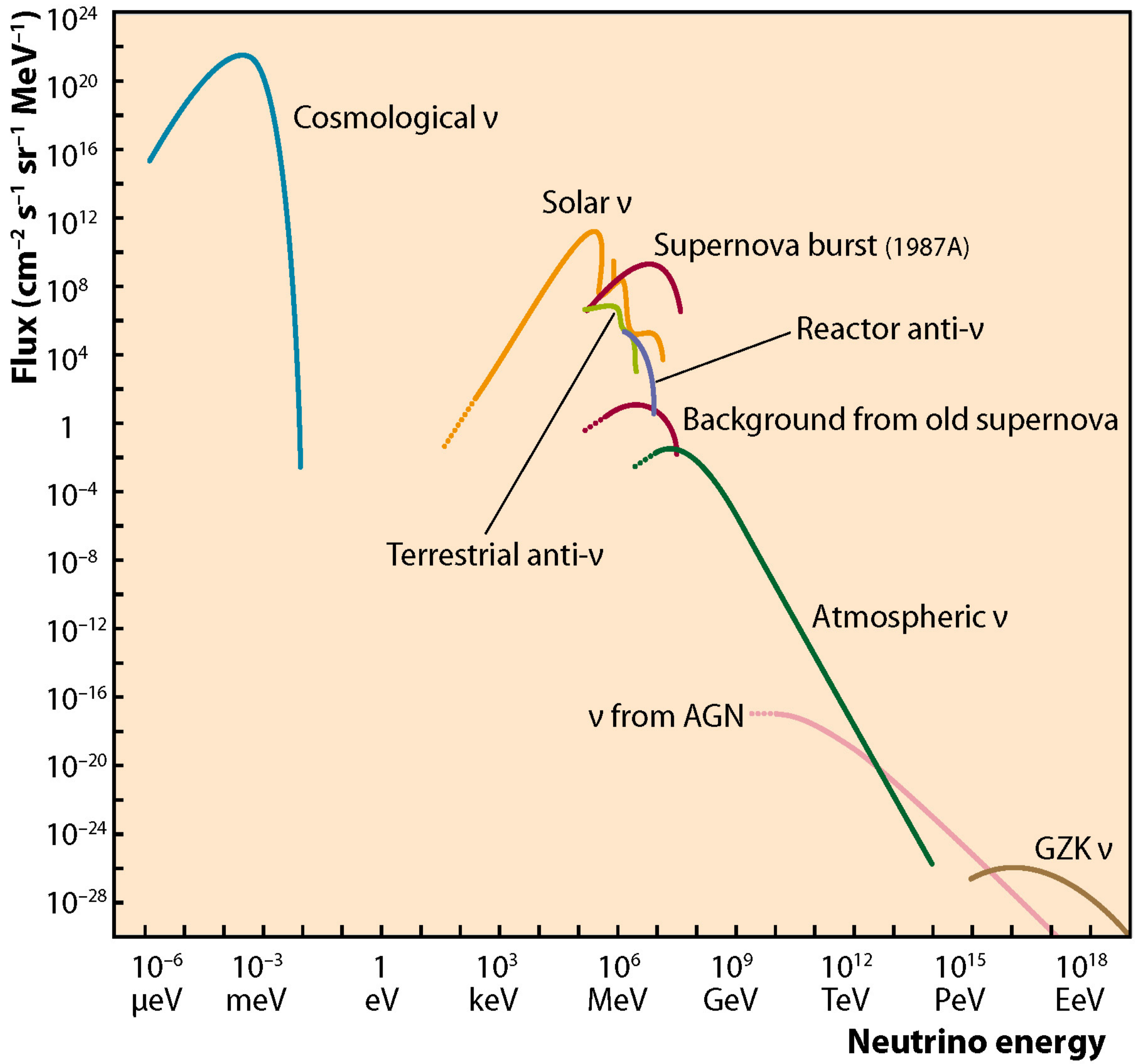
CHIPP School 2010 Ascona, Switzerland

Some perspectives in neutrino physics

(a brief selection)

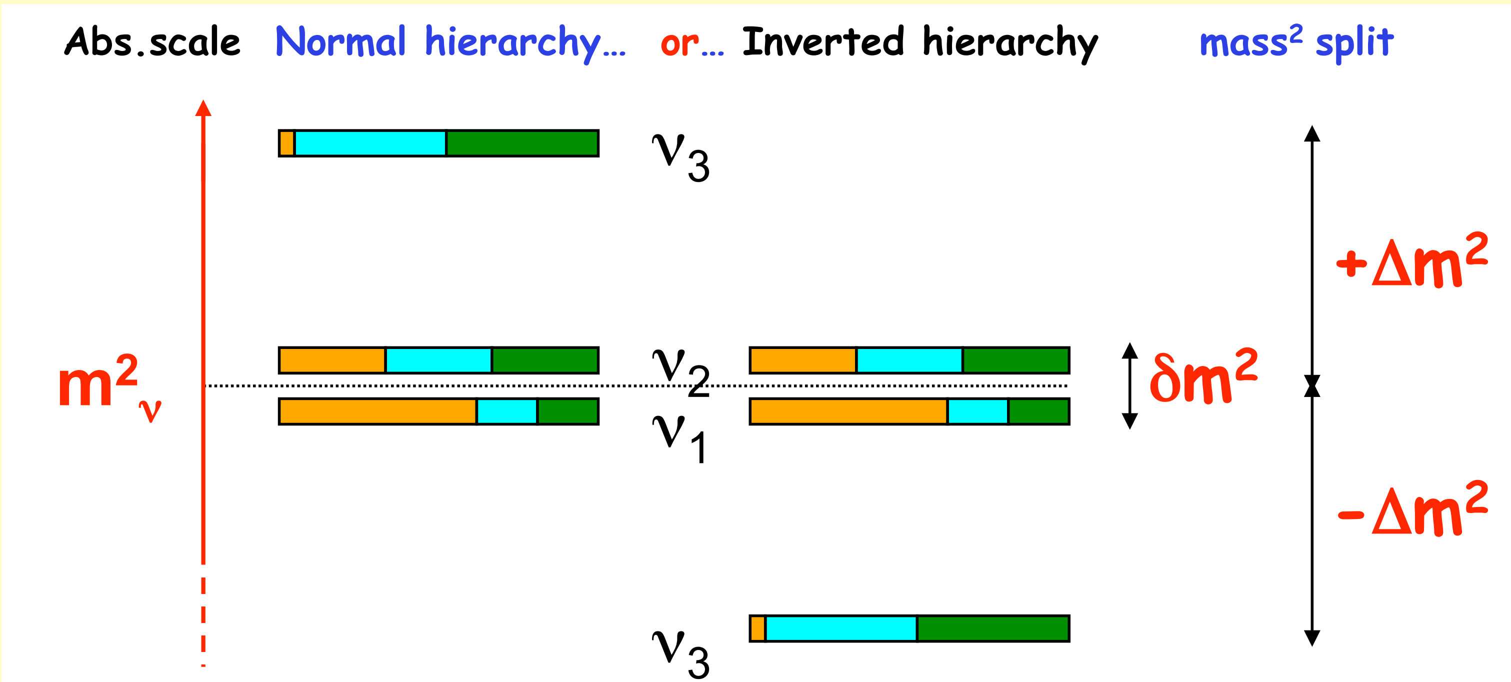
Eligio Lisi
INFN, Bari, Italy

Vast lands to be explored



A synoptic view of neutrino fluxes. (from ASPERA roadmap)

CURRENT STAGE (Flavors = e μ τ)



$\delta m^2 \sim 8 \times 10^{-5}\ \mathrm{eV}^2$ $\quad$ $\sin^2\theta_{12} \sim 0.3$

$\Delta m^2 \sim 3 \times 10^{-3}\ \mathrm{eV}^2$ $\quad$ $\sin^2\theta_{23} \sim 0.5$

} established

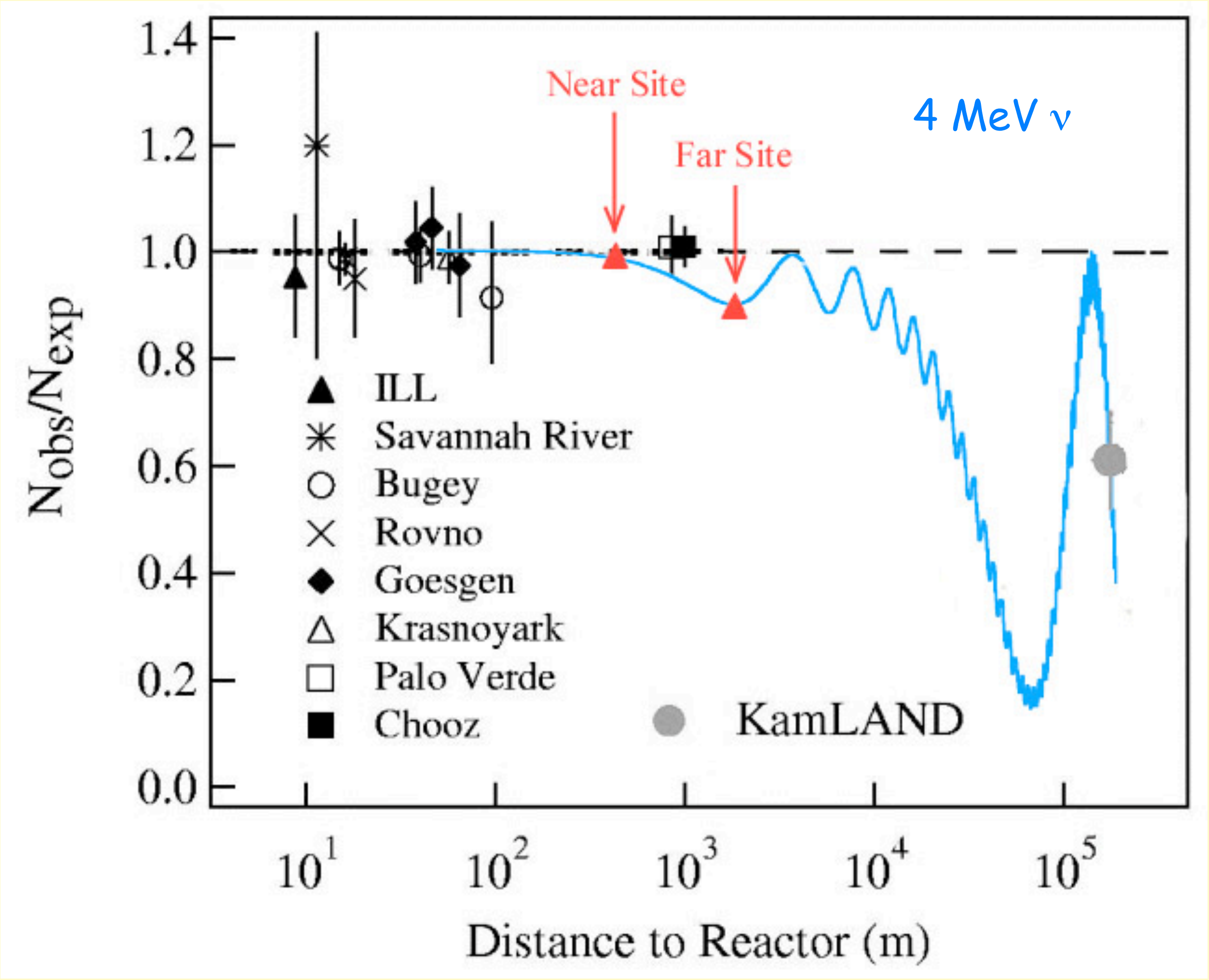
$m_\nu < O(1)\ \mathrm{eV}$ $\quad$ $\sin^2\theta_{13} < \mathrm{few}\%$

$\mathrm{sign}(\pm\Delta m^2)$ unknown $\quad$ δ (CP) unknown

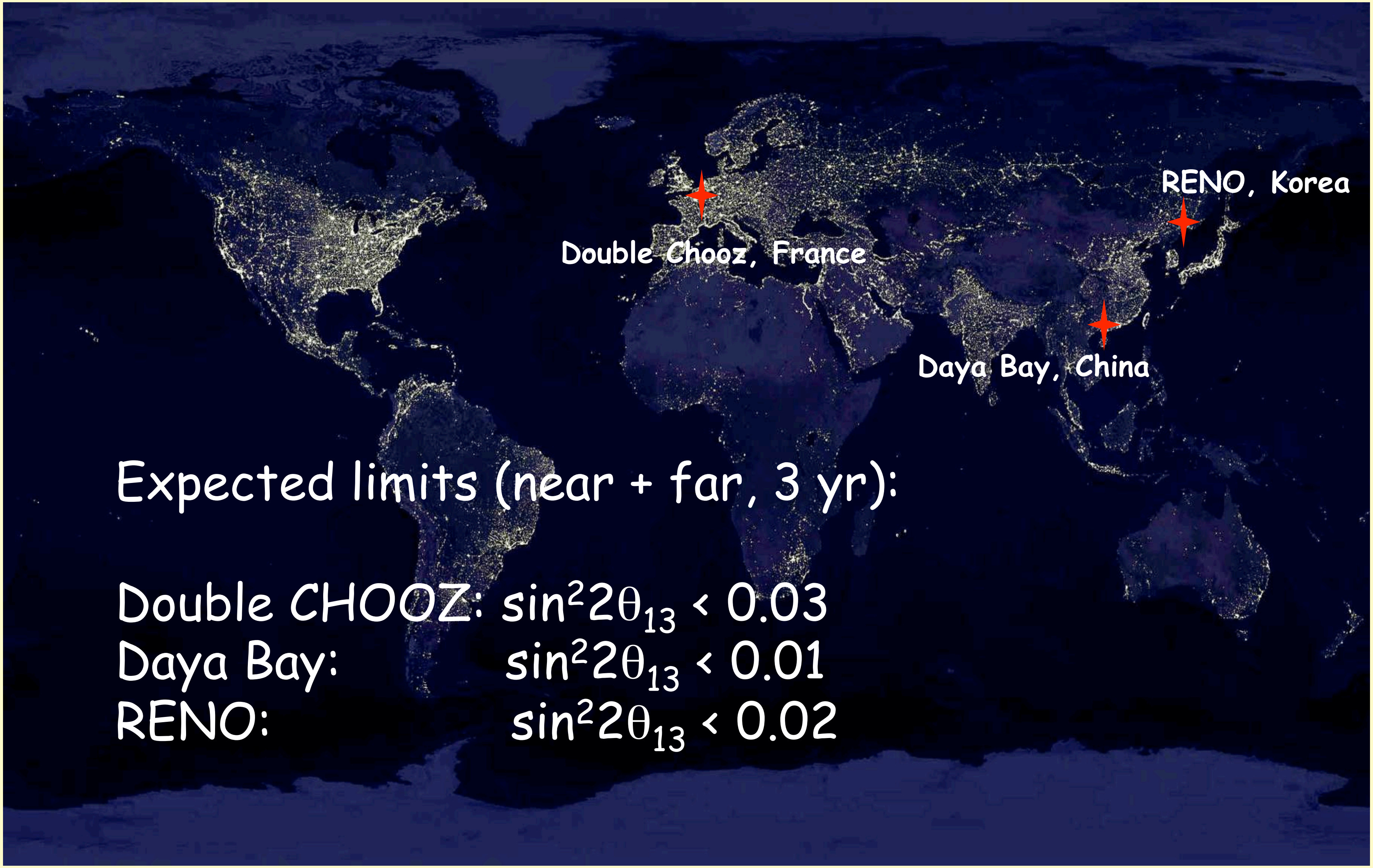
} open issues

New states or interactions: More open issues

Most urgent: θ_{13}. Probe at short baseline reactors with near+far detectors to reduce total error below 1%.



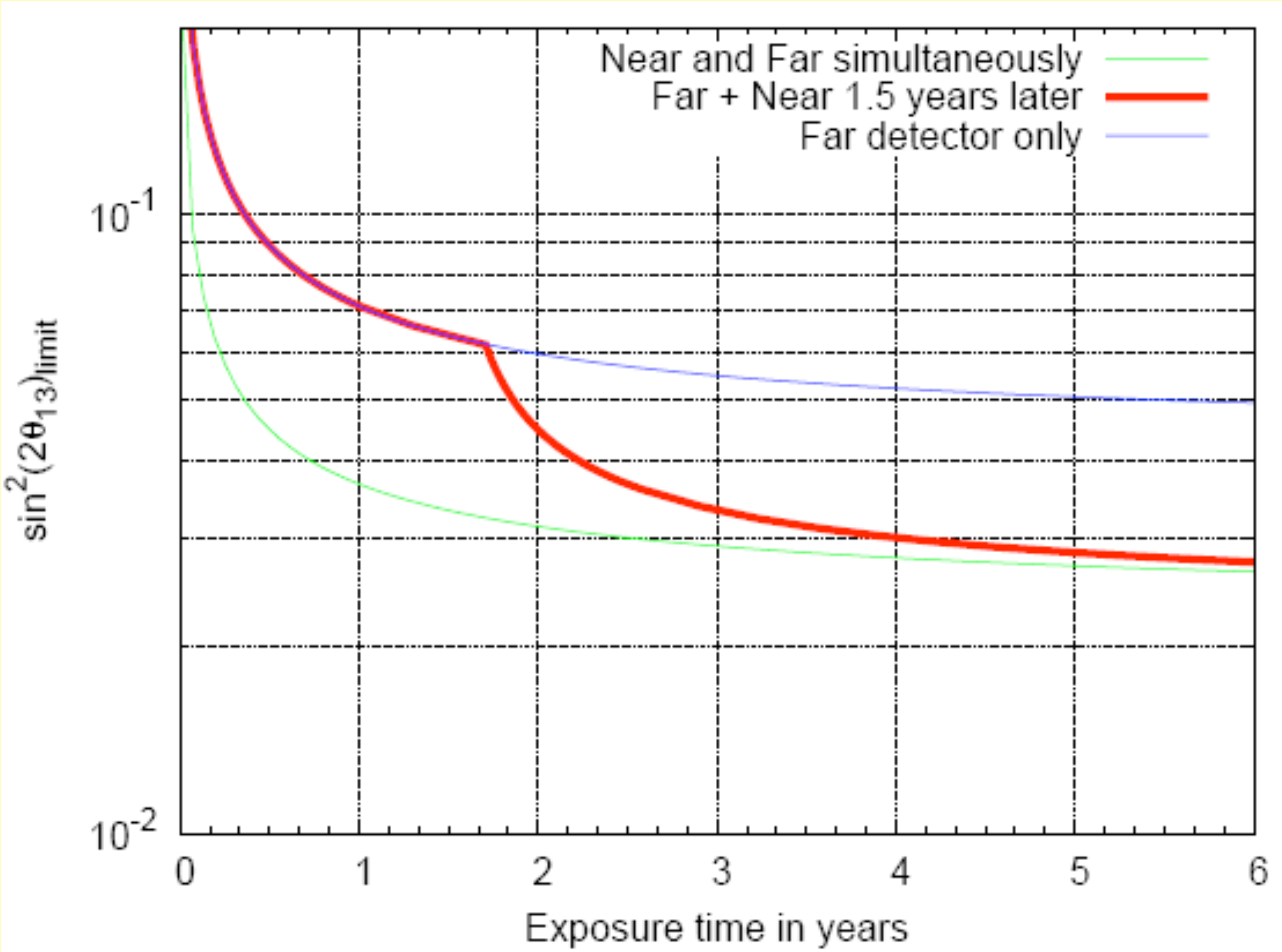
Experiments in (advanced) construction



Expected limits (near + far, 3 yr):

Double CHOOZ: $\sin^2 2\theta_{13} < 0.03$
Daya Bay: $\sin^2 2\theta_{13} < 0.01$
RENO: $\sin^2 2\theta_{13} < 0.02$

Impact of near detector (for Double CHOOZ)



(Sensitivity for discovery: typically weaker by factor ~2)

If search is successful: maybe can also test the full structure of the oscillations at reactors (e.g, Petcov et al.):

$$
\begin{aligned}
1 - P_{ee} \quad &= \quad 4|U_{e1}|^2|U_{e2}|^2 \sin^2\left(\frac{\delta m^2 L}{4E}\right) \\
&+ \quad 4|U_{e1}|^2|U_{e3}|^2 \sin^2\left(\frac{\pm\Delta m^2 + \delta m^2/2}{4E}\,L\right) \\
&+ \quad 4|U_{e2}|^2|U_{e3}|^2 \sin^2\left(\frac{\pm\Delta m^2 - \delta m^2/2}{4E}\,L\right)
\end{aligned}
$$

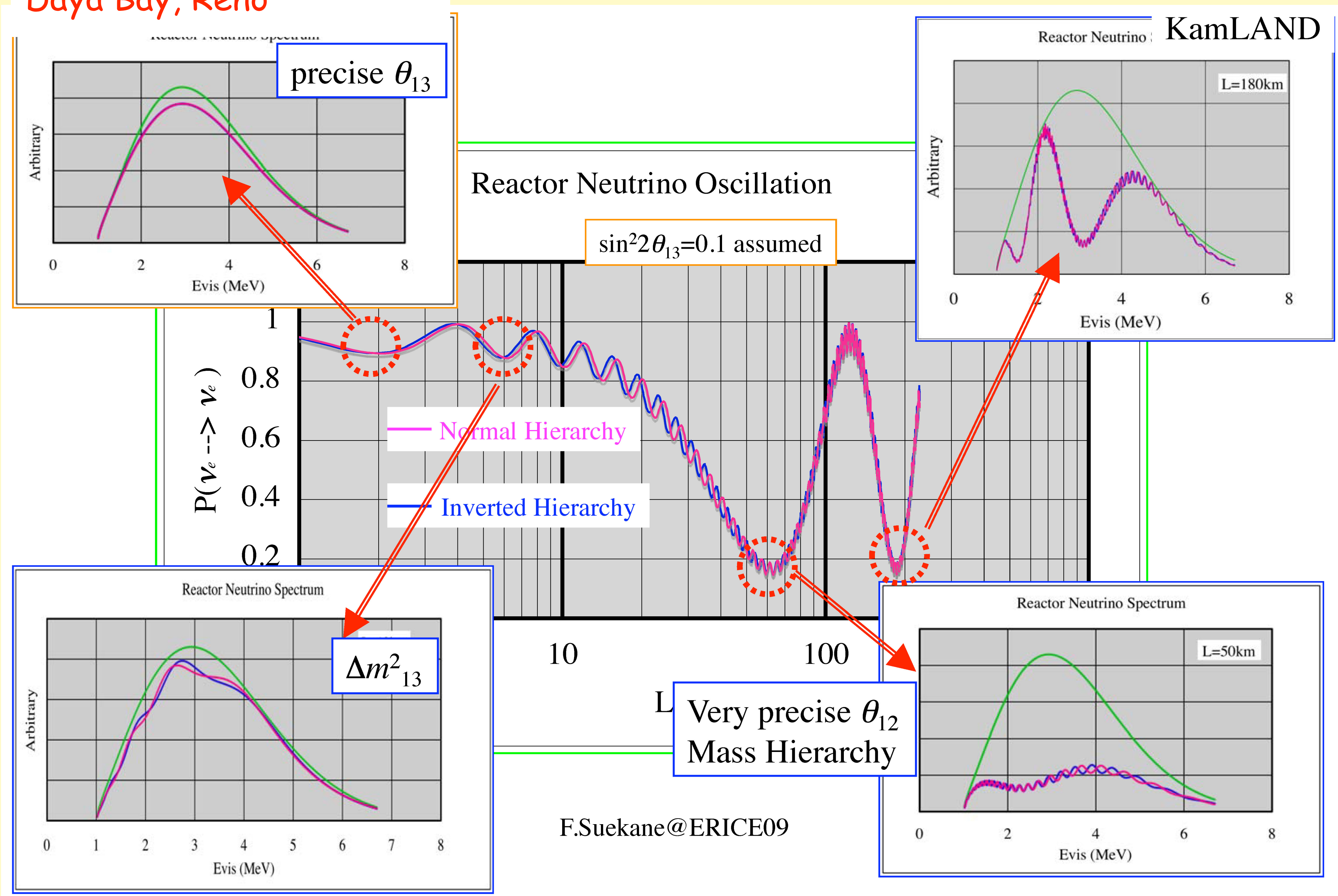
"slow osc."
(long baseline)

"fast osc."
(short baseline)

... Very difficult! Need very high accuracy & resolution.

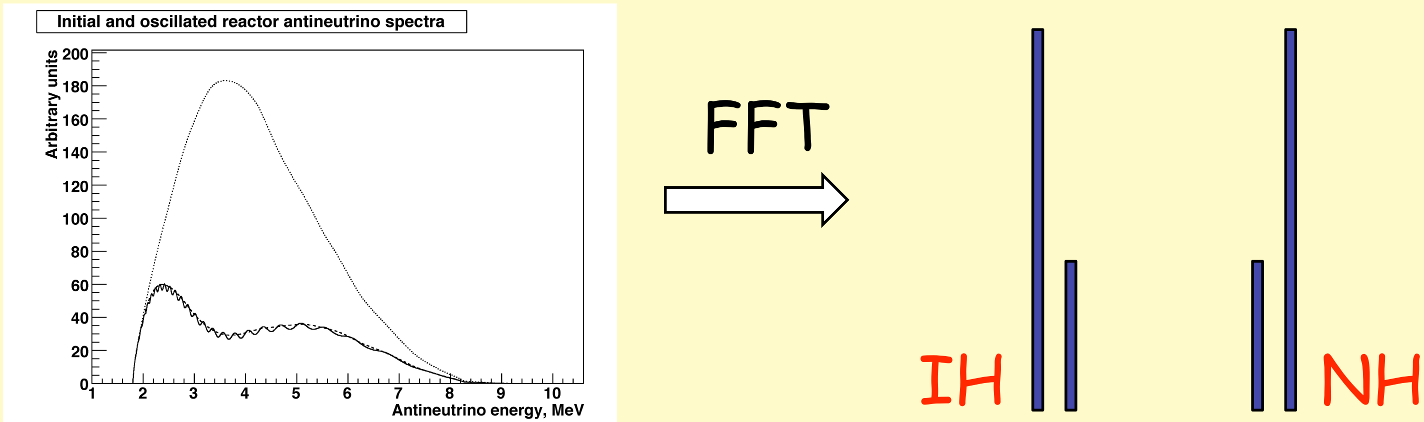
Double CHOOZ
Daya Bay, Reno

All in one slide...



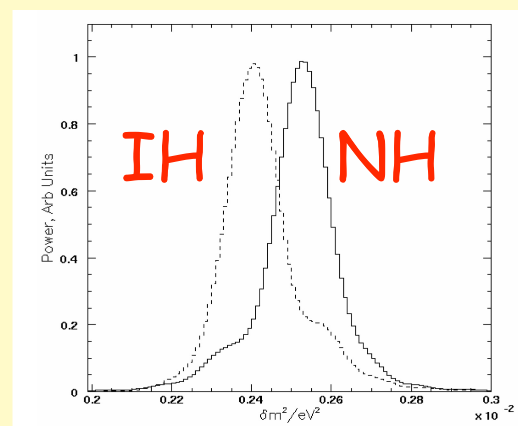
E.g.: <u>**Hierarchy**</u> via Fourier analysis of the fast oscillations (Learned et al.)

For perfect resolution, should find two high frequencies $\Delta m^2 \pm \delta m^2/2$ with different amplitudes:



For finite resolution, the two peaks would merge, but the lowest one should still survive as a "shoulder" on the left (NH) or on the right (IH) of the dominant peak.

But: very difficult to envisage peak shape measurements which can be accurate enough to tell them apart.

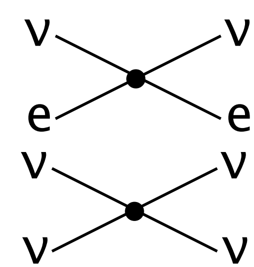


MORE ON MASS HIERARCHY: NORMAL vs INVERTED

The ambiguity related to hierarchy, namely, sign($\pm\Delta m^2$), can be addressed (in principle), via <u>interference</u> of Δm^2-driven oscillations with oscillations driven by some quantity <u>Q having a known sign</u>.

Barring states/interactions, the only known options are:

Q = δm^2 (Just examined with reactors)
Q = Electron density (MSW effect in Earth or SNe)
Q = Neutrino density (Collective effects in SNe)

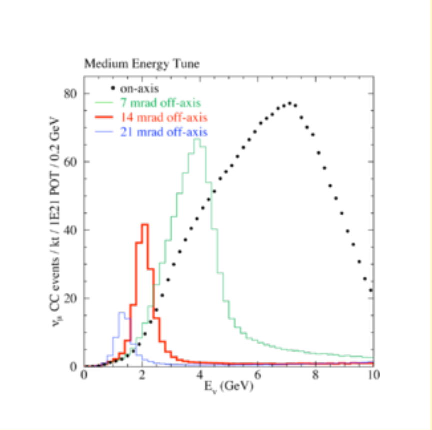


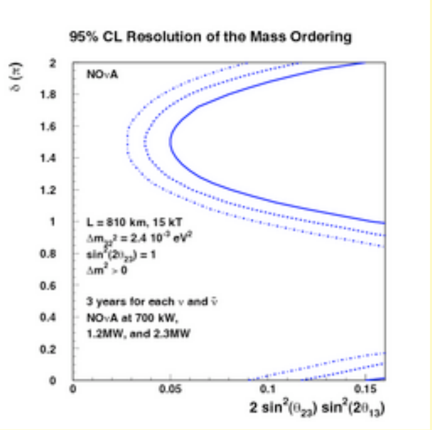
In addition, nonoscillation data provide another handle.

In any case, the name of the game is: high accuracy!

The second option is provided by the usual MSW effect (neutrino-matter forward scattering). Fractional variation of amplitude or phase is roughly $\pm 2\sqrt{2} G_F N_e E/(\pm \Delta m^2)$, where the first ± refers to nu/antinu and the second to NH/IH.

Variations can be up to ~30% in accelerator beams with relatively sharp E-spectra (off-axis) and relatively long L inside the Earth crust (optimal choice: ~oscillation maximum). E.g., NOvA:

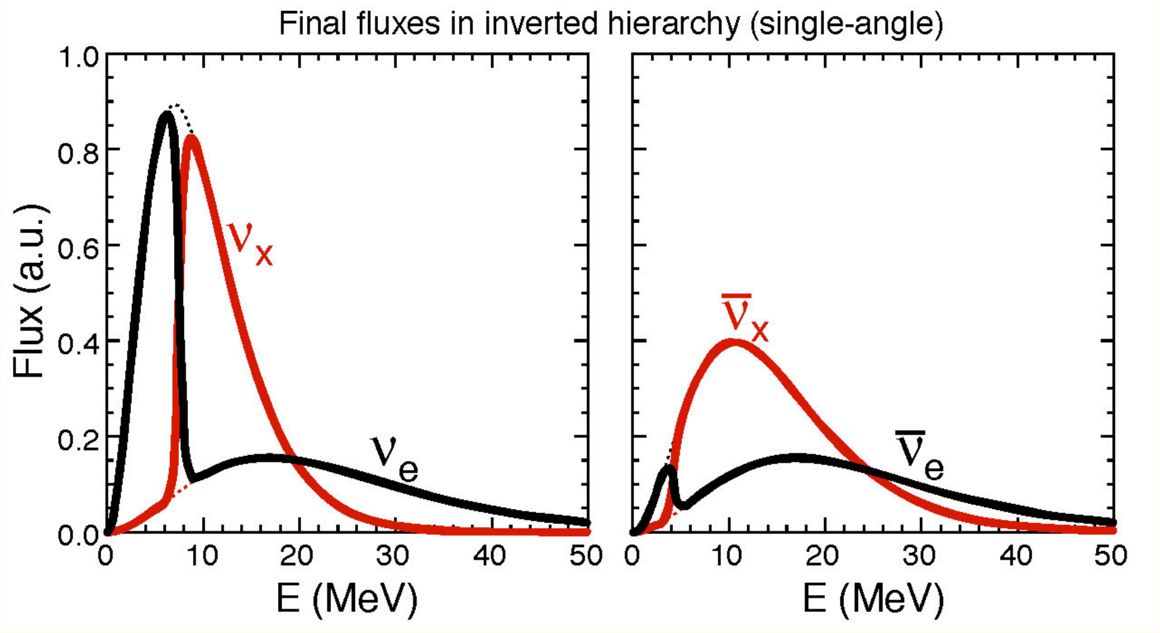




But: absolute amplitude of ν_μ->ν_e scales as $\sin^2\theta_{13}$, with strong δ dependence. Must be lucky with both parameters!

The third option may be provided by neutrino-neutrino forward scattering in core-collapse SN. In this case, $\pm\Delta m^2$ compares with $\pm 2\sqrt{2} G_F E$ * density (nu + antinu). Maybe the only place to test neutrino-neutrino interactions!

Recently revived after seminal work by UCSD group. Interesting and peculiar nonlinear phenomena arise, such as spectral split/swap effects in observable spectra (for I.H.)



Very interesting theoretically (coupled, nonlinear flavor histories)

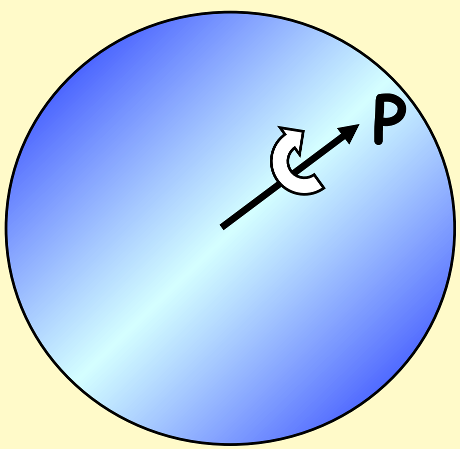
Coupled equations of motion (for 2 flavors, e and $x=\mu,\tau$)

Hamiltonian now depends on neutrino density -> use density matrix.

Liouville equations: $i\partial_t \rho=[H,\rho]$ (for each neutrino mode)

Decompose 2x2 (anti)neutrino density matrix over Pauli matrices to get a "**polarization**" (Bloch) 3-vector $\mathbf{P}=(P_1,P_2,P_3)=(P_x,P_y,P_z)$. [Ditto for H.]

Bloch equations: $\partial_t \mathbf{P} = \mathbf{V}\times\mathbf{P}$ (precession-like, $|P|$=const)



Any mode P moves on a Bloch sphere (abstract "flavor space").

"up" direction : ν_e flavor

"down" direct. : ν_x flavor

generic direct. : mixed flavor state

Probability P_{ee} related to $P_3=P_Z$

Coupled equations of motion (cont'd)

The problem is that there are lots of kinematical neutrino modes: continuous distributions over energy and angle(s) -> no less than ∞^2 !

Discretize over energy spectrum (**N_E bins**), and over angular distribution in multi-angle simulations (**N_Θ bins**) -> Get discrete index (indices), $\mathbf{P}_i$.

Evolution governed by **$6 \mathrm{x} N_E \mathrm{x} N_\Theta$ coupled Bloch equations** of the form:

$$\dot{\mathbf{P}}_i = \mathbf{V}_{\mathrm{ector}}[+\omega,\ \lambda,\ \mu,\ \mathbf{P}_j,\ \overline{\mathbf{P}}_j] \times \mathbf{P}_i$$

$$\dot{\overline{\mathbf{P}}}_i = \mathbf{V}_{\mathrm{ector}}[-\omega,\ \lambda,\ \mu,\ \underbrace{\mathbf{P}_j,\ \overline{\mathbf{P}}_j}_{\text{ij couplings}}] \times \overline{\mathbf{P}}_i$$

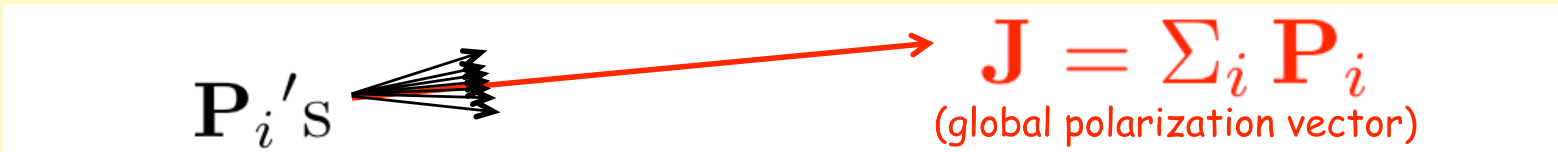
vacuum

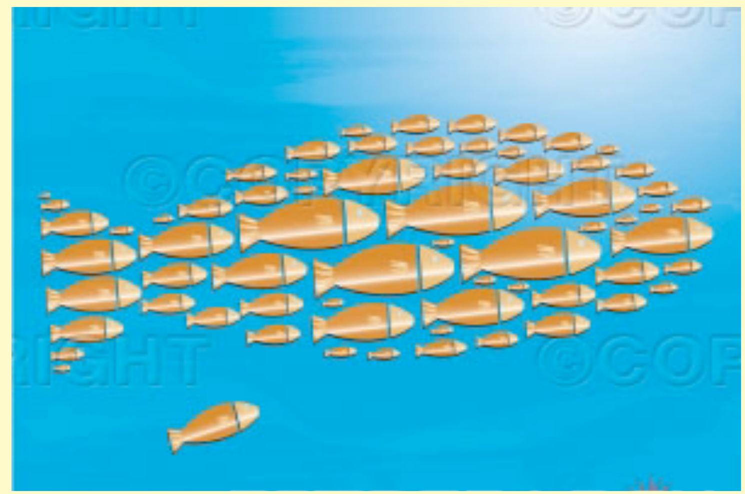
matter

self-interaction

Large, "stiff" set of (strongly) coupled differential equations.

Strong couplings between polarization vectors make the problem difficult, but also make an analytical understanding possible after all ! Key tool of "**near-alignment**" or "**strong polarization**", e.g.:





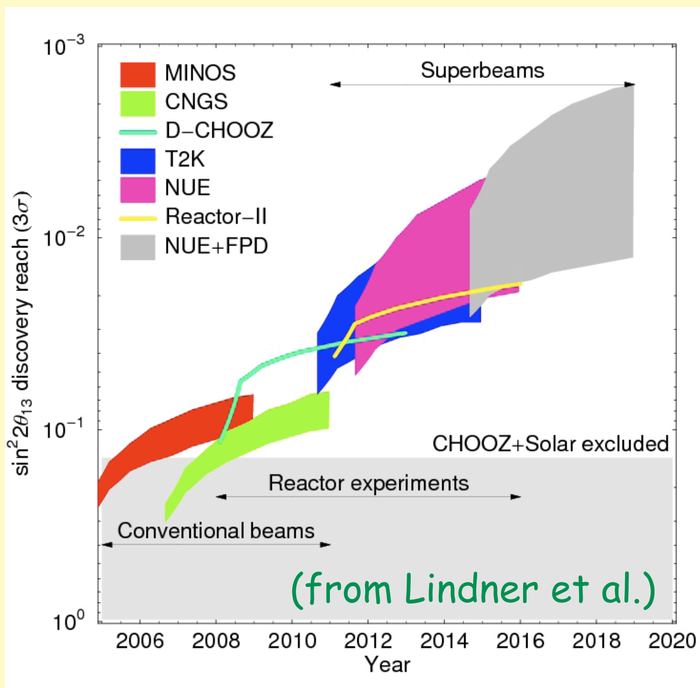
Neutrino "flavor polarizations" align at high density!
Recent wave of numerical+analytical papers, very surprising "collective" behavior found, significant dependence on hierarchy and on nonzero theta(13) (as well as on new interactions)

Back on θ_{13}: SBL reactors can provide a direct and clean measurement of (or limits on) θ_{13}, being essentially sensitive to

$$U_{e3}\, U_{e3}^{*} = \sin^2\theta_{13}$$

Next-generation LBL accelerator experiments will be sensitive to θ_{13} and to ther mixing parameters, e.g., via

$$U_{\mu 3}\, U_{e3}^{*} = \sin\theta_{23} \cos\theta_{13} \sin\theta_{13} \exp(i\delta_{CP})$$



(from Lindner et al.)

Note vertical spread for accel. expts, mainly due to unknown δ_{CP}

Remember the advanced exercises →

$\nu_\mu \leftrightarrow \nu_e$

$$
\begin{aligned}
P_{\mathrm{app}} \simeq\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
\pm\ & \alpha \sin 2\theta_{13}\, \xi \sin\delta_{\mathrm{CP}} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+\ & \alpha \sin 2\theta_{13}\, \xi \cos\delta_{\mathrm{CP}} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+\ & \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2},
\end{aligned}
$$

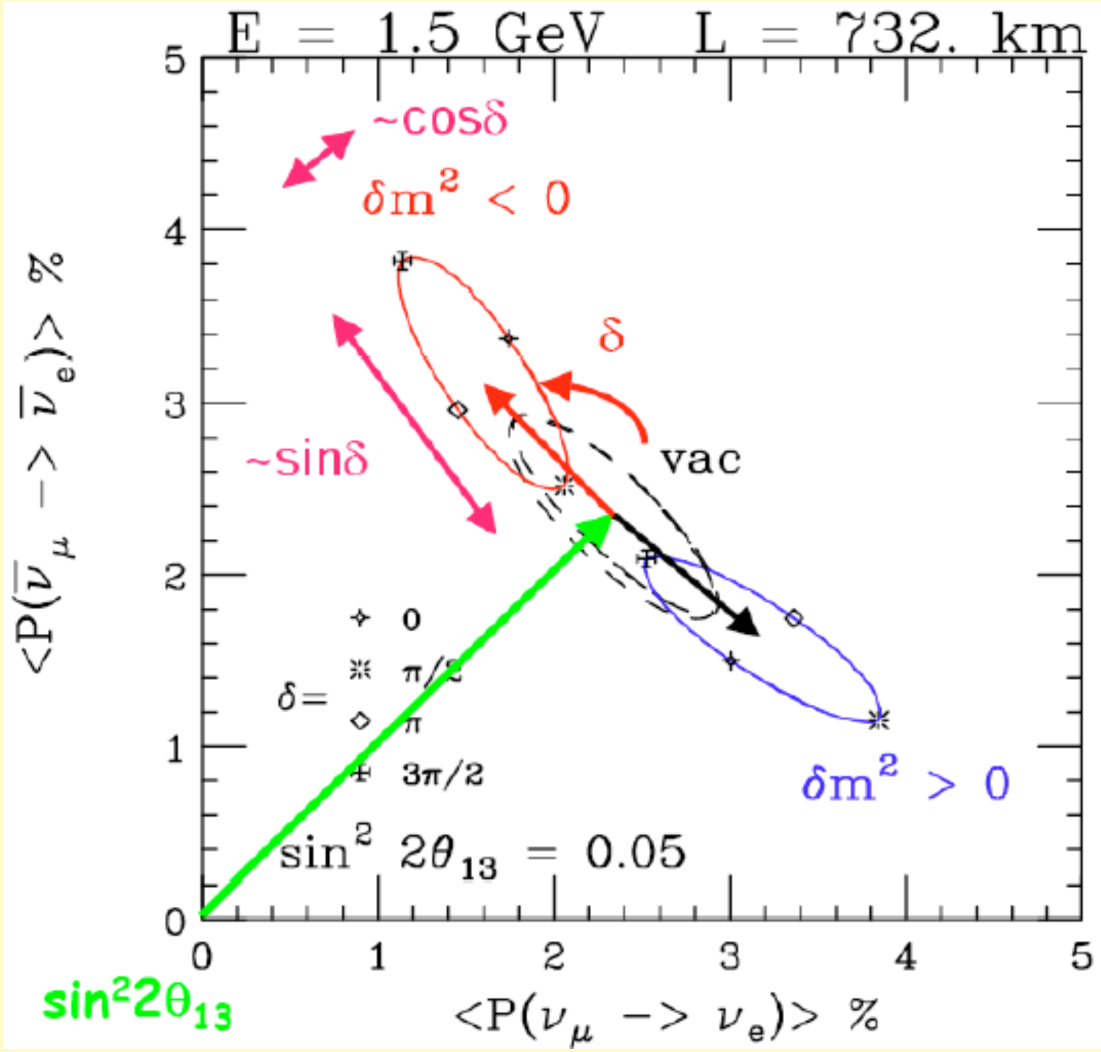
$$
\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \simeq \pm 0.03,\ \Delta \equiv \frac{\Delta m^2_{31} L}{4E},\ \xi \equiv \sin 2\theta_{12} \sin 2\theta_{23},\ \hat{A} \equiv \pm \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}}
$$

(Cervera et al. 2000; Freund, Huber, Lindner, 2000; Freund, 2001)

- Complicated, but all interesting information there: θ_{13}, δ_{CP}, mass hierarchy (via A)

Slide from: Walter Winter

→ Bi-probability plots



Multiple solutions! Degeneracies →

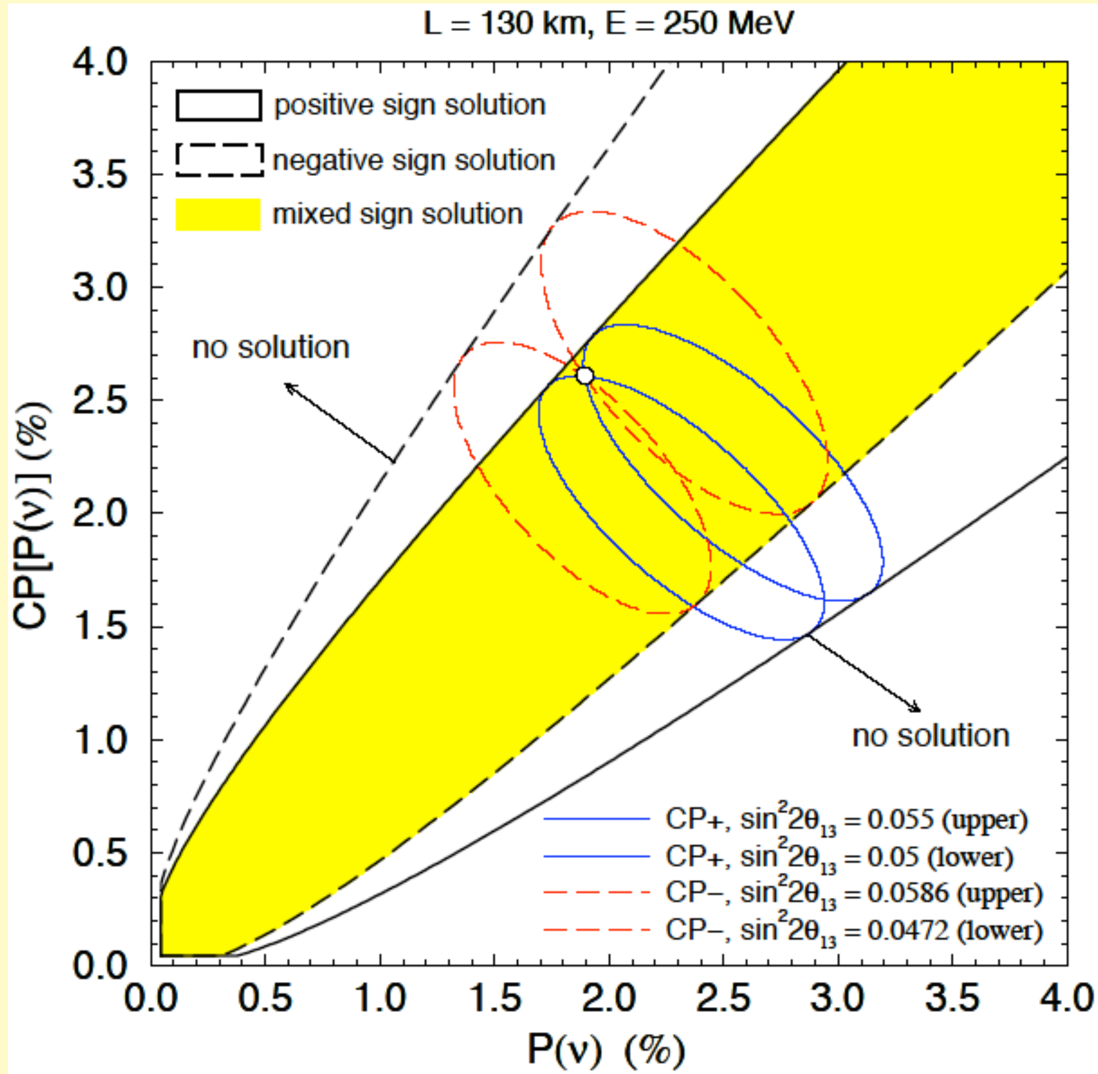
Cause of the degeneracy; easy to understand

- You can draw two ellipses from a point in P-Pbar space

➡ Intrinsic degeneracy

- Doubled by the unknown sign of Δm^2

➡ 4-fold degeneracy



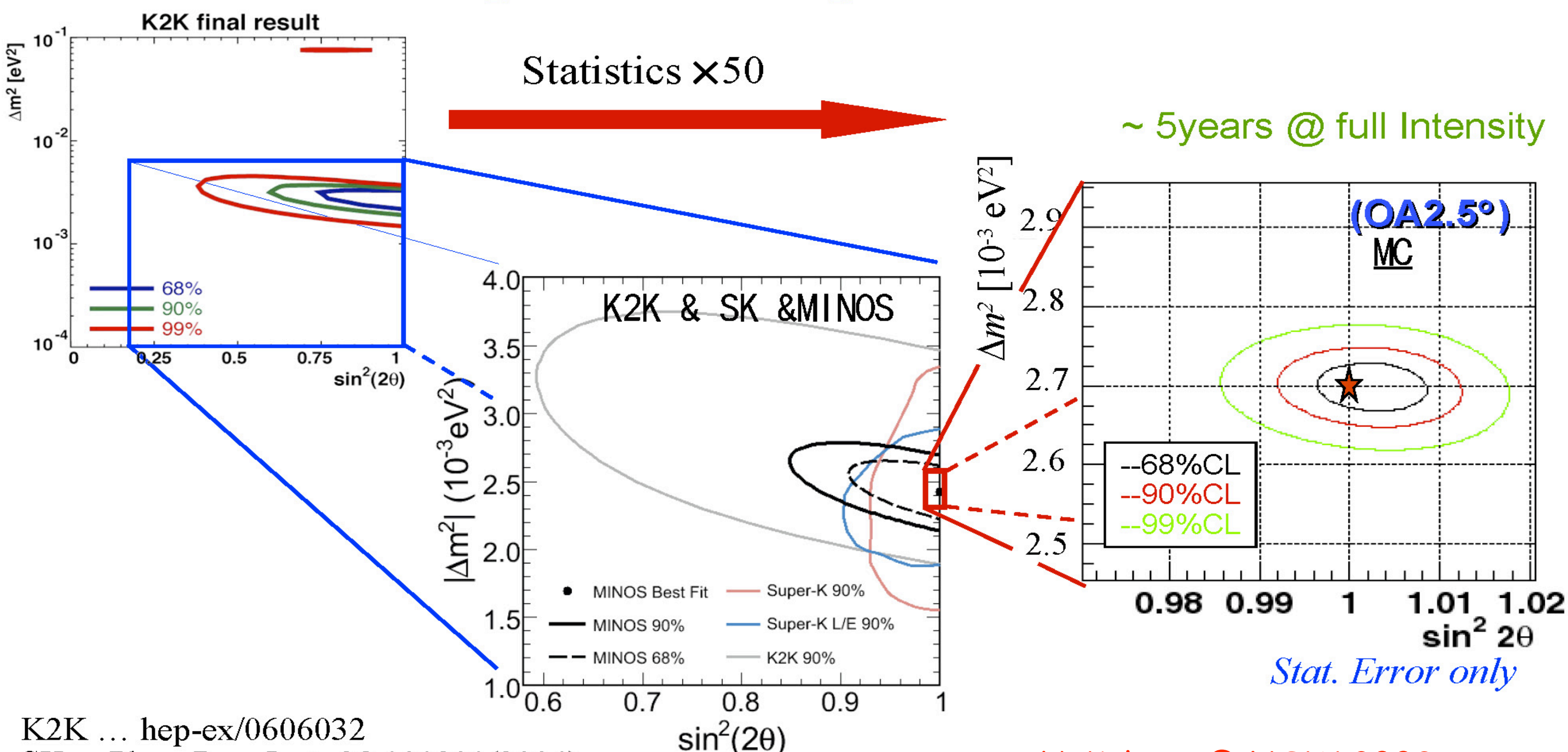
Taken From Minakata

In addition: octant of θ_{23} (if not maximal) leads to one more ambiguity → eightfold degeneracy!

Need several experiments in different oscillation channels, and at different L and E, in order to pin down the true parameters.

Large literature on this "degeneracy" or "clone" problem. Many far-future options considered.

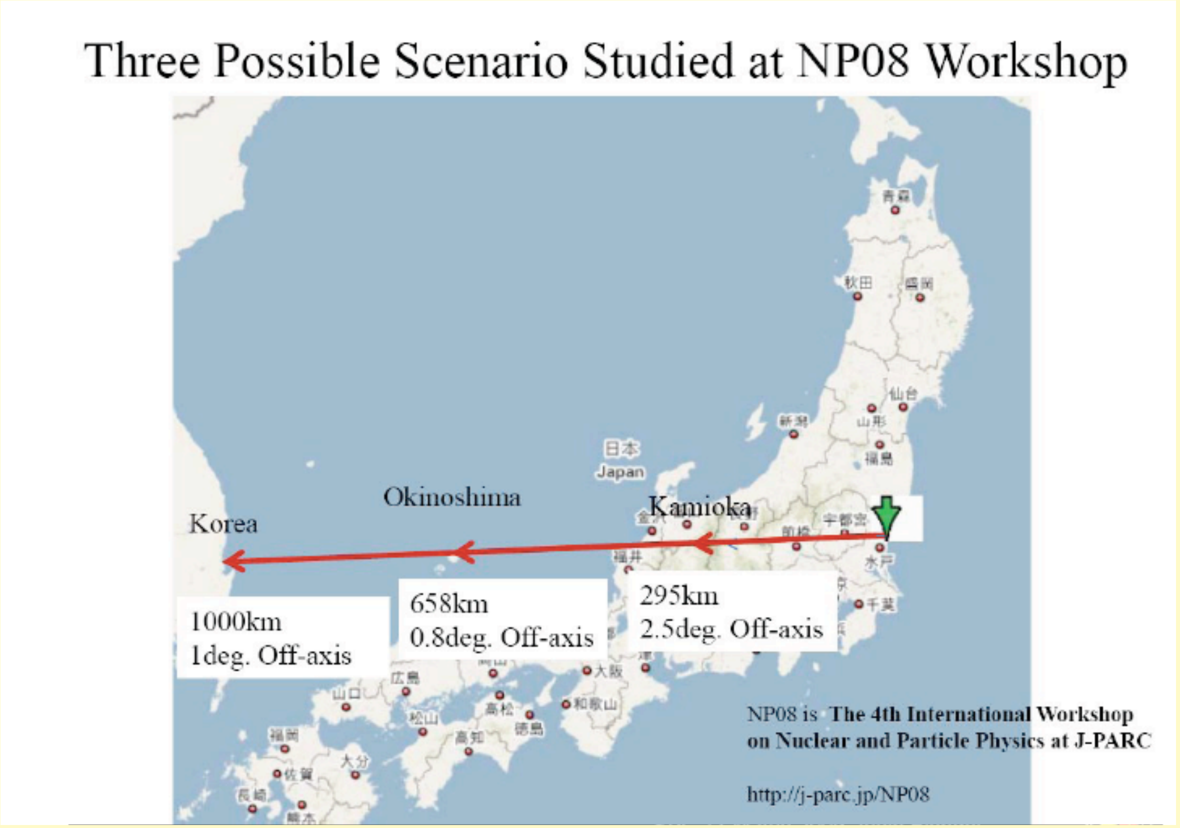
In the near future, expect to get better accuracy in $\sin^2 2\theta_{23}$ (and Δm^2) from T2K →



K2K … hep-ex/0606032
SK… Phys. Rev. Lett. **93**,101801(2004)
MINOS... hep-ex/0806.2237

H. Kakuno @ NOW 2008

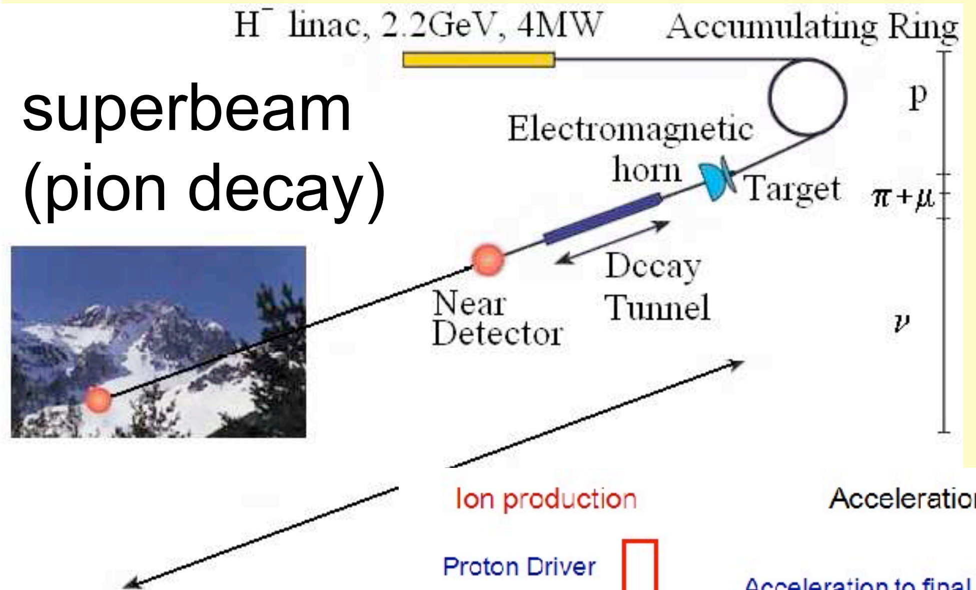
If θ_{13} also found, go farther (T2KK?) to probe CP…

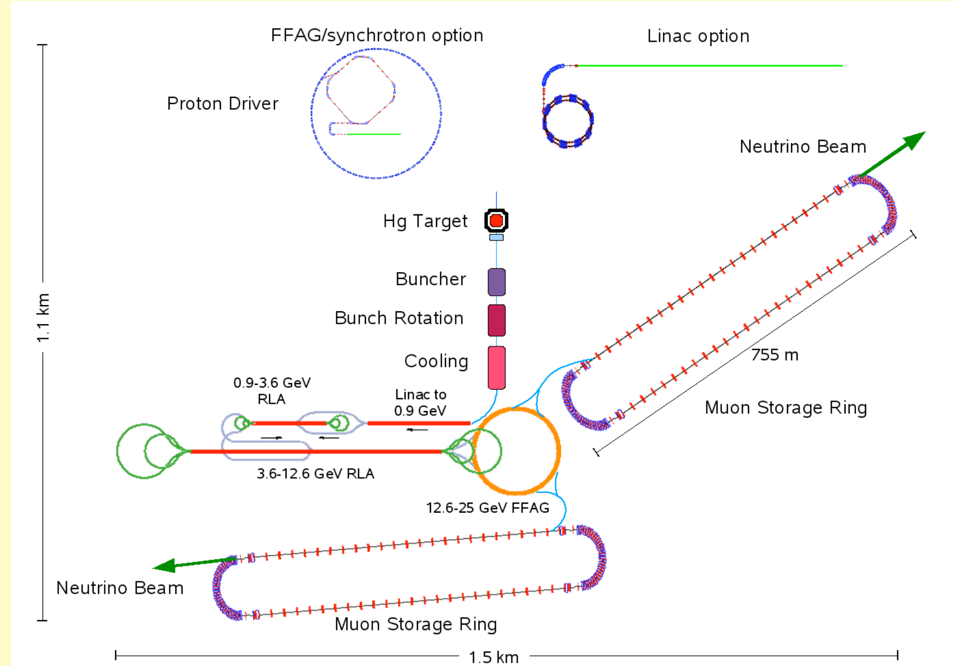


In general, need new powerful neutrino sources…

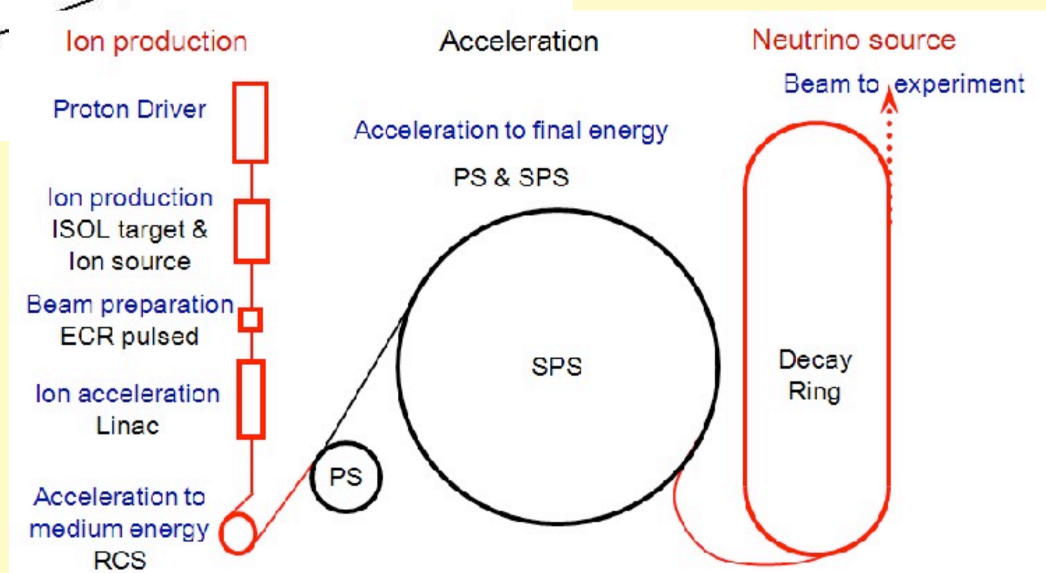
(from A. Blondel)

superbeam
(pion decay)





Neutrino Factory
(muon decay)

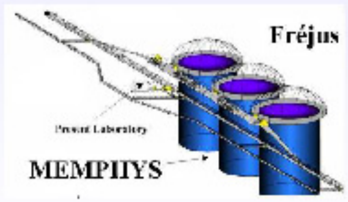


Beta-beam
ion decay 6He, 18Ne or 8Be, 8Li

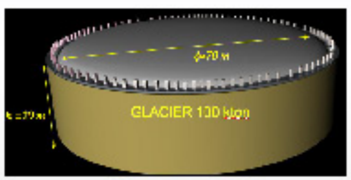
…and big detectors, also for other purposes (p-decay, SN, solar, atmospheric, geo-nu…).

Just one R&D example:

LAGUNA detector concepts



- MEMPHYS - MEgaton Mass PHYSics
  - 80 m heigth $\times$65 m $\varnothing$
  - $\sim$500 kt water Cherenkov detector
  - 81 000 PMTs per shaft (30% coverage)



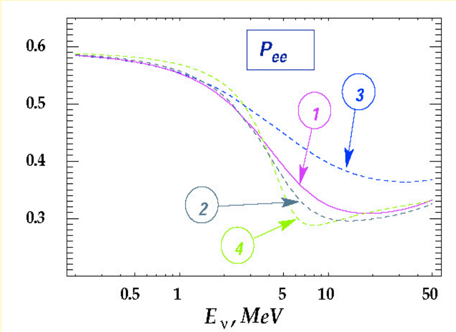
- GLACIER - Giant Liquid Argon Charge Imaging ExpeRiment
  - 20 m heigth $\times$70 m $\varnothing$
  - $\sim$ 100 kt liquid Ar TPC
  - Light (28 000 PMTs) + charge readout

- LENA - Low Energy Neutrino Astronomy
  - 100 m long $\times$ 30 m $\varnothing$
  - $\sim$ 50 kt liquid scintillator
  - 13 500 PMTs for 30% coverage

Neutrino Champagne 2009 Teresa Marrodán Undagoitia

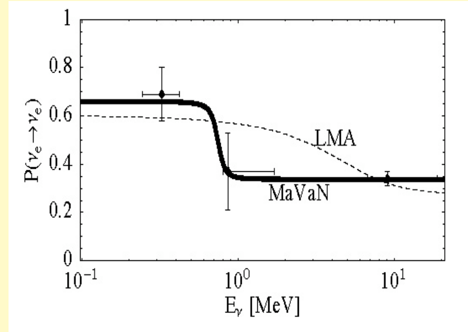
Decisions about sites/techniques: next few years (probably after results from first round of θ_{13} searches.)

Note: solar ν still have room for large nonstandard effects:



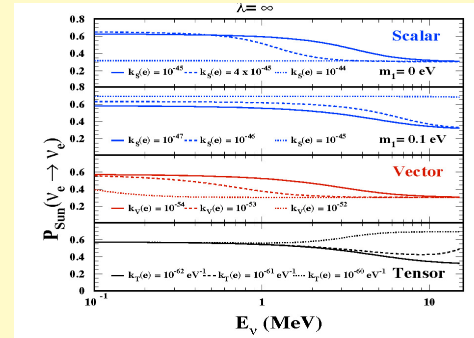
FCNC…

Friedland, Lunardini, Pena-Garay 2004
Guzzo, de Holanda, Peres 2004
Valle et al., 2006, 2009



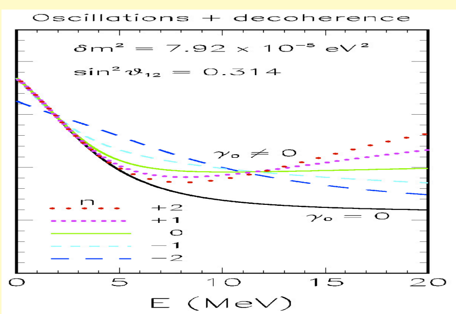
MaVaN…

Barger, Huber, Marfatia 2005
Gonzalez-Garcia et al., 2006



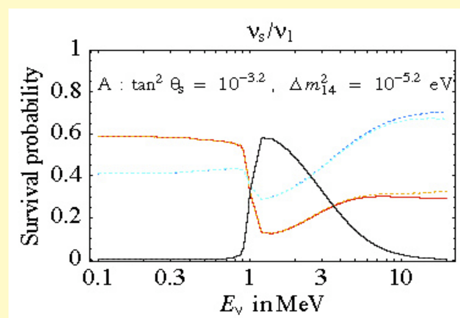
Long-range…

Gonzalez-Garcia et al., 2005



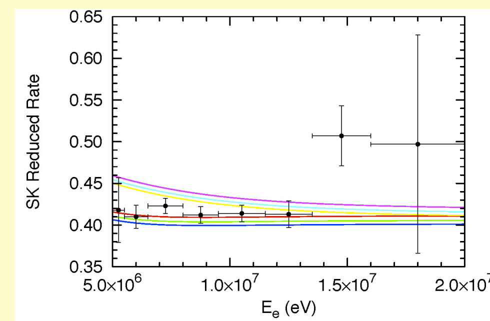
Decoher./fluct…

Fogli et al, 2007
Balentekin, Yuksel 2003
Burgess et al. 2004



Sterile…

Cirelli, Marandella, Strumia, Vissani 2004



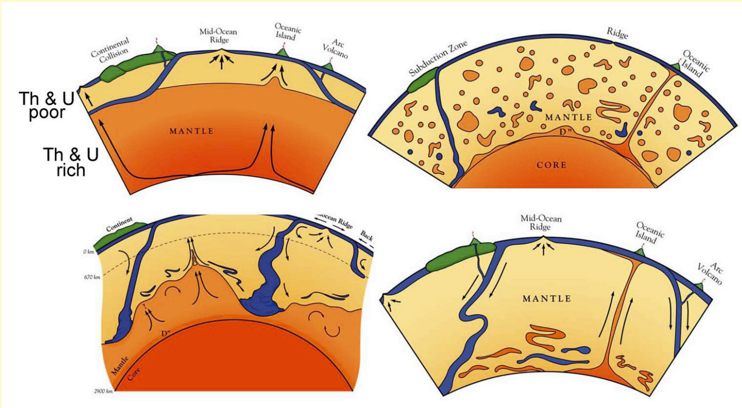
Magn. moment…

Das, Pulido, Picariello 2009

May induce unexpected "anomalies" in solar (& reactor) ν.

Also: FCNC may dangerously mimic θ_{13} effects!

Note: geo-ν from U, Th decays: address fundamental open issues!



[McDonough NUTECH'09]

5 Big Questions:

- What are earth's K/U & Th/U ratios? *planetary volatility curve*
- Radiogenic contribution to heat flow? *secular cooling*
- Distribution of reservoirs in mantle? *whole vs layered convection*
- Radiogenic elements in the core?? *Earth energy budget*
- Nature of the Core-Mantle Boundary? *hidden reservoirs*

Near future: New data from KamLAND, first data from Borexino

Far Future: More large-volume detectors
Goal: disentangle interesting sources (global, deep) from "uninteresting" ones (local, surface). Thus:

- Place at least one detector on the mantle (e.g., HanoHano)
- Build accurate local models (together with Earth scientists)
- Exploit directionality of inverse beta decay process

Great activity also in nonoscillation searches. $0\nu\beta\beta$:

Overview of Experiments

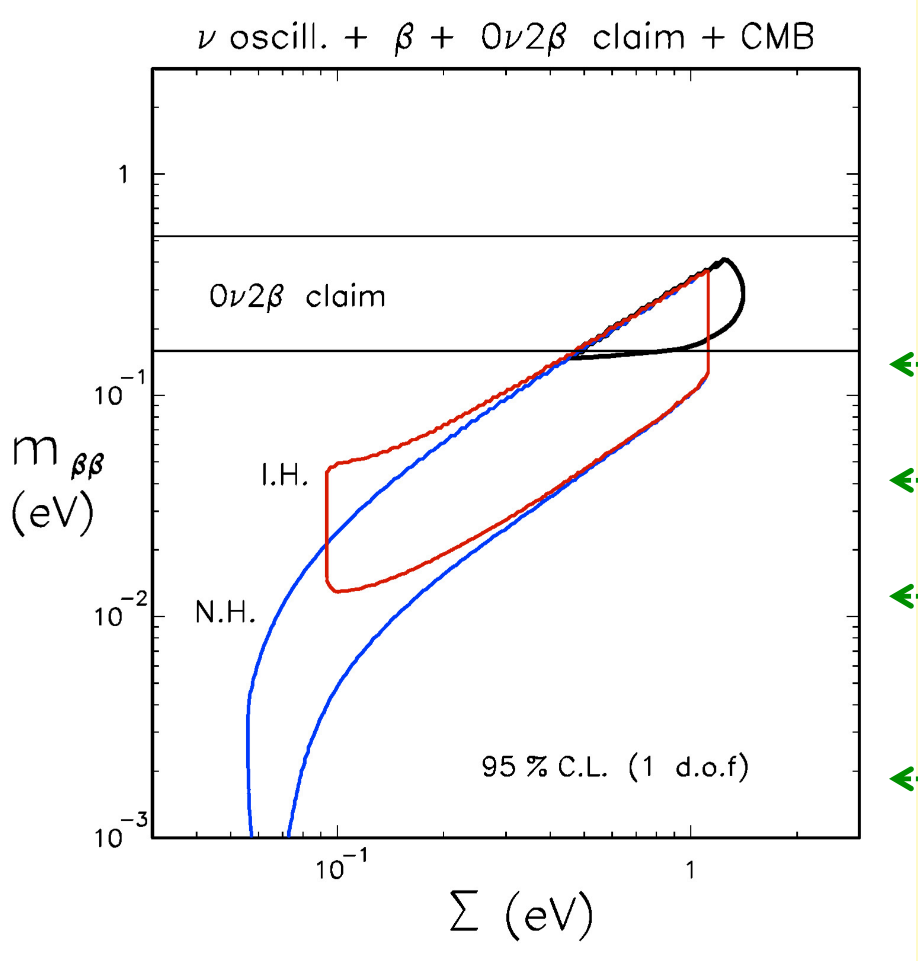
Name	Nucleus	Mass*	Method	Location	Time line
Operational & recently completed experiments					
CUORICINO	Te-130	11 kg	bolometric	LNGS	2003-2008
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM	until 2010
Construction funding					
CUORE	Te-130	200 kg	bolometric	LNGS	2012
EXO-200	Xe-136	160 kg	liquid TPC	WIPP	2009 (comiss.)
GERDA I/II	Ge-76	35 kg	ionization	LNGS	2009 (comiss.)
SNO+	Nd-150	56 kg	scintillation	SNOlab	2011
Substantial R&D funding / prototyping					
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka	2009
Majorana	Ge-76	26 kg	ionization	SUSL	2012
NEXT	Xe-136	80 kg	gas TPC	Canfranc	2013
SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM	2012 (first mod.)
R&D and/or conceptual design					
CARVEL	Ca-48	tbd	scintillation	Solotvina	
COBRA	Cd-116, Te-130	tbd	ionization	LNGS	
DCBA	Nd-150	tbd	drift chamber	Kamioka	
EXO gas	Xe-136	tbd	gas TPC	SNOlab	
MOON	Mo-100	tbd	tracking	Oto	
Other decay modes					
TGV	Cd-106		ionization	LSM	operational

***: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%**

S. Schönert, TAUP 2009

Also: efforts in improving/constraining theoretical nuclear matrix elements.

Staged approach - sensitivity goals



← - - - - - - 1: (Dis)prove current claim

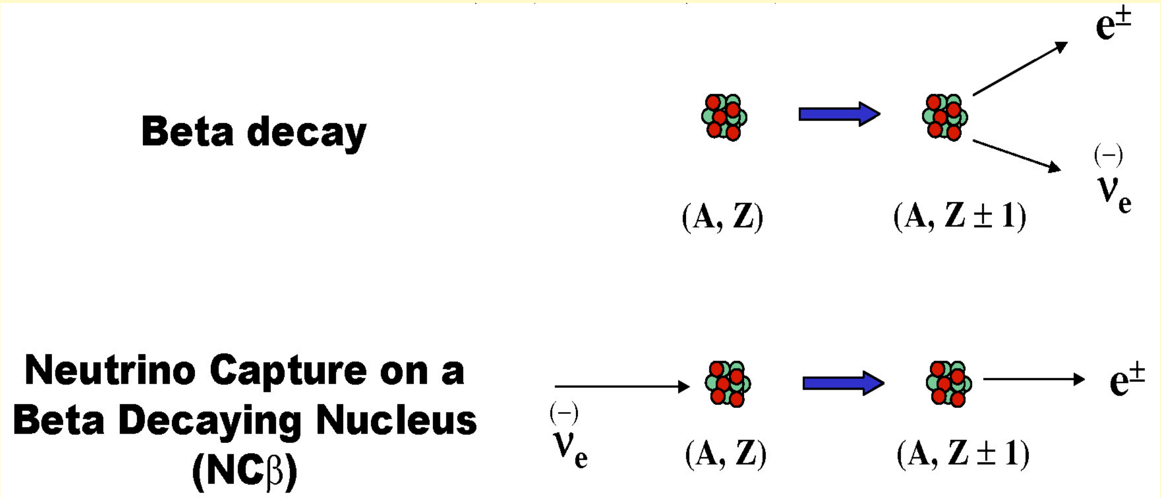
← - - - - - - 2: Approach inverted hierarchy

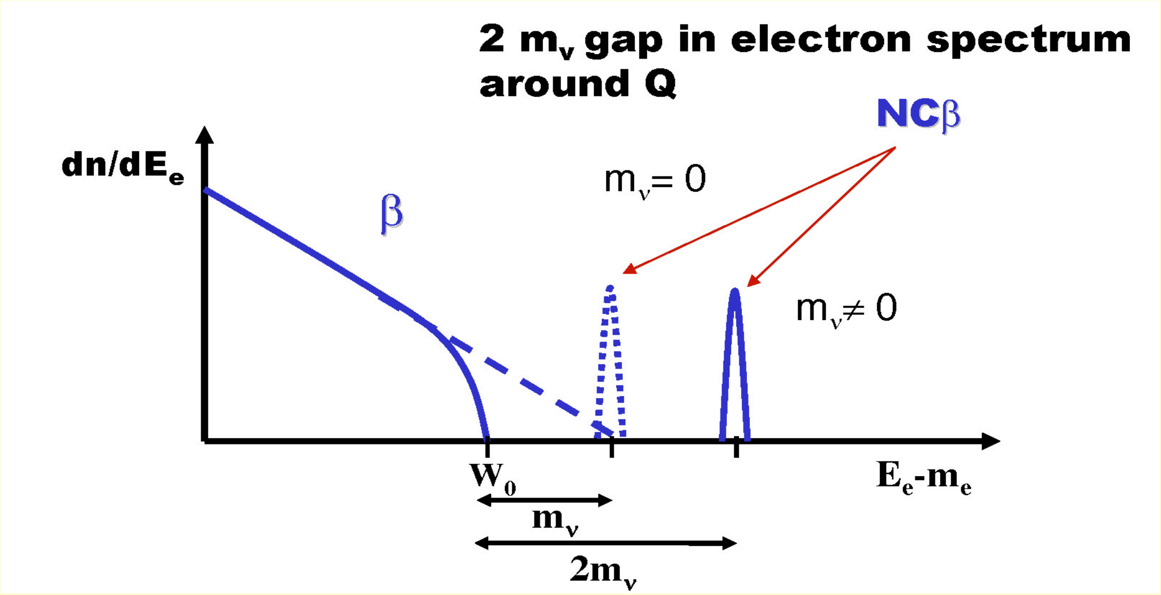
← - - - - - - 3: Cover inverted hierarchy

← - - - - - - (Need new ideas to get there…)

If signal not found & inverted hierarchy established by other means → Dirac neutrinos!
(barring cancellations due to possible interference with nonstandard 0vββ mechanisms)

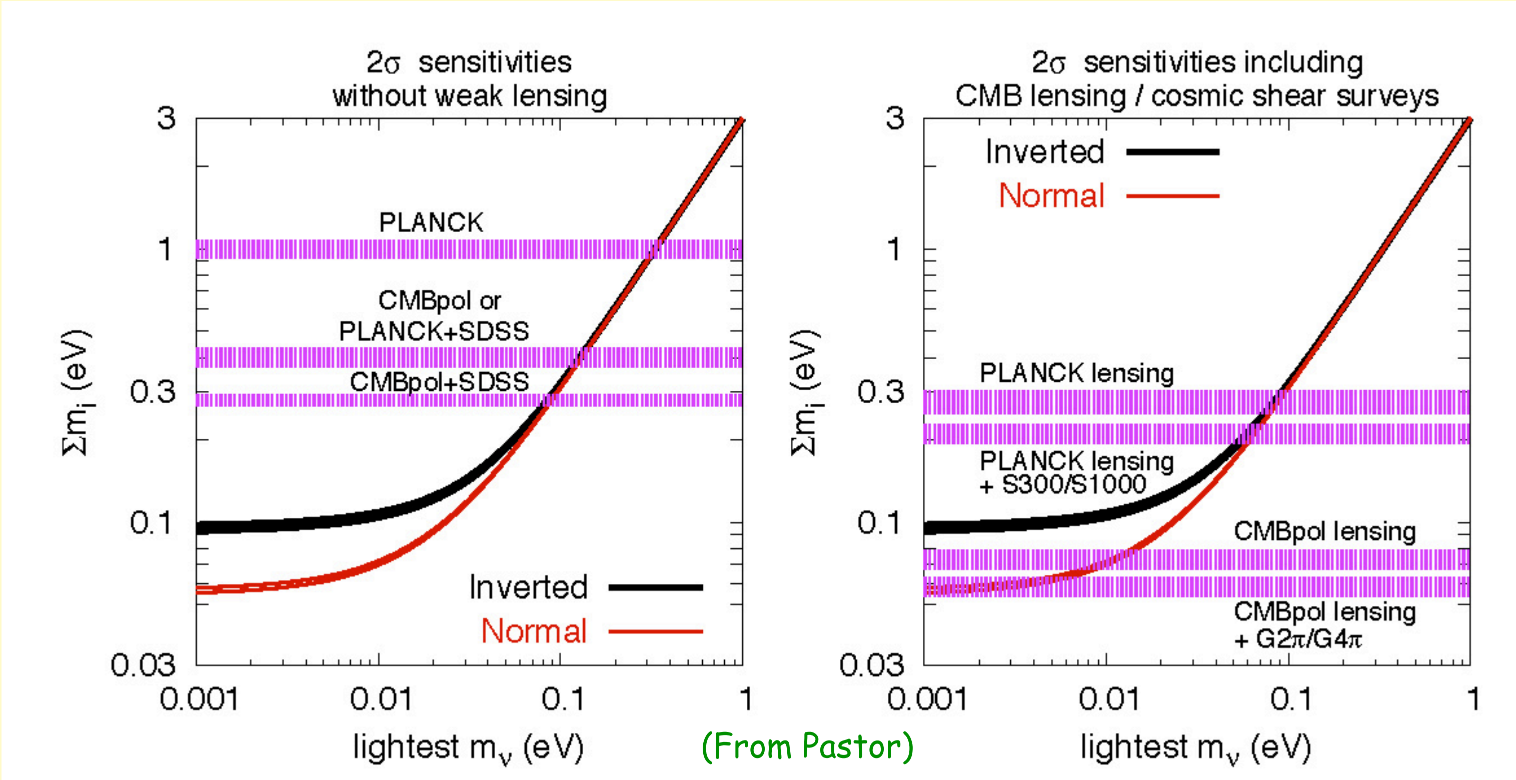
β decay: need new ideas to go beyond KATRIN (calorimetry?). Very far future … a possible observation of the relic neutrino bkgd ?





(Cocco, Mangano & Messina)

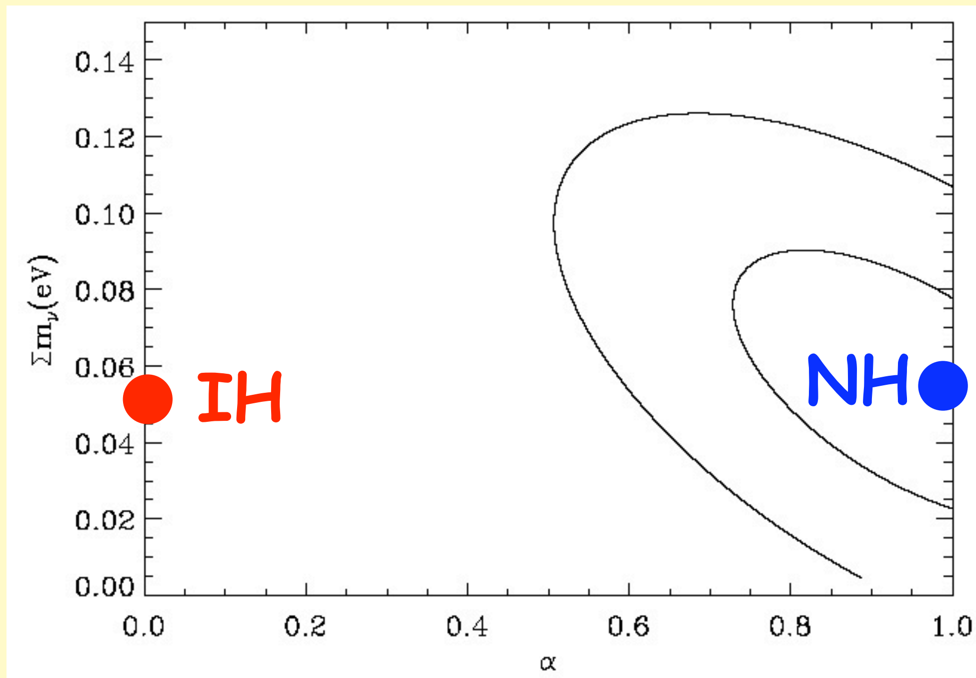
May we get hierarchy from high-precision cosmology?



After all, relic neutrinos with different masses become nonrelativistic at slightly different times…

Recent study (F. De Bernardis et al., 0907.1917):

Assuming $m_1=m_2$, and defining $\alpha=m_3/(m_1+m_2+m_3)=m_3/\Sigma$, they find that future galaxy survey + CMB data might constrain both Σ and α accurately enough to distinguish the hierarchy:



$m_3=0$

$m_{1,2}=0$

This possibility deserves further scrutiny.

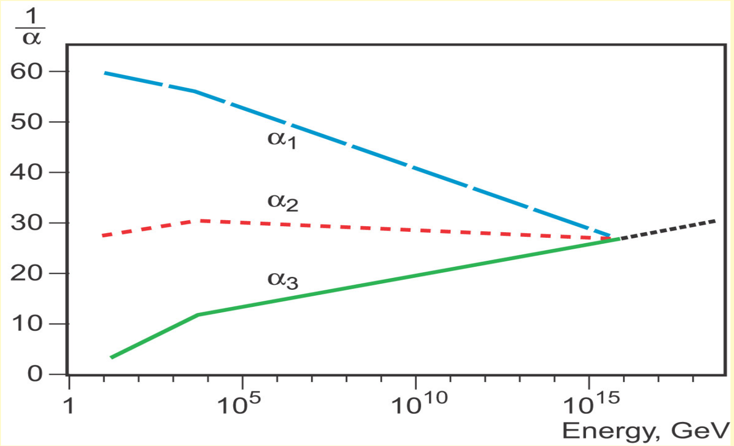
Towards a bigger theoretical picture…

Leptonic CP violation +Majorana neutrinos would make it plausible that heavy ν_R at a new-physics scale m_R may induce:

- Matter-antimatter asymmetry (via leptogenesis, $\nu_R \rightarrow l^+ \neq \nu_R \rightarrow l^-$)
- Small Majorana ν masses (via see-saw mechanism, $m \sim m_D^2/m_R$)

Possible m_R range very large…
for $m_D \sim m_e \ldots m_{top}$:
m_R from TeV to GUT scale,
models from LR to SO(10)

[adapted from Mohapatra @Erice 2009]



Further data will at least constrain the phase space of successful theories

Conclusions and Open Problems

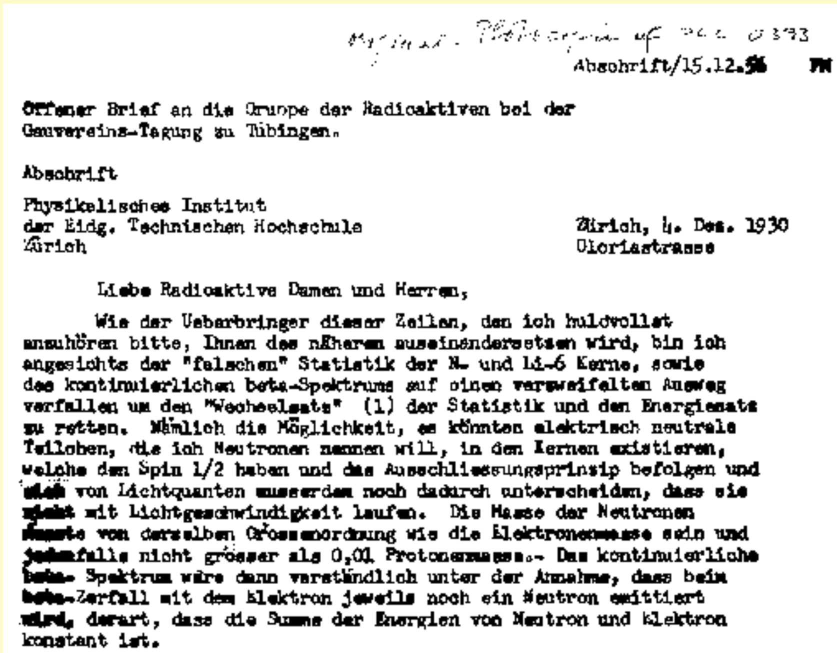
Great progress in recent years …

Neutrino mass & mixing: established fact
Determination of $(\delta m^2, \theta_{12})$ and $(\Delta m^2, \theta_{23})$
Upper bounds on θ_{13}
Observation of (half)-period of oscillations
Direct evidence for solar ν flavor change
Evidence for matter effects in the Sun
Upper bounds on ν masses in (sub)eV range
…………

Determination of θ_{13}
Appearance of ν_e, ν_τ
Leptonic CP violation
Absolute m_ν from β-decay and cosmology
Test of $0\nu2\beta$ claim and of Dirac/Majorana ν
Matter effects in the Earth, Supernovae…
Normal vs inverted hierarchy
(Dis)confirmation of standard 3ν scenario
Deeper theoretical understanding
…………

… and great challenges for the future!

After 80 years… (W. Pauli, Letter from Zurich, 1930)



Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

… the neutrino continues to surprise us!