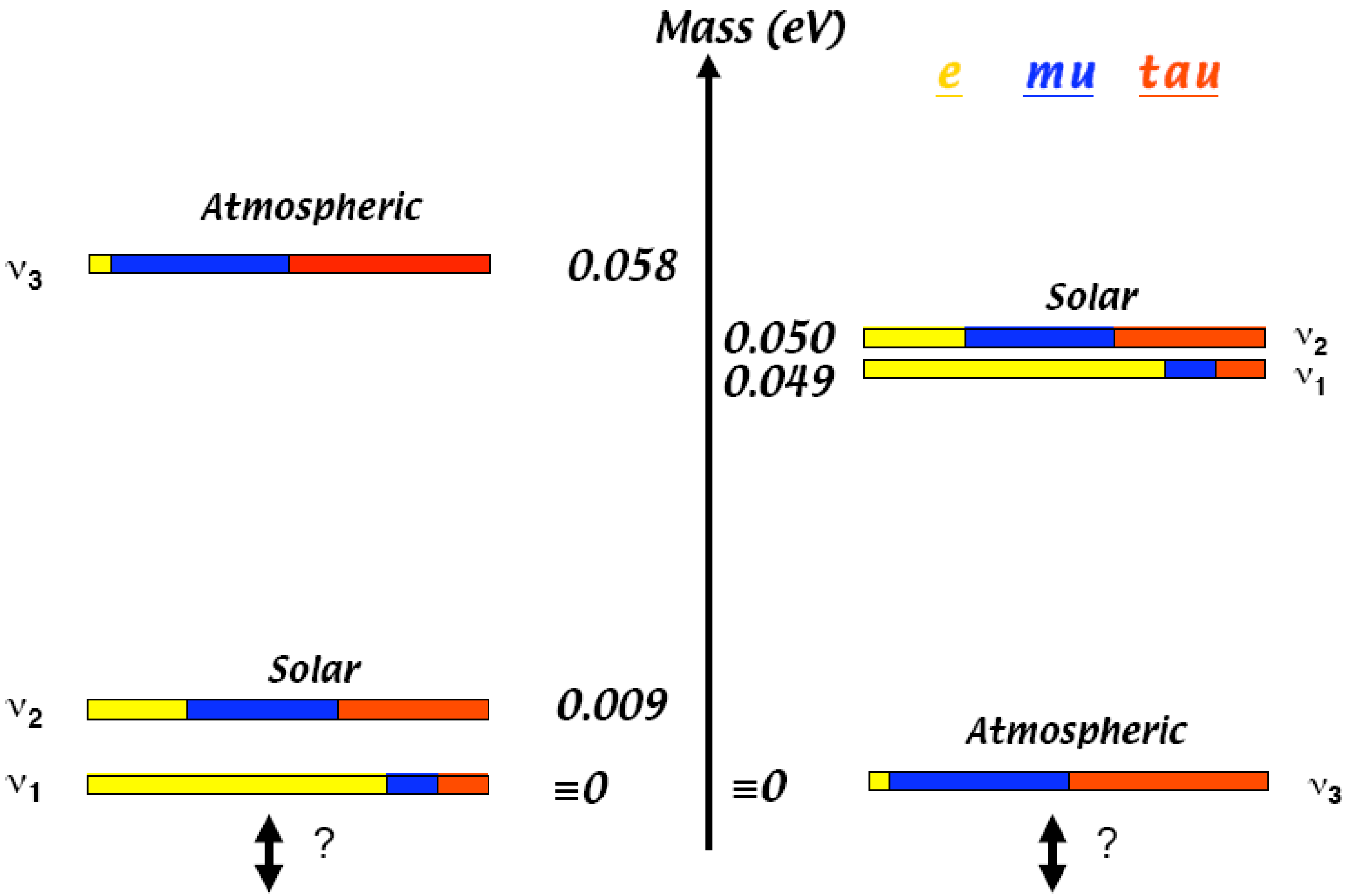
Neutrino Masses and Mixing



Neutrino Mixing versus Quark Mixing

Leptons

$$U_\ell = \begin{pmatrix} 0.85 & 0.52 & < 0.053 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & 0.59 & 0.70 \end{pmatrix}$$

Why so different???

Quarks

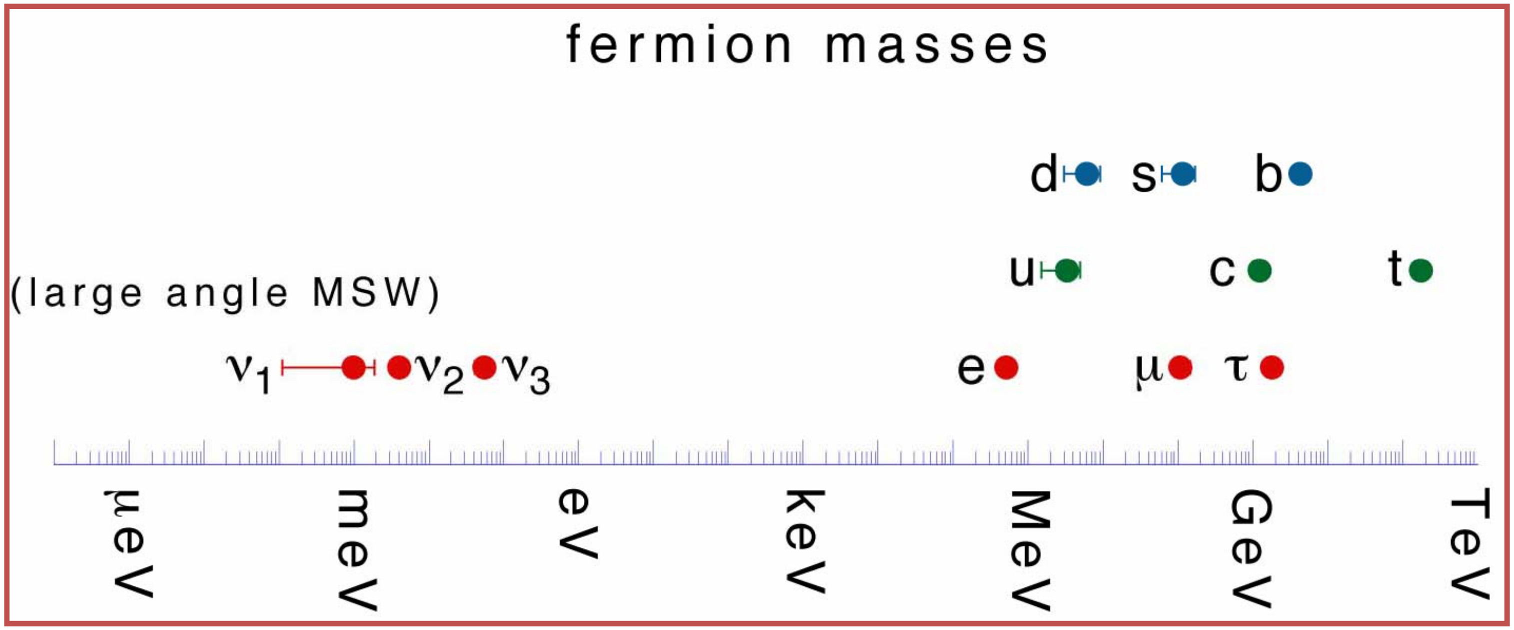
$$V_q = \begin{pmatrix} 0.976 & 0.22 & 0.003 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{pmatrix}$$

Tri-bimaximal neutrino mixing:

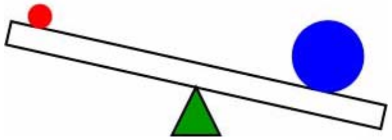
$$U_{\mathrm{TBM}} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -\sqrt{1/6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -\sqrt{1/6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

(Harrison, Perkins, Scott 1999)

The Mass Puzzle

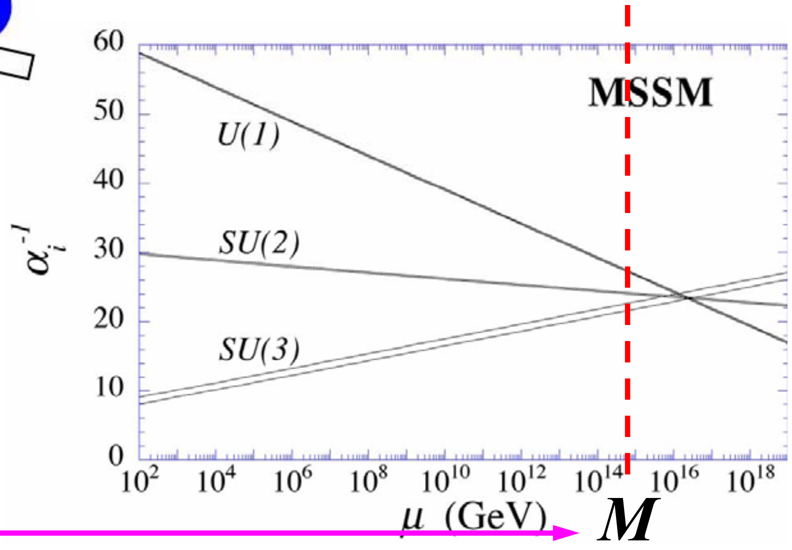


"Seesaw mechanism"



$$\overline{\ }_L \quad \overline{\ }_R \qquad \begin{array}{cc} & m_D \\ m_D & M \end{array} \qquad \begin{array}{c} L \\ R \end{array}$$

$$\boxed{m \qquad \frac{m_D^2}{M} \qquad m_D}$$



Heavy Majorana Neutrino

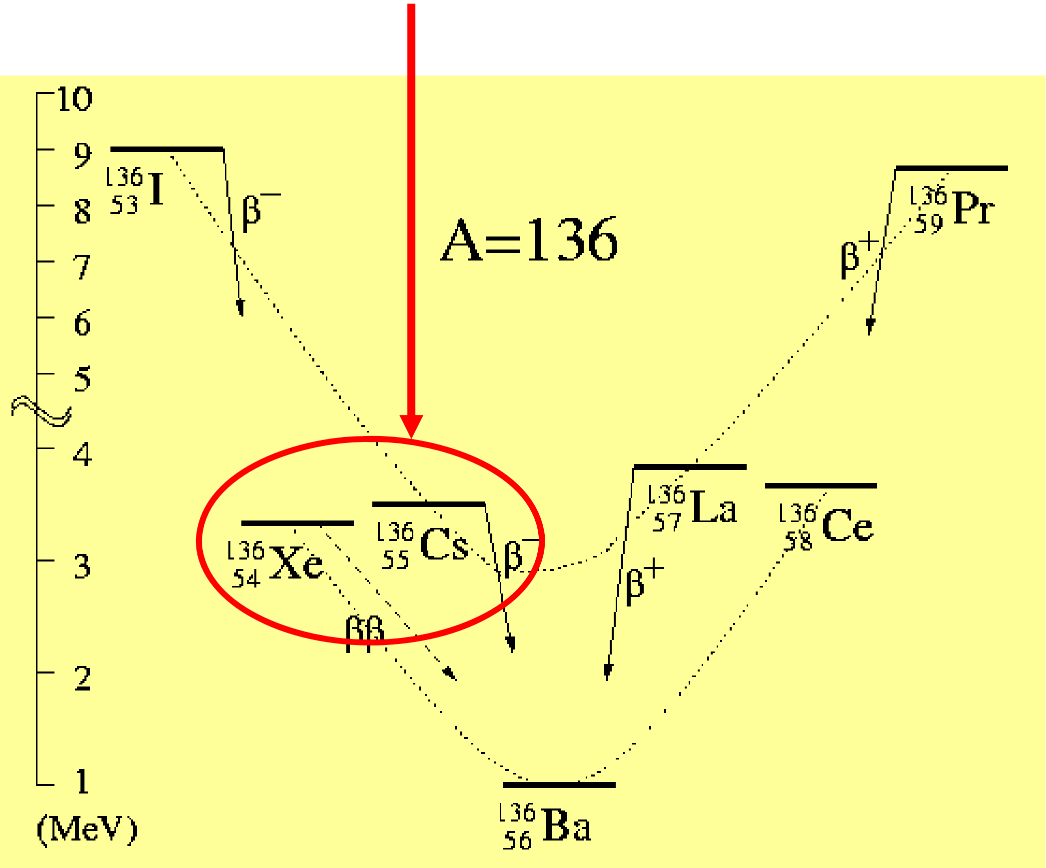
- Connection with high mass scales
- With CP violation provides a basis for "leptogenesis"
- Majorana neutrinos ($\nu = \overline{\nu}$)

Goals for the future

- Determine mass values
- Is neutrino = antineutrino?
- Establish θ_{13} non-zero
- Measure CP violation (matter-antimatter difference)

Double-beta decay:

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



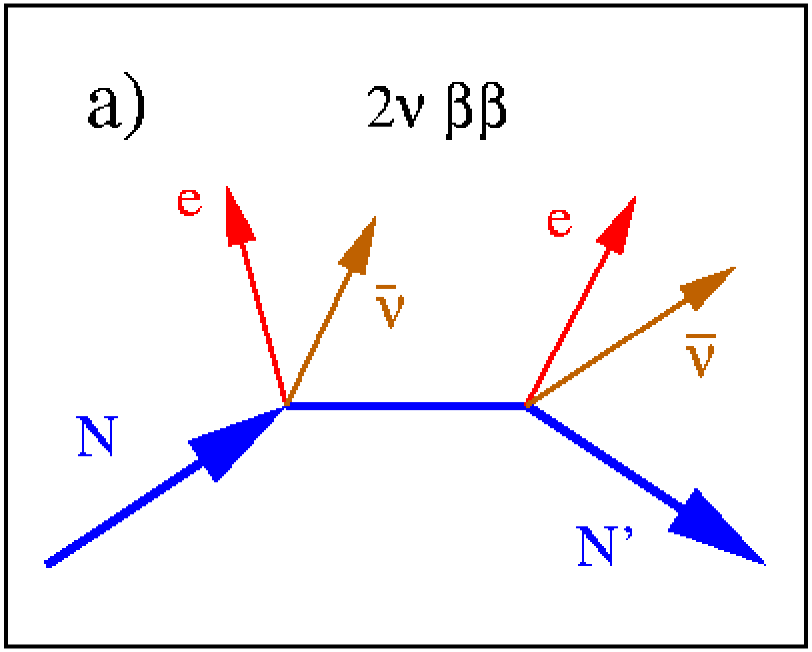
Candidate nuclei with Q>2 MeV

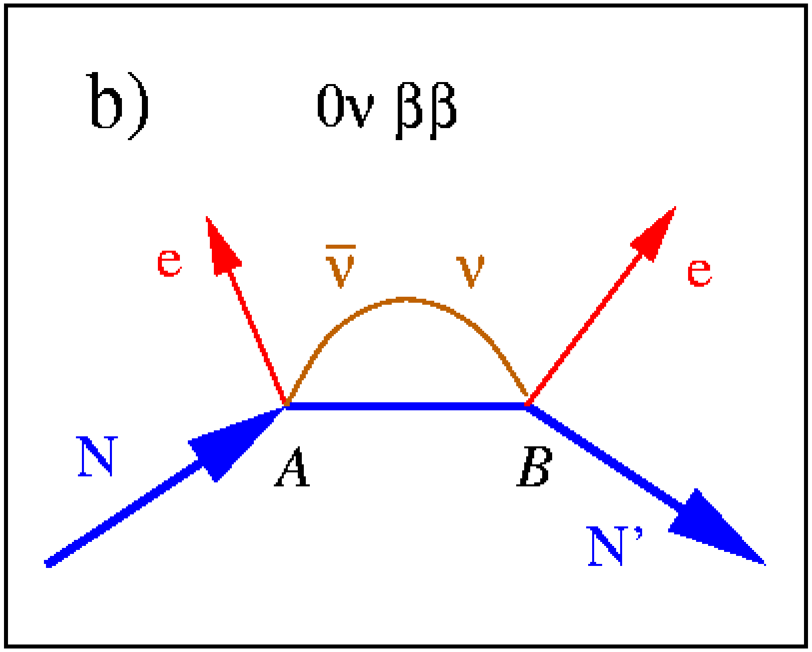
Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	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

There are two varieties of $\beta\beta$ decay

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

0ν mode: a hypothetical
process can happen
only if: $\nu = \bar{\nu}$ (Majorana)
$|\Delta L| = 2$
$|\Delta(B-L)| = 2$
$M_\nu \neq 0$ (helicity flip)



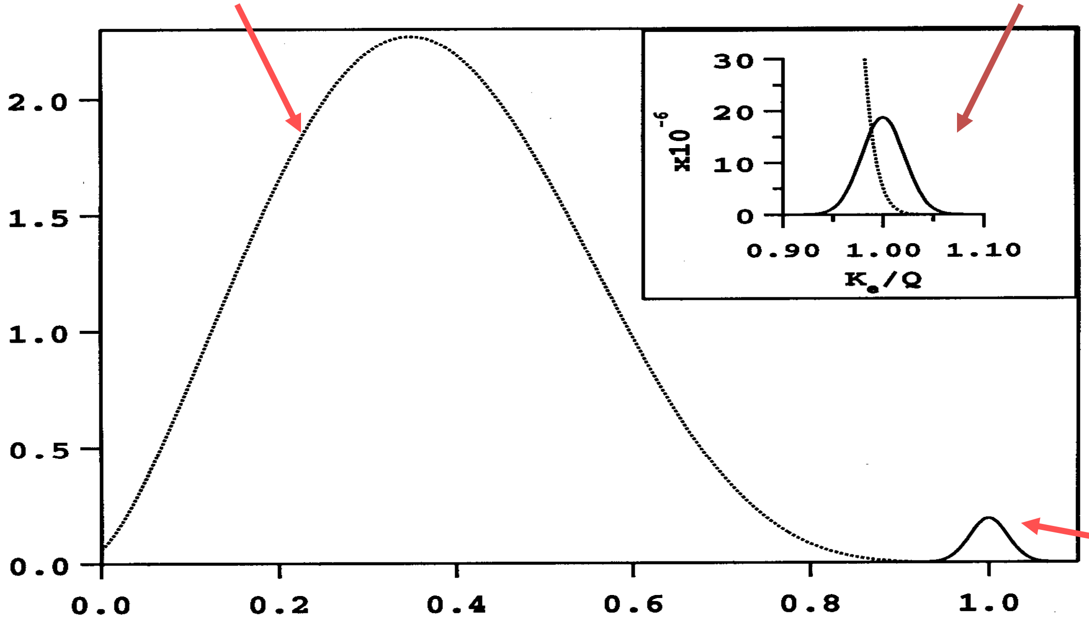


Background due to the Standard Model $2\nu\beta\beta$ decay

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

$2\nu\beta\beta$ spectrum
(normalized to 1)

$0\nu\beta\beta$ peak (5% FWHM)
(normalized to 10^{-6})

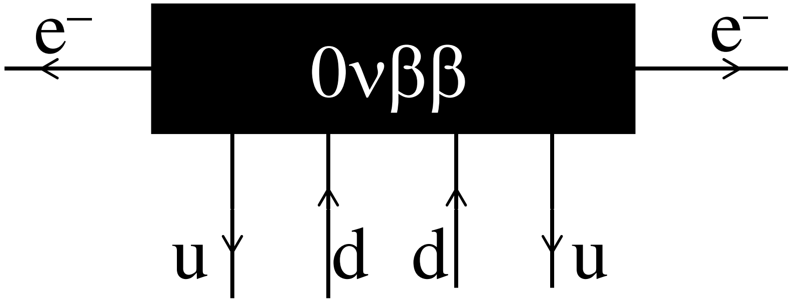


$0\nu\beta\beta$ peak (5% FWHM)
(normalized to 10^{-2})

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

Neutrinoless ββ Decay

Whatever processes cause 0νββ, its observation would imply the existence of a Majorana mass term and thus **would represent New Physics:** Schechter and Valle,82



By adding only Standard model interactions we obtain

$(\bar{\nu})_R \rightarrow (\nu)_L$ ***Majorana mass term***

→ Observing the 0νββ decay implies that ν are massive Majorana particles.

Majorana Phases

Most general form for 3 generation flavor mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} \; \nu_1 \\ e^{i\alpha_2/2} \; \nu_2 \\ \nu_3 \end{pmatrix}$$

- α's are CP violating phases (as is δ)
- α's do not contribute to oscillations)

0νββ Theory

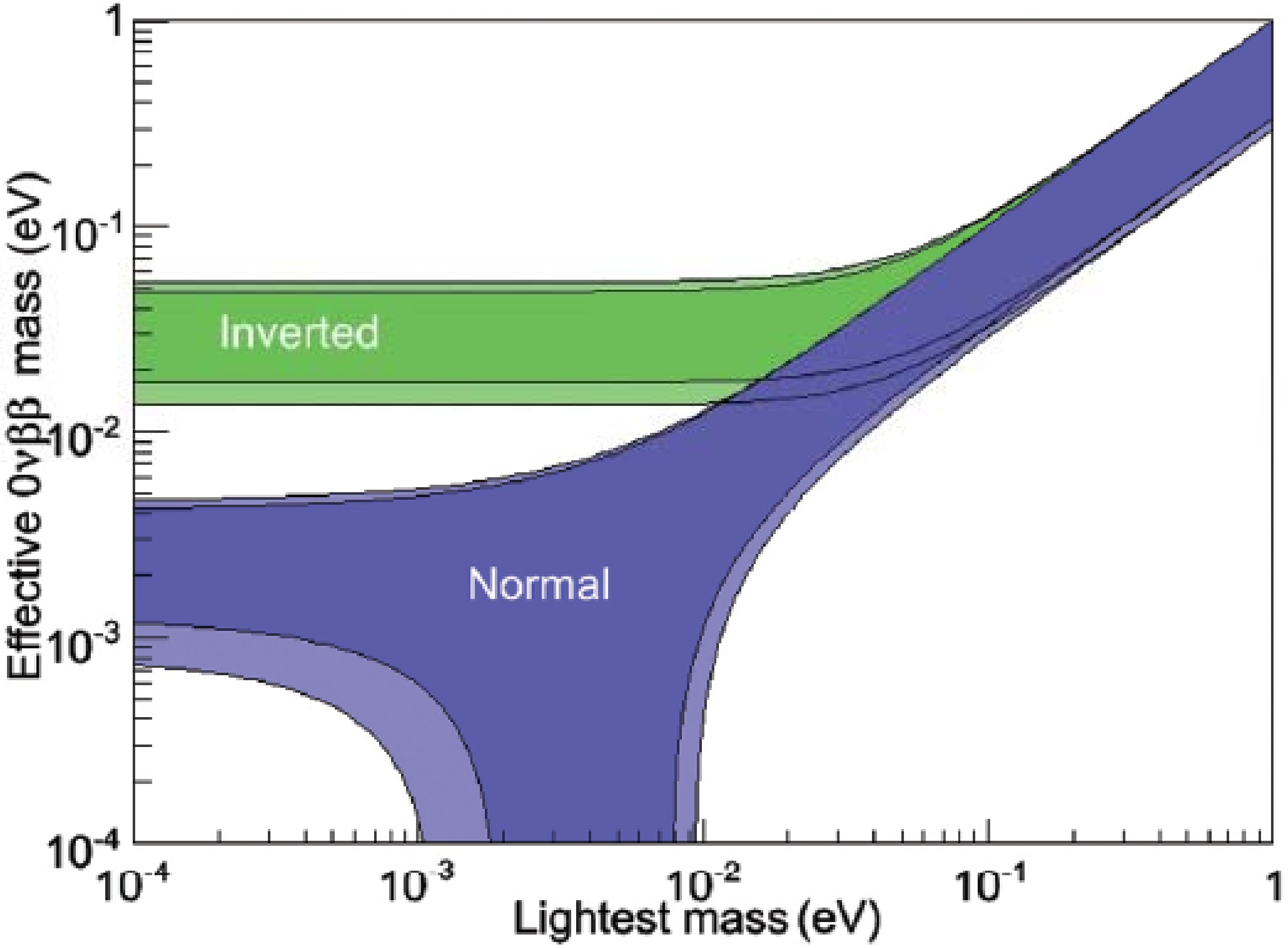
$$[T^{0\nu}_{1/2}(0^+ \to 0^+)]^{-1} \;=\; G^{0\nu}(E_0, Z)\left|M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2} M^{0\nu}_F\right|^2 \langle m_{\beta\beta}\rangle^2 \;, \qquad (37)$$

where $G^{0\nu}$ is the exactly calculable phase space integral, $\langle m_{\beta\beta}\rangle$ is the effective neutrino mass and $M^{0\nu}_{GT}$, $M^{0\nu}_F$ are the nuclear matrix elements.

The effective neutrino mass is

$$\langle m_{\beta\beta}\rangle = |\sum_i |U_{ei}|^2 m_{\nu_i} e^{i\alpha_i}| \;, \qquad (38)$$

where the sum is only over light neutrinos $(m_i < 10$ MeV$)$ ^{4}. The Majorana phases α_i were defined earlier in Eq.(9). If the neutrinos ν_i are CP eigenstates, α_i is either 0 or π. Due to the presence of these unknown phases, cancellation of terms in the sum in Eq.(38) is possible, and $\langle m_{\beta\beta}\rangle$ could be smaller than any of the m_{ν_i}.


Inverted
Normal
Effective 0νββ mass (eV)
Lightest mass (eV)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1

Nuclear Matrix Elements

The nuclear matrix elements, Gamow-Teller and Fermi, appear in the combination

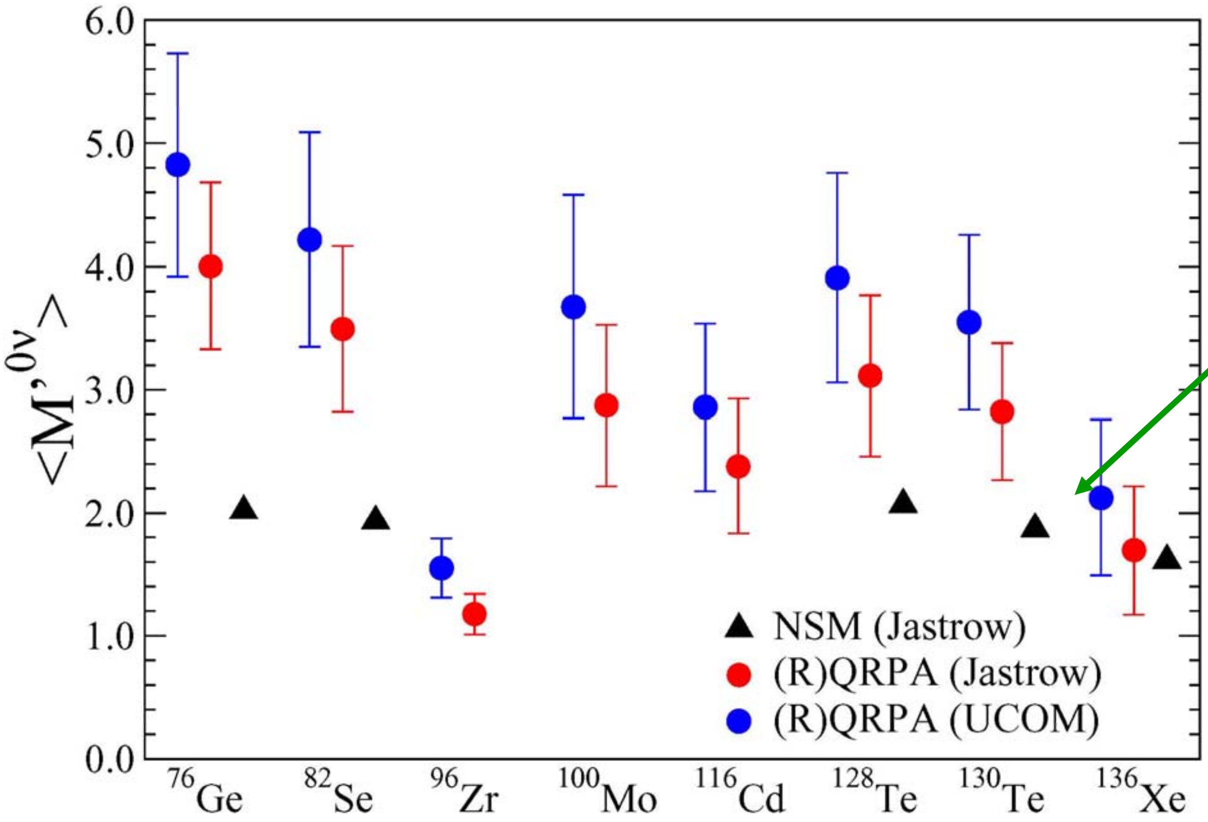
$$M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu} \equiv \langle f | \sum_{lk} H(r_{lk}, \bar{E}_m) \tau_l^+ \tau_k^+ \left(\vec{\sigma}_l \cdot \vec{\sigma}_k - \frac{g_V^2}{g_A^2} | i \rangle \right) \quad . \qquad (39)$$

The summation is over all nucleons, $|i\rangle, (|f\rangle)$ are the initial (final) nuclear states, and $H(r_{lk}, \bar{E}_m)$ is the 'neutrino potential' (Fourier transform of the neutrino propagator) that depends (essentially as $1/r$) on the internucleon distance. When evaluating these matrix elements the short-range nucleon-nucleon repulsion must be taken into account due to the mild emphasis on small nucleon separations.

Much progress made recently in accuracy of nuclear matrix elements.

(e.g. was found that main uncertainly in (R)QRPA calculations comes from the single particle space around the Fermi surface.

→ *Can use the measured $2\nu\beta\beta$ $T_{1/2}$ to make a correction.*)



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

F.Simkovic et al.
arXiv:0710.2055

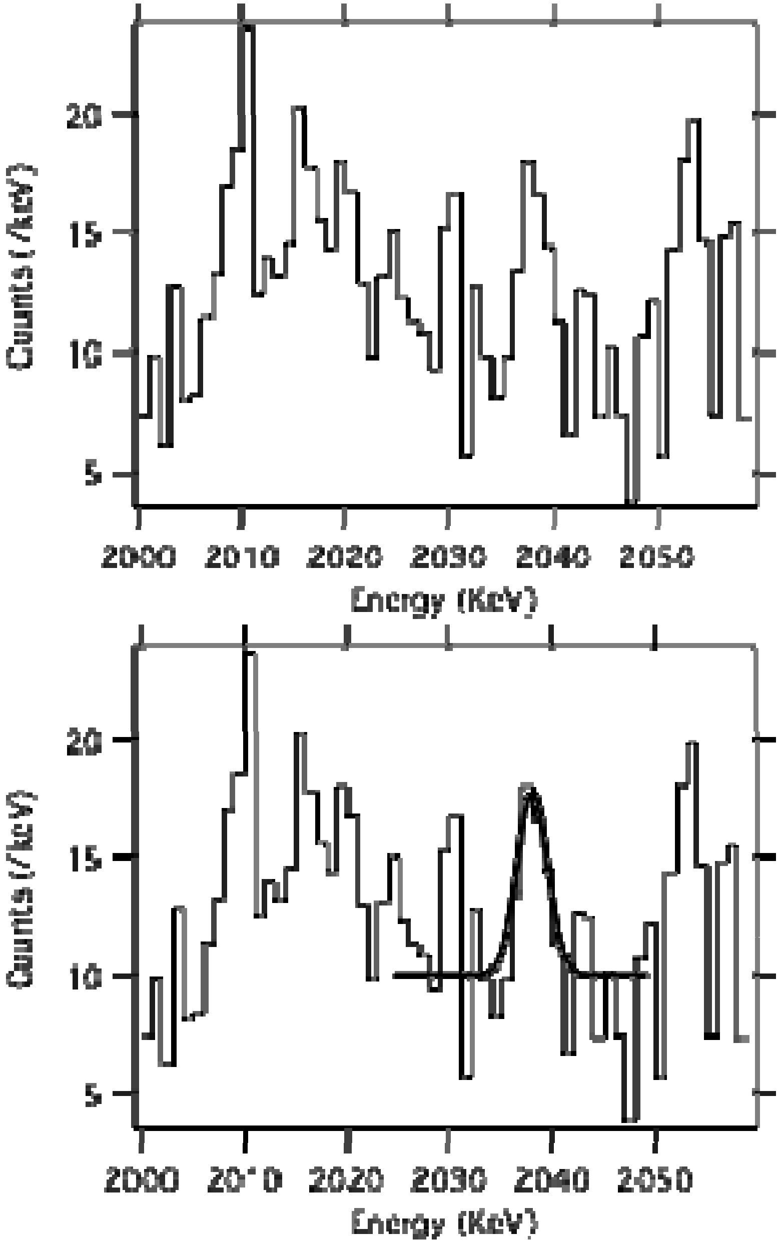
Still, if/once $0\nu\beta\beta$ decay is discovered, the $T_{1/2}$ in more than one nucleus will be needed to pin down neutrino masses

A Recent Claim for ^{76}Ge

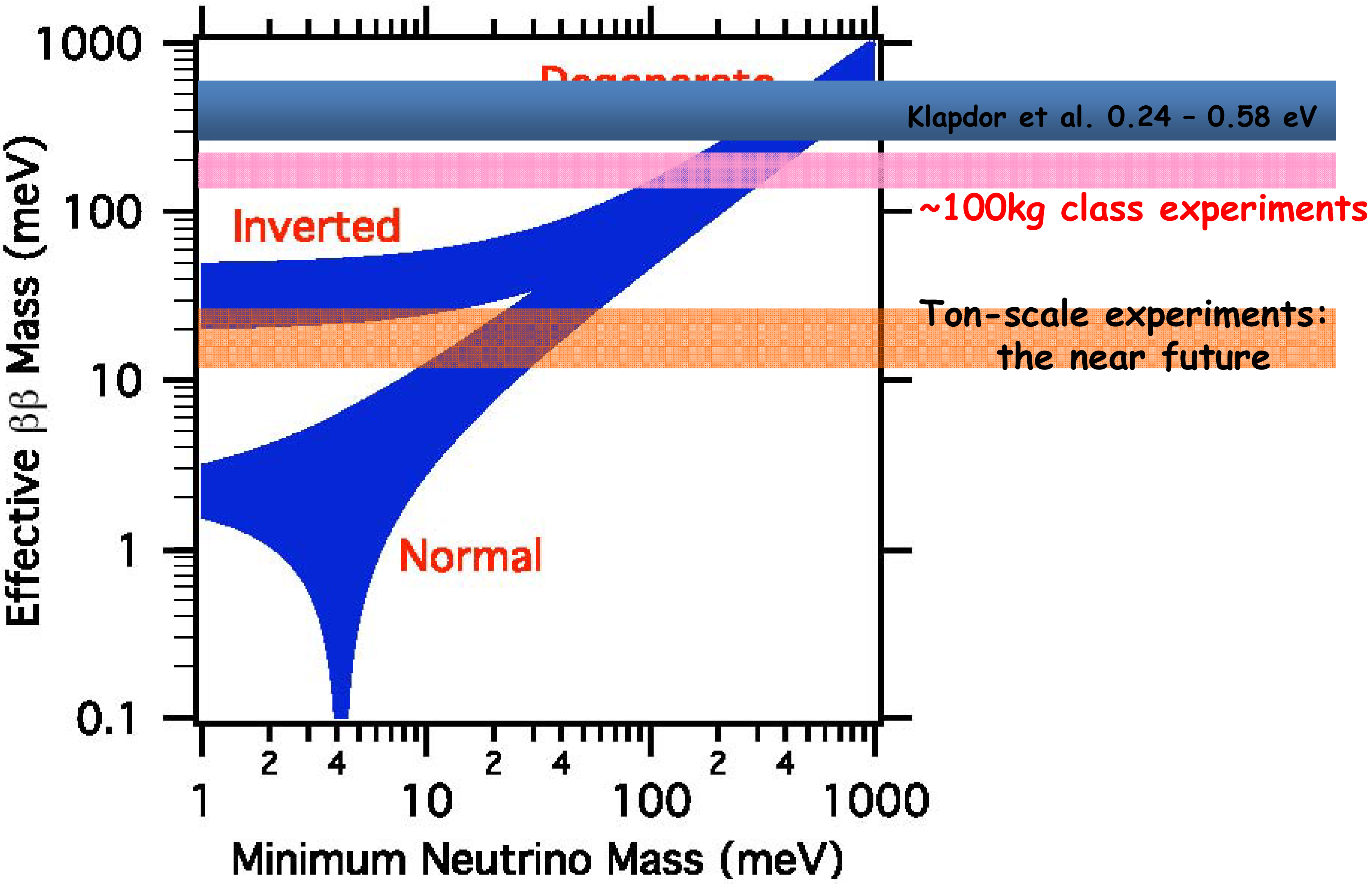
ββ is the search for a *very* rare peak on a continuum of background.

~70 kg-years of data
13 years

The "feature" at 2039 keV is arguably present.



NIM A522, 371 (2004)



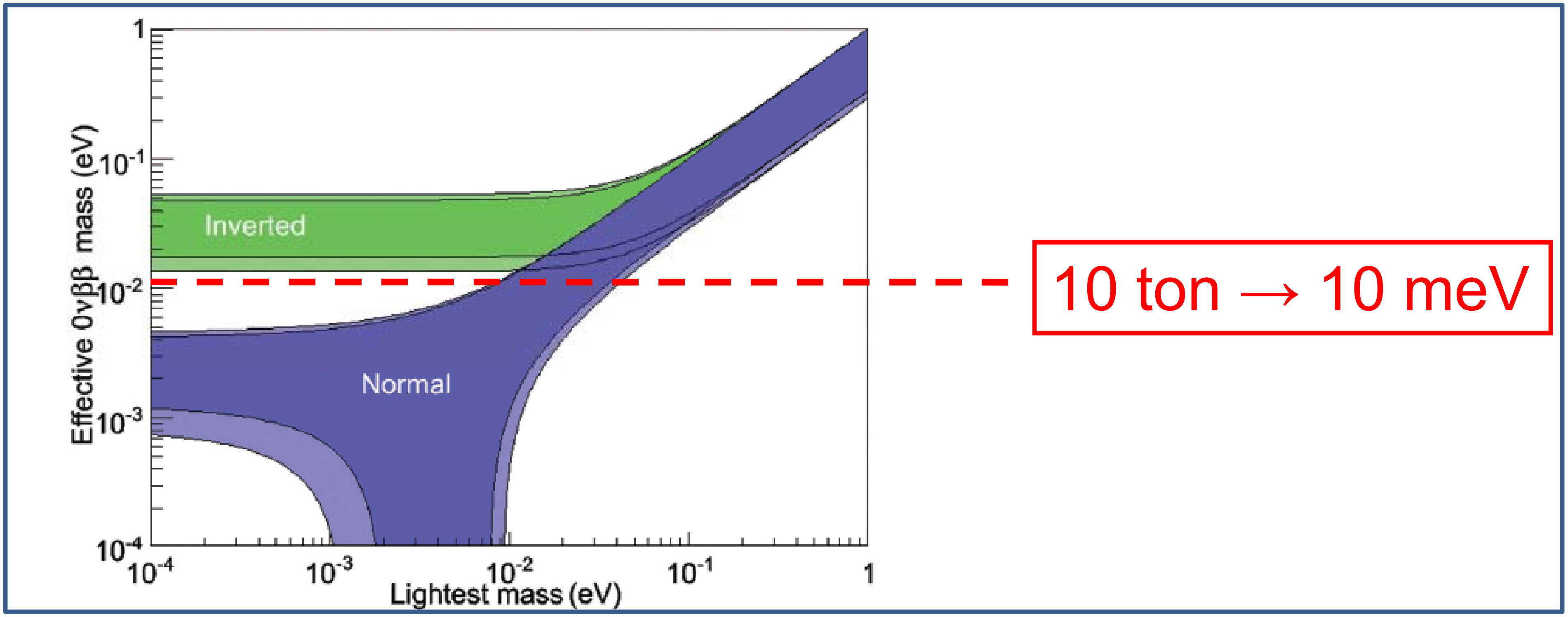
Klapdor et al. 0.24 – 0.58 eV

~100kg class experiments

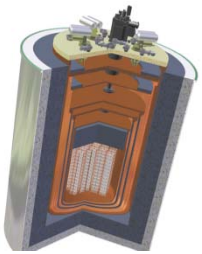
Ton-scale experiments:
the near future

Plot from Avignone, Elliott, Engel arXiv:0708.1033 (2007)

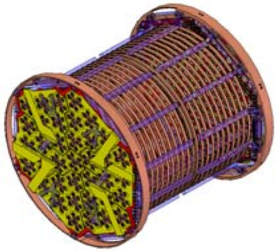
$\beta\beta$ Decay Experiments



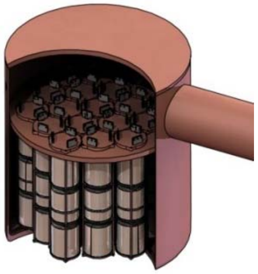
10 ton → 10 meV



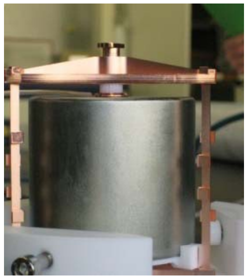
CUORE



EXO



Majorana



GERDA

Future experiments (a very broad brush, personal view)

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

Each exp above has a US component and some US funding. Funding source listed only if "major".
Experiments in red are US led.

[*] No isotopic enrichment in baseline design

[†] Plan to merge efforts for ton-scale experiment

[‡] Non-homogeneous detector

Back to Neutrino Mixing…

Maki - Nakagawa - Sakata Matrix

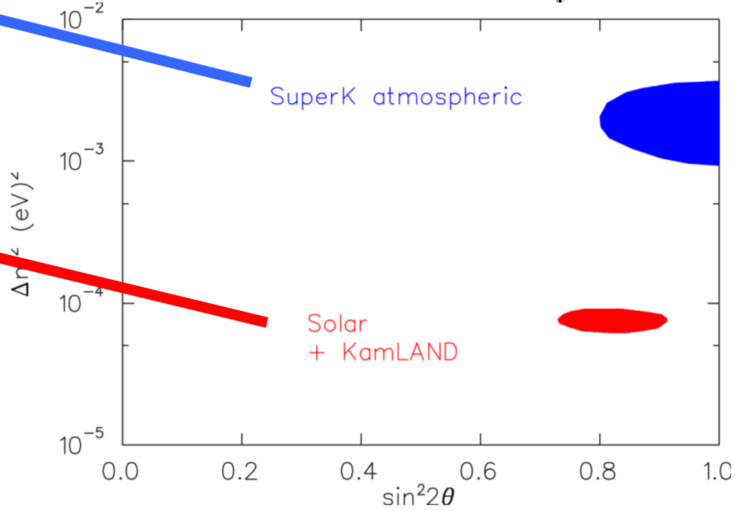
$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

$$\times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

Future Reactor Experiment!

CP violation



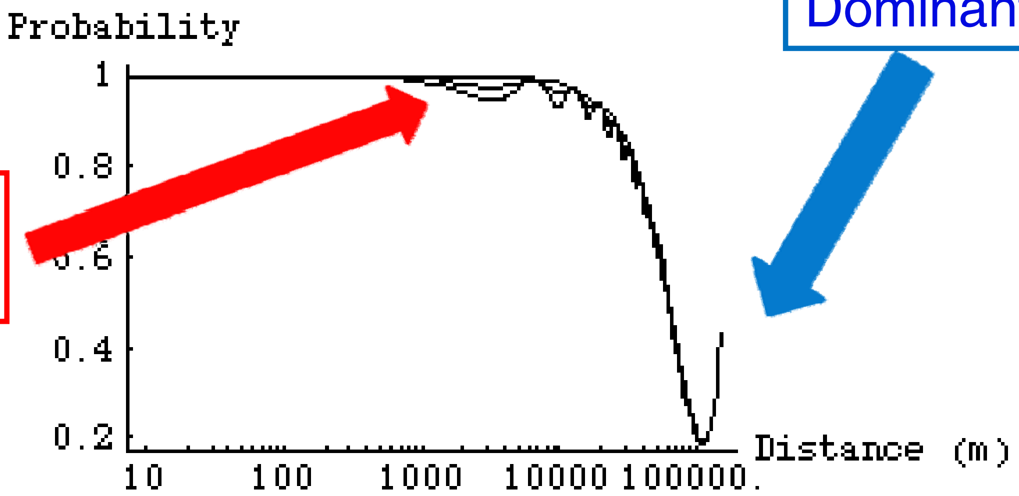
Reactor θ_{13} Neutrino Experiments

Under construction.

Proposed and R&D.

$\overline{\nu}_e$ Survival Probability

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



Dominant θ_{12} Oscillation

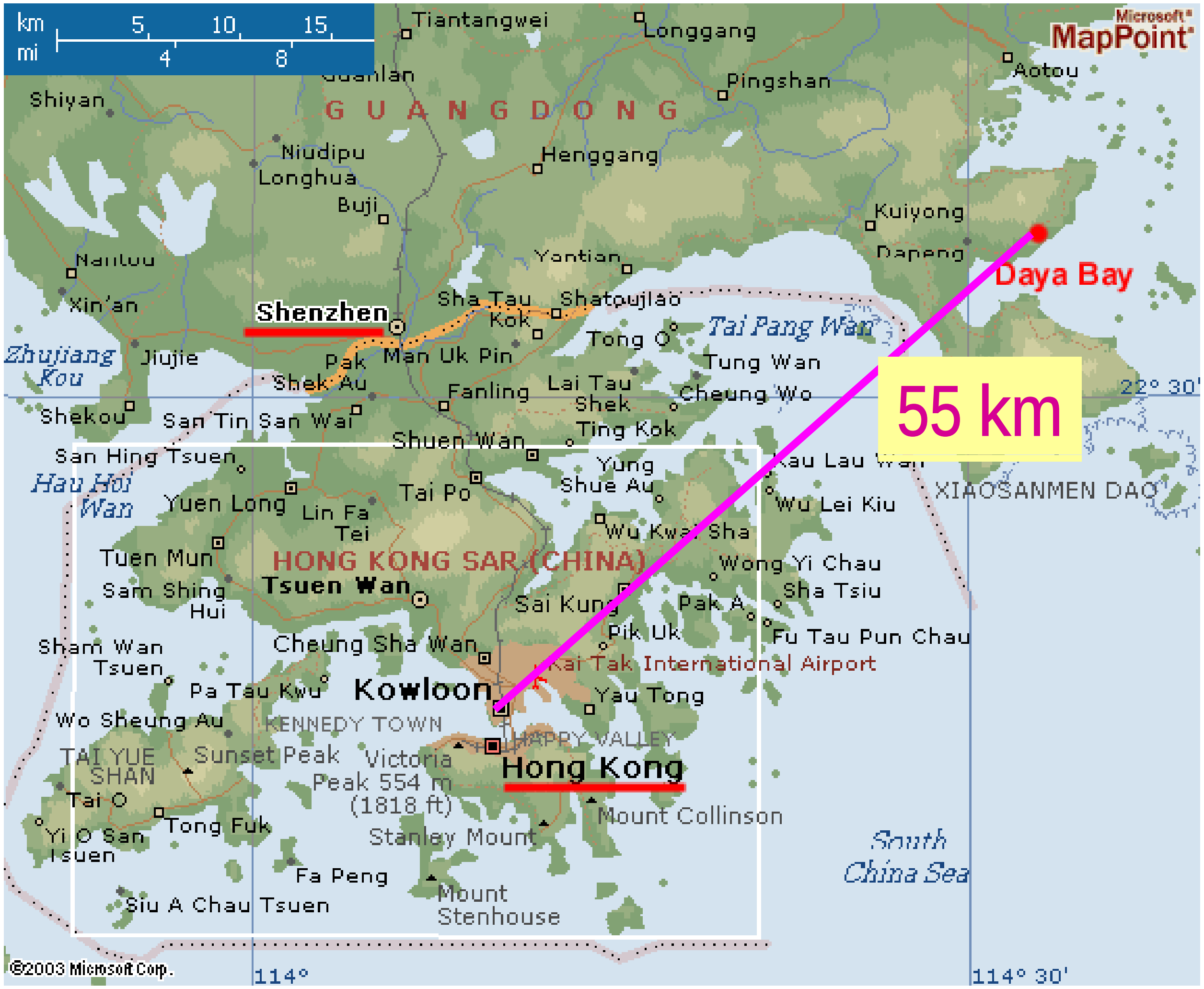
Subdominant θ_{13} Oscillation

- "Clean" measurements of θ, Δm^2
- No CP violation
- Negligible matter effects

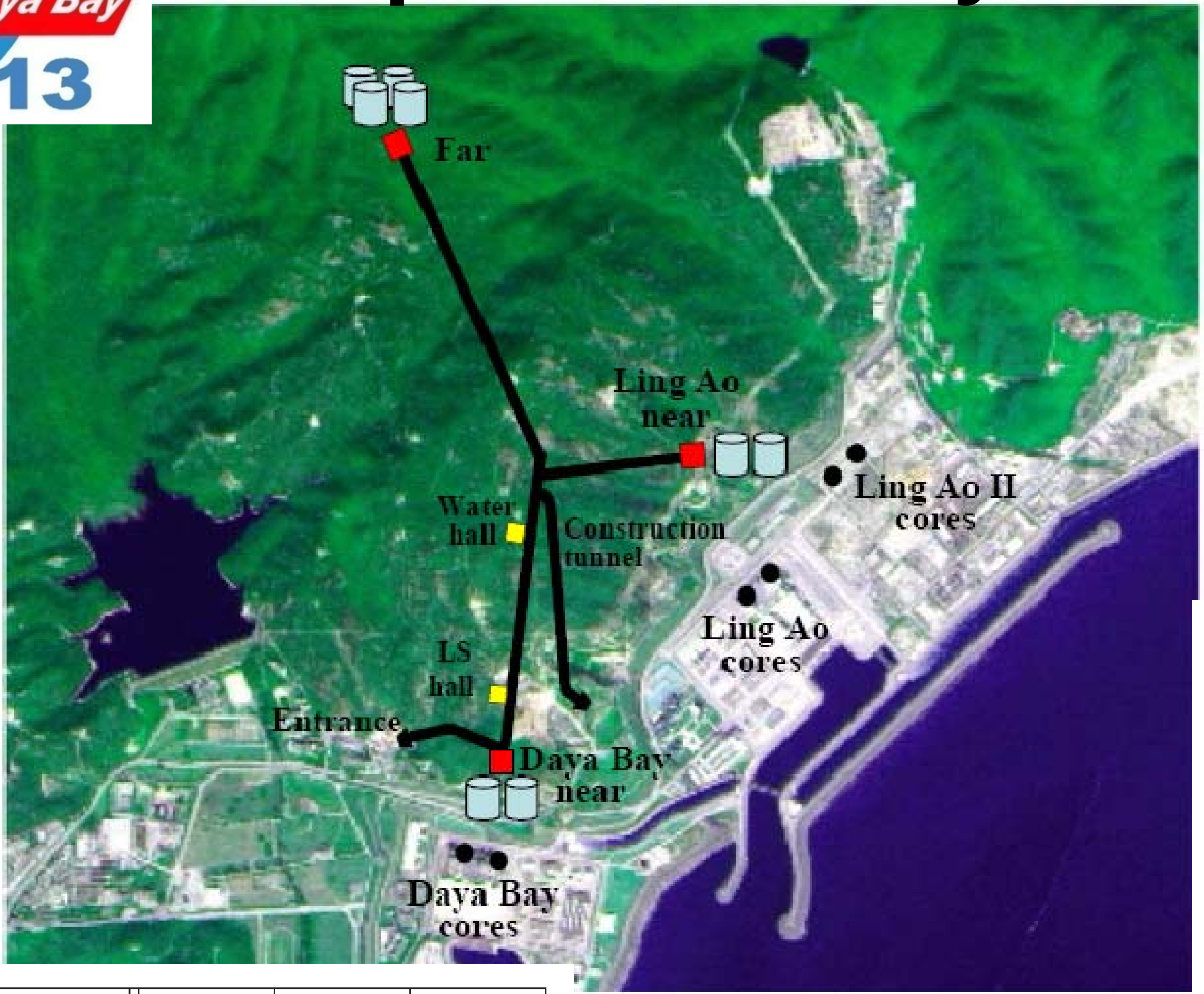
Daya Bay
Nuclear Power Plant

- 4 reactor cores, 11.6 GW
- 2 more cores in 2011, 5.8 GW
- Mountains provide overburden to shield cosmic-ray backgrounds
- Baseline ~2km
- Multiple detectors → measure <u>ratio</u>

Daya Bay NPP Location

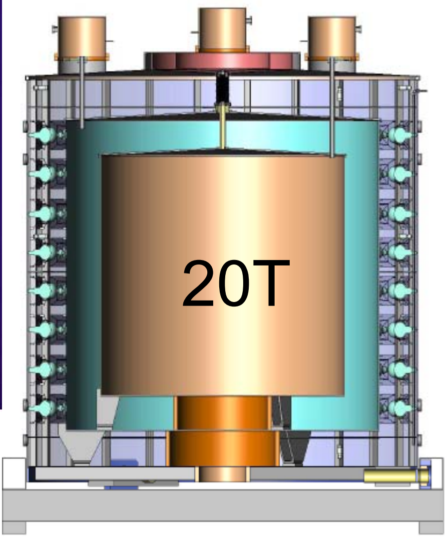


Experiment Layout



- Multiple detectors per site cross-check detector efficiency

- Two near sites sample flux from reactor groups



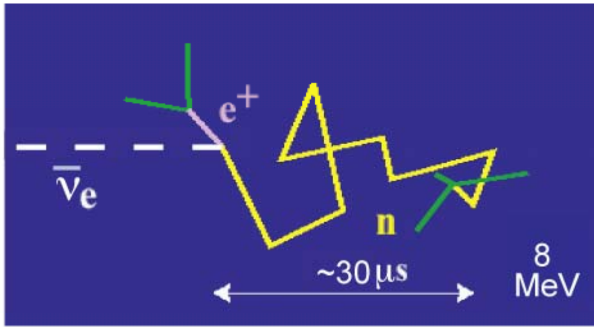
	DYB	LA	Far
DYB cores	363	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

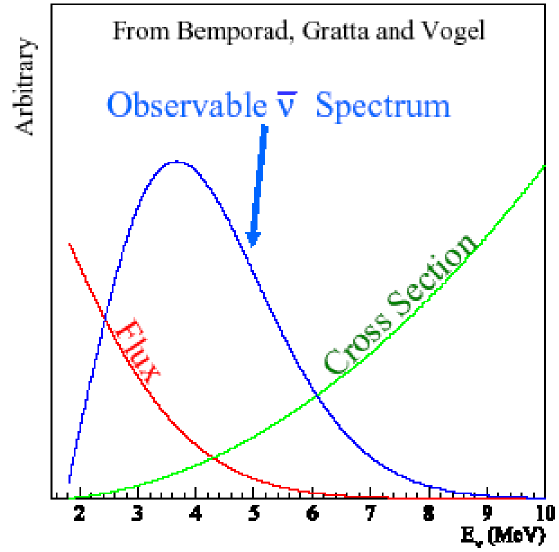
Total Tunnel length ~ 3000 m

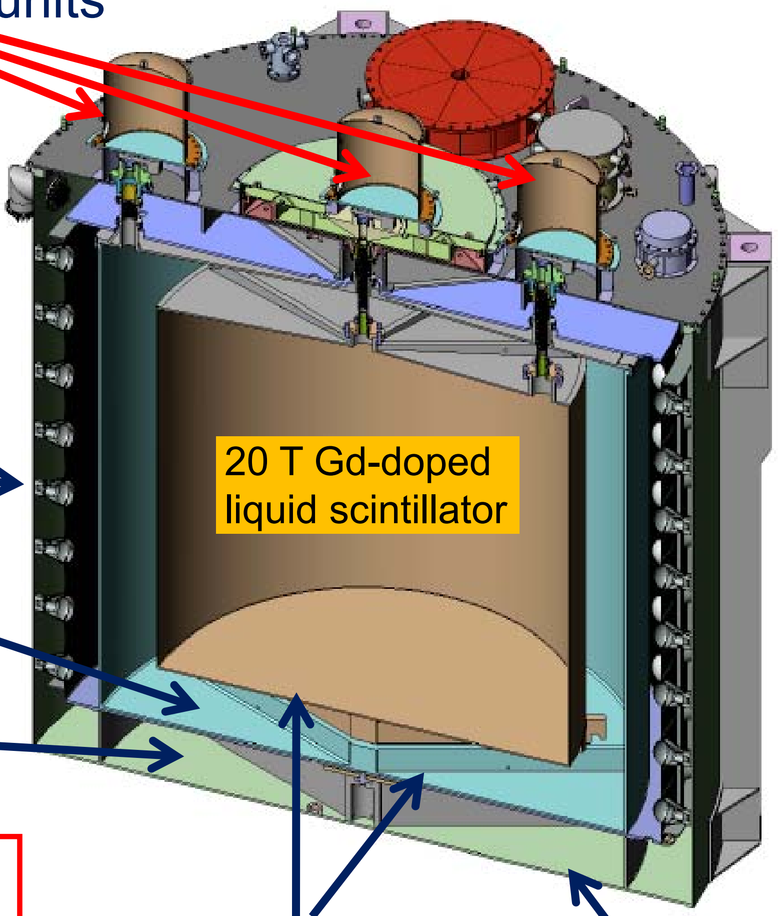
Antineutrino Detector

$\overline{\nu}_e$ +p → e^+ + n

n capture on Gd (30 μs delay)







Calibration units

192 8” PMT’s

Gamma catcher

Buffer oil

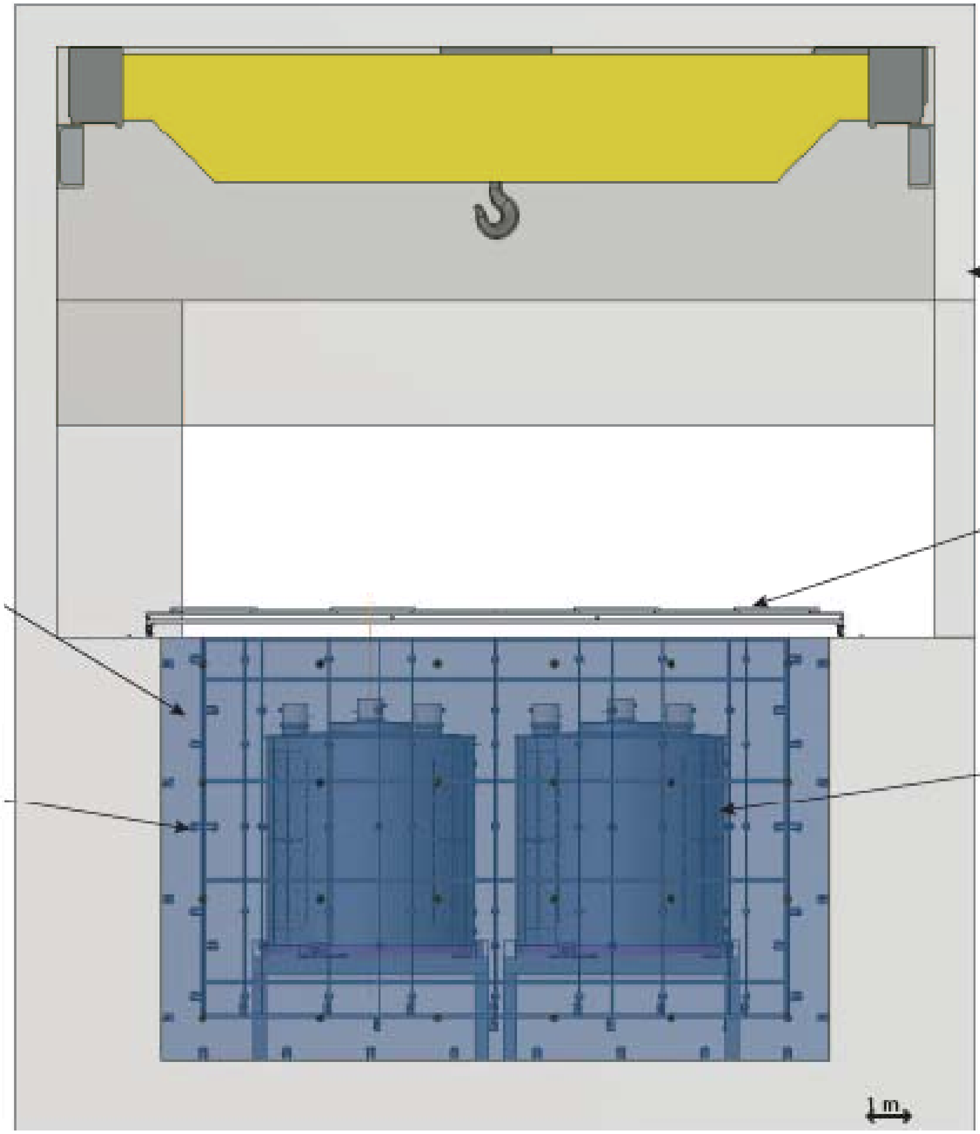
Acrylic
Vessels

SS Tank

- 3 zone design
- Uniform response
- No position cut
- 12%/√E resolution

Muon Veto System

Water Cerenkov (2 layers)



RPC's

Redundant veto system → 99.5% efficient muon rejection

Site Preparation

Daya Bay Near Hall construction (100m underground)

Assembly Building

Portal of Tunnel

Tunnel lining

Hardware Progress


SSV Prototype


4m Acrylic Vessel Prototype

Transporter


Calibration Units

Detector Assembly

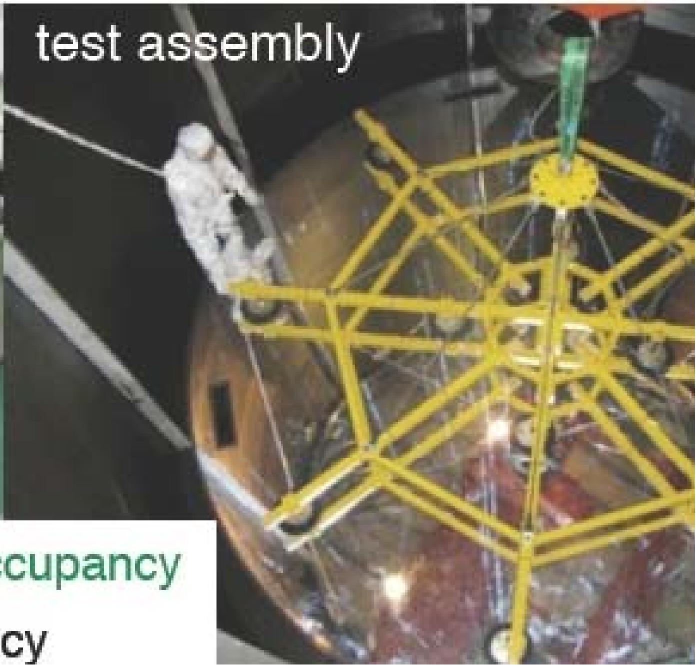

SS Tank delivery


Delivery of 4m AV


staging area


Clean Room


assembly pit

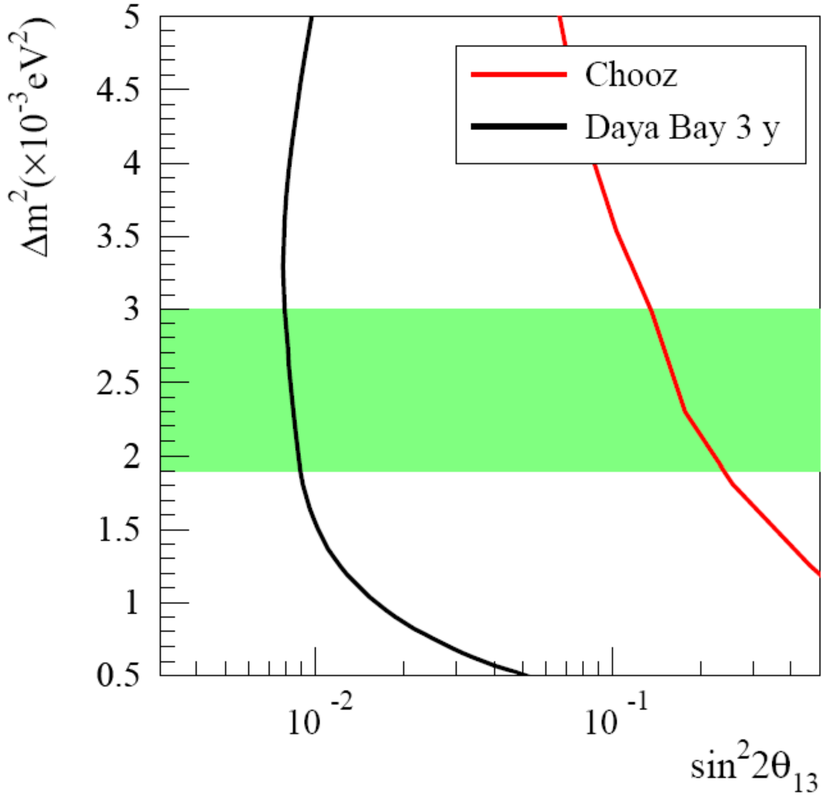

test assembly

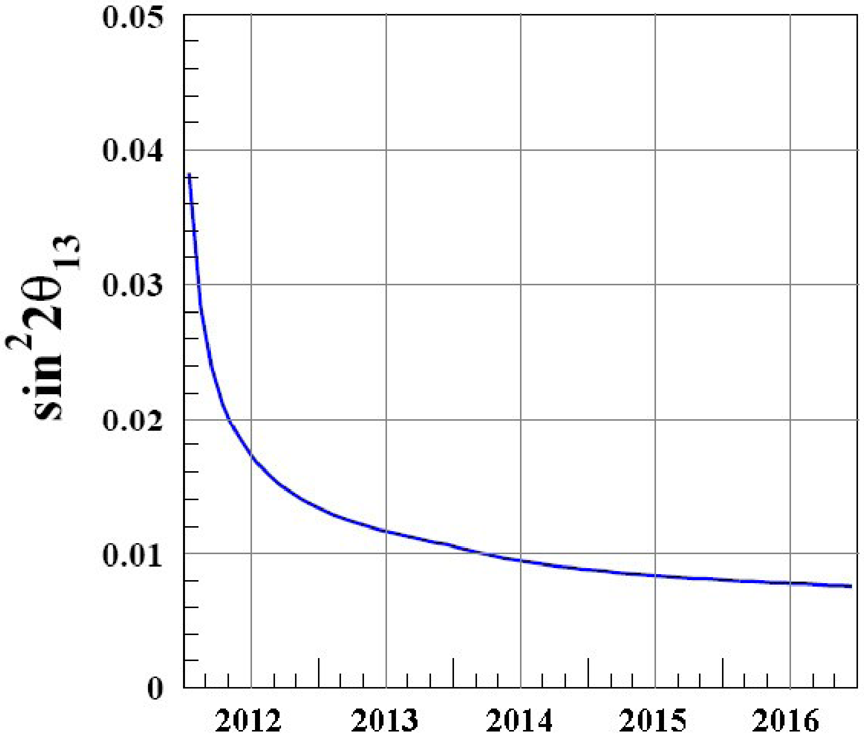
March 2009: Assembly building occupancy

Summer 2009: Near Hall occupancy

Sensitivity to Sin$^22\theta_{13}$

90% CL, 3 years





- Experiment construction: 2008-2011
- Start acquiring data: 2011
- 3 years running

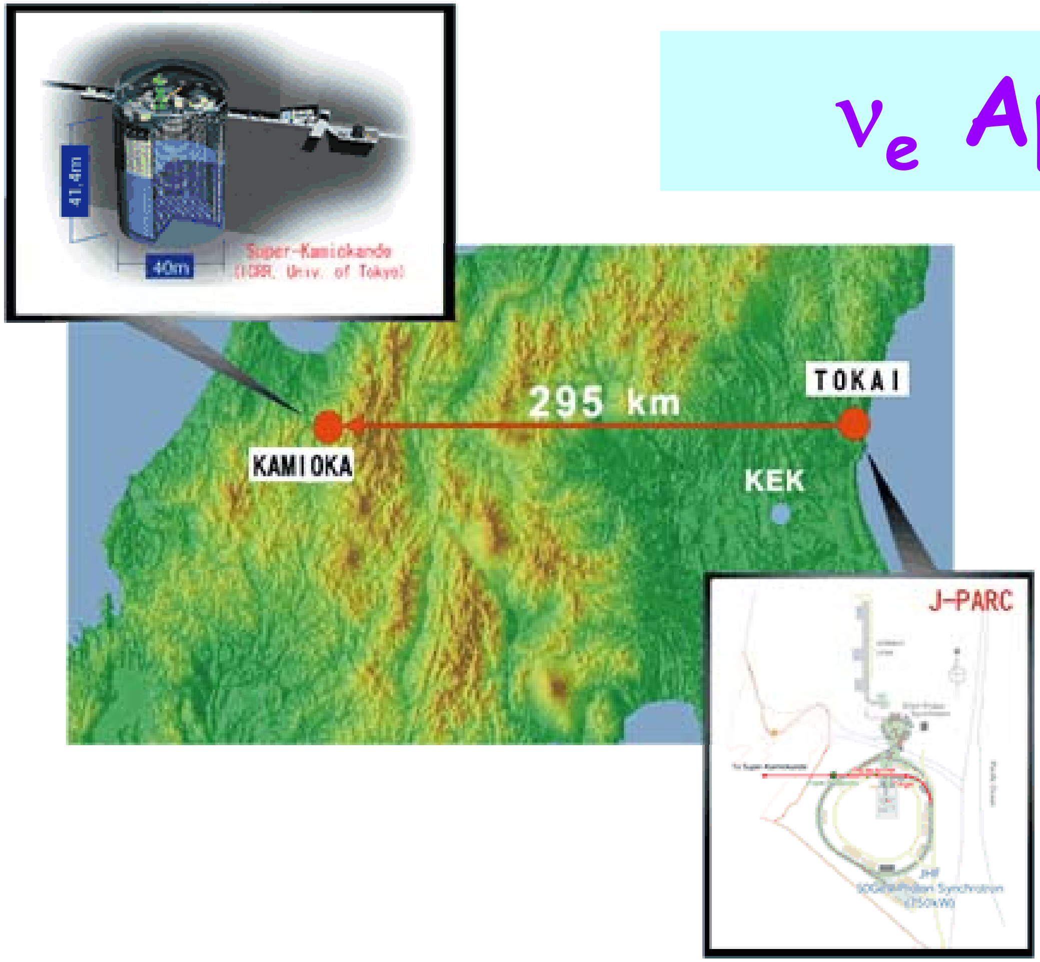
Project Schedule

- October 2007: Ground breaking
- August 2008: CD3 review (DOE start of construction)
- March 2009: Surface Assembly Building occupancy
- Summer 2009: Daya Bay Near Hall occupancy
- Fall 2009: First AD complete
- Summer 2010: Daya Bay Near Hall ready for data
- Summer 2011: Far Hall ready for data

  (3 years of data taking to reach goal sensitivity)

ν_e Appearance

T2K- *From Tokai To Kamioka*



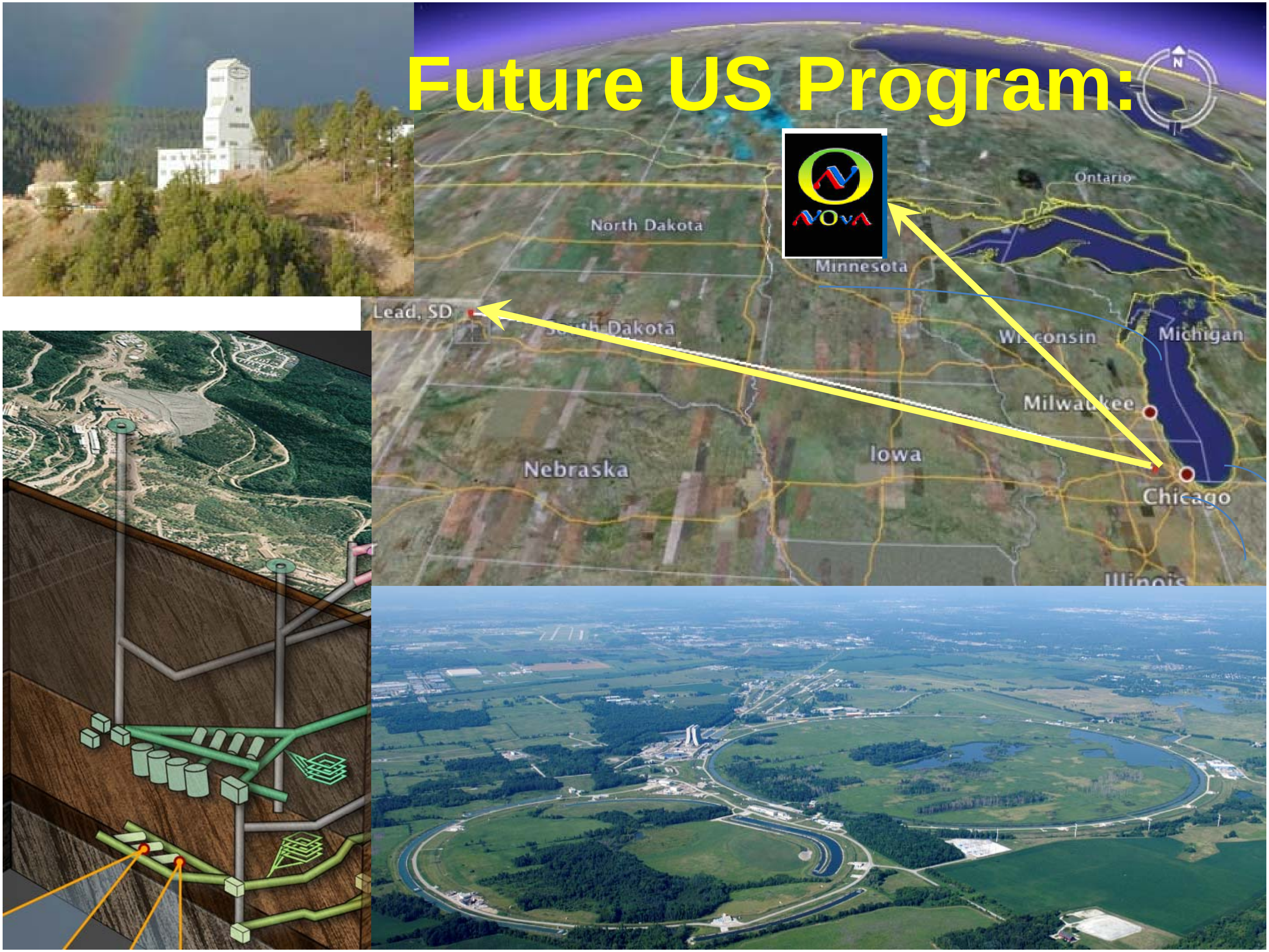
Mass hierarchy (+/-)

CP violation

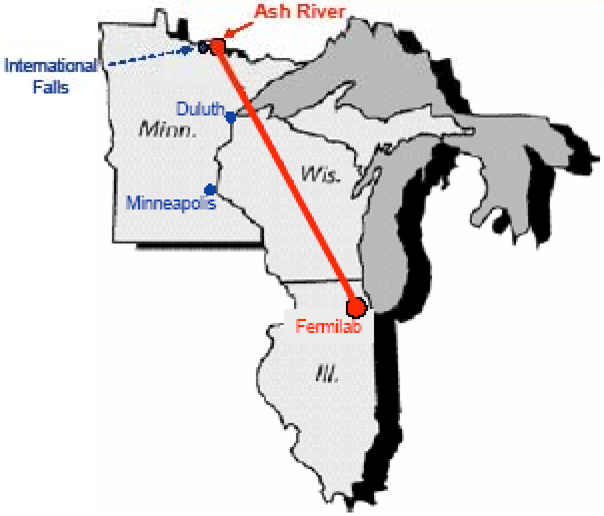
matter

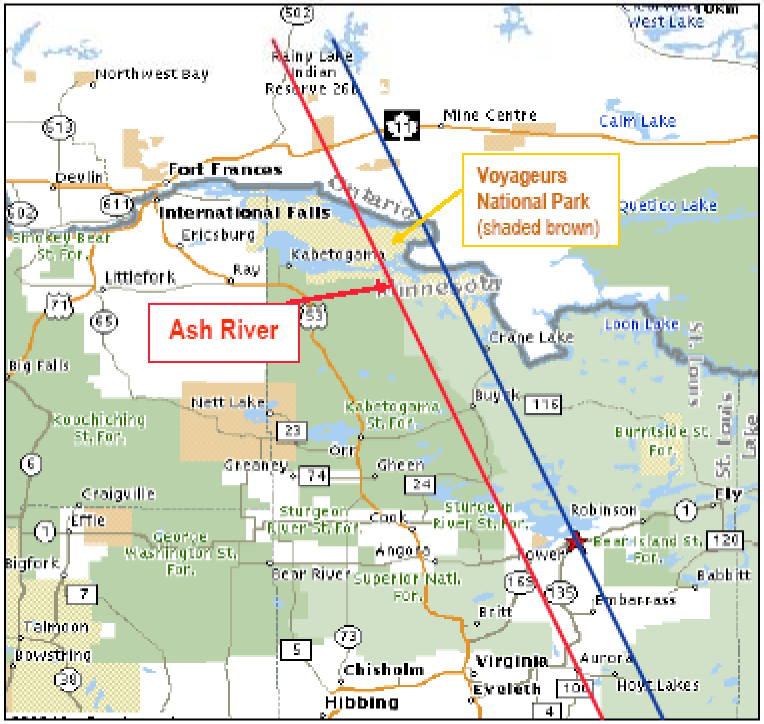
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\
& + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin \Delta_{31} [\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta] \sin \Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos \Delta_{32}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

Future US Program:



NOνA - New Fermilab Proposal

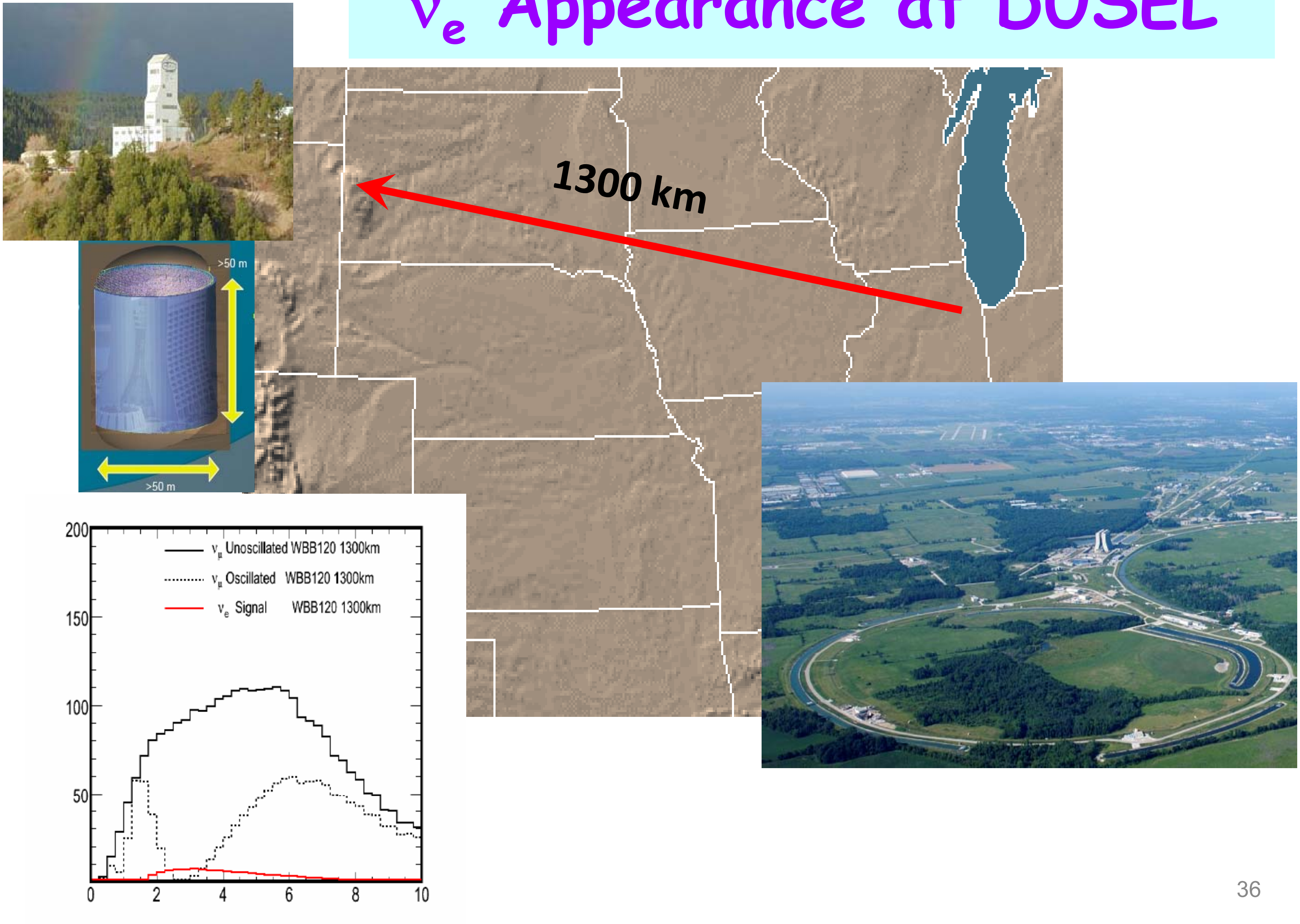




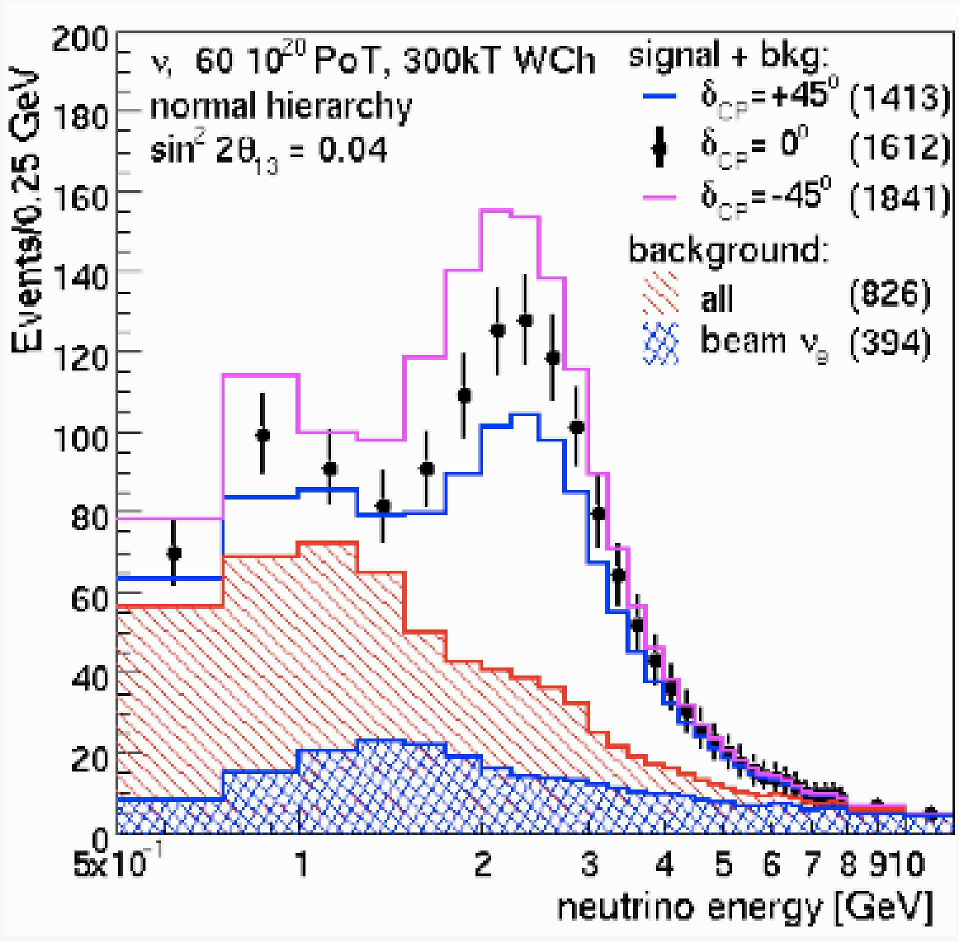
The Ash River site is the furthest available site from Fermilab along the NuMI beamline. This maximizes NOνA's sensitivity to the mass ordering.

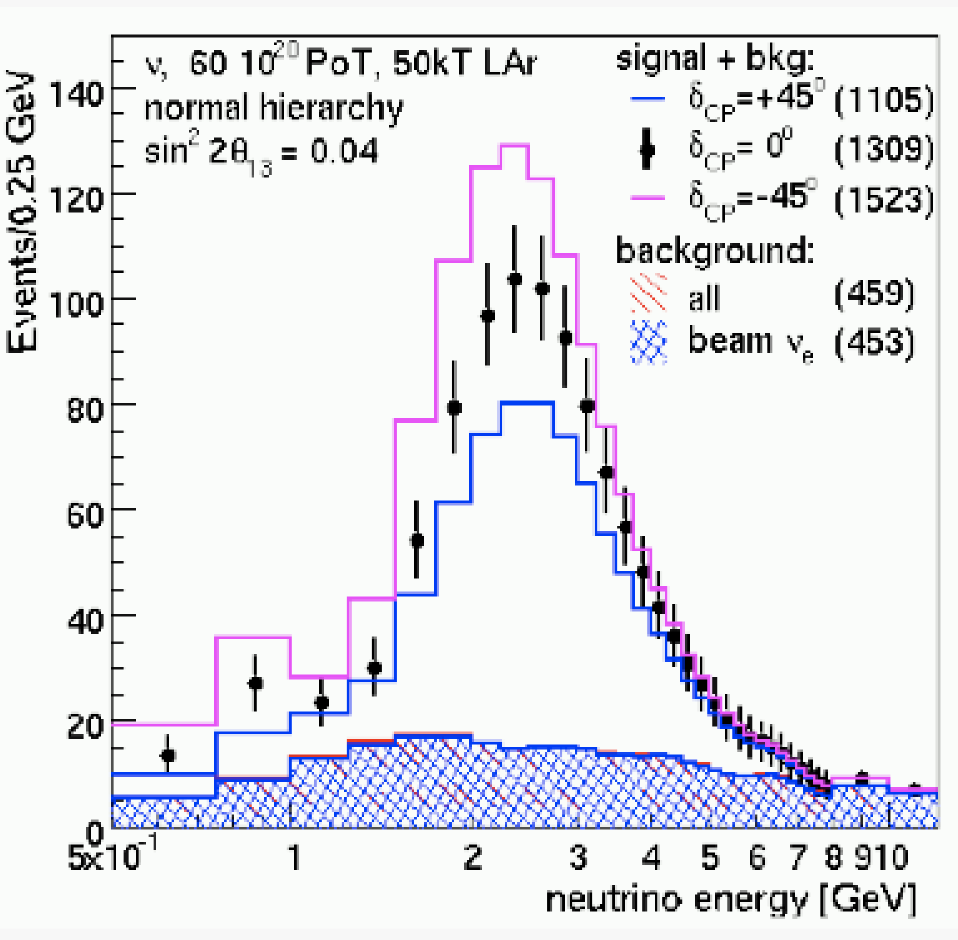
L = 810 km

ν_e Appearance at DUSEL

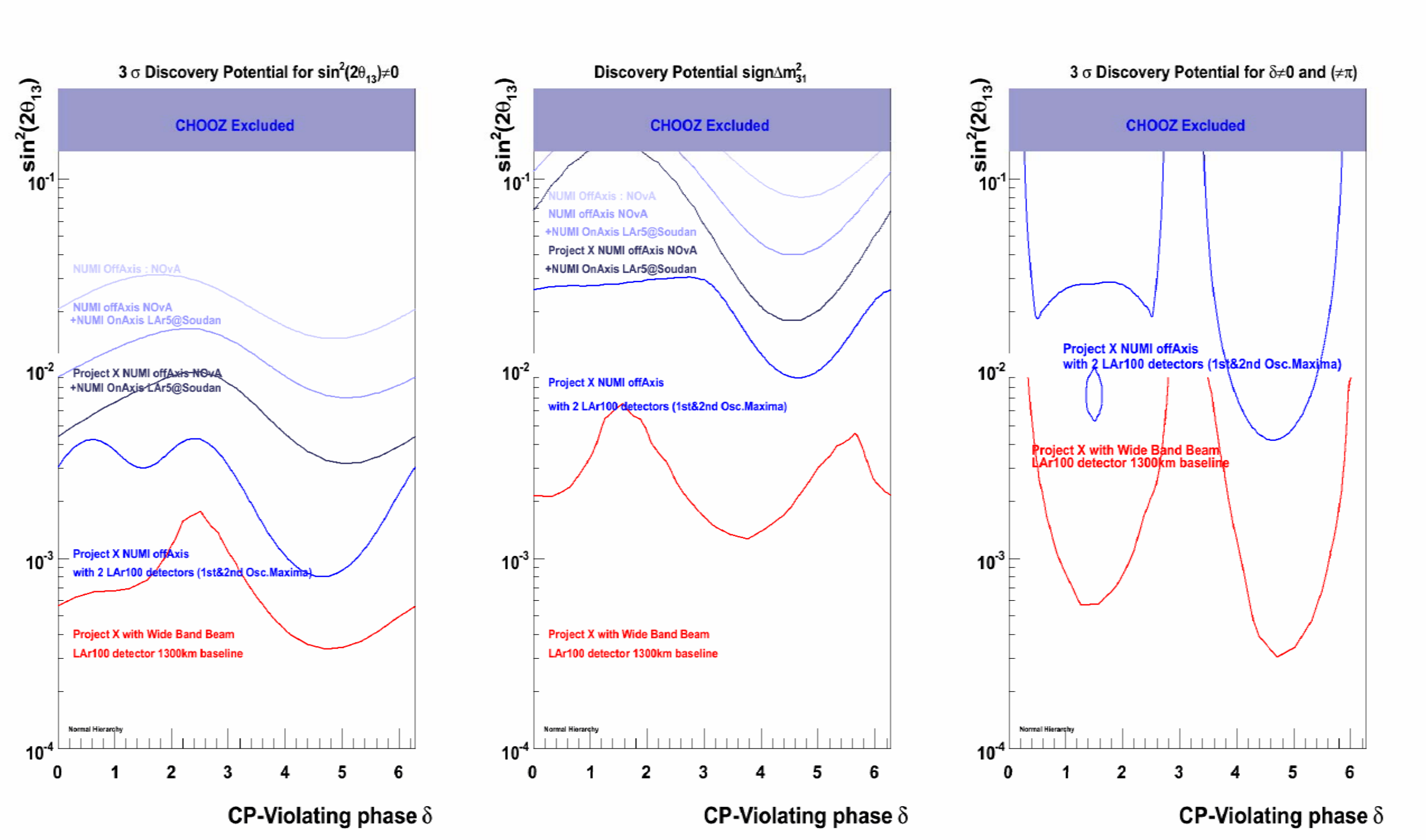


Water Cerenkov vs. Liquid Argon TPC





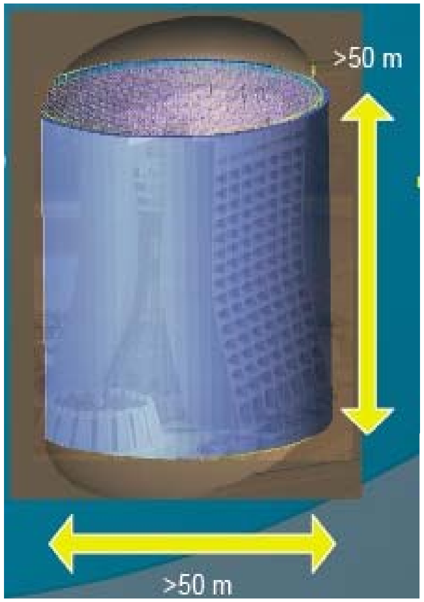
Mass Hierarchy and CP Violation



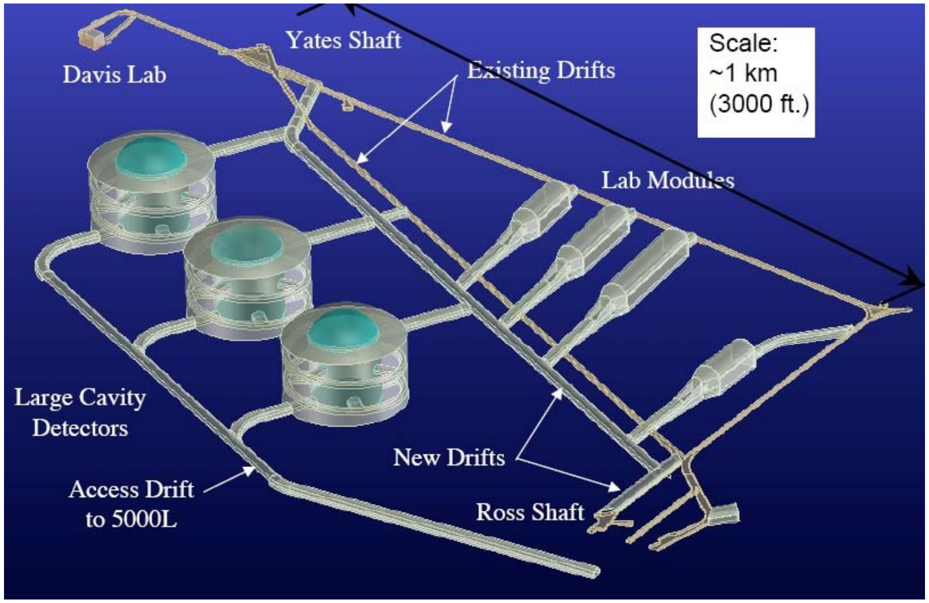
http://nwg.phy.bnl.gov/~diwan/nwg/fnal-bnl/

Large Underground Detector

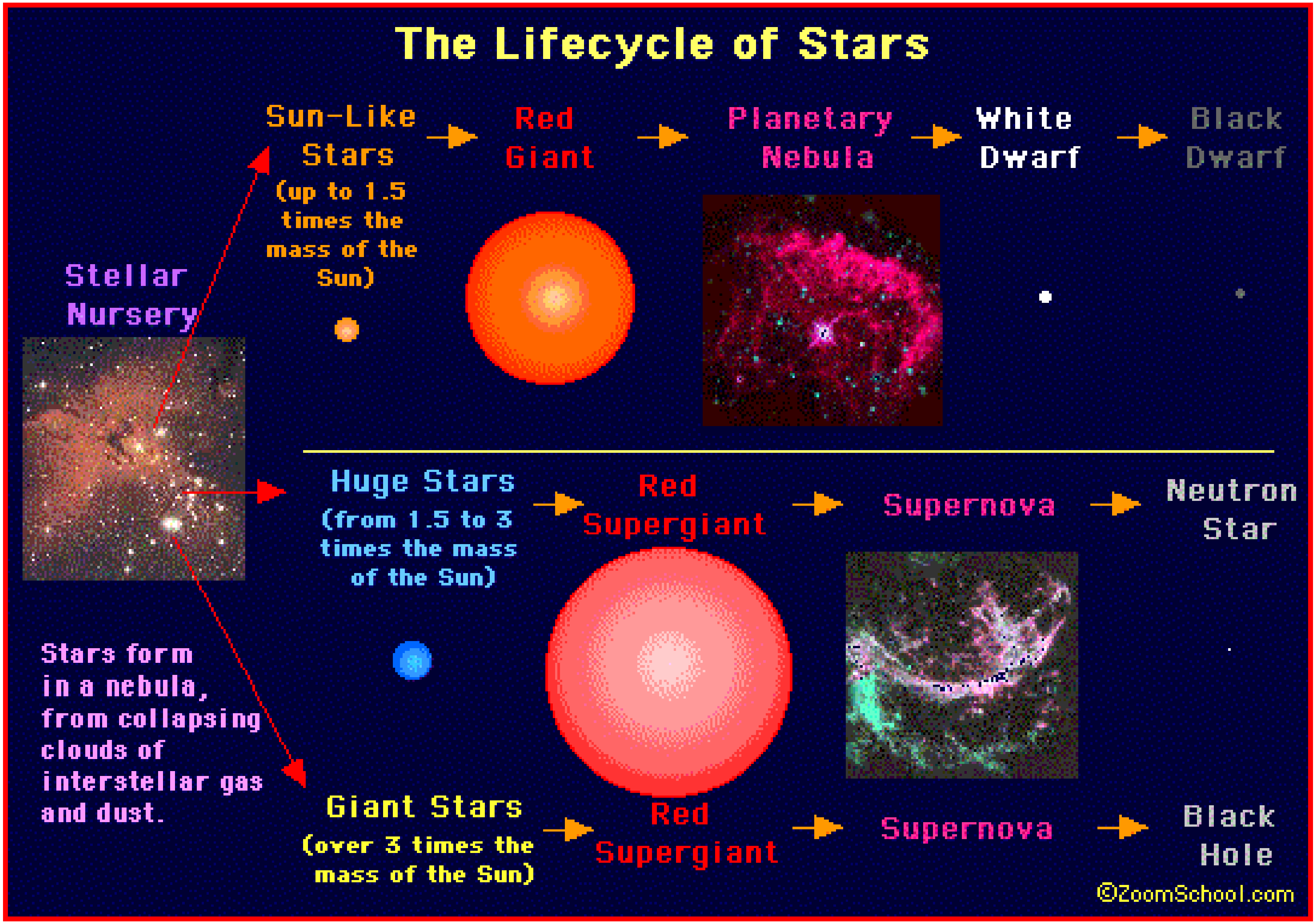
- Long Baseline Neutrino Oscillations
- Nucleon decay (B violation, Mass scale< M_{GUT}?)
- Supernova neutrino detection (θ_{13}, r-process?)



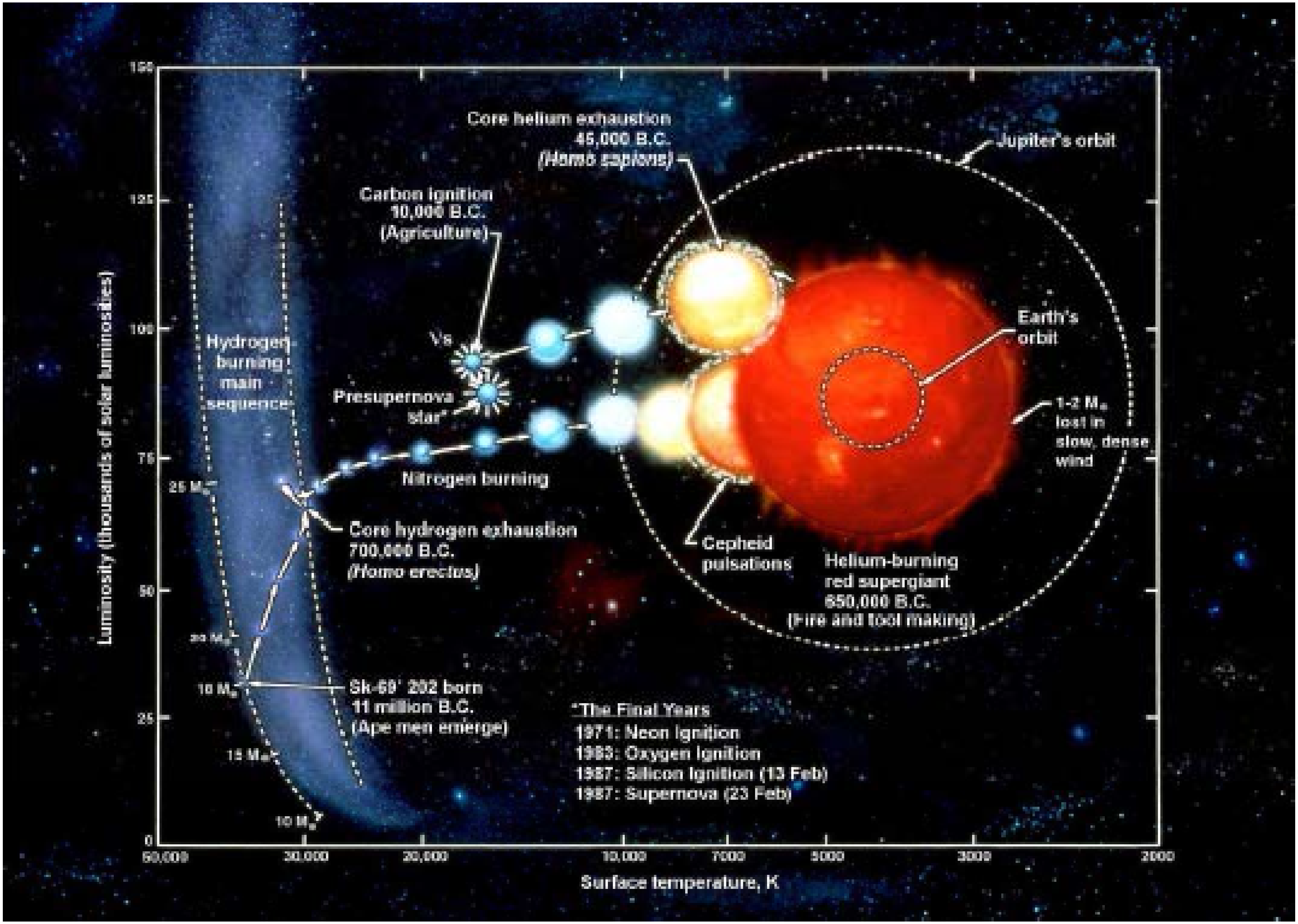
DUSEL



The Lifecycle of Stars



Evolution of 18 solar mass star



*The Final Years
1971: Neon ignition
1983: Oxygen ignition
1987: Silicon ignition (13 Feb)
1987: Supernova (23 Feb)

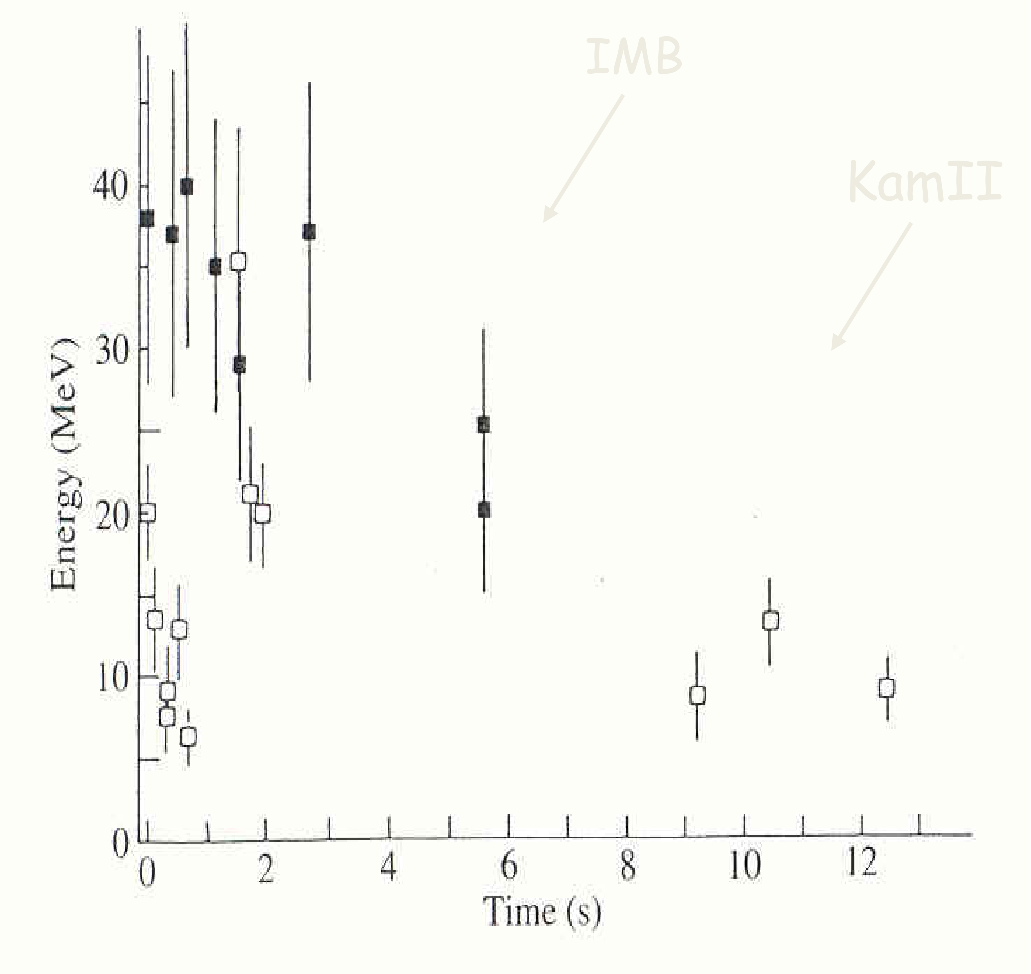
Neutrino spectra

The gravitational energy of the collapsed core (a few 10^{53} ergs) is radiated away in neutrinos of all types. There is a large luminosity in neutrinos ($L_\nu > 10^{52}$ ergs/s) for nearly 10 seconds, before it decreases. The luminosity is nearly the same for all neutrino types and is maintained by mass accretion onto the proto-neutron star where the kinetic energy of infall is converted into thermal energy. The neutrinos have approximately the Fermi-Dirac spectra with zero chemical potential. Then

$$\langle E_\nu \rangle = \pi T_\nu; \ \langle E_\nu^2 \rangle \approx 6 T_\nu^2$$

The average energy of the emitted neutrinos ($\sim$ 15 MeV) is much less than the energy of neutrinos produced in the high-density core ($\sim$ 150 MeV). When the neutrinos diffuse out of this core, they are down-scattered in energy. As they carry away the entire energy, there are about 10 neutrinos emitted for every one produced in the center.

Supernova Neutrino Detection



SN1987A:

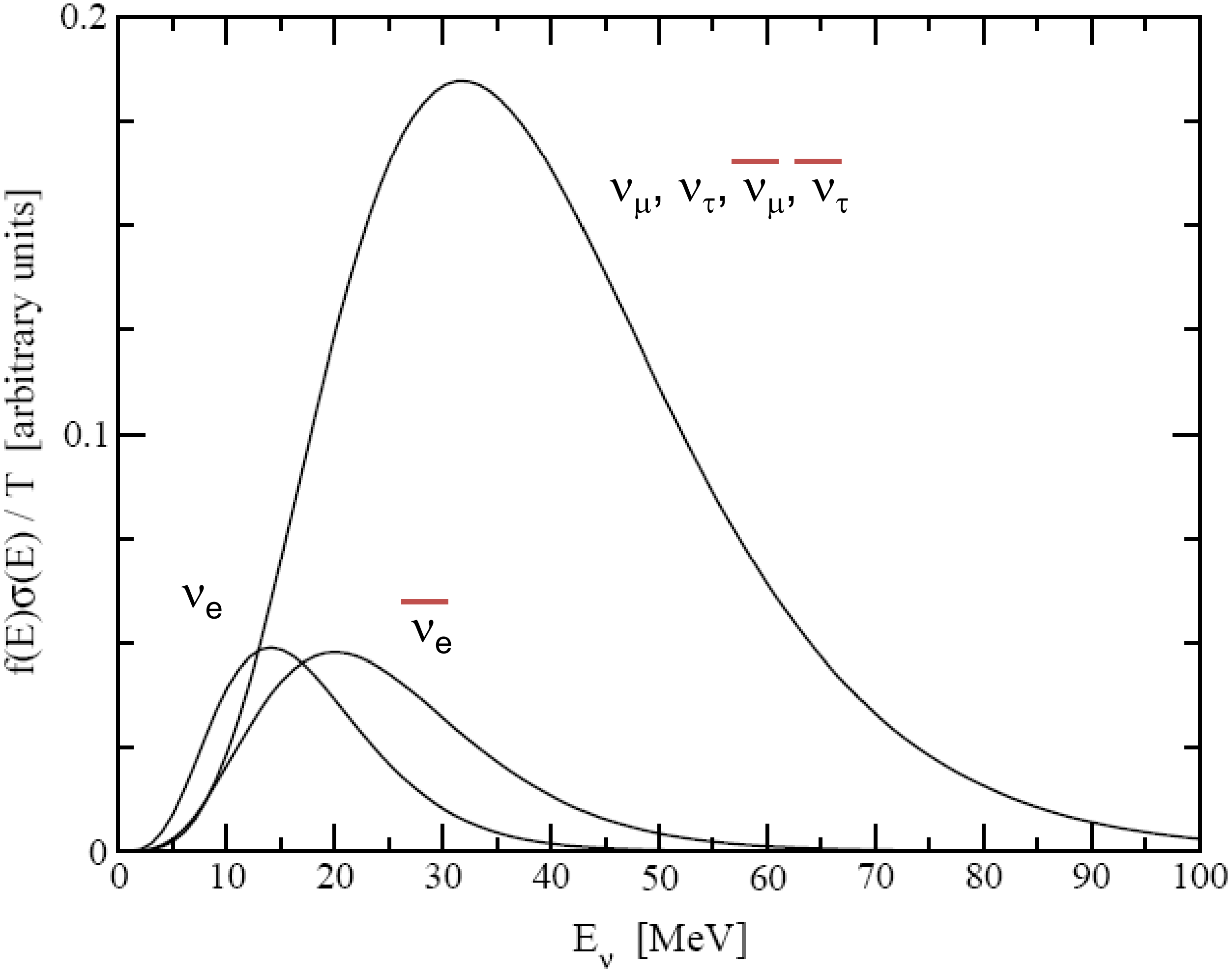
~ 20 $\bar{\nu}_e p \to e^+ n$ events

SN200??:

~ 10^4 CC events

~ 10^3 NC events

Spectrum x σ


0.2
0.1
0
0
10
20
30
40
50
60
70
80
90
100
f(E)σ(E) / T [arbitrary units]
E_ν [MeV]
ν_μ, ν_τ, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$
ν_e
$\bar{\nu}_e$

Spectrum modification due to neutrino mixing