PPC Workshop, Turin, July 12, 2010

Neutrinos: Phenomenological Review and Status

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Outline of the review*:

Prologue
1. Neutrino mixing and oscillations
2. Neutrino mixing and masses
3. Astrophysical sources of neutrinos

Epilogue

*This review largely benefits of recent theory/pheno results and discussions presented during the Neutrino 2010 Conference (June 13-19, Athens), and which I summarized there in the concluding session. My apologies to those who have already seen some of the following slides, including the "philological" prologue.

PROLOGUE

Old Latin saying:

Nomen [est] Omen

"Name [is] Destiny"

Neutrino - What's in a name?

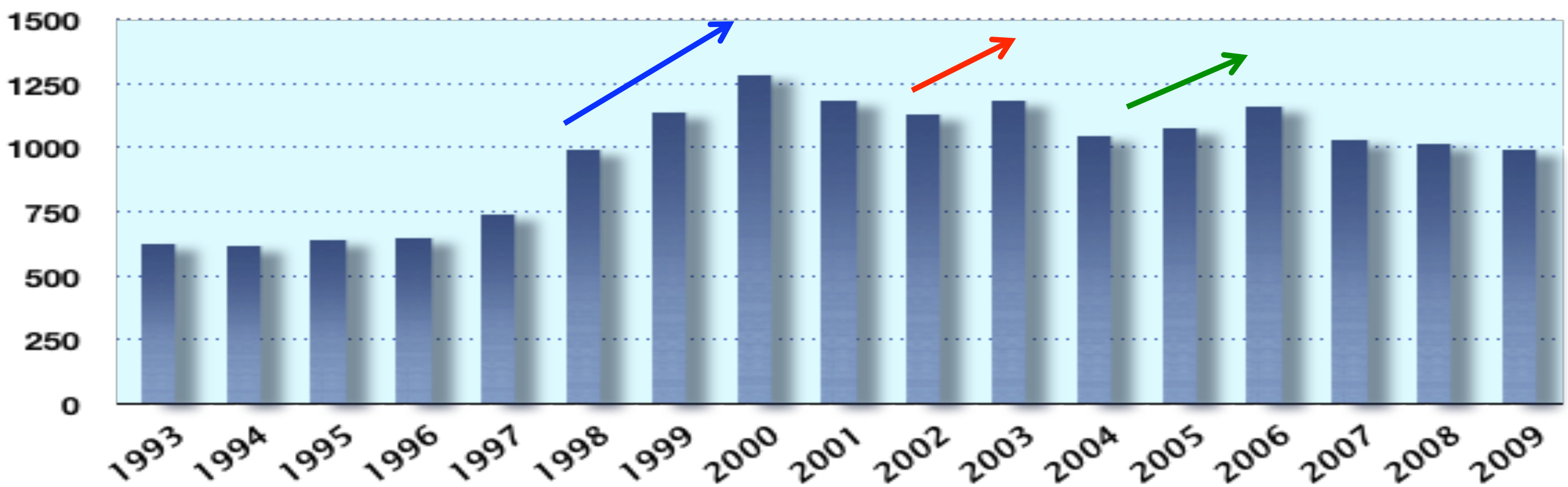
Language	Word tree	*…Some branches*	Meaning
Physics (Fermi 1934)	**NEUTR-INO**		**Little neutral one**
Italian	**NEUTRO**		**Neutral**
Latin	**NE-UTER**		**Not either; neutral**
Latin	**UTER**		**Either**
Greek		*OUDETEROS*	*Neutral*
Old High German		*HWEDAR*	*Which of two; whether*
Phonetic change/loss	[K]**UOTER**[US]		**Which of the two?**
Ionic Greek	**KOTEROS**		**Which of the two?**
Sanskrit	**KATARAS**		**Which of the two?**
Latin		*QUANTUS*	*How much?*
Sanskrit		*KATAMAS*	*Which out of many?*
Sanskrit		*KATHA*	*How?*
Sanskrit		*KAS*	*Who?*
Indo-European root	**KA** *or* **KWA**		**Interrogative base**

If "name is destiny," then … neutrino's destiny is to raise questions!

Answers to a major "which of..." question have dramatically raised the interest in neutrino physics in recent years...

Q. Which of the three neutrinos have mass ?

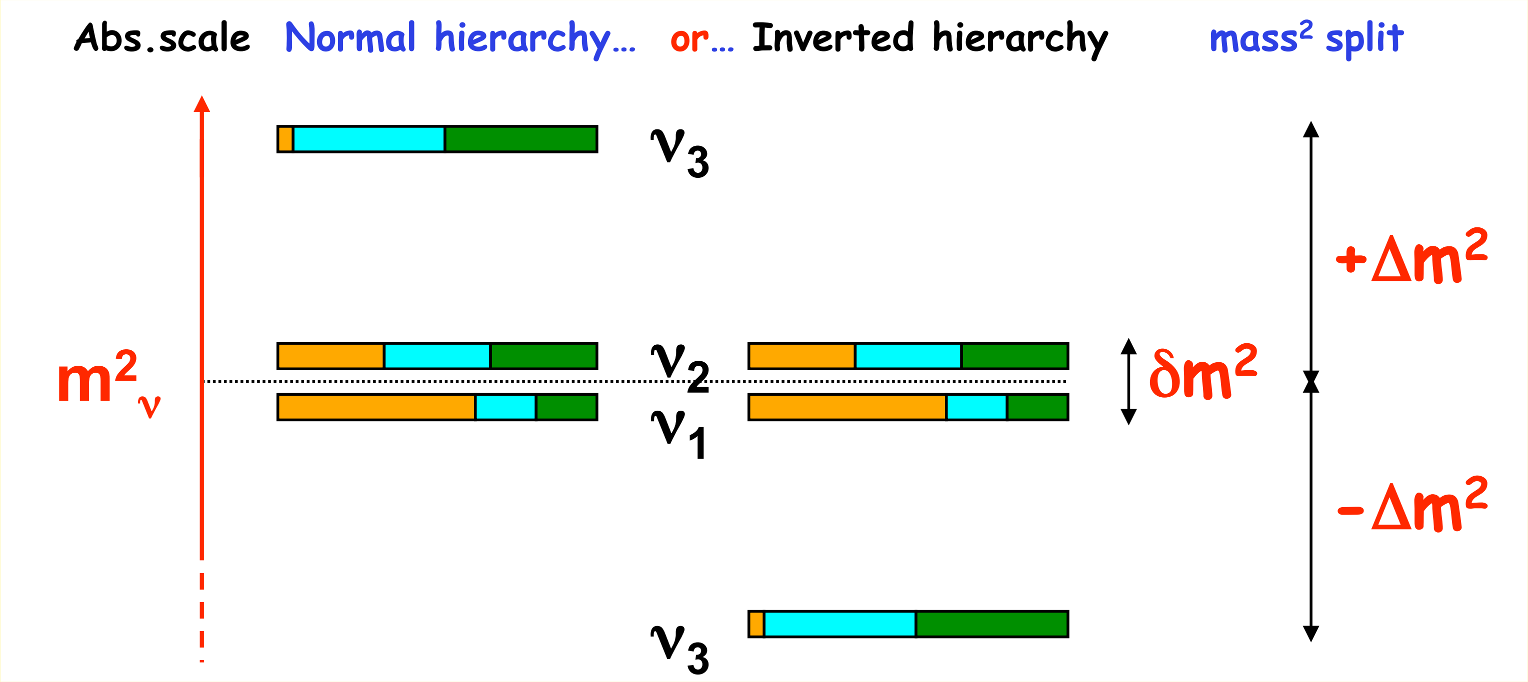
A. ...at least one! ...at least two! [...osc. cycles!]



papers with "neutrino(s)" in title (from SPIRES)

...providing us with fragments of new physics beyond the SM...

…which, in a 3ν framework, can be summarized in just one slide (with one-digit accuracy). Flavors = e μ τ



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

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

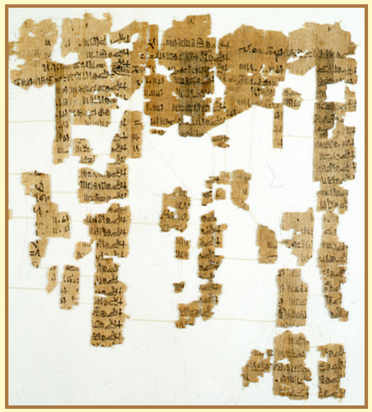
$$m_\nu < O(1)\ \mathrm{eV} \qquad \sin^2\theta_{13} < \mathrm{few}\%$$

$$\mathrm{sign}(\pm\Delta m^2)\ \mathrm{unknown} \qquad \delta\ (\mathrm{CP})\ \mathrm{unknown}$$

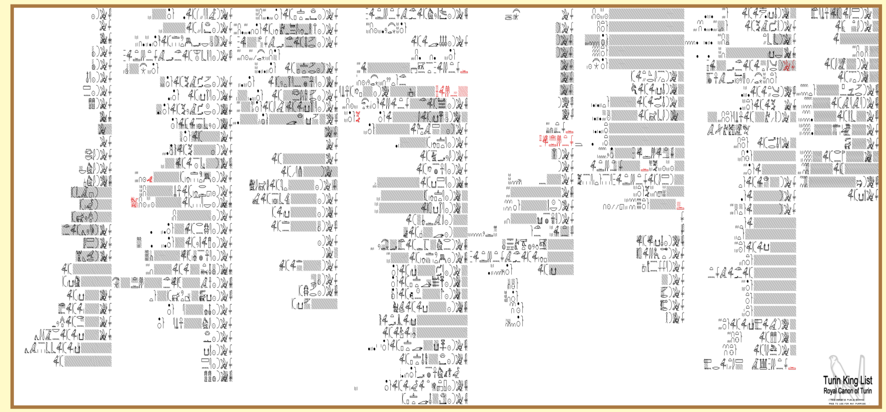
The dream:

find many fragments of new physics…

… piece them together…



… reconstruct the script



[Egyptian King list (“Royal Canon”) at Turin Egyptian Museum]

- Written ~1250 B.C., discovered 1820, forgotten fragments found in museum’s basement 2009 -

The nightmare:

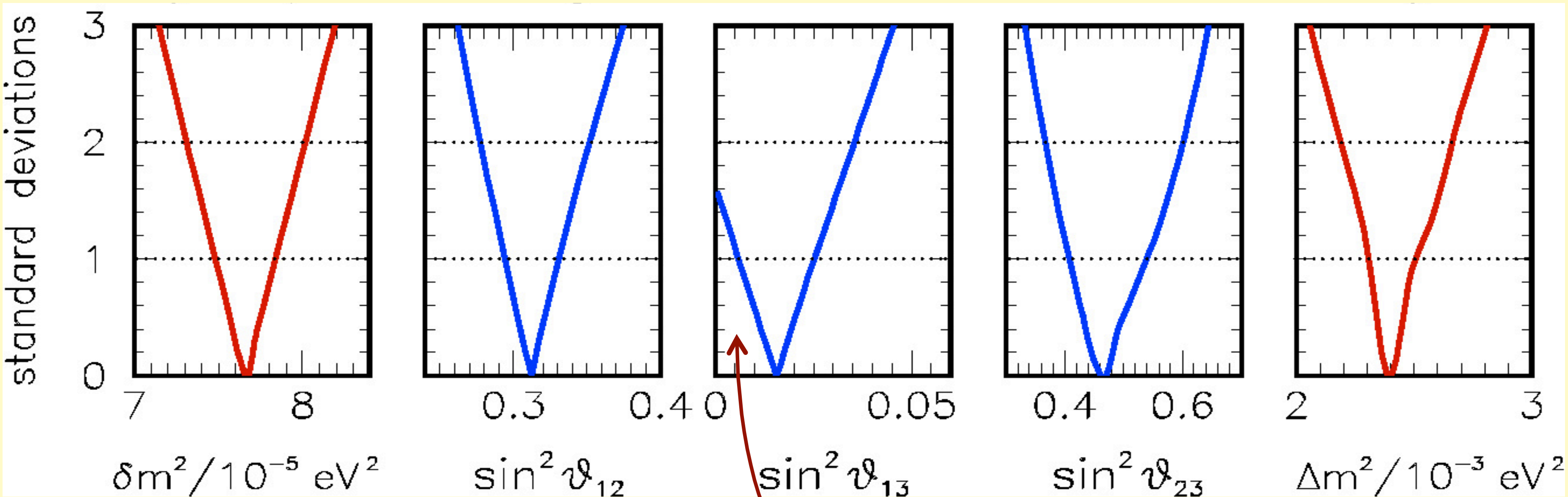
...disparate or few fragments
(or false leads!)

...tenuous links
(or just guesses!)

...multiple options for reconstruction
(or none !)

1. Neutrino mixing and oscillations

Oscillation parameters are currently constrained with 2-digit accuracy – see e.g.,
Fogli, E.L., Marrone, Melchiorri, Palazzo, Rotunno, Serra, Silk, Slosar arXiv:0805.2517



θ_{13} - focus of attention: gateway to leptonic CPV searches!

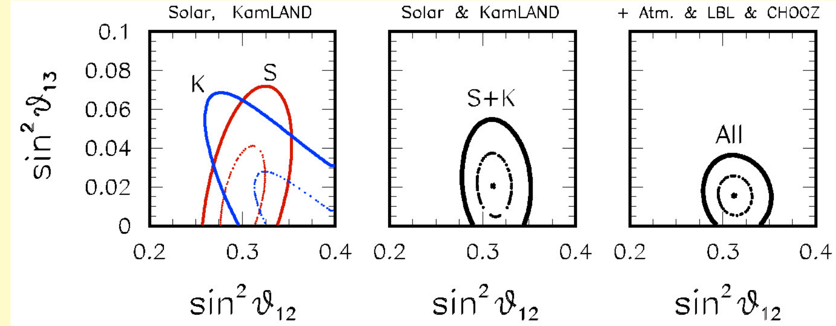
TABLE I: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

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	7.67	0.312	0.016	0.466	2.39
1σ range	7.48 – 7.83	0.294 – 0.331	0.006 – 0.026	0.408 – 0.539	2.31 – 2.50
2σ range	7.31 – 8.01	0.278 – 0.352	< 0.036	0.366 – 0.602	2.19 – 2.66
3σ range	7.14 – 8.19	0.263 – 0.375	< 0.046	0.331 – 0.644	2.06 – 2.81

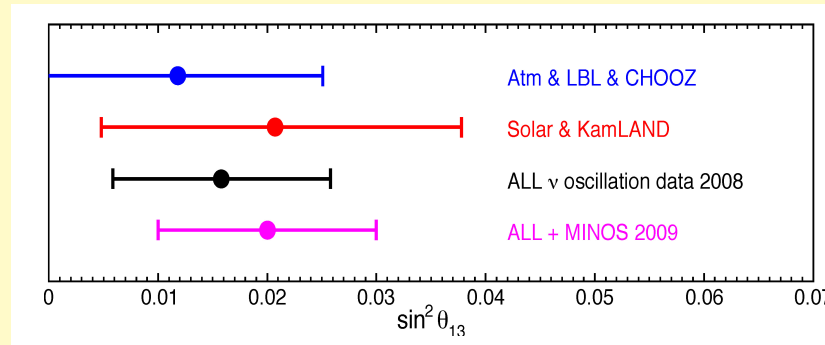
Possible hints of $\theta_{13}>0$ and their statistical significance have been the subject of intense discussion (& some fluctuations from new data…) in the last 2 years [Fogli, EL, Marrone, Palazzo, Rotunno, arXiv:0806.2649]

Our estimated global C.L. for $\theta_{13}>0$ hints:

~1.6σ (2008)

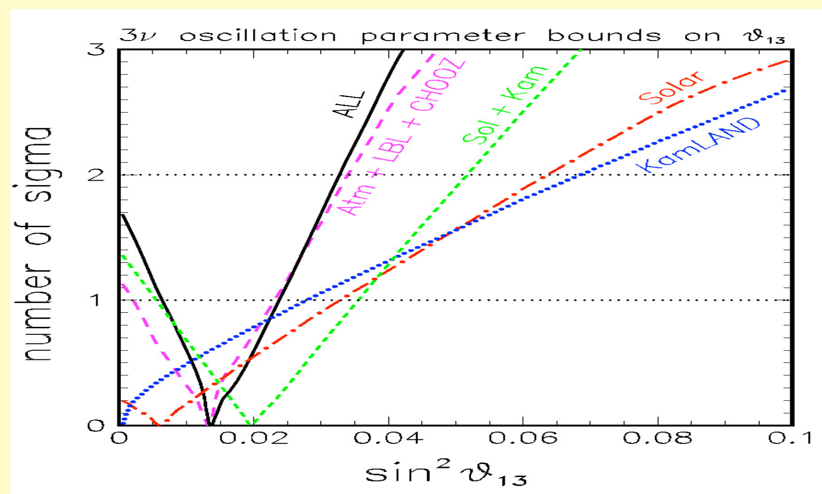


~2σ (2009)



~1.7σ (2010)

[Preliminary update, just before Neutrino 2010]



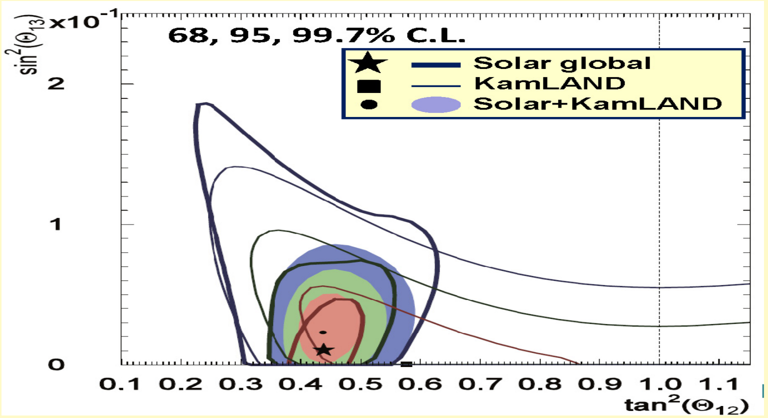
Independent, comparable global analyses differ by <0.5 σ (can't ask for better!)

STATUS of separate $\theta_{13}>0$ "hints," from presentations at ν 2010:

Solar+KamLAND: ~1.3σ

[Valle, Klein, Takeuchi]

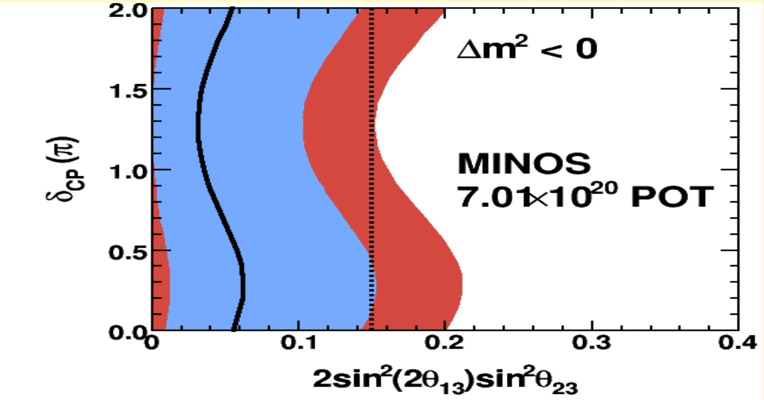
Note: new SK solar data! [Takeuchi]; new KamLAND data upcoming [Inoue]; final SNO analysis upcoming [Klein].



MINOS appearance ~0.7σ

[Vahle]

Note: new MINOS data upcoming



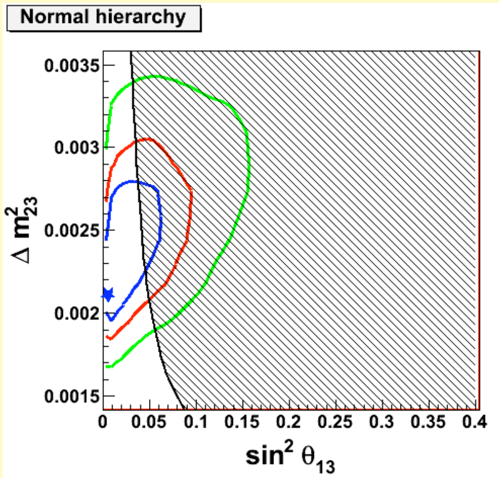
SK atmospheric: ~1.5σ

[Takeuchi]

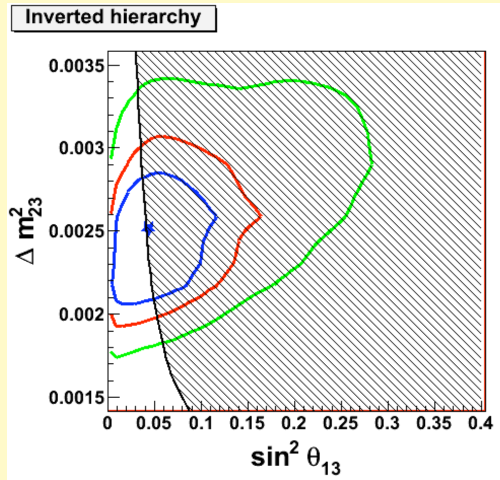
from a **full 3ν analysis (new!)**, showing also weak sensitivity (~1-1.5σ) to **NH/IH, δ_{CP}, θ_{23} octant**.

Parameter (IH)	Best point	90% C.L. allowed	68% C.L. allowed
Δm^2_{23} (x10^3)	2.51 eV^2	1.98 - 2.81 eV^2	2.09 - 2.64 eV^2
$\sin^2\theta_{23}$	0.575	0.426 - 0.644	0.501 - 0.623
$\sin^2\theta_{13}$	0.044	< 0.122	0.0122 - 0.0850
CP-δ	220°	121.4 - 319.1°	165.6 - 280.4°

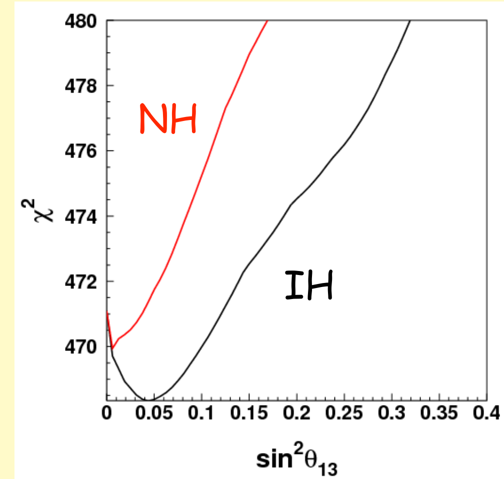
Normal



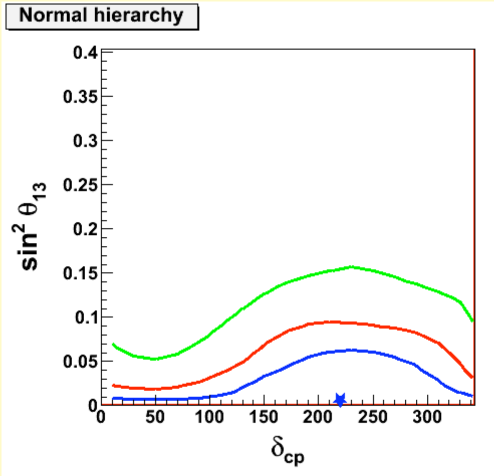
Inverted



NH vs IH



Normal



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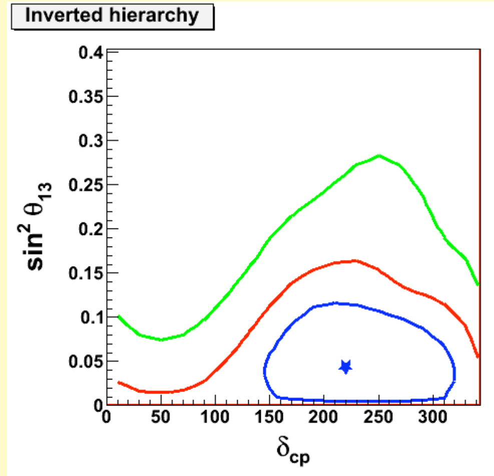
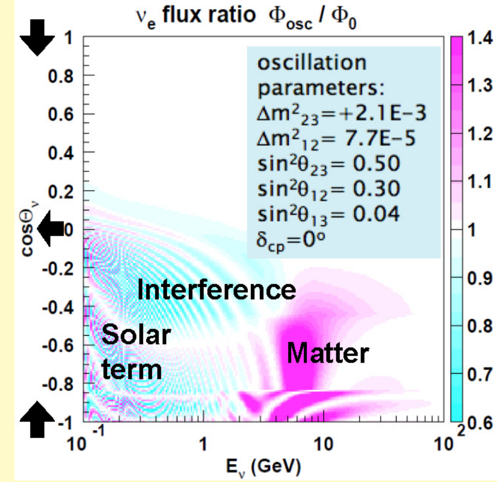


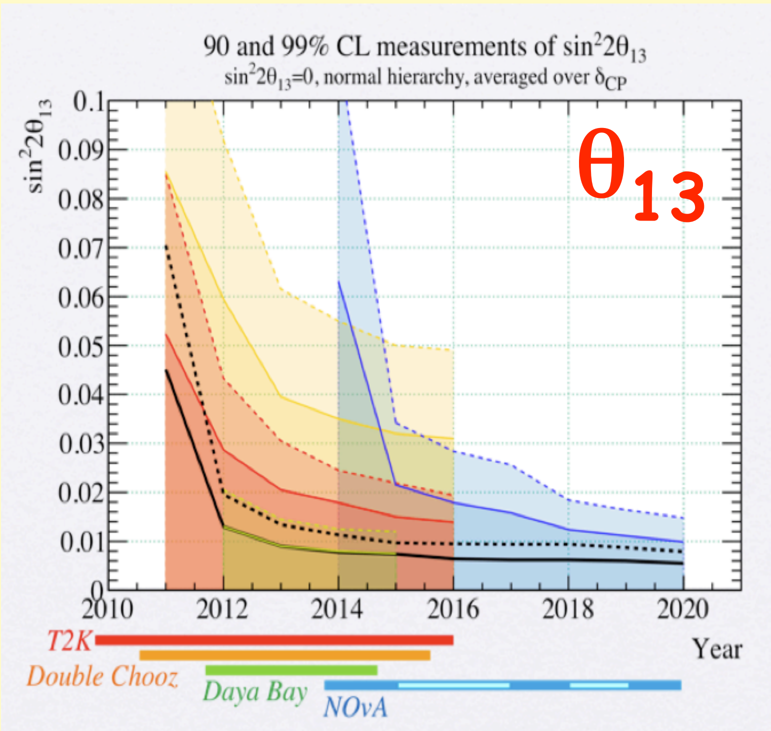
Theory



These "fragments" from SK atmospheric data deserve further study.

They add to the physics case for future large-volume detectors.

Prospects: Theory of 3ν oscillations (matter effects, degeneracies, …) under control → Phenomenology can provide realistic sensitivity estimates and optimizations for given SBL & LBL set-up and syst. error budget.



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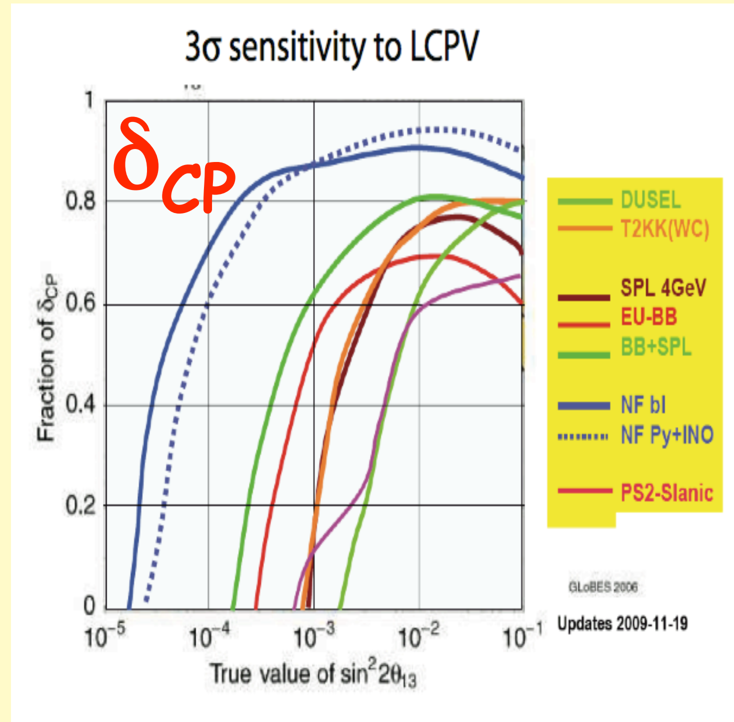
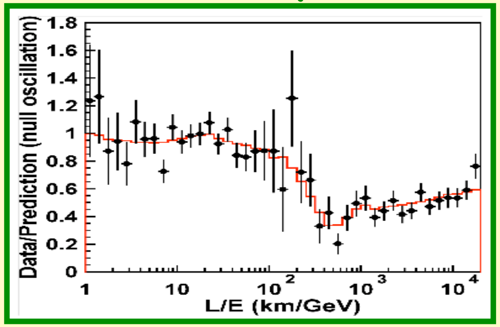


Current trends: more detailed studies of theoretical scenarios **beyond 3ν** oscillations (→ **new states, new interactions, new medium effects, new degeneracies**…) especially in the context of future beams/detectors. Well motivated by the fact that increased accuracy in reactor and accelerator experiments might lead to surprises, if there is new physics not far away.

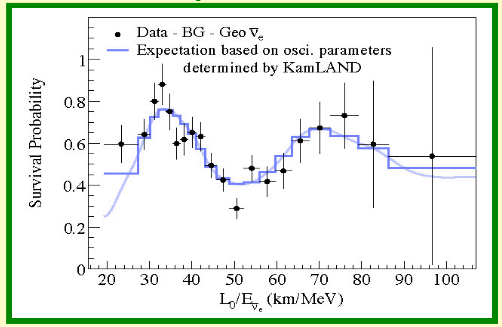
Indeed, it's not just matter of improving 3ν parameters…

Many other "fragments" should also fall in the right place – or not?

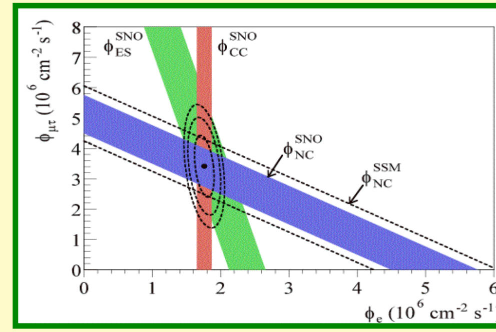
½ oscillation cycle (SK)



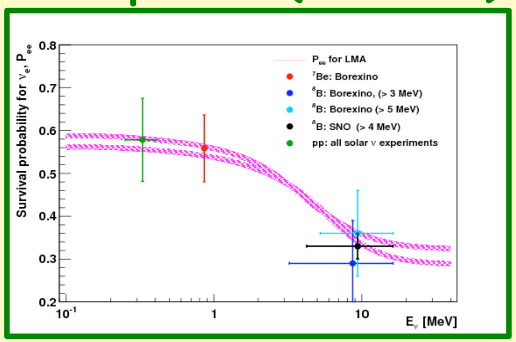
1 oscill.cycle (KamLAND)



^{8}B SSM flux test (SNO)



MSW profile (Borexino)



ν / anti-ν CPT (SK)

Neutrino:

$\Delta m_{23}^2 = 2.1 \times 10^{-3}\,\mathrm{eV}^2$

$\sin^2 2\theta_{23} = 1.0$

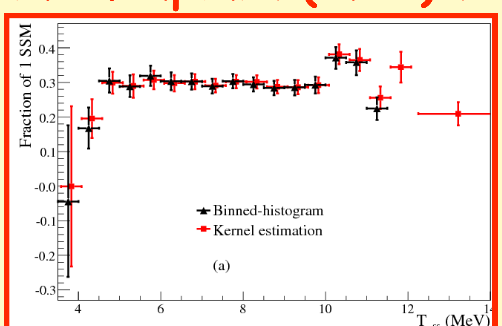
Anti-neutrino:

$\Delta m_{23}^2 = 2.0 \times 10^{-3}\,\mathrm{eV}^2$

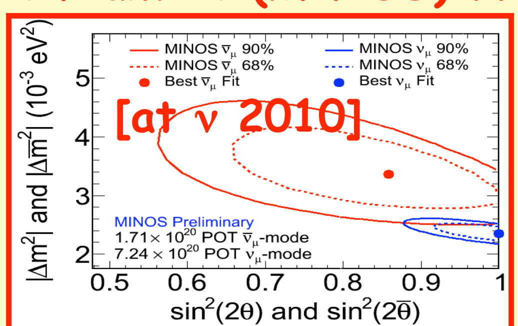
$\sin^2 2\theta_{23} = 1.0$

τ appearance (OPERA)

MSW upturn (SNO) ?



ν / anti-ν (MINOS) ??

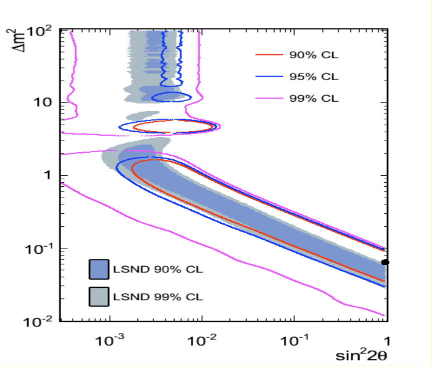


???

Your favorite anomaly here

Persistently anomalous fragments: LSND & MiniBooNE

ν_S oscillation interpr.: remains difficult after latest anti-ν results (2010)



Formally, one can always draw an effective 2ν oscillation region for each fragment … but there is no good fit to world data, either with 1 or 2 additional light sterile ν

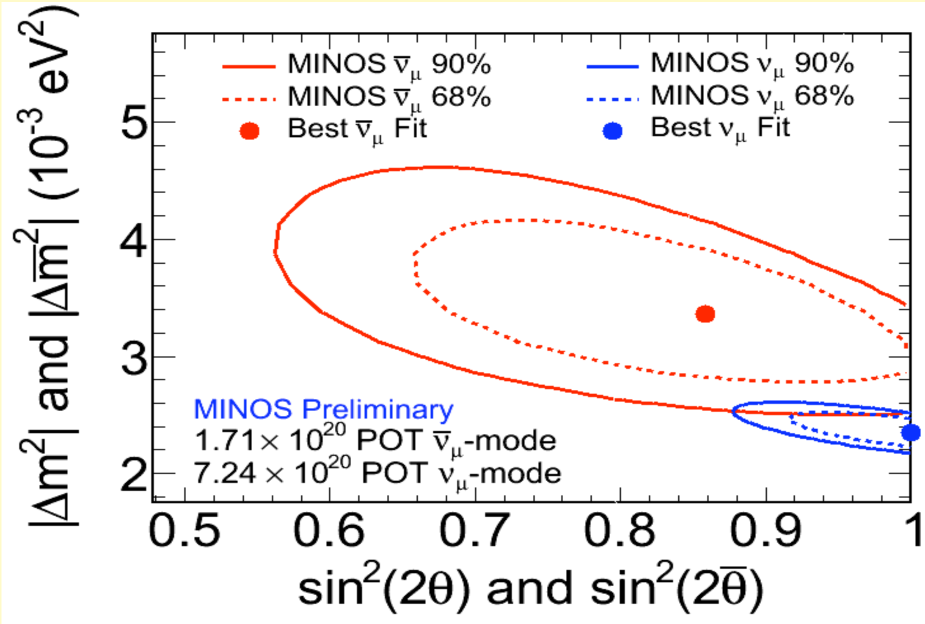
Analysis reveals tension between different datasets:
Low/high E, ν/antiν, appearance/disappear., SBL/atm…
Can be mitigated by selective choice/adjustment of data sets/errors, and/or by exotic new physics (CPTV?)

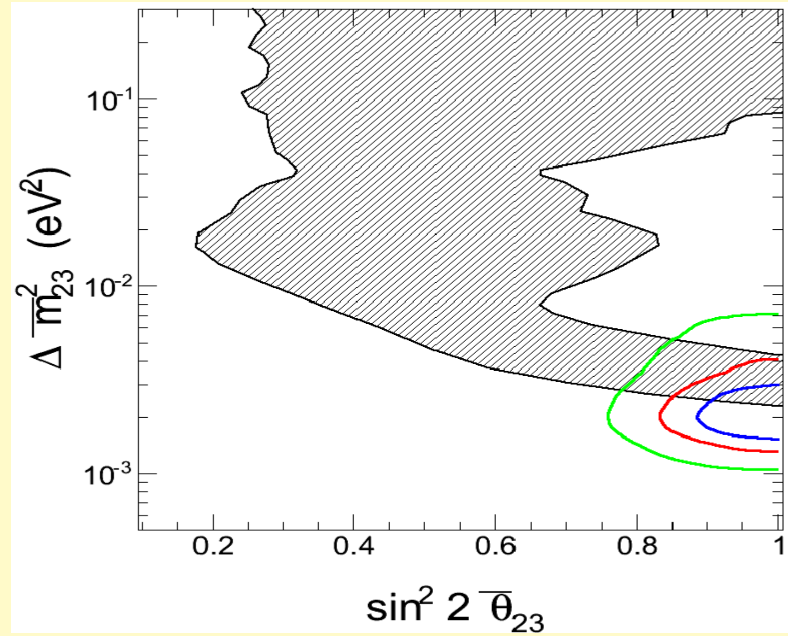
No obvious "single" theor. explanation. Possibly: several underlying effects of different origin (including cross sections)

Further experimental tests underway/proposed at comparable L/E

Note: If exotic new physics → "same L/E" tests may not be enough.

A new anomalous fragment? MINOS ν vs anti-ν (2010)





MINOS: some tension at 2σ level [But: not supported by SK data]

If a true signal → new ν physics in matter (FCNC) or in vacuum (CPTV) ?

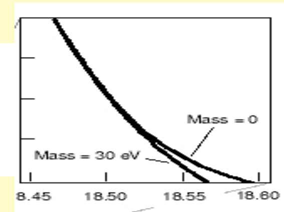
If a fluctuation → underestimated syst. error [of square mass difference] ?

We should be prepared to face ambiguities (fluctuations vs signals) more and more often in the future, as experim. timescales get longer and longer…

2. Neutrino mixing and masses: (m_β, $m_{\beta\beta}$, Σ)

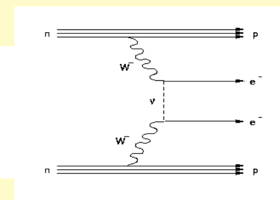
1) Single β decay: $m^2_i \neq 0$ alters the spectrum tail. Sensitive* to the so-called "effective mass of electron neutrino":

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



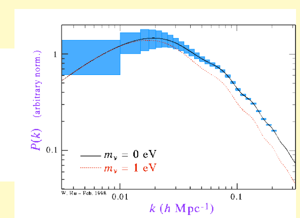
2) Double 0νββ decay: Iff $m^2_i \neq 0$ and ν=anti-ν (Majorana neutrinos). Sensitive* to the "effective Majorana mass" (and related phases):

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



3) Cosmology: $m^2_i \neq 0$ alters large scale structure formation within standard cosmology constrained by CMB+other data. Measures*:

$$\Sigma = m_1 + m_2 + m_3$$



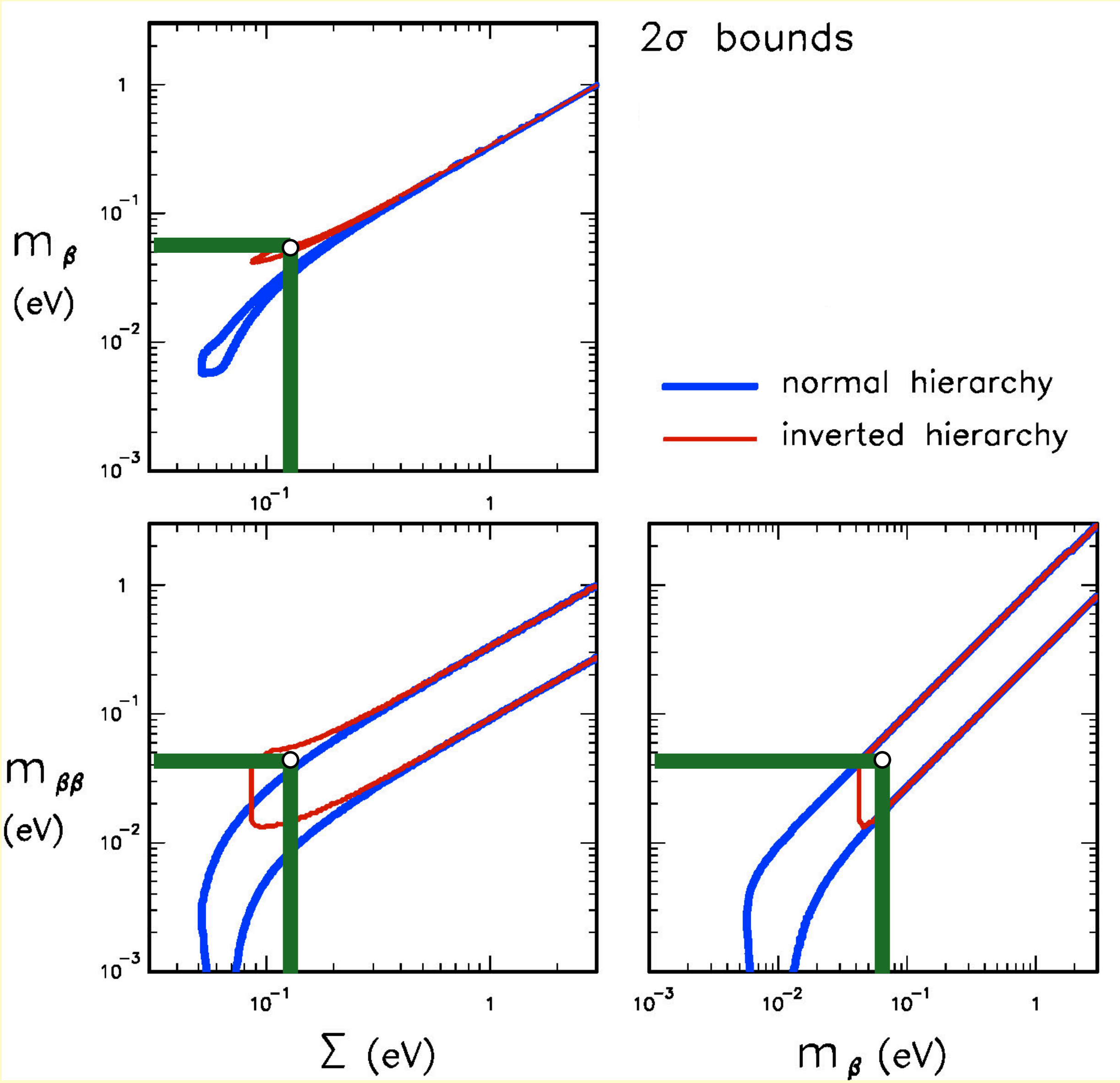
*in first approximation

The dream...: 3ν concordance of (osc, m_β, $m_{\beta\beta}$, Σ) fragments

Determine the mass scale...

Identify the hierarchy ...

Probe the Majorana nature and phase(s)...



Relevant to constrain/support leptogenesis & flavor symmetry models

Status [and prospects]

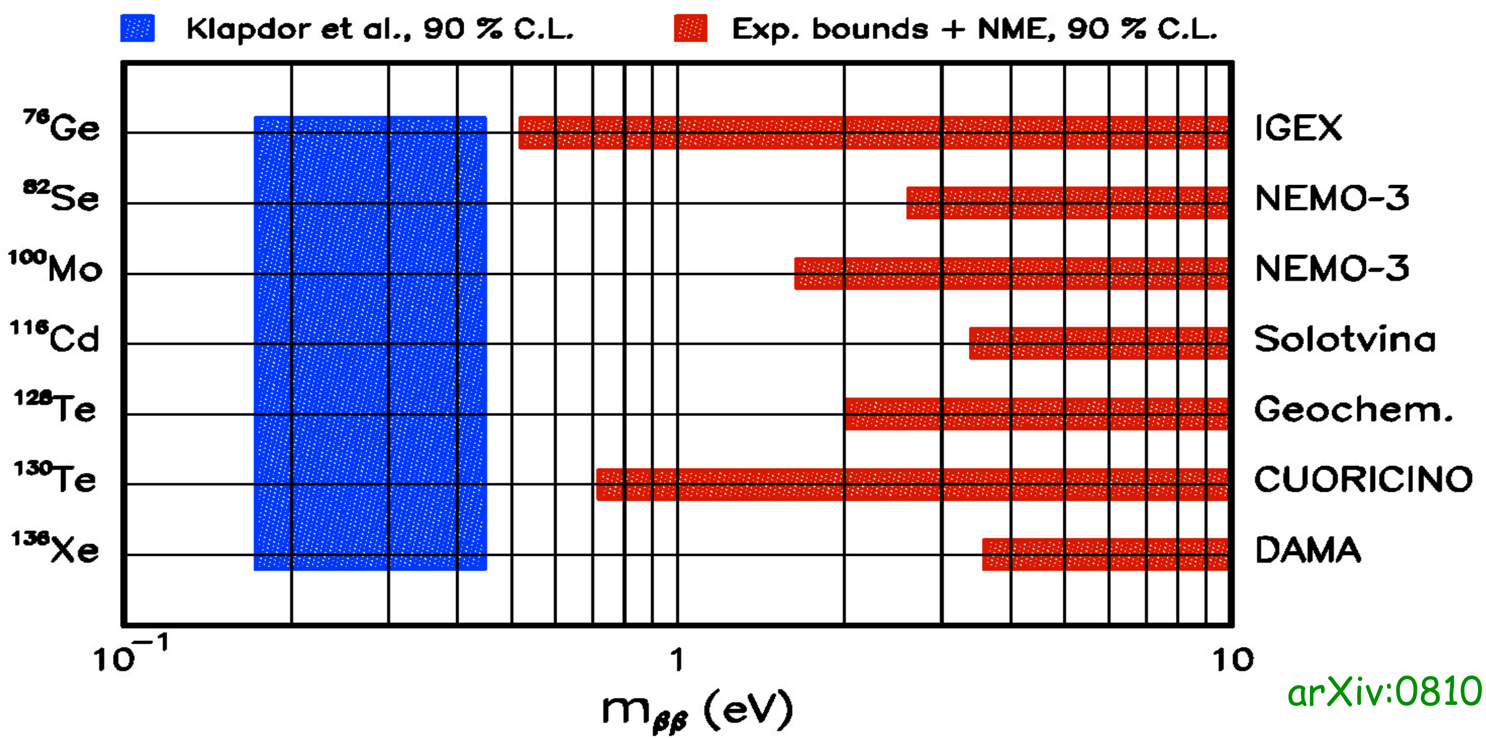
$m_\beta <\sim 2$ eV [expect x10 improvement from KATRIN]

$\Sigma <\sim 1$ eV ("conservative") down to

$<\sim 0.2$ eV ("aggressive")

[$<\sim 0.6$ eV: "consensus value", aim at x10 improvement]

$m_{\beta\beta}$

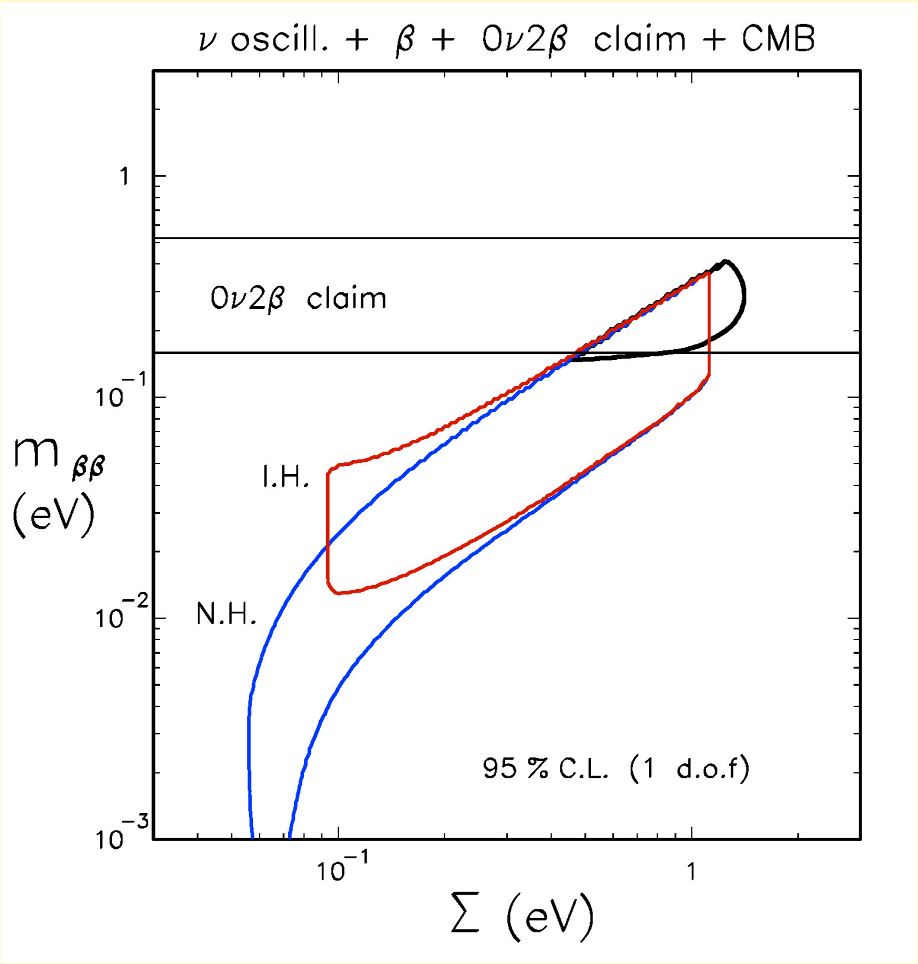


arXiv:0810.5733

[Expect to test soon Klapdor et al. claim; aim at x10 improvement]

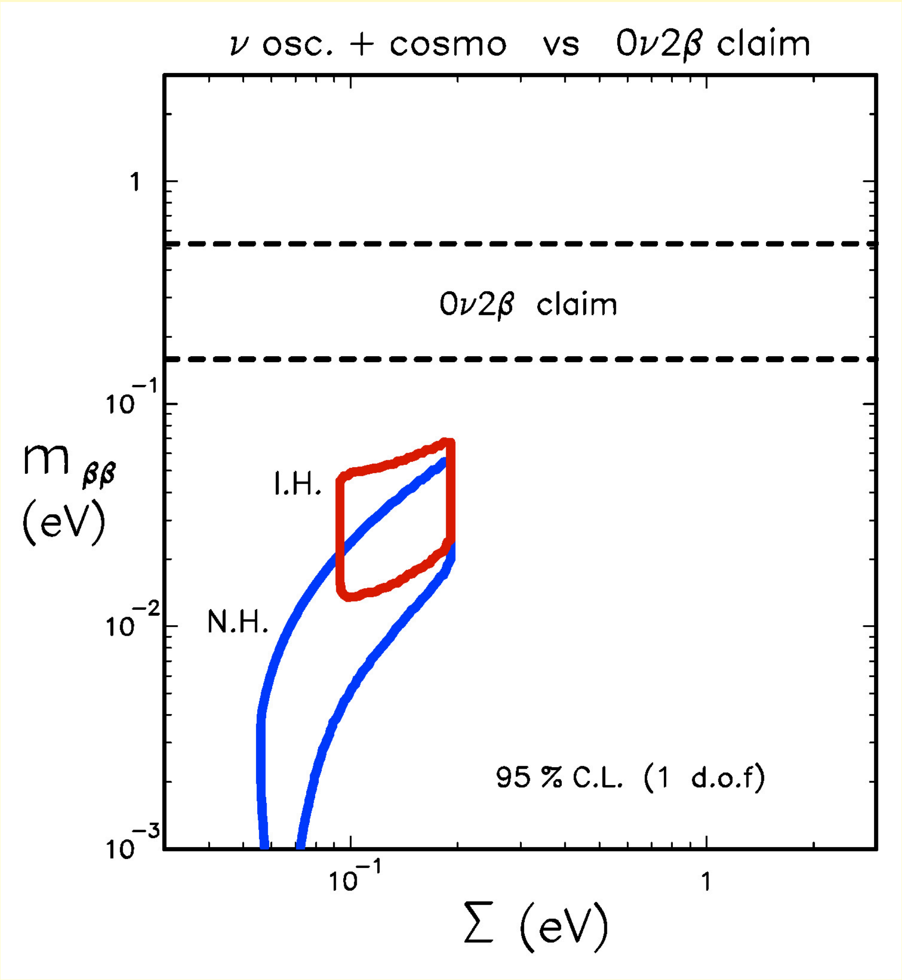
Currently: disputed claim & ambiguous "fragments reconstruction"

Cosmo-"conservative"



fragments can match…

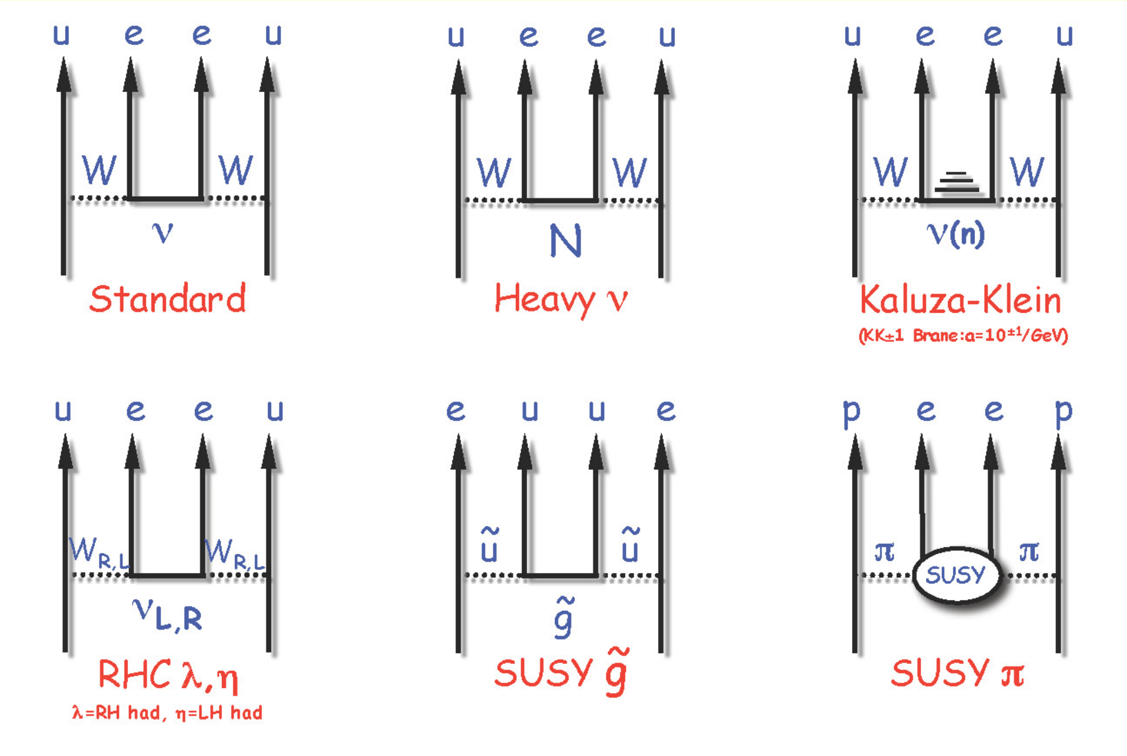
Cosmo-"aggressive"



fragments don't match…

What if no 3ν concordance? Pheno/theory nightmares …
… or new opportunities? → New physics!

Increasing activity in studying/revisiting **alternative mechanisms** for **0ν2β** decay (either dominant or concurrent), their links/roles in other areas (new particles at LHC, see-saw, leptogenesis, charged LFV, extraDim, MiniBoone…), and their possible **discrimination**. Improvements in nucl. matr. elem. mandatory.



[Note: the "standard" cosmological model may also require revision: extra radiation, dynamical DE, DE-DM interactions…]

2. Neutrino mixing and masses:

seeking a flavor structure and a new physics scale

Large mixing angles have been a surprise. Another surprise: they seem to have "special" values. Which of the two… options?

Remnants of some flavor symmetry … or accidents?

It makes sense to pursue the idea that there is a symmetry and, at the same time, try to challenge it through new or more accurate oscillation data or through correlations with other observables (e.g., $0\nu2\beta$). Usual (not unique) starting points:

Tri Bi Max

$$U_{TB} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{matrix} +O(\lambda_C^2) \\ +O(\lambda_C) \end{matrix}$$

Bi Max

$$U_{BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} +O(\lambda_C)$$

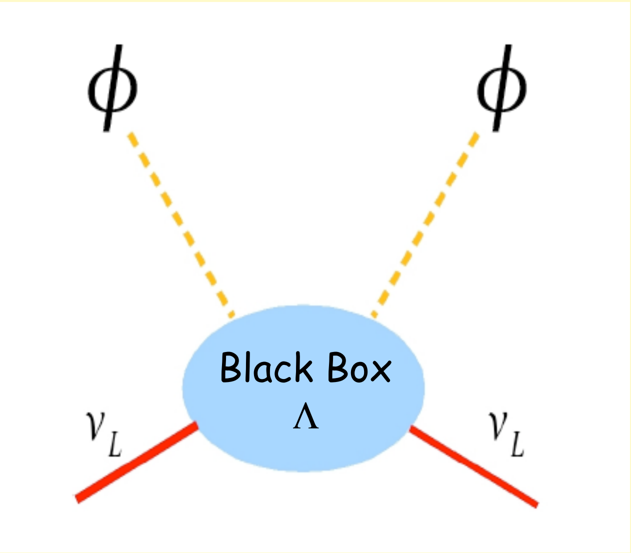
"Natural" Cabibbo param. $\lambda_C \sim 0.2$

$$\sqrt{\frac{\Delta m^2_\odot}{\Delta m^2_A}} \gtrsim \frac{1}{5} \simeq \sqrt{\frac{m_\mu}{m_\tau}} \simeq \sqrt{\frac{m_s}{m_b}} \simeq \sqrt{\sqrt{\frac{m_c}{m_t}}}$$

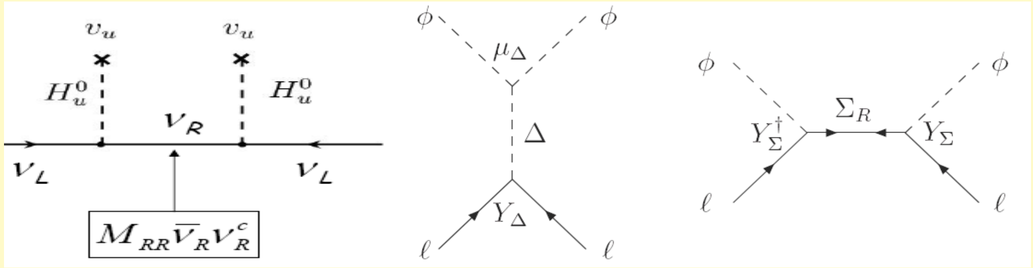
Current data accuracy: $O(\lambda^2)$ for θ_{12} and θ_{13}; $O(\lambda)$ for θ_{23}
Aim at another λ factor in expt accuracy to select models

ORIGIN OF MASS

Is there a see-saw mechanism? At which scale Λ? Of which type?



Type I, fermion singlet N, charge 0	Type II, scalar triplet δ, charge 0, 1, 2	Type III, fermion triplet Σ, charge 0, 1

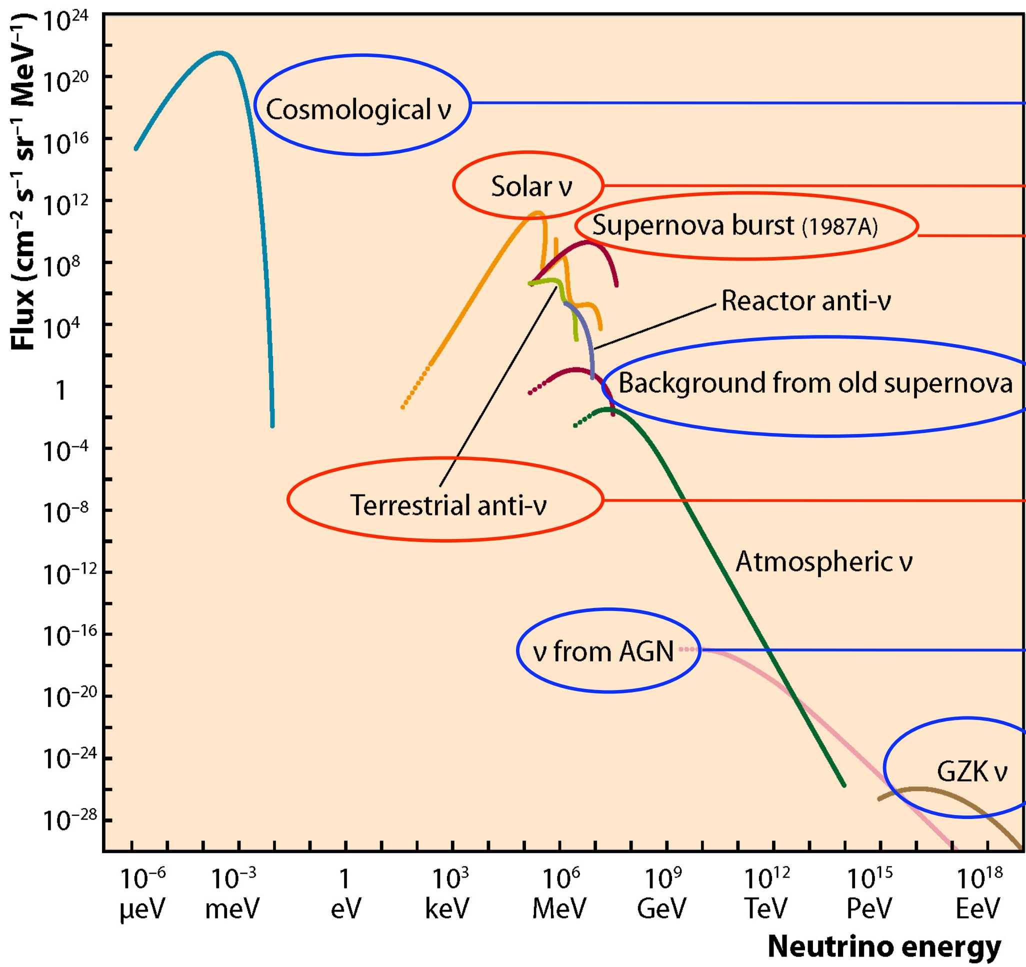


+ variants (inverse, +SUSY, +LR, +radiative,…)

Classical arguments in favor of high-scale, type-I see-saw have their beauty (simplicity, O(1) couplings + small masses +leptogenesis at ~GUT scale, ...)

But, in the **LHC era**: ϕ and the black box will be directly probed at Λ~O(TeV), provided that couplings are not too small…So, it is important to explore in detail the possibility that the "low" LHC scale may shed light on the ν mass origin, e.g., via observable production + decay of see-saw mediators.
Also: links with **charged LFV** processes in models [Mohapatra & Valle @ ν 2010]

3. Astrophysical sources of neutrinos



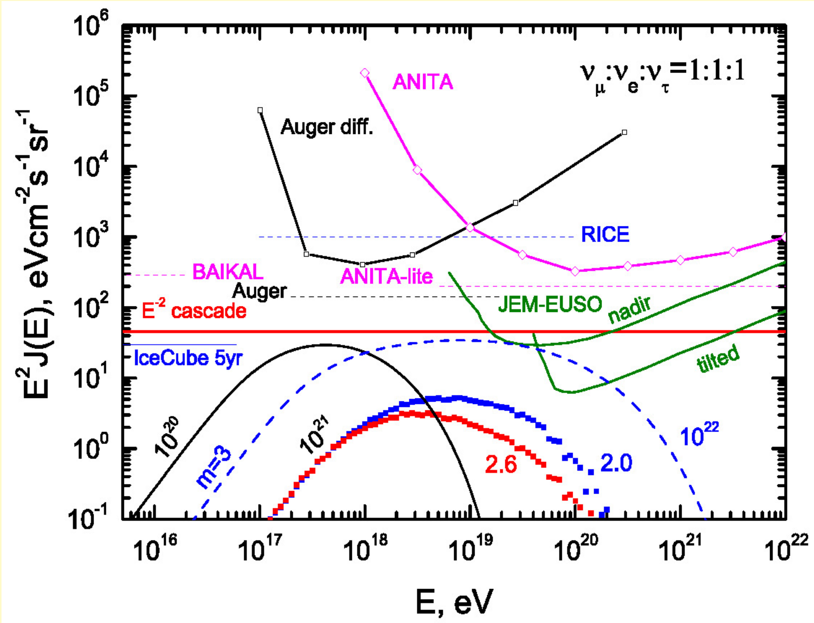
A synoptic view of neutrino fluxes. **(from ASPERA roadmap)**

Vast lands to be explored…

- Cosmological ν → Observable in principle (far future)
- Solar ν → Observed
- Supernova burst (1987A) → Observed
- Background from old supernova → Observable in ~near future
- Terrestrial anti-ν → Observed [Earth as anti-ν star!]
- ν from AGN → Observable in km^3 detect. [goal]
- GZK ν → Observable, but not in near future

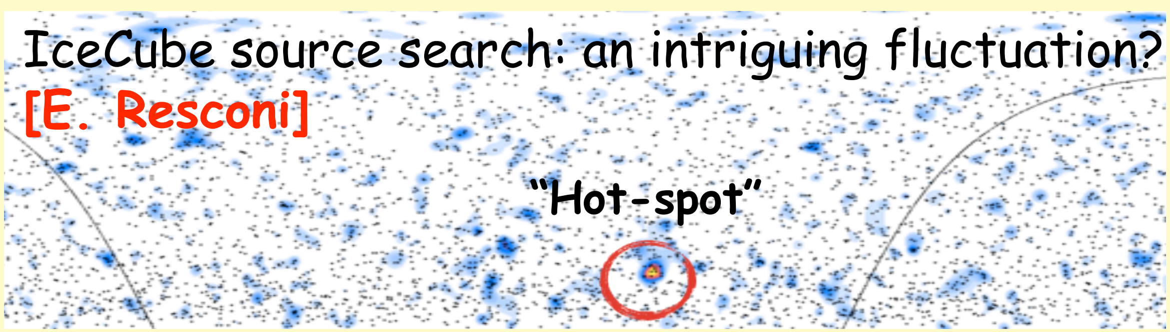
Also, fast-moving front: ν's as part of a multimessenger approach to DM searches

Status of cosmogenic ν flux estimates [Berezinsky @ ν 2010]



Recent theoretical assessment in dip model (protons) + Fermi cascade upper limit:
low flux, still out of reach; even more so if protons → heavy nuclei, as suggested by Auger data.
If something is found (radio-detection?), likely to be new physics (top-down)!

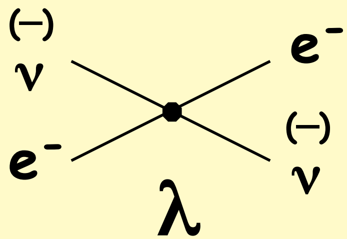
Main message for km³ detectors: priority for HE and UHE ν astronomy is to search for (SNR, AGN, GRB) ν **sources** and test SM for cosmic rays.

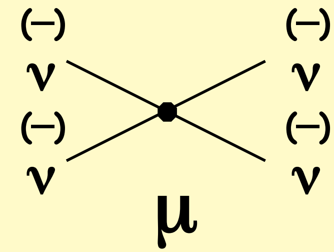


Interesting standard and nonstandard ν physics testable when sources will be discovered.

Supernovae and neutrino-neutrino interactions

In core-collapse supernovae, ν density is so high for a few seconds that,

besides 

(CC) one has to include 

(NC)

Evolution of flavor ("polarization vectors") becomes nonlinear.

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

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

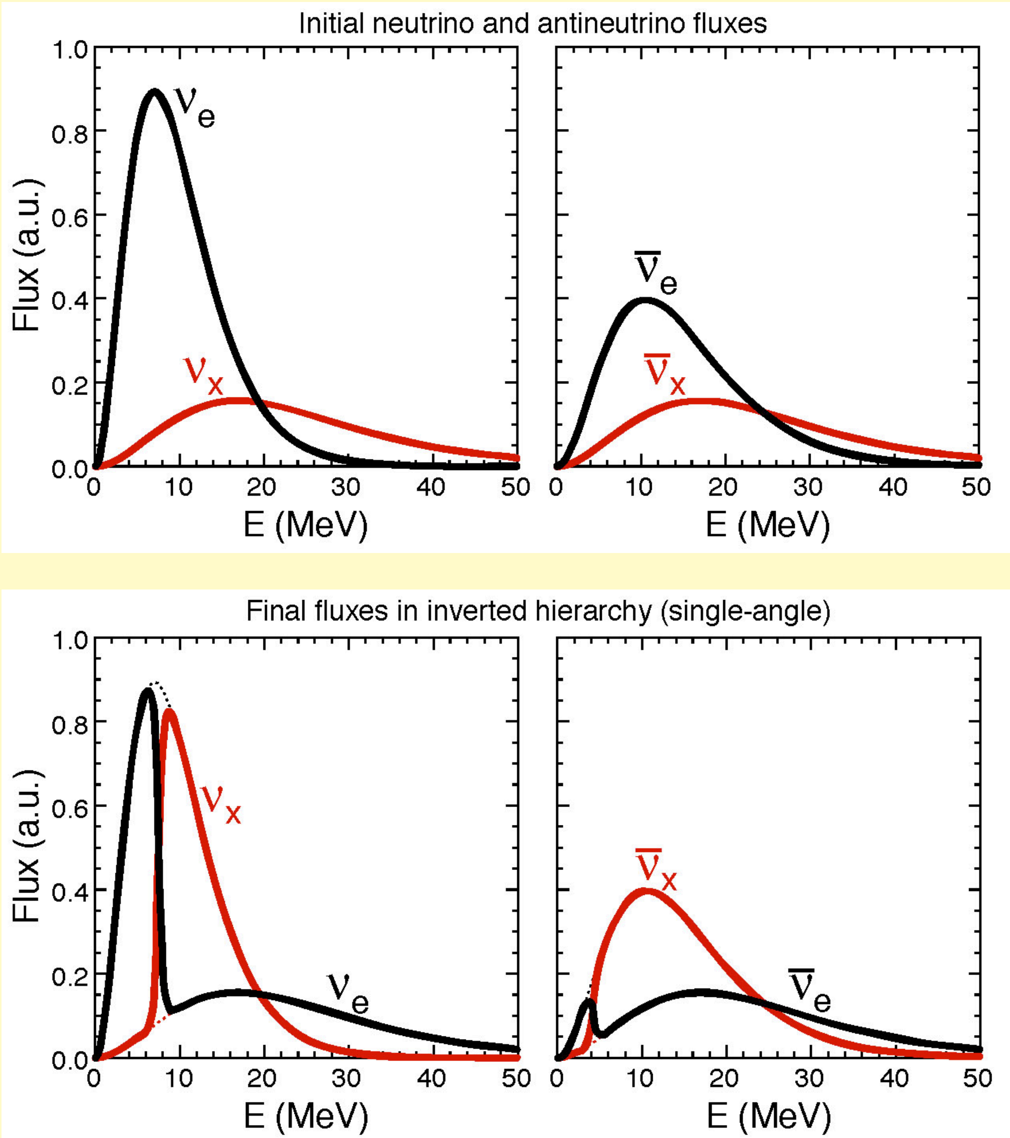
Vacuum frequency

matter

self-interaction

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

Supernovae and neutrino-neutrino interactions



Current research activity on SN neutrinos largely focused on such ν–ν effects →nonlinear collective flavor changes, which amplify small "instabilities"!

Strong dependence on mass hierarchy and on energy ("spectral splits").

Theoretical & computational challenges for many years, since effects have been studied only under some approximations.

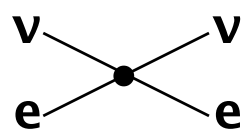
Remark on MASS HIERARCHY via flavor transitions:

The hierarchy, namely, sign($\pm\Delta m^2$), can be probed (in principle), via <u>interference</u> of Δm^2-driven oscillations with some other Q-driven oscillations, where Q is a quantity <u>with known sign</u>.

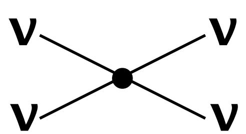
Barring new states/interactions, the only known options are:

Q = δm^2 (high-precision oscill. pattern; reactors?)

Q = Electron density (MSW effect in Earth or SN)



Q = Neutrino density (Collective effects in SN)

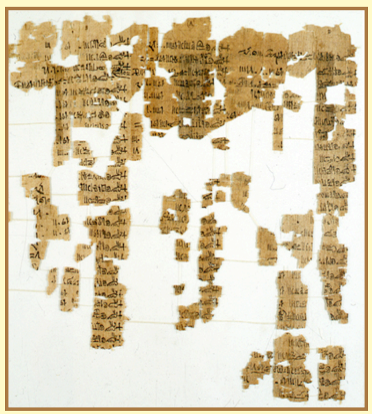


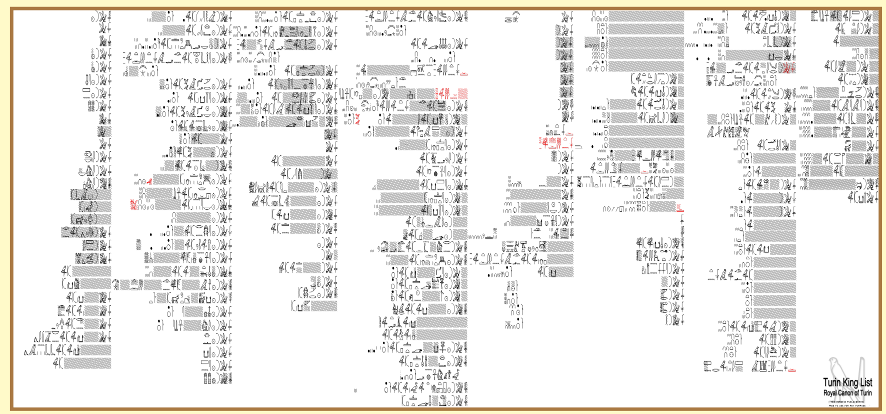
Which of the three… will succeed? Each one is very challenging, for rather different reasons. Non-oscillation observables might provide another handle. In any case: very high accuracy required.

… May we eventually get the hierarchy from high-precision cosmology? …

EPILOGUE

The destiny of neutrinos is to raise questions...
Their tiny masses are fragments of new physics,
which will hopefully match many other fragments
from ν, astroparticle, charged LFV and collider physics,
and provide us with a new script of Nature
... and with new questions.





- THANK YOU FOR YOUR ATTENTION -