Measurement of Neutrino Properties

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TeV Particle Astrophysics 2009
SLAC, 13 Jul 2009

Neutrinos at *TeV Particle Astrophysics 2009*

Three points of view:

- **Intrinsic properties of the neutrino** *(this talk)*
- **Neutrinos as tools to relay information on astrophysical phenomena** *(several talks on Wed)*
- **Neutrinos in cosmology, this can also be used to constrain neutrino properties connecting together very different threads, worlds, scales,…**
  (see Wendy Freedman's talk tomorrow)

Last 15 yrs in particle physics: the age of νs

Discovery of ν flavor change

- *Solar neutrinos (MSW effect)*
- *Reactor neutrinos (vacuum oscillation)*
- *Atmospheric neutrinos (vacuum oscillation)*
- *Accelerator neutrinos (vacuum oscillation)*

- ν masses are non-zero
- Lepton mixing matrix very different from that of quarks
- There are 2.984±0.008 ν (Z lineshape, PDG Phys Lett. B667 (08) 1)
- 3 ν flavors were active in Big Bang Nucleosynthesis
- The Sun emits neutrinos as expected
- Supernovae emit neutrinos

Our knowledge of the lepton mixing matrix

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

information on ~~CP~~ is here

Neutrino factory ?

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \bullet \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\alpha/2+i\beta} \end{pmatrix}$$

Atmospheric ν
K2K
Minos et al.

θ_{23}~45°

Chooz/Palo Verde
Off axis
Future reactors

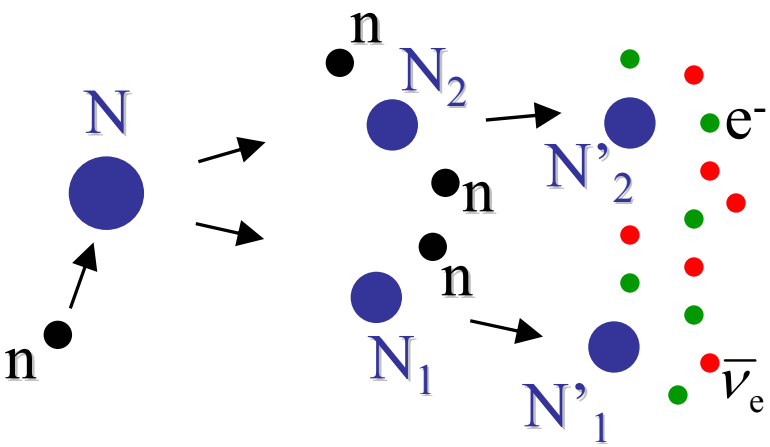
θ_{13}<7° @ 90%CL

Solar ν
KamLAND
Future solar ν exp.

θ_{12}~34°

Neutrinoless double beta decay

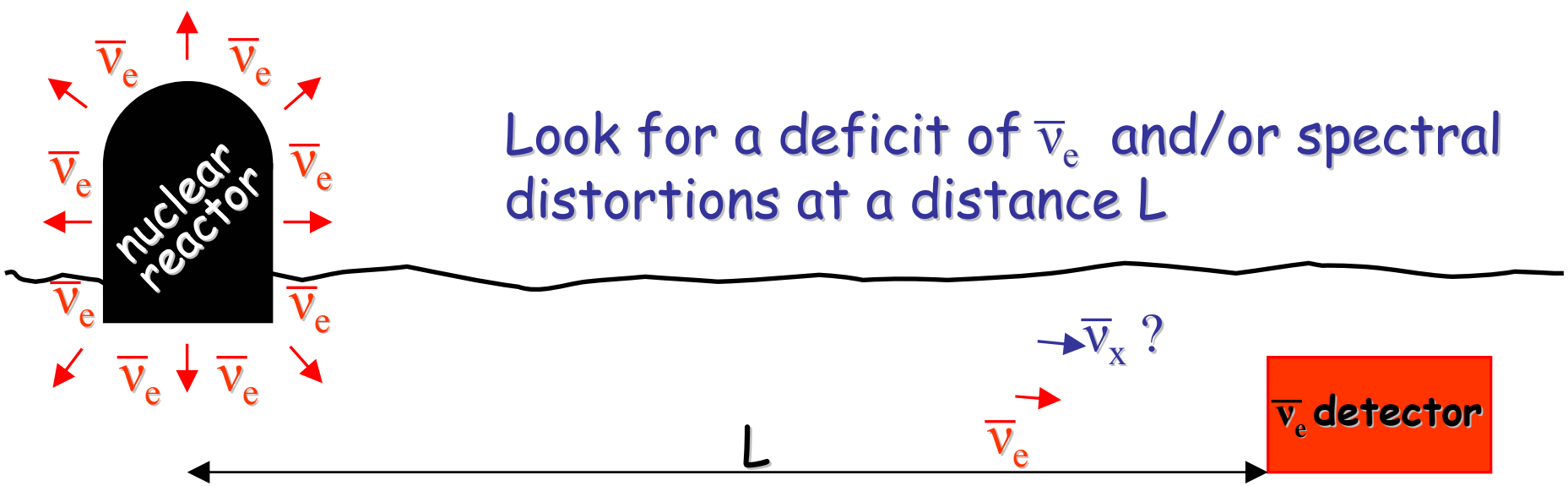
Nuclear reactors are very intense sources of $\bar{\nu}_e$ deriving from beta-decay of the neutron-rich fission fragments



$$Yield:$$

$$200 MeV / fission$$

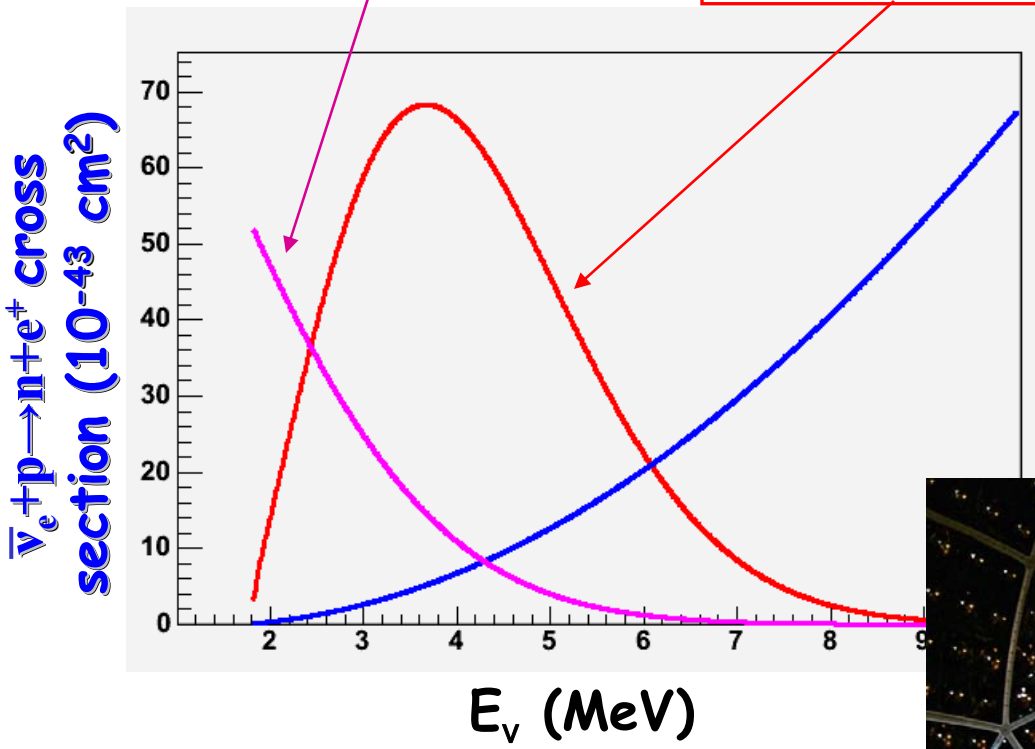
$$6\bar{\nu}_e / fission$$

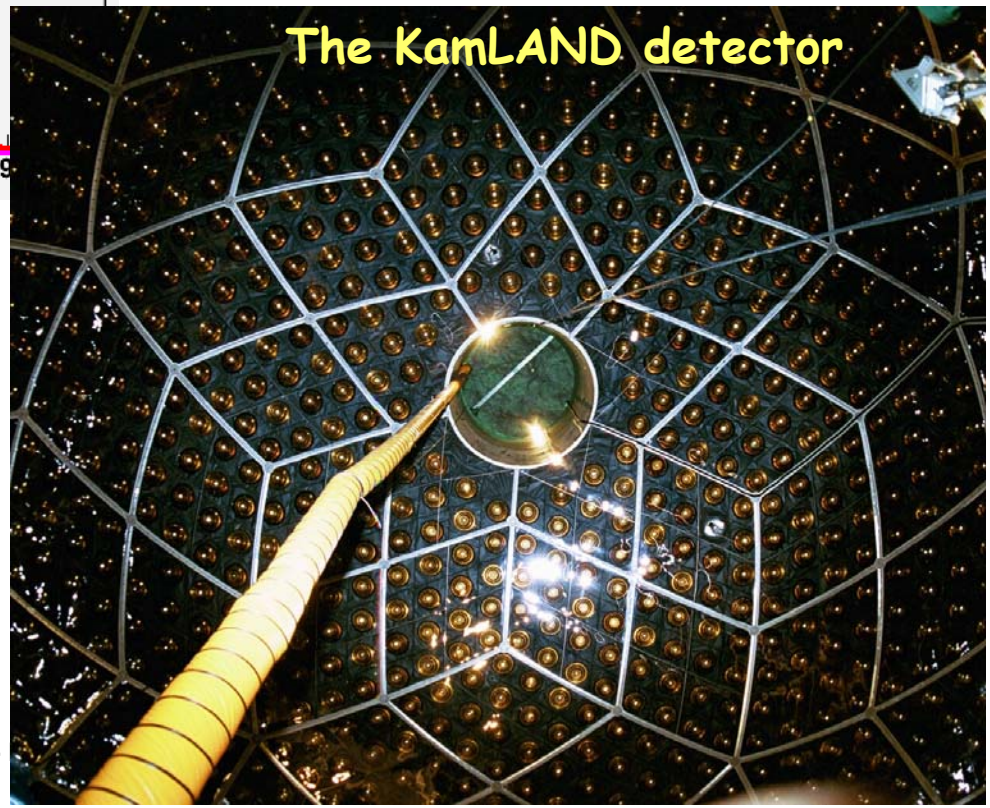


Look for a deficit of $\bar{\nu}_e$ and/or spectral distortions at a distance L

Reactor $\bar{\nu}_e$ spectrum

Observable spectrum using $\bar{\nu}_e + p \rightarrow n + e^+$ (a.u.)



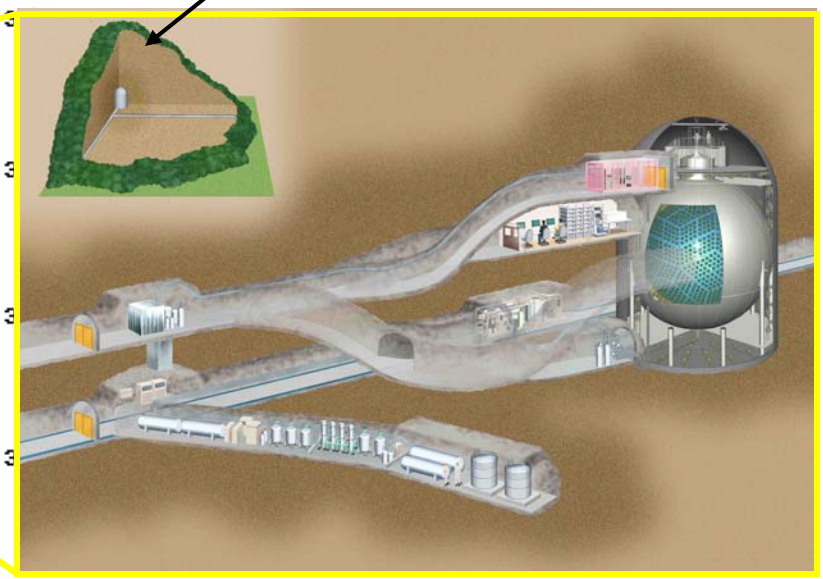


Until now only liquid Scintillators used

- Low threshold
- Neutron sensitivity (2.2MeV)
- Large quantity (KamLAND is 1kton)

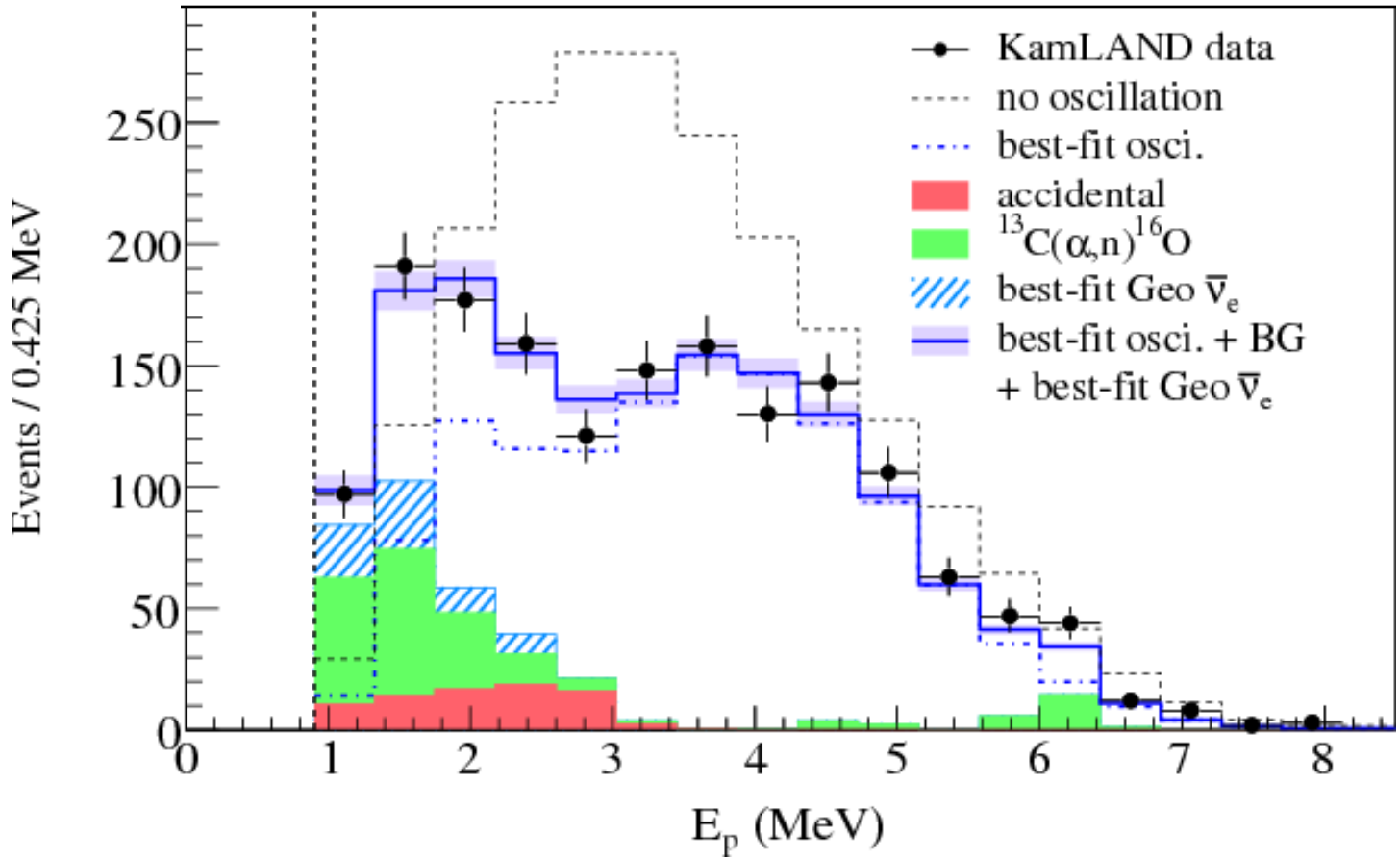
Over 50 reactors cores contribute to the signal in KamLAND

~1 km high
Mt Ikenoyama



See K.Nakamura this afternoon

The spectrum observed by KamLAND clearly reveals oscillations

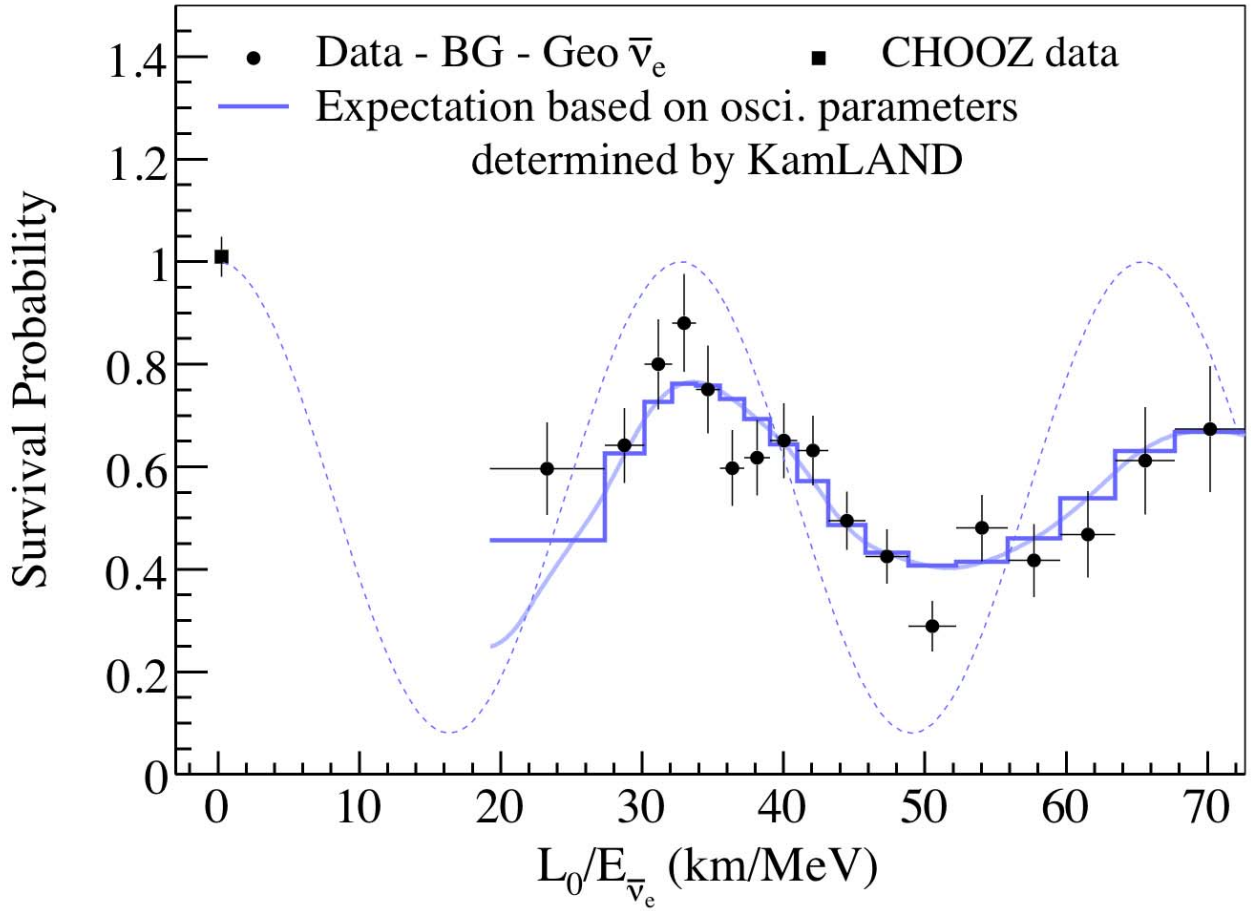


S. Abe, et al. PRL 100 (2008) 021101

Different look at the same spectrum

(unfortunately cannot point to source, so the baseline L_0 is the most probable value of 180km):

The "oscillatory behavior" of neutrino oscillations!



Different look at the same spectrum

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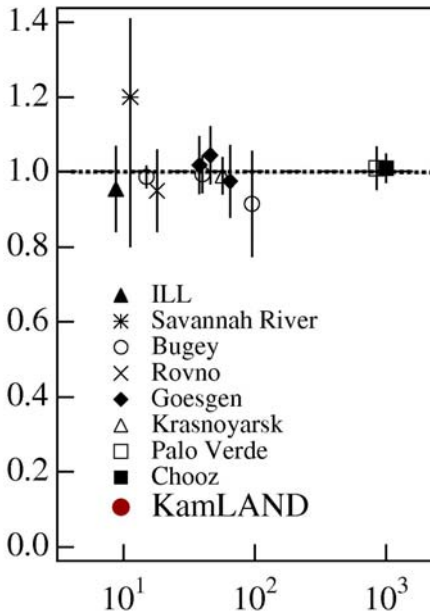
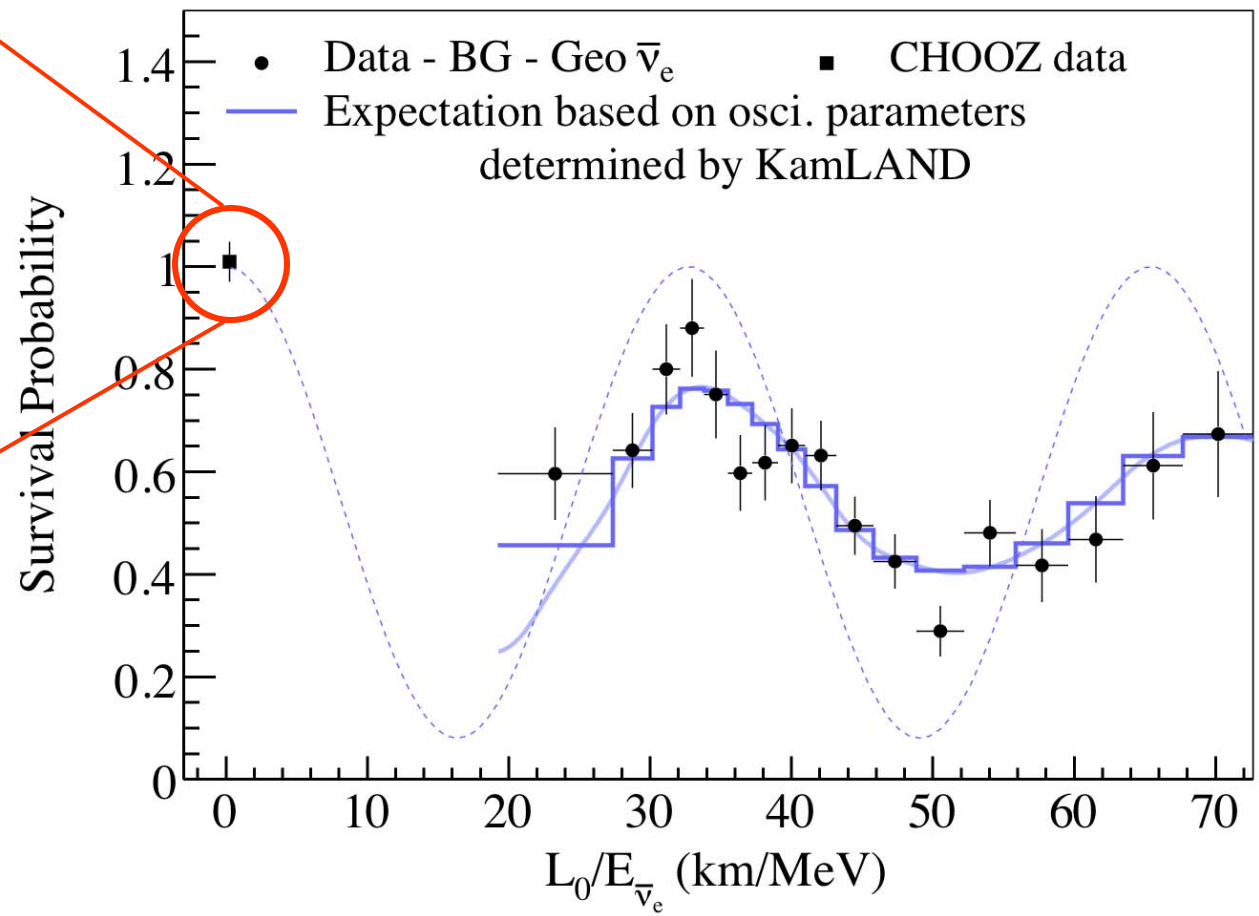
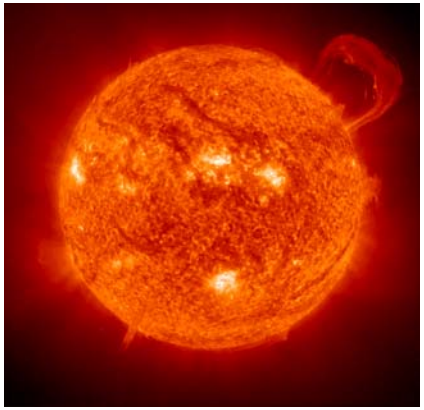
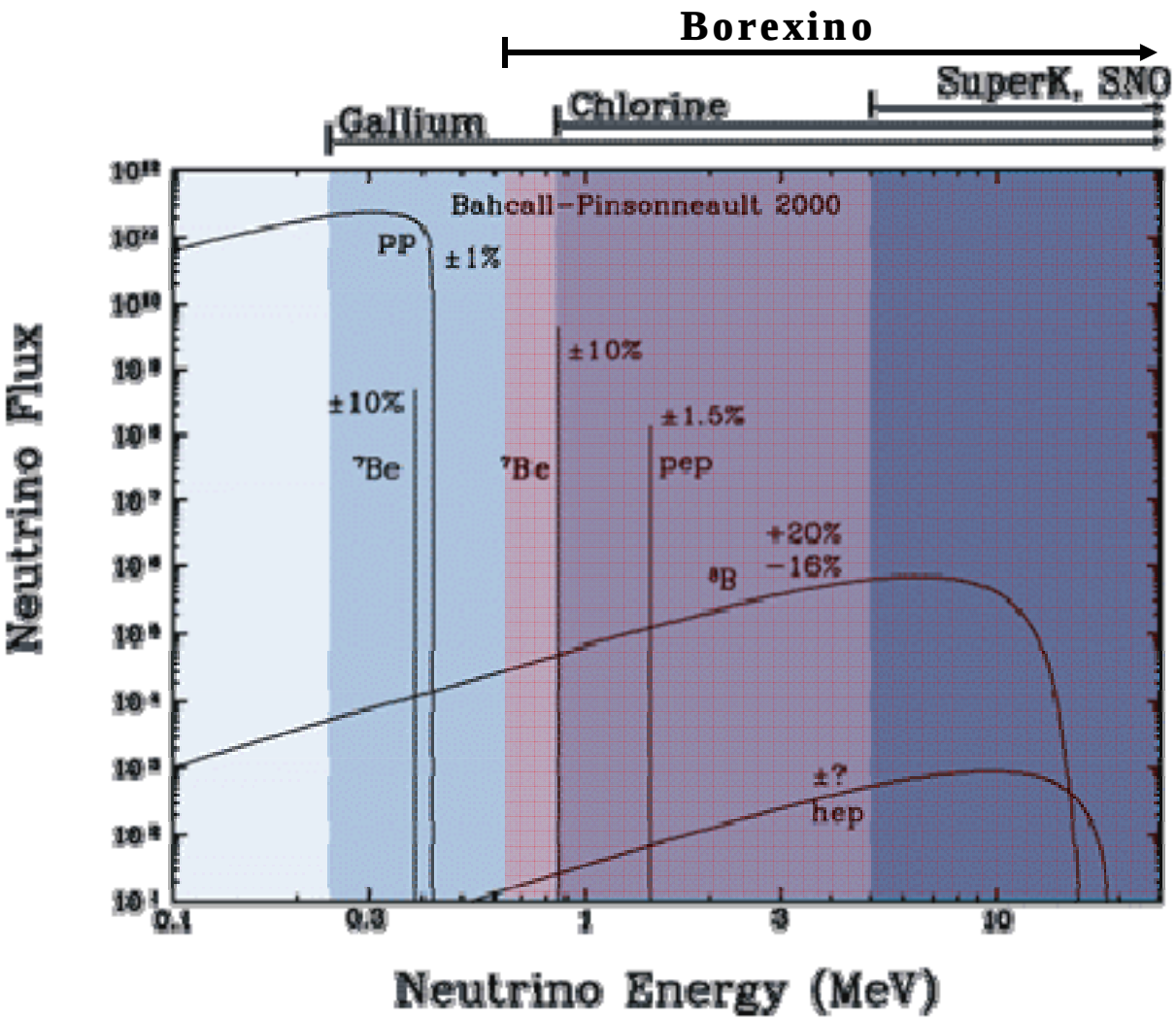




Solar Neutrinos



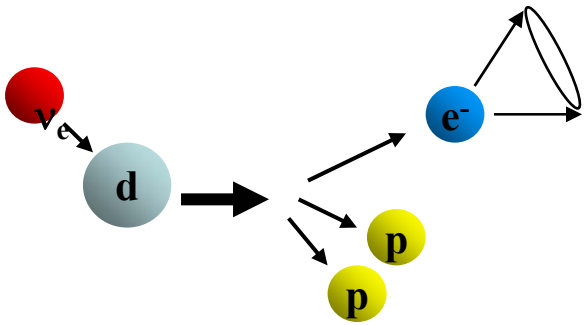


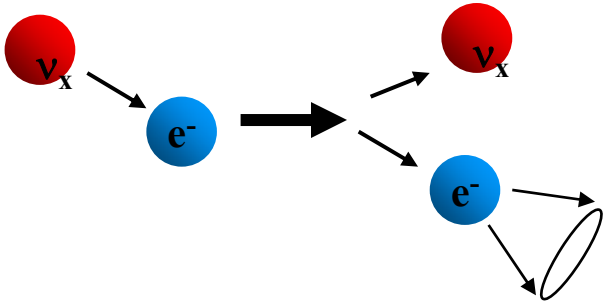
SNO: Neutrino interactions in D_2O

Charged Current (CC):

$\nu_e + d \Rightarrow p + p + e^-$

Electron neutrinos only





Elastic Scattering (ES):

$\nu_x + e^- \Rightarrow \nu_x + e^-$

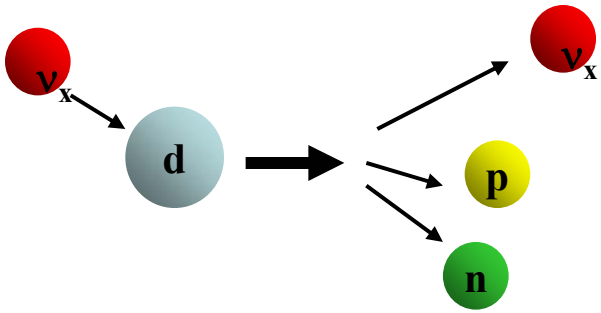
$0.154 \cdot \sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$

this is all SuperK sees

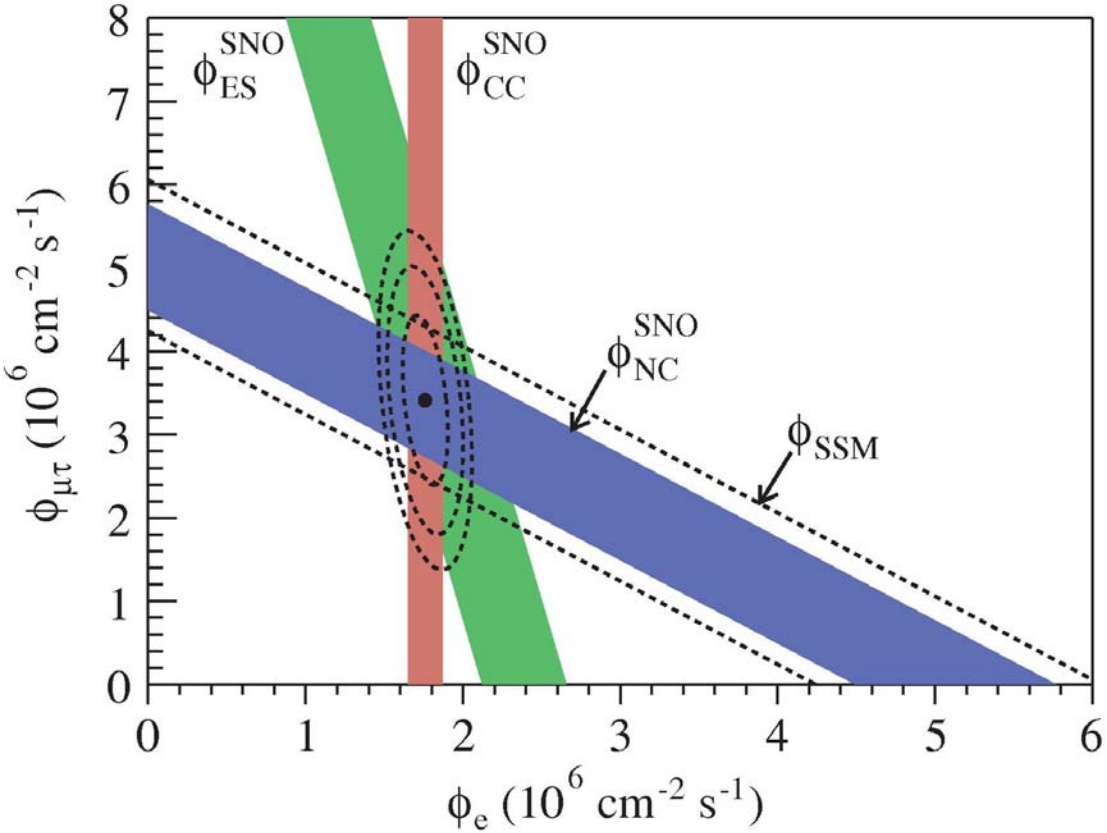
Neutral Current (NC):

$\nu_x + d \Rightarrow p + n + \nu_x$

Same for all neutrino flavors !



…and, indeed, SNO sees disappearance of ν_e but also appearance of ν_μ and ν_τ

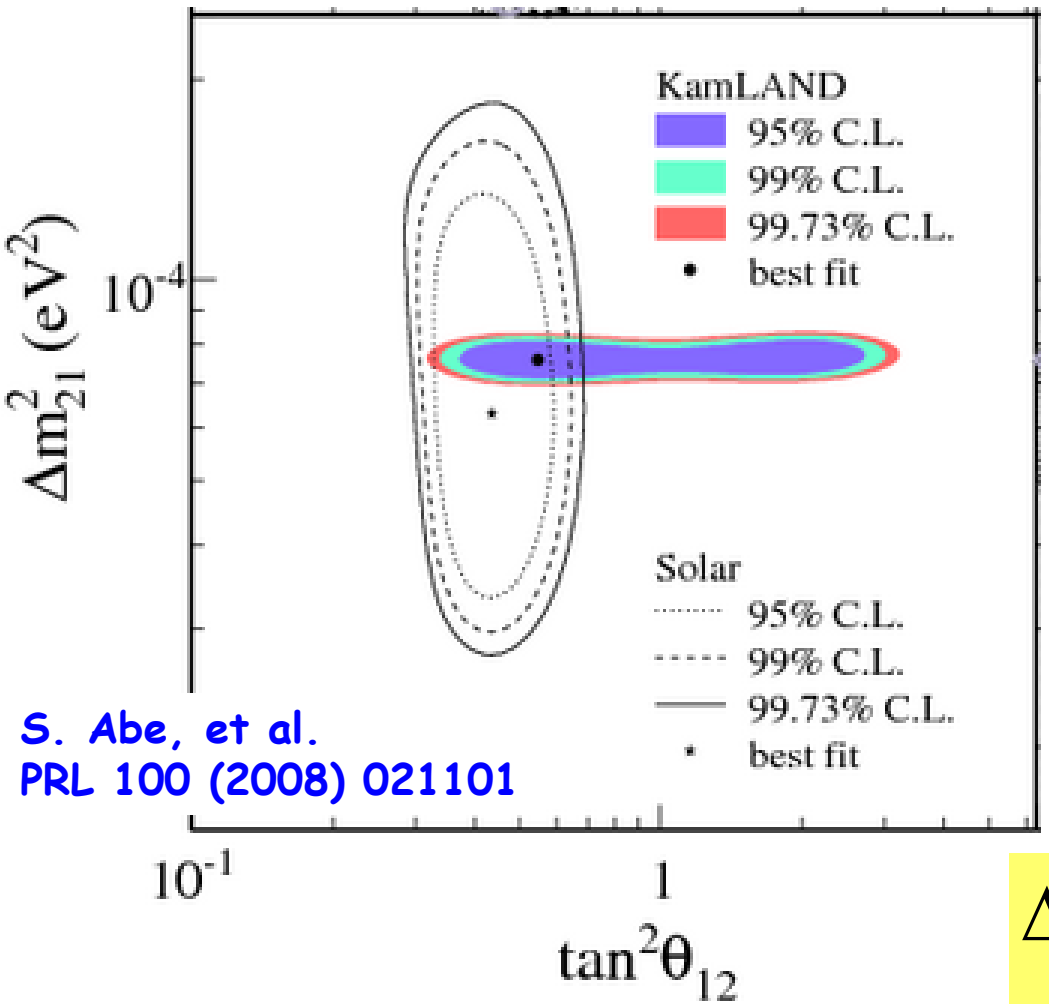


$$\varphi(\nu_e) = (1.76 \pm 0.05) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

$$\boldsymbol{\varphi(\nu_{\mu\tau}) = (3.41 \pm 0.45) \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \quad \neq 0 \text{ at a } 7.5\sigma \text{ level}}$$

B.Aharmim et al. PRC 75 (2007) 045502

Solar neutrinos meet reactor anti-neutrinos



S. Abe, et al.
PRL 100 (2008) 021101

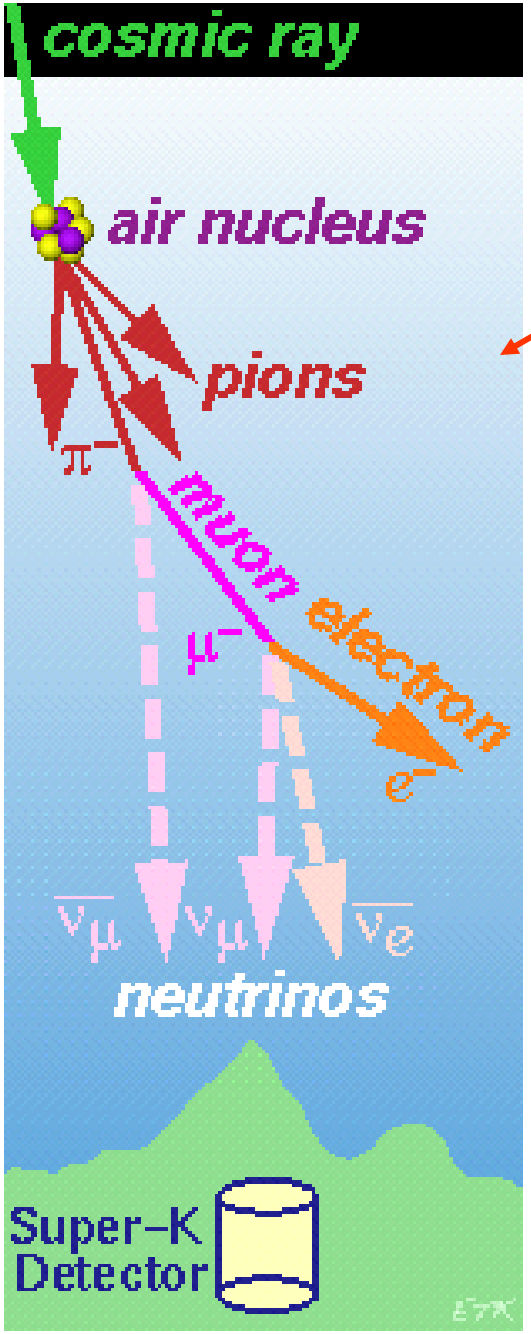
The fact that there is overlap between the two regions requires that:

- CPT is valid (ν mixing is same as $\bar{\nu}$ mixing)
- The phenomenology of MSW uses the same parameters as vacuum oscillations

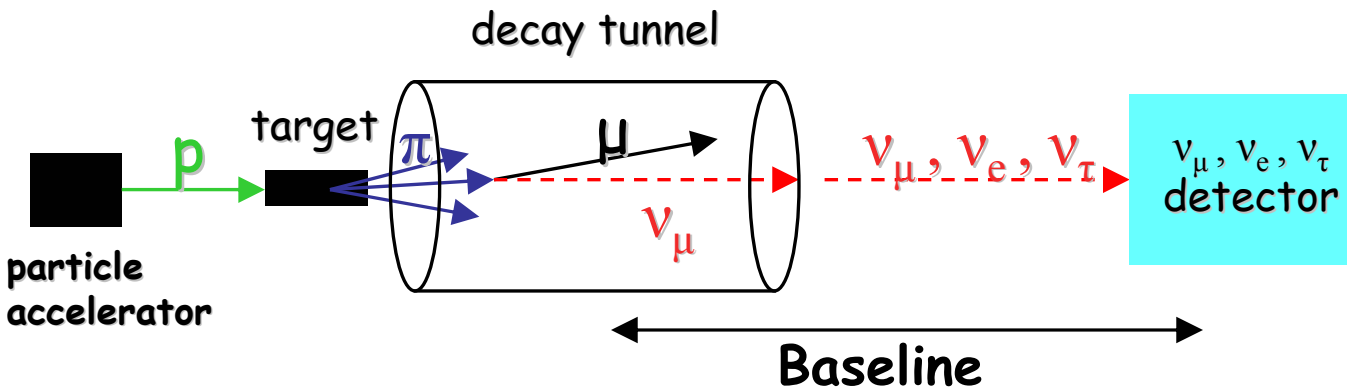
$$\Delta m^2_{12} = 7.59^{+0.19}_{-0.21} \times 10^{-5} eV^2$$

$$\theta_{12} = 34.4^{+1.3}_{-1.2} \deg$$

B.Aharmim, et al. PRL 101 (2008) 111301

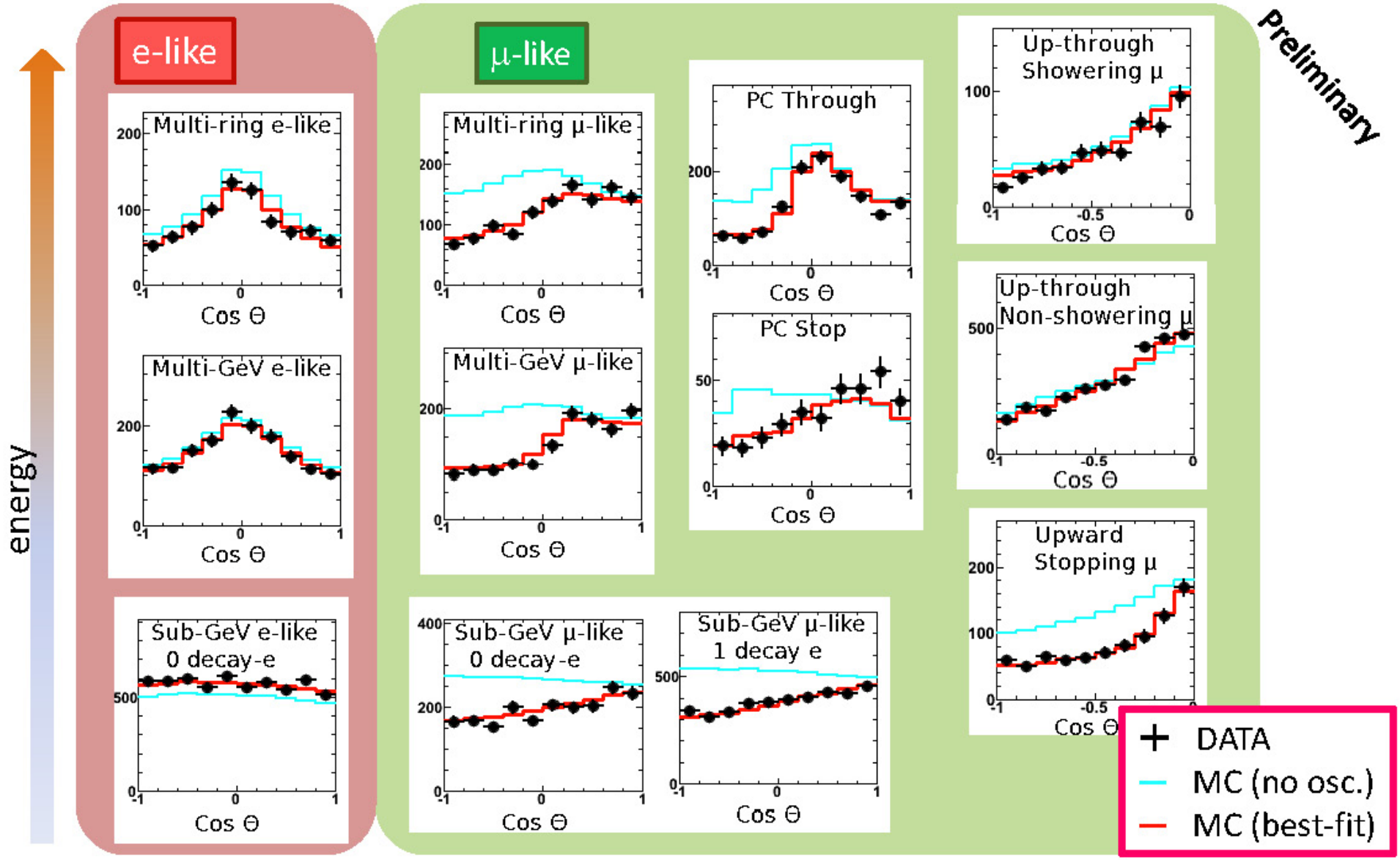


Atmospheric and accelerator neutrinos



Accelerators measurements have the advantage of high energy and the possibility to shoot and detect different flavors and polarities
(note: I did not say this is easy…)

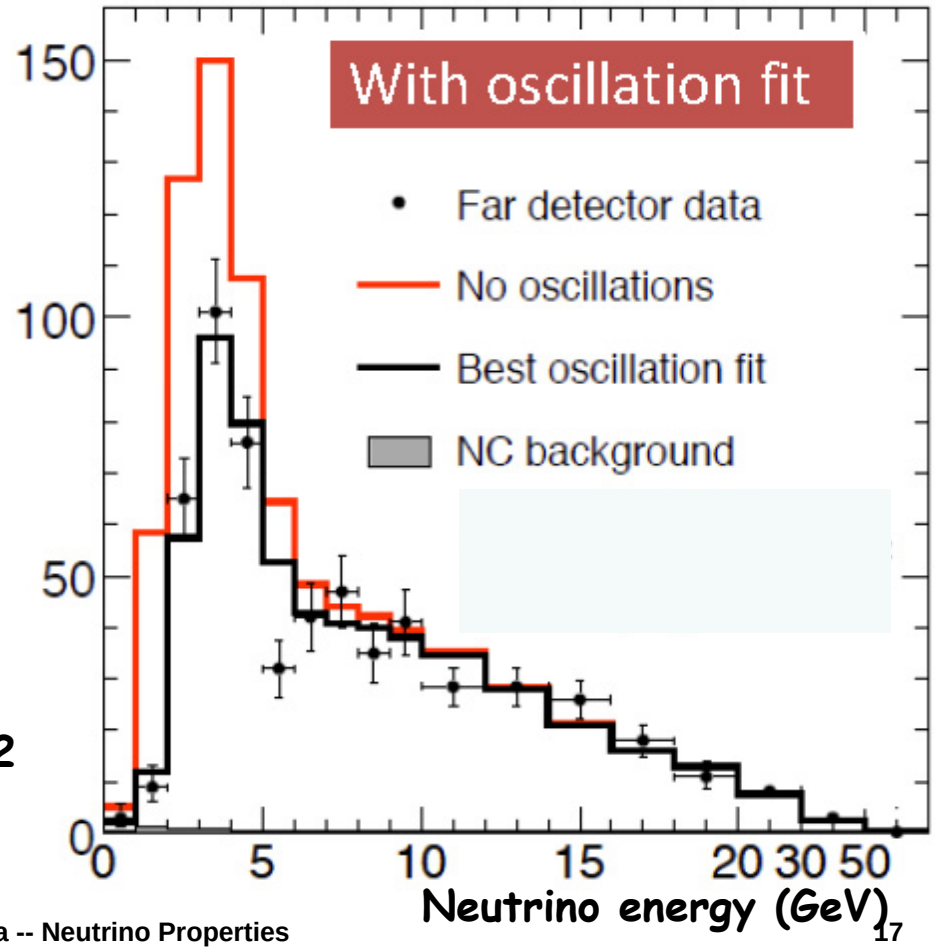
SuperK atm ν ~3000 d of data (180 kton-yr)



R.Wendell, TAUP, Rome, Jul 2009

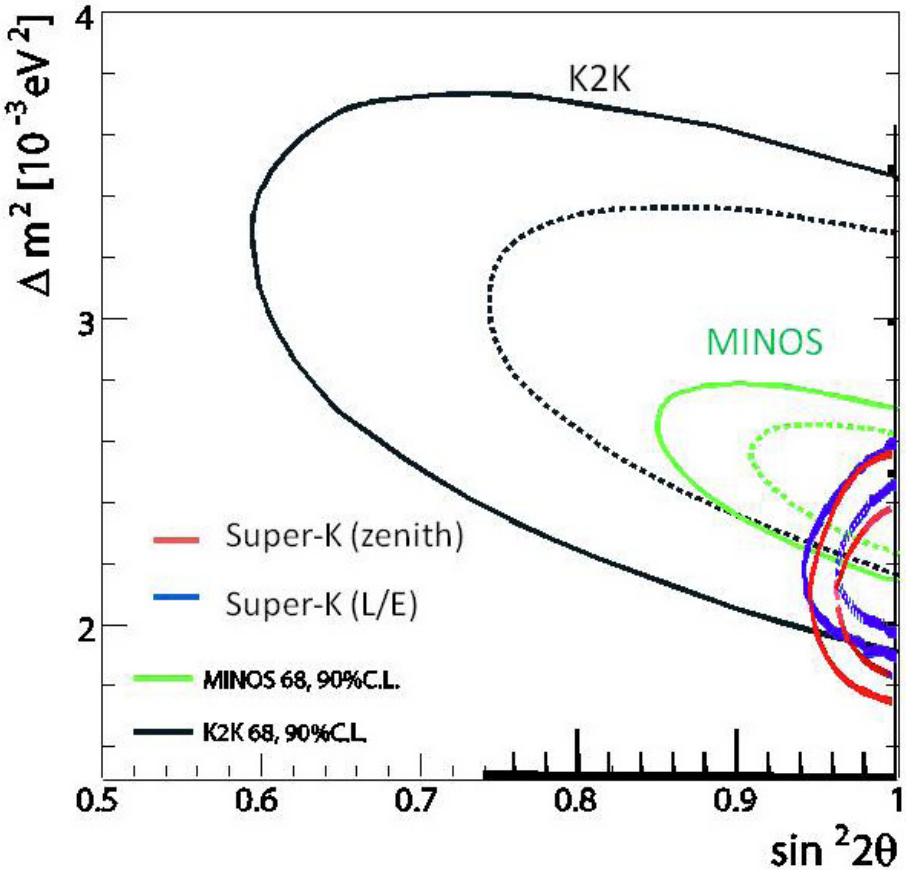
MINOS: clear energy-dependent ν_μ deficit

848 CC ν_μ candidate events detected
1065±60 (syst) expected
for no oscillations



P.Adamson et al. PRL 101 (2008) 131802

Again, there is good agreement between different Phenomena -atmospheric and accelerator neutrinos- (although in the case this is maybe less surprising -both are vacuum oscillations)



$$\Delta m^2_{23} = (2.43 \pm 0.13) \times 10^{-3} eV^2$$

$$\sin^2 2\theta_{23} > 0.92 \quad @\, 90\%\, CL$$

T.Kajita TAUP Rome Jul 2009,
Y. Ashie et al. PRD 71 (2005) 112005,
PDG Phys Lett B667 (2008) 1

θ_{13}

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

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

U contains the CP-violating phase δ_{CP} with coefficients of the type

$$\sin\theta_{12}\sin\theta_{23}\sin\theta_{13}$$

...so it is important to understand if θ_{13}~0

Present best limit is from reactors (Chooz and Palo Verde)

$\sin^2(2\theta_{13})<0.19$ @90% CL

PDG Phys Lett B667 (2008) 1

Future: mixing parameters

High precision (near/far detectors) reactor experiments dedicated to θ_{13}: Daya Bay (China, near Hong Kong)
Double Chooz (France)
RENO (Korea)

Runs expected to start in 2011 (but will take time to accumulate statistics and start the far detectors)

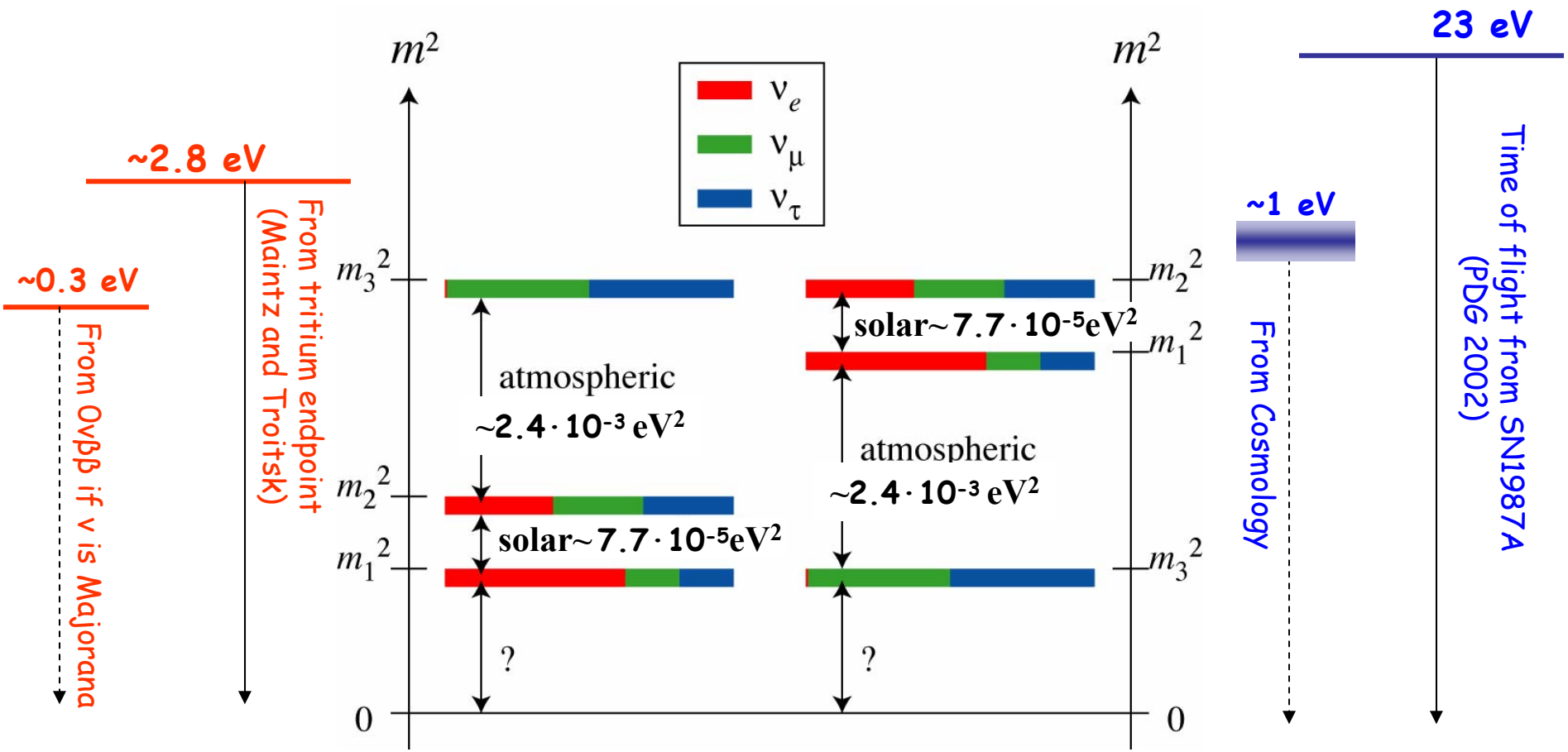
Expected sensitivities to θ_{13}:
$<10^{-2}$ (Daya Bay) to 3×10^{-2} (Double Chooz)

see D.McKee this afternoon

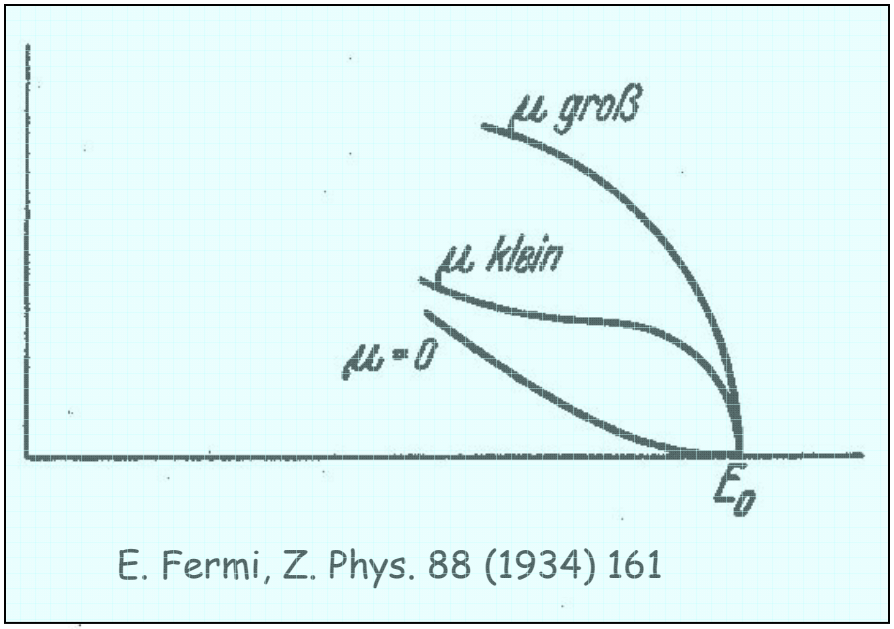
Off-axis, long baseline experiments: T2K (Japan, 2009-…)
NOvA (US, 2013-…)

Sensitivity to θ_{13} as low as 3×10^{-3} but this depends also on δ_{CP} and the hierarchy (so, if lucky get more than θ_{13}…)

The ν mass pattern/magnitude



Endpoint mass measurements



E. Fermi, Z. Phys. 88 (1934) 161

Study the spectral shape near the endpoint of a β decay

(note that the end-point value is generally *not* known well enough to use its absolute position)

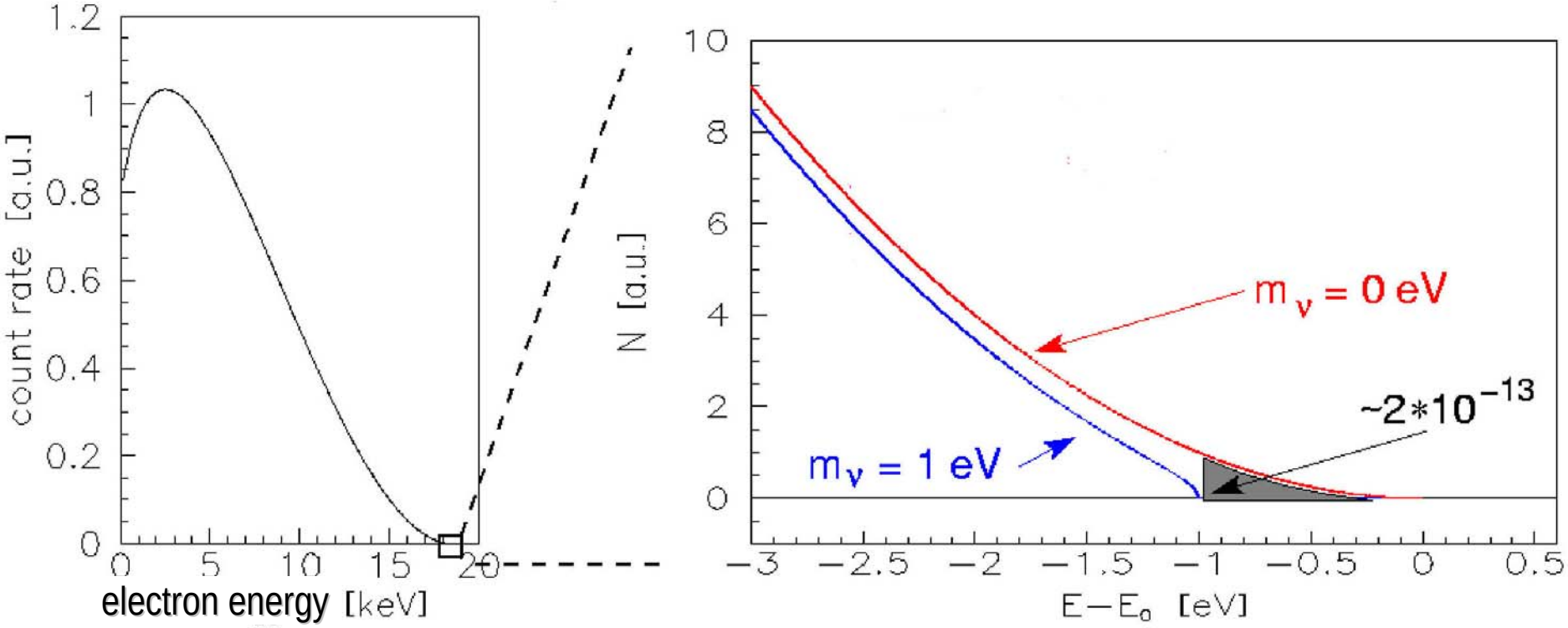
Measure the quantity:

$$m_{\nu_e}^{2\,(eff)} = \sum_i \left|U_{ei}\right|^2 m_i^2$$

If the experimental resolution is smaller than $m_i^2 - m_j^2$ then one should see a separate kink in the spectrum for each of the states i and j

Modern experiments use mainly $${}^{3}_{1}T \rightarrow {}^{3}_{2}He + e^{-} + \bar{\nu}_e$$

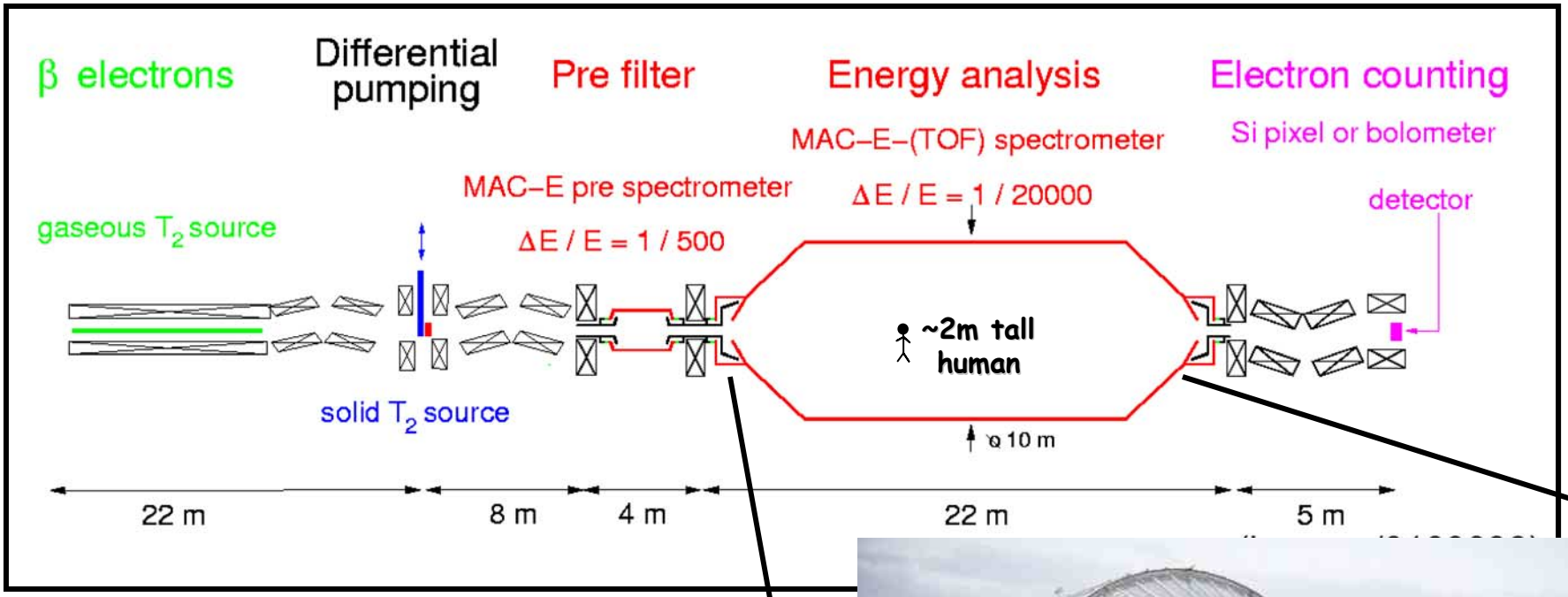
a super-allowed transition with rather good combination of low end point (E_0=18.6 keV) and short half life ($T_{1/2}$=12.3 yr)



Spectrometer requirements 1) very high resolution
2) very high luminosity (endpoint has no rate…)

Present limit $m^{eff}_{\nu_e} < 2eV$ *(PDG estimate based on Mainz and Troisk results)*

New, very large electrostatic, integrating spectrometer being built in Karlsruhe: "KATRIN"

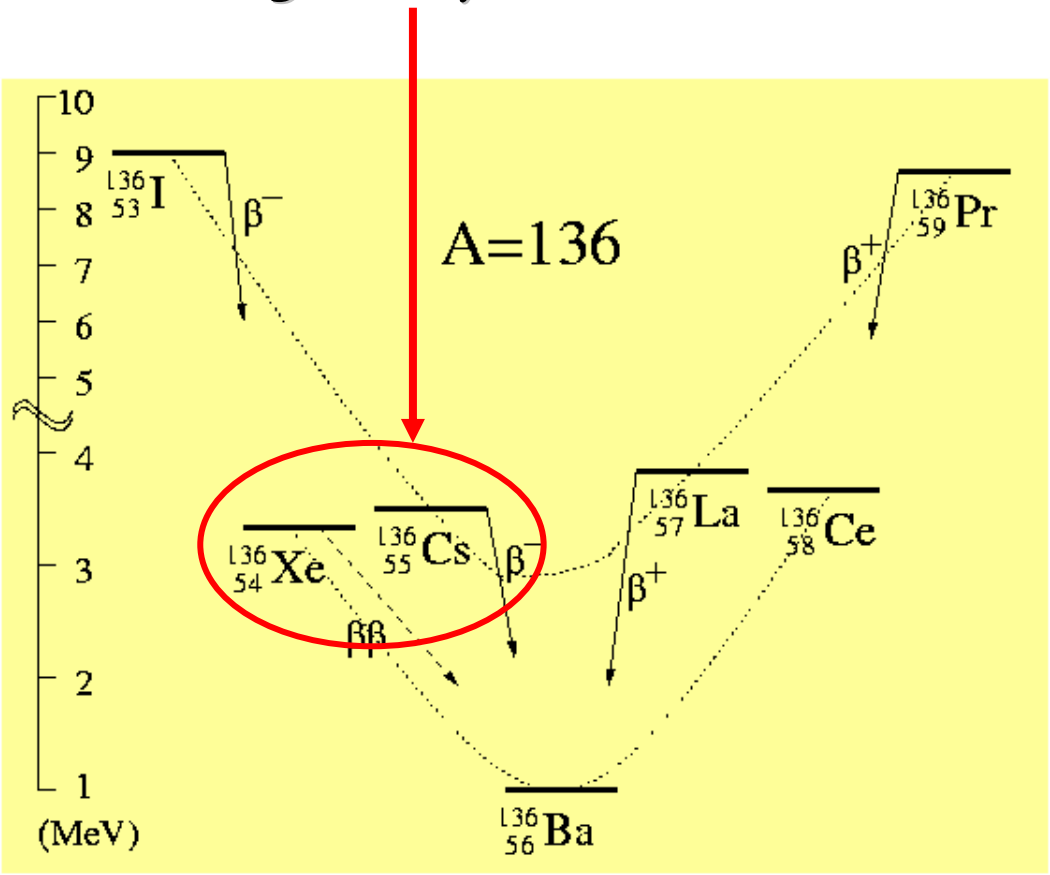


Expected sensitivity
0.20 - 0.25 eV

(assuming systematics are understood)

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

2 neutrino and neutrino-less ββ decay

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

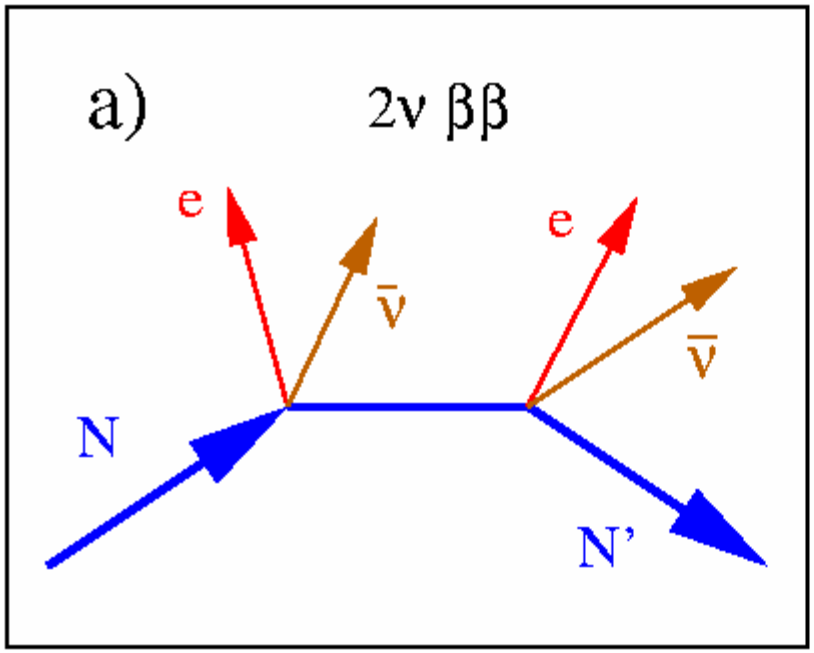
0ν mode: a hypothetical process can happen only if:

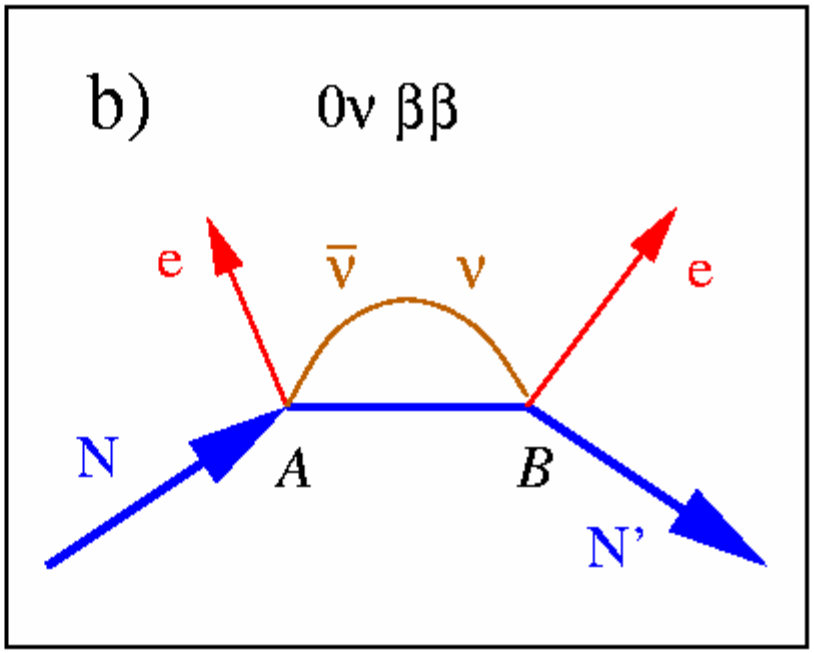
$$\left.\begin{array}{l} M_\nu \neq 0 \\ \nu = \bar{\nu} \end{array}\right\}$$

Since helicity has to "flip"

$|\Delta L| = 2$

$|\Delta(B-L)| = 2$





In the last 10 years there has been a transition

1) From a few kg detectors to 100s or 1000s kg detectors
→ Think big: qualitative transition from cottage industry to large experiments

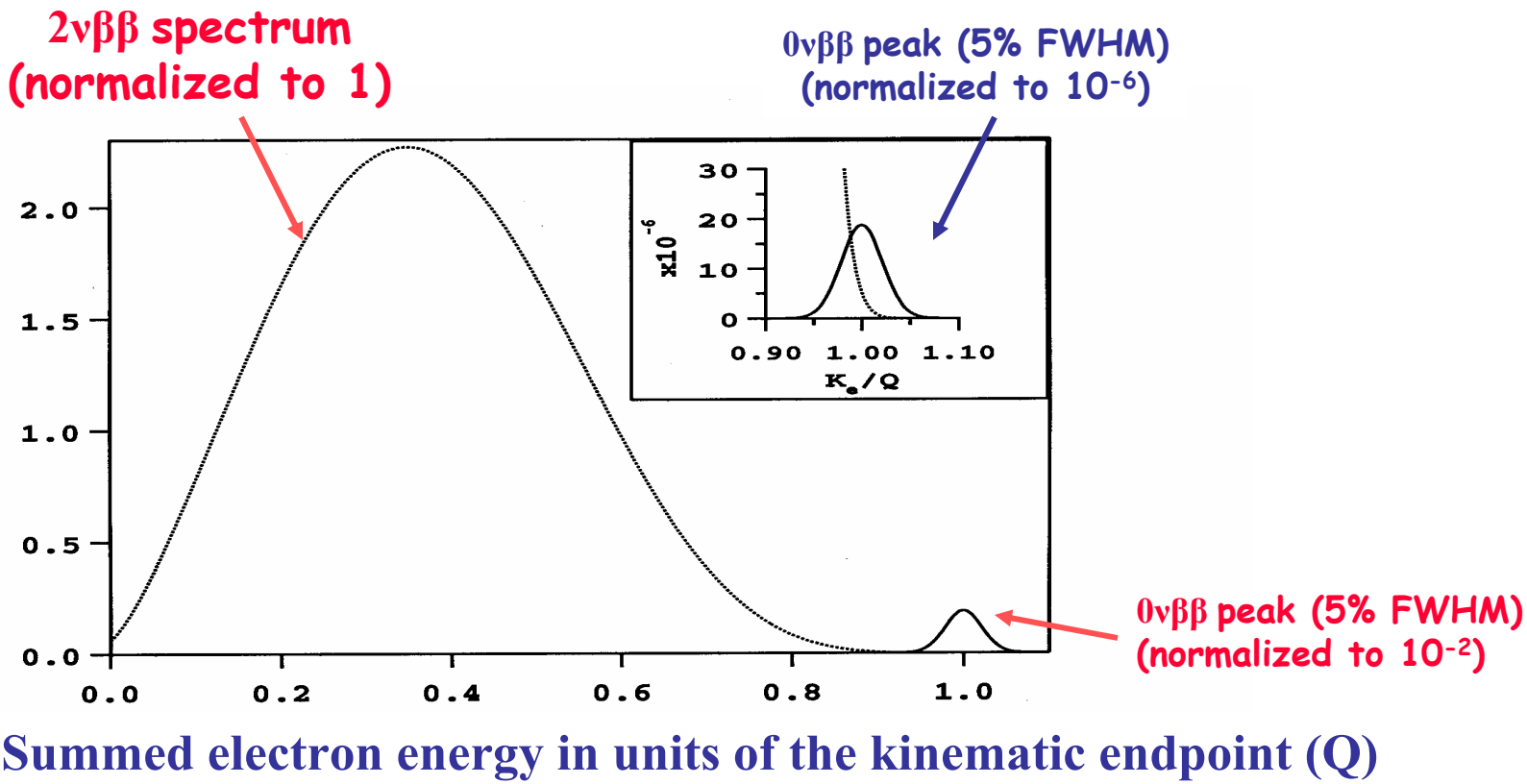
2) From "random shooting" to the knowledge that at least the inverted hierarchy will be tested

Discovering 0νββ decay:

→ *Discovery of the neutrino mass scale*
→ *Discovery of Majorana particles*
→ *Discovery of lepton number violation*

Background due to the Standard Model 2νββ decay

from S.R. Elliott and P. Vogel, Ann.Rev.Nucl.Part.Sci. **52** (2002) 115.



The two can be separated in a detector with good energy resolution

If $0\nu\beta\beta$ is due to light ν Majorana masses

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta}\, G^{0\nu\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

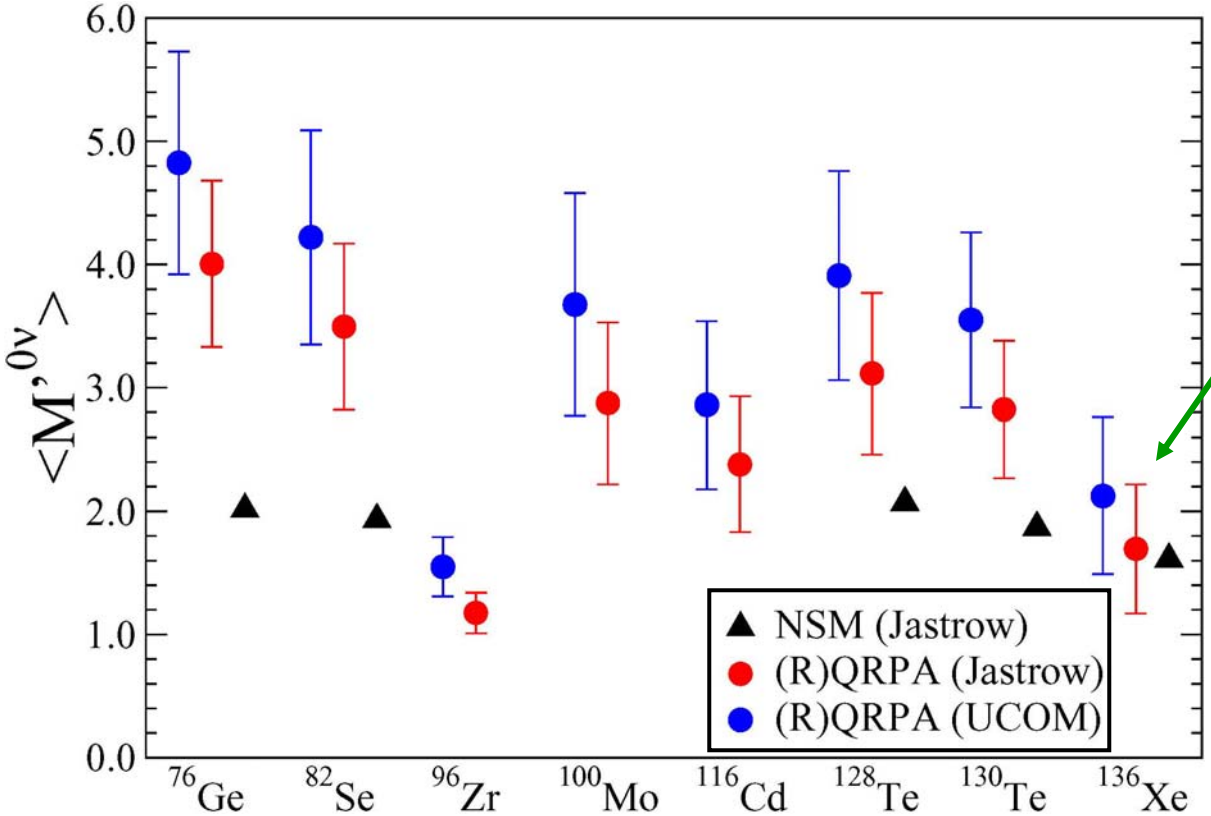
$G^{0\nu\beta\beta}$ a known phasespace factor

$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\langle m_\nu \rangle = \sum_{i=1}^{3} \left| U_{e,i} \right|^2 m_i\, \varepsilon_i$$

effective Majorana ν mass
($\varepsilon_i = \pm 1$ if CP is conserved)

Much progress made recently in accuracy of nuclear matrix elements.
(e.g. was found that the main uncertainly in (R)QRPA calculations comes from the single particle space around the Fermi surface.
→ Can *use the measured 2νββ $T_{1/2}$ to make a correction.*)



Lower bound on $T_{1/2}$ used for ^{136}Xe

F.Simkovic et al.
Phys.Rev.C 77 (2008) 045503

Still, if/once 0νββ decay is discovered, the $T_{1/2}$ in more than one nucleus will be needed to pin down neutrino masses

Present Limits for 0ν double beta decay

Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			$>1.4*10^{22}$ (90%CL)	
^{76}Ge	Ge diode	~47.7	$>1.9*10^{25}$ (90%CL)	<0.35
^{82}Se			$>2.1*10^{23}$ (90%CL)	
^{100}Mo			$>5.8*10^{23}$ (90%CL)	
^{116}Cd			$>1.7*10^{23}$ (90%CL)	
^{128}Te	TeO_2 cryo		$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~12	$>3*10^{24}$ (90%CL)	<0.19 – 0.68
^{136}Xe	Xe scint	~4.5	$>1.2*10^{24}$ (90%CL)	<1.1 - 2.9
^{150}Nd			$>1.2*10^{21}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

There is also a discovery claim (using ^{76}Ge)

EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

H.V. KLAPDOR-KLEINGROTHAUS[1,3],
A. DIETZ[1], H.L. HARNEY[1], I.V. KRIVOSHEINA[1,2]
[1] *Max-Planck-Institut für Kernphysik, Postfach 10 39 80, D-69029 Heidelberg, Germany*
[2] *Radiophysical-Research Institute, Nishnii-Novgorod, Russia*
[3] *Spokesman of the GENIUS and HEIDELBERG-MOSCOW Collaborations,*

Part of the Heidelberg-Moscow collaboration
Mod. Phys Lett. A27 (2001) 2409

With the values $T_{1/2}^{0\nu\beta\beta} = 2.23^{+0.44}_{-0.31}$ $m_\nu^{eff}=0.32\pm0.03$

…but this is a controversial matter (see details in)

C.A.Aalseth Mod. Phys. Lett. A17 (2002) 1475
F.Feruglio et al. Nucl.Phys. B637 (2002) 345
Addendum-ibid. B659 (2003) 359
Yu.Zdesenko et al. Phys.Lett. B 546 (2002) 206
H.L.Harney Mod.Phys.Lett. A16 (2001) 2409
A.M.Bakalyarov et al. hep-ex/0309016
H.V.Klapdor-Kleingrouthaus et al. Phys. Lett. B 586 (2004) 198
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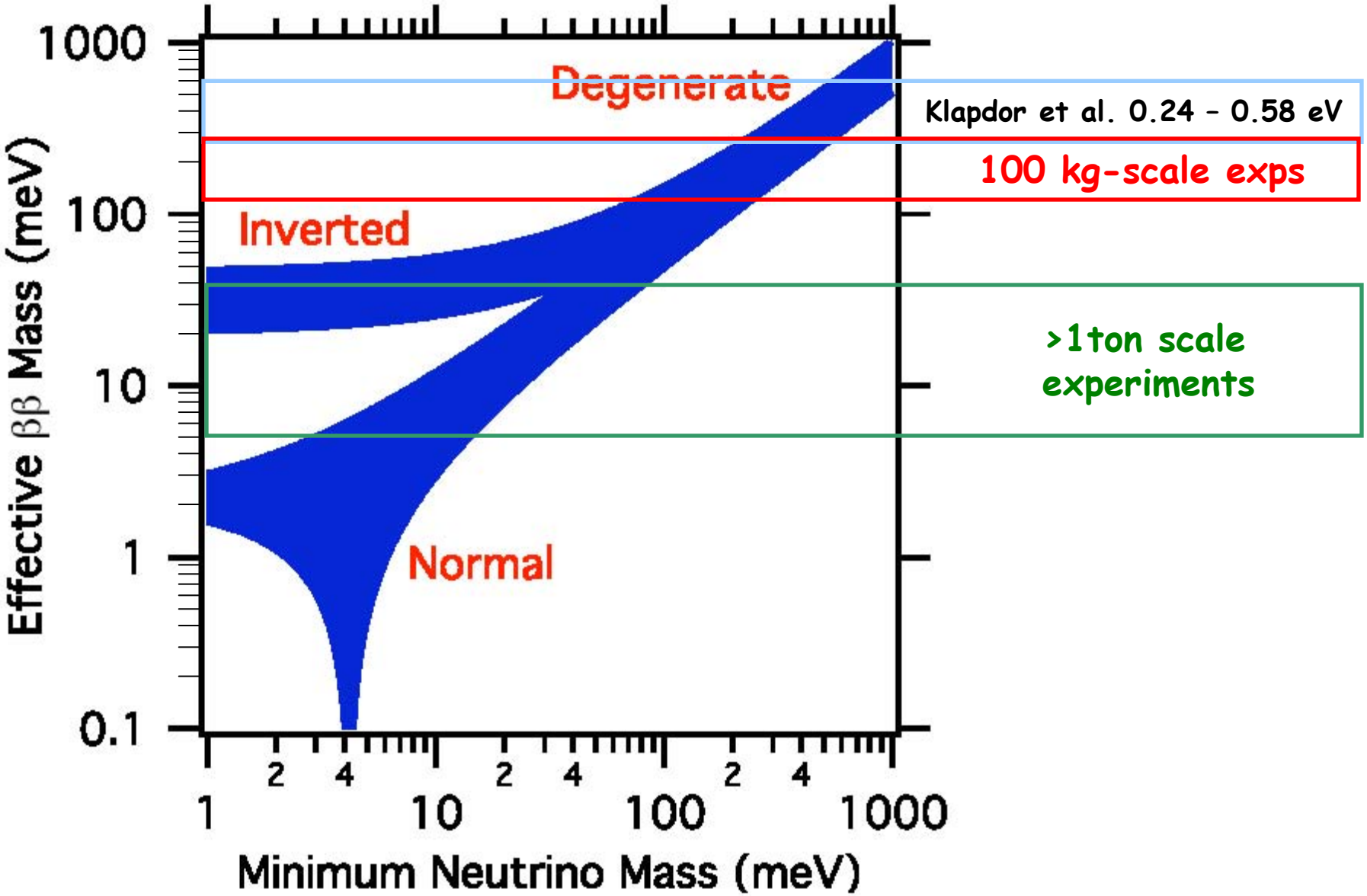
Future experiments (a very broad brush, personal view)

Isotope	Experiment	Main principle	Fid mass	Lab
^{76}Ge	Majorana†	Eres,2site tag, Cu shield	30-60kg	SUSEL
	Gerda†	Eres,2site tag, LAr shield	34.3 kg	G Sasso
	MaGe/GeMa	See above	~1ton	DUSEL? GS?
^{150}Nd	SNO+	Size/shielding	56 kg	SNOlab
^{150}Nd or ^{82}Se	SuperNEMO‡	Tracking	100 kg	Canfranc Frejus
^{130}Te*	CUORE	E Res.	204 kg	G Sasso
^{136}Xe	EXO	Tracking/Eres	150 kg	WIPP
		Ba tag, Track/Eres	1-10ton	DUSEL?

* No isotopic enrichment in baseline design
† Plan to merge efforts for ton-scale experiment
‡ Non-homogeneous detector

See this J.Loach and K.O'Sullivan

Sensitivity of future 0νββ decay experiments



Plot from Avignone, Elliott, Engel; Rev Mod Phys 80 (2008) 481

Conclusions

Last 15 years:
- discovery of neutrino oscillations
- confirm that MSW is the dominant mechanism for flavor conversion in the Sun
- begin precision measurements of mixing parameters
- begin the study of geological neutrinos

Next 15 years:
- discover the neutrino mass scale
- measure/bound θ_{13} to <1%
- observe SN neutrinos with SK, KamLAND, Ice^3, Borexino, LVD, SNO+, LIGO?,…
- study solar physics with neutrinos

Further out in the future…:
- precision geophysics with neutrinos
- CP violation in the lepton sector
- observe relic neutrinos