Double Chooz First Results

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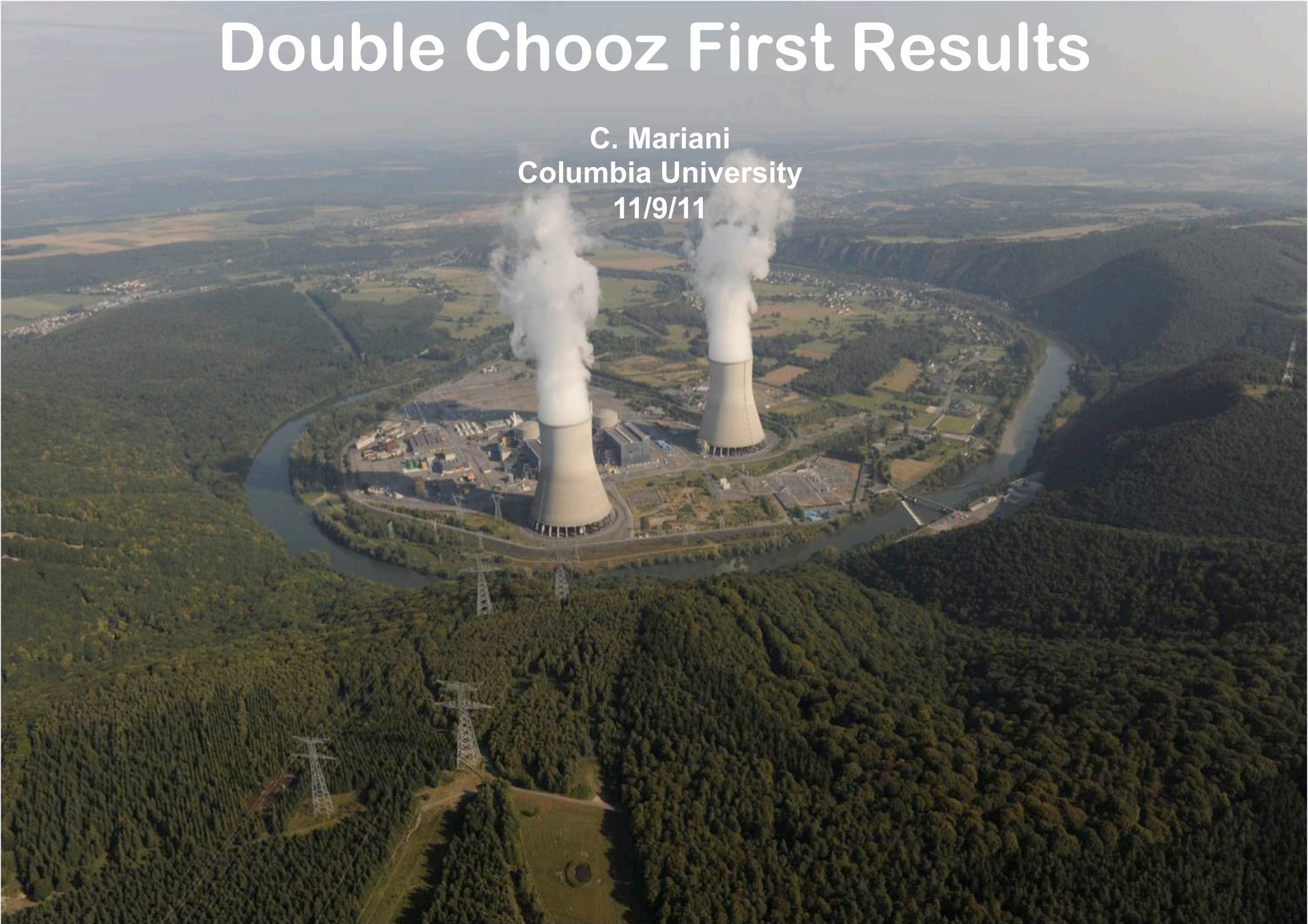
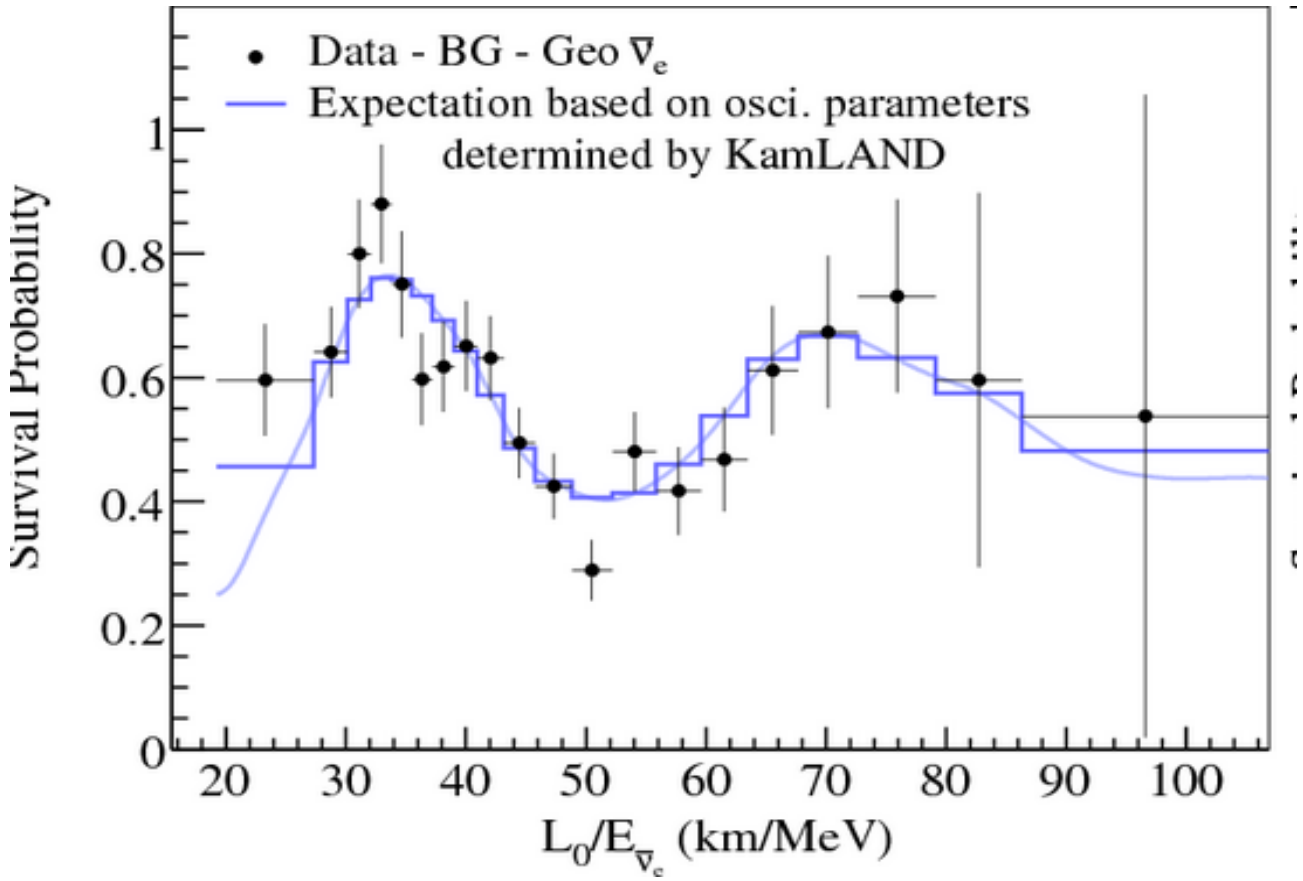
11/9/11



Outline

- Motivation
  - Little mixing angle θ_{13}
  - Difference between accelerator and reactor experiments
- Double Chooz Experiment:
  - Detector: site, description, construction
  - Far Detector only analysis

Neutrinos Oscillate!



→ Neutrinos have mass

→ New phenomenology to explore in "standard" model

Oscillations Parameterized by 3x3 Unitary Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} Flavor \\ Eigenstate \end{pmatrix} = (Mixing\ Matrix) \begin{pmatrix} Mass \\ Eigenstate \end{pmatrix}$$

Three mass splittings: $\Delta m^2_{12} = m^2_1 - m^2_2$, $\Delta m^2_{23} = m^2_2 - m^2_3$, $\Delta m^2_{31} = m^2_3 - m^2_1$

But only two are independent since only three masses

If $\delta \neq 0$, then have CP violation $\Rightarrow$ $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

Neutrino Mixing Matrix: what we know

solar atmospheric

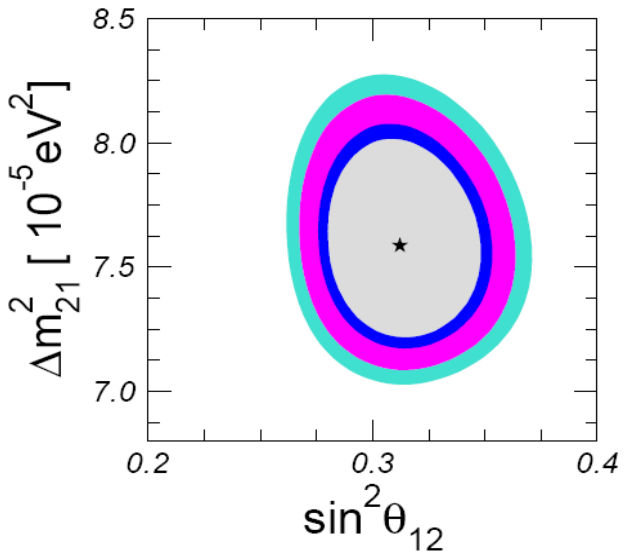
Current Measurements: $\Delta m^2_{12} = 8\times10^{-5}\ \mathrm{eV}^2\ ,\ \Delta m^2_{13} \approx \Delta m^2_{23} = 2.5\times10^{-3}\ \mathrm{eV}^2$

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

Solar: $\theta_{12} \sim 33°$

"Little mixing angle, $\theta_{13}<11°$"
$\sin^2 2\theta_{13} < 0.15$ at 90% CL
(CHOOZ limit)

Atmospheric: $\theta_{23} \sim 45°$

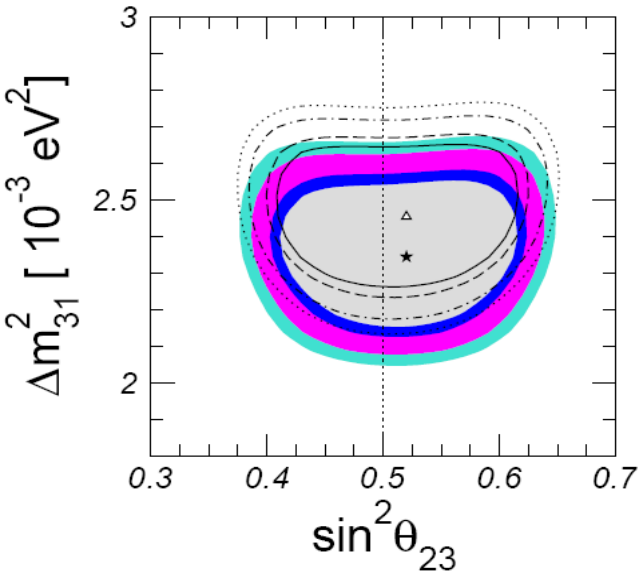


This is Quark Mixing

$$\begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$$

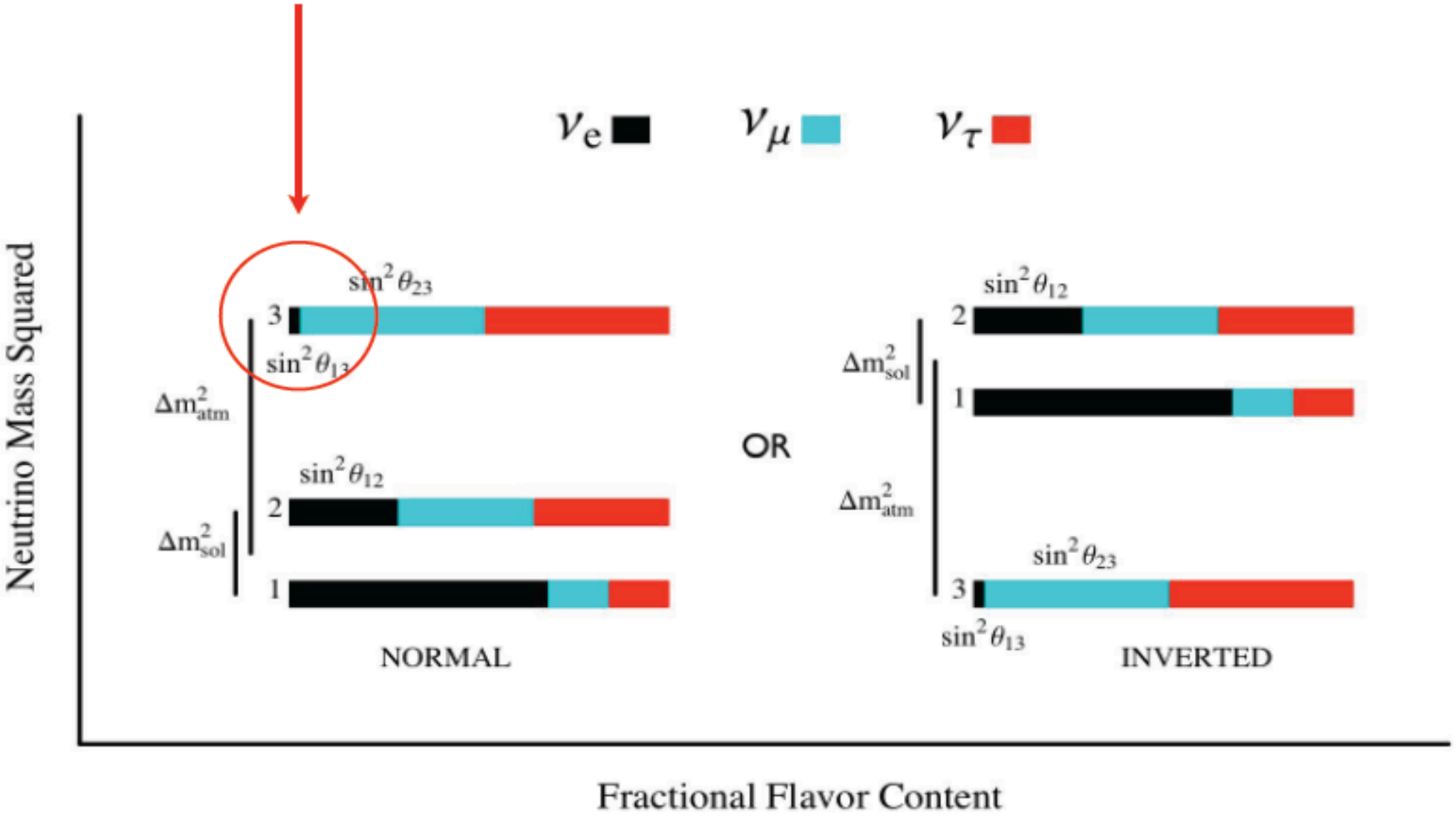
This is Neutrino Mixing

$$\begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$$

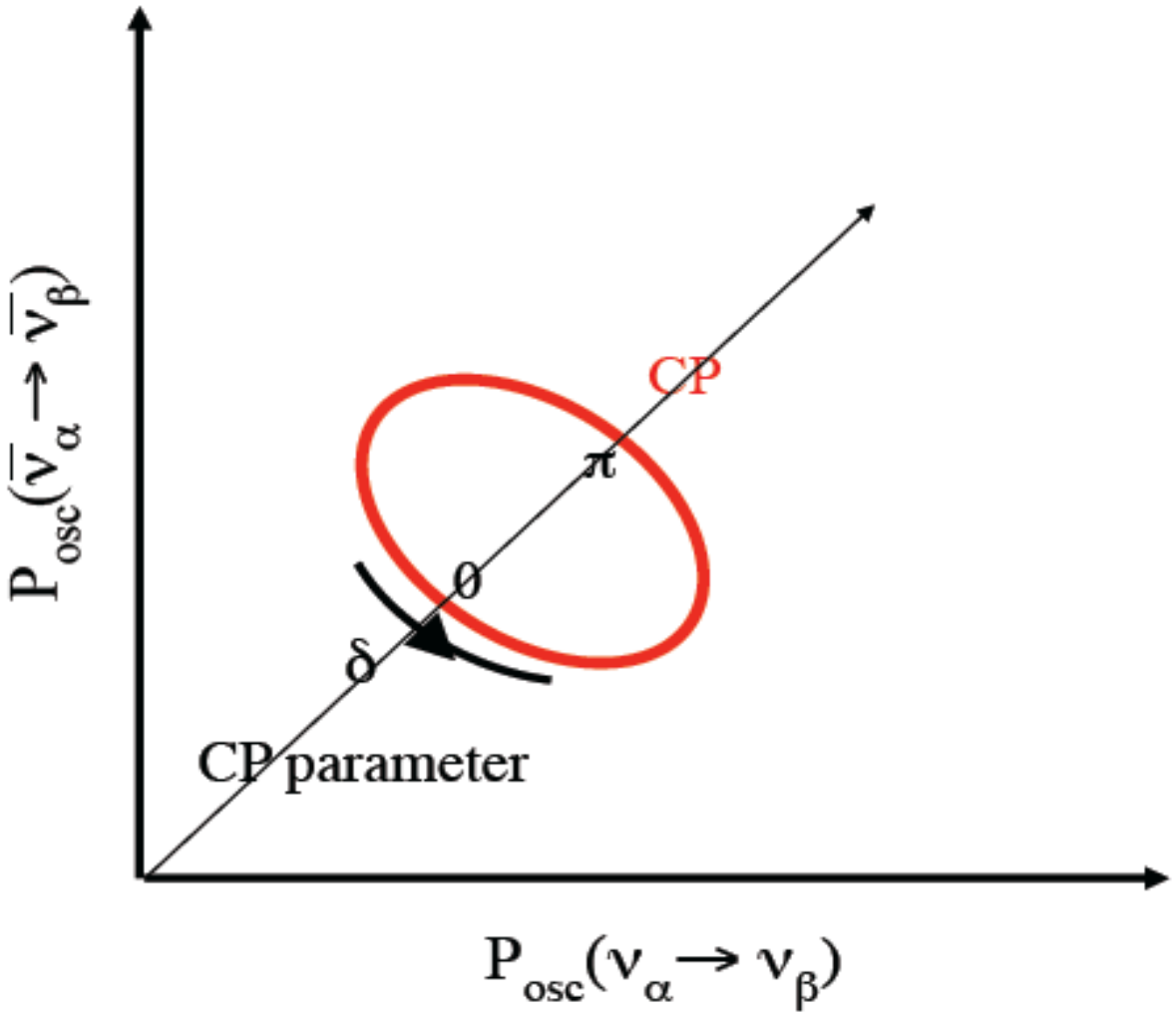


This is what we are trying to measure...

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Visualizing the effect of the CP phase.....



The size of the oval is proportional to θ_{13}.

Experimental Methods to Measure the "Little Mixing Angle", θ_{13}

- Long-Baseline Accelerators: Appearance ($\nu_\mu \rightarrow \nu_e$) at $\Delta m^2 \approx 2.4 \times 10^{-3}$ eV^2
  - Look for appearance of ν_e in a quite pure ν_μ beam vs. L and E
    - Use near detector to measure background ν_e's (beam and misid)

NOνA:
$\langle E_\nu \rangle = 2.3$ GeV
L = 810 km



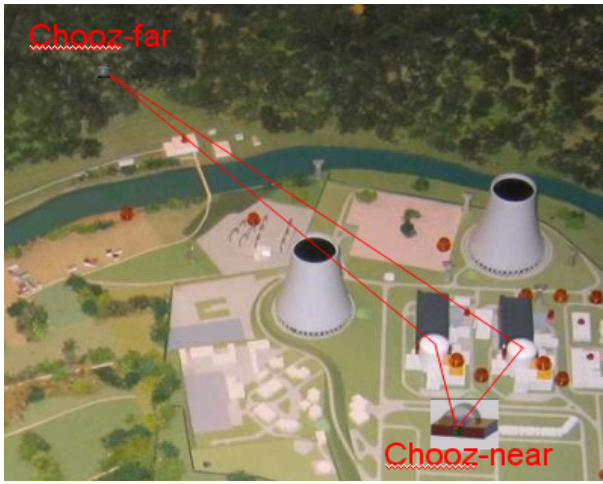
MINOS

T2K:
$\langle E_\nu \rangle = 0.7$ GeV
L = 295 km



- Reactors: Disappearance ($\overline{\nu}_e \rightarrow \overline{\nu}_e$) at $\Delta m^2 \approx 2.4 \times 10^{-3}$ eV^2
  - Look for a change in $\overline{\nu}_e$ flux as a function of L and E
    - Use near detector to measure the un-oscillated flux
    - Look for a non- $1/r^2$ behavior of the anti-ν_e rate

Double Chooz:
$\langle E_\nu \rangle = 3.5$ MeV
L = 1050 m



Oscillation probability

Long-Baseline Accelerator Appearance Experiments

- Oscillation probability complicated and dependent not only on θ_{13} but also:
  1. CP violation parameter (δ)
  2. Mass hierarchy (sign of Δm_{31}^2)
  3. Size of $\sin^2\theta_{23}$

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2S_{13}^2\right)\right)$$
$$+8C_{13}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\frac{\Delta m_{32}^2 L}{4E}\sin\frac{\Delta m_{31}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\frac{\Delta m_{32}^2 L}{4E}\sin\frac{\Delta m_{31}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$
$$+4S_{12}^2 C_{13}^2\left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\right\}\sin^2\frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 S_{13}^2 S_{23}^2\cos\frac{\Delta m_{32}^2 L}{4E}\sin\frac{\Delta m_{31}^2 L}{4E}\frac{aL}{4E}\left(1 - 2S_{13}^2\right)$$

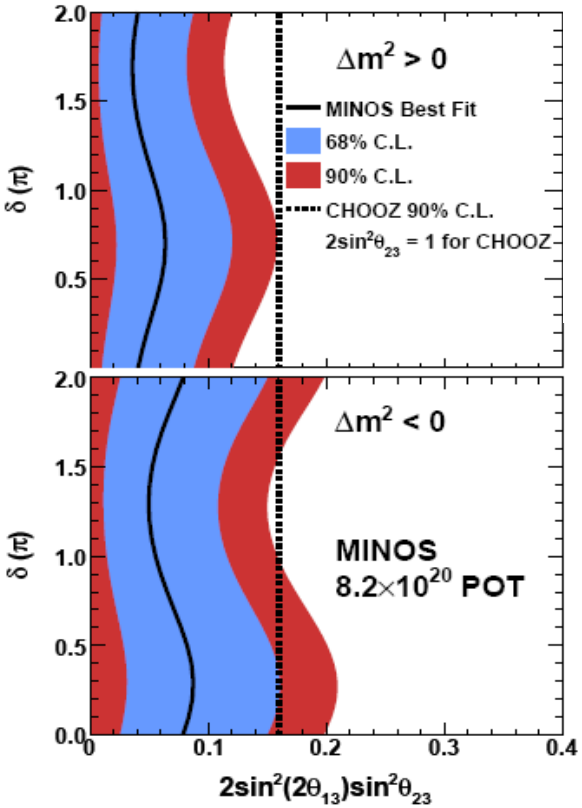
⇒ ***These extra dependencies are both a "curse" and a "blessing"***

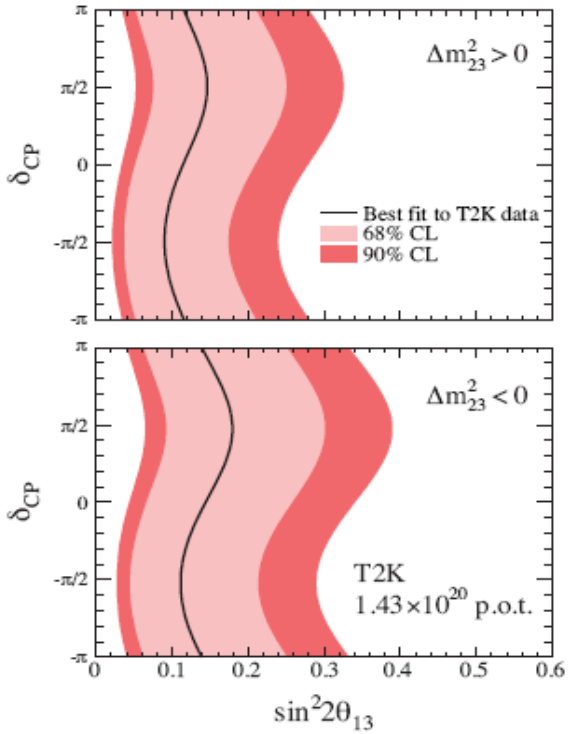
Reactor Disappearance Experiments

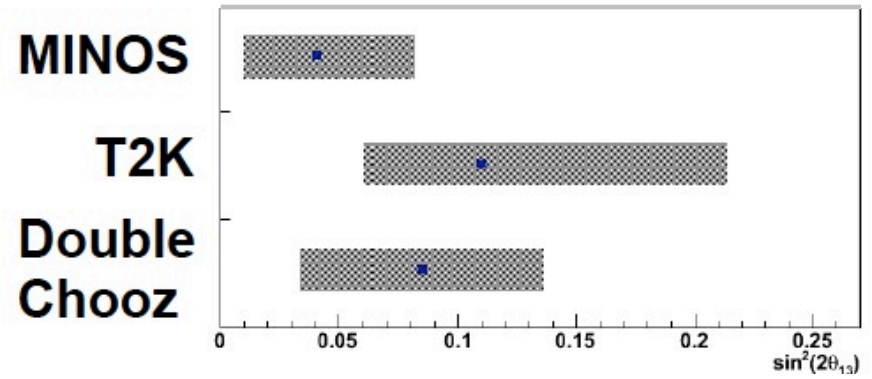
- Reactor disappearance measurements provide a straight forward method to measure θ_{13} with no dependence on matter effects and CP violation

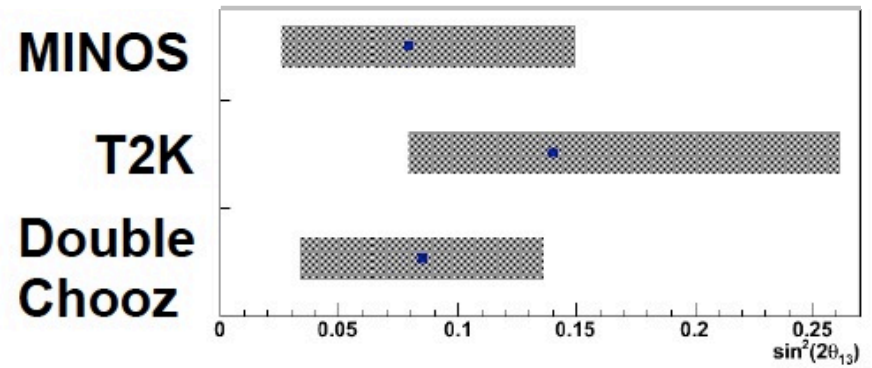
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\sin^2\frac{\Delta m_{13}^2 L}{4E} + \textit{ small terms}$$

"Indication" of nonzero θ_{13} from accelerator experiments





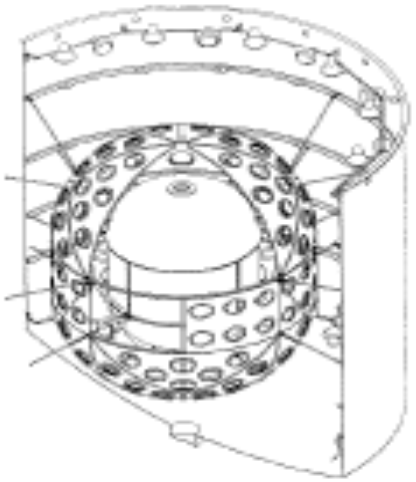




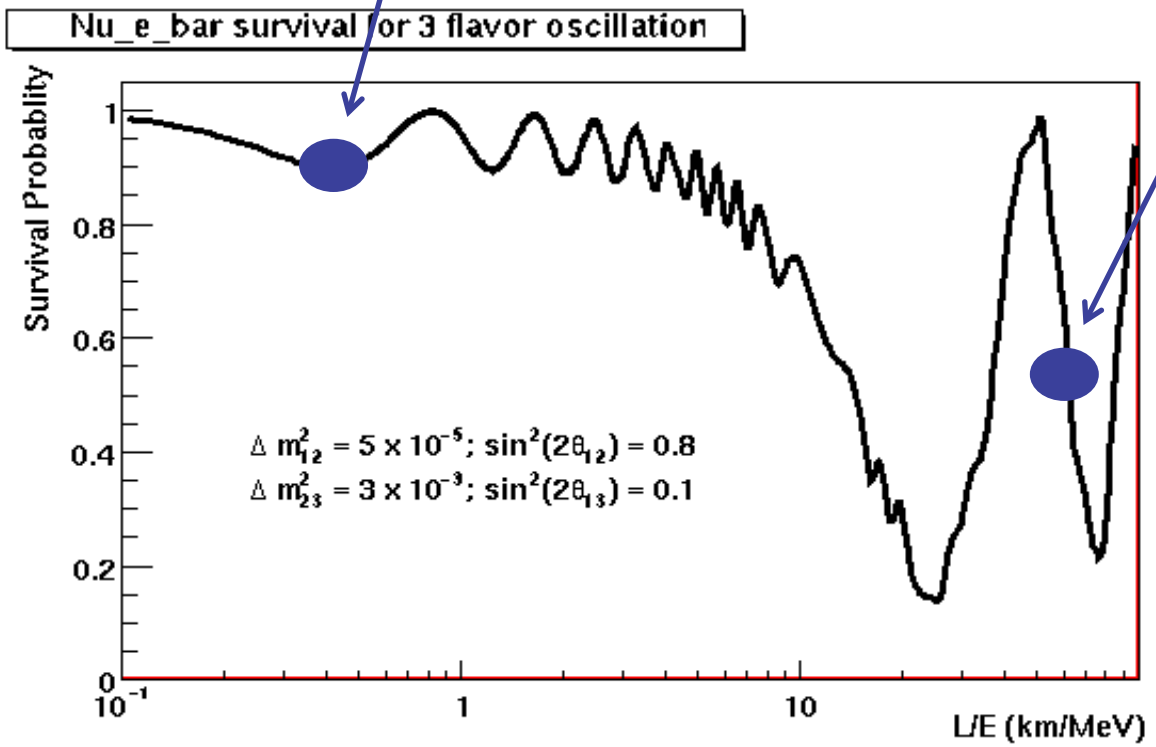
Reactor oscillation $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$

At small distances is not important

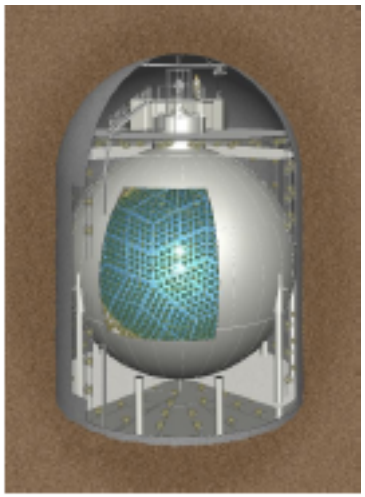
$$P\left(\bar{\nu}_e \rightarrow \bar{\nu}_e\right) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2_{13} L}{E_\nu}\right) - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m^2_{12} L}{E_\nu}\right)$$



Chooz



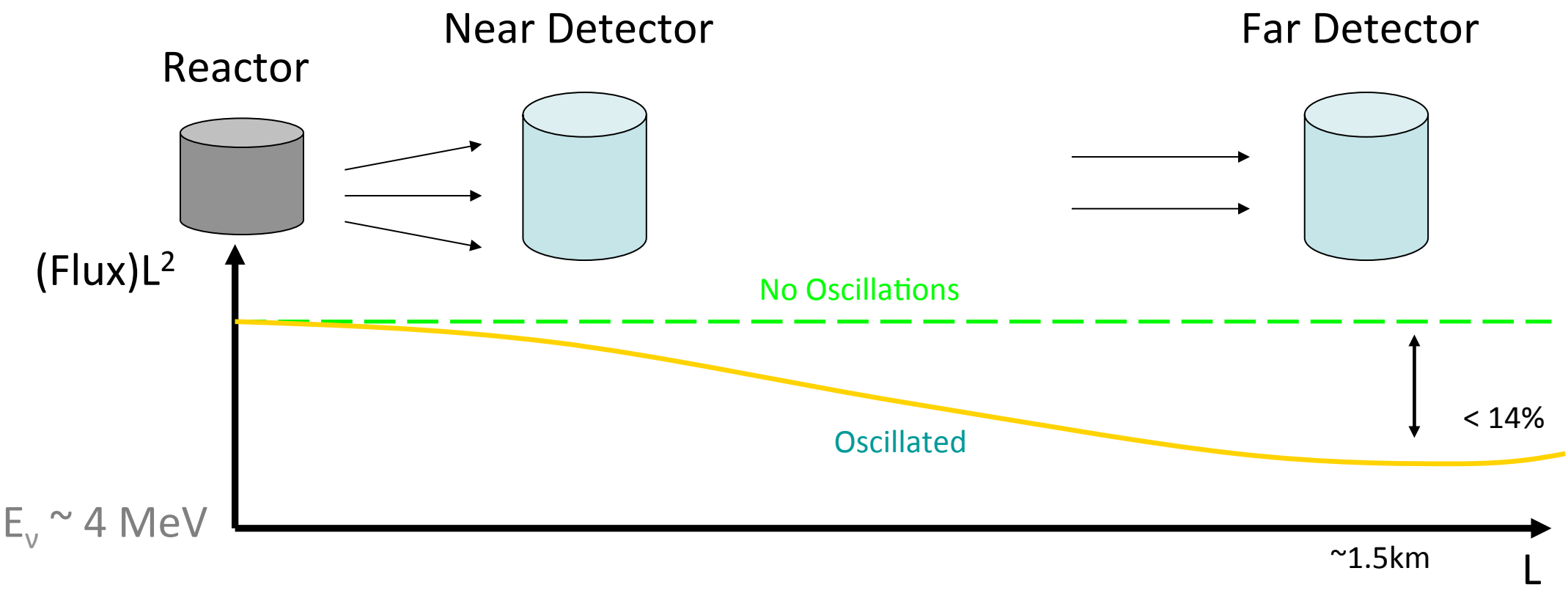
KamLand



Reactor Oscillation Experiment

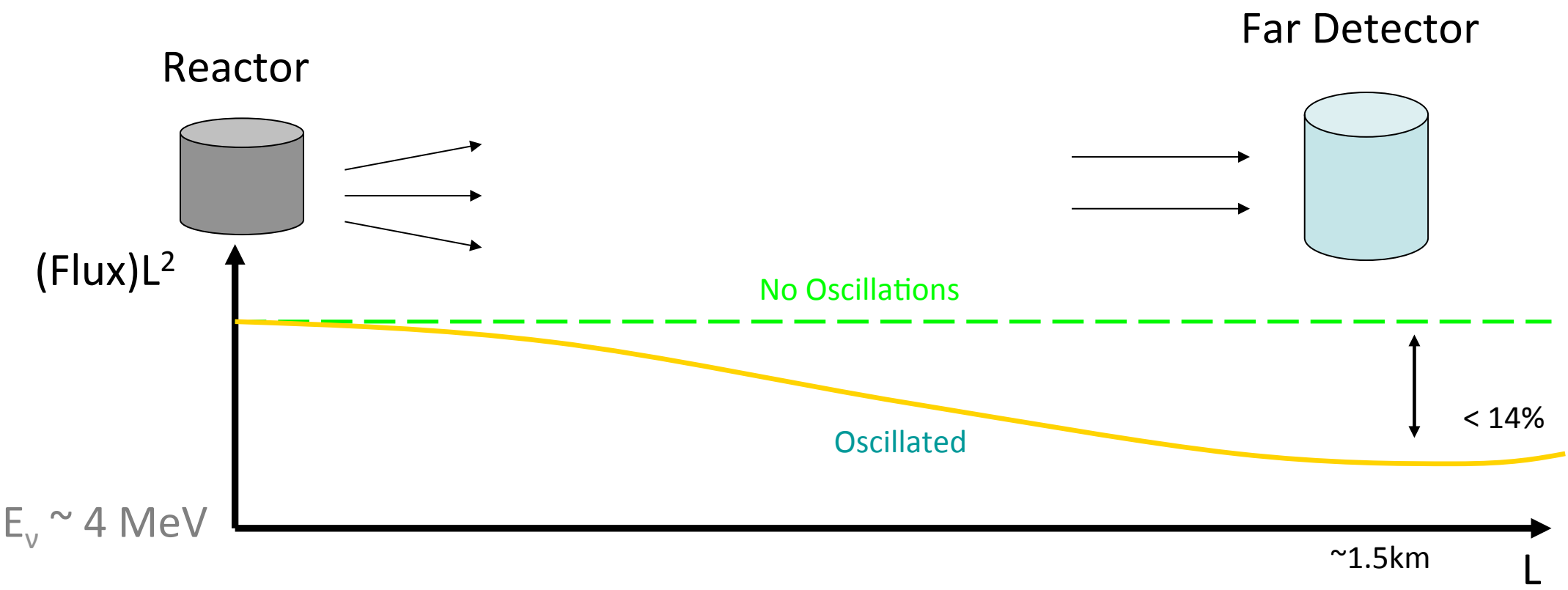
At short distances is not important

$$P\left(\bar{\nu}_e \rightarrow \bar{\nu}_e\right) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2_{13} L}{E_\nu}\right) - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m^2_{12} L}{E_\nu}\right)$$



Reactor Oscillation Experiment

$$P\left(\bar{\nu}_e \rightarrow \bar{\nu}_e\right) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2_{13} L}{E_\nu}\right)$$



Or with just a far detector: compare flux prediction to measured rate

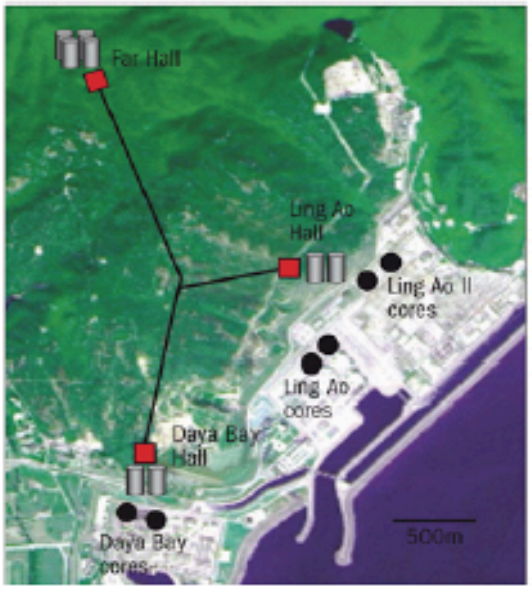
→ CHOOZ and Double Chooz first results

Reactor Oscillation Experiments

Daya Bay θ_{13}

RENO $\nu \sim\sim\sim\sim\sim\sim \theta_{13}$

DOUBLE CHOOZ







arXiv:hep-ex/0701029v1

P=11.6GWth/4
17.4GWth/6(2011~)
L~1.8km
(~2012-)

arXiv:1003.1391v1

P=16.1GWth/6
L~1.4km
(~2011-)

arXiv:hep-ex/0606025v4

P=9.4GWth/2
L=1.05(0.4)km
(~2011-)

Double Chooz Collaboration



Brazil

CBPF
UNICAMP
UFABC



France

APC
CEA/DSM/IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CNRS/IN2P3:
Subatech
IPHC
ULB/VUB



Germany

EKU Tübingen
MPIK Heidelberg
RWTH Aachen
TU München
U. Hamburg



Japan

Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst Tech.



Russia

INR RAS
IPC RAS
RRC Kurchatov



Spain

CIEMAT-Madrid



UK

Sussex

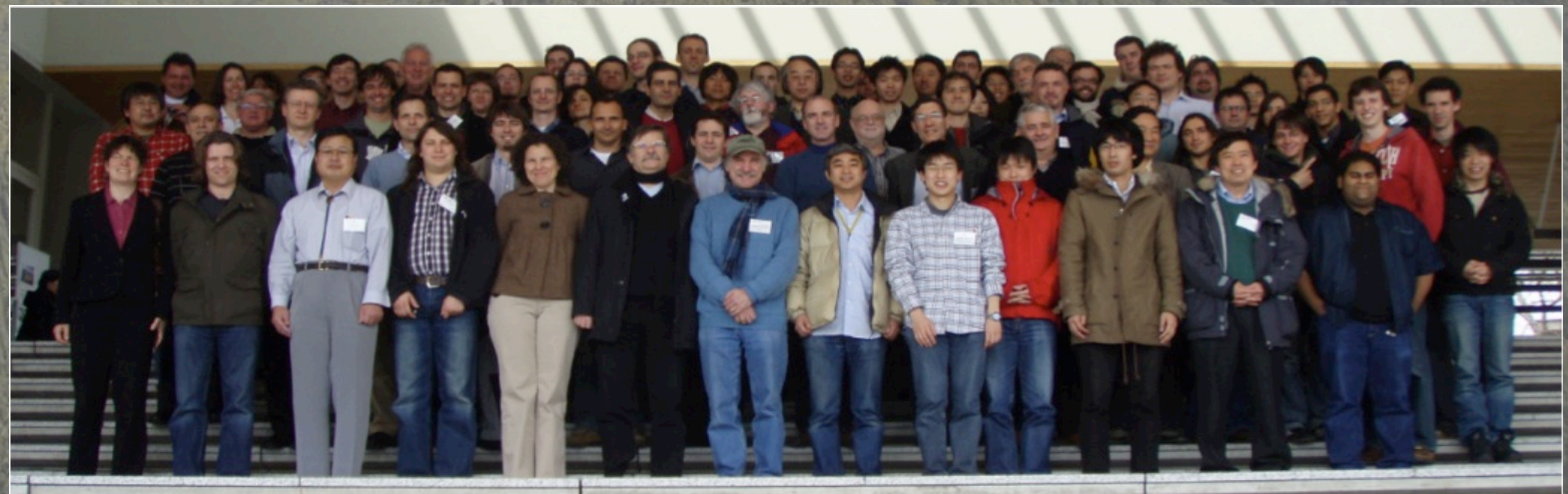


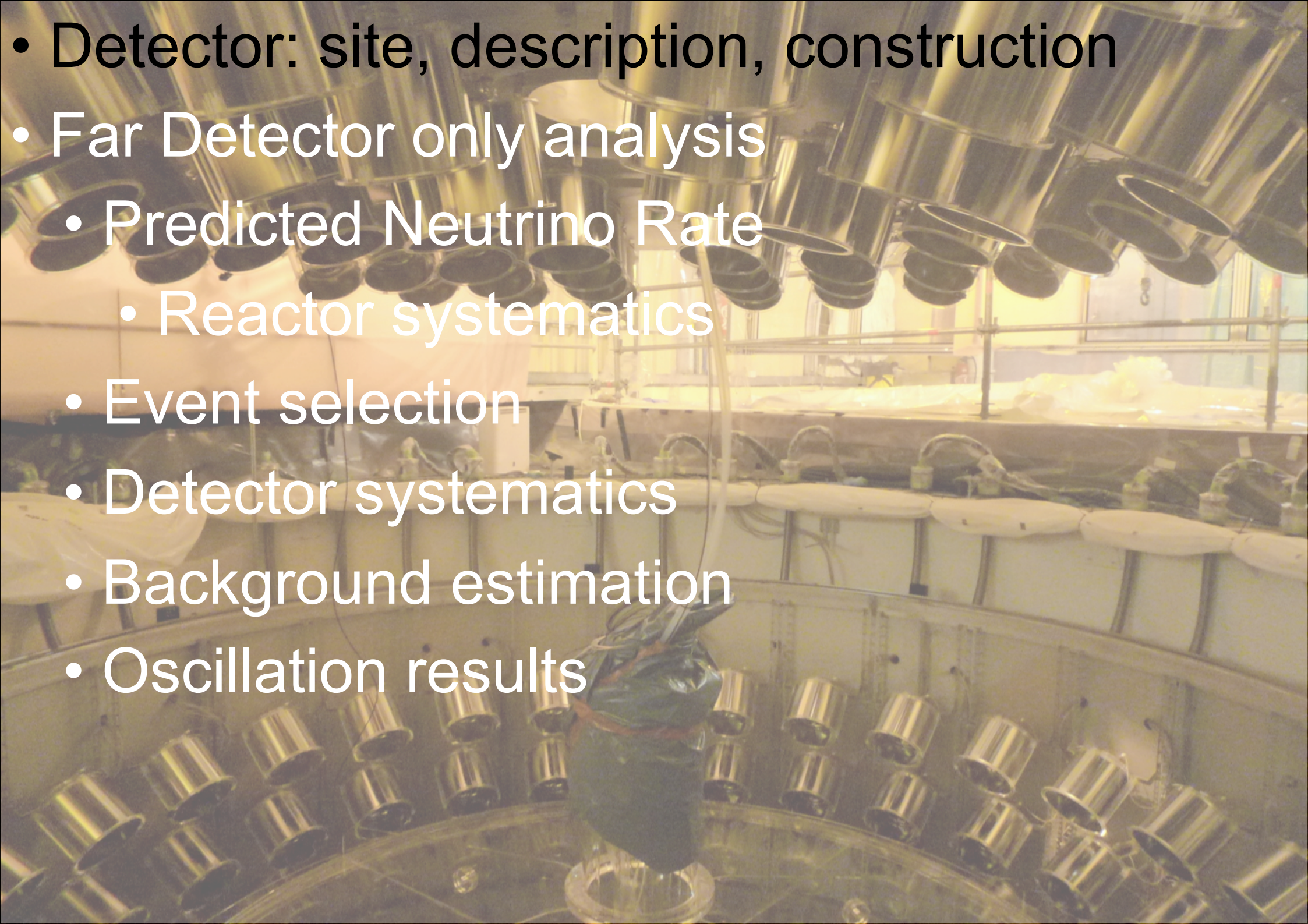
USA

U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
Sandia National Laboratories
U. Tennessee

Spokesperson: H. de Kerret (IN2P3)
Project Manager: Ch. Veyssière (CEA-Saclay)

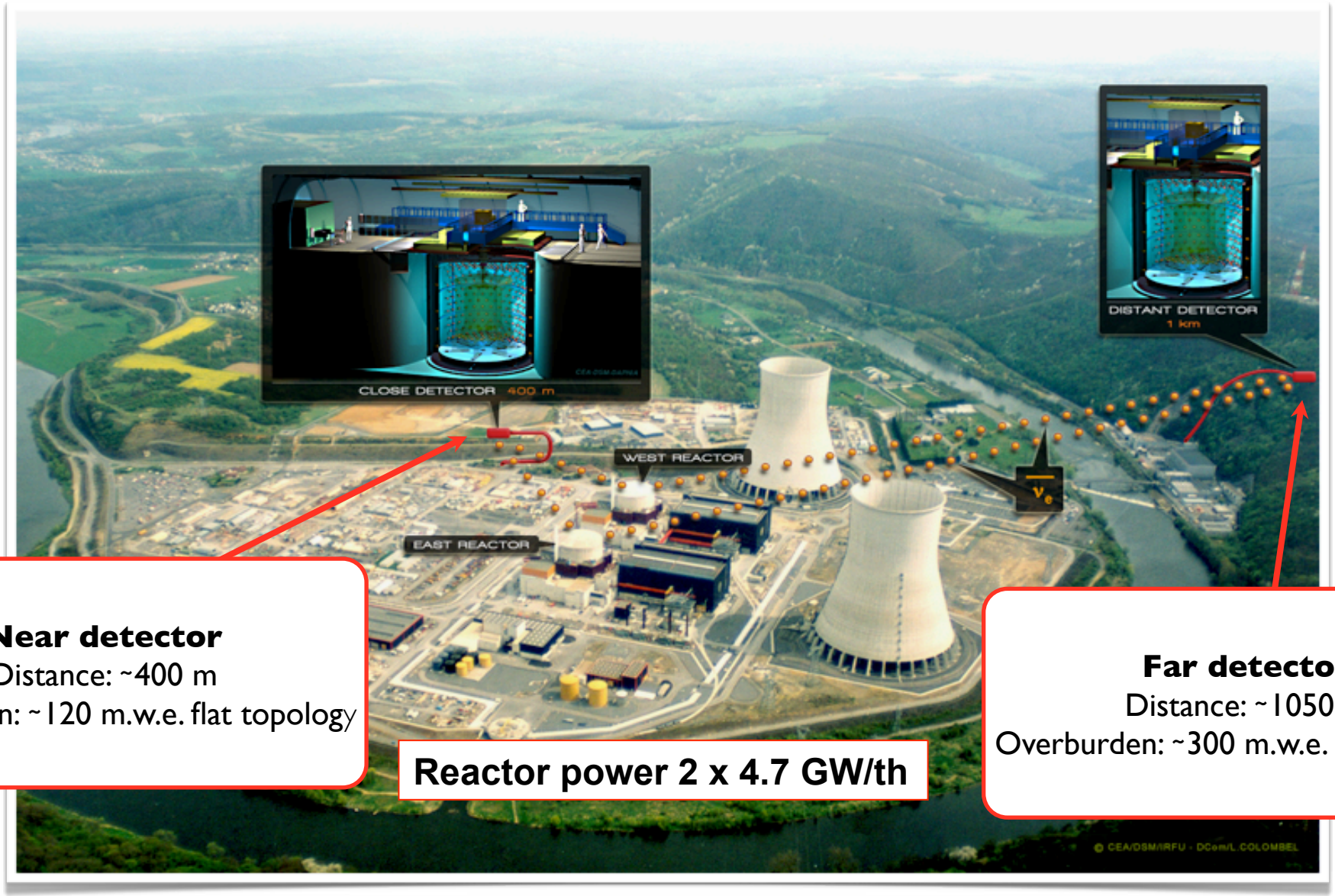
Web Site: www.doublechooz.org/





- Detector: site, description, construction
- Far Detector only analysis
  - Predicted Neutrino Rate
    - Reactor systematics
  - Event selection
  - Detector systematics
  - Background estimation
  - Oscillation results

Double Chooz Site in Ardennes, France



Near detector
Distance: ~400 m
Overburden: ~120 m.w.e. flat topology

Reactor power 2 x 4.7 GW/th

Far detector
Distance: ~1050 m
Overburden: ~300 m.w.e. hill topology

The Double Chooz Detector

Outer Veto (OV)
plastic scintillator strips

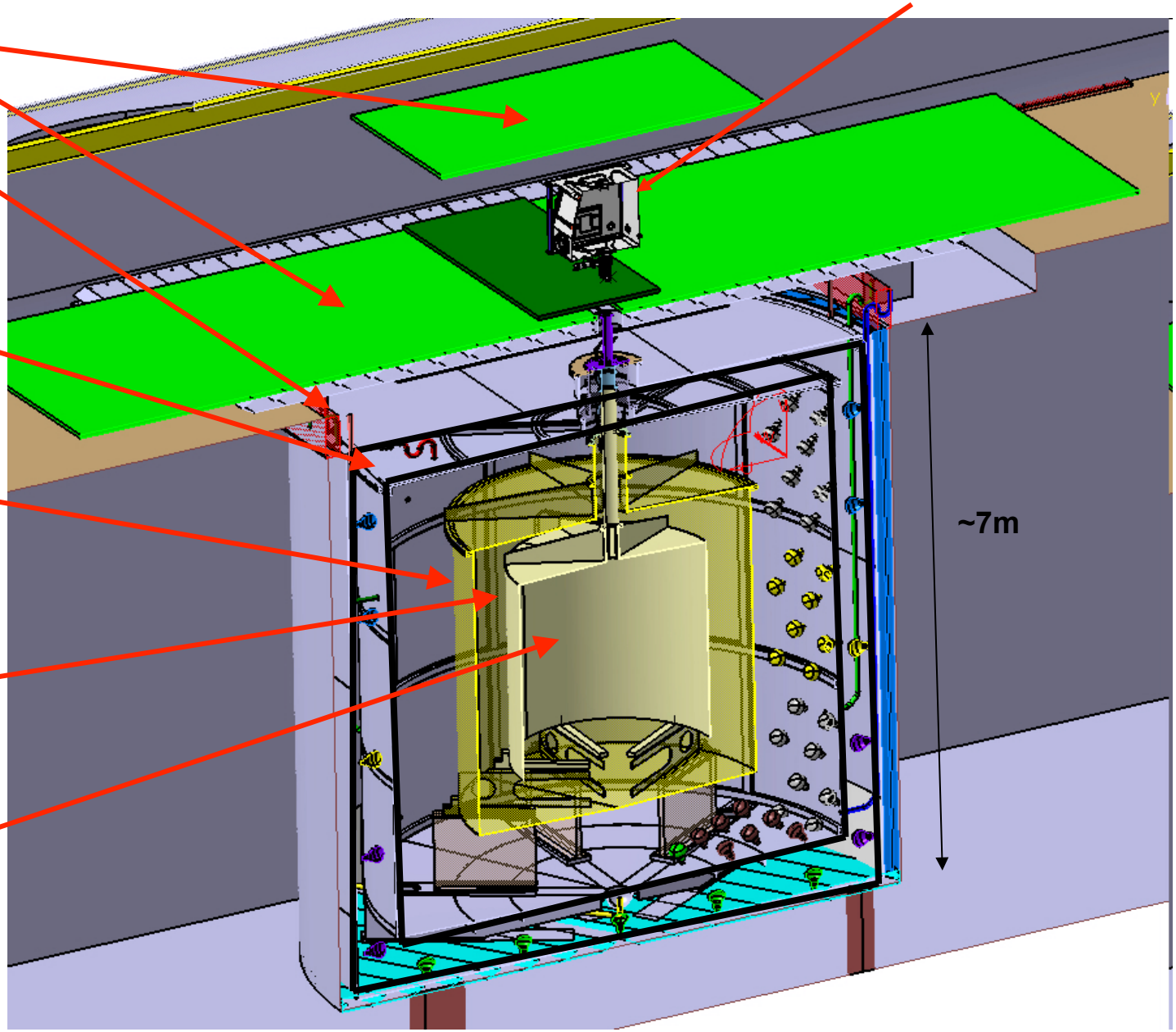
Outer-Shielding
250 t steel shielding (15 cm)

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

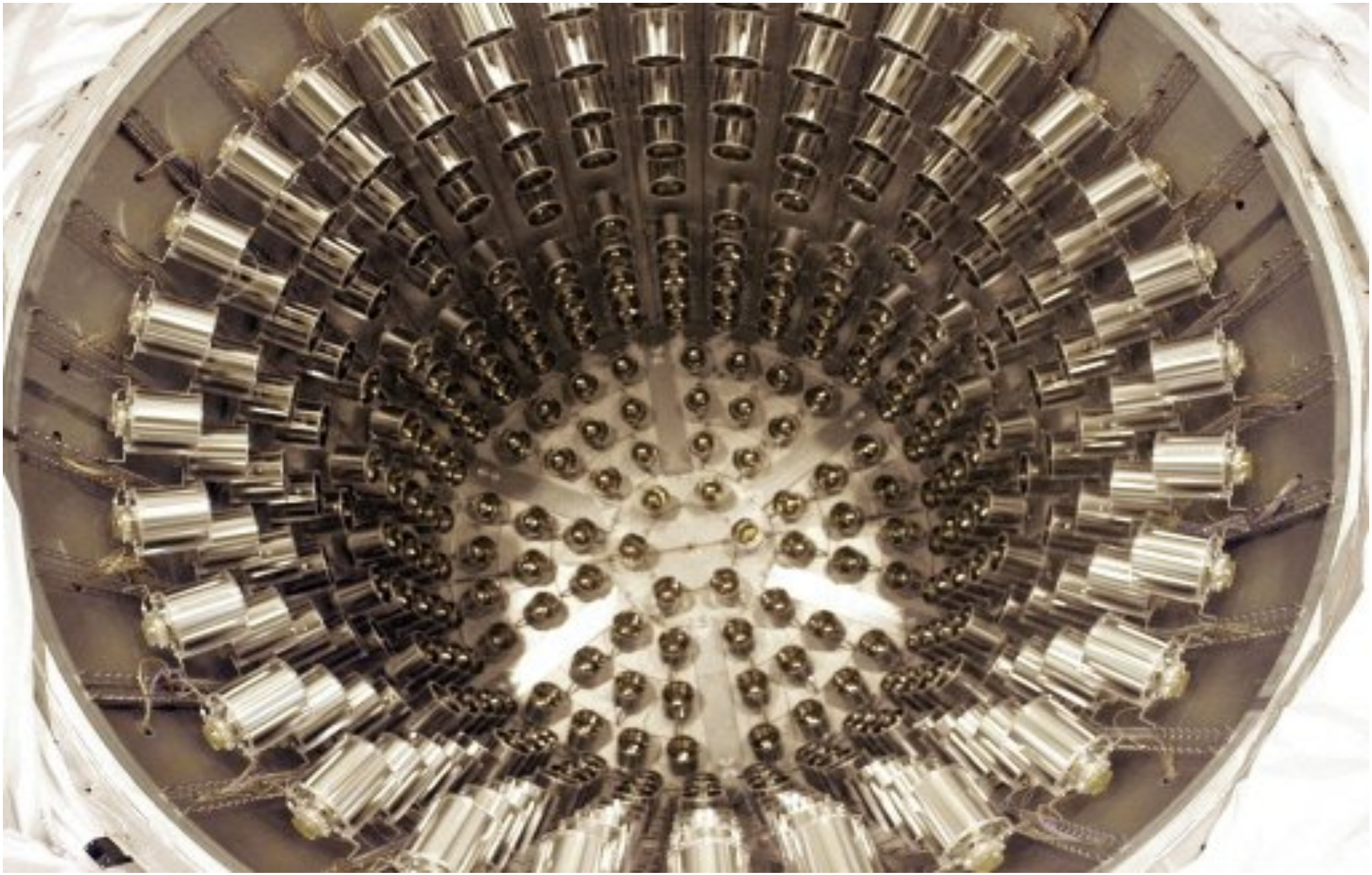
Buffer
110 m^3 of mineral oil in a steel vessel (3 mm) equipped with 390 PMTs (10 inches)

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

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



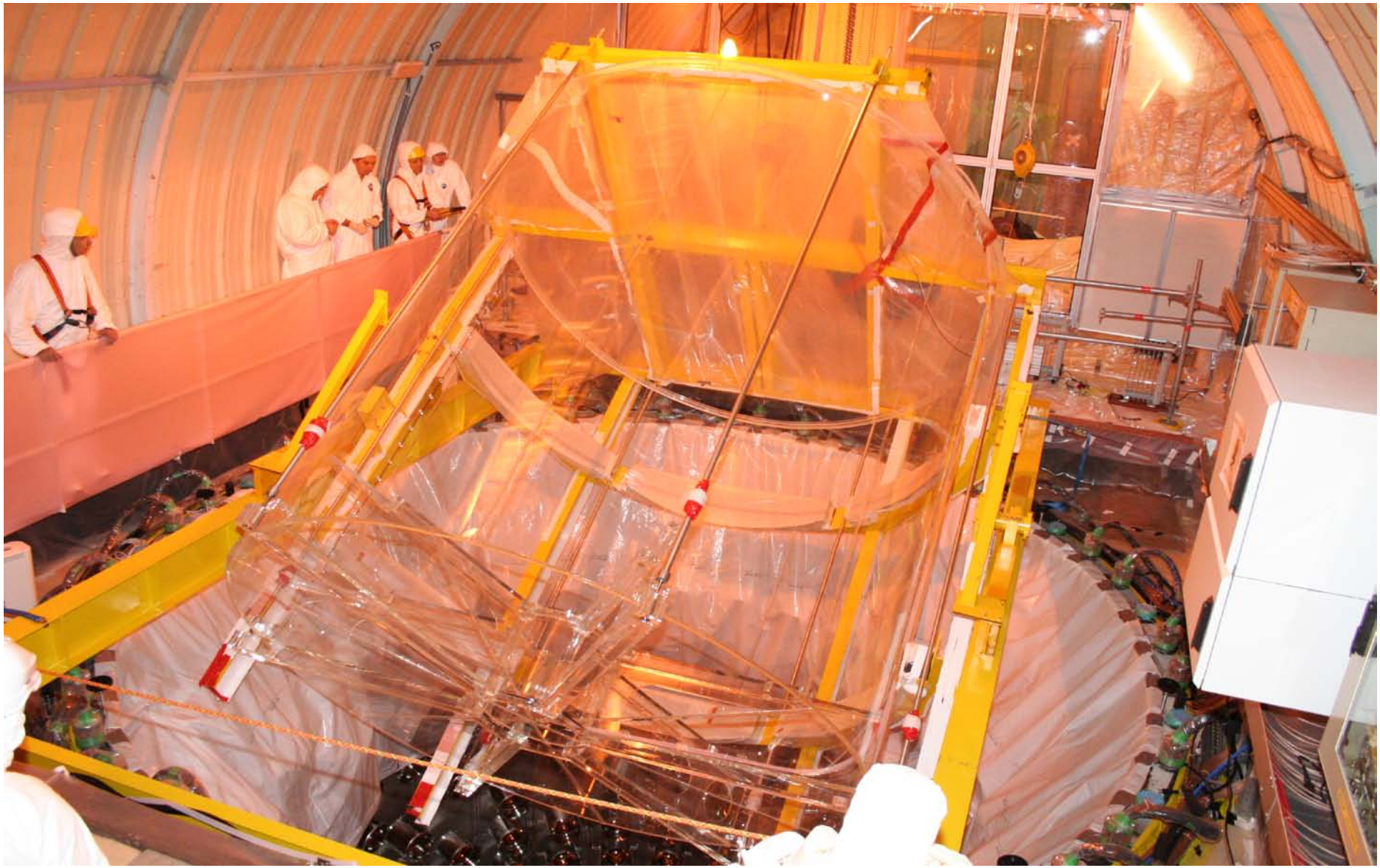
PMTs



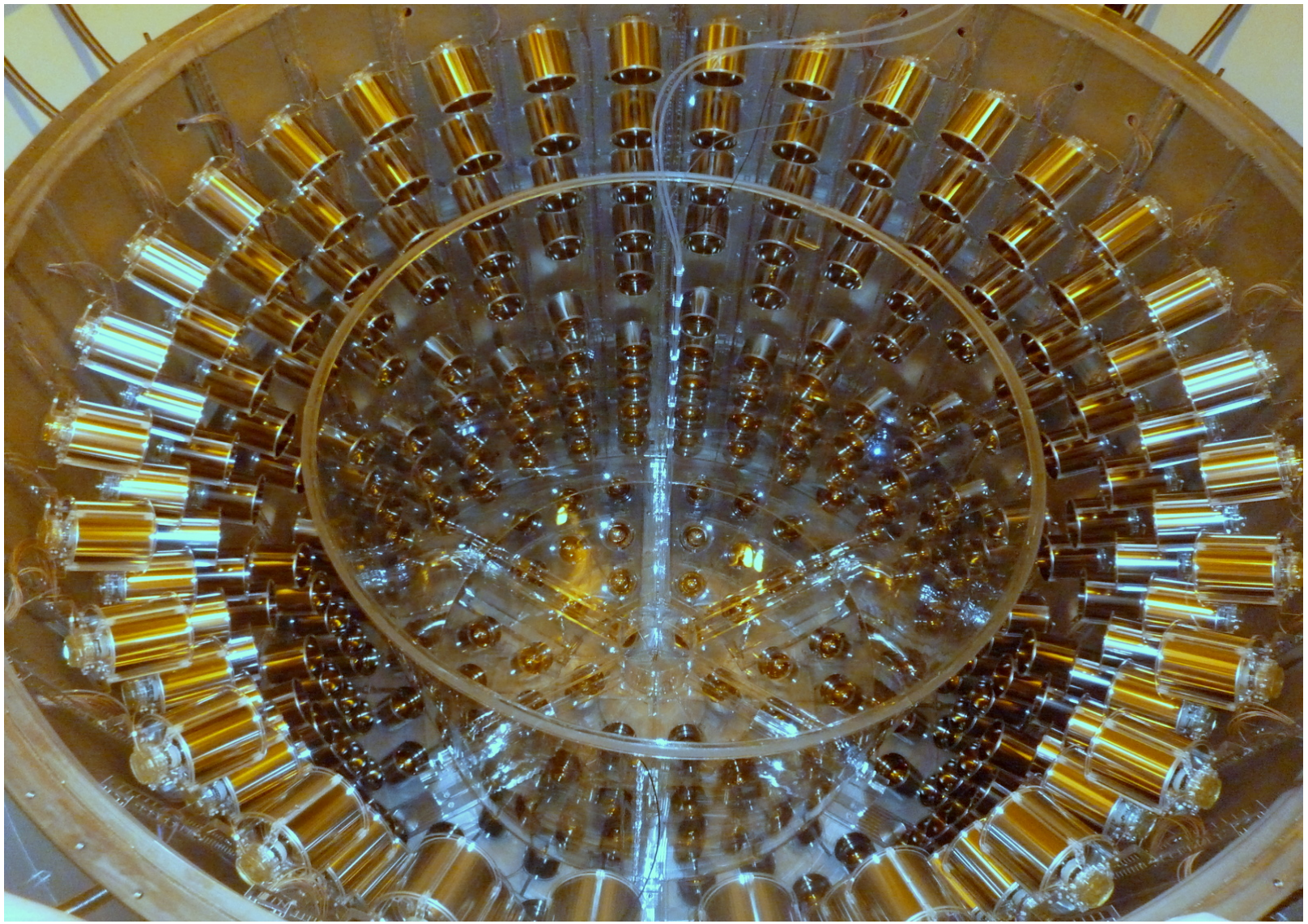
Far Detector construction



Gamma Catcher installation



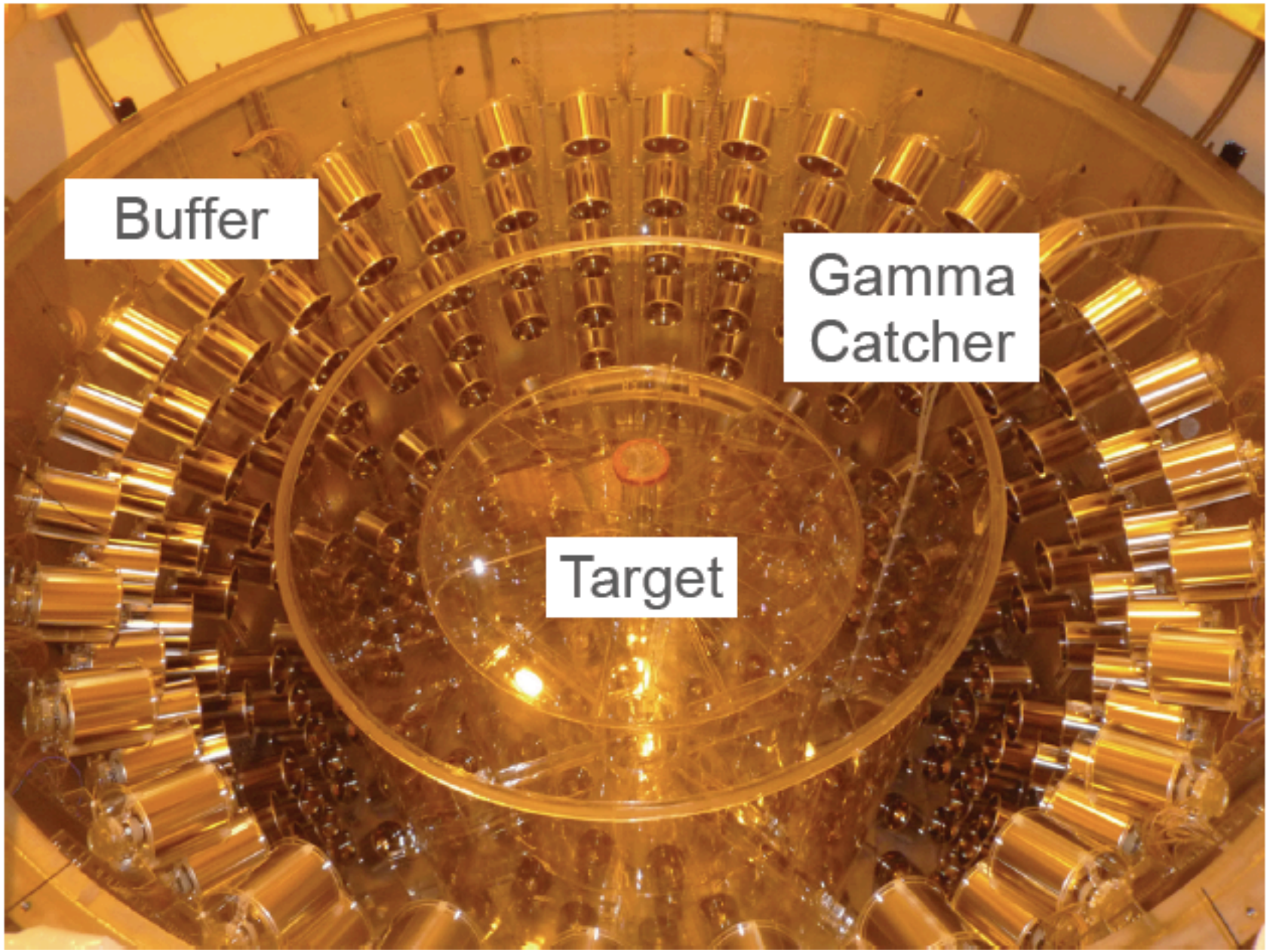
Gamma Catcher in place



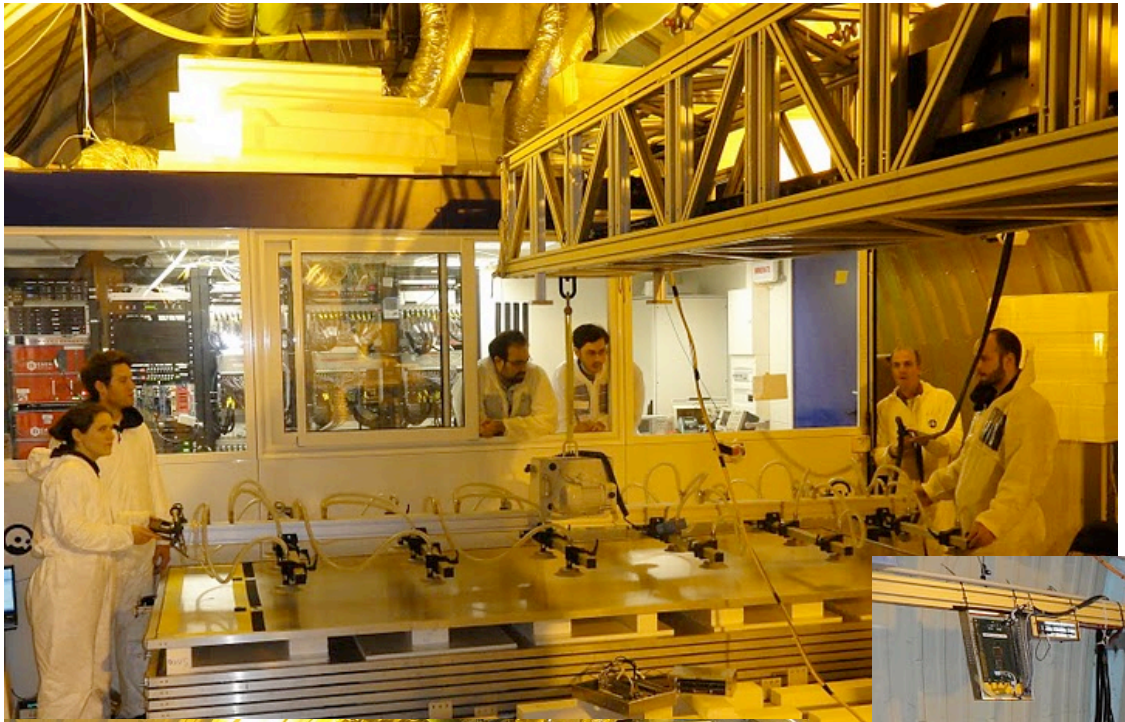
Target in place



3 sub-volumes

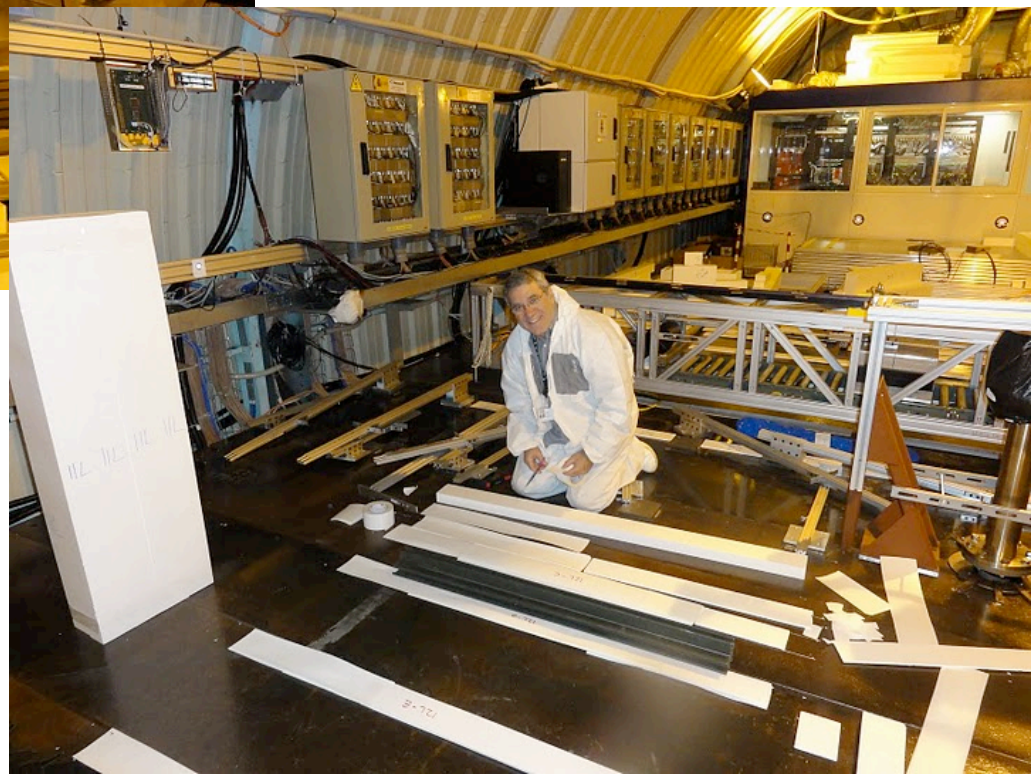


Outer Veto installation Apr.-May 2011

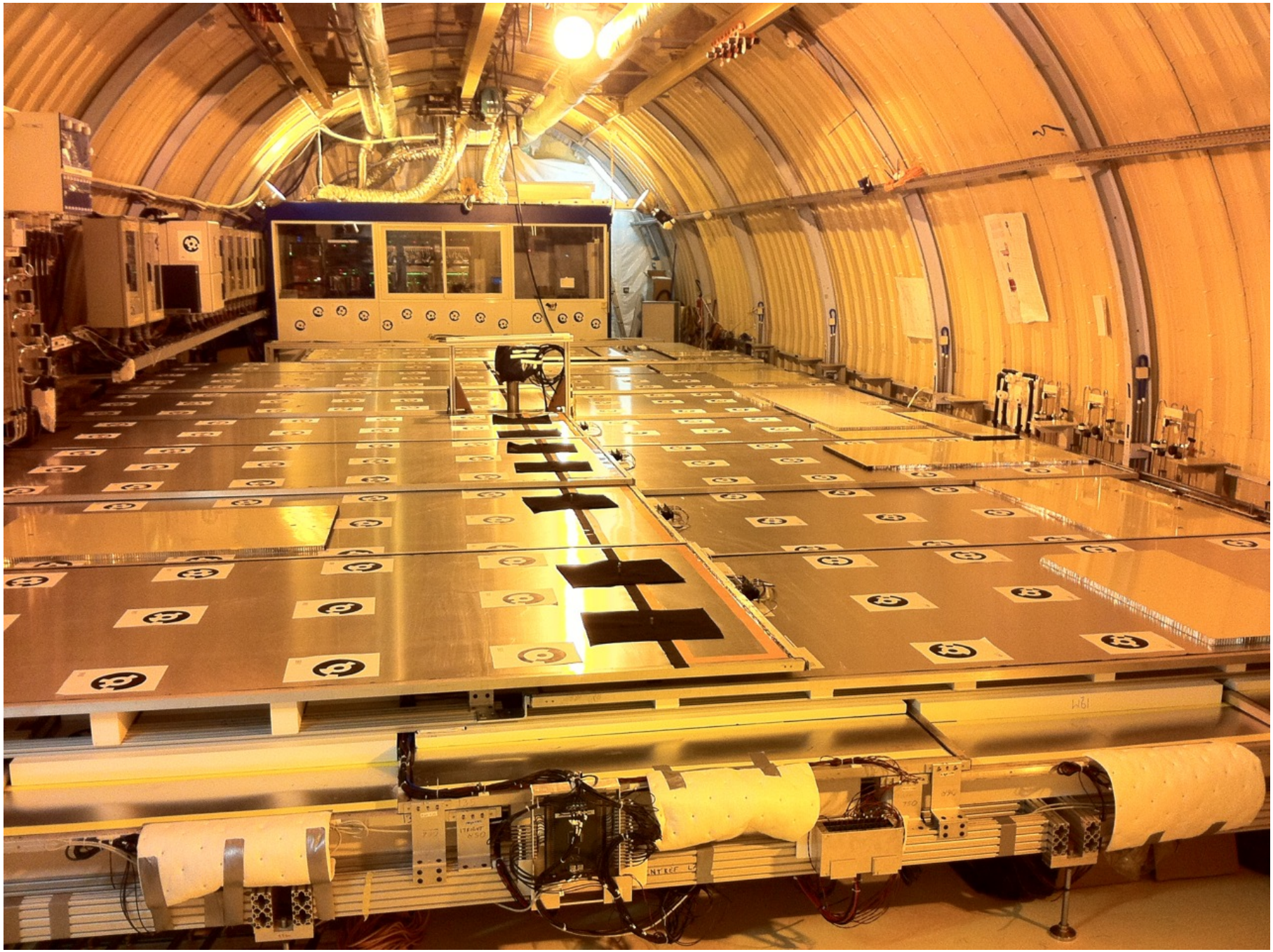




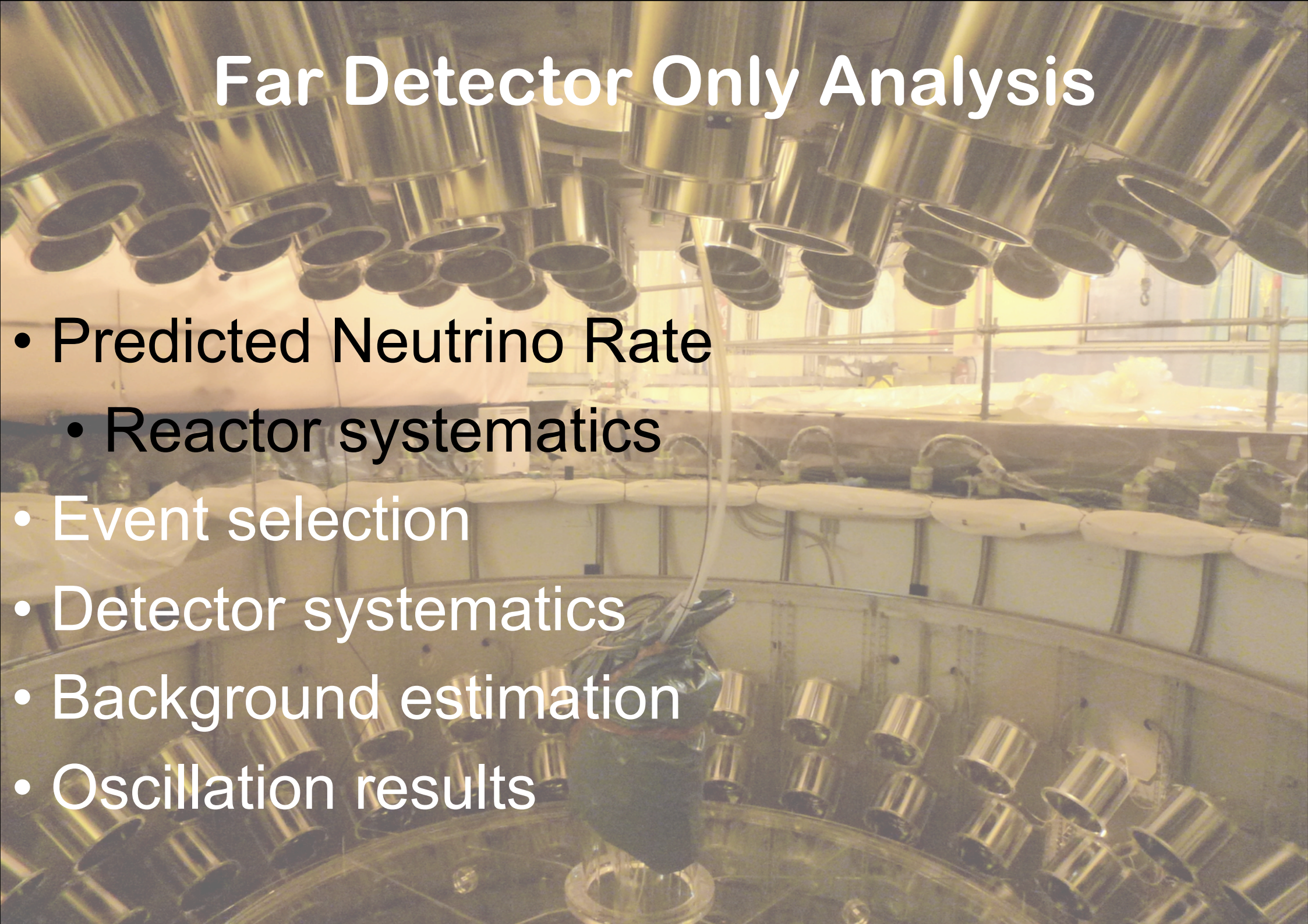




Outer Veto in place



Far Detector Only Analysis



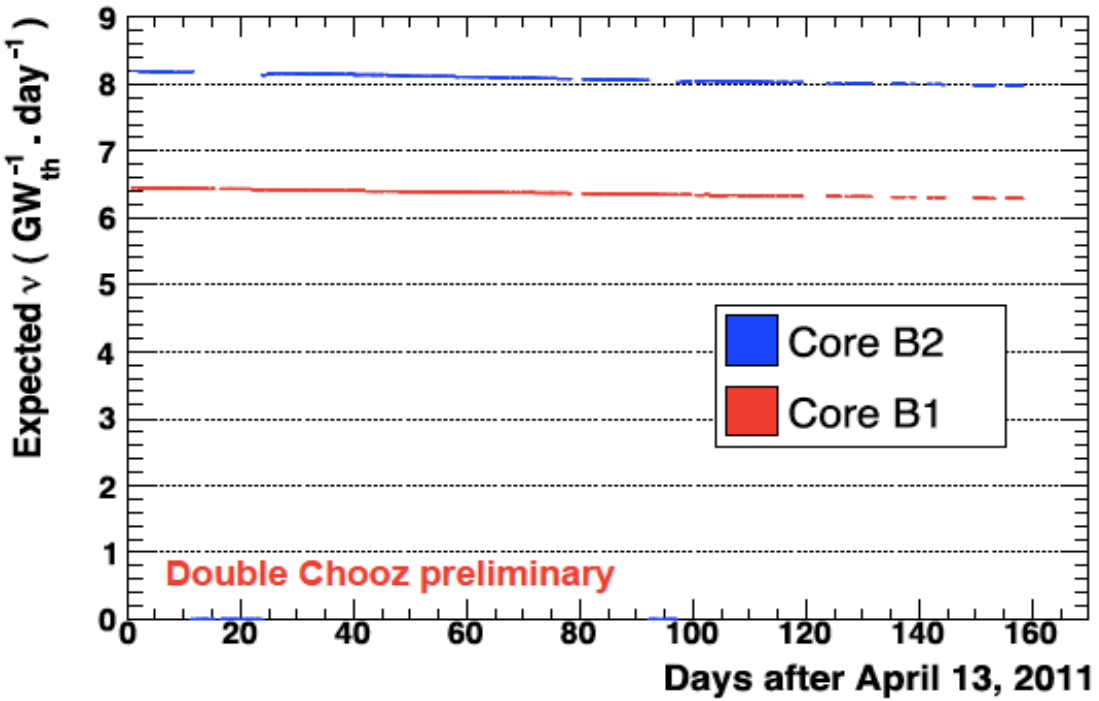
- Predicted Neutrino Rate
  - Reactor systematics
- Event selection
- Detector systematics
- Background estimation
- Oscillation results

Predicted Neutrino Rate

$$N_{\nu}^{\exp}(E,t) = \frac{N_p\,\varepsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

~2.5% reduction of neutrino rate during data taking due to accumulation of ^{239}Pu in the core

Reactor B1		2583.5
	+	
Reactor B2		2751.2
	=	
Total		**5334.7 ± 93** (1.74%)



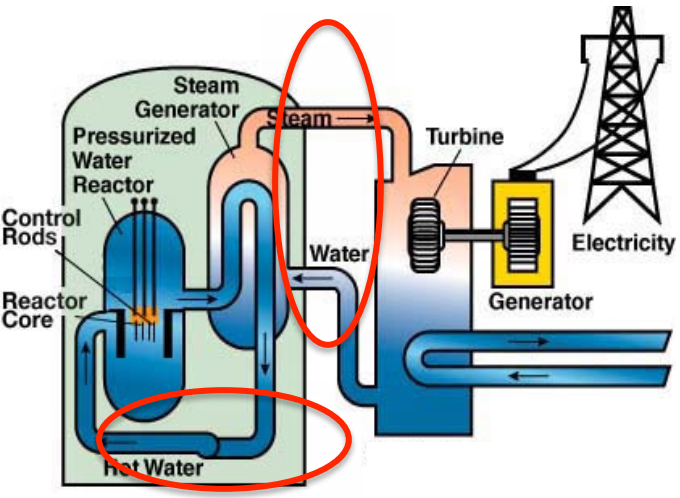
Predicted Neutrino Rate

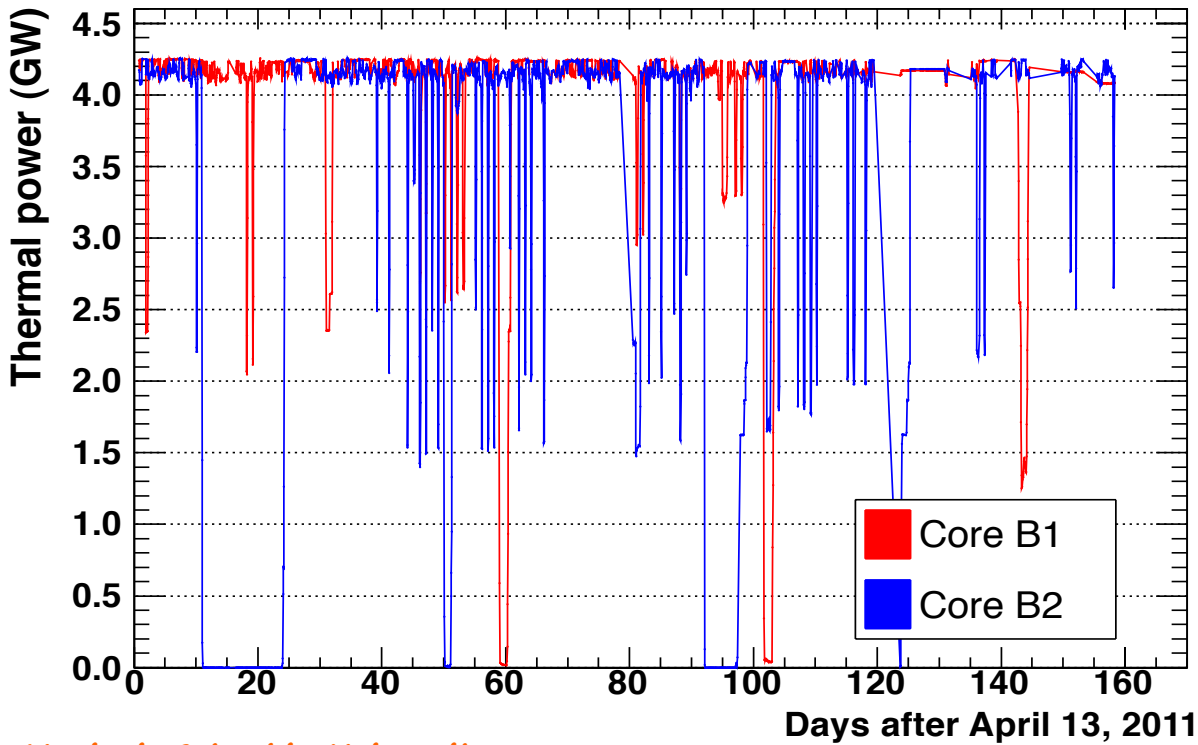
$$N_\nu^{\exp}(E,t) = \frac{N_p\,\varepsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

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

(1 sigma)

- Precise weekly anchor points by enthalpy balance at steam generators.
- Monitoring every minute based on temperature in primary loop.
- Full error treatment by EDF





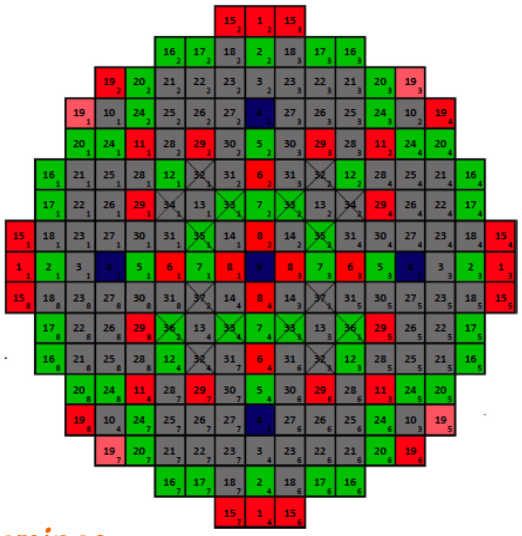
Predicted Neutrino Rate

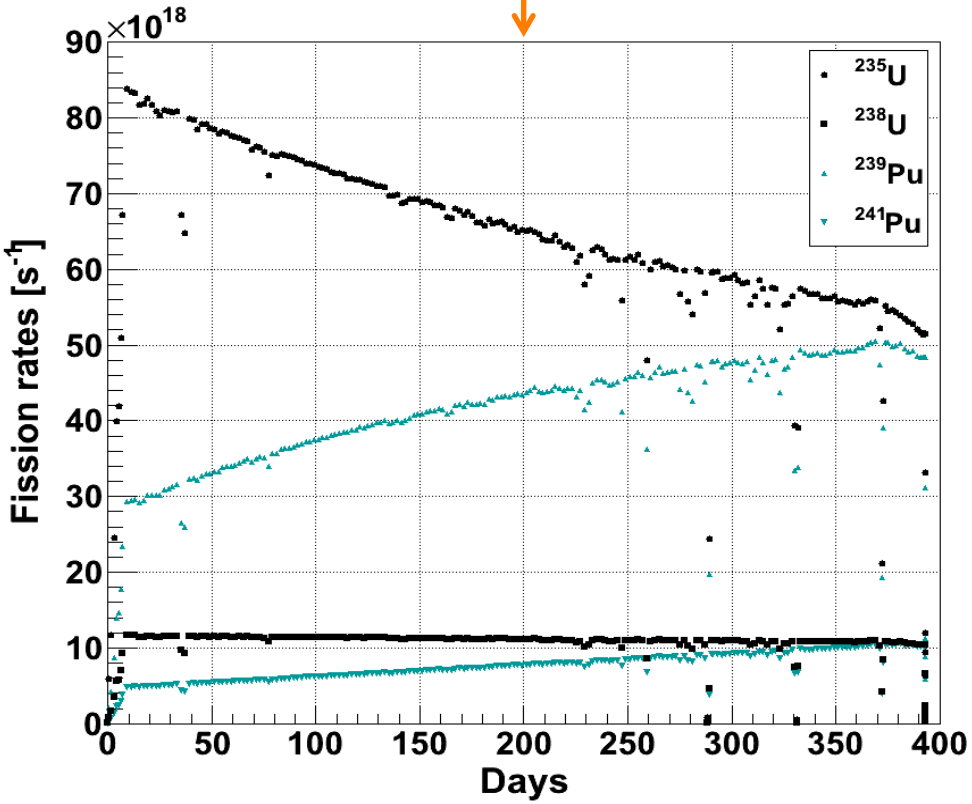
$$N_\nu^{\exp}(E,t) = \frac{N_p\,\varepsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_k \rangle$$

Need to know evolution as function of time

Two validated reactor codes: deterministic (DRAGON) and Monte-Carlo Code (MCNP Utility for Reactor Evolution)



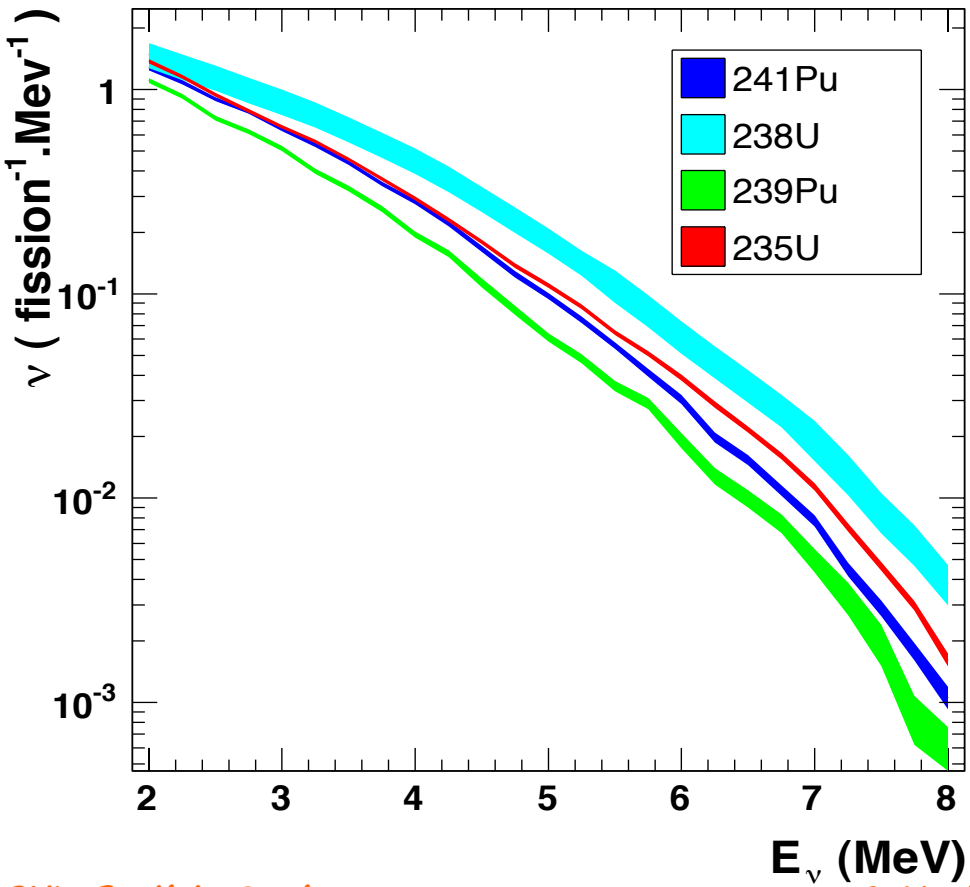


Predicted Neutrino Rate

$$N_\nu^{\exp}(E,t) = \frac{N_p\,\varepsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

Includes latest neutron life time
τ_n = 881.4 s, PDG2011

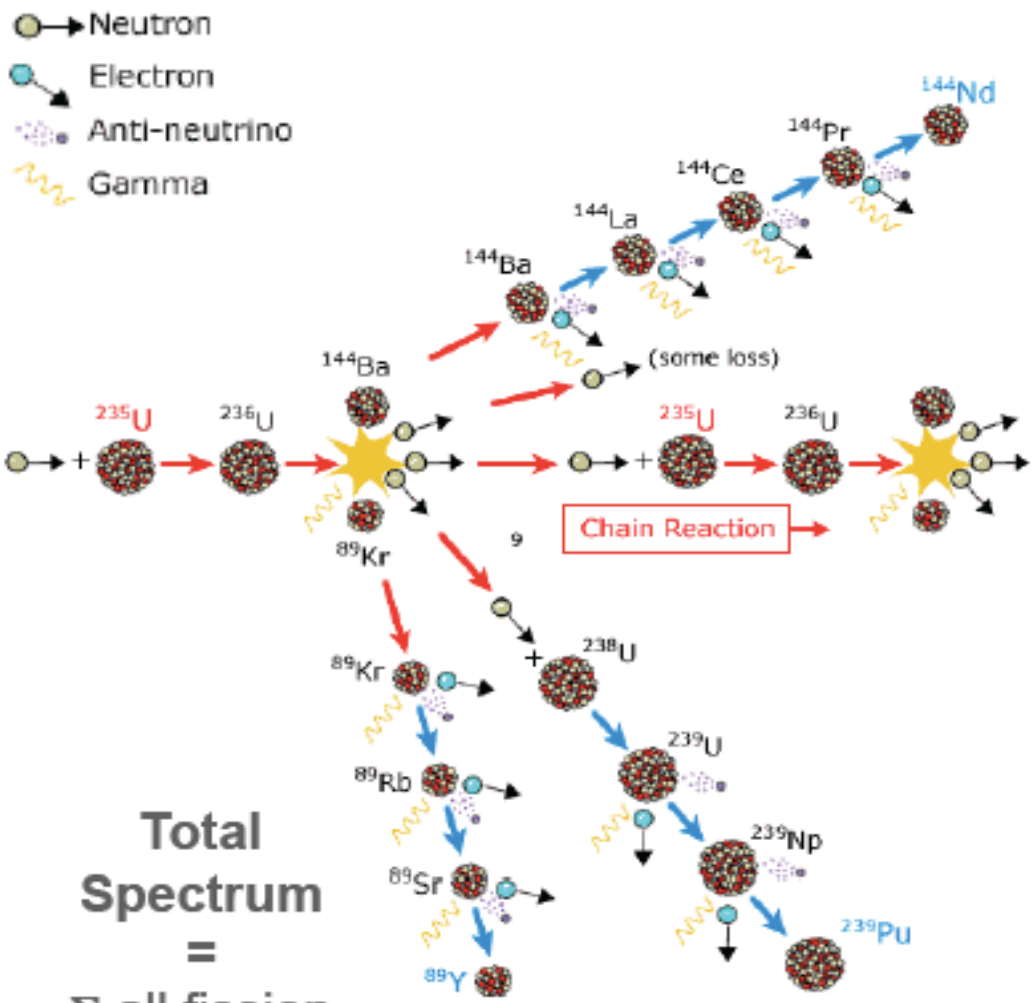
$$\langle \sigma_f \rangle_k = \int_0^\infty dE\, S_k(E)\, \sigma_{IBD}(E)$$



Complicated term, next few slides will try to explain it

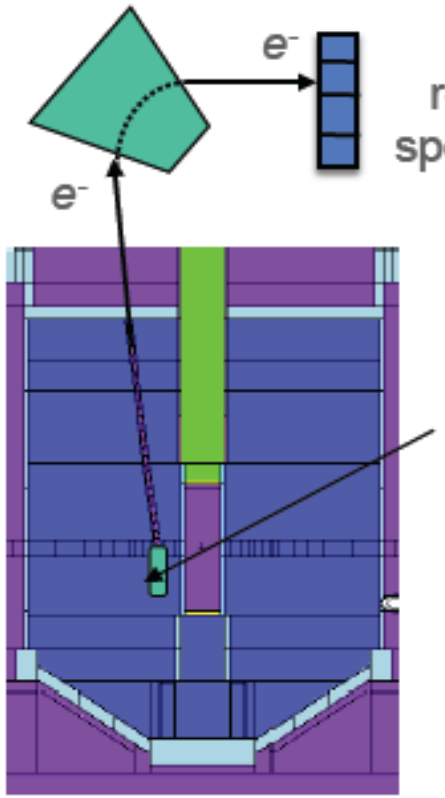
- Th.A. Mueller et al, Phys.Rev. C83(2011) 054615.
- P. Huber, Phys.Rev. C84 (2011) 024617

Reactor Neutrinos



Total Spectrum = Σ all fission products

Accurate total electron spectra from the β-decays of ^{235}U, ^{239}Pu and ^{241}Pu fission products.

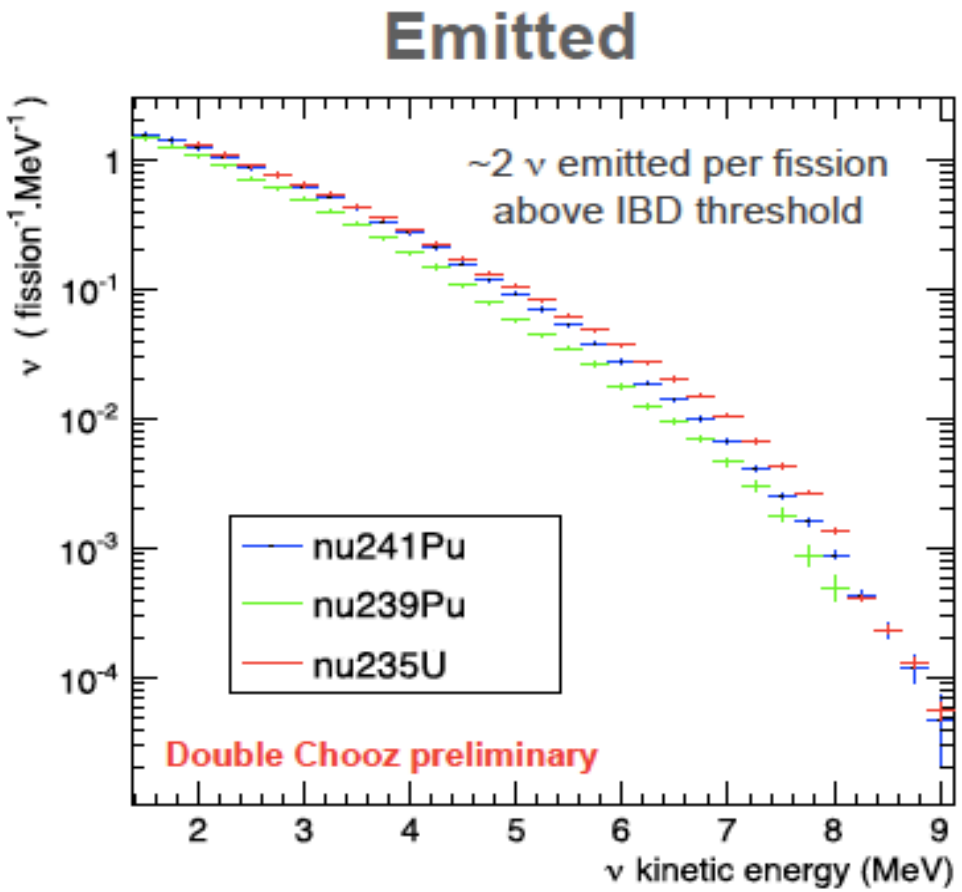


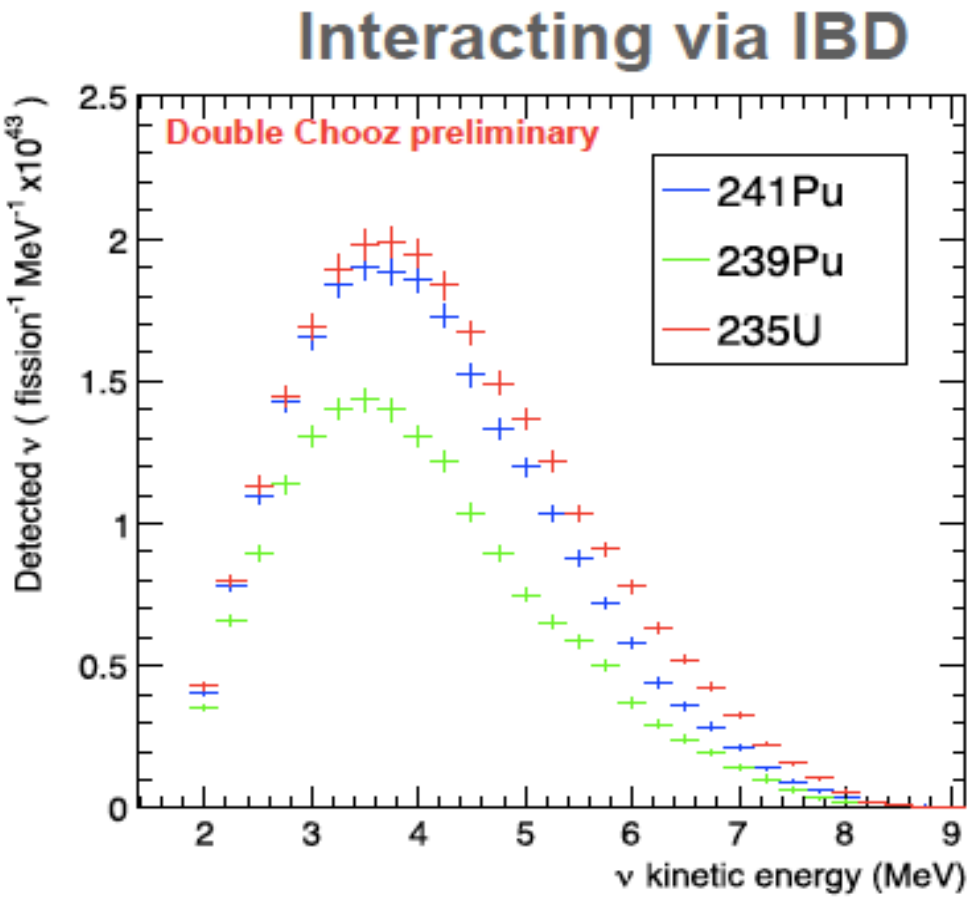
High resolution spectrometer

Target foil (^{235}U, ^{239}Pu, ^{241}Pu) in thermal n flux

ILL research reactor (Grenoble, France)

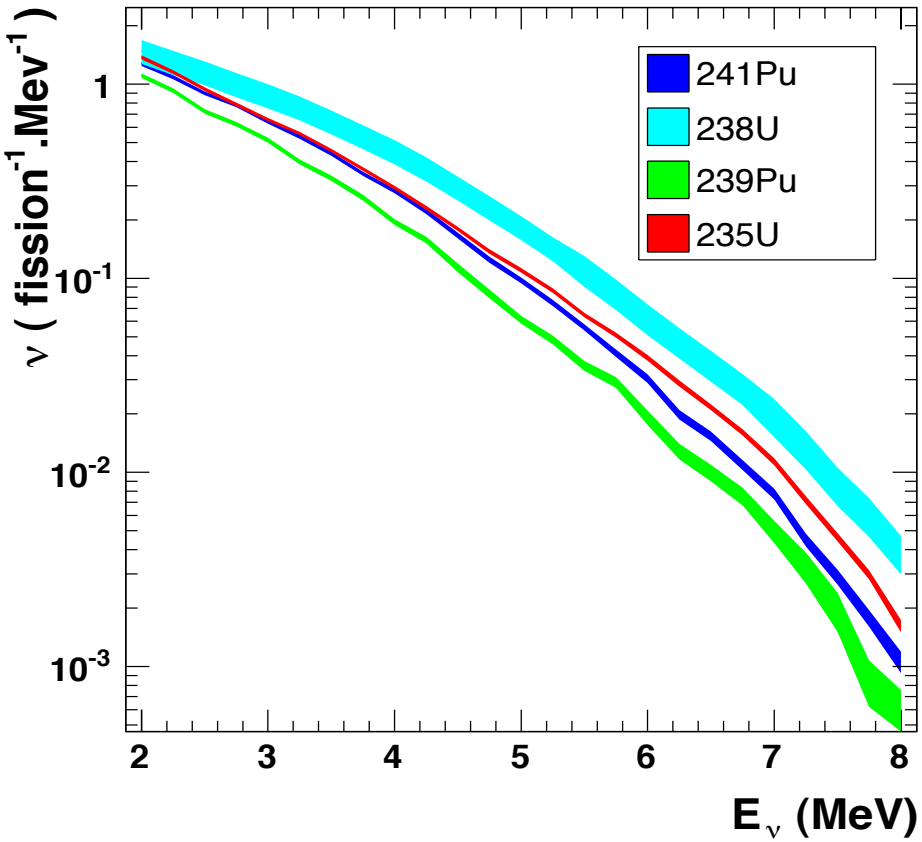
ILL ν spectra





- Reference spectra over the last 25 years

Reference ν Spectra



- Recent re-evaluations by

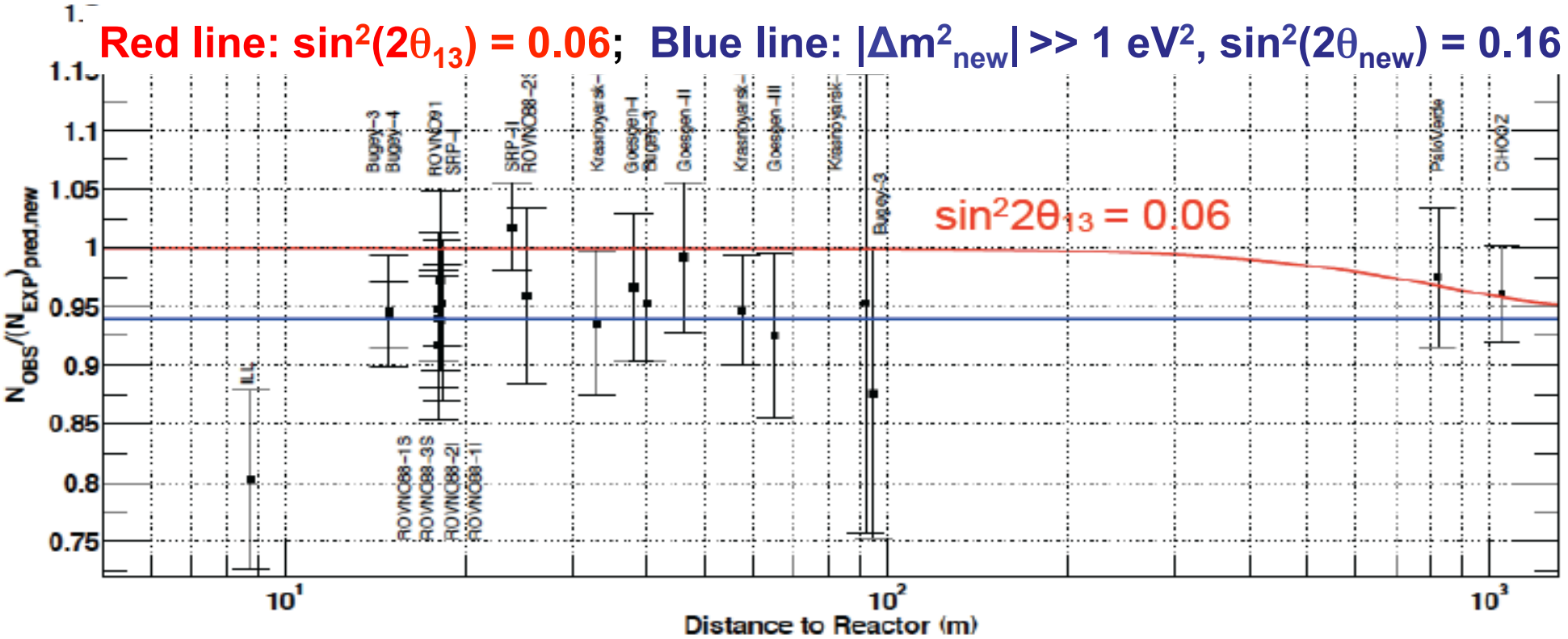
- Th.A. Mueller et al, Phys.Rev. C83(2011) 054615.
- P. Huber, Phys.Rev. C84 (2011) 024617

- Off-equilibrium corrections included

Reactor Antineutrino Anomaly

The flux is now higher by 6%
All reactor neutrino experiment are below

arXiv:1101.2755v4



- Use accurate experimental mean value at short distances as an absolute normalization.
- Includes all interpretations of the anomaly.

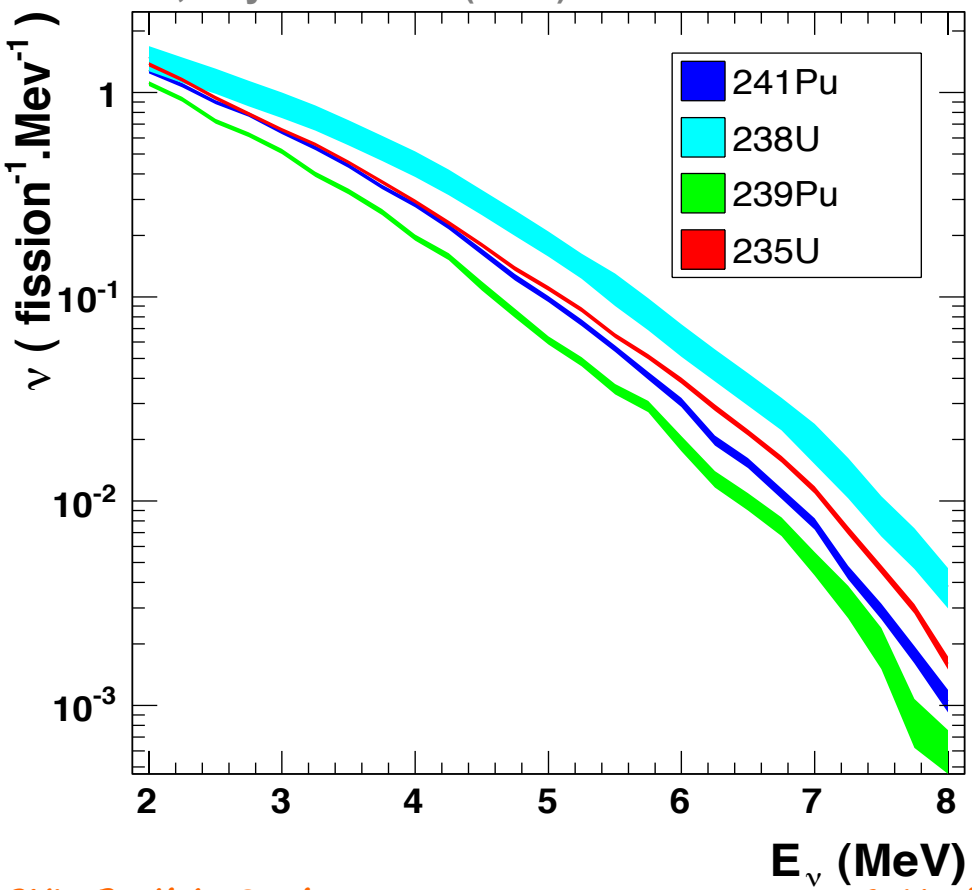
Reference spectra + Bugey exp.

$$N_\nu^{\exp}(E,t) = \frac{N_p\,\varepsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

Includes latest neutron life time
τ_n = 881.4 s, PDG2011

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

- Th.A. Mueller et al, Phys.Rev. C83(2011) 054615.
- P. Huber, Phys.Rev. C84 (2011) 024617

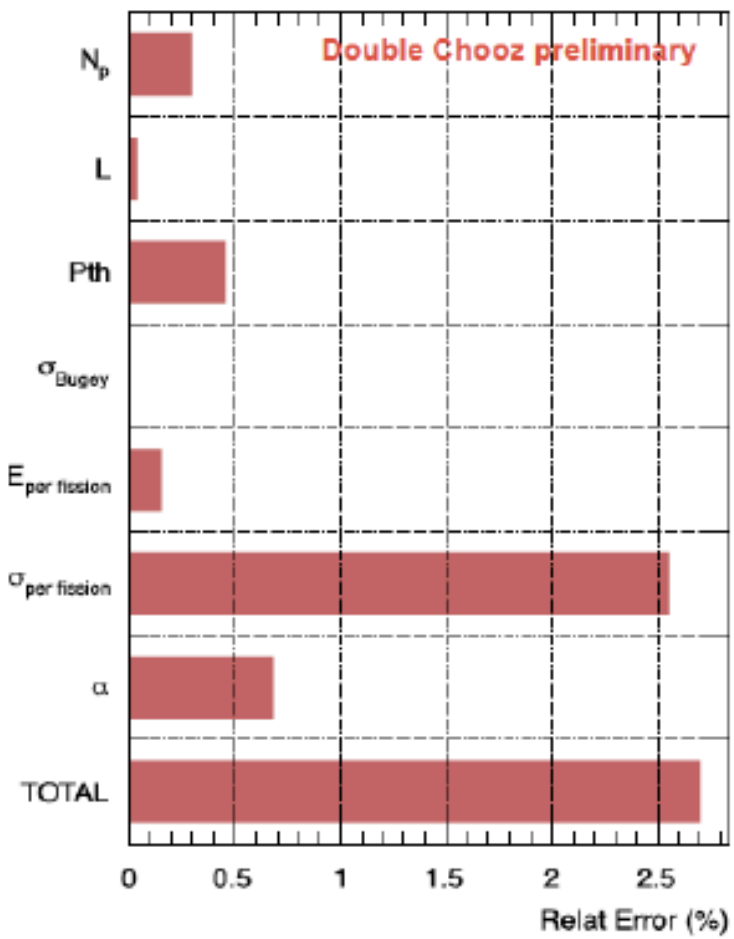


+

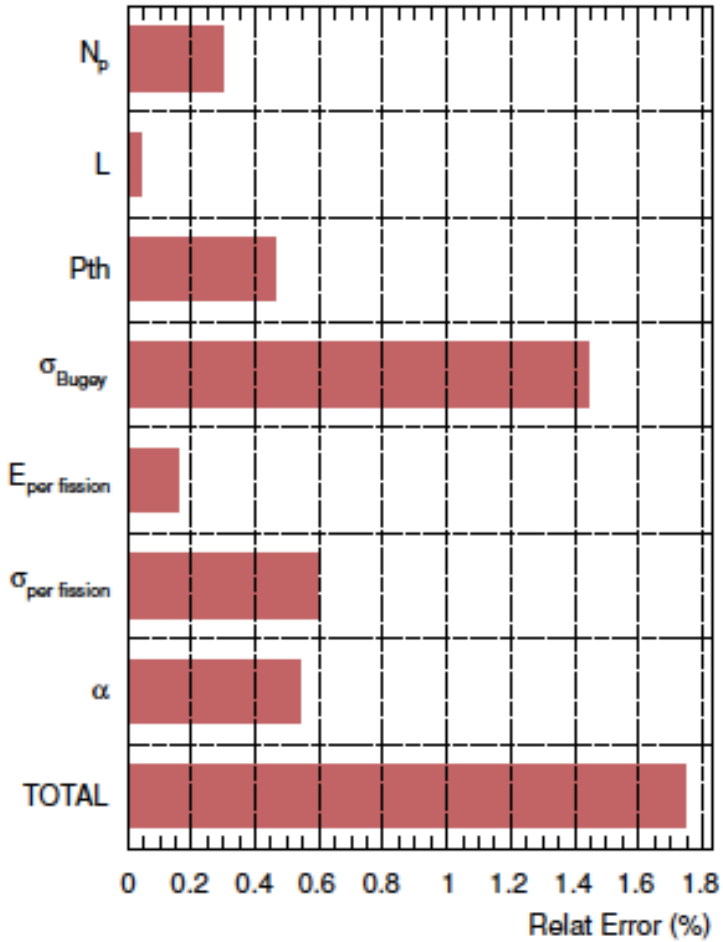
Use as normalization the experimental data from Bugey 4

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

Errors of Reactor Predictions



Without Anchor: 2.70% error

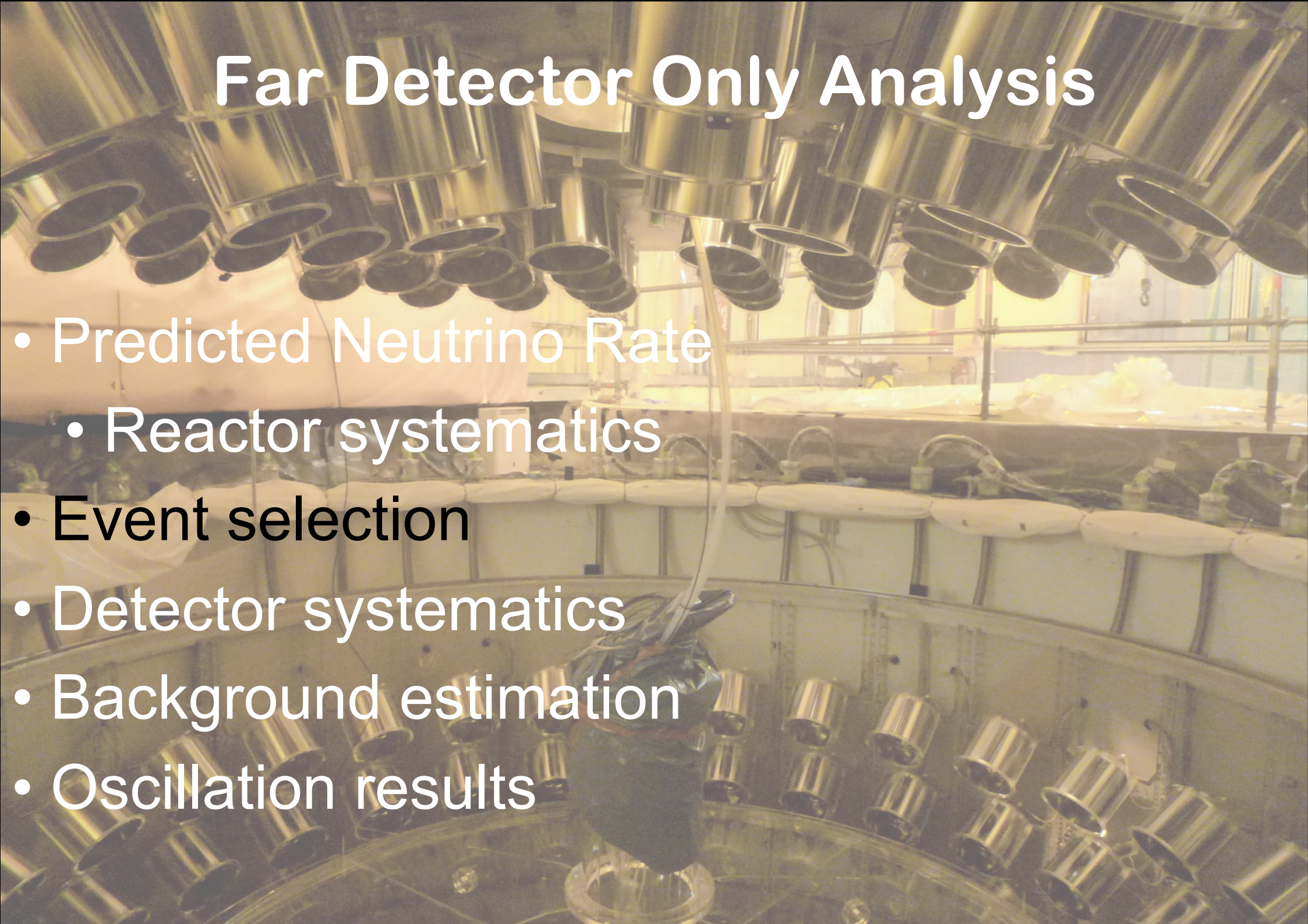


With Anchor: 1.74% error

1.74% total error (only relevant for 1-detector experiment, Chooz error = 2%)

- Bugey4 measurement suppresses sensitivity to reference spectra uncertainties
- Accurate reactor simulation (MURE) keeps uncertainty on fission rates low

Far Detector Only Analysis



- Predicted Neutrino Rate
  - Reactor systematics
- Event selection
- Detector systematics
- Background estimation
- Oscillation results

Experimental Signal

- The reaction process is inverse β-decay followed by neutron capture
  - Two part coincidence signal is crucial for background reduction.

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

$$\hookrightarrow n\ capture$$

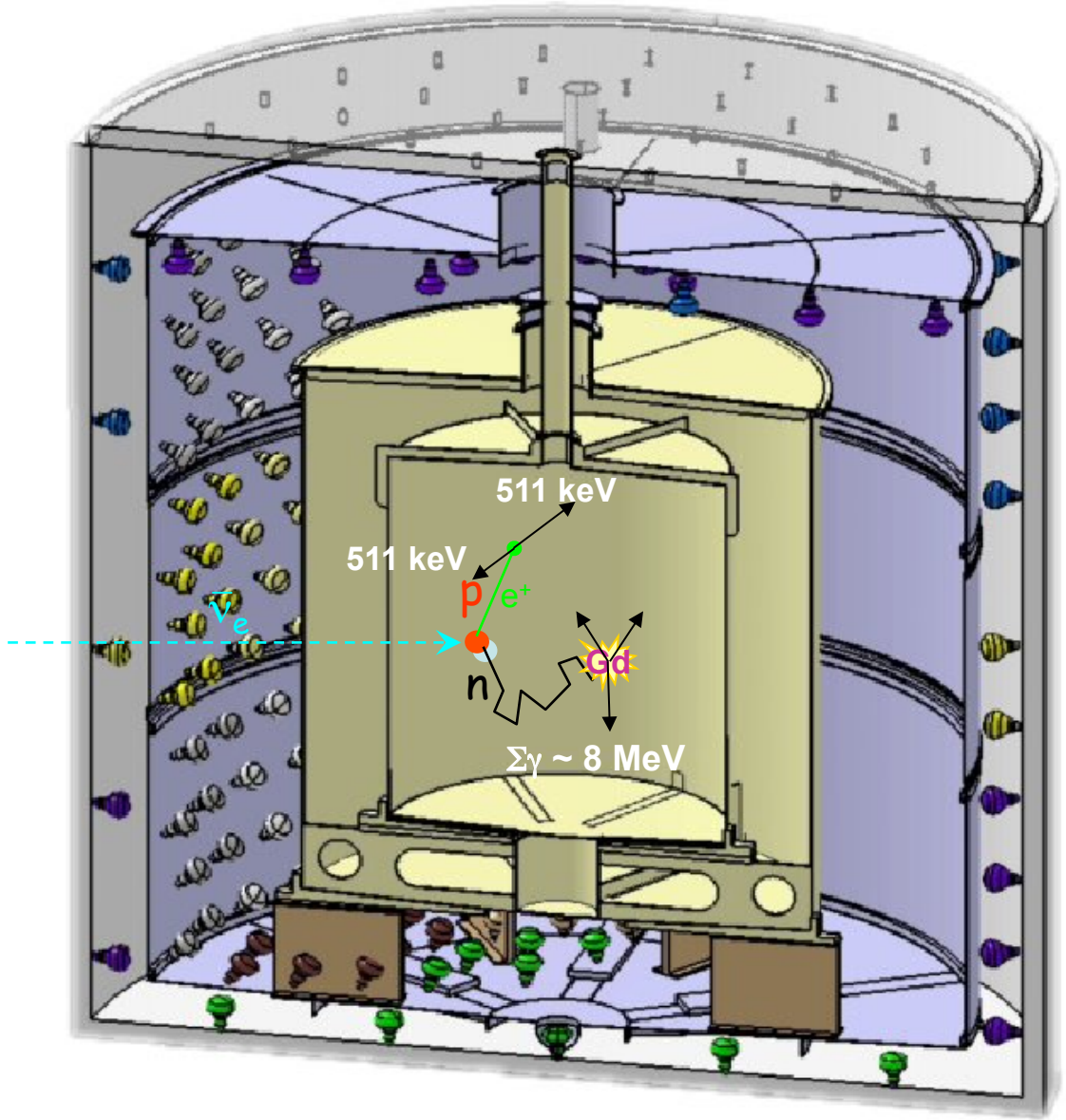
- Positron energy spectrum implies the neutrino spectrum ($e^+e^- \rightarrow \gamma\gamma$)

$$E_\nu = E_{vis} + 1.8\ MeV - 2m_e$$

ν threshold 1.8 MeV

- The scintillator is doped with gadolinium to enhance capture

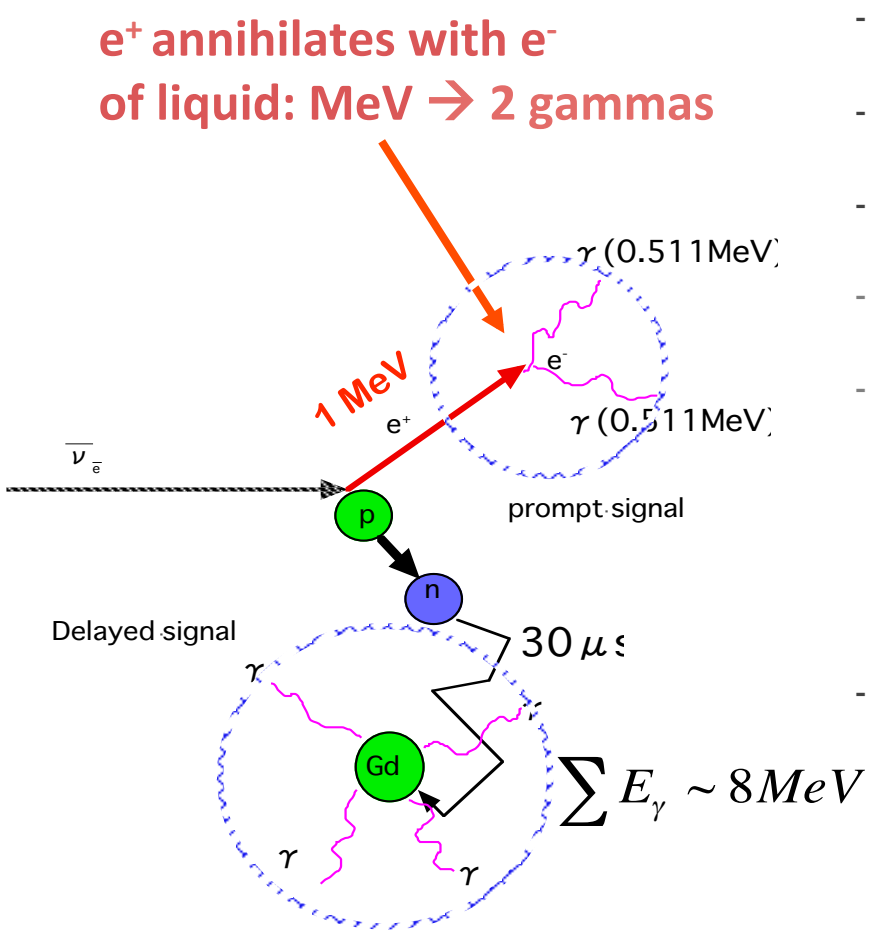
$$n\ {}^{m}Gd \rightarrow {}^{m+1}Gd\ \gamma\text{'s}\ (8\ MeV)$$



Signal = Positron signal + Neutron signal within 100 μsec

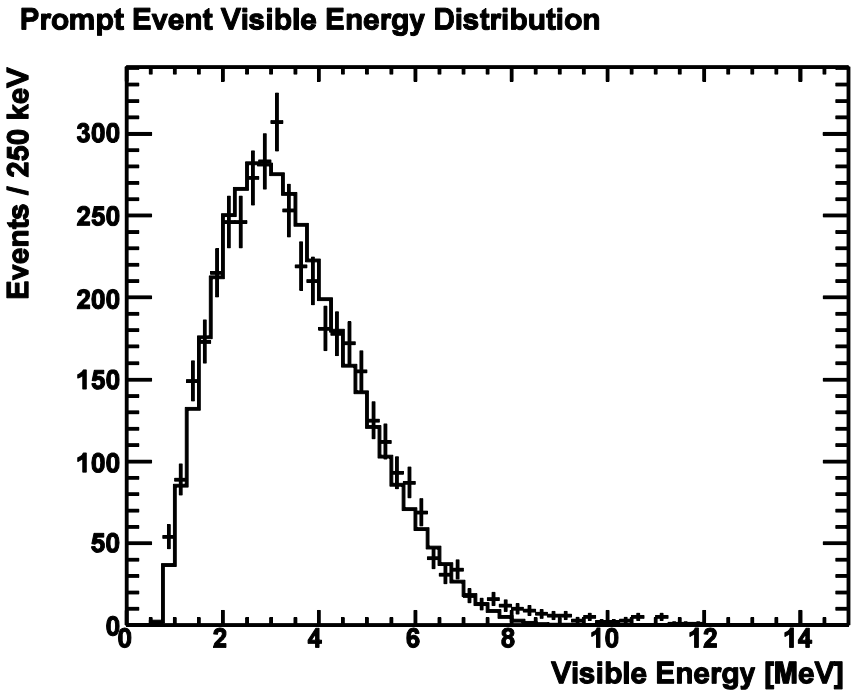
Neutrino Candidate Selection

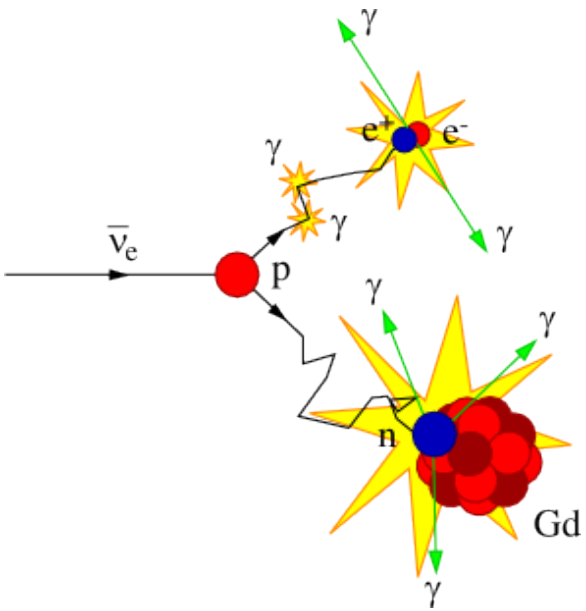
- Preliminary selection of neutrino candidates (i.e. neutrinos and background):
  - Prompt signal within [0.7,12]MeV
  - Delayed signal within [6,12]MeV
  - Coincidence window between [2, 100] μs
  - Discard all triggers in 1ms after each muon (mainly tagged by inner-veto)
  - PMT spontaneous light emission rejection cuts (14PMT switched OFF)
    - ensure light approx. homogeneously spread across (use ratio Q_{max}/Q_{total})
    - ensure light arrives at approx. the same time (use RMS of hit-time per PMT)
  - Multiplicity condition:
    - » No trigger with energy > 500keV in between prompt and delayed
    - » No trigger 100 μs before or 400 μs after the prompt (multiplicity cut)



n captured by Gadolinium:
8 MeV of photons emitted within 10's of μsec.

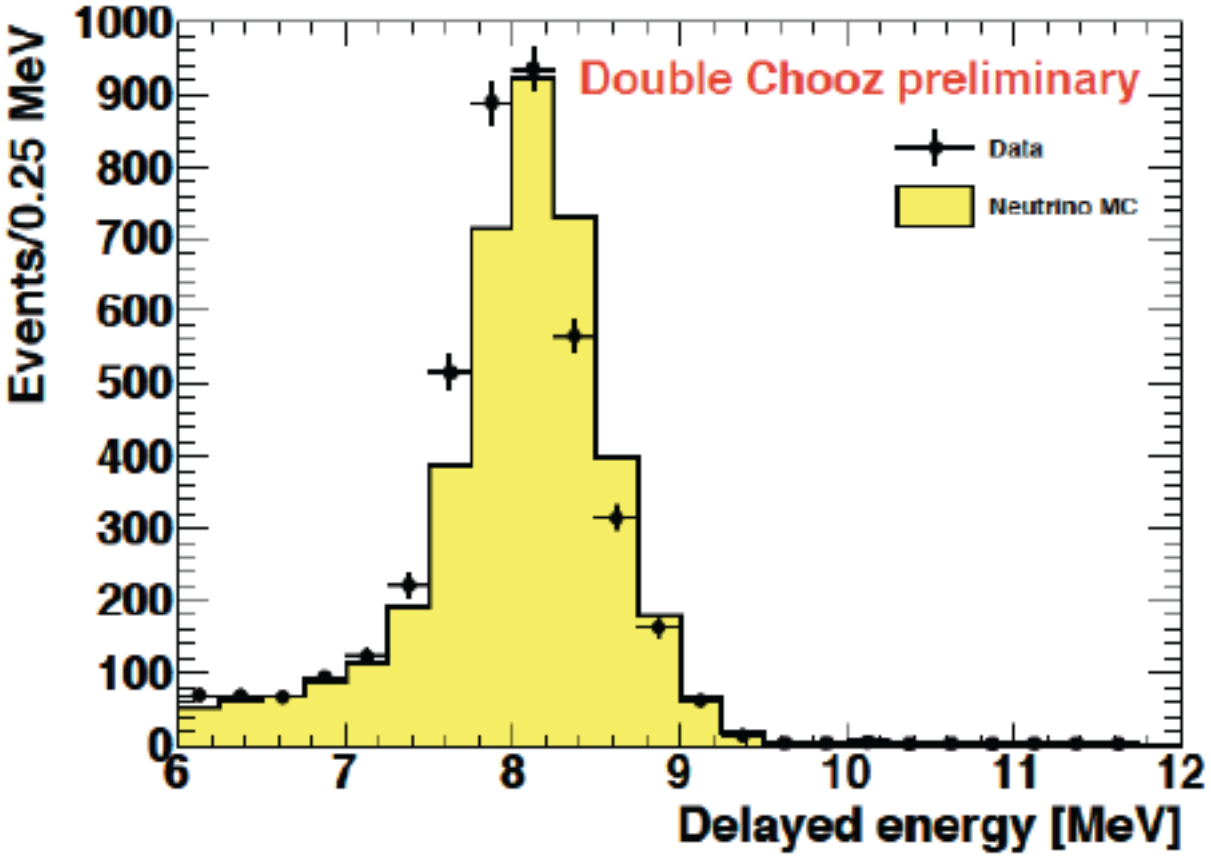
Neutrino Candidate Selection



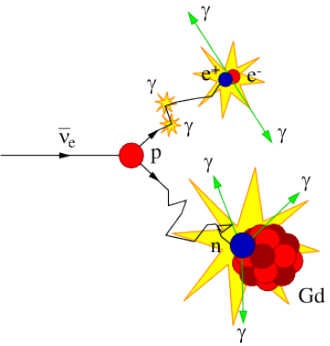


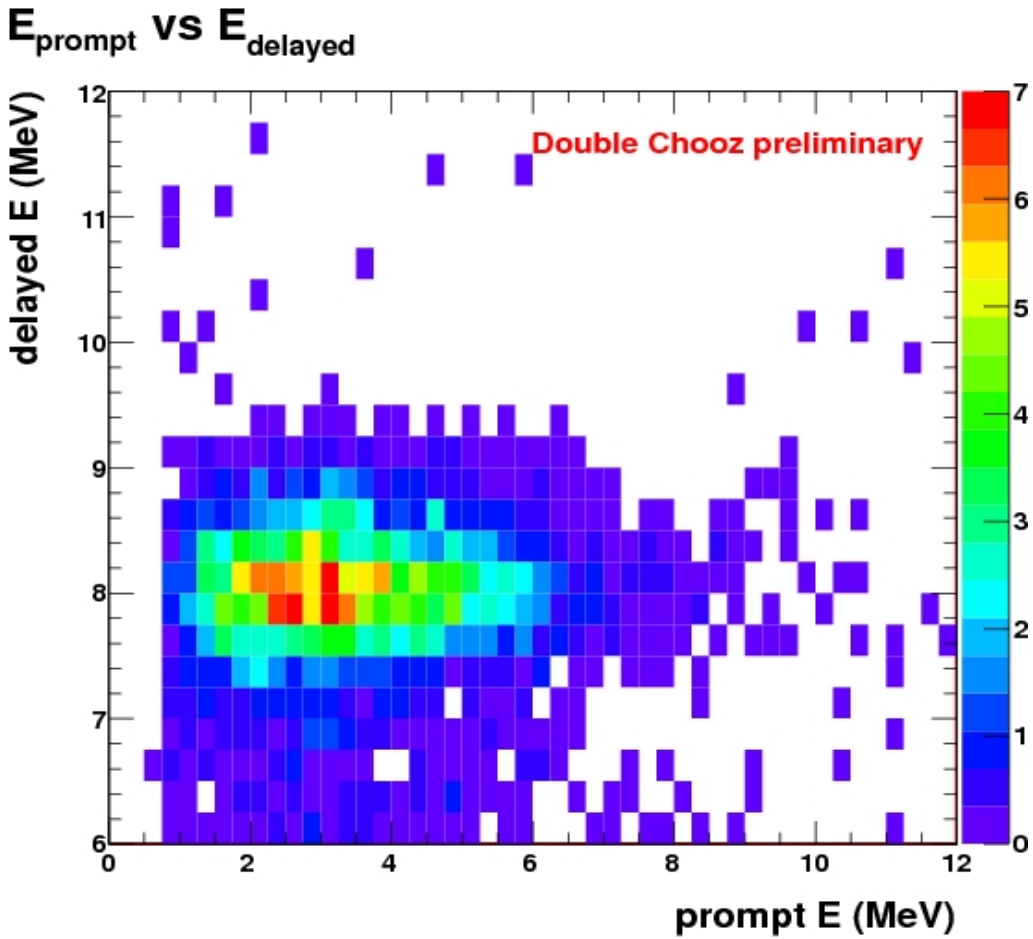
The Gd capture energy peak is the key for Double Chooz:

- Selection of Neutron Capture on Gd only
- Allow to define the fiducial volume by the mass of the Gd-loaded LS

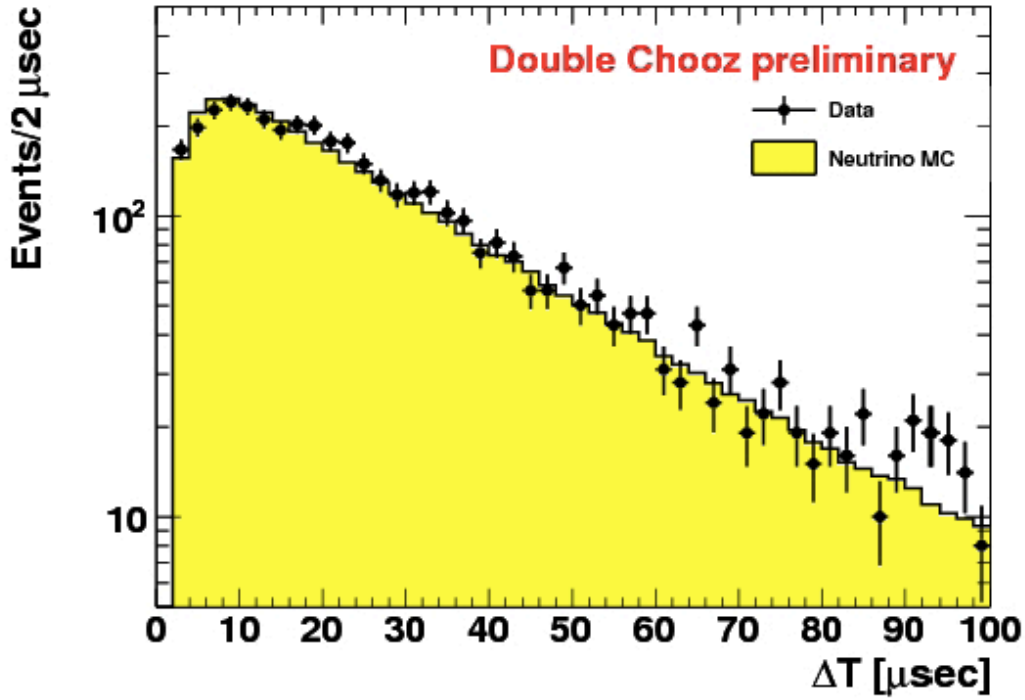


Neutrino Candidates: Energy & Time Correlations



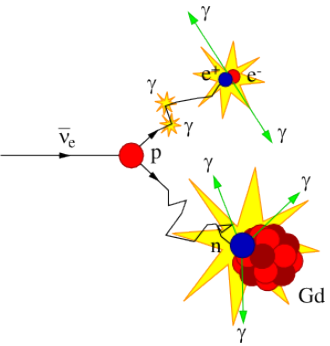


- KeV neutrons thermalize within a few μs
- Then neutrons get captured on Gd with τ = 27μs
- Good agreement with the MC expectation

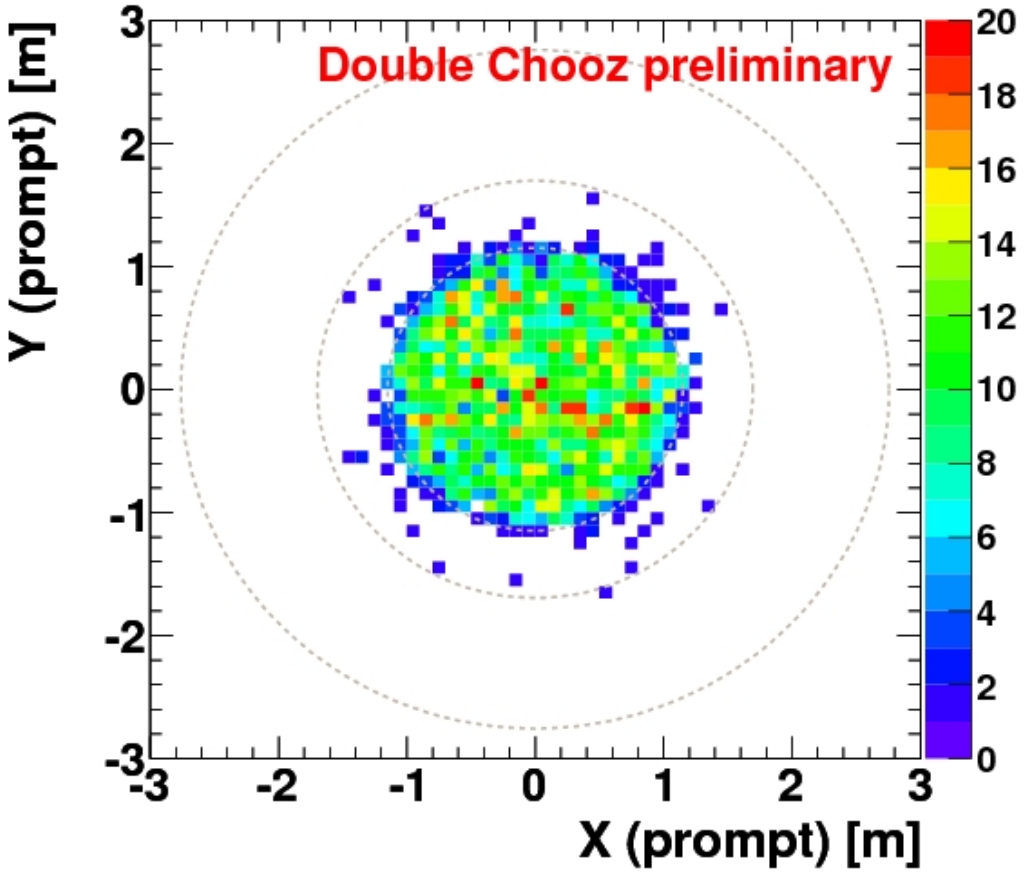


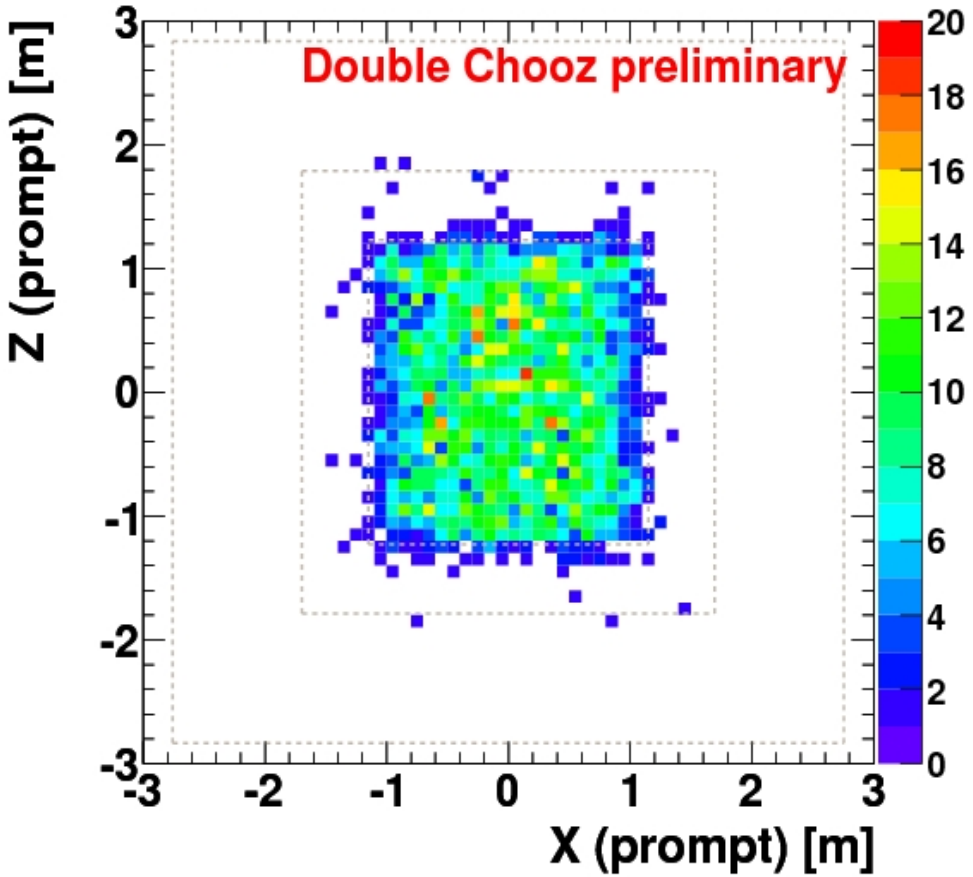
The efficiency within [2,100] μs is 0.965 ± 0.5%

Cross-check: Reconstructed Vertex Position

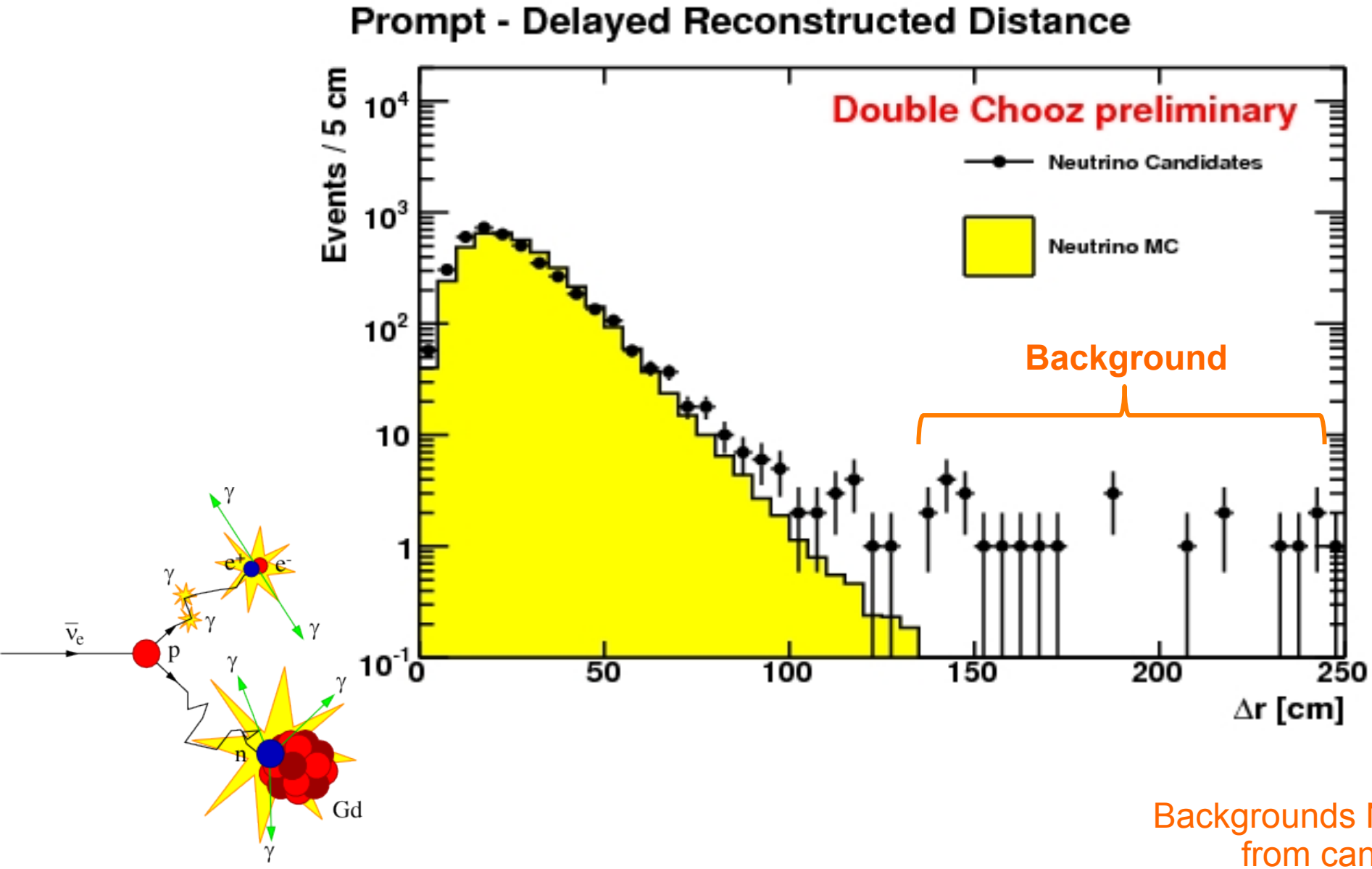


Well localized in target volume without vertex cut



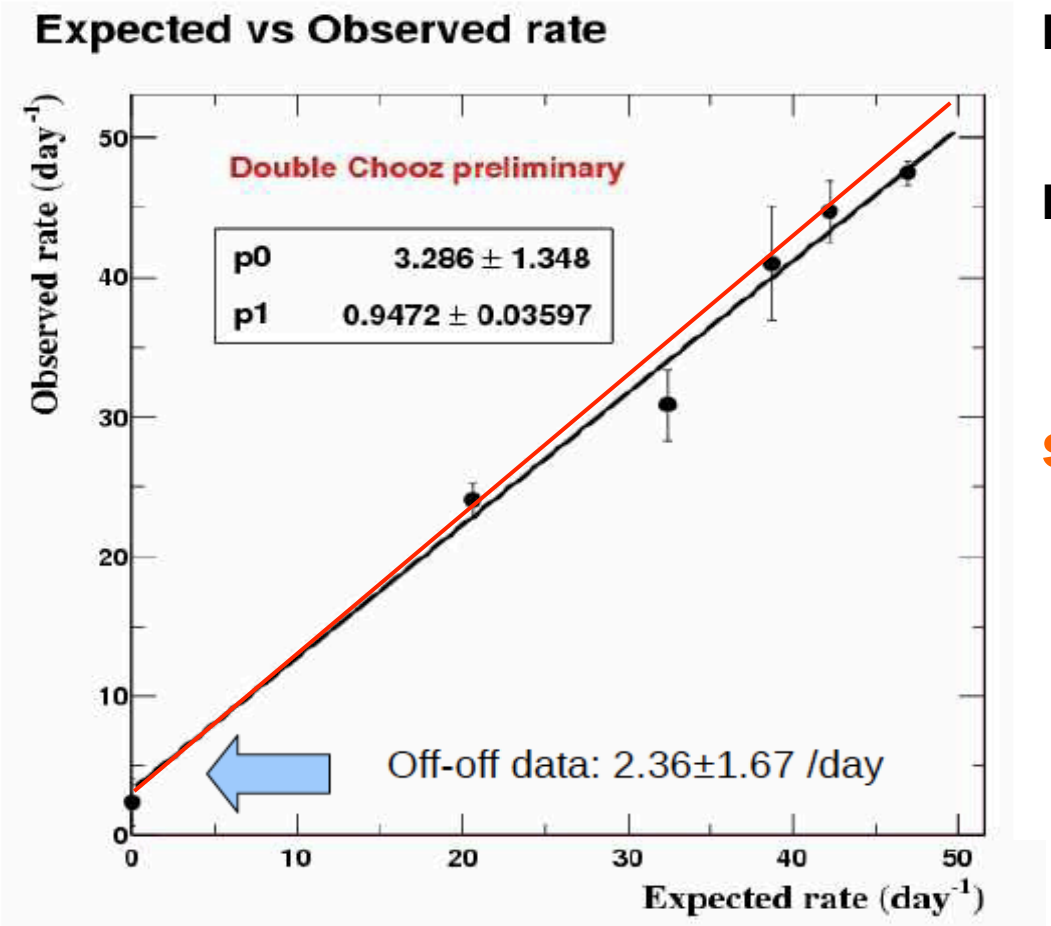


Cross-check: Position Correlation



Backgrounds NOT subtracted from candidates sample

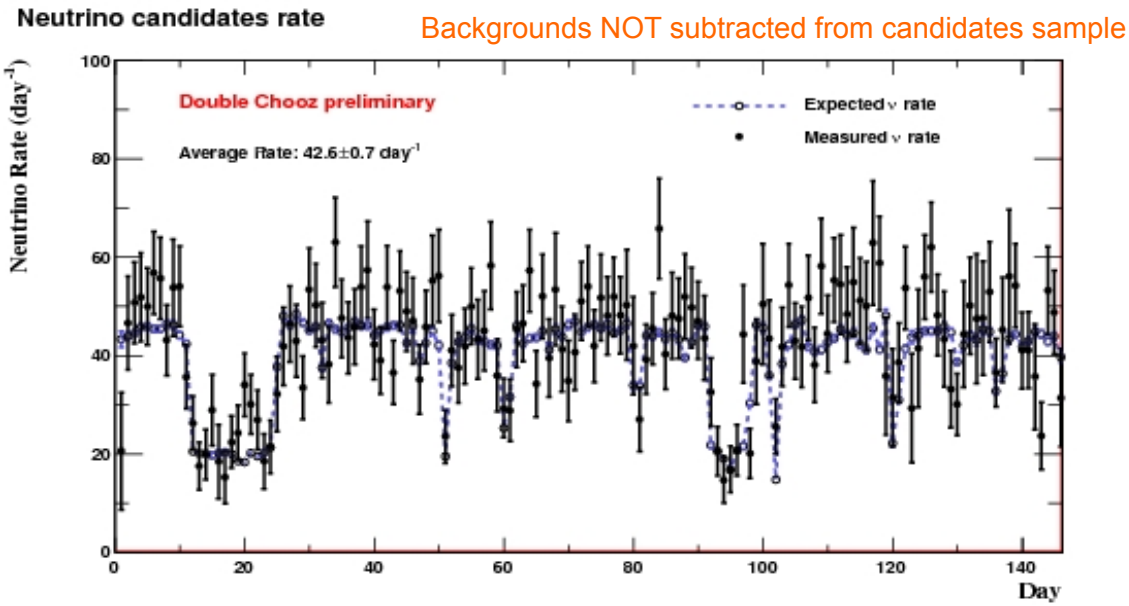
Cross-check: Neutrino Rate Variation with Reactor Power



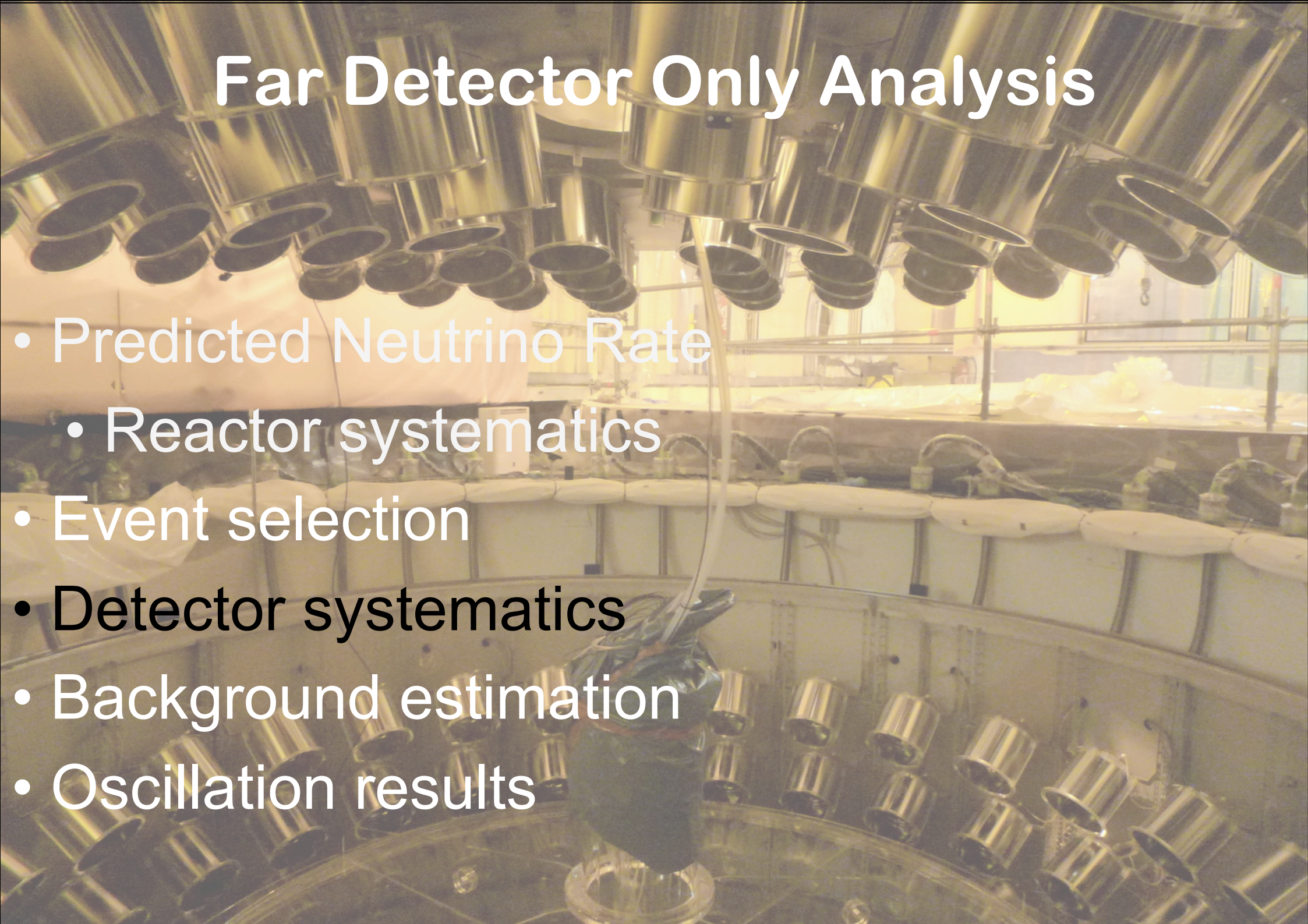
Background from fit:
3.3±1.3 /day

Disappearance:
1-0.947=0.0528
Average oscillation for full mixing: 0.5362

$\sin^2(2\theta_{13}) \cong 0.098 \pm 0.067$

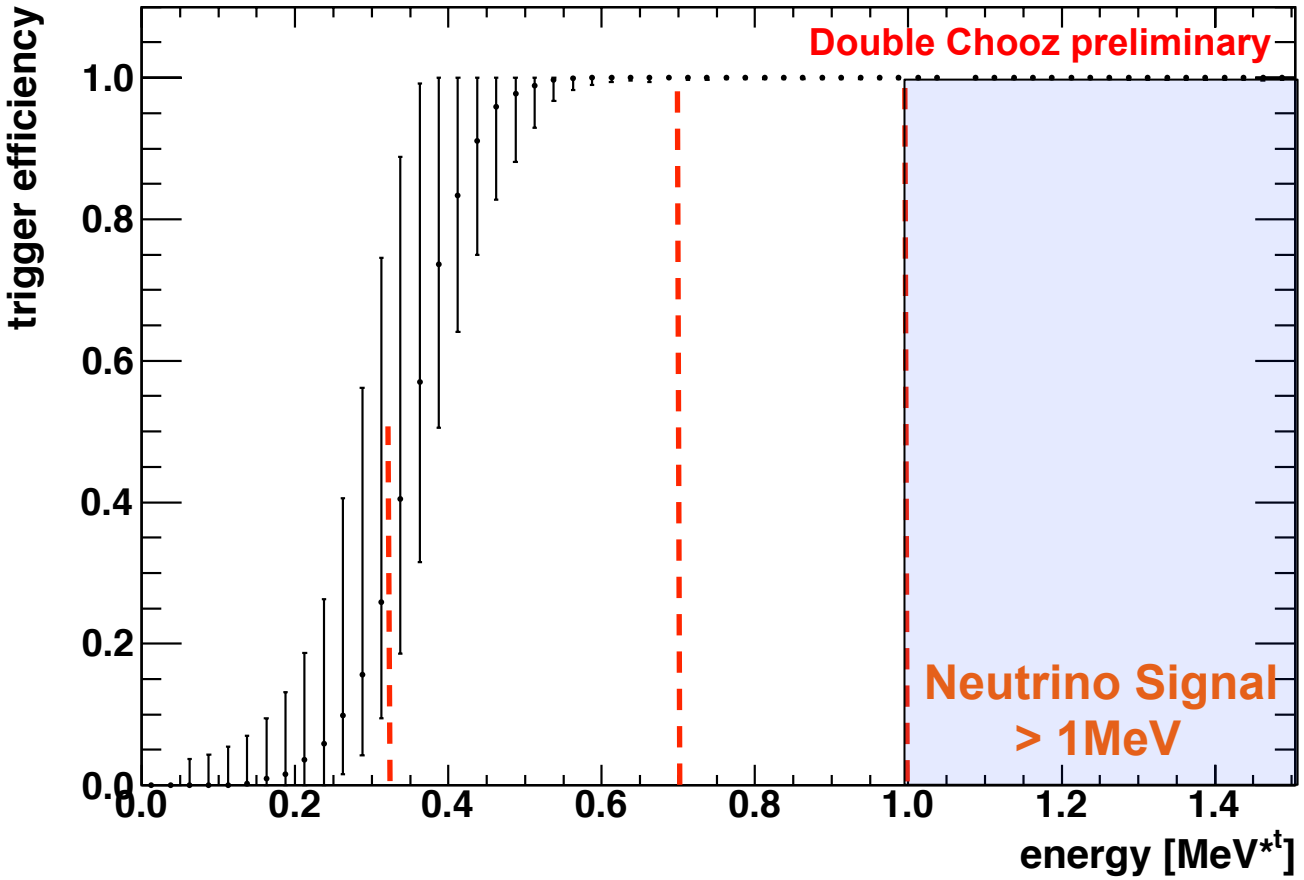


Far Detector Only Analysis



- Predicted Neutrino Rate
  - Reactor systematics
- Event selection
- Detector systematics
- Background estimation
- Oscillation results

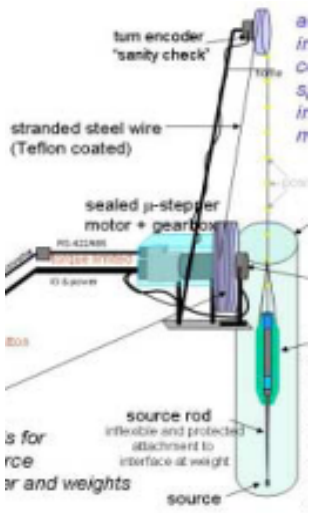
Trigger Efficiency

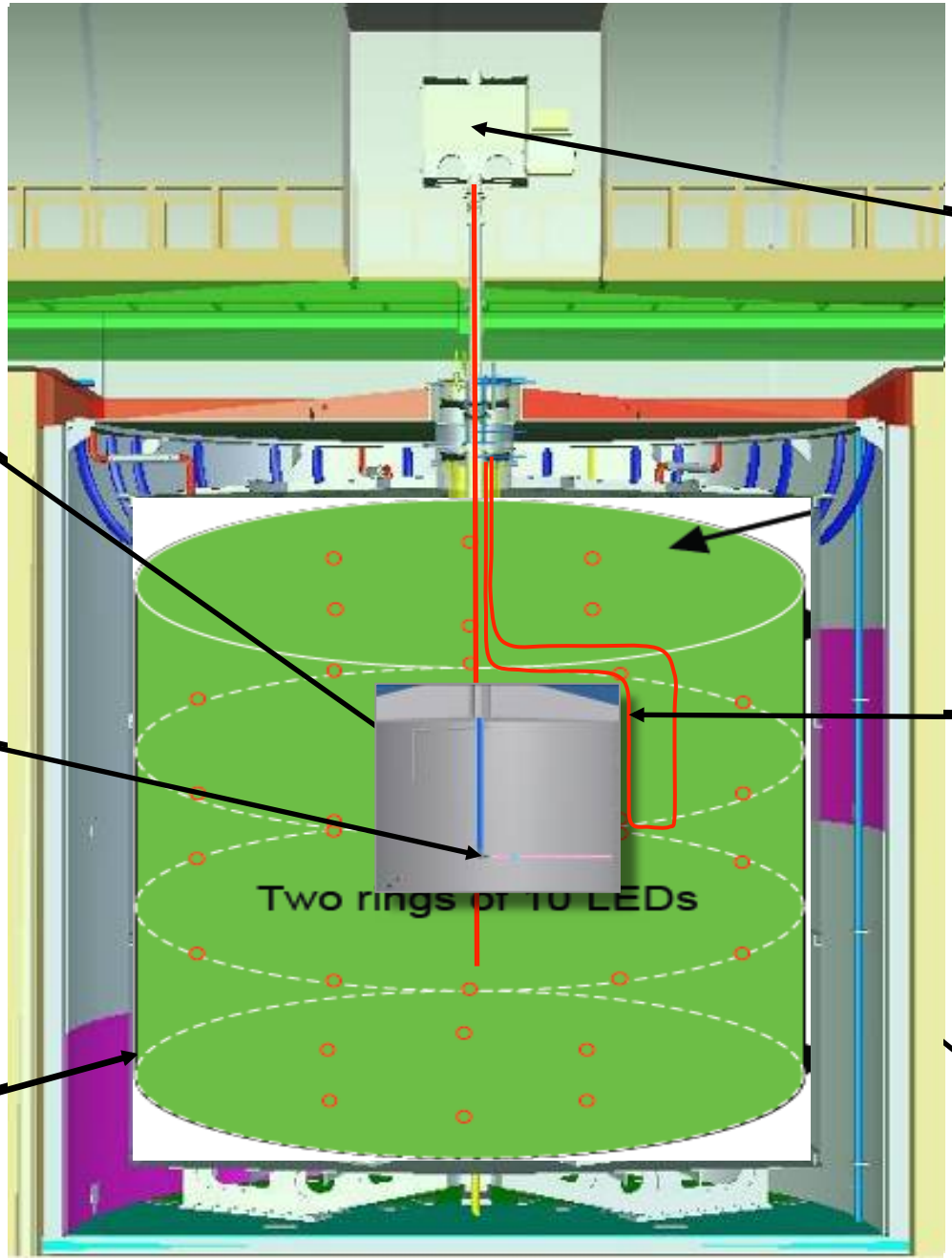


- Trigger threshold (50% efficiency) : 350 keV
- Trigger efficiency :100% +0/- 0.4% for E>700 keV
- Prompt Energy Cut Efficiency : > 99.9%

Calibration Systems

Fish-line





Glove Box

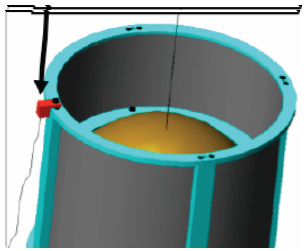


GC guide Tube



Articulated Arm

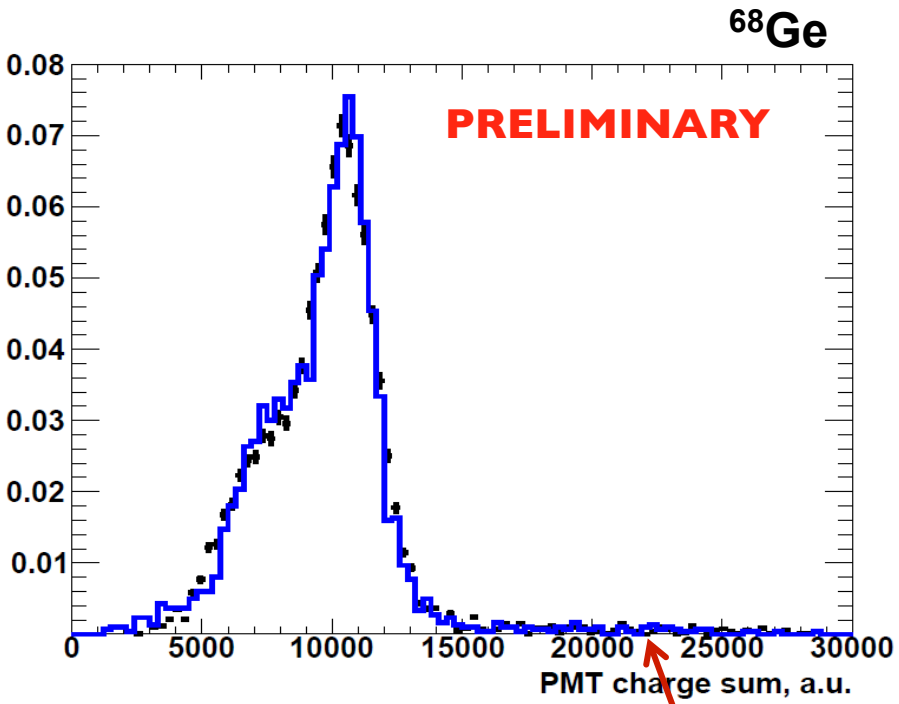
Embedded LED calibration system 385, 420, 470 nm

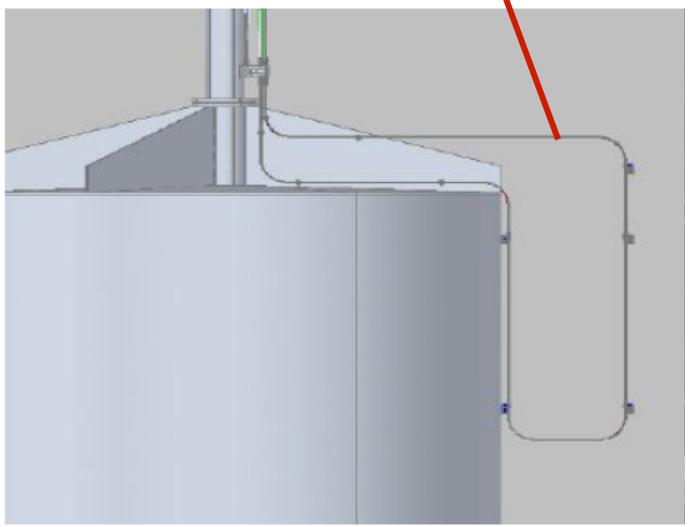


Buffer guide Tube

Calibration systems cont'd

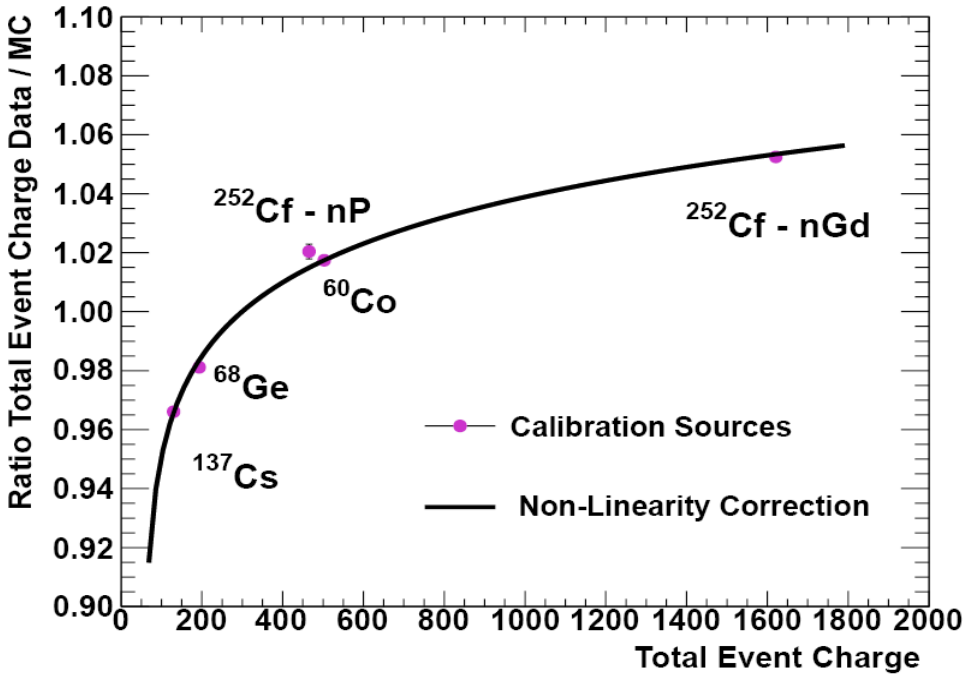
- Light injector (inner-detector and inner-veto)
- Laser (UV and green)
- Sources (^{68}Ge,^{37}Cs, ^{60}Co, ^{252}Cf)
  - In the target-volume
  - In the gamma-catcher volume
- Deployment systems
  - vertical axis
  - (future) articulated arm

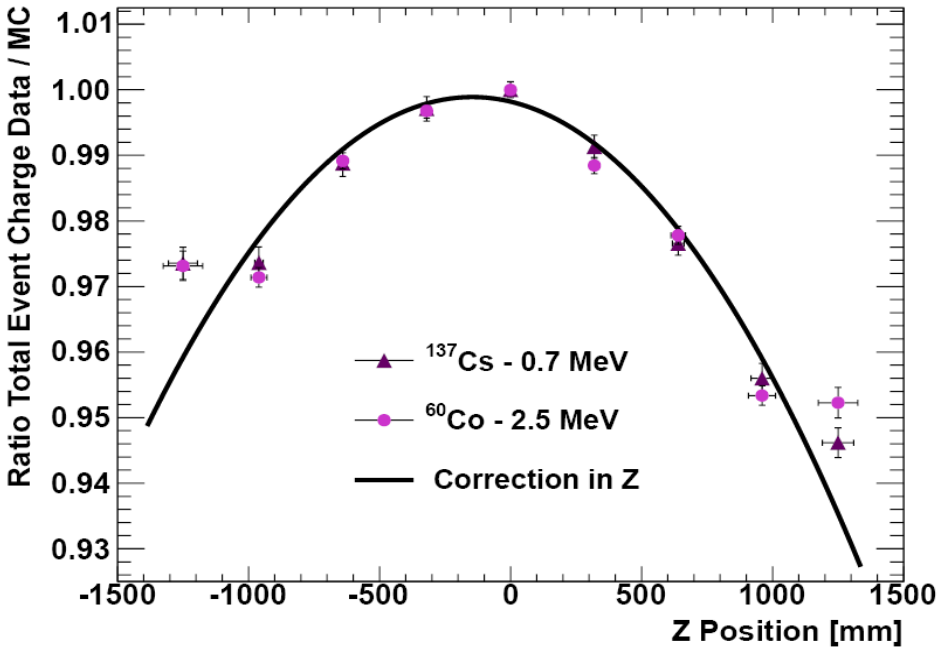




Energy Scale Uncertainties

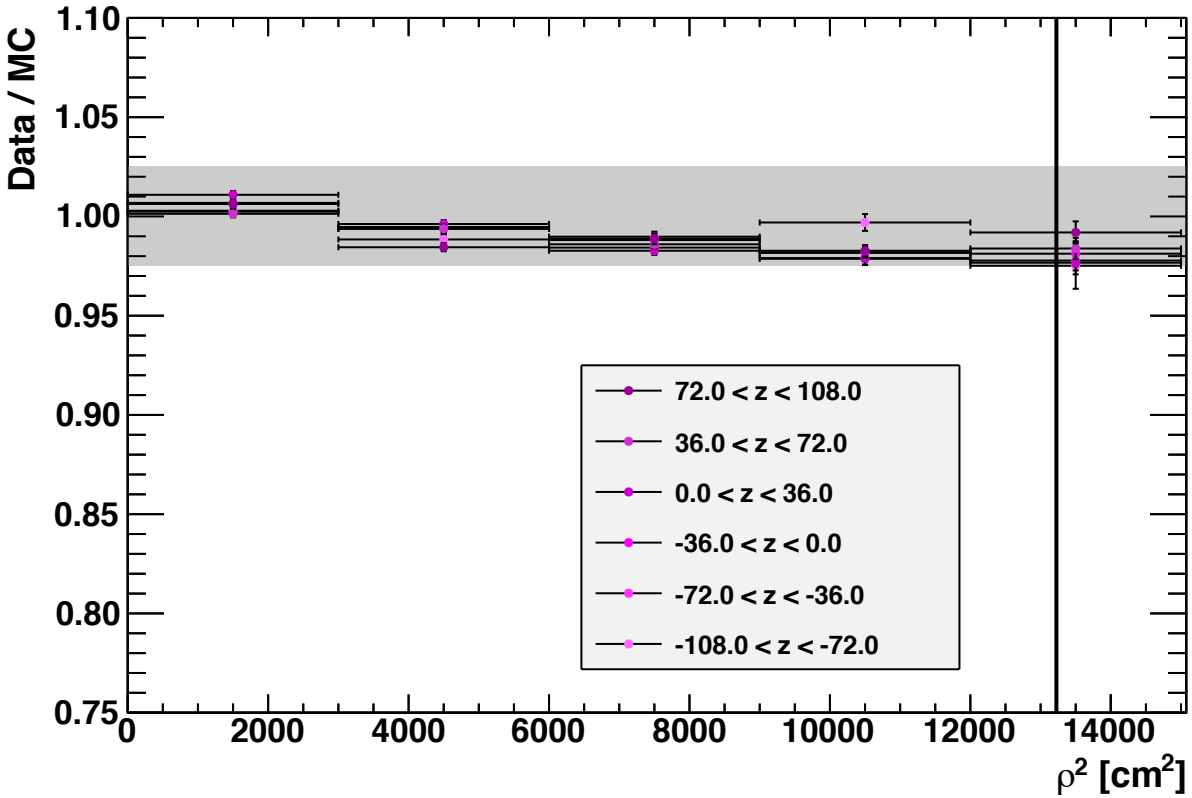
- Use fit to phenomenological model to correct data/MC differences
- Full covariance matrix determined from event shifts from 1000 simulations probing parameter space allowed by fit parameters
- Matrix then expanded to cover any remaining data/MC differences

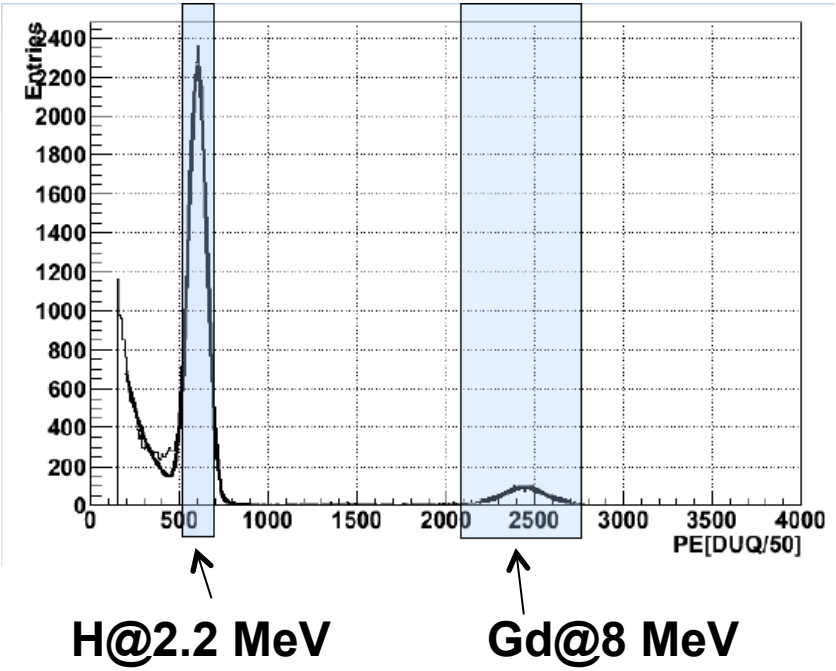




Spallation Neutrons

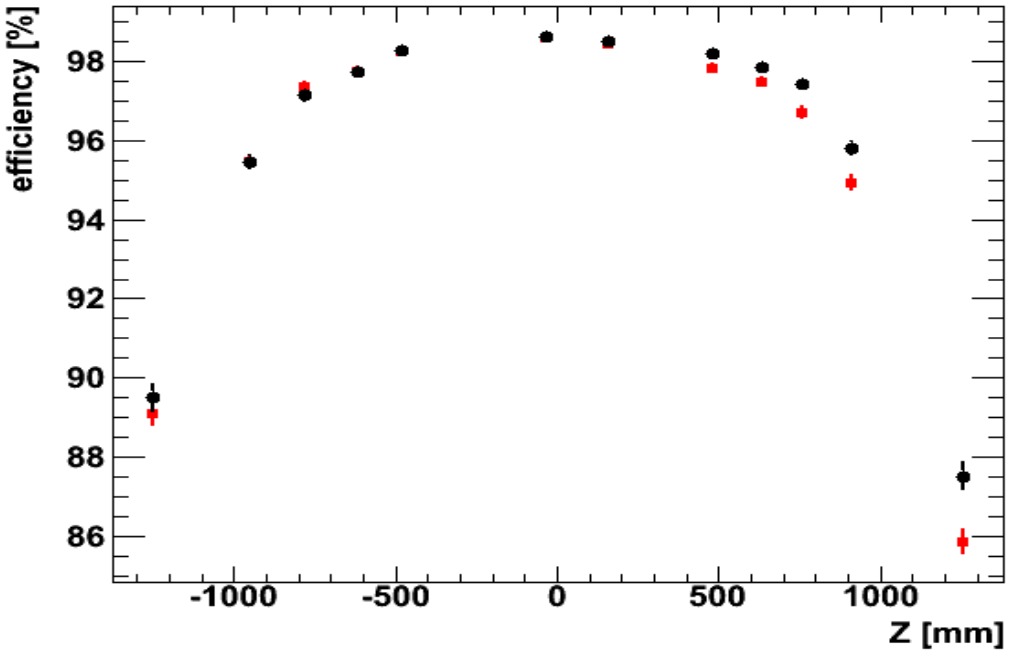
- Evaluation of the (Q, Z) correction in all volumes
- Study of spallation neutrons in $\rho^2 = x^2+y^2$ in slices of z
- Capture on Gd peak (8 MeV)
- Except for the extremes of the GC all is within ±2.5%.





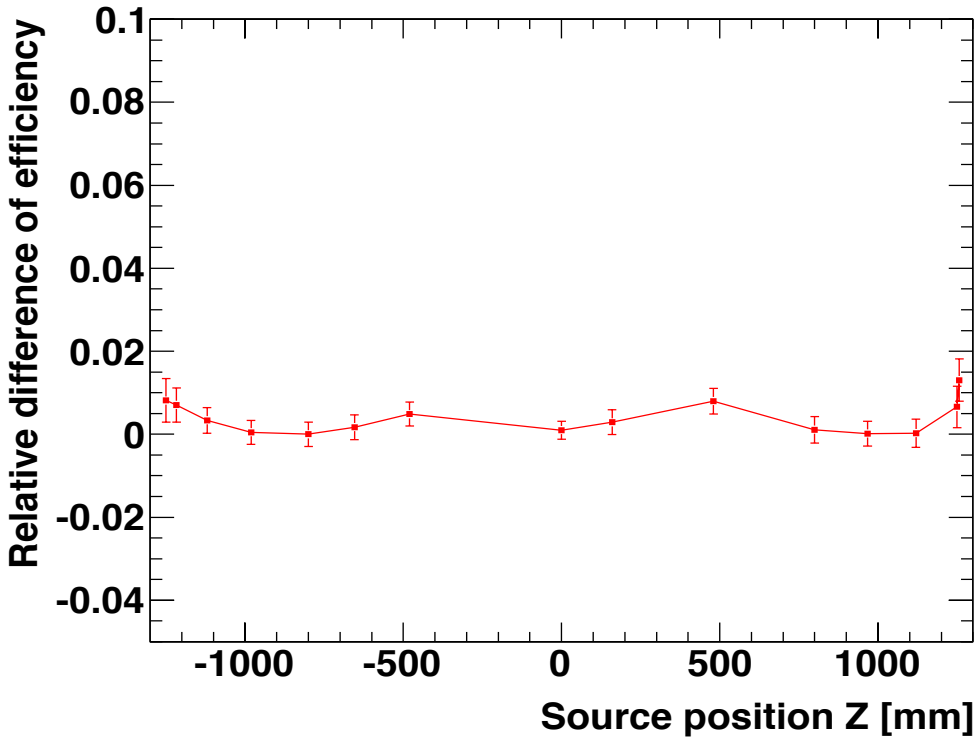
Energy Cut Efficiency, ΔT efficiency

capture **[6,12]** MeV / # capture **[4,12]**
252Cf data and MC along Z-axis



Averaged (Data-MC)/Data relative difference: ≤ 0.6%

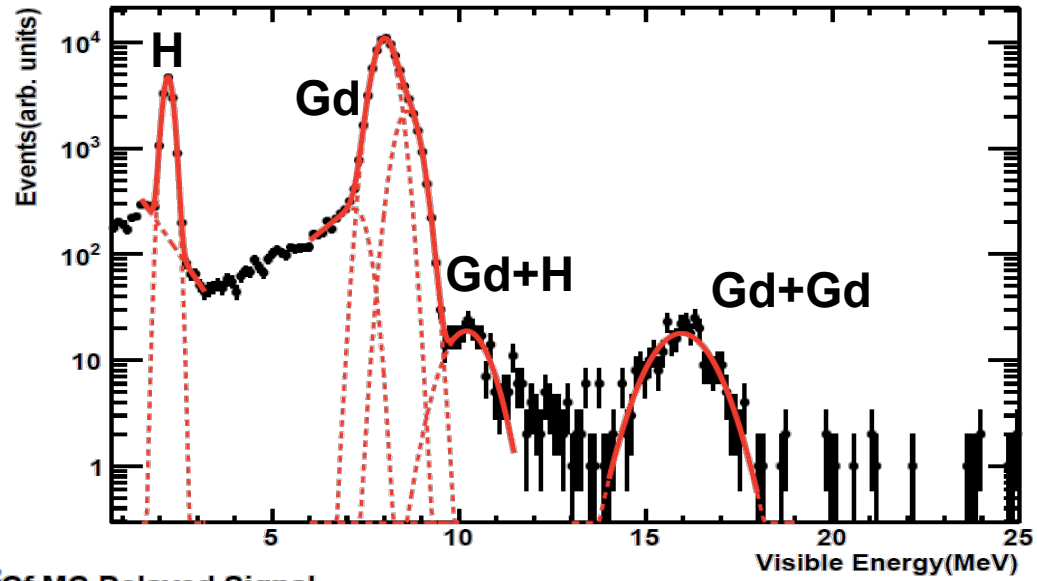
ΔT efficiency $2<\Delta T<100$ μs
^{252}Cf data and MC along Z-axis



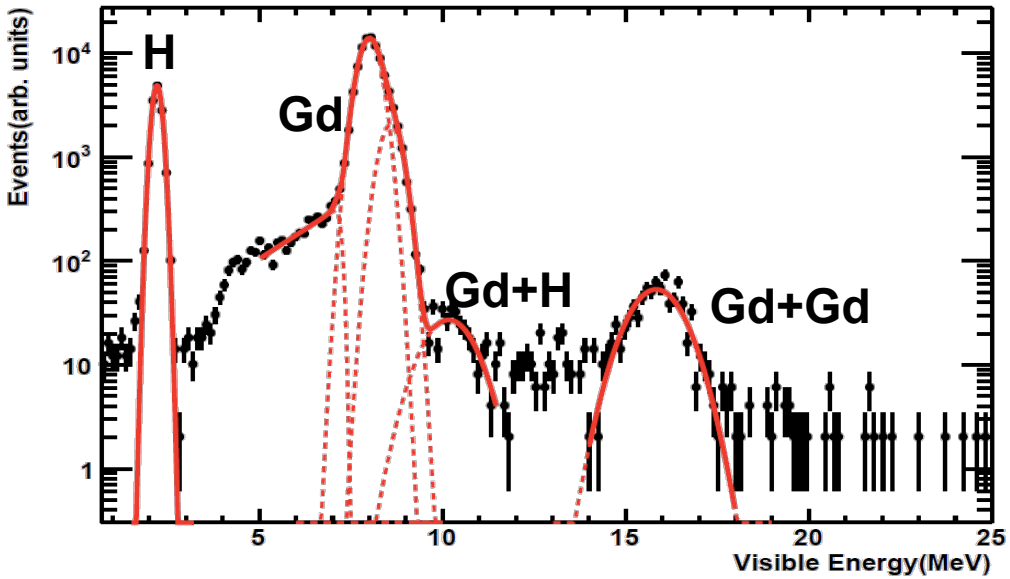
Relative difference: ≤ 0.5%

Gd Capture Fraction

^{252}Cf Data Delayed Signal



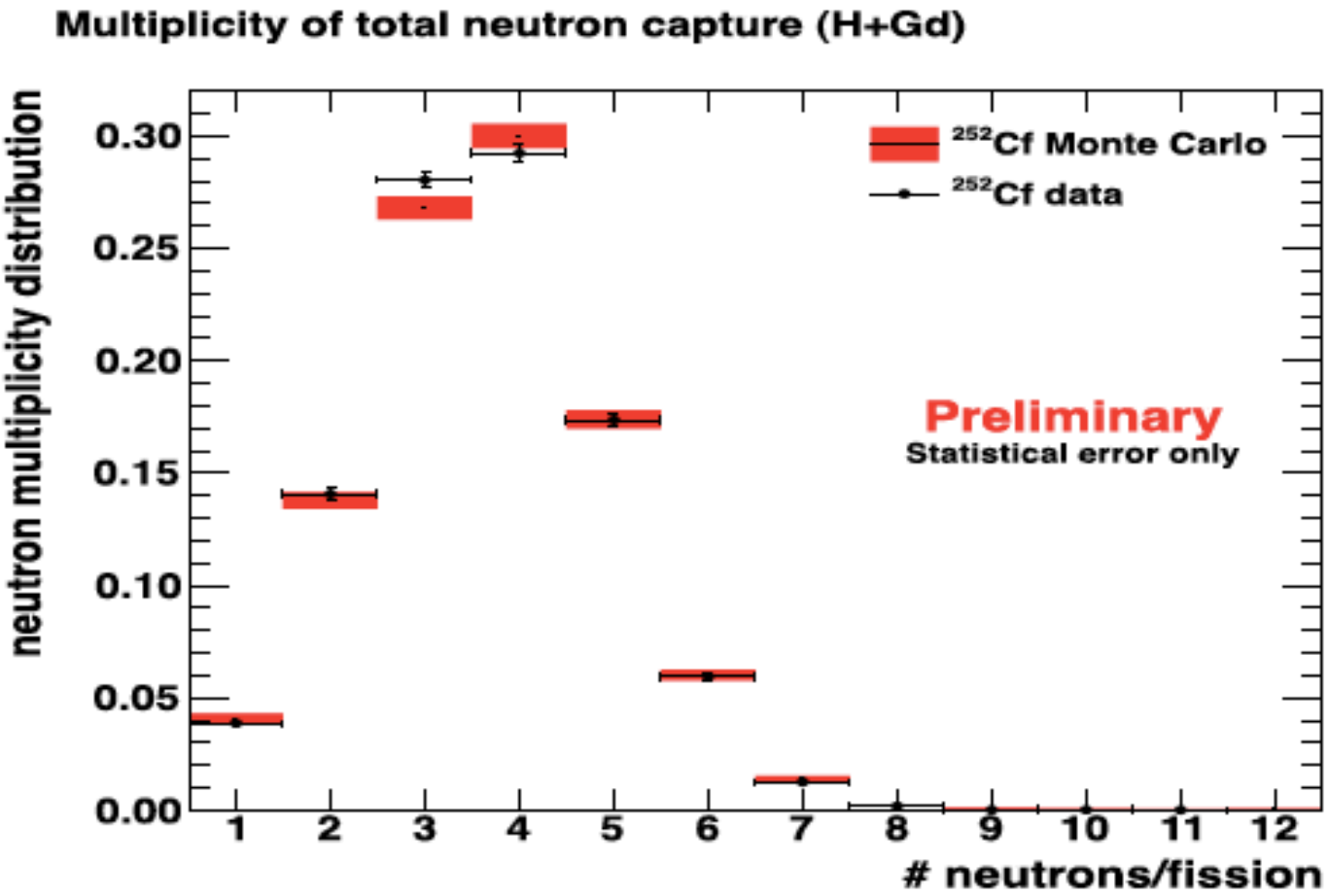
^{252}Cf MC Delayed Signal



- Calibration with a ^{252}Cf source in the central target region
- Deployment along the z-axis (7 positions)
- Compute Gd/(H+Gd) capture rate
- 2% correction between data & MC
- The 6 MeV cut efficiency is 0.86 ± 0.006 (0.6%)

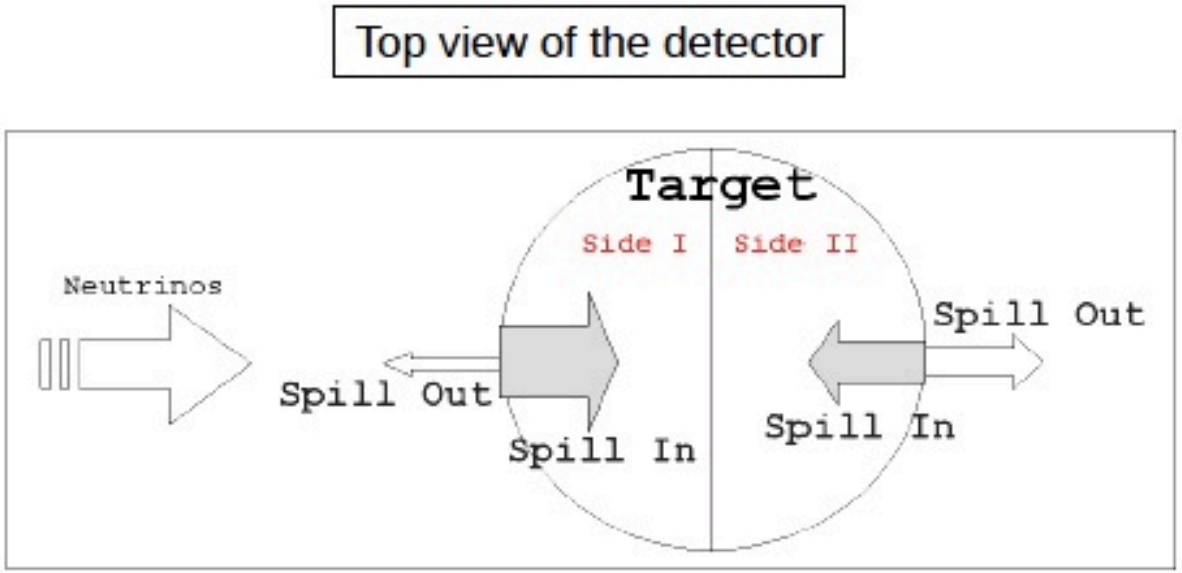
^{252}Cf Neutron multiplicity

- Important verification of the neutron detection efficiency



- Using the first 8 neutron per fission only:
- Average neutron multiplicity **data: 3.659 +/- 0.008 (stat)**
- Average neutron multiplicity **MC : 3.677 +/- 0.013 (stat)**

Spill IN/OUT



Due to the directionality of the IBD neutrons: larger Spill-In Current in side 1 than in side 2.

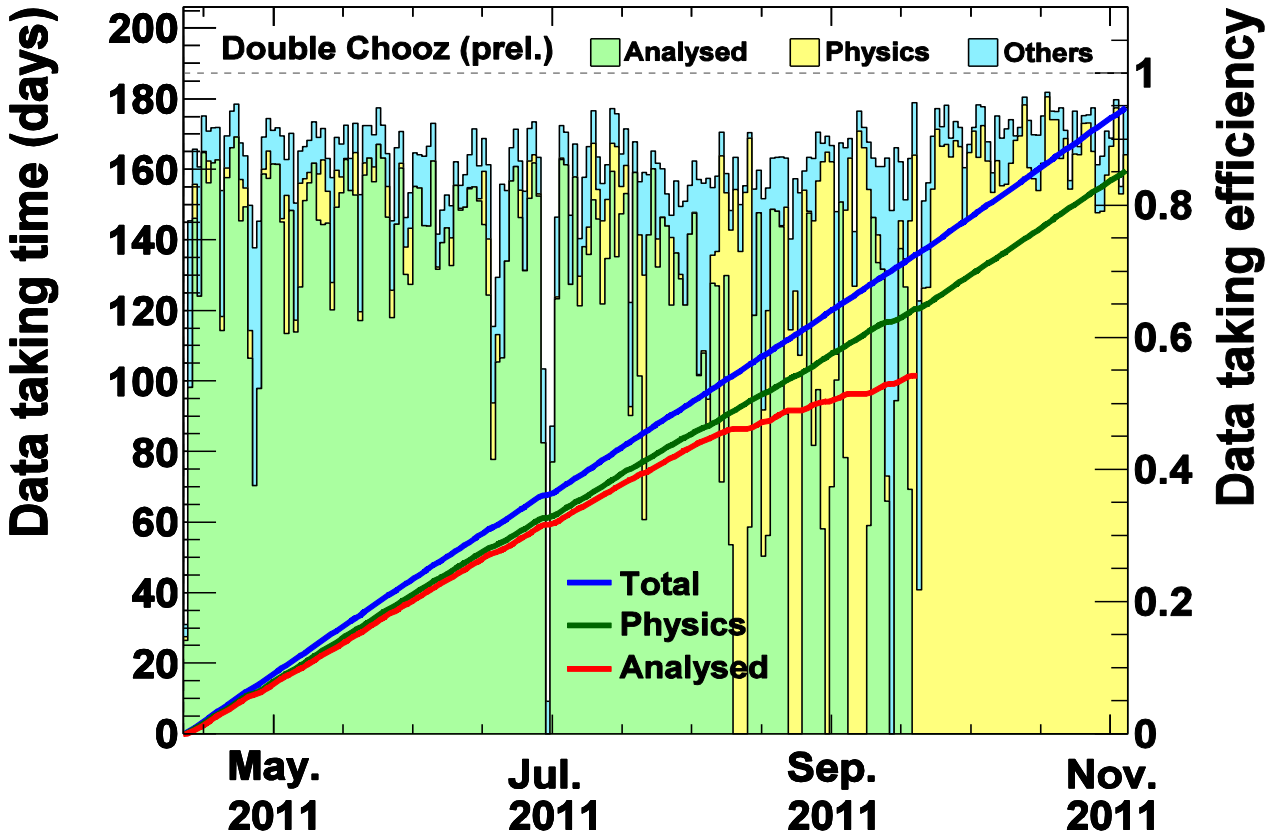
In MC: 8.4% Spill-In Current in side 1 and 4.63% in side 2.

Using different MC and Calibration data: 0.4% systematics

Detector Systematics:

Number of Protons	0.3%
Trigger Eff.	0.4%
Live time	-
Spill In / Out	0.4%
Gd /(H+Gd)	0.58%
Δt Cut	0.5%
Delayed Energy cut Eff.	0.6%
Total	1.1%

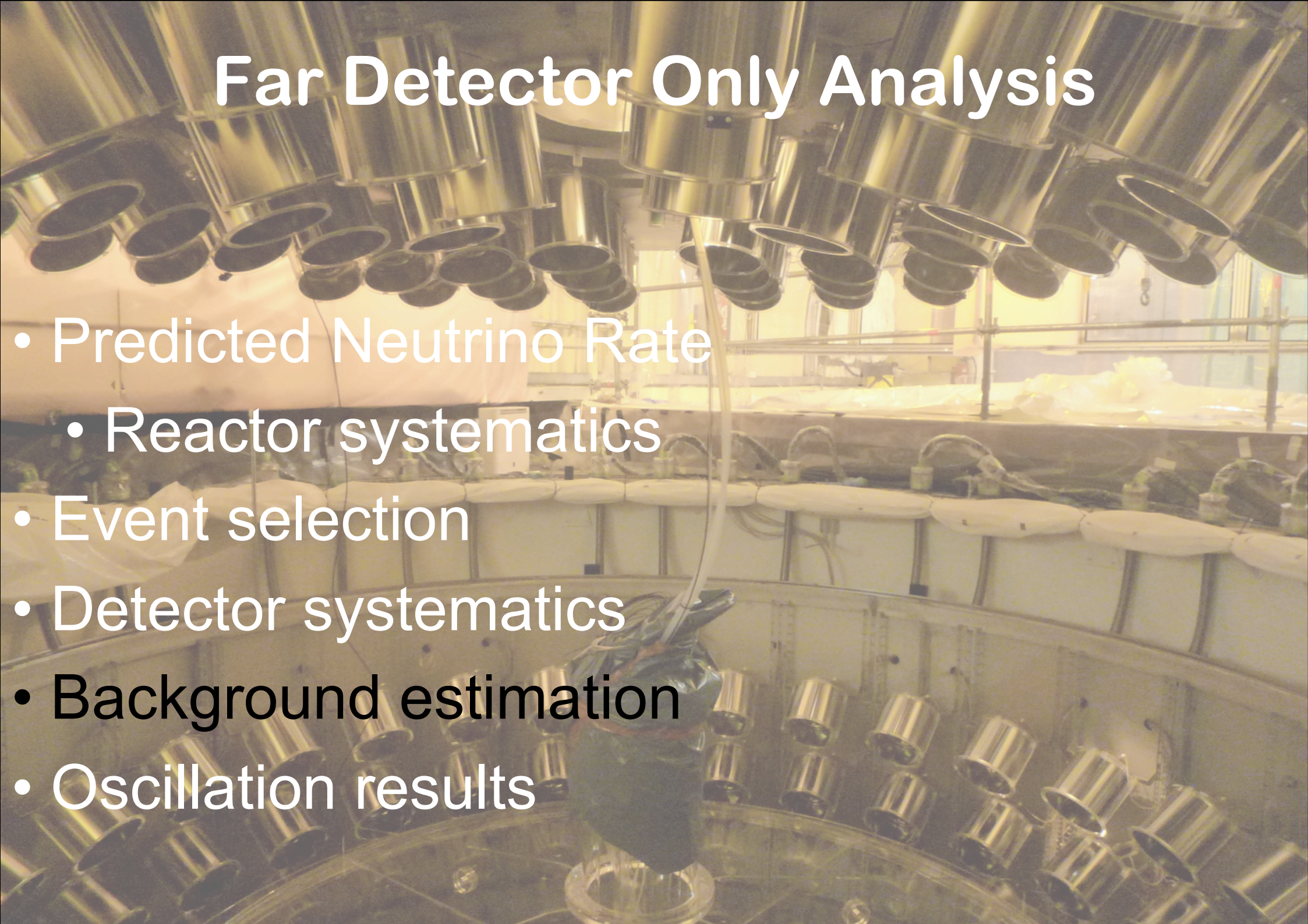
Data Taking: analyzed data



- Number of data taking in days: 206
- Average data taking efficiency in total: 86.2%
- Average data taking efficiency for physics: 77.5%
- Integrated data taking time in total in days: 177.4
- Integrated data taking time for physics in days: 159.6

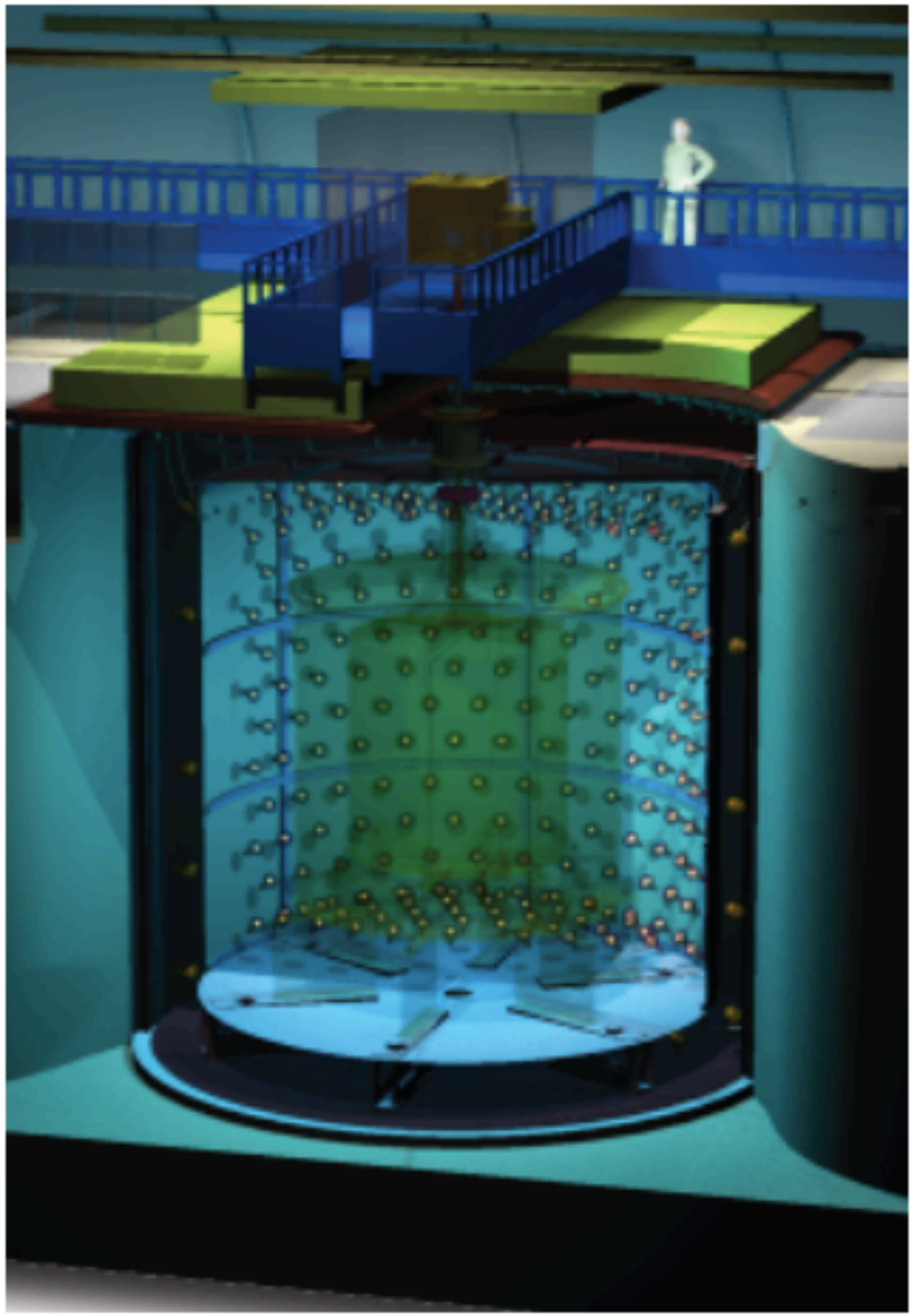
101.5 days analyzed for this result, corresponding to a livetime of 96.7 days

Far Detector Only Analysis



- Predicted Neutrino Rate
  - Reactor systematics
- Event selection
- Detector systematics
- Background estimation
- Oscillation results

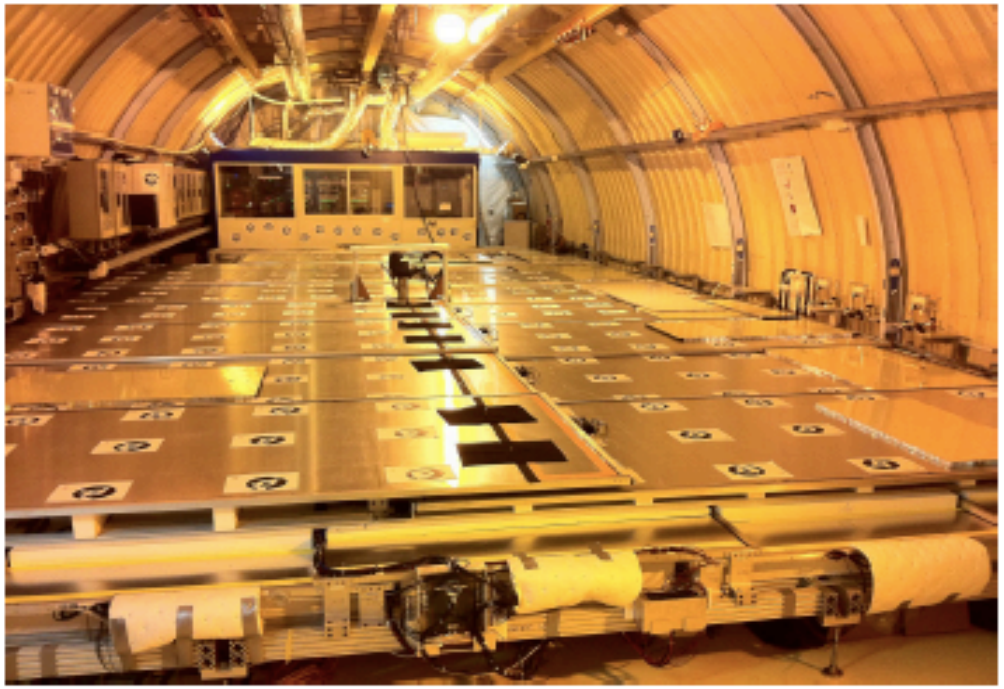
- Target volume protected by several concentric layers.
- Radiopurity
- Efficient muon tagging by inner and outer veto.

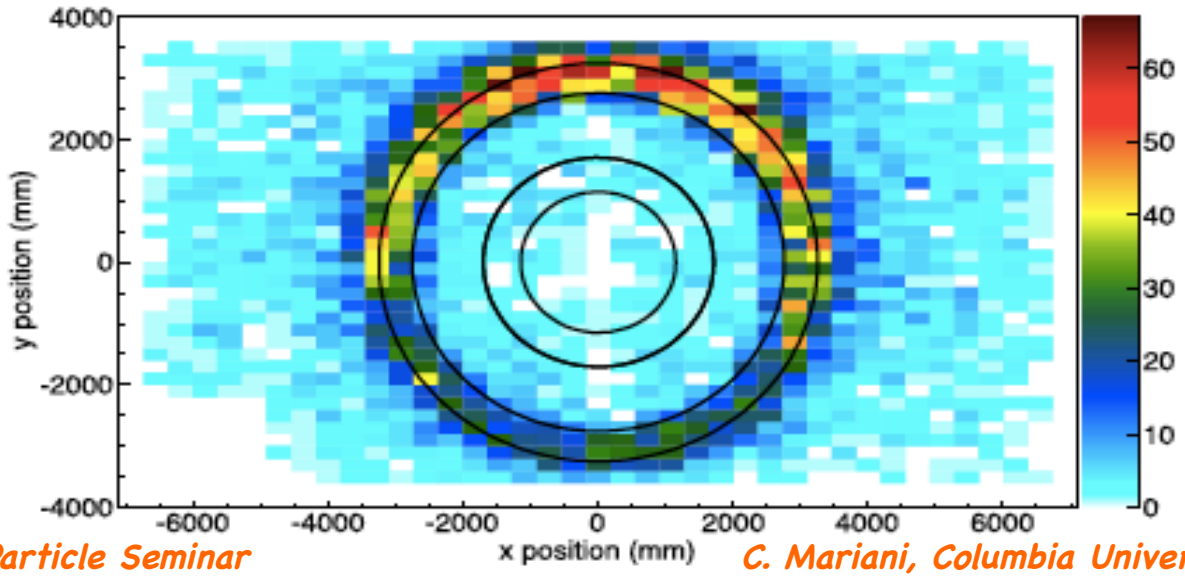


Outer Veto & Inner Veto

Very large charge required in inner veto

→ selecting vertical μ going through all inner veto height.

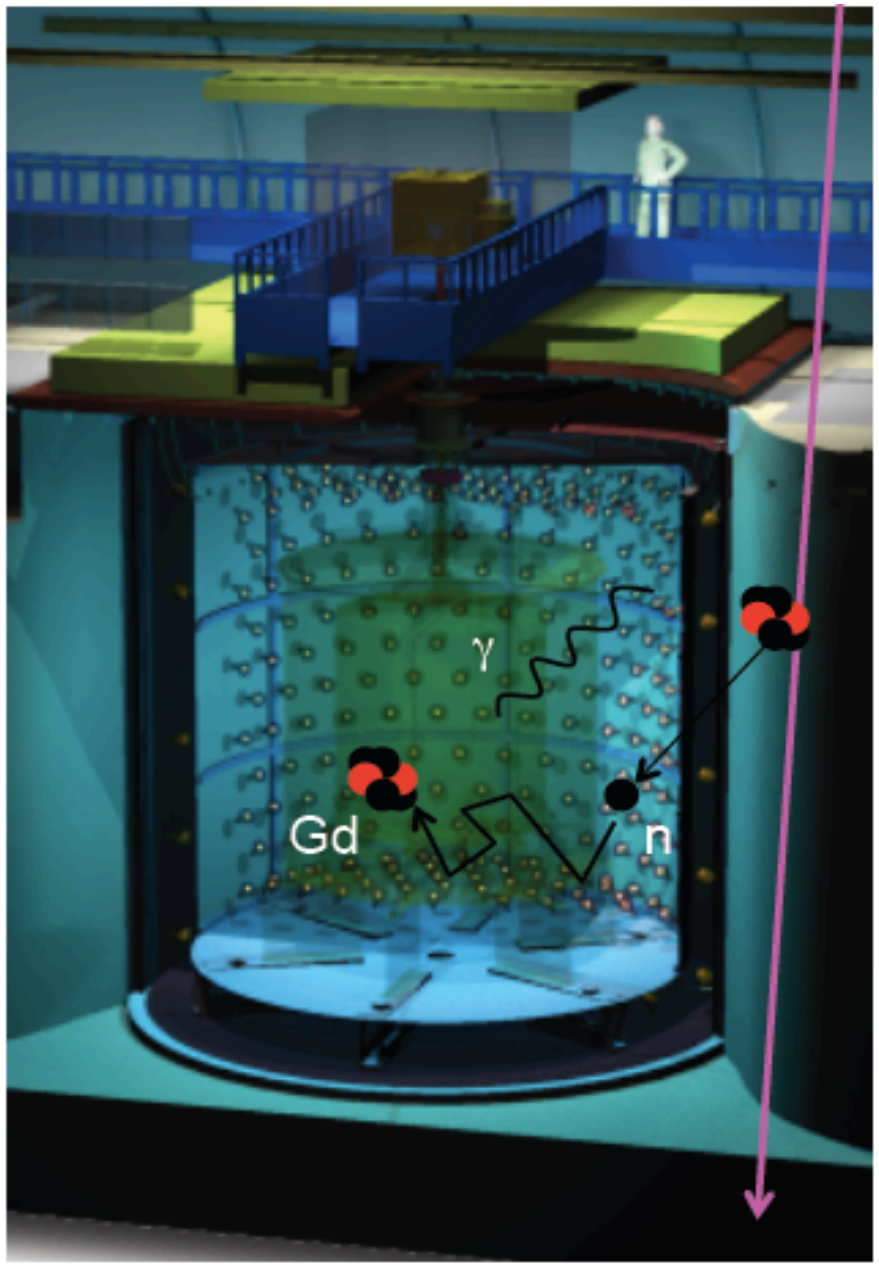




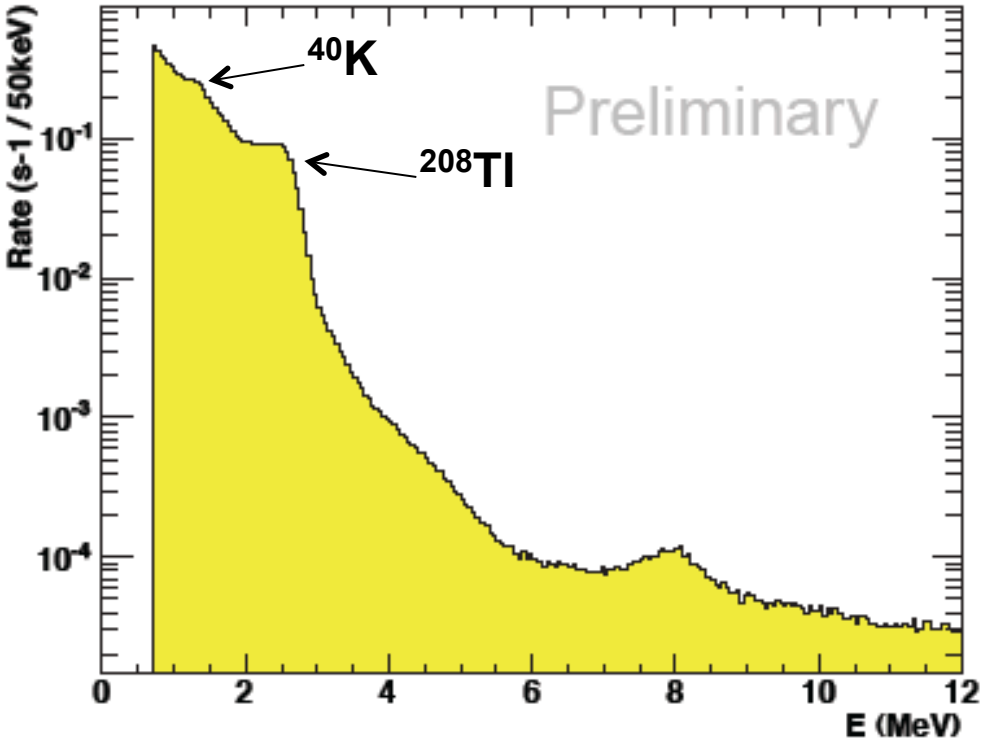
The *Uncorrelated* Backgrounds

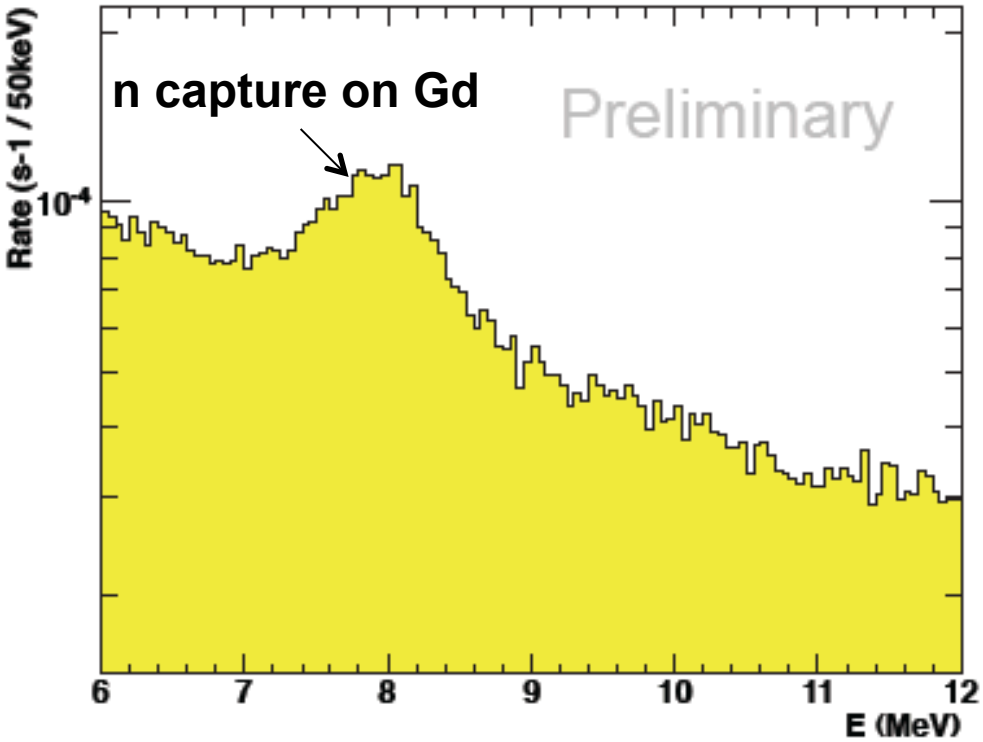
- Accidentals:

- μ-induced fast neutron
- Prompt = recoil proton
- Delayed = neutron capture on Gd.
- Proposal: 2.0 +/- 0.9 / day



Accidental Background

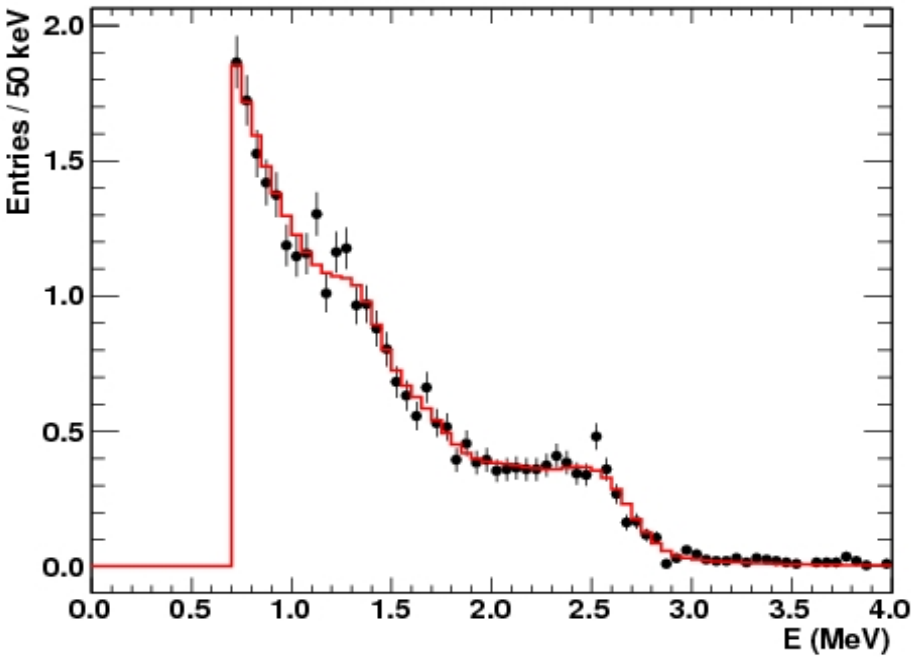


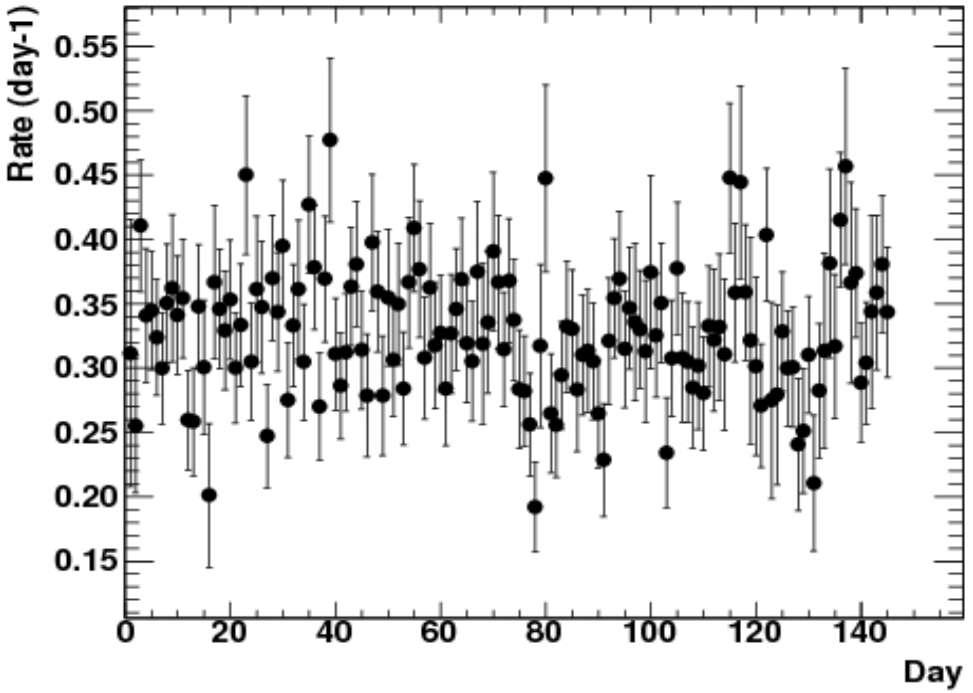


The accidental rate can be calculated or can be obtained from an off time window.

Accidental Background

- Can be computed from singles rates, or
- Measured using off-time window



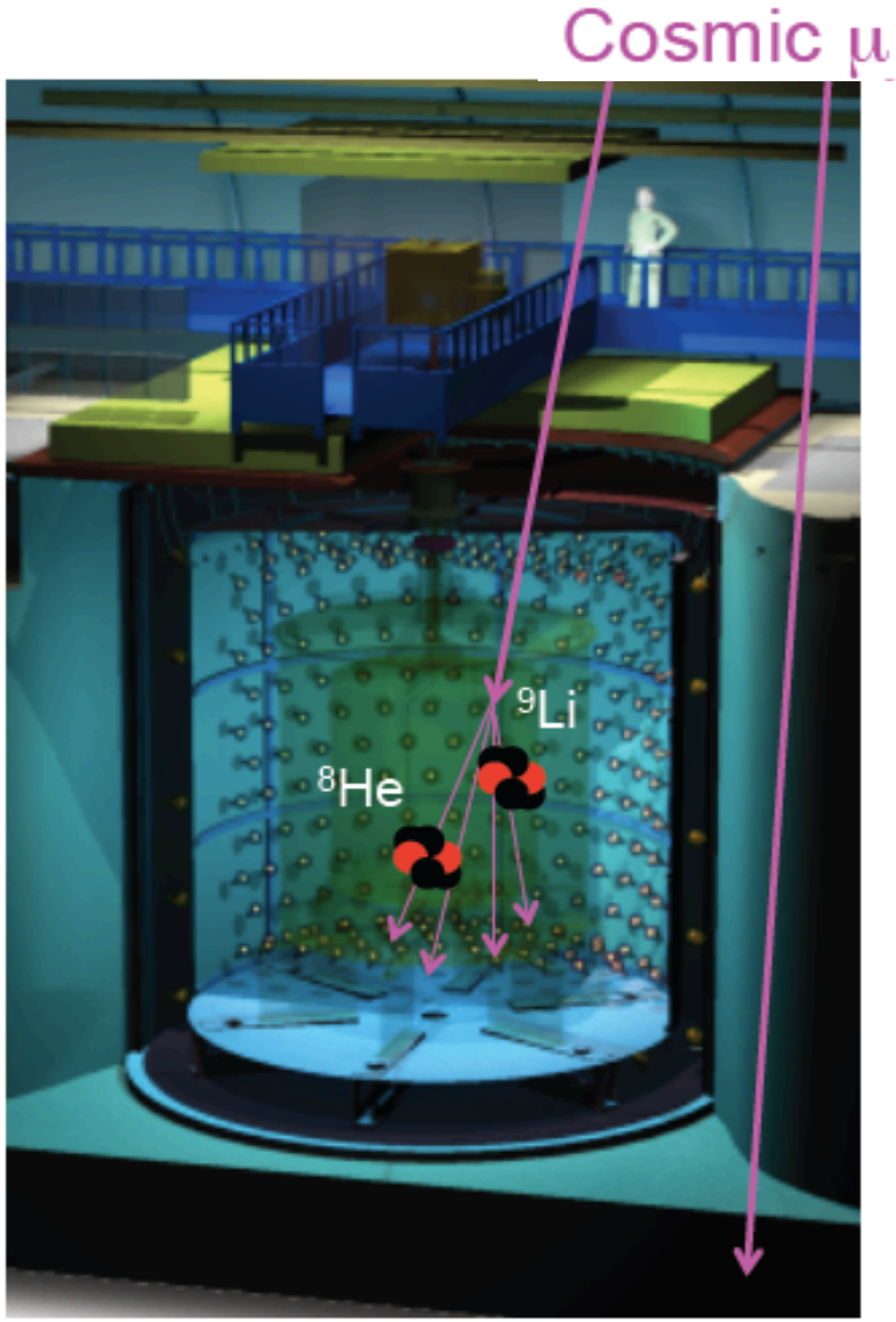


Measured rate: 0.332 ± 0.004 d^{-1}

The *Correlated* Backgrounds

- Correlated:

- ^{9}Li and ^{8}He can be produced by μ-induced spallation processes
- β-n emitters, perfectly mimic the ν signal.
- Life time ~250 ms, can't veto it completely because of excessive dead time.
- Proposal : 1.4 +/- 0.5 / day



^{9}Li estimates from Δt_μ

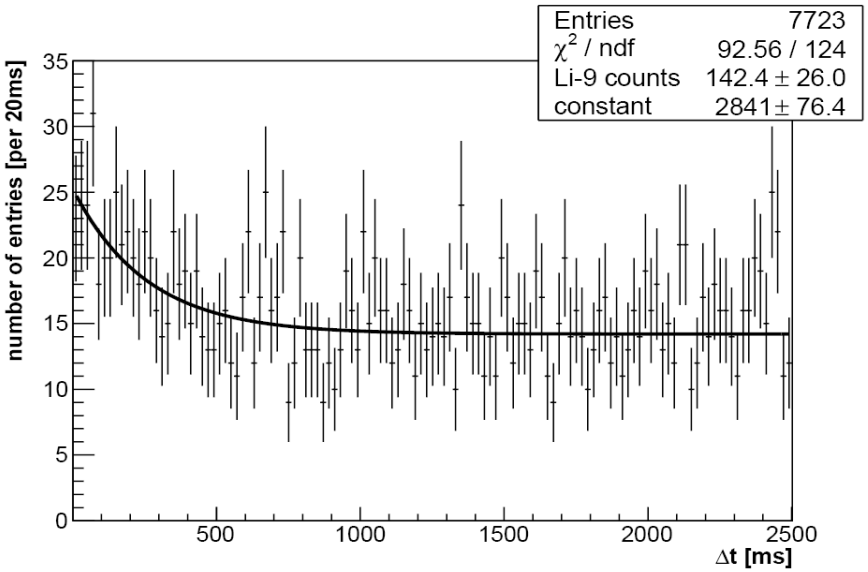
Upper Limit:

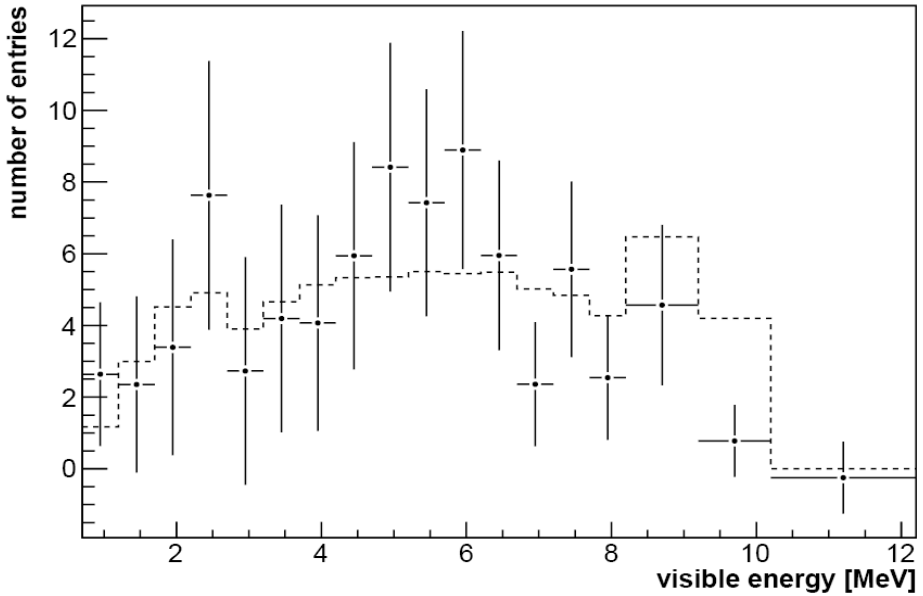
Fit raw Δt_μ to exponential (fixed at ^{9}Li lifetime) + constant

Lower Limit:

Only consider high energy / showering muons

Fit restricted Δt_μ distribution





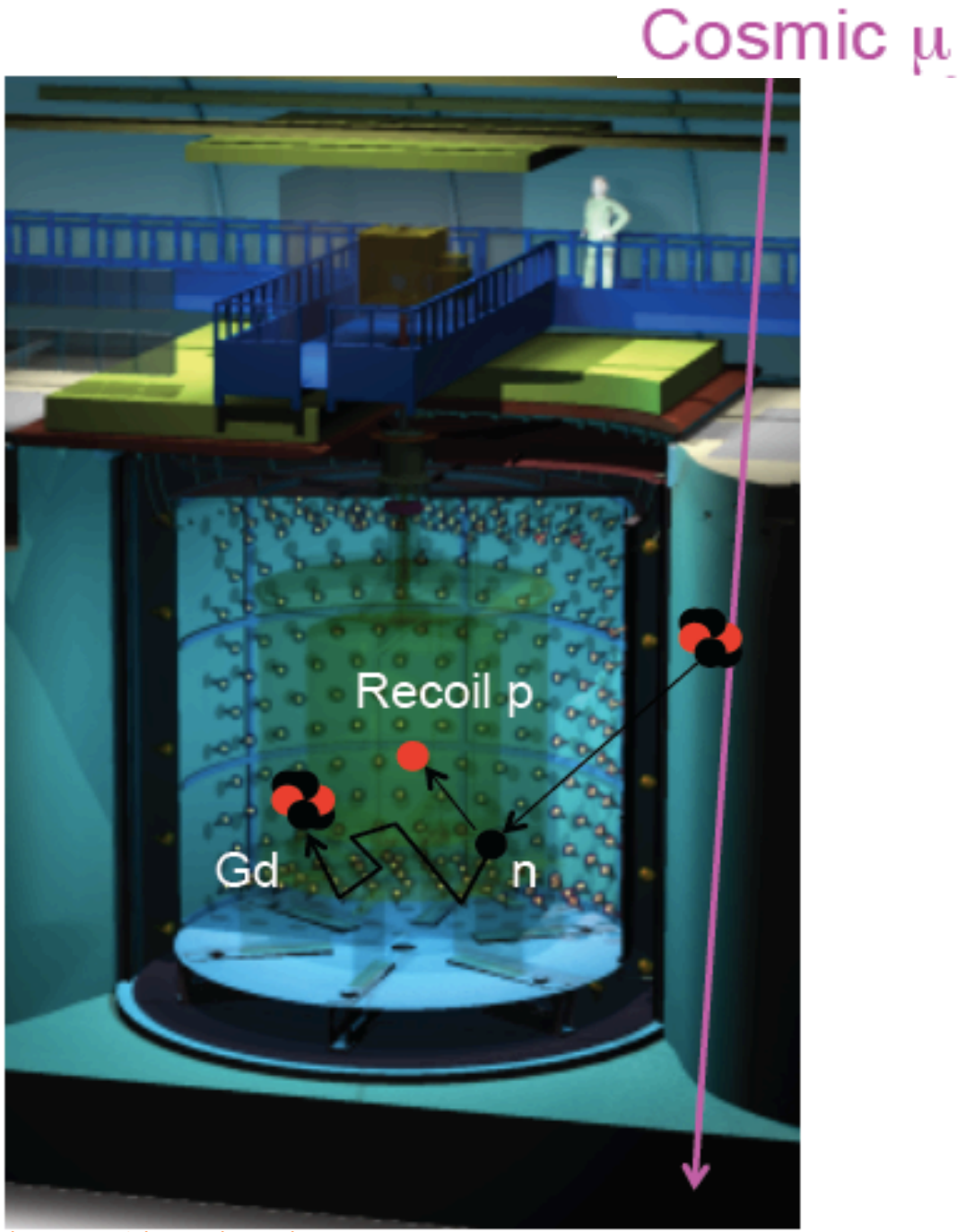
ν-subtracted ^{9}Li spectrum

Rate: 2.3 +/- 1.2 d^{-1}

The *Correlated* Backgrounds

- Correlated:

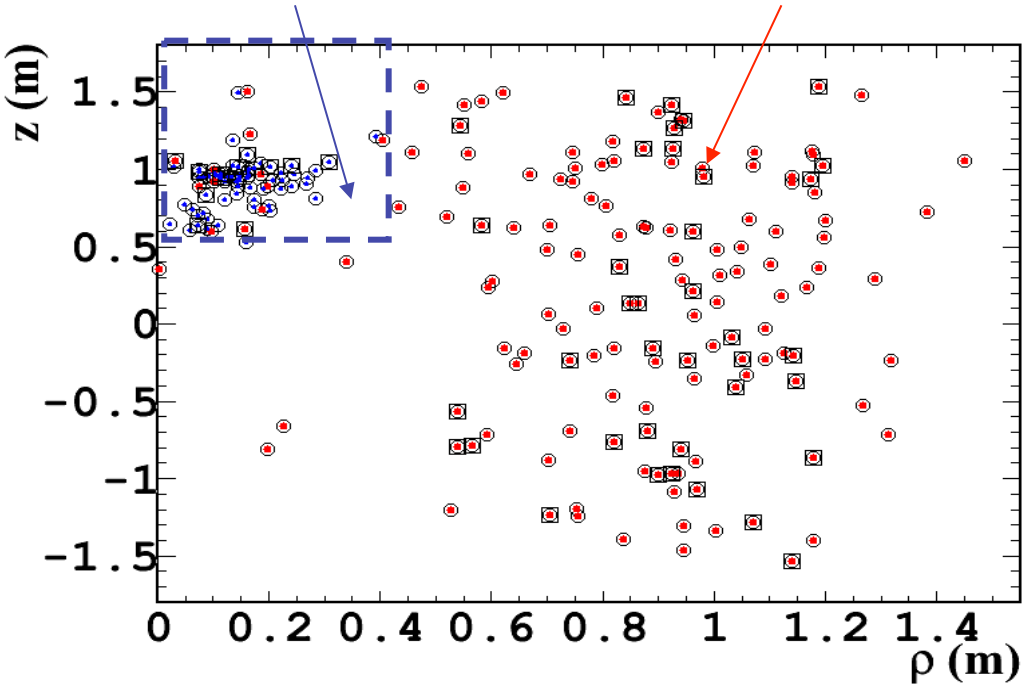
- μ-induced fast neutron
- Prompt = recoil proton
- Delayed = neutron capture on Gd.
- Proposal : 0.2 +/- 0.2 /day



Rough Separation

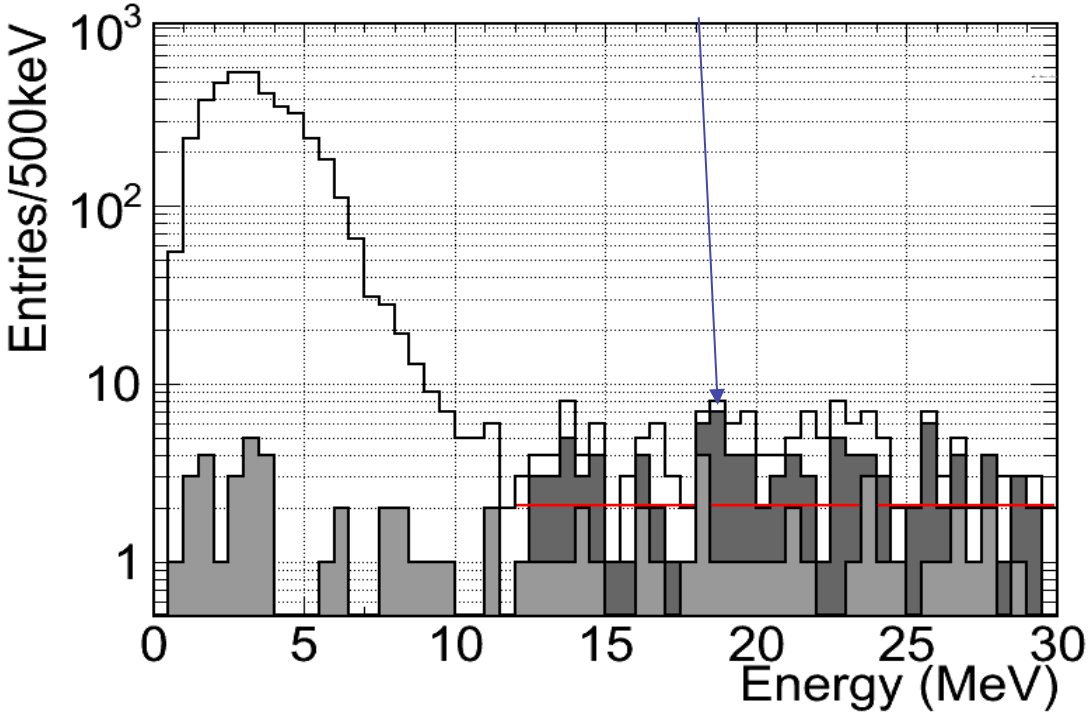
Stopped muons (Δt < 6.6μs)

Fast neutrons (Δt > 6.6μs)



Square points are tagged by inner veto

Stopped muons (Δt < 6.6μs)



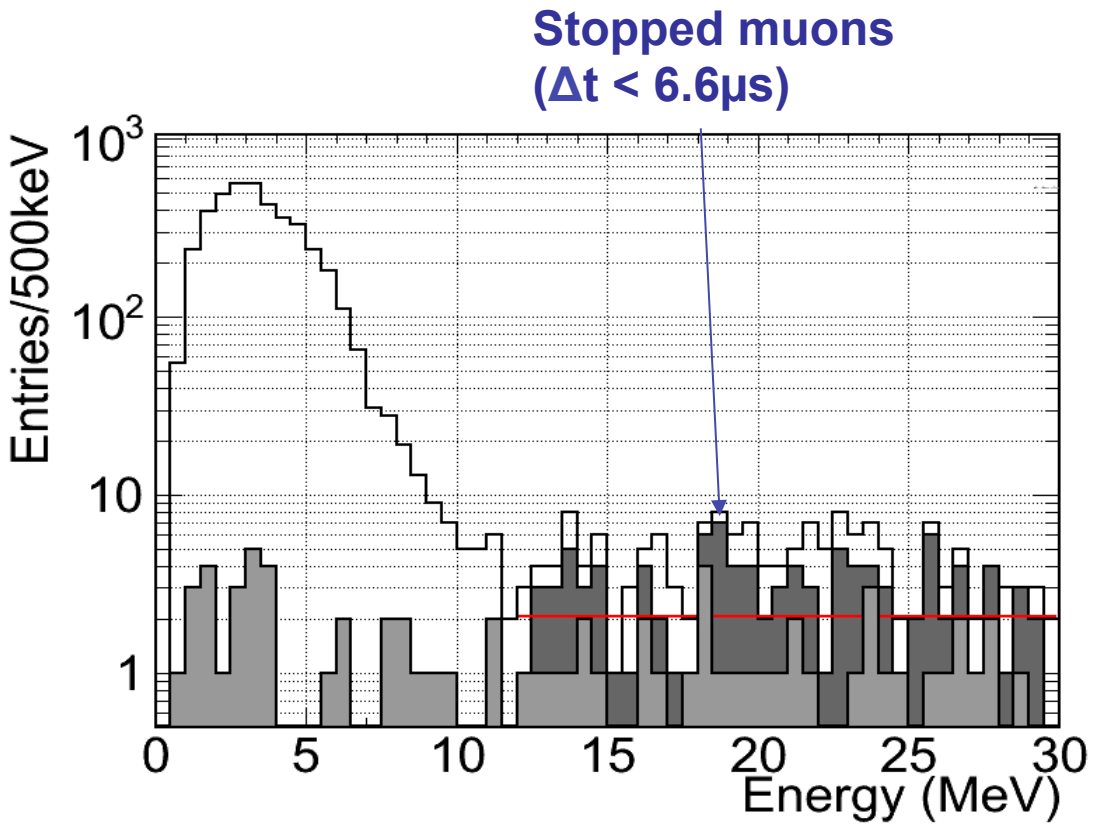
Stopped muon contribution expected to be suppressed at low energies due to Bragg peak

Rate Estimation

Flat fast neutron background hypothesis used to extrapolate rate to low energies

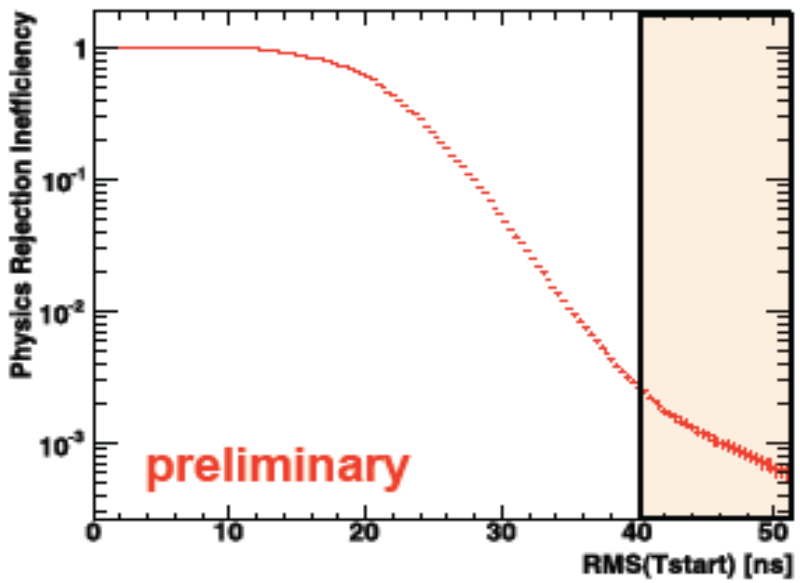
- Uncertainty taken from the rate of stopping muons above 12 MeV
- Shape uncertainty from measured μ-tagged spectrum
- Corrected by ratio of tagged fast neutrons in low energy [0.7, 12 MeV] and high energy [12, 30 MeV] window

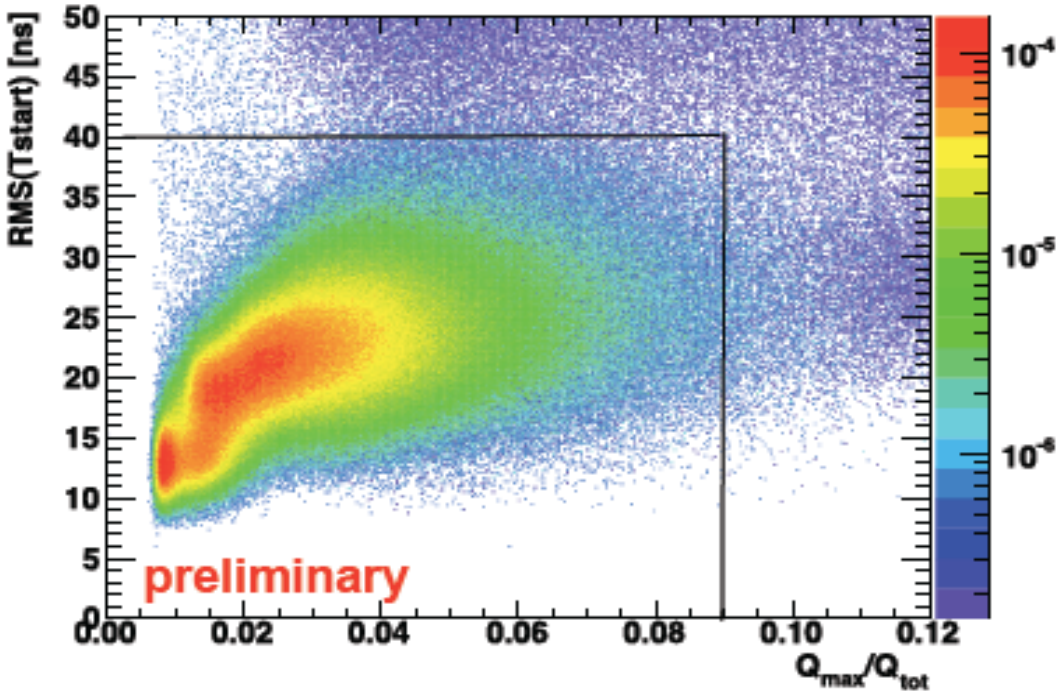
Rate: 0.7 +/- 0.5 d^{-1}



Stopped muon contribution expected to be suppressed at low energies due to Bragg peak

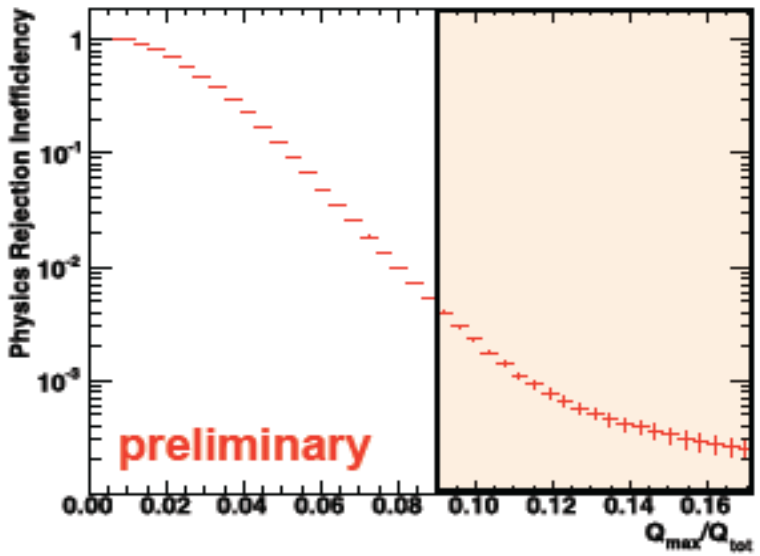
Light Noise: a surprise …



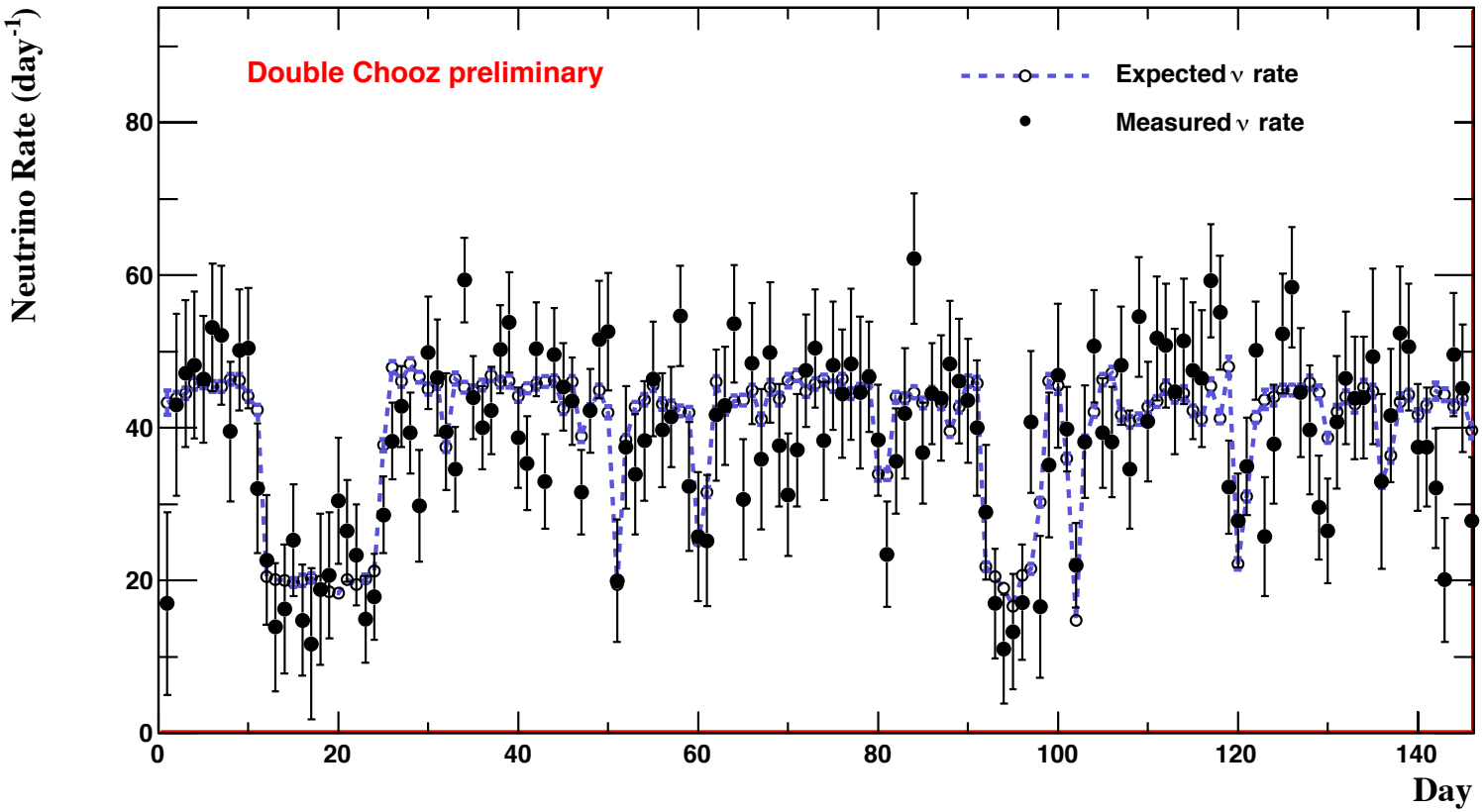


Parasitic light emitted by some PMTs.
15 PMTs turned off + effective rejection based on anisotropic light collection:

- PMT sees its own light
  → Qmax/Qtot
- Large dispersion of start time of PMT signals → rms(T_{start})



Events Summary



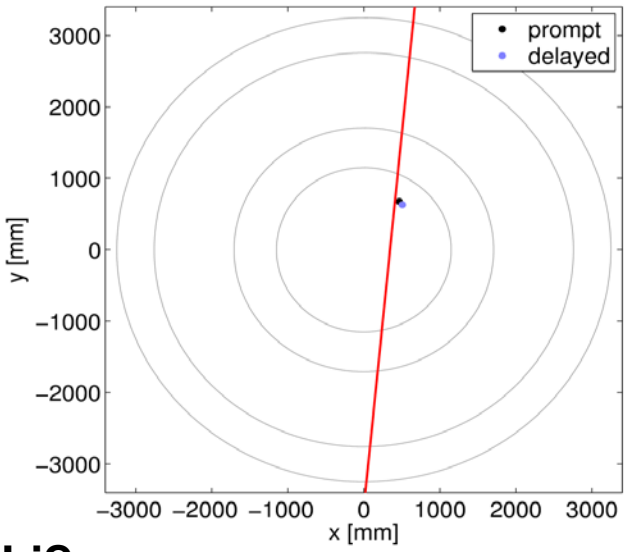
Type	#Evts	Rate/Day	σ/Day
- Neutrino Candidates	4121	42.6	0.7
- Expected Accidentals	31.60	0.32	0.06
- Expected ^{9}Li	227.3	2.3	1.2
- Expected Fast-n	69.2	0.7	0.5

Both Reactors Off!
2+1 Candidates Found in ~24 hours

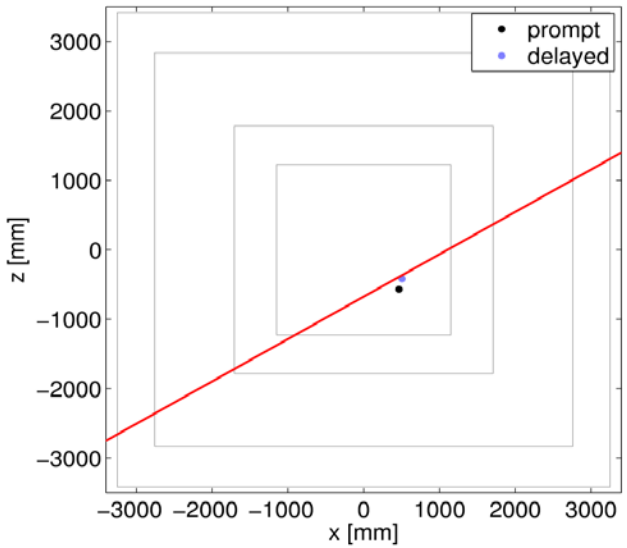


A Unique Opportunity to validate our background estimates!

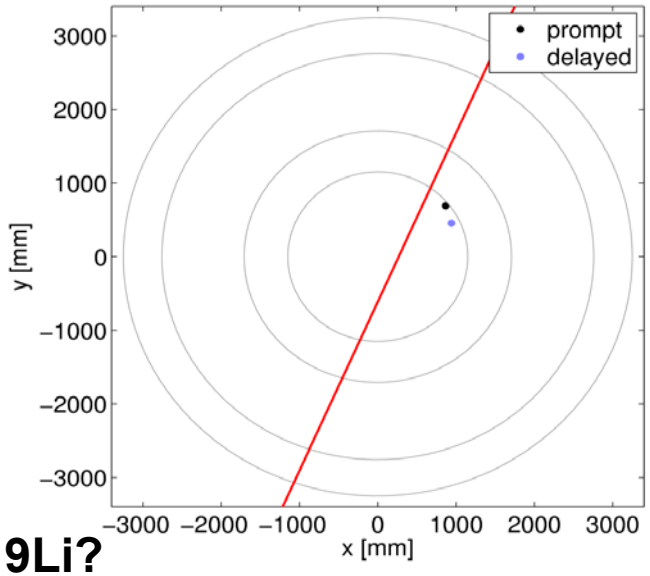
Bkg Verification: ~24 hrs Both Reactors Off



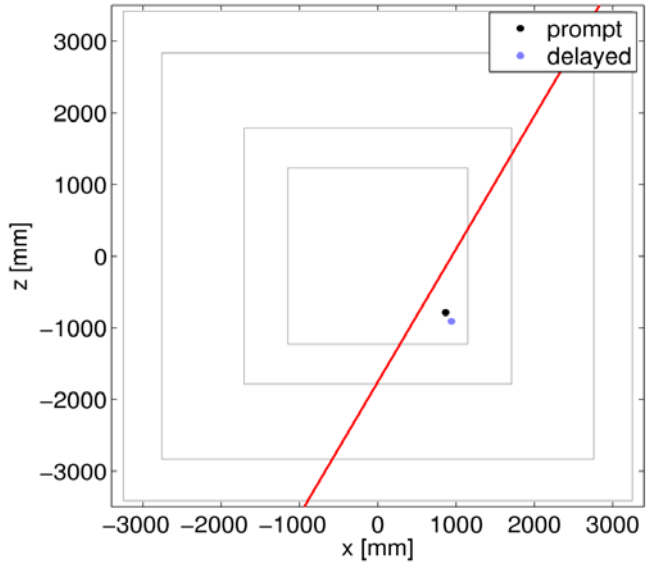
^{9}Li?



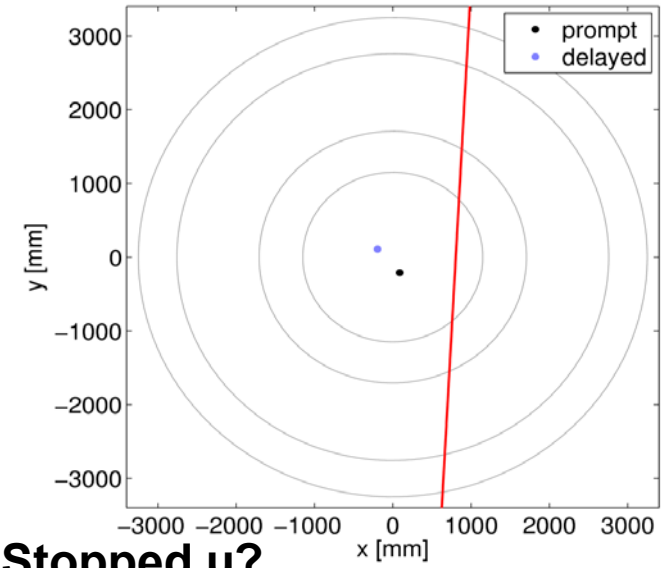
Prompt Energy: 9.8 MeV
Δt: 4.1 μs
Δt_{μ} (739 MeV): 201 ms



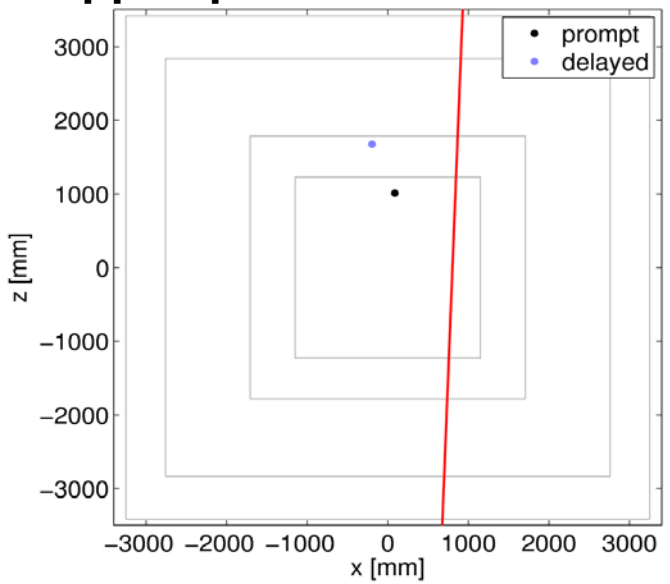
9Li?



Prompt Energy: 4.8 MeV
Δt: 26 μs
Δt_{μ} (627 MeV): 241 ms

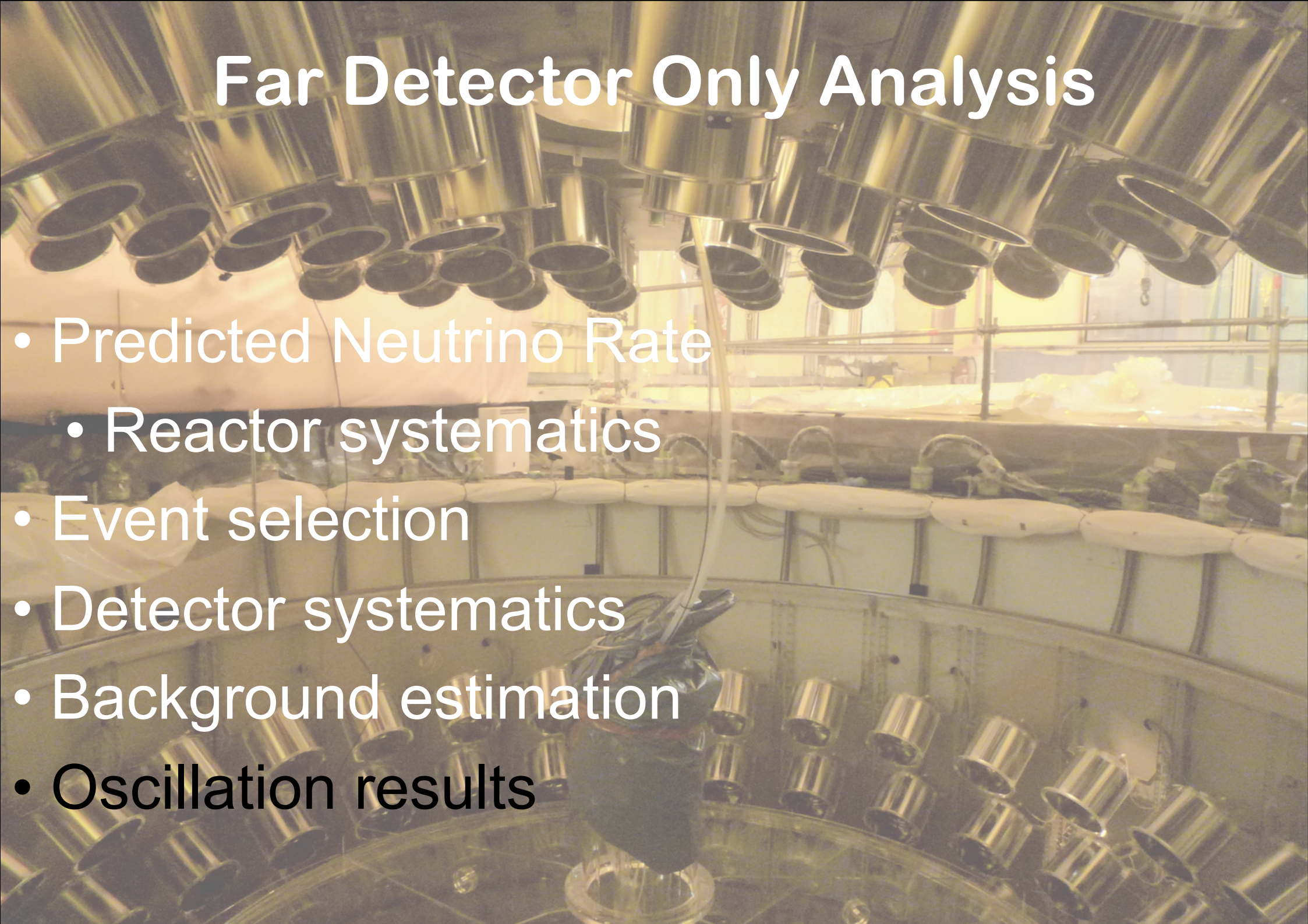


Stopped μ?



Prompt Energy: 26.5 MeV
Δt: 2.2 μs
Δt_{μ} (523 MeV): 206 ms

Far Detector Only Analysis



- Predicted Neutrino Rate
  - Reactor systematics
- Event selection
- Detector systematics
- Background estimation
- Oscillation results

Summary of all the systematics

Statistics:	1.6%
Reactor:	1.74%
Detector:	1.1%
Backgrounds:	3.1%

Summary of events per day

PRELIMINARY

	Events per Day
^{9}Li	2.3±1.2
Fast-N + Stopped Muons	0.7±0.5
Accidental	0.332±0.004
Total	3.3±1.3
Candidates	42.6

We have 3.1% uncertainty due to the backgrounds, but they can be constrained in a Rate + Shape analysis.

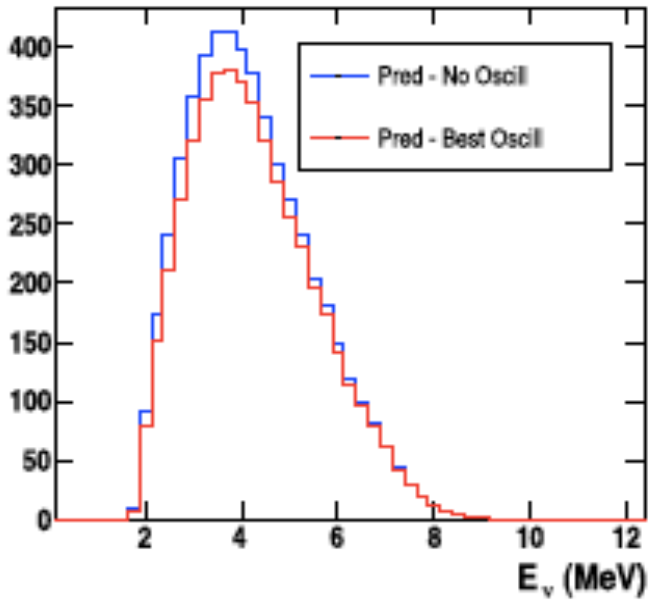
Oscillation Analysis

Reactor → Detector

$N_{predicted} \longleftrightarrow N_{observed}$

- Rate only: $N_{observed} = N_{predicted} \times \left\langle P_{ee}(\sin^2(2\theta_{13})) \right\rangle$

- Rate + Shape:



Back of the envelope calculation

- Data (Neutrino Candidates) : 4121 (bkg = 328)
- MC (Expected Signal) : 5339

- $\text{Neutrinos}_{\text{obs}} = (4121 - 328) = 3793$
- $\text{Neutrinos}_{\text{pred}} = 5339 \times 0.743 = 3967$

$$\sin^2(2\theta_{13}) = \frac{\left(1 - \frac{N_{obs}}{N_{pred}}\right)}{1 - 0.54} \approx 0.096 \pm 0.074$$

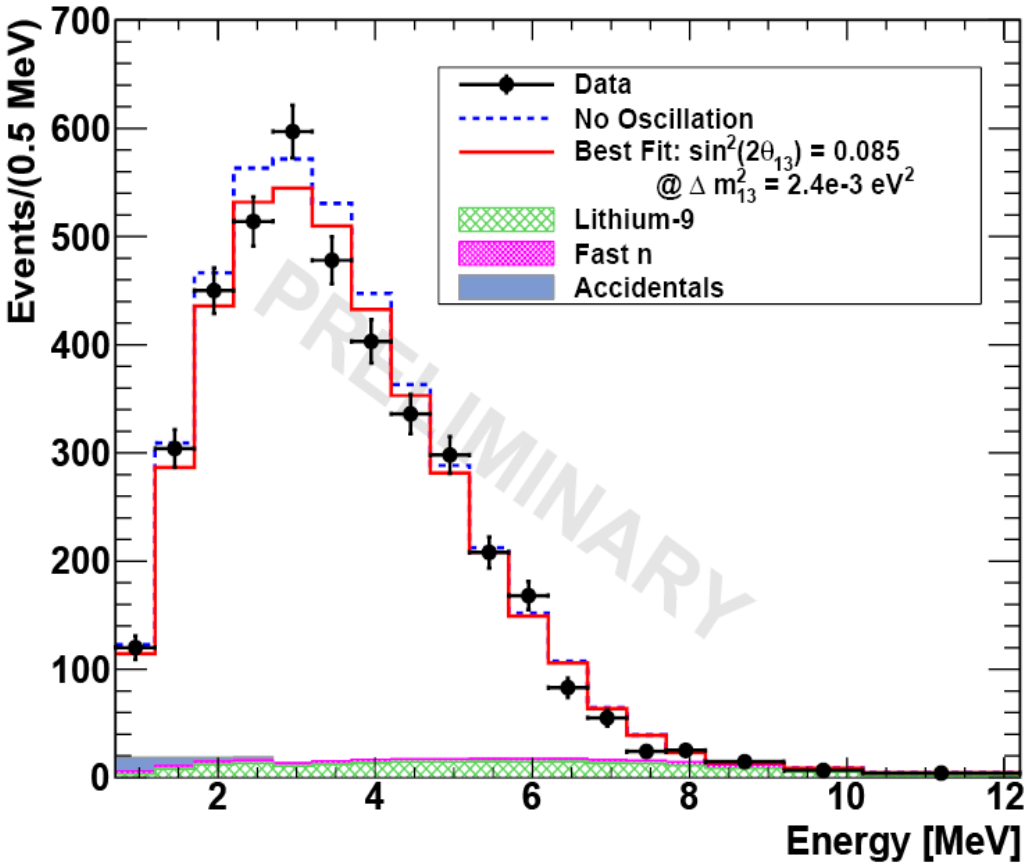
Oscillation Fit strategy

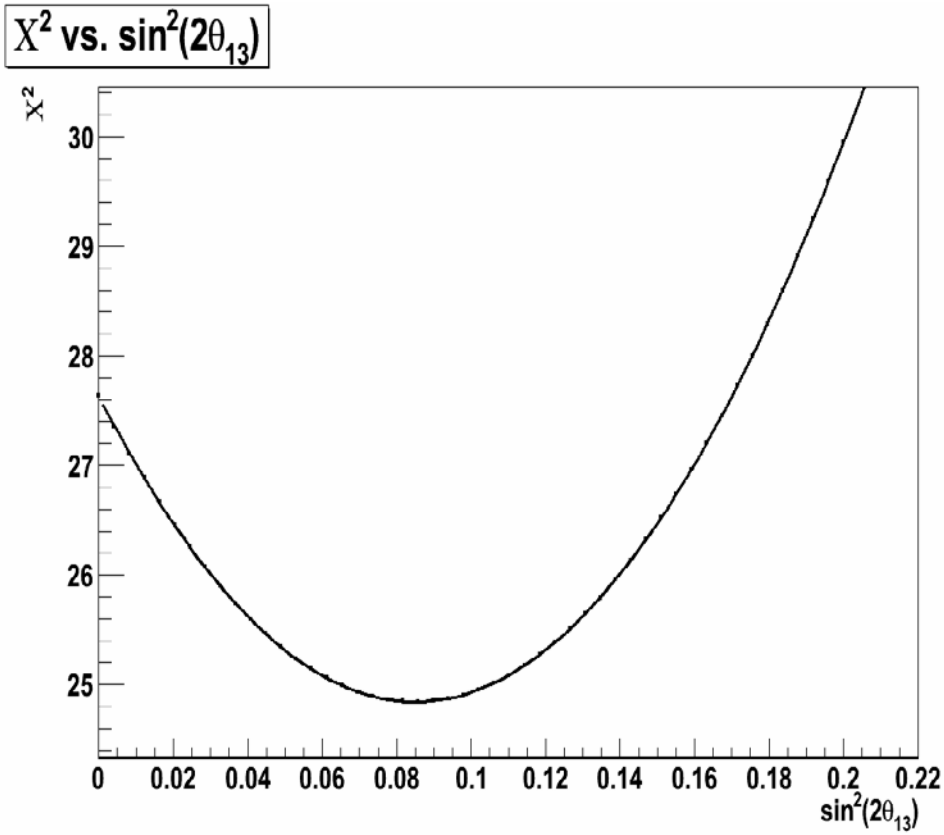
- MC Events & Data flow handled in parallel
- Correction for MC/Data differences

$$\chi^2 = \left(N_i - \sum_{R}^{\text{Reactors}} N_i^{\nu,R} \right) \times \left(M_{ij}^{\text{Reactors}} + M_{ij}^{\text{detector}} + M_{ij}^{\text{stat}} + \sum_{b}^{\text{bkgnds.}} M_{ij}^{\text{b}} \right)^{-1} \times \left(N_j - \sum_{R}^{\text{Reactors}} N_j^{\nu,R} \right)^{\text{T}}$$

Used Blind Analysis (reactor prediction not known better than 10% until the selection cuts were frozen.

Fit Results





Rate + Shape Fit: $\sin^2 2\theta_{13} = 0.085 \pm 0.041(stat.) \pm 0.030(syst.)$

Rate Only Fit: $\sin^2 2\theta_{13} = 0.093 \pm 0.079$

Frequentist approach: Null Oscillation Prob = 7.4%

Rate vs Rate+Shape

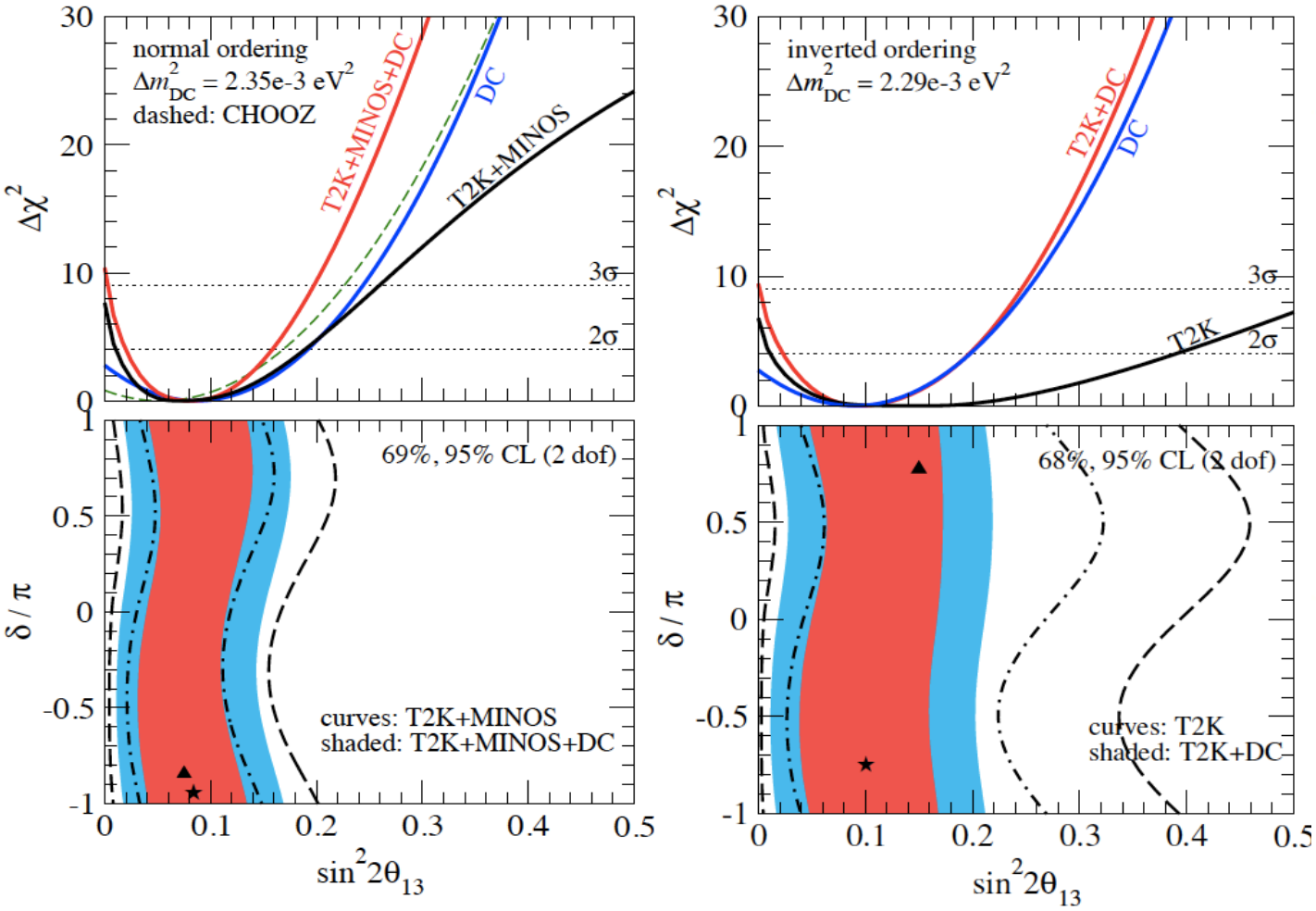
Rate + Shape:

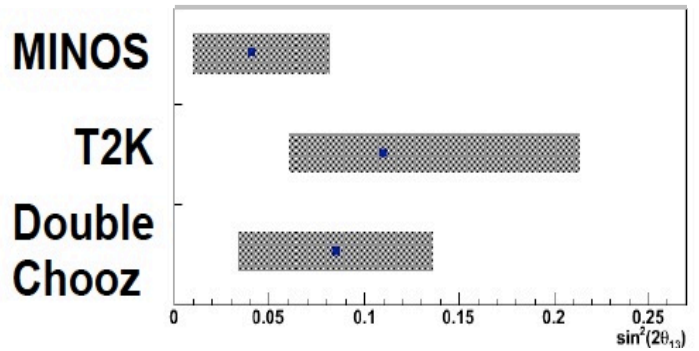
- **constraints background due to Fast Neutron and Li9 and reactor flux**
- **big improvement still possible due to large statistical error**
- **Energy Scale playing a role (positron spectrum)**

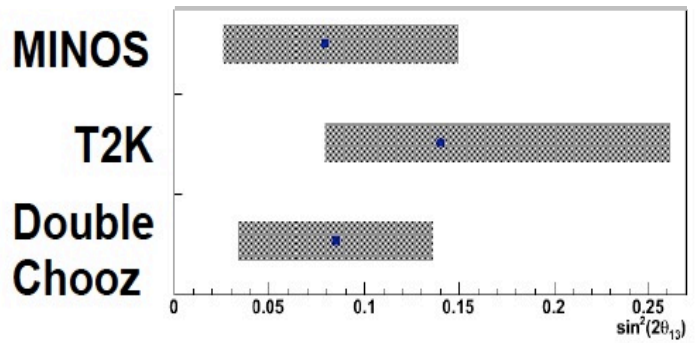
Rate:

- **Simpler and Faster, can be easily calculated**

Global DC + T2K Analysis







$\sin^2 2\theta_{13}$	best fit	1σ	2σ	3σ	$\Delta\chi^2(\theta_{13}=0)$
normal ordering:	0.092	0.051–0.140	0.021–0.186	0.002–0.233	9.50
inverted ordering:	0.092	0.056–0.146	0.024–0.198	0.002–0.246	9.43

Conclusion

- Double Chooz is running as designed (3 months of data better than Chooz limit)
- Report of Analysis of 3 months of data. Hint for positive value of θ_{13}

$$\sin^2(2\theta_{13}) = 0.085 \pm 0.041(stat.) \pm 0.030(syst.)$$
$$No-Oscillation\ Excluded\ at\ 92.6\%\ CL$$

- The near detector will be operational by early 2013
- Great prospect towards the most precise measurement θ_{13} with 2 nuclear cores
  - Simple site configuration. Reactor Off-Off periods for in-situ bkg measurement
  - Comprehensive set of Calibration Systems

Stay tuned, near detector is coming …

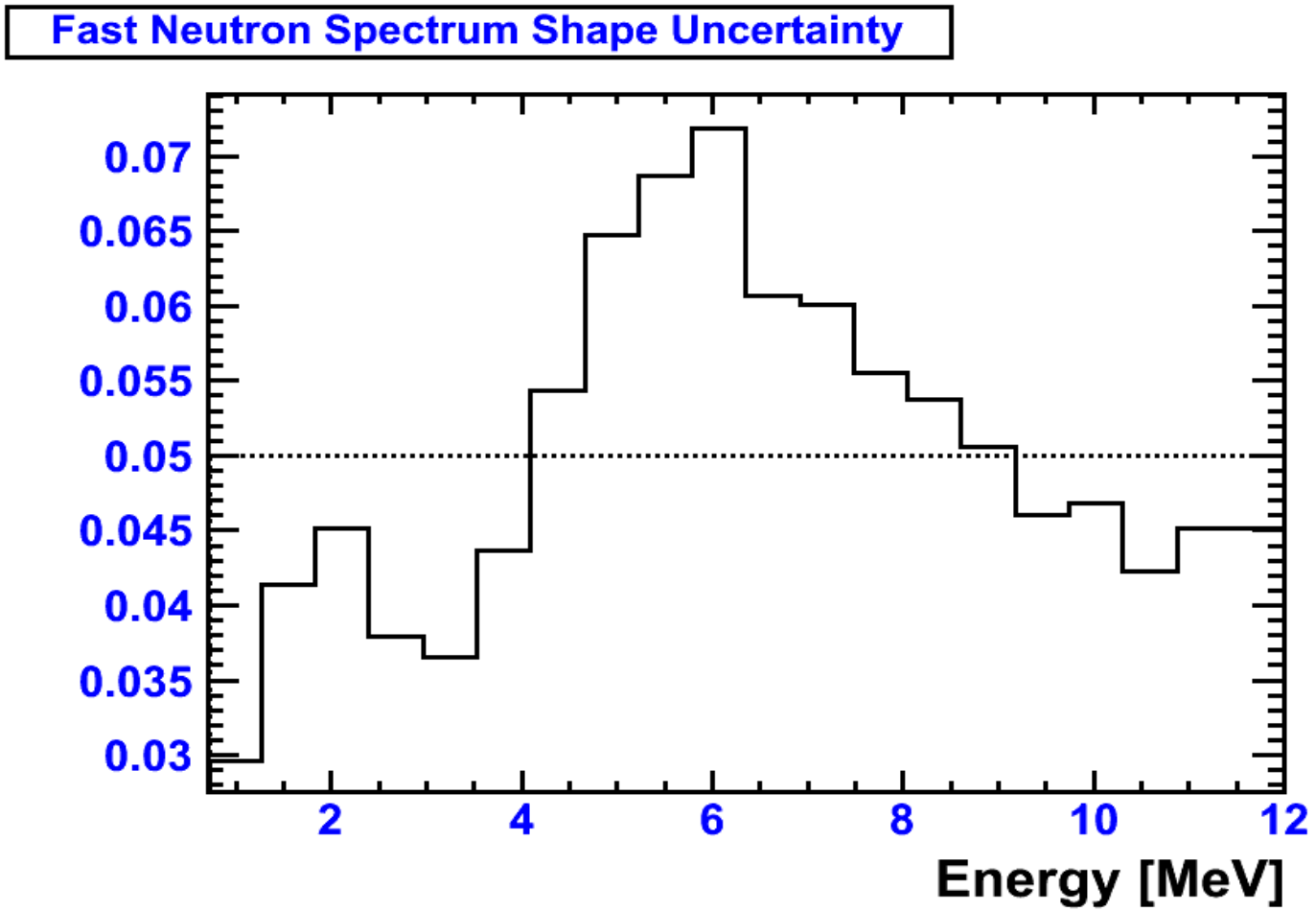


Double Chooz near detector lab excavation

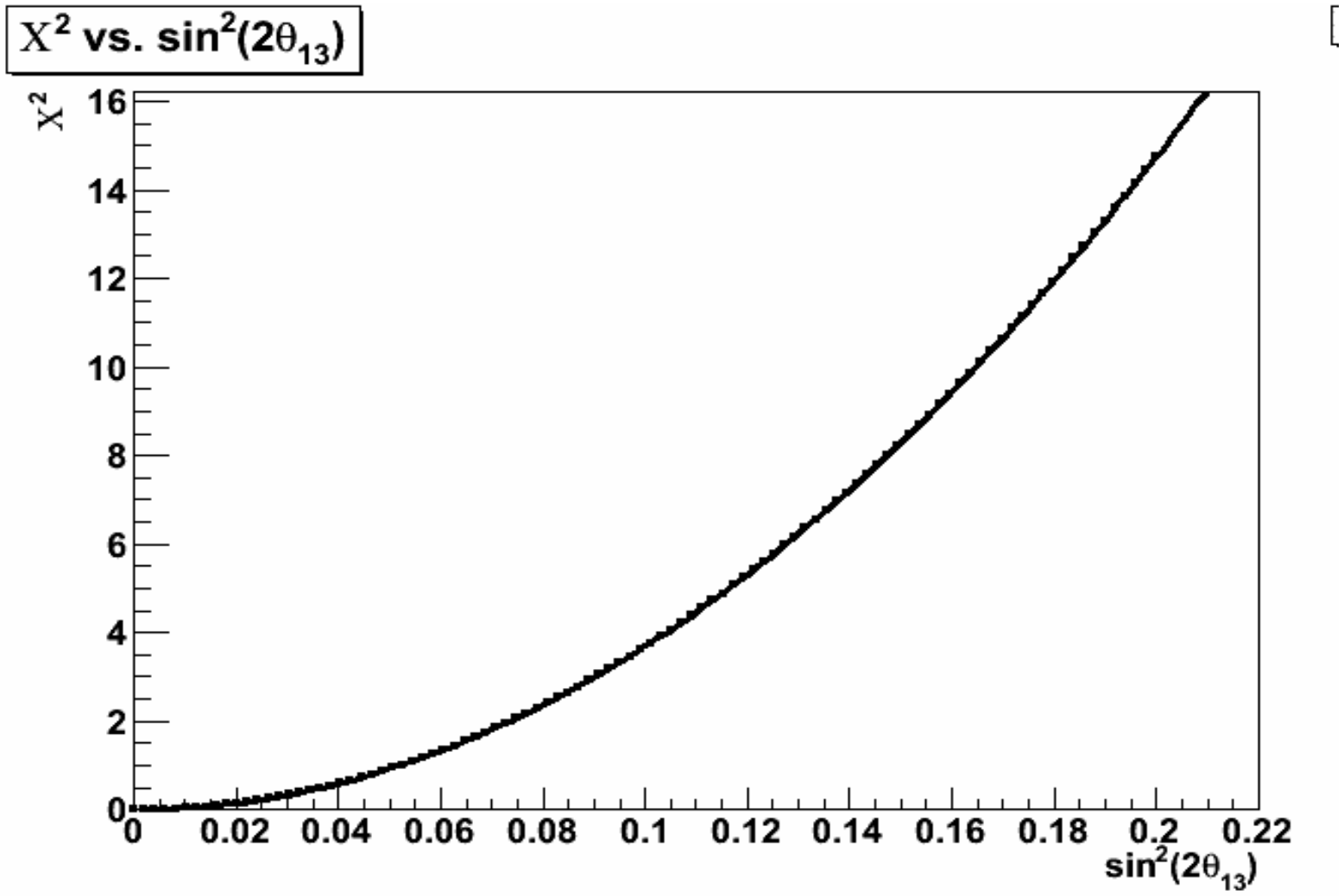
Backup

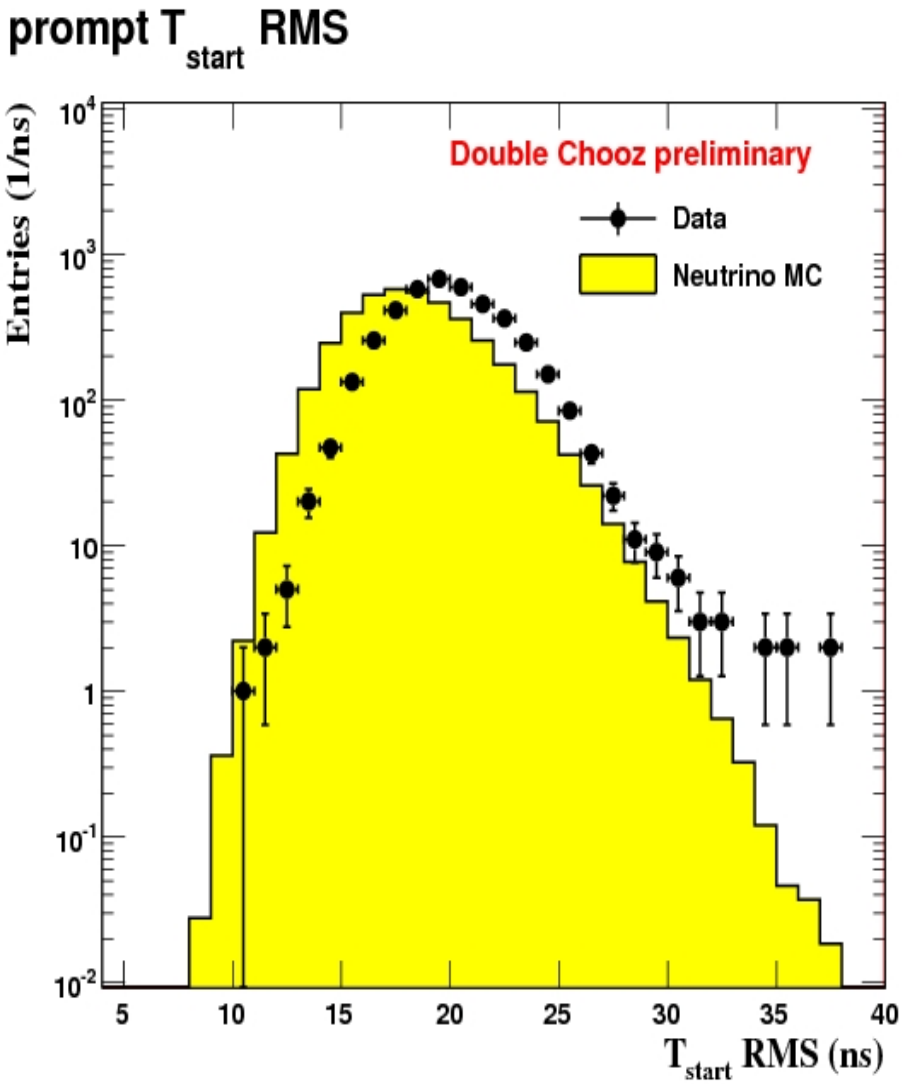
Spectral Uncertainty

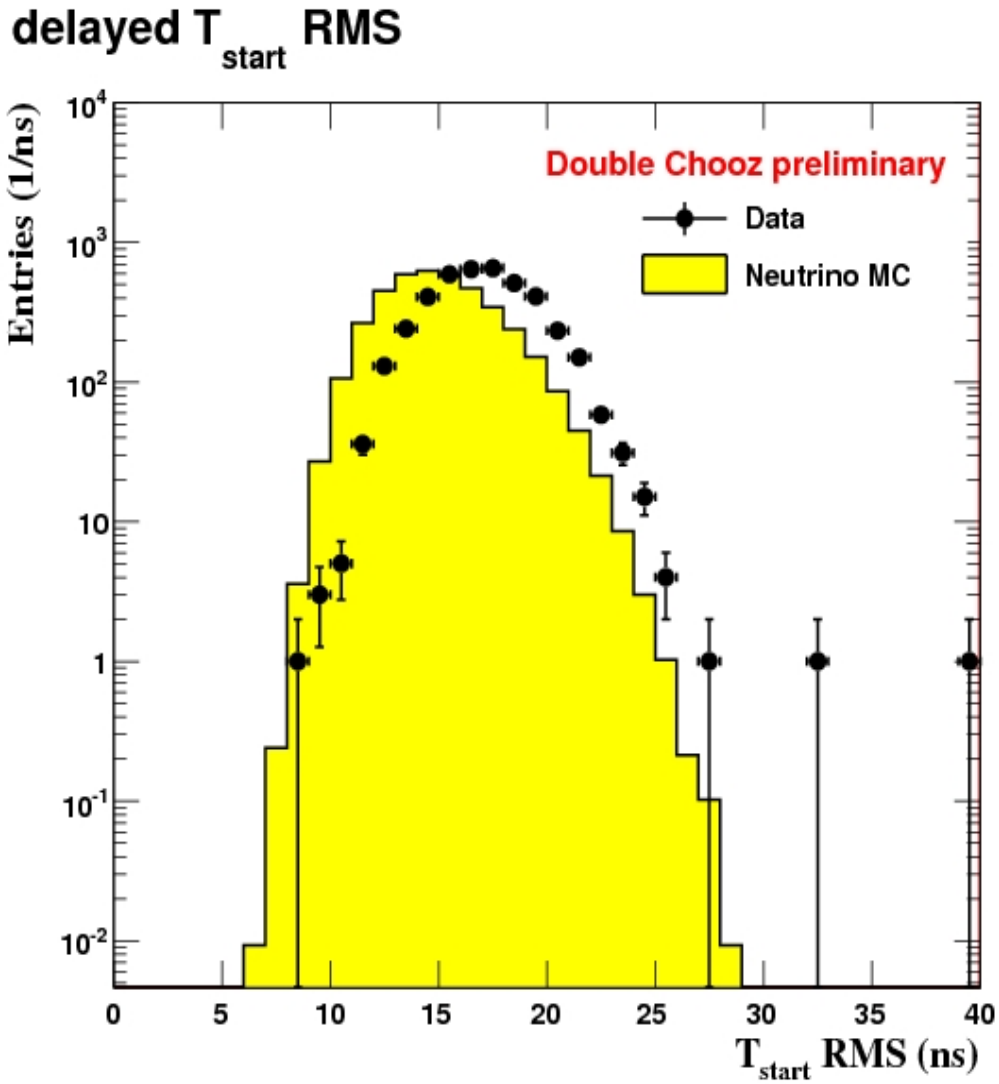
Independent sample of stopping muons and fast neutrons obtained by inner veto tag. Spectral uncertainty taken from difference of measured spectrum and flat background hypothesis



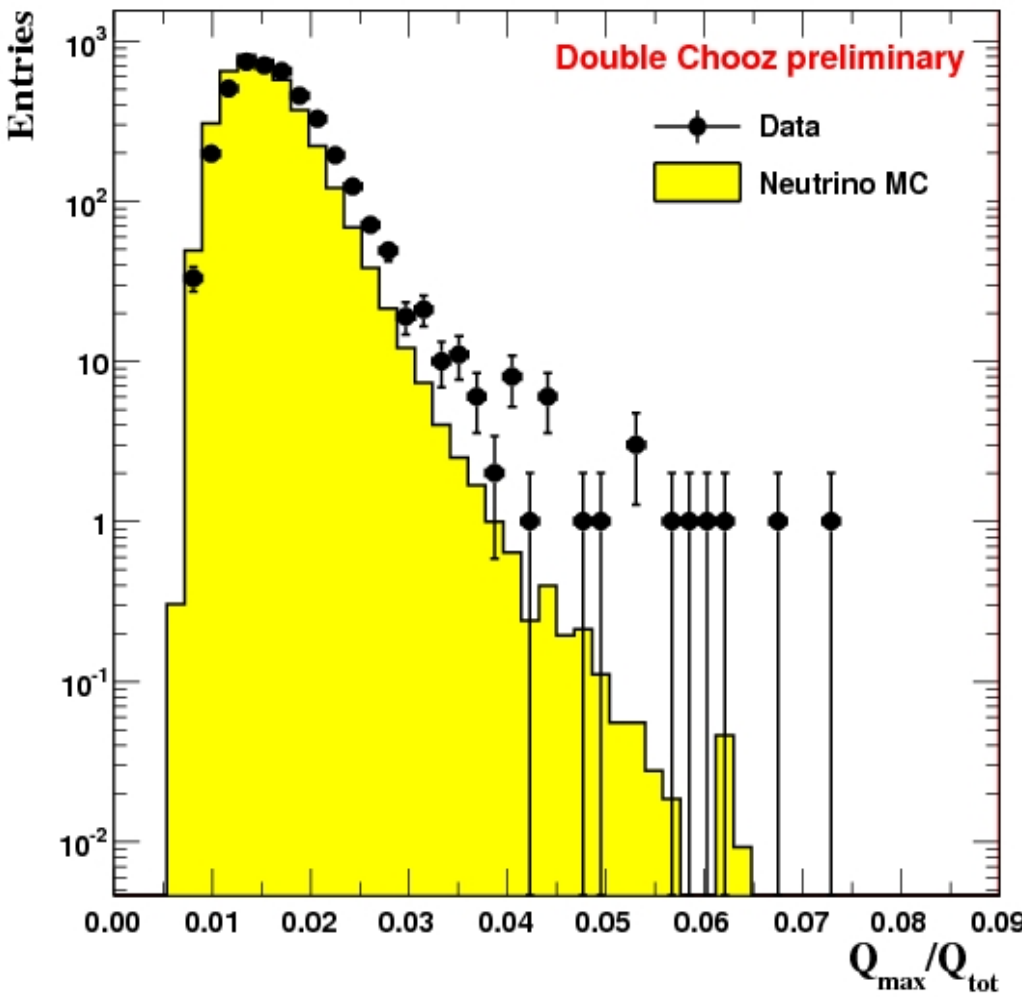
Backup: Null Oscillation



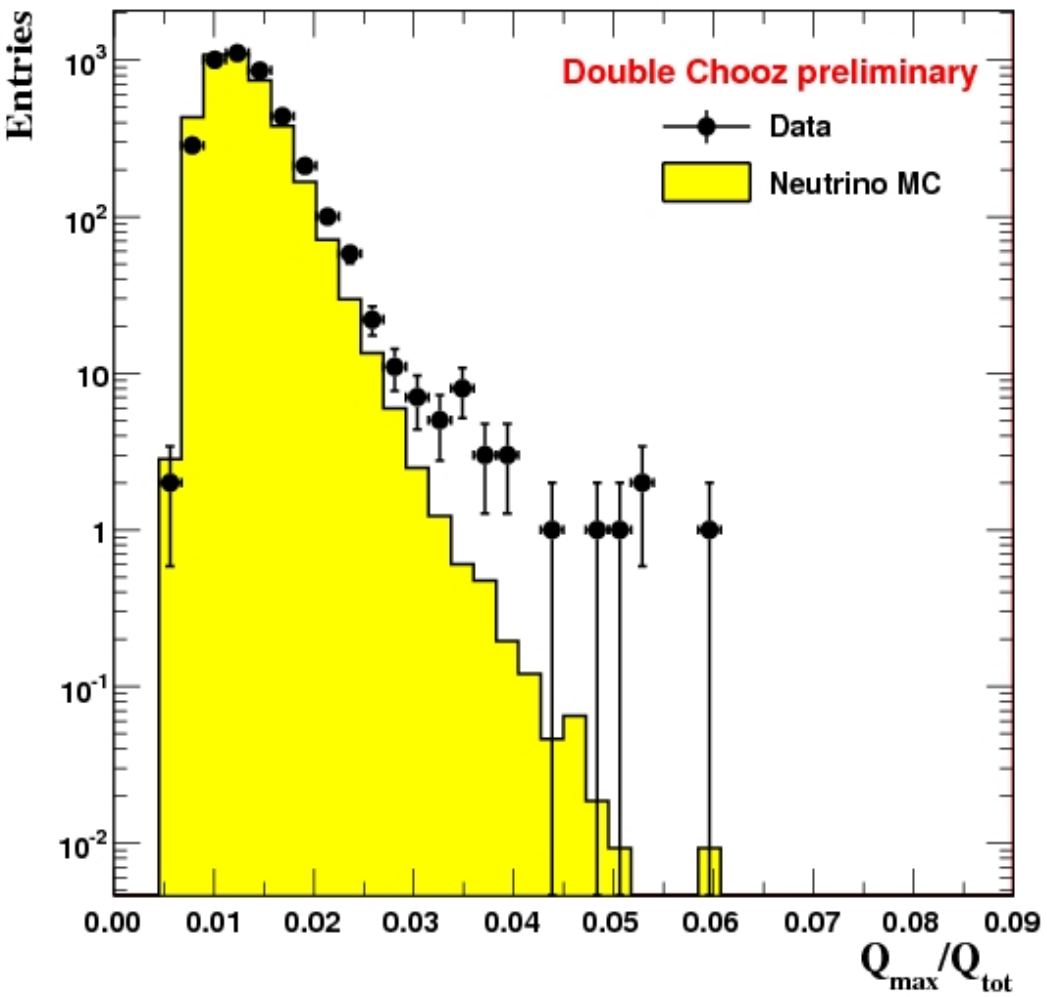

prompt T start RMS
Double Chooz preliminary
Data
Neutrino MC
Entries (1/ns)
T start RMS (ns)

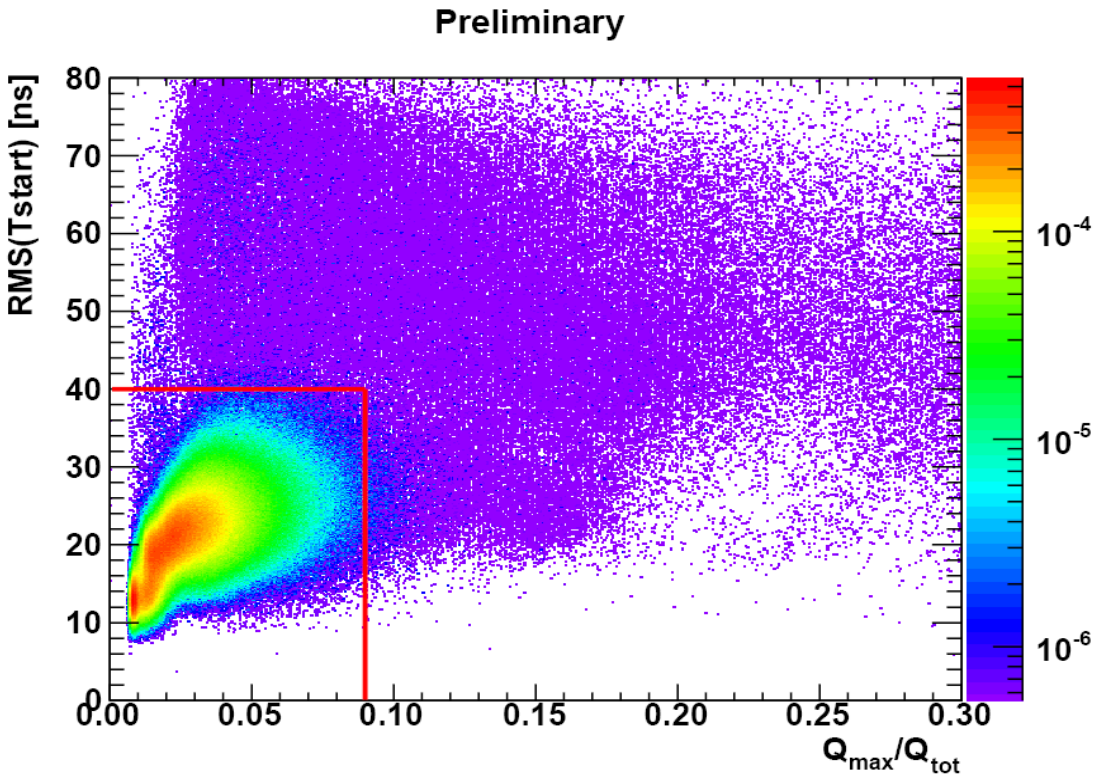

delayed T start RMS
Double Chooz preliminary
Data
Neutrino MC
Entries (1/ns)
T start RMS (ns)

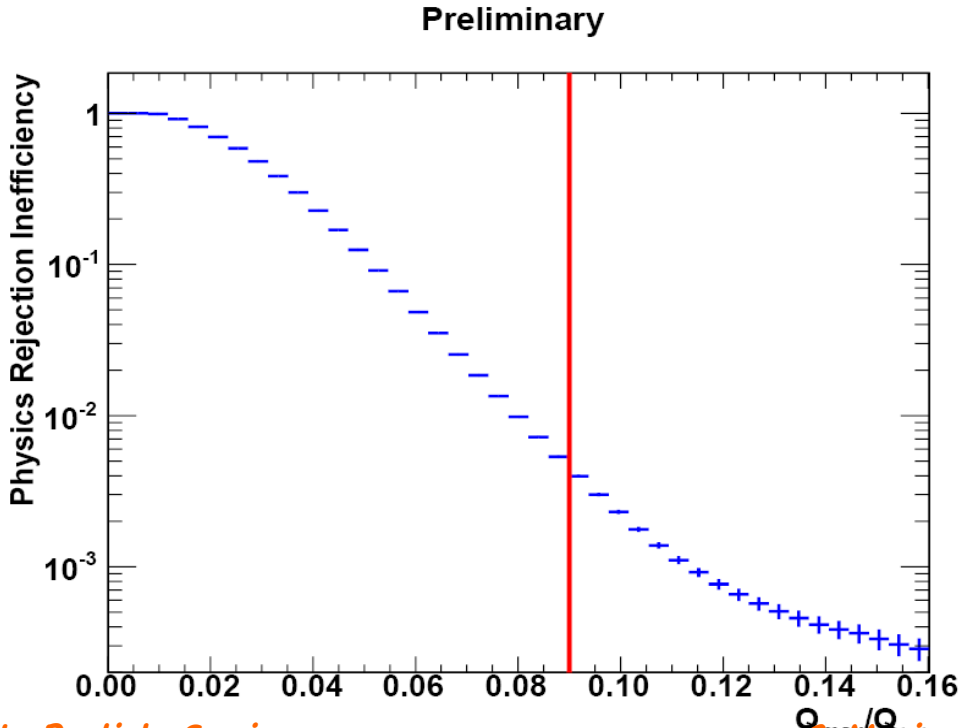
prompt Q_{max}/Q_{tot} ratio

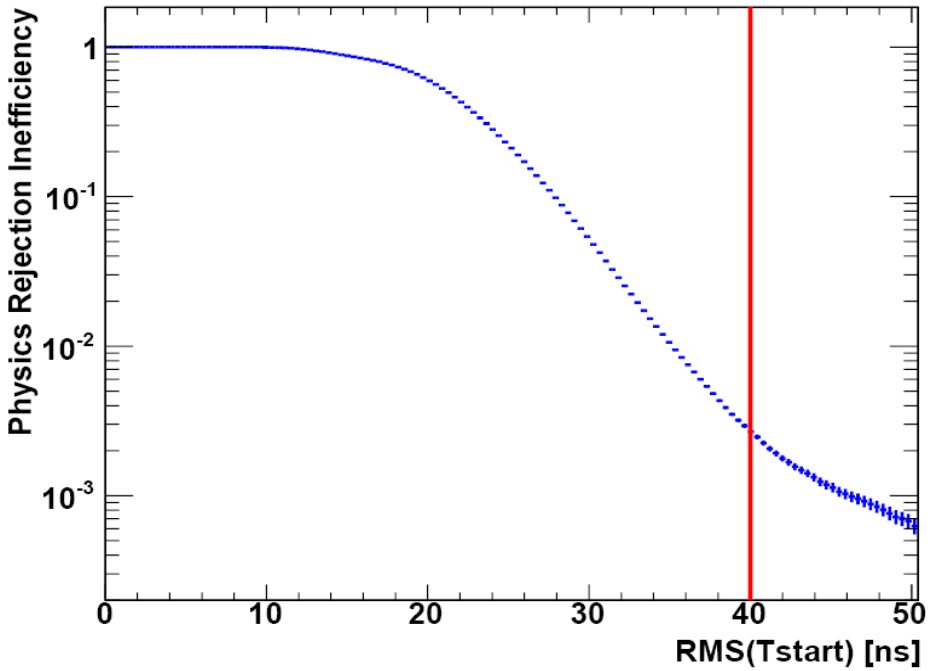


delayed Q_{max}/Q_{tot} ratio



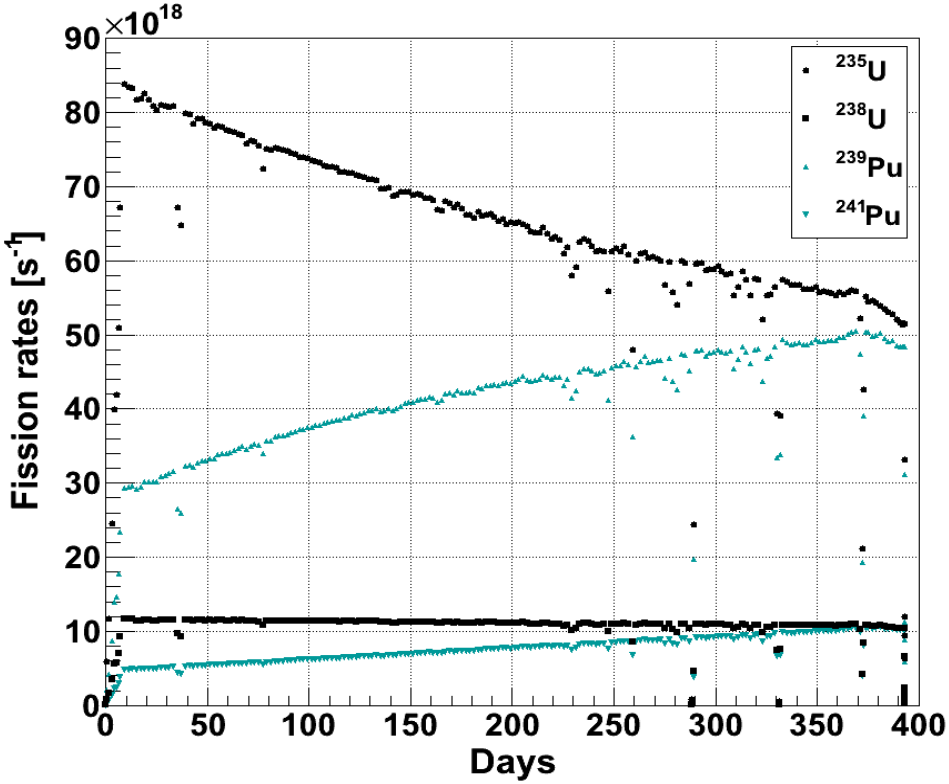

Preliminary
RMS(Tstart) [ns]
80
70
60
50
40
30
20
10
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Q_{max}/Q_{tot}
10^{-4}
10^{-5}
10^{-6}

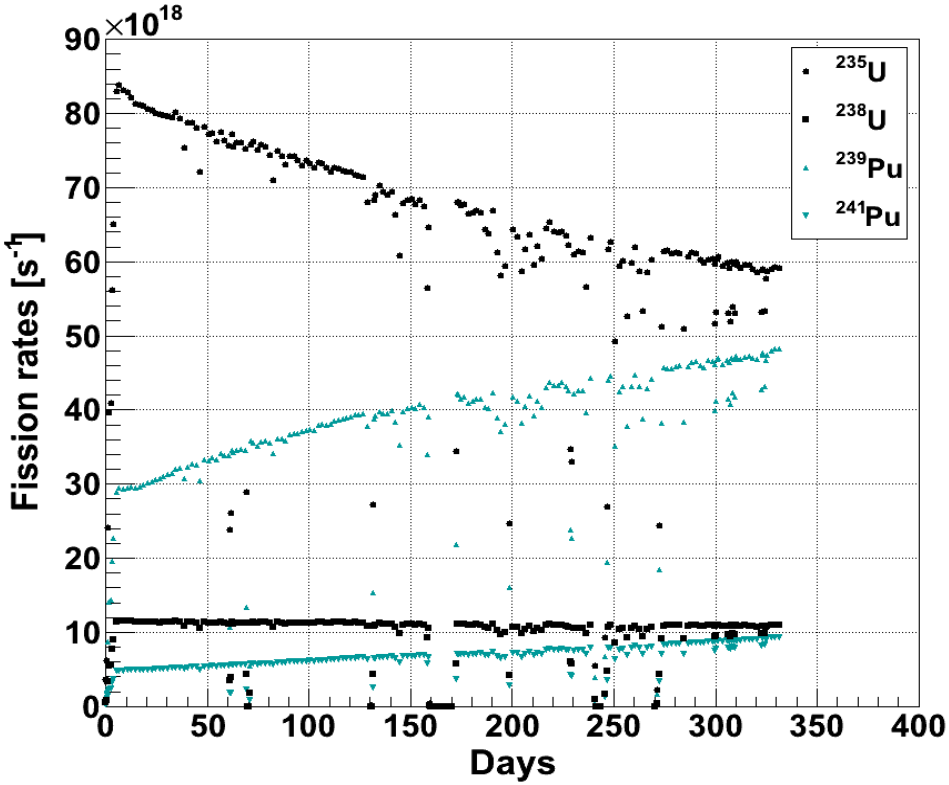

Preliminary
Physics Rejection Inefficiency
1
10^{-1}
10^{-2}
10^{-3}
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
Q_{max}/Q_{tot}


Physics Rejection Inefficiency
1
10^{-1}
10^{-2}
10^{-3}
0
10
20
30
40
50
RMS(Tstart) [ns]

Fission rates

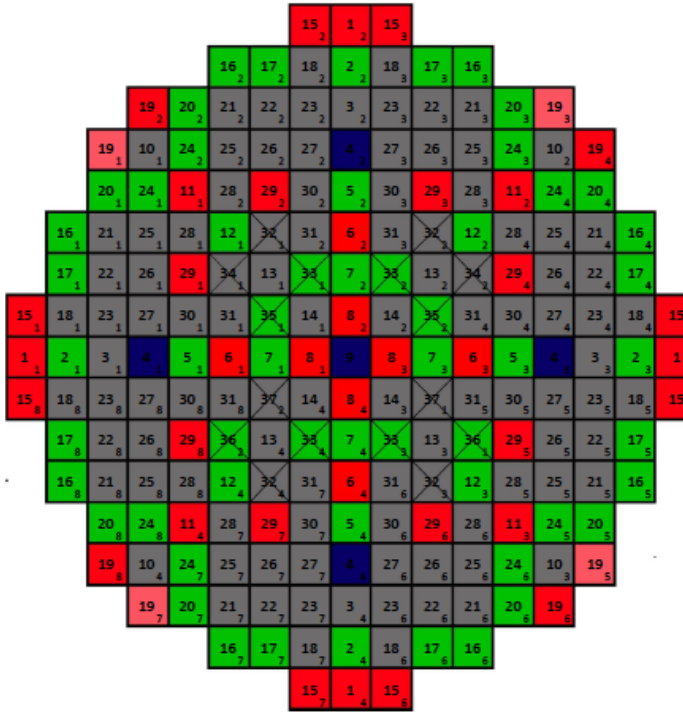
Fission rates as a function of time:





Reactor core simulation strategy

- Use of **2 validated reactor codes** widely used worlwide and already used for PWR simulations : **deterministic (DRAGON) and Monte-Carlo Code (MCNP Utility for Reactor Evolution)**



- **Validation of simulations and discrepancies assessment:** DRAGON and MURE benchmark + benchmark containing measured inventories :
  - ∫ rod, assembly scale: **Takahama benchmark**

=> C. Jones et al. arxiv.org/pdf/1109.5379 : good agreement & code and use validation

- **Development of the full core simulation, following the core history:**
  - ∫ main advantage = **knowledge and control of inputs**, compute fission rates at any time following the core history corresponding to the data taken, even with sudden changes in the power history
  - ∫ 2 codes: **full reactor simulation with MURE, important fast x-checks with DRAGON@assembly level**

=> A lot of input needed (geometrical parameters, material & fuel composition, power & boron concentration history …): provided by EDF

Sensitivity studies for reactor systematics

- Sensitivity studies to compute the **uncertainties on the predicted fission rates:**

⇒ In order to compute the covariance matrix V_{ij}^{F} associated to the fission rates, as a function of burnup:

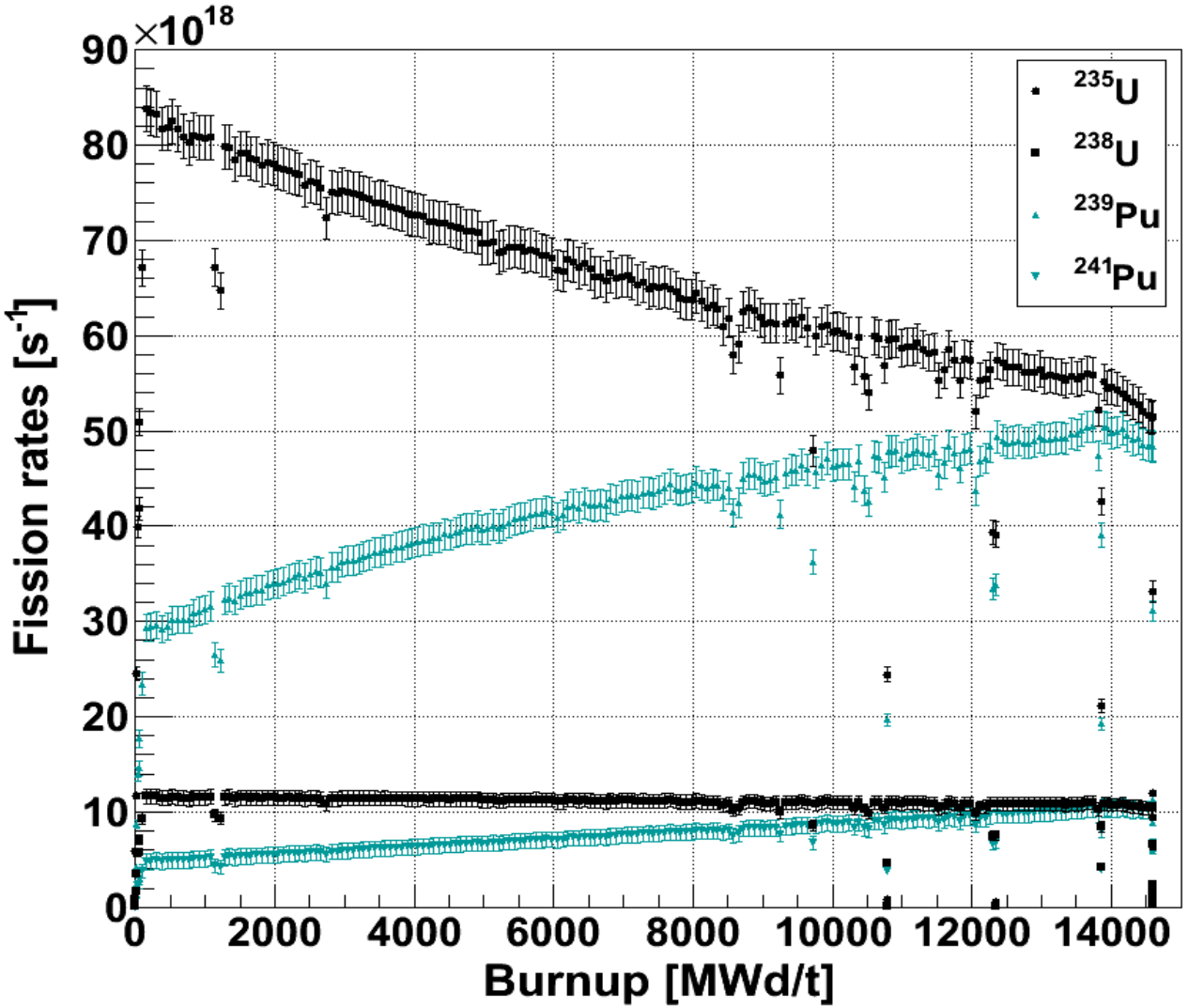
- All the quoted errors are computed numerically by varying one parameter at a time over a large range of values in the assembly simulation (with MURE).

- The relationship between the fission rates as a function of these variations is then deduced by fitting the simulation results.

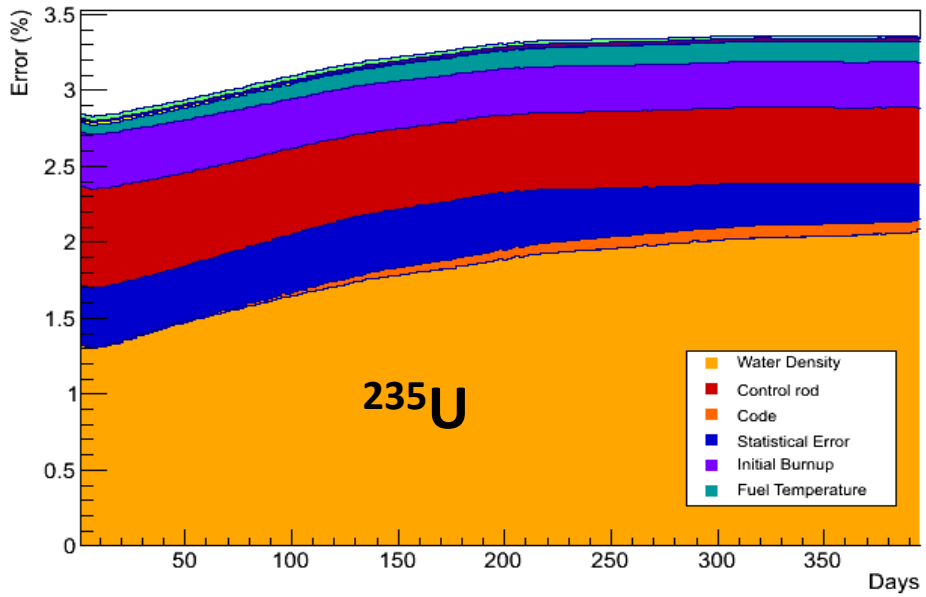
- Determination of the correlation matrix through core fission rate fits

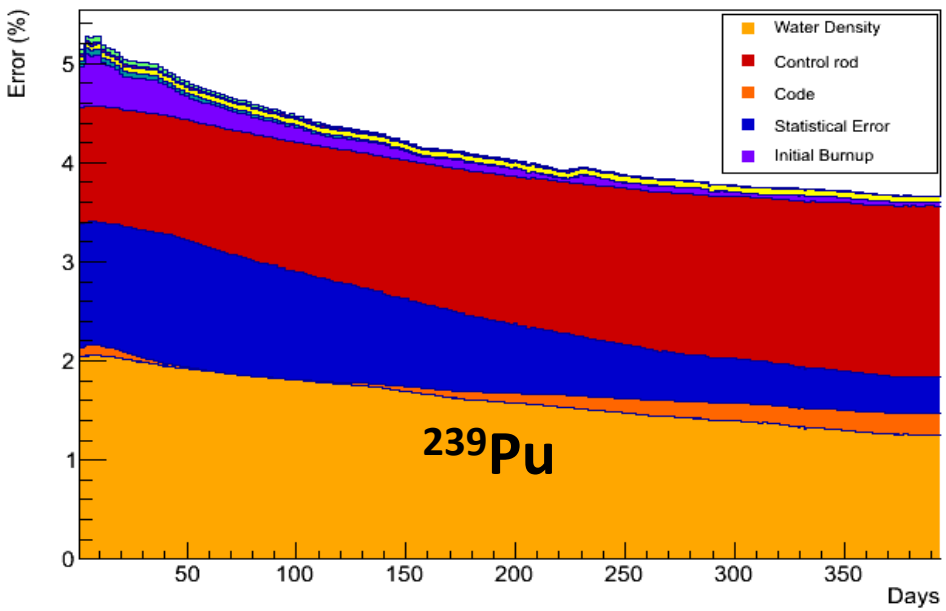
Fission rates

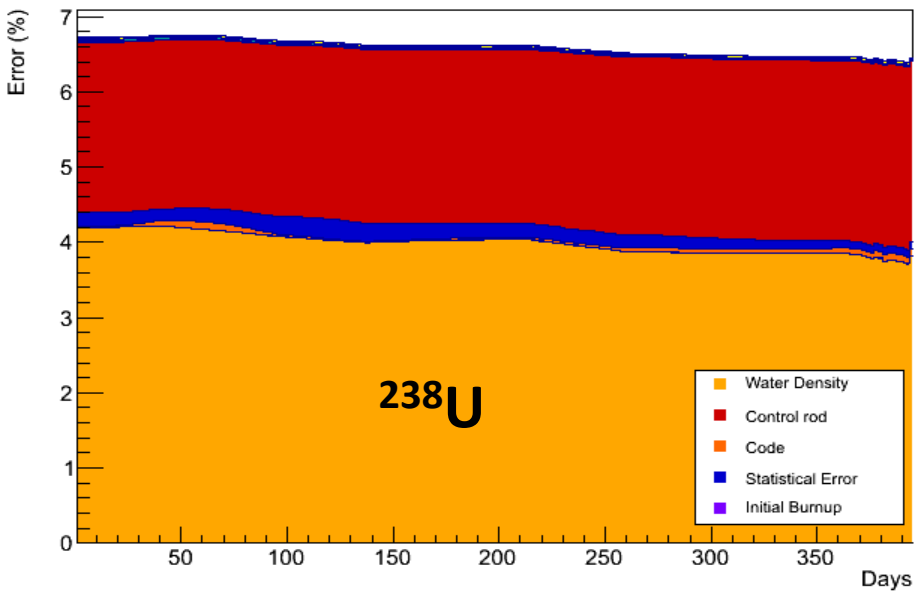
Fission rates with error bars as a function of time:

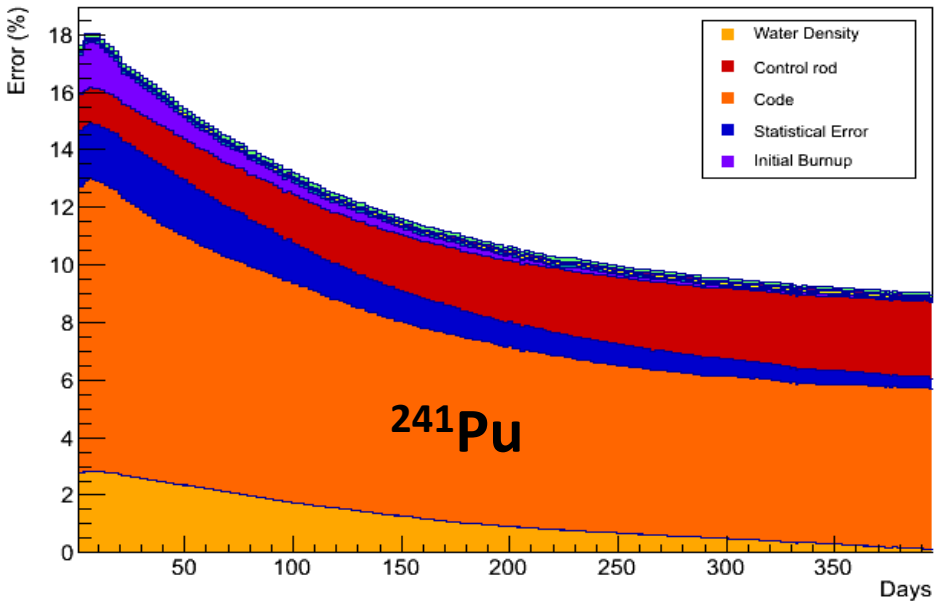


Breakdown of reactor systematics









Sensitivity studies for reactor systematics

⇒ **In order to compute the covariance matrix V_{ij}^F associated to the fission rates, as a function of burnup**

The diagonal terms are given by:

$$\sigma_{f_i}^2 = \sigma_{C_B}^2 + \sigma_{W_{th}}^2 + \sigma_{T_{fuel}}^2 + \sigma_{T_{water}}^2 + \sigma_{density}^2 + \sigma_{code}^2 + \sigma_{\text{nuclear data}}^2 + \sigma_{e_i}^2 + \sigma_{\text{geom}}^2$$

C_B: boron concentration
W_{th}: thermal power
Temperature, Density: water and fuel temperatures and densities
Code: systematics arising from the computational method (M-C vs deterministic)
Nuclear database choice
e_i: energy released per fission
Geom: error arising from geometrical approx. (including dimensions, fuel enrichment, geometrical simplifications, initial inventories)

- **All the quoted errors are computed numerically by varying one parameter at a time over a large range of values in the assembly simulation (with MURE).**
- **The relationship between the fission rates as a function of these variations is then deduced by fitting the simulation results.**
- **Determination of the correlation matrix through core fission rate fits**

Reactor simulation strategy – Choice of core input parameters

▪ **General parameters :**

- Cross-section databases: **JEFF3.1** (also tested for systematics : ENDFB6.8, and JENDL2.2 in Takahama)
- Energy per fission: **Kopeinkin's** (also tested for systematics : EPF_{MURE}, EPF_{DRAGON})
- Water density**: 0.697 g/cm^3** (Density used by EDF for EPR simulation)
- Time steps : **48h + 24h/12h** when strong variations of the power

=> **One cooling phase added before the start of simulation:** (in order to take into account the variations of the neutron absorbing nuclei during the refuelling of the core : Impact on the neutron energy spectrum at the start of the core and on the fission rate distributions)

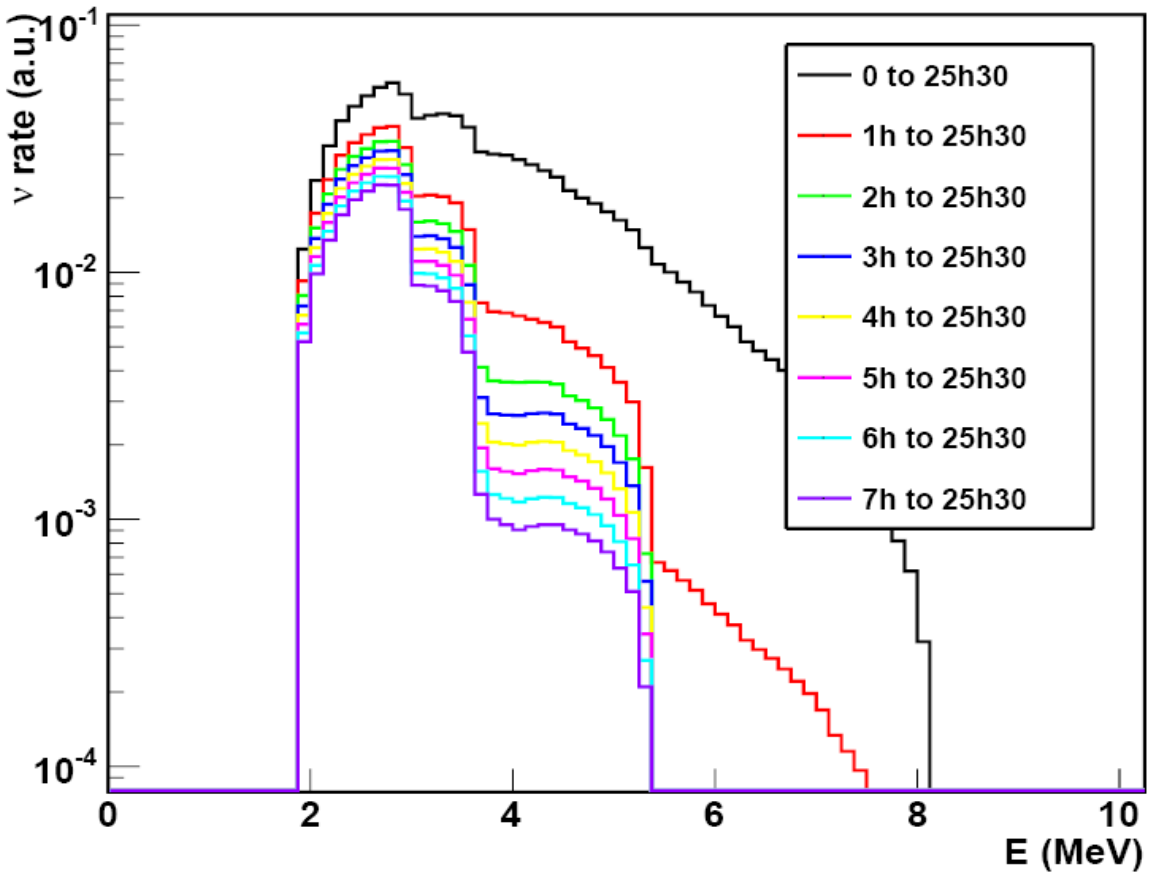
- B1 : 2010-05-09 01:52:00 -> 2010-08-26 20:20:00 (2634 hours)
- B2 : 2010-10-02 01:10:00 -> 2010-11-15 13:00:00 (1067 hours)

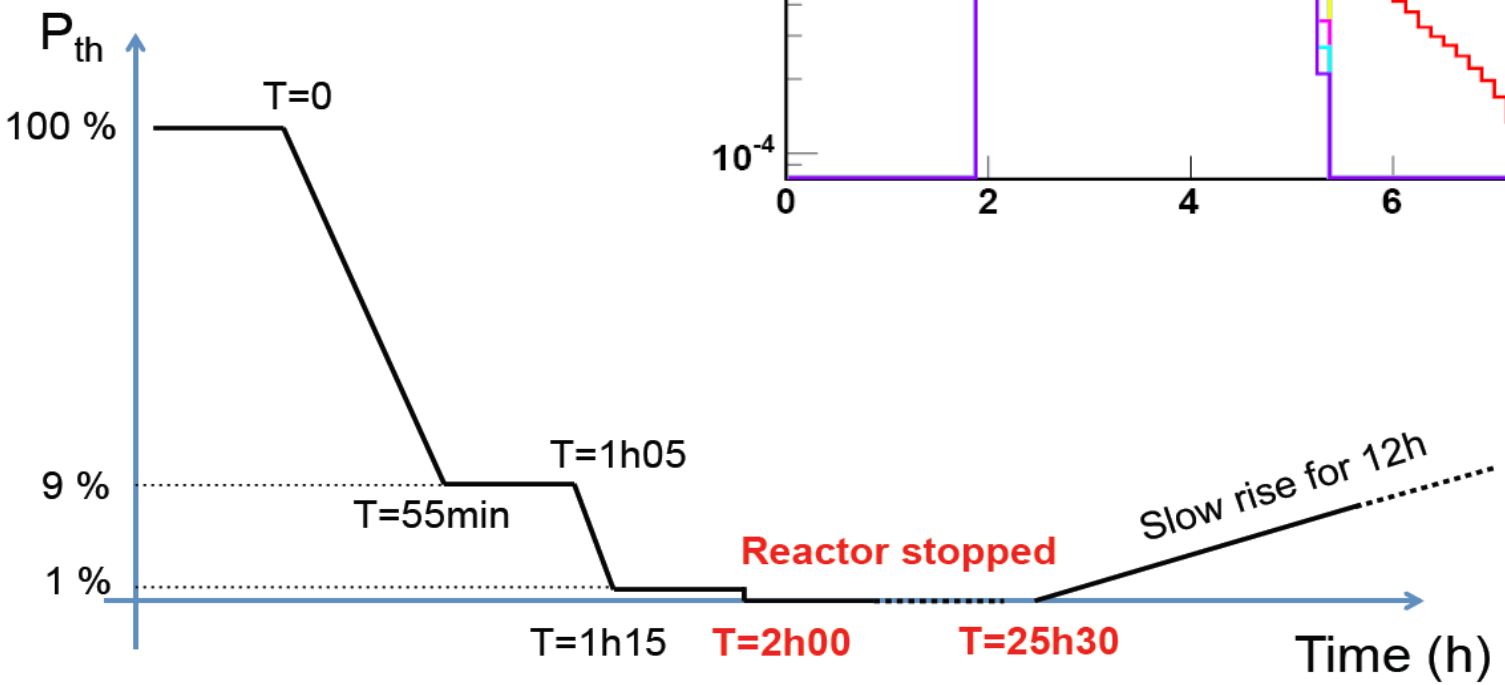
▪ **Specific MURE parameters :**

◊ Multigroup option with 179000 energy bins ("classical " multigroup option: 17900 bins)

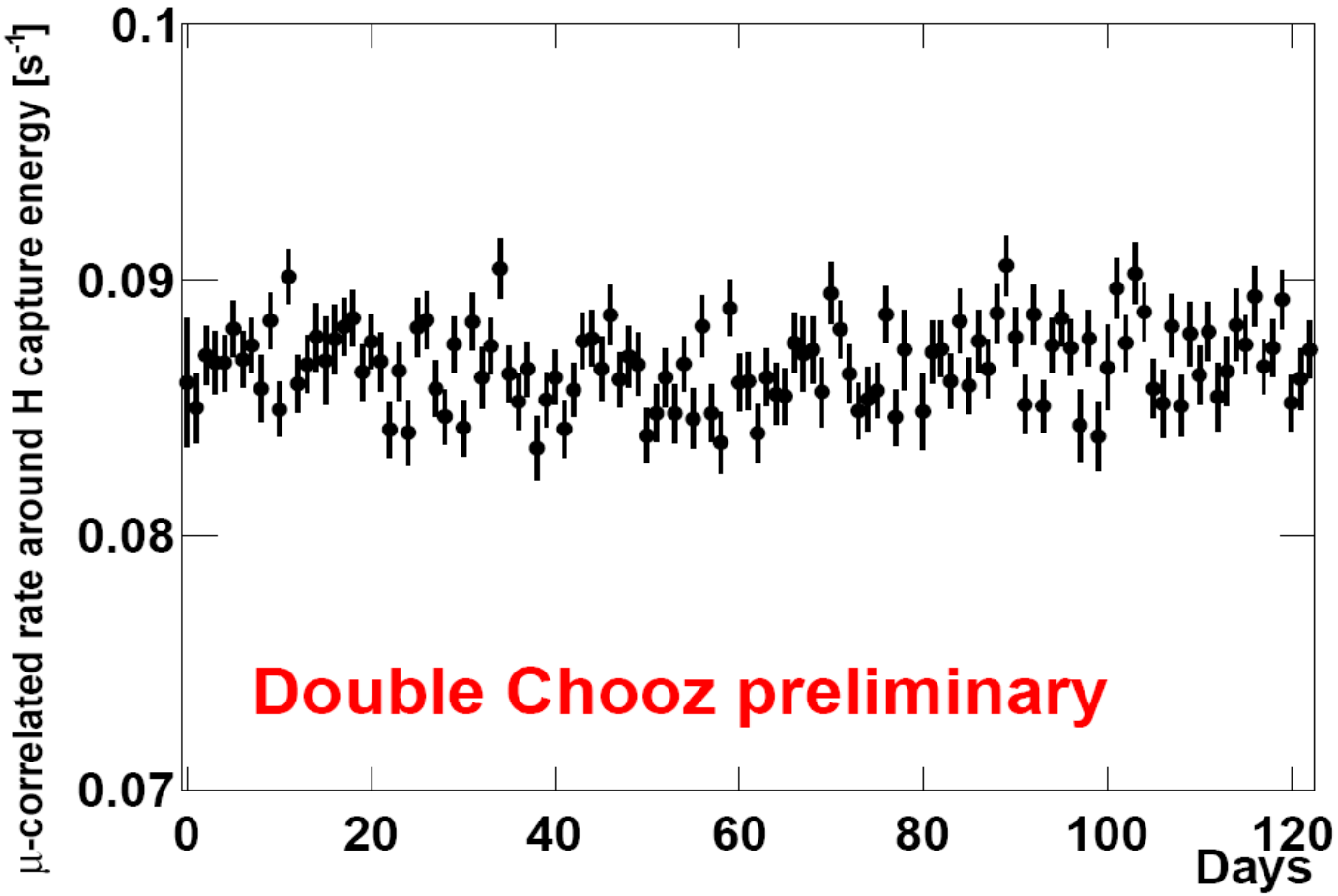
◊ At each MCNP run : 200 000 neutrons/batch, 120 batch
(with 12 cpu : ~3h needed for each MCNP step)

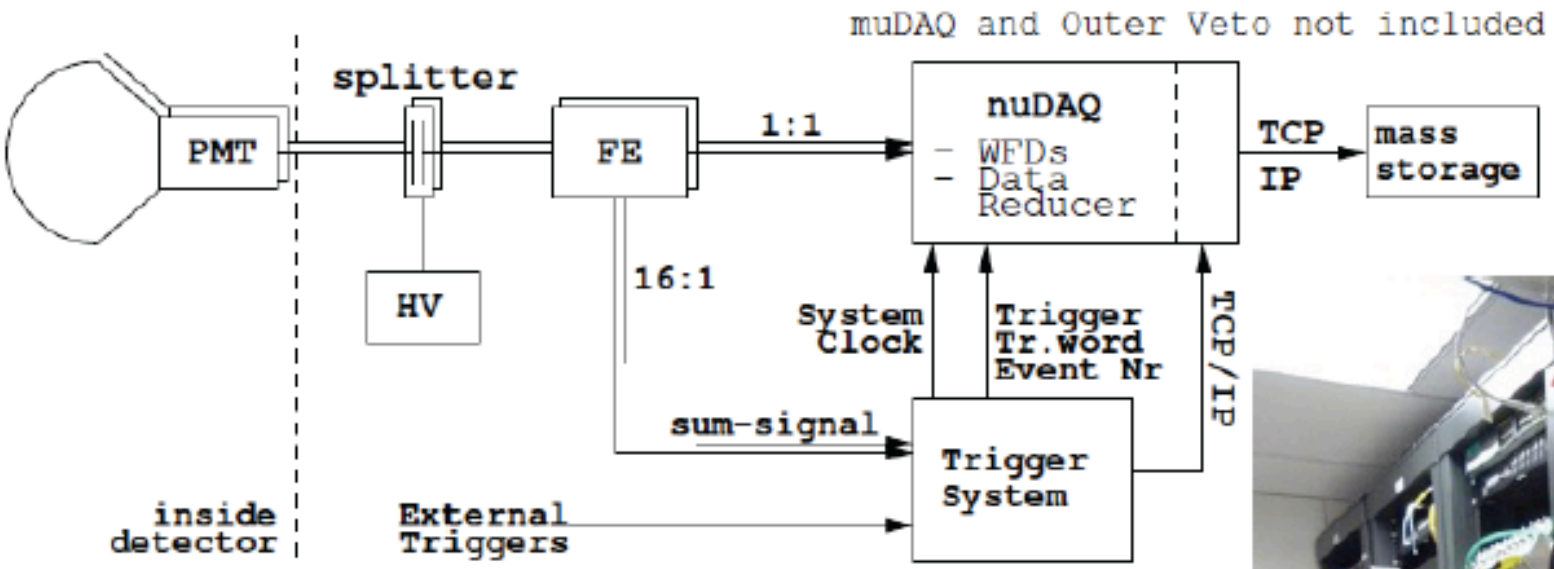
=> Around ~250 times steps to simulate one complete core cycle (~700h)


ν rate (a.u.)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10
E (MeV)
0 to 25h30
1h to 25h30
2h to 25h30
3h to 25h30
4h to 25h30
5h to 25h30
6h to 25h30
7h to 25h30


P_{th}
100 %
T=0
9 %
T=55min
T=1h05
1 %
T=1h15
T=2h00
Reactor stopped
T=25h30
Slow rise for 12h
Time (h)

Stability


μ-correlated rate around H capture energy [s⁻¹]
0.1
0.09
0.08
0.07
0
20
40
60
80
100
120
Days
Double Chooz preliminary





The Electronics:

- Signal + HV on one cable.
- Frontend cards shape pulses, corrects baseline and integrates charge.
- Analog Trigger triggers on photoelectron equivalent.
- 500MHz Caen digitizers record pulses.
- Subset of PMTs sent to second system to record muon events.