DOUBLE CHOOZ RESULTS

PPC 2012 meeting, Seoul

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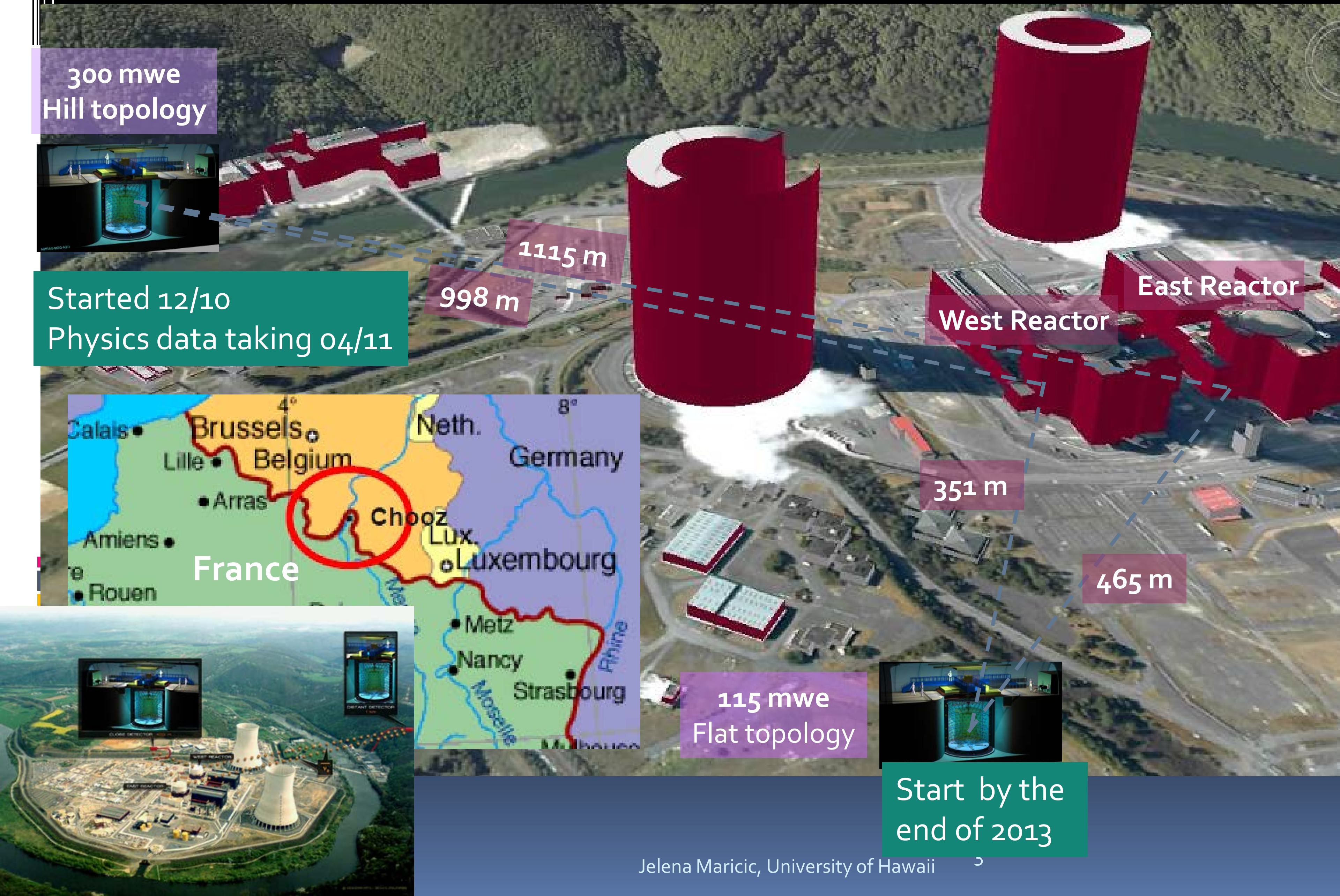
University of Hawaii
November 8, 2012

Outline

- Introduction: observing neutrinos from nuclear reactors with Double Chooz
- Detector - overview
- Double Chooz data analysis
  - Predicted neutrino rate and spectrum
  - Signal and event selection criteria
  - Detector systematic errors
  - Background estimation and measurement
- Oscillation analysis results and future prospects

Site in French Ardennes



Reactor Neutrino Detection Signature

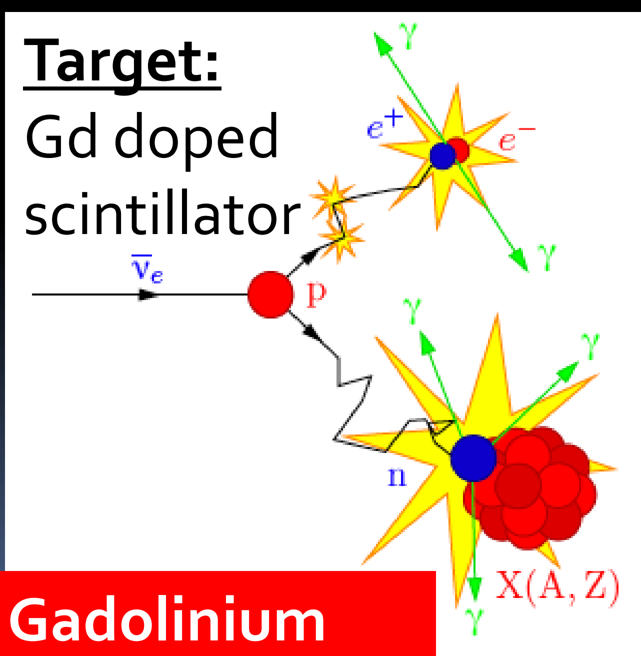
- Reactors as neutrino sources:

$$N_\nu\left(s^{-1}\right)=6N_{Fiss}\left(s^{-1}\right)\approx 2\times10^{11}P\left(s^{-1}\right)$$

Chooz: P =2x4.25 $GW_{th} \Rightarrow N_\nu \sim 2x10^{21} s^{-1}$

Neutrino detection via inverse β decay

$$\bar{\nu}_e + p^+ \rightarrow e^+ + n$$

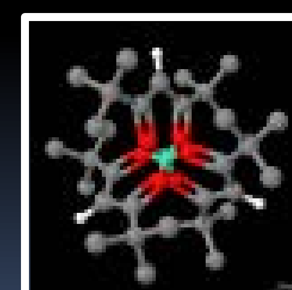


Double Chooz Scintillator

- Double Chooz scintillator:

-Solvent: 20% PXE ($C_{16}H_{18}$) + 80% Dodecane ($C_{12}H_{24}$) + PPO/Bis-MSB.

- 1 g/l $Gd(dpm)_3$ tris-(2,6-tetramethyl-3,5-heptanedione) Gd(III)



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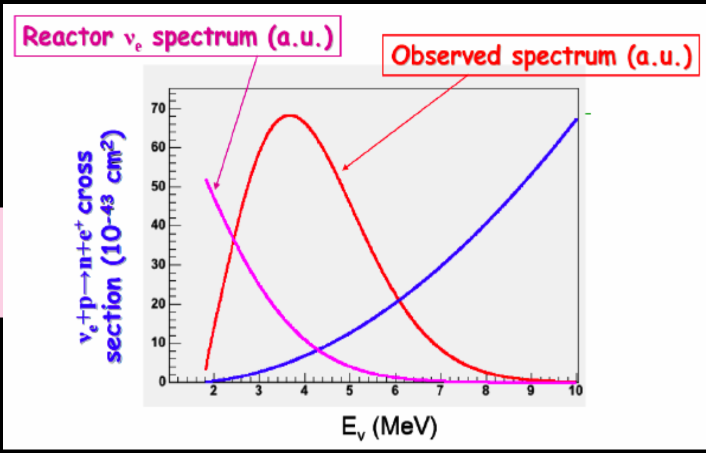

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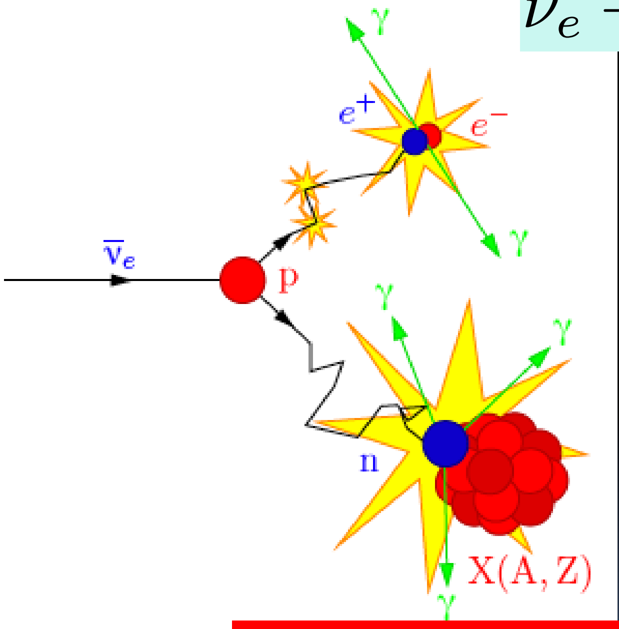


Gadolinium

Distinctive two-step signature:

-**prompt event**

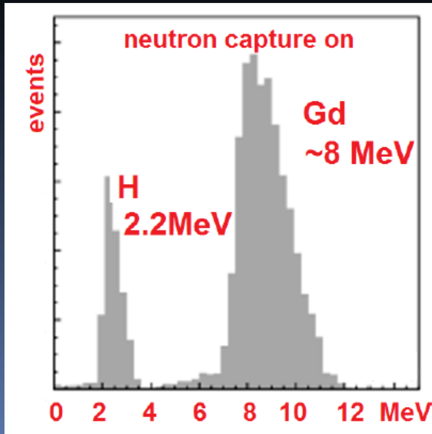
Photons from e^+ annihilation

$E_e = E_\nu$ - 0.8 MeV + $O(E_e/m_n)$

-**delayed event**

Photons from n capture on dedicated nuclei (Gd)

Δt ~ 30 μs   E ~ 8 MeV



The Double Chooz Far Detector

<u>Outer Veto (OV)</u>
plastic scintillator strips

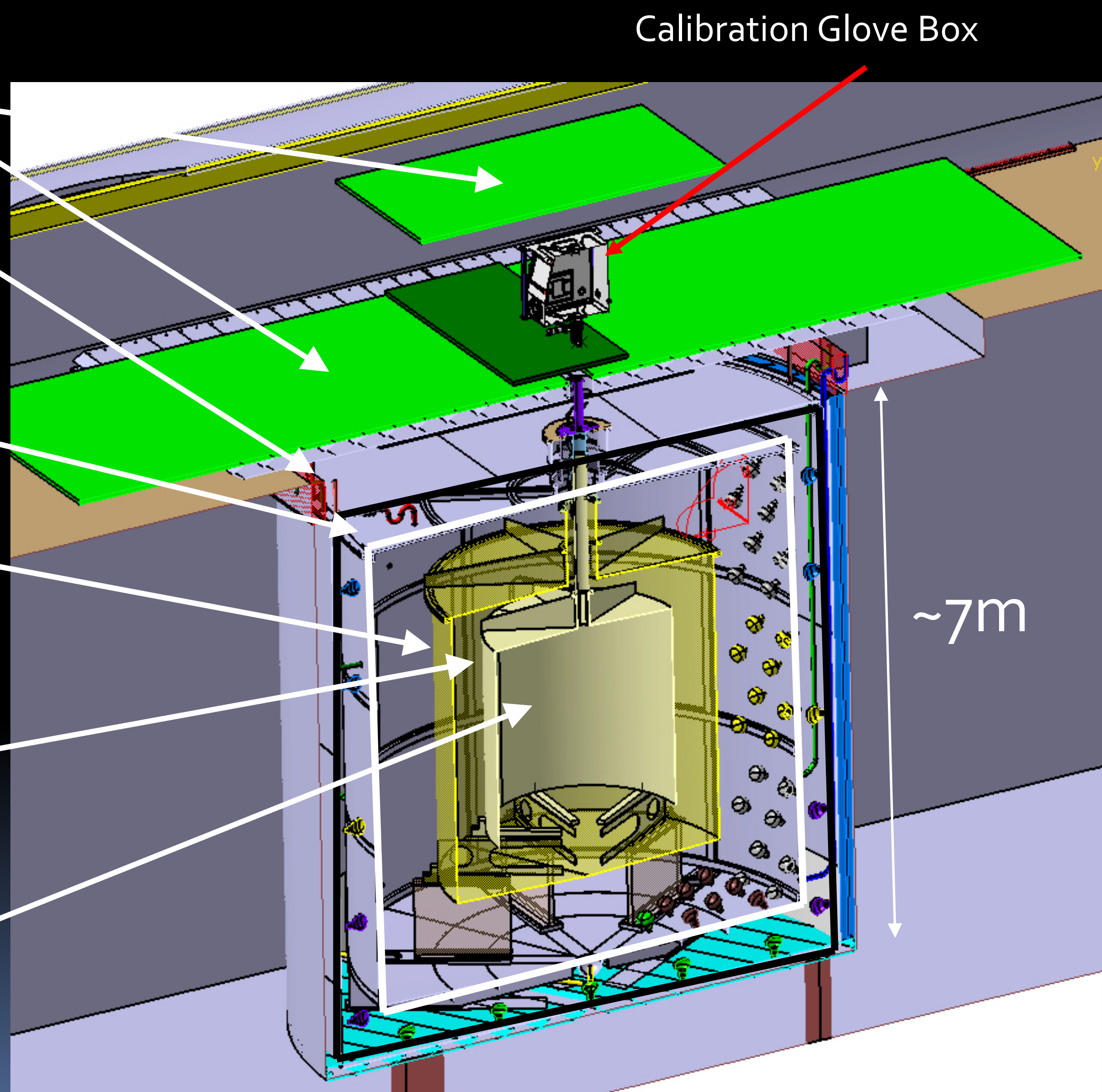
<u>Outer Steel Shielding</u>
250 t steel (15 cm)

<u>Inner Veto (IV)</u>
90 m^3 of scintillator in a steel vessel (10 mm) equipped with 78 PMTs (8 inches)

<u>Buffer</u>
110 m^3 of mineral oil in a steel vessel (3 mm) equipped with 390 PMTs (10 inches)

<u>γ-Catcher (GC)</u>
22.3 m^3 scintillator in an acrylic vessel (12 mm)

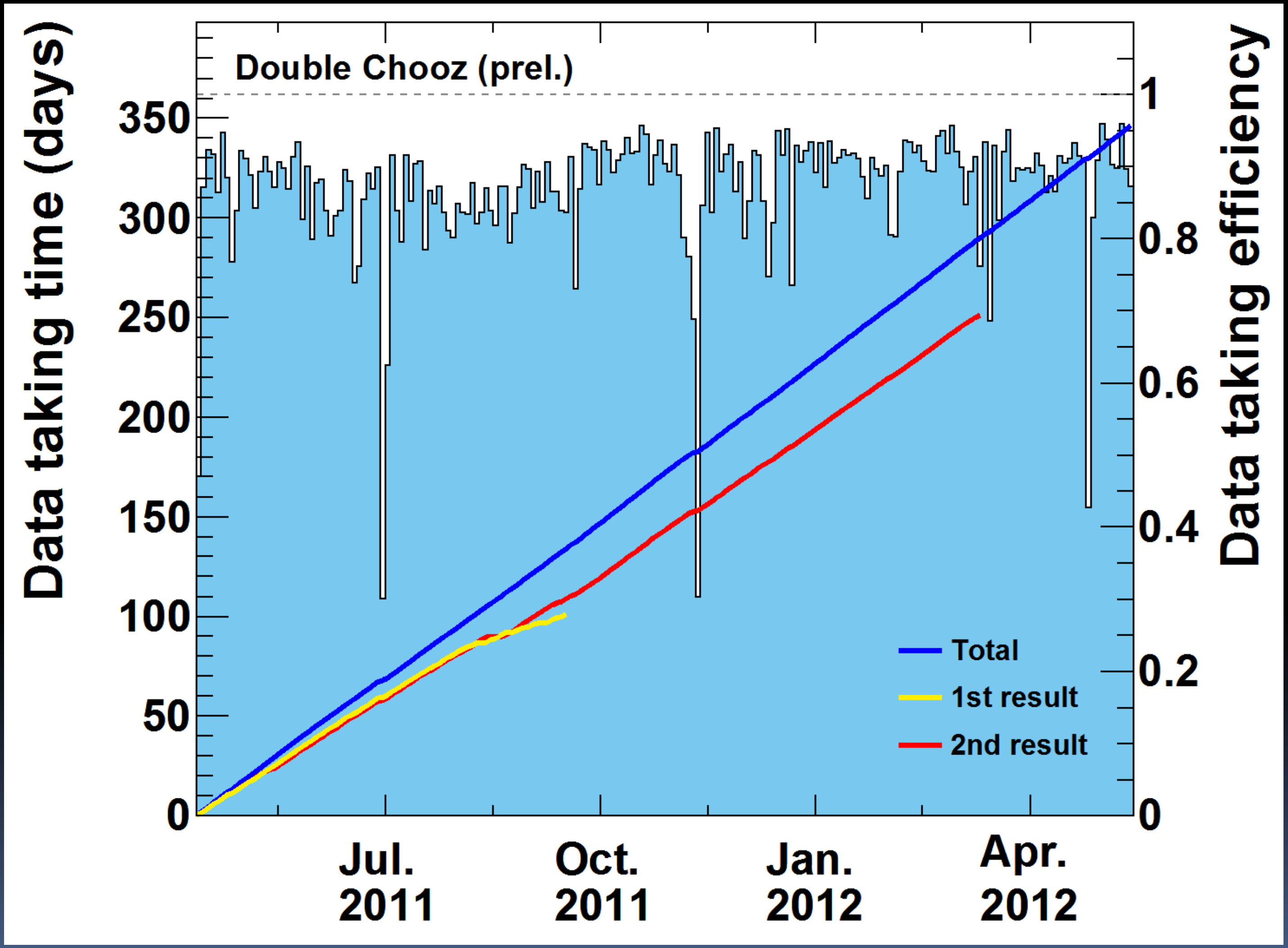
<u>Target</u>
10.3 m^3 scintillator doped with 1g/l of Gd compound in an acrylic vessel (8 mm)



Double Chooz θ_{13} Data Analysis

θ_{13}

Data taking is stable



Expected Neutrino Rate

Number of protons in the target

IBD detection efficiency

Reactor thermal power

$$N_{\nu}^{\exp}(E,t) = \sum_{\substack{\text{Reactors} \\ R=\{1,2\}}} \frac{N_p \varepsilon}{4\pi L_R^2} \times \frac{P_{th,R}(t)}{\langle E_f \rangle_R (t)} \times \langle \sigma_f \rangle_R (E,t)$$

Neutrino traveled distance

Average energy released per fission

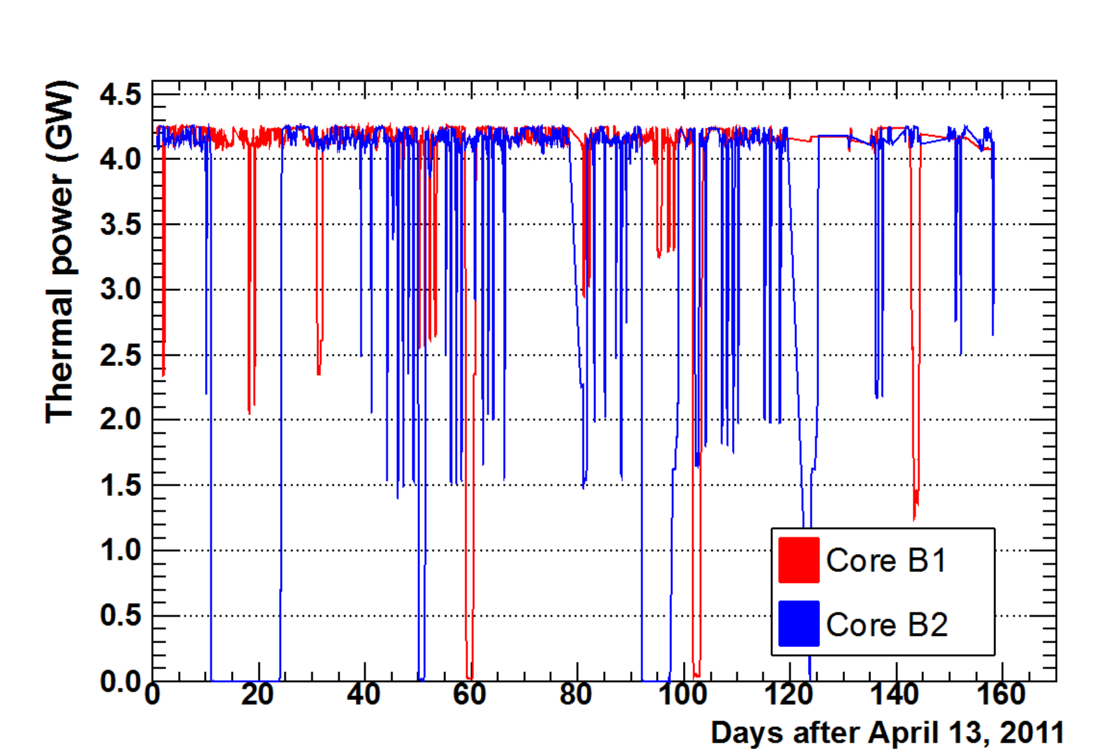
Neutrino interaction c-s: The probability that an average reactor fission will create a neutrino interaction with a single target proton.

Core thermal power

$$N_{\nu}^{\exp}(E,t) = \sum_{\substack{\text{Reactors} \\ R=\{1,2\}}} \frac{N_p \varepsilon}{4\pi L_R^2} \times \frac{P_{th,R}(t)}{\langle E_f \rangle_R (t)} \times \langle \sigma_f \rangle_R (E,t)$$

- Precise weekly measurements of steam generator enthalpy balance.
- Monitoring every minute based on temperature in primary loop.
- Full error treatment by EDF

$\delta P_{th}/P_{th} = 0.46\%$

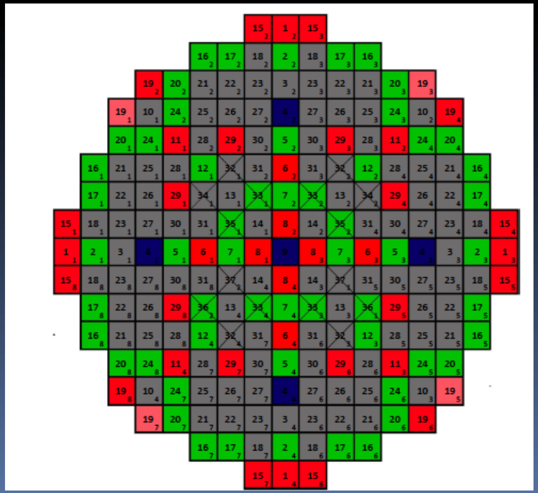


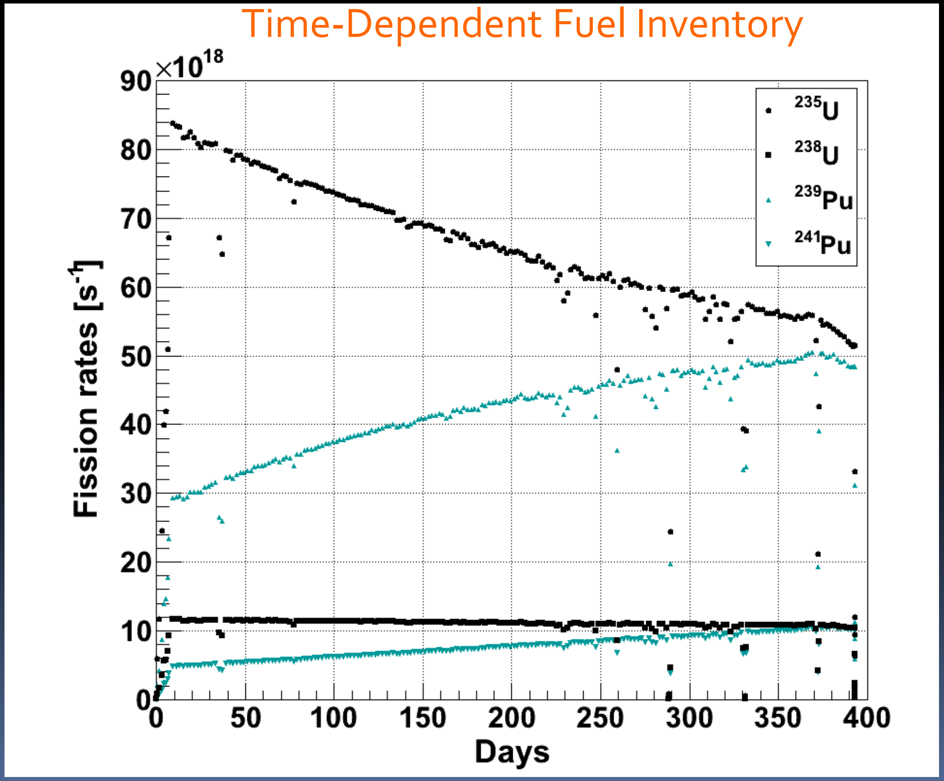
Reactor core fuel composition

$$N_{\nu}^{\exp}(E,t) = \sum_{\substack{\text{Reactors}\\ R=\{1,2\}}} \frac{N_p \varepsilon}{4\pi L_R^2} \times \frac{P_{th,R}(t)}{\langle E_f \rangle_R (t)} \times \langle \sigma_f \rangle_R (E,t)$$

Two validated reactor simulations:

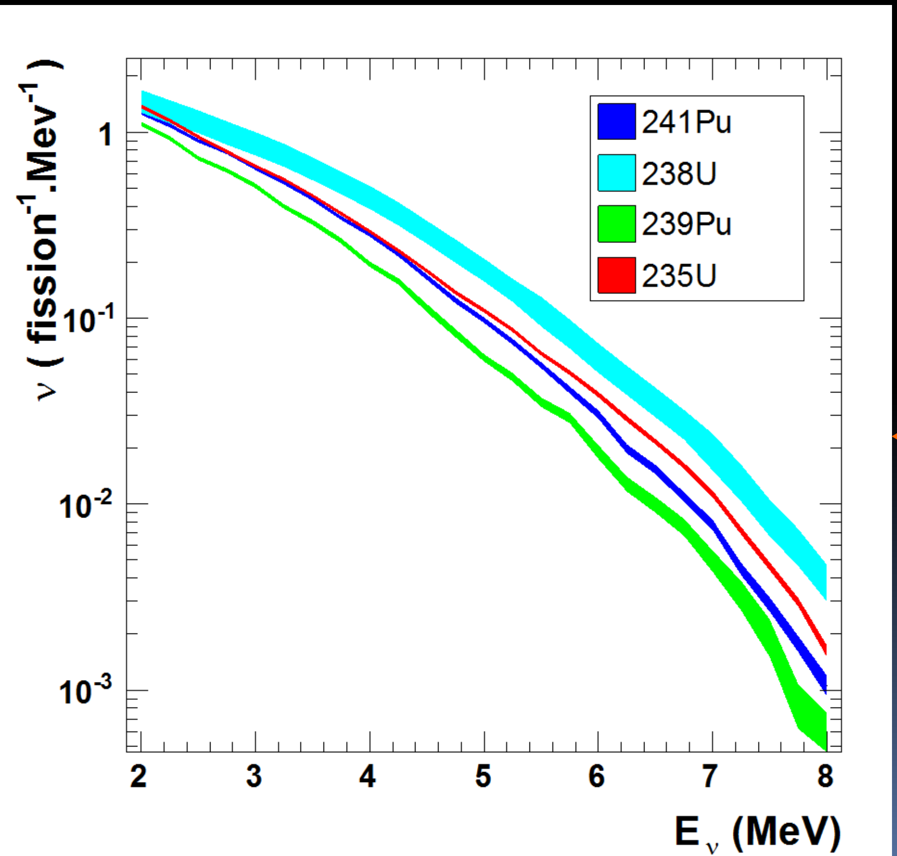
- DRAGON: deterministic
- MURE (MCNP Utility for Reactor Evolution): Monte-Carlo Based
- Benchmarked against fuel assays: C. Jones et al. arxiv.org/pdf/1109.5379





Interaction Cross-Section

$$N_{\nu}^{\exp}(E,t) = \sum_{\substack{\text{Reactors}\\ R=\{1,2\}}} \frac{N_p \varepsilon}{4\pi L_R^2} \times \frac{P_{th,R}(t)}{\langle E_f \rangle_R(t)} \times \langle \sigma_f \rangle_R(E,t)$$



$$\langle \sigma_f \rangle_k = \int_0^{\infty} dE\, S_k(E)\, \sigma_{IBD}(E)$$

- Recalculations of spectra introduced normalization shift; "anomaly"?
  - Th.A. Mueller et al, Phys.Rev. C83(2011) 054615.
  - P. Huber, Phys.Rev. C84 (2011) 024617

Reference Spectra + Bugey4 "Anchor"

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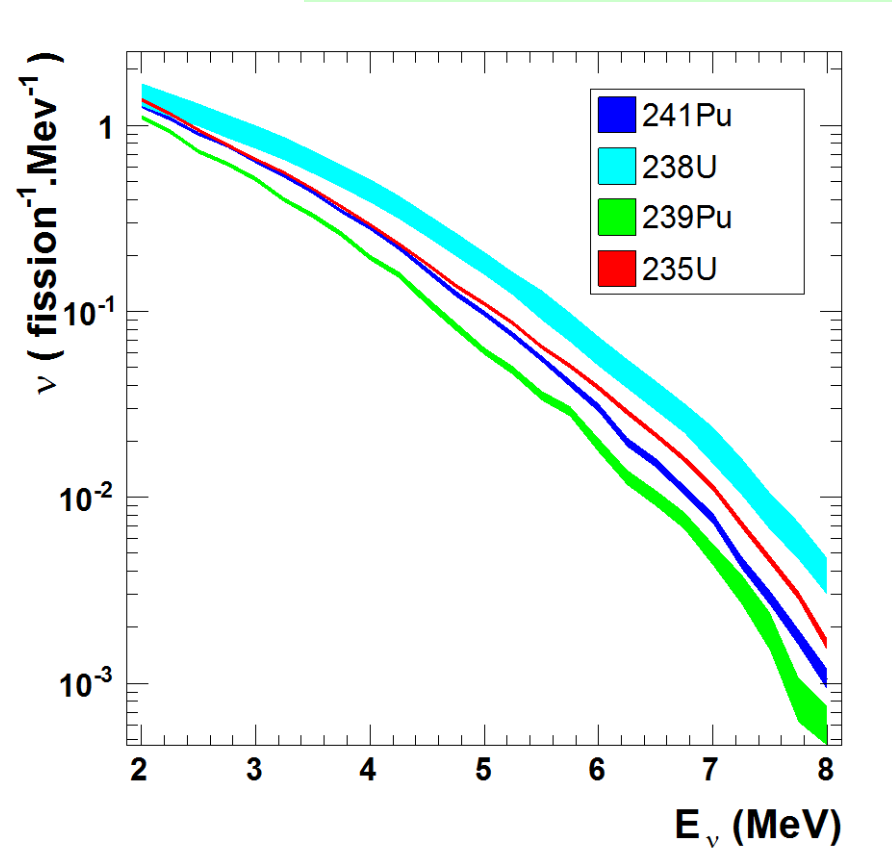

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\+ Normalize to Total Rate Measurement of Bugey4 (14 m from reactor core)

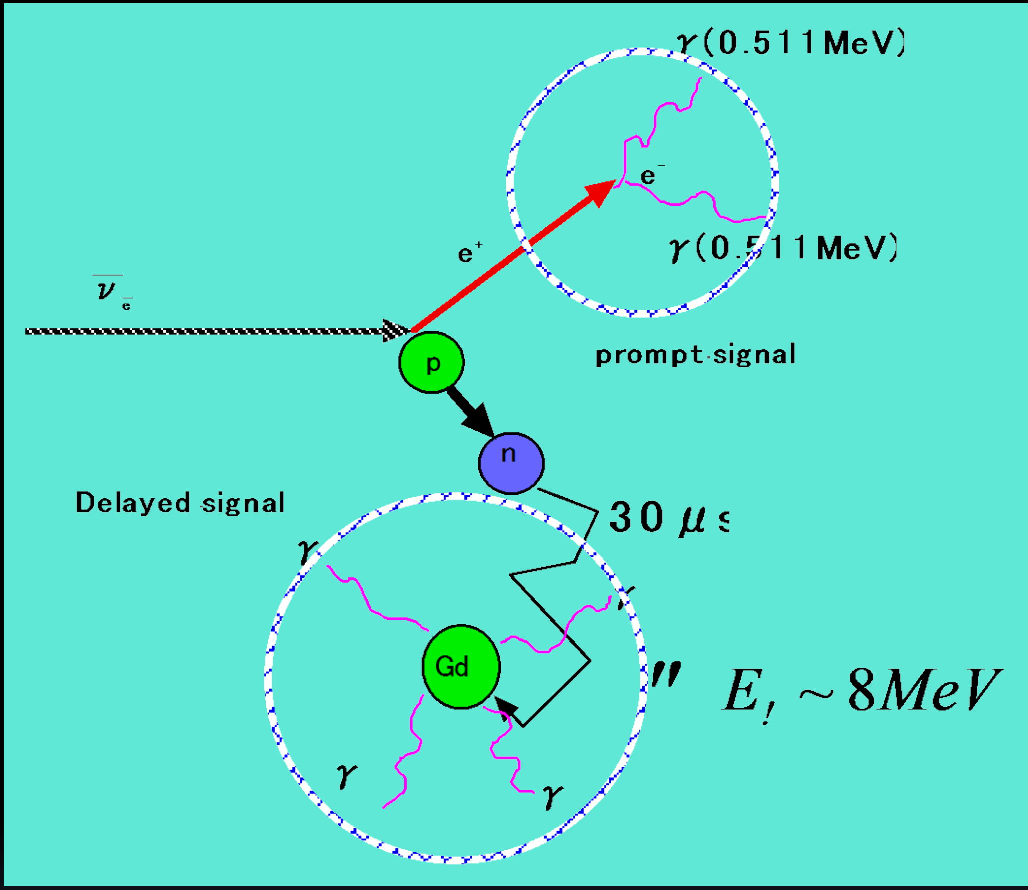
$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k \left(\alpha_k^{DC}(t) - \alpha_k^{Bugey}(t) \right) \langle \sigma_f \rangle_k$$

Reduces reactor normalization uncertainty from 2.70% to 1.76%

Neutrino Candidate Selection

- Prompt signal Evis = [0.7, 12.2] MeV
- Delayed signal Evis = [6.0, 12.0] MeV
- Delayed Coincidence Δt = [2, 100] μsec
- Require Δt_{μ} > 1 msec
- PMT light noise rejection cuts
  - PMT hits approx. homogeneous
  - PMT hits approx. coincident in time
- Multiplicity conditions:
  - No extra events around signal

    (100 μs prior and 400 μs after prompt ev)
- Background rejection:
  - No coincident signal in OV
  - Require Δt_{μ} > 500 msec if E_{μ} > 600 MeV



<u>Plus three irreducible backgrounds</u>:

- Accidentals
- Cosmogenic ^{9}Li
- Fast neutrons/stopping muons

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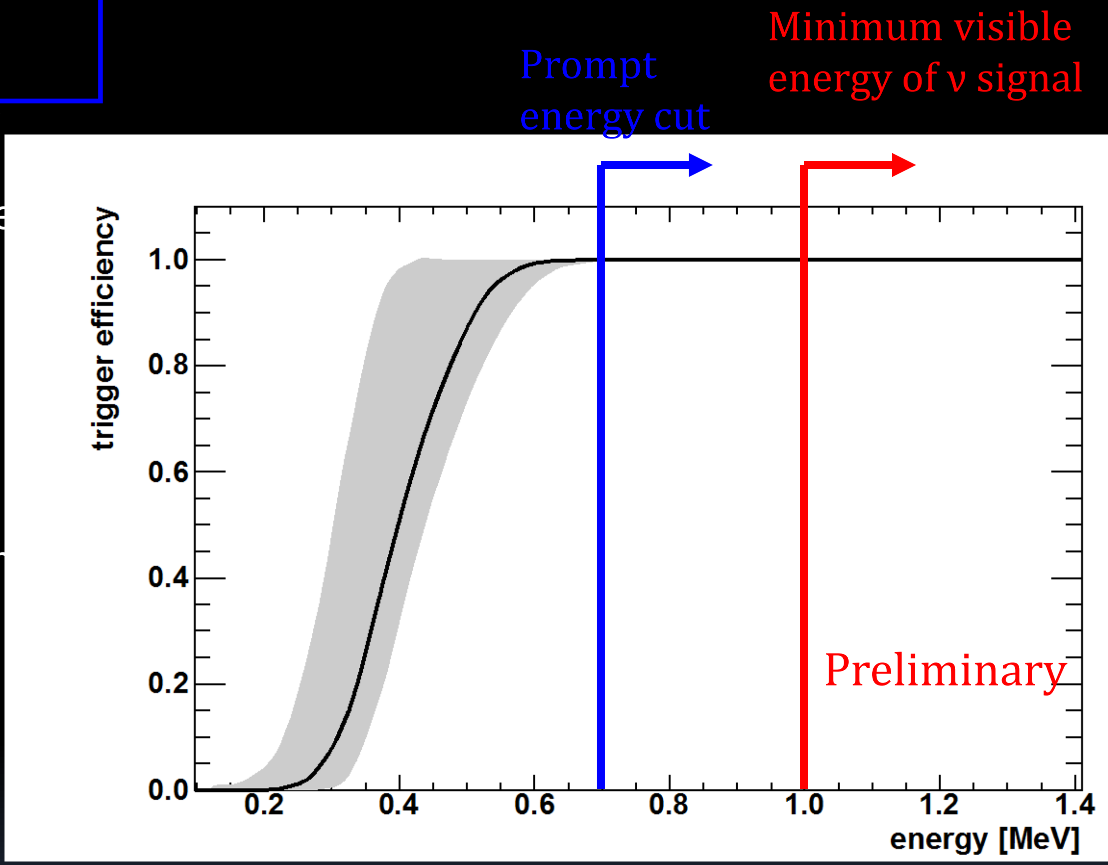

Trigger efficiency

- Threshold at 400keV (ε=50%)
- ε=100% above 700keV

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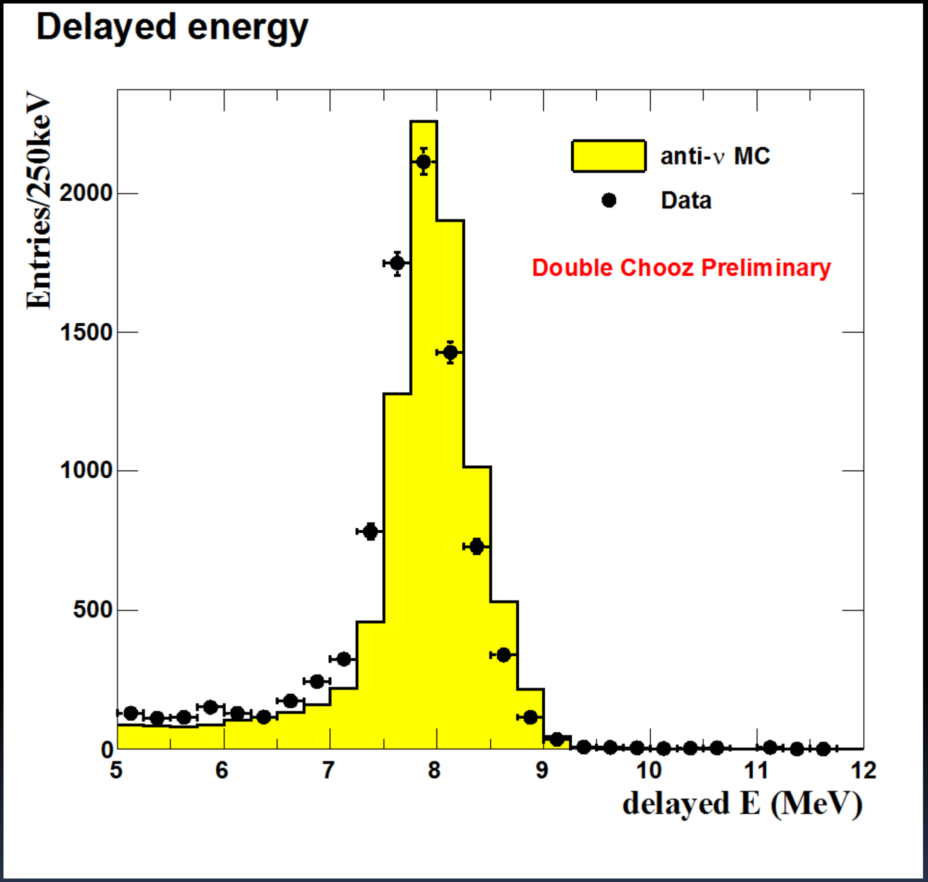

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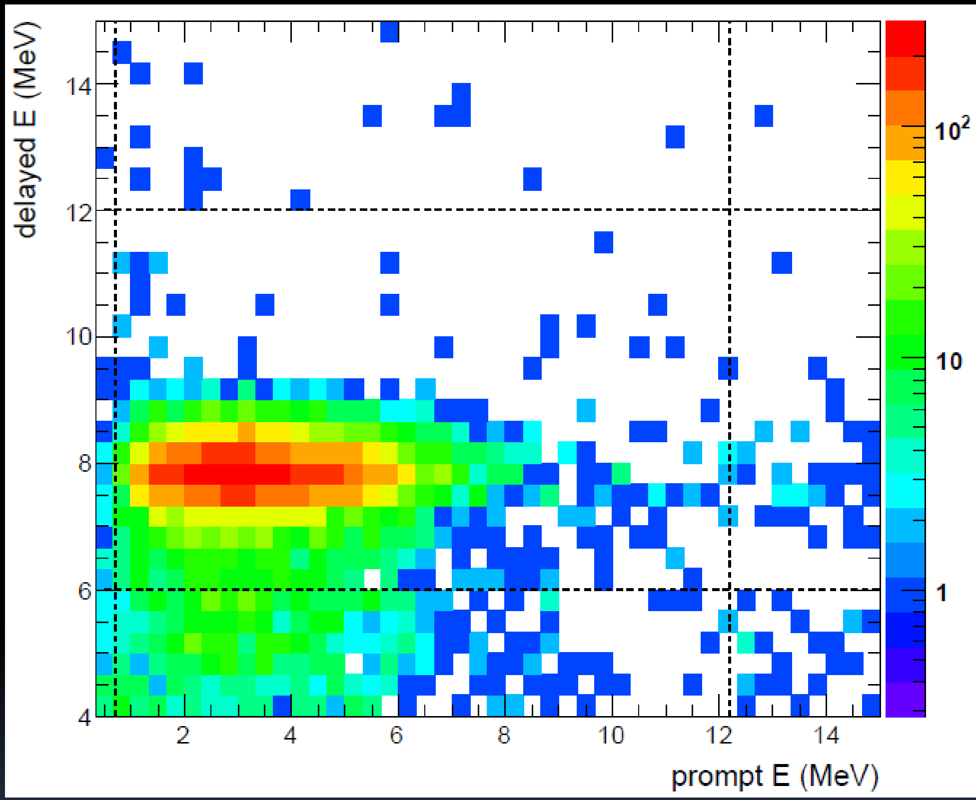

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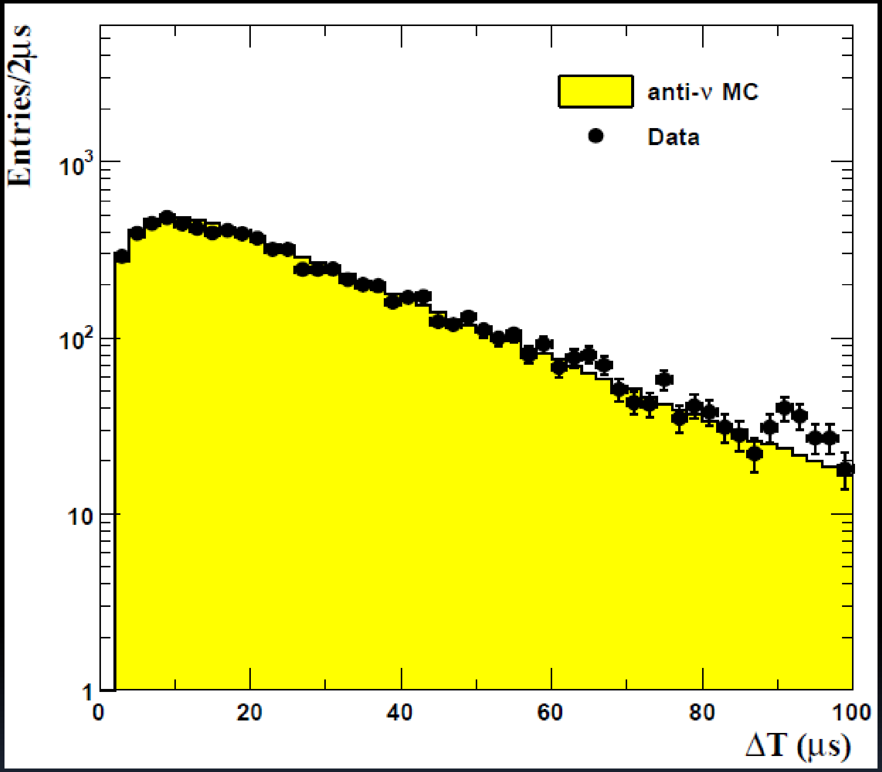

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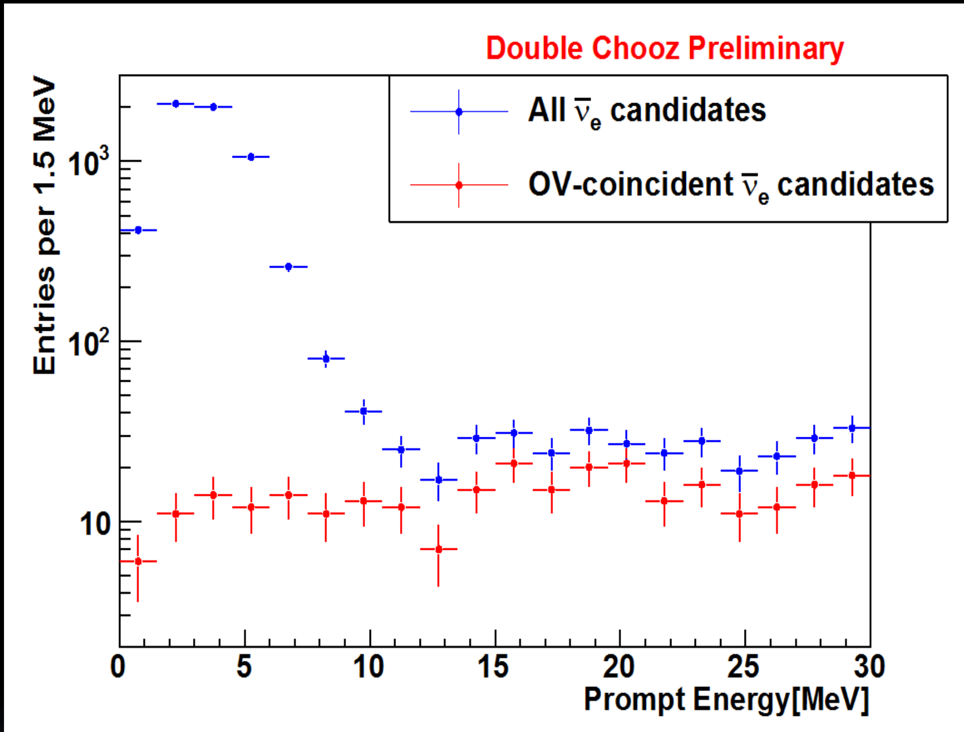
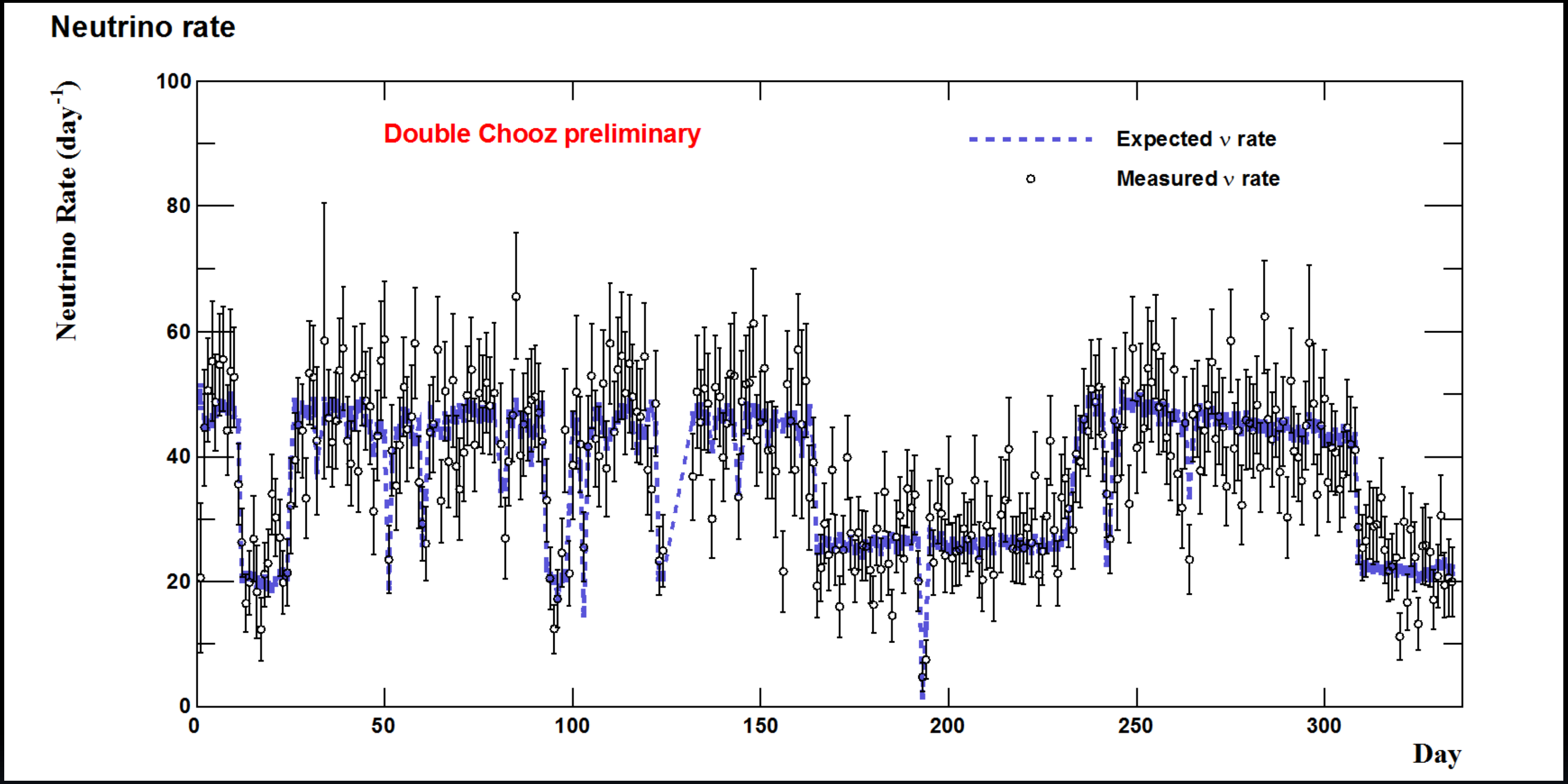


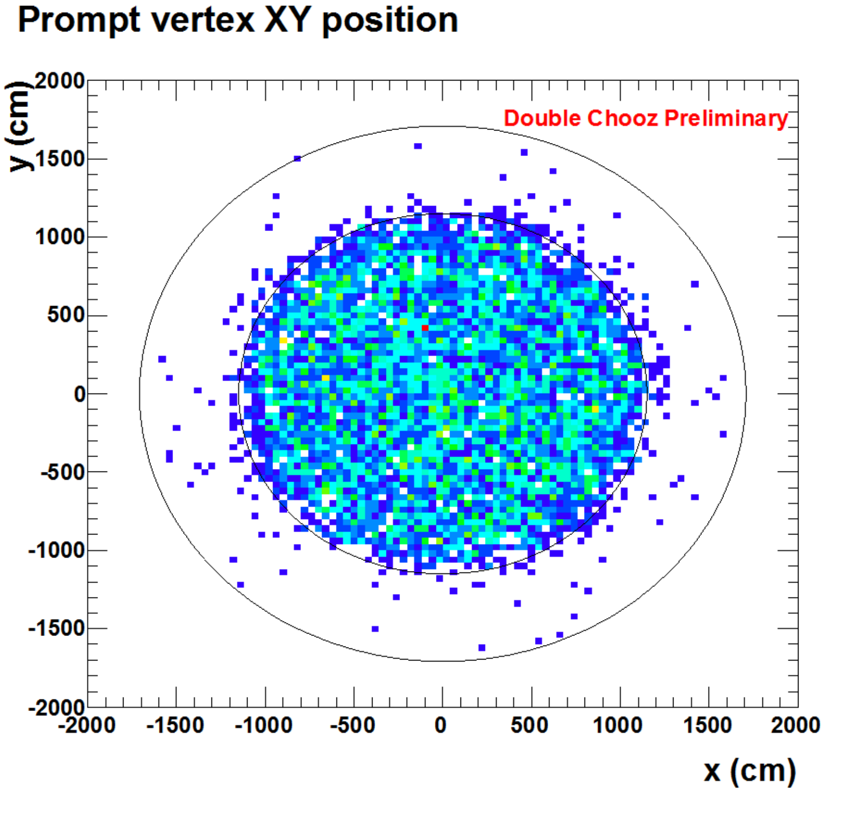
- 41% of ^{9}Li BG is rejected by additional muon veto (~5% live-time loss)
- 28% of fast neutron/stop μ BG is rejected by OV anticoincidence

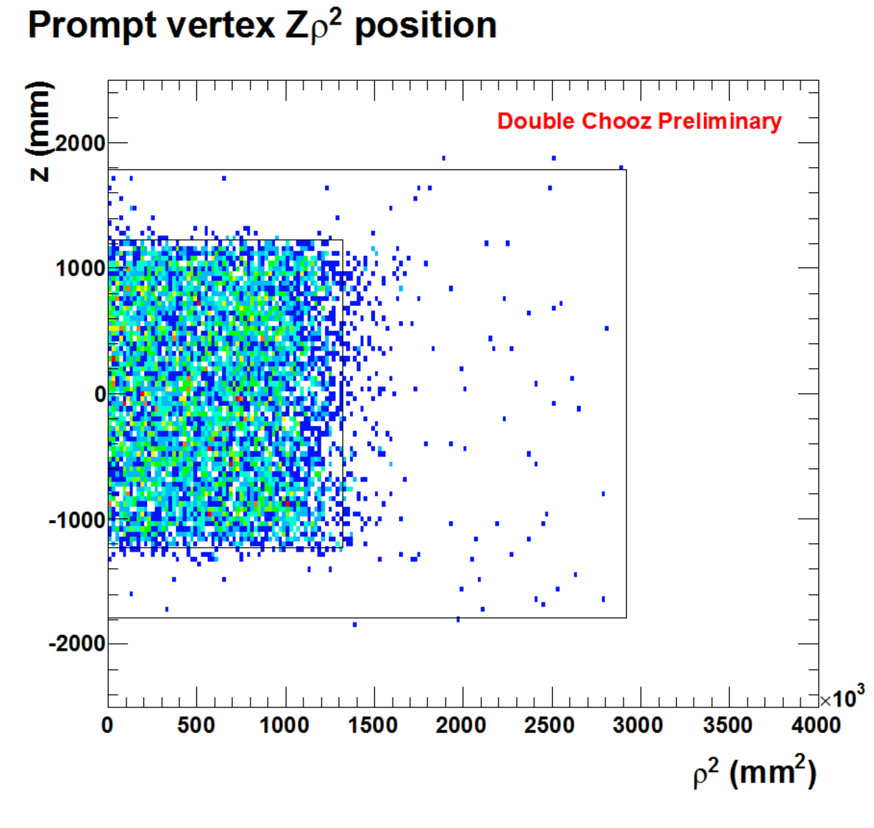
Candidate Rate Variation



- Before ^{9}Li reduction cut, no OV anticoincidence applied
- Not background-subtracted
- Rate consistent with expectation

Cross-check: Reconstructed Vertex Position





- Events well-localized within target
- Note: no spatial cuts applied in candidate selection

Detector calibration

Energy calibration: PMT and electronics gain non-linearity, correct for position dependence, correct for time stability, energy scale non-linearity

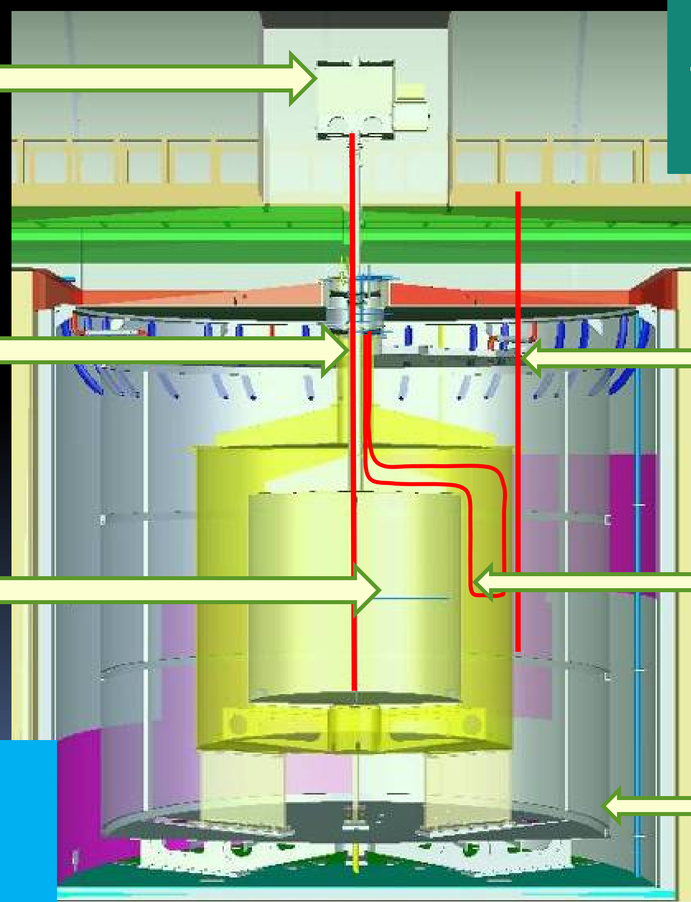
Neutron detection efficiency calibration:

Energy & time window, Gd fraction, spill in/out effects

Goal: 0.5% total systematic error with 2 detectors!

Natural sources:

- Spallation nH-capture peak – spacial non-unif.
- Spallation n Gd-capture peak – time stability



Glovebox

Fish-line
Energy scale
Neutron det. eff.

Buffer guide tube

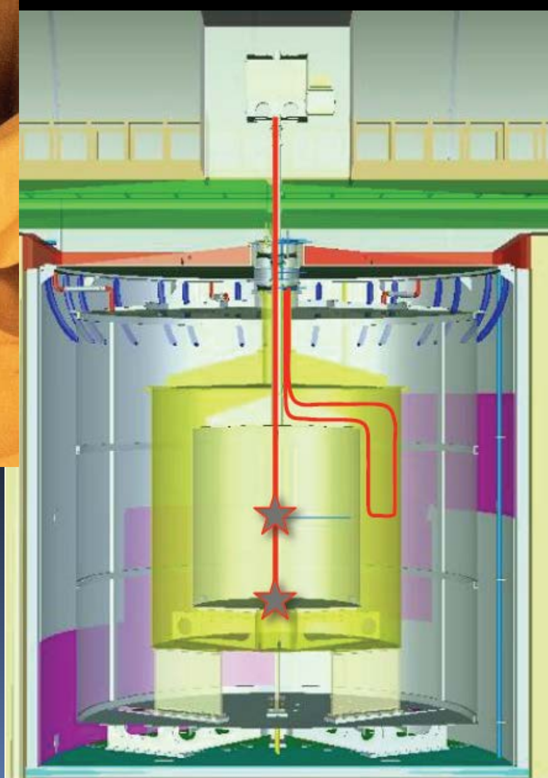
Articulated Arm
Energy scale
Spill-out
Neutron det. Eff.

Gamma-catcher guide tube
Energy scale
Spill-in
Neutron det. Eff.

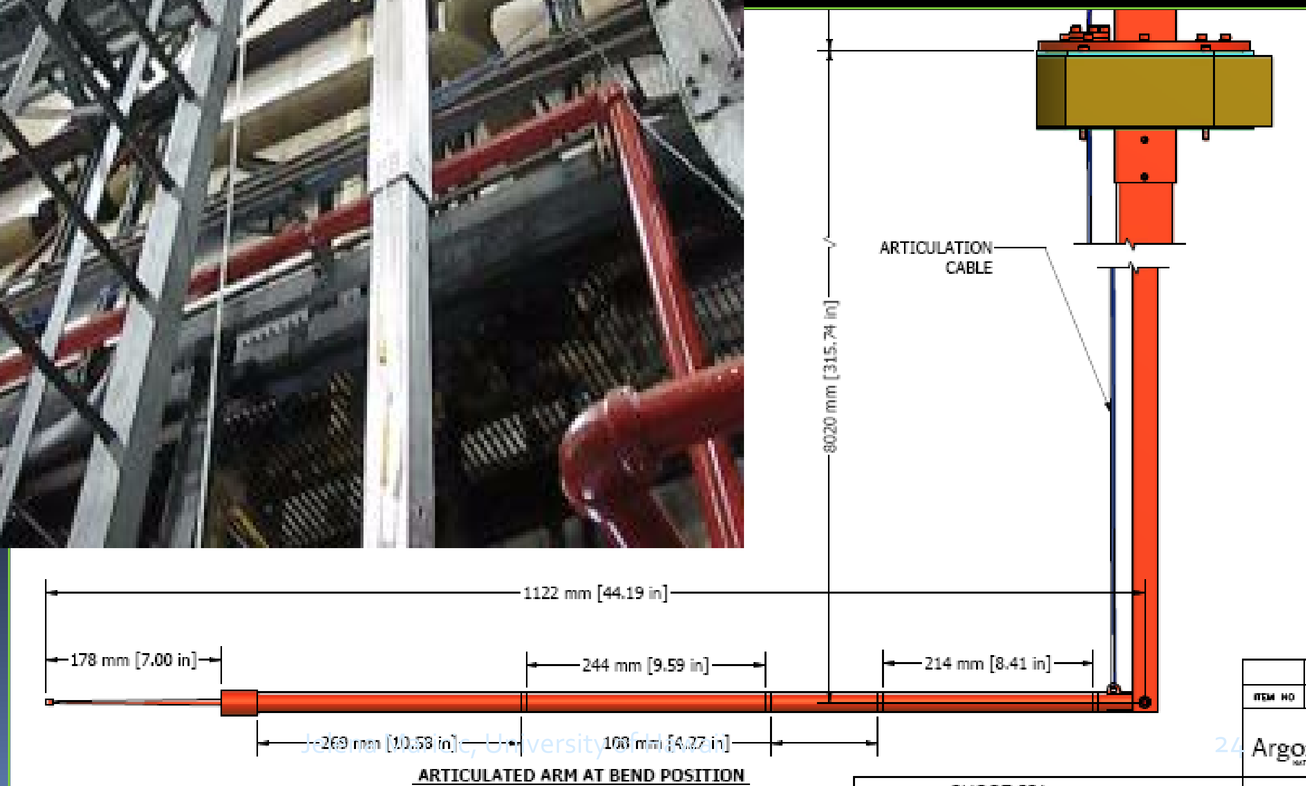
LED LI system
PMT and electronic gain non-linearity calibration

Deployed in NT and GC:
^{137}Cs, ^{60}Co, ^{68}Ge, ^{252}Cf

Z-axis (fish-line) and guide tube

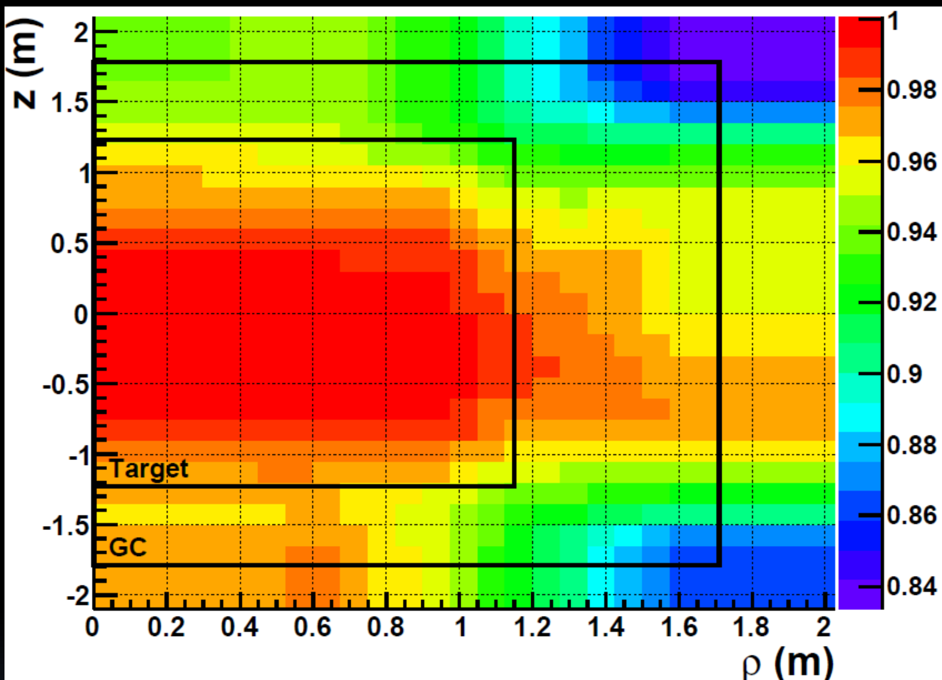


Design details: Articulated Arm



Detector Calibration

Energy Calibration

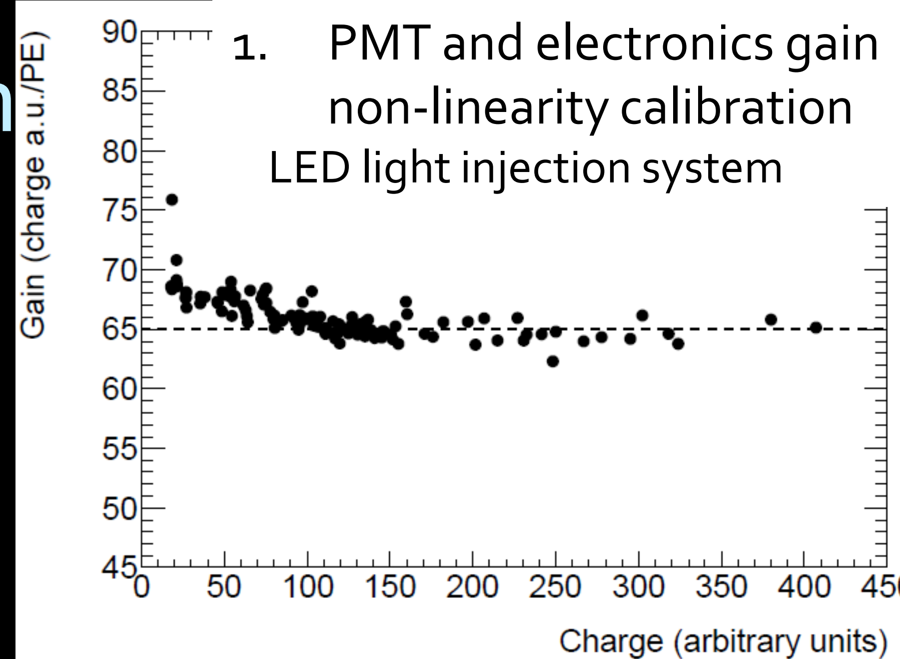


Correct for position dependence

Spallation neutron H captures

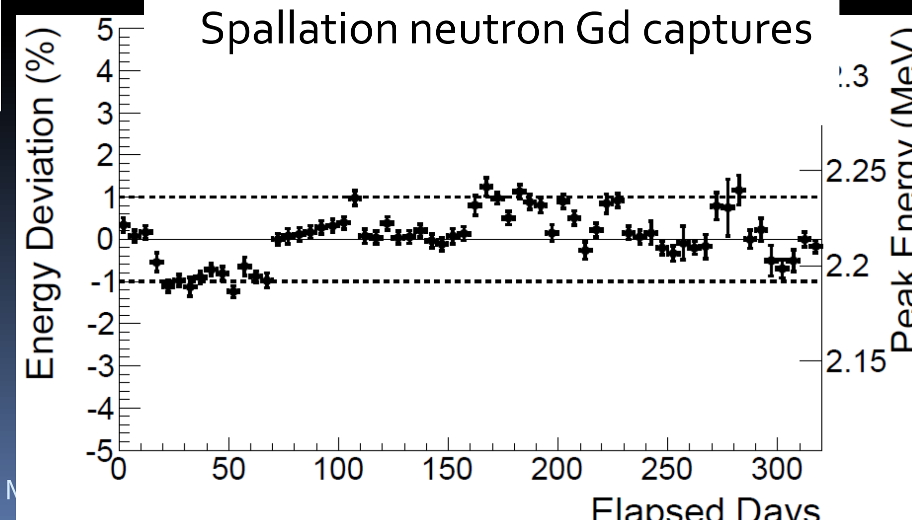
1. PMT and electronics gain non-linearity calibration

LED light injection system



Correct for time stability

Spallation neutron Gd captures



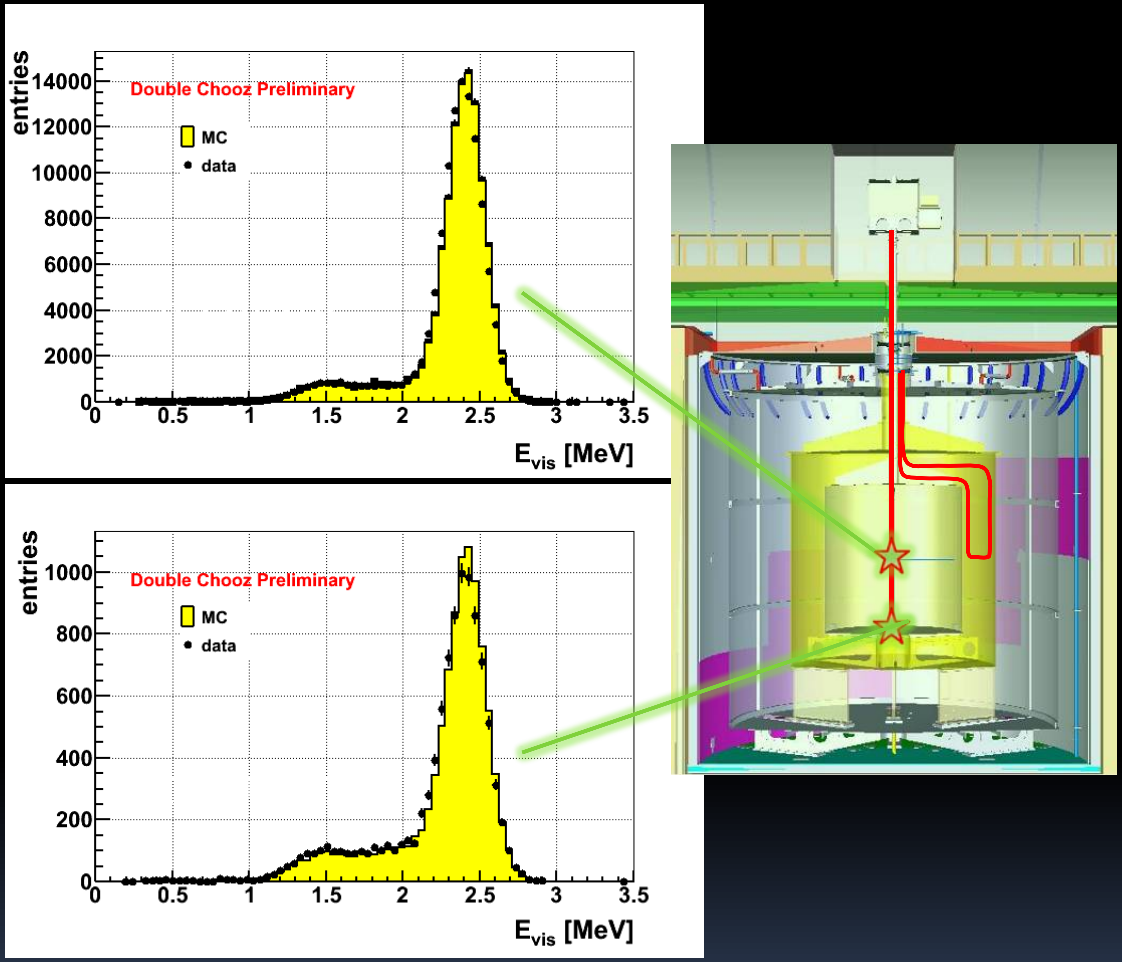
Detector Calibration

Energy Calibration

Energy scale

- Radioactive sources deployed into ν-target and γ-catcher

- **Deployed in NT and GC:**
- **^{137}Cs, ^{60}Co, ^{68}Ge, ^{252}Cf**

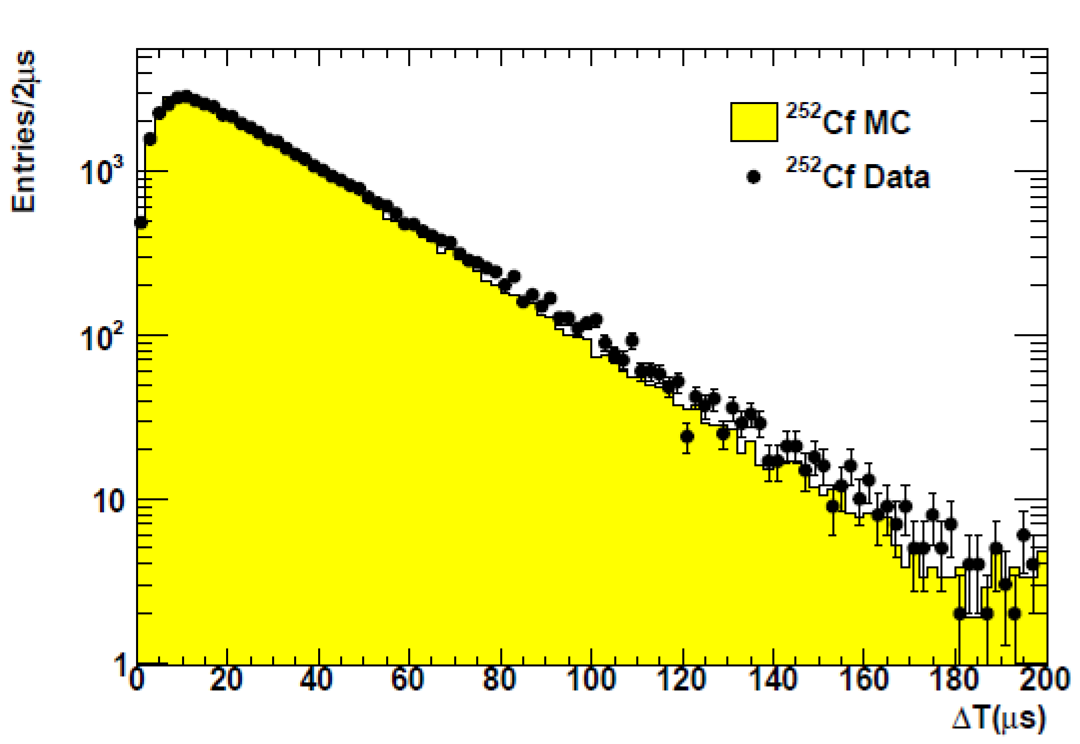


Detector Calibration

Neutron Detection Efficiency

Energy & time window, Gd fraction, spill in/out effects

- ^{252}Cf source deployed into ν-target and γ-catcher



Backgrounds

Accidentals

- Prompt: radiation hit on PMT
- Delayed: spallation neutron capture
- Prevented by radiopurity & shielding
- Measured from off-time windows:

0.261 +/- 0.002 day^{-1}

Cosmogenic ^{9}Li

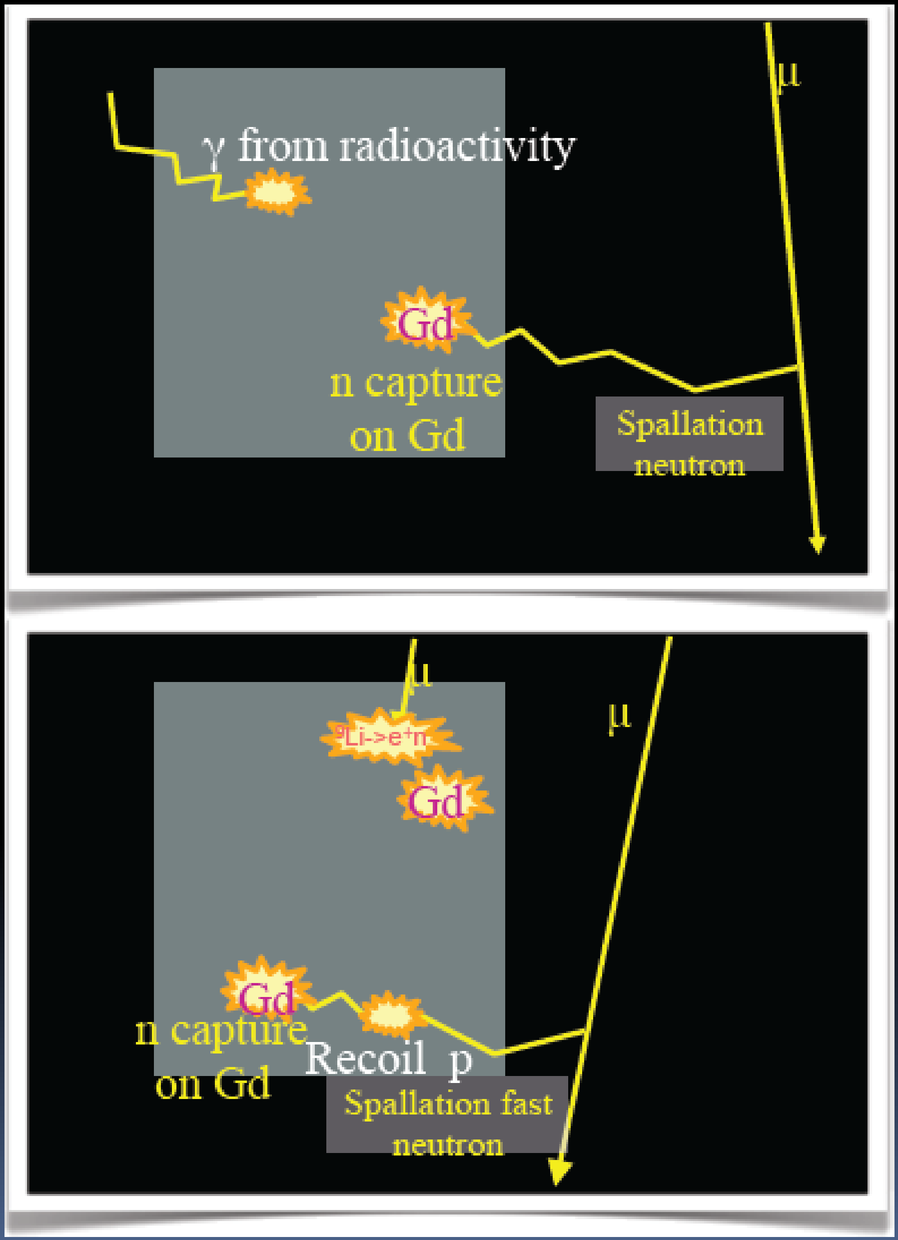
- Prompt: beta emission
- Delayed: neutrons from long-lived decays
- Measured from Δt_{μ} & spatial muon coincidence:

1.25 +/- 0.54 day^{-1}

Fast-n & Stopping muons

- Prompt: proton recoil or muon track
- Delayed: neutron capture or muon decay
- Measured from high-energy spectrum:

0.67 +/- 0.20 day^{-1}

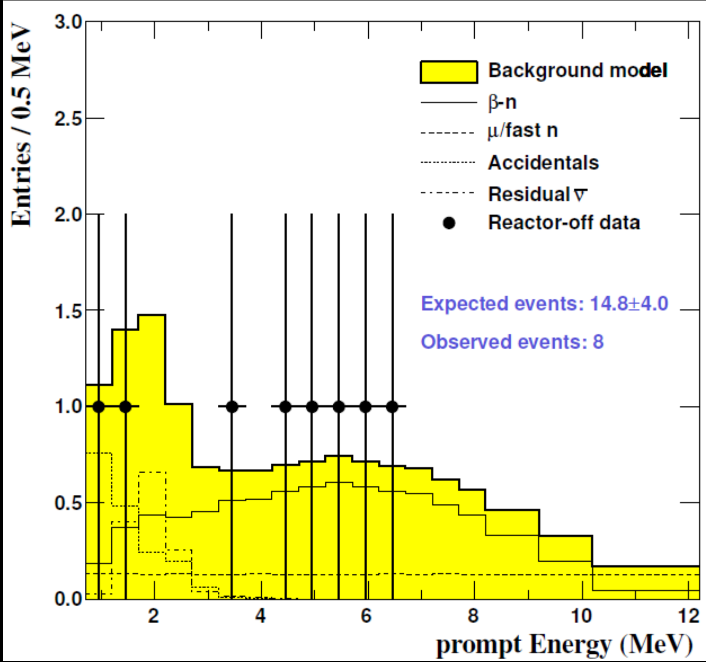


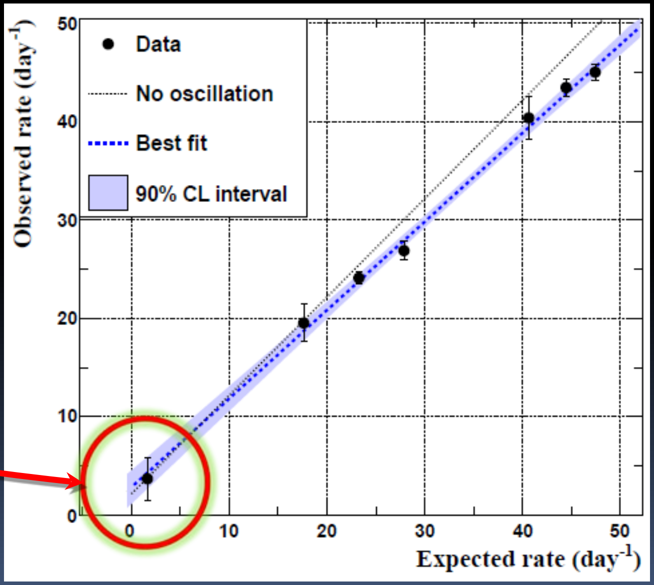
Check Rate vs. Reactor Power

One week of both reactors off data obtained.
BG rate measured:
1.0 ±0.4 events/day

→ Background rate consistent with estimation (2.0±0.6 event/day)

arXiv:1210.3748





Summary of Rate Uncertainties

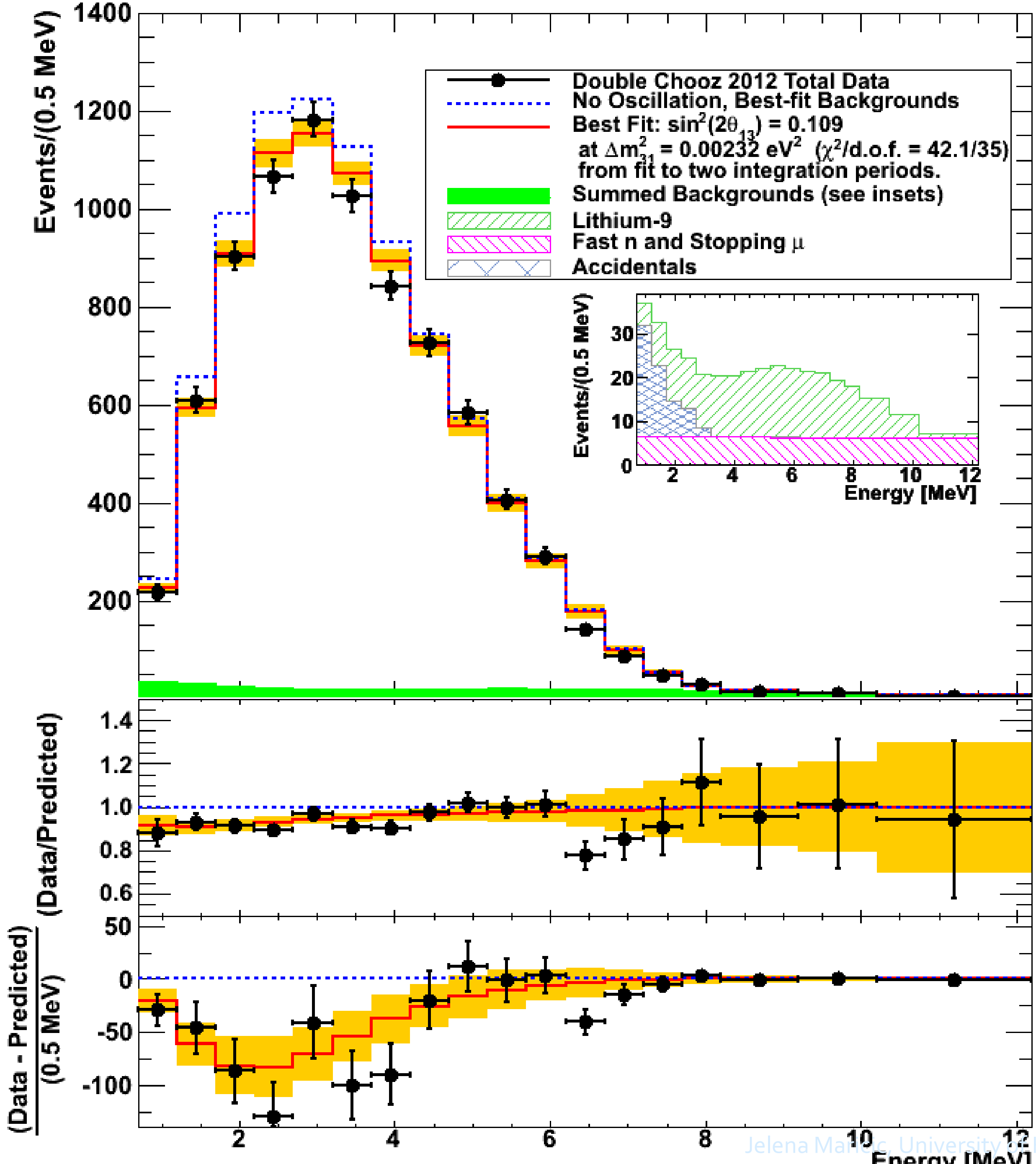
Source		Uncertainty w.r.t. signal	
Statistics		1.1%	
Flux		1.7%	
Detector	Energy response	0.3%	1.0%
	E_{delay} containment	0.7%	
	Gd fraction	0.3%	
	Δt cut	0.5%	
	Spill in/out	0.3%	
	Trigger efficiency	<0.1%	
	Target H	0.3%	
Background	Accidental	<0.1%	1.6%
	Fast-n + stop μ	0.5%	
	^{9}Li	1.4%	

Summary of Candidates

	Both Reactors On	One Reactor $P_{th} < 20\%$	Total
Livetime [days]	139.27	88.66	227.93
IBD Candidates	6088	2161	8249
Prediction			
Reactor B1 ν	2910.9	774.6	3685.5
Reactor B2 ν	3422.4	1331.7	4754.1
^{9}Li	174.1	110.8	284.9
FN & SM	93.3	59.4	152.7
Accidentals	36.4	23.1	59.5
Total Prediction	6637.1	2299.7	8936.8

- Data divided into two integration periods based on reactor power
  - Allows use of changing signal/background ratio in fit

Double Chooz Prompt Spectrum



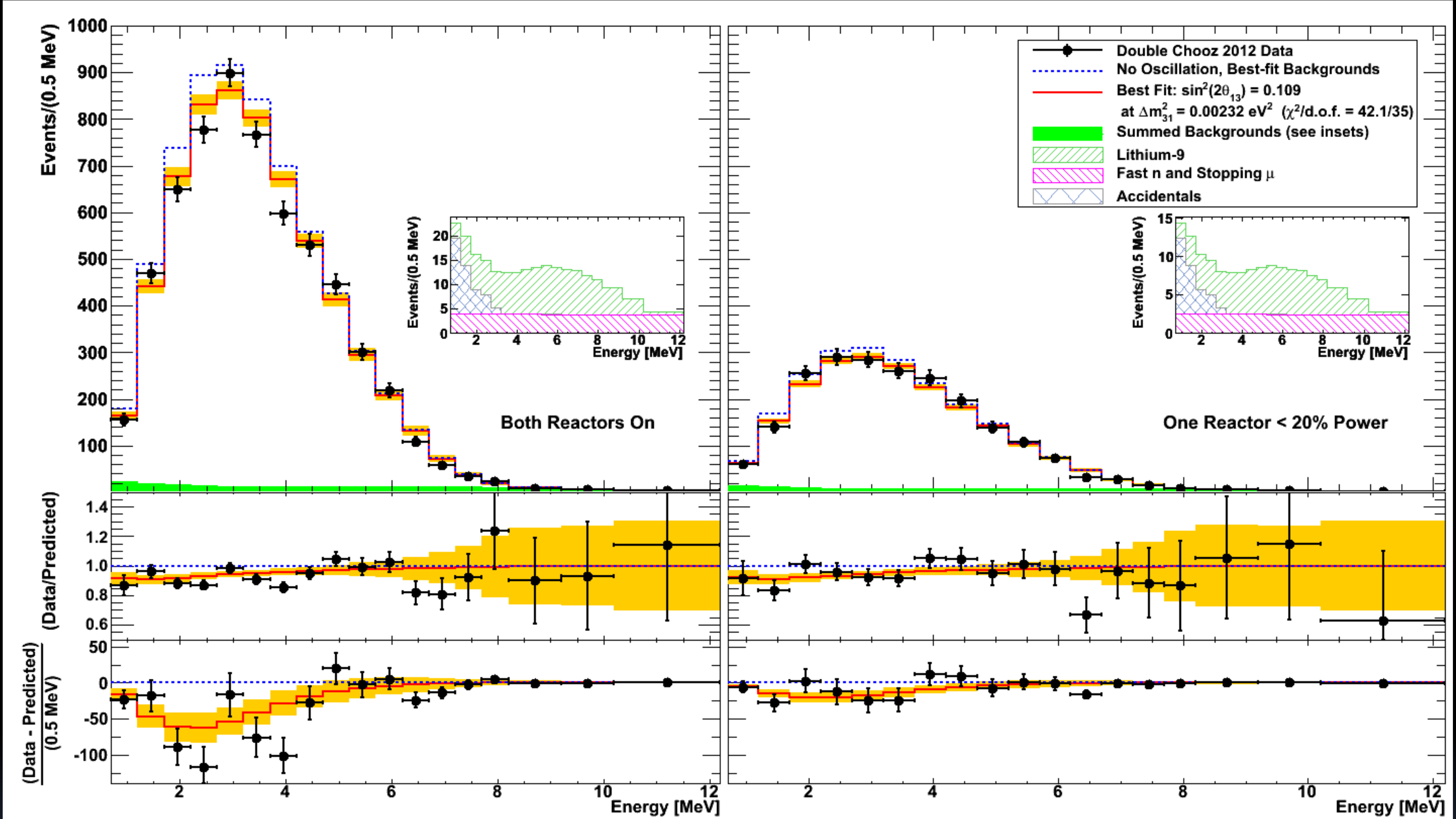
Data w/ Stat. Error Bars

Best Fit Prediction

(w/ Syst. Errors)

Null Oscillation Prediction

Backgrounds



Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030$ (stat.) $\pm\ 0.025$ (syst.)

$\chi^2/\text{d.o.f.} = 42.1/35$

Rate-only: $\sin^2 2\theta_{13} = 0.170 \pm 0.035$ (stat.) $\pm\ 0.040$ (syst.)

Frequentist analysis: $\sin^2 2\theta_{13} = 0$ excluded at 99.8% (2.9σ)

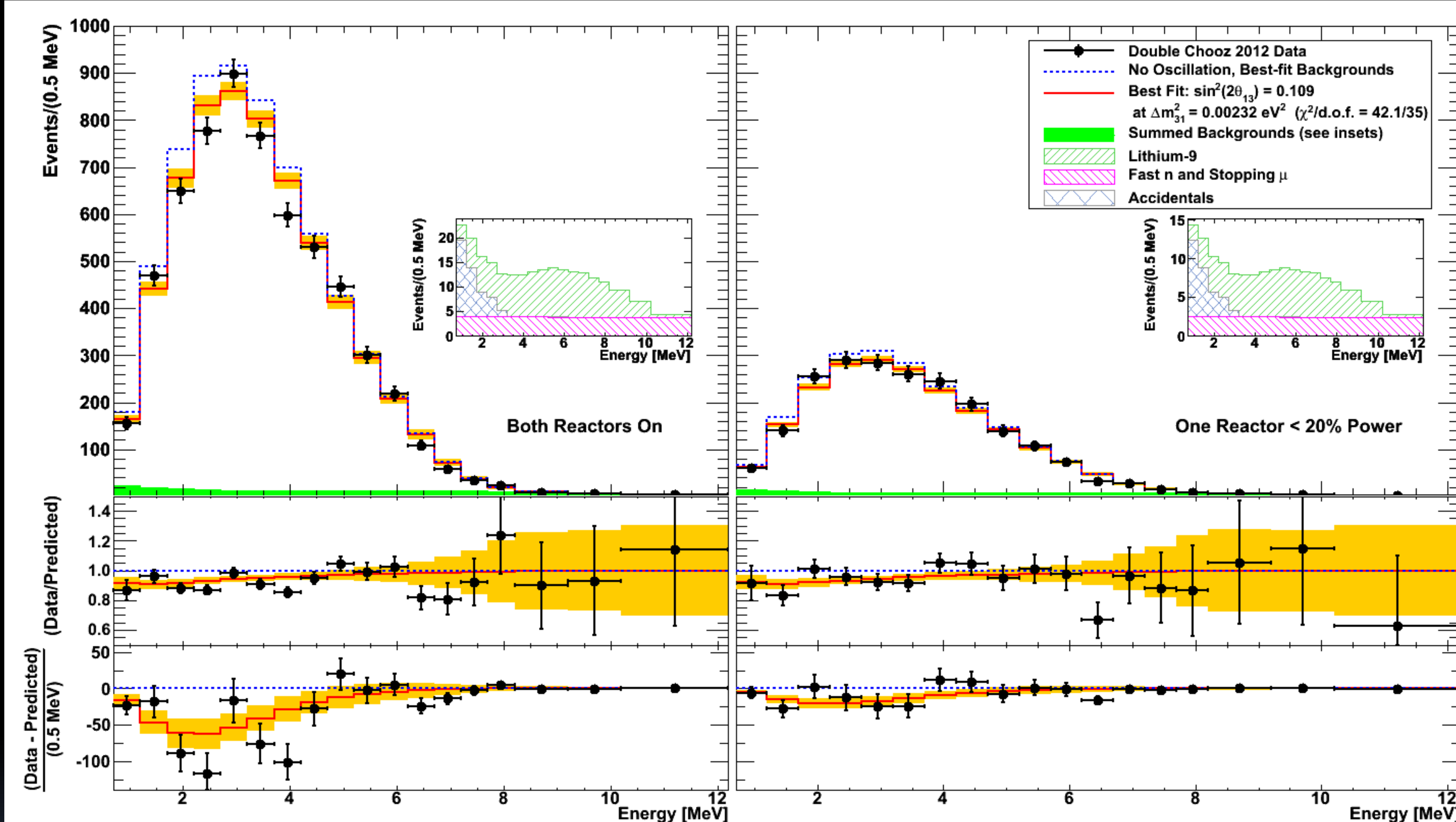
Presented in arXiv:1207.6632, accepted by PRD

Summary and Prospects

- Double Chooz updated measurement of θ_{13}, that includes rate + energy spectrum shape fit:

Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030\ (\text{stat.}) \pm 0.025\ (\text{syst.})$

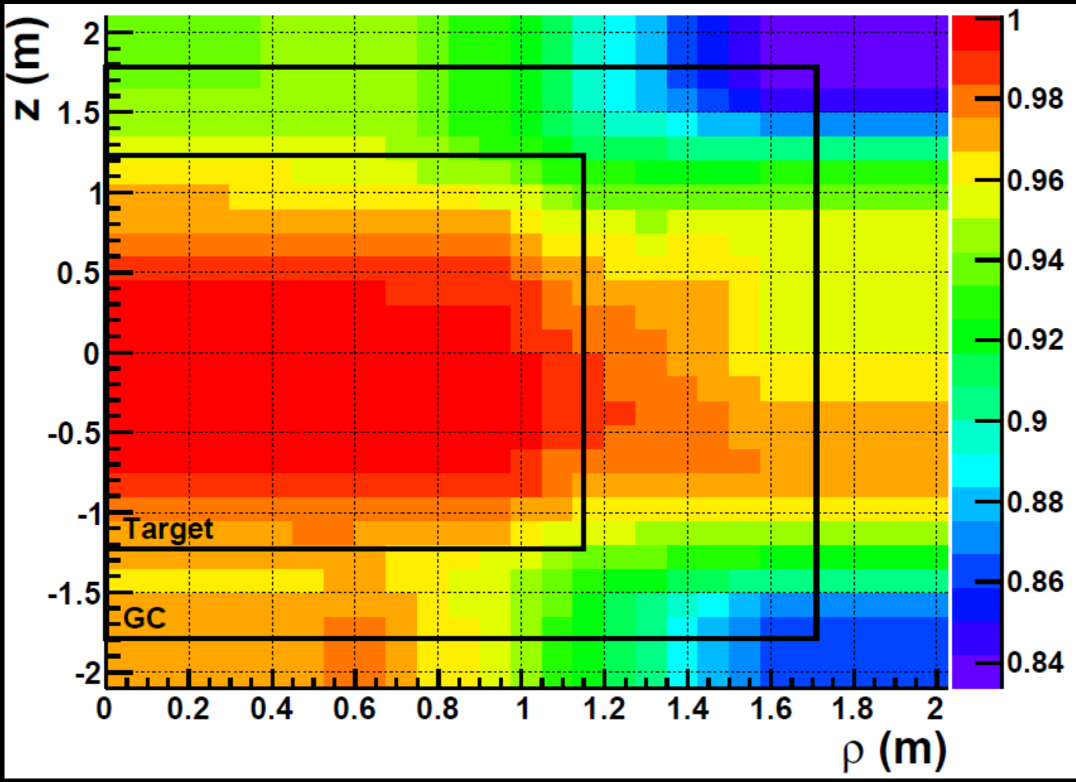
- Results obtained with far detector only: 99.8% exclusion of the zero θ_{13}.
- One full week of data taking with both reactors off : directly cross-check background estimates.
- Two detector phase to commence by the end of 2013.



Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030$ (stat.) $\pm$ 0.025 (syst.)

Fit Parameter	Initial Value	Best-Fit Value
^{9}Li Bkg. $\epsilon_{^9\mathrm{Li}}$	$(1.25 \pm 0.54)\ \mathrm{d}^{-1}$	$(1.00 \pm 0.29)\ \mathrm{d}^{-1}$
FN/SM Bkg. $\epsilon_{FN/SM}$	$(0.67 \pm 0.20)\ \mathrm{d}^{-1}$	$(0.64 \pm 0.13)\ \mathrm{d}^{-1}$
Energy Scale α_E	1.000 ± 0.011	0.986 ± 0.007
Δm^2_{31} (10^{-3} eV^2)	2.32 ± 0.12	2.32 ± 0.12

Detector Calibration



Spallation n-H
Detector Response Map

Energy Calibration

1. PMT and electronics gain non-linearity calibration
   - LED light injection system
2. Correct for position dependence
   - Spallation neutron H captures
3. Correct for time stability
   - Spallation neutron Gd captures
4. Energy scale
   - Radioactive sources deployed into ν-target and γ-catcher

Neutron Detection Efficiency

Energy & time window, Gd fraction, spill in/out effects

- ^{252}Cf source deployed into ν-target and γ-catcher

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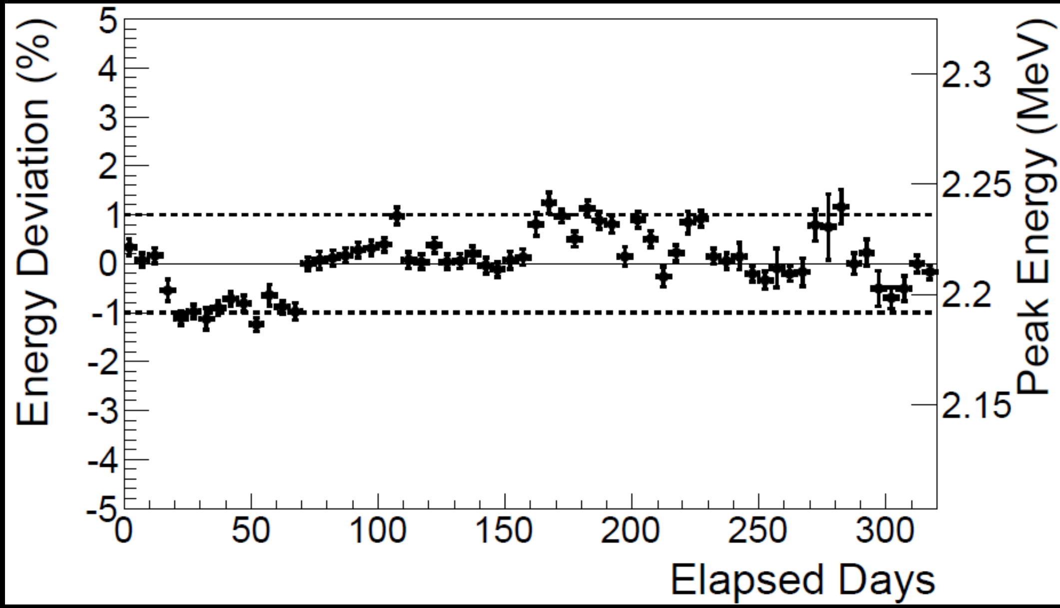

Spallation n-H capture peak position after stability correction

Neutron Detection Efficiency

Energy & time window, Gd fraction, spill in/out effects

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Backgrounds

Accidentals

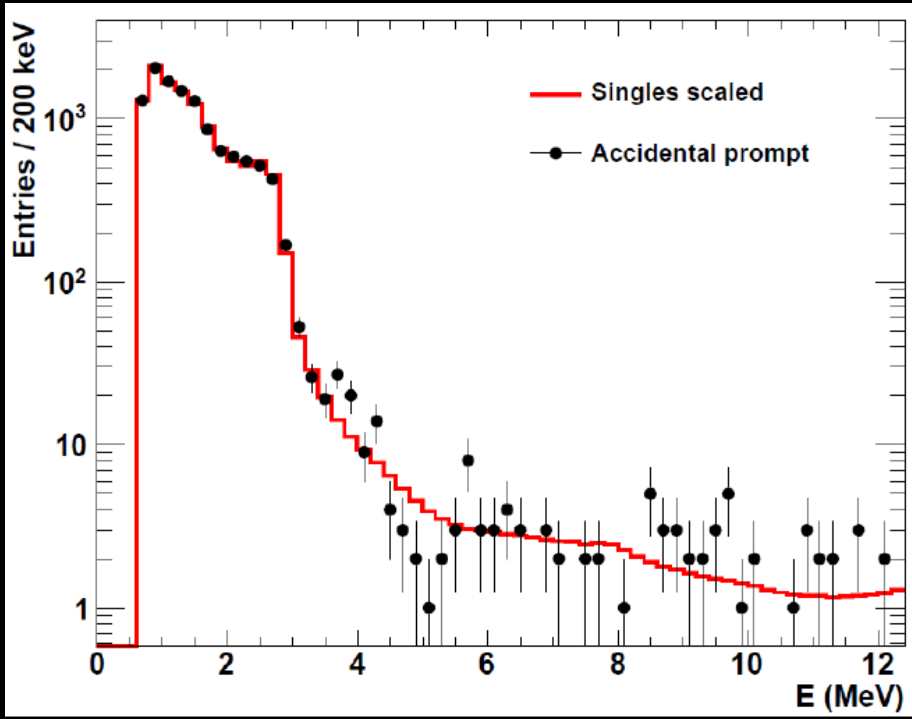
- Prompt: radiation hit on PMT
- Delayed: spallation neutron capture
- Prevented by radiopurity & shielding
- Measured from off-time windows: 0.261 +/- 0.002 day^{-1}

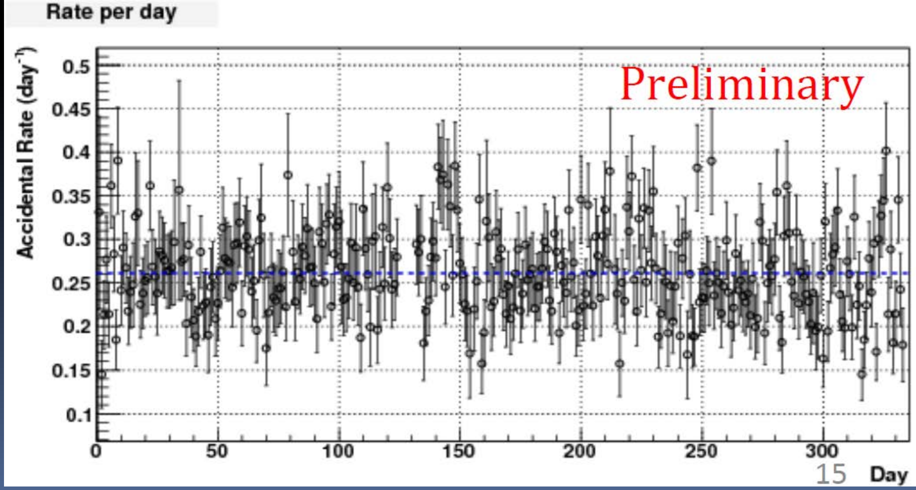
Cosmogenic ^{9}Li

- Prompt: beta emission
- Delayed: neutrons from long-lived decays
- Measured from Δt_μ & spatial muon coincidence: 1.25 +/- 0.54 day^{-1}

Fast-n & Stopping muons

- Prompt: proton recoil or muon track
- Delayed: neutron capture or muon decay
- Measured from high-energy spectrum: 0.67 +/- 0.20 day^{-1}





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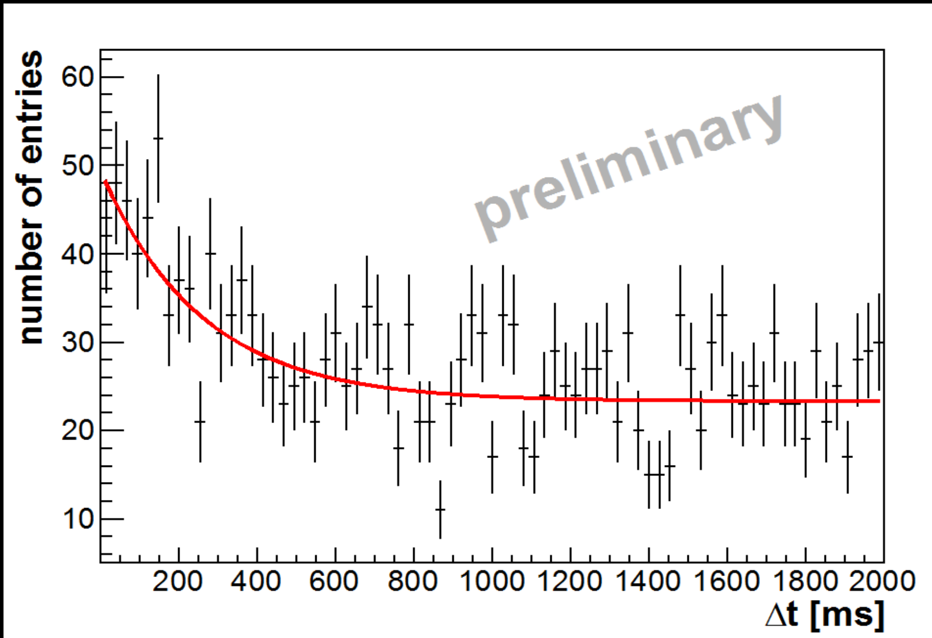

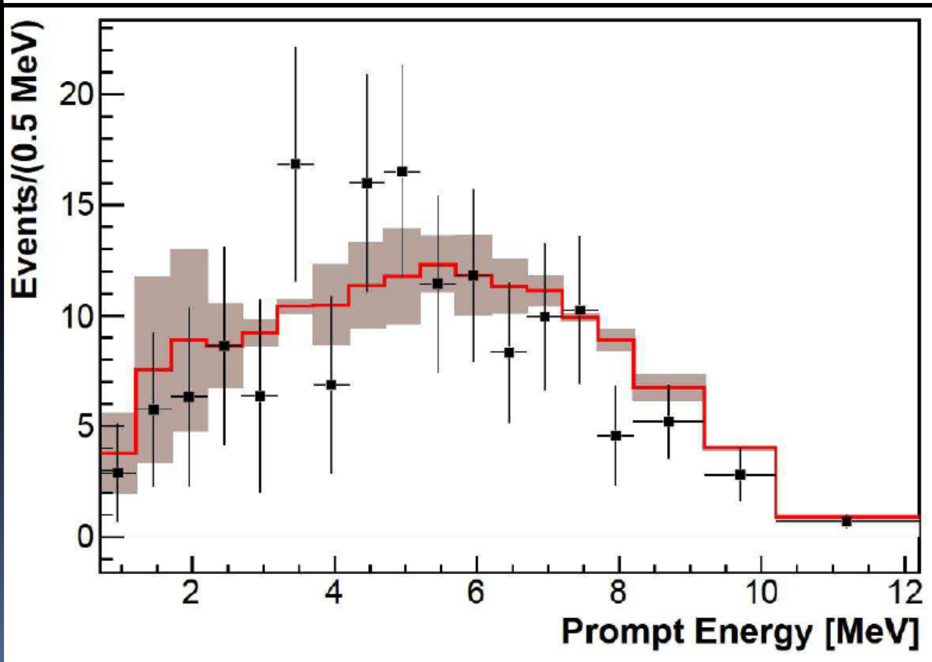

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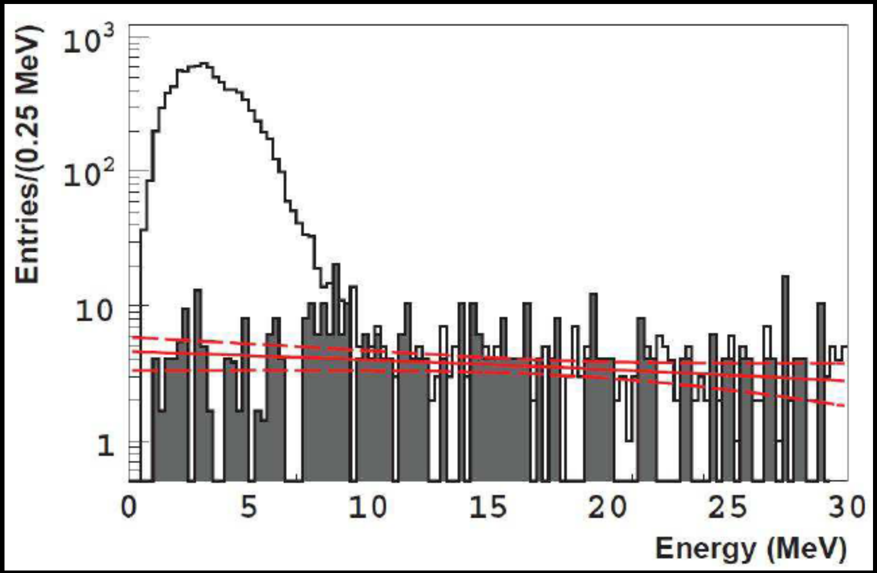

Red: Best-fit Spectrum
Grey: Tagged background events
White: IBD Signal