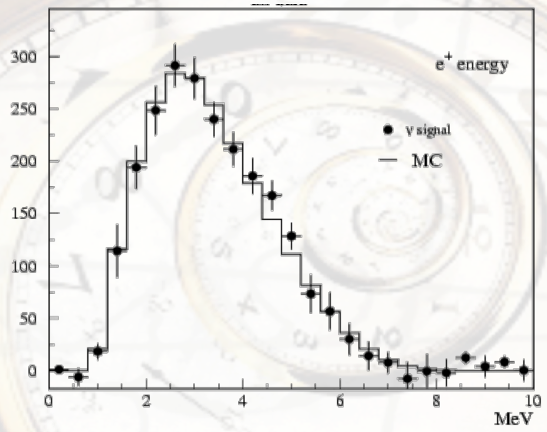
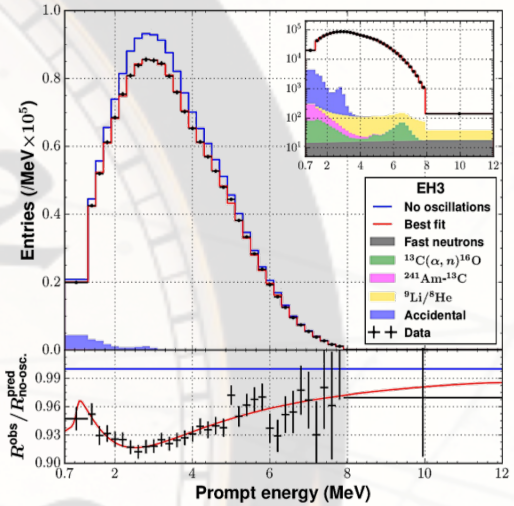
Reactor Neutrinos

1995 - 2018

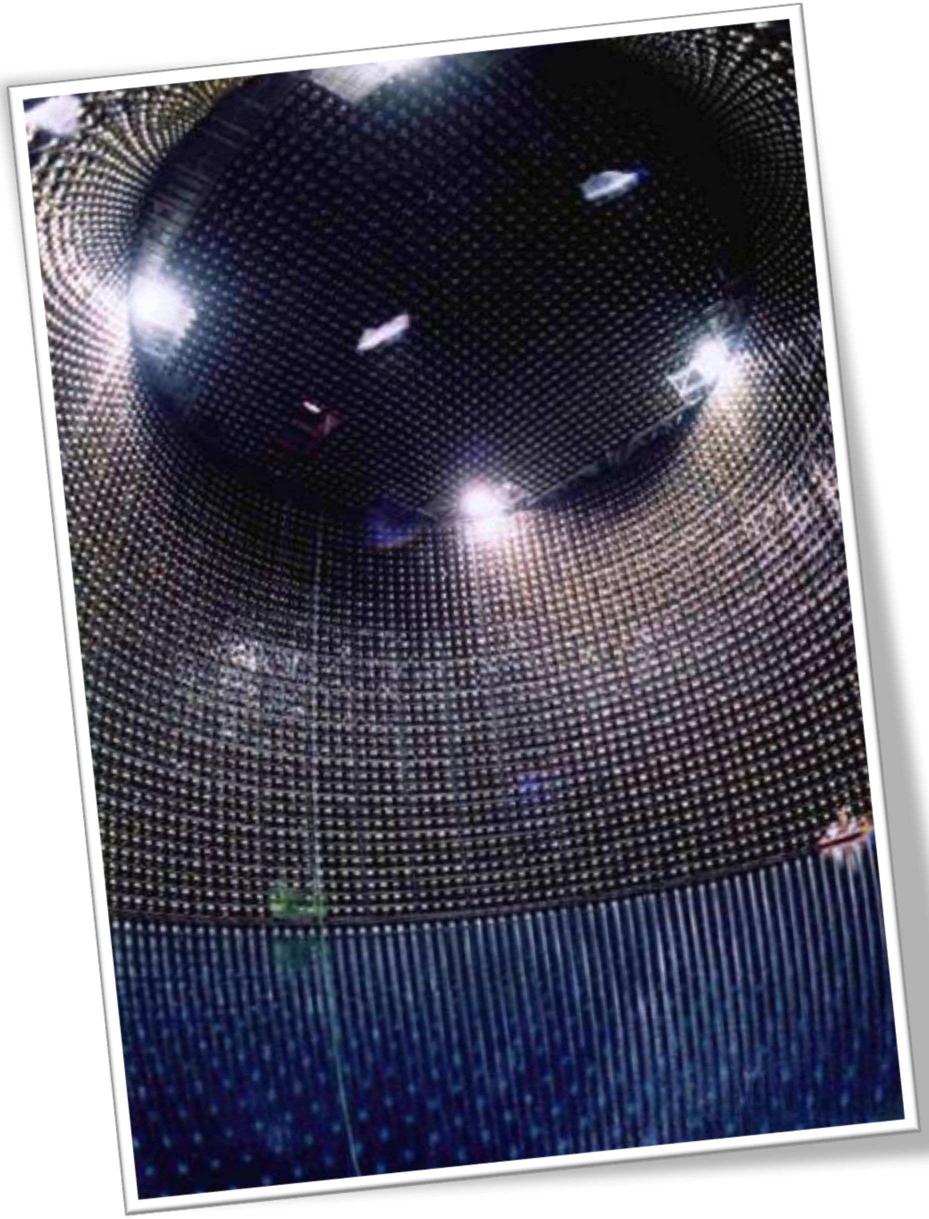




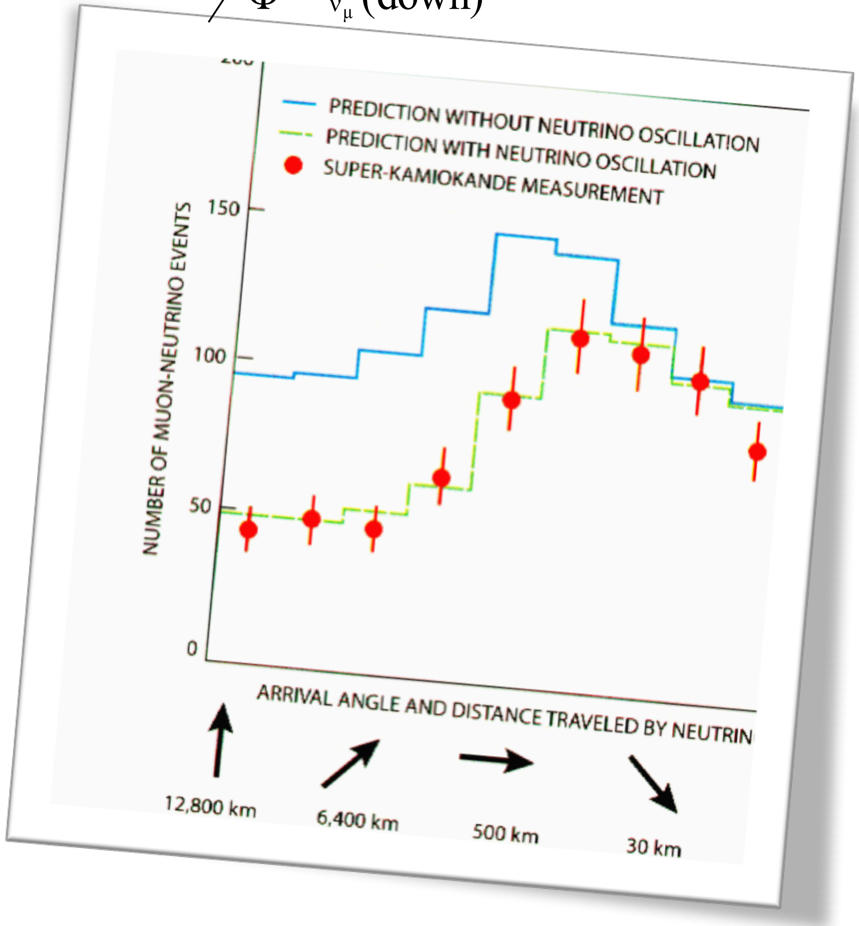
International conference on the History of the Neutrino
Paris, 07/09/2018

Thierry Lasserre
CEA-Saclay – APC – TUM/MPP

Context: Atmospheric Neutrino Anomaly

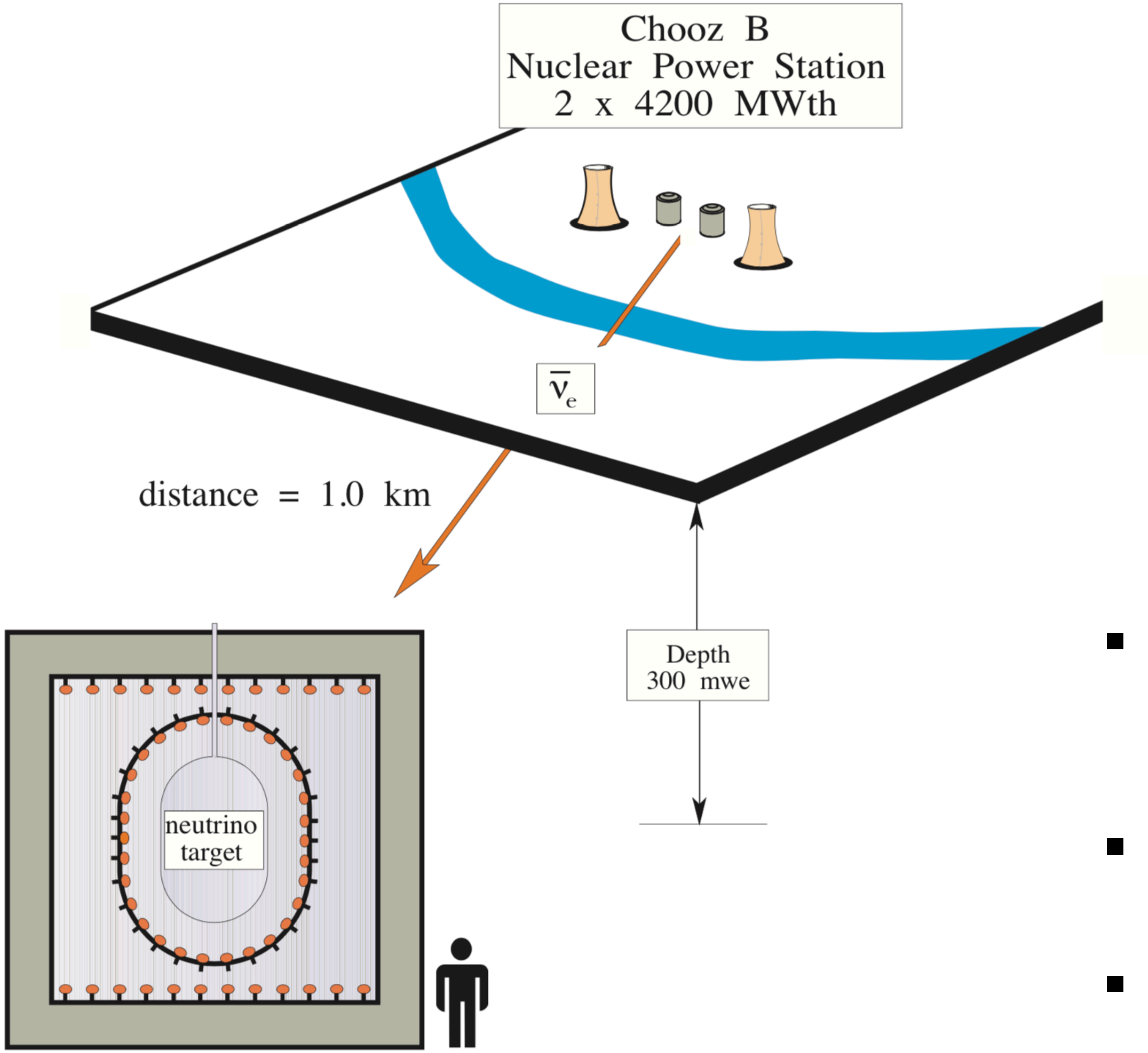


$$\Phi^{Atm}_{\nu_\mu}(up) \Big/ \Phi^{Atm}_{\nu_\mu}(down) = 0.54 \pm 0.04$$



Neutrino do have mass and mix

CHOOZ (1997-1998)

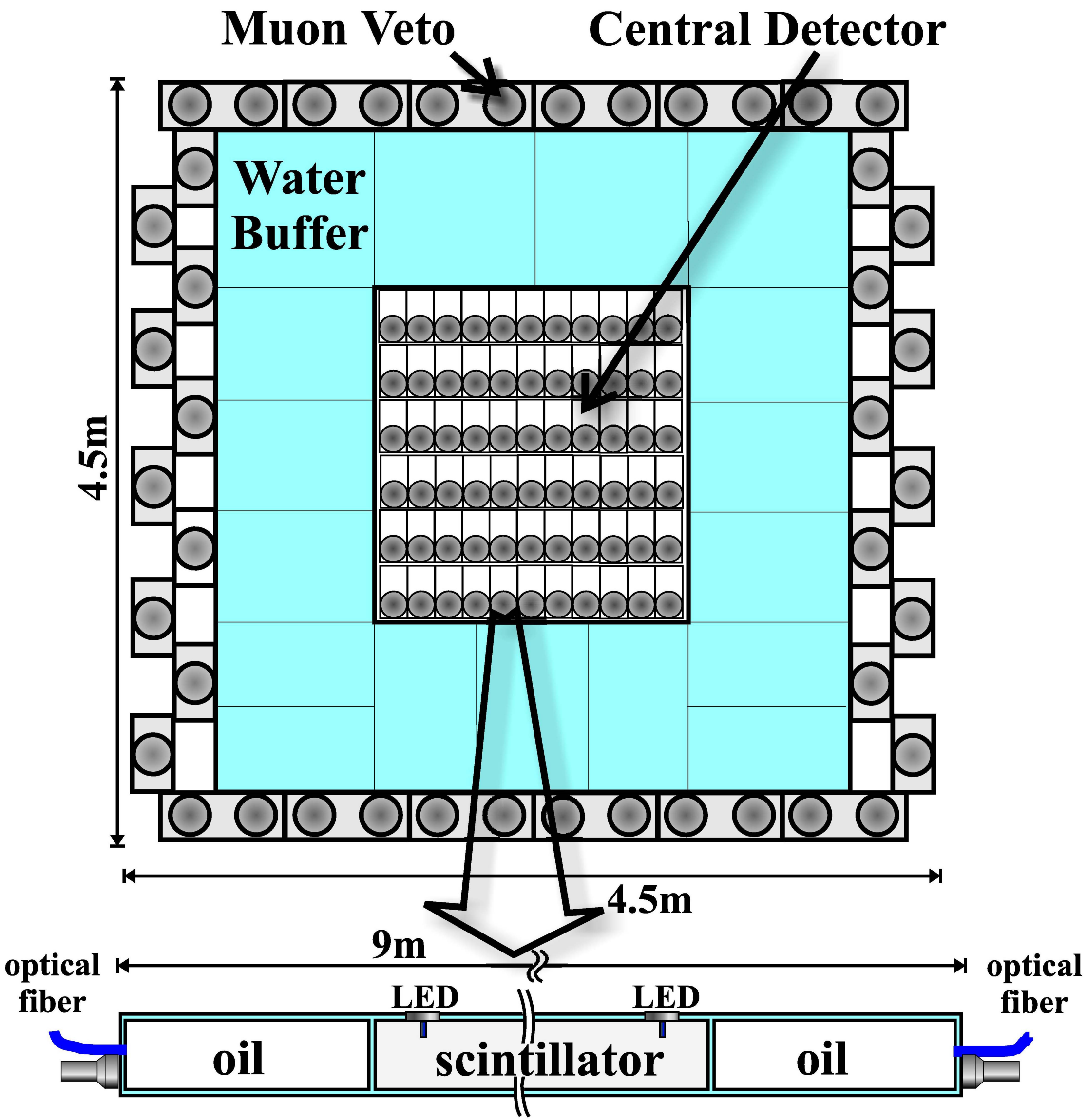


- CHOOZ reactor, Ardennes (France) Underground gallery (300 mwe) found by the Mother of H. de Kerret!

- First large underground monolithic detector for reactor neutrinos.
- 2 cores: 2 x 4.2 GW
- 5 tons of Gd-doped liquid scintillator (degradation of its attenuation over time)

Palo Verde (1998-2000)

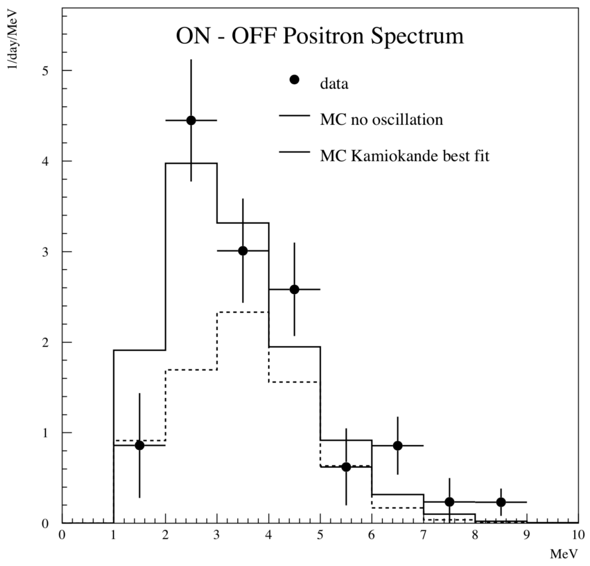
- Palo Verde Generating Station, Arizona, USA - 3 reactors: 11.6 GW
- Segmented detector
  (best suited for shallow depth, 32 mwe)
- 11.3 ton, Gd-loaded liquid scintillator
- 820 m baseline



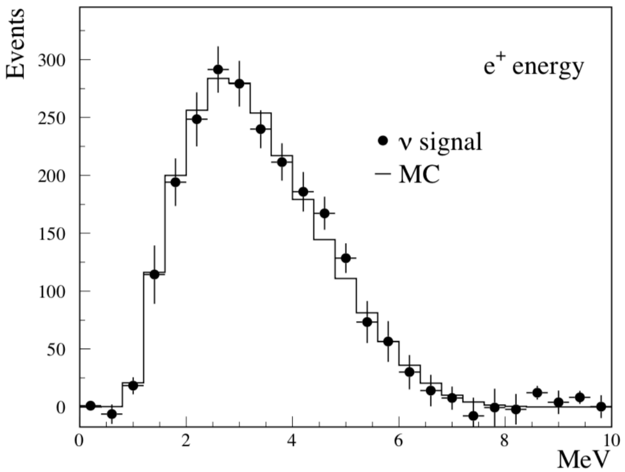
Results

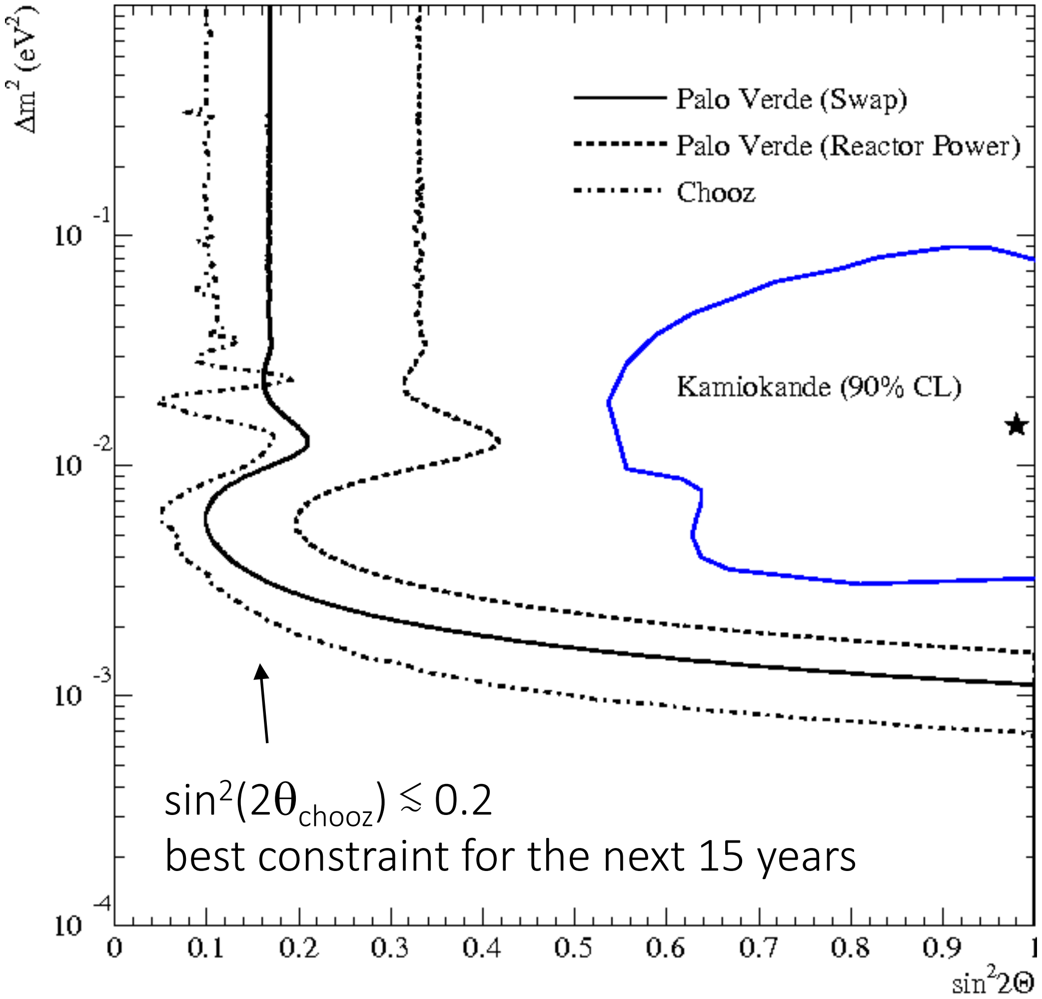
Neither Chooz nor Palo-Verde reported oscillation. This null-result eliminated $\nu_\mu \rightarrow \nu_e$ as the primary mechanism for the (Super-)Kamiokande atmospheric deficit

Palo-Verde
1000 evts



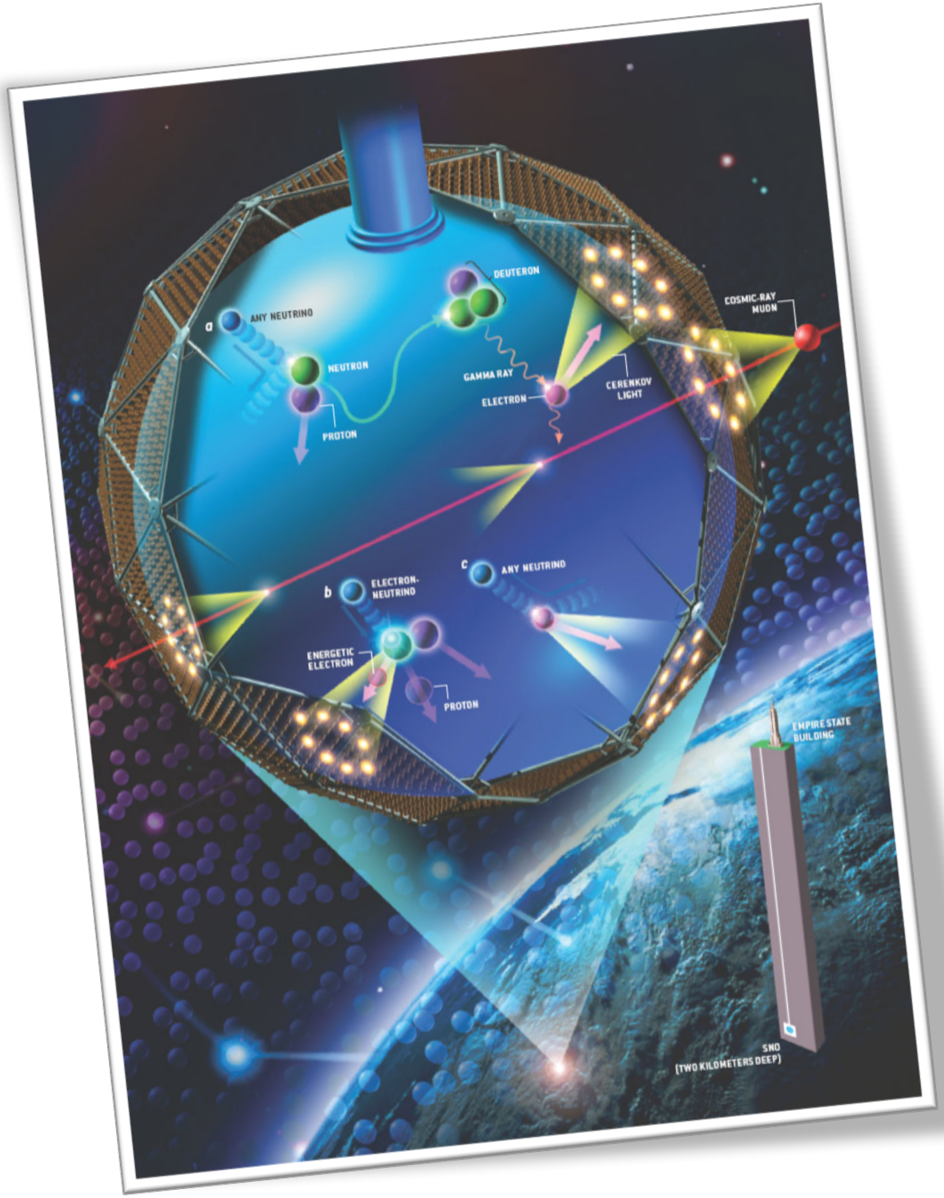
Chooz
1000 evts

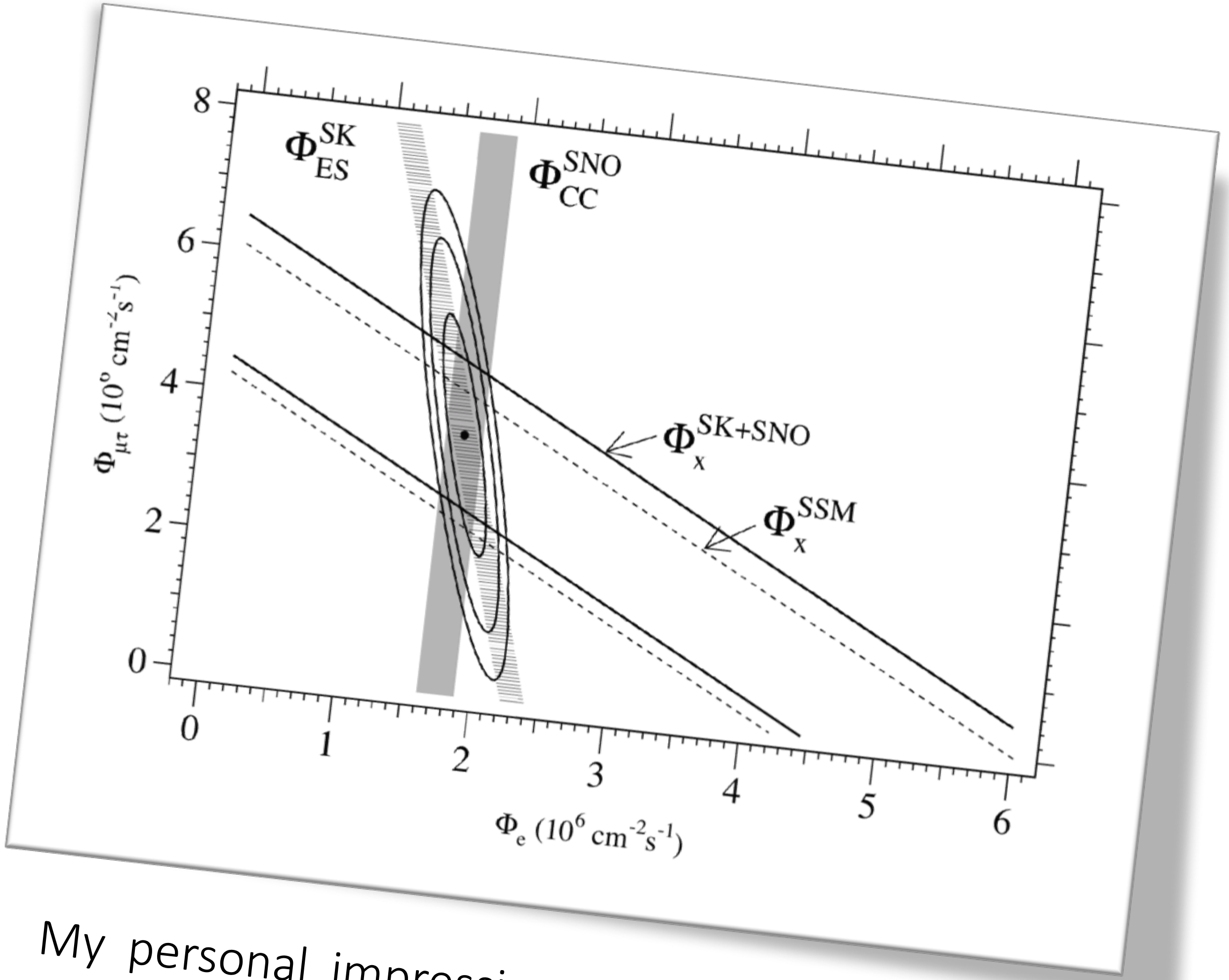




$\sin^2(2\theta_{chooz}) \lesssim 0.2$
best constraint for the next 15 years

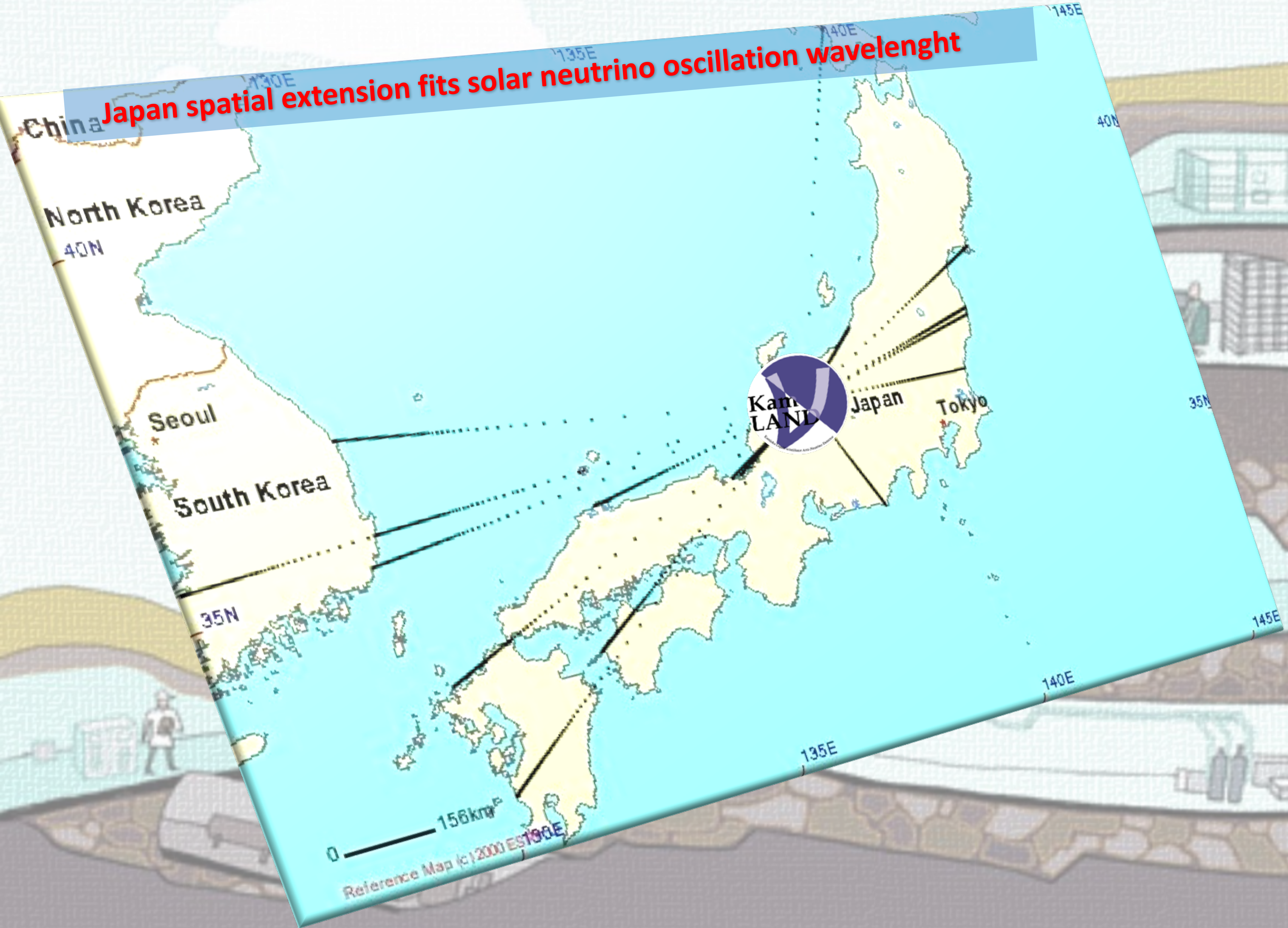
Context: Solar neutrinos till first SNO results (2001)





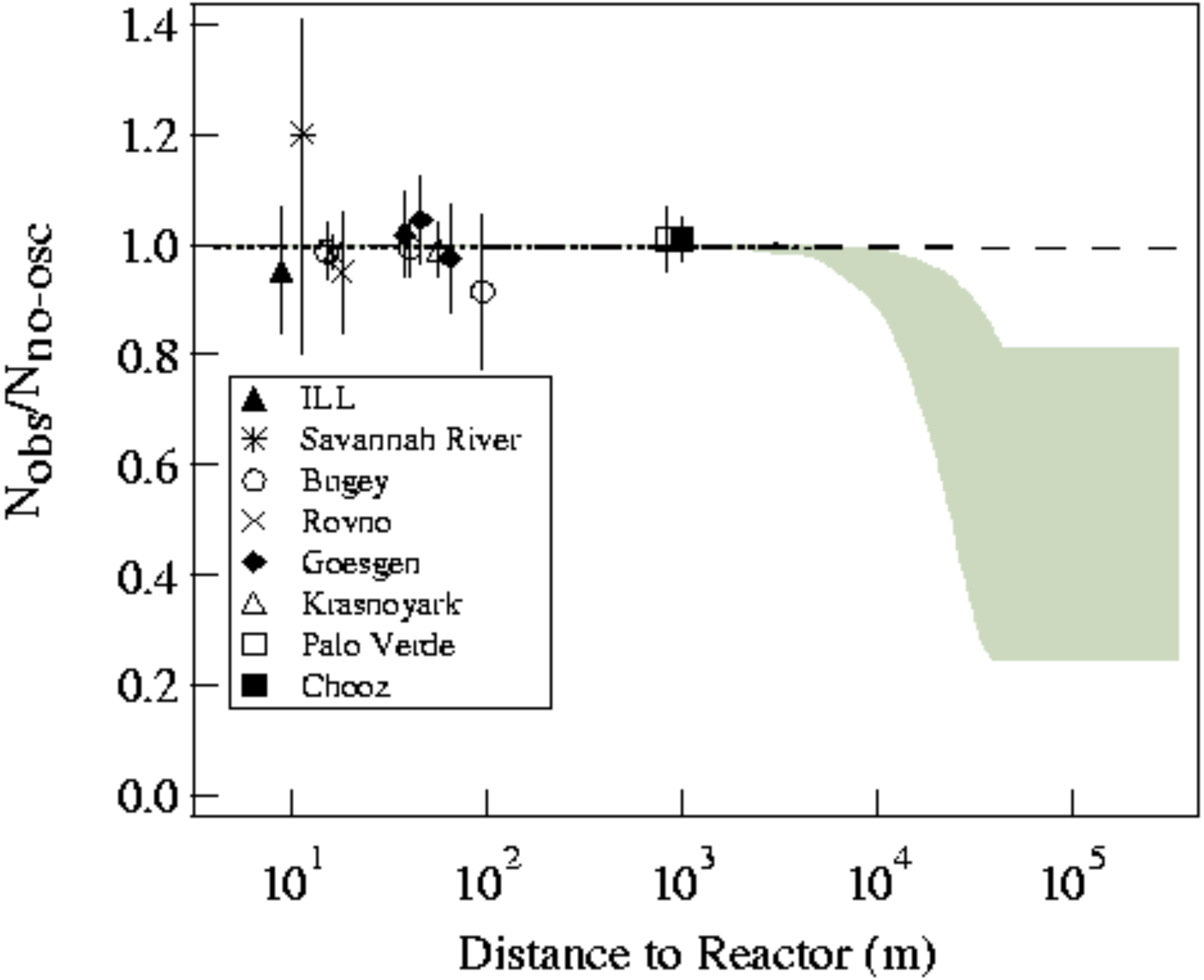
My personal impression at that time: a sizable fraction of the community considered neutrino beams as the –only – future of neutrino physics

Japan and Neutrino Oscillations: A perfect match…

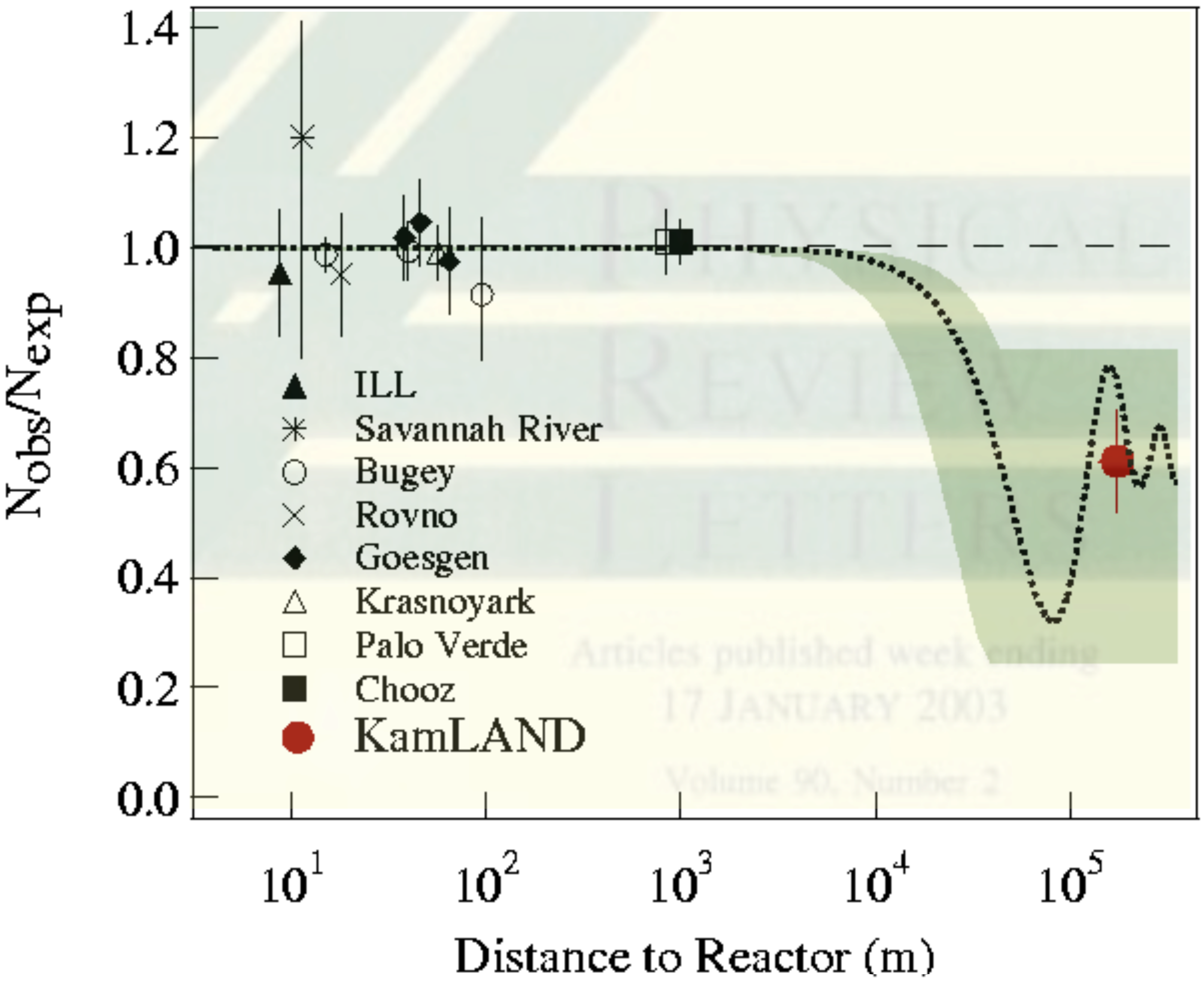


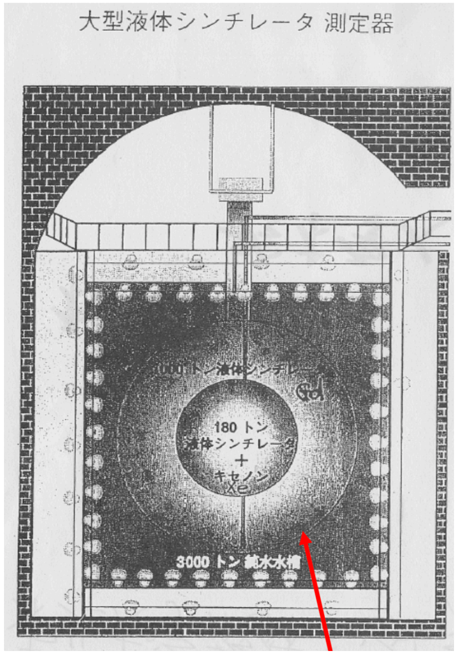
Thierry Lasserre – 7/9/2018

First KamLAND Results (2002)



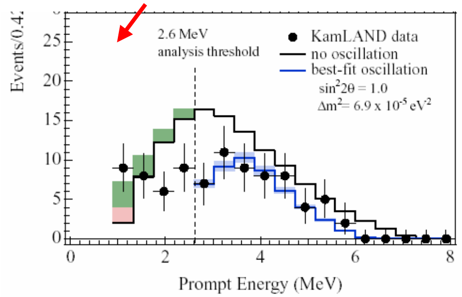
First KamLAND Results (2002)



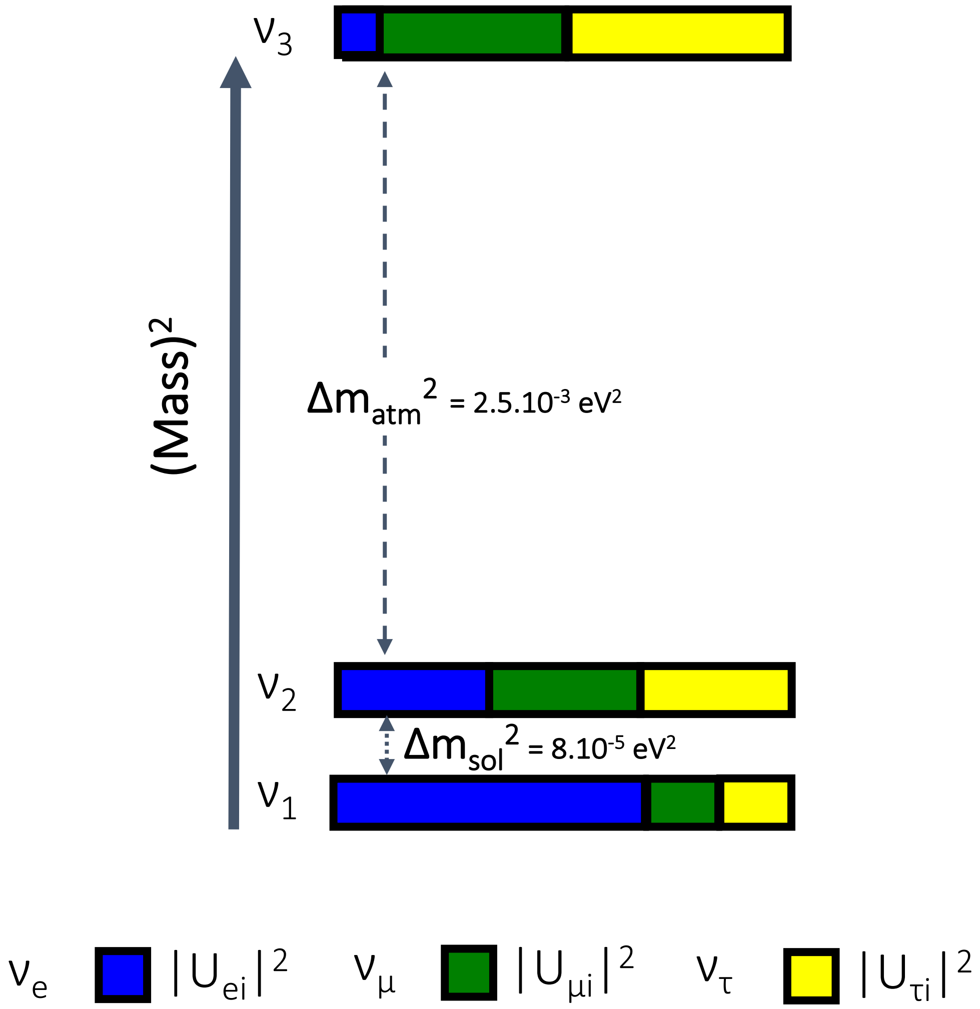


1995 design

2002 results



End of 2002

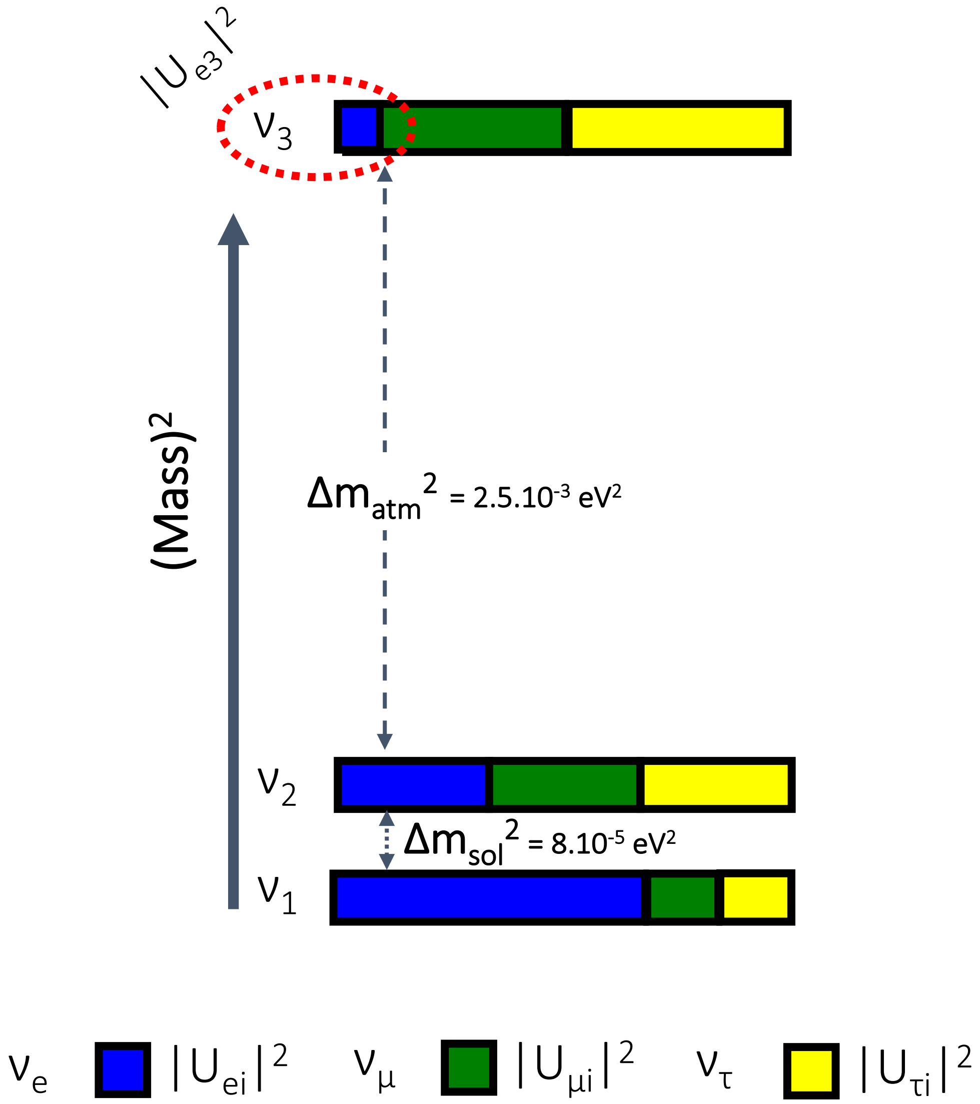


$$\sin(2\theta_{13})^2 < 0.2$$

$$\sin(2\theta_{23})^2 \geq 0.9$$

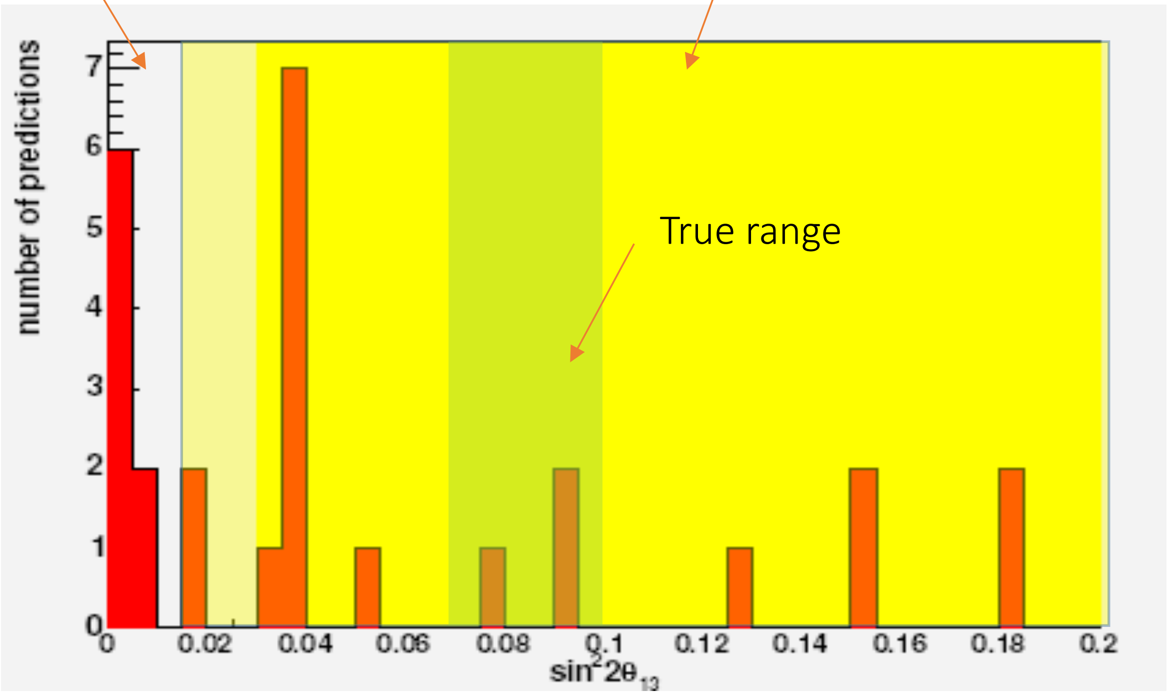
$$\sin(2\theta_{12})^2 \approx 0.8$$

θ_{13} made it to the top priority list



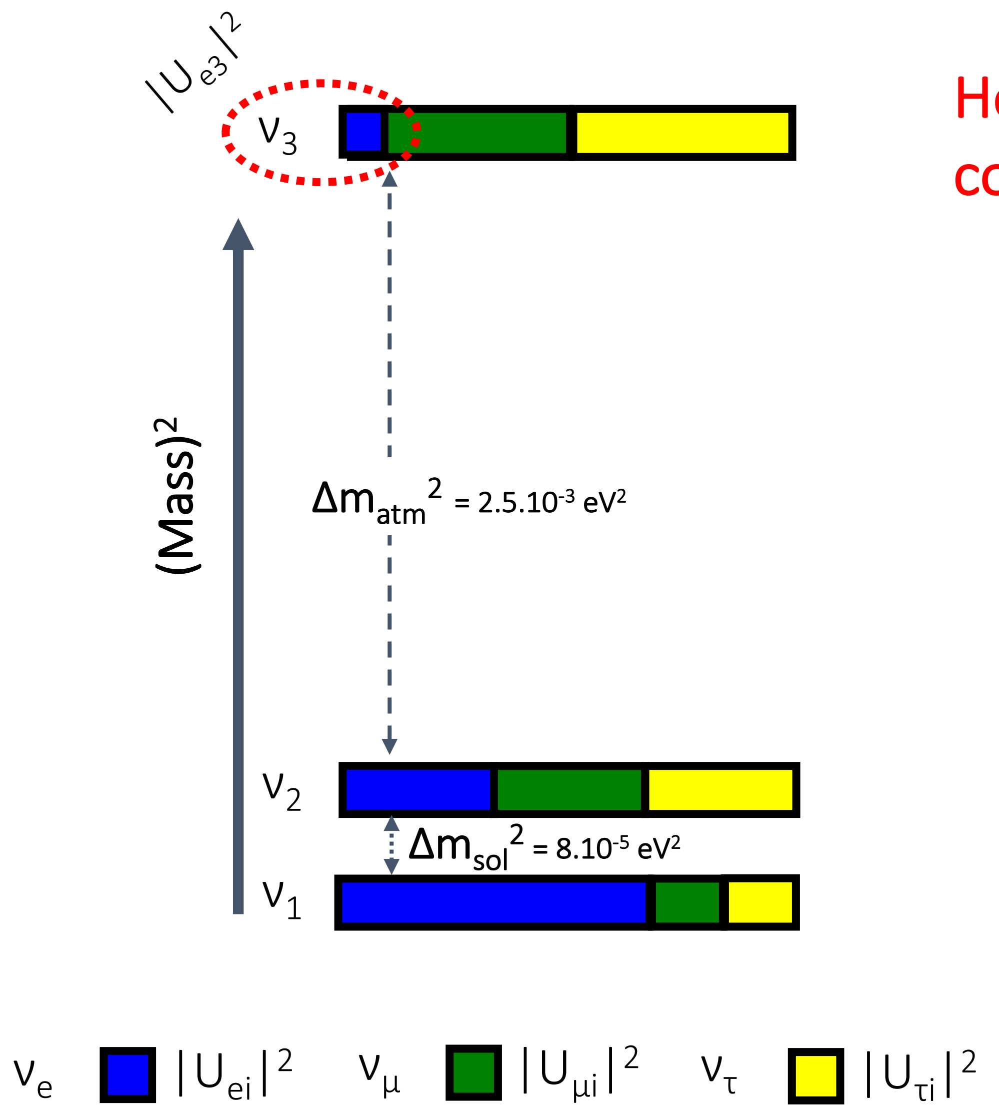
By 2002…

Reference	sin θ	if $\sin^2 2\theta_{13} < 0.01$
SO(10)		
Goh, Mohapatra, Ng [40]	0.18	~~0.13~~
Orbifold SO(10)		
Asaka, Buchmüller, Covi [41]	0.1	~~0.04~~
SO(10) + flavor symmetry		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
Blazek, Raby, Tobe [43]	0.05	0.01
Kitano, Mimura [44]	0.22	~~0.18~~
Albright, Barr [45]	0.014	$7.8 \cdot 10^{-4}$
Maekawa [46]	0.22	~~0.18~~
Ross, Velasco-Sevilla [47]	0.07	~~0.02~~
Chen, Mahanthappa [48]	0.15	~~0.09~~
Raby [49]	0.1	~~0.04~~
SO(10) + texture		
Buchmüller, Wyler [50]	0.1	~~0.04~~
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
Flavor symmetries		
Grimus, Lavoura [52, 53]	0	0
Grimus, Lavoura [52]	0.3	~~0.3~~
Babu, Ma, Valle [54]	0.14	~~0.08~~
Kuchimanchi, Mohapatra [55]	0.08 .. 0.4	~~0.03 .. 0.3~~
Ohlsson, Seidl [56]	0.07 .. 0.14	~~0.02 .. 0.08~~
King, Ross [57]	0.2	~~0.15~~
Textures		
Honda, Kaneko, Tanimoto [58]	0.08 .. 0.20	~~0.03 .. 0.15~~
Lebed, Martin [59]	0.1	~~0.04~~
Bando, Kaneko, Obara, Tanimoto [60]	0.01 .. 0.05	$4 \cdot 10^{-4}$ .. 0.01
Ibarra, Ross [61]	0.2	~~0.15~~
3 × 2 see-saw		
Appelquist, Piai, Shrock [62, 63]	0.05	0.01
Frampton, Glashow, Yanagida [64]	0.1	~~0.04~~
Mei, Xing [65] (normal hierarchy)	0.07	~~0.02~~
(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
Anarchy		
de Gouvêa, Murayama [66]	> 0.1	~~> 0.04~~
Renormalization group enhancement		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	~~0.03 .. 0.04~~



The difference between theory and practice is larger in practice than the difference between theory and practice in theory.

θ_{13} made it to the top priority list



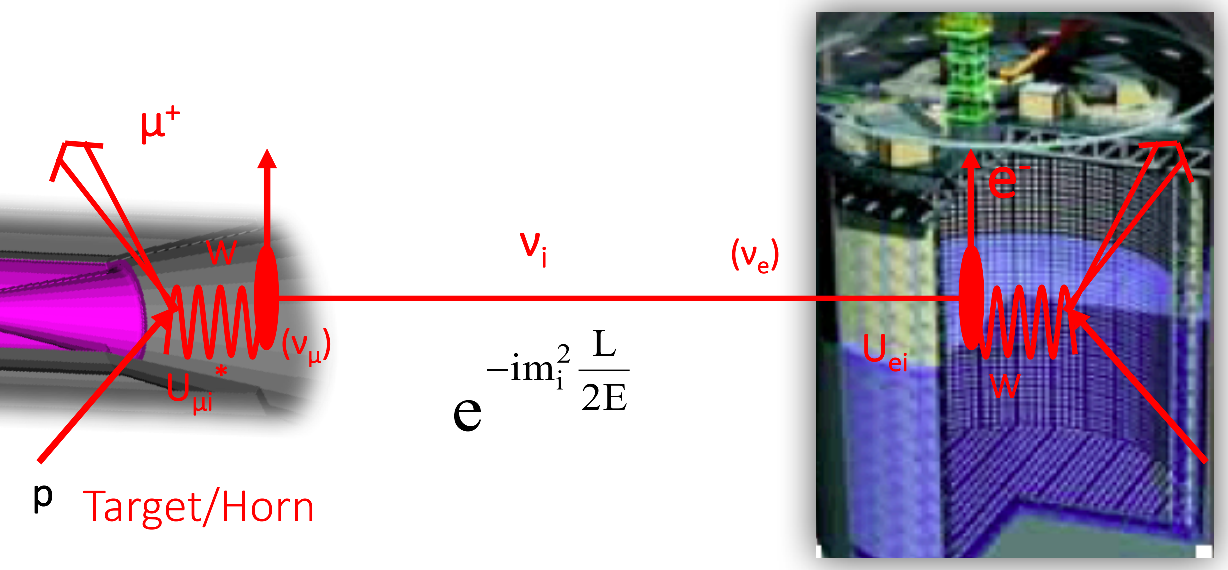
How to measure θ_{13} ?
connect ν_e state to the 'isolated' neutrino Δm_{atm}^2

- L = 1-2 km, E = MeV
  - disappearance channel. @reactor
  - θ_{13} only

or

- L = 100- 1000 km, E = GeV
  - **appearance channel**
  - θ_{13}, NH/IH, δ_{CP} are entangled

Beam



$$P(\nu_\mu \to \nu_e) = \left[\sum_i U_{\mu i}^* e^{-im_i^2 \frac{L}{2E}} U_{ei} \right]^2$$

- Complex oscillation formula

➔ depends on $\sin^2(2\theta_{13})$, Δm_{31}^2, sign(Δm_{31}^2), δ

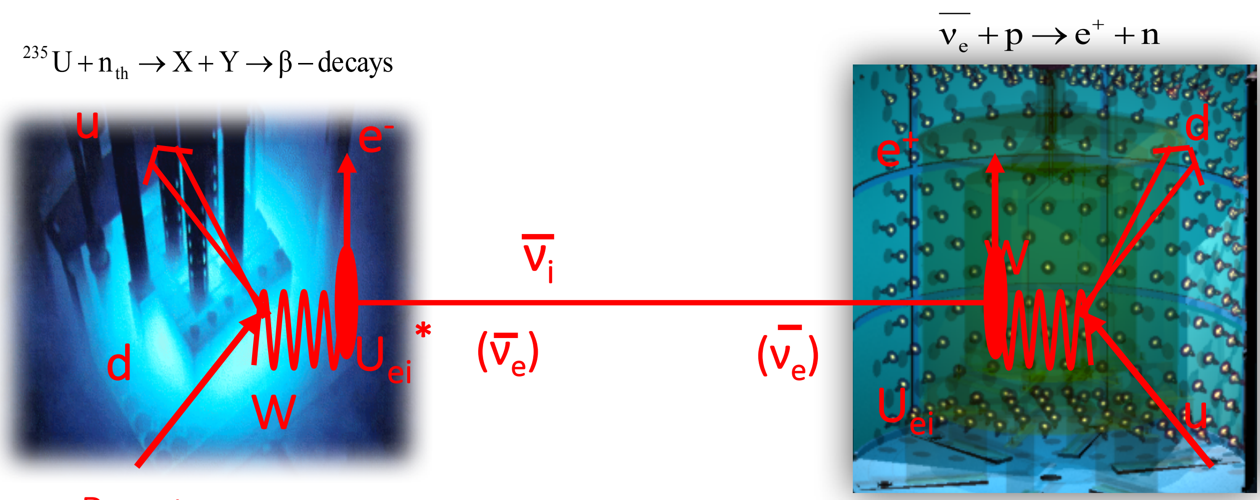
- appearance experiments

➔ $\sin^2(2\theta_{13})$ measurement depends on δ-CP

- matter effects

➔ High potential for detecting θ_{13}, less for measuring it precisely

Reactor



$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \left[\sin\left(1.27 \frac{\Delta m_{atm}^2 \ (eV^2) L \ (m)}{E \ (MeV)}\right) + O\left(\frac{\Delta m_{sol}^2}{\Delta m_{atm}^2}\right) \right]$$

- Simple oscillation formula

➔ depends $\sin^2(2\theta_{13})$ & Δm_{atm}^2, weakly on Δm_{sol}^2

- disappearance experiment

➔ $\sin^2(2\theta_{13})$ measurement independent of δ-CP

- no matter effects

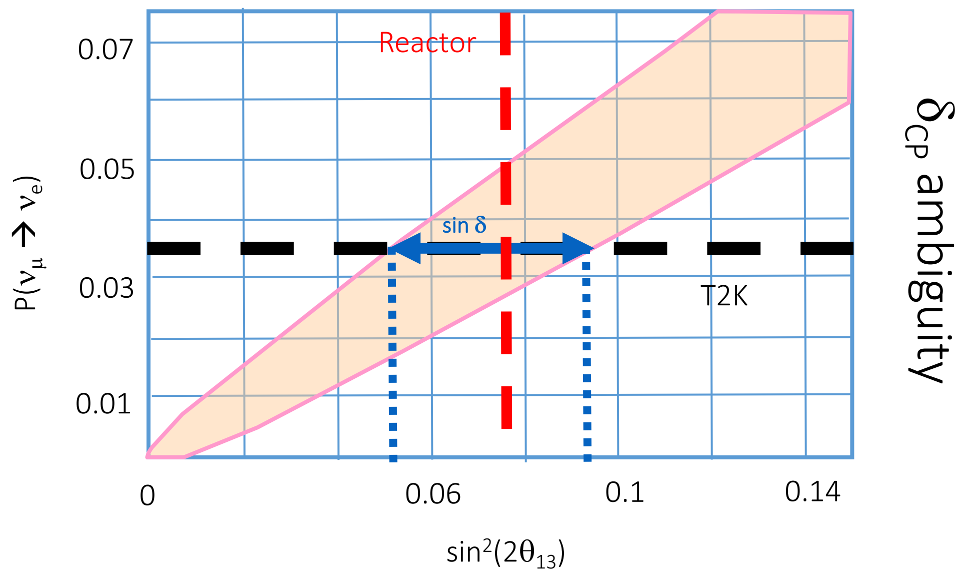
➔ $\sin^2(2\theta_{13})$ measurement independent of mass hierarchy

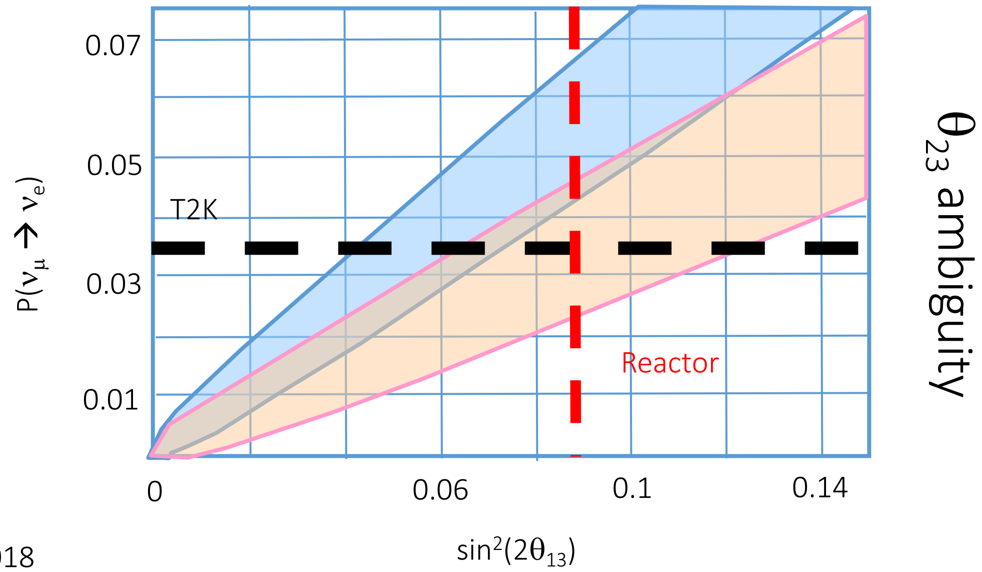
Some Sensitivity predictions (2002)

Table laid down on the CEA-DAPNIA director desk on Oct. 2002

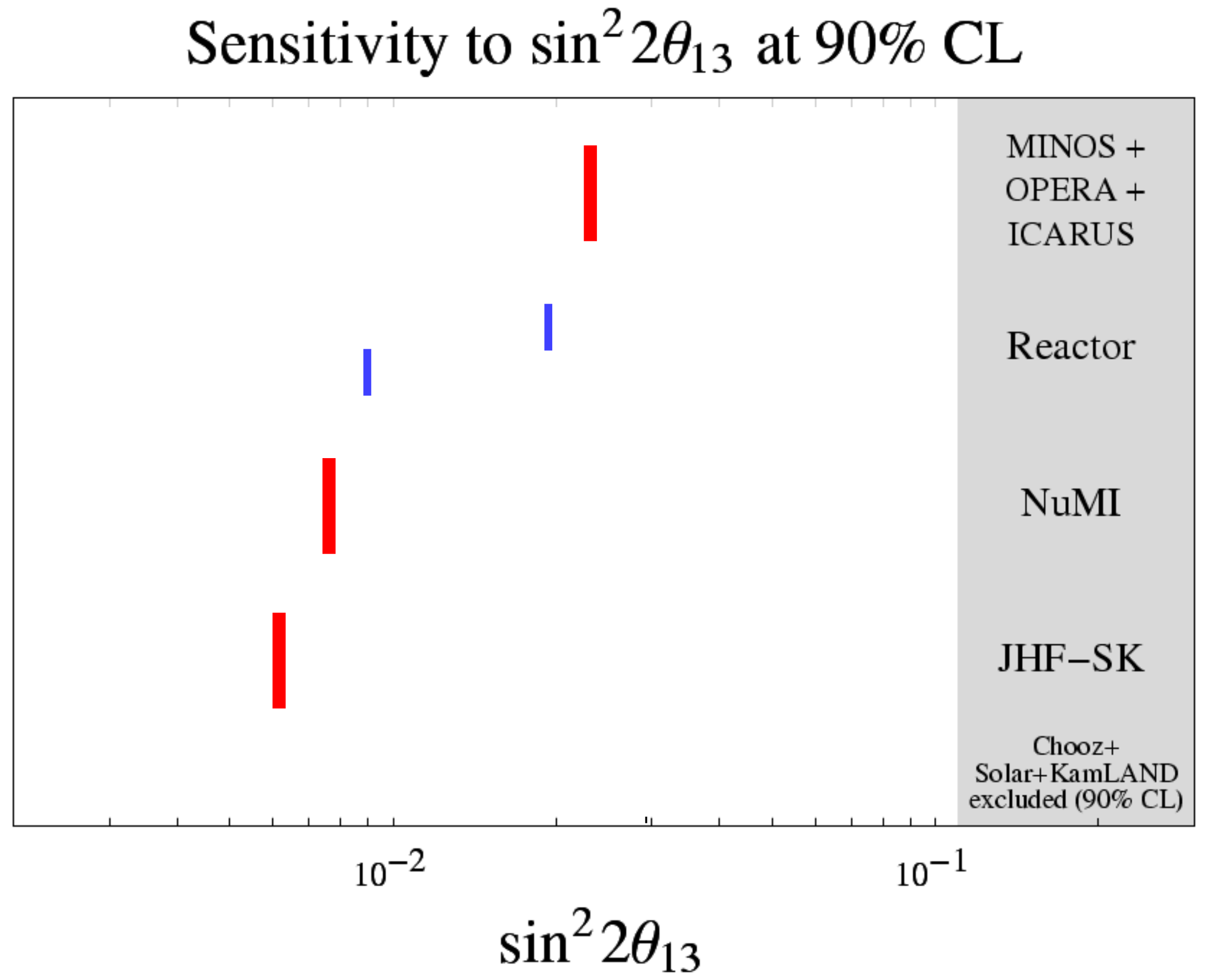
Experiment	$\sin^2(2\theta_{13})$ 90% C.L.	Expected start
CHOOZ	<0.14	-
MINOS	<0.06	?
ICARUS	<0.04	2007 ?
OPERA	<0.06	2007 ?
JHF2K (T2K)	<0.006	2009 ?
Kr2Det - Russia	<0.02	?
Kaska - Japan	>0.02	?
XXX – France/EU With a near detector	**< 0.025**	**2006 ?**

$\Delta m^2_{atm} = 2.5\ 10^{-3}\ eV^2$





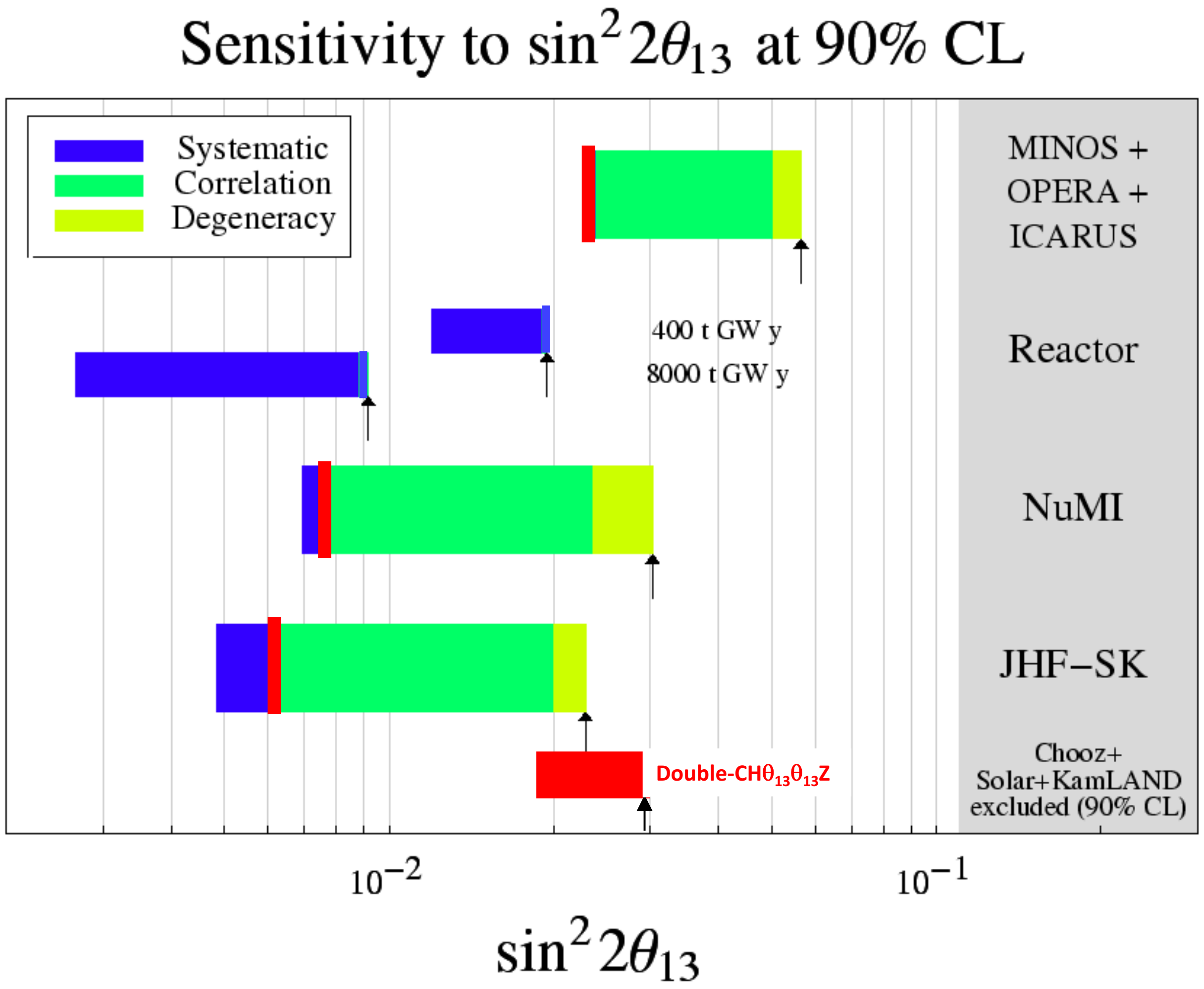
Reactor Versus Beam Experiments



Towards a fair comparison

driven by systematics

affected by correlations
and degeneracies

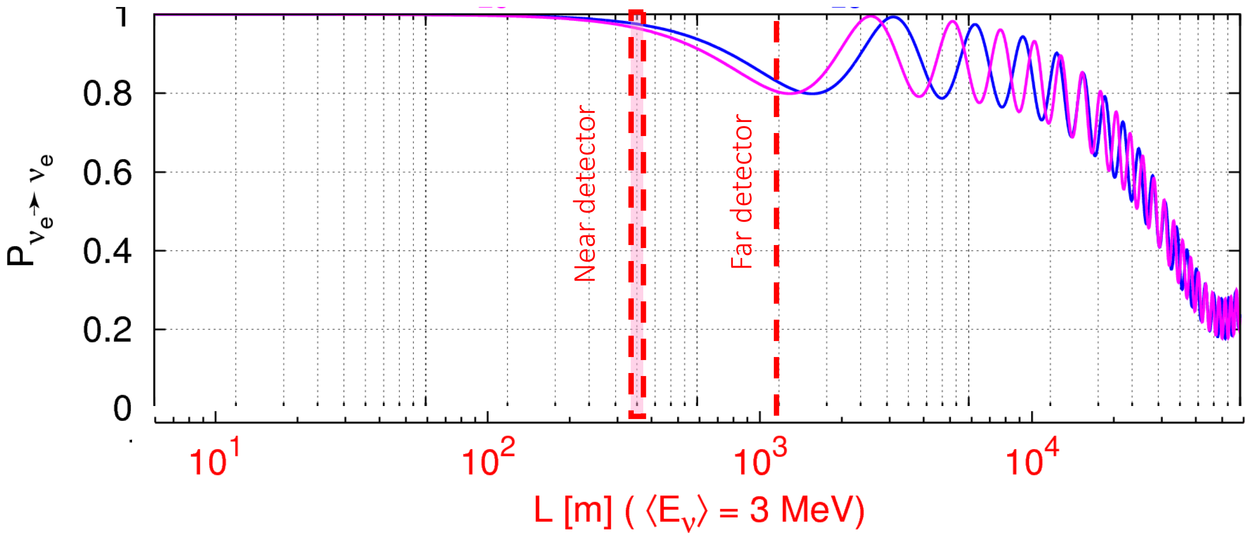


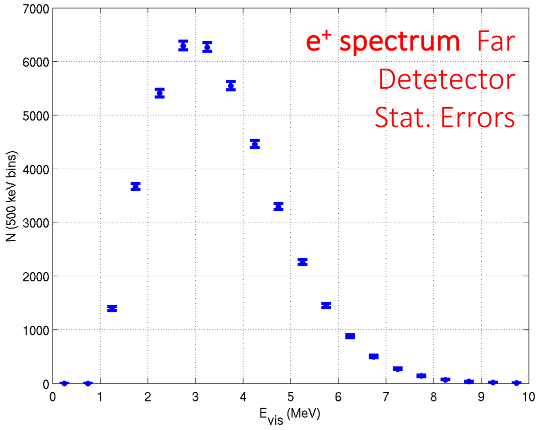
Nuclear Physics B 665 (2003) 487–519

CP-violation asymmetry 'proportional' to $\sin\theta_{13}$. Synergy was finally established and accepted

The - new - concept – no so new, indeed!

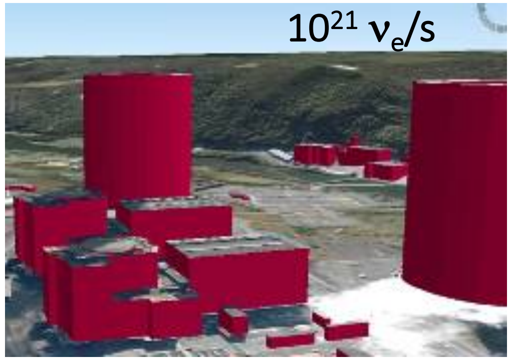
$P(\nu_e \rightarrow \nu_e) = 1-\sin^2(2\theta_{13})\sin^2(1.27\Delta m^2_{31}L/E)$



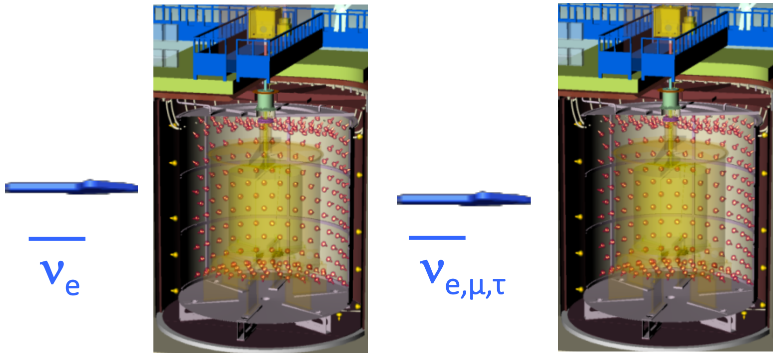


Δm^2_{atm}= 3.0 10^{-3} eV^2

$\sin^2(2\theta_{13})$=0.12

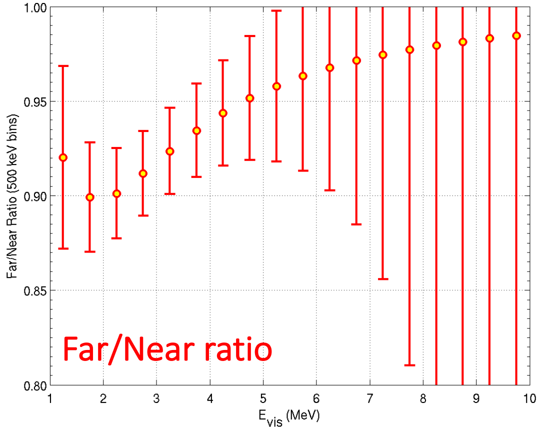


Nuclear Power Station

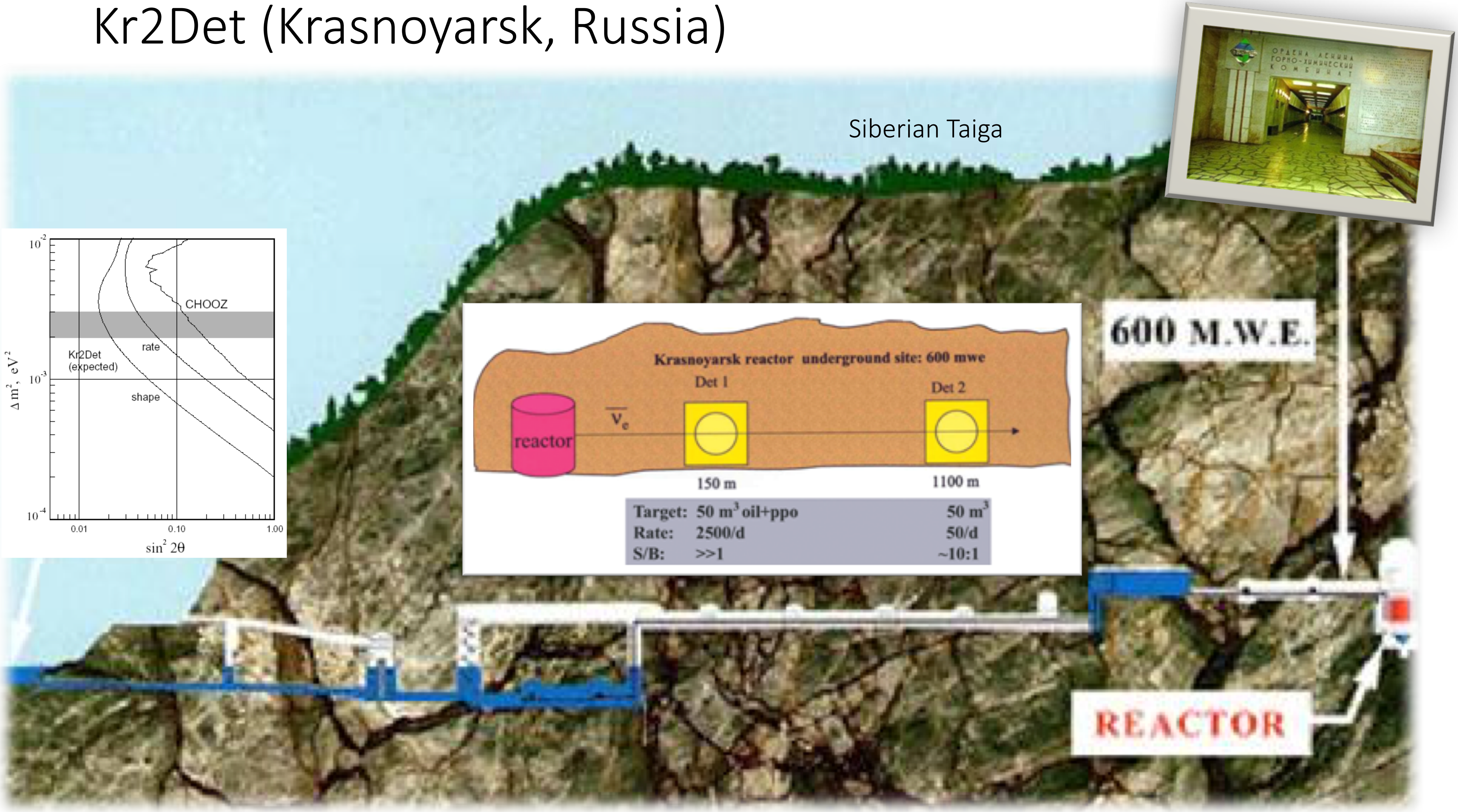


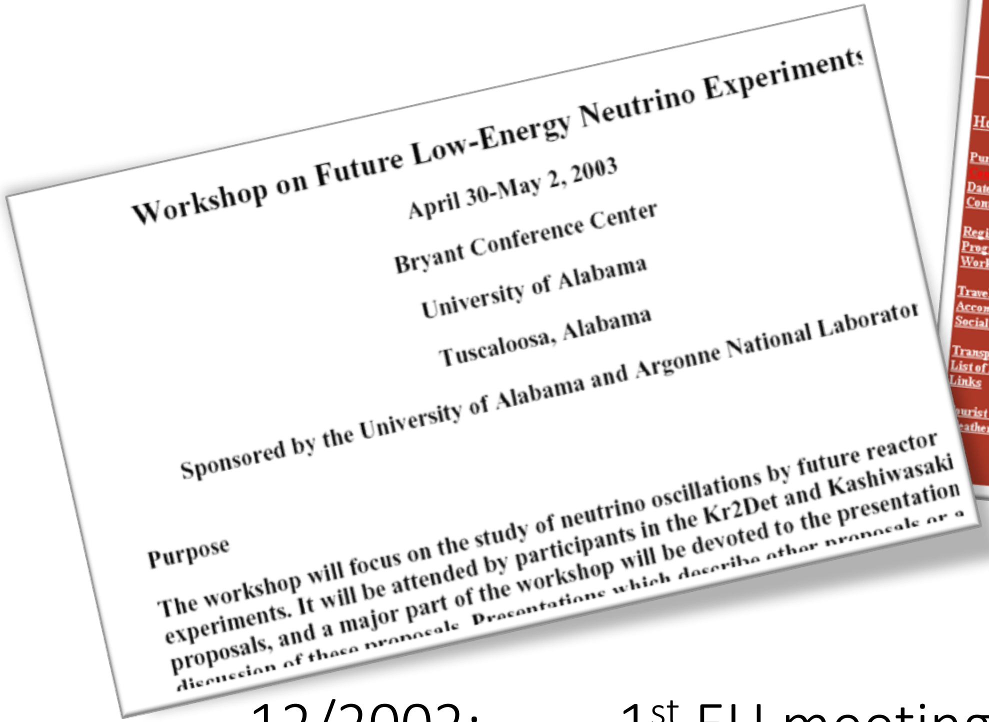
Near detector <500 m

Far detector 1-2 km



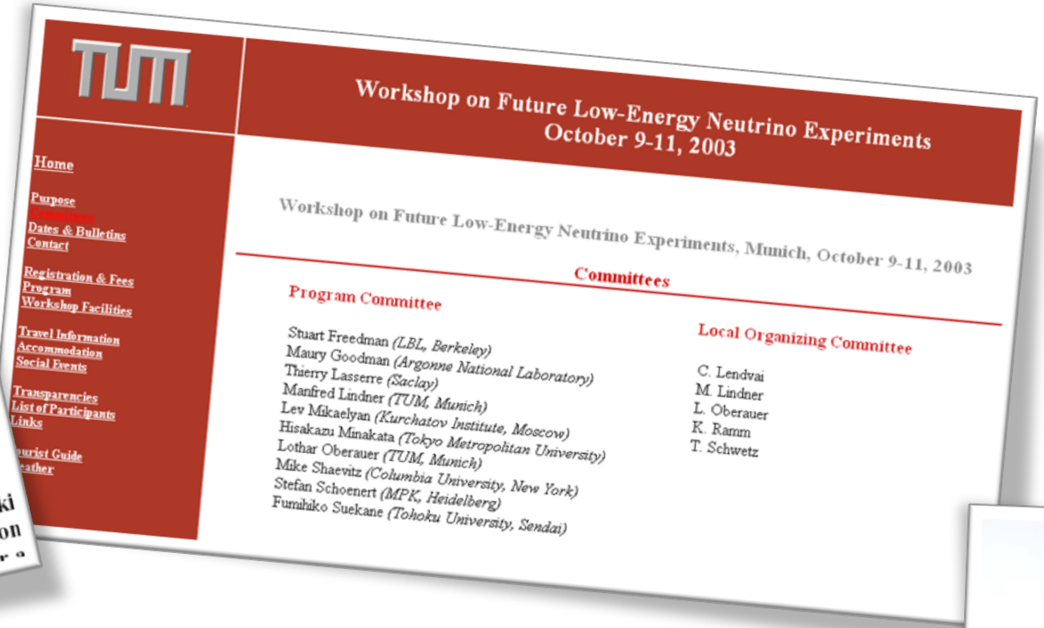
Kr2Det (Krasnoyarsk, Russia)




Workshop on Future Low-Energy Neutrino Experiments
April 30-May 2, 2003
Bryant Conference Center
University of Alabama
Tuscaloosa, Alabama

Sponsored by the University of Alabama and Argonne National Laborator

Purpose
The workshop will focus on the study of neutrino oscillations by future reactor experiments. It will be attended by participants in the Kr2Det and Kashiwasaki proposals, and a major part of the workshop will be devoted to the presentation


TUM

Workshop on Future Low-Energy Neutrino Experiments
October 9-11, 2003

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Travel Information
Accommodation
Social Events
Transparencies
List of Participants
Links

Workshop on Future Low-Energy Neutrino Experiments, Munich, October 9-11, 2003

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Manfred Lindner *(TUM, Munich)*
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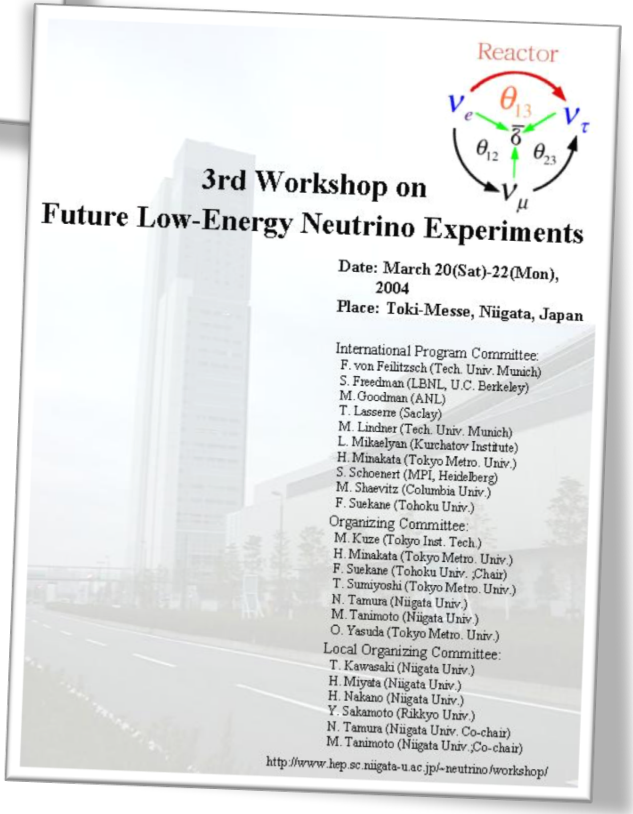

3rd Workshop on
Future Low-Energy Neutrino Experiments

Date: March 20(Sat)-22(Mon), 2004
Place: Toki-Messe, Niigata, Japan

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M. Goodman (ANL)
T. Lasserre (Saclay)
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http://www.hep.sc.niigata-u.ac.jp/~neutrino/workshop/

12/2002: 1st EU meeting, MPIK Heidelberg
04/2003: 2nd EU meeting, PCC, Paris
05/2003: 1st international meeting, Alabama Univ, USA
10/2003: 2nd international meeting , TUM, Germany
03/2004: 3rd international meeting, Niigata, Japan
(first presentation of Daya Bay)

… Put 3 experiments on-track: Daya Baya, Double Chooz, RENO

θ_{13} White Paper - hep-ex/0402041

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January 26, 2004

125 authors
40 institutions
9 countries

Challenges towards $\sin^2(2\theta_{13}) \approx 0.01$

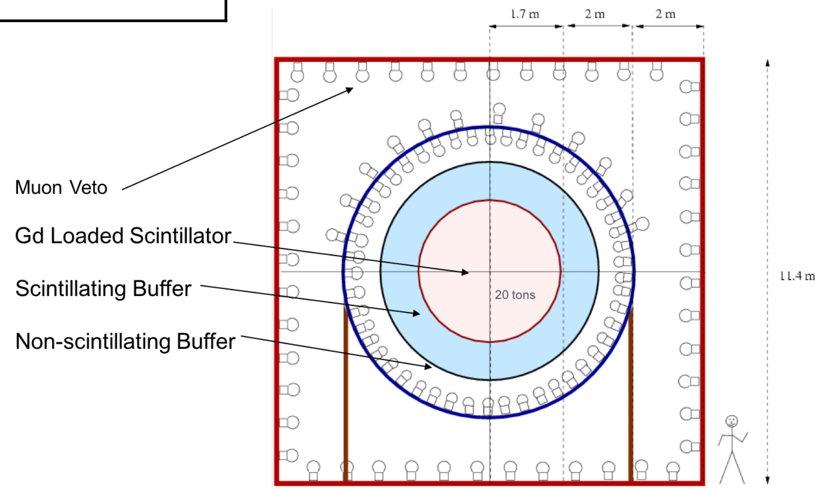
Best Sensitivity (Chooz): obs/pred = 1.01 ± 2.8%(stat) ± 2.7%(syst)

Statistics	CHOOZ	DoubleChooz	DayaBay
Baseline	1 km	1 km	2 km
Reactor Power	2 x 8 GW	x 1	X 4
Detector Volume	5 m^3	X 2	x 16
Data Taking Time	0.5 y	X 10	X 10
Candidates	10^3	10^5	10^6

← Baseline optimization

Systematics	CHOOZ	DoubleChooz
Reactor Flux	1.9 %	---
Detection Efficiency	0.8 %	< 0.2 %
Energy scale		<< 1%
Target Volume	1.5 %	< 0.5 %

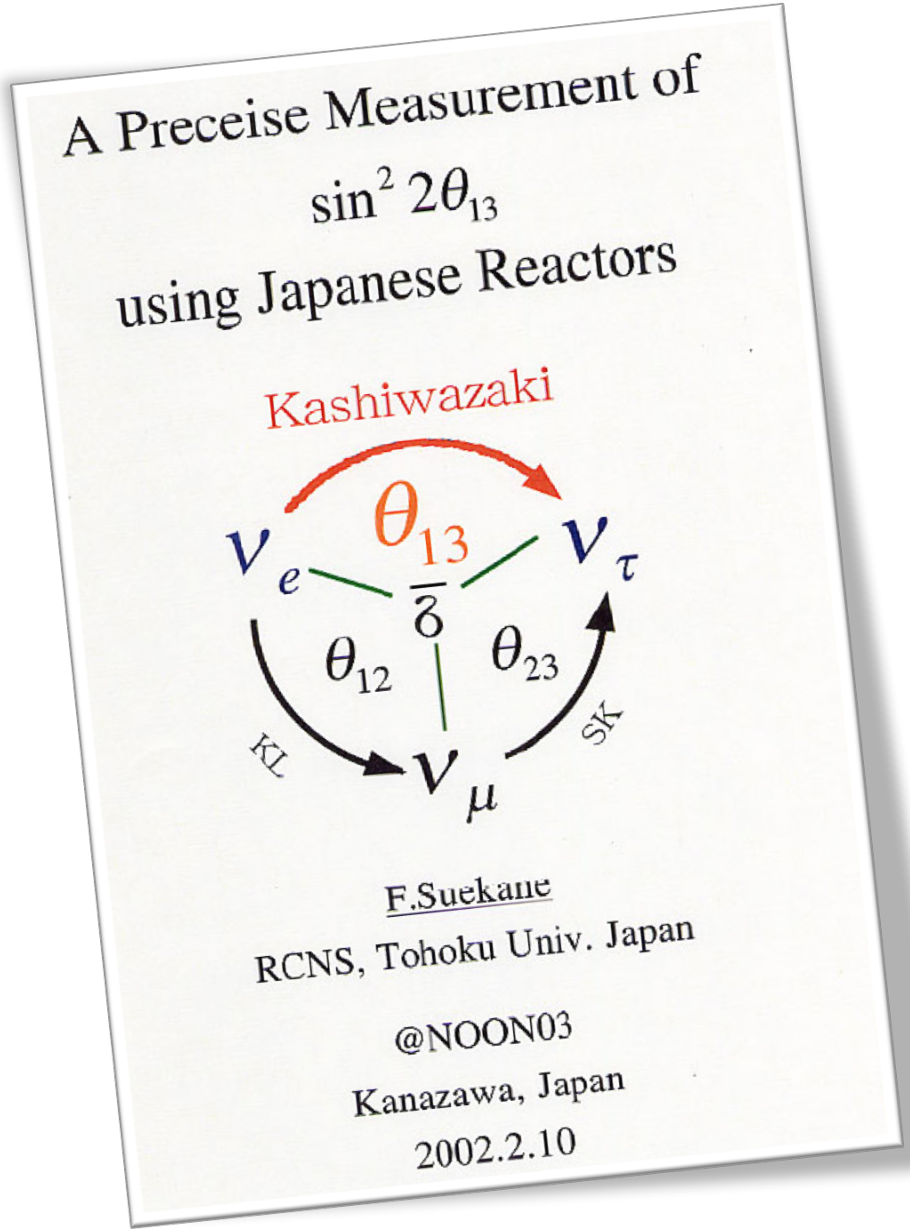
Background reduction: accidentals / 100…

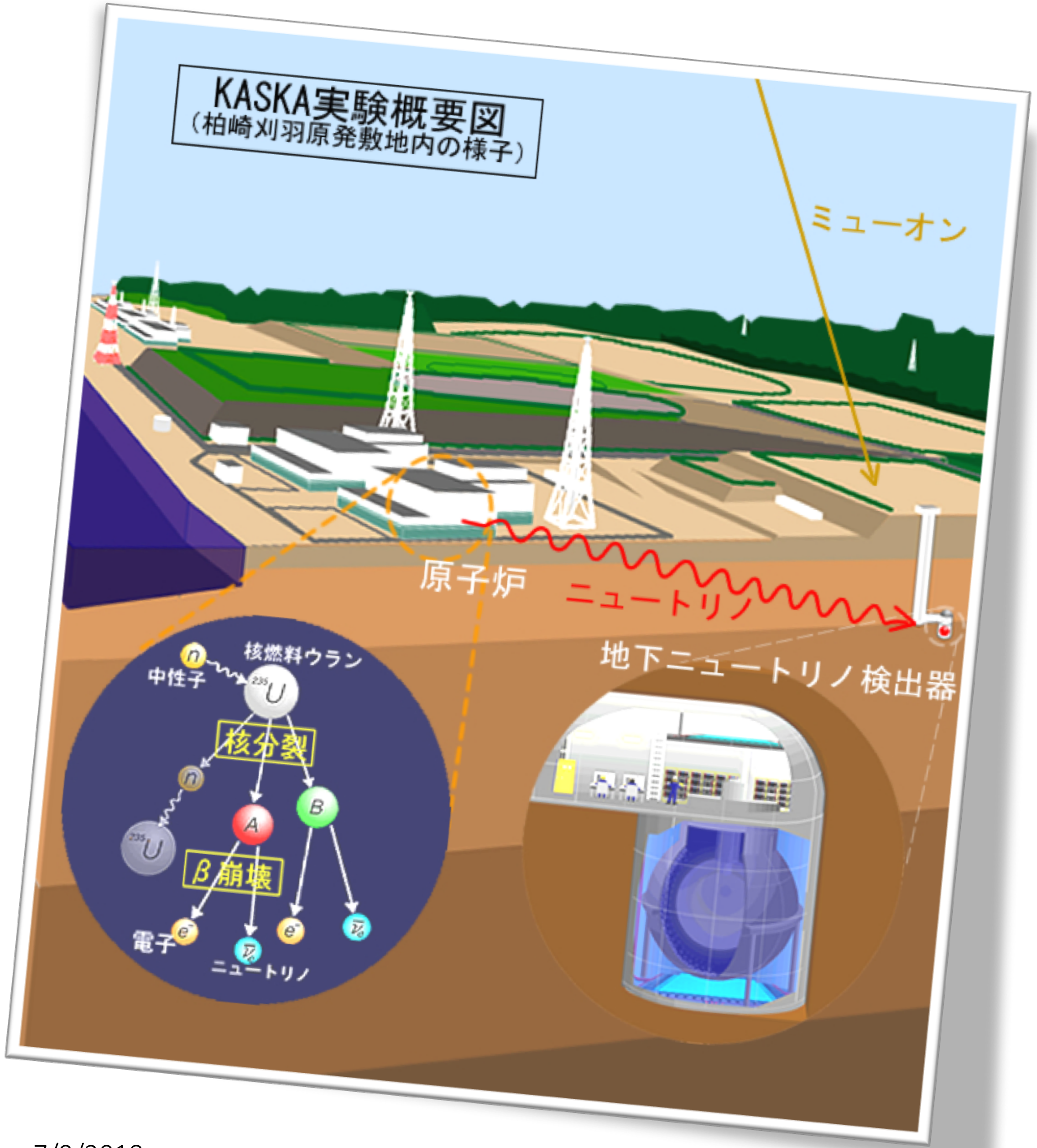


New 4-region large detector concept
Proposed by Double Chooz (2003)

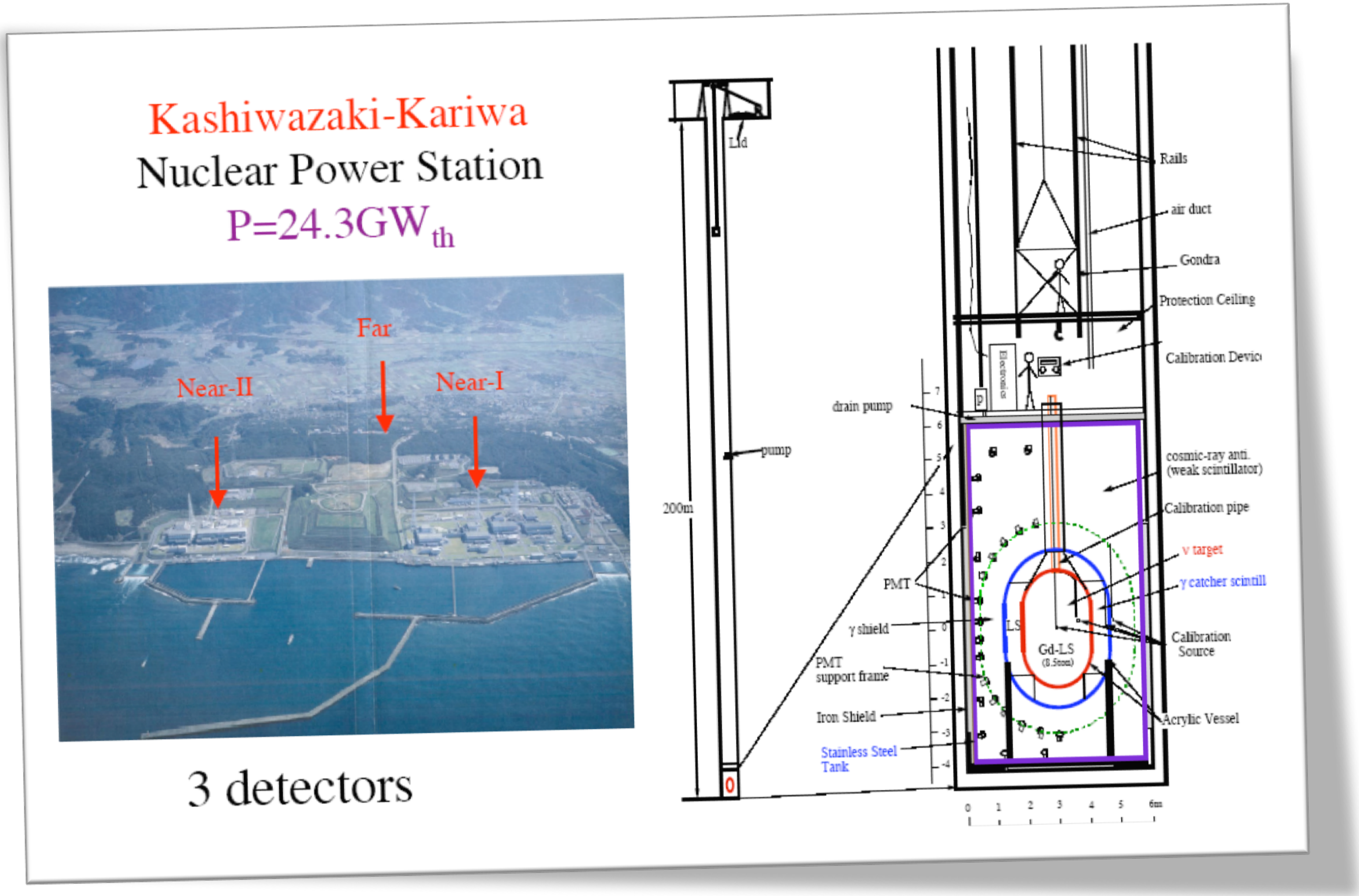
A plethora of sites investigated (2002-2005)

KASA (Kashiwasaki, Japan)





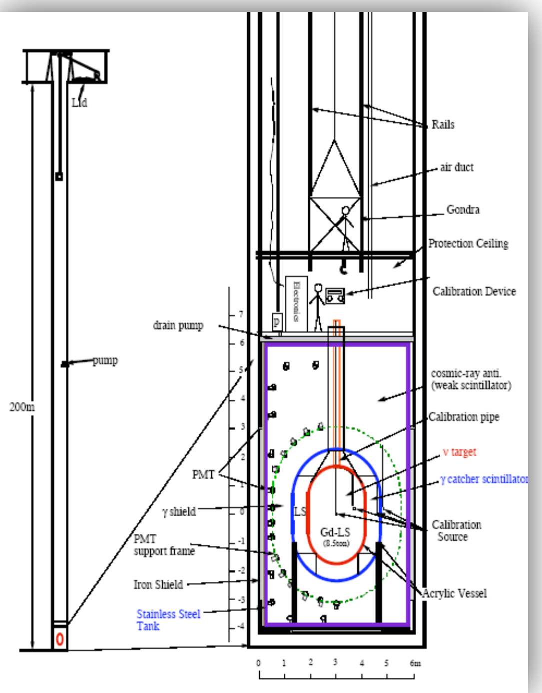
KASA (Kashiwasaki, Japan)



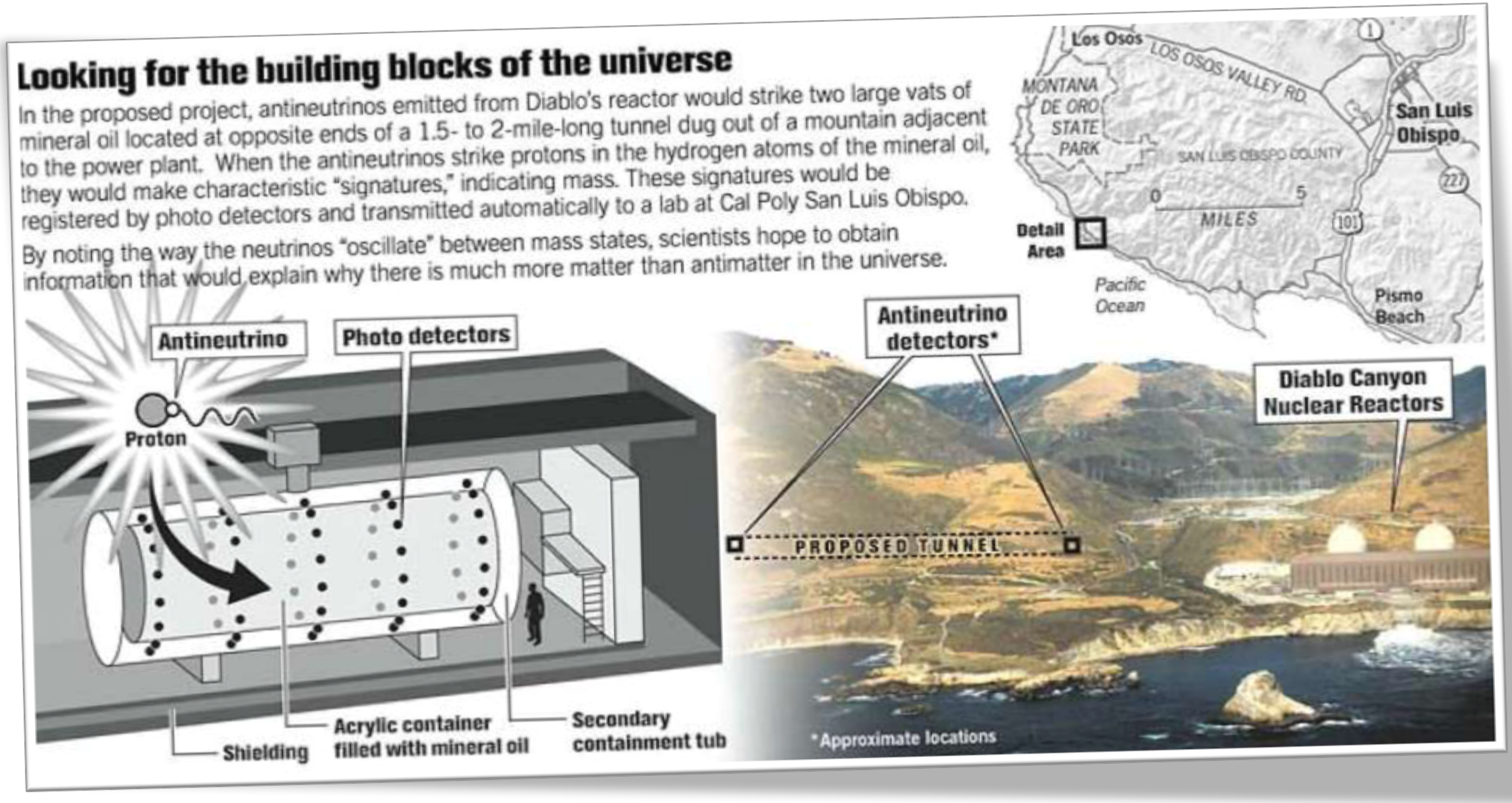
2002: KASKA Group was formed
2003: Conceptual Design
Solving Site Availability Issues
2004: Detector R&D,
2005: Detector R&D
2006: Construction
2007: Construction
2008: Start Data Taking
2009: Initial results
2010:
2011: Final results

Project abandoned (2009) and merged with Double Chooz

2011 Earthquake
Major shutdown of Japanese reactors



Diablo Canyon (California, USA)



Canyon located at 1.8 km from the reactor cores

Detector hall would have been accessible with modest civil engineering…

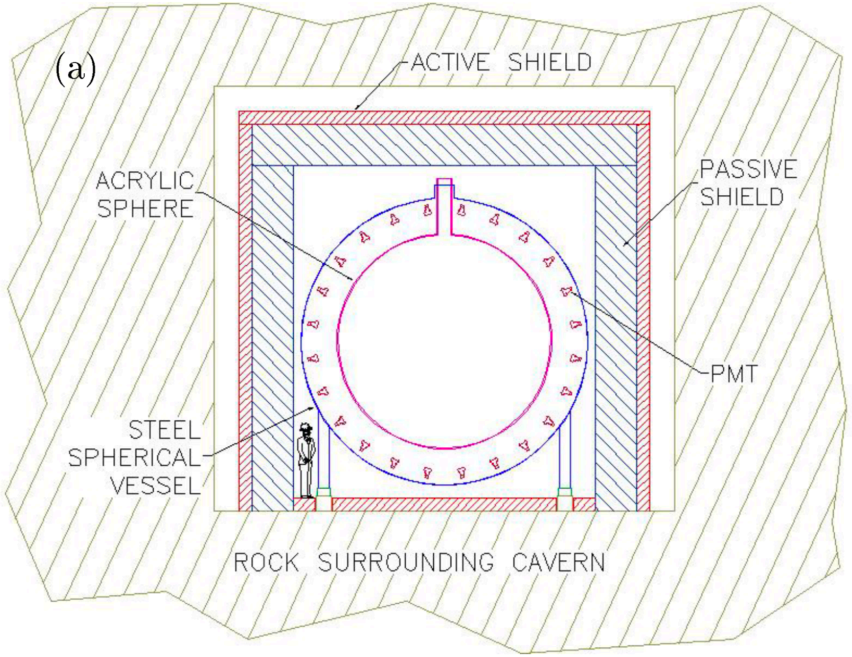
Nuclear power plant company under pressure by environmentalists

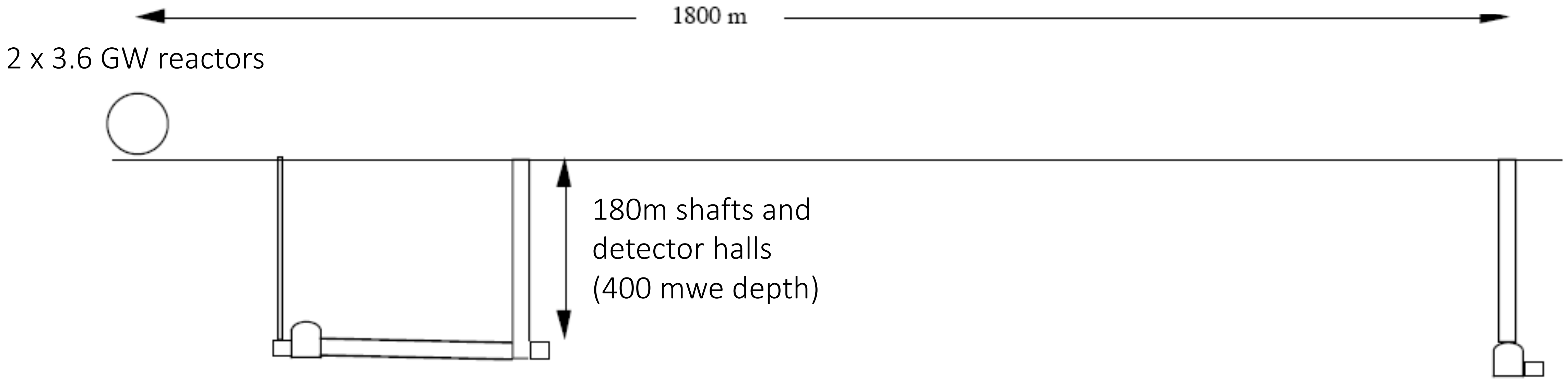
Project abandoned (2004) and somehow realized in China

Braidwood (Illinois, USA)

- 2 x 3.6 GW reactors
- 180m shafts and halls at 450 mwe depth

- Detector:
  - 2 x 65 ton near detectors at 270 / 1510 m
  - Spherical shape
  - No-gadolinium





65 ton near detectors at 270 m

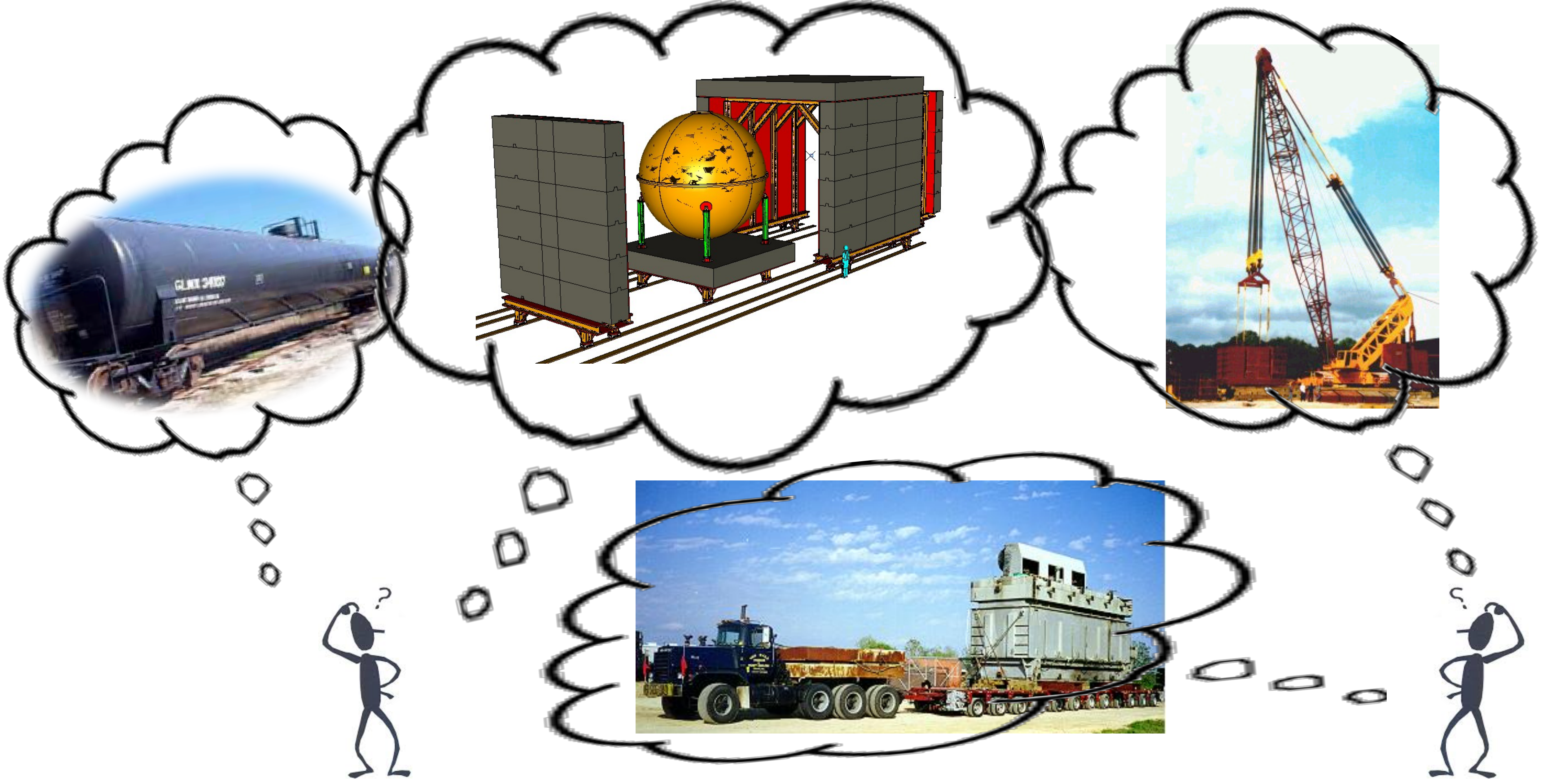
65 ton far detectors at 1500 m

Angra (Brazil)

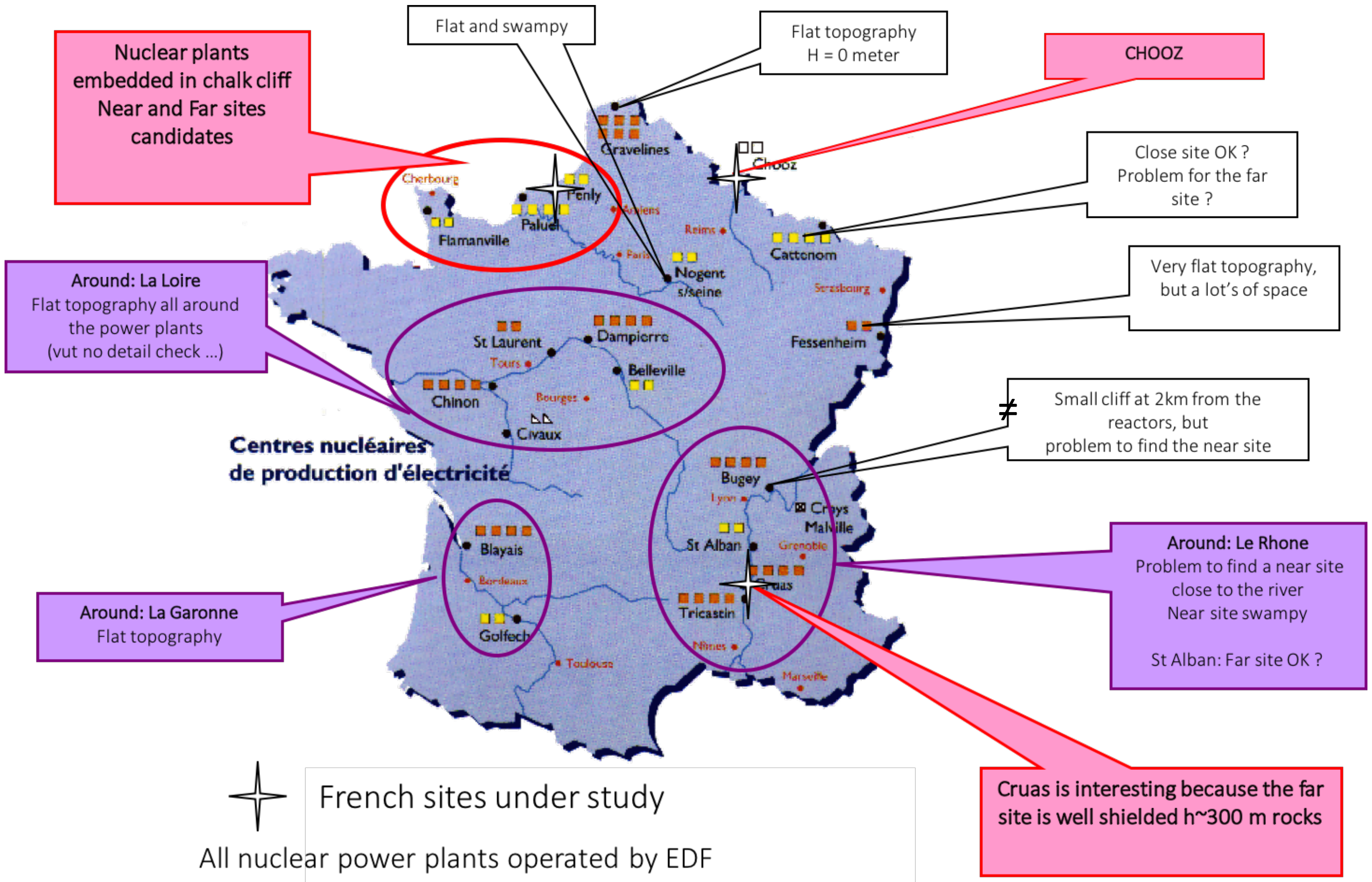
θ_{13} project too big to be supported by Brazil

Led to a new reactor neutrino facility (non-proliferation, Connie, …)

Braidwood / Diablo Canyon / Daya Bay: Swaping/Moving detectors…



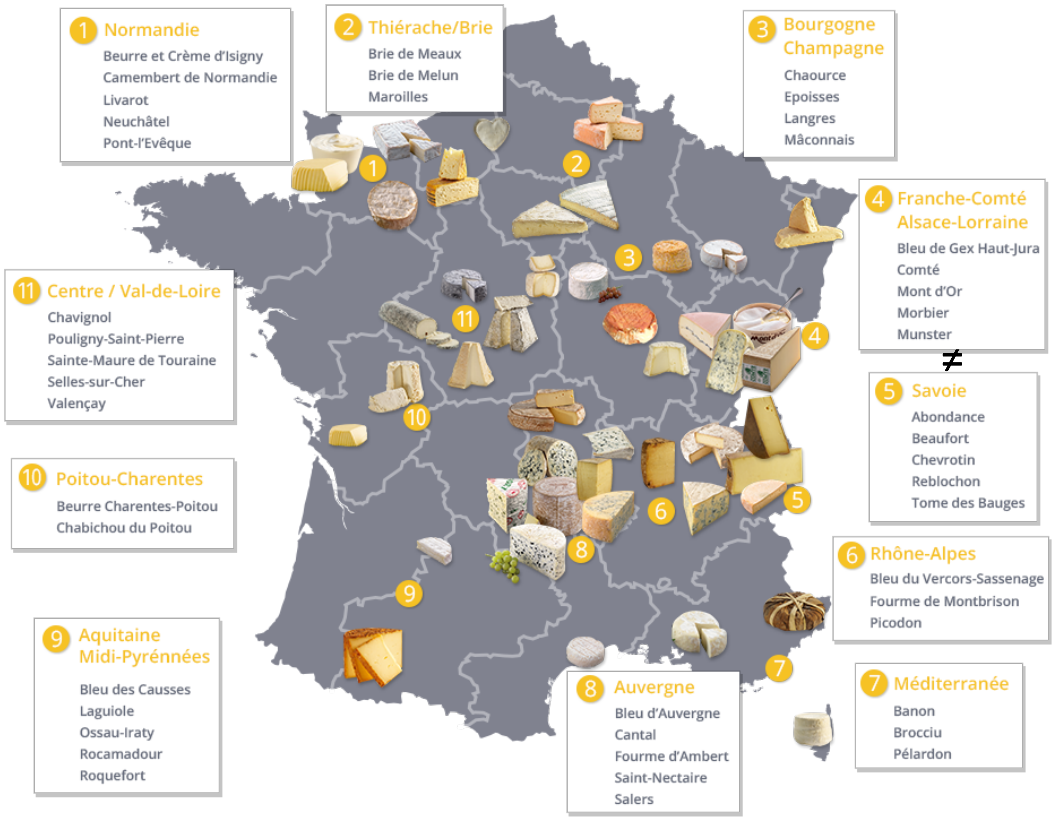
Site Investigations in France



French sites under study

All nuclear power plants operated by EDF

Site Investigations in France



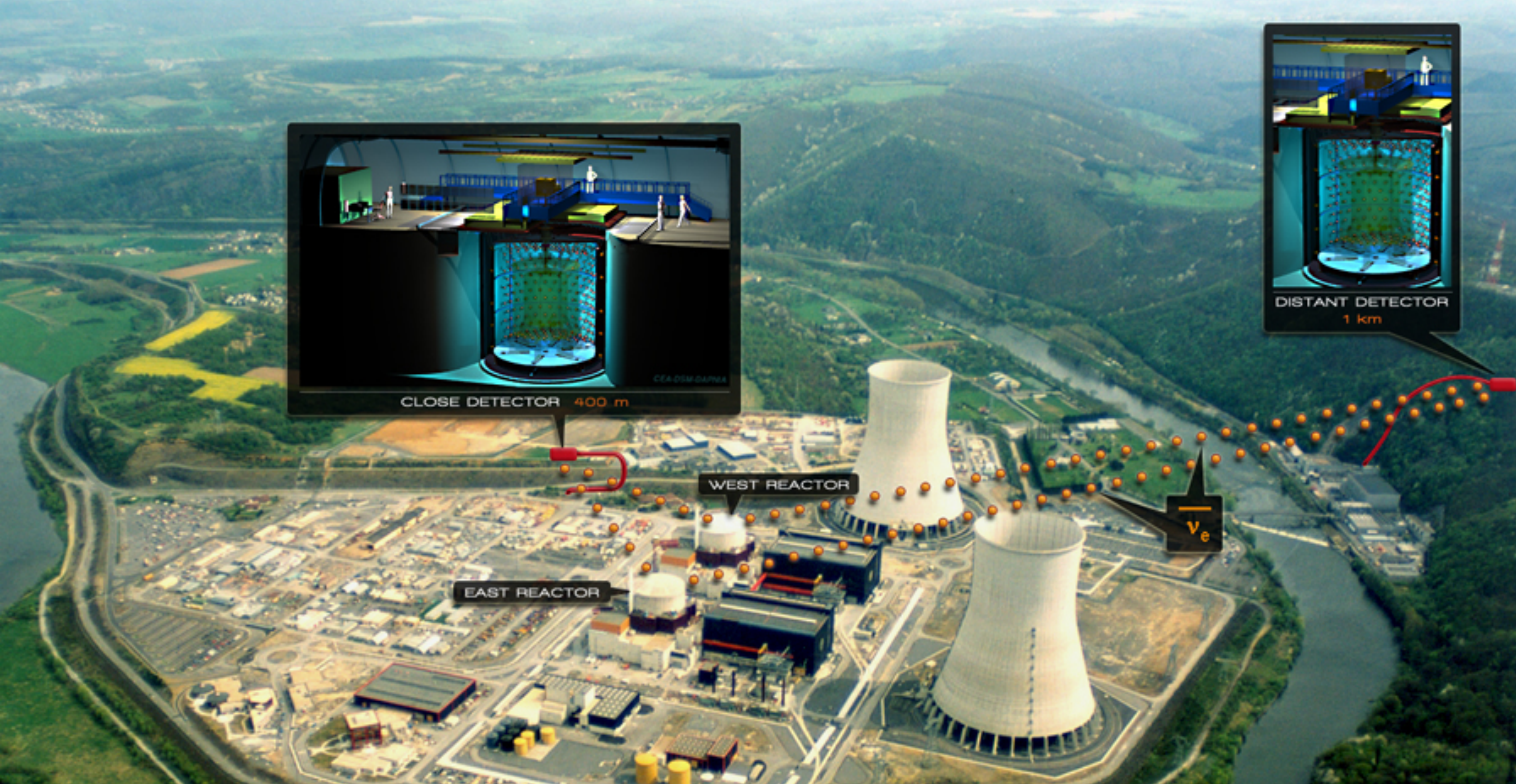
≠

1 type of nuclear reactor
100 type of cheese

1 type of cheese
100 type of nuclear reactors

Les gendarmes de Tricastin…

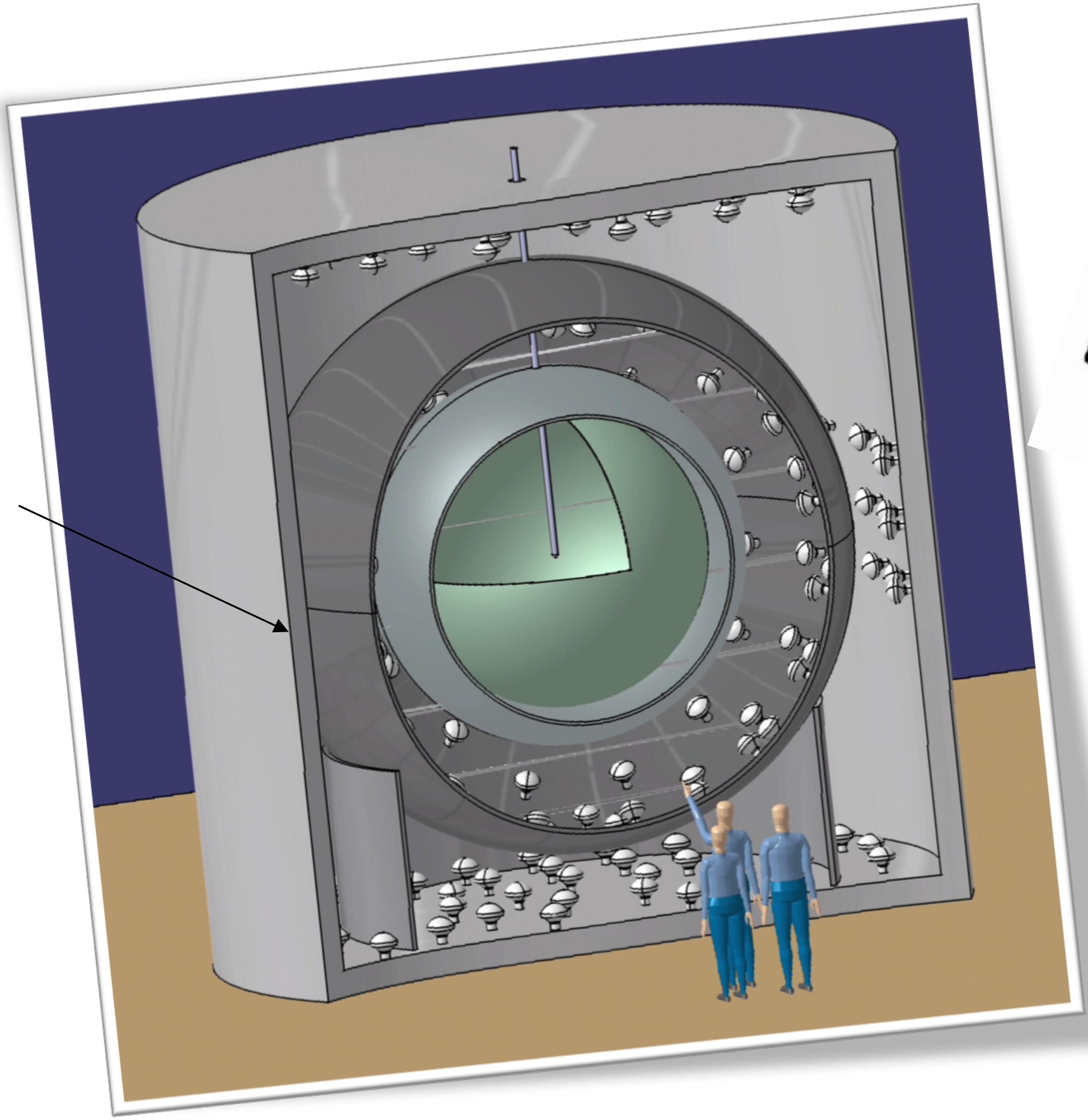
First Come back to Chooz (2003)

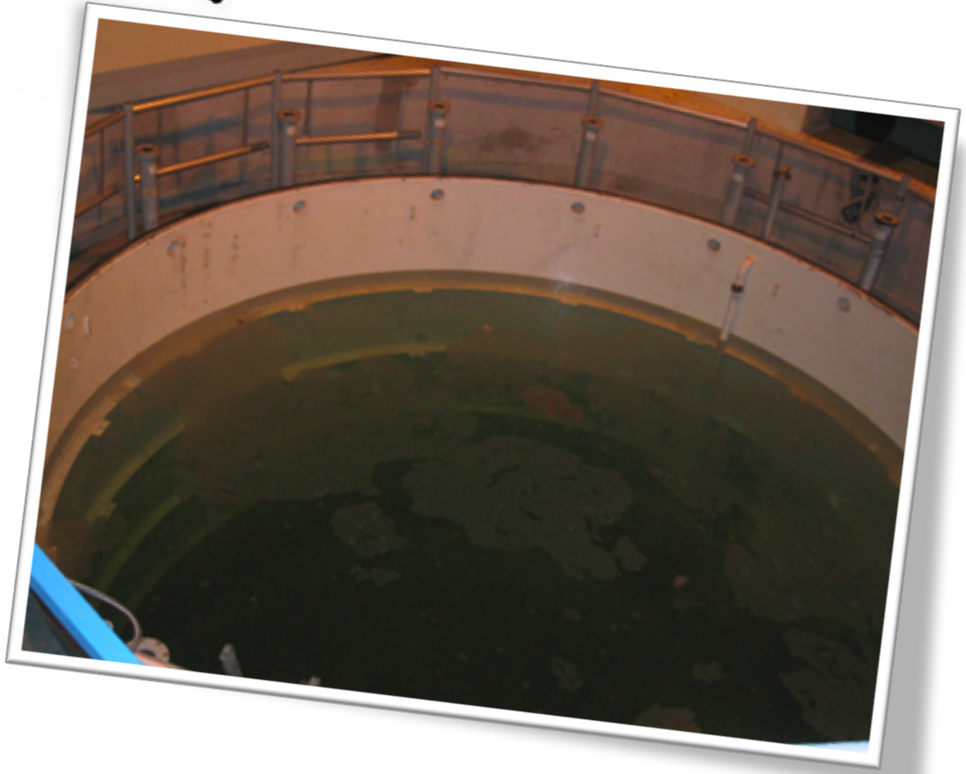


First Come back to Chooz (2003)

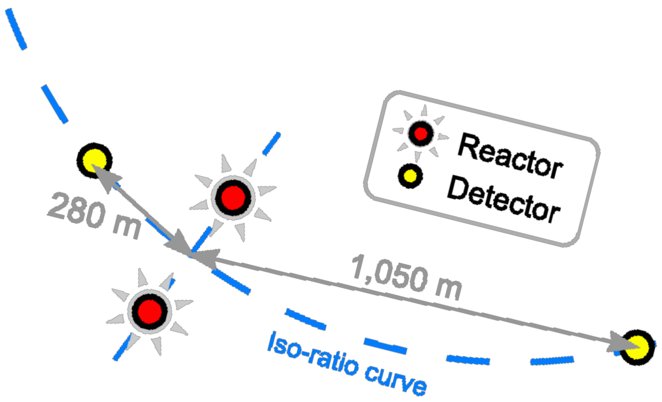
First Double Chooz – spherical- Design - 2003

Existing CHOOZ tank

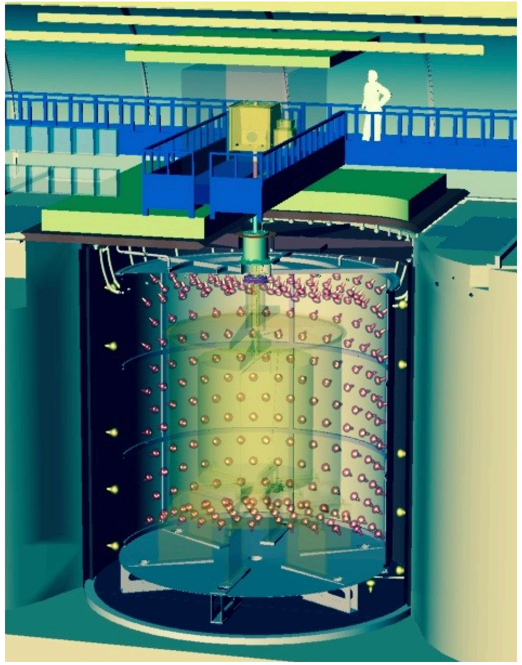


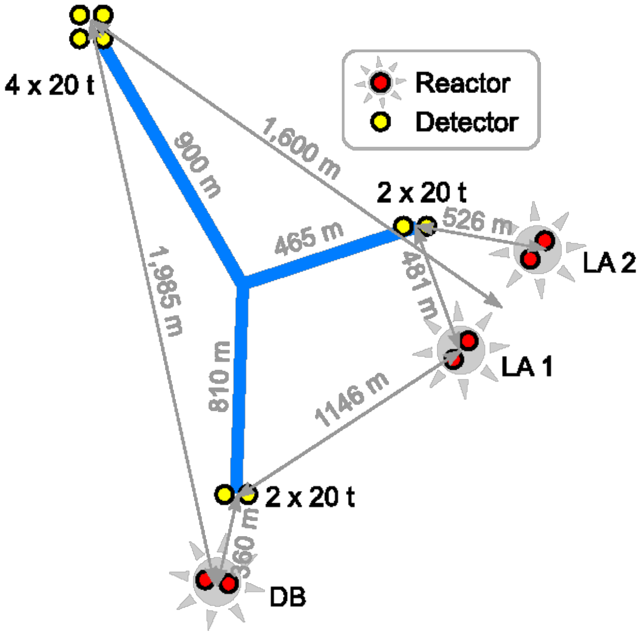


12 identical – cylindrical – detectors…

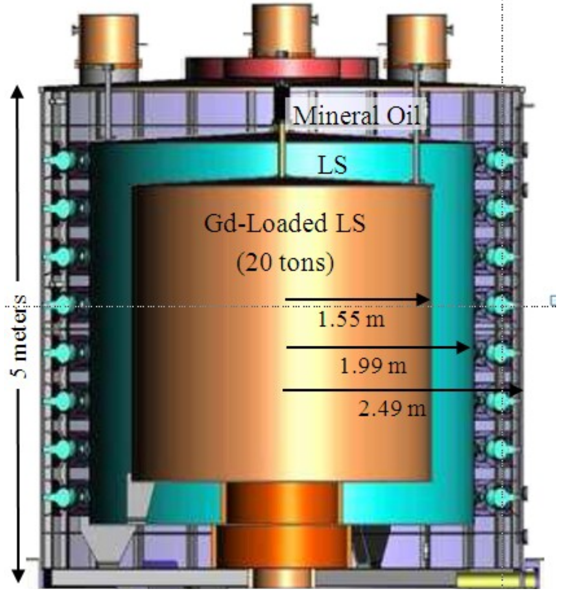


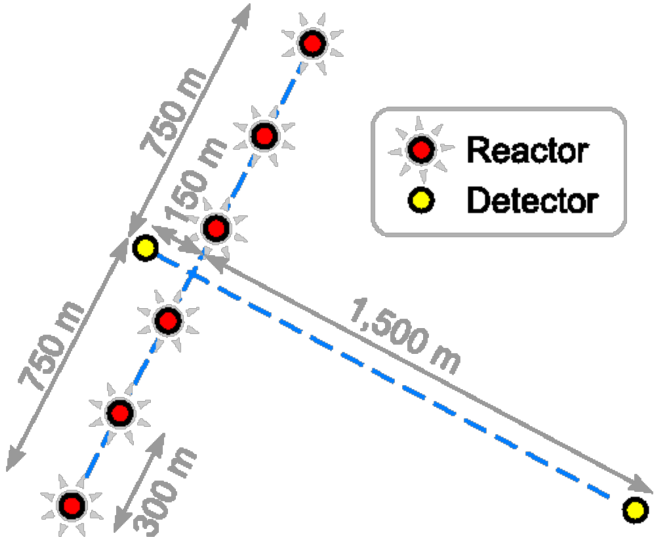
2 detectors Gd-volume: 20 m^3



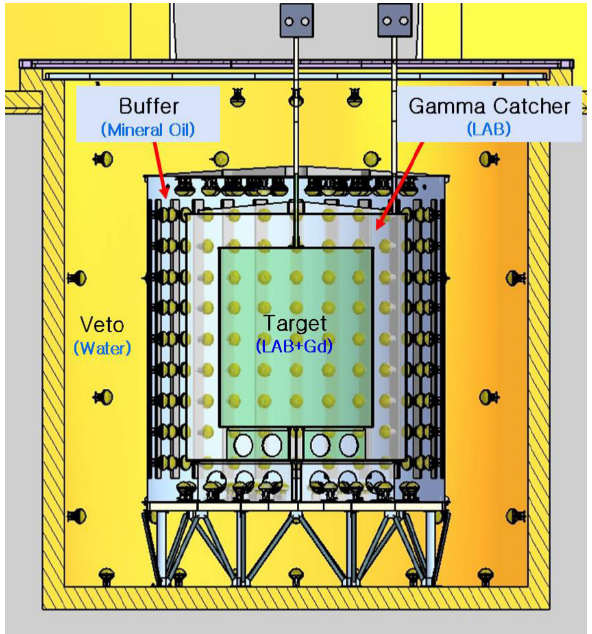


8 detectors Gd-volume: 200 m^3



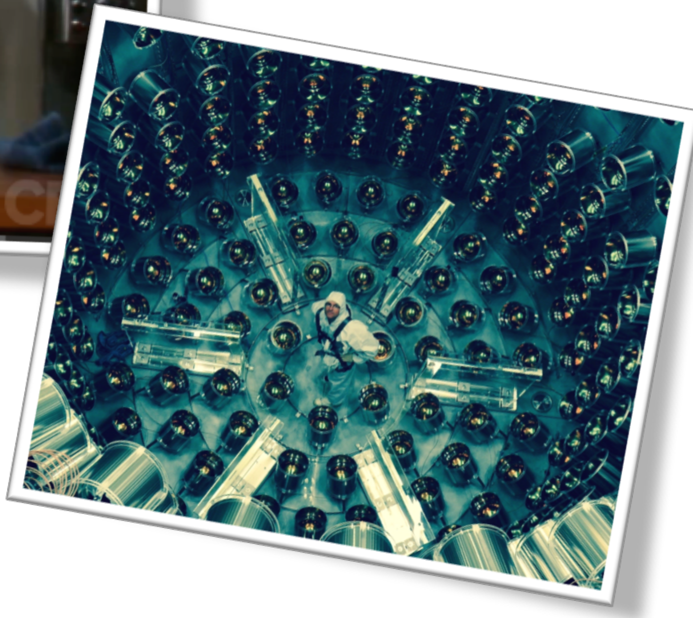


2 detectors, Gd-volume: 40 m^3



Double Chooz

First Double Chooz result in 2011, illustrated in The Big-Bang Theory (CBS)



Started in 2002

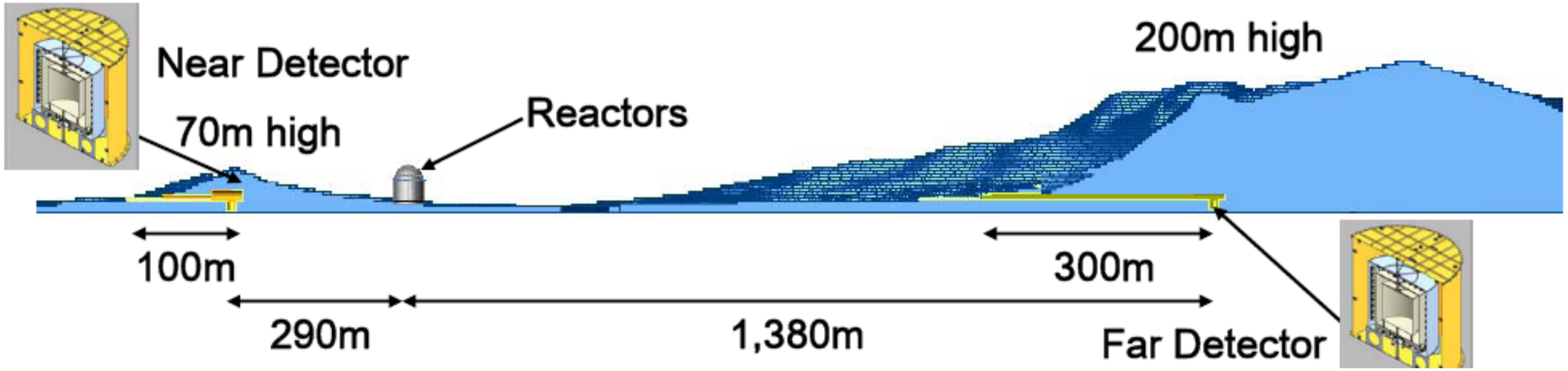
Approved in 2004

Far detector data taking in 2010

(Late) Near laboratory excavation in 2010-12...

Near detector data taking in 2014

RENO



A Korean-only effort

Starting with (very) little expertise in 2004

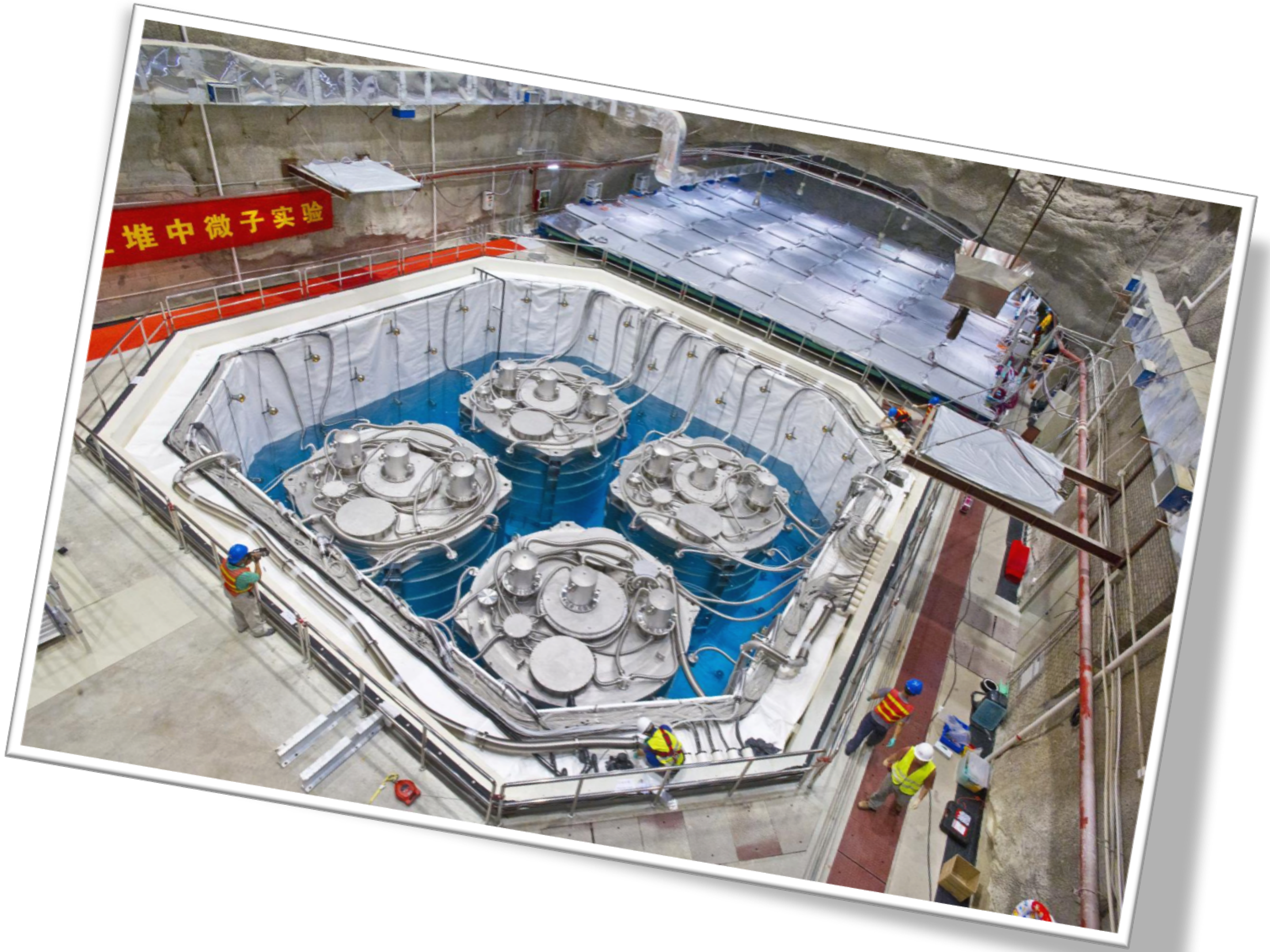
About 30 people!

Some cut&paste…

And a great achievement

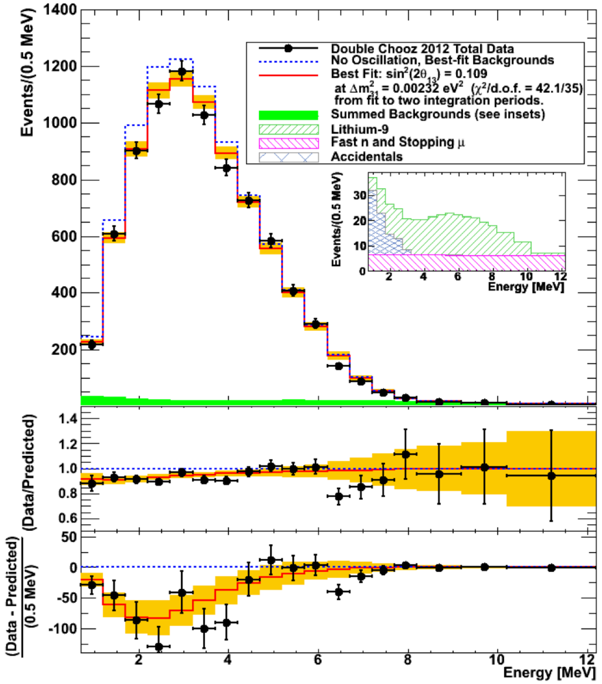
Daya Bay: A colossal experiment

2006, a high-level political decision leading to the largest international collaboration in basic science in China and the biggest US-China collaboration.



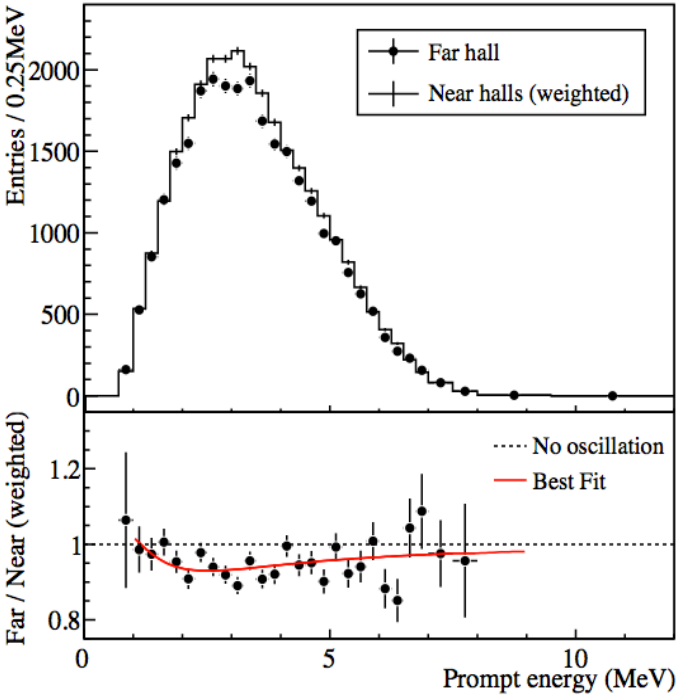
First Reactor Results (2011-2012)

Double Chooz (Oct. 2011)



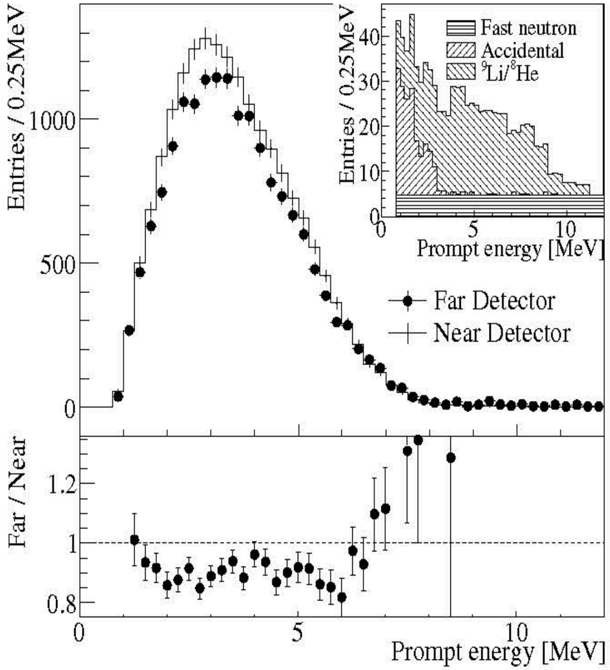
Rate+shape
98%

Daya Bay (March 2012)



rate only
5 σ
Leading precision - 15% error

RENO (April 2012)

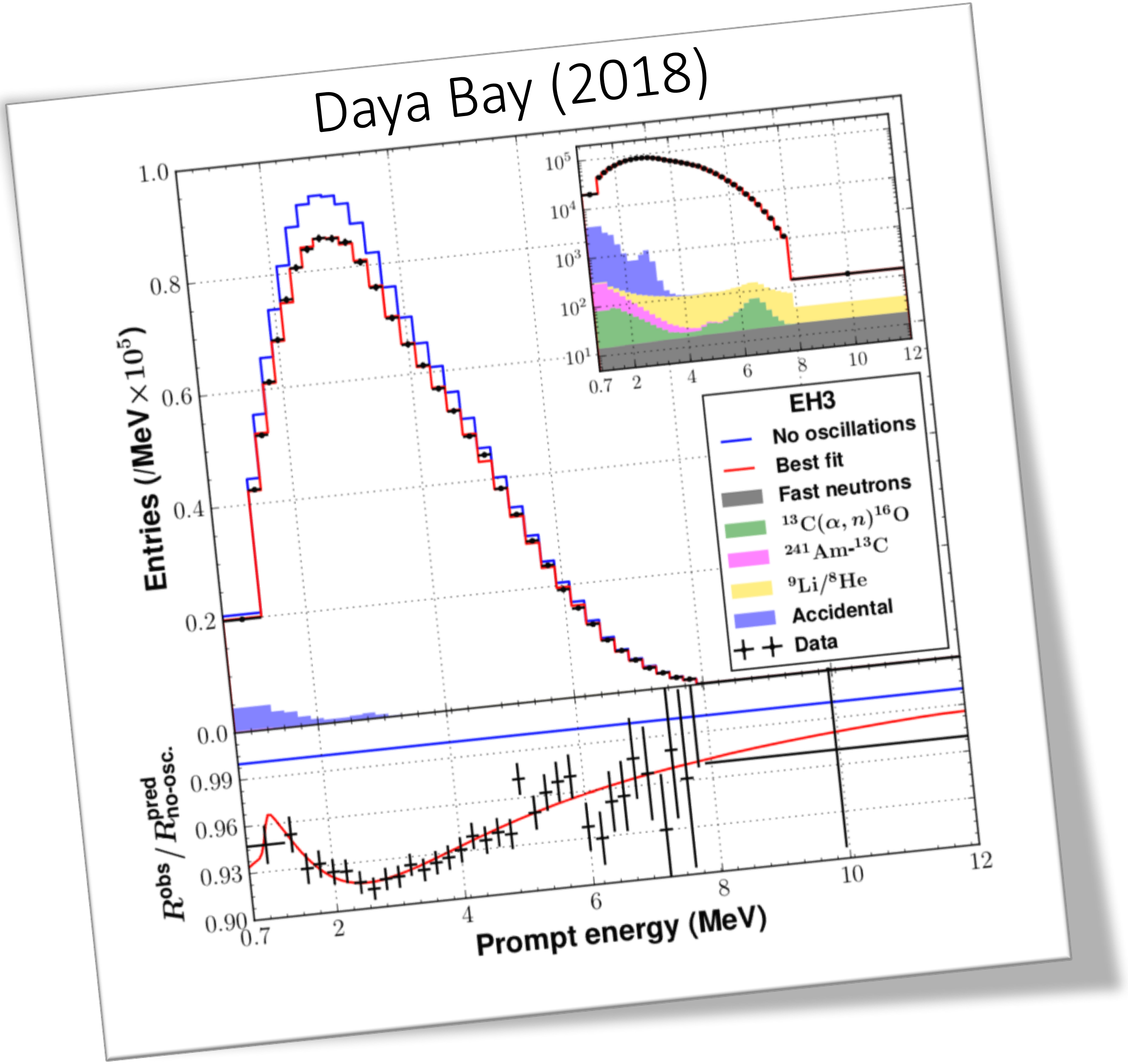


Rate only
Almost 5 σ

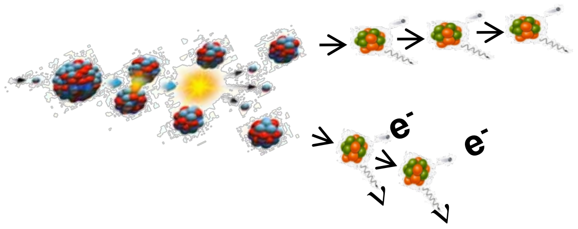
Reactor experiments provide the most precise value of θ_{13}

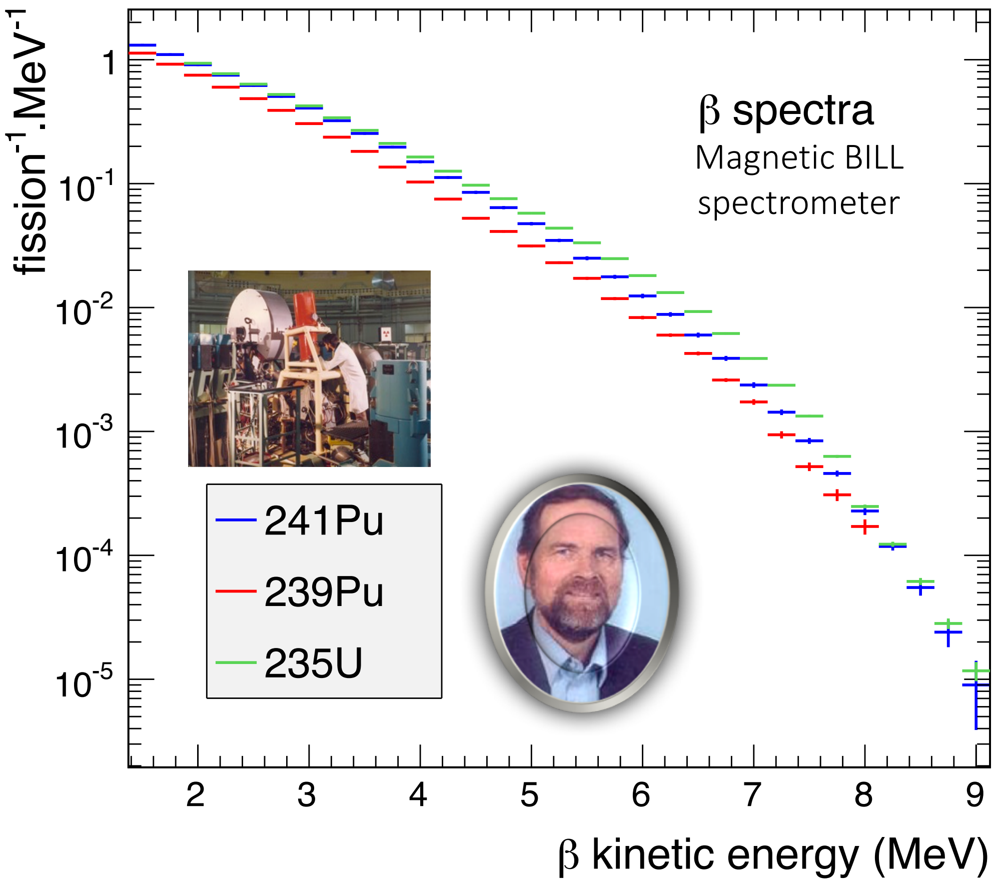
Δm^2	1.4 %
δm^2	2.2 %
$\sin^2\theta_{13}$	3.8 %
$\sin^2\theta_{12}$	4.4 %
$\sin^2\theta_{23}$	~ 5 %

(1 σ uncertainty)



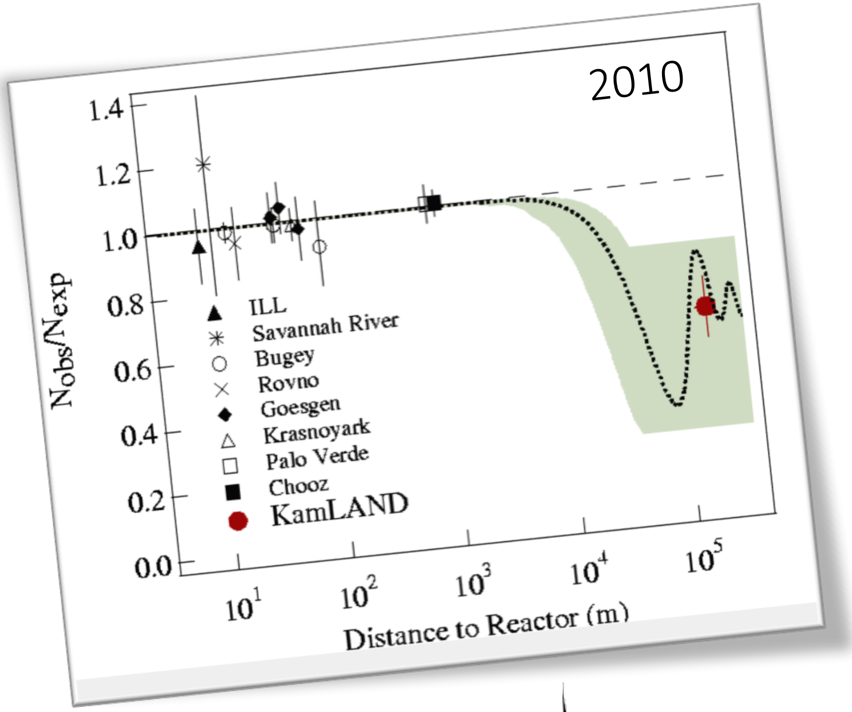
Reactor Neutrino Flux and Spectra

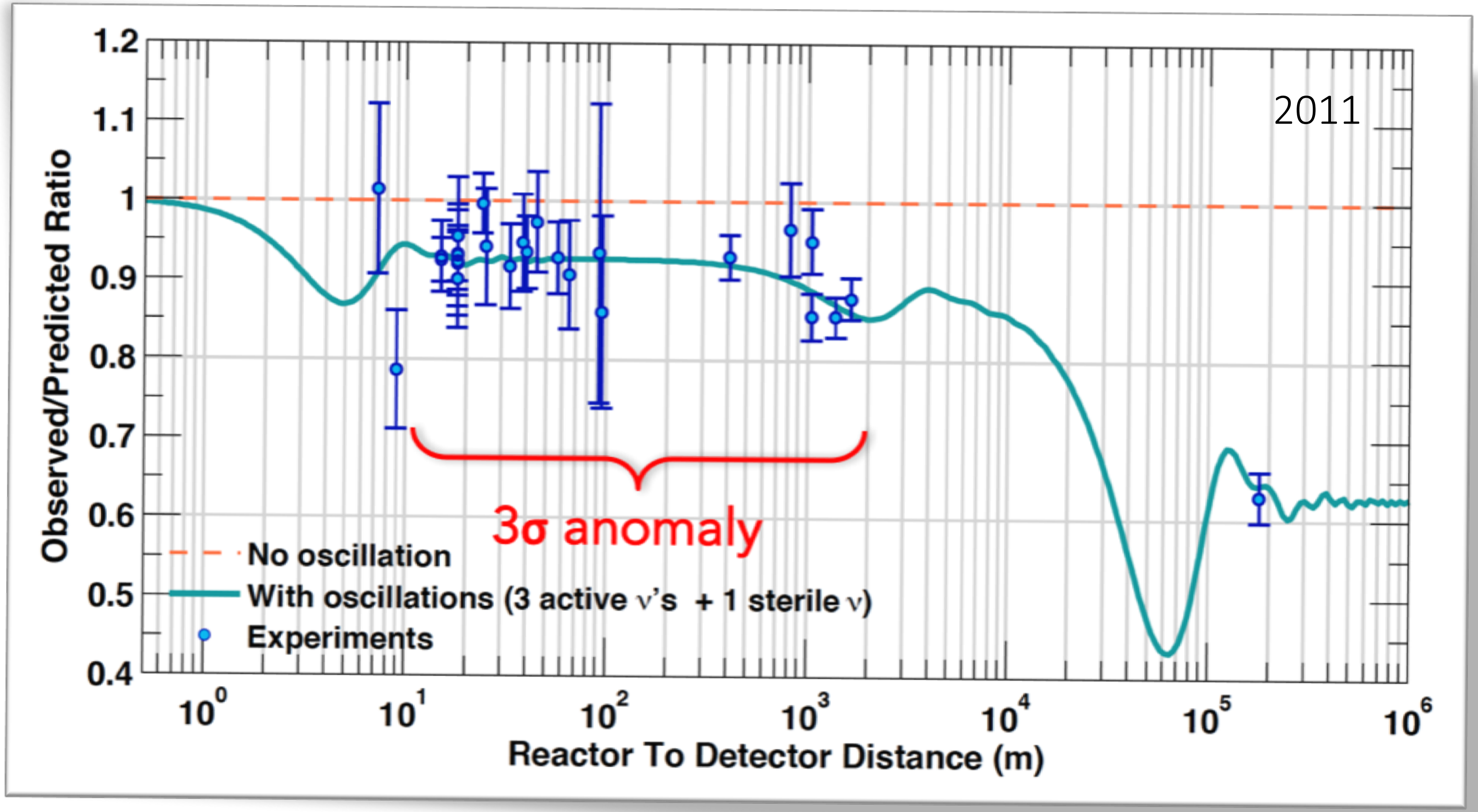




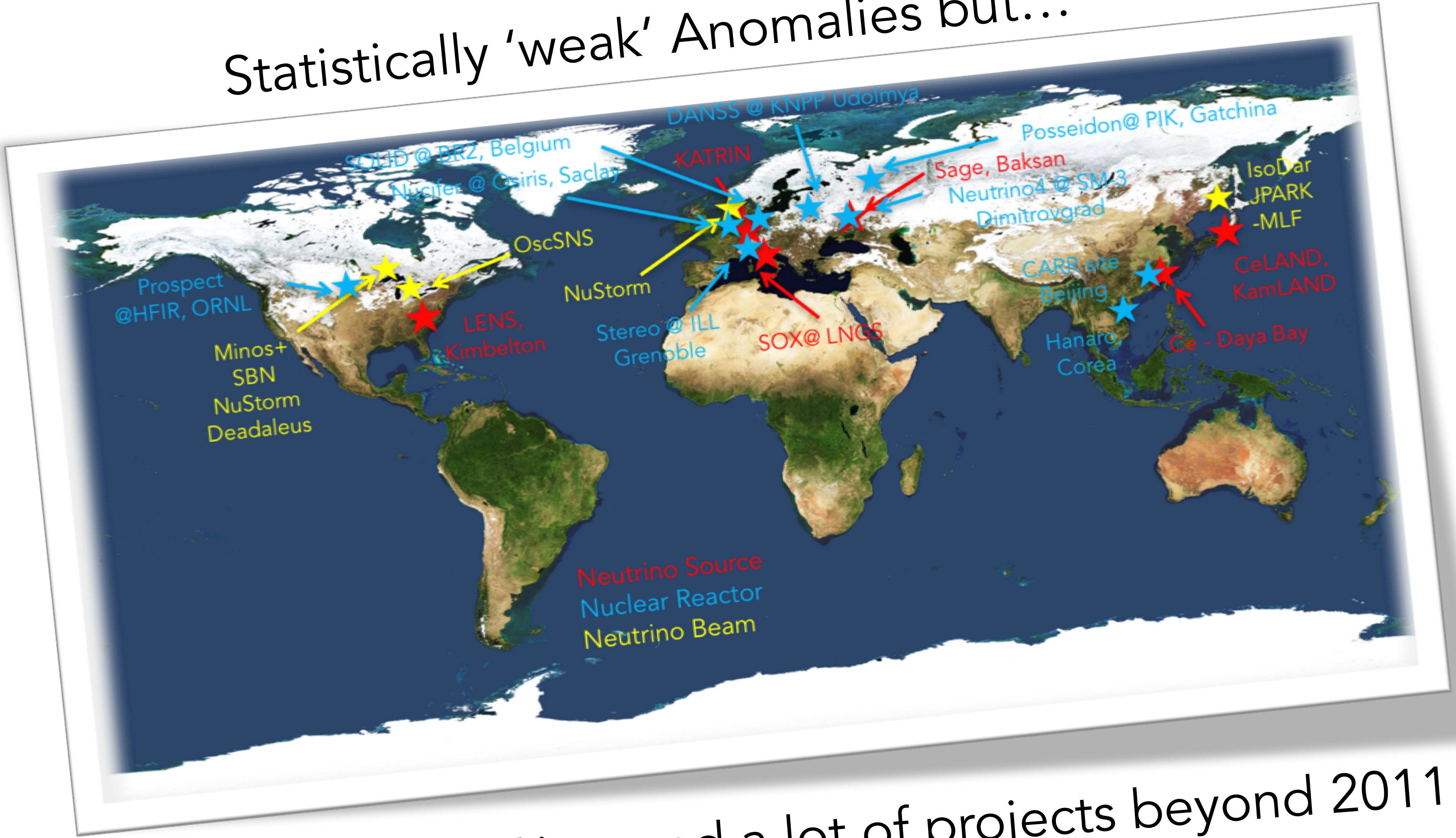
2011: Reevaluation of the $e-\nu$ conversion procedure – Flux reevaluated at + 3.5%!
(motivation: interpret Double Chooz results, without near detector)

Reactor Antineutrino Anomaly - 2011





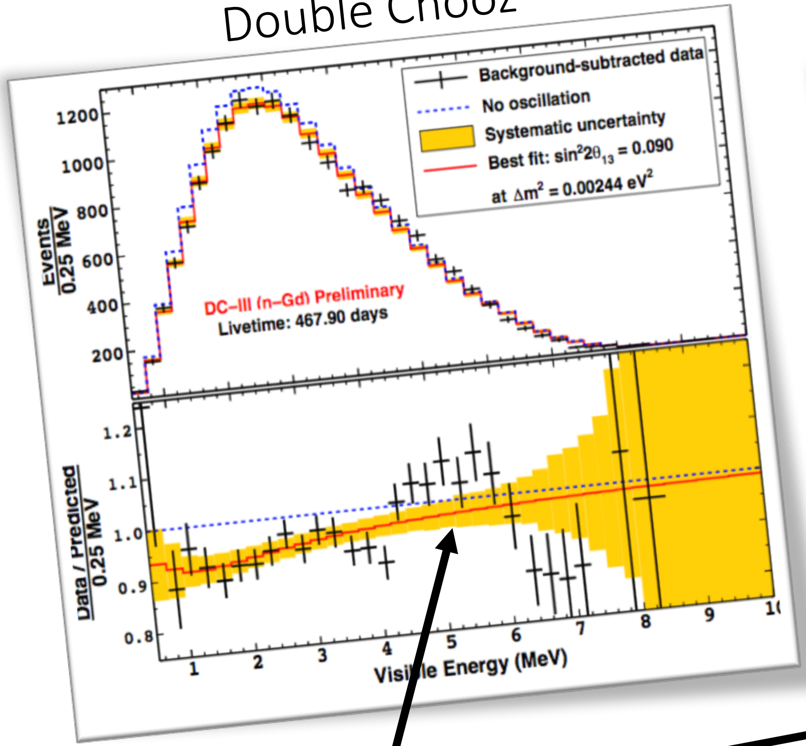
Statistically 'weak' Anomalies but…



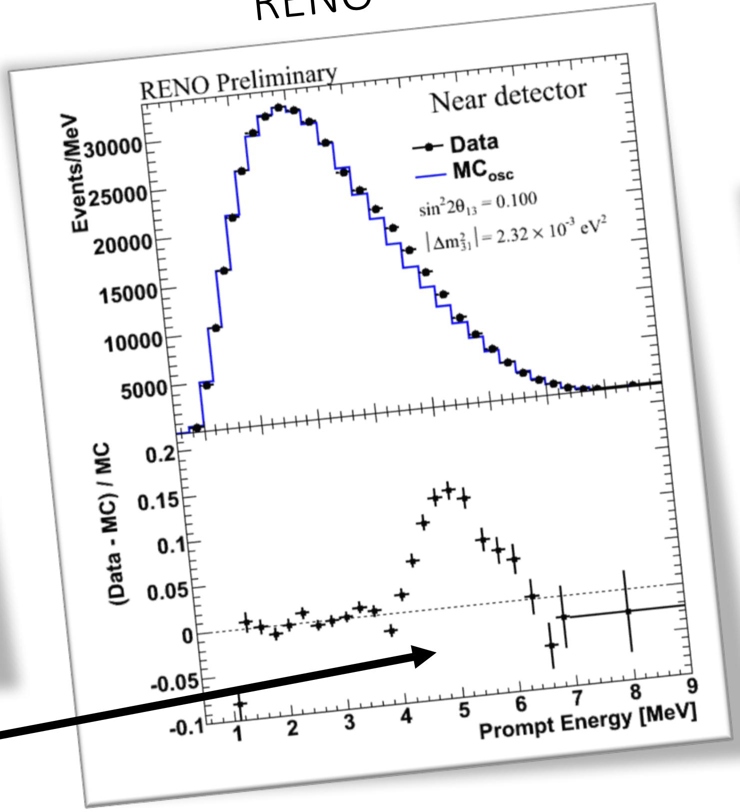
Triggered a lot of projects beyond 2011

A new anomaly (almost) revealed

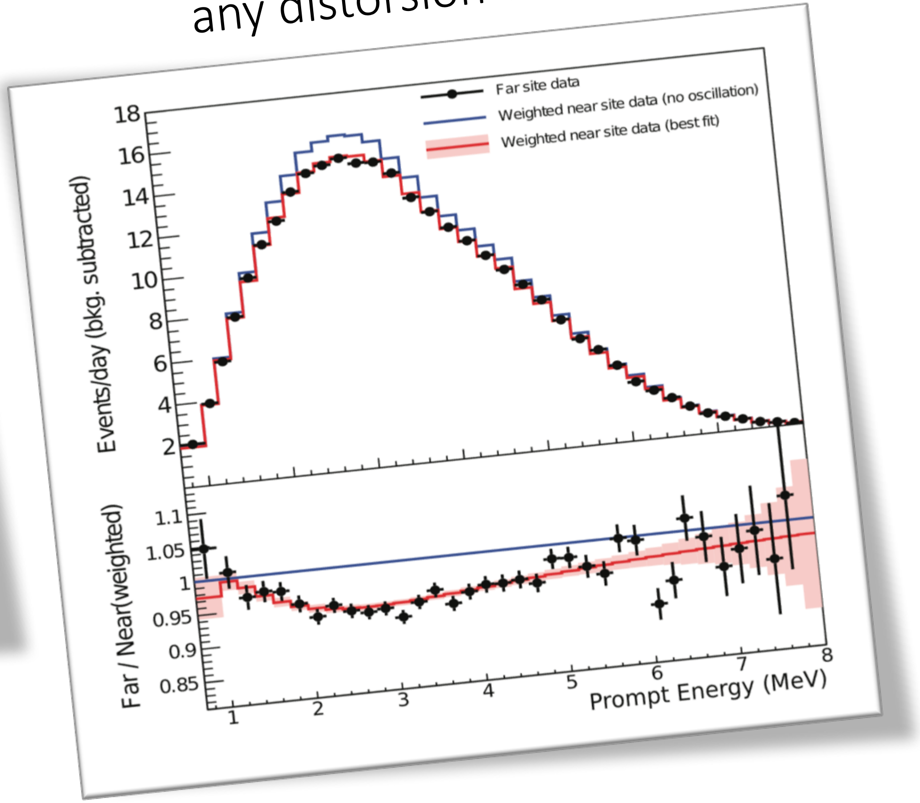
Double Chooz



RENO

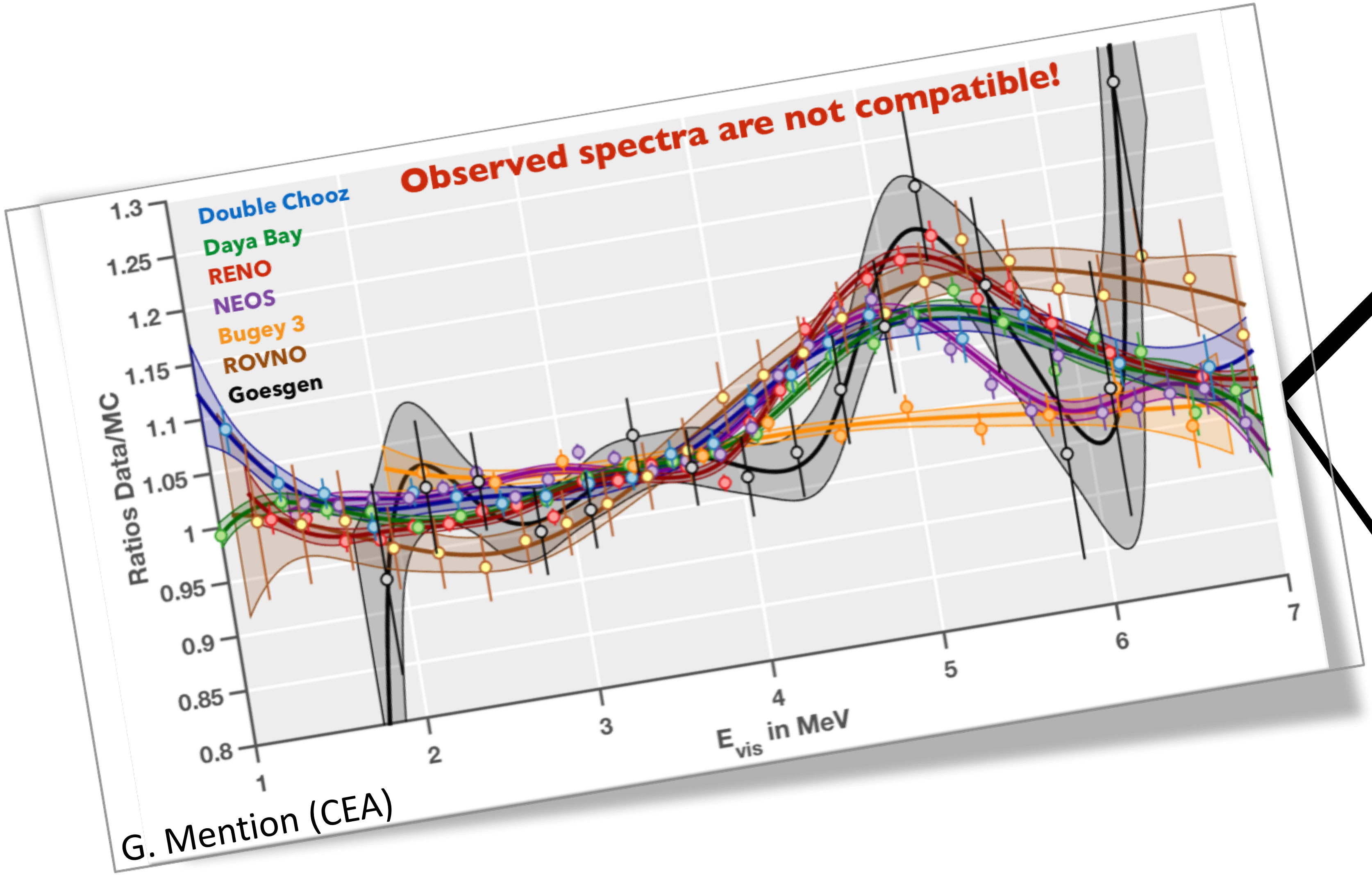


BUT Daya Bay did not report any distorsion YET…



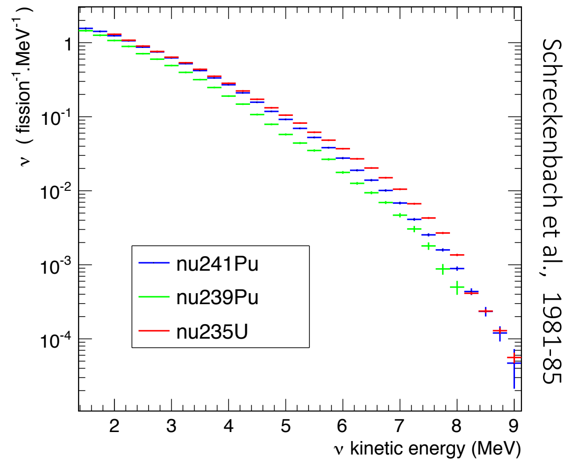
So-called 5 MeV bump

4-6 MeV spectral distortion still unexplained...



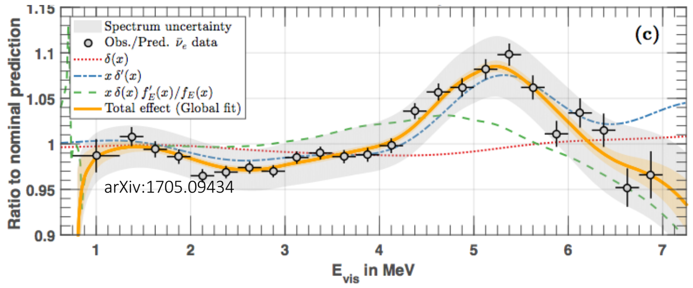
Reactor ν-spectra?

Bias? Underestimated systematics?



Detector response?

1% E-scale non-linarity?



To Hervé de Kerret (1947-2017)

Double-CH$\theta_{13}\theta_{13}$Z ?

θ_{CHOOZ} ?

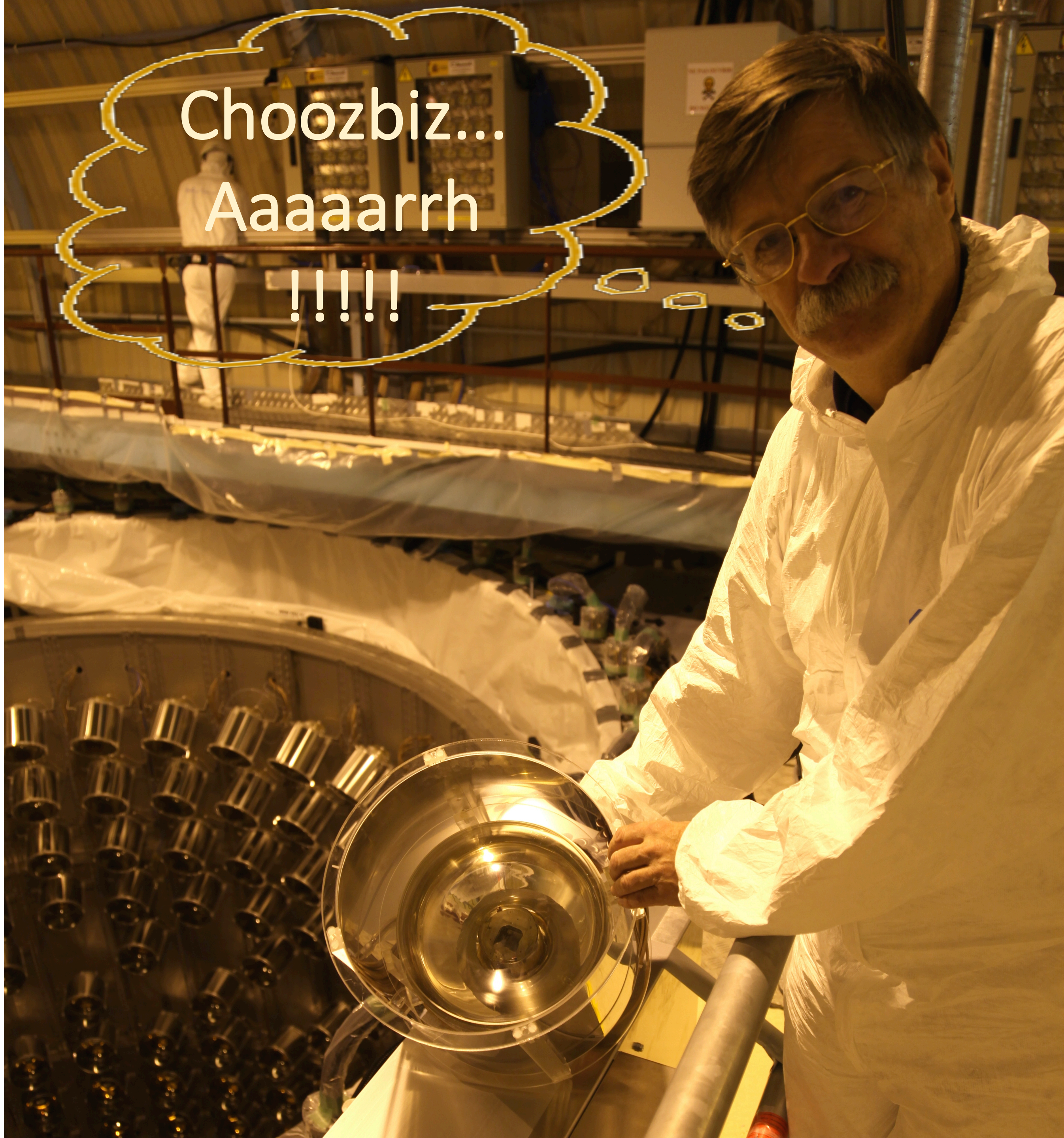
CH$\theta_{13}\theta_{13}$Z-2D ?

CH$\theta_{13}\theta_{13}$Z ?

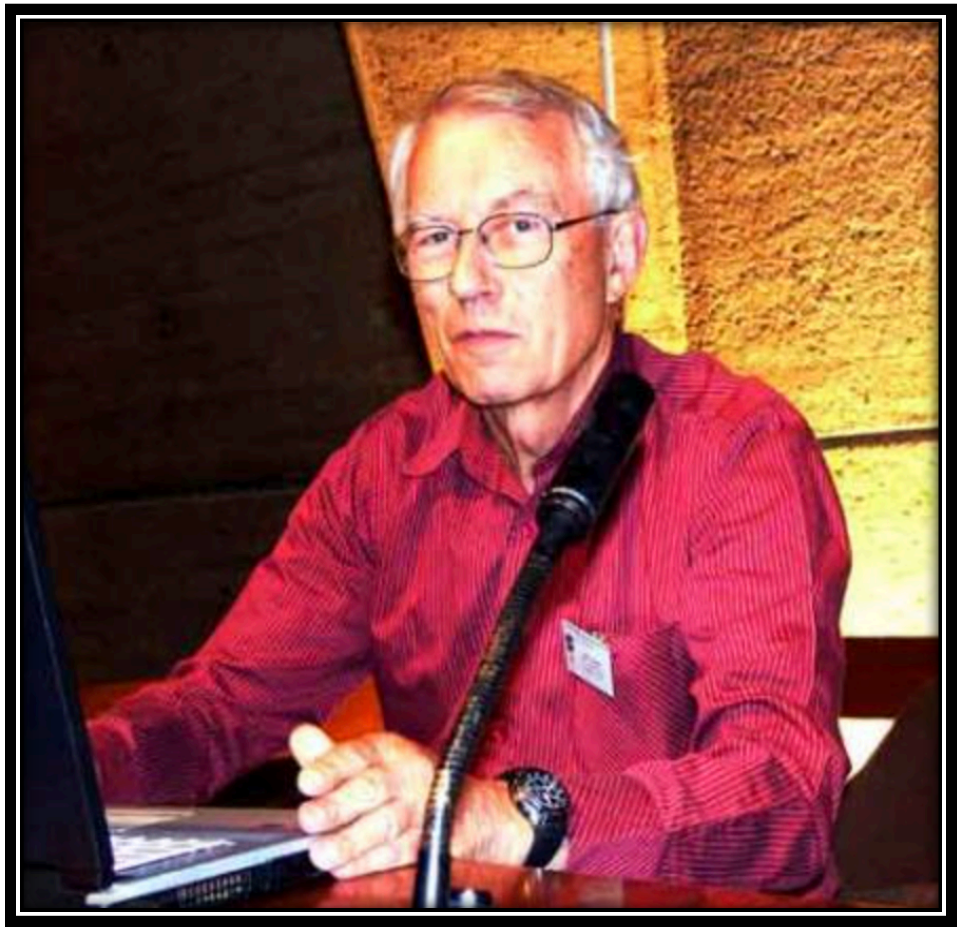
Super-CH$\theta_{13}\theta_{13}$Z ?

CH$\theta_{13}\theta_{13}$Z-II

....



Thank you!



Objet: The Reactor Neutrino Anomaly...
Date: 19 décembre 2010 à 17:27:14 UTC+1

Reactor Antineutrino Anomaly – 12/2010

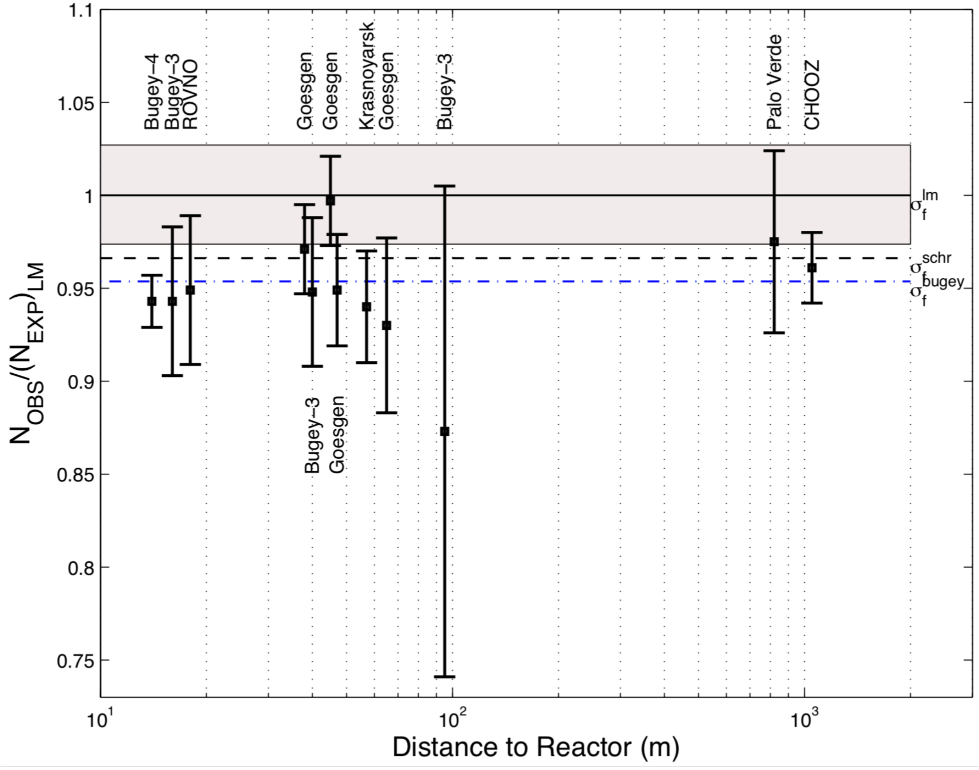
I synthesized all the known measurements at short distances (<Chooz)… You will see that the result of this synthesis are really very surprising....

ALL measurements (except 1) are more than 1 sigma from the LM prediction. The average of the effect is 0.943 and the sigma is 0.03 …

The options available to us:
- Anomaly in the calculation of the new reactor neutrino spectra

OR
- Anomaly in the measurement of neutrinos
- Case 1: All the experiments underestimate their errors and/or do a bad count, but strange that it is always in the same direction?
- Case 2: Neutrino oscillation but without spectrum distortion to match Bugey3 & Goesgen spectrum ratios, so only possible with massive neutrinos, >>1 eV (keV?). This solution is ULTRA-hypothetical but I prefer to list it as a possibility for completeness. An effect of 1-0.943=0.057 would result, at high Dm2_41, in sin2(2theta14)=0.114 ... which is so large that it could be incompatible with other neutrino oscillation results (solar, atm, beams, etc.), wouldn't it? Thank you for clarifying this point.

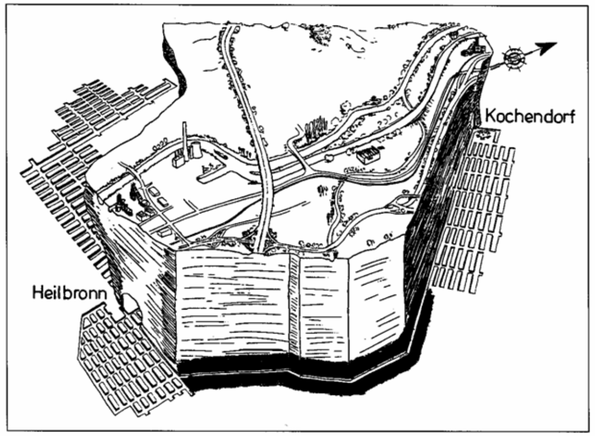
- The neutrinos are still surprising us....



Thierry Lasserre – 7/9/2018

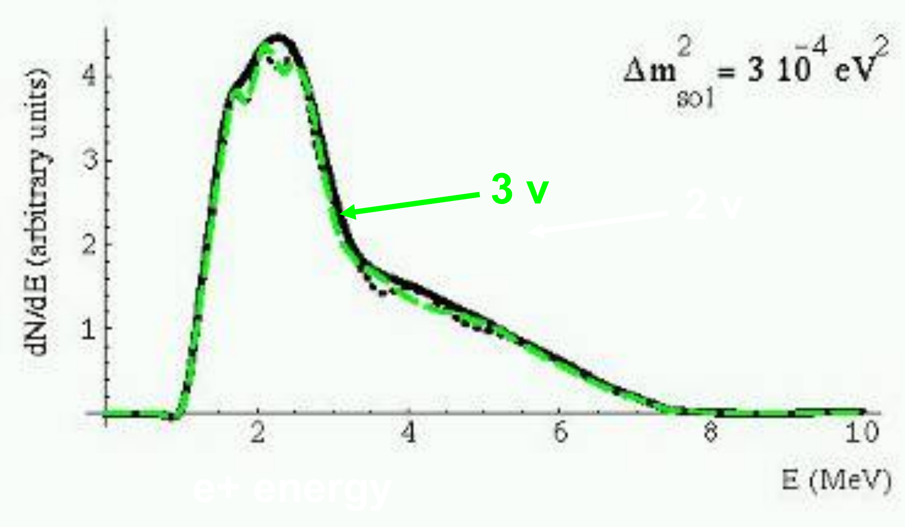
HLMA: a failed attempt

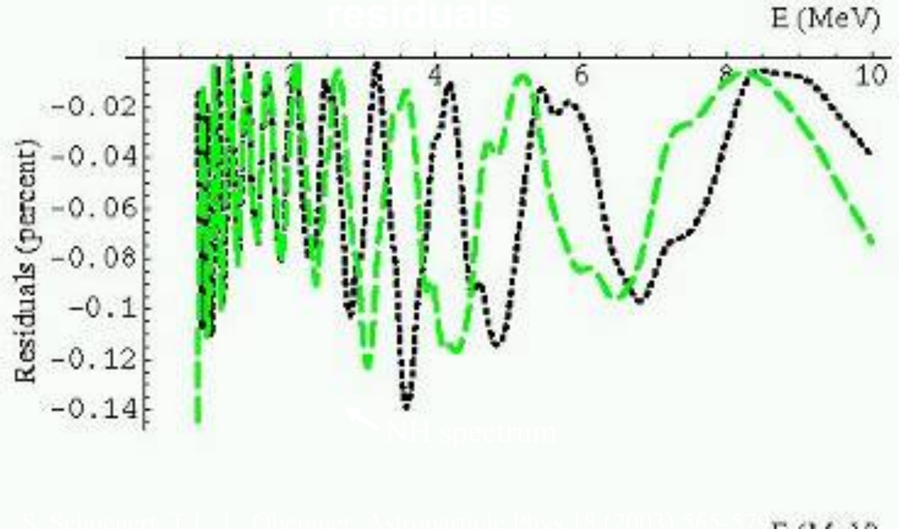
The Heilbronn salt mine



- Context <2003: KamLAND could not have measured Δm_{sol}^2 if greater than **2 10^{-4}** eV^2
- Study of the **HLMA**: a new reactor neutrino project – relevant only if $\Delta m^2 > 2\ 10^{-4}$ eV^2

- **By products with a 1 kiloton detector Heilbronn Mine (20 km baseline)**
  - **constraint on $(\sin^2 2\theta_{13})>0.05$**
  - **probe of the ν mass hierarchy**





$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \underbrace{2|U_{e3}|^2\left(1-|U_{e3}|^2\right)(1-\cos\Delta_{31})}_{\text{atm}} - \underbrace{\frac{1}{2}\left(1-|U_{e3}|^2\right)^2 \sin^2(2\theta_{12})(1-\cos\Delta_{21})}_{\text{solar}}$$

$$+ \underbrace{2|U_{e3}|^2\left(1-|U_{e3}|^2\right)\sin/\cos^2(\theta_{12})\left(\cos(\Delta_{31}-\Delta_{21})-\cos\Delta_{31}\right)}_{\text{inteference}}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{2E}$$