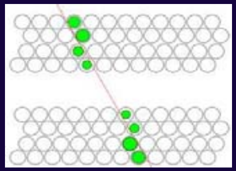
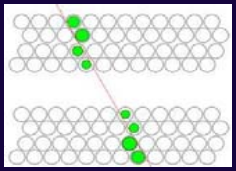


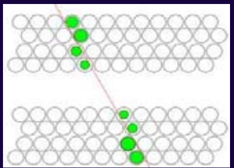
Status and Future of ν-physics

What do I talk about?



- Motivations
- Oscillations
- Status
- Open Questions
- Near Future
- Not so far Future
- Conclusions

Why are we doing ν-physics?



- SM is very successful
- but it leaves a lot of questions open

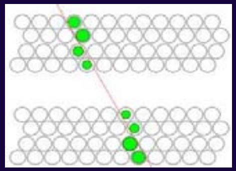
(e.g. astrophysical questions, like big bang, matter-antimatter asymmetry, supernovaes, etc.)

⟶ we want to understand physics beyond the SM

- There are two ways to do that:
  - High Energies ⟶ bigger accelerators
  - Study rare, tiny effects

    ⟶ more statistics, lower background

Why are we doing ν-physics?

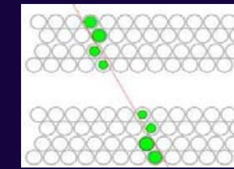


- Tiny effect $(m_\nu/E_\nu)^2 \sim (eV/GeV)^2 = 10^{-18}$!
- Suitable methode: Interferometry
  - Needs coherent source
  - Needs Interference (i.e., large mixing angles)
  - Needs long baseline
- *All this is given us by nature:*

> Neutrino Interferometry (Oscillations) is a unique tool to study physics at very high scales !!!

Lowest order effect of physics at short distances !!!

What are ν-oscillations?



- Flavour eigenstates $\nu_{e,\mu,\tau}$ are not the mass eigenstates $\nu_{1,2,3}$

  ⟶ neutrino mixing

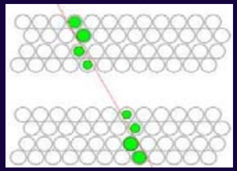
Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

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

- This leads to oscillations between the $\nu_{e,\mu,\tau}$ like in the Kaon system
- ν must have different masses (not all are massless)
- Leptonflavour is not strictly conserved

} Already beyond the SM !

What are ν-oscillations?

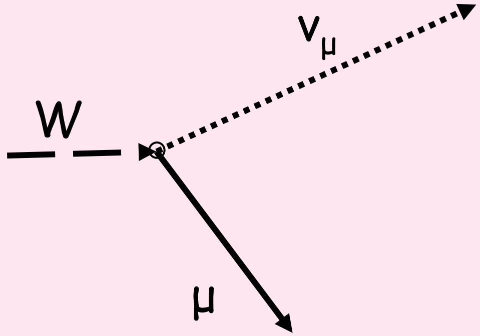


$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} C_{23} & S_{23} \\ -S_{23} & C_{23} \end{pmatrix} \cdot \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

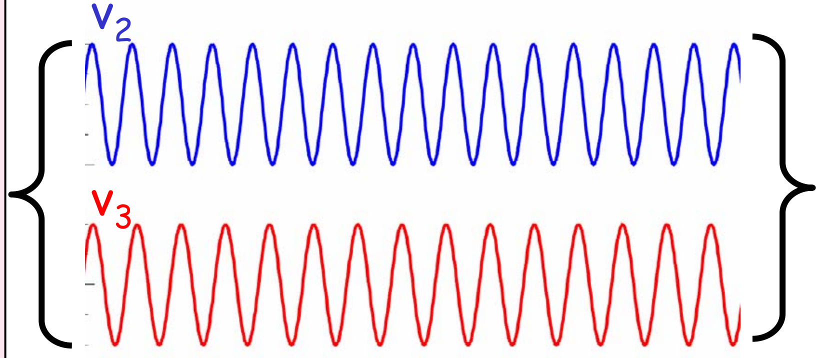
Flavor eigenstates ν_μ, ν_τ

Mass eigenstates ν_2,ν_3 with m_2, m_3

source creates flavor-eigenstates



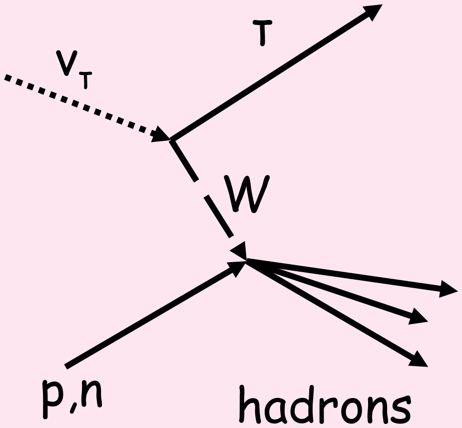
propagation determined by mass-eigenstates



$$\omega_{2,3} = E_{2,3} = \sqrt{p^2 + m_{2,3}^2}$$

slightly different frequencies
→ phase difference changes

detector sees flavor-eigenstates

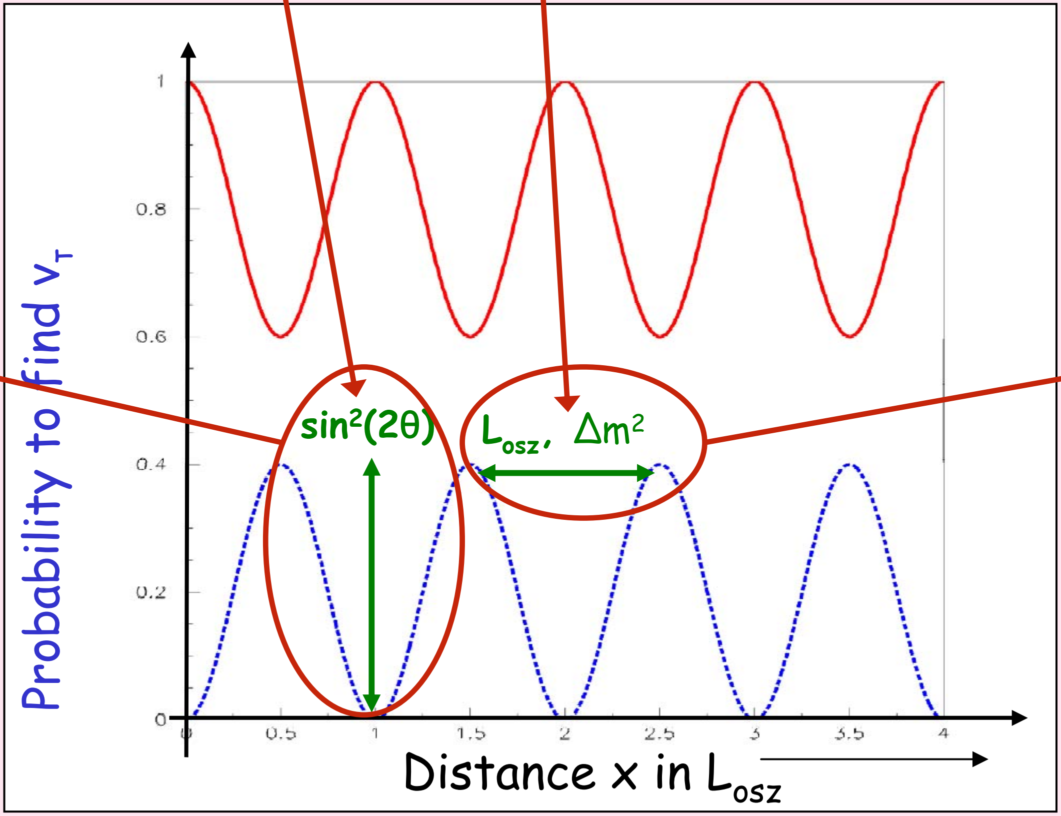


What are ν-oscillations?

- **Oscillation probability**

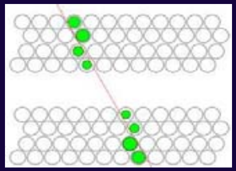
$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \cdot \sin^2 \frac{\Delta}{2} \quad \text{with} \quad \Delta = \frac{\delta m^2}{2} \cdot \frac{L}{E}$$

experiment needs statistics



experiment needs energy resolution

What are ν-oscillations?



Three flavour mixing:

3 mixing angles and 1 CP-violating phase

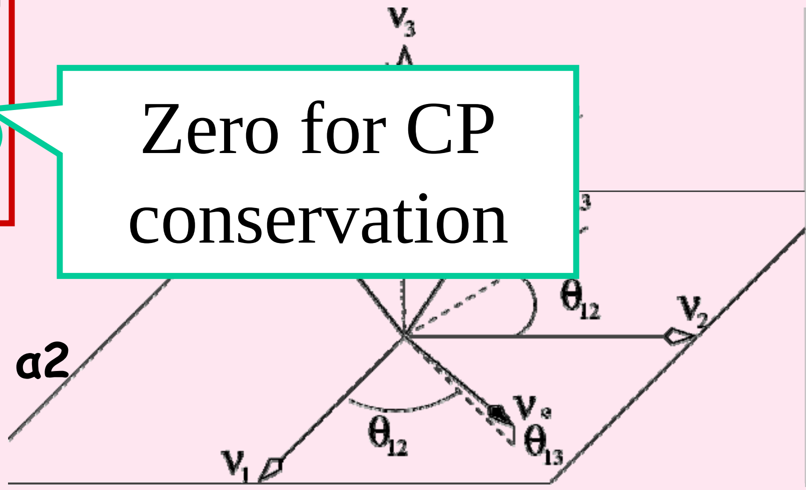
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$\pm 2\sum_{i>j} \Im(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

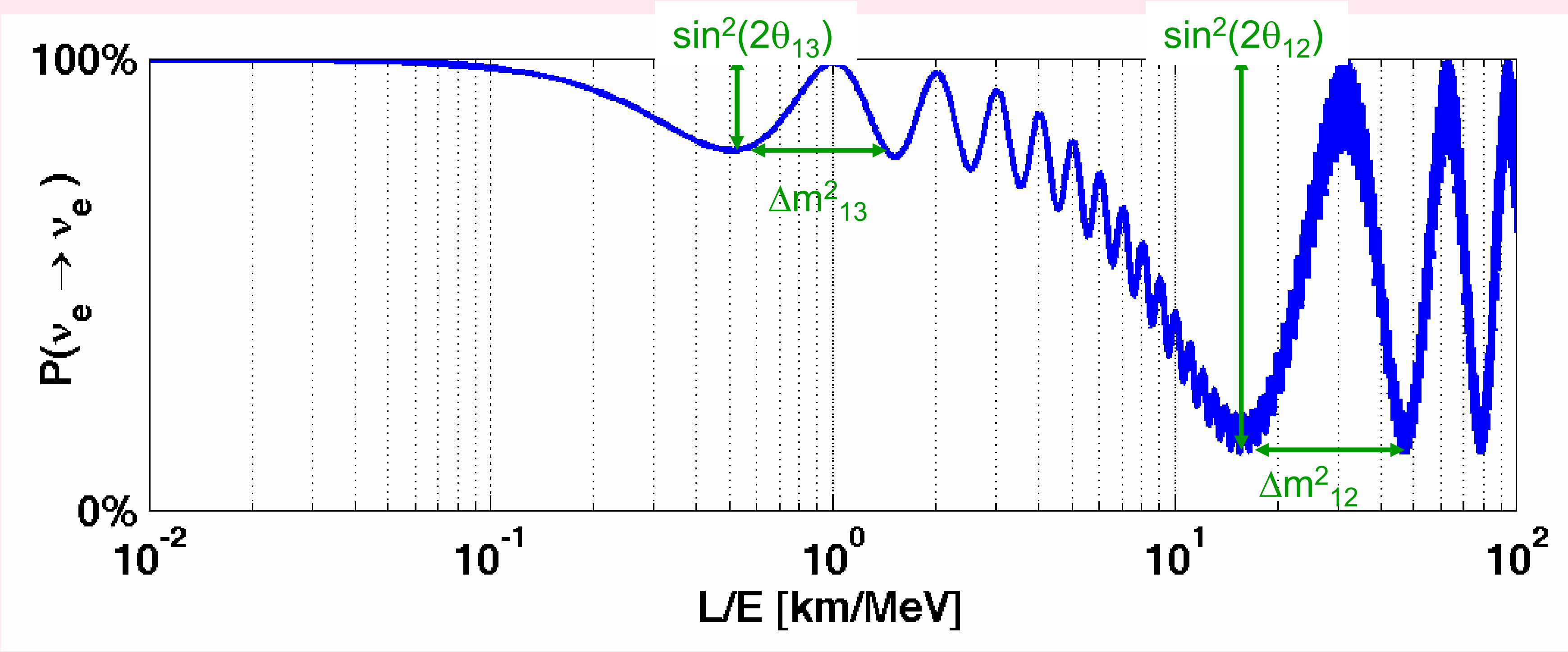
Zero for CP conservation

If neutrinos are Majorana particles:
2 additional Majorana-Phases (CPV): α1, α2



Example for 3 flavour Oscillation probability !

L/E is crucial !

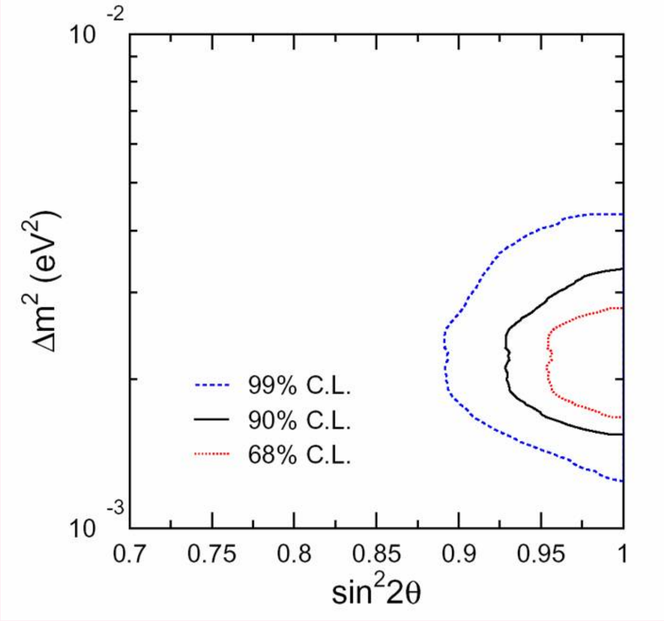


What do we know?

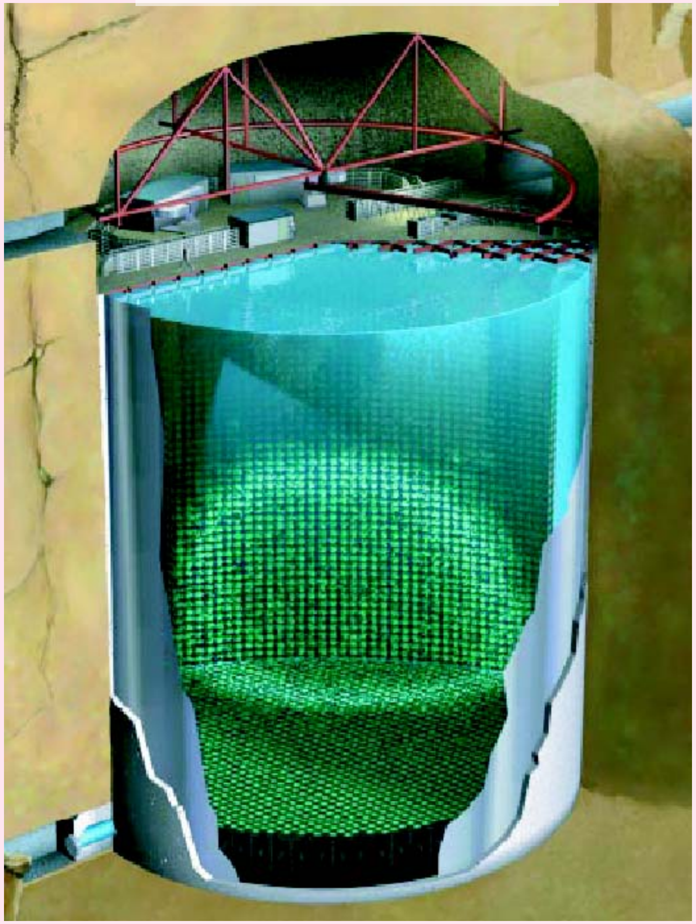
- **Atmospheric neutrinos** $\nu_\mu \rightarrow \nu_\tau$

$$\left|\Delta m^2_{23}\right| = 2.4^{+0.6}_{-0.5} \times 10^{-3} eV^2$$

$$\sin^2 2\theta_{23} > 0.9$$

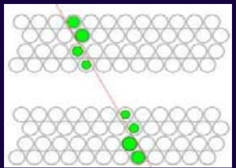


Super-Kamiokande



Atmosphärische ν
Beschleuniger ν

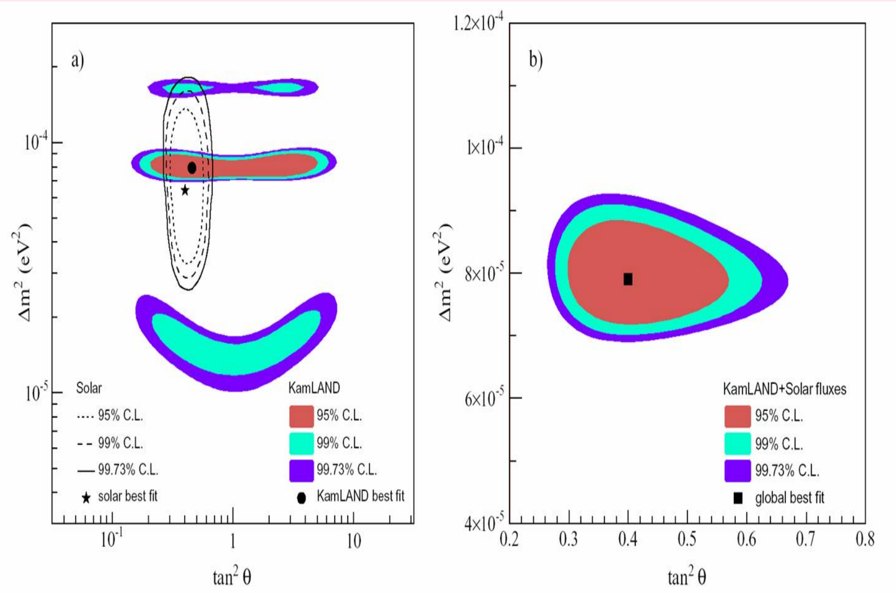
What do we know?

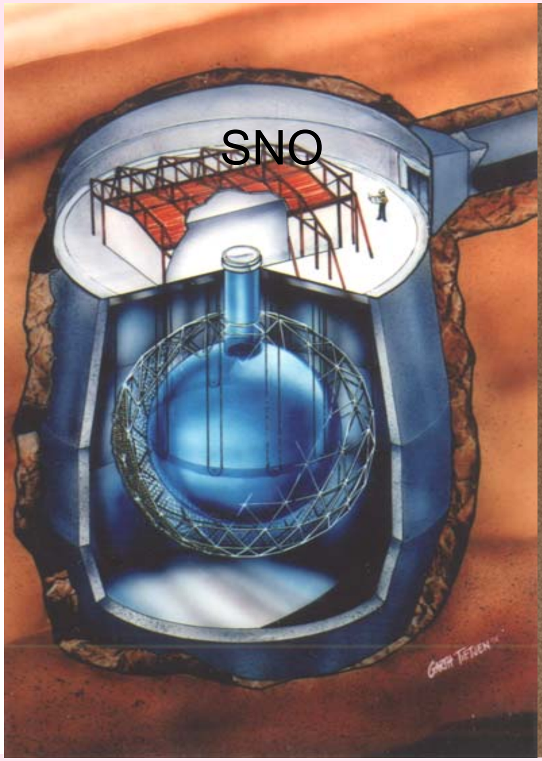


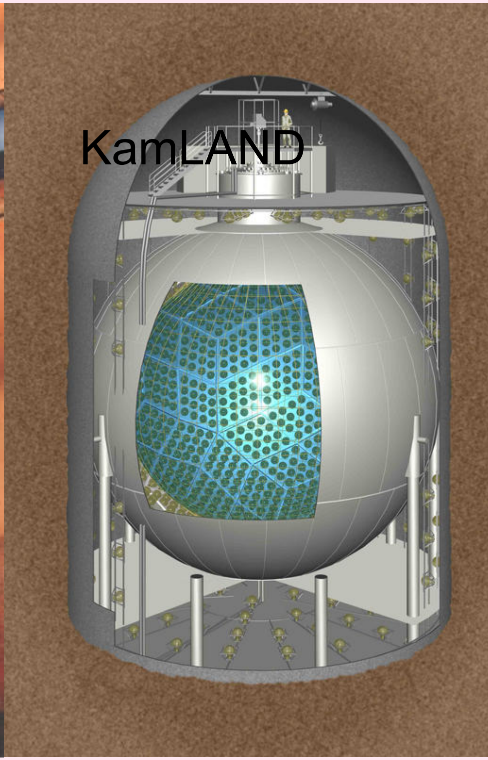
- **Solar neutrinos** $\nu_e \rightarrow \nu_{\mu,\tau}$

$$\Delta m_{12}^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

$$\tan^2 \theta_{12} = 0.40^{+0.1}_{-0.07}$$





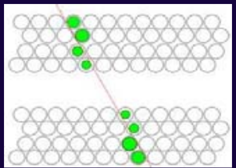


Mass effects in the sun dominate !

Solar-ν

Reaktor-ν

What are ν-oscillations?



Three flavour mixing:

3 mixing angles and 1 CP-violating phase

$$\theta_{23} = 45^\circ \pm 10^\circ \approx \pi/4 \qquad \theta_{13} \le 13^\circ \qquad \theta_{12} = 30^\circ \pm 10^\circ \approx \pi/6$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\theta_{13} \approx 0, \quad s_{12} \approx \frac{1}{2}, \quad c_{12} \approx \frac{\sqrt{3}}{2}$$

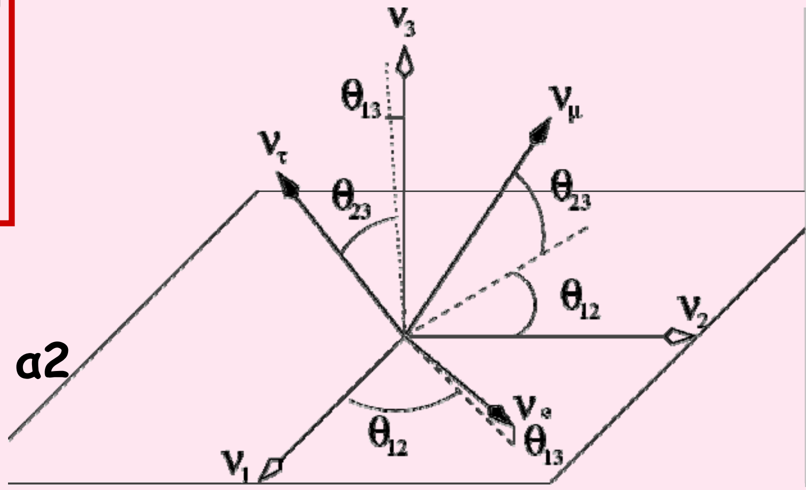
Very different Δm^2 in different sectors

→ Solar and atmospheric oscillations can be regarded as independent

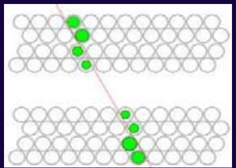
→ 2 flavor discription is sufficient

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) \pm 2\sum_{i>j} \Im(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

If neutrinos are Majorana particles:
2 additional Majorana-Phases (CPV): α1, α2



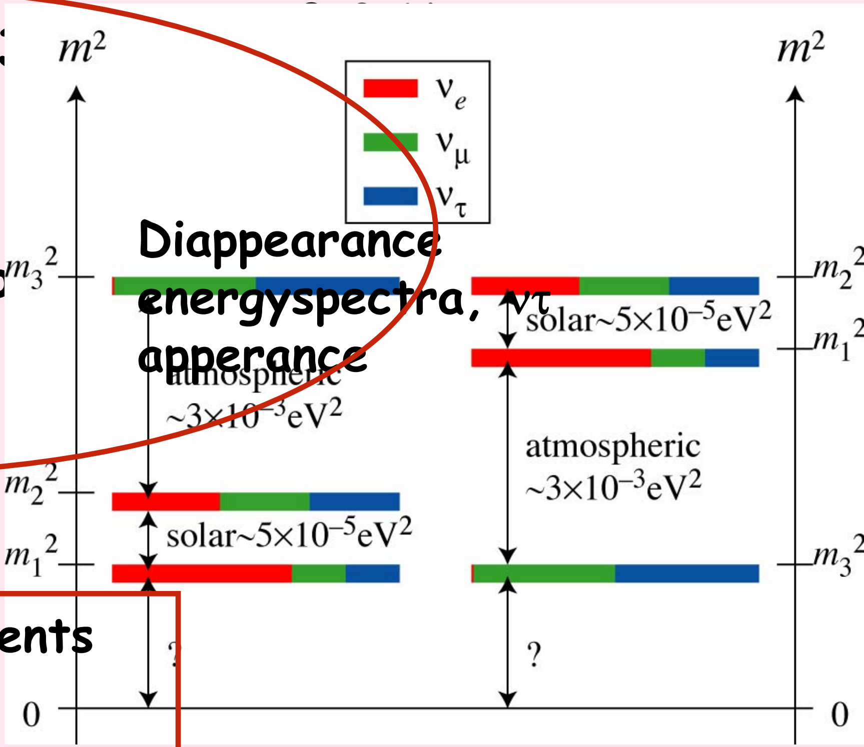
What do we want to know?



- Dirac or Majorana ?
- Absolute mass scale ?
- How small is θ1
- CP-violation ?
- Mass hierarchy
- Verify Ocsillatio
- LSND ? Sterile
  CPT-violation ?

ββ0ν: claim by Klapdor-Kleingrothaus !

direct measurement: Katrin aims for



Diappearance energyspectra, ντ apperance

- can be adressed by oscillation experiments
- need specialised experiments

What comes next?

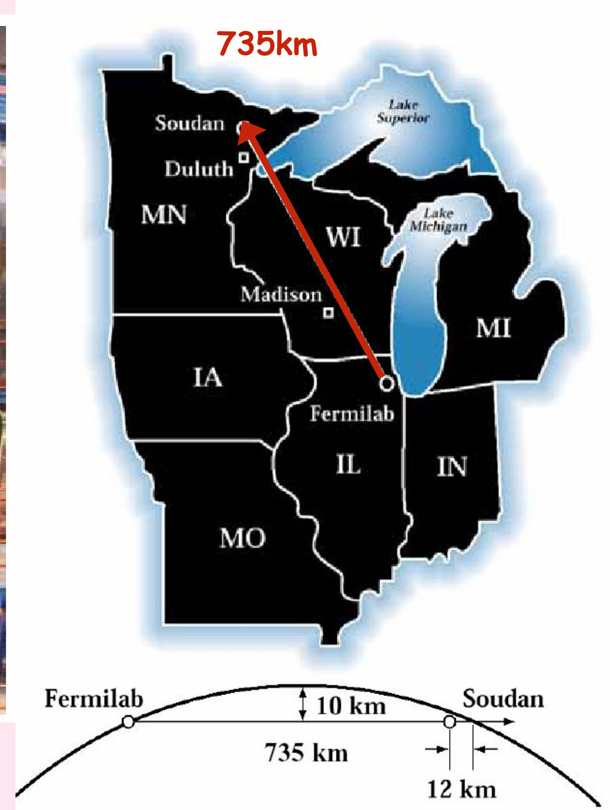
NUMI

MINOS

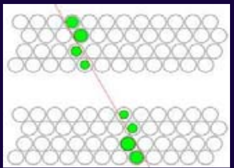
Minos

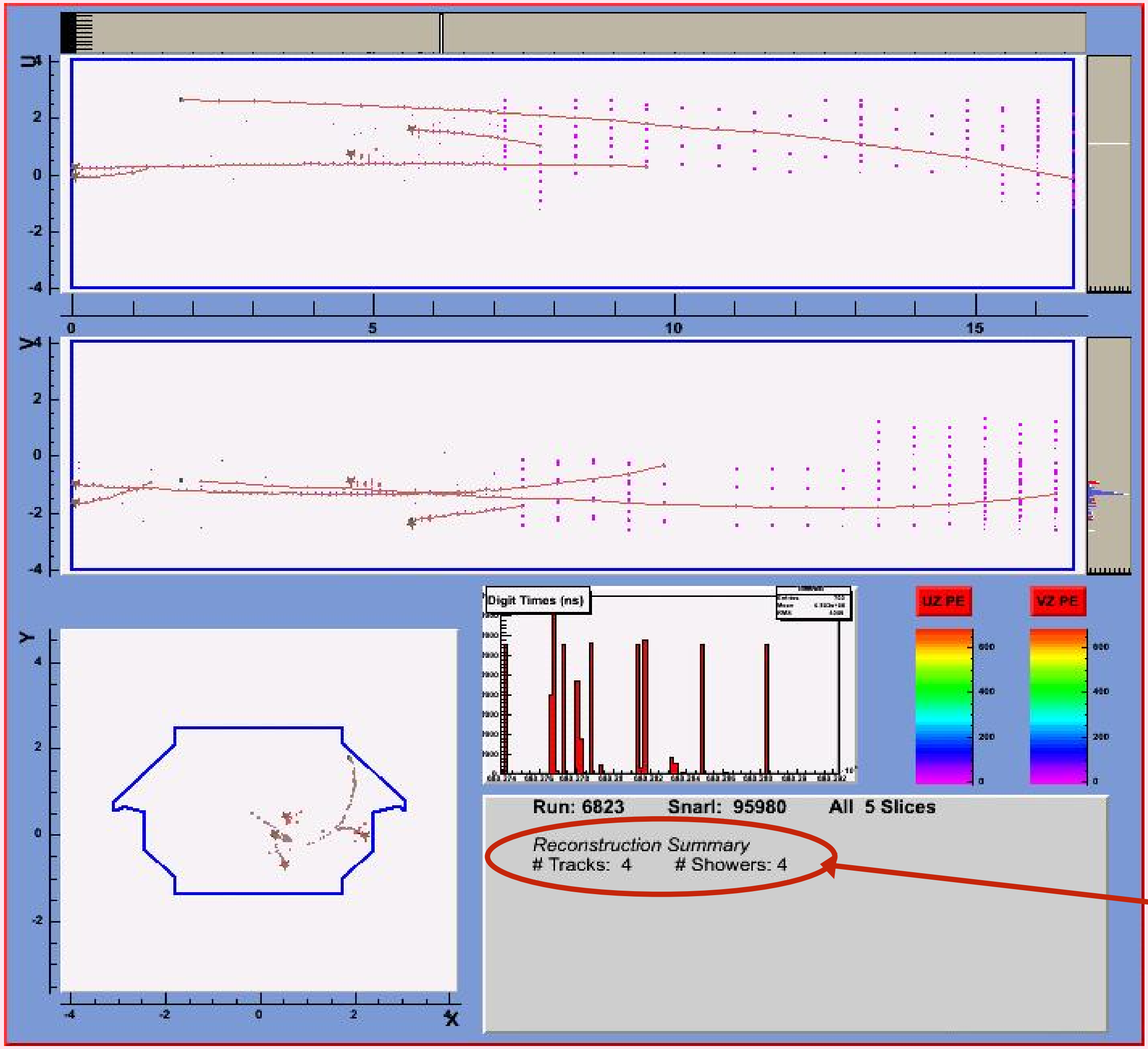
started this year

Magnetized steel/scintillator calorimeter



- low E neutrinos (few GeV): ν_μ disappearance experiment
- 4 x10^{20} pot/year → 2500 ν_μ CC/year
- compare Det1-Det2 response vs E → in 2-6 years sensitivity to Δm^2_{atm}
- main goal: reduce the errors on Δm^2_{23} and $\sin^2 2\theta_{23}$ as needed for $\sin^2 2\theta_{13}$ measurement

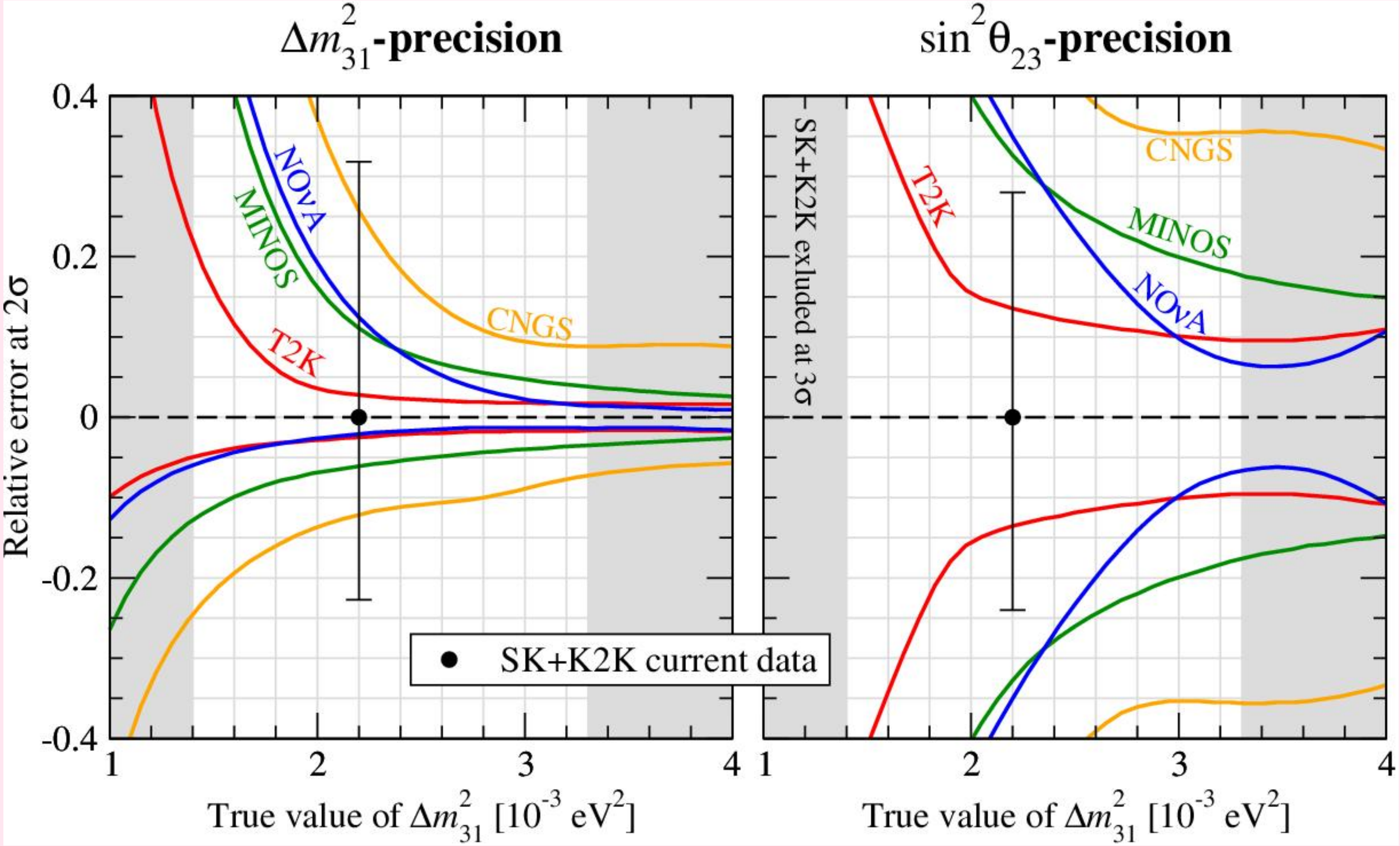




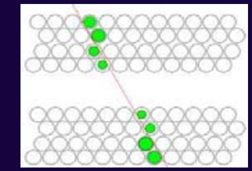
- 8m Octagonal Tracking Calori
- 486 layers of 2.54cm Fe
- 2 sections, each 15m long
- 4.1cm wide solid scintillator strips with WLS fiber readout
- 25,800 m^2 active detector planes
- Magnet coil provides $\langle B \rangle \approx 1.3T$
- 5.4kt total mass

NC/CC ratio measured

contains four neutrino interactions


Δm^2_{31}-precision
$\sin^2\theta_{23}$-precision
Relative error at 2σ
0.4
0.2
0
-0.2
-0.4
1
2
3
4
True value of Δm^2_{31} [10^{-3} eV^2]
NOvA
MINOS
T2K
CNGS
SK+K2K exluded at 3σ
SK+K2K current data

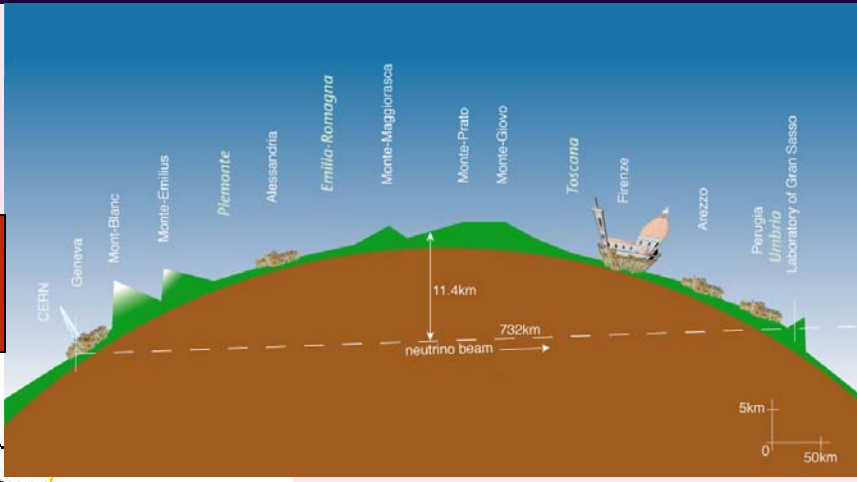
What comes next?

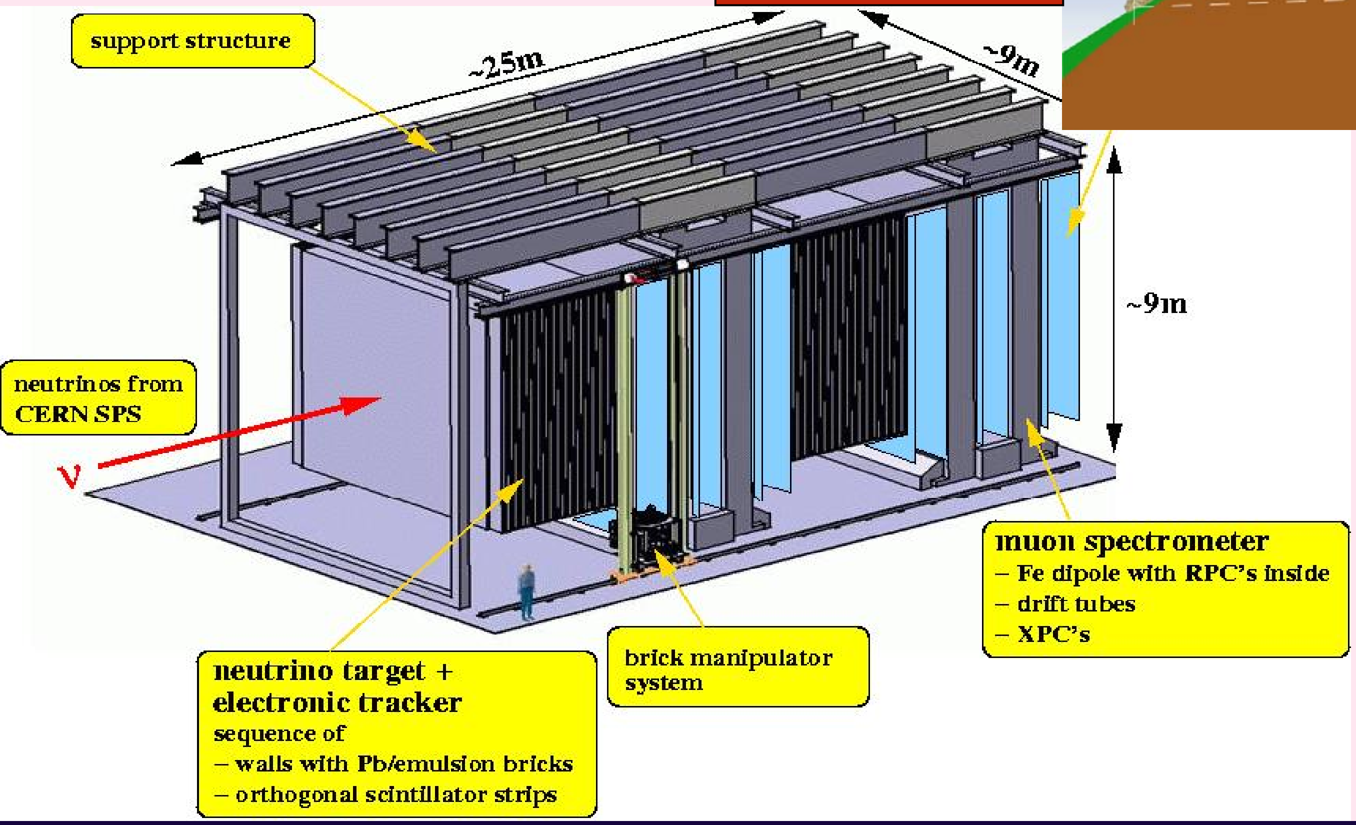


ν_τ appearance experiment

(search for θ_{13})

start end 2006





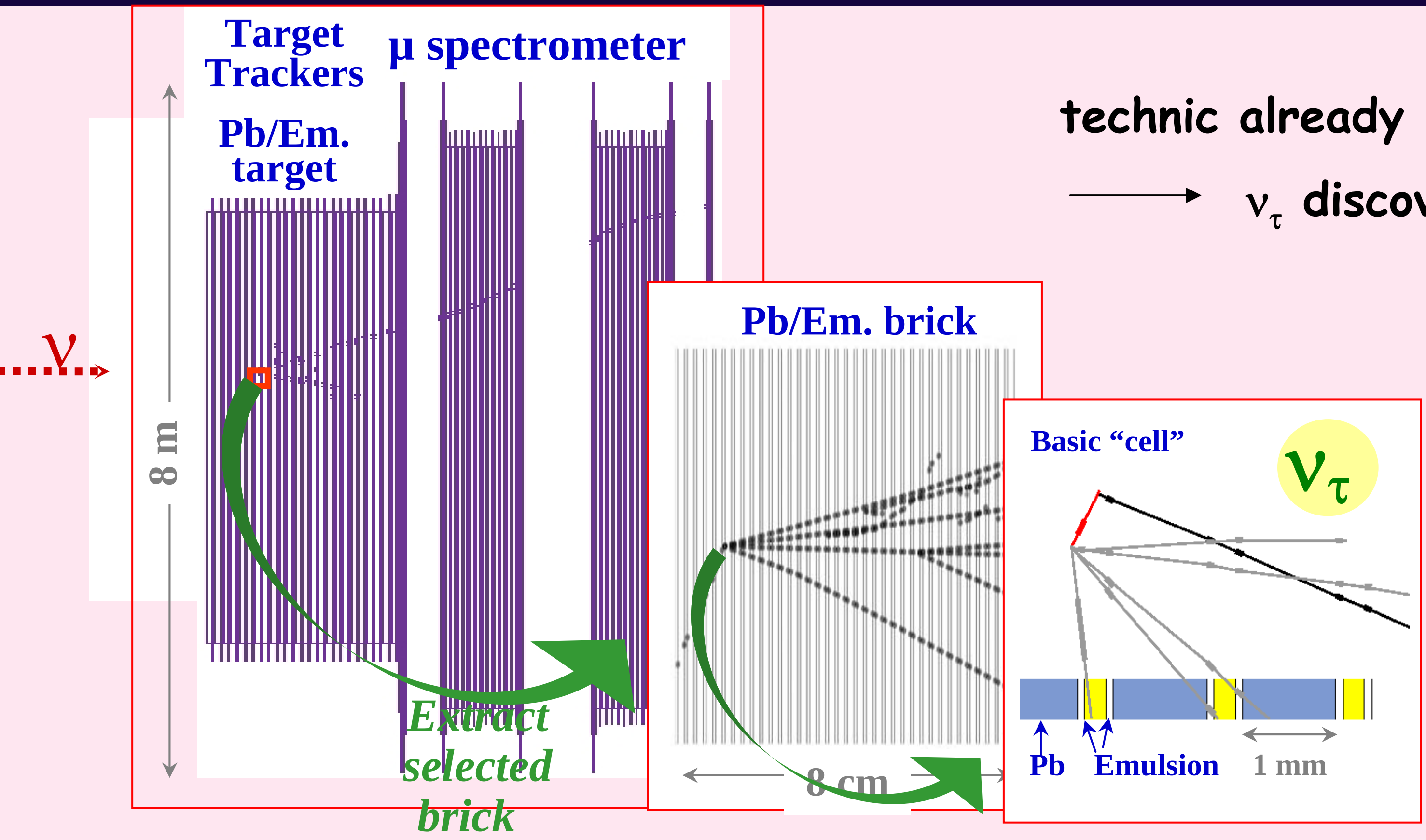
Emulsion Cloud Chamber (ECC)

1,8 kton mass

$E_n \approx 17$ GeV

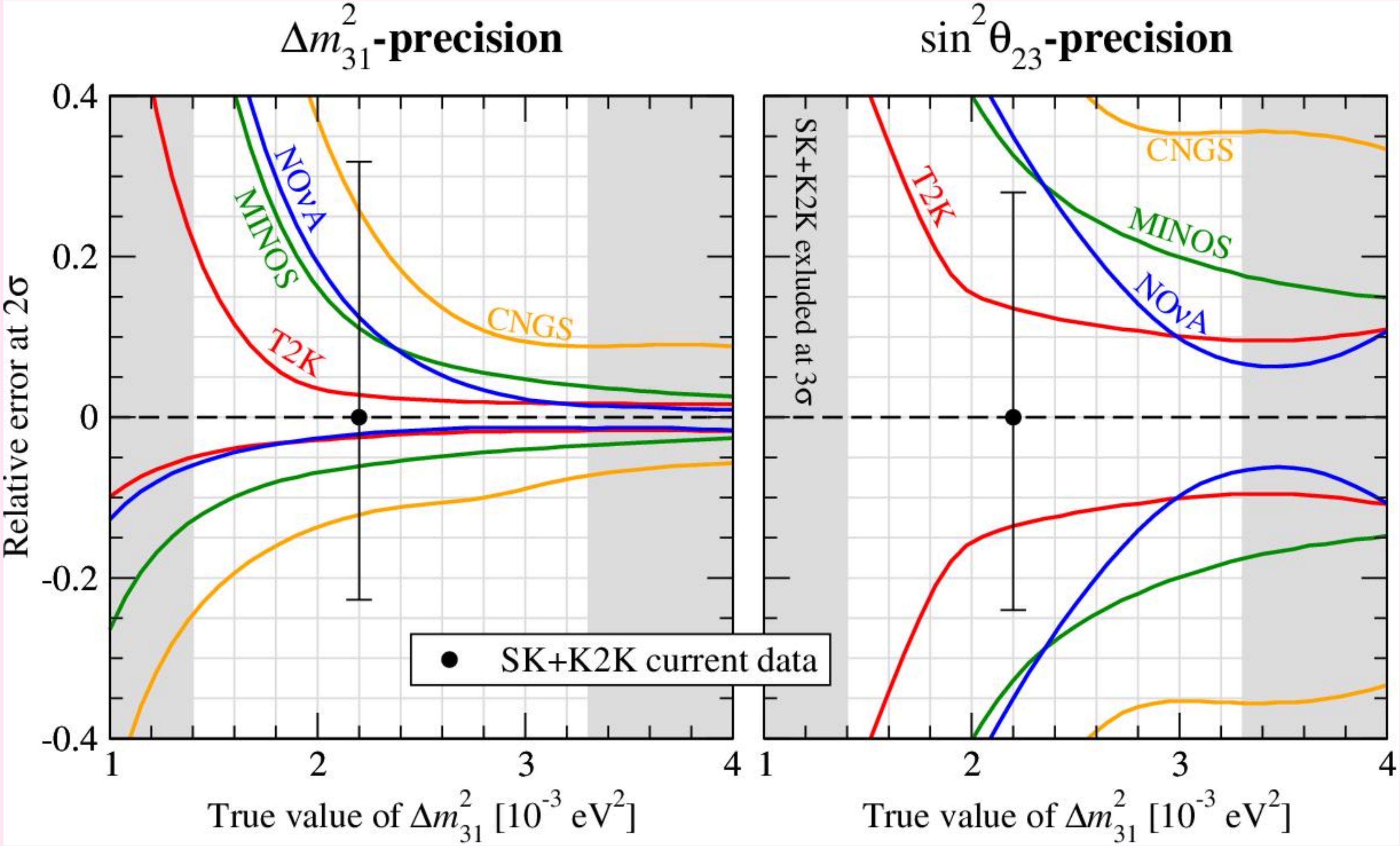
technic already used by Donut

→ ν_τ discovery anno 2000



Electronic detectors
select ν interacting brick
μ ID, charge and p

Emulsion Analysis
Vertex search
Decay search
e/γ ID, kinematics

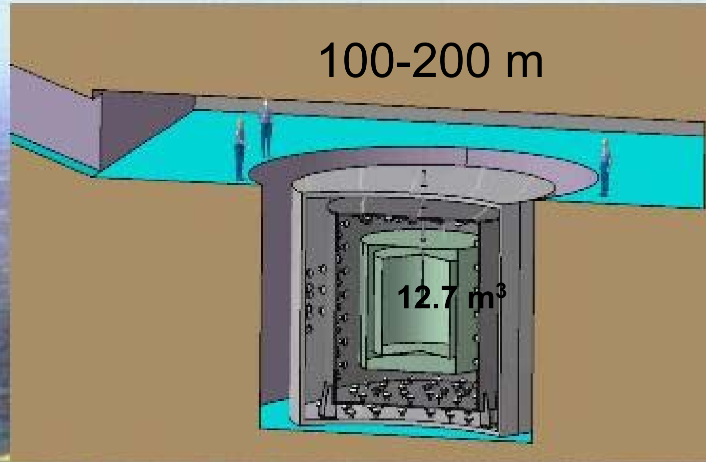


Δm^2_{31}-precision
$\sin^2\theta_{23}$-precision
0.4
0.2
0
-0.2
-0.4
Relative error at 2σ
NOνA
MINOS
CNGS
T2K
SK+K2K exluded at 3σ
SK+K2K current data
1
2
3
4
True value of Δm^2_{31} [10^{-3} eV^2]

What comes next?

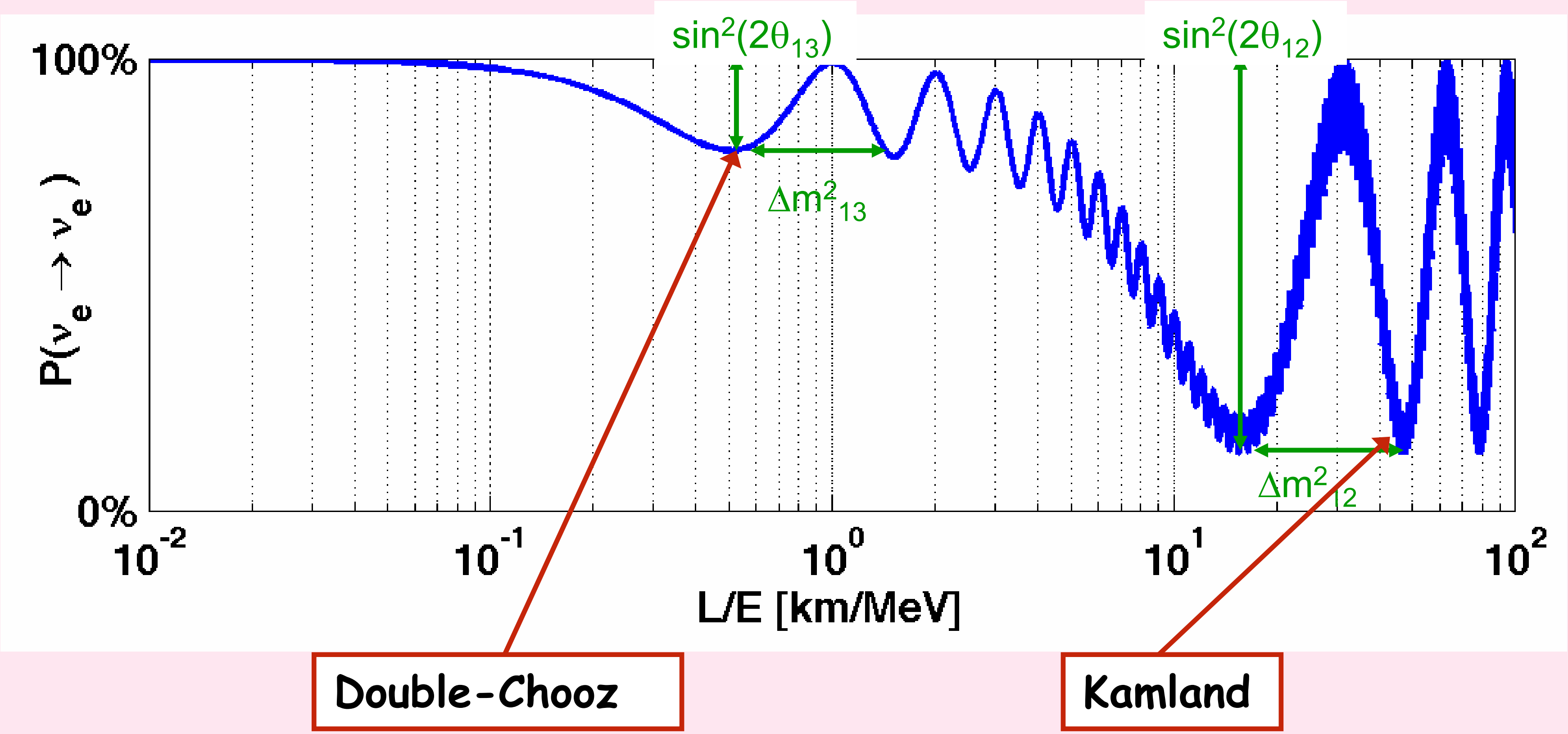
Search for θ_{13}:

Doppel-CHOOZ
Reaktorneutrino
experiment
(France)



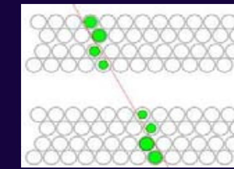
first data taking beginning 2007

Double-Chooz sensitivity for (Δm^2 = 2.0-2.5 10-3 eV^2):
$\sin^2(2\theta_{13})$ < 0.025-0.03, 90% C.L.

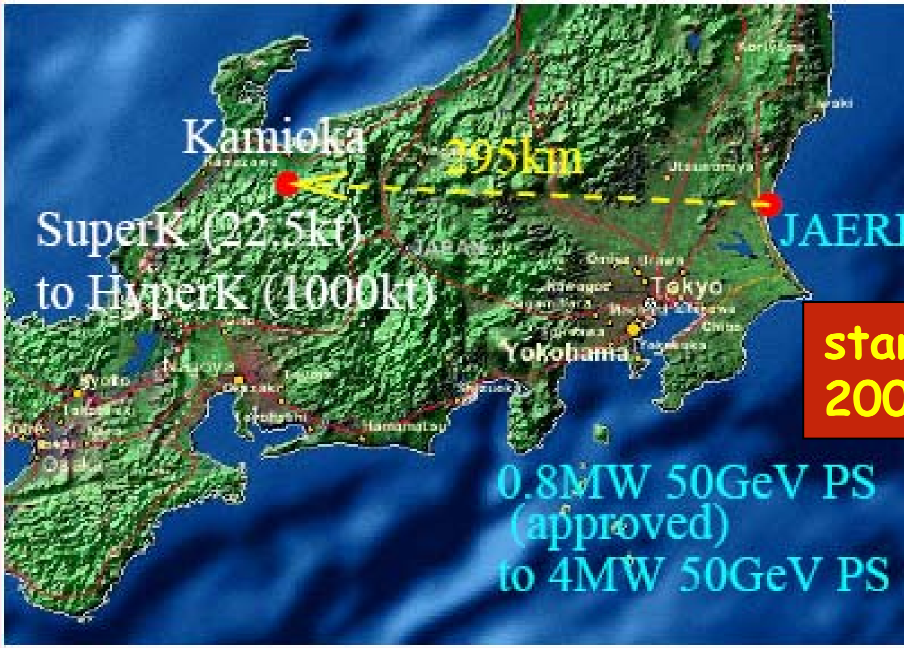


100%
0%
P(νe → νe)
sin2(2θ13)
Δm2 13
sin2(2θ12)
Δm2 12
10-2
10-1
100
101
102
L/E [km/MeV]
Double-Chooz
Kamland

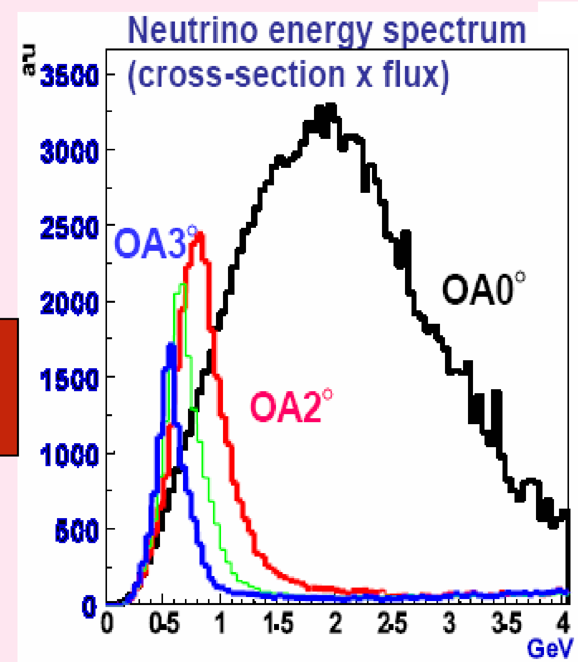
What comes next to next?

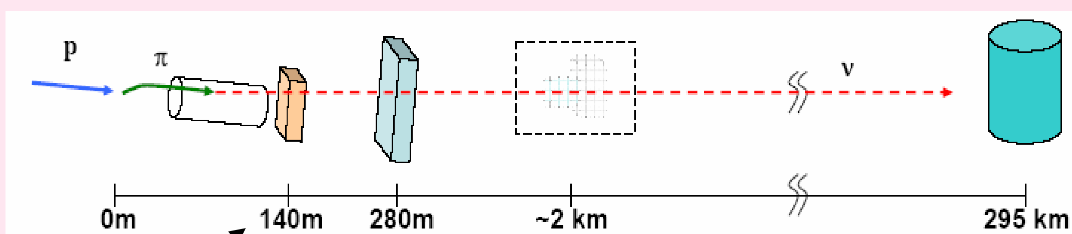


The first Super-Beam: off-axis T2K, from Tokai to SK



start around 2009





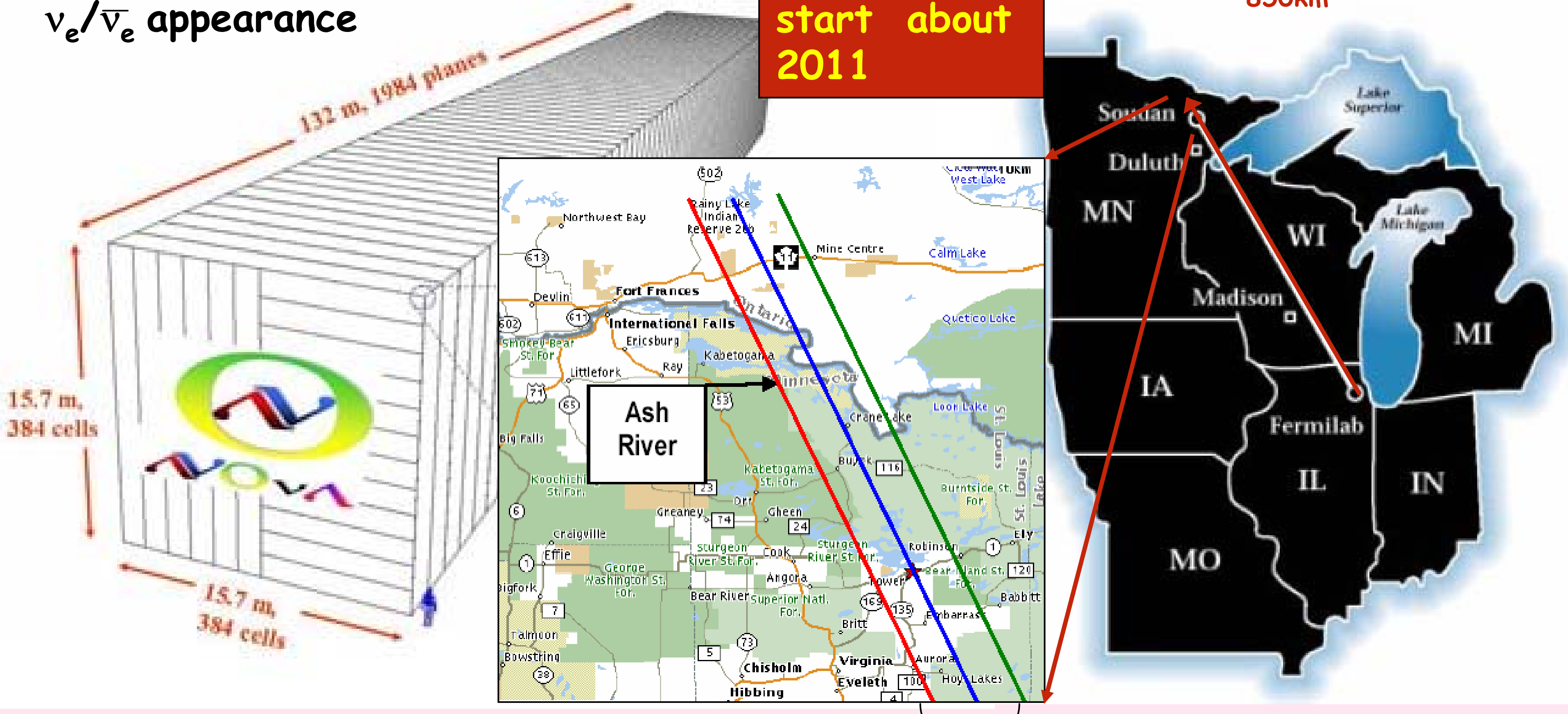
μ monitor (beam direction and intensity)

ν energy spectrum and intensity

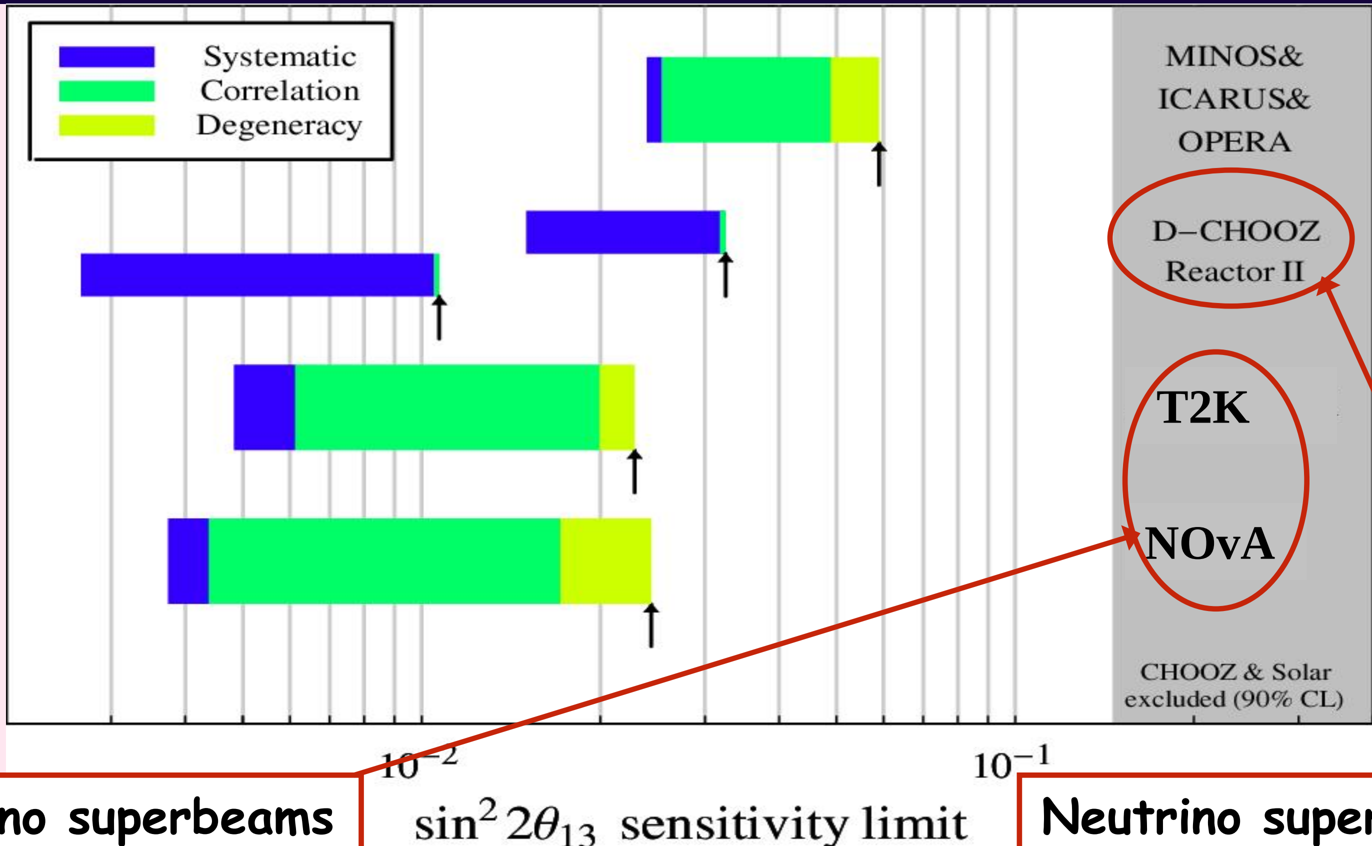
Same spectrum as SK, BG measurement

$\nu_e/\bar{\nu}_e$ appearance

start about 2011



30kt liquid Scintillator detector
NUMI beam with 6.5 x 10^{20} pot/yr
With a new Proton Driver, 25 x 10^{20} pot/yr ⟶ Superbeam!
Bunch time information used ⟶ ν-physics comes back to surface



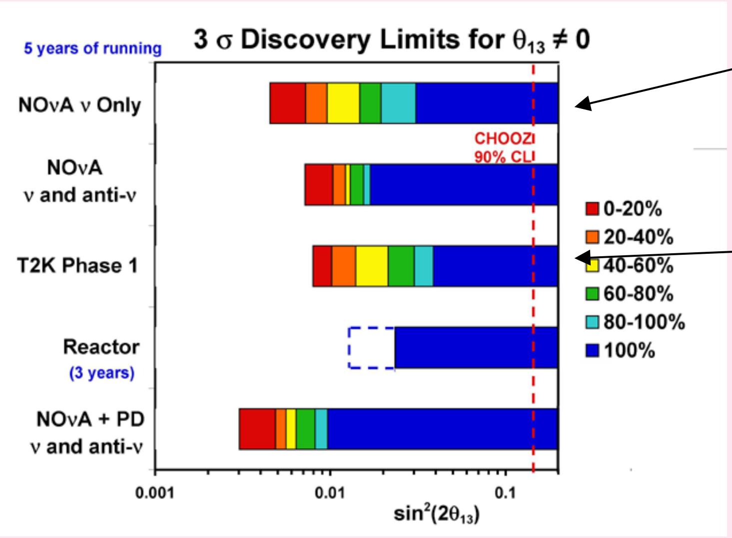
Neutrino superbeams

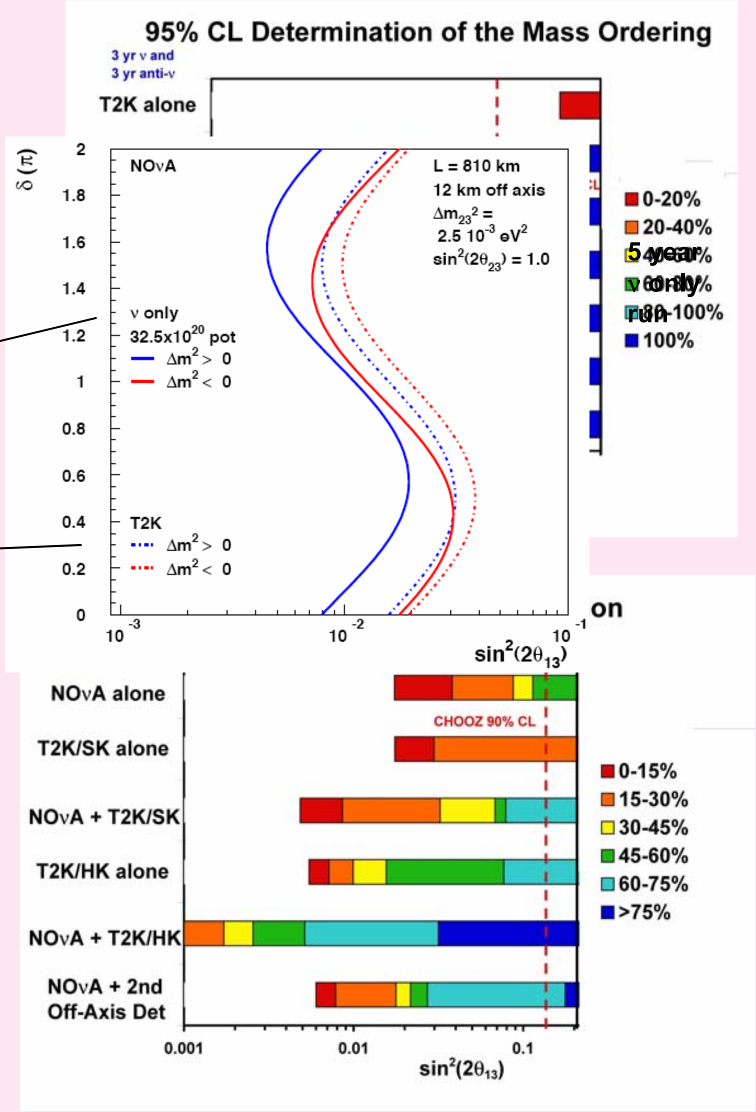
Neutrino superbeams

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \Delta$$
$$\mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta$$
$$+ \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \sin^2 \Delta$$
$$+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta$$

$$1 - P(\overline{\nu_e} \to \overline{\nu_e}) \cong \sin^2 2\theta_{13} \sin^2 \Delta + \alpha^2 \Delta^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

with $\Delta \equiv \Delta m^2{}_{31} L / (4E_\nu)$ $\quad \alpha \equiv \Delta m^2{}_{21} / \Delta m^2_{31}$





for maximal atmospheric mixing

with $\Delta m^2 \approx 2{,}5 \cdot 10^{-3}$ eV²

What have we learned?

- Smart way to reach high energy scales
- Already physics beyond the SM
- A lot of interesting open questions
- First measurements were highly succesfull

  ⟶ time for precision measurements
- A new intertesting experiment every year

  ⟶ fast growing knowledge