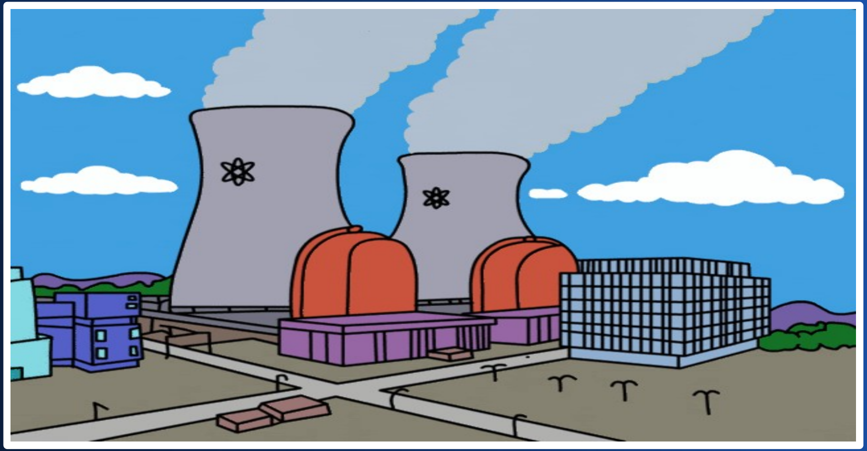
Reactor neutrinos

θ_{13}

The ultimate measurement?



Pau Novella
CNRS/APC

Overview

- Neutrino oscillations and the last mixing angle
- Reactor neutrinos as a probe to θ_{13}
- Unrevealing θ_{13} with reactor neutrino data
- Experimental results: critical view
- Towards the ultimate value of θ_{13}

Neutrino Oscillations and the last mixing angle

In the beginning...

ν?

- 1930 Pauli postulates ν
- 1956: reactor neutrinos detected
- 1990's: neutrino oscillations...

Physics Beyond the Standard Model

Today...

Reactors play a major role again!

Neutrino mixing

ν_e

ν_μ

ν_τ

$$\nu_{\alpha L} = \sum_{k=1}^{n} U_{\alpha k} \nu_{kL}$$

m_1

m_2

m_3

Oscillation physics

$\beta\beta0\nu$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric sector

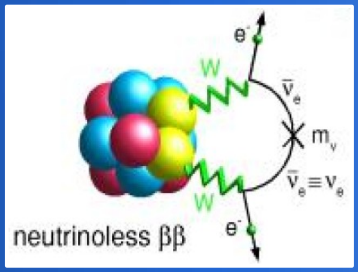
θ_{23}

interference sector

θ_{13}, δ

Solar sector

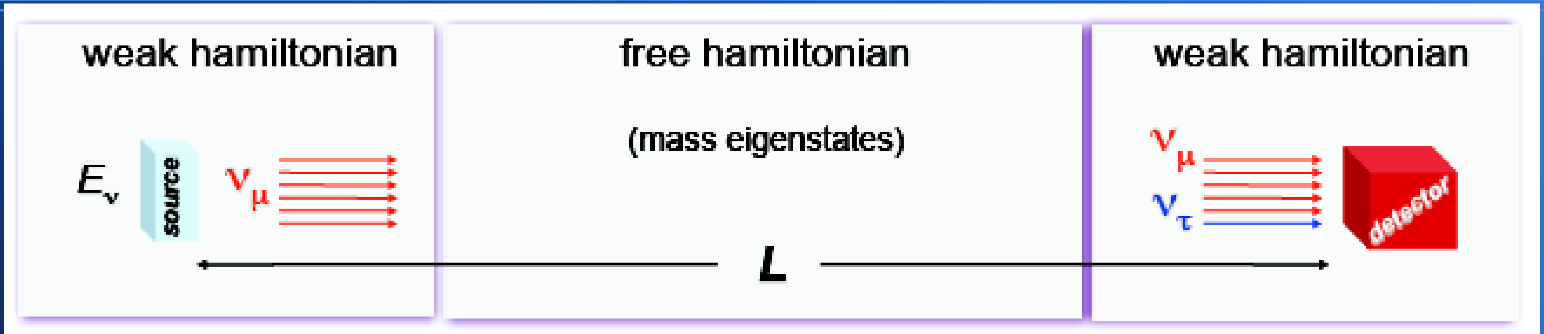
θ_{12}



α_1, α_2

Neutrino Oscillations

- If neutrinos are massive and have different masses...

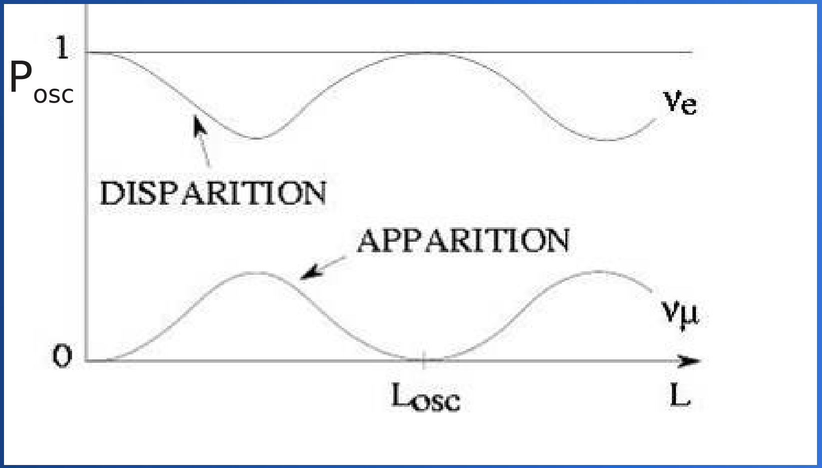


Oscillation parameters: $(\theta_{12}, \theta_{13}, \theta_{23})$, $(\Delta m^2_{21}, \Delta m^2_{31})$, δ

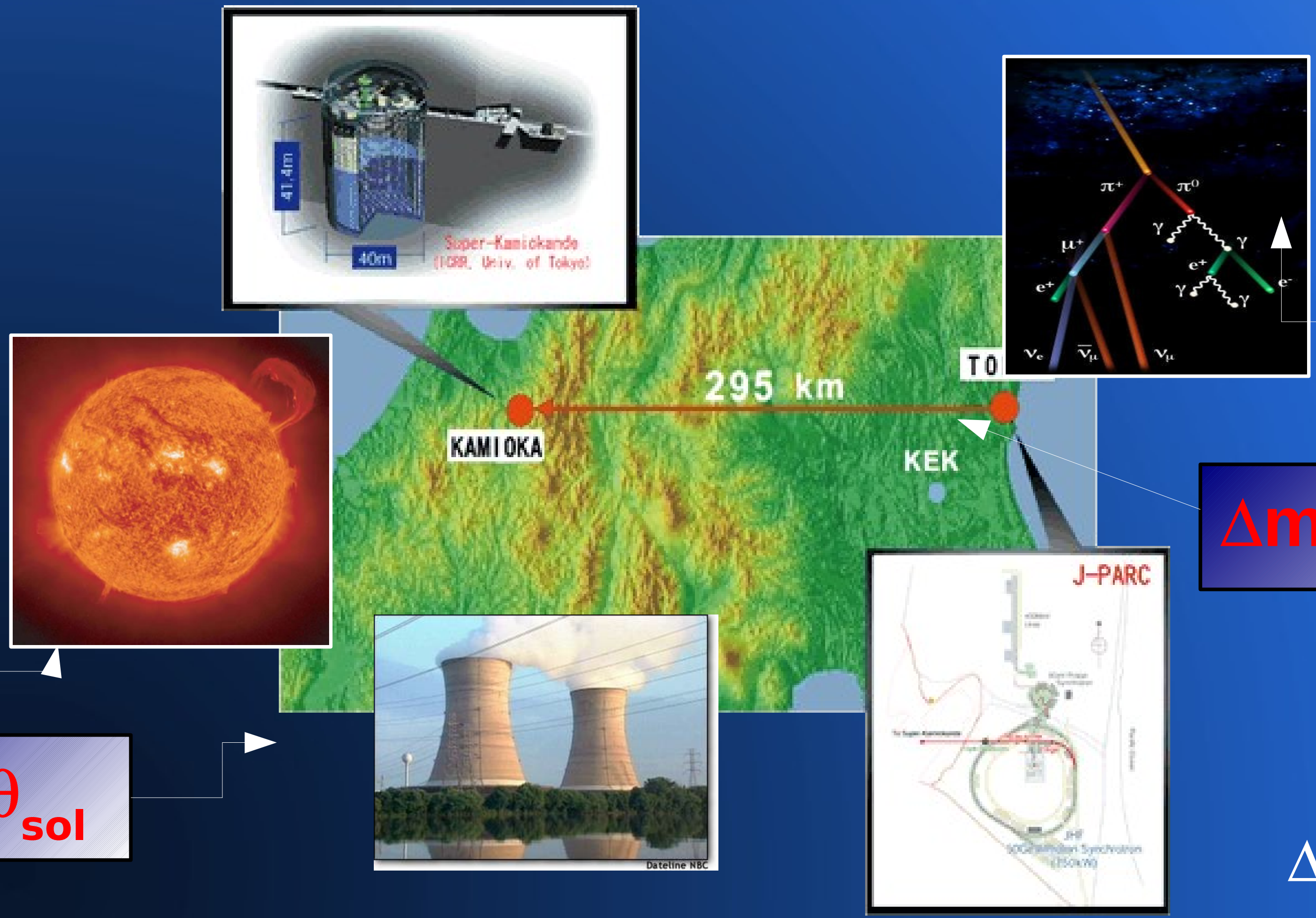
If θ_{13} small and $\Delta m^2_{21} << \Delta m^2_{32}$:

amplitude | frequency

$$P_{\alpha\beta} = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 L}{4 \cdot E_\nu}\right)$$



Neutrino Sources

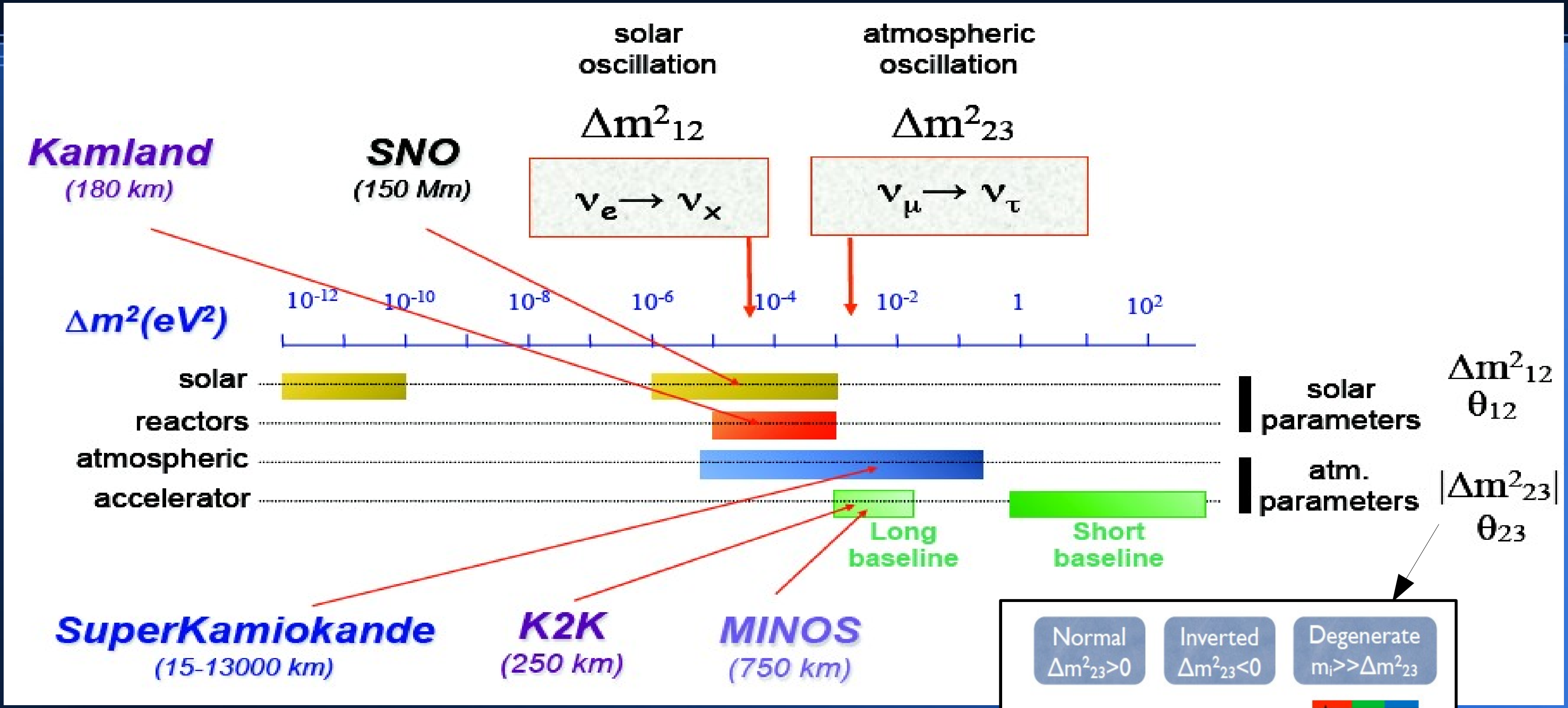


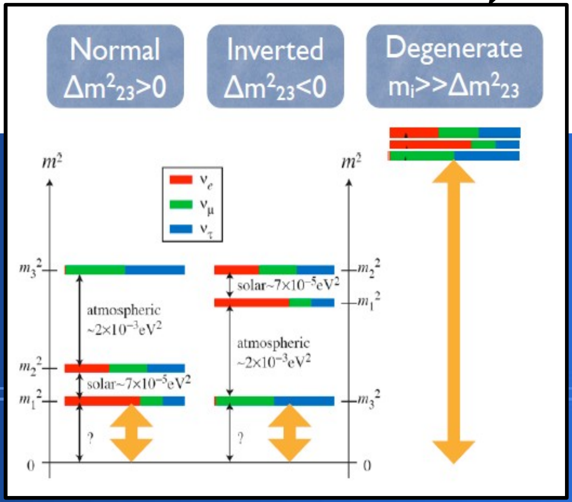
Δm_{atm} , θ_{atm}

Δm_{sol} , θ_{sol}

$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$

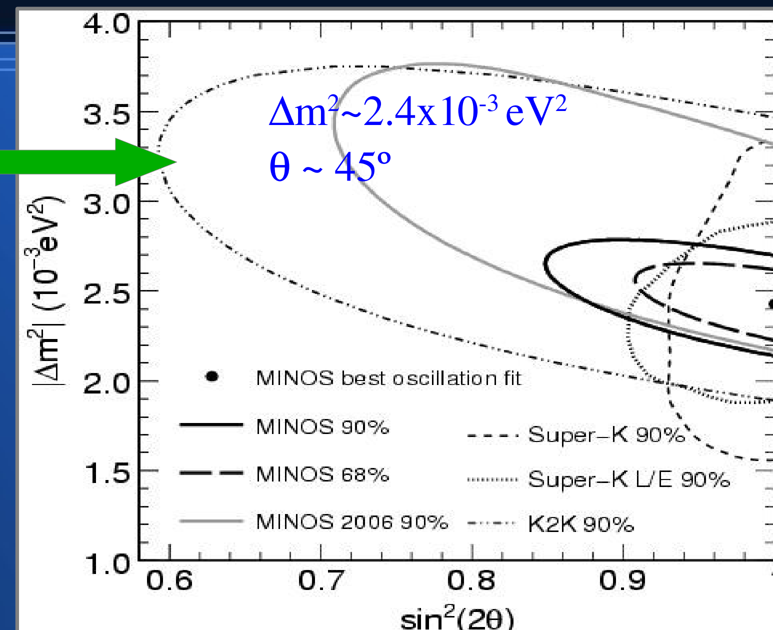
First Generation Of Experiments





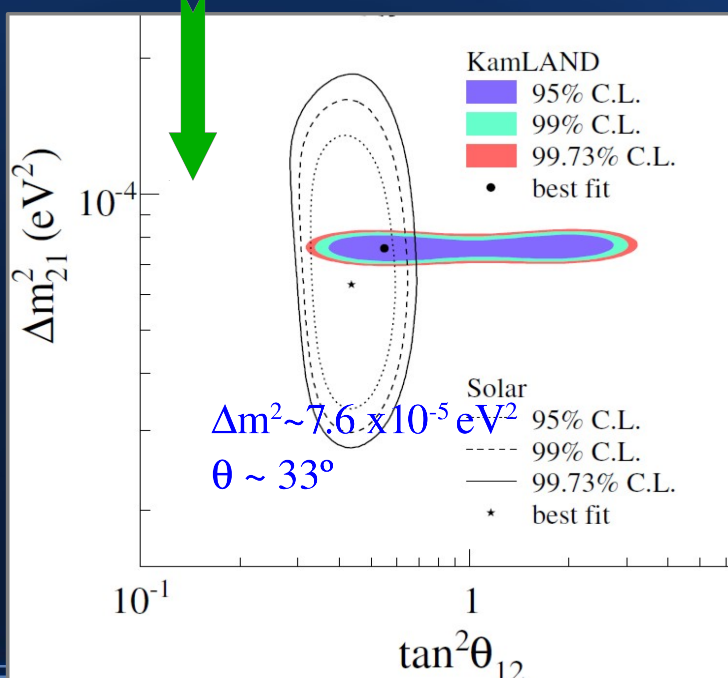
Exploring the sectors...

- Atmospheric oscillation:
  - $(|\Delta m^2_{atm}|, \theta_{atm})$ → K2K, MINOS, Super-K



Phys. Rev. Lett. 101:131802,2008

- Solar oscillation:
  - $(\Delta m^2_{sol}, \theta_{sol})$ → KamLAND and solar data



Phys. Rev. Lett. 100:221803, 2008

- Interference sector:

Unrevealed until 2011!!!

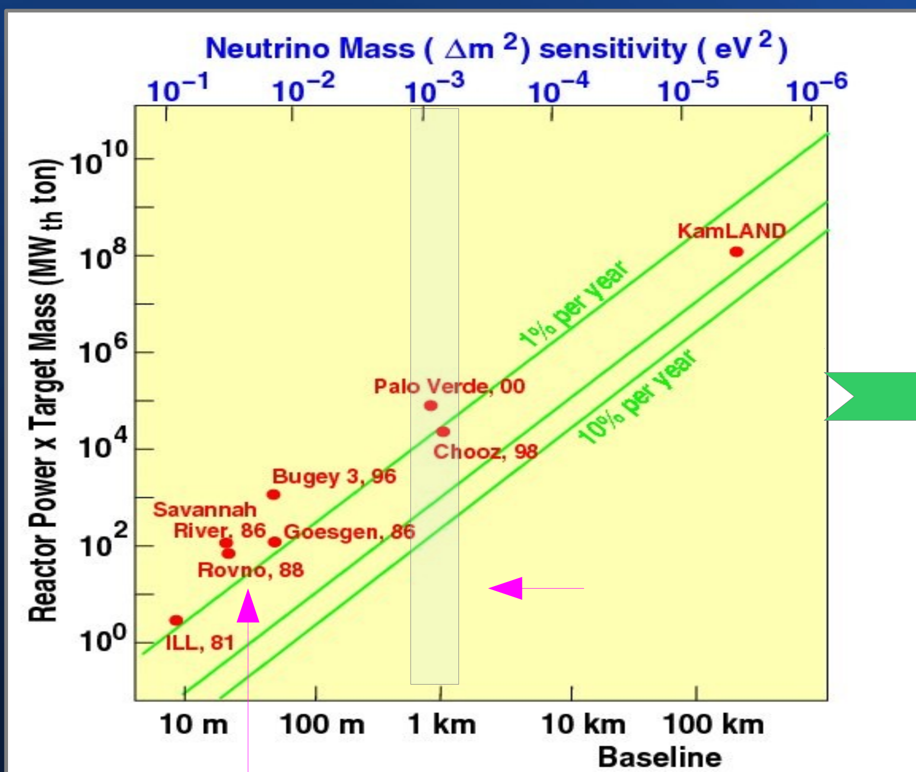
θ_{13}

- Measurement of δ_{cp}
- Mass hierarchy, θ_{23} octant
- Design of next experiments

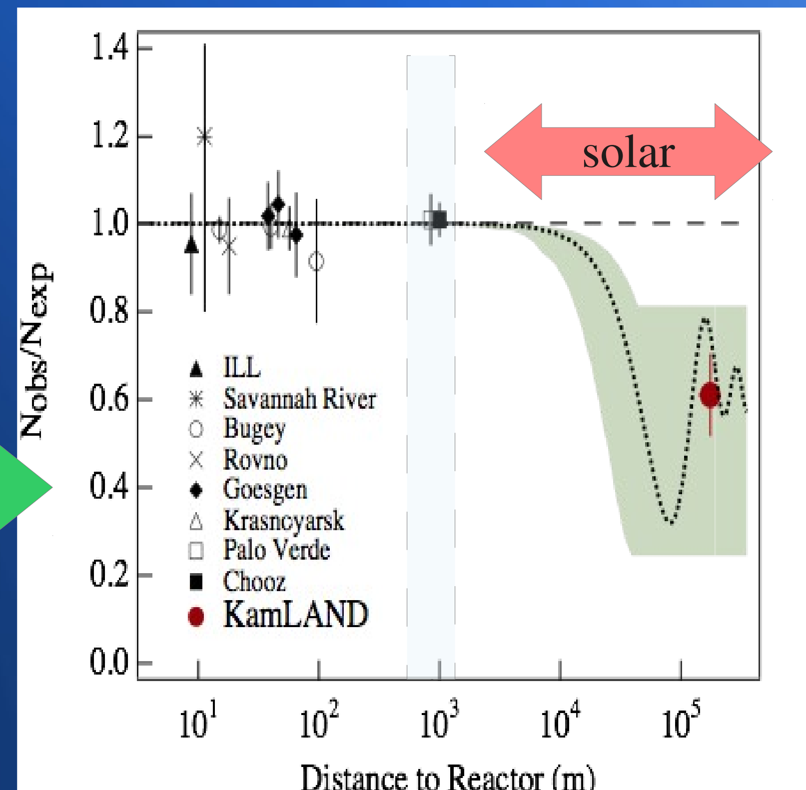
Interference sector as of 2010:
SBL Reactor experiments

- Past reactor experiments...

Gratta et Al. Rev. Mod. Phys, 74, 2002



Measurement of reactor flux

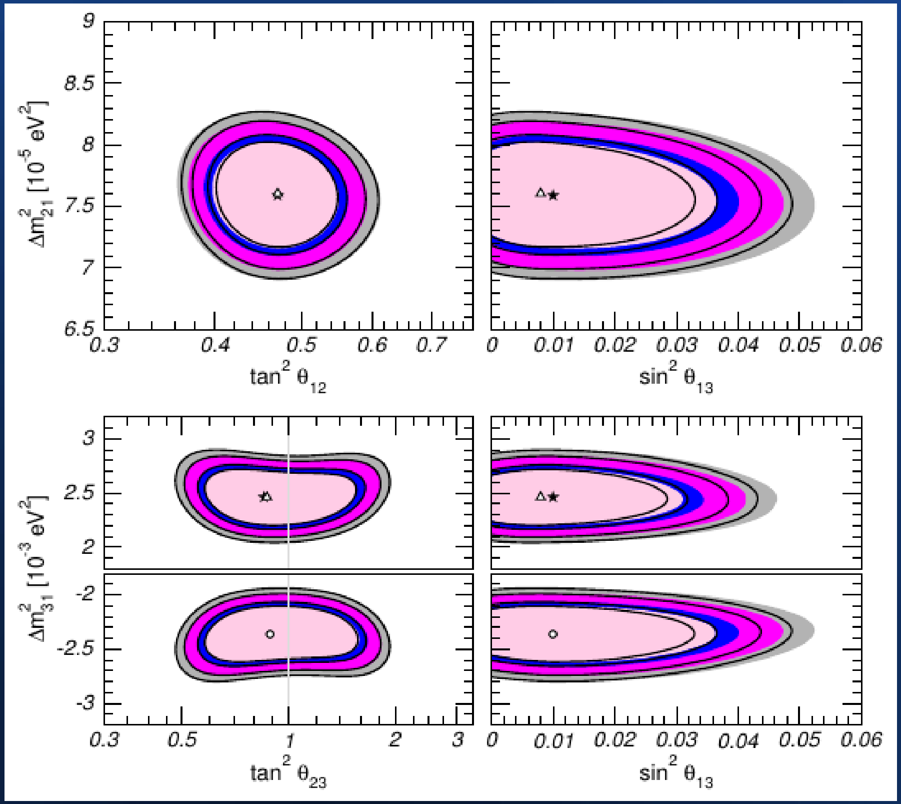


Phys. Rev. Lett. 90, 021802 (2003)

- From CHOOZ: $\sin^2(2\theta_{13}) < 0.15$, δ?

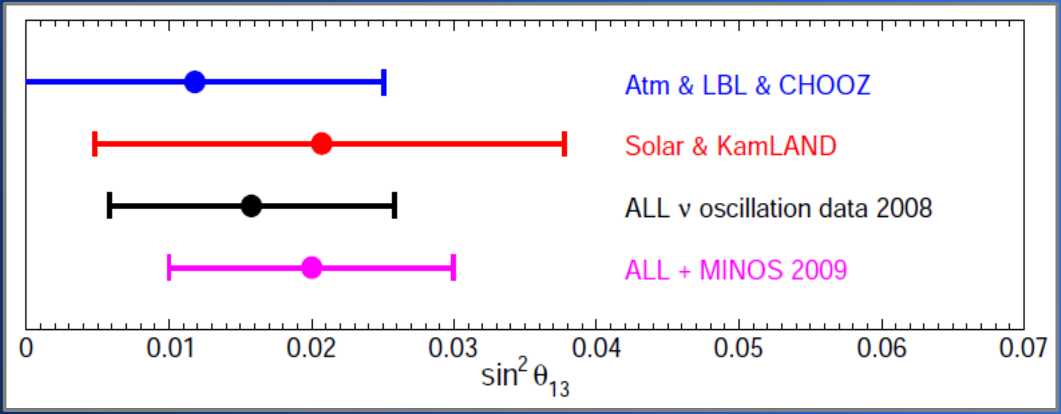
3ν Global Analysis in 2010

Gonzalez-Garcia et Al., JHEP 1004 (2010) 056



- Global fit for 3-flavour scenario
  - Preference for $\theta_{13} \neq 0$
- First hint of θ_{13} : $\sin^2(\theta_{13}) \sim 0.01\text{-}0.02$

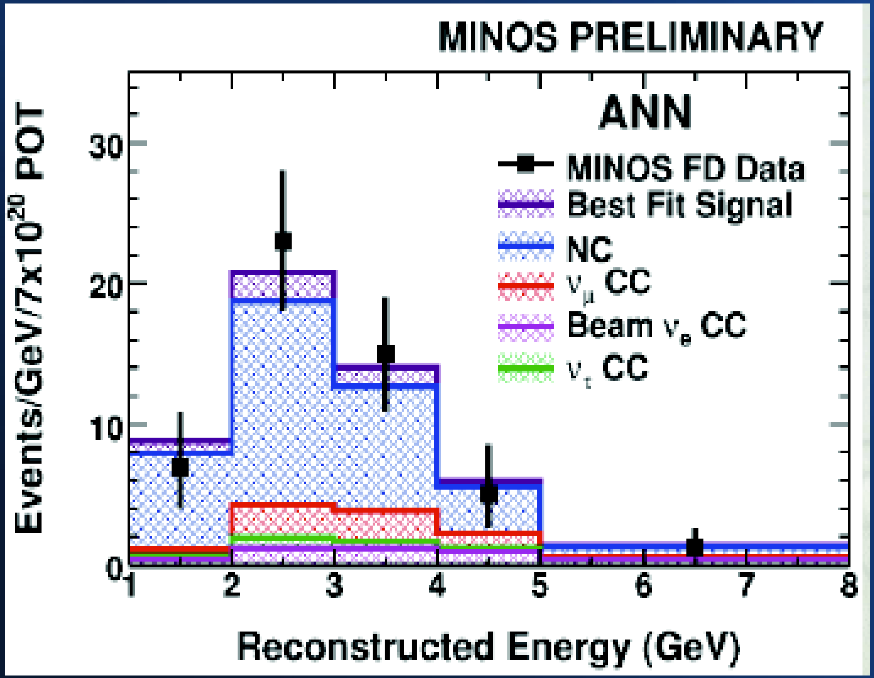
G.L. Fogli et Al, hep/ph 0905.3549v2

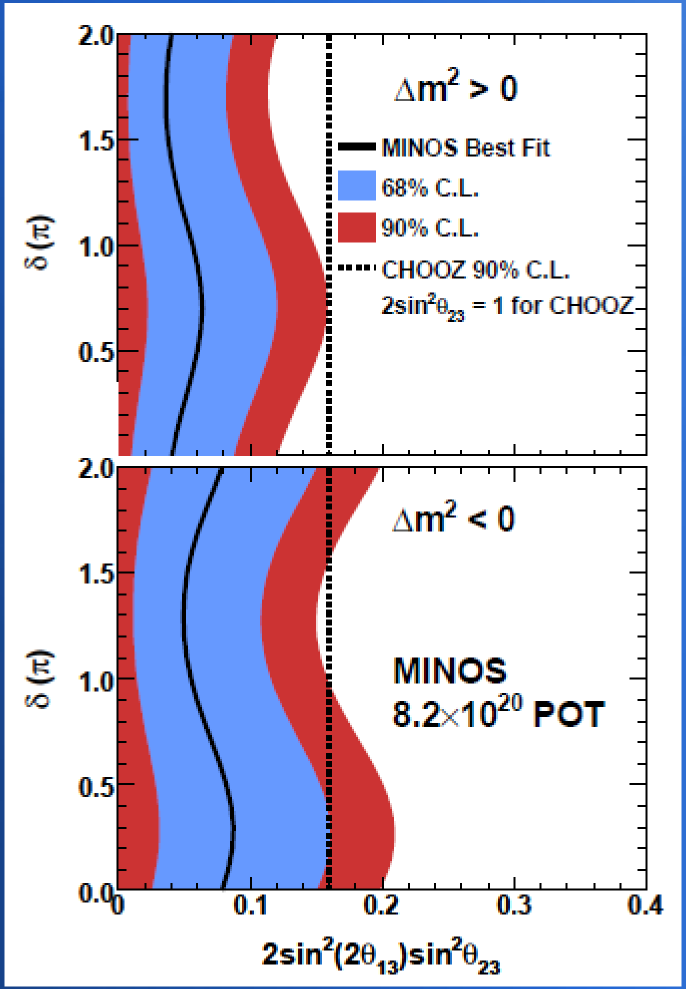


First direct indications: MINOS

- Appareance analysis: θ_{13} from $\nu_\mu \rightarrow \nu_e$

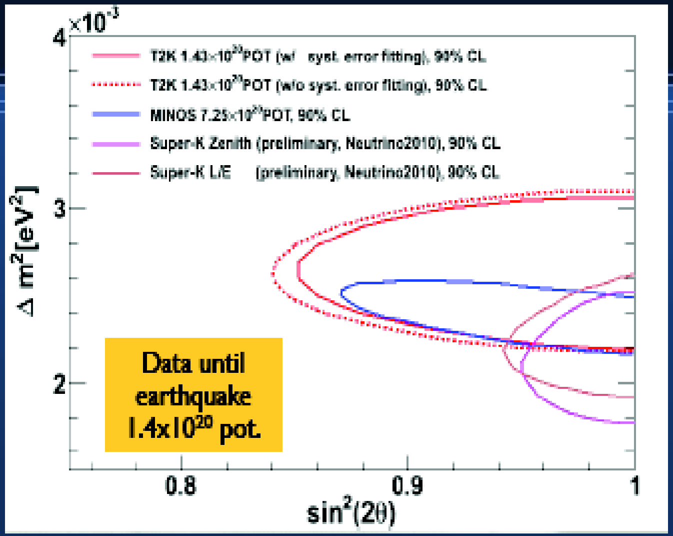
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2(1.27\Delta m^2_{atm}(L/E))$$





Phys.Rev.Lett. 107 (2011) 181802

First direct indications: T2K

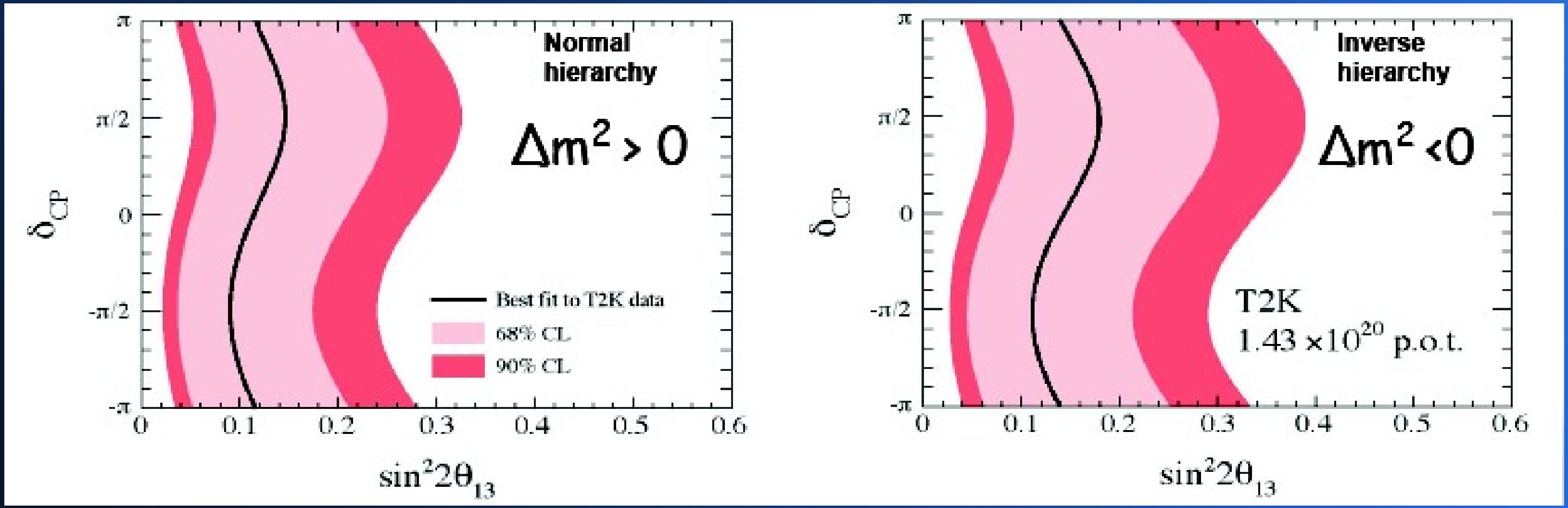


- First results on ν_μ disappearance with 1.4×10^{20} pot
- ν_e appearance: 6 events over background of 1.5 (2.5σ)

NH (δ=0) $\sin^2(2\theta_{13})=0.11$ and $0.03<\sin^2(2\theta_{13})<0.28$ @ 90% C.L.

IH (δ=0) $\sin^2(2\theta_{13})=0.14$ and $0.04<\sin^2(2\theta_{13})<0.34$ @ 90% C.L.

The 5σ appearance result is expected by June 2013!



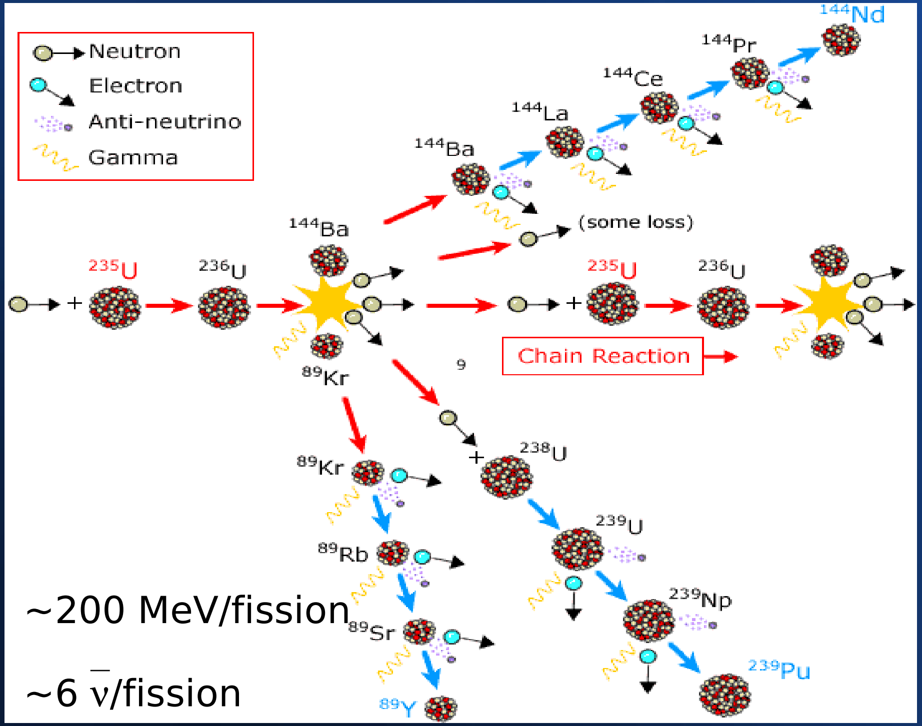
Published in Phys. Rev. Lett. 107, 041801 (2011)

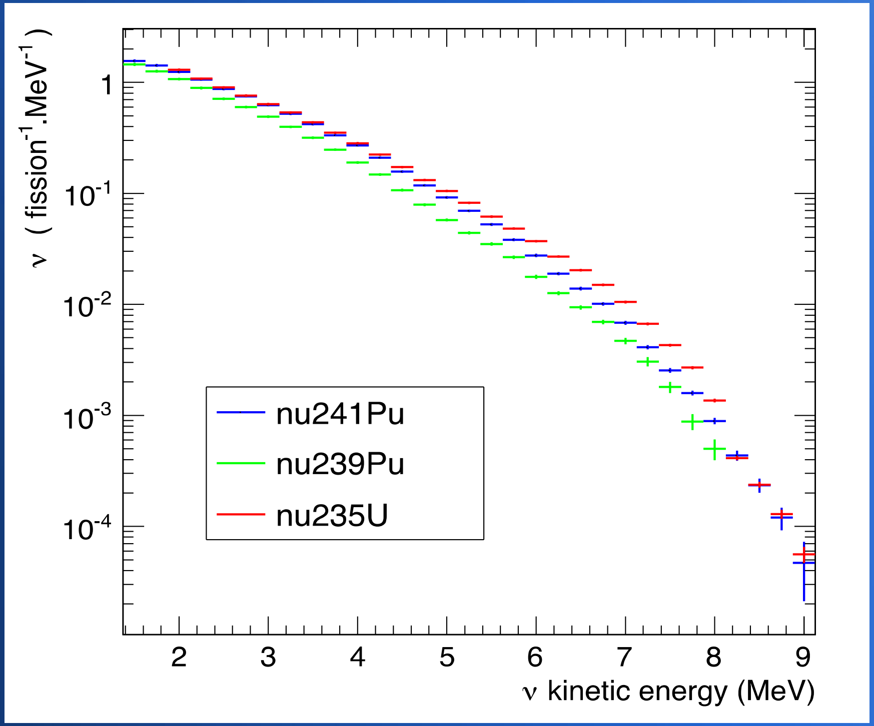
Reactor Neutrinos

as a probe to θ_{13}

Nuclear Reactors as a ν source

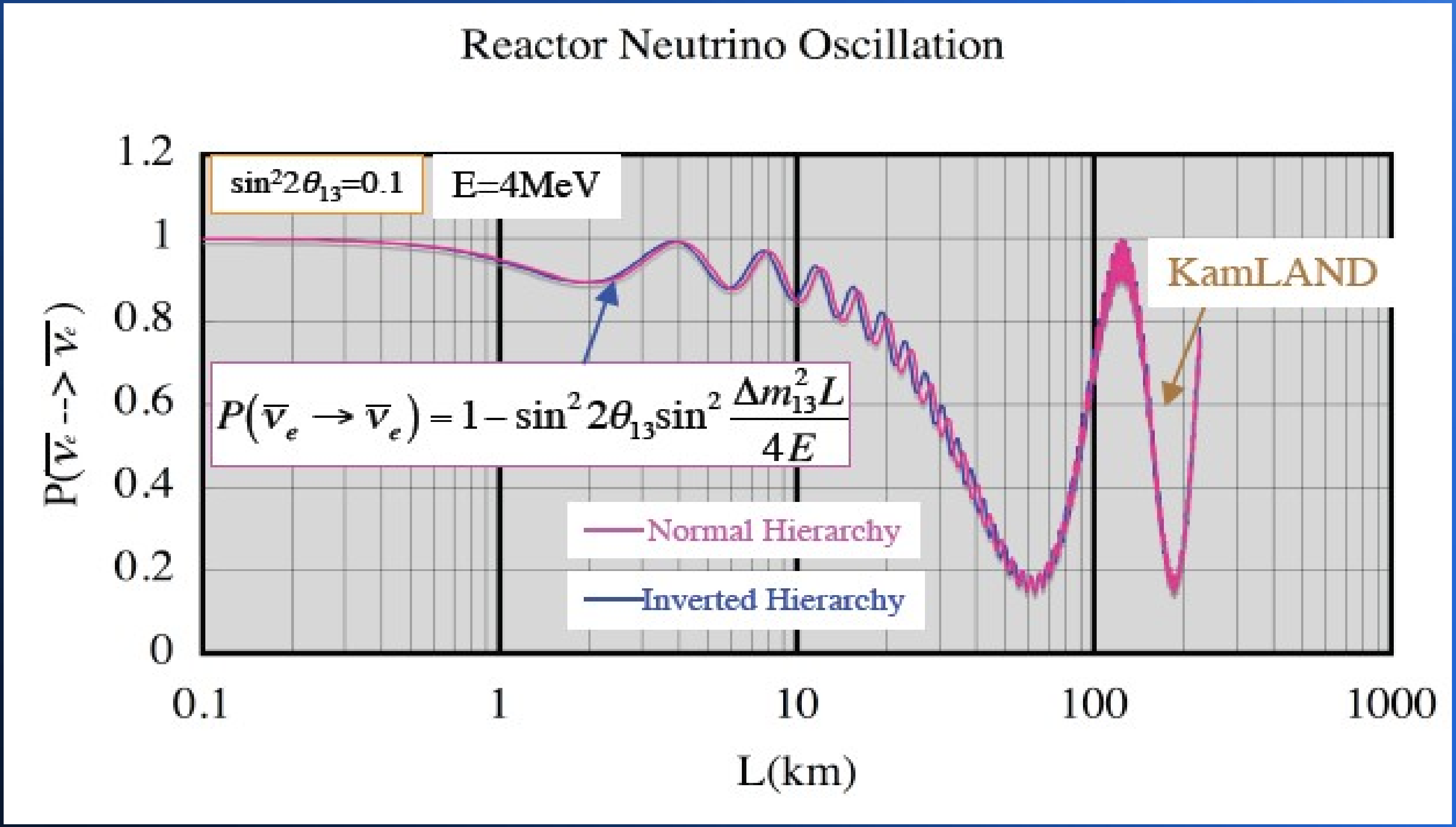
- $\bar{\nu}_e$ Neutrino flux: sum of all fission products from ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu
- Flux depends on fuel composition (f(t)): $1GW_{th}$ -> 2×10^{20} $\bar{\nu}$/s



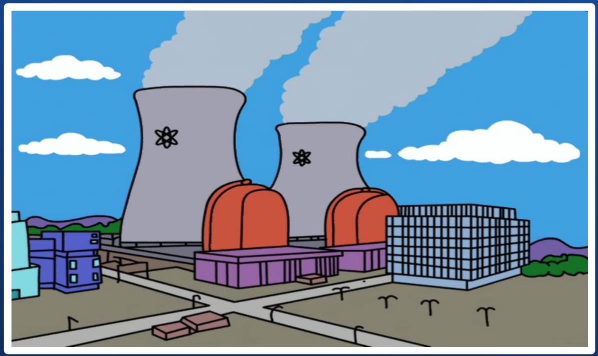


- ILL spectra (reference last 25 years)

Reactor neutrino oscillation

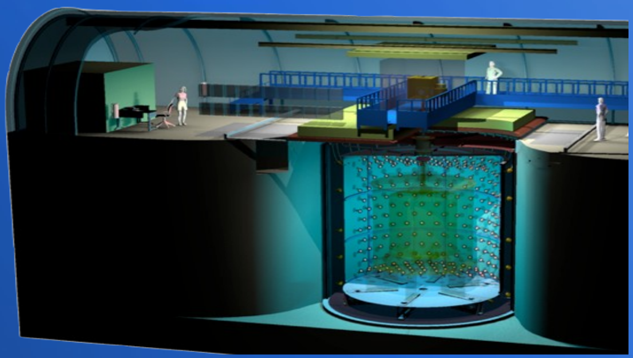


θ_{13}: Why reactor neutrinos?



L ~ 1 km

$P(\bar{\nu}_e \rightarrow \bar{\nu}_x)$



- In contrast to accelerator experiments...

$$P_{ee}(E_{\overline{\nu}_e}, L, \Delta m^2_{31}, \theta_{13}) = 1 - \sin^2(2\theta_{13}) \sin^2\left(1.27 \frac{\Delta m^2_{31}[10^{-3}\ \mathrm{eV}^2] L[\mathrm{km}]}{E_{\overline{\nu}_e}[\mathrm{MeV}]}\right)$$

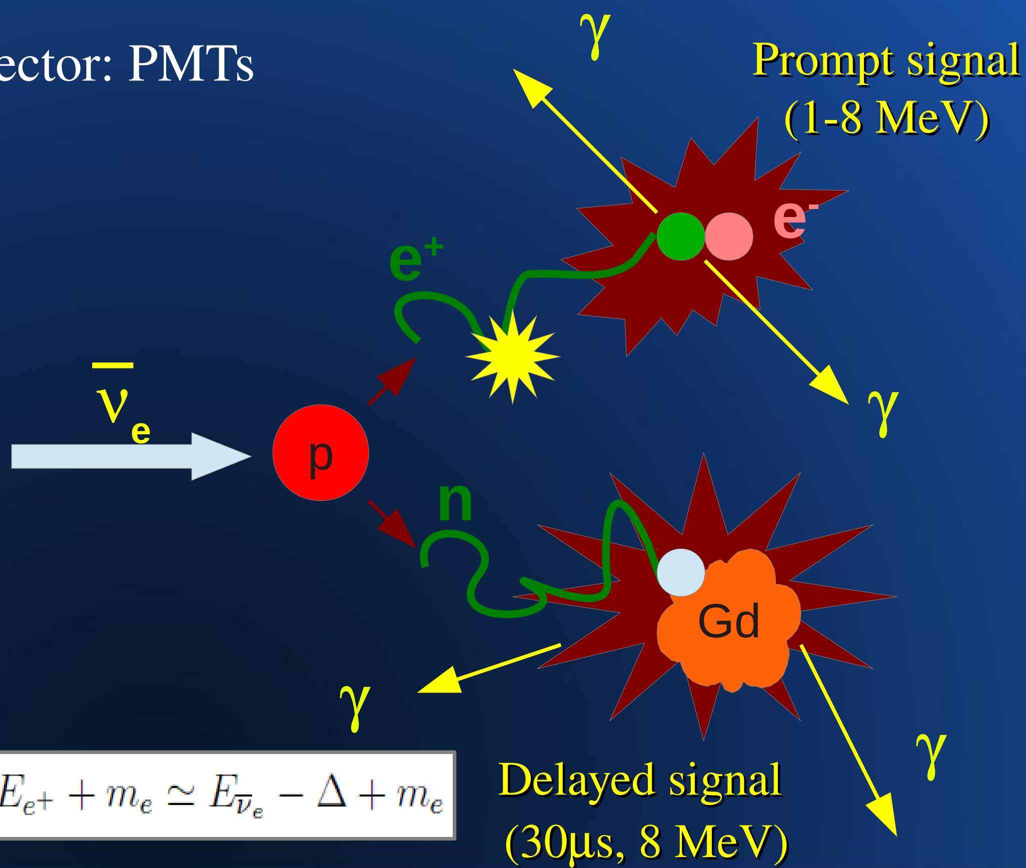
- No parameter correlations
- Pure $\bar{\nu}_e$ beam
- Low energy
- No matter effects
- Cheap, as source exists
- High flux and large xsection

Detecting reactor neutrinos

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

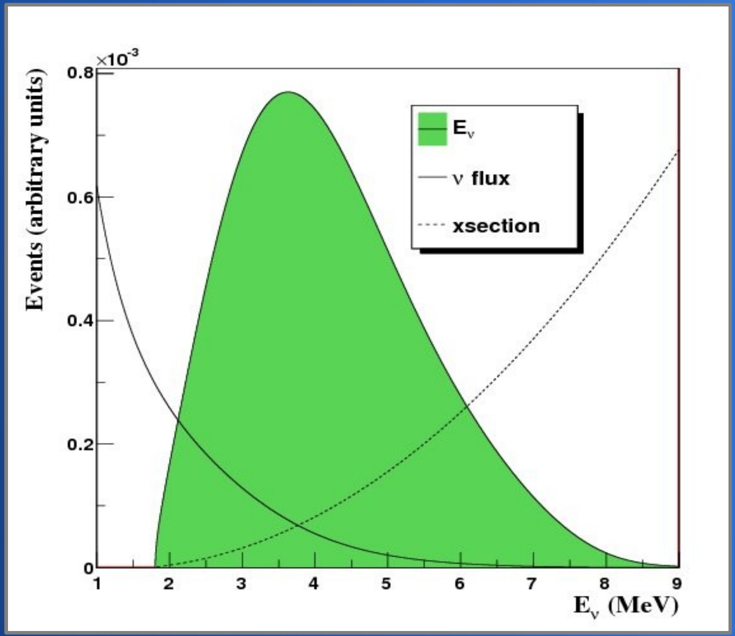
Th: 1.8 MeV. **Disappearance!**

- Target: scintillator + n-catcher (Gd)
- Detector: PMTs

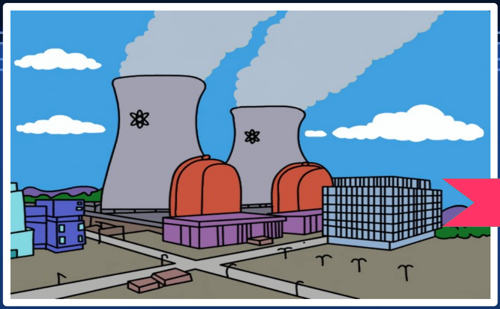


$$E_{\text{vis}} = E_{e^+} + m_e \simeq E_{\overline{\nu}_e} - \Delta + m_e$$

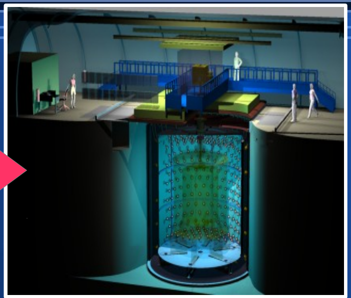
E_ν spectrum



Expected oscillation signal

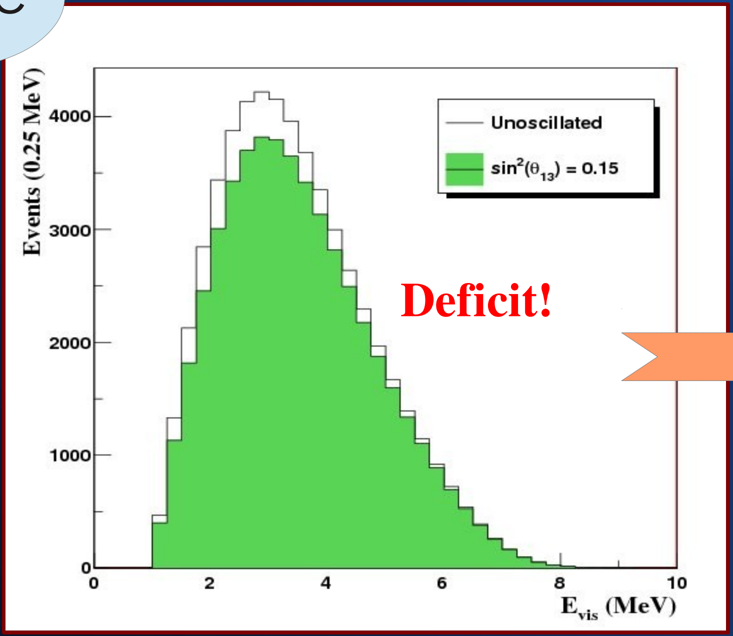


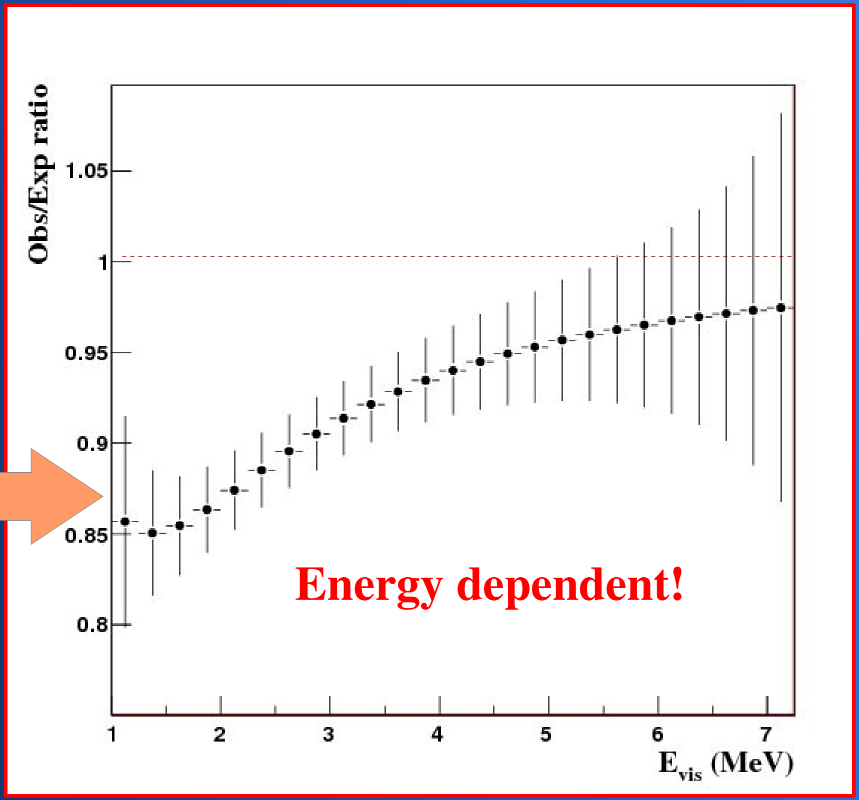
1 km



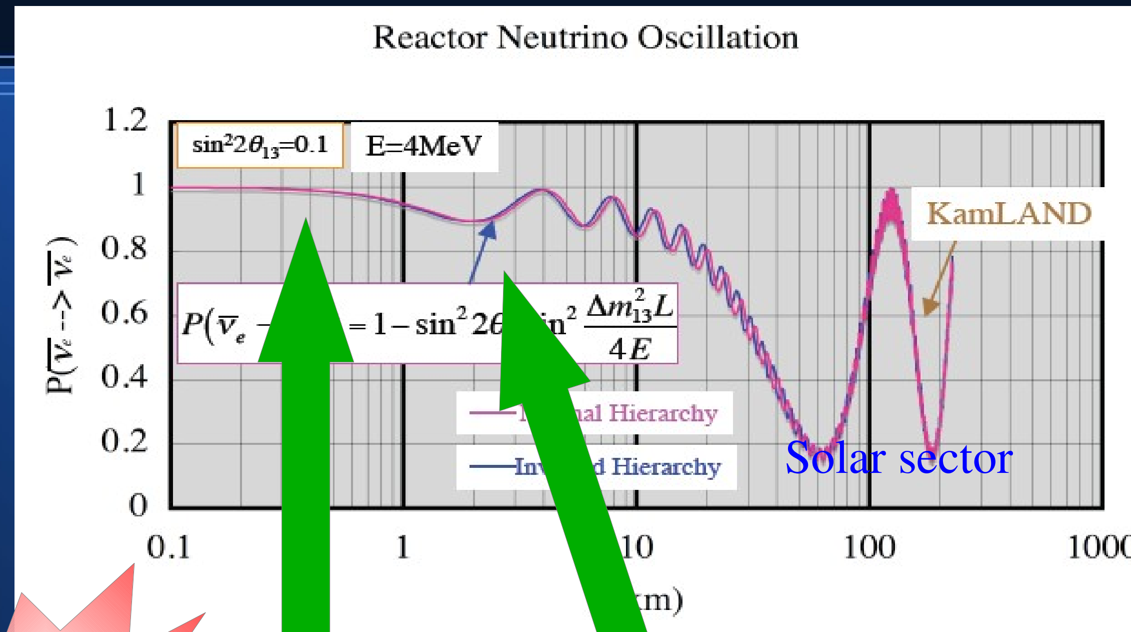
- Deficit in the number of neutrinos
- Characteristic L/E pattern: θ_{13}

Toy MC



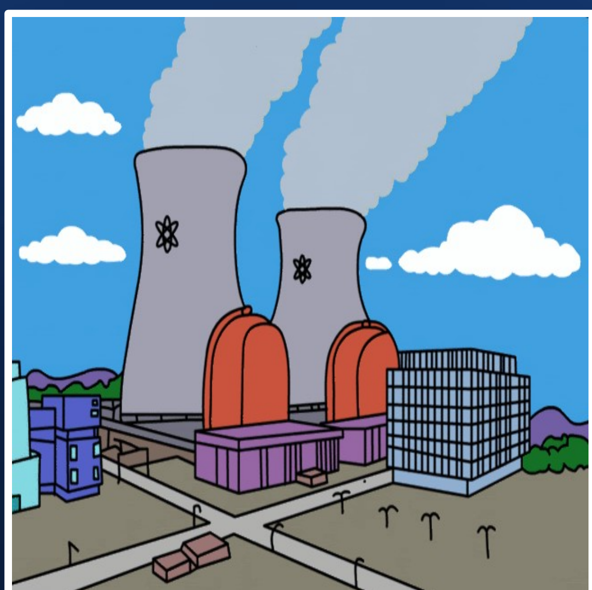


Setting up the experiment

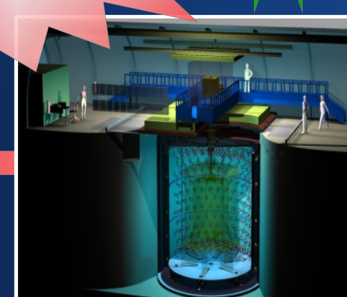


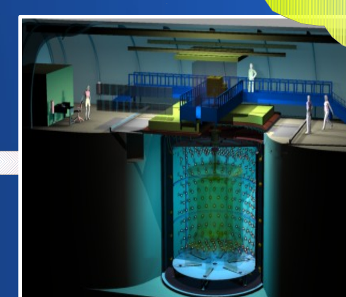
Reactor neutrinos:

$\langle E_\nu \rangle \sim 4$ MeV



Systematics!





Oscillation!

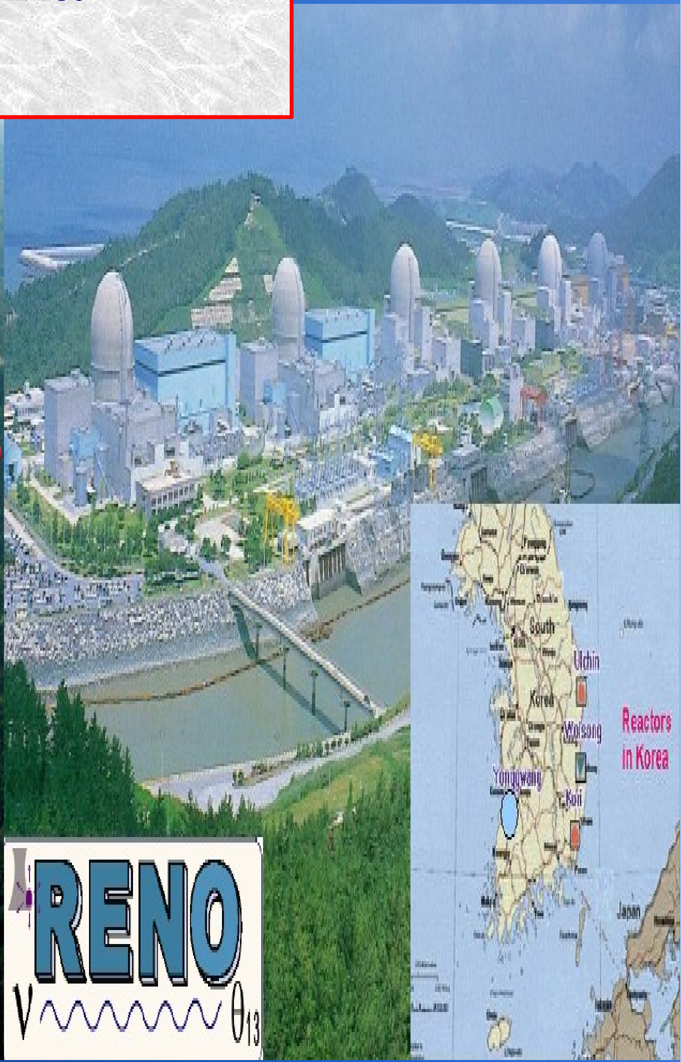
~ 100 m

~ 1 km

Unrevealing θ_{13} with reactor neutrinos

Reactor neutrino experiments

IBD detection in Gd-doped scint.
Multi-detector setups



The Double Chooz Experiment

Neutrino yield per fission

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

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

Bugey4 measurement as anchor point

Fission fraction in CHOOZ core

Near Detector
L = 400m
$10m^3$ target
120 m.w.e.
2013

Far Detector
L = 1050m
$10m^3$ target
300m.w.e.
April 2011 ~

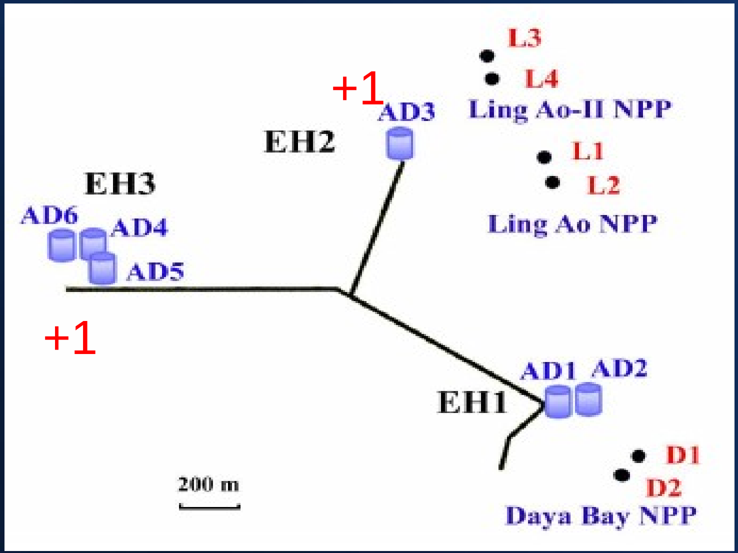
Chooz Reactors
$4.27GW_{th}$ x 2 cores

- Pioneered reactor experiments after CHOOZ:
  - Experimental concept of using two detectors
  - New detector structure: 4 layers detector
  - Low background (S/N ~ 20, proven by reactor OFF)
  - Stable Gd loaded LS developed

Daya Bay and RENO

Power	Target (x2x4)
17.4 GW	20 tons

Near (x2)	Far
360-500 m/ 260 mwe	1.6-2.0 km/910 wme



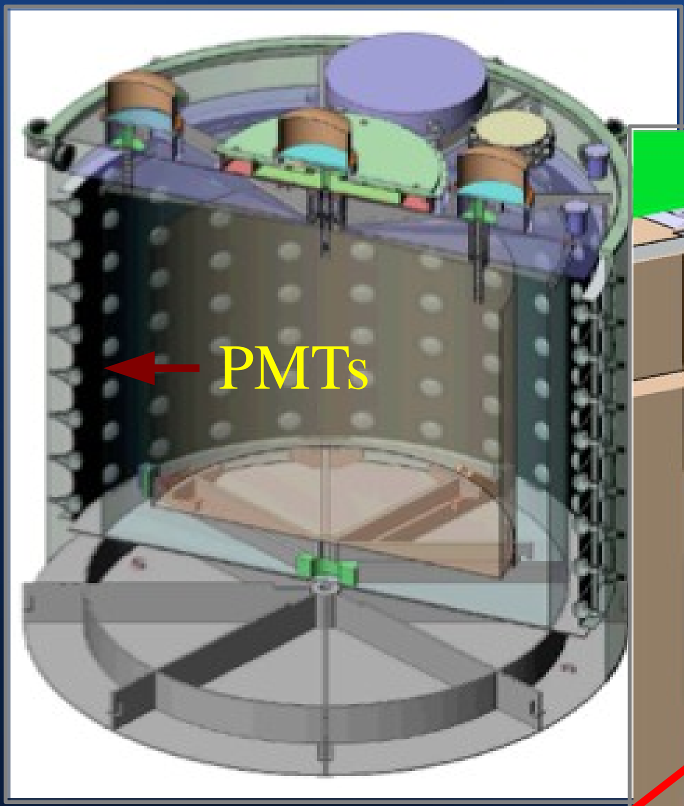
Power	Target
17.3 GW	16 tons

Near	Far
290 m/130 wme	1.38 km/460 wme

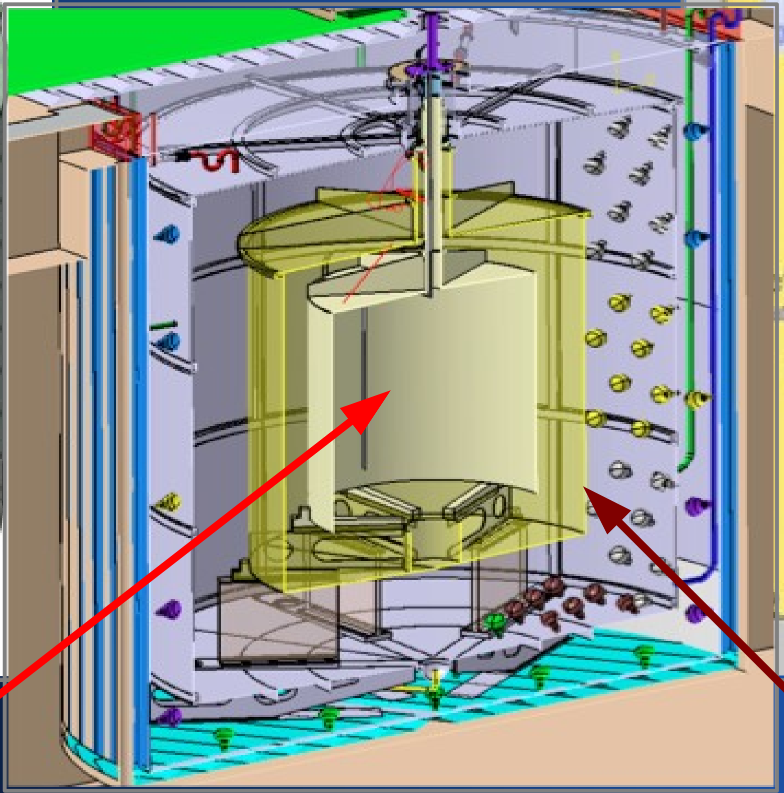
Detector technology

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

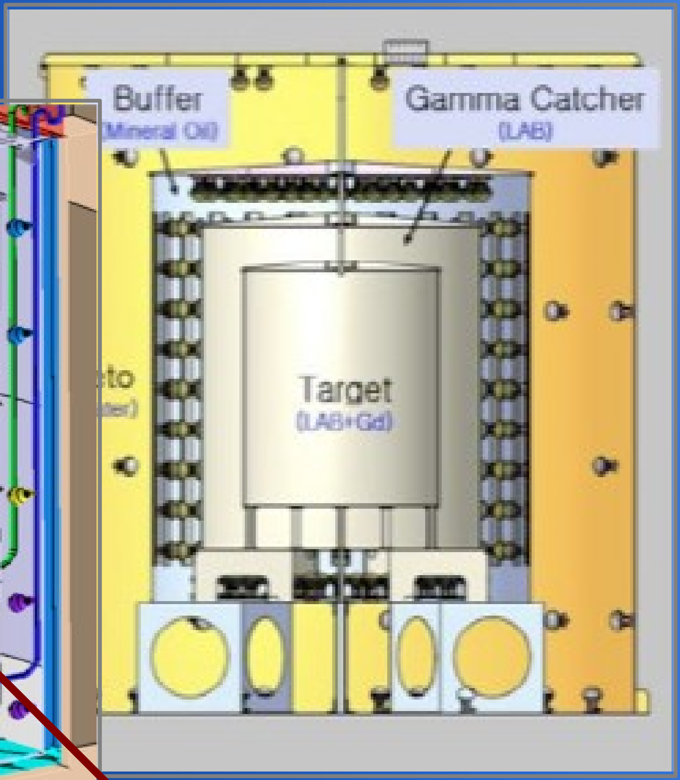
Daya Bay



Double Chooz



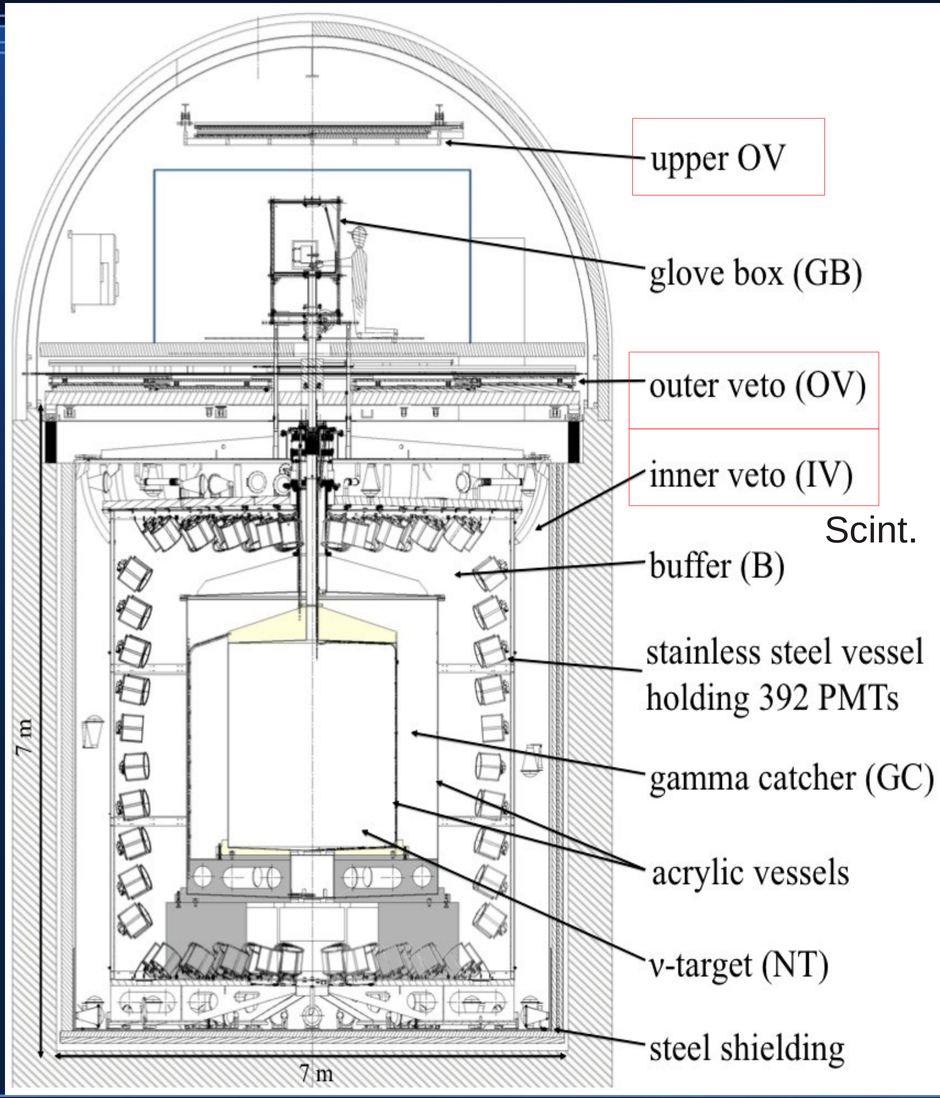
RENO



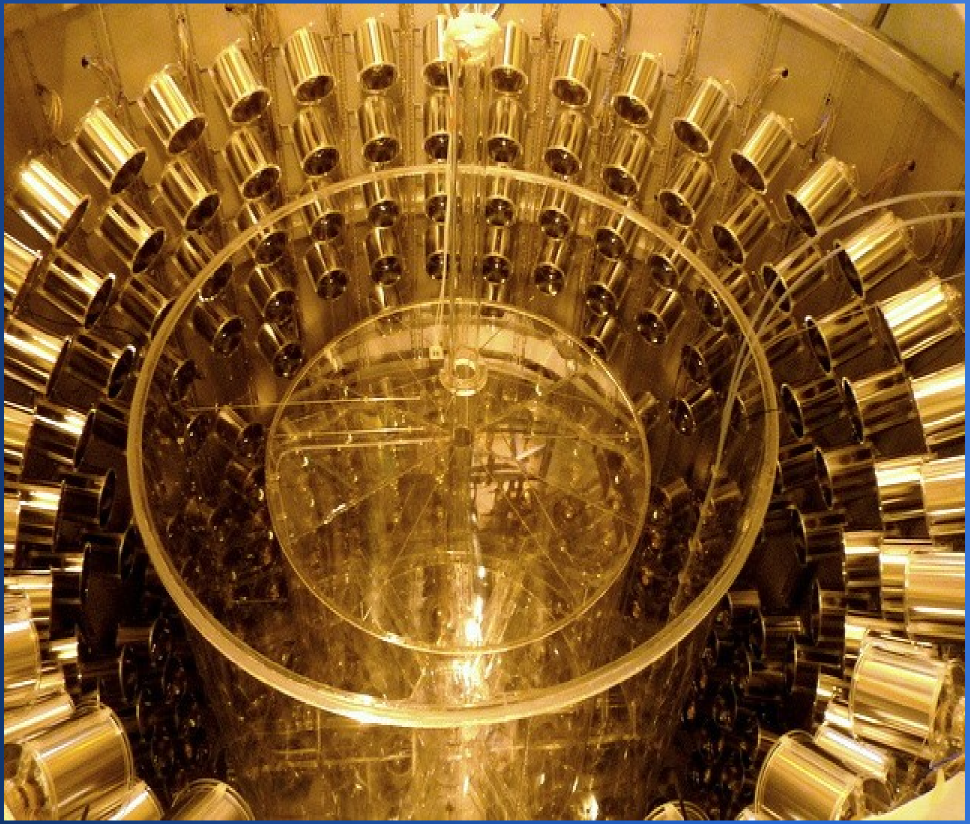
Target: scin + Gd

Gamma catcher

Detector Design: Double Chooz

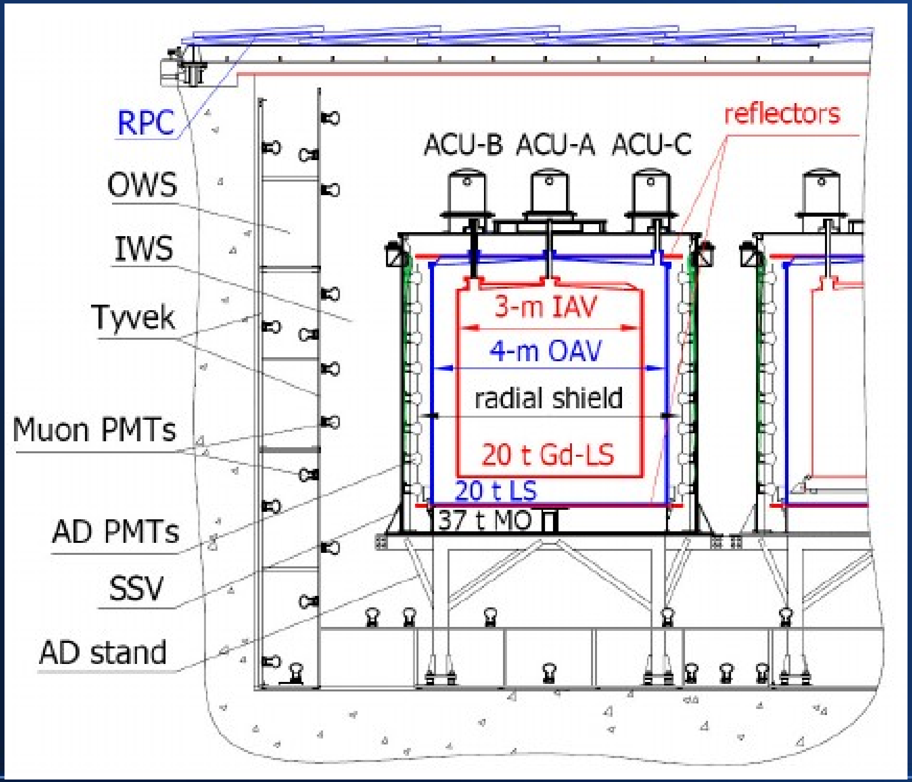


- Far Detector operating since early 2011

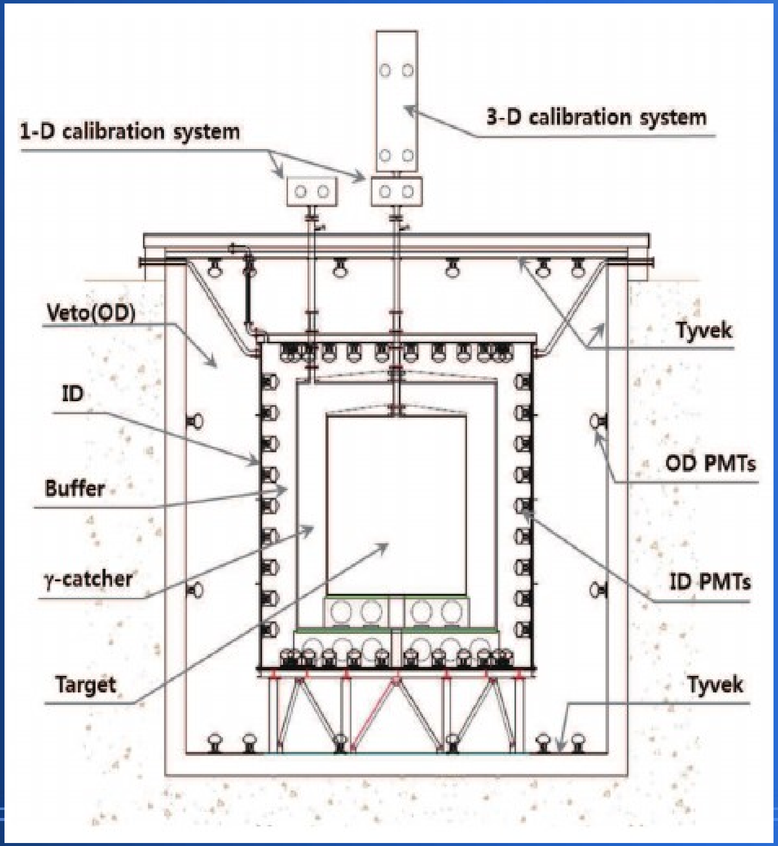


Detector Design: DB and RENO

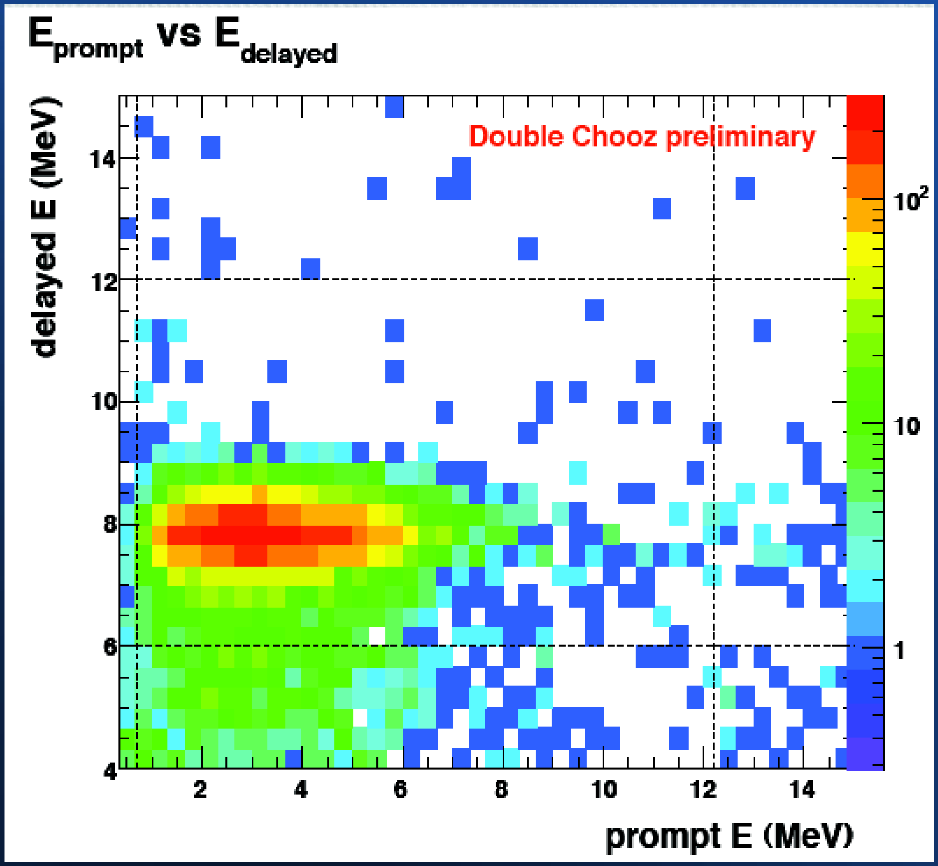
- Daya Bay:
  - Muon IV: Water pool (no scint.)
  - Muon OV: RPCs

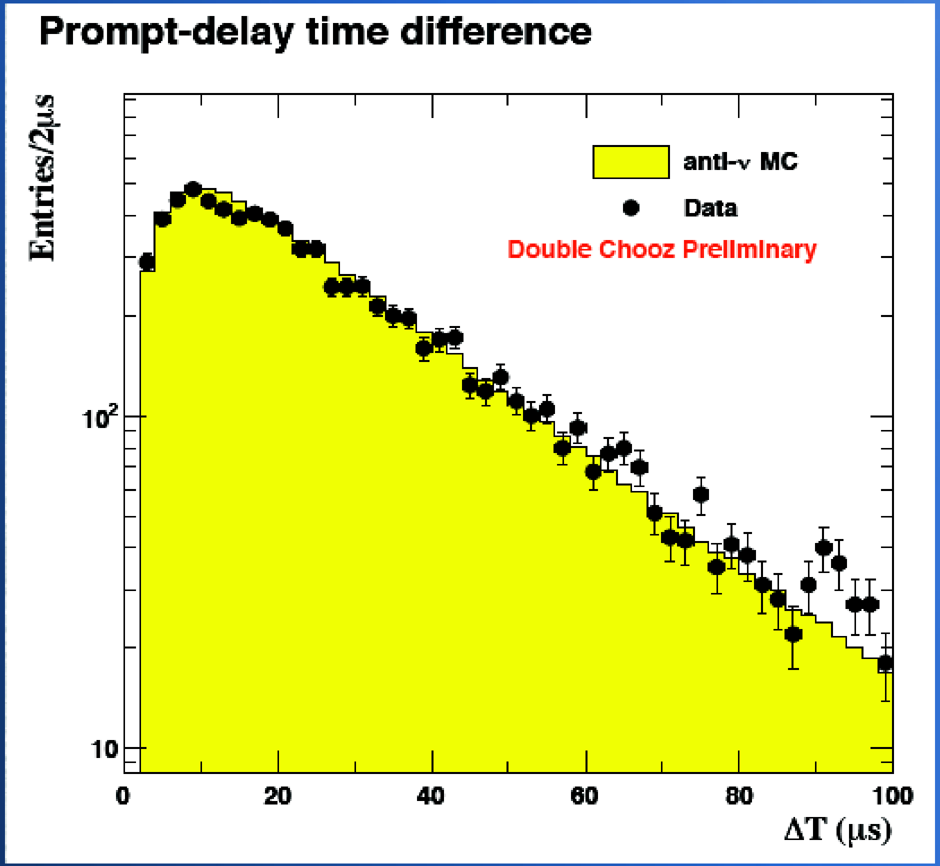


- RENO:
  - No Outer Muon veto
  - IV: water (no scint.)



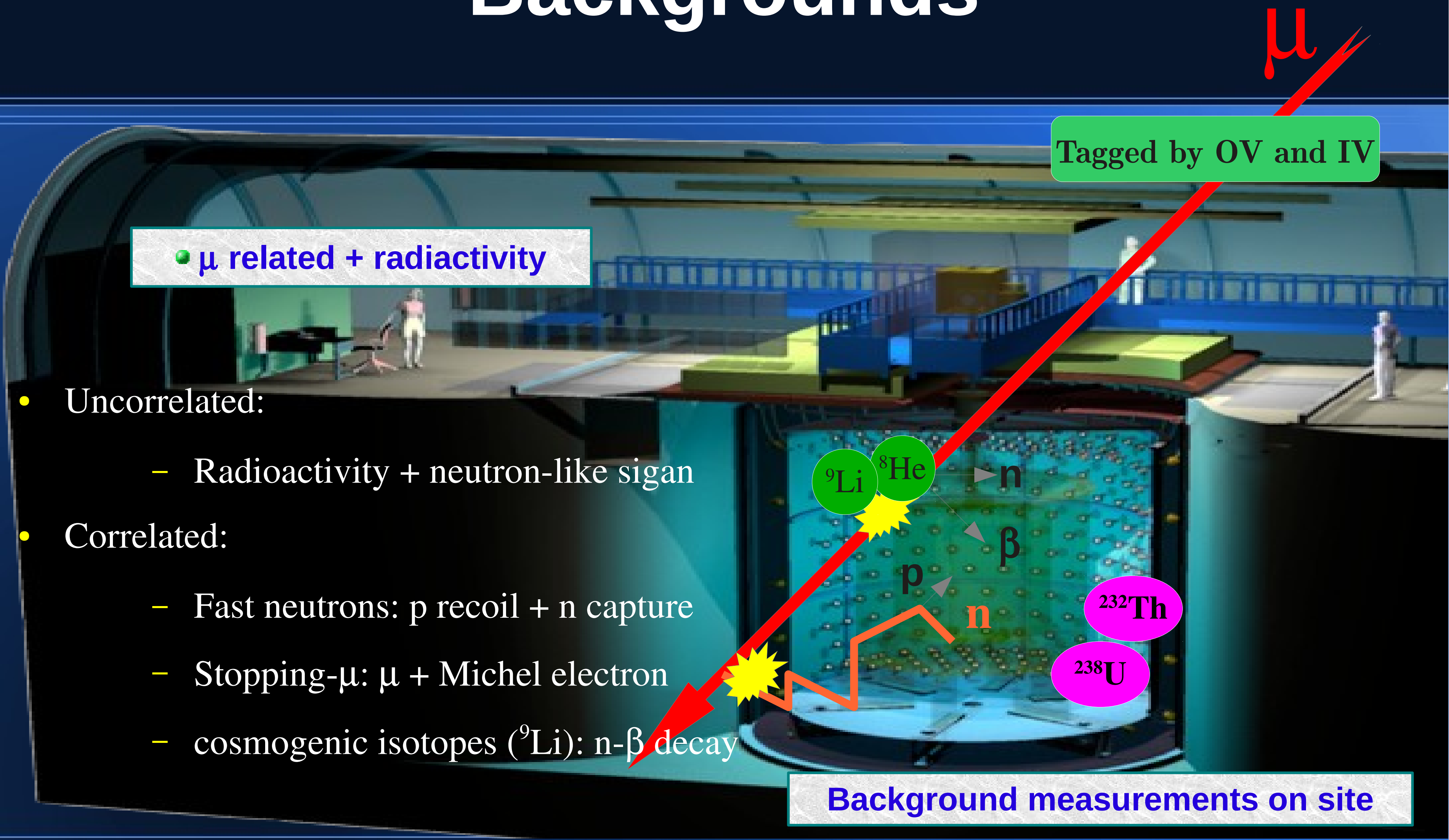
Neutrino Selection





- Prompt signal energy cut
- Delayed signal energy cut
- ΔT between prompt-delayed
- Multiplicity cut

Backgrounds



- Uncorrelated:
  - Radioactivity + neutron-like sigan
- Correlated:
  - Fast neutrons: p recoil + n capture
  - Stopping-μ: μ + Michel electron
  - cosmogenic isotopes (^{9}Li): n-β decay

Experimental results on θ_{13}:

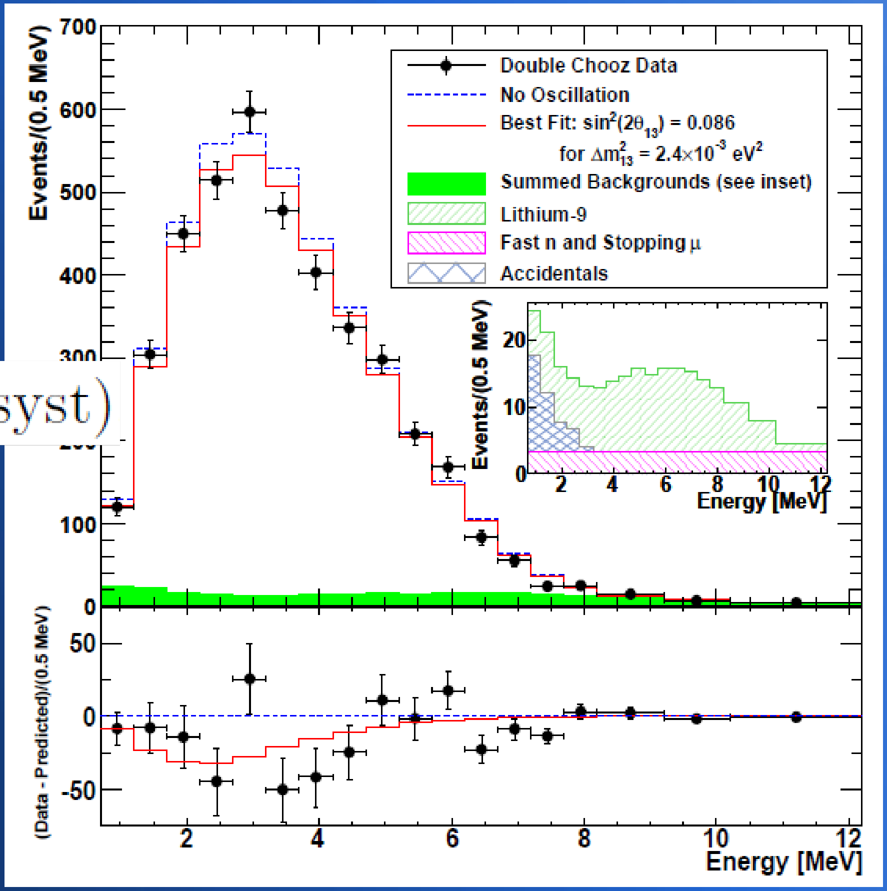
Critical view

Double Chooz first results

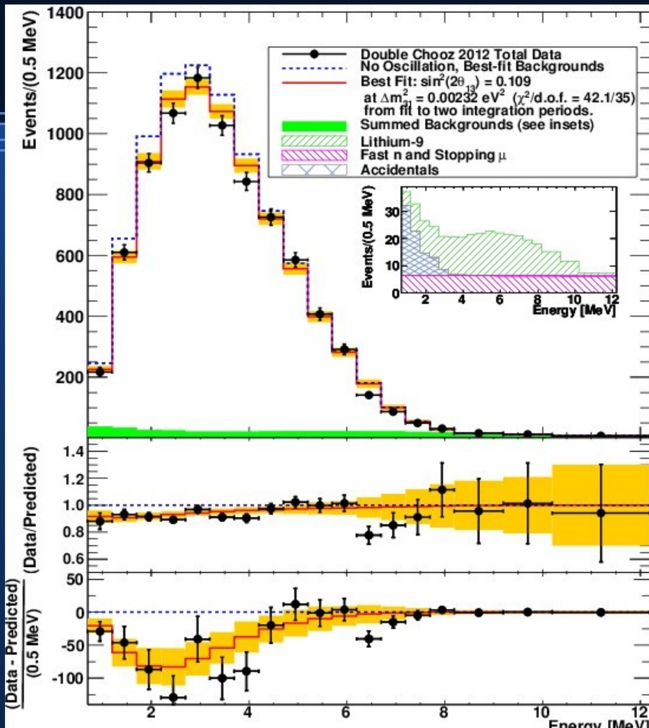
- **First results on θ_{13} from reactor experiments**
  - 100 days of data, FD only, Nov 2011
  - Rate + Shape analysis

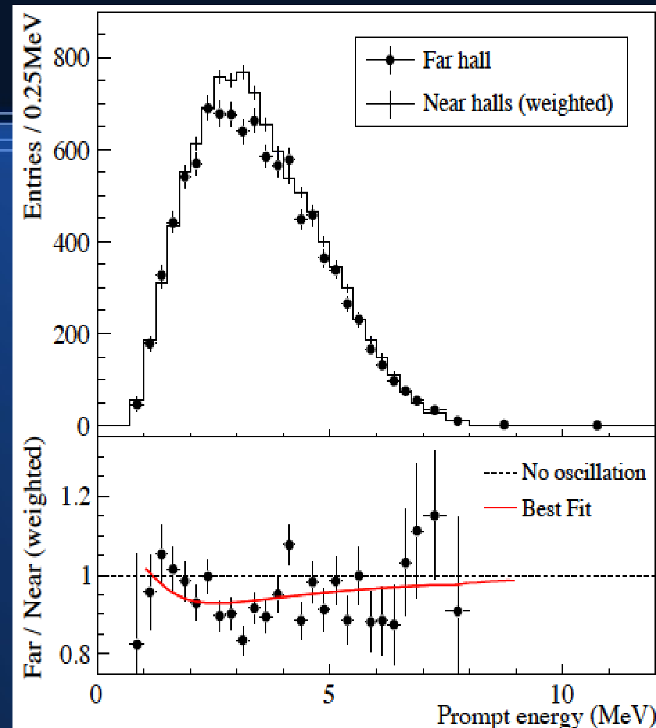
$$\sin^2 2\theta_{13} = 0.086 \pm 0.041\ (\text{stat}) \pm 0.030\ (\text{syst})$$

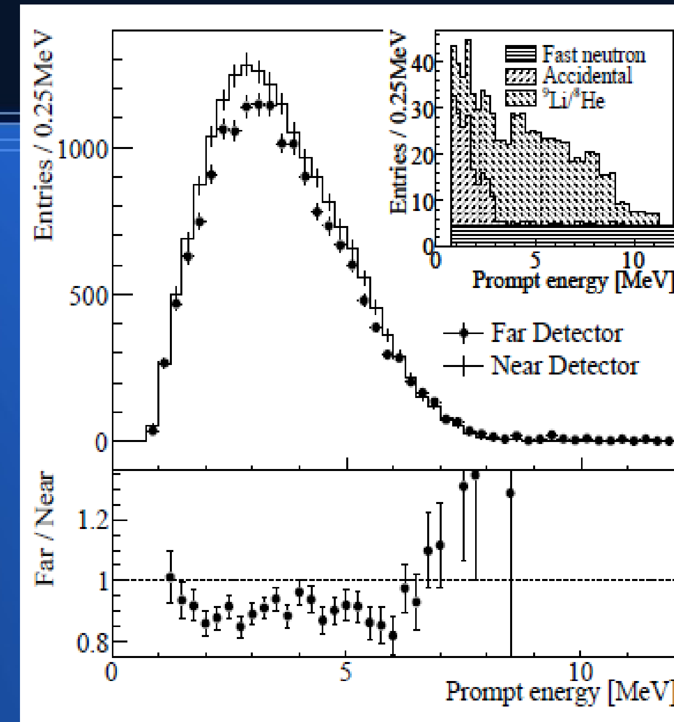
- DC released new results on 2012
  - Smaller systematic in detector response
  - Larger background reduction
    - OV+ dedicated showering muon veto



Summary of 2012 results



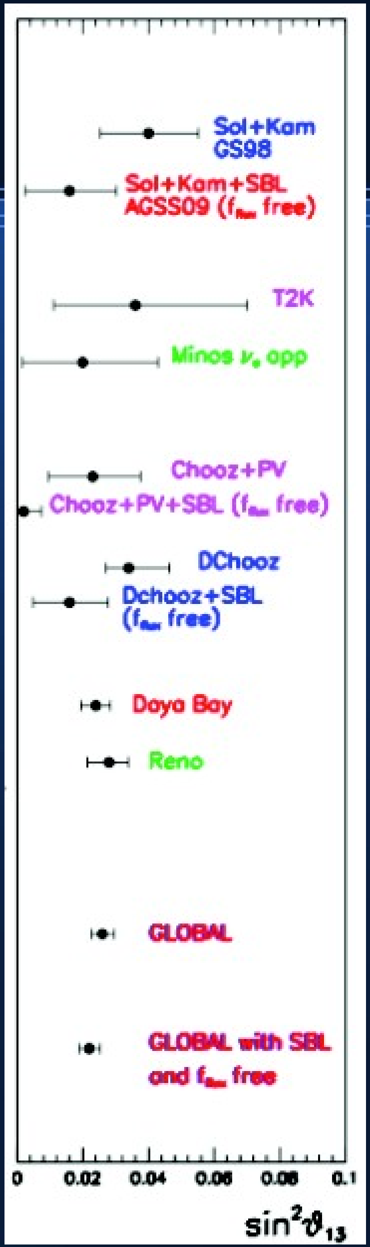


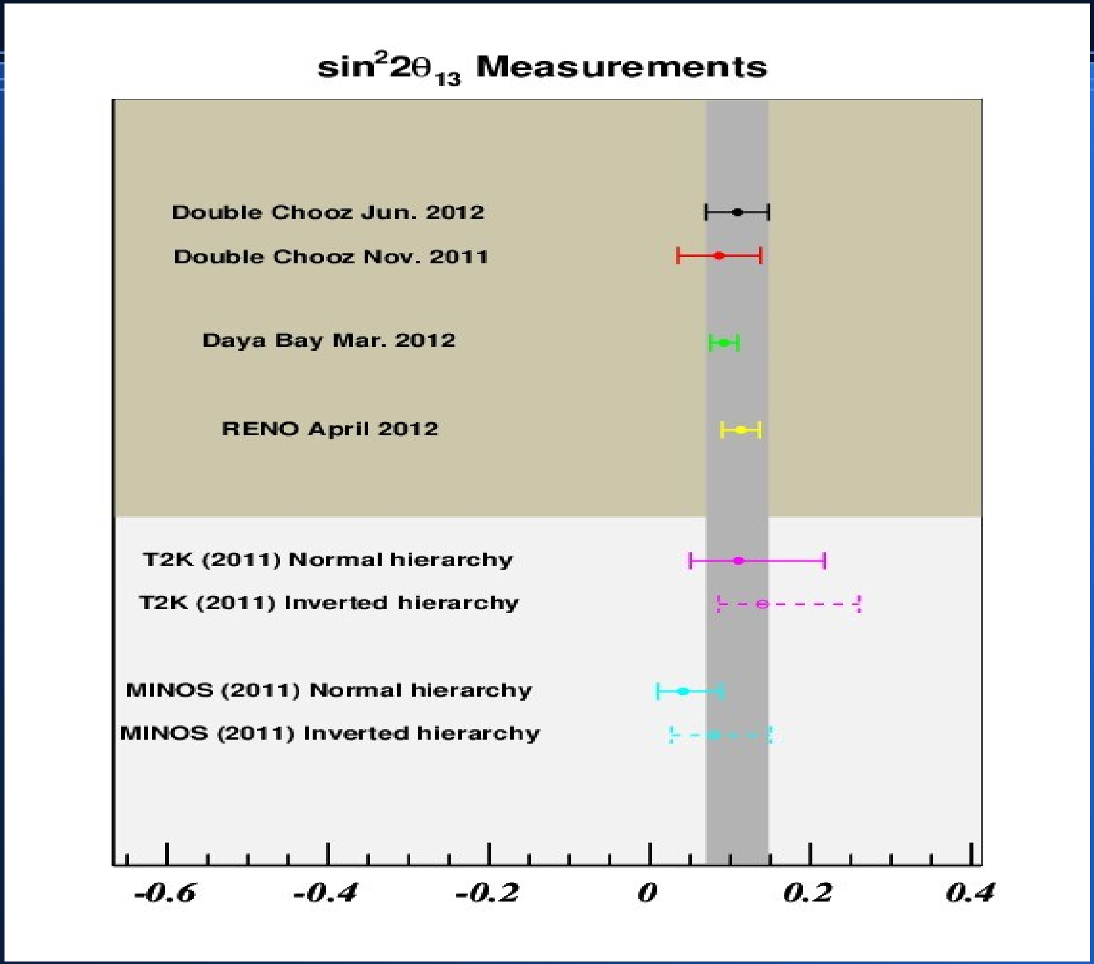


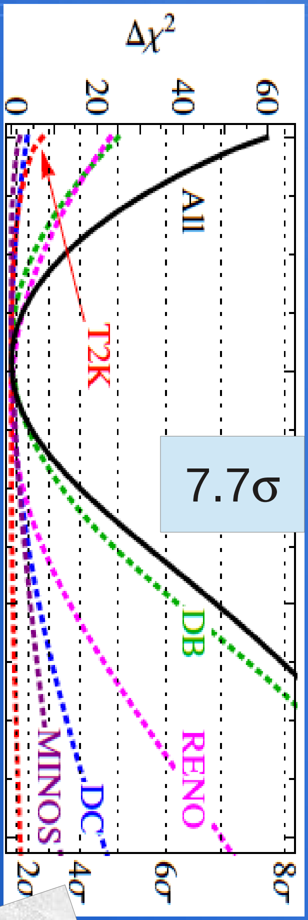
2 integration periods!

	$\sin^2(2\theta_{13})$	days	arXiv
DC-I(rate+shape)	$0.086\pm0.051(0.041^{stat}\pm0.030^{sys})$	96.8	1112.6353
DB(rate only)	$0.092\pm0.017(0.016^{stat}\pm0.005^{sys})$	55	1203.1669
RENO(rate only)	$0.113\pm0.023(0.013^{stat}\pm0.019^{sys})$	229	1204.0626
DC-II(rate only)	$0.170\pm0.053(0.035^{stat}\pm0.040^{sys})$	251	1207.6632
DC-II(rate+shape)	$0.109\pm0.039(0.030^{stat}\pm0.025^{sys})$	251	1207.6632
DB-II(rate only)	$0.089\pm0.011(0.010^{stat}\pm0.005^{sys})$	126	Nu2012

Summary on θ_{13}







Minakata

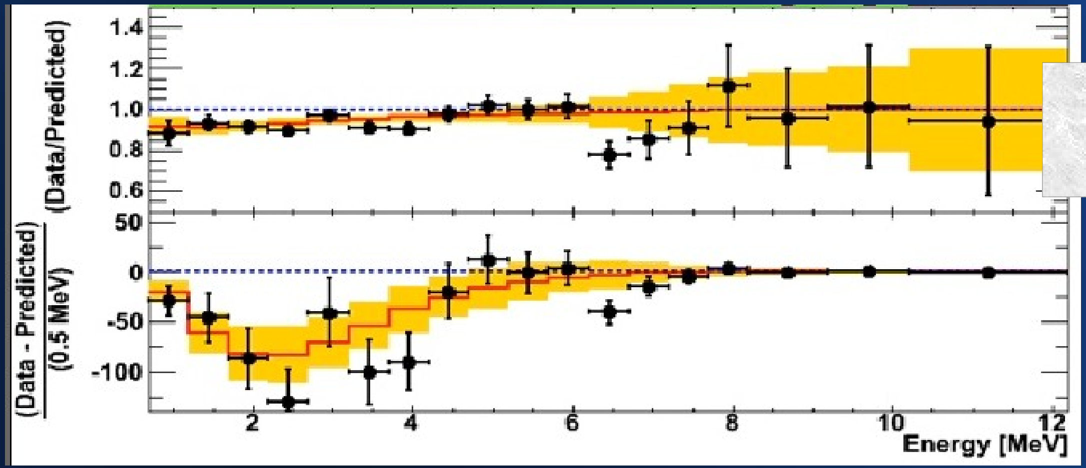
T.Schwetz

- Is this the end of the road?

Precision vs Accuracy

“Missing” piece: L/E analysis

- Spectral shape fit is a must to measure θ_{13}:
  - Compatibility with θ_{13}-driven oscillation
  - Rate analysis: any deficit interpreted as θ_{13}
  - Background model may bias the value of θ_{13}

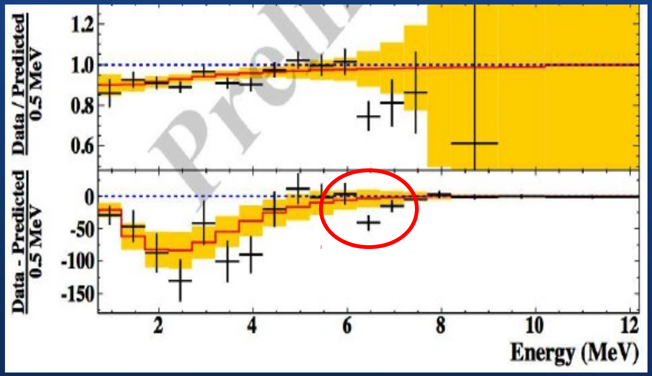


So far, only in Double Chooz:

- Spectral fit to θ_{13} and backgrounds
- Consistent with θ_{13} oscillation

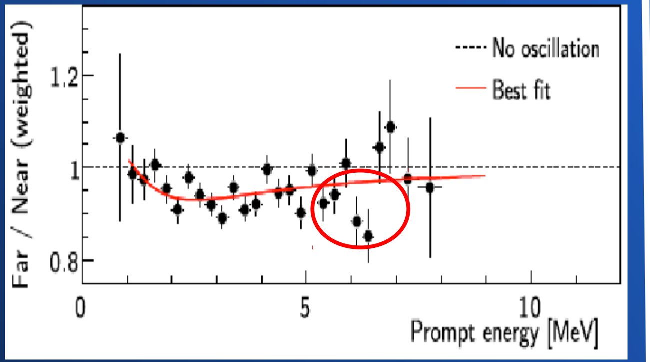
“Missing” piece: L/E analysis

Double Chooz



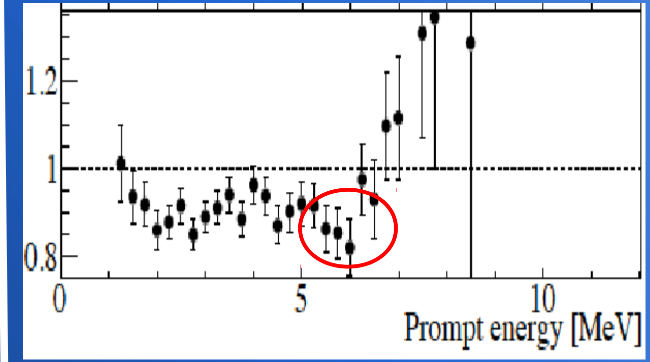
- **R+S analysis**
- N_{obs}/N_{exp}: MC
- short E/L: no rise

Daya Bay



- R-only analysis
- “Healthy” shape
- Longer BL: rise

RENO

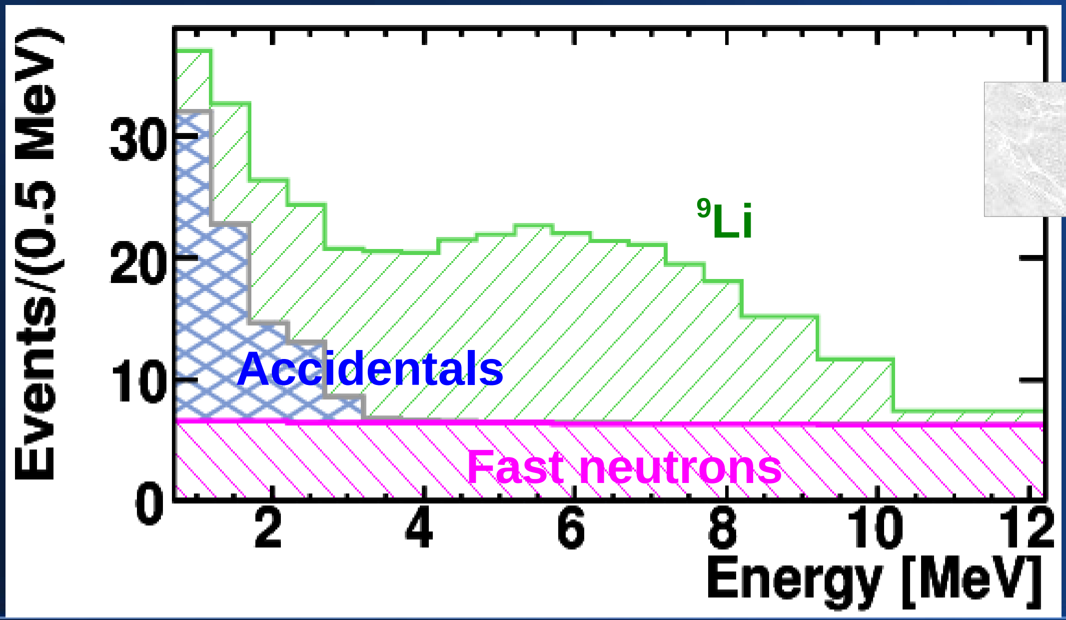


- R-only analysis
- Unique shape (?)
  - θ_{13}?

- All experiments show a feature around 6 MeV (?)
  - Rate-Only: this deficit *impacts* the θ_{13} value...

“Missing” piece: backgrounds

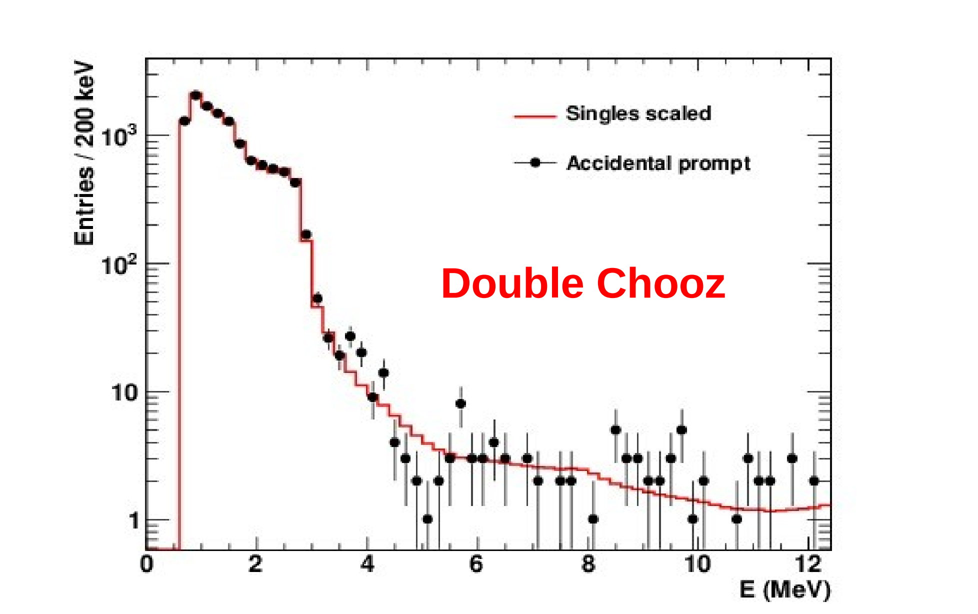
- Once correlated systematics are canceled (multi-detector setup)...
  - Backgrounds are one of the main systematics sources
  - Need an accurate Rate+Shape knowledge
    - Fast-n and cosmogenics might bias θ_{13}



So far, only in Double Chooz:

- R+S background analysis
- Up to five independent x-checks
  - Shape: limited by stats

Accidentals



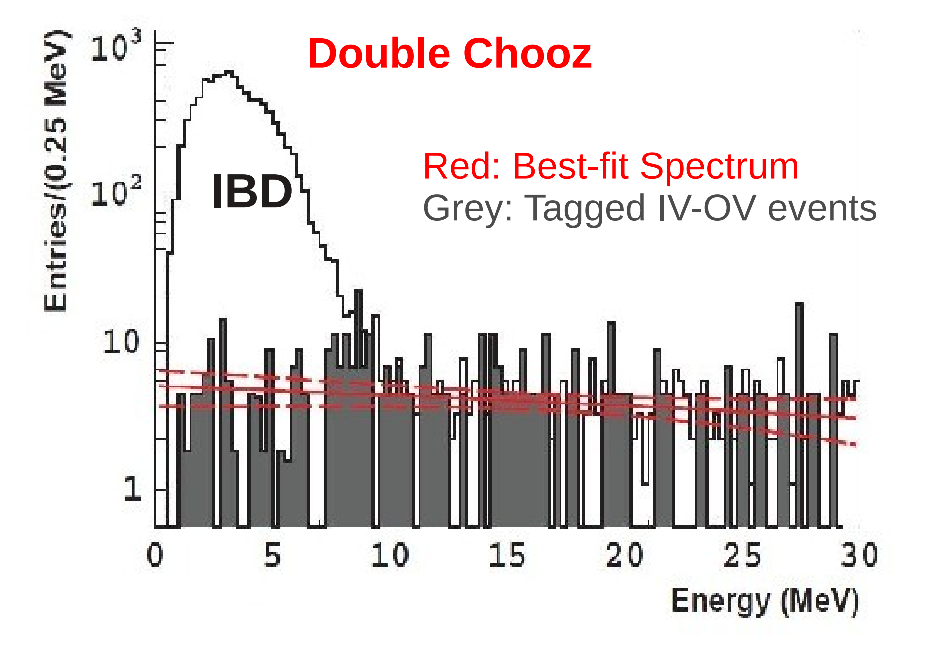
Random coincidences of β-decay + n-like

- coincidences in off-time window
- Very well known: no impact on θ_{13}
  - δBG/Signal ~0

S = signal rate
B = background rate

FAR DET.	Rate (d^{-1})	δB/B (%)	B/S (%)	δB/S (%)	S(d^{-1})
DC	0.261±0.002	0.8%	**0.6%**	0	45
DB	3.30±0.03	0.9%	4.7%	0	70
RENO	0.68±0.03	4.4%	0.9%	0	73

Fast neutrons and stop-μ

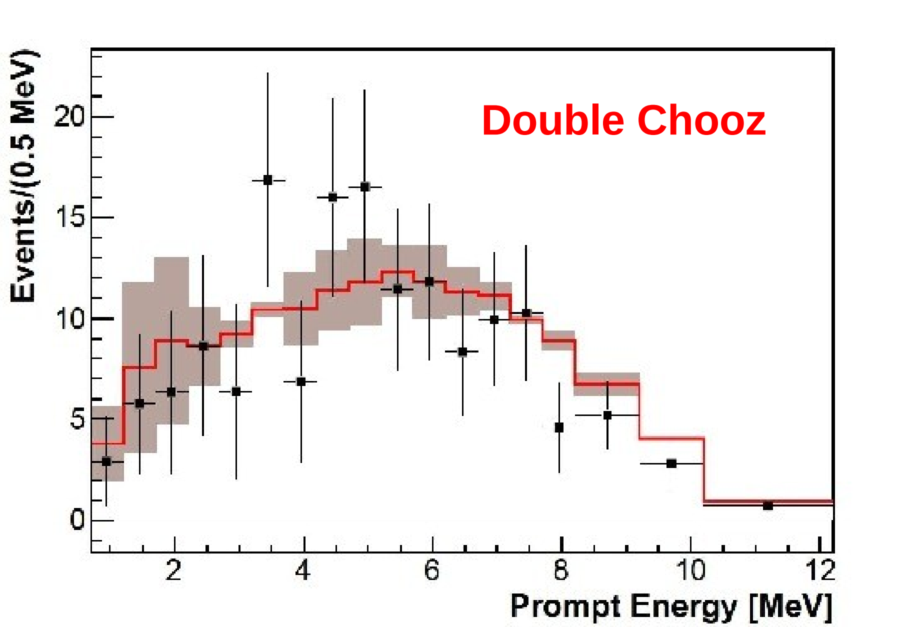


- Fast-n: proton recoil+ n-capture
- Stop-μ: muon + Michel e (DC, RENO?)
- **DB** and **RENO**:
  - Flat distribution, extrap. from E>12
    - possible bias up to 25%
      - If slope, bias on θ_{13}!
- **DC**: Fit to IV and OV tagged events (<12MeV!)
  - Best fit: slope, consistent with flat
  - θ_{13} Fit: pull for rate consistent

FD	Rate (d^{-1})	δB/B (%)	B/S (%)	δB/S (%)
DC	0.67±0.20	30%	1.5%	0.4%
DB	0.04±0.04	100%	0%	0%
RENO	0.97.±0.06	6%	1.3%	0%

Cosmogenics

- Spallation products from μ: β-n emitters (^{9}Li,^{8}He)

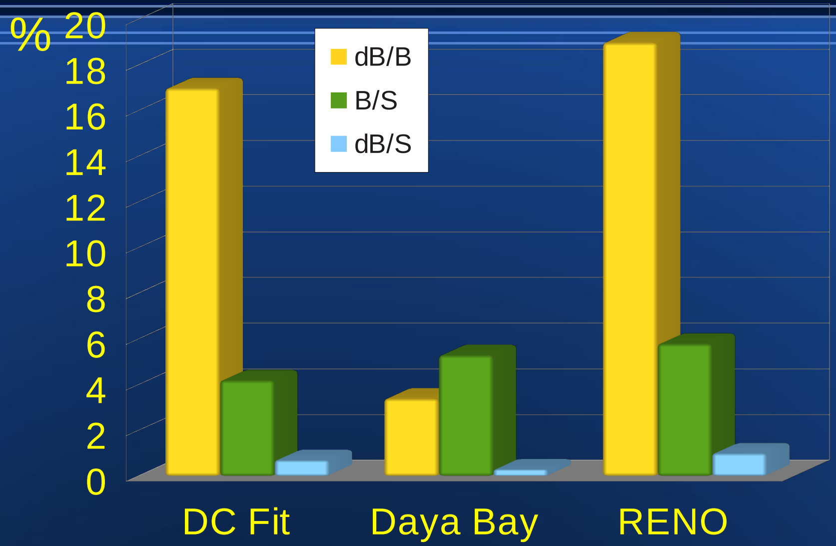


- DC, DB, RENO:
  - Rate estimated from time distribution w.r.t to last muon
- DC: rate+shape in θ_{13} fit
  - Shape: MC(KamLAND) + DC data
  - Consistent fit pull, error reduced

FAR DET.	Rate (d^{-1})	δB/B (%)	B/S (%)	δB/S (%)
DC	1.25±0.54	43%	2.7%	1.2%
DC fit	1.00±0.29	29%	2.2%	0.6%
DB	0.16±0.11	69%	0.2%	0.2%
RENO	2.59±0.75	29%	3.5%	1.0%

Large δBG/Signal:
The most important background

Total background



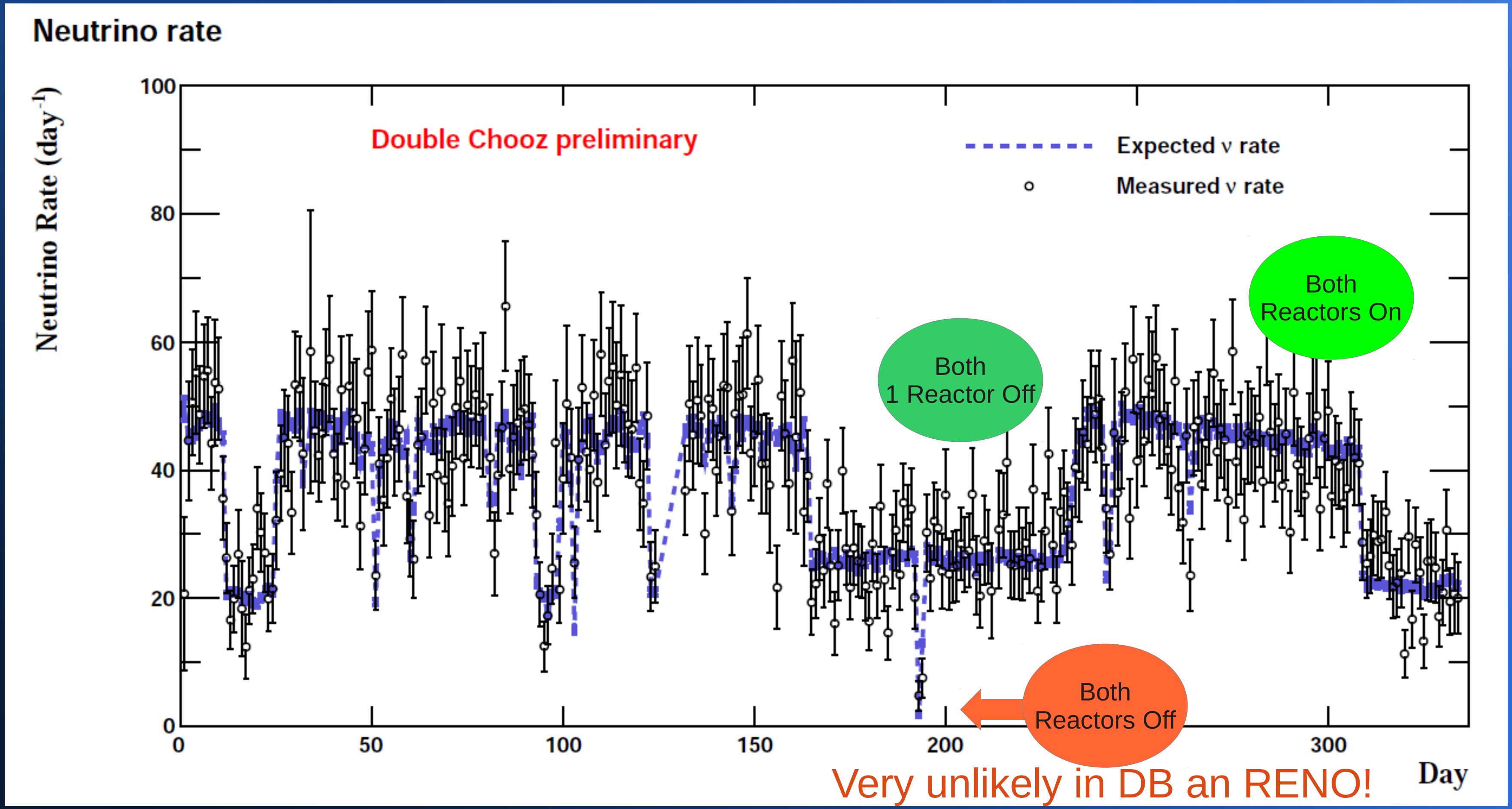
FAR DET.	Rate (d^{-1})	δB/B (%)	B/S (%)	δB/S (%)
DC	2.2±0.6	27	4.9	1.3
DC fit	1.9±0.3	17	4.2	**0.7**
DB*	3.7±0.2	3.4	5.3	**0.3**
RENO	4.2±0.8	19	5.8	1.0

*DB: extra bkg of 0.2±0.2 events/day from Am-C calibration source

- Day Bay: impressive δB/S (almost no cosmogenics and fast-n background)
- DC: best B/S and unique in providing x-checks:
  - Pulls in a shape-constrained θ_{13} fit
  - Two integration periods (2R-1R) in θ_{13} fit
  - **Fit of the Observed vs expected rate and reactor-off data**

Total DC background

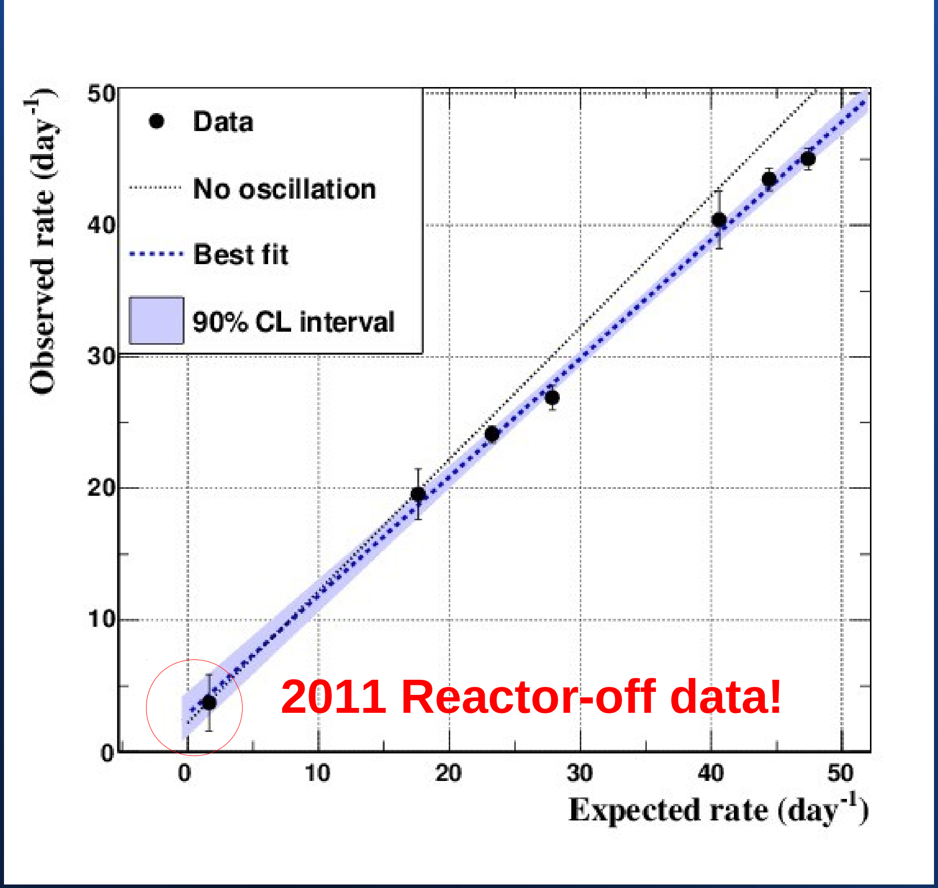
Observed vs Expected Candidates



Data: not background subtracted

Total DC background

Observed vs Expected Candidates

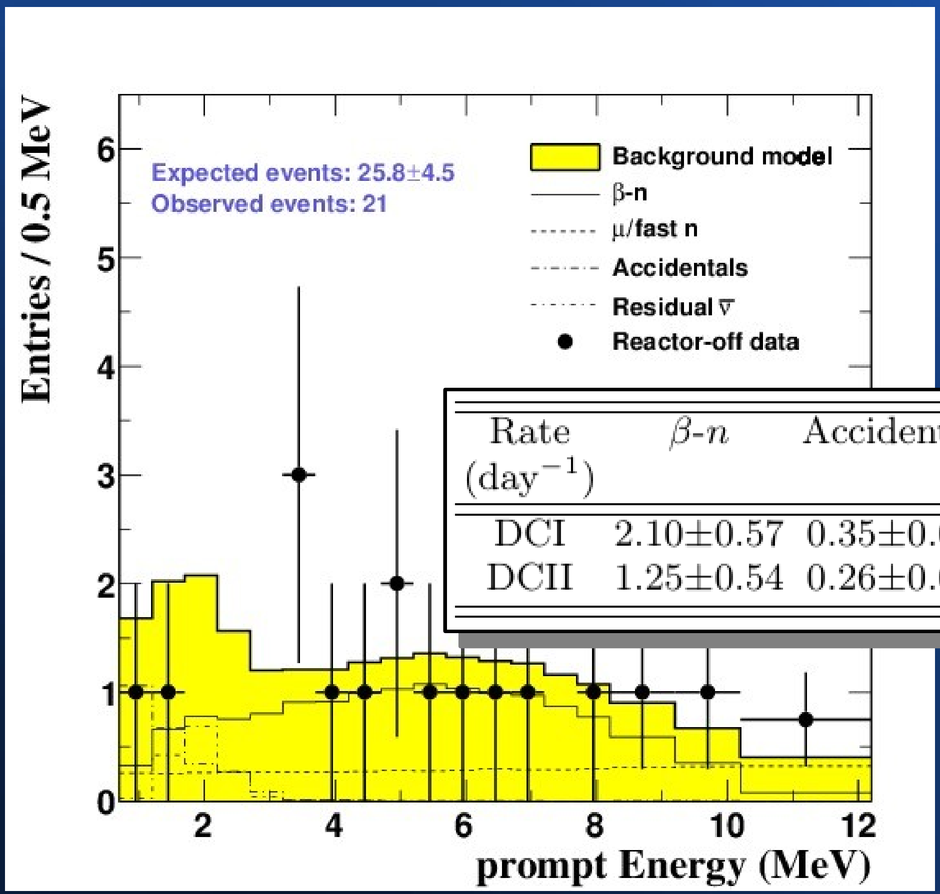


- 2011 Reactor-off data: 0.84 day
  - Direct total BKG measurement:
  - BKG rate = **2.2 events/day**
  - Consistent with estimation:
    - 2.2 ±0.6 event/day
- Best fit extrapolation @ N_{exp} = 0:
  - **2.9 ± 1.1 event/day**
    - ***Independent BG measurement!***

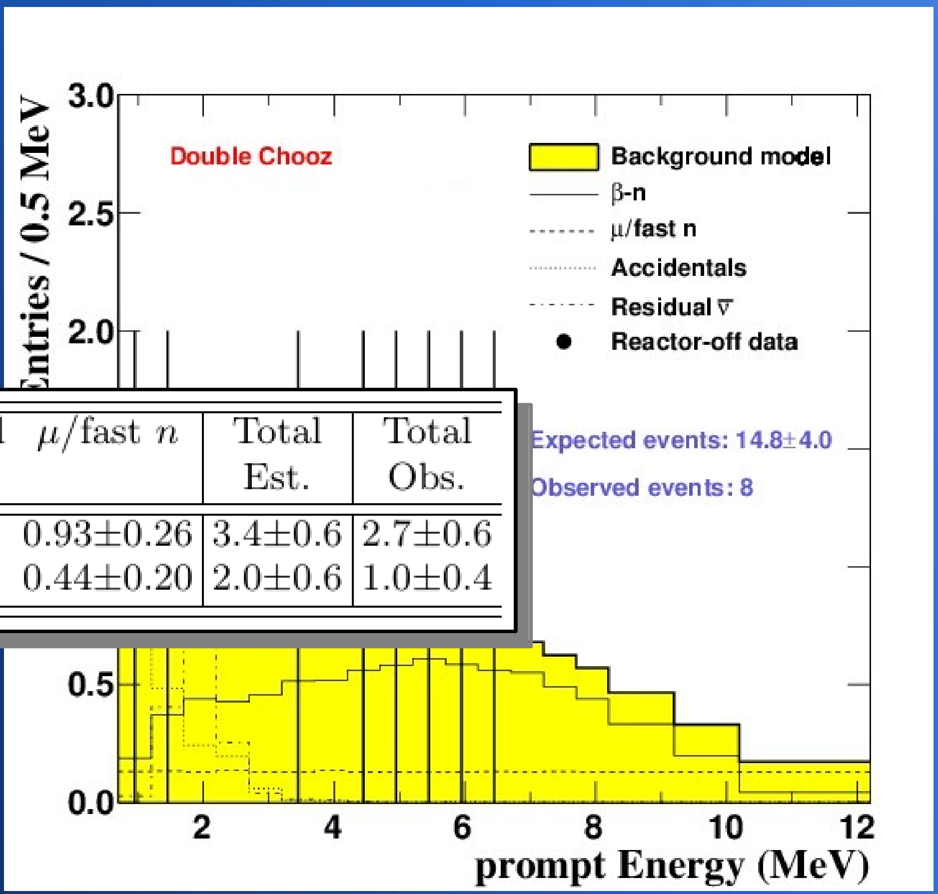
Total DC background

Reactor-Off data

2011 and 2012 reactor-off data samples: 7.53 days



IBD selection in first DC publication



IBD selection in second DC publication

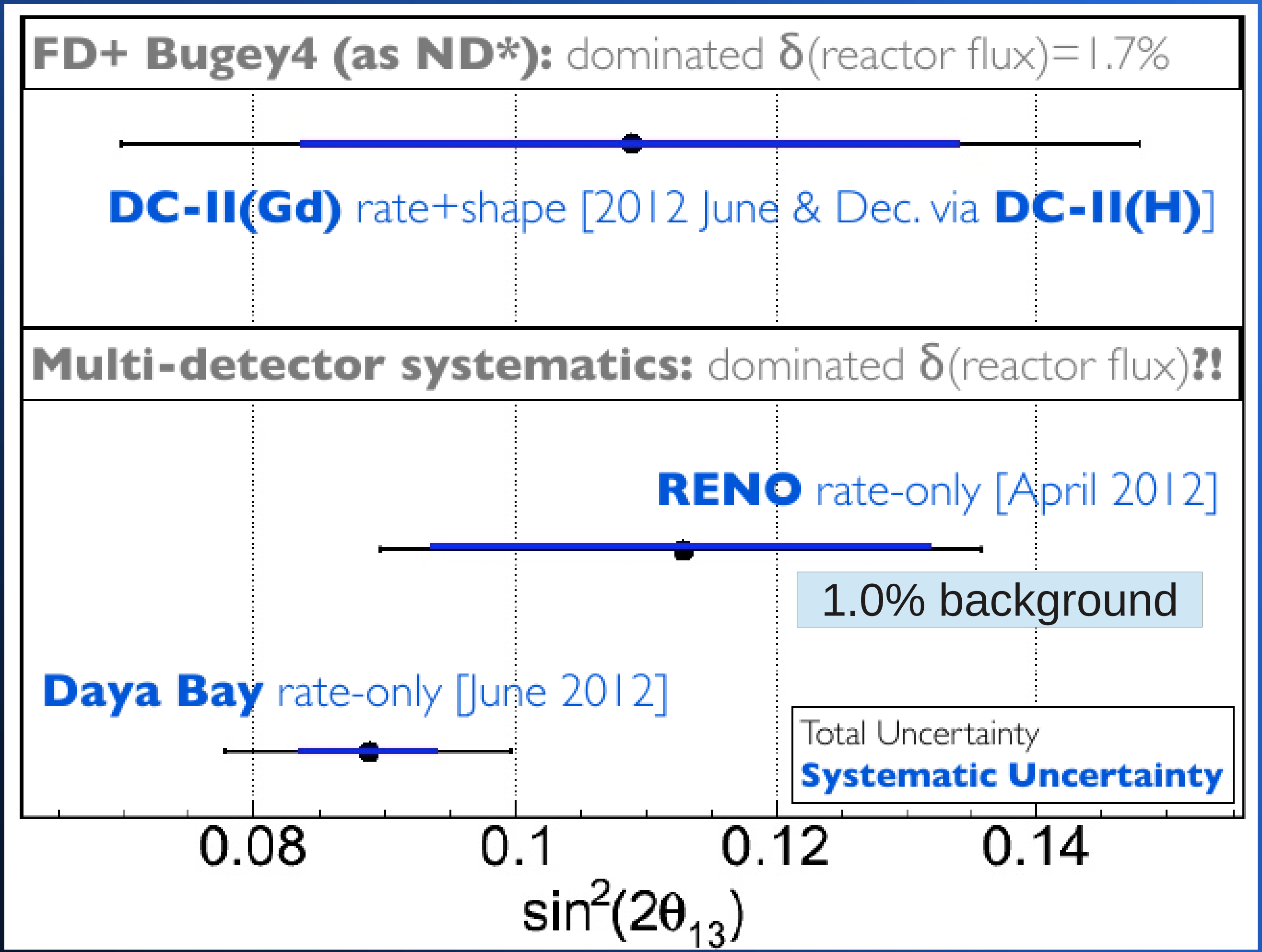
Rate (day^{-1})	β-n	Accidental	μ/fast n	Total Est.	Total Obs.
DCI	2.10±0.57	0.35±0.02	0.93±0.26	3.4±0.6	2.7±0.6
DCII	1.25±0.54	0.26±0.02	0.44±0.20	2.0±0.6	1.0±0.4

arXiv:1210.3748

The Ultimate value of θ_{13}

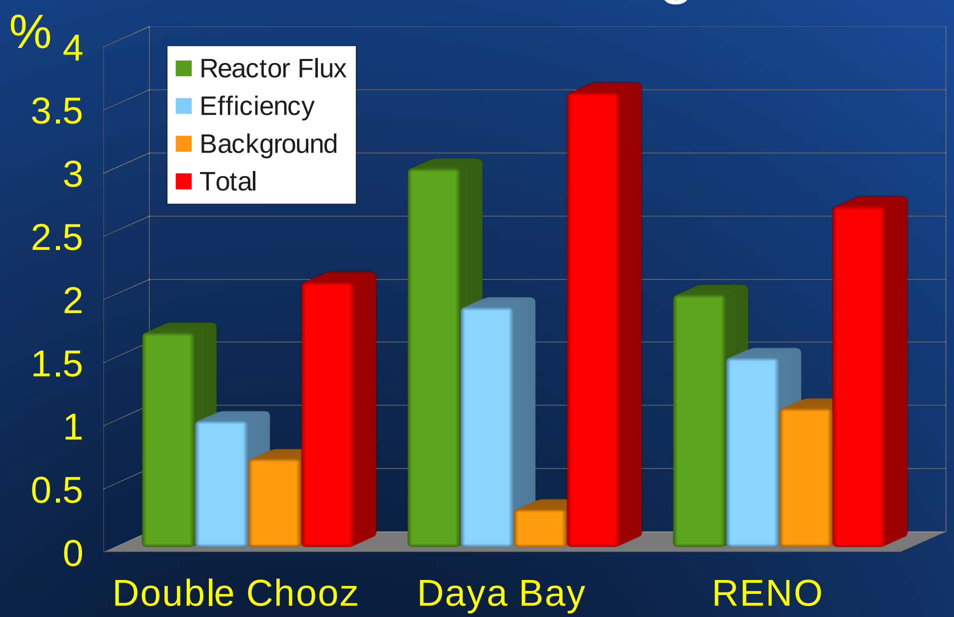
- Backgrounds
- Systematics
- Predictions

Current limiting systematics



Rate Systematics: FD only

- Without canceling the correlated systematics...



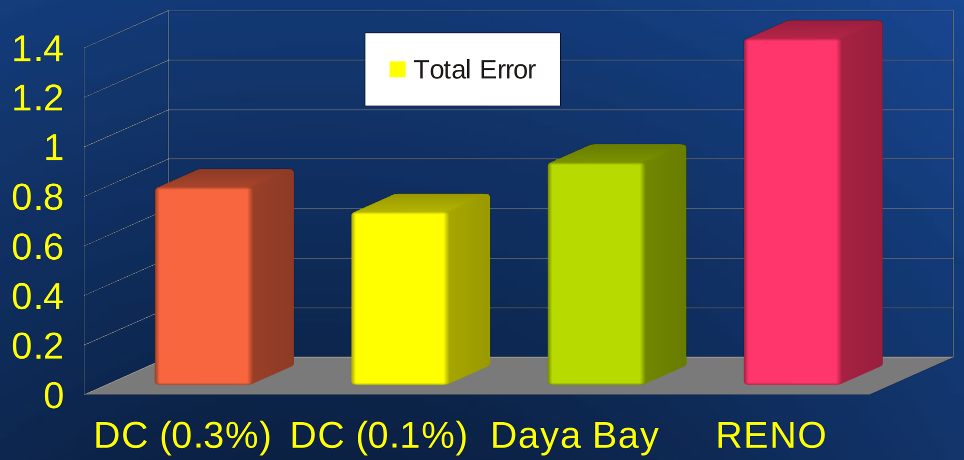
Normalization uncertainties

Error (%)	DC	DB	RENO
Reactor	1.7	3.0	2.0
Efficiency	1.0	1.9	1.5
BKG	0.7	0.3	1.1
TOTAL	**2.1**	**3.6**	**2.7**

- **Double Chooz**: the best one-detector experiment
  - most accurate knowledge on reactor fluxes
  - The smallest detection systematics

Rate Systematics: FD + ND

- Canceling the correlated systematics with the ND...

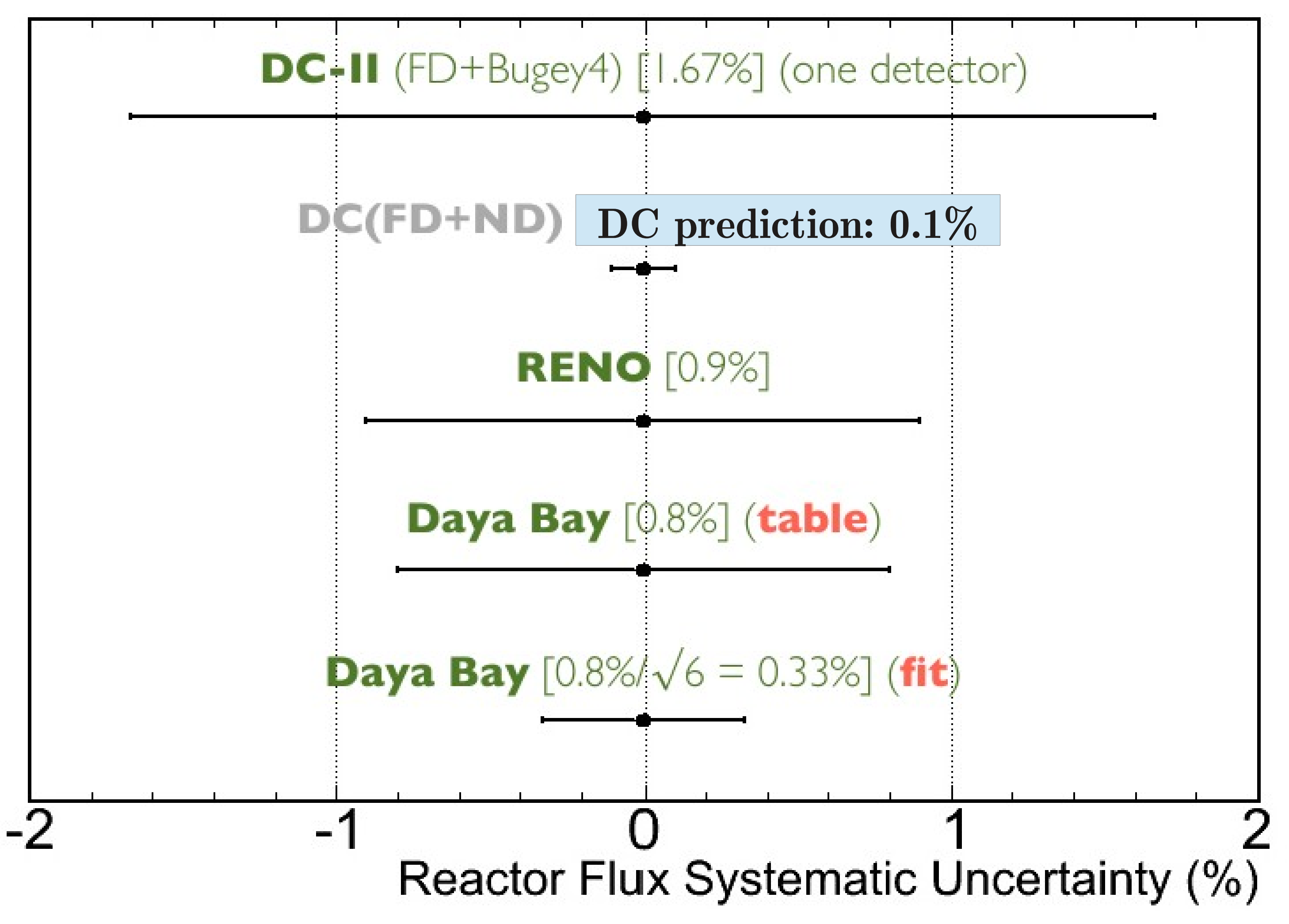


* DC estimates

Error (%)	DC*	DB	RENO
Reactor	0.1 ~~0.3~~	0.8	0.9
Efficiency	0.2	0.2	0.2
BKG	0.7	0.3	1.0
TOTAL	0.7-0.8	0.9	1.4

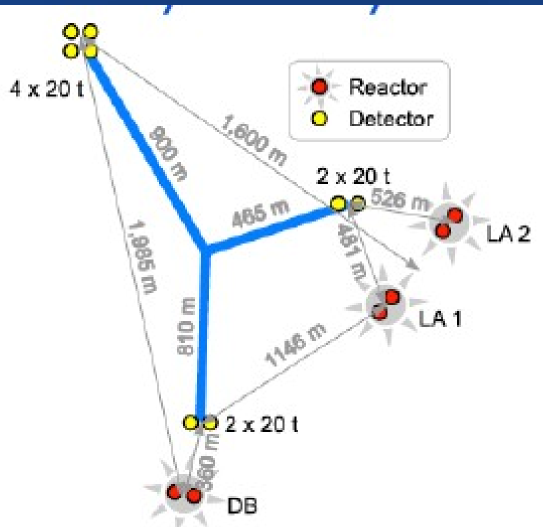
- **Daya Bay**: so far the best multi-detector experiment
  - Limited by the uncorrelated reactor systematics
- **Double Chooz**: expected competitive with DB
  - Room for improvement in background uncertainty

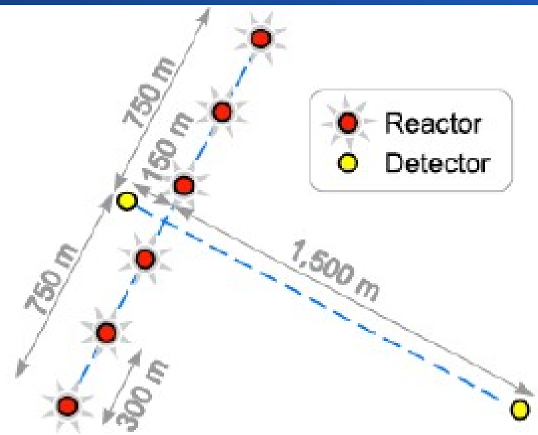
The dominant systematic

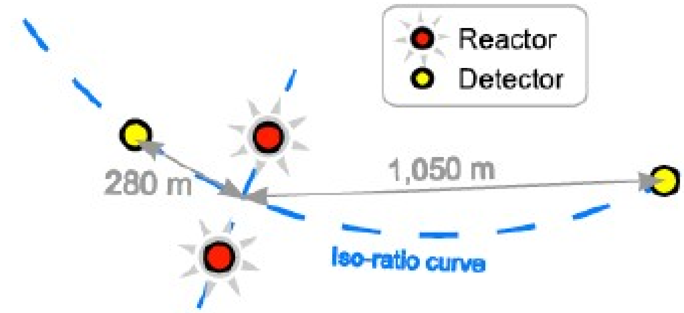


Uncorrelated flux uncertainty

Daya Bay	RENO	Double Chooz







- Each ND *sees different reactors*
- DB geometry: 0.8%/√6 = 0.3% (?)
- RENO: 0.9%
- **Limiting systematic in Daya Bay and RENO**

- ND sees 1 *virtual* reactor
  - isoflux
- **Error: 0.1% (under study)**

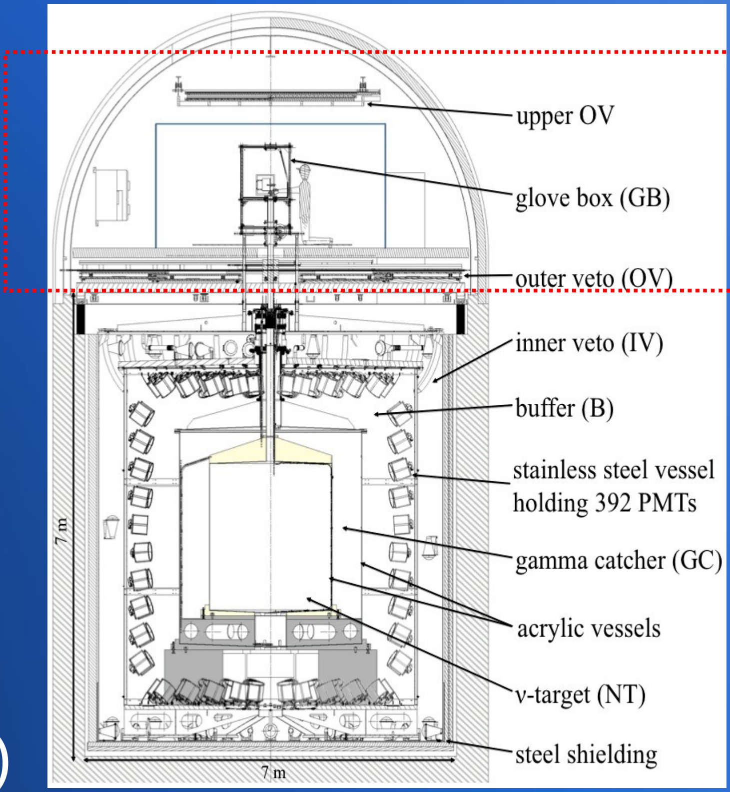
Towards the ultimate Θ_{13} value

Ultimate = systematics limited, reliable background model, and R+S fit

- **Daya Bay: the most precise result so far**
  - Precision limited by uncor. flux uncertainty (0.8%)
  - Also limited ways to test the background model
  - Oscillation shape results not yet available
- **RENO: good precision, but *debatable* numbers and results**
  - Precision limited by uncor. flux uncertainty (0.9%)
  - Also limited by backgrounds (1%): No OV, no scint. IV (can improve?)
- **Double Chooz**: shape results, precise background model (can improve!)
  - The best FD-only experiment: good prospects for FD+ND
  - Not limited by uncorrelated flux uncertainty
  - ND not yet available: long time to get enough stats

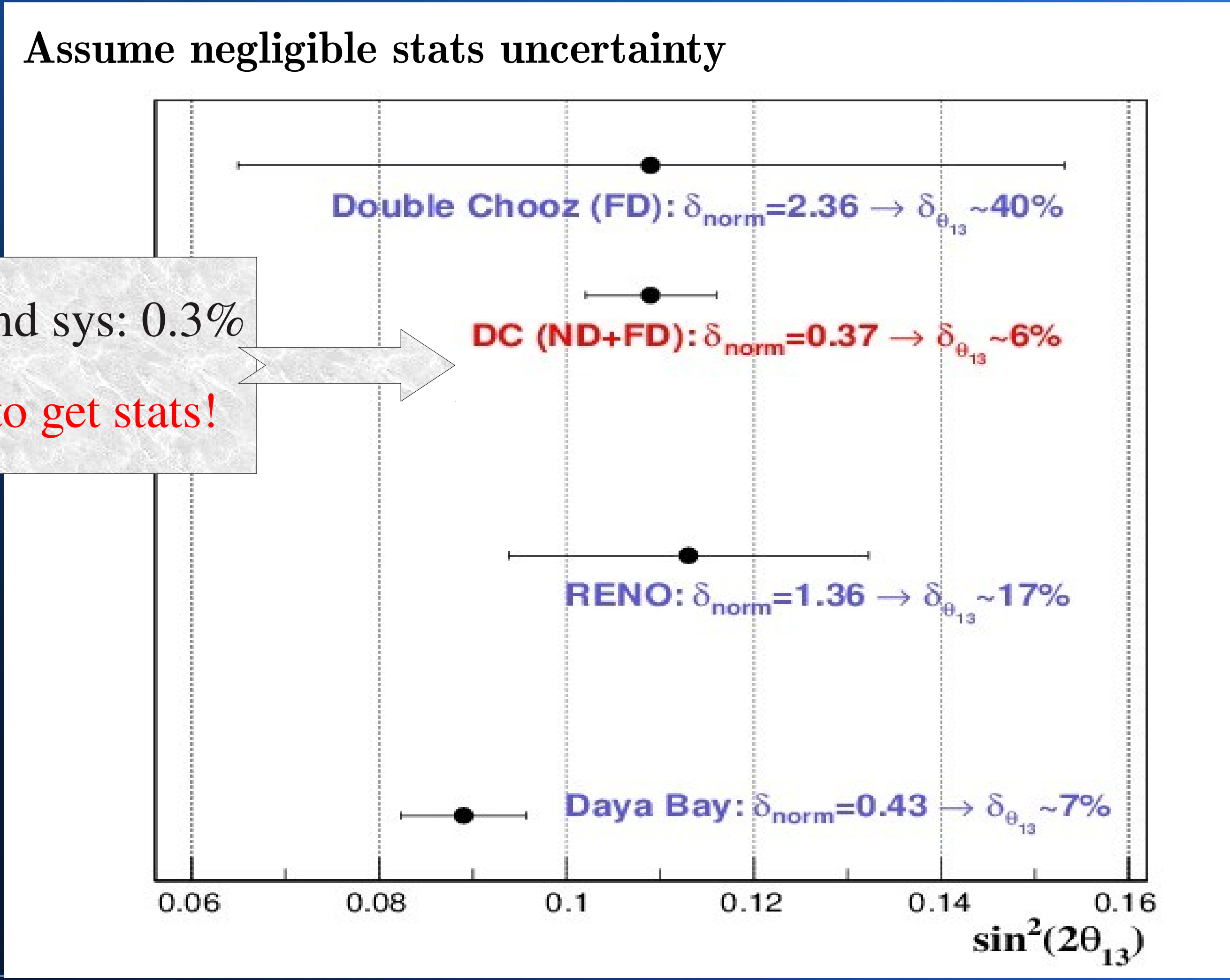
Improving DC backgrounds

- More reactor Off-Off data?
- Cosmogenics:
  - Getting more statistics
  - Fitting ^{9}Li R+S in θ_{13} fit
- Correlated background (FN/SM)
  - Getting larger stats sample
  - Fully exploiting the IV tagging (FN)
  - Use of the outer muon veto (SM)



$\delta B/S \sim 0.3\%$

The ultimate θ_{13} value?



- Bkackground sys: 0.3%
- Long time to get stats!

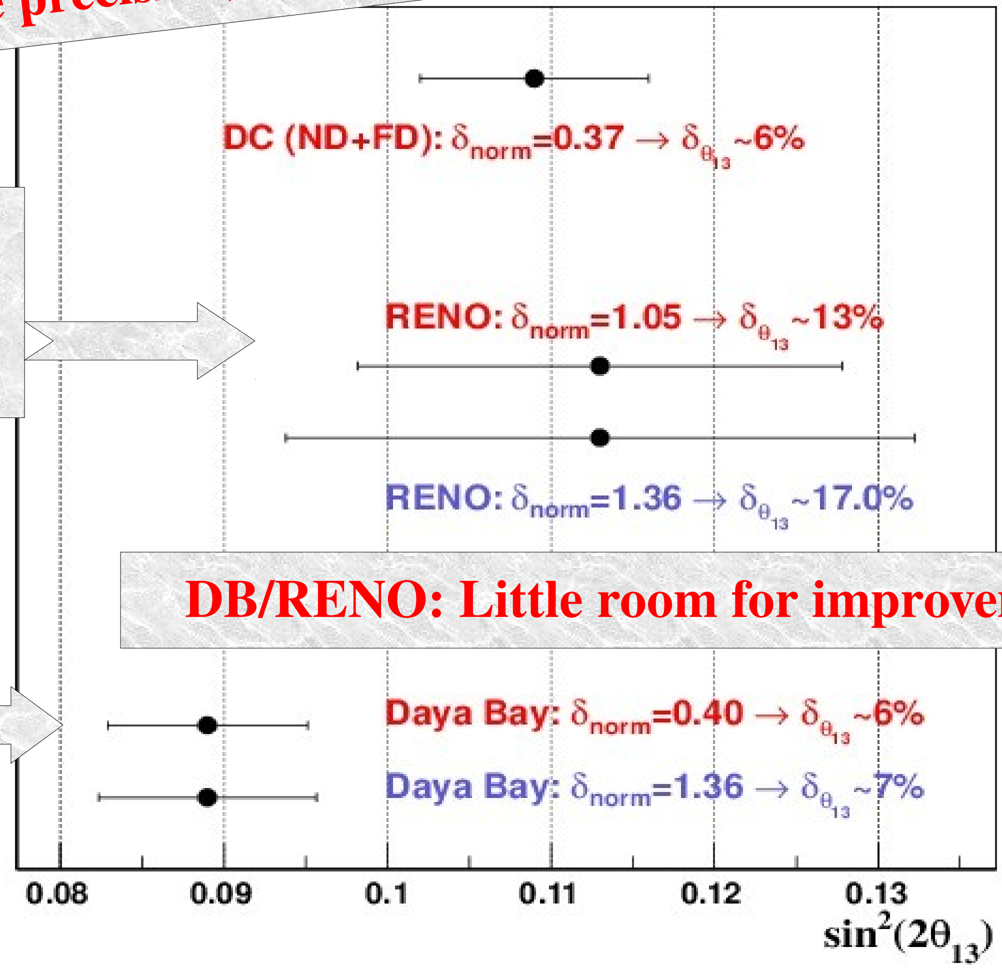
unofficial predictions. Rate Only!

The ultimate θ_{13} value?

Shape analysis will increase precision, but dificult to quantify

- Background sys: 0.5%
- x2 improvement

- Background sys: 0.5%
- x3 improvement



DB/RENO: Little room for improvement!

unofficial estimates. Rate Only!

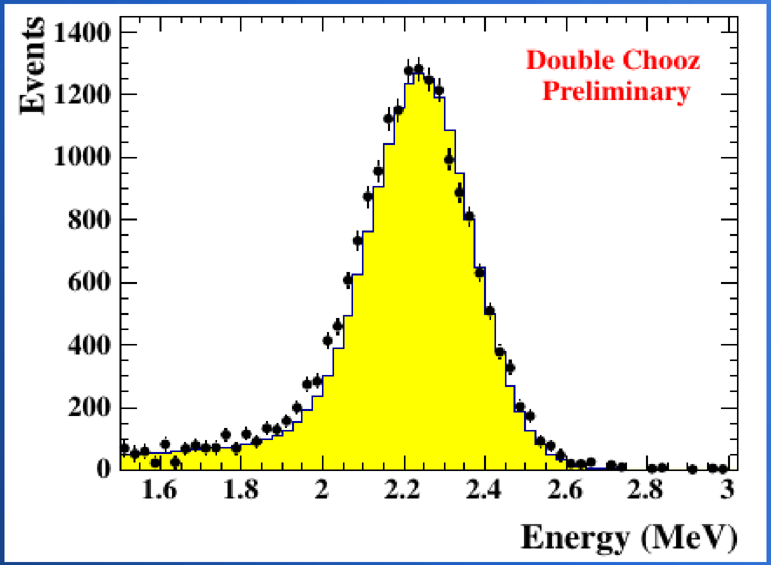
Beyond the “standard”

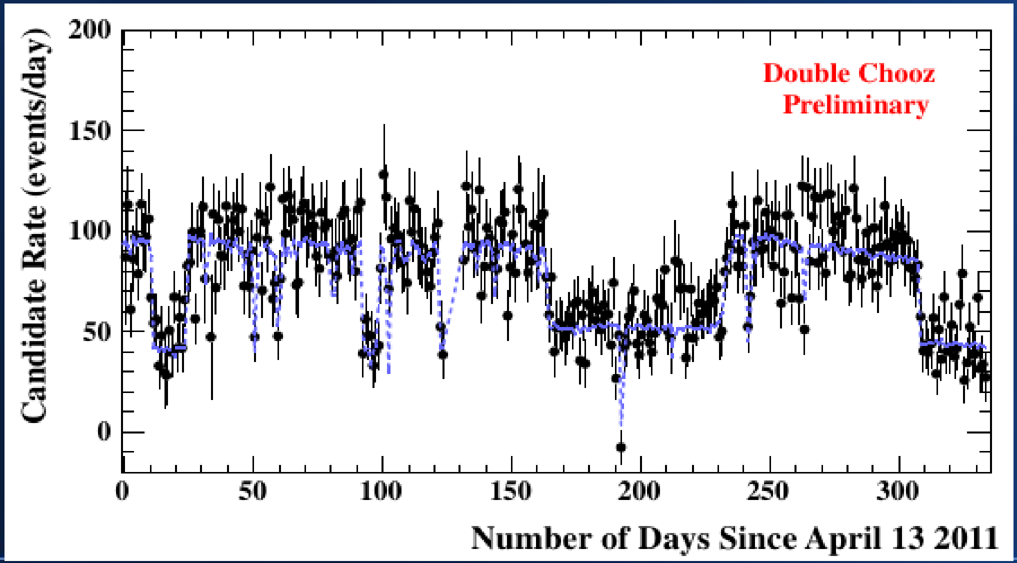
θ_{13} analysis

Double Chooz n-H analysis

Neutrino selection based on n captures in H, instead of Gd (F. Suekane)

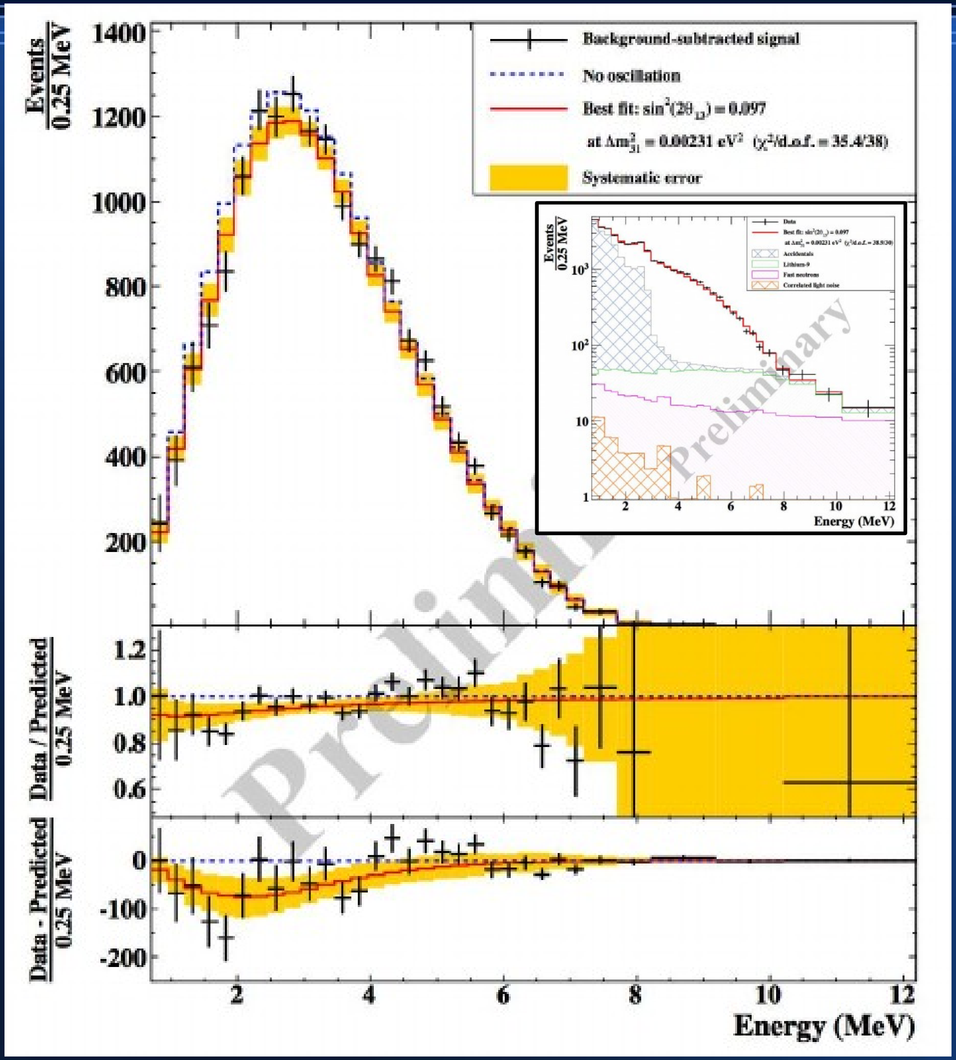
- Provides x2 signal statistics (NT + GC)
- Data sample completely independent
    - Systematic uncertainty very different
    - Excellent x-check of Gd analysis result
- Better constrain on θ_{13} by combining H+Gd?.

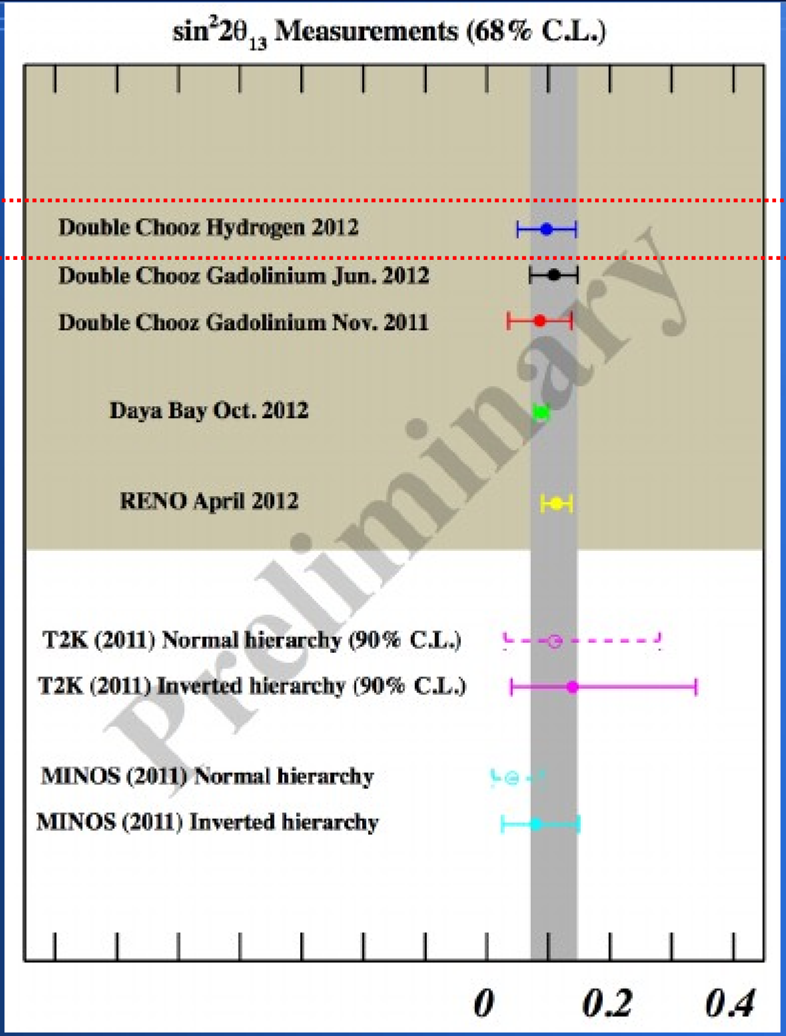




- Delayed IBD signal below 3.5 MeV
- Extended ΔT cut
- Dominant background: Accidentals
    - But uncertainty very small!.

Double Chooz: n-H results





Paper in preparation

All in all...

Summary

- Reactor experiments have proven $\theta_{13}>0$
  - Daya Bay, RENO and Double Chooz
  - DB: $>5\sigma$, DC: shape analysis, backgrounds
- Is this the end of the road?
  - Accuracy vs precision: beyond the # of σ
- The most accurate θ_{13}:
  - Oscillation shape analysis
  - Improved background model
  - Reduced uncorr. reactor flux sys?

Summary (II)

The Ultimate measurement still to come!

- DB: powerful setup and great performance
  - 8 different detectors, high fluxes, small backgrounds, …
  - Limited by reactor flux uncertainties
- RENO: large exposure, *debatable* numbers
  - Limited by flux uncertainty (background also?)
  - Difficult to predict its evolution
- Double Chooz: can be competitive with DB
  - Very precise knowledge of the background, reactor-off
  - Simple baseline: L/E, negligible flux systematic (ND+FD)
  - n-H analysis: improve precision on θ_{13}?
  - No Near Detector yet... so need to wait!


Thank you!
Photo: Lola Garrido