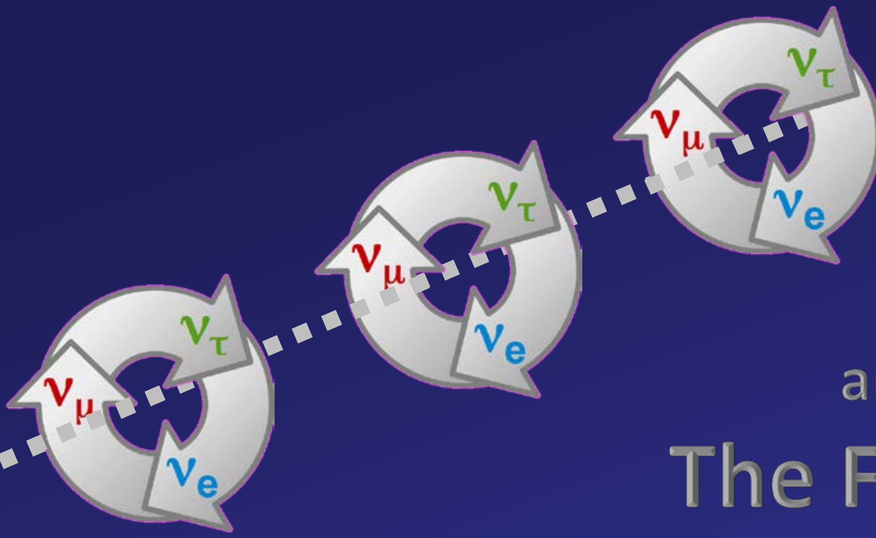
Colloquium – DESY Zeuthen

JUNO



and

The Fate of Antimatter

Achim Stahl – RWTH Aachen University – JARA-FAME

In the beginning ...

created matter and antimatter
in equal amounts

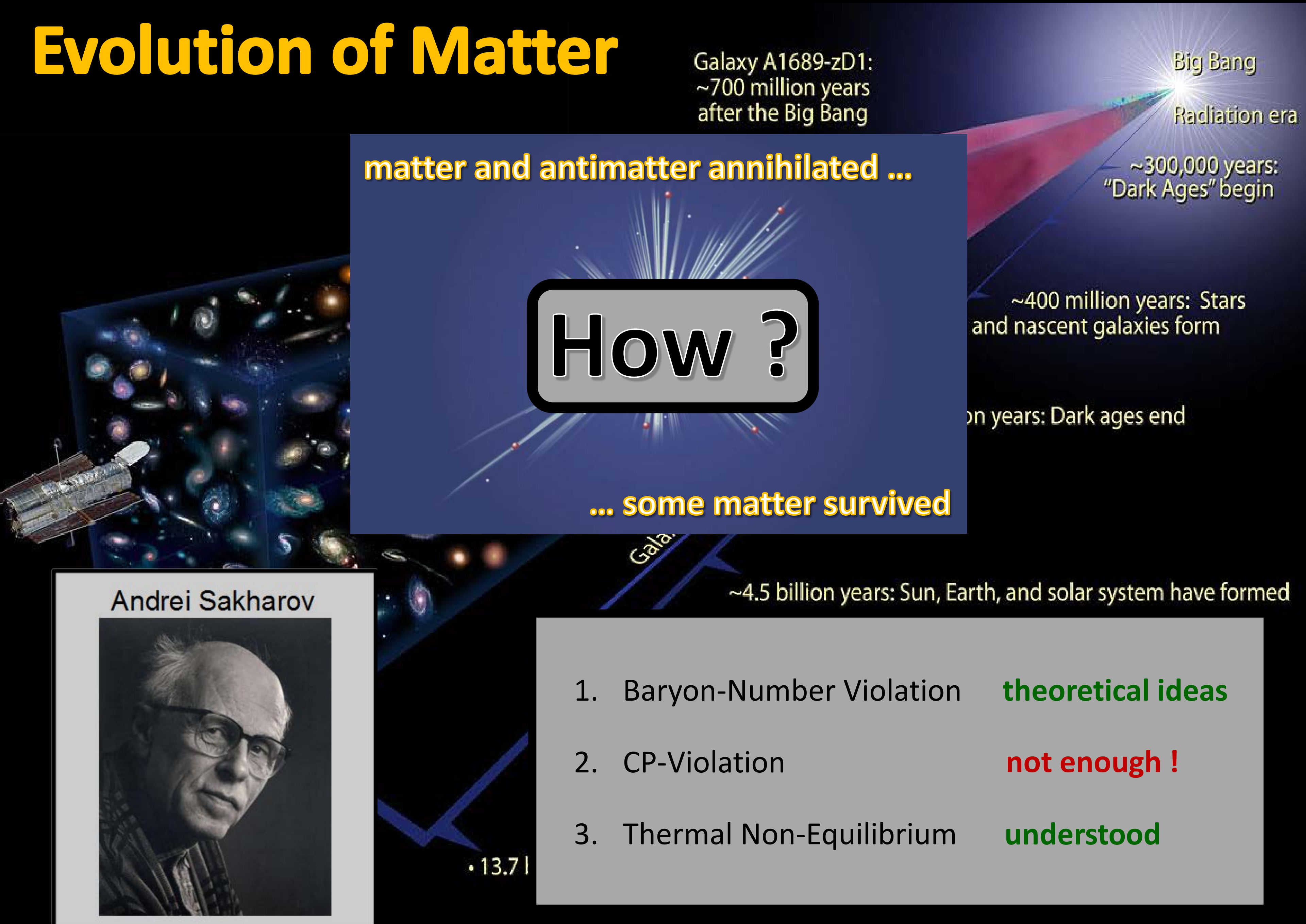
tested in the lab

„a million times“

... the Big Bang


Today …
… we only find matter

Evolution of Matter



1. Baryon-Number Violation — **theoretical ideas**
2. CP-Violation — **not enough !**
3. Thermal Non-Equilibrium — **understood**

Today …

Baryon to Photon Ratio:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 5 \cdot 10^{-10}$$

$$n_\gamma \approx 0.4/mm^3$$

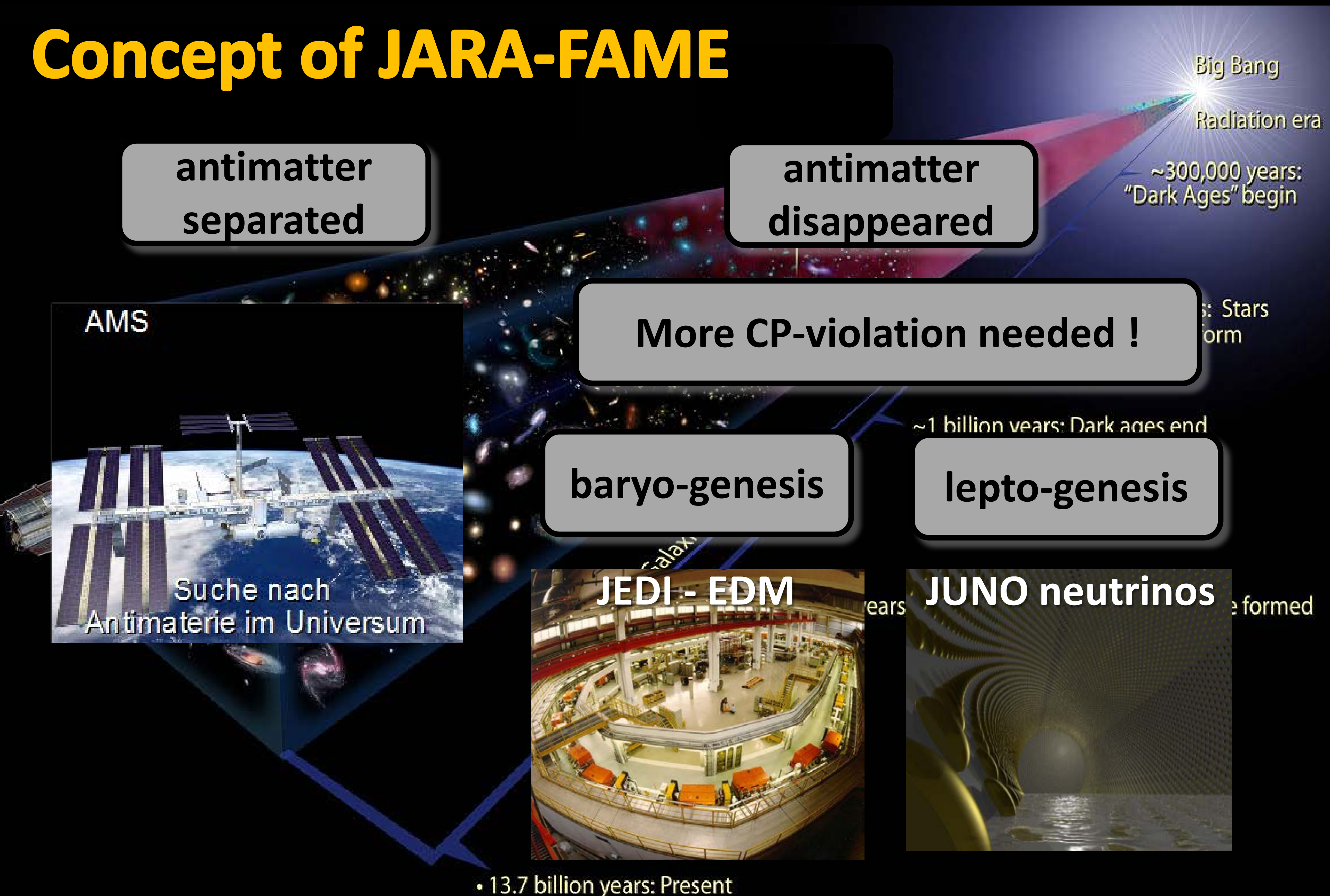
$$n_B \approx 0.2/m^3$$

$$n_{\bar{B}} \approx 0$$

Standard Model fails by many orders of magnitude

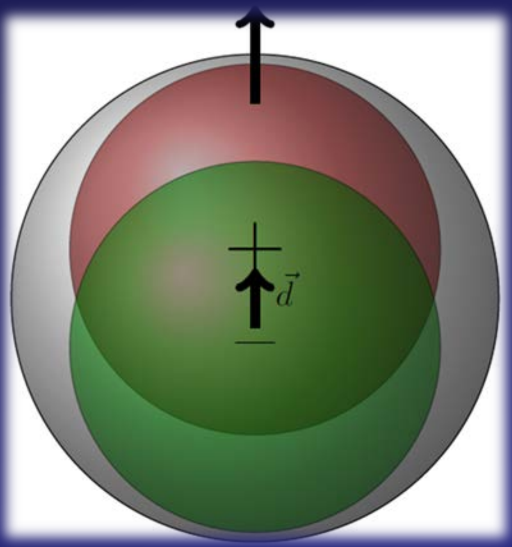
… we only find matter

Concept of JARA-FAME

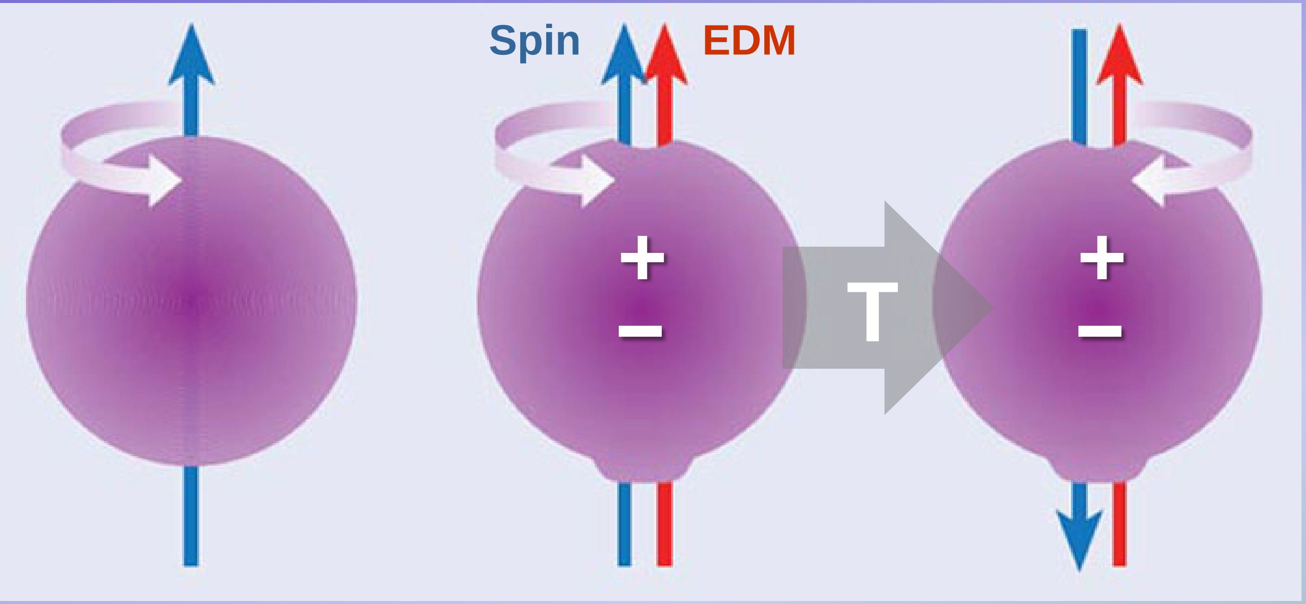


Content

Electric Dipole Moments

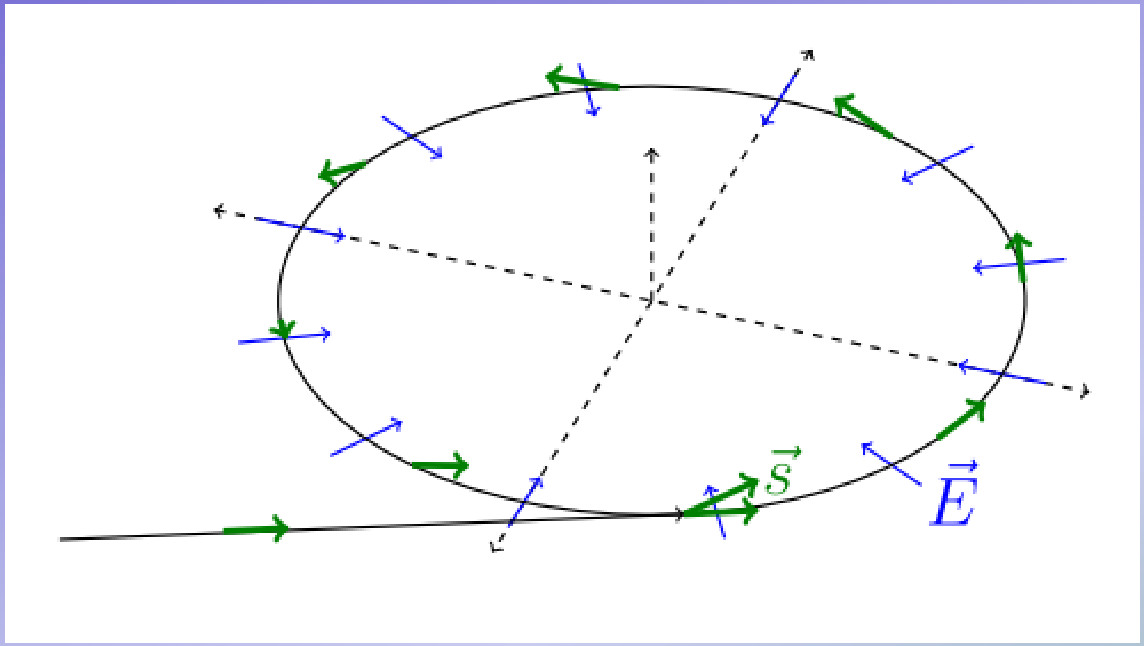


ELECTRIC DIPOLE MOMENTS



Electric Dipole Moments
→ Violate P- and T-Symmetry
→ CPT-Theorem: violate CP-Symmetry

STORAGE RING EDM



frozen spin @ $\mathrm{p_p} = 700.740\ \mathrm{MeV/c}$ (magic momentum)

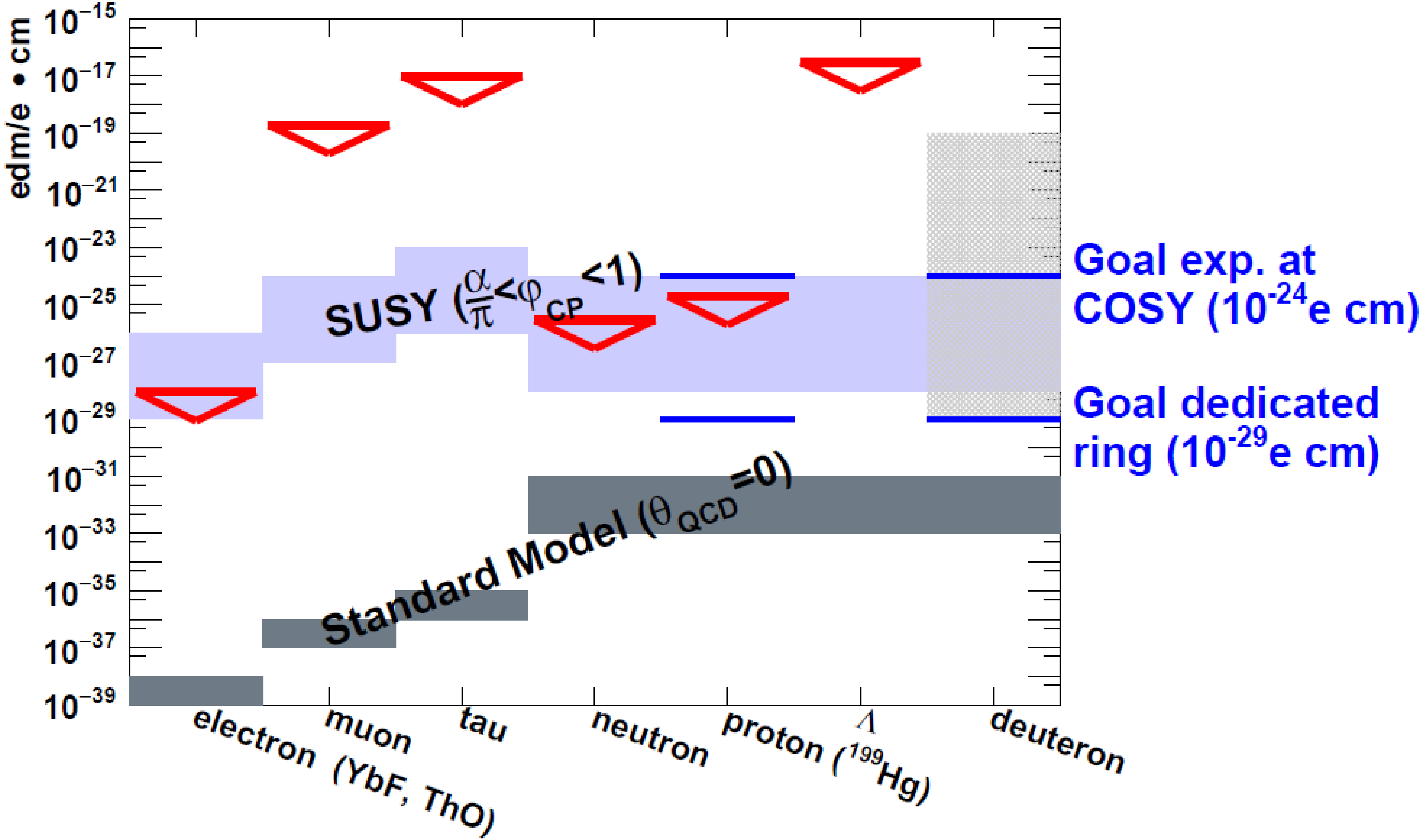
EDM turns spin out of accelerator plane

PRECURSER EXPERIMENT

JEDI

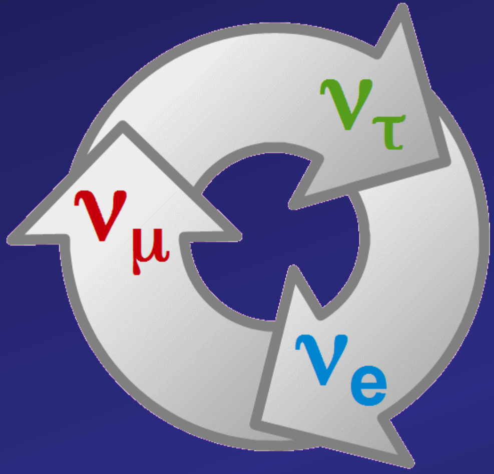
Jülich
Electric
Dipole moment
Investigation

magnetic ring
RF-Wien filters
introduce f-Field



edm/e • cm
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
10^{-25}
10^{-27}
10^{-29}
10^{-31}
10^{-33}
10^{-35}
10^{-37}
10^{-39}
SUSY ($\frac{\alpha}{\pi}<\varphi_{CP}<1$)
Standard Model ($\theta_{QCD}=0$)
electron (YbF, ThO)
muon
tau
neutron
proton (^{199}Hg)
Λ
deuteron
Goal exp. at COSY (10^{-24}e cm)
Goal dedicated ring (10^{-29}e cm)

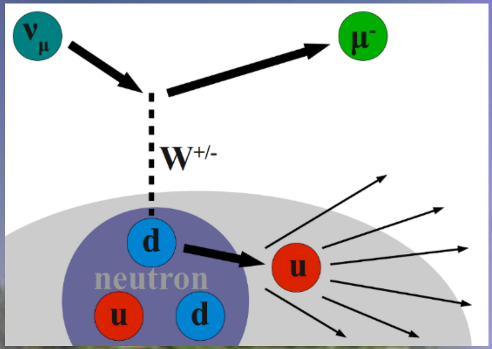
Neutrinos-Oscillations



NEUTRINO OSCILLATIONS

Flavour Eigenstates

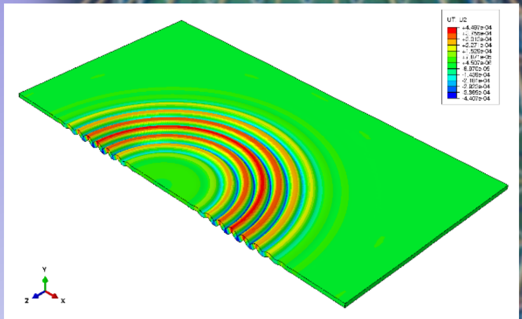
Mass Eigenstates



$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i} |\nu_i\rangle$$

e μ τ

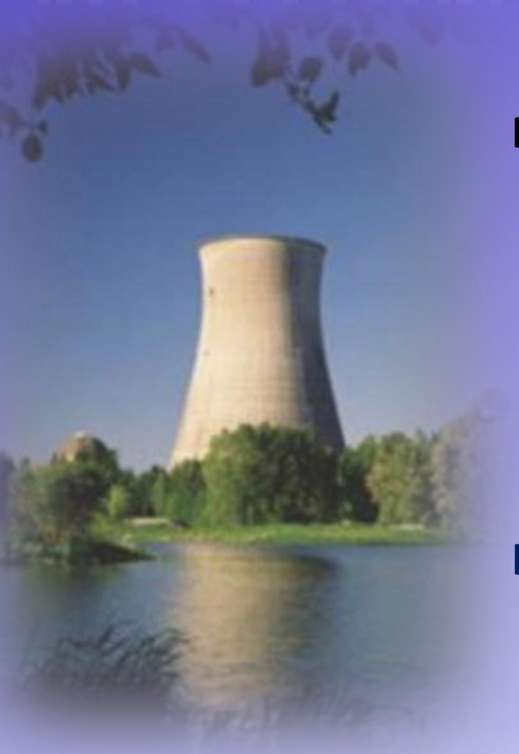
1 2 3



How neutrinos interact

How neutrinos propagate

NEUTRINO OSCILLATIONS



Flavour Eigenstates

Mass Eigenstates

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i} |\nu_i\rangle$$

e μ τ

1 2 3

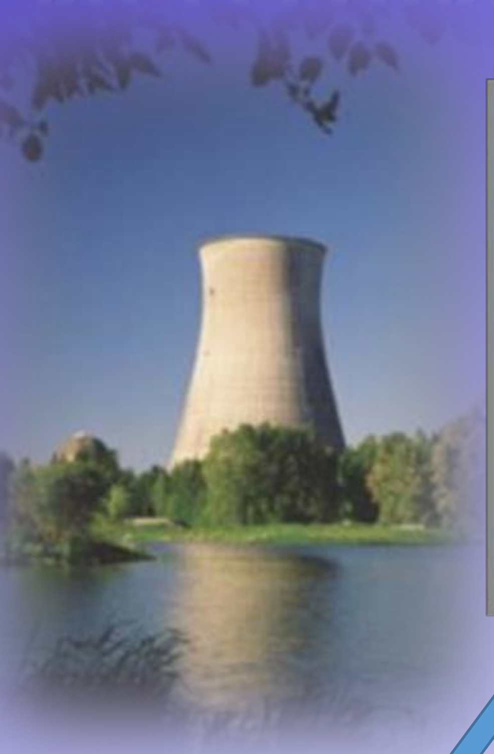
How neutrinos interact

How neutrinos propagate

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

Pontecorvo **M**aki **N**akagawa **S**akata - matrix

NEUTRINO OSCILLATIONS



Flavour

Mass states

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$\Delta m^2 \approx 2.4\ 10^{-3}\ eV^2$$
$$\theta_{23} \approx 45°$$

Atmospheric Oscillations

2 3

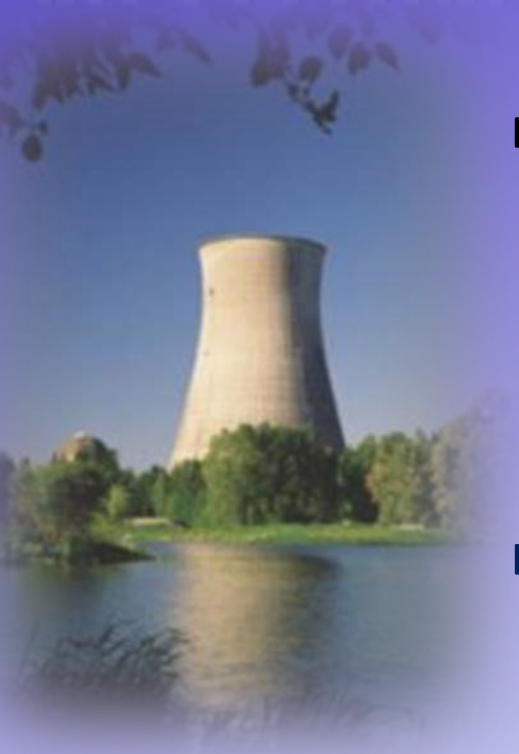
interact

neutrinos propagate

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

Pontecorvo **M**aki **N**akagawa **S**akata - matrix

NEUTRINO OSCILLATIONS



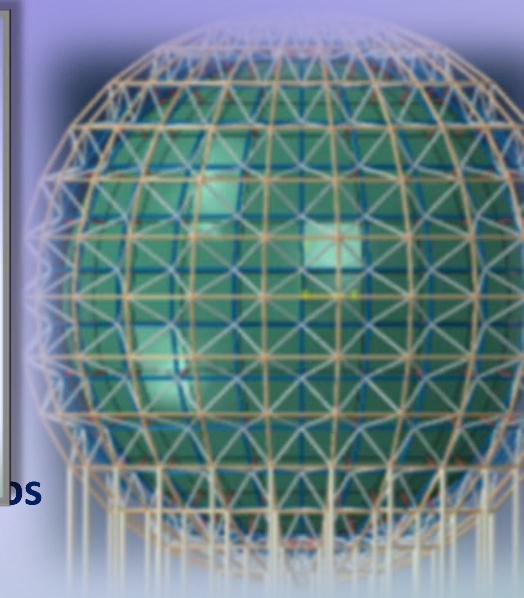
Flavour
Eigensta

Mass

e μ

How ne
interact

os
prop gate



$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

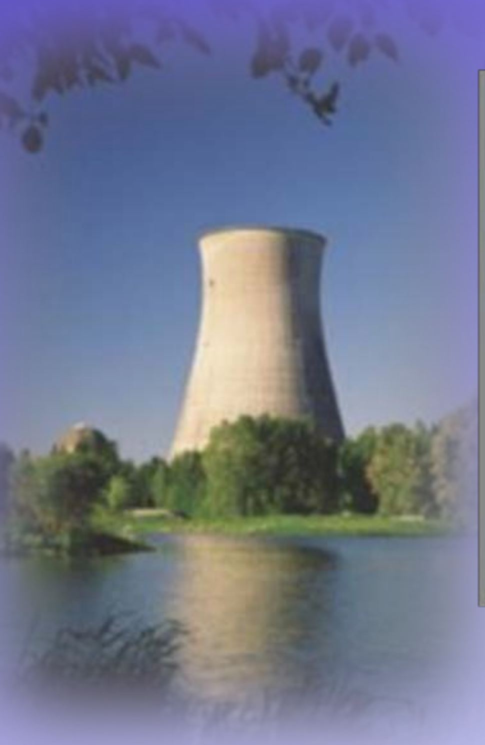
$$\Delta m^2 \approx 7.6\ 10^{-5}\ eV^2$$
$$\theta_{23} \approx 35°$$

Solar Oscillations

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

Pontecorvo **M**aki **N**akagawa **S**akata - matrix

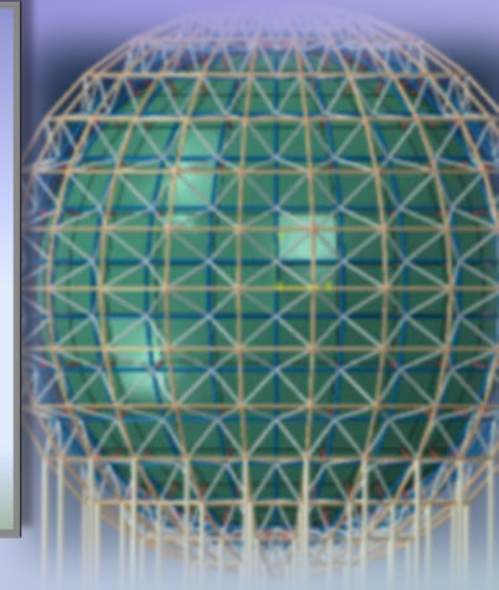
NEUTRINO OSCILLATIONS



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

$$\Delta m^2 \approx 2.4\ 10^{-3}\ eV^2$$
$$\theta_{13} \approx 9^\circ$$

Reactor Oscillations



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

Pontecorvo **M**aki **N**akagawa **S**akata - matrix

NEUTRINO OSCILLATIONS

Special case: 2 flavours only

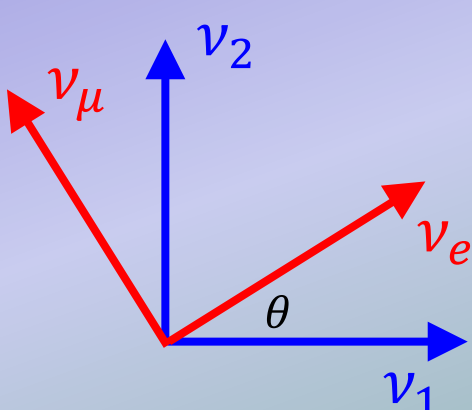
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

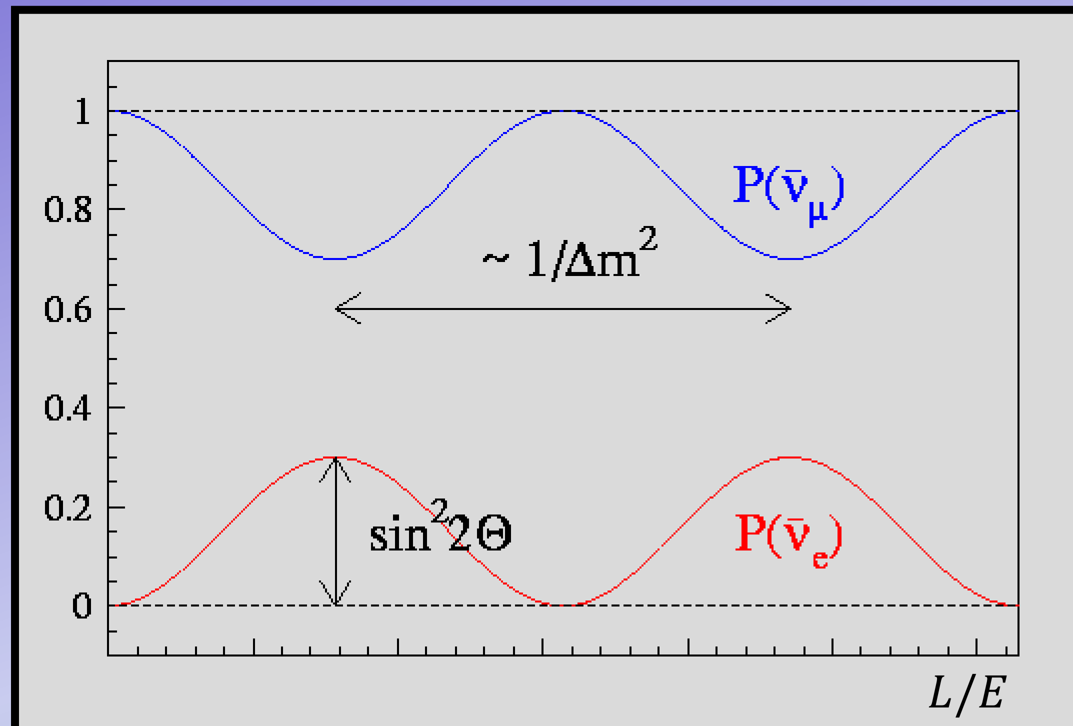
Mass difference $\Delta m^2 = m_2^2 - m_1^2$

Mixing anlge θ

Oscillation length:

$$\frac{4\pi\, E_\nu}{\Delta m^2} \approx 2.48 \text{ m} \,\frac{E_\nu\ [MeV]}{\Delta m^2\ [eV^2]}$$





Disappearance: $P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4\, E_\nu}$

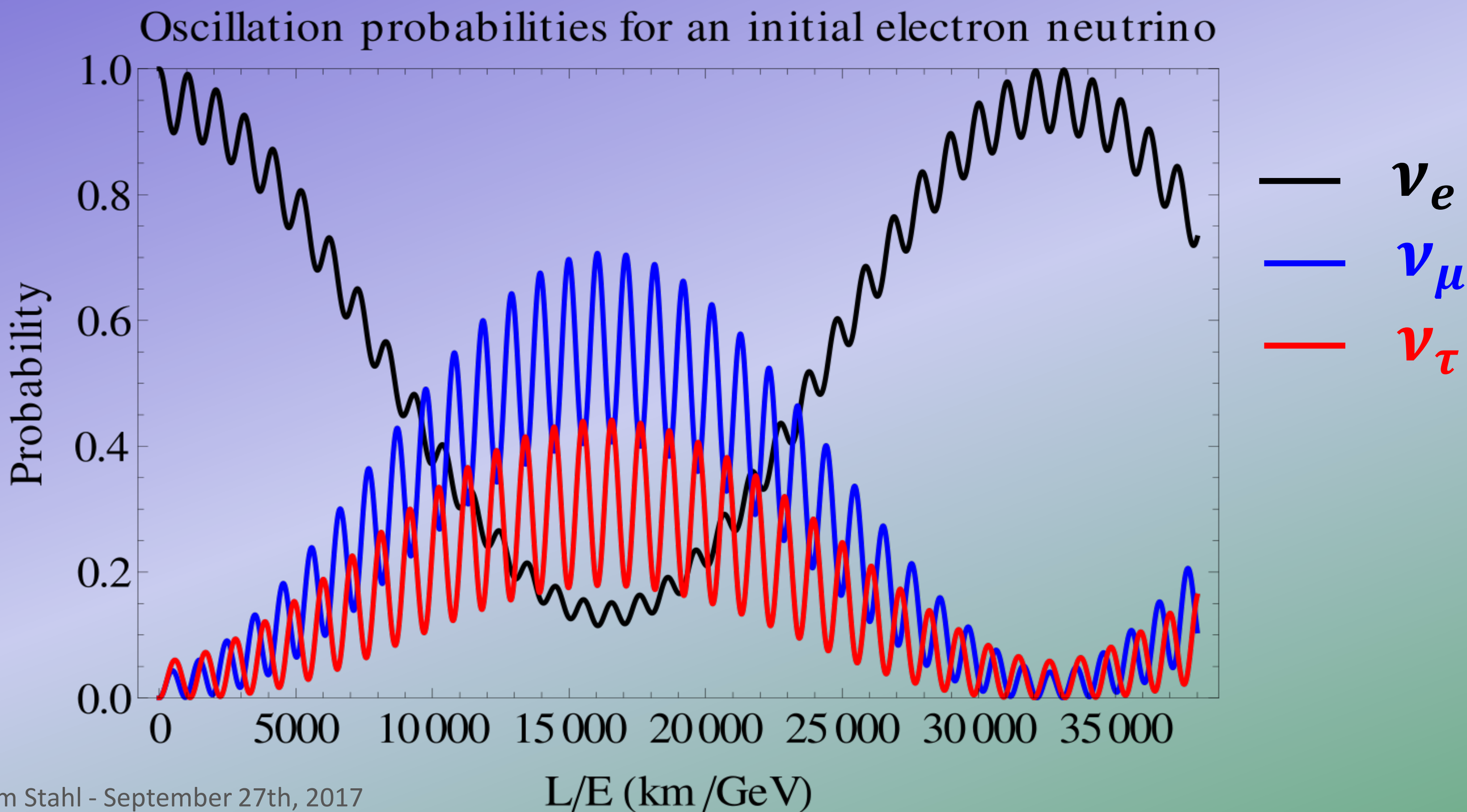
Appearance: $P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4\, E_\nu}$

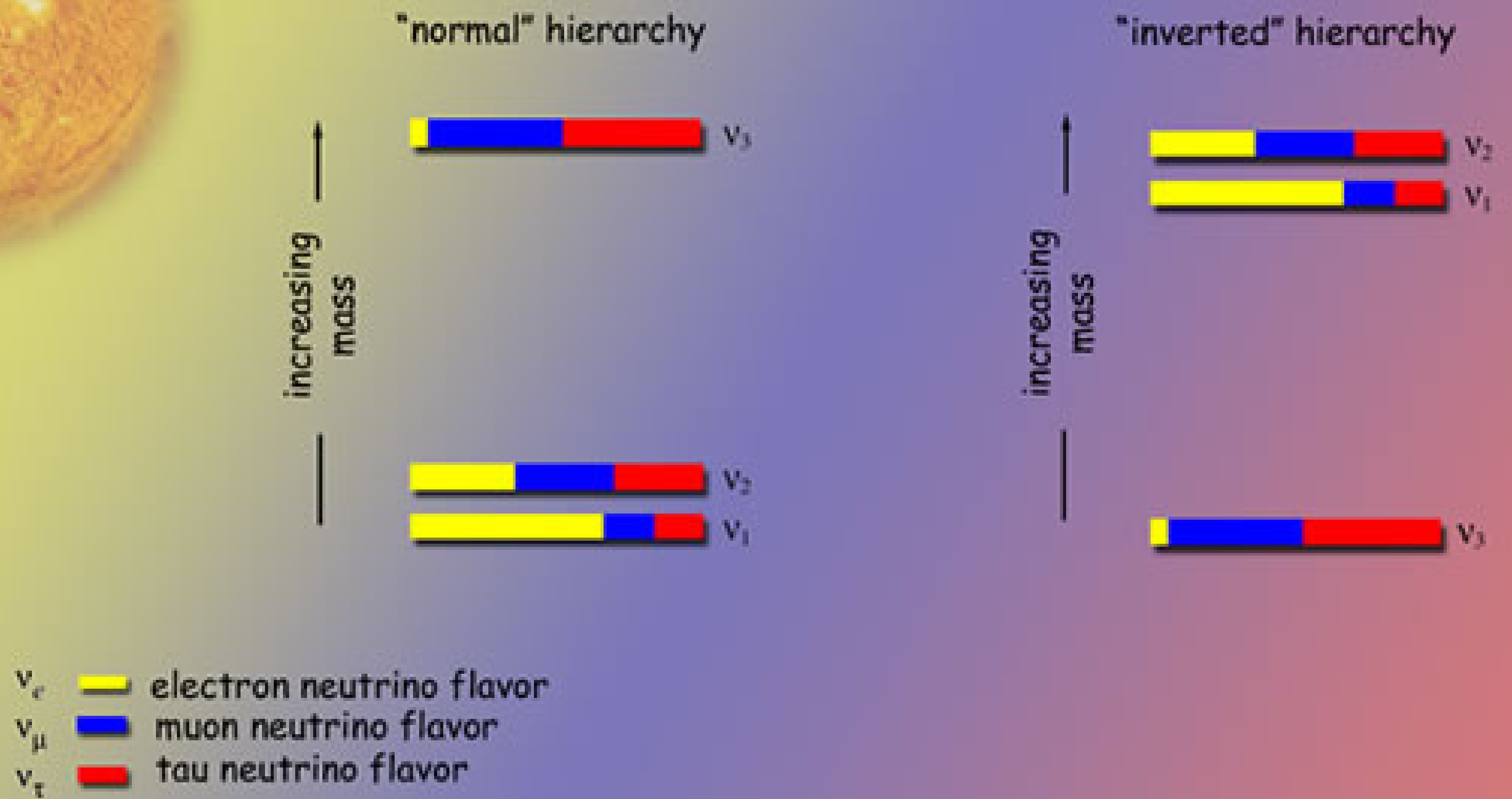
OSCILLATIONEN

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left(U_{\alpha i}^{*}U_{\beta i}U_{\alpha j}U_{\beta j}^{*}\right)\sin^2\frac{(m_i^2 - m_j^2)L}{4E}$$

$$+2\sum_{i>j} Im\left(U_{\alpha i}^{*}U_{\beta i}U_{\alpha j}U_{\beta j}^{*}\right)\sin\frac{(m_i^2 - m_j^2)L}{2E}$$

Oscillations require some $m_i \neq 0$





Normal or inverted hierarchy ? ➢ Osc.: reactor, atmos., beam

Only 3 generations ? ➢ Osc.: precision measurements

Majorana or Dirac neutrinos ? ➢ $2\beta0\nu$-experiments

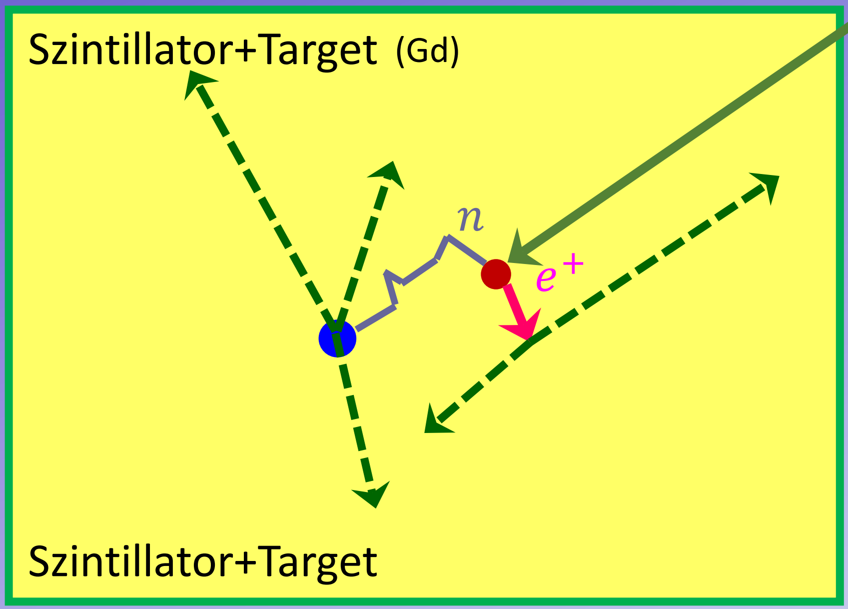
CP-violation ? ➢ Osc.: beam

Absolute mass scale ? ➢ KATRIN, but beyond ?

Reactor Neutrino Experiments

DETECTION

Reactor:
$n \rightarrow p^{+}\, e^{-}\, \bar{\nu}_e$



$\bar{\boldsymbol{\nu}}_{\boldsymbol{e}} + \boldsymbol{p} \rightarrow \boldsymbol{n} + \boldsymbol{e}^{+}$

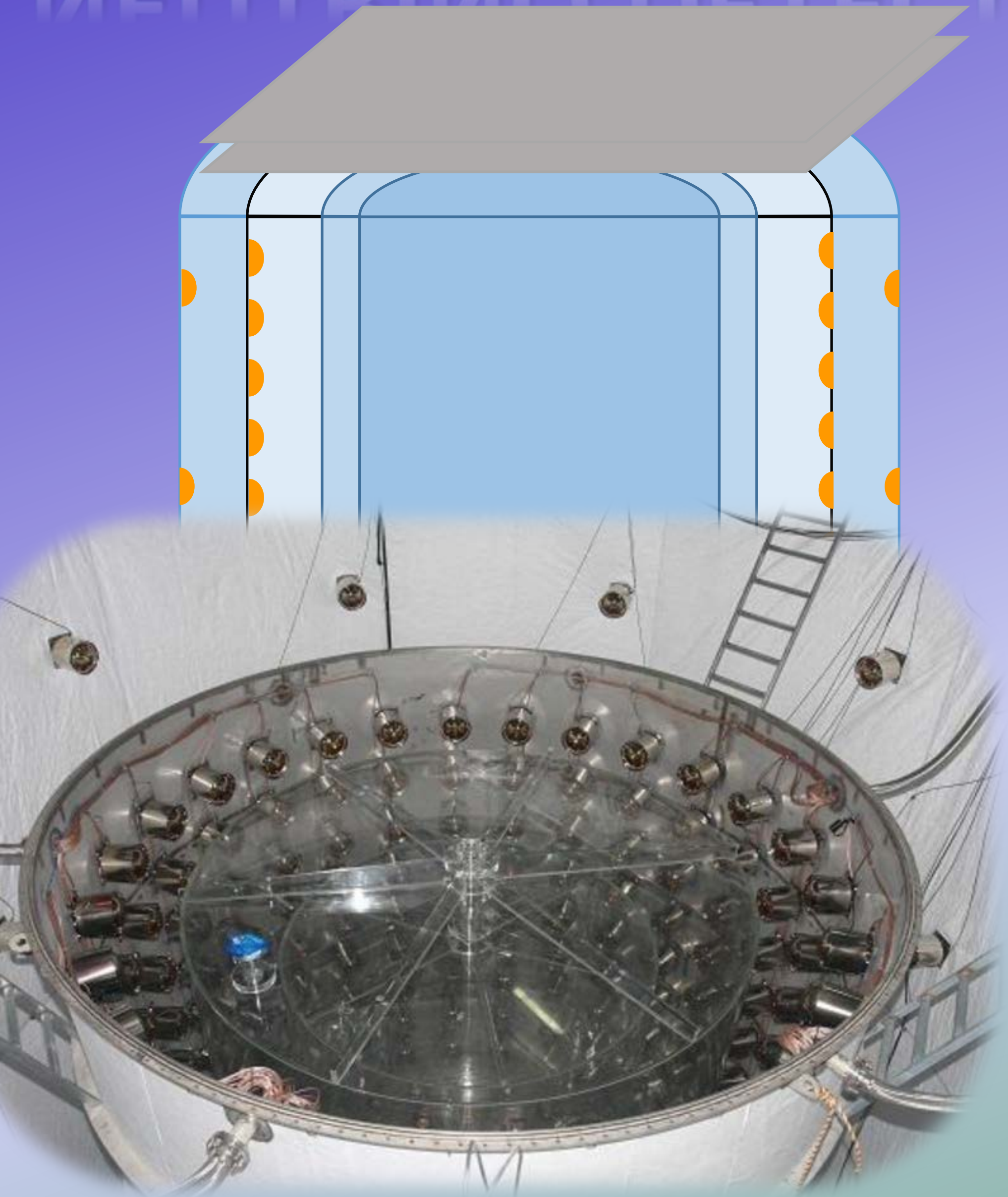
inverse β-decay (IBD)

1. prompt event: $\boldsymbol{e}^{+} \rightarrow \boldsymbol{\gamma\gamma}$
2. delayed event: $\boldsymbol{n}$ thermalization
   + capture on Gd

Energy Measurement:

1. **prompt event**
   scintillation from positron
   gammas from annihilation
   $E(\bar{\nu}_e) = E_{\text{prompt}} + Q - 2m_e$
2. **delayed event**
   Gd: 30 μsec delay, 8 MeV
   H: 200 μsec delay, 2.2 MeV

NEUTRINO DETECTOR



1. **Target:** Scintillator + 0.1 % Gd
2. **γ-catcher:** Scintillator
3. **Buffer:** Oil
4. **Veto:** Water or Scintillator
5. **Muon Tracker**

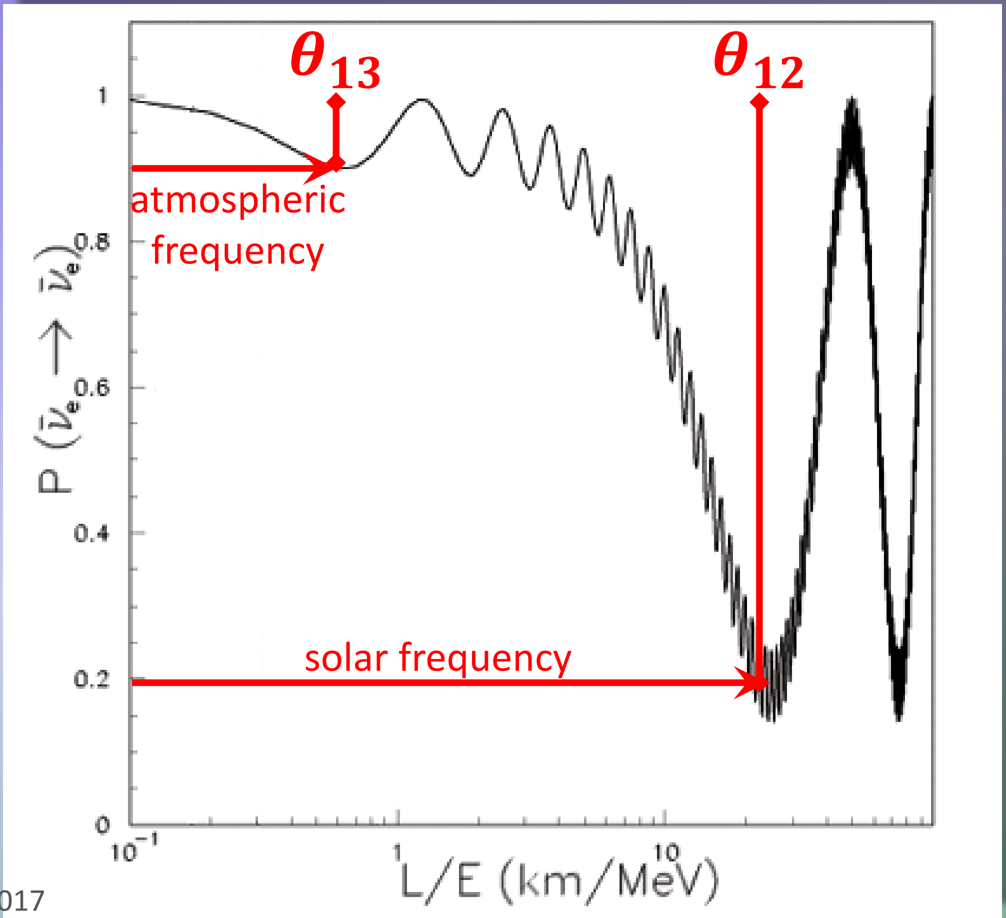
RENO far detector

OSCILLATION PATTERN

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin^2 \frac{(m_i^2 - m_j^2)L}{4E}$$

$$+2\sum_{i>j} Im\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin \frac{(m_i^2 - m_j^2)L}{2E}$$

Reactor Experiment
$\bar{\nu}_e$-disappearance

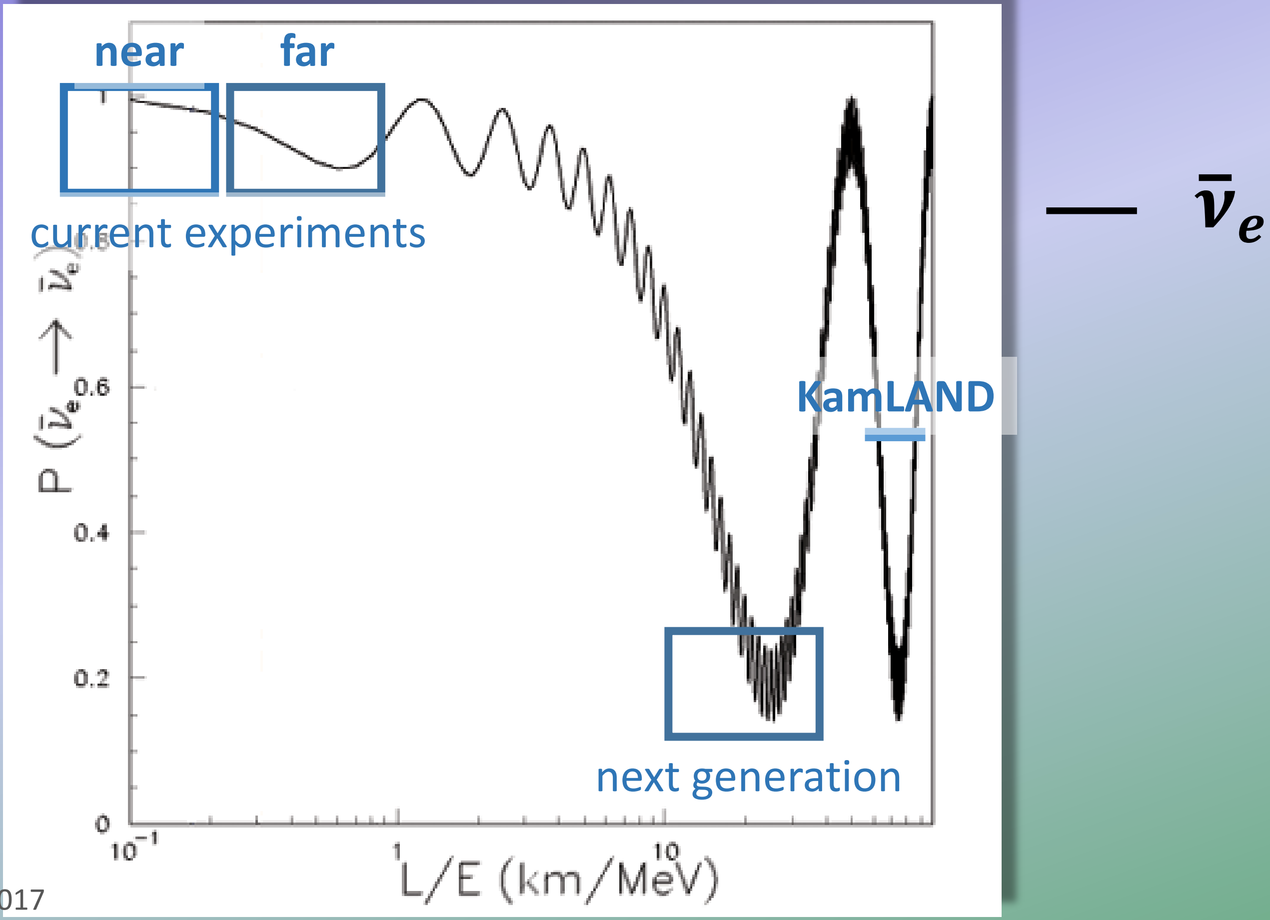


— $\bar{\nu}_e$

OSCILLATION PATTERN

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

Reactor Experiment
$\bar{\nu}_e$-disappearance



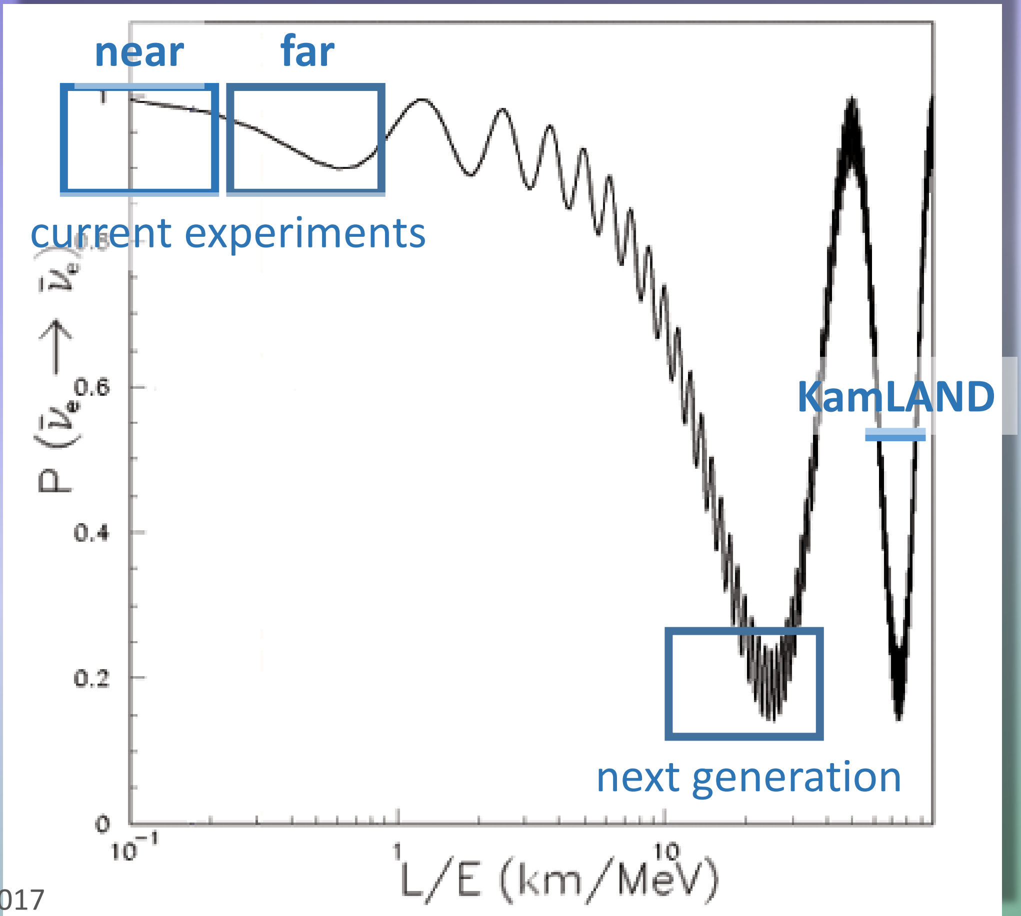
OSCILLATION PATTERN

leading terms:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{ee} L}{4E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

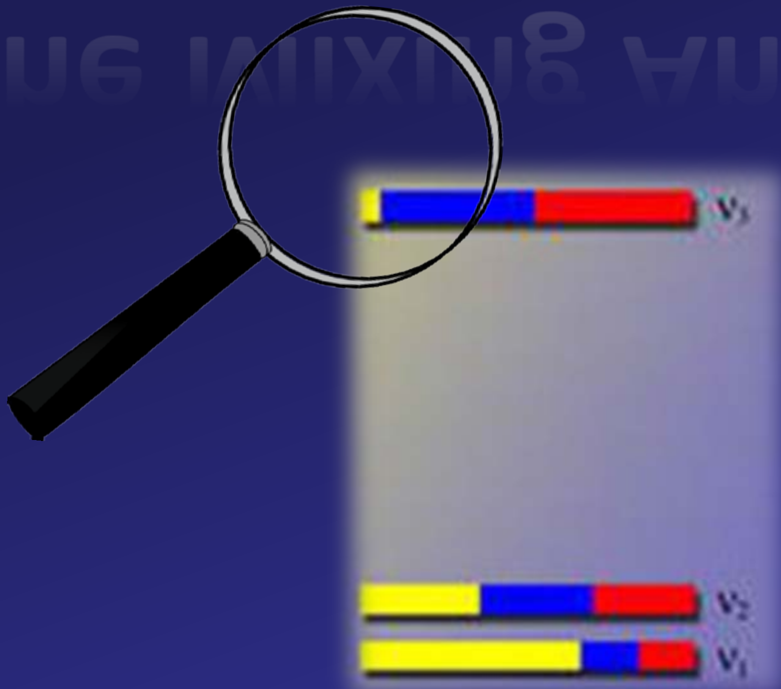
$$\sin^2 \frac{\Delta m^2_{ee} L}{4E} = \cos^2 \theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2 \theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E}, \quad \Delta m^2_{ij} = m^2_i - m^2_j$$

Reactor Experiment
$\bar{\nu}_e$-disappearance



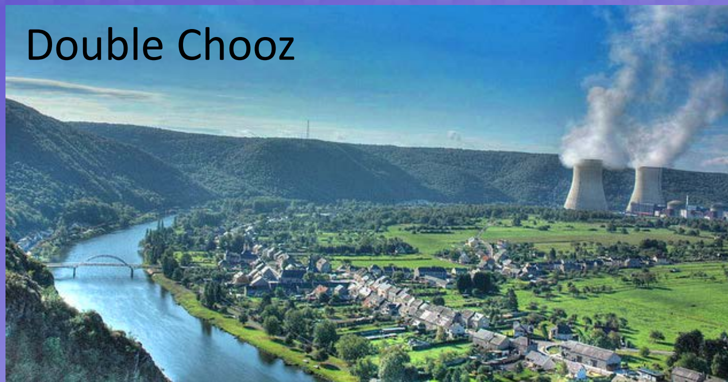
— $\bar{\nu}_e$

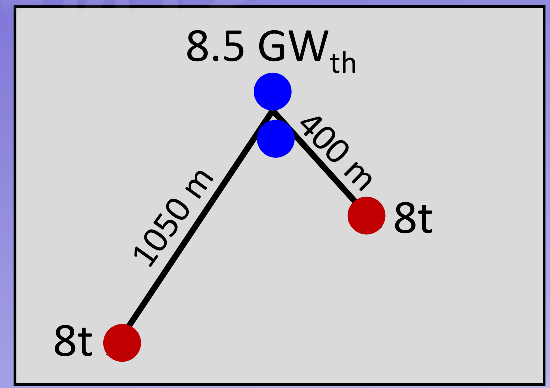
The Mixing Angle θ_{13}



THE 3 EXPERIMENTS

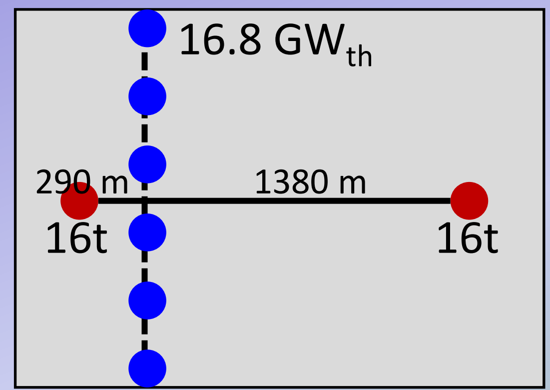
THE 3 EXPERIMENTS





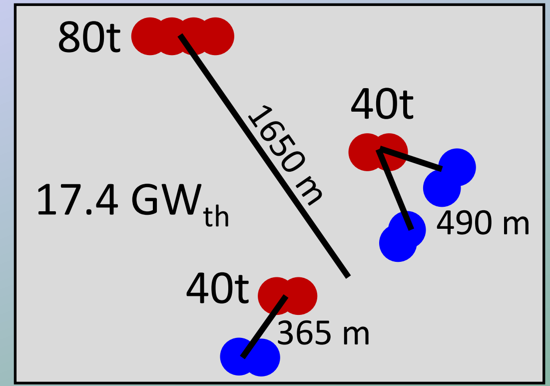
energy res. 6% (1 MeV)
overburden: 300m
statistics: 40 000 IBD

far detector



energy res. 7% (1 MeV)
overburden: 450m
statistics: 60 000 IBD

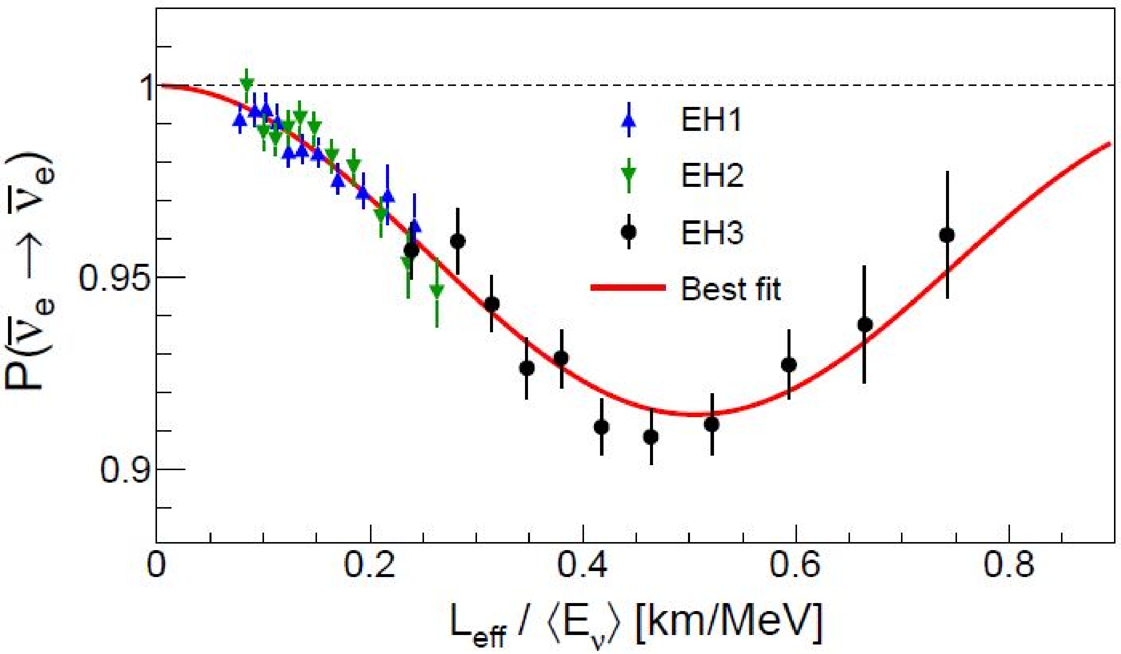
far detector



energy res. 8% (1 MeV)
overburden: 860m
statistics: 150 000 IBD

far detector

MEASURED SPECTRUM

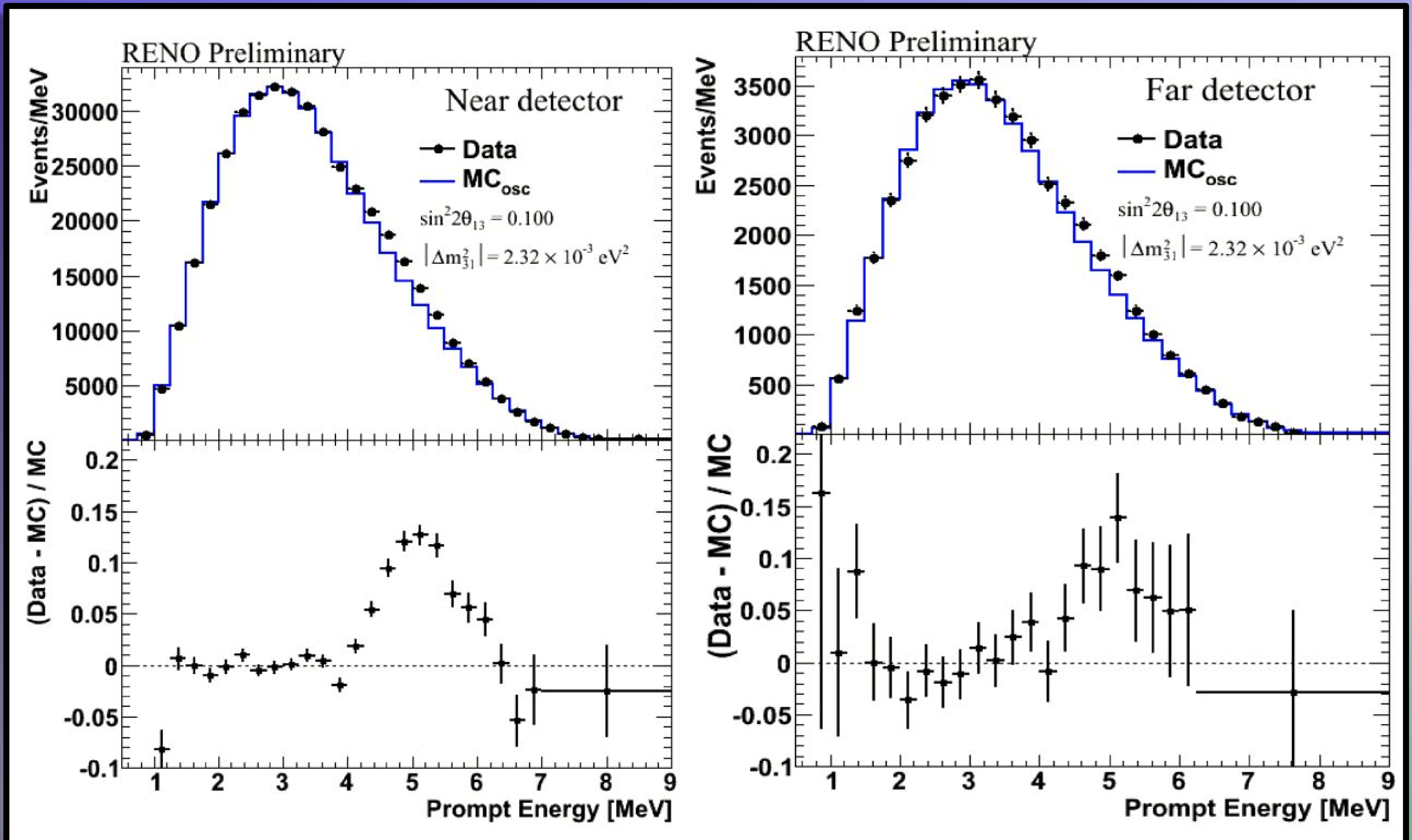


$\Longrightarrow \sin^2 2\theta_{13}$ from fit

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

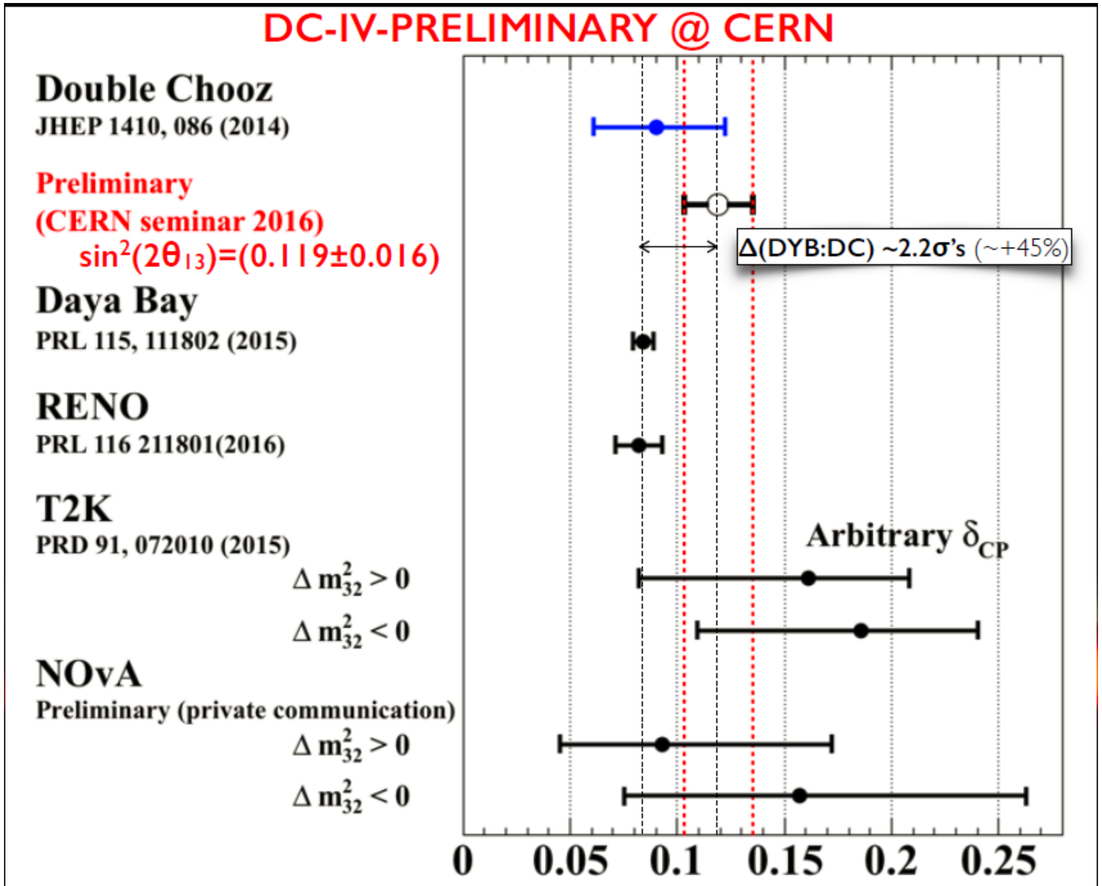
F.P. An et al.
arXiv 1505.03456
May, 2015

THE 5 MeV EXCESS



S.-H. Seo (for the RENO) collab.; arXiv 1410.7987

WORLD COMPARISON



(Many thanks to NOvA: latest reference)

$$\sin^2 2\theta_{13} = 0.119 \pm 0.016$$

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$\sin^2 2\theta_{13} = 0.086 \pm 0.008$$

$$\theta_{13} = 8.4^\circ \pm 0.3^\circ$$

CP-Violation

Matter = Anti-Matter?

CP-VIOLATION

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\frac{(m_i^2-m_j^2)L}{4E}$$
$$+2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\frac{(m_i^2-m_j^2)L}{2E}$$

Example: Neutrino Beams

Numerically relevant terms only

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) =$$

$$4\cdot s_{13}^2\cdot c_{13}^2\cdot s_{23}^2\cdot\sin^2\frac{\Delta m_{13}^2 L}{4E}$$ θ_{13}

$$+8\cdot c_{13}^2\cdot s_{12}s_{13}s_{23}\cdot(c_{12}c_{23}\cdot\cos\delta - s_{12}s_{13}s_{23})\cdot\cos\frac{\Delta m_{23}^2 L}{4E}\cdot\sin\frac{\Delta m_{13}^2 L}{4E}\cdot\sin\frac{\Delta m_{12}^2 L}{4E}$$ CP-even

$$\pm 8\cdot c_{13}^2\cdot c_{12}c_{23}s_{12}s_{13}s_{23}\cdot\sin\delta\cdot\sin\frac{\Delta m_{23}^2 L}{4E}\cdot\sin\frac{\Delta m_{13}^2 L}{4E}\cdot\sin\frac{\Delta m_{12}^2 L}{4E}$$ CP-odd

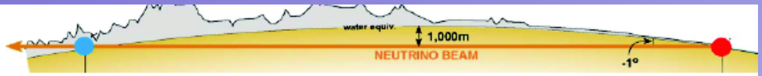
$$+4\cdot s_{12}^2\cdot c_{13}^2\cdot(c_{12}^2c_{23}^2 + s_{12}^2s_{23}^2s_{13}^2 - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta)\cdot\sin\frac{\Delta m_{12}^2 L}{4E}$$ solare Skala

$$\pm 8\cdot c_{13}^2\cdot s_{13}^2\cdot s_{23}^2\cdot\cos\frac{\Delta m_{23}^2 L}{4E}\cdot\sin\frac{\Delta m_{13}^2 L}{4E}\cdot\frac{a\cdot L}{4E}\cdot(1-2s_{13}^2)$$ Materie-Effekt (CP-odd)

Jarlskog's Determinant for neutrinos: $0.28\sin\delta$ (quarks: $4\cdot 10^{-5}$)

CP-VIOLATION

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$



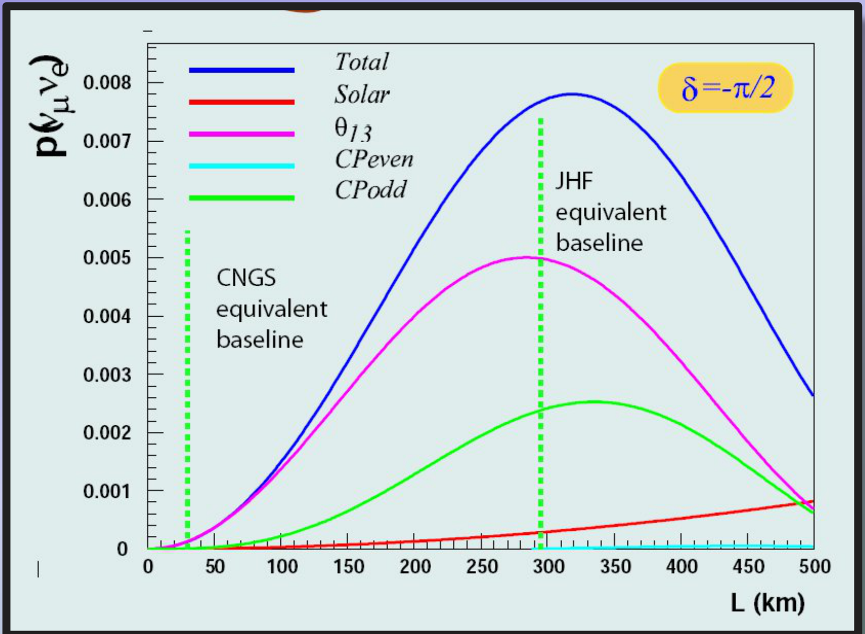
$$4 \cdot s_{13}^2 \, c_{13}^2 \cdot s_{23}^2 \cdot \sin^2 \frac{\Delta m_{13}^2 L}{4E}$$ θ_{13}

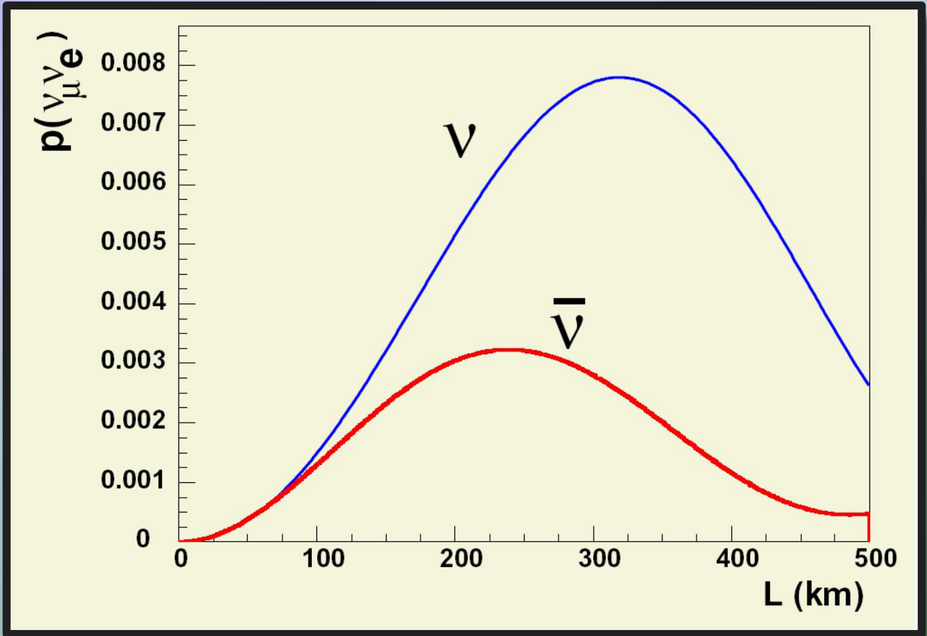
$$+\, 8 \cdot c_{13}^2 \cdot s_{12} s_{13} s_{23} \cdot (c_{12} c_{23} \cdot \cos\delta - s_{12} s_{13} s_{23}) \cdot \cos\frac{\Delta m_{23}^2 L}{4E} \cdot \sin\frac{\Delta m_{13}^2 L}{4E} \cdot \sin\frac{\Delta m_{12}^2 L}{4E}$$ CP-even

$$\pm\, 8 \cdot c_{13}^2 \cdot c_{12} c_{23} s_{12} s_{13} s_{23} \cdot \sin\delta \cdot \sin\frac{\Delta m_{23}^2 L}{4E} \cdot \sin\frac{\Delta m_{13}^2 L}{4E} \cdot \sin\frac{\Delta m_{12}^2 L}{4E}$$ CP-odd

$$+\, 4 \cdot s_{12}^2 \, c_{13}^2 \cdot (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{13} s_{23} \cos\delta) \cdot \sin\frac{\Delta m_{12}^2 L}{4E}$$ solare Skala

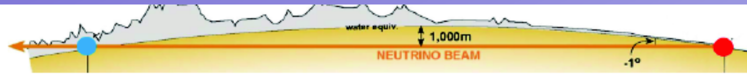
$$\pm\, 8 \cdot c_{13}^2 \cdot s_{13}^2 \cdot s_{23}^2 \cdot \cos\frac{\Delta m_{23}^2 L}{4E} \cdot \sin\frac{\Delta m_{13}^2 L}{4E} \cdot \frac{a \cdot L}{4E} (1 - 2 s_{13}^2)$$ Materie-Effekt (CP-odd)





CP-VIOLATION

$P(\bar{\nu}_\mu \to \bar{\nu}_e) =$



$$4 \cdot \boxed{s_{13}^2} \cdot c_{13}^2 \cdot s_{23}^2 \cdot \sin^2 \frac{\Delta m_{13}^2 L}{4E}$$ θ_{13}

$$+ 8 \cdot c_{13}^2 \cdot s_{12} s_{13} s_{23} \cdot (c_{12} c_{23} \cdot \boxed{\cos\delta} - s_{12} s_{13} s_{23}) \cdot \cos \frac{\Delta m_{23}^2 L}{4E} \cdot \sin \frac{\Delta m_{13}^2 L}{4E} \cdot \sin \frac{\Delta m_{12}^2 L}{4E}$$ CP-even

$$\pm 8 \cdot c_{13}^2 \cdot c_{12} c_{23} s_{12} s_{13} s_{23} \cdot \boxed{\sin\delta} \cdot \sin \frac{\Delta m_{23}^2 L}{4E} \cdot \sin \frac{\Delta m_{13}^2 L}{4E} \cdot \sin \frac{\Delta m_{12}^2 L}{4E}$$ CP-odd

$$+ 4 \cdot \boxed{s_{12}^2} \cdot c_{13}^2 \cdot (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{13} s_{23} \cos\delta) \cdot \sin \frac{\Delta m_{12}^2 L}{4E}$$ solare Skala

$$\pm 8 \cdot c_{13}^2 \cdot s_{13}^2 \cdot s_{23}^2 \cdot \cos \frac{\Delta m_{23}^2 L}{4E} \cdot \sin \frac{\Delta m_{13}^2 L}{4E} \cdot \boxed{\frac{a \cdot L}{4E}} \cdot (1 - 2 s_{13}^2)$$ Materie-Effekt (CP-odd)

CP-VIOLATION: INDIRECT

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) =$ reactor

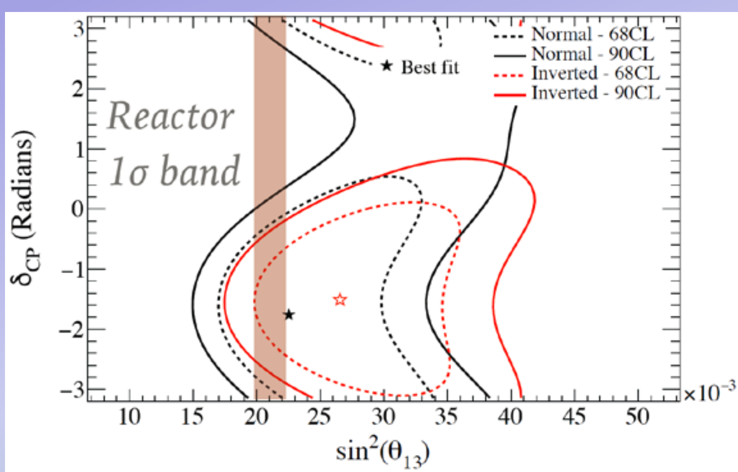
$$4 \cdot s_{13}^2 \, c_{13}^2 \cdot s_{23}^2 \cdot \sin^2 \frac{\Delta m_{13}^2 L}{4E}$$ θ_{13}

$$+ 8 \cdot c_{13}^2 \cdot s_{12} s_{13} s_{23} \cdot (c_{12} c_{23} \cdot \cos\delta - s_{12} s_{13} s_{23}) \cdot \cos\frac{\Delta m_{23}^2 L}{4E} \cdot \sin\frac{\Delta m_{13}^2 L}{4E} \cdot \sin\frac{\Delta m_{12}^2 L}{4E}$$ CP-even

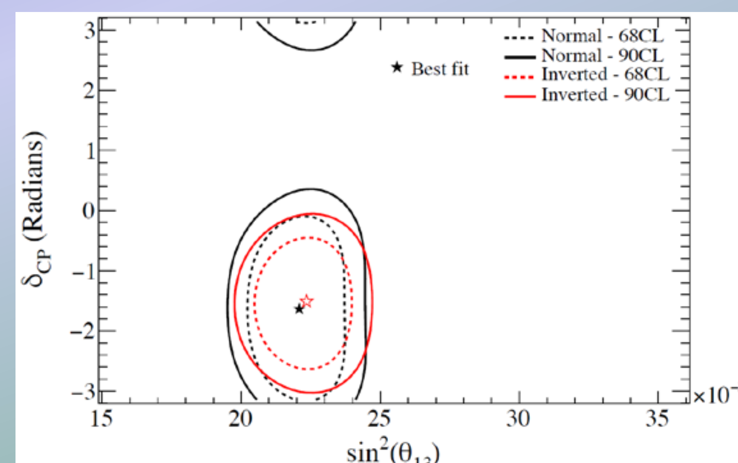
$$\pm 8 \cdot c_{13}^2 \cdot c_{12} c_{23} s_{12} s_{13} s_{23} \cdot \sin\delta \cdot \sin\frac{\Delta m_{23}^2 L}{4E} \cdot \sin\frac{\Delta m_{13}^2 L}{4E} \cdot \sin\frac{\Delta m_{12}^2 L}{4E}$$ CP-odd

$$+ 4 \cdot s_{12}^2 \cdot c_{13}^2 \cdot (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{13} s_{23} \cos\delta) \cdot \sin\frac{\Delta m_{12}^2 L}{4E}$$ solare Skala

$$\pm 8 \cdot c_{13}^2 \cdot s_{13}^2 \cdot s_{23}^2 \cdot \cos\frac{\Delta m_{23}^2 L}{4E} \cdot \sin\frac{\Delta m_{13}^2 L}{4E} \cdot \frac{a \cdot L}{4E} (1 - 2 s_{13}^2)$$ Materie-Effekt (CP-odd)



T2K (run 1-8)



T2K + reactor exp.

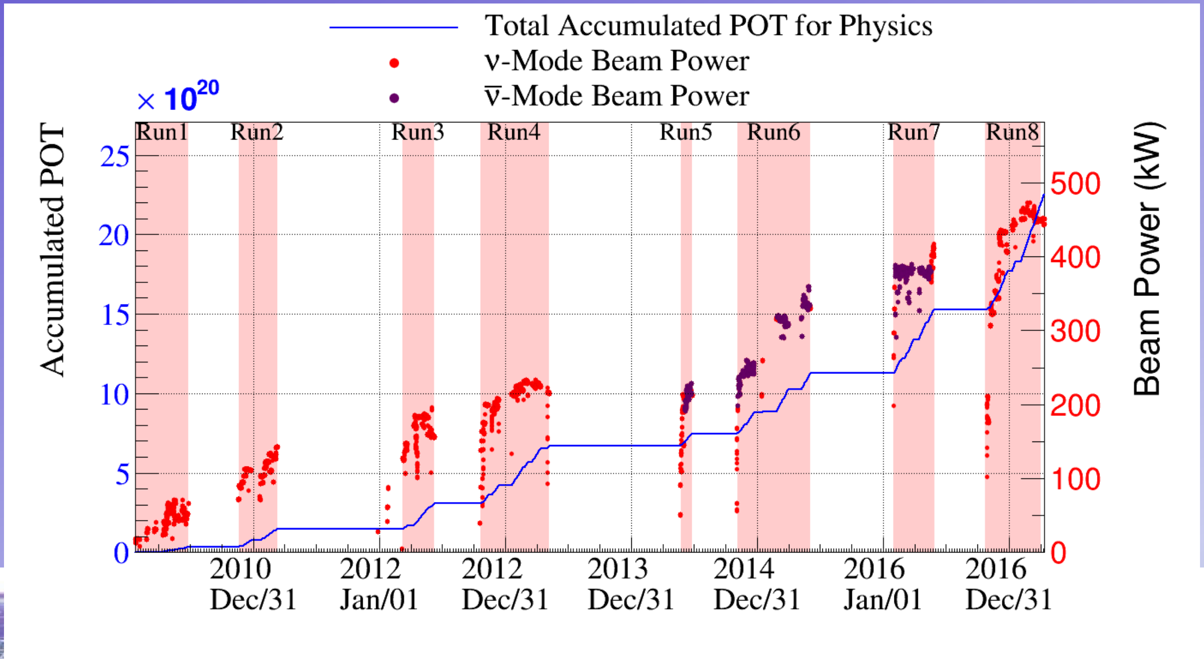
Run 1-7:

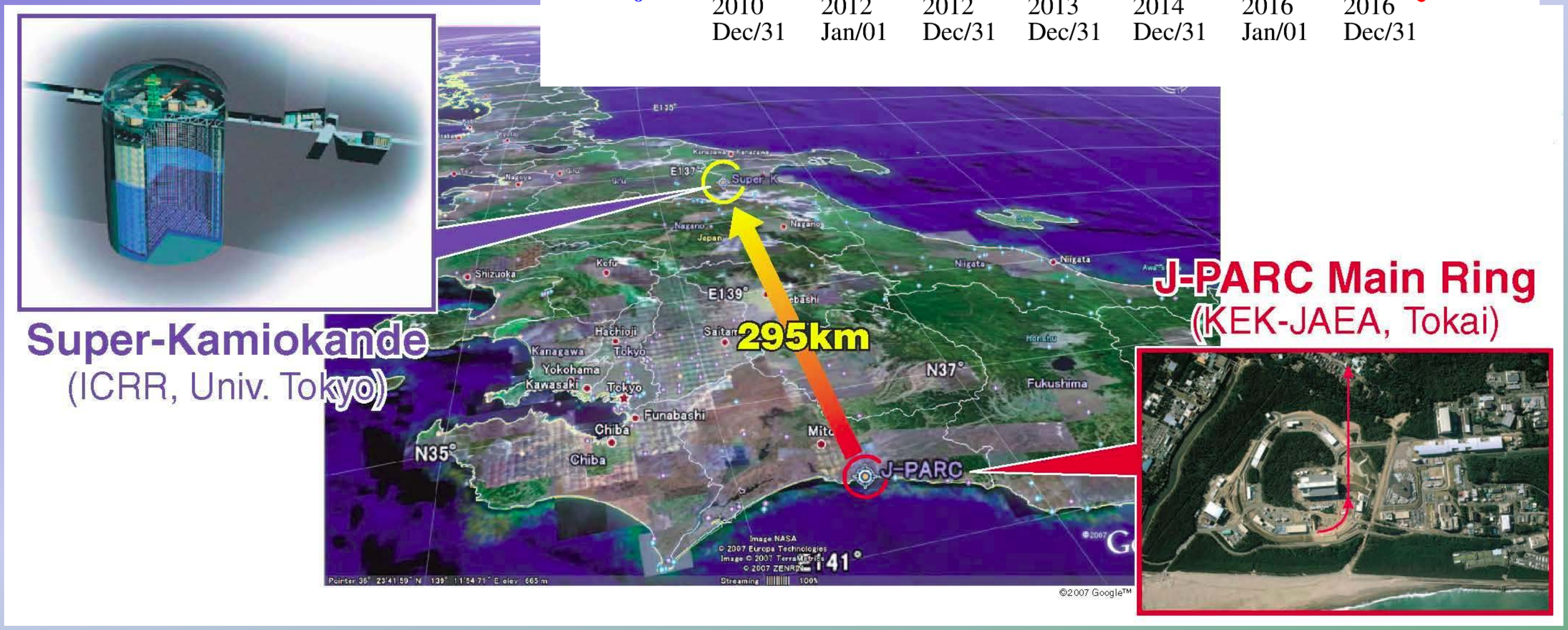
ν: $7.48 \times 10^{20}\ pot$

$\bar{\nu}$: $7.53 \times 10^{20} pot$

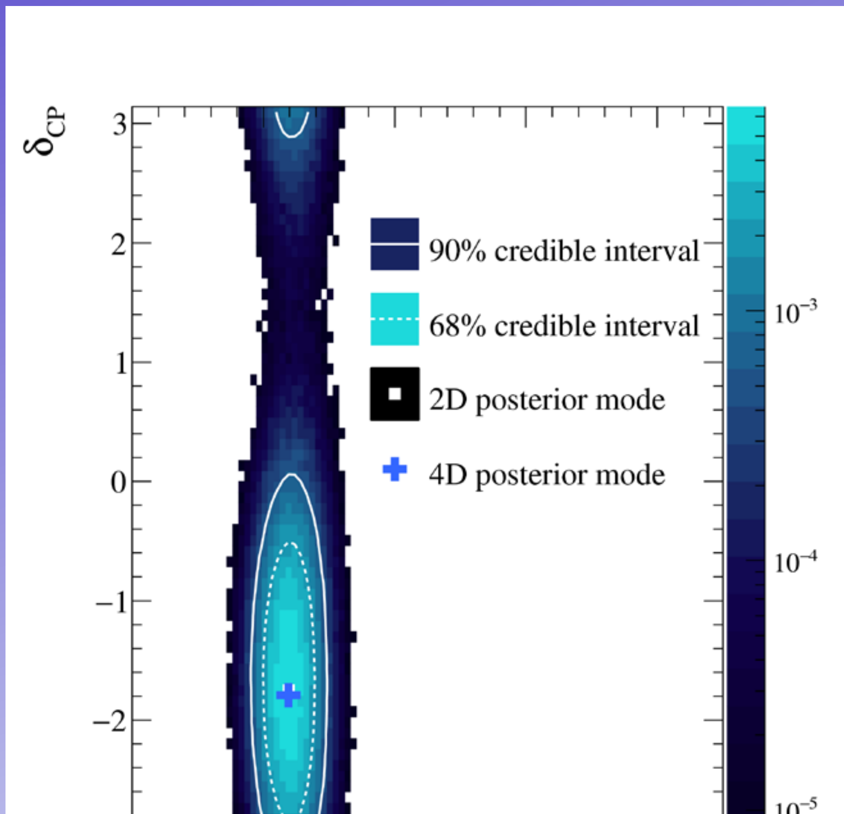
Run 8:

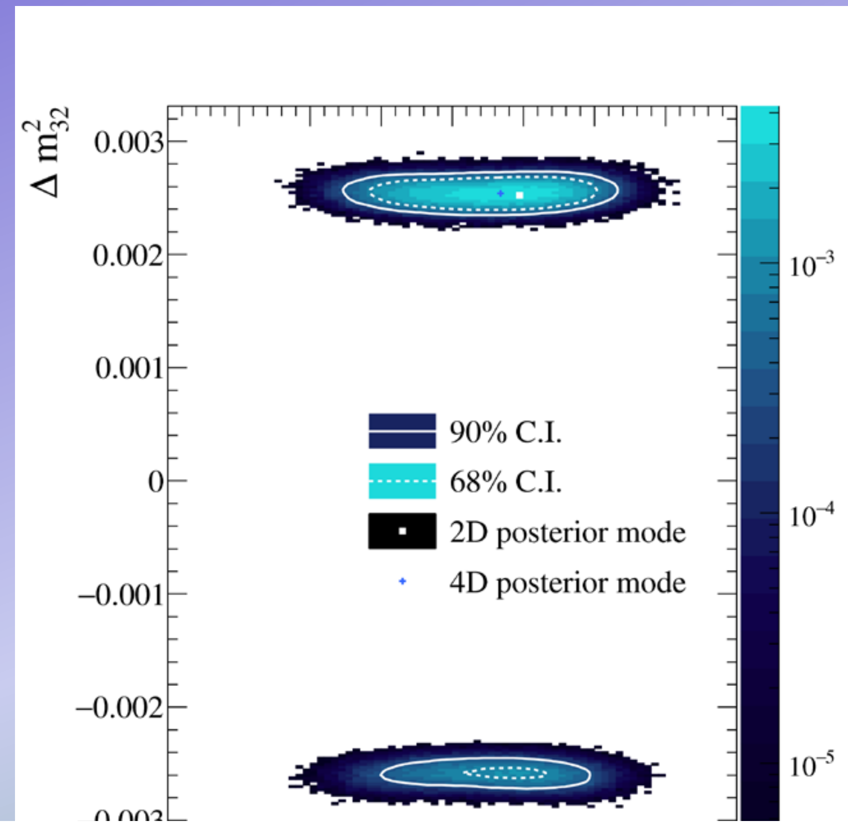
ν: $7.48 \times 10^{20} pot$





T2K-RESULTS

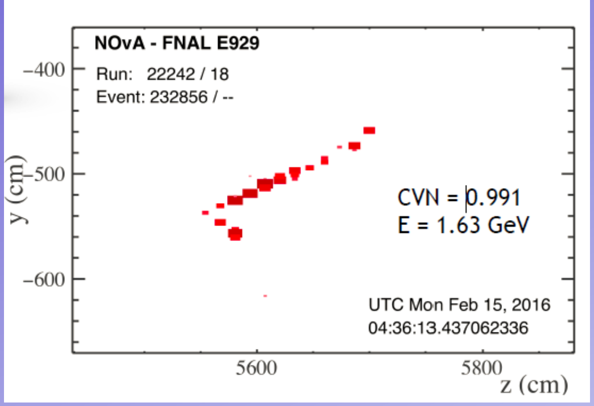


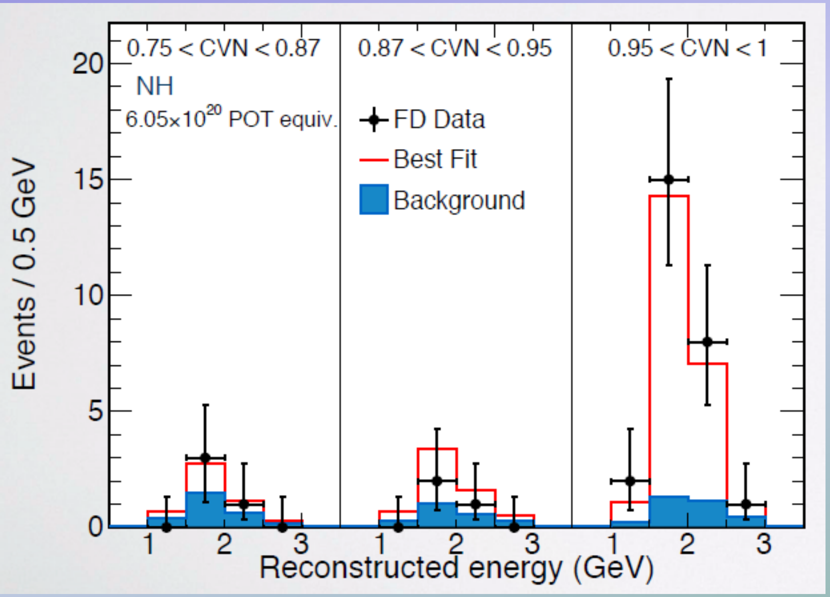


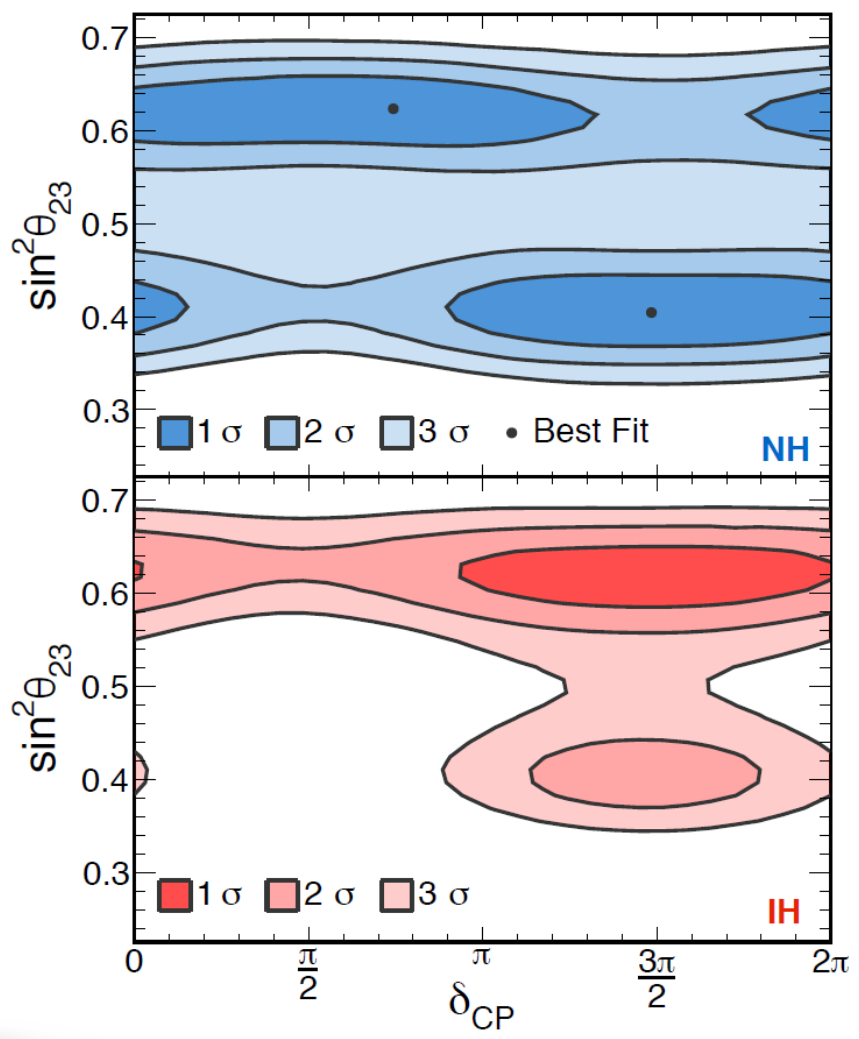
No CP-violation „excluded“ at 90% c.l.

Parameter	Best-fit	$\pm 1\sigma$
δ_{CP}	-1.789	[-2.450; -0.880]
$\sin^2\theta_{13}$	0.0219	[0.0208; 0.0233]
$\sin^2\theta_{23}$	0.534	[0.490 ; 0.580]
Δm^2_{32}	$2.539 \times 10^{-3}\ \mathrm{eV}^2/c^4$	[-3.000; -2.952] $\times 10^{-3} eV^2/c^4$ [2.424; 2.664]$\times 10^{-3} eV^2/c^4$

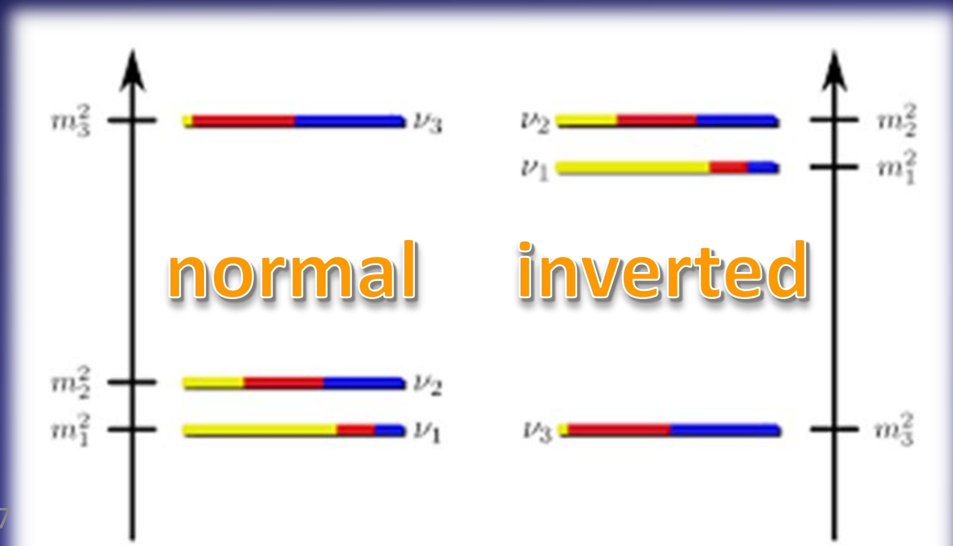
NOVA-APPEARANCE



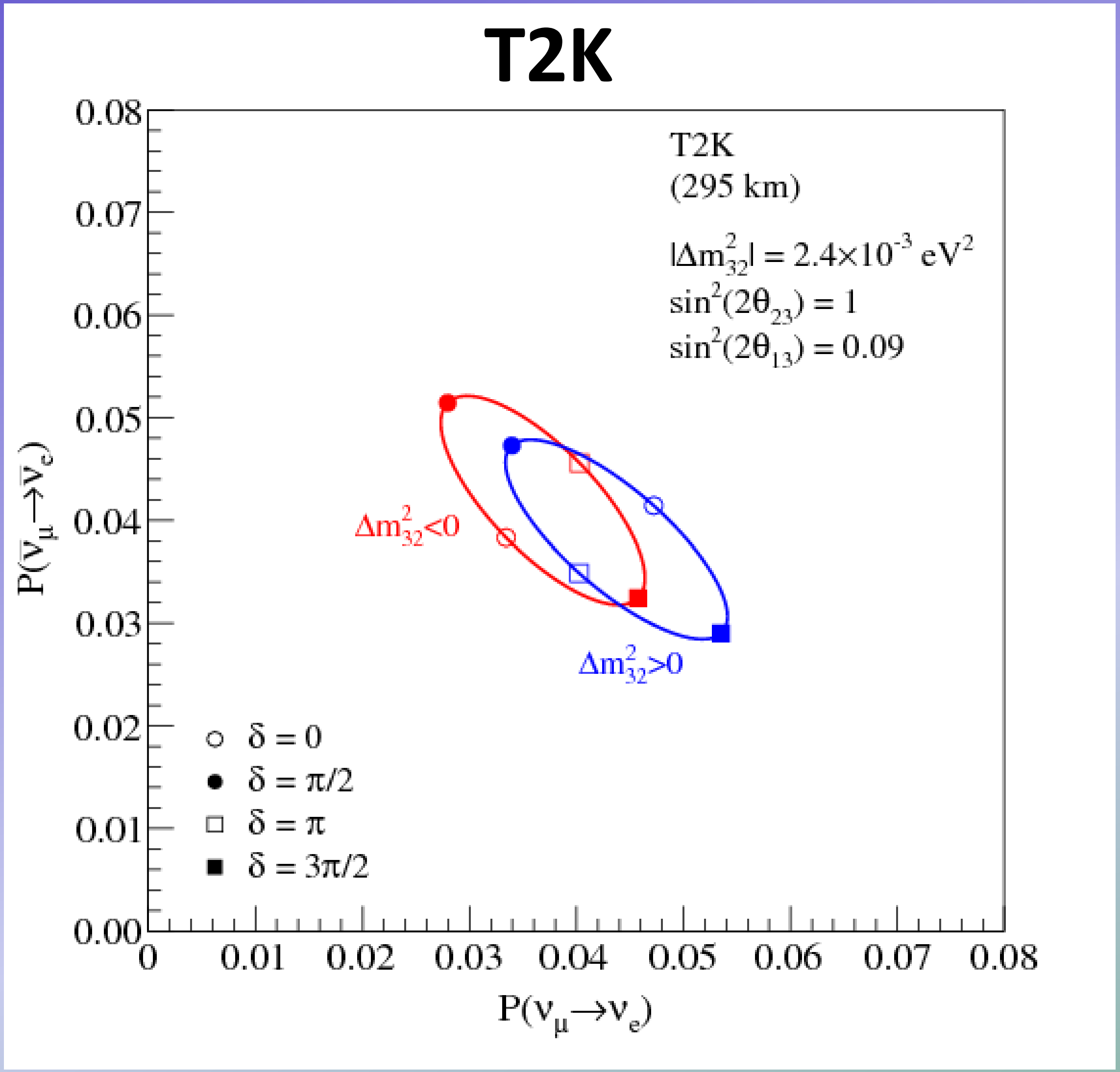




The Mass Hierarchy



MASS HIERARCHY AND CP

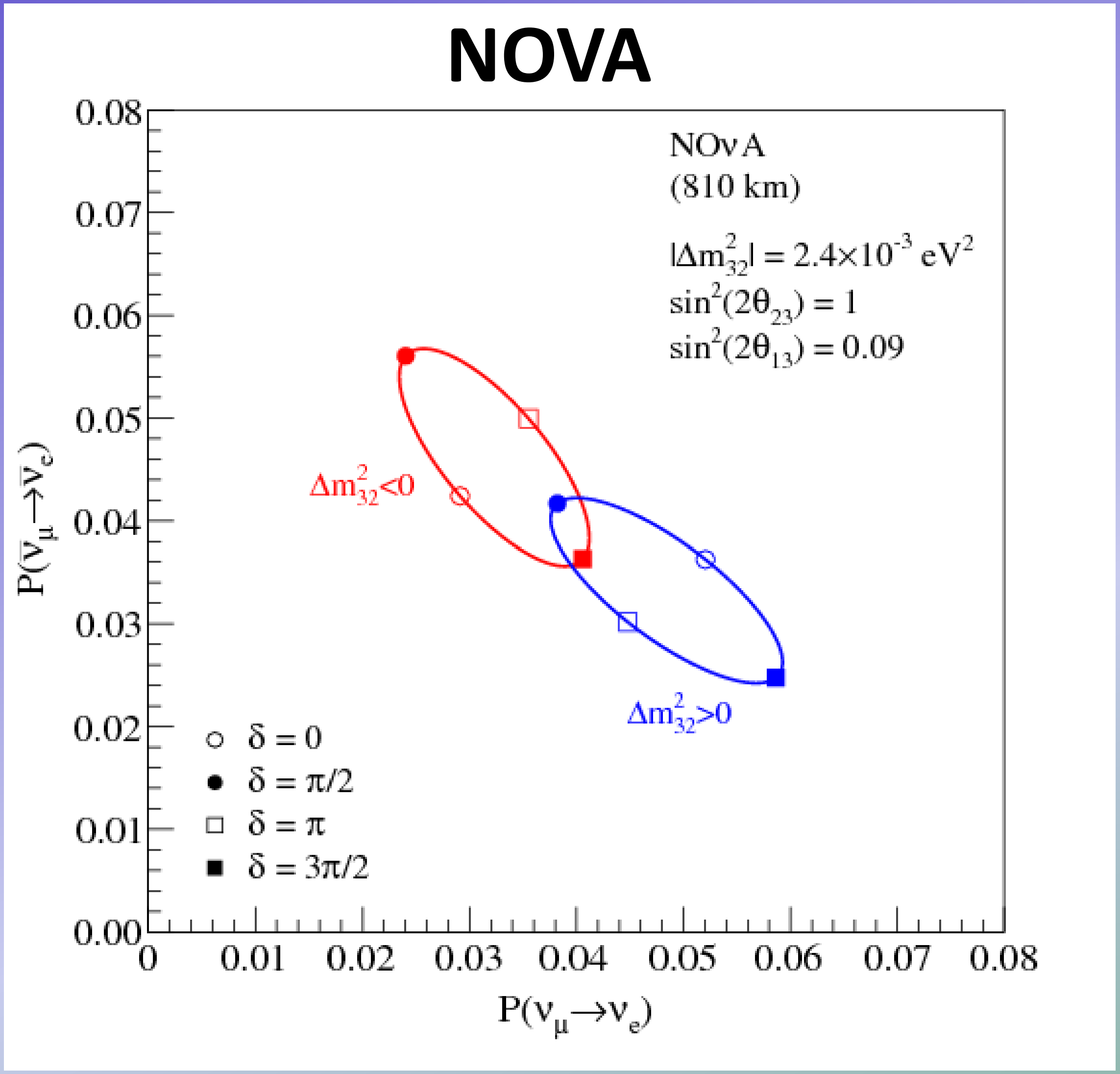


arXiv:1506.07917

„theorist's plot"

- No experimental uncertainties
- No uncertainties of external parameters

MASS HIERARCHY AND CP

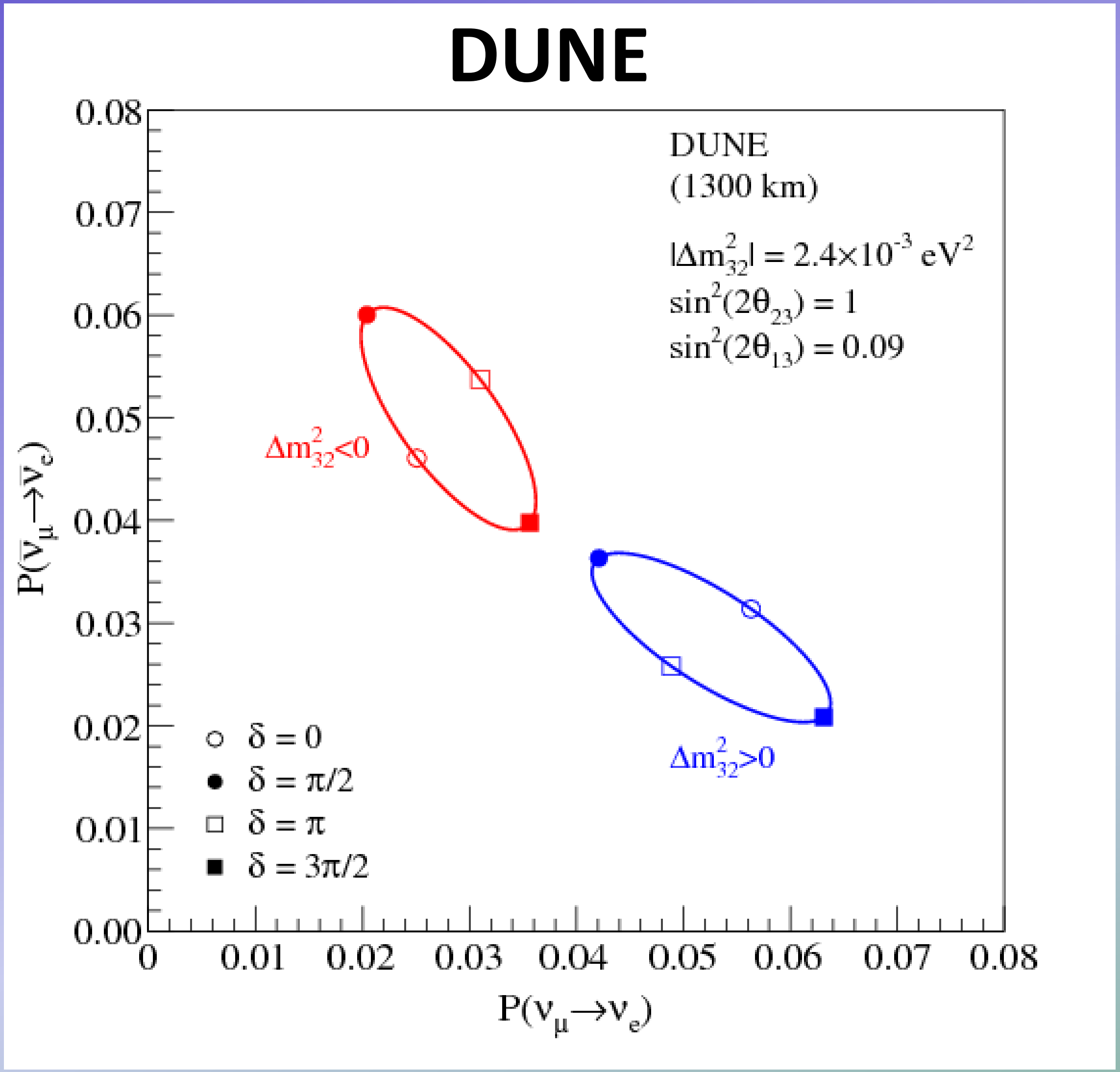


arXiv:1506.07917

„theorist‘s plot“

- No experimental uncertainties
- No uncertainties of external parameters

MASS HIERARCHY AND CP



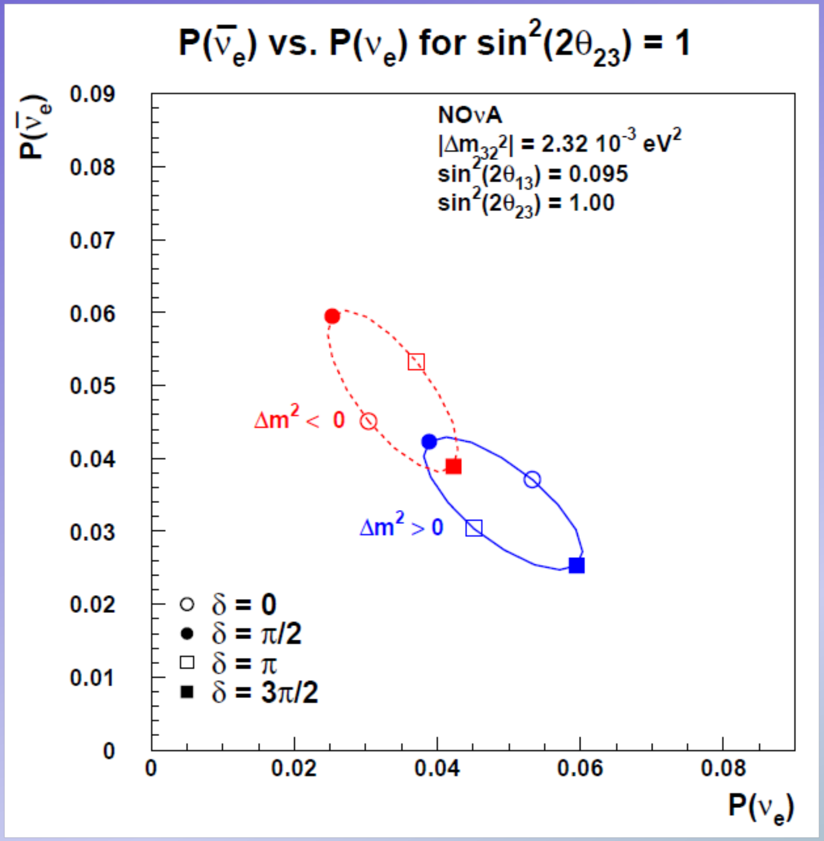
arXiv:1506.07917

„theorist's plot"

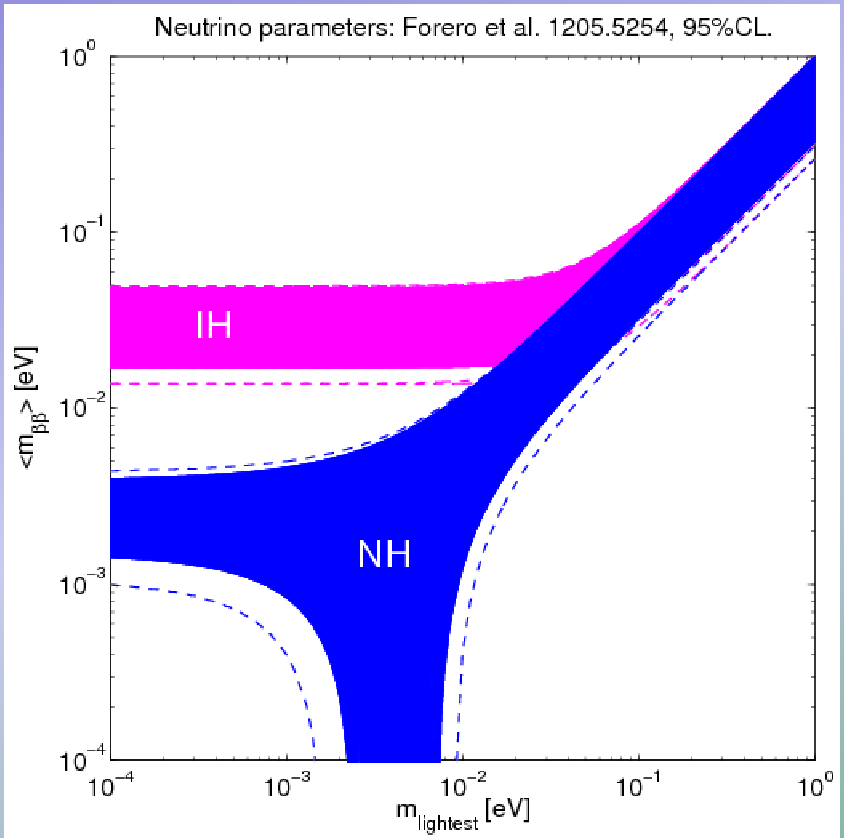
- No experimental uncertainties
- No uncertainties of external parameters

Impact of the Mass Hierarchy

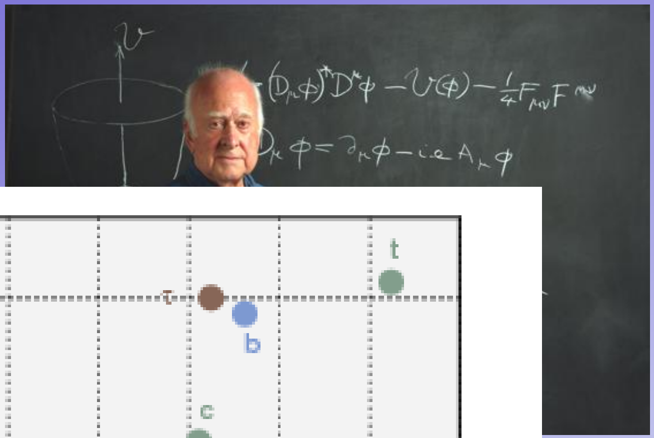
CP Violation



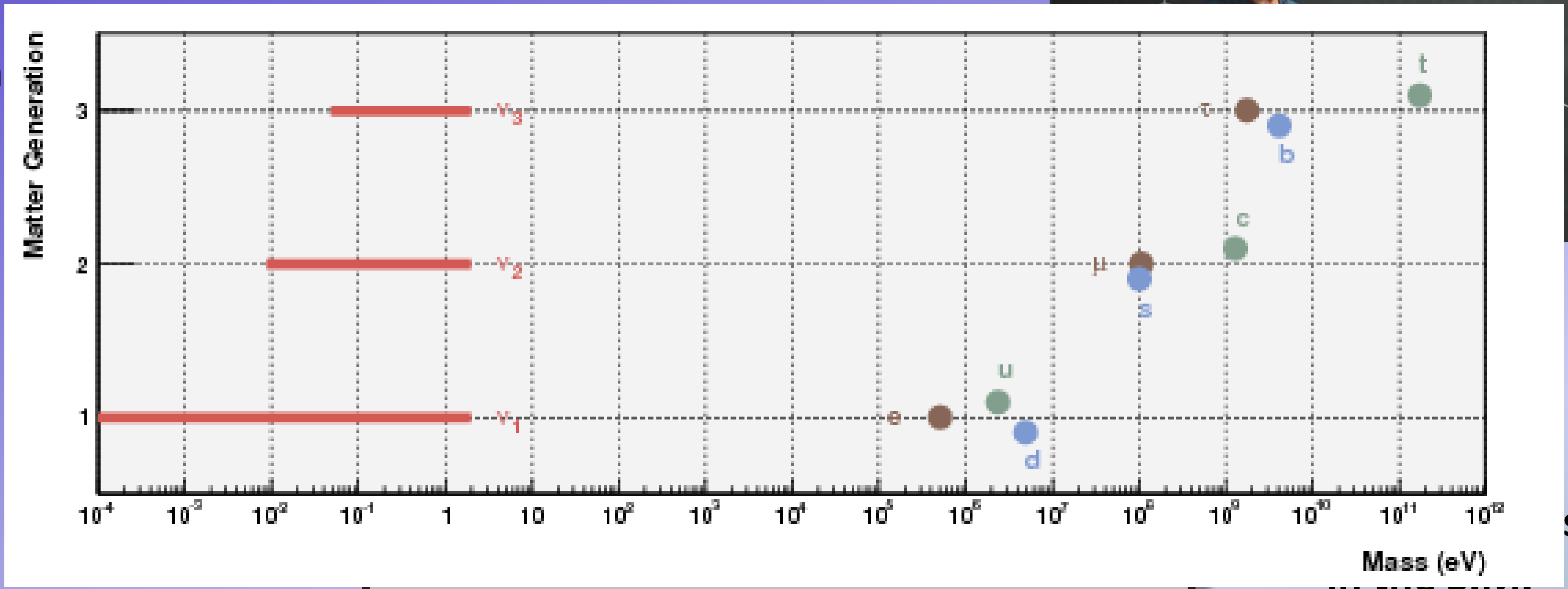
Majorana Neutrinos



Neutrino Masses



Ch



st

$\langle \overline{\Psi_{L_\nu}} | 1 | \Psi_{R_\nu} \rangle$

$= \langle \overline{(1-\gamma_5)\Psi_\nu} | 1 | ($

$= \langle \bar{\Psi}_\nu (1+\gamma_5) | (1$

$= \langle \bar{\Psi}_\nu | (1+\gamma_5)(1$

$= \langle \bar{\Psi}_\nu | 1 | (1+\gamma_5)\Psi_\nu \rangle$

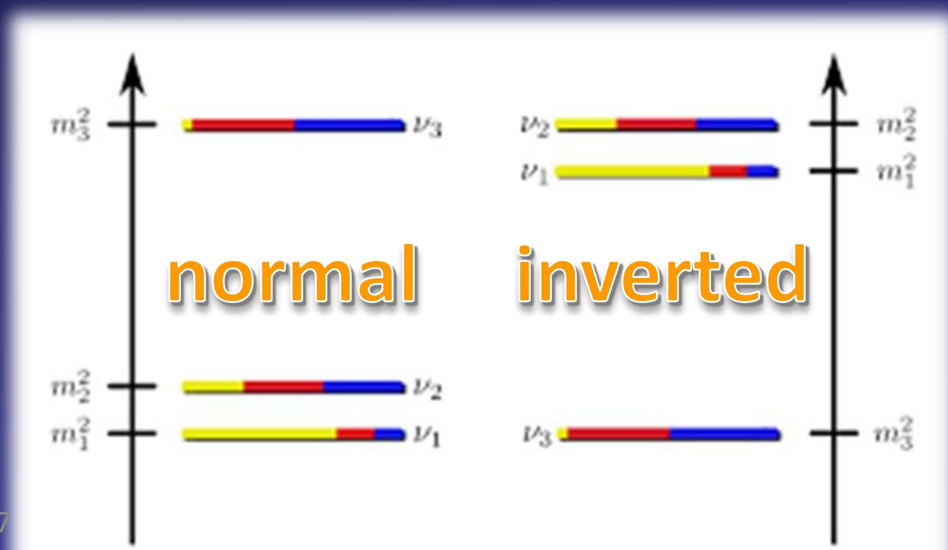
Is there something on top of the Higgs Mechanism?

Do they have the same hierarchy as the other ferminons?

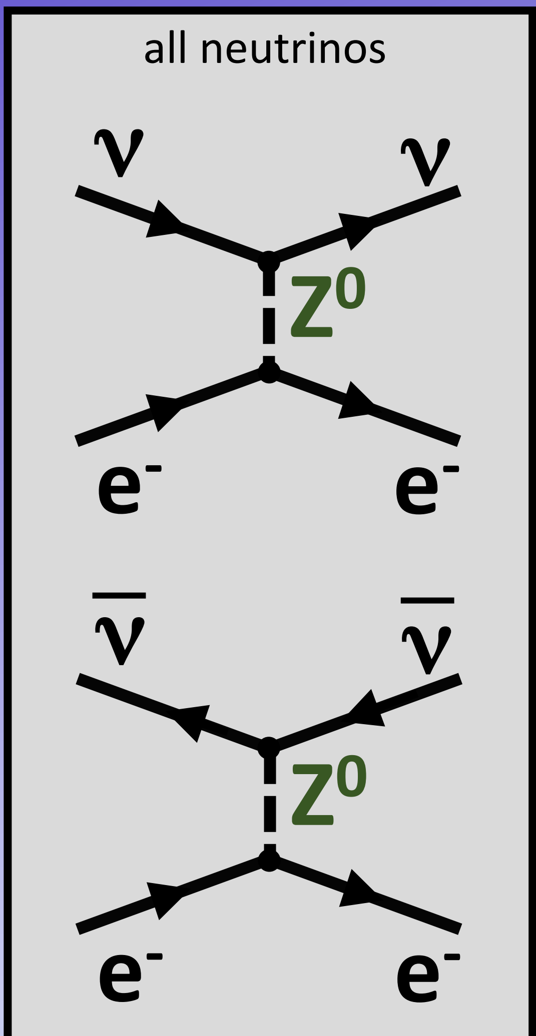
It's a sterile component

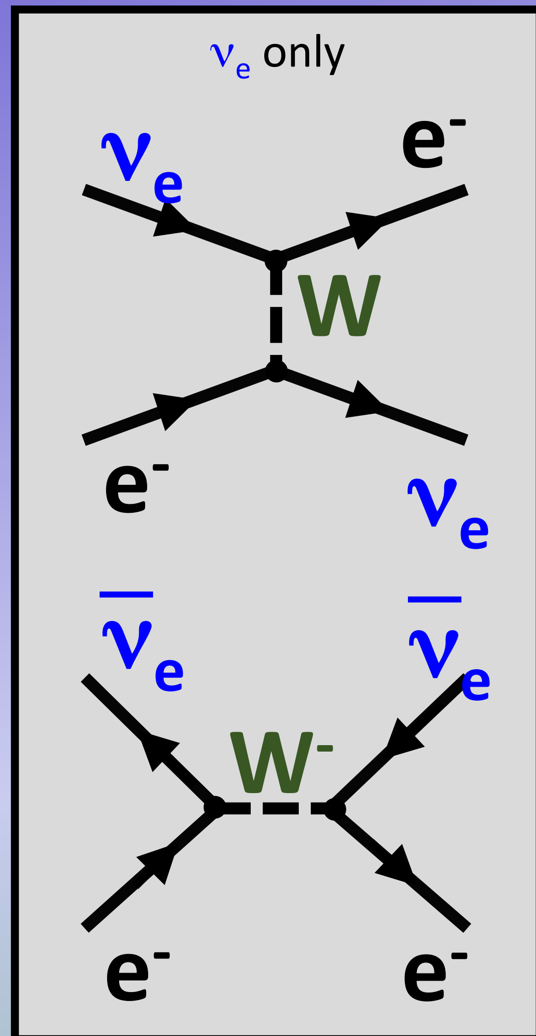
chirality flipping

The Mass Hierarchy



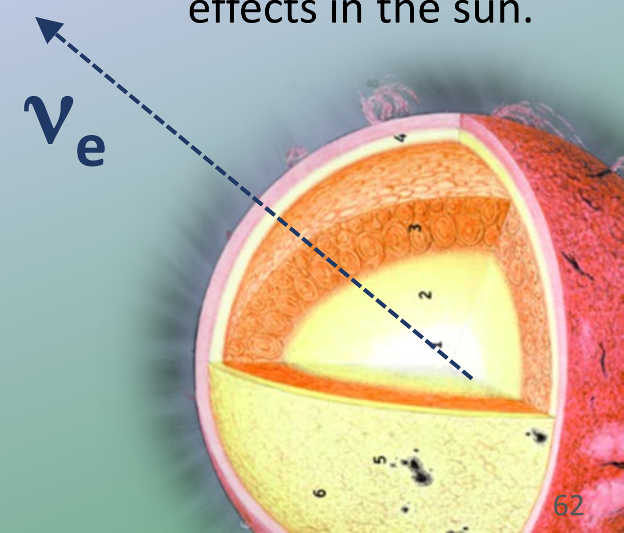
Method 1: MATTER EFFECTS





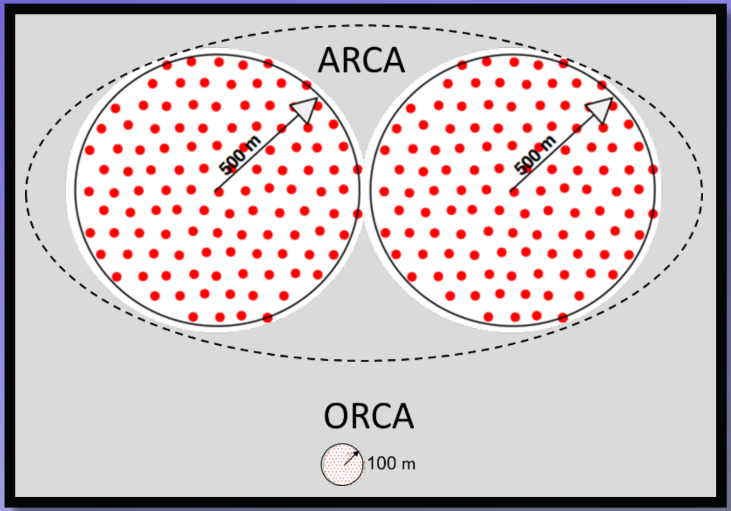
$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} = \ldots\ldots\ldots\ldots\ldots\ldots$$
$$+ \ldots\ldots\ldots\ldots\ldots\ldots$$
$$- \ldots \frac{aL}{4\,E} \cos \frac{\Delta m^2_{23} L}{4\,E} \sin \frac{\Delta m^2_{13} L}{4E}$$

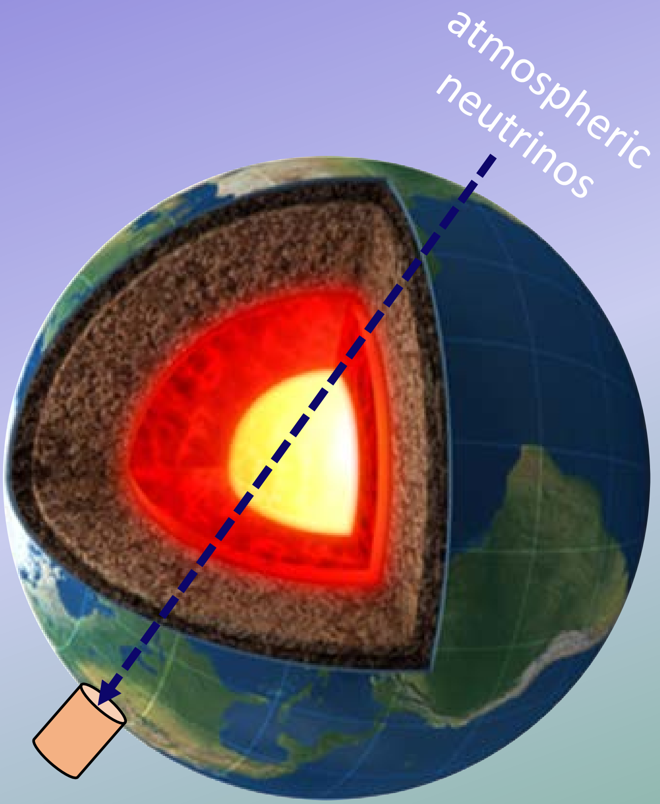
Hierarchy of ν_1 and ν_2
Determined from matter
effects in the sun.

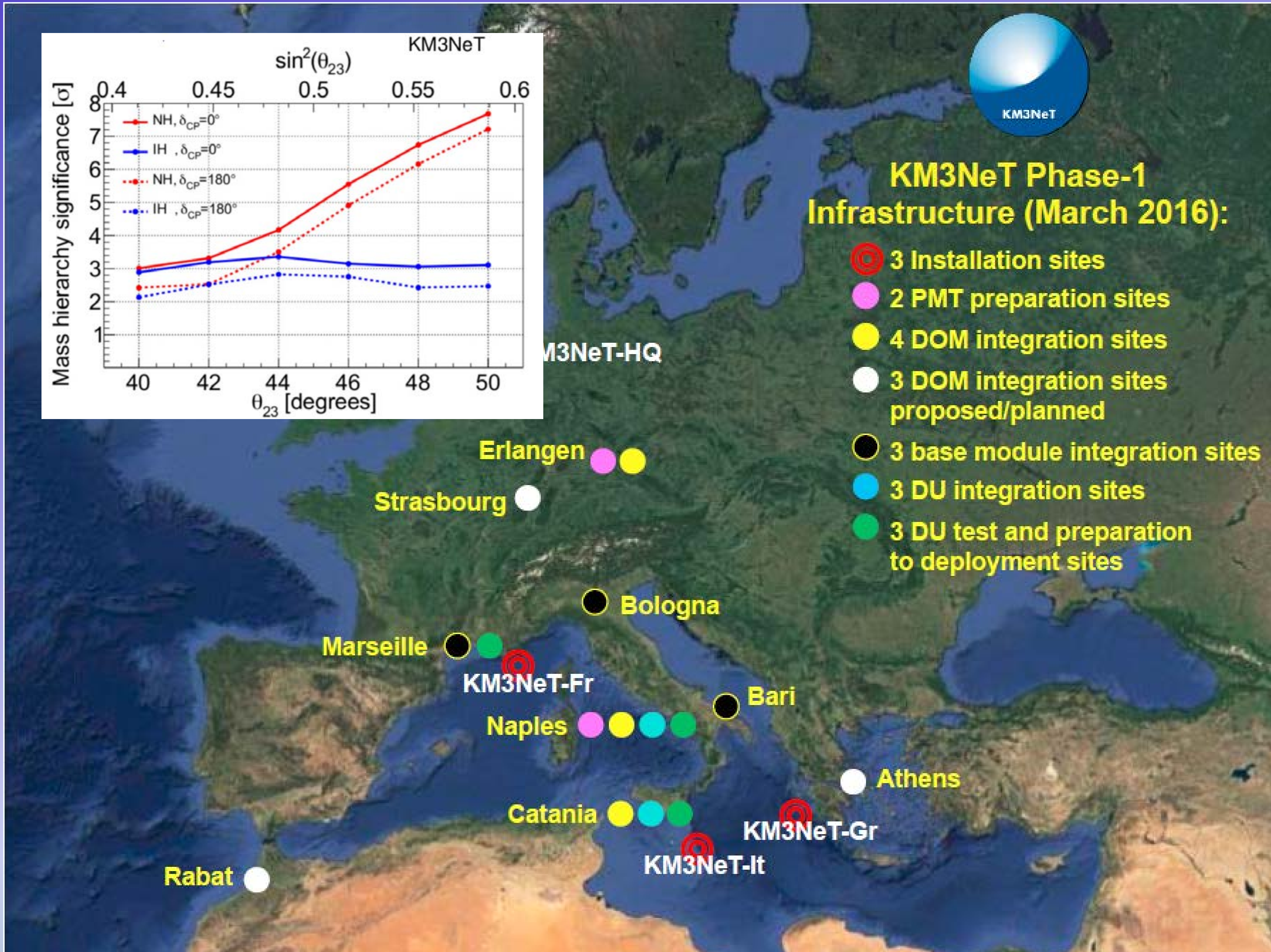


MATTER EFFECTS: ORCA

Resonant transition (MSW) near the core of the earth





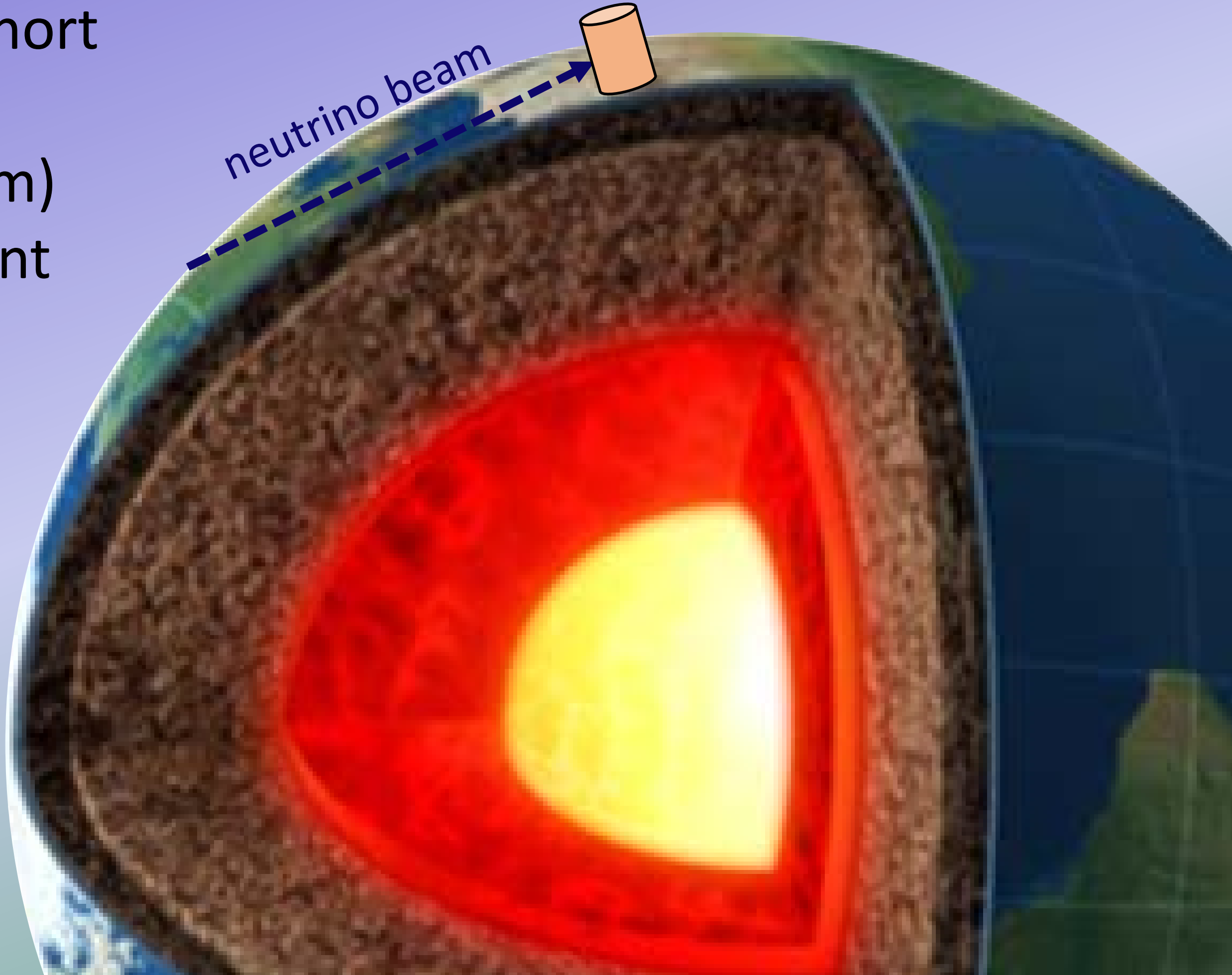

KM3NeT
$\sin^2(\theta_{23})$
0.4
0.45
0.5
0.55
0.6
Mass hierarchy significance [σ]
NH, δ_{CP}=0°
IH , δ_{CP}=0°
NH, δ_{CP}=180°
IH , δ_{CP}=180°
θ_{23} [degrees]
40
42
44
46
48
50
KM3NeT
KM3NeT Phase-1
Infrastructure (March 2016):
3 Installation sites
2 PMT preparation sites
4 DOM integration sites
3 DOM integration sites
proposed/planned
3 base module integration sites
3 DU integration sites
3 DU test and preparation
to deployment sites
M3NeT-HQ
Erlangen
Strasbourg
Bologna
Marseille
KM3NeT-Fr
Bari
Naples
Athens
Catania
KM3NeT-Gr
KM3NeT-It
Rabat

Method 1: MATTER EFFECTS

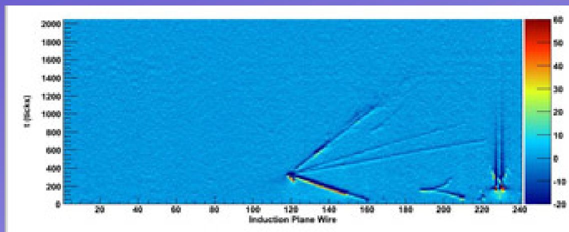
Matter Effect is proportional to L!

Long baseline Beams

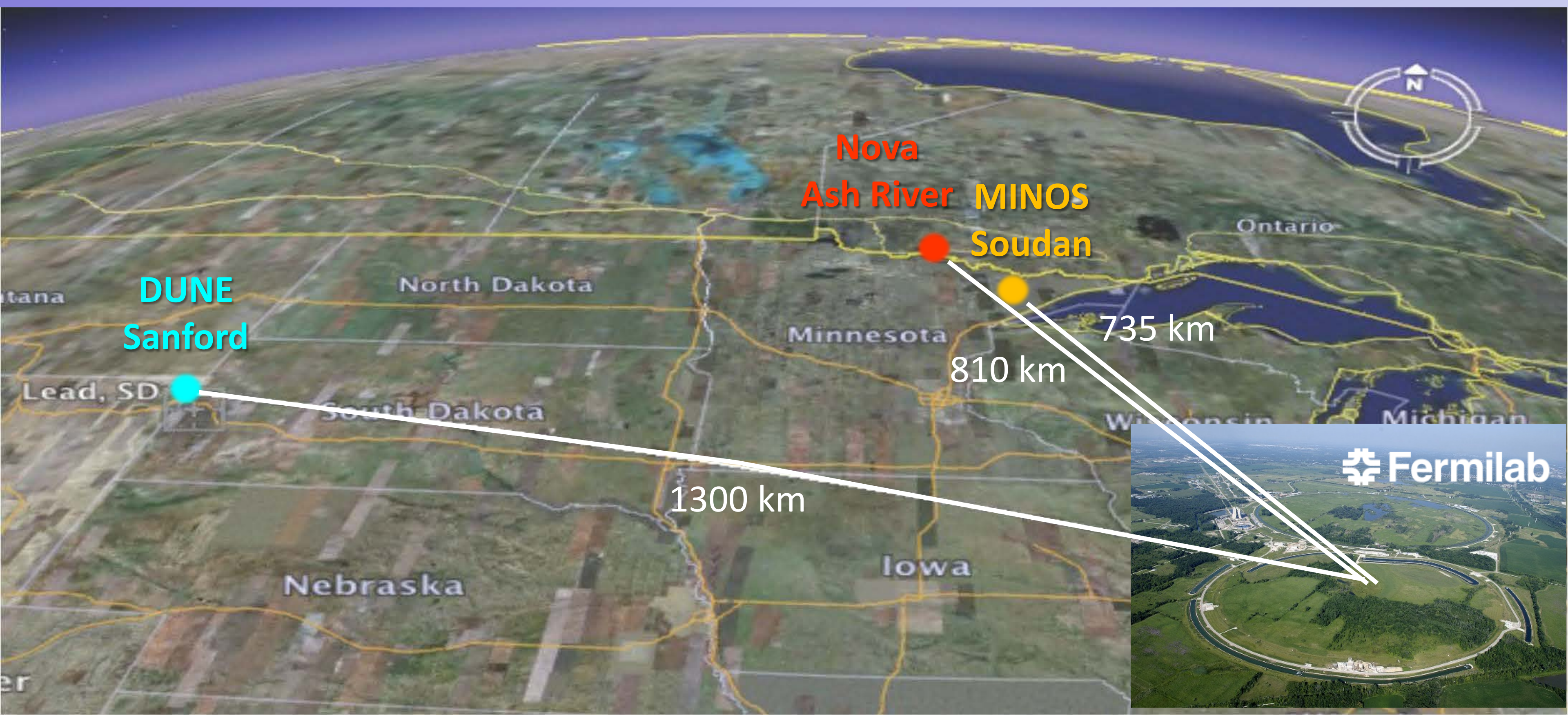
- **T2K** (295 km) too short
- **Nova** (810 km) 2σ
- **LBNE/DUNE** (1300 km) excellent



FUTURE: DUNE



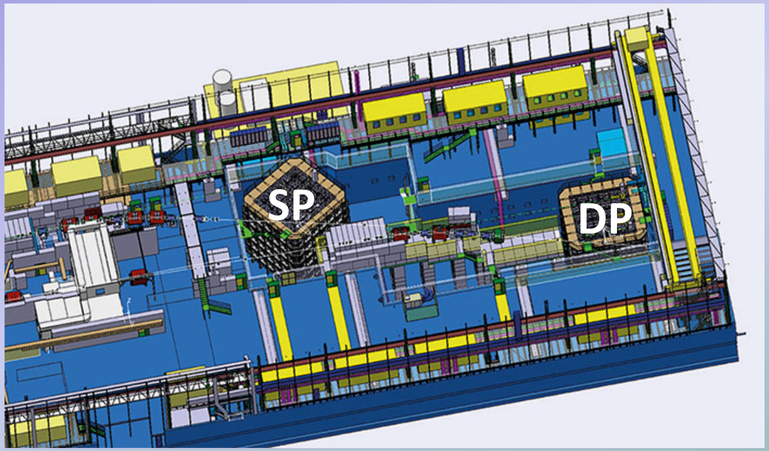
1…4 Liquid Argon TPCs; 10 kt each

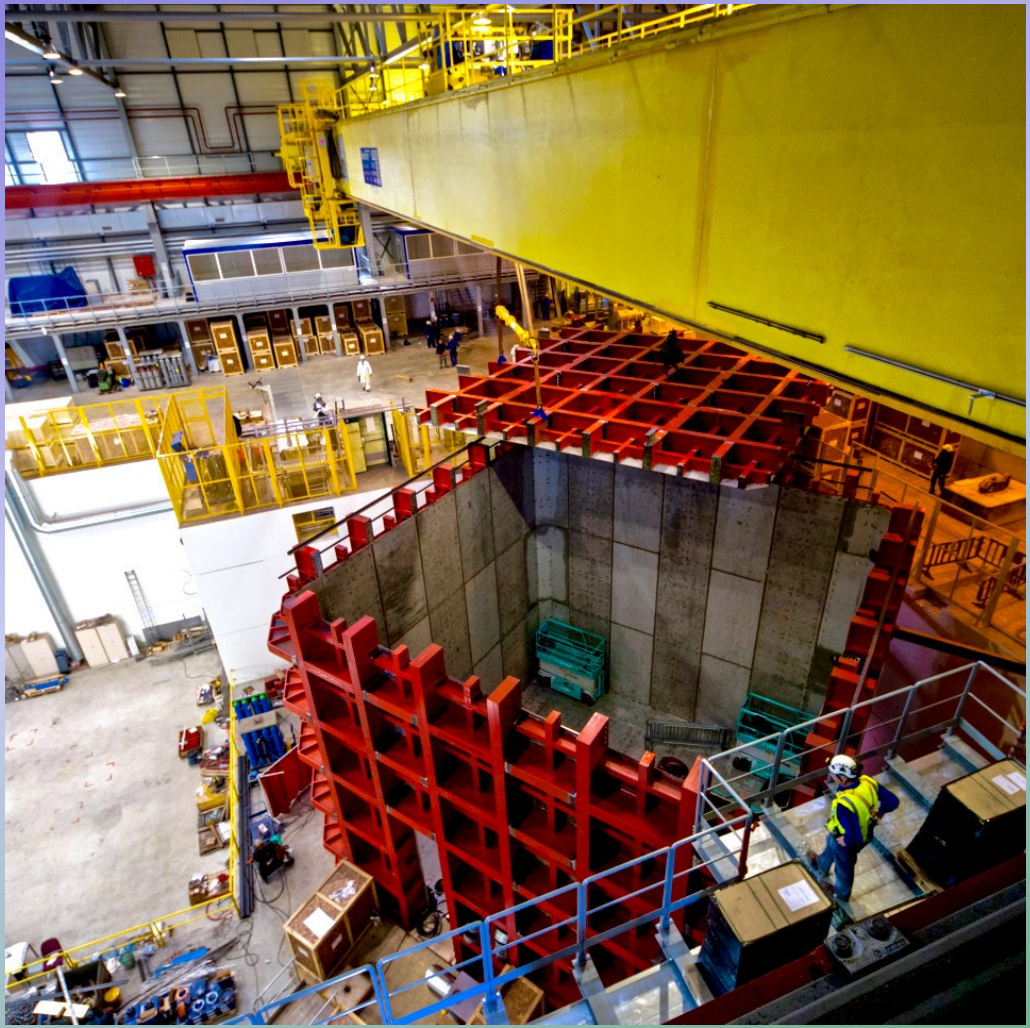


DUNE: R&D

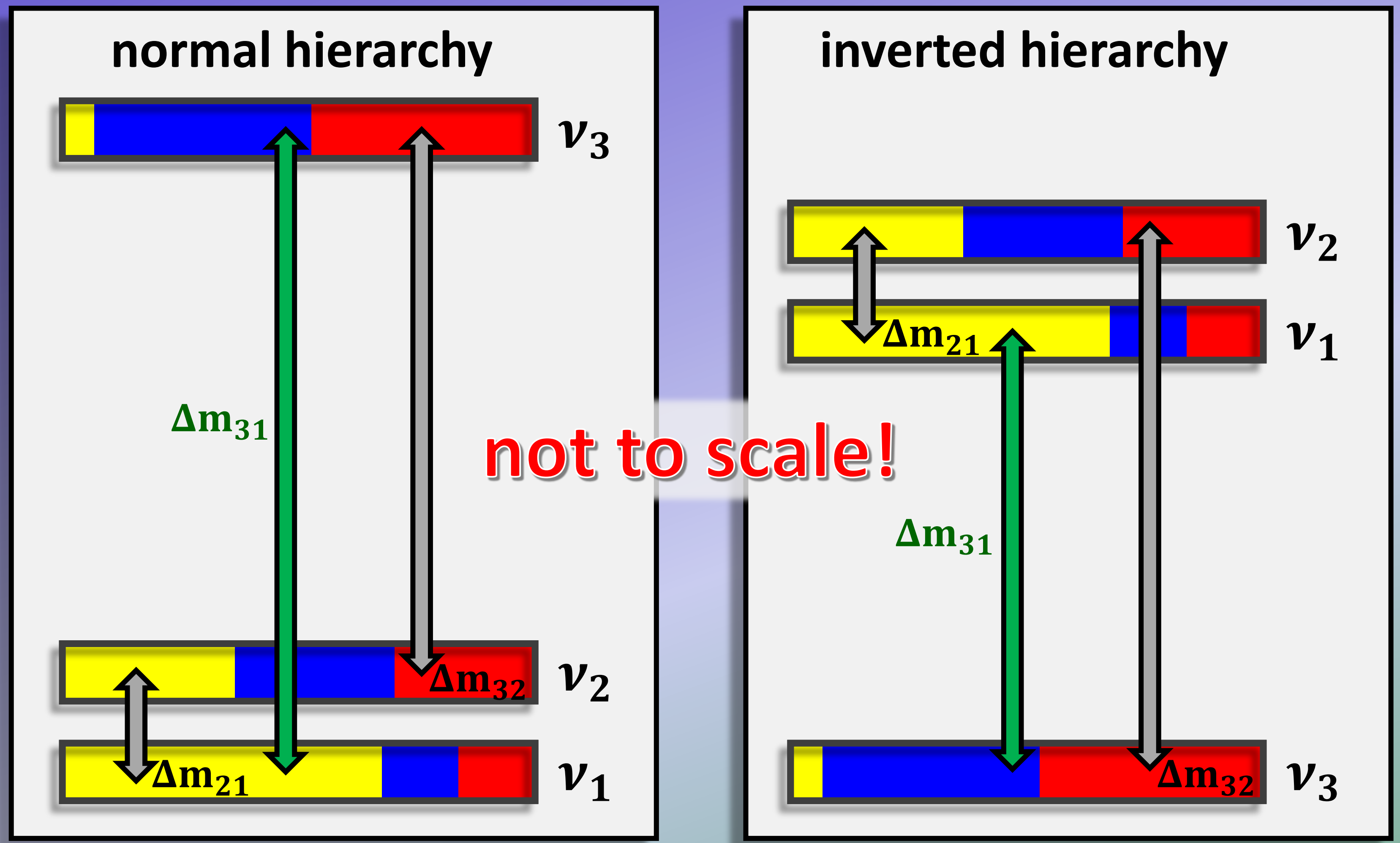
ICARUS: 600 t
MicroBooNE: 170 t
⋮
Prototypes
⋮
DUNE: 10 000 t

CERN: Neutrino Platform
600t prototypes DUNE SP/DP





Method 2: 3-Falvour-Interference



$$\Delta m_{31,\mathrm{normal}} > \Delta m_{31,\mathrm{inverted}}$$

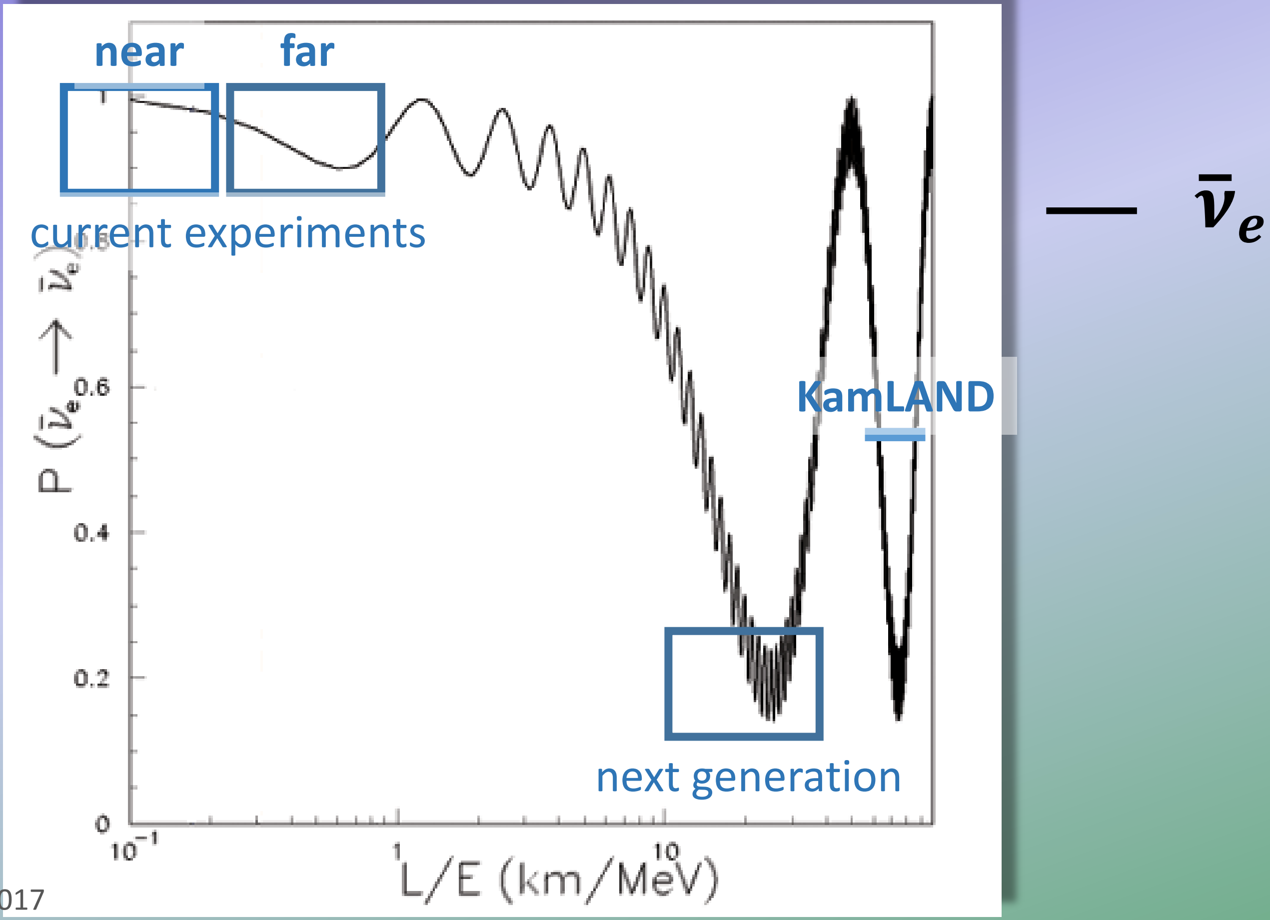
OSCILLATION PATTERN

leading terms:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{ee} L}{4E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

$$\sin^2 \frac{\Delta m^2_{ee} L}{4E} = \cos^2 \theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2 \theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E}, \quad \Delta m^2_{ij} = m_i^2 - m_j^2$$

Reactor Experiment
$\bar{\nu}_e$-disappearance



OSCILLATION PATTERN

Yu-Feng Li et al.,
Phys.Rev. D88 (2013) 013008

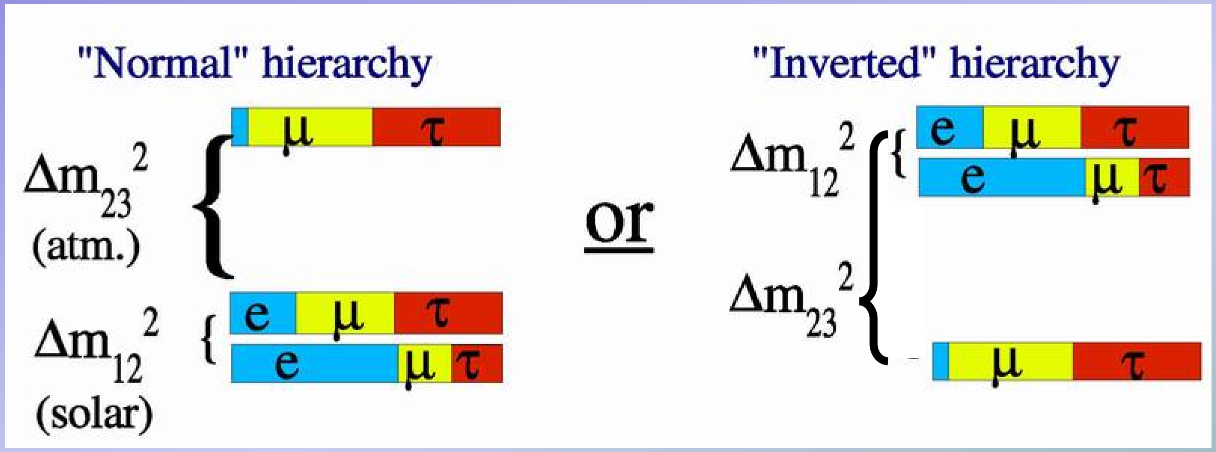
leading terms:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - cos^2\theta_{12} \sin^2 2\theta_{13}\, sin^2 \frac{\Delta m^2_{31} L}{4E}$$ ← **high frequency**

$$- \sin^2 \theta_{12} \sin^2 2\theta_{13}\, sin^2 \frac{\Delta m^2_{32} L}{4E}$$ ← **high frequency**

$$- \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$ ← **low frequency**

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



$$|\Delta m^2_{31}| = |\Delta m^2_{23}| + |\Delta m^2_{12}|$$

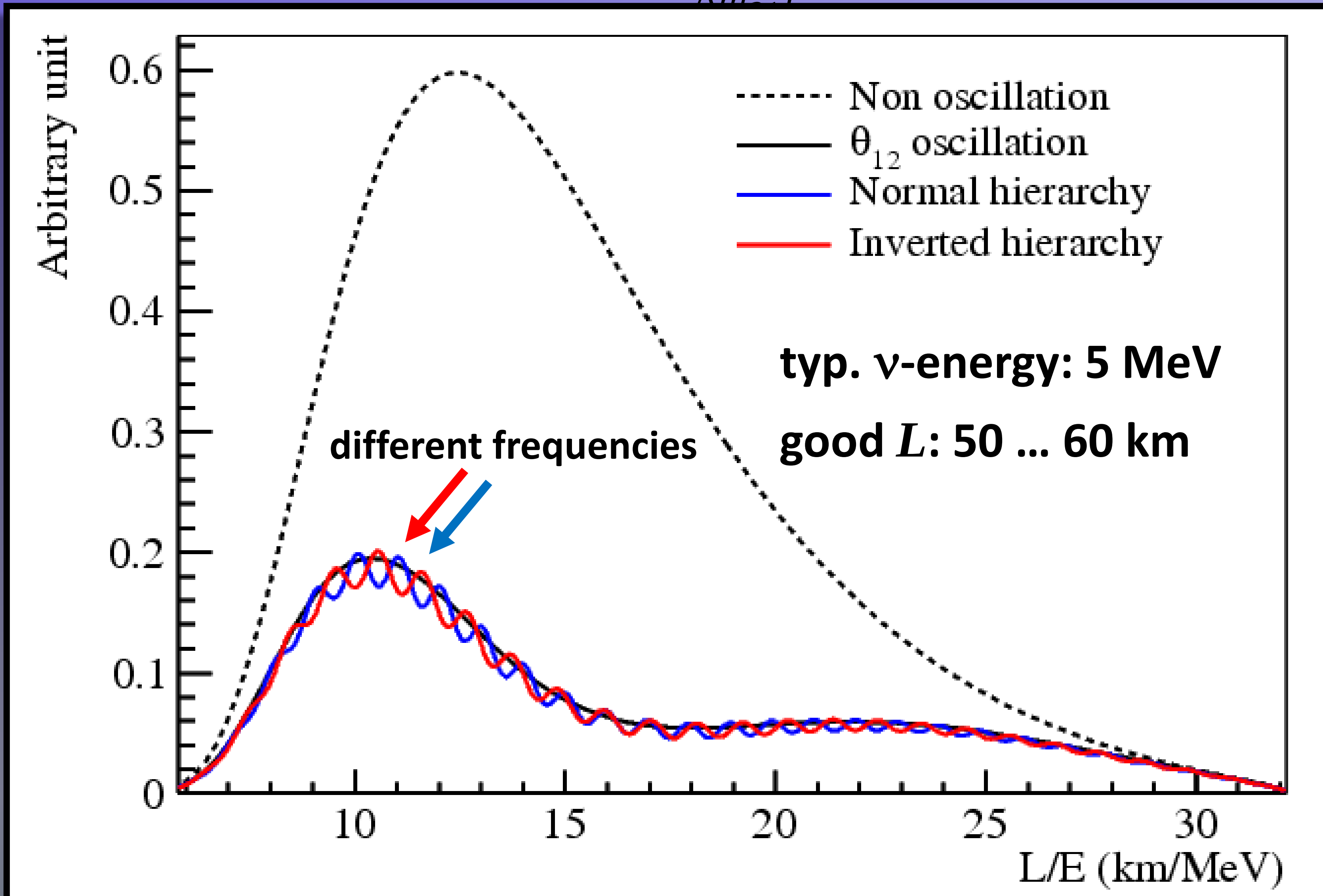
$$|\Delta m^2_{31}| = |\Delta m^2_{23}| - |\Delta m^2_{12}|$$

Yu-Feng Li et al.,
Phys.Rev. D88 (2013) 013008

OSCILLATION PATTERN

Yu-Feng Li et al.,
Phys.Rev. D88 (2013) 013008

leading terms:



EXPERIMENTAL LANDSCAPE

Matter-Effects:

		approval status	
1. atmospheric neutrinos	PINGU	😐	4 σ
	ORCA	😐	4 σ
	INO	☺	2 σ
2. beam neutrinos	Noνa	☺	2 σ
	DUNE/LBNE	😐	>5 σ

3-Flavour Interference:	JUNO	☺	3-4 σ
	RENO50	☹	?

The JUNO Project

THE JUNO PROJECT

550 scientists, 70 institutions, 1/3 from Europe

Armenia, Belgium, Brazil, Chili, Chinese Republic, Czech Republic, Germany, Finland, France, Italy, Latvia, Pakistan, Russia, Slovakia, Thailand, Taiwan, and the United States

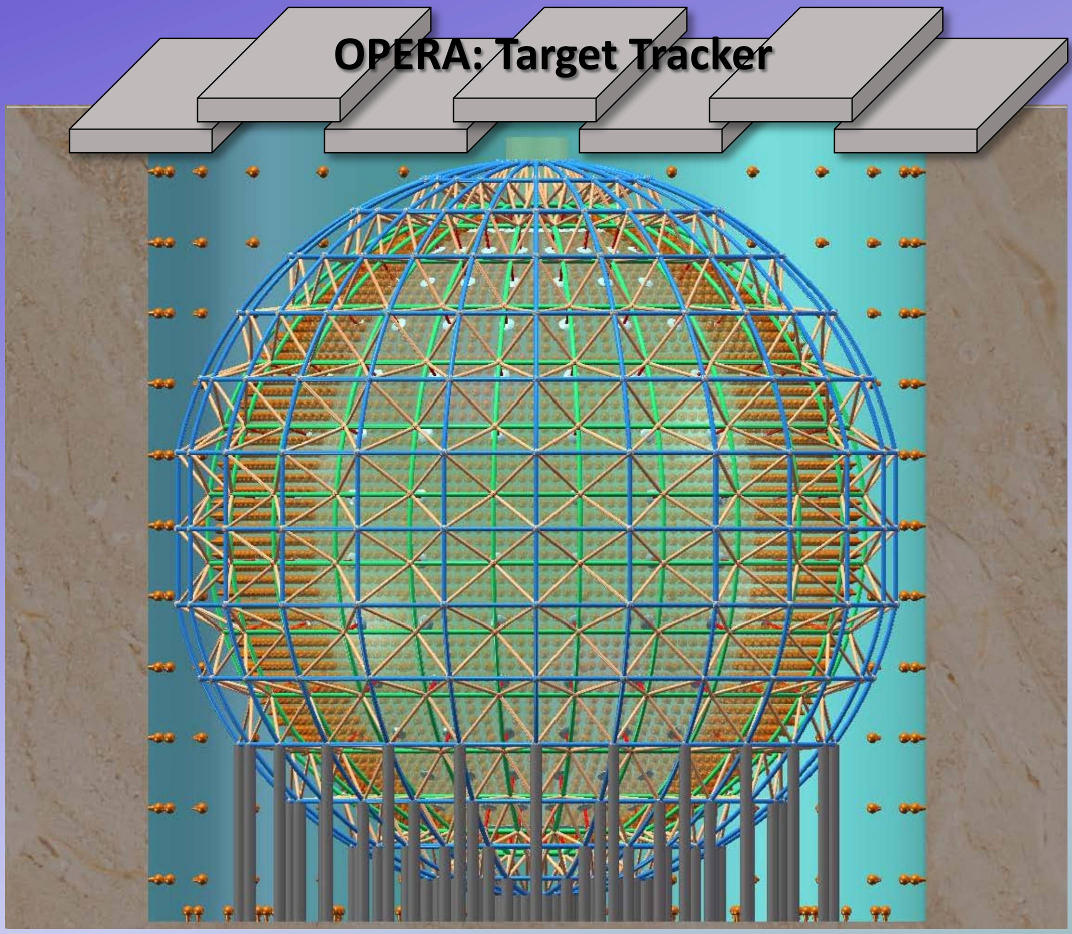
Jiangmen
Underground
Neutrino
Observatory

supported by

Deutsche Forschungsgemeinschaft DFG

RWTH AACHEN UNIVERSITY · Universität Hamburg – DER FORSCHUNG | DER LEHRE | DER BILDUNG · JÜLICH FORSCHUNGSZENTRUM · JOHANNES GUTENBERG UNIVERSITÄT MAINZ · Technische Universität München · EBERHARD KARLS UNIVERSITÄT TÜBINGEN

THE JUNO PROJECT



Liquid Scintillator

Ultra-high purity (BOREXINO technology)

20.000 t fiducial volume

acrylic sphere (Ø35.5 m)

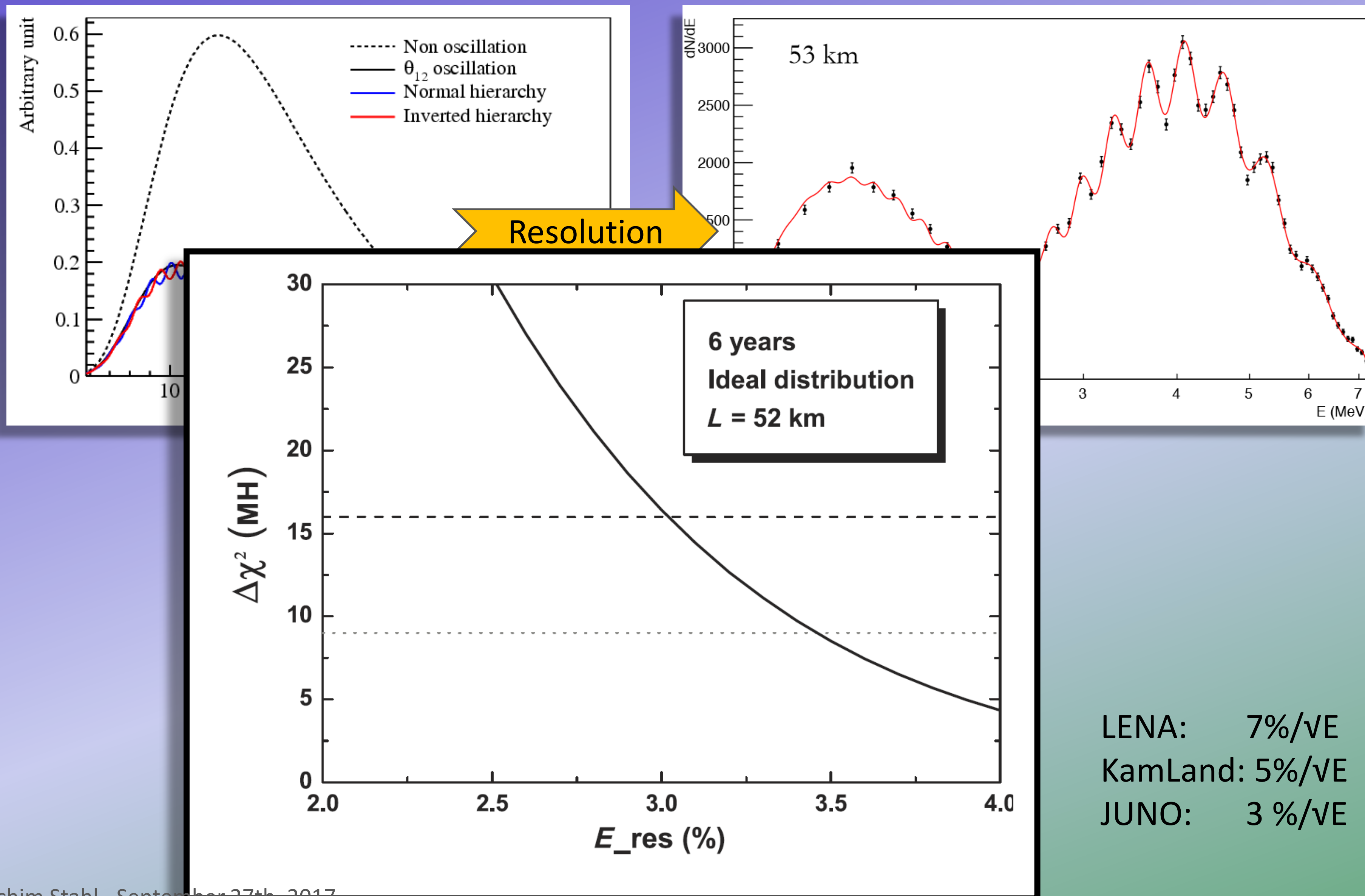
2m water buffer

20.000 PMTs (20“)

embedded in a water Čerenkov veto

Muon tracker on top

THE CHALLENGE



LENA: 7%/√E

KamLand: 5%/√E

JUNO: 3 %/√E

THE CHALLENGE

Excellent Energy Resolution (3% @ 1 MeV)

Photonstatistics

- high lightyield
- good transparency
- PMT-coverage
- PMT-DE

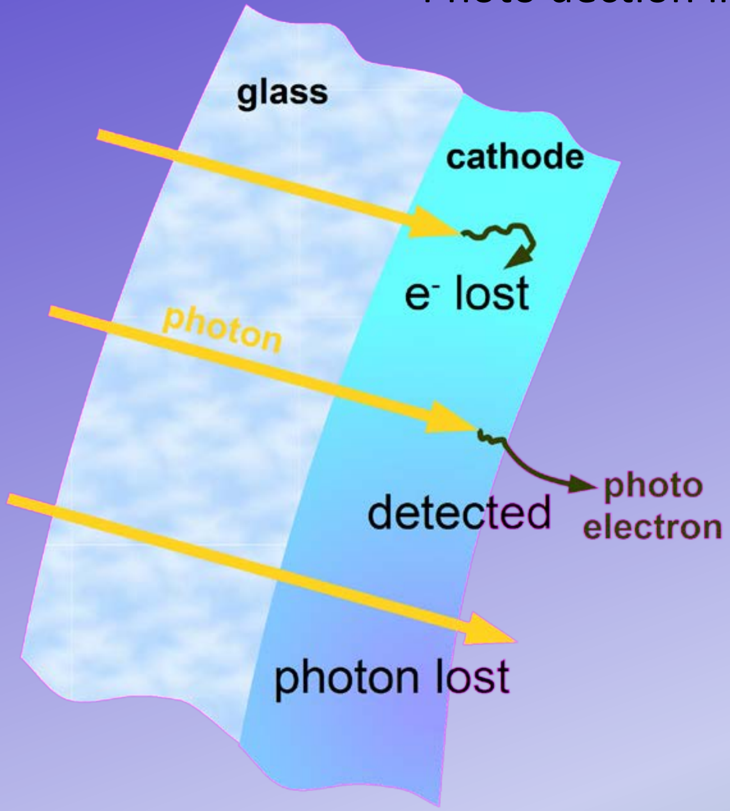
&

Calibration

- $\alpha/\beta/\gamma$ sources
  (in all positions)
- light pulsers
  (in all positions)
- UV-laser
  (in many positions)
- e^+ beam
  (along axis)

The MCP-PMT

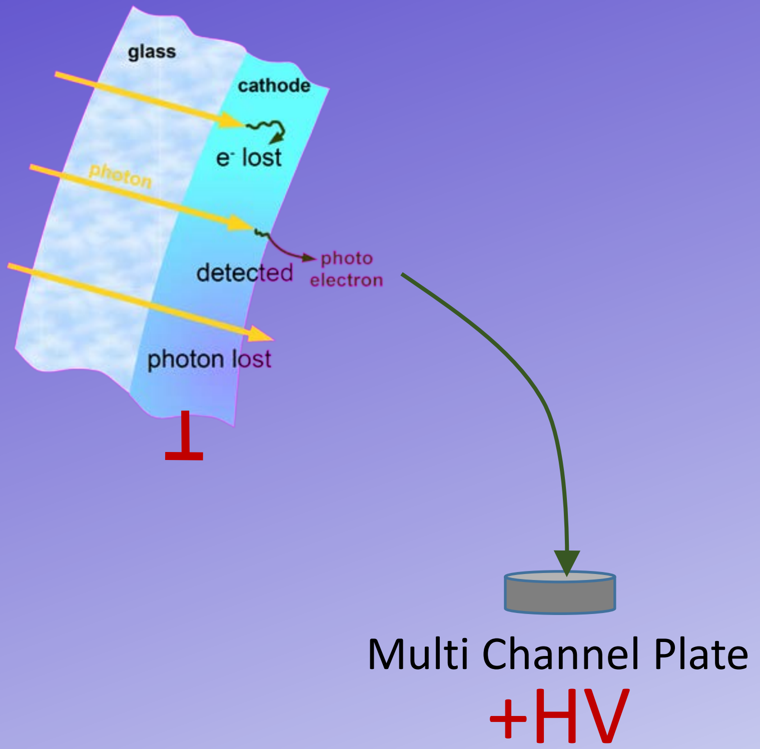
Photo dection in the cathode



Hamamatsu R12860 (20"PMT)

Detection efficiency =	
quantum efficiency	Typ. 27%
	Spec. > 24%
x collection efficiency	
x area coverage	

The MCP-PMT



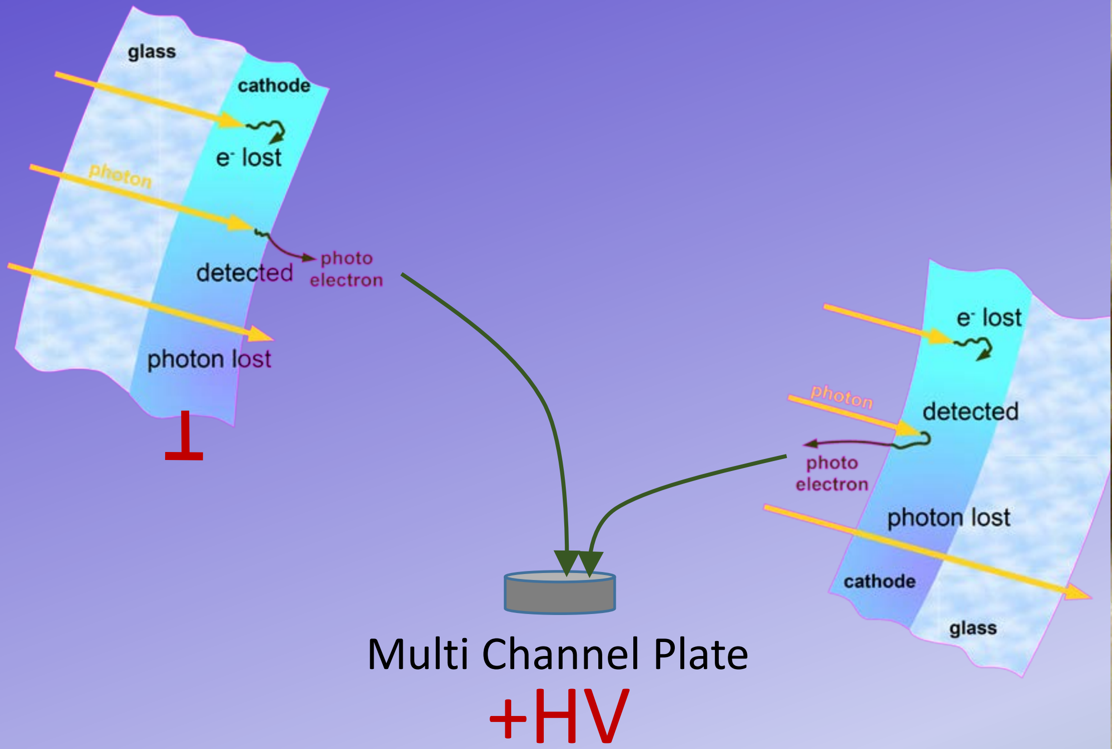
Detection efficiency =
quantum efficiency
x collection efficiency
x area coverage

Typ. 27%
Spec. > 24%

Night Vision / China

MCP-PMT 8“ prototype

The MCP-PMT



Detection efficiency = quantum efficiency x collection efficiency x area coverage

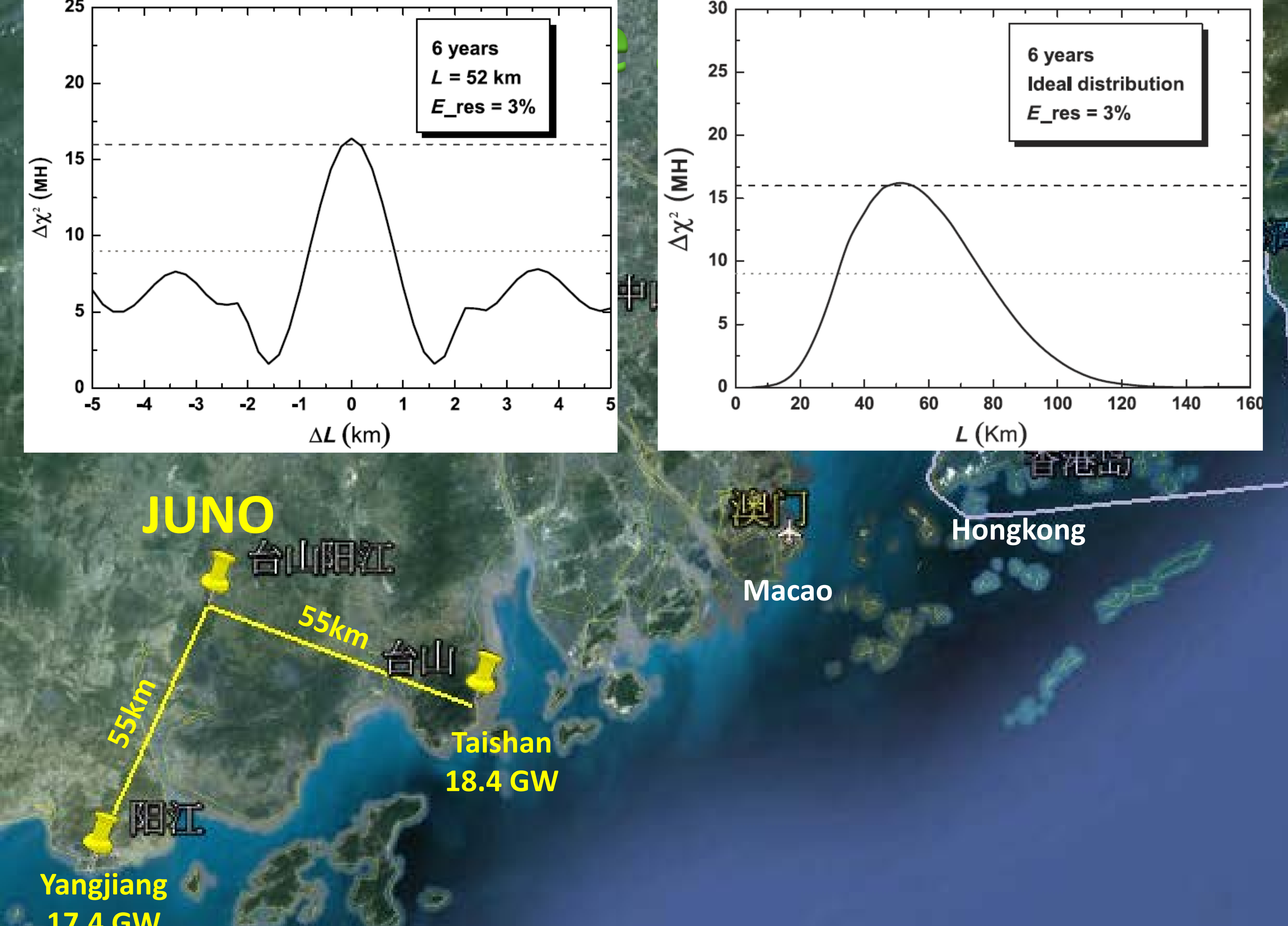
Typ. 27%
Spec. > 24%

Night Vision / China

MCP-PMT 8" prototype

The Site

Guangdong province
Jiangmen prefecture
Kaiping city

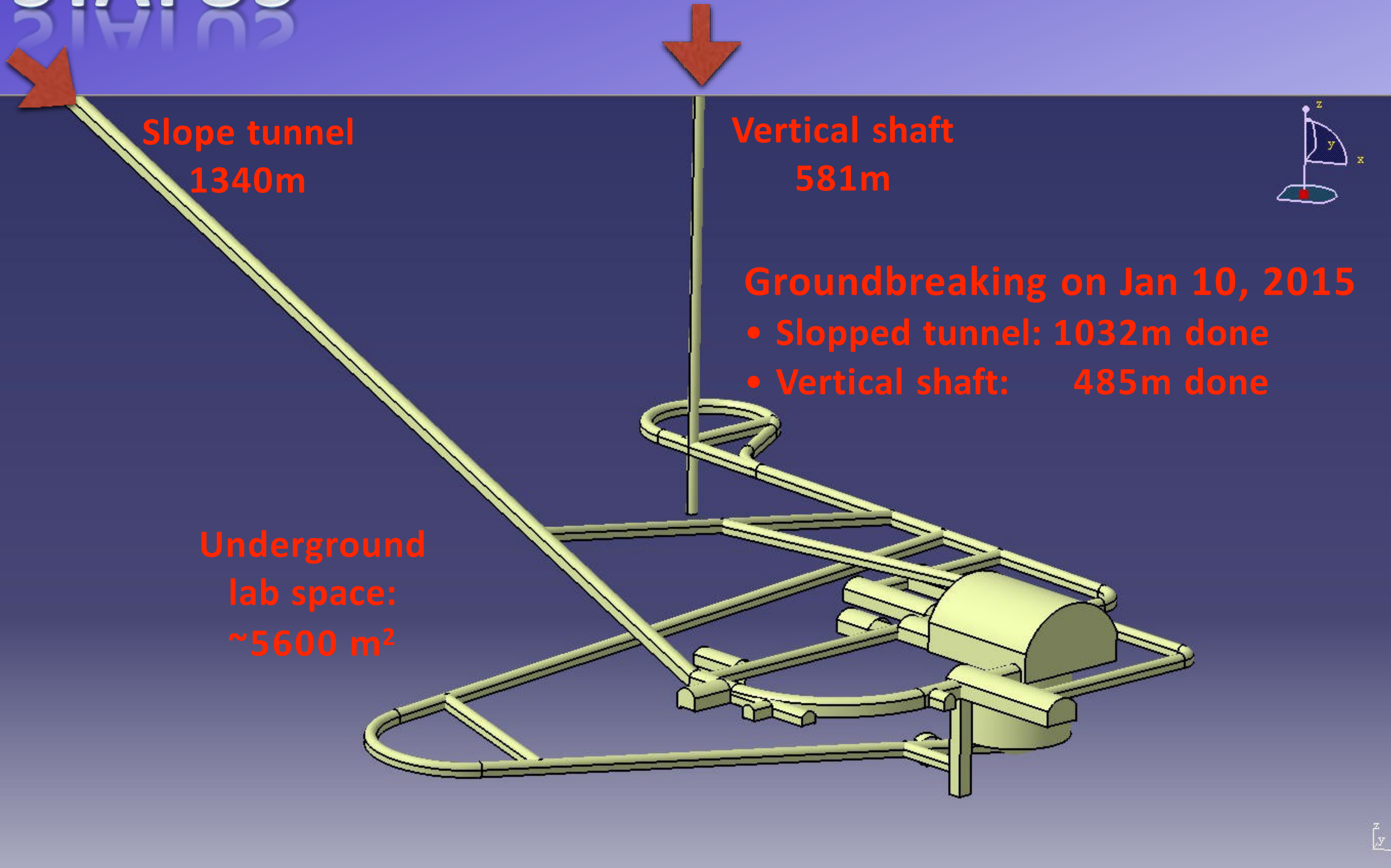

6 years
L = 52 km
E_res = 3%
Δχ² (MH)
ΔL (km)
6 years
Ideal distribution
E_res = 3%
Δχ² (MH)
L (Km)
JUNO
台山阳江
55km
55km
台山
阳江
Taishan
18.4 GW
Yangjiang
17.4 GW
澳门
Macao
Hongkong
香港岛


Hongkong

THE SURFACE LAB

STATUS

Civil engineering: Completion July 2018



Groundbreaking on Jan 10, 2015

- **Slopped tunnel: 1032m done**
- **Vertical shaft: 485m done**

THE JUNO PROJECT

start datataking in 2020

mass hierarchy to 3...4 sigma in 6 years

Physics of JUNO

Mass Hierarchy

MC-studies:

>3 sigma in 4 years

(3% resolution @ 1 MeV)

ν-oscillations with reactor neutrinos:
Mass hierarchy
Precision Measurements

Others

Super Nova
- **Direct observation**
- **Diffuse Super Nova background**

Solar Neutrinos
- **Oscillation parameters**
- **Metallicity**

Atmospheric Neutrinos
- **Oscillations**
- **Mass hierarchy ?**

Geo Neutrinos
- **Models of the earth‘s interior**
- **Heat production → climate**

Nucleon Decay
- **i.e. $p \rightarrow K^+ \nu$**

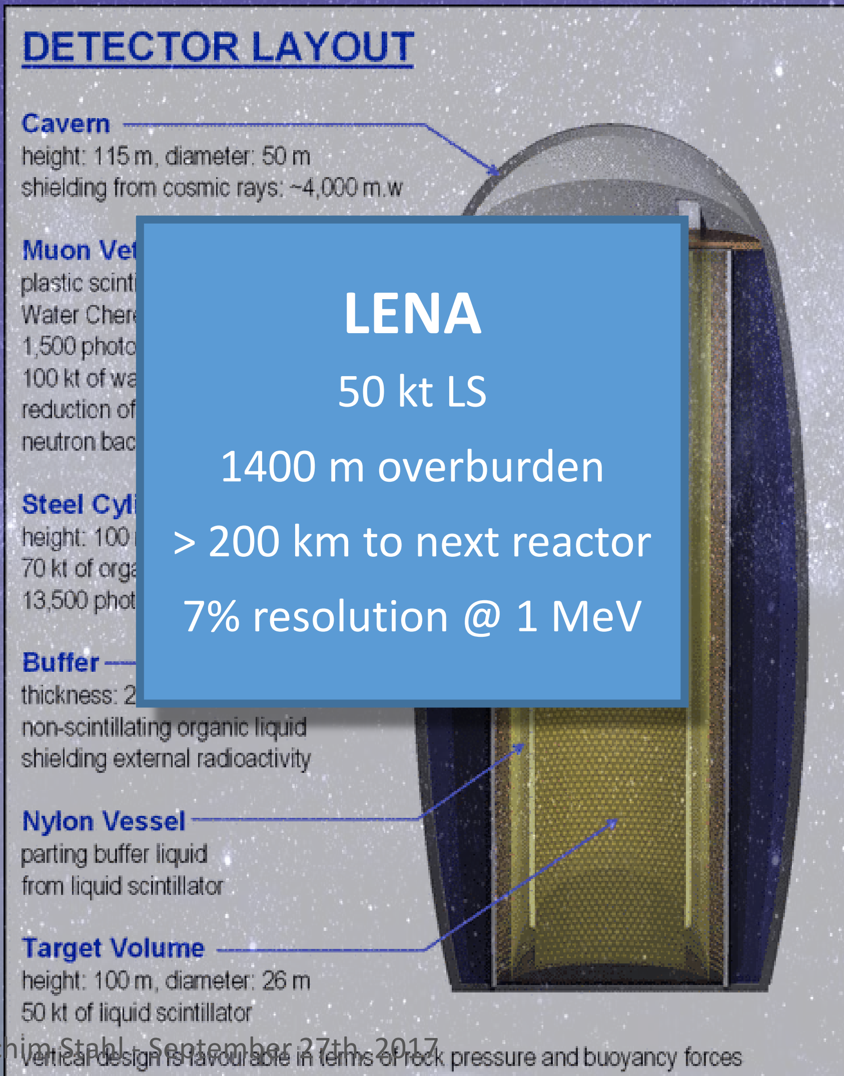
Dark Matter
- **$\chi \rightarrow \nu\nu$**

Sterile Neutrinos
- **With radioactive sources**

Physics of LS-Detectors

Others

LENA @ Phyäsalmi



LENA

50 kt LS

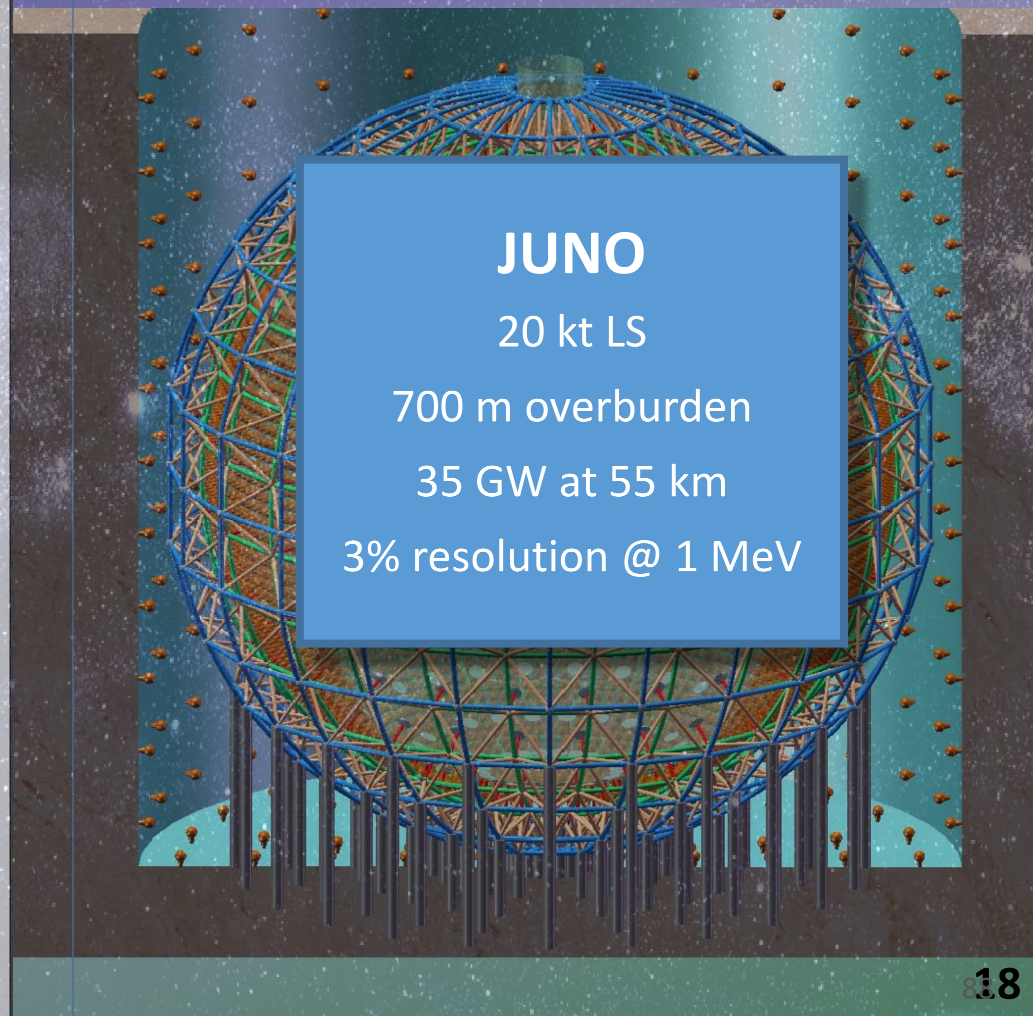
1400 m overburden

> 200 km to next reactor

7% resolution @ 1 MeV

Others

JUNO @ Jiangmen



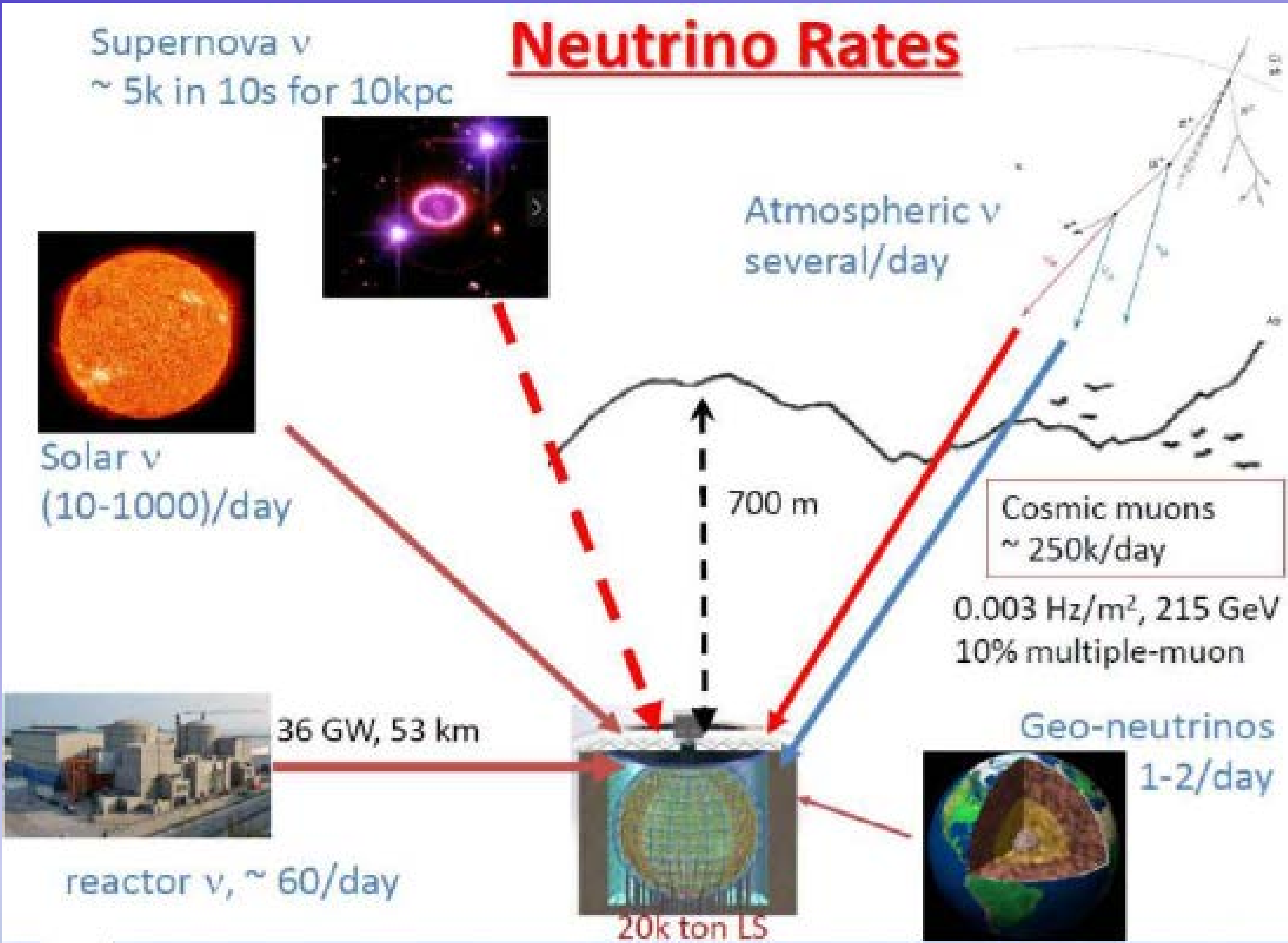
JUNO

20 kt LS

700 m overburden

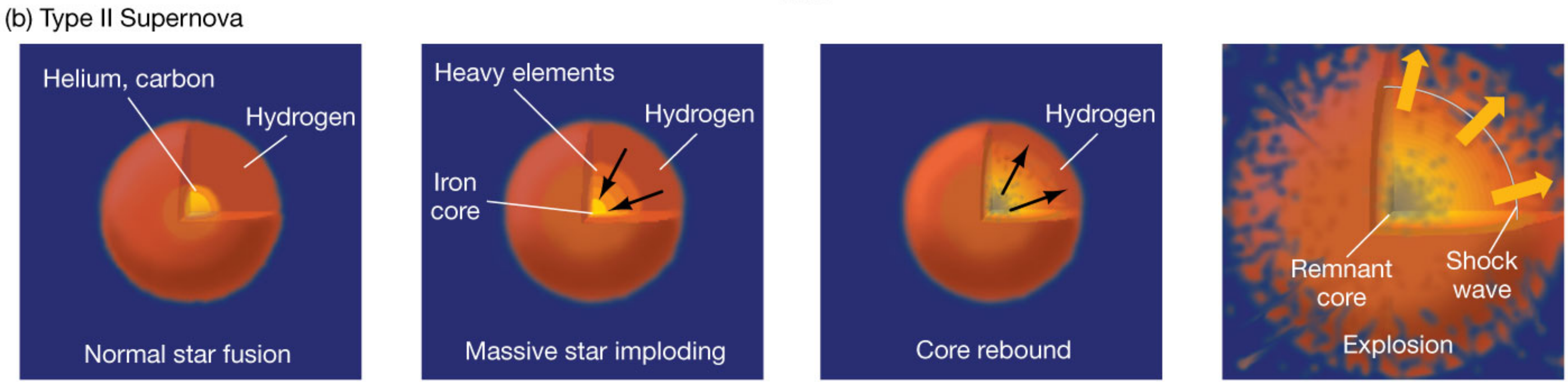
35 GW at 55 km

3% resolution @ 1 MeV

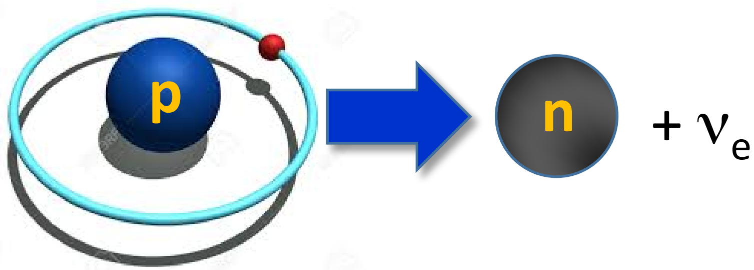

Neutrino Rates
Supernova ν
~ 5k in 10s for 10kpc
Atmospheric ν
several/day
Solar ν
(10-1000)/day
700 m
Cosmic muons
~ 250k/day
0.003 Hz/m², 215 GeV
10% multiple-muon
36 GW, 53 km
Geo-neutrinos
1-2/day
reactor ν, ~ 60/day
20k ton LS

Super Nova

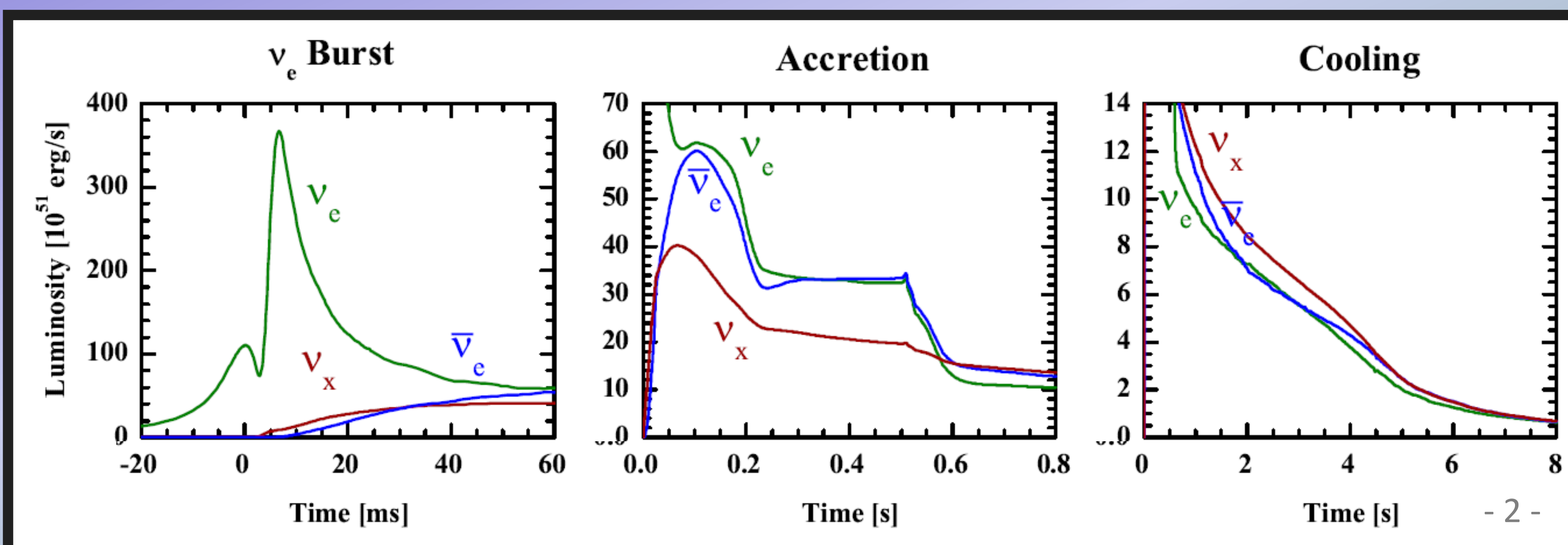
What will we detect?
What can we learn about super novae?



(b) Type II Supernova
Helium, carbon
Hydrogen
Normal star fusion
Heavy elements
Hydrogen
Iron core
Massive star imploding
Hydrogen
Core rebound
Remnant core
Shock wave
Explosion

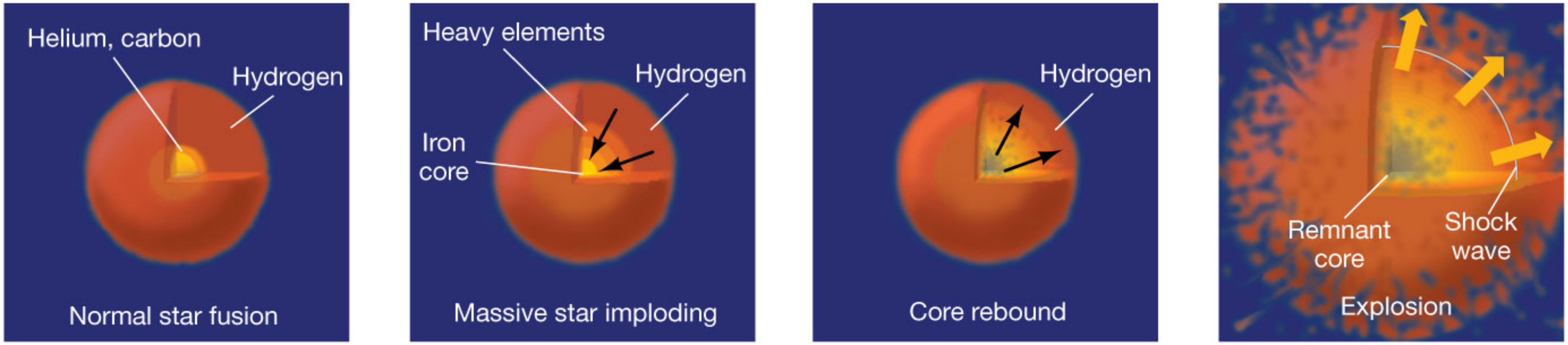


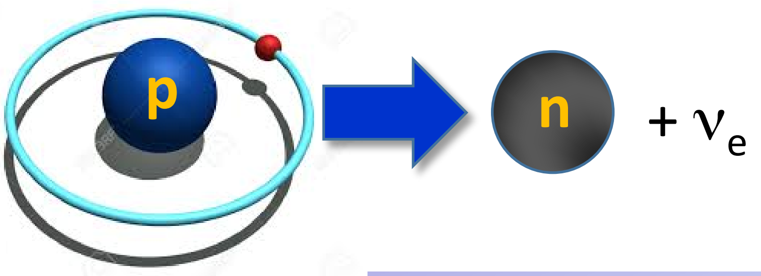
p
n
+ ν_e



ν_e Burst
Accretion
Cooling
Luminosity [10^{51} erg/s]
400
300
200
100
0
-20
0
20
40
60
Time [ms]
ν_e
ν_x
$\bar{\nu}_e$
70
60
50
40
30
20
10
0
0.0
0.2
0.4
0.6
0.8
Time [s]
14
12
10
8
6
4
2
0
2
4
6
8

(b) Type II Supernova





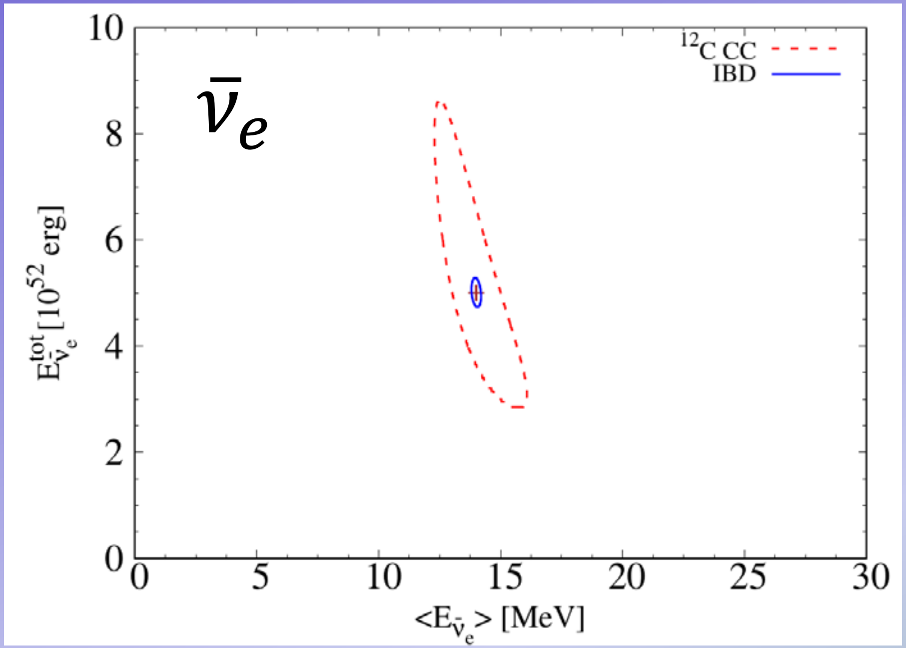
10 kpc

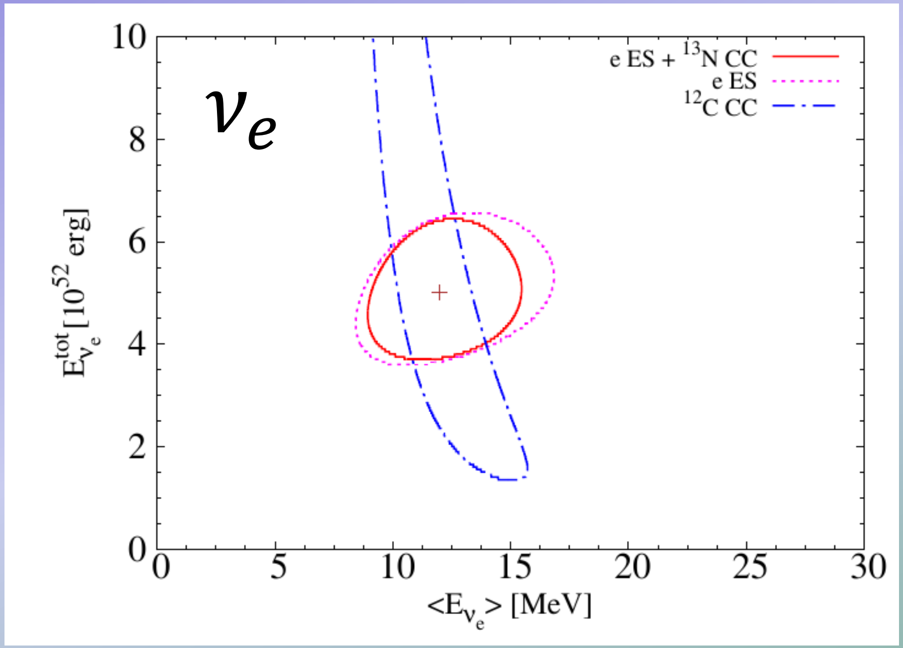
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	0.6×10^2	1.1×10^2	1.6×10^2

Neutrino Spectrum

Type IIa; standard paramters; 10 kpc

J.-S. Lu et al., Phys.Rev. D94 023006

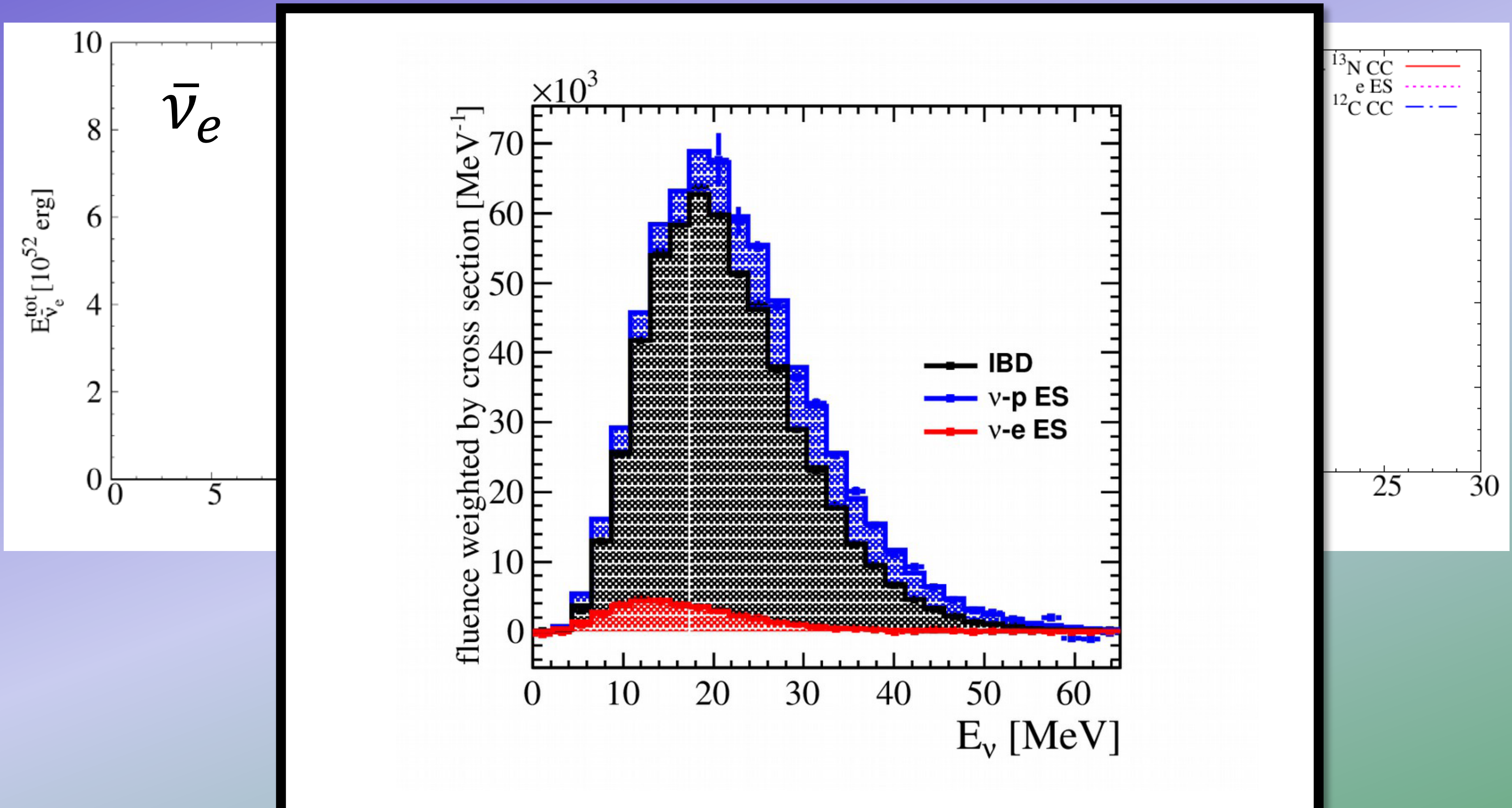




Neutrino Spectrum

Type IIa; standard paramters; 10 kpc

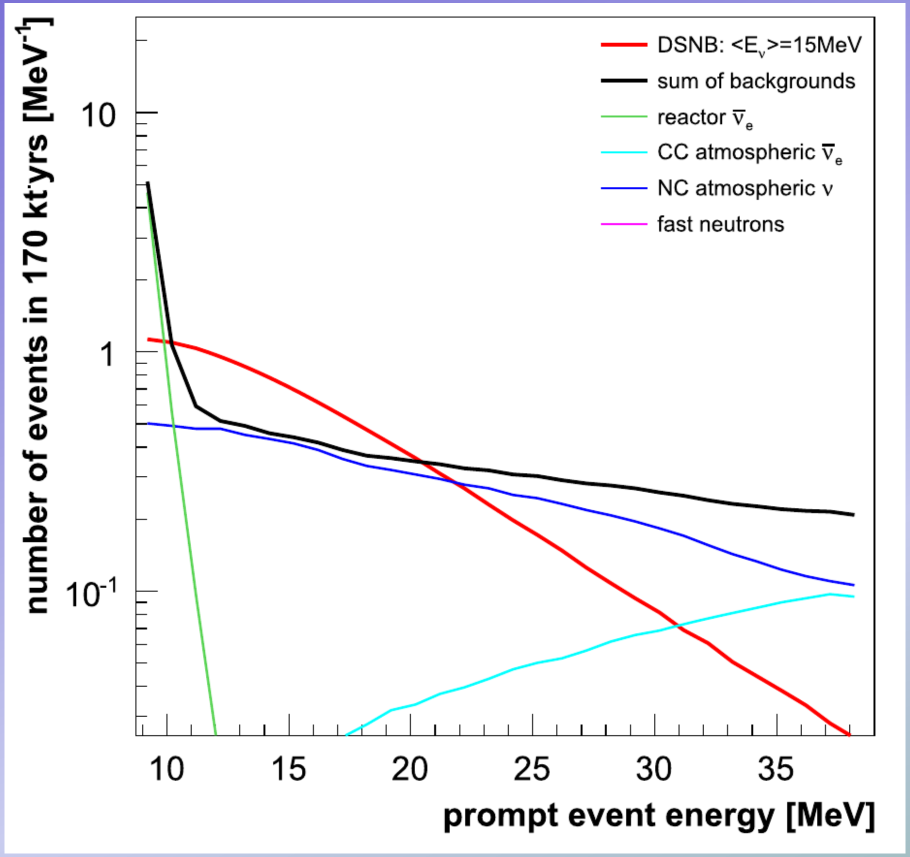
J.-S. Lu et al., Phys.Rev. D94 023006



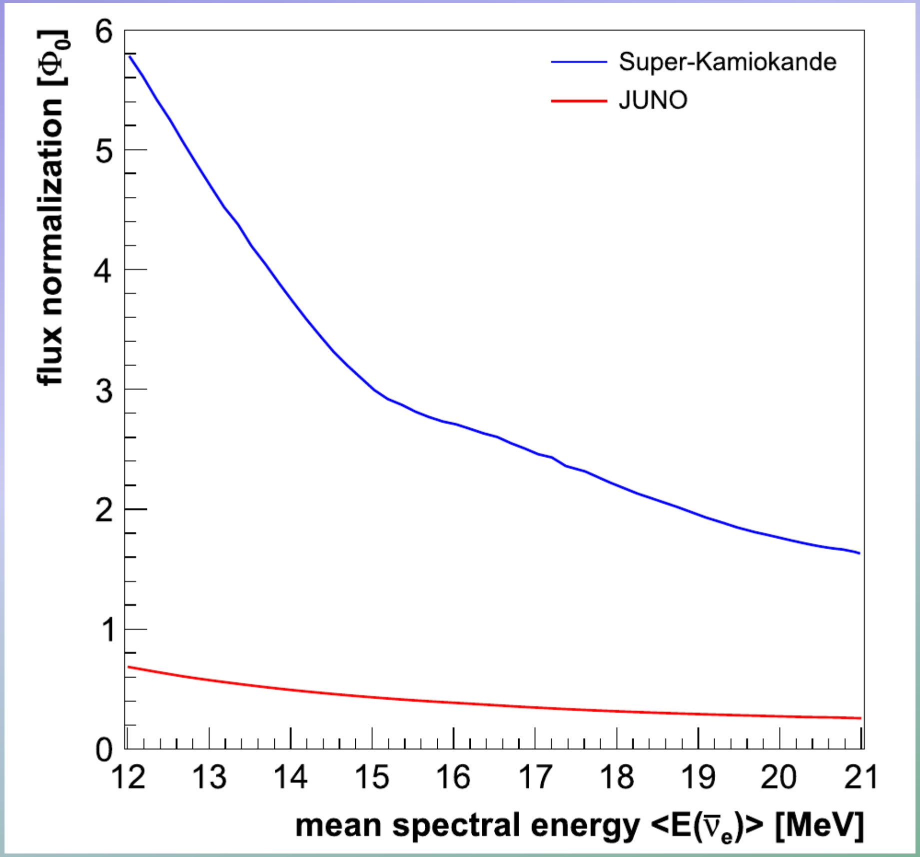
Diffuse Supernova Neutrino Background

Averaged neutrino signal from all supernovae in the universe

spectrum

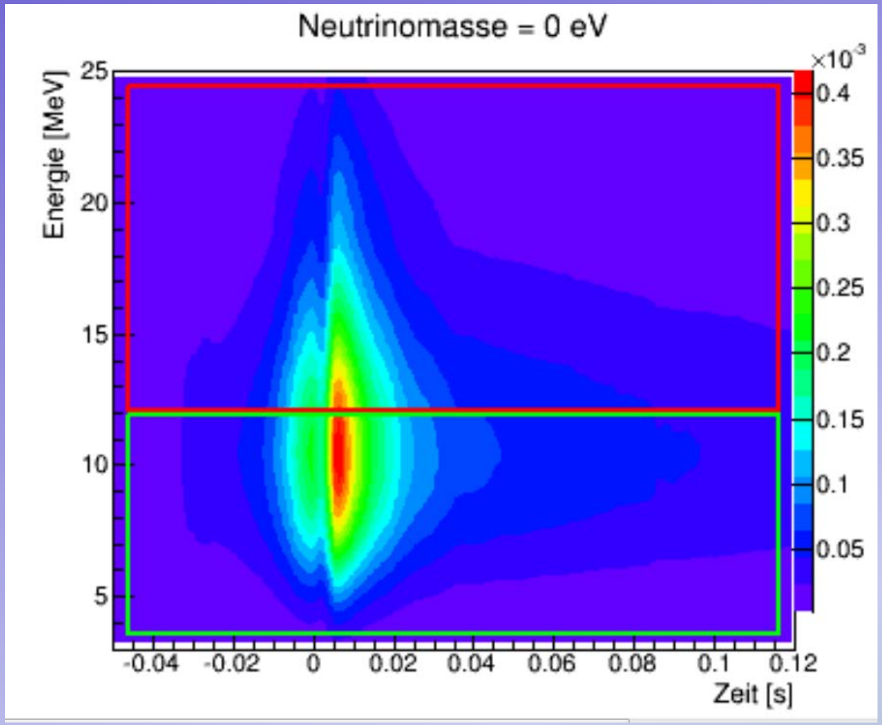


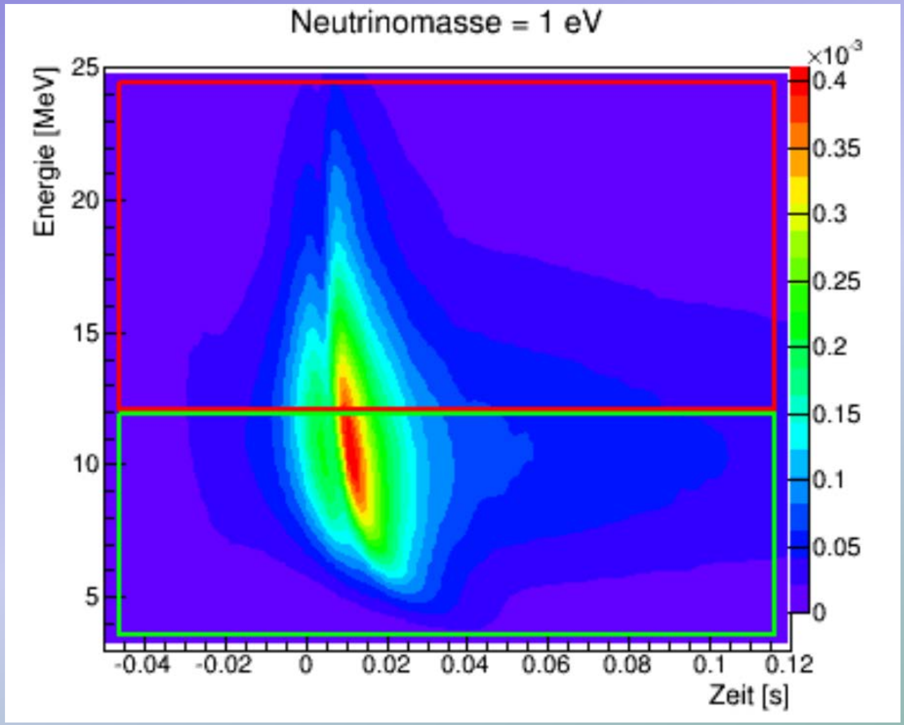
flux



Neutrino Mass from Time-of-Flight

Type IIa; standard paramters; 10 kpc





- Sensitivity ~ 1 eV
- Independent of distance

Conclusions

Conclusions

- Neutrino Physics is a very active field

Conclusions

T2K running with anti-neutrinos

$2\beta0\nu$: GERDA with strong German constribution

IceCube: cosmic ν and more

Nova just started

Waiting for first results from KATRIN

Japan: HyperK?

Many activities on sterile ν: SOX, Soliδ, ...

US longe baseline approaching approval

Will PINGU/ORCA come?

LENA: not forgotten!

Conclusions

- Neutrino Physics is a very active field
- Oscillation parameters reaching % region
- The precision on θ_{13} is still improving
- Mass hierarchy is the next step
- JUNO has been approved.
  Construction started Jan. 2015

Colloquium – DESY Zeuthen

NuFIT 3.0 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \rightarrow 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \rightarrow 0.345$	$0.271 \rightarrow 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \rightarrow 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \rightarrow 35.99$	$31.38 \rightarrow 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \rightarrow 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \rightarrow 0.640$	$0.385 \rightarrow 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \rightarrow 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \rightarrow 53.1$	$38.4 \rightarrow 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \rightarrow 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \rightarrow 0.02408$	$0.01934 \rightarrow 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \rightarrow 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \rightarrow 8.93$	$7.99 \rightarrow 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \rightarrow 360$	277^{+40}_{-46}	$145 \rightarrow 391$	$0 \rightarrow 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \rightarrow 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \rightarrow 8.09$	$7.03 \rightarrow 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \rightarrow +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \rightarrow -2.399$	$\begin{bmatrix} +2.407 \rightarrow +2.643 \\ -2.629 \rightarrow -2.405 \end{bmatrix}$

www.nu-fit.org

Neutrinos

www.nu-fit.org

NuFIT 3.0 (2016)

$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

Quarks

PDG 2017

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$