Neutrino physics (4-2)

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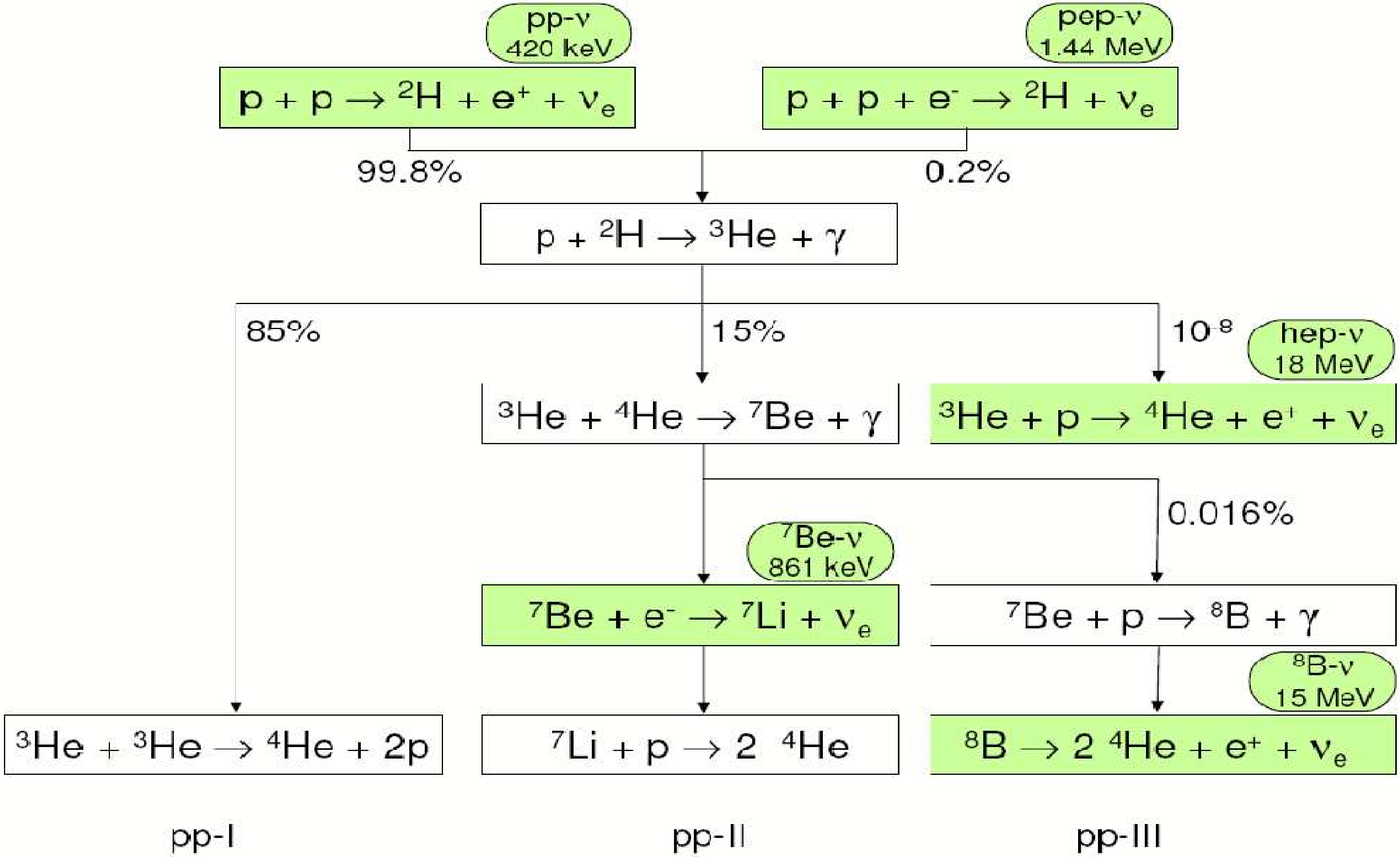
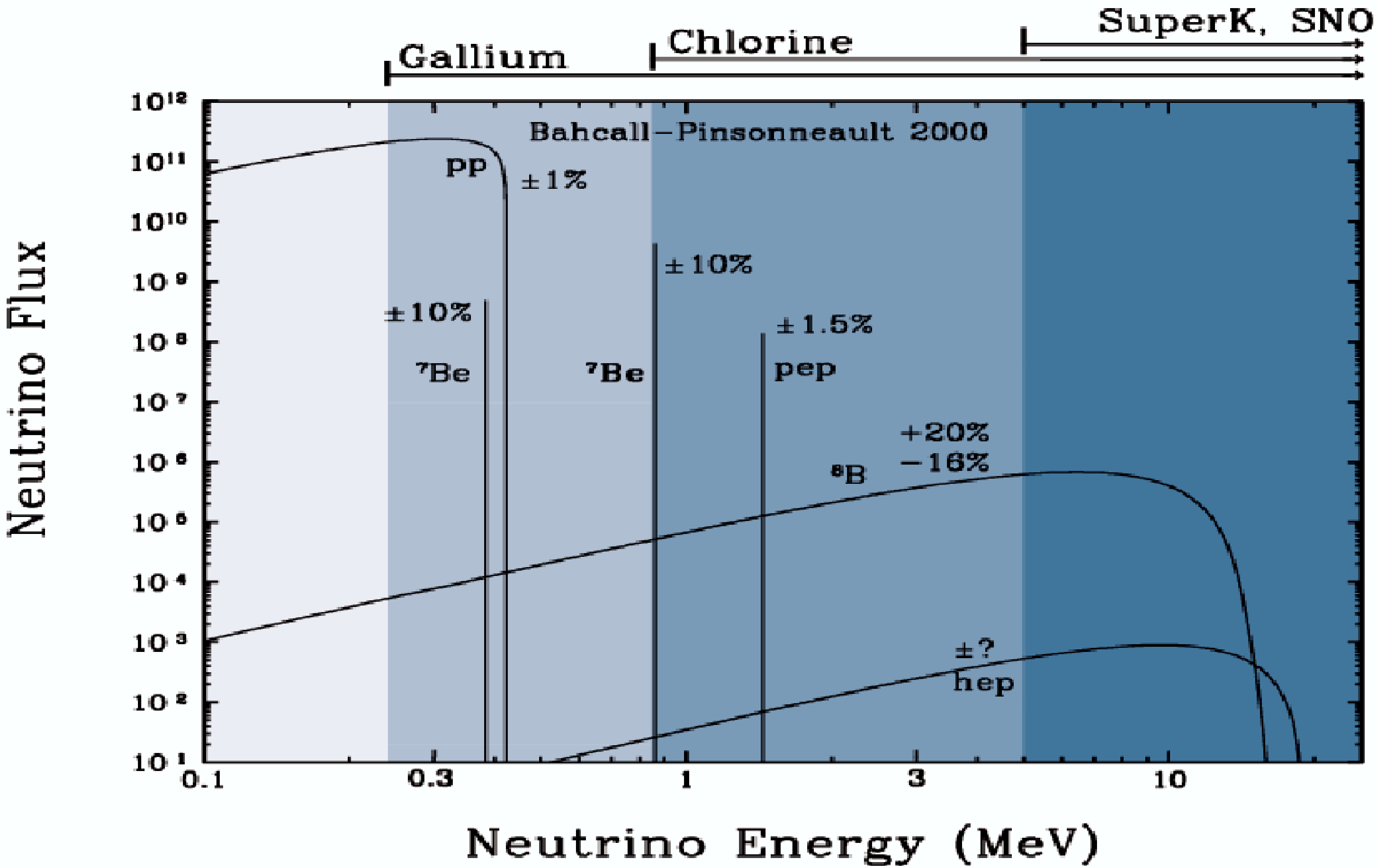
Solar neutrinos

Solar pp-cycle



Overall reaction: $4p \to \alpha + 2e^+ + 2\nu_e + 26.7$ MeV

Solar Neutrino Fluxes



Short history of solar ν experiments in 1 slide

70's-80's: Homestake (R. Davies): Radiochemistry: E_ν > 814 keV
- ✓ $^{37}Cl + \nu \rightarrow {}^{37}Ar + e^-$
- ✓ **THE FIRST DETECTION!** deficit in the observed flux, skepticism
- ✓ final triumph, **Nobel prize 2002**
- ✓ **J. Bahcall** continues the development of the Standard Solar Model

80's-90's: (super)Kamiokande: Water Cherenkov: E_ν > 5 MeV
- ✓ confirms deficit on ^8B-ν and with real-time technique
- ✓ first neutrino picture of the Sun (directionality)
- ✓ neutrinos from other stars observed (supernova SN1987-A)

90's: Gallex (GNO) and Sage: Radiochemistry: E_ν > 233 keV
- ✓ $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
- ✓ deficit observed also at low energy, but is energy dependent!

2001: SNO: Water Cherenkov: E_ν > 5 MeV
- ✓ **oscillation of solar neutrinos proved**
- ✓ CC (electron flavor) and NC (all flavors) interactions separately in **D_2O**
- ✓ total flux agrees with Standard Solar Model !

2002: KamLAND: Liquid scintillator
- ✓ observes and measures oscillations of electron anti-neutrinos from reactors;

2007: Borexino: Liquid scintillator of extreme radiopurity: : E_ν > 303 keV
- ✓ First real-time observation of ^7Be, pep, pp neutrinos
- ✓ best limit on CNO
- ✓ Low-energy ^8B neuttrinos (> 3 MeV recoiled e^-)

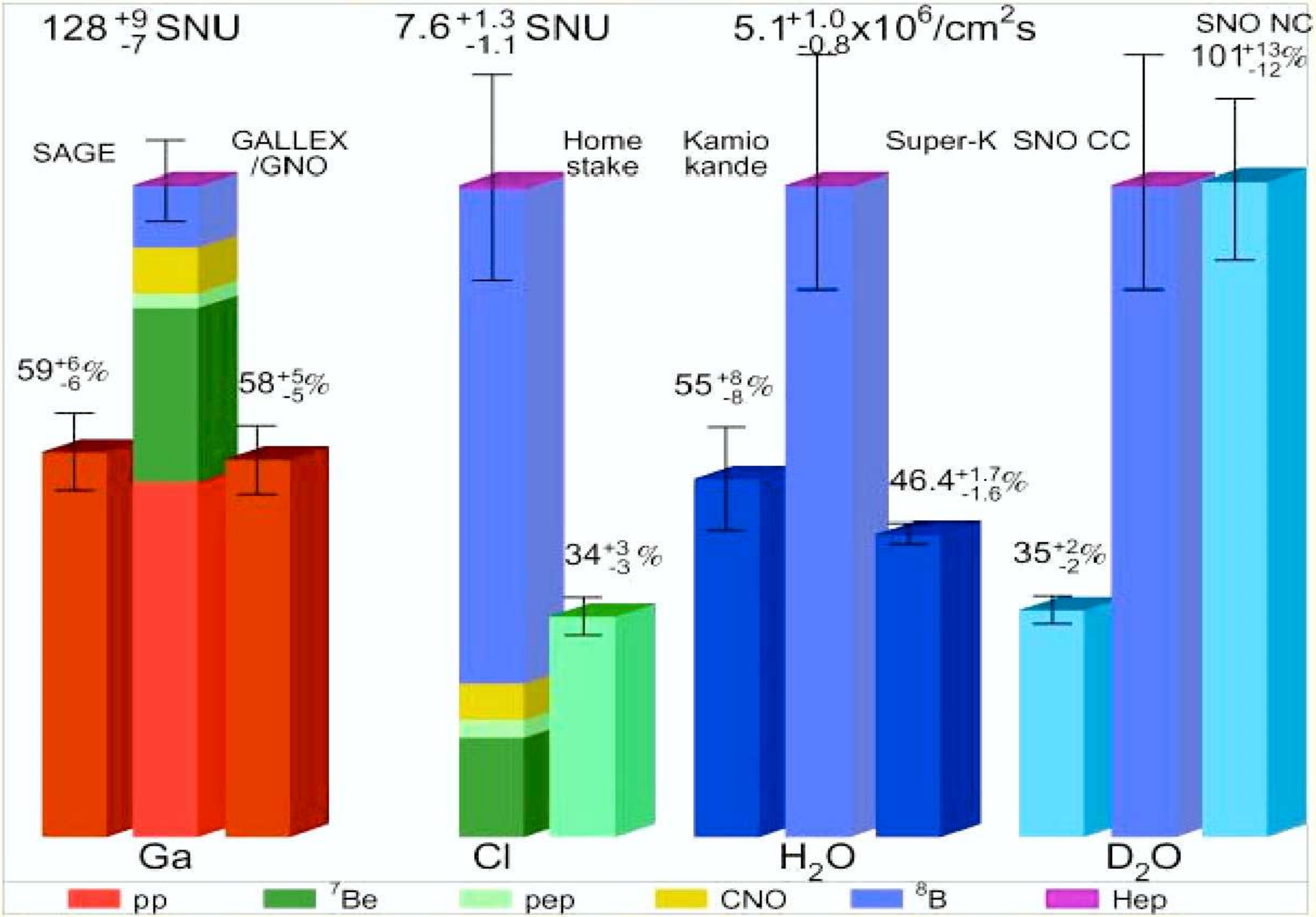
First detection

Solar-neutrino puzzle

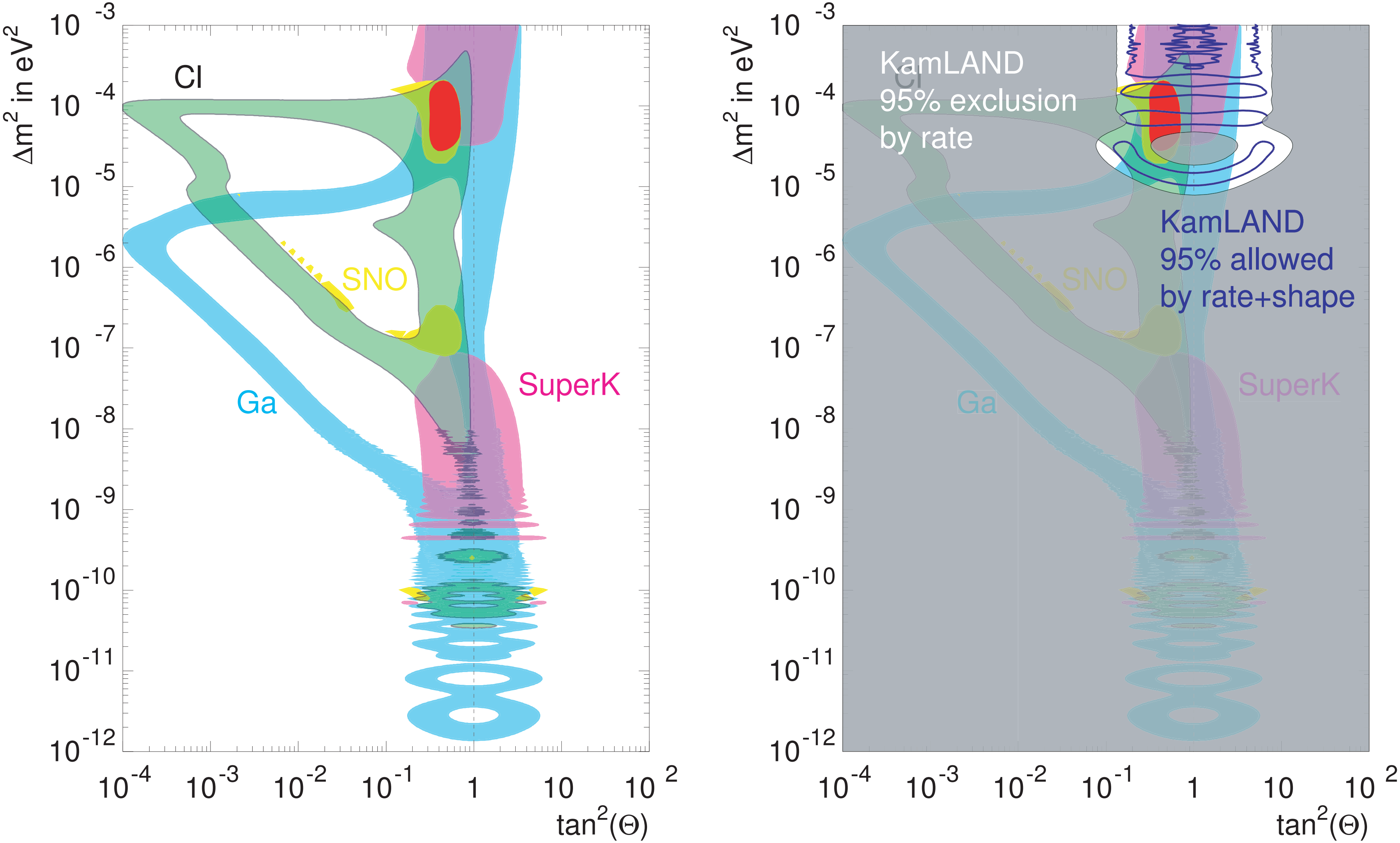
Solution:
Neutrino oscillations!

Real-time
precision spectroscopy

Solar ν Problem

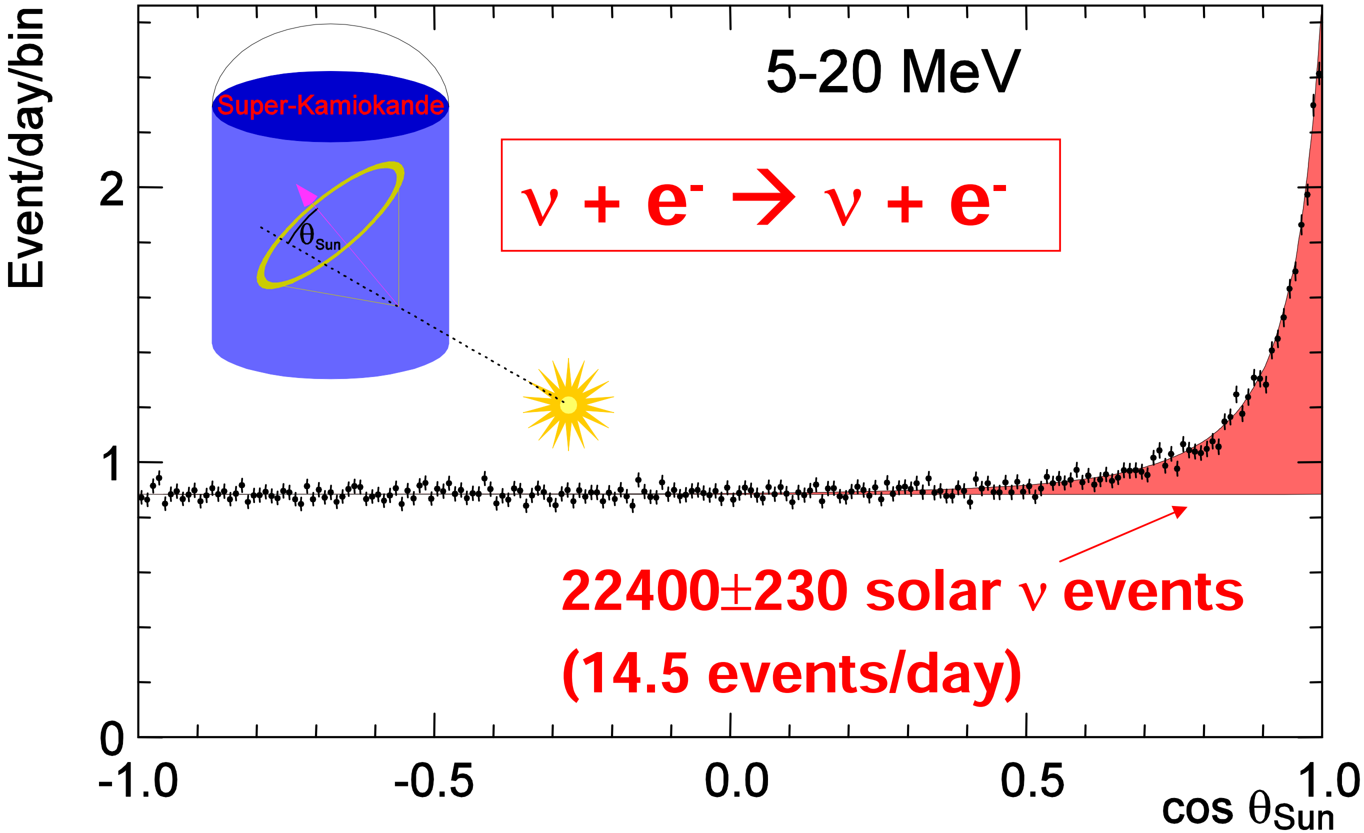


Michael Smy, UC Irvine


Cl
SNO
SuperK
Ga
KamLAND
95% exclusion
by rate
KamLAND
95% allowed
by rate+shape
Δm^2 in eV^2
$\tan^2(\Theta)$

Super-Kamiokande-I solar neutrino data

May 31, 1996 – July 13, 2001 (1496 days)

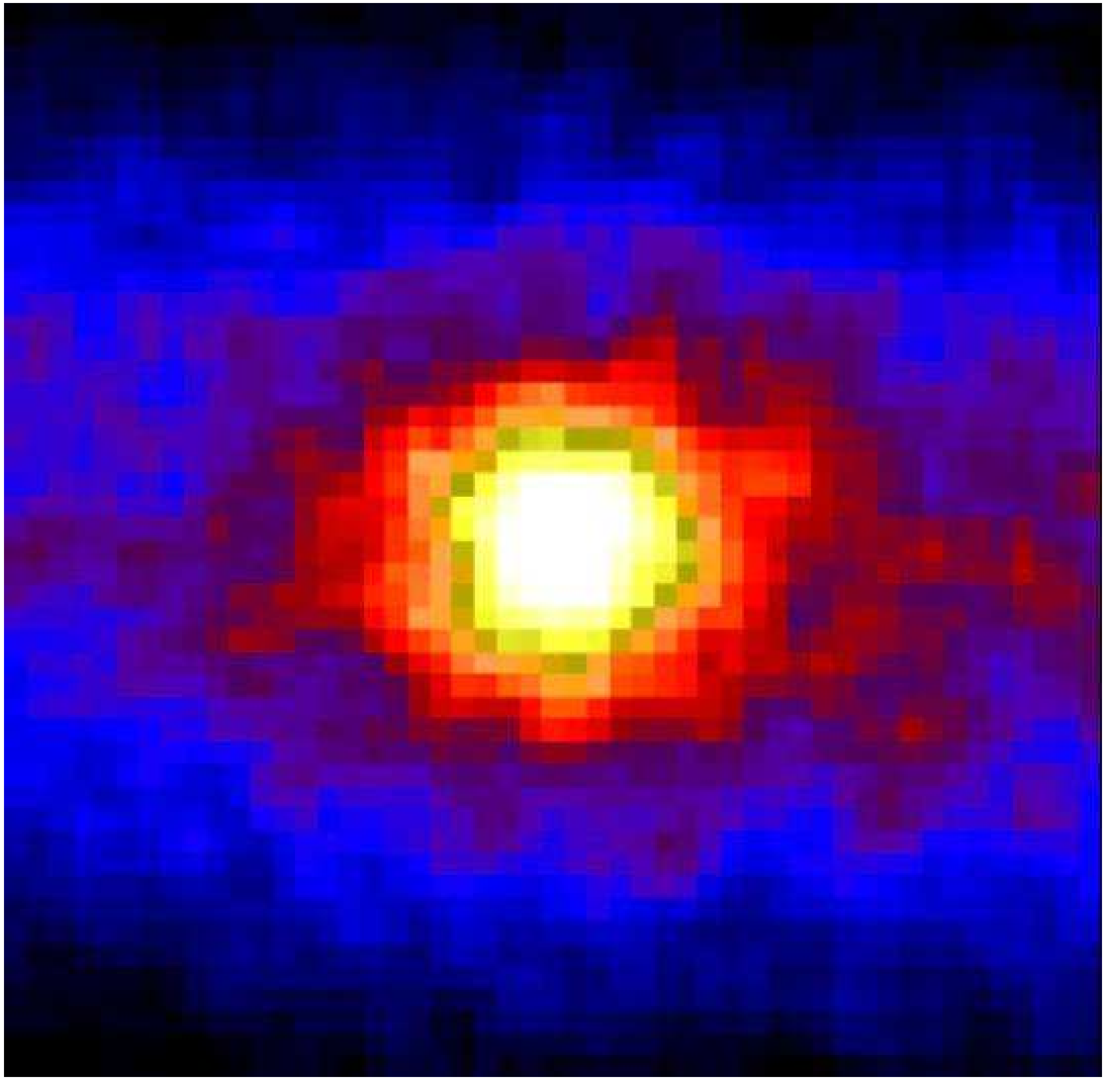


^{8}B flux : 2.35 ± 0.02 ± 0.08 [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 \,^{+0.014}_{-0.013}$$

(Data/SSM(BP2000) = 0.465 ±0.005 +0.016/-0.015)

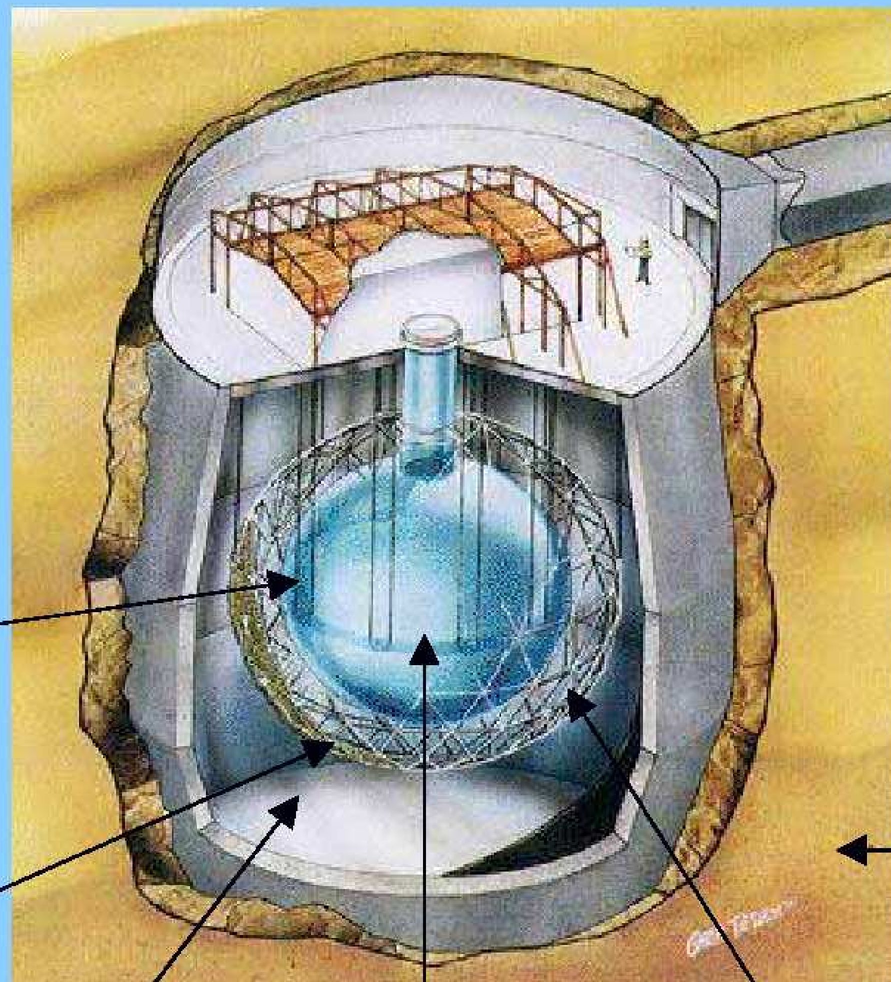
Seeing the Sun underground



The Sun still shines!

The SNO Detector

2039 m to surface



9438 Inward-Looking PMTs

91 Outward Looking PMTs (Veto)

12 m diameter Acrylic vessel

Norite Rock

PMT Support Structure (PSUP)

5300 tonnes light water

1000 tonnes heavy water

1700 tonnes light water

Neutrino Reactions in SNO

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

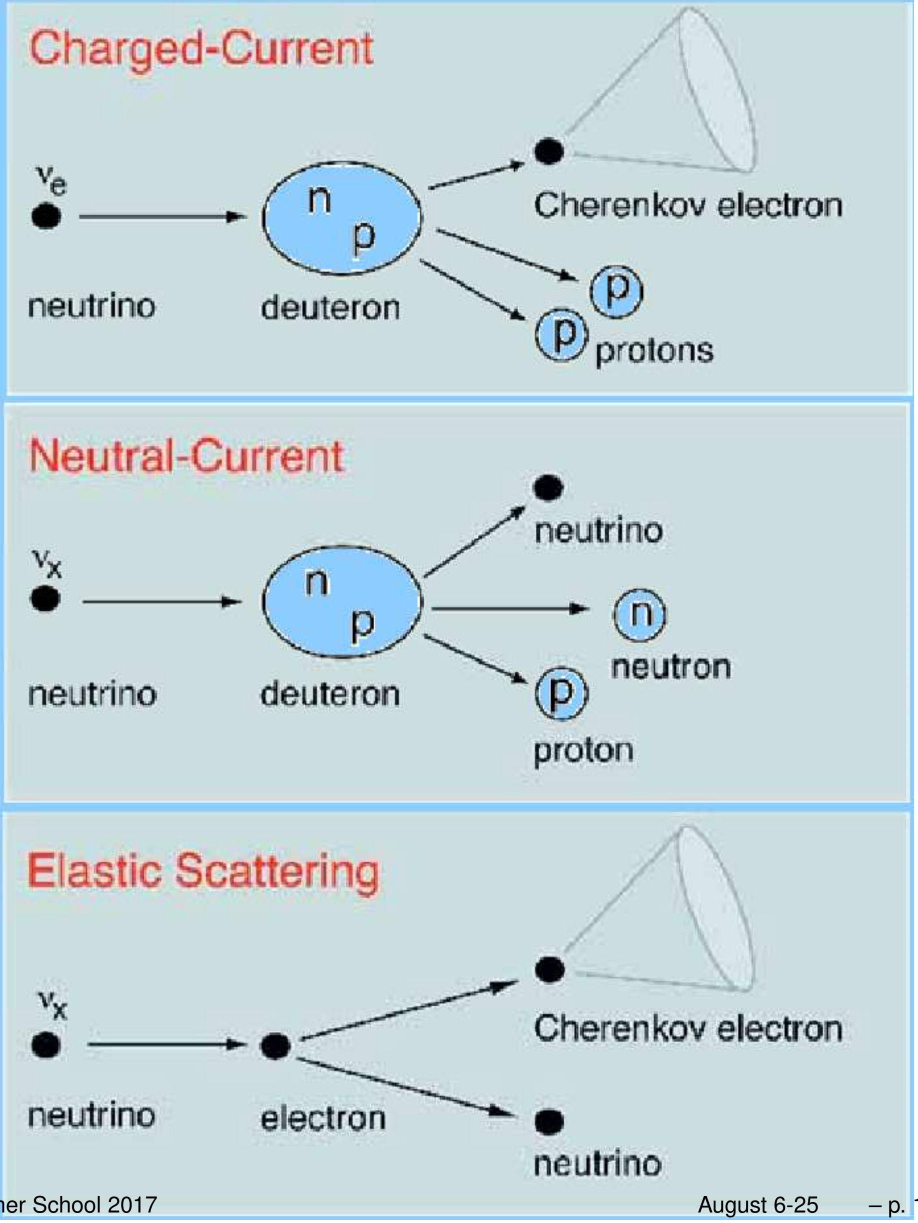
- Q = 1.445 MeV
- good measurement of ν_e energy spectrum
- some directional info $\propto (1 - 1/3 \cos\theta)$
- ν_e only

NC $\nu_x + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{n} + \nu_x$

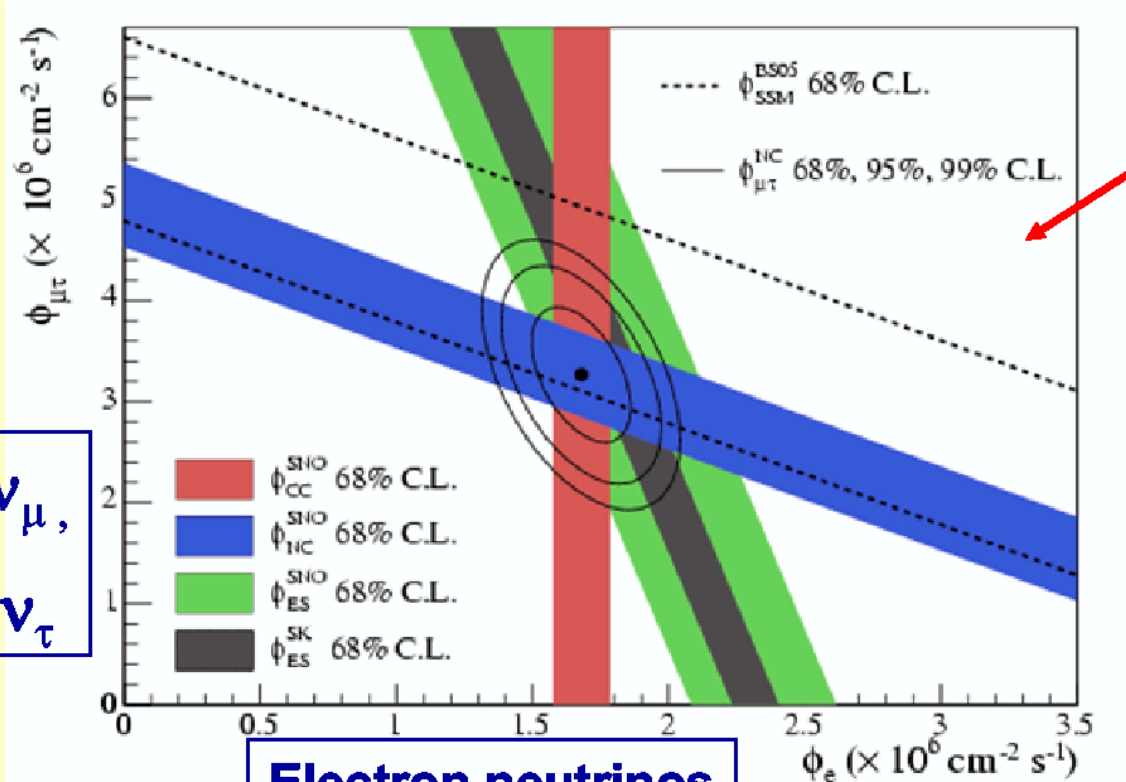
- Q = 2.22 MeV
- measures total ^{8}B ν flux from the Sun
- equal cross section for all ν types

ES $\nu_x + \mathrm{e}^- \rightarrow \nu_x + \mathrm{e}^-$

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity



ν_μ, ν_τ



Electron neutrinos

Flavor change determined by > 7 σ.

CC, NC FLUXES MEASURED INDEPENDENTLY

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

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

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

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

The Total Flux of Active Neutrinos is measured independently (NC) and agrees well with solar model Calculations:

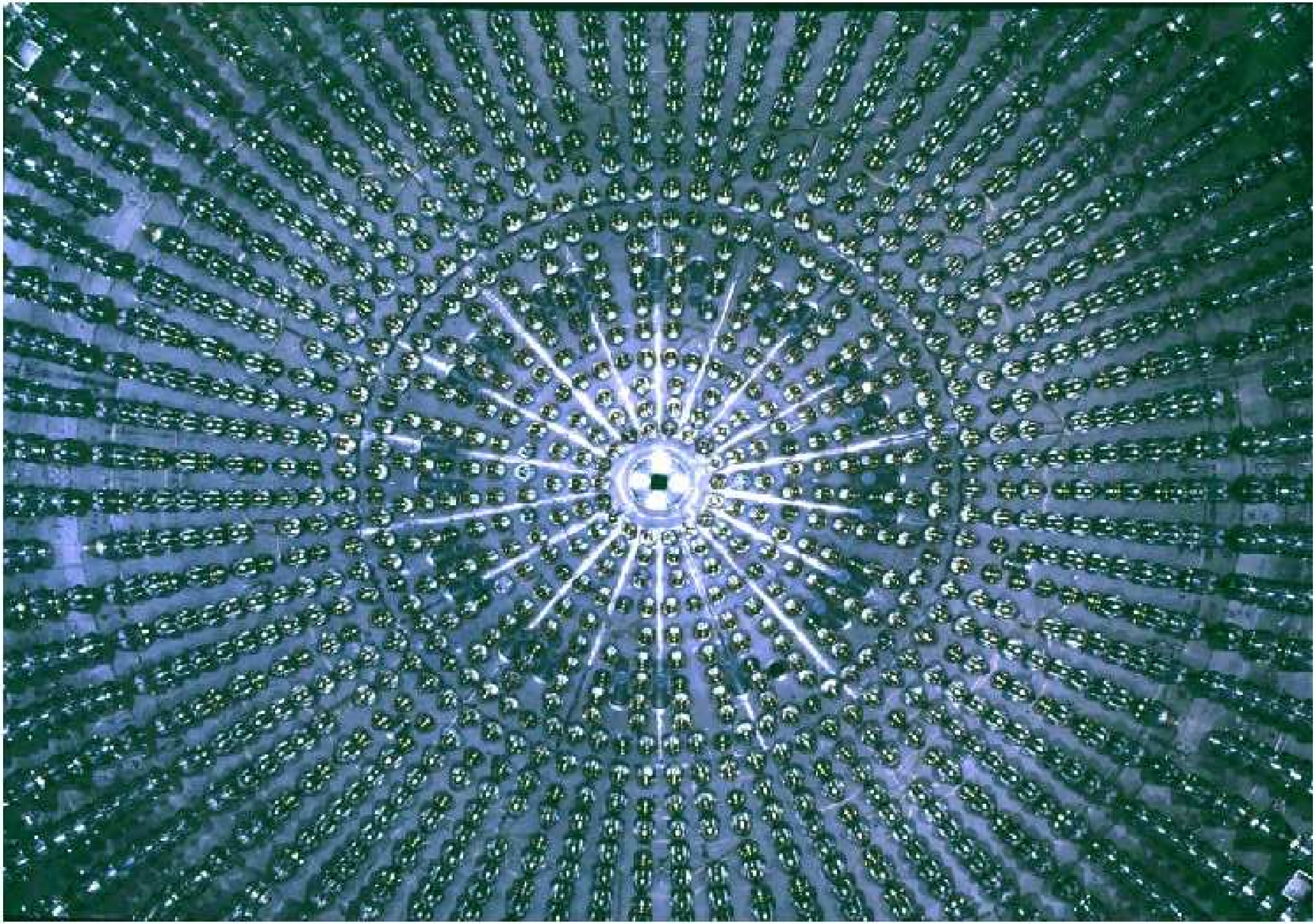
5.82 +- 1.3 (Bahcall et al),

5.31 +- 0.6 (Turck-Chieze et al)

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031} = \cos^4\theta_{13}\sin^2\theta_{12}$$

Improved accuracy for θ_{12}.

Borexino experiment in Gran Sasso



Latest results from Borexino   Meeting of the SFB/TR27 "Neutrinos and Beyond" – KIT, June 13,2008   S. Schönert, MPI für Kernphysik, Heidelberg

•Borexino is located under the Gran Sasso mountain which provides a shield against cosmic rays (4000 m water equivalent);

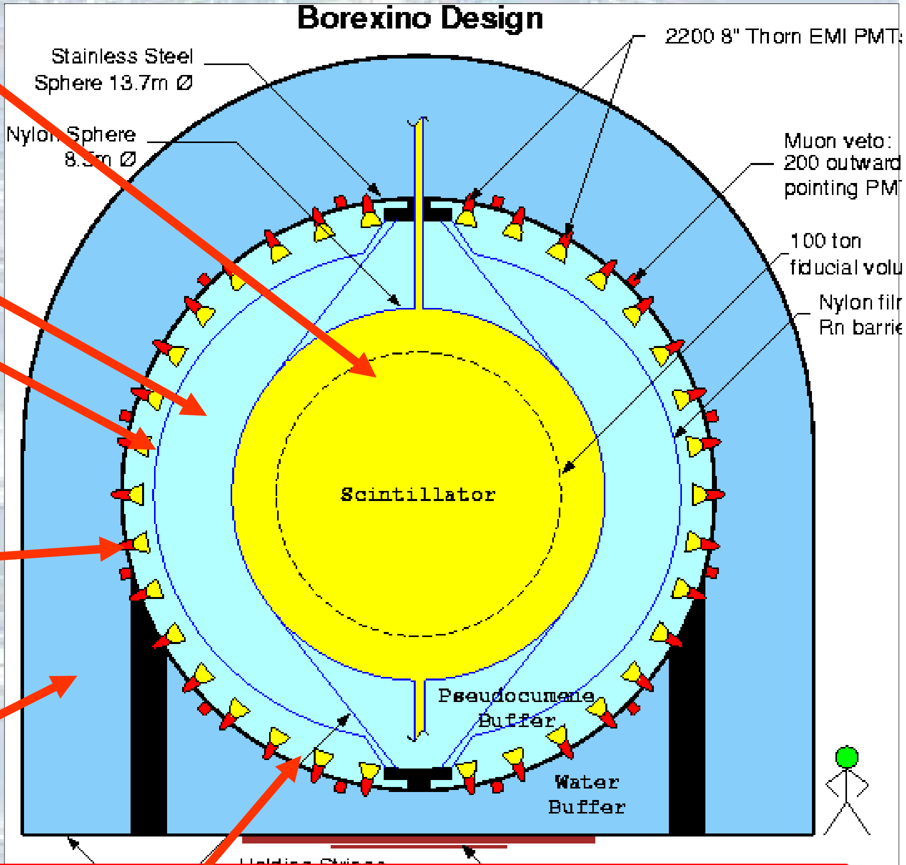
Core of the detector: 278 tons of liquid scintillator contained in a nylon vessel of 4.25 m radius (PC+PPO);

1st shield: 890 tons of ultra-pure buffer liquid (PC+quencher) contained in a stainless steel sphere of 6.75 m radius;

External nylon vessel; it is a barrier against Rn emitted by PMT and s.steel

2214 photomultipliers pointing towards the center to view the light emitted by the scintillator (1843 with opt. concentr.)

2nd shield: 2100 tons of ultra-pure water contained in a cylindrical dome;



200 PMTs mounted on the SSS pointing outwards to detect light emitted in the water by muons crossing the detector;

Implications of solar ^{7}Be neutrino result

- Borexino exp. result:

  $49 \pm 3_{stat} \pm 4_{sys}$ / (d 100t)
- Solar model (***high*** metallicity, neutrino mixing, MSW): **48 ± 4 / (d 100t)**
- Solar model (***low*** metallicity, neutrino mixing, MSW): **44 ± 4 / (d 100t)**
- Solar model, but no neutrino mixing:

  74 ± 4 / (d 100t)

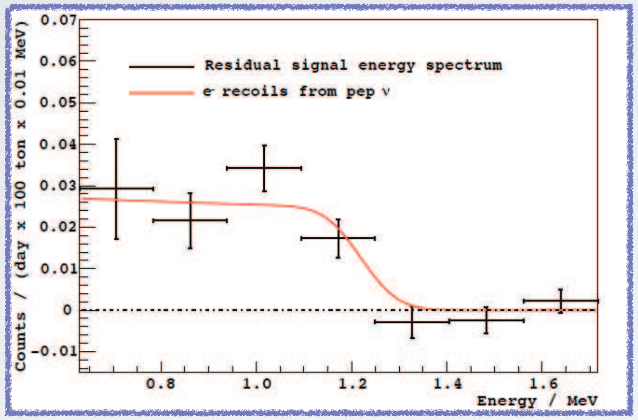
Clear confirmation of neutrino mixing and MSW

L. Oberauer, TUM

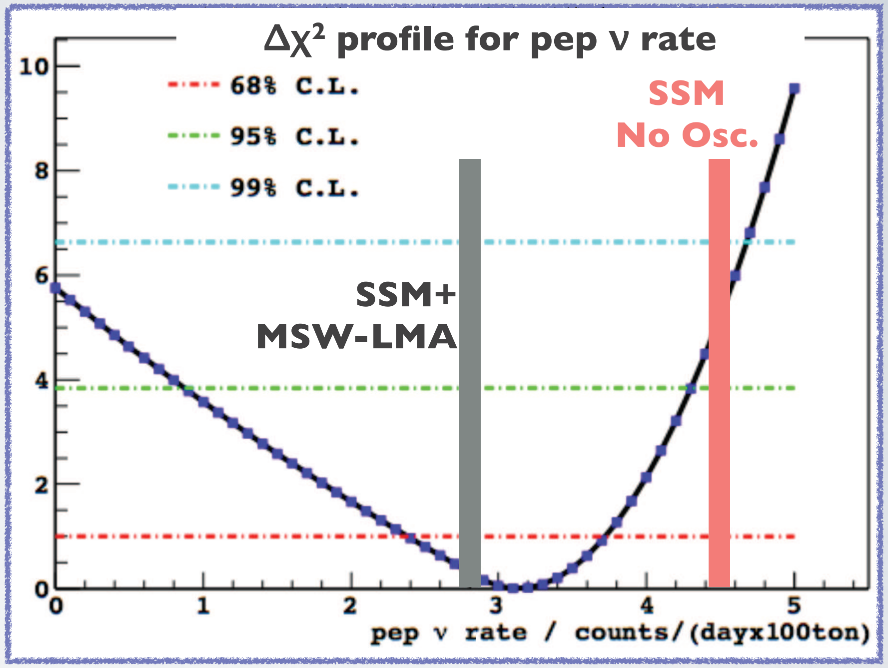
FIRST DETECTION OF PEP NEUTRINOS (V)

- Rate: **3.1 ± 0.6$_{(stat)}$ ± 0.3$_{(sys)}$ cpd/100 t**

PRL 108, 051302 (2012)

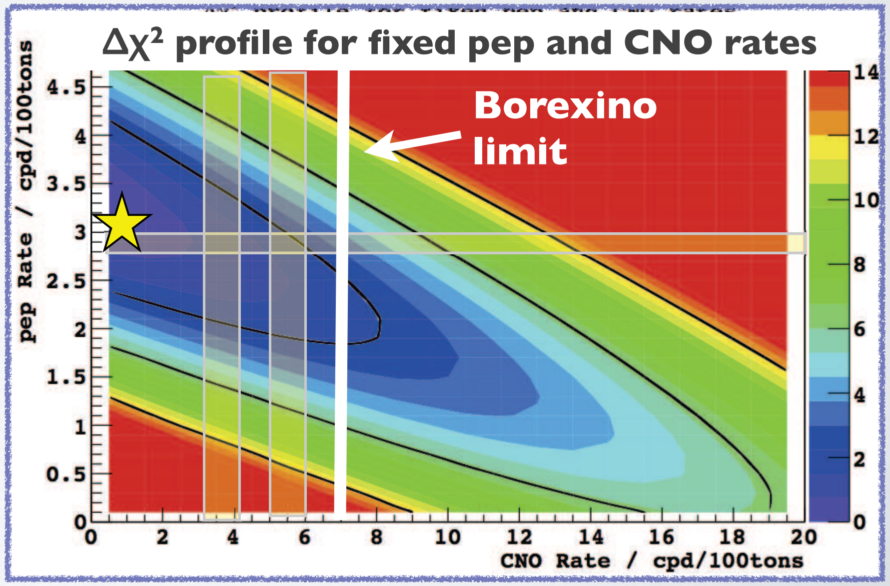


- No oscillations excluded at **97% c.l.**
- Absence of pep solar ν excluded at 98%



- Assuming MSW-LMA:
  - $\Phi_{pep} = 1.6 \pm 0.3\ 10^8\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

- CNO limit obtained assuming pep @ SSM



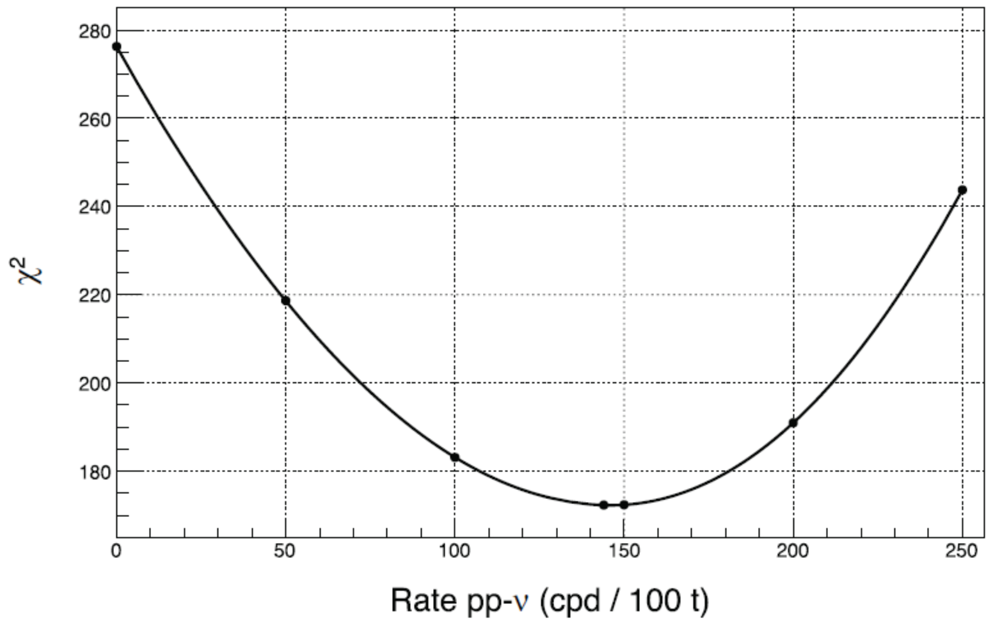
- **CNO rate < 7.1 cpd/100 t (95% c.l.)**

First real-time measurement of pp-neutrino flux (~11% precision)

pp = 144 ± 13 (stat) ± 10 (syst) cpd/100 t

compared to expected (MSW/LMA,HM)

131±2 cpd/100 t



pp neutrino flux:

$(6.6 \pm 0.7) \cdot 10^{10}$ $cm^{-2}s^{-1}$

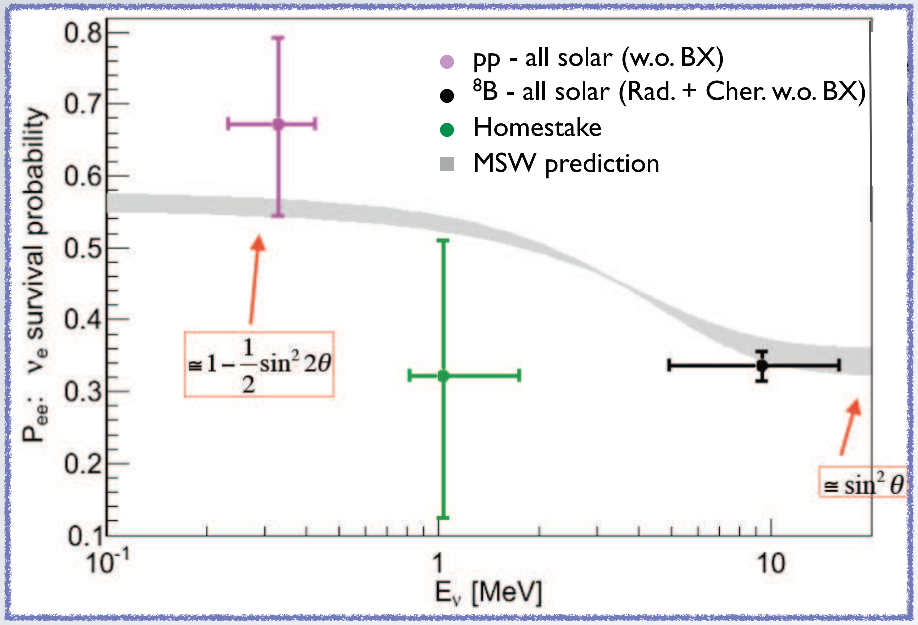
vs

$(5.98 \pm 0.04) \cdot 10^{10}$ $cm^{-2}s^{-1}$

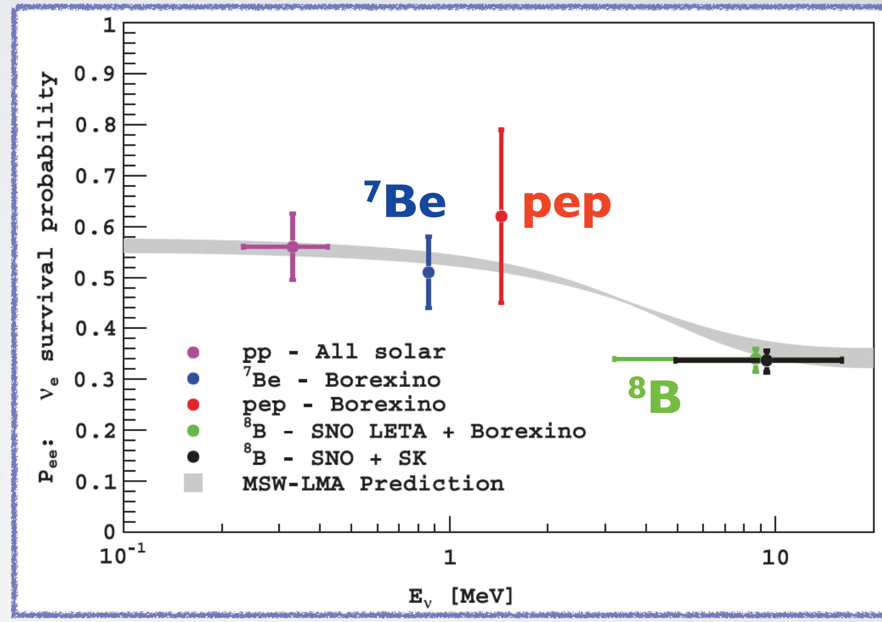
Zero pp count is excluded at 10σ level

BOREXINO IMPACT ON SOLAR NEUTRINO PHYSICS

Before Borexino

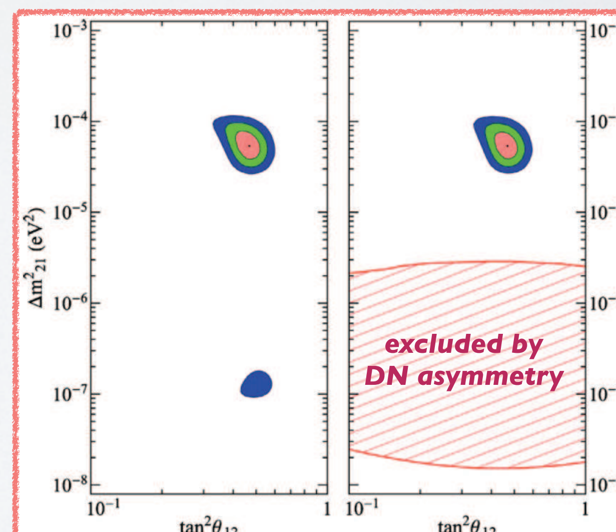


Borexino 2012

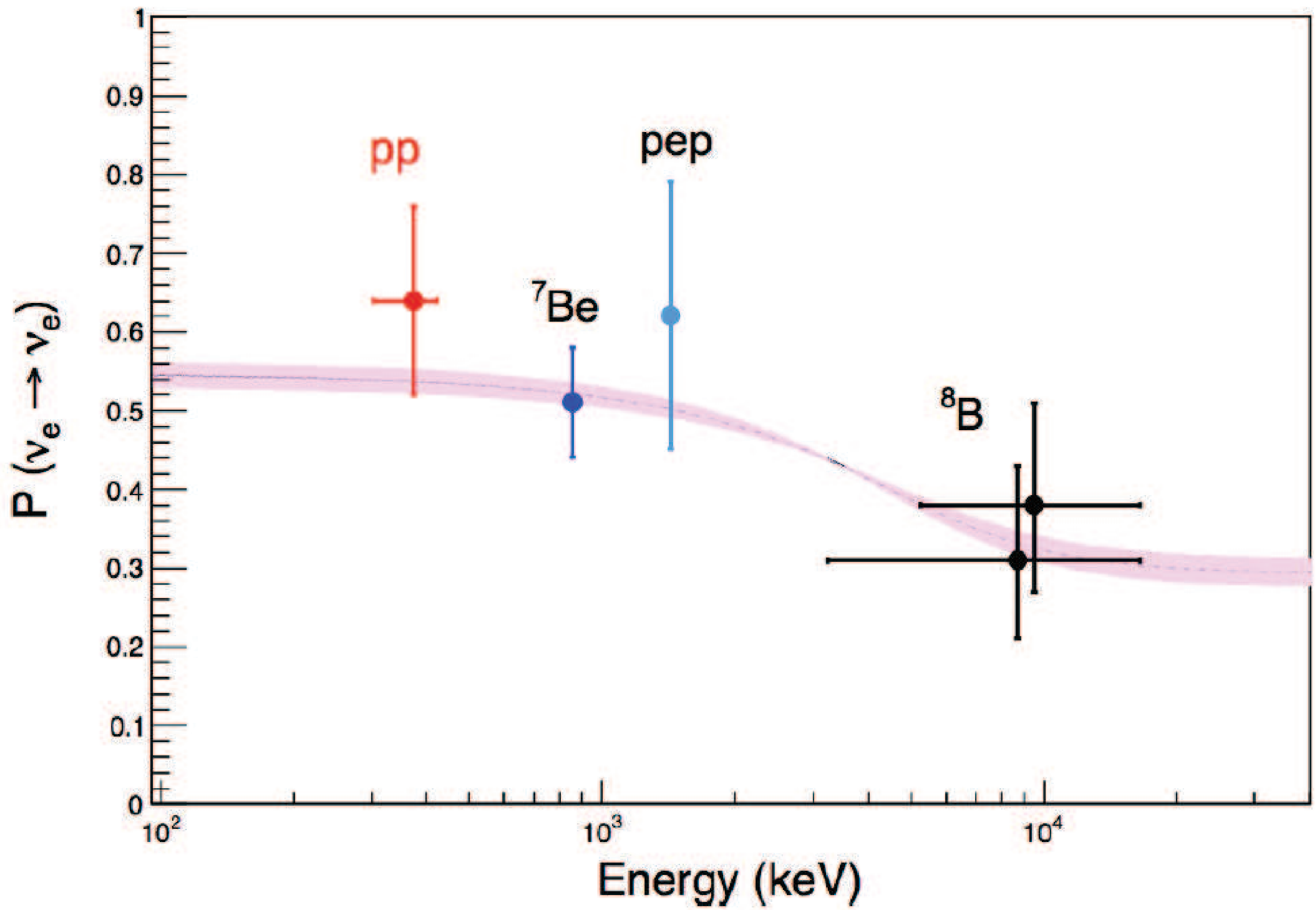


In the near future (Phase 2: 2012-2013)

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

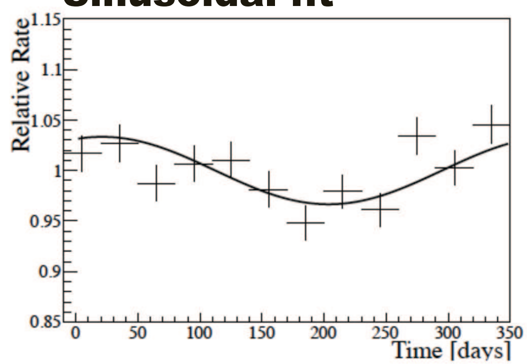


Borexino measured electron neutrino survival probability for 4 different nuclear reactions

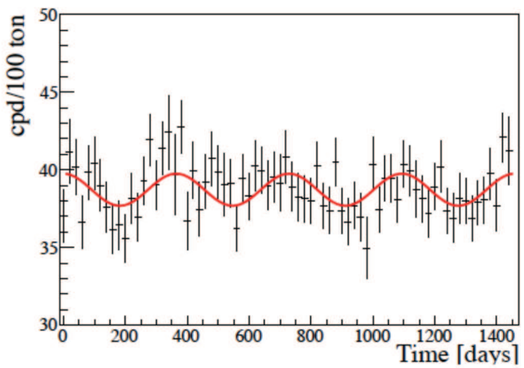


Borexino: annual modulations

Sinusoidal fit

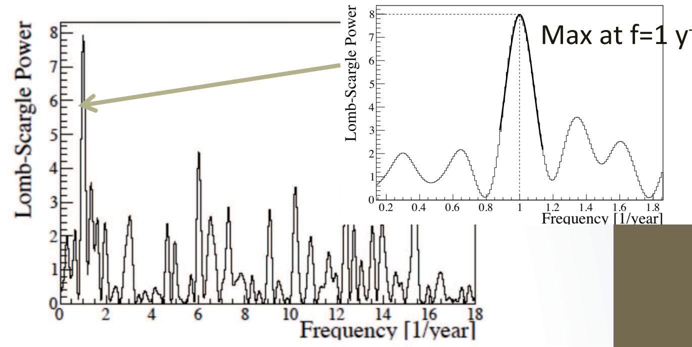


30 day bins- 4 years data cumulated

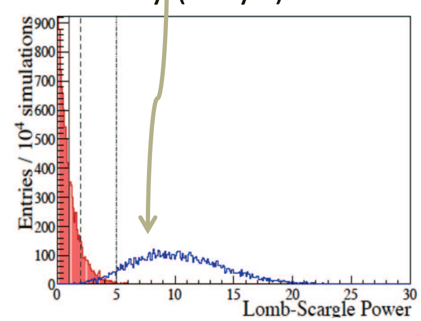


20 days bins-

Lomb-Scargle analysis



L-S Normalized Spectrum Power Density $(f=1y^{-1}) \cong 8$



Gianpaolo Bellini Milano
Neutrino Telescopes 2017 Venezia

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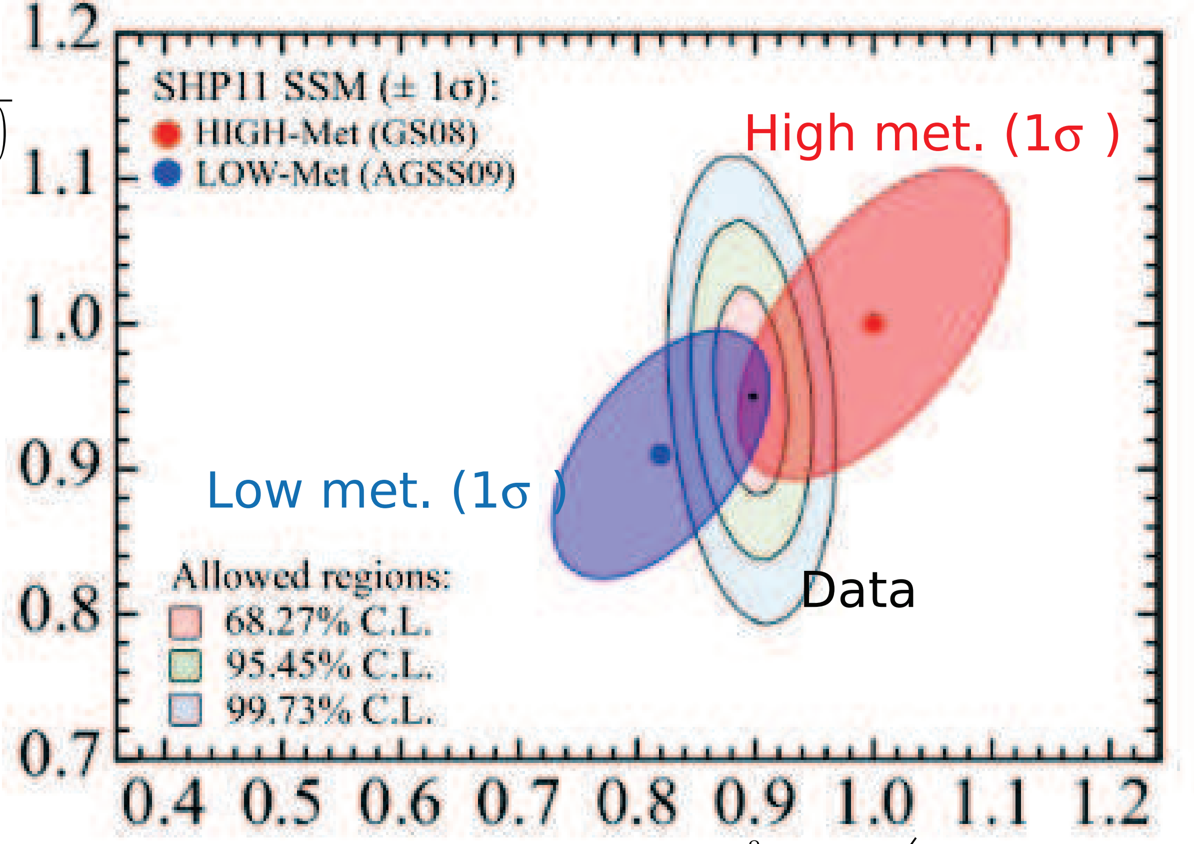
Null hypothesis rejected at 3.91σ (99.99% C.L.)
modulation amplitude (6.8±1.9)%
best-t period is **T = 369. 0 ±11 days**.
phase=-12±28 days (to be compared with January 3th).

From Lomb Scargle analysis:
Period 1 year
Absence of modulation rejected
at 99.99% C.L (>3.5 σ).

Borexino experiment in Gran Sasso

Physics implication of the solar ν Borexino results:
high and low metallicity solar models

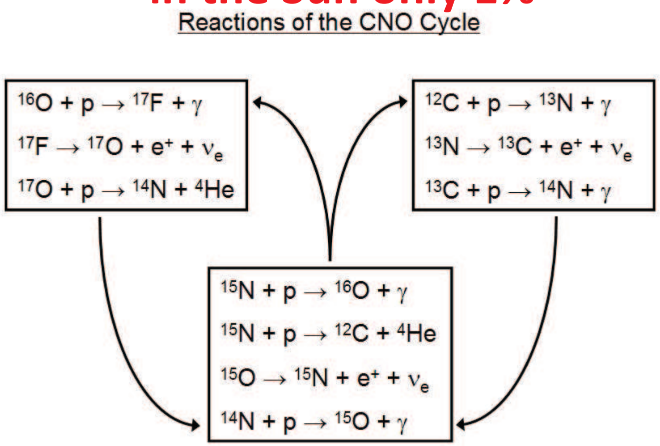
$$\frac{^{7}Be\ flux}{^{7}Be\,(SSM\ high\,met.)}$$



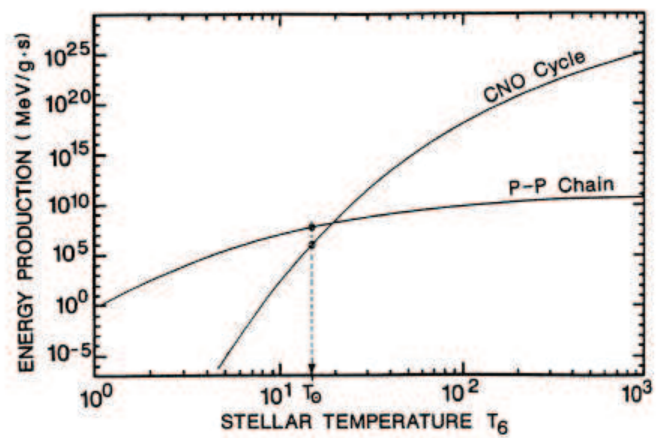
$$^{8}B\ flux \Big/ {}^{8}B\,(SSM\ high\,met.)$$

Borexino experiment in Gran Sasso

CNO cycle
in the Sun only 1%



hypothesized as the primary cycle in the massive stars and then for hydrogen burning in the Universe

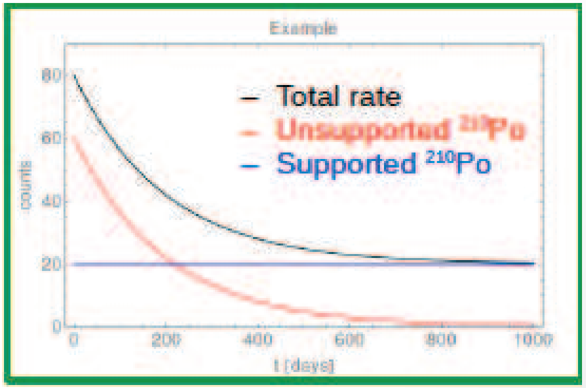


astr

strategy: need of an independent constraint on ^{210}Bi rate (remove degeneracy with CNO spectrum)

from ^{210}Po: two components:

- embedded on the lines (138.376 days half time)
- ^{210}Pb → ^{210}Bi (β) → ^{210} Po (α)
- easily identified via pulse shape discrimination



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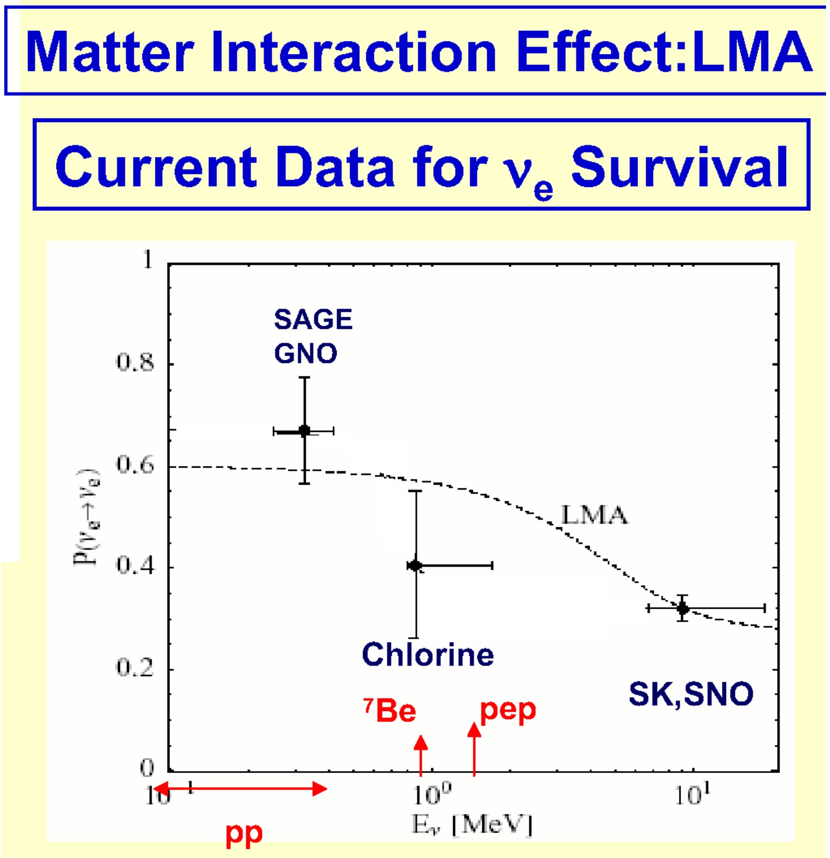
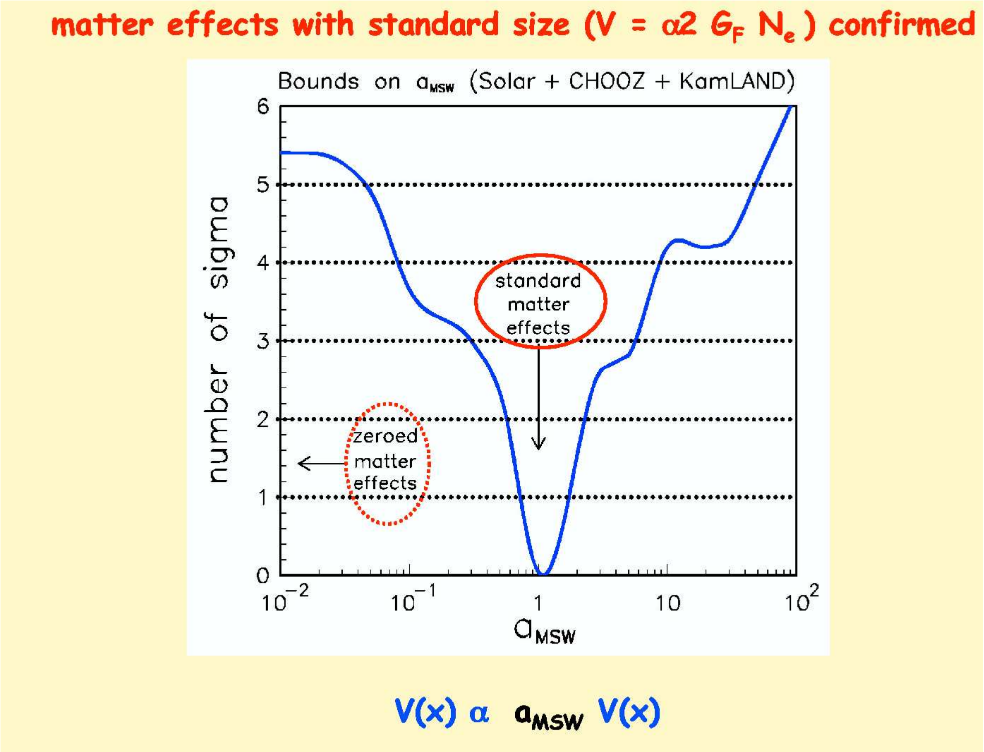
Evidence for the MSW effect



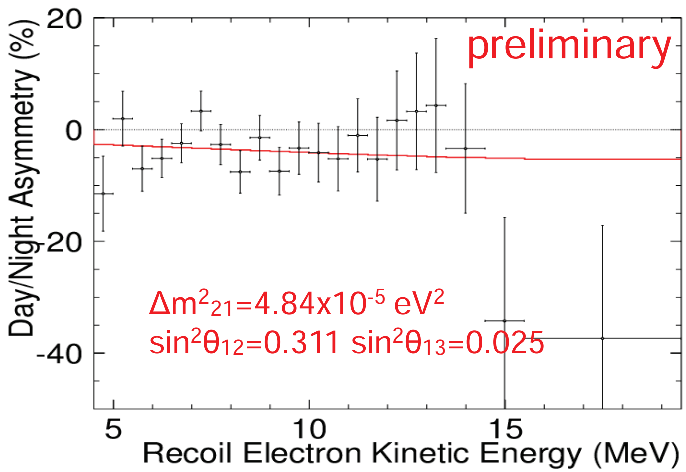


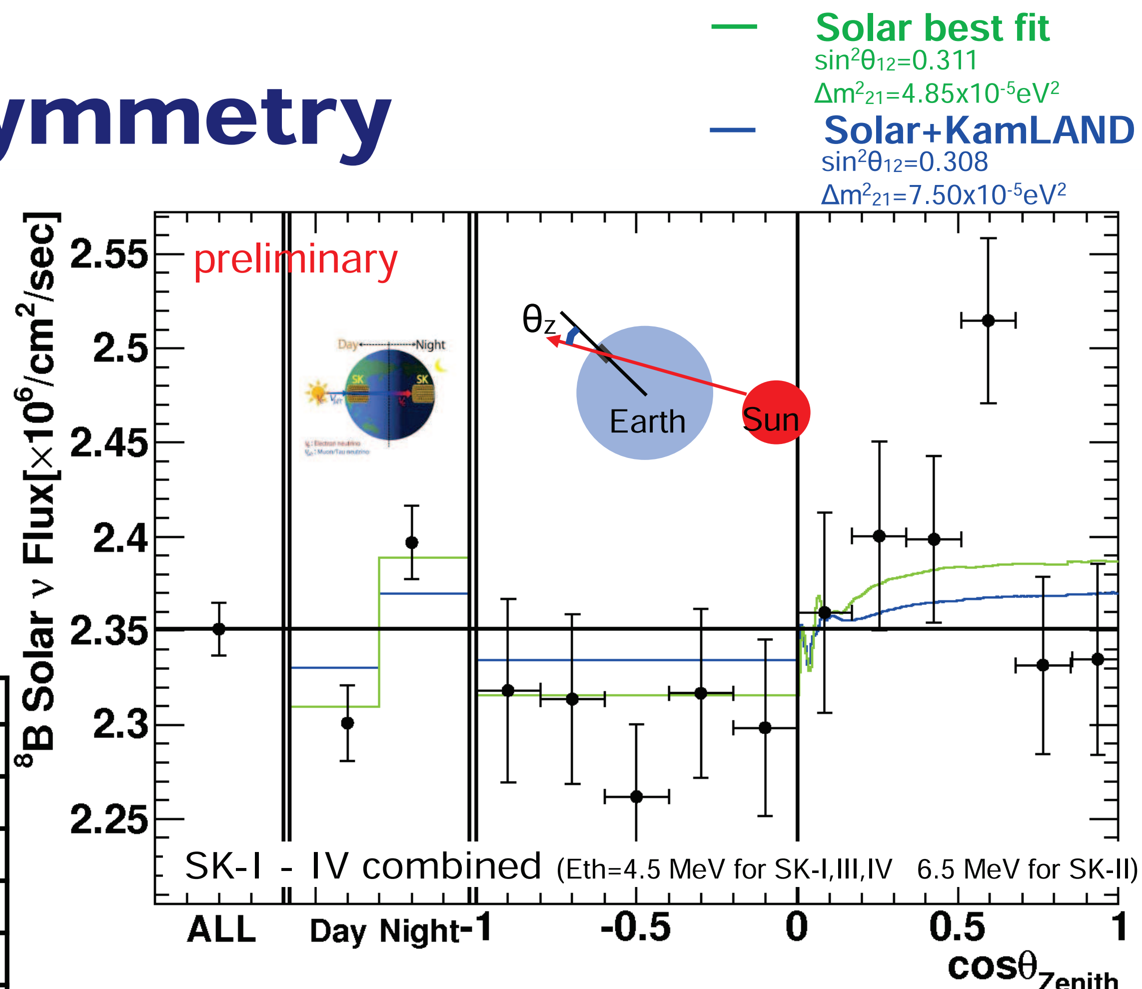
$V(x) \Rightarrow a_{\rm MSW} V(x)$; $a_{\rm MSW} = 1$ strongly favoured

(Fogli et al. 2003, 2004; Fogli & Lisi 2004)

SuperK: Earth matter effect

Day-Night flux asymmetry





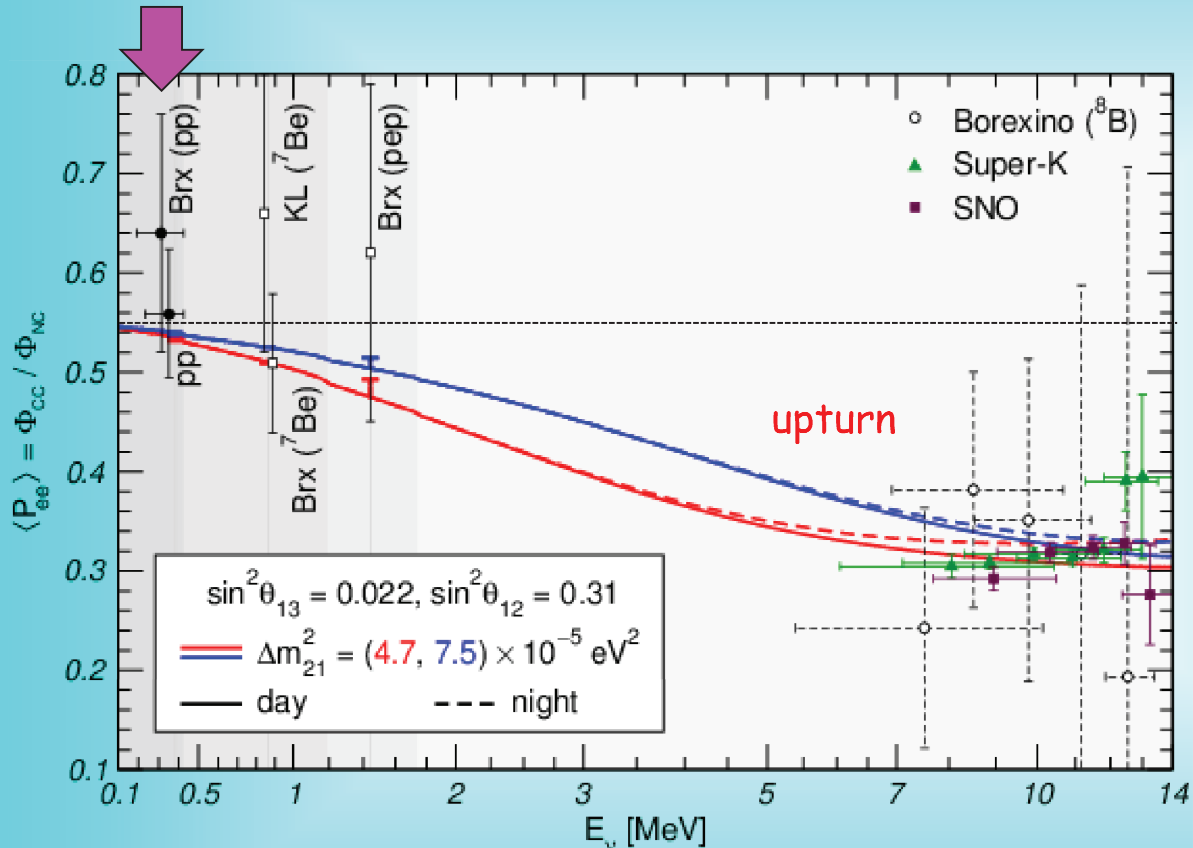
	Fitted asymmetry amplitude	
	$\Delta m^2_{21}=4.84\times10^{-5}$ eV^2	$\Delta m^2_{21}=7.50\times10^{-5}$ eV^2
SK-I	-2.0±1.8±1.0%	-1.9±1.7±1.0%
SK-II	-4.4±3.8±1.0%	-4.4±3.6±1.0%
SK-III	-4.2±2.7±0.7%	-3.8±2.6±0.7%
SK-IV	-3.6±1.6±0.6%	-3.3±1.5±0.6%
combined	-3.3±1.0±0.5%	-3.1±1.0±0.5%
non-zero significance	3.0σ	2.8σ

- This is the "direct" indication for matter enhanced neutrino oscillation

Remaining problems/tensions?

Profile of the effect

M. Maltoni, A.Y.S. to appear



for two different values of Δm_{21}^2

- best fit value from solar data
- best global fit

Vacuum dominated

Transition region resonance turn on

Matter dominated region

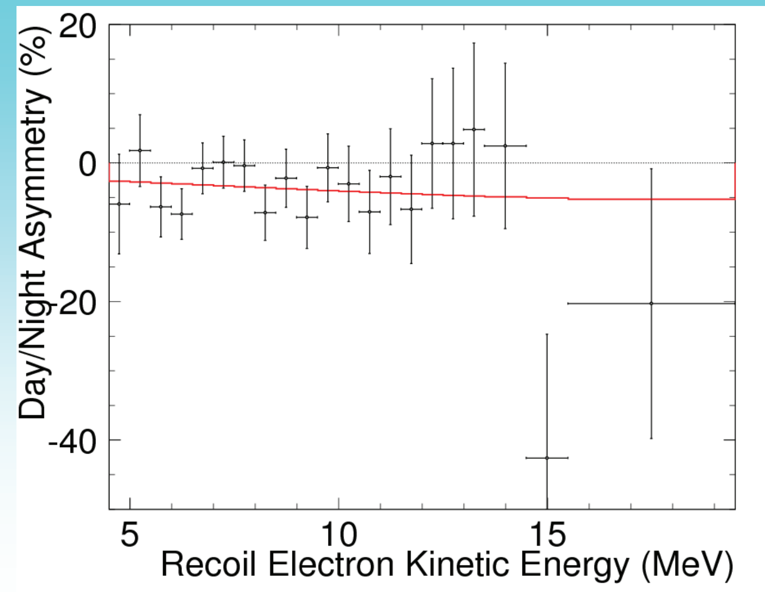
Reconstructed exp. points for SK, SNO and BOREXINO at high energies

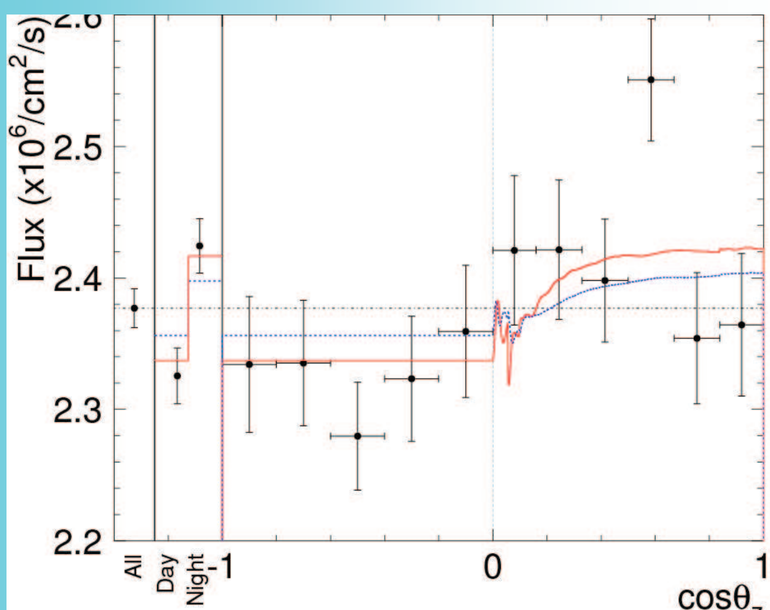
Remaining problems/tensions?

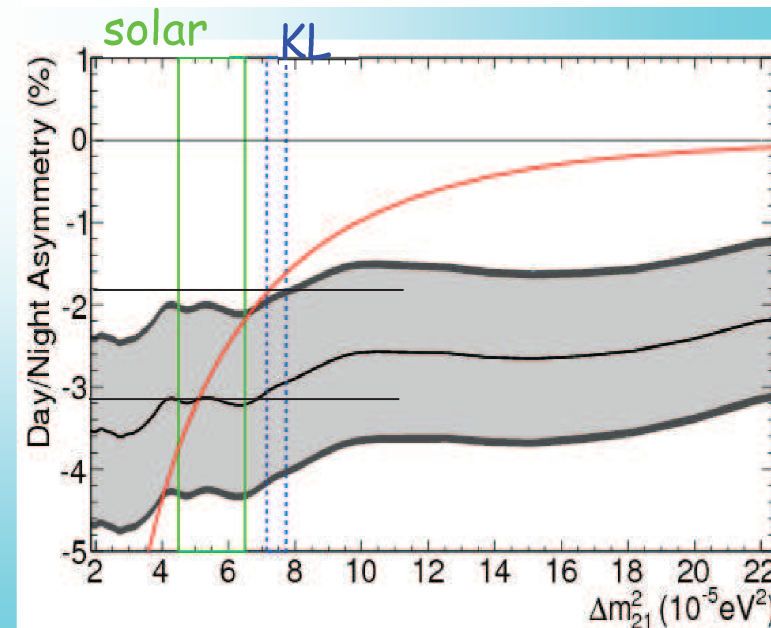
Day-Night effect

First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation

Super-Kamiokande collaboration (Renshaw, A. et al.) Phys.Rev.Lett. 112 (2014) 091805 arXiv:1312.5176



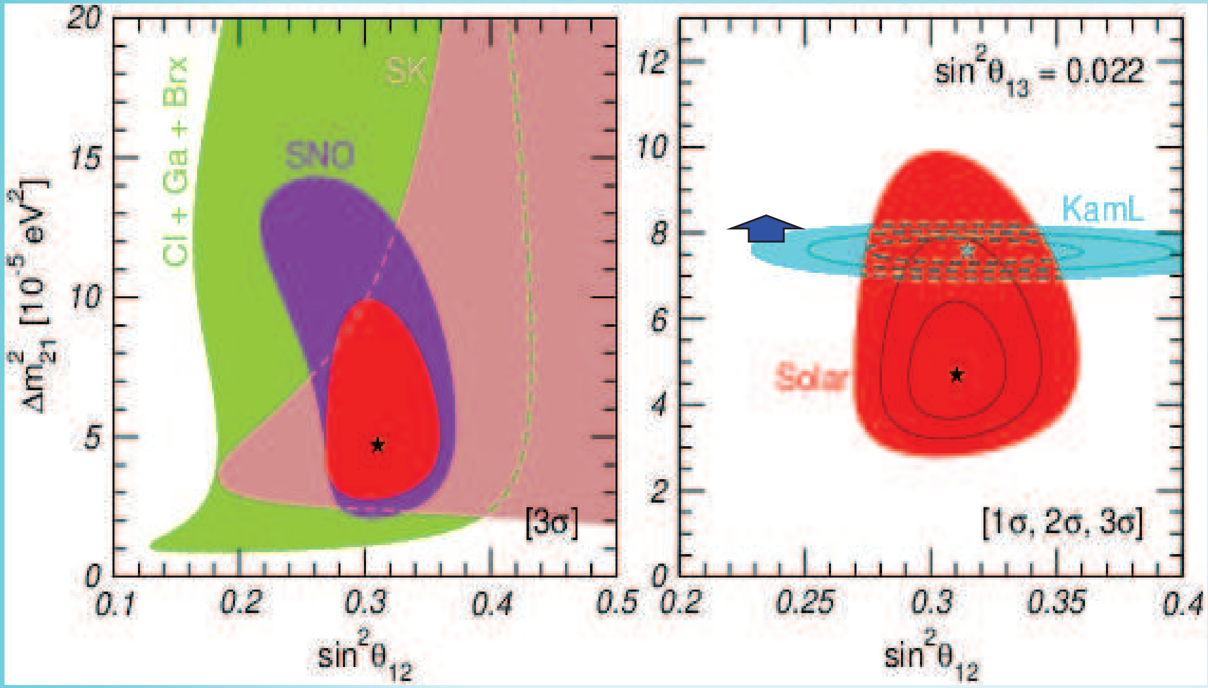




Remaining problems/tensions?

Neutrino parameters

Solar neutrinos
Vs. KamLAND



M. Maltoni, A.Y.S. to appear

Δm^2_{21} : about 2σ descrepancy of the KL and solar values

Red regions: all solar neutrino data

also restrictions from individual experiments

$\sin^2\theta_{13}$ as fit parameter then marginalized

b.f.: $\sin^2\theta_{13} = 0.017$

$\sin^2\theta_{13}$ fixed by reactor experiments

KamLAND data reanalized in view of reactor anomaly (no front detector) bump at 4 -6 MeV

Δm^2_{21} increases by $0.5\ 10^{-5}$ eV^2

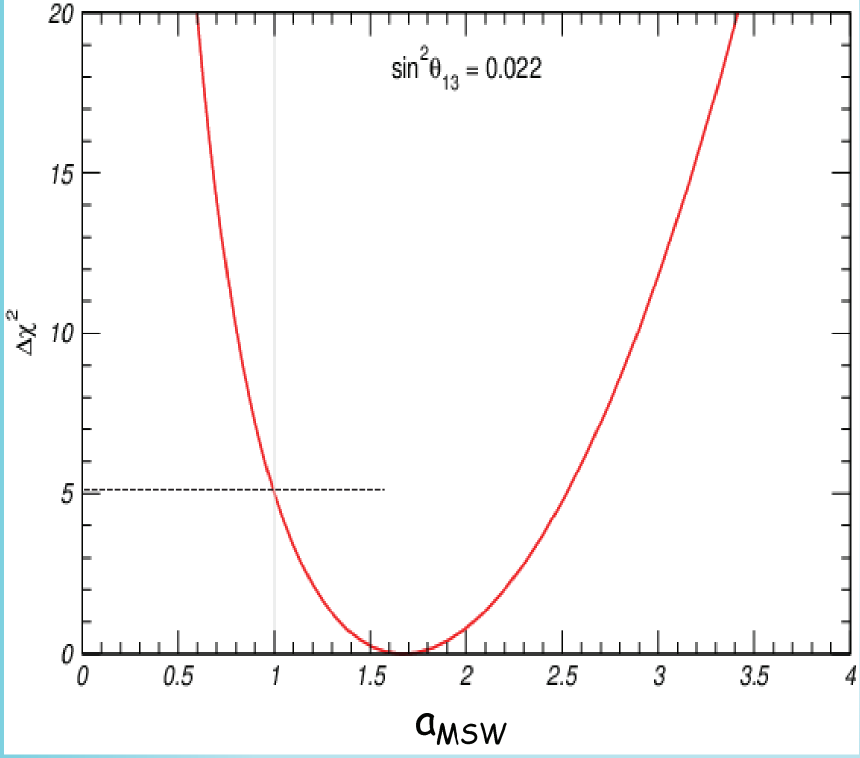
Remaining problems/tensions?

Matter potential

G. L Fogli et al hep-ph/0309100

C. Pena-Garay, H. Minakata, hep-ph 1009.4869 [hep-ph]

M. Maltoni, A.Y.S. to appear



$V = a_{MSW} V_{stand}$

$a_{MSW} = 0$ is disfavoured by > 15 σ

the best fit value $a_{MSW} = 1.66$

$a_{MSW} = 1.0$ is disfavoured by > 2 σ

related to discrepancy of Δm^2_{21} from solar and KamLAND:

$$\frac{\Delta m^2_{21}\,(KL)}{\Delta m^2_{21}\,(Sun)} = 1.6$$

Determination of the matter potential from the solar plus KamLAND data using a_{MSW} as free parameter

Potential enters the probability in combination

$$\frac{V}{\Delta m^2_{21}}$$

Remaining problems/tensions?

Open issues

at about 3σ - level

- Absence of upturn of the spectrum
- Large D-N asymmetry
- Difference of values of Δm^2_{21} extracted from solar and KamLAND data
- Large value of matter potential extracted from global fit

KamLAND

another reactor anomaly?

Solar data alone have very good and consistent description at small Δm^2_{21}

Reactor anomaly should affect KamLAND result

New physics

in solar neutrinos?

Non-standard Neutrino interaction

Very light Sterile neutrinos

New sub-leading effects

Reactor $\bar{\nu}_e$ oscillations

Reactor $\bar{\nu}_e$ oscillations

$\bar{\nu}_e$ survival probability (in vacuum):

$$\diamondsuit \;\; P_{\bar{e}\bar{e}} \simeq 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m_{31}^2}{4E}L\right) - c_{13}^4 \sin^2 2\theta_{12} \cdot \sin^2\left(\frac{\Delta m_{21}^2}{4E}L\right)$$

- Chooz, Palo Verde, DChooz, Daya Bay, Reno,... ($L \sim 1-2$ km)

$$\overline{E} \sim 4\ \text{MeV}\,; \qquad \frac{\Delta m_{31}^2}{4E}\,L \sim 1\,; \qquad \frac{\Delta m_{21}^2}{4E}\,L \ll 1$$

One mass scale dominance (2f) approximation (SBL expts.):

$$\diamond \;\; P(\bar{\nu}_e \to \bar{\nu}_e; L) = 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m_{31}^2}{4E}\,L\right)$$

Reactor $\bar{\nu}_e$ oscillations – contd.

- KamLAND $(\bar{L} \simeq 170$ km)

$$\frac{\Delta m^2_{21}}{4E}\,L \gtrsim 1\,; \qquad \frac{\Delta m^2_{31}}{4E}\,L \gg 1$$

Averaging over fast oscillations due to $\Delta m^2_{\rm atm} = \Delta m^2_{31}$:

◇ $P(\bar{\nu}_e \to \bar{\nu}_e) = c_{13}^4 P_{2\bar{e}\bar{e}}(\Delta m^2_{21},\,\theta_{12},\,V_{\rm eff}) + s_{13}^4\,, \qquad V_{\rm eff} = c_{13}^2 V$

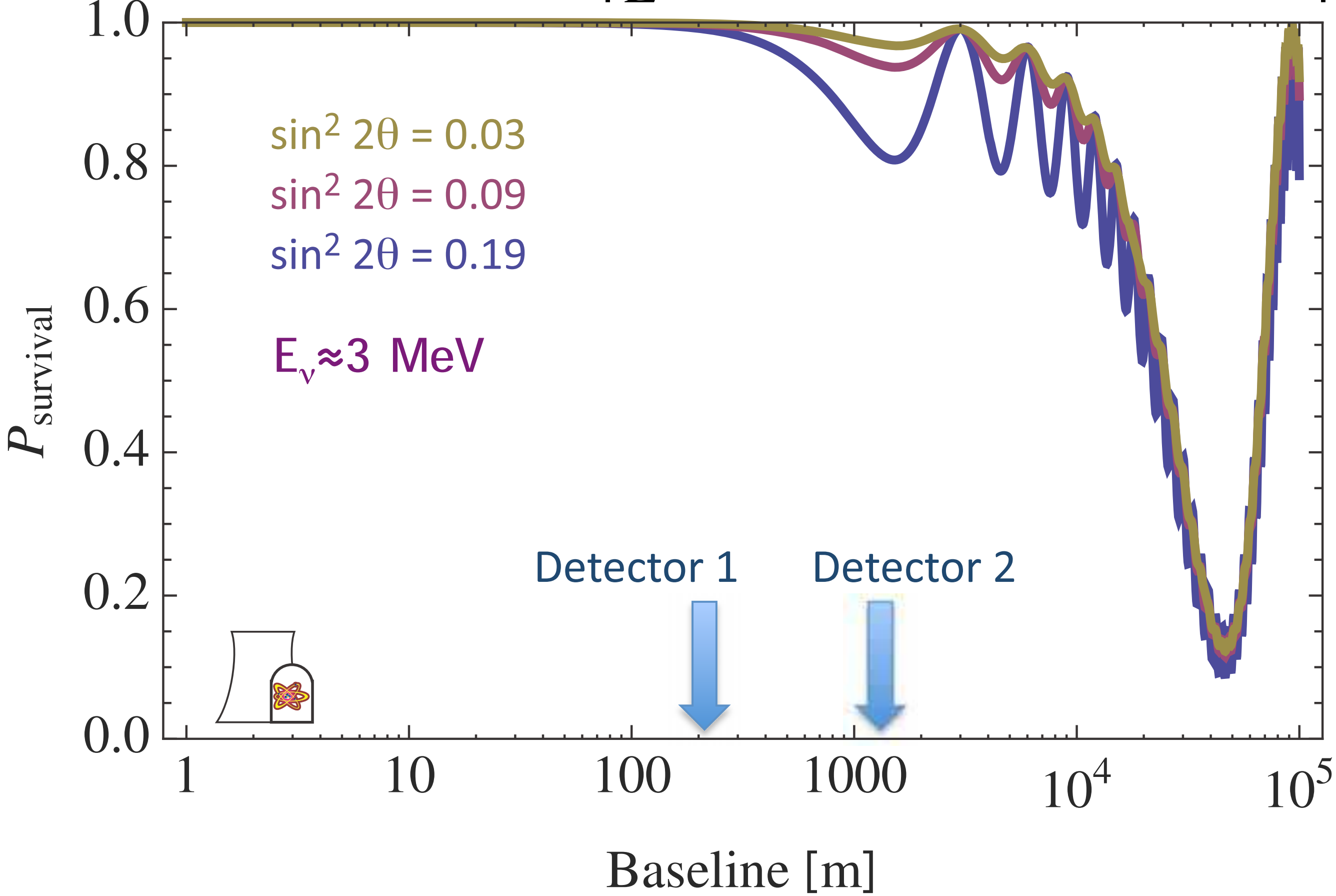
Differs from 2f probability by $\sim 5\%$ (energy-independent suppression)

N.B.: Matter effects a few % – comparable with effects of $\theta_{13} \neq 0$!

Precision Reactor Experiments

L. Mikaelyan, arXiv:hep-ex/0008046v2 (Krasnoyarsk)

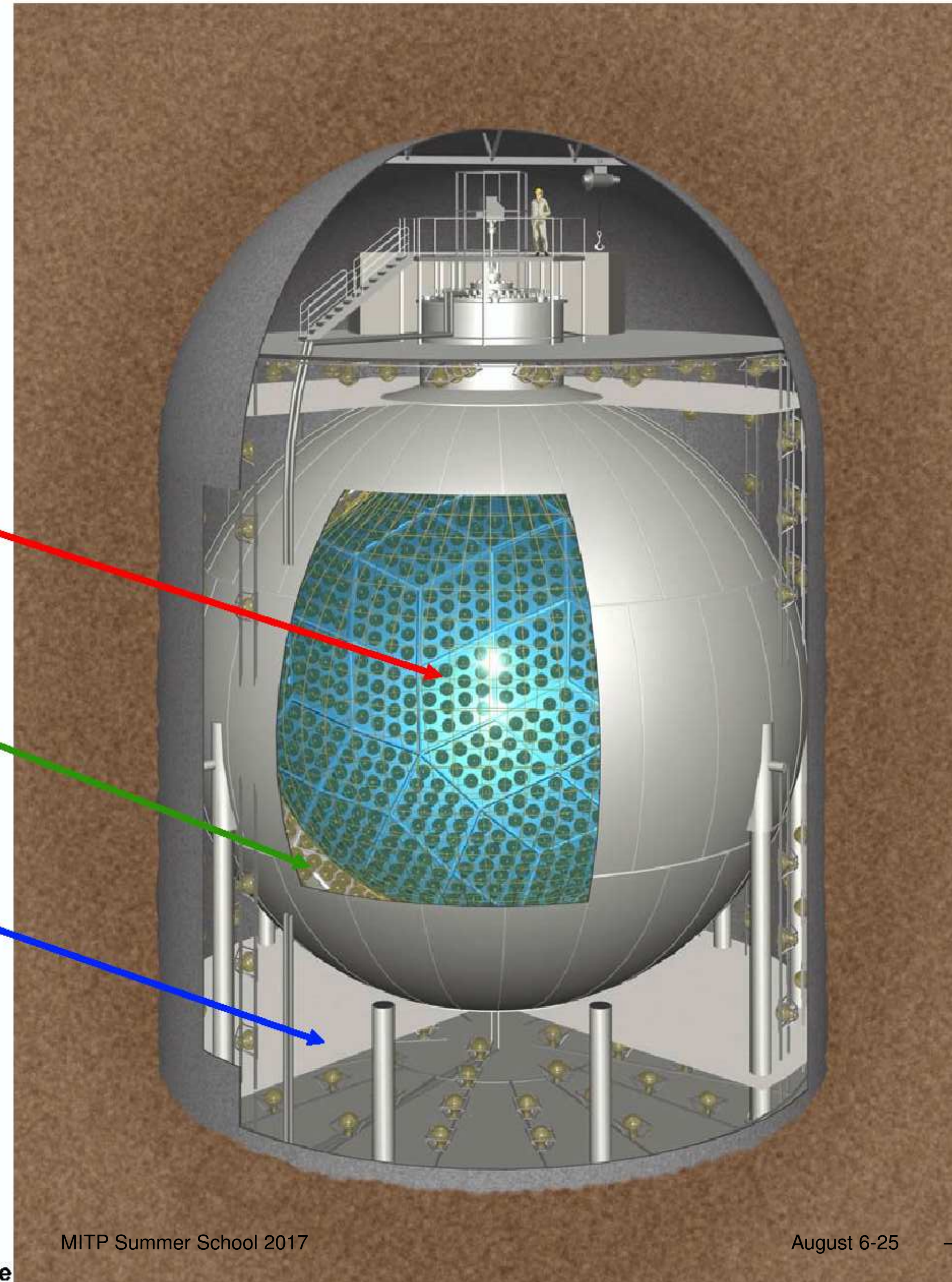
$$P \cong 1 - \sin^2 2\theta_{13} \sin^2 \Delta m_{13}^2 \frac{L}{4E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta m_{12}^2 \frac{L}{4E}$$

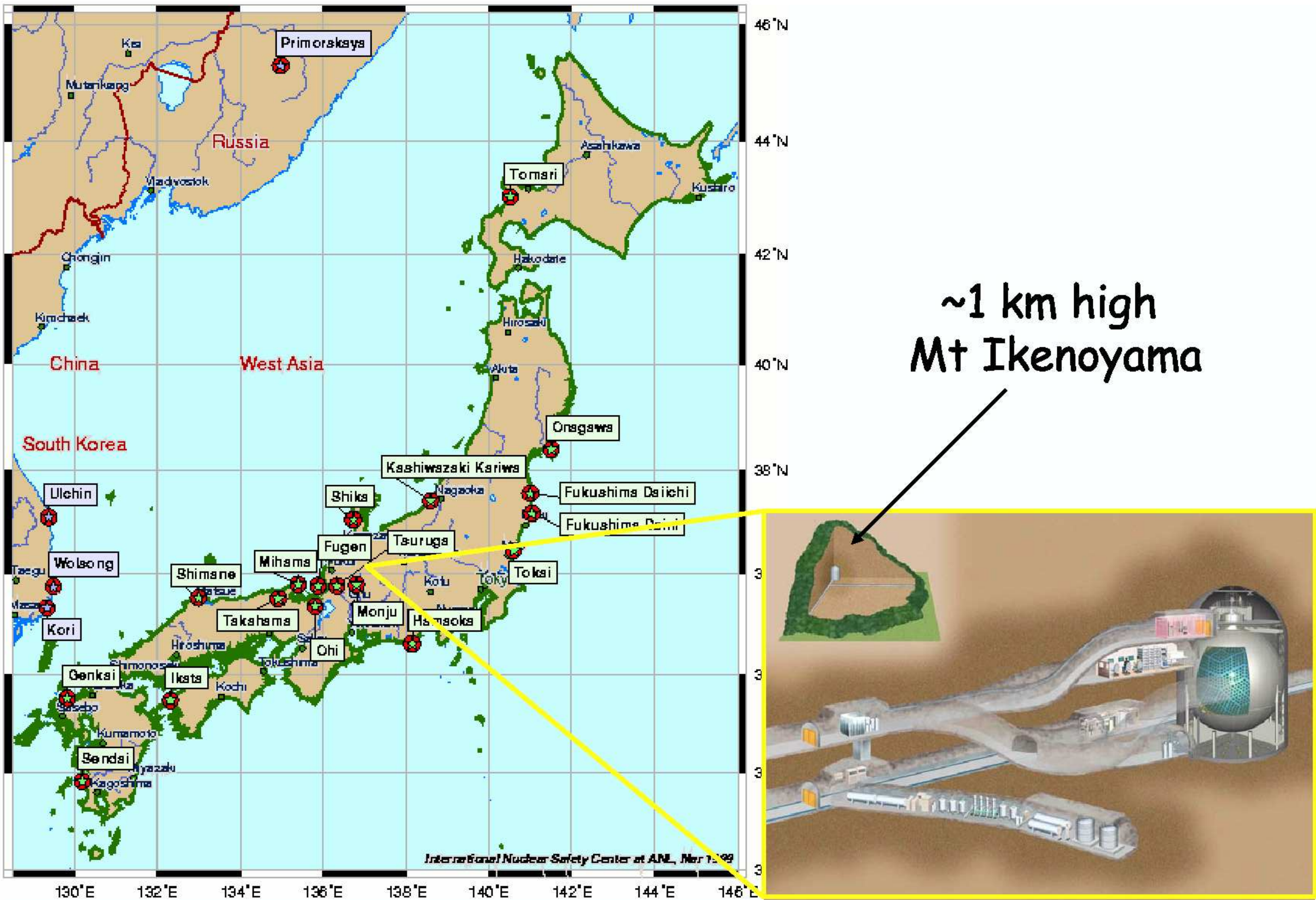


build nearly identical detectors with nearly identical efficiency

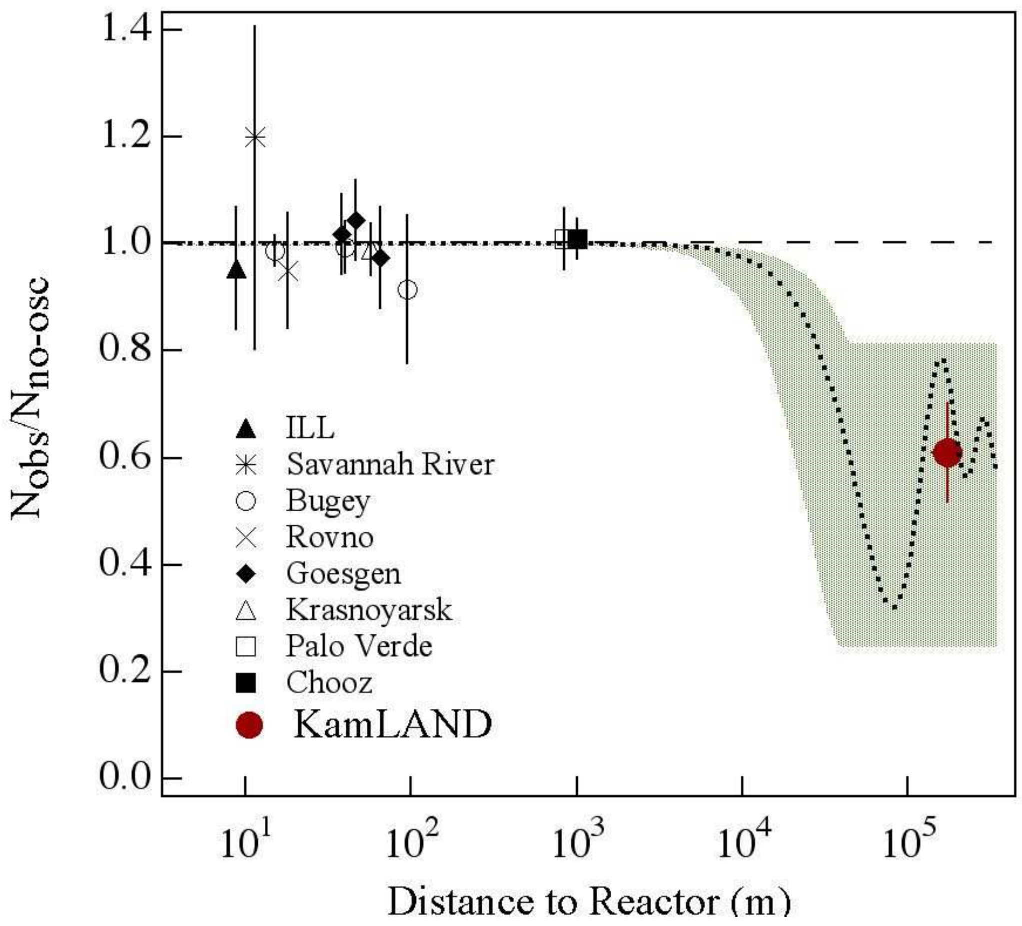
KamLAND:
Kamioka Liquid scintillator AntiNeutrino Detector

- 1 kton liq. Scint. Detector in the Kamiokande cavern
- 1325 17" fast PMTs
- 554 20" large area PMTs
- 34% photocathode coverage
- H_2O Cerenkov veto counter





Neutrino 2004 **New Results from KamLAND** 6



Expected: 365.2 ± 23.7

Background: 17.8 ± 7.3

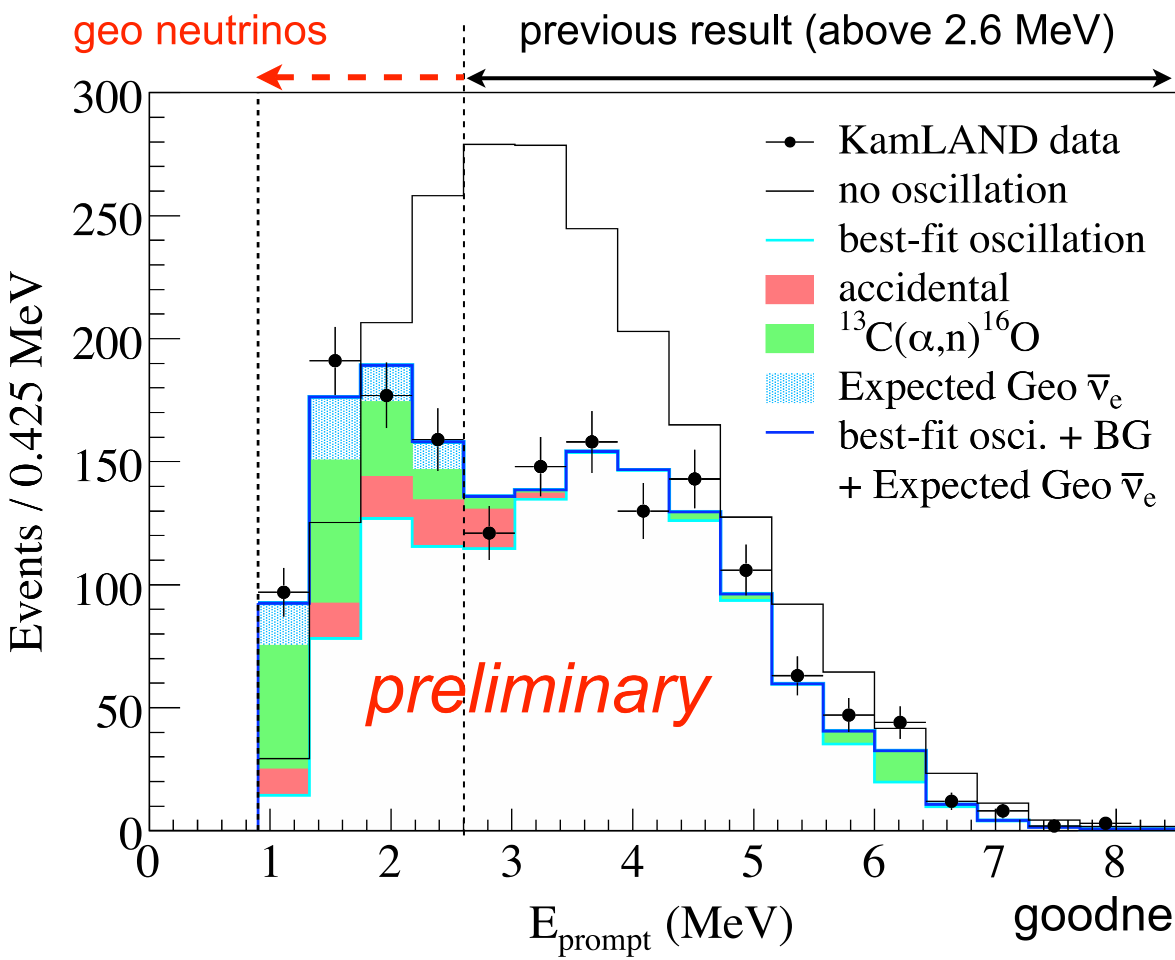
Observed: 258

$$R = \frac{N_{\rm obs} - N_{\rm bgr}}{N_{\rm expected}} = 0.658 \pm 0.044({\rm stat}) \pm 0.047({\rm syst})$$

Stat. significance of reactor $\bar{\nu}_e$ disappearance: 99.998%

Energy Spectrum above 0.9 MeV

exposure : 2881 ton-year (3.8 × 766 ton-year for “KamLAND 2004”)



“Geo + Reactor” combined analysis

No osci. expected	**2178**
Background (w/o geo neutrino)	**276**
(Ichimura and Minekawa et al.)	
Observed events	**1609**

best-fit

$(\tan^2\theta, \Delta m^2) = (0.56, 7.58 \times 10^{-5}\ \text{eV}^2)$

free parameter : geo neutrinos
(U, Th) = (39.3, 29.4) events

goodness of fit using equal probability bins

best-fit χ^2 / ndf = 21.0 / 16 (18.0% C.L.)

no osci. χ^2 / ndf = 63.9 / 17

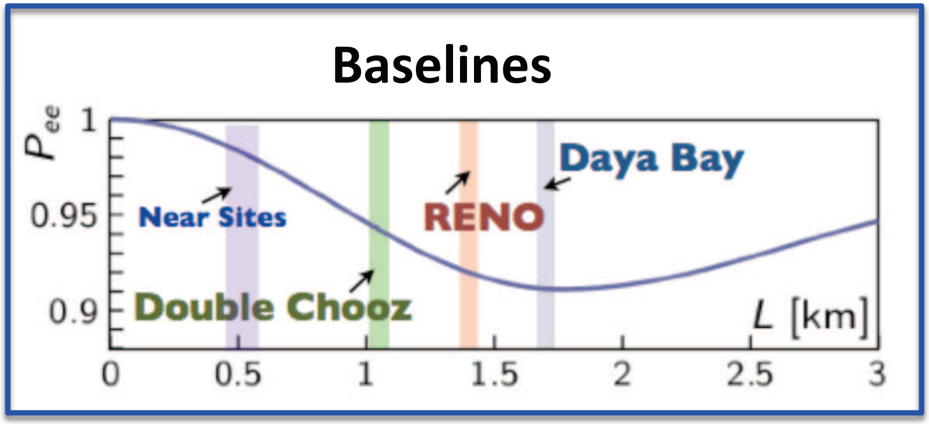
Scaled no oscillation spectrum is excluded at 5.2σ

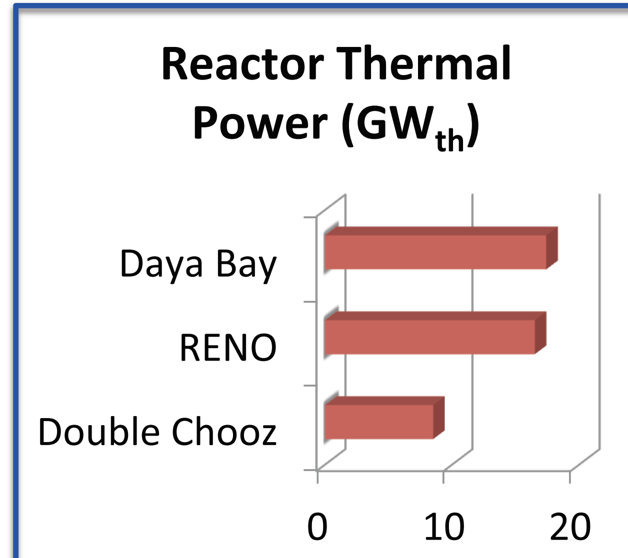
SBL reactor experiments

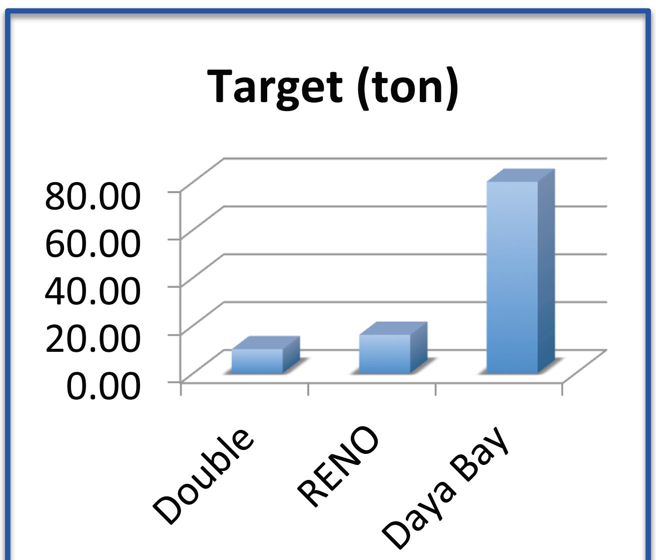
Reactor ν Experiments

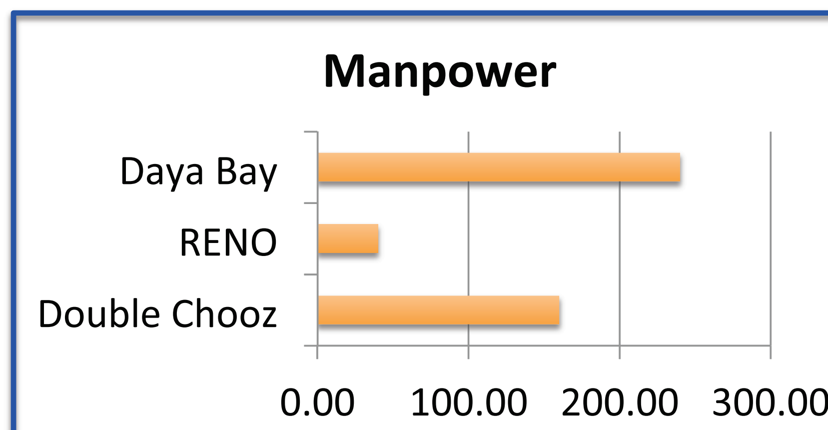
Experiment (location)	Thermal Power (GW)	Distance Near/Far (m)	Depth Near/Far (mwe)	Target mass (ton)	Cost (US $)	# of members
Double Chooz (France)	8.5	400/ 1050	120/ 300	10/ 10	?	> 160
RENO (Korea)	16.8	290/ 1380	120/ 450	16/ 16	~10 M	< 30
Daya Bay (China)	17.4	360(500)/ 1985(1613)	260/ 860	40x2/ 80	?	~ 230

Comparisons

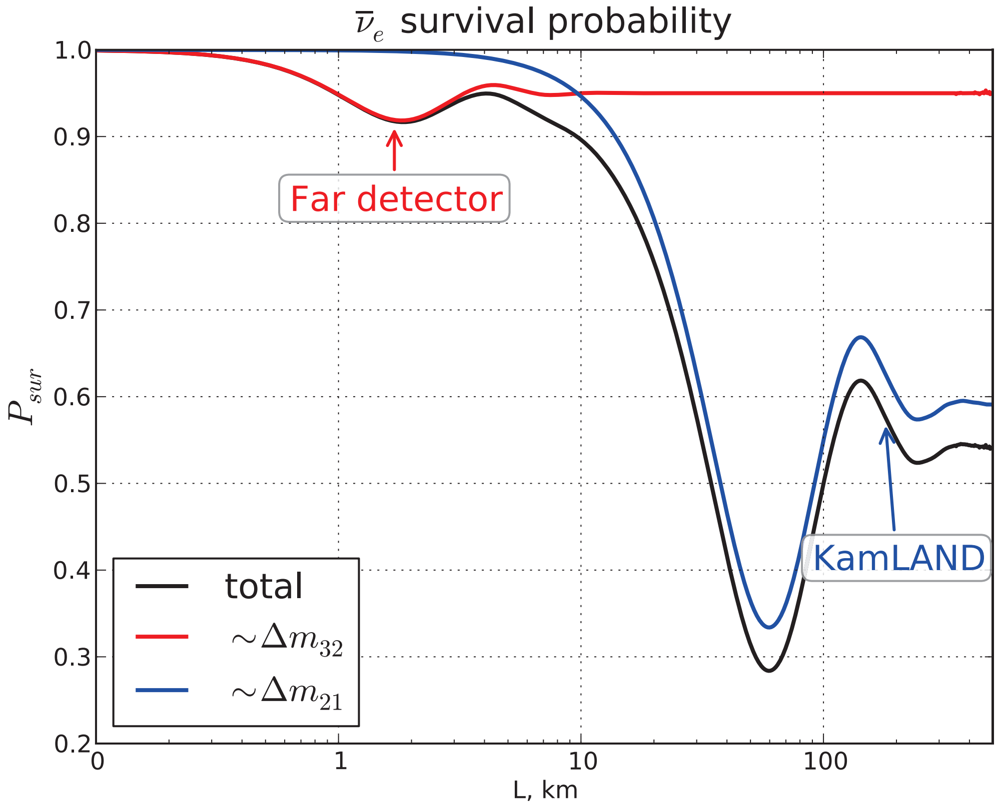








Oscillation analysis



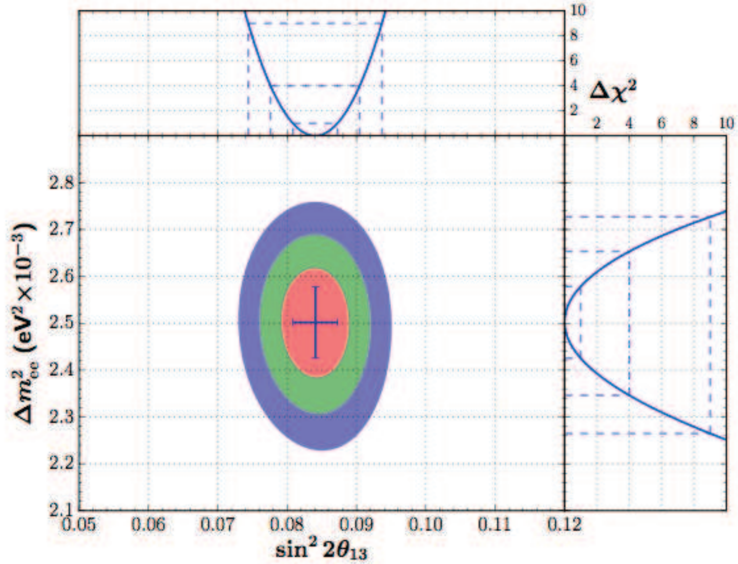
$$P_{\text{dis}} = \sin^2 2\theta_{13} \left(\sin^2\theta_{12}\sin^2\Delta_{32} + \cos^2\theta_{12}\sin^2\Delta_{31}\right) + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

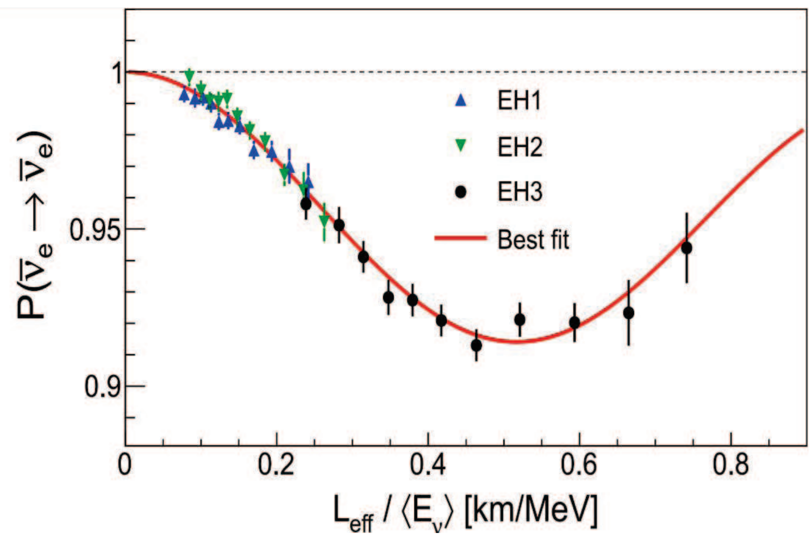
$$= \sin^2 2\theta_{13}\sin^2\Delta_{ee} + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}, \quad \Delta_{jk} = 1267 \cdot \frac{\Delta m^2_{jk}}{\text{eV}^2} \frac{L}{E} \left[\frac{\text{MeV}}{\text{km}}\right]$$

Phys. Rev. D 95, 072006 (2017)

nGd Oscillation Analysis Results

$$P_{\bar\nu_e\to\bar\nu_e} = 1 - \sin^2 2\theta_{13}\sin^2\left(\Delta m^2_{ee}\frac{L}{4E}\right) - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\left(\Delta m^2_{21}\frac{L}{4E}\right)$$





$\sin^2 2\theta_{13}$ = 0.0841 ±0.0027(stat.) ±0.0019(sys.) ← still statistics dominated!

$|\Delta m^2_{ee}|$ = [2.50 ±0.06(stat.) ±0.06(sys.)] ×10^{-3}eV^2

χ^2/NDF = 234.7/263

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Global Comparison

Most precise measurement

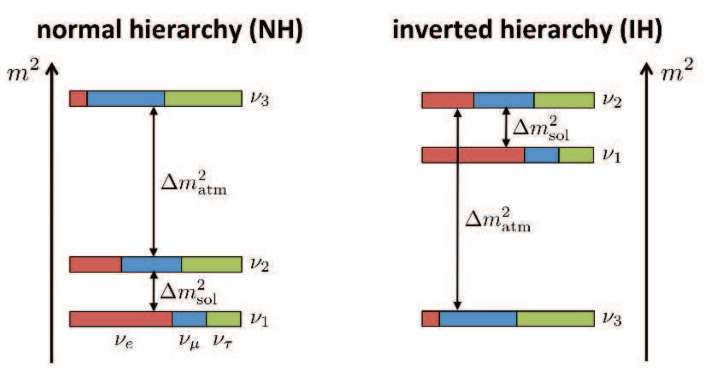
- $\sin^2 2\theta_{13}$ uncertainty: 3.9%
- Δm^2_{32} uncertainty: 3.4%

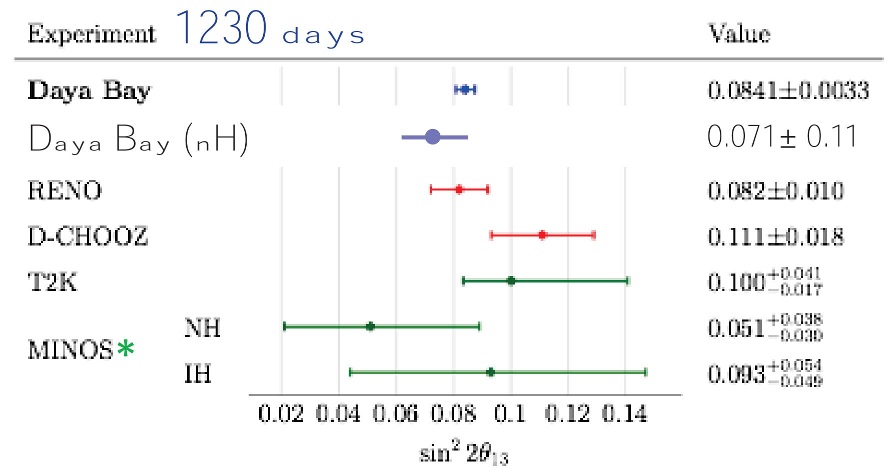
Consistent results with reactor and accelerator experiments

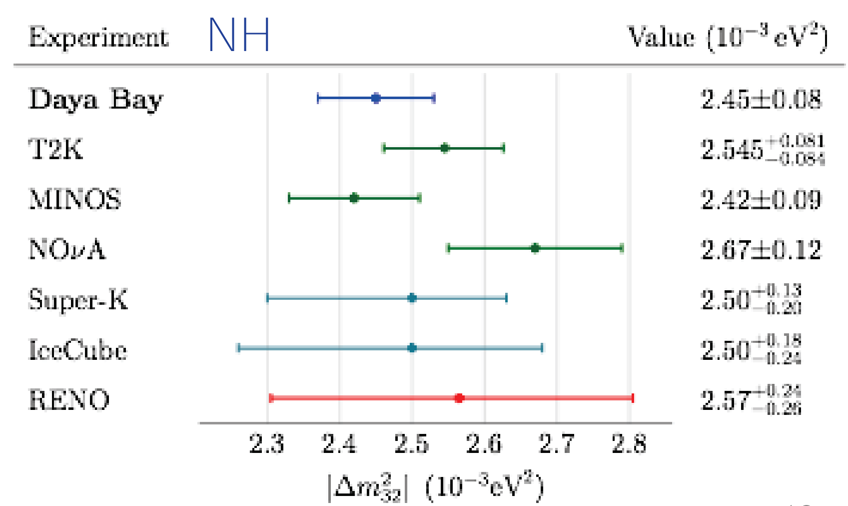
$|\Delta m^2_{ee}| = |\Delta m^2_{32}| \pm 0.05 \times 10^{-3}$ eV^2

NH: $\Delta m^2_{32} = [2.45 \pm 0.08] \times 10^{-3}$ eV^2

IH: $\Delta m^2_{32} = [-2.56 \pm 0.08] \times 10^{-3}$ eV^2







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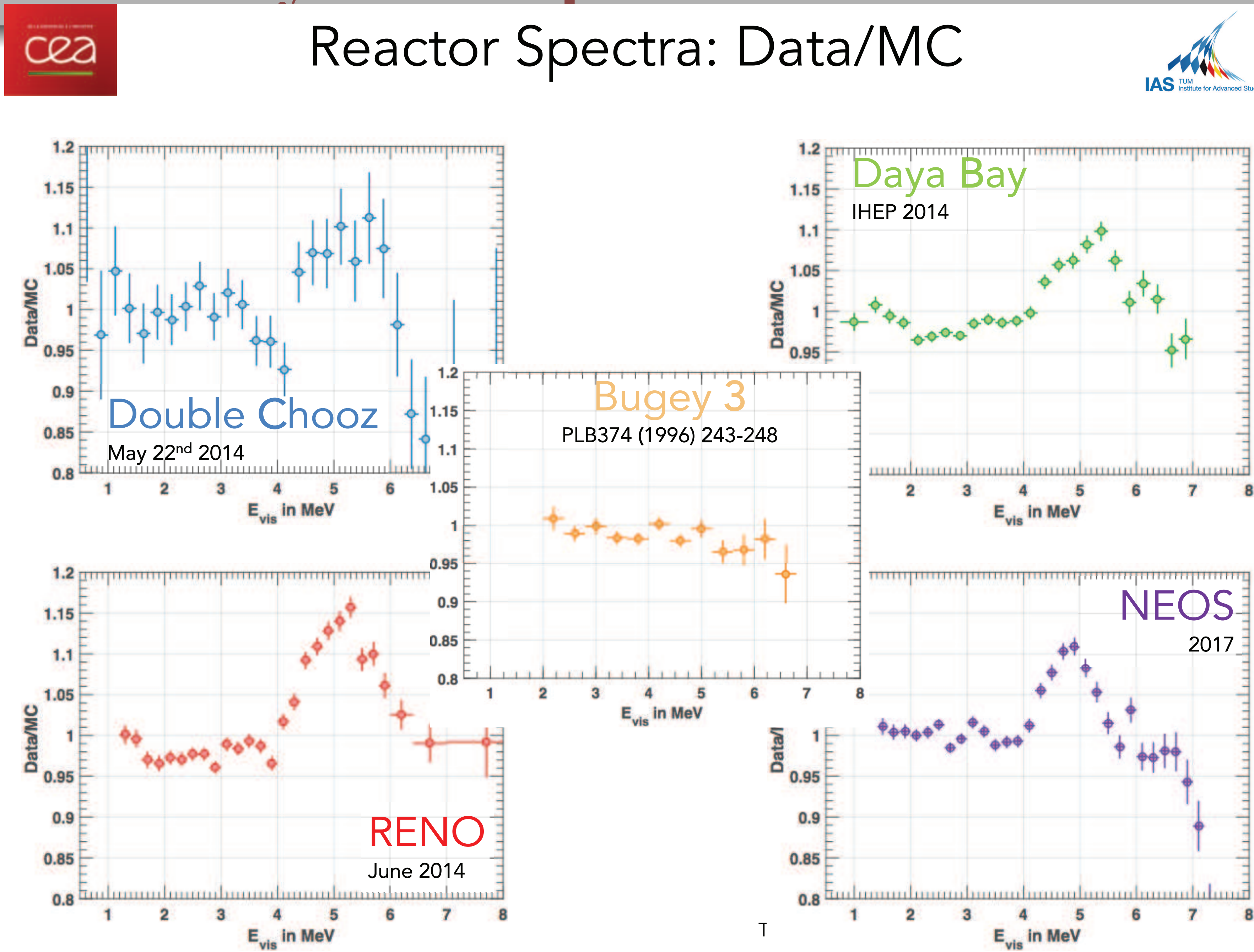
*: combined fit results for $2\sin^2\theta_{23}\sin^2 2\theta_{13}$

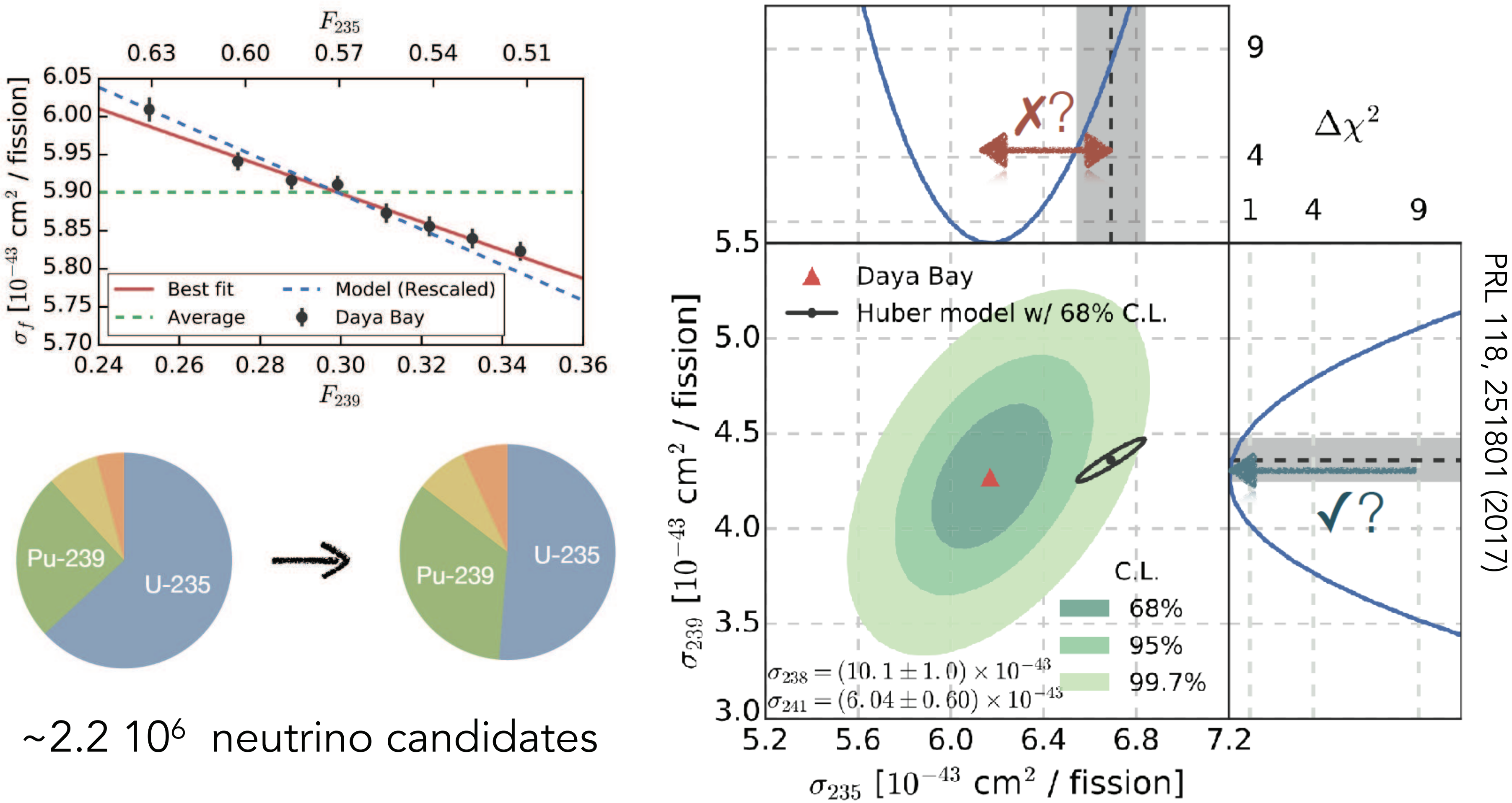
An anomaly in the spectrum?

Reactor Spectra: Data/MC



Reactor Neutrino Spectra (Daya Bay)

Mismatch concerning ^{235}U ν-flux in reactor models?

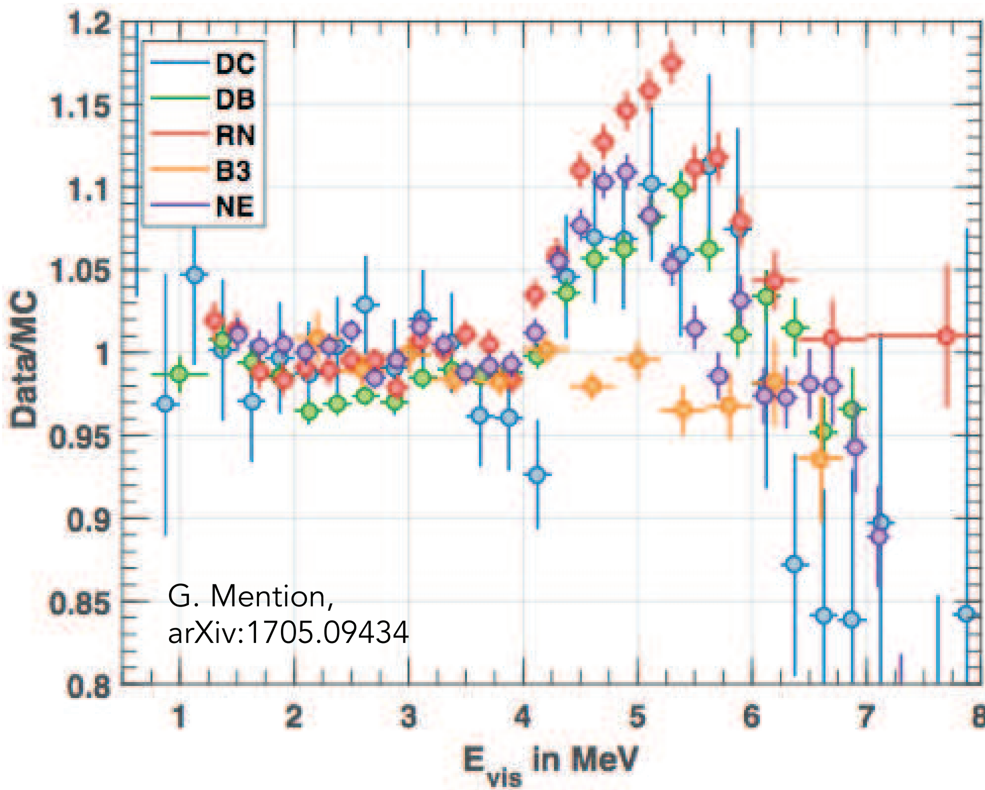


~2.2 10^6 neutrino candidates

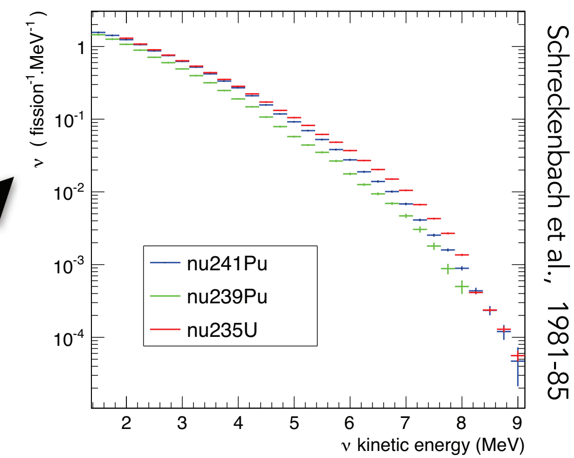
Th. Lasserre – HEP 2017

A two fold origin?

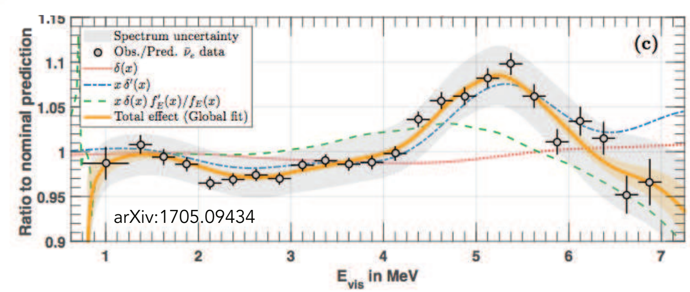
Spectral shapes are not compatible at 6.4σ



Reactor ν-spectra
Bias? Underestimated systematics?

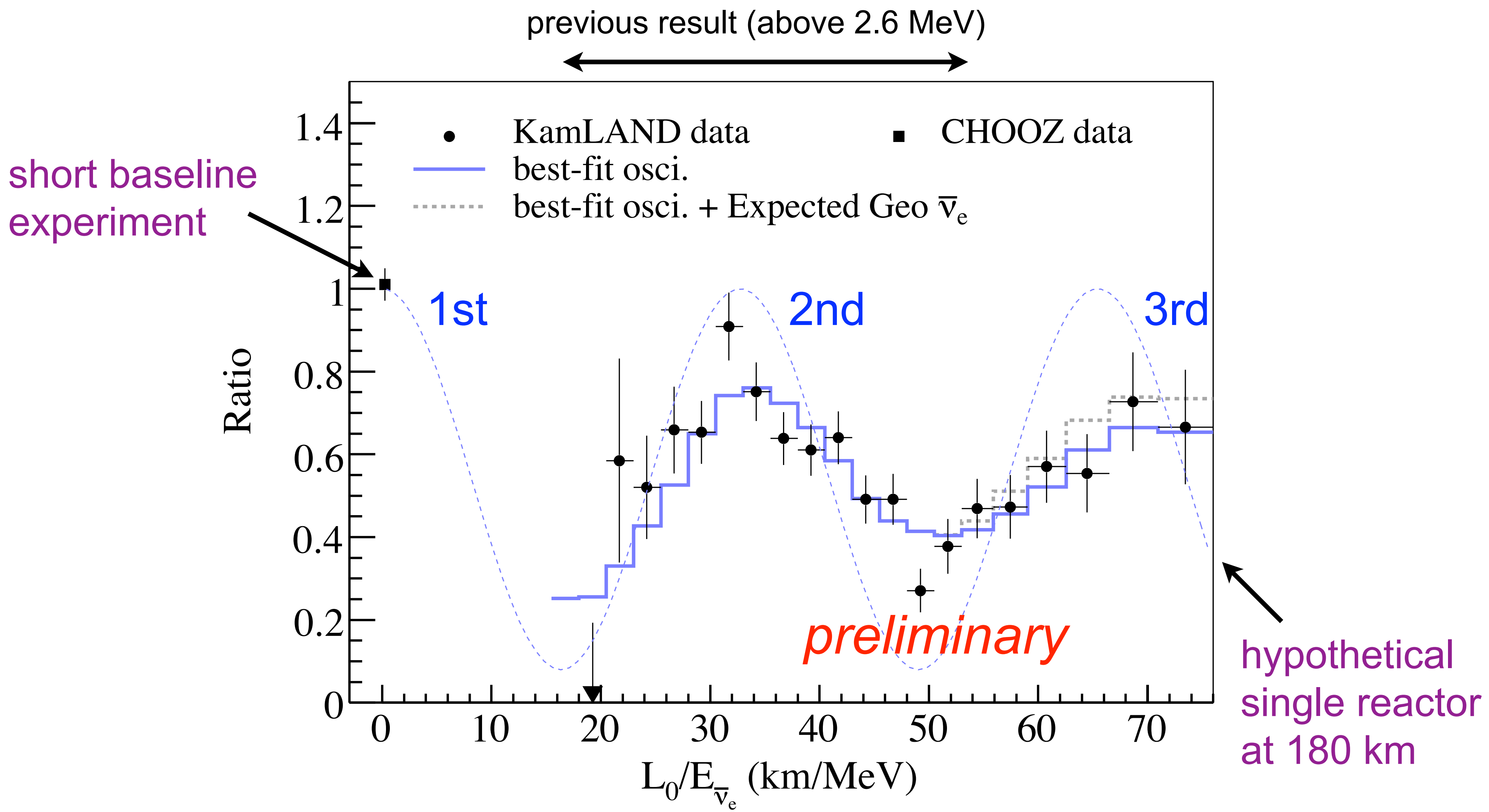


Detector calibration
1% E-scale non-linarity?



Oscillatory nature of neutrino flavour conversion

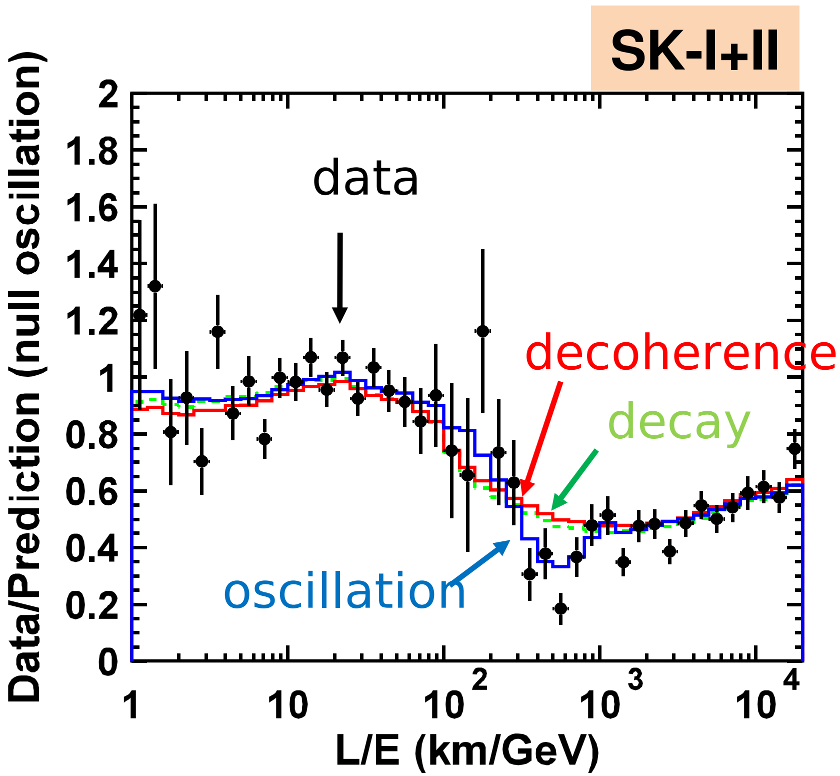
Neutrino Oscillation

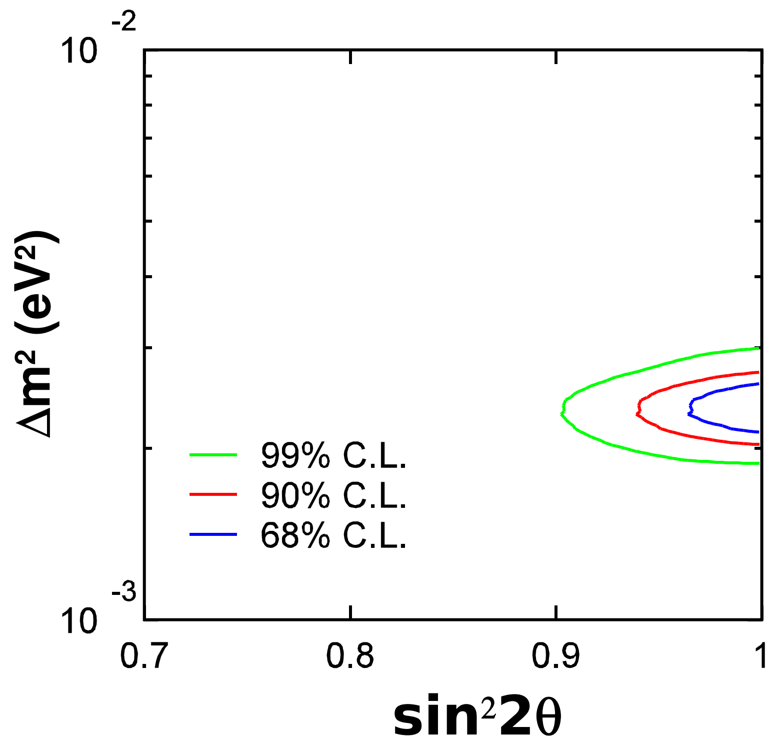


KamLAND covers the 2nd and 3rd maximum

→ **characteristic of neutrino oscillation**

SK-I+II L/E oscillation analysis





χ^2_{osc} = 83.9/82 d.o.f

χ^2_{dcy} = 107.1/82 d.o.f, $\Delta\chi^2$ = 23.2 (4.8σ)

χ^2_{dec} = 112.5/82 d.o.f, $\Delta\chi^2$ = 27.6 (5.3σ)

$\nu_\mu - \nu_\tau$ 2 flavor analysis

χ^2_{min} = 83.9/82 d.o.f

@($\sin^2 2\theta, \Delta m^2$)= (1.00,2.3x10^{-3}eV^2)

Neutrino decay and decoherence are disfavored at ~5 σ

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Neutrino parameter determination – global fits

- Madrid-Barcelona-Karlsruhe
  (Gonzalez-Garcia, Maltoni, Salvado & Schwetz)
- Valencia group (Tortola, Valle et al.)
- Bari group (Fogli, Lisi et al.)

(With some inter-relations between the 1st and the 2nd groups)

Global fits:

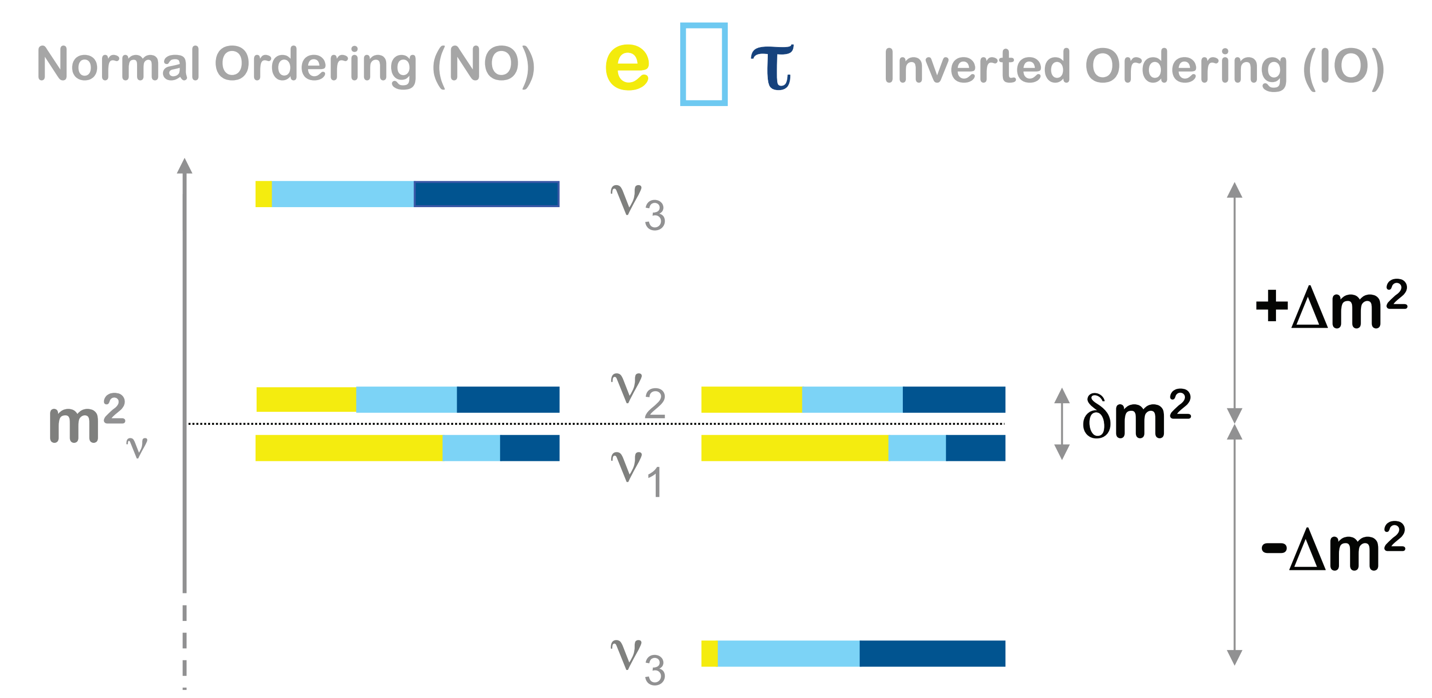
“Broad-brush” picture (with 1-digit accuracy)

Knowns:

$\delta m^2 \sim 7 \times 10^{-5}$ eV^2
$\Delta m^2 \sim 2 \times 10^{-3}$ eV^2
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

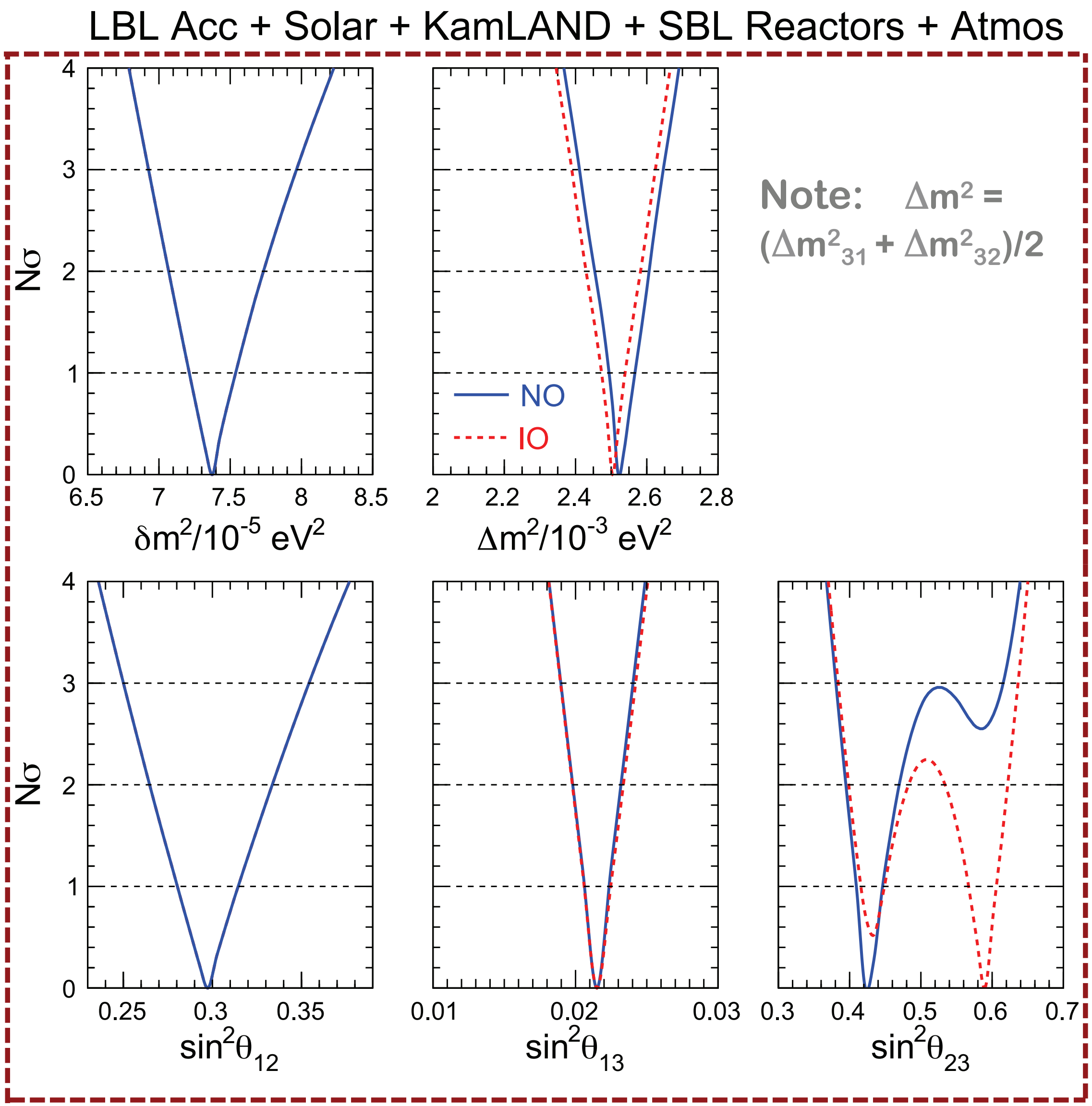
Unknowns:

δ(CP)
sign(Δm^2) = ordering
octant(θ_{23})
absolute mass scale
Dirac/Majorana nature



Global fits – Bari group

Five known oscillation parameters:



Note: $\Delta m^2 = (\Delta m^2_{31} + \Delta m^2_{32})/2$

Current 1σ errors (1/6 of ±3σ range):

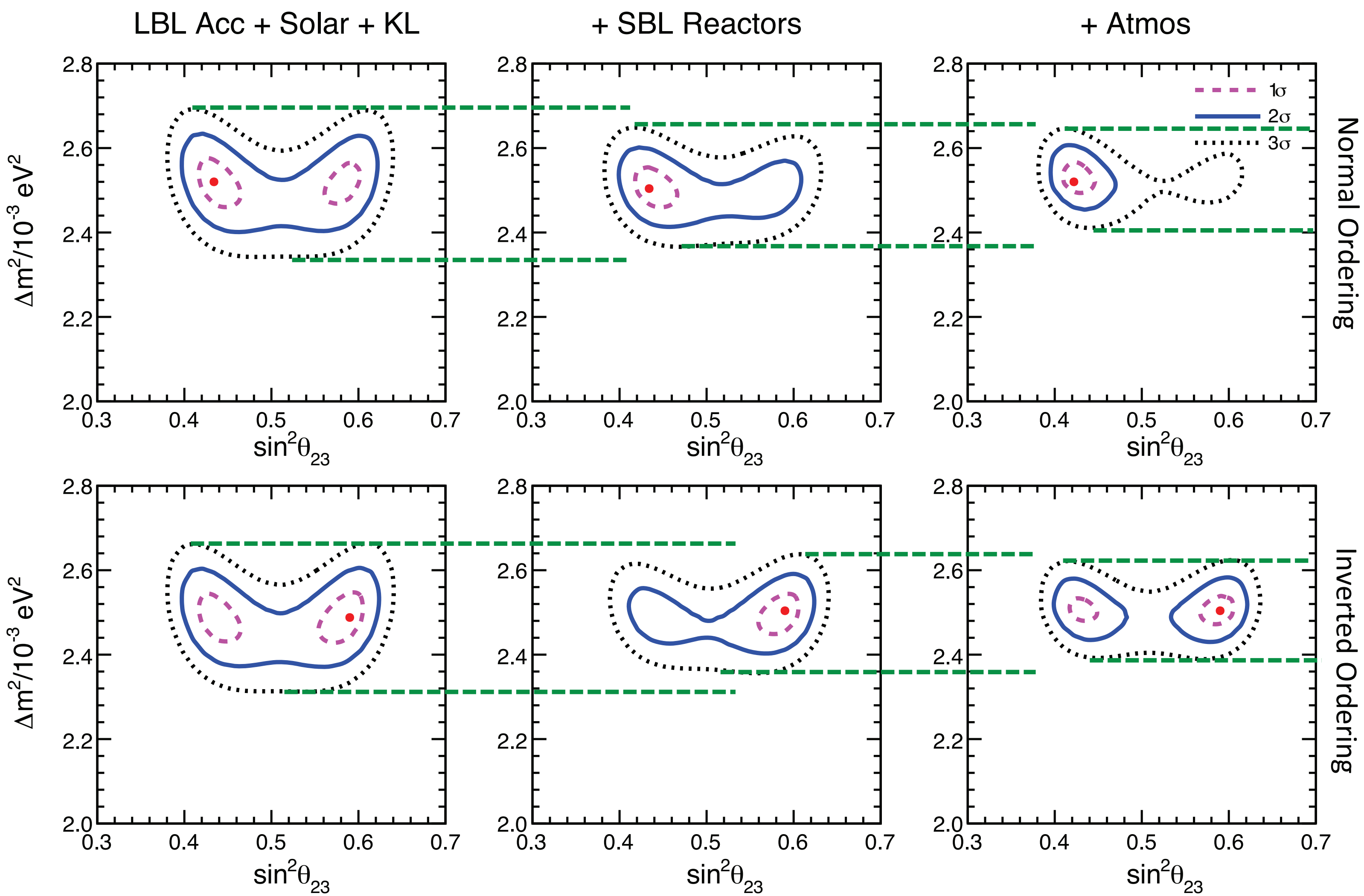
δm^2	2.3 %
Δm^2	1.6 %
$\sin^2\theta_{12}$	5.8 %
$\sin^2\theta_{13}$	4.0 %
$\sin^2\theta_{23}$	~ 9 %

all < 10%...

Precision Era!

[but PMNS still very far from CKM accuracy]

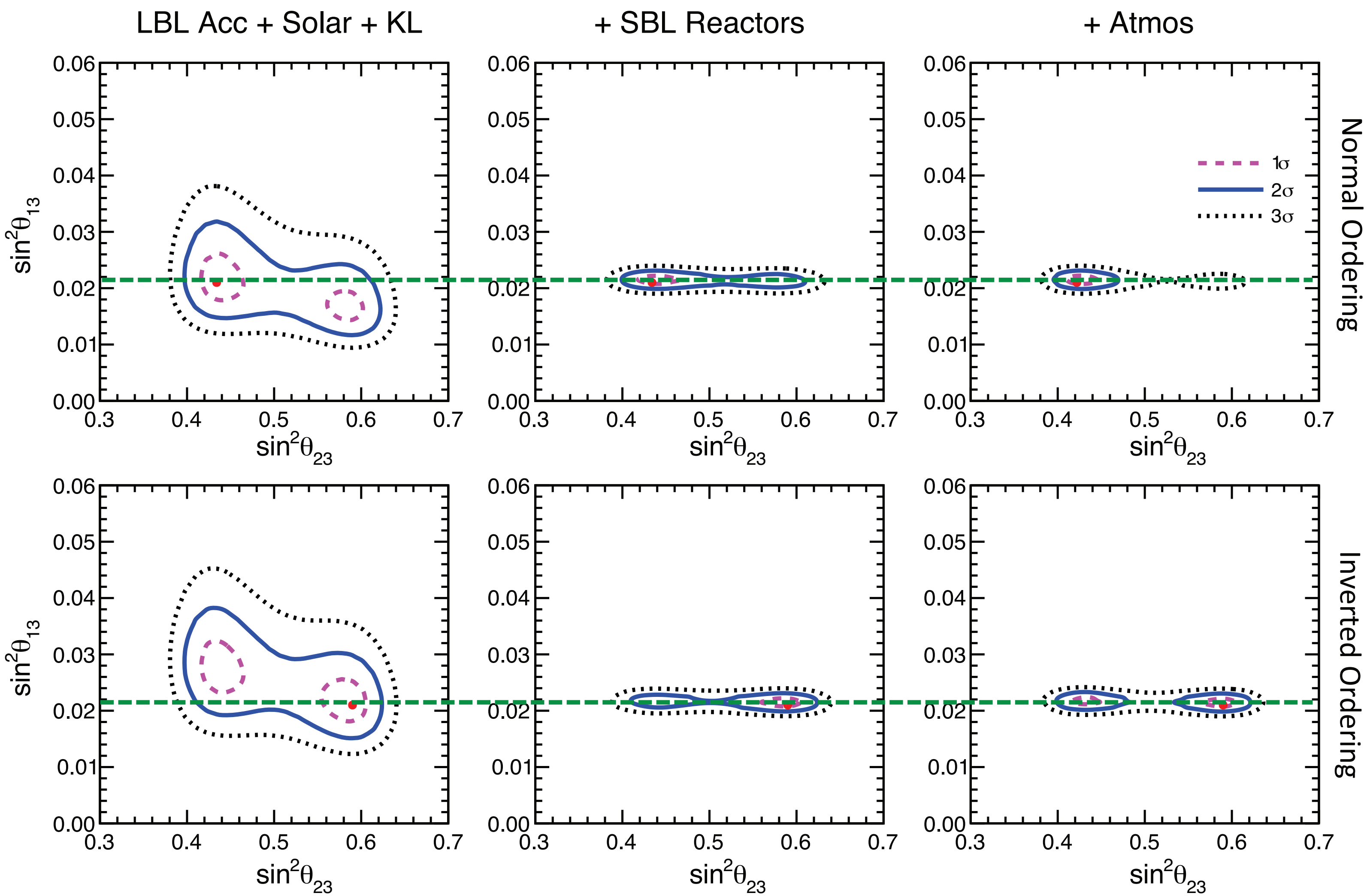
More on known oscillation parameters: sinergy on Δm^2



All data sets contribute to Δm^2

Global fits – Bari group

More on known oscillation parameters: sinergy on θ_{13}



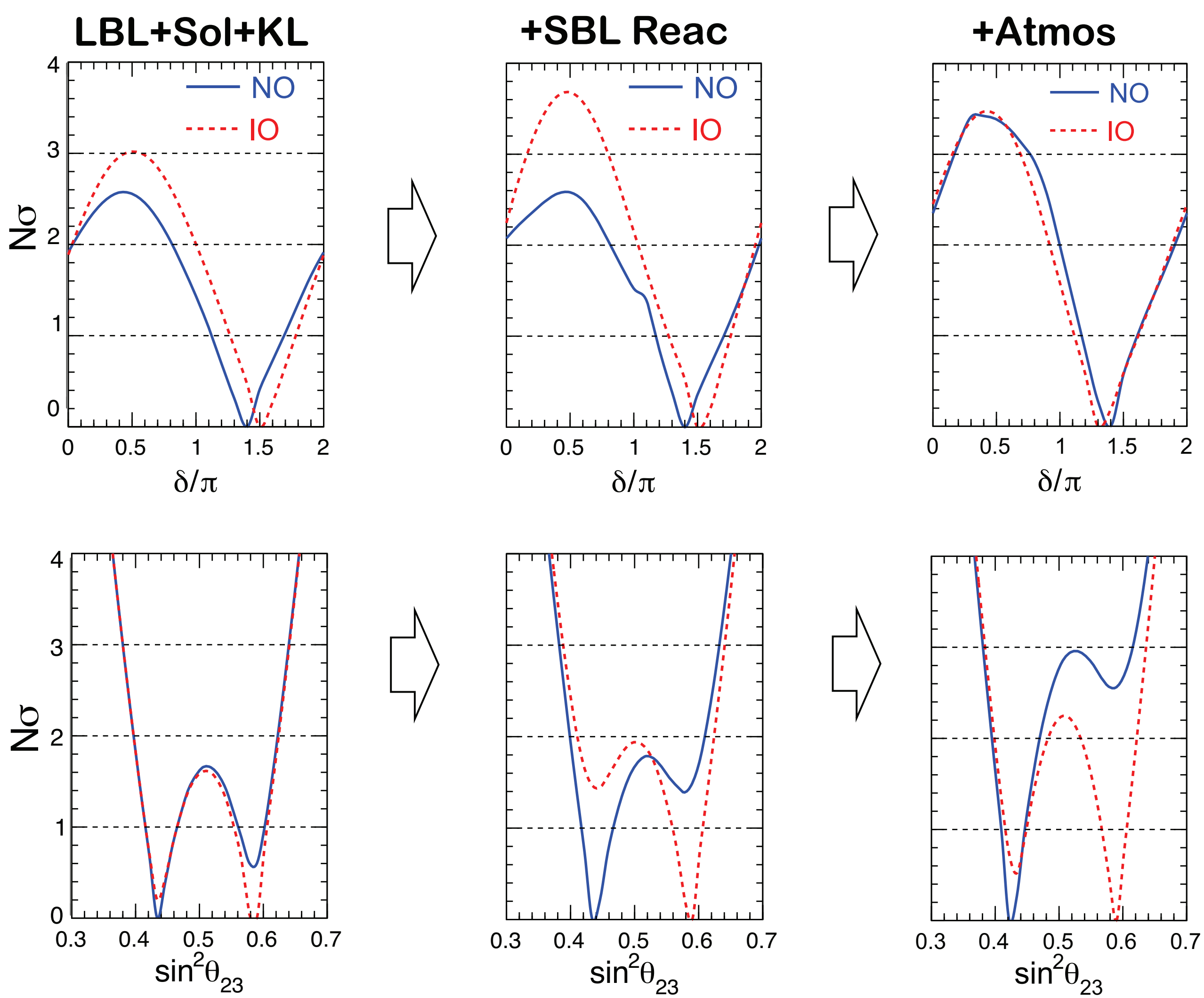
LBL + solar + KL prefer the same θ_{13} as reactors (within large uncertainties)

Global fits – Bari group

More on unknown oscillation parameters:

δ_{CP}

θ_{23} octant



sin δ ~ -1
(or sin δ < 0)
favored;
sin δ ~ +1
excluded

Max-mixing disfavored;
octant flips with NO/IO

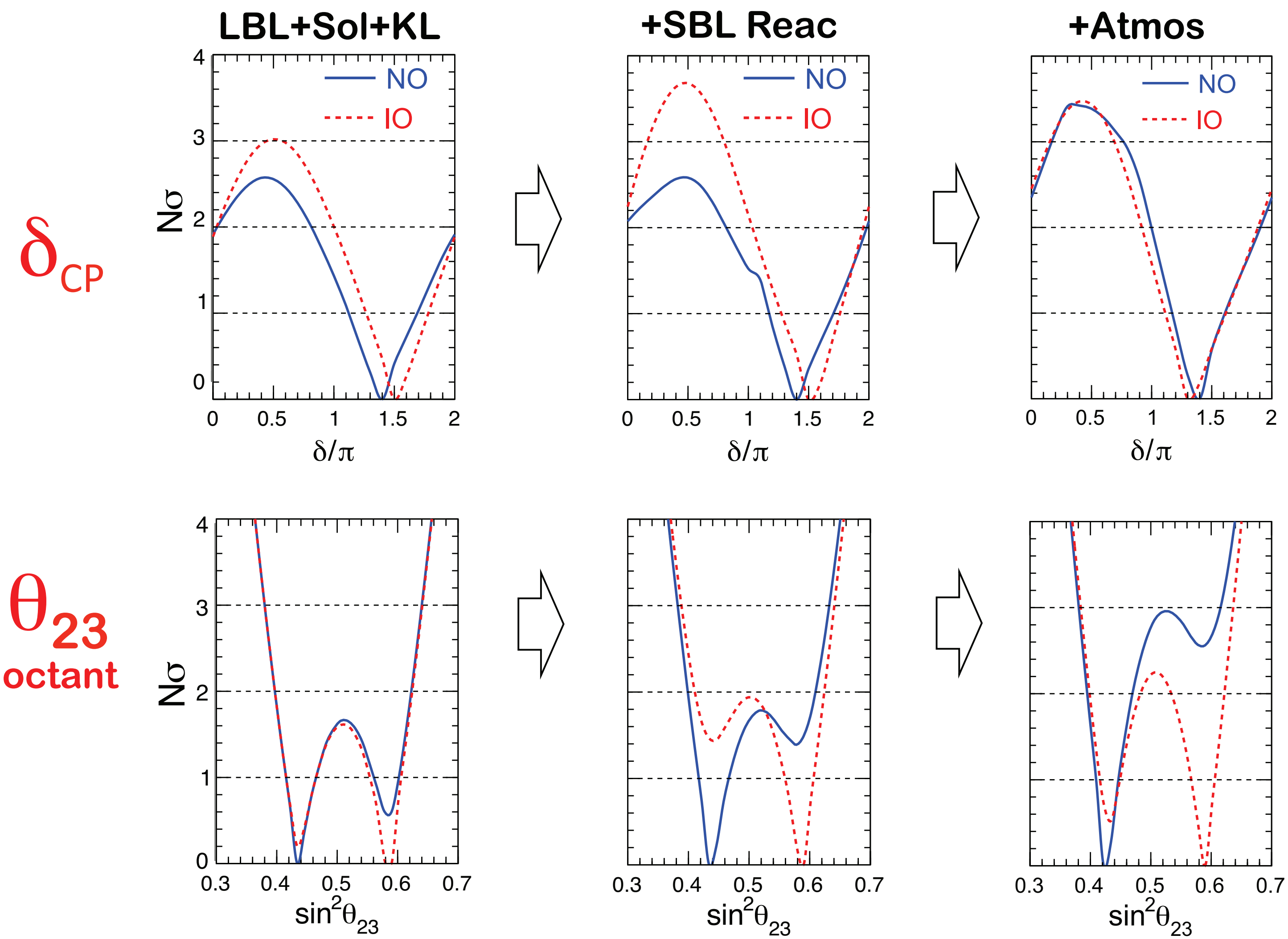
$\Delta\chi^2$ (IO-NO)

+1.1	+1.1	+3.6

Intriguing!
NO favored

Global fits – Bari group

Compare the current results (circa 2017) with...



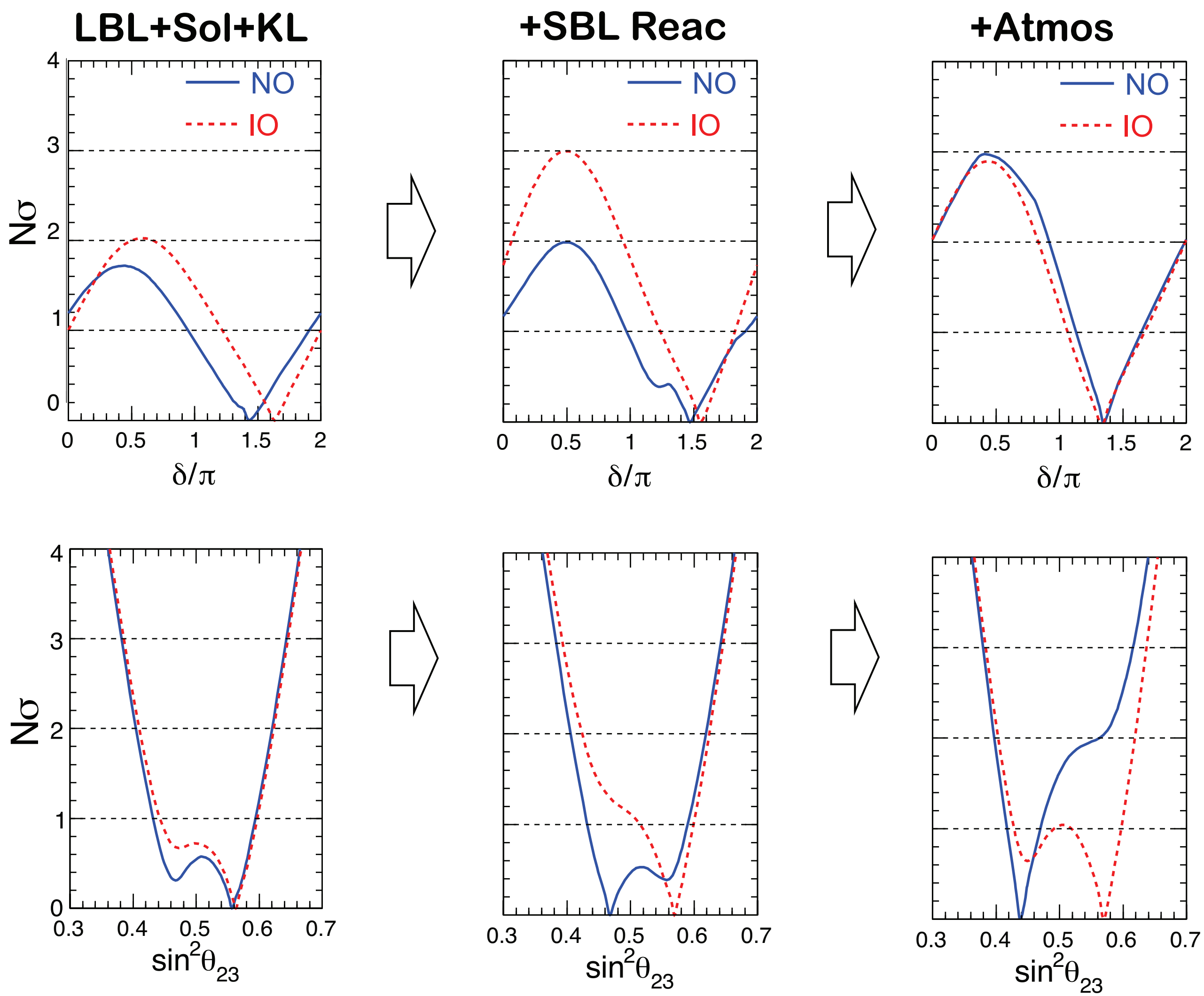
	LBL+Sol+KL	+SBL Reac	+Atmos
$\Delta\chi^2$ (IO-NO)	+1.1	+1.1	+3.6

Global fits – Bari group

… 1yr ago, 2016: trends were somewhat weaker

δ_{CP}

θ_{23} octant

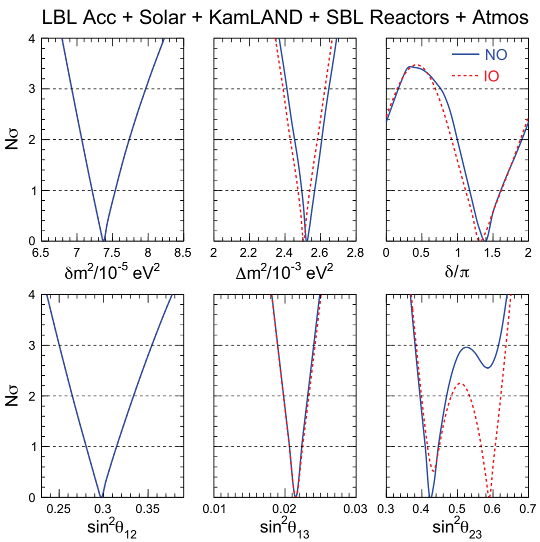


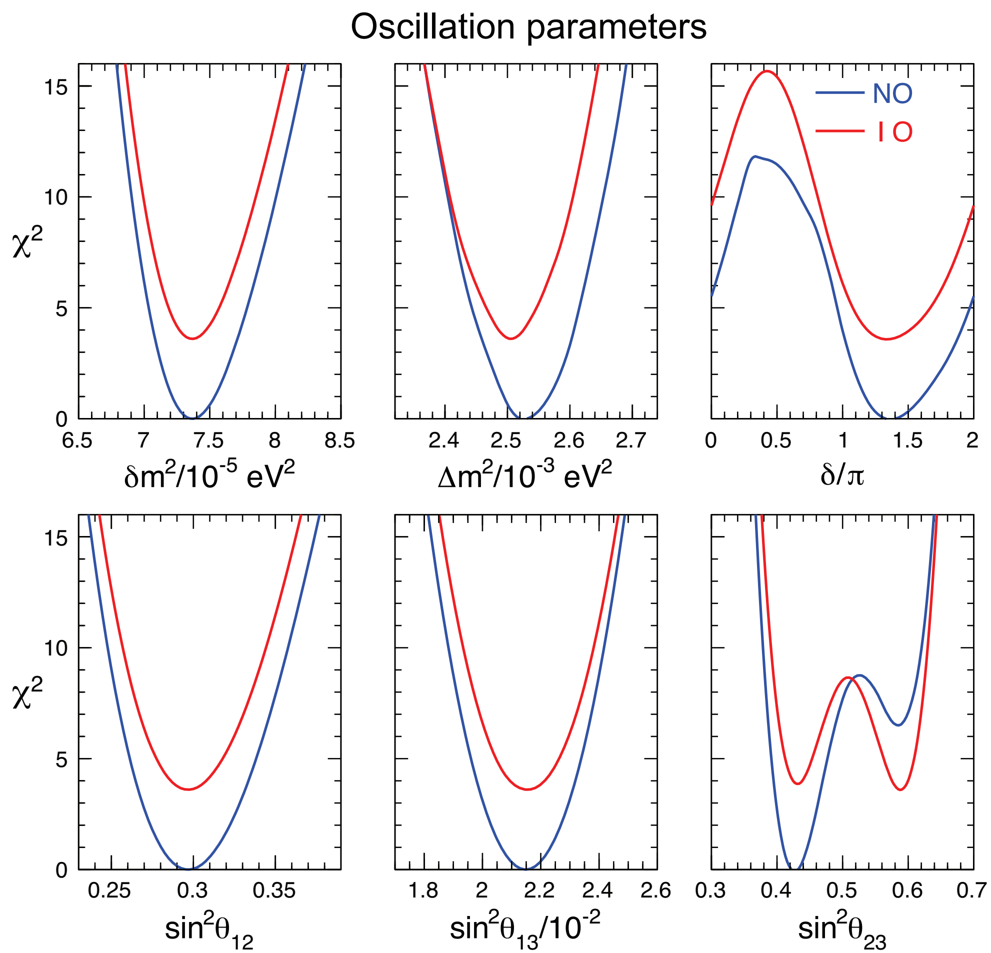
$\Delta\chi^2$ (IO-NO): -1.2 → -0.9 → +1.0

Global fits – Bari group

Current indication $\Delta\chi^2_{IO-NO} = 3.6$ from oscill. data starts to be interesting.

Useful to see the effect of excluding/including this offset in the analysis:



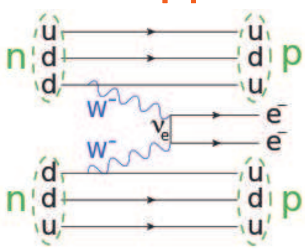


Two different ways of marginalizing over mass ordering(s) →

Global fits – Bari group

Absolute neutrino mass observables

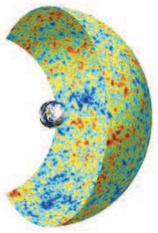
0νββ

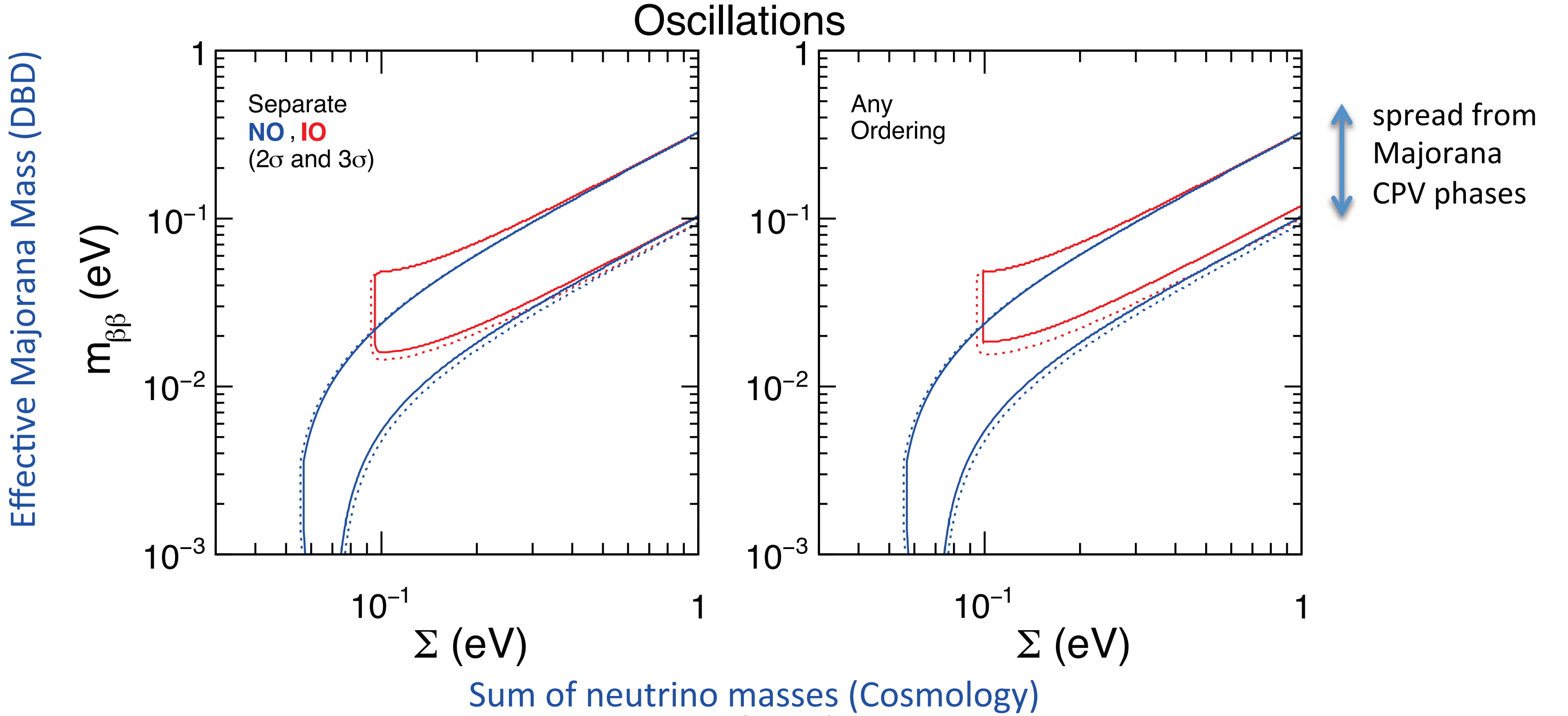


$$m_{\beta\beta} = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

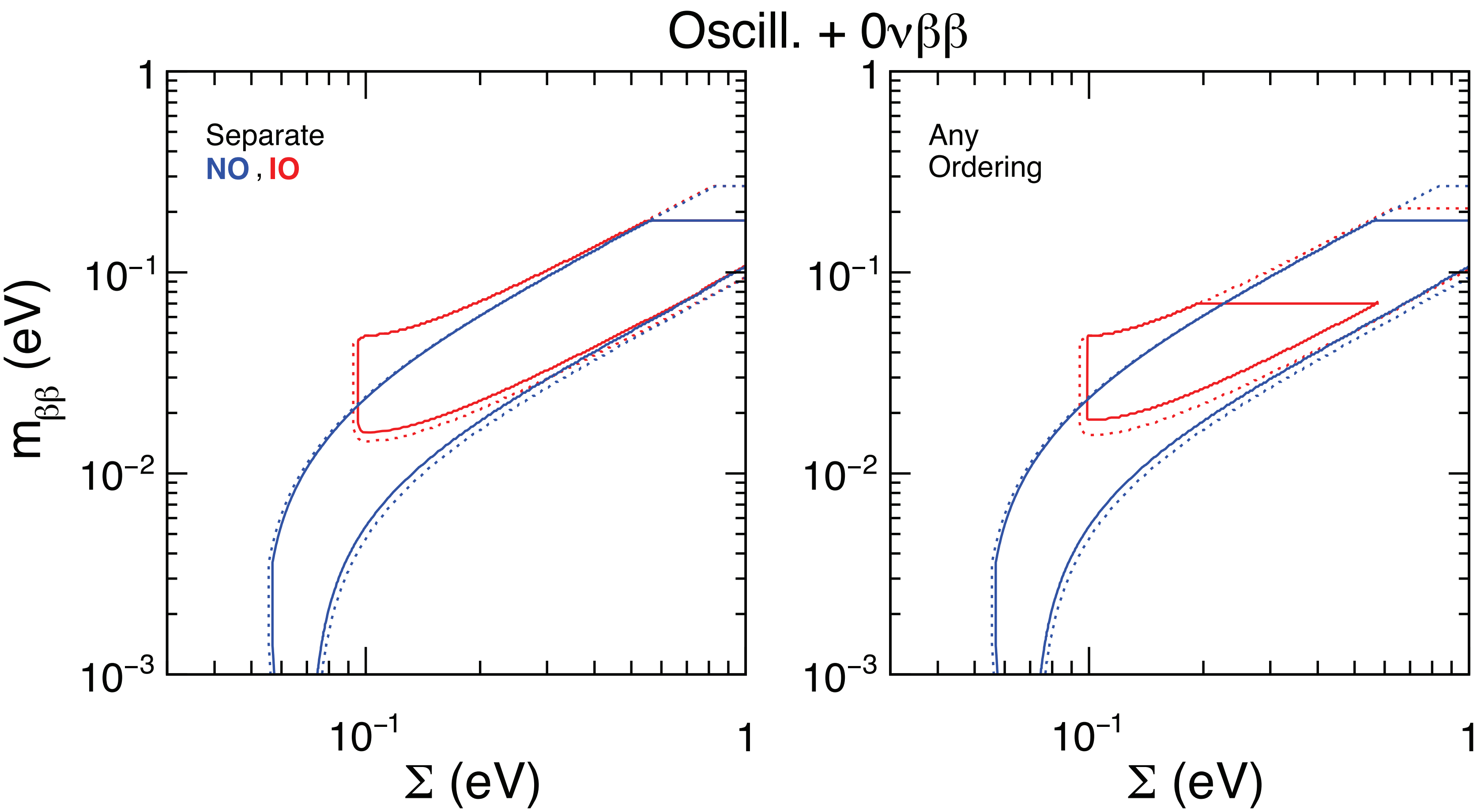
$$\Sigma = m_1 + m_2 + m_3$$

Cosmo





Global fits – Bari group



Global fits – Bari group

Cosmological constraints (circa 2017)

Analysis of various **datasets** within standard (6-param.) **ΛCDM model** augmented with Σ
plus one possible 1 extra parameter **A_{lens}**, to account for syst's or nonstandard effects
[**A_{lens}** > 1 may be typically traded for higher values of the sum of neutrino mass Σ]

Code: **CosmoMC with NO / IO options explicitly included in Σ**, via the two mass^2 differences
→ unphysical spectra of neutrino masses (e.g., Σ = 0) not allowed by construction.
→ expect small NO-IO differences at low Σ, but vanishing at high Σ (degenerate spectrum)

Results on Σ (upper bounds) **and on $\Delta\chi^2_{\text{IO-NO}}$:**

TABLE II: Results of the global 3ν analysis of cosmological data within the standard $\Lambda\text{CDM} + \Sigma$ and extended $\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$ models. The datasets refer to various combinations of the Planck power angular CMB temperature power spectrum (TT) plus polarization power spectra (TE, EE), reionization optical depth τ_{HFI}, lensing potential power spectrum (lensing), and BAO measurements. For each of the 12 cases we report the 2σ upper bounds on $\Sigma = m_1 + m_2 + m_3$ for NO and IO, together with the $\Delta\chi^2$ difference between the two mass orderings (with one digit after decimal point). For any Σ, the masses m_i are taken to obey the δm^2 and Δm^2 constraints coming from oscillation data. See the text for more details.

#	Model	Cosmological data set	Σ/eV (2σ), NO	Σ/eV (2σ), IO	$\Delta\chi^2_{\text{IO-NO}}$
1	$\Lambda\text{CDM} + \Sigma$	Planck TT + τ_{HFI}	< 0.72	< 0.80	0.7
2	$\Lambda\text{CDM} + \Sigma$	Planck TT + τ_{HFI} + lensing	< 0.64	< 0.63	0.2
3	$\Lambda\text{CDM} + \Sigma$	Planck TT + τ_{HFI} + BAO	< 0.21	< 0.23	1.2
4	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + τ_{HFI}	< 0.44	< 0.48	0.6
5	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.45	< 0.47	0.3
6	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.18	< 0.20	1.6
7	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT + τ_{HFI}	< 1.08	< 1.08	-0.1
8	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT + τ_{HFI} + lensing	< 0.91	< 0.93	0.0
9	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT + τ_{HFI} + BAO	< 0.45	< 0.46	0.2
10	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + τ_{HFI}	< 1.04	< 1.03	0.0
11	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.89	< 0.89	0.1
12	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.31	< 0.32	0.3

Global fits – Bari group

Grand total of IO-NO differences:

	LBL+Sol+KL		+SBL Reac		+Atmos		+DBD, Cosmo
$\Delta\chi^2$ (IO-NO)	+1.1	⇨	+1.1	⇨	+3.6	⇨	+3.6 … +4.4

Small but coherent steps: **N.O. favored**... Overall preference at $1.9\sigma - 2.1\sigma$

TABLE III: Values of $\Delta\chi^2_{\mathrm{IO-NO}}$ from the global analysis of oscillation and non oscillation data (numbered according to the adopted cosmological datasets as in Table II), to be compared with the value 3.6 from oscillation data only [Eq. (9)]. An overall preference emerges for NO, at the level of 1.9–2.1σ.

#	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta\chi^2_{\mathrm{IO-NO}}$	4.3	3.8	4.4	4.2	3.9	4.4	3.6	3.7	3.8	3.7	3.8	3.9

The statistical significance of possible hints about ordering is currently debated.
If they are not fluctuations, expect (fractional) improvements in upcoming years
Dedicated projects are planned with reactor, atmospheric, accelerator neutrinos

SUMMARY

- **Status of known 3ν oscillation parameters:**
  Precision era (but PMNS accuracy far from CKM)

- **Trends of unknown oscillation parameters:**
  Favoring **CPV** with $\sin\delta<0$, nonmax θ_{23}, and NO

- **Status of constraints from $0\nu\beta\beta$ & Cosmology:**
  Sub-eV sensitivity; Cosmo analysis with NO vs IO

- **Oscillation + nonoscillation global analysis:**
  Corroborates **NO with respect to IO** at $\sim 2\sigma$ level

PROSPECTS - oscillations

- **Known 3ν oscillation parameters:**
  Higher accuracy with LBL acceler., JUNO react. + others

- **CPV:**
  If **sinδ ~ -1**, then **T2K+NOvA may probe CPV** at $\sim 3\sigma$
  Higher C.L. requires future LBL acc. (DUNE, Hyper-K)

- **Hierarchy:**
  Expect progress from T2K+NOvA and future expts:
  JUNO reactor, LBL acceler., Large-volume atmospheric

- **Octant of θ_{23} (if significantly nonmaximal):**
  Lifting degeneracy **possible, but not easy** at high CL

Light sterile neutrinos?

Several indications of existence of relatively light ($\Delta m^2 \sim 1\ \mathrm{eV}^2$) extra neutrino species.

Must be an electroweak singlet (sterile) due to the LEP results on the invisible width of Z^0 boson!

- LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ appearance)
- MiniBooNE ($\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance)
- Gallium anomaly (ν_e disappearance)
- Reactor anomaly ($\bar{\nu}_e$ disappearance)

There are also hints for existence light sterile neutrinos with masses in the eV, keV or even MeV range r-process supernova nucleosynthesis, pulsar kicks, warm dark matter and leptogenesis scenarios.

Also: very light ν_s ($\Delta m^2 \sim 10^{-5}\ \mathrm{eV}^2$) from the solar neutrino spectrum?

(de Holanda & Smirnov, 2004, 2011; Das, Pulido, Picariello, 2009)

LSND

Search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation at baseline $L = 30$ m, $\langle E_\nu \rangle \sim 30$ MeV.
An excess of $87.9 \pm 22.4 \pm 6.0$ events over expected background (3.8σ) $\Rightarrow$

$$P_{av.}(\bar{\nu}_\mu \to \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$$

The oscillation interpretation requires $\Delta m^2 \simeq (0.2 - 1)\ \mathrm{eV}^2$ – incompatible with 3f schemes! At least one ν_s necessary.
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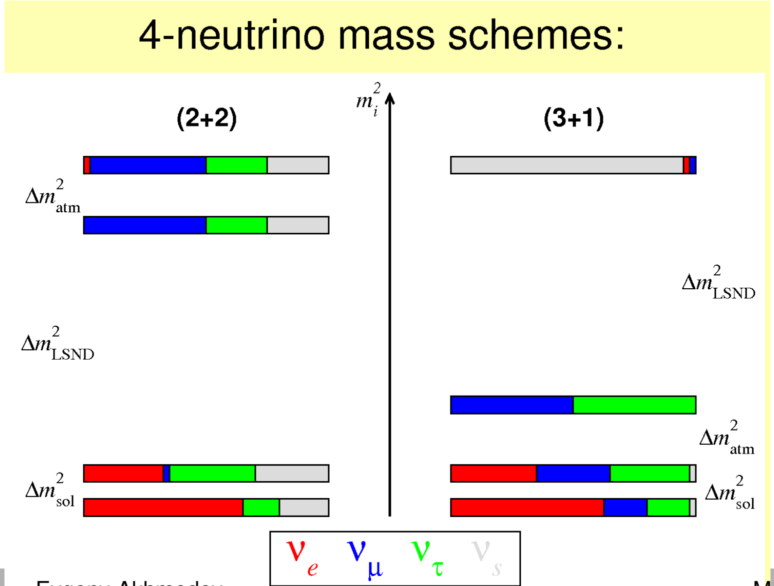

2+2 schemes: ruled out by combination of solar and atm. ν experiments.

3+1 scheme: strongly disfavoured by SBL expts.

MiniBooNE

MiniBooNE: a dedicated experiment to test the LSND claim.

Baseline $L = 540$ m, $\langle E_\nu \rangle \sim 600$ MeV; L/E approximately the same as in LSND.

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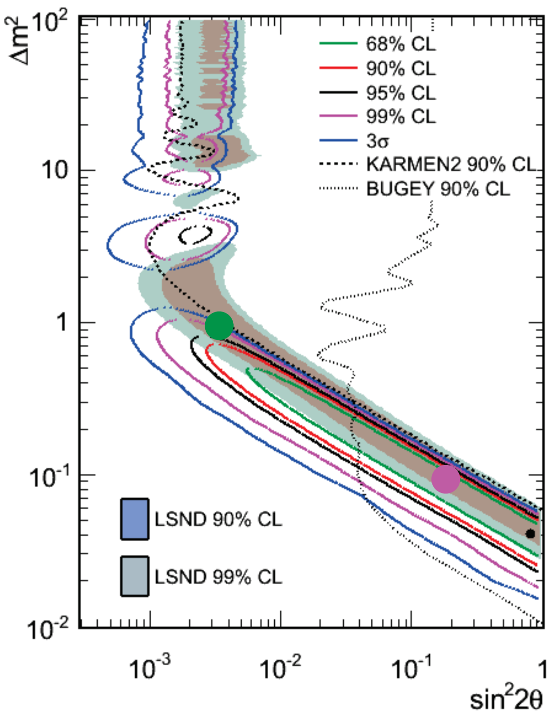
Data in neutrino and antineutrino modes are now consistent (no hints for CP violation) and are also consistent with the LSND claim.

A significant tension with data of previous SBL experiments (esp. ν_μ disappearance)!

Appearance results from MiniBooNE

Chris Polly @ Neutrino2012, 1207.4809

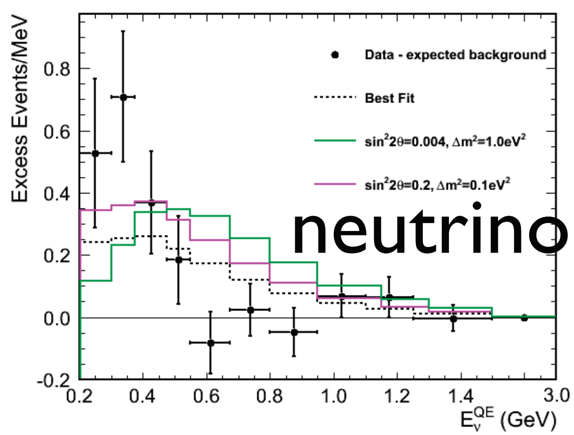
Simultaneous 3+1 fit to ν and anti-ν data



- WS accounted for properly
- Construction of correlated systematic error matrix (Z. Pavlovic)
- E>200 MeV BF preferred at 3.8σ over null

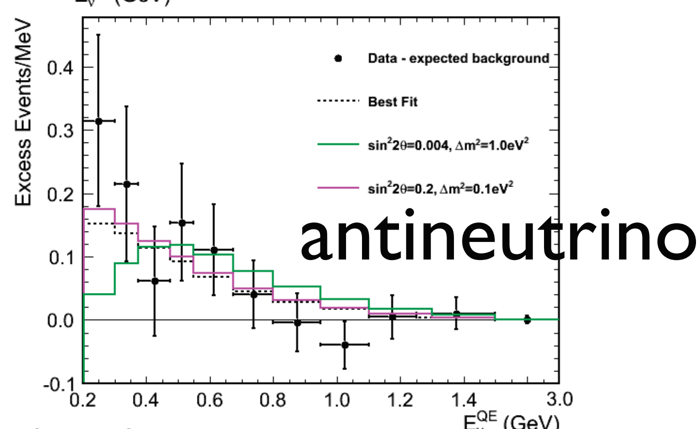
Total Excess: 240.3 +/- 34.5 +/- 52.6

LSND: 3.8σ



* Simultaneous fit (E>200 MeV) with fully-correlated systematic to entire MB neutrino and anti-neutrino data

combined	E > 200 MeV	E > 475 MeV
χ^2(null)	42.53	12.87
Prob(null)	0.1%	35.8%
χ^2(bf)	24.72	10.67
Prob(bf)	6.7%	35.8%



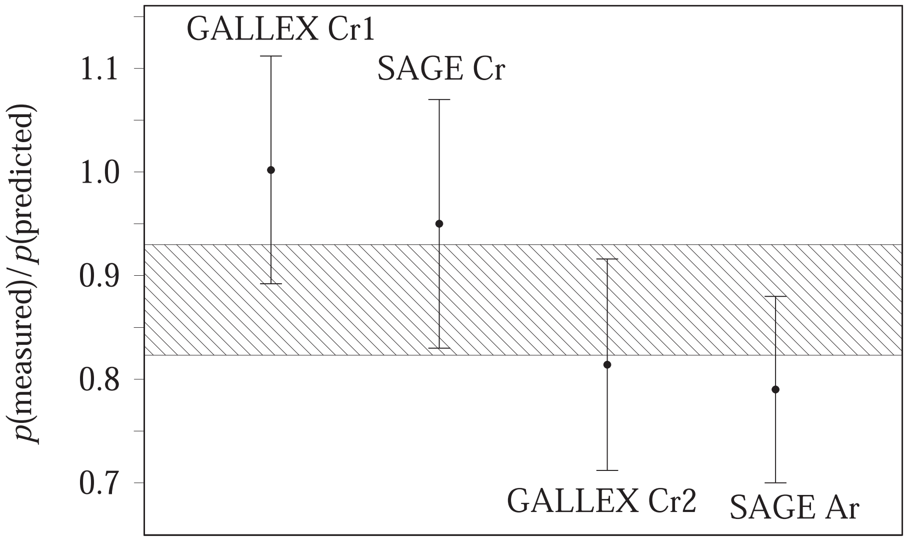
Gallium Anomaly

Gallium Radioactive Source Experiments

Tests of the solar neutrino detectors GALLEX (Cr1, Cr2) and SAGE (Cr, Ar)

Detection Process: $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$

ν_e Sources: $e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$ $\quad e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$



$E \sim 0.7\,\mathrm{MeV}$

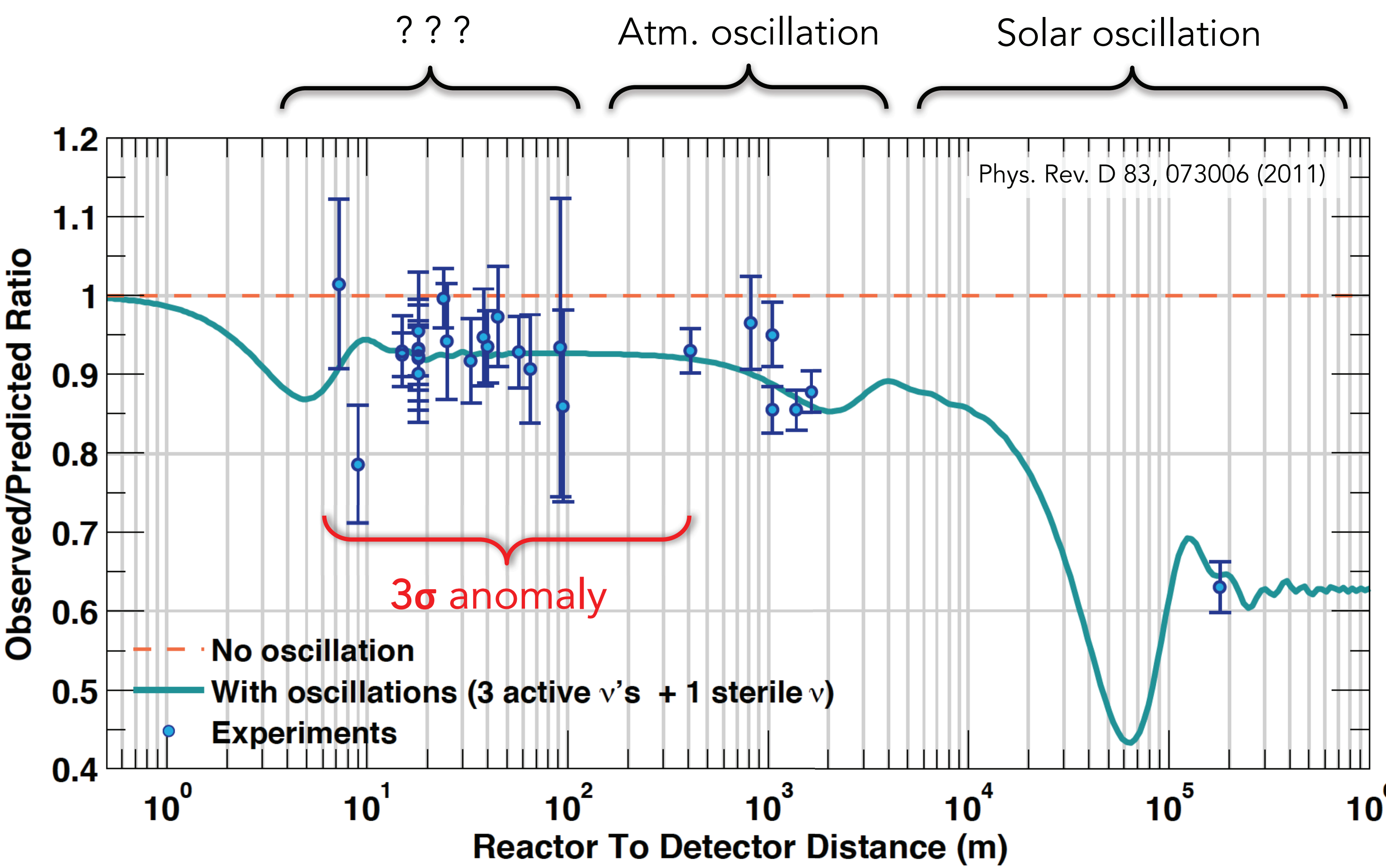
$\langle L \rangle_{\mathrm{GALLEX}} = 1.9\,\mathrm{m}$

$\langle L \rangle_{\mathrm{SAGE}} = 0.6\,\mathrm{m}$

$\overline{R}_{\mathrm{B}} = 0.86 \pm 0.05$

[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

The Reactor Anomaly (RAA)



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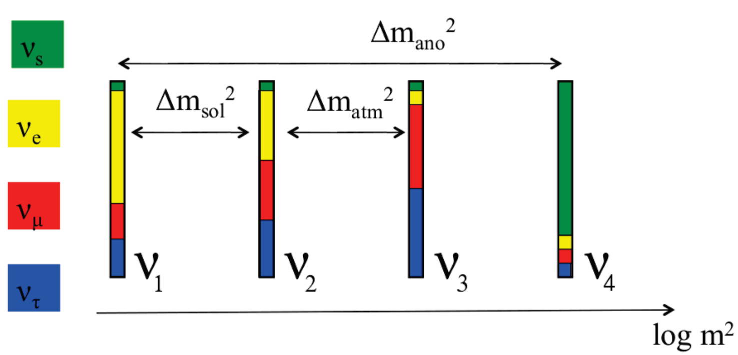
ν mixing and sterile neutrinos

active neutrino mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

eV–keV mass
→ does not directly couple to W/Z boson

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



3+1 scenario

minimal extension

$|U_{s4}|^2 \approx 1$

$|U_{e4}|^2, |U_{\mu 4}|^2, |U_{\tau 4}|^2 \ll 1$

Fitting all together?

3+1 SBL oscillations

appearance

$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2 |U_{\mu 4}|^2$$

disappearance ($\alpha = e, \mu$)

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

- effective 2-flavour oscillations
- no CP violation $\rightarrow$ same results for $\bar{\nu}$ (LSND, MB) and ν (MB) data

Fitting all together?

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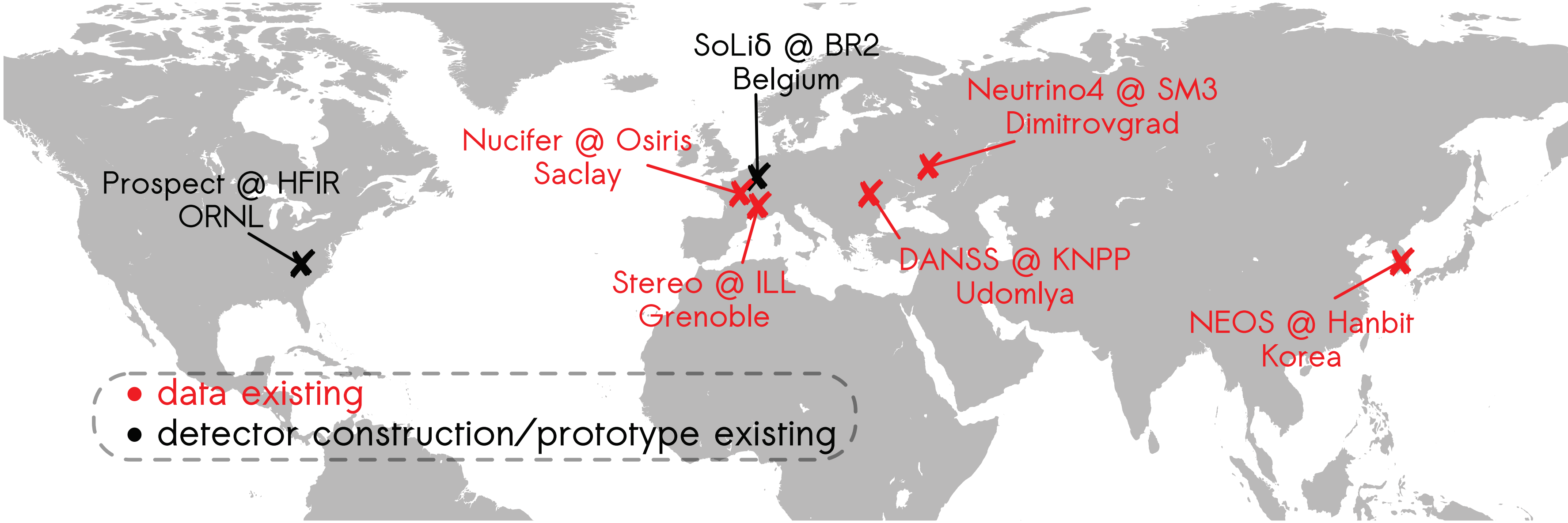
$$\boxed{\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}}$$

$\nu_\mu \to \nu_e$ app. signal requires also signal in both, ν_e and ν_μ disappearance (appearance mixing angle quadratically suppressed)

Searches of eV – scale sterile neutrinos

- $\bar{\nu}_e$ and ν_e disappearance in VSBL reactor exeriments and expts. with radioactive sources
- $\nu_\mu \to \nu_e$ appearance experiments with accelerator neutrinos
- ν_μ disappearance experiments with accelerator neutrinos
- $\bar{\nu}_\mu$ disappearance at TeV energies at IceCube
- Constraints on m_4 and U_{e4} in direct neutrino mass measurement experiments and $2\beta 0\nu$ decay
- Constraints from cosmology (depend on degree of thermalization of ν_s)

Reactor experiments



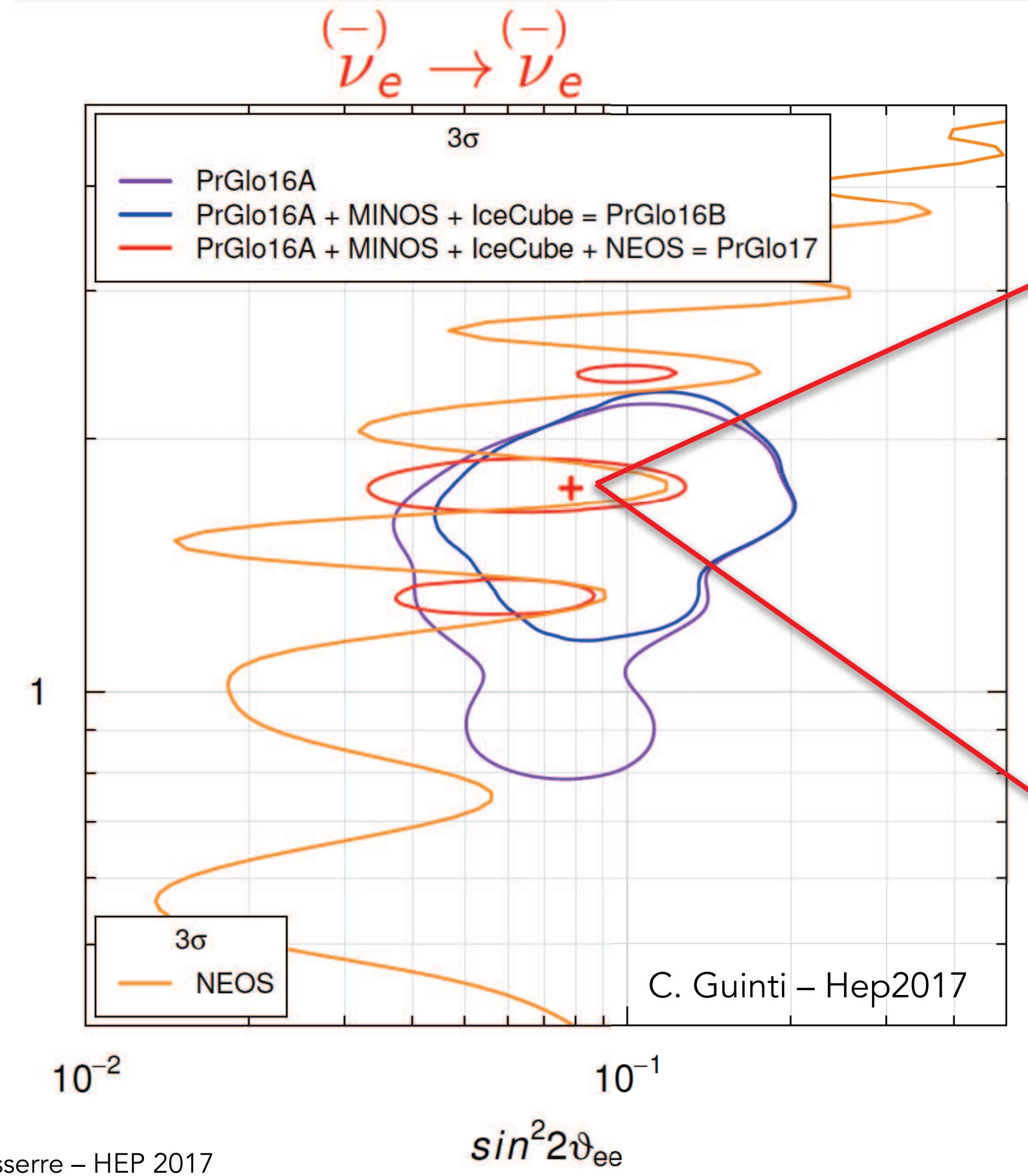
experiment	technology	m_t [t]	P_{th} [MW]	L [m]	S/B	$\sigma_{E,Ph}/E$
DANSS	Gd-PS	0.9	3000	10.7-12.7	100	0.18
NEOS	Gd-LS	1	2800	25	23	0.05
Neutrino4	Gd-LS	0.3	100	7-11	<1	-
Nucifer	Gd-LS	1	70	7	<1	0.1
SoLiδ	^{6}Li-PS	1.6	60-80	5.7	3	0.14
Stereo	Gd-LS	1.8	57	8.9-11.1	1.5	0.05
Prospect I	^{6}Li-PS	1.5	85	7-12	3	0.045

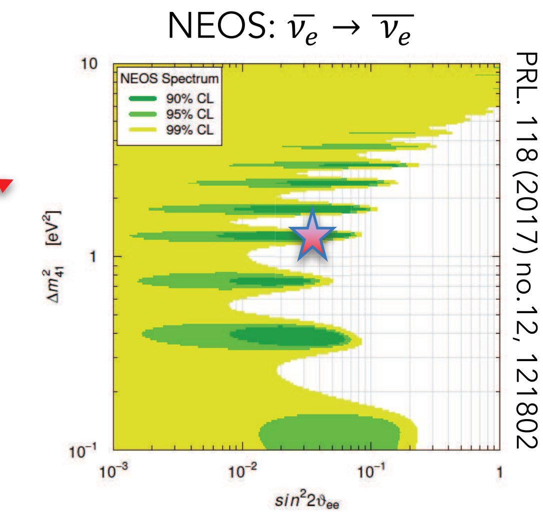
$\sigma_{E,Ph}/E$: photon statistical energy resolution @ 1MeV visible energy

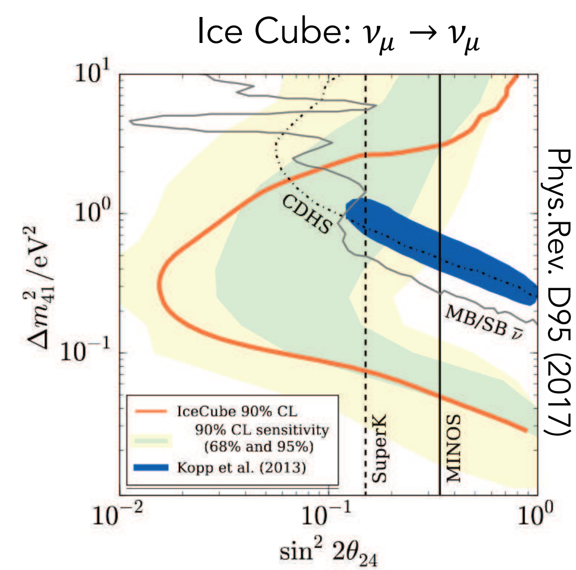
- highly segmented
- highly segmented & inhomogeneous neutron detection
- movable detector

2017/06/01 18

$\overset{(-)}{\nu}_e$ disappearance global fit (3+1)







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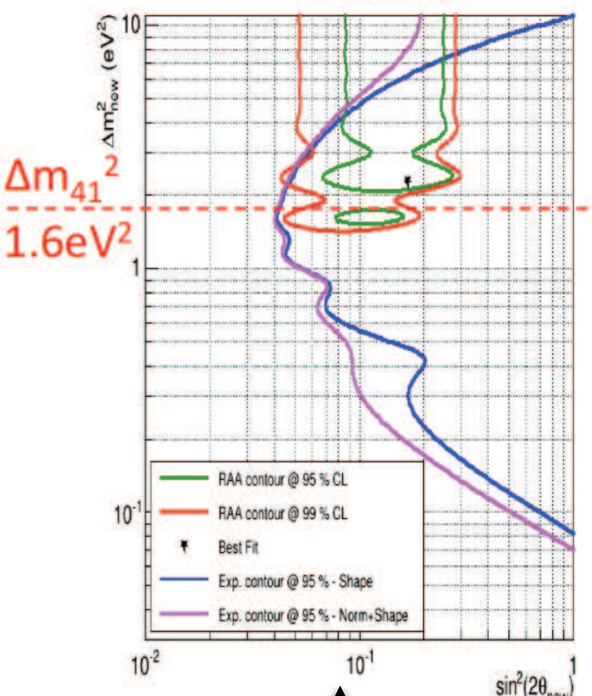
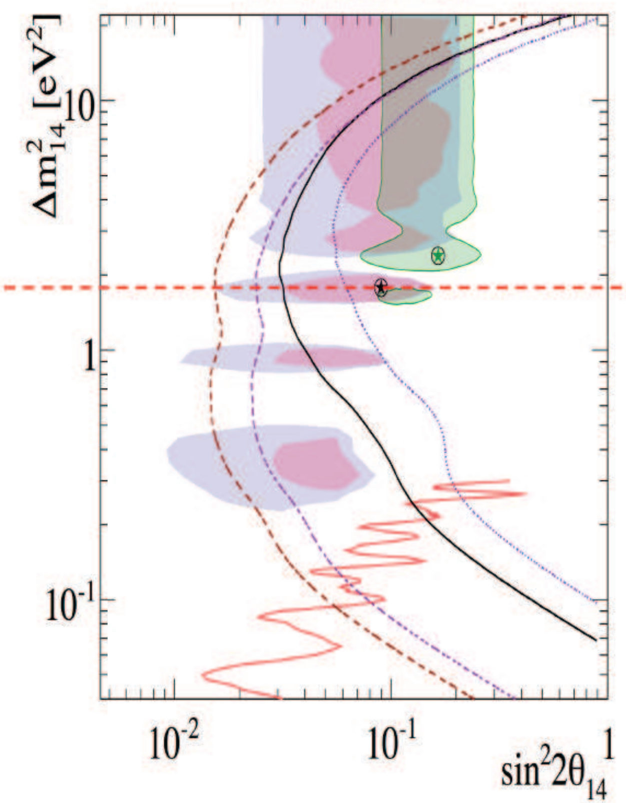
Projected Sensitivities @Reactor

STEREO

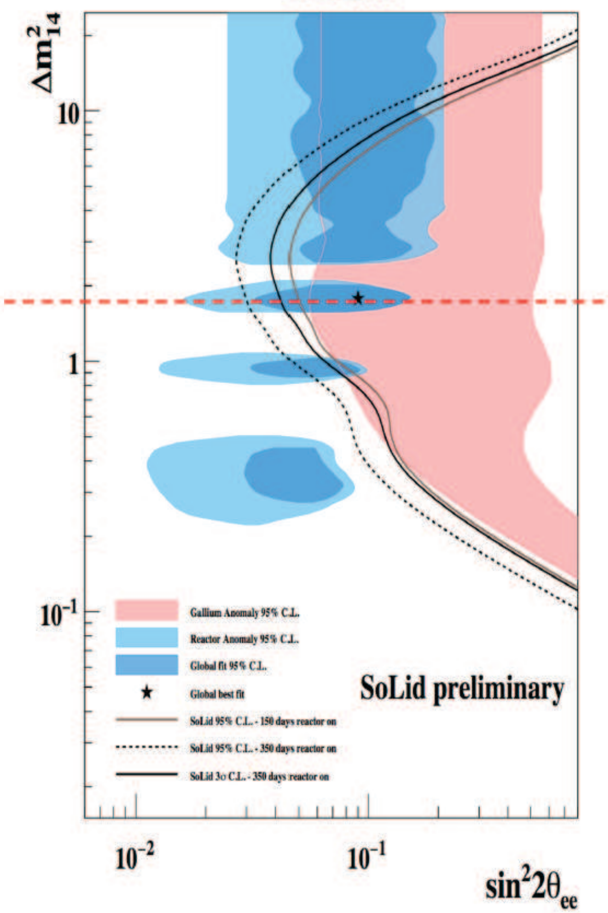


data taking

PROSPECT



SoLid



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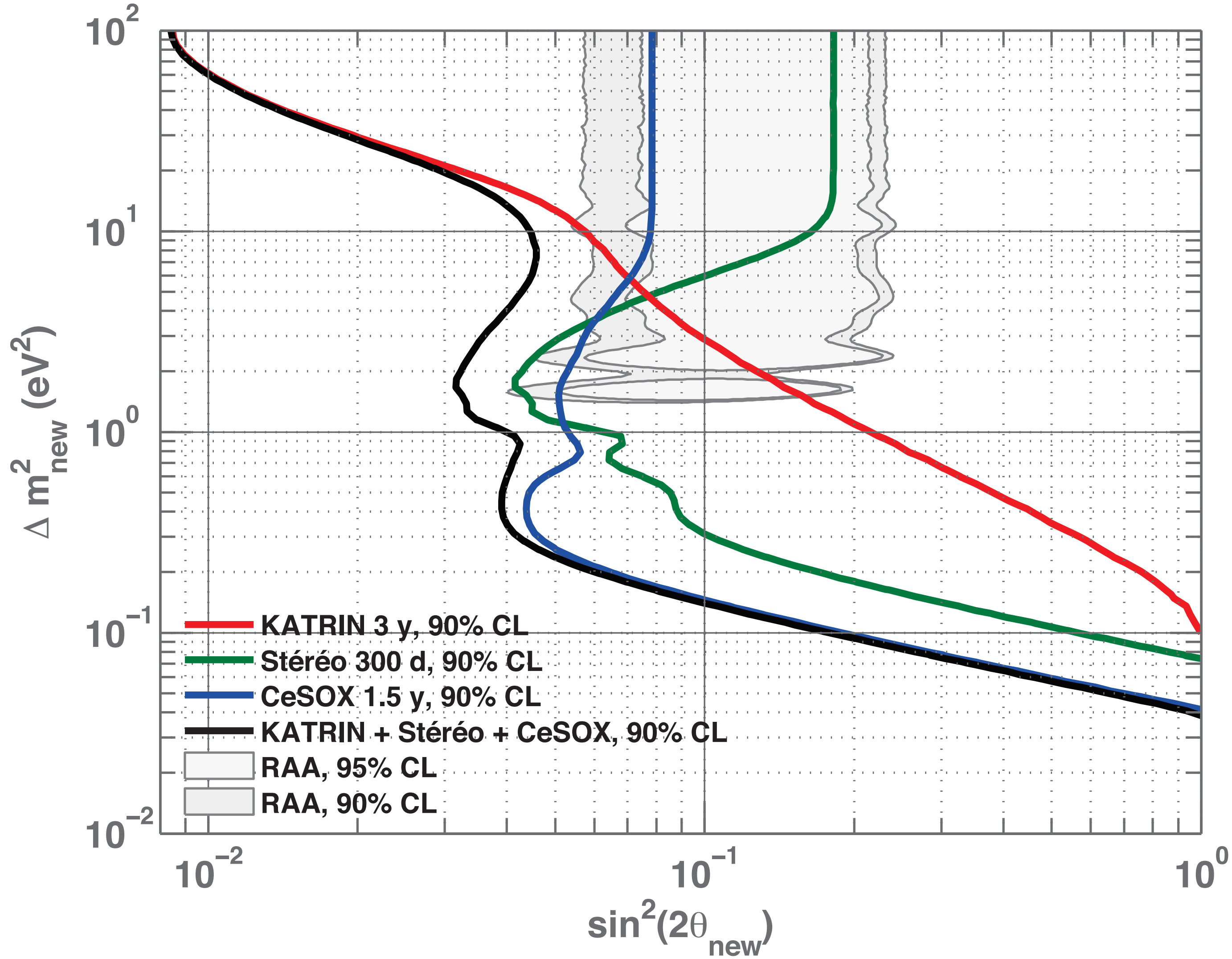
Example: KATRIN + Stéréo + CeSOX

The RAA+GAA parameter space is probed at 98% C.L.



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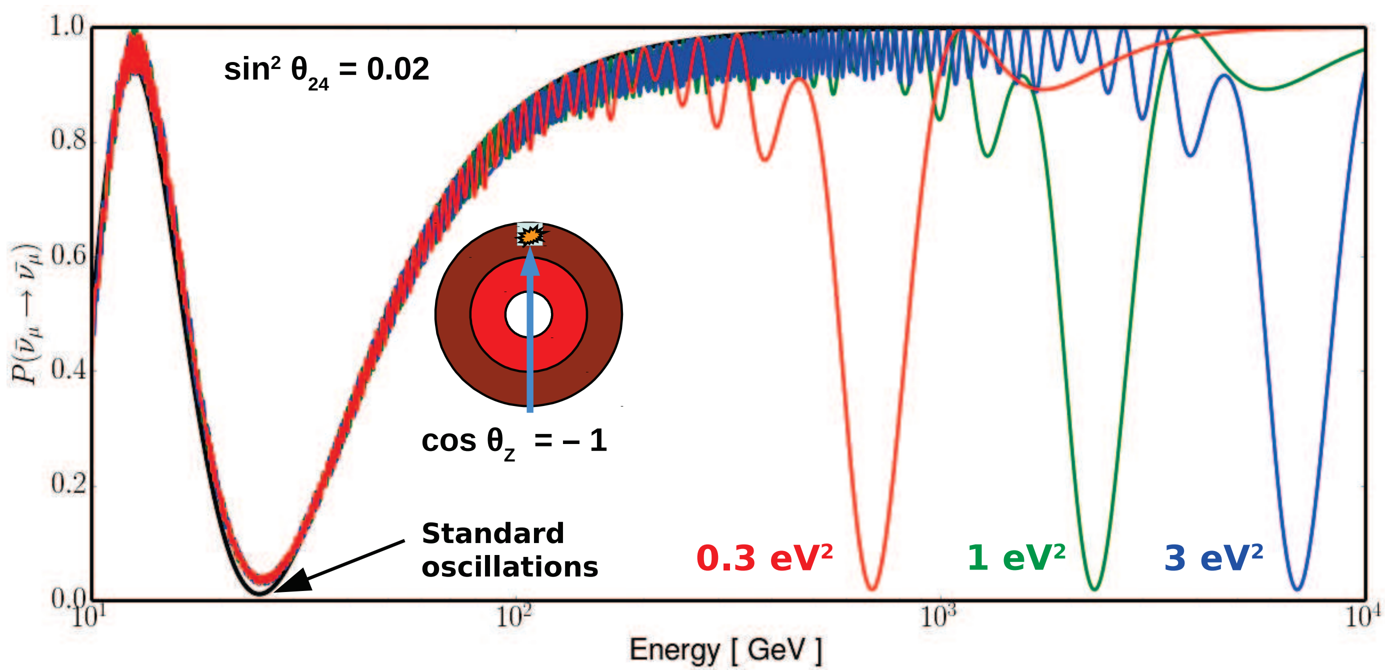
IceCube: $\bar{\nu}_\mu \to \bar{\nu}_s$ res. at $E \sim$ TeV

The resonant enhancement

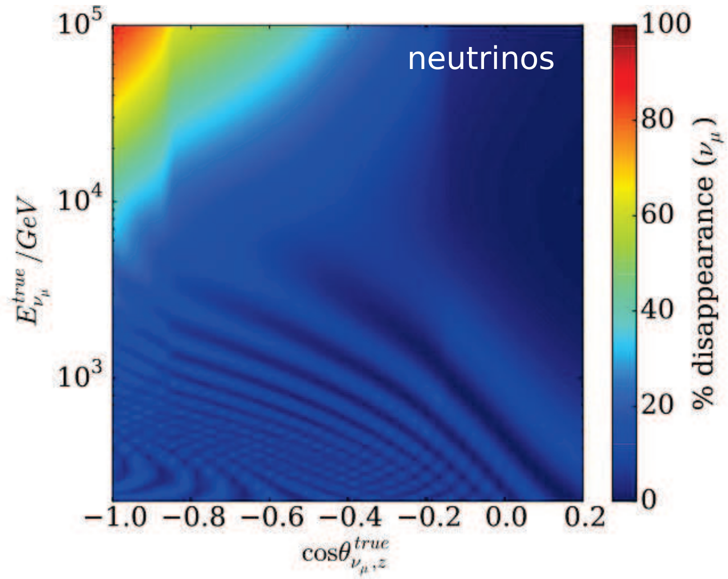


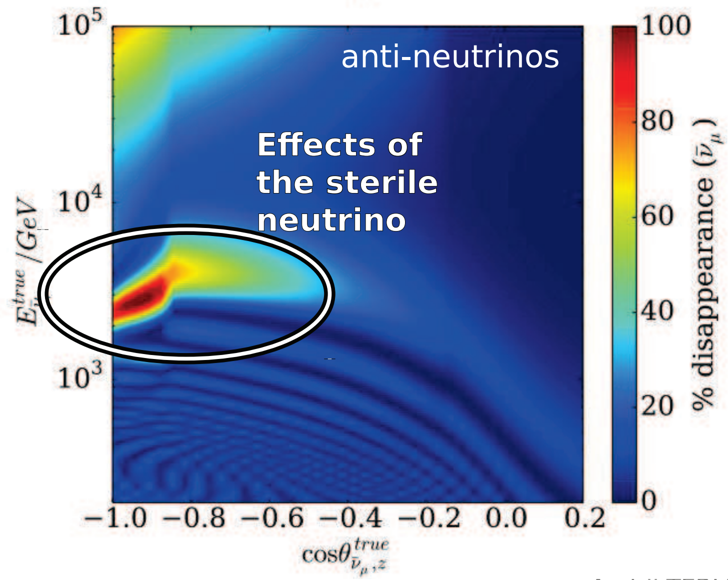
> Energy of the resonance proportional to the mass splitting

> Sensitivity to $|U_{\mu4}|^2$ (or θ_{24}) and sterile mass

> Sensitivity with IceCube using high energy atmospheric neutrinos

Sterile neutrinos at high energies

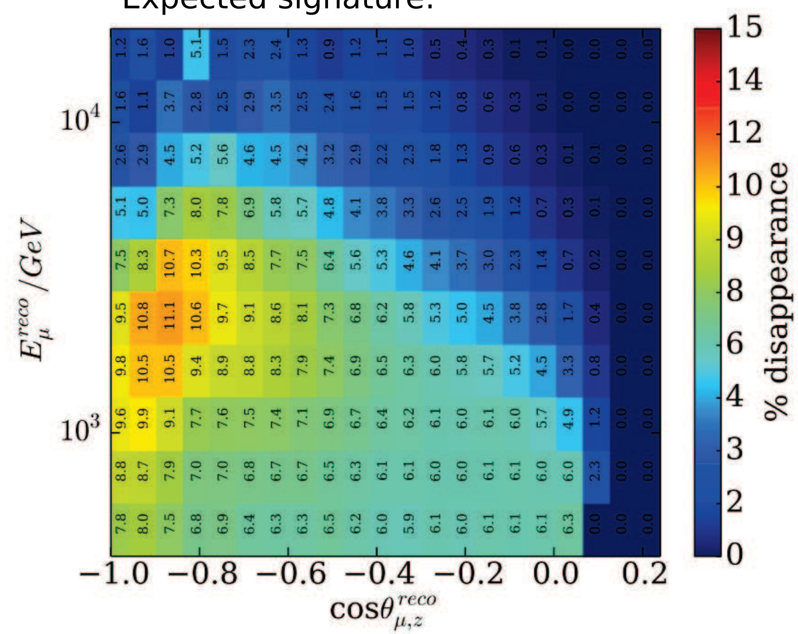




> Effects above 100 GeV:

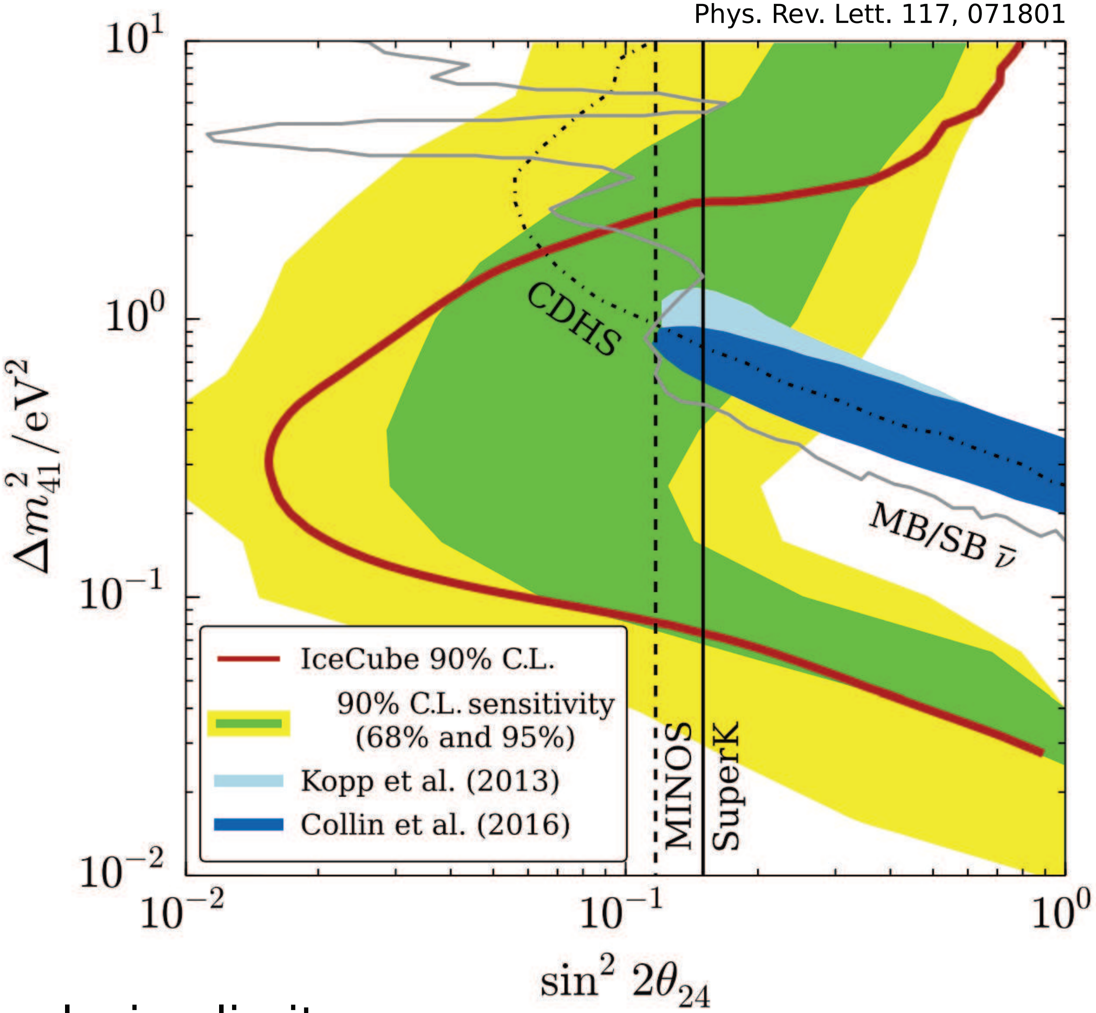
- MSW resonance-like transition to sterile state
- Muon-anti neutrinos
- Energy of resonance $\sim \Delta m^2_{41}$
- Sensitive to angle θ_{24}

Expected signature:



Sterile neutrinos at high energies: results

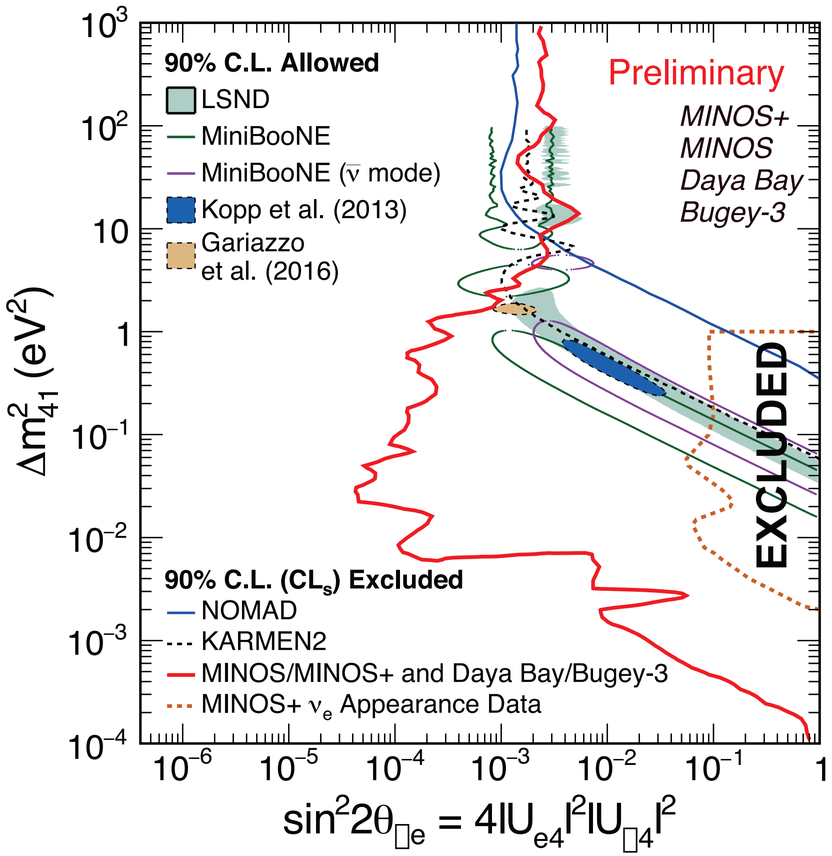
Phys. Rev. Lett. 117, 071801



- Strong exclusion limits
- Only 1 year of data used

MANCHESTER 1824
The University of Manchester

Sterile neutrinos



Consistent appearance and disappearance exclusions

- Three times as much appearance data still to analyse

Summary - sterile neutrinos

- *hints from reactor and Ga anomalies at $\sim 3\sigma$ (not in tension with other data)*
- *hints from LSND, MiniBooNE $\sim 3.8\sigma$ low-E MiniB data not well fitted (few% prob)*
- *strong tension in global fit (constraints from ν_μ disappearance experiments)*
- *no significant improvement by more sterile neutrinos*

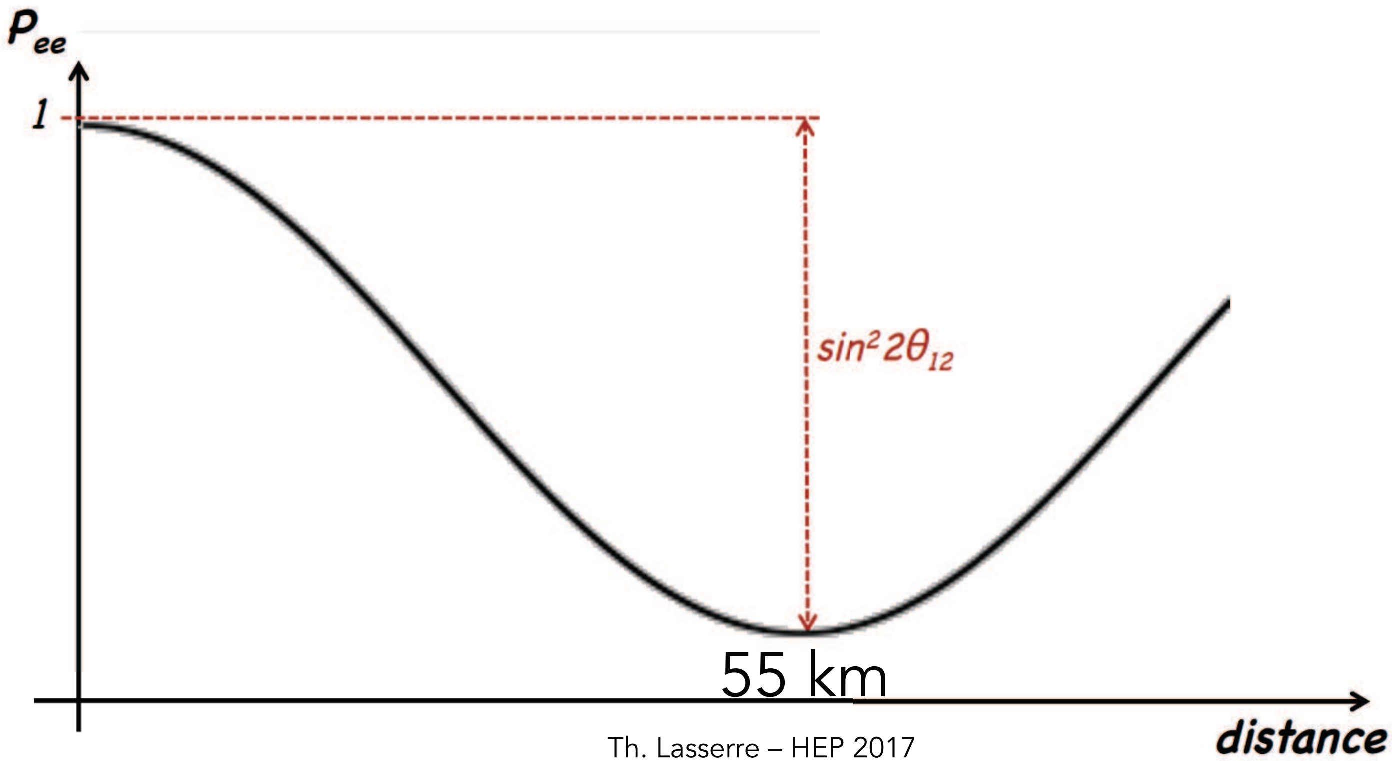
Ways to find out neutrino mass ordering:

- Earth matter effects on $(\Delta m^2_{31},\, \theta_{13})$ – driven oscillations
  - LBL accelerator experiments
  - atmospheric ν experiments with very large detectors (PINGU, ORCA,...)
  - Supernova neutrinos
- Very accurate spectroscopic measurements in reactor expts. with $L \simeq 50 - 60$ km (JUNO, RENO-50)

sign(Δm^2_{31}) with reactor neutrinos

$$P_{\bar\nu_e\to\bar\nu_e} = 1 - \frac{1}{2}(1-|U_{e3}|^2)^2 \sin^2 2\Theta_{12}\left(1-\cos\frac{\Delta m^2_{21}L}{2E}\right)$$

Solar



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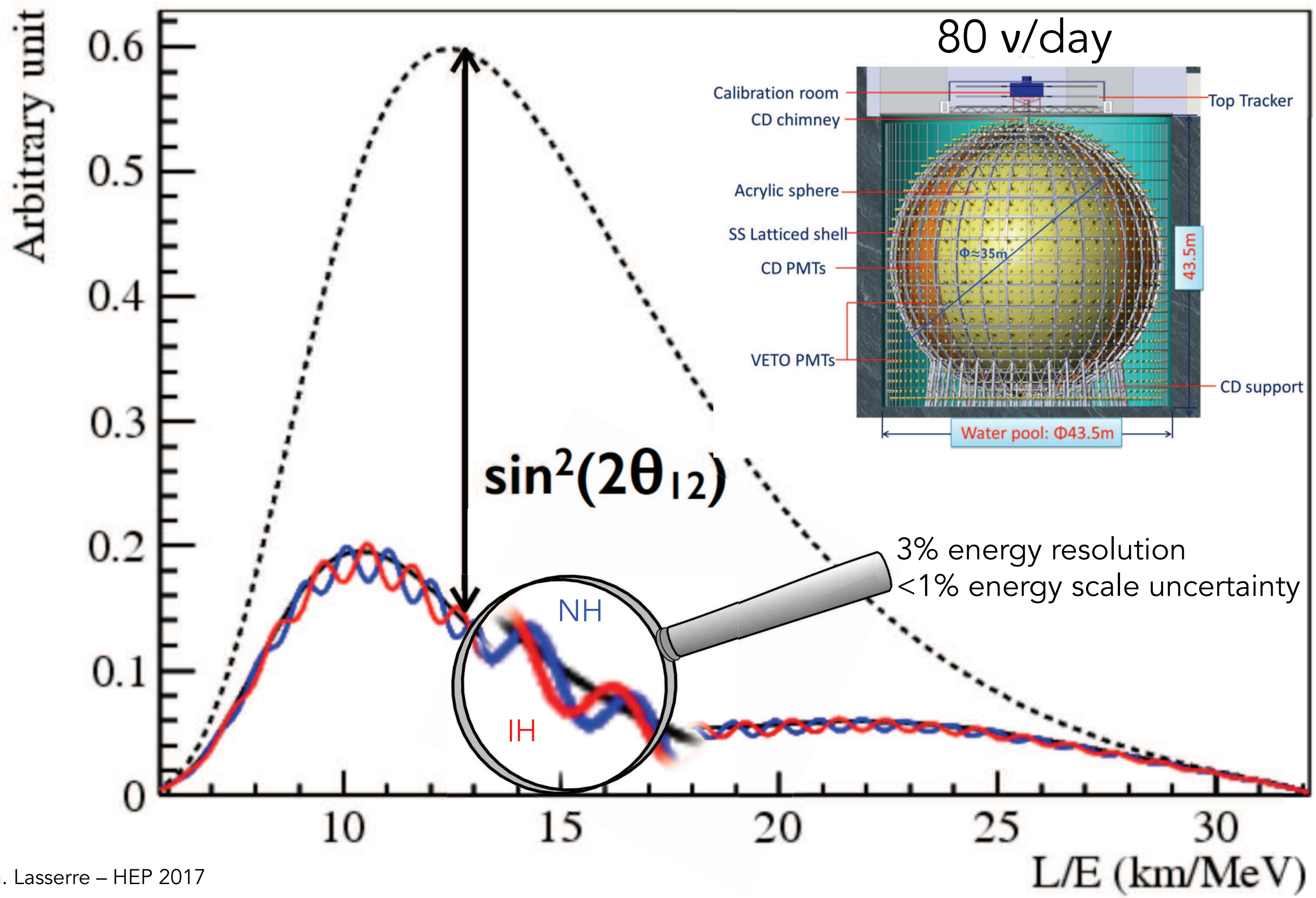
Response function $\sigma(E) \cdot f(E)$ vs. L/E

20 kt JUNO Experiment (China, 2020)



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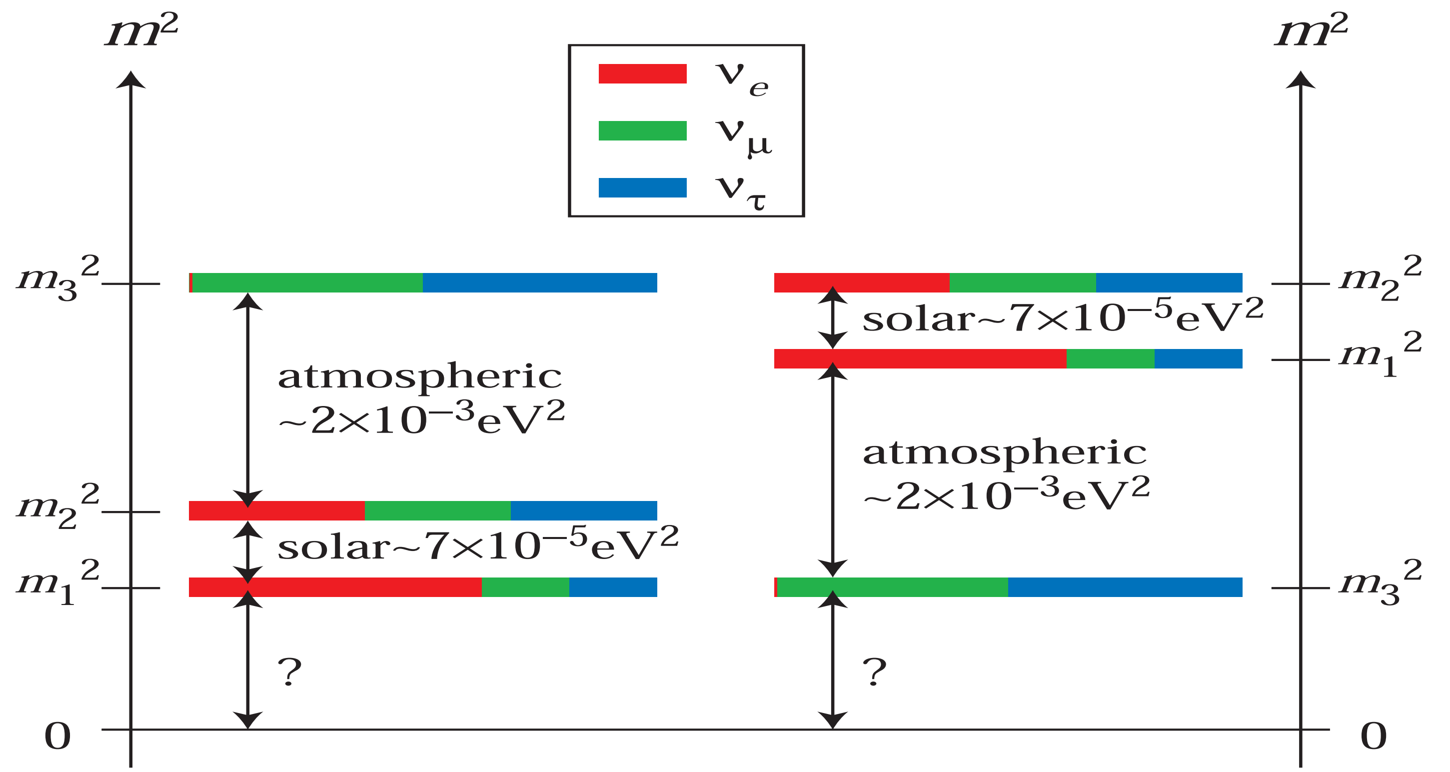
Contributions of different Δm^2_{ij} to P_{ee}

$$P_{ee} = 1 - 4\sum_{i<j} |U_{ei}|^2 |U_{ej}|^2 \sin^2 \frac{\Delta_{ij}}{2}$$

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij}}{2E} L$$



The Long and Winding Road

Impressive achievements but the road wasn't always straight ...

A number of wrong results and claims –

- S- and T-variants of weak interaction rather than V- and A-variants in β-decay of ^{6}He (BNL, 1953, 1955)
- Claim of discovery of ν oscillations in Bugey experiment (1980)
- $m_\nu \simeq 30\ \mathrm{eV}$ in ITEP tritium β-decay experiment (1980, 1987)
- Majoron emission in $2\beta0\nu$-decay (PNL/USC, 1987)
- 17-keV neutrino in decays of ^{3}H, ^{35}S and ^{14}C (Guelph, Oxford and Berkeley, 1985-1991)
- KARMEN time distribution anomaly (1995)
- Time variations of m_ν^2 in tritium β decay (Troitsk, 1997-2000)
- OPERA faster than light neutrinos

. . . .

Neutrino experiments are very difficult – caution is advised !

What we don't know yet

(but would like to know)

- Dirac or Majorana? – 2β decay experiments, SN PNB $\nu_e \to \bar{\nu}_e$ conversion/collective effects in $\nu_e \leftrightarrow \bar{\nu}_{\mu,\tau}$ (?)
- The absolute mass scale? – Direct mass measurement experiments (KATRIN, ECHo, Project 8,...); 2β decay, cosmology
- NO or IO mass ordering? – Matter effects in atm. and accel. neutrino experiments and for SN neutrinos; reactor experiments at $\sim$ 60 km (JUNO, RENO-50)
- Dirac-type CPV phase? – LBL accelerator experiments (T2K, NoVa, ...), atmospheric neutrino experiments
- Majorana-type CPV phases? – 2β decay (?)
- Light sterile neutrinos? (SBL reactor expts., radiactive source expts., SBL accelerator expts., IceCube, β-decay, $2\beta0\nu$-decay)

We would also like to:

- Study directly matter effects (MSW, parametric) on ν oscillations
- Improve the accuracy of determination of the already known parameters ($|\Delta m^2_{31}|,\ \Delta m^2_{21},\ \theta_{13},\ \theta_{12},\ \theta_{23}$ – octant?)
- Improve our knowledge of the solar energy production (CNO neutrinos, high vs. low metallicity solar models, ...)
- Study matter dominated – vacuum dominated transition in the dynamics of solar neutrino oscillations
- Study (discover or put more stringent limits limits on) non-standard neutrino interactions, neutrino magnetic moments, mass varying neutrinos, etc. (possible subdominant transition effects in solar, atm., accel. and SN ν expts.)

On the theory side...

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◇ Neutrino models: too many, but no clear leader. Most attempted some type of symmetry to arrive at the tri-bi-maximal mixing pattern – now disfavoured.

On the theory side...

- Non-standard oscillation phenomenology: subleading effects. Interesting constraints obtained.
- New development in standard neutrino oscillations: collective effects in oscillations of SN neutrinos (many papers). Interesting spectral splits.

♢ Theory of neutrino oscillations: Surprizingly, 60 years after the suggestions of neutrino oscillations and 19 years after their experimenta discovery some basic questions of the theory are still being debated.

♢ Ultimate goal – Unravel physics underlying neutrino mass generation

– New interesting results (new surprizes?) expected.

Neutrino revolution continues !