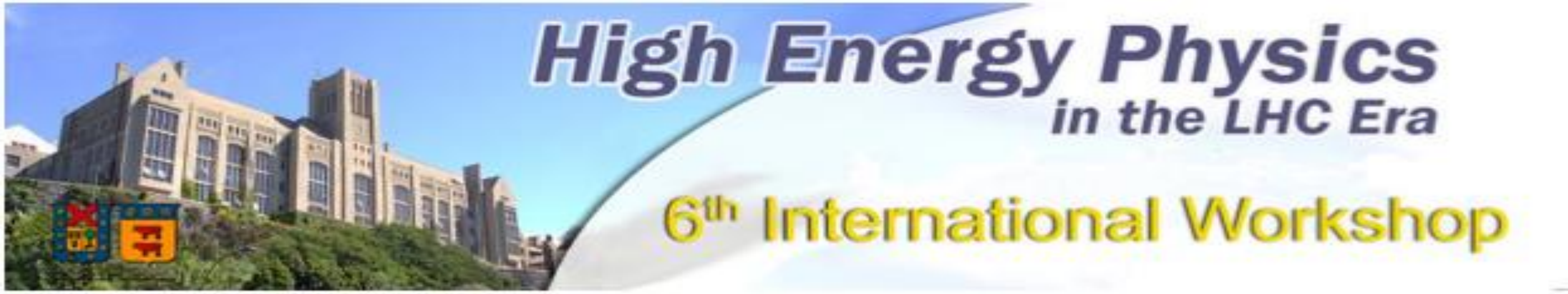


Recent Results from the Double Chooz Experiment for the Neutrino Mixing Angle Theta13

João dos Anjos

Observatório Nacional & CBPF - Rio de Janeiro

UTFSM, Valparaiso, 11 January, 2016

Neutrino Oscillations

A short reminder

Neutrino flavors are a superposition of mass eigenstates

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\Delta m^2_{31}} \underbrace{\begin{pmatrix}c_{13} & 0 & e^{-i\delta}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta}s_{13} & 0 & c_{13}\end{pmatrix}}_{\Delta m^2_{31}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\Delta m^2_{21}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\sin^2 2\theta_{23} \approx 1$ atmospheric ν

$\sin^2 2\theta_{13} \approx 0.1$ accelerator+reactor

$\sin^2 2\theta_{12} \approx 0.8$ solar ν

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

Propagation of states leads to oscillation phenomenon

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$
$$+ \sin^2(2\theta_{13})\sin^2(\theta_{12})\left[\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \sin^2\left(\frac{\left(\Delta m^2_{31} - \Delta m^2_{21}\right) L}{4E}\right)\right]$$

Neutrino Mixing Matrix

Experimental situation by 2010:

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric | Reactor and LBL | Solar

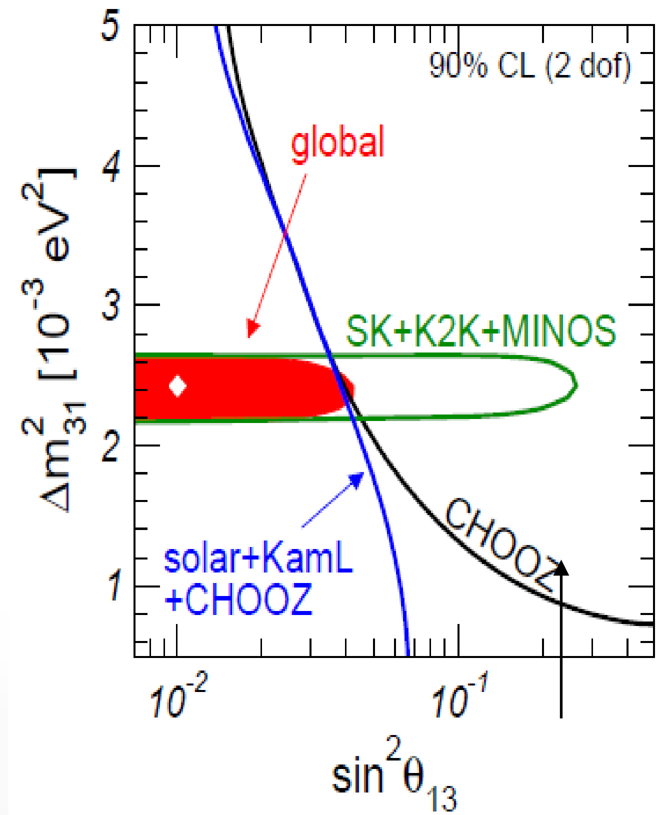
- The parameters θ_{23} and Δm^2_{23} determined using atmospheric neutrino data from Super-Kamiokande, K2K and Minos. (10% level)
- Data from SNO, KamLAND and Super-Kamiokande used to determine θ_{12} and Δm^2_{12} with 10 – 20% precision.
- Only a limit for θ_{13} by the reactor experiment CHOOZ (2003).

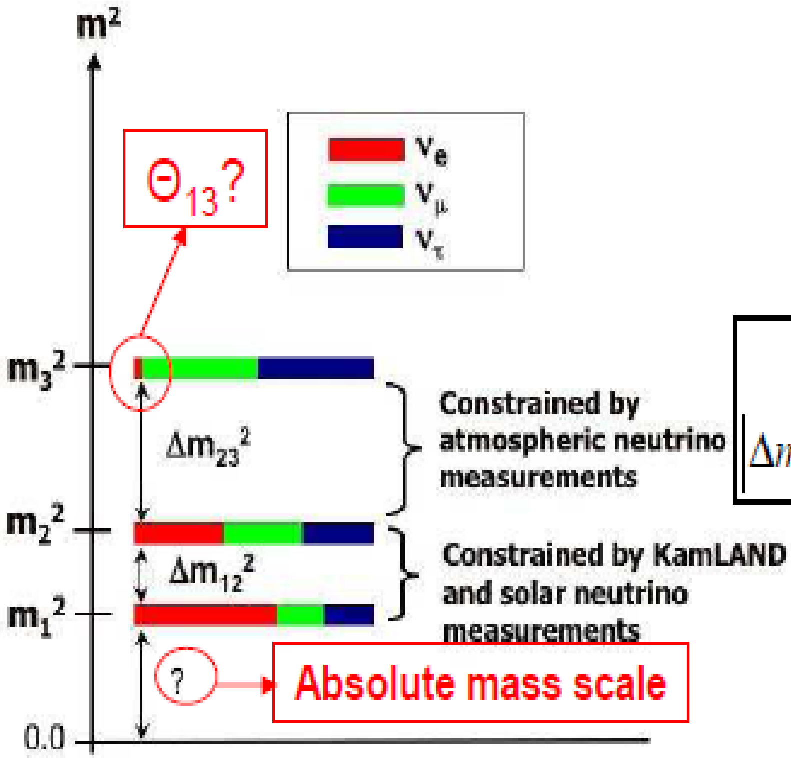
$$\sin^2(2\theta_{13}) < 0.2$$

•Neutrino Oscillations: open questions 2010

- Size of θ_{13}
- CP violaton effects
- Mass hierarchy
- Absolute mass scale

arxiv:0812.3161





$\theta_{13} < 9.5\,\mathrm{deg}$ @ 90% CL

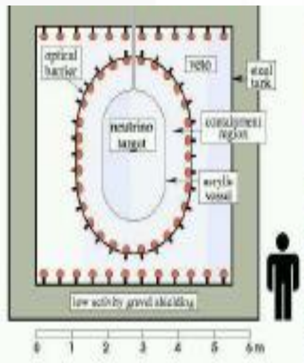
$$\theta_{23} = 45^{+4.}_{-3.4}$$

$$\left|\Delta m^2_{13}\right| = 2.40 \pm 0.12 \times 10^{-3} eV^2$$

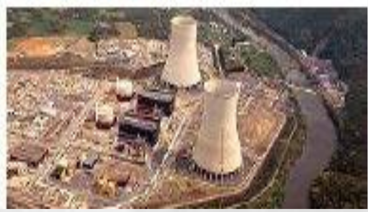
$$\theta_{12} = 33.5^{+1.3}_{-1.0}$$

$$\Delta m^2_{12} = 7.65^{+0.23}_{-0.20} \times 10^{-5} eV^2$$

@1σ arXiv:0808.2016



The main limit comes from CHOOZ reactor experiment ´97



The main goal of upcoming experiments is the determination of θ_{13}

World Competition in Reactor Neutrino Experiments

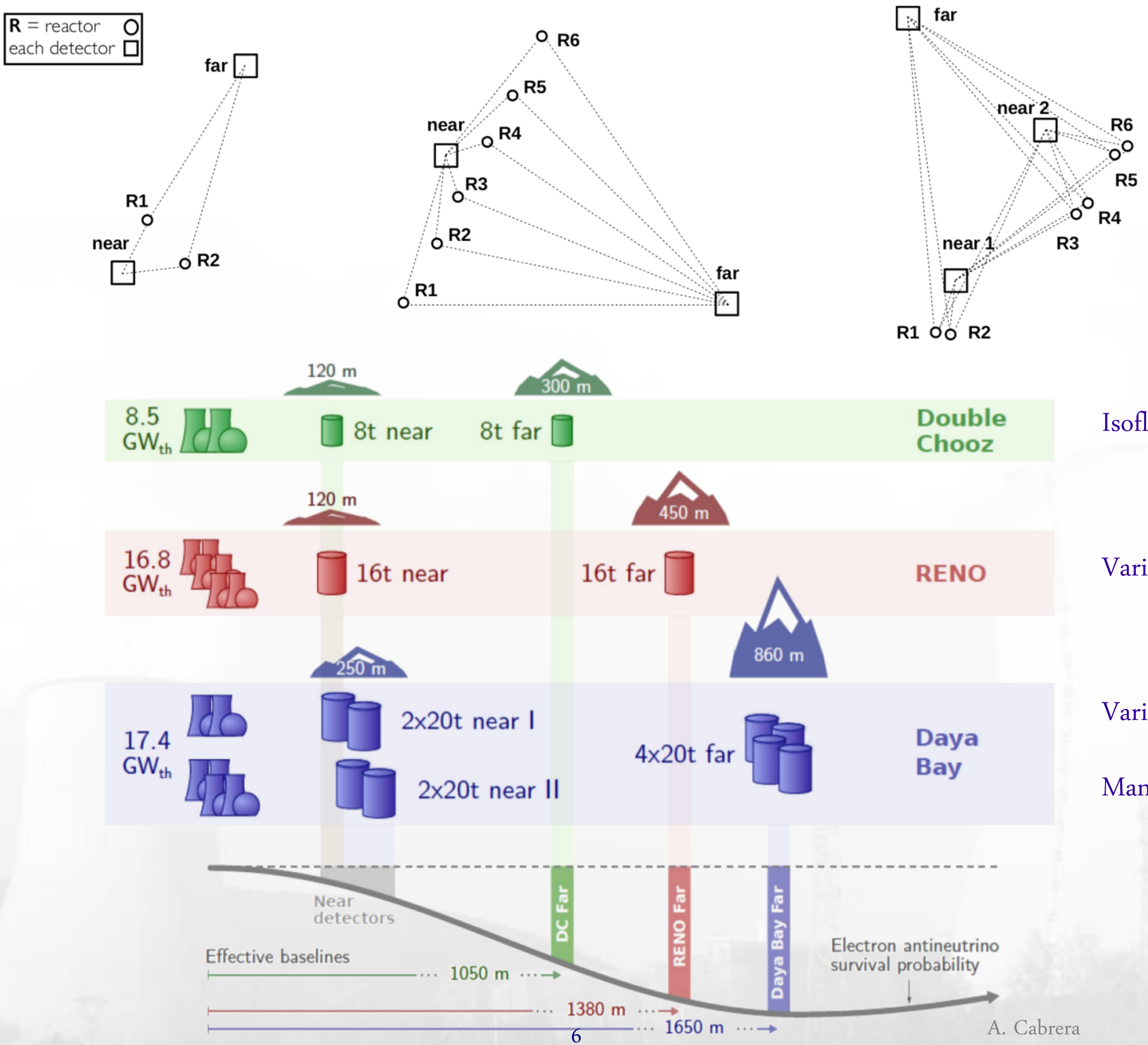
Experiments	Location	Thermal Power (GW)	Distances Near/Far (m)	Depth Near/Far (mwe)	Target Mass (tons)	$\sin^2(2\theta_{13})$ 90% C.L.
Double-CHOOZ	France	8.7	410/1050	115/300	8/8	0.03
RENO	Korea	17.3	290/1380	120/450	16/16	0.02
Daya Bay	China	17.4	360(500)/1985(1613)	260/910	40X2/80	0.01

Double-CHOOZ

RENO

Daya Bay

Experimental Geometries



Isoflux lines

Various baselines

Various baselines

Many detectors

Neutrino Oscillations

Reactor neutrino experiments predestined for measuring θ_{13}

- Strongest man-made neutrino sources (good statistics)
- Pure source of antineutrinos (no flavor contaminations)
- Antineutrinos rather than neutrinos (no matter effects)

Tremendous effort: θ_{13} from unknown to best known in a few years

Why are we interested in θ_{13}?

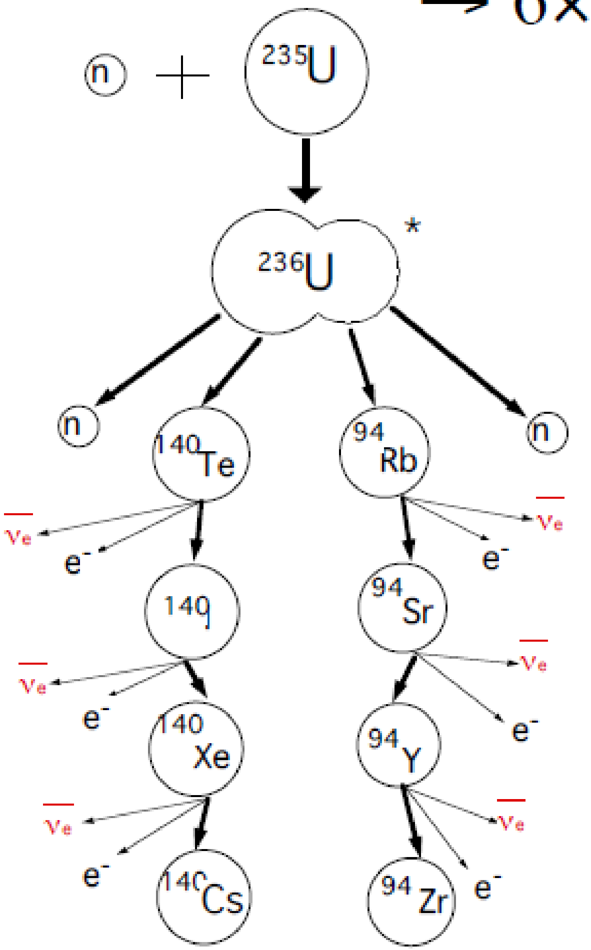
- Measure CP violation in lepton sector (matter asymmetry in the universe)
- Determine mass hierarchy ($\longrightarrow$ future experiments; understanding of ν mass)
- Understand the structure of mixing matrix (guide development of new theories)

Why reactors?

- ~6 ν's/fission, ~200MeV/fission

  → 6×10^{20} ν/sec for a typical commercial reactor

  (1GW power ~ 3GW thermal)



(example)

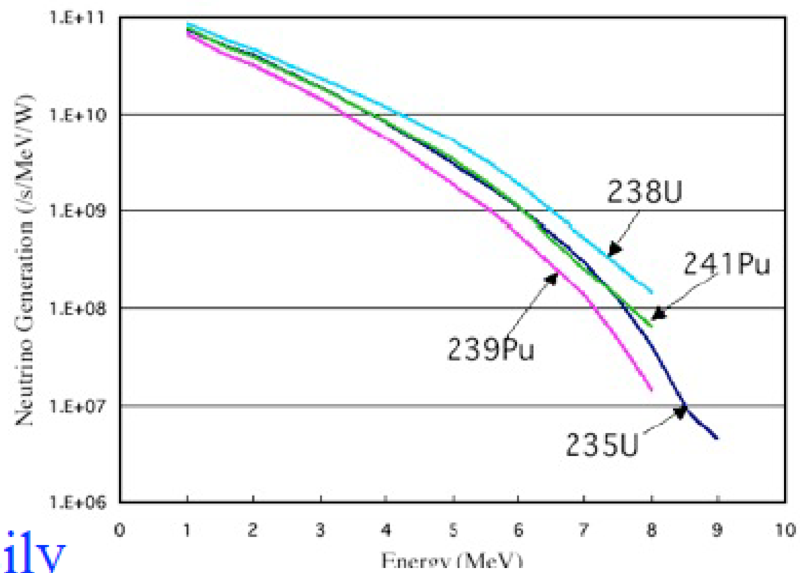
Reactors are powerful and "free" sources of low-energy (isotropic) neutrinos

E_ν~ a few MeV

Always full power

↕

Can't switch off easily



Double Chooz collaboration

Brazil	France	Germany	Japan	Russia	Spain	USA
CBPF **UNICAMP** **UFABC**	**APC** **CEA/DSM/** **IRFU:** **SPP** **SPhN** **SEDI** **SIS** **SENAC** **CNRS/IN2P3:** **Subatech** **IPHC**	**EKU Tübingen** **MPIK** **Heidelberg** **RWTH Aachen** **TU München** **U. Hamburg**	**Tohoku U.** **Tokyo Inst. Tech.** **Tokyo Metro. U.** **Niigata U.** **Kobe U.** **Tohoku Gakuin U.** **Hiroshima Inst. Tech.**	**INR RAS** **IPC RAS** **RRC** **Kurchatov**	**CIEMAT-** **Madrid**	**U. Alabama** **ANL** **U. Chicago** **Columbia U.** **UCDavis** **Drexel U.** **IIT** **KSU** **LLNL** **MIT** **U. Notre Dame** **U. Tennessee**

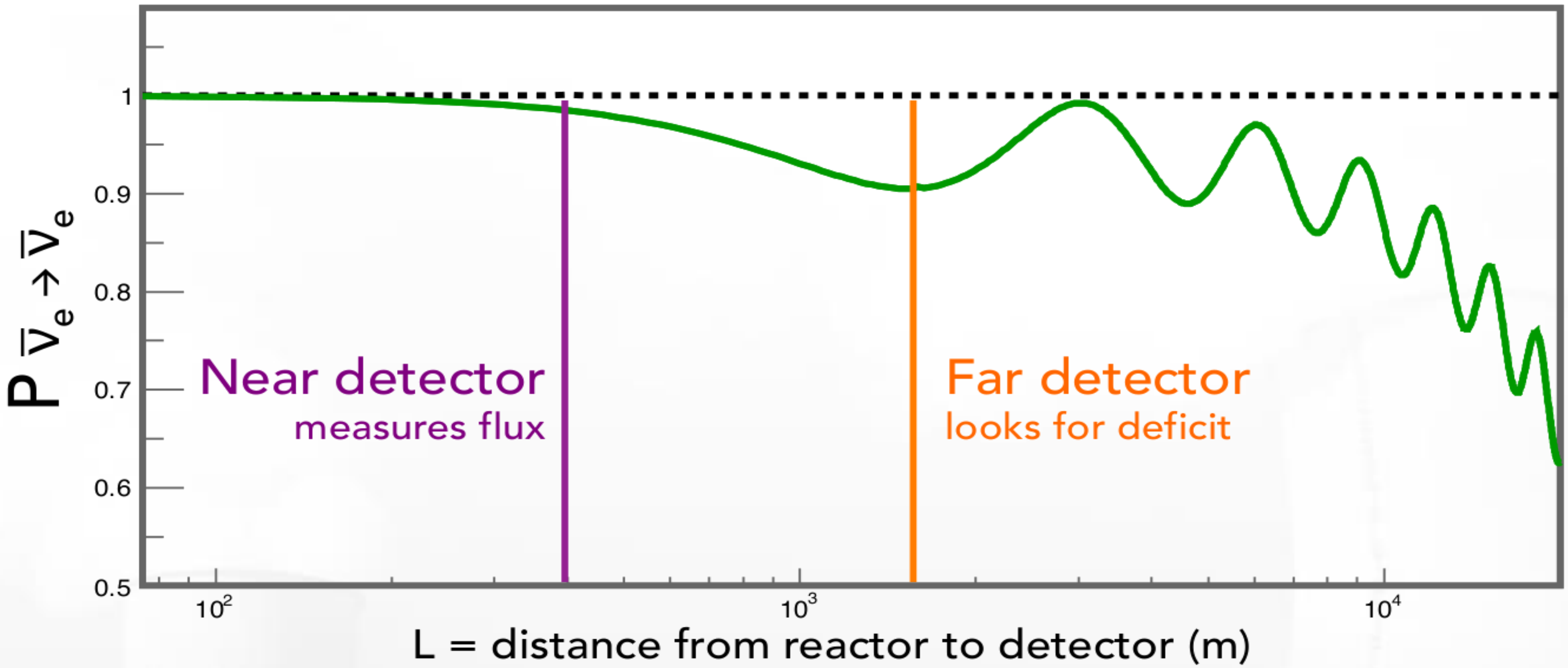
Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

Experimental Concept

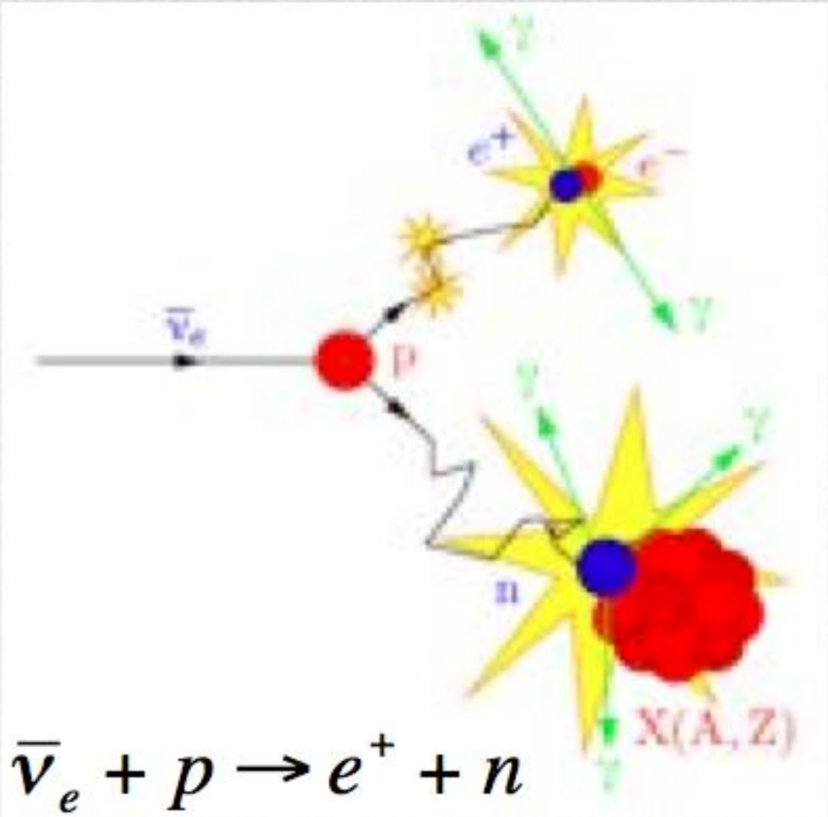
$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \boxed{\sin^2 2\theta_{13}} \sin^2 \left(1.27\, \Delta m^2_{23}(\text{eV}^2)\, \frac{L(\text{m})}{E(\text{MeV})}\right)$$



- **Short baseline:** reduce parameter correlations
- **Two-detector-concept:** reduction of systematics

θ_{13} measurement with reactor neutrinos

- Reactor is a free and rich electron antineutrino source
- Direct measurement of θ_{13} with no parameter degeneracy
- Background is strongly suppressed by delayed coincidence



Prompt signal:
positron + annihilation γ's:
1 ~ 12MeV

Delayed signal:
γ's from neutron capture
on Gd: 8MeV

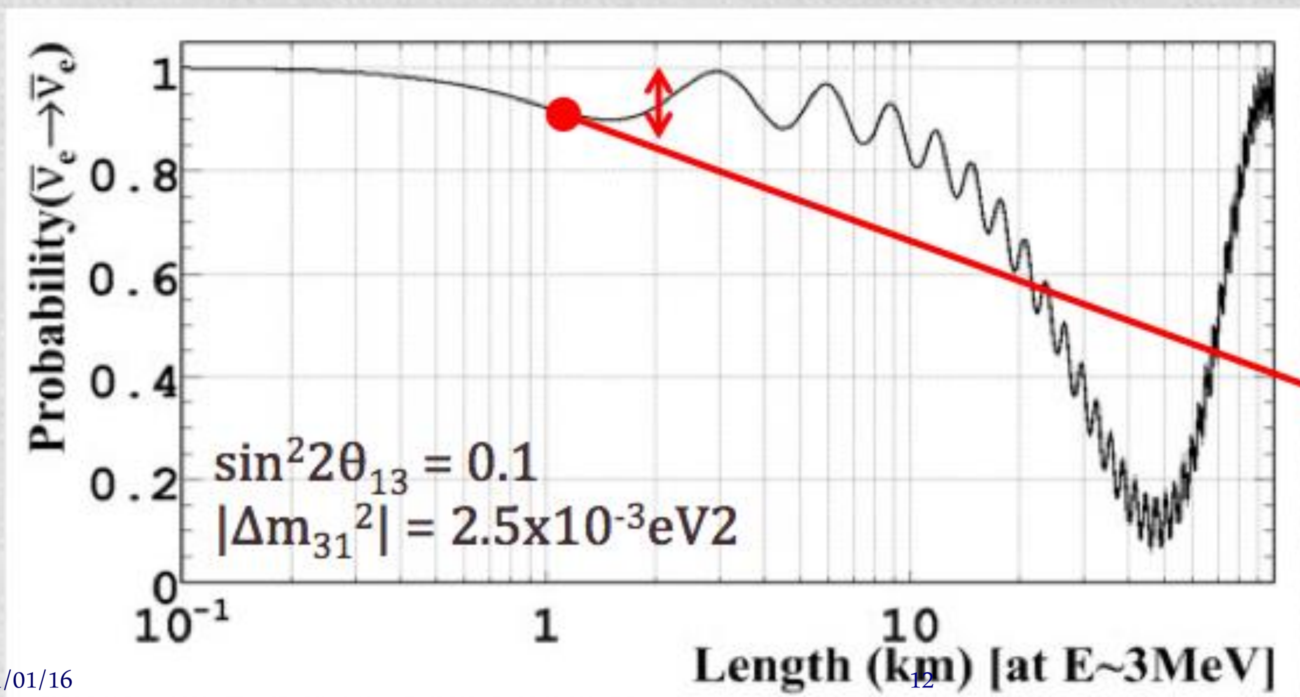
Time interval:
$\Delta t \sim 30\mu sec$

θ_{13} measurement with reactor neutrinos

- Reactor is a free and rich electron antineutrino source
- Direct measurement of θ_{13} with no parameter degeneracy
  - Reactor neutrino survival probability

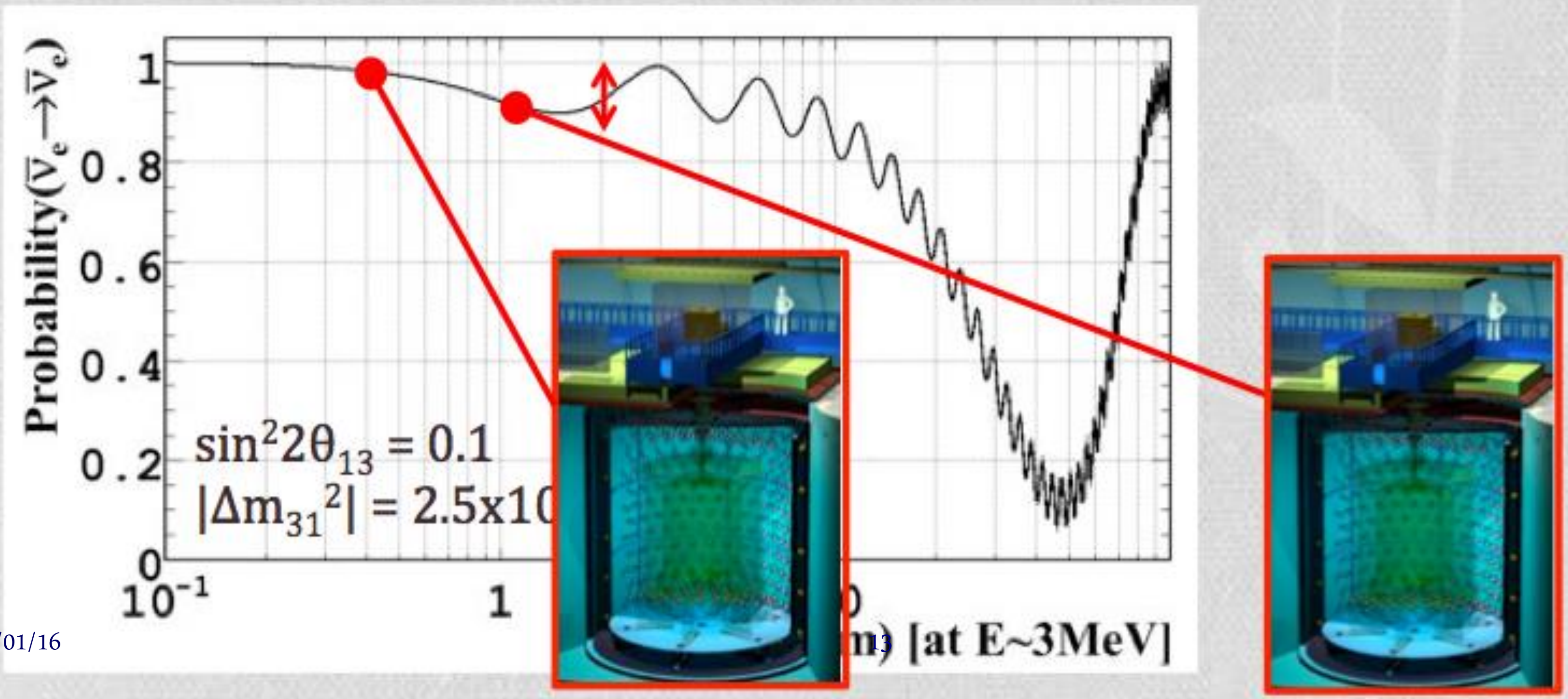
$$P\left[\overline{\nu_e} \rightarrow \overline{\nu_e}\right] \cong 1 - \boxed{\sin^2 2\theta_{13}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \quad \cdots$$

Simple 2 flavor oscillation formula is valid at L~1km with no matter effect



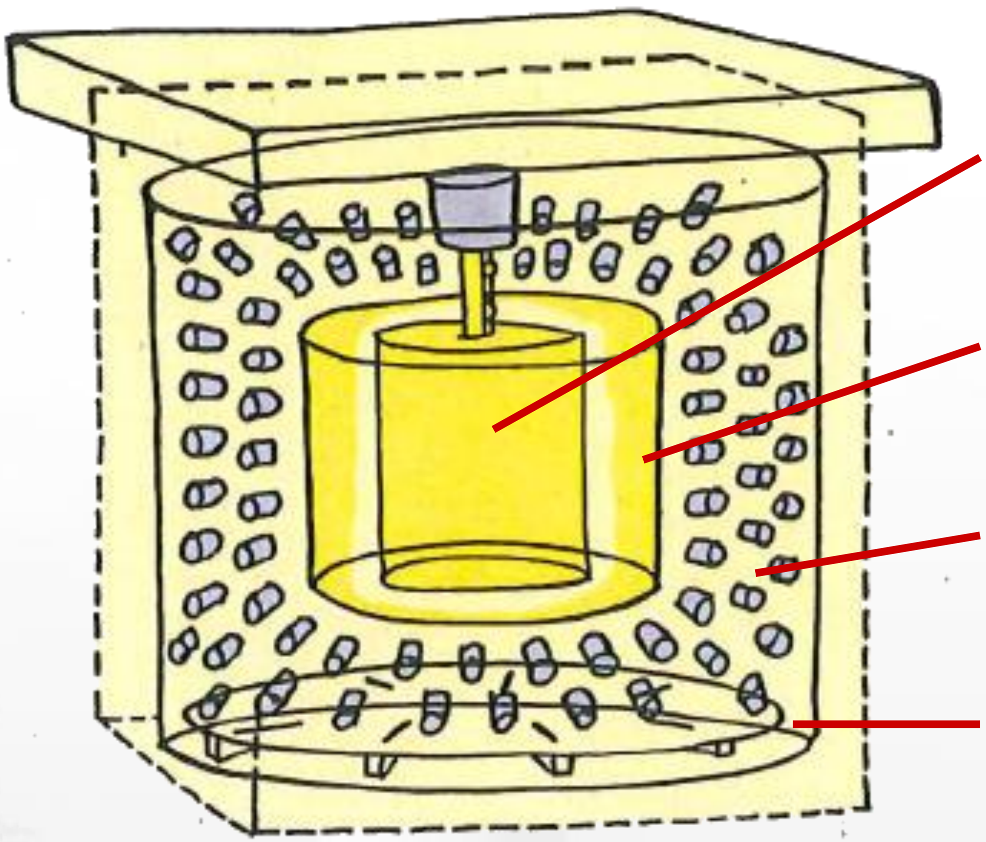
θ_{13} measurement with reactor neutrinos

- Reactor is a free and rich electron antineutrino source
- Direct measurement of θ_{13} with no parameter degeneracy
- Background is strongly suppressed by delayed coincidence
- Flux expectation within 2% uncertainties
- Systematic uncertainties are further reduced (<1%) using two detectors at different baselines



Generic Detector Design

„Standard“ multi-volume organic liquid scintillators detector design



Spirou #3849, 2012

Outer Veto

- Plastic scintillator for muon detection + tracking

Neutrino Target

- Gd-loaded LS for neutrino detection (n-Gd)

Gamma Catcher

- Unloaded LS for γ containment (E-scale)

Buffer Volume

- Mineral oil to shield inner volumes; PMTs

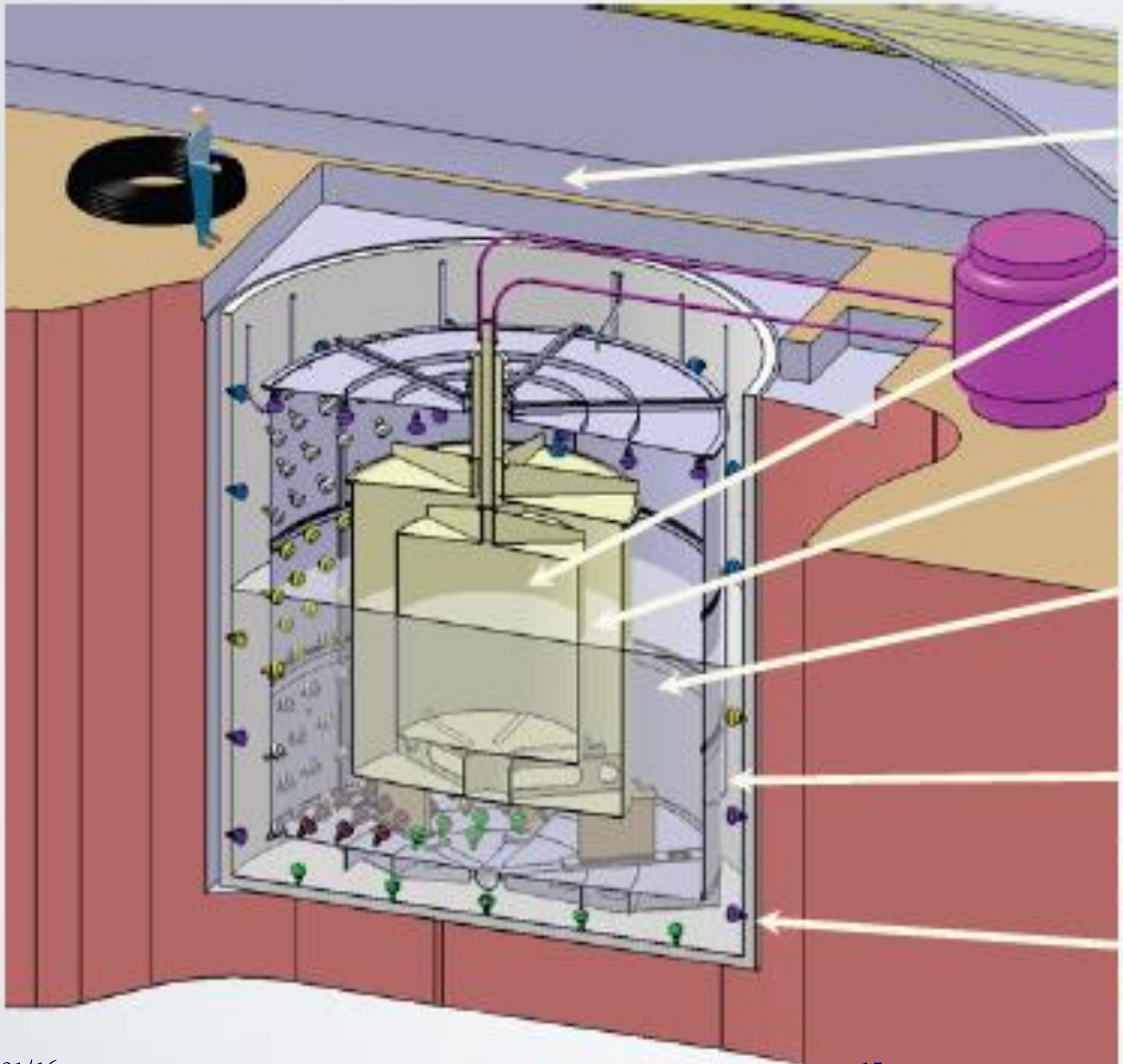
Inner Veto

- Rejection of muons and external radioactivity

Passive Shielding

- Overburden + shielding

Detector Design



Outer Veto: plastic scintillator strips

ν-Target: 10.3 m³ scintillator doped with 0,1g/l of Gd compound in an acrylic vessel (8 mm)

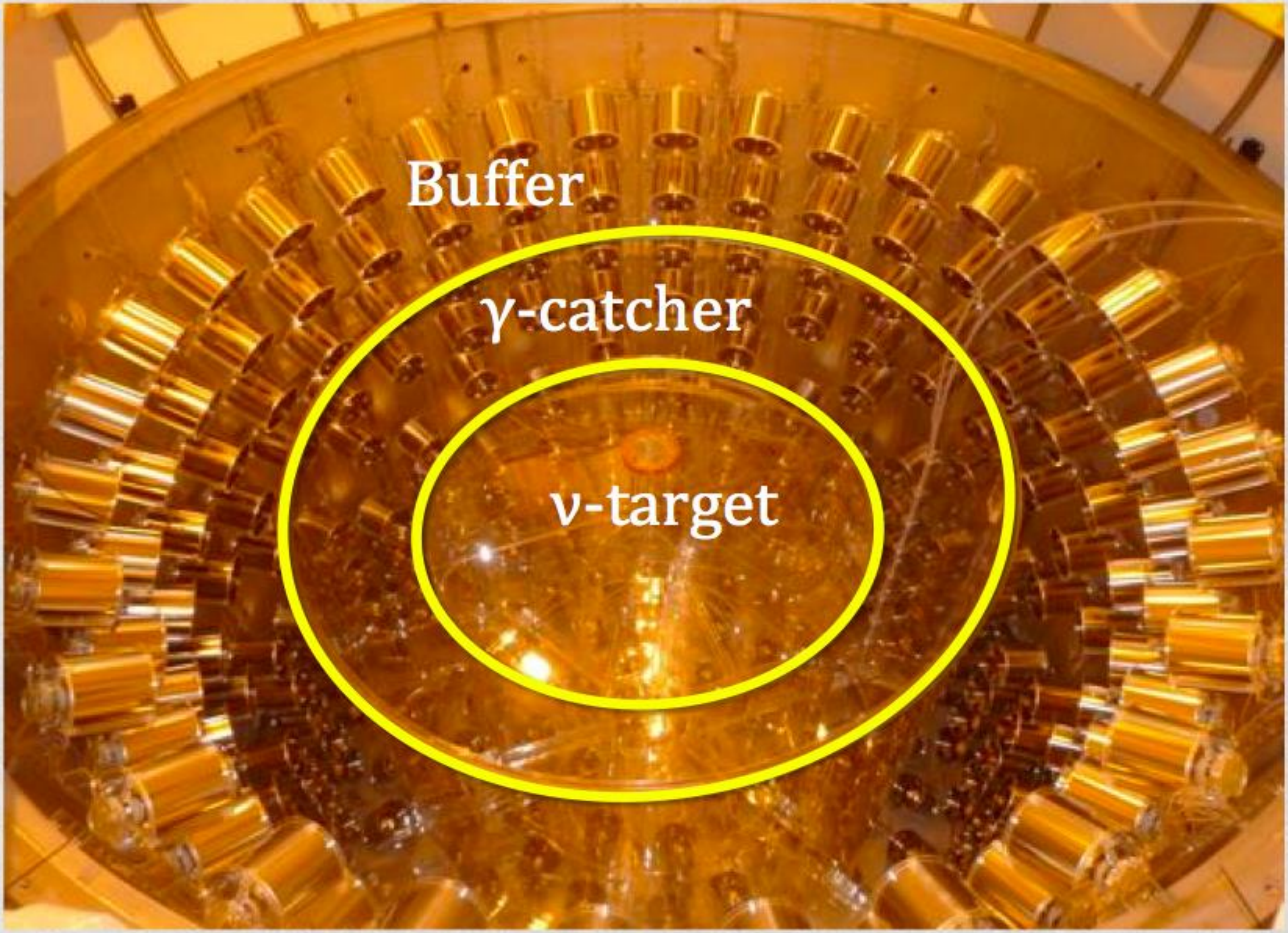
γ-Catcher: 22.3 m³ scintillator in an acrylic vessel (12 mm)

Buffer: 110 m³ of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs (10 inches)

Inner Veto: 90m³ of scintillator in a steel vessel (10 mm) equipped with 78 PMTs (8 inches)

Shielding: about 250t steel shielding (150 mm)

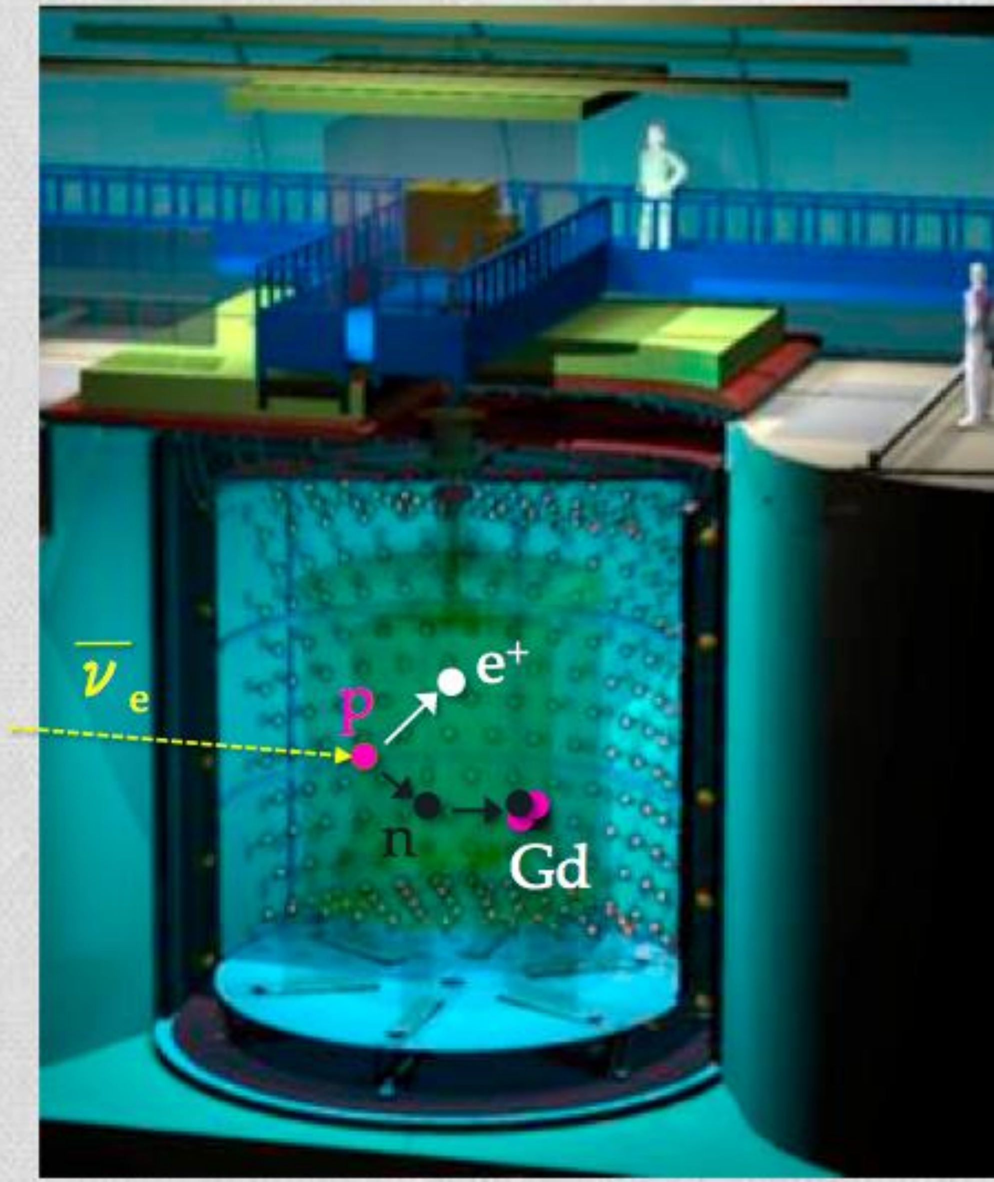
Double Chooz detector



Neutrino selection

- **Muon veto**
  - No coincidence signal in IV
  - $\Delta t_\mu > 1$ msec
- **Prompt event**
  - 0.7 < Evis < 12.2 MeV
  - PMT light noise cuts
- **Delayed event**
  - 6 < Evis < 12 MeV
  - PMT light noise cuts
- **Delayed coincidence**
  - $2 < \Delta t < 100$ μsec
- **Multiplicity**
  - No extra events around signal

- **Further BG reduction**
  - $\Delta t_\mu > 500$ msec ($E_\mu > 600$MeV)
  - No coincidence signal in OV



Neutrino selection

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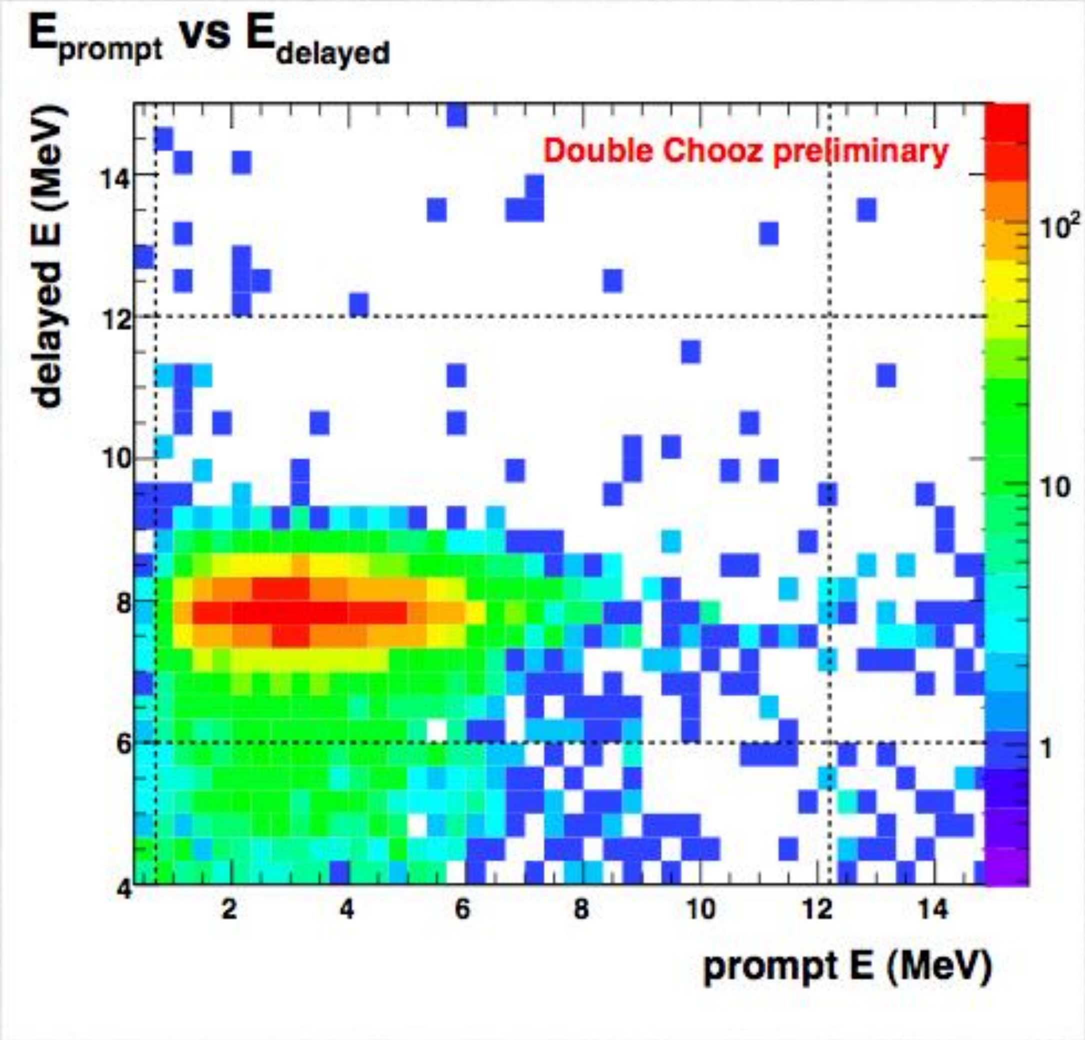
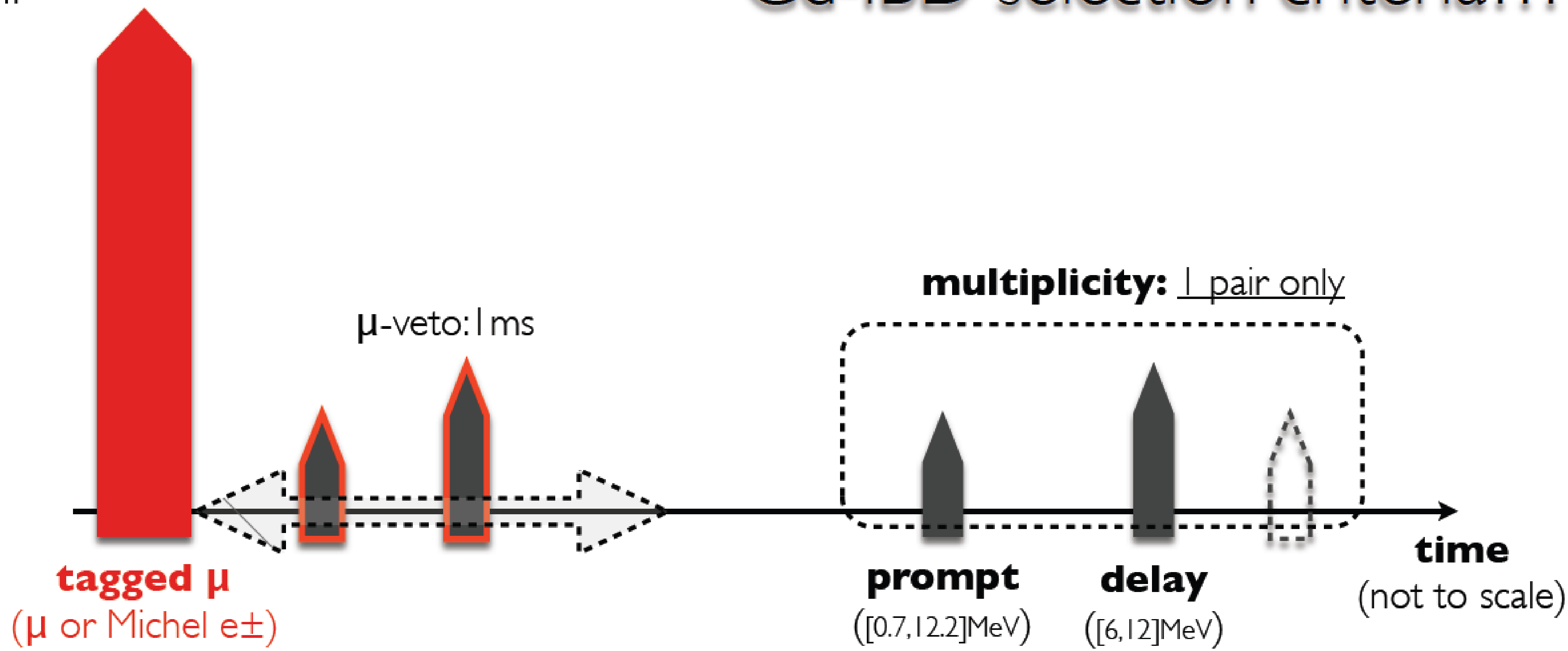
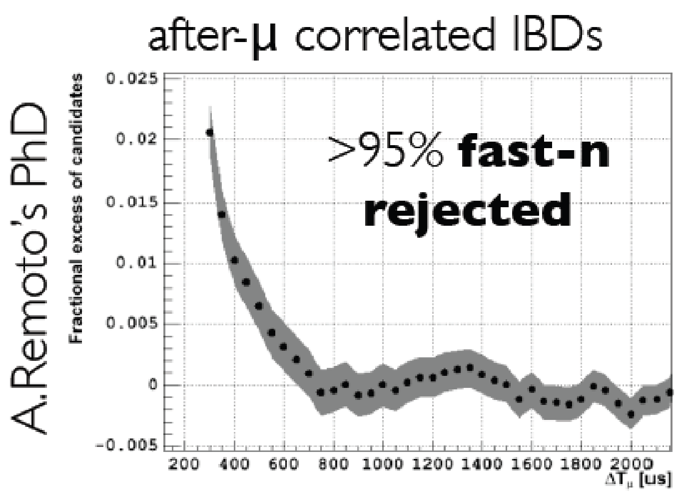
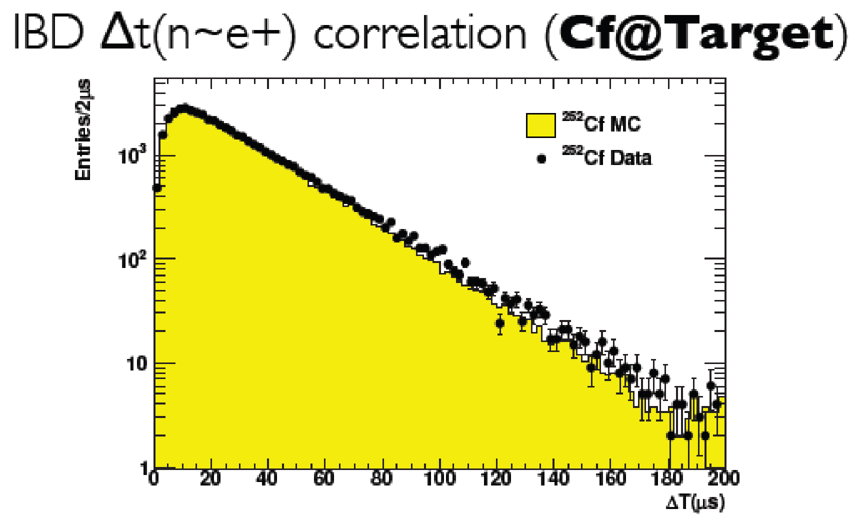


Gd-IBD selection criteria…



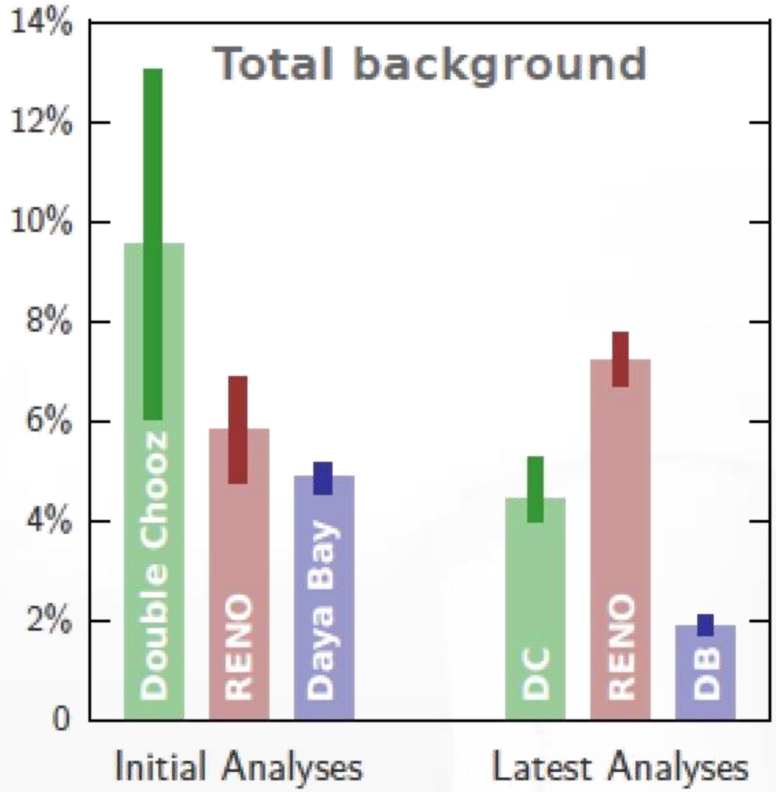




Anatael Cabrera (CNRS-IN2P3 & APC)

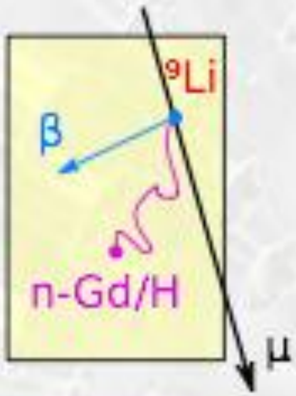
Background Contributions

- **Accidentals:** negligible for n-Gd, still important for n-H
- **Correlated (stopping-μ, fast n):** μ-induced, reduced with increasing overburden
- **Cosmogenic β-n emitters (^{9}Li, ^{8}He):** concern to all experiments
- All experiments significantly improved their BG understanding
- New methods developed to reject BG

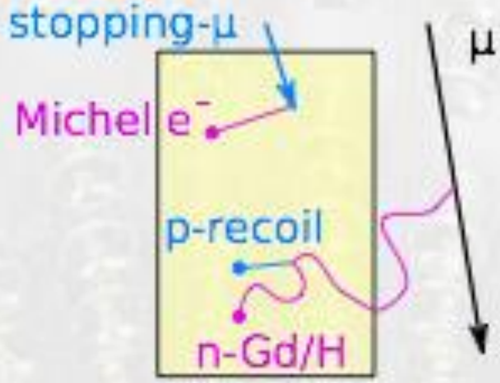


@ Far Detector sites, n-Gd analyses

Background

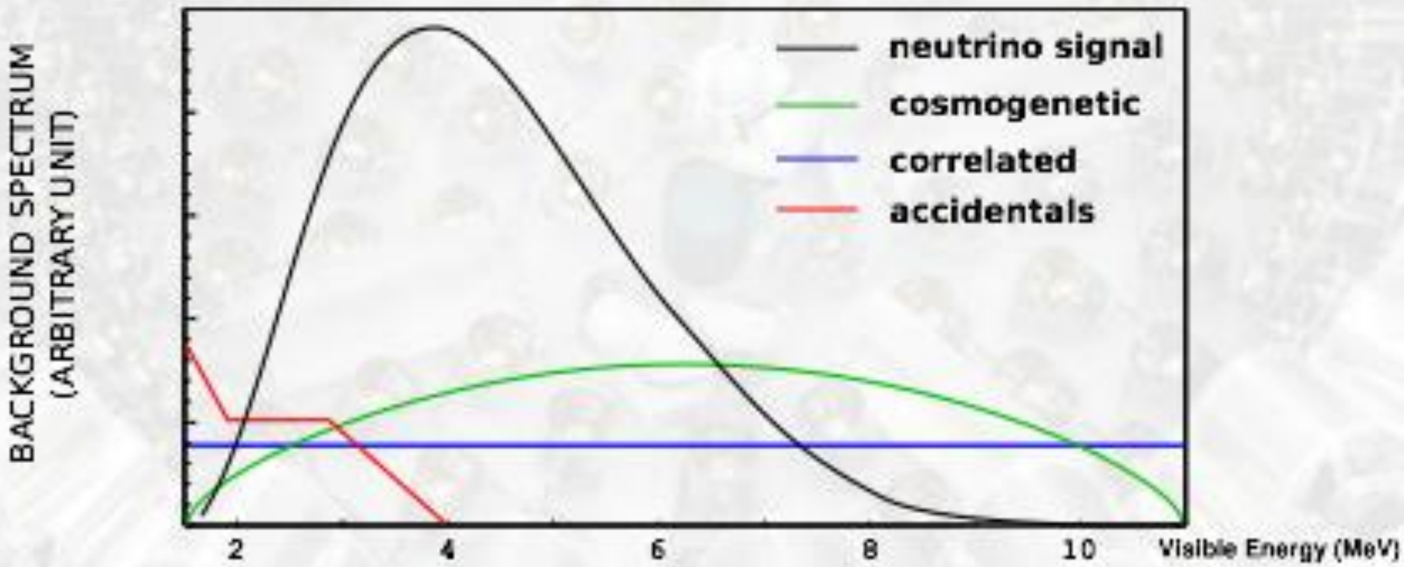


COSMOGENETIC
long lifetime β-n emitter
(mainly ^{9}Li)



CORRELATED
fast neutrons from μ spallation,
stopping-μ (acceptance hole)

ACCIDENTALS
natural radioactivity: ^{40}K, ^{208}Tl
→ dominant in H-analysis



New θ_{13} Results

Daya Bay

Double Chooz

RENO

New Analysis started around 2013

2 new ideas:

Neutron Capture on Hidrogen

- Look for IBD interactions in the Gamma-Catcher volume (22.3 tons), twice the target volume (10.3 tons) looking at neutron capture in hidrogen.

Theta13 via a reactor rate modulation analysis

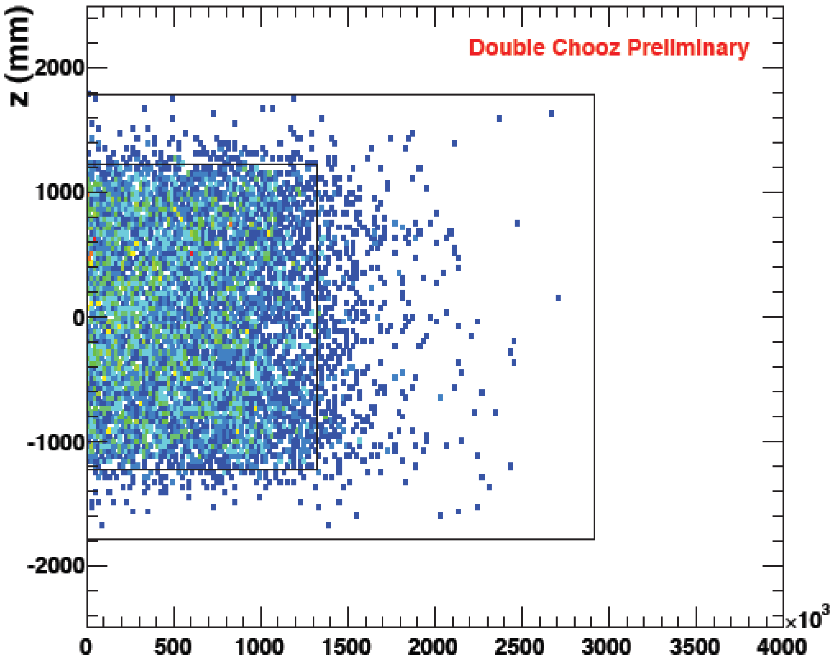
Look for antineutrino disappearance as a function of the reactor power fitting the observed IBD rate as a function of the predicted rate, which depends on the reactor power.

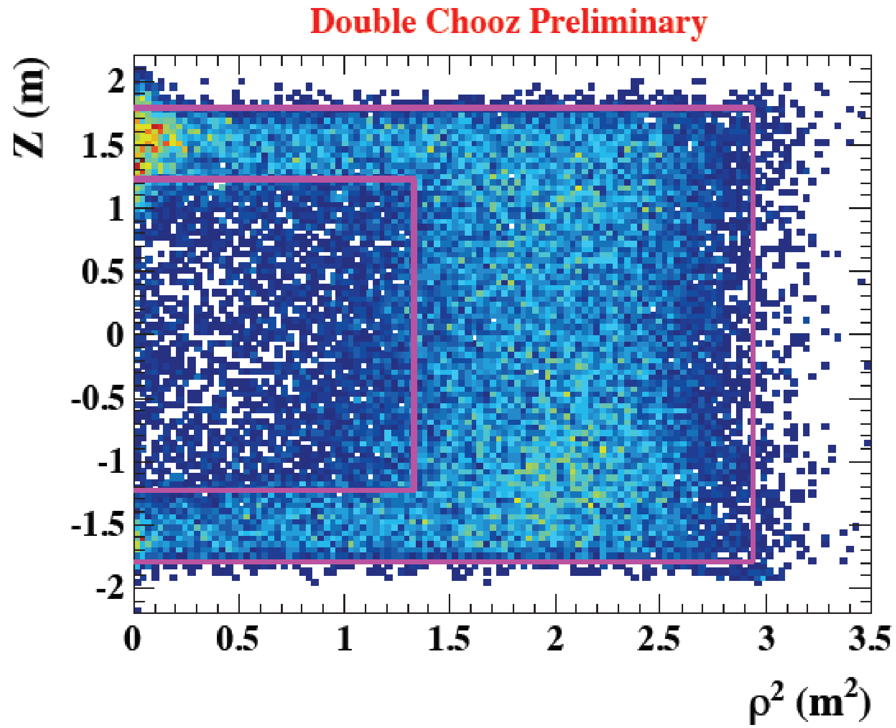
- Good Background constraint thanks to two reactor OFF periods
- Background model independent fit (no constraints on B)

This method is independent of the reactor $\bar{\nu}_e$ flux energy distribution, a fact that became important after the observation of unexpected distortions of the reactor flux at about 6MeV $\bar{\nu}_e$ energy

Neutron capture from IBD in **Gd** or in **H**

IBD features...





Gd-IBD

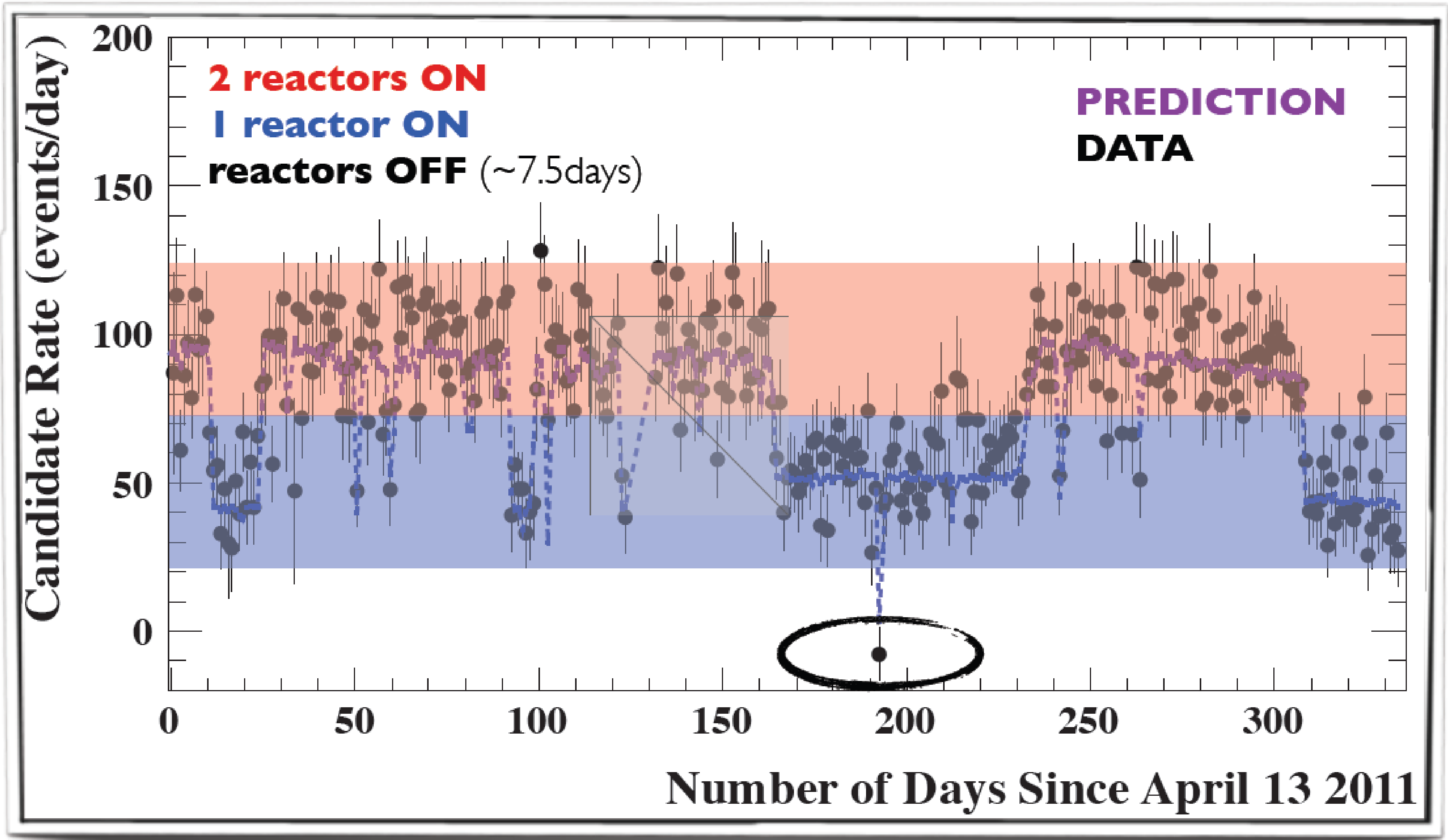
Signal/BG ~19

H-IBD

Signal/BG ~0.95

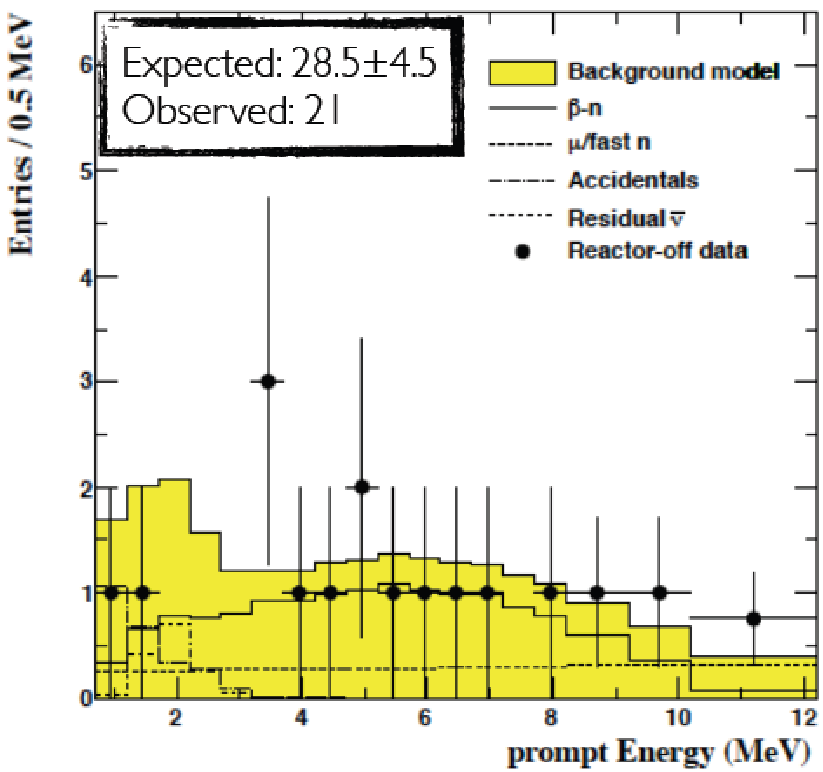
(First n-H paper)

observed vs expected rate…

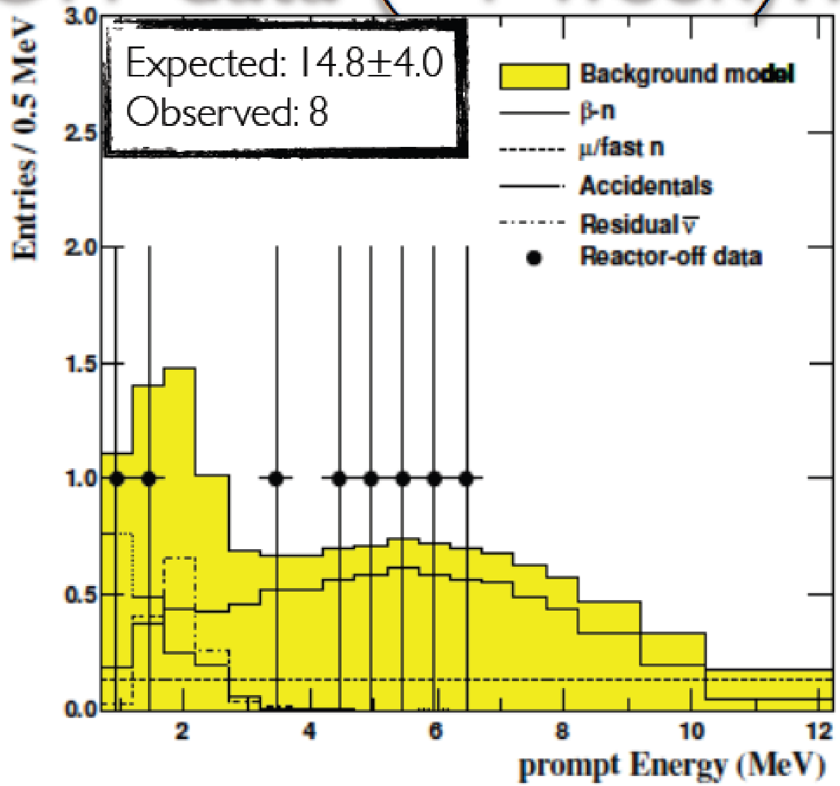


next: plot observed vs expected IBD rate per day

Background reactor OFF data (~1 week)…



Gd Selection (no BG rejection cuts)
(2x more BG)



Gd Selection (standard)
(mainly Spallation-μ veto)

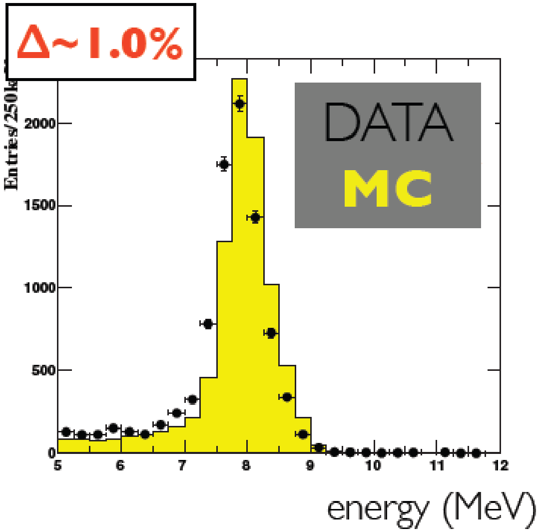
Rate (day^{-1})	β-n	Accidental	μ/fast n	Total Est.	Total Obs.
DCI	2.10±0.57	0.35±0.02	0.93±0.26	3.4±0.6	2.7±0.6
DCII	1.25±0.54	0.26±0.02	0.44±0.20	2.0±0.6	1.0±0.4

two different selections "DC-I" & "DC-II" (BG rate varies ~2x)

BG(observed) < BG(expected)

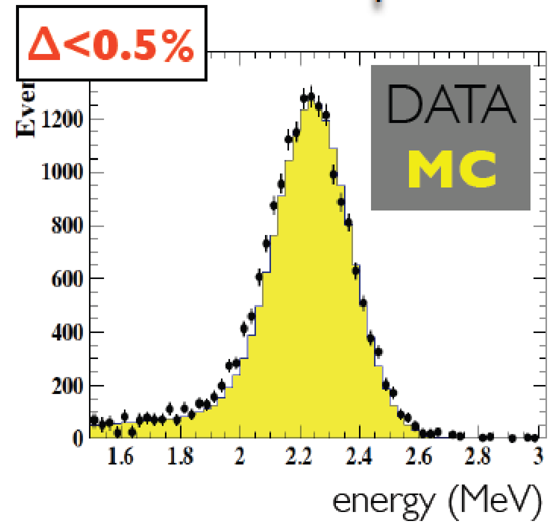
agreement within ~1.5σ (statistics limited)

selections output…



δ(energy):1.13%

~1.0%
(non-linear)



Gd-IBD

Signal/BG ~19

H-IBD

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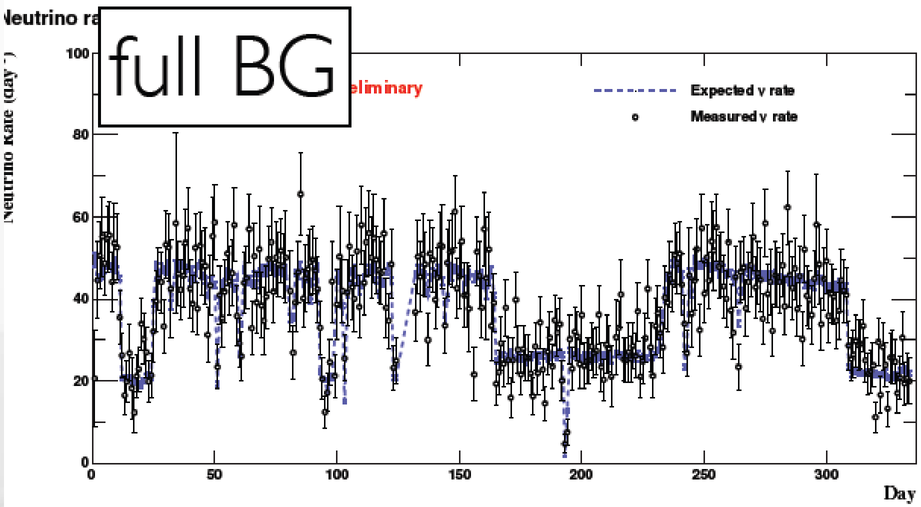
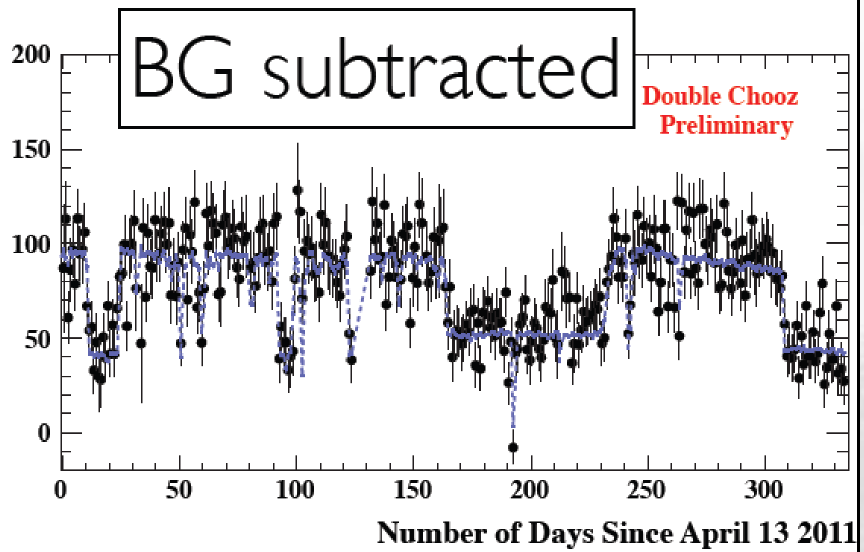
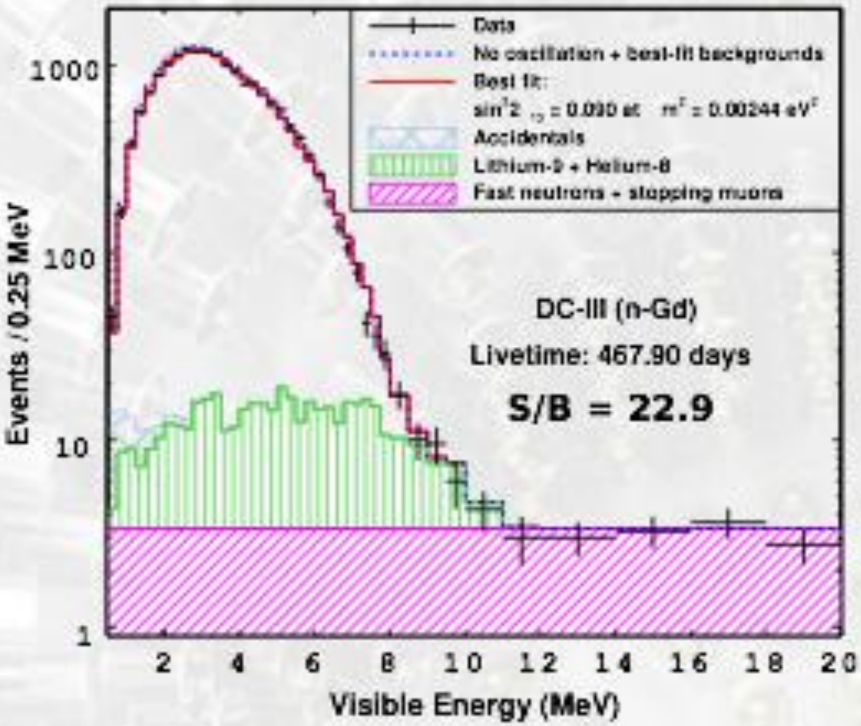
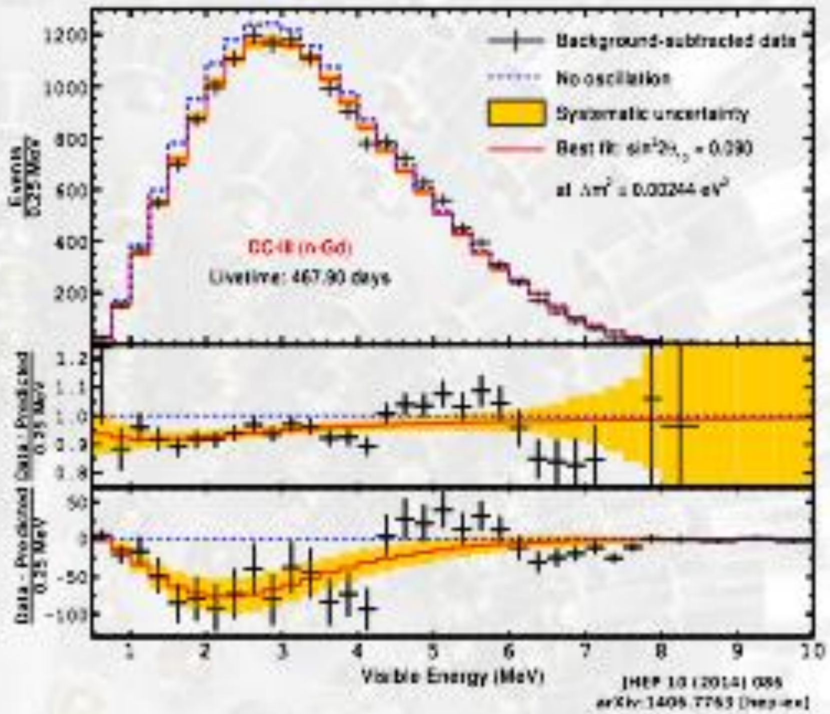




Highlight of last Gd analysis (2014)





- new analysis with opened selection (more signal) + new vetos (less background)
- excellent spectral distortion in 0.5 – 4 MeV region constraining θ_{13} fit

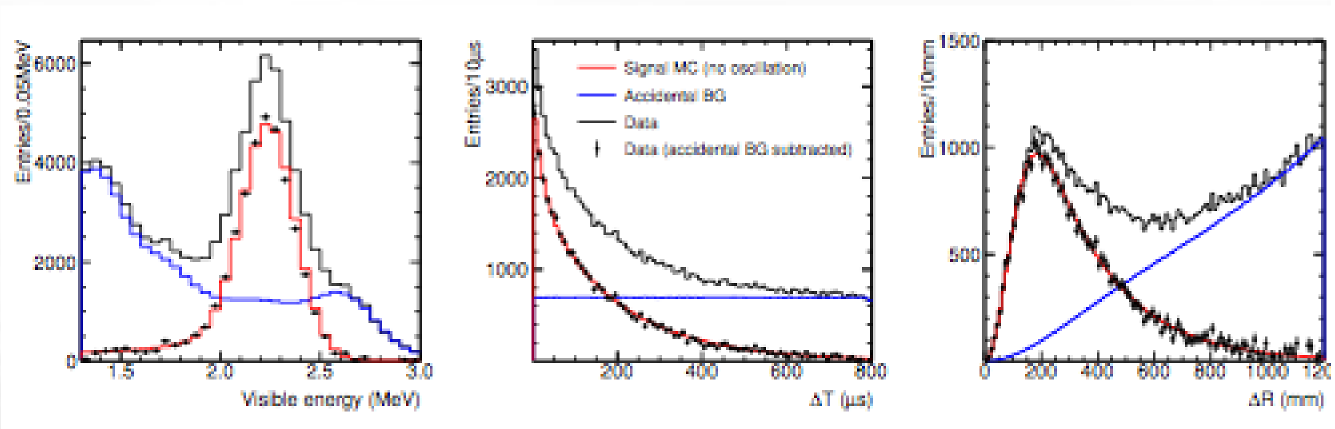
  $\sin^2(2\theta_{13}) = 0.090\ ^{+0.032}_{-0.029}$ previous Gd results: 0.109 ± 0.039
- unexpected E/L structure > 4 MeV (only published experimental observation)

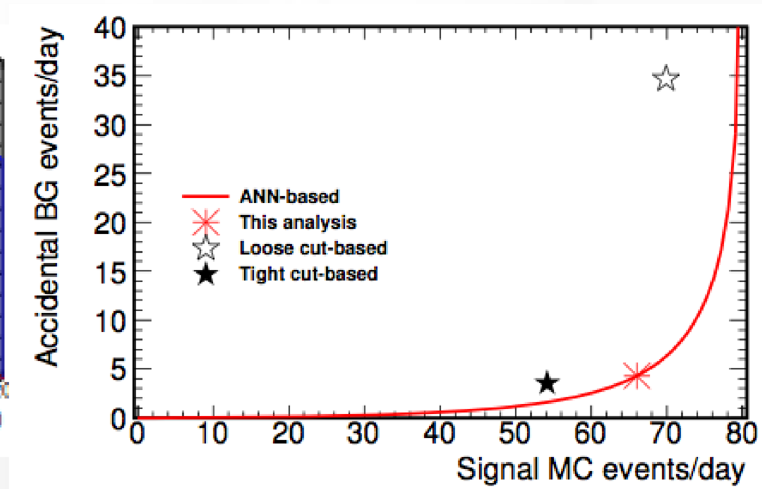
Double Chooz θ_{13} new Results

New n-H analysis

Multiple Variable analysis instead of cut based approach:

- Input: delayed energy, time and space correlation
- Maximise signal/background for unprecedented accidental reduction
- Multivariate BG rejection ANN (artificial neural network based)





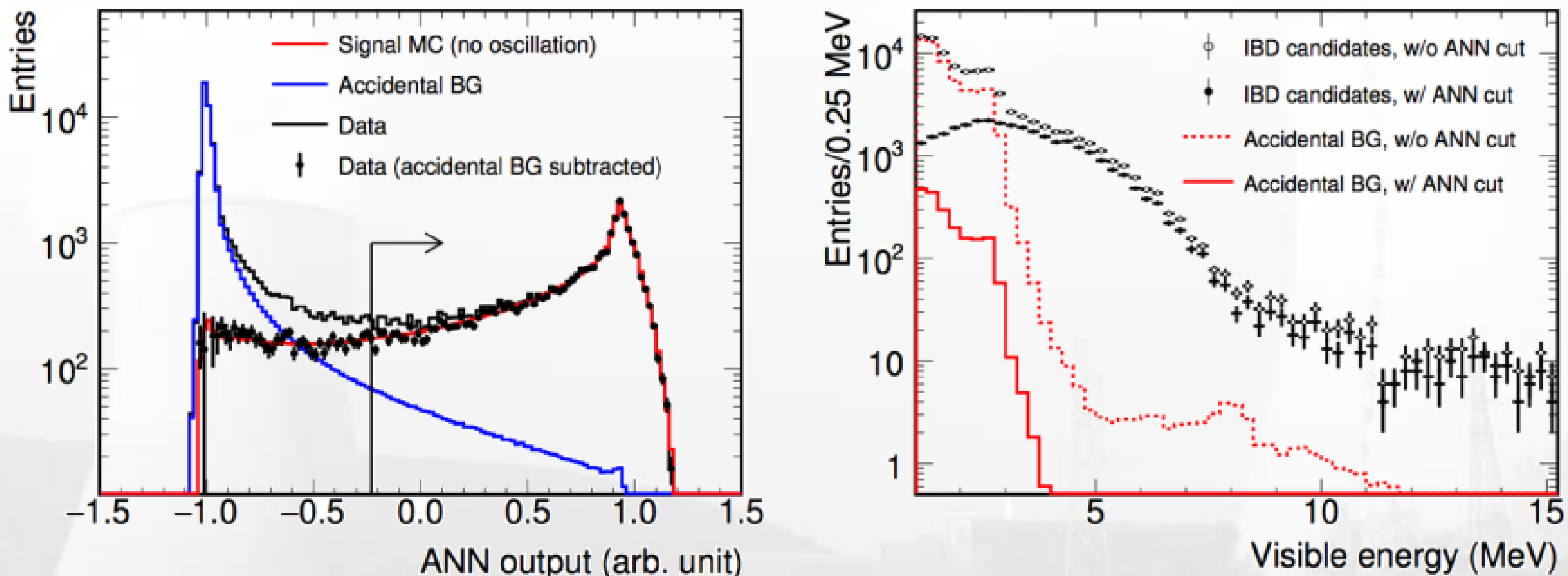
T. Lasserre, TAUP 2015

Double Chooz θ_{13} Results

n-H analysis

Improvements over last nH result:

- Significantly larger data set (~240 days ⟶ ~460 days)
- Multivariate BG rejection ANN (artificial neural network based)
- Multiplicity Pulse Shape veto against FN (Fast Neutrons)



T. Lasserre, TAUP 2015

Double Chooz θ_{13} Results

n-H analysis

Improvements over last nH result:

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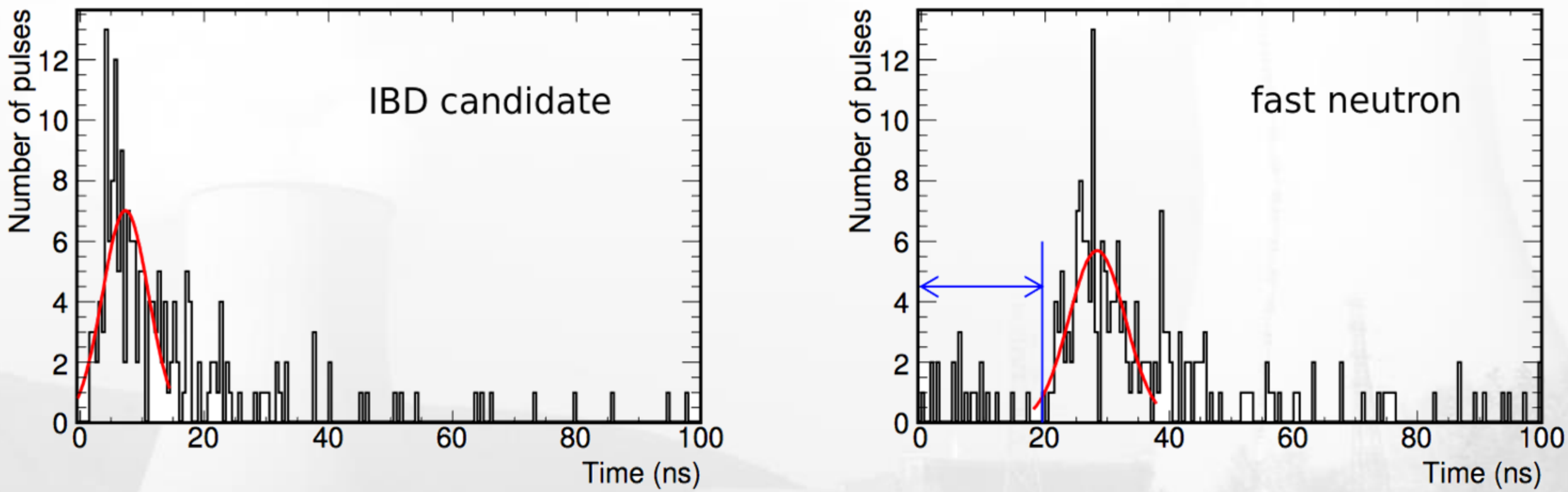
- Multivariate BG rejection (ANN-based)
- Multiplicity Pulse Shape (MPS) veto against Fast Neutrons - FN



T. Lasserre, TAUP 2015

Double Chooz θ_{13} new Results

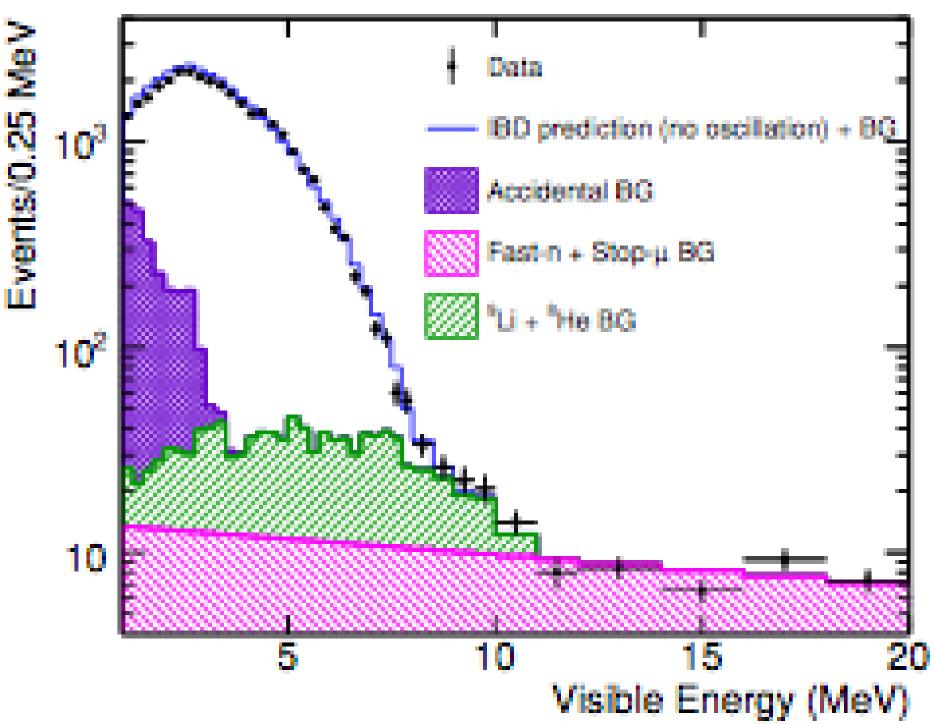
n-HIII analysis (Rate + Shape)

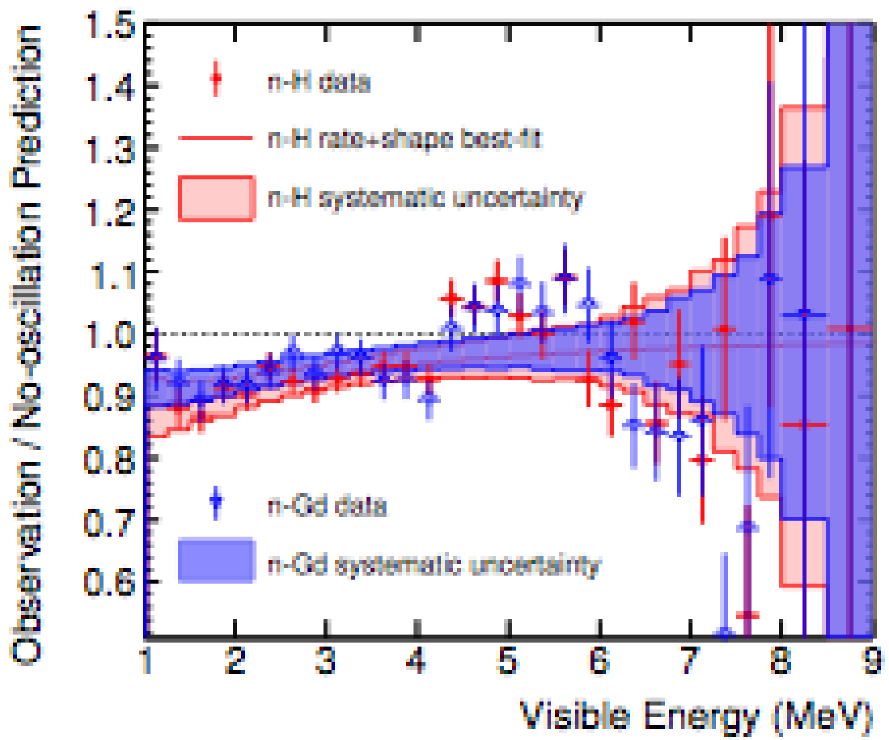
⇒ S/BG ratio improved by factor of ~20!

Rate+shape analysis: $\sin^2 2\theta_{13} = 0.124^{+0.030}_{-0.039}$

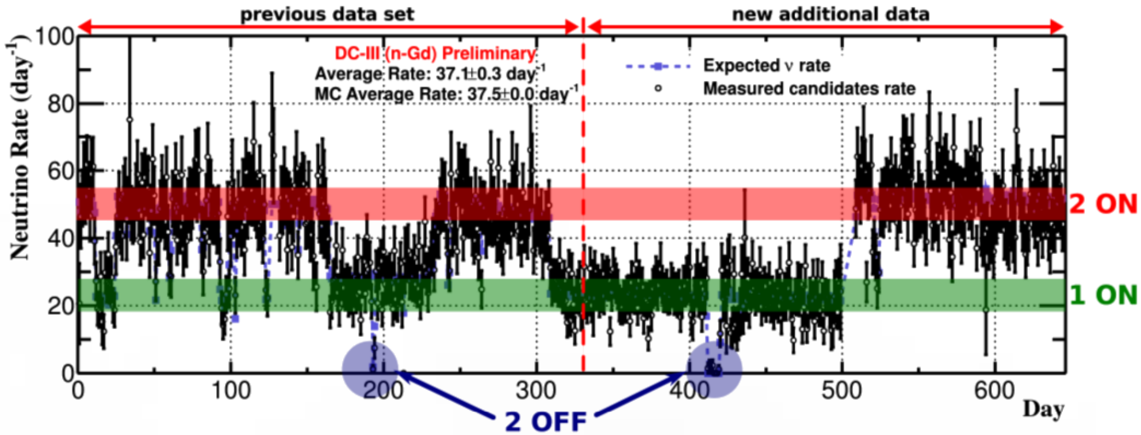
Gd-III: $0.090^{+0.032}_{-0.029}$

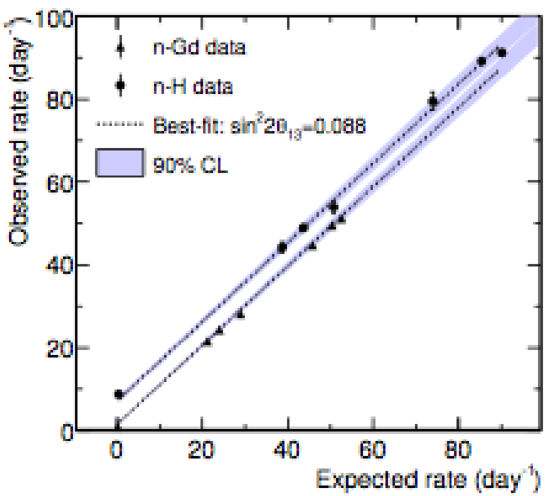
H-II: 0.097 ± 0.048

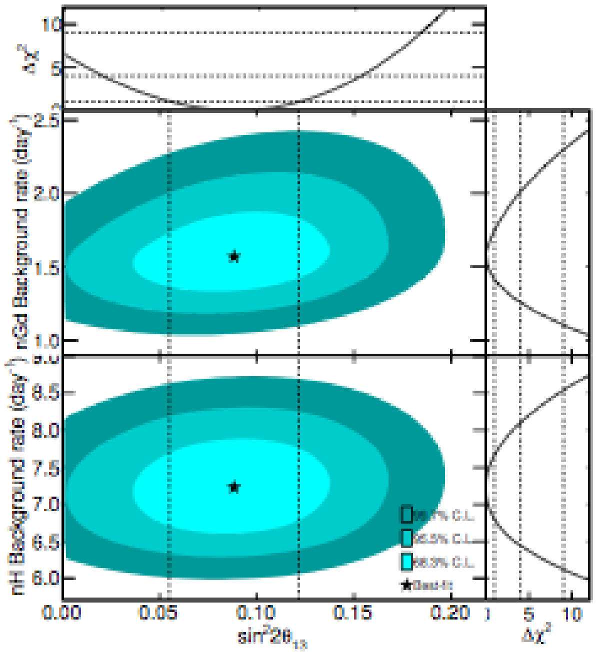




Double Chooz θ_{13} Results







T. Lasserre, TAUP 2015

Reactor-Rate-Modulation

- Compares IBD rates for different reactor powers
- Measurement of θ_{13} and BG rate at the same time
- Independent of neutrino energy distribution
- BG model independent measurement or using BG model to increase precision
- Combined Gd-III + H-III fit:

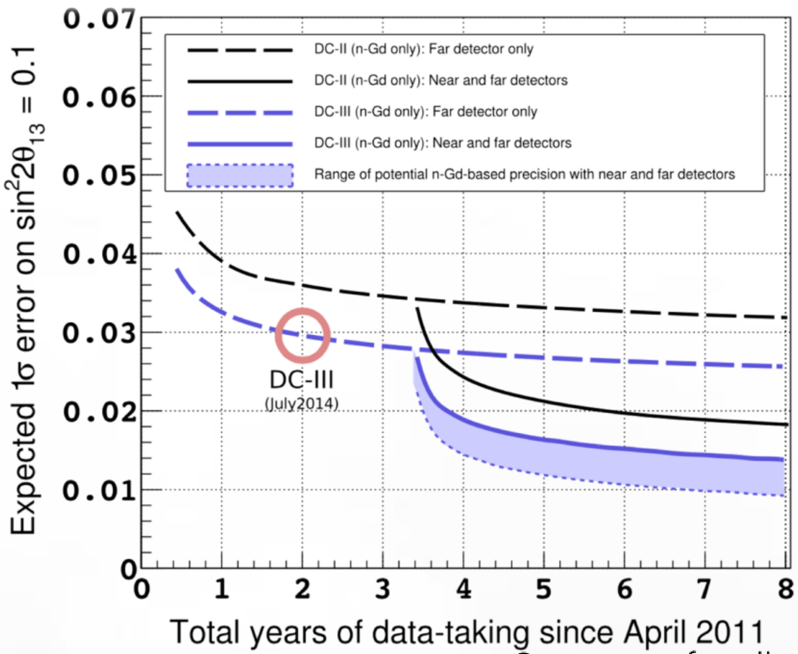
$\sin^2 2\theta_{13} = 0.088 \pm 0.033$

BG rate = $7.27 \pm 0.49\ d^{-1}$

Double Chooz θ_{13} new Results

- **n-H analysis results - Reactor Rate Modulation:**
- Measurement based in 462.72 live days data at FD
- Novel techniques developed to reduce background
- Accidental coincidences supressed by factor > 10
- Improvements demonstrate capacity of precise measurements of reactor antineutrinos without Gadolinium loading.
- Fit to event rate as a function of reactor power (RRM)
- **n-H** analysis result $\sin^2 2\theta_{13} = 0.095^{+0.038}_{-0.039}$ (stat+syst)
- **Reactor Rate Modulation combined fit:**
- **n-H + n-Gd** result $\sin^2 2\theta_{13} = 0.088 \pm 0.33$ (stat+syst)

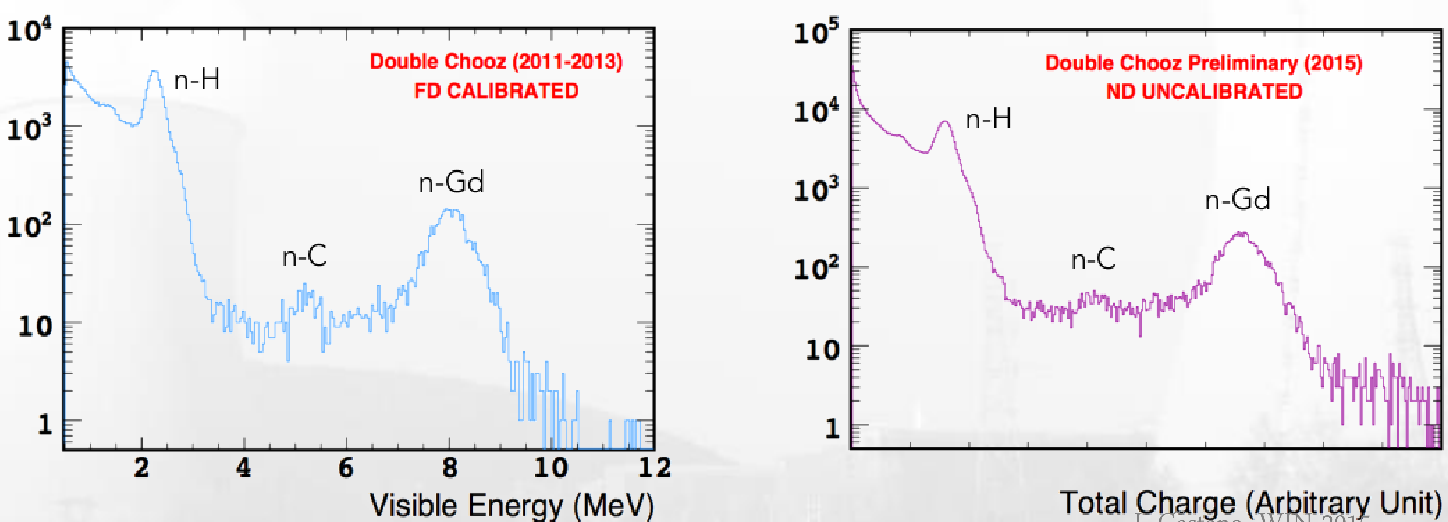
Double Chooz θ_{13} outlook



2-detector phase

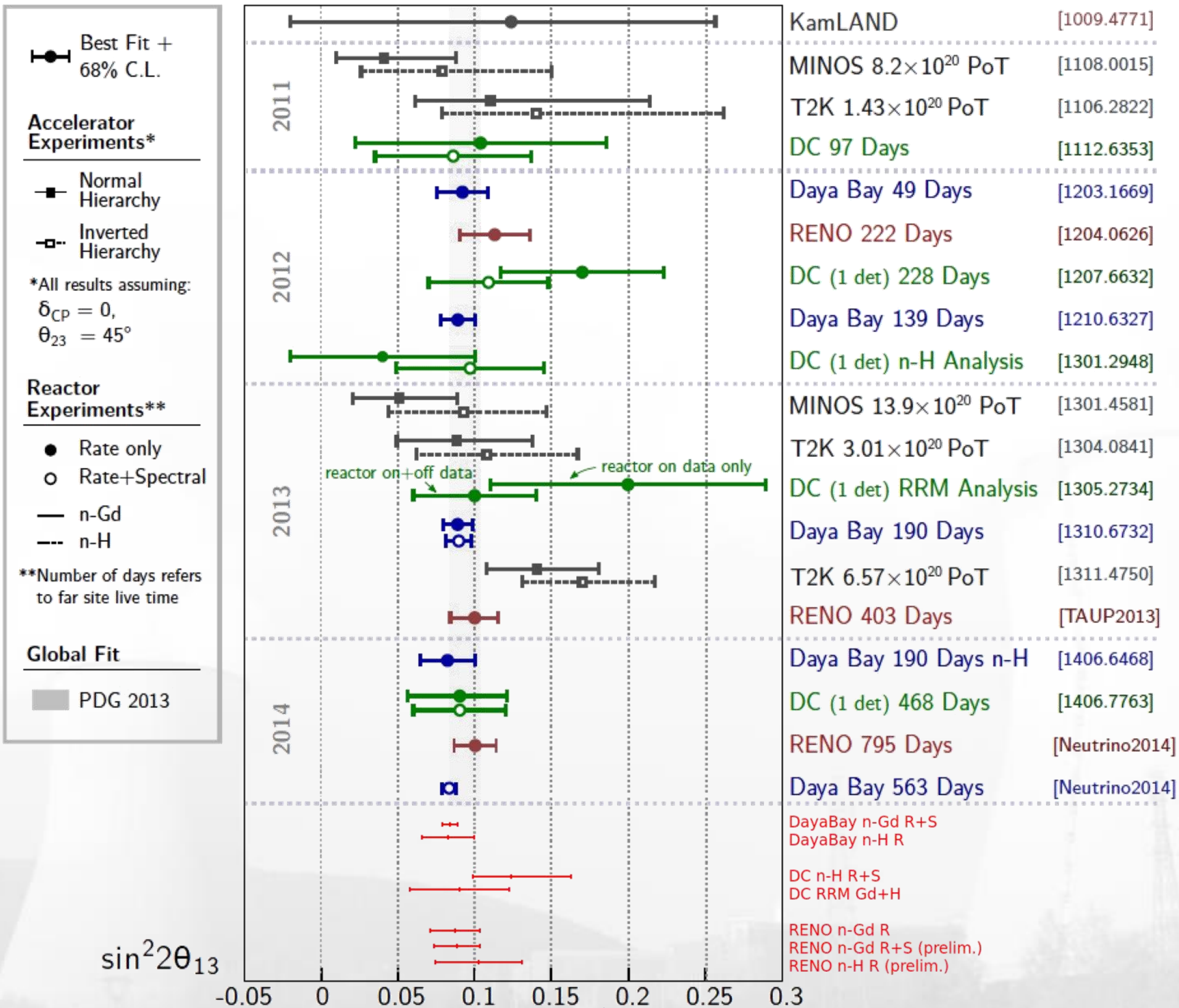
- Near detector completed
- Taking data since January 2015
- Prospect to lower 1σ-uncertainty to below 10% in 3 years.

Spectrum of spallation neutron captures following crossing muons



J. Castano, WIN 2015

θ_{13} Summary



Thank you for your attention!

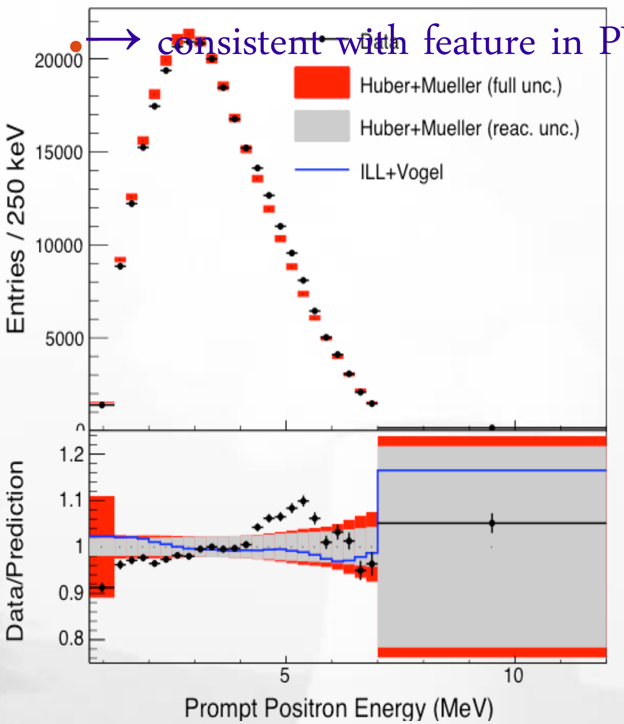
New Results Beyond θ_{13}

Spectral Distortion

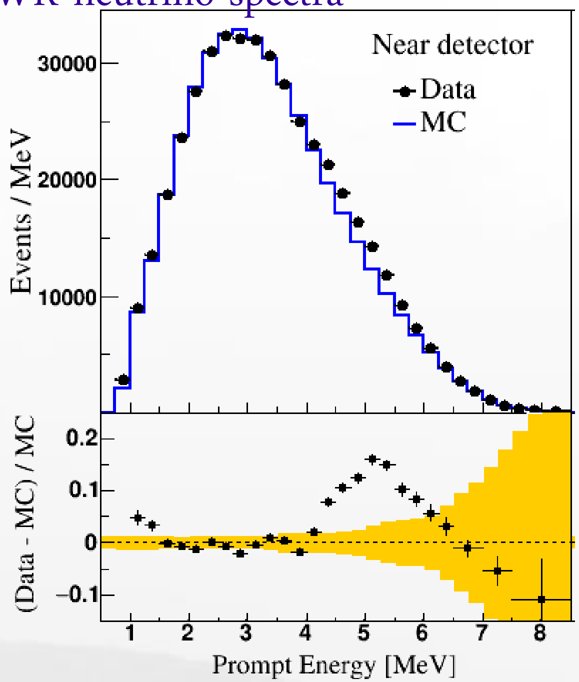
„5 MeV bump“ observed in all three experiments (in ND and FD)

- Events have IBD characteristics
- Correlation with reactor power
- → consistent with feature in PWR neutrino spectra

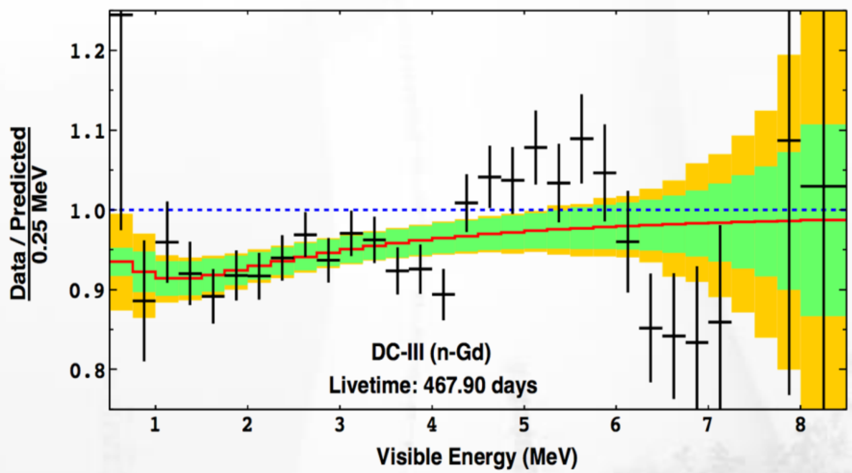
- Appears in Gd and H analyses alike
- Measurement of θ_{13} is not affected!



Daya Bay ND



RENO ND



Double Chooz FD

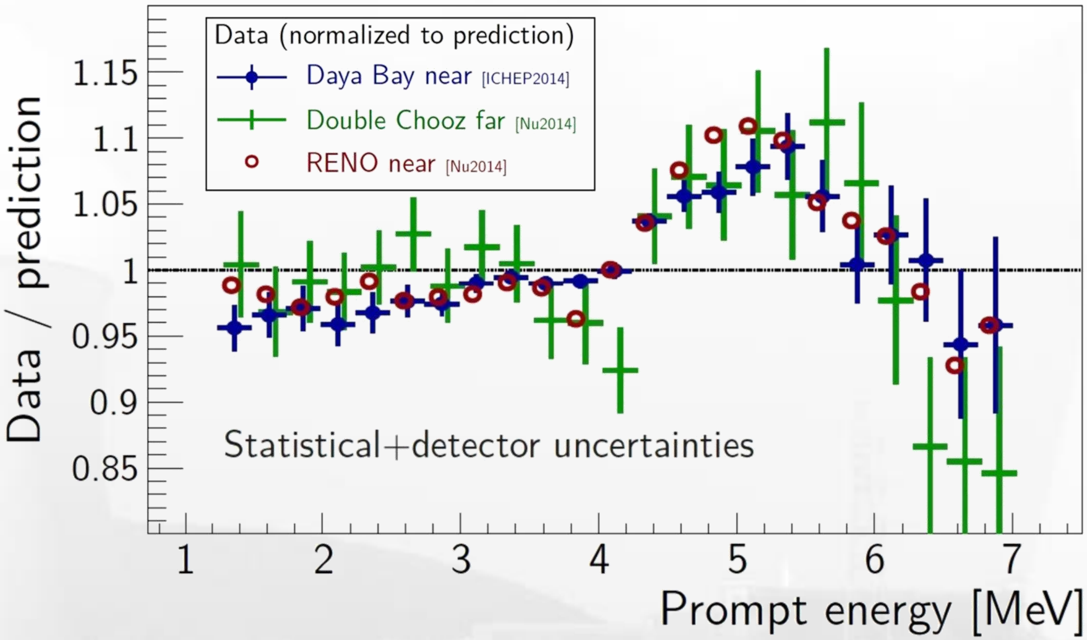
Spectral Distortion

Possible SM explanations are available [e.g. PR D 92, 033015 (2015)]

- Non-fission contributions
- Forbidden transitions
- U-238 fission daughters

- PWR neutron spectrum
- Possible error in original measurement at ILL

Need for new reactor neutrino experiments with different reactor types



Conclusions

Improved results for θ_{13} (all compatible)

- Daya Bay: $\sin^2 2\theta_{13} = 0.084 \pm 0.005$ (n-Gd R+S), also $|\Delta m^2_{ee}| = (2.42 \pm 0.11)\cdot 10^{-3}$ eV²
- Double Chooz: $\sin^2 2\theta_{13} = 0.088 \pm 0.033$ (RRM Gd+H)
- RENO: $\sin^2 2\theta_{13} = 0.087 \pm 0.016$ (n-Gd R)

Further improvements expected

- General improvements in data analysis and understanding of BG
- DC will start 2-detector phase
- RENO is preparing R+S analysis and n-H analysis

Physics beyond θ_{13}

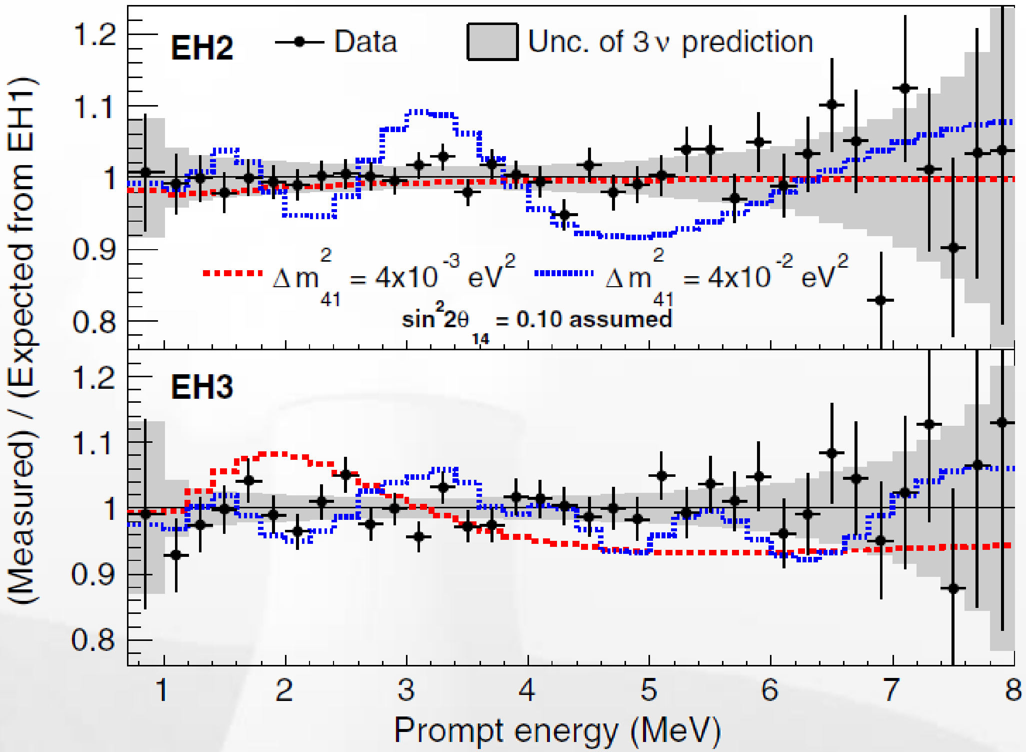
- Discovery of spectral distortion by all three experiments
- No sterile neutrinos found in $0.001 \text{ eV}^2 < \Delta m^2_{41} < 0.1 \text{ eV}^2$ by DB
- Broad physics program possible

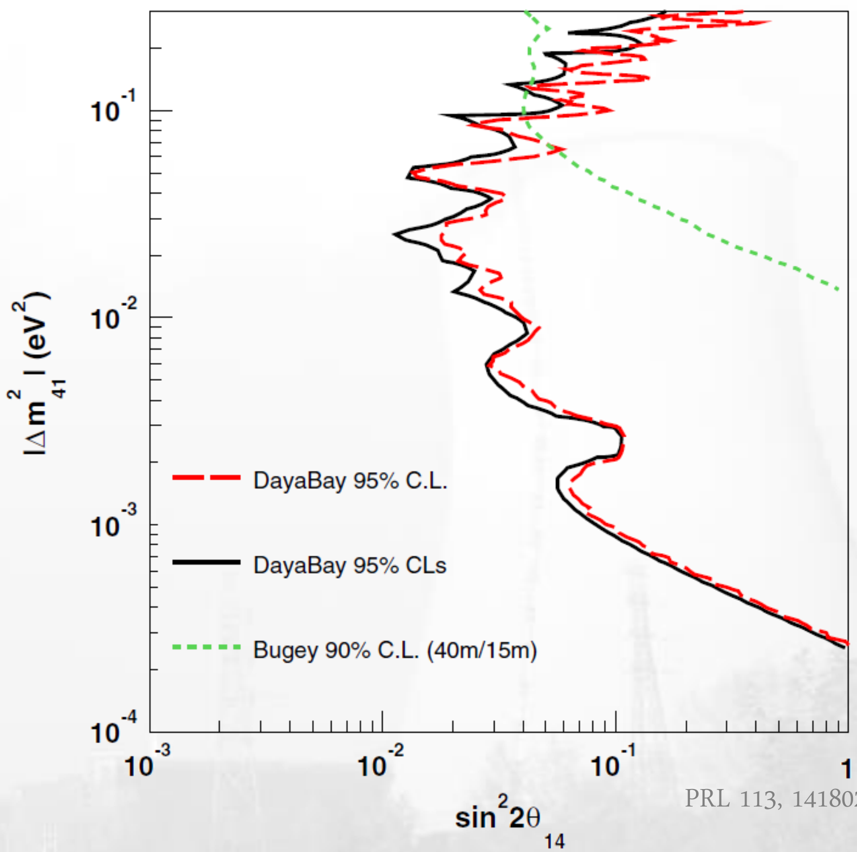
Sterile Neutrino Results

⇒ Talk by C. Giunti later this session

Search for light sterile νs performed by DB

- Relative measurements at various baselines (350, 500, 1600m)
- No signal observed, consistent with standard 3 oscillation
- Most stringent limit for $0.001\ eV^2 < \Delta m^2_{41} < 0.1\ eV^2$





PRL 113, 141802 (2014)

Further Studies

Other physics results and development of analysis methods
of general interest

- Background studies [1210.3748]
- Test of Lorentz violation [1209.5810]
- o-Positronium detection [1407.6913]
- Muon reconstruction [1405.6227, 1407.0275]
- Supernova neutrinos ?
- Nonstandard interactions
- Neutrino directionality
- Pulse shape analyses
- ...

Achievements of Double Chooz

- **Pioneered reactor experiments (improvements from CHOOZ)**
  - Experimental concept to use two detectors
  - New detector structure
    - 4 layers detector structure becomes standard of forthcoming reactor experiments
    - Low background measurement (S/N ~ 20) proved by reactor OFF
    - Stable Gd loaded LS developed
- **Announced results in November 2011**
  - First θ_{13} measurement by reactor experiment since CHOOZ
  - Indication of non-zero θ_{13} at 94% C.L. and hint for a large value of θ_{13}
  - Evidence for non-zero θ_{13} at 3σ by combination with long baseline experiments (MINOS & T2K)

$$R^{obs} = \left(1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right)\right) R^{IBD} + B$$


THANK YOU
Neutrino Oscillations:
Unveiling the last mixing angle
João dos Anjos
UTFSM, Valparaiso, Chile
11 January 2016