Excerpts from XVI International Workshop on Neutrino Telescopes

Venezia 2-6 March 2015

A. Paoloni

Frascati, 26 March 2015

Excerpts from XVI International Workshop on Neutrino Telescopes

Venezia 2-6 March 2015

Covered (partially) topics:
Neutrino masses
Neutrino mixing (3 ν)
Sterile neutrino
Neutrino Cross-sections
Astrophysical neutrinos

Not covered topics:
Cosmology
Dark matter
Interesting talks about theory (neutrinos from SuperNovae, unitarity of mixing Matrix ?, etc.)

A. Paoloni

Frascati, 26 March 2015

Neutrino masses

Neutrino Masses

- β decay: $m_j \neq 0$ affect β−spectrum endpoint. Sensitive to the "effective electron neutrino mass":

  $\mathbf{m}_\beta = \{ \Sigma_j m_j^2 \, |U_{ej}|^2 \}^{1/2}$

  Flavor-Mass Mixing Parameter

- 0ν2β decay: can occur if $m_j \neq 0$. Sensitive to the "effective Majorana mass":

  $\mathbf{m}_{\beta\beta} = \{ \Sigma_j m_j \, |U_{ej}|^2 e^{i\varphi_j} \}$

  Flavor-Mass Mixing parameter
  + imaginary phase

- Cosmology: $m_j \neq 0$ can affect large scale structures in (standard) cosmology constrained by CMB and not CMB (LSS,Lyα) data. Sensitive to:

  $\mathbf{m} = \Sigma_j m_j$

  Flavor-Mass Mixing independent

Sabino Matarrese talk

Planck Constraints on Neutrinos

see also Licie Verde's talk

$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck} \text{ TT+lowP};$$
$$\sum m_\nu < 0.21 \text{ eV} \quad \textit{Planck} \text{ TT+lowP+BAO};$$
$$\sum m_\nu < 0.49 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP};$$
$$\sum m_\nu < 0.17 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP+BAO}.$$

95% CL

$$N_{\text{eff}} = 3.13 \pm 0.32 \quad \textit{Planck} \text{ TT+lowP};$$
$$N_{\text{eff}} = 3.15 \pm 0.23 \quad \textit{Planck} \text{ TT+lowP+BAO};$$
$$N_{\text{eff}} = 2.99 \pm 0.20 \quad \textit{Planck} \text{ TT, TE, EE+lowP};$$
$$N_{\text{eff}} = 3.04 \pm 0.18 \quad \textit{Planck} \text{ TT, TE, EE+lowP+BAO}.$$

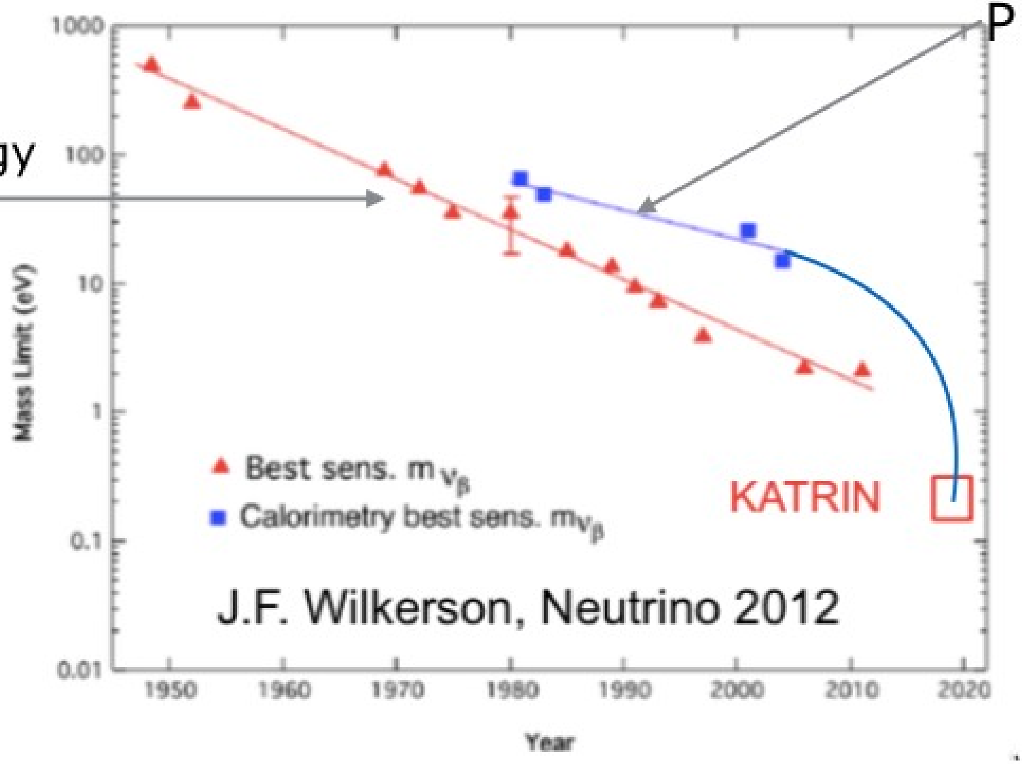
68% CL

Planck collaboration 2015

Direct Measurement

Experiment with established technology

Proof of Concept



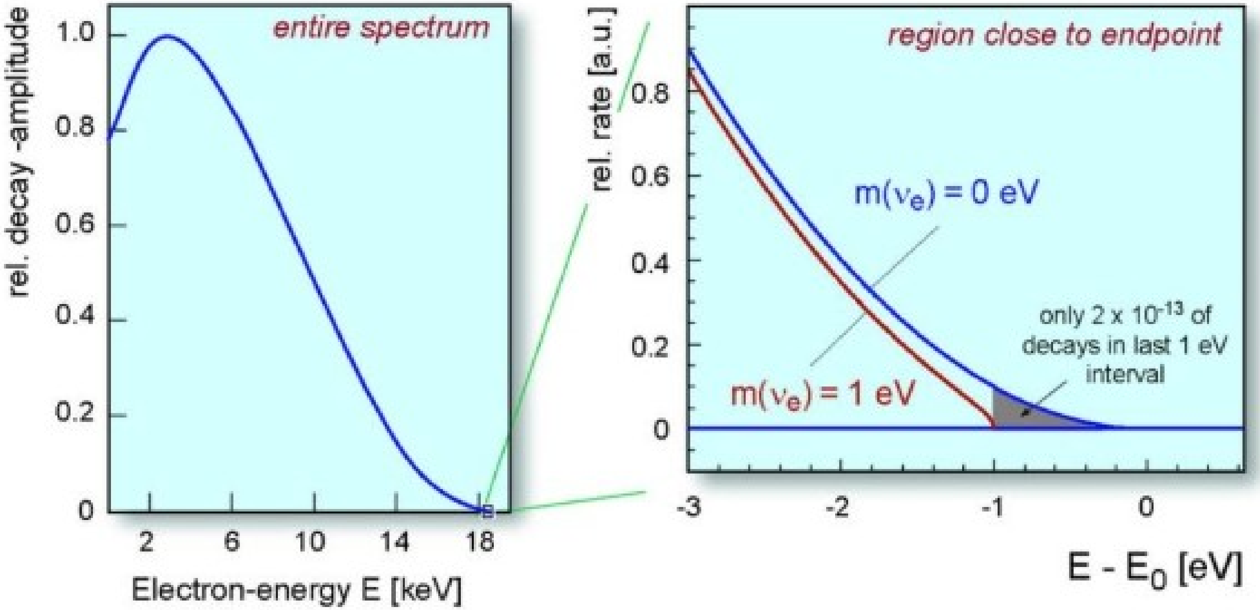
Talk by:
Flavio Gatti
Noah Oblath
Philipp Ranitzsch

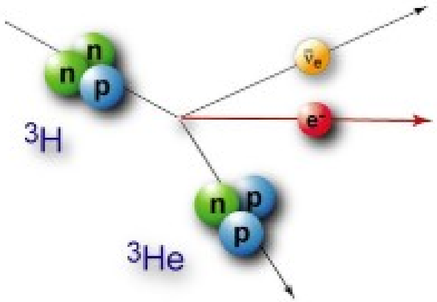
- KATRIN was the only proposal based on proved technology
- MARE was proposed as very ambitious project later after the R&D of MANU and MIbeta projects
- Now HOLMES, ECHo, US-Ho (LANL) point to a realistic goal in the sub eV range
- Project8 is a very promising technique beyond KATRIN

CRES=Cyclotron Radiation Emission Spectroscopy

(Tritium) β-decay and neutrino mass

β-decay: ${}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+1}X_{N-1} + e^{-} + \bar{\nu}_{e}$





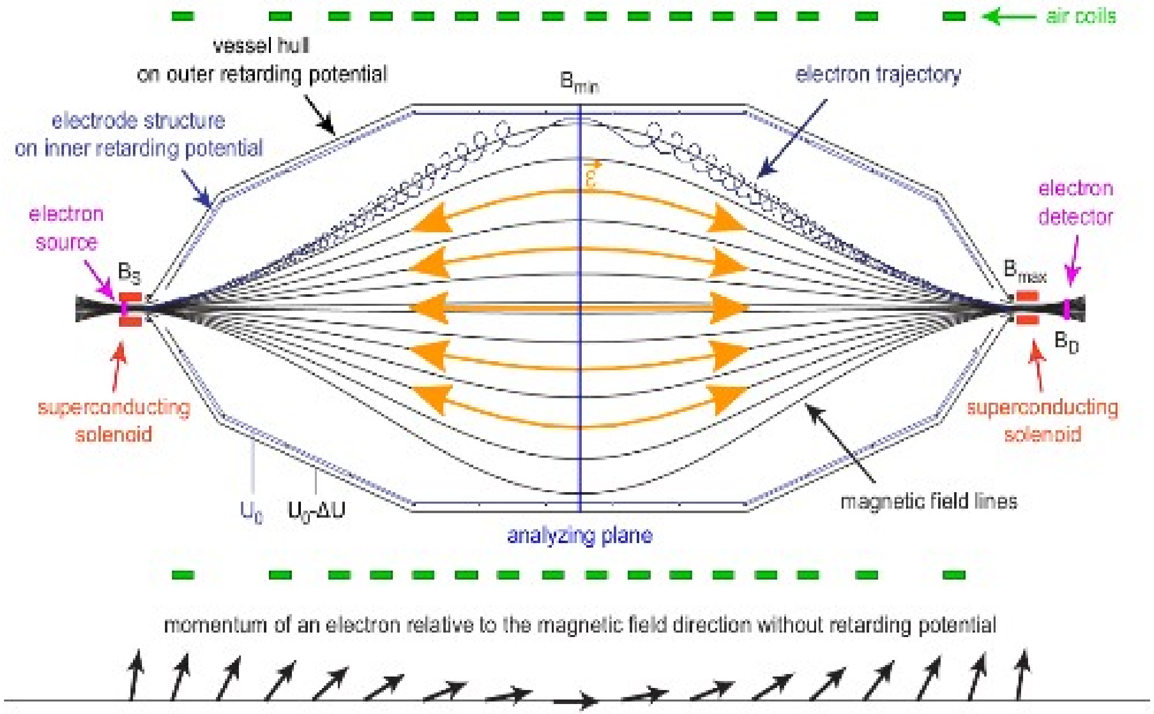
Tritium ^{3}H:
$E_0 = 18.6$ keV
$T_{1/2} = 12.3$ y

Rhenium ^{187}Re:
$E_0 = 2.47$ keV
$T_{1/2} = 4.3\ 10^{10}$ y

$$\frac{dN}{dE} = K\ F(E,Z)\ p\ (E_e + m_e)(E_0 - E_e)\sqrt{(E_0 - E_e)^2 - m(\bar{\nu}_e)^2}$$

MAC-E Filter

Magnetic **A**diabatic **C**ollimation and **E**lectrostatic Filter:



Magnetic guiding and collimation of e$^-$

- ➢ Transform $E_\perp$ to $E_\parallel$

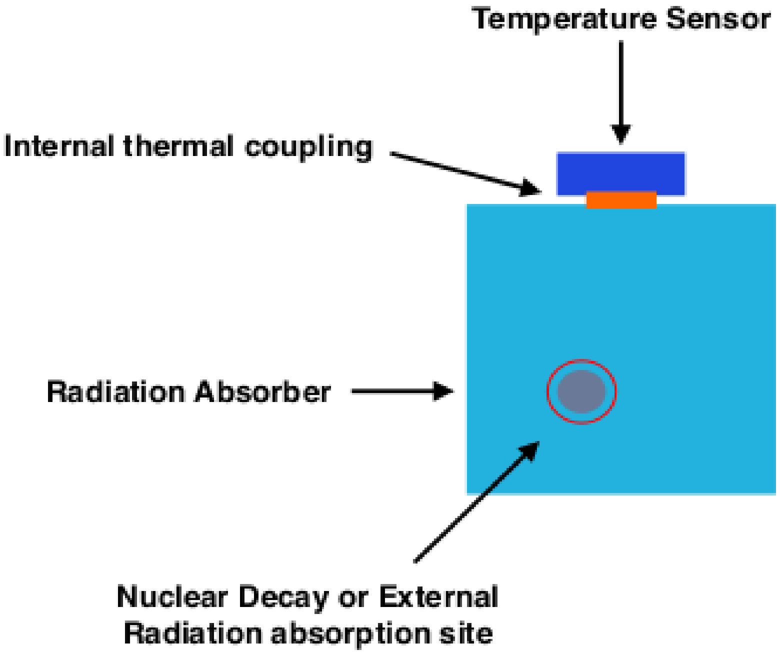
Electrostatic field for energy analysis

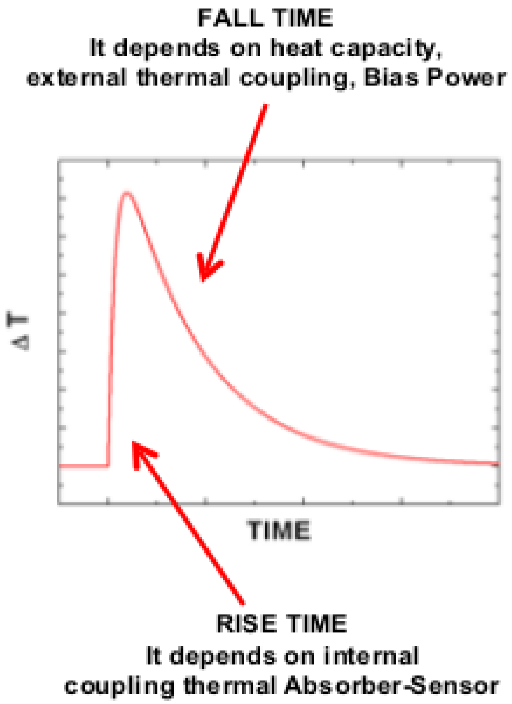
- ➢ Sharp transmission depending on:
  - ➢ Emission angle
  - ➢ Radius in at $B_{\min}$

Integrated energy resolution:

$$\Delta E = E \ \frac{B_{\min}}{B_{\max}}$$

Mass measurement with cryogenic μ-calorimeter



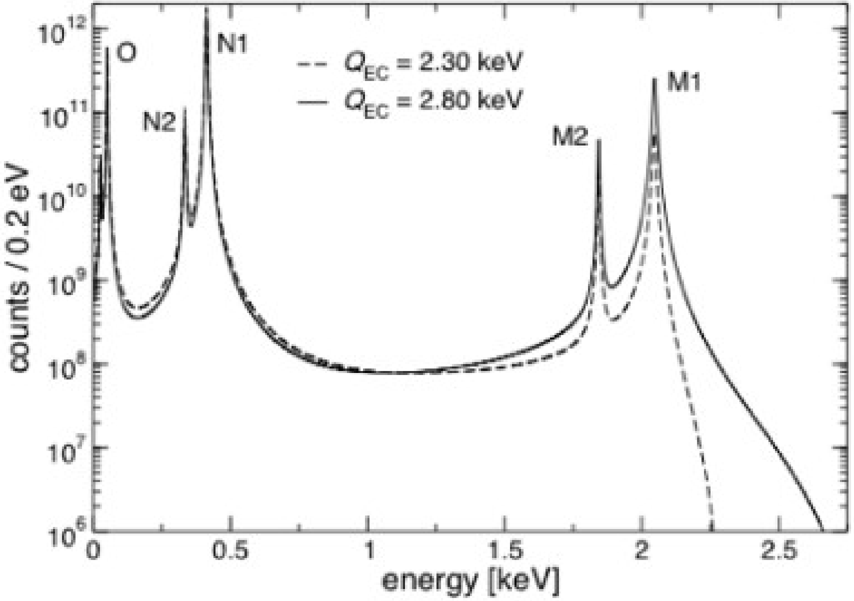


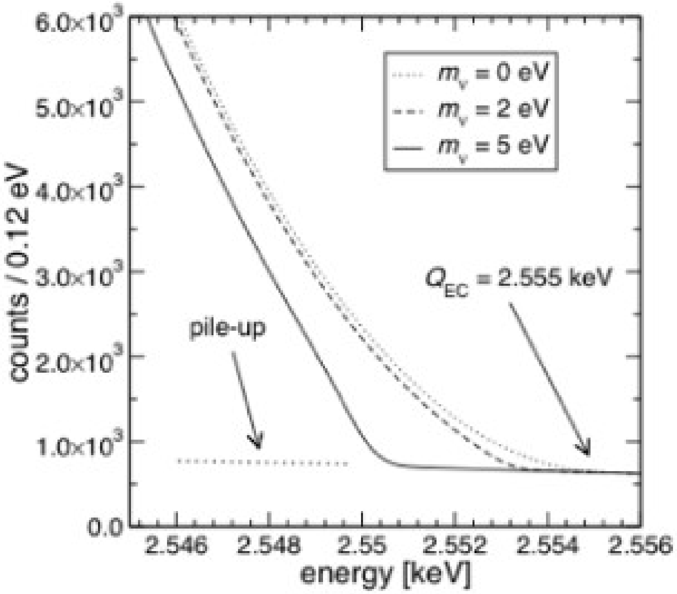
- It's ideally an Energy Dispersive Spectroscopical Detector
- It's a fast (0.1-1 μs) true thermal calorimeter
- Energy Sensitivity at the eV scale needs very low heat capacity at the scale less than pJ/K
- The Energy Resolution Intrinsic is ultimately limited by the thermal fluctuation noise:
- Sub-K operating temperatures are needed (0.01-0.1 K) to reach eV resolutions
- IN PRINCIPLE THEY ARE A TOOL FOR VERY DEEP SEARCHES IN SUB-eV range

The project HOLMES

$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e$ electron capture decay

(A. De Rujula and M.Lusignoli, Phys. Lett. 9 (1982)





- First calorimetric measurement of ^{163}Ho endpoint energy: Q = 2.80 ± 0.05 keV (with Ho-oxide embedded in Sn absorber (F. Gatti, et al, Physics Letters B, 1997)

Why 0νββ double beta decay

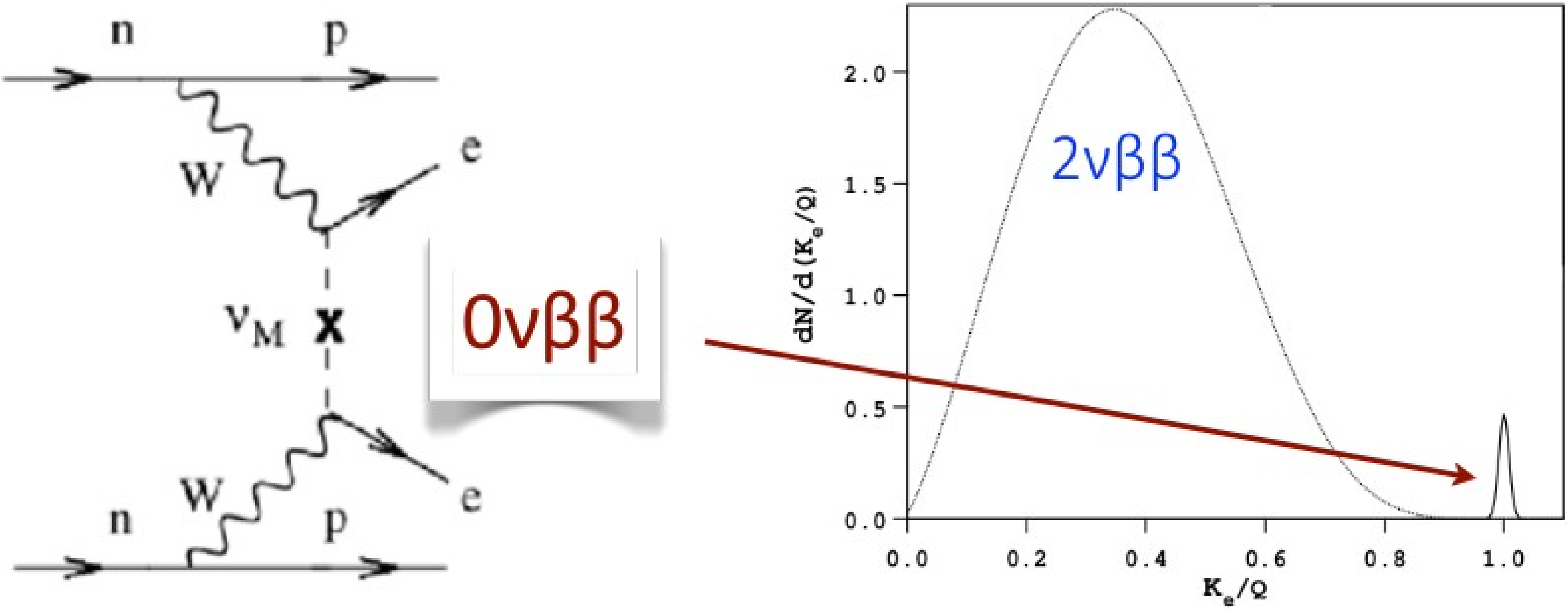
Andrea Pocar talk

observation of 0νββ decay:

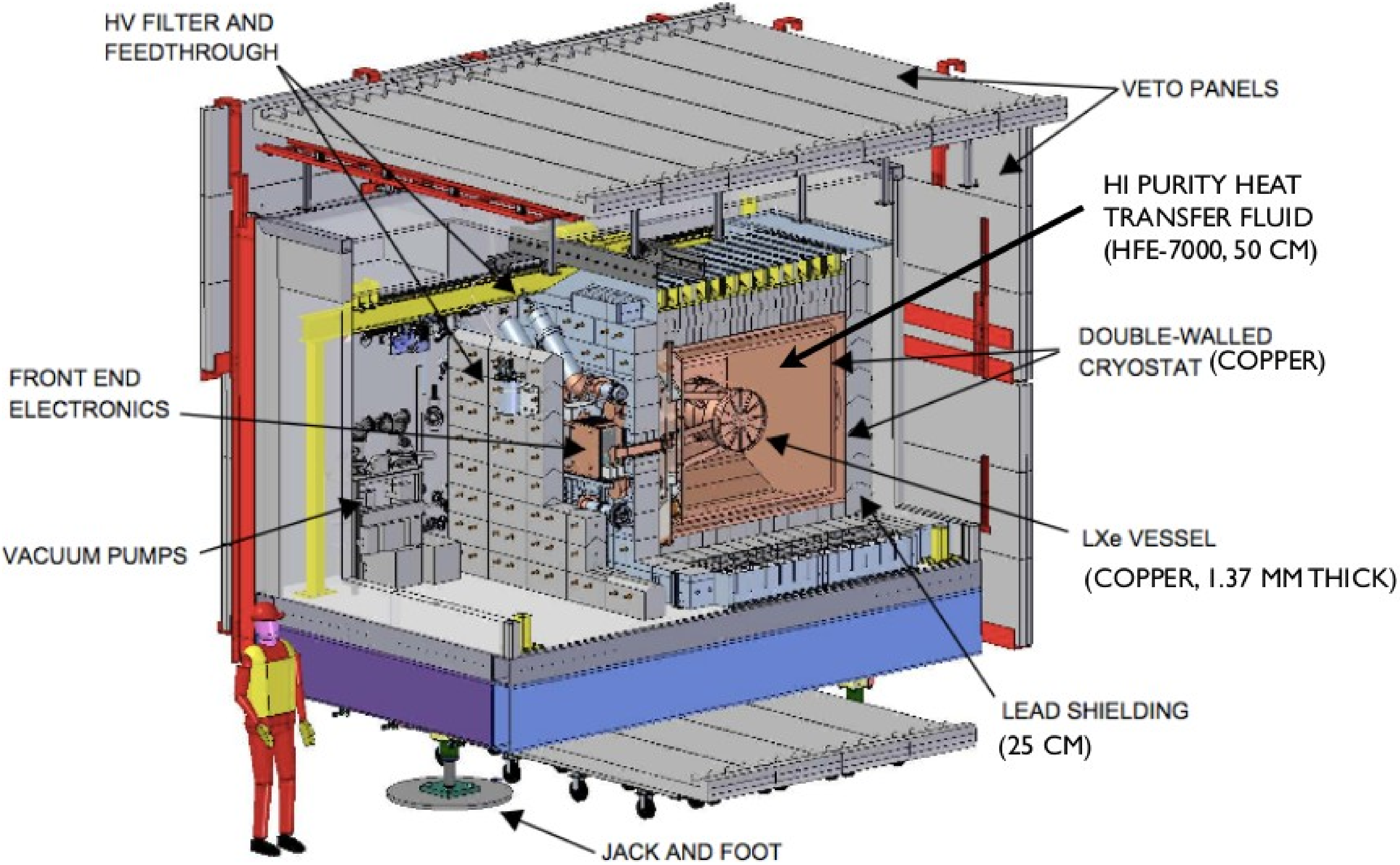
- massive, Majorana neutrinos
- lepton number violation

0νββ rate

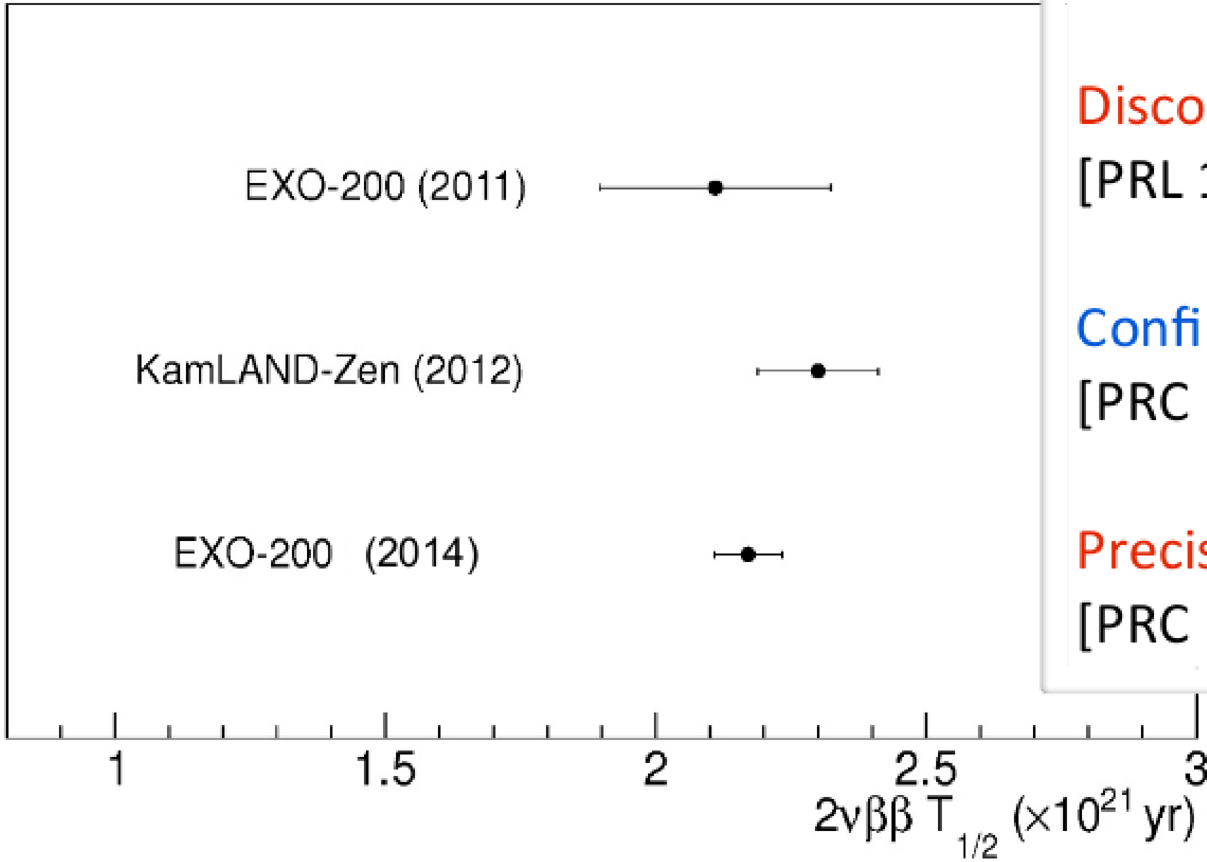
- absolute neutrino mass (model dependent)



The EXO-200 detector at WIPP (~1,500 m.w.e.)



EXO-200: precision measurement of 2νββ decay of ^{136}Xe



Start data taking in June 2011

Discovery of 2νββ decay of 136Xe
[PRL 107, 212501 (2011)]

Confirmation by KamLAND-Zen
[PRC 85, 045504 (2012)]

Precision measurement (~3%)
[PRC 89, 015502 (2014)]

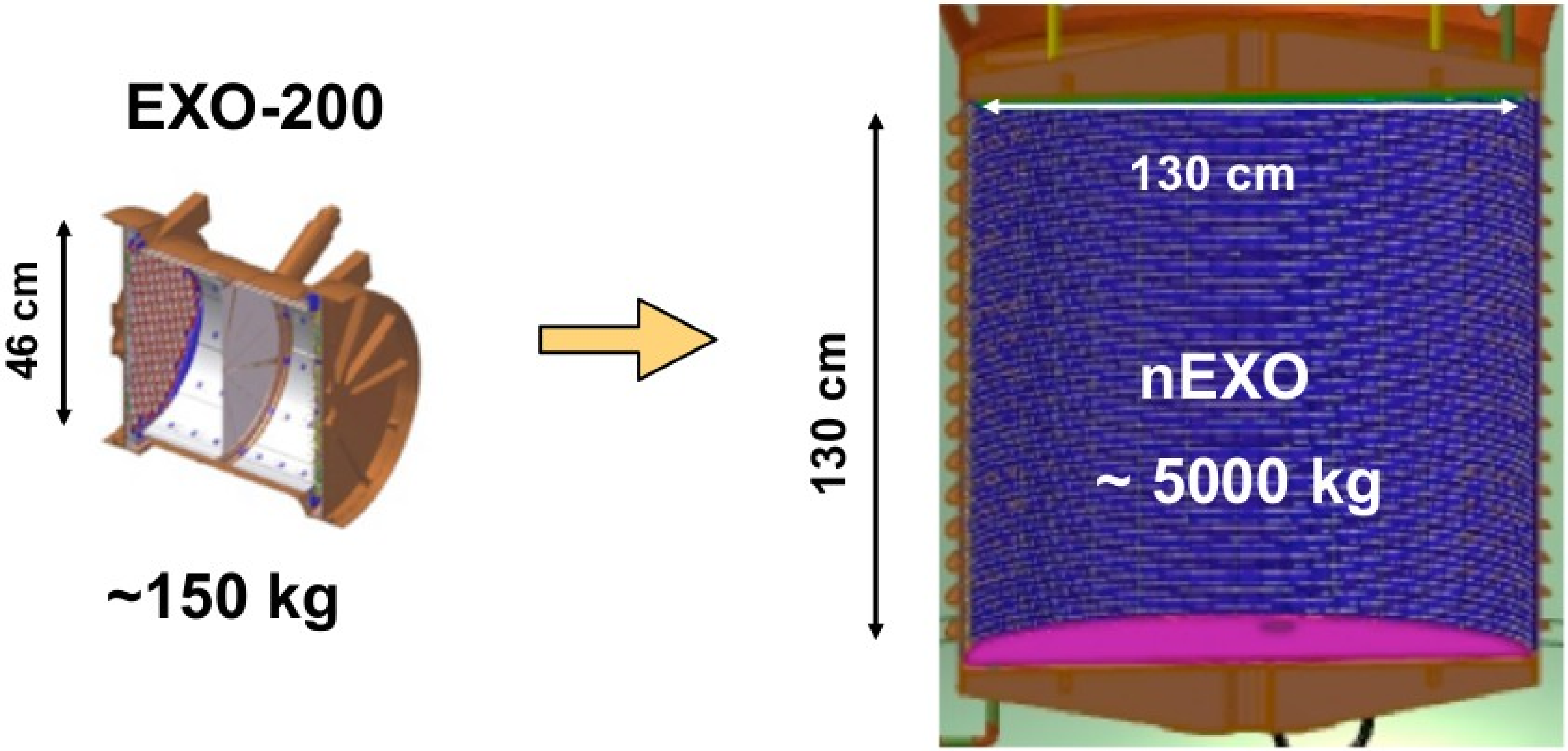
$$\mathbf{T^{2\nu\beta\beta}_{1/2} = (2.165 \pm 0.016(stat) \pm 0.059(syst)) \times 10^{21} yr}$$

(longest, yet most precisely measured 2νββ decay of all 'practical' isotopes)

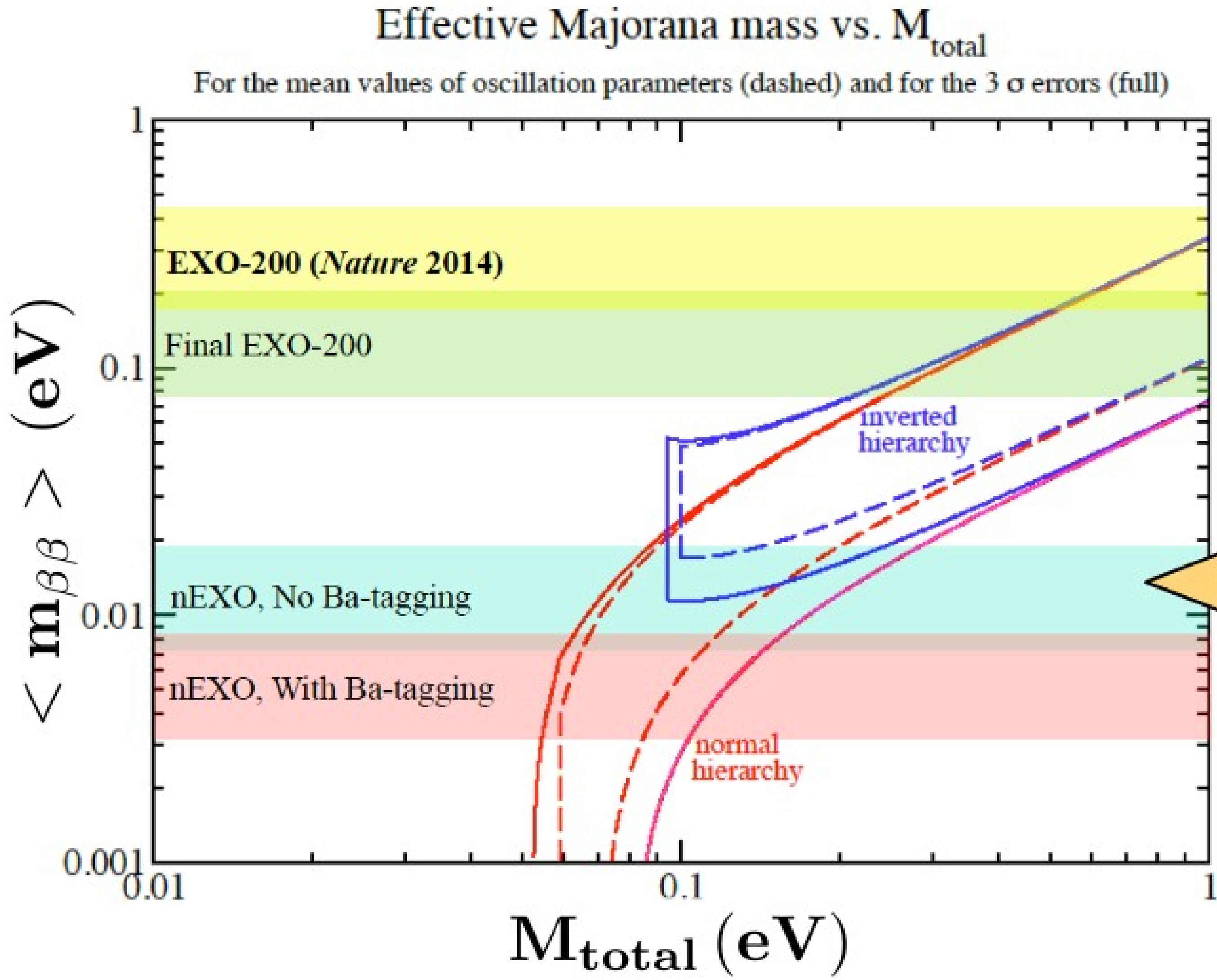
From EXO-200 to nEXO

- 5 tonnes of enriched LXe
- enhanced self-shielding
- x100 better $T_{1/2}$ sensitivity

- < 1% energy resolution
- no central cathode
- *no* Ba tagging (initially)



nEXO Physics Sensitivity



$T_{1/2} = 6 \times 10^{27}$ yr in 5 years of counting

Majorana neutrino mass $<m_{\beta\beta}>$ sensitivity of 7-18 meV

Alberto Remoto talk

NEMO-3

ββ decay experiment combining tracker and calorimetric measurement

Located at the Modane underground laboratory (~4800 m.w.e.)

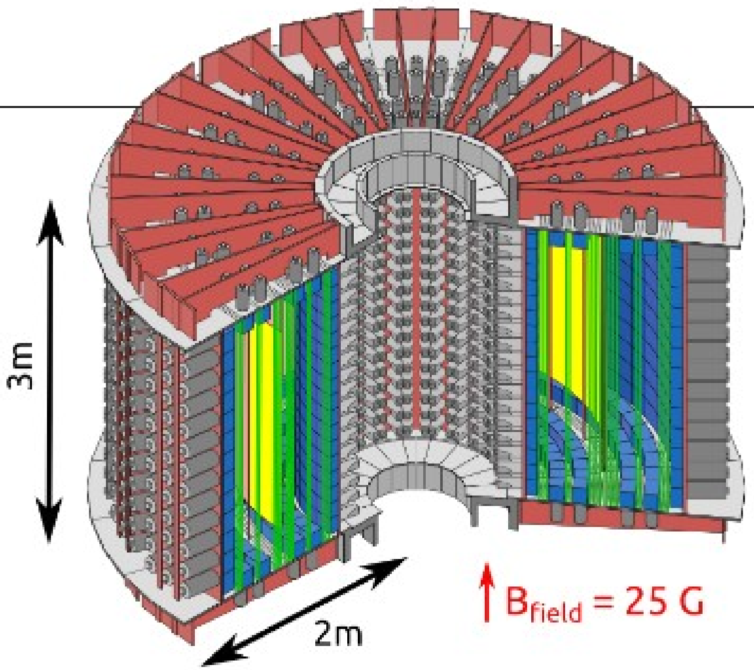
10 kg of different ββ isotopes

Taking data from February 2003 to January 2011

Full reconstruction of $2e^-$ kinematics: unique!

Excellent background rejection

Equivalent to best calorimetric experiment

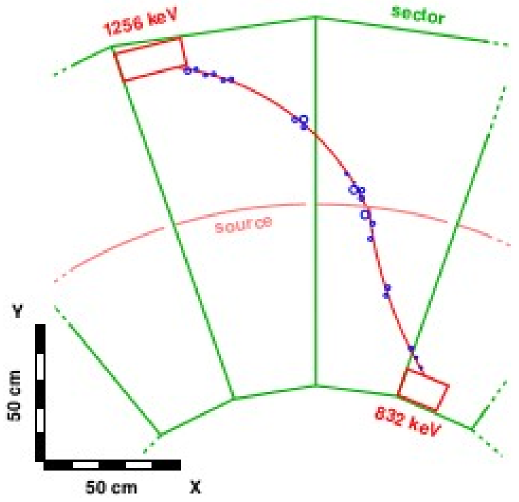


sources
60 mg/cm² foils
10 kg of ββ isotopes

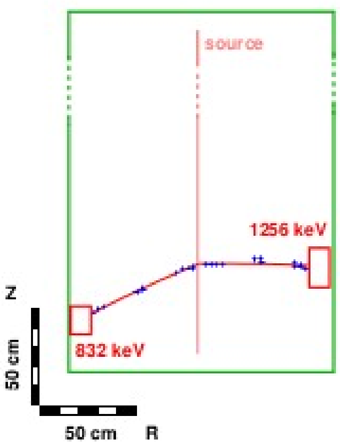
tracker
6180 Geiger cells
vertex resolution :
$\sigma_{xy} \sim 3$ mm $\sigma_z \sim 10$ mm

calorimeter
1940 optical modules :
polystyren scintillators
+ 3" and 5" PMTs
$FWHM_E \sim 15\% / \sqrt{E_{MeV}}$
$\sigma_t \sim 250$ ps

Top view



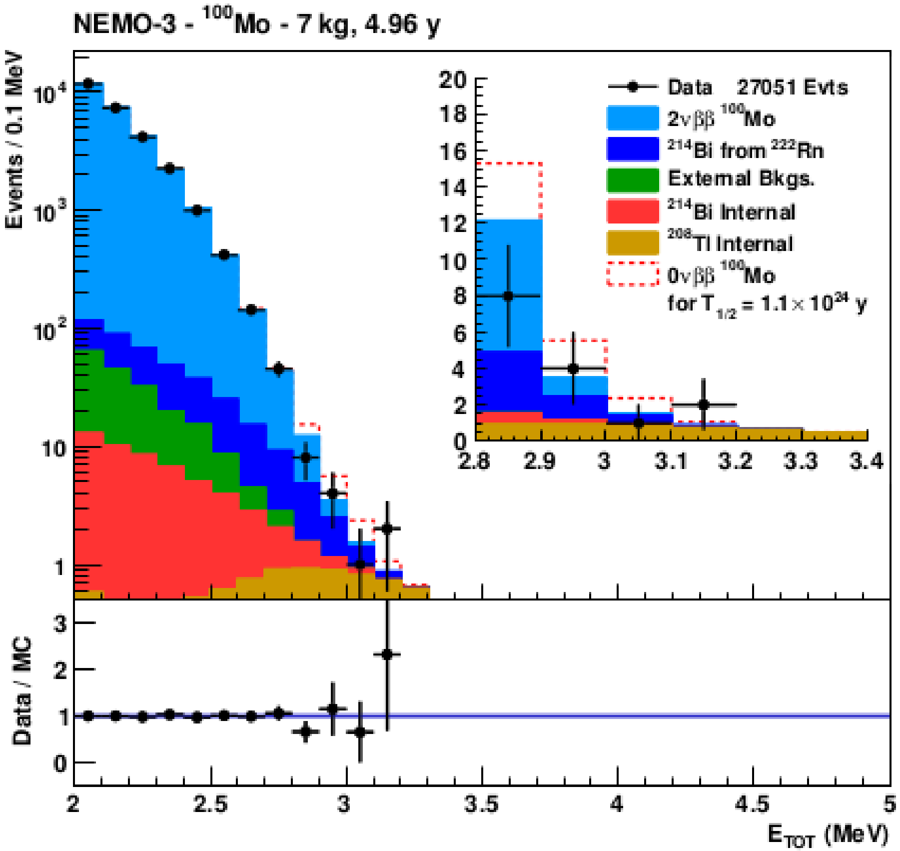
Longitudinal view



NEMO-3: ^{100}Mo 0νββ result

Detailed paper to be published in the following weeks

- No event excess after 34.3 kg×y exposure
- $T^{0\nu}_{1/2} > 1.1\times10^{24}$ y (90 % C.L.) → $\langle m_\nu \rangle < 0.3 - 0.9$ eV



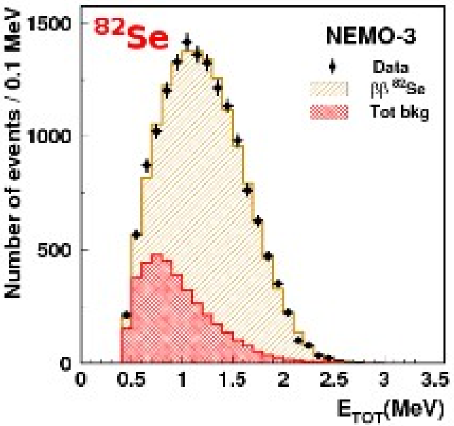
Expected background in [2.8 - 3.2] MeV

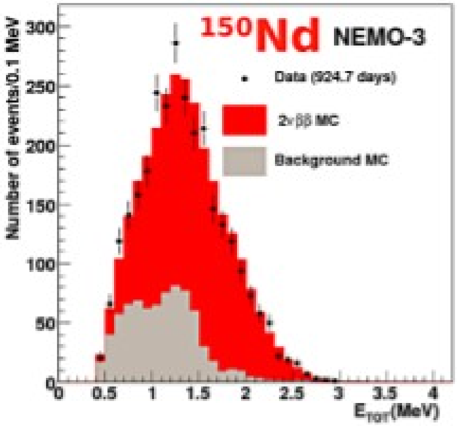
2νββ	8.45 ± 0.05
^{214}Bi from radon	5.2 ± 0.5
External	< 0.2
^{214}Bi internal	1.0 ± 0.1
^{208}Tl internal	3.3 ± 0.3
Total	18.0 ± 0.3
Data	15

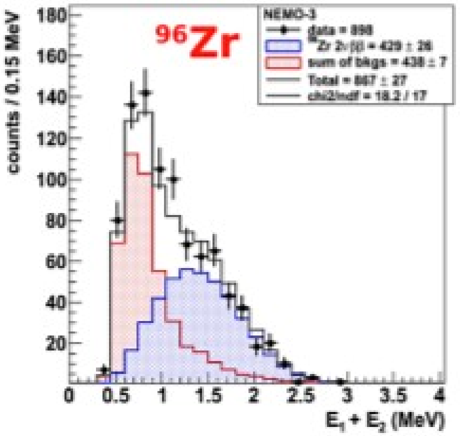
Total background: 1.3×10^{-3}cts / (keV×kg×y)

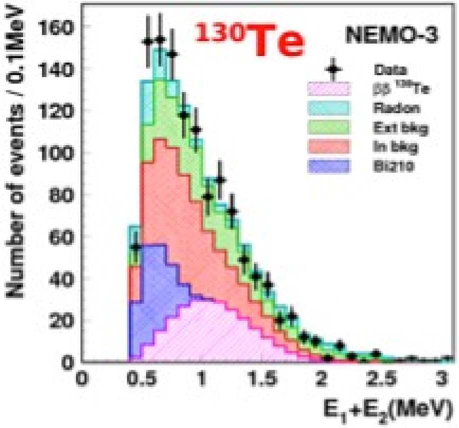
NEMO-3: other results

Other isotopes: only partial exposure has been published









Isotope	Mass [g]	Exposure [days]	$T_{1/2}$ (2ν) [x 10^{19} y]	$T_{1/2}$ (0ν) [y] @ 90% C.L.	⟨$m_ν$⟩ [eV] @ 90% C.L.	Reference
^{82}Se	932	389	9.6 ± 1.0	> 1.0 x 10^{23}	< 1.7 - 4.9	Phys.Rev.Lett. 95 (2005) 182302
^{150}Nd	37	925	0.90 ± 0.07	> 1.8 x 10^{22}	< 4.0 - 6.3	Phys. Rev. C 80, 032501 (2009)
^{96}Zr	9.4	1221	2.35 ± 0.21			Nucl.Phys.A 847(2010) 168
^{130}Te	454	1275	70 ± 14			Phys. Rev. Lett. 107, 062504 (2011)

Analysis of whole statistics ongoing (^{82}Se, ^{48}Ca, ^{96}Zr, ^{116}Cd, ^{150}Nd)…stay tuned!

^{100}Mo 0νββ decay to the ^{100}Ru excited states [Nuclear Physics A781 (2007) 209-226]

Carla Macolino talk

GERDA Building

The GERDA collaboration, Eur. Phys. J. C 73 (2013)

- 8 enriched Coaxial detectors: working mass 14.6 kg - **avg energy resolution 4.8 keV** (2 of them are not working due to high leakage current)
- GTF112 natural Ge: 3.0 kg
- 5 enriched BEGe: working mass 3.0 kg - **avg energy resolution 3.2 keV** (testing Phase II concept)

The GERDA collaboration, Phys. Rev. Lett. 111 (2013) 122503

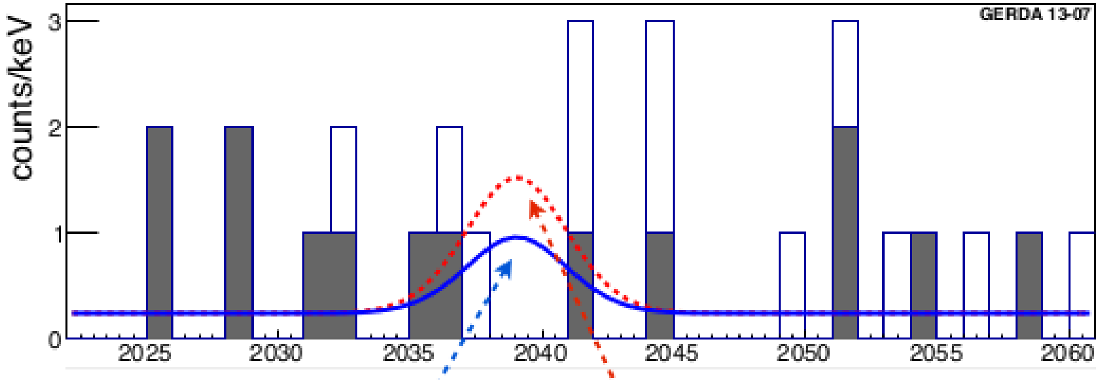
Comparison with claim from Phys. Lett. B 586 (2004) 198

Compare two hypotheses:

- H_1: $T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr
- H_0: background only

GERDA only:

- Profile likelihood
  $P(N^{0\nu}{=}0|H_1) = 0.01$
- Bayes factor
  $P(H_1)/P(H_0) = 0.024$



"Claim", PLB586 (2004)

$T^{0\nu}_{1/2} = \; 1.19 \times 10^{25}\,\mathrm{yr}$

Compatible with no signal events

$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr

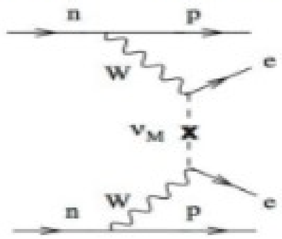
Claim strongly disfavoured!

N.B.: $T^{0\nu}_{1/2}$ from Mod. Phys. Lett. A 21 (2006) 157 not considered because of inconsistencies (missing efficiency factors) pointed out in Ann. Phys. 525 (2013) 259 by B. Schwingenheuer.

Maura Pavan talk

$0\nu\beta\beta$ - ^{130}Te

$(A,Z) \rightarrow (A,Z+2) + 2\,e^-$

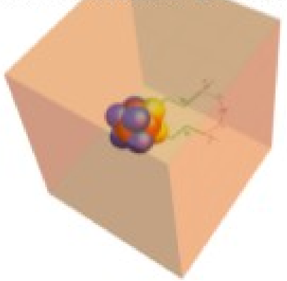


lepton violation

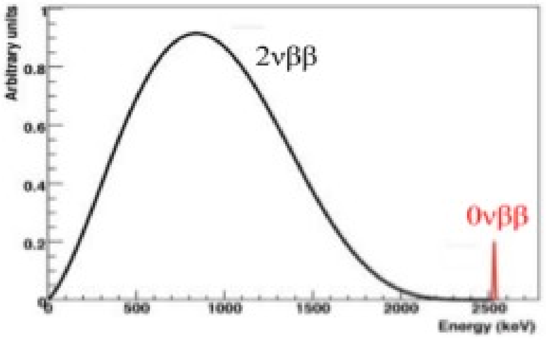
if observed ν is Majorana

Source = Detector

the detector is a crystal with the DBD candidate in its molecule



SIGNATURE



ISOTOPE CHOICE

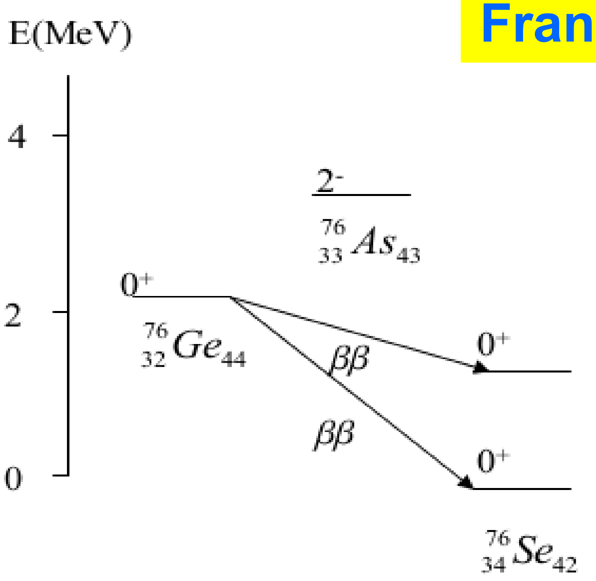
^{130}Te

- High nat. isotopic abundance ~ 34.2% NEED NO ENRICHEMENT
- High Q-value = 2527.518 ± 0.013 keV LOW BACKGROUND
- Good Nuclear Factor of Merit

DOUBLE BETA DECAY

Francesco Iachello talk

$${}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z\pm2}Y_{N\mp2} + 2e^{\mp} + anything$$



Half-life for processes not allowed by the standard model:

$$\left[\tau_{1/2}^{0\nu\beta\beta}(0^{+}\rightarrow 0^{+})\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^{2}\left|f(m_{i},U_{ei})\right|^{2}$$

Beyond the standard model
(Particle physics)

Phase-space factor
(Atomic physics)
PSF

Matrix elements
(Nuclear physics)
NME

$$f = \frac{\langle m_{\nu} \rangle}{m_{e}}$$

$$M_{0\nu} = g_{A}^{2} M^{(0\nu)}$$

$$M^{(0\nu)} \equiv M_{GT}^{(0\nu)} - \left(\frac{g_{V}}{g_{A}}\right)^{2} M_{F}^{(0\nu)} + M_{T}^{(0\nu)}$$

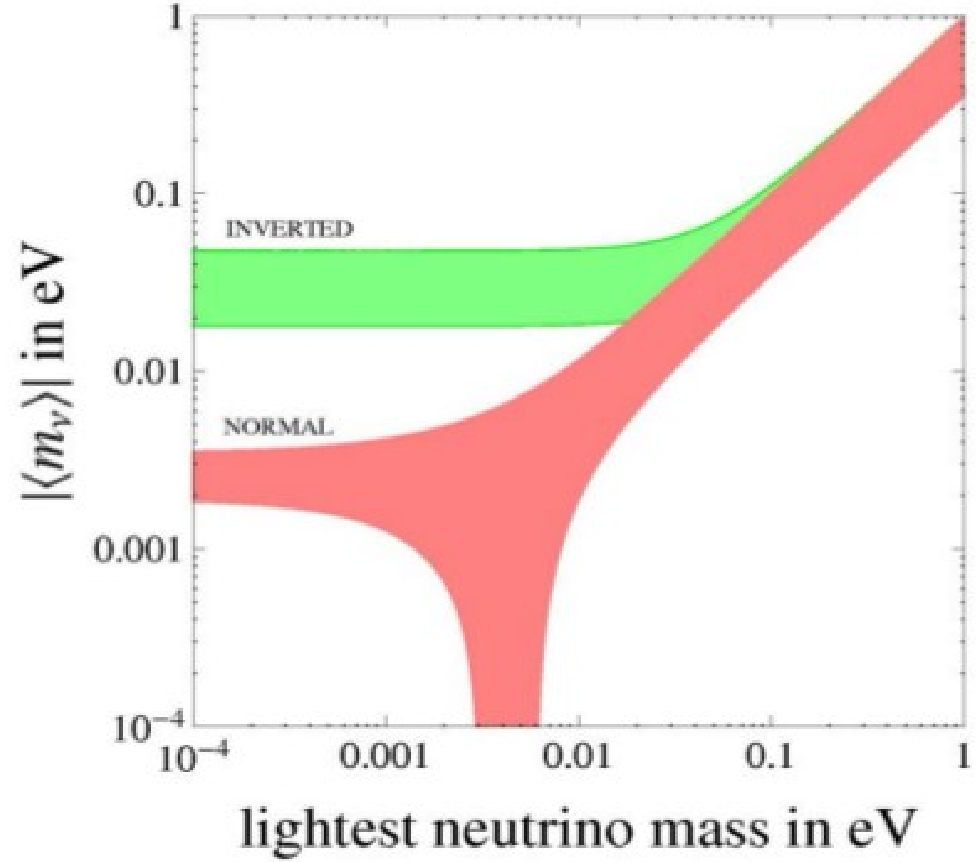
$$\langle m_{\nu} \rangle = \sum_{k=ligth} (U_{ek})^{2} m_{k}$$

The average light neutrino mass can be written as

$$\langle m_\nu \rangle = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\varphi_2} + s_{13}^2 m_3 e^{i\varphi_3} \right|$$

$$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}, \varphi_{2,3} = [0, 2\pi]$$

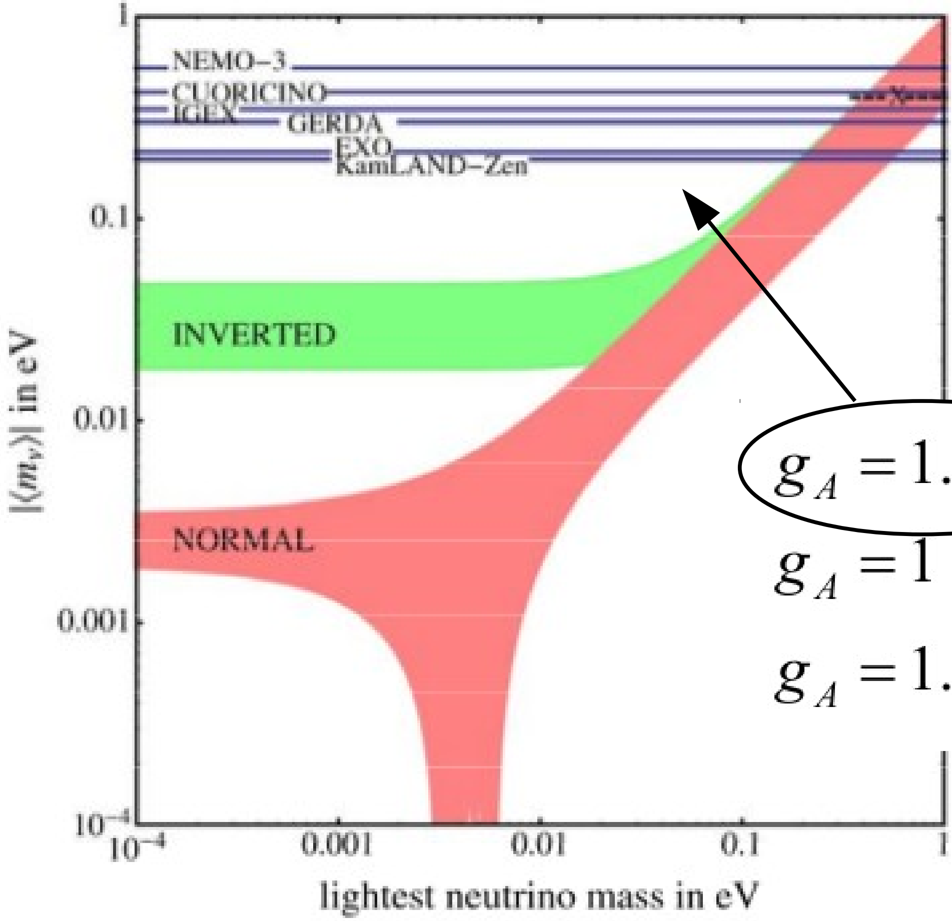
$$\left(m_1^2, m_2^2, m_3^2\right) = \frac{m_1^2 + m_2^2}{2} + \left(-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm \Delta m^2\right)$$



Vissani-Strumia plot ¶

¶ F. Vissani,
J. High Energy
Phys. 06, 022
(1999)

Present results



$g_A = 1.269$ ← Free value

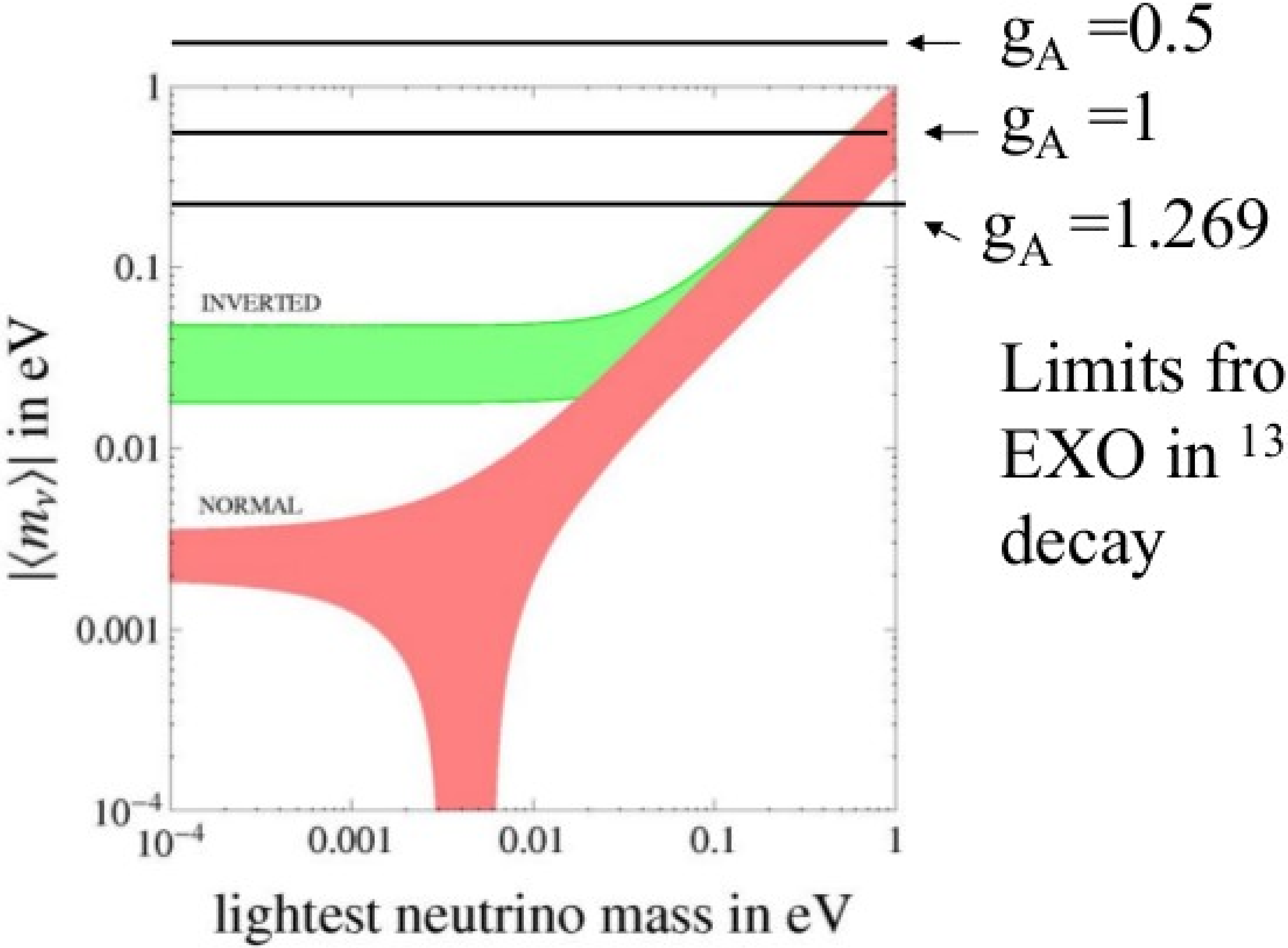
$g_A = 1$ ← Quark value

$g_A = 1.269\,A^{-0.18}$ ← Maximal quenching

g_A renormalization in nuclei: well known from β and ββ decays.

g_A in ββ without 2ν is expected to be similar to ββ with 2ν.

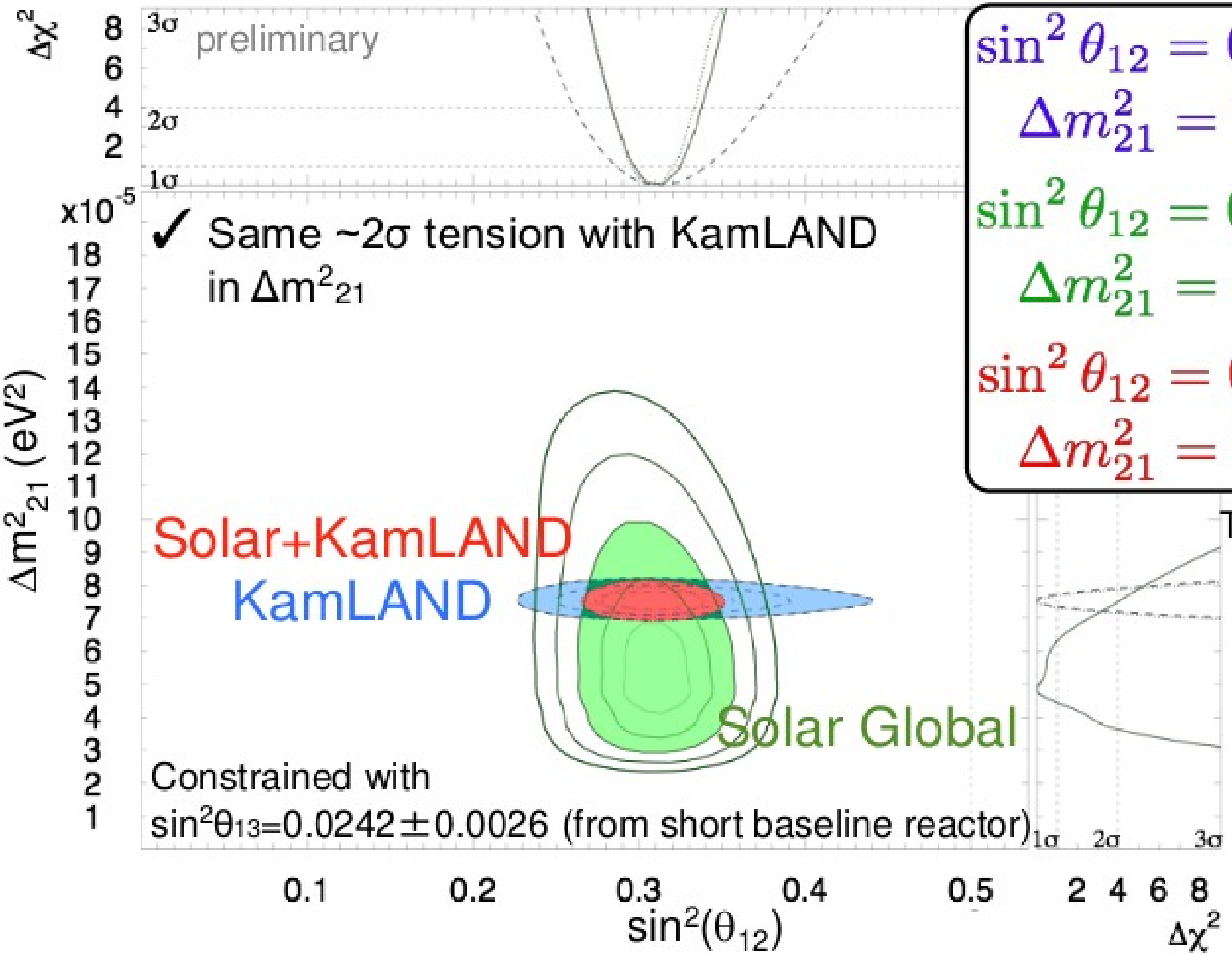
If g_A is renormalized to ~0.8-0.5, all estimates for half-lives should be increased by a factor of ~6-34 and limits on the average neutrino mass should be increased by a factor ~2.5-6, making it impossible to reach in the foreseeable future even the inverted region.



Limits from EXO in ^{136}Xe decay

Neutrino mixing

θ_{12} and Δm^2_{21} from Solar Global vs. KamLAND



✓ Same ~2σ tension with KamLAND in Δm^2_{21}

Constrained with $\sin^2\theta_{13}=0.0242\pm0.0026$ (from short baseline reactor)

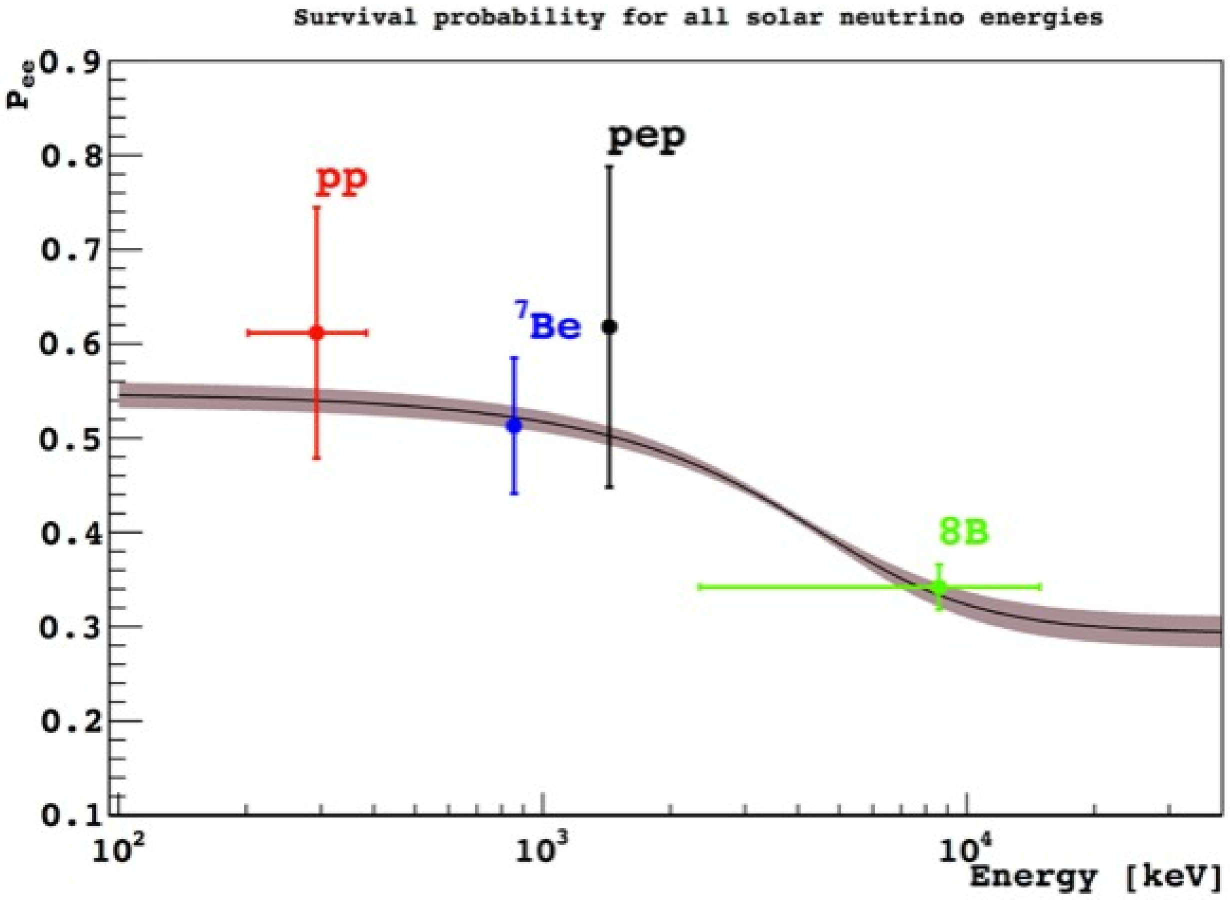
$$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$

$$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$$
$$\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$$

$$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$$
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$$

The unit of Δm^2_{21} is 10^{-5} eV^2

Interpretation:
Survival probability measurement

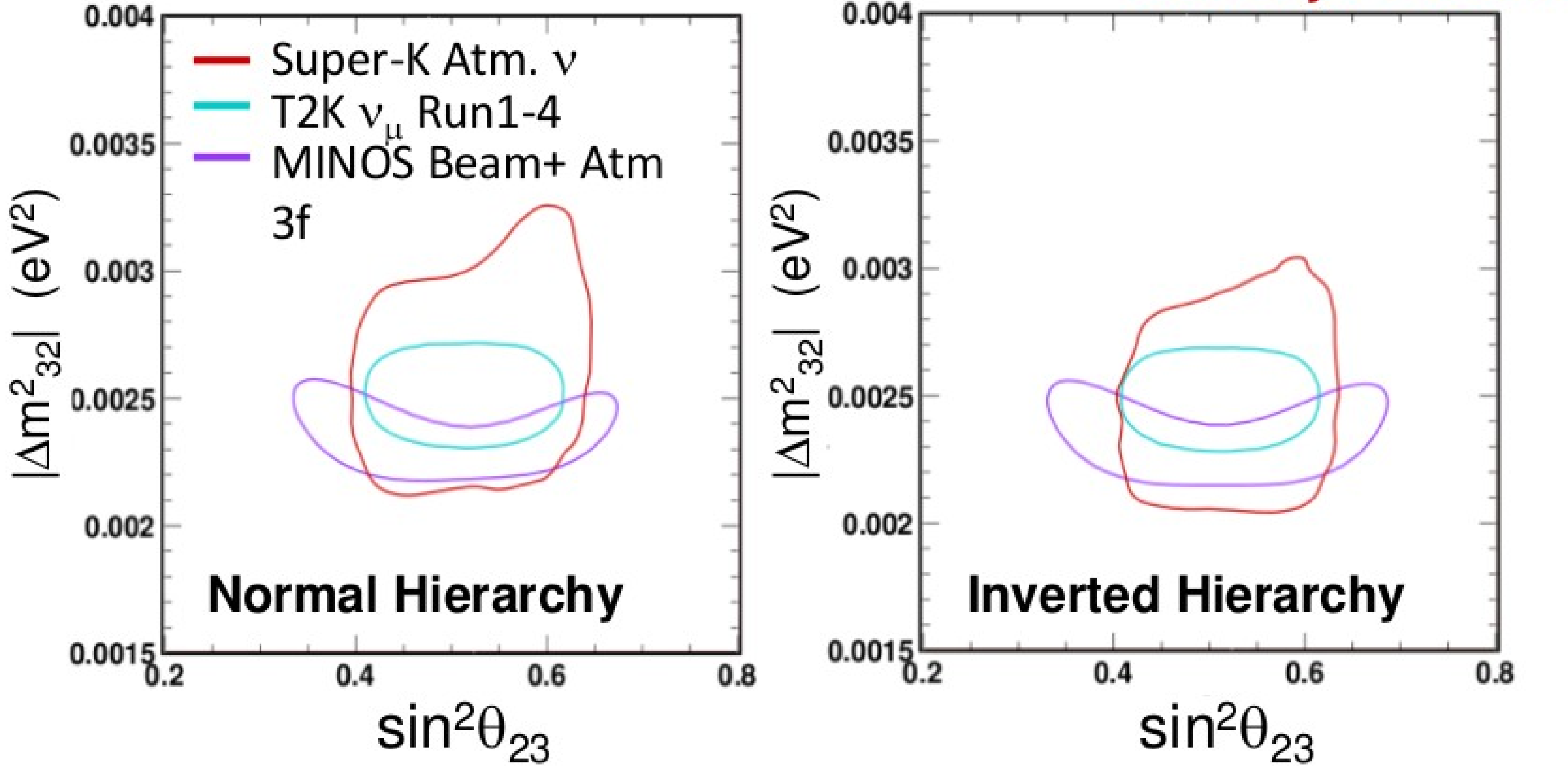


Borexino

$$P_{ee} = \begin{cases} 0.612 \pm 0.133 & \text{measured} \\ 0.543 \pm 0.013 & \text{expected} \end{cases}$$

Comparison with T2K and MINOS

4581 days Preliminary

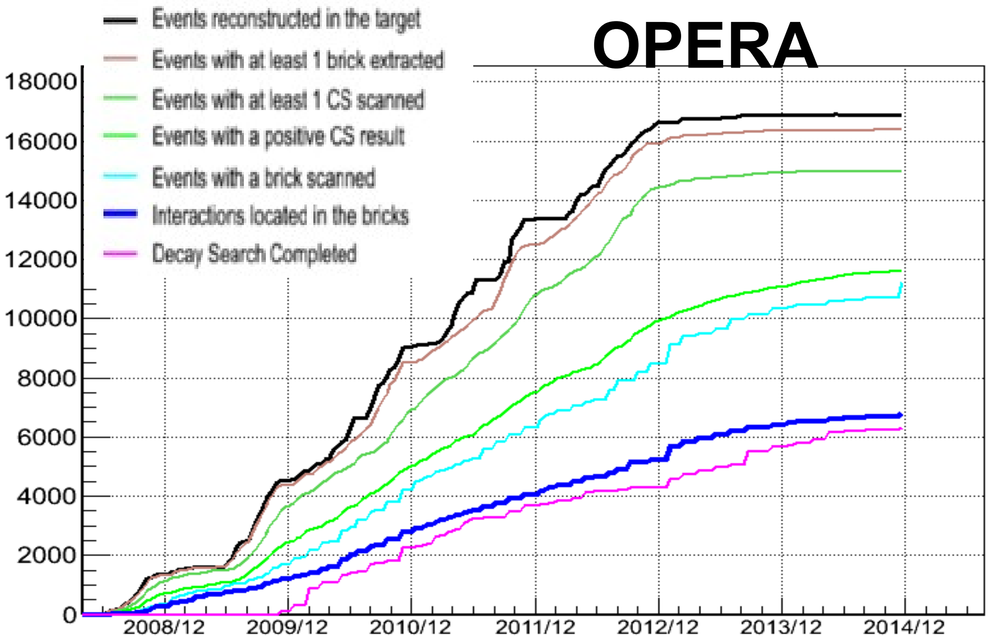


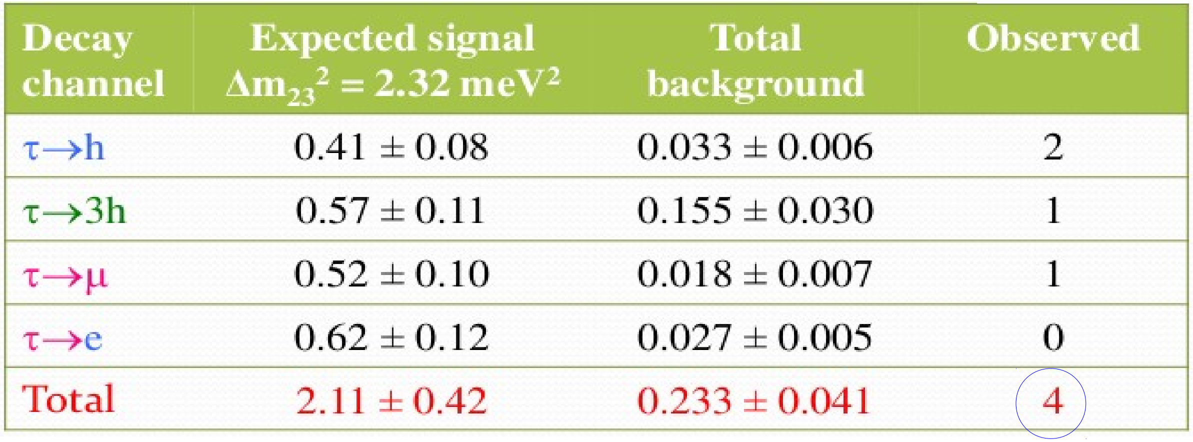
- They are consistent to each other.
- SK's sensitivity in Mass Hierarchy and δCP can be improved by incorporating constraints from these measurements.

ν_τ analysis results

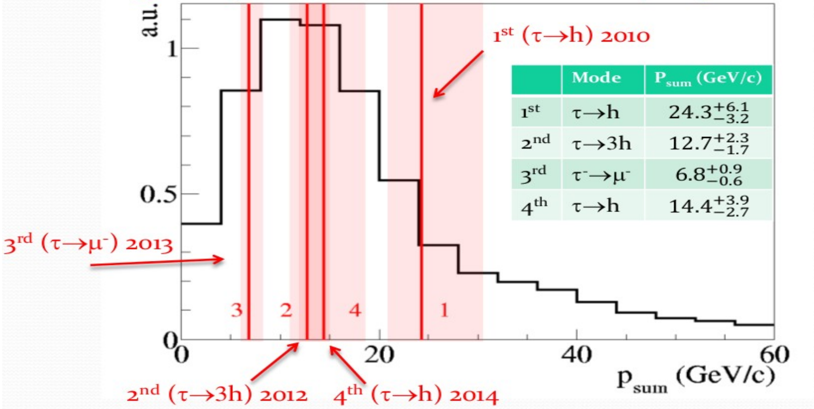
Status of the analysis:
The presented results correspond to about 70% of the total sample
2008-2009: 1st and 2nd brick completed
2010-2012: 1st brick completed

Analysis in progress.
Updates in summer conferences.





Decay channel	Expected signal $\Delta m_{23}^2 = 2.32$ meV²	Total background	Observed
τ→h	0.41 ± 0.08	0.033 ± 0.006	2
τ→3h	0.57 ± 0.11	0.155 ± 0.030	1
τ→μ	0.52 ± 0.10	0.018 ± 0.007	1
τ→e	0.62 ± 0.12	0.027 ± 0.005	0
Total	2.11 ± 0.42	0.233 ± 0.041	4



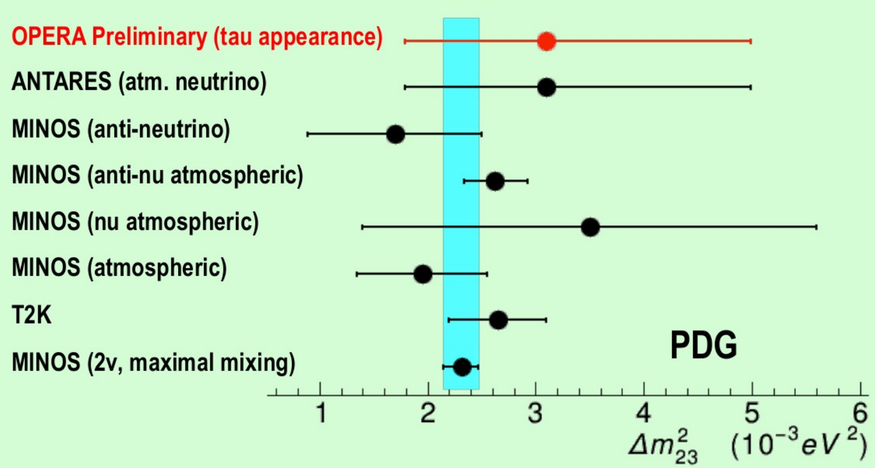
	Mode	P_{sum} (GeV/c)
1st	τ→h	$24.3^{+6.1}_{-3.2}$
2nd	τ→3h	$12.7^{+2.3}_{-1.7}$
3rd	$\tau^- \to \mu^-$	$6.8^{+0.9}_{-0.6}$
4th	τ→h	$14.4^{+3.9}_{-2.7}$

3 hadronic + 1 muonic candidates observed

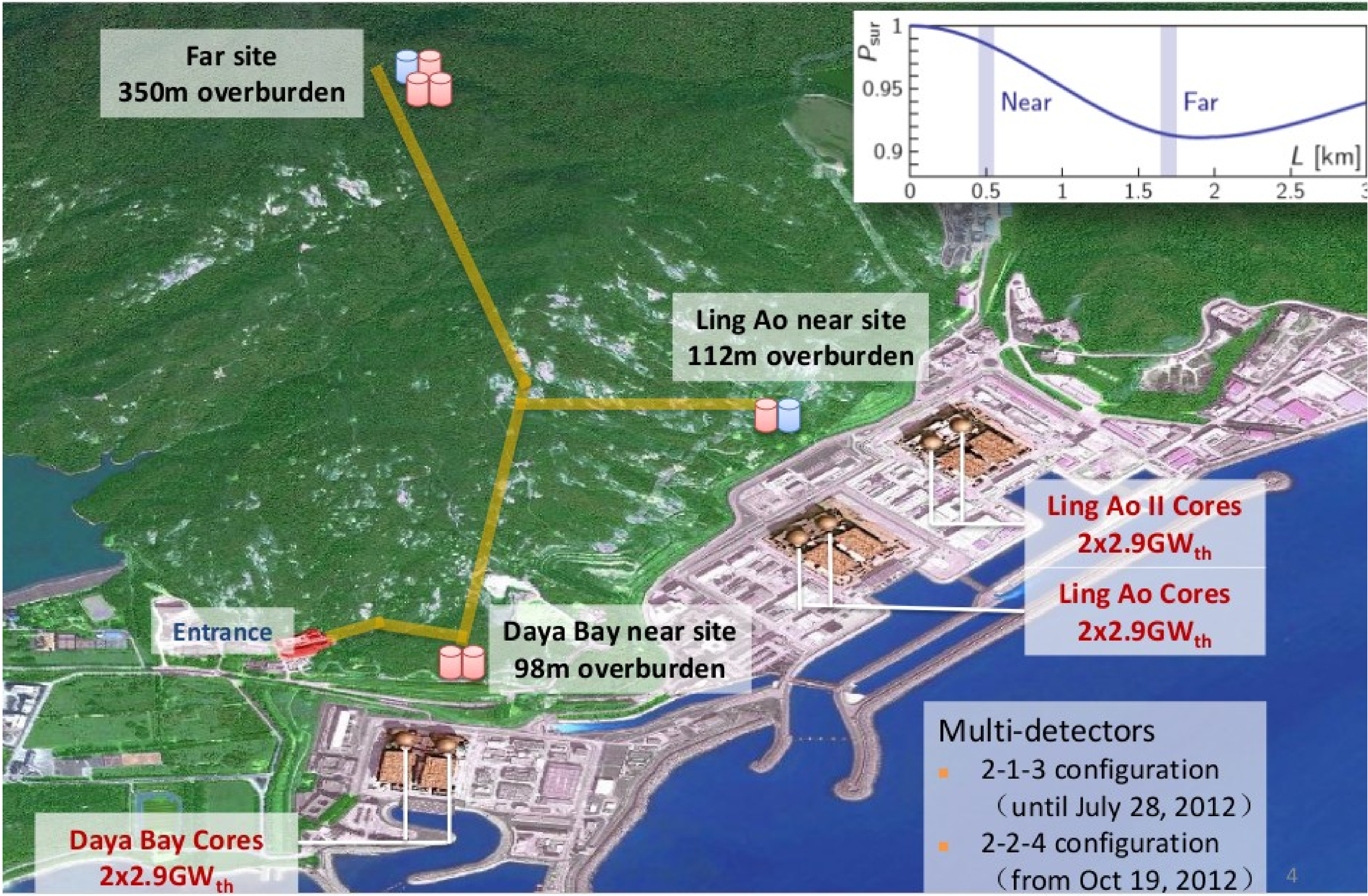
Exclusion of null hypothesis: 4.2 σ

p-value = 1.03 x 10^{-5}

- Fisher combination of single channel p-value
- Likelihood ratio



The Daya Bay experiment

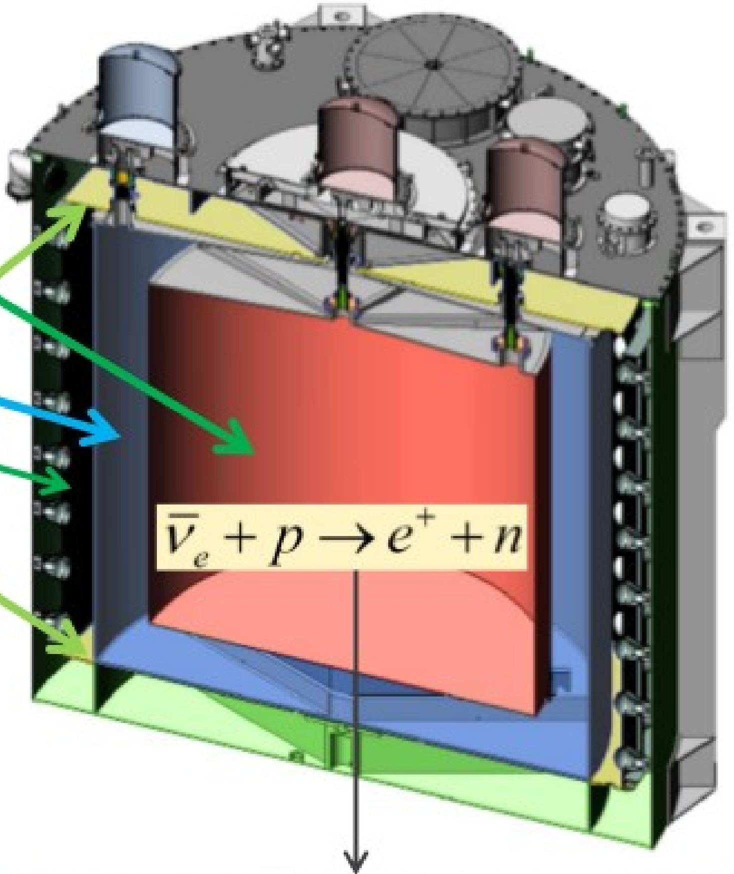


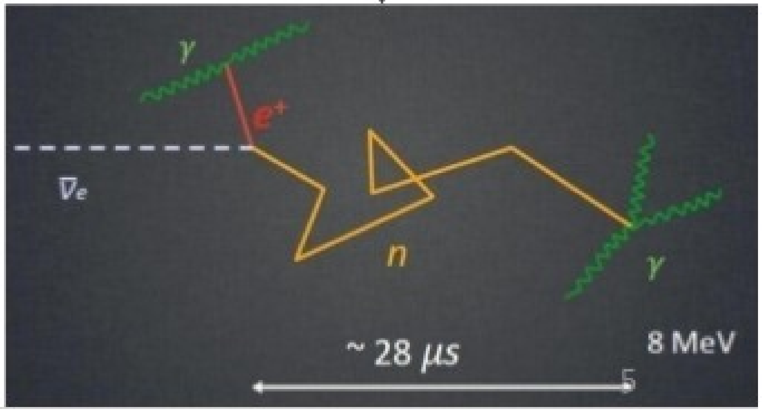
Multi-detectors

- 2-1-3 configuration（until July 28, 2012）
- 2-2-4 configuration（from Oct 19, 2012）

Antineutrino detector

- Three zones structure:
    - Target: 20 t 0.1% Gd-loaded scintillator
    - γ-catcher: 20 t scintillator
    - Buffer shielding: mineral oil
- Top and bottom optical reflectors double the photon coverage.
- 192 8'' PMTs collect ~160 p.e./MeV





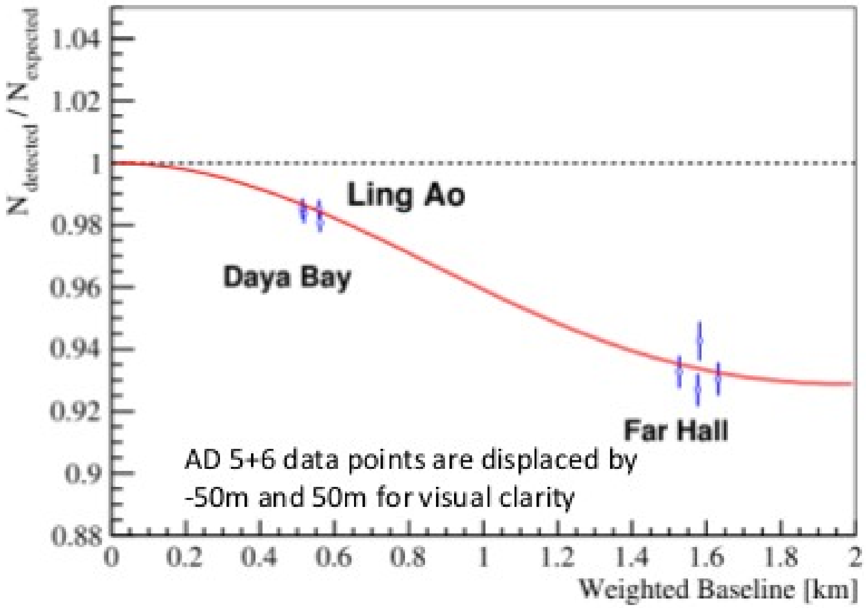
8 identically designed detectors to reduce systematic uncertainties

$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

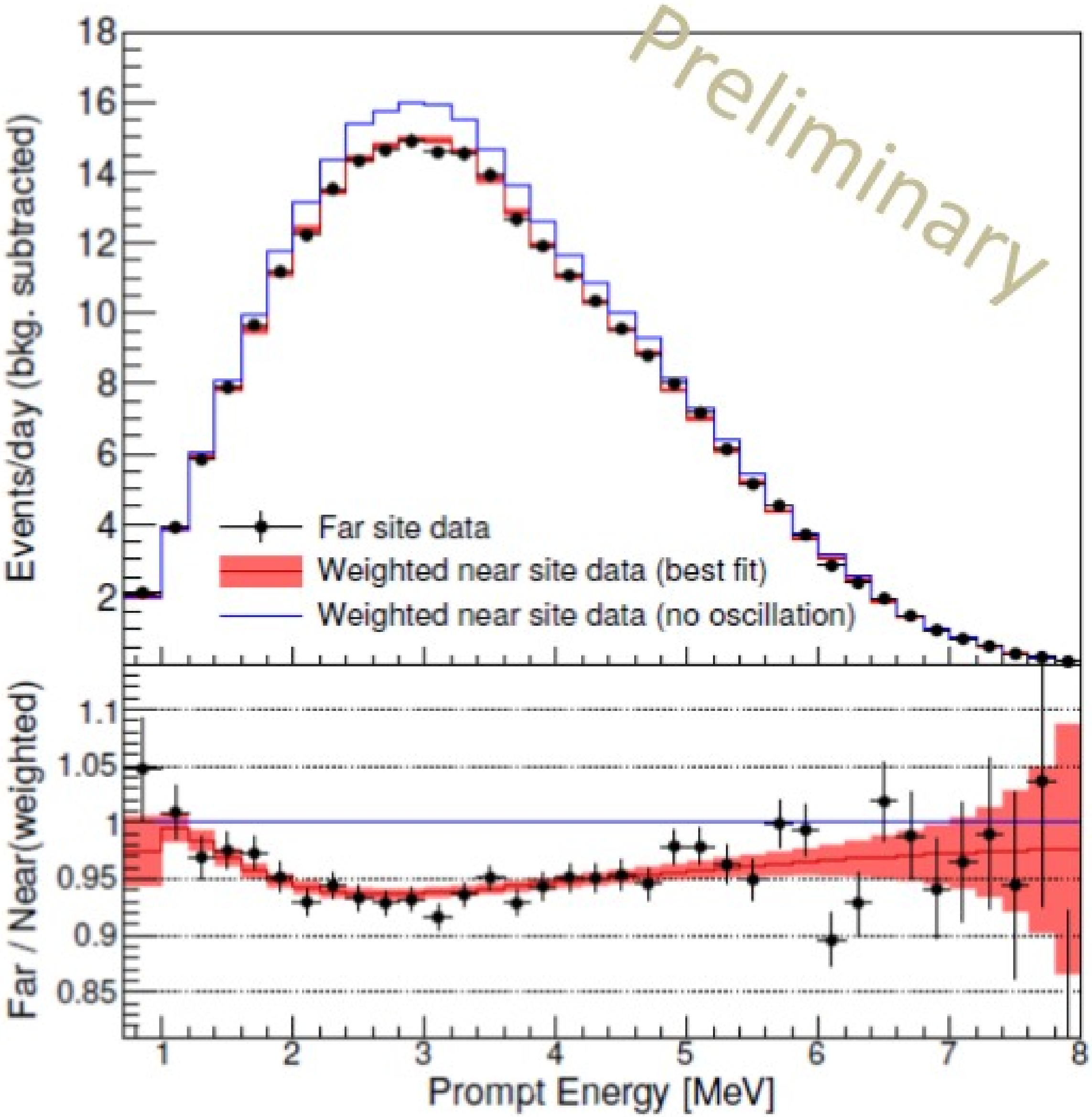
Target mass

efficiency

Rate deficit and spectrum distortion



AD 5+6 data points are displaced by -50m and 50m for visual clarity



- Near/Far relative measurement
- Observed data highly consistent with oscillation interpretation

Oscillation results

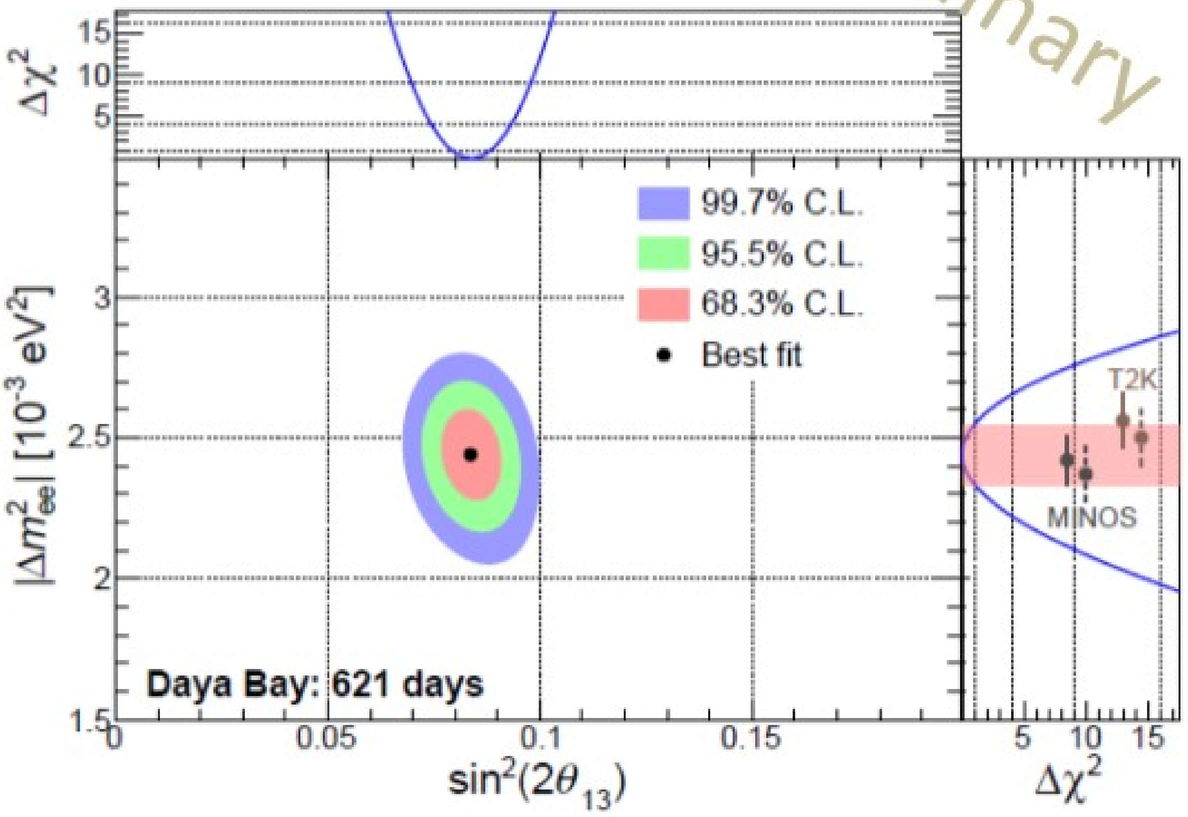
Preliminary

$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3} (eV^2)$$

$$\chi^2 / NDF = 134.7 / 146$$

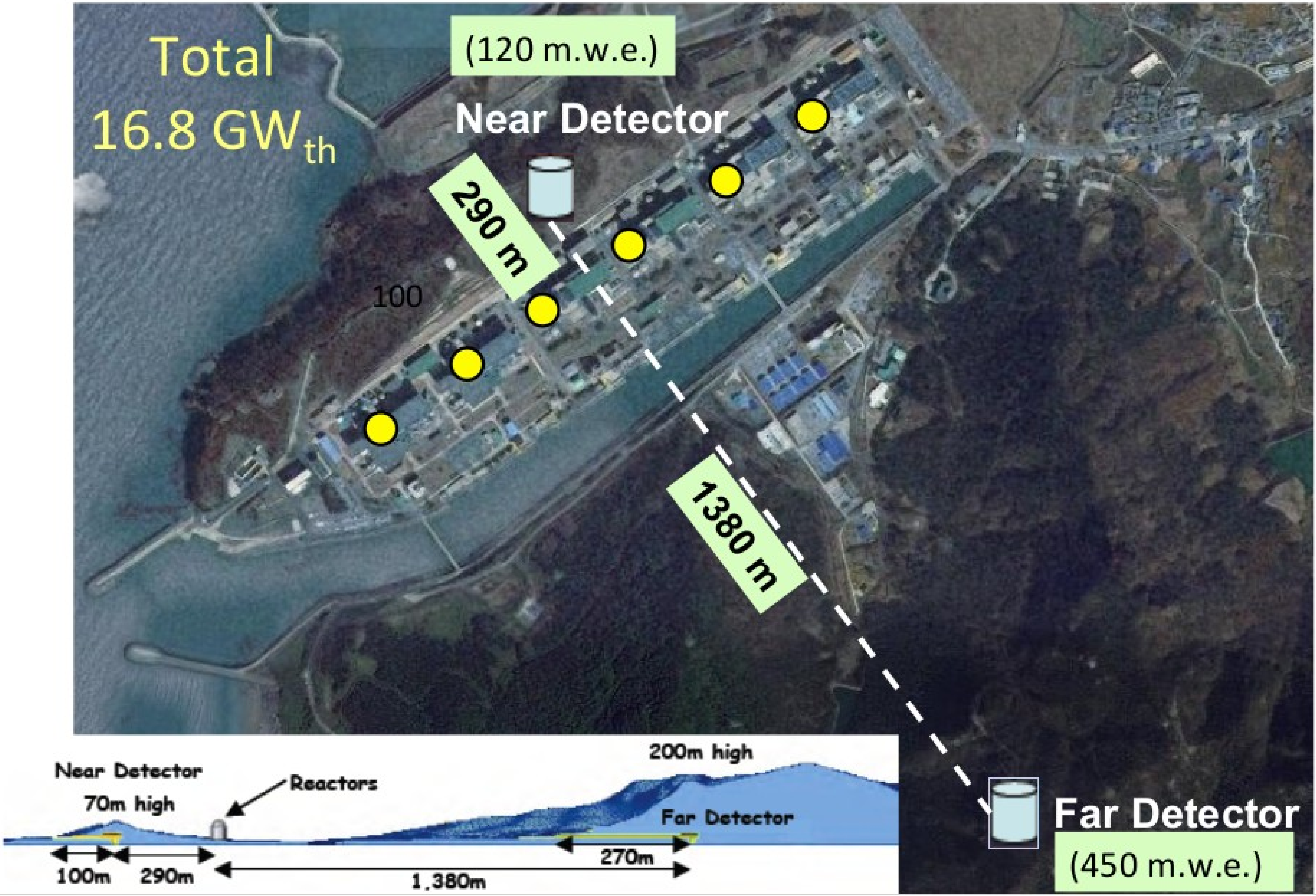
- Most precise measurement of $\sin^2 2\theta_{13}$ (6%)
- Most precise measurement of Δm^2_{ee} in the electron neutrino disappearance channel (4%)
  - Consistent with the muon neutrino disappearance experiments
  - Comparable precision



MINOS: PRL, **112**, 191801 (2014)
T2K: PRL, **112**, 181801 (2014)

Publication in preparation

RENO Experimental Setup

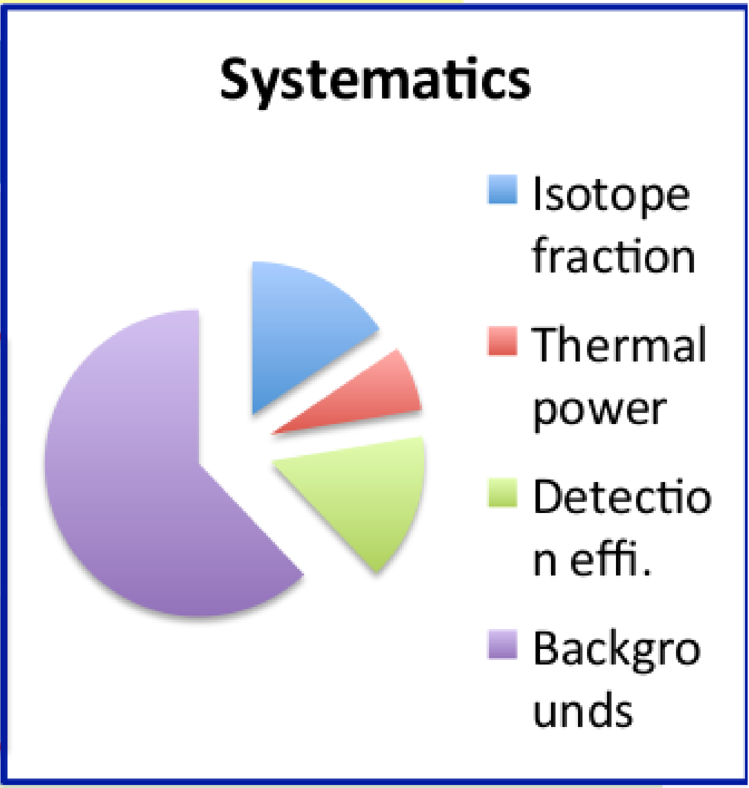


New θ_{13} Measurement by Rate-only Analysis

(Preliminary)

$$\sin^2 2\theta_{13} = 0.090 \pm 0.008(\text{stat.}) \pm 0.008(\text{syst.})$$

Uncertainties sources	Uncertainties (%)	Errors of $\sin^2 2\theta_{13}$ Error (fraction)
Statistics (near) (far)	0.21 % 0.54 %	0.008
Isotope fraction	0.7 %	0.003 → 15.6 %
Thermal power	0.5 %	0.002 → 6.9 %
Detection efficiency	0.2 %	0.003 → 15.6 %
Backgrounds (near) (far)	0.14 % 0.51 %	0.006 → 62.3 %



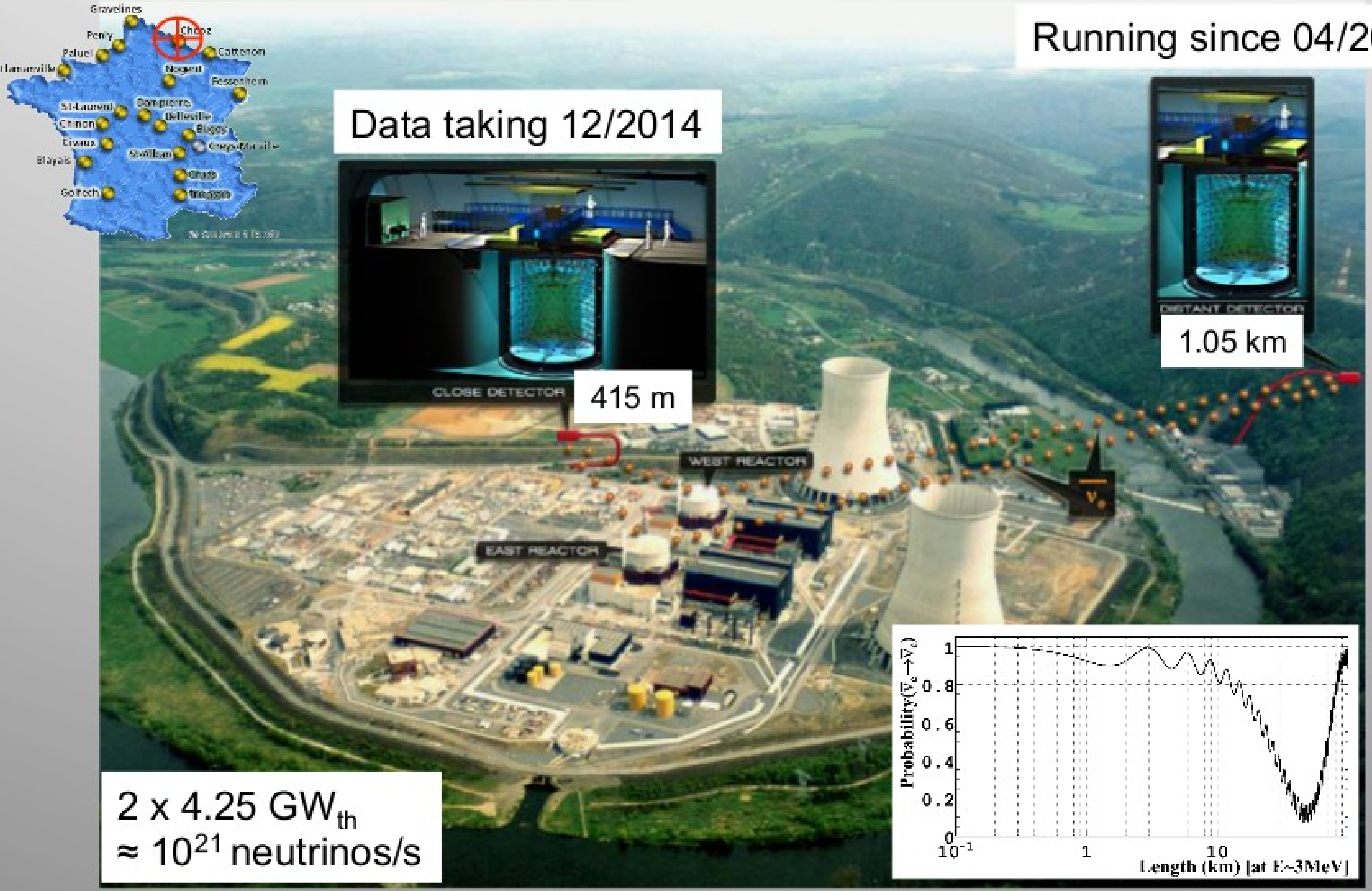
$$\sin^2 2\theta_{13} = 0.113 \pm 0.023$$ 4.9 σ (Neutrino 2012)

$$\rightarrow 0.100 \pm 0.016$$ 6.3 σ (TAUP/WIN 2013)

$$\rightarrow 0.101 \pm 0.013$$ 7.8 σ (Neutrino 2014)

$$\rightarrow 0.090 \pm 0.011$$ 8.2 σ (Singapore 2015)

Double Chooz site



Running since 04/2011

Data taking 12/2014

1.05 km

415 m

2 x 4.25 GW_{th}
≈ 10^{21} neutrinos/s

RRM results

	Free BG	**off-off**	**BG constr.**
$\sin^2 2\Theta_{13}$	0.089 ± 0.052	0.060 ± 0.039	$0.090^{+0.034}_{-0.035}$
BG rate (ev/day)	1.56 ± 0.86	$0.093^{+0.43}_{-0.36}$	$1.56^{+0.18}_{-0.16}$

Comparison with rate + shape analysis:

$$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$$

$$BG(ev / day) = 1.64^{+0.41}_{-0.17}$$

1. The data set

Gianluigi Fogli talk

- Oscillation parameters are extracted with their correlations from solar, atmospheric, accelerator and reactor neutrino data.

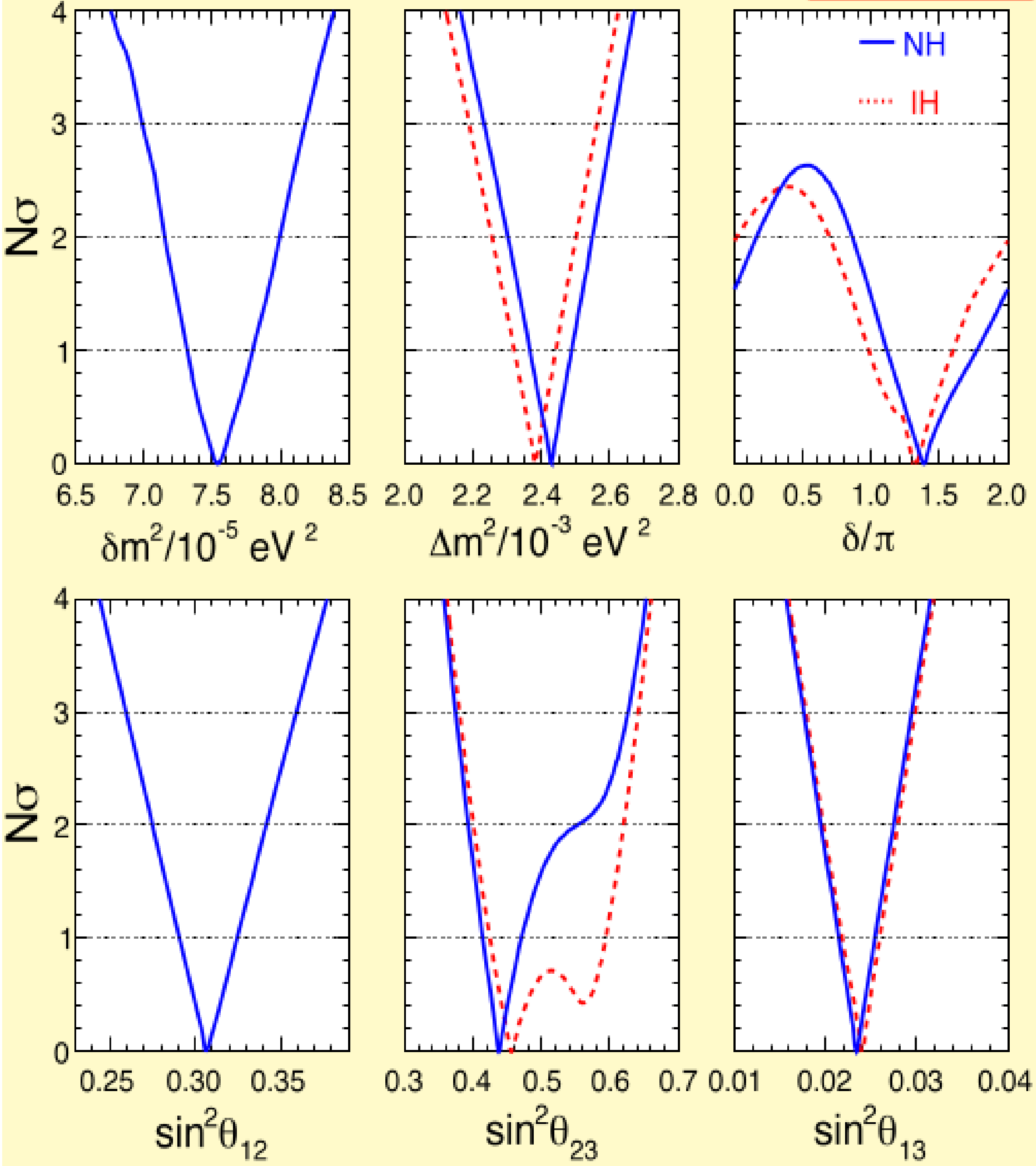
- Data set:

  LBL Accelerators → K2K + T2K + MINOS
  Solar → Homestake, Gallex/GNO, SAGE, SK, SNO, Borexino
  KamLAND → KamLAND reactor data
  SBL Reactors → Double Chooz + RENO + Daya Bay
  SK Atm → Super-Kamiokande Atmospheric data

- In particular they include neutrino appearance and disappearance data published in 2013 and at the beginning of 2014 from **T2K** and **MINOS**, together with the data of **SBL reactors** presented at Neutrino '14 in Boston.

- Full 3ν probabilities included, no approximation.

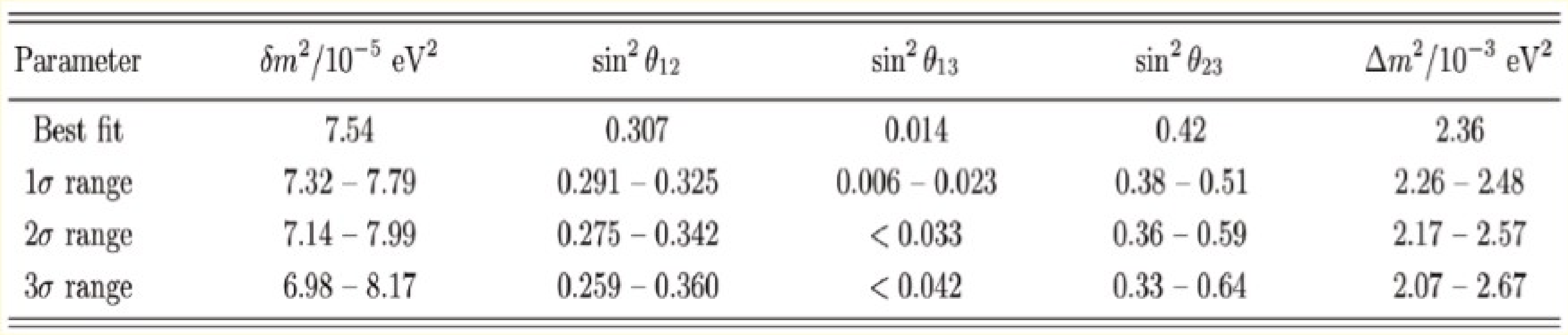
LBL Acc + Solar + KL + SBL Reactors + SK Atm



- Some effects on the $\nu_\mu \to \nu_\tau$ dominant parameters
  (Δm^2, θ_{23})

- Preference for $\delta \sim 1.4\ \pi$

- Preference for non-maximal θ_{23} and 1st octant in NH, much weaker in IH:
  somewhat fragile



Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.54	0.307	0.014	0.42	2.36
1σ range	7.32 – 7.79	0.291 – 0.325	0.006 – 0.023	0.38 – 0.51	2.26 – 2.48
2σ range	7.14 – 7.99	0.275 – 0.342	< 0.033	0.36 – 0.59	2.17 – 2.57
3σ range	6.98 – 8.17	0.259 – 0.360	< 0.042	0.33 – 0.64	2.07 – 2.67

Fractional 1σ accuracy [defined as 1/6 of ±3σ range]

δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	Δm^2
2.6%	5.4%	~ 0.008	~12%	4.2%

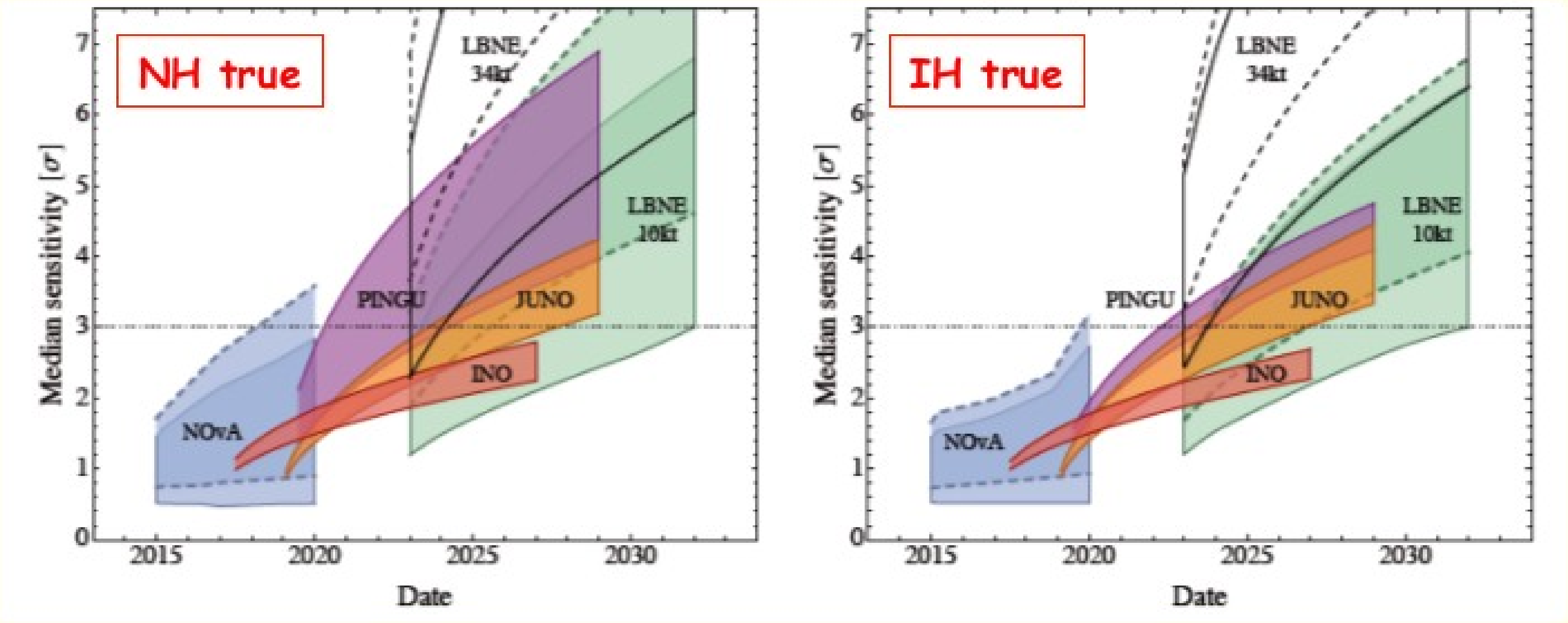
Moreover …

- No significant hierarchy preference from the global fit [$\Delta\chi^2$(I-N) = -0.3]
- Weak preference for the 1st octant (more fragile after T2K 2014 data).
- Intriguing hint of nonzero CP violation, with $\sin\delta < 0$ …

  [Similar CP hint: Gonzalez-Garcia, Maltoni, Schwetz, Salvado 2013/14; SK, T2K official data analyses 2013/14]

We close with a recent detailed comparison of the sensitivity of each of the cited experiments, in terms of number of σ's, plotted in terms of the time-scale.

M. Blennow, P. Coloma, P. Huber and T. Schwetz, JHEP 02 (2014) 028 [arXiv:1311.1822v2[hep-ph]]



Due to the dichotomous character of the neutrino mass ordering, the sensitivity is plotted on the left for rejecting IH if NH is true, and viceversa on the right.

The width of each band depends on the range of values of the parameters relevant in the estimates, in particular:

- δ_{CP} and the true θ_{23} for LBL accelerator experiments, NOνA and LBNE
- θ_{23} for atmospheric experiments, INO and PINGU
- energy resolution for MBL reactor experiment, specifically JUNO

ELBNF and LBNF

ELBNF: An Experimental Program in Neutrino Physics, Nucleon Decay, and Astroparticle Physics at the Fermilab Long Baseline Neutrino Facility (LBNF)

A merger of previous efforts and any other interested parties to build, operate, exploit

- a (staged) 40 kt LAr detector, at the Sanford Underground Research Facility (SURF), 1300 km from Fermilab
- a high granularity/high precision near detector
- exposed to a 1.2 MW, tunable, wide-band ν beam produced by the PIP-II upgrade at FNAL by 2024, evolving to a power of 2.4 MW by ~ 2030

Neutrino Spectra and Oscillation Probabilities

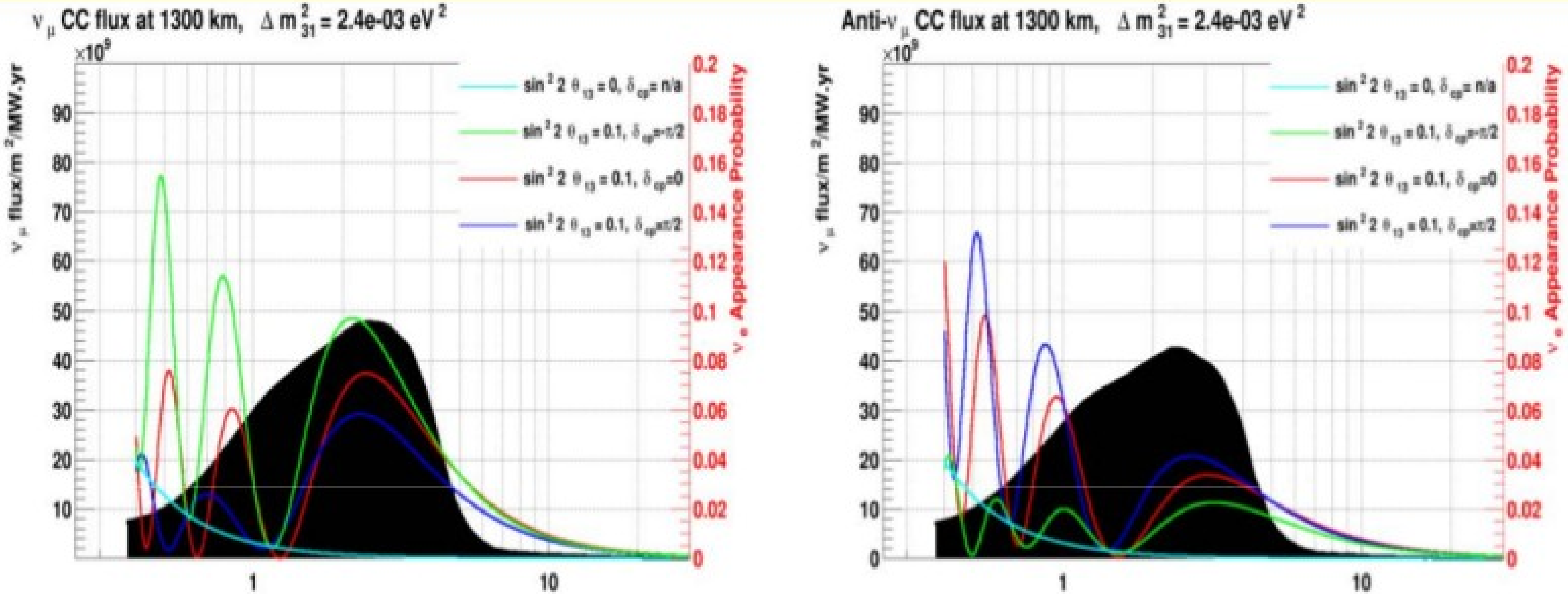


FIGURE 1: *The colored curves represent $P(\nu_\mu \rightarrow \nu_e)$ at a baseline of 1300 km, as a function of neutrino energy, for $\delta_{CP} = \pi/2$ (blue), 0 (red), and $-\pi/2$ (green), for neutrinos (left) and antineutrinos (right), for normal hierarchy. The cyan curve indicates the oscillation probability if θ_{13} were equal to zero. The black solid histogram is the unoscillated ν_μ (left) and $\bar{\nu}_\mu$ (right) flux at 1300 km from an 80GeV MI beam using NuMI horns for focusing.*

Expected Sensitivities to MH and CPV

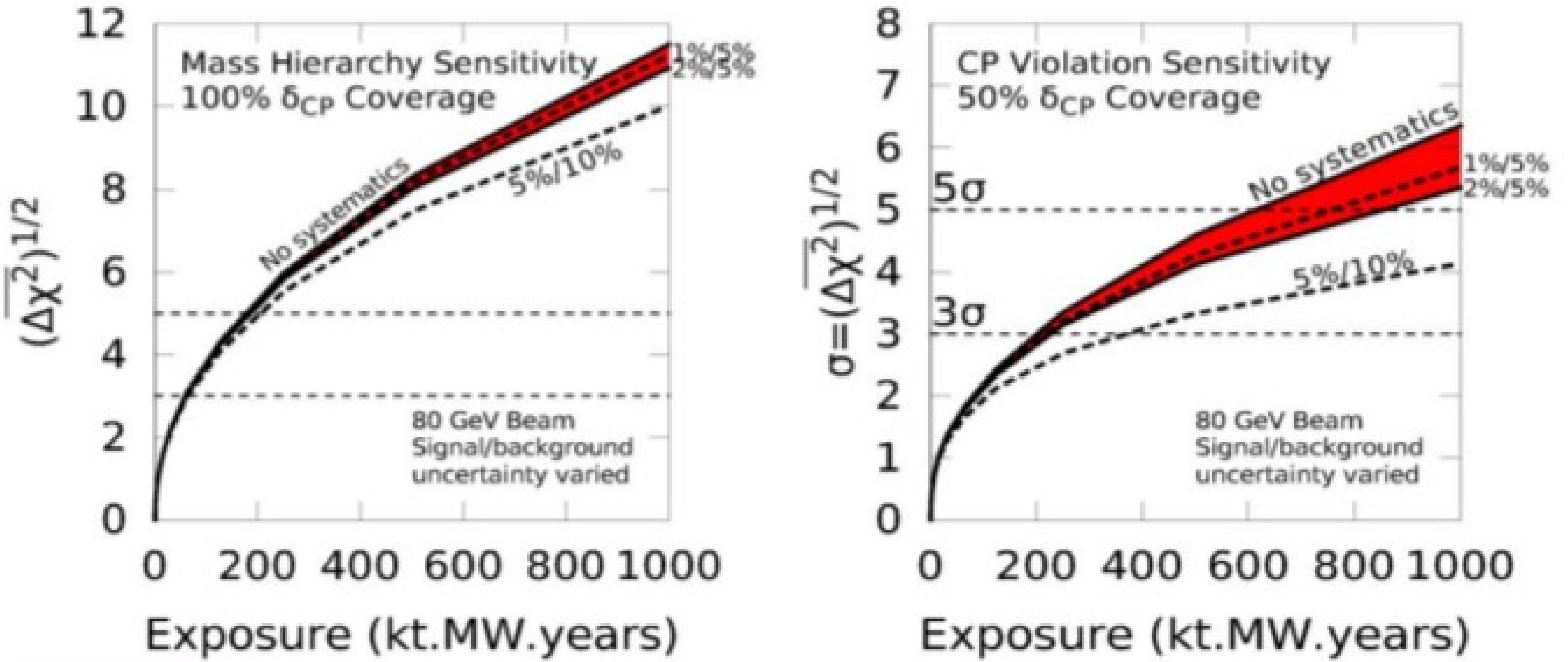


FIGURE 8: *Expected sensitivity of ELBNF to determination of the neutrino mass hierarchy (left) and discovery of CP violation, i.e. $\delta_{CP} \neq 0$ or π, (right) as a function of exposure in kt-MW-years, assuming equal running in neutrino and antineutrino mode, for a range of values for the residual ν_e and $\overline{\nu}_e$ signal and background normalization uncertainties. The sensitivities quoted are the minimum sensitivity for 100% of δ_{CP} values in the case of mass hierarchy and 50% of δ_{CP} values in the case of CP violation. Sensitivities are for true normal hierarchy; neutrino mass hierarchy is assumed to be unknown in the CPV fits.*

Far Detector: Single- or Dual-Phase LAr TPC

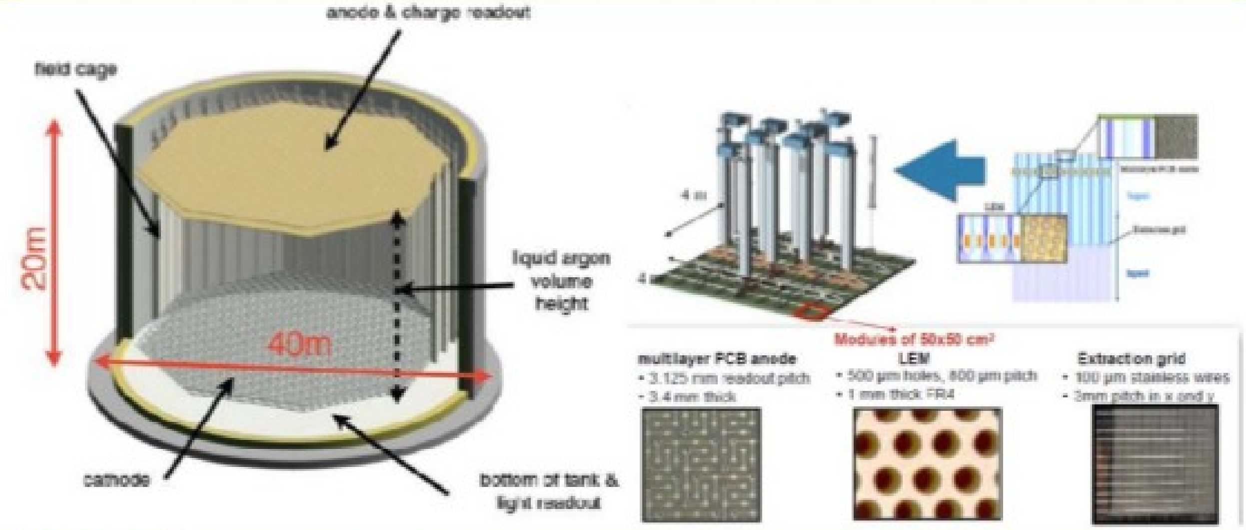


FIGURE 15. *Schematic view (left) of the 20-kt double-phase LAr detector optimized for the Pyhäsalmi mine location. Engineering work is presently being performed to optimize the geometry to a SURF location (right) the basic 4x4 m² double-phase readout unit with their extraction, LEM amplifying stage, and anode layer. In total 65 such units of 4x4 m² will be needed for the 23.3-kt detector.*

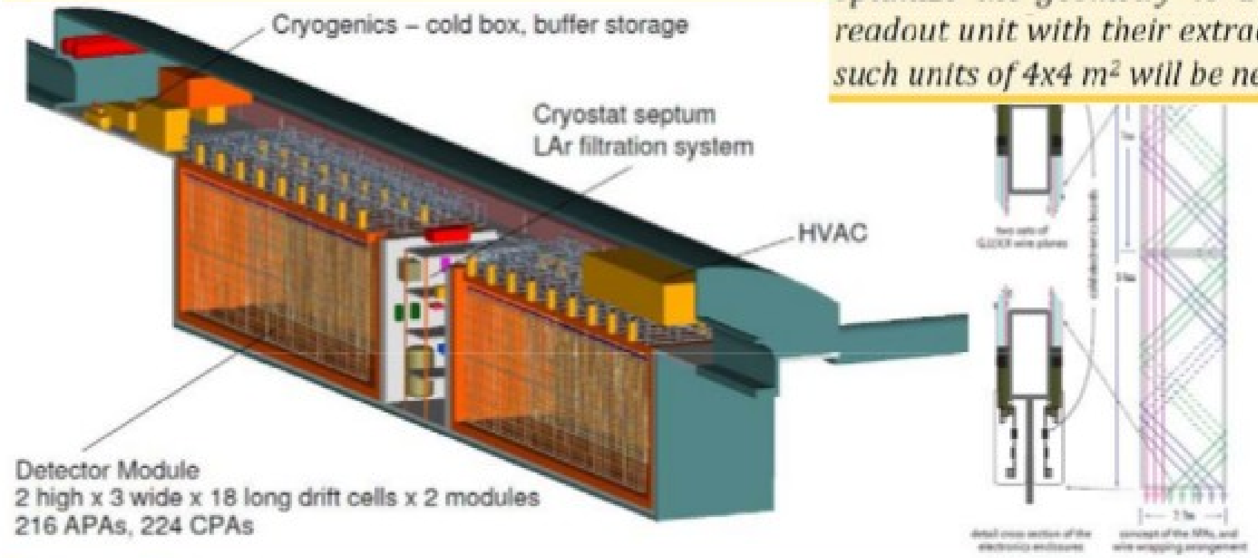


FIGURE 16. *Schematic of a 34-kt fiducial mass LArTPC design (left). The detector comprises two 17-kt fiducial mass LArTPC detectors. The design of a pair of Anode Plane Assemblies is shown at right.*

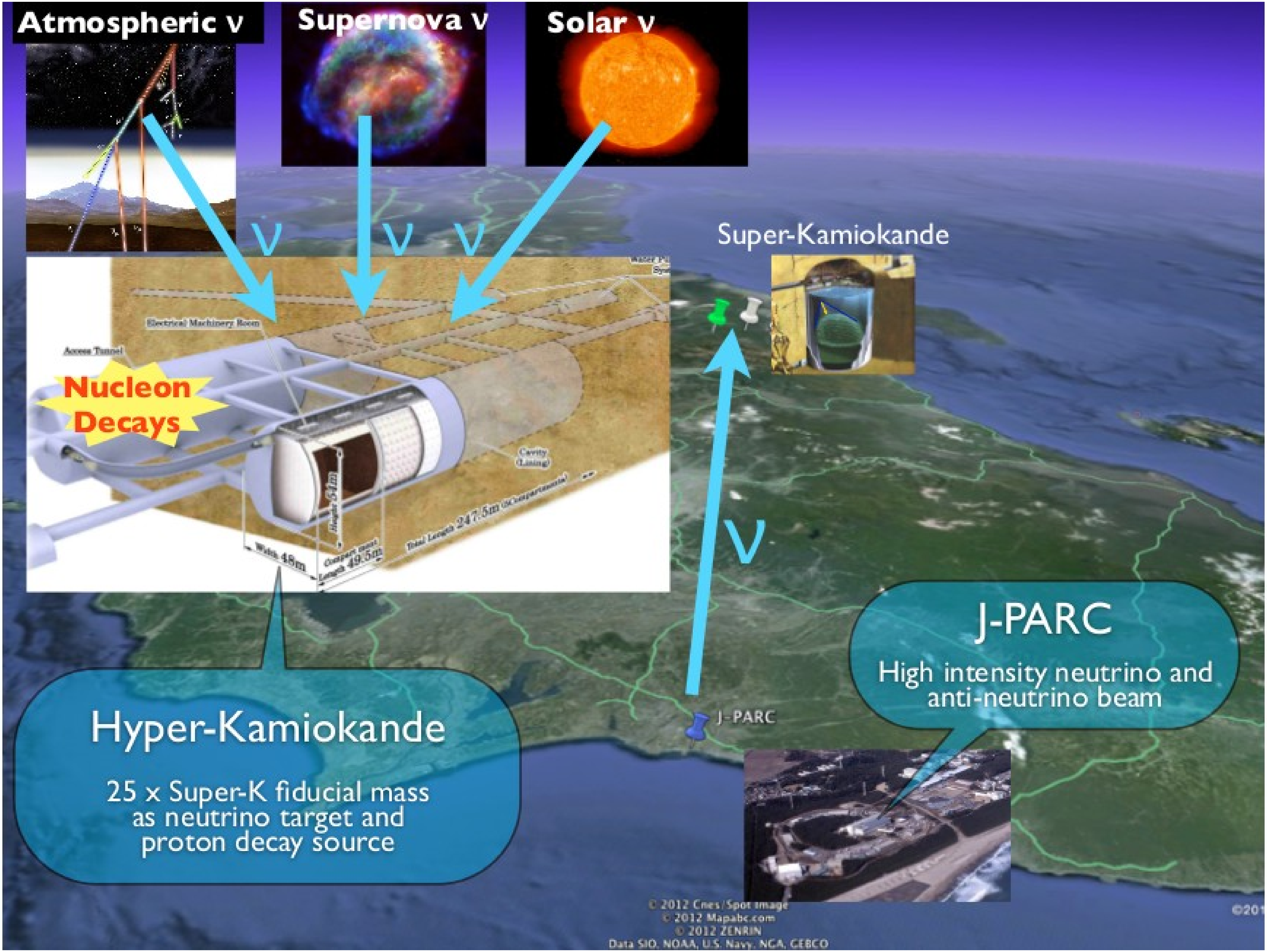
ELBNF LOI Signatures* from 142 Institutions

UFABC
Alabama
Alfenas
Aligarh Muslim
APC - Paris
Argonne
ASCR
Atlantico
Banaras
Bartoszek Engineering
Bern
Bhabha
Boston
Brookhaven
Brown
Budker
California (Berkeley)
California (Davis)
California (Irvine)
California (Los Angeles)
Caltech
Cambridge
Campinas
Catania
CBPF
CERN
Charles University
Chicago
Ciemat
Cincinnati
Cinvestav
Colima
Colorado
Colorado State
Columbia
COMSATS IIT
CTU
Dakota State
Delhi
DESY
Drexel
Duke
ETHZ
Feira de Santana
Fermilab
Goias
Gran Sasso
Guwahati
Hamburg
Harish-Chandra
Hawaii
Houston
Huddersfield
Hyderabad
Idaho State
IFAE
IFC
IIT
Indiana
Institute for Nuclear Search
Iowa State
IPM
IPNL Lyon
IPPP Durham
Jammu
JG Boissevain Design
Kansas State
KEK
Koneru Lakshmaiah
Lancaster
LAPP
Lawrence Berkeley National Lab
Liege
Liverpool
London UCL
Los Alamos National Laboratory
Louisiana State
Lucknow
Manchester
Maryland
Max Planck MPP
MIT
Michigan State
Milano
Milano & INFN Bicocca
Minnesota
Minnesota (Duluth)
Napoli
NCBJ
Nehru
New Mexico
NIKHEF
Northern Illinois
Northwestern
Notre Dame
Observatorio Nacional
Ohio State
Order of Engineers Genoa
Oregon State
Oxford
Ozark Integrated Circuits Co
Padova
Panjab
Pavia
Pennsylvania State
Pisa
Pittsburgh
Princeton
Punjab
Rochester
Saclay
SLAC
STFC Rutherford Appleton
Sheffield
Sofia
South Carolina
South Dakota
SD School of Mines & Technology
SURF
South Dakota State
Southern Methodist
Stanford
Stony Brook
Sussex
Syracuse
Tennessee
Texas (Arlington)
Texas (Austin)
Tubitak
Tufts
VECC
Virginia Tech
Warwick
Warsaw
Washington
Wichita State
William and Mary
Wisconsin
Wroclaw
Yale
Yerevan
York

*As of 11 Jan 2015

CERN ν Platform Initial Mandate

- Assist the various groups in their R&D phase (detectors and components) in the short and medium term and give coherence to a fragmented European Neutrino Community
- Provide to the ν community a test beam infrastructure (charged particles)
- Bring R&D at the level of technology demonstrators in view of major technical decisions
- Continue R&D on ν beam, as a possible base for further collaborations
- Support the short baseline activities (infrastructure & detectors)
- Support the long baseline activities (infrastructure & detectors)



Hyper-Kamiokande

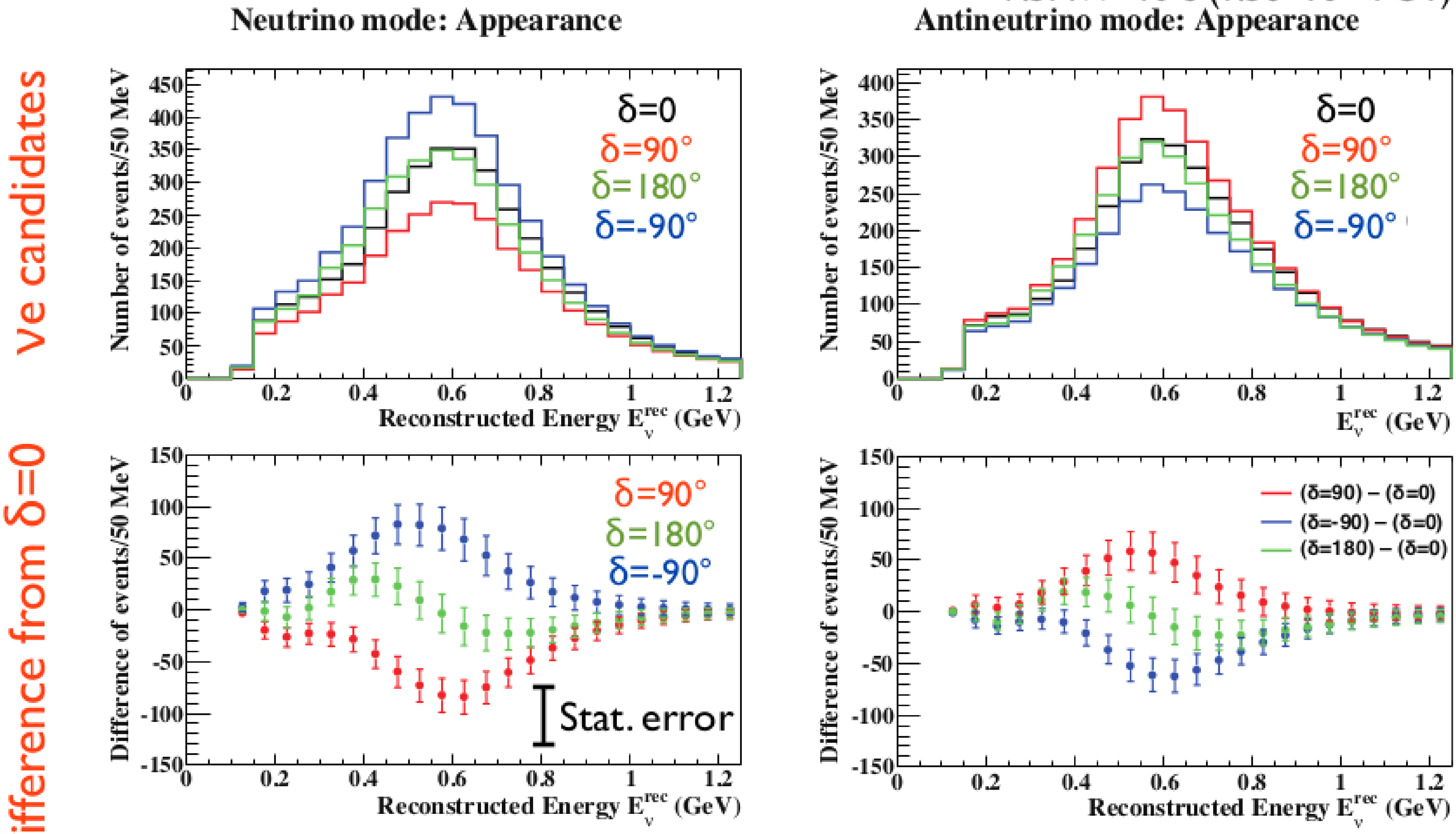
25 x Super-K fiducial mass
as neutrino target and
proton decay source

J-PARC

High intensity neutrino and
anti-neutrino beam

δ_{CP} dependence of observables

7.5MW×10^7s (1.56×10^{22} POT)



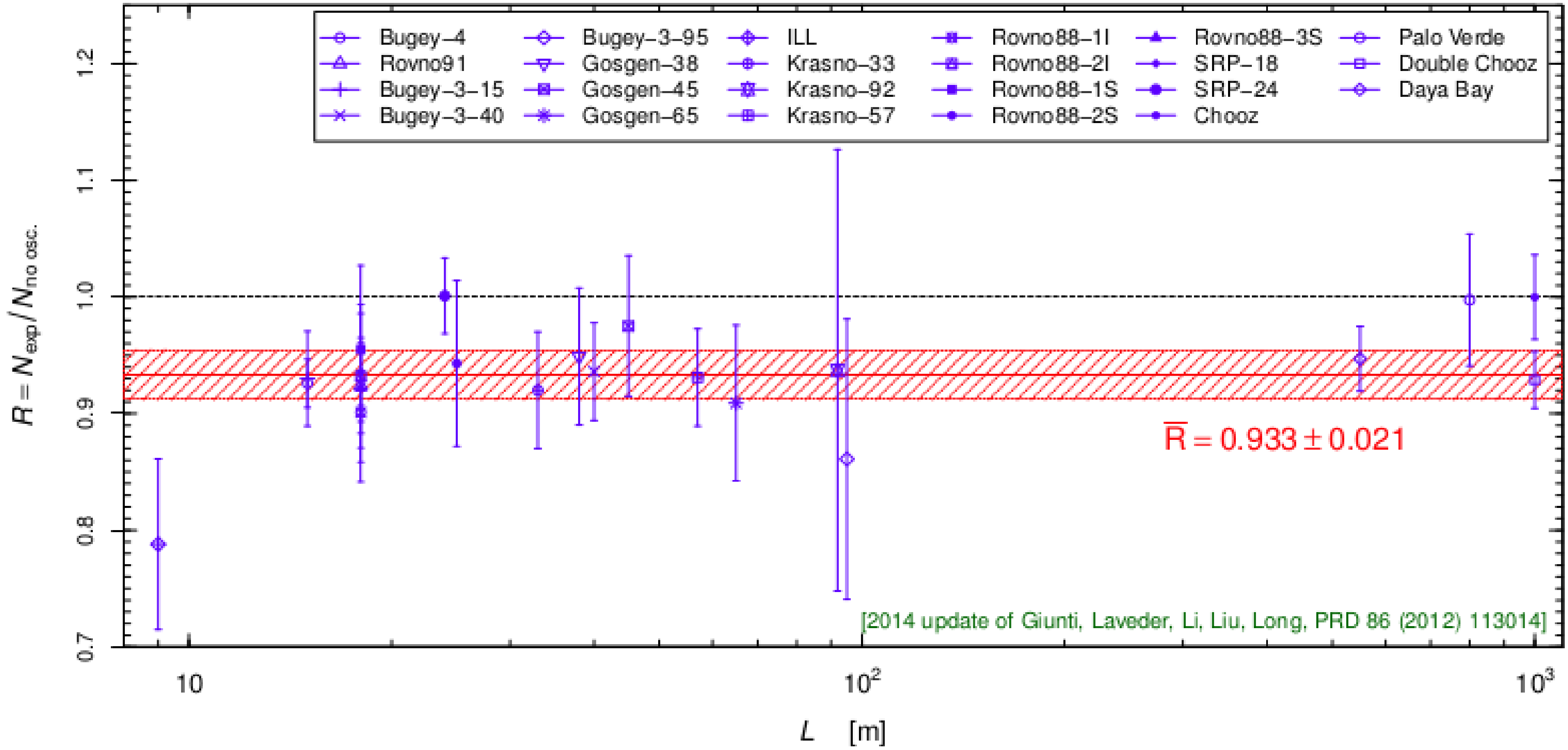
Sensitive to all values of δ with numbers + shape

Sterile neutrinos

Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006; update in White Paper, arXiv:1204.5379]

New reactor $\bar{\nu}_e$ fluxes [Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



[2014 update of Giunti, Laveder, Li, Liu, Long, PRD 86 (2012) 113014]

$\bar{\nu}_e \to \bar{\nu}_e$ $L \sim 10 - 100\,\text{m}$ $E \sim 4\,\text{MeV}$

Nominal ≈ 3.1σ deficit $\Delta m^2 \gtrsim 0.5\,\text{eV}^2$ $(\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

[see also: Sinev, arXiv:1103.2452; Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Zhang, Qian, Vogel, PRD 87 (2013) 073018; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Ivanov et al, PRC 88 (2013) 055501]

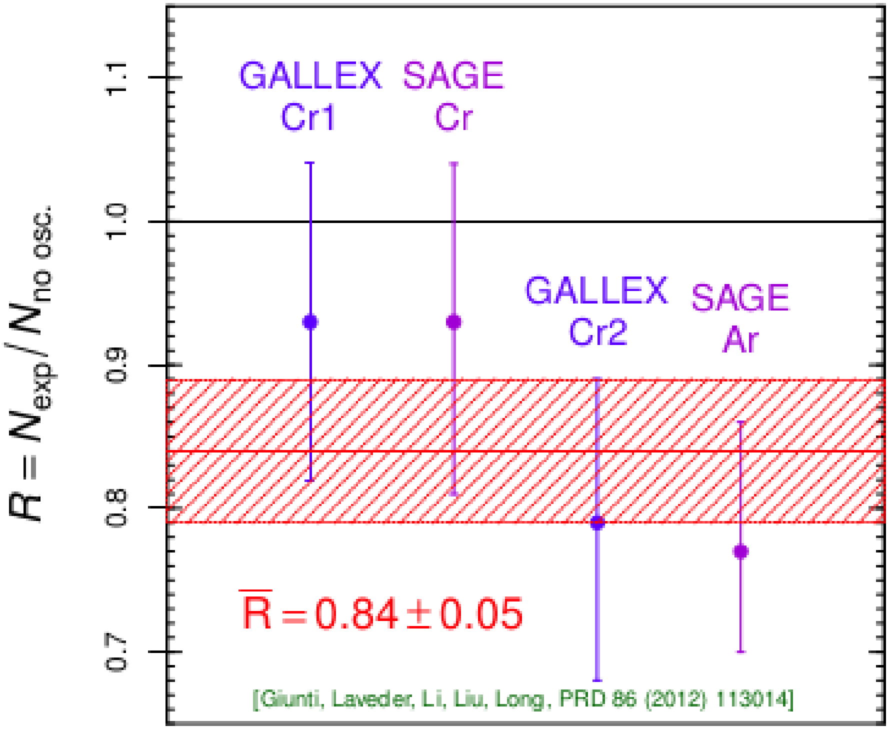
unknown $\bar{\nu}_e$ flux uncertainties: Daniel Dwyer talk

Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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



[Giunti, Laveder, Li, Liu, Long, PRD 86 (2012) 113014]

$\bar{\nu}_e \to \bar{\nu}_e$ $E \sim 0.7\,\text{MeV}$

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

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

Nominal $\approx 2.9\sigma$ anomaly

$\Delta m^2 \gtrsim 1\,\text{eV}^2$ $(\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807]

[Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344; MPLA 22 (2007) 2499; PRD 78 (2008) 073009; PRC 83 (2011) 065504]

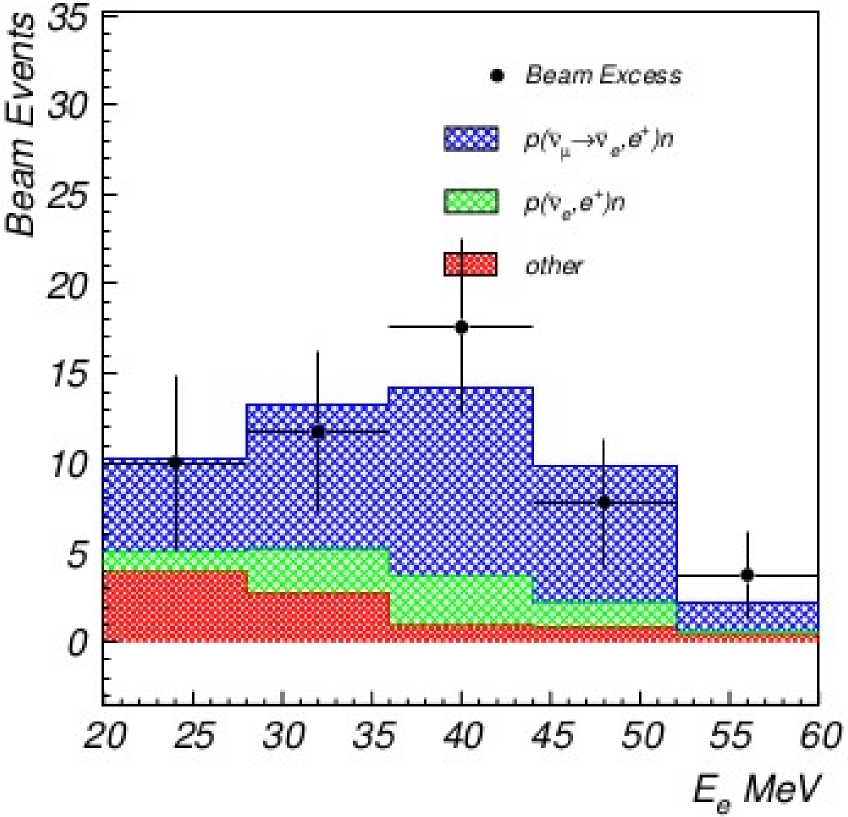
[Mention et al, PRD 83 (2011) 073006]

- ${}^{3}\text{He} + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + {}^{3}\text{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]
- $E_{\text{th}}(\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-) = 233.5 \pm 1.2\,\text{keV}$ [Frekers et al., PLB 722 (2013) 233]

LSND

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $L \simeq 30\,\mathrm{m}$ $20\,\mathrm{MeV} \leq E \leq 60\,\mathrm{MeV}$



- Well known source of $\bar{\nu}_\mu$:

$$\mu^+ \text{ at rest} \to e^+ + \nu_e + \bar{\nu}_\mu$$

- $\bar{\nu}_\mu \xrightarrow[L\simeq 30\text{ m}]{} \bar{\nu}_e$
- Well known detection process of $\bar{\nu}_e$:

$$\bar{\nu}_e + p \to n + e^+$$

- But signal not seen by KARMEN with same method at $L \simeq 18\,\mathrm{m}$

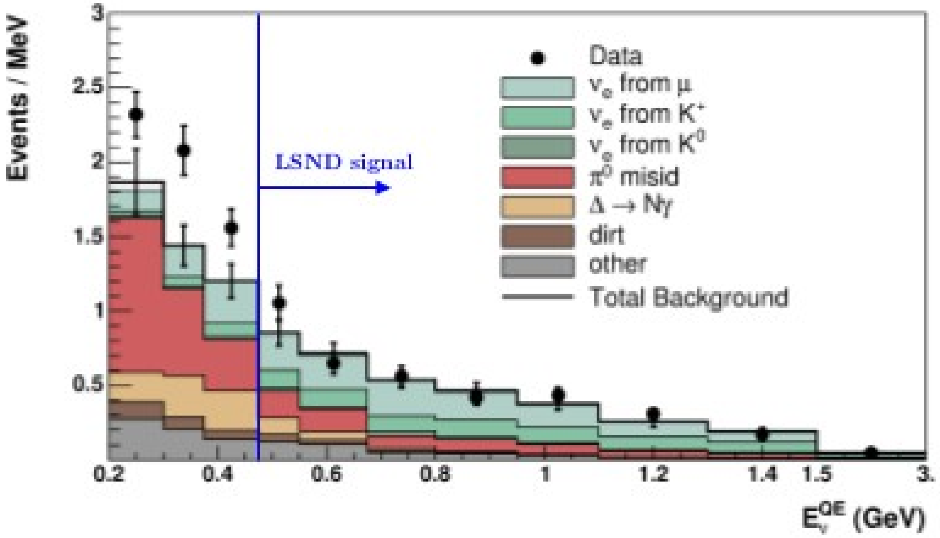
[PRD 65 (2002) 112001]

Nominal $\approx 3.8\sigma$ excess $\Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2$ $(\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

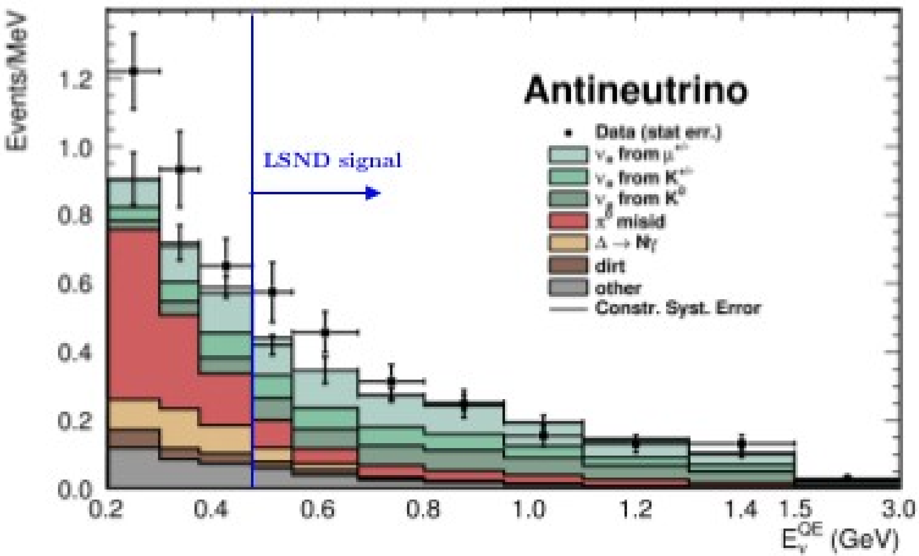
MiniBooNE

$L \simeq 541\,\mathrm{m}$ $\qquad$ $200\,\mathrm{MeV} \leq E \lesssim 3\,\mathrm{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802]

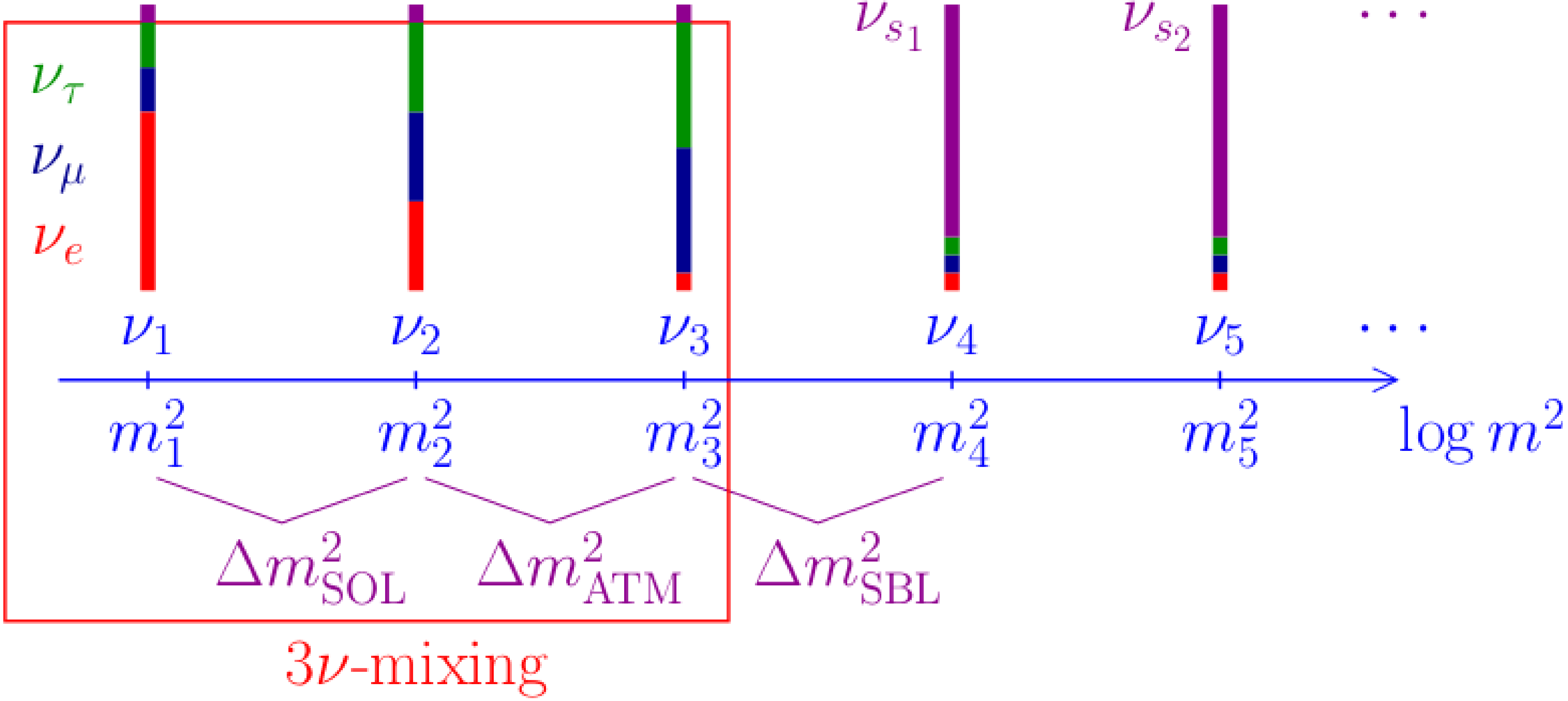


$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\mathrm{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Terminology:	a eV-scale sterile neutrino
means:	a eV-scale massive neutrino which is mainly sterile

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

Perturbation of 3ν Mixing: $|U_{e4}|^2 \ll 1\,,\ |U_{\mu 4}|^2 \ll 1\,,\ |U_{\tau 4}|^2 \ll 1\,,\ |U_{s4}|^2 \simeq 1$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases
- But CP violation is not observable in current SBL experiments!
- May be observable in future high-precision solar exp. sensitive to Δm^2_{21} [Long, Li, Giunti, PRD 87, 113004 (2013) 113004] and accelerator exp. sensitive to Δm^2_{31} [de Gouvea, Kelly, Kobach, arXiv:1412.1479]

3+1: Appearance vs Disappearance

- Amplitude of ν_e disappearance:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- Amplitude of ν_μ disappearance:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) \simeq 4|U_{\mu 4}|^2$$

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

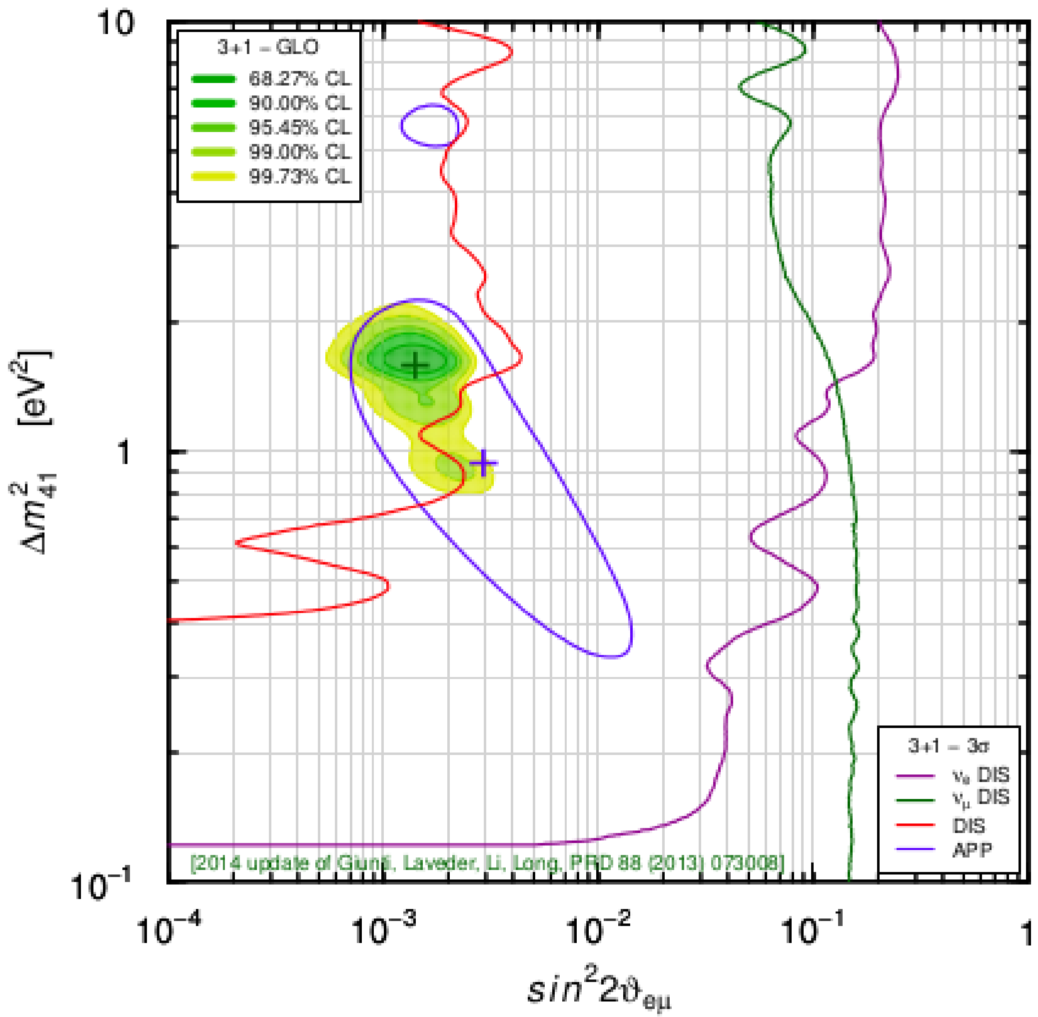
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

- Upper bounds on ν_e and ν_μ disappearance ⇒ strong limit on $\nu_\mu \to \nu_e$

[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

- Similar constraint in 3+2, 3+3, . . . , 3+N_s !

Pragmatic 3+1 Fit



[2014 update of Giunti, Laveder, Li, Long, PRD 88 (2013) 073008]

MiniBooNE $E > 475\,\text{MeV}$

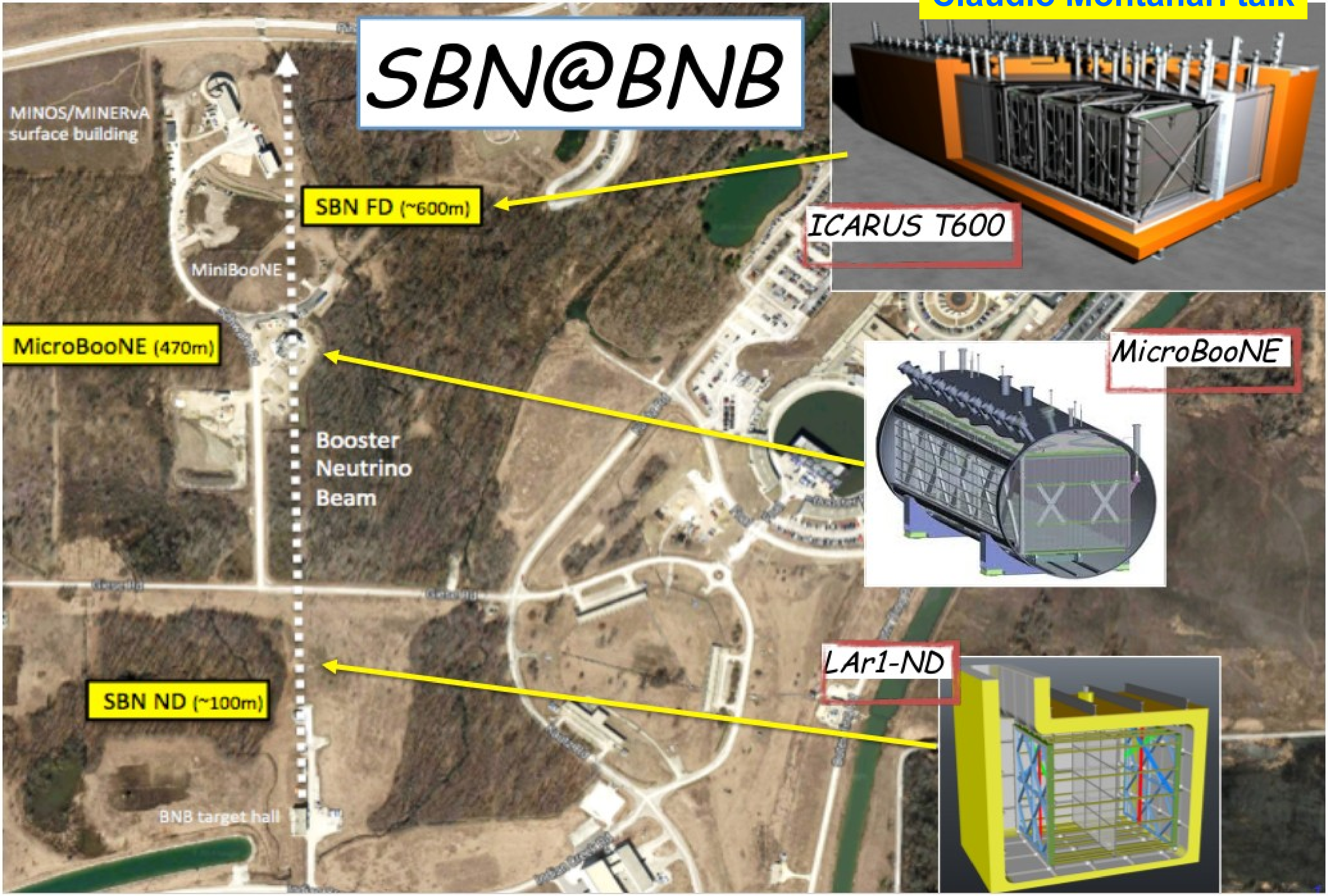
GoF = 26%   PGoF = 7%

- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA ($\cancel{\nu_s}$), ICARUS ($\cancel{\nu_s}$), KARMEN ($\cancel{\nu_s}$), NOMAD ($\cancel{\nu_s}$), BNL-E776 ($\cancel{\nu_s}$)
- DIS ν_e & $\bar{\nu}_e$: Reactors (ν_s), Gallium (ν_s), ν_eC ($\cancel{\nu_s}$), Solar ($\cancel{\nu_s}$)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW ($\cancel{\nu_s}$), MINOS ($\cancel{\nu_s}$), Atmospheric ($\cancel{\nu_s}$), MiniBooNE/SciBooNE ($\cancel{\nu_s}$)

No Osc. nominally disfavored
at $\approx 6.3\sigma$
$\Delta\chi^2/\text{NDF} = 47.7/3$

Claudio Montanari talk

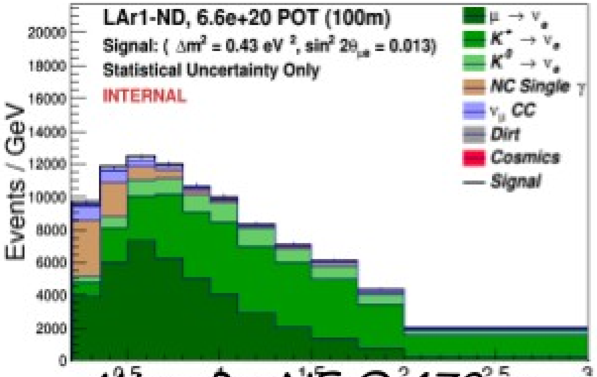
SBN@BNB



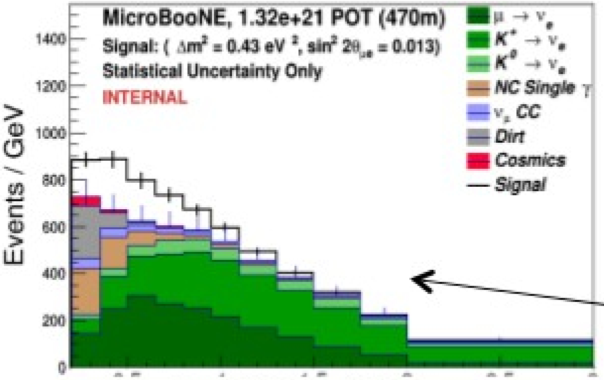
$\nu_\mu \rightarrow \nu_e$ appearance sensitivity

- Expected exposure sensitivity of $\nu\mu$ -> νe oscillations for 3 years - 6.6 10^{20} pot BNB positive focusing (6 years for MicroBooNE).

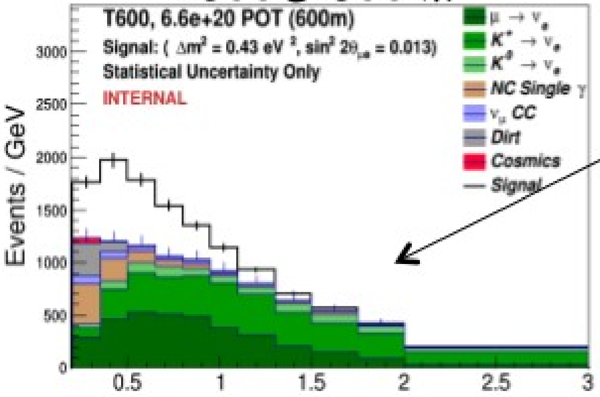
LAr1ND @ 100 m



MicroBooNE @ 470 m



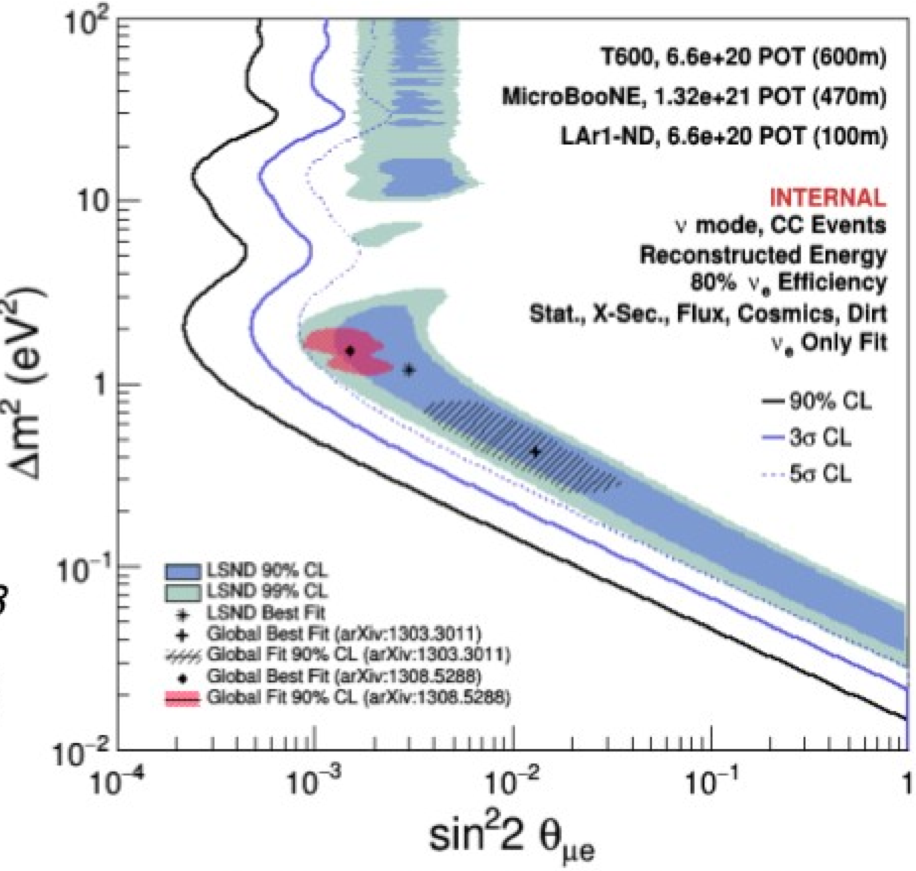
T600@ 600 m



Example for

($\sin^2(2\theta)=0.013$

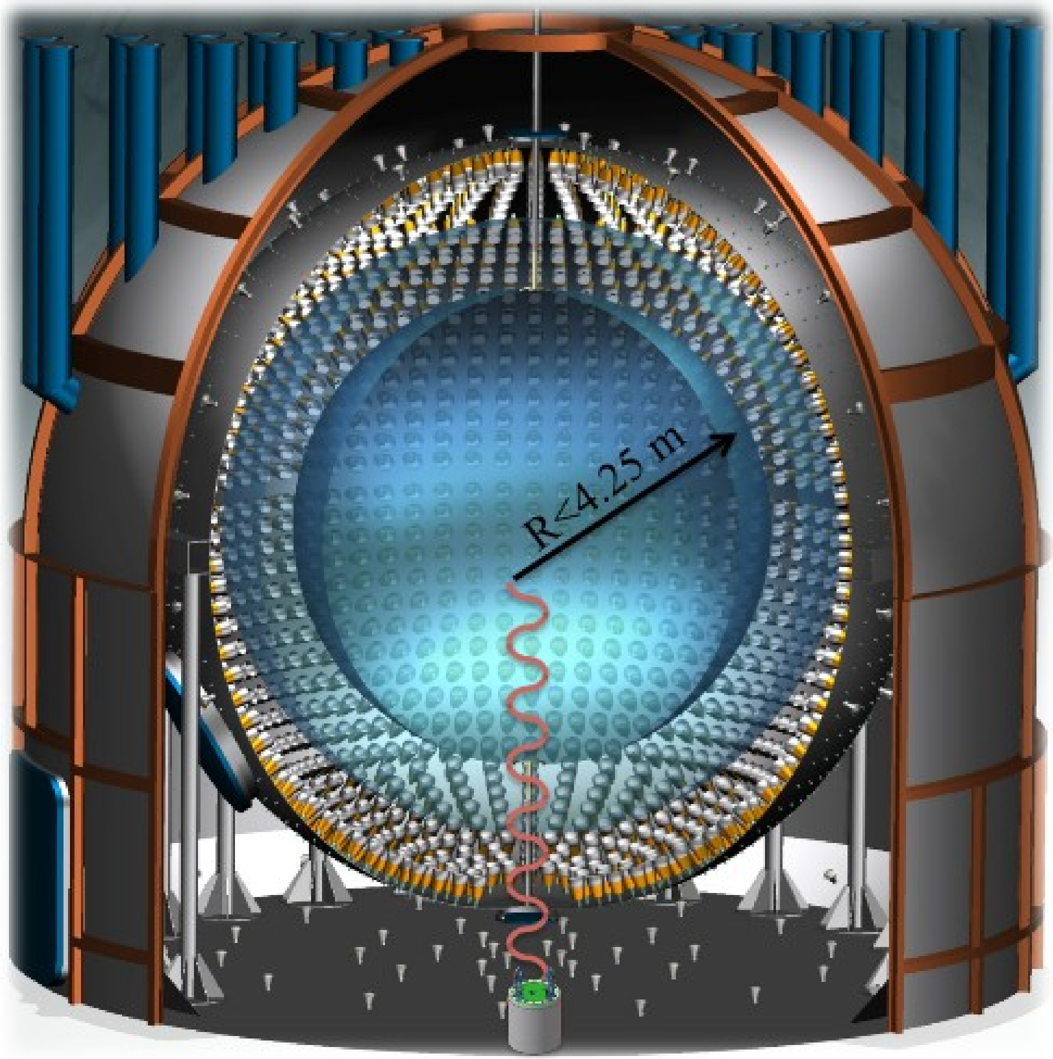
$\Delta m^2=0.43\ eV^2$)



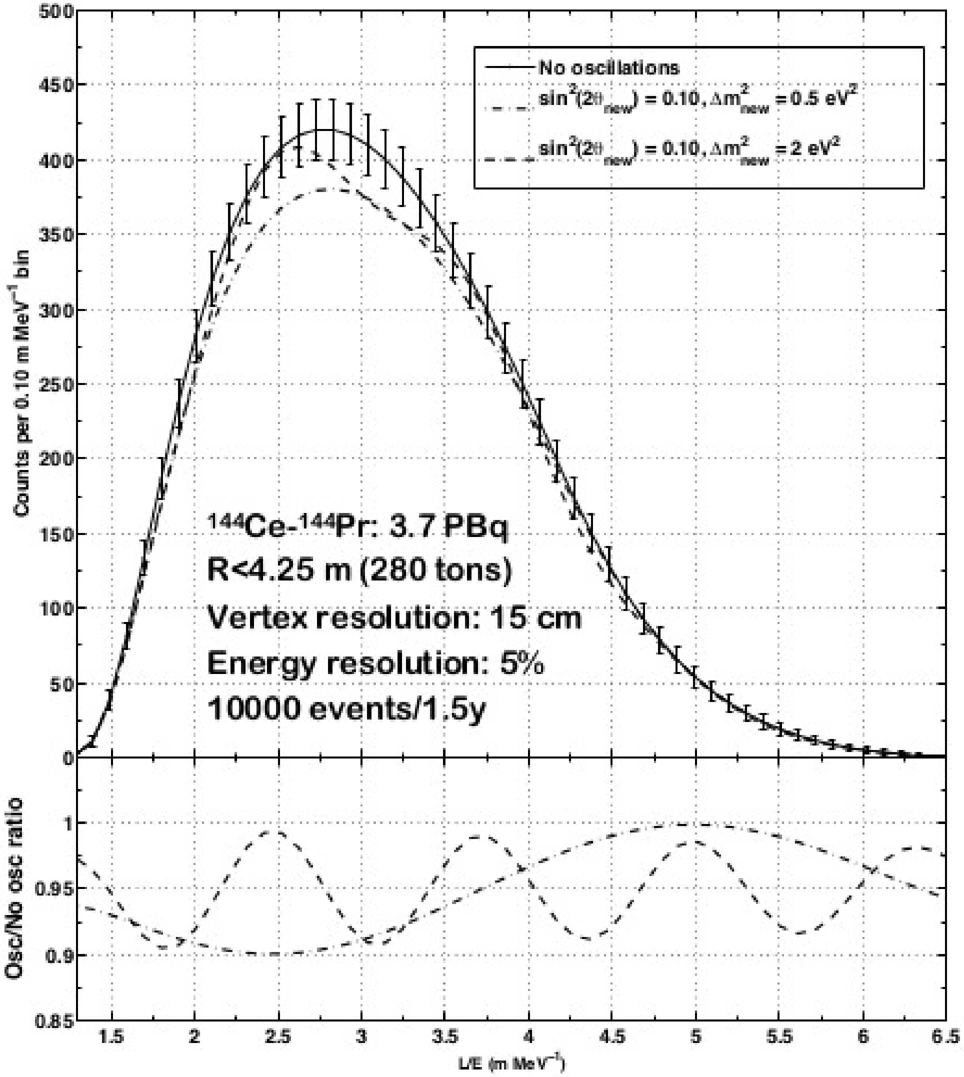
The LSND 99%CL region is covered at the ~5σ level

Oscillometry in BOREXINO

Search for an L/E oscillation pattern inside LS target
Compare observed to expected ν rate (no oscillation)



8.3 m from Bx Center



^{144}Ce-^{144}Pr: 3.7 PBq
R<4.25 m (280 tons)
Vertex resolution: 15 cm
Energy resolution: 5%
10000 events/1.5y

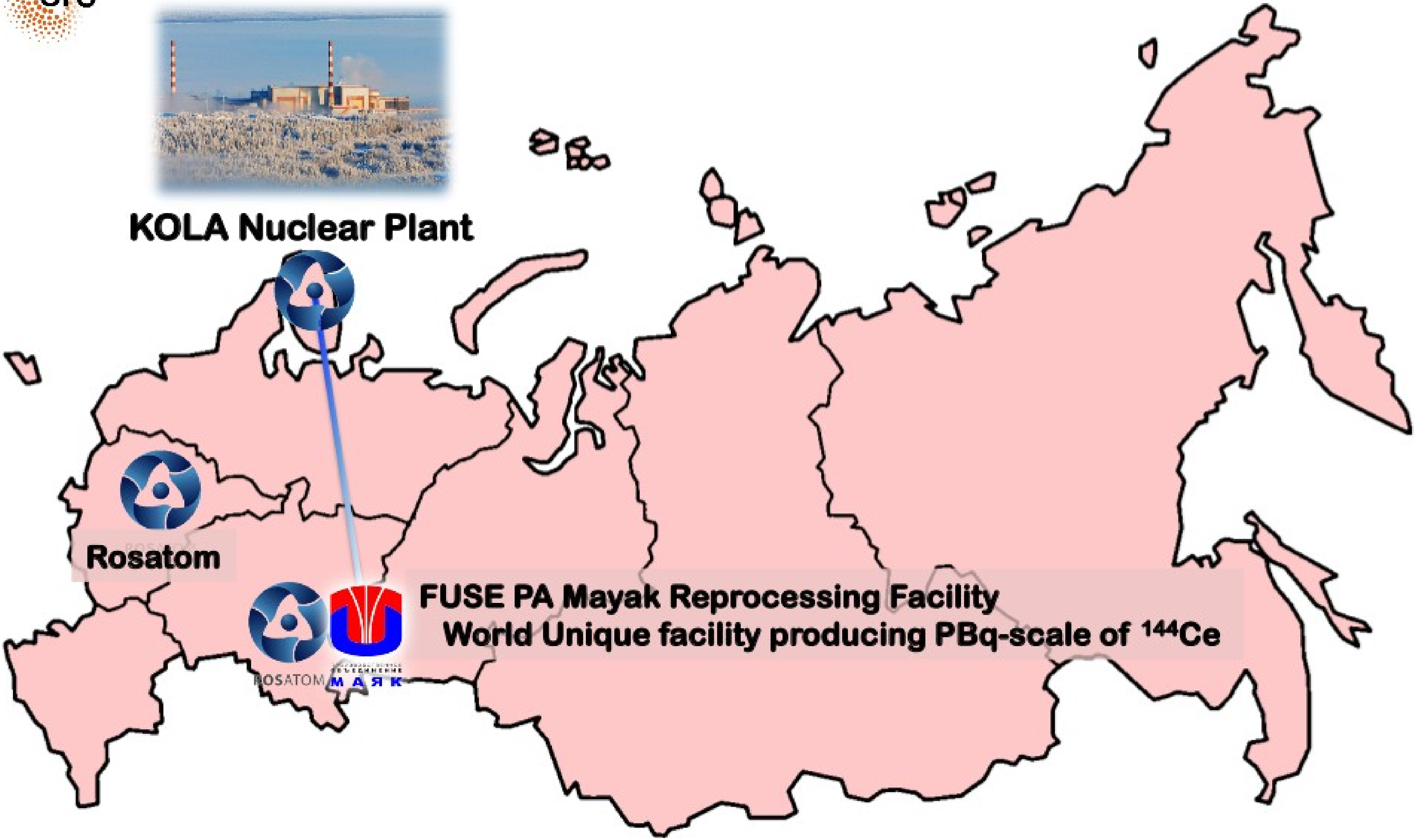
Thierry Lasserre talk

CeANG: Specifications

- ß activity (in ^{144}Ce)
  - 3.7 PBq
- Extracted from fresh spent nuclear fuel (<2 years cooling)
- Chemical form : CeO_2
- Density : between 4 and 6 g/cm^3

- Fitting inside a D:H=15:15 cm double capsule of Special Form of Radioactive Material (ISO 9978 - IAEA regulation)
- Purity requirements
  - Content of any others REE (*γ-emitters*) $\leq 10^{-3}$ Bq / Bq of ^{144}Ce
  - Content of Pu and TPE (*actinides*) $\leq 10^{-5}$ Bq / Bq of ^{144}Ce

CeANG production in Russia



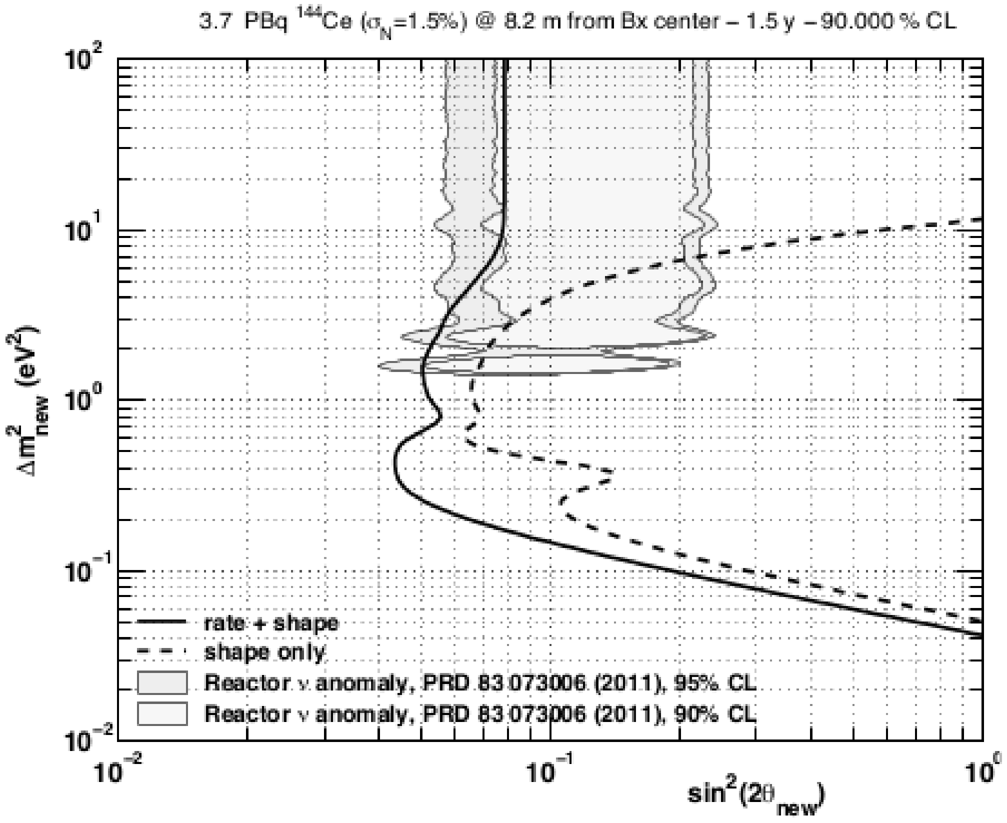
KOLA Nuclear Plant

Rosatom

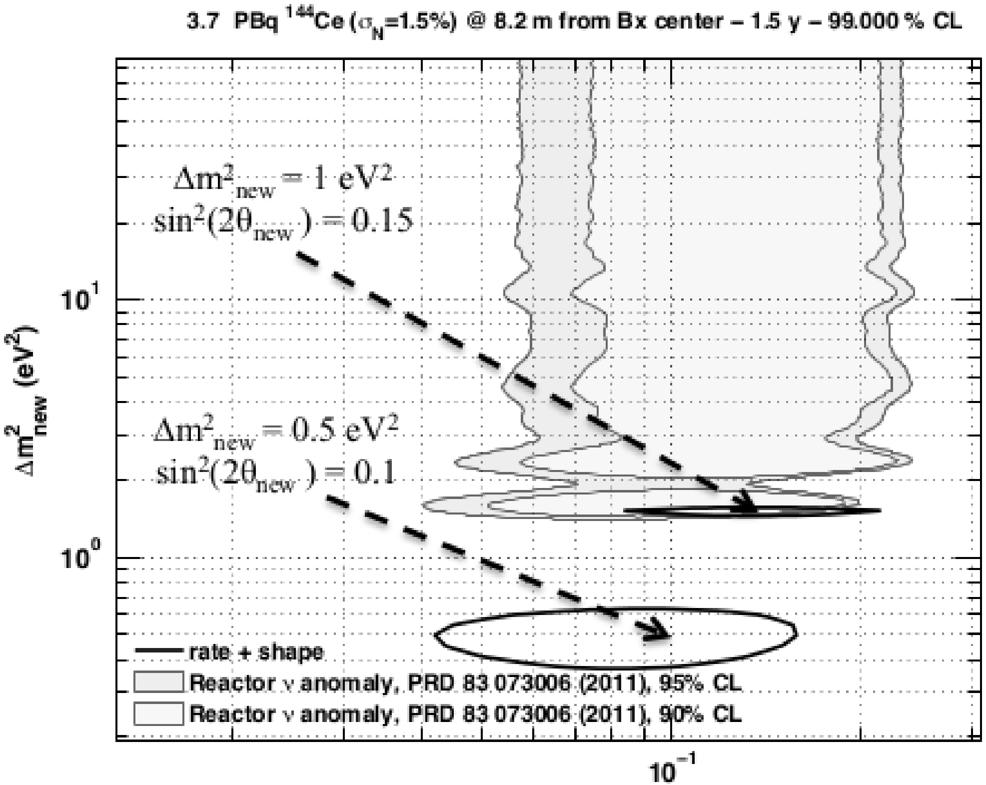
FUSE PA Mayak Reprocessing Facility
World Unique facility producing PBq-scale of ^{144}Ce

Sensitivity Studies

3.7 PBq (100 kCi) - 1.5 year of data taking
Activity measurement uncertainty: 1.5%
Shape only analysis (- - -) & Rate + Shape analysis (---)



Exclusion contour (90% CL)



Discovery potential (99% CL)

Here Be Dragons…

$\overline{\nu}_e$ fluxes from reactors

Dan Dwyer talk

Significant uncertainty when directly calculating energy spectrum.

Missing Details:

Are tabulated fission and decay data comprehensive?

- Fission: What about possible very short-lived unstable daughters?
- Decay: 6% of yield has no corresponding ENDF decay information

eg. Phys. Rev. C24, 1543 (1981)

Biased Data:

Are there systematic biases in the yield or beta decay data?

- Uncertainty from assumption of reactor equilibrium, parent fission rates.
- Pandemonium Effect: Tabulated branches biased toward high-endpoints.

eg. Phys. Rev. Lett. 109, 202504 (2012)

Beta Decay Shape Corrections:

How do forbidden decay corrections impact spectrum?

- Mismatch of decay initial-final spin and parity can distort spectrum

eg. Phys. Rev. Lett. 112, 202501 (2014)

Approach: Choose simplest assumption at each step (all allowed shapes, etc.)

β^- Conversion

Alternative: Use cumulative β^- spectrum to predict $\overline{\nu}_e$ spectrum

Method:

Expose fission parents to thermal neutrons

Measure total outgoing β- energy spectra

Predict corresponding $\overline{\nu}_e$ spectra

Phys. Lett. B160, 325 (1985), Phys. Lett. B118, 162 (1982)
Phys. Lett. B218, 365 (1989), Phys. Rev. Lett. 112, 122501 (2014)
Phys. Rev. C83, 054615 (2011)
Phys. Rev. C84, 024617 (2011)

Results:

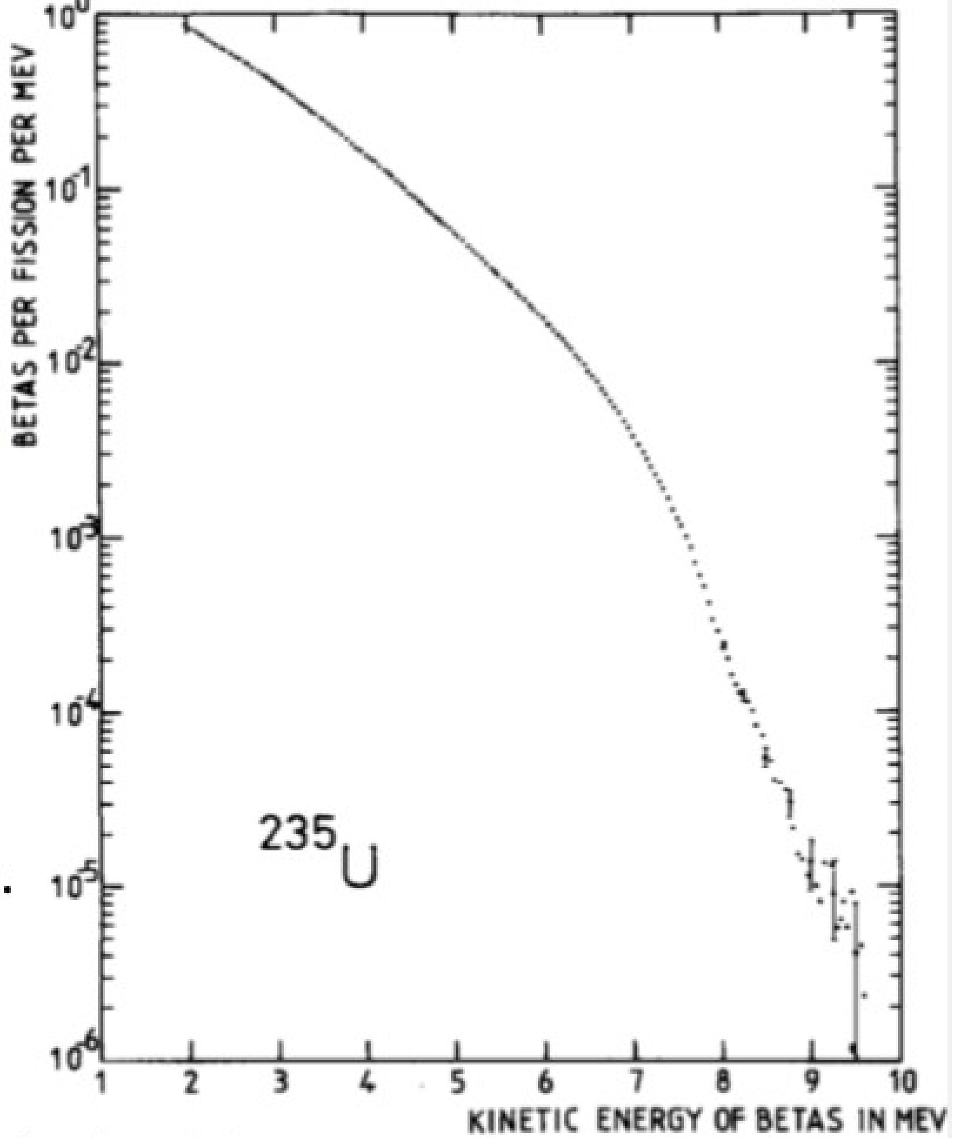
More precise than *ab initio* predictions

Standard approach for ~30 years

Predicts 6% higher flux than reactor msmts.

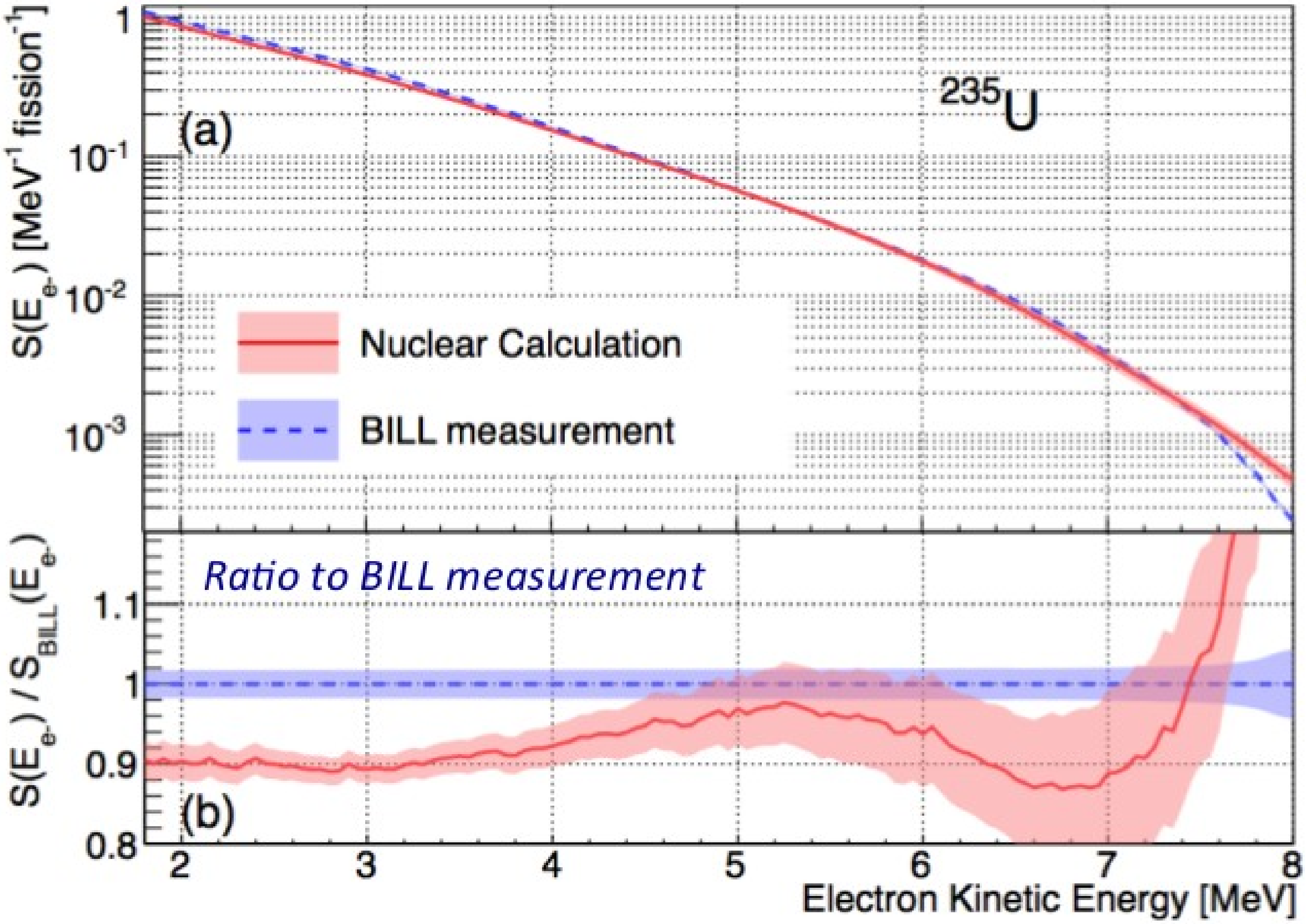
Reactor Anomaly, Sterile Neutrinos?

Phys. Rev. D83, 073006 (2011)



β- Spectrum Disagreement

Direct calculation of ^{235}U β- spectrum disagrees with BILL msmt.



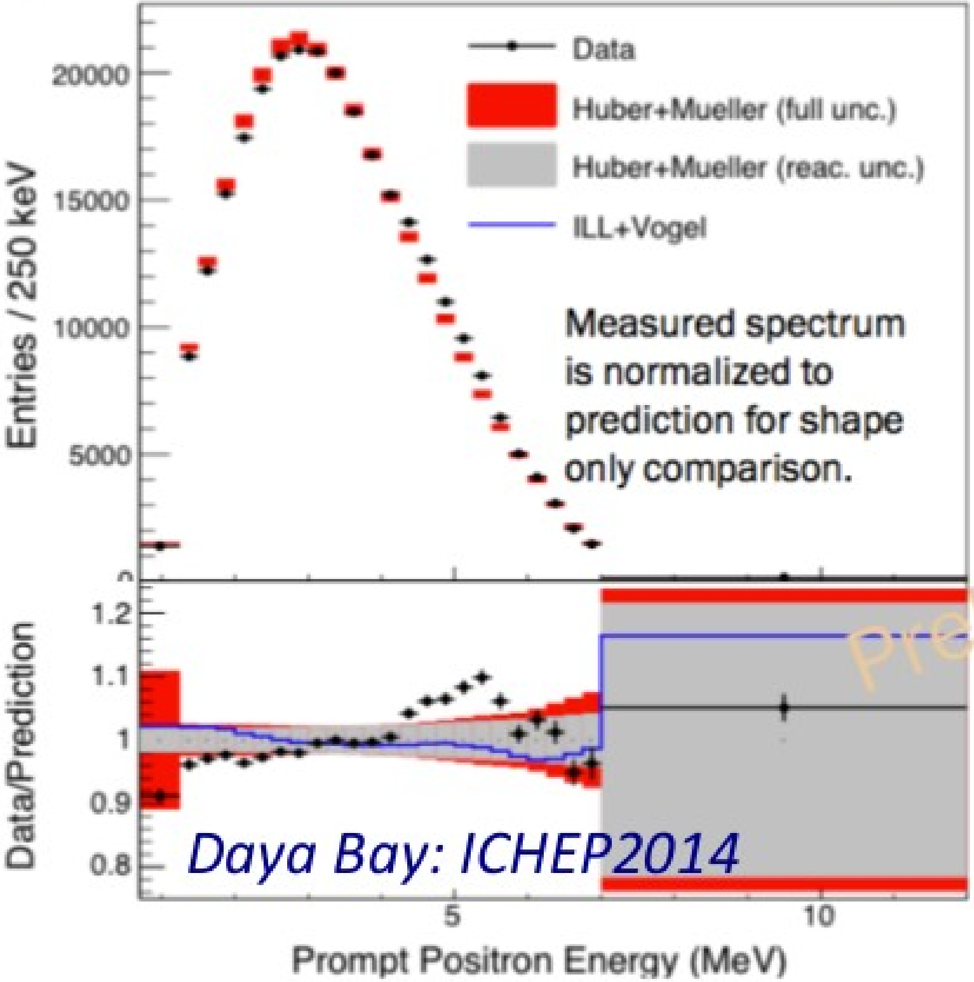
Note:
Uncertainty band for calc. is a lower bound.

Only includes tabulated yield+branch uncertainties.

Occam's razor:
Something wrong with calculation?

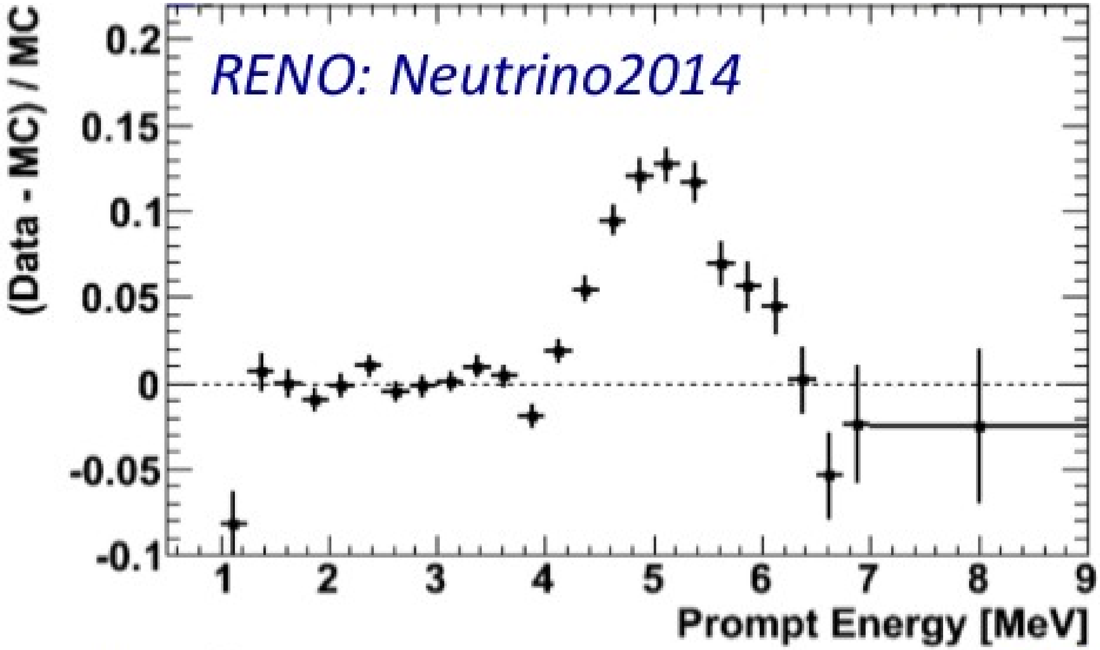
$\overline{\nu}_e$ Spectrum Disagreement

Recent $\overline{\nu}_e$ measurements also disagree with BILL-derived spectra.

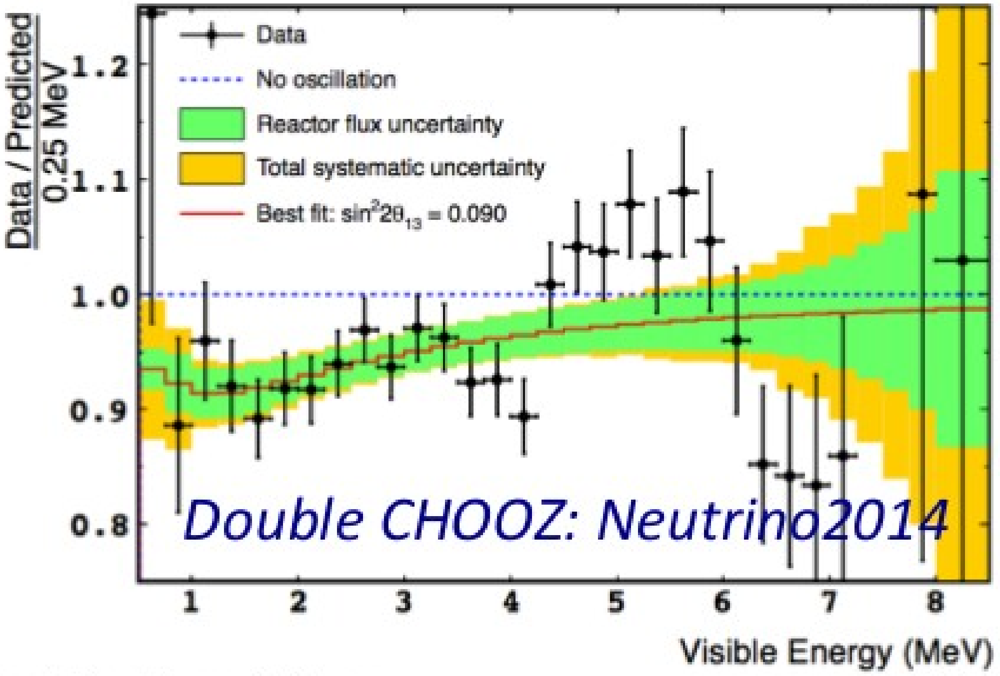


Measured spectrum is normalized to prediction for shape only comparison.

Daya Bay: ICHEP2014



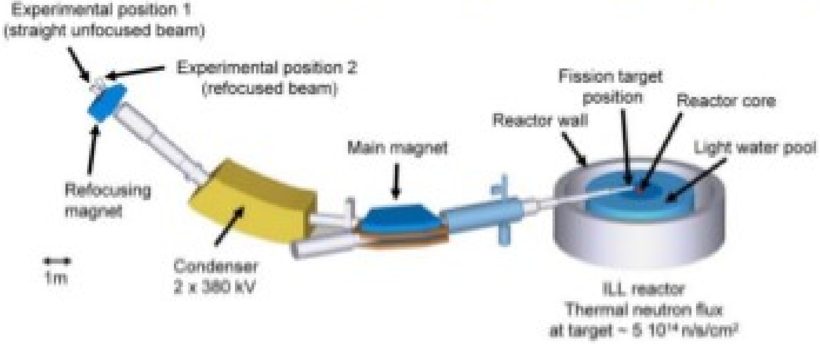
RENO: Neutrino2014



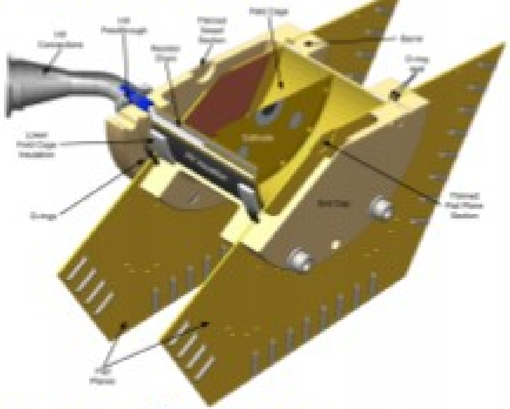
Double CHOOZ: Neutrino2014

Upcoming Measurements

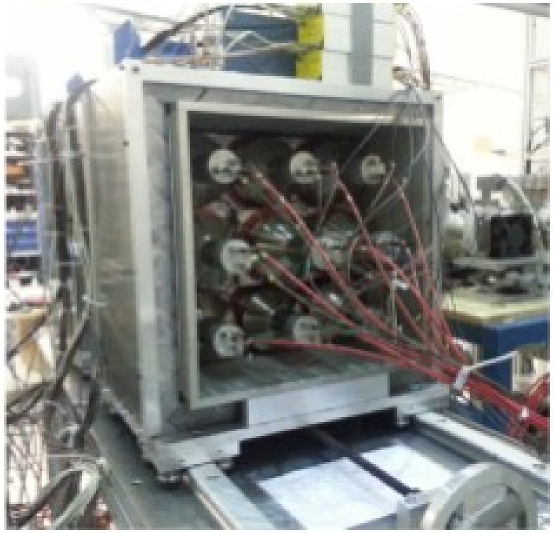
Fission Yields @ ILL (Lohengrin)



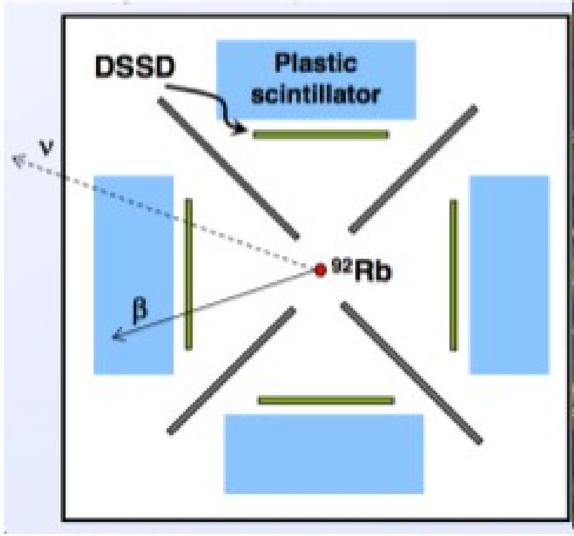
Fission Yields
@ LANSCE (NIFFTE)

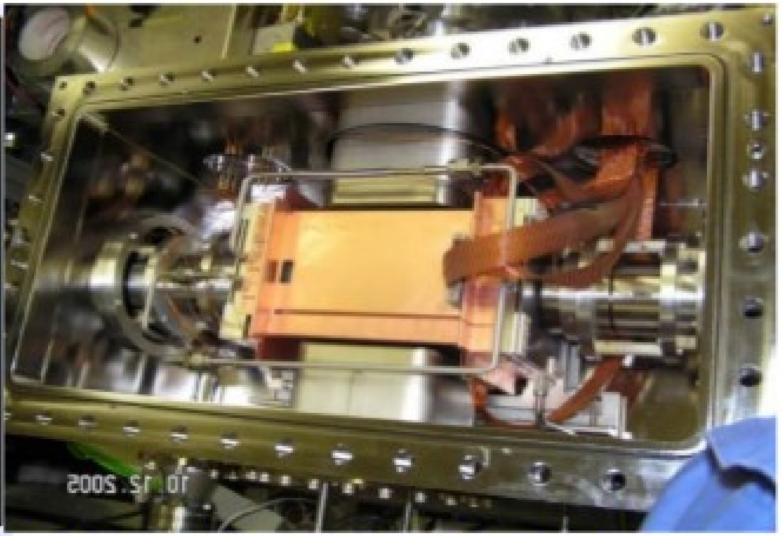


Total Absorp. Spec.
@ IGISOL (DTAS)



Precision β⁻ Spec. with Trapped Ions @ ANL/CARIBU





Total Absorp. Spec.
@ ORNL (MTAS)

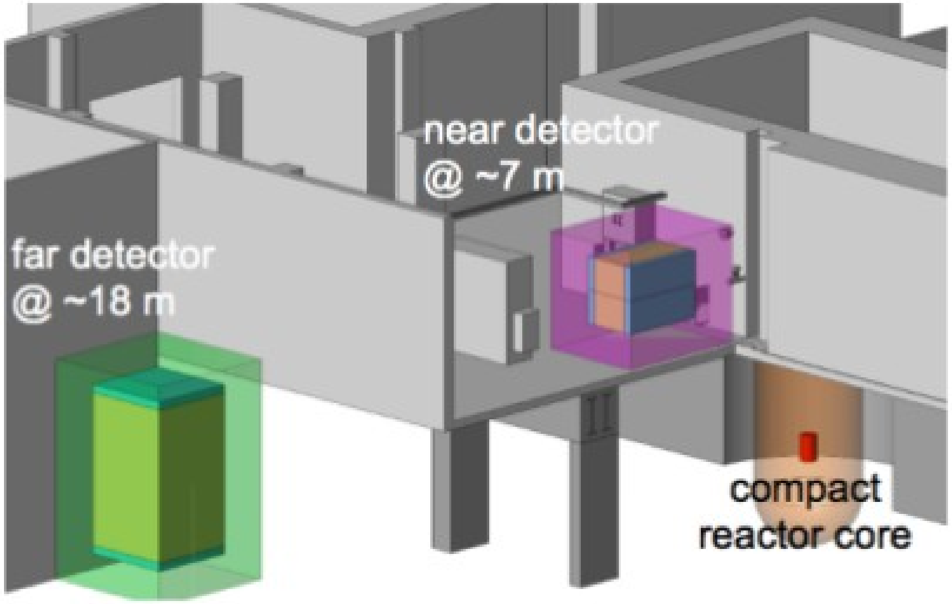
Some examples of planned measurements of these decays:

N.D. Scielzo, private comm. [G.Li et al., PRL 110, 092502 (2013)]
A.-A. Zakari-Issoufou et al., EPJ Web of Conferences 66, 10019 (2014)
M. Heffner et al. (NIFFTE Collaboration), arXiv:1403.6771

Precision $\overline{\nu}_e$ Spectra?

Precision reactor $\overline{\nu}_e$ measurements as accurate benchmarks

Short-baseline reactor experiments

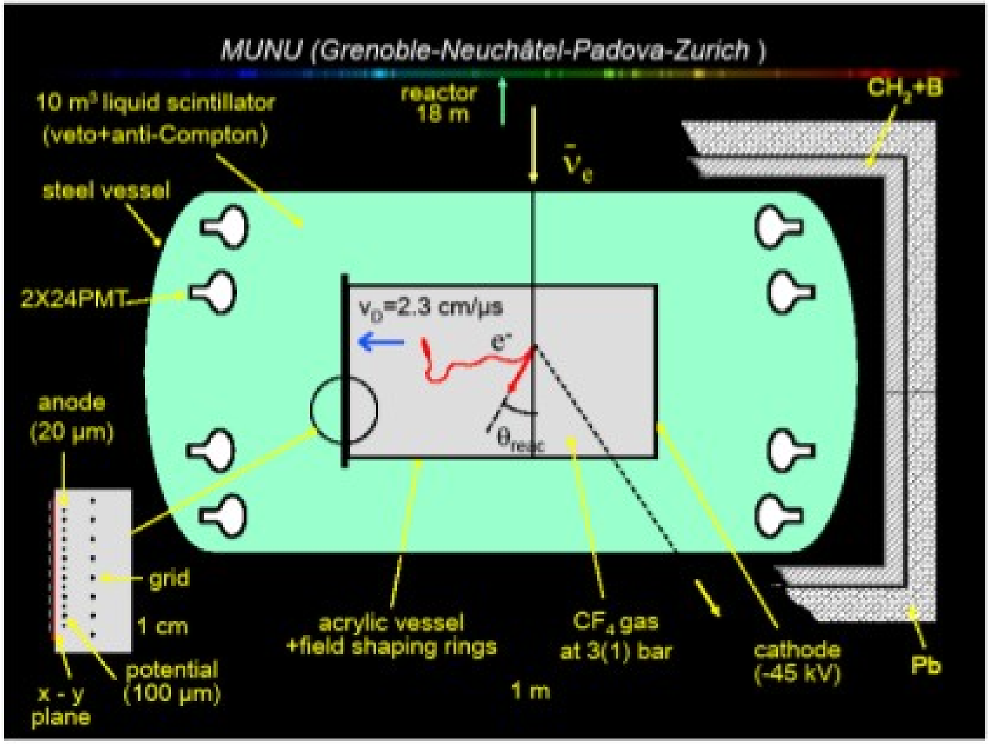


Example: PROSPECT @ ORNL, $\sigma_E \approx 4.5\%$

Precision measurement of ^{235}U $\overline{\nu}_e$
 - Strong constraint of models

Challenges: controlling backgrounds.

High-pressure gas TPC (IHEP-Beijing)



Similar to MUNU Gas TPC design

Potent for higher energy resolution

Sterile Neutrino Oscillations in Atmospheric Neutrinos

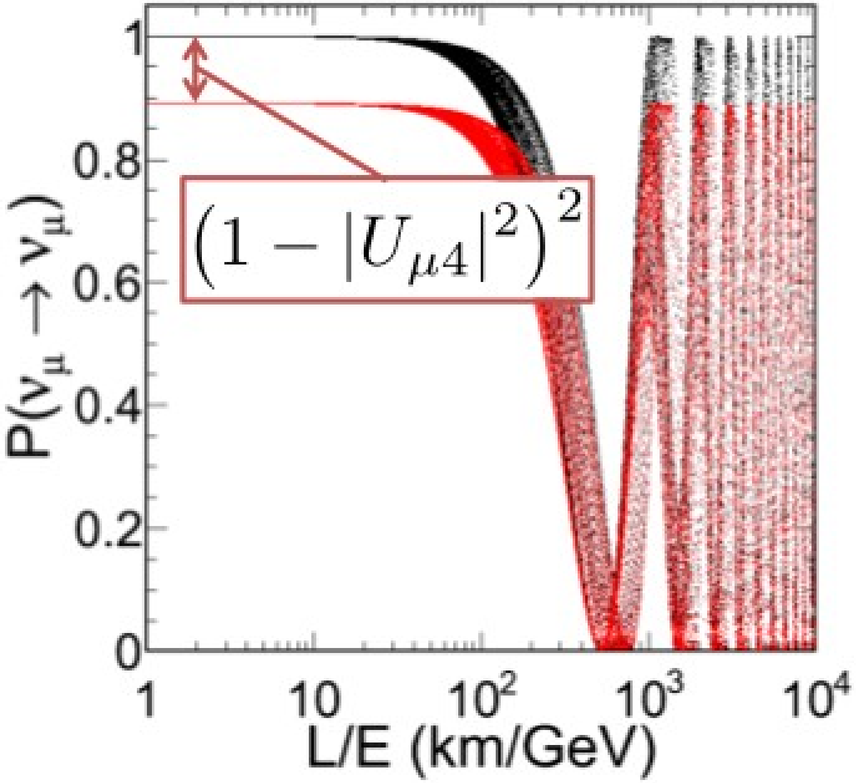
$$U = \begin{array}{c} \begin{array}{ccccc} \multicolumn{3}{c}{\text{PMNS}} & \text{Sterile} & \end{array} \\ \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \cdots \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \end{array}$$

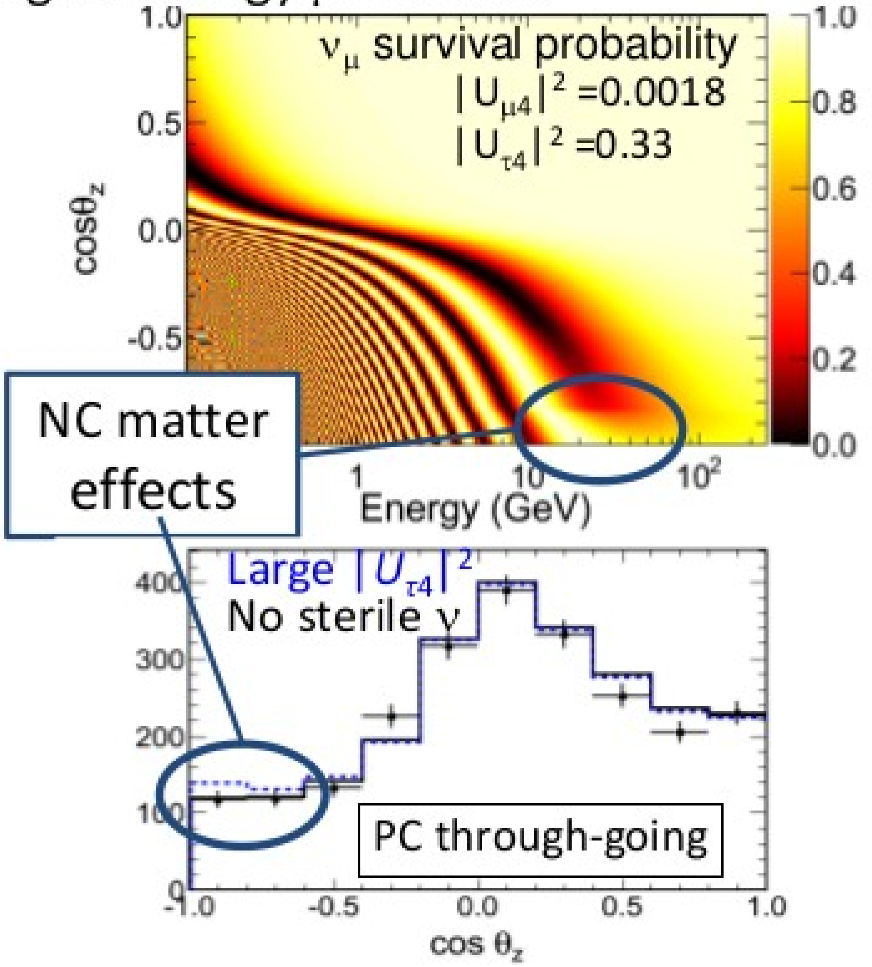
- **$|U_{\mu4}|^2$**

  Induces a decrease in event rate of μ-like data of all energies and zenith angles

- **$|U_{\tau4}|^2$**

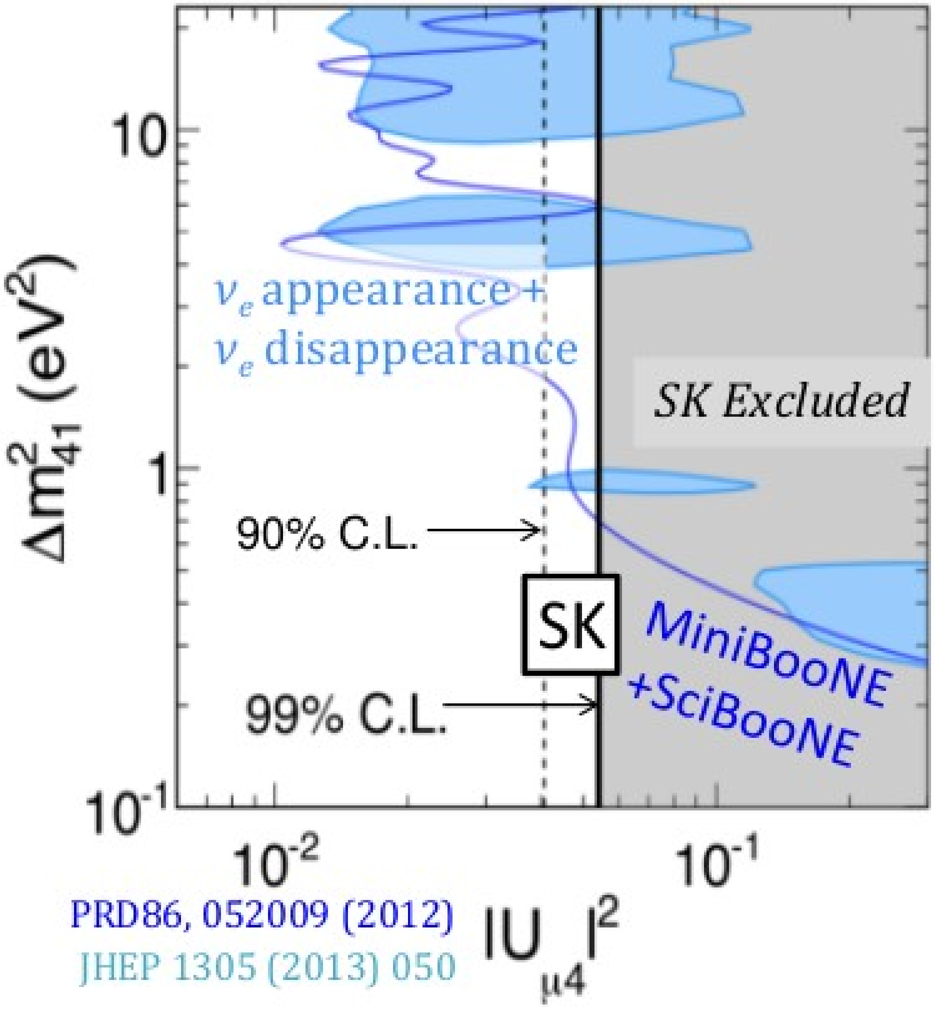
  Shape distortion of angular distribution of higher energy μ-like data



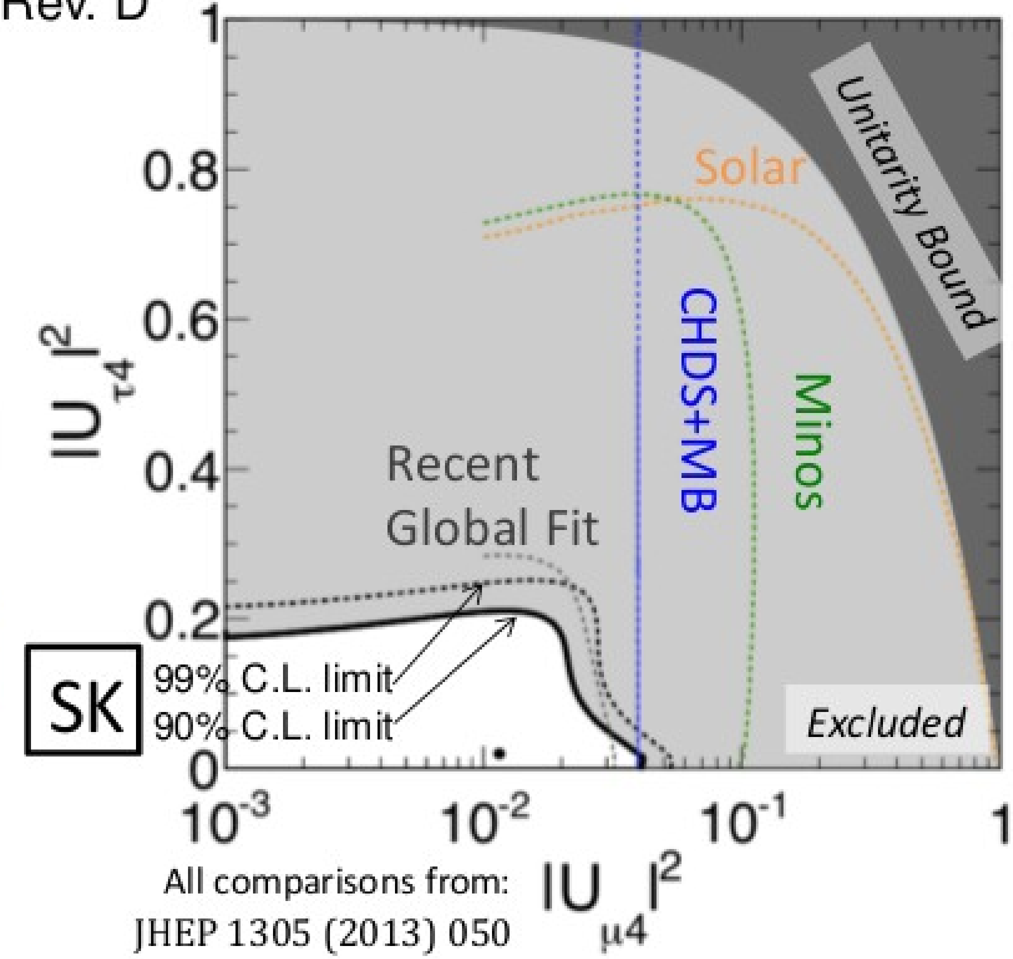


Limits on Sterile Neutrino Oscillations

arXiv:1410.2008, accepted by Phys. Rev. D



PRD86, 052009 (2012)
JHEP 1305 (2013) 050



All comparisons from:
JHEP 1305 (2013) 050

$|U_{\mu4}|^2 < 0.041$ at 90% C.L.

$|U_{\mu4}|^2 < 0.054$ at 99% C.L.

$|U_{\tau4}|^2 < 0.23$ at 99% C.L.

Lack of sterile matter effects places a strong constraint.

$(\nu_\mu \rightarrow \nu_\tau)+(\nu_\mu \rightarrow \nu_s)$ oscillation is not favored.

$\nu_\mu \to \nu_\tau$: Preliminary results on sterile ν

standard

$$P(\nu_\mu \to \nu_\tau) = 4|U_{\mu 3}^{2}||U_{\tau 3}^{2}|\sin^2\frac{\Delta_{31}}{2}$$

(normal hierarchy)

exotic

$$+4|U_{\mu 4}^{2}||U_{\tau 4}^{2}|\sin^2\frac{\Delta_{41}}{2}$$

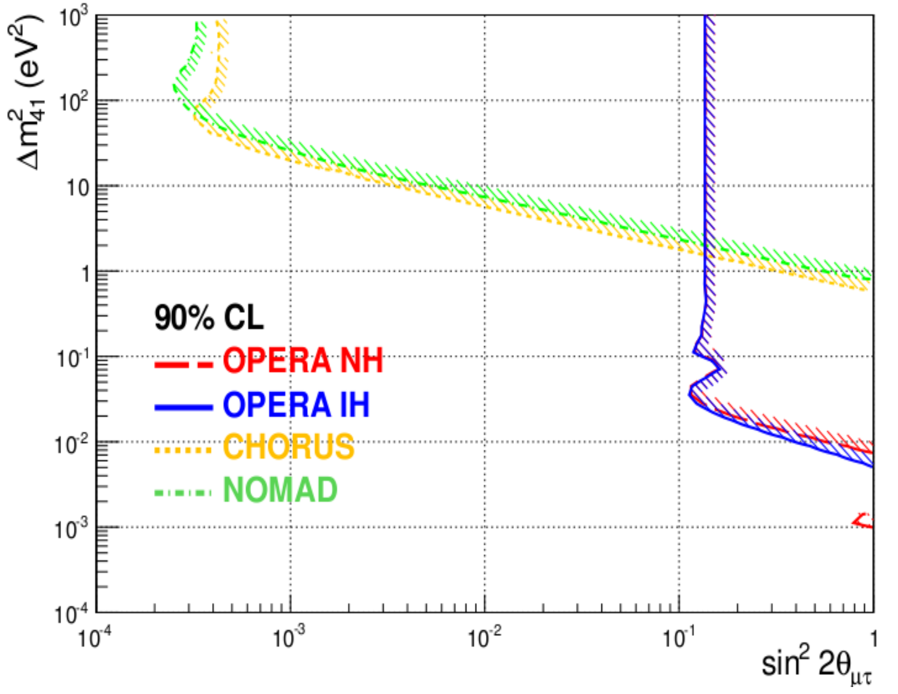
$$+2\Re[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}]\sin\Delta_{31}\sin\Delta_{41}$$
$$-4\Im[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}]\sin^2\frac{\Delta_{31}}{2}\sin\Delta_{41}$$
$$+8\Re[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}]\sin^2\frac{\Delta_{31}}{2}\sin\frac{\Delta_{41}}{2}$$
$$+4\Im[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}]\sin\Delta_{31}\sin\frac{\Delta_{41}}{2}$$

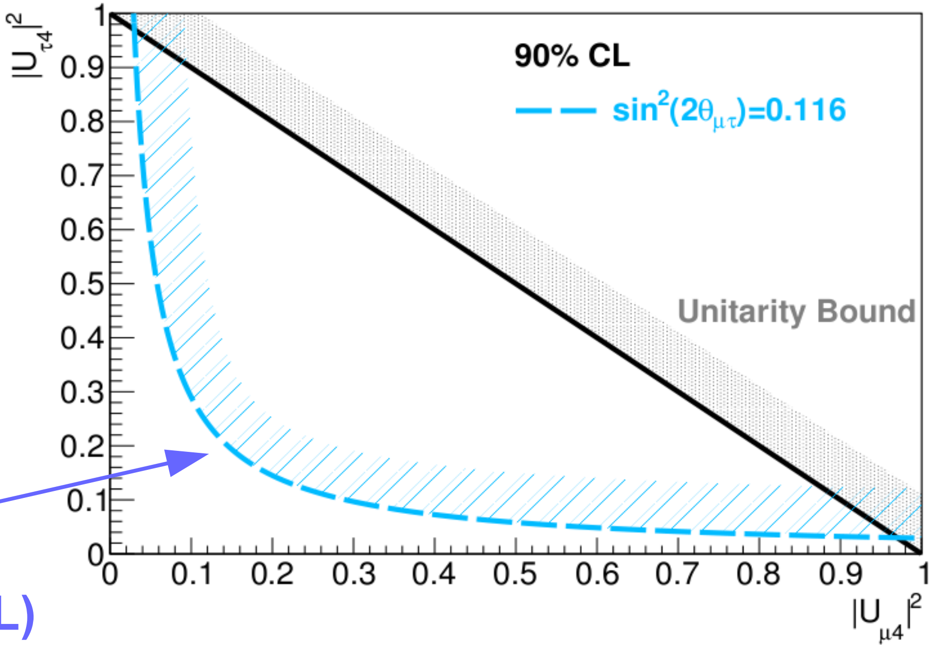
$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{2E}$$

Interference term

OPERA

Profile likelihood on τ number





@ Δm^2_{41} > 1 eV^2 (3+1 model)

$4\,|U_{\mu 4}|^2\,|U_{\tau 4}|^2 = \sin^2(2\theta_{\mu\tau}) < 0.116$ (90% CL)

Neutrino Cross Sections

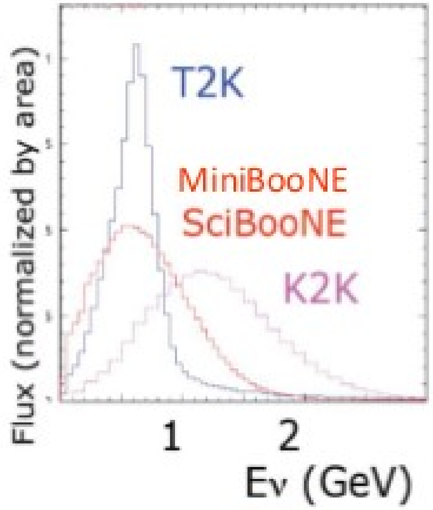
Marco Martini talk

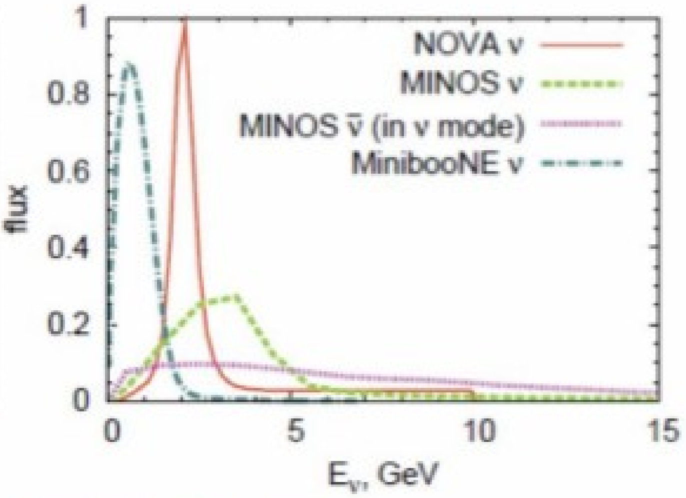
Some crucial points

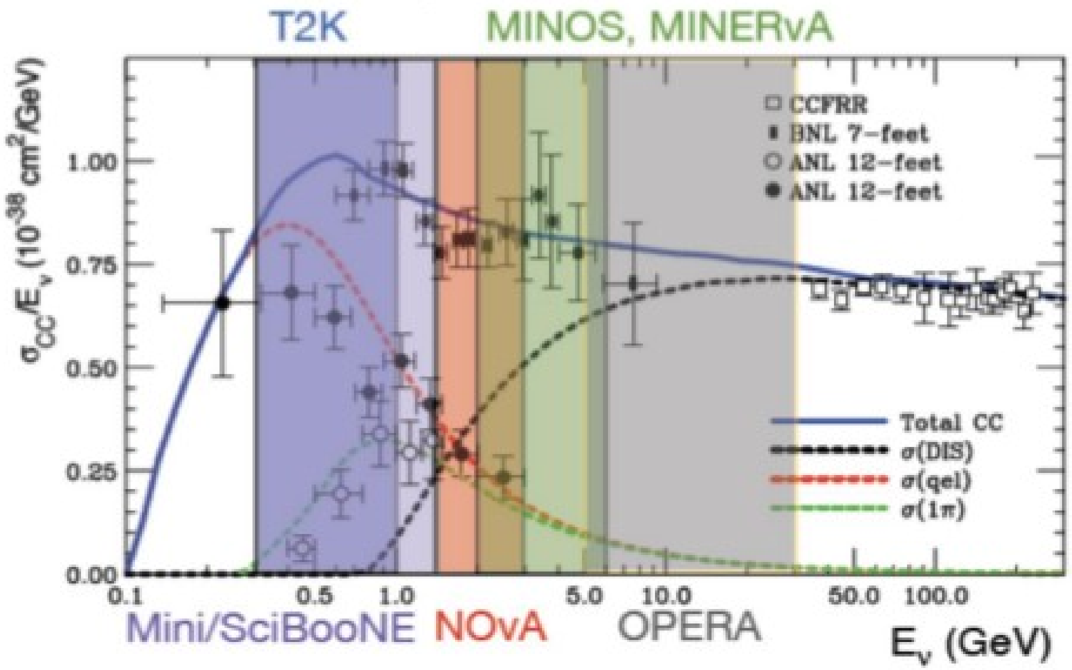
- Neutrino beams are not monochromatic
  (at difference with respect to electron beams).
  They span a wide range of energies

- The neutrino energy is reconstructed
  from the final states of the reaction
  (typically from CC Quasielastic events)

- Different reaction mechanisms
  contribute to the cross section
  in the modern experiments



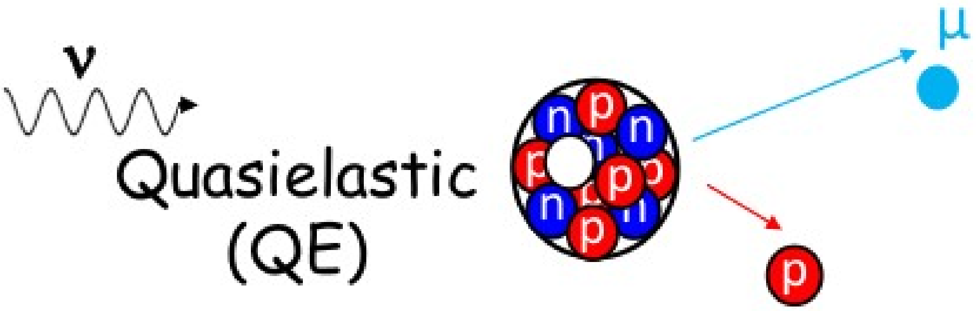




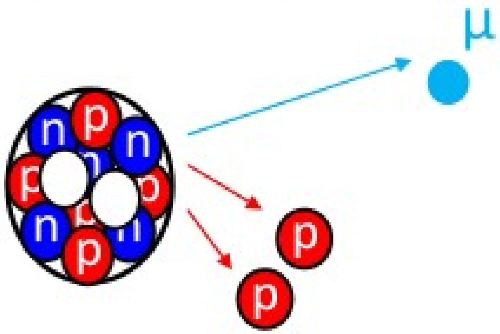
Neutrino - nucleus interaction @ $E_\nu \sim O$ (1 GeV)

[MiniBooNE, T2K energies]

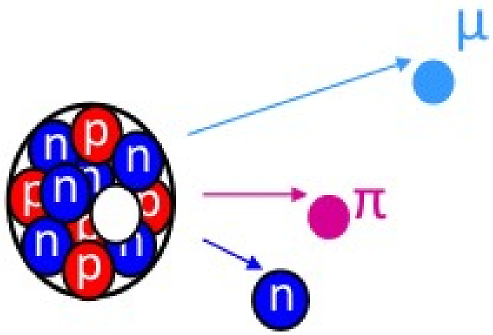
Quasielastic (QE)



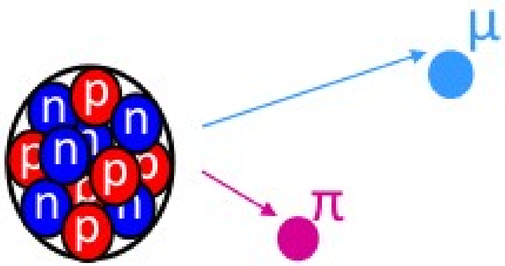
Two Nucleons knock-out (2p-2h)



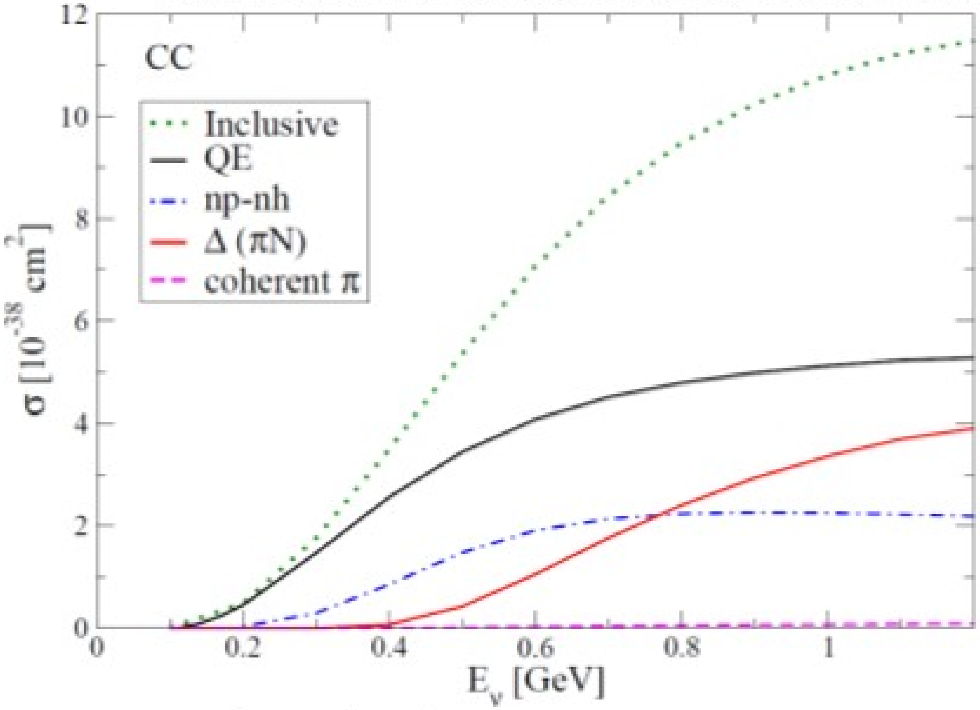
Incoherent π production



Coherent π production



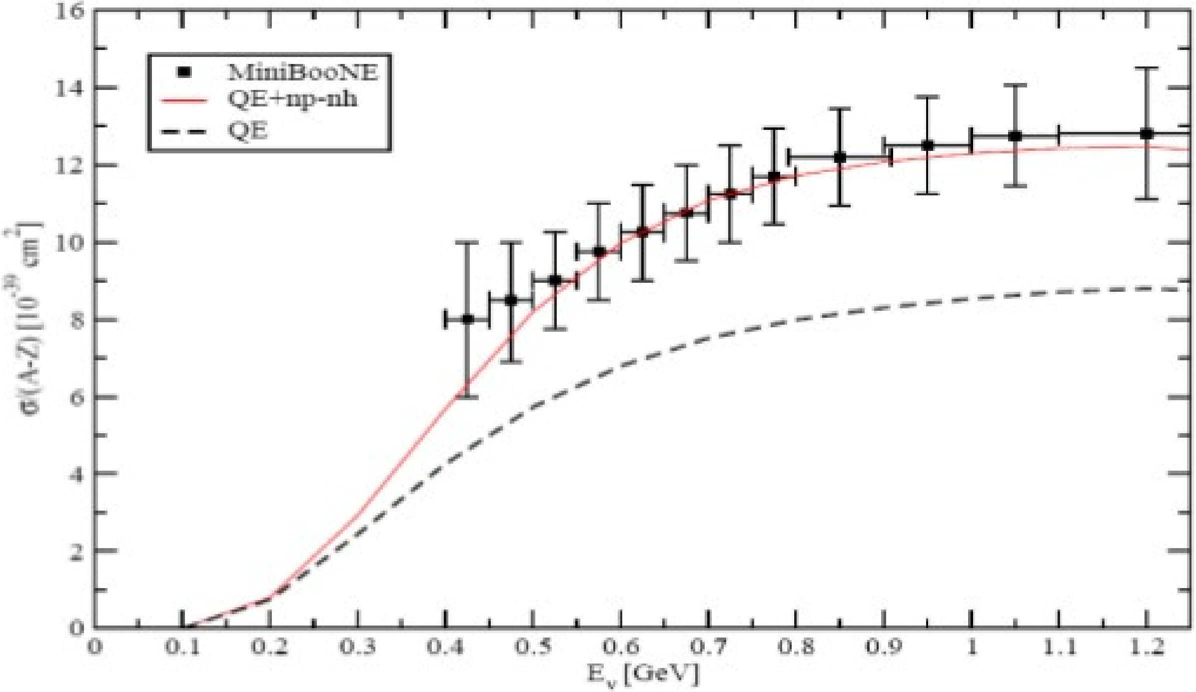
M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)

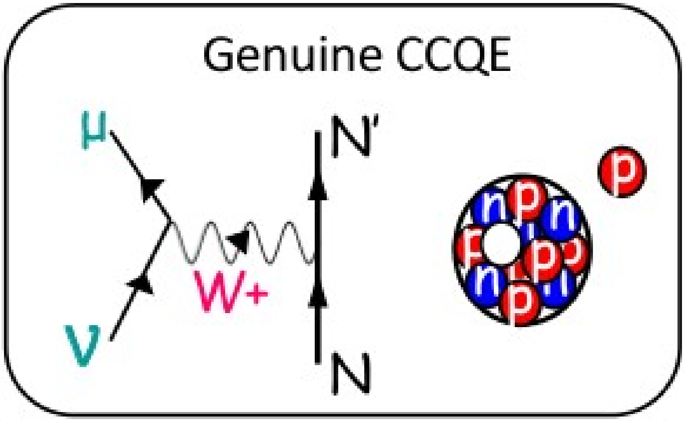


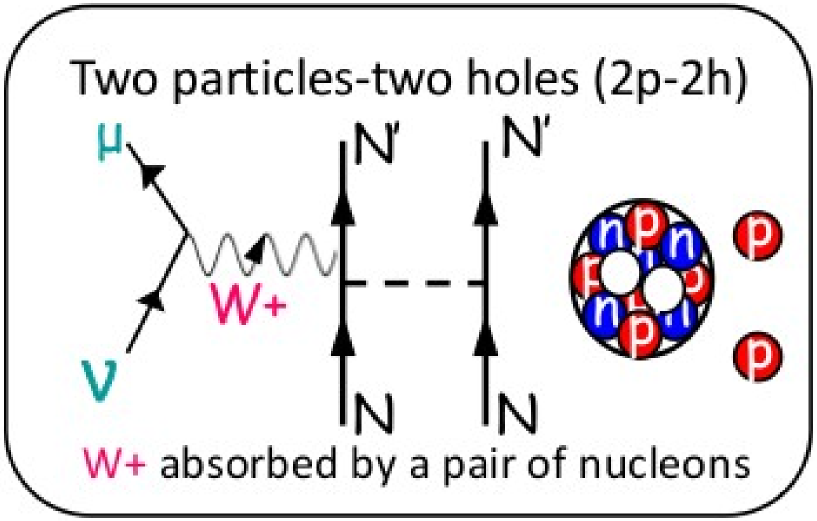
Different processes are entangled

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)




Genuine CCQE


Two particles-two holes (2p-2h)

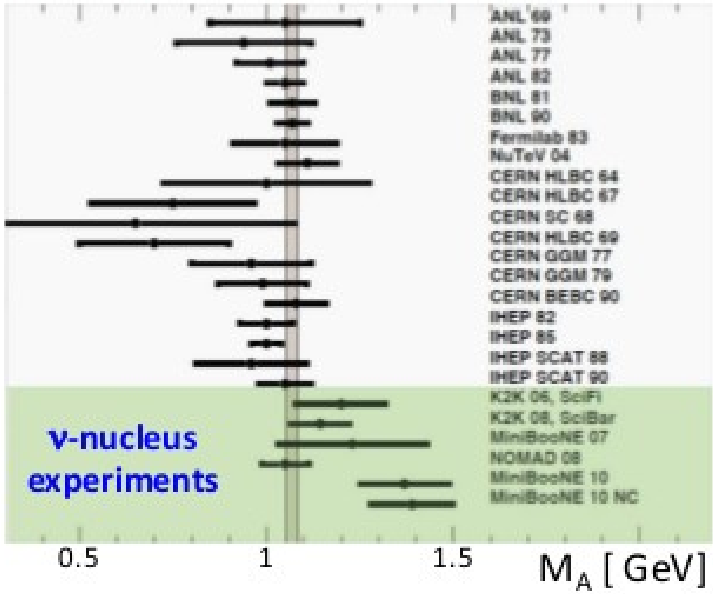
W+ absorbed by a pair of nucleons

M. Martini, M. Ericson, G. Chanfray, J. Marteau   Phys. Rev. C 80 065501 (2009)

Agreement with MiniBooNE without increasing M_A

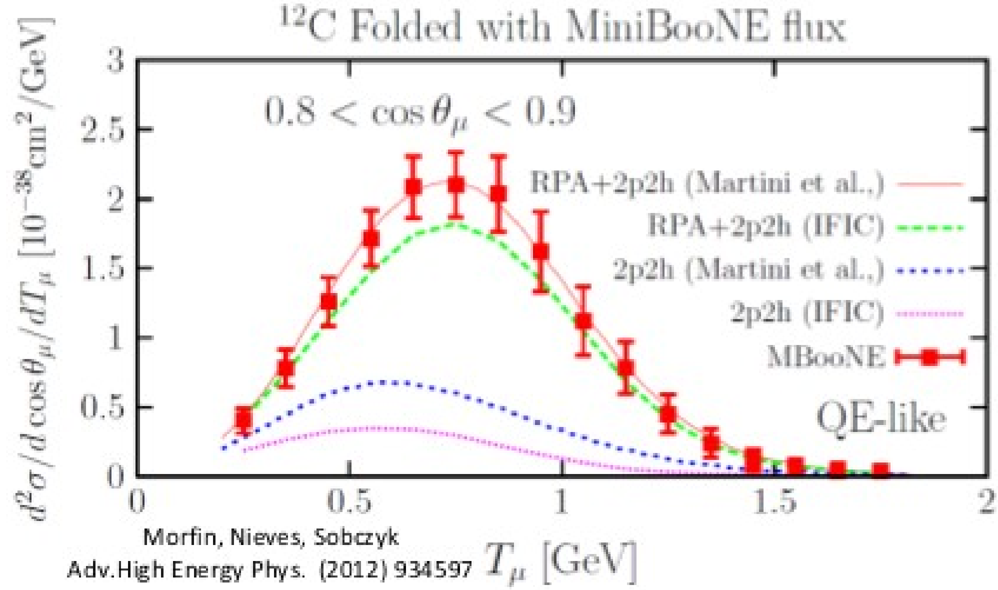
The multinucleon emission channel (or np-nh, or 2p-2h)

- A lot of interest in these last years
- Explanation of the axial mass puzzle
- It was not included in the generators used for the analyses of ν cross sections and oscillations experiments
- Today there is an effort to include this np-nh channel in several Monte Carlo



- Several theoretical calculations agree on its crucial role to explain data but there are some differences on the results obtained for this channel

[In the following I will focus essentially on this channel]

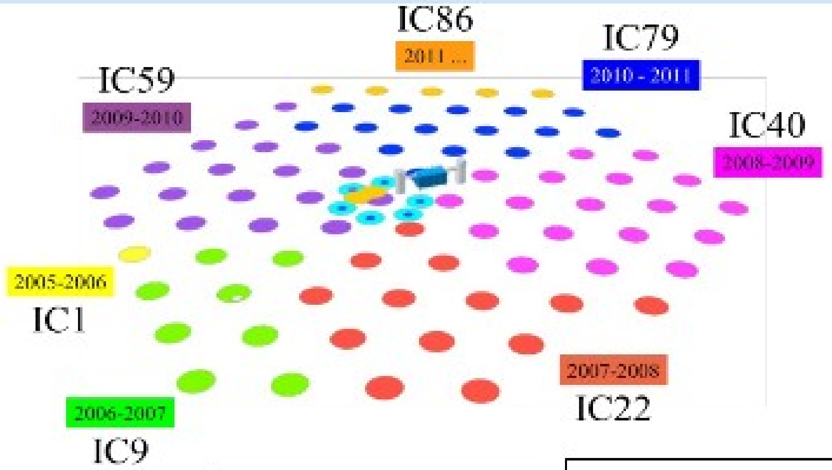


Morfin, Nieves, Sobczyk
Adv.High Energy Phys. (2012) 934597

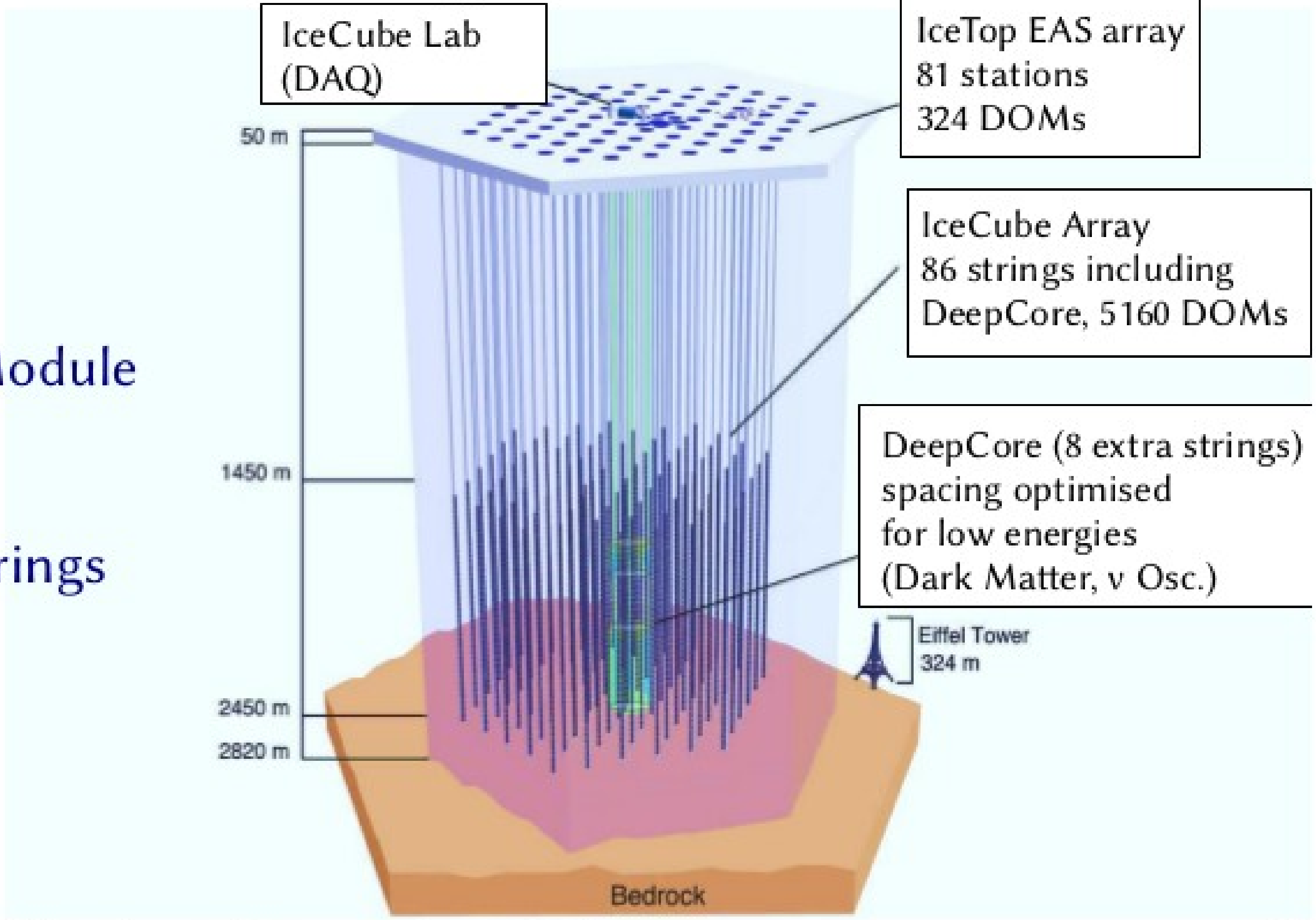
Astrophysical neutrinos

IceCube – Timeline

1993 : First AMANDA string
2000 : AMANDA completed; detection of atmospheric ν:s
2005 : IC1 deployed
2010 : IceCube completed
2013 : Detection of astrophysical ν flux
2015 : NOW
~2025: IceCube Gen2



Digital Optical Module (DOM)
17m spacing
125m between strings



IceCube Lab (DAQ)

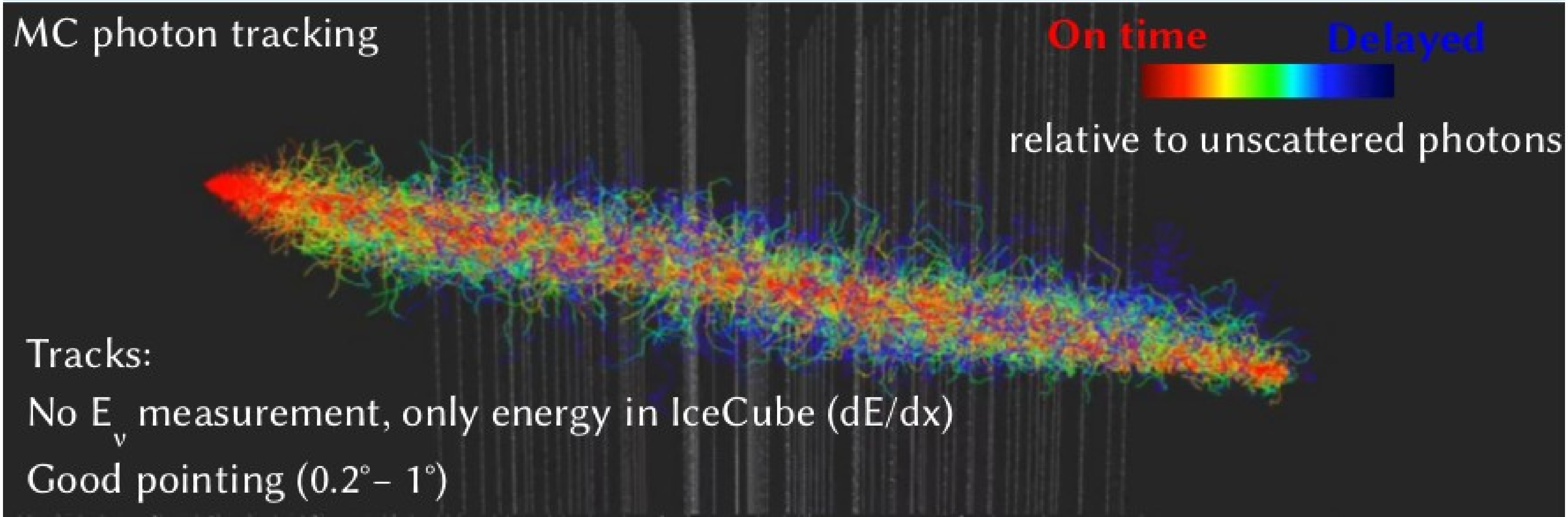
IceTop EAS array
81 stations
324 DOMs

IceCube Array
86 strings including DeepCore, 5160 DOMs

DeepCore (8 extra strings)
spacing optimised for low energies
(Dark Matter, ν Osc.)

Track & Cascade events

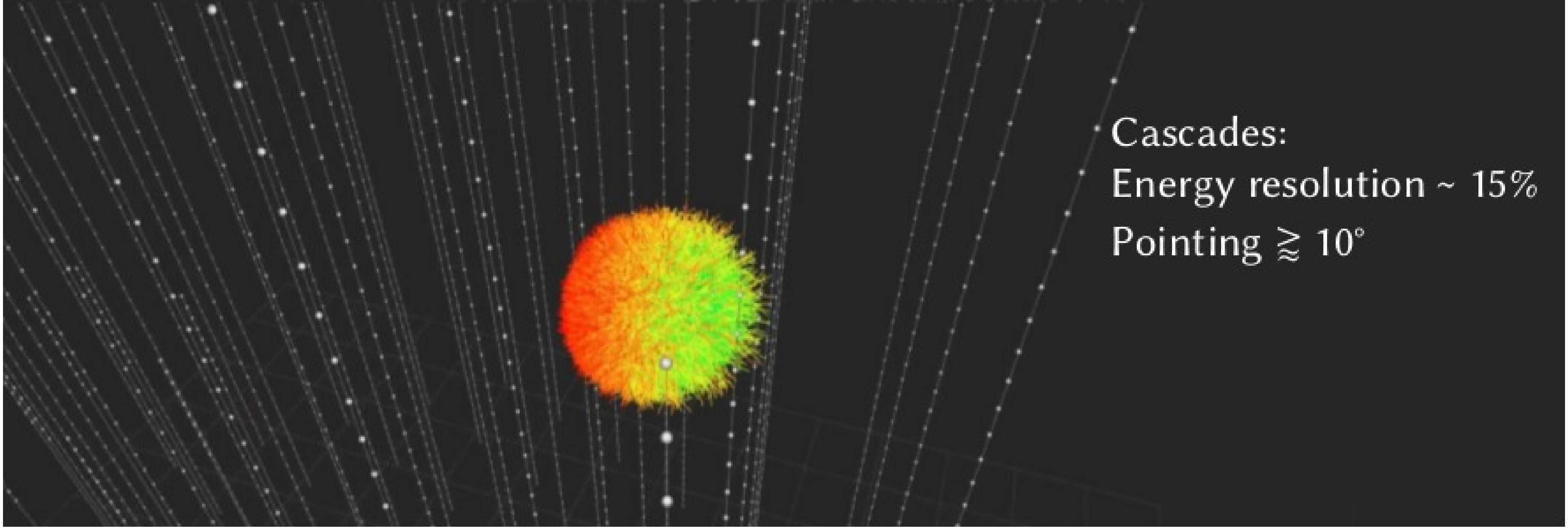
MC photon tracking



Tracks:

No E_ν measurement, only energy in IceCube (dE/dx)

Good pointing (0.2°– 1°)



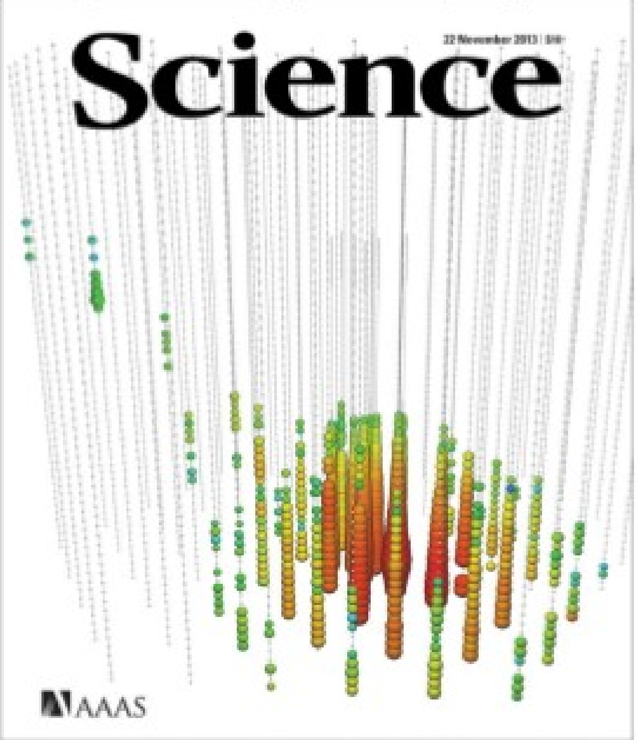
Cascades:

Energy resolution ~ 15%

Pointing $\gtrapprox$ 10°

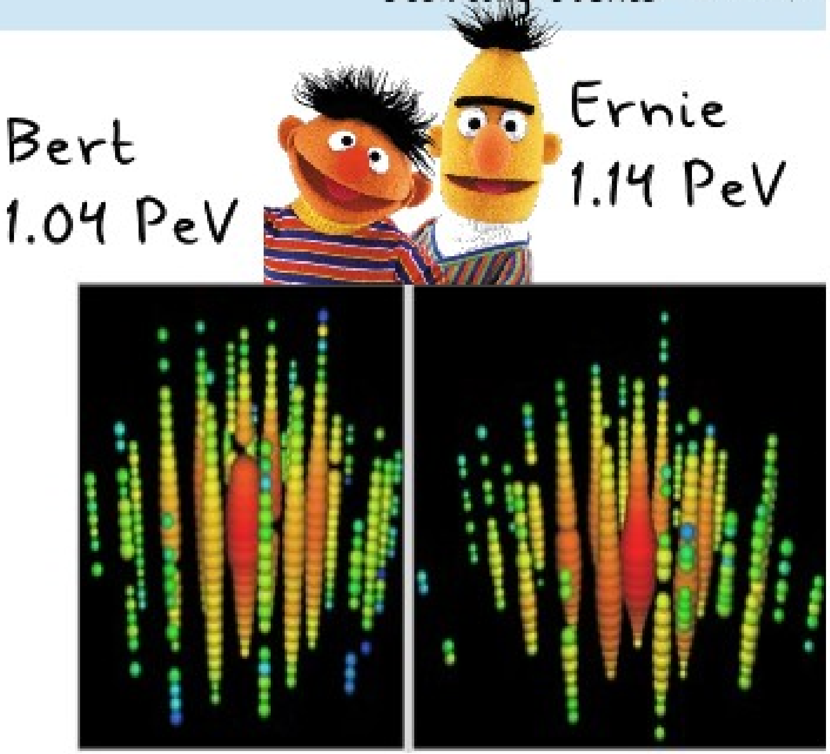
The Muppet Show

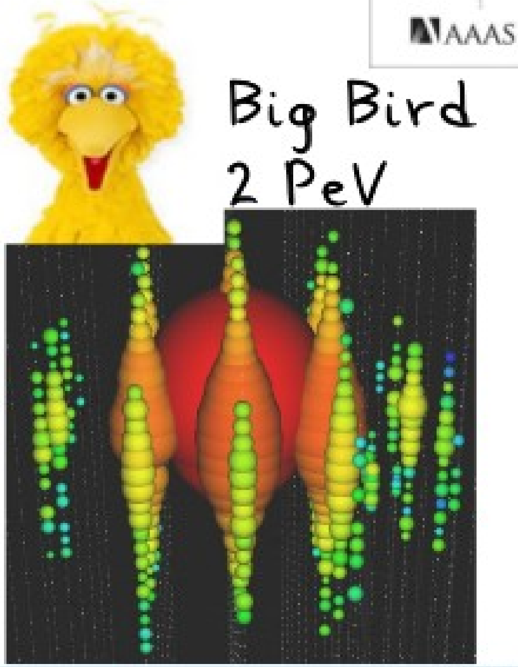
or the discovery of the high energy astrophysical neutrino flux:



Science

AAAS





Bert&Ernie found in 2 year EeV ν search (IC79+86)
PRL 111(2013)021103

Follow-up for events with less light detected found another 26 events at lower energy
Science 342 (2013) 1242856

Third year included Big Bird
PRL 113 (2014) 101101

Four-year analysis almost completed

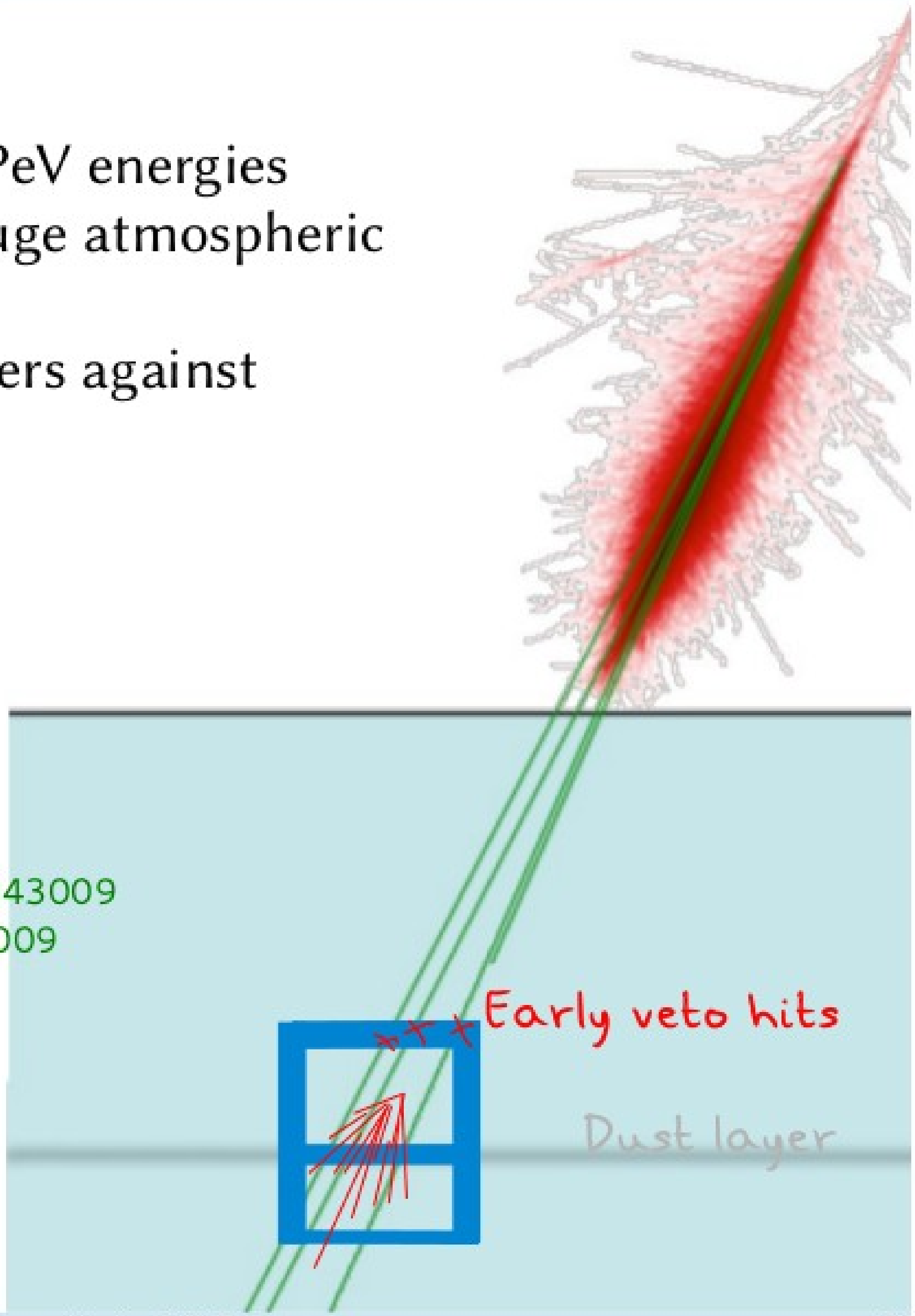
High Energy Starting Events (HESE)

- Follow-up to Bert & Ernie
- Earth is not transparent any more at ~PeV energies
- Need to look for downgoing events - huge atmospheric muon background!
- Use outer detector layers as veto counters against entering muons

→ Smaller effective detection volume

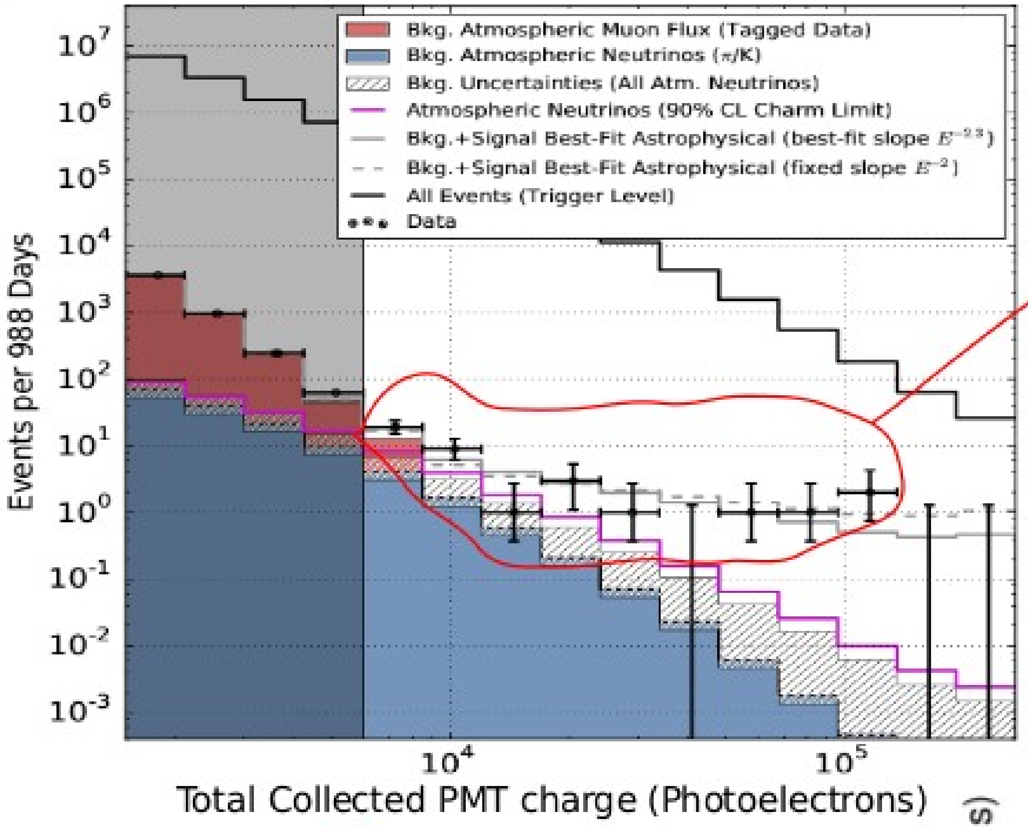
BUT: Veto works also against down-going neutrinos from CR showers!

Schönert, Gaisser, Resconi, Schultz, Phys Rev D79 (2009) 043009
Gaisser, Jero, Karle, van Santen, Phys Rev D90 (2014) 023009



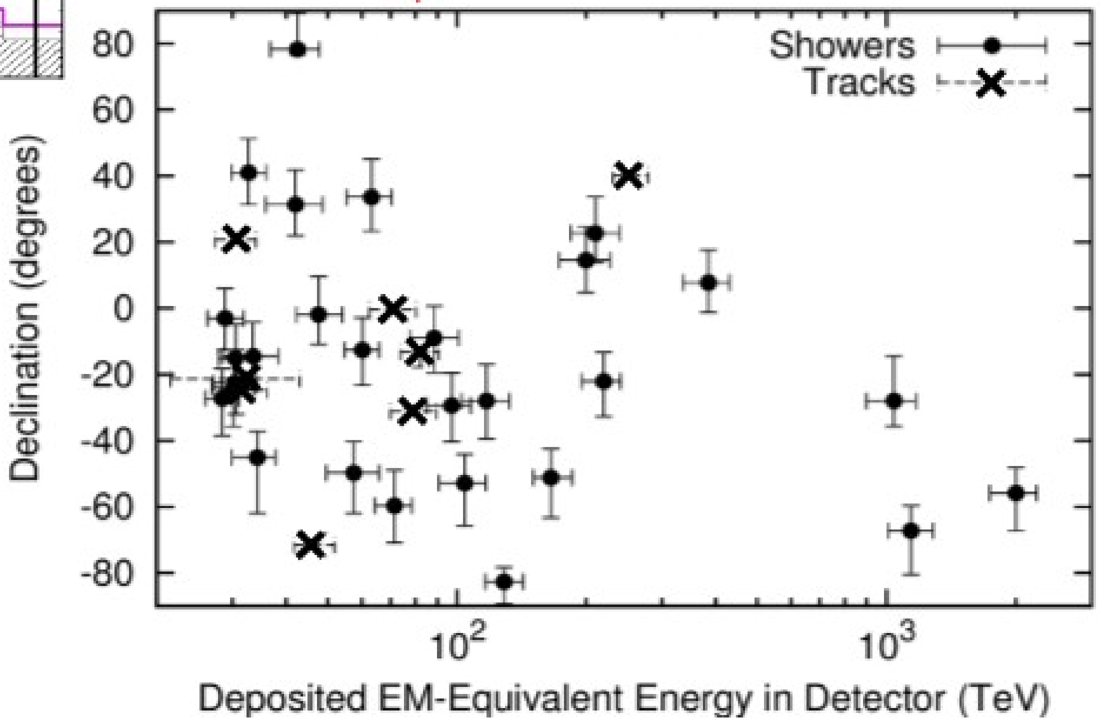
HESE 3 year results

PRL 113 (2014) 101101



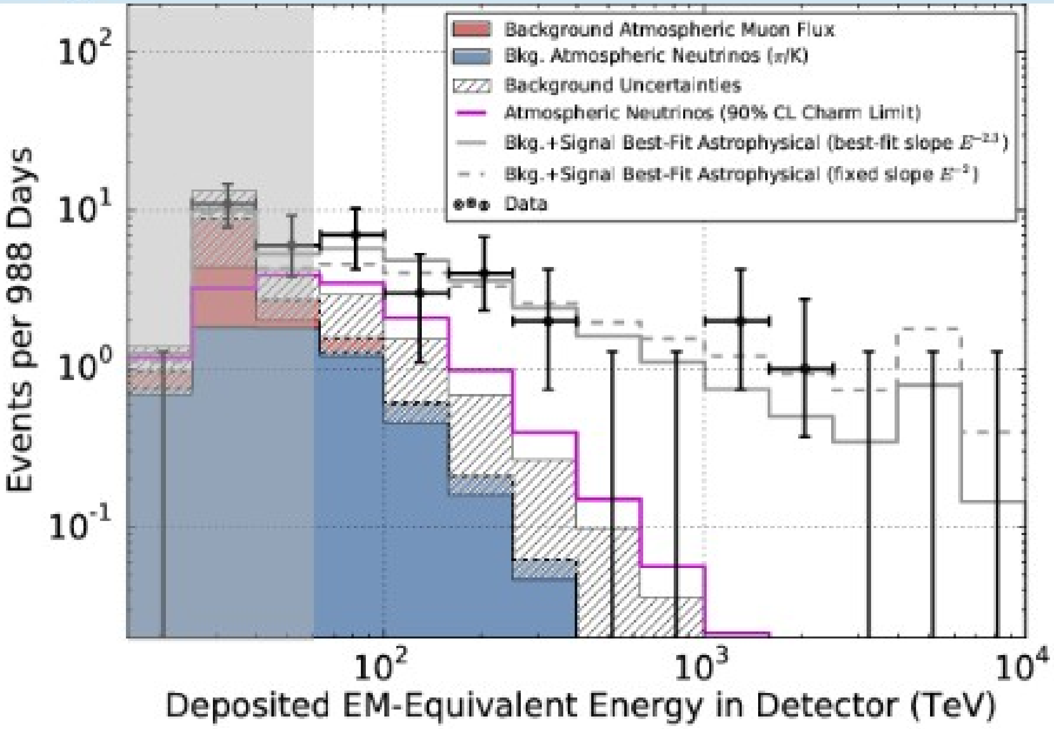
36 events selected

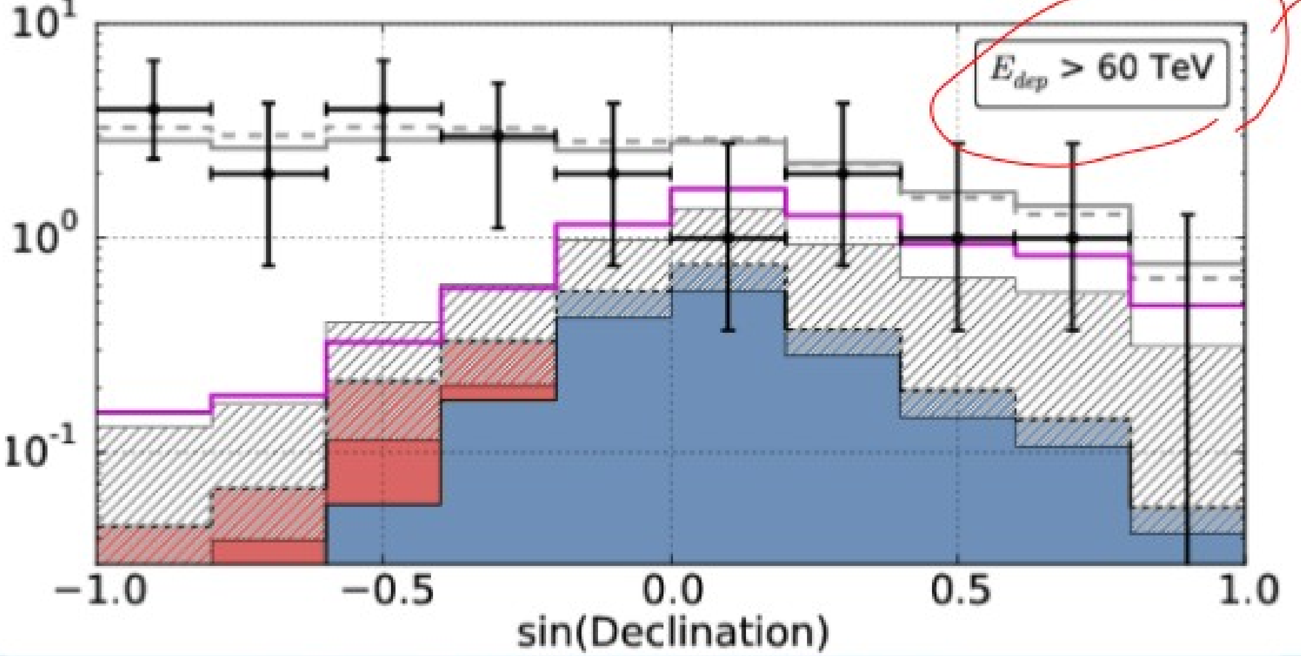
Cut at 6000 PE



HESE 3 year self-veto turn-on

PRL 113 (2014) 101101





Used for fit

HESE 3 year results

PRL 113 (2014) 101101

Best fit unbroken $\boldsymbol{E^{-2}}$ spectrum to data above 60 TeV is

$$E^2\Phi = (0.95 \pm 0.3)\times10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

Favoured at 5.7 σ compared to purely atmospheric flux

Best fit power law is $E^{-2.3}$ (prompt flux fits to zero):

$$E^2\Phi = 1.5\times10^{-8}\ (E/100\ \mathrm{TeV})^{-0.3}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

(or $\Phi = 1.5\times10^{-18}\ (E/100\ \mathrm{TeV})^{-2.3}\ \mathrm{GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)

Consistent with isotropic flux with ν_e:ν_μ:ν_τ=1:1:1