Experimental

Neutrino Oscillation Physics

XL International Meeting on Fundamental Physics

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CIEMAT

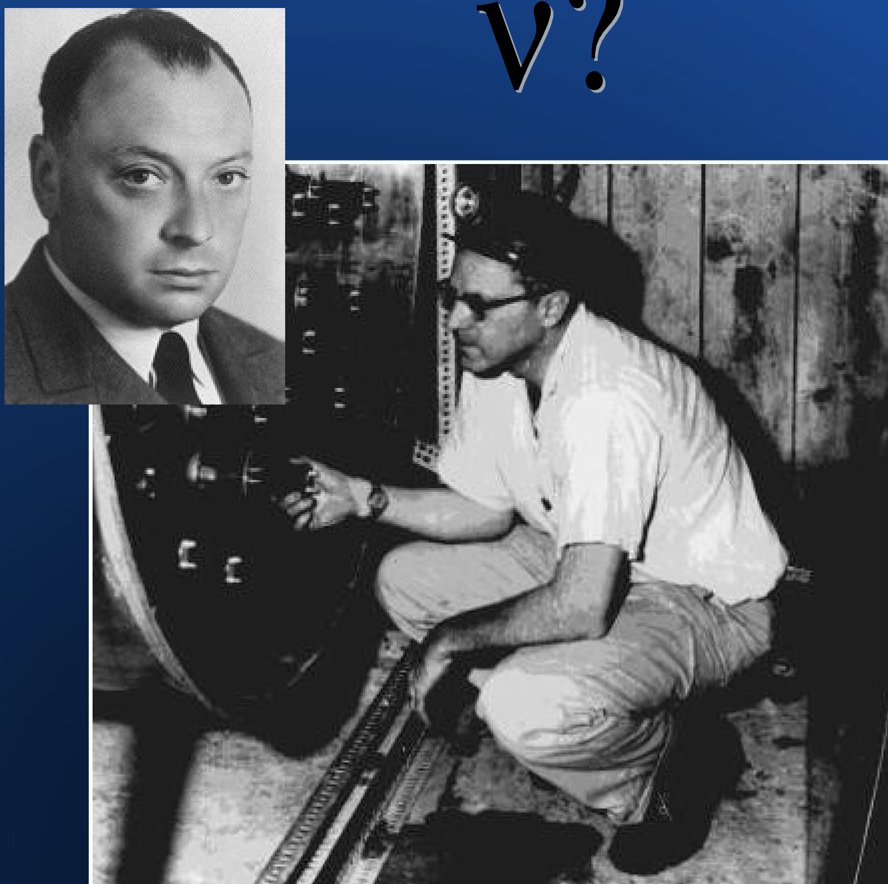
GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Overview

- Neutrino Oscillation physics
- Measuring the oscillation
- The first generation
- The precision generation
- The latest mixing angle
- What's next?
- All in all...

Neutrino Oscillation Physics

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

ββ0ν

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

Atmospheric sector

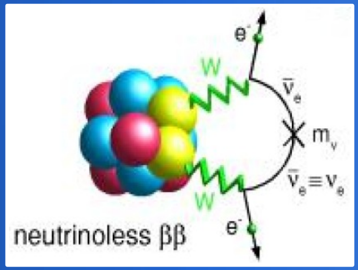
θ_{23}

interference sector

θ_{13}, δ

Solar sector

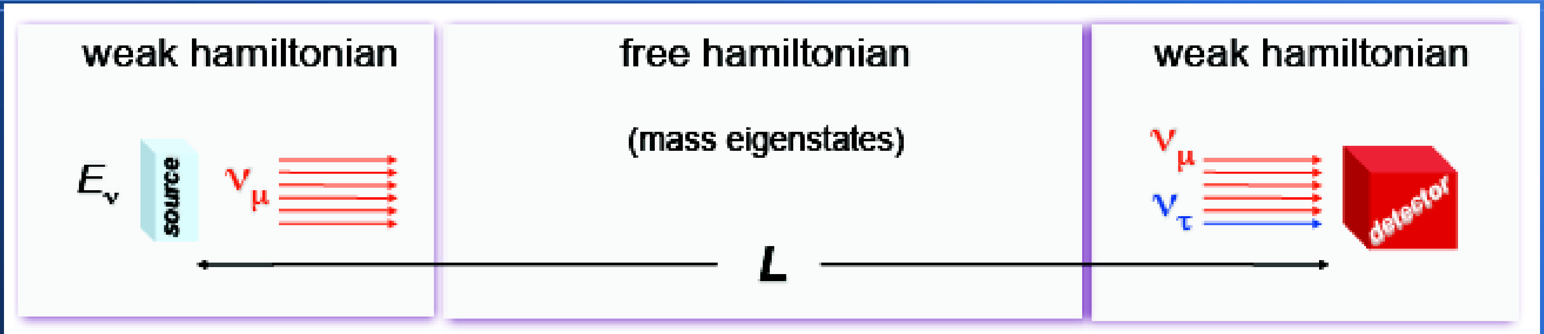
θ_{12}



α_1, α_2

Neutrino Oscillations

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

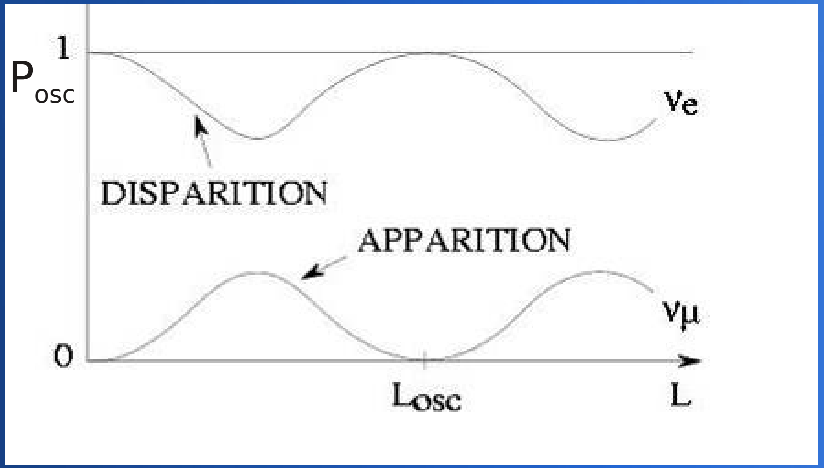


Oscillation parameters: $(\theta_{12}, \theta_{13}, \theta_{23})$, $(\Delta m^2_{21}, \Delta m^2_{31})$, δ

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

amplitude frequency

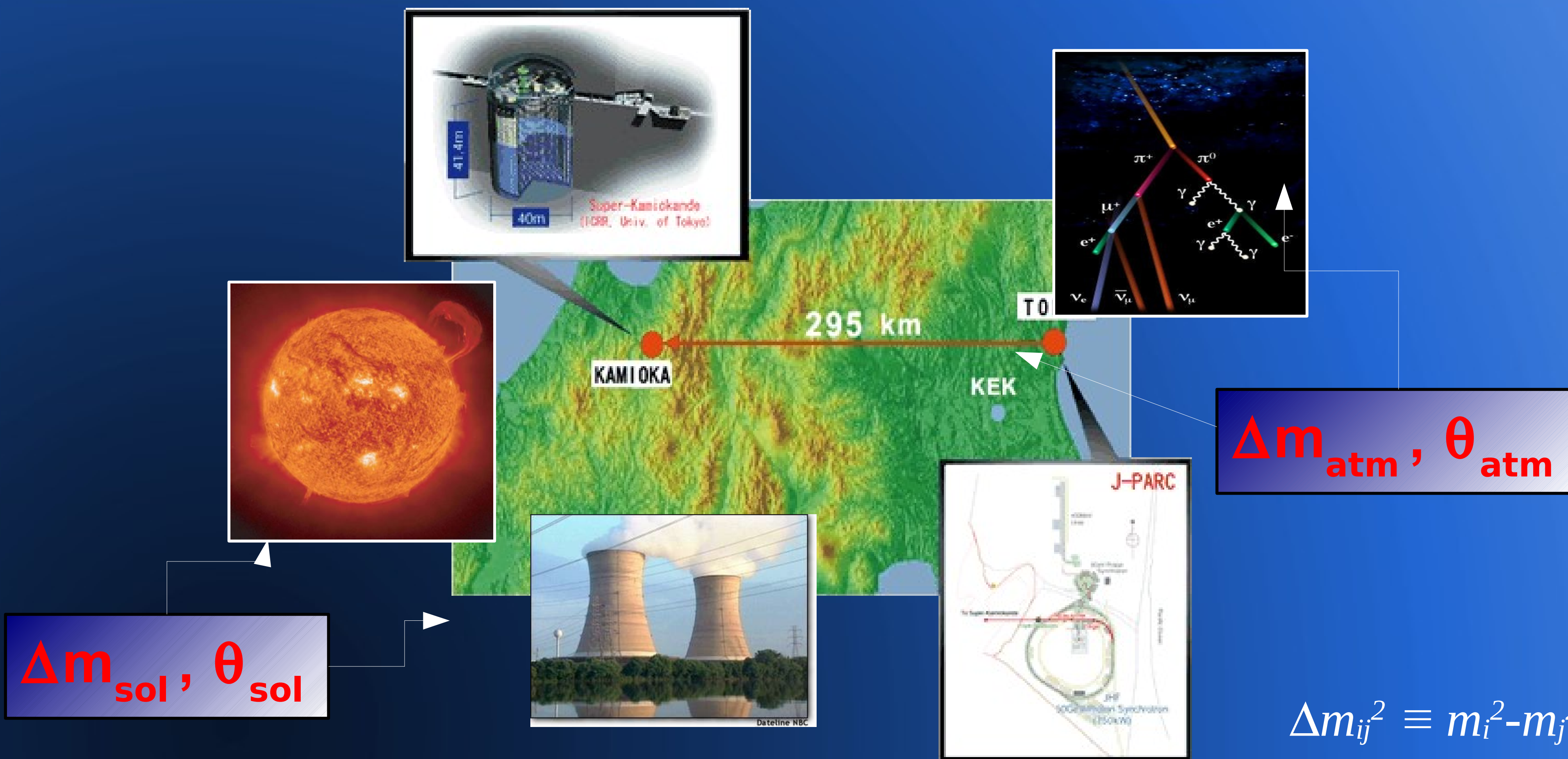
$$P_{\alpha\beta} = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 L}{4 \cdot E_\nu}\right)$$



Measuring

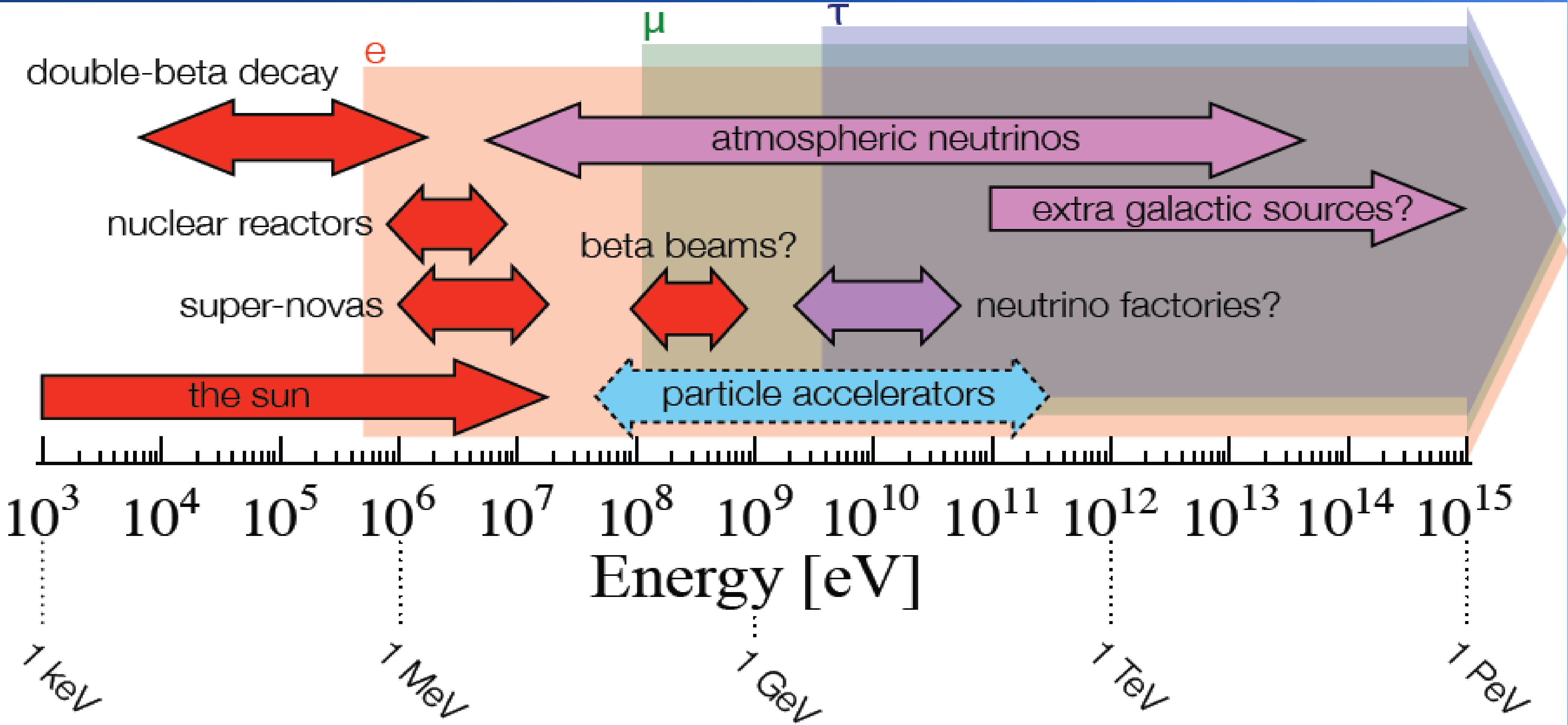
The Oscillation

Neutrino Sources



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

Neutrino Energies

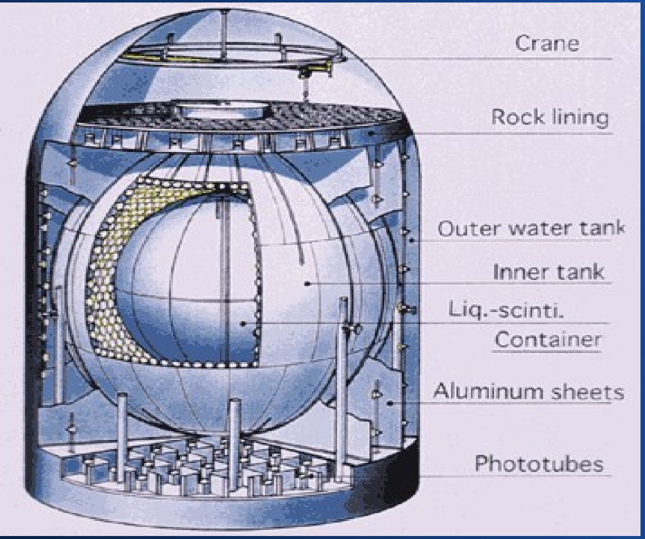


Hunting neutrinos

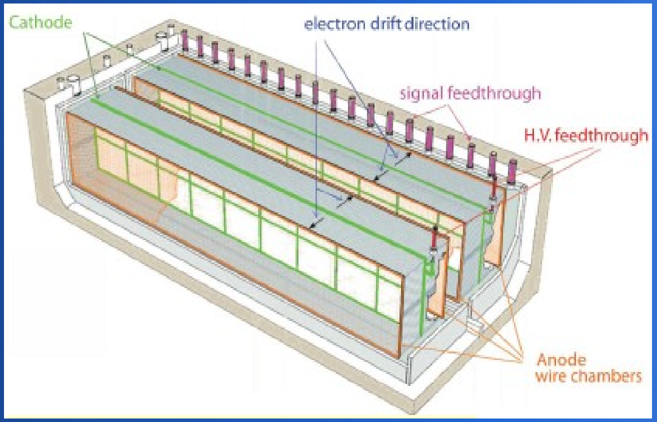
- Radiochemical experiments: Homestake, Gallex, ...
- Cherenkov: SuperKamiokande, MiniBooNE,...
- Scintillator calorimeters: KamLAND, Double Chooz..
- Tracking calorimeters: MINOS, NOvA, …
- LAr TPCs: ICARUS, MicroBooNE
- Emulsions: OPERA

MINOS

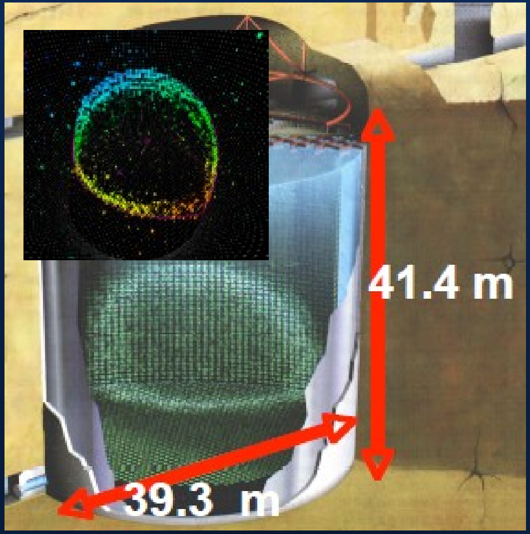
KamLAND



ICARUS

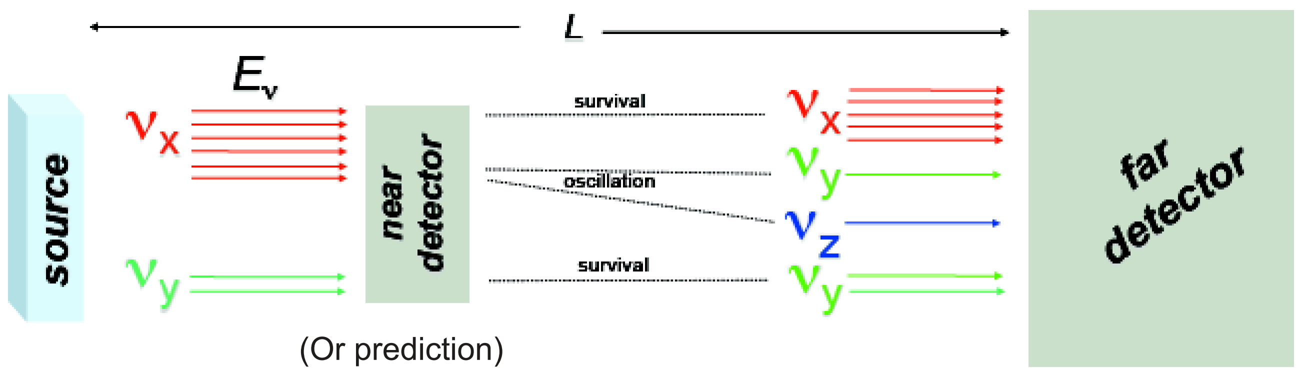


SuperK



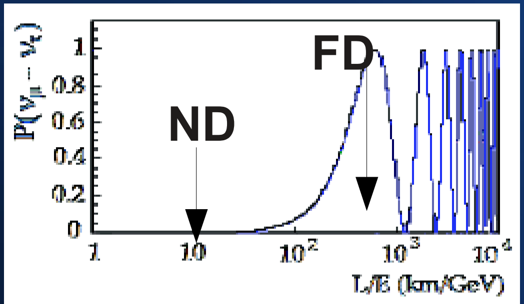
Setting up the experiment

Known flux before oscillation



(Or prediction)

Comparison with no-oscillation expectation



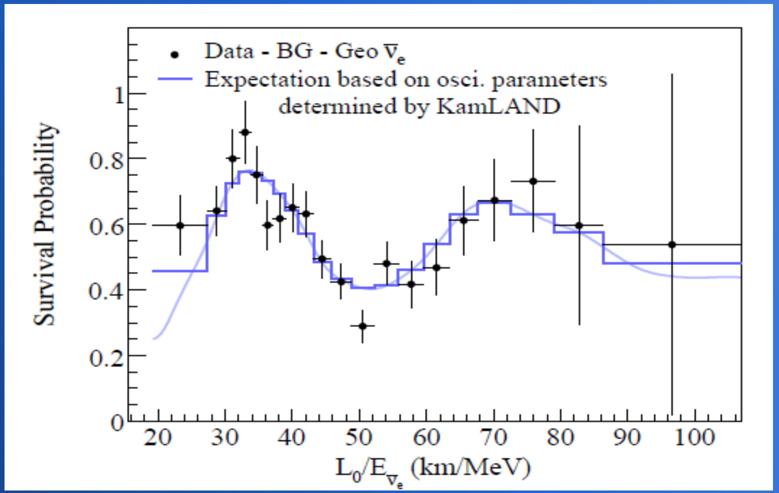
$$P_{\alpha\beta} = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4 \cdot E_\nu}\right)$$

Experiment	L (m)	E (MeV)	Δm^2 (eV^2)
Solar	10^{10}	1	10^{-10}
Atmospheric	$10^4 - 10^7$	10^2–10^5	$10^{-1} - 10^{-4}$
Reactor SBL	$10^2 - 10^3$	1	$10^{-2} - 10^{-3}$
Reactor LBL	$10^4 - 10^5$		$10^{-4} - 10^{-5}$
Accelerator SBL	10^2	10^3–10^4	> 0.1
Accelerator LBL	$10^5 - 10^6$	10^4	$10^{-2} - 10^{-3}$

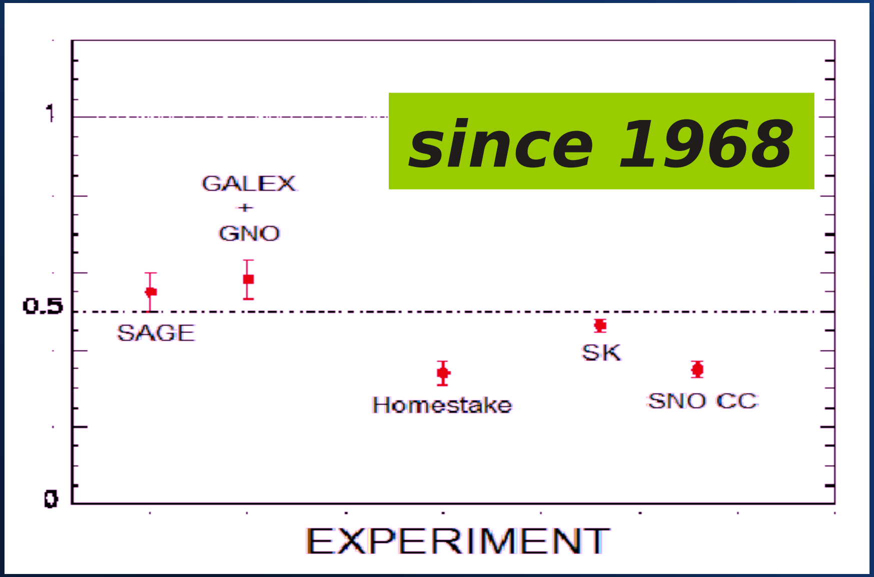
The first Generation

The Solar Sector

- Solar experiments:
  - Radiochemical experiments: Homestake, Gallex,...
  - Water cherenkov: SuperKamiokande
  - Heavy water: SNO
  - Liquid scintillator: Borexino



33-50% lower flux than the theoretical predictions

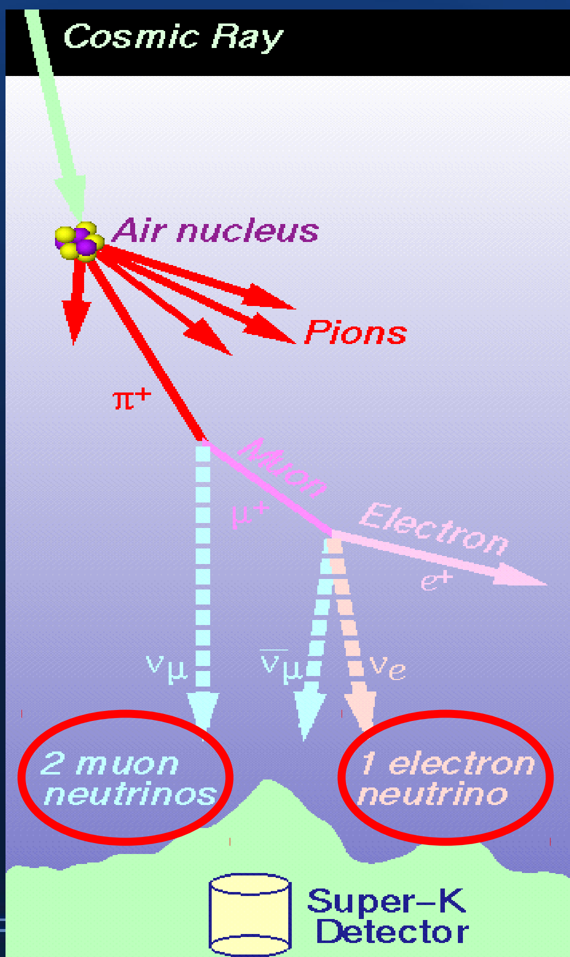


- Reactor experiment:
  - KamLAND
    - oscillation confirmed
    - Oscillarion parameters measured

$$\theta_{12} \qquad \Delta m^2_{12}$$

The Atmospheric Sector

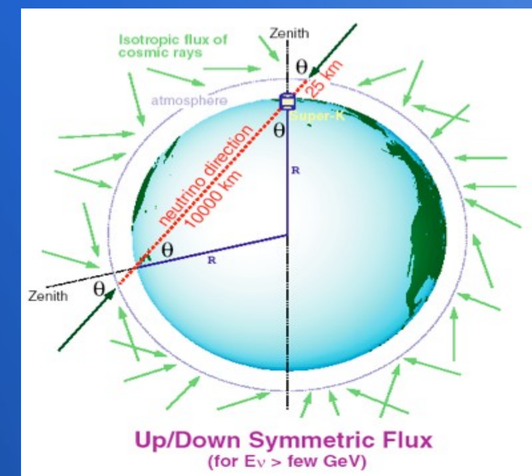
- Atmospheric neutrinos



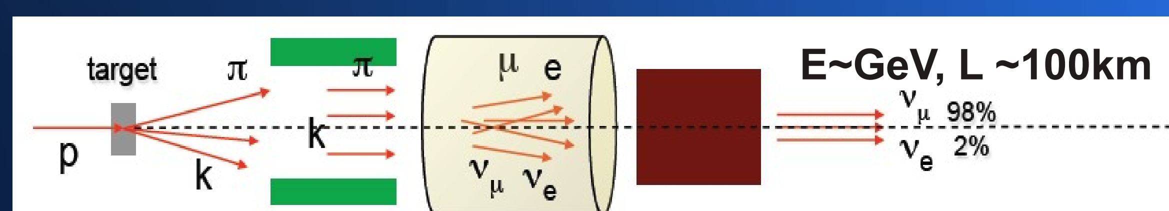
- Atmospheric experiments:
  - SuperKamiokande

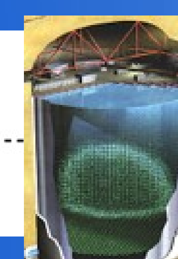
$$P_{\nu_\mu \nu_\tau} = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4E_\nu}\right)$$

$$L/E \sim 1 - 10^4 \text{ km/GeV}$$



- Accelerator experiments:
  - K2K, MINOS



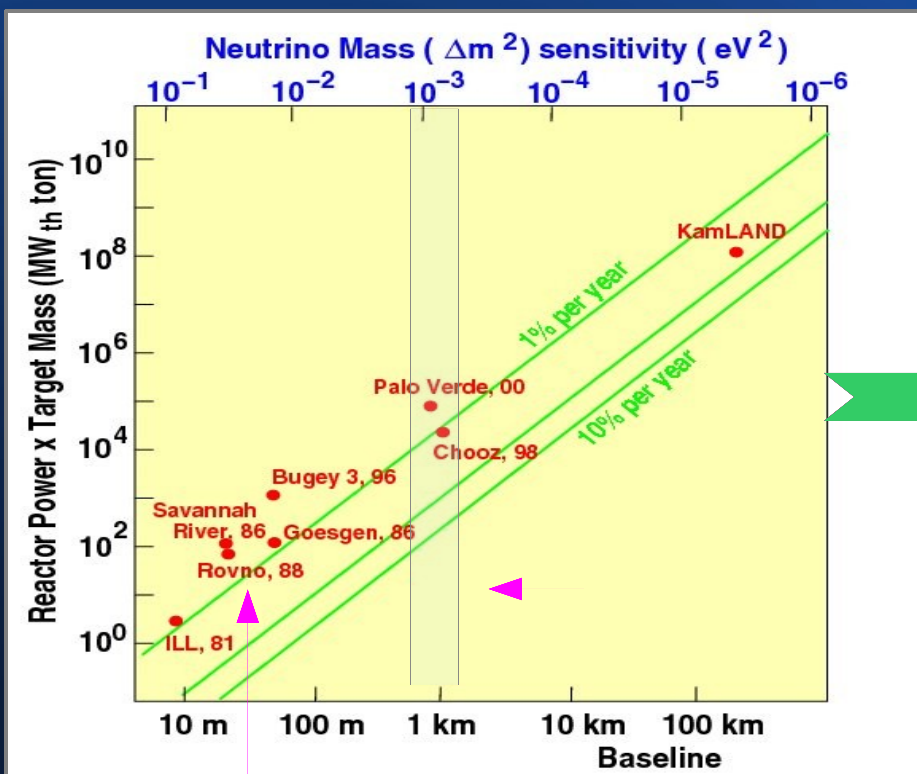


$$\theta_{23} \quad |\Delta m^2_{23}|$$

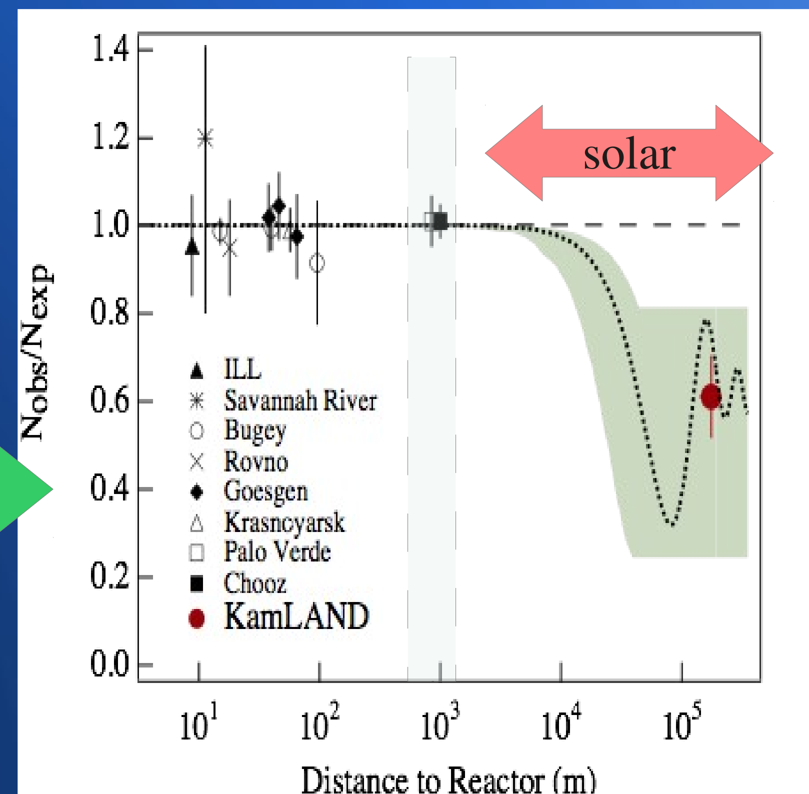
Interference sector: SBL Reactor experiments

- Past reactor experiments...

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



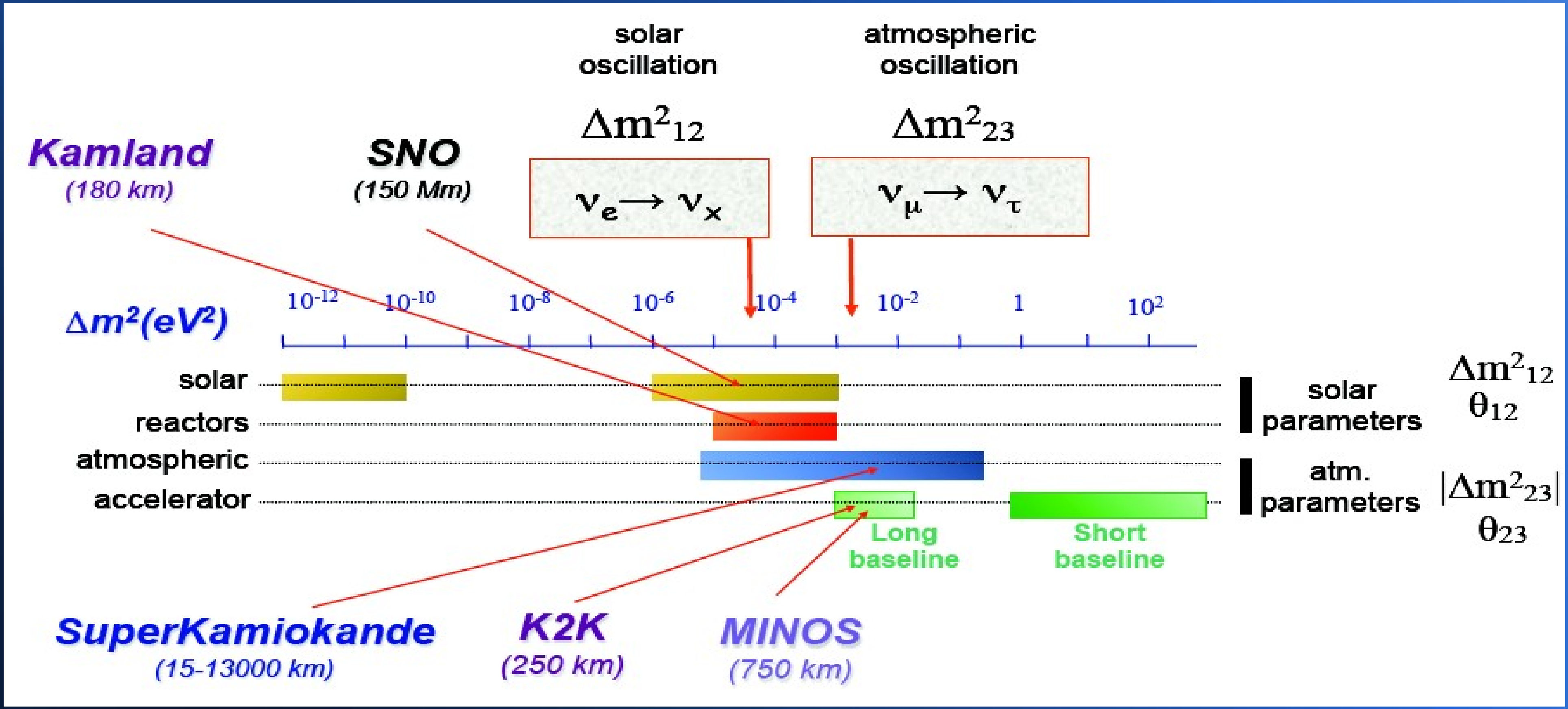
Measurement of reactor flux



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

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

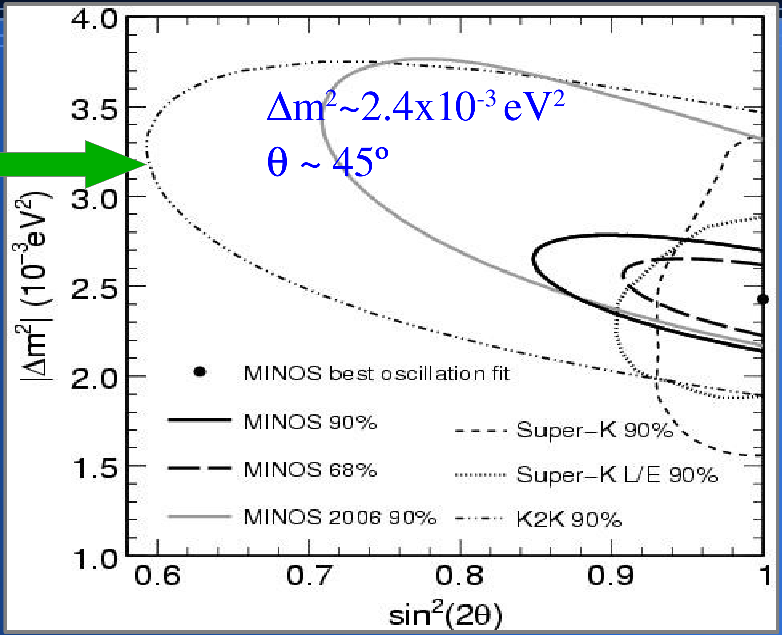
Summary of the 1st Generation



Global Analysis in 2008

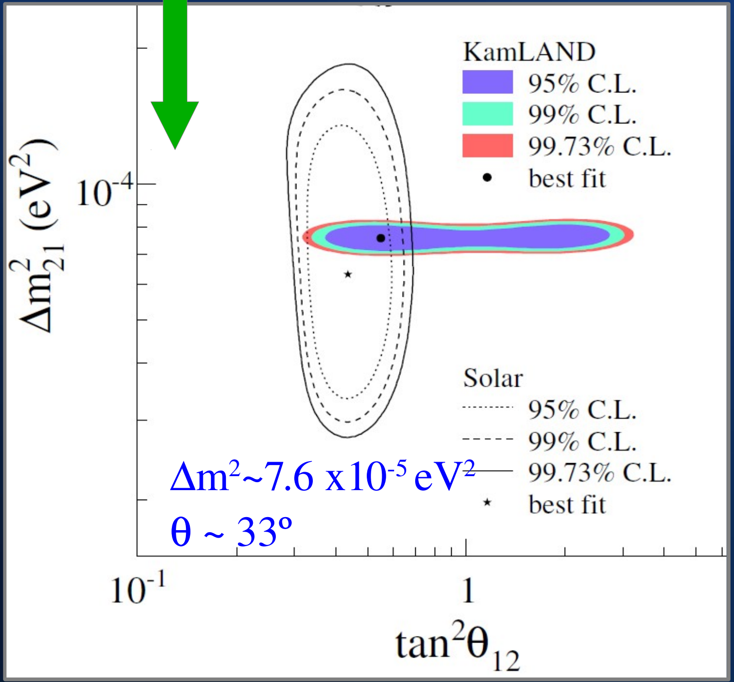
- Experimental results:

- $(|\Delta m^2_{atm}|, \theta_{atm})$ → Minos and Super-K
- $(\Delta m^2_{sol}, \theta_{sol})$ → Kamland and solar data



$\Delta m^2 \sim 2.4 \times 10^{-3}$ eV^2
$\theta \sim 45^o$

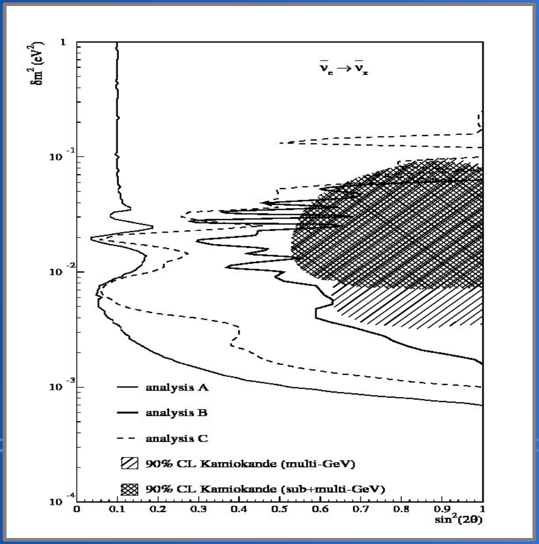
Phys. Rev. Lett. 101:131802,2008



$\Delta m^2 \sim 7.6 \times 10^{-5}$ eV^2
$\theta \sim 33^o$

Phys. Rev. Lett. 100:221803, 2008

- $\sin^2(2\theta_{13}) < 0.15$
  → Chooz
- δ?



P. Novella, IMFP 2012

3ν Global Analysis in 2010

$$\Delta m^2_{21} = 7.59 \pm 0.20 \left({}^{+0.61}_{-0.69}\right) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{31} = \begin{cases} -2.36 \pm 0.11\ (\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \\ +2.46 \pm 0.12\ (\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \end{cases}$$

$$\theta_{12} = 34.4 \pm 1.0 \left({}^{+3.2}_{-2.9}\right)^\circ$$

$$\theta_{23} = 42.8\,{}^{+4.7}_{-2.9} \left({}^{+10.7}_{-7.3}\right)^\circ$$

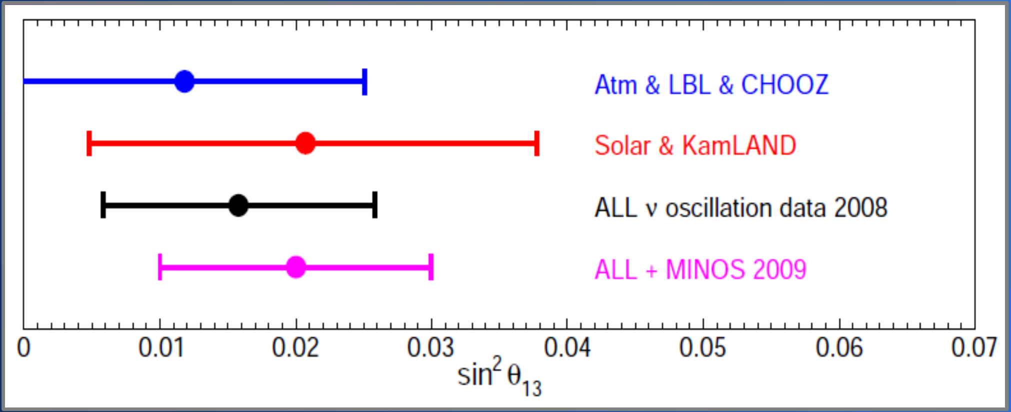
$$\theta_{13} = 5.6\,{}^{+3.0}_{-2.7}\ (\leq 12.5)^\circ$$

$$\left[\sin^2\theta_{13} = 0.0095\,{}^{+0.013}_{-0.007}\ (\leq 0.047)\right]$$

$$\delta_{\mathrm{CP}} \in [0, 360]$$

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

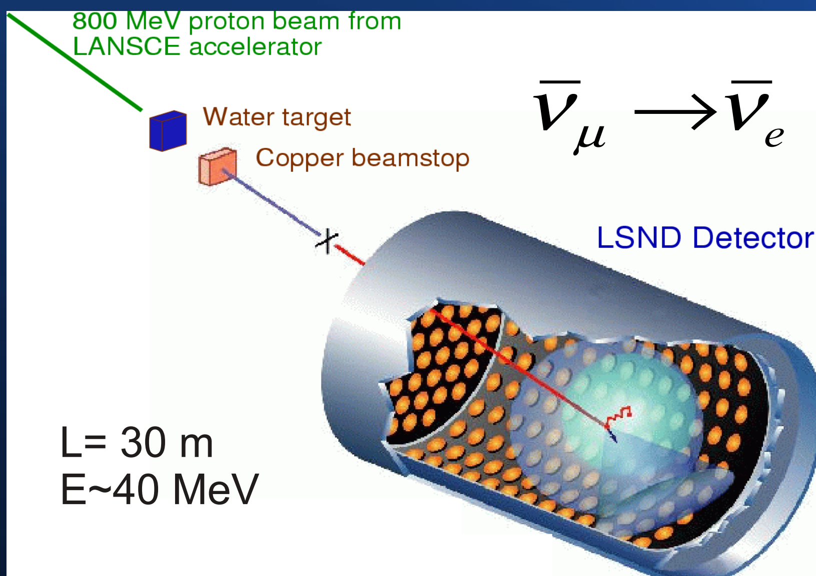
G.L. Fogli et Al, hep/ph 0905.3549v2

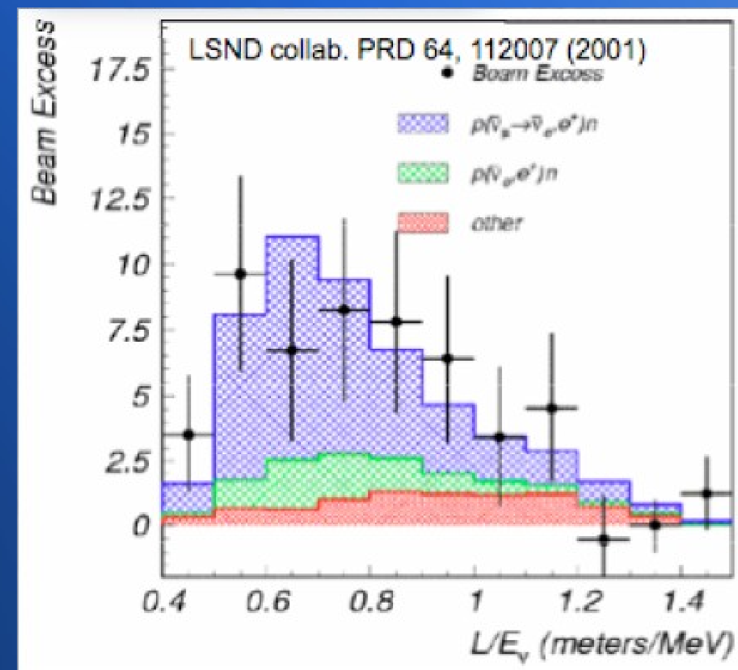


Three flavor scenario?

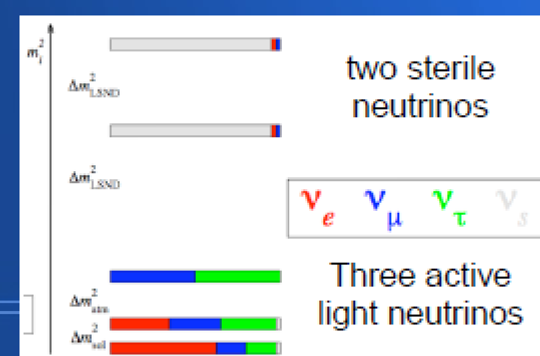
LSND

- Liquid scintillator detector
- Search for $\bar{\nu}_e$ appearance



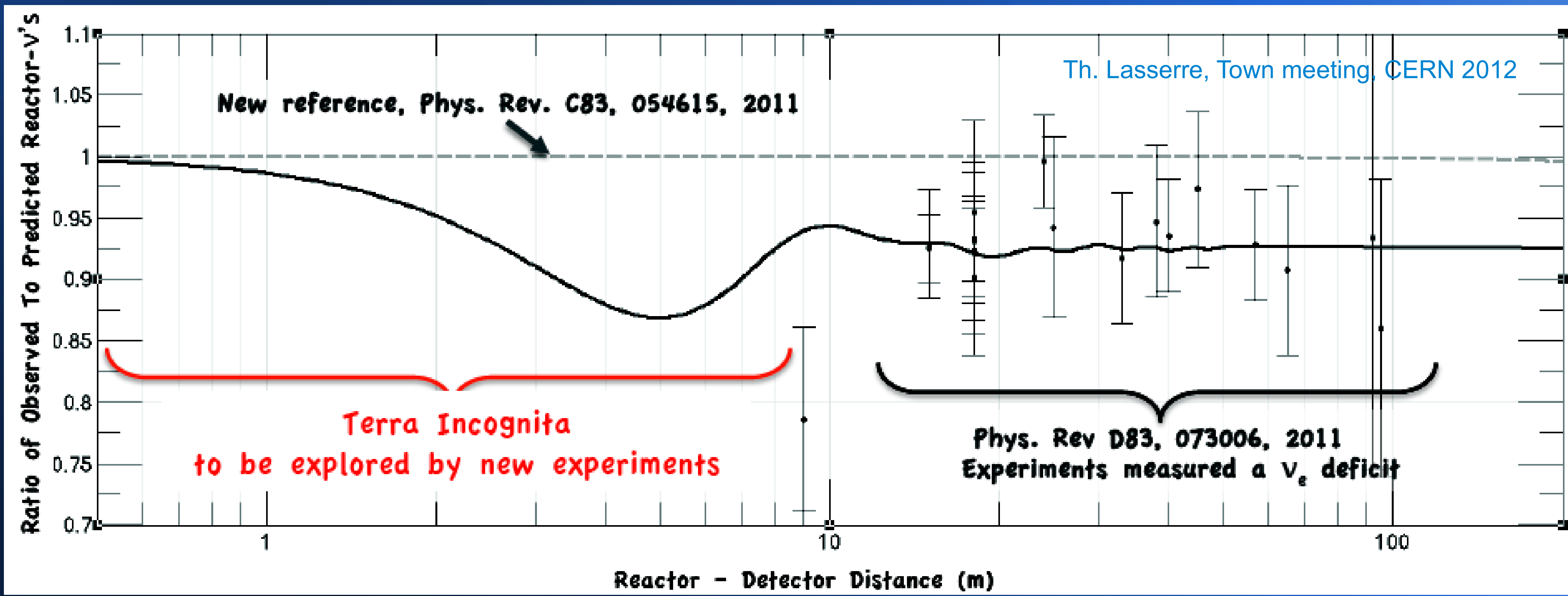


- Excess of $\bar{\nu}_e$ (3.8σ): $\Delta m^2 = .3$ to $3\ eV^2$
- Can be fitted withing 3-flavor scenario



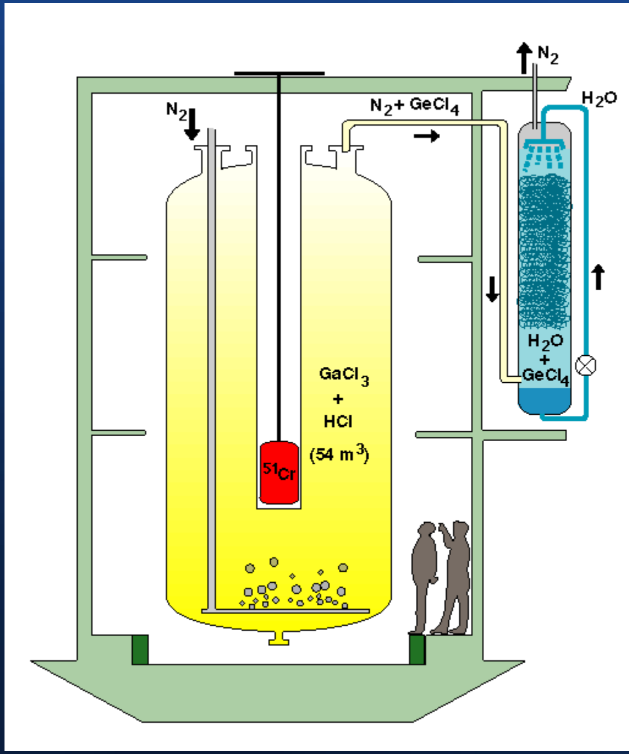
Reactor neutrino anomaly

- New reference Reactor Neutrino Spectra PRC83 054615 & PRC84, 024617 (2011)
- Re-analysis 19 short Baseline Experiments Results PRD83, 073006 (2011)

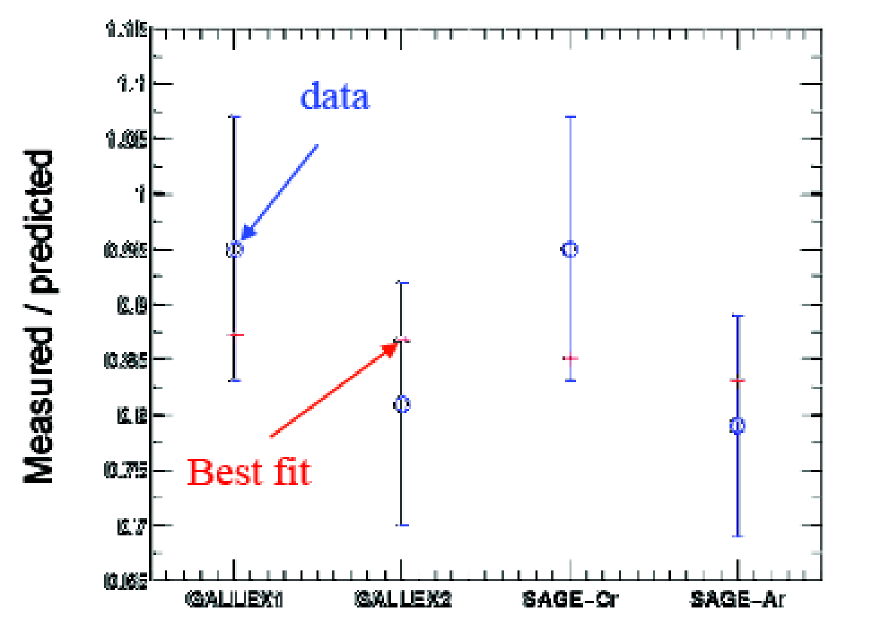


R=0.927±0.023: 3.0 σ deviation with respect to R=1 (rate only)

Gallium Neutrino Anomaly



- ≈1 MCi ν Calibration runs of GALLEX and SAGE detectors
  - Gallex: ^{51}Cr source (750 keV)
  - SAGE: ^{51}Cr and ^{37}Ar (810 keV)
- **Observed/Expected Event Ratio: R=0.86±0.05**



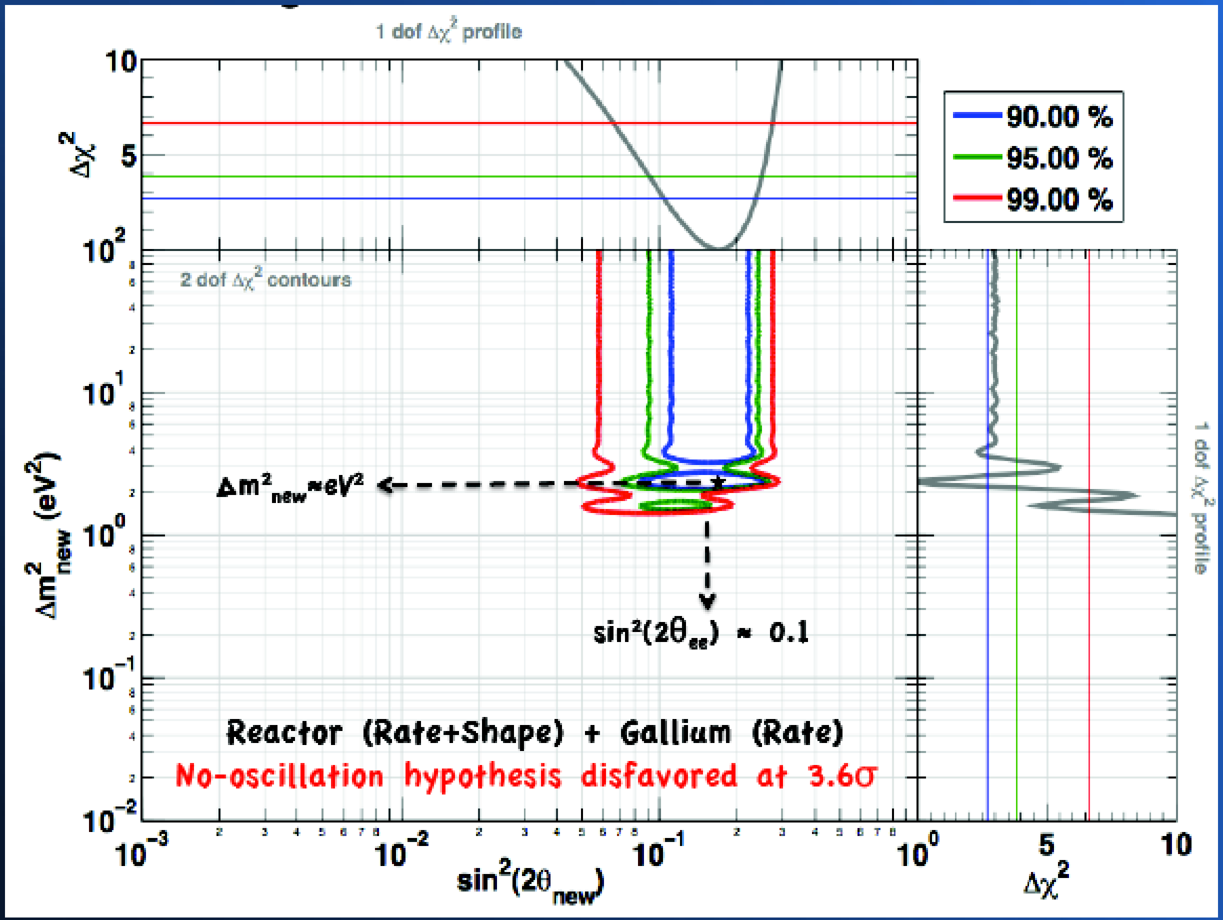
Phys. Rev. D 82, 053005 (2010); arXiv:1006.3244

- No-oscillation hypothesis disfavored at about 2.7σ

Reactor/Gallium anomalies

$$P_{\nu_e \to \nu_e}(L,E) = 1 - \sin^2(2\theta_{\rm new}) \sin^2\left(\frac{\Delta m^2_{\rm new} L}{E}\right)$$

Th. Lasserre, Town meeting, CERN 2012

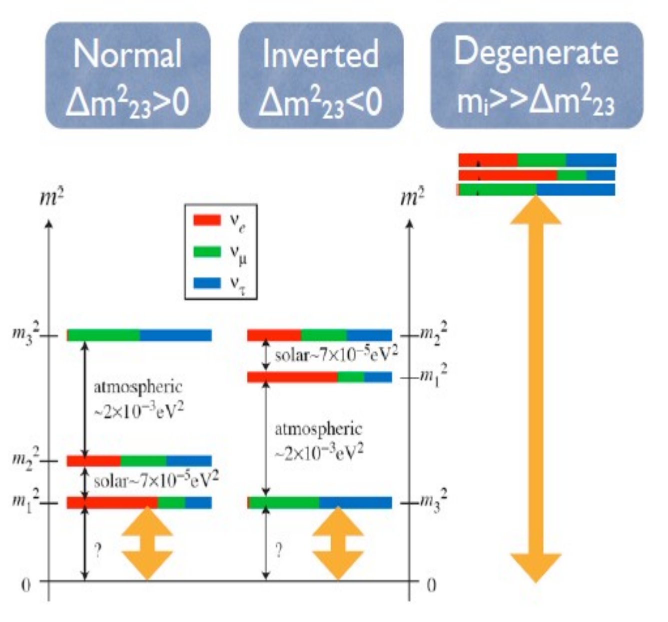


- But not consistent with LSND
  - Phys.Rev. D85 (2012) 013017

So after the first round of experiments...

After 1st round of experiments...

- Oscillation measured: massive neutrinos
  - but need for precision
- Still several questions
  - Mass hierarchy?
  - $\theta_{13} \neq 0$?
  - θ_{23} maximal?
  - CP violation in the leptonic sector?
  - Sterile neutrinos?



Let's go for a 2nd (and 3rd) round

θ_{13}	sign(Δm^2_{23})
δ_{cp}	¿ $\theta_{23} = 45^o$?

The Precision Generation

Second Generation

- Accelerators
  - MINOS
  - T2K
  - MiniBooNe
  - Nova (2013)
  - OPERA & ICARUS

Appearance
Atm Sector
θ_{13}, δ
Sterile ν

- Reactors:
  - Double Chooz
  - Daya Bay
  - RENO

θ_{13}

- Solar/Atmospheric:
  - SuperKamiokande
  - Borexino
  - INO (design)

Solar/Atm Sectors
θ_{13}, δ
Sterile ν

- Supporting experiments
  - ν flux and energy spectrum: SHINE (NA61)
  - ν-N cross-sections: SciBooNE, MINERVA, T2K,...

2^{nd} Generation: Accelerator experiments

Oscillation analysis in 3D

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = |\sum_{i=1}^{n} \sum_{j=1}^{n} U^*_{\alpha i} U_{\beta j} \langle \nu_j | \nu_i(t) \rangle|^2$$

- (θ_{13},δ): need to analyze oscillations in the 3-flavor scenario

atmospheric | interference | solar

$$P^{\pm}_{e\mu} = \boxed{X^{\pm}_{\mu}} \sin^2 2\boxed{\theta_{13}} \boxed{+} (Y^{\pm}_{c} \cos \boxed{\delta} \mp Y^{\pm}_{s} \sin \boxed{\delta}) \sin 2\boxed{\theta_{13}} + \boxed{Z_{\mu}}$$

$\theta_{23}>45^o$ or $\theta_{23}<45^o$ octant | sign Δm^2_{23} | $\theta_{23}>45^o$ or $\theta_{23}<45^o$ octant

- Oscillation parameter correlated
- Still unknown parameters

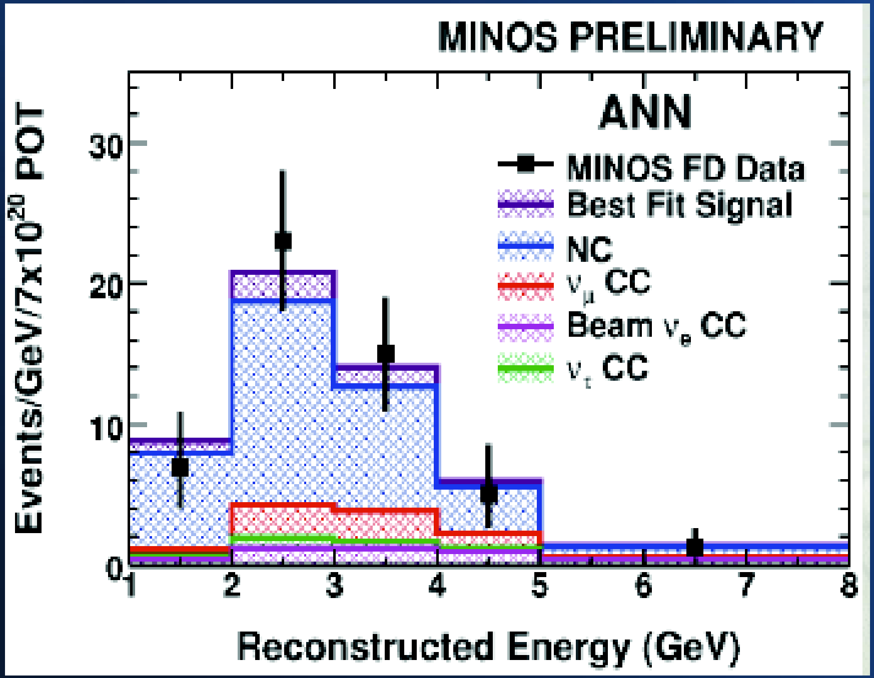
θ_{13}	sign(Δm^2_{23})
δ_{cp}	¿ $\theta_{23} = 45^o$?

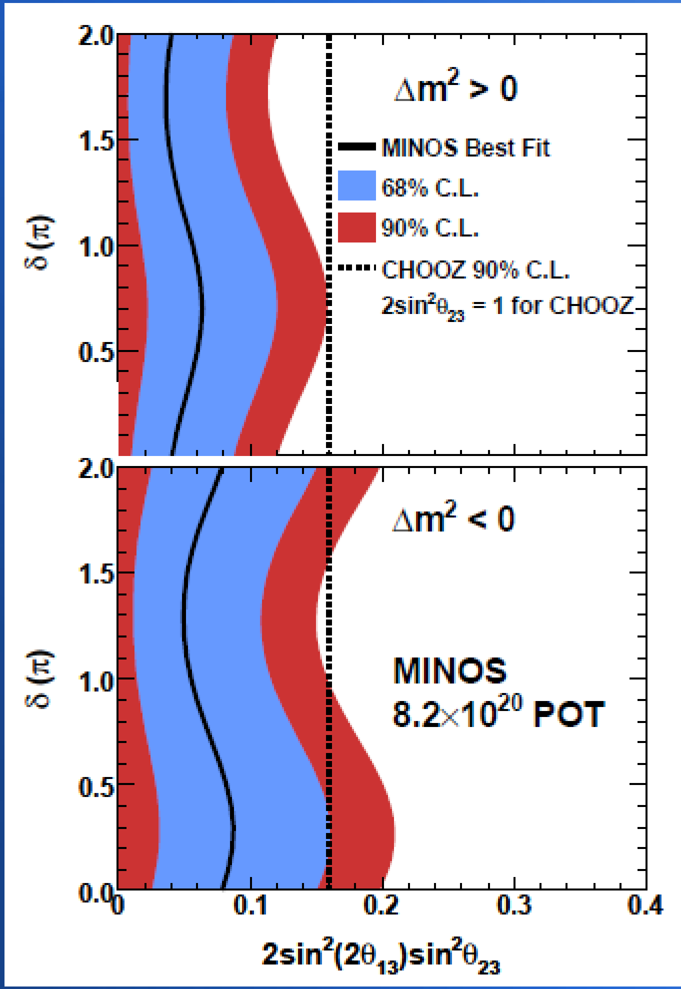
→ Degeneracies → Several Channels, Different energies, Different BL, Matter effects

MINOS (II)

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

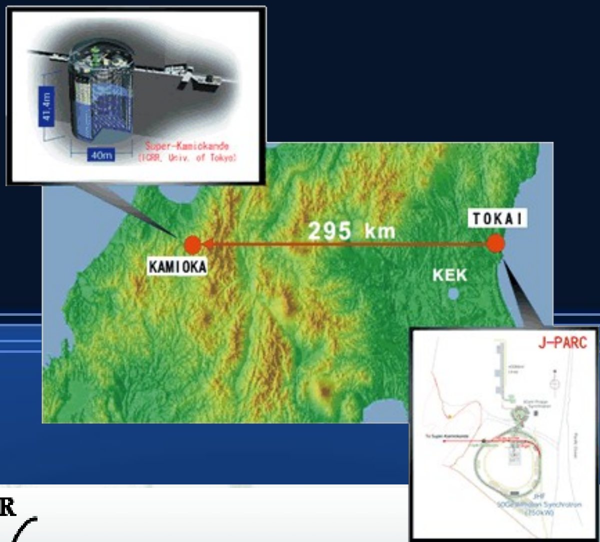
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2(1.27\Delta m^2_{atm}(L/E))$$



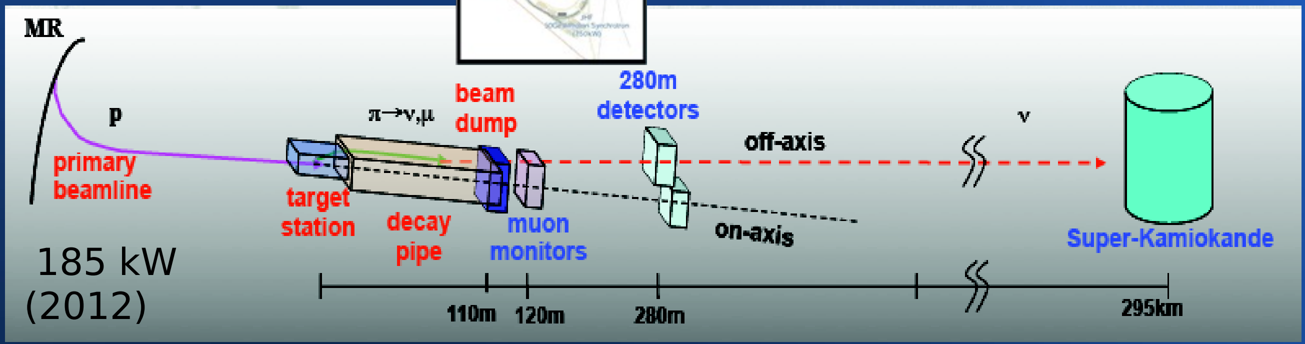


Phys.Rev.Lett. 107 (2011) 181802

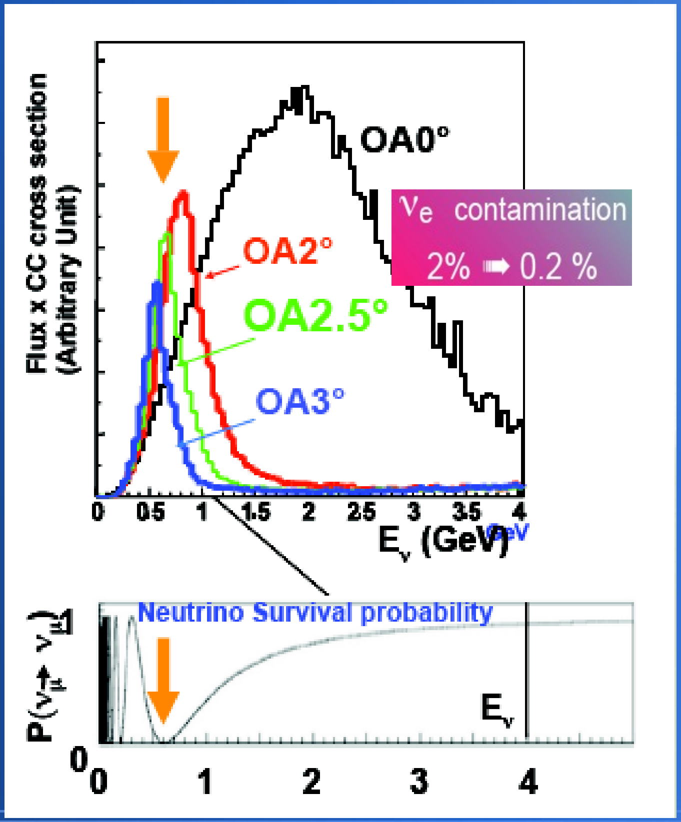
T2K



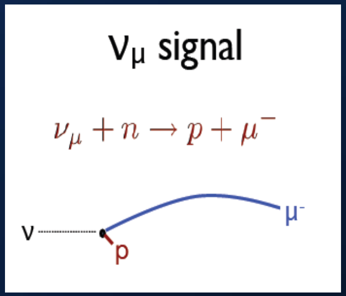
- Precision measurement of atm. sector and θ_{13}



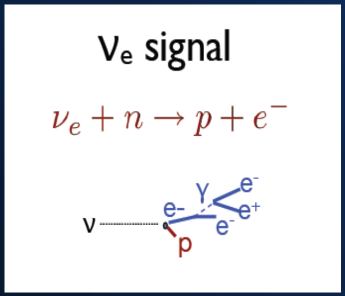
- Off-axis beam:



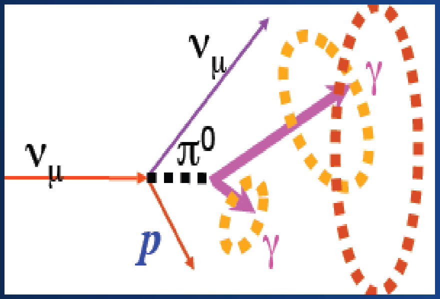
- disapearance



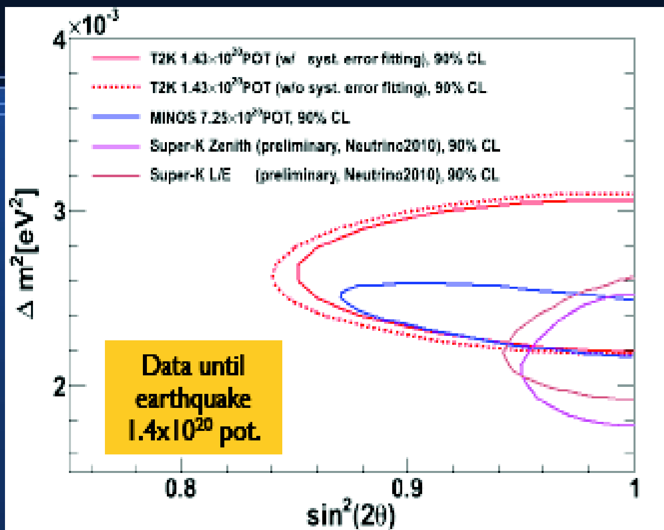
- appearance



- Backgrounds:
  - ν_e in beam
  - π^0 in NC



T2K Results

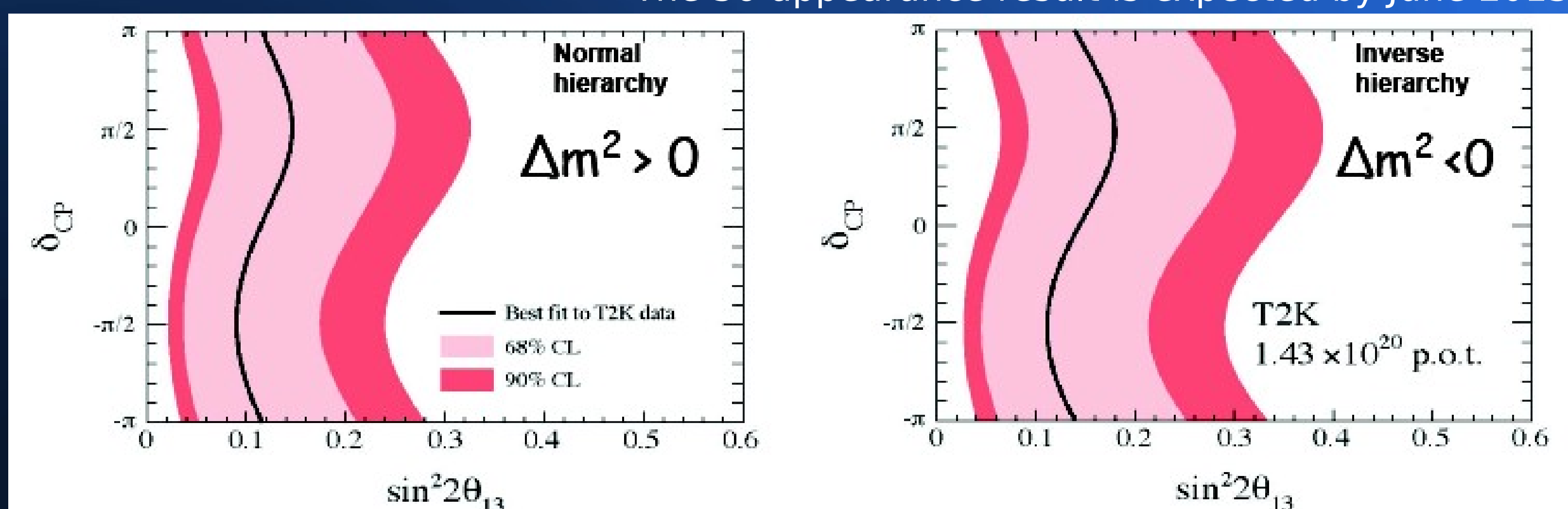


- First results on ν_μ disappearance with 1.4×10^{20} pot
- ν_e appearance: 6 events over background of 1.5 (2.5σ)

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

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

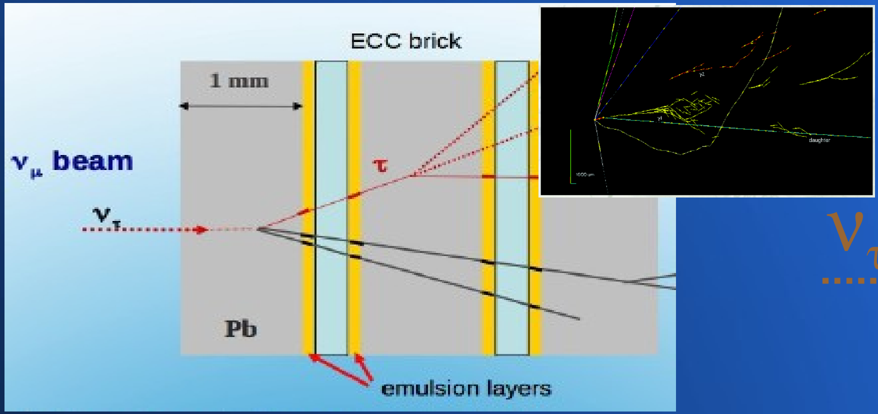
The 5σ appearance result is expected by June 2013.

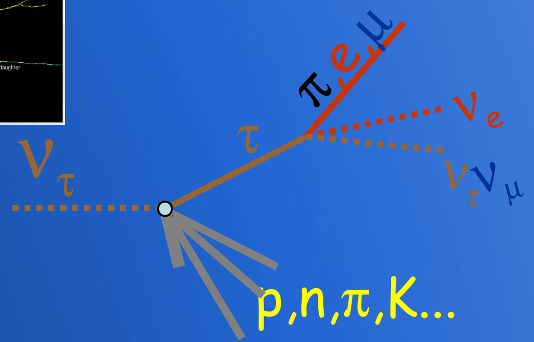


Published in Phys. Rev. Lett. 107, 041801 (2011)

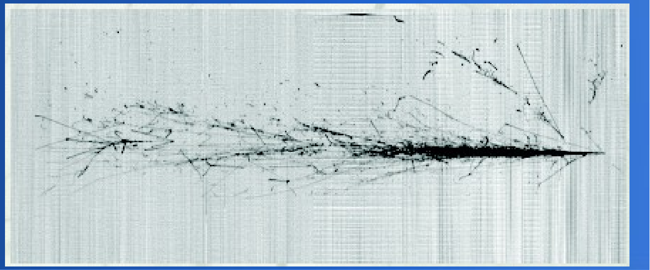
Opera and Icarus

- OPERA: direct detection of $\nu_\mu \rightarrow \nu_\tau$ (appearance)
  - Emulsion Cloud Chambers (granularity!) + trackers





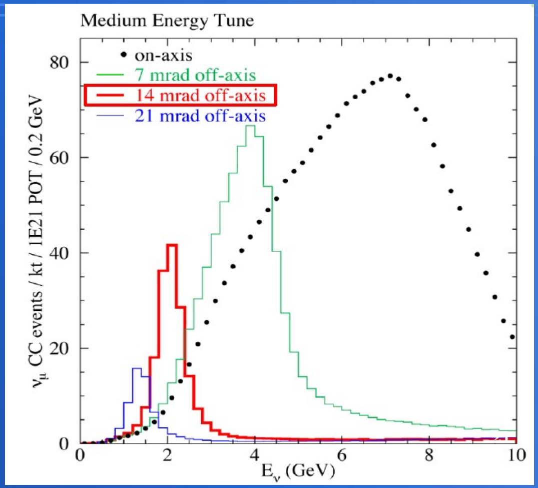
- ICARUS: 1st large scale ν detector with LAr (600 tons)
  - Milestone towards future Mton detectors
  - Searches for $\nu_\mu \rightarrow \nu_\tau$ statistically
  - Atm/solar sectors, sterile ν, ...



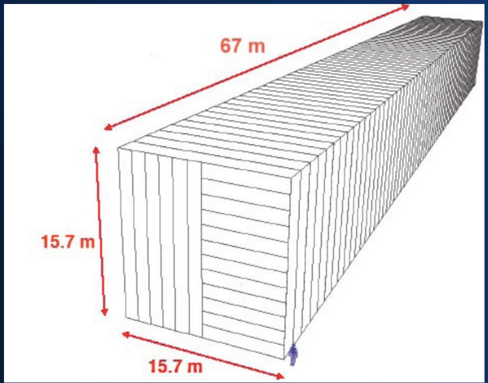
NOνA

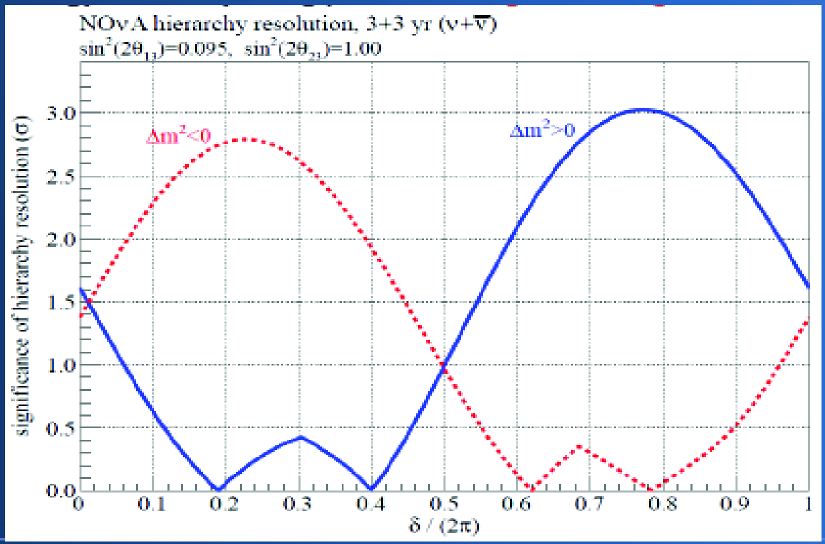
2013

- LBL Off-axis experiment (NuMI, 700 kW)
  - Searches for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - LBL: matter effects!
  - Mass hierarchy, θ_{13}, δ

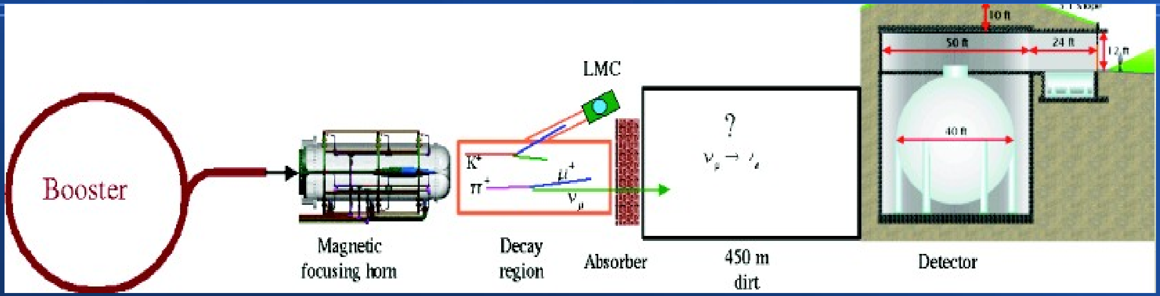


- Totally active tracking liq. Scint.
  - FD: 15 kton
  - ND: 220 ton

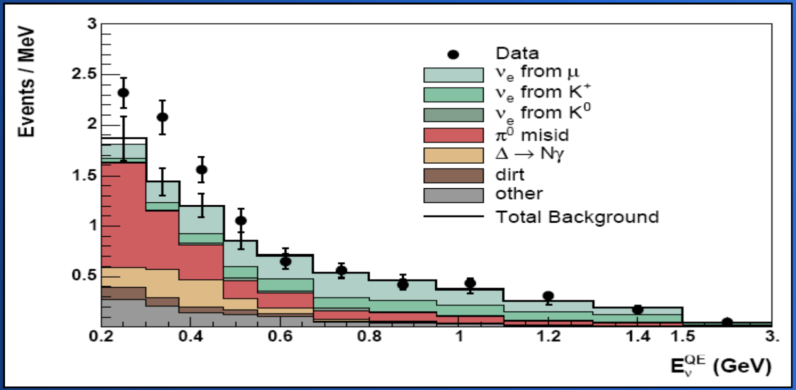




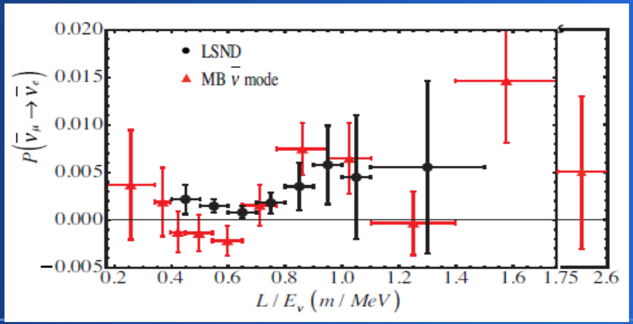
MiniBooNE



- Check LSND results (same L/E)
  - ν_μ and $\bar{\nu}_\mu$ modes



- ν_μ mode:
  - E<475 MeV: 3σ excess in e-like events
    - MicroBooNE: LAr TPC
  - E>475 MeV: inconsistent with LNSD @ 90% CL



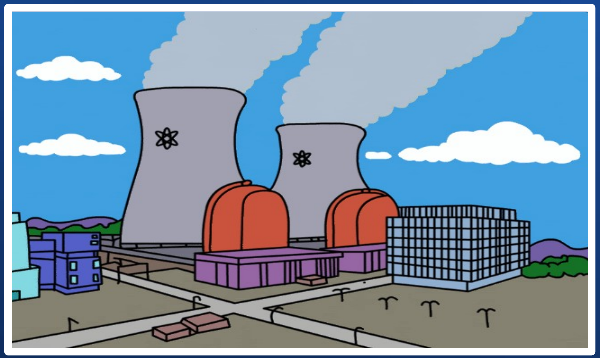
- $\bar{\nu}_\mu$ mode:
  - E<475 MeV: 1.3σ excess in e-like events
  - E>475 MeV: 2ν fit consistent with LSND @ 99.4 CL

- Data taking is over

The Latest Mixing Angle: θ_{13}

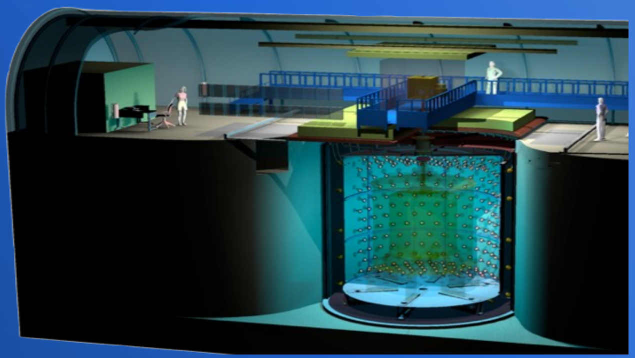
Reactor experiments

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

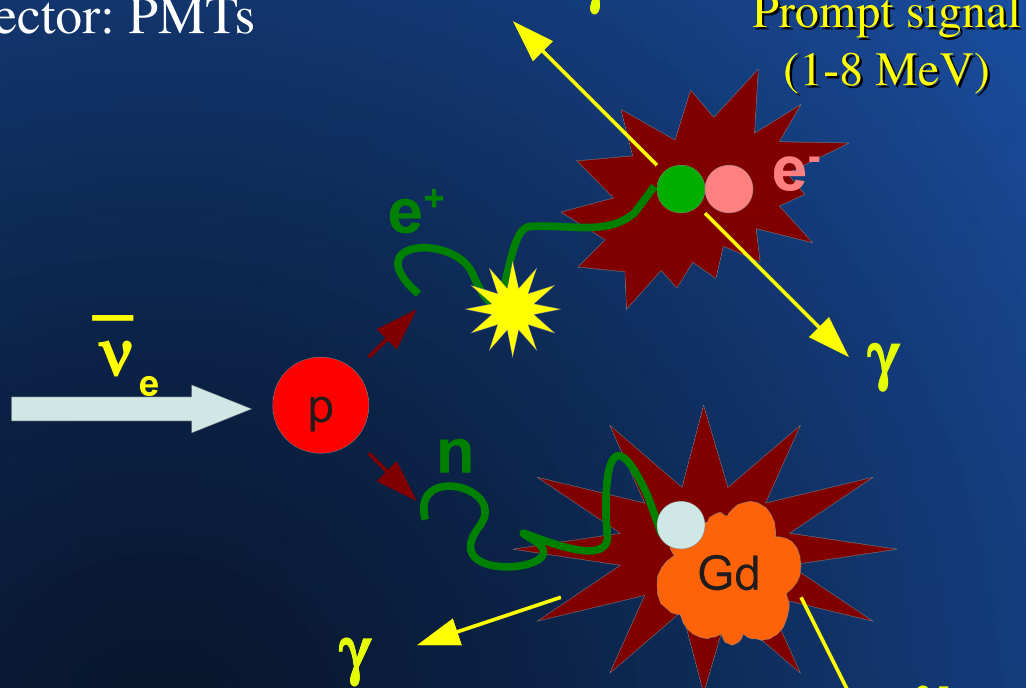
- No matter effects
- Cheap, as source exists
- High flux and large xsection

Detecting reactor neutrinos

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

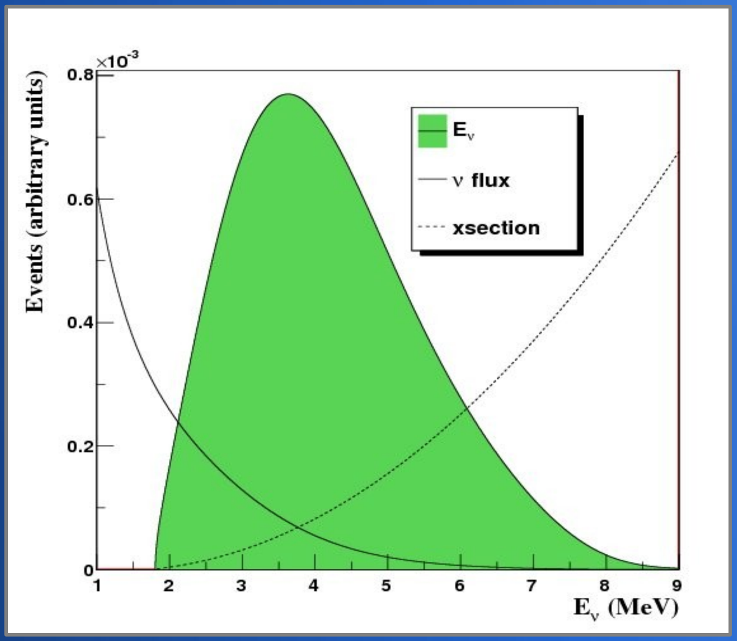
Th: 1.8 MeV. **Disappearance!**

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



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

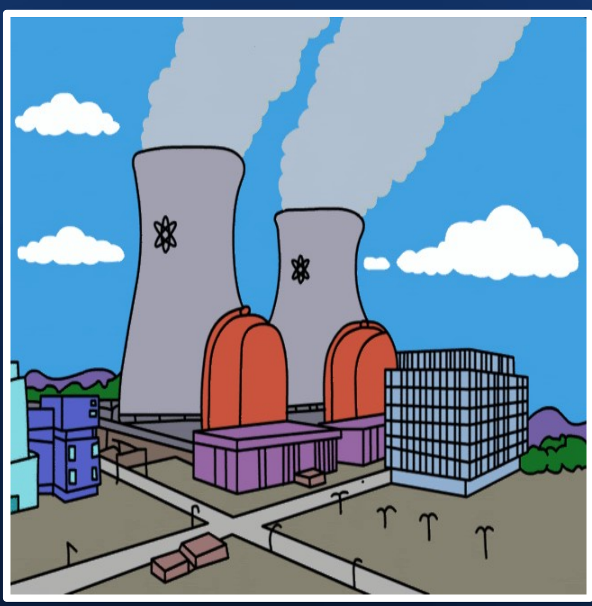
E_ν spectrum

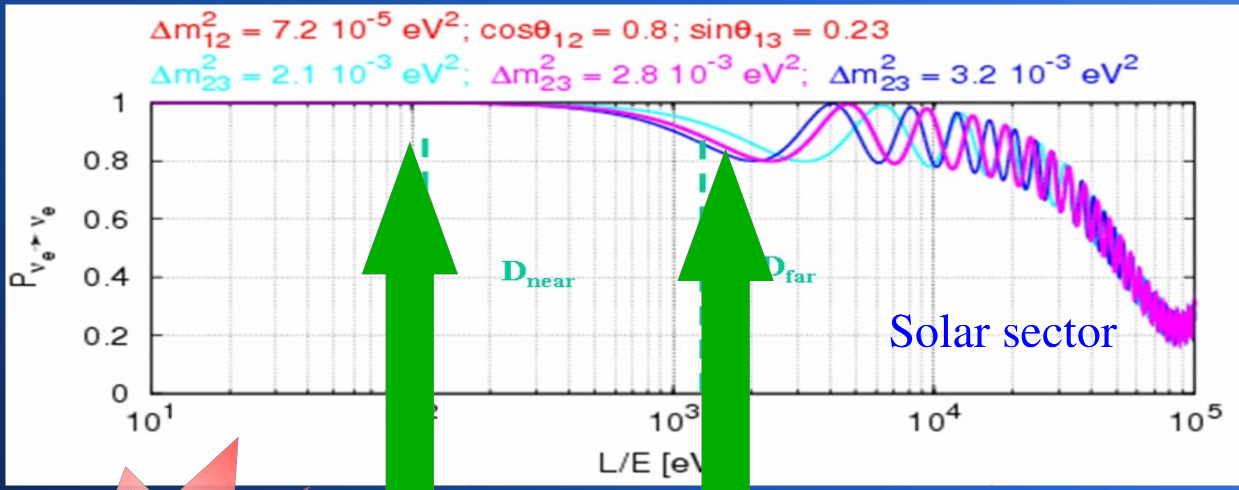


Setting up the experiment

Reactor neutrinos:

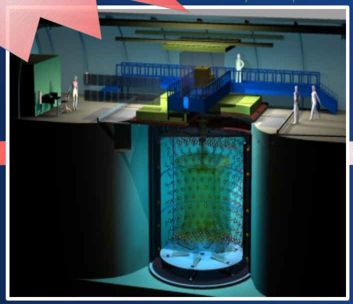
$<E_\nu> \sim 4$ MeV

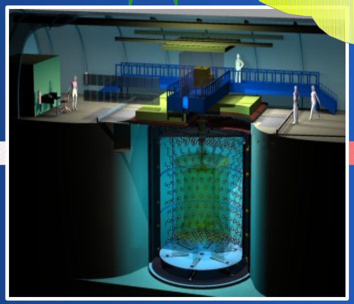




Systematics!

Oscillation!



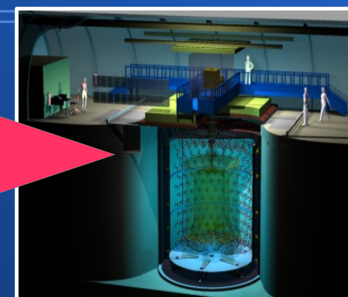


~ 100 m

~ 1 km

Expected oscillation signal

1 km

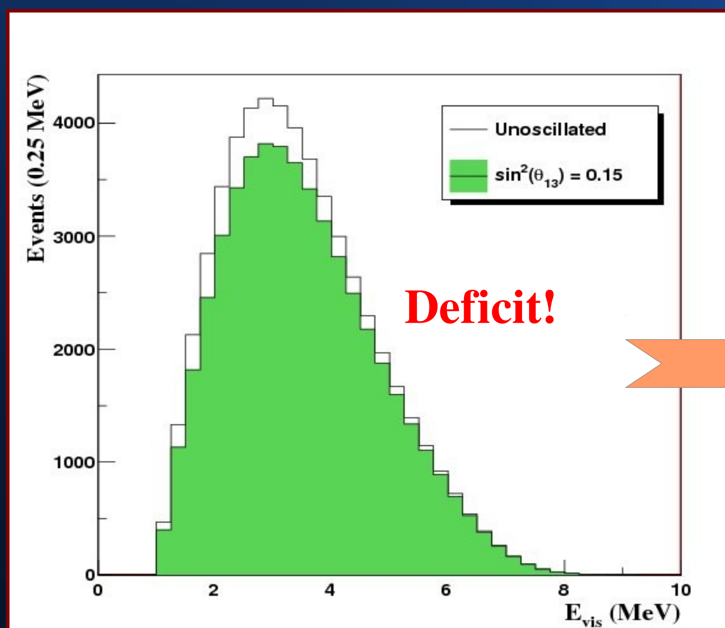


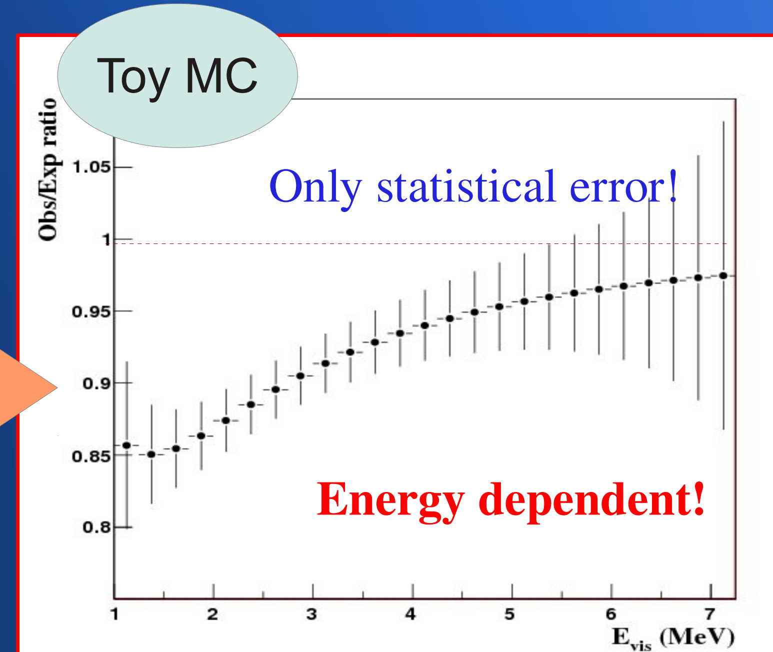
Toy Monte Carlo

- $8x10^{29}$ free protons
- Detection efficiency 80%

3 years:

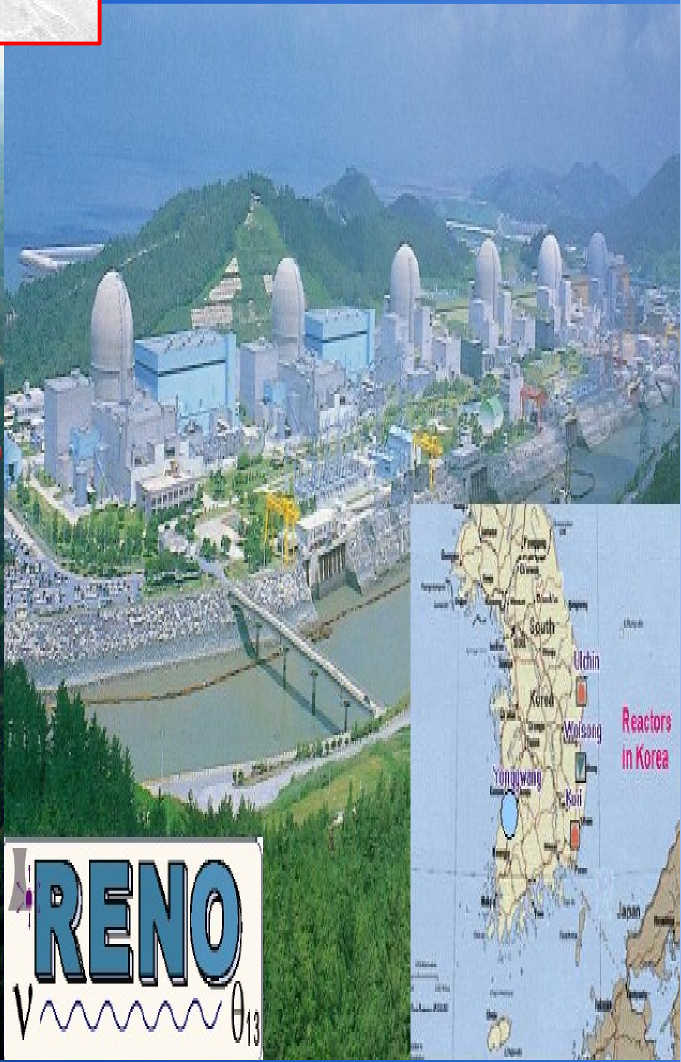
~ 50.000 events expected





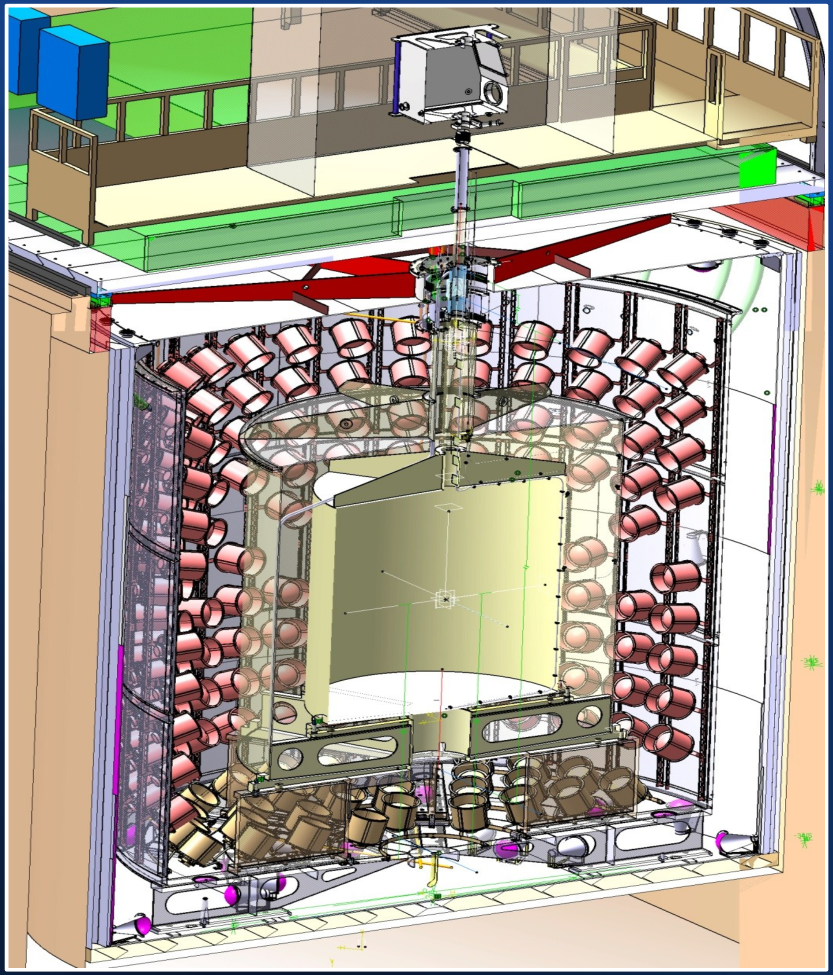
New Generation Experiments

Multi-detector setups!

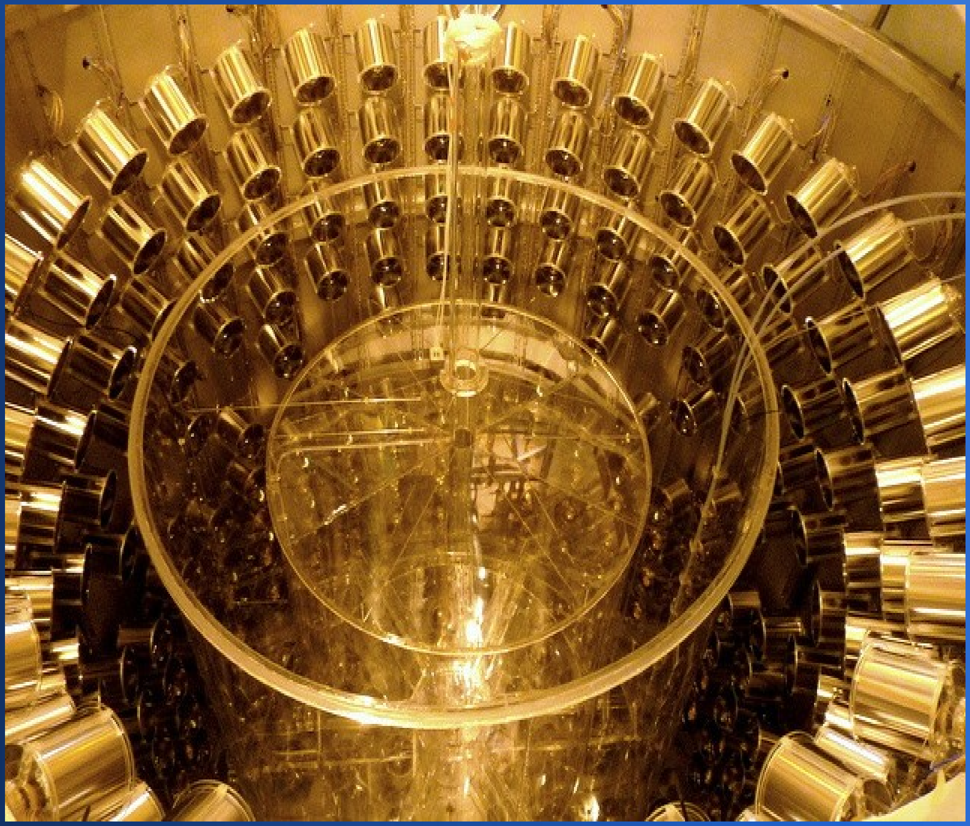


The Double Chooz Experiment

The Double Chooz Detector

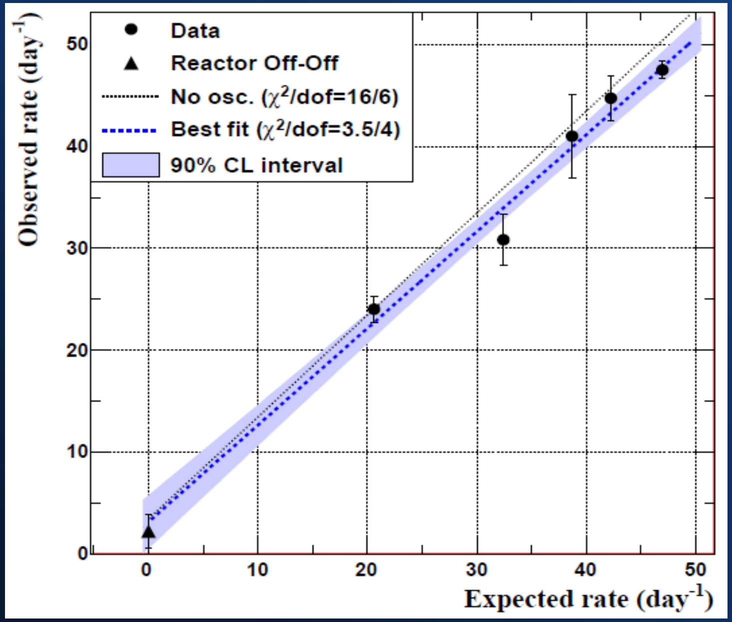


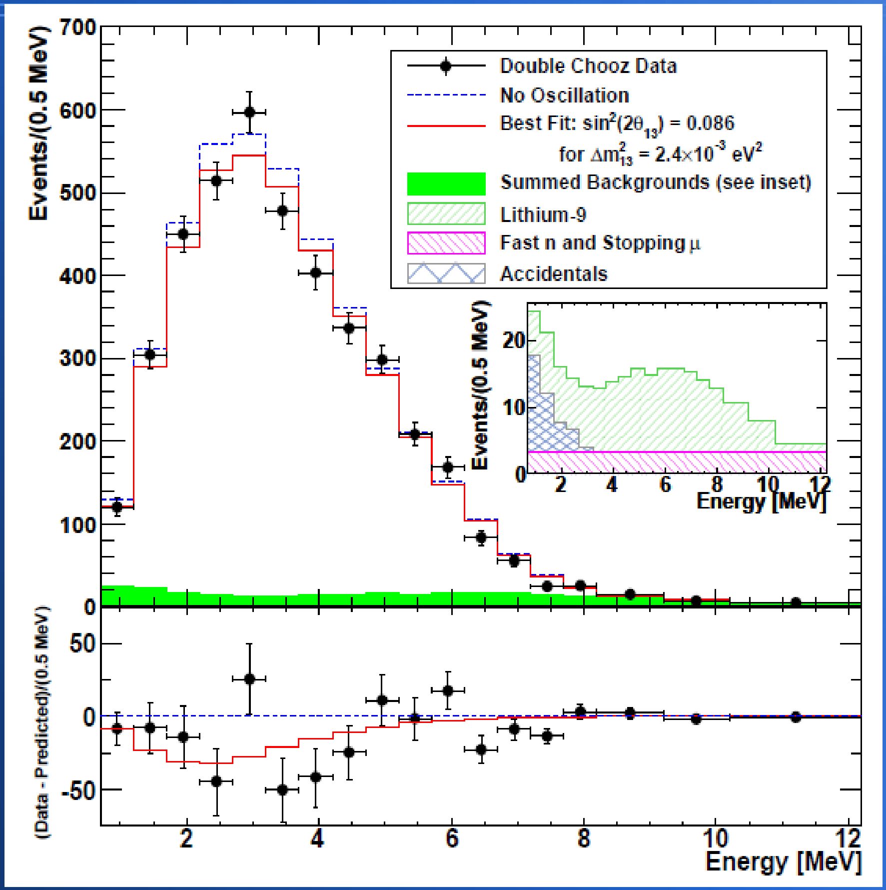
- Far Detector operating since early 2011



Double Chooz Results

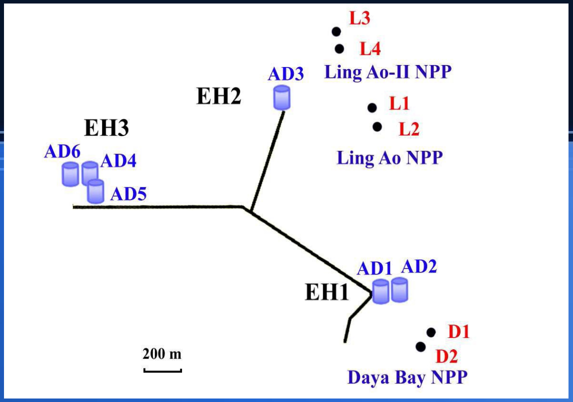
- First results on θ_{13} form reactor experiments
  - 100 days of data, FD only, 2011
  - Rate + Shape analysis



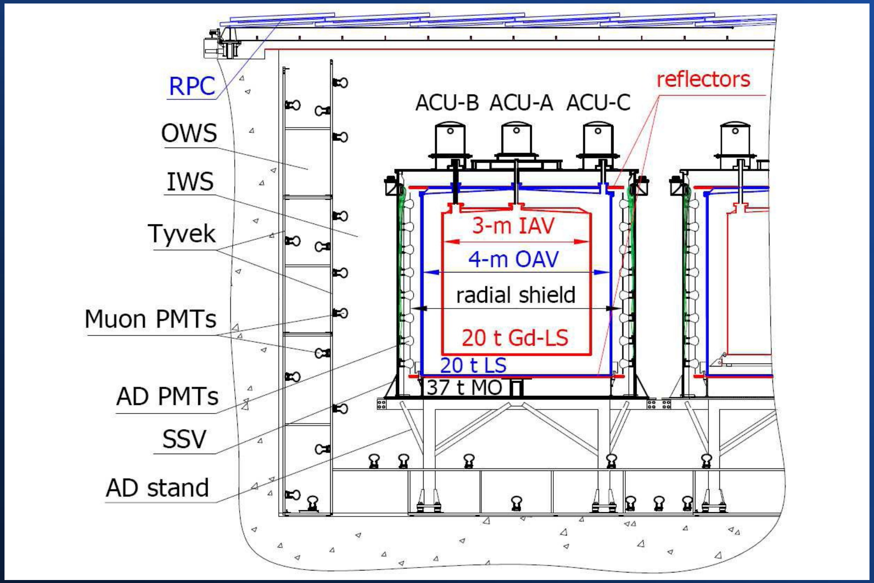


$$\sin^2 2\theta_{13} = 0.086 \pm 0.041\ (\mathrm{stat}) \pm 0.030\ (\mathrm{syst})$$

Daya Bay

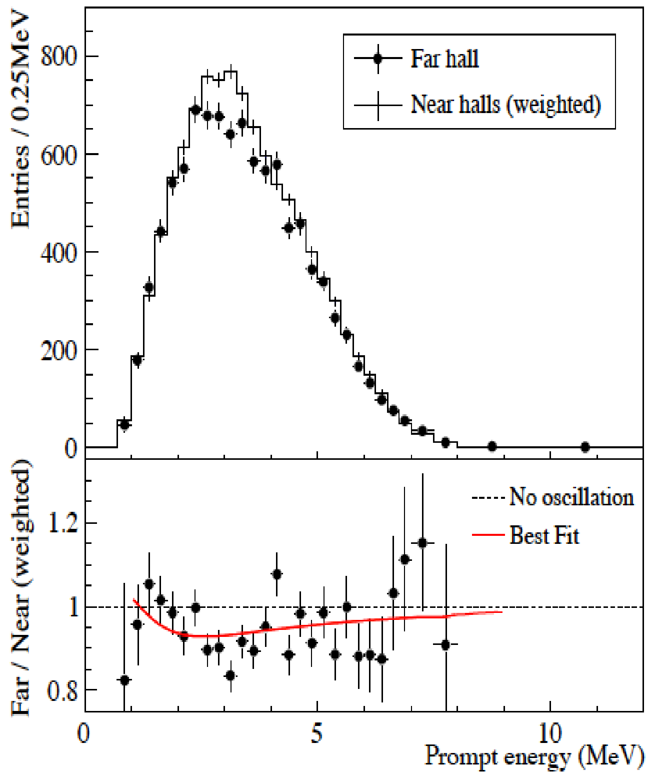


- Flux from 6 x 2.9 GW_{th} reactors
- 6 detectors in 2 Near (~500m) and 1 Far (1648m) sites



- Rate only analysis (55 days): 5.2σ signal (2012)

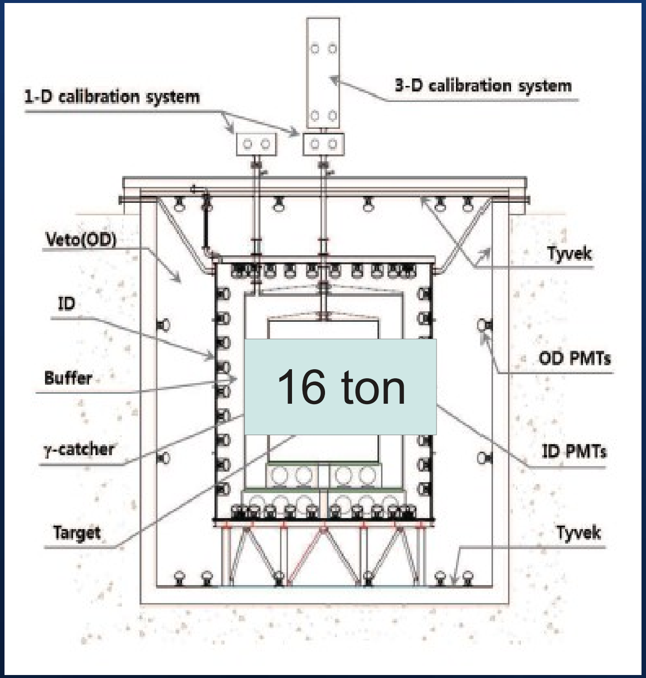
$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$



Phys.Rev.Lett. 108 (2012) 171803

RENO

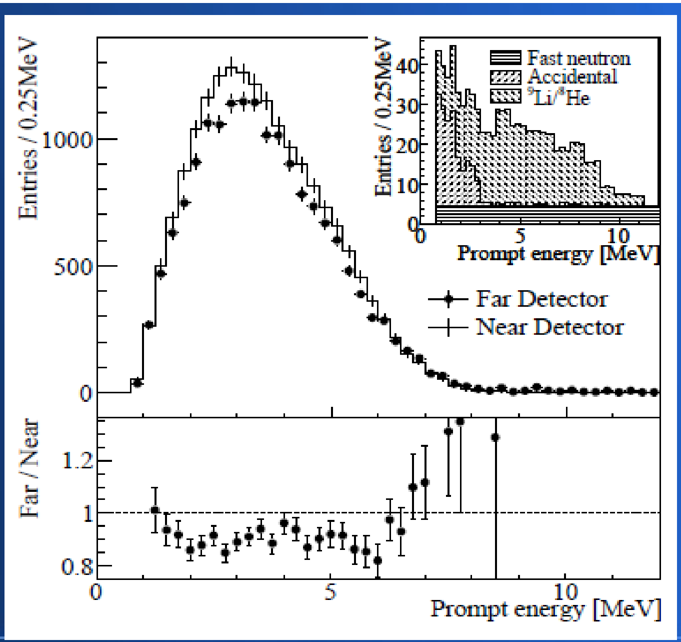
- Flux from 6 x 2.8 Gw_{th} reactors
- Two identical Near (409m) and far detectors (1444m)



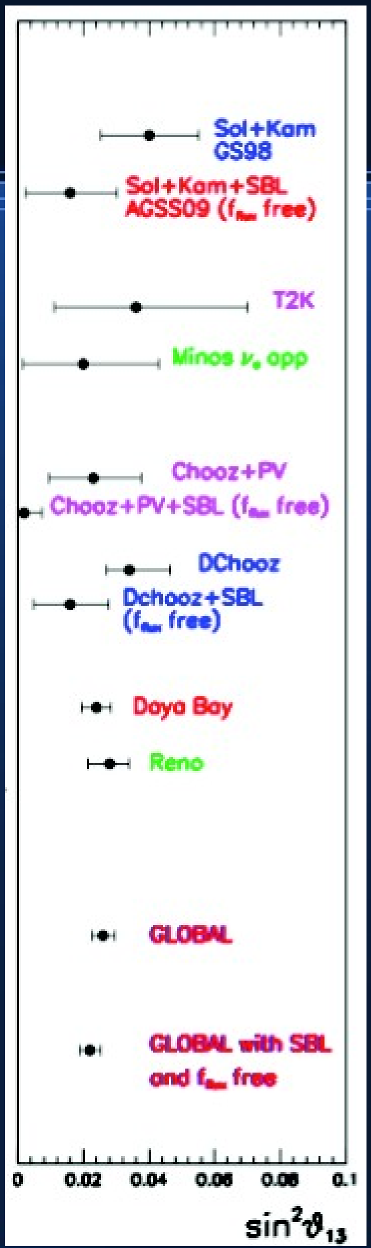
- Rate only analysis: 4.9σ signal (2012)

$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat.}) \pm 0.019(\text{syst.})$$

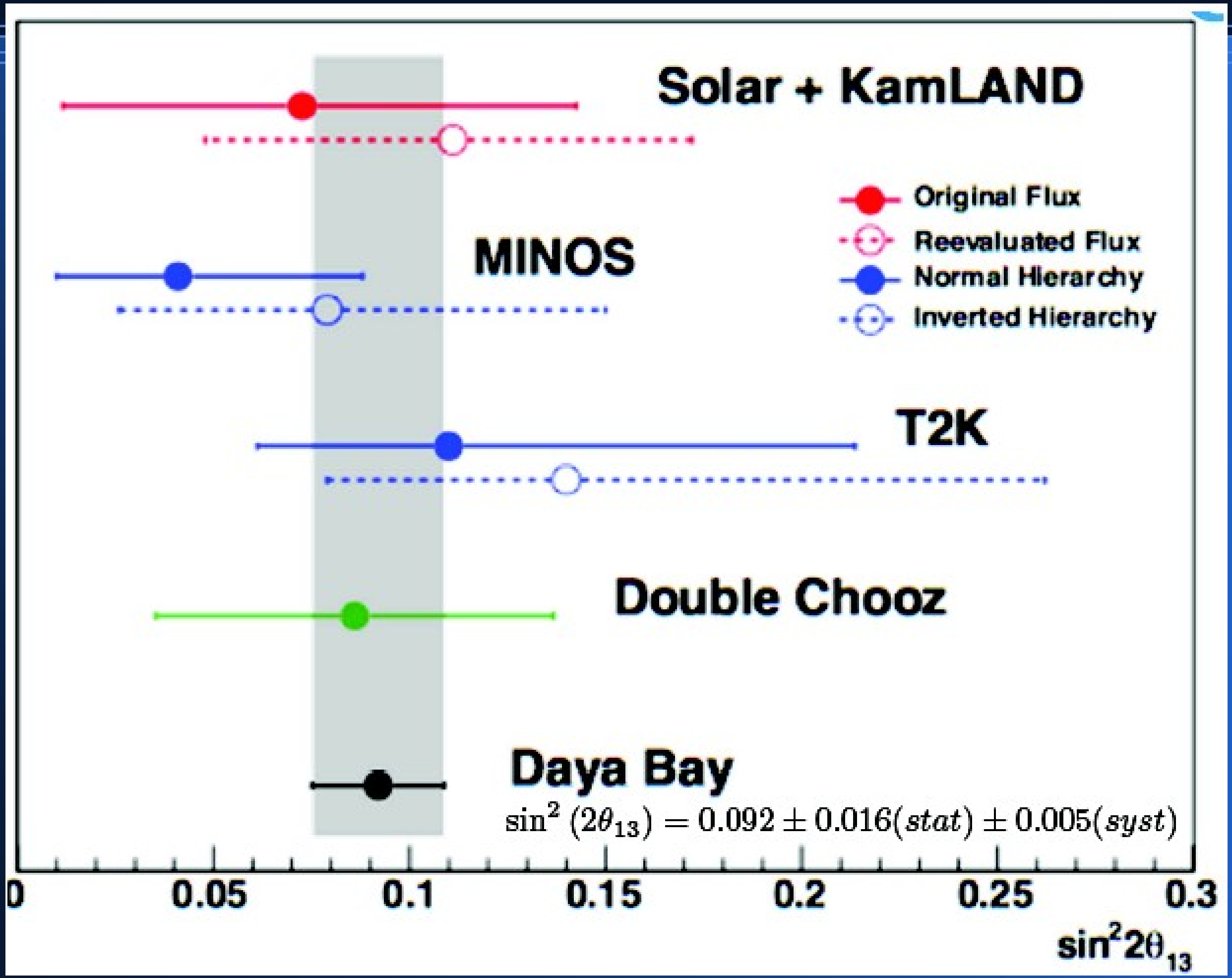
Phys.Rev.Lett. 108 (2012) 191802

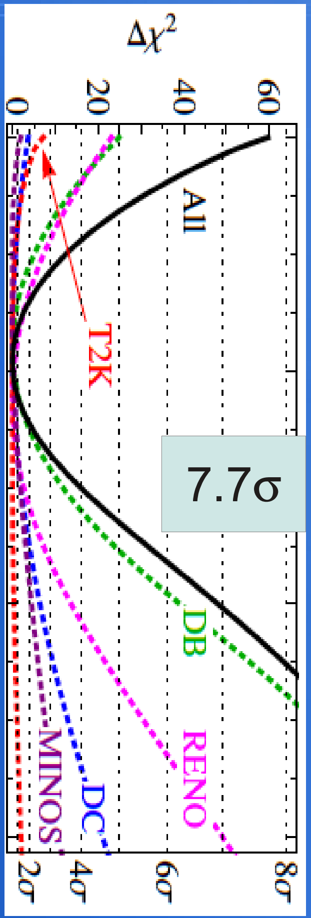


Summary on θ_{13}



T.Schwetz





H. Minakata

- But we are not done: shape analysis!!!

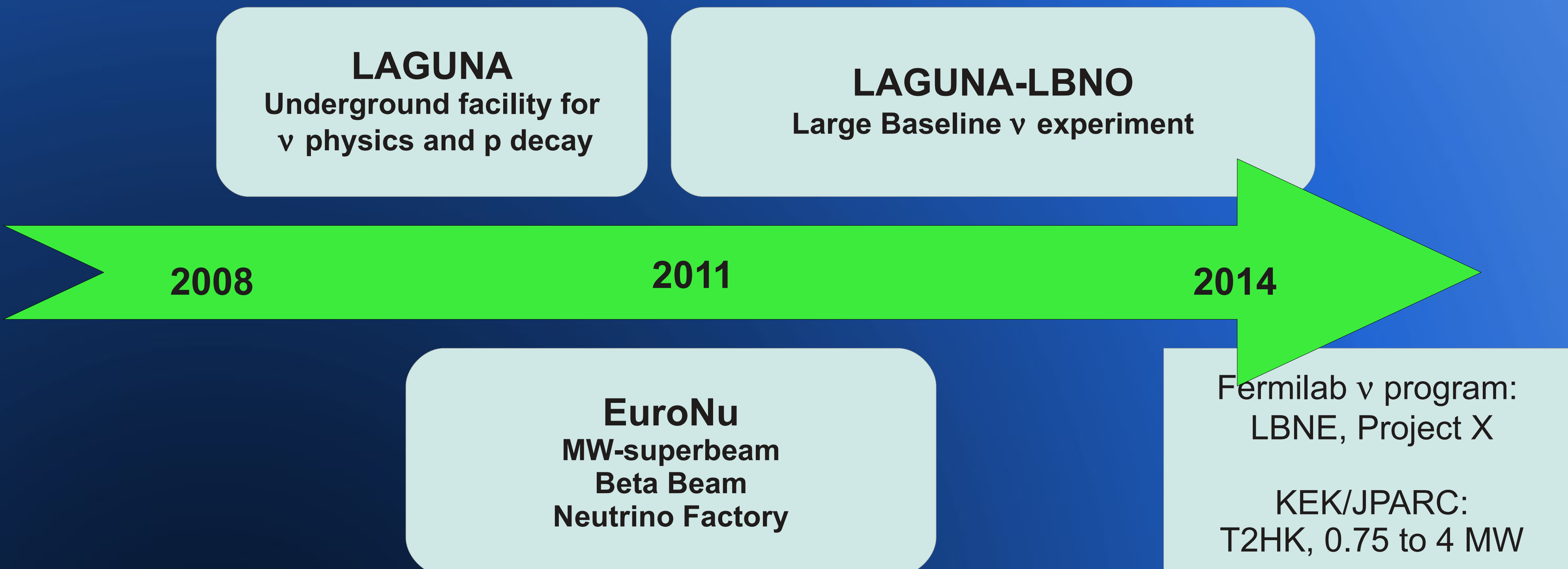
What's next?

Open questions after 2nd round...

- Mass hierarchy?
- $\theta_{23} = \pi/4$, $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$?
- CP violation?

- To address these questions, **Super-Beams**, **Beta-Beams** and **NF** are being studied...
- θ_{13} is now known... and it is large!
  - Is there a fast/easy/cheap way to resolve the above questions?
  - What can be achieved with the current facilities?
  - Can they be upgraded? New kTon detectors?
  - Can we answer any of these questions within ~10 year
- Discussion ongoing to define the roadmap for neutrino physics
  - NuTURN 2012 and Town meeting: European Strategy for Neutrino Oscillation physics
  - Spanish community also planning about next steps

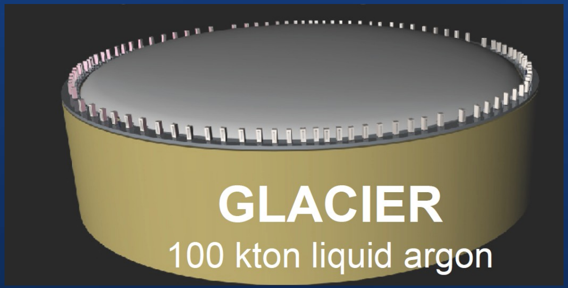
International efforts

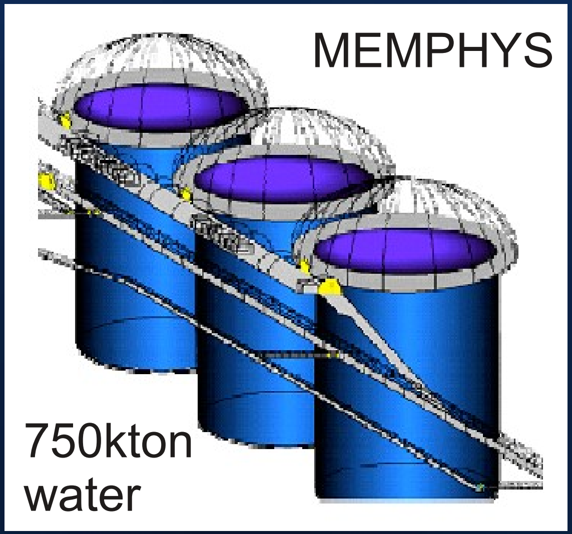


- Combining results from current experiments: maybe MO and θ_{23}, but no CP
  - Upgraded beams: more energy, power (>700 kW) and purity
  - Detectors: more massive, more granularity and energy resolution
  - Degeneracies: **different energies, baselines, channels**

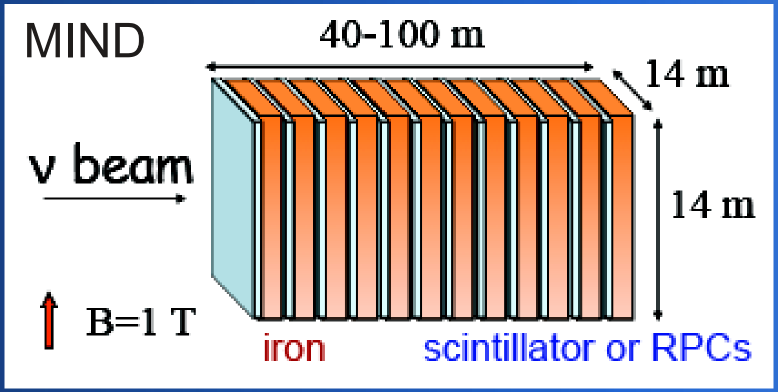
Detectors

- **LAGUNA:** proton decay, ν astrophysics and CP-violation in the lepton sector



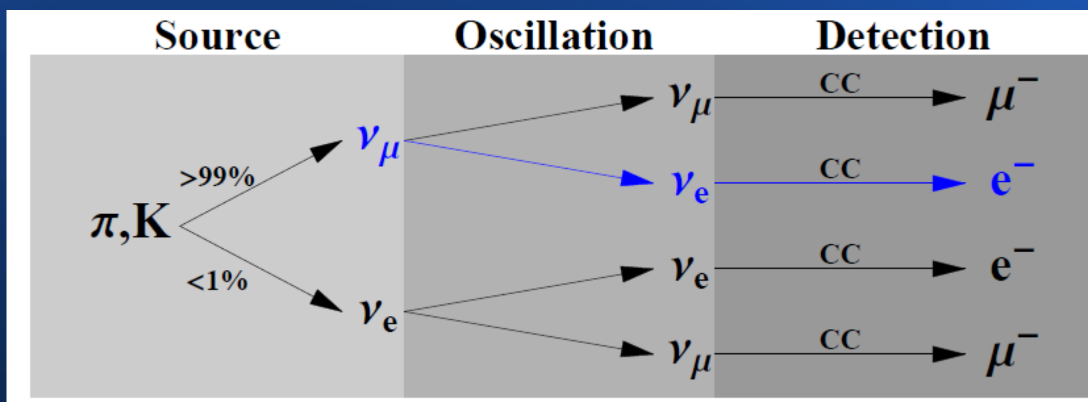


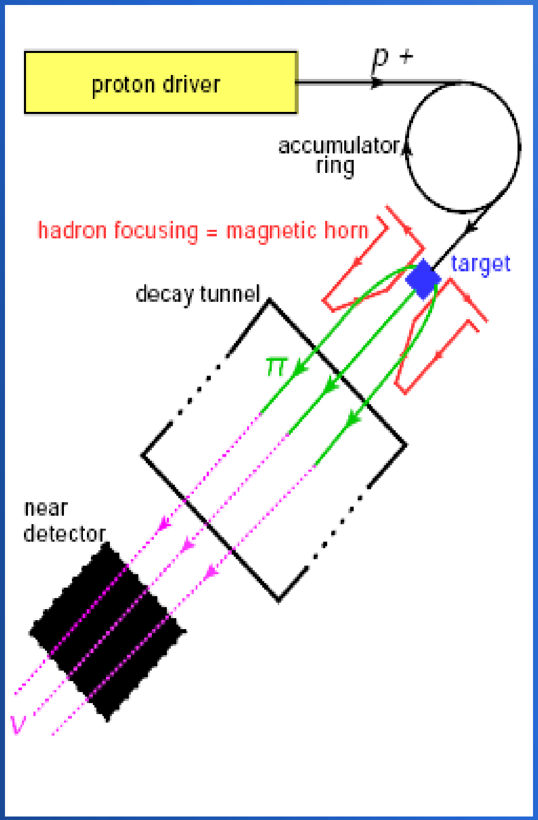
- Detectors for **Neutrino Factory**:
  - MIND: magnetized, MINOS-like
  - TASD: magnetized NOVA-like
  - Magnetized LAr



SuperBeams

- Muon Neutrino beam from pion decay:





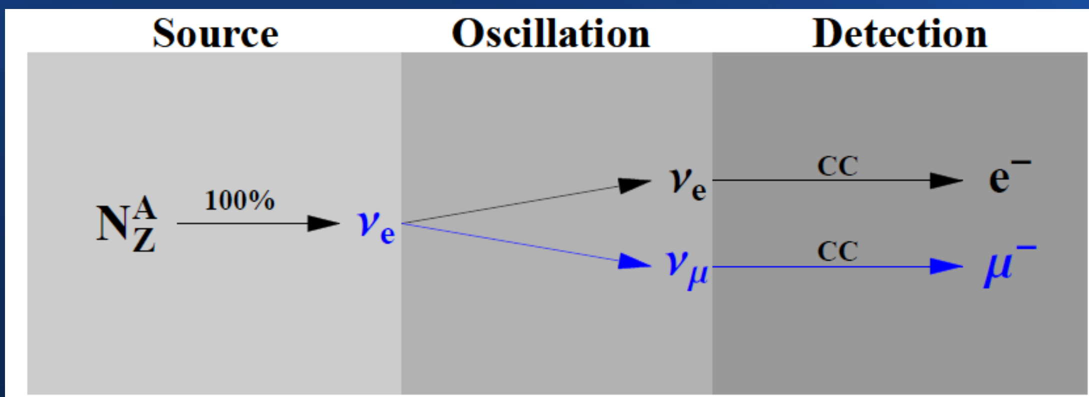
- beam power 1-4 MW
- E_ν ~ 5 GeV, On/off axis
- detectors mass ~100 kton
- Long baseline: mass hierarchy
- Data taking: 10 years

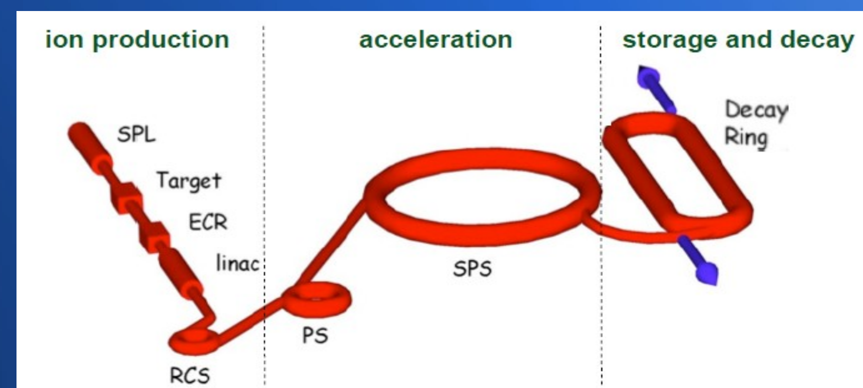
Beta-Beams

- Electron Neutrino beam from beta decay:

$$ {}^{6}_{2}He \rightarrow {}^{6}_{3}Li\, e^{-}\, \bar{\nu}_e $$

$$ {}^{18}_{10}Ne \rightarrow {}^{18}_{9}Fe\quad e^{+}\quad \nu_e $$

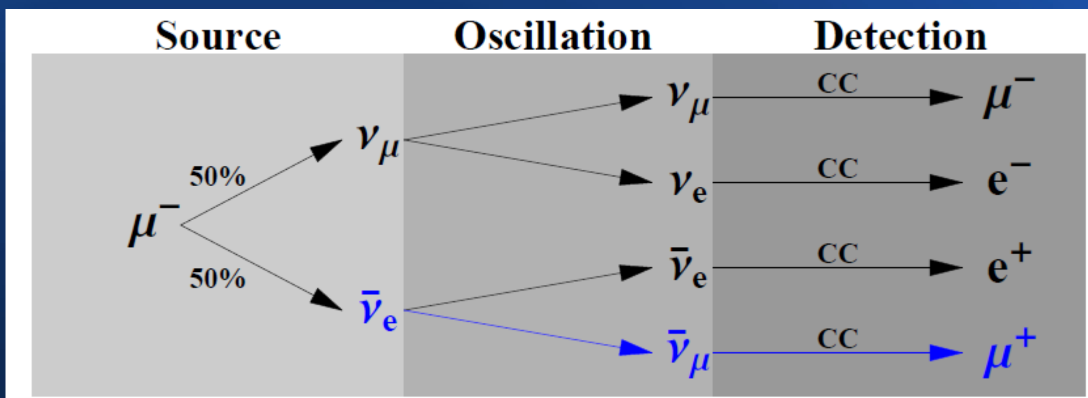




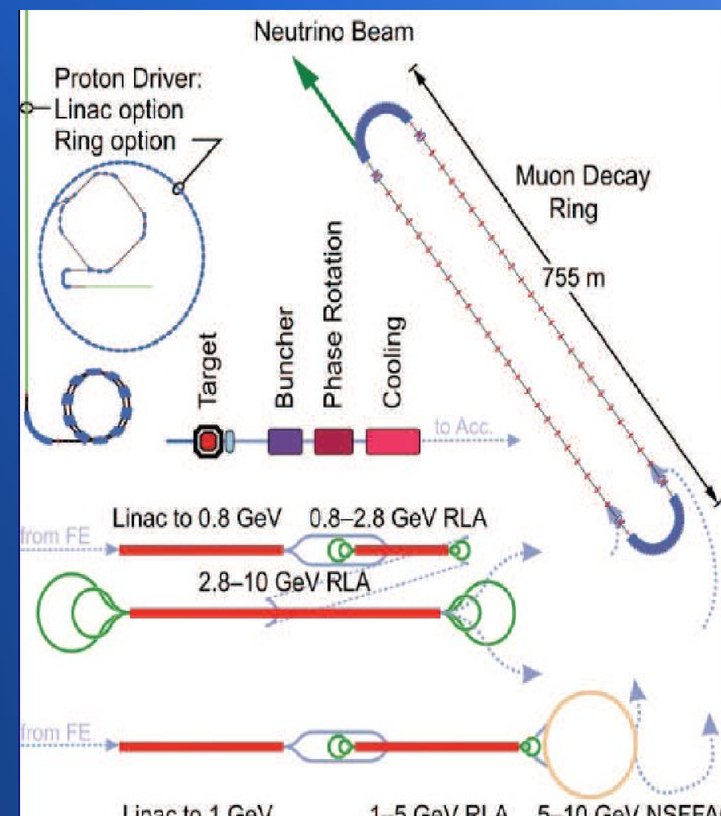
- Pure ν_e beam: smaller beam systematics and backgrounds
- Best detectors: water Cerenkov and LAr (LE) and iron calorimeter (HE)
- No ν_μ disappearance: no θ_{23} measurement
- Technical challenges: ion production, acceleration, storage ring

Neutrino Factory

- Muon Neutrino beam from muon decay:

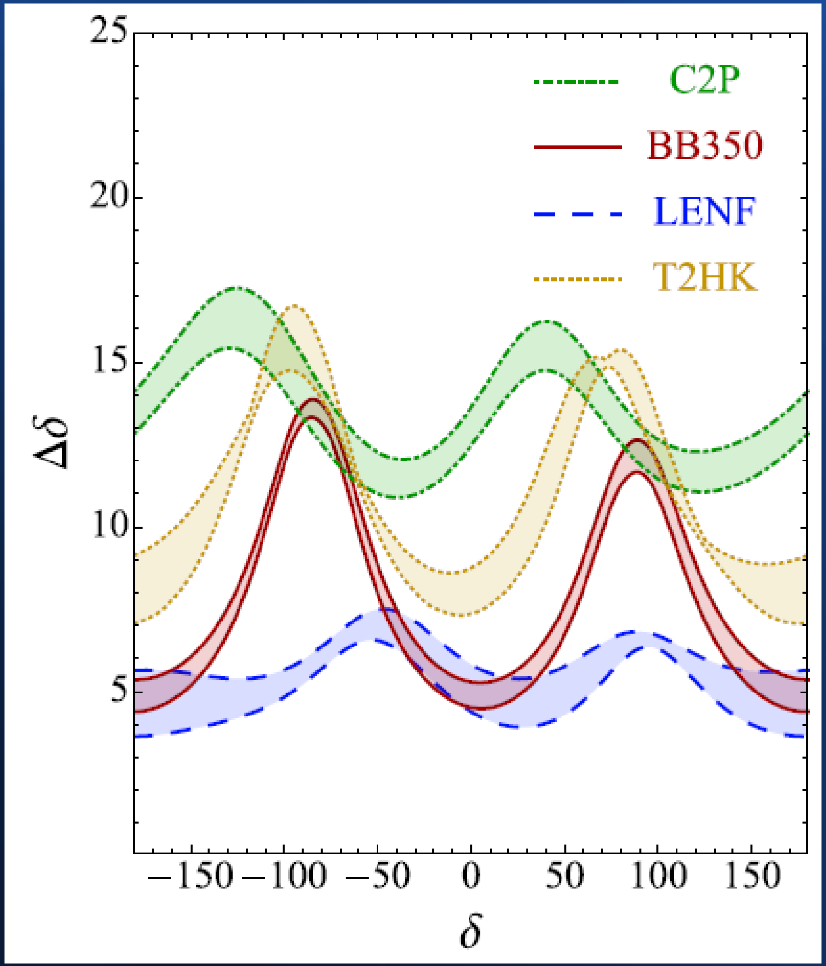


- Dectector able to measure charge μ^+/μ^-
  - Magnetized Iron calorimeters (MIND)
- muon production (MERIT), cooling (MICE) , acceleration (EMMA)
- IDS-NF: www.ids-nf.org



Comparing facilities

P. Coloma et al, arXiv:1203:5651



- Requirements:
  - CPV: 2 complementary channels
  - Degeneracies: different E/L
  - Mass hierarchy: LBL
- Comparison:
  - θ_{13} is measured (large!):
    - Discovery potential not really useful
    - Small CP asymmetries (systematics!)

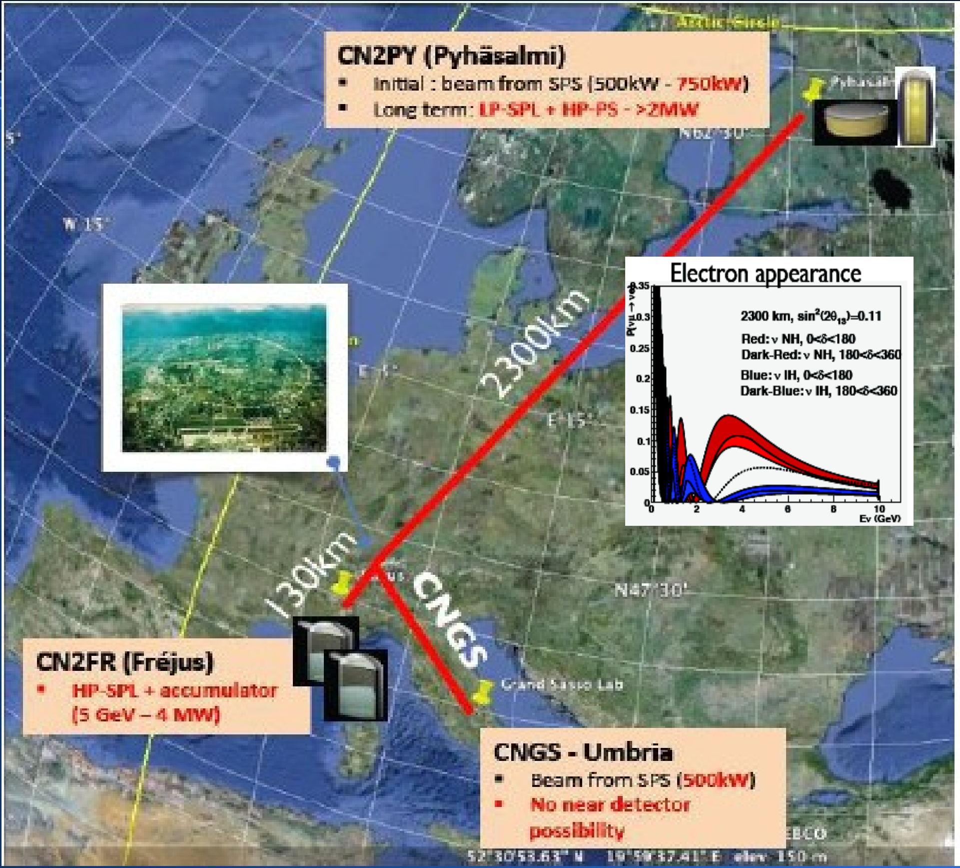
$$\frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \propto \frac{1}{\sin 2\theta_{13}}$$

Better compare in terms of precision!

Projects for Next Generation

LAGUNA-LBNO

- CERN to Fréjus (SBL):
  - SuperBeam (5GeV, 4MW)
  - Water Cherenkov
  - Upgrade: Beta-Beam
- CERN to Phyhäsalmi (LBL):
  - SuperBeam (5GeV, 4MW)
  - LAr+Mag. Iron, Liq. Scint.
  - Upgrade: Neutrino Factory



LAGUNA_LBNO

- T2HK
  - JPARC 4 MW, H2K
- LBNE
  - Fermilab 2.3 MW beam, LAr

- CERN to Kamioka (arXiv:1204.4217v1)
  - SuperBeam (~5GeV, 4MW)
  - Super-Kamiokande (8770 km)

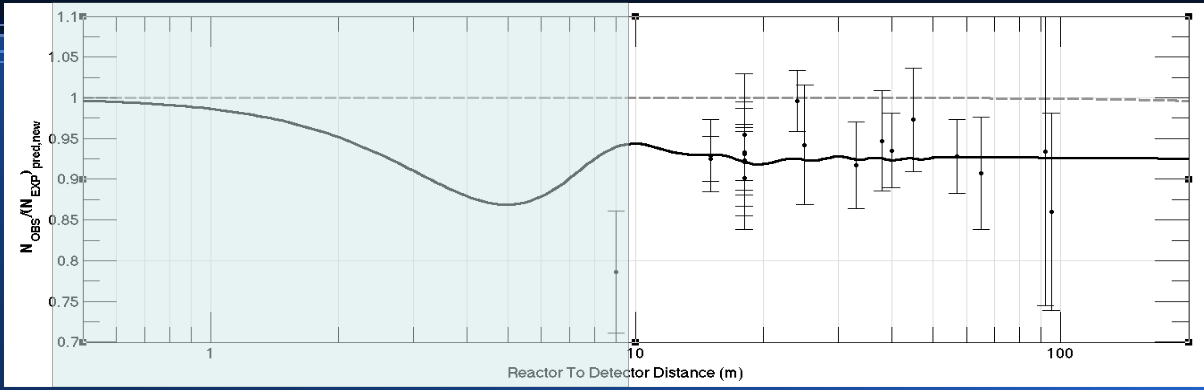
All based on SuperBeams!

Still one more question...

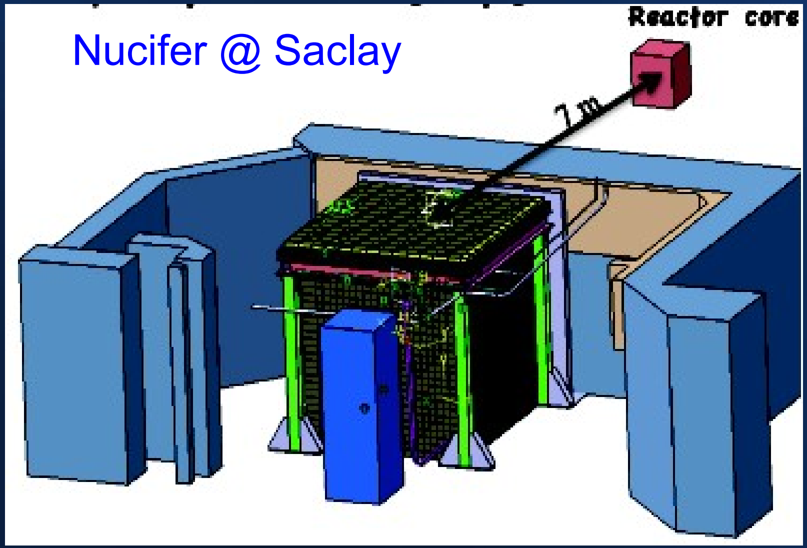
Sterile neutrinos?

- Indications that three-flavor mixing might not be the sufficient:
  - SBL reactor anti-neutrino measurements: reactor flux anomaly
  - Radioactive source measurements: Gallium anomaly
  - Accelerator-based experiments: LSND & MiniBooNE

Testing the Reactor Flux Anomaly



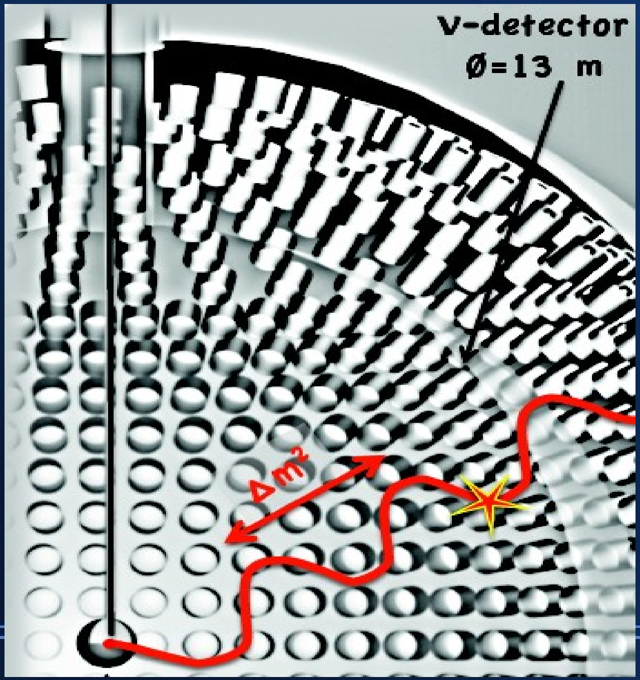
- Anti-ν detectors close to compact reactor cores (~10m)

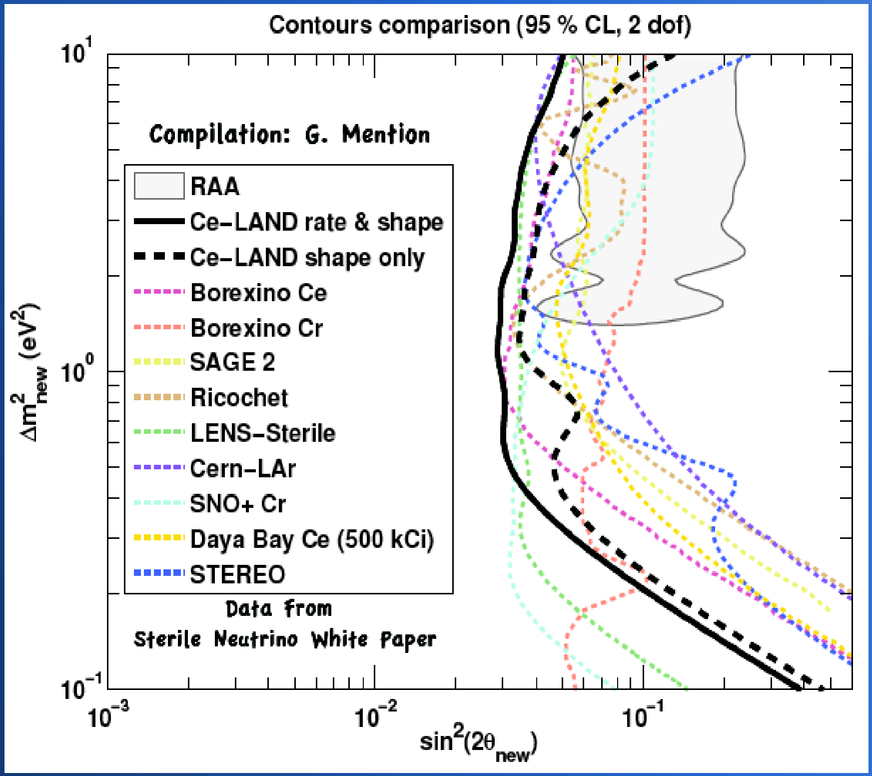


- First experiment already at commissioning stage:
  - Nucifer (Non Proliferation: Pth & Fuel Composition)
    - $1m^3$ Gd-LS detector
    - Osiris Site in Saclay (70 MW)
- Other projects:
  - Stereo, SCRAMM, DANSS (building), NIST

Testing the Gallium anomaly

- Place $\nu/\bar{\nu}$ source close/inside ν detectors
  - Existing detectors (KamLAND, Borexino, ...)
  - Several options:
    - ^{51}Cr: Borexino, SNO+, Baksan
    - ^{144}Ce: Ce-LAND in KamLAND/Borexino, ...



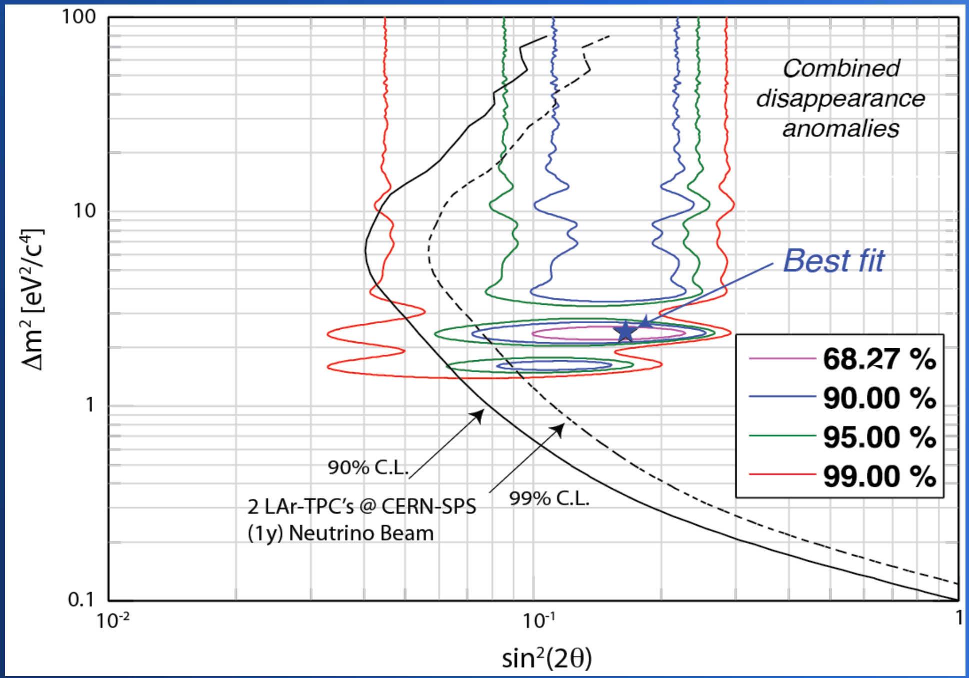


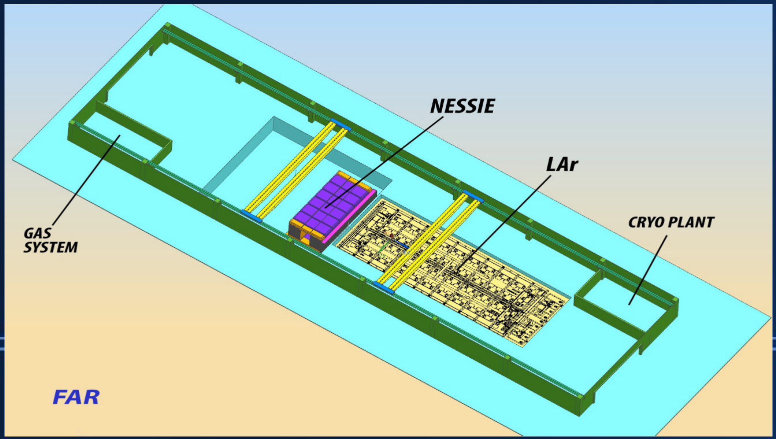
arXiv:1204.5379

Sterile neutrinos with accelerators

- Accelerator based short baseline proposals: LAr detectors @CERN & Fermilab
- Requested features for a definitive experiment:
  - L/E matching Δm^2
  - $\nu/\bar{\nu}$ run modes
  - At least two detection locations
  - ν_e appearance and ν_μ disappearance
- Fermilab: BooNE, LArLAr, SBL Nova
- CERN: ICARUS/NESSIE
  - LAr (1kton) + Muon spectrometer (3kton)

ICARUS/NESSIE





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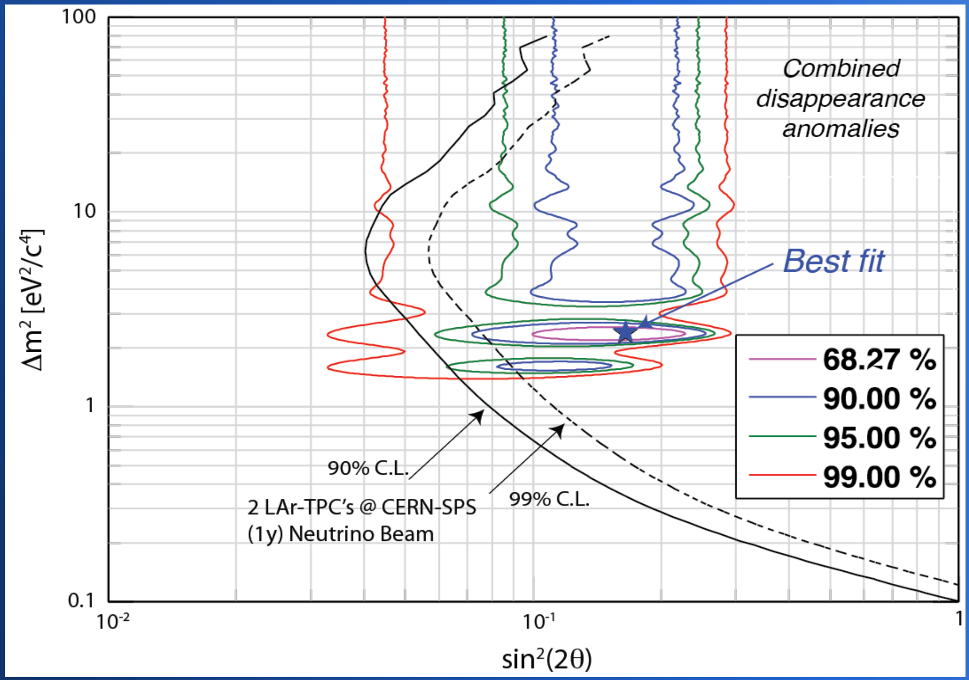
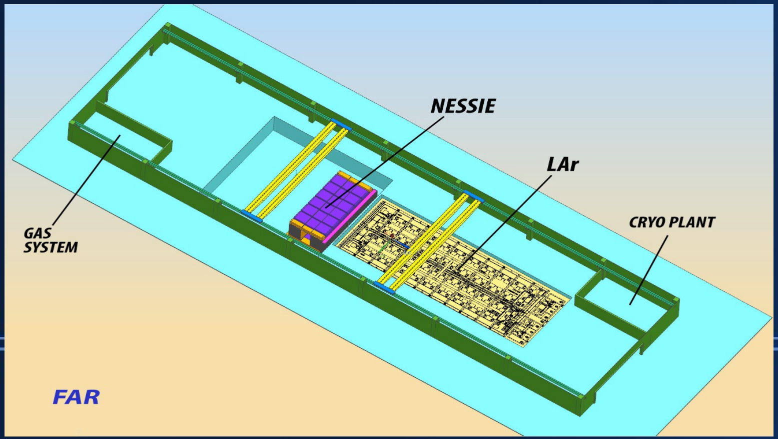
ICARUS/NESSIE





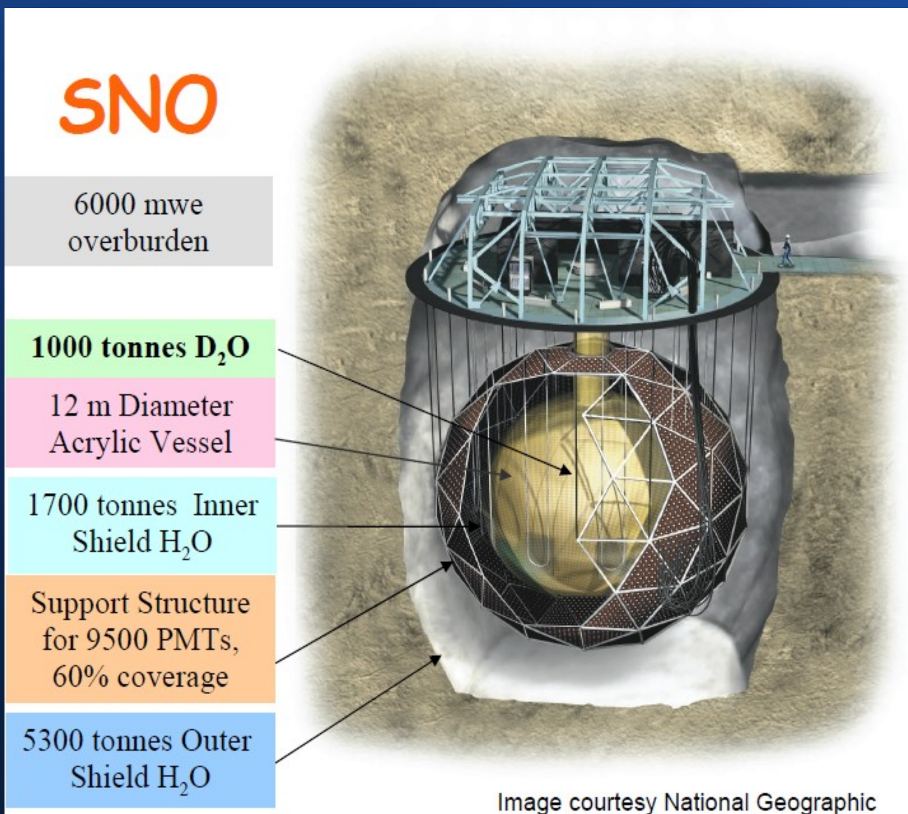
Where we are...

Summary

- Atm/sol oscillation parameters have been measured
  - Time for precision: mass hierarchy, θ_{23}?
  - Interference sector...
- θ_{13} is large: need to define the next step
  - Search for CPV in leptonic sector (δ)
  - **Super-beams**, beta-beams?, NF?
    - Mass ordering, θ_{23}, … CP?
- Not everything understood in current results:
  - Sterile neutrinos?: SBL experiments
- Exciting times!

Thank you!

SNO



- Sensitive to all flavors:

CC	$\nu_e + d \Rightarrow p + p + e^-$	$\Phi_{CC} = \phi_e$
ES	$\nu_x + e^- \Rightarrow \nu_x + e^-$	$\Phi_{ES} = \phi_e + 0.15 \cdot \phi_{\mu\tau}$
NC	$\nu_x + d \Rightarrow p + n + \nu_x$	$\Phi_{NC} = \phi_e + \phi_{\mu\tau}$

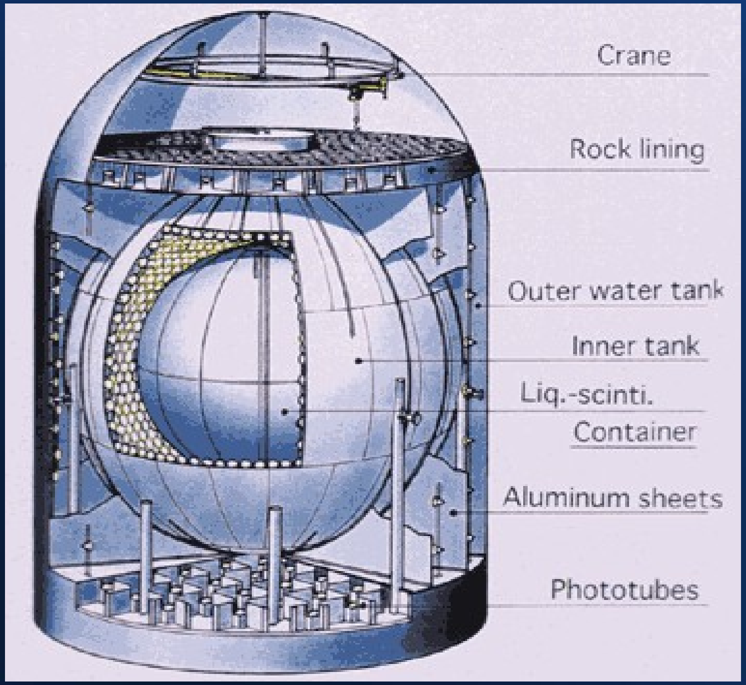
In case of no oscillations:

$$\Phi_{CC} = \Phi_{NC} = \Phi_{ES}$$

$$\boxed{\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033 \ (\text{total})}$$

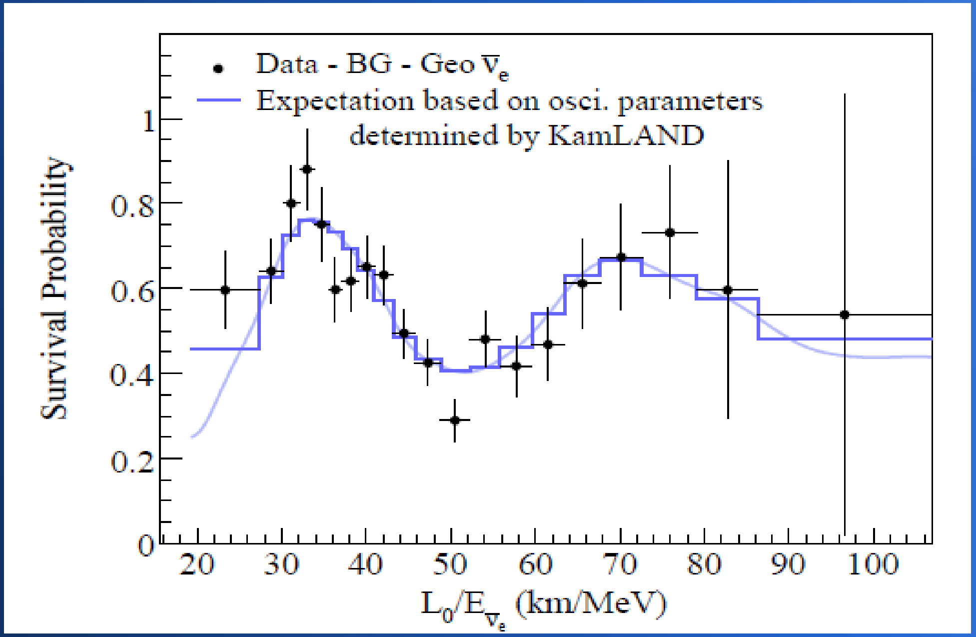
KamLAND

- **Rector neutrino experiment** (Kamioka)
  - 1 KT liquid scintillator
  - L = 180 Km, E ~ 3 MeV
  - Disappearance of $\bar{\nu}_e$



- Solar sector:

L/E~180/0.003 = 60000 Km/GeV



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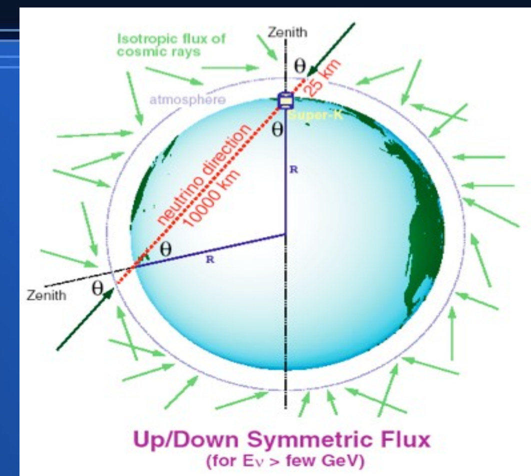
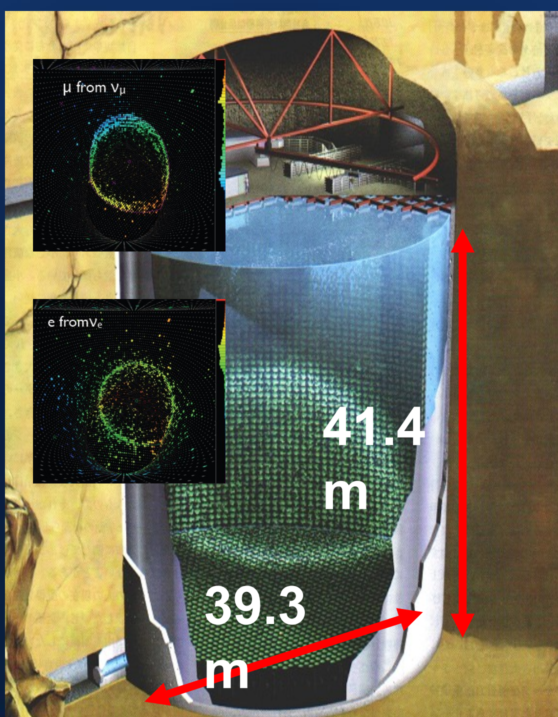
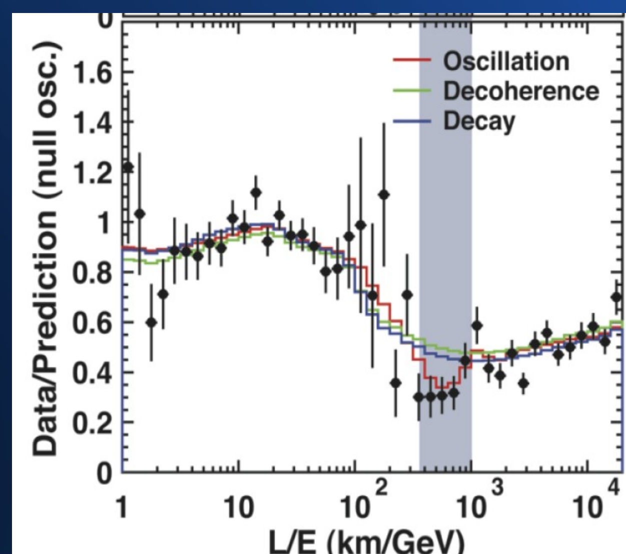
SuperKamiokande

- 50 kton water cherenkov detector
- ν_μ deficit: different energies and baselines

$L/E \sim 1 - 10^4$ km/GeV







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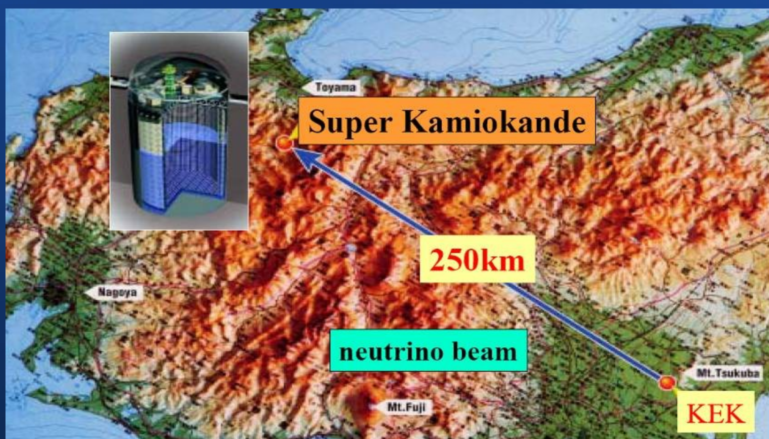
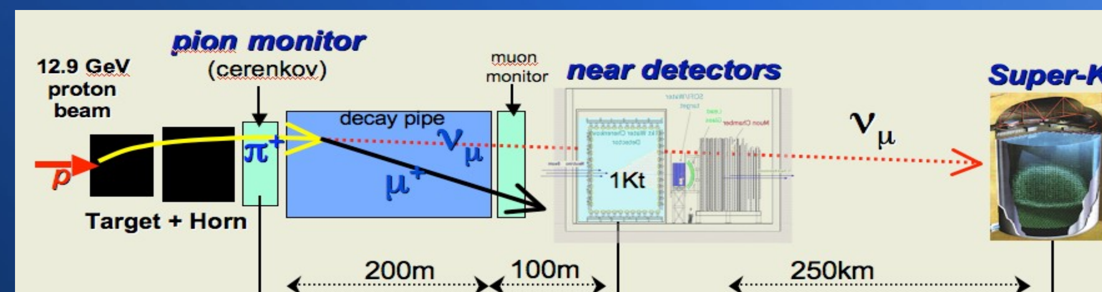
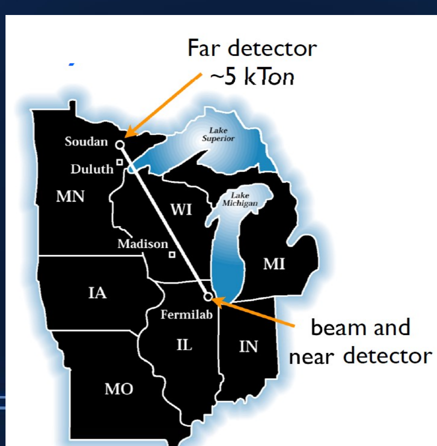
K2K and MINOS



- K2K: first accelerator LBL experiment



- MINOS: precision accelerator LBL experiment



- Muon neutrino beam @ Fermilab
- Magnetized iron calorimeters
  - Steel planes + scint. strips
- Near detector @ 1.04 km from target
- Far detector @ 735 km (Minnesota)