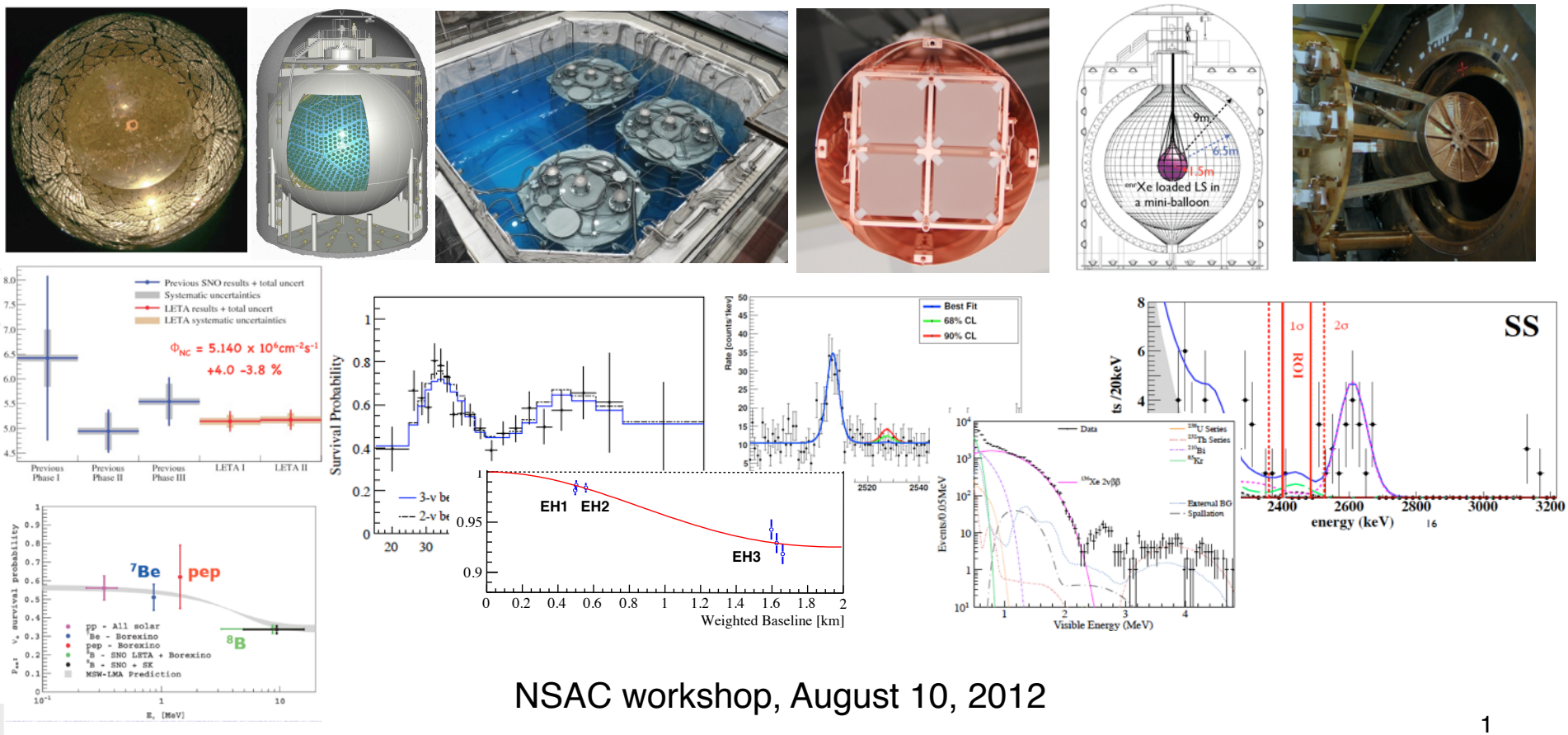
Neutrino Oscillations and Interactions

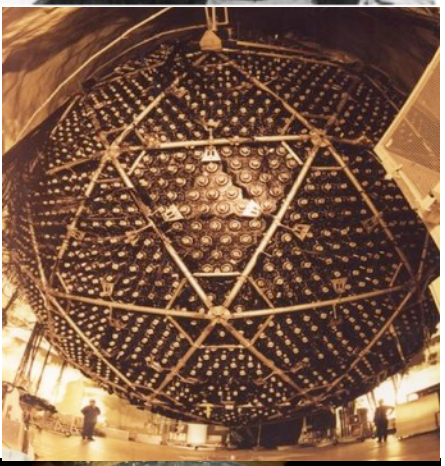
Karsten M. Heeger

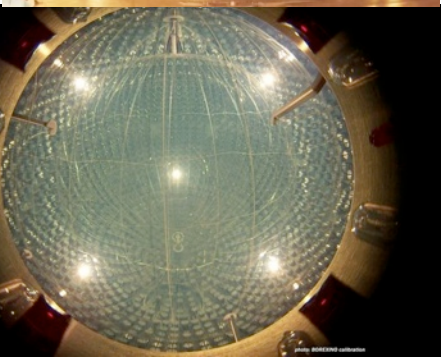
University of Wisconsin



NSAC workshop, August 10, 2012

Neutrino Discoveries - A Success Story





1968 Ray Davis detects 1/3 of expected solar neutrinos.
(Nobel prize in 2002)

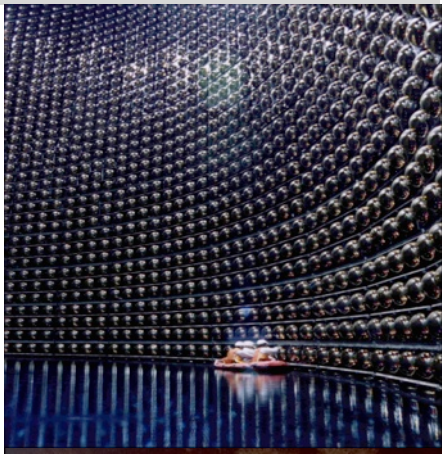
1998 SuperK reports evidence for oscillation of atmospheric neutrinos.

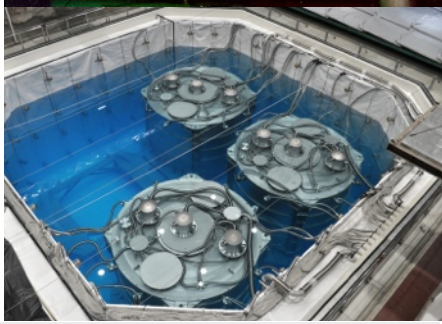
2001/2002 SNO finds evidence for solar ν_e flavor change.

2003 KamLAND discovers disappearance of reactor $\bar{\nu}_e$

2007 Borexino detection of ^{7}Be solar neutrinos

2012 Daya Bay, RENO, DC measure θ_{13}

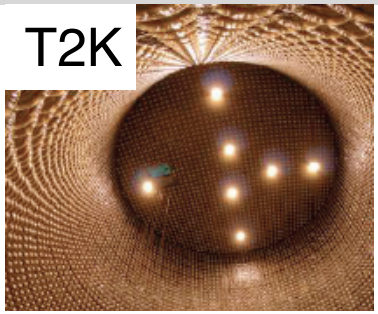




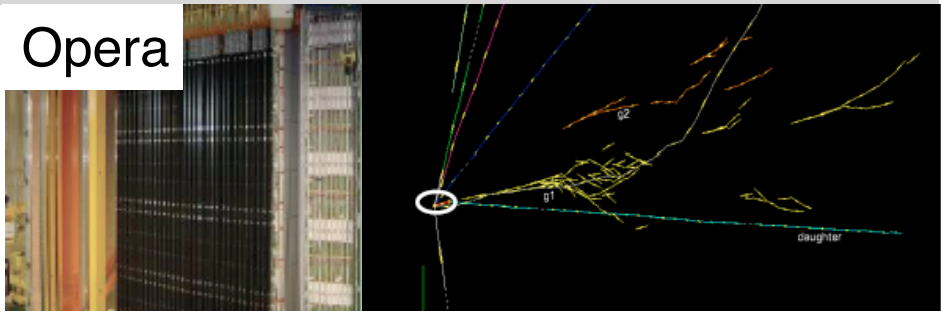
Accelerator Neutrino Oscillation Studies

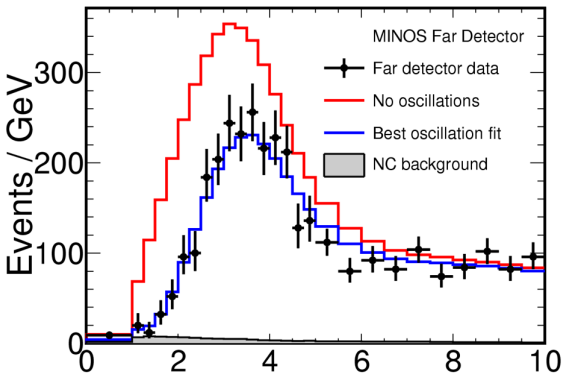
Minos

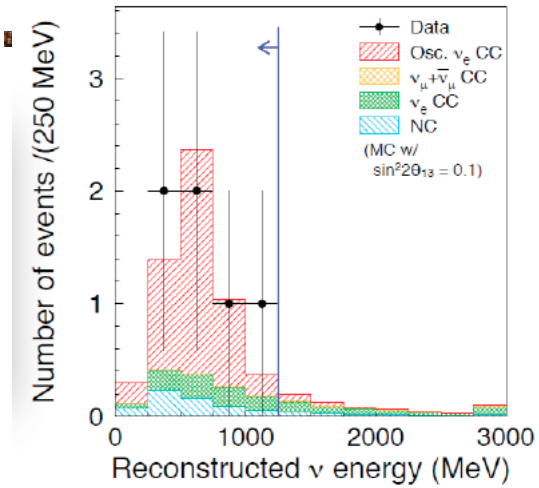
T2K



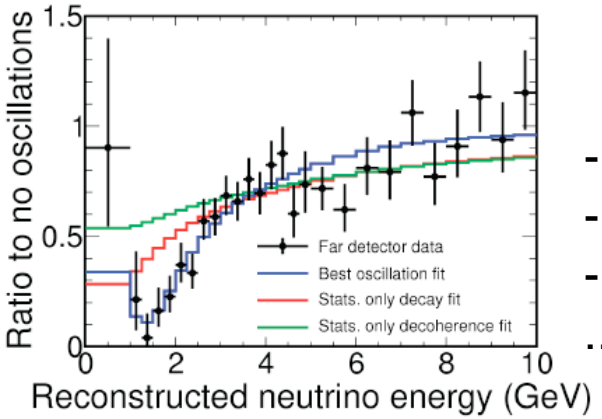
Opera





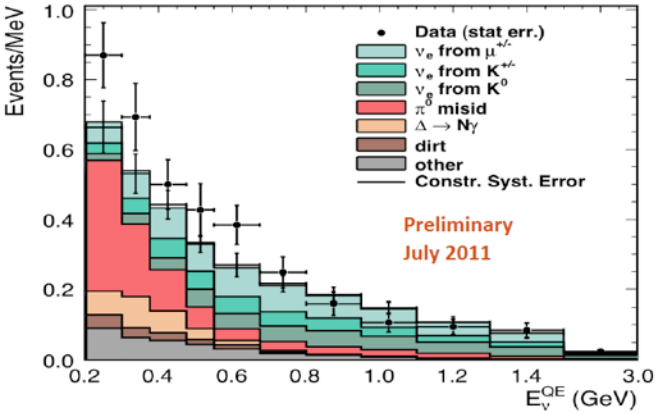


MiniBoone



- precision measurements
- indications of ν_e appearance
- anomalies

... + much more



Neutrino Oscillation

neutrino flavor change occurs if neutrinos have mass and leptons mix

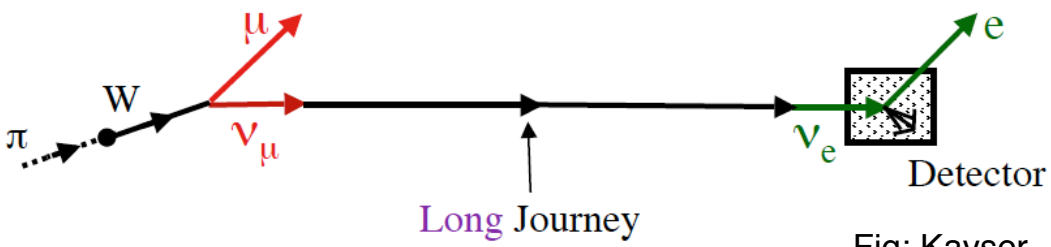
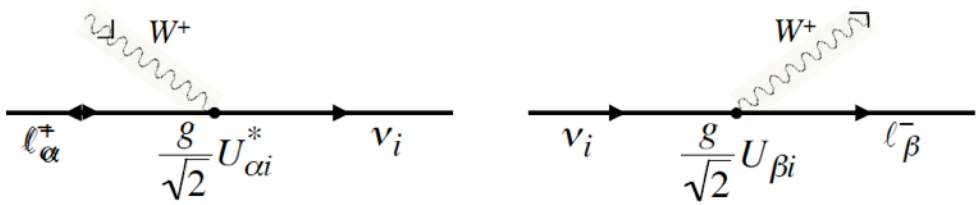


Fig: Kayser

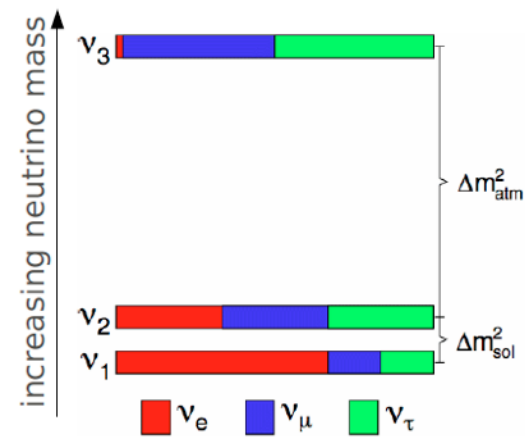
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

mixing matrix



$$U = \begin{array}{c} \\ e \\ \mu \\ \tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \end{array}$$

mass eigenstates



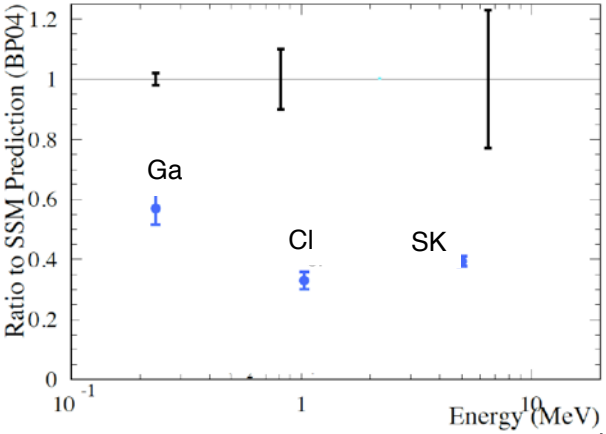
Experiments study flavor conversion as a function of energy, distance and determine mixing angle and mass splitting

2-neutrino case, vacuum

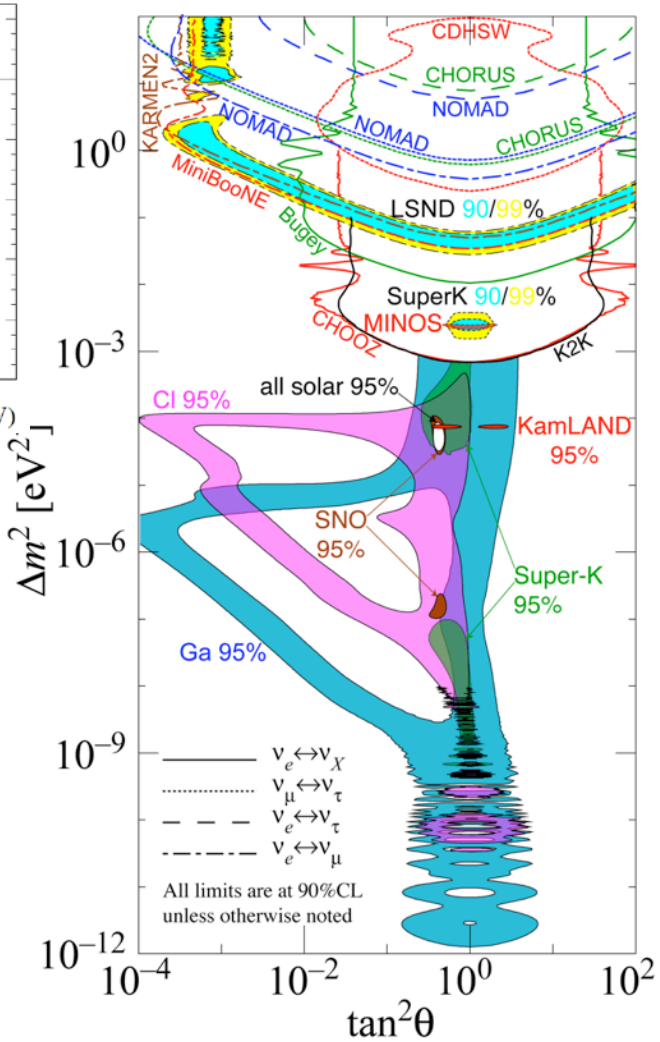
$$P_{i \to i} = \sin^2 2\theta \sin^2\left(1.27 \Delta m^2 \frac{L}{E}\right)$$

From Anomalies to Precision Oscillation Physics

solar neutrino problem

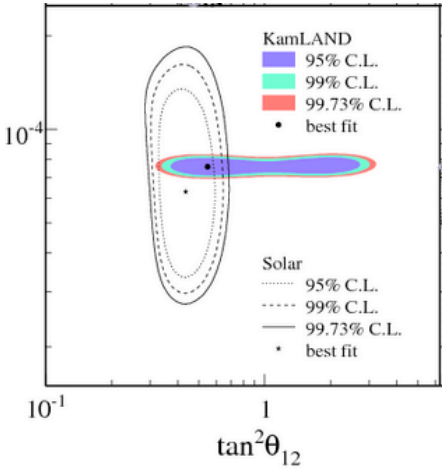


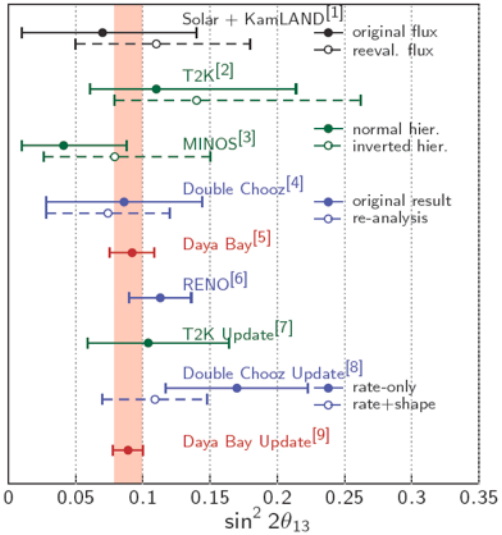
oscillation searches



http://hitoshi.berkeley.edu/neutrino

precision measurements

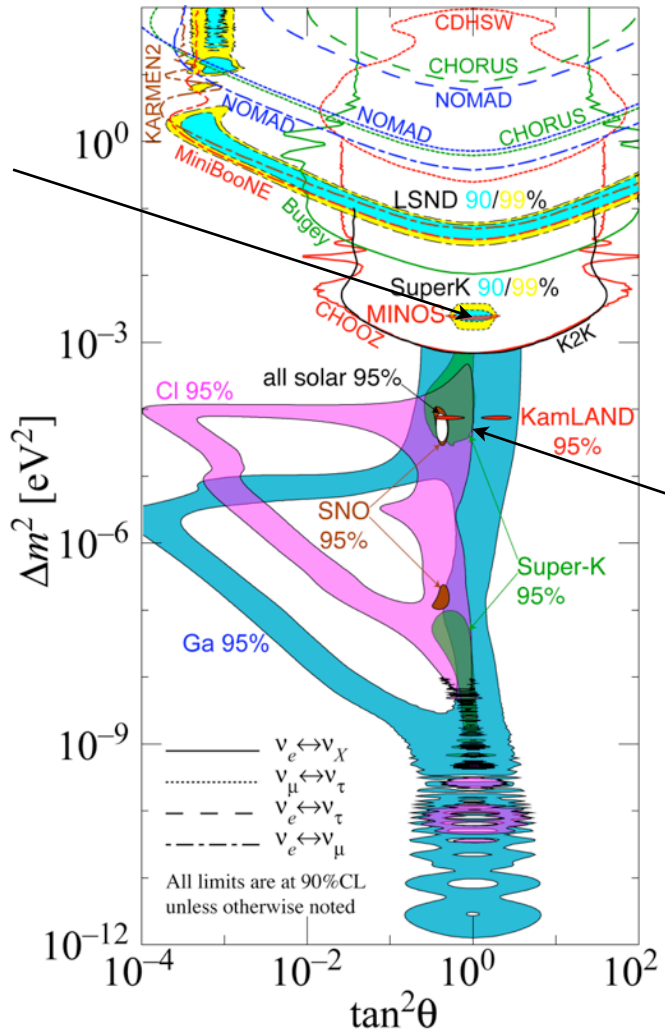




From 2-ν to 3-ν Oscillation Picture

atmospheric/beam neutrinos

θ_{23}, Δm^2_{23}



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solar/reactor neutrinos

θ_{12}, Δm^2_{12}

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

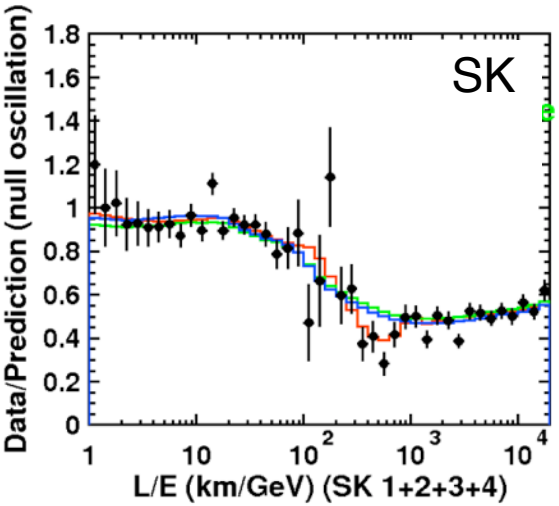
3-flavor picture needed

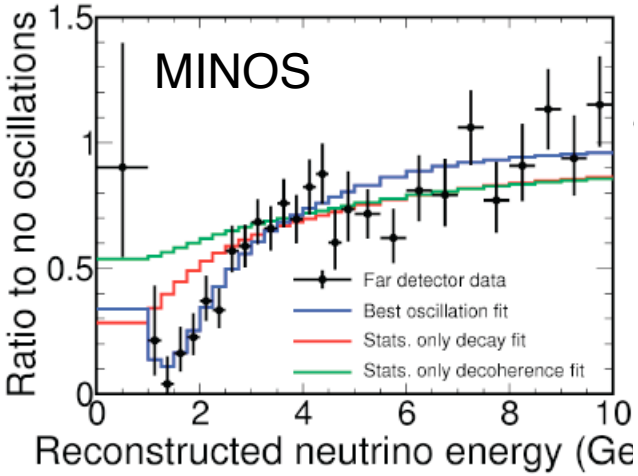
Neutrino Observations

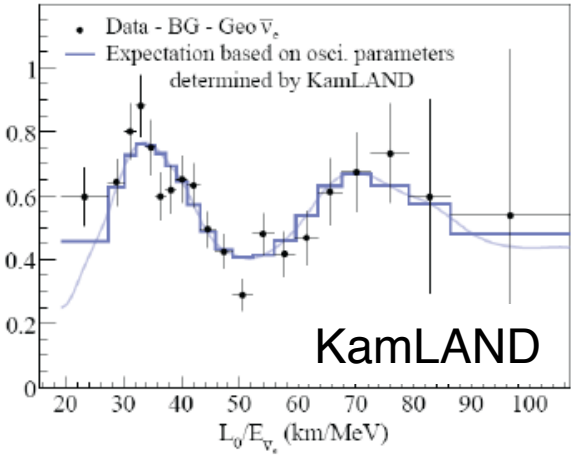
By 2012 we now have a suite of data ....

- atmospheric ν_μ and $\bar{\nu}_\mu$ disappear most likely to ν_τ (SK, MINOS)
- accelerator ν_μ and $\bar{\nu}_\mu$ disappear at L~250, 700 km (K2K, T2K, MINOS)
- some accelerator ν_μ appear as ν_μ at L~250, 700 km (T2K, MINOS)
- solar ν_e convert to ν_μ/ν_τ (Cl, Ga, SK, SNO, Borexino)
- reactor $\bar{\nu}_e$ disappear at L~200 km (KamLAND)
- reactor $\bar{\nu}_e$ disappear at L~1 km (DC, Daya Bay RENO)

Vacuum oscillation L/E pattern







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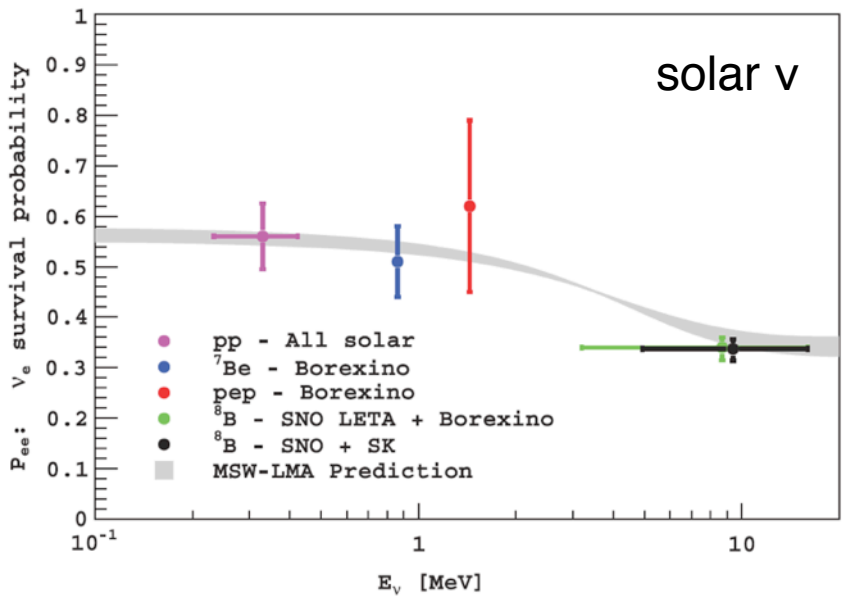
MSW conversion in Sun



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Determining Oscillation Parameters

	Dominant	Important
Solar Experiments	$\rightarrow \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\rightarrow \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	$\rightarrow \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\rightarrow \theta_{23}$	$\Delta m^2_{\rm atm}$, θ_{13} ,$\delta_{\rm cp}$
Accelerator LBL ν_μ Disapp (Minos)	$\rightarrow \Delta m^2_{\rm atm}$	θ_{23}
Accelerator LBL ν_e App (Minos,T2K)	$\rightarrow \delta_{\rm cp}$	θ_{13} , θ_{23}

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Neutrino Oscillation

Mixing Angles & Mass Splittings

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, K2K}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor and accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

$\theta_{23} = 40.4^\circ {}^{+0.8^\circ}_{-1.8^\circ}$ — maximal?

$\theta_{13} = 8.7^\circ \pm 0.45^\circ$ — not so small

$\theta_{12} = 32.4^\circ \pm 0.8^\circ$ — large, but not maximal!

All three neutrino mixing angles are now known!

Neutrino Oscillation

Mixing Angles & Mass Splittings

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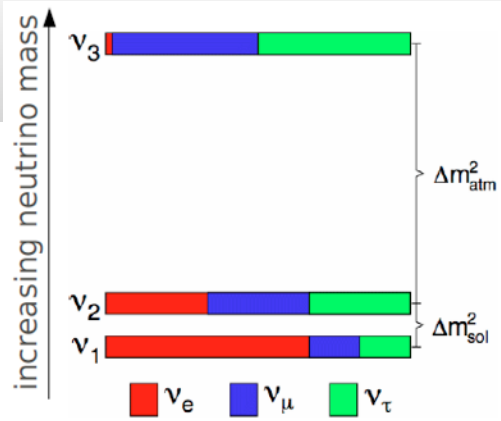
$$|U|_{\mathrm{LEP}(3\sigma)} = \begin{pmatrix} 0.795 \to 0.841 & 0.517 \to 0.584 & 0.141 \to 0.179 \\ 0.213 \to 0.543 & 0.425 \to 0.728 & 0.575 \to 0.802 \\ 0.213 \to 0.541 & 0.411 \to 0.720 & 0.576 \to 0.802 \end{pmatrix}$$

Neutrino Oscillation



Mixing Angles & Mass Splittings

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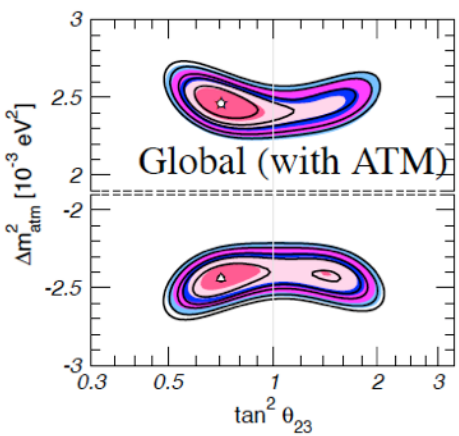
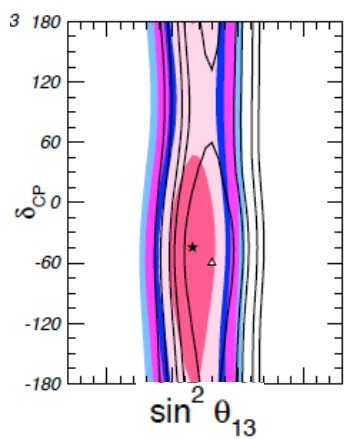
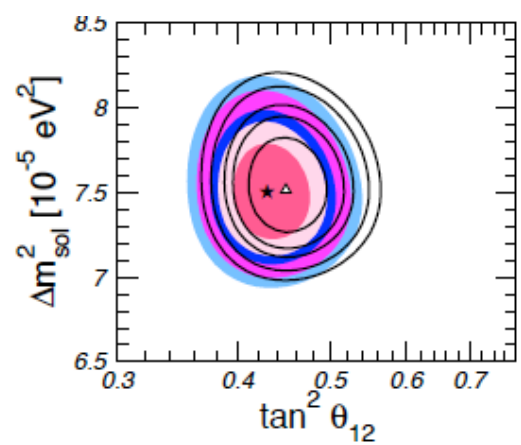
$$P_{i\to i} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{CI}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{}$$

atmospheric, K2K | reactor and accelerator | SNO, solar SK, KamLAND | $0\nu\beta\beta$







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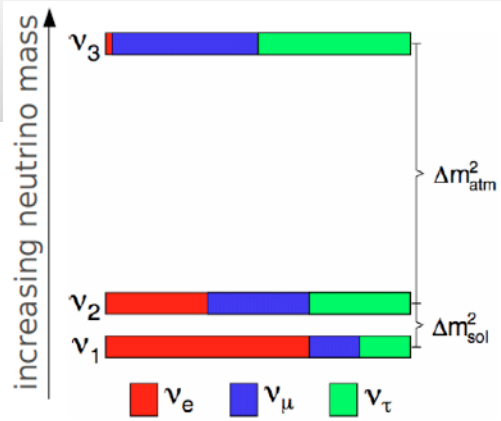
Neutrino Oscillation

Mixing Angles & Mass Splittings



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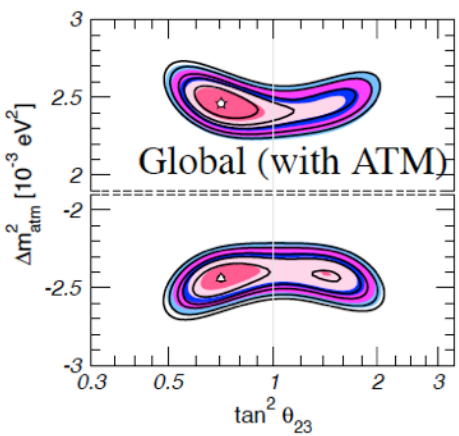
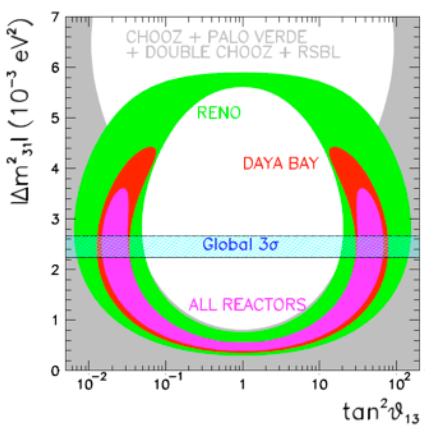
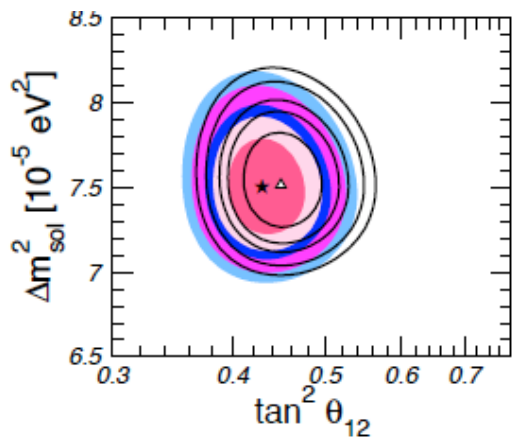
atmospheric, K2K | reactor and accelerator | SNO, solar SK, KamLAND | $0\nu\beta\beta$







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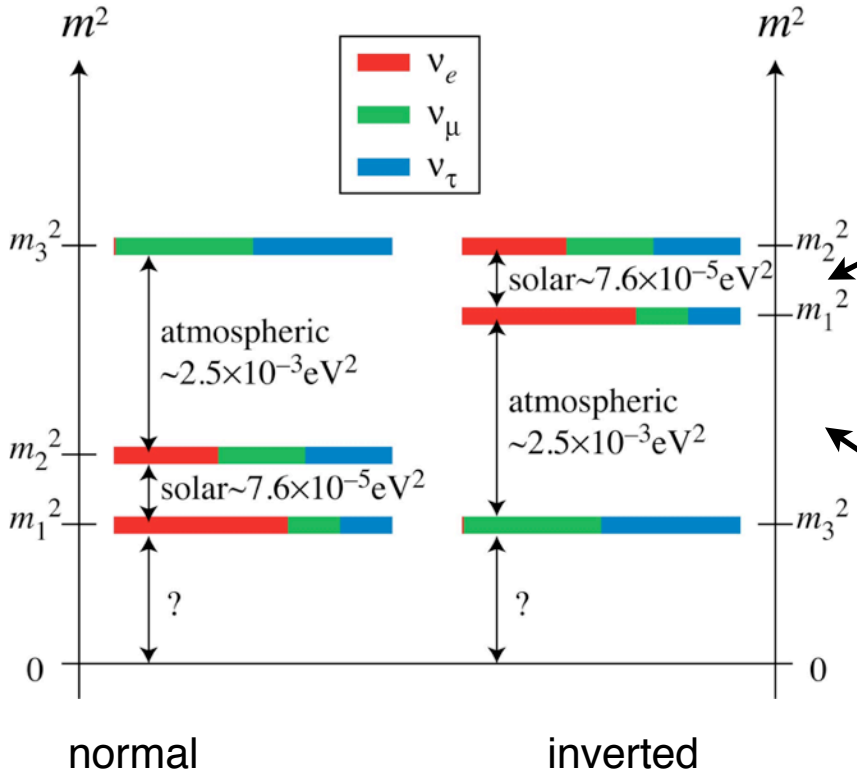
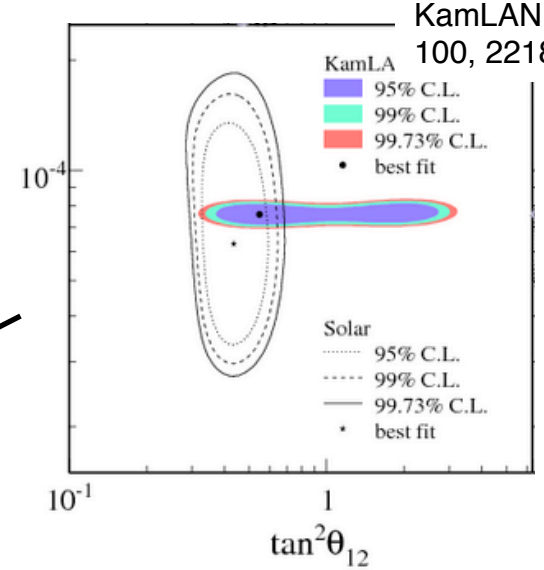
Neutrino Oscillation

Mass Splittings

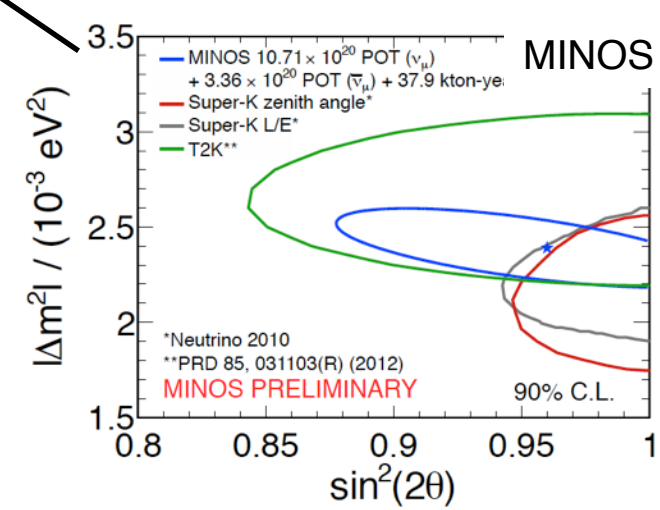


KamLAND, PRL. 100, 221803 (2008)



KamLAND has measured Δm_{12}^2 to ~2.8%

MINOS Nu2012



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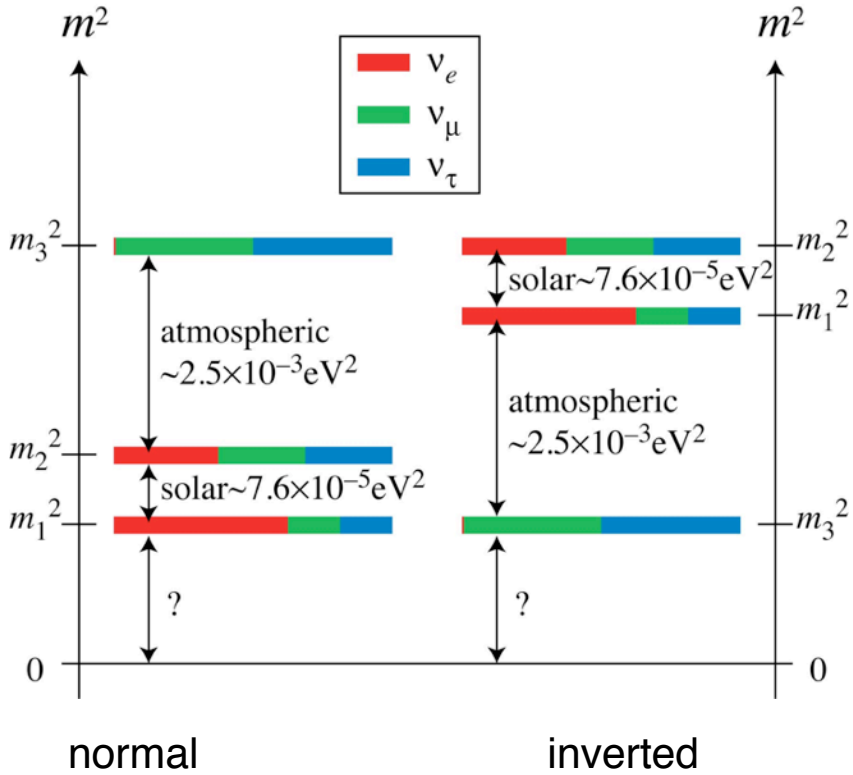


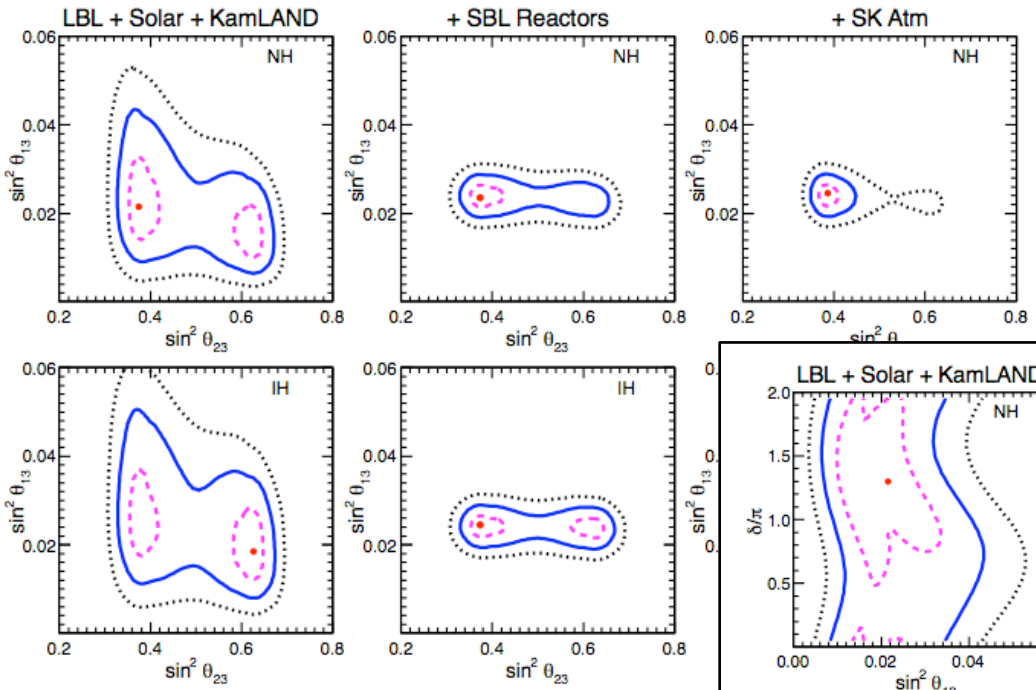
$$\Delta m^2_{21} = 7.5 \pm 0.19 \left(^{+0.59}_{-0.50}\right) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{31}(\mathrm{N}) = 2.45^{+0.067}_{-0.071} \left(^{+0.22}_{-0.20}\right) \times 10^{-3}\ \mathrm{eV}^2$$

$$|\Delta m^2_{32}|(\mathrm{I}) = 2.43 \pm 0.068 \left(^{+0.22}_{-0.20}\right) \times 10^{-3}\ \mathrm{eV}^2$$

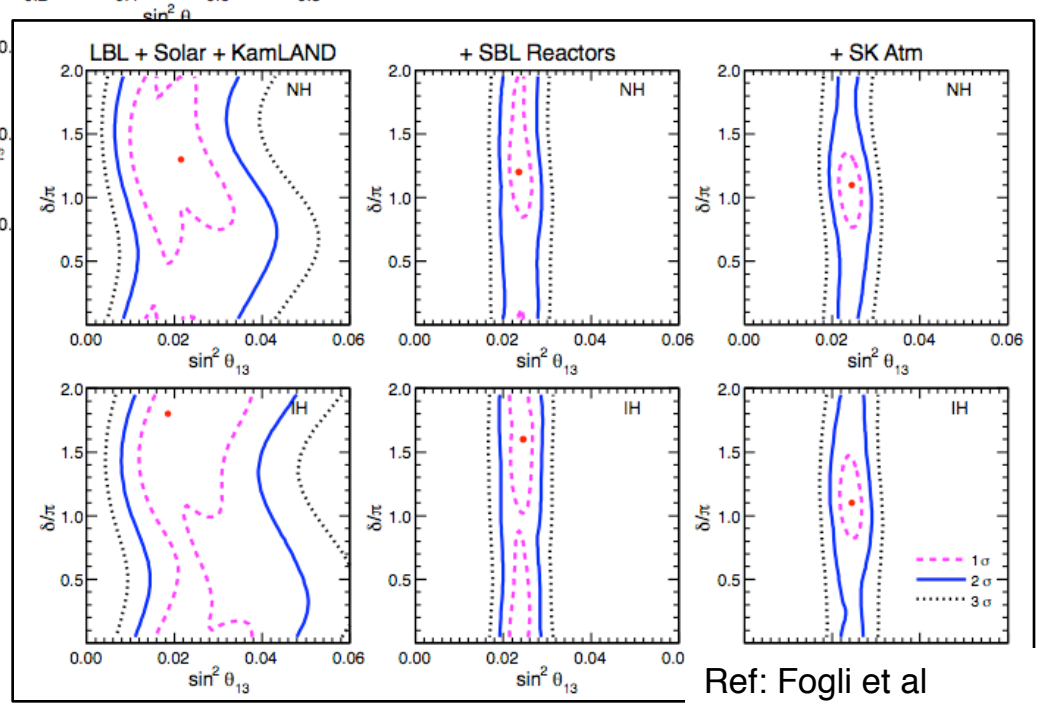
Neutrino Oscillation

3-ν Global Analyses in 2012



preference for θ_{23} in first octant, difficult to say much about hierarchy

most interesting question for global analyses: θ_{23} octant and δ_{CP}



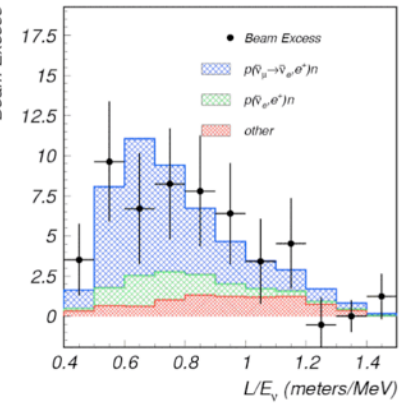
1σ preference for θ~π

enhances interference oscillation terms and gives extra electron appearance for atmospheric events O(GeV), part of SK electron excess

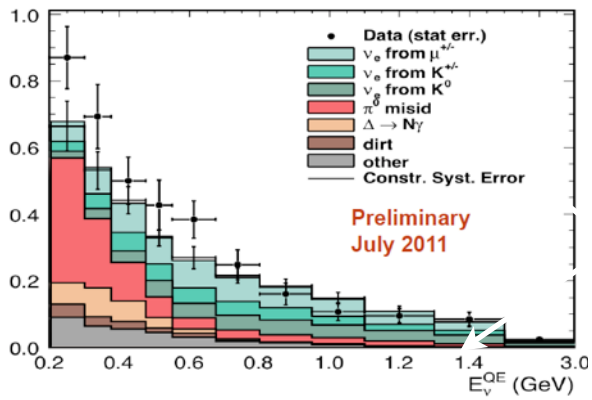
Ref: Fogli et al 1205.5254 and Nu2012

Neutrino Anomalies

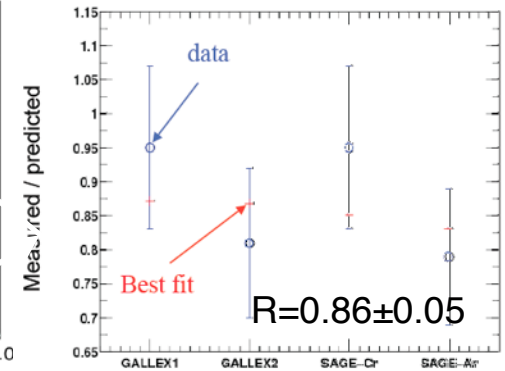
LSND



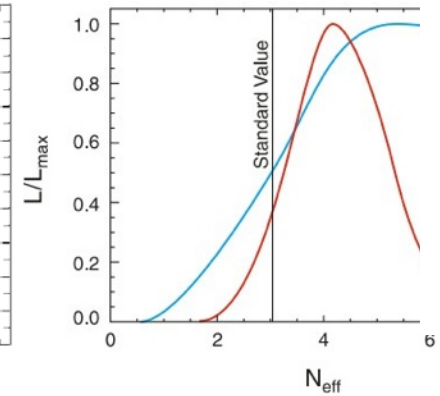
MiniBoone



Ga Source Exp



Cosmology (WMAP)



Anomalies in 3-ν interpretation of global neutrino oscillation data

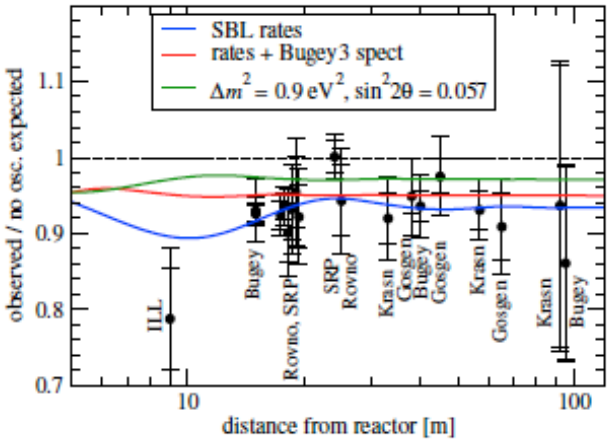
LSND ($\overline{\nu}_e$ appearance)
MiniBoone ($\overline{\nu}_e$ appearance)
Ga anomaly
N_{eff} in cosmology
Short-baseline reactor anomaly ($\overline{\nu}_e$ disappearance)

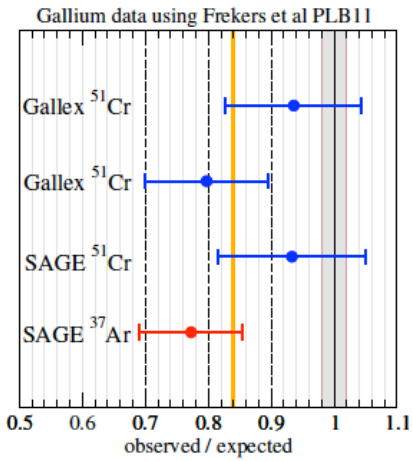
if new oscillation signal, requires $\Delta m^2 \sim O(1eV^2)$ and $\sin^2 2\theta > 10^{-3}$

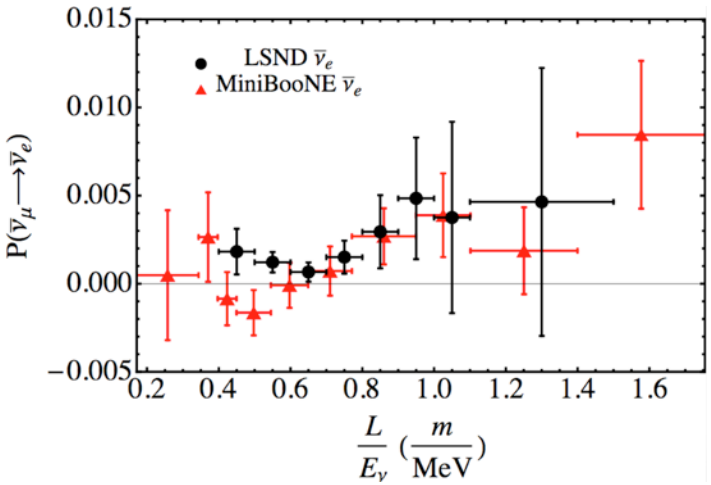
systematics or experimental effects?
➔ need to test each experimental effect

Beyond 3ν - Sterile Neutrinos?

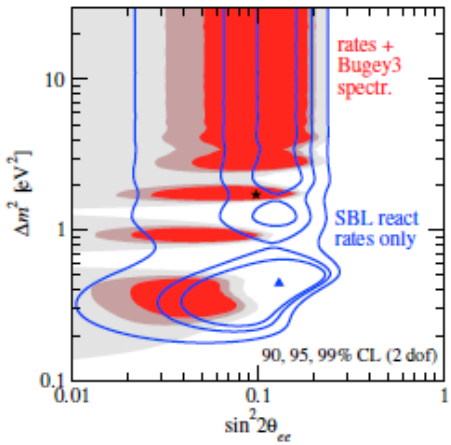
Anomalies

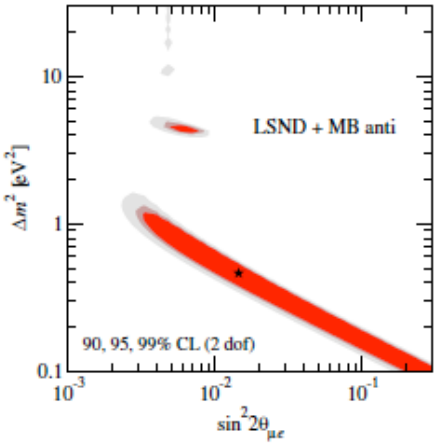


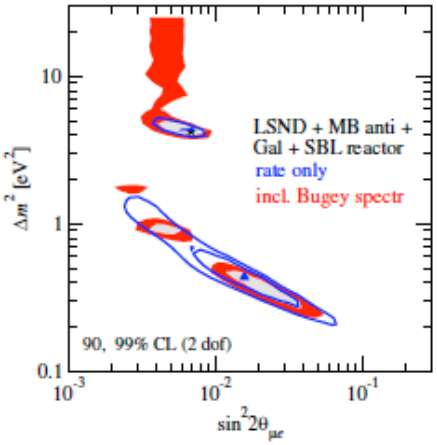




Are $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_e$ consistent?







$\nu_e \to \nu_e$ disappearance $\sin^2 2\theta_{ee}$
$\nu_\mu \to \nu_\mu$ disappearance $\sin^2 2\theta_{\mu\mu}$
$\nu_\mu \to \nu_e$ appearance $\sin^2 2\theta_{\mu e}$

strong tension if all three are combined, tension also in 3+2 fit

Neutrino Mass

Mass Measurements

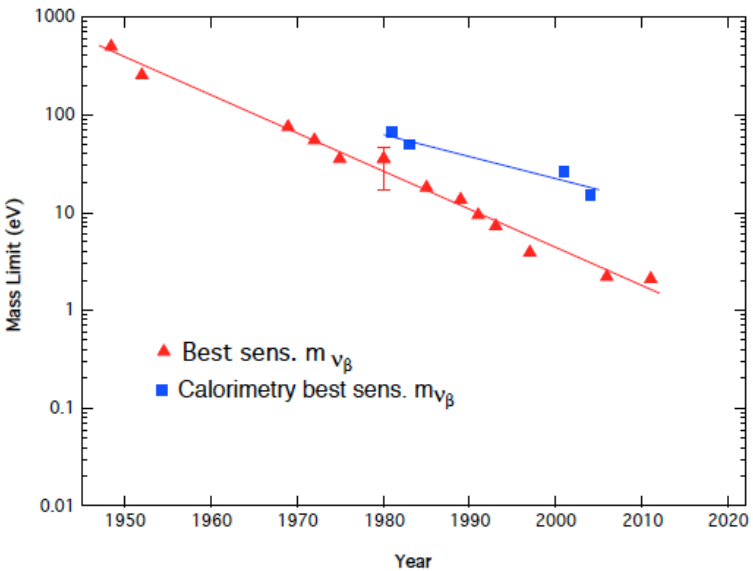


Fig: Wilkerson, Nu2012

Masses of Neutrinos, Leptons, Quarks

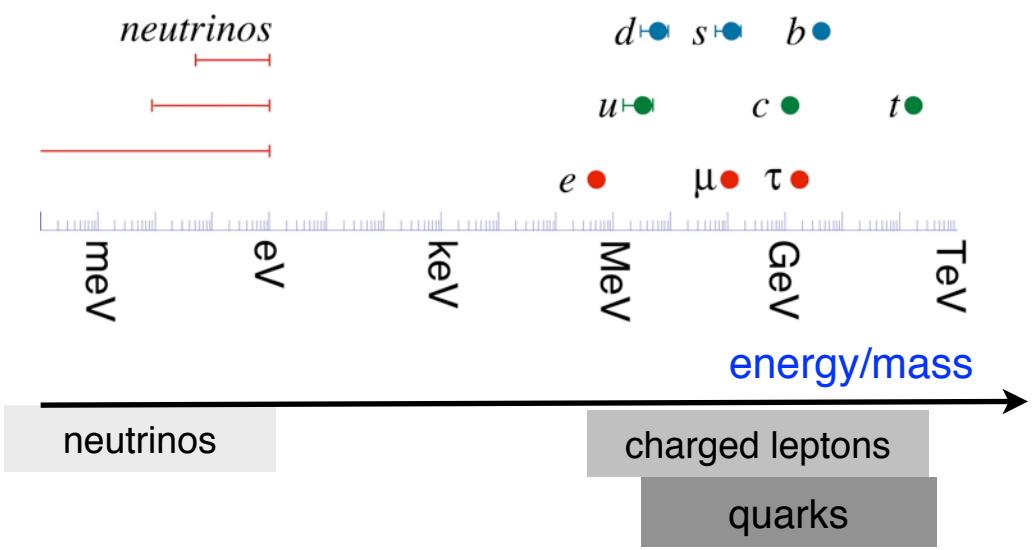


Fig: Murayama

Neutrino Mass and Mixing

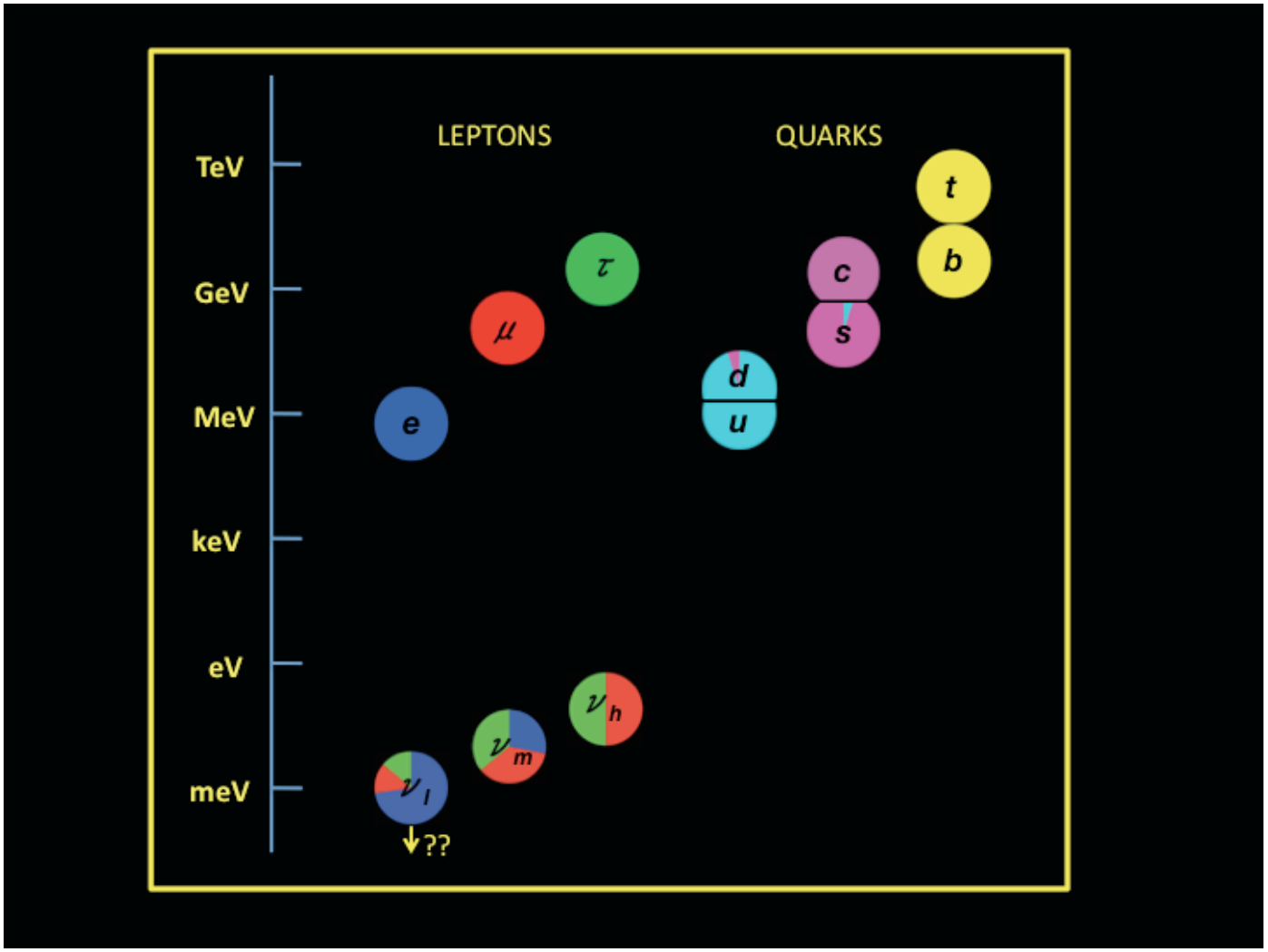
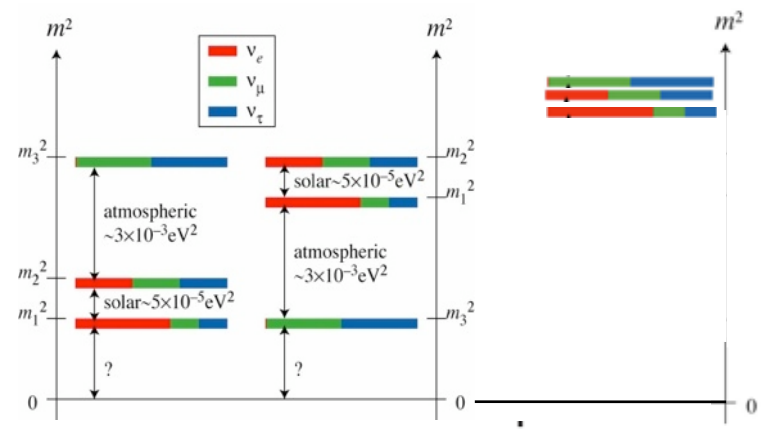


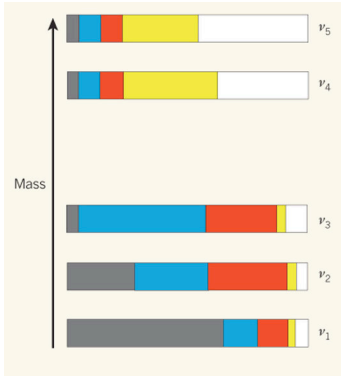
Fig: NRC NP2010, Robertson

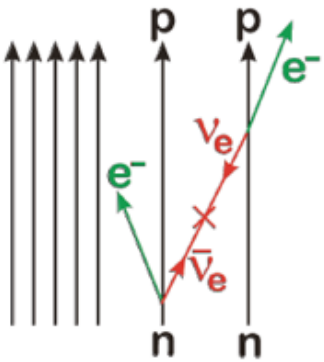
Neutrinos - Open Questions

The Origin of Mass

- Why are neutrinos so light?
- Do neutrinos have Majorana mass?
- What is the absolute mass scale?
- Normal or inverted mass ordering?
- Are there more than 3ν?



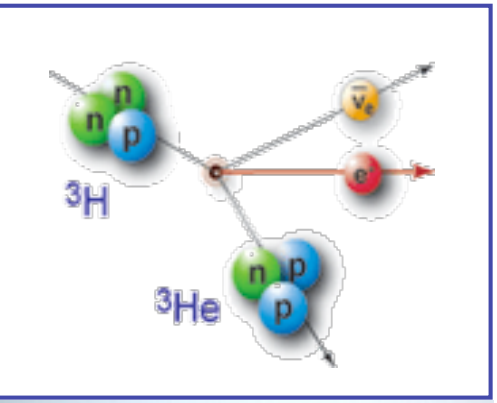




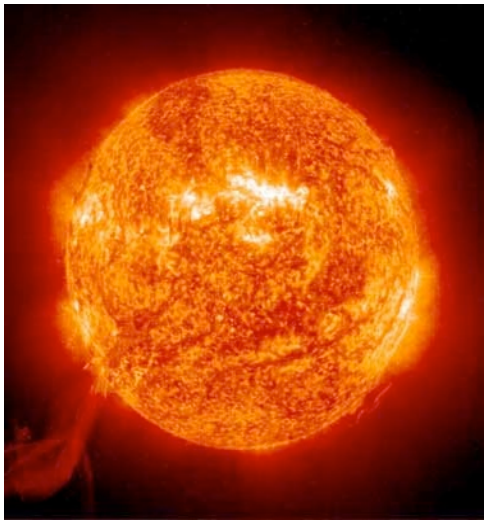
The Flavor Puzzle

- Why is lepton mixing so different from quarks?
- CP violation?
- θ_{23} octant?

Neutrino Sources and Energies



β-decay ~ keV



Neutrinos from the Sun < 20 MeV
depending of their origin.

Antineutrinos from nuclear reactors < 10.0 MeV

Atmospheric neutrinos ~ GeV

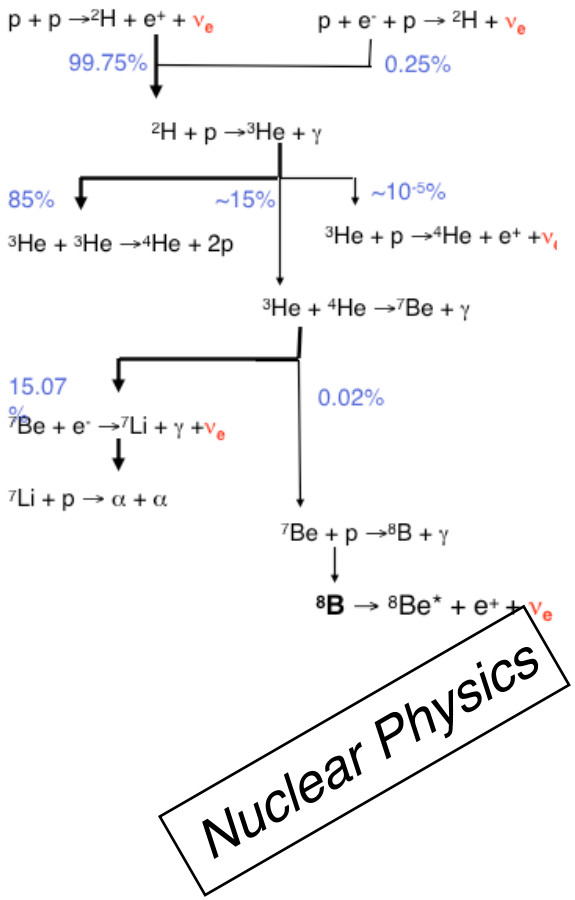
Neutrinos from accelerators
up to GeV (10^9 eV)

Neutrino Sources, Flavors, Environment

Solar Neutrinos

pure ν_e

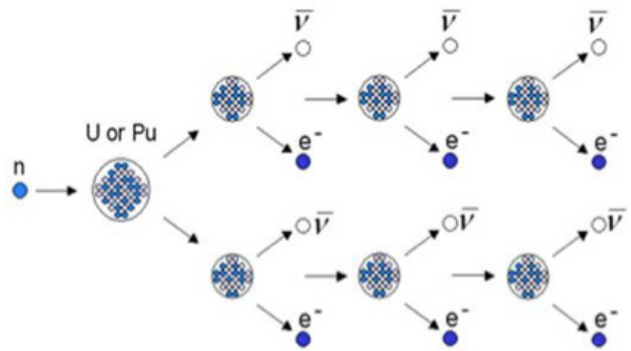
matter effects, large distances



Reactor Neutrinos

pure $\overline{\nu}_e$

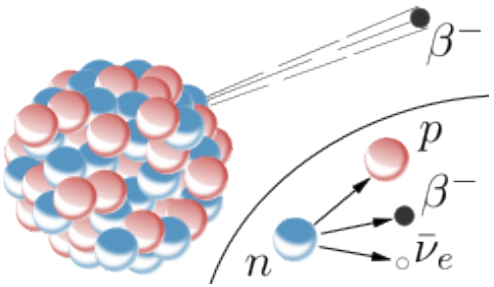
a vacuum environment



Nuclear β-decays

pure $\overline{\nu}_e$

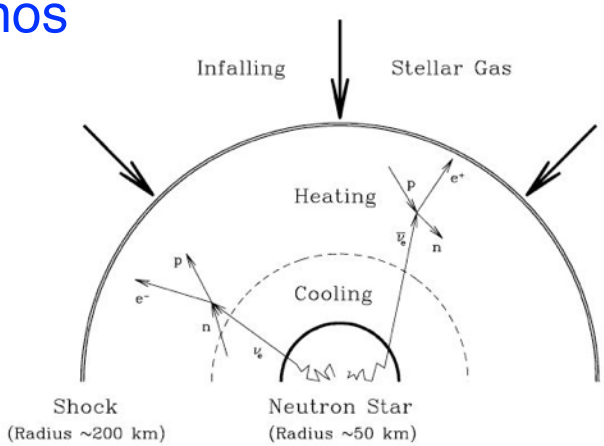
nucleus as a laboratory



Supernova Neutrinos

ν_e, $\overline{\nu}_e$, ν_x (all species)

extreme densities

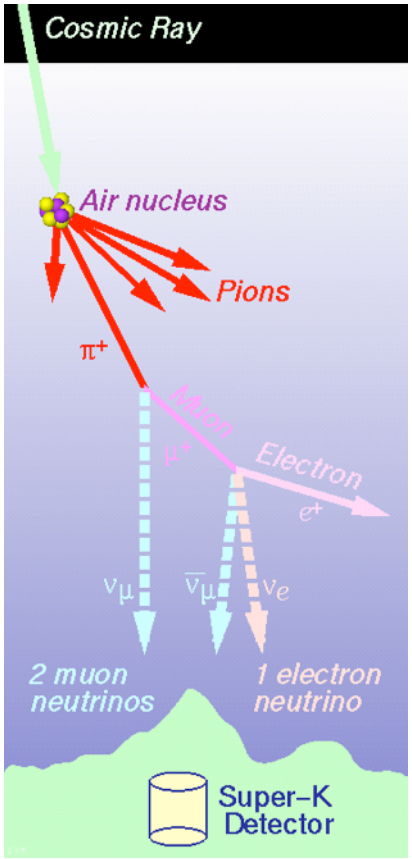


Neutrino Sources, Flavors, Environment

Atmospheric Neutrinos

ν_μ, $\bar{\nu}_\mu$, ν_e

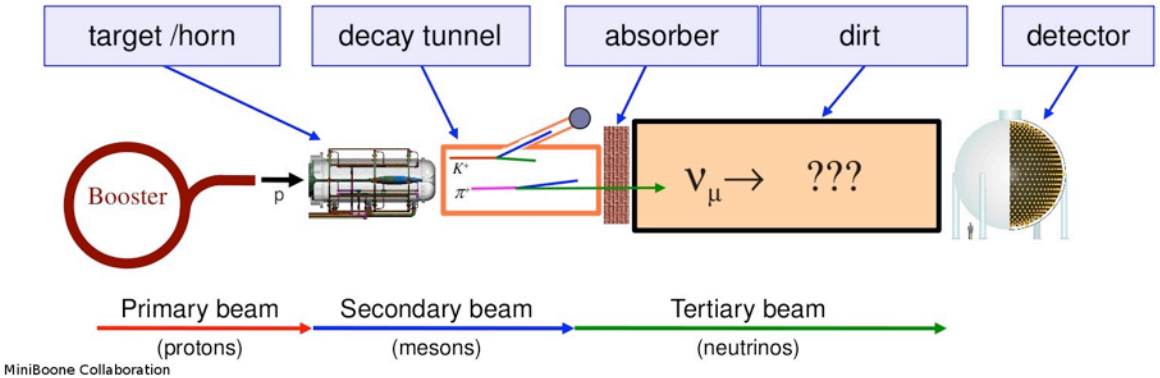
long baselines, Earth effects

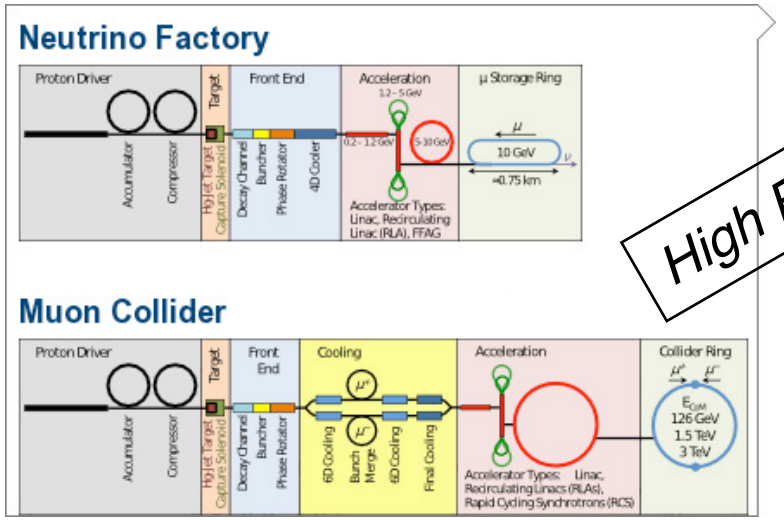


Accelerator Neutrinos

ν_μ (with some ν_e contamination)

long baselines, Earth effects





High Energy Physics

Oscillation Experiments

reactor **($\bar{\nu}_e$ disappearance)**

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

- disappearance experiment $\nu_e \rightarrow \nu_e$
- rate deviations from $1/r^2$ and spectral distortions
- baseline *O(1 km),* no matter effects

accelerator **(ν_e appearance)**

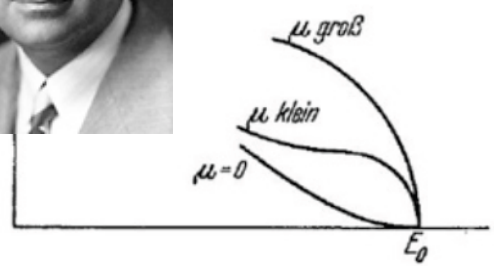
$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\ & + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin \Delta_{31} [\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta] \sin \Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} \\ & + 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta] \sin^2 \Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin \Delta_{31} \left[\cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}}\right] . \end{aligned}$$

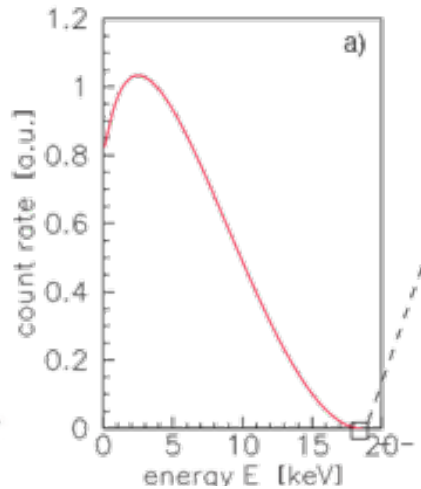
- appearance experiment $\nu_\mu \rightarrow \nu_e$
- baseline *O(100 -1000 km),* matter effects present

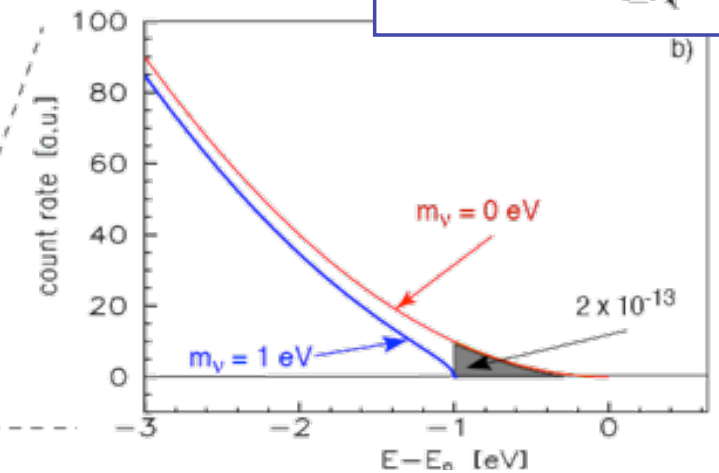
complementary approaches to understand all aspects of ν oscillation

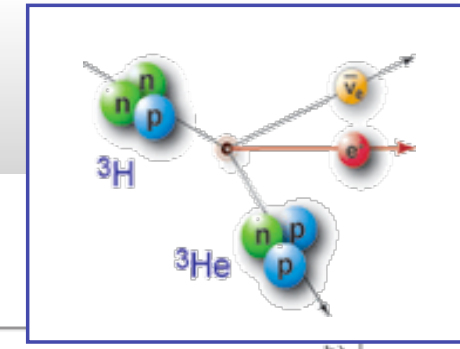
Beta Decay Spectra

Precision Studies of the Energy Spectrum

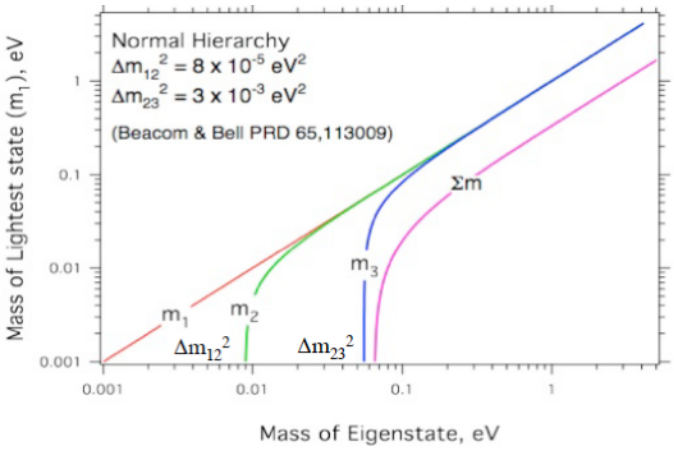








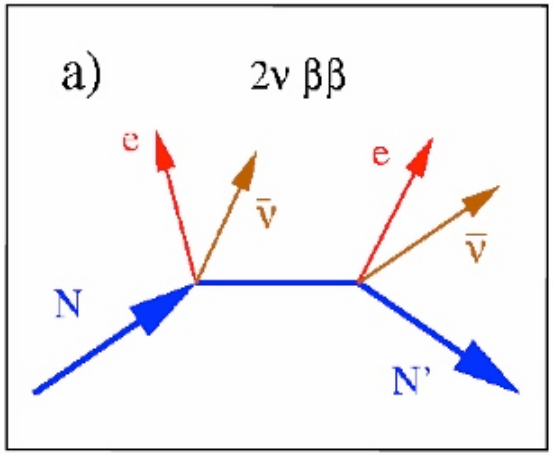
$$\frac{dN}{dT} = \frac{G_F \cos\theta_C}{2\pi^3} |M_{\rm nuc}|^2 F(Z,T)(T+m)(T^2+2mT)^{1/2}(T_0-T)\sum_i |U_{ei}|^2 \left[(T_0-T)^2 - m_i^2\right]^{1/2}$$



For m1≳100 eV and no sterile neutrinos, the beta spectrum simplifies to an “effective mass”

$$m_\beta = \left[\sum_i |U_{ei}|^2 m_i^2\right]^{\frac{1}{2}}$$

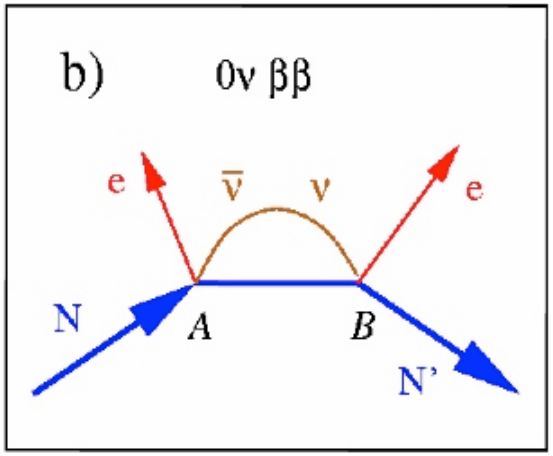
Neutrinoless Double Beta Decay: 0νββ



2ν mode: conventional 2nd order process in nuclear physics

$$\Gamma_{2\nu} = G_{2\nu} \mid M_{2\nu} \mid^2$$

G are phase space factors



0ν mode: hypothetical process only if $M_\nu \neq 0$ AND $\nu = \bar{\nu}$

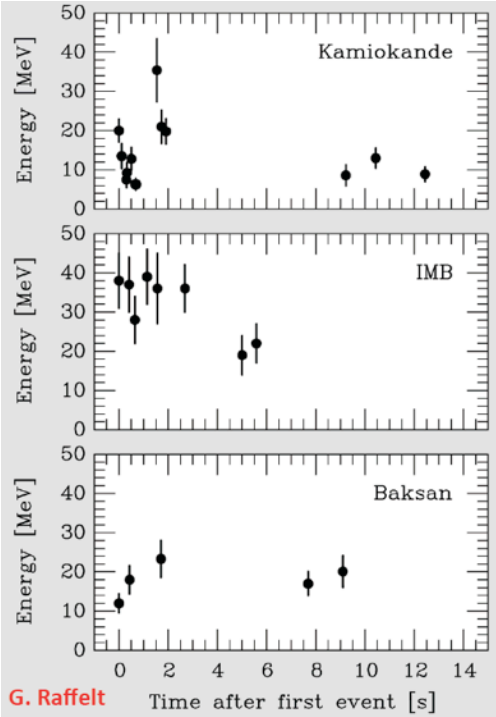
$$\Gamma_{0\nu} = G_{0\nu} \mid M_{0\nu} \mid^2 \left\langle m_{\beta\beta} \right\rangle^2$$

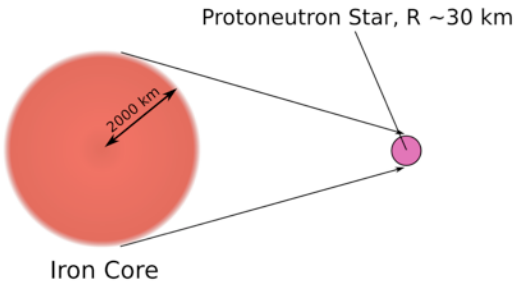
$G_{0\nu} \sim Q^5$

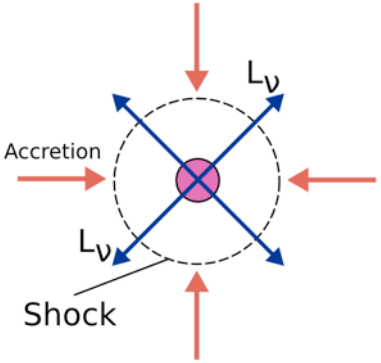
0νββ would imply
- lepton number non-conservation
- Majorana nature of neutrinos

0νββ may allow us to determine
- effective neutrino mass

Neutrinos in Astrophysics: Supernovae





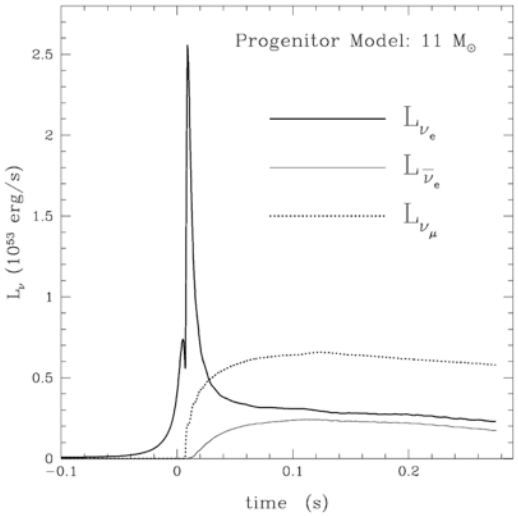


neutrinos from SN 1987A confirmed the basic SN model,
99% of energy emitted in neutrinos over 10s of sec
but what mechanism mediates explosion?

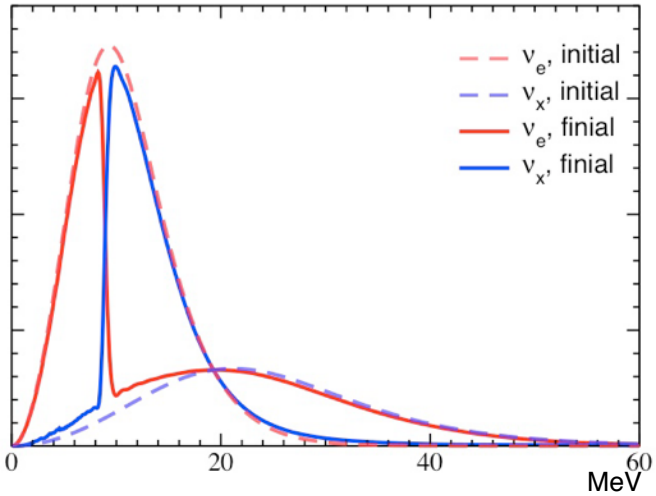
$$e^- p \rightleftharpoons \nu_e n$$
$$e^+ n \rightleftharpoons \bar{\nu}_e p$$

$$e^- e^+ \rightleftharpoons \nu_i \bar{\nu}_i$$
$$NN \rightleftharpoons \nu_i \bar{\nu}_i$$
$$\tilde{\gamma} \rightleftharpoons \nu_i \bar{\nu}_i$$

neutrino burst



various kinds of oscillations:
vacuum, MSW, collective (non-linear, ν-ν scattering) in high ν density

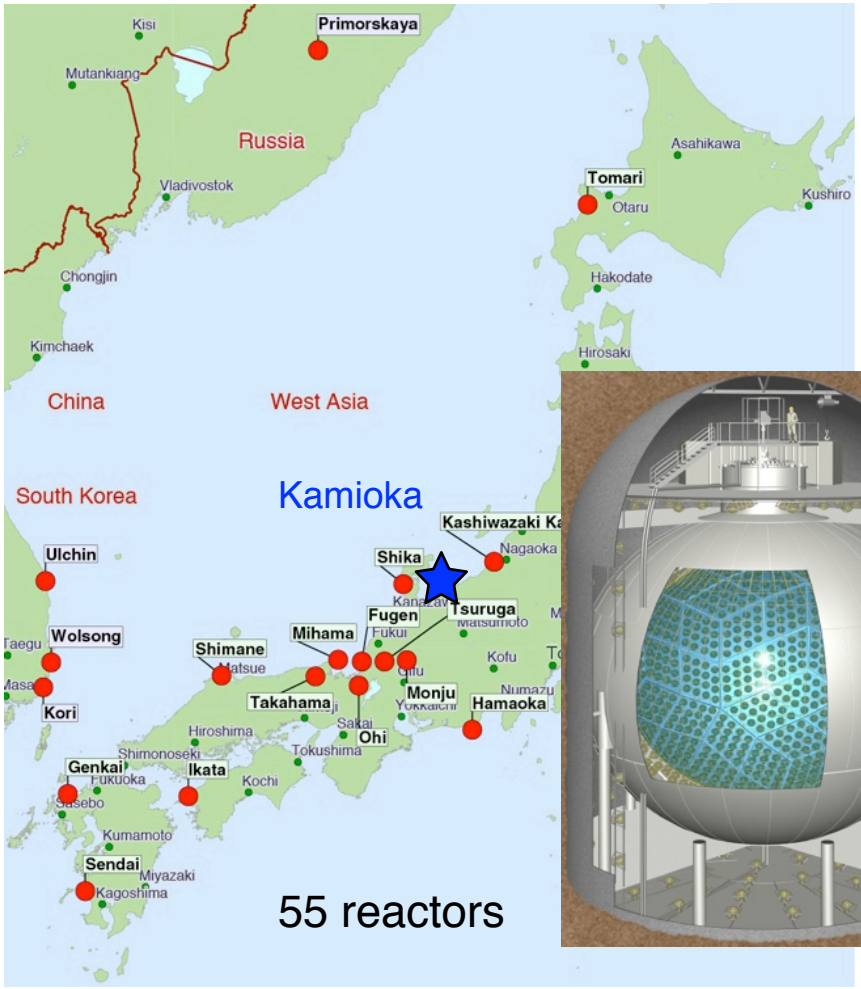


What have we accomplished since 2007?

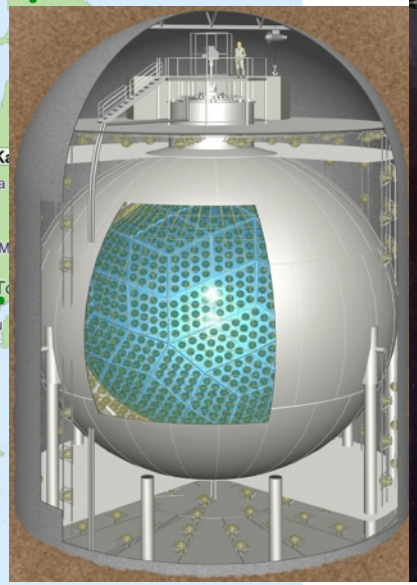
What’s next?

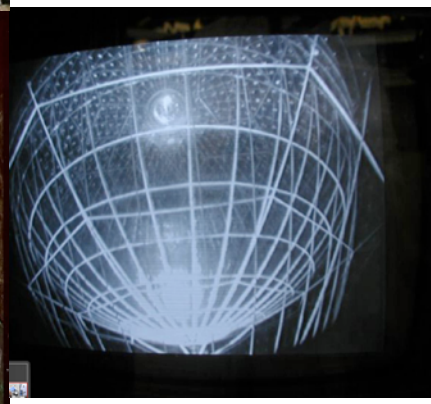
Observation of Reactor $\bar{\nu}$ Oscillation with KamLAND

Reactors in Japan



KamLAND



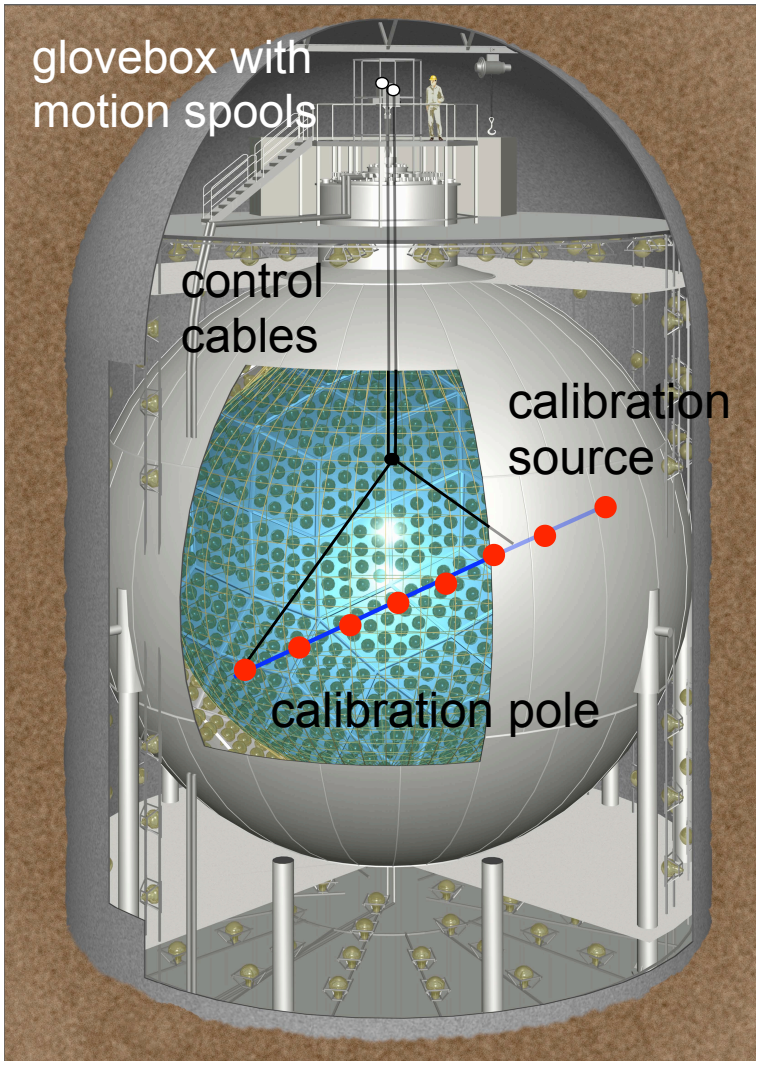


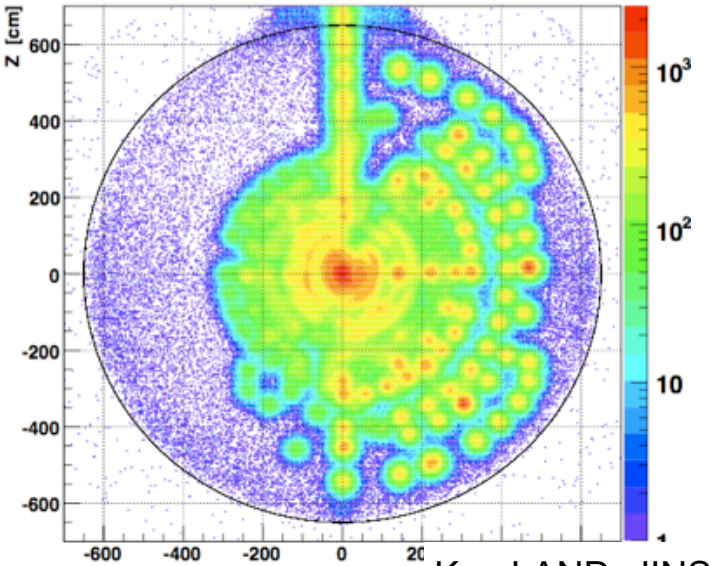
1kt liquid scintillator detector

mean, flux-weighted reactor distance ~ 180km

Observation of Reactor $\bar{\nu}$ Oscillation with KamLAND

Calibrating fiducial volume for reduced systematics in target mass





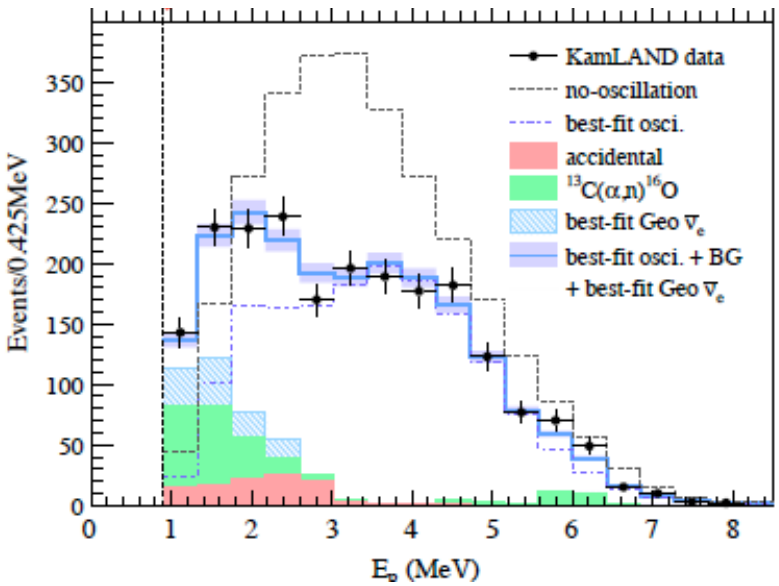
KamLAND, JINST 4 (2009) P04017

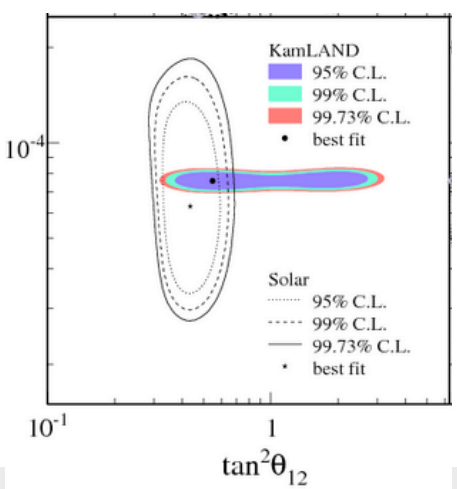
	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.9	$\bar{\nu}_e$-spectra [7]	0.6
Event rate	Fiducial volume	1.8	$\bar{\nu}_e$-spectra	2.4
	Energy threshold	1.5	Reactor power	2.1
	Efficiency	0.6	Fuel composition	1.0
	Cross section	0.2	Long-lived nuclei	0.3

fiducial volume and reactor flux important for precision reactor experiments

Observation of Reactor $\bar{\nu}$ Oscillation with KamLAND

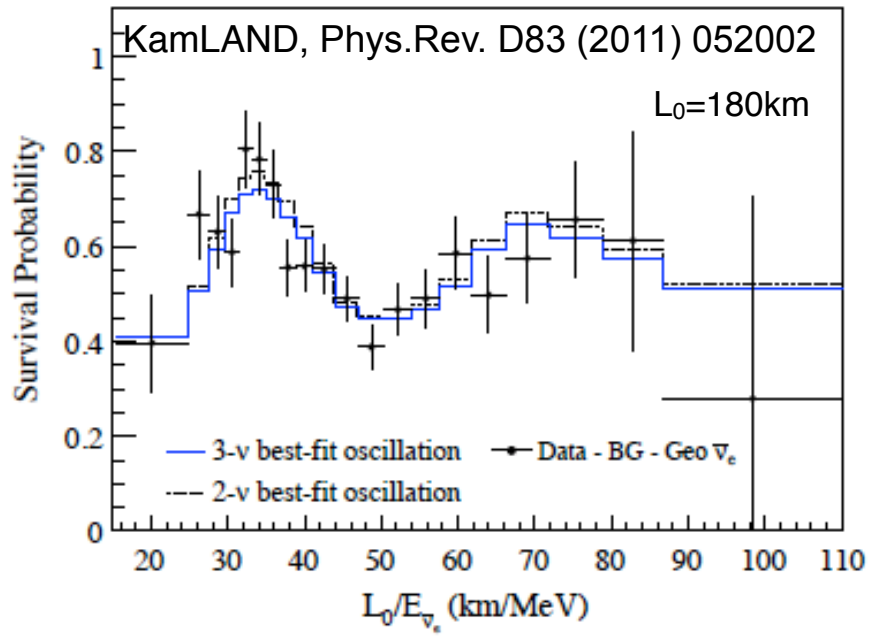
Reactor Antineutrino Spectrum





KamLAND has measured Δm_{12}^2 to ~2.8%

Direct Evidence for Oscillation



$$P_{i\to i} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

Oscillation Experiments with Reactors

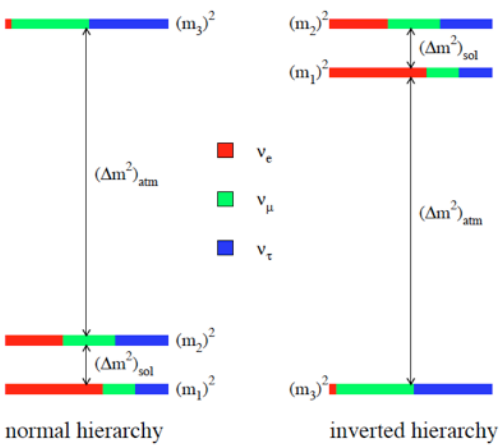
Measure (non)-1/r² behavior of $\overline{\nu}_e$ interaction rate

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

L/E → Δm^2

amplitude of oscillation → θ

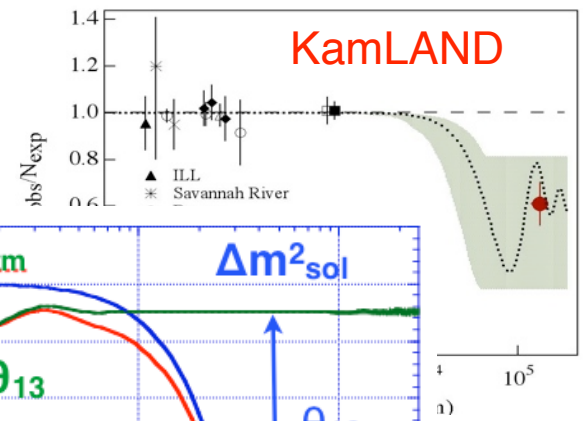
for 3 active ν, two different oscillation length scales: Δm^2_{12}, Δm^2_{23}

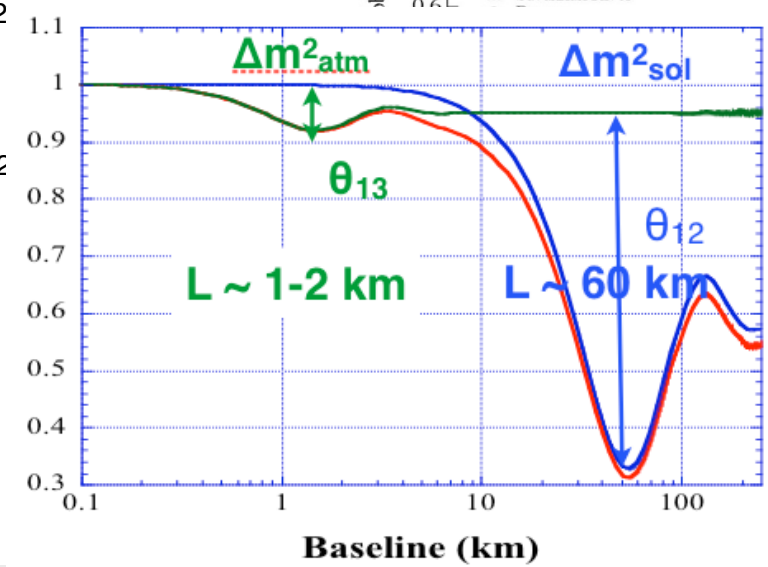


$\Delta m^2_{12} \sim 7.6 \times 10^{-5}$ eV²

$\Delta m^2_{23} \sim 2.4 \times 10^{-3}$ eV²

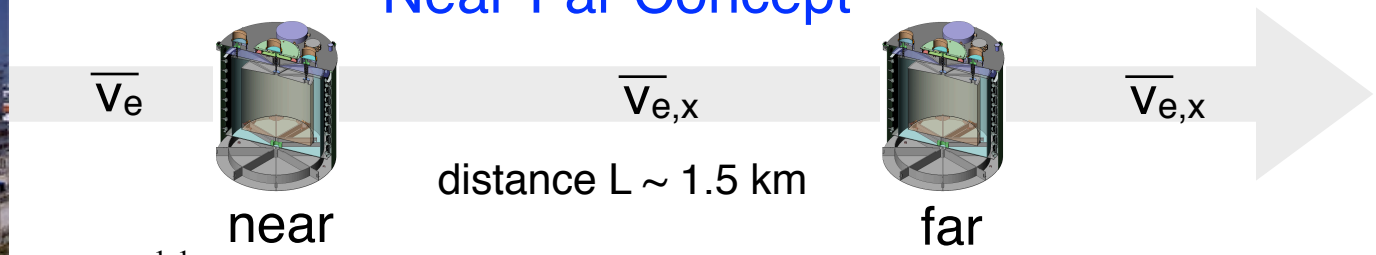
$\Delta m^2_{23} \approx \Delta m^2_{13}$

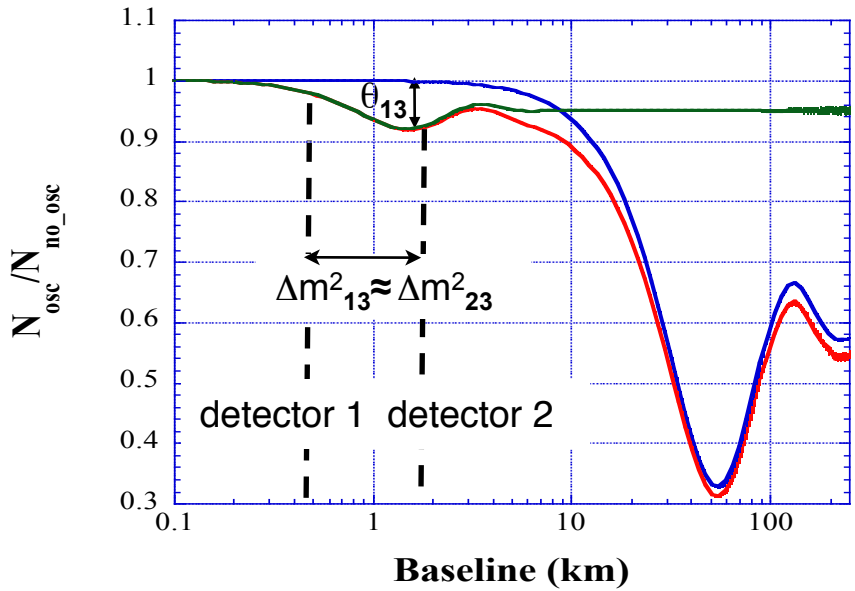




Measuring θ_{13} with Reactor Experiments

Near-Far Concept





Absolute Reactor Flux
Largest uncertainty in previous measurements

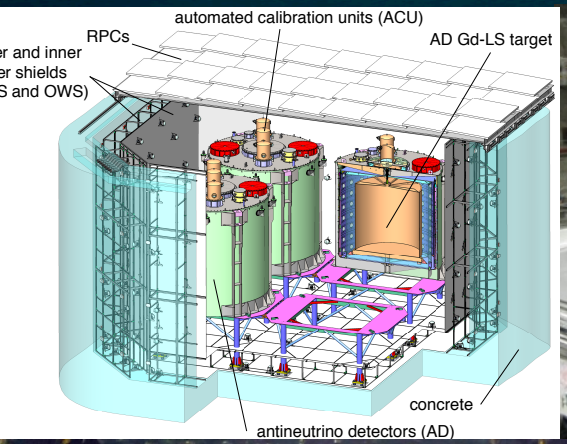
Relative Measurement
Removes absolute uncertainties!

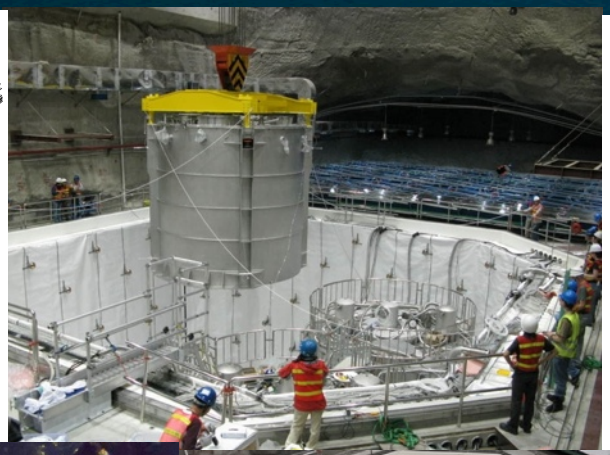
First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)

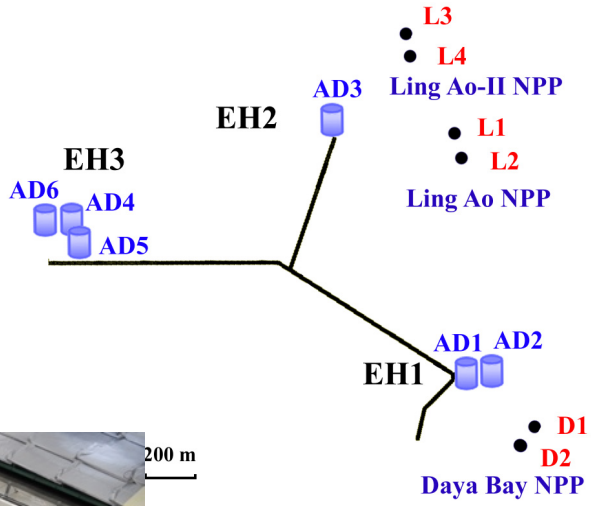
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

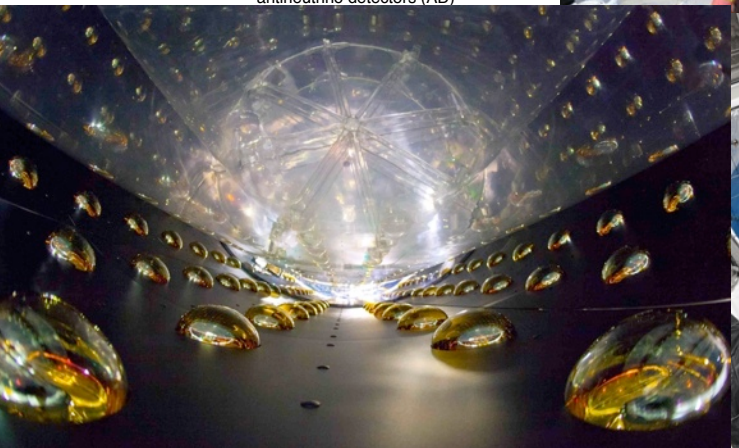
far/near $\overline{\nu}_e$ ratio — target mass — distances — efficiency — oscillation deficit

Daya Bay





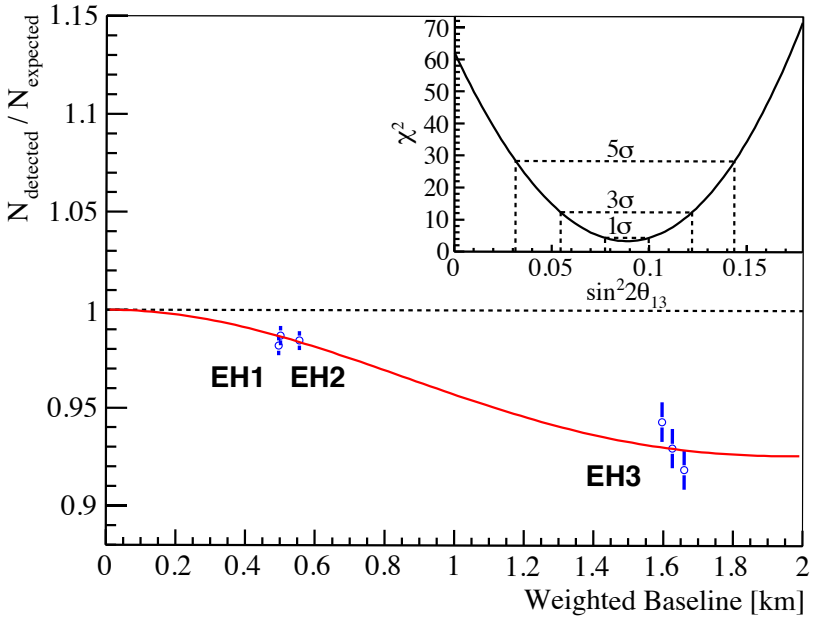




6 reactor cores
3 experimental halls
6 detectors
(2 still under construction)

Daya Bay Reactor Antineutrino Studies

Observation of Electron Antineutrino Disappearance over 1-2km

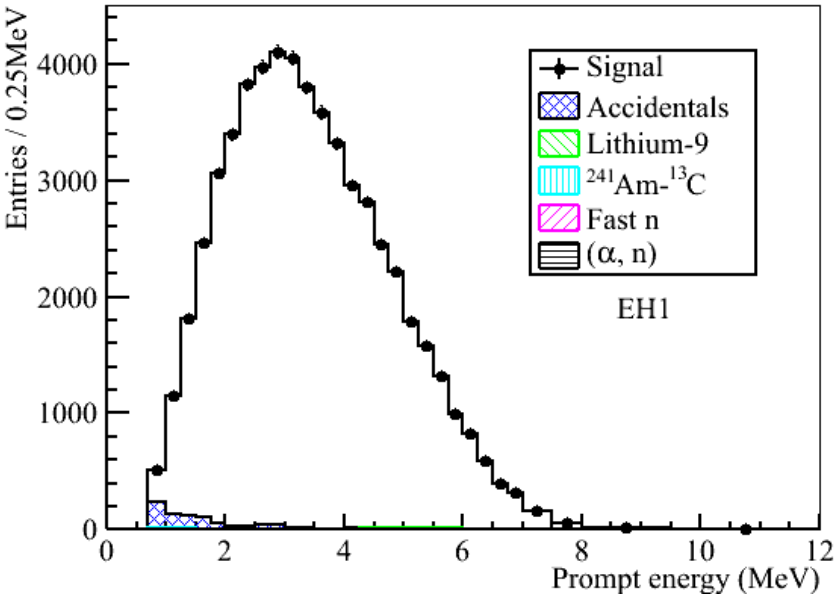


Far vs. near relative measurement

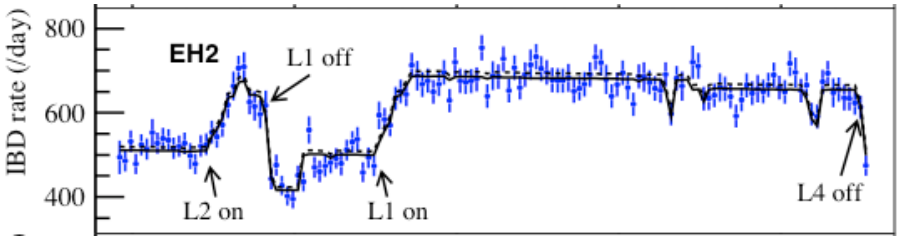
$\sin^2 2\theta_{13}$ =
0.089 ± 0.010 (stat) ± 0.005 (syst)

Most precise measurement of $\sin^2 2\theta_{13}$ to date.

Precision Reactor Spectrum > 200,000 events at near site



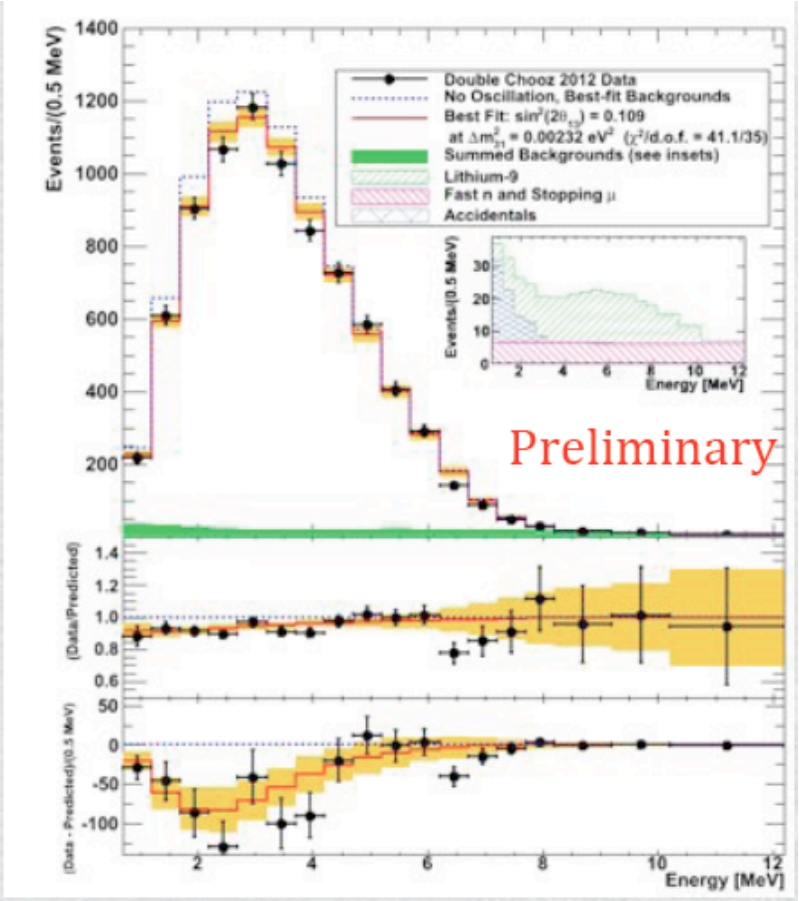
Reactor Antineutrino Flux Variation



Ref: Daya Bay, Nu2012

Other Reactor θ_{13} Experiments

Double Chooz

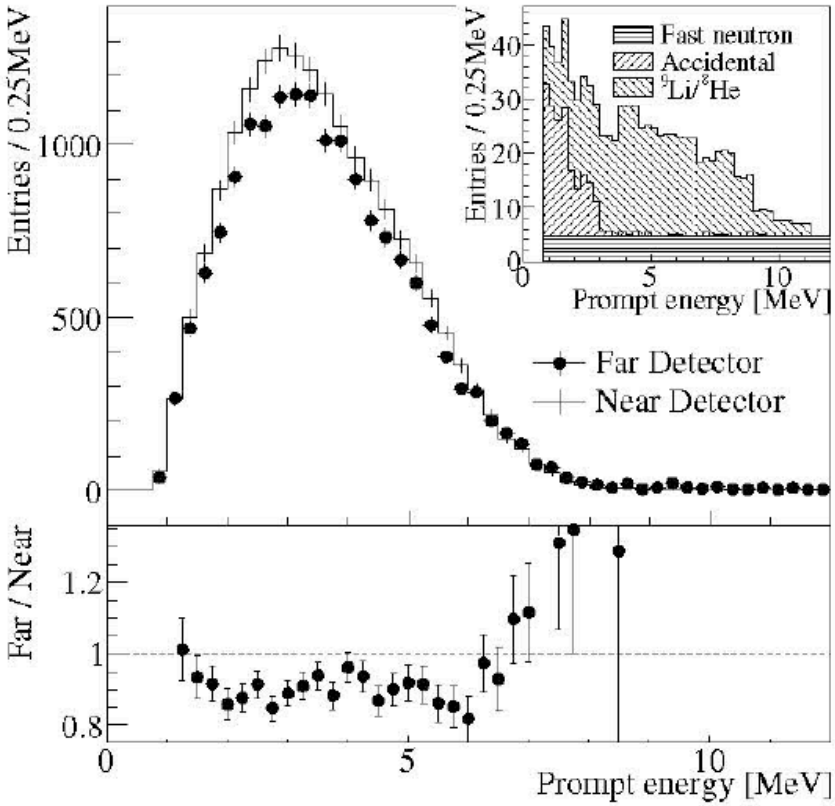


Rate only: $\sin^2 2\theta_{13} = 0.170 \pm 0.035(\text{stat}) \pm 0.040(\text{syst})$

Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$

Ref: Ishitsuka, Neutrino2012

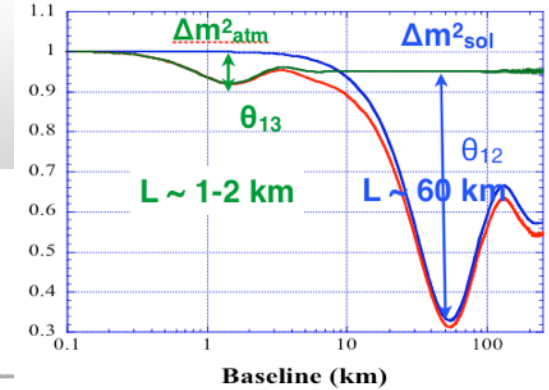
RENO



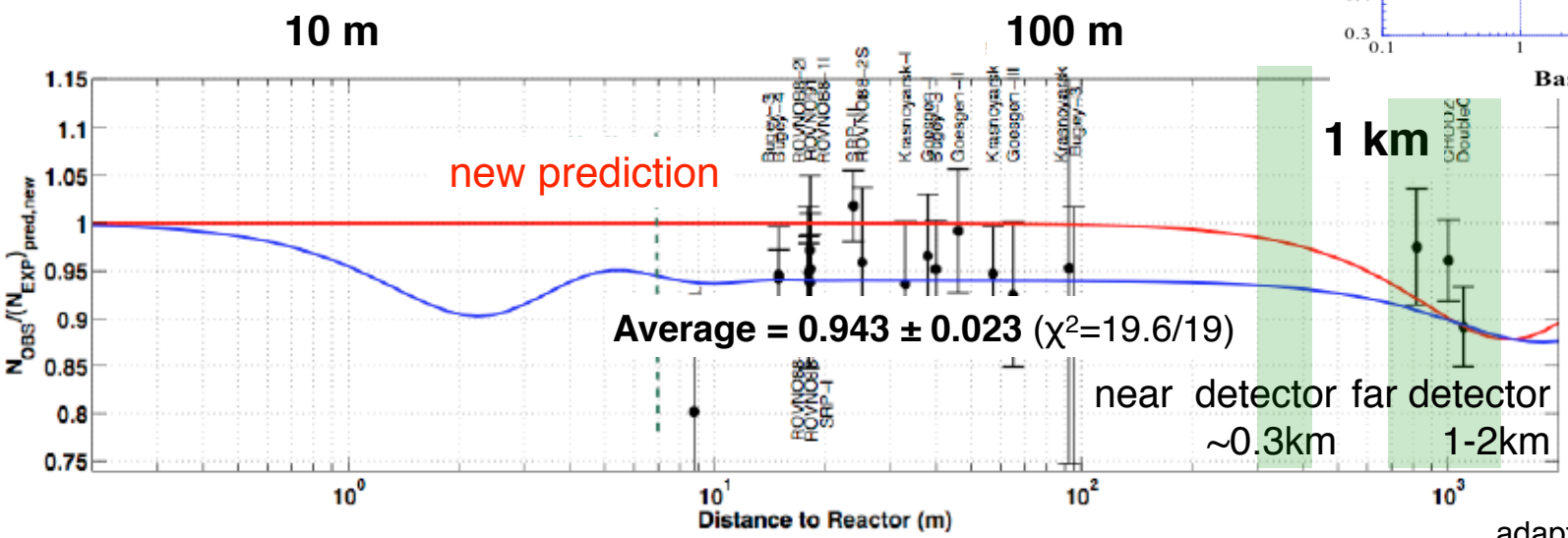
$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$$

PRL, 108 (2012) 191802

Reactor Flux Predictions



Reactor Anomaly: Beyond 3ν?



adapted from Schwetz Neutrino2012

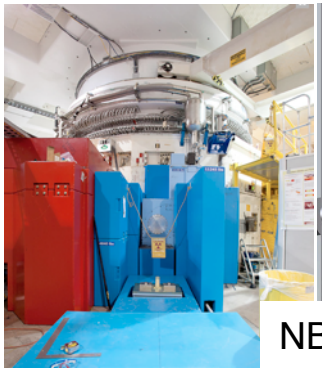
2011 $\bar{\nu}_e$ flux predictions
- new reactor antineutrino spectra
- re-analysis of 19 short-baseline reactor results
- neutron lifetime correction, off-equilibrium effects

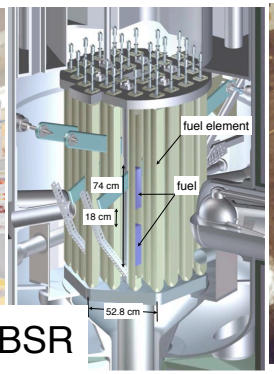
→ net 3% upward shift in energy averaged fluxes

deficit from flux normalization problem or from additional oscillation at L~O(1-10m)?

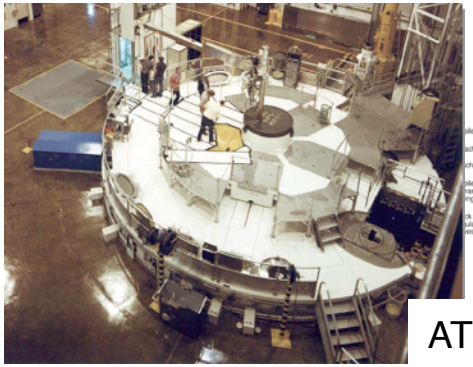
nuclear physics or new physics?

Opportunities for a Reactor Experiment in the US

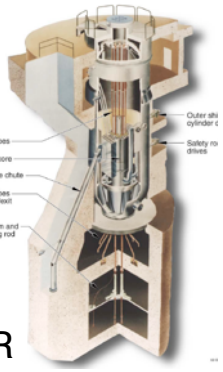


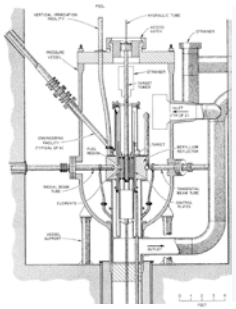


NBSR



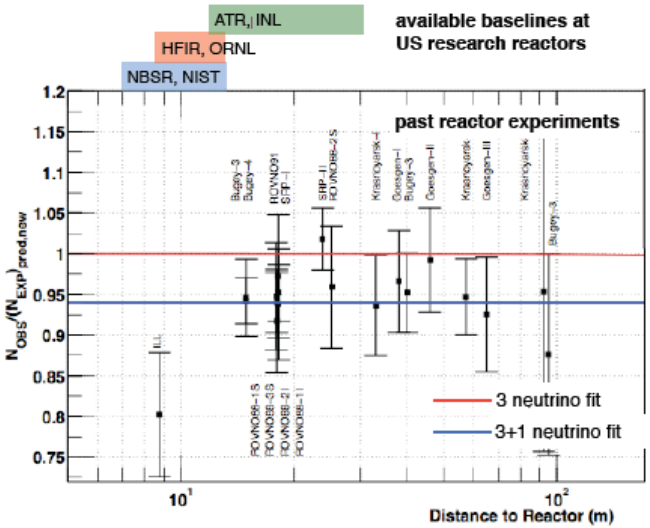
ATR

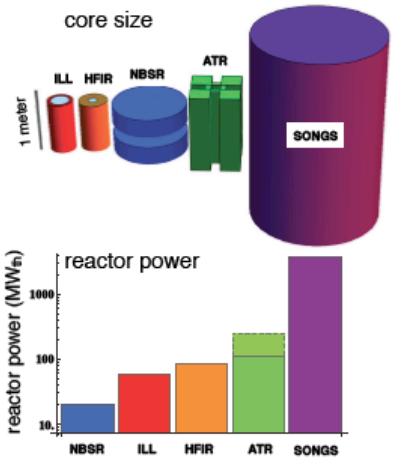


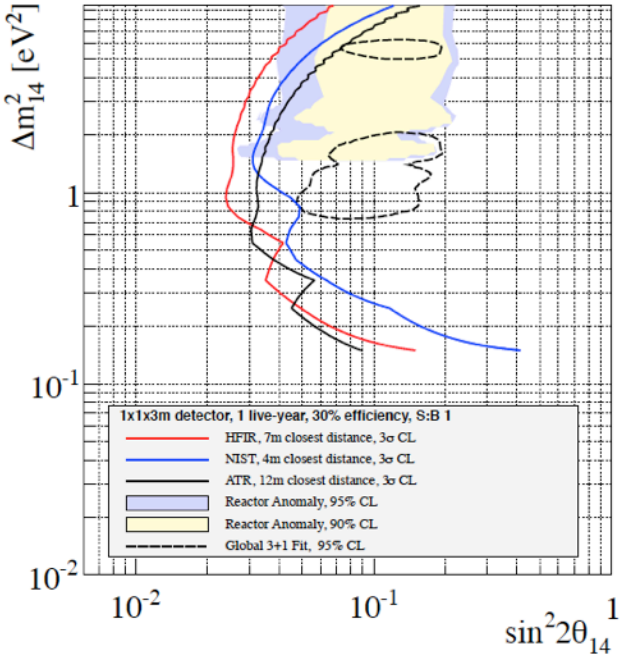


HFIR

SONGS

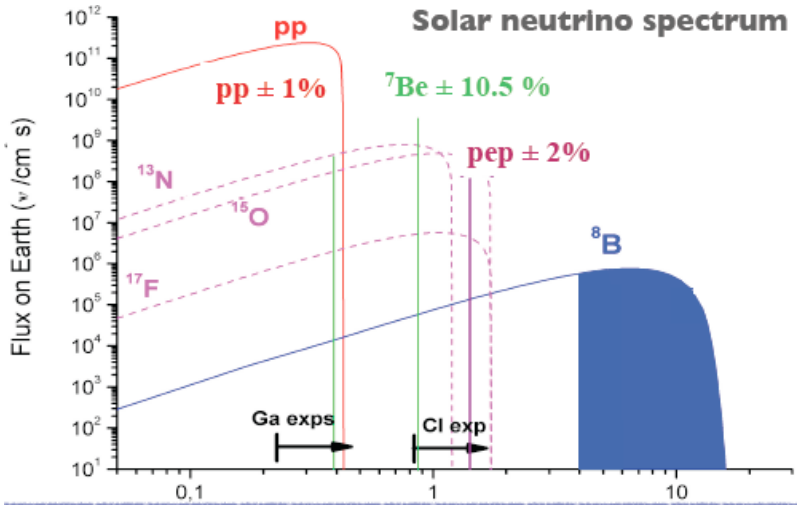




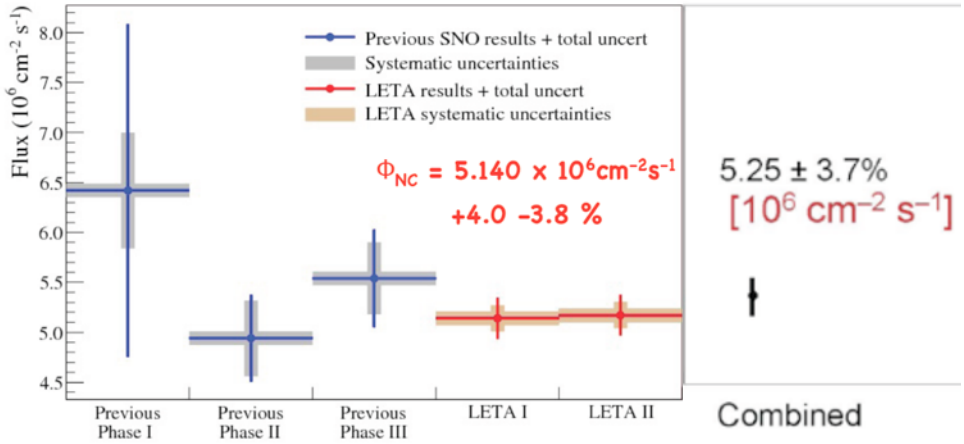


neutron and near-surface backgrounds are key issues

Solar Neutrino Measurements

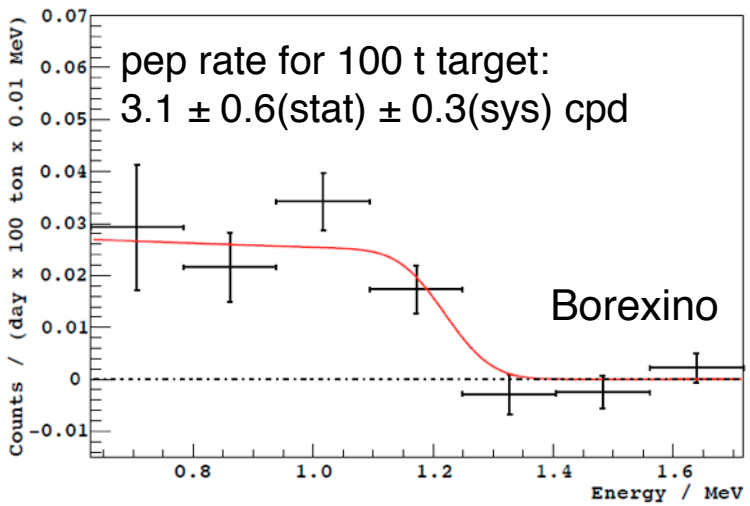


^{8}B Flux (SNO LETA + combined)

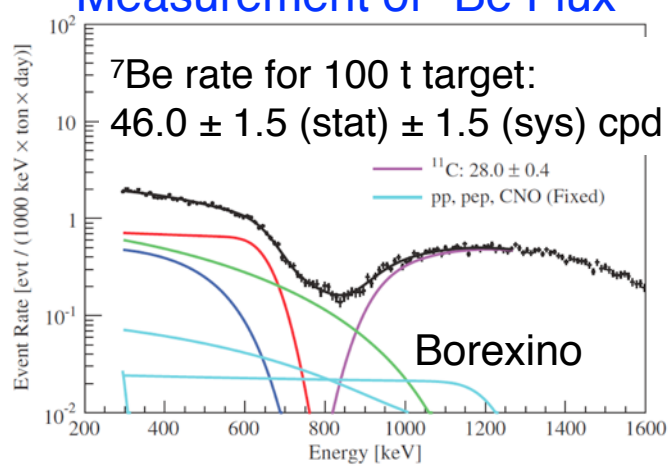


3.5MeV thresholds achieved in SNO & SK
first direct extraction of ν_e survival probability

Detection of pep neutrinos

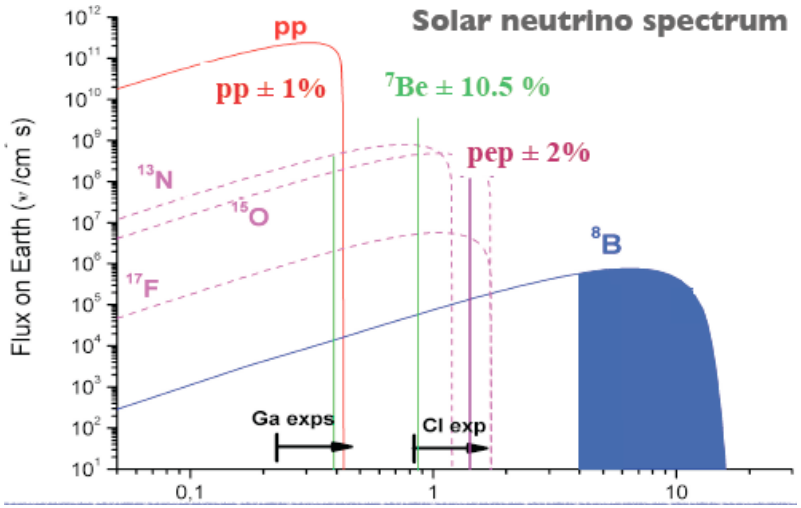


Measurement of ^{7}Be Flux

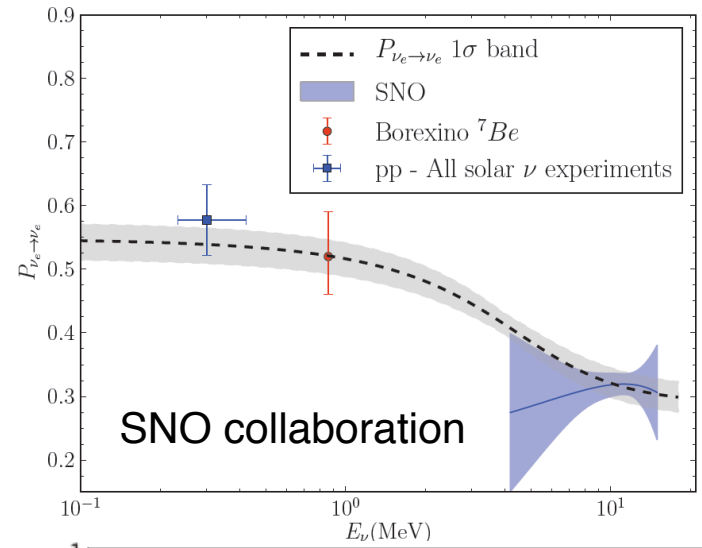


Limit on CNO rate
< 7.1 cpd/100 t

Solar Neutrino Measurements

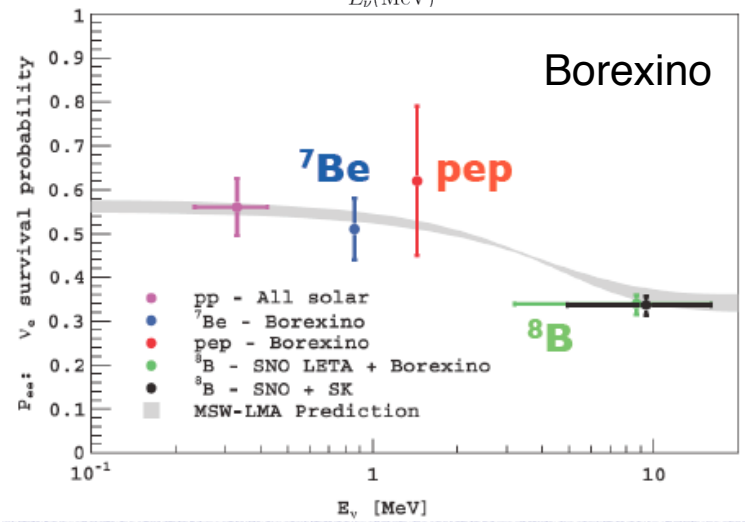


Probing vacuum/matter transition



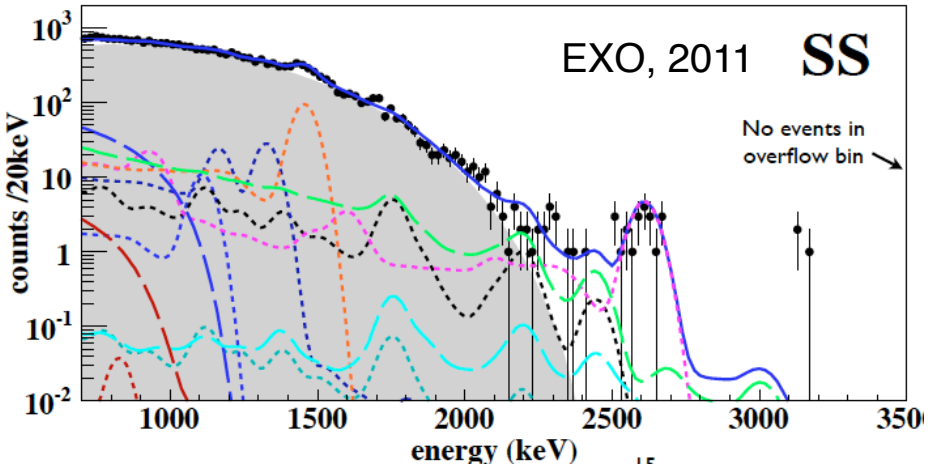
Near future (2012-2015)

- Improve ^{7}Be, ^{8}B
  → test of MSW
- Confirm pep at >3σ and reduce error
- Improve upper limit on CNO
  → probe metallicity
- Attempt direct pp measurement



Recent Results in the Search for 0νββ

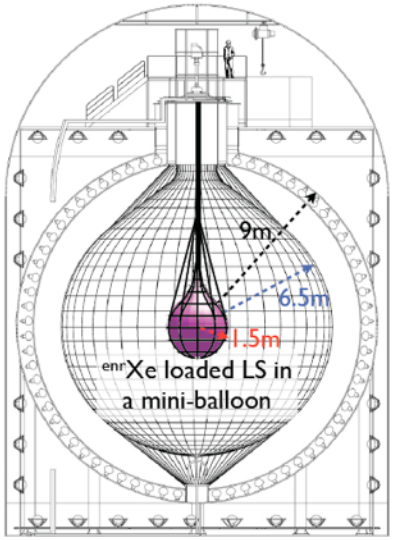
2νββ Measurements

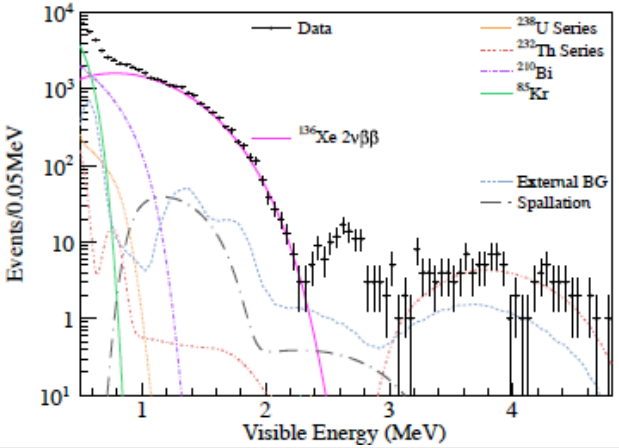


$T_{2\nu}1/2 = 2.23 \pm 0.017(\text{stat}) \pm 0.22(\text{sys}) \times 10^{21}$ y

$\langle m_{\beta\beta} \rangle < 140–380$ meV (90% C.L.)

see Piepke's talk



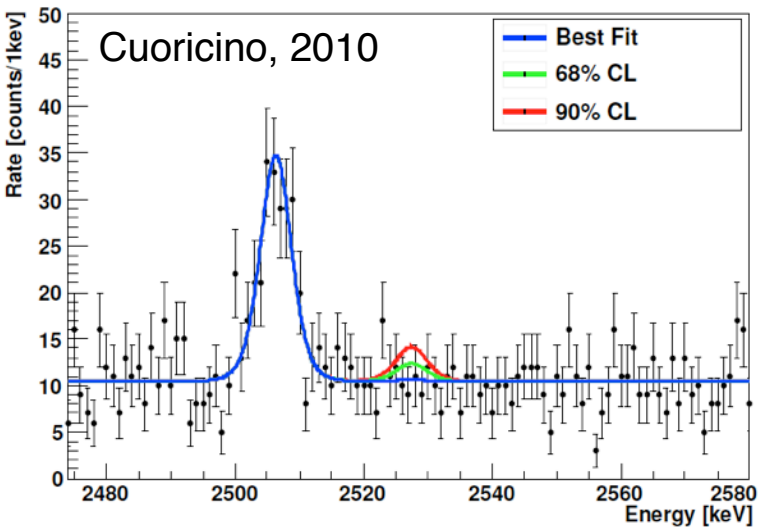


KamLAND, 2011

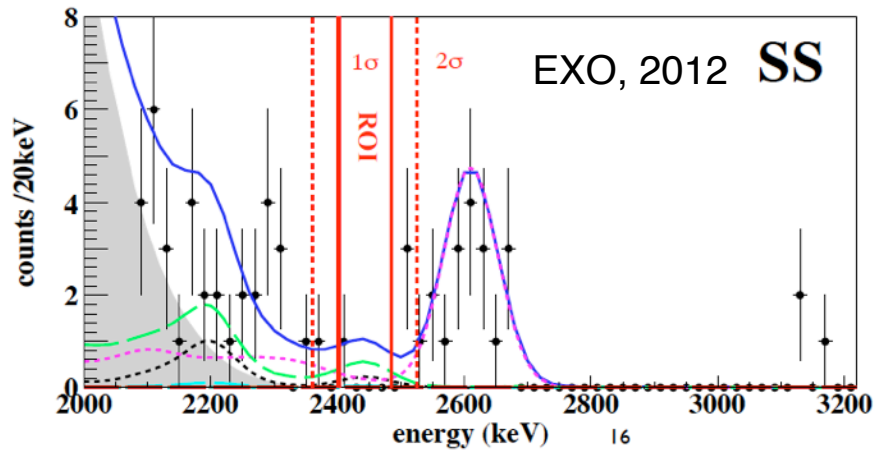
$T_{2\nu}1/2 = 2.38 \pm 0.02(\text{stat}) \pm 0.14(\text{syst}) \times 10^{21}$ years

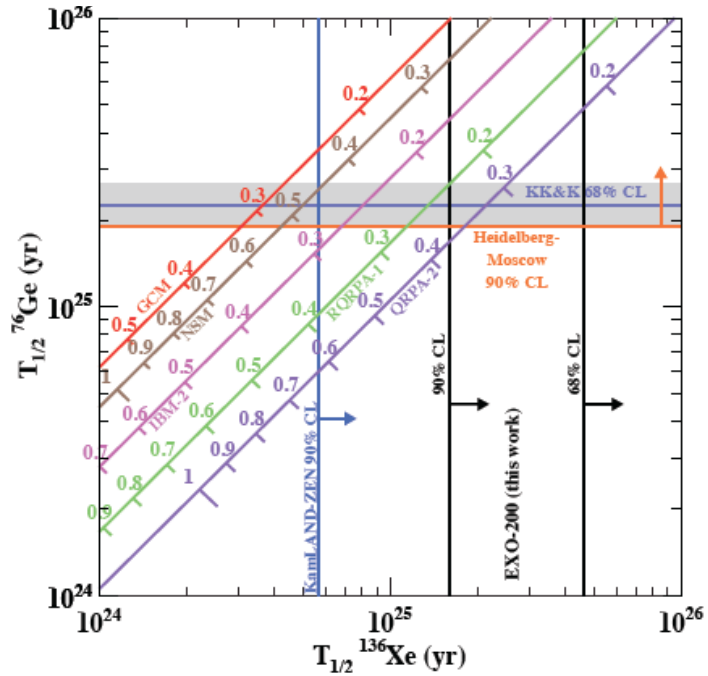
Recent Results in the Search for 0νββ

Limits on 0νββ



$T_{0\nu}1/2 > 2.8\times10^{24}$ y at 90% C.L.
$m_{\beta\beta} < 0.3 - 0.7$ eV



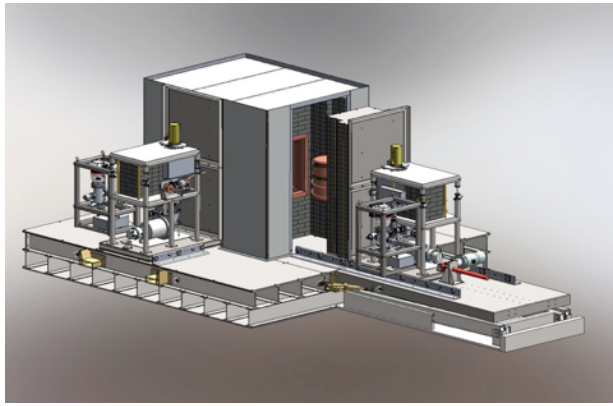


EXO, 2012

$T_{0\nu}1/2 > 1.6\times10^{25}$ y
$\langle m_{\beta\beta}\rangle < 140–380$ meV (90% C.L.)

Preparations for the Next 0νββ Search

Majorana Demonstrator



see Poon's talk

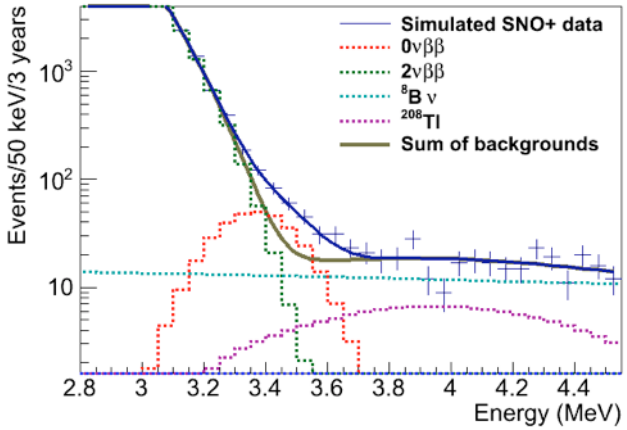
Three Phases

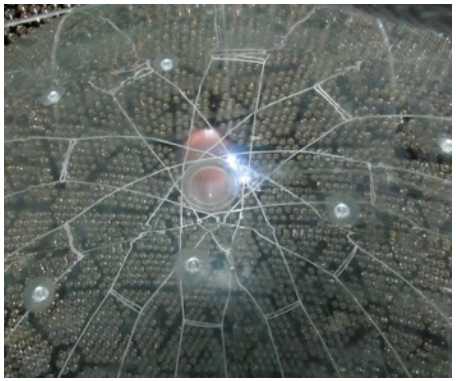
- Prototype cryostat (2 strings, ^{nat}Ge) **(End 2012)**

  1st order of ^{enr}Ge (20 kg) on hand. 2nd order in process. Refinement/ processing facility in Oak Ridge (via NSF) has completed testing with ^{nat}Ge.
- Cryostat 1 (3 strings ^{enr}Ge & 4 strings ^{nat}Ge) **(Fall 2013)**
- Cryostat 2 (up to 7 strings ^{enr}Ge) **(Fall 2014)**

SNO+

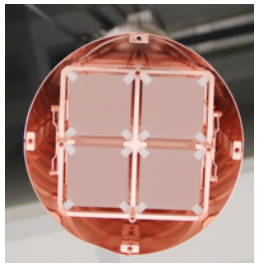
dissolve ^{nat}Nd salt in liquid scintillator

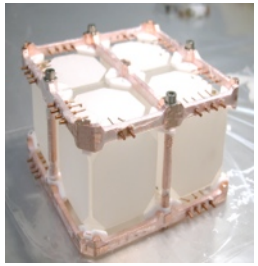




see Klein's talk

CUORE-0/CUORE





CUORE-0 is being cooled down
CUORE under construction

see Kolomensky's talk

Theoretical Progress

Nuclear Matrix Elements for 0νββ

$$\left[T_{1/2}^{0\nu\beta\beta}(0^+ \to 0^+)\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|f_b(m_i, U_{ei})\right|^2$$

Beyond the standard model
(Particle physics)

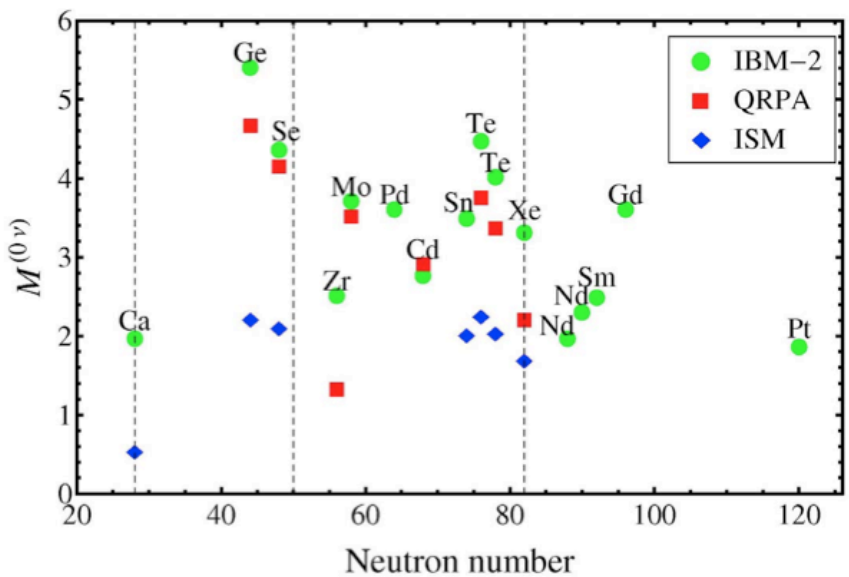
Phase-space factor
(Atomic physics)

Matrix elements
(Nuclear physics)

Using the values of $g_{A,eff}$ extracted from 2νββ one can make "absolute" predictions for 0νββ life-times.

Decay	$\tau_{1/2}^{0\nu}(10^{24}\,\mathrm{yr})$ IBM-2 ren.	ISM ren.
$^{48}Ca \to ^{48}Ti$	22.887	89.243
$^{76}Ge \to ^{76}Se$	46.416	69.1217
$^{82}Se \to ^{82}Kr$	17.627	18.4572
$^{96}Zr \to ^{96}Mo$	29.546	
$^{100}Mo \to ^{100}Ru$	18.137	
$^{110}Pd \to ^{110}Cd$	68.640	
$^{116}Cd \to ^{116}Sn$	35.050	
$^{124}Sn \to ^{124}Te$	42.922	27.603
$^{128}Te \to ^{128}Xe$	413.792	344.356
$^{130}Te \to ^{130}Xe$	21.443	17.601
$^{136}Xe \to ^{136}Ba$	31.785	25.260
$^{148}Nd \to ^{148}Sm$	145.971	
$^{150}Nd \to ^{150}Sm$	16.400	
$^{154}Sm \to ^{154}Gd$	300.019	
$^{160}Gd \to ^{160}Dy$	46.557	
$^{198}Pt \to ^{198}Hg$	259.526	

IBM-2 RESULTS (JAN 2012)
LIGHT NEUTRINO EXCHANGE



IBM-2 from J. Barea and F. Iachello, Phys. Rev. C 79, 044301 (2009) and to be published.
QRPA from F. Šimkovic *et al.*, Phys. Rev. C 77, 045503 (2008).
ISM from E. Caurier *et al.*, Phys. Rev. Lett. 100, 052503 (2008).

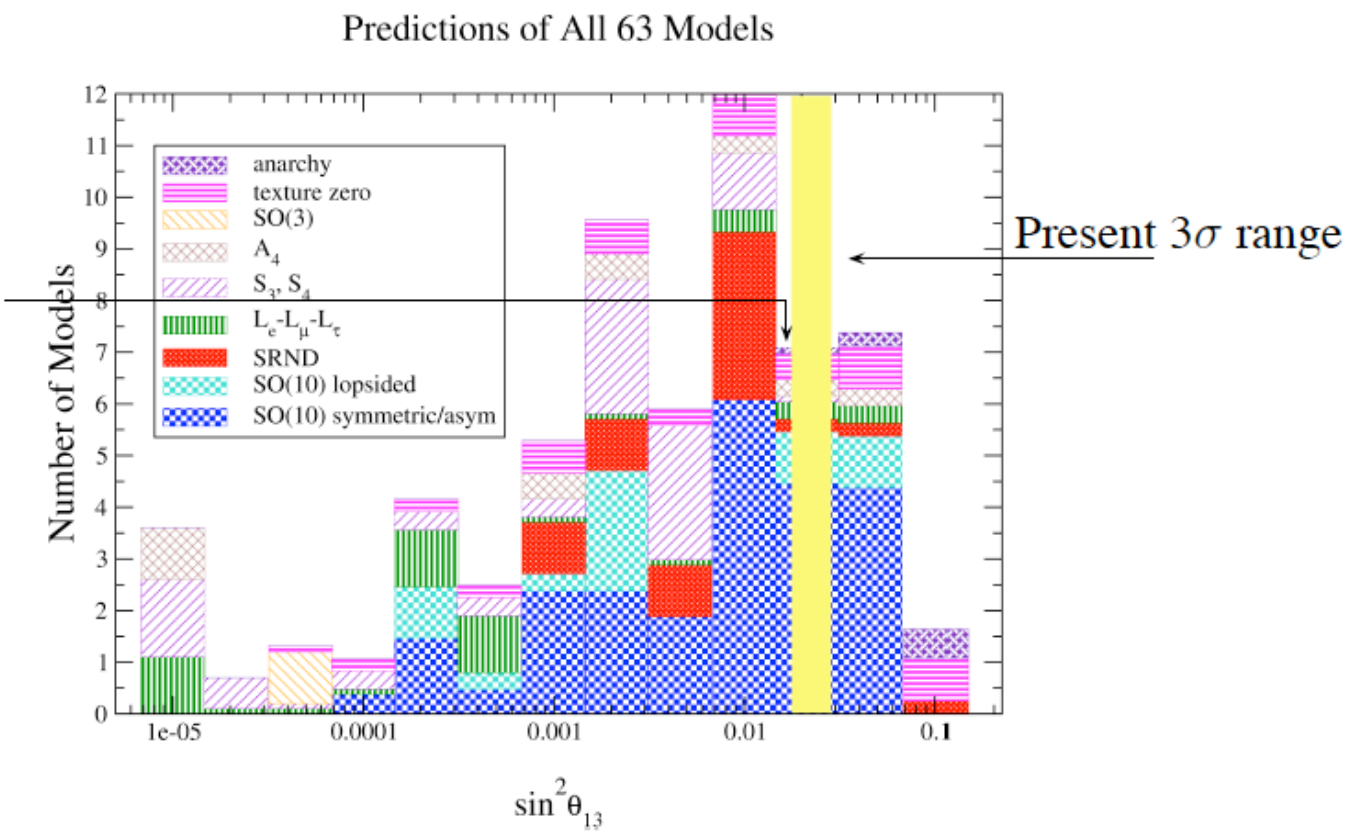
Ref: Iachello, NDM2012

Theoretical Progress

Neutrino Mixing Models

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

Only 7 got it right !



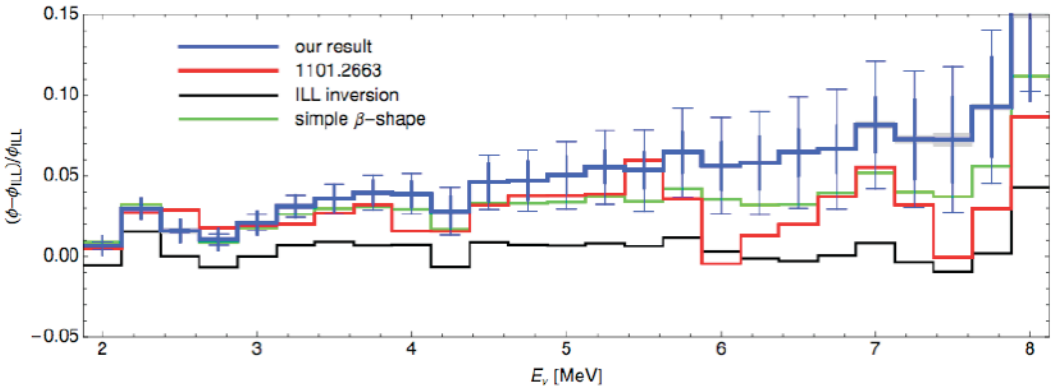
Gonzalez-Garcia et al, ICHEP2012

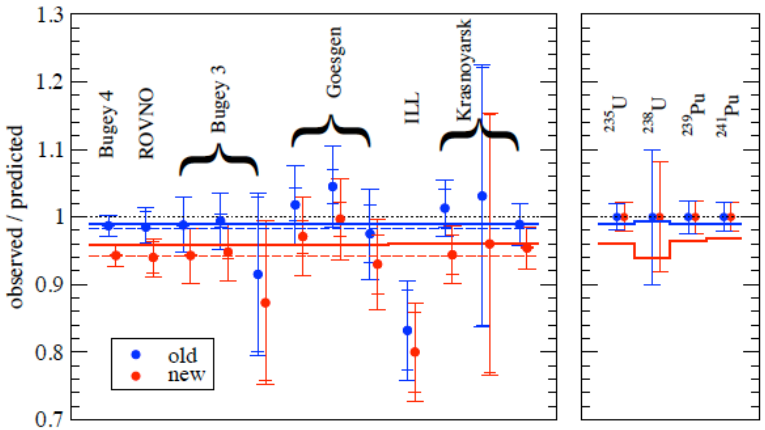
Theoretical Progress

Antineutrino Emission from Nuclear Reactors

Recently the reactor $\bar{\nu}_e$ fluxes have been recalculated

T.A. Mueller et al.,[arXiv:1101.2663].;P. Huber, [arXiv:1106.0687].

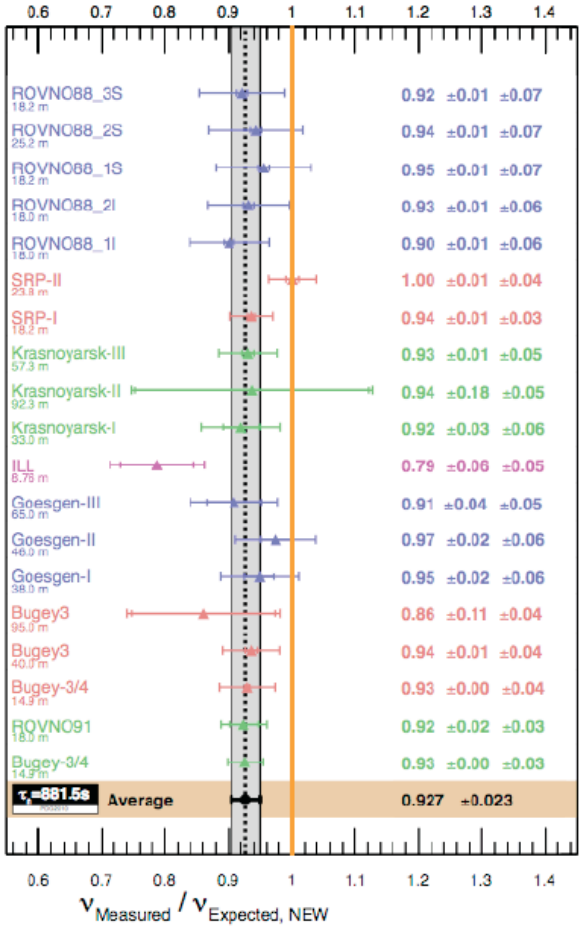




re-evaluations find higher fluxes by about 3.5%

^{235}U	^{239}Pu	^{241}Pu	^{238}U
3.7%	4.2%	4.7%	9.8%

Reactor Anomaly

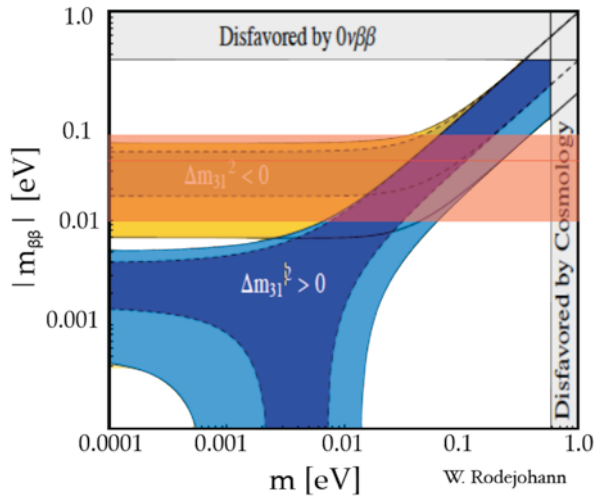


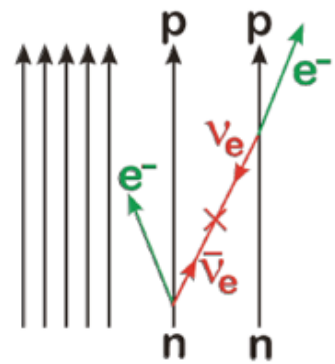
Ref: Mention et al, 1101.2755 (2012 upd)

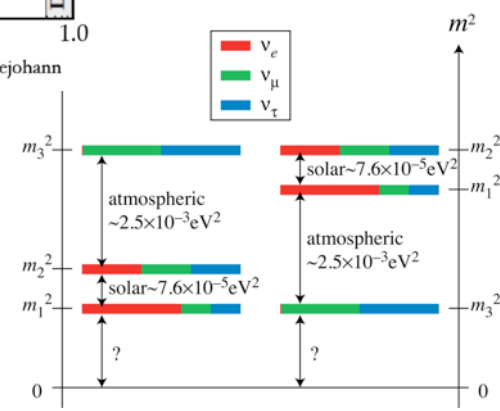
2020 and Beyond

Long-Term Scientific Questions in 3-ν Framework

- 0νββ
  - towards a1-ton experiment
  - confirm/measure with different nuclei
- absolute neutrino mass
  - KATRIN operations
  - confirm/improve with Project 8 or ECHO?
- Mass hierarchy
- δ_{CP}
- precision solar spectroscopy
(Sun as a calibrated source of neutrinos)



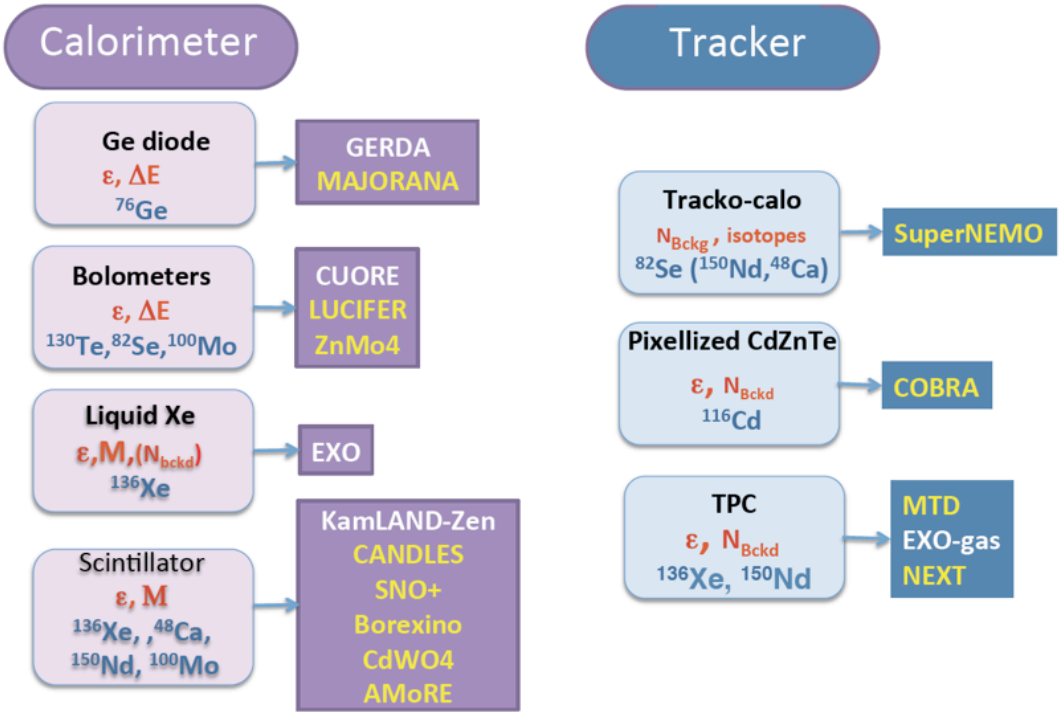




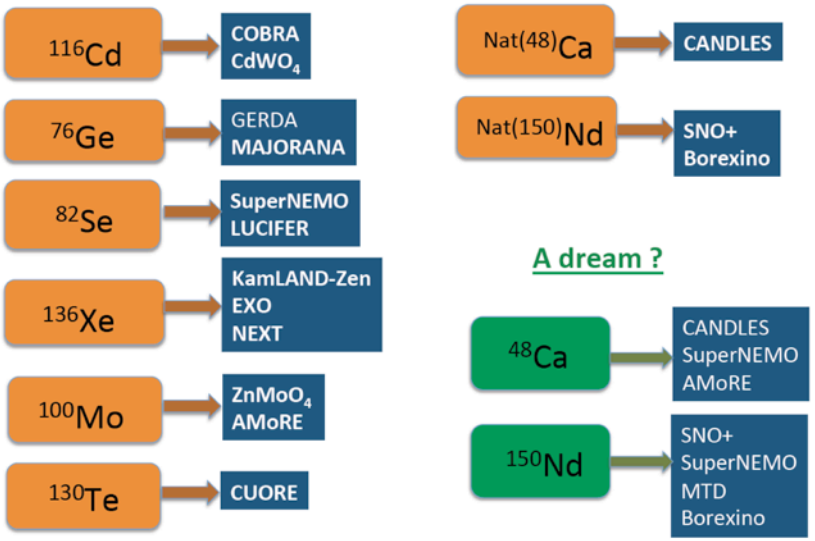
If neutrino anomalies are confirmed and evidence for sterile neutrinos....

Next-Generation 0νββ Experiments

Techniques



Isotopes



- many R&D efforts
- few options scale for a a 1-ton experiment
- improvements of backgrounds needed, active background discrimination helpful

Fig: Piquemal, Nu2012

see S. Elliott's talk

Next-Generation 0νββ Experiments

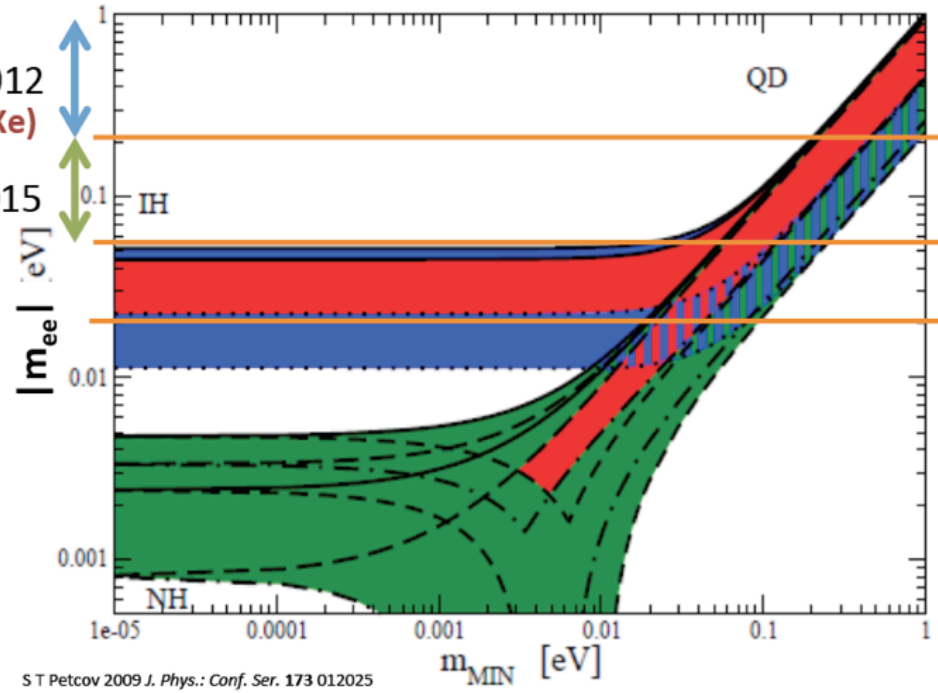
Sensitivity Goals

Isotope mass

~ 10 kg 2012
(200 – 400kg ^{136}Xe)

~ 100 kg 2015

~ 1000 kg



S T Petcov 2009 *J. Phys.: Conf. Ser.* **173** 012025

Required background level in the ROI

100 – 1000 cts/yr/ton

1 – 10 cts/yr/ton

0.1 – 1 cts/yr/ton

deep location important

not all isotopes or detectors scale to 1-ton experiment

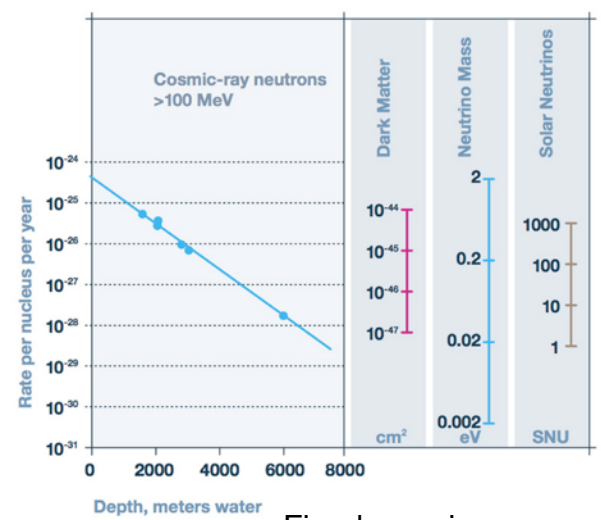


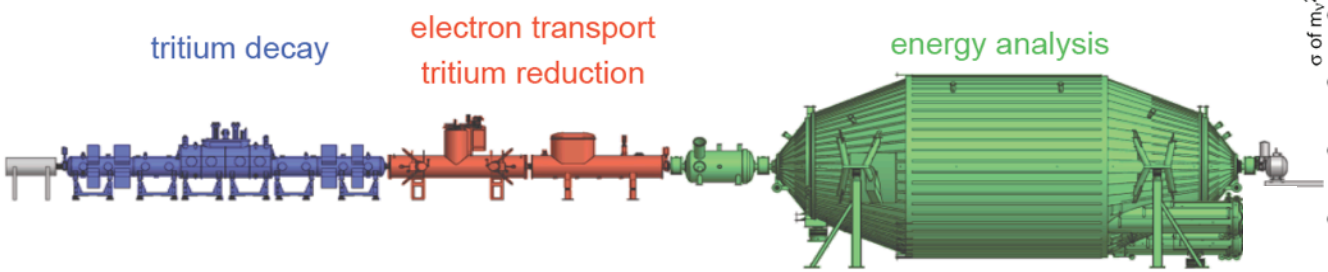
Fig: deepscience.org

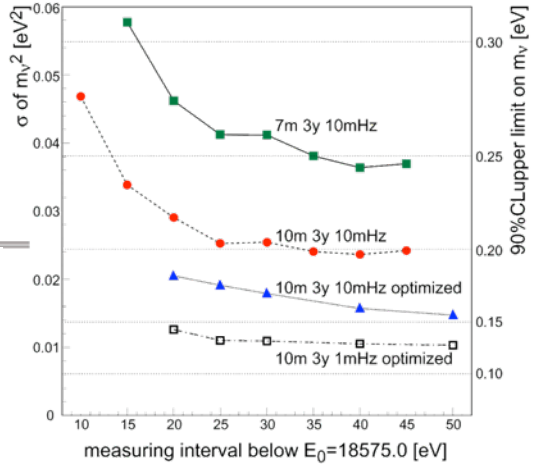
see S. Elliott's talk

Towards an Absolute Neutrino Mass Measurement

KATRIN

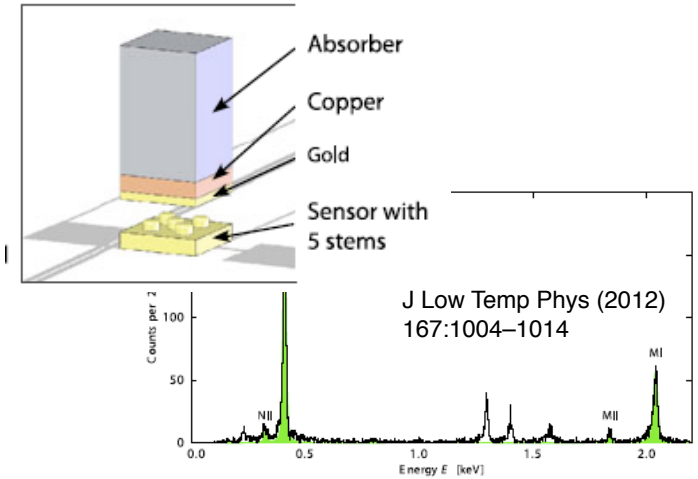
under construction, expected data taking in 2015





EC on ^{163}Ho

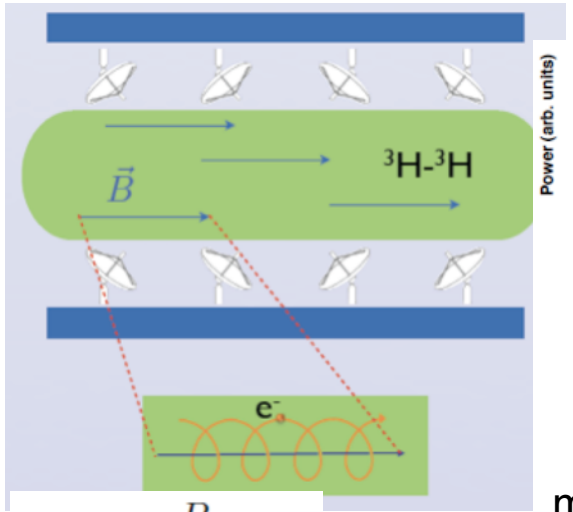
R&D



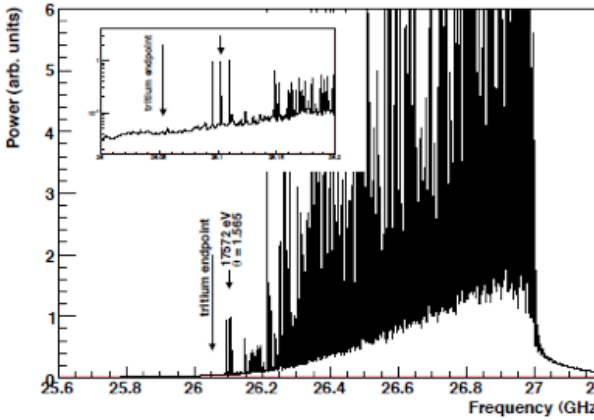
low-temperature metallic magnetic calorimeters to study both ^{187}Re and ^{163}Ho.

Project 8

R&D



$$\omega = \frac{qB}{\gamma m} \equiv \frac{\omega_c}{\gamma}$$

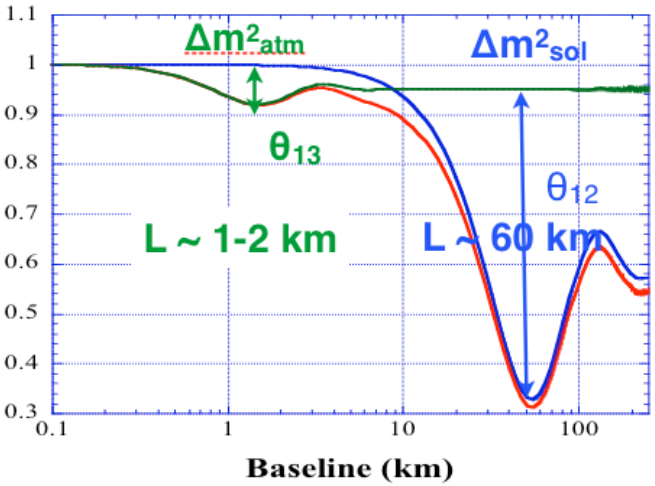


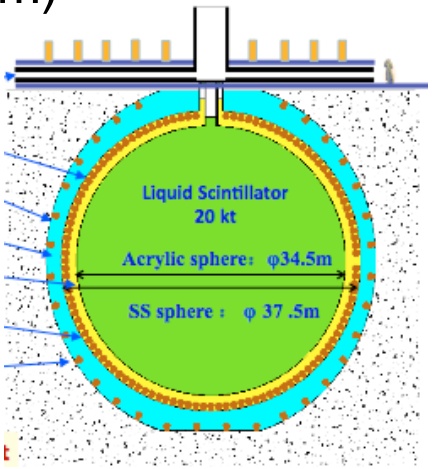
measure β-frequency
proof of principle underway

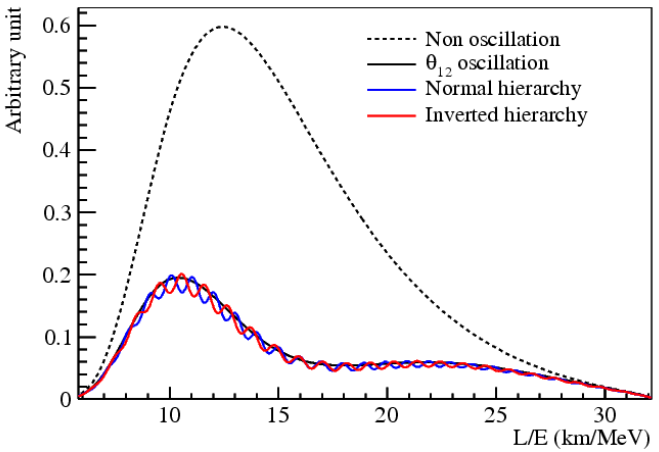
Reactor Neutrinos and Mass Hierarchy

Daya Bay II (and RENO 50km)

Fig: Y. Wang, NuFact2012



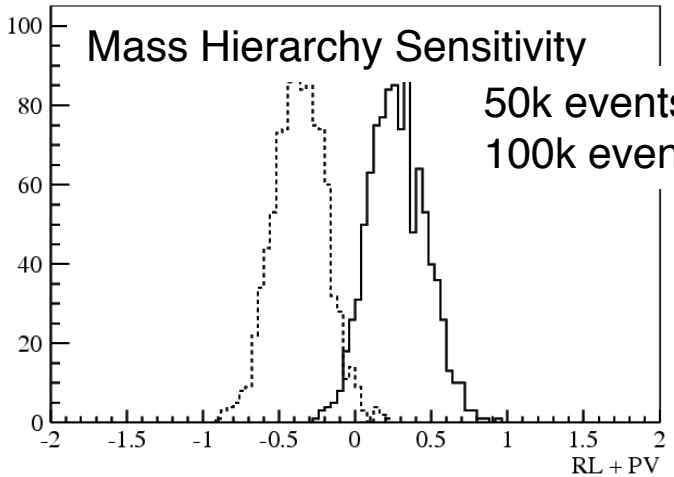




determine mass hierarchy from precisio measurements of $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$

$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$
$$\text{NH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$
$$\text{IH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

Δm^2_{21} is only 3% of $|\Delta m^2_{32}|$

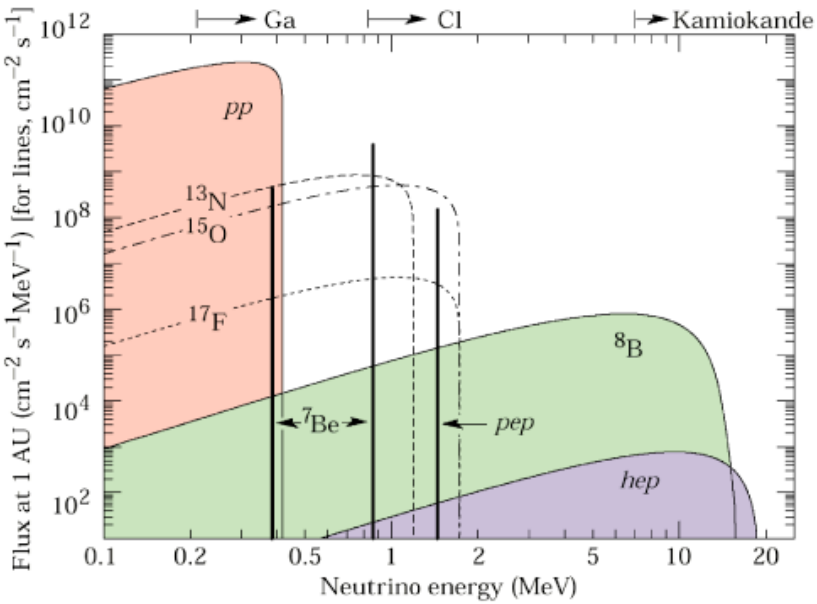


50k events, 3 years → 96%
100k events → 3σ

must understand energy scale non-linearity at fraction of %

Qian et al. arXiv: 1208.1551

Precision Solar Spectroscopy



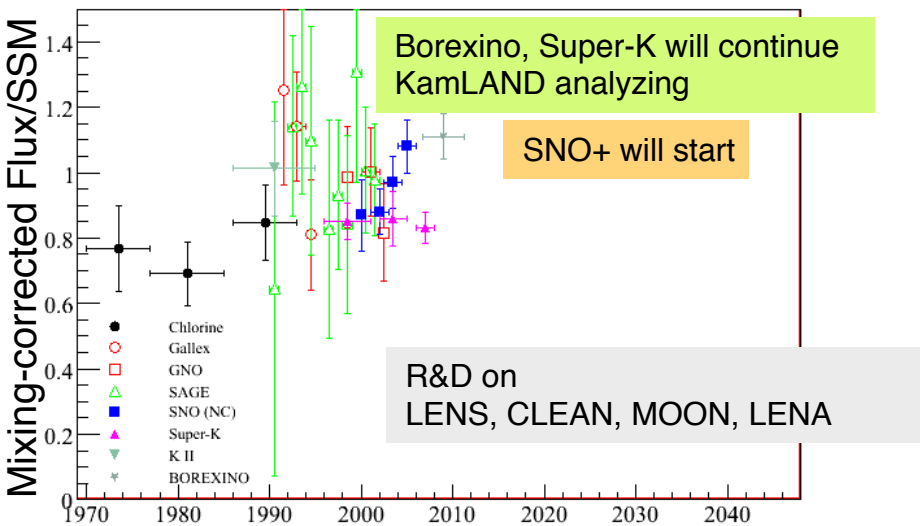


Fig: Klein, Intensity Frontier 2011

Solar Neutrino Physics Topics

- **exclusive, precision measurement of pp flux**
  - Test luminosity constraint
- **exclusive precision measurement of CNO flux**
  - Resolve solar metallicity
- improved measurement of pep flux
  - Probe vacuum-matter transition region
  - Search for new physics and/or confirm MSW
- Low-energy 8B measurement with LS detectors
  - Probe transition region, search for predicted upturn

With luminosity constraint:

$$\phi(\mathrm{pp})_{\mathrm{measured}} = (1.02 \pm 0.02 \pm 0.01)\phi(\mathrm{pp})_{\mathrm{theory}}$$
$$\phi(^8\mathrm{B})_{\mathrm{measured}} = (0.88 \pm 0.04 \pm 0.23)\phi(^8\mathrm{B})_{\mathrm{theory}}$$
$$\phi(^7\mathrm{Be})_{\mathrm{measured}} = (0.91^{+0.24}_{-0.62} \pm 0.11)\phi(^7\mathrm{Be})_{\mathrm{theory}}$$

Without constraint:

$L_\nu/L_\odot$ known to 20-40%

testing L integrates over a lot of new physics

Neutrino science is international

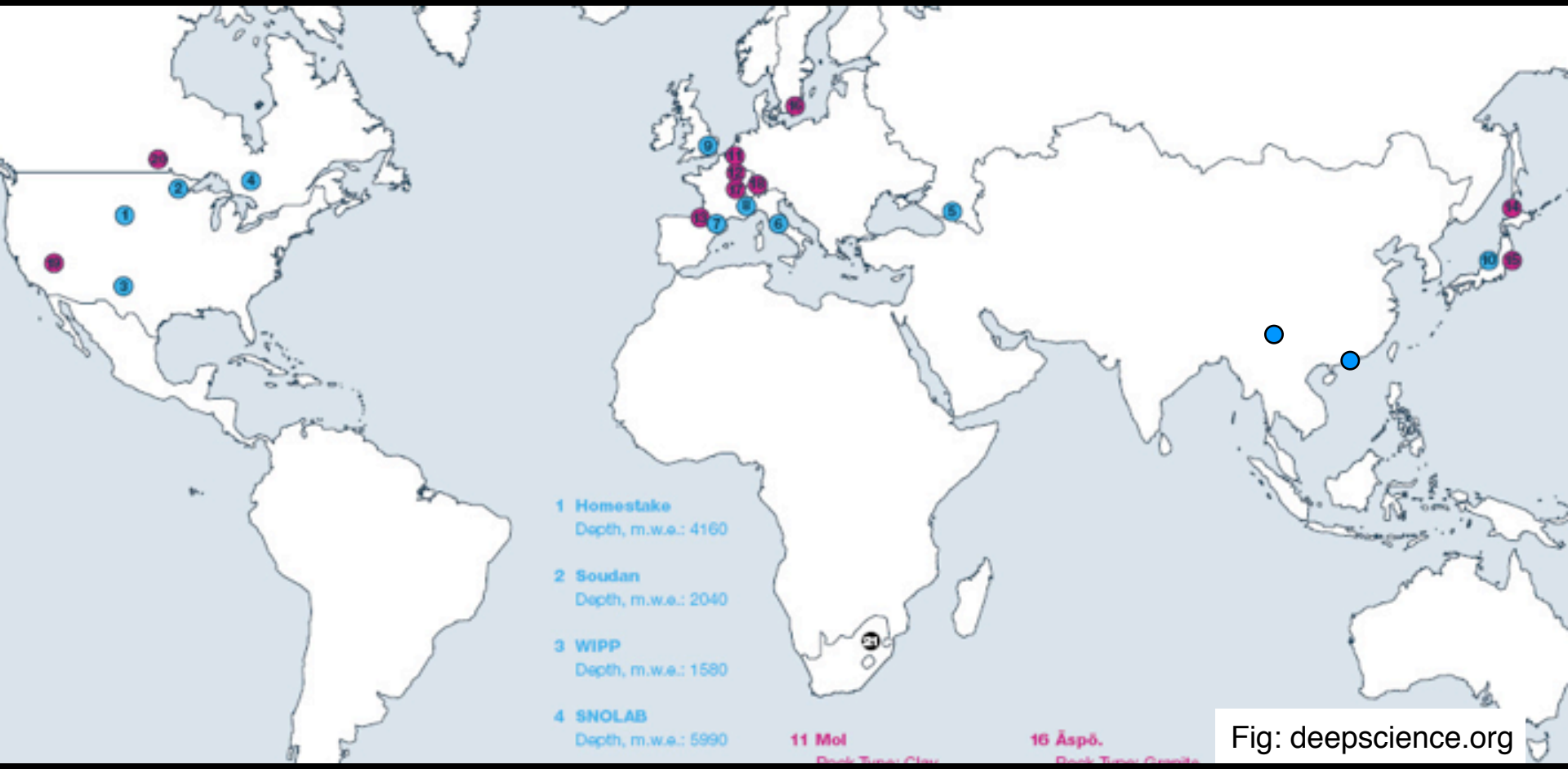


Fig: deepscience.org

many experiments require some kind of underground location

US neutrino physicists worldwide

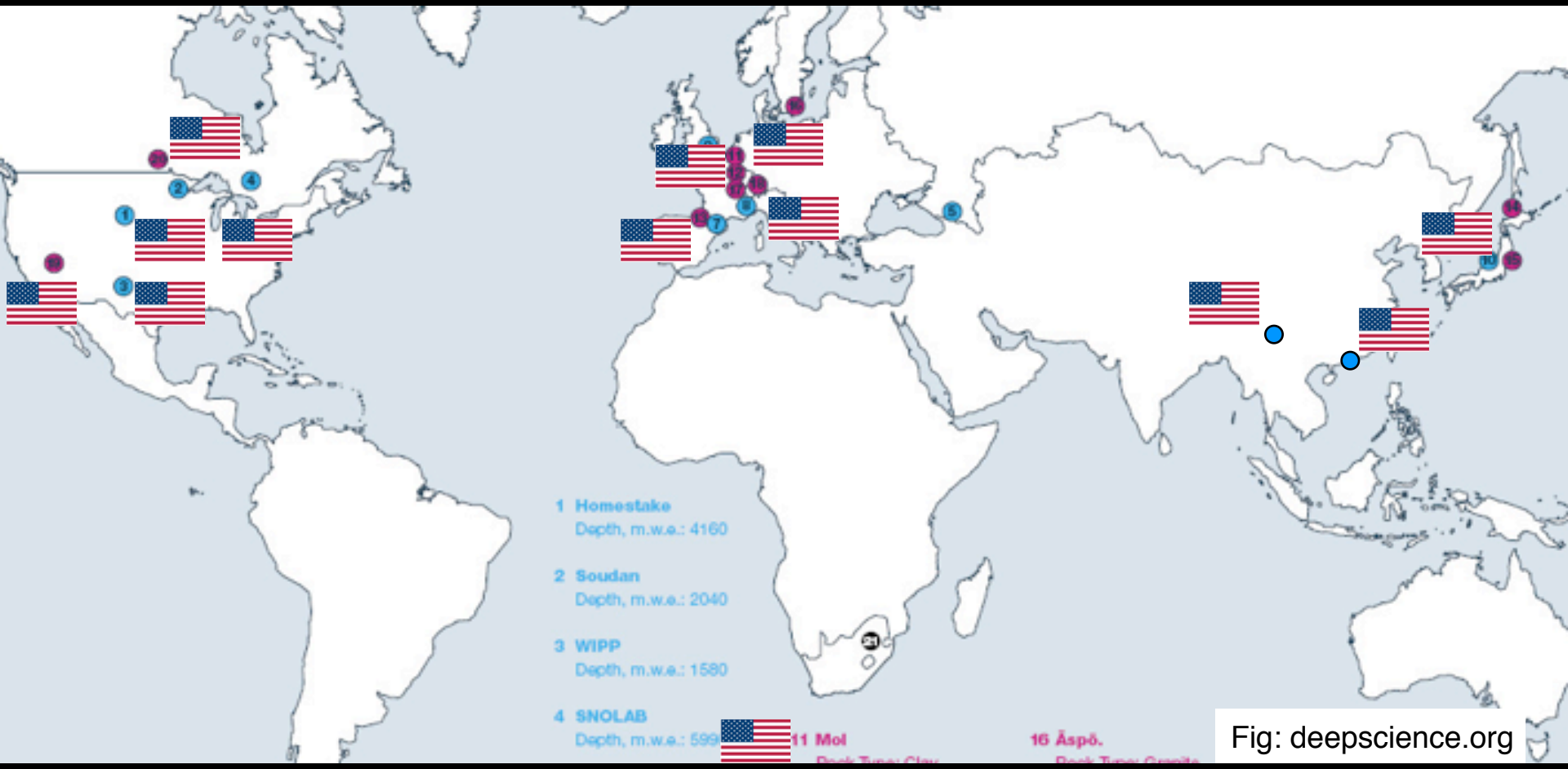


Fig: deepscience.org

US physicists engaged in many experiments overseas
many collaborations are truly international

see B. Plaster's talk

US neutrino physics worldwide

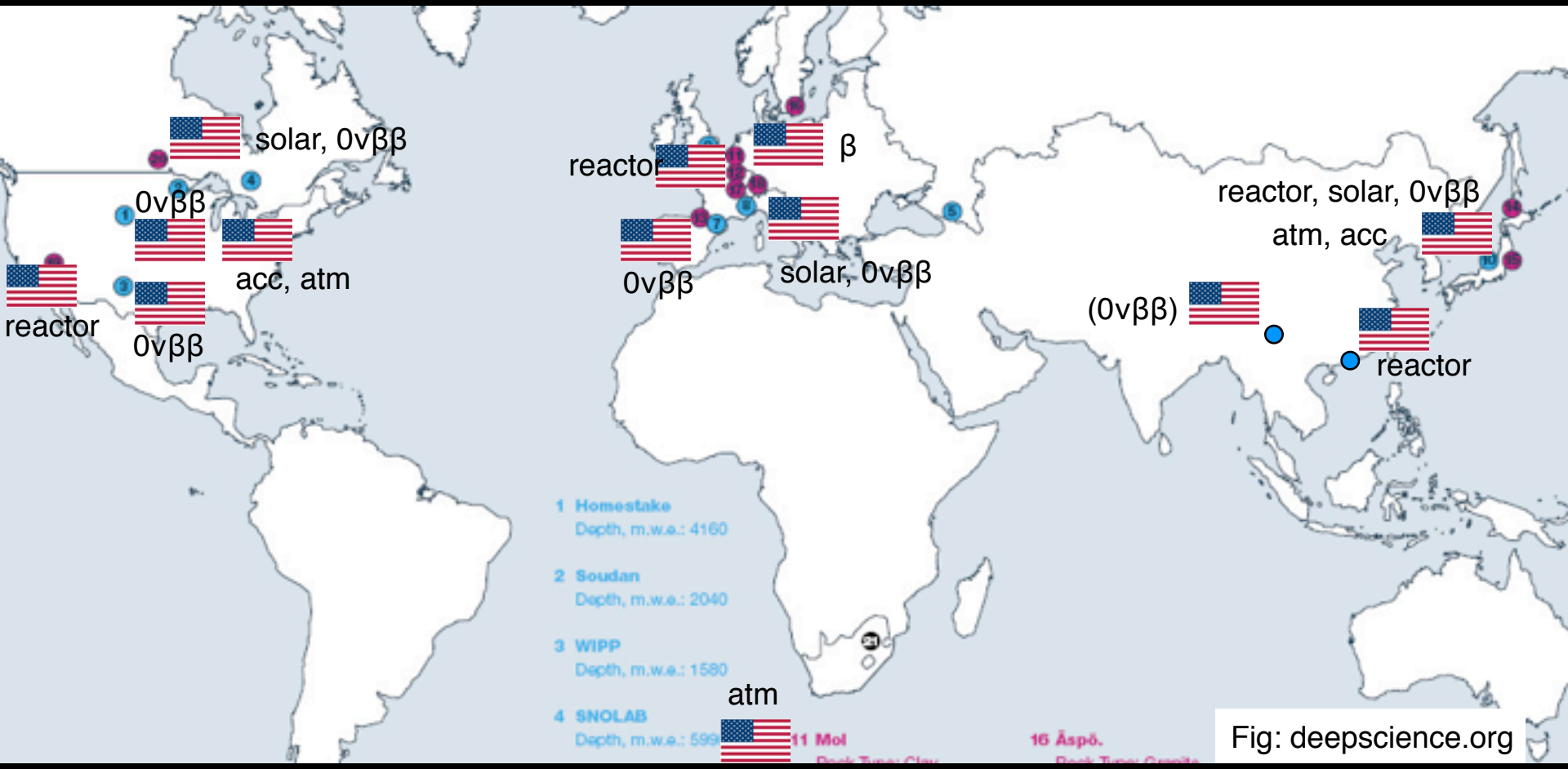


Fig: deepscience.org

recent discoveries in neutrino physics from international collaborations

- US leads 0νββ and acc experiments
- partners in reactor and 0νββ experiments
- participates in β-decay, solar and atm experiments

Summary

Neutrino experiments have been enormously successful.

Neutrino experiments address questions about the origin of mass and the flavor puzzle. Important for understanding physics beyond the SM.

Broad current and near-term program. Big questions require planning beyond 2020.

Nuclear physicists play a key role in neutrino science.

Recent discoveries enabled by international collaborations.

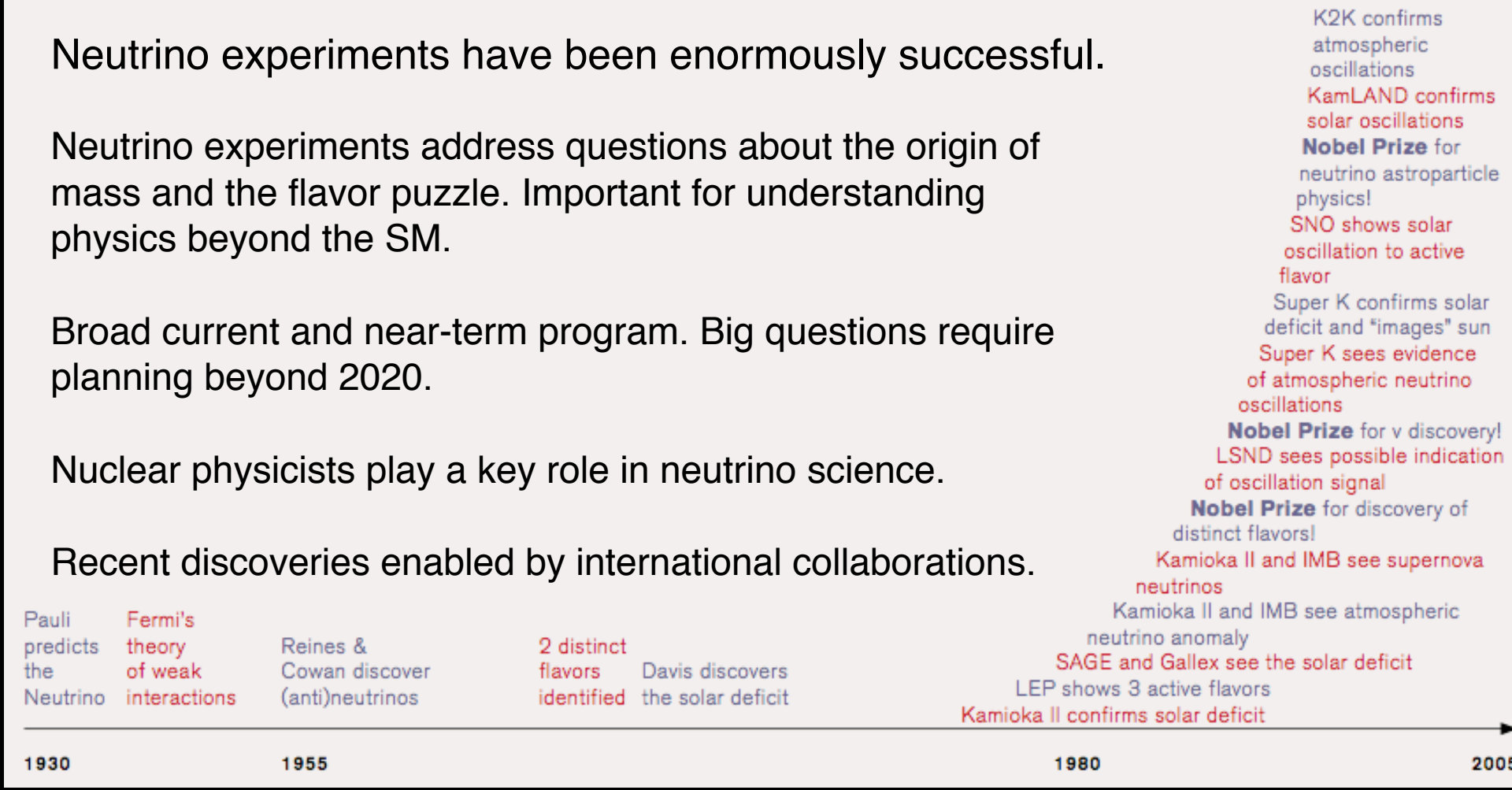


Fig: Neutrino Matrix, 2004

Thanks to many colleagues for slides, materials, and discussions