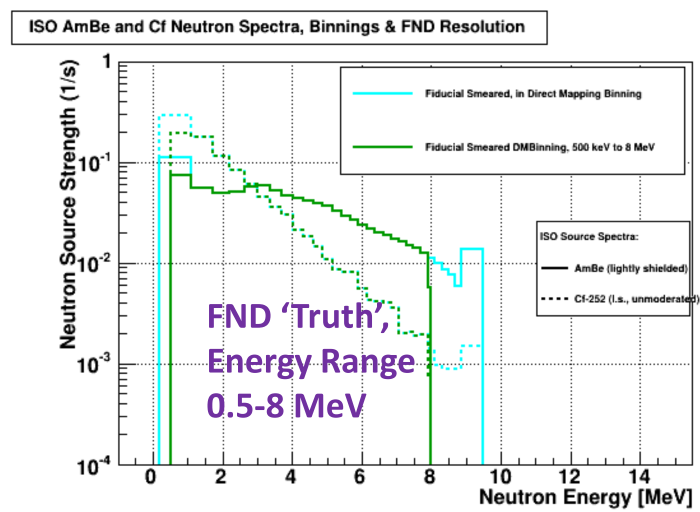
- Created 'truth' distributions from ISO for AmBe and Cf sources:
apply detector resolution, direct mapping binning and energy range selection (0.5-8 MeV)
* Cf ISO binning mostly too wide for smearing to have effect;











2c) Direct Mapping/Conversion Spectral Match Test

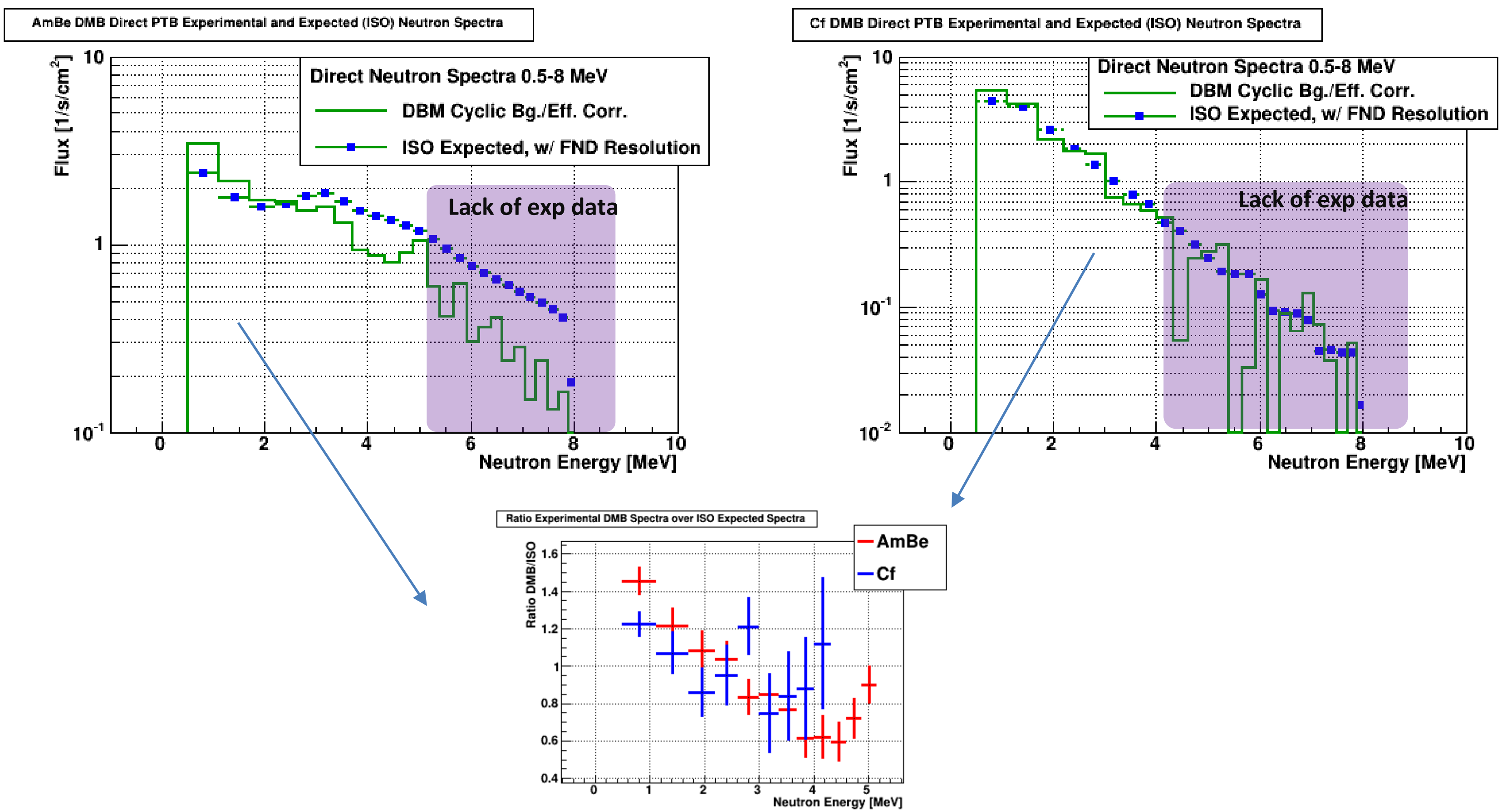
- Scale 'truth' histograms with PTB reported (adjusted) neutron flux
- Comparison with GAS analysis results statistics-limited to <~ 5 MeV (only spotty shadow cone and background subtraction data at higher chn bins):

@ Expected: Low energy spectrum overestimated, medium/high energy spectrum underestimated

@ AmBe spectrum shows structure in ISO-truth, not reflected in DBM spectrum: deviations +45% to -41%;

@ Cf spectrum closer (statistics limited): overestimate at low bins ~22%, medium energy bins large uncertainties, in part consistent;

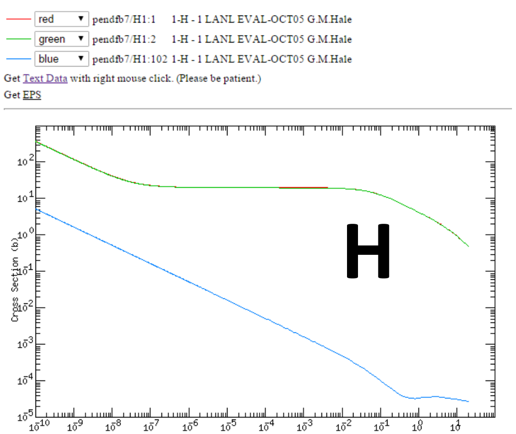
- Conclusion: Direct Mapping/Conversion analysis method by design shows limitations in reproducing neutron energy spectra.

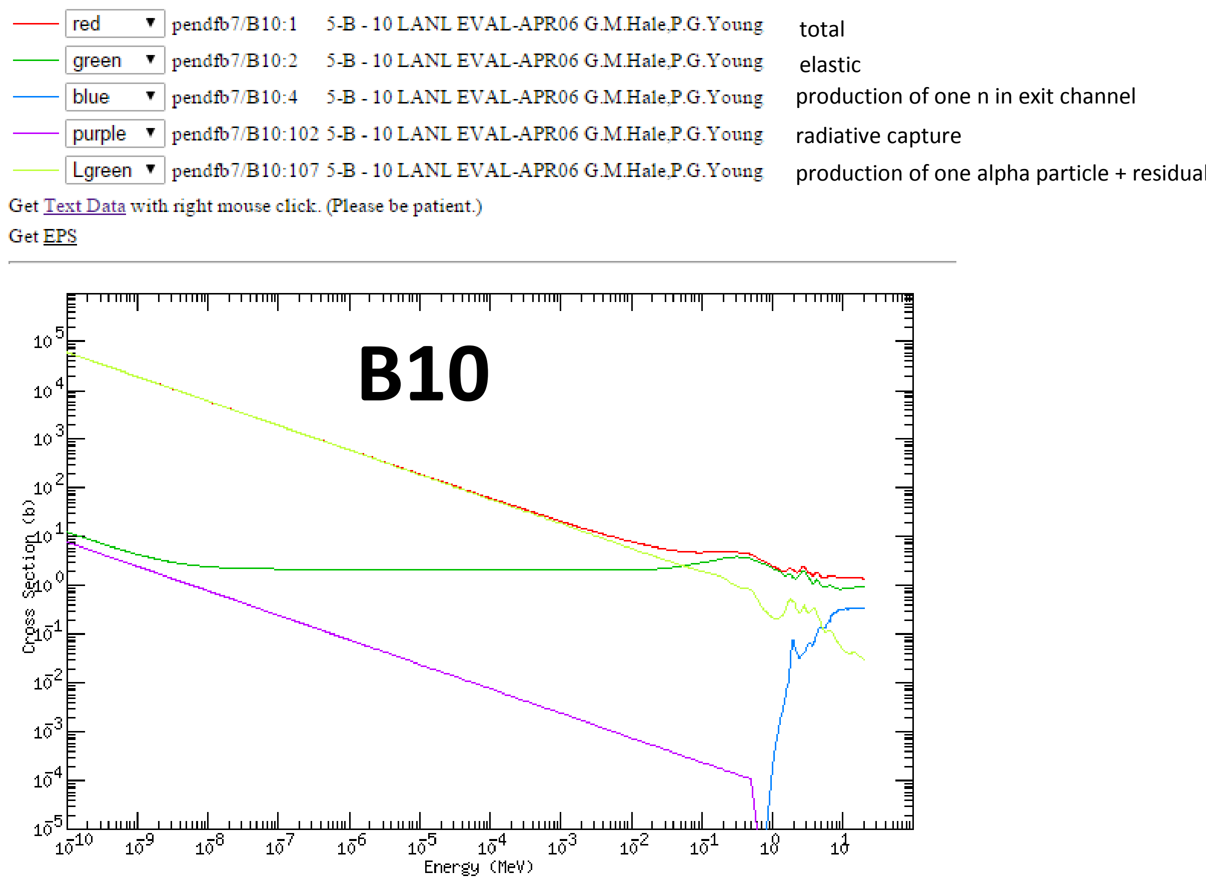


B: MCNP Neutron Cross Sections

4.1a Simulation of Neutron Energy Deposits: MCNP-PoliMi

- for all materials use ENDF-VII library at 300 K, assembled in 2005; max energy 20 MeV, 500-3500 energies depending on material





4.1a Simulation of Neutron Energy Deposits: MCNP-PoliMi

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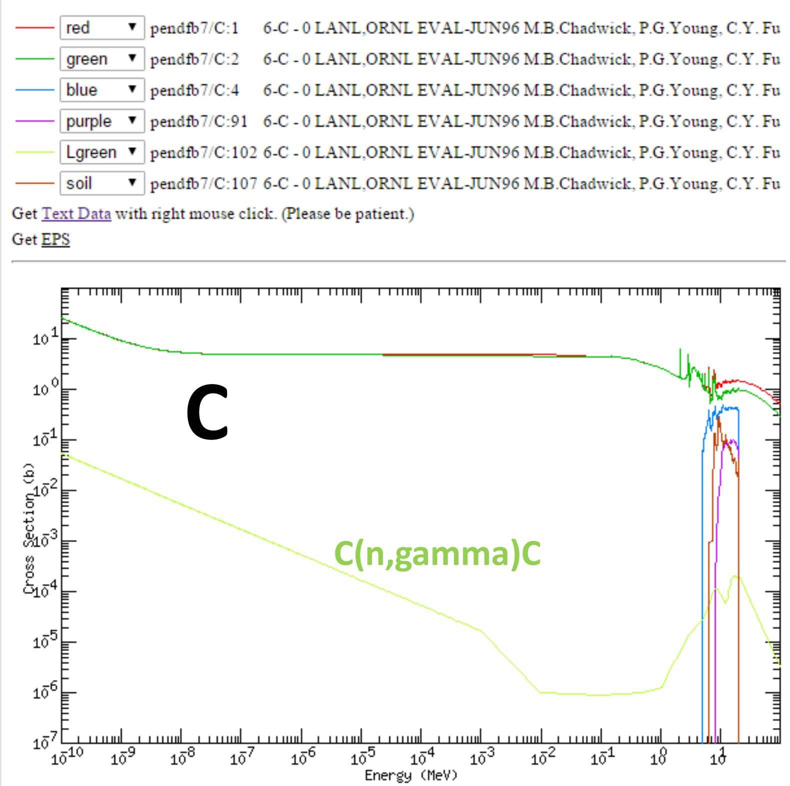
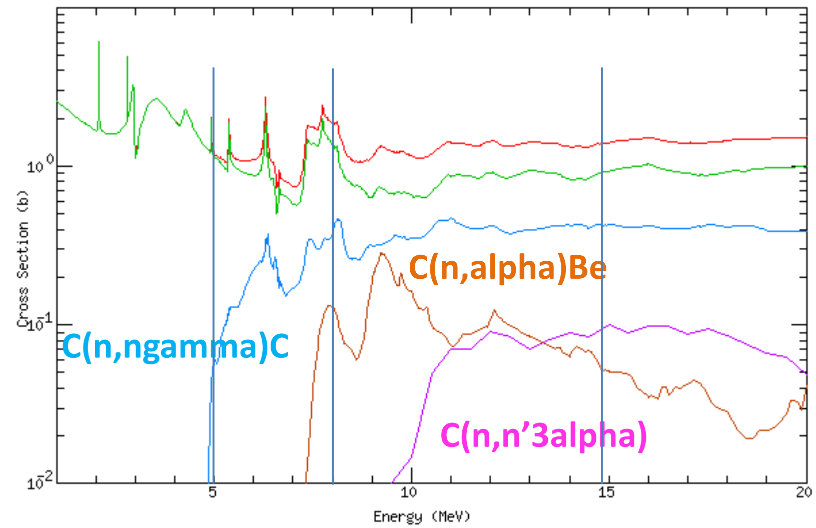


total
elastic
production of one n in exit channel
production of one n in continuum not included in separate listings
radiative capture
production of one alpha particle + residual



B: Photon Calibration Nonlinearities

6) Low Energy Nonlinear Light Output in Literature

Literature c)

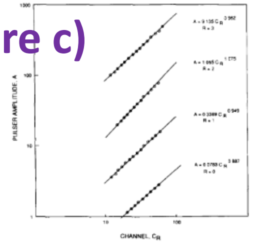
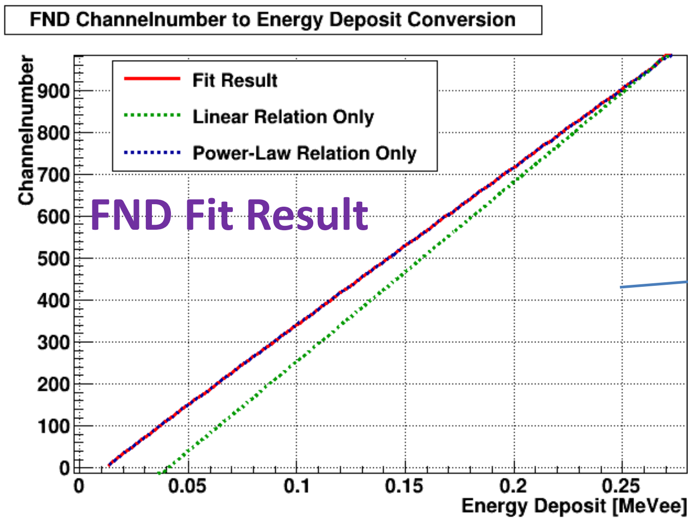


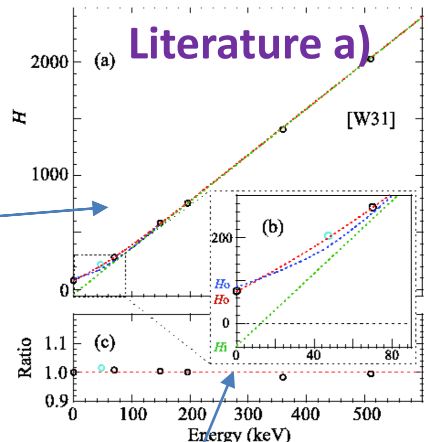
Fig. 4. Pulser calibration data for the rod-1 ADC and the associated gated-integrator assembly of the ABE detector. R denotes the range of amplification fed to the 6-bit ADC.

Feldman et al, NIM A 306 (1991) 350 ff

FND Fit Result:
A ~ C^(1.02)

Energy deposit -> Light Yield -> Channelnumber





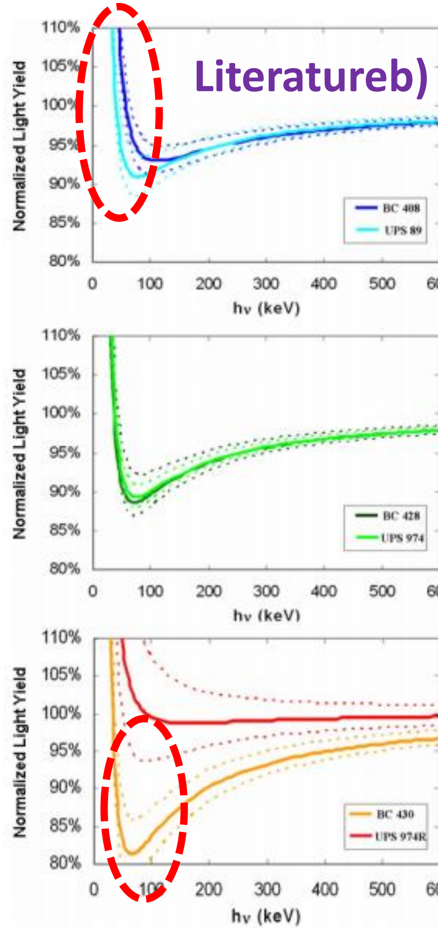
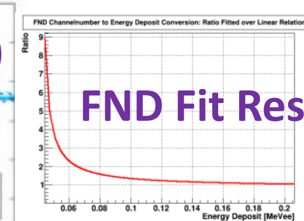
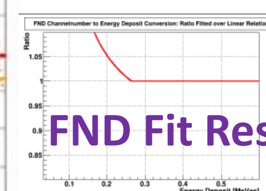
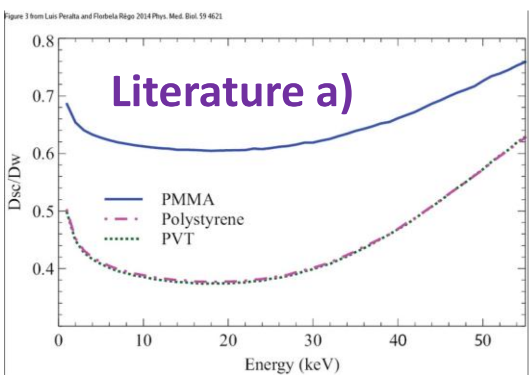


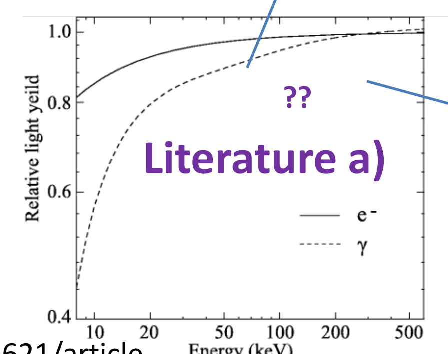
Fig. 11. Mean light amount for photons for the blue, green, and red scintillators (from top to bottom). The dotted lines represent the experimental uncertainties.



Assumed linear







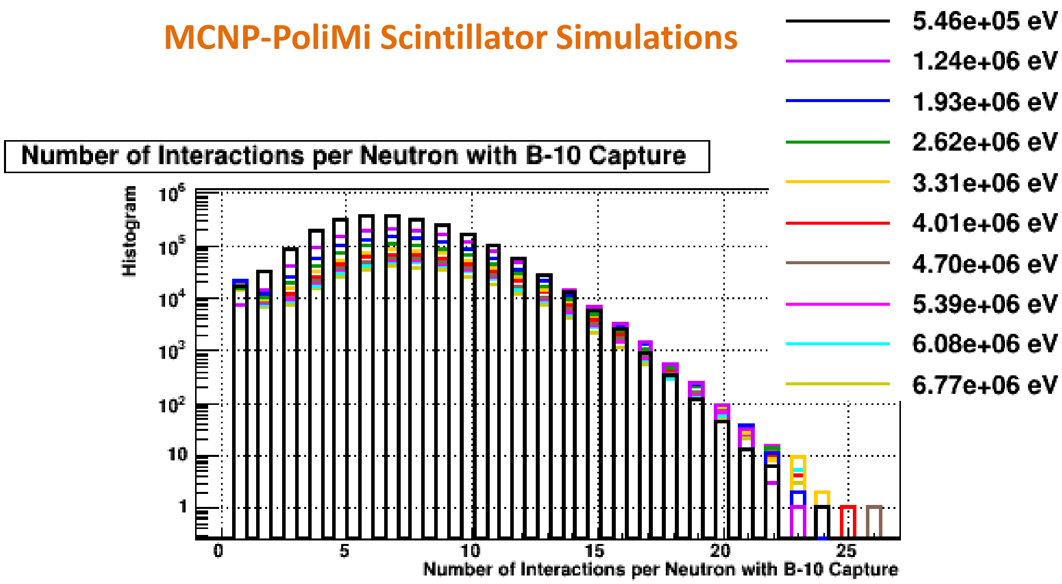
http://iopscience.iop.org/0031-9155/59/16/4621/article

http://pasj.asj.or.jp/v63/sp3/63s303/63s303-frame.html

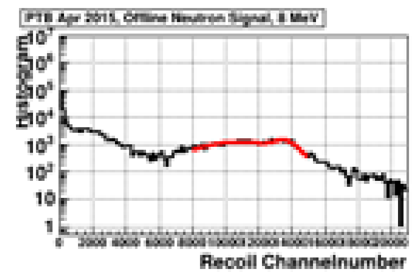
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4696573

4. Scintillation Light Creation/Propagation: Light Function Formalism

MCNP-PoliMi Scintillator Simulations



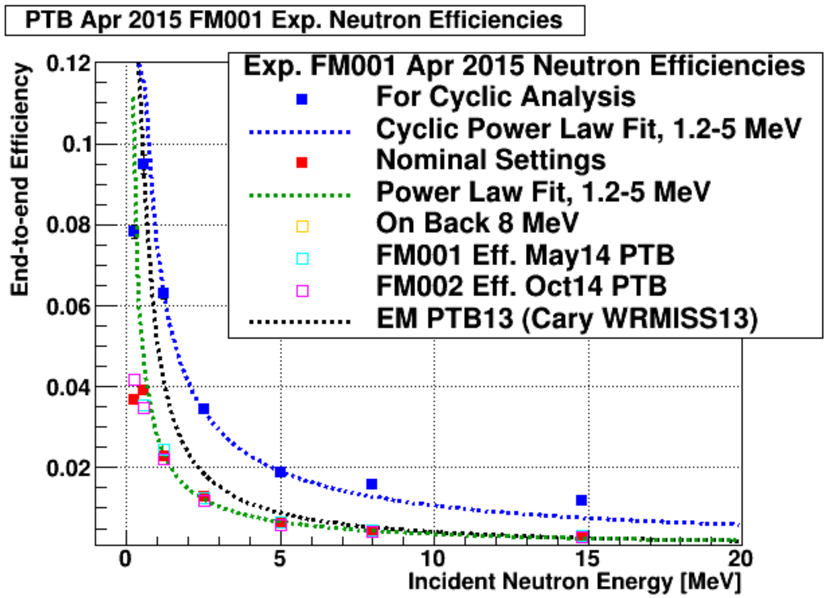
Exp. Recoil of 8 MeV Monoenergetic



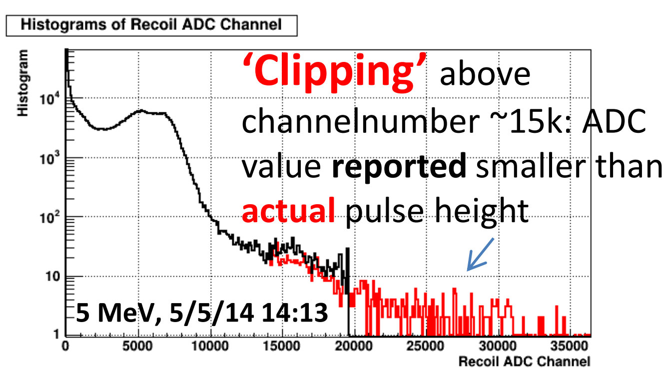
B: Misc Auxiliary Analysis Items

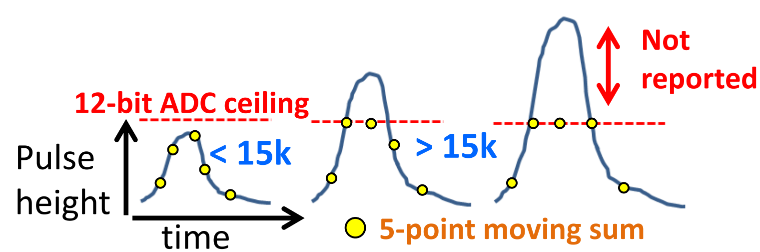
2) Neutron Efficiency Results, ADC Saturation

- Efficiencies from PTB datasets: Rel. uncertainties 2-3%;



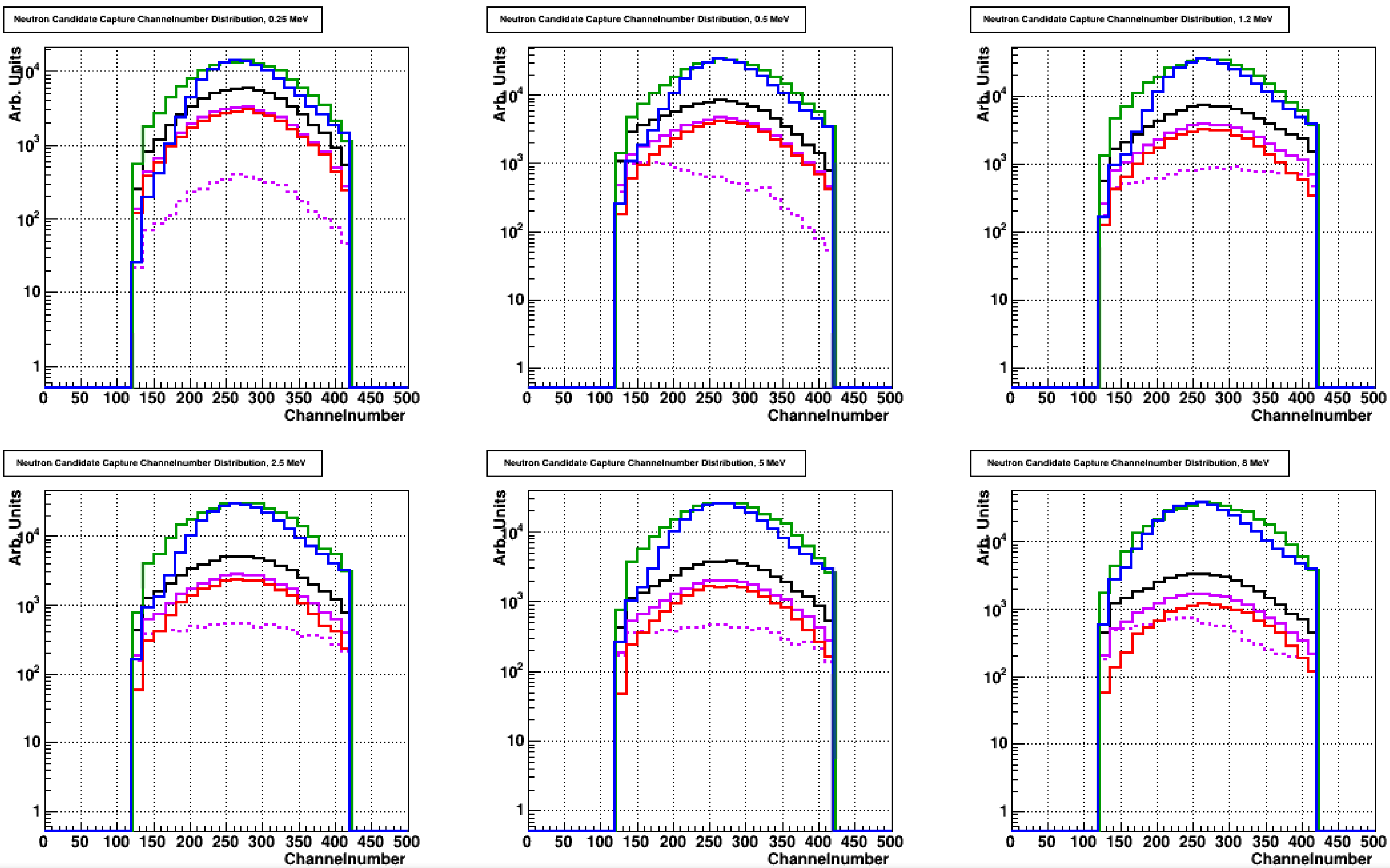
- ADC saturation for high pulse heights





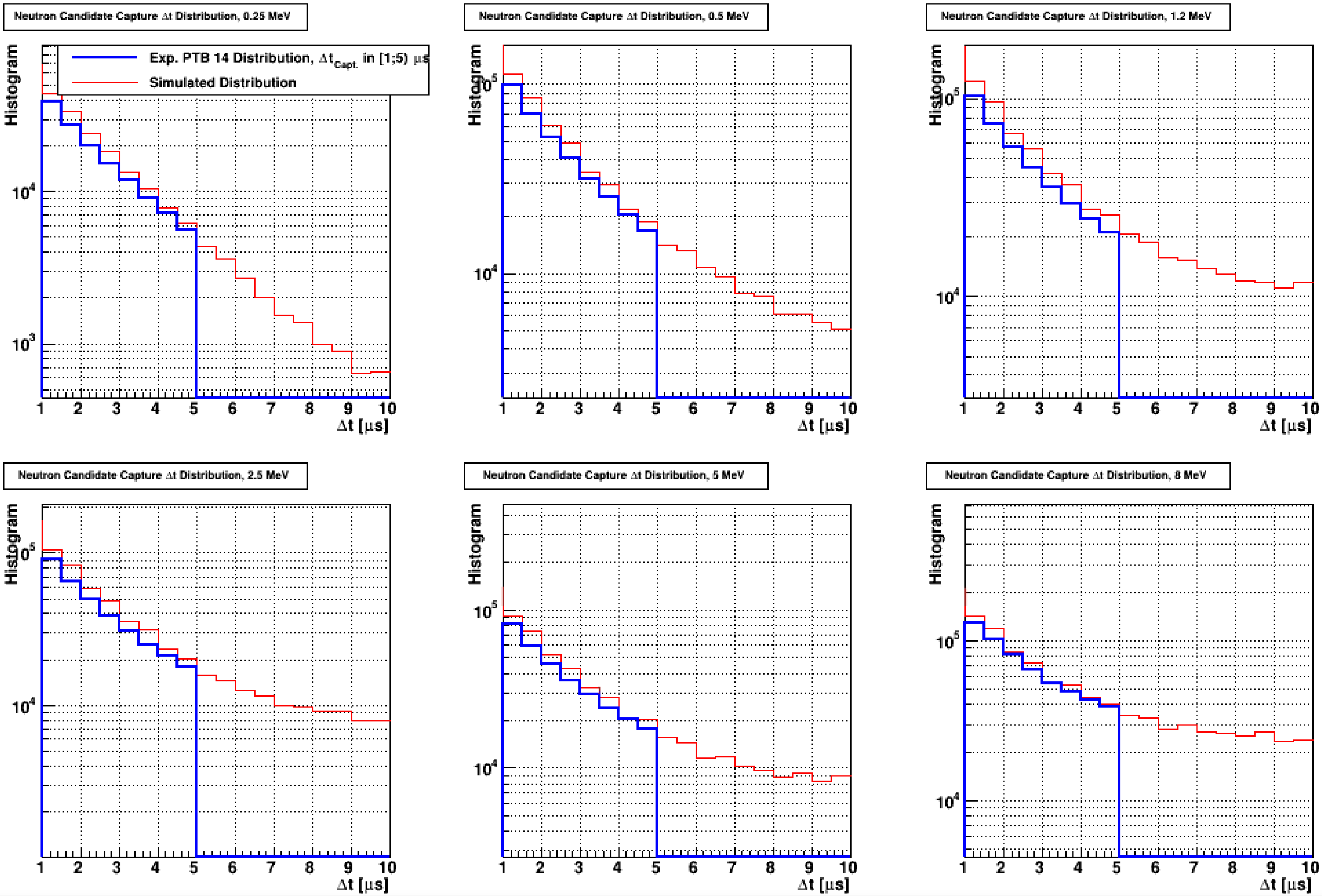
2) Preliminary Fit Result to Capture Pulse Distributions

- Experimental data not corrected for beam background/room return



2) Preliminary Simulation Result for Delta t Capture Distribition

- Experimental data not corrected for beam background/room return

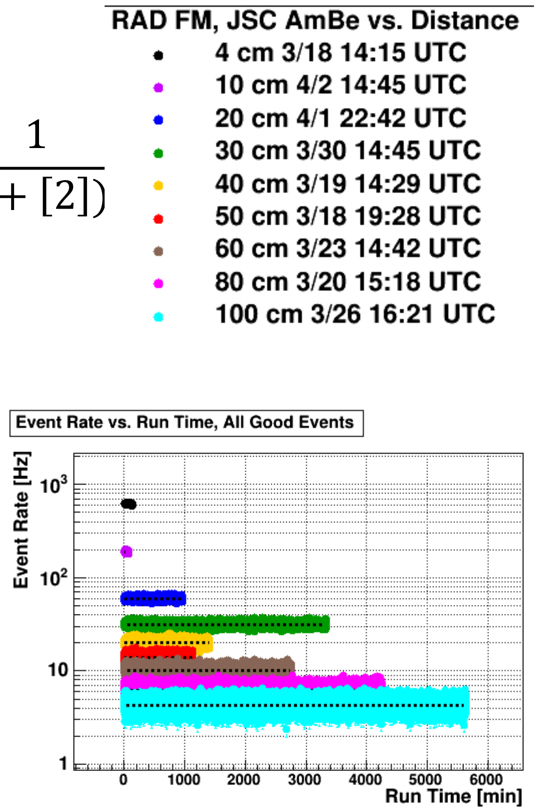


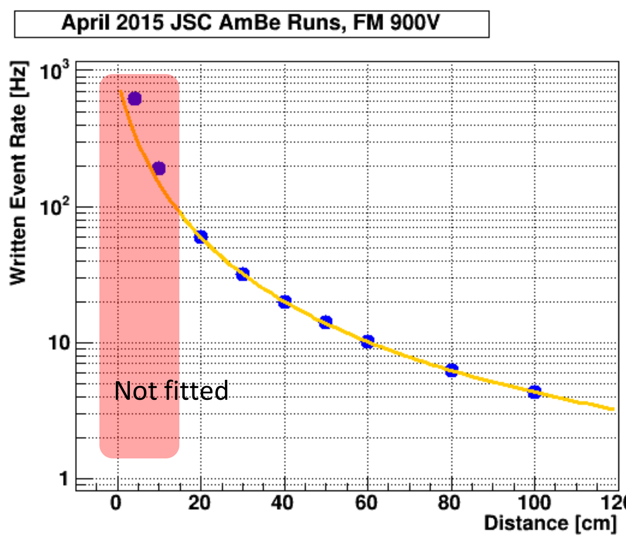
B2) Test: AmBe vs. Distance, Extraction of Absorption Depth

- To be able to approximate FND as point detector
- fit doubles rates with shifted inverse squares:

$$f(d) = [0] + [1] * \frac{1}{(d + [2])}$$

* only fit >=20cm data to avoid geometry issues (point source approximation);
* fit results:
    @ [0]: background rate 0.5 +- 0.07 Hz;
    @ [2]: **effective absorption depth** of RAD = **7.2 +- 0.5 cm**
* deduce distance from JSC source to expose FND to roughly 50 muSv/hr for reference (neglecting room scattering, probably ~20%):
    @ JSC calibration 5/21/14: source strength 2.380e+05 Hz;
    @ with ICRP74 AmBe conversion factor 391 pSv*cm^2 per n:
        -> distance from absorption center to source = 23.1 cm;
        -> distance from side of FND stack to source = **15.9 cm.**





red chisq. of fit = 5.52/4 = 1.38