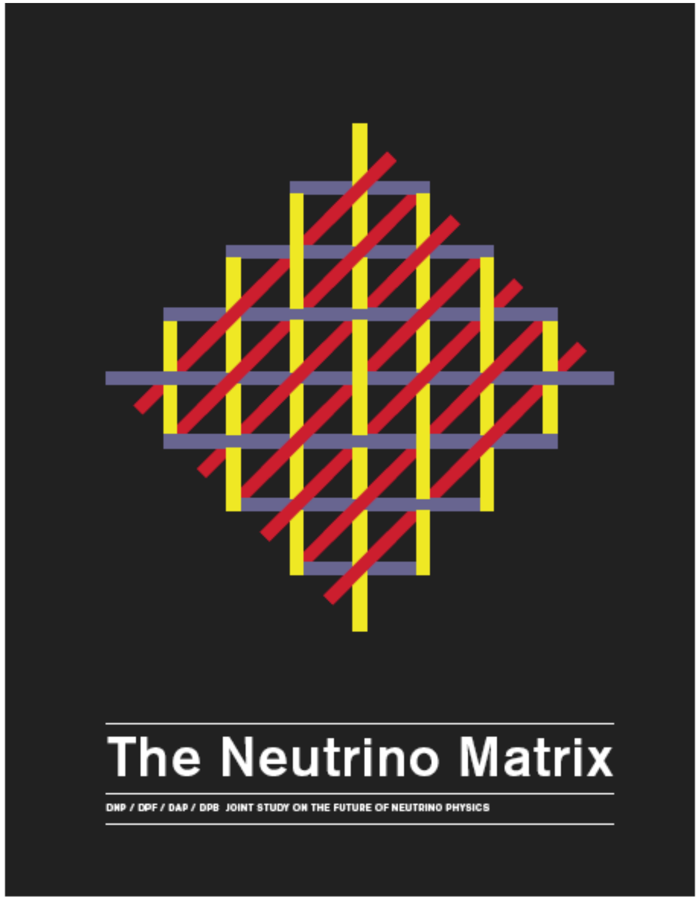
Neutrino mass and mixing constrained by double beta decay

H. Minakata
(Faculty of Urban Liberal Arts, TMU)

Special thanks to H.Nunokawa

APS Neutrino Study



WE RECOMMEND, AS A HIGH PRIORITY, THAT A PHASED PROGRAM OF SENSITIVE SEARCHES FOR NEUTRINOLESS NUCLEAR DOUBLE BETA DECAY BE INITIATED AS SOON AS POSSIBLE.

Neutrinoless double beta decay is the only practical way to discover if neutrinos are their own antiparticles and, thus, a new form of matter. Without this information, the construction of the New Standard Model cannot be completed. The lifetime for neutrinoless double beta decay is inversely proportional to an effective neutrino mass. Hence, in order to observe a signal experimentally, not only must the neutrinos be their own antiparticles, they must also be sufficiently massive.

Great enthusiasm for $0\nu\beta\beta$ decay !

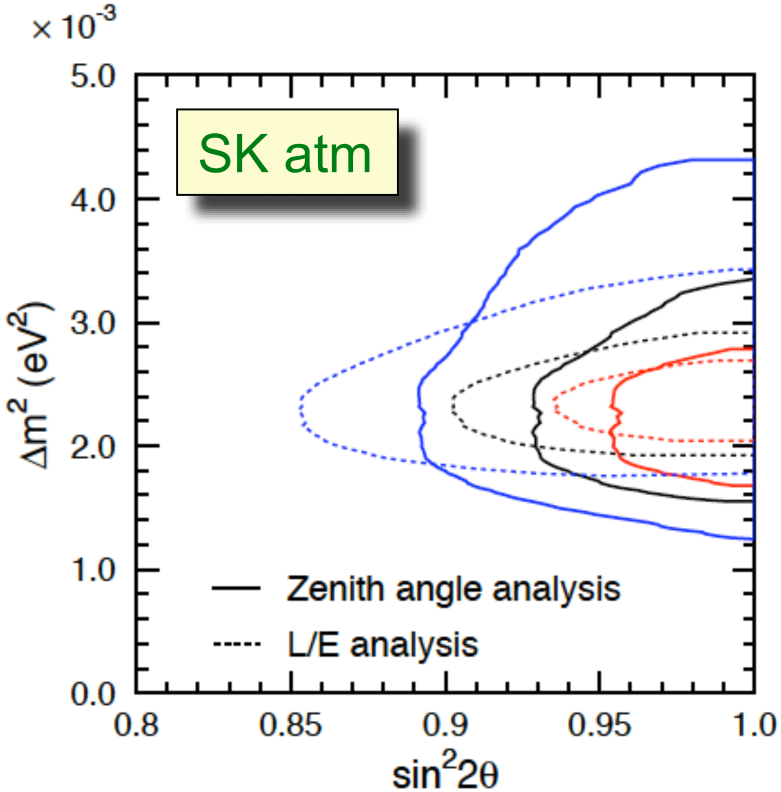
MNS matrix and ν mass pattern

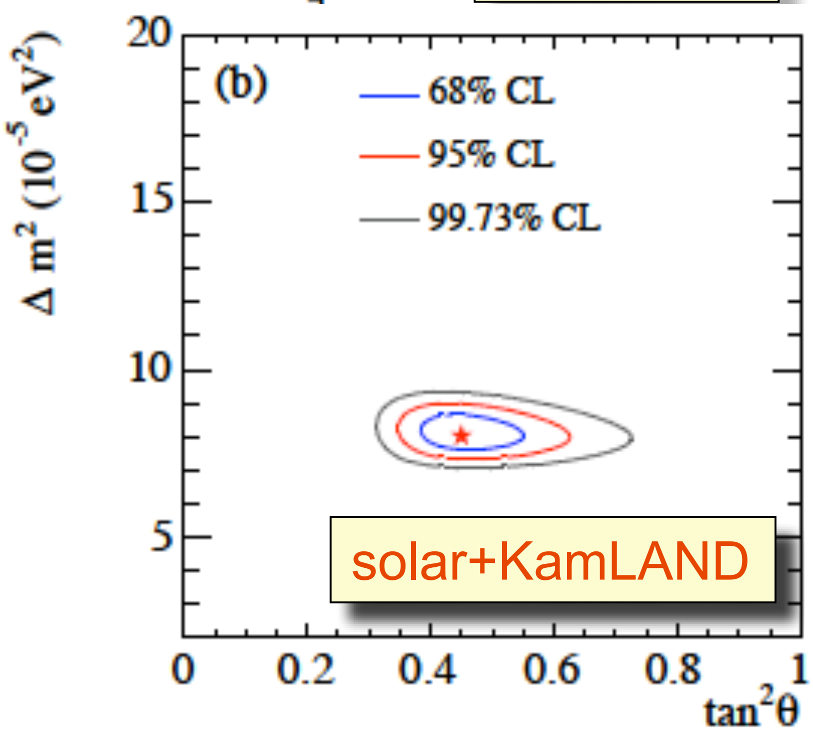
$\nu_\alpha = U_{\alpha i}\, \nu_i$

Atm. ν =>

$$U \equiv U_{\rm MNS} \cdot \Gamma = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times {\rm diag}(1, e^{i\beta}, e^{i\gamma})$$

<= solar + reactor ν





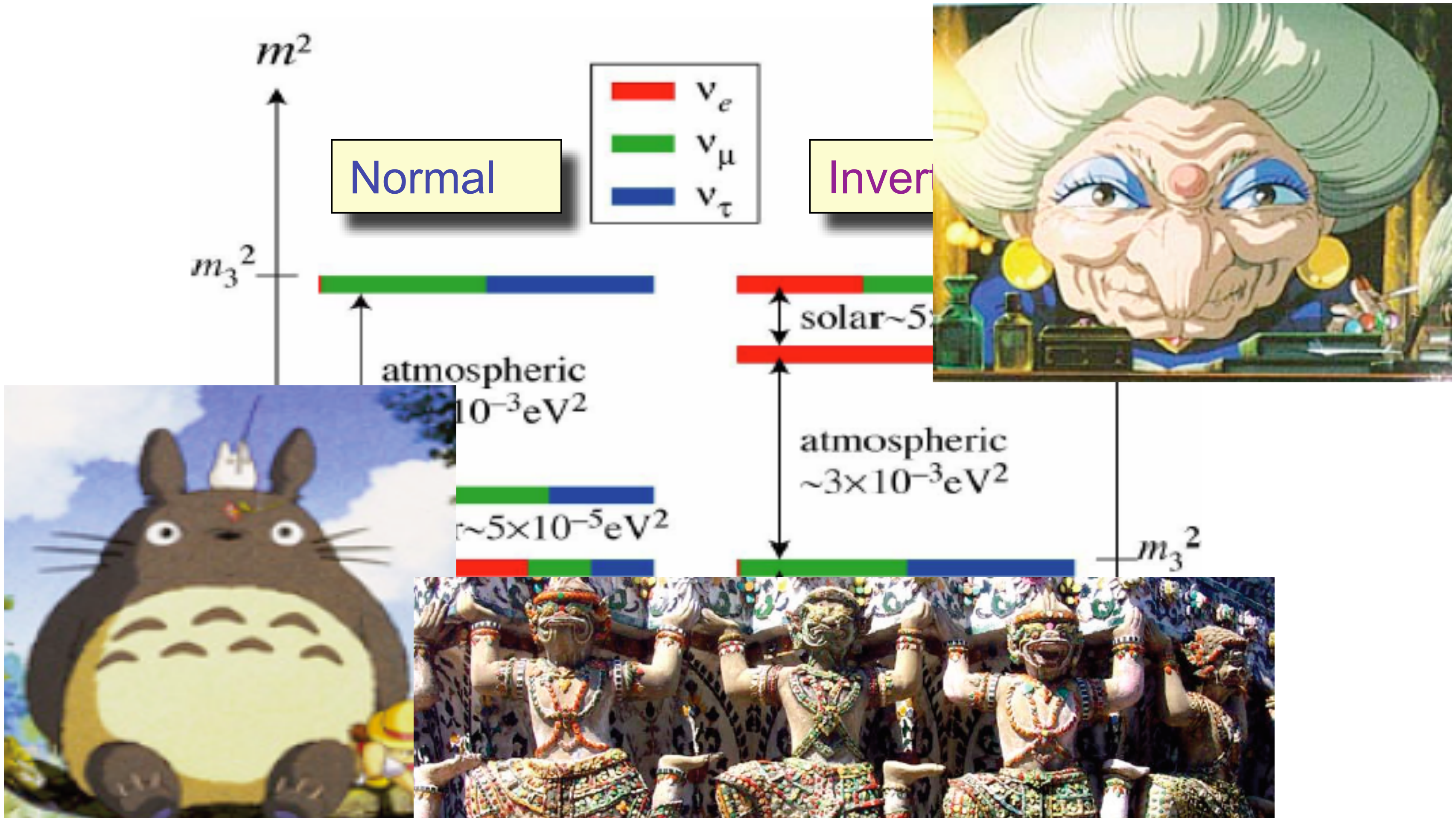
Some people start to feel that ν physics is done, …

- Number of parameters in lepton/neutrino sector = 3 masses + 3 mixing angles + 1 KM phase + 2 Majorana phases (none if Dirac ν) = 9 (7)
- Number of parameters "determined" = 2 Δm^2 + 2 angles = only 4 !!!

→

- We went through less than half a way !

What is left: ν mass hierarchy & absolute mass scale



We don't know yet "electron mass" in ν sector!

ν absolute mass

KATRIN =>
$m_\nu \sim 0.2$ eV

- Endpoint of beta decay spectrum
- 0νββ decay
- cosmology : WMAP + SDSS + …

$m_\nu < \sim 0.6$ eV

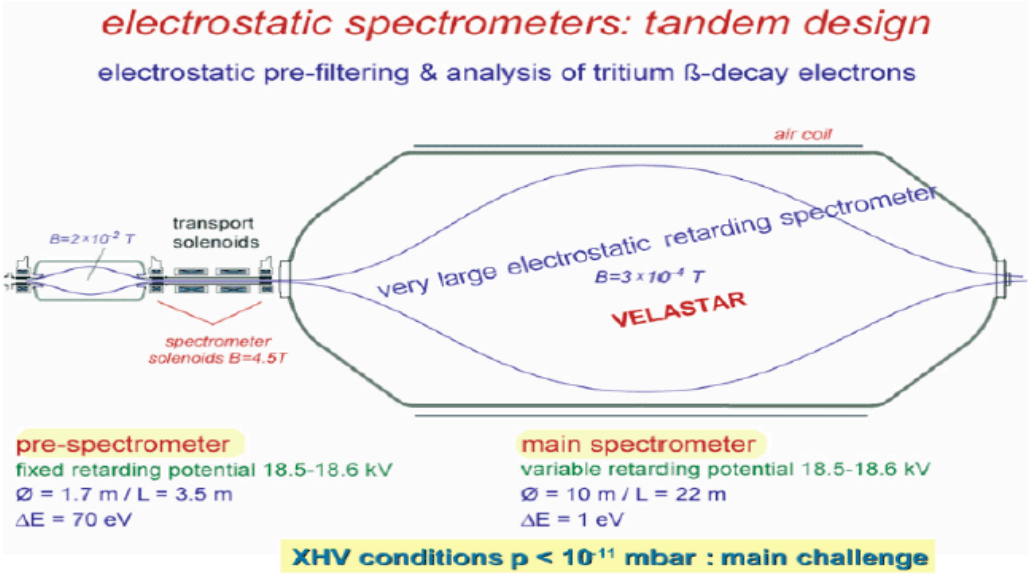
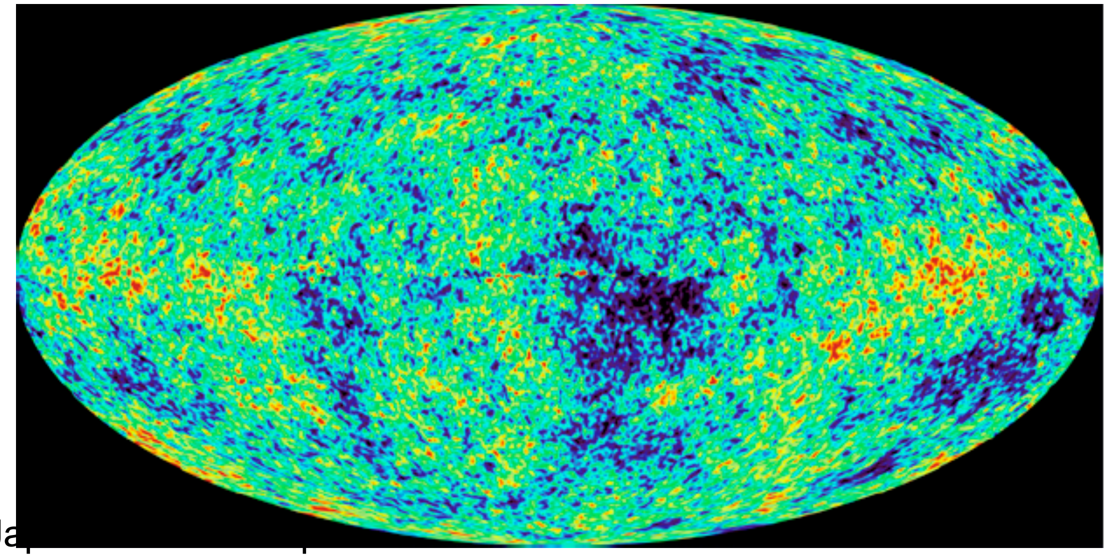


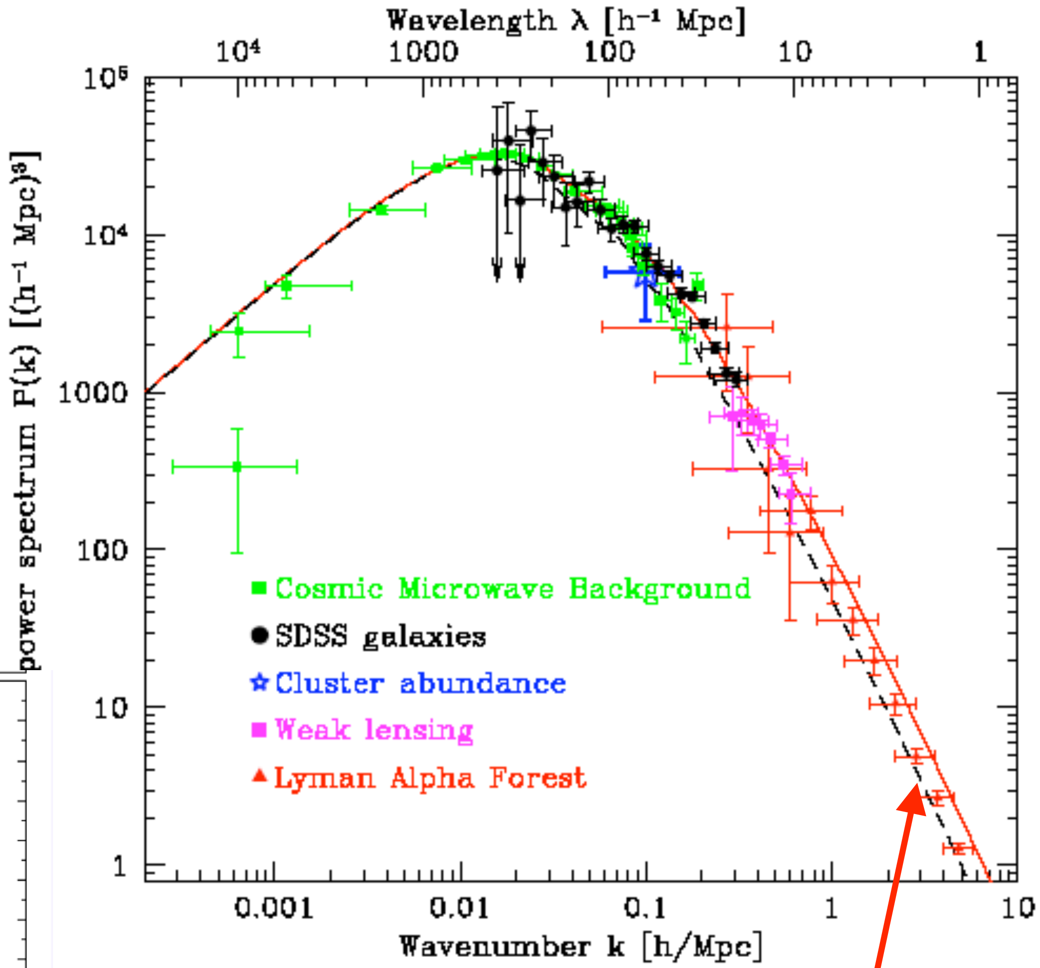
Figure: Pre-Spectrometer and Main Spectrometer



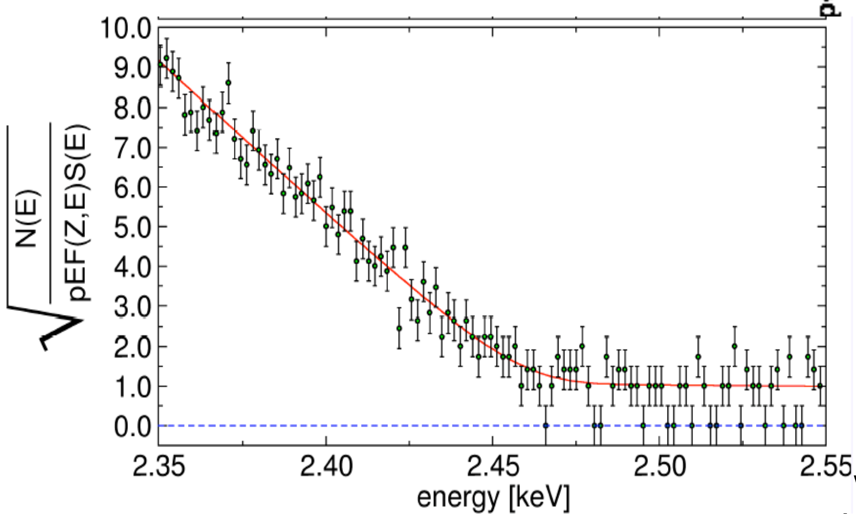
beta decay

They are sensitive to m_ν because..

Future micro-lensing obs. would reach mν ~ 0.04 eV



Σ m = 1 eV



workshop on double beta decay

Lifetime of 0νββ decay

Phase space factor

nuclear matrix element — **uncertainties**

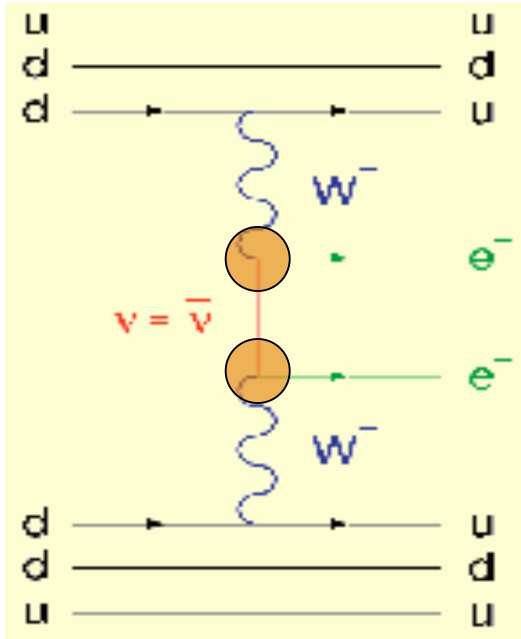
$$\tau^{-1} = G_{0\nu} \left| M^{0\nu} \right|^2 \left| \langle m_\nu \rangle \right|^2$$

Effective neutrino mass

Effective mass parameter =

$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

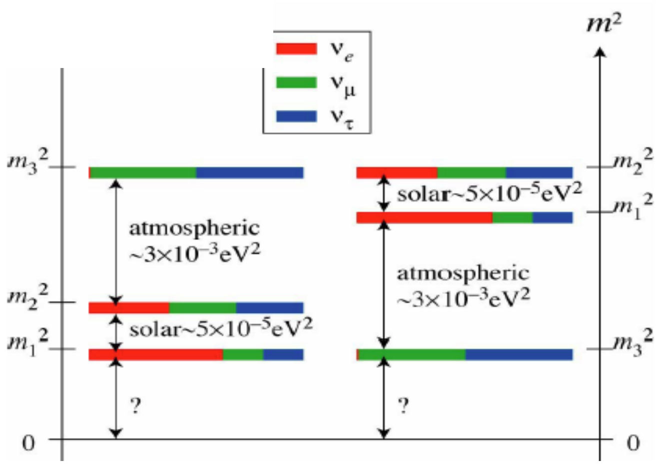
$$= \left| c_{12}^2 c_{13}^2 m_1 e^{i\phi_1} + s_{12}^2 c_{13}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$



Lowest neutrino mass as the unique parameter

$$
\begin{aligned}
m_3 &= \sqrt{\Delta m^2_{atm} + \Delta m^2_{\odot} + m^2_{lowest}} \\
m_2 &= \sqrt{\Delta m^2_{\odot} + m^2_{lowest}} \\
m_1 &= m_{lowest}
\end{aligned}
$$

Normal



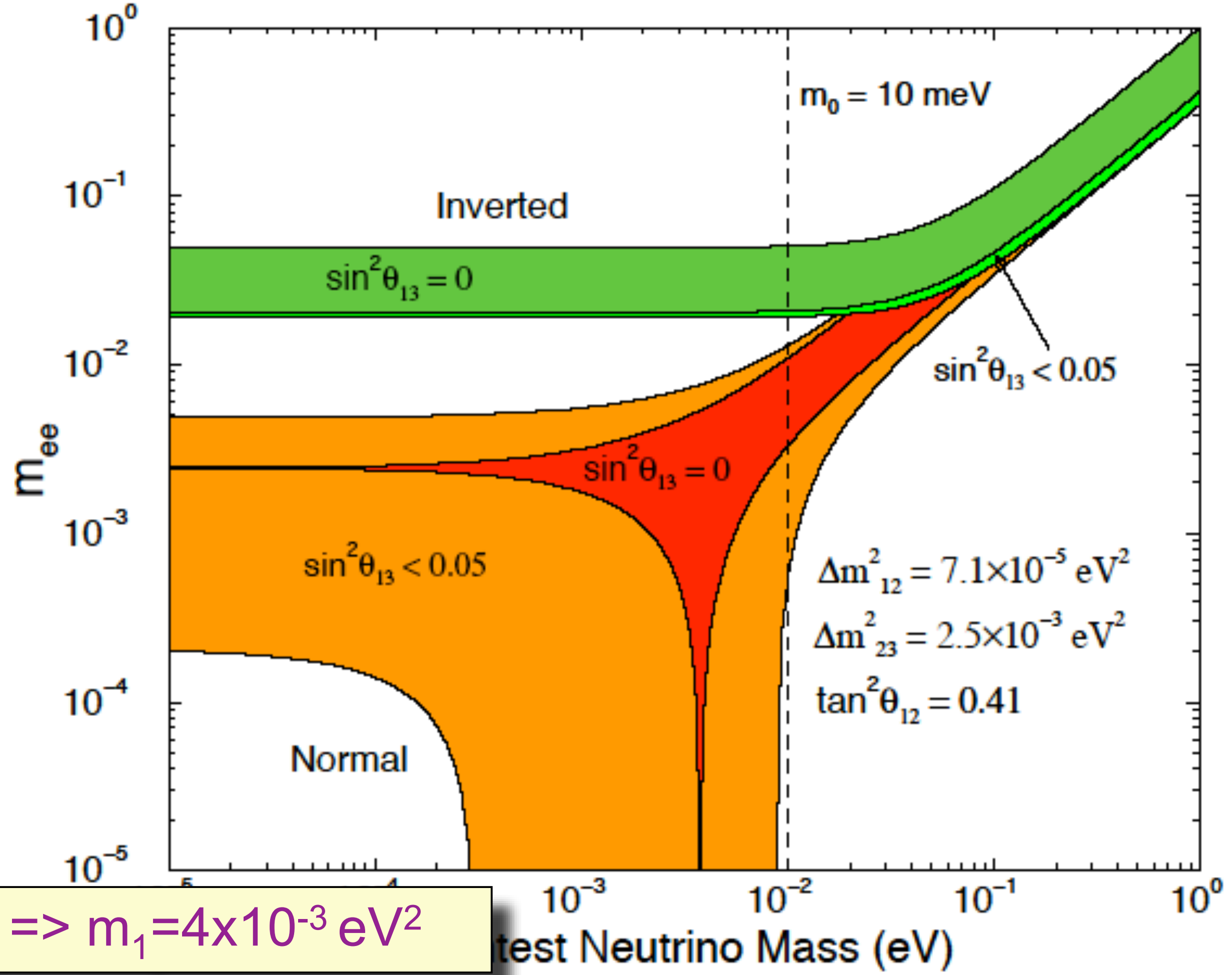
Inverted

$$
\begin{aligned}
m_2 &= \sqrt{\Delta m^2_{atm} + \Delta m^2_{\odot} + m^2_{lowest}} \\
m_1 &= \sqrt{\Delta m^2_{atm} + m^2_{lowest}} \\
m_3 &= m_{lowest}
\end{aligned}
$$

m_{ee} vs. lowest ν mass

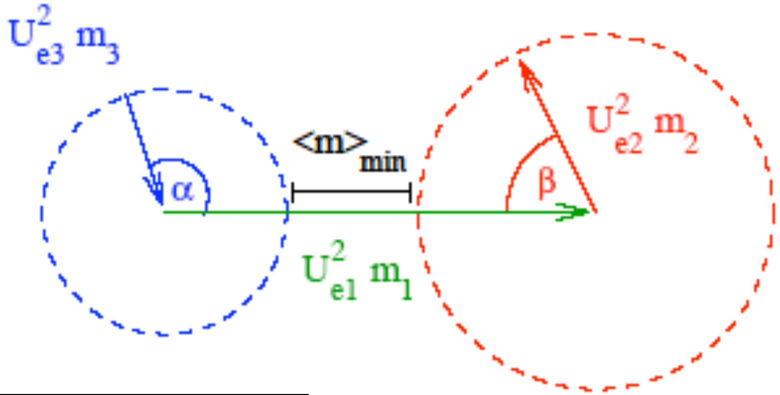
$$\langle m \rangle_{ee} = \left| c_{12}^2 c_{13}^2 m_1 e^{i\phi_1} + s_{12}^2 c_{13}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

Normal vs. inverted mass hierarchy discriminable?

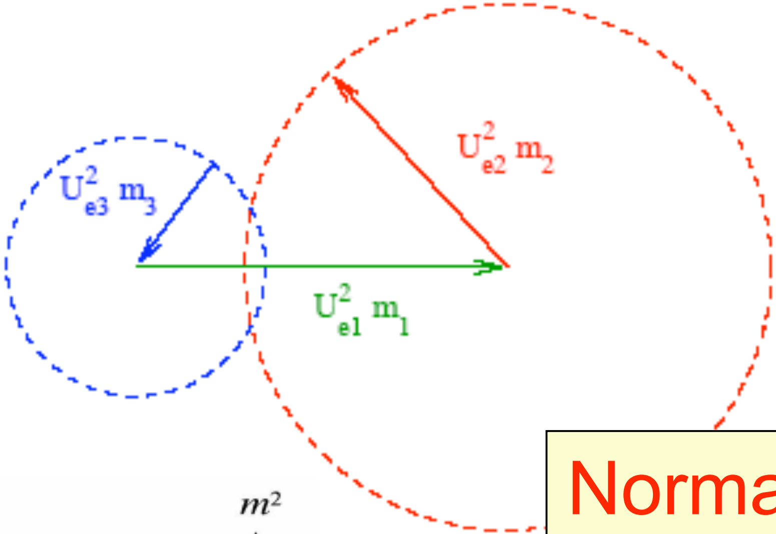


If θ_{13}=0, <m_{ee}>=0, => m_1=4x10^{-3} eV^2

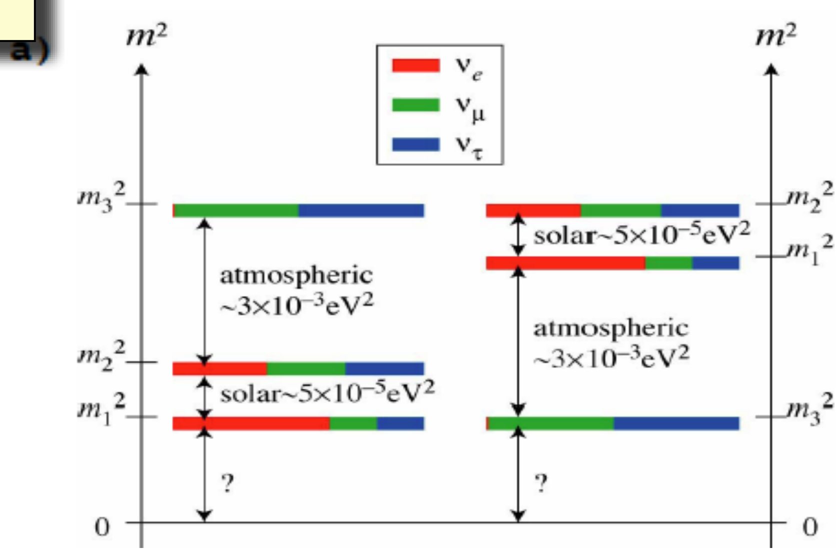
Why minimum m_{ee}



Inverted

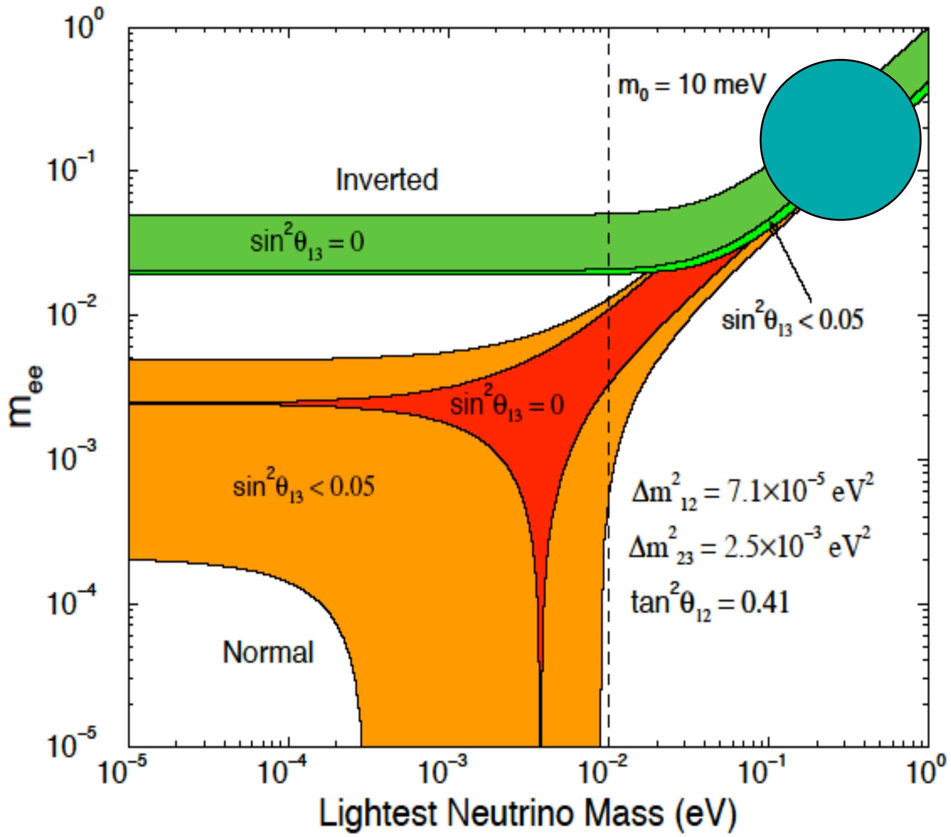


Normal



Klapdor-Kleingrothous-Pess-Smirnov

Degenerate ν mass



Experimentally the clearest situation !

- If m_{ee} discovered in "degenerate mass region" (as claimed by Klapdor et al) it implies that there is new mass scale ≠ sqrt{Δm^2}
- => most probably new scale different from GUT

m_{ee} vs. sum of ν masses

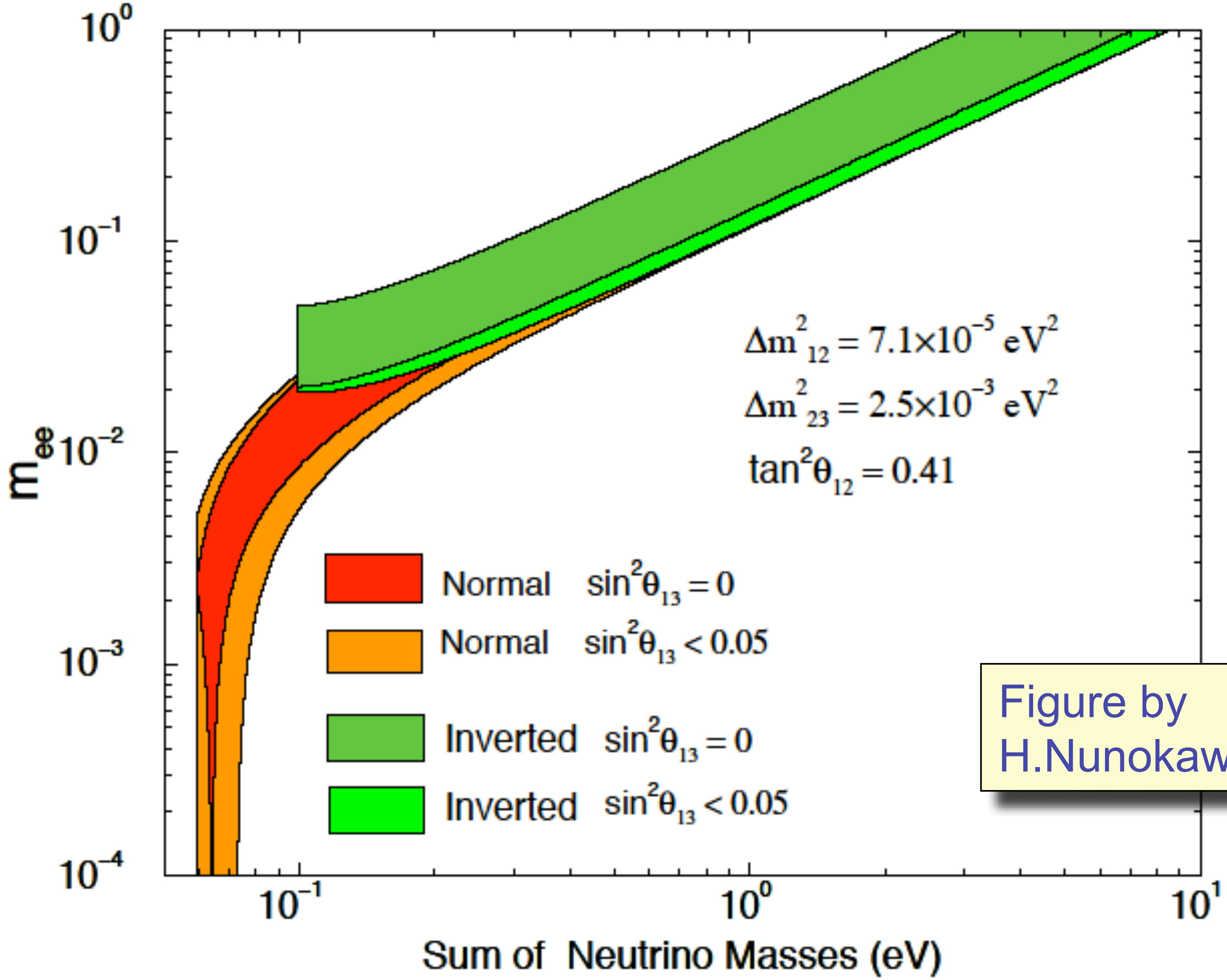
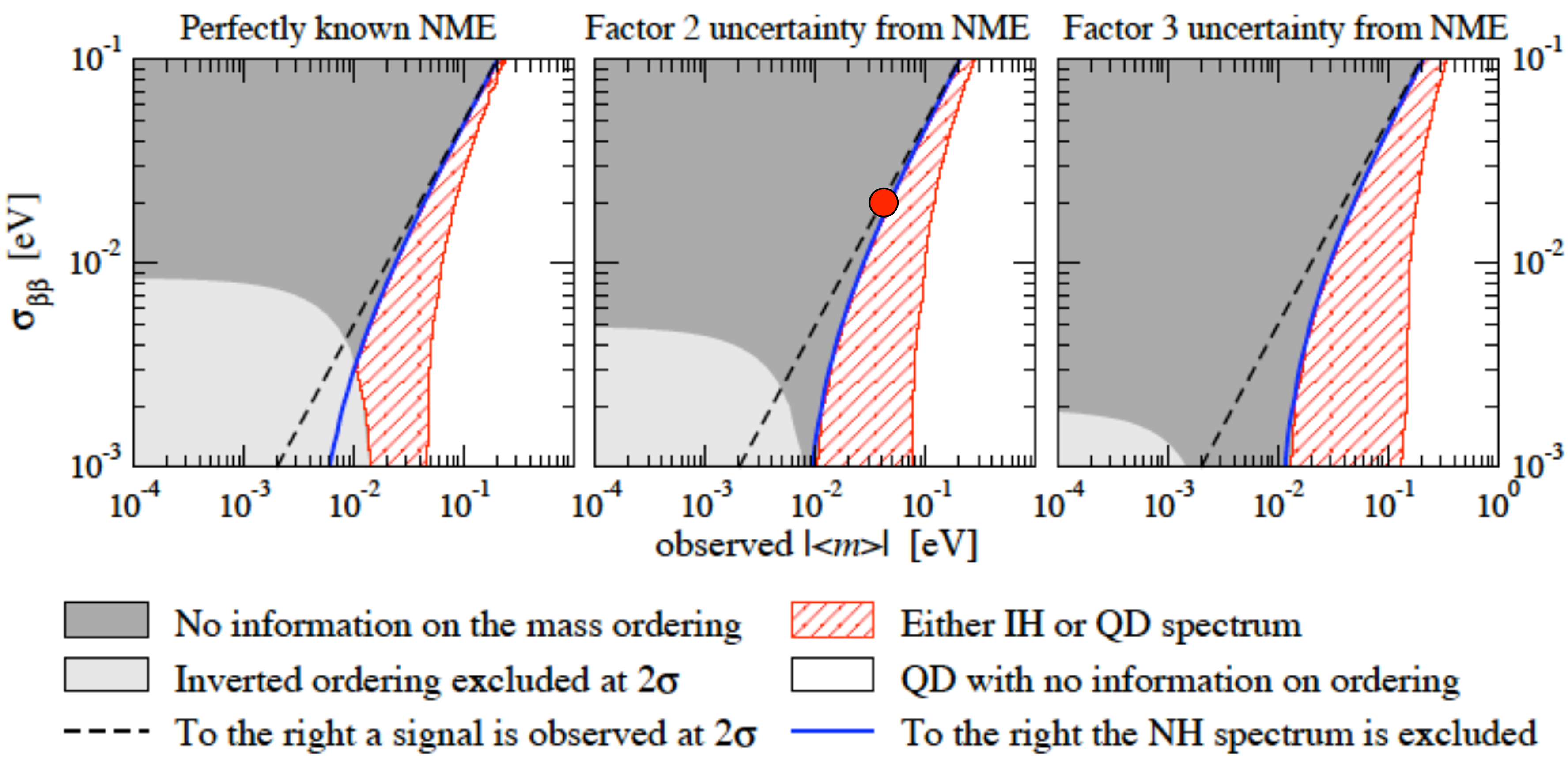


Figure by H.Nunokawa

To distinguish mass hierarchy …



$\sin^2\theta_{13} = 0.03 \pm 0.006,\ \sin^2\theta_{12} = 0.31 \pm 3\%,\ \Delta m^2_{21} = 8\text{x}10^{-5} \pm 2\%,\ |\Delta m^2_{31}| = 2.2\text{x}10^{-3} \pm 3\%$

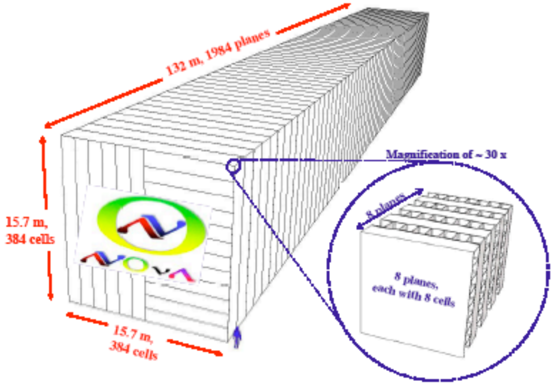
Pascoli-Petcov-Schwetz=PPS hep-ph/0505226

Alternative attitude

- One may take the alternative attitude

→

- Determine mass hierarchy in some other places and look back to $0\nu\beta\beta$ decay



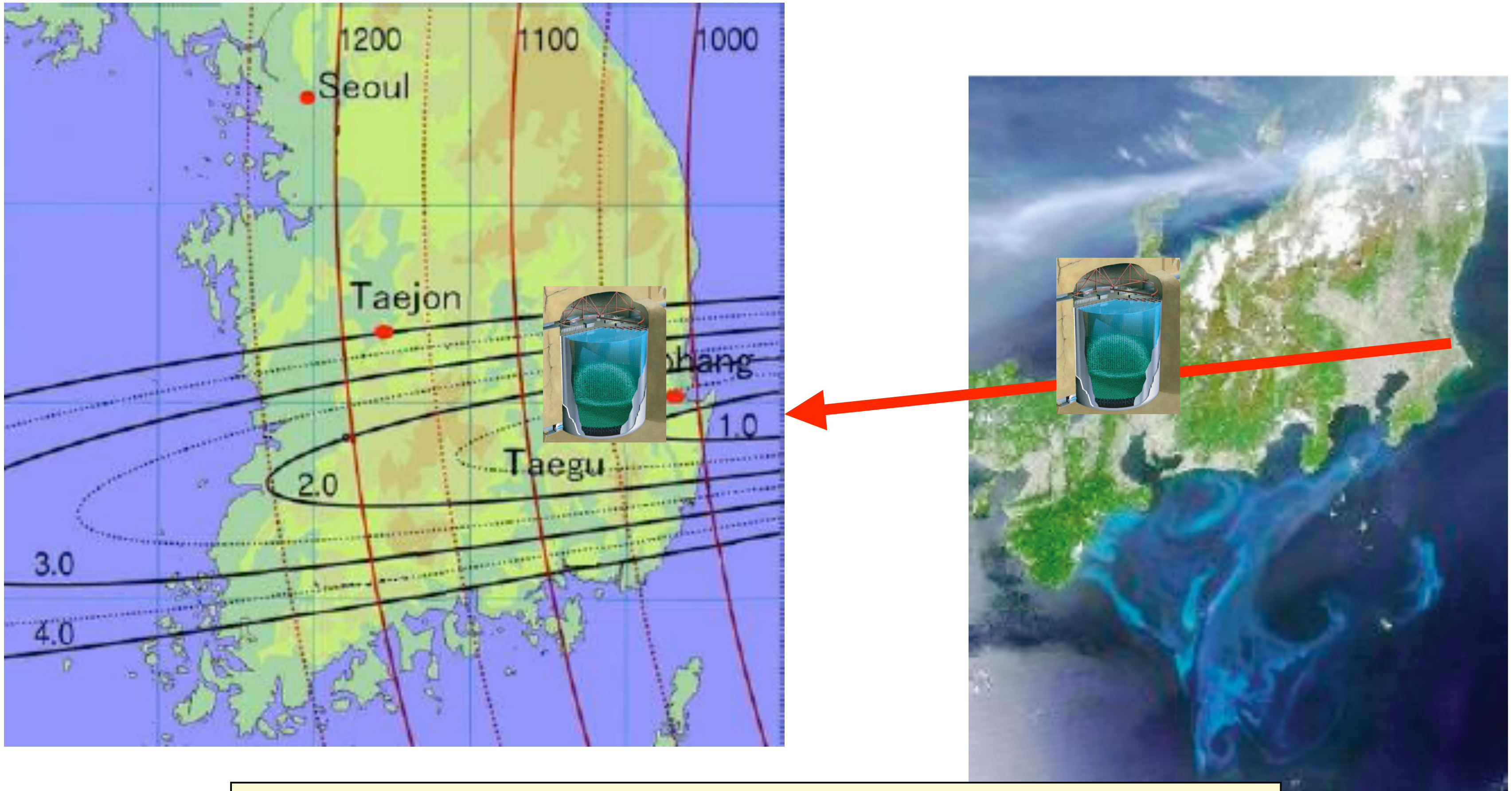
NuMI Off-Axis ν_e Appearance Experiment

March 21, 2005

The NOvA Collaboration

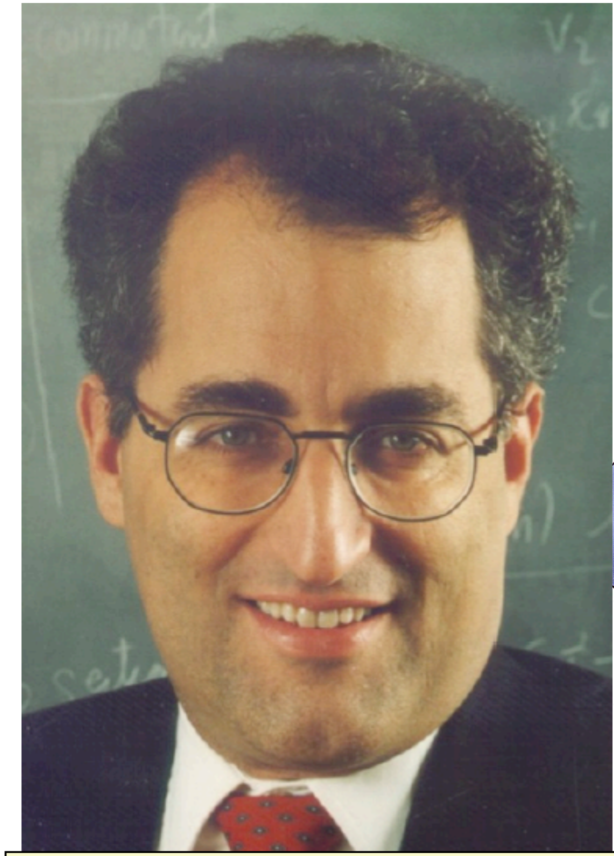
Argonne, Athens, Caltech, UCLA, Fermilab, College de France, Harvard, Indiana, ITEP, Lebedev, Michigan State, Minnesota/Duluth, Minnesota/Minneapolis, Munich, Stony Brook, Northern Illinois, Ohio, Ohio State, Oxford, Rio de Janeiro, Rutherford, South Carolina, Stanford, Texas A&M, Texas/Austin, Tufts, Virginia, Washington, William & Mary

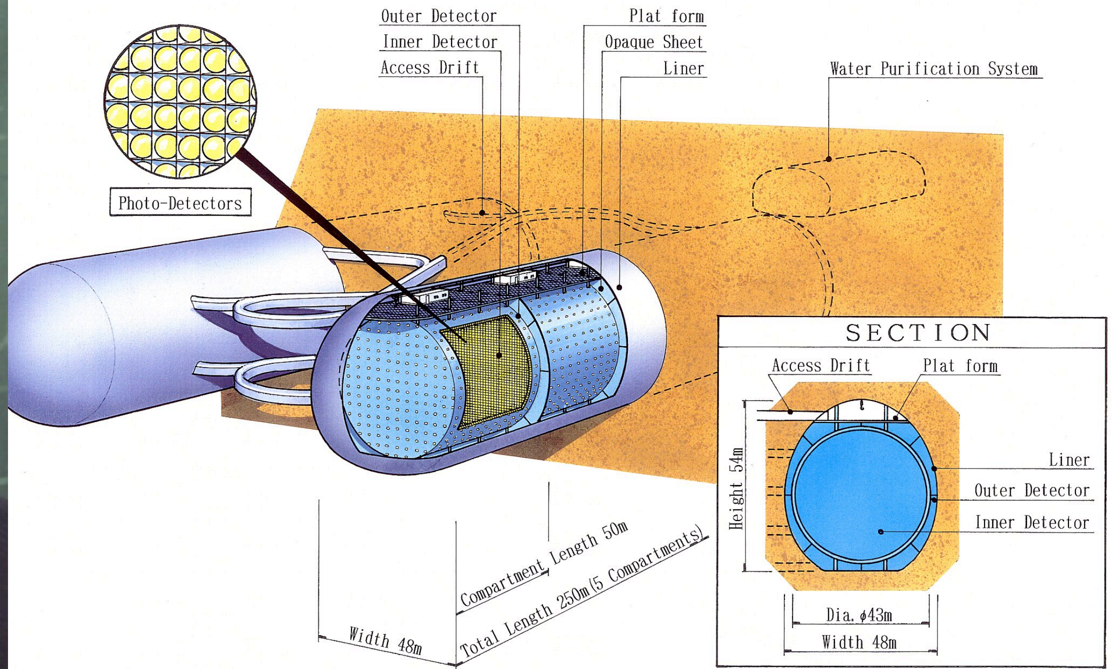
T2KK; Tokai to Kamioka-Korea twin HK complex



Ishitsuka-Kajita-HM-Nunokawa hep-ph/0504026

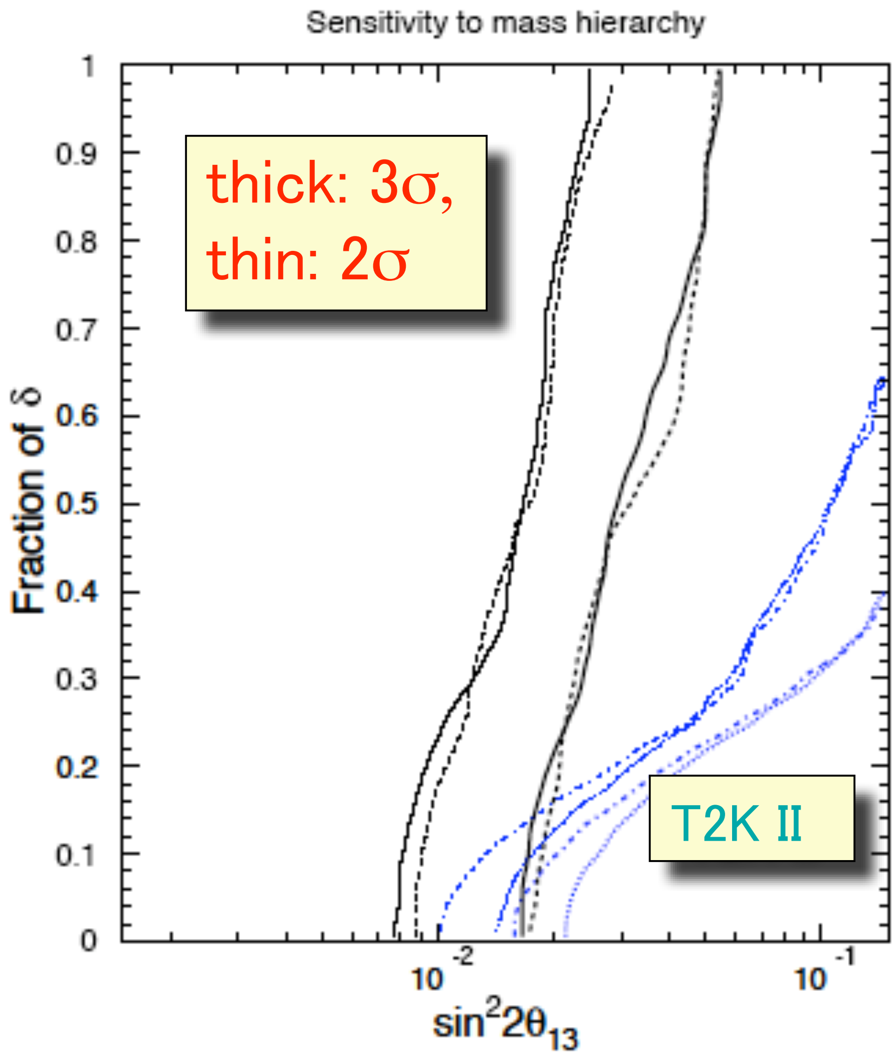
Current design of Hyper-Kamiokande contains 2 tanks !

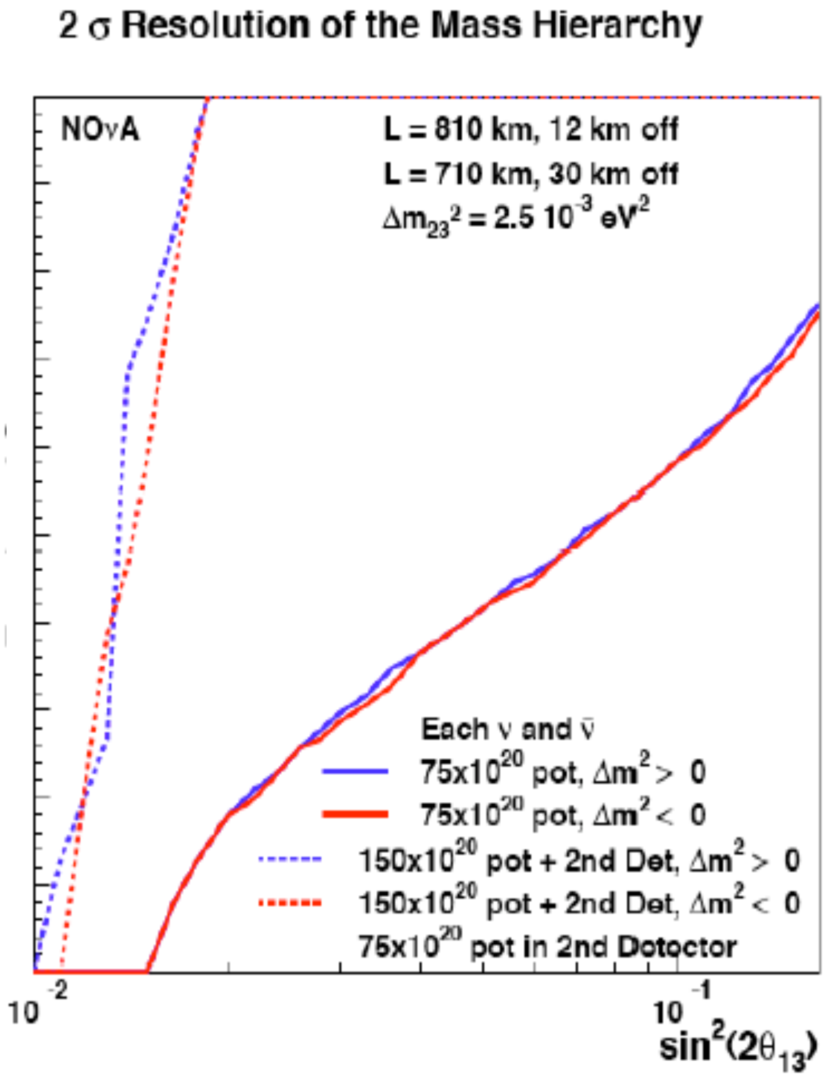




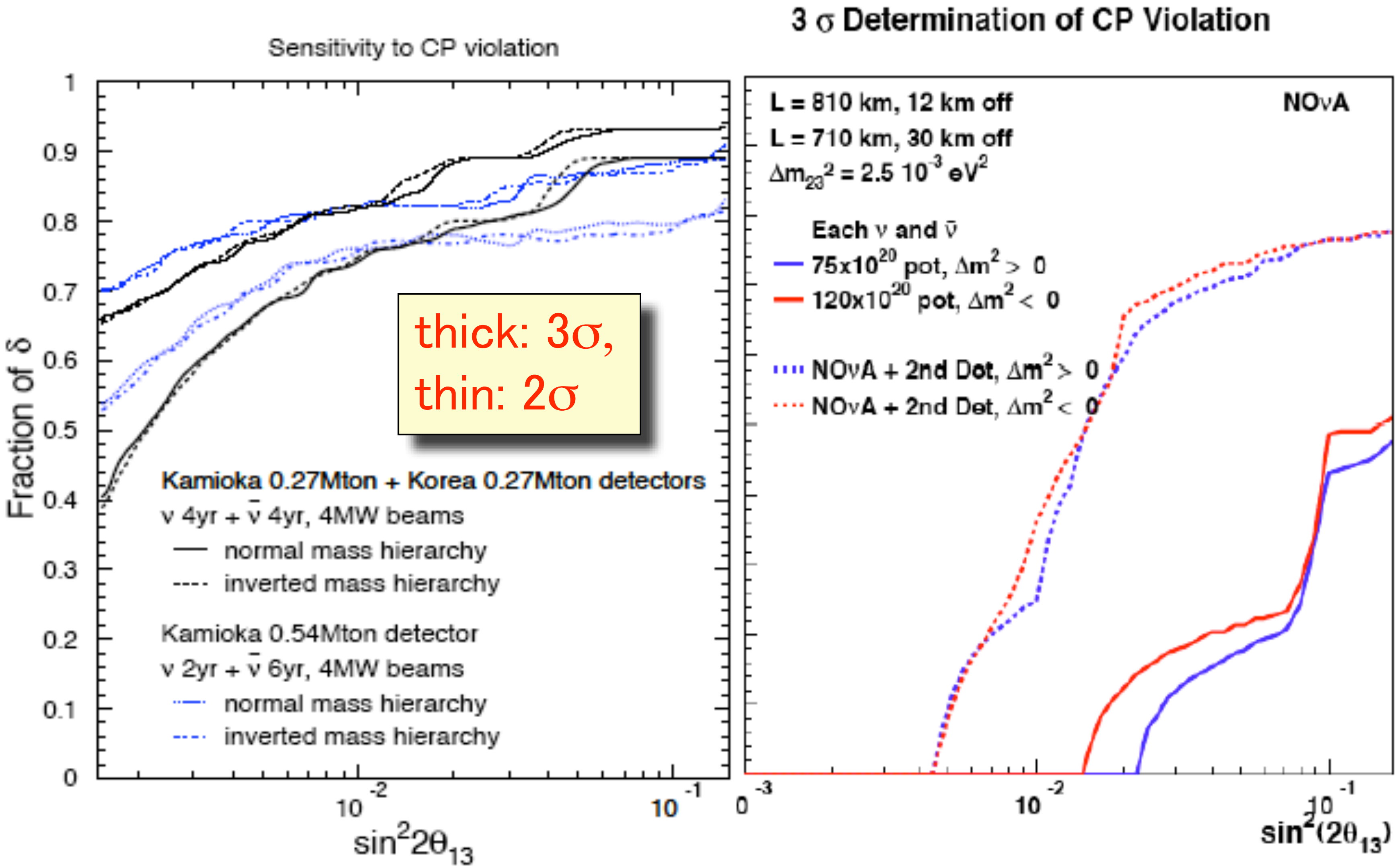
Why don’t you bring one of the 2 tanks to Korea?

T2KK vs. NOνA; mass hierarchy





T2KK vs. NOνA; CP

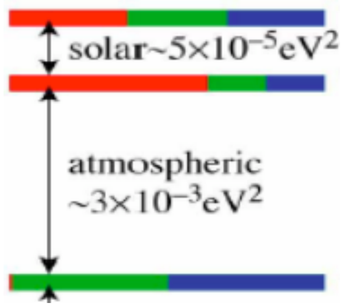


Signal at ~50 meV; what does it mean?

Inverted mass hierarchy without extra m_0

- m_0~0 can be inferred, e.g., by Planck satellite

$$\langle m \rangle_{ee} \approx \left| c_{12}^2 m_1 + s_{12}^2 m_2 e^{i(\phi_2 - \phi_1)} \right|$$



$$c_{12}^2 m_1 \simeq c_{12}^2 \sqrt{\Delta m_{atm}^2} \simeq 0.035\ eV$$
$$s_{12}^2 m_2 \simeq s_{12}^2 \sqrt{\Delta m_{atm}^2} \simeq 0.015\ eV$$
$$s_{13}^2 m_3 \simeq s_{13}^2 \sqrt{\Delta m_{\odot}^2} < 0.025 \times 9 \cdot 10^{-3} \simeq 2.2 \times 10^{-4}\ eV$$

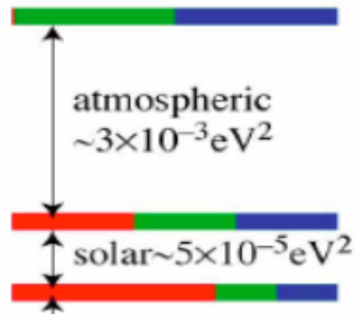
$$0.02\ eV < \sqrt{\Delta m_{atm}^2} \cos 2\theta_{12} < \langle m \rangle_{ee} < \sqrt{\Delta m_{atm}^2} = 0.05\ eV$$

Majorana phase may be measured

Signal at ~50 meV; what does it mean?

Normal mass hierarchy without extra m_0

$$\langle m \rangle_{ee} \approx \left| c_{12}^2 m_1 e^{i\phi_1} + s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$



$$c_{12}^2 m_1 \simeq c_{12}^2 \sqrt{\Delta m_\odot^2} \simeq (6.2 \times 10^{-3} \leftrightarrow 0.0)\ eV$$

$$s_{12}^2 m_2 \simeq s_{12}^2 \sqrt{\Delta m_\odot^2} \simeq 2.7 \times 10^{-3}\ eV$$

$$s_{13}^2 m_3 \simeq s_{13}^2 \sqrt{\Delta m_{atm}^2} \approx 0.025 \times 0.05\ eV \simeq 1.3 \times 10^{-3}\ eV$$

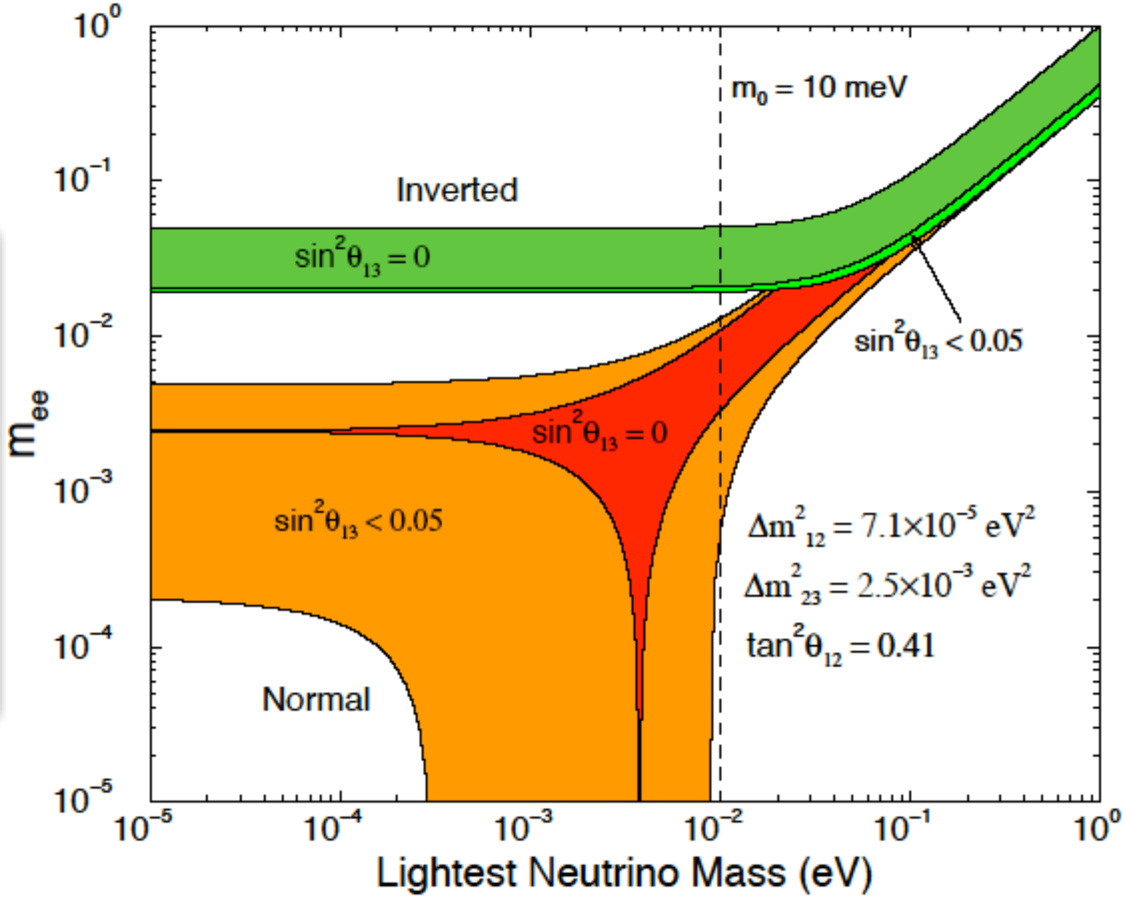
$$0\ eV < \langle m \rangle_{ee} \sim \text{(a few - several)}\ meV < \sqrt{\Delta m_\odot^2} = 0.01\ eV$$

- Definitely implies extra mass scale m_0
- Harder to obtain Majorana phase information

Majorana phase?

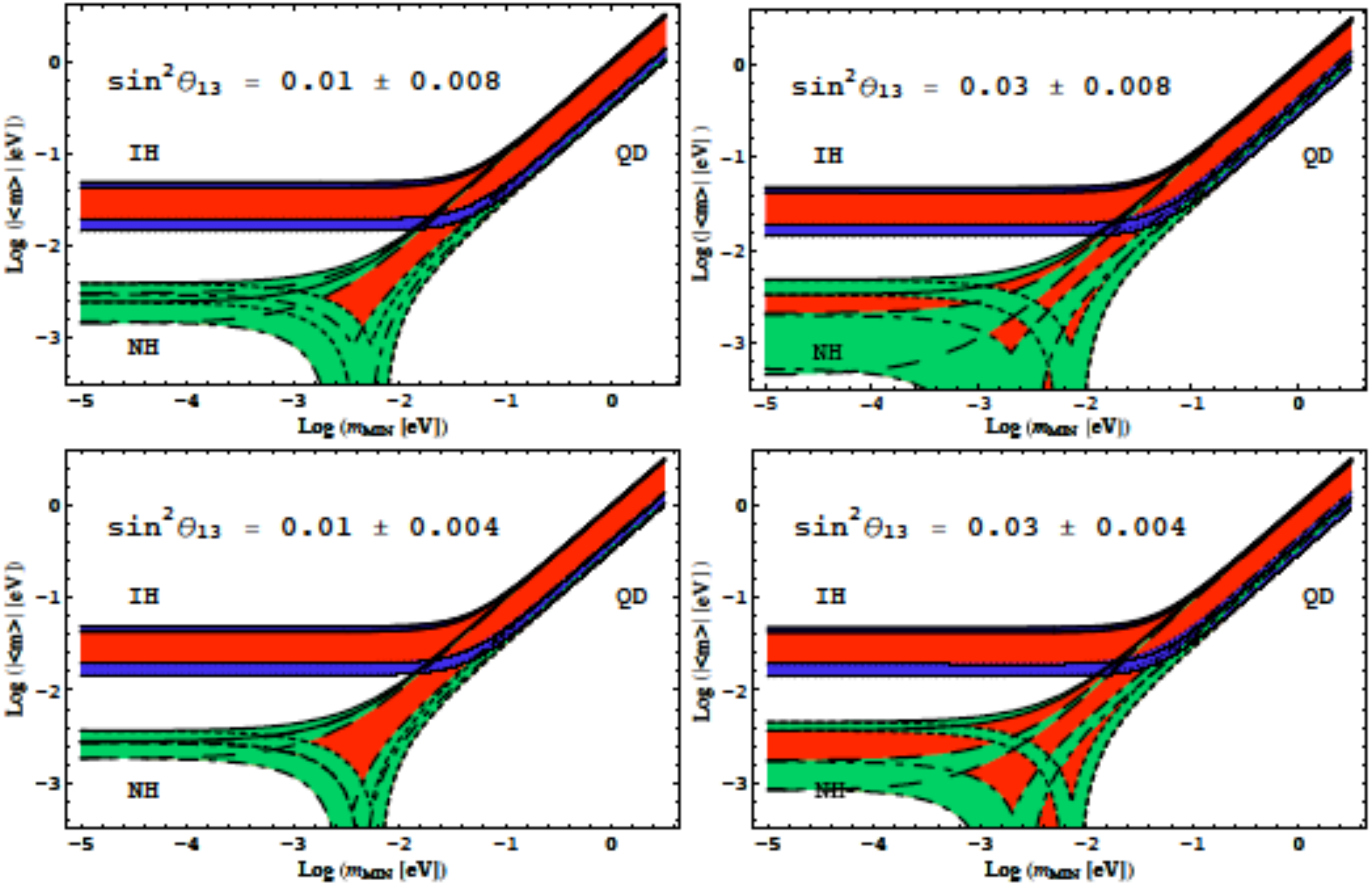
$$\langle m \rangle_{ee} = \left| c_{12}^2 c_{13}^2 m_1 e^{i\phi_1} + s_{12}^2 c_{13}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

Basics: Width of the band represents effect of CP phases



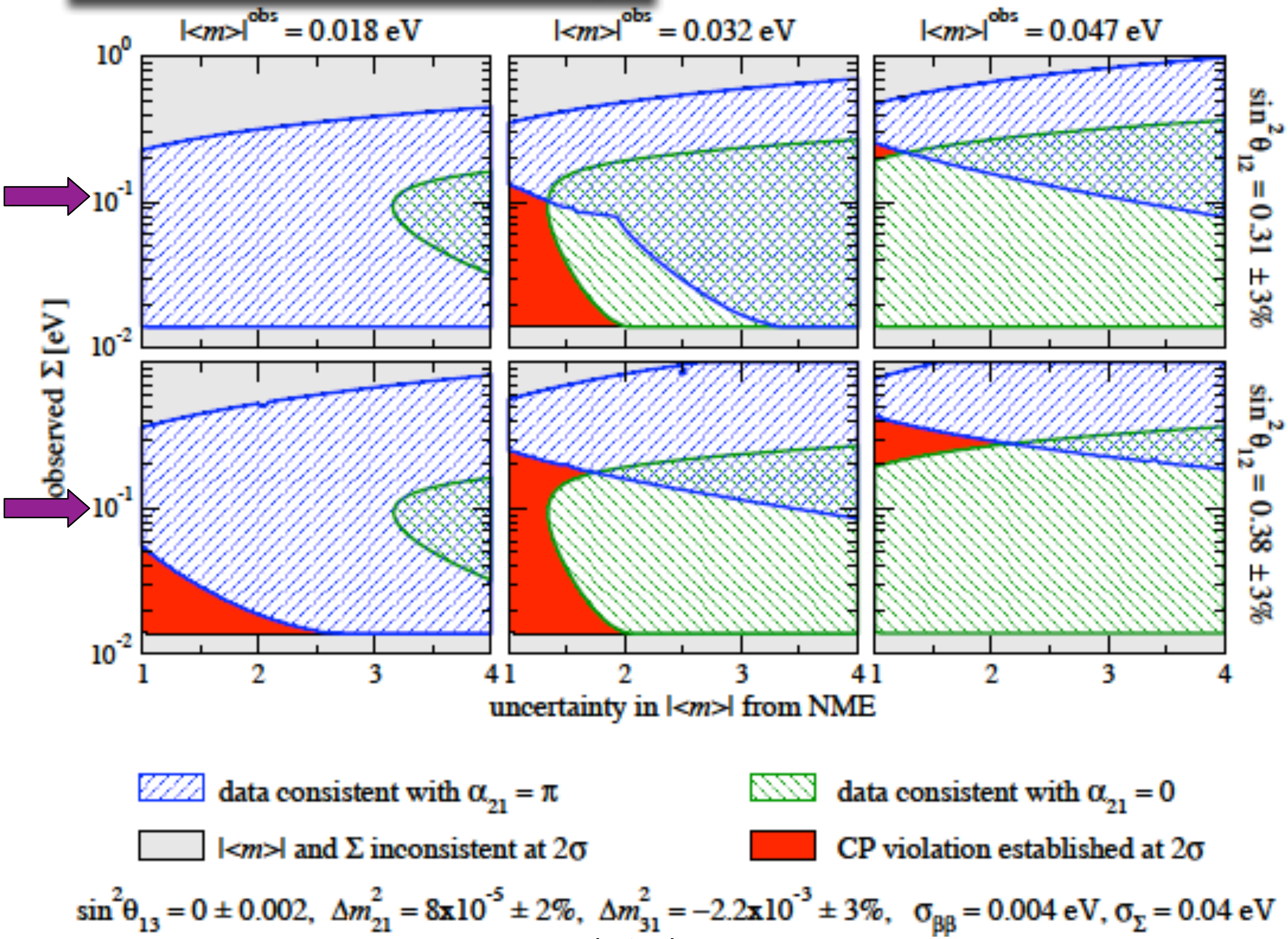
If θ_{13}=0, $<m_{ee}>$=0, => m_1=4x10^{-3} eV^2

In reality, …



Red=CPV (PPS)

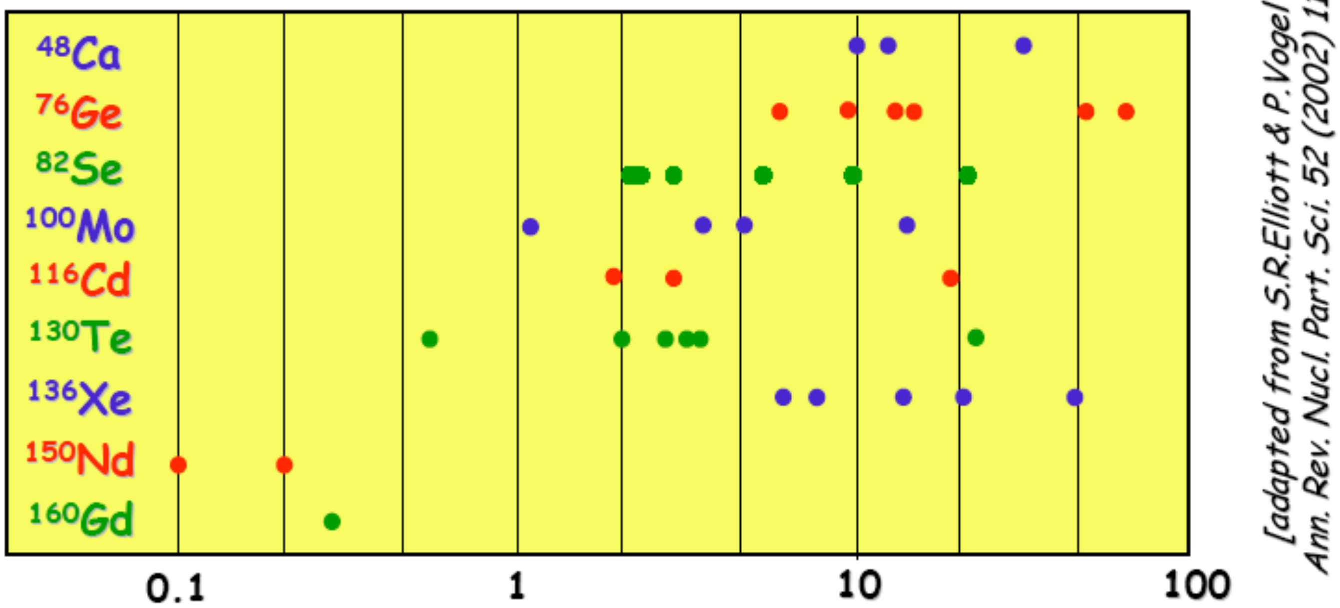
Inverted mass hierarchy



beta decay

Uncertainty of nuclear matrix elements

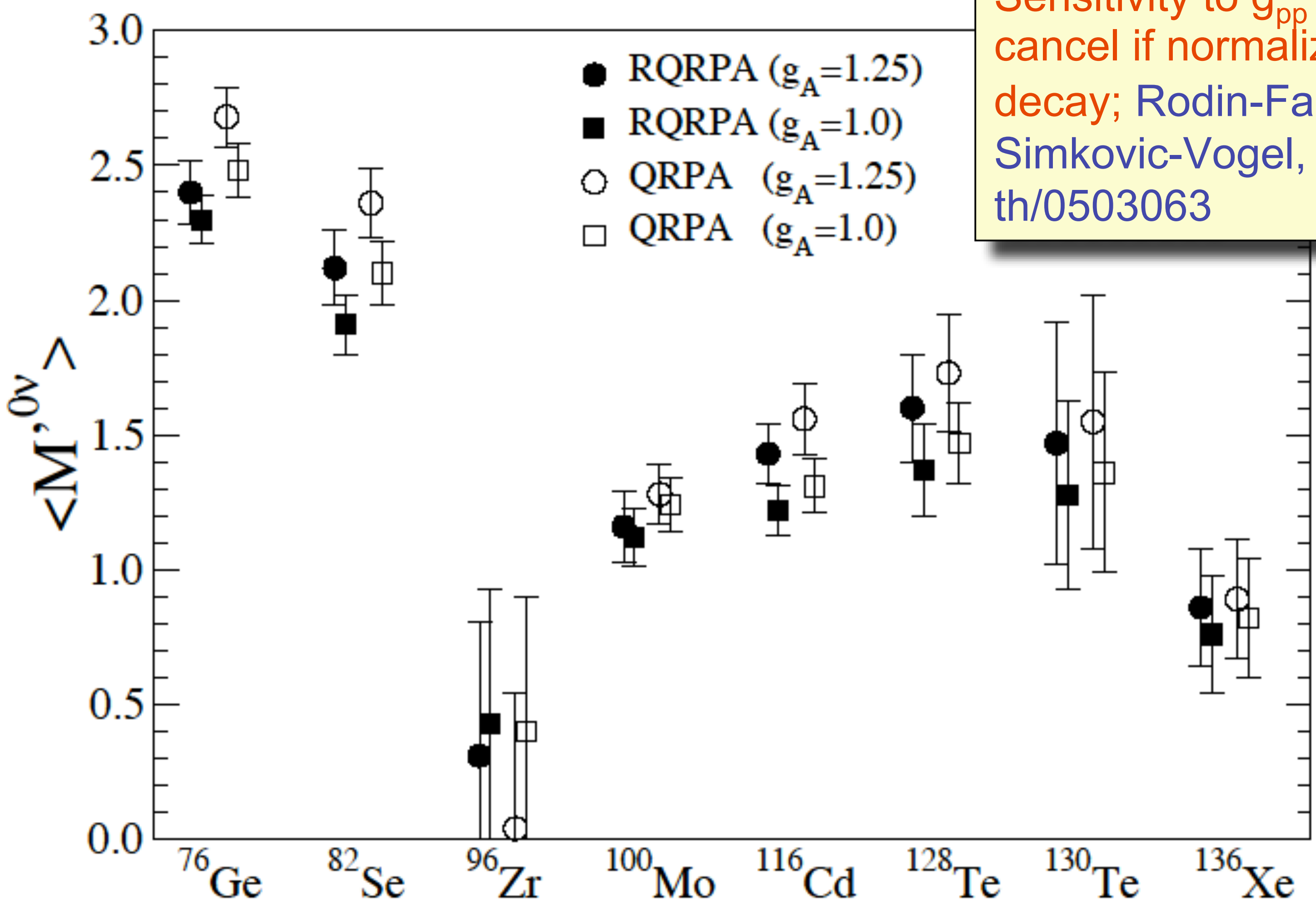
0νββ decay half lives in 10^{26} yr units for $\langle m_\nu \rangle$ = 50 meV according to different nuclear matrix element calculations



Unfortunately it is not trivial to use the 2ν matrix element to normalize the 0ν one:

- $|M_{2\nu}|$ – has stronger dependence on intermediate states
- $|M_{0\nu}|$ – all multipoles contribute
  - ν propagator results in long range potential

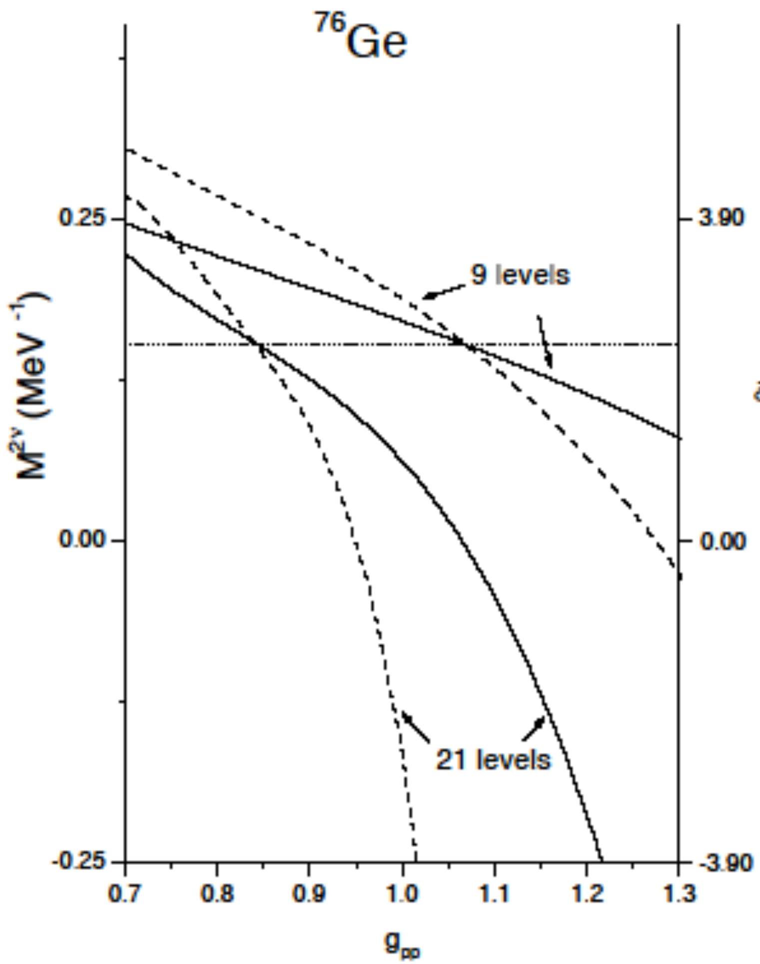
Now, we have hope

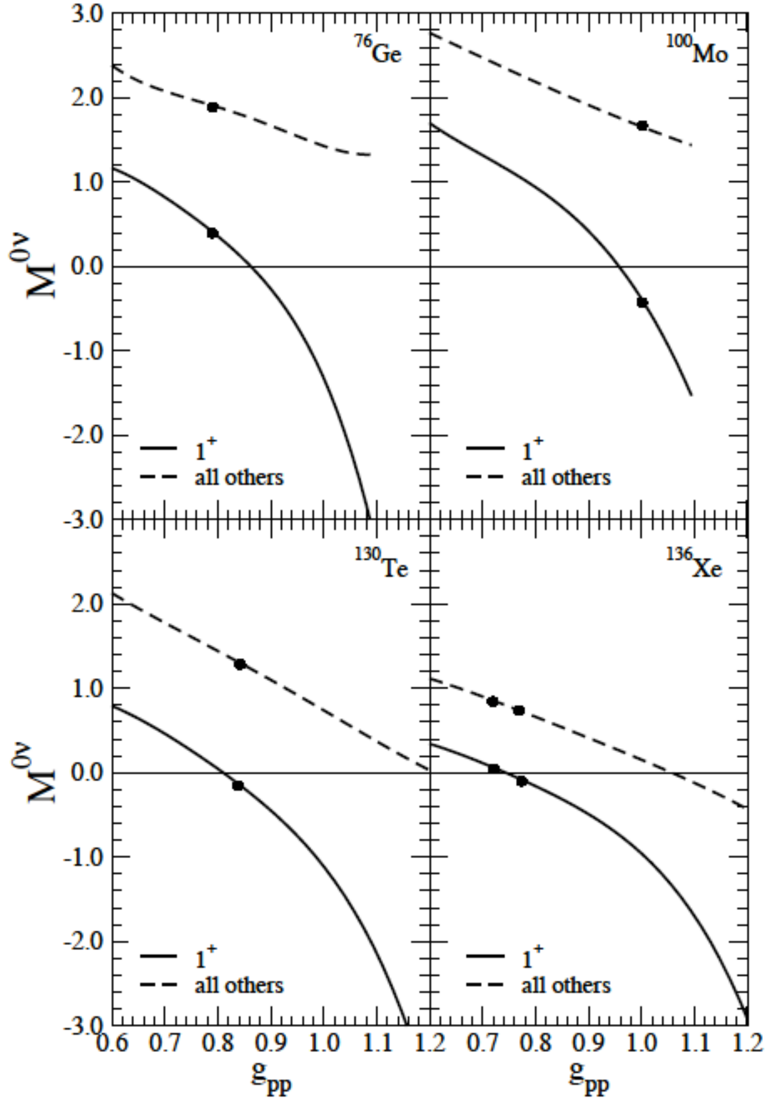


Sensitivity to g_{pp} partially cancel if normalized by 2ν decay; Rodin-Faessler-Simkovic-Vogel, nucl-th/0503063

FIG. 2: Average nuclear matrix elements $\langle M'^{0\nu} \rangle$ and their variance (including the error coming from the experimental uncertainty in $M^{2\nu}$) for both methods and for all considered nuclei. For ^{136}Xe the error bars encompass the whole interval related to the unknown rate of the $2\nu\beta\beta$ decay.

Sensitivity to g_{pp} cancel against its 2ν counterpart





Shell model vs. QRPA

TABLE XVII Calculated $T^{2\nu}_{1/2}$ half-lives for several nuclei and $0^+ \rightarrow 0^+$ transitions

Parent	^{48}Ca	^{76}Ge	^{82}Se
$T^{2\nu}_{1/2}$ th.(y)	3.7×10^{19}	2.6×10^{21}	3.7×10^{19}
$T^{2\nu}_{1/2}$ exp.(y)	4.3×10^{19}	1.8×10^{21}	8.0×10^{19}

TABLE XVIII 0ν matrix elements and upper bounds on the neutrino mass for $T^{0\nu}_{1/2} \geq 10^{25}$ y. $\langle m_\nu \rangle$ in eV.

Parent	^{48}Ca	^{76}Ge	^{82}Se
$M^{0\nu}_{GT}$	0.63	1.58	1.97
$M^{0\nu}_{F}$	-0.09	0.19	-0.22
$\langle m_\nu \rangle$	0.94	1.33	0.49

Caurier et al., nucl-th/0402046

$M^{0\nu}$: Shell model:

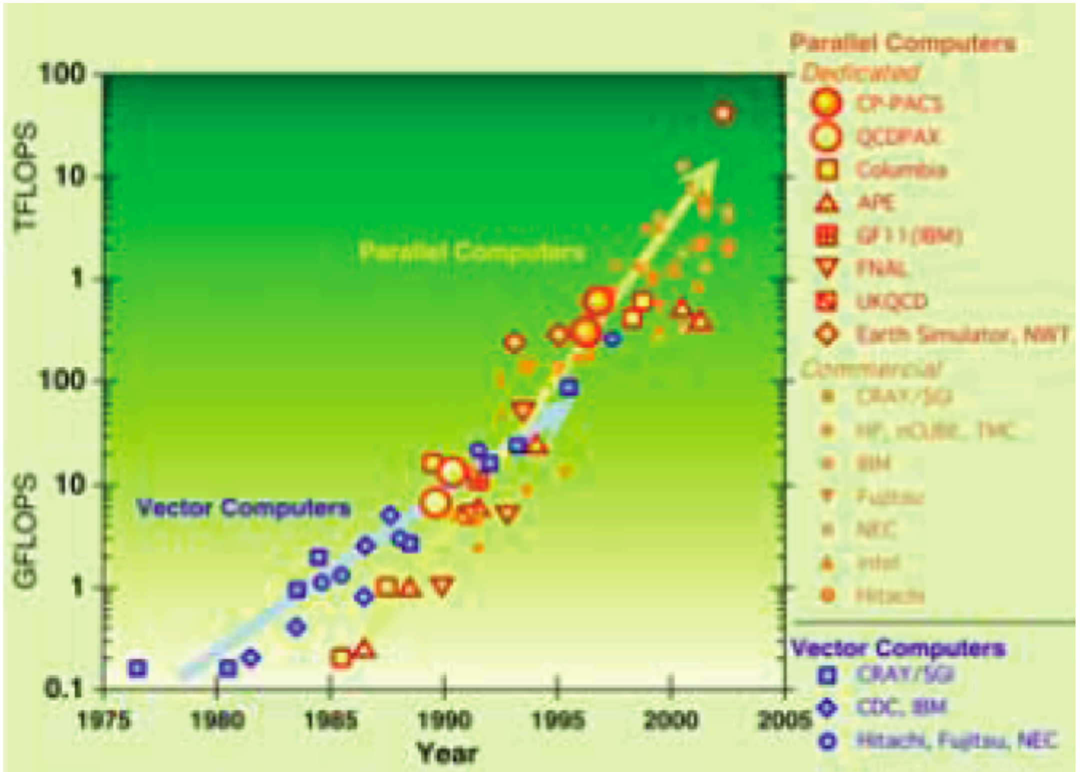
1.5, 2.1, 1.1, and 0.7 for ^{76}Ge, ^{82}Se, ^{130}Te and ^{136}Xe,

$M^{0\nu}$: RQRPA

2.4, 2.1, 1.5, and 0.7-1.0

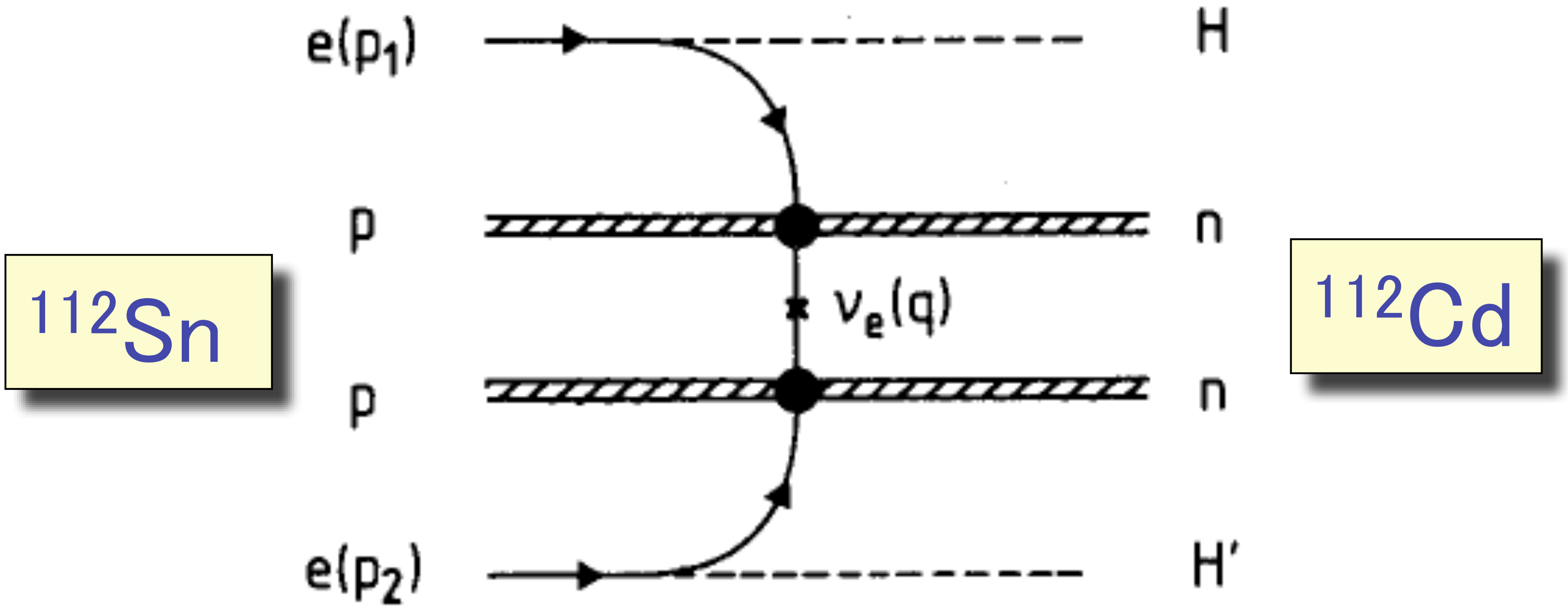
Shell model computation of 0νββ decay?

- # of basis
- Current = 10^9
- Ge, Se -> ~10^{20} (Muto-san's estimate)
- Is it impossible?
- Computational power get larger by 10^3 in every 10 years



Computer Center for Double Beta Decay !?

Alternative processes?



Double electron capture (Bernabeu-De Rujula-Jarlskog '83)

→ Life time 10^{27}-10^{31} years (m_ν=0.1 eV)

- Enhancement of a related process by laser pumping (Yoshimura et al)

Conclusion

- $0\nu\beta\beta$ decay: unique for demonstrating Majorana ν + indispensible for absolute mass determination
- Uncertainty of nuclear matrix elements = most important problem for interpretation of the results
- Mass hierarchy determination by LBL helps
- Great opportunity in the 2nd half stage of exploring ν masses and lepton mixing