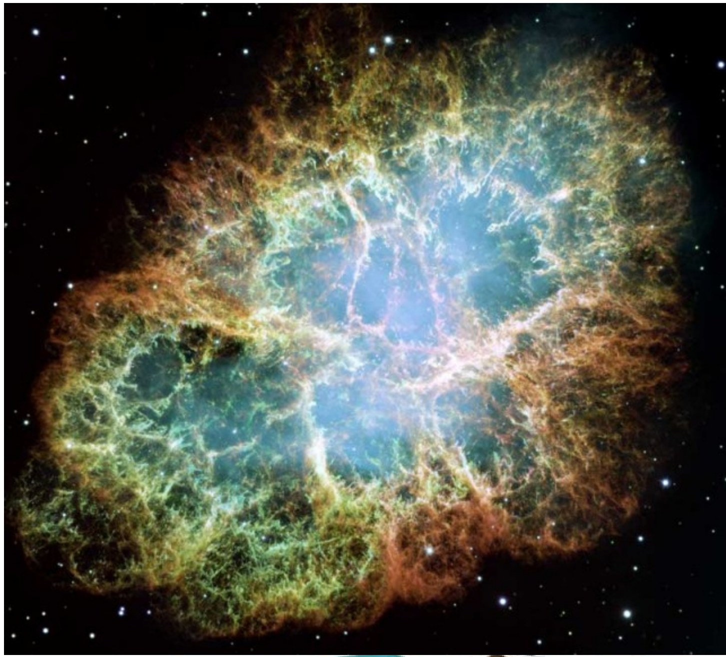
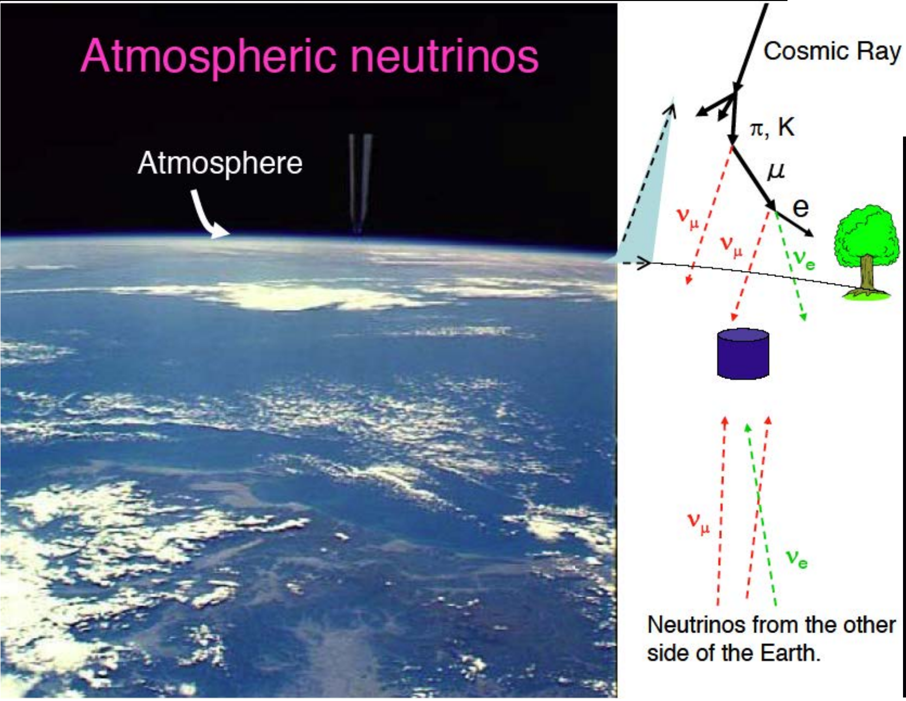
Neutrinos: Kage-Musha in nature which however have a key to understand her fundamental structure

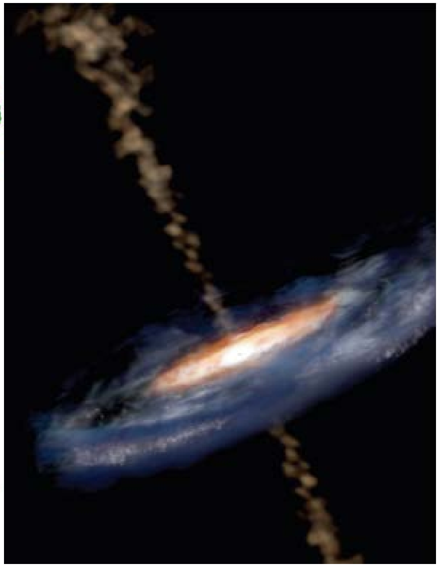
Hisakazu Minakata

Neutrinos: interdiscipl inary science

Neutrinos come from natural sources

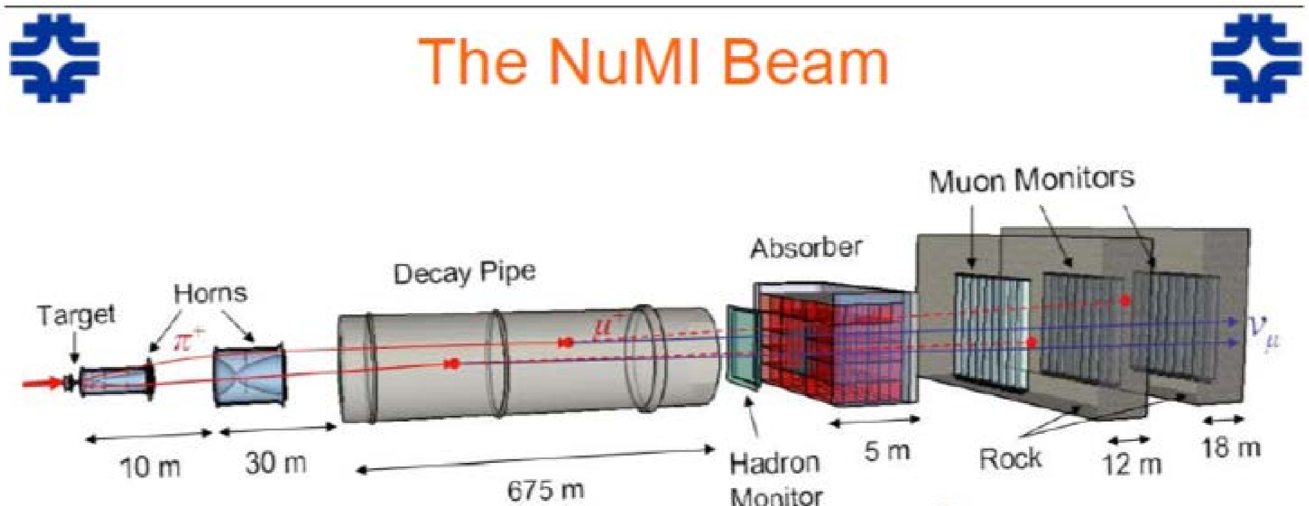


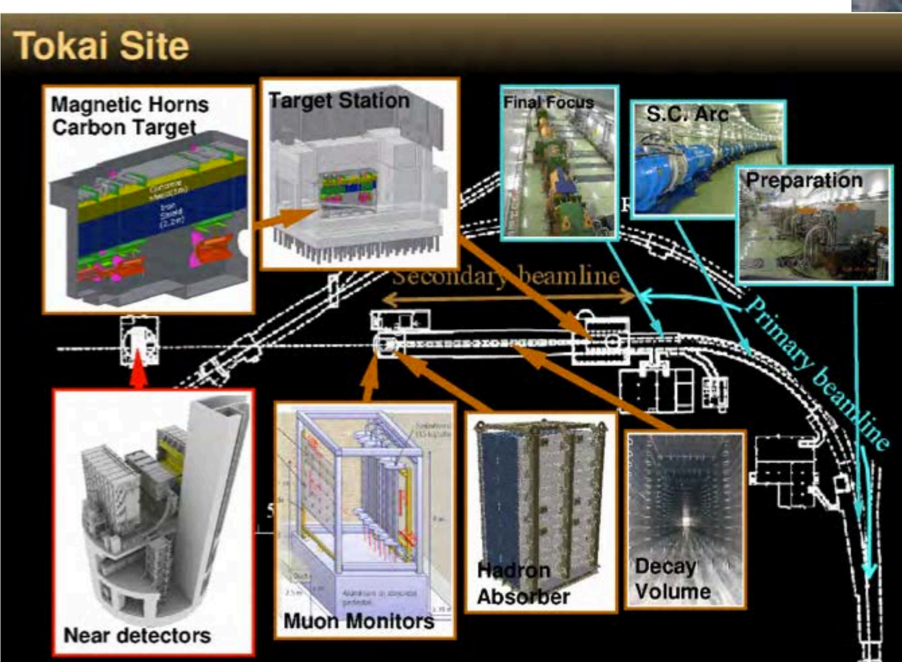




Nature **436**, 499-503 (28 July 2005)

Neutrinos come from artificial sources





Two aspects of neutrino physics

Understanding phenomena in nature through neutrinos

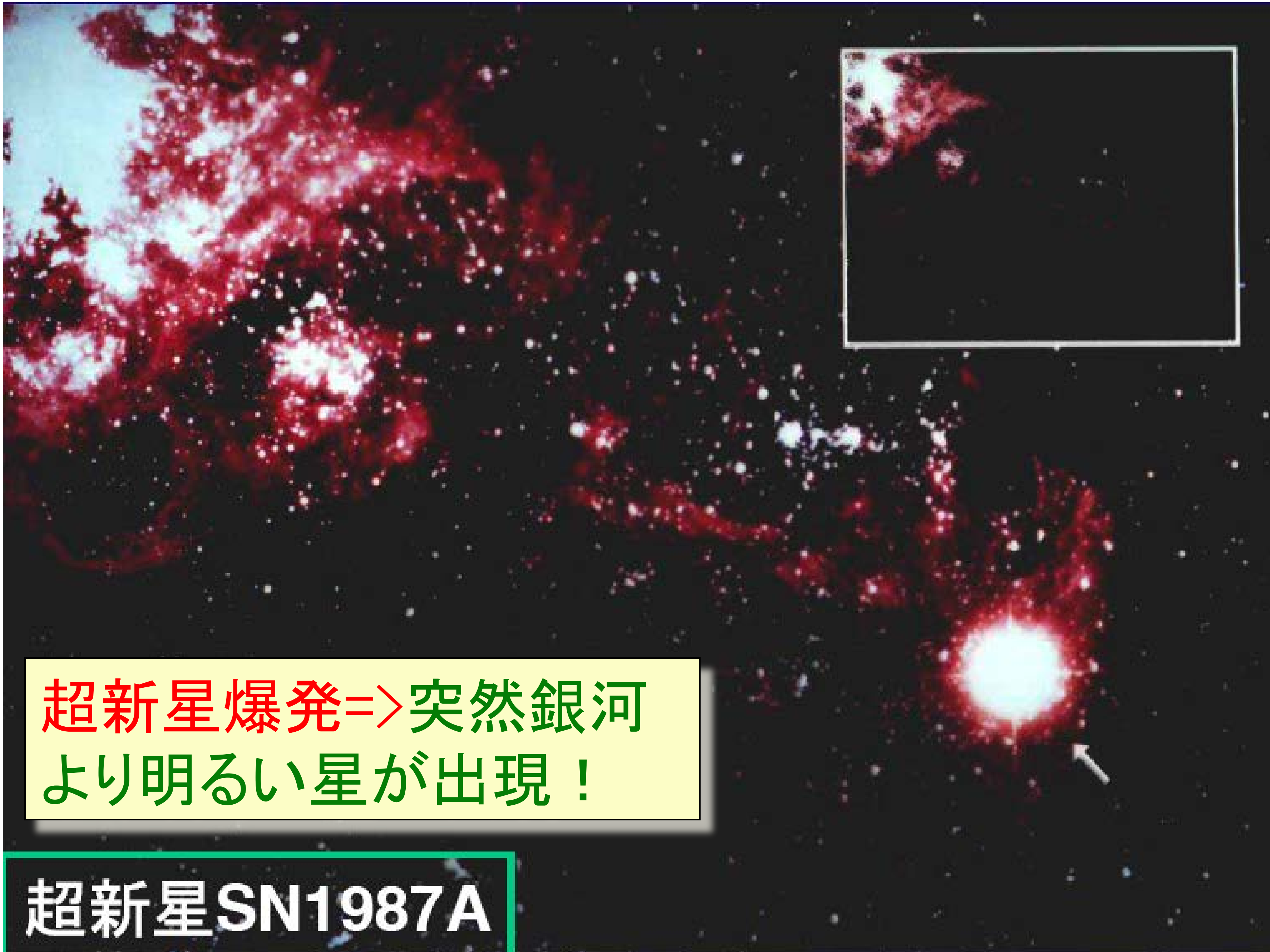
- core collapse SN explosion: cannot occur without neutrinos
- Sun does not shine without neutrinos
- BBN not OK without ν
- Geo-neutrinos
- Ex-high energy ν?

Understanding nature using neutrinos as probe

- Pure chirality of ν leads to chiral picture of fundamental particles
- Neutrino mass probes high-energy worlds
- Through-ν discovered lepton flavor mixing shed light on quark-lepton relation

Both aspects interact with each other !

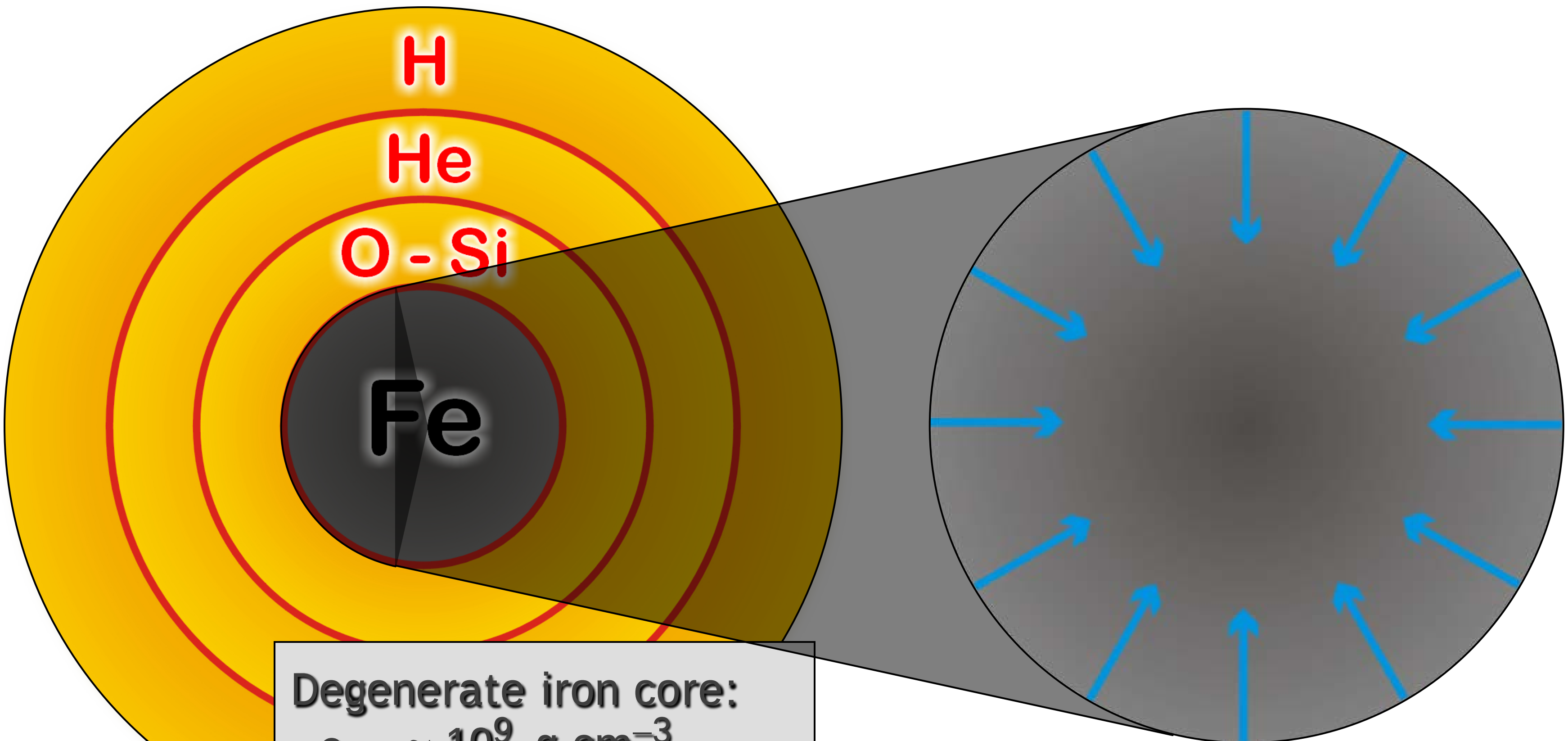
Neutrinos arrived from outside our galaxy !


超新星爆発=>突然銀河
より明るい星が出現！
超新星SN1987A

Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)



Degenerate iron core:

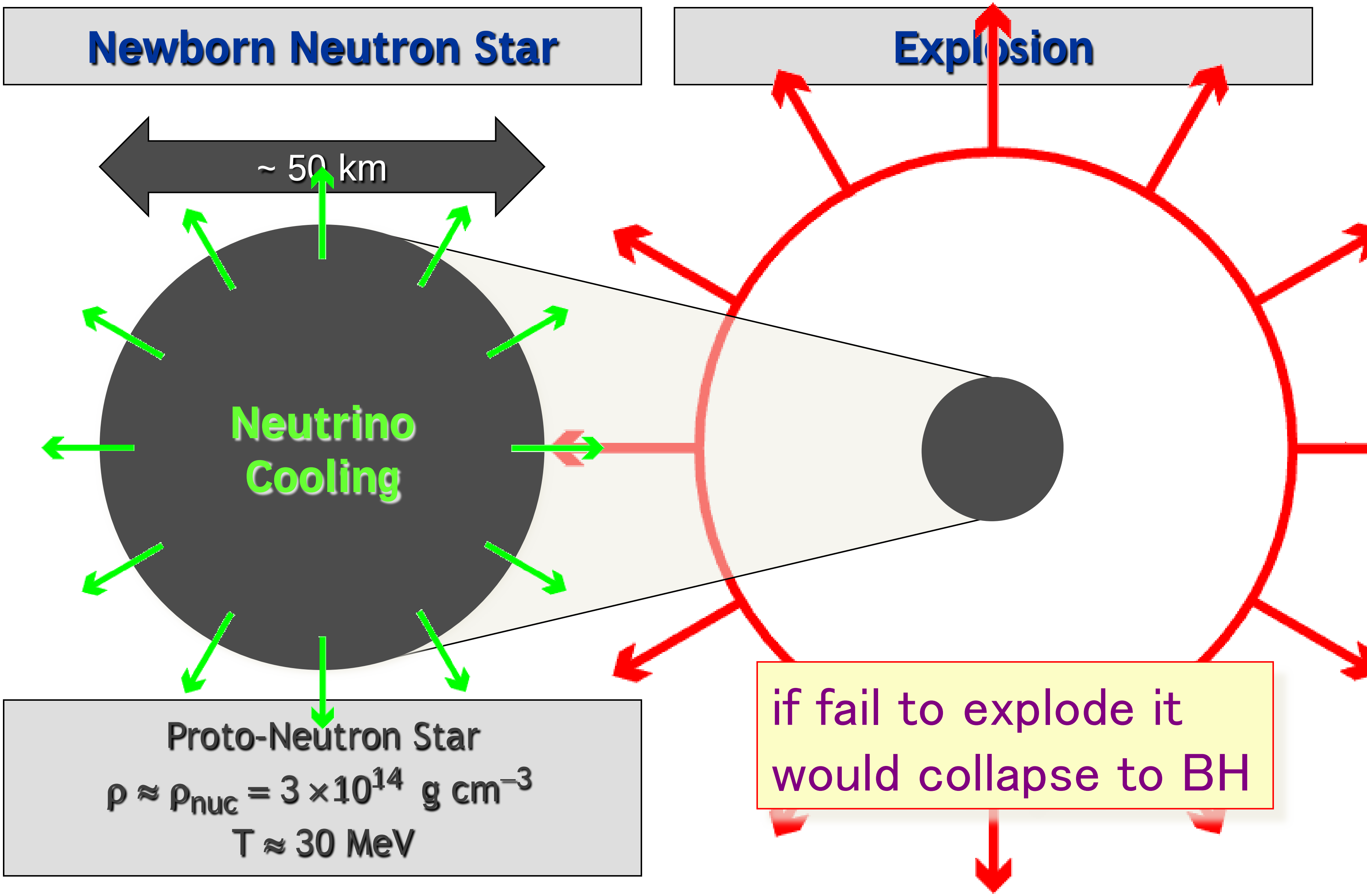
$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 8000$ km

Stellar Collapse and Supernova Explosion



Supernova energy budget

- How big amount of energy is released ?

→ simple to compute!

- To form neutron star how much energy should be extracted? A = grav. binding energy = 10^{46} J
- How can it be transported to outside star in 10 s? → Neutrinos!
- 99% of 10^{46} J are carried away by ν
- Only remaining 1% explodes outer progenitor

Neutrino IS the major player in core collapse suparnova !

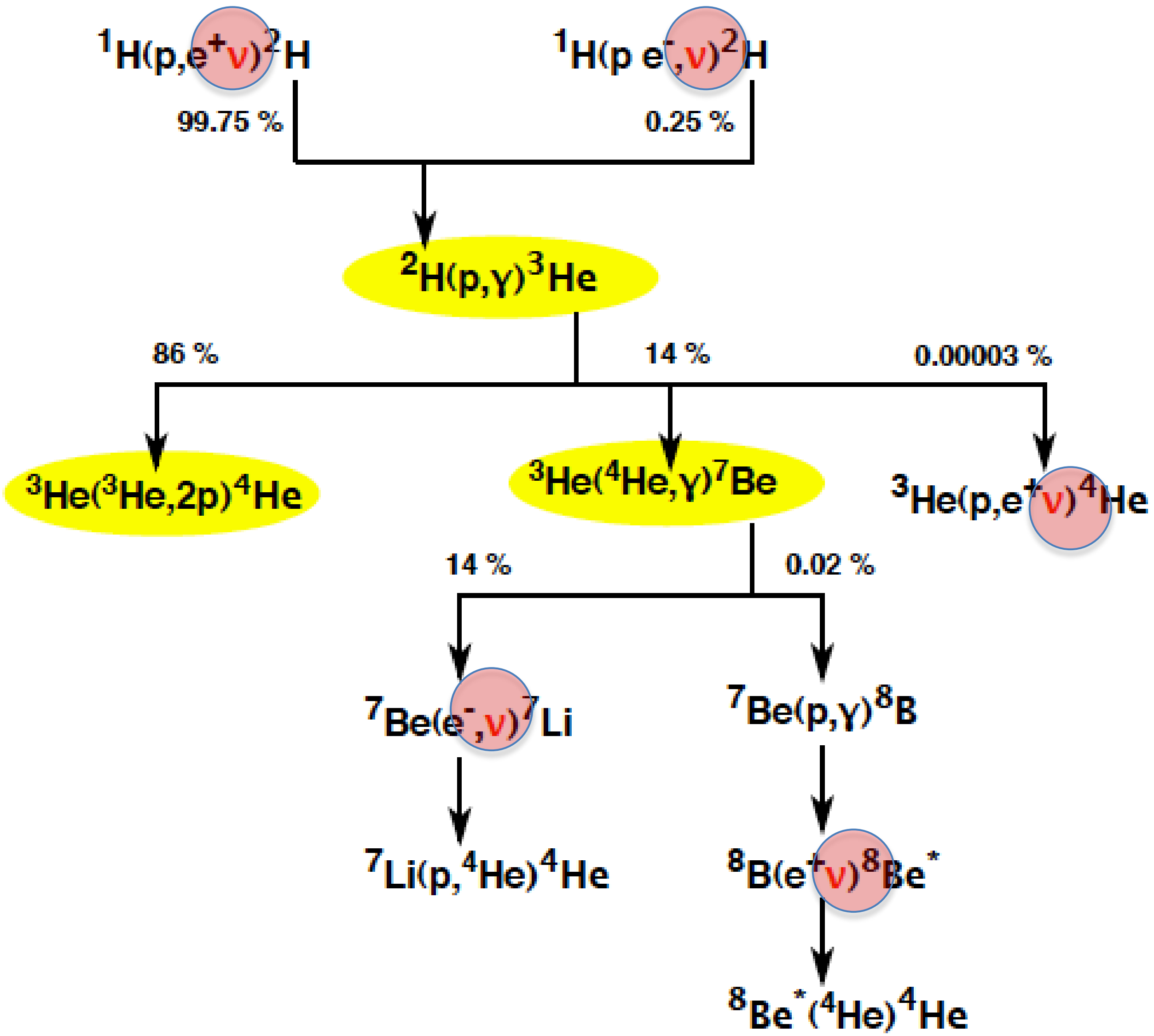
SN1054 now: crab

Ejected material is expanding with velocity ～ 600km/s

中心部には高速回転するパルサーがある。(毎秒30回、回転している)

Solar neutrino problem

Sun does not shine without neutrinos: Nuclear chain reaction in the Sun



Net reaction: pppp -> $^4He + 2e^+ + 2\nu_e$ + ~25 MeV

pp I chain (termination 85%)

$$
\begin{aligned}
p+p &\rightarrow {}^2H + e^+ + \nu_e \\
p+p &\rightarrow {}^2H + e^+ + \nu_e \\
{}^2H + p &\rightarrow {}^3He + \gamma \\
{}^2H + p &\rightarrow {}^3He + \gamma \\
{}^3He + {}^3He &\rightarrow {}^4He + p + p
\end{aligned}
$$

$$p+p+p+p \rightarrow {}^4He + 2e^+ + 2\nu_e(pp) + 2\gamma$$

ppI: main engine of the Sun

pp II chain (termination 15%)

$$
\begin{aligned}
p+p &\rightarrow {}^2H + e^+ + \nu_e \\
{}^2H + p &\rightarrow {}^3He + \gamma \\
{}^3He + {}^4He &\rightarrow {}^7Be + \gamma \\
{}^7Be + e^- &\rightarrow {}^7Li + \nu_e \\
{}^7Be + p &\rightarrow {}^4He + {}^4He
\end{aligned}
$$

$$p+p+p+p+e^- \rightarrow {}^4He + e^+ + \nu_e(pp) + \nu_e({}^7Be) + 2\gamma$$

pp III chain (termination 0.02%)

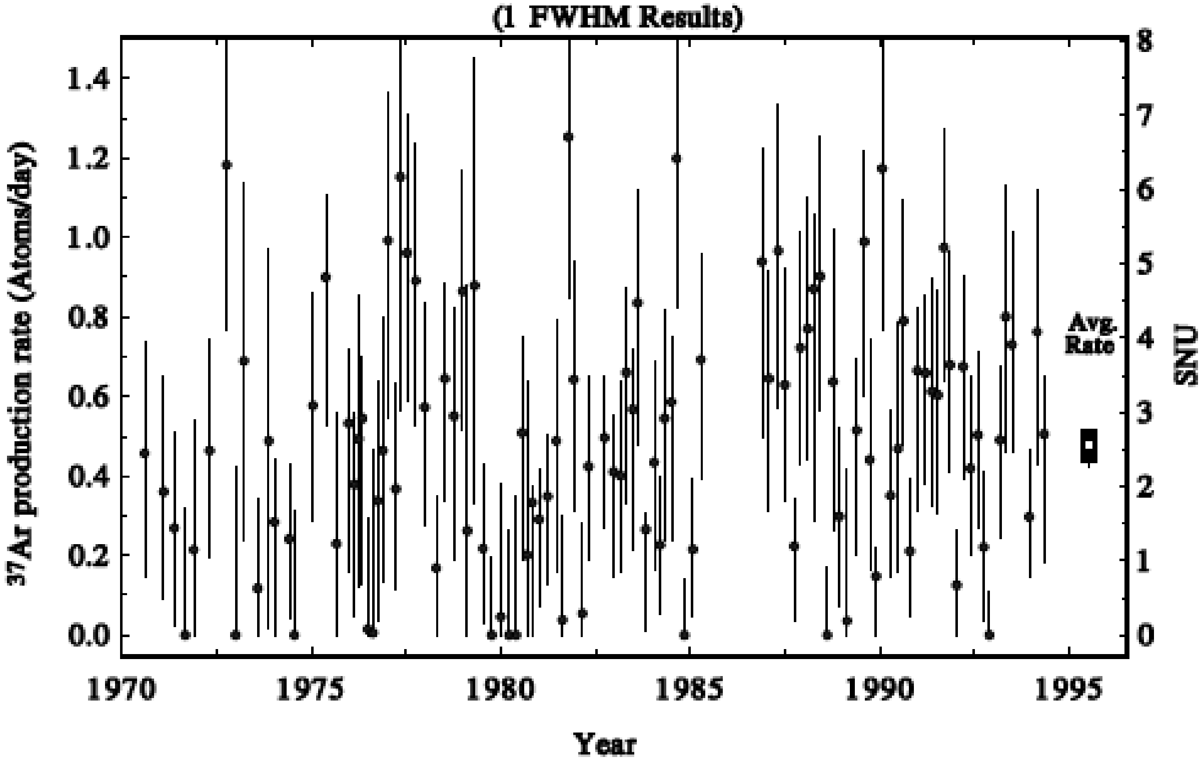
$$
\begin{aligned}
p+p &\rightarrow {}^2H + e^+ + \nu_e \\
{}^2H + p &\rightarrow {}^3He + \gamma \\
{}^3He + {}^4He &\rightarrow {}^7Be + \gamma \\
{}^7Be + p &\rightarrow {}^8B + \gamma \\
{}^8B &\rightarrow {}^8Be^* + e^+ + \nu_e \\
{}^8Be^* &\rightarrow {}^4He + {}^4He
\end{aligned}
$$

$$p+p+p+p \rightarrow {}^4He + 2e^+ + \nu_e(pp) + \nu_e({}^8B) + 3\gamma$$

Solar neutrino problem since 60's

Raymond David Jr. (left) and John Bahcall in miner's clothing and protective hats. The photograph was taken in 1967 about a mile underground in the Homestake Gold Mine in Lead, South Dakota, USA. Davis is pictured showing Bahcall his newly constructed steel ank (6 meters in diameter, 15 meters long), which contained a large amount of cleaning fluid (40,000 liters) and was used to capture neutrinos from the Sun.
Photo: Courtesy of Raymond Davis, Jr. and John Bahcall

Result of ^{37}Cl experiment : ^{37}Ar production rate

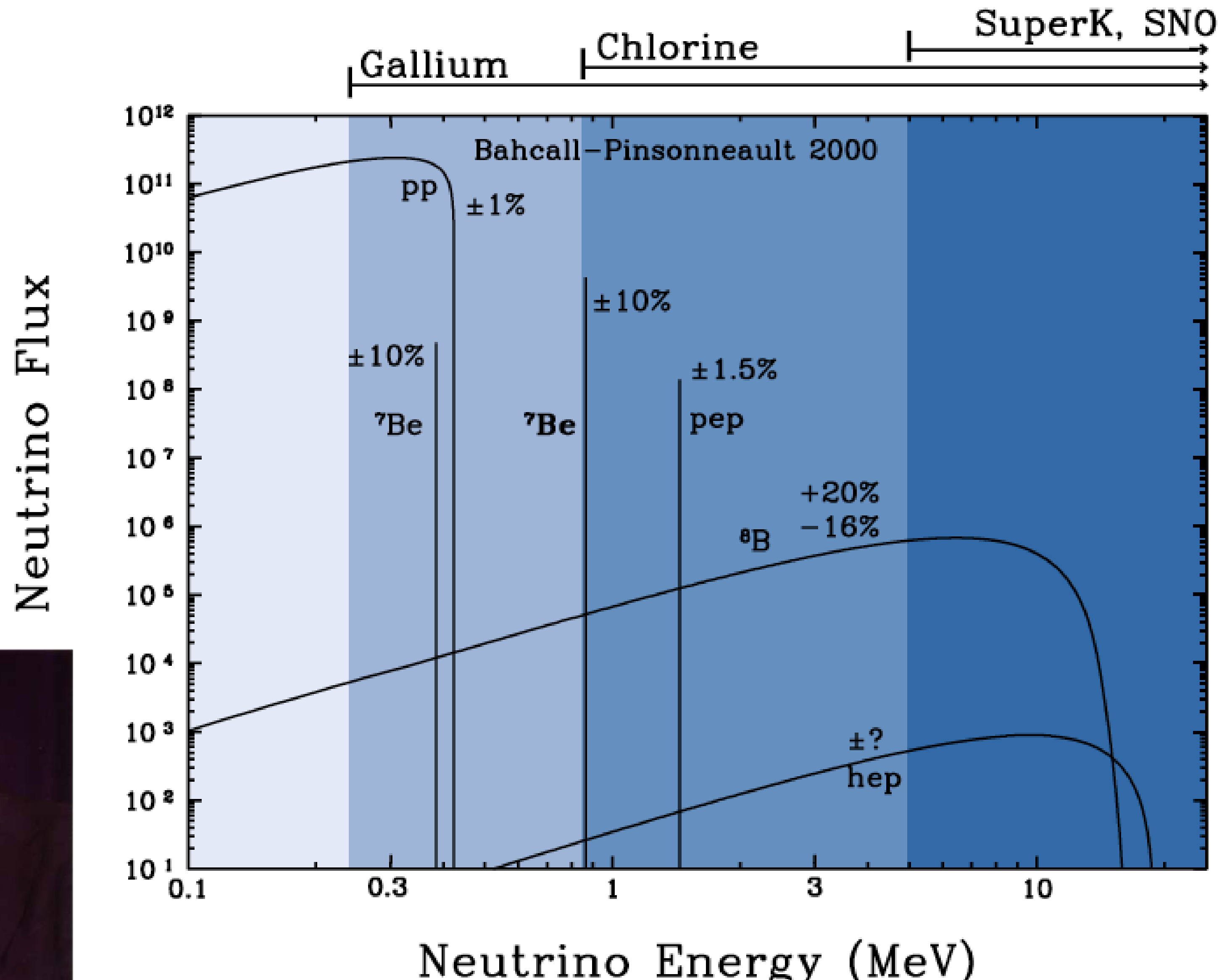


1 SNU = 10^{-36} events / (No. of target atom sec)

~1/3 of SSM prediction

FIG. 13.—Homestake Experiment—one FWHM results. Results for 108 individual solar neutrino observations made with the Homestake chlorine detector. The production rate of ^{37}Ar shown has already had all known sources of nonsolar ^{37}Ar production subtracted from it. The errors shown for individual measurements are statistical errors only and are significantly non-Gaussian for results near zero. The error shown for the cumulative result is the combination of the statistical and systematic errors in quadrature.

計算された太陽ニュートリノ強度(flux)



2039m underground

SNO

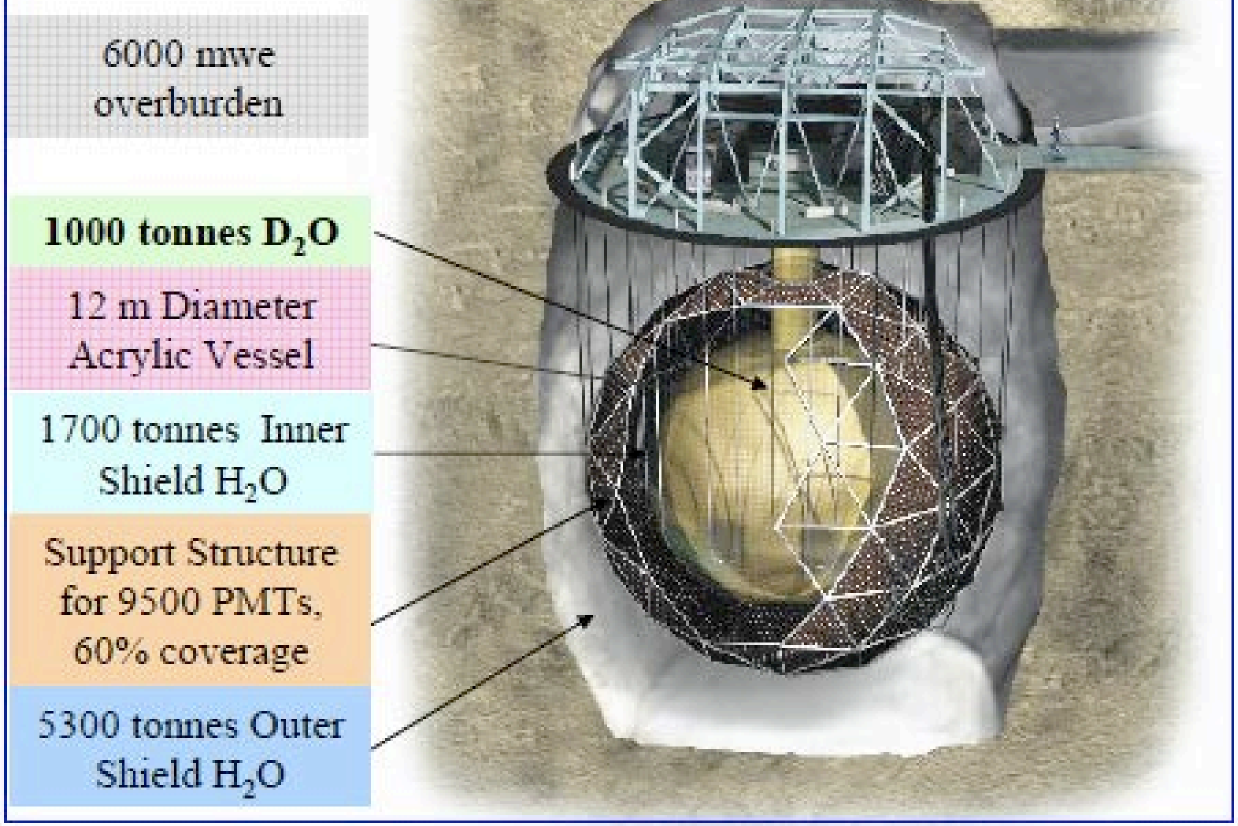


Image courtesy National Geographic

3 Reactions:

$\nu_x + e^- \rightarrow \nu_x + e^-$ ES

$\nu_e + d \rightarrow p + p + e^-$ CC

$\nu_x + d \rightarrow p + n + \nu_x$ NC

3 neutron detection methods:

$n + d \rightarrow t + \gamma + 6.25$ MeV

$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6$ MeV

$n + {}^{3}He \rightarrow p + t + 0.76$ MeV

3 Phases:

- Just D_2O
- D_2O + 2 tonnes NaCl
- D_2O + ^{3}He Proportional Counters (“NCDs”)

391 days salt data – in numbers

$$\phi_{CC} = 1.68\ ^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

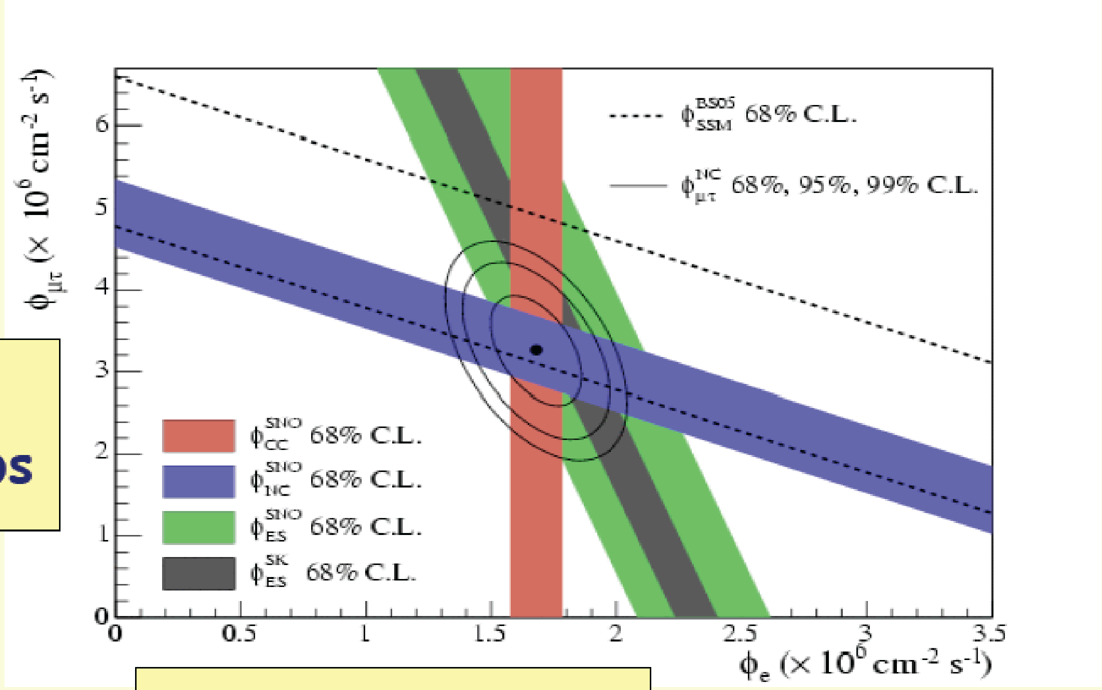
$$\phi_{NC} = 4.94\ ^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35\ ^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

$5.25 \pm 3.7\%$ $[10^6\ cm^{-2}\ s^{-1}]$

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

(In units of $10^6 cm^{-2}s^{-1}$)



μ, τ neutrinos

electron ν

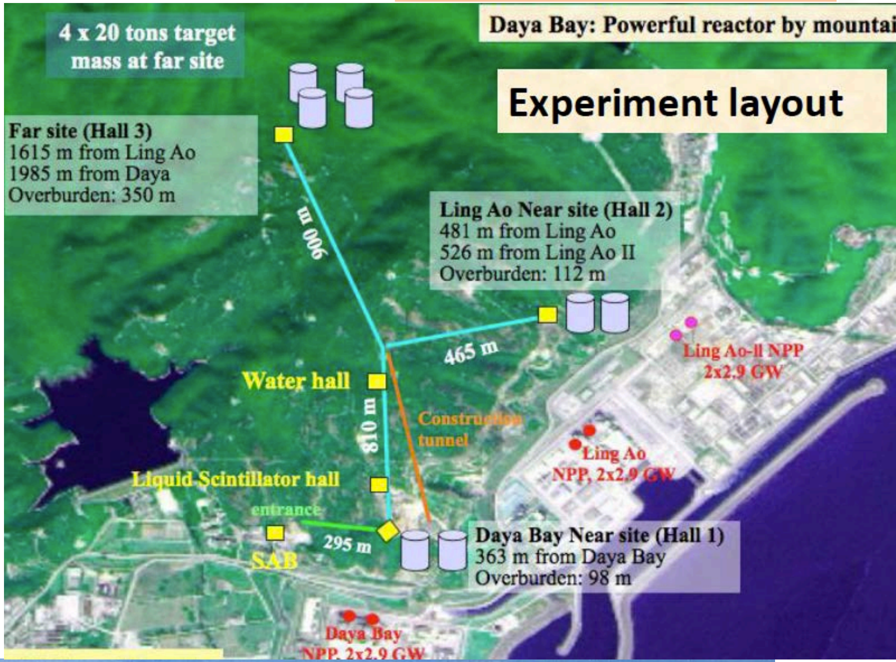
fluxes for all neutrinos

SNO solves the solar neutrino problem

The same physics was seen by reactor ν

Reactor is powerful ν source

Daya-Bay, Ling-Ao (China)

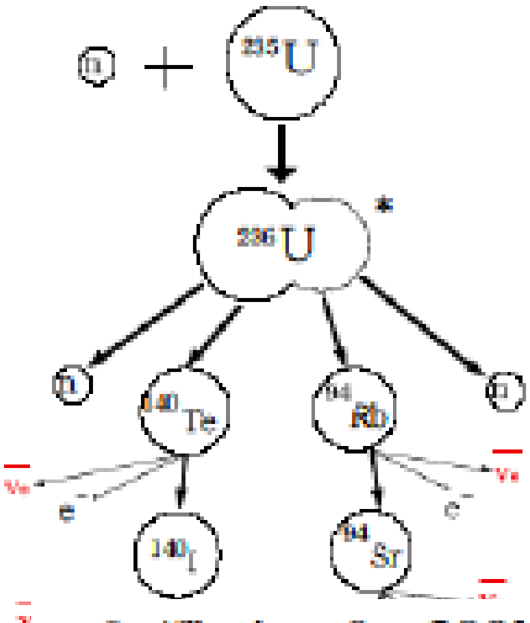


Kashiwazaki-Kariwa (Japan)

YongGwang(Korea)

原子炉ニュートリノ実験

Reactor $\bar{\nu}_e$



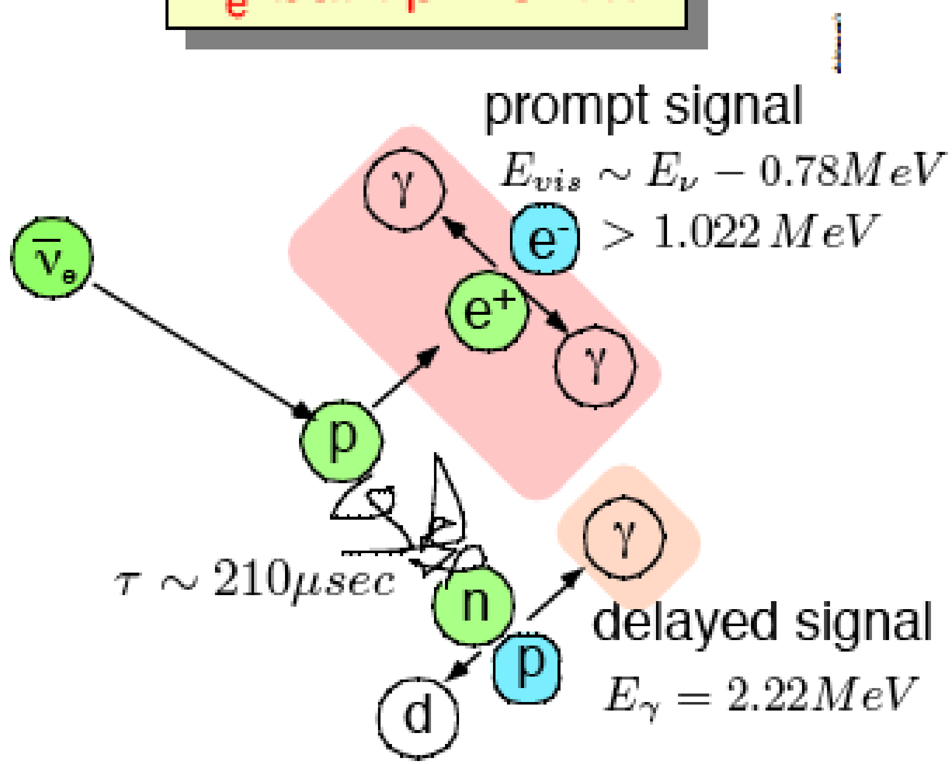
$\sim 6\nu$/fission & ~200MeV/fiss

$\Downarrow$

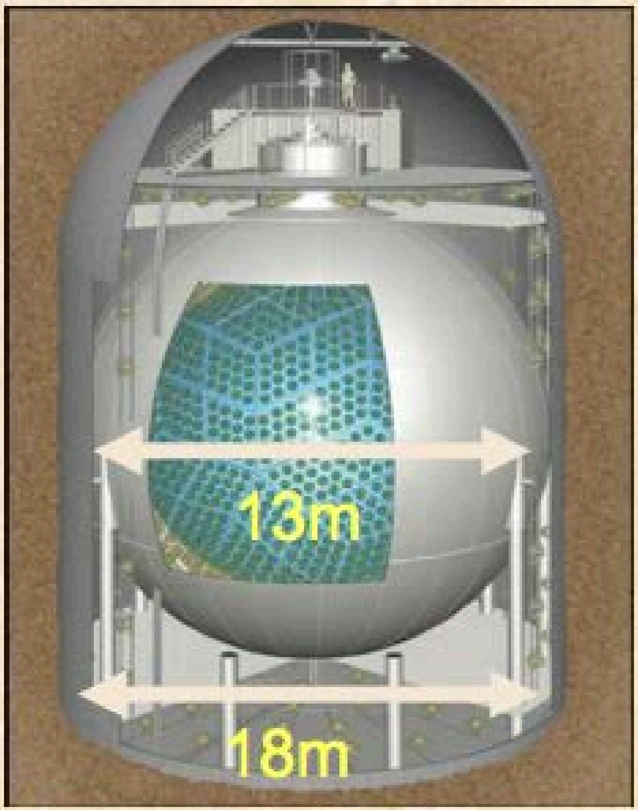
$\sim 6 \times 10^{20}\, \bar{\nu}_e / s / reactor$ (1GWe)

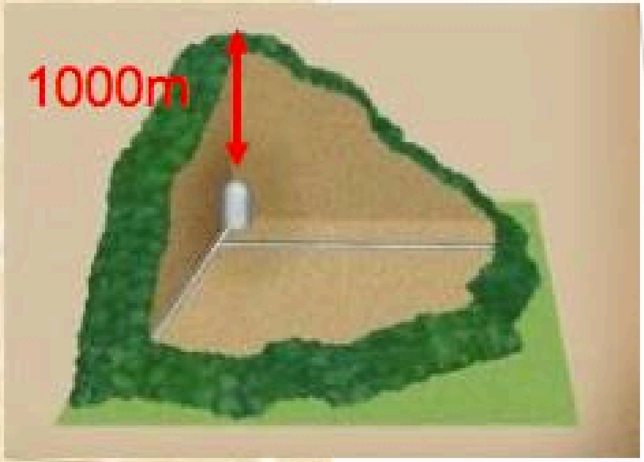
$\bar{\nu}_e$ Detection

ν_e-bar+p->e^++n



KamLAND : calorimeter type detector





Shield of cosmic ray background $\sim 10^{-5}$ than ground

1,000 tons pure liquid scintillator (LS)

Buffer oil : for environmental radiation

PMT : 17inch :1325 + 20inch : 554

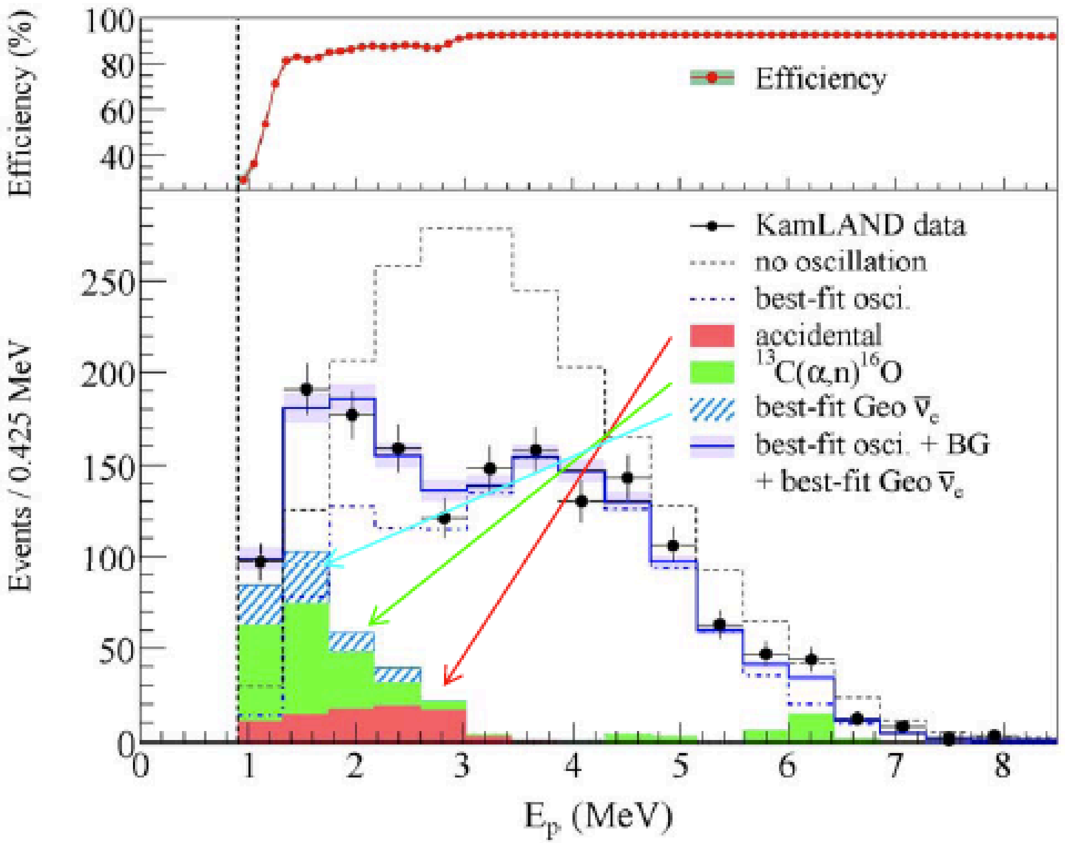
Water cherencov anti counter

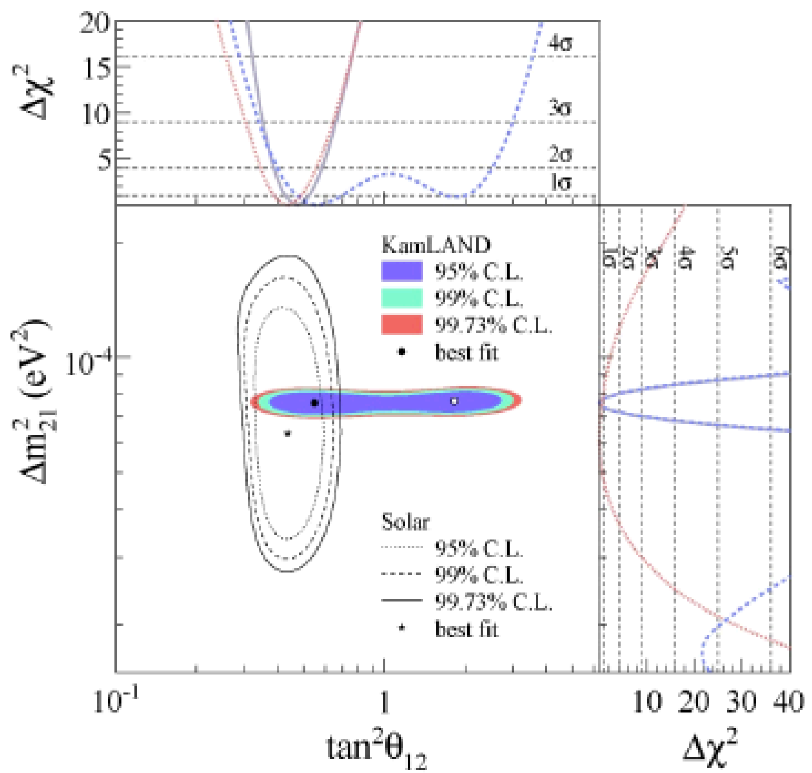
225 20inch PMT with water

Resolution : $\sim 12cm / \sqrt{E(MeV)}$

$\sim 6.4\% / \sqrt{E(MeV)}$

Reactor neutrino energy spectrum





Fit to scaled no-oscillation spectrum : exclude at 5.1 σ

$\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5} eV^2$

$\tan^2\theta = 0.56^{+0.14}_{-0.09}$

Cleanest signature of neutrino oscillation by KamLAND

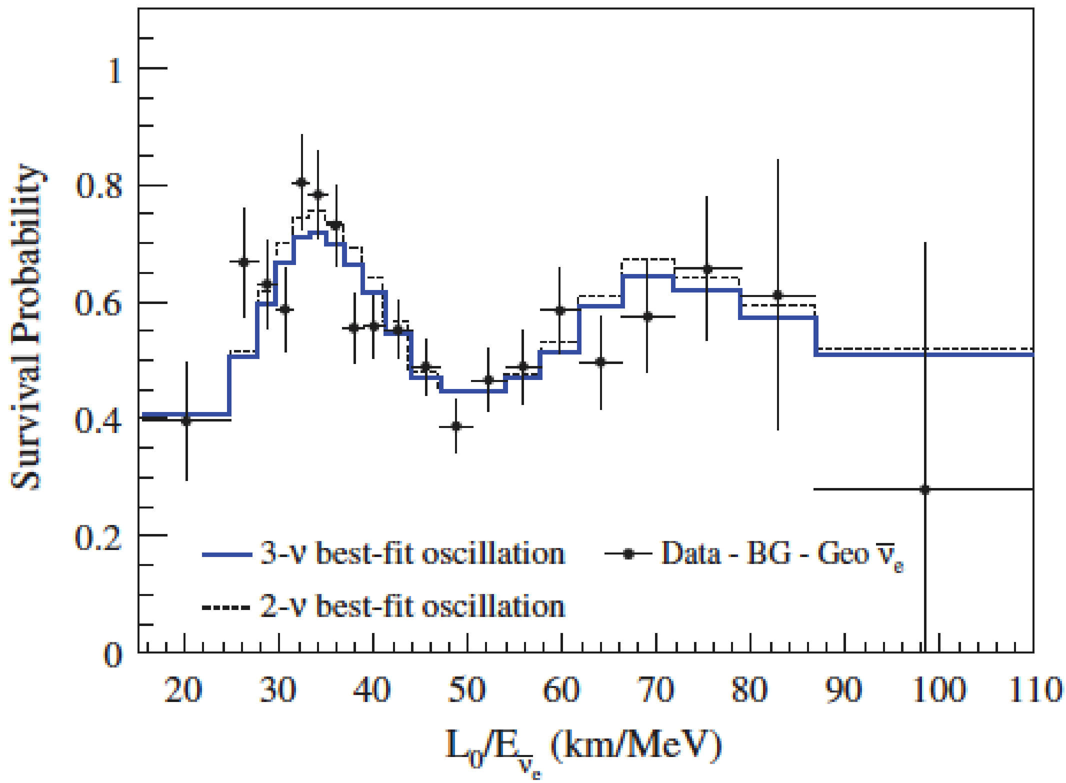
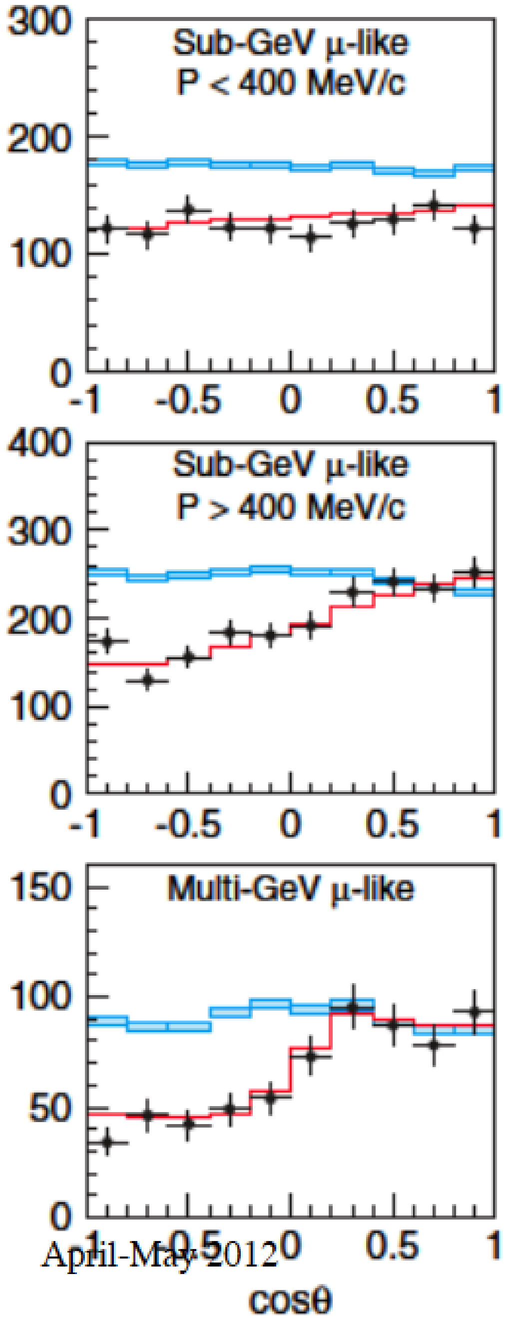
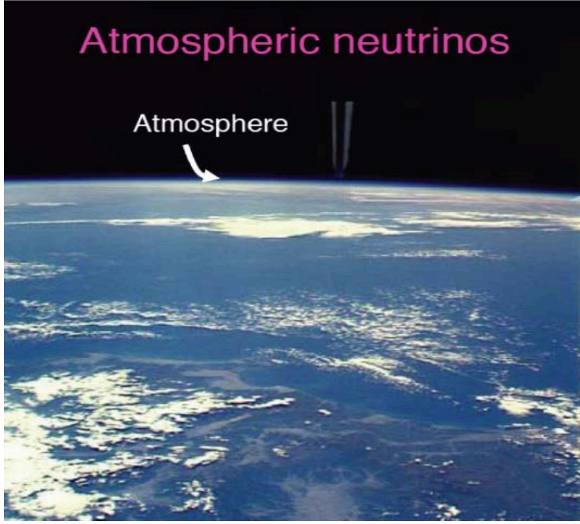


FIG. 5 (color). Ratio of the observed $\bar{\nu}_e$ spectrum to the expectation for no-oscillation versus L_0/E for the KamLAND data. $L_0 = 180$ km is the flux-weighted average reactor baseline. The 2-ν and 3-ν histograms are the expected distributions based on the best-fit parameter values from the two- and three-flavor unbinned maximum-likelihood analyses of the KamLAND data.

Atmospheric neutrinos

Atmospheric ν in a nutshell





- μ-like events at medium-high energies have strong zenith angle dependence (not in MC)
- μ-like events at low energies do not have strong zenith angle dependence

→ consistent with ν oscillation

Neutrino 1998 @Takayama

ν98, @Takayam
June 1998

Atmospheric neutrino results
from Super-Kamiokande & Kamiokand

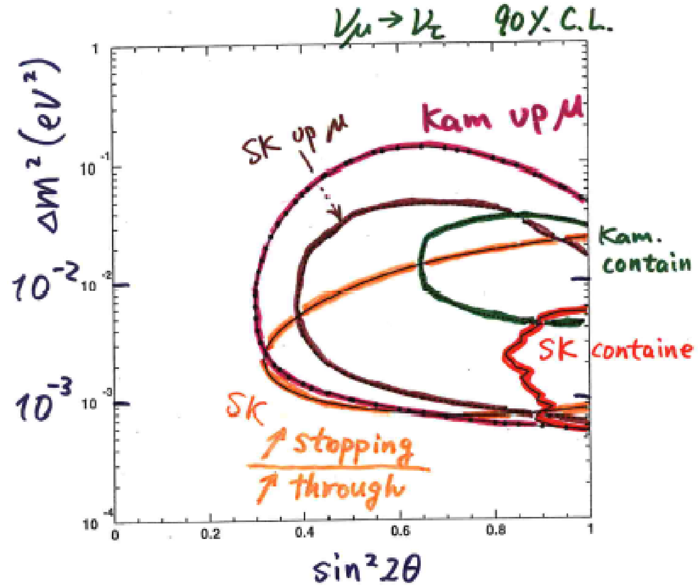
— Evidence for ν_μ oscillations —

T. Kajita
Kamioka observatory, Univ. of Tokyo

for the {Kamiokande / Super-Kamiokande} Collaborations

Summary

Evidence for ν_μ oscillations

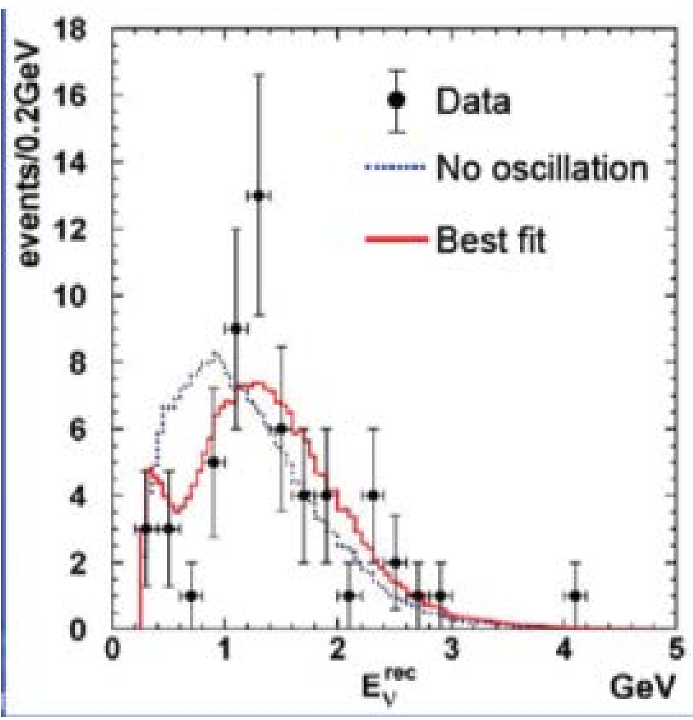


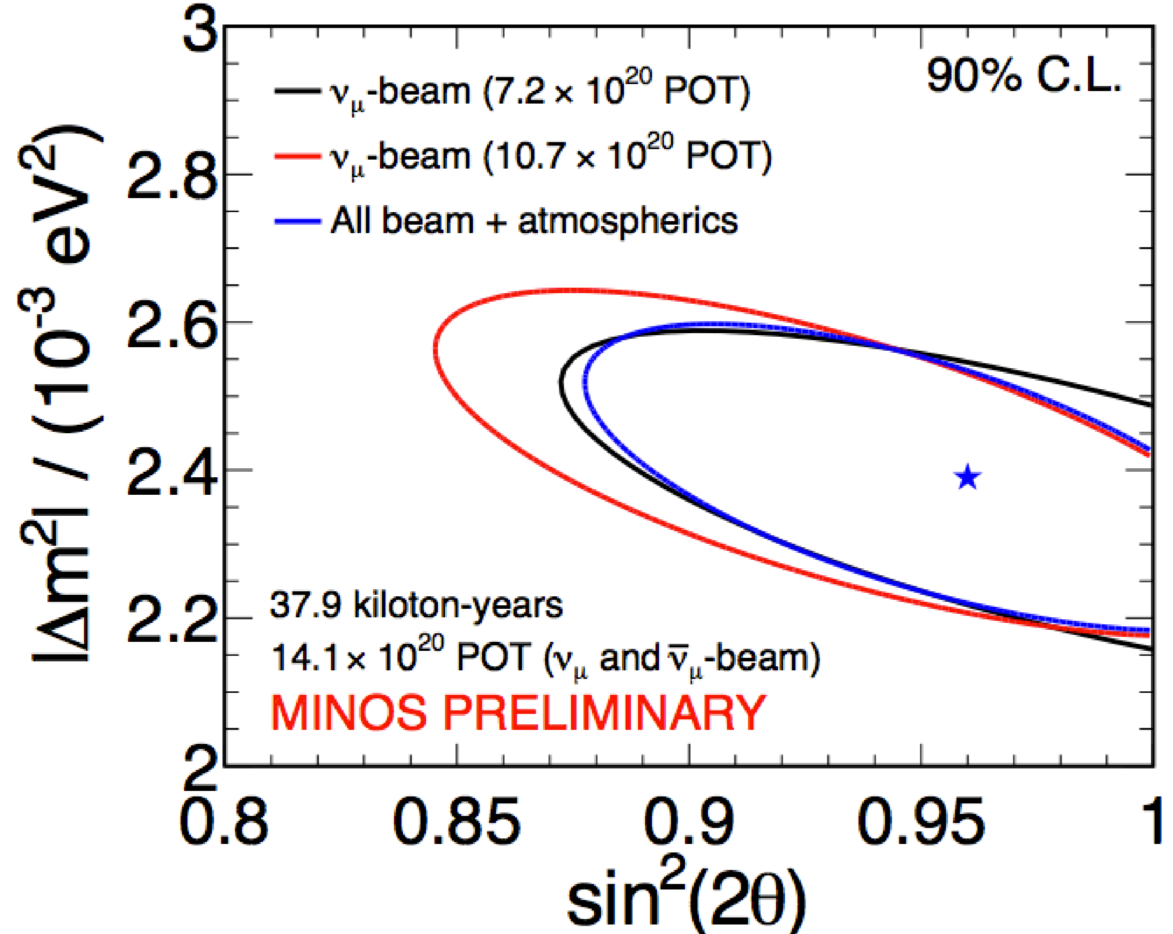
• $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)


K2K
KEK
250km
Super-KAMIOKANDE


Soudan
Duluth
Lake Superior
Lake Michigan
MN
WI
MI
Madison
IA
Fermilab
IL
IN
MO

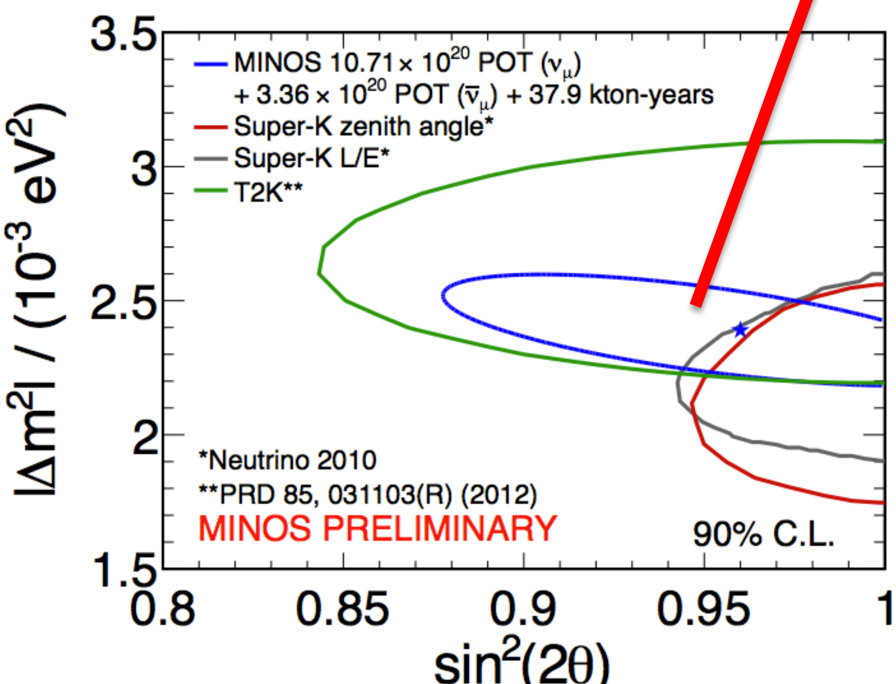

events/0.2GeV
Data
No oscillation
Best fit
E_ν^{rec}
GeV
0
1
2
3
4
5
0
2
4
6
8
10
12
14
16
18


$|\Delta m^2| / (10^{-3}\ eV^2)$
$\sin^2(2\theta)$
90% C.L.
ν_μ-beam (7.2×10^{20} POT)
ν_μ-beam (10.7×10^{20} POT)
All beam + atmospherics
37.9 kiloton-years
14.1×10^{20} POT (ν_μ and $\bar{\nu}_\mu$-beam)
MINOS PRELIMINARY
0.8
0.85
0.9
0.95
1
2
2.2
2.4
2.6
2.8
3

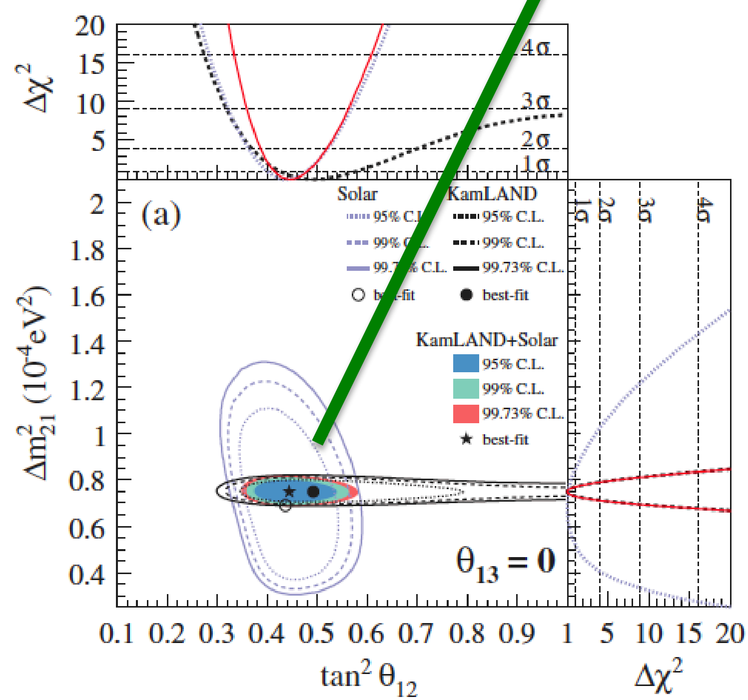
We enjoy redundancy: Each of θ_{12} and θ_{23} is measured by two ways

$\nu_\alpha = U_{\alpha i}\, \nu_i$

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



SK-atm+T2K+MINOS



solar+KamLAND

Anthropic principle?

- Two neutrino mass^2 difference turn out to be comparable to sizes in the solar system:
- Δm^2_{atm} /E ~ (earth radius)$^{-1}$
- Δm^2_{solar} /E ~ solar density /G_F

Nature's kindness or something behind?

A year from June 2011-June 2012: Year of θ_{13}

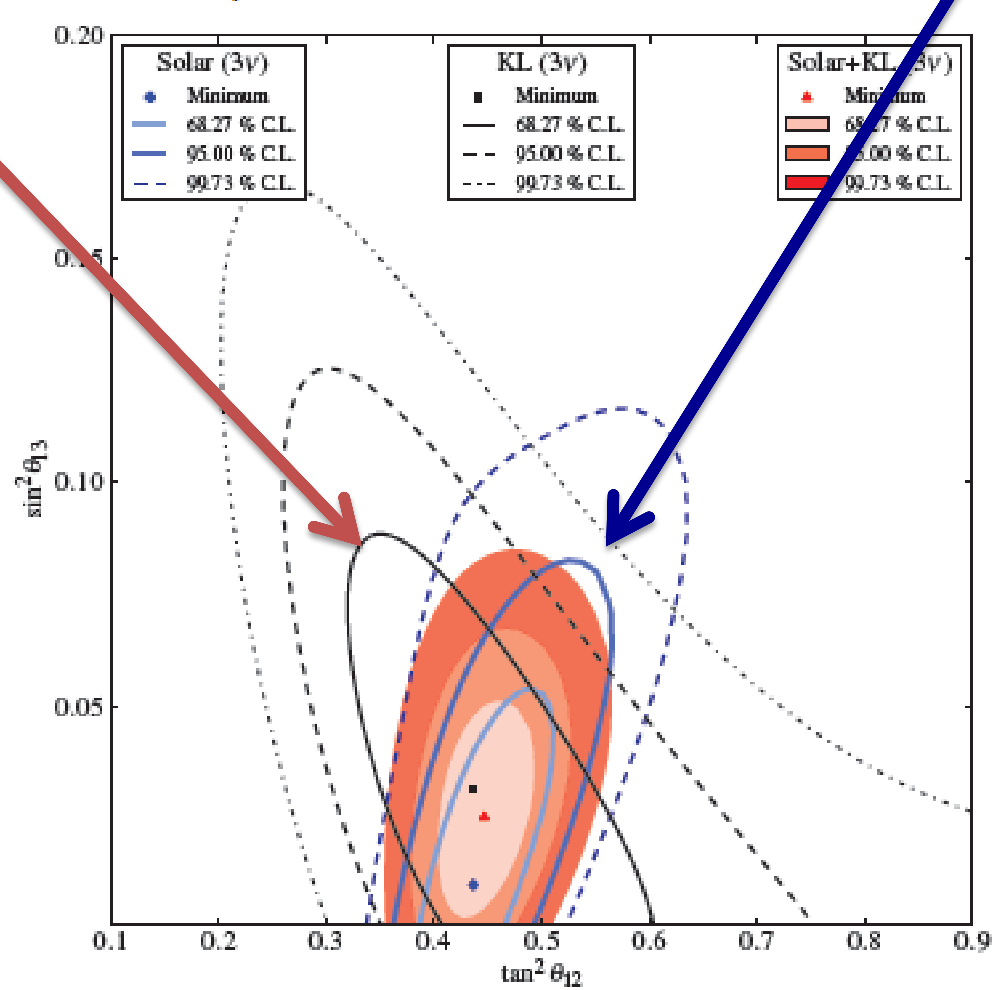
θ_{13} before direct measurement (2010-2011)

KamLAND

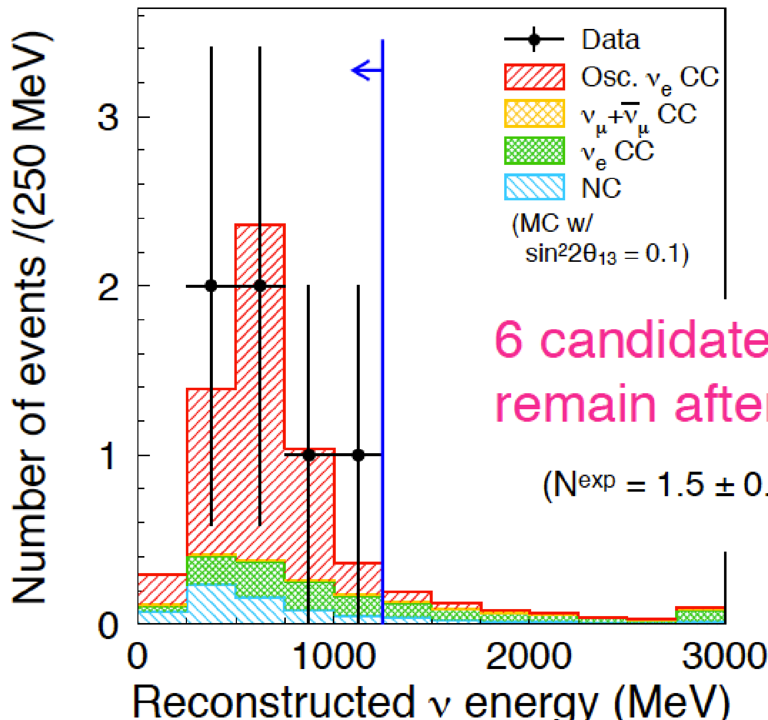
$$P_{ee} \approx \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right)$$

solar

$$P_{ee} \approx \cos^4\theta_{13}\sin^2\theta_{12}$$

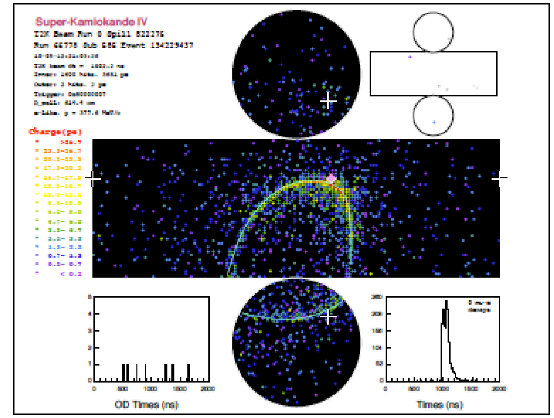


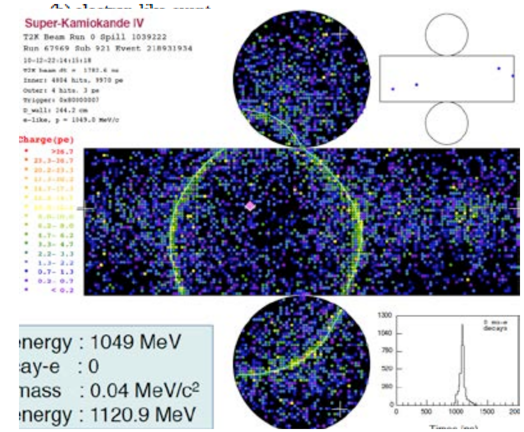
June 2011: T2K 6 events: start of year of θ_{13}

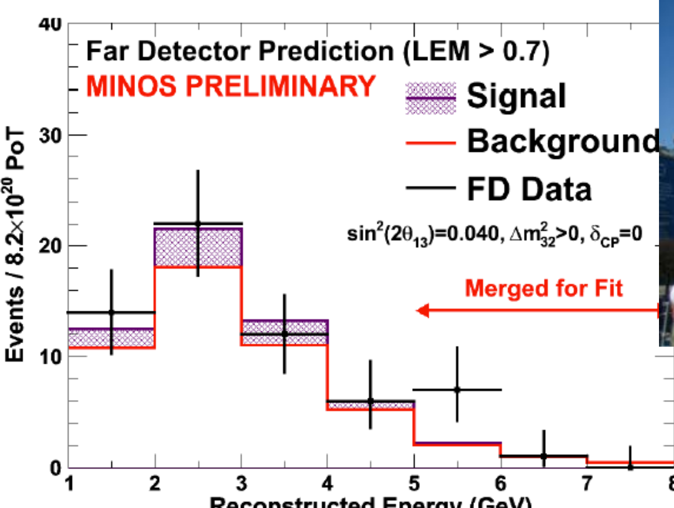


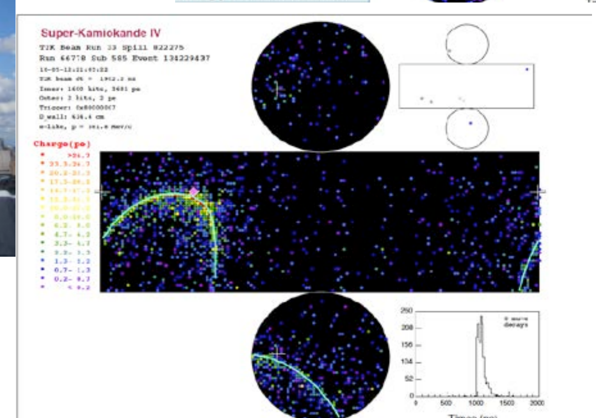
6 candidate events remain after all cuts !!

($N^{exp} = 1.5 \pm 0.3$ at $\sin^2 2\theta_{13}=0$)







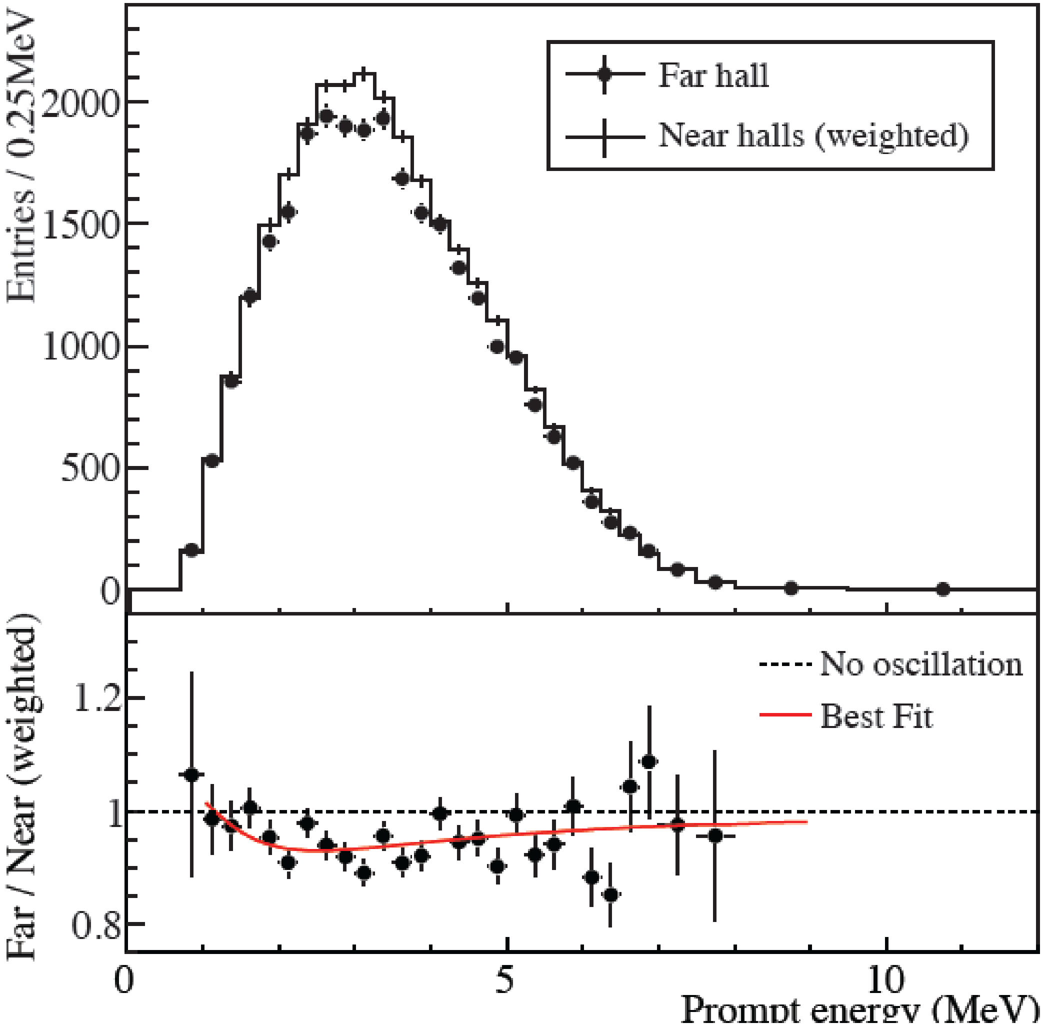


Auror @Saint Petersburg

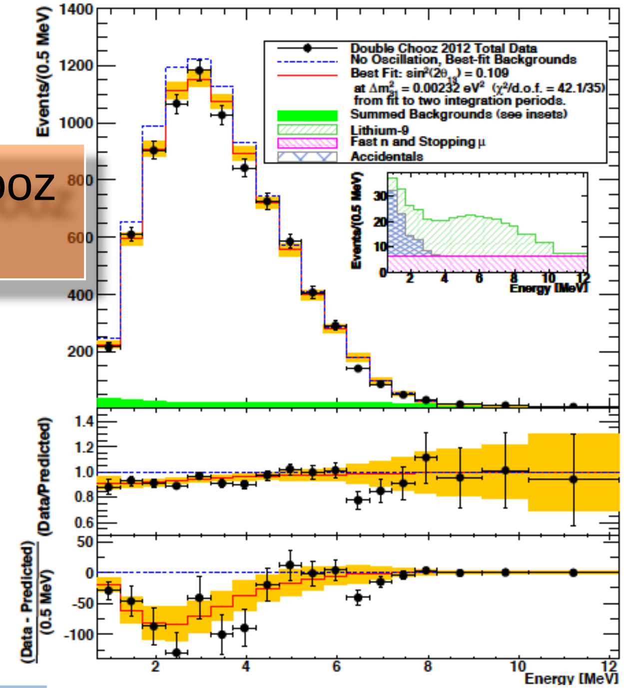
Reactor θ_{13} experiments

Daya Bay (Nu2012)

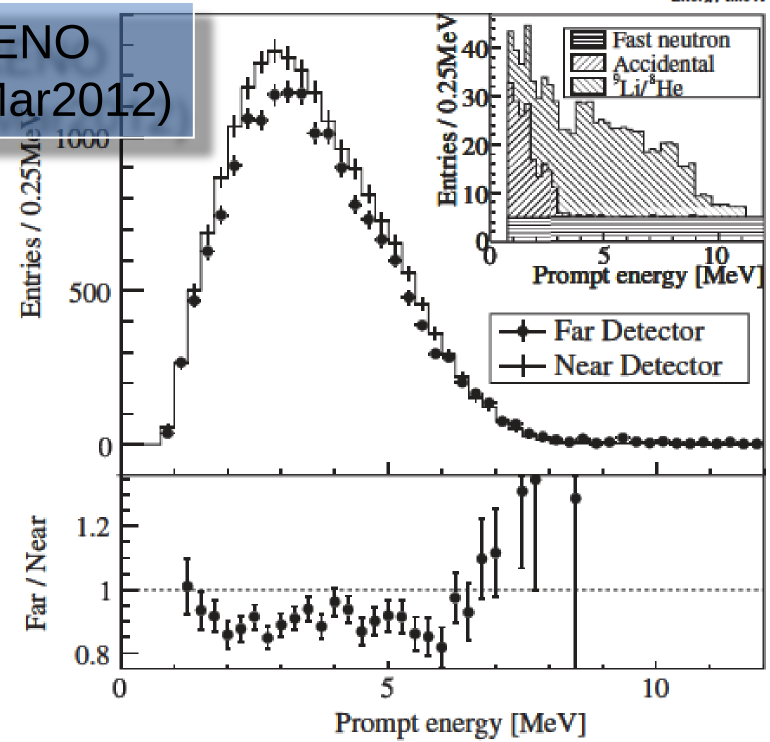
7.7 σ evidence for nonzero θ_{13} !



Double Chooz (Jul.2012)



RENO (Mar2012)

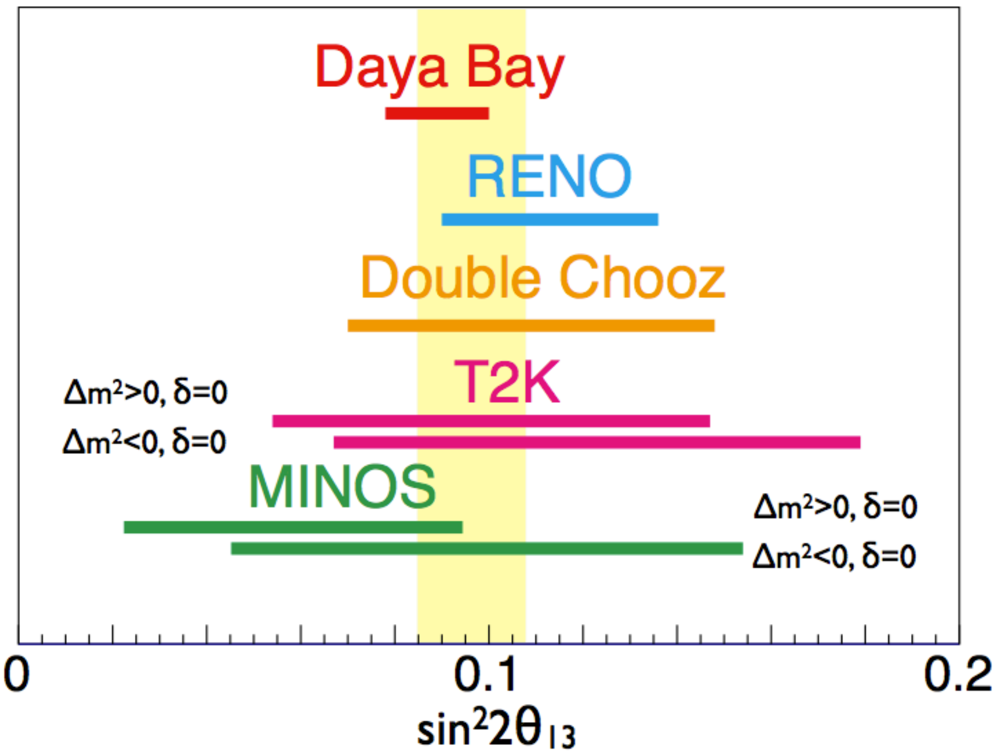


PMU

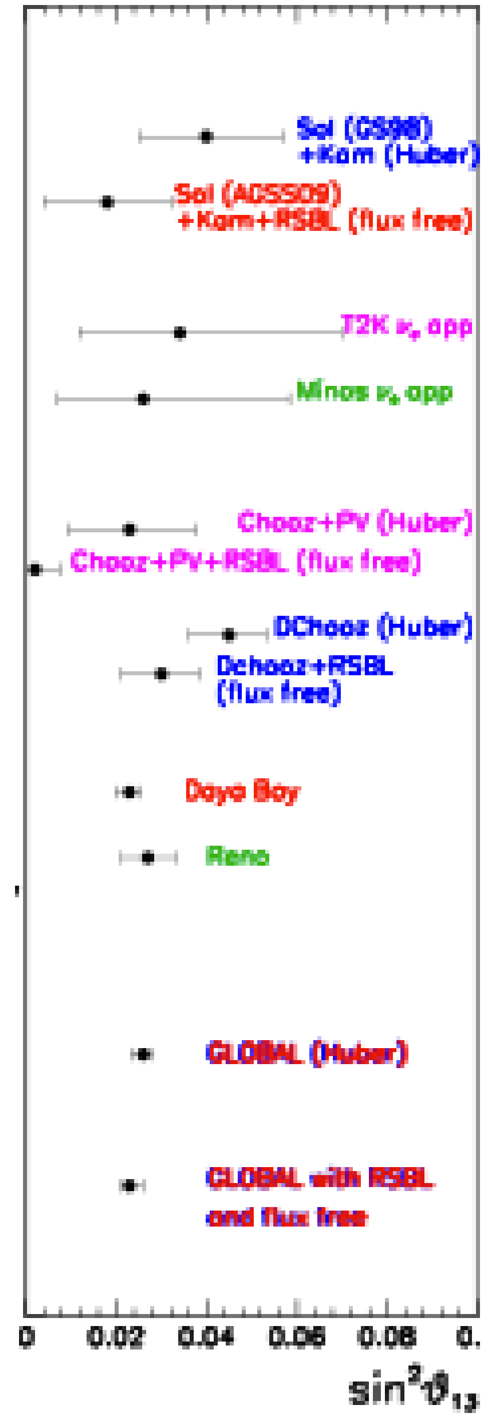
$$\sin^2 2\theta_{13} = 0.090^{+0.008(0.027)}_{-0.010(0.029)}$$

M.C.Gonzalez-Garcia et al. 2012

$\theta_{13} \neq 0$ established...



Now is the time to move forward to the next step!



What large θ_{13} means?

- It is natural because $U_{MNS}=U_l^{+}U_{\nu}$ and θ_{12} and θ_{23} are large it is unlikely that only θ_{13} is extremely small

HM in Nu2008 at Christchurch

- This argument is invalidated if there is a symmetry which enforce $\theta_{13}=0$
- So my interpretation is: there is no such symmetry (sorry, negative statement)
- Anarchy ?

Director's choice

- I have my own favorite (see later)

We now know all the 3 lepton mixing angles!

What we know

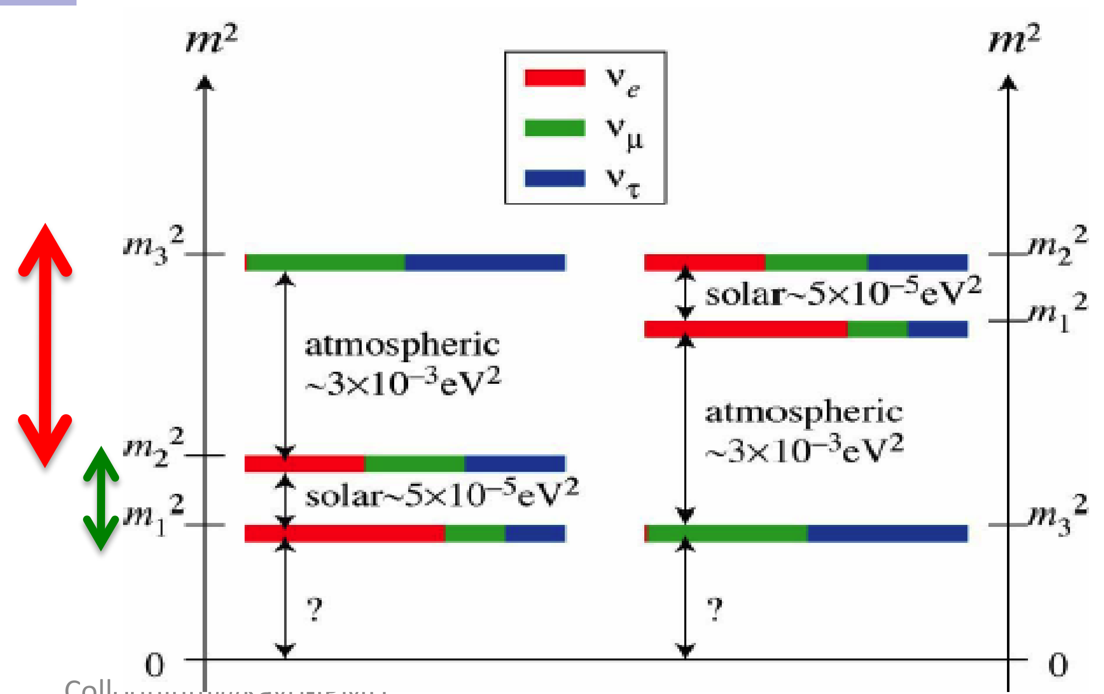
$\nu_\alpha = U_{\alpha i}\,\nu_i$

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

$\theta_{12} = 34^o,\ \theta_{23} \sim 45^o,\ \theta_{13} = 9^o$

Atmospheric mass^2 splitting = 2.4×10^{-3} eV^2

Solar mass^2 splitting = 7.5×10^{-5} eV^2



What we do not know

Lepton KM phase

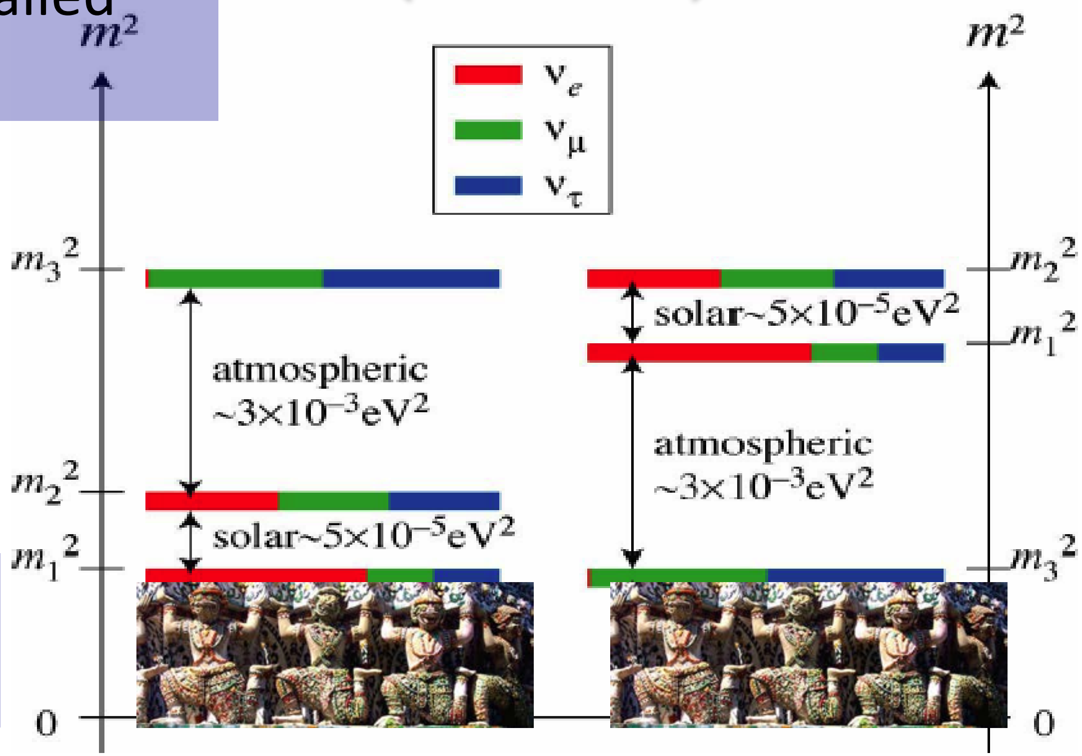
Another CP phases: If Majorana

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

Which mass pattern? (sometimes called "hierarchy")

Normal ordering

inverted ordering



Absolute ν masses

Then what is remain to be understood?

There are 2 aspects

Experimentally

- We now know 3 mixing angles and Δm^2_{solar}, Δm^2_{atm}
- What's remain to be explored experimentally?
- Two "disjoint" frontier

Theoretically

- We roughly know nu mass scale
- What the mass scale means?
- Lepton mixing pattern is quite different from quarks, what that means?

1. Lepton KM phase, mass pattern

2. Absolute ν mass, Majorana vs. Dirac, Majorana phase

Absolute ν mass, Majorana vs. Dirac

KATRIN: endpoint of beta decay spectrum..

Sensitivity reach
$m_\nu \sim 0.2$ eV

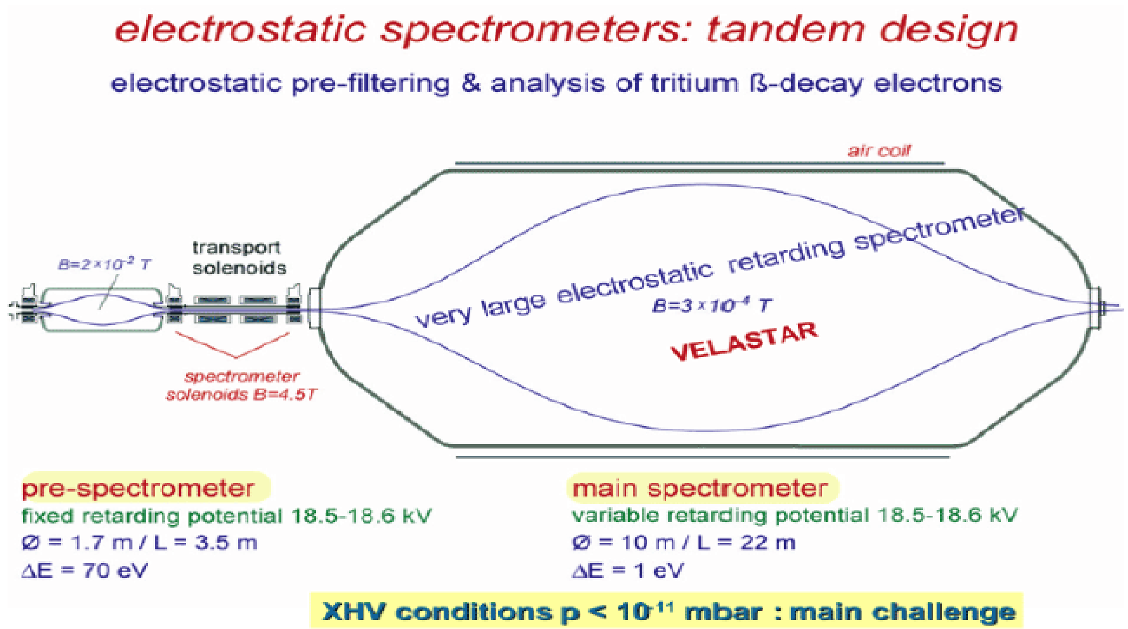
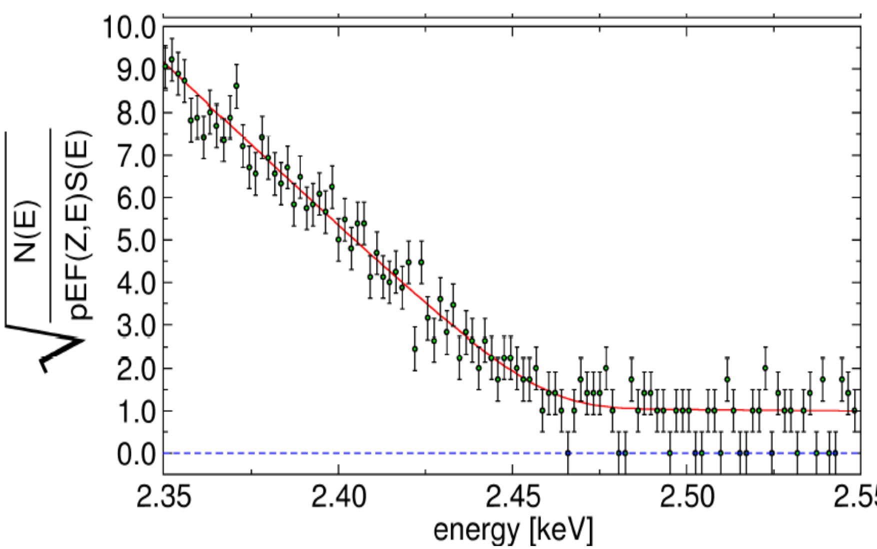
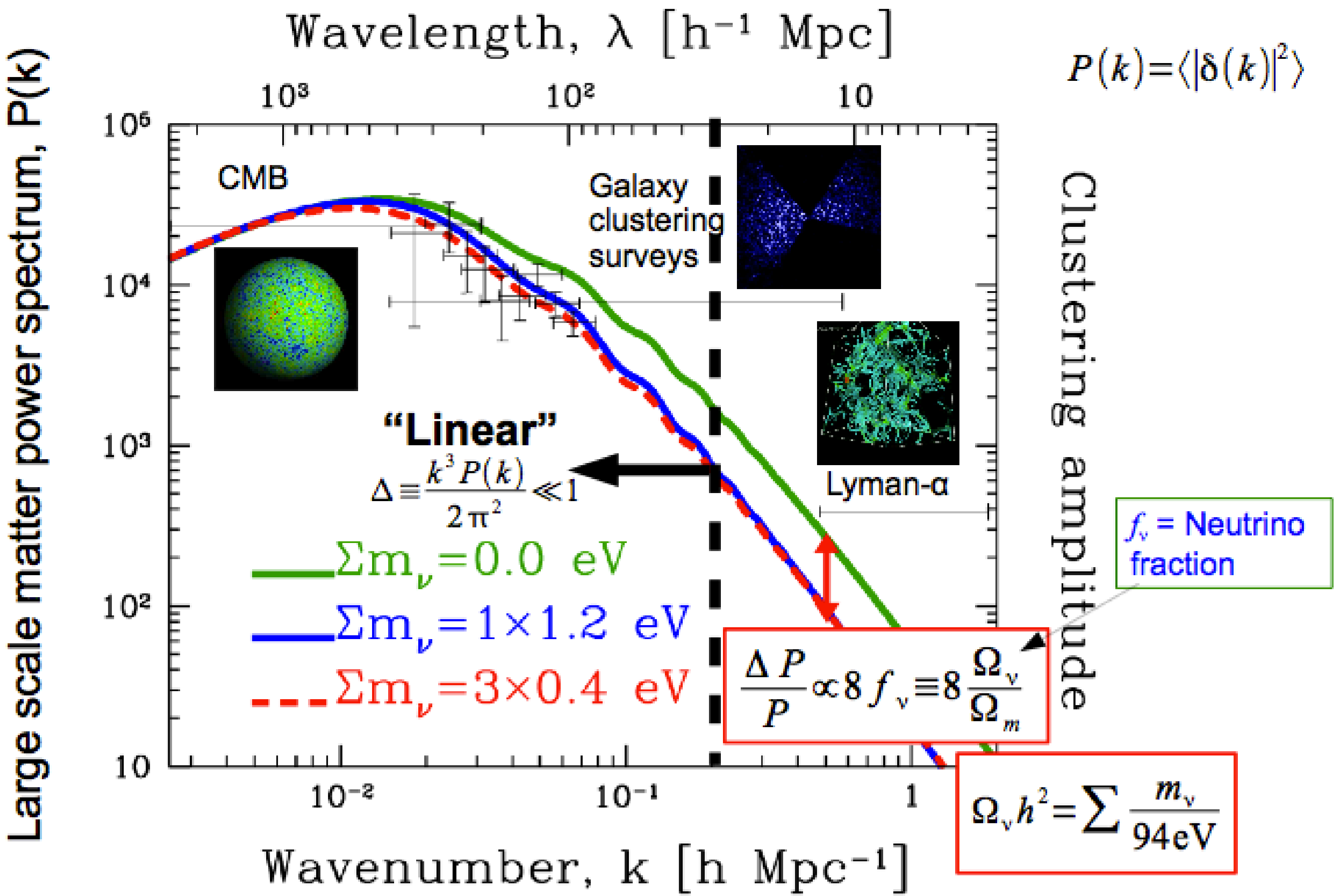


Figure: Pre-Spectrometer and Main Spectrometer

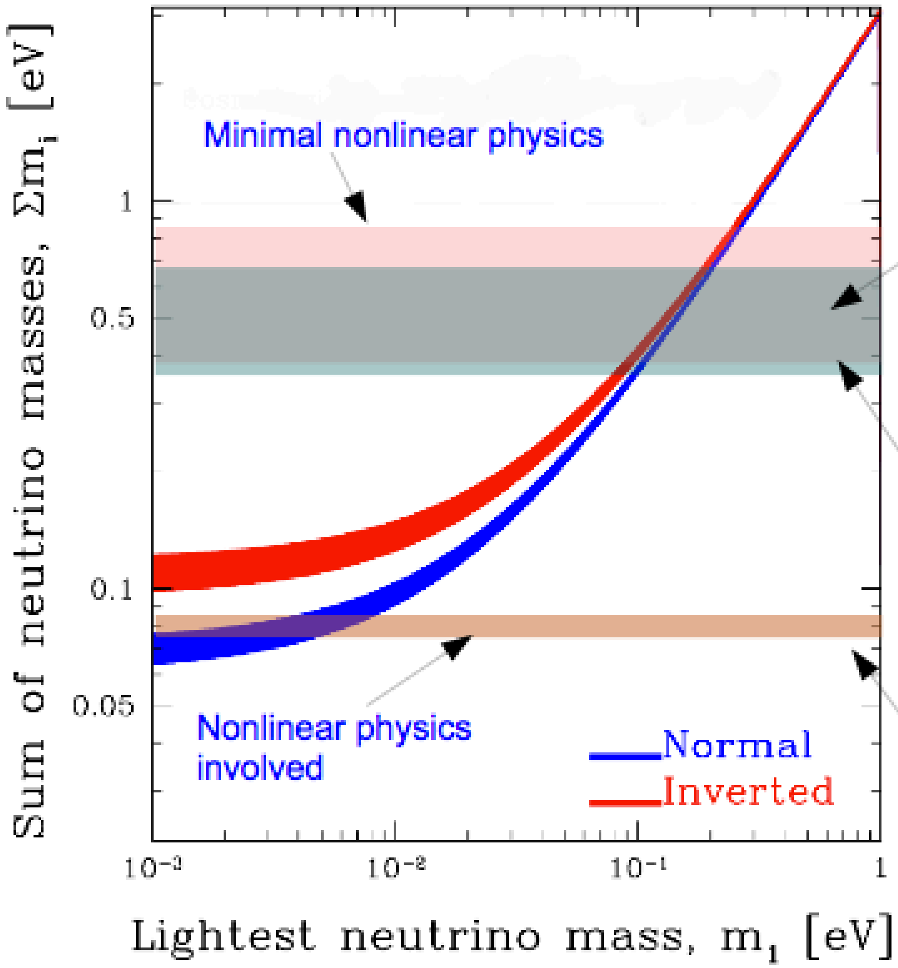


Cosmology: ν suppresses small scale structure



Yvone Wong, Neutrino summer school 2012

Present constraints and future sensitivities...



CMB (WMAP7+ACBAR+BICEP+QuaD)
+ LSS (SDSS-HPS)
+ H_0+SNIa

$$\sum m_\nu < 0.36 \rightarrow 0.76\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y³W 2010
Gonzalez-Garcia et al. 2010
de Putter et al. 2011, etc.

Planck alone (1 year) 2013

$$\sum m_\nu < 0.38 \rightarrow 0.84\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

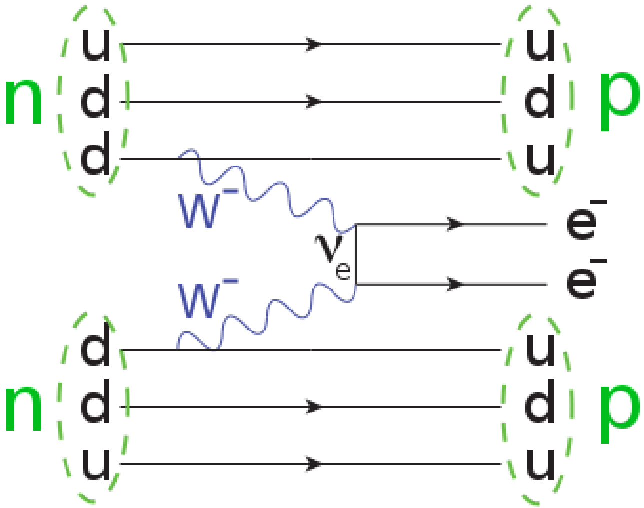
Perotto et al. 2006

Planck+Weak lensing (**Euclid**) 2020+

$$\sum m_\nu < 0.074 \rightarrow 0.086\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

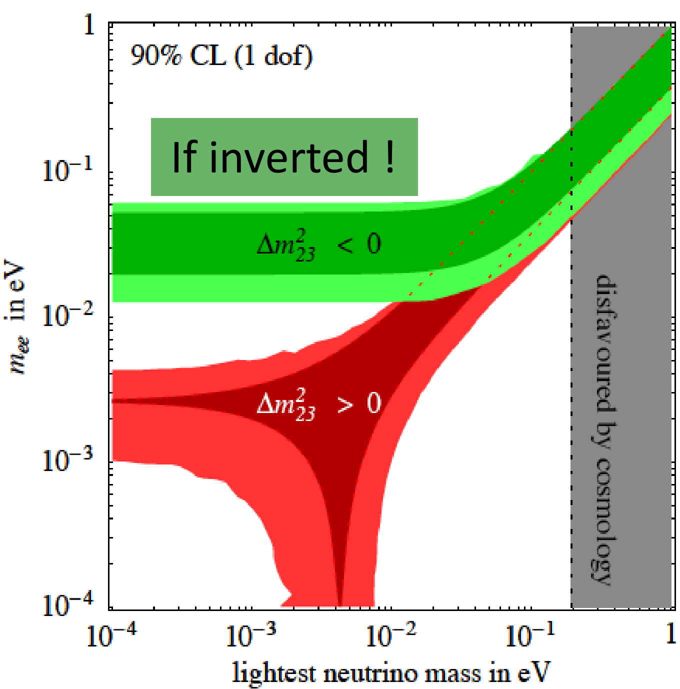
Hannestad, Tu & Y³W 2006

Majorana vs. Dirac: double β decay



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\langle m_{ee}\rangle^2$$

$$\langle m_{ee}\rangle = \left|\sum_i U^2_{ei}\, m_i\right|$$



Simplified List of Limits for ββ0ν decay

Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			>$5.8*10^{22}$ (90%CL)	
^{76}Ge	Ge diode	~47.7	>$1.9*10^{25}$ (90%CL)	<0.35
^{82}Se			>$2.1*10^{23}$ (90%CL)	
^{96}Zr			>$9.2*10^{21}$ (90%CL)	
^{100}Mo	Foil.Geiger tubes		>$5.8*10^{23}$ (90%CL)	
^{116}Cd			>$1.7*10^{23}$ (90%CL)	
^{128}Te			>$1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~12	>$3*10^{24}$ (90%CL)	<0.19 - 0.68
^{136}Xe	Xe scint	~4.5	>$1.2*10^{24}$ (90%CL)	<1.1 - 2.9
^{150}Nd			>$1.8*10^{22}$ (90%CL)	
^{160}Gd			>$1.3*10^{21}$ (90%CL)	

With regard to mass hierarchy & CP we have clearer view

Is large θ_{13} good news? Matter vs. CP

- $P_{\mu e} = P_{atm}(\text{matter}) + P_{interfere}(\delta) + P_{solar}$

$(\theta_{13})^2$

$(\theta_{13})^1$

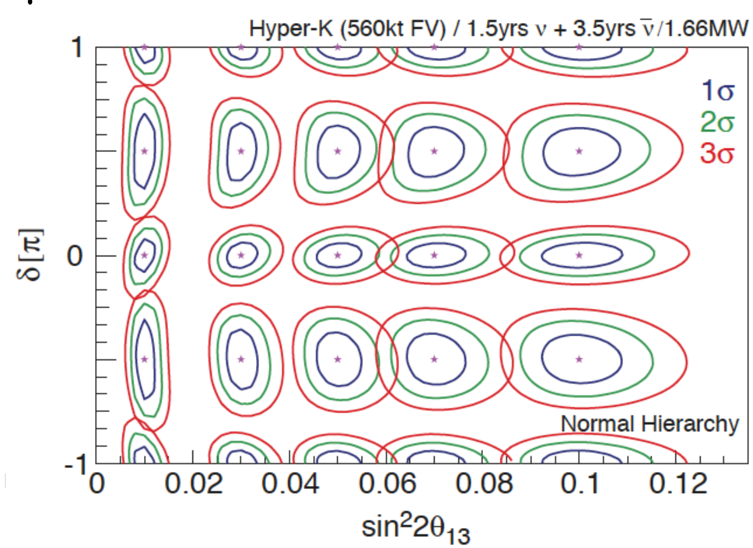
θ_{13}-indep

Merit for mass hierarchy

Merit / demerit for δ

- IS a good news for mass hierarchy
- Need not be a good news for CP because:
- $A = (P_{\mu e} - \text{anti-}P_{\mu e}) / (P_{\mu e} + \text{anti-}P_{\mu e}) \sim 1/\theta_{13}$

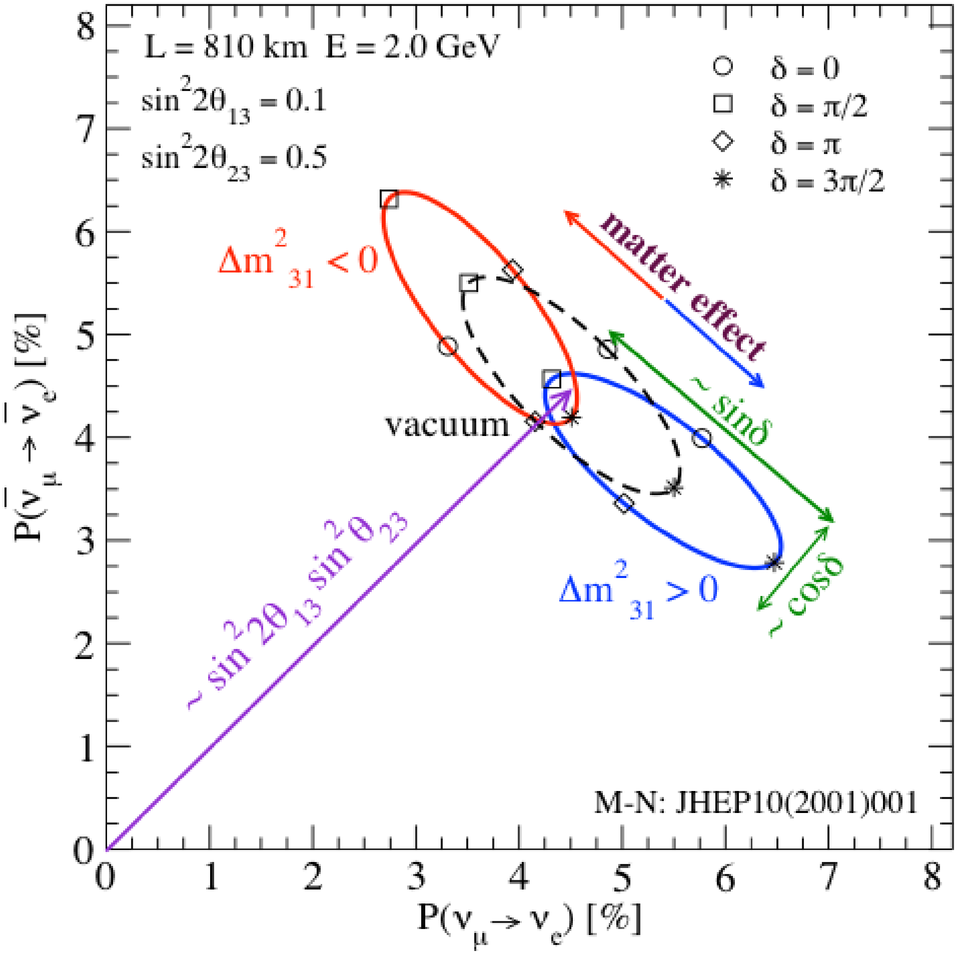
Sensitivity to δ is roughly independent of θ_{13} (HK-LOI)

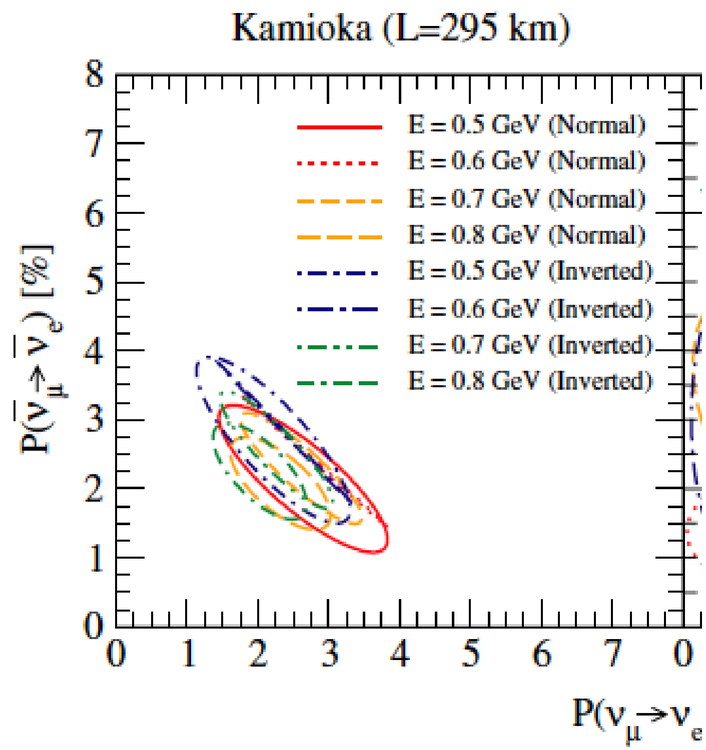


Mass hierarchy

Mass hierarchy resolution and CP: understanding principle

NOVA



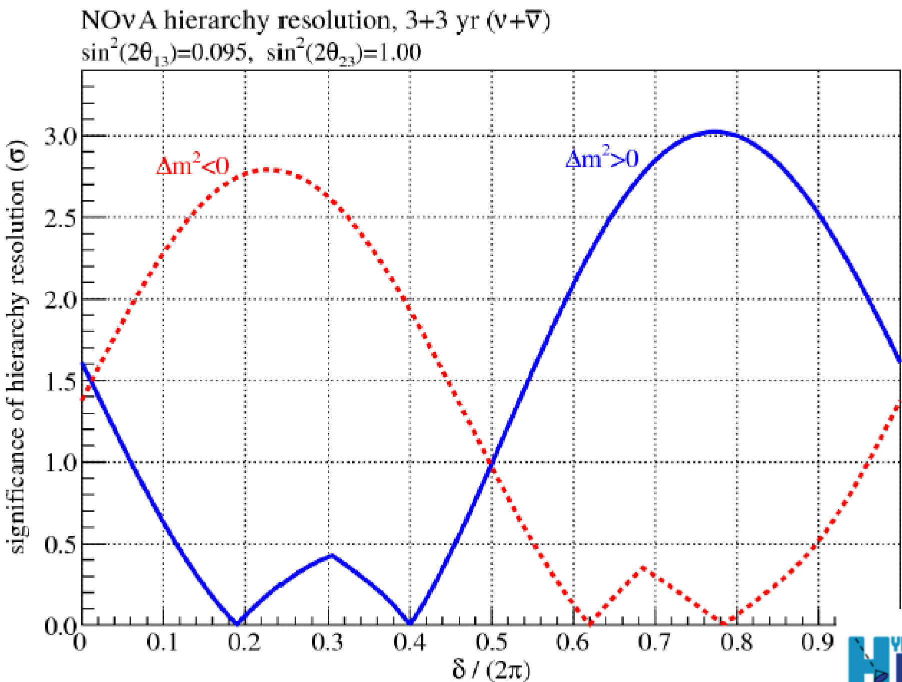


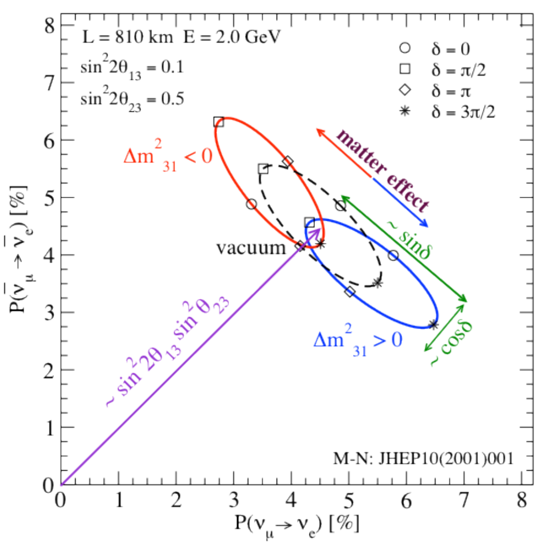
bi-probability plot in $P_{\mu e}$ – anti-$P_{\mu e}$ space

HM-H.Nunokawa,JHEP01

Mass hierarchy: a shopping list

- NOVA, if lucky
- NOVA+INO (up to 3 σ)
- JPARC-HK, if lucky
- LBNE (but ?? if on surface..)
- T2KK (Tokai-Kamioka-Korea)
- JPARC-Okinoshima
- CERN-Pihasarmi
- Atmospheric neutrinos (earth matter effect)
- Reactor neutrinos (atm wiggle at solar scale oscillation)

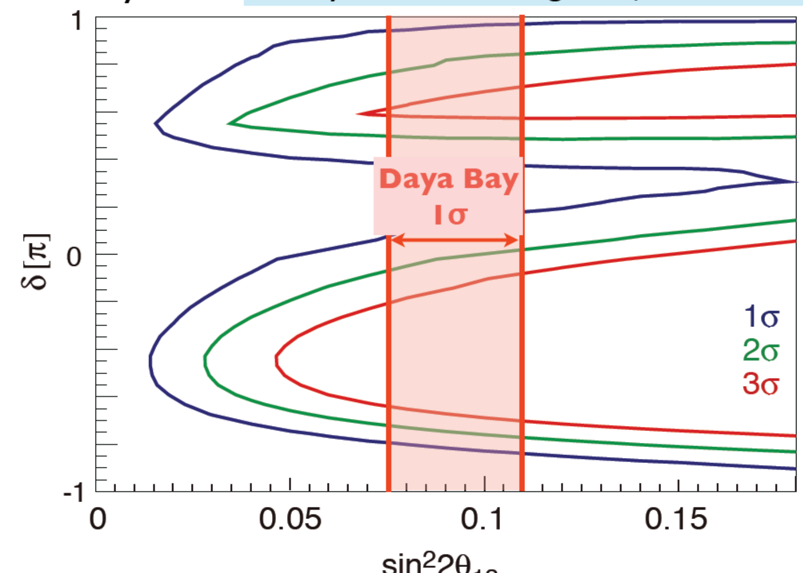




Mass hierarchy

0.75MW×10yrs

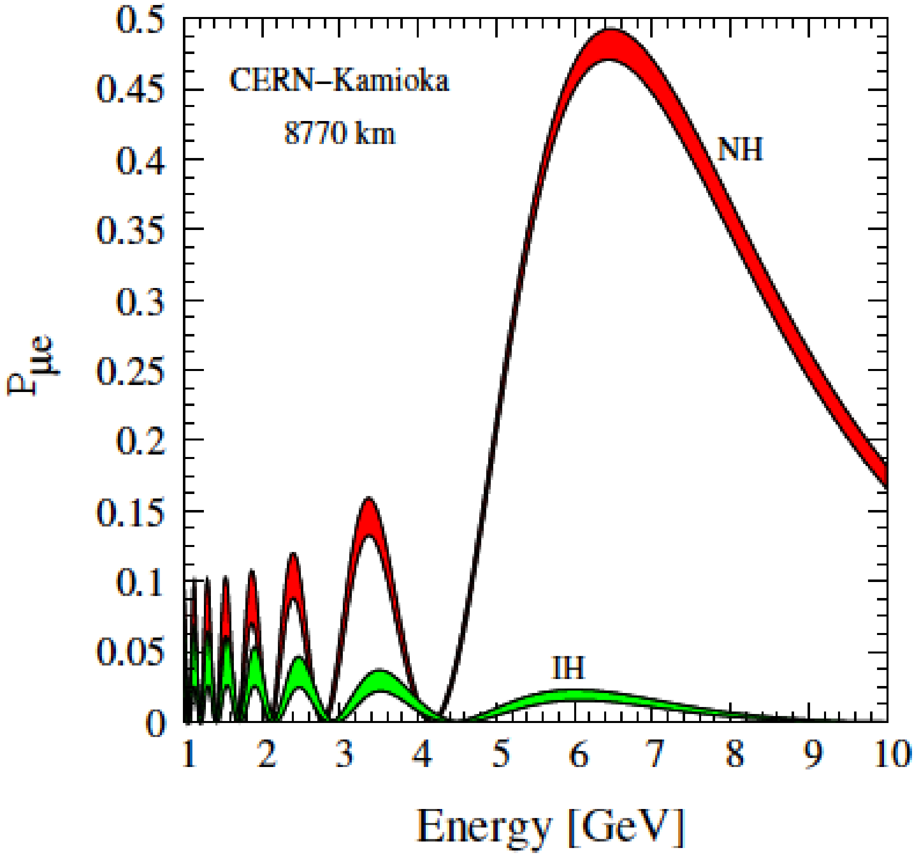
5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$

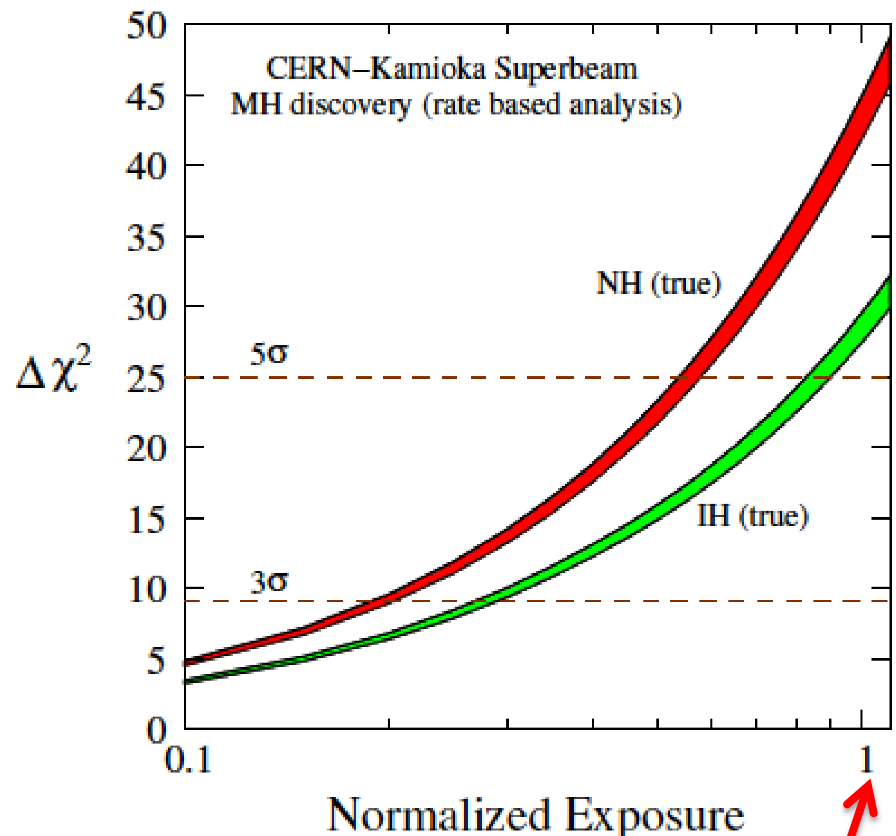


Chance to determine MH! See also later talk (atm ν)

CERN-Super-K (8870 km)

Agarwalla-Hernandez April 12

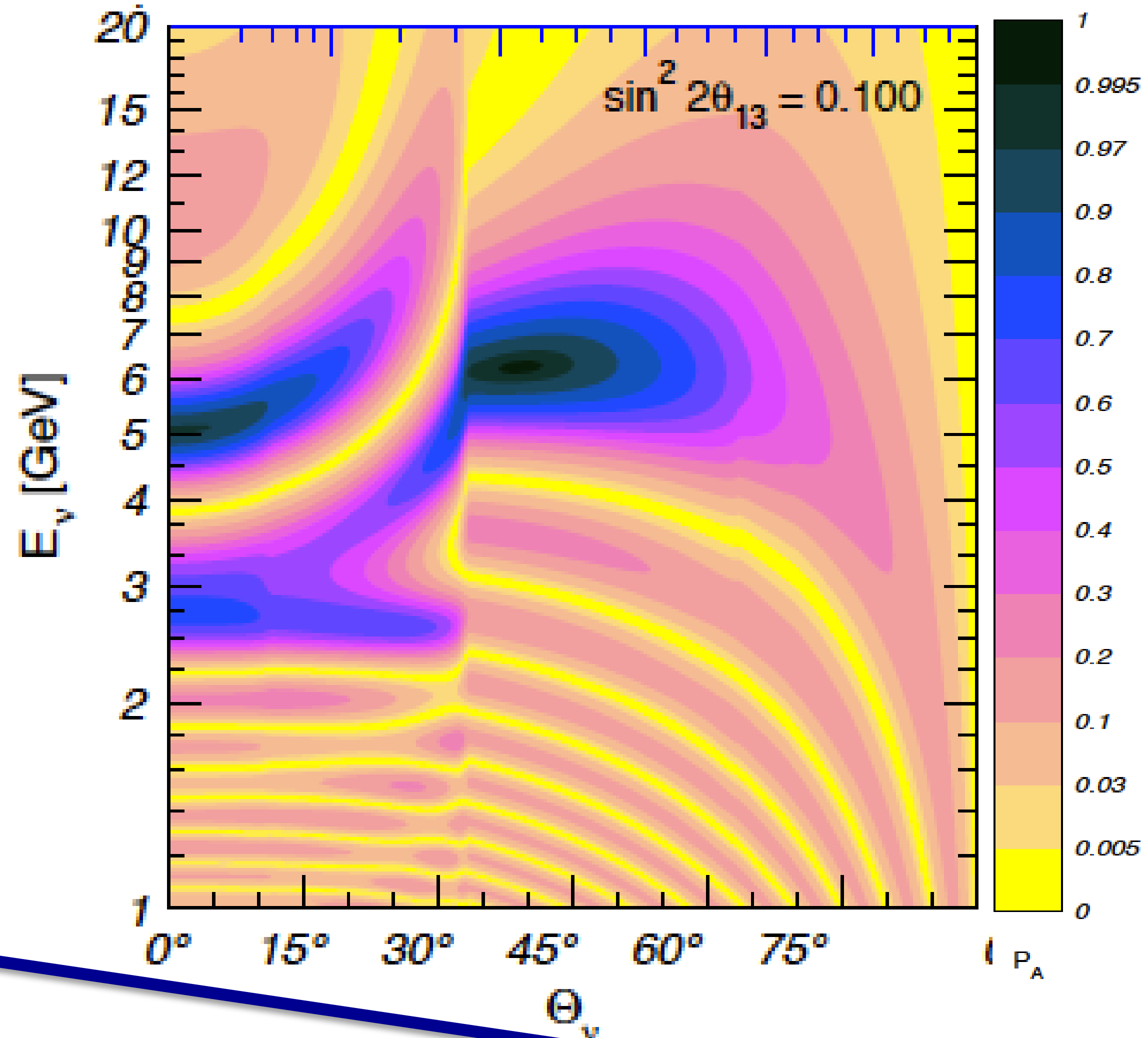




Channel	CERN-Kamioka (8870 km)	
	Signal	Background
	CC-1 ring	Int+Mis-id+NC = Total
$\nu_\mu \to \nu_e$ (NH)	**44**	1+2+16=**19**
$\nu_\mu \to \nu_e$ (IH)	**2**	1+3+16=**20**
$\nu_\mu \to \nu_\mu$ (NH)	**83**	**2**
$\nu_\mu \to \nu_\mu$ (IH)	**91**	**2**

5×10^{21} pot.

Use of atmospheric ν for mass hierarchy



Akhmedov et al
JHEP07

$$P_{ee} = 1 - P_A \,,$$
$$P_{\mu e} = P_{e\mu} = s_{23}^2 P_A \,,$$
$$P_{e\tau} = c_{23}^2 P_A \,,$$
$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta_{23} - s_{23}^4 P_A + \frac{1}{2}\sin^2 2\theta_{23}\sqrt{1-P_A}\cos\phi_X \,,$$
$$P_{\mu\tau} = \frac{1}{2}\sin^2 2\theta_{23} - s_{23}^2 c_{23}^2 P_A - \frac{1}{2}\sin^2 2\theta_{23}\sqrt{1-P_A}\cos\phi_X \,,$$

-IPMU

P_A

Atmospheric ν @PINGU

Doug Cowen, NuSky, ICTP, June 2011

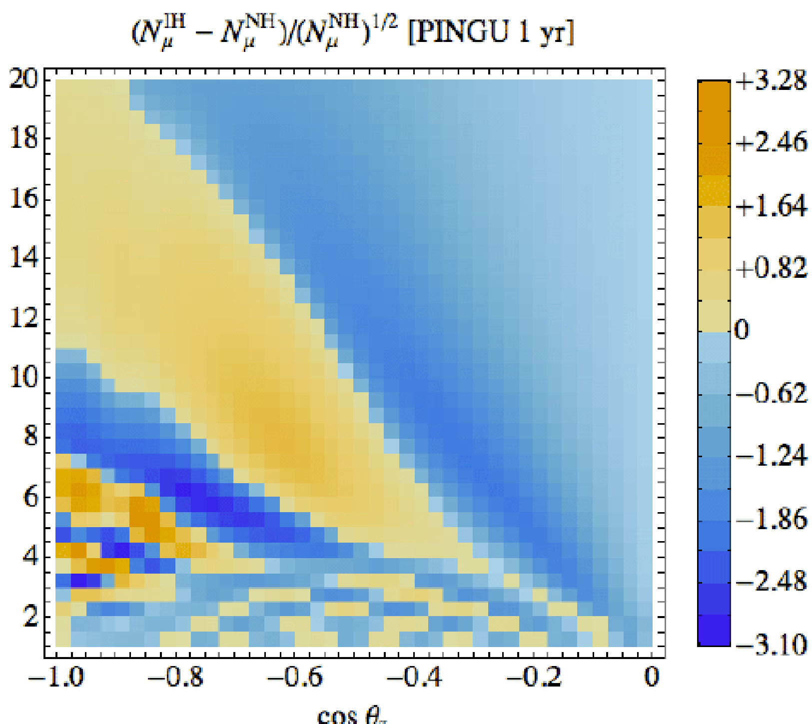
IceCube → DeepCore → ***PINGU***

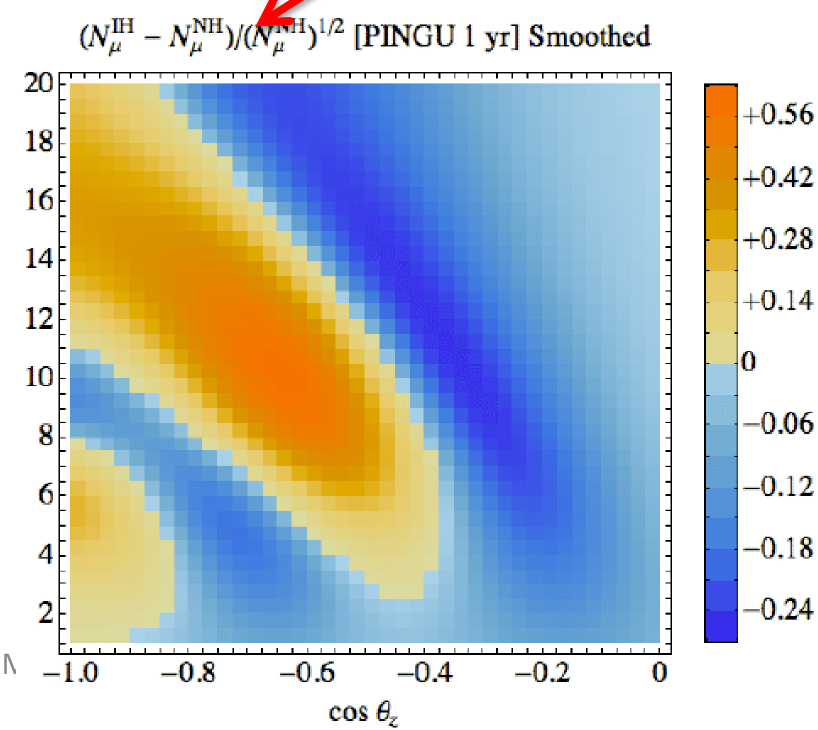
- *~20 additional strings within DeepCore*
- *lower threshold to few GeV*
- *~10 Mt effective volume*
- *construction within 1 yr, ~$25 M*

Akhmedov-Razzaque-Smirnov June 12

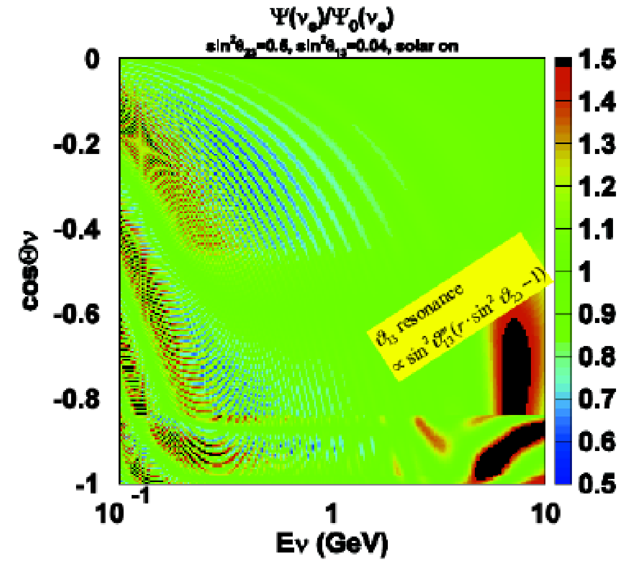
MH resolution 4σ-11σ in 5 years !

σ_E=2 GeV
σ_θ=11.25°

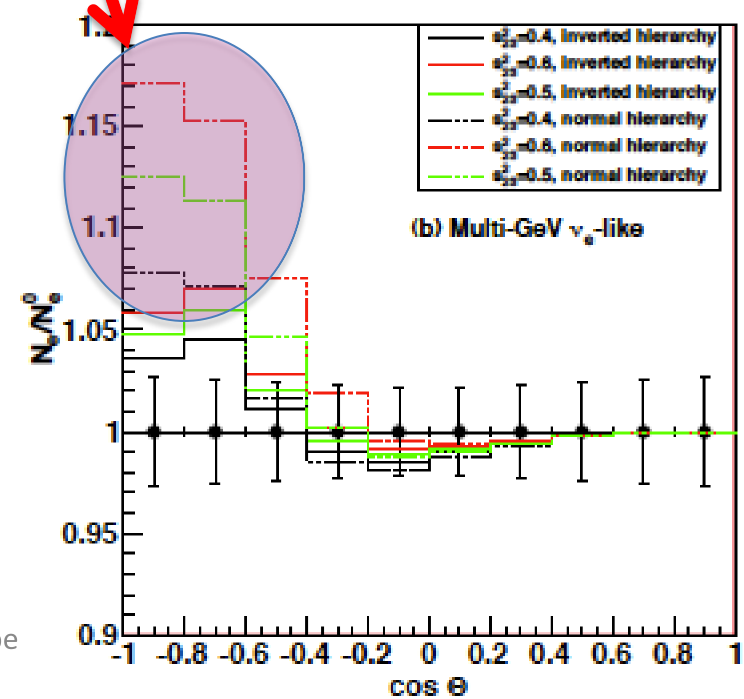


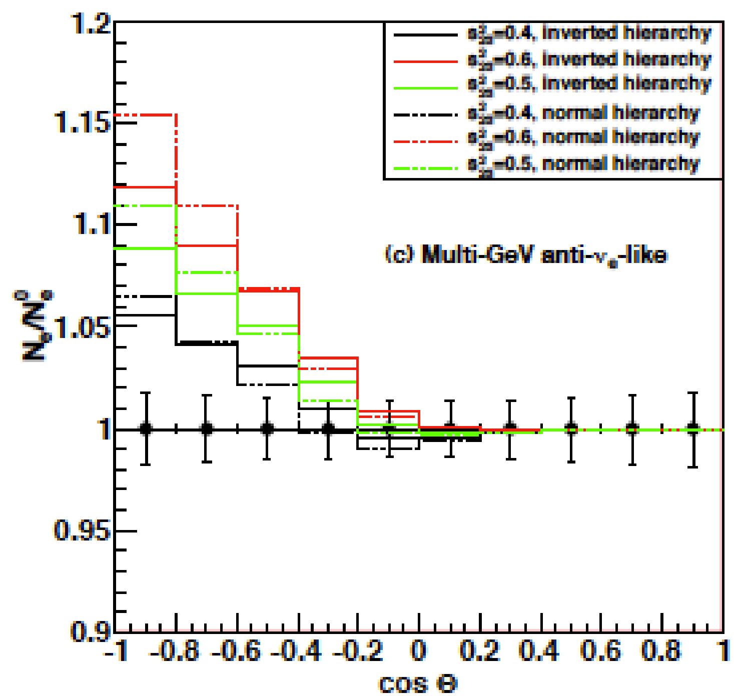


Use of atmospheric ν for mass hierarchy: SK & HK

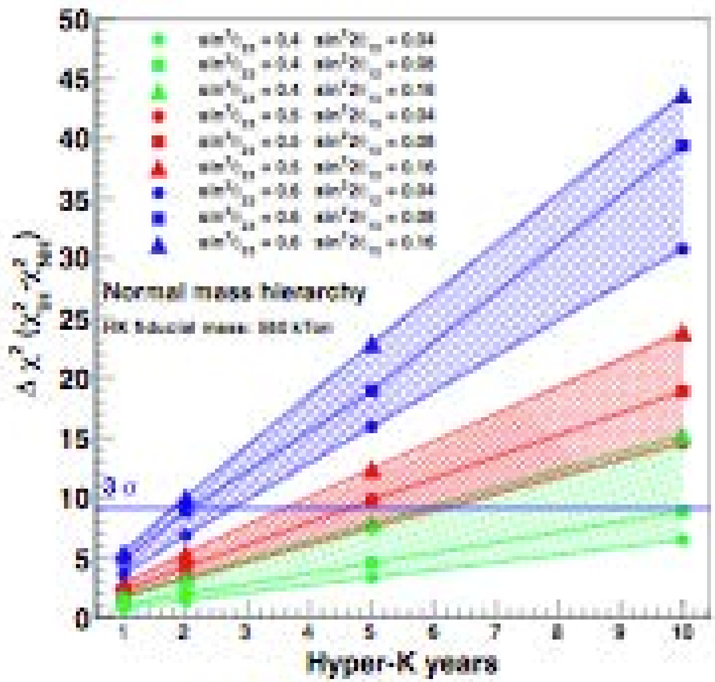


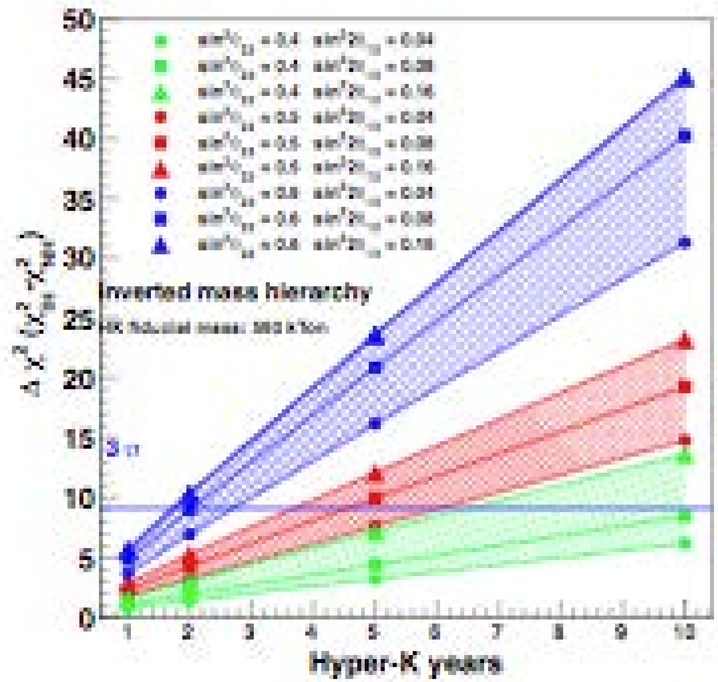
e-like larger for normal hierarchy

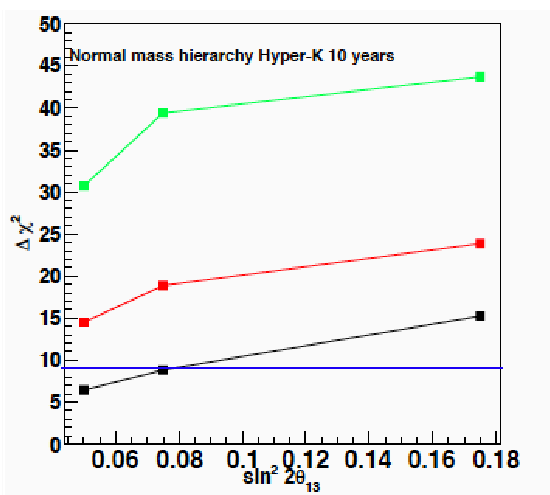


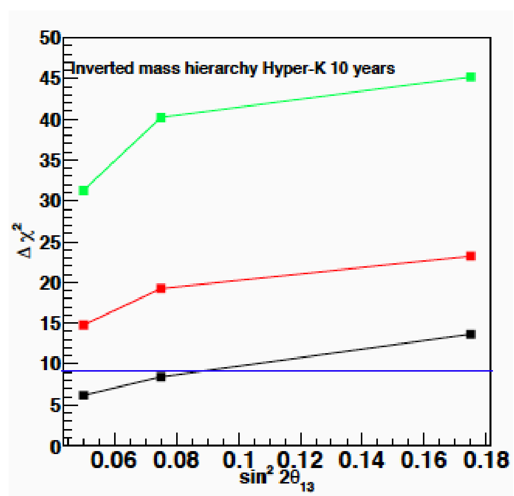


Hyper-K; Good MH sensitivity, depend on θ_{23}









$s_{23}^2=0.6$

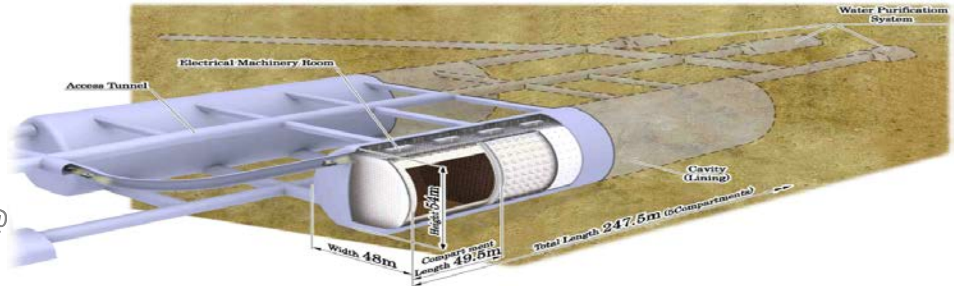
$s_{23}^2=0.5$

$s_{23}^2=0.4$

Hyper-K LOI

What is really good with large θ_{13}: "All in one" approach:

- With large θ_{13} there arises an exciting possibility that CP and Mass hierarchy can be determined in situ in a single apparatus (concrete example: Hyper-K)
- With intense ν and ν-bar beam it can measure δ
- With gigantic atmospheric ν events it could determine the mass hierarchy
- ~ megaton scale water Cherenkov can do
- ~100 kt scale Liquid Ar detector can do
- It can do proton decay, interesting astrophysics ..

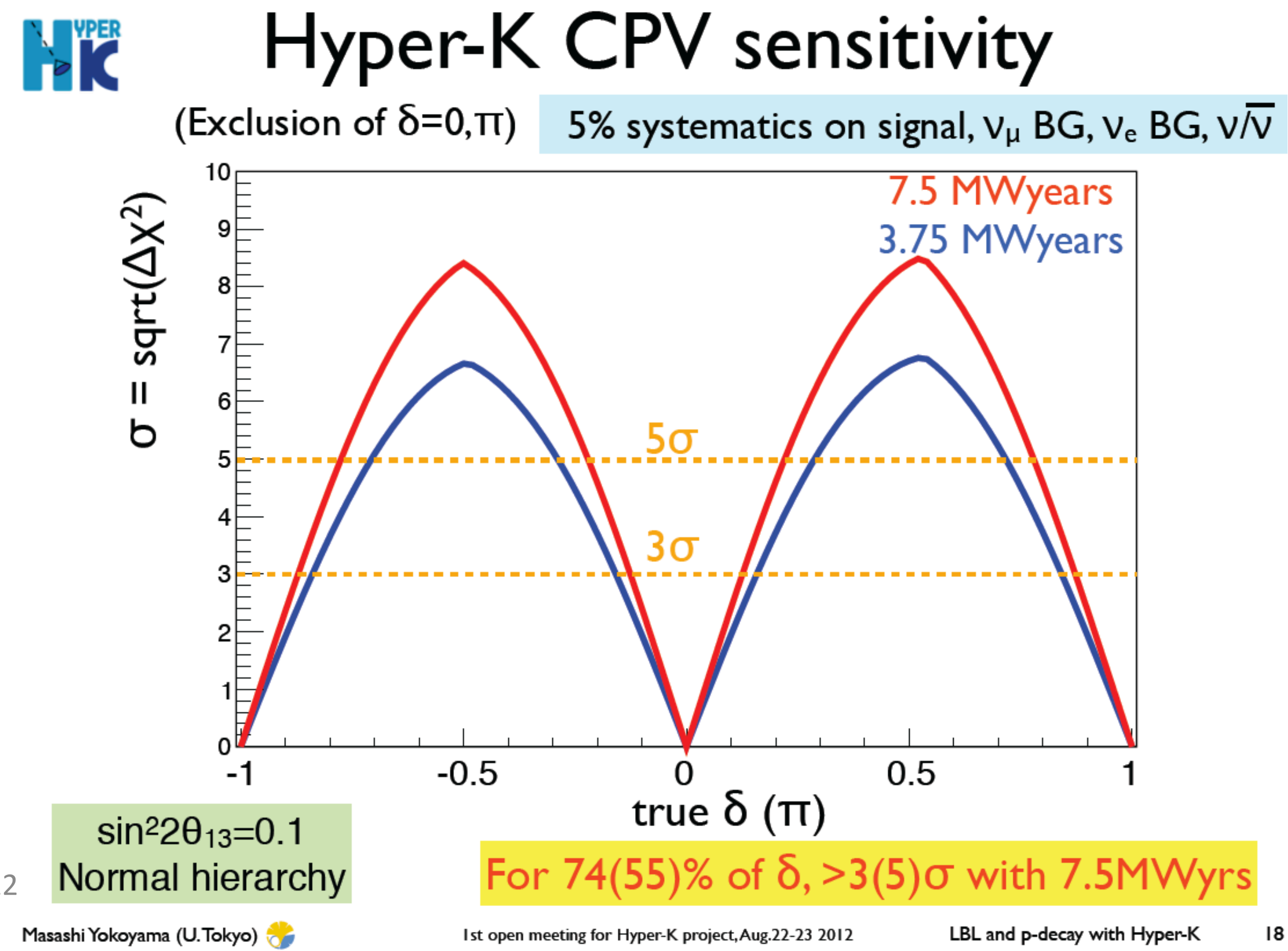


CP Violation: more difficult to see

Need for dedicated machine for CP

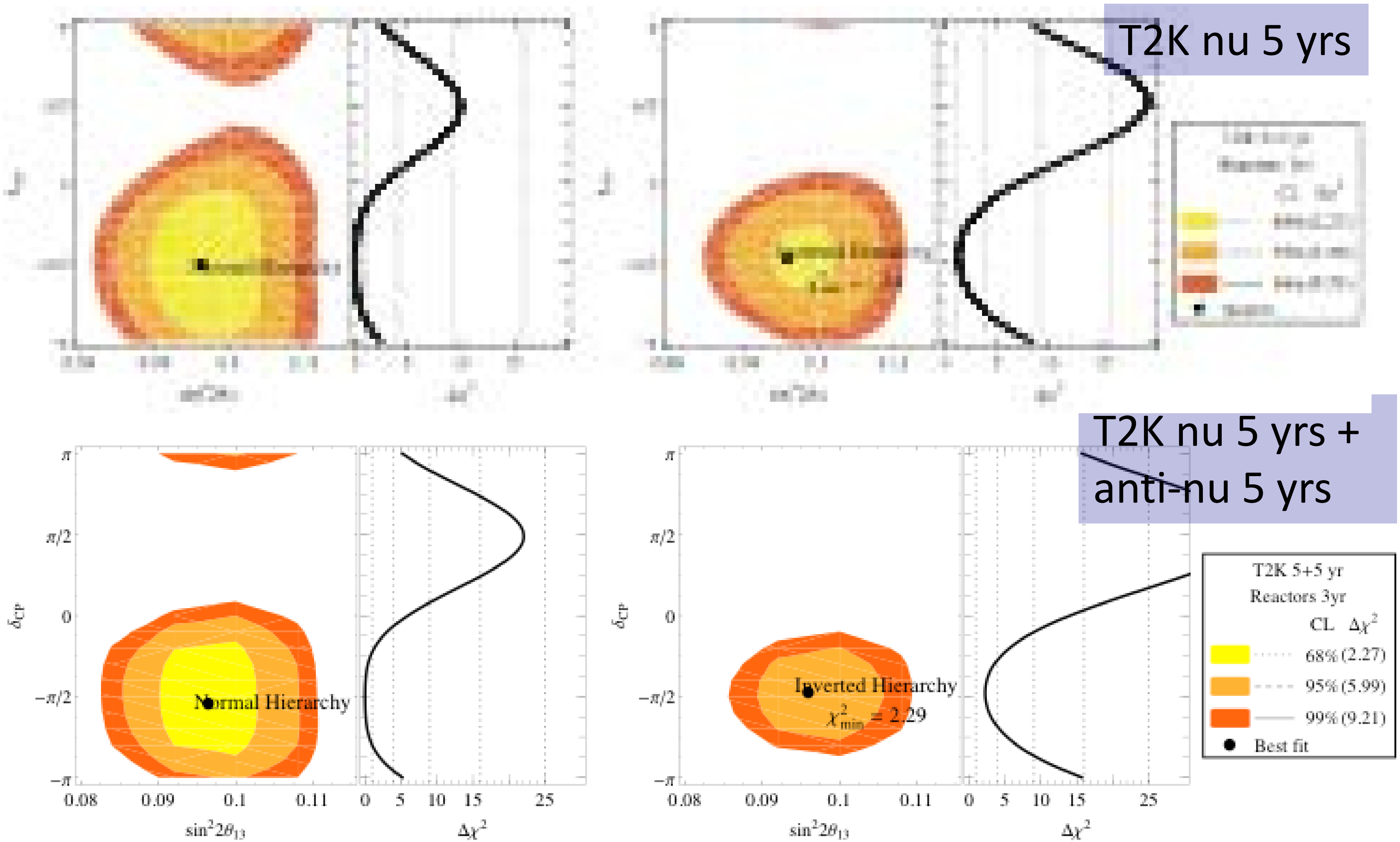
- Effect of δ (cosine and sine) has to be tiny because it is suppressed by two small numbers:

$\Delta m^2_{21}/\Delta m^2_{31} \sim 0.031$, $J_r = c_{12}s_{12}c_{23}s_{23}s_{13} \sim 0.035$



Reactor-accelerator method for CP

Reactor 3 years +T2K 5/10 years



P.A.N.Machado, HM, H.Nunokawa, R.Zukanovich Funchal, in prep.

Why do you want to measure δ and mass hierarchy so much?

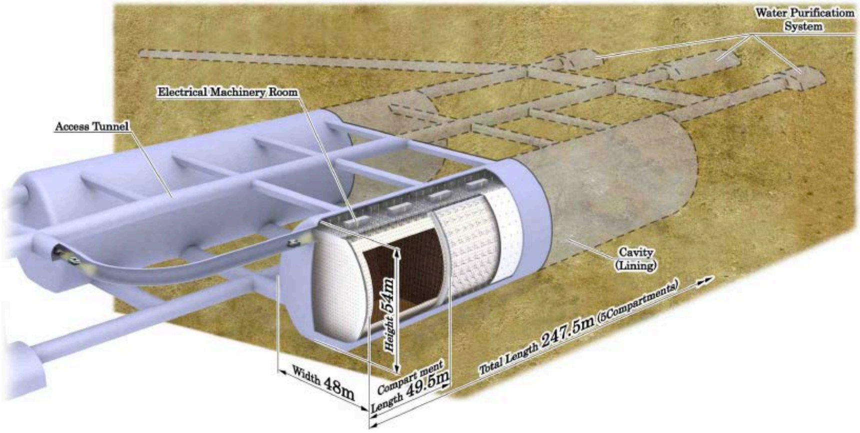
My prejudice !

- In SM quarks and leptons are related through anomaly (short distance phenomena)
- It can be interpreted as indication of quark-lepton relation in a much deeper level than the SM scale
- Leptons and quarks have similarity (quark & charged lepton mass spectra..) and dissimilarity (small vs. large mixing angles..)
- So we want to know every feature of quark and lepton correspondence

ν mass and large lepton mixing: what we are seeing

Fermi told us about the meaning of higher dimensional operators

- $H_W=(1/v_{higgs})^2\ \psi\psi\psi\psi$
- $L_{mass}=(1/\ M_{NP})<\phi>^2\nu\nu$
- $M_{NP} \sim 10^{15}$ GeV → what the scale means?
- If GUT, $L_{BV}=(1/\ M_{NP})^2$ uude
- Simplest model for L_{mass} (seesaw) predict lepton# violation=>leptogenesis



From where large mixing come?

Since $U_{MNS}=U_l^{+}U_\nu$

- It can come from neutrino sector
- Example: Seesaw enhancement
- $L = N^c Y_\nu LH - E^c Y_\nu LH + (1/2)\, N^c M N$
- $m_\nu = Y_\nu{}^T (M)^{-1} Y_\nu$
- Natural because there is no N sector in charged leptons

- It can come from charged lepton sector
- Example: lopsided mass matrix (see next sheet)
- Interesting implications: large mixing can propagate to other lepton flavor violation (e.g., $\mu \to e\gamma$)

Lopsided lepton mass matrix (explanatory sheet)

- Consider SU(5) GUT

  $5^* = [d^c, (\nu, e)_L]$

  $10 = [u^c, (u, d)_L, e^c]$
- Quark mass

  $m_{LR}^{down} = 10 \cdot 5^* \langle H_1 \rangle$
- Charged lepton mass

  $m_{LR}^{lepton} = 5^* \cdot 10 \langle H_2 \rangle$

==> $m^{lepton} = (m^{down})^T$

==> lopsided structure; left-handed mixing of m^{lepton} = right-handed mixing of m^{down}

- $m^{d,l} m^{d,l+} = S m_i^2 S^+$
- $U_{MNS} = S^{(lepton)+} S^{(\nu)}$

$$m^{\rm down} = c \begin{bmatrix} \lambda^4 & \lambda^3 & \lambda^4 \\ x & \lambda^2 & \lambda^2 \\ y & z & 1 \end{bmatrix}, \quad m^{\rm down}(m^{\rm down})^\dagger = c^2 \begin{bmatrix} \lambda^6 & \lambda^5 & \lambda^4 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^4 & \lambda^2 & 1 \end{bmatrix}$$

$$m^{\rm lepton}(m^{\rm lepton})^\dagger = c'^2 \begin{bmatrix} x^2+y^2 & yz+\lambda^2 x & y+\lambda^2 x \\ yz+\lambda^2 x & z^2 & z \\ y+\lambda^2 x & z & 1 \end{bmatrix}$$

λ=0.2, x, y, z = O(1)==> Large lepton mixing arises from quark mass

Quark-
lepton
complement
arity

$\theta_{Cabibbo} + \theta_{solar} = \pi / 4$

QLC embedded into GUTs

$U_{MNS}=U_{lepton}^{+} U_n$, $V_{CKM}=V_{up}^{+} V_{down}$

- Neutrino-induced bimaximal

$$U_\nu = U_{bimaximal} \qquad V_{up} = I$$
$$U_{lepton} = V_{CKM} \qquad V_{down} = V_{CKM}$$

Seesaw enhance?

<= GUTs =>

- Lepton-induced bimaximal

$$U_\nu = V_{CKM}^\dagger \qquad V_{up} = V_{CKM}^\dagger$$
$$U_{lepton} = U_{bimaximal} \qquad V_{down} = I$$

<= GUTs =>

<= Lopsided

Large θ_{13} in QLC context

"bimaximal minus CKM mixing."

HM-A.Smirnov 04

Bi-maximal from neutrinos	Bi-maximal from charge leptons
$U_\nu = R^m_{23} R^m_{12}, \qquad U_l = V^{\rm CKM}.$	$V_\nu = V^{\rm CKM\dagger}, \qquad V_l = R^{m\dagger}_{12} R^{m\dagger}_{23}.$
$U_{\rm MNS} = V^{\rm CKM\dagger}\Gamma_\delta R^m_{23} R^m_{12} = R^{\rm CKM\dagger}_{12} R^{\rm CKM\dagger}_{13} R^{\rm CKM\dagger}_{23}\Gamma_\delta R^m_{23} R^m_{12},$	$U_{\rm MNS} = R^m_{23}\Gamma_\delta R^m_{12} V^{\rm CKM\dagger}$
$\Rightarrow \sin\theta_{13} \simeq \frac{1}{\sqrt{2}}\sin\theta_C$	$\Rightarrow \sin\theta_{13} \approx -\sin\theta_{\rm sun}\lvert V_{cb}\rvert,$
$\sin^2\theta_{13} = 0.026 \pm 0.008$	$\sin^2 2\theta_{13} = 1.9\times 10^{-3}$

IN QLC context, large θ_{13} implies that large mixing comes from neutrino sector!

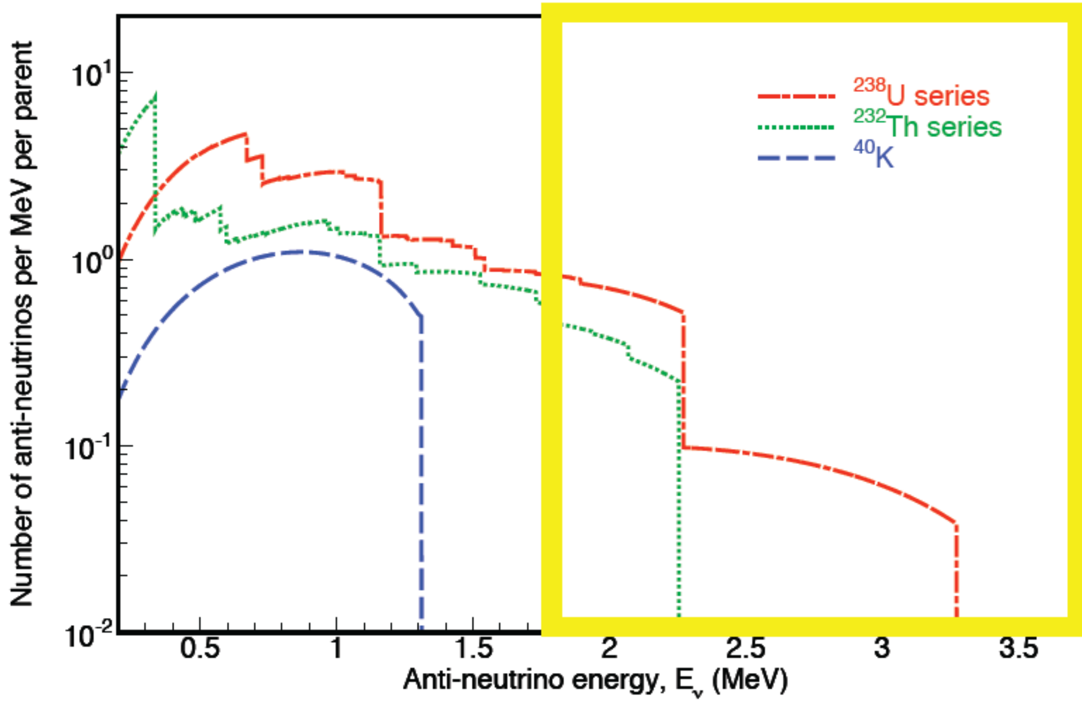
Conclusion

- We know know all the three lepton mixing angles and after this our next goal is well defined: δ and ν mass hierarchy
- We need "guaranteeing machine" to meet the goal but what is good with large θ_{13} is "all in one" approach becomes possible
- Large θ_{13} triggers "hundred flowers" situation for method for determining MH
- Absolute n mass, Majorana phase ..
- How we can make solid step-by-step progress in understanding physics?

Supplementary slides

地球内部起源ニュートリノ

反ニュートリノフラックス



KamLAND
での観測領域

β崩壊

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8{}^{4}\mathrm{He} + 6e^{-} + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}\ (100\%)$$

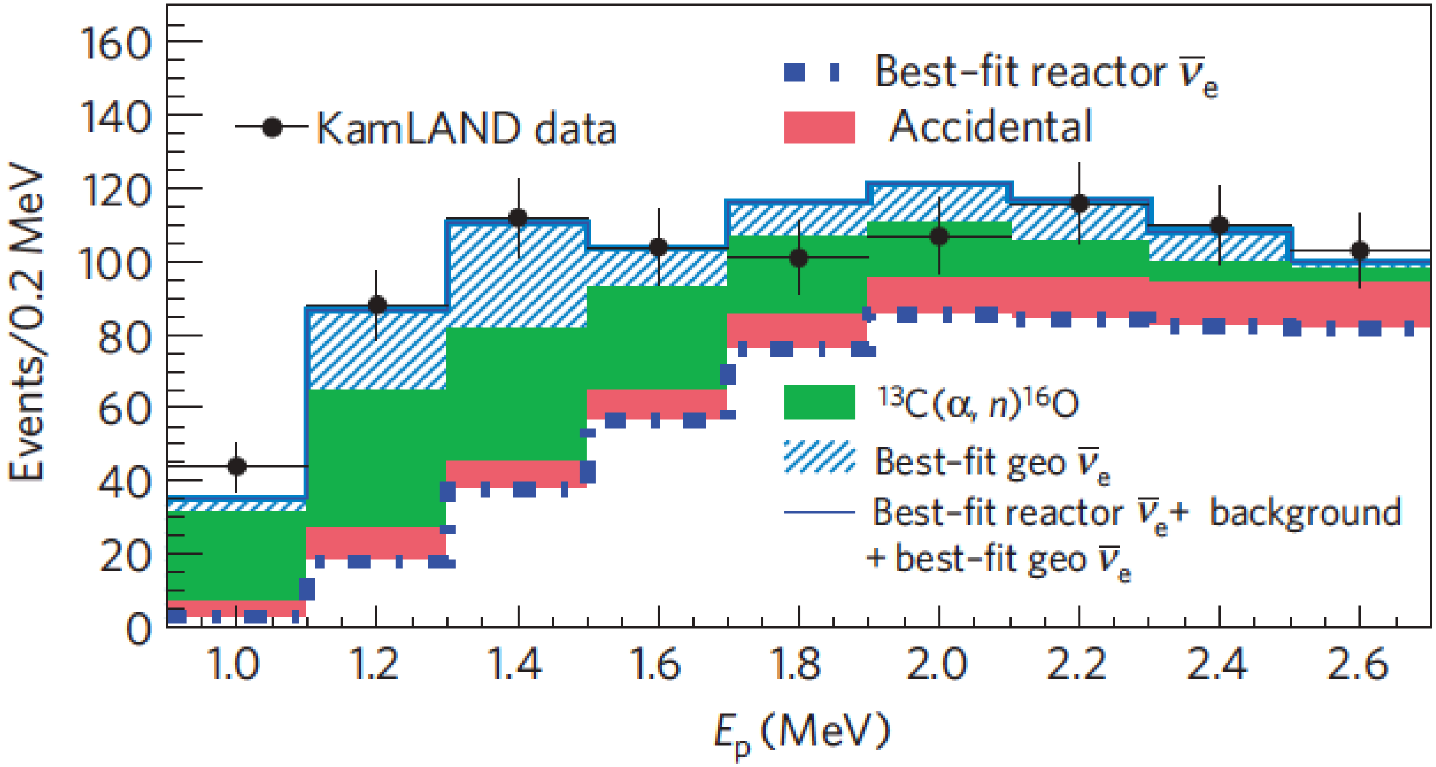
$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6{}^{4}\mathrm{He} + 4e^{-} + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}\ (100\%)$$

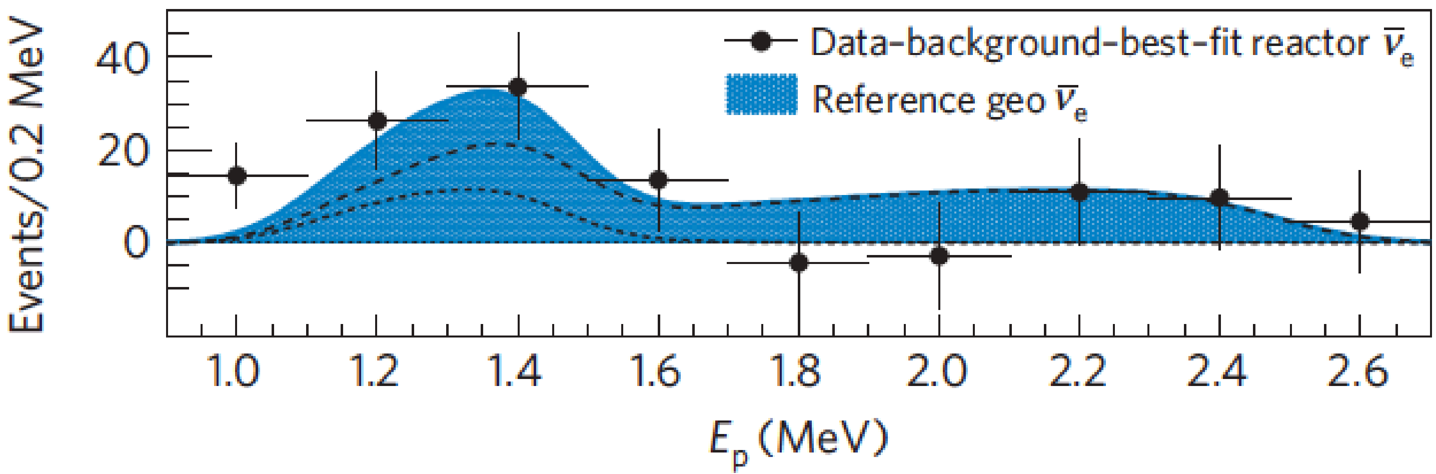
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^{-} + \bar{\nu}_e + 1.31\ \mathrm{MeV}\ (89.28\%)$$

$$^{40}\mathrm{K} + e^{-} \rightarrow {}^{40}\mathrm{Ar} + \nu_e + 1.51\mathrm{MeV}(10.72\%)$$

KamLAND result 2011

NATURE GEOSCIENCE DOI: 10.1038/NGEO1205





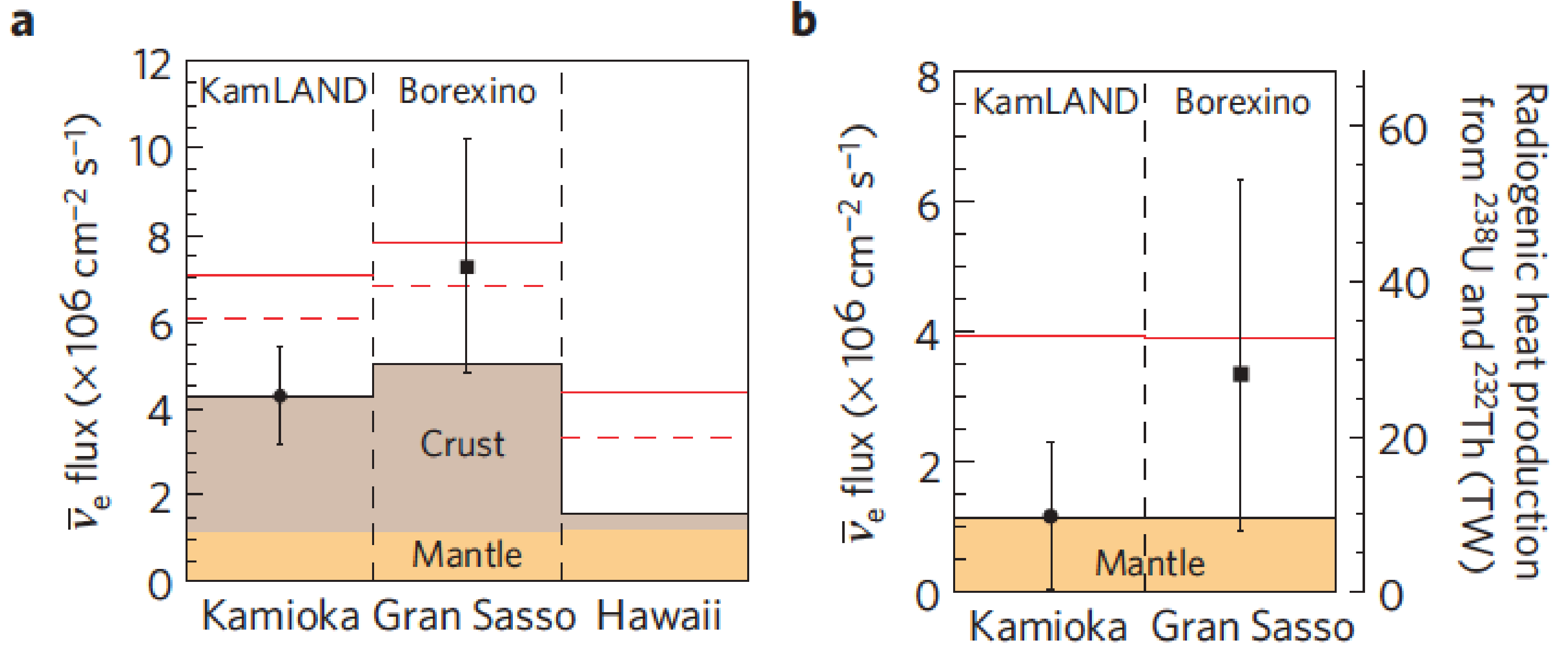


Figure 4 | Measured geoneutrino flux and models. a, Measured geoneutrino flux at Kamioka and Gran Sasso, and expected fluxes at these sites and Hawaii[4]. The solid and dashed red lines represent, respectively, the fluxes for a fully radiogenic model assuming the homogeneous and sunken-layer hypotheses. **b**, Measured geoneutrino flux after subtracting the estimated crustal contribution. No modelling uncertainties are shown. The right axis shows the corresponding radiogenic heat production assuming a homogeneous mantle. The solid red line indicates the fully radiogenic model where the contributions from the crust (7.0 TW) and the other isotopes[6,24] (4.3 TW) are subtracted from the total heat flow[7] (44.2 TW). Error bars, see text.

Oct

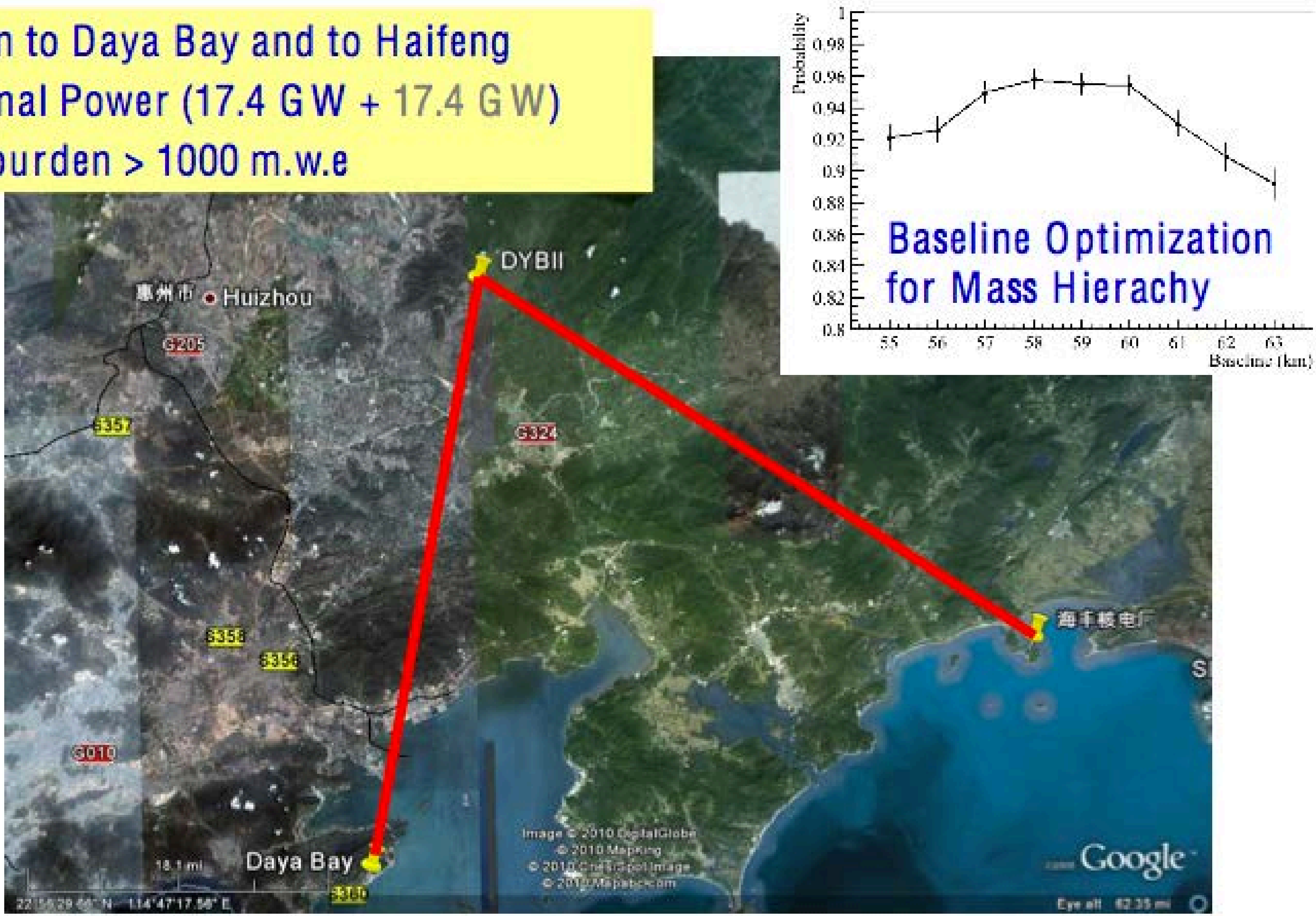
Daya Bay II Site Investigation

J.Cao@ NuTURN12

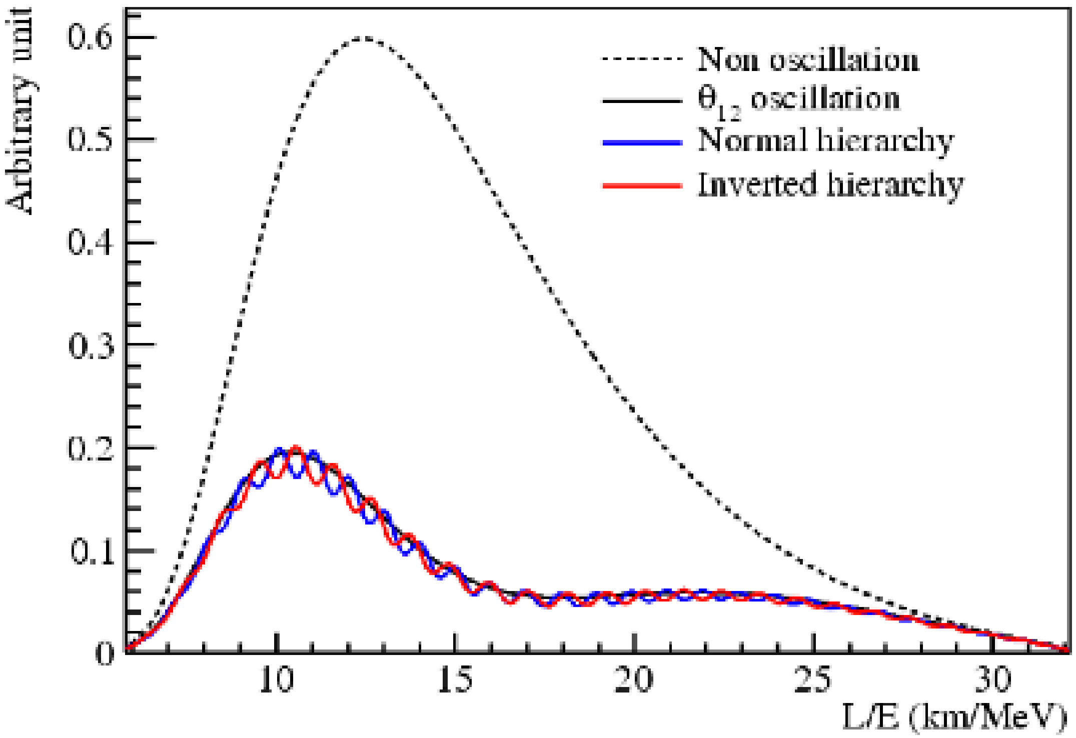
~60km to Daya Bay and to Haifeng

Thermal Power (17.4 GW + 17.4 GW)

Overburden > 1000 m.w.e



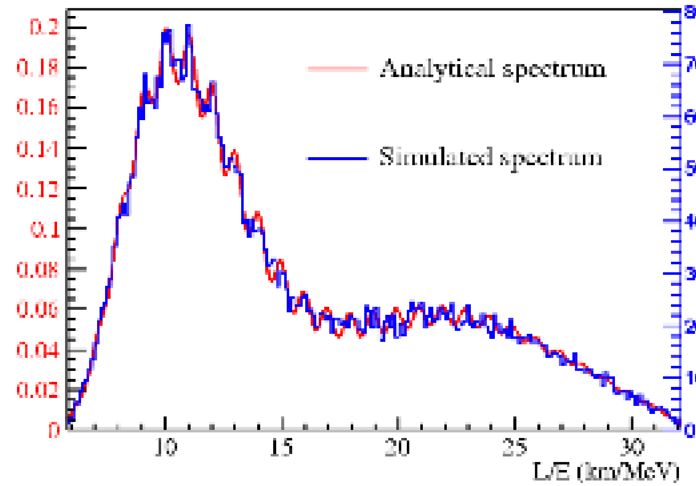
Reactor Exp. to determine MH



S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022

L. Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$



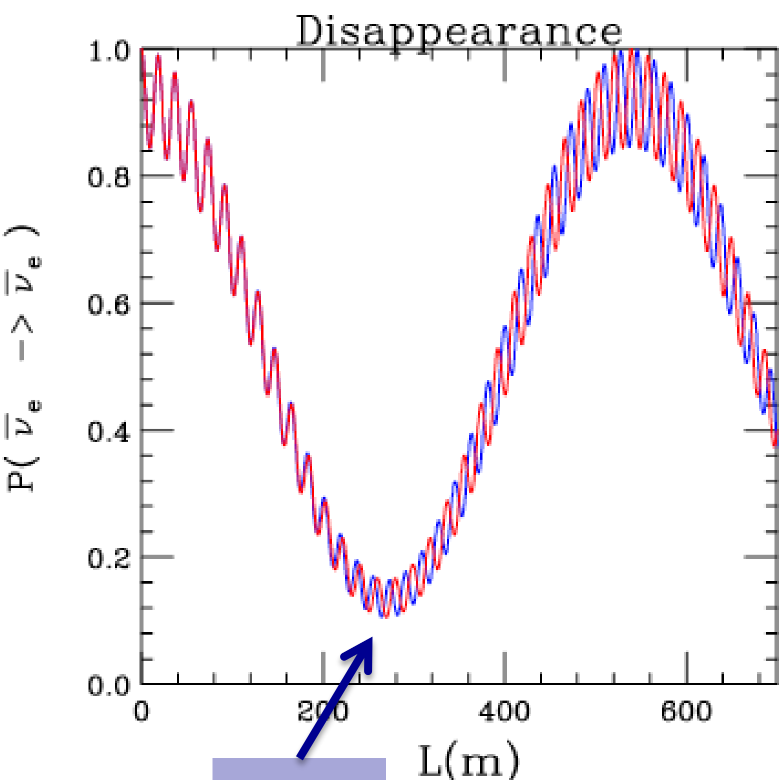
Phase advancement vs. retardation

$$P(\nu_e \to \nu_e) = 1 - \tfrac{1}{2}\sin^2 2\theta_{13}\left[1 - \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}\right.$$
$$\left.\times \cos(2\Delta_{ee} \pm \phi_\odot)\right] - P_\odot,$$

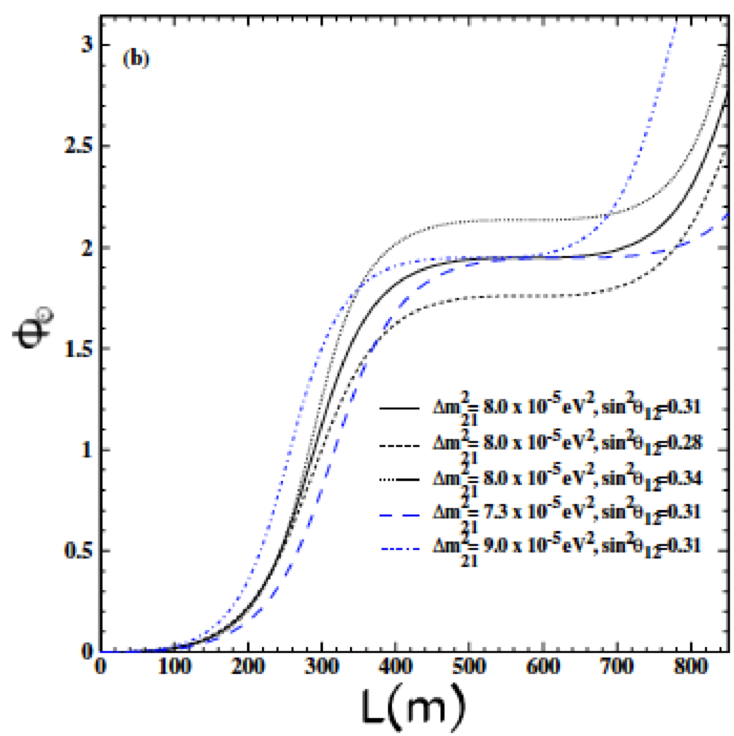
$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|.$$

$$\sin\phi_\odot = \frac{c^2_{12}\sin(2s^2_{12}\Delta_{21}) - s^2_{12}\sin(2c^2_{12}\Delta_{21})}{\sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}},$$

Hierarchy sign



60 km



HM, Nunokawa, Parke, Zukanovich-Finchal 07

Mass hierarchy confusion

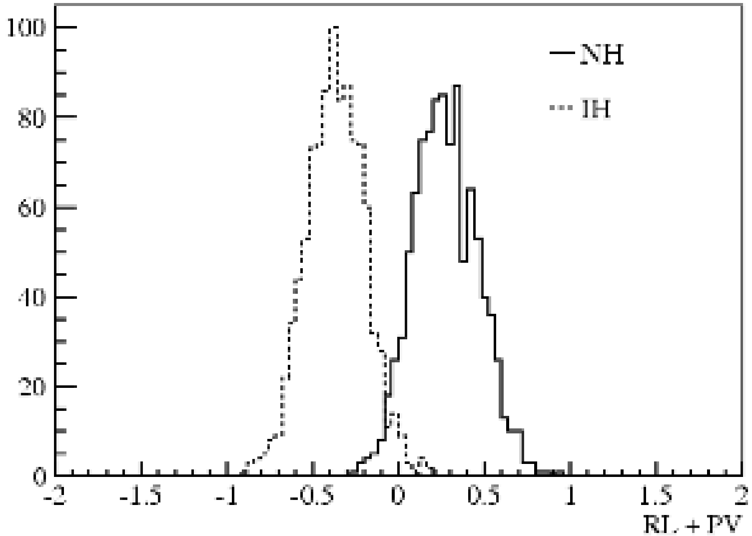
$$P(\nu_e \to \nu_e) = 1 - \tfrac{1}{2}\sin^2 2\theta_{13}[1 - \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}$$
$$\times \cos(2\Delta_{ee} \pm \phi_\odot)] - P_\odot, \qquad ($$

If accuracy of Δm^2_{atm} is not good enough

$$2\Delta_{ee}|_{NH} + \phi_\odot = 2\Delta_{ee}|_{IH} - \phi_\odot$$

→ complete confusion of mass hierarchy

One need to watch over many wiggles ➔ Fourier transform

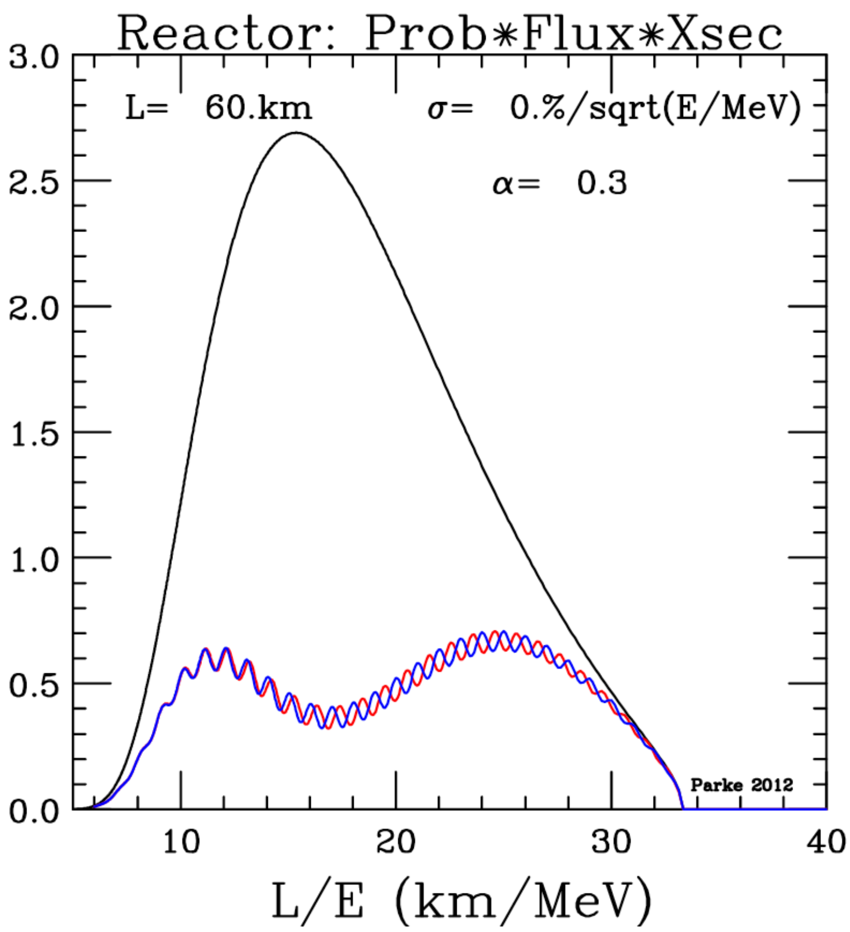


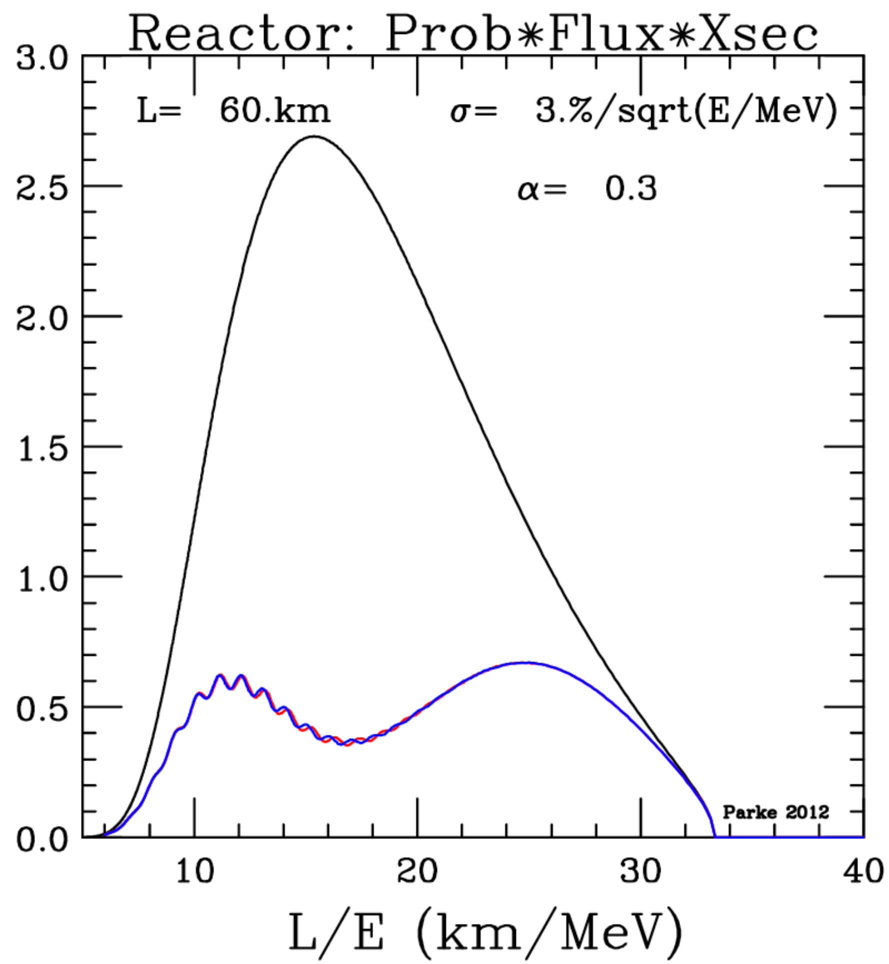
Energy resolution	3%/sqrt(E)
Baseline	58 km
Thermal Power	35 GW

50k events =20k tons X 3 years

50k events: 96% probability

Then, energy resolution (absolute & relative) is the issue





See X.~Qian, et al. arXiv:1208.1551 [hep-ex] for experimental requirements

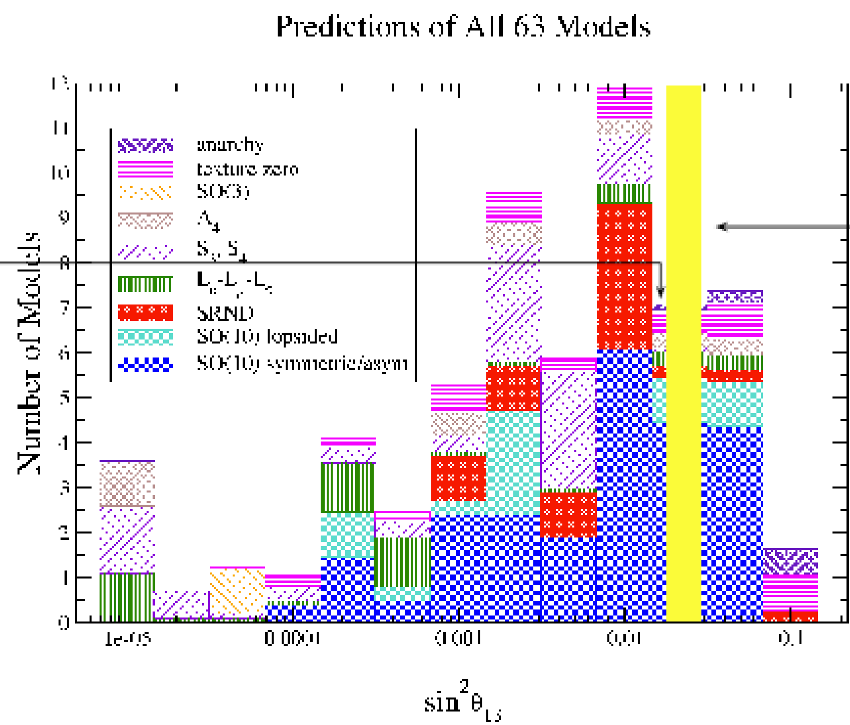
Implication of large θ_{13} to the theory is NOT that clear..

Concha@ICHEP2012

Implications

- Survey of 63 ν mass models in 2006 (Albright, M-C Chen,hep-ph/0608136)

Only 7
got it right !



Present 3σ range

S. Antusch