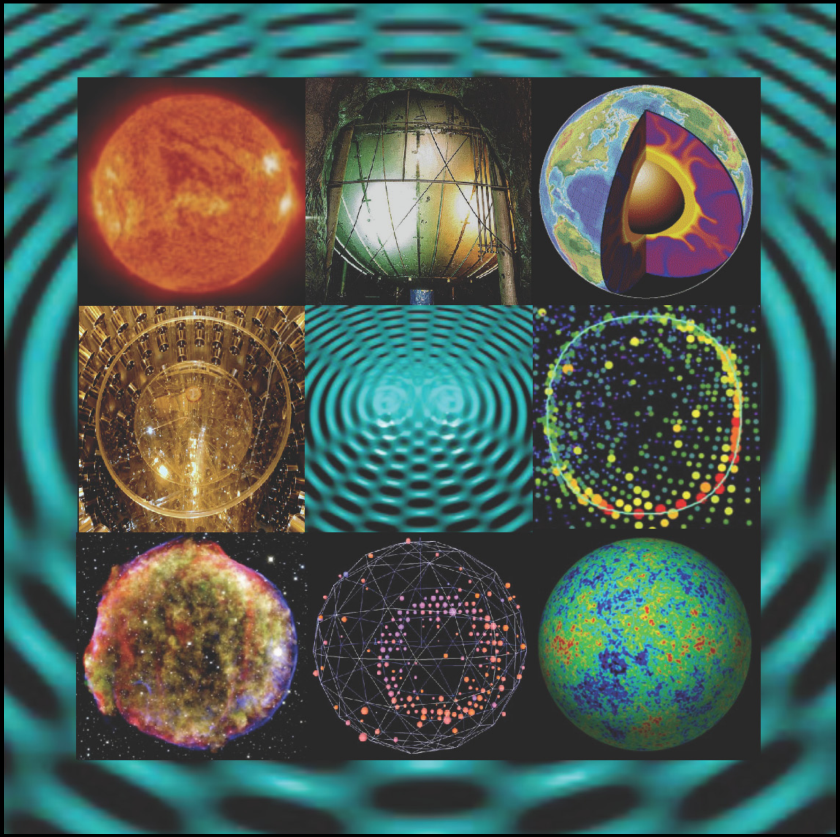
NEUTEL 2013, Venice

The ν_e as a superposition of states



Eligio Lisi, INFN, Bari, Italy

Introduction: Praising ν_e

The (anti)ν_e plays a prominent role in ν physics,
being the partner of the **lightest** (=stable) **charged lepton.**

→ "easily" produced and absorbed in a variety of processes
→ can be used to probe different kinematical regimes:

ultrarelativistic	$E \sim p + m^2/2p$ → Δm^2
non-relativistic	$E \sim m + p^2/2m$ → m
chirality flips	$O(m/p)$ → Dirac/Majorana

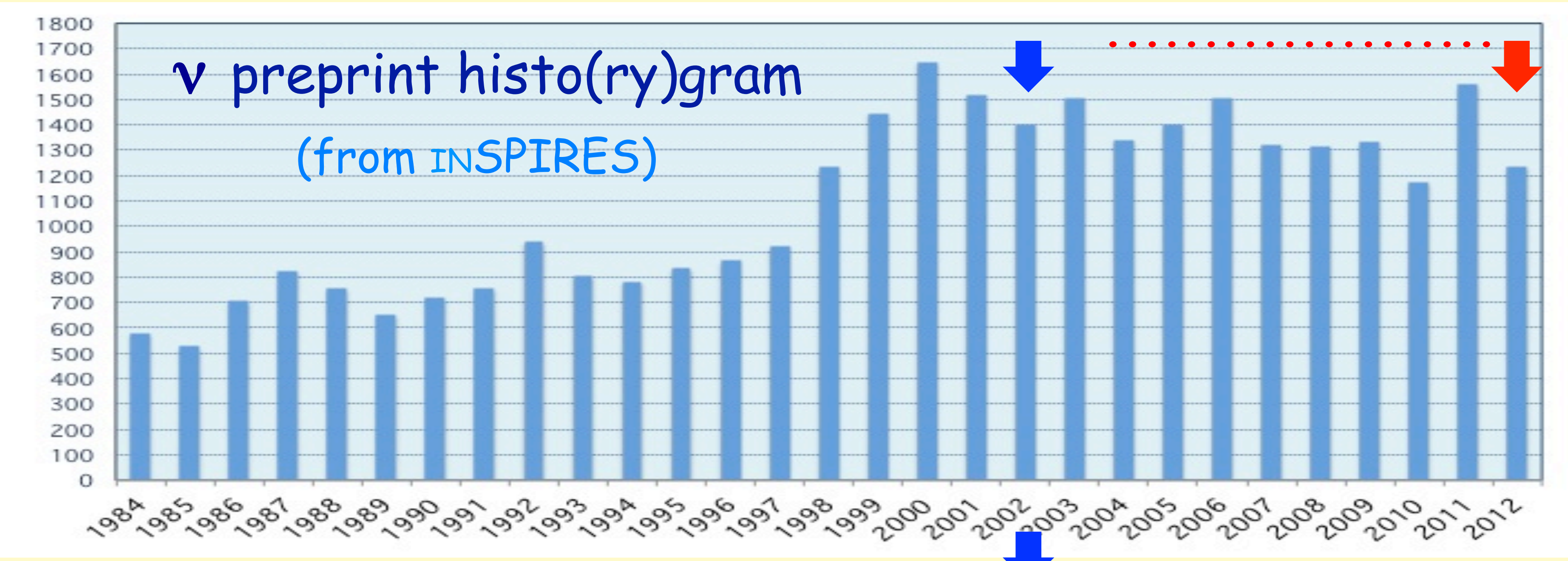
→ dynamically feels background e^-
with number density N_e : $O(G_F N_e E/\Delta m^2)$ → MSW

And, coming from a distant SN in 1987, triggered this Workshop series and "un altro modo di guardare il cielo…"

In just one decade, we have learned that the ν_e is a superposition of (at least) three massive states...

2002: Annus Mirabilis ...

...2012: Decennium Mirabilis !



$$\nu_e = U_{e1}\,\nu_1 + U_{e2}\,\nu_2$$

$$\nu_e = U_{e1}\,\nu_1 + U_{e2}\,\nu_2 + U_{e3}\,\nu_3$$

... the superposition coefficients being
(to the best of our current knowledge, see later):

$$\nu_e \sim 0.82\ \nu_1 + 0.55\ \nu_2 - 0.16\ \nu_3$$

... with energy level splittings proportional to:

$$\delta m^2 = m_2^2 - m_1^2 \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2 = |m_3^2 - m_{1,2}^2| \sim 2.4 \times 10^{-3}\ \mathrm{eV}^2$$

I'll review the status of these and related parameters,
with emphasis on what we can learn from ν_e only,
even by turning history upside down...

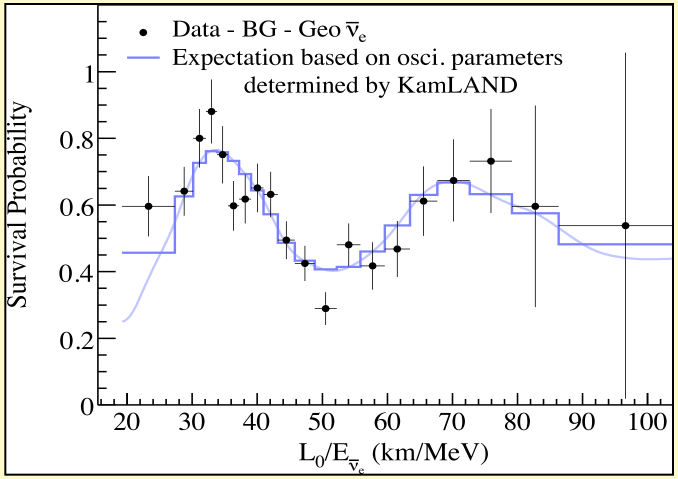
Learning from ν_e only...

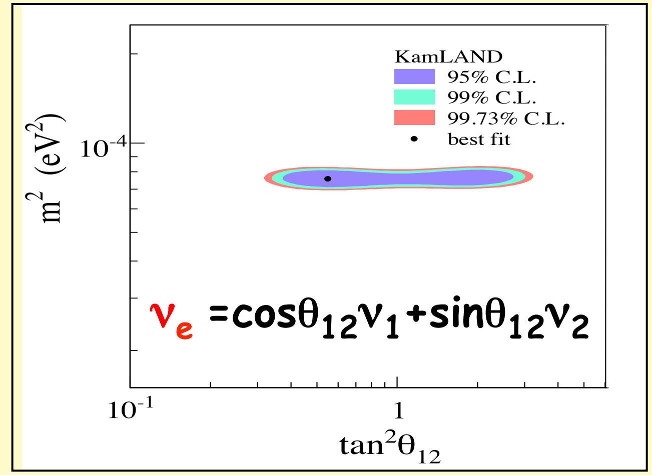
...in another universe, where expt's follow the path

KamLAND → Solar → CHOOZ → DYB, RENO, DC ...

and a galactic SN explodes, on a lucky day...

Had we started with LBL reactor $\nu_e \rightarrow \nu_e$ (KamLAND)...

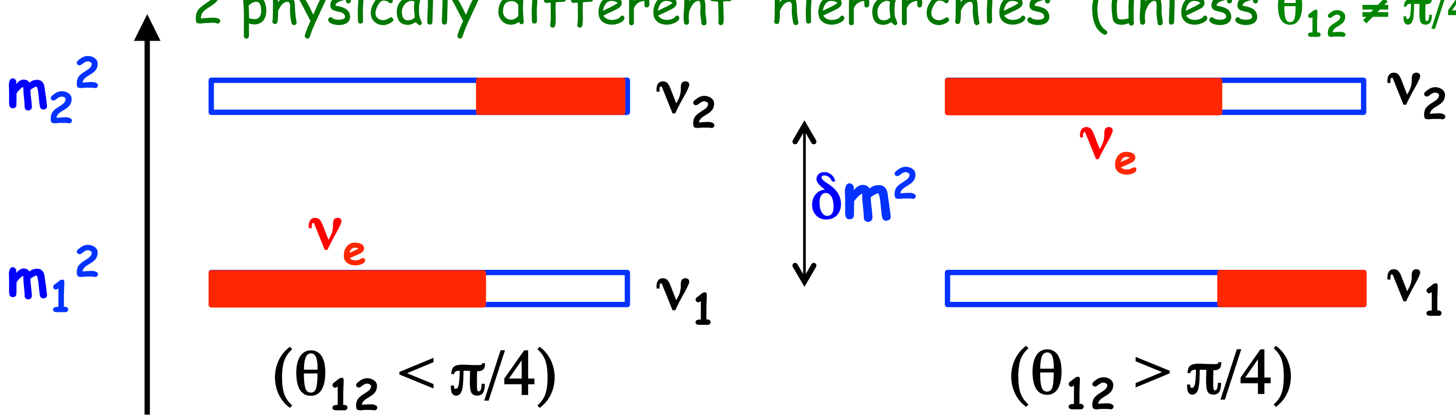




well-defined **frequency** → accurate $\delta m^2 = m_2^2 - m_1^2$

~nonmaximal **amplitude** → best fit at $\theta_{12} \neq \pi/4$

2 physically different "hierarchies" (unless $\theta_{12} \neq \pi/4$):

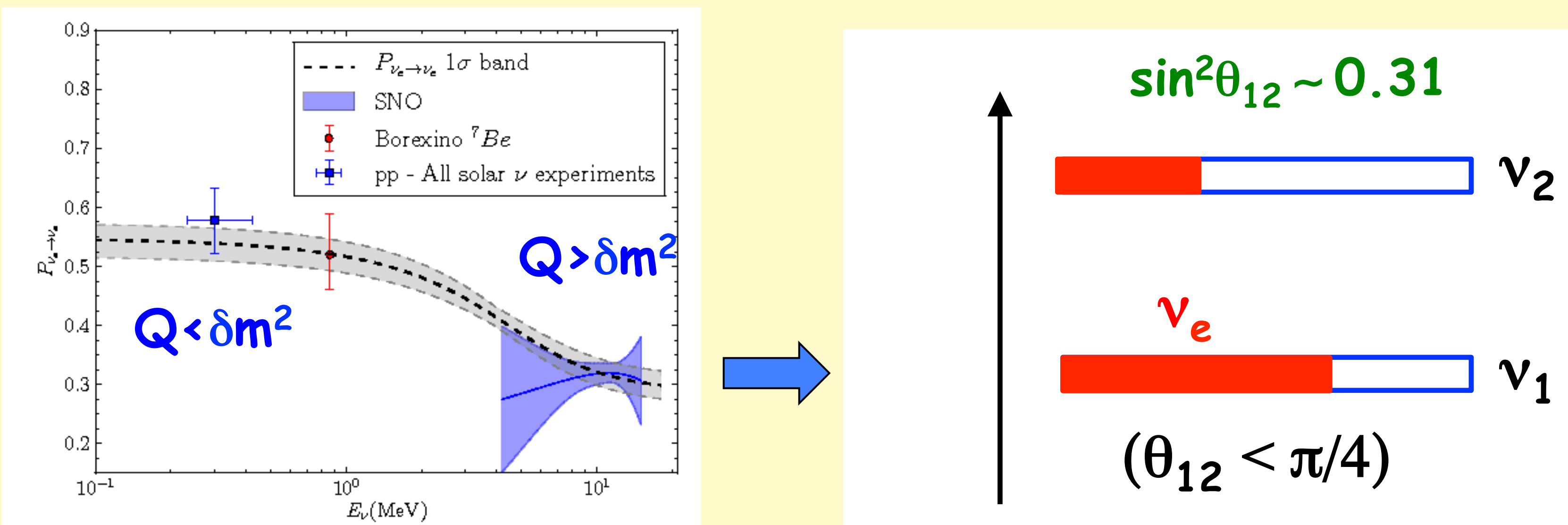


Solar $\nu_e \rightarrow \nu_e$ would offer the only chance (MSW)...

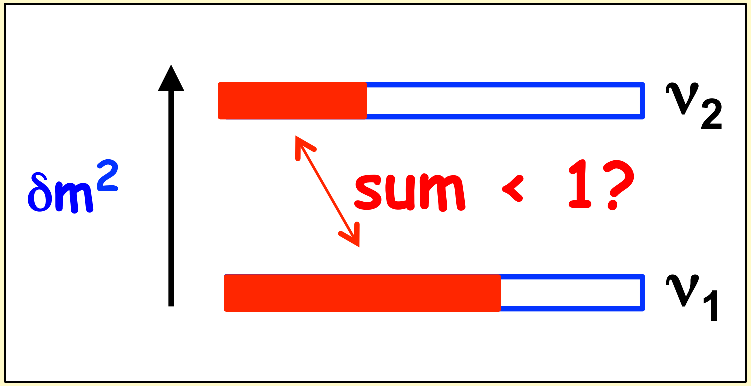
To solve hierarchy (octant) ambiguity, need to beat (ν_1, ν_2) oscillations with some Q-driven oscillations with known **sign(Q)** and at similar scale $Q \sim O(\delta m^2)$.

Only one Q with known sign: $Q = 2\sqrt{2}\, G_F N_e E$ (matter)

Nature kind enough to set: $Q \sim O(\delta m^2)$ in the Sun...



Next: check ν_e unitarity at δm^2 scale...



Assume ν_e "leakage" onto a state ν_3, with splitting Δm^2 high enough to be unresolved in solar+KamLAND, $\Delta m^2 \gg \delta m^2$

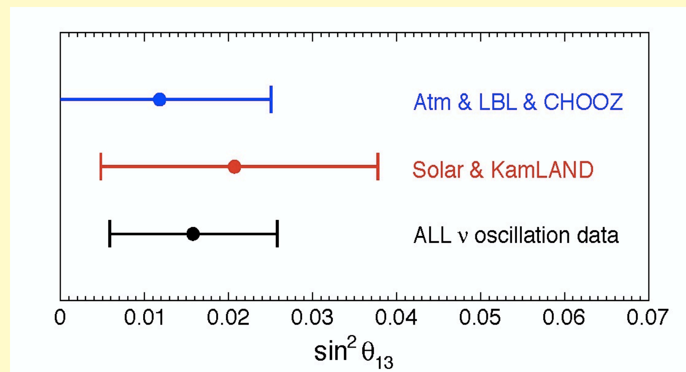
$$\nu_e = \cos\theta_{13} \, (\cos\theta_{12} \, \nu_1 + \sin\theta_{12} \, \nu_2) + e^{-i\delta} \sin\theta_{13} \, \nu_3$$

(but: *CP* phase δ not observable in disappearance)

Hints of ν_e leakage to ν_3 emerge already from solar+KamLAND...

...with $\sin^2\theta_{13} \sim O(10^{-2})$

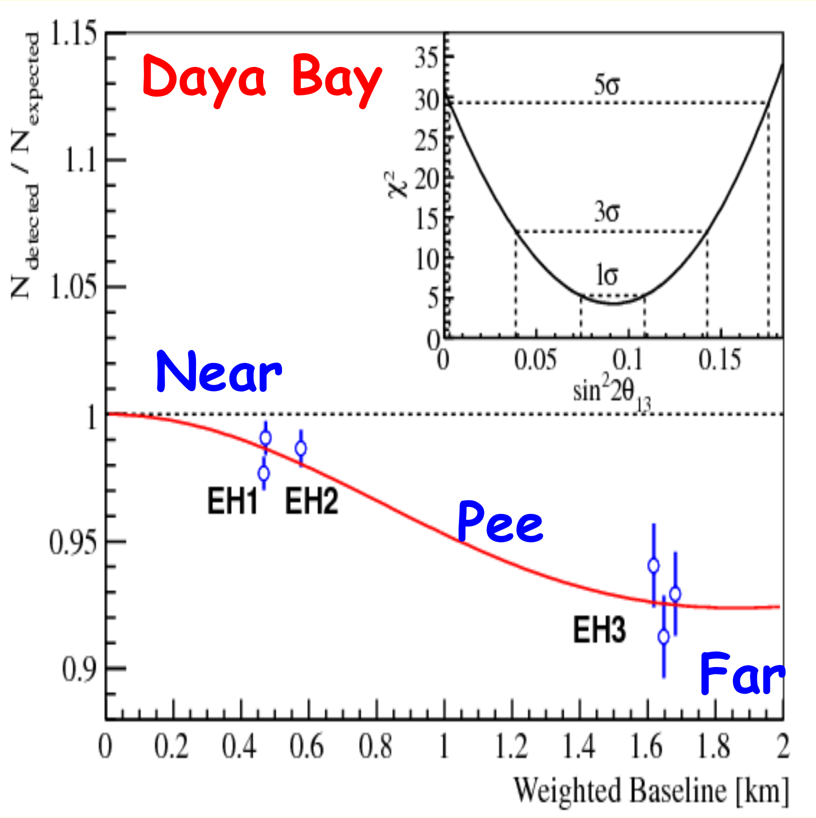
(talk by GL Fogli at NO-VE 2008)

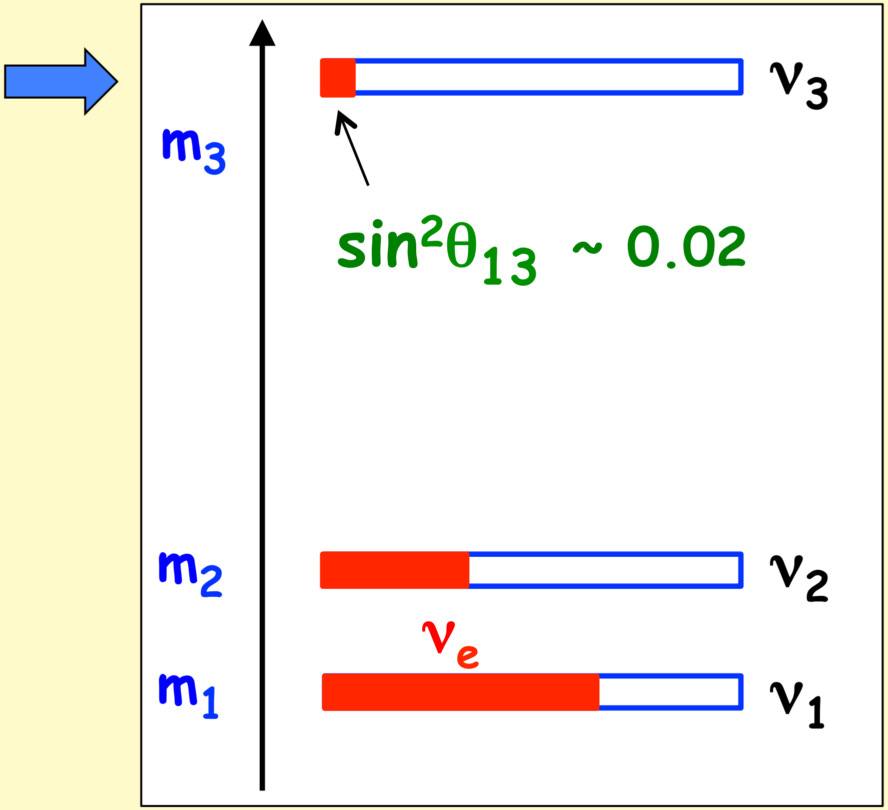


Then... move to SBL reactors to access high Δm^2 scale

1st attempt gets really close ... but not quite (CHOOZ).

2nd attempt gets right there, by far/near improvement!

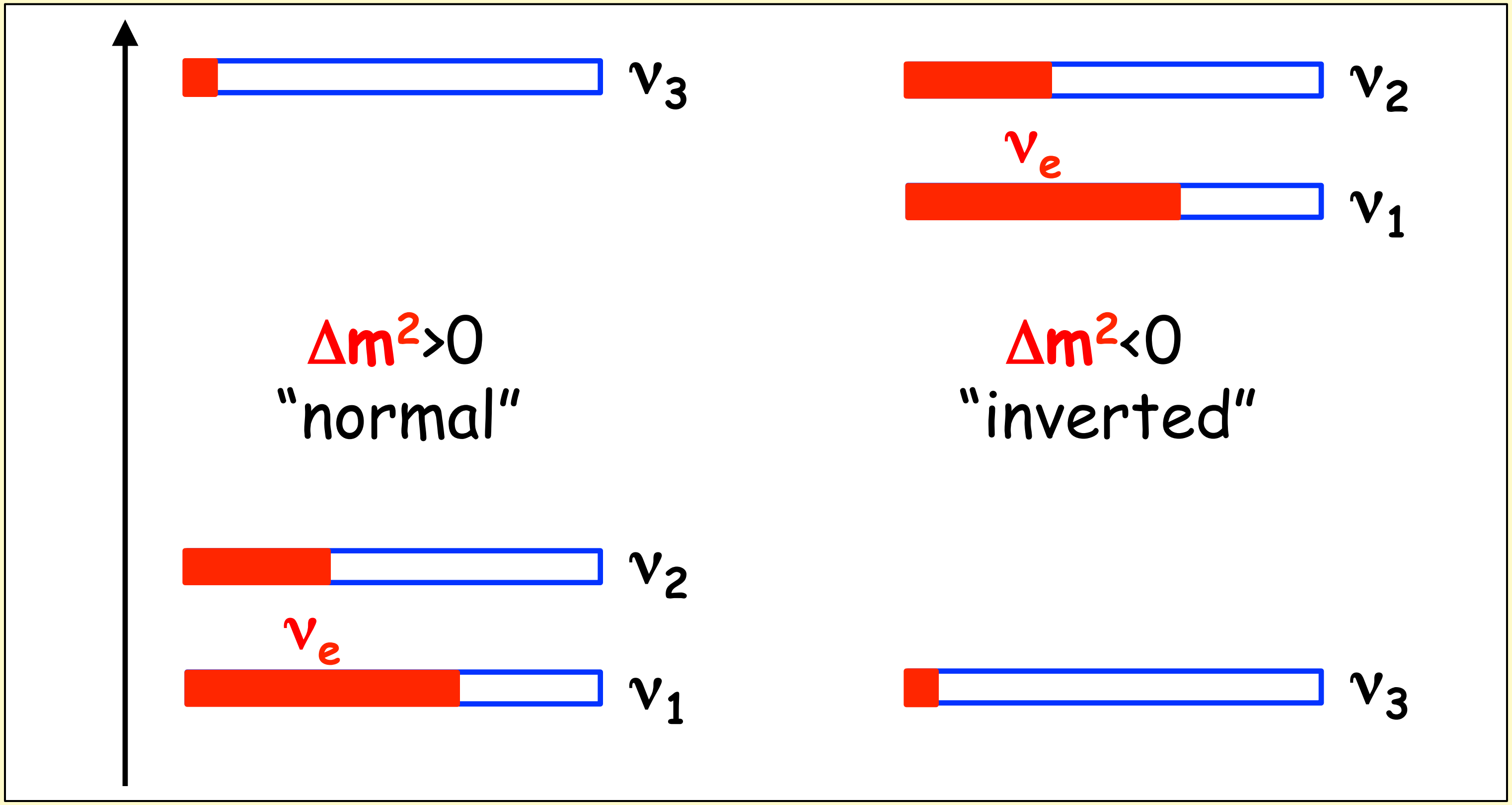




+ RENO

+ Double Chooz (Bugey=near)

Stumble upon a new hierarchy problem ...



Now may solve it with **two** Q-driven $\nu_e \rightarrow \nu_e$ oscillations:

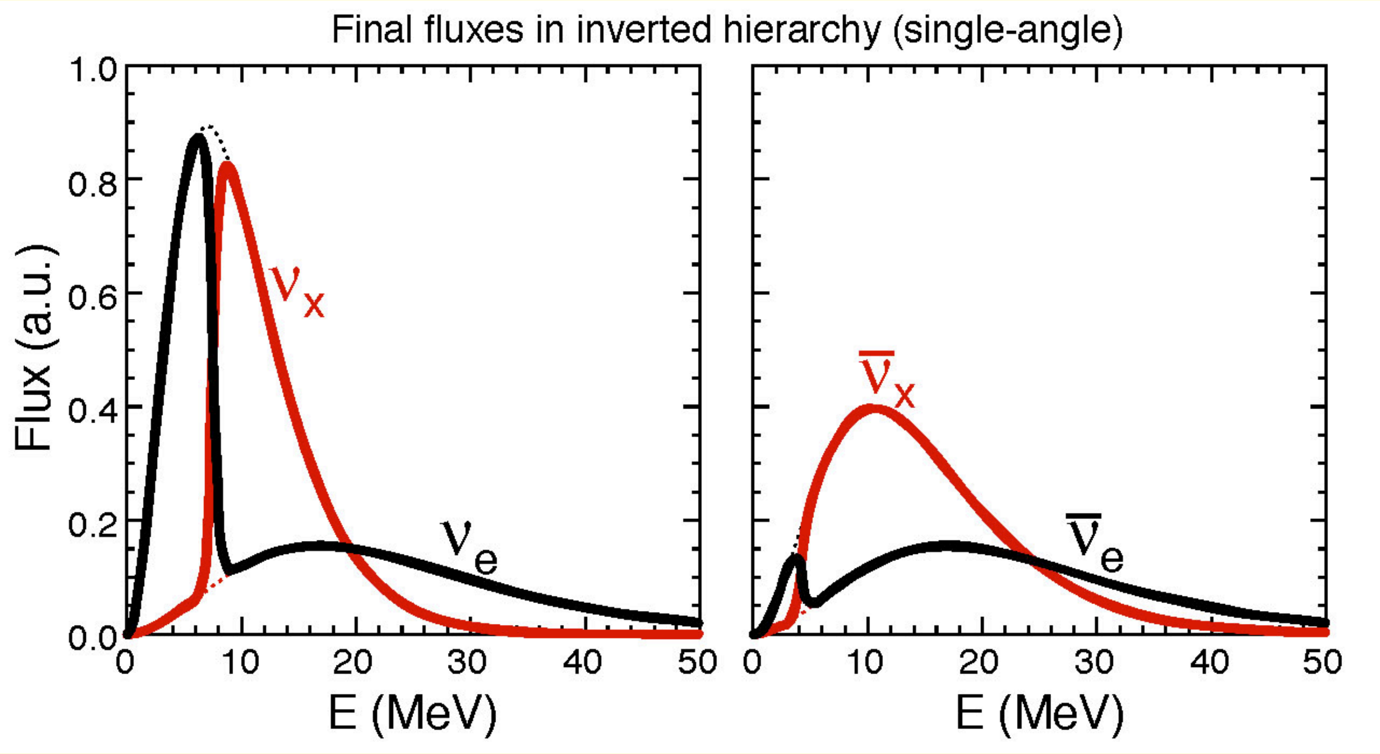
$Q = 2\sqrt{2}\, G_F N_e E \sim O(\Delta m^2)$ at high N_e (core-collapse SN)

$Q = \delta m^2$ in medium-baseline reactors: DYBII, RENO-50

There may even be a third, intriguing possibility:

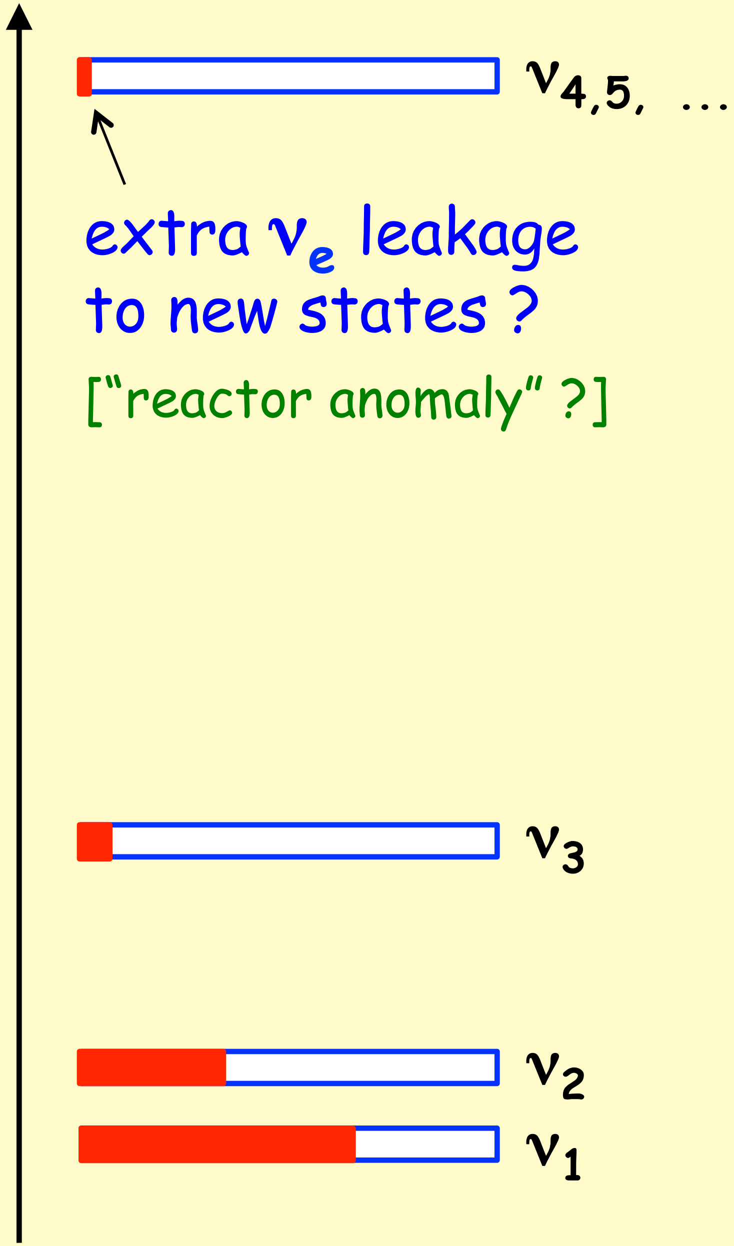
$Q = 2\sqrt{2}\, G_F N_\nu E \sim O(\Delta m^2)$ in core-collapse SNe

(neutrino nonlinear evolution in a neutrino background)



Many studies on collective effects and "spectral split" signatures in I.H.; but effects & observable features seem to be fragile in the dense, turbulent SN core.

Pattern repeats itself with more (sterile) neutrinos?



Decrease L to access higher ΔM^2 scales ... (very SBL reactors, radioactive sources)

If ν_e leakage to ν_4 found, new hierarchy problem:

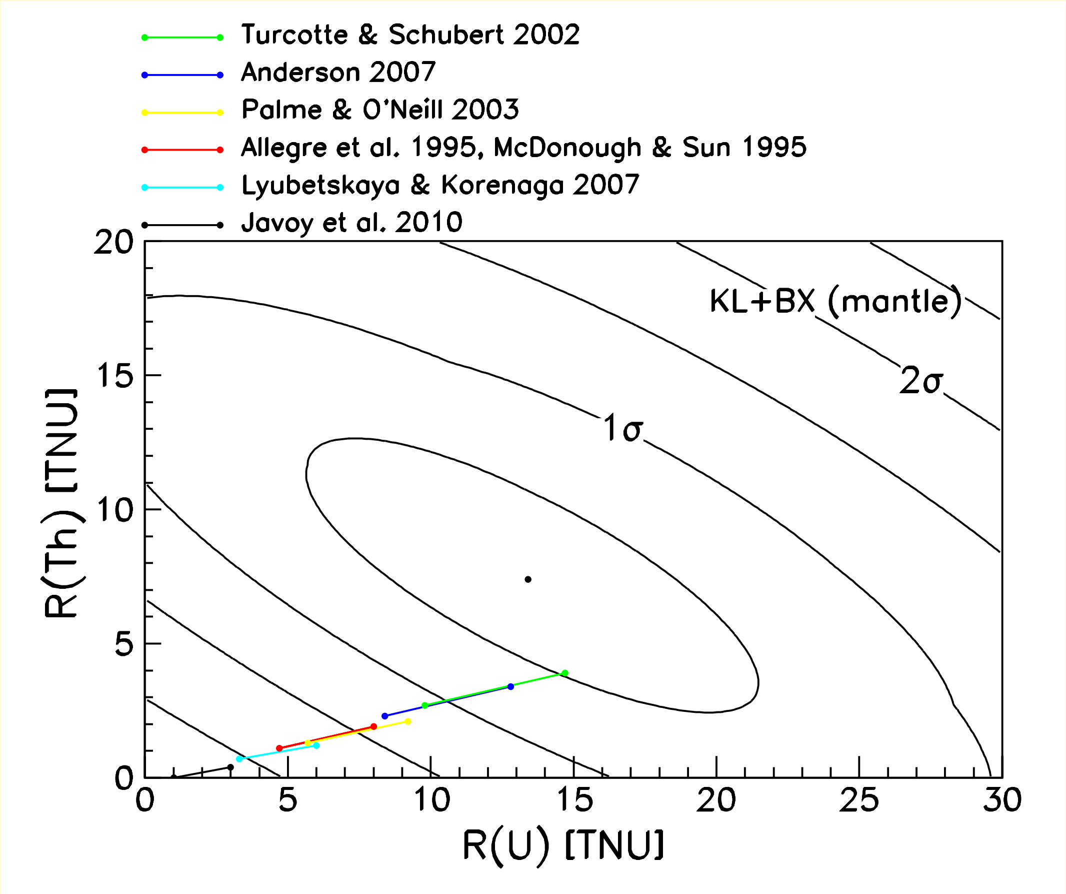
sign(ΔM^2); try with:

$$Q = 2\sqrt{2}\, G_F N_e E$$
$$Q = \delta m^2$$
$$Q = \Delta m^2$$
....

$\nu_{4,5,\ldots}$: not discussed herein, see talks tomorrow morning

Interesting by-product of $\nu_e \rightarrow \nu_e$ oscillation searches...

Geoneutrinos. E.g., hint of mantle flux at ~2.4σ from 2012 analysis of Borexino + KamLAND:



Fiorentini, Fogli, EL, Mantovani, Rotunno, arXiv:1204.1923

Learning from $\nu_{e,\mu}$

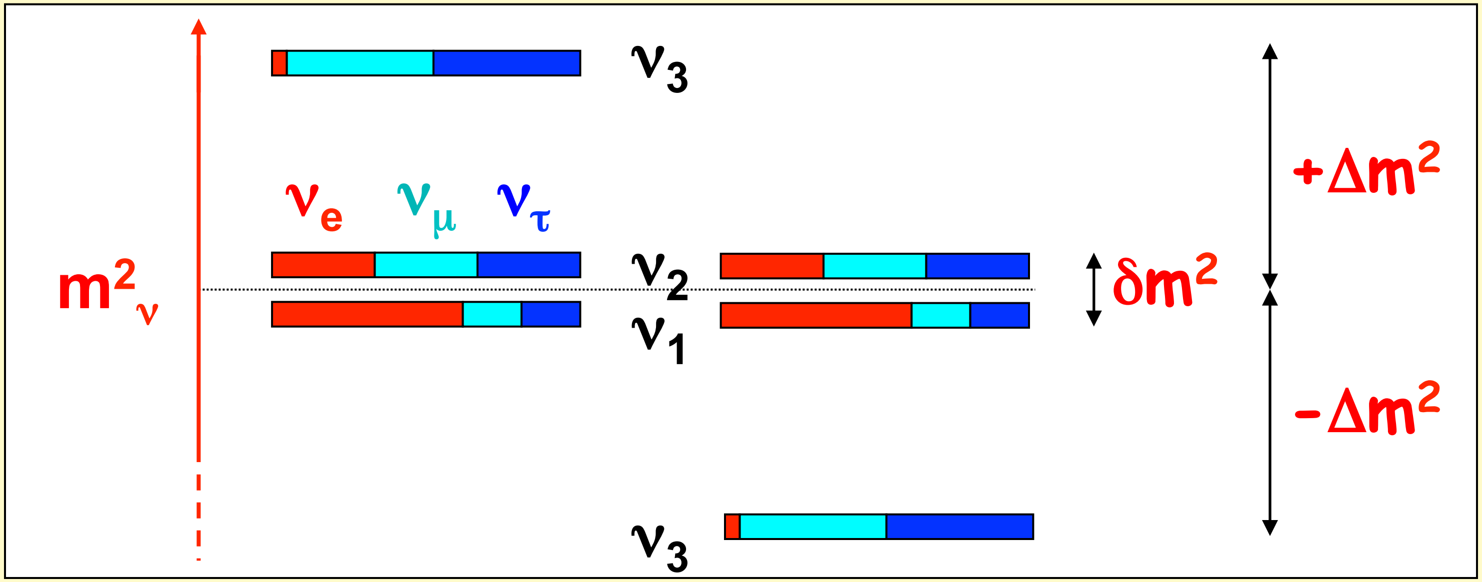
... in our universe, now

With $\nu_e \rightarrow \nu_e$ only, cannot probe:

- Complex coefficients (i.e., CP-violating phase δ)

$$\nu_e = \cos\theta_{13} (\cos\theta_{12}\, \nu_1 + \sin\theta_{12}\, \nu_2) + e^{-i\delta} \sin\theta_{13}\, \nu_3$$

- Distribution of ν_μ (and ν_τ) flavors (i.e., angle θ_{23})



Need $\nu_\mu \rightarrow \nu_{e,\mu,\tau}$, which also add constraints to previous parameters probed by $\nu_e \rightarrow \nu_e$.

Global neutrino data analyses can highlight the interplay between different ν_e, ν_μ oscill. channels.

Still, purely $\nu_e \rightarrow \nu_e$ data remain outstanding from a methodological viewpoint:

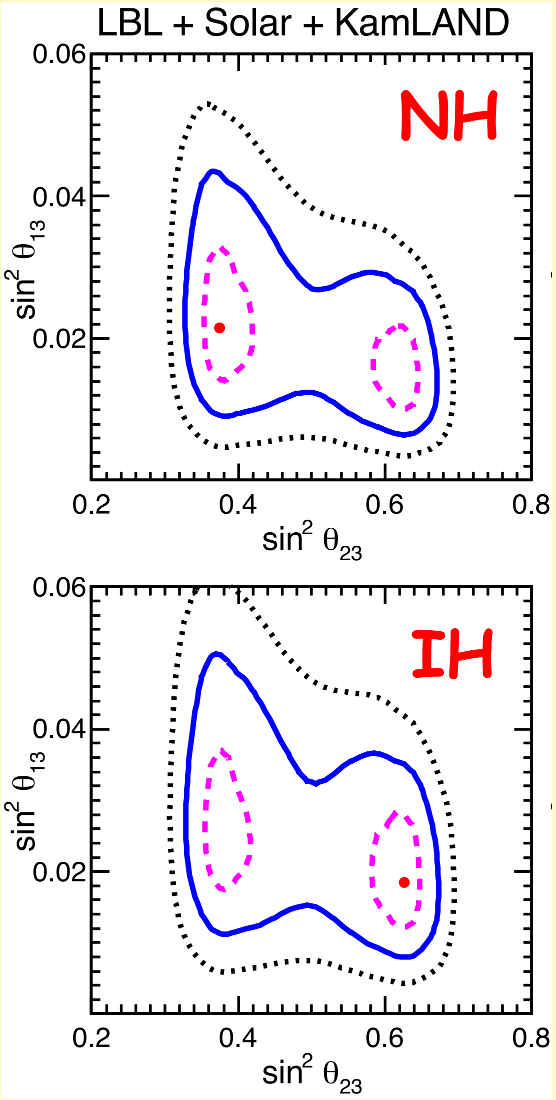
solar+KamLAND data give the (δm^2, θ_{12}) input for subleading oscillations in Δm^2-sensitive data: LBL accel. (MINOS+T2K), SBL reac., atmos.(SK).

SBL reactor data provide clean (δ-independent) constraints on θ_{13} at the Δm^2 scale

Progressive constraints (ν 2012 data), arXiv:1205.5254 →

(LBL+solar+KL)... +(SBL reactor)... +(atmospheric)

$(\sin^2\theta_{13}, \sin^2\theta_{23})$ from LBL app. + disapp. data plus solar + KamLAND data:



[1,2,3σ contours for 1 dof]

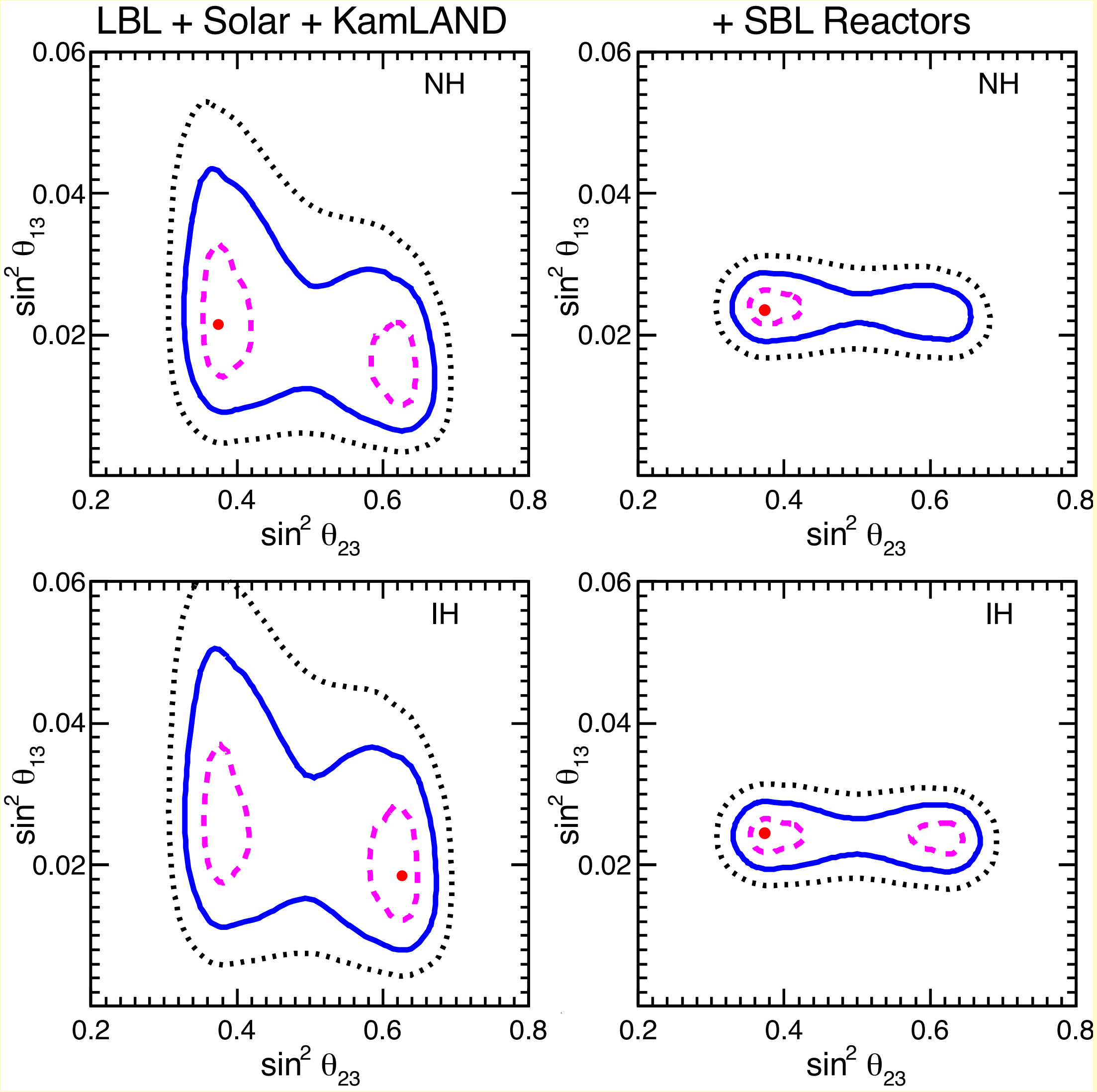
2012 LBL disappearance data from MINOS (+ T2K) favor nonmaximal θ_{23}
→ θ_{23} octant degeneracy

Since LBL appearance ~ $\sin^2\theta_{23}\sin^2(2\theta_{13})$,
θ_{23} values anticorrelated with θ_{13}
(slightly above and below $\sin^2\theta_{13} \sim 0.02$).
The two octants merge above ~1σ.

Solar+KL data happen to prefer just $\sin^2\theta_{13} \sim 0.02$ → unable to lift degeneracy.
The two minima differ by only ~0.3σ.

Differences between NH and IH: « 1σ.

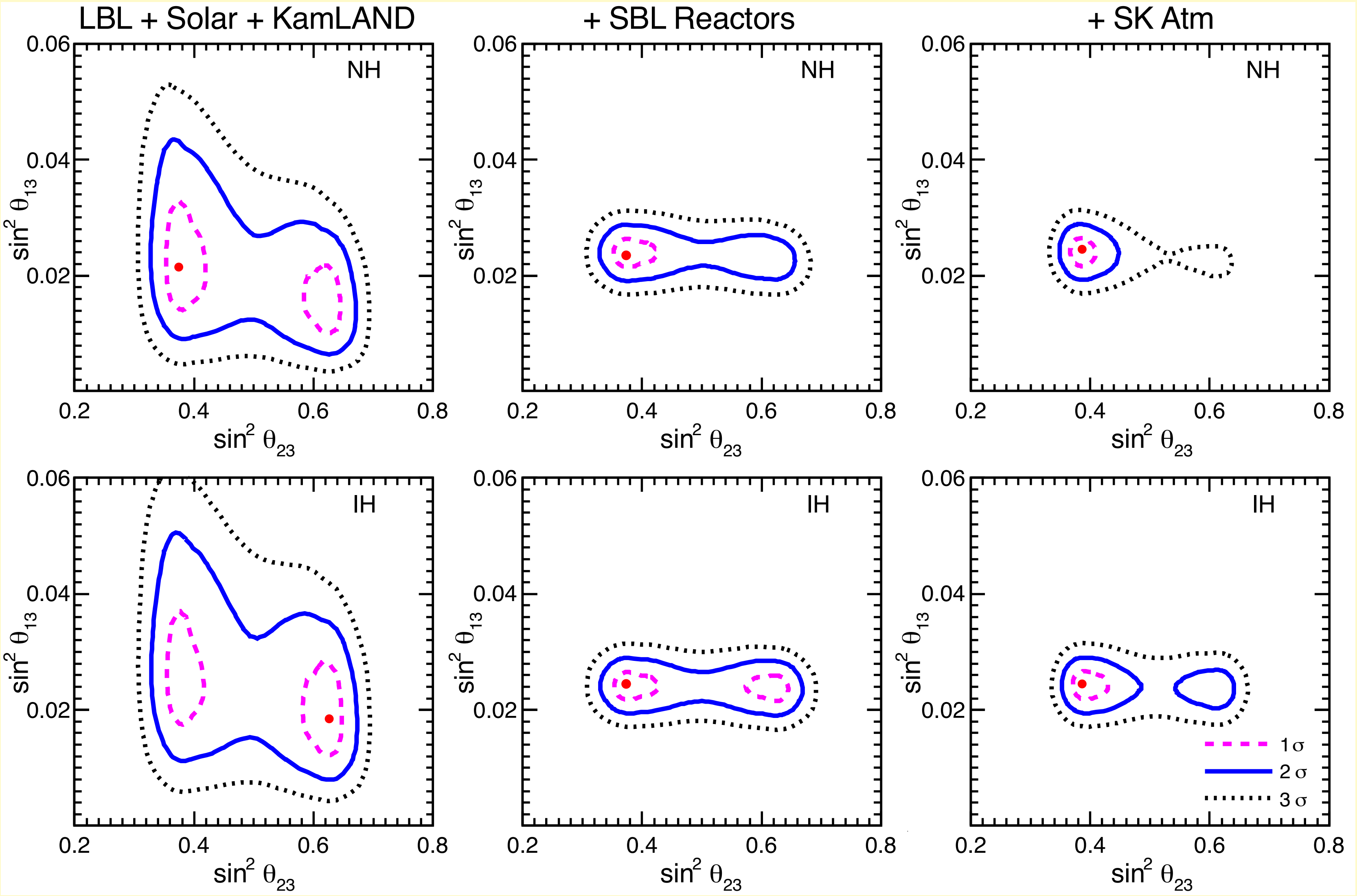
Adding ν2012 SBL reactor constraints (Daya Bay, RENO, Double Chooz):



Some preference emerges for the 1^{st} octant solution at higher θ_{13} and lower θ_{23}, especially in NH.

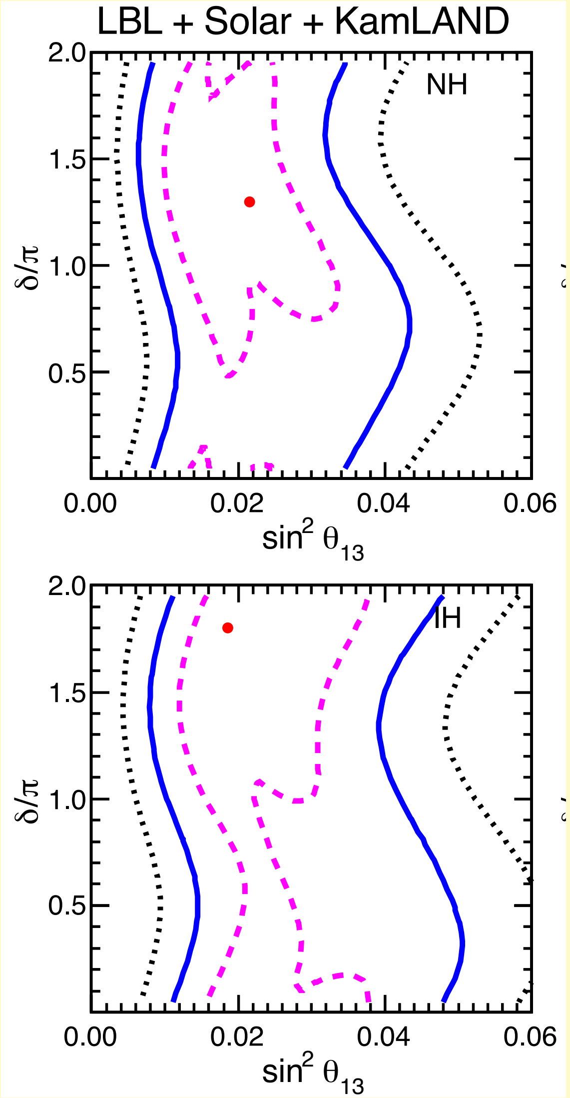
(Should future SBL reactor data prefer lower θ_{13} values, the preference might flip to the 2^{nd} octant)

Adding 2012 SK atmospheric neutrino data:



Further hints for θ_{23} in 1st octant. Yet, no significant hierarchy discrimination.

CP phase: ($\sin^2\theta_{13}$, δ) from LBL app. + disapp. data plus solar + KamLAND data:

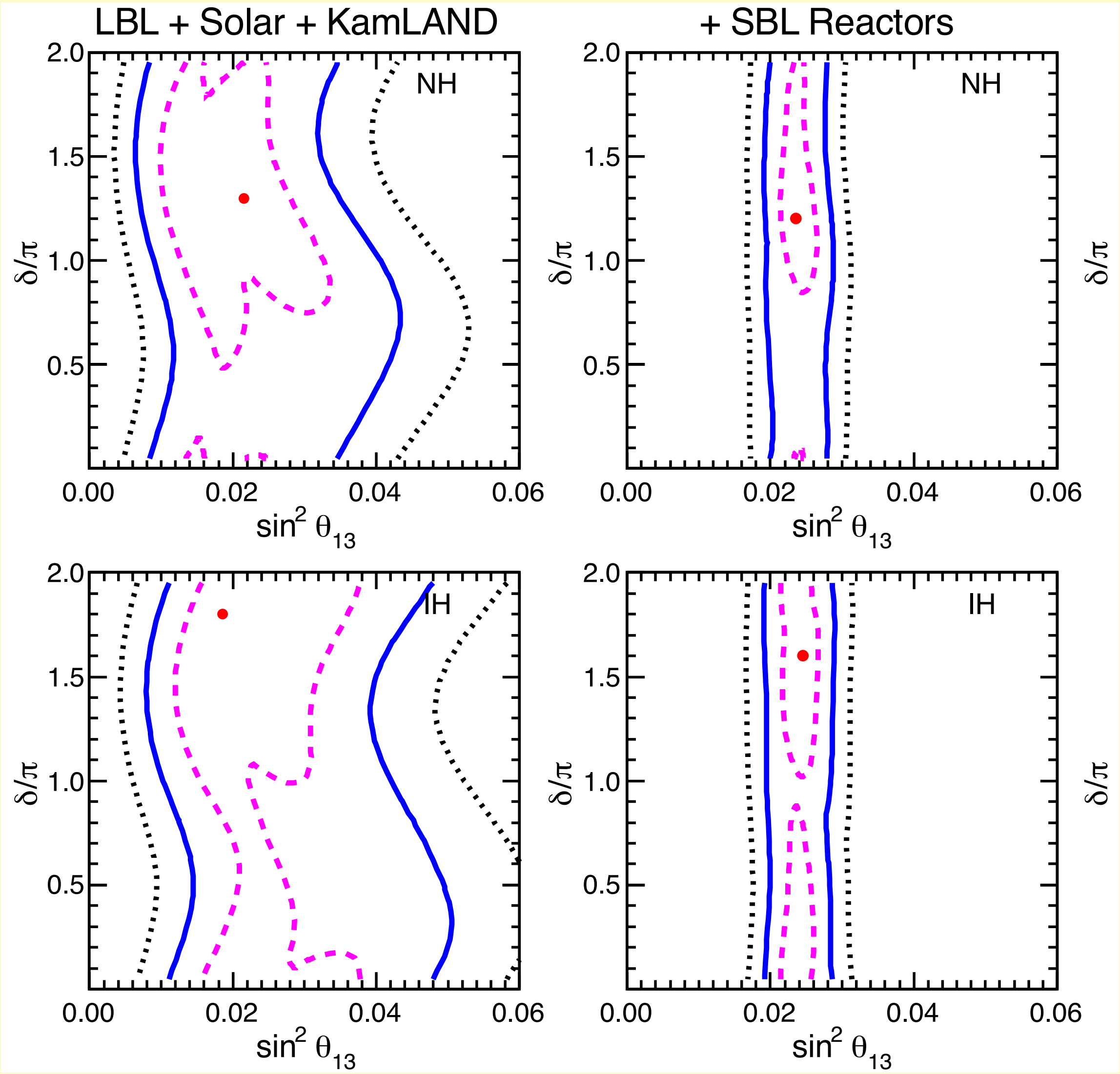


δ is basically unconstrained at $\sim 1\sigma$.

Fuzzy 1σ contours are a side effect of θ_{23} degeneracy: the two θ_{23} minima correspond to slightly different θ_{13} ranges, and thus lead to two slightly overlapping "wavy bands" in the plot. Minima flip easily from one band to the other.

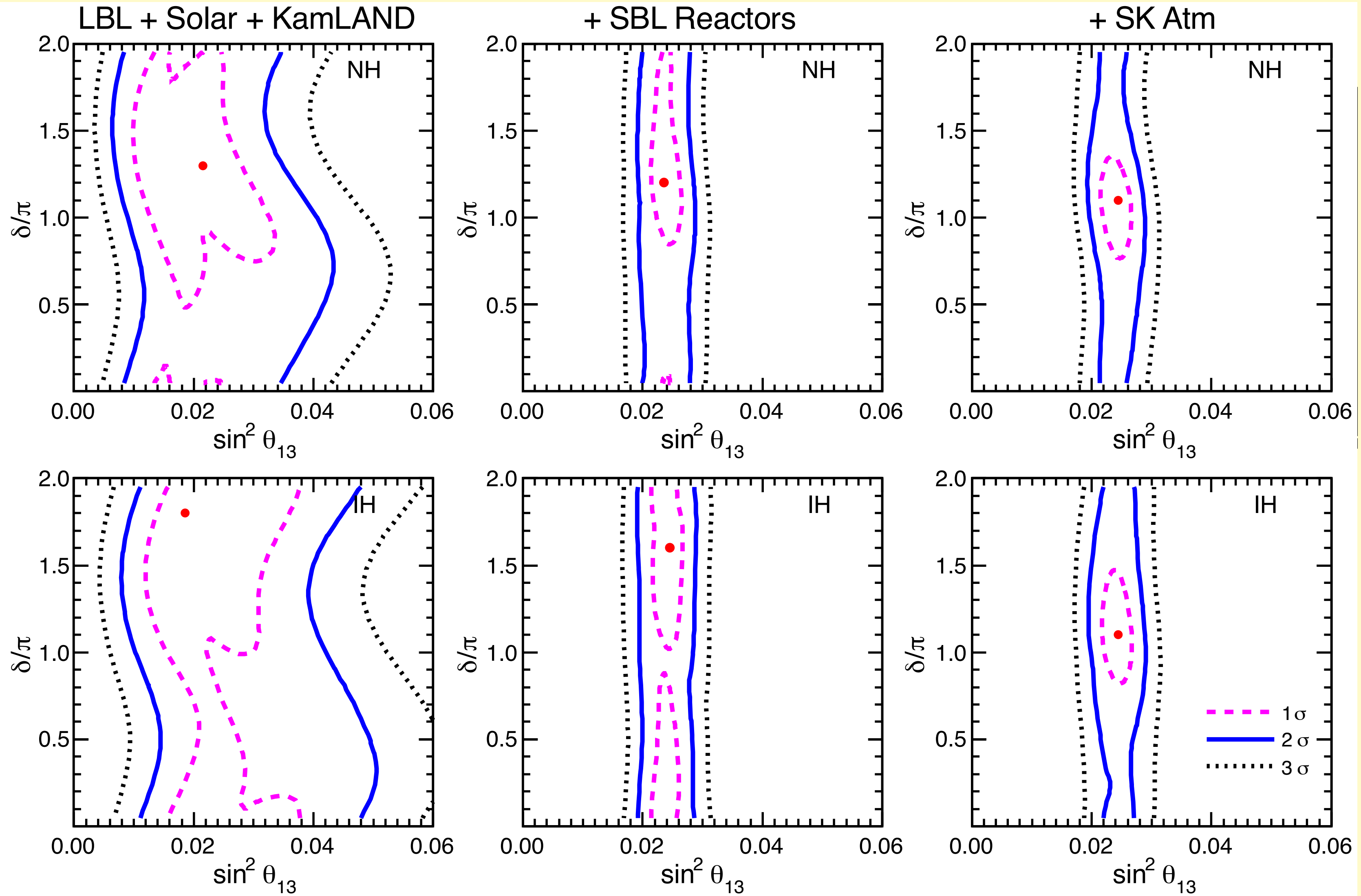
Fuzziness disappears at higher CL, but just because larger bands overlap more.

Adding 2012 SBL reactor constraints (Daya Bay, RENO, Double Chooz):



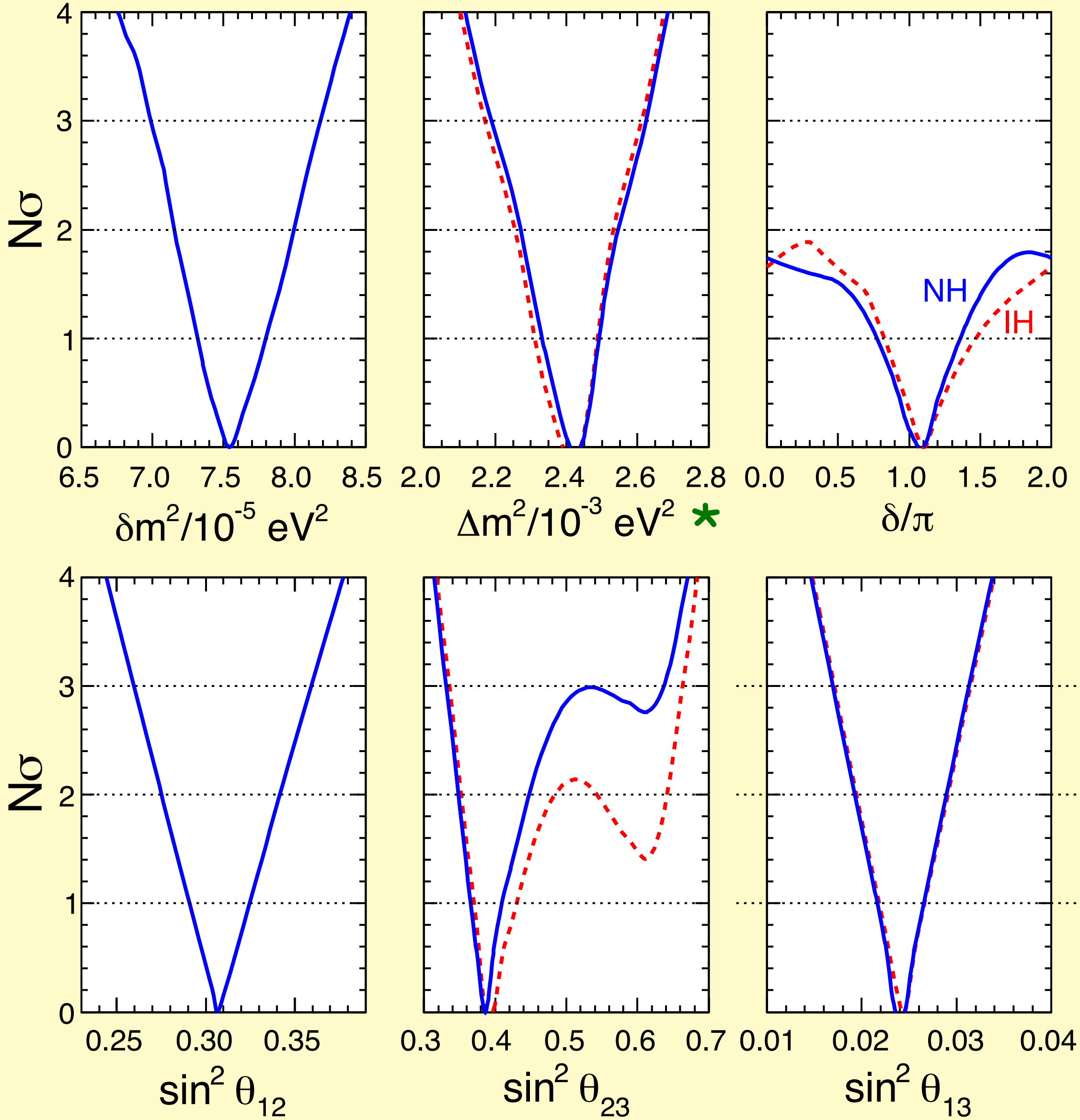
SBL reactor data squeeze θ_{13} range & reduce degeneracy effects on the nσ contours.

Adding 2012 SK atmospheric neutrino data:



We find a preference for $\delta \sim \pi$ (helps fitting sub-GeV e-like excess in SK)

Synopsis of global 3ν oscillation analysis



The 2008 hints of $\theta_{13} > 0$ are now **measurements**! (and basically independent of absolute reactor fluxes)

Some hints of $\theta_{23} < \pi/4$ are emerging at $\sim 2\sigma$, worth exploring by means of atm. and LBL+reac. data

A (weaker) hint of $\delta_{CP} \sim \pi$ emerging from atm. data: real PMNS matrix with $\exp(-i\delta) \sim -1$?

So far, no hints for NH ⟷ IH

(*) $\Delta m^2 = \frac{1}{2}(\Delta m^2_{31} + \Delta m^2_{32})$

Numerical 1σ, 2σ, 3σ ranges:

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH.

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67	1.94 – 2.91	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10	3.48 – 4.48	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31	3.53 – 4.84 ⊕ 5.43 – 6.41	3.35 – 6.63
δ/π (NH)	1.08	0.77 – 1.36	—	—
δ/π (IH)	1.09	0.83 – 1.47	—	—

Fractional 1σ accuracy [defined as 1/6 of ±3σ range]

δm^2	Δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
2.6%	3.0%	5.4%	10%	14%

$$\nu_e = \cos\theta_{13}\,(\cos\theta_{12}\,\nu_1 + \sin\theta_{12}\,\nu_2) + e^{-i\delta}\sin\theta_{13}\,\nu_3$$

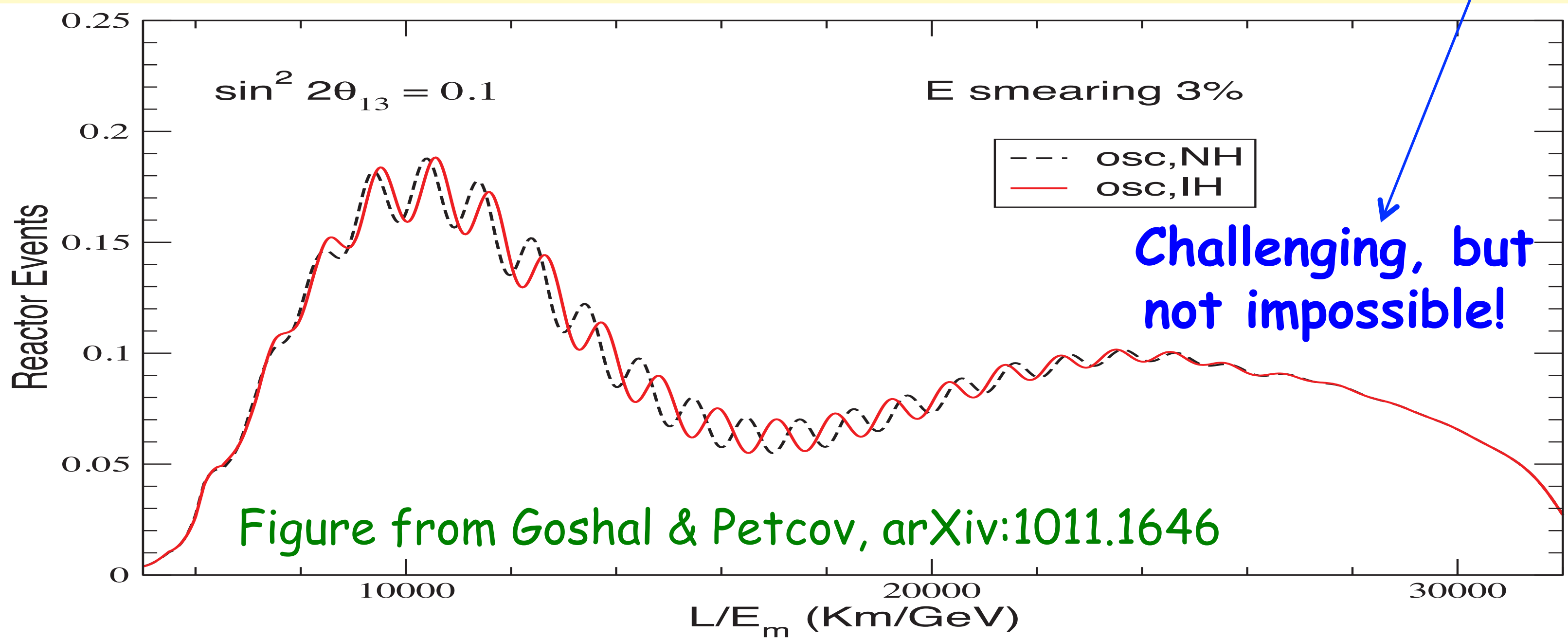
$$\sim 0.82\,\nu_1 + 0.55\,\nu_2 - 0.16\,\nu_3 \quad \text{(rounded best fit)}$$

Fractional 1σ accuracy [defined as 1/6 of $\pm3\sigma$ range]

δm^2	Δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
2.6%	3.0%	5.4%	10%	14%

Future: 4 param. + hierarchy can be probed in a single reactor exp. at L~50km, with **x5** accuracy gain (except θ_{13}): **DYBII, RENO-50**

→ Ultimate oscill. probe of ν_e as a superposition of states ?



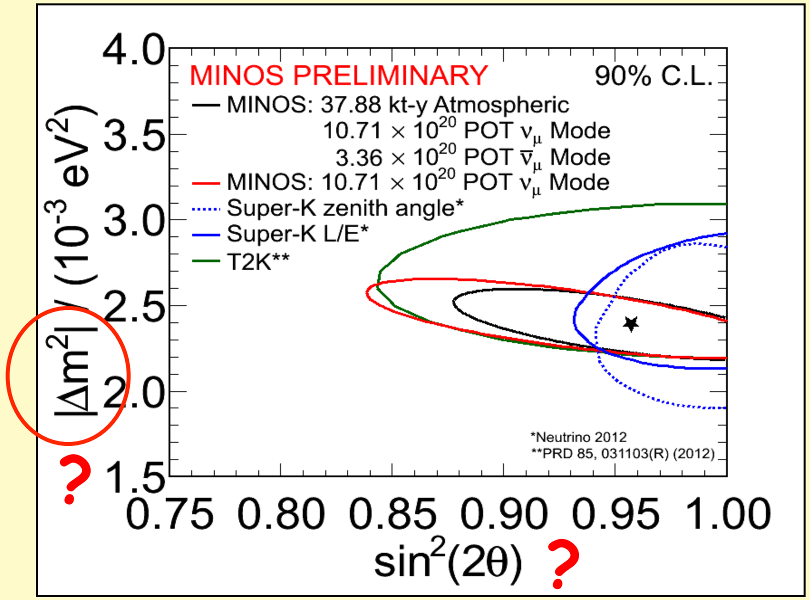
Challenging, but not impossible!

Figure from Goshal & Petcov, arXiv:1011.1646

NOTE:

a MBL reactor expt will greatly benefit from accurate Δm^2 at LBL accelerators

→ abandon 2ν plots!



$\pm\delta m^2$ ~ $\pm 1\sigma$ now!

It is important that the MINOS and T2K(+SK) collaborations perform full-fledged 3ν analyses of combined appearance+disappearance data sets.

Non-oscillation probes of ν_e superpositions: (m_β, $m_{\beta\beta}$, Σ)

1) β decay: Sensitive to "effective electron neutrino mass":
(incoherent superposition of states)

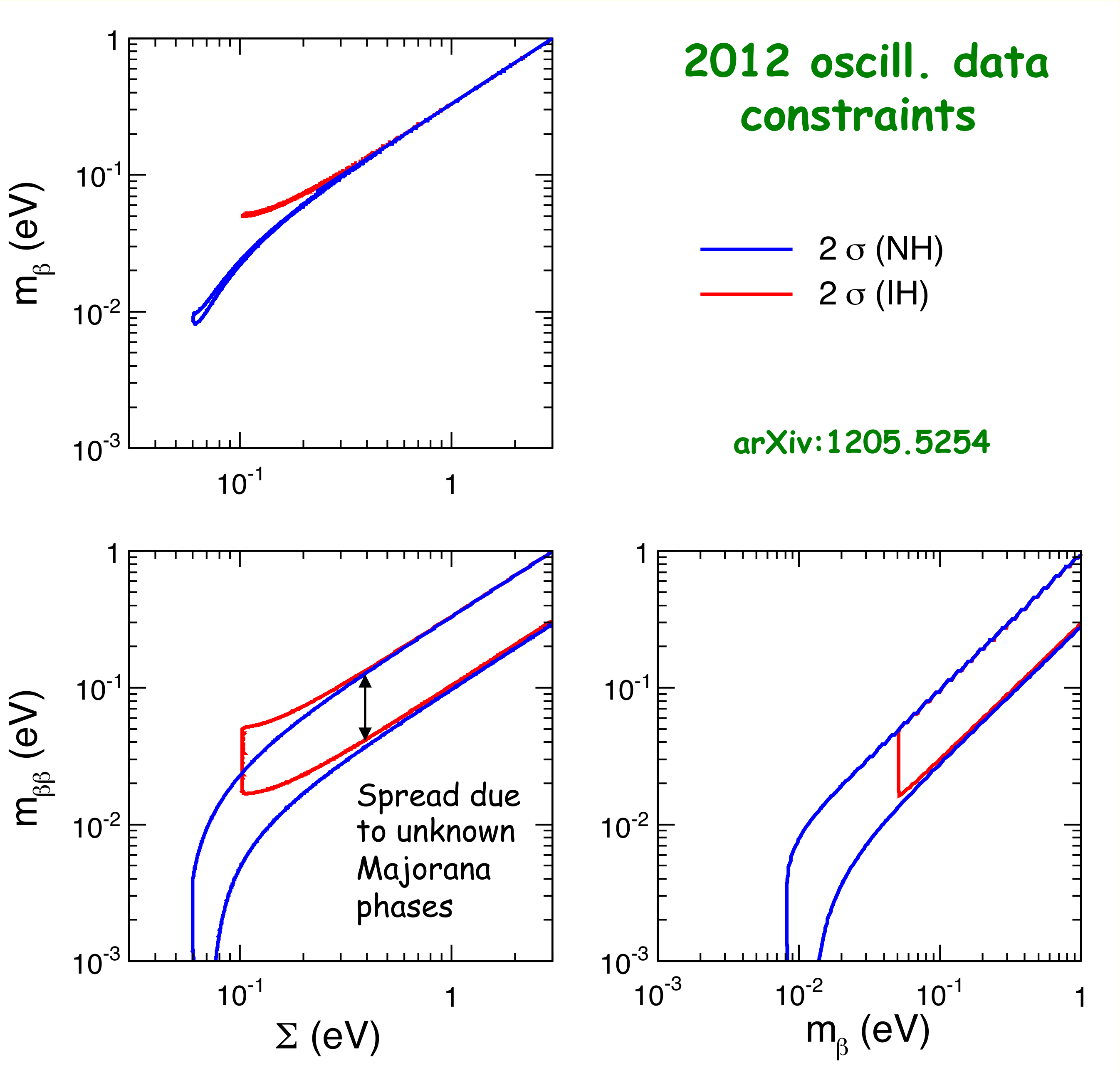
$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

2) $0\nu\beta\beta$ decay: Sensitive to the "effective Majorana mass"
(coherent superposition of states)

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

3) Cosmology: flavor-blind, probes average mass scale

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


2012 oscill. data constraints
2 σ (NH)
2 σ (IH)
arXiv:1205.5254
mβ (eV)
1
10-1
10-2
10-3
10-1
1
mββ (eV)
Spread due to unknown Majorana phases
Σ (eV)
10-3
10-2
mβ (eV)

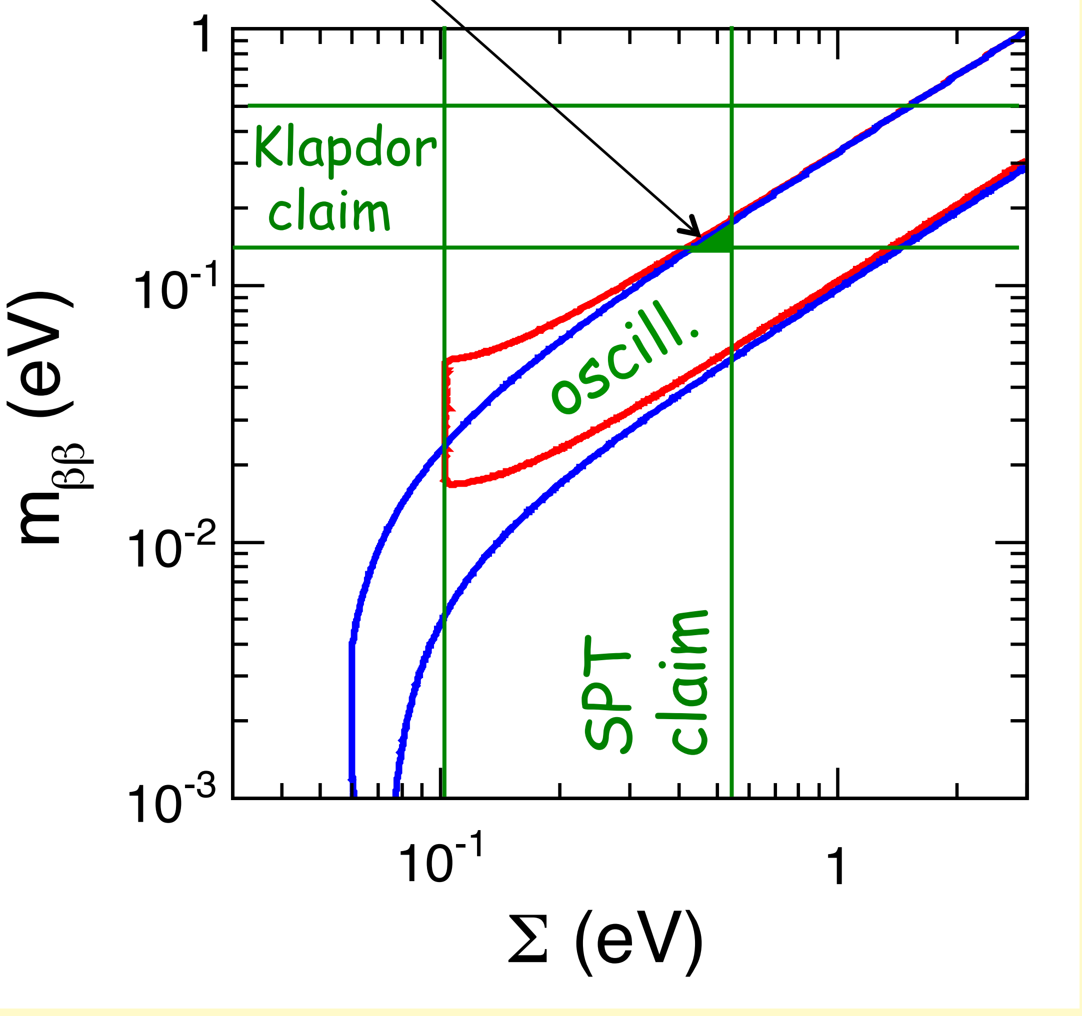
Exercise: assume $m_{\beta\beta}$ from Klapdor et al. claim, and Σ from SPT claim (both at $\pm 2\sigma$). Overall compatibility with 2σ osc. constraints is marginal, but still possible in ~mass-degenerate region:

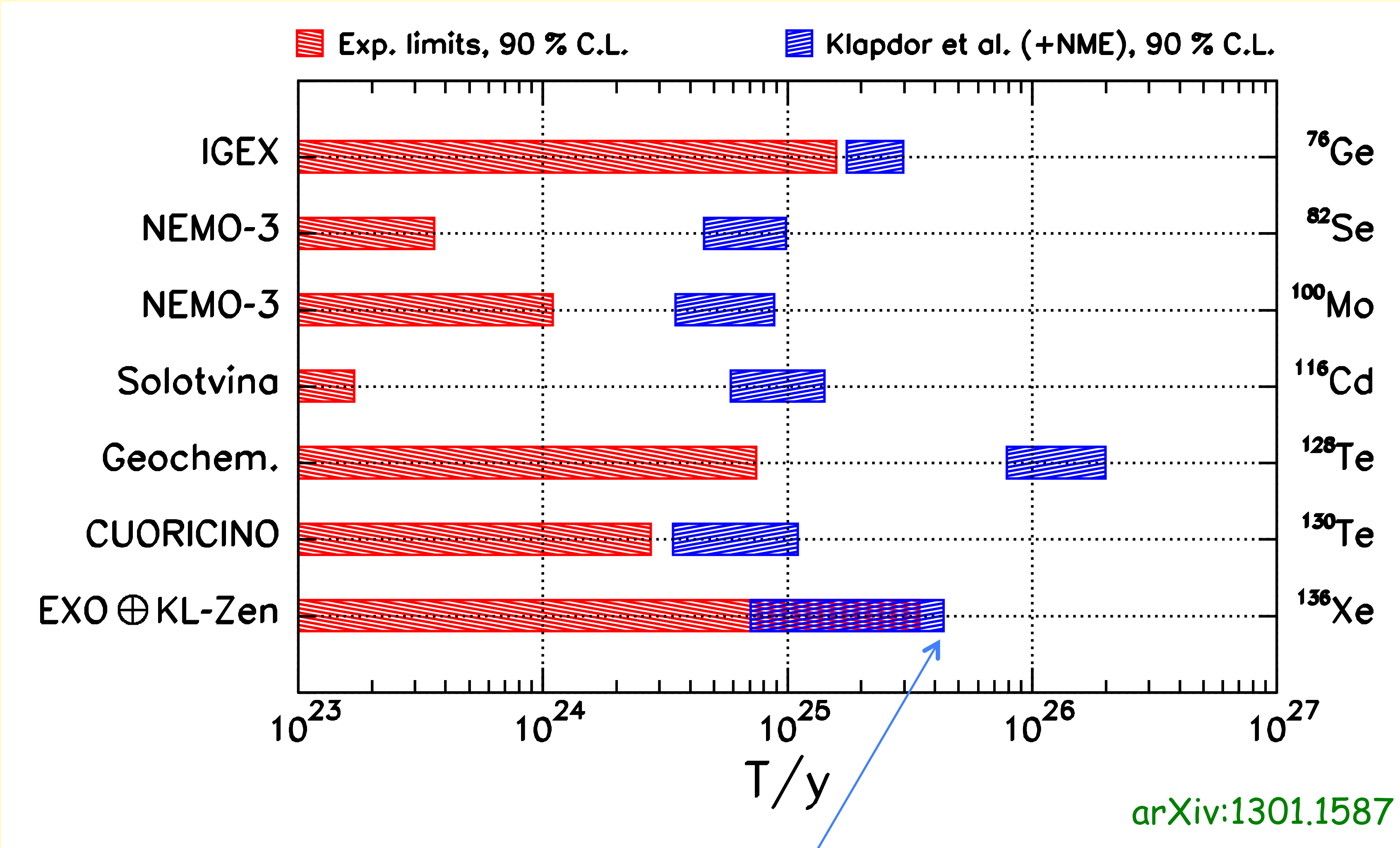
$m_{\beta\beta}$ ~ 0.15-0.50 eV (2σ)

Klapdor + QRPA NME from arXiv:0810.5733

Σ ~ 0.10-0.54 eV (2σ)

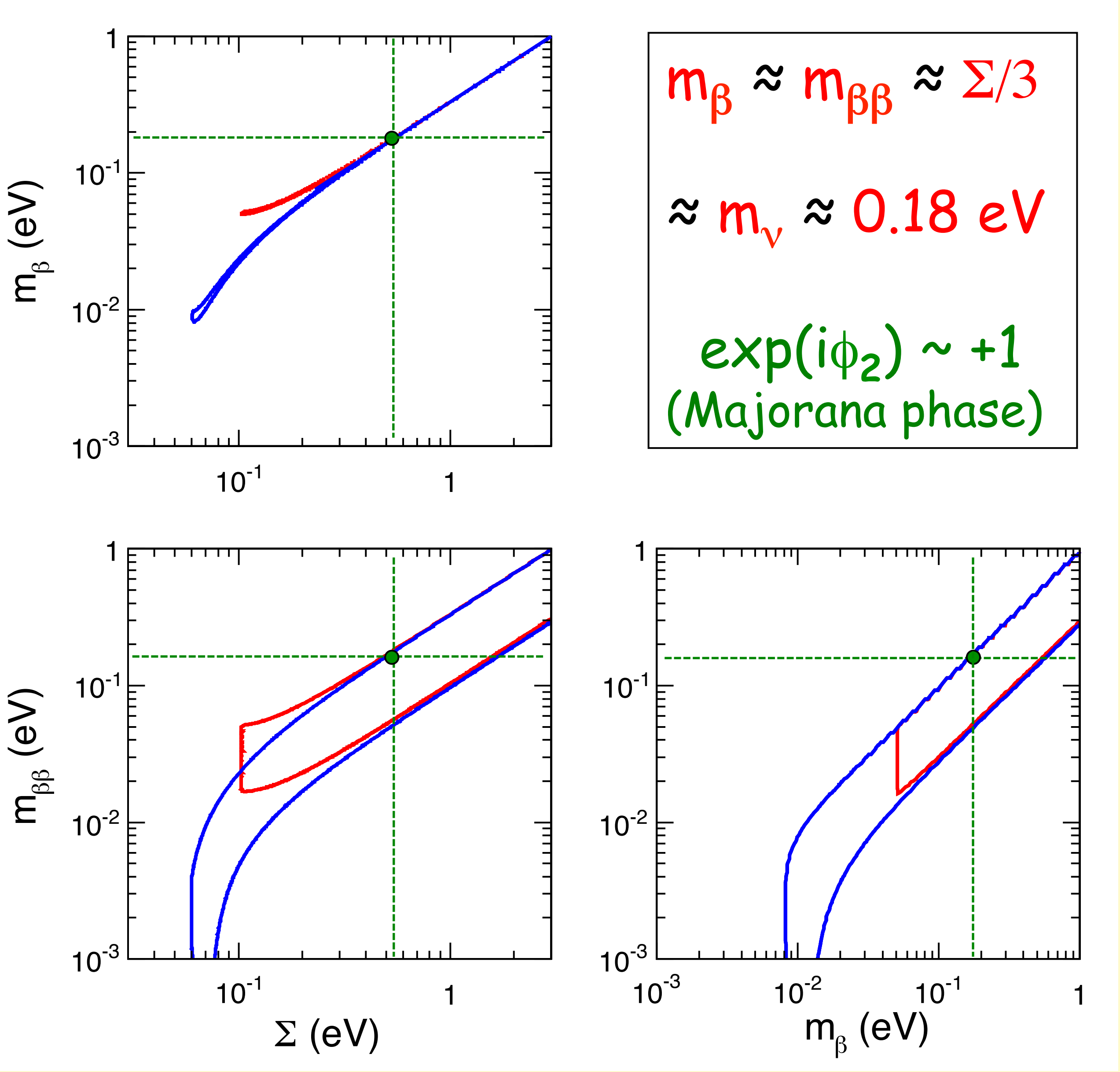
South Pole Telescope arXiv:1212.6267





[Lowest $m_{\beta\beta}$ (=highest $T_{1/2}$) fraction of $0\nu\beta\beta$ claim not ruled out yet]

Then, mass of each ν expected slightly below 0.2 eV (< KATRIN...)
... but in the reach of Planck (few days?) and of 0νββ experiments!



$m_\beta \approx m_{\beta\beta} \approx \Sigma/3$

$\approx m_\nu \approx 0.18$ eV

$\exp(i\phi_2) \sim +1$
(Majorana phase)

Conclusions

Current data, at best fit, indicate that:

$$\nu_e \sim 0.82\,\nu_1 + 0.55\,\nu_2 - 0.16\,\nu_3$$

but with... a very uncertain CPV phase:

$$\nu_e \sim 0.82\,\nu_1 + 0.55\,\nu_2 + e^{-i\delta}\,0.16\,\nu_3$$

... no clue about absolute mass, hierarchy, nature:

$m_i = ?$ $\quad$ $\mathrm{sign}(\Delta m^2) = ?$ $\quad$ $\nu_i = \bar{\nu}_i\,?$

... and, maybe, small mixing with new states...

$$\nu_e \sim U_{e1}\,\nu_1 + U_{e2}\,\nu_2 + U_{e3}\,\nu_3 + U_{e4}\,\nu_4 \ldots$$

We still have a lot to learn about ν_e as a superposition of states, in many different, interesting (& surprising?) ways

Thank you for you attention

Based on work with GL Fogli, A Marrone, D Montanino, A Palazzo, AM Rotunno, ...