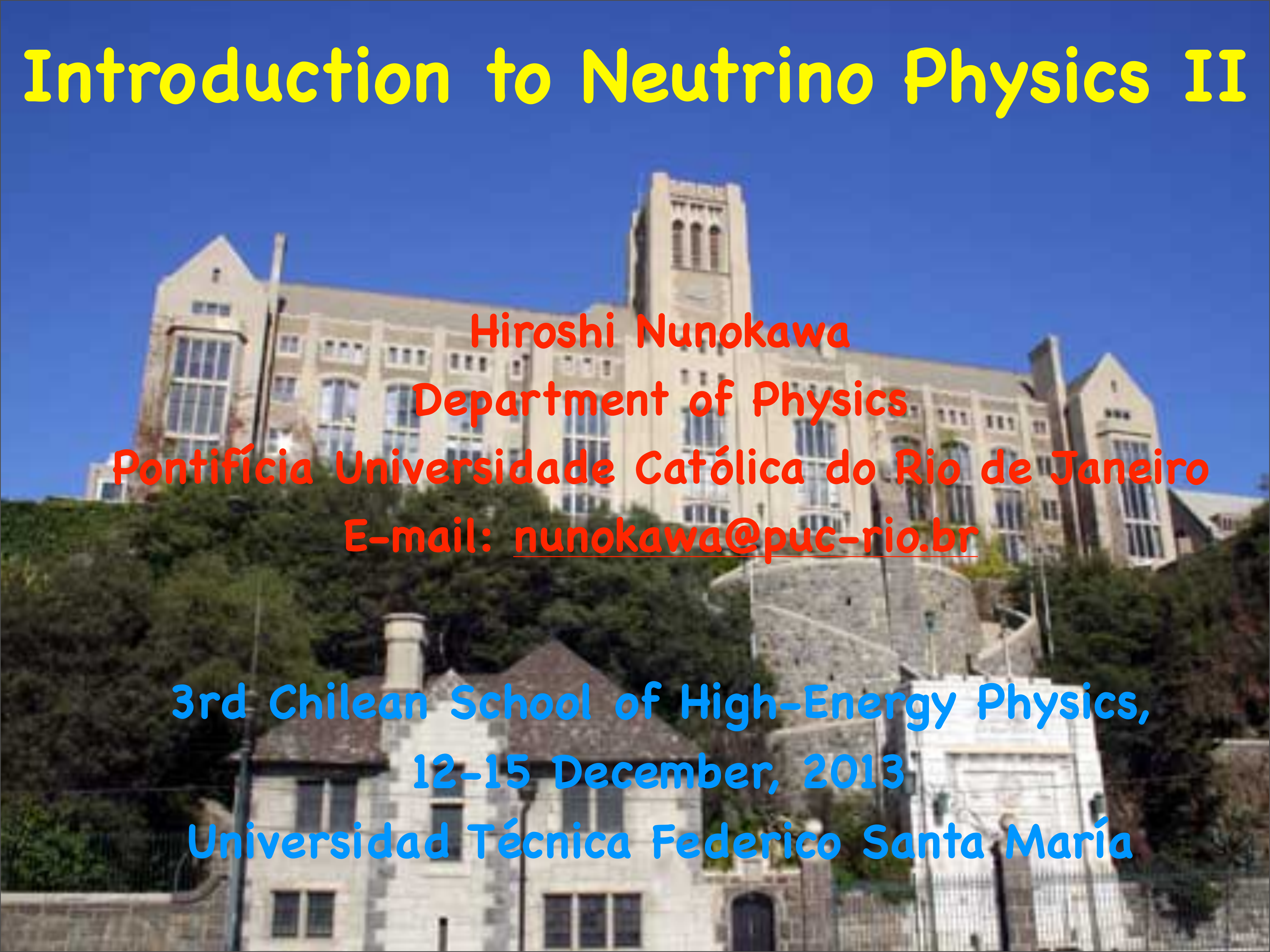


Introduction to Neutrino Physics II

Hiroshi Nunokawa
Department of Physics
Pontifícia Universidade Católica do Rio de Janeiro
E-mail: nunokawa@puc-rio.br

3rd Chilean School of High-Energy Physics,
12-15 December, 2013
Universidad Técnica Federico Santa María

Outline

Introduction

What we have learned so far

neutrino oscillations and present status

What we would like to know more

open questions and future prospects

Summary

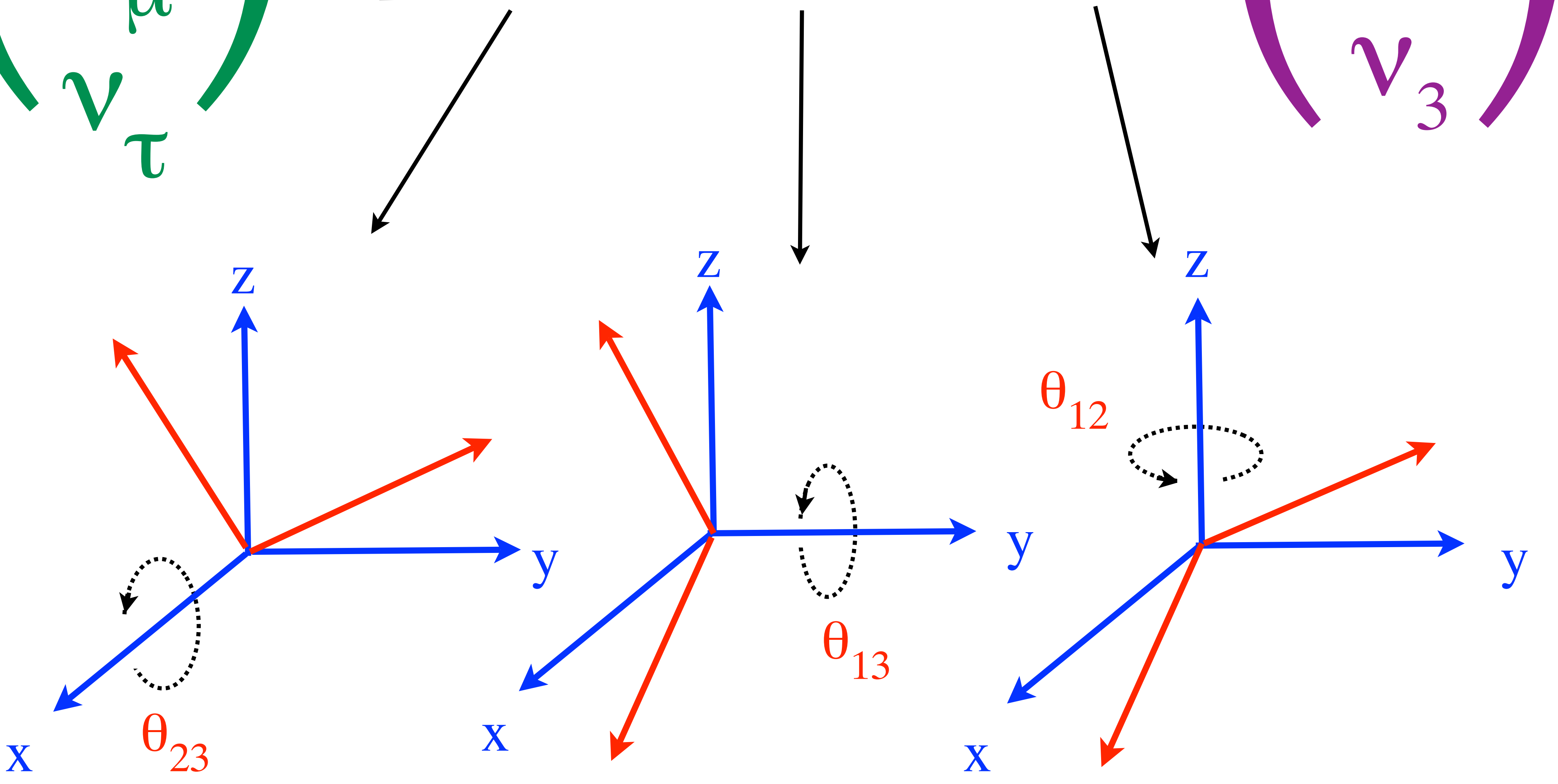
Current Status of the Knowledge on Mixing Parameteres

Current Status of the Knowledge on Mixing Paramteres

Effects of Three Falvor start to be important

mixing for three neutrinos

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underline{R_x(\theta_{23})}\,\underline{R_y(\theta_{13})}\,\underline{R_z(\theta_{12})}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



Mixing between 3 flavor of neutrinos

flavor eigenstates

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_\nu \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

mass eigenstates

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

$$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij}$$

atmospheric ν osc.

reactor ν osc.

solar ν osc.

θ_{ij}: mixing angle

δ: CP phase

for antineutrinos, $U_\nu \longrightarrow U_\nu^*$

Current Best Fitted Values of Mixing Parameters from the Global Analysis

See e.g., Capozzi et al, arXiv:1312.2878 [hep-ph]

$\Delta m_{21}^2 \equiv m_2^2 - m_1^2 \simeq 7.5 \times 10^{-5}\ \mathrm{eV}^2$ [error ~ 3%]

$\Delta m_{31}^2 \equiv m_3^2 - m_1^2 \simeq \Delta m_{32}^2 \equiv m_3^2 - m_2^2 \simeq\ \pm 2.4 \times 10^{-3} \mathrm{eV}^2$

[+(-): normal (inverted) mass hierarchy, error ~ 3%]

$\sin^2\theta_{12} \simeq 0.31$ [error ~ 5%]

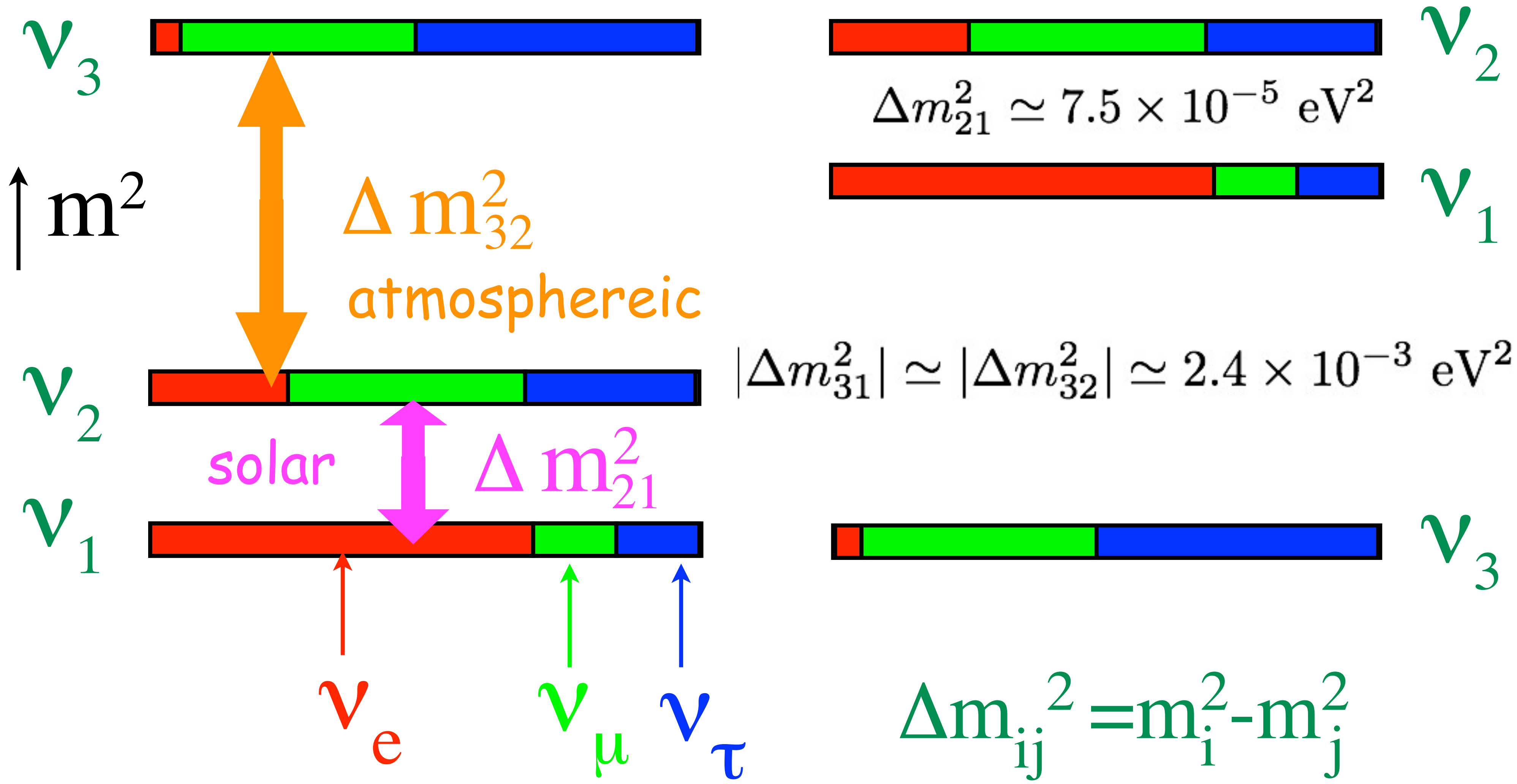
$\sin^2\theta_{23} \simeq 0.4 \text{ or } 0.6$ [error ~ 8%, ~ 0.4 is favored]

$\sin^2\theta_{13} \simeq 0.02$ [error ~ 7-10%]

$\delta_{CP} \in [-\pi, \pi]$: unknown but $\delta_{CP} < 0$ is favored

Mass Spectrum: normal or inverted ?

normal hierarchy **inverted hierarchy**



$\Delta m_{21}^2 \simeq 7.5 \times 10^{-5}\ \mathrm{eV}^2$

$|\Delta m_{31}^2| \simeq |\Delta m_{32}^2| \simeq 2.4 \times 10^{-3}\ \mathrm{eV}^2$

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

Mixing in the Quark Sector

$$V_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

Mixing in the Neutrino Sector

$$U_{\nu} = \begin{bmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0.178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{bmatrix}$$

M.C.Gonzalez-Garcia et al, JHEP12(2012) 123

Very different from the CKM Matrix!

What we would like to know more?

Open Questions

- What is the absolute mass scale of neutrinos?

- What is the mass ordering (hierarchy) of neutrinos? Is ν_3 heaviest (normal hierarchy) or lightest (inverted hiearchy)?

- Does CP violate in the lepton sector? Or what is the value of the CP phase, δ_{CP} ?

- Neutrinos are Marjorana or Dirac particles?

Open Questions

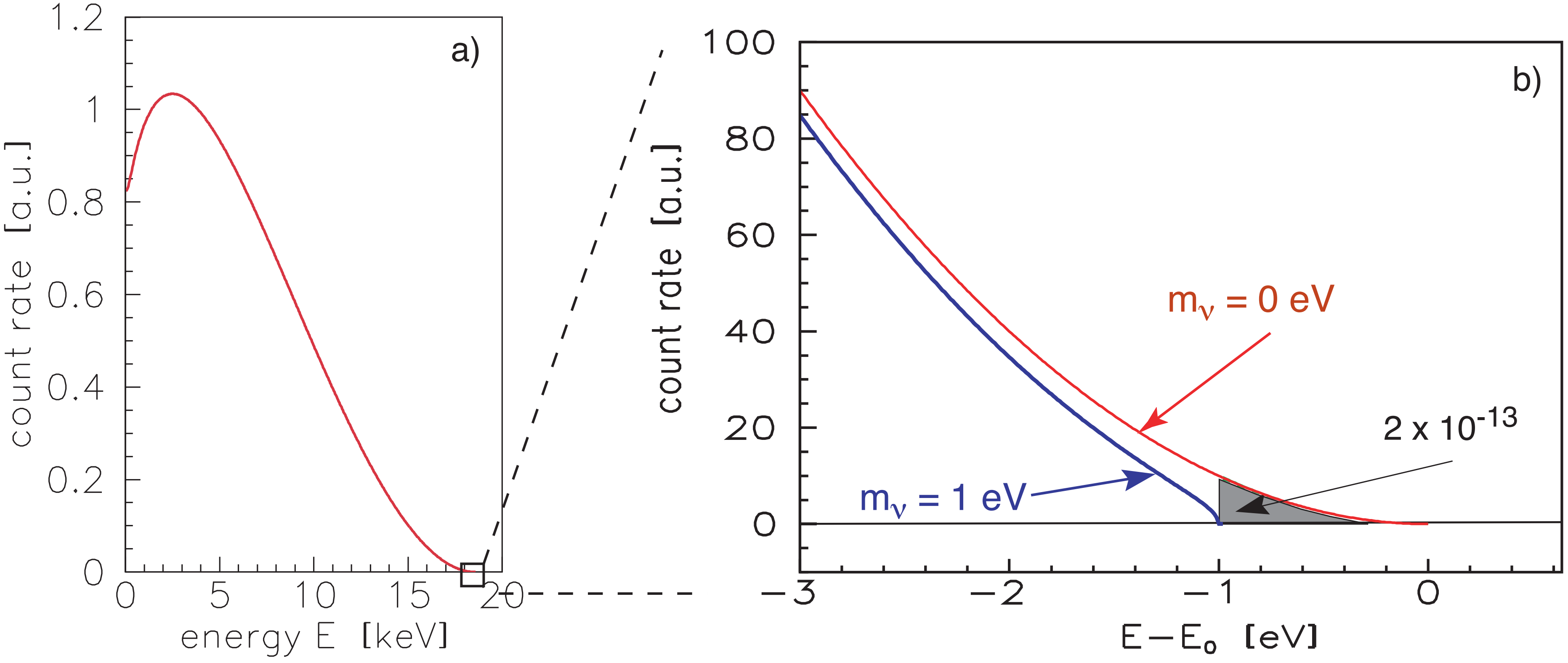
- Are there more than 3 neutrinos? Or steile neutrino exist?

- Do neutrinos have some new interactions or new properties (apart from masses and mixing) beyond what is expected form the starnd model?

Direct Measurement of Neutrino Mass

requires precise measurement of the end of the beta spectrum

$$^{3}H \rightarrow {}^{3}He + e^{-} + \nu_e$$

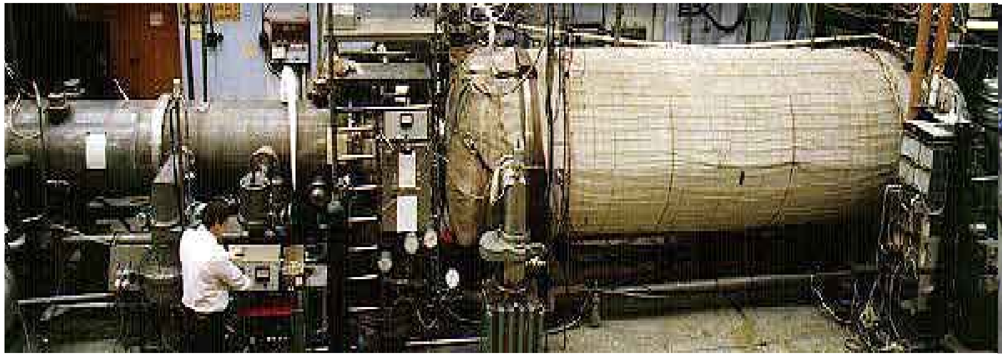


what can be actually measured is the effective mass,

$$m_\beta \equiv \left[m_1^2\,|U_{e1}|^2 + m_2^2\,|U_{e2}|^2 + m_3^2\,|U_{e3}|^2\right]^{\frac{1}{2}}$$

Status of previous tritium experiments

Mainz & Troitsk have reached their intrinsic limit of sensitivity



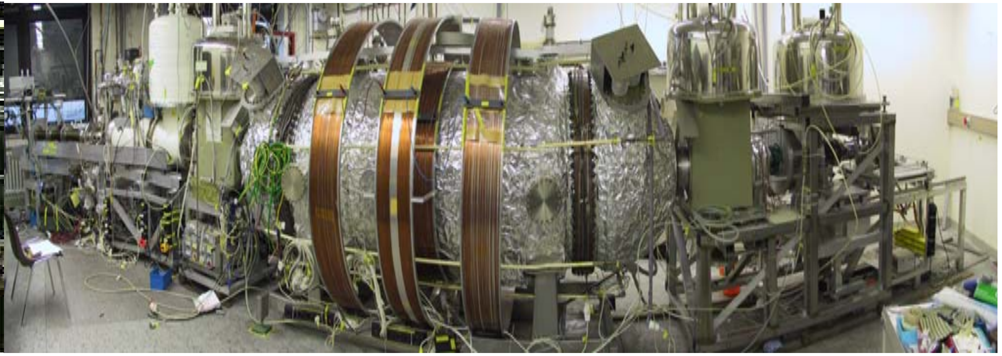
Troitsk

windowless gaseous T_2 source

analysis 1994 to 1999, 2001

$m_\nu^2 = -2.3 \pm 2.5 \pm 2.0 \text{ eV}^2$

$m_\nu \leq$ 2.2 eV (95% CL.)



Mainz

quench condensed solid T_2 source

analysis 1998/99, 2001/02

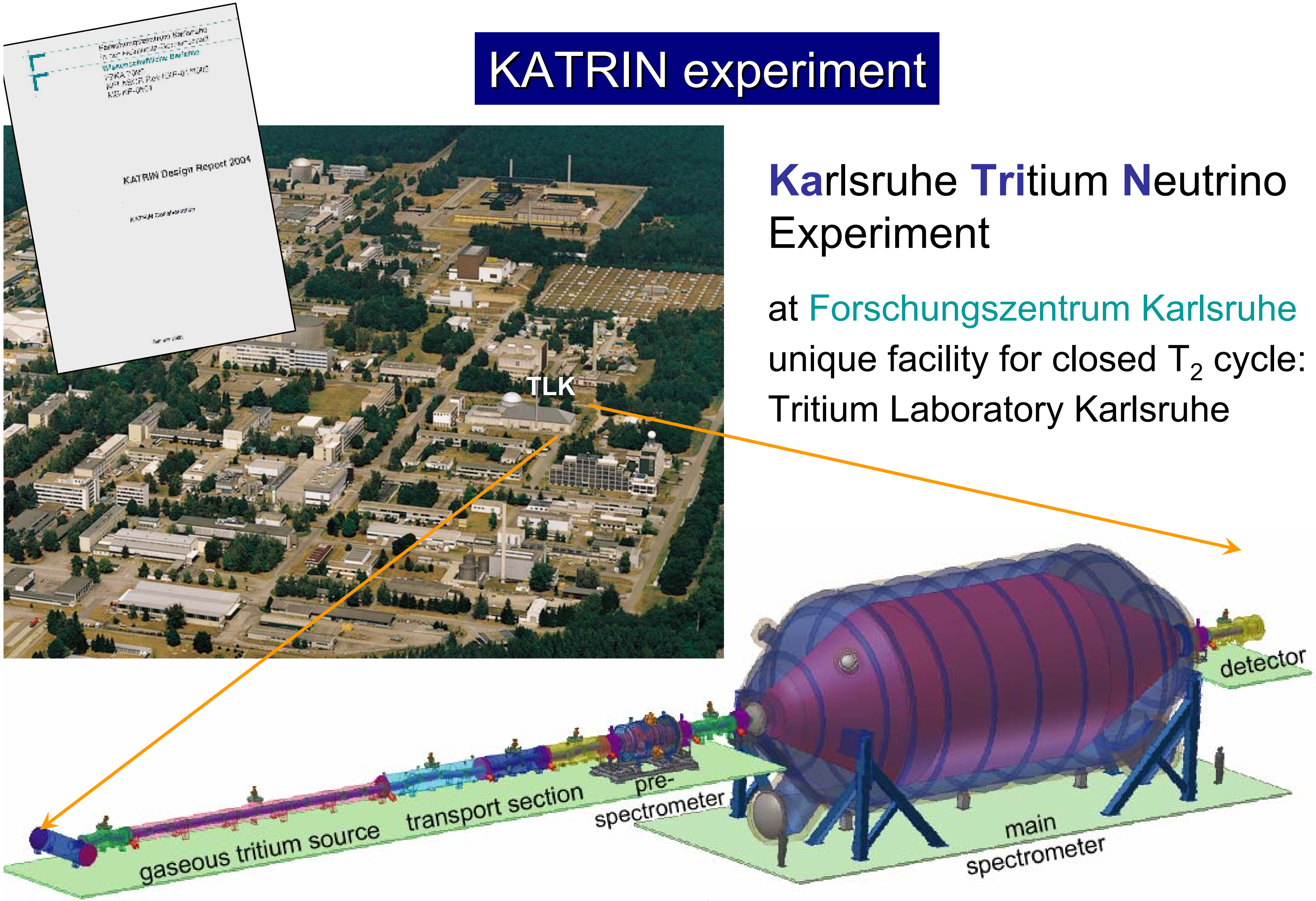
$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1 \text{ eV}^2$

$m_\nu \leq$ 2.2 eV (95% CL.)

both experiments now used for systematic investigations

Karlsruhe **Tri**tium **N**eutrino Experiment

KATRIN experiment



KATRIN Design Report 2004

KATRIN Collaboration

Karlsruhe **Tri**tium **N**eutrino Experiment

at Forschungszentrum Karlsruhe
unique facility for closed T_2 cycle:
Tritium Laboratory Karlsruhe

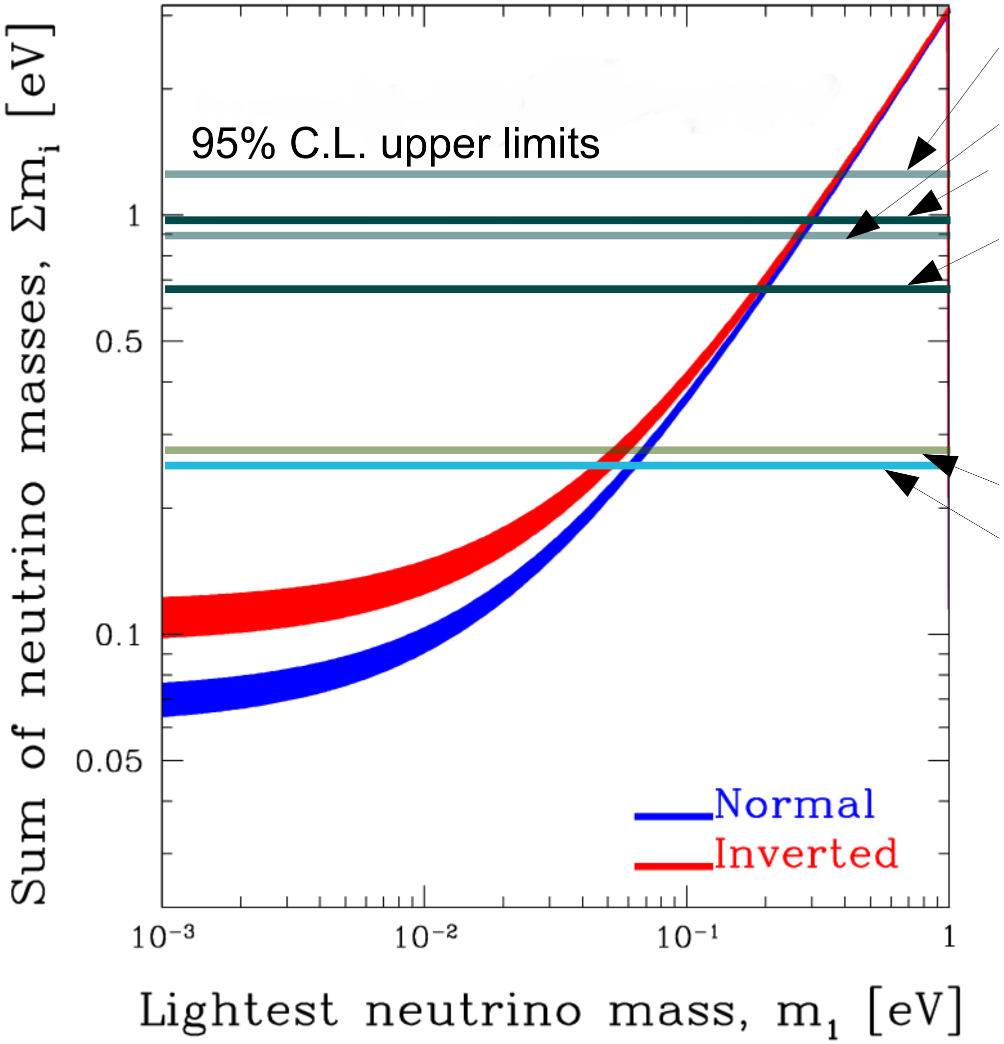
~ 75 m linear setup with 40 s.c. solenoids

sensitivity: m_ν ~0.2 eV @90% CL

Cosmological Bounds on Neutrino Masses

Cosmology is sensitive to sum of the neutrino masses

Post-Planck... Ade et al.[Planck] 2013



ΛCDM+neutrino mass (7 parameters)

WMAP (9 years)

W9 + ACT

Planck + WMAP Polarisation

Planck + WP + ACT $\ell > 1000$ + SPT $\ell > 2000$

$$\sum m_\nu < 0.66 \text{ eV} \quad (95\% \text{ C.L.})$$

Best CMB-only bound

W7+ matter power spectrum + HST H_0

Planck + WP + (ACT $\ell > 1000$ + SPT $\ell > 2000$) + baryon acoustic oscillations

$$\sum m_\nu < 0.25 \text{ eV} \quad (95\% \text{ C.L.})$$

Best minimal bound

Formally similar to the pre-Planck best minimal bound, but arguably less prone to issues of nonlinearities.

Y. Wong @ NuFact2013, Beijing, August, 2013

Cosmology may determine better neutrino masses

The cosmic neutrino background: energy density...

The present-day neutrino energy density depends on whether the neutrinos are relativistic or nonrelativistic.

- **Relativistic** (m << T):

Photon energy density

$$\rho_\nu = \frac{7}{8}\frac{\pi^2}{15}T_\nu^4 = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma \longleftarrow \frac{3\rho_\nu}{\rho_\gamma} \sim 0.68$$

- **Nonrelativistic** (m >> T ~ 10^{-4} eV):

ΛCDM (since Planck)

$$\rho_\nu = m_\nu n_\nu \longrightarrow \boxed{\Omega_{\nu,0}h^2 = \frac{m_\nu}{94\,\mathrm{eV}} > 0.1\,\% h^2}$$

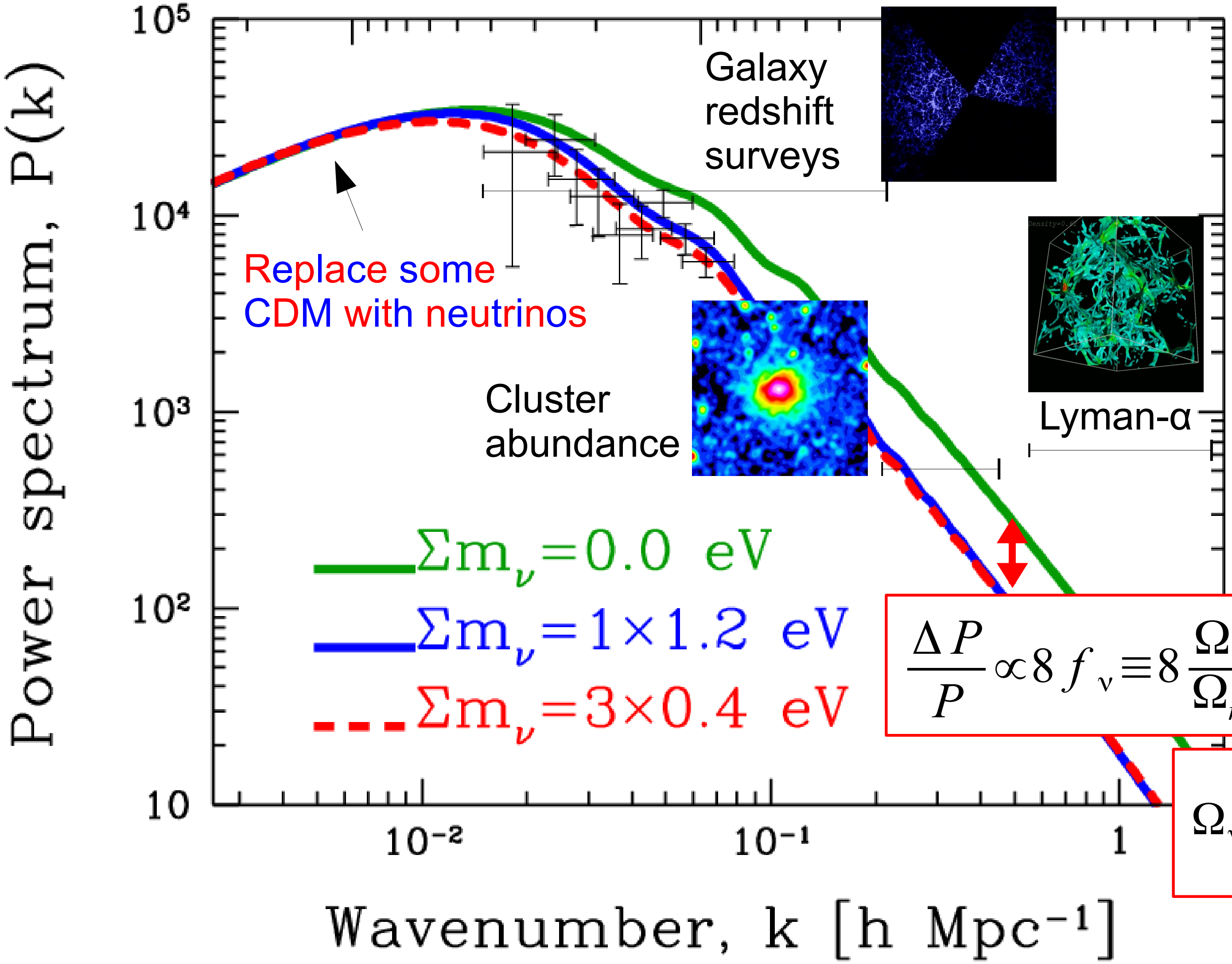
From neutrino oscillations $m_\nu > 0.05$ eV

Neutrino dark matter!

neutrinos tend to supress the smaller scale structures

Large-scale matter distribution...

$$P(k) = \langle |\delta(k)|^2 \rangle$$



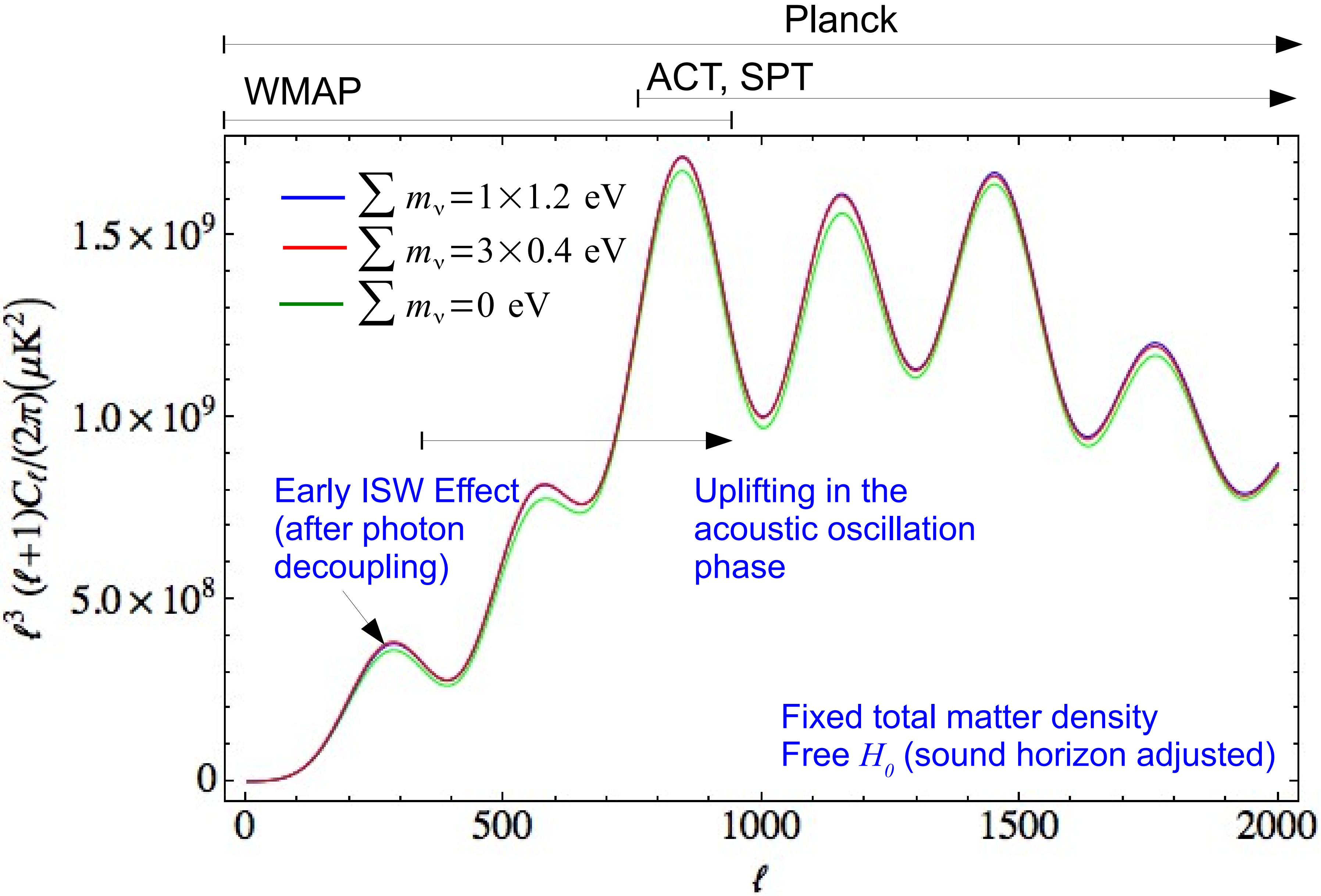
f_ν = Neutrino fraction

$$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$$

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{94\,\mathrm{eV}}$$

Y. Y. Y. Wong @ NuFact2013, Beijing, August, 2013

CMB anisotropies...



Early ISW Effect (after photon decoupling)

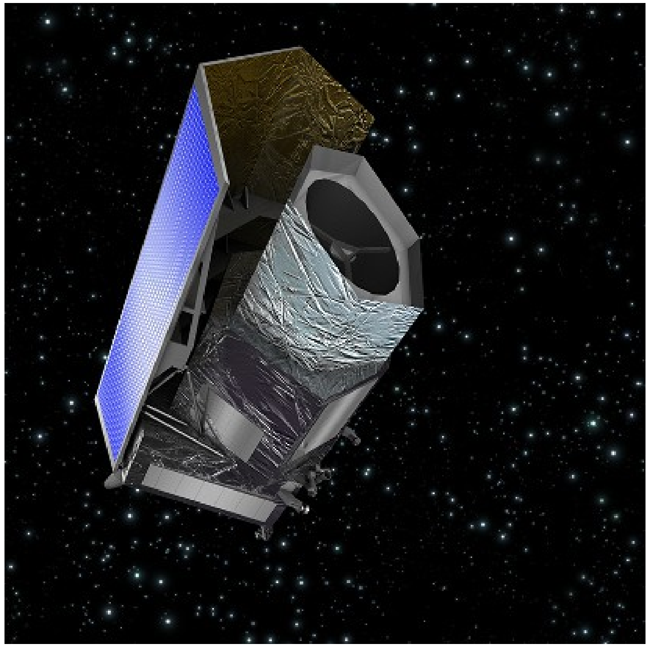
Uplifting in the acoustic oscillation phase

Fixed total matter density
Free H_0 (sound horizon adjusted)

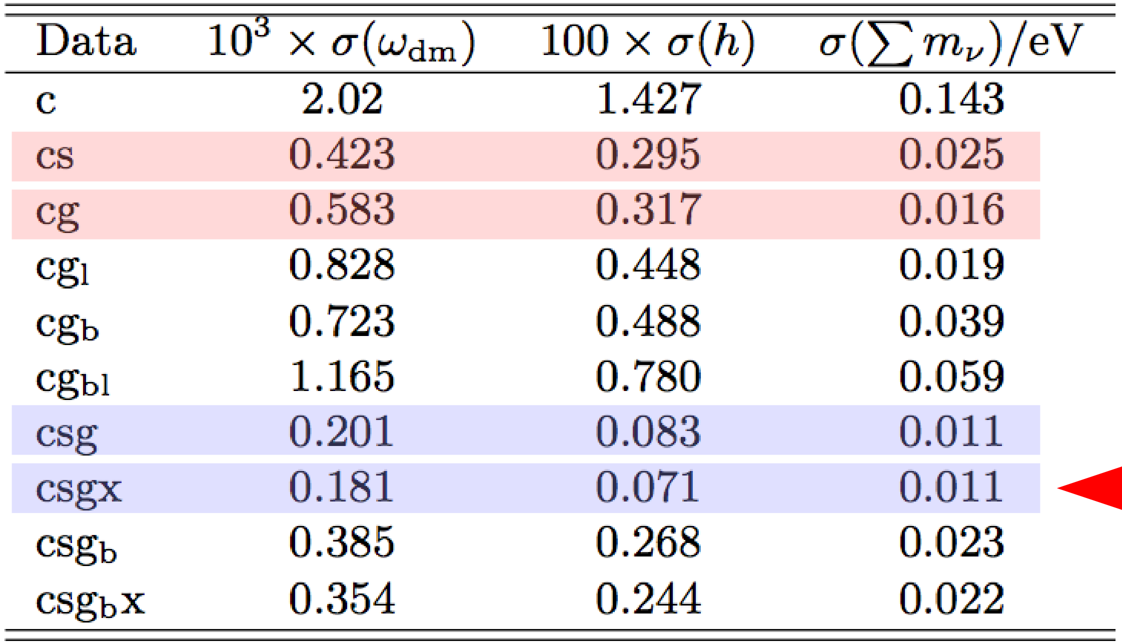
Cosmology may determine better neutrino masses

Expected sensitivity...

ESA Euclid Misson



A **7-parameter forecast**: Hamann, Hannestad & Y^{3}W 2012



Data	$10^3 \times \sigma(\omega_{\rm dm})$	$100 \times \sigma(h)$	$\sigma(\sum m_\nu)/\mathrm{eV}$
c	2.02	1.427	0.143
cs	0.423	0.295	0.025
cg	0.583	0.317	0.016
$\mathrm{cg_l}$	0.828	0.448	0.019
$\mathrm{cg_b}$	0.723	0.488	0.039
$\mathrm{cg_{bl}}$	1.165	0.780	0.059
csg	0.201	0.083	0.011
csgx	0.181	0.071	0.011
$\mathrm{csg_b}$	0.385	0.268	0.023
$\mathrm{csg_b x}$	0.354	0.244	0.022

Most optimistic

Σm_ν potentially detectable at 5σ+ with Planck+Euclid (assuming nonlinearities to be completely under control)

c = CMB (Planck); g = Euclid galaxy clustering
s = Euclid cosmic shear; x = Euclid shear-galaxy cross

Massive Neutrinos: Dirac or Majorana ?

If neutrinos have masses, they can be either Dirac or Majorana Fermions

Dirac Fermion: particles and anti-particles are different, like electron

Majorana Fermion: particles and anti-particles are identical (such particles can not have electric charge)

Majorana Fermion

particle = anti-particle

$$\chi^c = \chi$$

c: charge conjugation $\psi^c \equiv C\gamma^0\psi^*$

$$\chi \equiv \psi_L + \psi_L^c \quad \text{or } \omega \equiv \psi_R^c + \psi_R$$

$$L_M = -\frac{1}{2}M\,\bar{\chi}\,\chi = -\frac{1}{2}M(\,\overline{\psi}_L^c\,\psi_L + \text{h.c.})$$

$\rightarrow$ + 2 CP violating phases

Majorana CP phases can not be measured by neutrino oscillation

Dirac vs Majorana Mass term

Dirac: $L_D = -m\ \overline{\nu}_R \nu_L - m\ \overline{\nu}_L \nu_R$

→ conserve lepton number

Majorana: $L_M = \frac{1}{2} M\ \overline{\nu}_L^c \nu_L$

→ violate lepton number

only L_D → Dirac particle

L_M or $L_M + L_D$ → Majorana particle

If neutrinos are Majorana particles,

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_\nu \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_\nu = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{-i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij}$$

$$U_\nu \longrightarrow U_\nu \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{bmatrix}$$

Majorana CP phases

⟶ can not be measured by oscillation

Seesaw Mechanism


Minkowski


Yanagida


Gell-Mann


Ramond
Slansky

$$-\mathcal{L}_{\mathbf{mass}} = m\overline{\nu}_L\nu_R + \frac{1}{2}M\overline{\nu}^c_R\nu_R + \mathrm{h.c.}$$

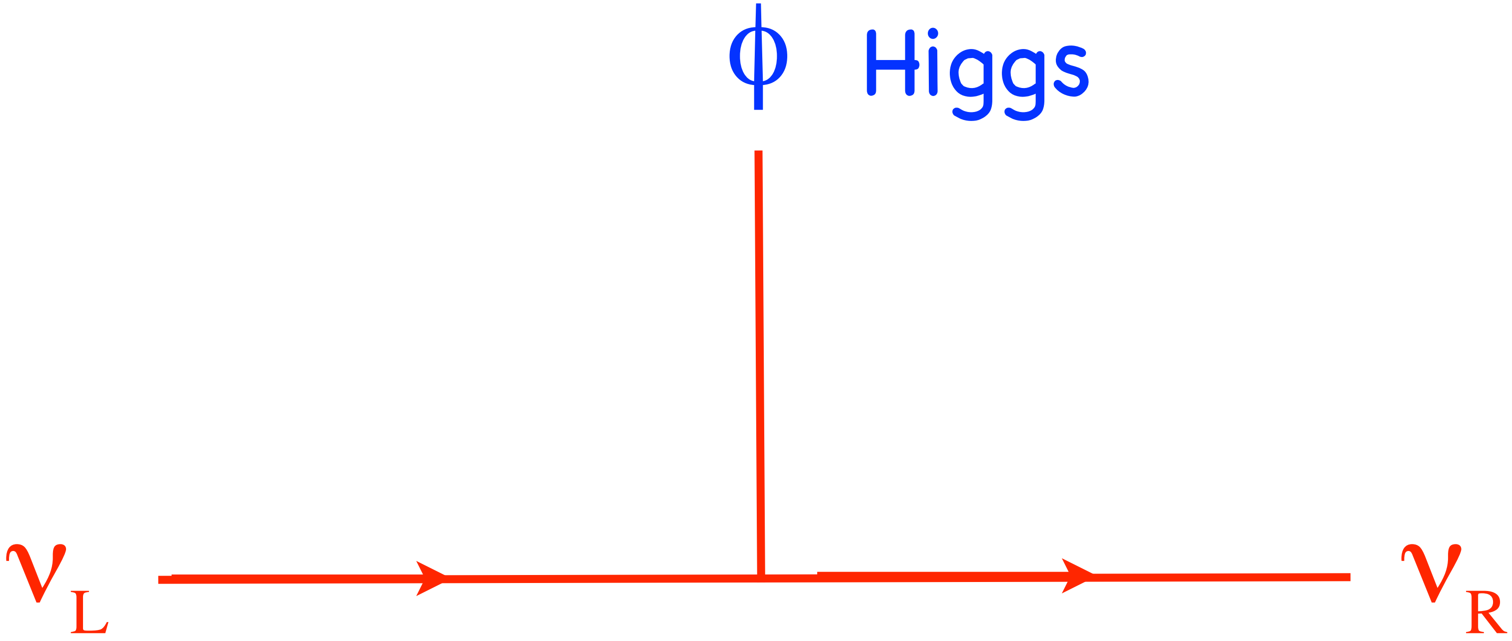
$$= \frac{1}{2}\left[\overline{\nu}^c_L\ \overline{\nu}_R\right]\begin{bmatrix}0 & m\\ m & M\end{bmatrix}\begin{bmatrix}\nu_L\\ \nu^c_R\end{bmatrix} + \mathrm{h.c.}$$

Eigenvalues of the mass matrix

$$m_\nu \approx \frac{m^2}{M},\ m_{\mathrm{heavy}} \approx M$$

$$(m \ll M)$$

Order of m ~ masses of charged leptons

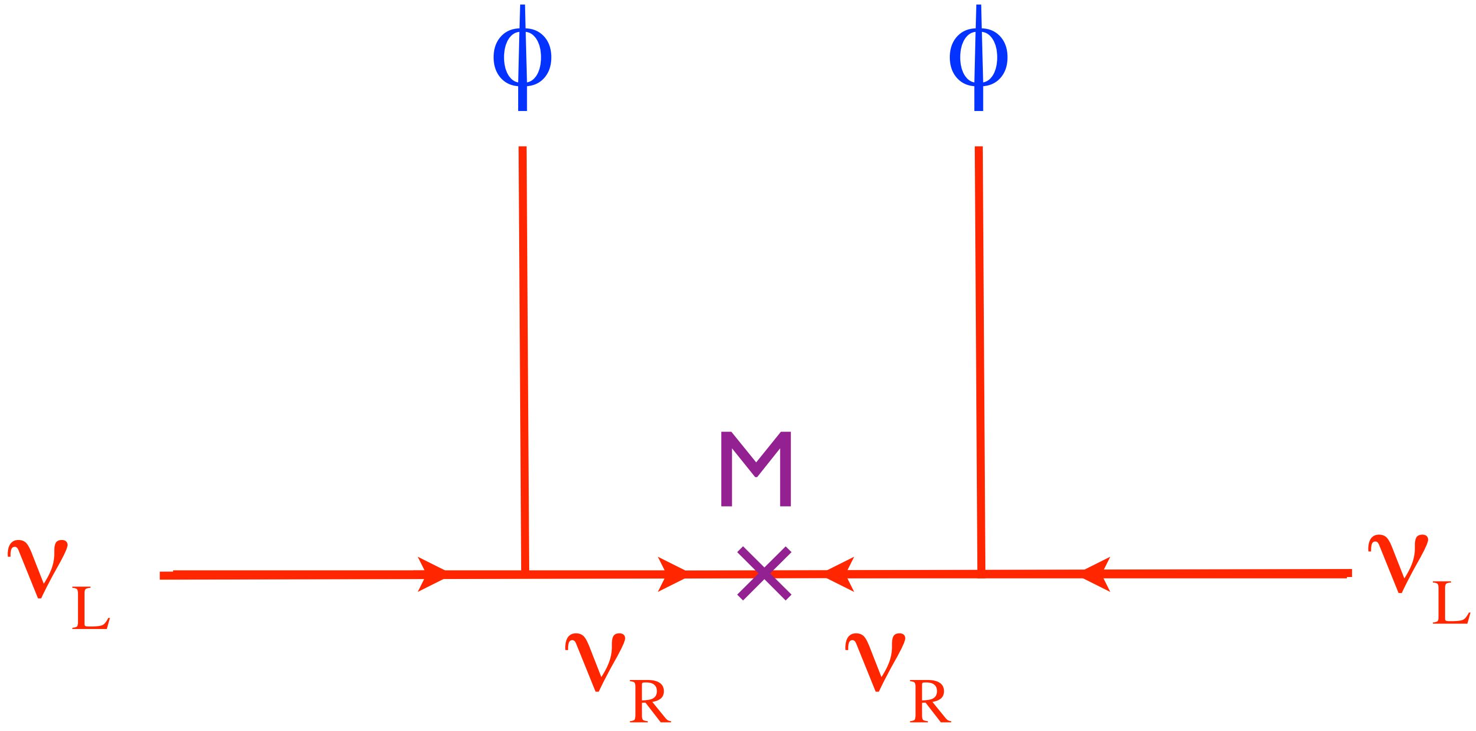


$$m \sim f \langle \phi \rangle$$

f: Yukawa coupling

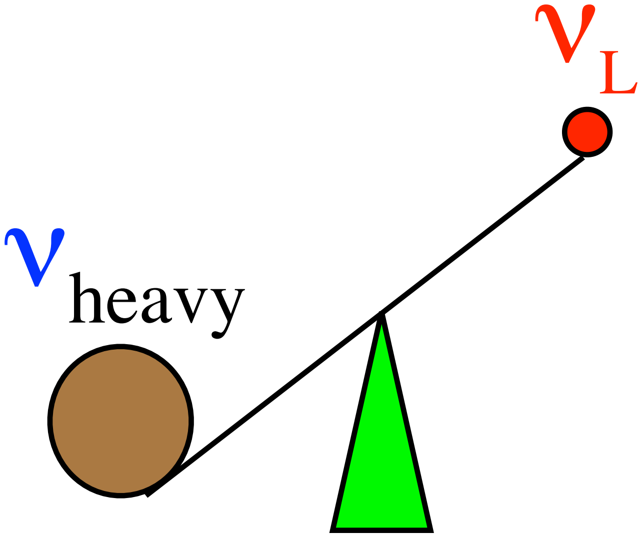
$\langle \phi \rangle$: vacuum expectation value of Higgs ~ 250 GeV

Seesaw Mechanism



$$m_\nu \approx \frac{m^2}{M} \qquad m \ll M$$

M ~ GUT scale



CP Violation in the lepton sector may explain asymetry between matter and anti-matter in the universe

Bariogenesis via Leptogensis

Yanagida and Fukugita, PLB174(1986)45

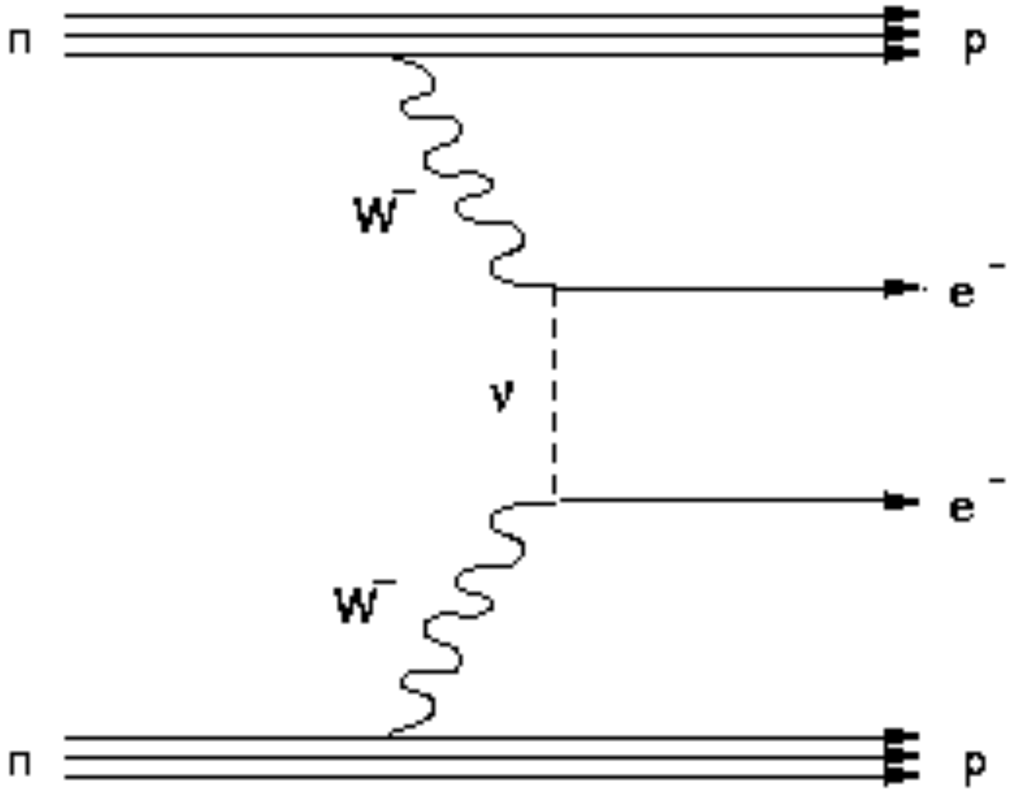
Sakharov's conditions for generating asymmetric universe starting from $\Delta B = 0$

- Baryon number non-conservation
- C and CP violation
- Deviation from thermal equilibrium

Leptogensis can satisfy all of them

How to test Majorana nature of neutrinos?

neutinoless double beta decay



violates lepton number by 2 units

decay rate ∝ effective neutrino mass

$$m_{0\nu\beta\beta} \equiv \left| \, m_1|U_{e1}|^2 + m_2|U_{e2}|^2 \mathrm{e}^{i\alpha_{21}} + m_3|U_{e3}|^2 \mathrm{e}^{i\alpha_{31}} \right|$$

α_{21}, α_{31} : Majorana CP phases

What is actually measured is the decay rate or life time of the 0νββ decay

half life time

effective mass

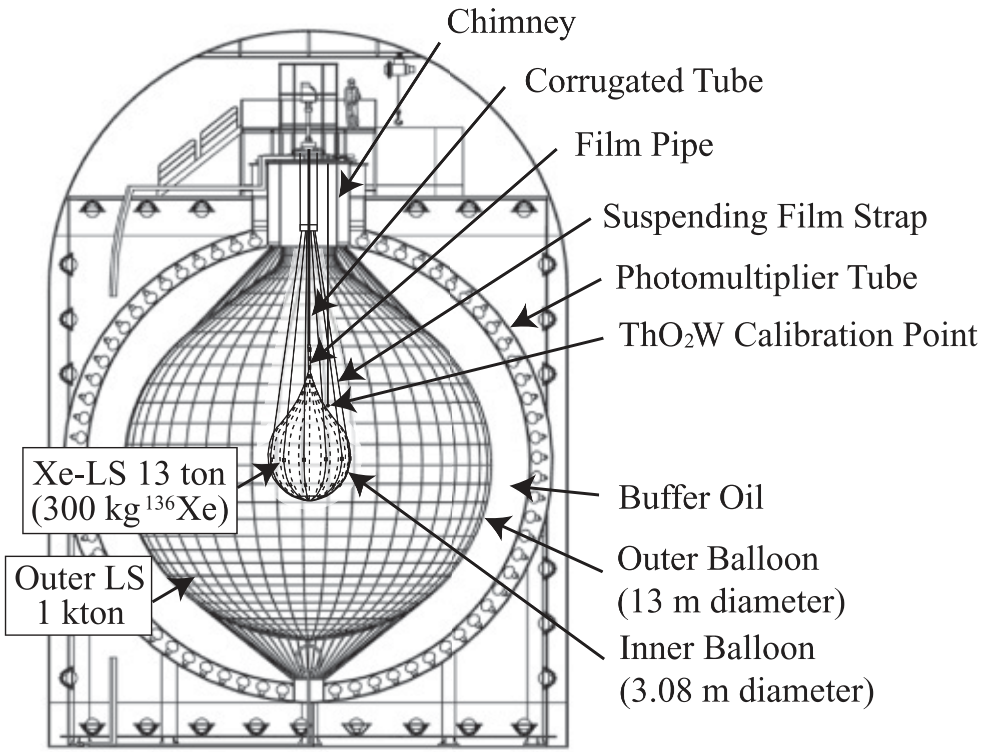
$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu} \left| \mathcal{M}^{(0\nu)} \right|^2 (m_{0\nu\beta\beta})^2$$

phase spcae factor

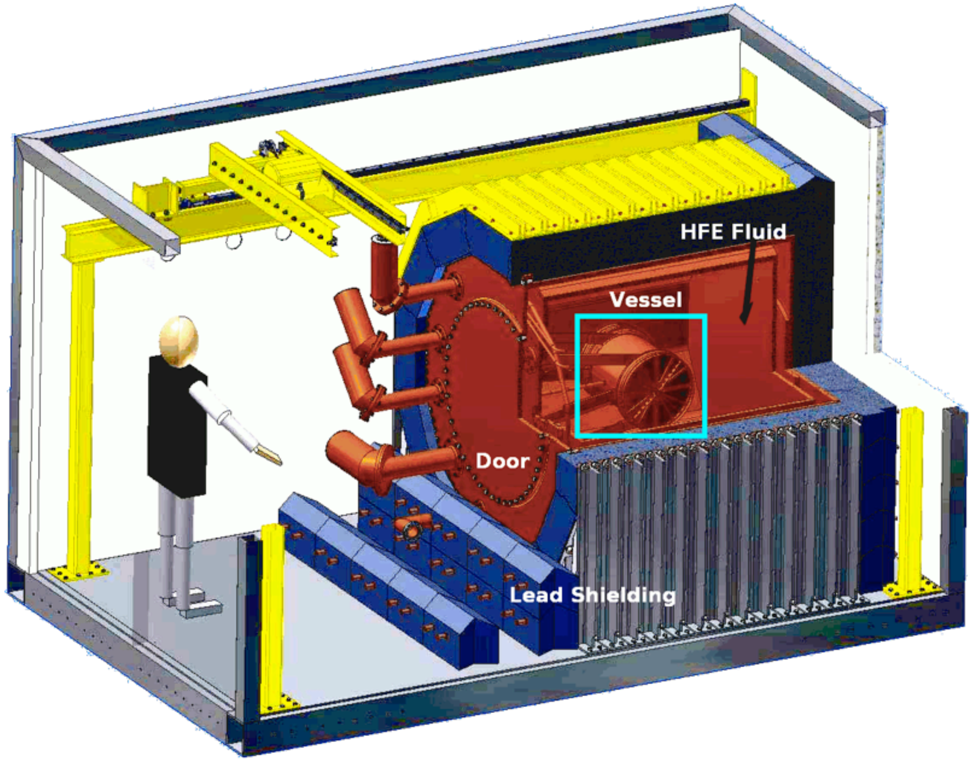
Nuclear Matrix Element (NME)

Problem: NME has a large uncertainty, typically factor of ~2 or more

Current bound on the effective Majorana mass



KamLAND-Zen detector



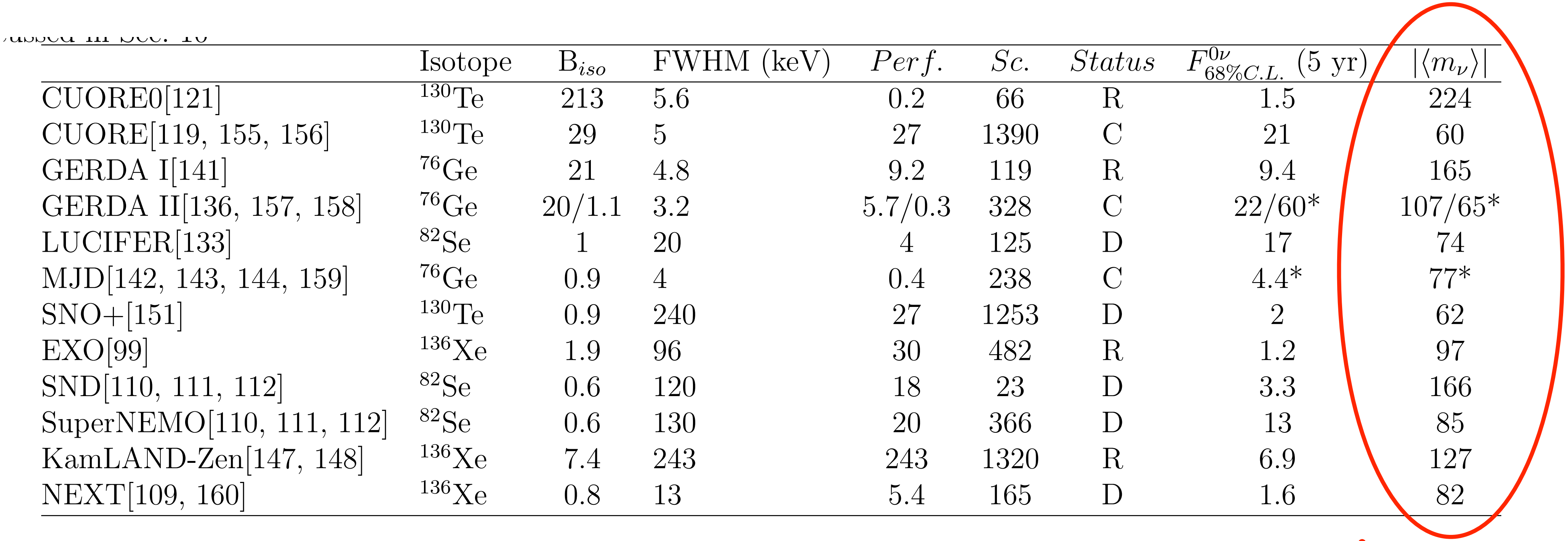
Exo-200 detector

Exo-200: $T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 1.6 \times 10^{25}\ \mathrm{yr}\ (90\%\mathrm{CL})$

KamLAND: $T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 1.9 \times 10^{25}\ \mathrm{yr}\ (90\%\mathrm{CL})$

Combined: $m_{0\nu\beta\beta} < (0.12 - 0.25)\ \mathrm{eV}\ (90\%\mathrm{CL})$

Expected Sensitivities of some of the advanced 0νββ decay experiments

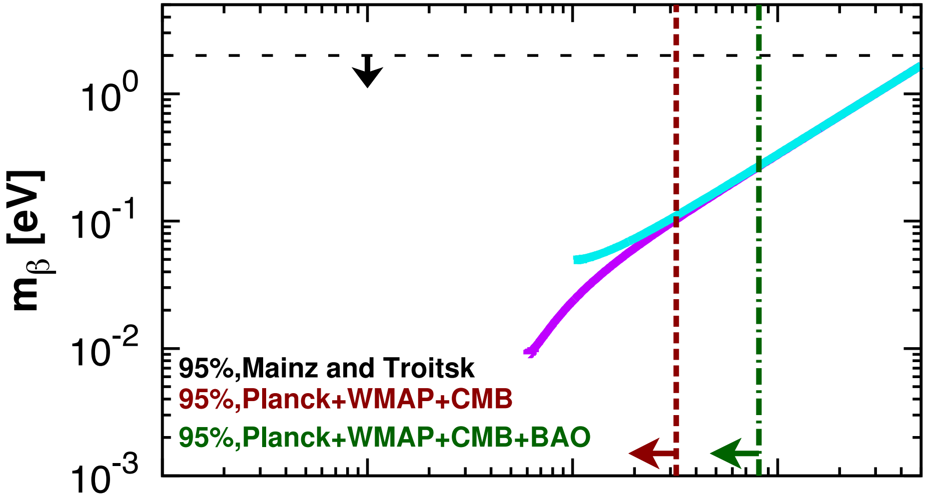


	Isotope	B_{iso}	FWHM (keV)	$Perf.$	$Sc.$	$Status$	$F^{0\nu}_{68\%C.L.}$ (5 yr)	$\lvert\langle m_\nu\rangle\rvert$
CUORE0[121]	^{130}Te	213	5.6	0.2	66	R	1.5	224
CUORE[119, 155, 156]	^{130}Te	29	5	27	1390	C	21	60
GERDA I[141]	^{76}Ge	21	4.8	9.2	119	R	9.4	165
GERDA II[136, 157, 158]	^{76}Ge	20/1.1	3.2	5.7/0.3	328	C	22/60*	107/65*
LUCIFER[133]	^{82}Se	1	20	4	125	D	17	74
MJD[142, 143, 144, 159]	^{76}Ge	0.9	4	0.4	238	C	4.4*	77*
SNO+[151]	^{130}Te	0.9	240	27	1253	D	2	62
EXO[99]	^{136}Xe	1.9	96	30	482	R	1.2	97
SND[110, 111, 112]	^{82}Se	0.6	120	18	23	D	3.3	166
SuperNEMO[110, 111, 112]	^{82}Se	0.6	130	20	366	D	13	85
KamLAND-Zen[147, 148]	^{136}Xe	7.4	243	243	1320	R	6.9	127
NEXT[109, 160]	^{136}Xe	0.8	13	5.4	165	D	1.6	82

in meV

Cremonesi and Pavan, arXiv: 1310.4692 [physics.ins-det]

summary of the current bounds on mass related observables



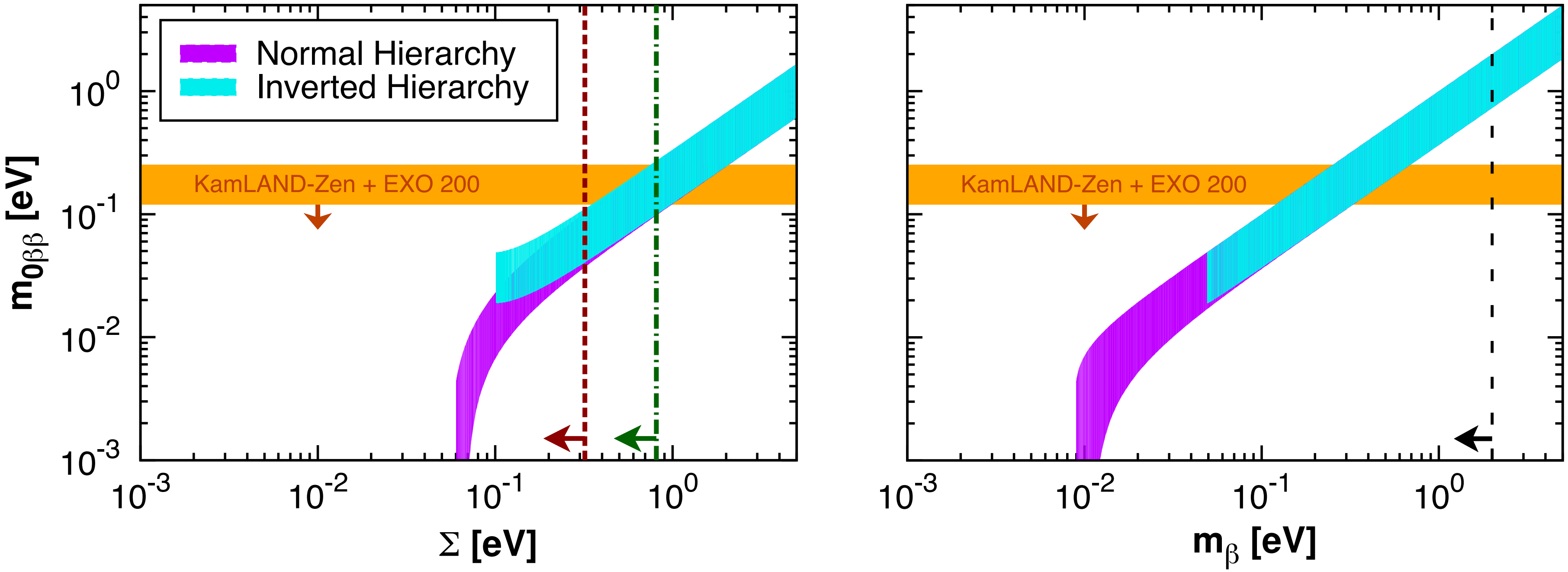
Inputs:

Δm^2_{21}= 7.5X10^{-5} eV^2

$\sin^2\theta_{21}$= 0.302

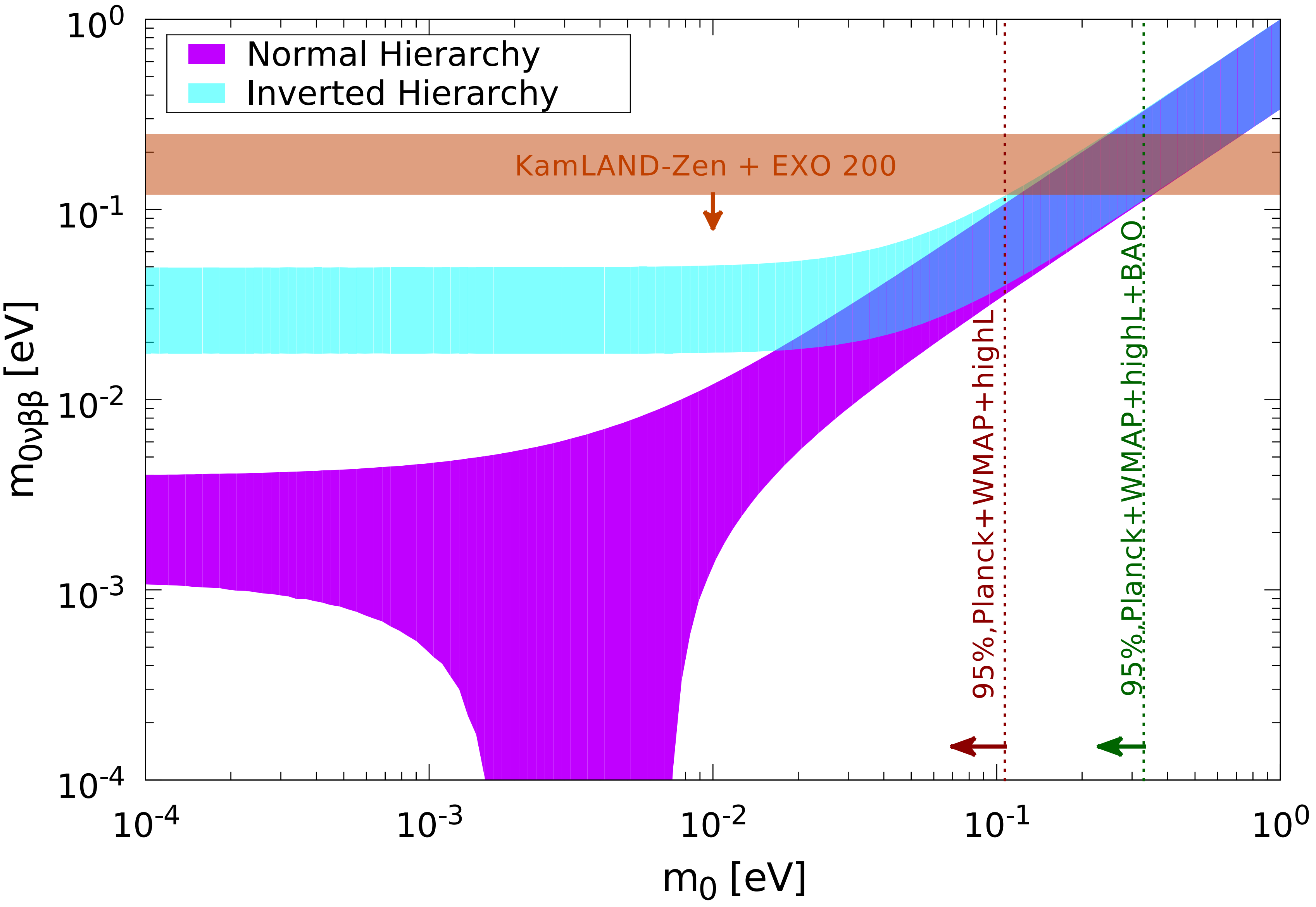
$|\Delta m^2_{31}|$= 2.47X10^{-3} eV^2

$\sin^2\theta_{31}$= 2.27X10^{-2}



prepared by A.Quiroga

Effective Majorana Mass as a function of the lightest neutrino mass



$m_0 \equiv m_1$ **for normal hierarchy**

$m_0 \equiv m_3$ **for inverted hierarchy**

prepared by A.Quiroga

How to Determine Mass Hierarchy and KM type CP phase?

How to Determine Mass Hierarchy and KM type CP phase?

The most promising way is provided by long-baseline oscillation experiments

possible alternatives, e.g., PINGU?

MSW (Matter) effect is sensitive to the mass hierarchy

matter potential $\propto$ effective ν_e ($\overline{\nu}_e$) mass

$$V_e(r) = \sqrt{2} G_F N_e(r)$$ for ν_e

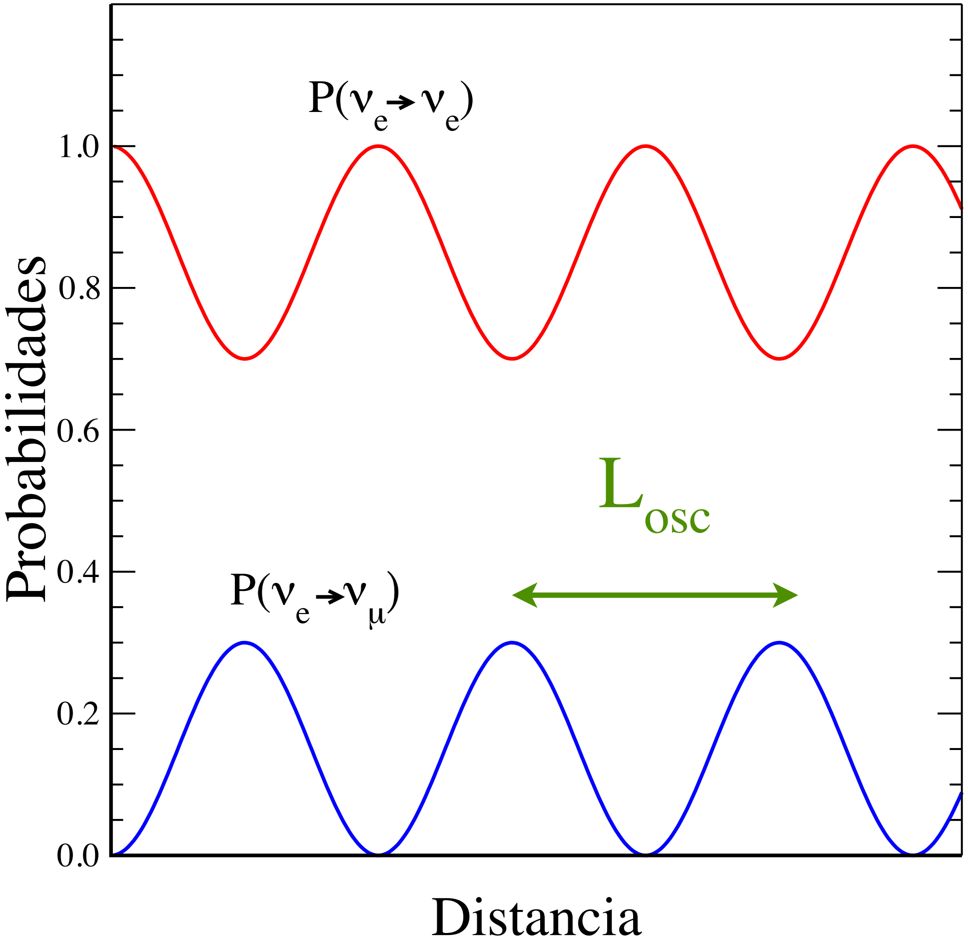
$$V_e(r) = -\sqrt{2} G_F N_e(r)$$ for $\overline{\nu}_e$

normal hierarchy ν_1 ($\sim\nu_e$) is lighter

inverted hierarchy ν_1 ($\sim\nu_e$) is heavier

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$



oscillation length

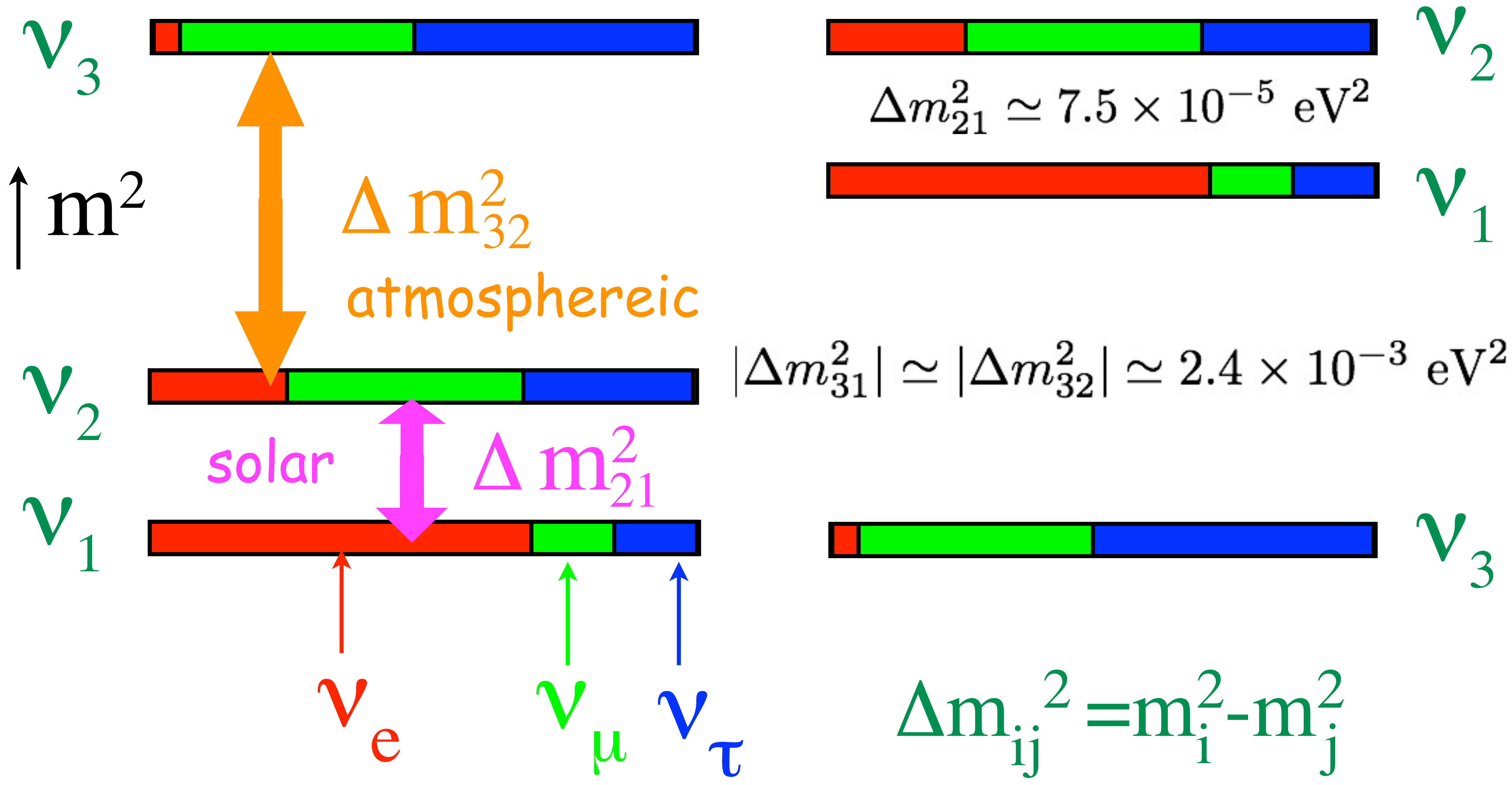
$$L_{osc} = \frac{4\pi E}{\Delta m^2}$$

$$\approx 2.5 \frac{E}{\text{MeV}} \frac{1\ \text{eV}^2}{\Delta m^2}\ \text{m}$$

By choosing E and L, one can probe very small or the desired value of Δm^2

Mass Spectrum: normal or inverted ?

normal hierarchy **inverted hierarchy**



ν_3

$\uparrow m^2$

Δm^2_{32}

atmosphereic

ν_2

solar Δm^2_{21}

ν_1

ν_e ν_μ ν_τ

ν_2

$\Delta m^2_{21} \simeq 7.5 \times 10^{-5}\ \mathrm{eV}^2$

ν_1

$|\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.4 \times 10^{-3}\ \mathrm{eV}^2$

ν_3

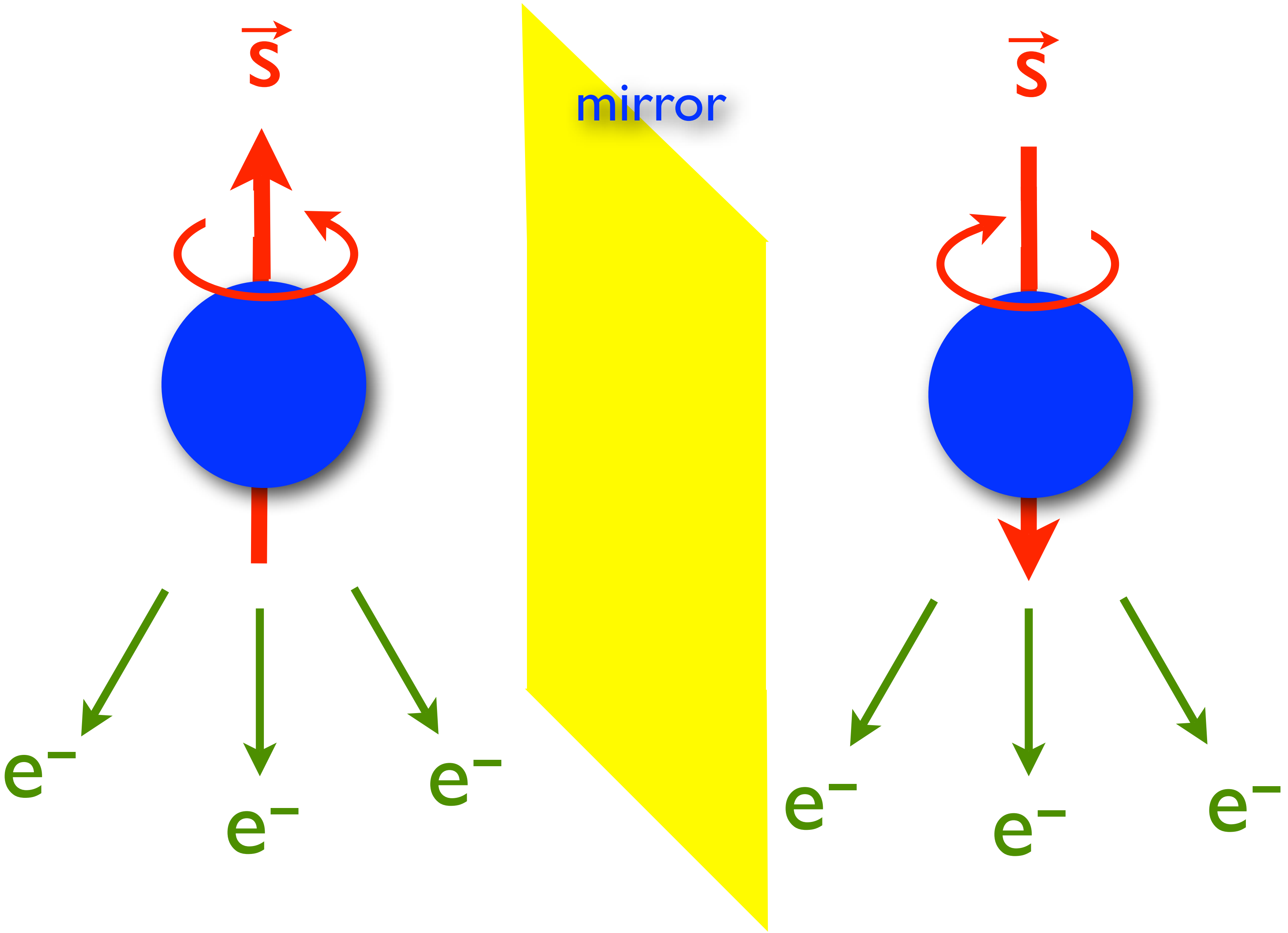
$\Delta m_{ij}^2 = m_i^2 - m_j^2$

CP Violation in Neutrino Oscillation

Electroweak Interaction Violates P

$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$

1957

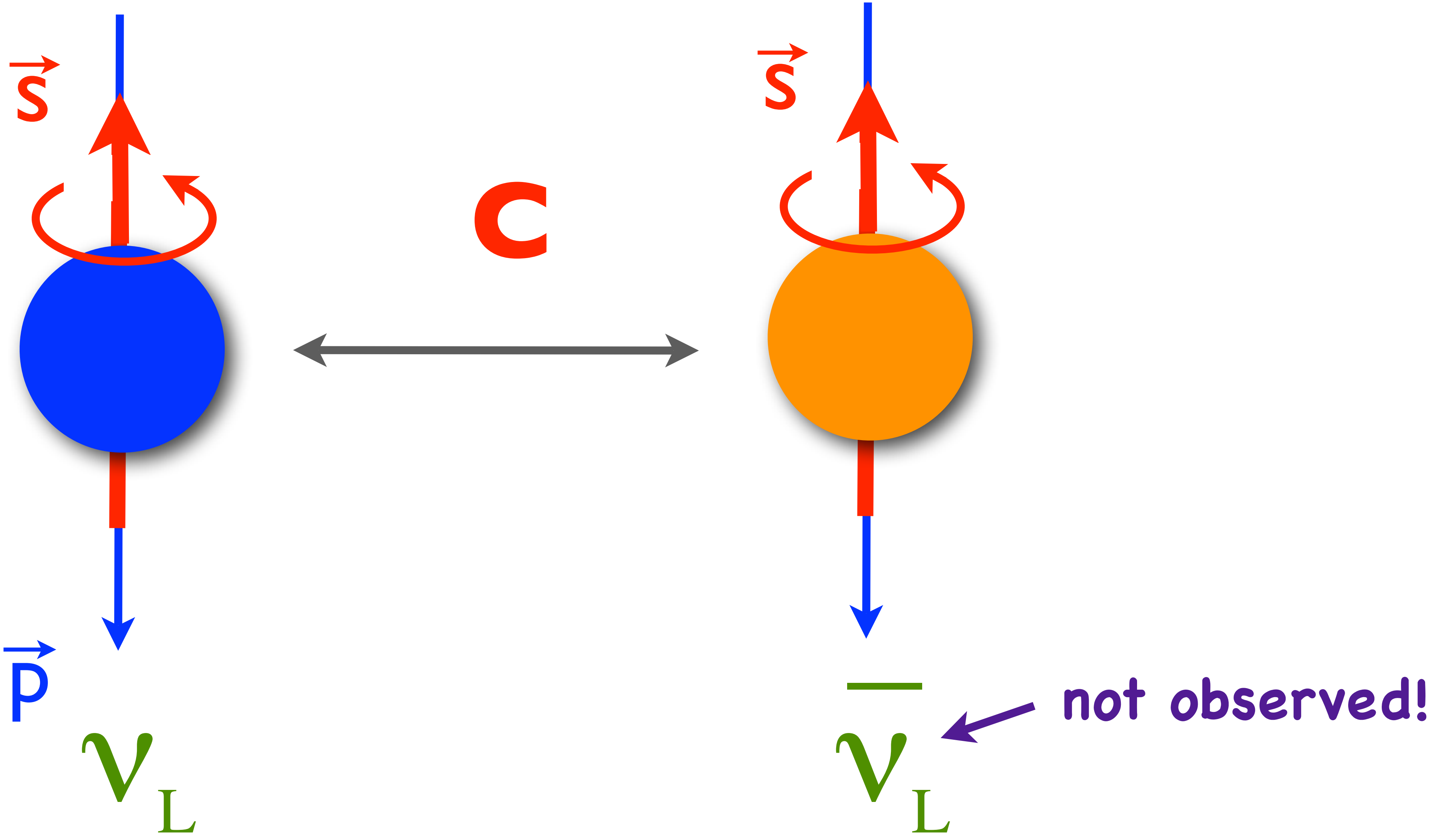


T.D.Lee

C.N.Yang

C. S. Wu

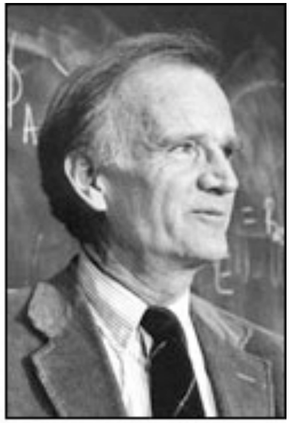
Electroweak Interaction violates C!



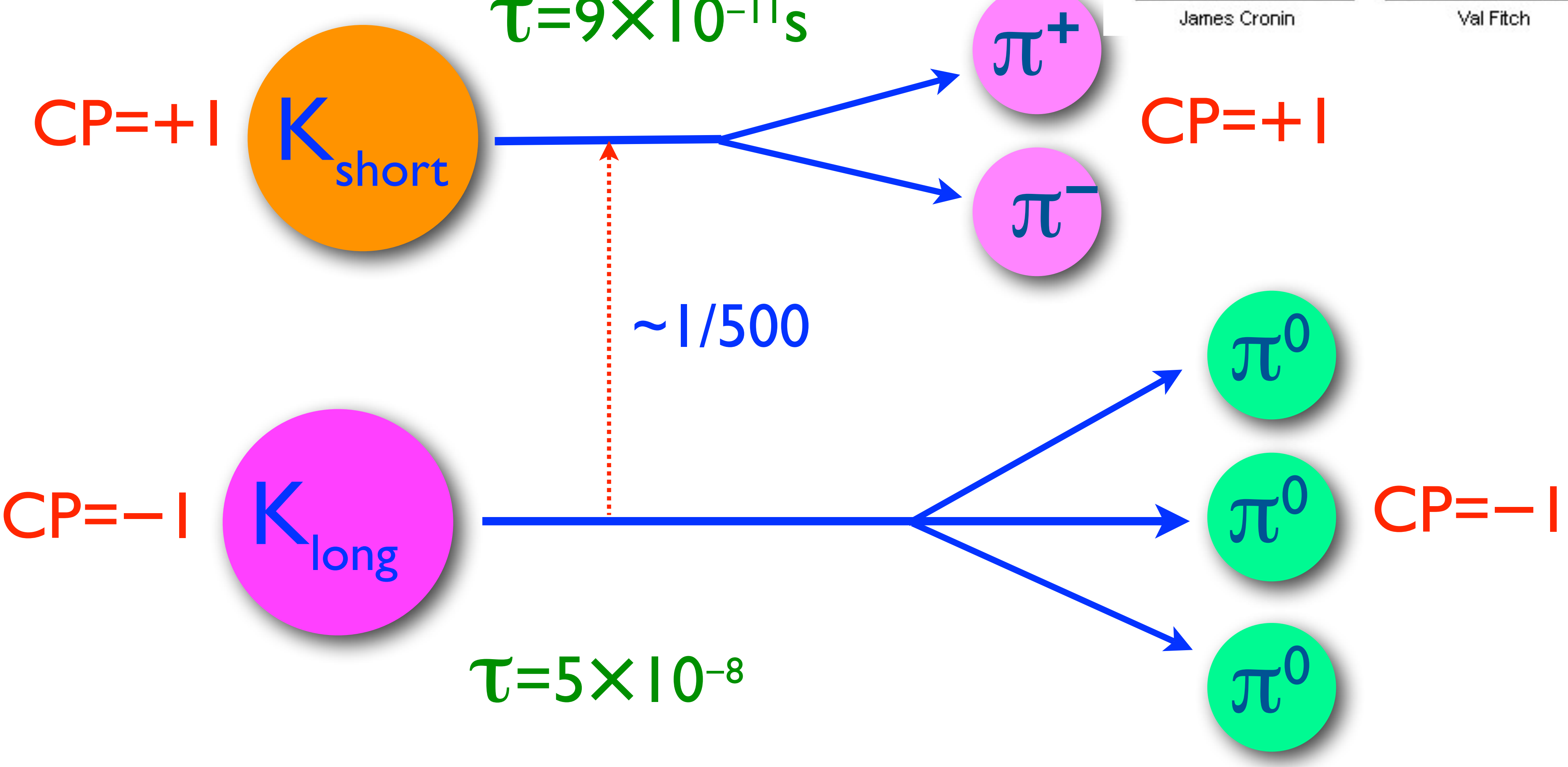
Electroweak Interactions violate CP!

1964

James Cronin



Val Fitch



$\tau=9\times10^{-11}\mathrm{s}$

CP=+1 K_{short} → π^+ π^- CP=+1

~1/500

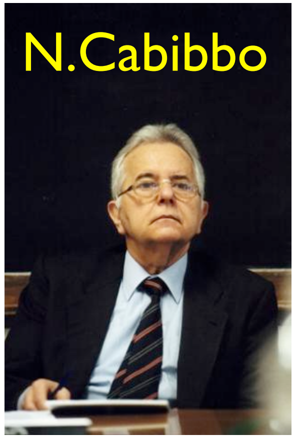
CP=−1 K_{long} → π^0 π^0 π^0 CP=−1

$\tau=5\times10^{-8}$

Origin of Violation of **CP**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = U_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$U_{CKM} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{\bigcirc{i\delta}} \\ 0 & 1 & 0 \\ -s_{13}e^{\bigcirc{-i\delta}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

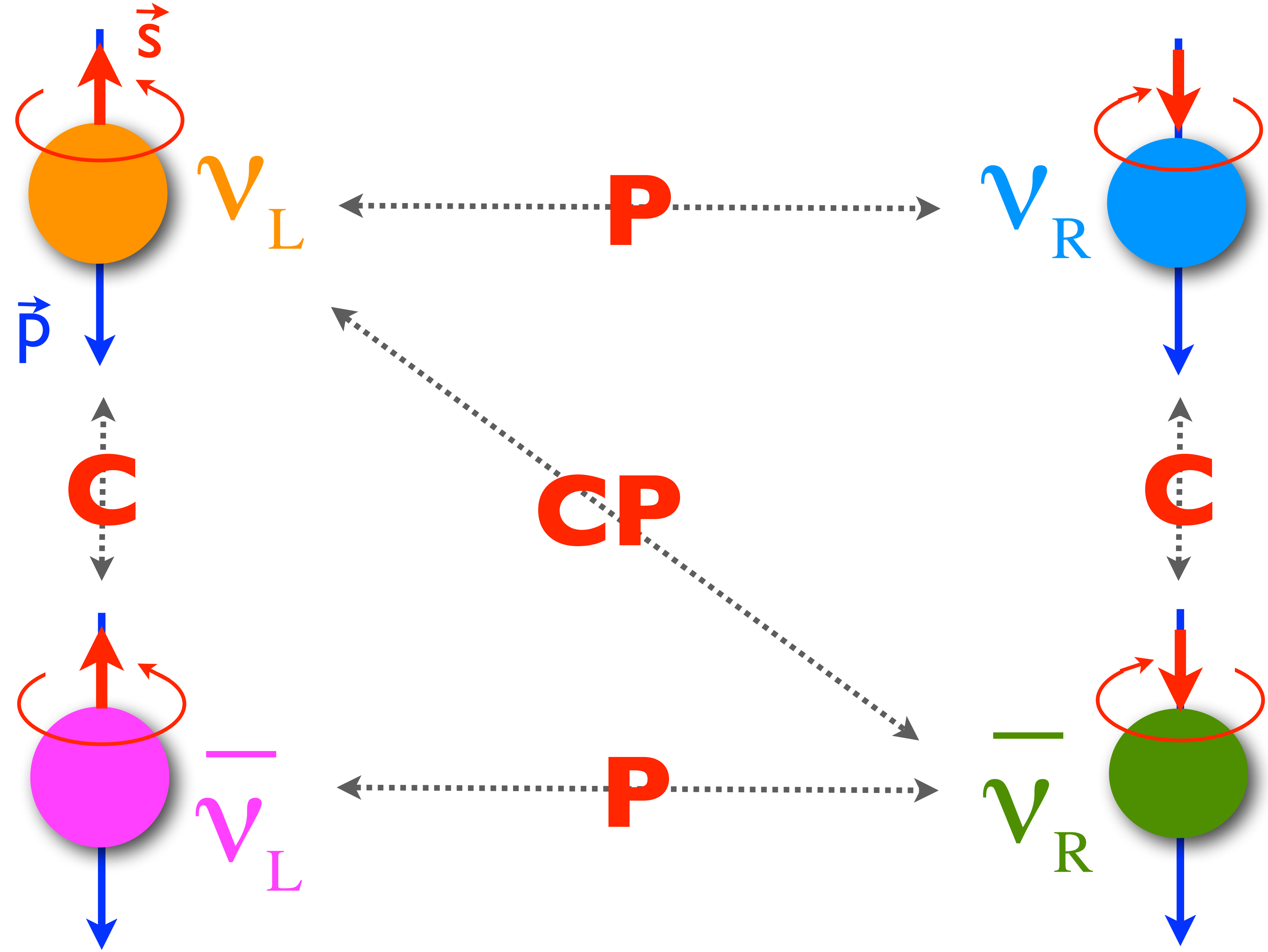


$$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij}$$

δ: **CP** phase

U_{CKM}: Cabbibo-Kobayashi-Maskawa Matrix

Transformation of **C,P e CP**



$\vec{s}$

ν_L

$\vec{p}$

P

ν_R

C

CP

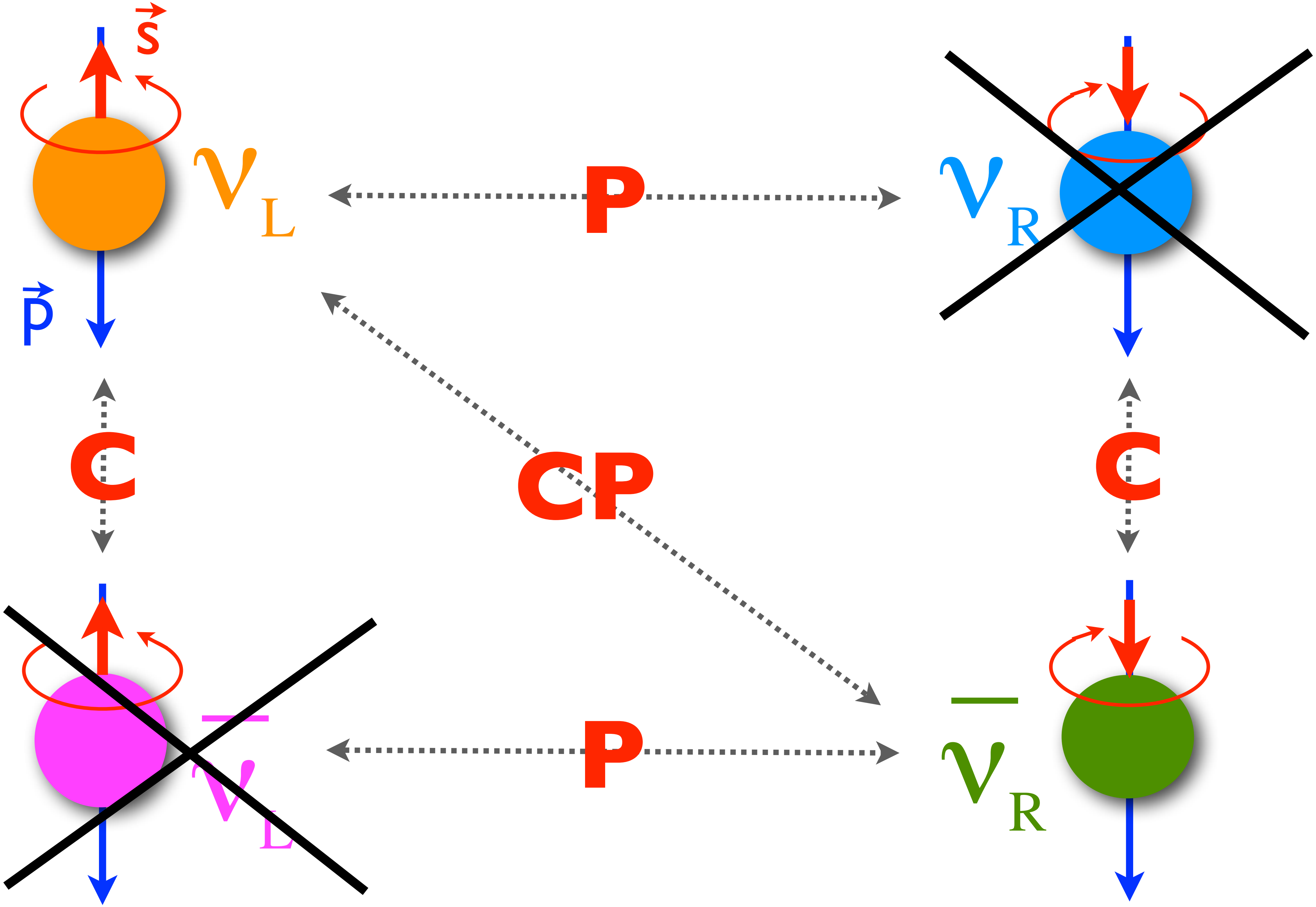
C

$\bar{\nu}_L$

P

$\bar{\nu}_R$

Transformation of **C,P e CP**



How can we study **CP** violation?

$$\begin{tikzcd}
\nu_\mu \arrow[r] \arrow[d, leftrightarrow, "T"'] & \nu_e \arrow[r, leftrightarrow, "CP"] \arrow[dr, leftrightarrow, "CPT"'] & \overline{\nu}_\mu \arrow[r] & \overline{\nu}_e \arrow[d, leftrightarrow, "T"] \\
\nu_e \arrow[r] & \nu_\mu \arrow[r, leftrightarrow, "CP"'] & \overline{\nu}_e \arrow[r] & \overline{\nu}_\mu
\end{tikzcd}$$

$$\Delta P_{\mu e} \equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$$ (in vacuum)

$$= -16\, J \sin\Delta_{12} \sin\Delta_{31} \sin\Delta_{23} \; (= \Delta P_{\tau\mu} = \Delta P_{e\tau})$$

$J \equiv s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}^2 \sin\delta$: Jarskog factor

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{4E} L \qquad \Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

ΔP can be non-zero if and only if ,

(1) $\delta \neq 0, \pi$

(2) all the mixing angles $\neq 0$

(3) all the masses should be different

Oscillation Probabilities (Approx.)

$$P(\nu_e \to \nu_\mu) \approx \left| \sqrt{P}_{atm} e^{-i(\Delta_{32}-\delta)} - \sqrt{P}_{sol} \right|^2$$

$$= \boxed{P_{atm}} + 2\sqrt{P}_{atm}\sqrt{P}_{sol}\cos(\Delta_{32}-\delta) + P_{sol}$$

main osc. term

$$\sqrt{P}_{atm} \equiv \sin\theta_{23}\sin 2\theta_{13}\,\Delta_{31}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}$$

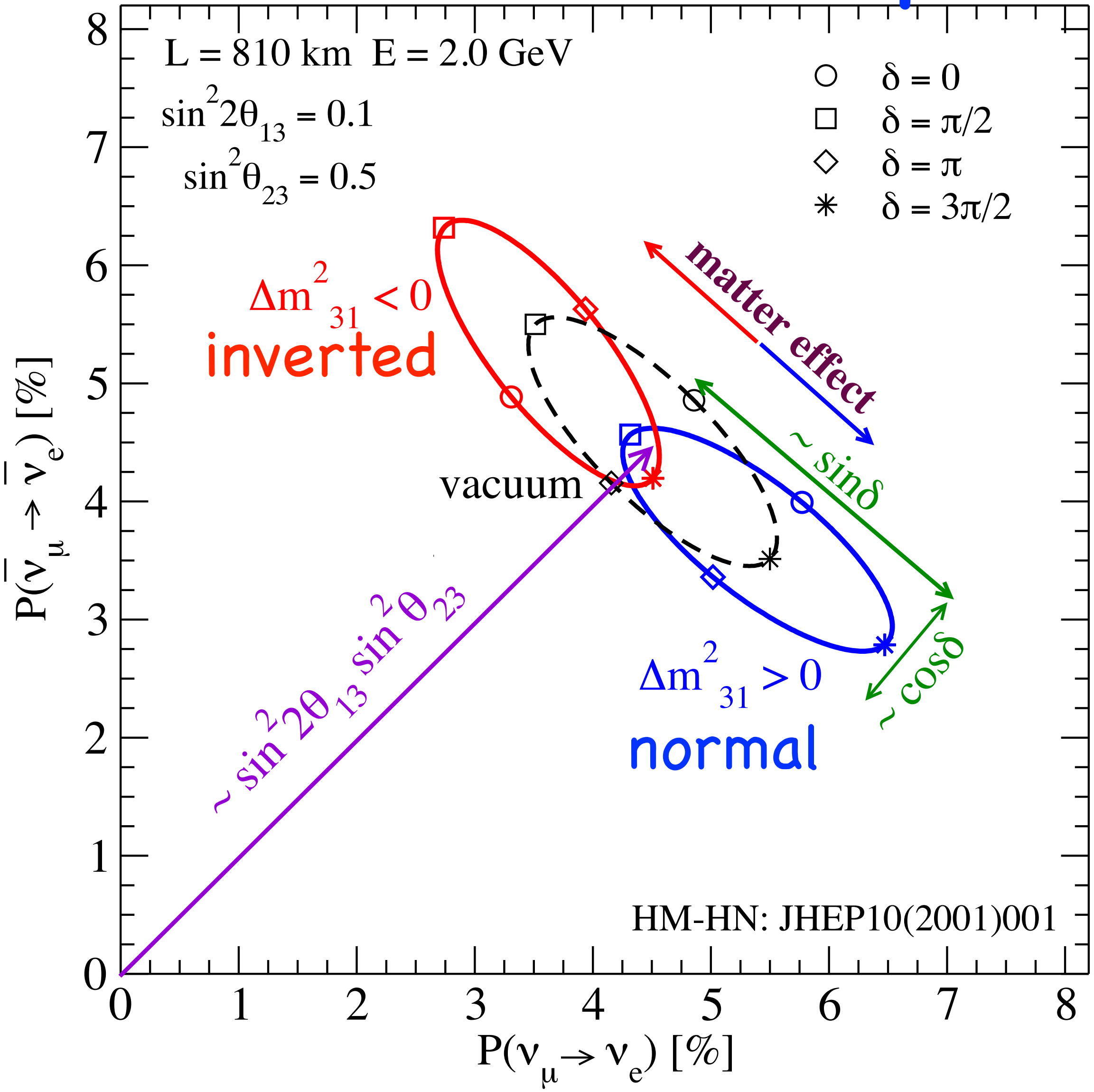
$$\sqrt{P}_{sol} \equiv \cos\theta_{23}\sin 2\theta_{12}\,\Delta_{21}\frac{\sin(aL)}{aL}$$

$\Delta_{ij} \equiv \Delta m_{ij}^2 L/4E$ $\quad$ $a \equiv G_F N_e/\sqrt{2}$

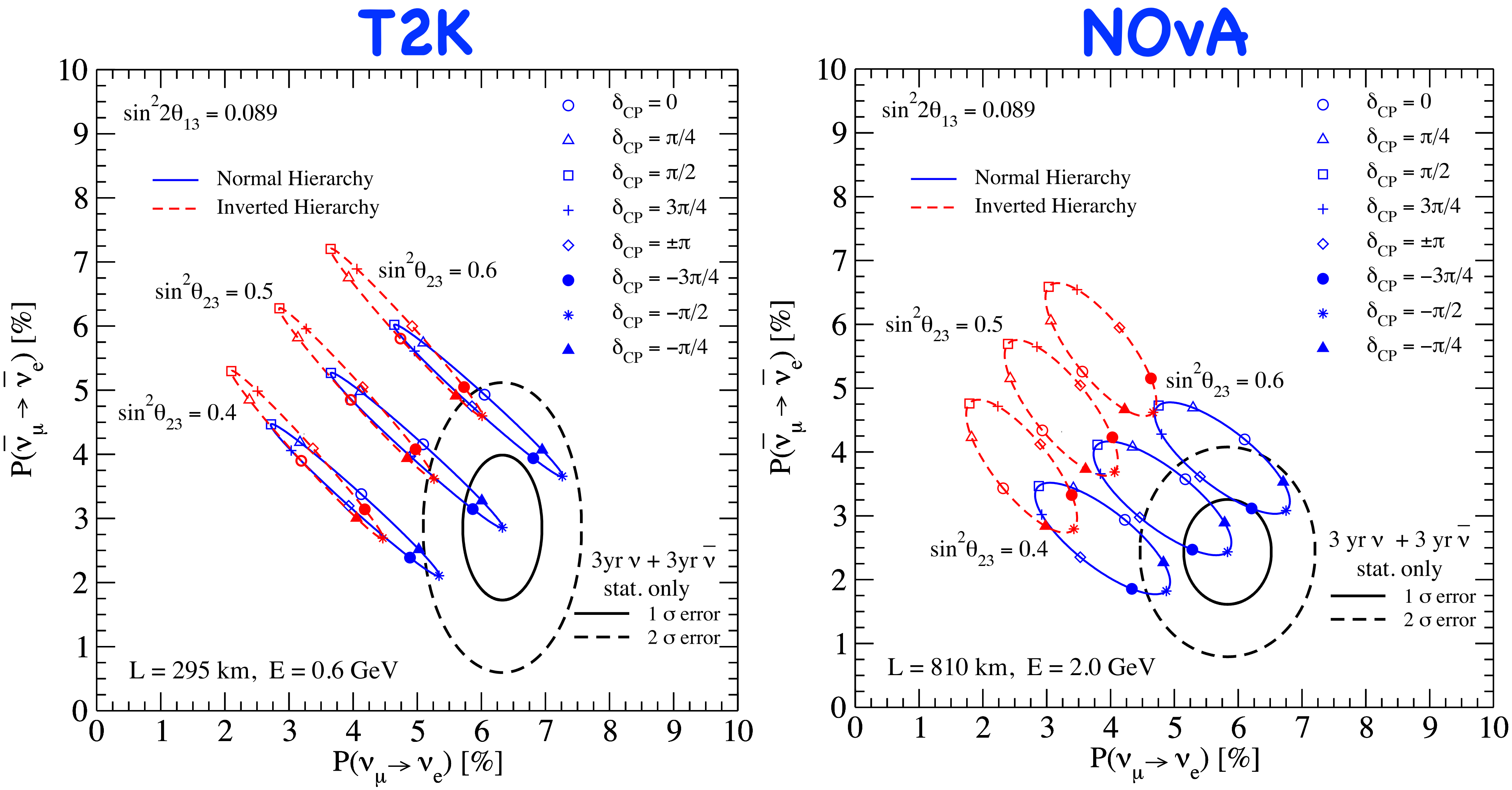
Cervera et al, hep-ph/0002108

Bi-Probability Plot: useful tool (diagram) to see the impact of the matter effect and CP phase

For NOvA set up



Expectations for the Near Future



T2K is better in restricting CP phase

NOvA is better in determining mass hierarchy

P. A. N. Machado et al. arXiv: 1307.3248 [hep-ph]

Sensitivities of T2K and NOvA (combined with reactor experiments) are not good enough to determine the mass hierarchy and CP phase with large significance

We need some new longbase line experiments !

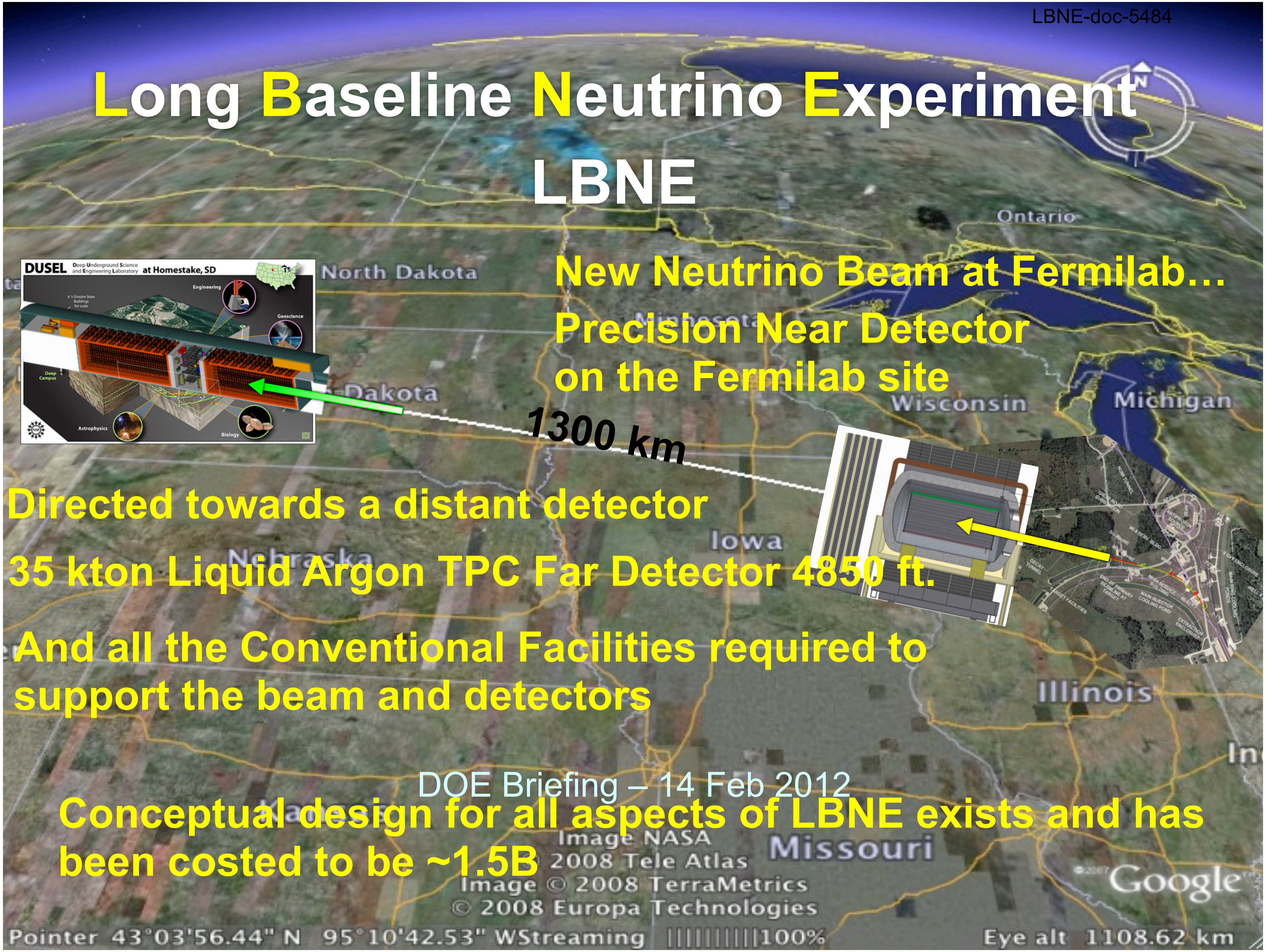
There are some proposals, for exemple,

In US: LBNE (discussed yesterday)

In Japan: Hyper-Kamiokande

In Europe: LAGUNA-LBNO

Long Baseline Neutrino Experiment
LBNE



New Neutrino Beam at Fermilab…

Precision Near Detector on the Fermilab site

Directed towards a distant detector

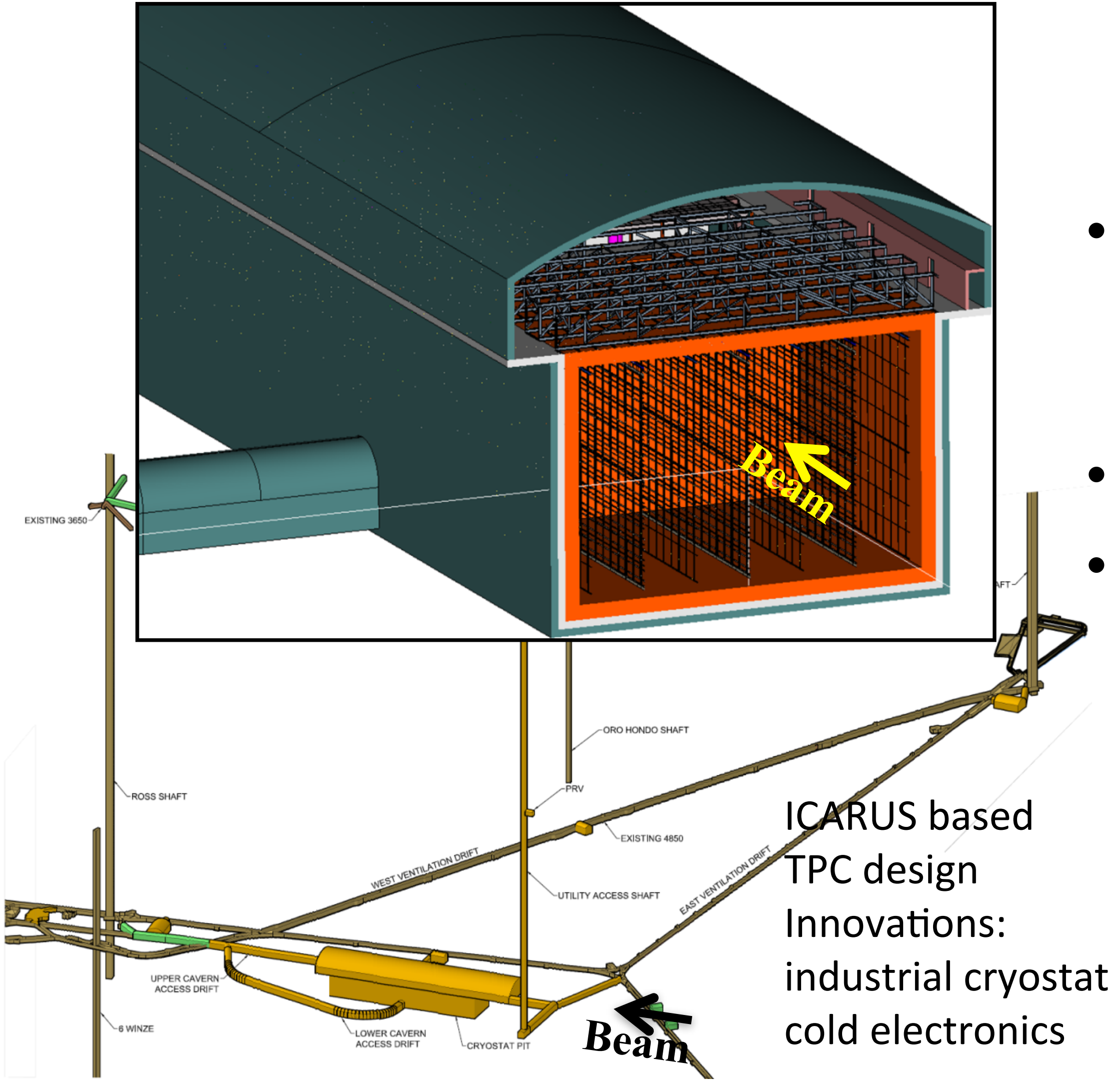
35 kton Liquid Argon TPC Far Detector 4850 ft.

And all the Conventional Facilities required to support the beam and detectors

DOE Briefing – 14 Feb 2012

Conceptual design for all aspects of LBNE exists and has been costed to be ~1.5B

Far Detector Design at depth:
LAr TPC Detector at 4850 ft

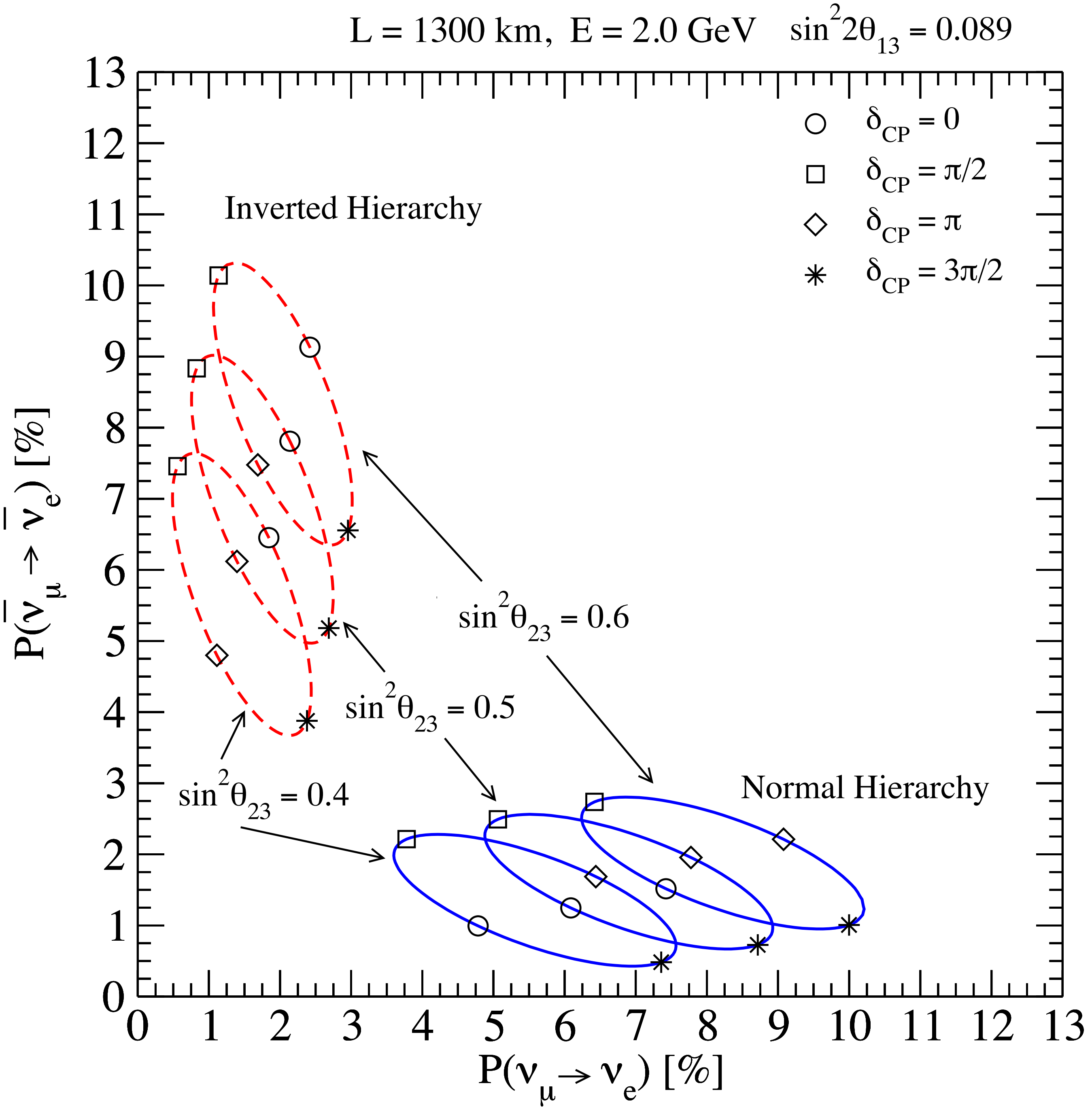


ICARUS based TPC design Innovations: industrial cryostat, cold electronics

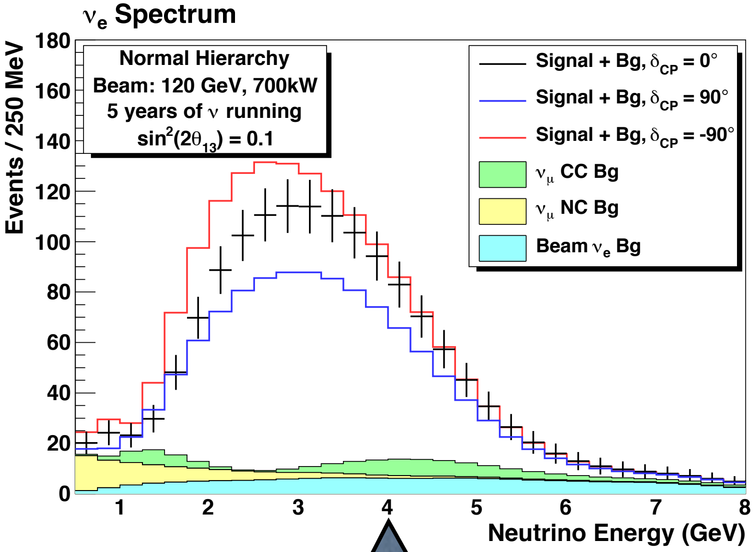
- Two detectors in a common cavern at 4850 ft. depth
- Active volume of each detector:
  $22.4 \times 14 \times 45.6$ m^3
- 34 kt fiducial mass
- TPC design:
  - 3.7 m drift length
  - 5 mm wire spacing
  - three stereo views
  - 2X108 anode chambers
  - 2 X 275k channels
  - S/N ~ 10

Challenges for scale up are under control : Purity, installation, safety

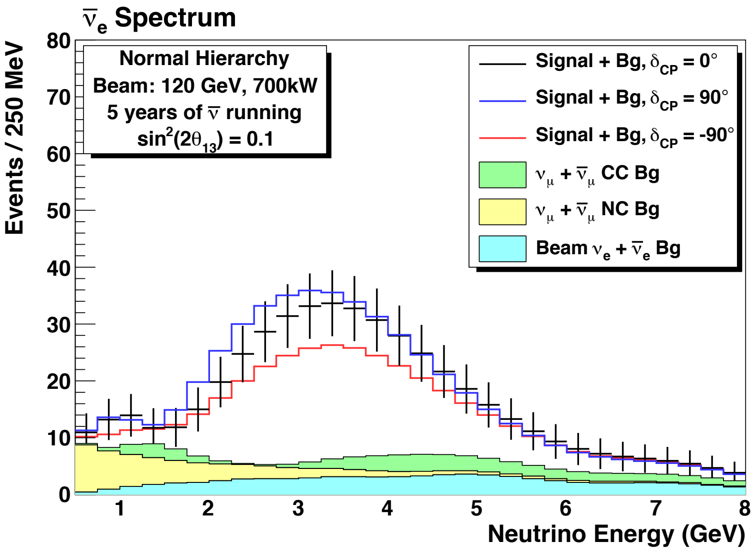
For LBNE set up



LBNE 34 kTon performance



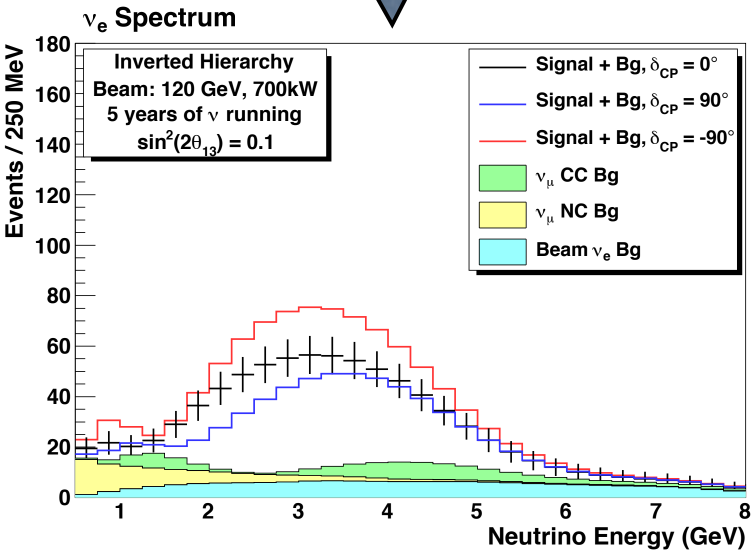
1074

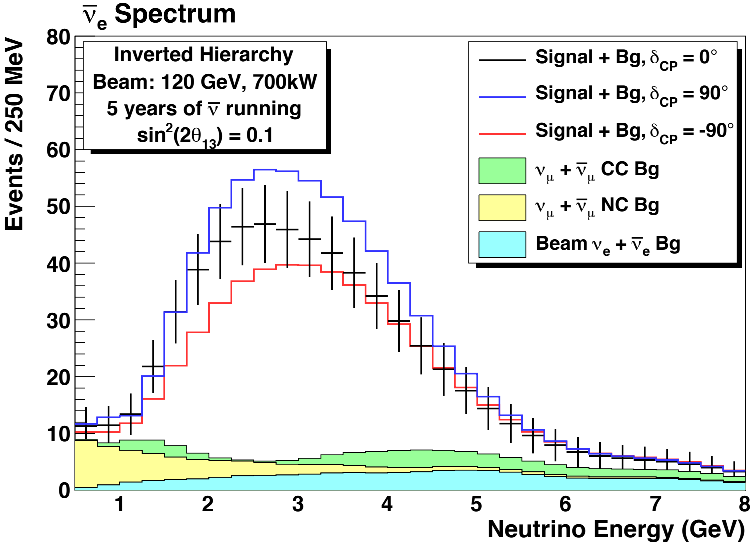


279

diff due to mass ordering

477





440

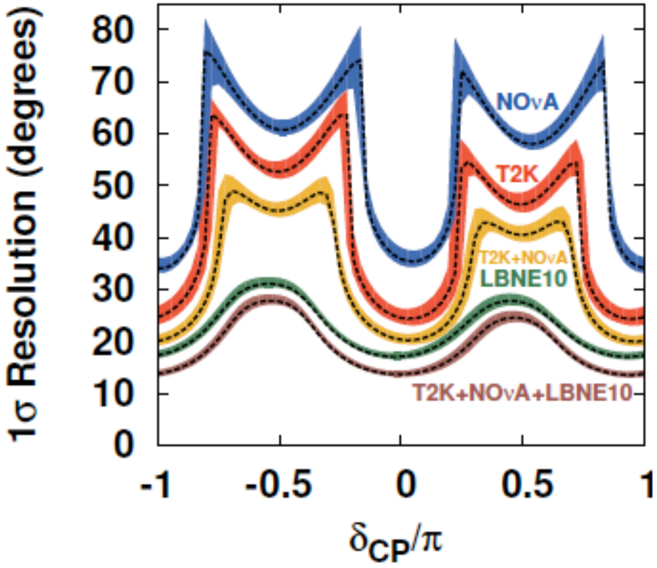
The mass ordering will be the first item to resolve.

LBNE10 Would be a Major Advance

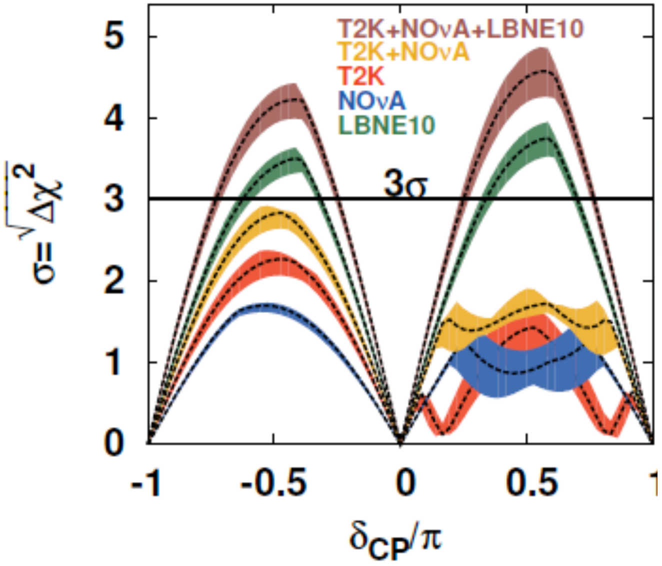
L = 1300 km

δ_{CP} Resolution

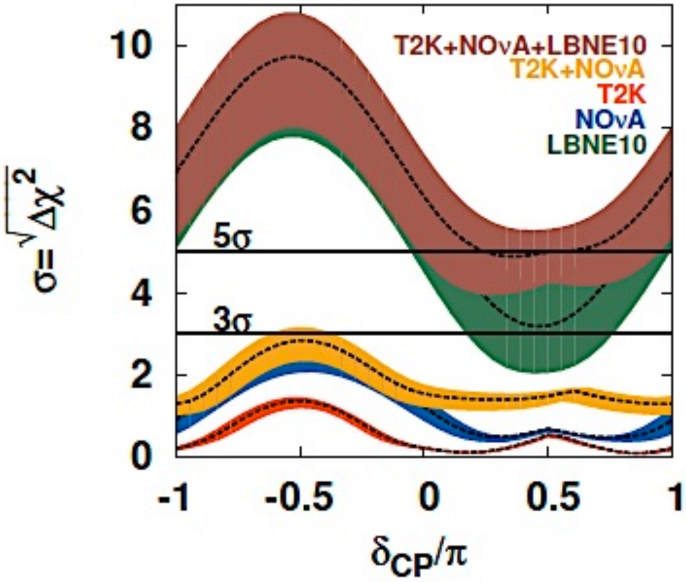
Assumes known (Normal) Mass Hierarchy



CP Violation Sensitivity



Mass Hierarchy Sensitivity



Bands: 1σ variations of θ_{13}, θ_{23}, Δm_{31}^2 (Fogli et al. arXiv:1205.5254v3)

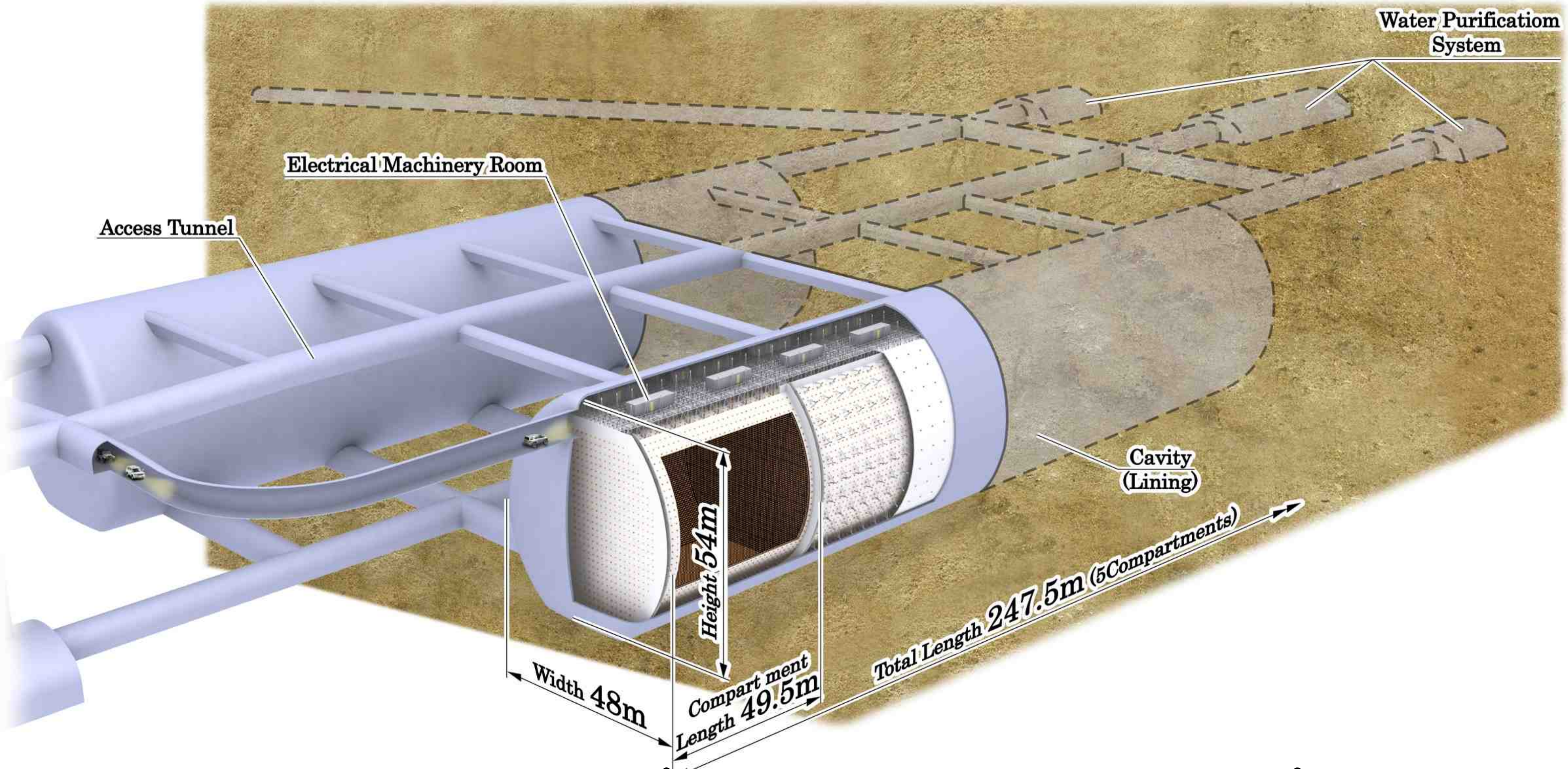
T2K 750 kW x 5 yr ν L = 295 km

NOνA 700 kW x (3 yr ν + 3 yr $\bar{\nu}$) L = 810 km

LBNE10 (80 GeV*) 700 kW x (5 yr ν + 5 yr $\bar{\nu}$)

*Improved over CDR 2012 120 GeV MI proton beam

Hyper-Kamiokande Project

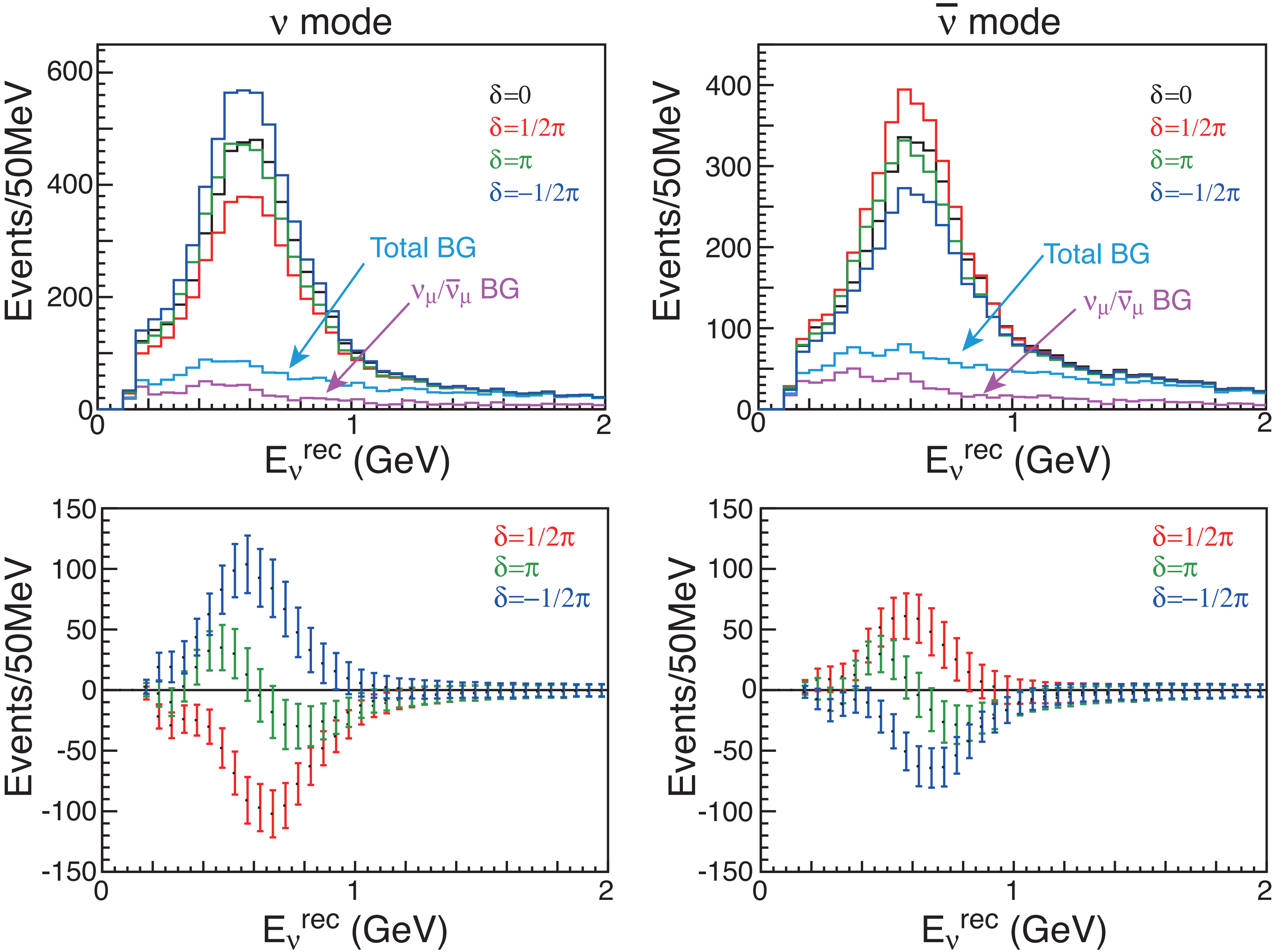


L = 295 km (JPARC - Kamioka)

V = 1 Mton (V_{fid}=0.54Mt)

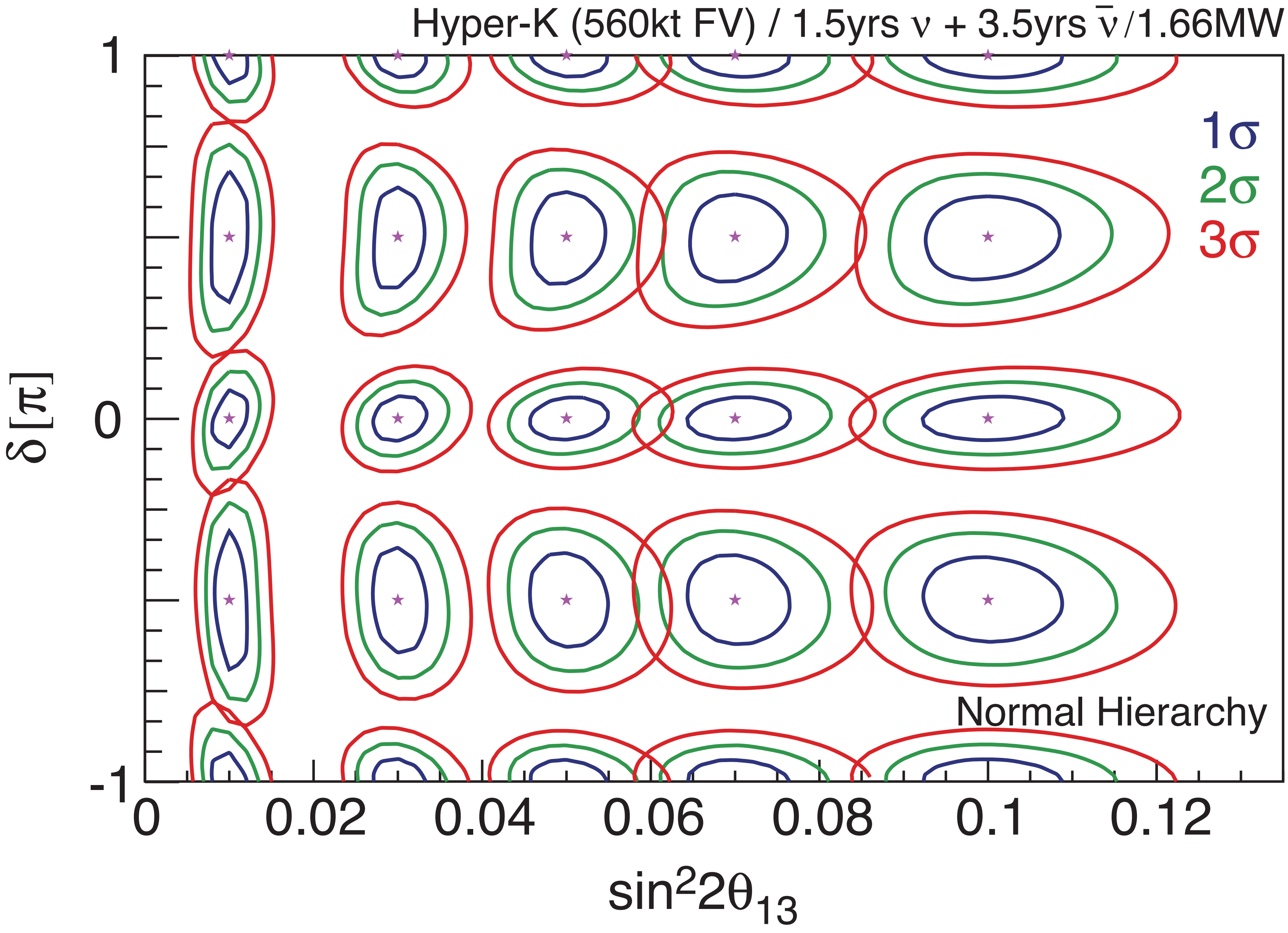
Abe et al., arXiv: 1109.3262 [hep-ex]

Expected number of events at HK



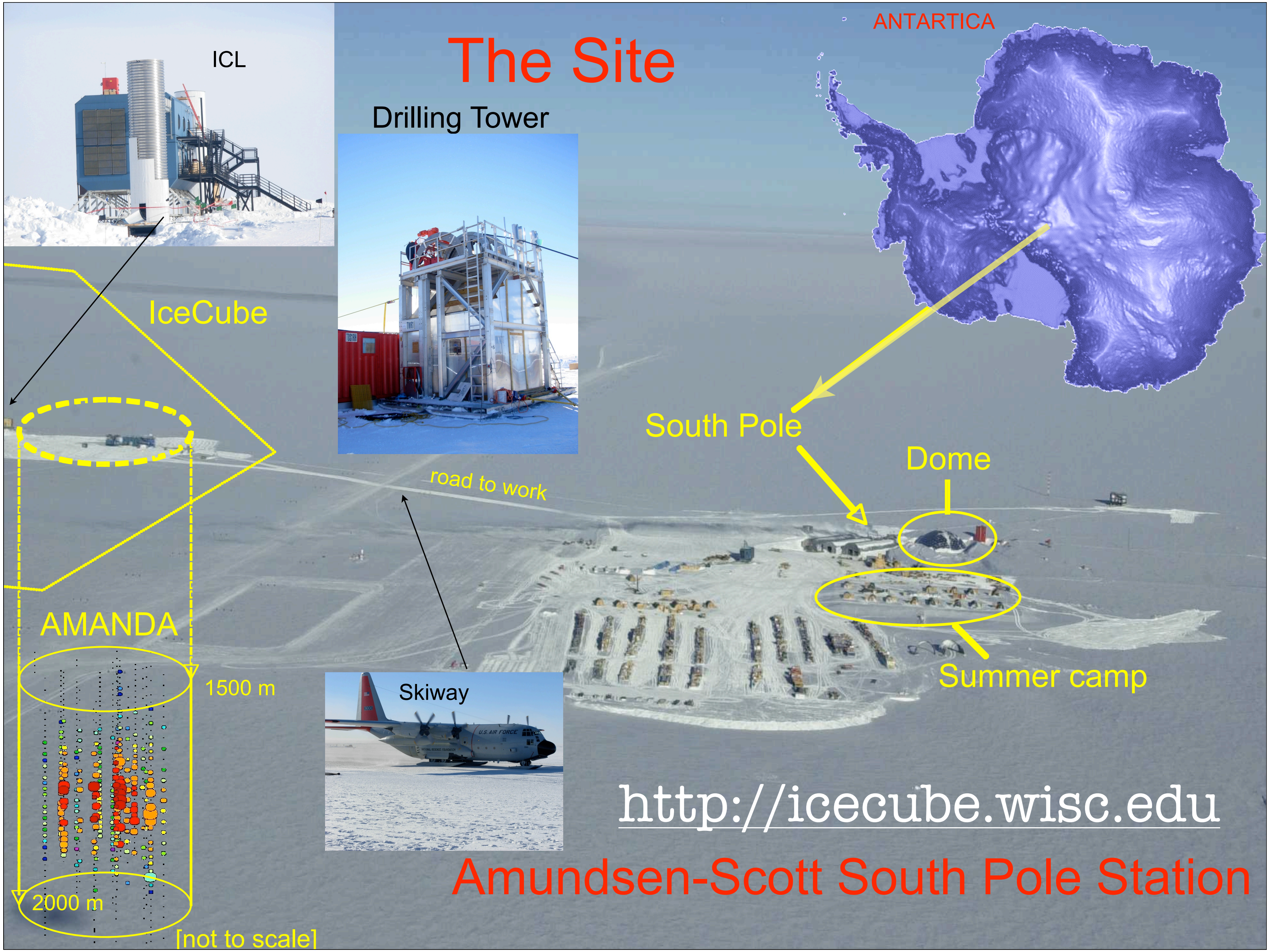
Abe et al., arXiv: 1109.3262 [hep-ex]

Expected allowed regions for HK



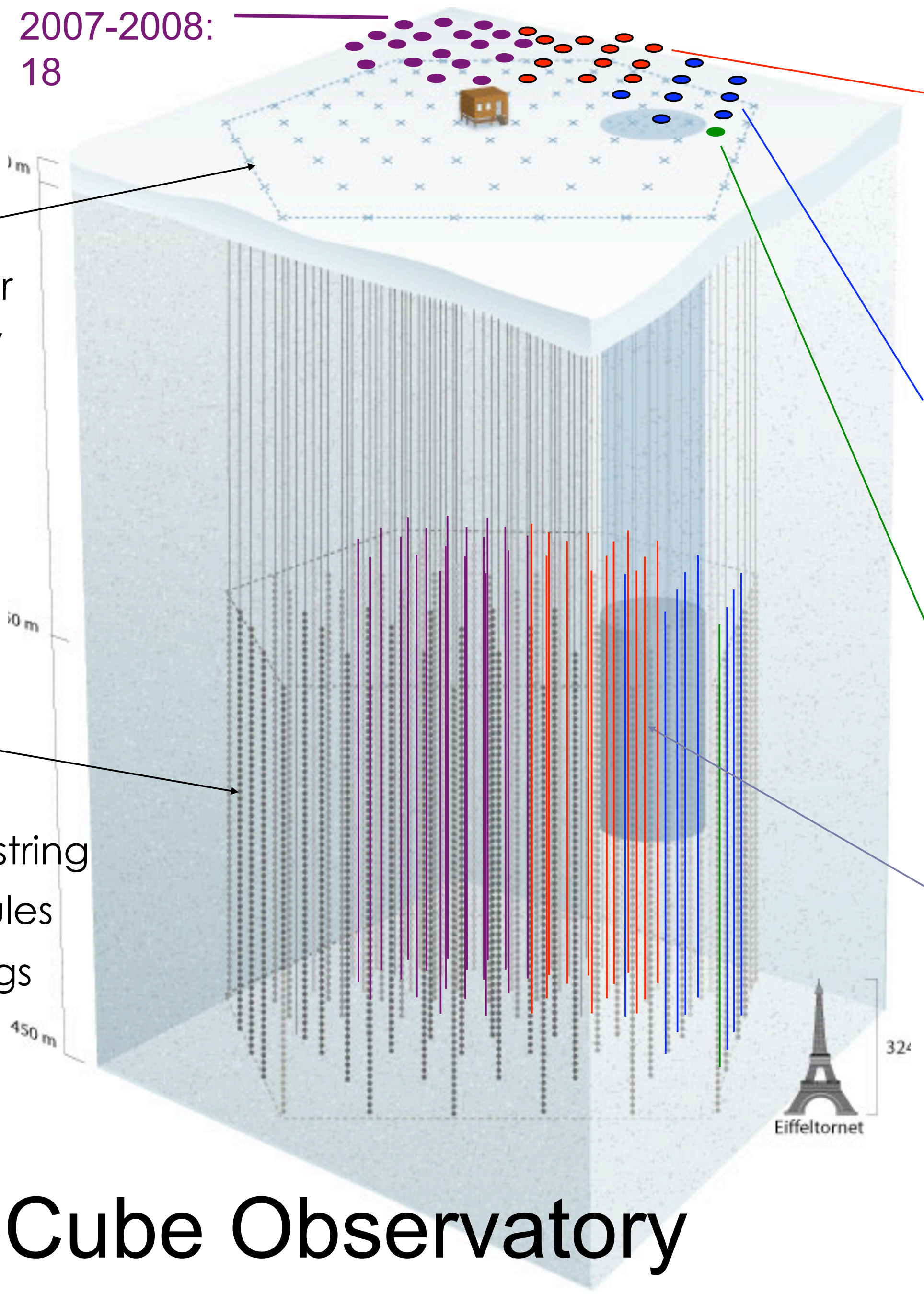
Abe et al., arXiv: 1109.3262 [hep-ex]

IceCube


The Site
ANTARTICA
ICL
Drilling Tower
IceCube
South Pole
Dome
road to work
AMANDA
1500 m
2000 m
[not to scale]
Skiway
Summer camp
http://icecube.wisc.edu
Amundsen-Scott South Pole Station

The IceCube Observatory

total of 40 Strings



2007-2008:
18

2006-2007:
13 Strings

2005-2006: 8 Strings

2004-2005 : 1 String

first data 2005
upgoing muon 18. July 2005

IceTop

Air shower detector
threshold ~ 300 TeV

InIce

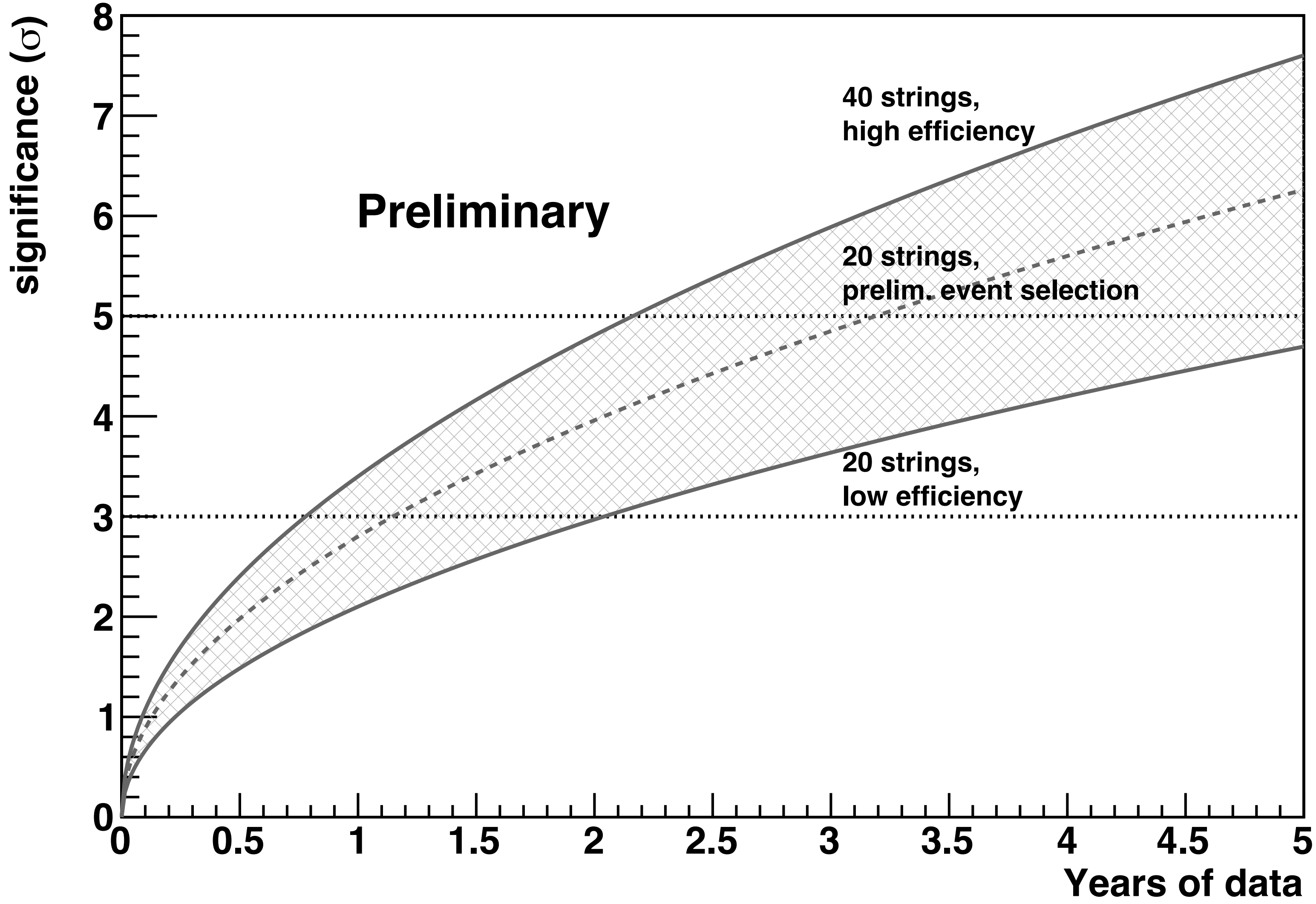
80 Strings
60 Optical Modules/string
17 m between Modules
125 m between Strings

AMANDA
19 Strings
677 Modules

Volumen do detetor ~ 1 km^3 !!

PINGU (Precision IceCube Next Generation Upgrade) has some potential to determine the mass hierarchy

M. G. Artsen et al. arXiv: 1306.5846 [astro-ph.IM]



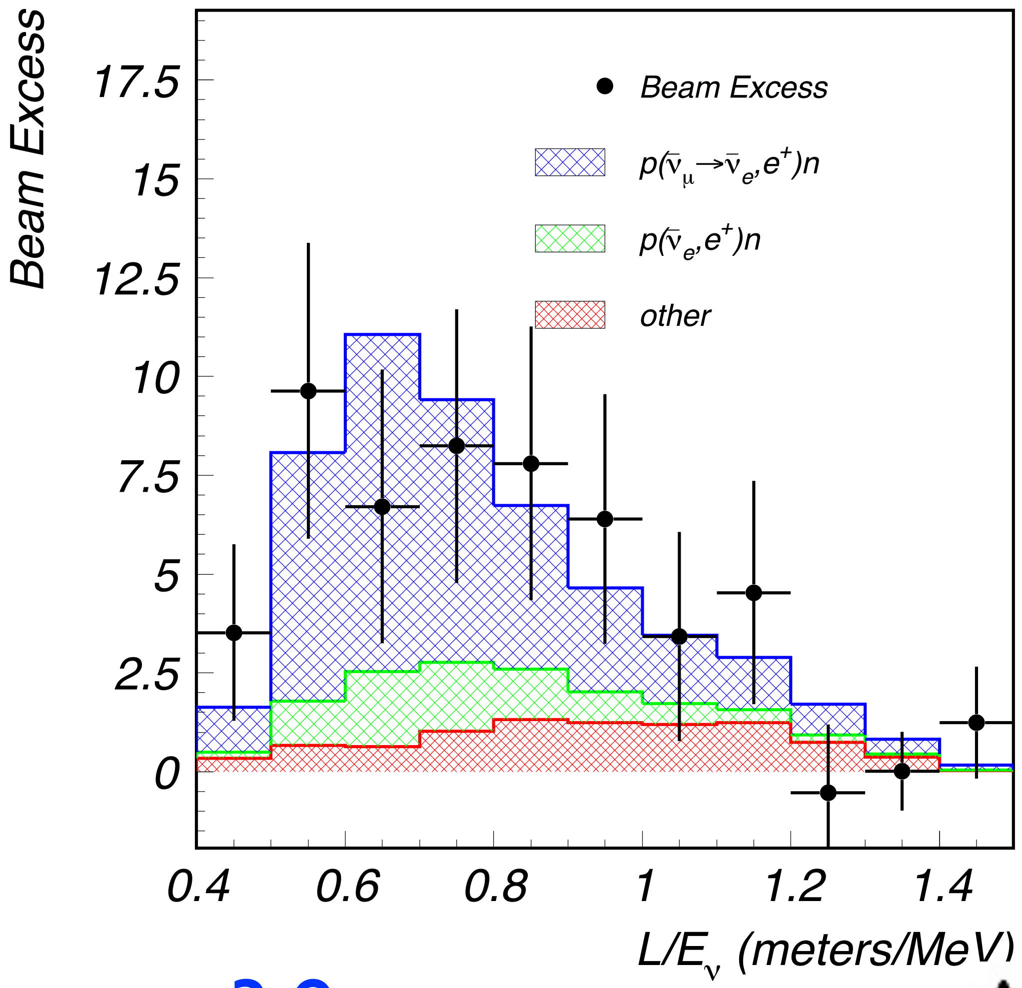
Is the Standard Three Neutrino Paradigm correct?

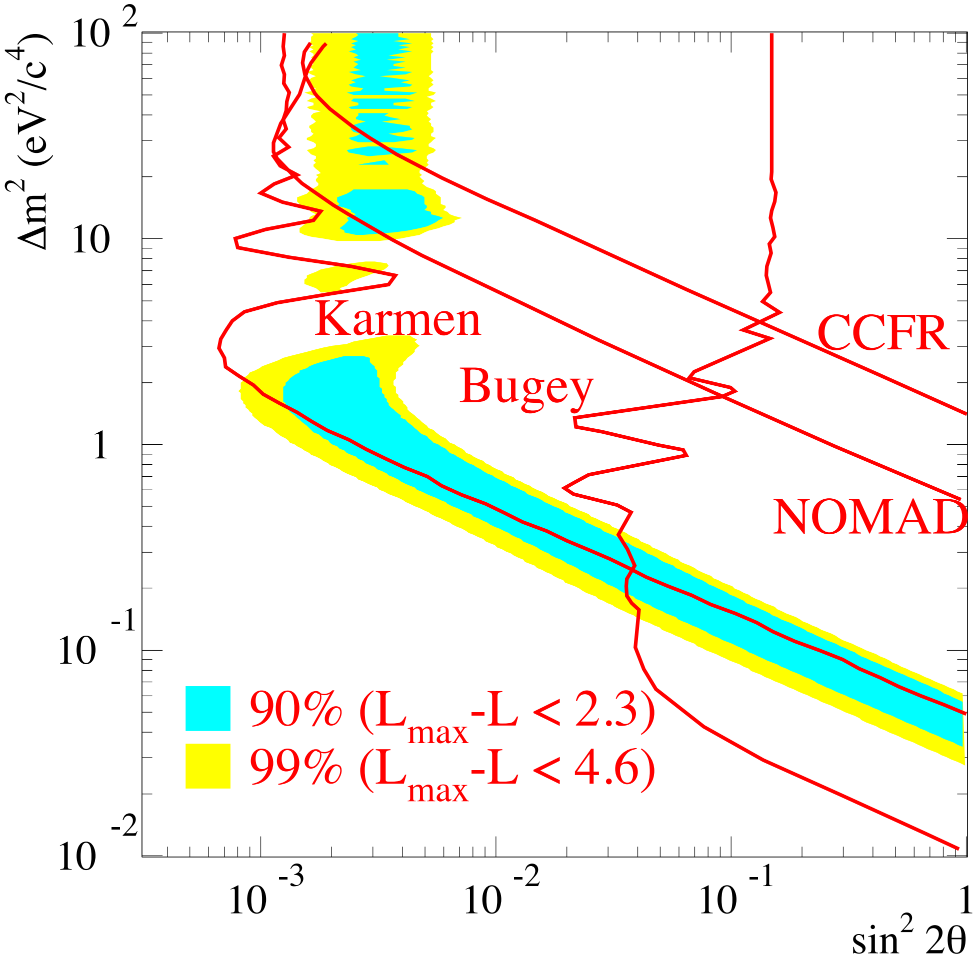
Sterile Neutrino Exist ?

LSND Results

Aguilar et al, PRD 64 (2001)112007

L ~30 m, E ~ 20-200 MeV



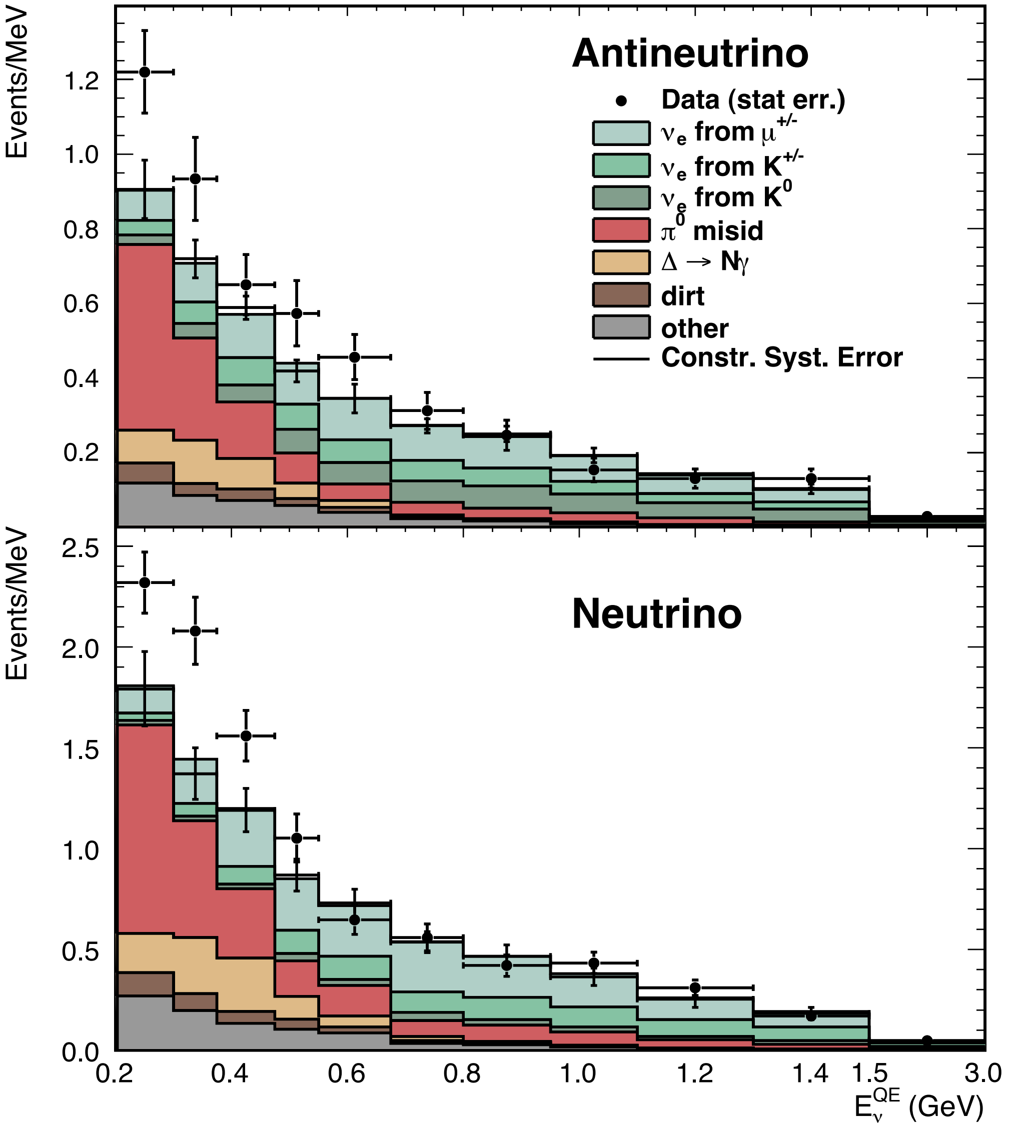


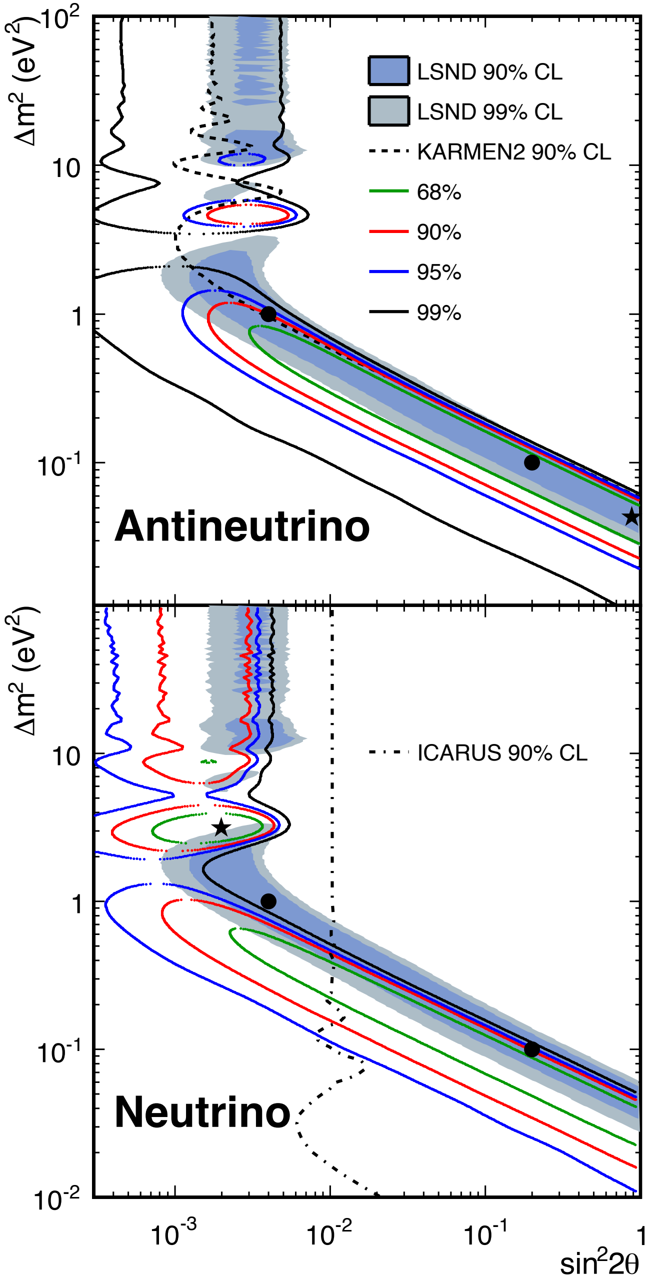
~3.8 σ excess

$$\Delta m^2 \sim 0.2 - 10\ \mathrm{eV}^2$$

MiniBooNe Results

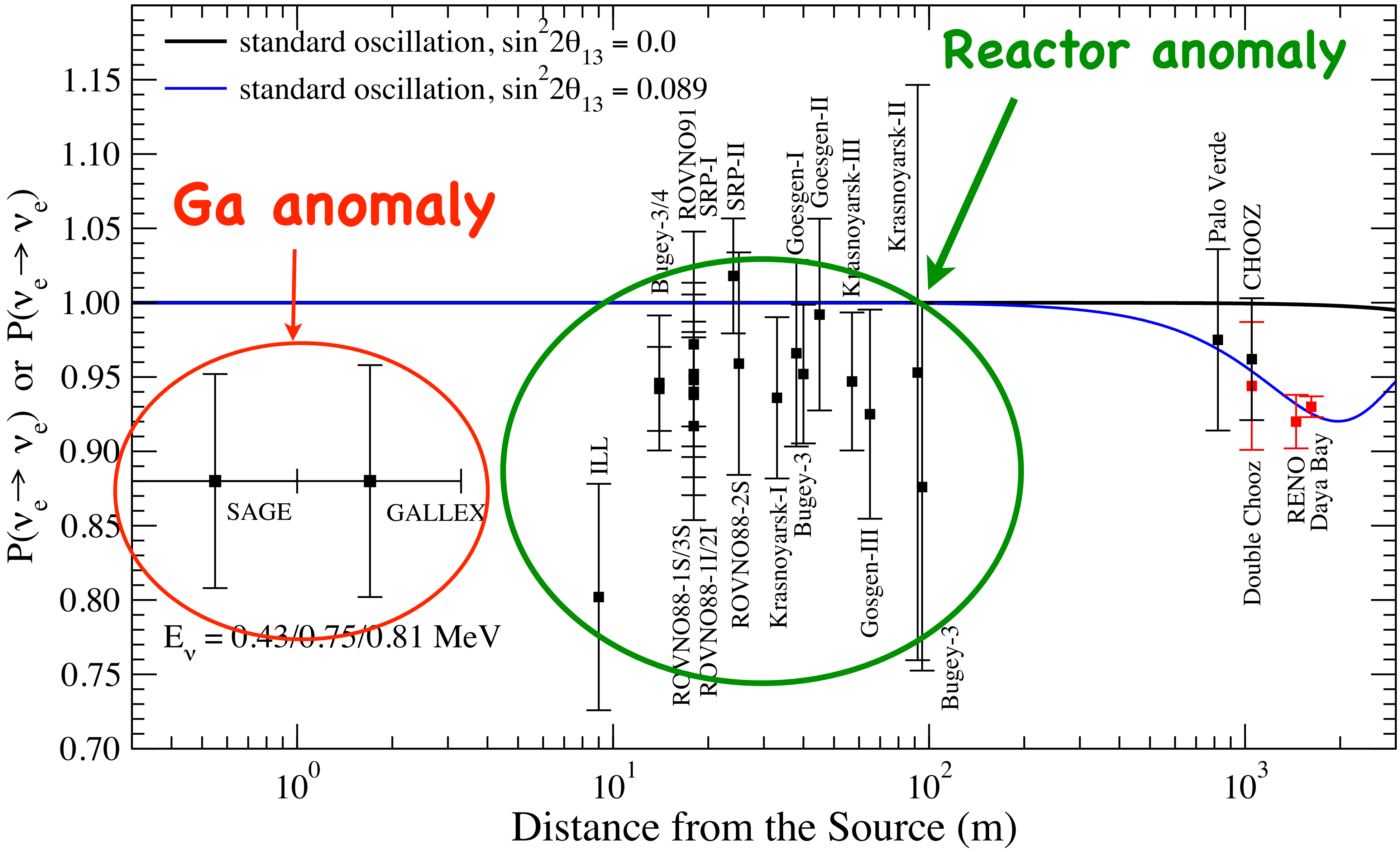
Aguilar-Acrevola et al, PRL 110 (2013)161801





~3 σ excess

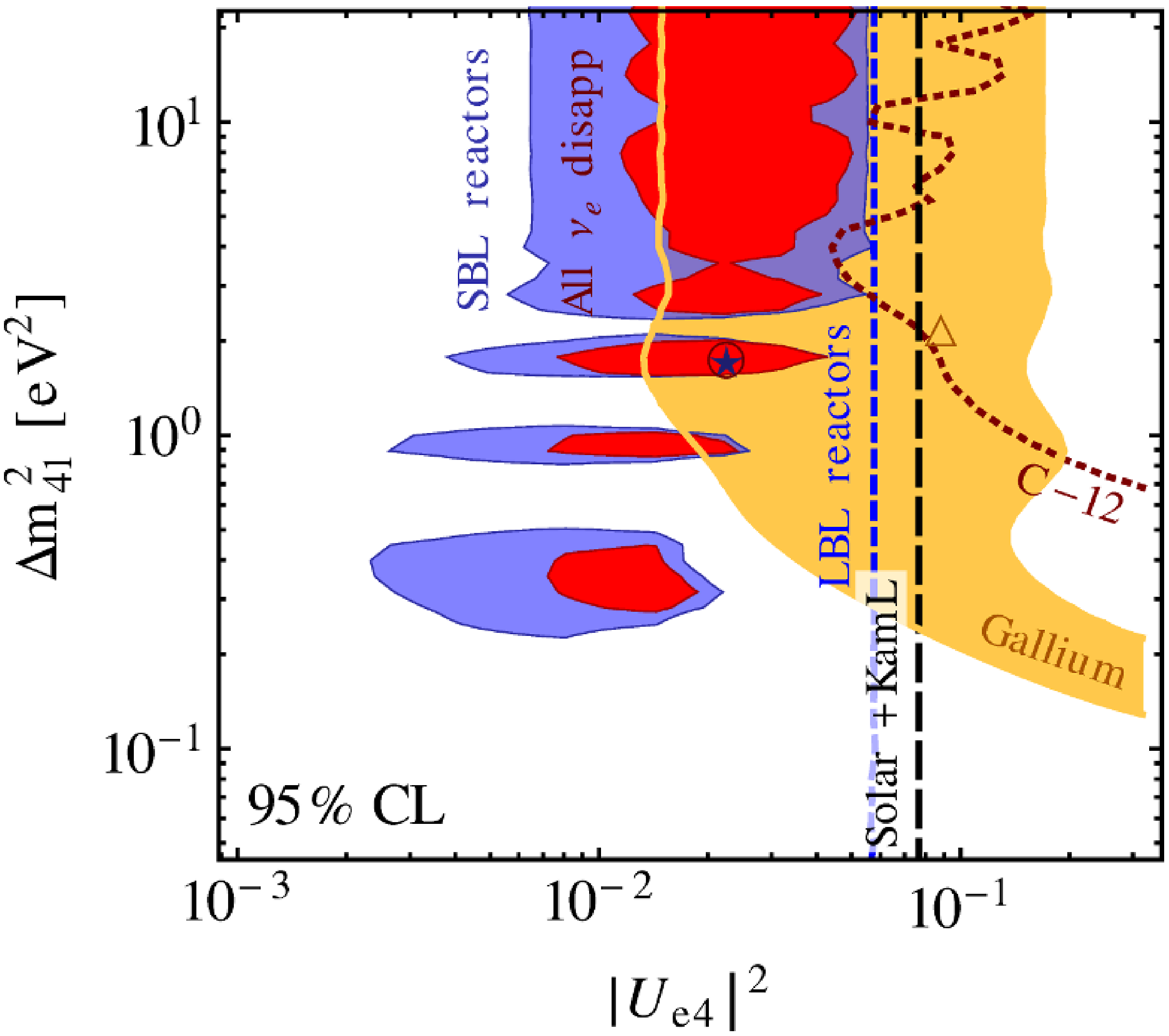
Ga neutrino and Reactor anti-neutrino Anomaly



Ga anomaly

Reactor anomaly

Explanation by 3+1 model



Kopp et al, JHEP05 (2013)050

Oscillometry inside a ν-detector

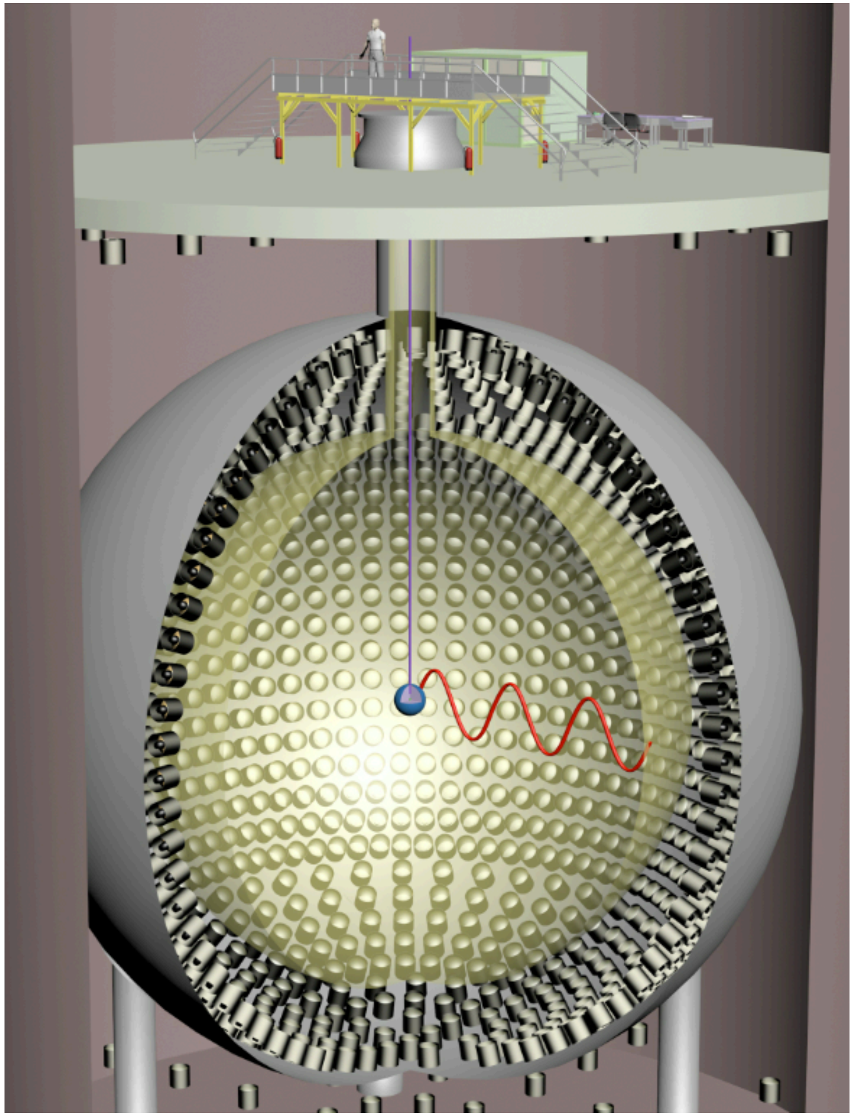
- **Place the ν-emitter inside or close to existing detectors**
  - **Very short Baseline (few m)**
  - **Low Background**

i) ν-source at center

- $$\frac{dN_\nu}{dR} \propto \left[1 - \sin^2(2\theta)\ \sin^2\left(1.27\ \frac{\Delta m^2 R}{\langle E\rangle}\right)\right]$$

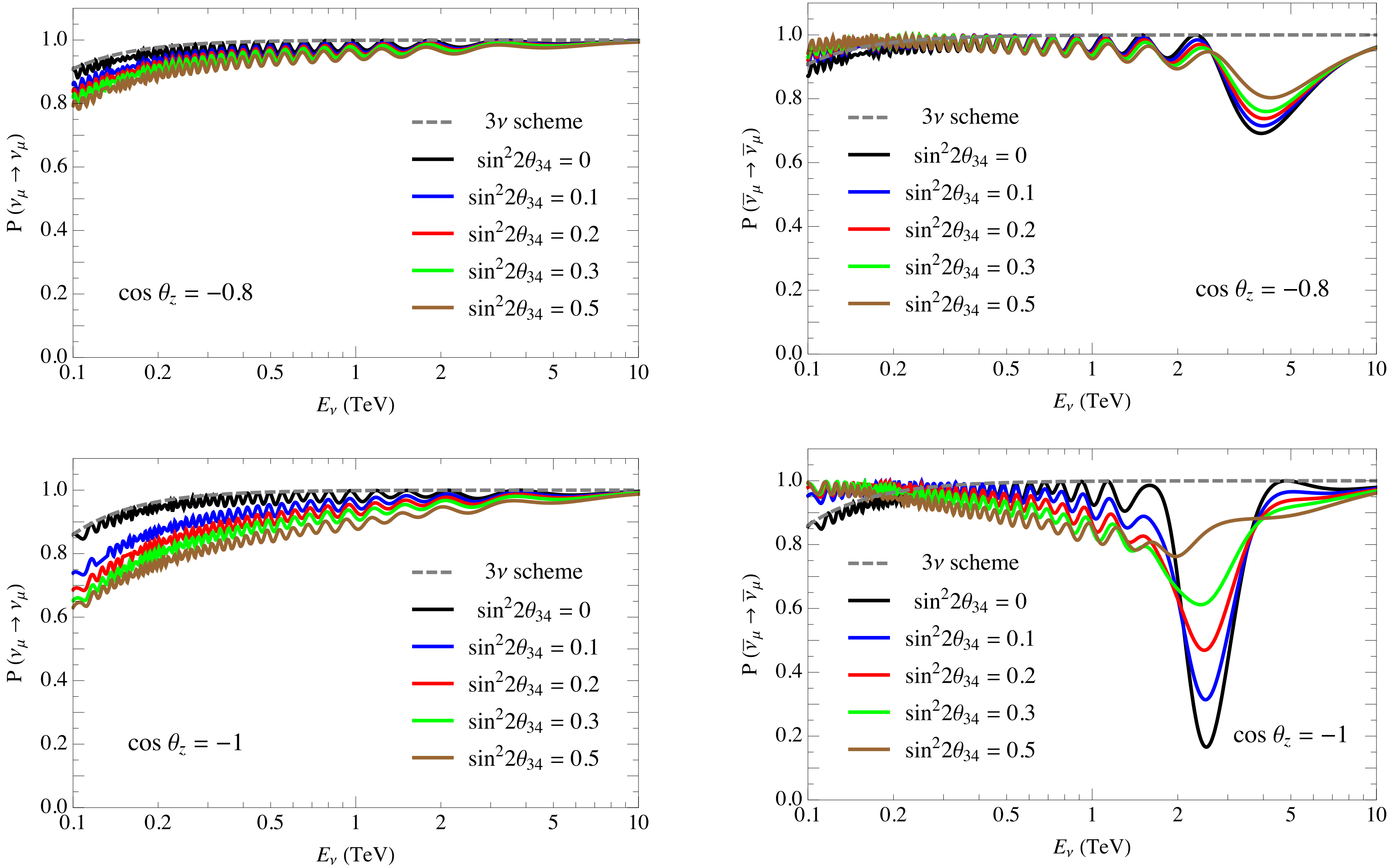
ii) ν-source Outside LS

- **Specific oscillation pattern analytically computable**



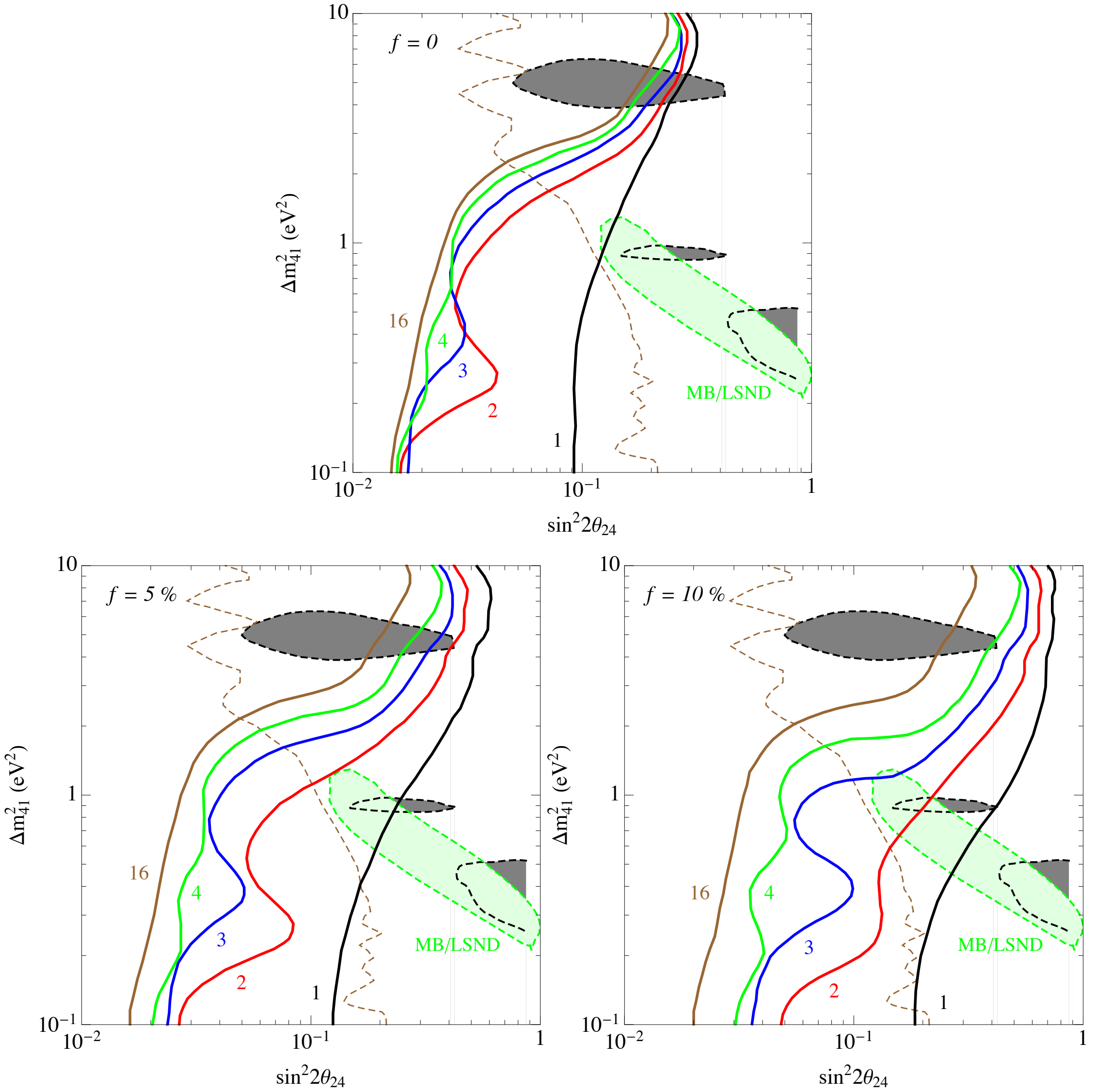
Can LSND/MiniBooNe Sterile Neutrino Signal be excluded by IceCube?

Esmaili and Smirnov, arXiv:1307.6824 [hep-ph]



(see also Nunokawa, Peres, Zuaknovich Funchal, PLB562 (2003)279)

Can LSND/MiniBooNe Sterile Neutrino Signal be excluded by IceCube?

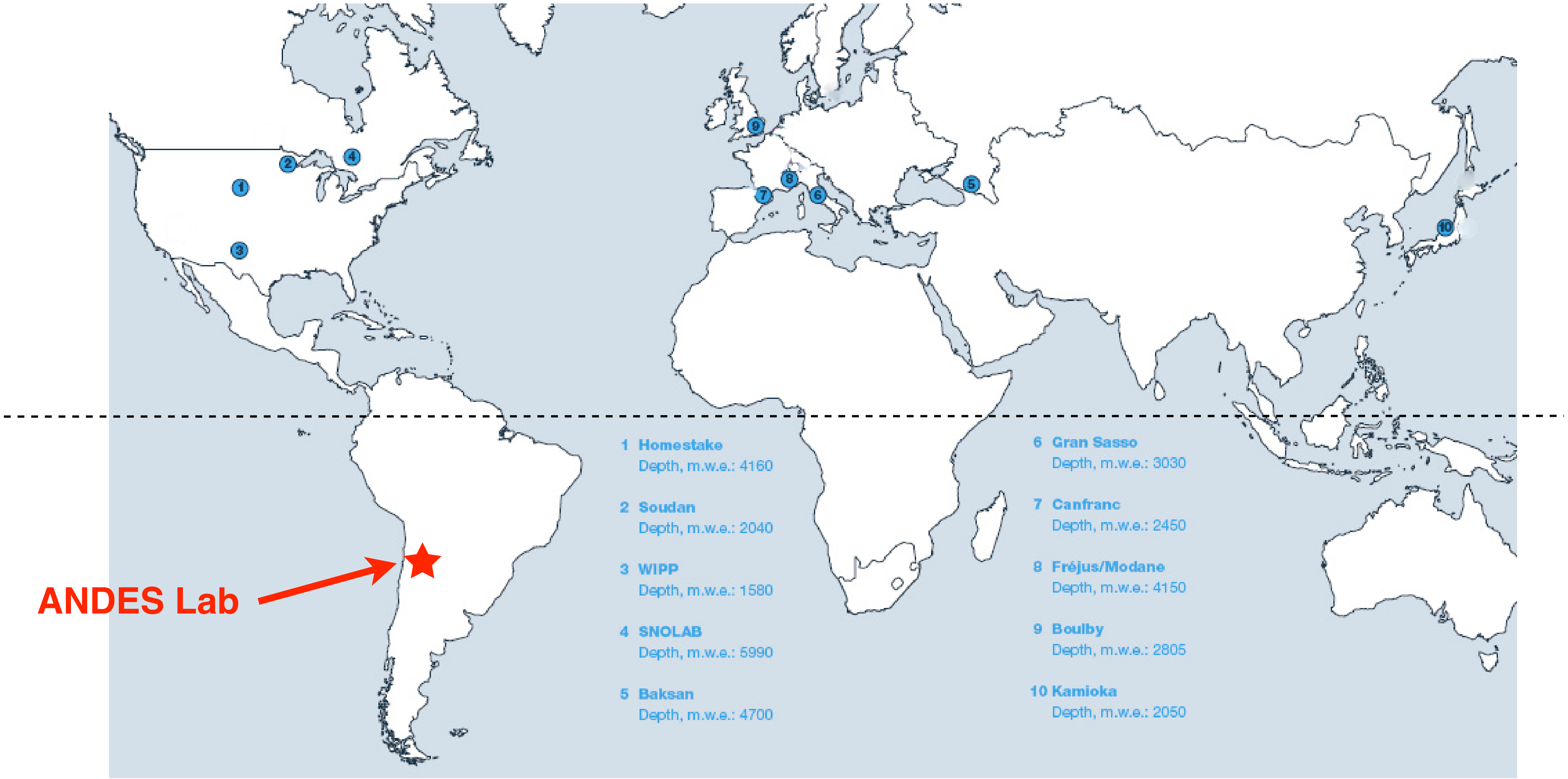


Esmaili and Smirnov, arXiv:1307.6824 [hep-ph]

Agua **N**egra **D**eep **E**xperiment **S**ite
ANDES

-First Underground Laboratory in
the Southern Hemisphere-

Deep Underground Laboratories in the World



- + China, Korea, India
- ▸ None in the southern hemisphere

- ▸ Plan to build the first deep underground laboratory in the southern hemisphere

Bi-Oceanic Corridor

Pacific Ocean

Atlantic Ocean

Chile

Brazil

COQUIMBO

PORTO ALEGRE

Argentina

valparaiso

Urguay

montevideo

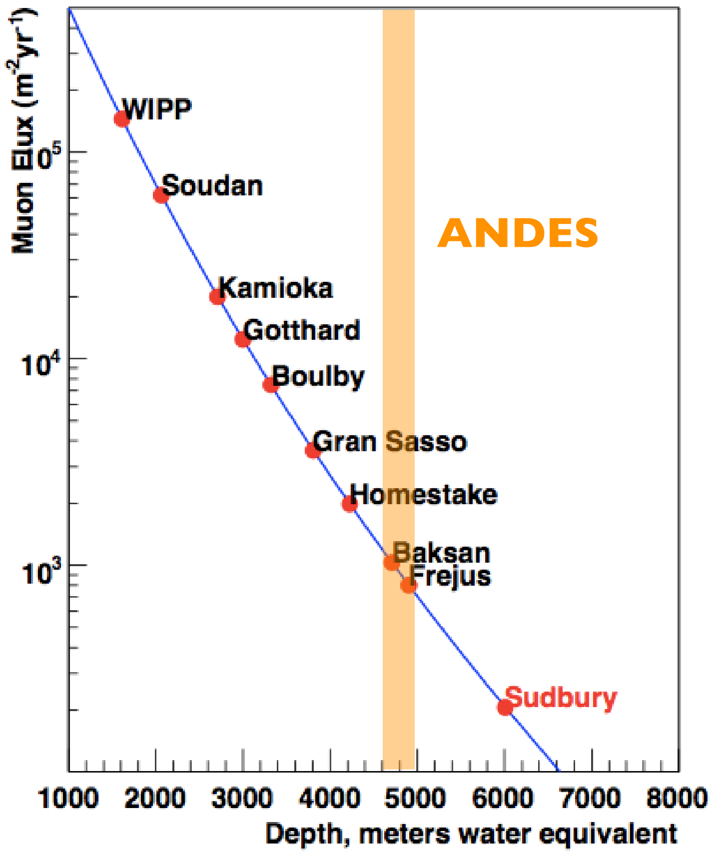
buenos aires

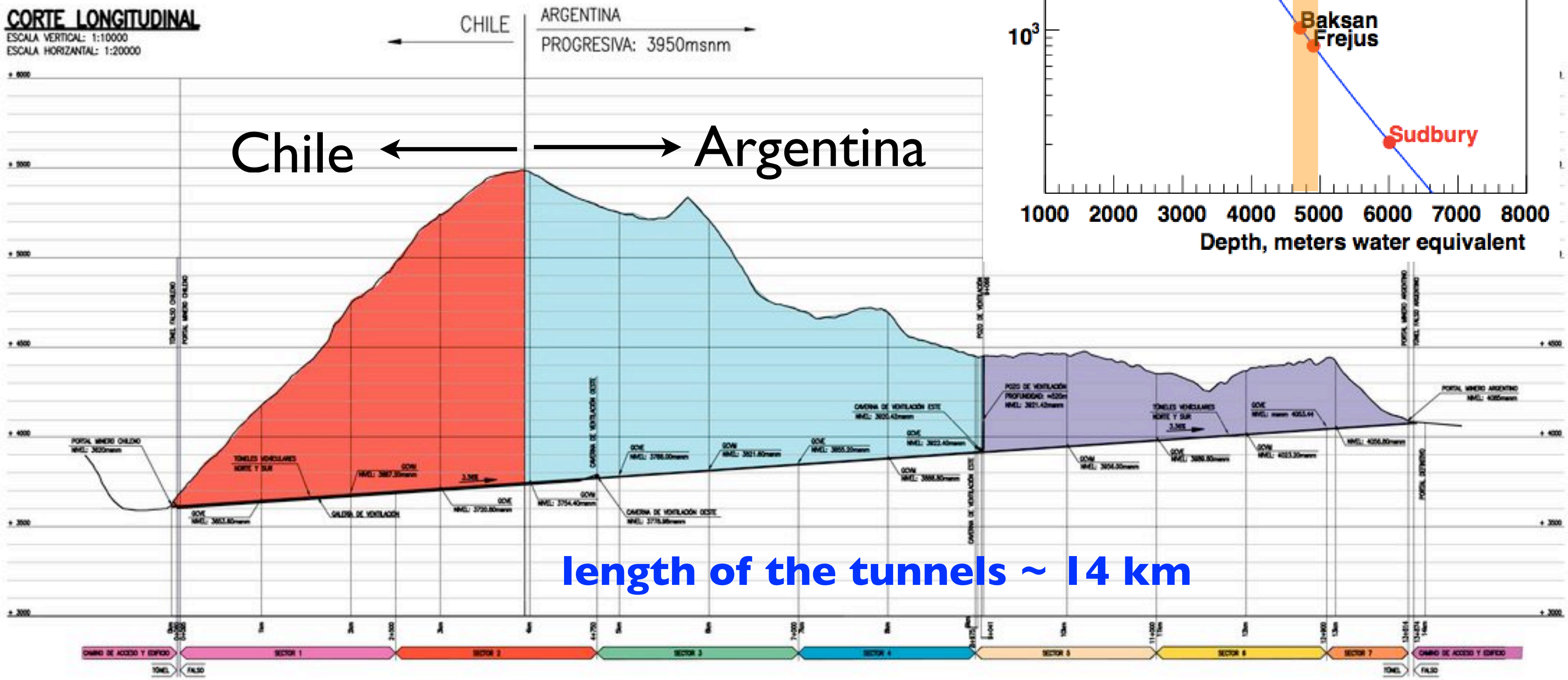
Agua Negra Tunnels

Agua Negra Tunnels

there will be 2 tunnels

~4600-5000 mwe





length of the tunnels ~ 14 km

maximum overburden ~ 1.7 km

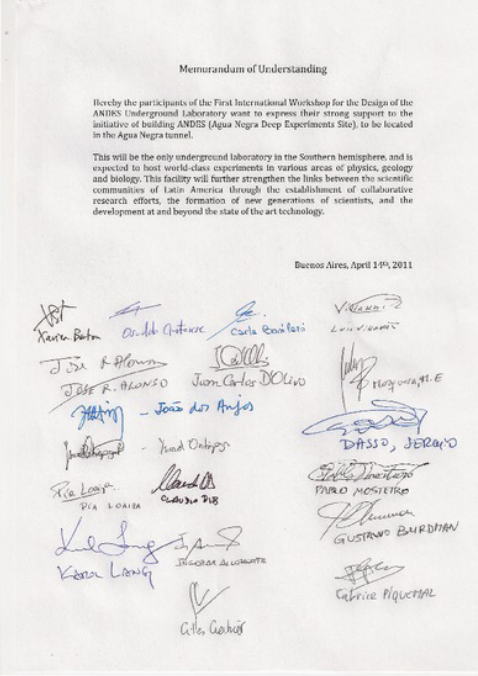
Tunnel proposal updates

- Pre-feasibility study done in 2005, feasibility in 2008.
- 2009, October: presidents of Argentina and Chile signed a Bi-National Integration Treaty, including San Juan-Coquimbo.
- 2010, August: MERCOCUR Meeting in San Juan: “strong support for Agua Negra Tunnel”, with President of Brazil pushing for tunnel tender.
- 2011, December: Argentina Congress voted a 800 MU$D guarantee fund for the Agua Negra tunnel.
- 2012, March: presidents of Argentina and Chile signed international agreement asking for the tender of the tunnel.
- 2013, June: Call for tender.
- 2014 – 2021: Construction

Current status

- 20 support letters from International community

  (underground lab directors, intl. exp spokespersons, natl. physics associations and academies,…)
- Regional interest: 26 letters from latin american groups.
- Official support from MinCyT (Argentina) and EBITAN (Entidad Binacional Túnel Agua Negra).



Memorandum of Understanding

Hereby the participants of the First International Workshop for the Design of the ANDES Underground Laboratory want to express their strong support to the initiative of building ANDES (Agua Negra Deep Experiments Site), to be located in the Agua Negra tunnel.

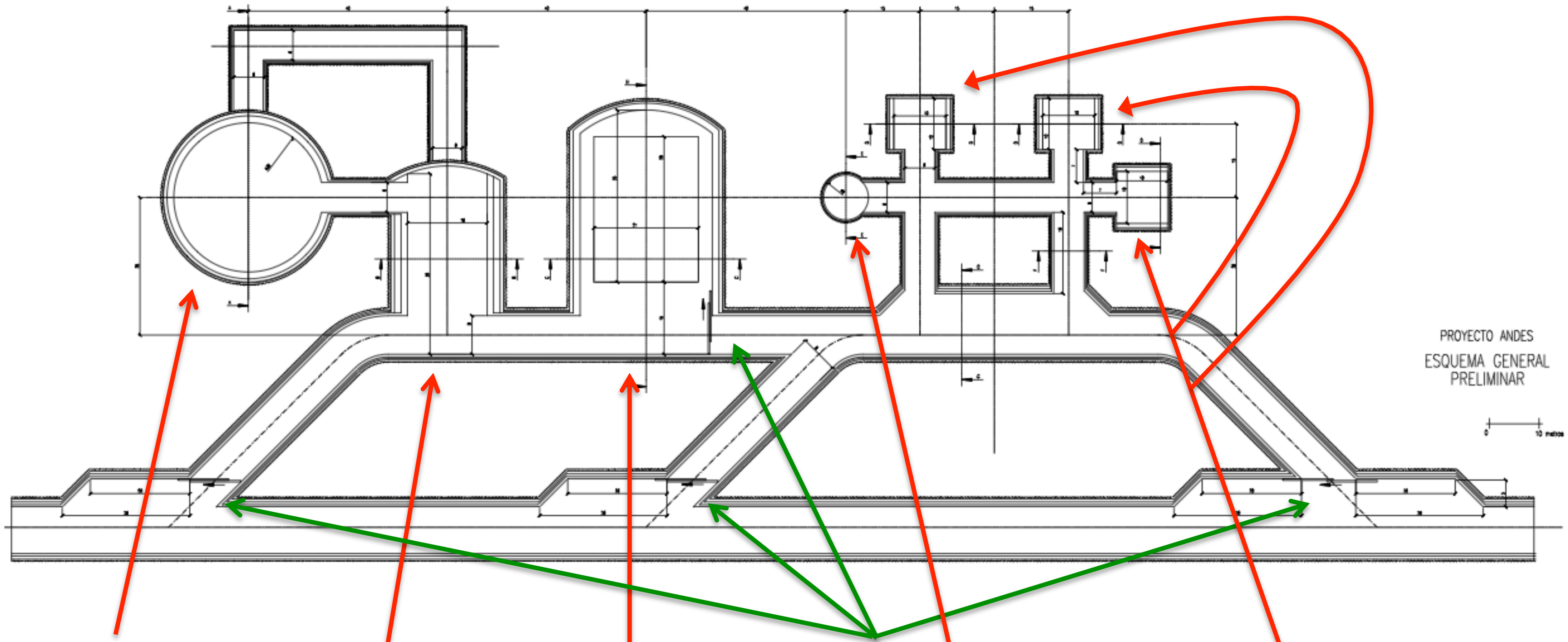
This will be the only underground laboratory in the Southern hemisphere, and is expected to host world-class experiments in various areas of physics, geology and biology. This facility will further strengthen the links between the scientific communities of Latin America through the establishment of collaborative research efforts, the formation of new generations of scientists, and the development at and beyond the state of the art technology.

Buenos Aires, April 14th, 2011

JOSE R. ALONSO
Juan Carlos D'Olivo
João dos Anjos
DASSO
PIA LOAIZA
CLAUDIO DIB
PABLO MOSTEIRO
GUSTAVO BURDMAN
Fabrice Piquemal

- 3 workshops for the Lab design (Argentina, Brazil, Chile).
- In process: Lab. engineering study, to be included in the tunnel design.
- 4th Workshop early 2014 (Mexico).

Current Design of Laboratory



Gates

Large pit
30 m diam
42 m deep

Access:
at 30 m high
and
at bottom

Service hall
40 m long
16 m wide
15 m high
Oval section

Main hall
50 m long
21 m wide
23 m high
Oval section

Ultra low radiation pit
9 m diam
15 m deep

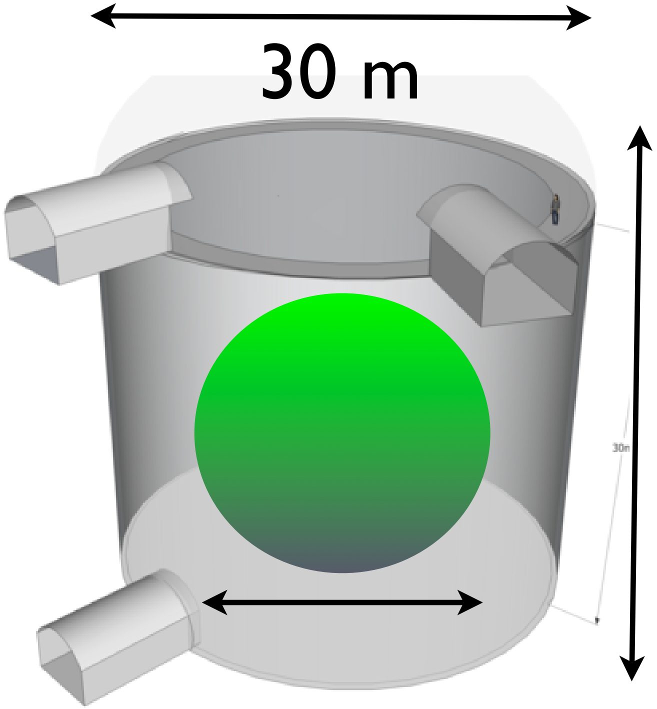
Access:
At 10 m high
and bottom

3 secondary caverns
10 x 10 x 10 m

ANDES initial Scientific Programme

- Neutrino physics:
  - host double beta decay experiments
  - large neutrino detector (similar to KamLAND / Borexino)
    - focused on low energies (solar / SN / geoneutrinos)
- Dark Matter
  - modulation measurements
  - new technologies
- Geophysics
  - link Chile-Argentina seismograph networks
- Biology
- Low radiation measurements
- Nuclear Astrophysics (low energy beams)

ANDES Neutrino Detector (suggestion)



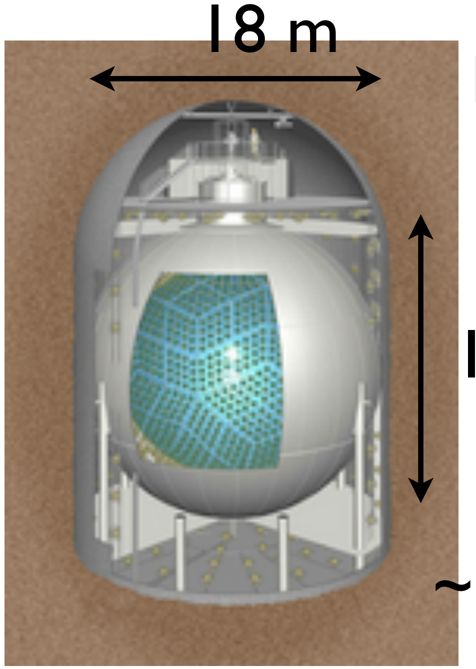
30 m

30 m

~20 m

construction of the detector like KamLAND/ SNO+ of ~3-5 kt

KamLAND

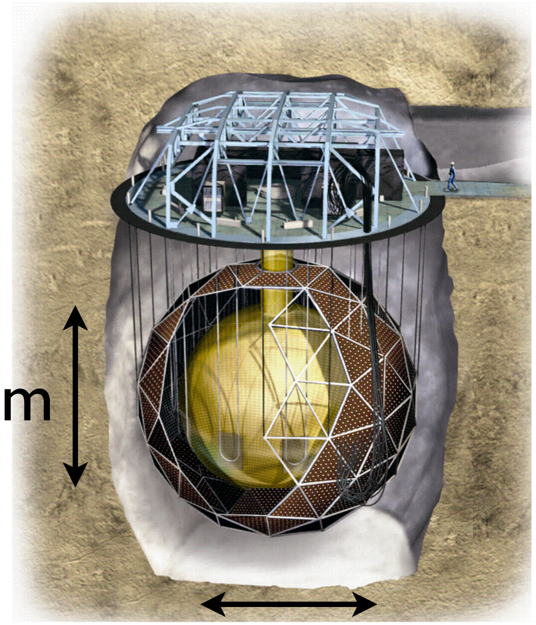


18 m

18 m

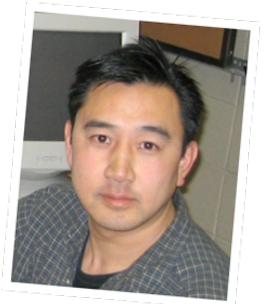
K. Inoue

~1kt de cintilador



12 m

12 m



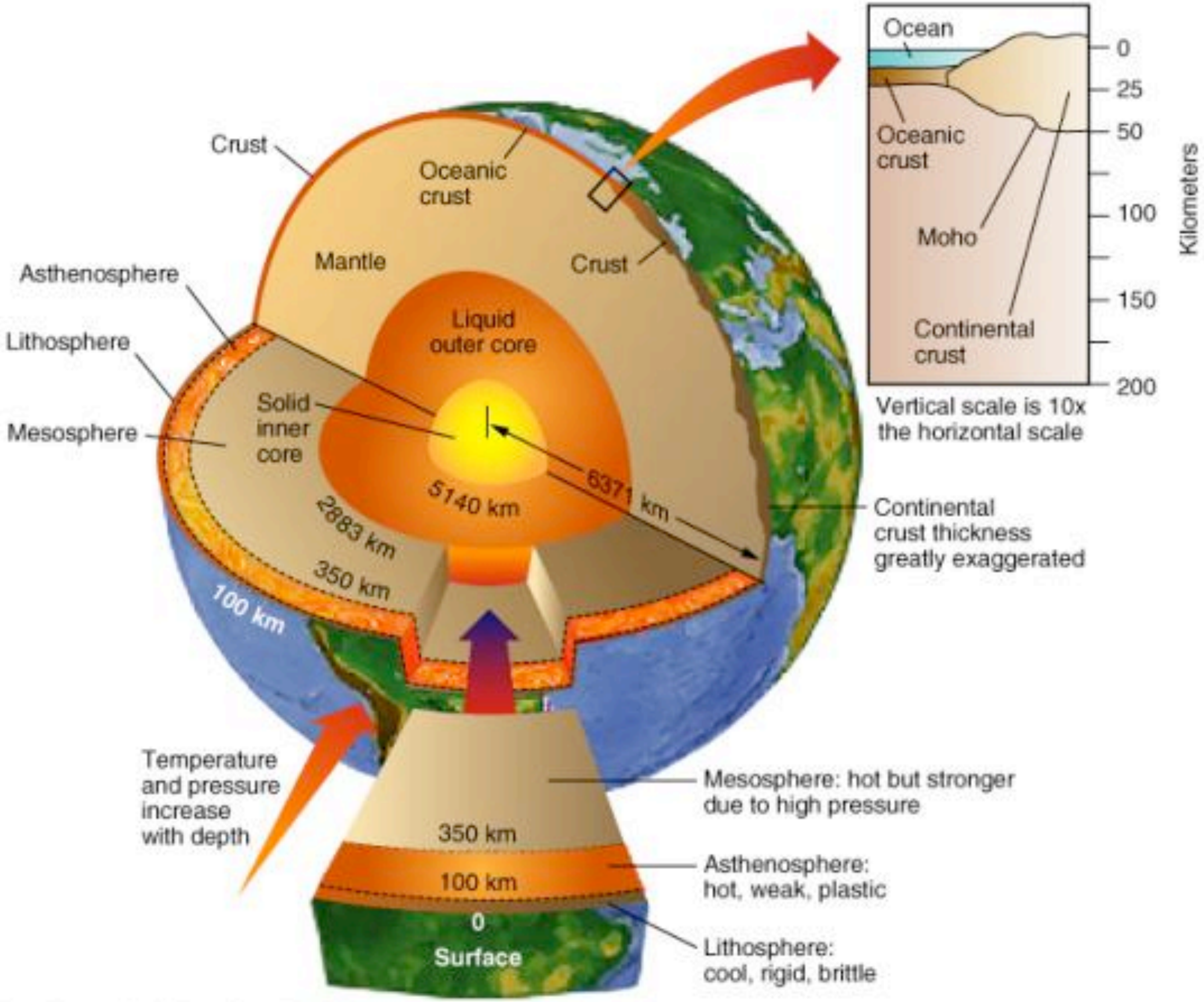
M.Chen

~0.8 kt de cintilador

SNO+

Observation of Geoneutrinos at ANDES

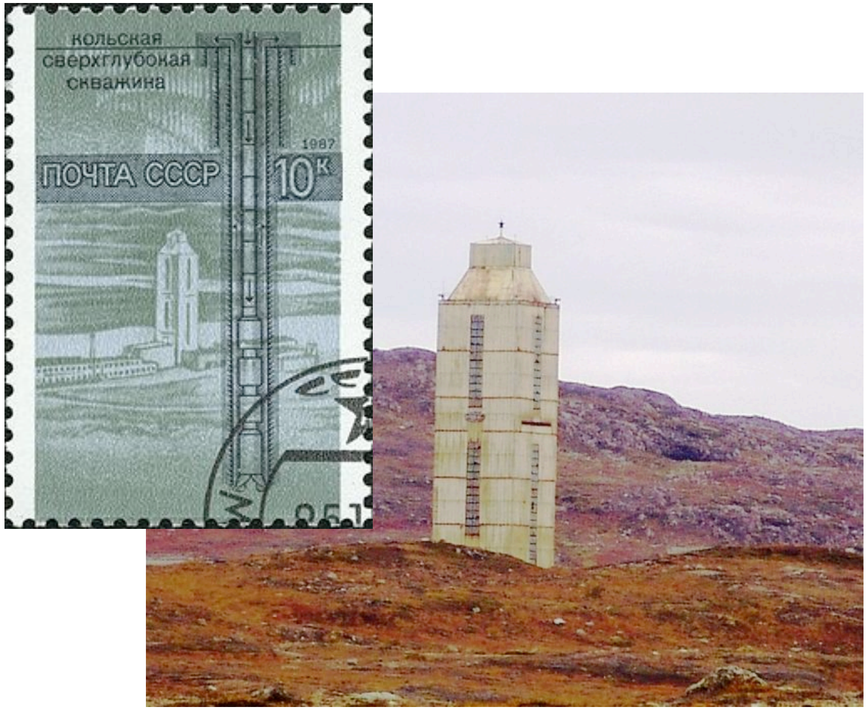
We know that Earth Interior should be something like below ...



but not so easy to probe directly ...

deepest hole in the Earth ~ 12 km depth

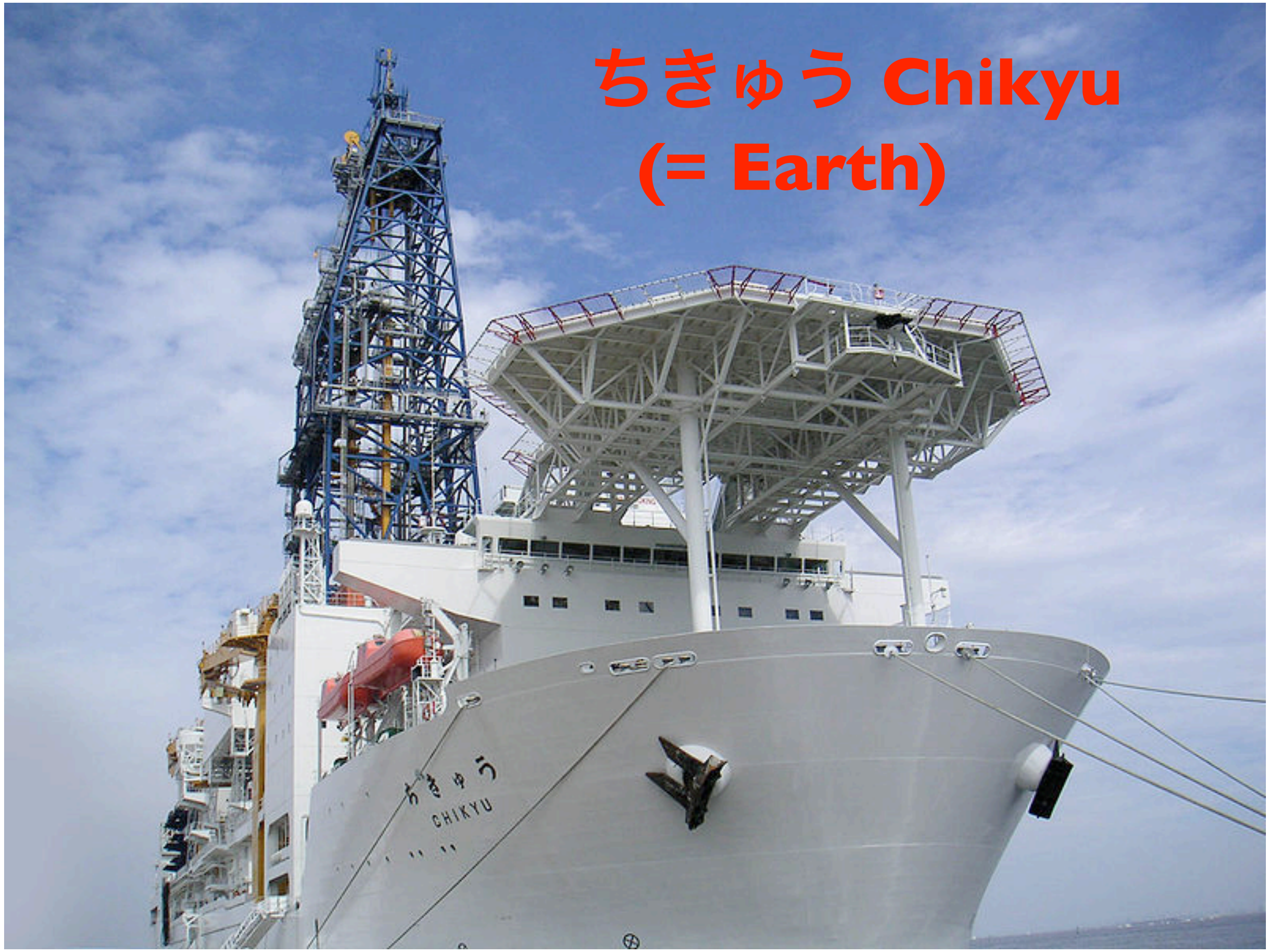
only ~ 0.2 % of the Earth Radius,
only upper part of the Earth crust !



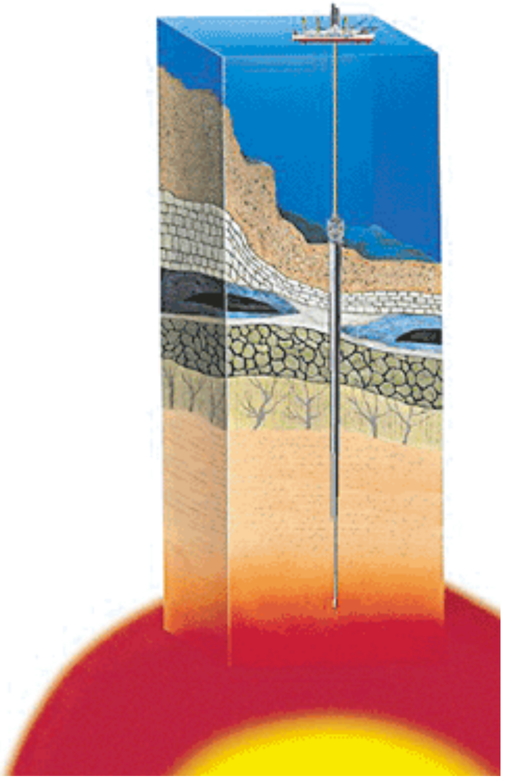
deepest hole of 12.262 m depth 1989

Kola Superdeep Barehole (Soviet Union)

Integrated Ocean Driling Program (IODP)



ちきゅう Chikyu
(= Earth)



capable to dig more than 7 km from the seabed

one of the purposes: direct access to the Earth Mantle

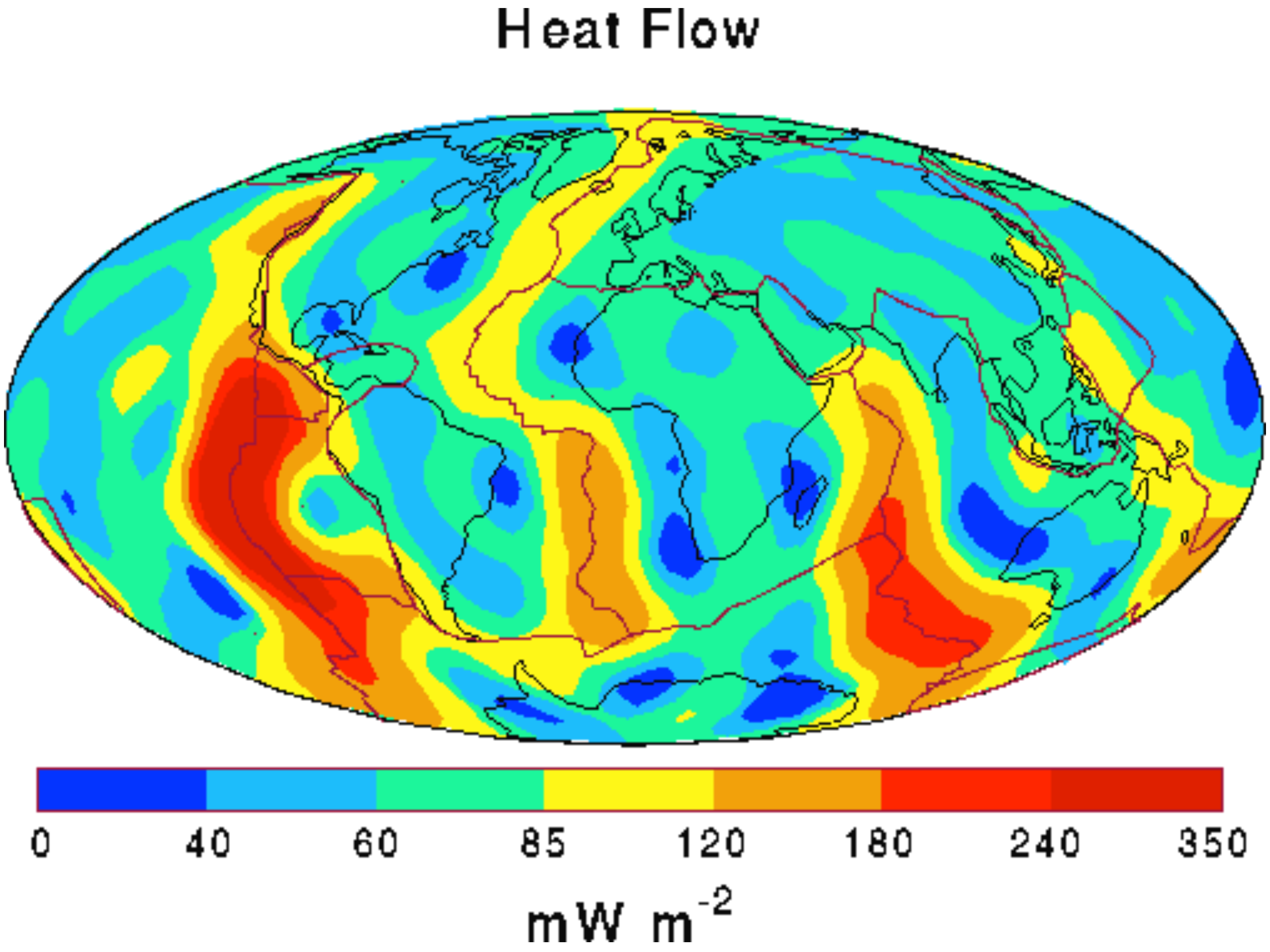
Methods to study Earth Interior

geochemistry: analysis of samples from the crust and upper mantle (deepest hole ~ 12 km, deepst rock samples from ~ 200 km)

seismology: it is possible to reconstruct the density profile of the Earth (and ditinguish solid from liquid) but not the compositions

geoneutrinos: new probe to study Earth Interior

Origin of the Earth Heat?

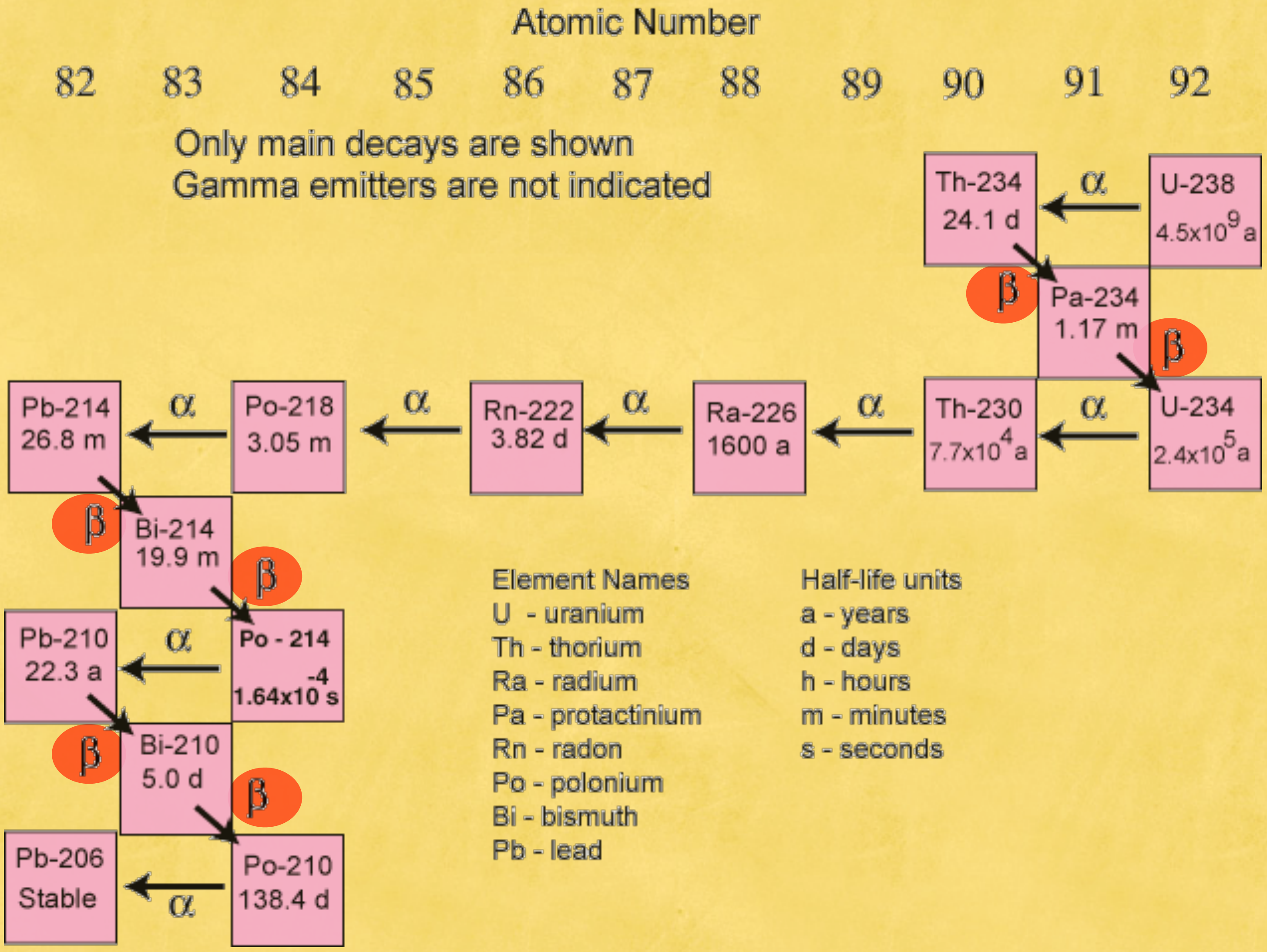


Observed (estimated): ~ 44 ± 1 TW

Theoretical Predictions: ~ 20 - 45 TW

large uncertainty

The Uranium-238 Decay Chain



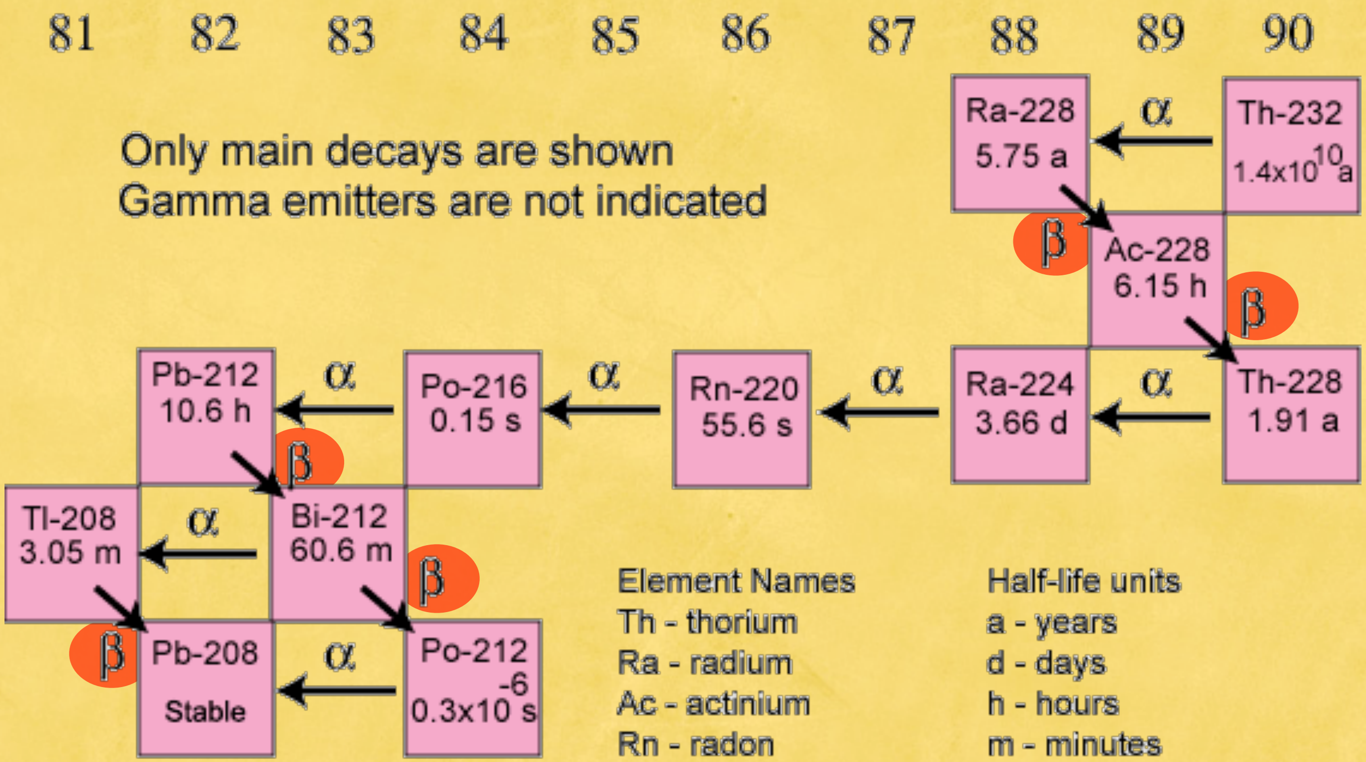
Only main decays are shown
Gamma emitters are not indicated

Element Names
U - uranium
Th - thorium
Ra - radium
Pa - protactinium
Rn - radon
Po - polonium
Bi - bismuth
Pb - lead

Half-life units
a - years
d - days
h - hours
m - minutes
s - seconds

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6\,\mathrm{e}^{-} + 6\,\bar{\nu}_{\mathrm{e}} + 51.7\ [\mathrm{MeV}]$$

The Thorium-232 Decay Chain



Atomic Number

81 82 83 84 85 86 87 88 89 90

Ra-228 5.75 a

Th-232 $1.4x10^{10}$ a

Ac-228 6.15 h

Pb-212 10.6 h

Po-216 0.15 s

Rn-220 55.6 s

Ra-224 3.66 d

Th-228 1.91 a

Tl-208 3.05 m

Bi-212 60.6 m

Pb-208 Stable

Po-212 $0.3x10^{-6}$ s

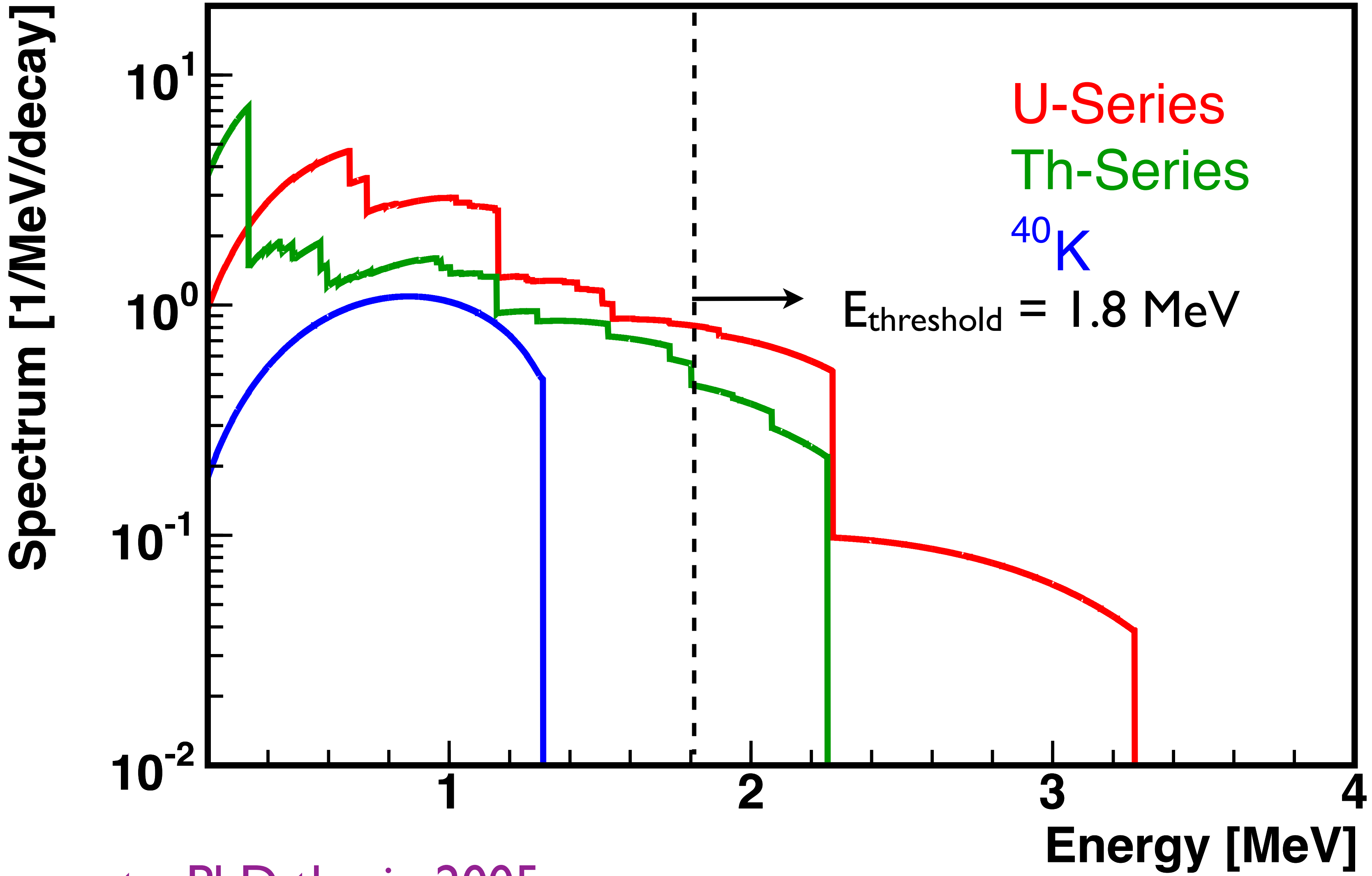
Only main decays are shown
Gamma emitters are not indicated

Element Names
Th - thorium
Ra - radium
Ac - actinium
Rn - radon
Po - polonium
Bi - bismuth
Pb - lead
Tl - thallium

Half-life units
a - years
d - days
h - hours
m - minutes
s - seconds

$$^{232}\mathrm{Th} \rightarrow {}^{206}\mathrm{Pb} + 6\,{}^{4}\mathrm{He} + 4\,\mathrm{e}^{-} + 4\,\bar{\nu}_{\mathrm{e}} + 42.7\ [\mathrm{MeV}]$$

Expected Geoneutrino Spectra



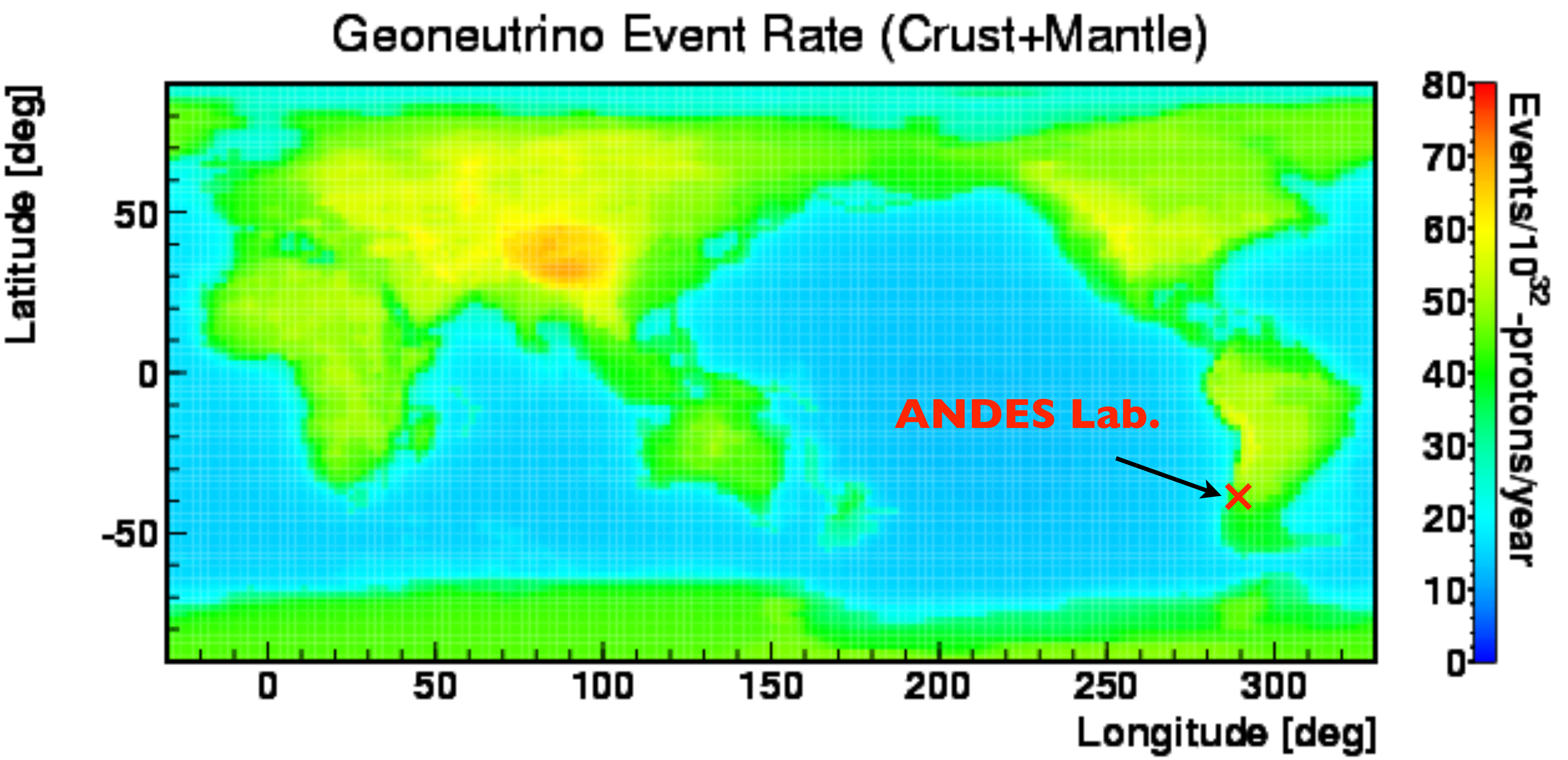
Enomoto, PhD thesis, 2005

Can be detected by the inverse beta decay reaction

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

$E_{threshold}$ = 1.8 MeV

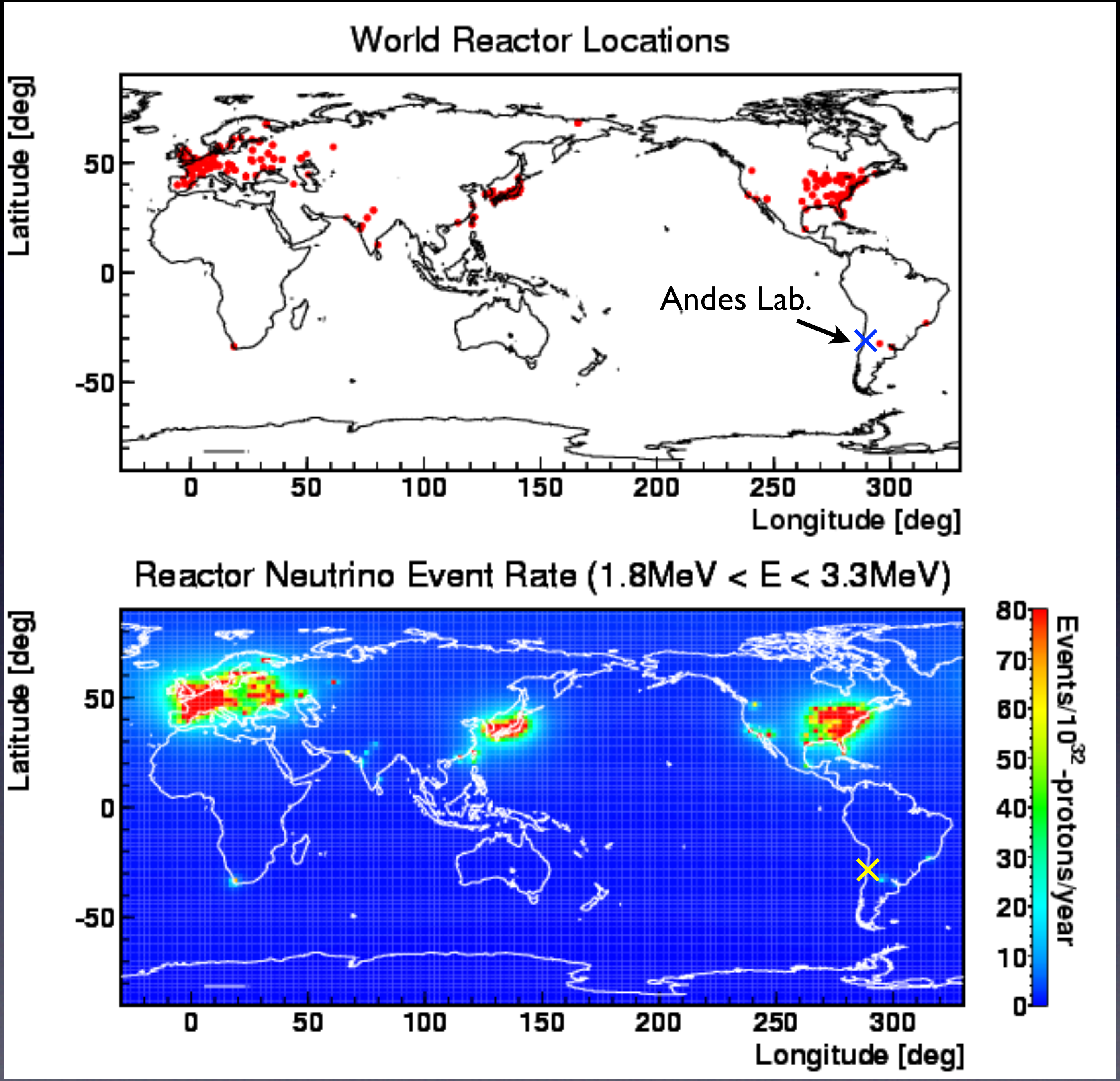
Interesting place because of larger flux of Geo-neutrinos (to confirm site dependence)



Enomoto, Neutrino Sciences 2007

U and Th are more concentrated in the continental crust

Another Advantage: Very few reactors



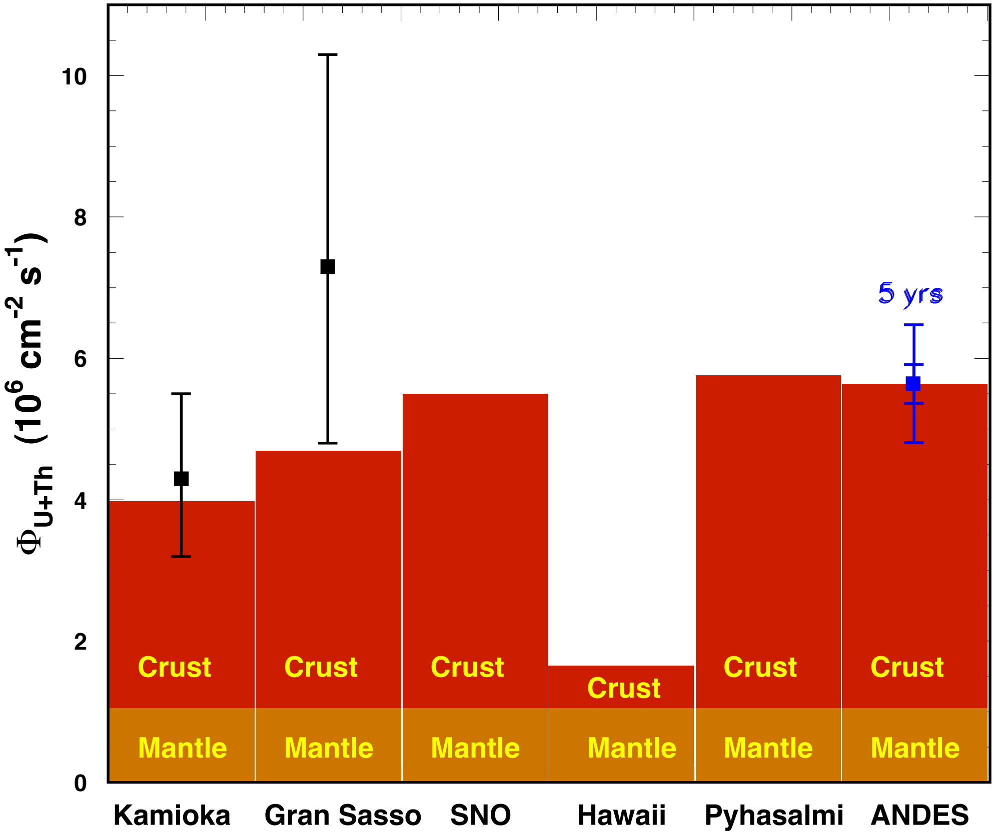
Enomoto, Neutrino Sciences 2007

distance to nearest reactor ~ 600 km

$N_{\text{reac BG}}$ ~ 2 event for 3 kt/yr at Andes Laboratory

Expected Geoneutrino flux and events at ANDES

comparison with other sites



of event /3 kt/yr

Location	Number from U	Number from Th	Total
Gran Sasso	53.8	14.7	68.5
Kamioka	45.7	12.4	58.1
Hawaii	27.3	7.4	34.7
Sudbury	63.2	17.2	80.4
Pyhäsalmi	66.1	18.0	84.1
ANDES	64.8	17.6	82.4

Machado et al, PRD86, 125001 (2012) [arXiv:1207.5454[hep-ph]]

See http://andeslab.org/workshop/

First Circular, November 22, 2013

Fourth International Workshop for the Design of the ANDES Underground Laboratory

Universidad Nacional Autónoma de
México, México, D.F.
30 January - 1 February 2014

The construction of the Agua Negra tunnel under the Andes Mountains between Argentina and Chile gives the scientific community a unique opportunity to build ANDES (Agua Negra Deep Experiment Site): an Underground Laboratory inside the tunnel at its deepest point.

This site will be 1750 m deep under the Earth surface, and will be the first of its kind in the Southern Hemisphere. The planning of ANDES is expected to be finished by end of 2014, before the excavation of the tunnel begins. The completion of the Agua Negra

Conclusions

Neutrino physics entered into a new phase since all the mixing angles and mass squared differences (apart from sign) are determined

But there are still several important open questions to be answered, and hopefully, more new interesting results (or surprise) will come!

Thank you very much
for your attention!