RECENT DEVELOPMENTS IN NEUTRINO PHYSICS

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IPM, Tehran

elusives
neutrinos, dark matter & dark energy physics

invisiblesPlus

How much recent?

- Recent 20 years (Since 1997)

- Recent 5 years (since 2012)

Atmospheric neutrinos

Cosmic rays hit atmosphere and create pions.

$$\pi^+ \to \mu^+ \nu_\mu \qquad \mu^+ \to \bar{\nu}_\mu e^+ \nu_e$$

$$\pi^- \to \mu^- \bar{\nu}_\mu \qquad \mu^- \to \nu_\mu e^- \bar{\nu}_e$$

Detection of atmospheric neutrinos

$$E_\nu > 500\ \text{MeV}$$

$$\nu_e + N \rightarrow e^- + X$$

$$\nu_\mu + N \rightarrow \mu^- + X$$

Distinguishable

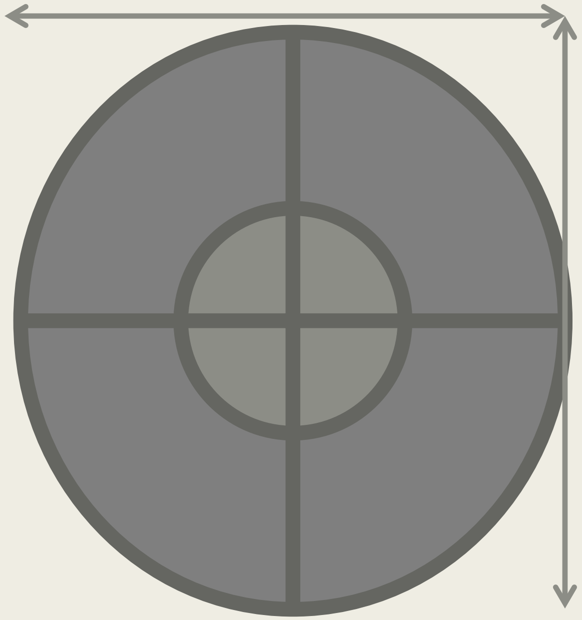
Cherenkov light at Super-Kamiokande

Atmospheric neutrinos

$$\pi^+ \to \mu^+ \nu_\mu \qquad \mu^+ \to \bar{\nu}_\mu e^+ \nu_e$$

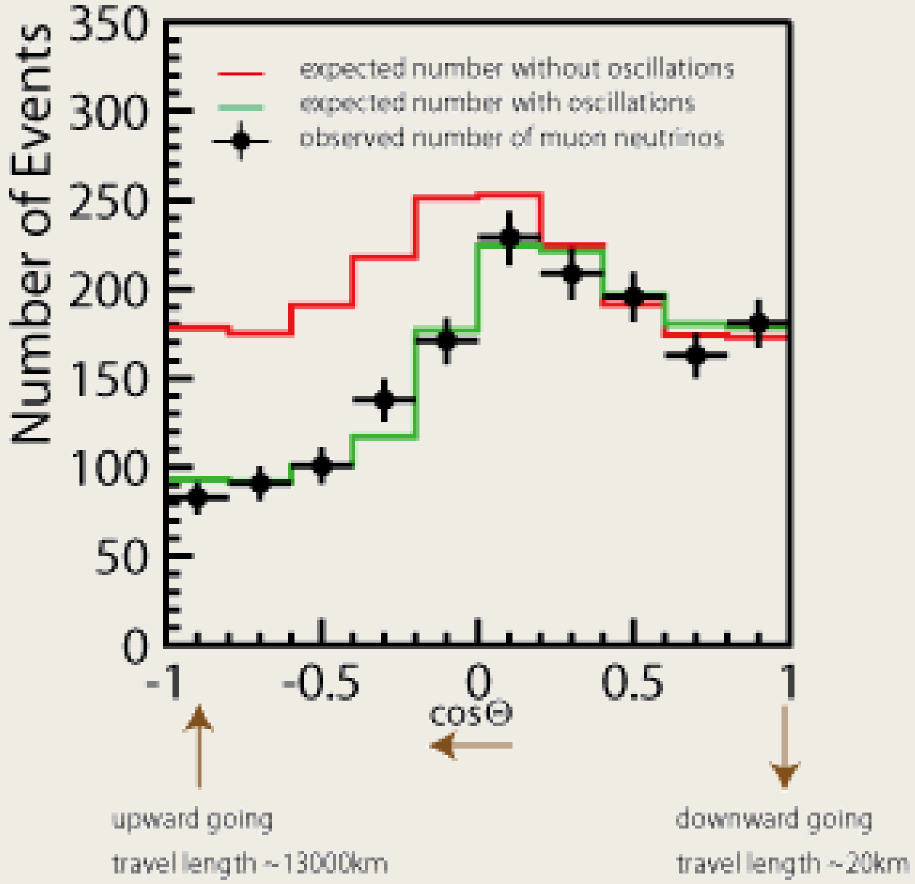
$$\pi^- \to \mu^- \bar{\nu}_\mu \qquad \mu^- \to \nu_\mu e^- \bar{\nu}_e$$

$$E_\nu \gtrsim 1 \text{ GeV}$$



$$2R_\oplus$$

Muon neutrino events



Famous 1998 Super-Kamiokande results

Super-Kamiokande homepage

Nobel Prize 2015

- Takaaki Kakita
- PI of Japan node of elusives: ICRR, Kavli IPMU, University of Tokyo
- Network sponsored by European union
- 12 European node; 21 non-European nodes: Including physics school, IPM

Propagation

- Within Old SM with $m_\nu = 0$ the flavor of neutrino do not change in propagation.

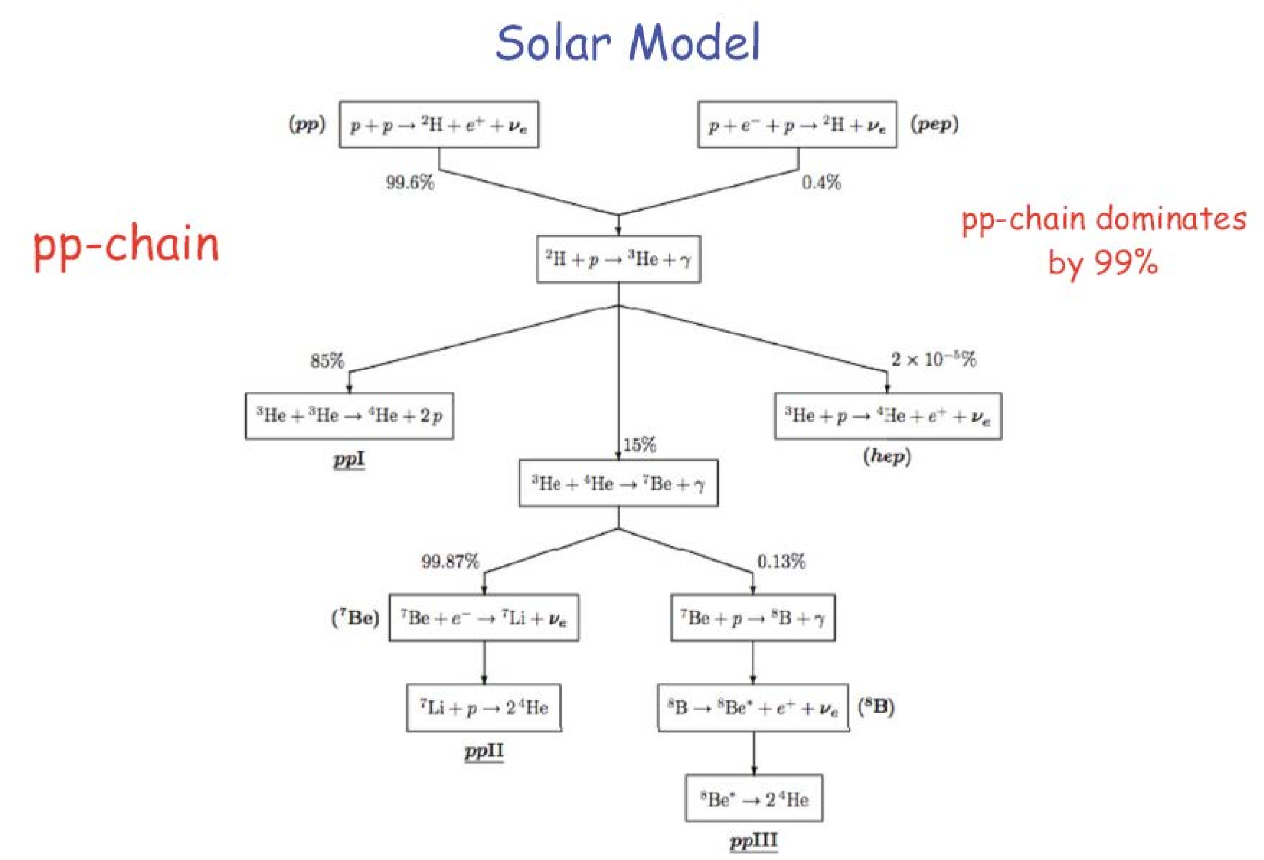
ν_e remains ν_e

ν_μ remains ν_μ

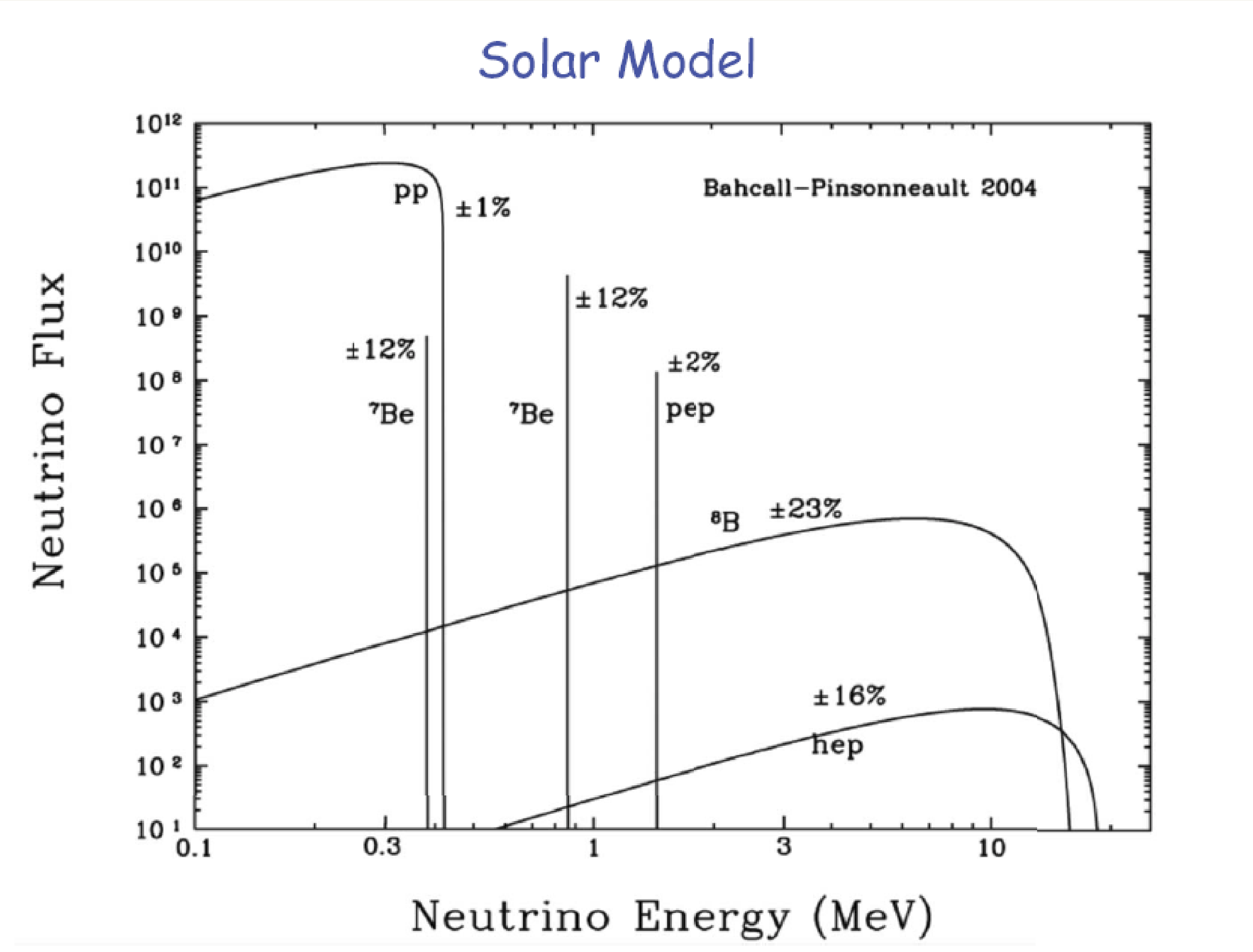
ν_τ remains ν_τ

Solar neutrinos

- Hydrogen fusion $$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e$$



Spectrum



Solar Model
Bahcall–Pinsonneault 2004
pp
±1%
±12%
^{7}Be
±12%
^{7}Be
±2%
pep
^{8}B
±23%
±16%
hep
Neutrino Flux
Neutrino Energy (MeV)
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
0.1
0.3
1
3
10

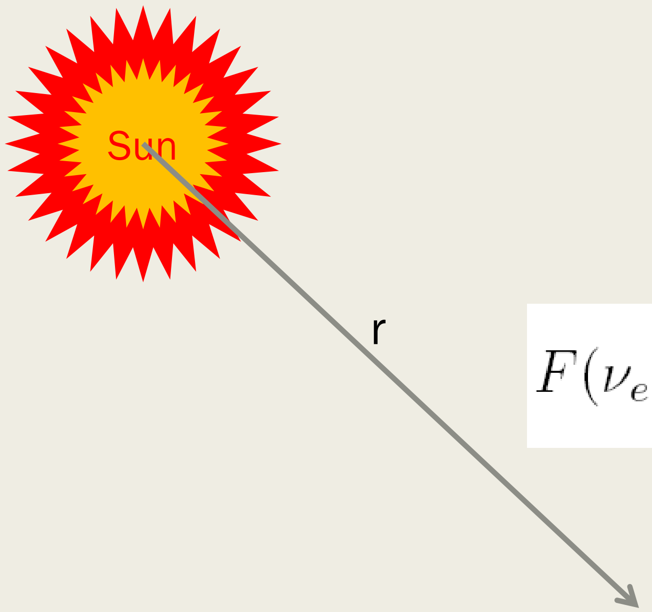
Propagation in OLD SM

- Within Old SM with $m_\nu = 0$ the flavor of neutrino do not change in propagation.

ν_e remains ν_e

ν_μ remains ν_μ

ν_τ remains ν_τ



$$F(\nu_e) \propto \frac{1}{r^2}$$

	BP00	BP04	BSB05(GS98)	BSB05(AGS05)
$\Phi_{pp} / 10^{10}$	$5.95\,(1 \pm 0.01)$	$5.94\,(1 \pm 0.01)$	$5.99\,(1 \pm 0.009)$	$6.06\,(1 \pm 0.007)$
$\Phi_{pep} / 10^{8}$	$1.40\,(1 \pm 0.015)$	$1.40\,(1 \pm 0.02)$	$1.42\,(1 \pm 0.015)$	$1.45\,(1 \pm 0.011)$
$\Phi_{hep} / 10^{3}$	9.3	$7.88\,(1 \pm 0.16)$	$7.93\,(1 \pm 0.155)$	$8.25\,(1 \pm 0.155)$
$\Phi_{^7\mathrm{Be}} / 10^{9}$	$4.77\,(1 \pm 0.10)$	$4.86\,(1 \pm 0.12)$	$4.84\,(1 \pm 0.105)$	$4.34\,(1 \pm 0.093)$
$\Phi_{^8\mathrm{B}} / 10^{6}$	$5.05\,(1 ^{+0.20}_{-0.16})$	$5.79\,(1 \pm 0.23)$	$5.69\,(1 ^{+0.173}_{-0.147})$	$4.51\,(1 ^{+0.127}_{-0.113})$
$\Phi_{^{13}\mathrm{N}} / 10^{8}$	$5.48\,(1 ^{+0.21}_{-0.17})$	$5.71\,(1 ^{+0.37}_{-0.35})$	$3.05\,(1 ^{+0.366}_{-0.268})$	$2.00\,(1 ^{+0.145}_{-0.127})$
$\Phi_{^{15}\mathrm{O}} / 10^{8}$	$4.80\,(1 ^{+0.25}_{-0.19})$	$5.03\,(1 ^{+0.43}_{-0.39})$	$2.31\,(1 ^{+0.374}_{-0.272})$	$1.44\,(1 ^{+0.165}_{-0.142})$
$\Phi_{^{17}\mathrm{F}} / 10^{6}$	$5.63\,(1 \pm 0.25)$	$5.91\,(1 ^{+0.44}_{-0.44})$	$5.83\,(1 ^{+0.724}_{-0.420})$	$3.25\,(1 ^{+0.166}_{-0.142})$

C. Giunti and C. W. Kim
Fundamentals of neutrino physics and astrophysics

observation= (1/3) of expected

Davis, Harmer and Hoffman, PRL (1968)

Solar neutrinos

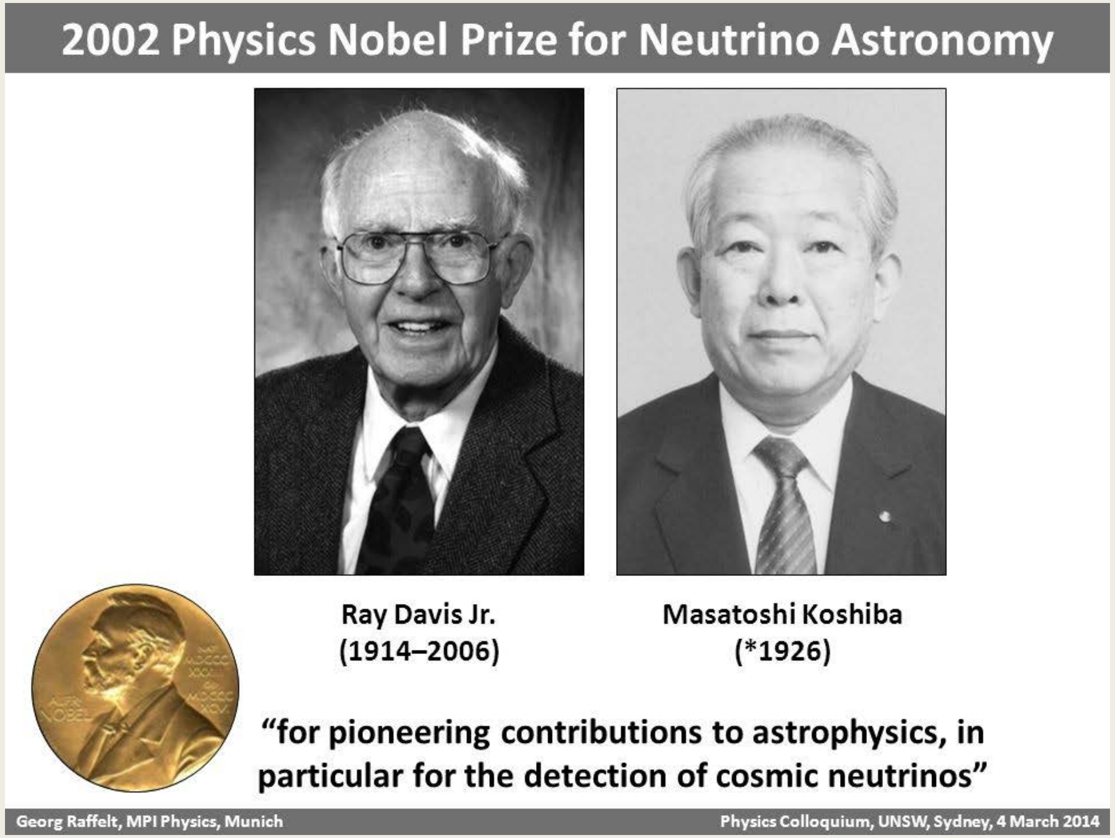
Homestake: 1968-1994

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

Neutrino oscillation appears as deficit.

$$\nu_e \longrightarrow \nu_\mu, \nu_\tau$$

Solar neutrinos



Raymond Davis, 2002 Nobel prize, along with Koshiba from Kamiokande for detecting 1987a supernova neutrinos

Solution of the puzzle

- Neutrino oscillation

- Pontecorvo proposed in 1957 in analogy of

$$K^0 \leftrightarrows \bar{K}^0$$

Even before solar neutrinos were discovered!!!

Neutrino mixing

$$\bar{\nu}_{eL}\gamma^{\nu}e_L + \bar{\nu}_{\mu L}\gamma^{\nu}\mu_L + \bar{\nu}_{\tau L}\gamma^{\nu}\tau_L$$

Charged leptons have definite mass

Neutrino mixing

$$\bar{\nu}_{eL}\gamma^{\nu}e_L + \bar{\nu}_{\mu L}\gamma^{\nu}\mu_L + \bar{\nu}_{\tau L}\gamma^{\nu}\tau_L$$

Flavor neutrino do not have definite mass

Neutrino mixing

$$\bar{\nu}_{eL}\gamma^{\nu}e_L + \bar{\nu}_{\mu L}\gamma^{\nu}\mu_L + \bar{\nu}_{\tau L}\gamma^{\nu}\tau_L$$

Flavor neutrino do not have definite mass

They are admixtures of neutrinos with definite mass.

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

Flavor Mass

PMNS matrix
Pontecorvo-Maki-Nakagawa-Sakata

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

$U_{\alpha i}$ is a unitary matrix.

$$\sum_i U_{\alpha i} U^*_{\beta i} = \delta_{\alpha\beta} \qquad \sum_\alpha U_{\alpha i} U^*_{\alpha j} = \delta_{ij}$$

Evolution in time

$$|\psi\rangle \to e^{-iHt}|\psi\rangle$$

$$|\nu_i\rangle \to e^{-iE_it}|\nu_i\rangle \qquad E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2p}$$

$$|\nu_\alpha; t\rangle = \sum_i U_{\alpha i}^* e^{-iE_it}|\nu_i\rangle = e^{-ipt}\sum_i U_{\alpha i}^* e^{-im_i^2 t/(2p)}|\nu_i\rangle$$

$$|\bar{\nu}_\alpha; t\rangle = \sum_i U_{\alpha i} e^{-iE_it}|\bar{\nu}_i\rangle = e^{-ipt}\sum_i U_{\alpha i} e^{-im_i^2 t/(2p)}|\bar{\nu}_i\rangle$$

Oscillation probability

$$|\nu_\alpha;t\rangle = \sum_i U^*_{\alpha i} e^{-iE_it} |\nu_i\rangle = e^{-ipt} \sum_i U^*_{\alpha i} e^{-im_i^2 t/(2p)} |\nu_i\rangle$$

$$|\bar{\nu}_\alpha;t\rangle = \sum_i U_{\alpha i} e^{-iE_it} |\bar{\nu}_i\rangle = e^{-ipt} \sum_i U_{\alpha i} e^{-im_i^2 t/(2p)} |\bar{\nu}_i\rangle$$

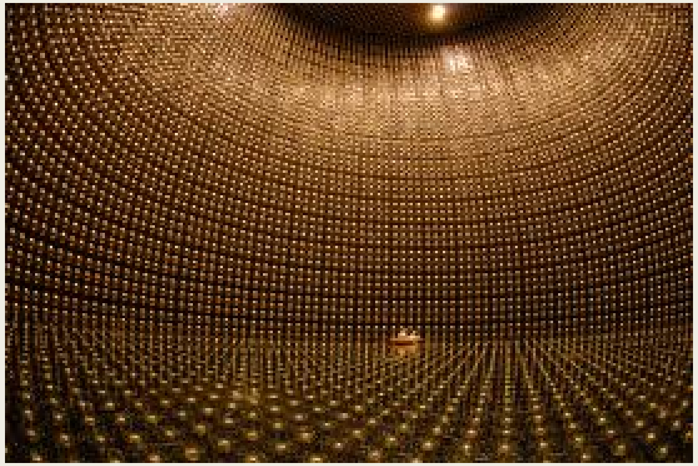
$$P(\nu_\alpha \to \nu_\beta) = |\ \langle \nu_\beta | \nu_\alpha; t\rangle\ |^2 = \sum_{i,j} U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j} e^{i \frac{\Delta m^2_{ji}}{2p} t}$$

$$P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = |\ \langle \bar{\nu}_\beta | \bar{\nu}_\alpha; t\rangle\ |^2 = \sum_{i,j} U^*_{\beta i} U_{\alpha i} U_{\beta j} U^*_{\alpha j} e^{i \frac{\Delta m^2_{ji}}{2p} t}$$

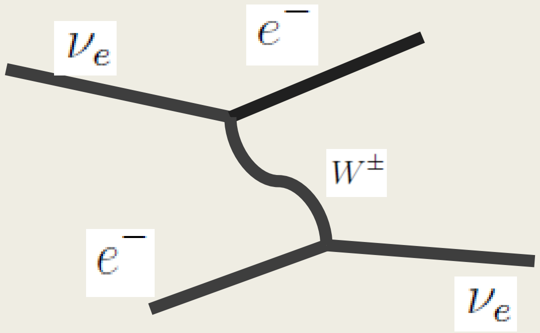
Water Cherenkov experiments

- Like super-kamiokande in Japan
- And its predecessor Kamiokande

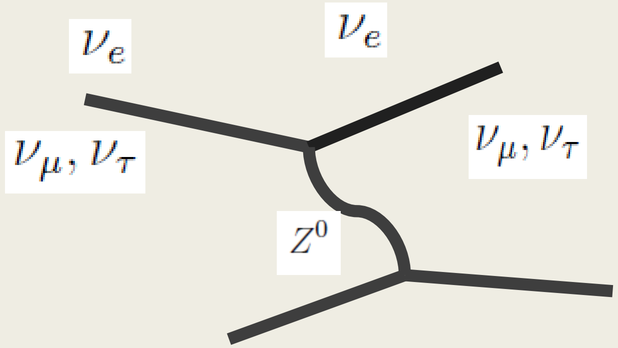
- IMB in the USA



Solar neutrino



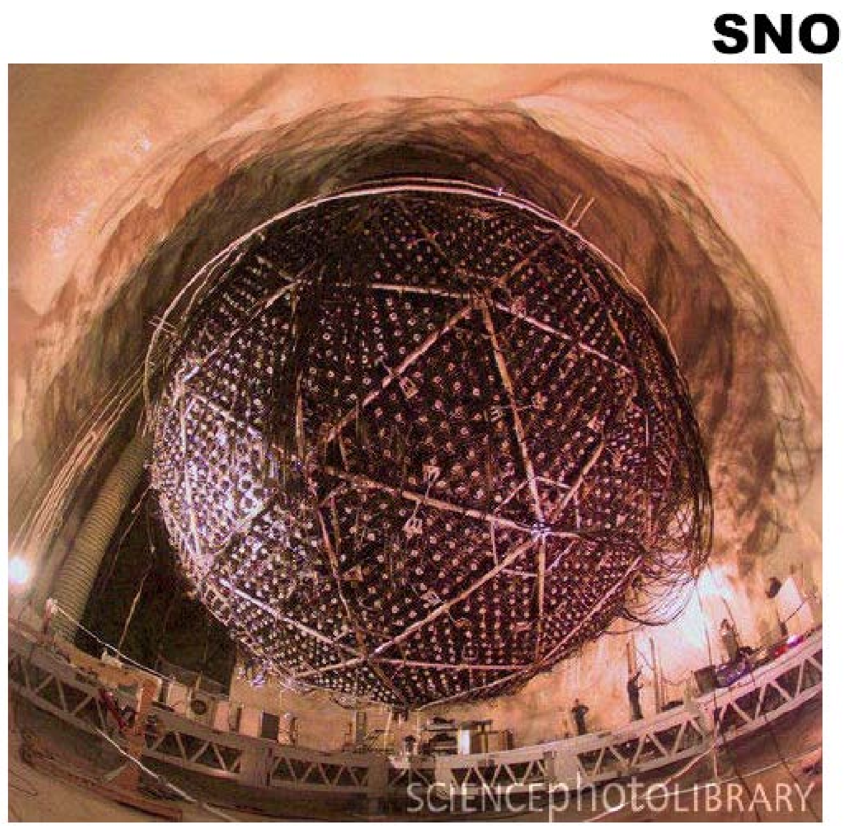
Super-Kamiokande:



SNO:

$$F(\nu_e) + F(\nu_\mu) + F(\nu_\tau)|_{observed} = F(\nu_e)|_{predicted}$$

SNO in Canada



1000 tones D_2O

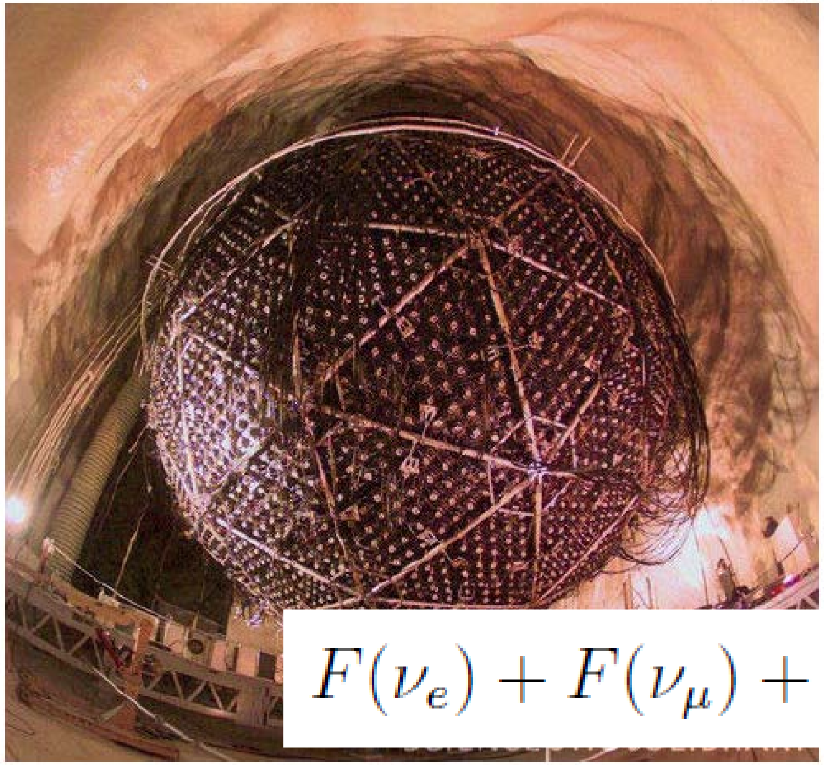
$$\mathrm{CC}: \quad \nu_e + d \rightarrow p + p + e^-$$

$$\mathrm{NC}: \quad \nu_\alpha + d \rightarrow p + n + \nu_\alpha$$

$$\mathrm{ES}: \quad \nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$$

SNO in Canada

SNO



1000 tones D_2O

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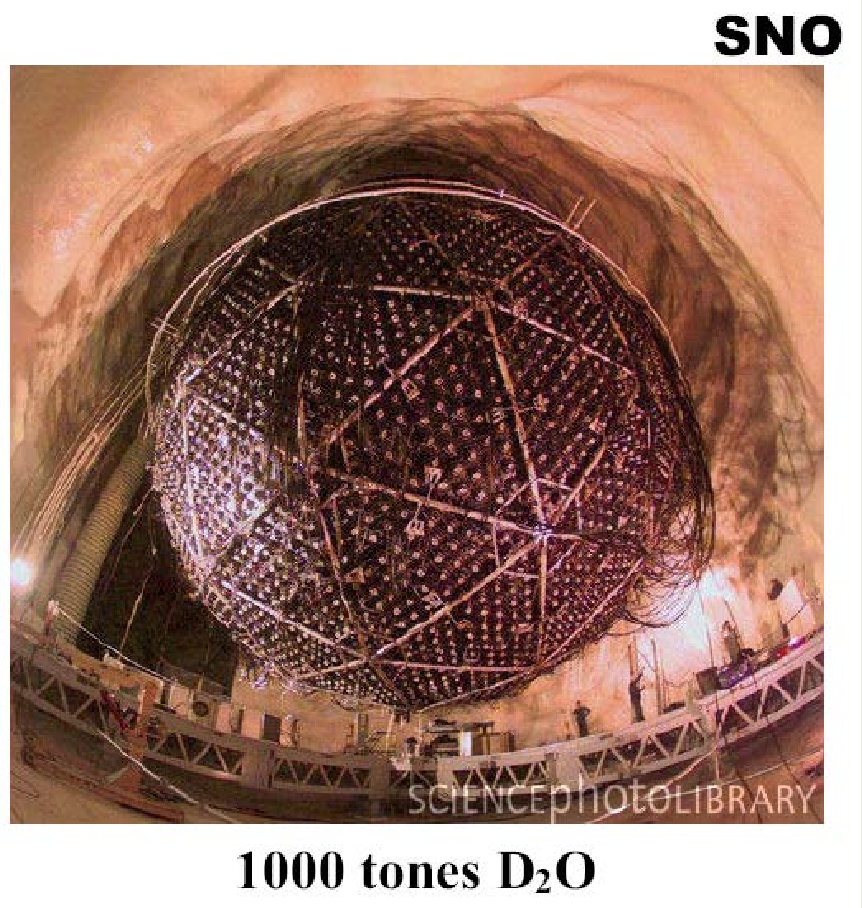
$$\mathrm{NC}: \quad \nu_\alpha + d \rightarrow p + n + \nu_\alpha$$

$$\mathrm{ES}: \quad \nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$$

$$F(\nu_e) + F(\nu_\mu) + F(\nu_\tau)|_{observed} = F(\nu_e)|_{predicted}$$

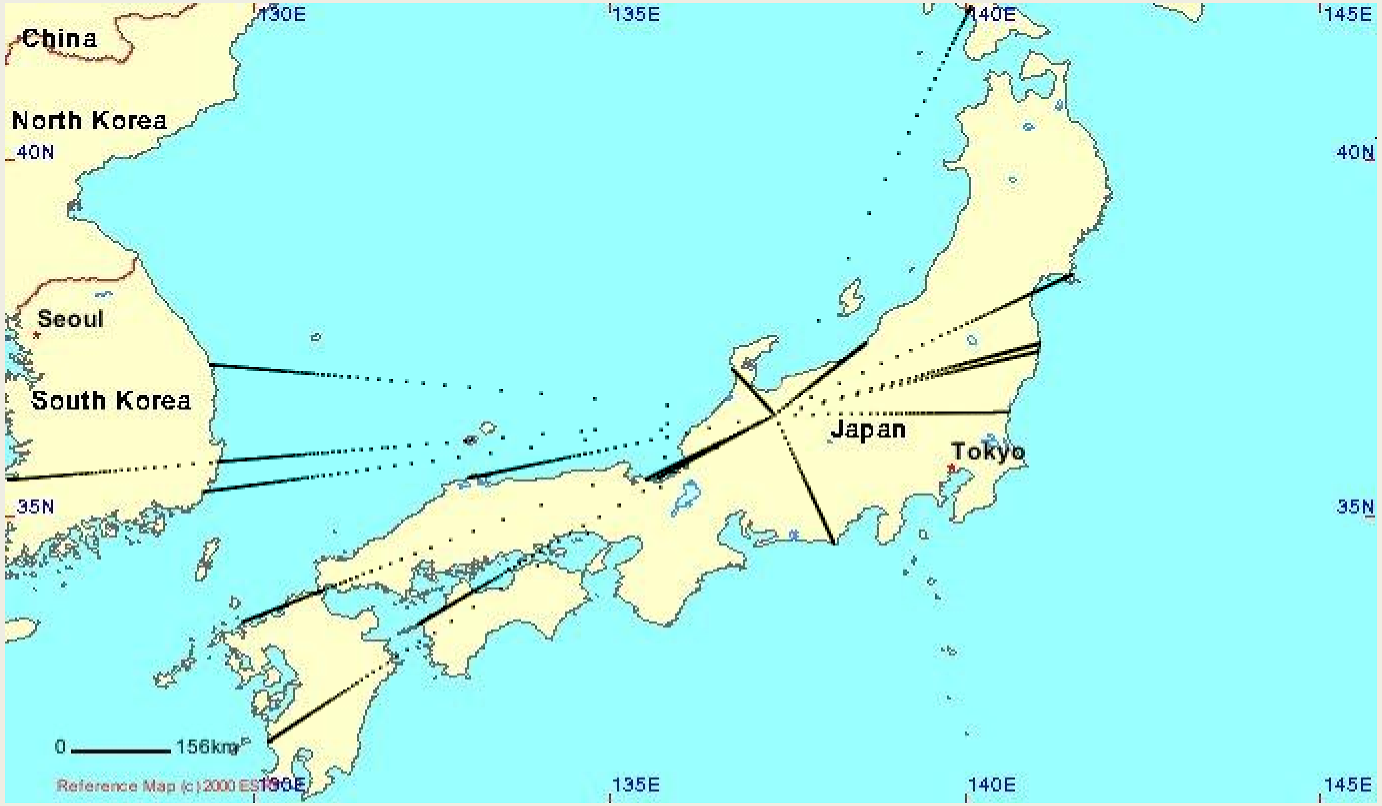
2015 Nobel Laureate: Arthur McDonald



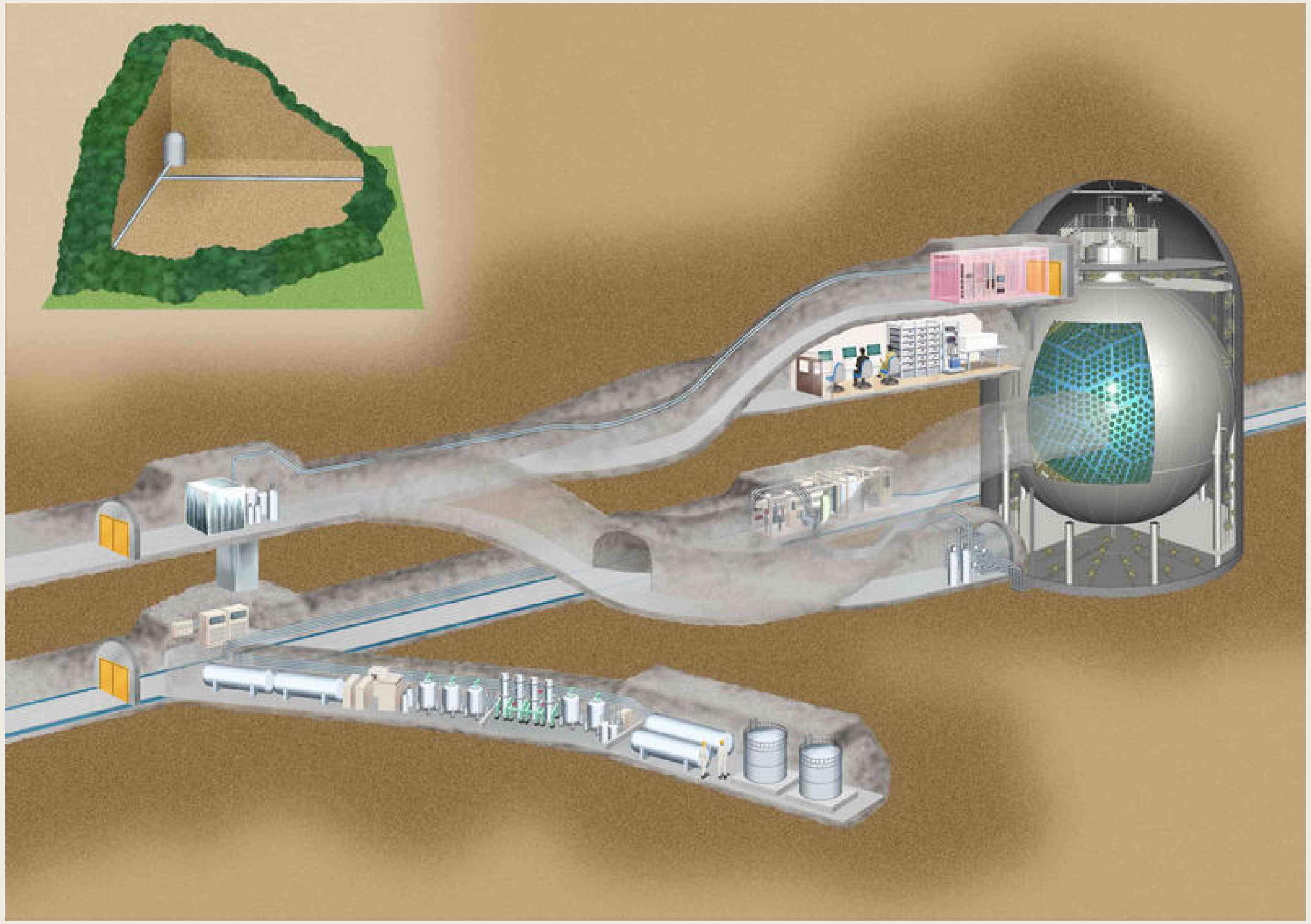
KamLAND

$\bar{\nu}_e \longrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$

$\bar{\nu}_e$ deficit

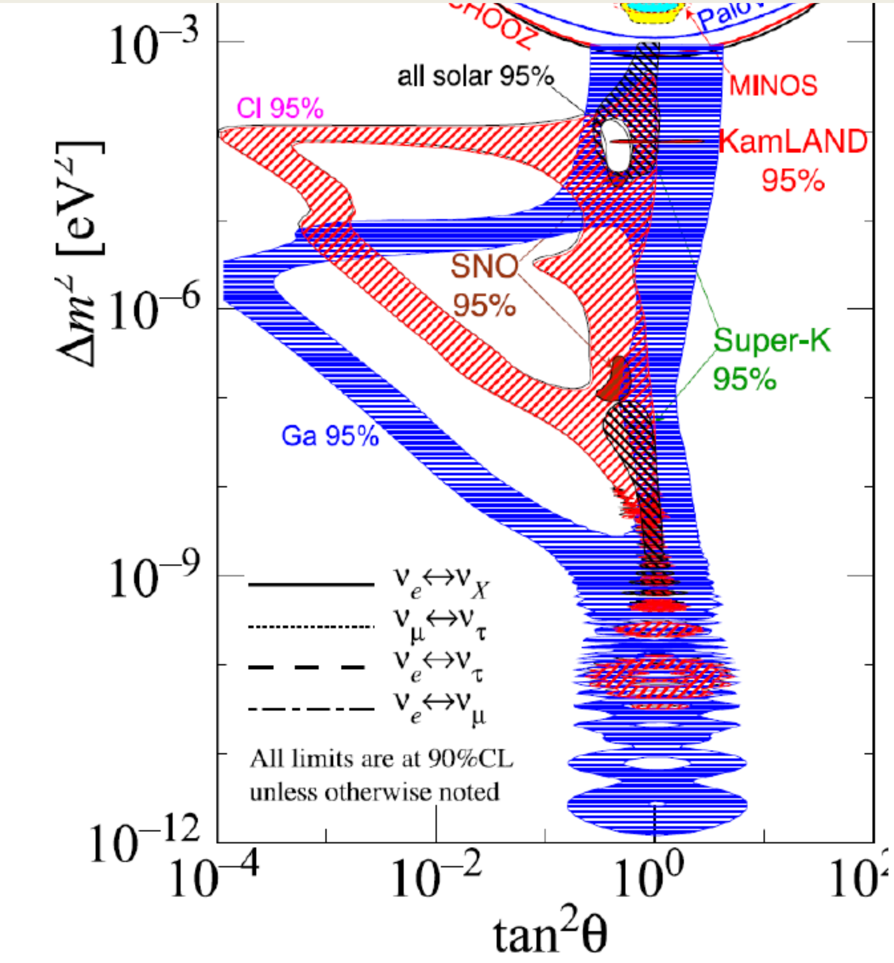


KamLAND

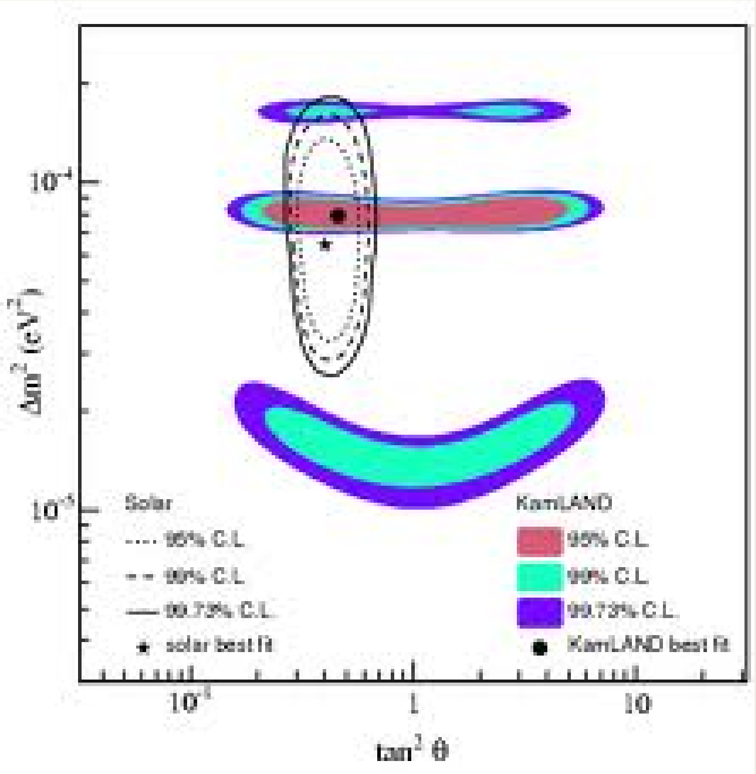


KamLAND massacre!

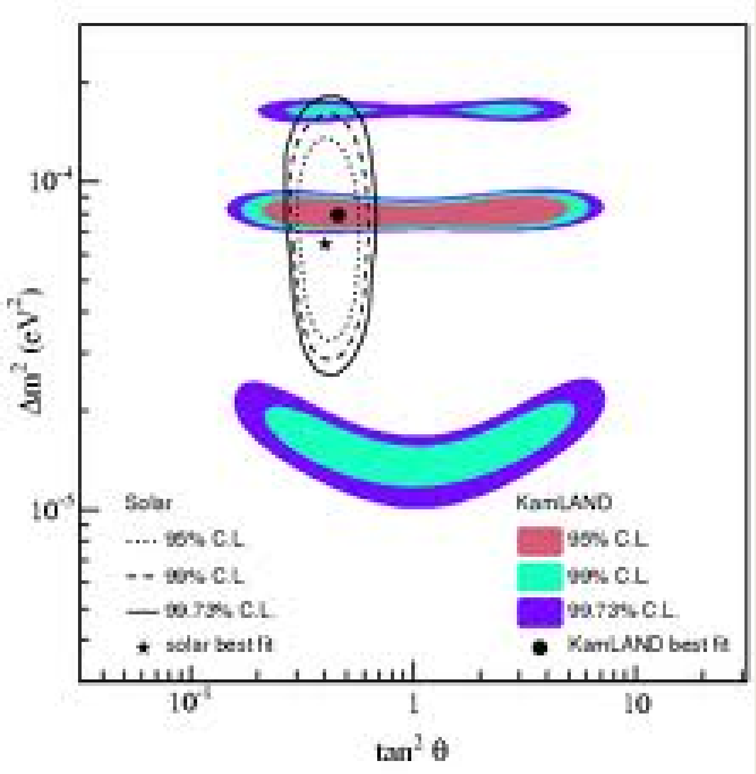
~~Magnetic transition moment solution~~



CLOWN Diagram



CLOWN Diagram



Maskara in turkish!

Neutrino mass parameters

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U_{PMNS} \cdot \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$m_1 \; m_2 \; m_3$$

Mixing parameters

$$U_{PMNS} = O_{23} O_{13} O_{12} \Phi$$

$$O_{23} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix}$$

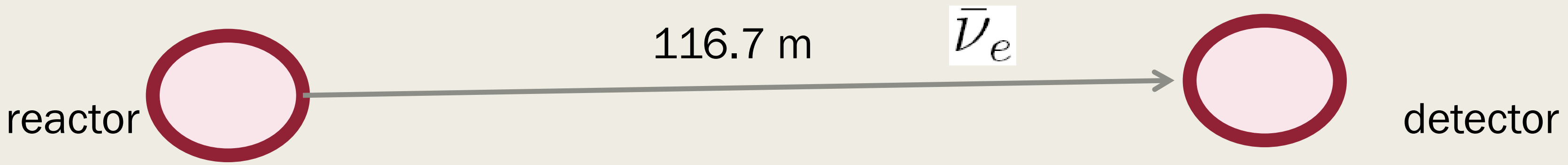
$$O_{13} = \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{bmatrix}$$

$$\Phi = \mathrm{Diag}[e^{i\phi_1}, e^{i\phi_2}, e^{i\phi_3}]$$

$$O_{12} = \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Are ϕ_i observable?

CHOOZ experiment



$$V_{CC}L,\ \frac{\Delta m^2_{21}L}{E} \ll \frac{\Delta m^2_{31}L}{E} \sim 1$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31}L}{4E}$$

Observation: $P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1$ $\Rightarrow$ $\theta_{13} < 10^\circ$

Solar and KamLAND data

- $\theta_{12},\ m_2^2 - m_1^2$

$$|\nu_e\rangle = c_{12}c_{13}|\nu_1\rangle + s_{12}c_{13}|\nu_2\rangle + s_{13}e^{-i\delta}|\nu_3\rangle$$

$$\Downarrow$$

$$|\nu_e\rangle = c_{12}|\nu_1\rangle + s_{12}|\nu_2\rangle$$

Long baseline and atmospheric neutrino experiments

- K2K, MINOS, CERN to Gran Sasso, T2K+ atmospheric neutrinos

⇓

Δm^2_{31} θ_{23}

- With more precise data, two neutrino approximation is no good anymore.

- Global analysis became popular in late years first decade of 21^{st} century.
- Some neutrino physicists were first skeptical but .....

Global analysis in 2011

$$0.05 < \sin^2 2\theta_{13} < 0.10$$

Schwetz et al., New J phys 13 (2011)

Fogli et al., PRD 84 (2011) 53007

Double CHOOZ

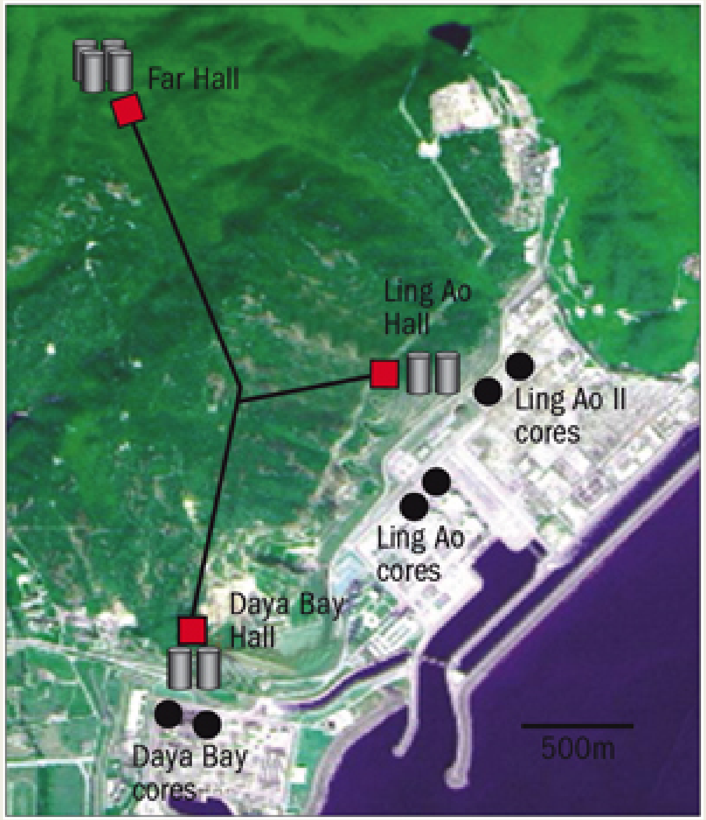
Recent Double CHOOZ results

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

Abe, Double CHOOZ collaboration, (2011)

~~No oscillation~~ Ruled out at $94.6\ \%\ \mathrm{C.L.}$

Daya Bay


Far Hall
Ling Ao
Hall
Ling Ao II
cores
Ling Ao
cores
Daya Bay
Hall
Daya Bay
cores
500m

Daya Bay

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

Daya Bay collaboration, PRL 108 (2012) 171803

a significance of 5.2 standard deviations.

Daya Bay

- Yifang Wang

elusives
neutrinos, dark matter & dark energy physics

2016 Breakthrough prize

SNO
KamLAND
Daya Bay
Super-Kamiokande
K2K/T2K

Unknown parameters

$$\delta??$$

$$\mathrm{sgn}(m_3^2 - m_1^2)??$$

$$m_1??$$

Kinematics of Tritium beta decay

- Studying the energy spectrum of the electron in Tritium beta decay
- Mainz experiment : m<2.2 eV

$$^3\mathrm{H} \rightarrow ^3\mathrm{He} + \bar{\nu}_e + e$$

Bonn et al., NPPS 91 (2001) 273

Cosmological precision revolution

- 2003 WMAP results:
- WMAP+2 dF Galaxy Redshift Survey: m<0.23 eV at 95 % C.L.

WMAP collaboration, “first year Wilkinson Microwave Anisotropy Probe (WMAP) observations: determination of cosmological parameter, Astrophys J Supp 148 (2003) 175

PLANCK collaboration

Developments in last 5 years

- New observations and precision measurement

- Theoretical development

- Future plans

Global results

- www.nu-fit.org

Present:

Ivan Esteban
Concha Gonzalez Garcia
Michele Maltoni
Ivan Martinez Soler
Thomas Schwetz

Past:

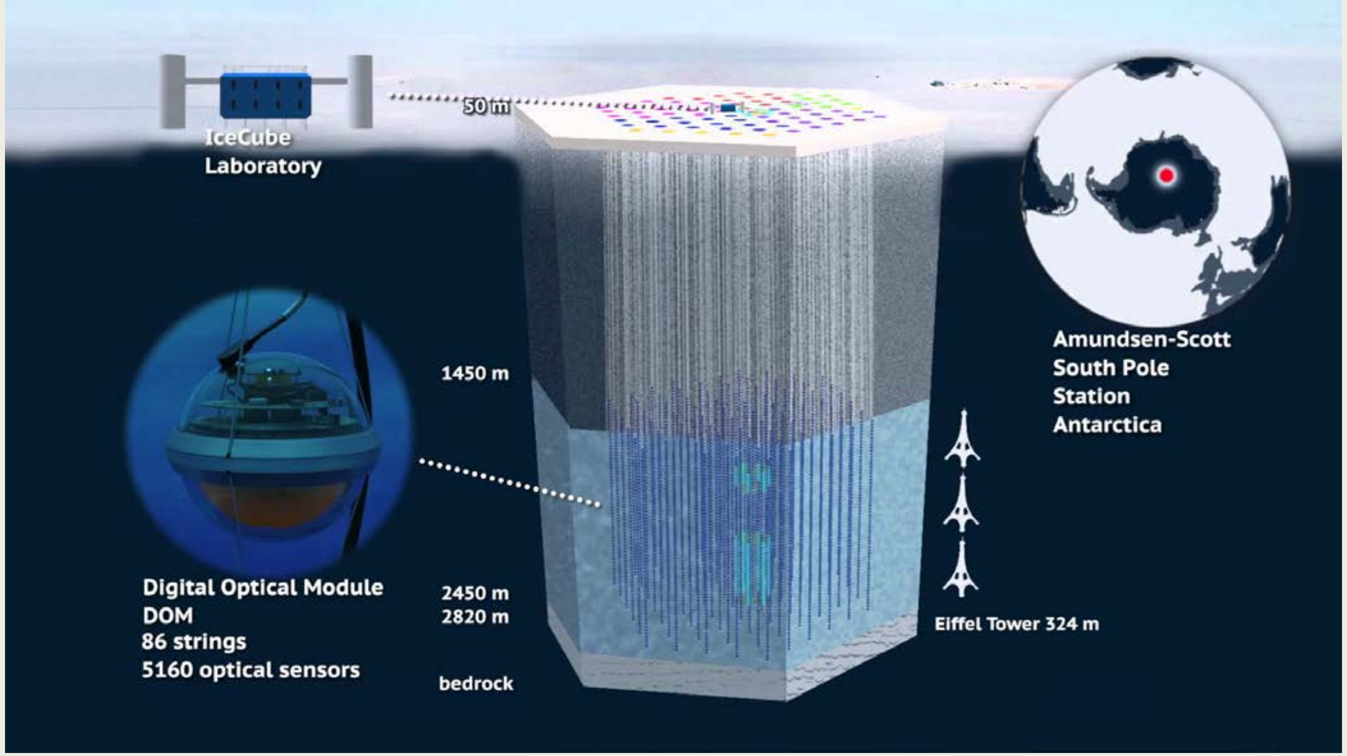
Johannes Bergström
Jordi Salvado

NuFIT is supported by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 674896 «ELUSIVES».

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

ICECUBE



50 m
IceCube
Laboratory
Amundsen-Scott
South Pole
Station
Antarctica
1450 m
Digital Optical Module
DOM
86 strings
5160 optical sensors
2450 m
2820 m
bedrock
Eiffel Tower 324 m

Our High hopes

- GRB produce both UHCR and lots of neutrinos
- We shall study the high energy neutrinos and derive information on neutrino properties.
- Neutrino flux from DM annihilations
- Many group around the world speculated on these, including our group.

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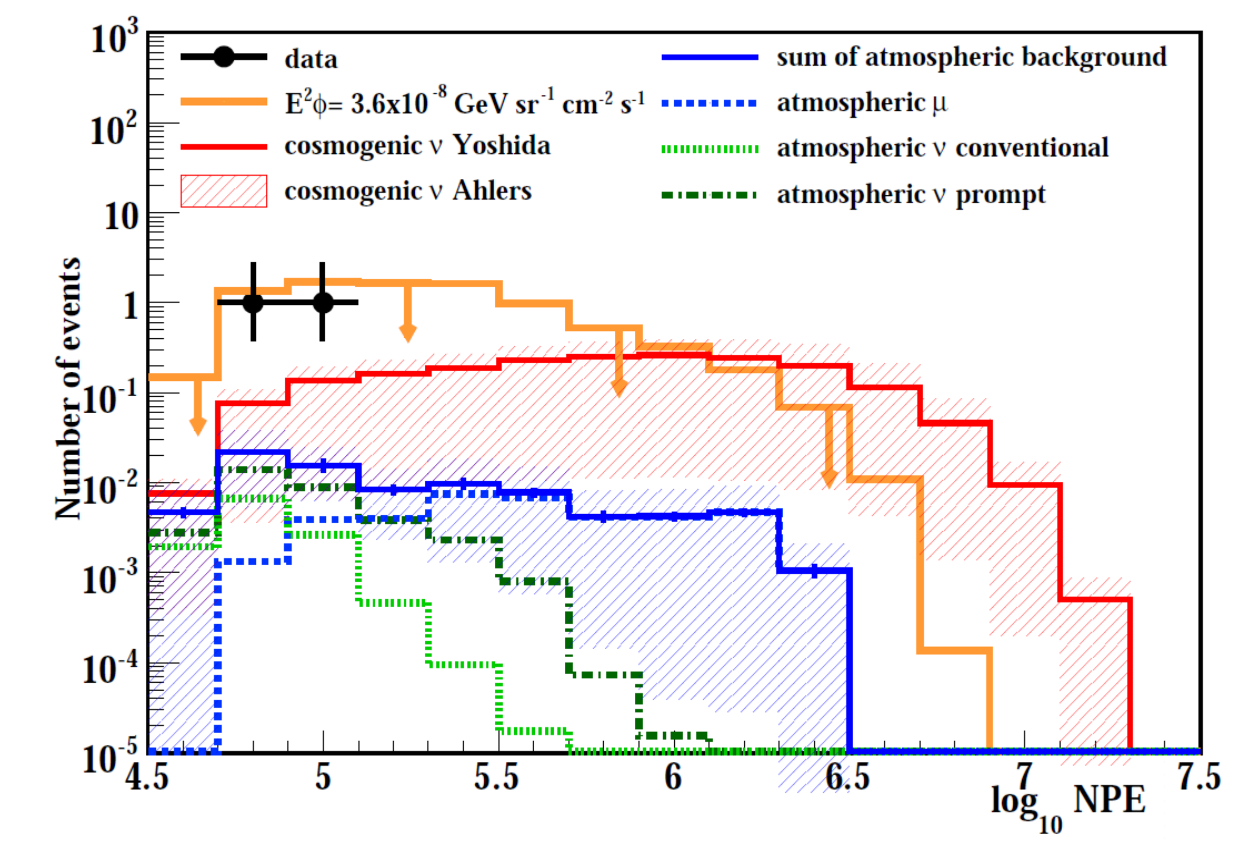
Y.F. and Smirnov, "Leptonic unitarity triangle and CP-violation," PRD 65 (2002); A. Esmaili and YF, NPB 821 (2009); A. Esmaili and YF, PRD 81 (2010); A. Esmaili and YF, JCAP 1104 (2011)

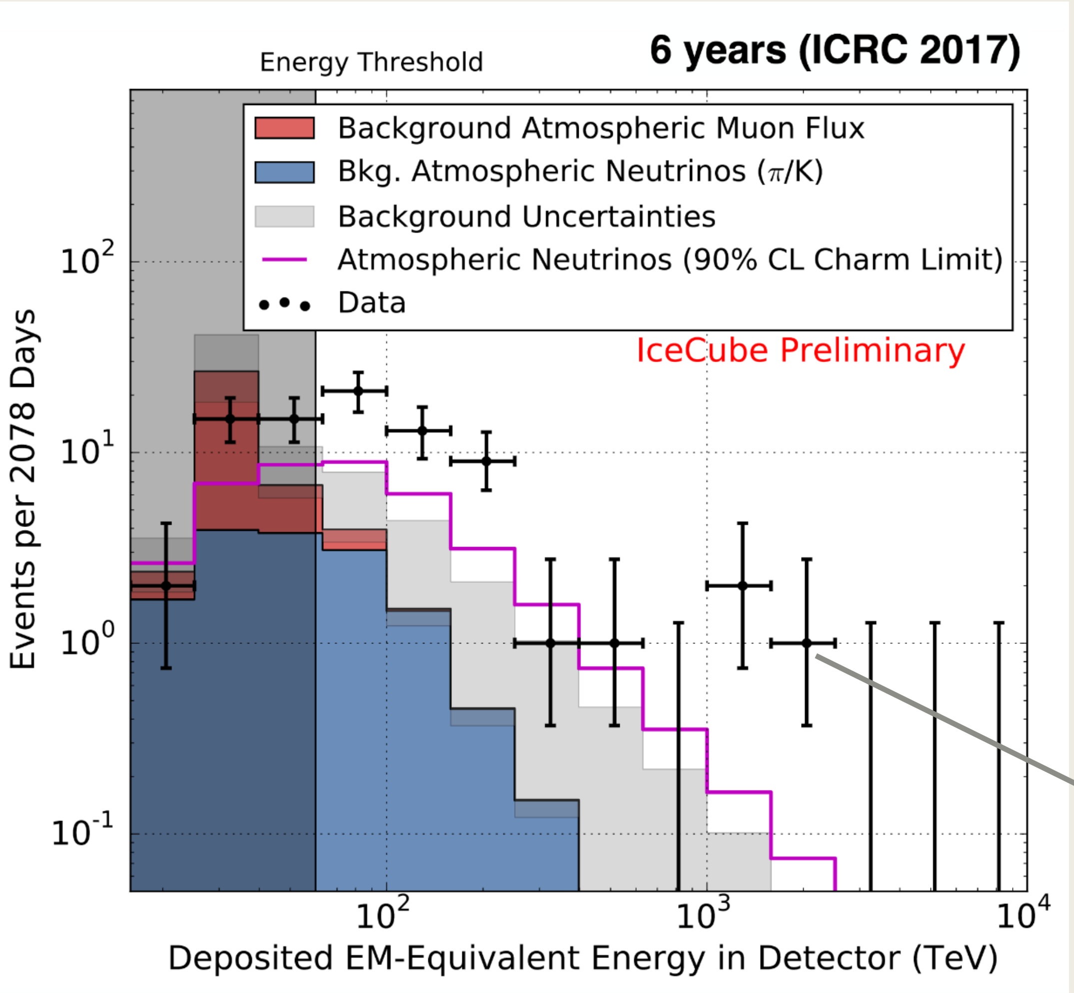
آرزو بر جوانان عیب نیست!

First observation of PeV energy neutrinos with ICECUBE



ICECUBE, PRL 111 (2013)

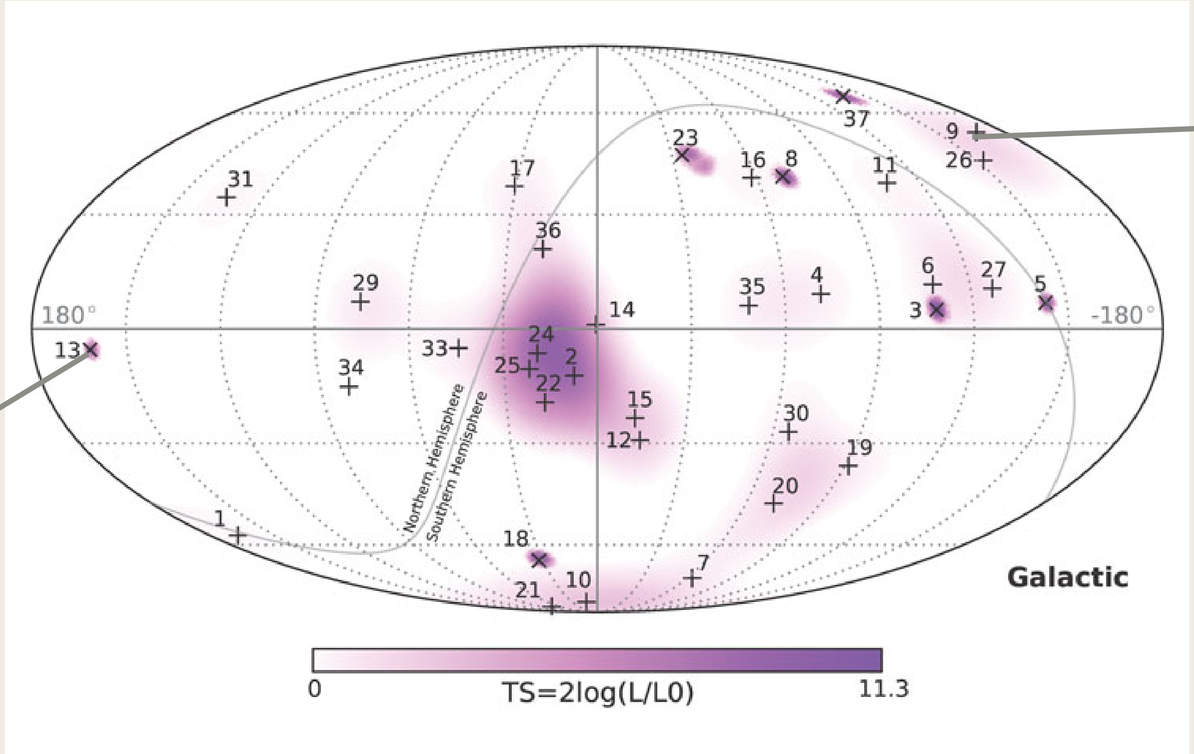
1.04±0.16 PeV
1.14±0.17 PeV



82 HESE tracks+showers

HESE= High Energy Starting Events

Third event with energy of 2 PeV



Shower from NC and Electron neutrino

Muon track

Information

- Energy spectrum
- Arrival direction and clustering
- Flavor composition

Information

- Energy spectrum
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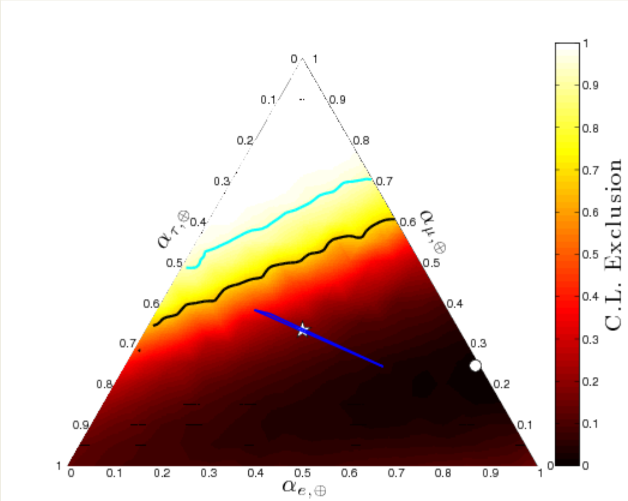


What is the source?

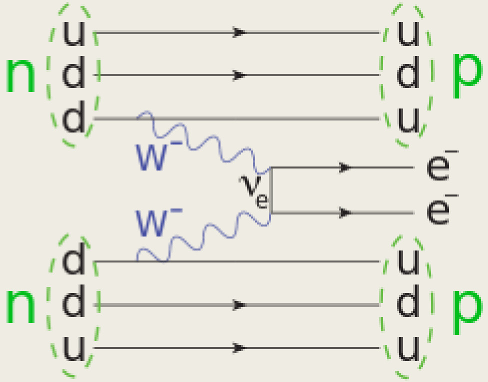
- GRB (disfavored because of not seeing accompanying GeV-TeV gamma rays)
- AGN (disfavored because of not seeing accompanying GeV-TeV gamma rays)
- Dark matter decay (disfavored because of energy spectrum shape)
- More recent suggestions: Tidal disruption of star by supermassive black hole

Lunardini and Winter, PRD 95 (2017)

- Origin is still an open question

Are neutrinos Majorana or Dirac?

- Is lepton number violated in nature?



- Various experiments around the world

Unknown parameters

$m_1??$ → KATRIN experiment in Karlsluhe

$\delta??$

$\text{sgn}(m_3^2 - m_1^2)??$

Long baseline experiments:
Current: T2K, Nova
Future: DUNE, T2HK, T2HKK

Are we sure we are in 3 nu paradigm?

- Are there new neutrinos?

- Do neutrinos have non-standard interaction?

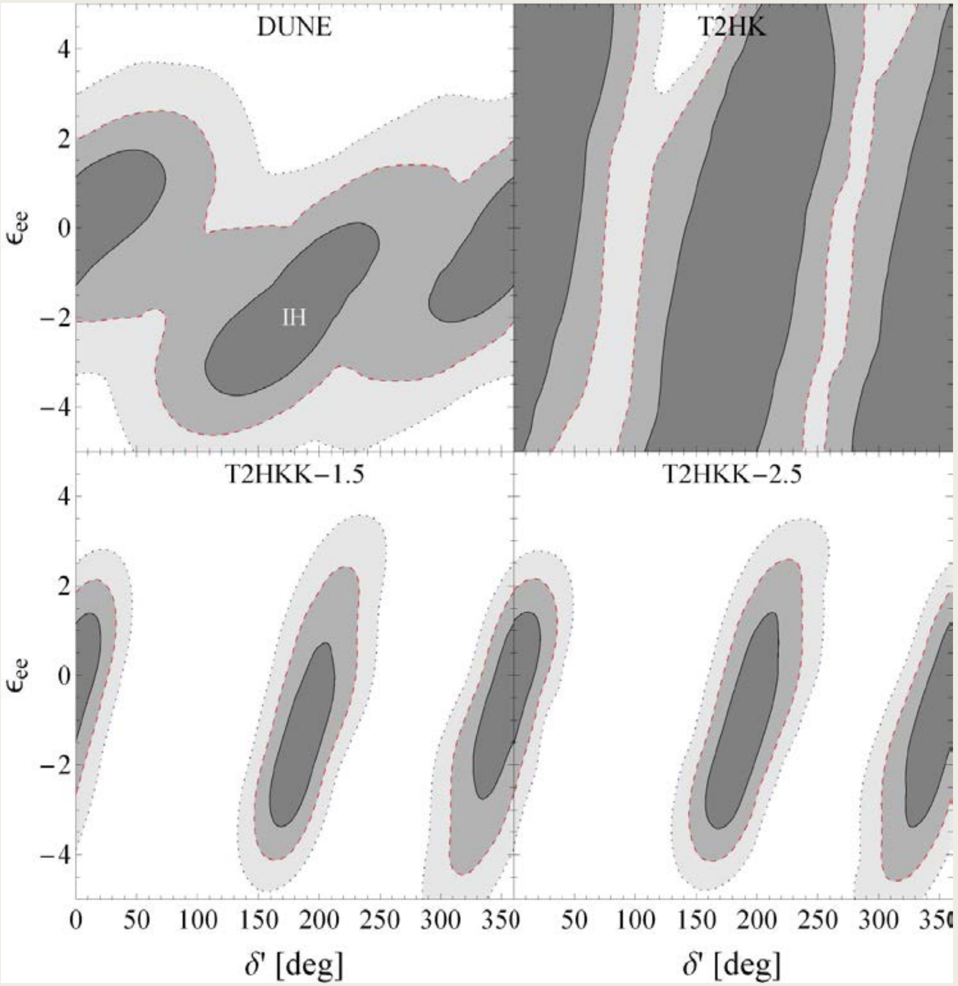
Neutral current NSI

$$\mathcal{L}_{\text{NSI}} = 2\sqrt{2} G_F \epsilon_{\alpha\beta}^{fC} \left[\overline{\nu}_\alpha \gamma^\rho P_L \nu_\beta\right] \left[\bar{f} \gamma_\rho P_C f\right]$$

$$H = \frac{1}{2E}\left[U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \delta m_{21}^2 & 0 \\ 0 & 0 & \delta m_{31}^2 \end{pmatrix} U^\dagger + V\right]$$

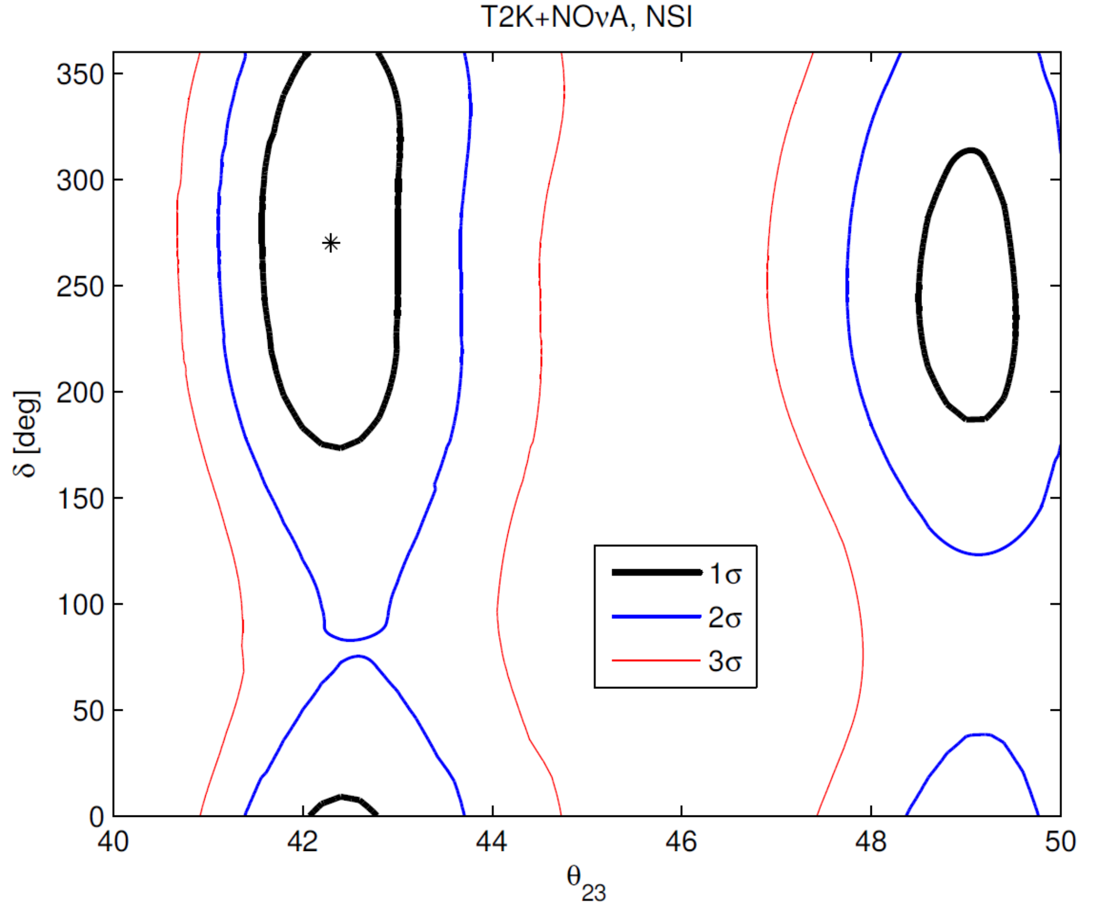
$$V = A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} e^{i\phi_{e\mu}} & \epsilon_{e\tau} e^{i\phi_{e\tau}} \\ \epsilon_{e\mu} e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau} e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau} e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}$$

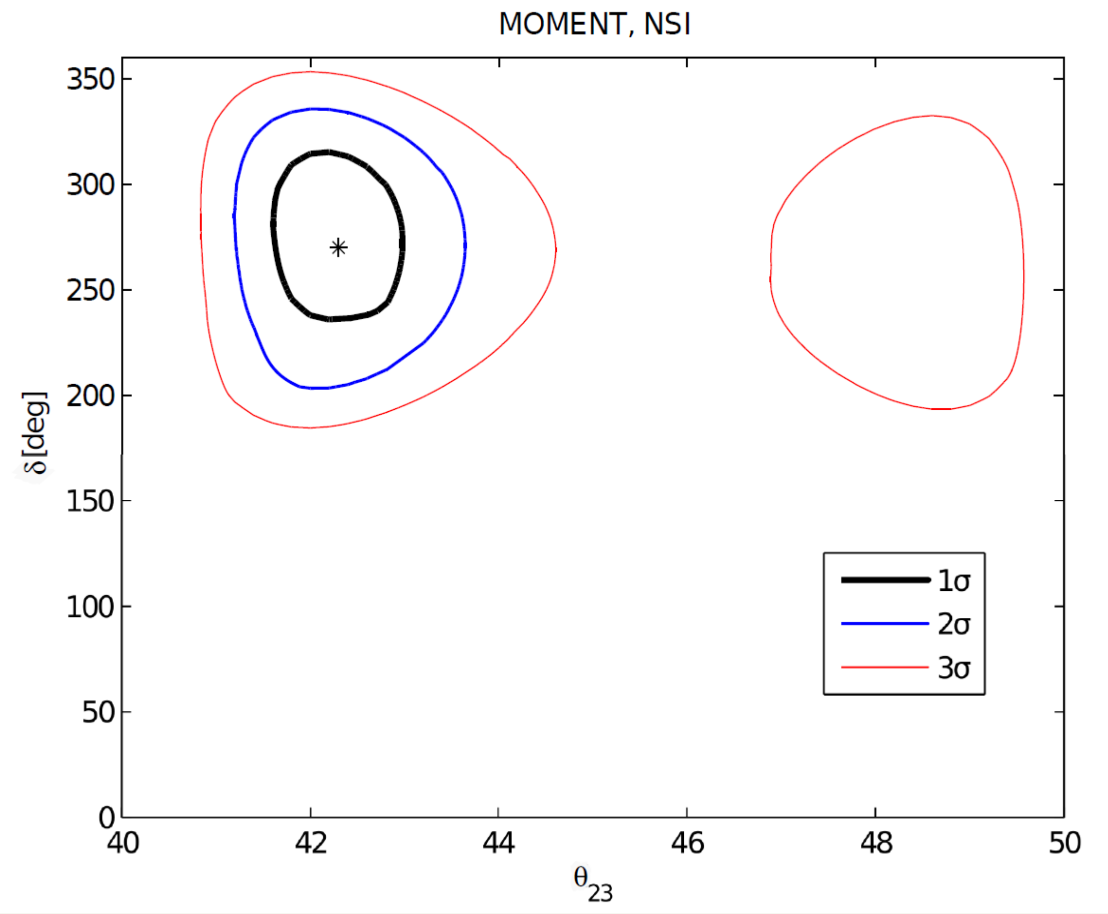
NSI of neutrino with matter field can induce degeneracy



Liao, Marfatia and Whisnant, JHEP 01 (2017) 071

How to solve degeneracies?





Bakhti and YF, JHEP 07 (2014) 064; JHEP 07 (2016) 109

Origin of large NSI

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F\epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu L\nu_\beta)(\bar{f}\gamma_\mu P\ f)$$

$$\epsilon \sim \left(\frac{g_X^2}{m_X^2}\right) G_F^{-1}$$

$m_X \gg 100\ \mathrm{GeV}$ ⇒ $\epsilon \ll 1$

Suggestion

- What if $m_X \sim 10 \text{ MeV}$

$$\epsilon \sim 1 \Rightarrow g_X \sim 10^{-4} - 10^{-5}$$

- Bounds can be avoided not because mass of the intermediate state is high

But because coupling is small!

YF, A model for large non-standard interactions leading to LMA-Dark solution,
Phys. Lett. B748 (2015) 311-315; YF and J Heeck PRD 94 (2016); YF and Shoemaker, JHEP 1607 (2016) 033
YF. and M Tortola, recent review

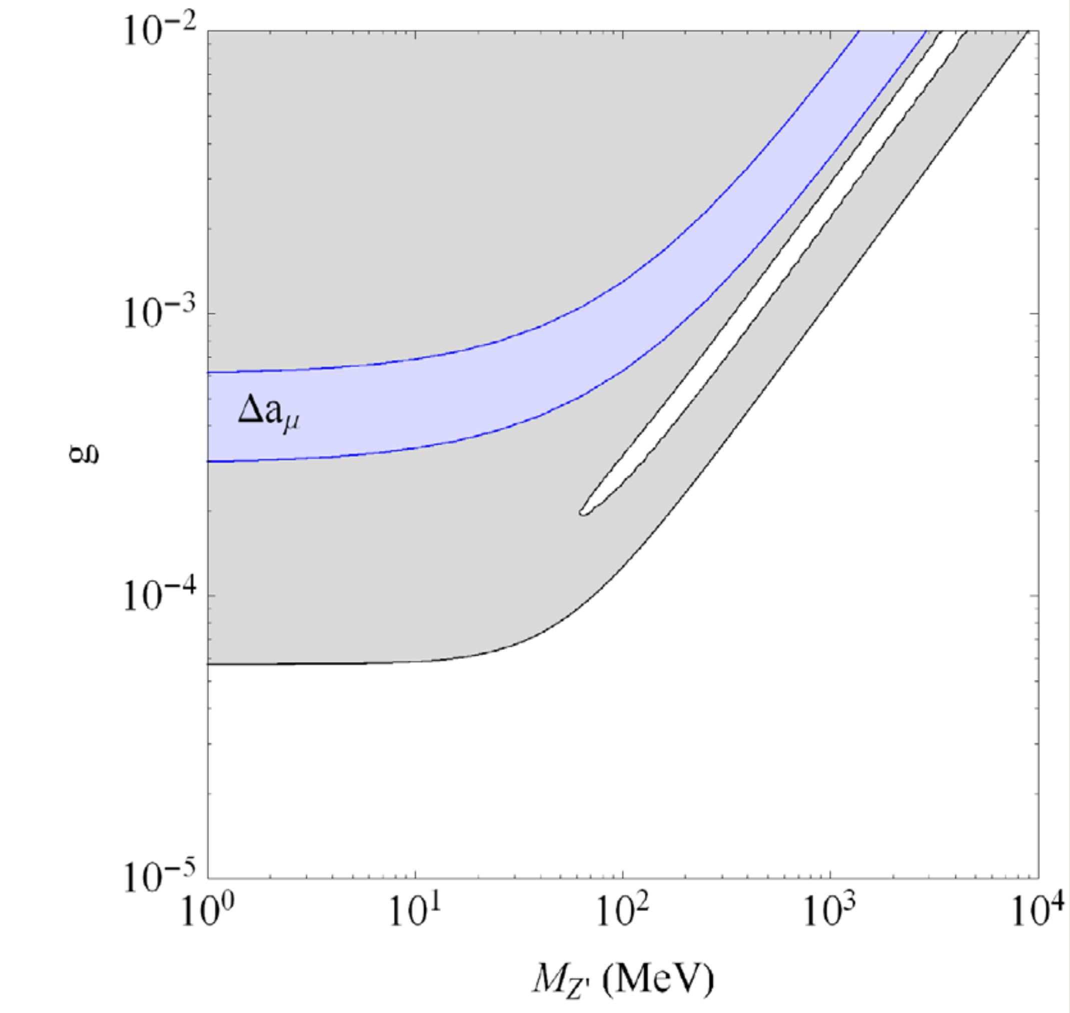
Test

- Solar neutrino flux scattering in next generation direct dark matter search experiments

- Low energy (MeV) neutrino flux scattering

COHERENT experiment

Akimov et al, “observation of coherent elastic Electron neutrino-nucleus scattering,” arXiv:1708.01294



Coloma et al, arXiv:1708.02899
Liao and Marfatia, arXiv:1708.0425

Mainstream topics

- Determination of unknown neutrino parameters: mass scale, mass ordering, CP
- Theoretically explaining smallness of neutrino masses: various seesaw mechanisms, loop level mass production
- Majorana vs Dirac (lepton number violation), neutrinoless double beta decay
- Relating CKM and PMNS and prediction of unknown neutrino parameters: mass scale, mass ordering, CP
- Discrete symmetries and neutrino parameters
- More neutrinos?
- Non-standard interaction?