Neutrino mass-mixing parameters:
Global analysis and short-term prospects

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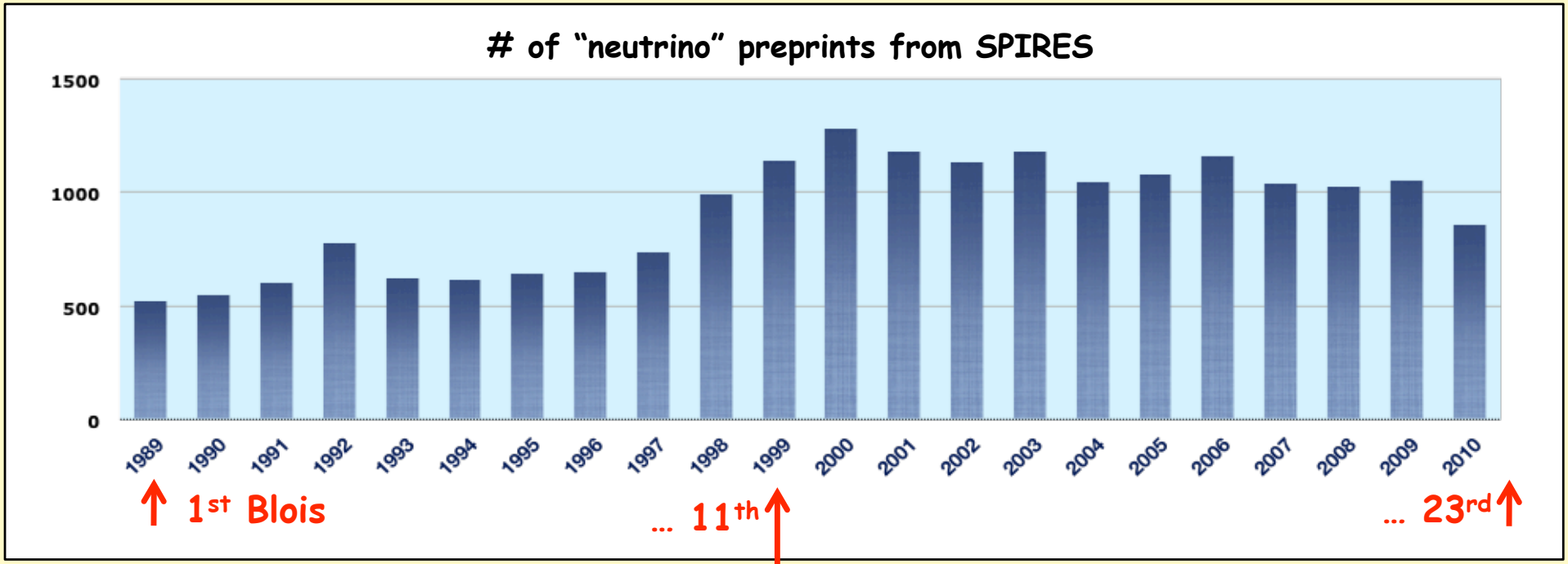
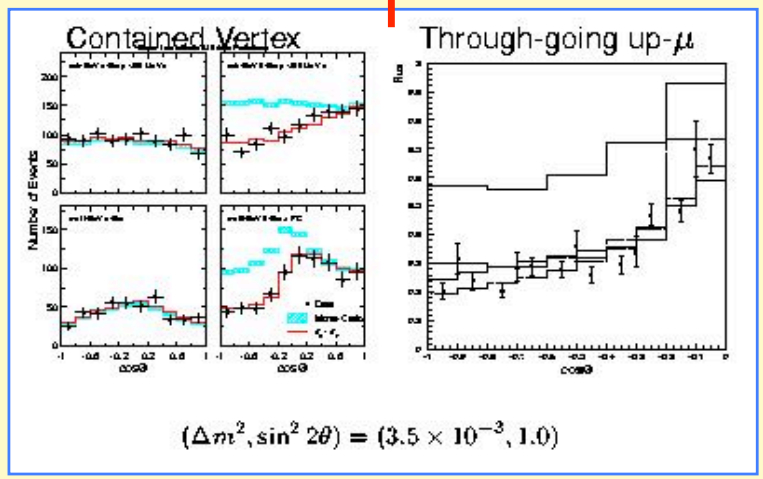
Blois 2011

Based in part on work done in collab. with: Fogli, Marrone, Palazzo, Rotunno; Melchiorri et al.; Faessler and Simkovic.

PROLOGUE

In the last 23 years, the Rencontres de Blois series has witnessed great discoveries and tremendous progress in neutrino physics…



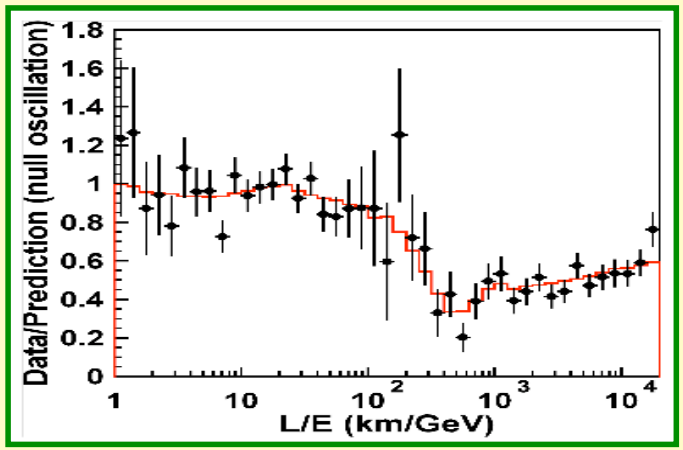


Clark McGrew, Blois 1999
← "Atmospheric Neutrinos"

... as a result of clear answers to a fundamental question:

Q.: Do any of the three known neutrinos have mass?

A1.: At least one massive ν needed for large-amplitude flavor transitions of atmos. and LBL acceler. neutrinos

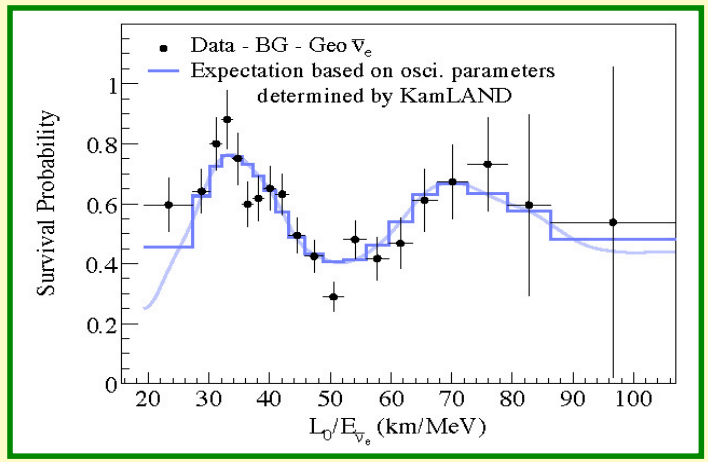


$(\Delta m^2,\ \sin^2\theta_{23})$

frequency

amplitude

A2.: At least two massive ν to allow also large-amplitude flavor transitions of solar and LBL reactor neutrinos



$(\delta m^2,\ \sin^2\theta_{12})$

frequency

amplitude

3x3 mixing matrix: $(\nu_e, \nu_\mu, \nu_\tau)^T = U\,(\nu_1, \nu_2, \nu_3)^T$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Large rotation (~maximal)	Small rotation (maybe null ?)	Large rotation (< maximal)
$\sin^2\theta_{23}\sim 1/2$	$\sin^2\theta_{13}\sim 0$	$\sin^2\theta_{12}\sim 1/3$

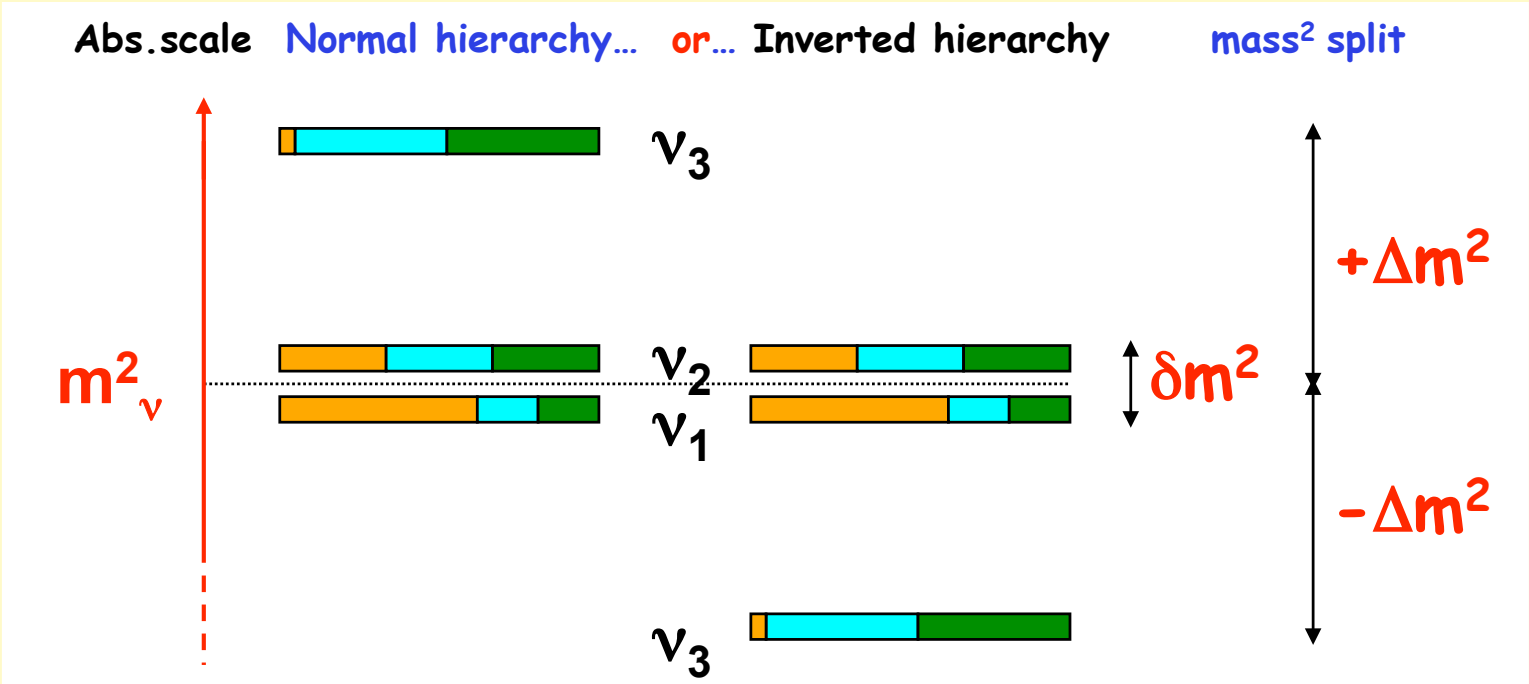
Theory: Is this pattern accidental or "symmetric" ?

Expts: How can we measure θ_{13}? And δ afterwards?

Higher accuracy (data+models) needed in any case

...if we care only about 1 digit accuracy:

3ν mass-mixing overview. Flavors = e μ τ



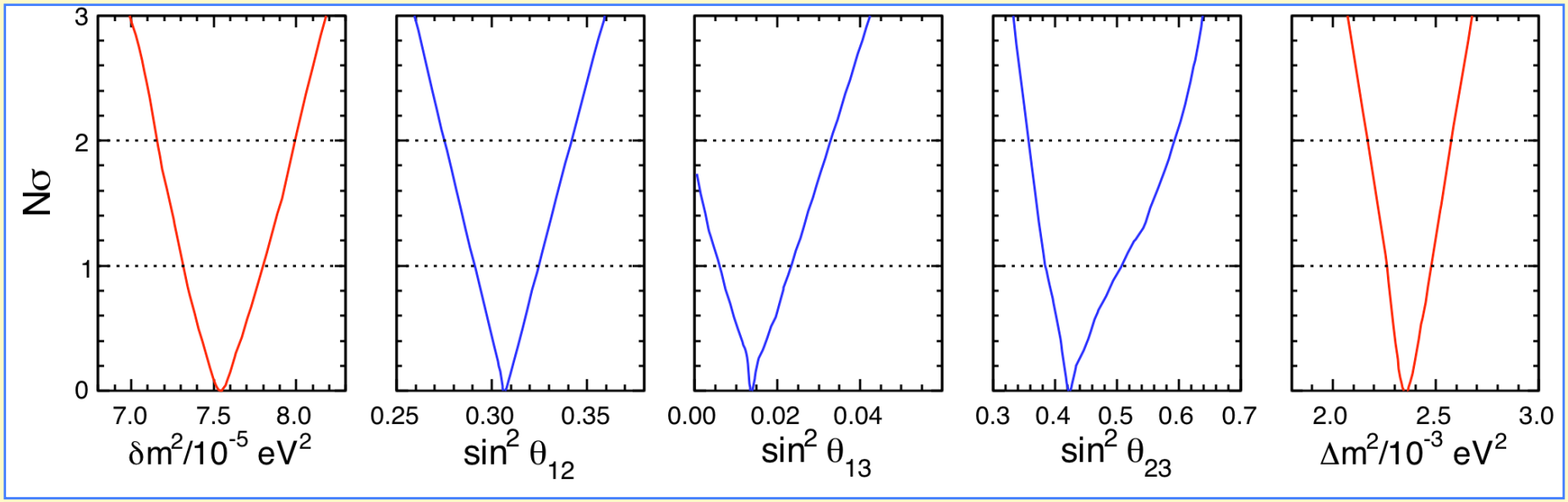
$\delta m^2 \sim 8 \times 10^{-5}\ \mathrm{eV}^2$ $\quad \sin^2\theta_{12} \sim 0.3$

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

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

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

More digits: our 2011 update of [Fogli et al. arXiv:0805.2517], in preparation*



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	7.54	0.307	0.014	0.42	2.36
1σ range	7.32 – 7.79	0.291 – 0.325	0.006 – 0.023	0.38 – 0.51	2.26 – 2.48
2σ range	7.14 – 7.99	0.275 – 0.342	< 0.033	0.36 – 0.59	2.17 – 2.57
3σ range	6.98 – 8.17	0.259 – 0.360	< 0.042	0.33 – 0.64	2.07 – 2.67

*Includes SK-I+II+III, MINOS app.+disapp., latest KamLAND and solar data.

Other recent global analyses: Gonzalez-Garcia et al, arXiv:1006.3795;
Schwetz et al., arXiv:1103.0734 (includes new evaluation of reactor fluxes)

We are already in the era of precision neutrino physics…

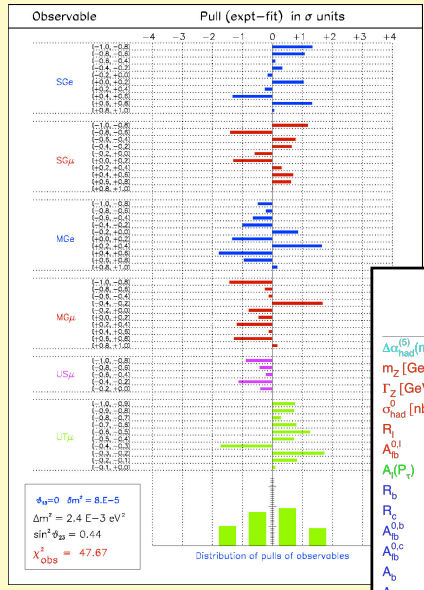
3ν parameter accuracy:

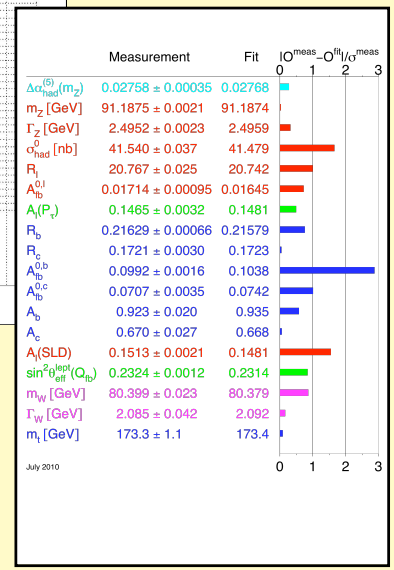
$\sigma(\delta m^2)$ ~ 2.5%
$\sigma(\Delta m^2)$ ~ 4%
$\sigma(\sin^2\theta_{12})$ ~ 5%
$\sigma(\sin^2\theta_{23})$ ~ 12%

$\sigma(\sin^2\theta_{13})$ ~ 0.01

Different analyses agree within ~$\frac{1}{2}\sigma$
(can't ask for more!)

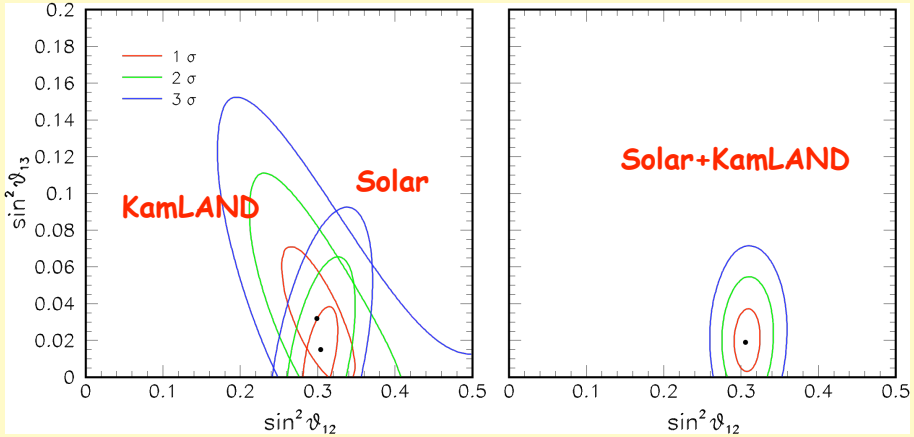
Bari group, solar ν data pulls





LEP-EW working group, EW precision data pulls

...and may even squeeze possible ~2σ hints of $\theta_{13}>0$ from global data analyses...



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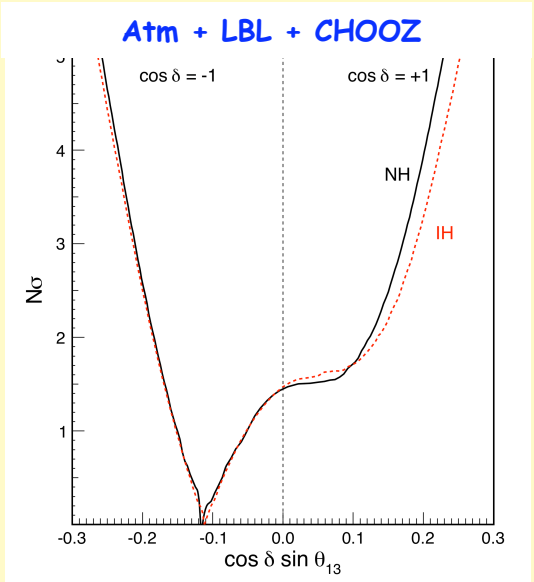

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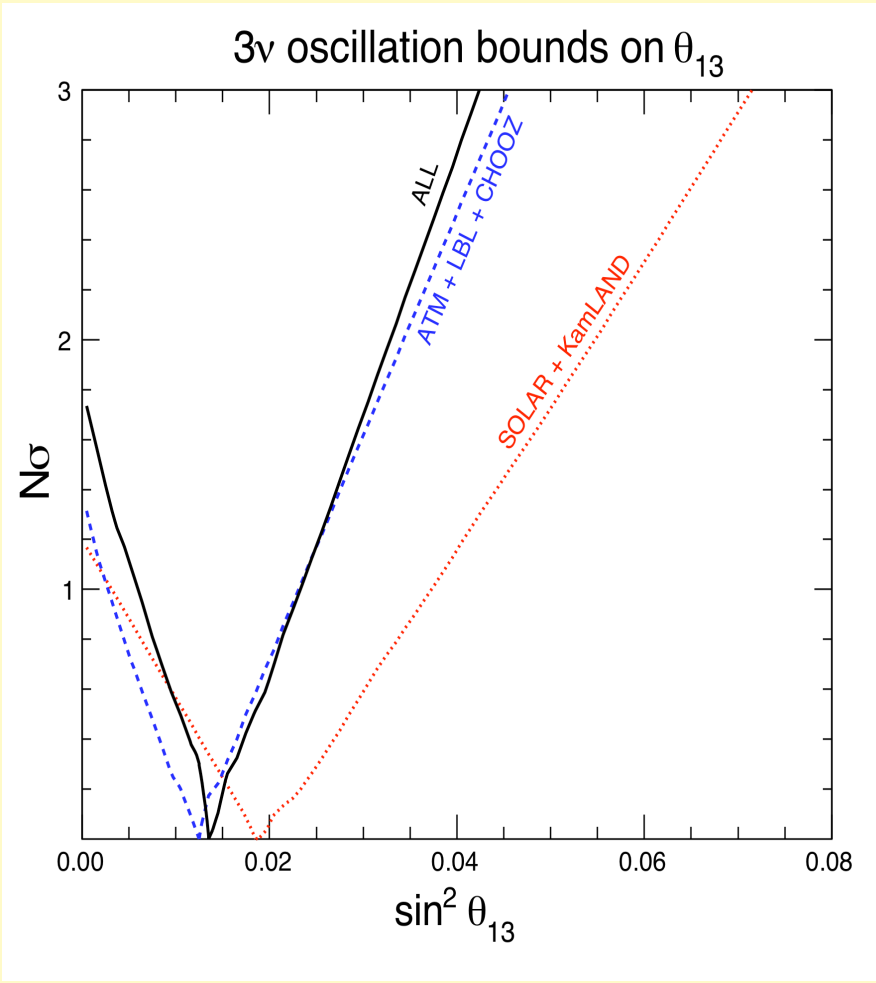


$\sin^2\theta_{13}\sim 0.014\pm 0.008$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

If $U_{e3}=\sin\theta_{13} > 0$: access to leptonic CP violation.

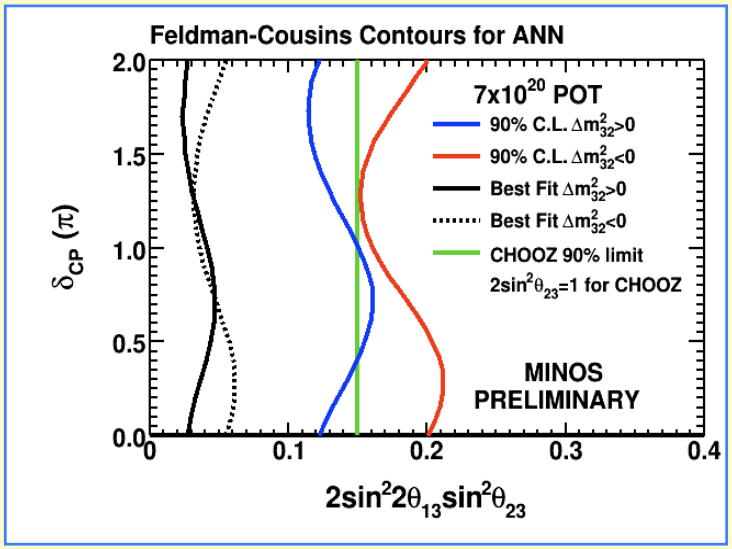
$$P_{\alpha\beta}(\nu) - P_{\alpha\beta}(\bar{\nu}) = 2 \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta \times \sin\left(\frac{\Delta m^2 - \frac{\delta m^2}{2}}{4E} L\right) \sin\left(\frac{\Delta m^2 + \frac{\delta m^2}{2}}{4E} L\right) \sin\left(\frac{\delta m^2}{4E} L\right)$$

Crucial issue for future oscillation searches. Probes:

$\nu(\mu) \rightarrow \nu(e)$ at long-baseline accelerators: $\sim |U_{\mu 3}\, U_{e3}|$

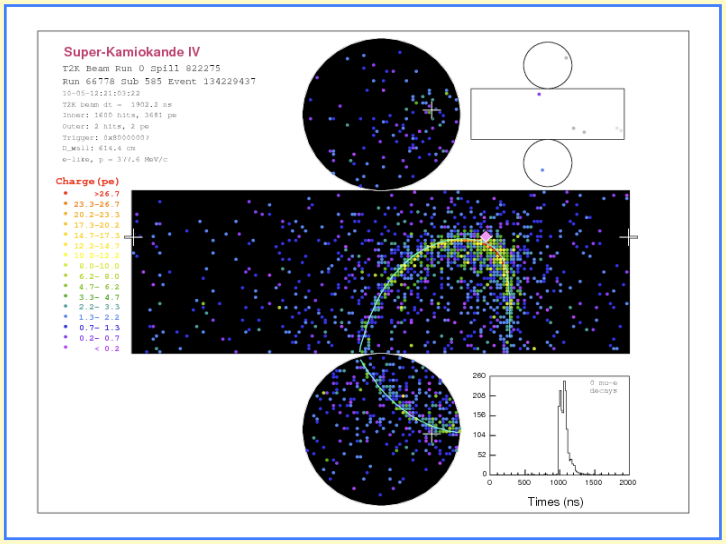
$\nu(e) \rightarrow \nu(e)$ at short-baseline reactor expts: $\sim |U_{e3}|$

Short-term θ_{13} prospects at long-baseline accelerators:



MINOS 2010: ν(e) excess in appearance mode not statistically significant (0.7σ).

More data (POT) and a new analysis expected this year.



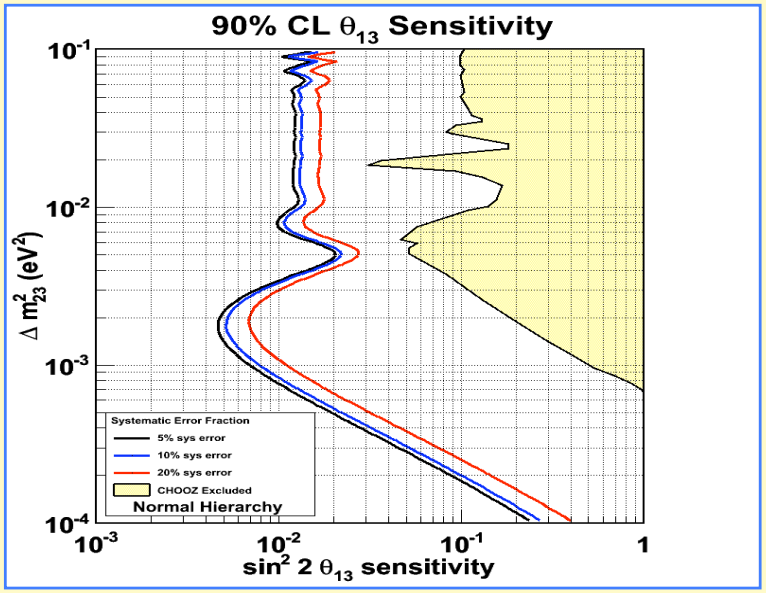
T2K 2011: first candidate ν(e) event passing all cuts! Background = 0.3 events.

Pre-earthquake data analysis expected this year.

From KEK Director General, Atsuto Suzuki: "First of all, I would like to express my deepest appreciation for the messages of concern, sympathy and encouragement that we received from all over the world since the major earthquake of March 11th. We are working to restore KEK as quickly as possible to its original condition so it can once again function as the exceptional research facility it was hitherto. Your messages do help a great deal in this difficult time."

Fortunately, tsunami did not hit JPARC

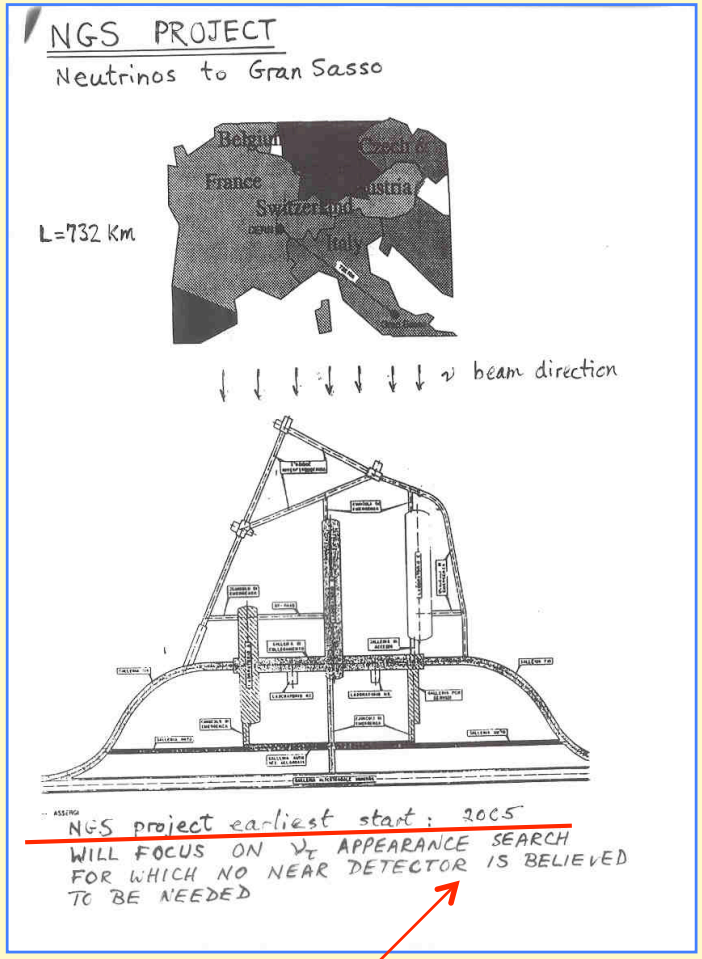
Goals delayed by ~1y or less



We wish success to our Japanese colleagues in the reconstruction effort!

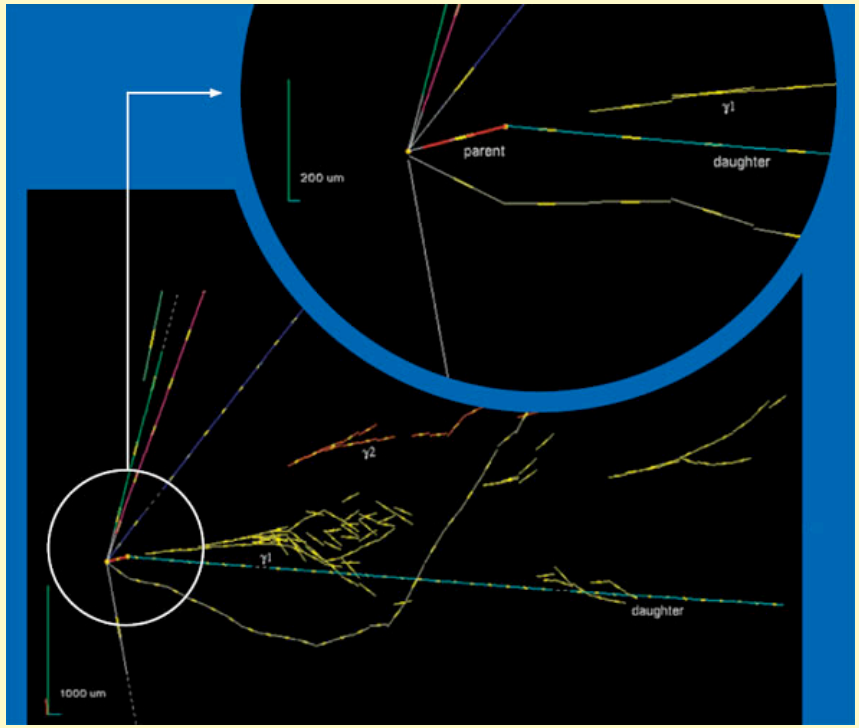
LBL in Europe: $\nu(\mu) \rightarrow \nu(\tau)$ appearance search with CNGS

M. Spiro @ Blois 1999:



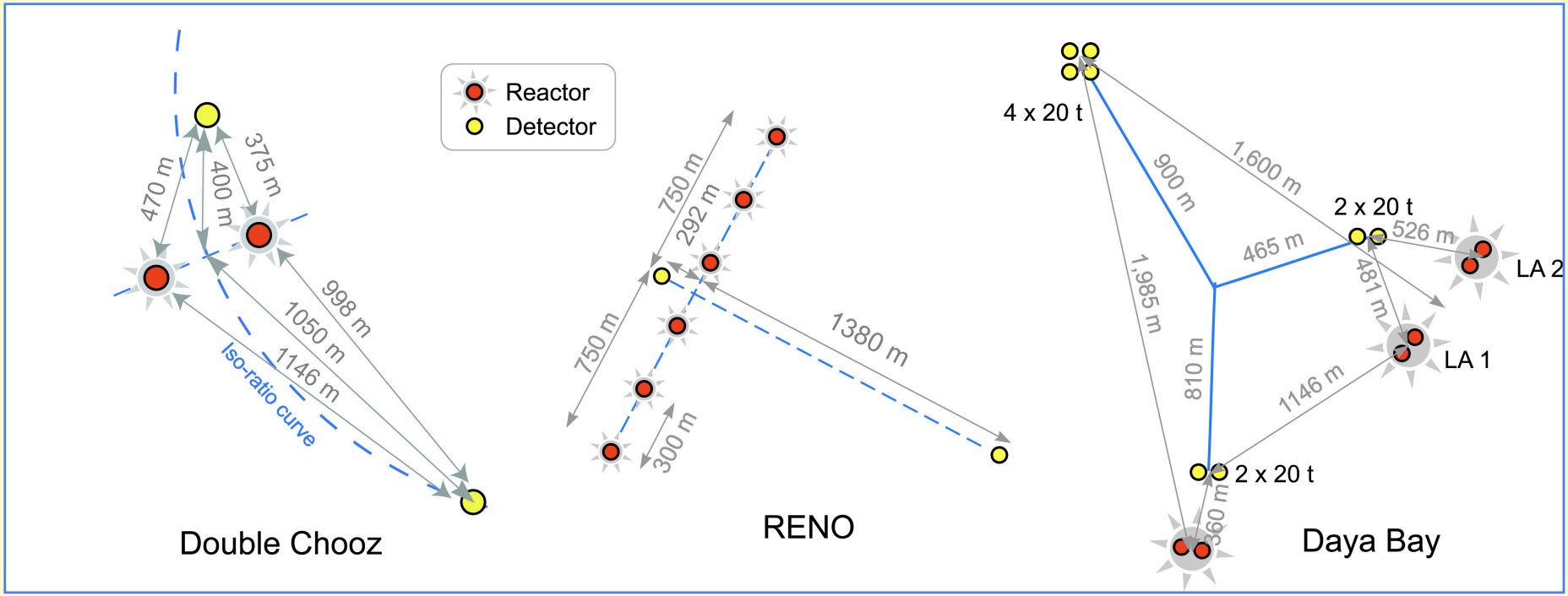
Good estimate… first $\nu(\mu)$ events in August 2006

OPERA, 2010:
1 candidate tau event
(background = 0.02 ev.)



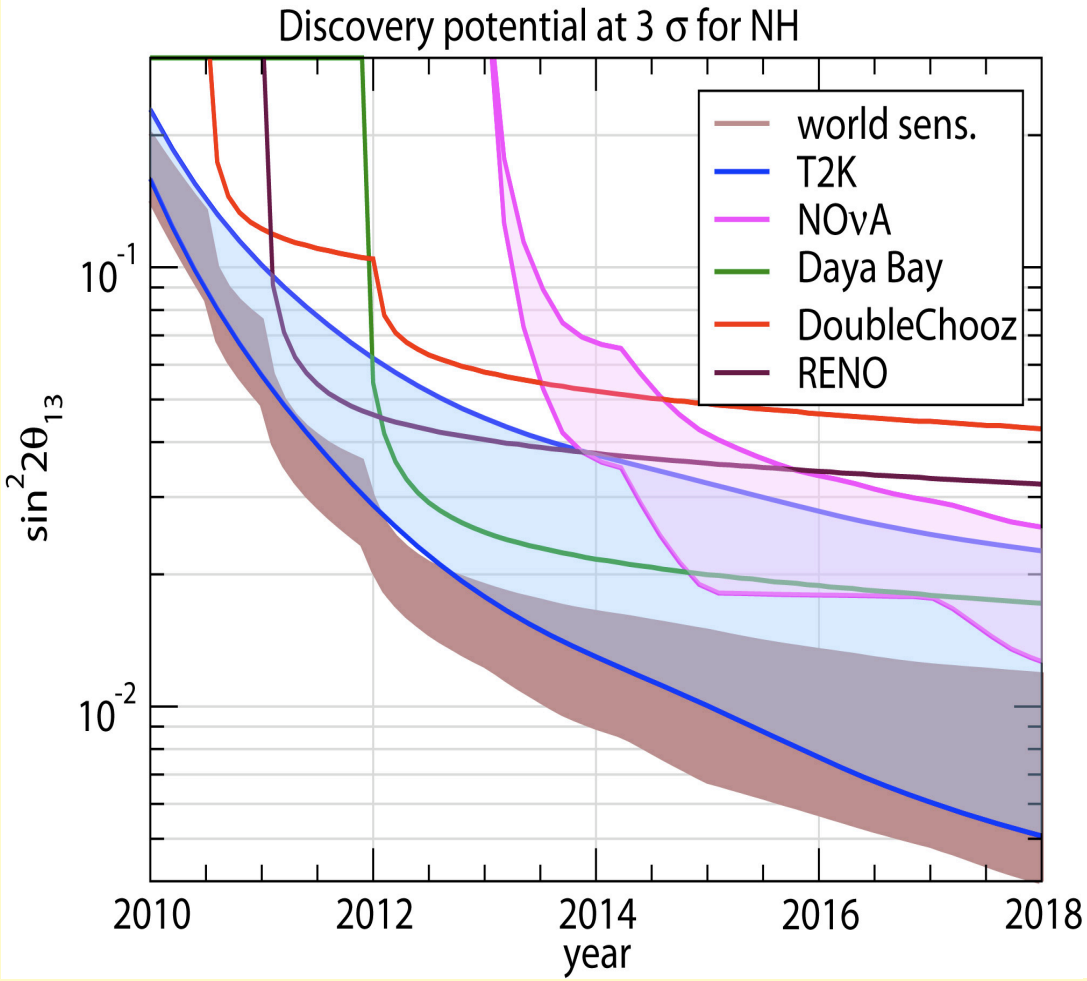
New data+analysis release expected this year

Searches for θ_{13} at reactor experiments



Double-CHOOZ, RENO, Daya Bay:
will take advantage of high statistics and far/near ratios to reduce uncertainties

Short-term prospects and comparison with LBL-accel:



The race has started!

Can reach and (dis)prove current θ_{13} hints in a few years

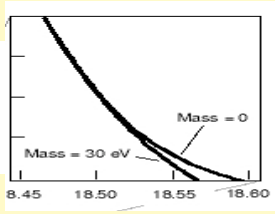
(courtesy of M. Mezzetto)

[Also: plenary talk by S. Pascoli]

3ν framework: probing absolute masses via (m_β, $m_{\beta\beta}$, Σ)

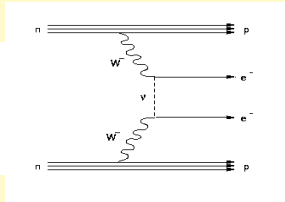
1) Single β decay: $m^2_i \neq 0$ alters the spectrum tail. Sensitive* to the so-called "effective mass of electron neutrino":

$$m_\beta = \left[c^2_{13}c^2_{12}m^2_1 + c^2_{13}s^2_{12}m^2_2 + s^2_{13}m^2_3\right]^{\frac{1}{2}}$$



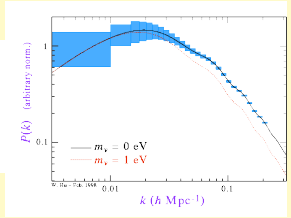
2) Double 0νββ decay: Iff $m^2_i \neq 0$ and ν=anti-ν (Majorana neutrinos). Sensitive* to the "effective Majorana mass" (and related phases):

$$m_{\beta\beta} = \left|c^2_{13}c^2_{12}m_1 + c^2_{13}s^2_{12}m_2e^{i\phi_2} + s^2_{13}m_3e^{i\phi_3}\right|$$



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

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



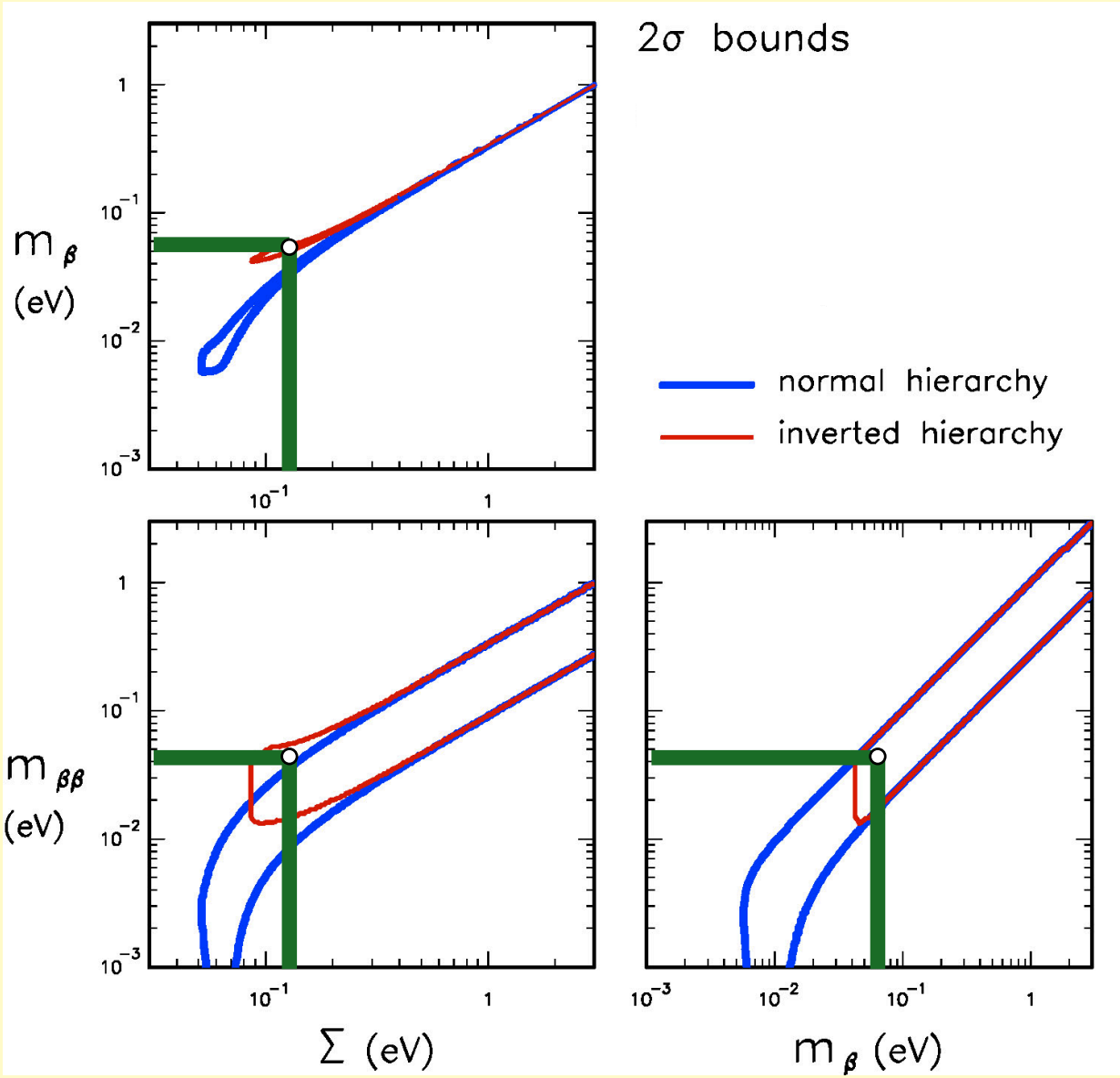
*in first approximation

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

Determine the mass scale…

Identify the hierarchy …

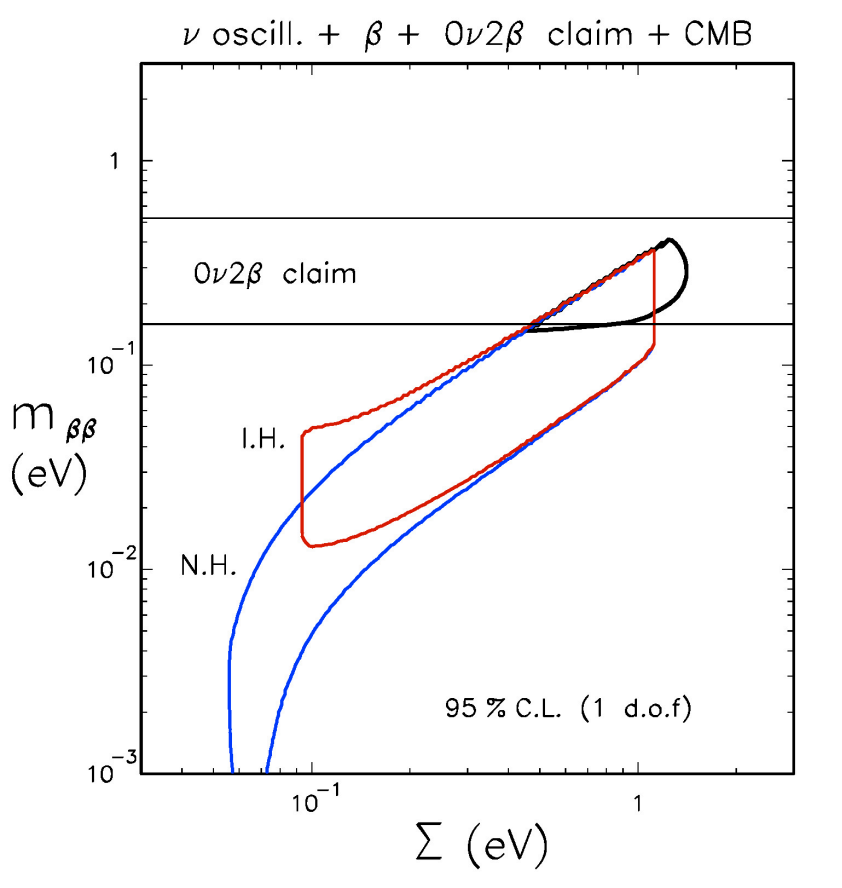
Probe the Majorana nature and phase(s)…



Relevant to constrain/support leptogenesis & flavor symmetry models

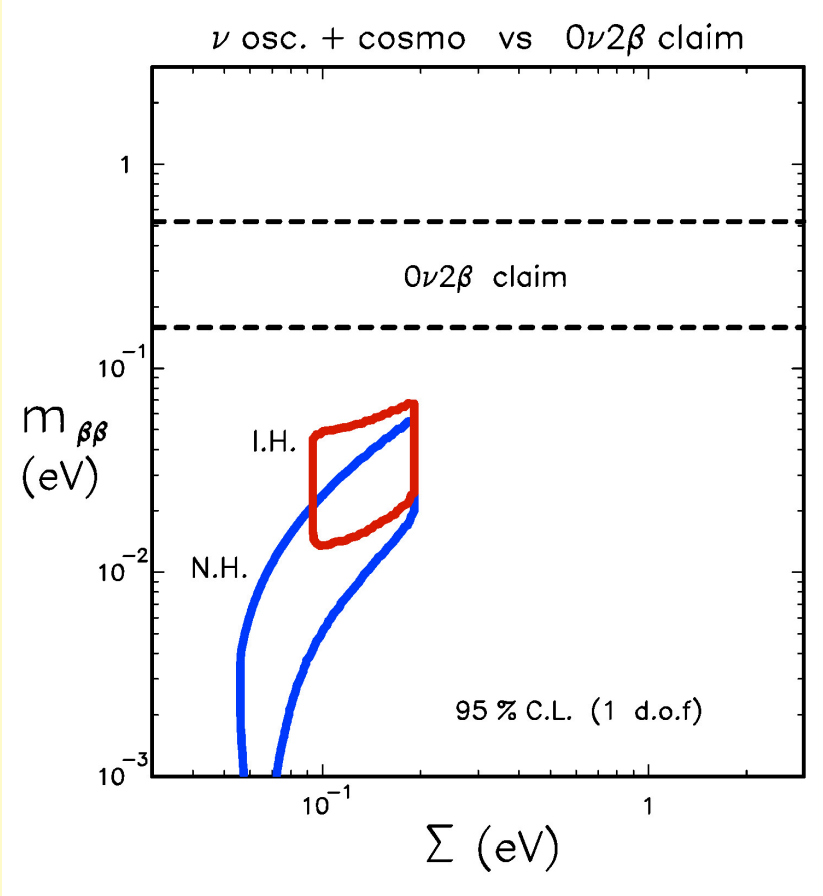
Current situation inconclusive, e.g., wrt to disputed $0\nu2\beta$ claim

"Conservative" cosmo limits:



matching data...

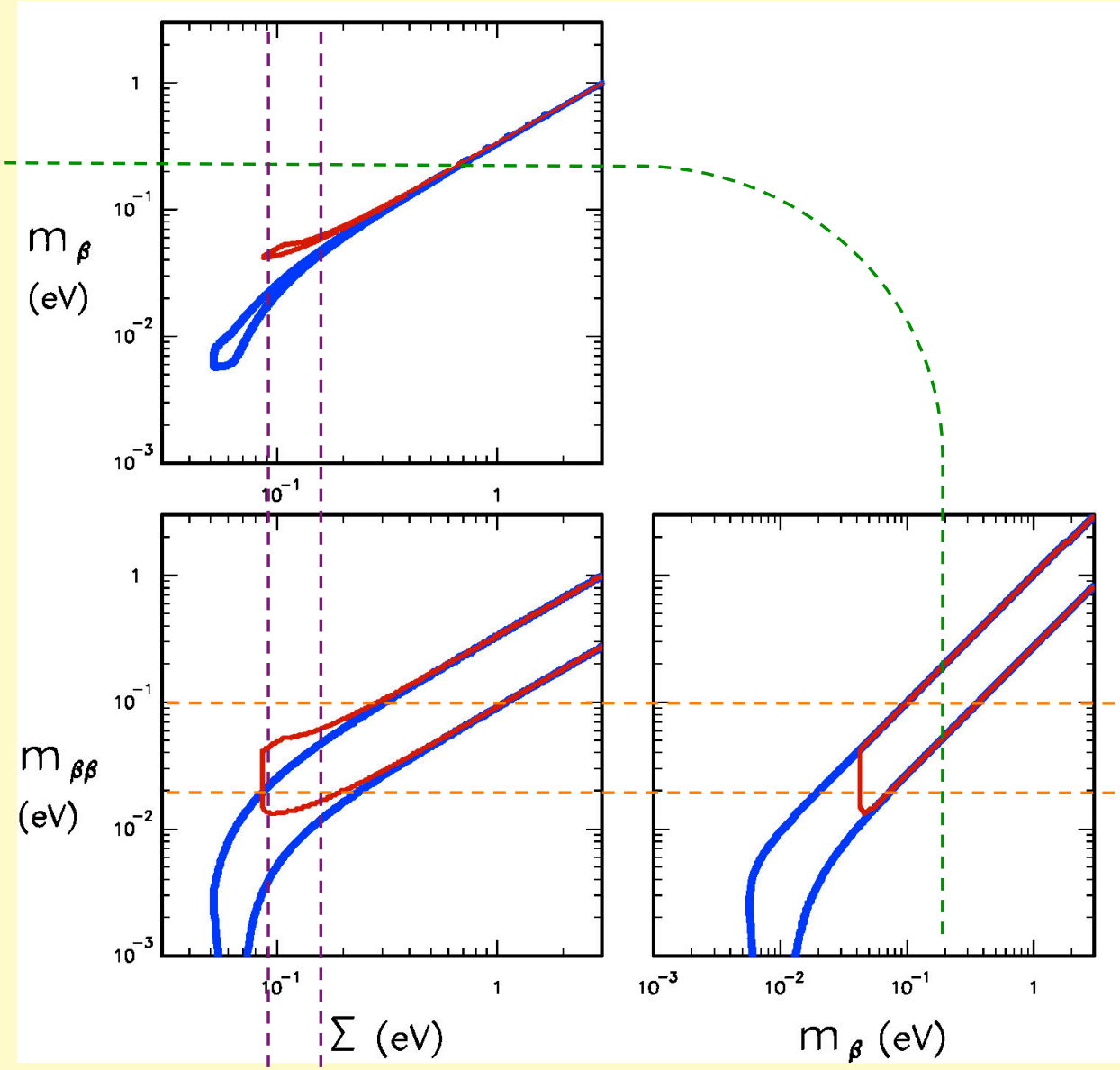
"Aggressive" cosmo limits:



unmatching data...

[Note: the "standard" cosmological model might require revision: extra radiation, dynamical DE, DE-DM interactions...]

Short(?)-term sensitivity on absolute masses (and hierarchy)



3ν framework: MASS HIERARCHY via flavor transitions

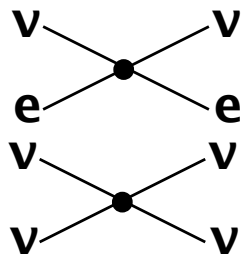
The hierarchy, namely, sign($\pm\Delta m^2$), can also be probed (in principle), via interference of Δm^2-driven oscillations with some other Q-driven oscillations, where Q is a quantity with known sign.

At present, the only known possibilities (barring new physics) are:

Q = δm^2 (e.g., high-precision oscillometry in vacuum)

Q = Electron density (e.g., matter effects in Earth)

Q = Neutrino density (SN ν–ν interaction effects)



Each one is very challenging, for rather different reasons.

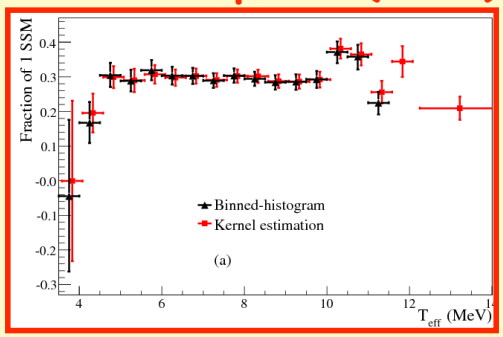
The latter possibility has recently raised increasing interest, being associated with **highly nonlinear flavor evolution effects** – for a few seconds- in core-collapse supernovae **[See plenary talk by Lunardini]**

3ν framework rather solid, but…

Neutrino oscillation "anomalies"

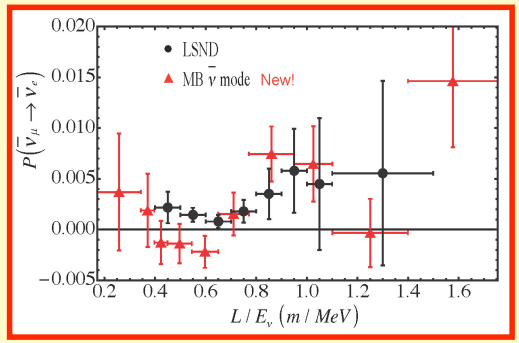
Not all results seem to match the standard 3ν picture, e.g.,

No MSW upturn (solar)?



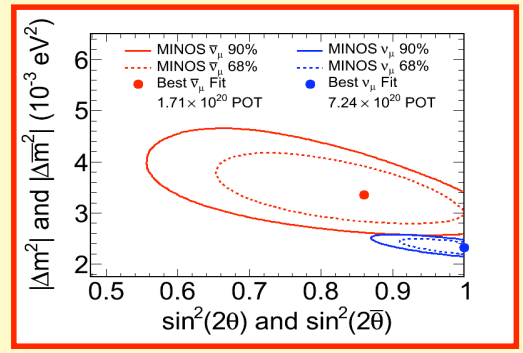
[Parallel talk by Bellerive]

LSND/MiniBooNE (SBL)?



[Parallel talk by Zimmerman]

ν / anti-ν (MINOS) ?



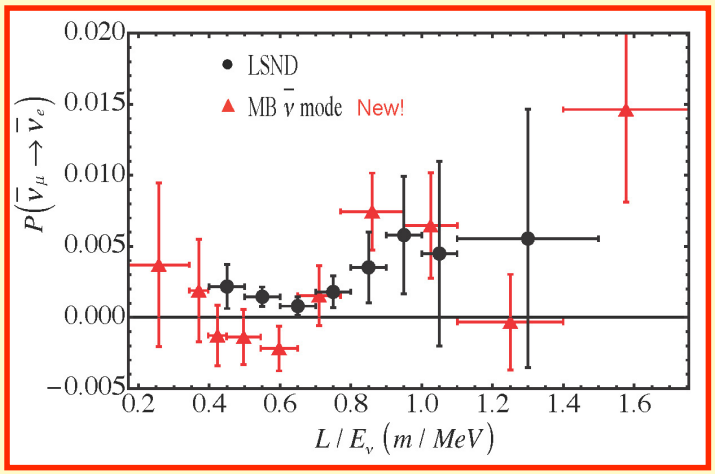
[Parallel talk by Mehdiyev]

New physics at work? [See plenary talk by Lindner]

Large literature on possible solutions to these and other anomalies invoking new states (sterile neutrinos) and/or new interactions (e.g., FCNC, decay,…) and/or symmetry violations (Lorentz, CPT,…). Often: "ad hoc" solutions.

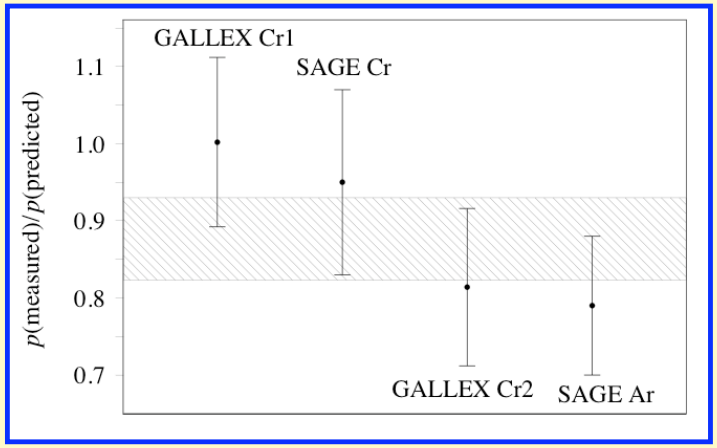
Recently, however a few independent hints seem to favor O(eV) sterile neutrino state(s) with small ν(e) mixing

"Older" anomalies:



LSND/MiniBoone:
SBL ν(μ)→ν(e) appearance at (sub)eV scale?

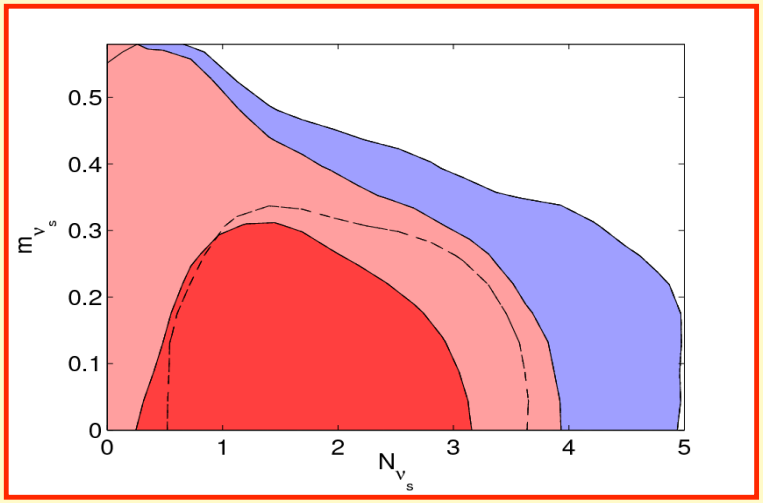
[Parallel talk by Zimmerman]



Gallium anomaly:
very SBL ν(e) disappearance ?

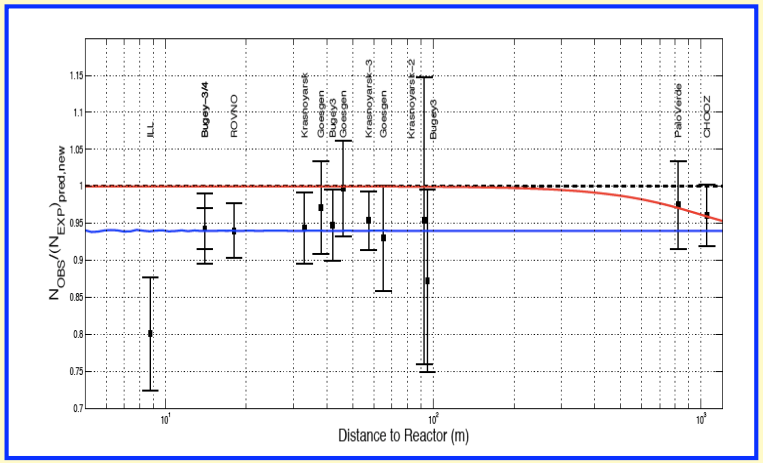
[Giunti, Laveder, et al.]

"Newer" anomalies:



Precision cosmology:
extra radiation
due to sub-eV
sterile neutrino(s)?

[Hamann et al 2010;
←Giusarma et al 2011]



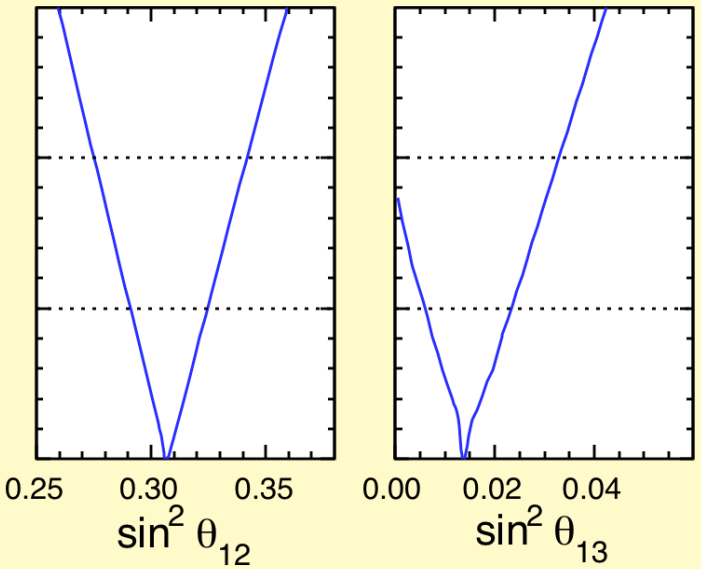
Reactor anomaly:
very SBL ν(e)
disappearance ?

[Parallel talk by Mueller]

Reactor anomaly: prompted by careful re-evaluation of unoscillated reactor fluxes (**+3.5% shift** in normalization.) [Parallel talk by Mueller]

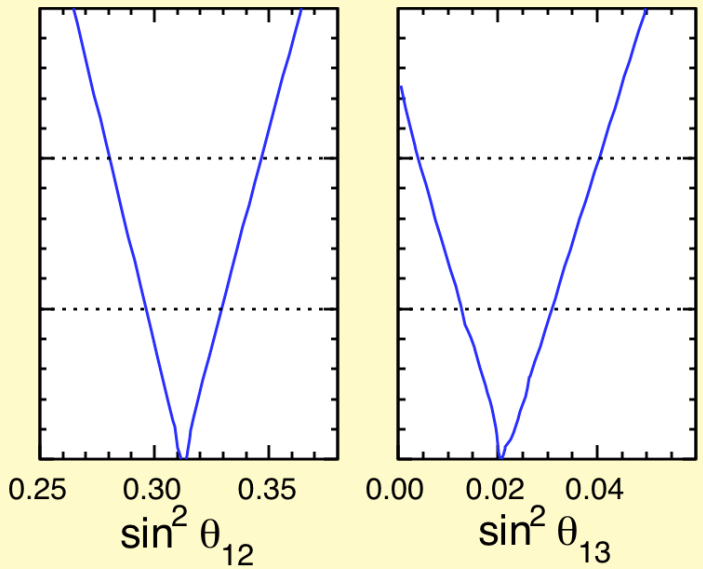
Even **within the 3ν paradigm**, new fluxes allows "extra ν_e disappearance" in CHOOZ and KamLAND reactor expts. → thus slightly larger θ_{12} and θ_{13}
[Other parameters: ~no change.]

We find that both $\sin^2\theta_{12}$ and $\sin^2\theta_{13}$ bounds are shifted by +0.007:



("**old**" fluxes, previous slide #6)

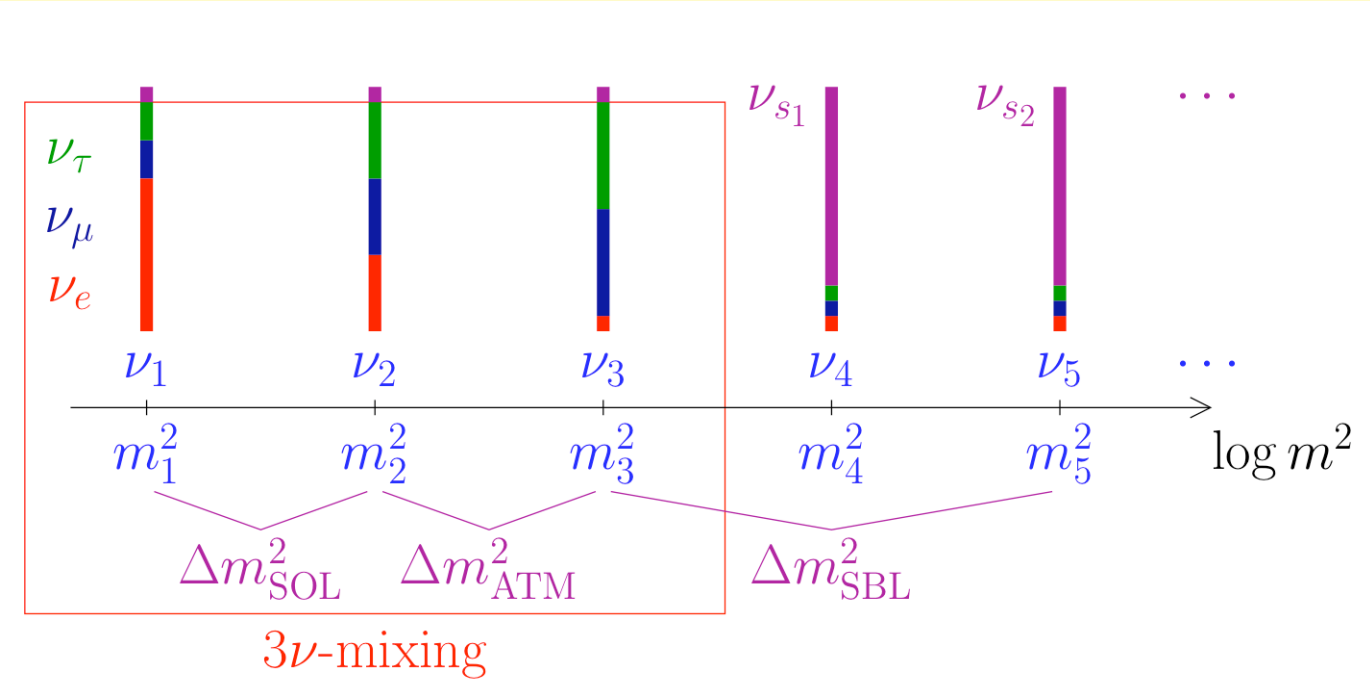
$\sin^2\theta_{13}$~0.014±0.008



("**new**" reactor fluxes)

$\sin^2\theta_{13}$~0.021±0.009

But, assuming sterile neutrino(s), hints for $U_{e3}>0$ disappear, "eaten" by hints for $\mathbf{U_{eJ}>0}$... (J=4,5...)



However, no clear "3+$N_{sterile}$" scenario emerging, due to tension among different sets of data.

Some data may have nothing to do with ν_s ...

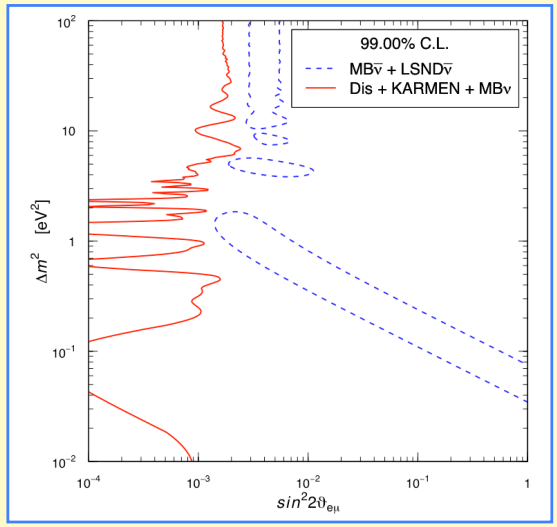
[Figure taken by C. Giunti]

3+1: tension between appear./disappearance data

$\nu(\mu) \rightarrow \nu(e)$: $\sim |U_{\mu 4} \times U_{e4}|$ if mediated by ν_4 (small x small)

Factors constrained by disappearance data. Double suppression too strong to account for LSND/MiniBoone signal. Also, tension between SBL neutrino/antineutrino data (no CP violation.) Basically, 3+1 does not work.

[E.g., Kopp, Maltoni, Schwetz 2011; Giunti and Laveder 2011]

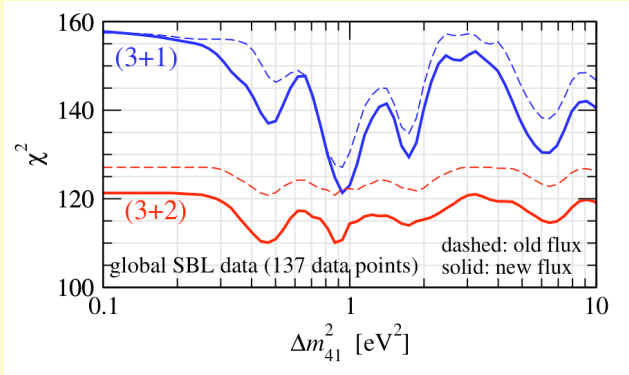


Note: a significant $\nu(e)$ appearance signal in T2K (and MINOS) would instead rescue $\theta_{13}>0$!

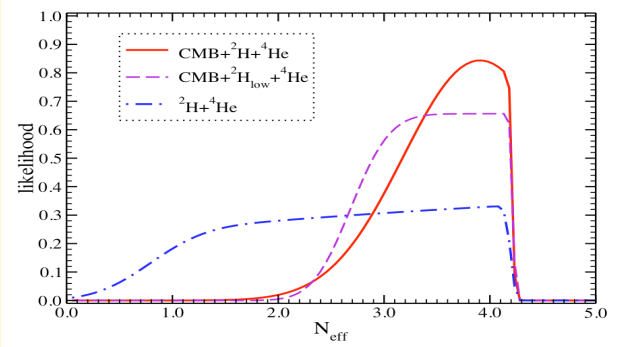
$\nu(\mu) \rightarrow \nu(e)$: $\sim |U_{\mu 3} \times U_{e3}|$ if mediated by ν_3 (large x small)

3+2: tension reduced, but not yet a really good fit…

Global analysis:
CP violation may reconcile to some extent SBL neutrino/antineutrino data; but, still <1% probability to reconcile app/disapp.
[Kopp, Maltoni, Schwetz 2011]



In addition, not obvious that 3+2 can be reconciled with BBN bounds
[Mangano & Serpico 2011]



3+2 best fit, roughly:

$U^2_{e4} \sim U^2_{\mu 4} \sim U^2_{e5} \sim U^2_{\mu 5} \sim 0.02$
not easy to test such small mixings

$\Delta m^2_{51} \sim 0.9\ eV^2 \sim 2\ \Delta m^2_{41}$
not easy to disentangle two new frequencies

Sterile neutrinos would have profound implications.
The situation should be clarified experimentally.
Significant activity worldwide: new ideas, proposals, …

WORKSHOP ON STERILE NEUTRINOS AND THE REACTOR (ANTI-) NEUTRINO ANOMALY
8 February 2011, Garching, Munich, Germany

BEYOND 3NU, Workshop on Beyond Three Family Neutrino Oscillations,
3-4 May 2011, LNGS, Assergi, Italy

SHORT-BASELINE NEUTRINO WORKSHOP,
12-14 May 2011, Fermilab, Batavia, Illinois, USA

SNAC 2011, Sterile Neutrinos at the Crossroads,
26-28 September 2011, Virginia Tech, Blacksburg, VA, USA

Some short-term prospects:

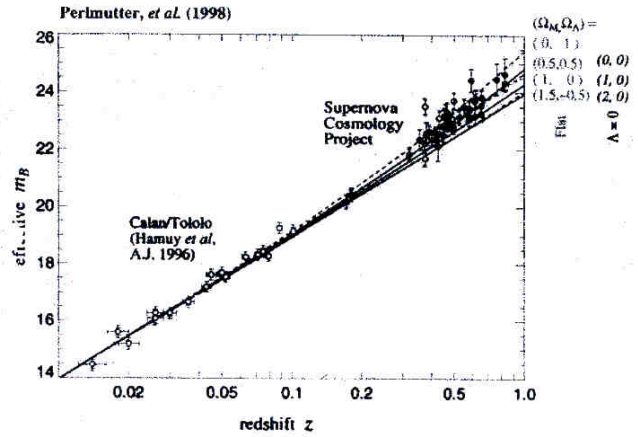
New MiniBoone data expected this year…
New (very) SBL experiment proposals in US, Europe…
Neutrino counting from cosmology (Planck next year?)…
…

Once more, a slide from Blois 1999…

COSMOLOGY

$\Lambda \neq 0$?

Silk



In flat universe: $\Omega_M = 0.28$ [± 0.085 statistical] [± 0.05 systematic]

Prob. of fit to $\Lambda = 0$ universe 1%

exciting but should be cautious :

- 20% effet in magnitude (dimming)
- could it be a systematic effect ?
  - SN Ia model
  - dust in the way

M. Davier: Summary talk at Blois 1999 (quoting talk by J. Silk)

Lesson: ~2σ hints may grow - be open to the unexpected !

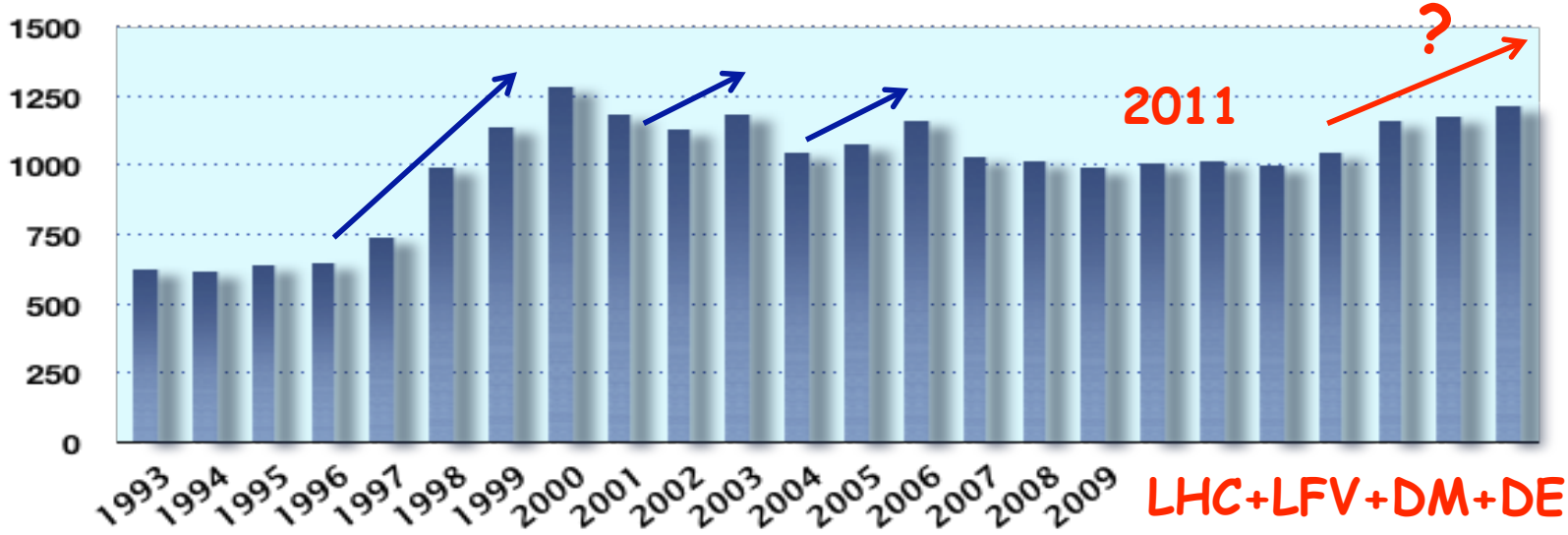
Epilogue – 3ν still the reference framework in global analyses, but…

?

ν_3

ν_2

ν_1



Blois 20XX…