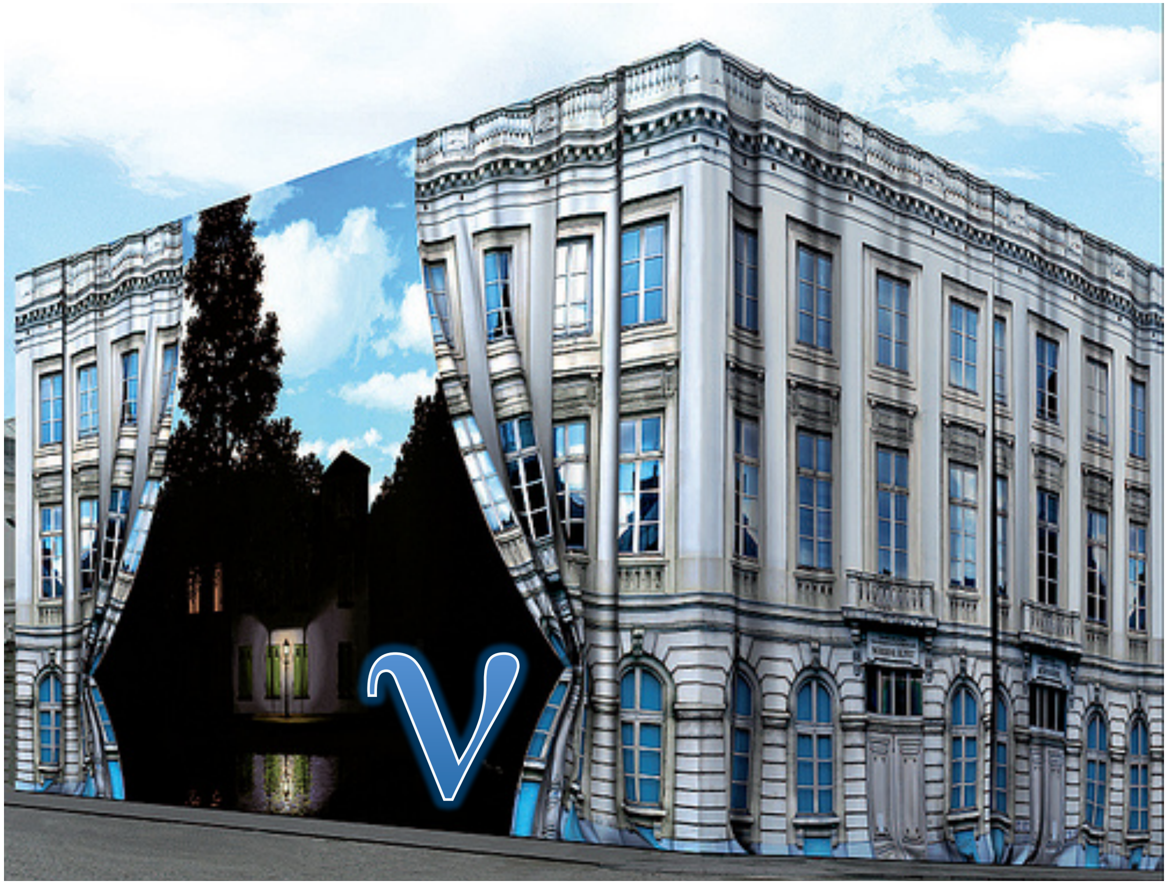
Surreal Neutrinos



Eligio Lisi, INFN, Bari, Italy

Solvay-Francqui Neutrino Workshop, May 2015

surreal [\sə-ˈrē(-ə)l]

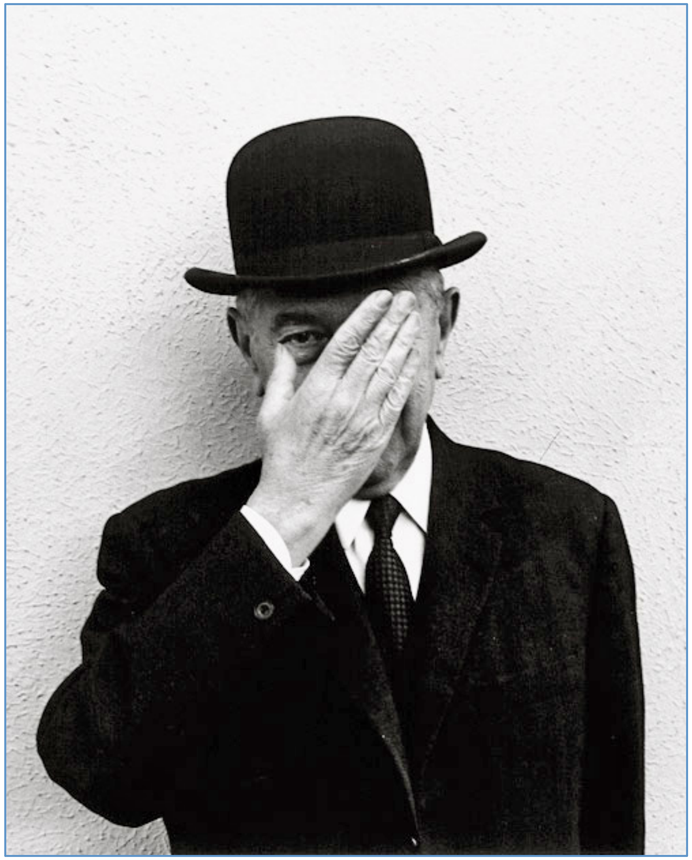
very strange or unusual: having the quality of a dream

[Merriam-Webster Dictionary]

… seems quite appropriate to neutrinos!

René Magritte, Belgian surrealist artist

The Son of Man (self portrait, 1964)



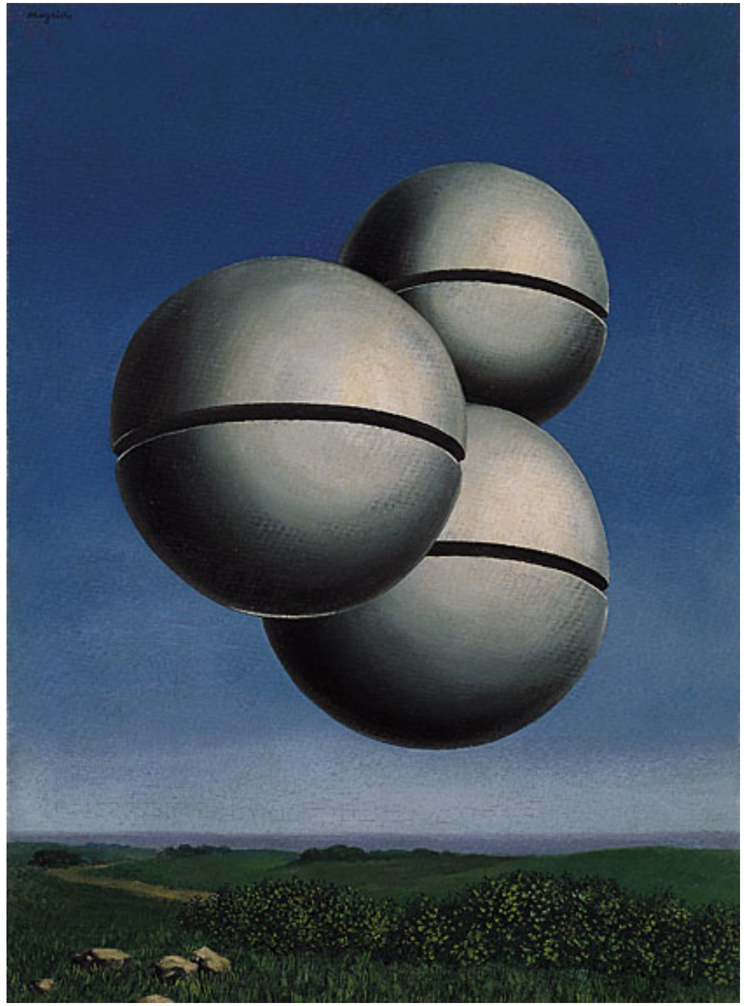
"Everything we see hides another thing, we always want to see what is hidden by what we see."

TALK OUTLINE:

- **what we see**
- **what we expect to see**
- **what is hidden by what we see...**

... with homages to Magritte

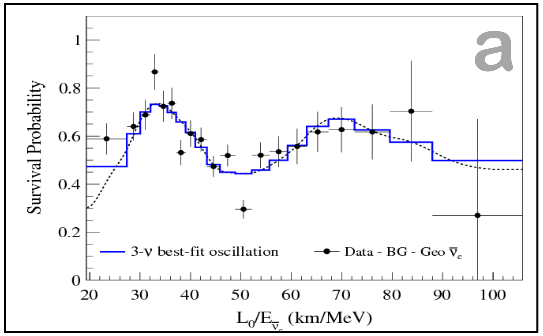
Three-neutrino oscillations



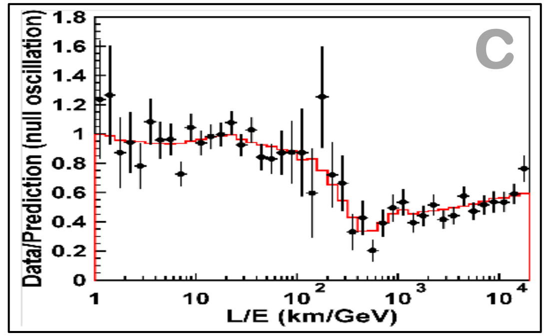
Voice of the space (1931)

What we have seen: $\alpha \rightarrow \beta$ oscillations in vacuum and matter

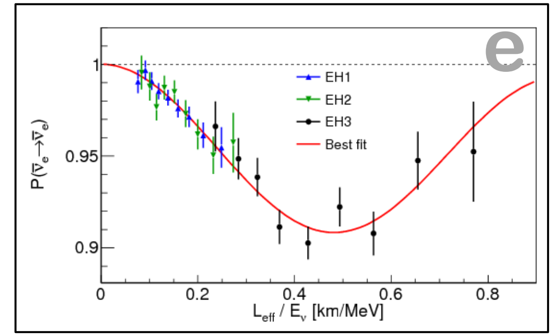
e→e



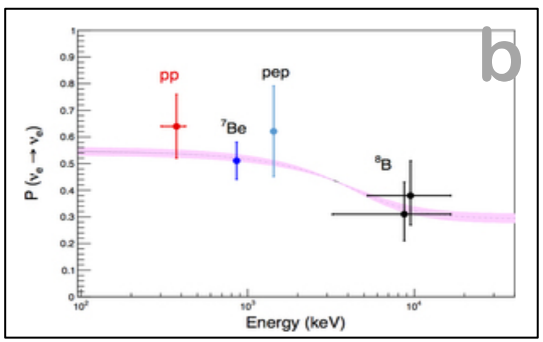
μ→μ



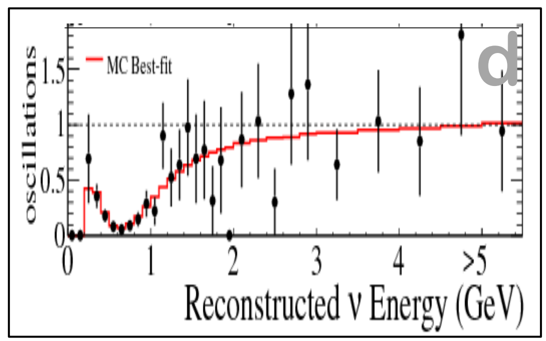
e→e



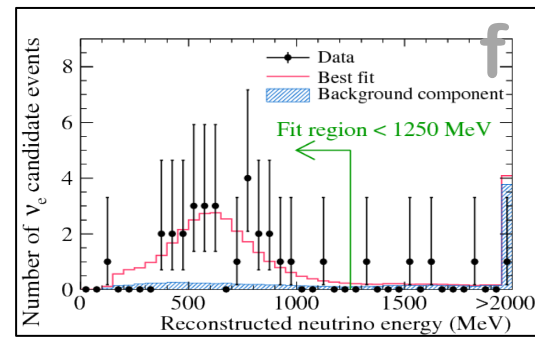
e→e



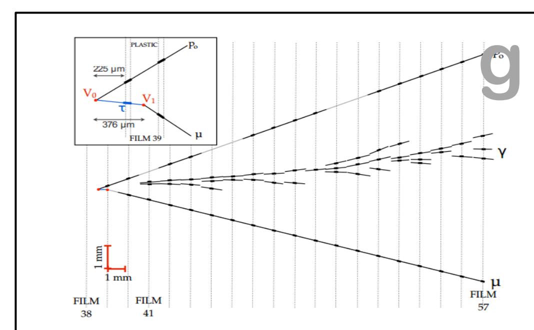
μ→μ



μ→e



μ→τ

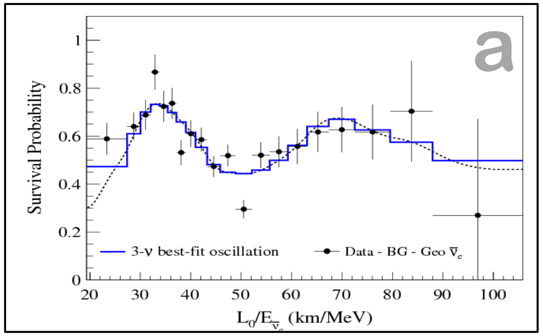


Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

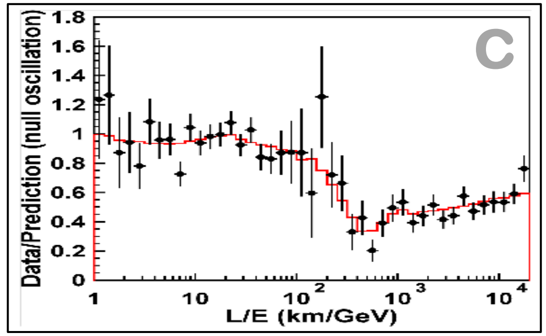
(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], MACRO, MINOS etc.; (d) T2K (plot), MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS; (g) OPERA [plot], Super-K atmospheric.

...can be interpreted in a simple 3ν theoretical framework

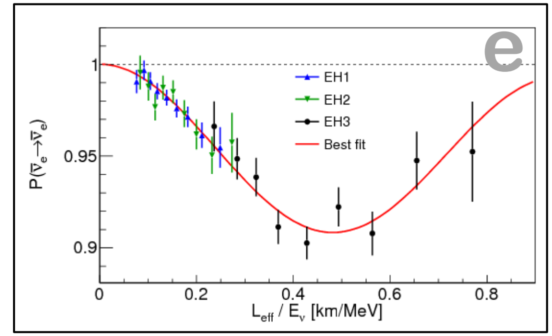
e→e (δm^2 , θ_{12})



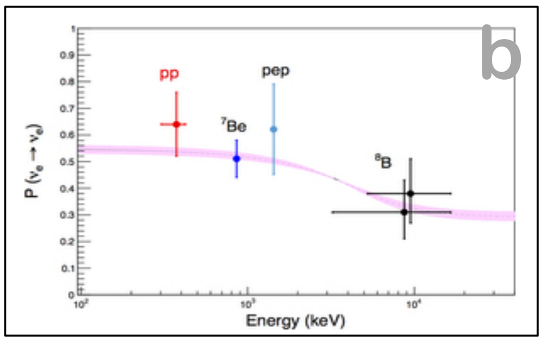
μ→μ (Δm^2 , θ_{23})



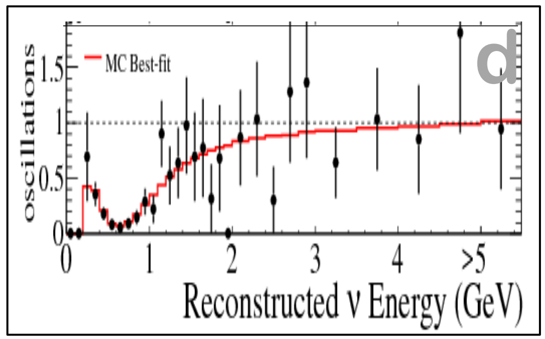
e→e (Δm^2 , θ_{13})



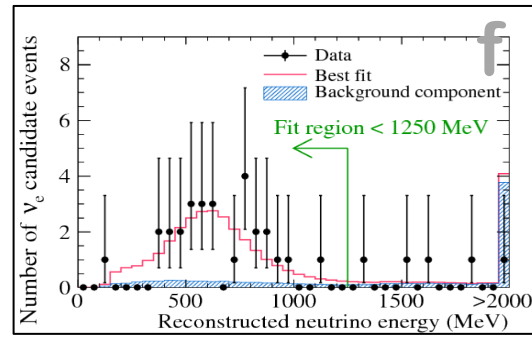
e→e (δm^2 , θ_{12})



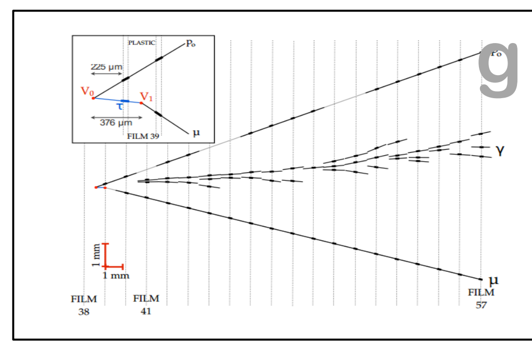
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



Known parameters:

δm^2 $|\Delta m^2|$ θ_{12} θ_{23} θ_{13}

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

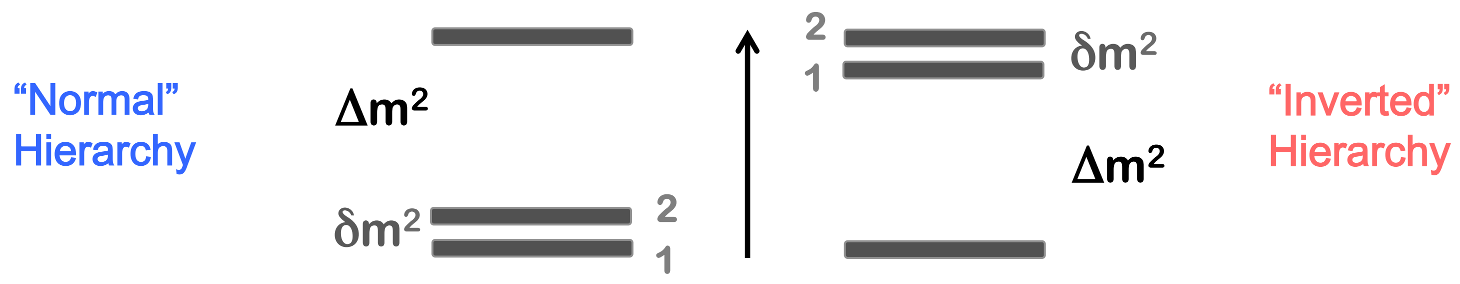
$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

[only if Majorana]

Mixing angles θ_{23}, θ_{13}, θ_{12} : known ✔

CP-violat. phase(s) δ (α, β) : unknown ✗

Mass-squared spectrum (up to absolute scale)



[+ contribution in matter ~ $G_F \cdot E \cdot$ density]

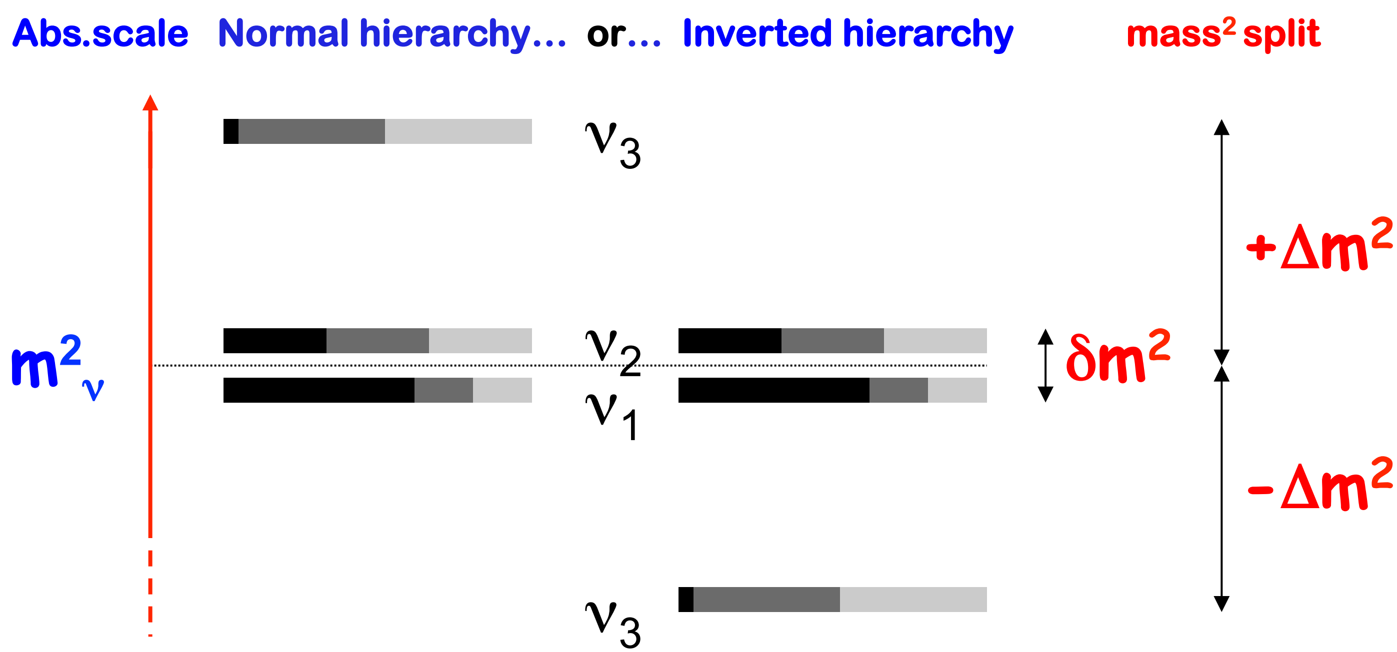
δm^2, $|\Delta m^2|$: known ✔

Matter effects (solar ν): ✔

Hierarchy : unknown ✗

Current 3ν picture in just one slide (with 1-digit accuracy)

Flavors = e μ τ



We see:

$\delta m^2 \sim 8 \times 10^{-5}\ eV^2$
$\Delta m^2 \sim 2 \times 10^{-3}\ eV^2$
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

We expect to see:

δ (CP)
sign(Δm^2)
octant(θ_{23})
absolute mass scale
Dirac/Majorana nature

Heraclitus Bridge (1935)

Exploring what we see with more digits: global analysis →

Analysis includes increasingly rich oscill. data sets:

LBL Acc + Solar + KL

LBL Acc + Solar + KL + SBL Reactor

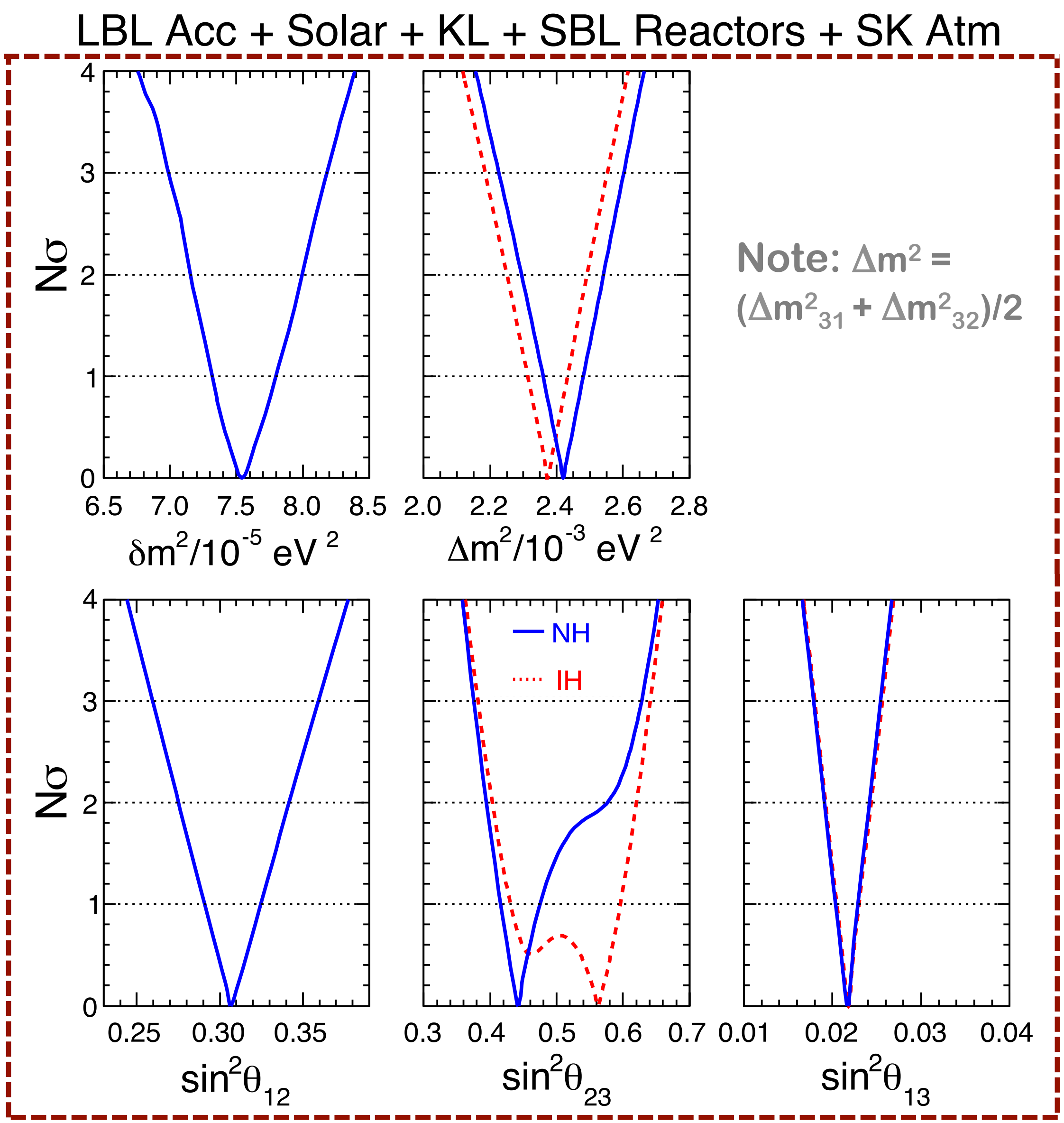
LBL Acc + Solar + KL + SBL Reactor + SK Atm.

Parameters not shown are marginalized away.

C.L.'s refer to $N\sigma = \sqrt{\Delta\chi^2} = 1, 2, 3, \ldots$

Results from Capozzi et al., arXiv:1312.2878, updated with "Reactor 2014"
See also: Forero et al., 1405.7540; Gonzalez-Garcia et al., 1409.5439.

Single oscillation parameters



Note: $\Delta m^2 = (\Delta m^2_{31} + \Delta m^2_{32})/2$

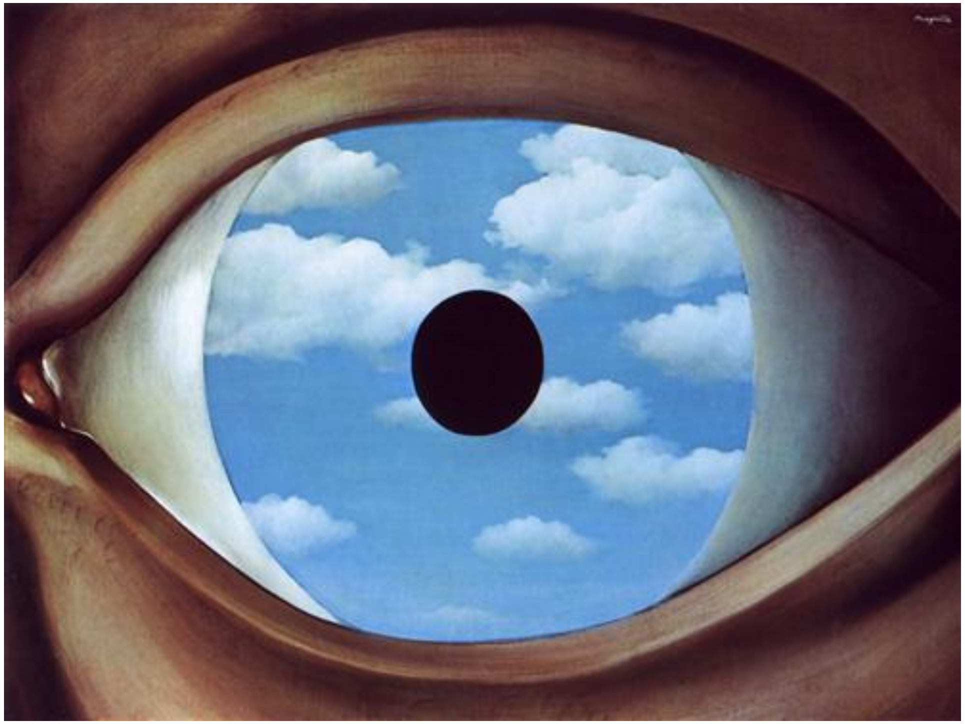
Current accuracy:

δm^2	2.6 %
Δm^2	2.6 %
$\sin^2\theta_{12}$	5.4 %
$\sin^2\theta_{13}$	5.8 %
$\sin^2\theta_{23}$	~ 10 %

Precision Era!

Mass-mixing parameters: are they suggestive of some “simmetry”?

Or is the symmetry only in our eyes... and is there just randomness?



The false mirror (1928)

Many interesting ideas, but still looking for an “illumination”...

Specific outcomes (a few examples from a vast literature)

No organizing principle
("anarchy")

Discrete family simmetries
("geometry")

linear relations between
$\theta_{13}\cos\delta$ and θ_{12}, θ_{23}

Continuous flavor simmetries
("dynamics")

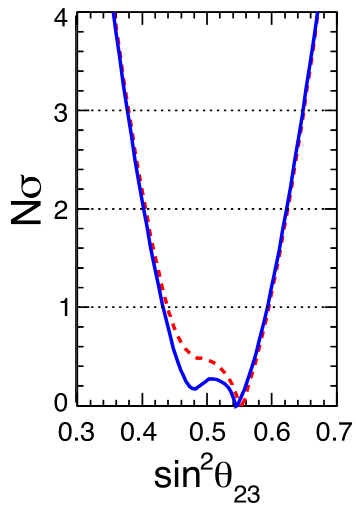
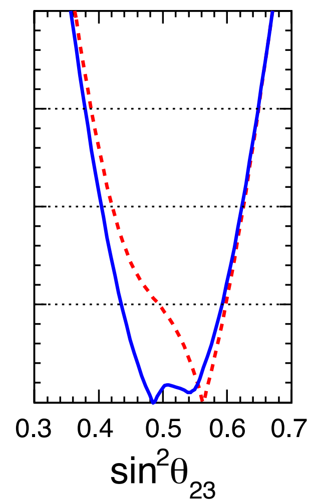
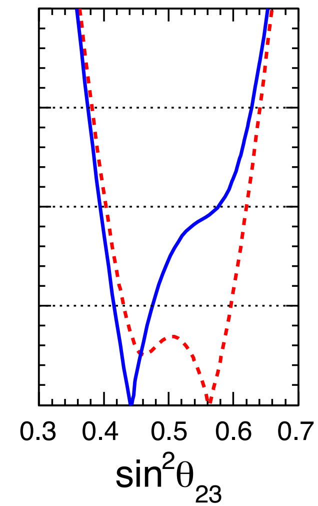
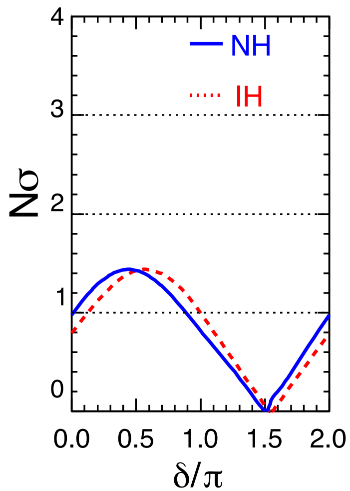
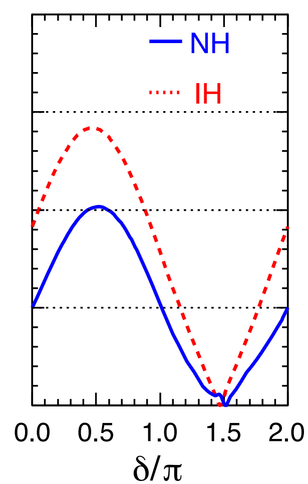
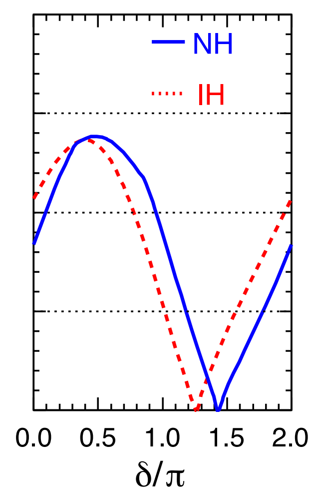
links between neutrino
spectra/angles/phases

Common quark/lepton features
("complementarity")

links between
θ_{13} and θ_C

Model selection will anyway benefit from new data!

Single parameters – What is still hiding

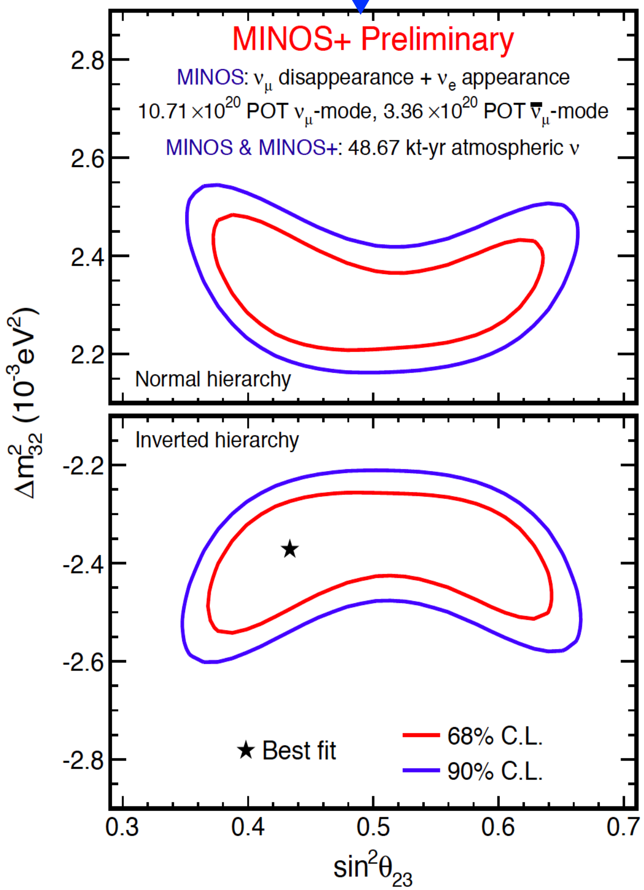
	LBL+Sol+KL		+SBL Reac		+SK atm	
θ_{23} octant						currently unstable, fragile
$\Delta\chi^2$ (IH-NH)	-1.4		-0.9		-0.1	negligible
δ_{CP}						intriguing, $\sin\delta \sim -1$ (or $\sin\delta < 0$) favored

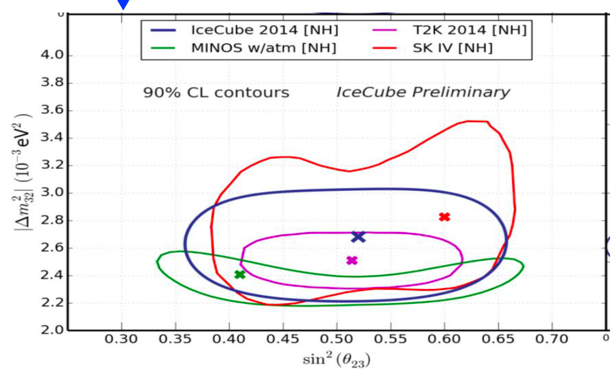
Comments on θ_{23} octant

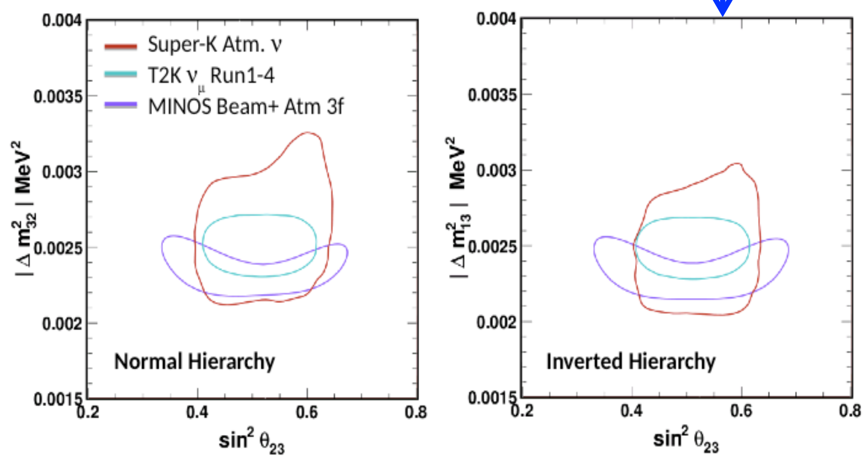
Current instability stems from the data themselves

MINOS+, IceCube & T2K, SK atm. 2014/15 (*)

$<\pi/4$ $\sim\pi/4$ $>\pi/4$



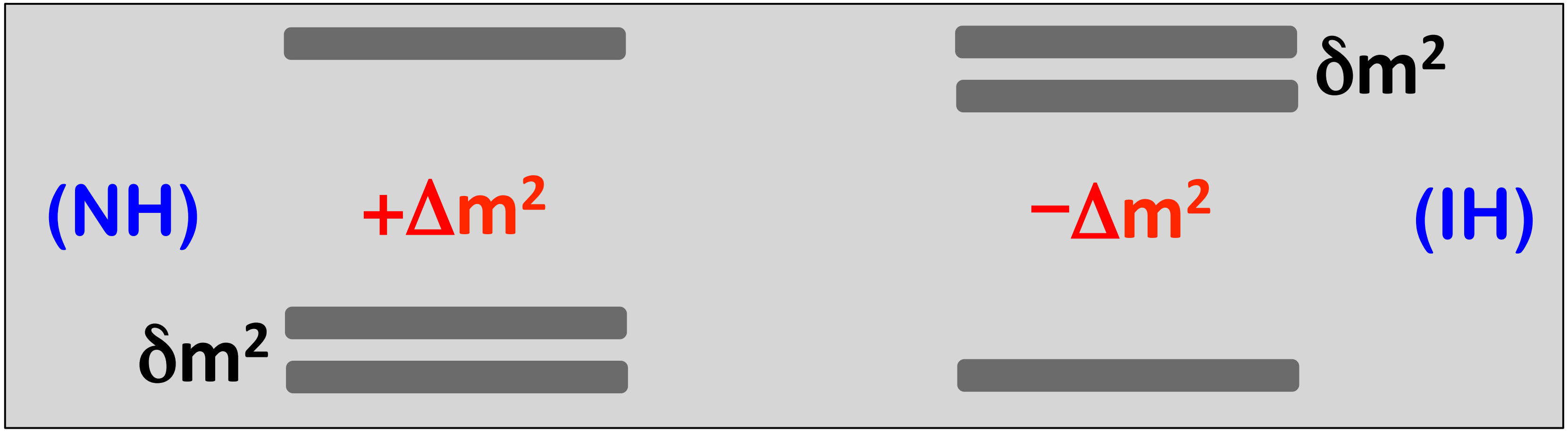




(*) To be included in our next global analysis.

Comments on hierarchy

No hints so far, but we'll get there via oscillations...



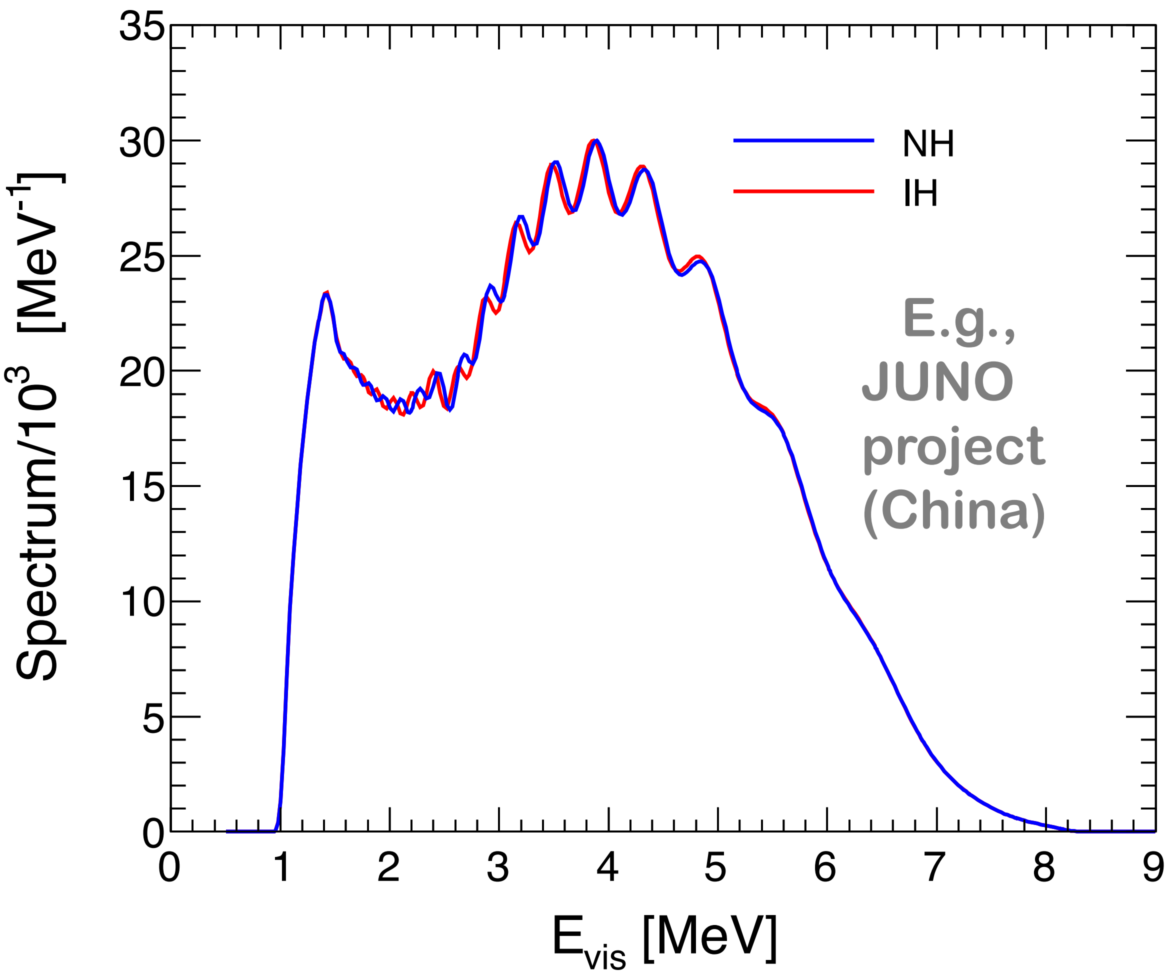
... if we can observe interference of oscill. driven by $\pm\Delta m^2$ with oscill. driven by another quantity Q with known sign. Three options:

$Q = \delta m^2$	(medium-baseline reactors)
$Q = 2\sqrt{2}\, G_F\, N_e\, E$	(matter effects in accel./atmosph. ν)
$Q = 2\sqrt{2}\, G_F\, N_\nu\, E$	(collective effects in supernovae)

[Nonoscillation searches may provide further handles]

Make ± Δm^2 interfere with δm^2 at medium-baseline reactors

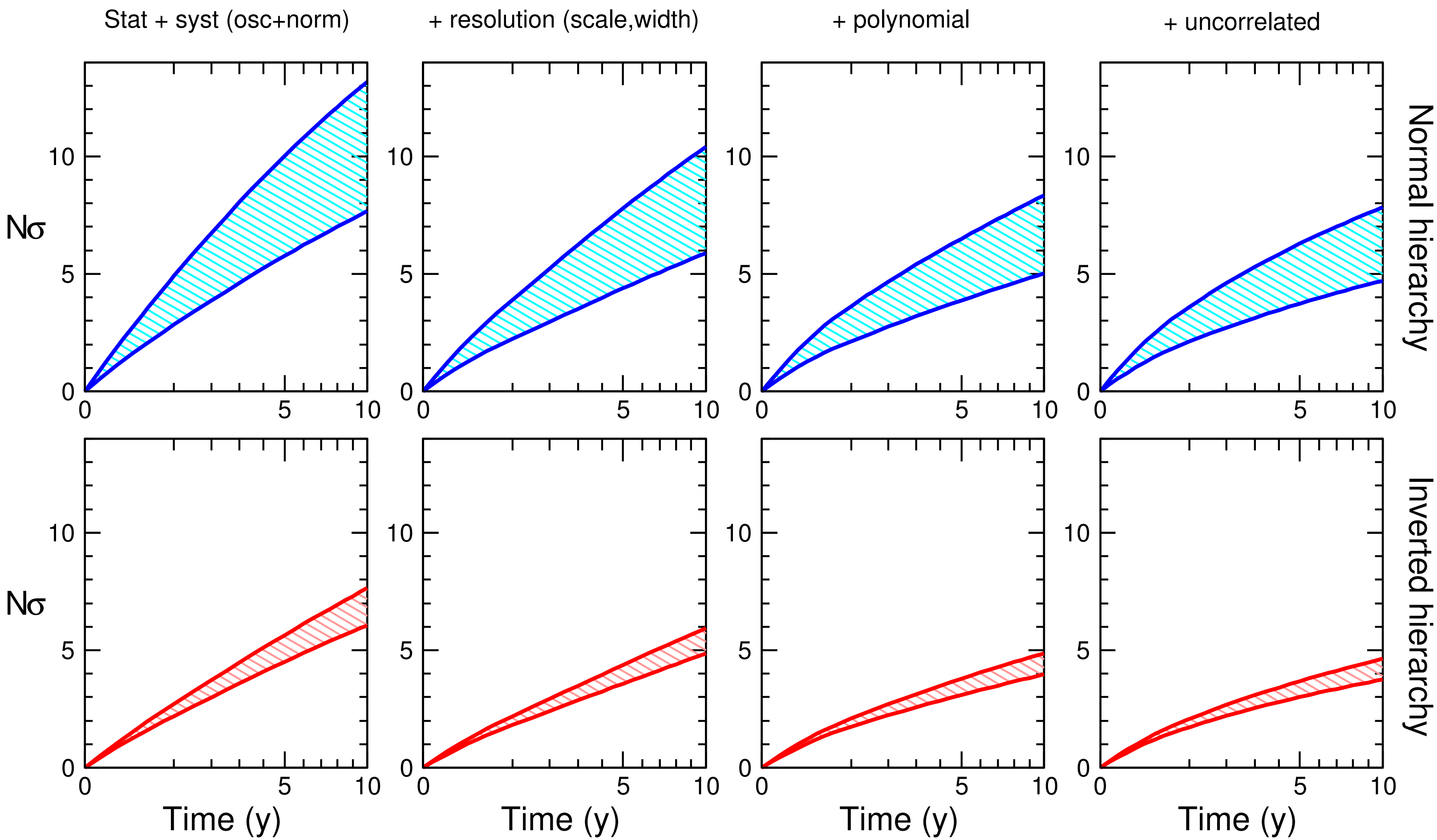
Very challenging!



Will also improve δm^2 and θ_{12} accuracy by O(10)

Make $\pm\,\Delta m^2$ interfere with $G_F N_e E$ in atmospheric expts

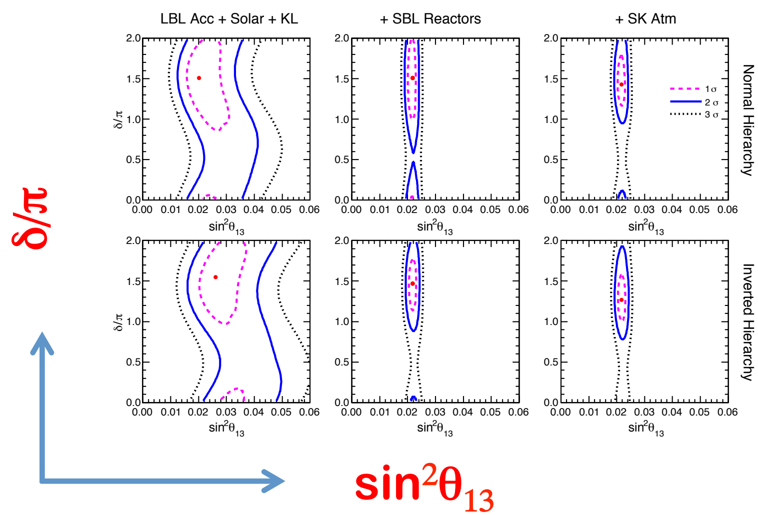
NH/IH atm. oscillation analyses will face new systematics challenges



An example of hierarchy sensitivity study for PINGU, arXiv:1503.01999
Must account for "shape" syst's of energy-angle atmospheric ν spectra

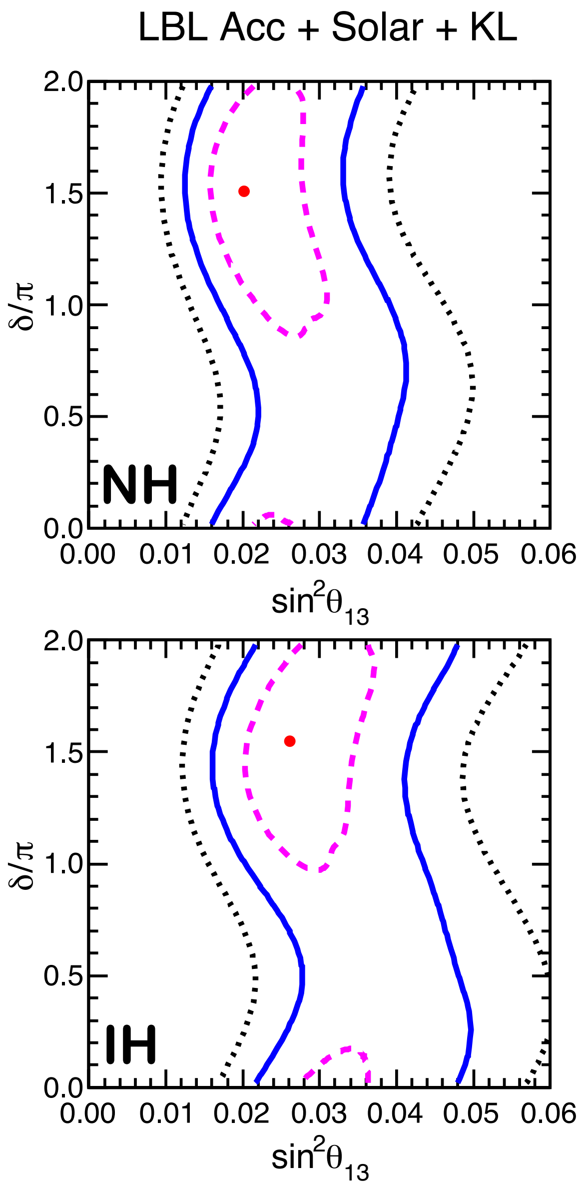
Comments on CPV phase

From variances to <u>co</u>variances: analysis of a 2D plot



Leading appearance amplitude at LBL Acc. ~ $\sin^2\theta_{23}\,\sin^2(2\theta_{13})$
→ uncertainty on θ_{23} somewhat affects subleading terms

Subleading CPV appearance amplitude for ν ~ $-\sin\delta$
→ T2K signal maximized for $\sin\delta \sim -1$ ($\delta \sim 1.5\pi$)

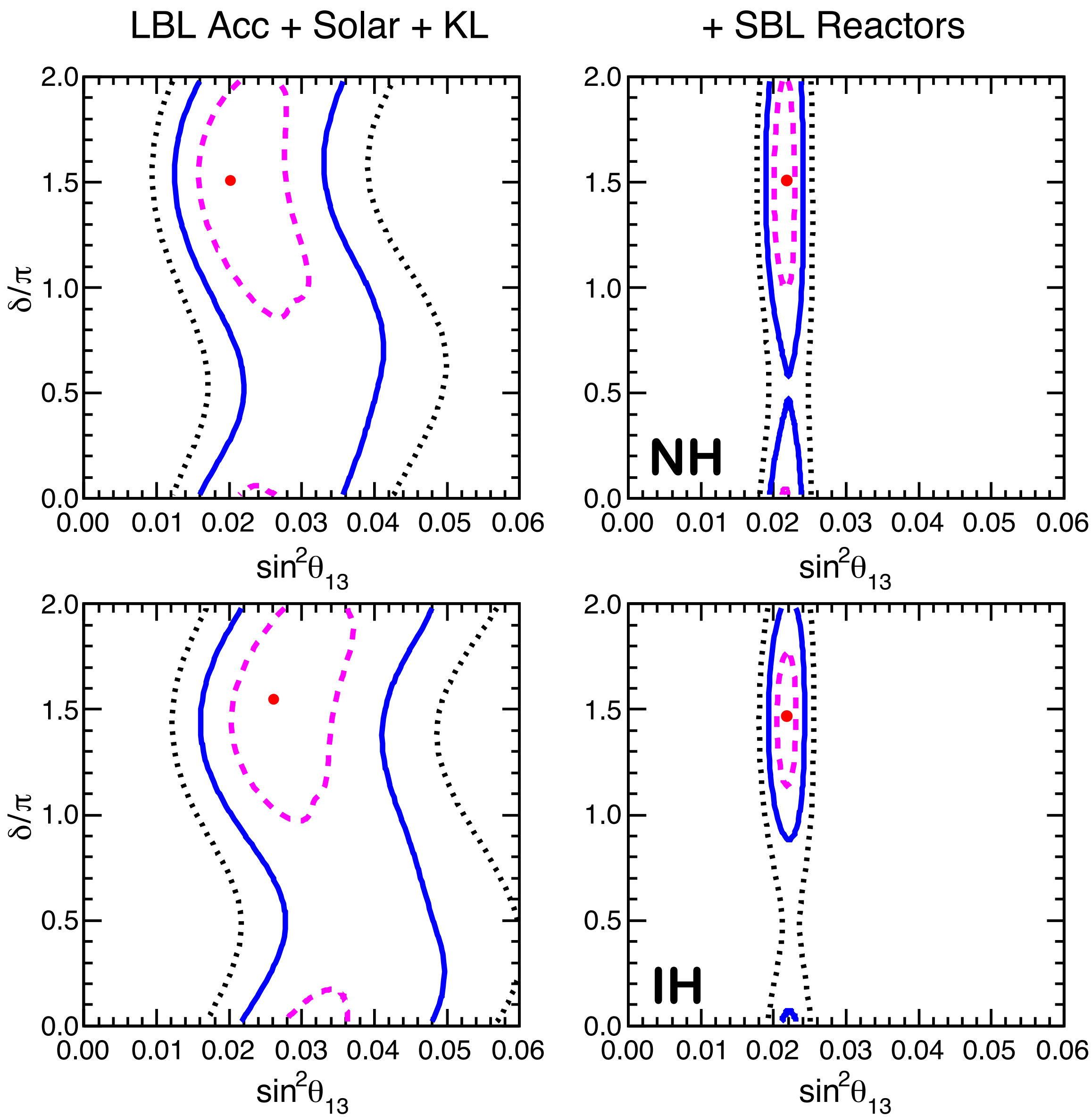


Each wavy band is in part determined by superposition of "two bands" for the two θ_{23} octants [it was more evident in older fits]

For the relatively "low" value $\sin^2\theta_{13}$~0.02 preferred by Solar + KL data, appearance ν signal in T2K maximized by subleading CP-odd term for $\sin\delta < 0$ [i.e., $1<\delta/\pi<2$]

Best agreement with relatively "strong" T2K appearance signal is for $\delta/\pi \sim 1.5$, irrespective of the hierarchy.

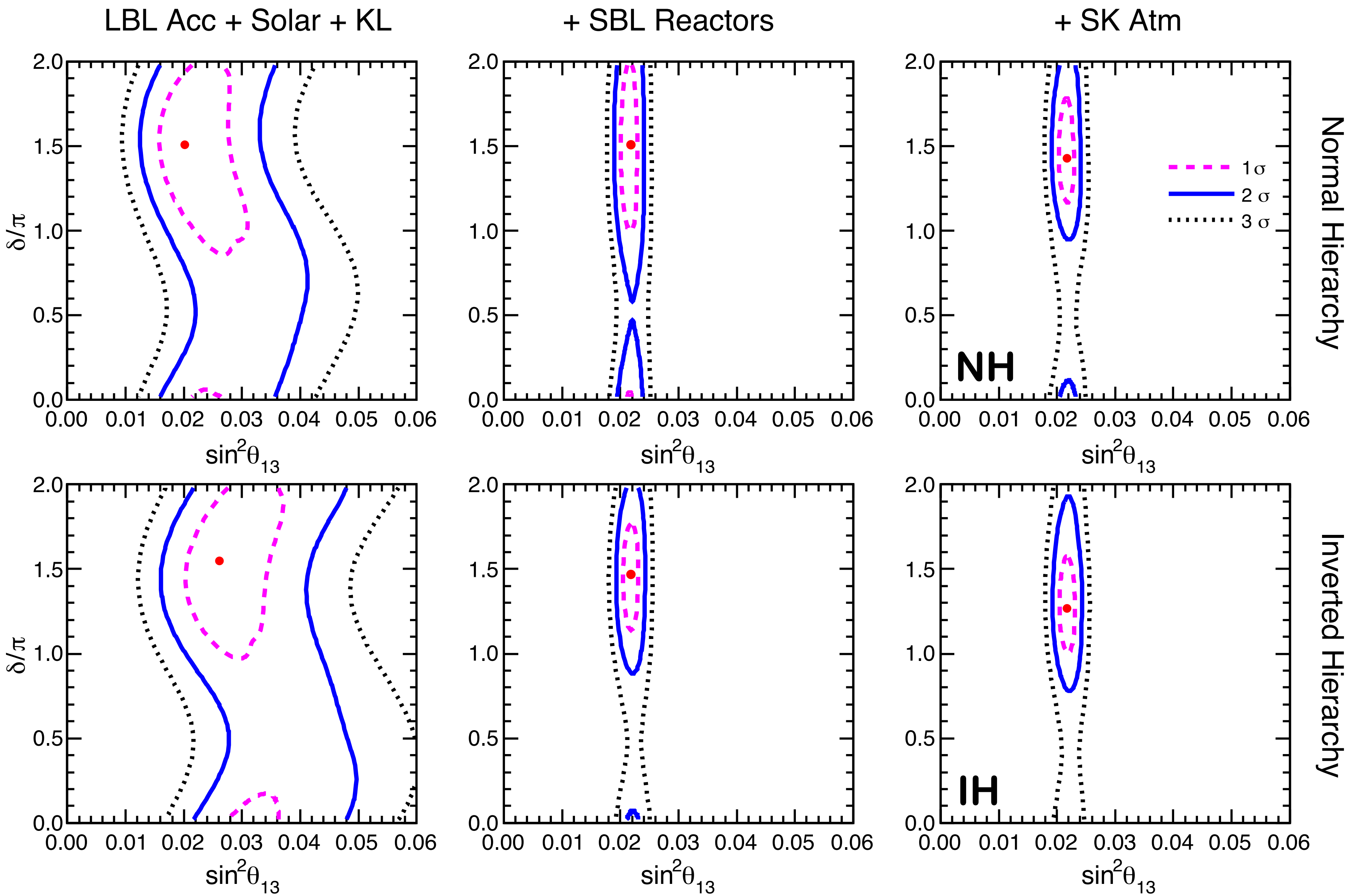
This trend wins over weaker MINOS appearance signal, which tends to prefer $\sin\delta > 0$ at best fit.



Reactor data shrink the band around $\sin^2\theta_{13} \sim 0.022$,

a bit higher than Solar+KL but still on the leftmost side of the band:

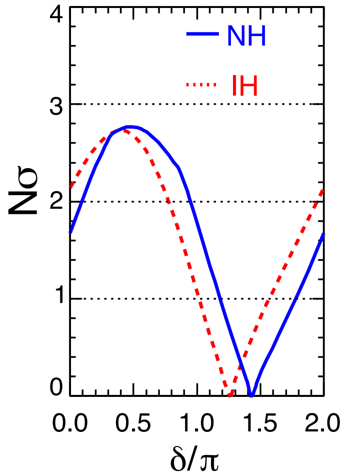
preference for $\delta/\pi \sim 1.5$ persists



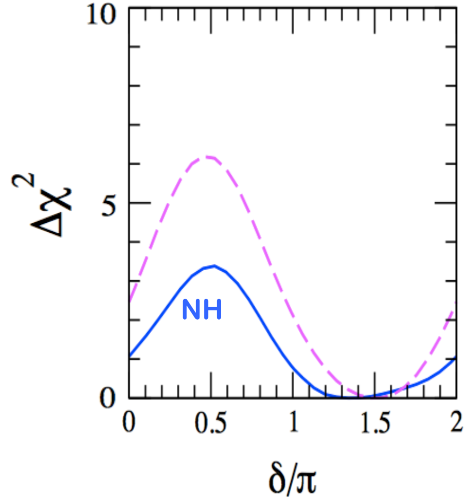
SK atm: in combination, these data **further shrink the allowed regions** and slightly lower the preferred value to **$\delta/\pi \sim 1.3\text{-}1.4$**

For comparison:

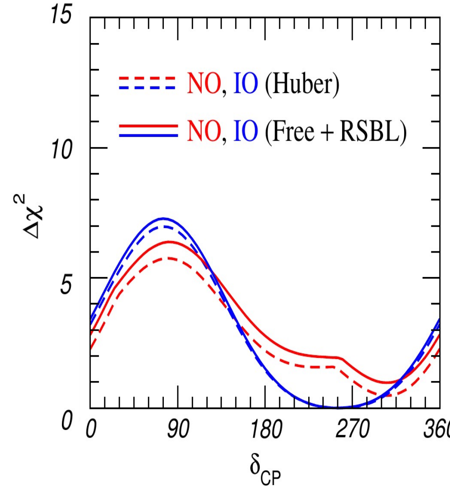
This talk



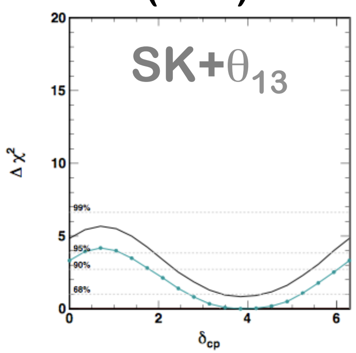
Forero et al.



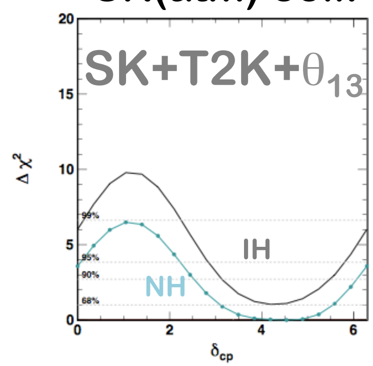
G.-Garcia et al.



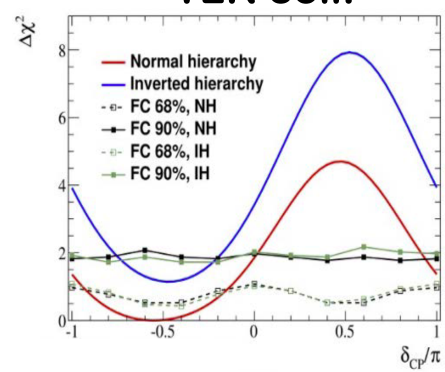
SK(atm) coll.



SK(atm) coll.



T2K coll.



Status of representative CP phase values (in various fits):

$\delta/\pi \sim 3/2$: preferred (nearly maximal CPV with $\sin\delta \sim -1$)

$\delta/\pi \sim 1/5$: disfavored (by ~2-2.6 sigma w.r.t. to preferred value)

$\delta/\pi \sim 0$ or ~ 1: in between (~1-1.3 sigma away from best fit)

Reminder: CP violation requires that:

3 mixing angles should be nonvanishing ✔

2 mass gaps should be nonvanishing ✔

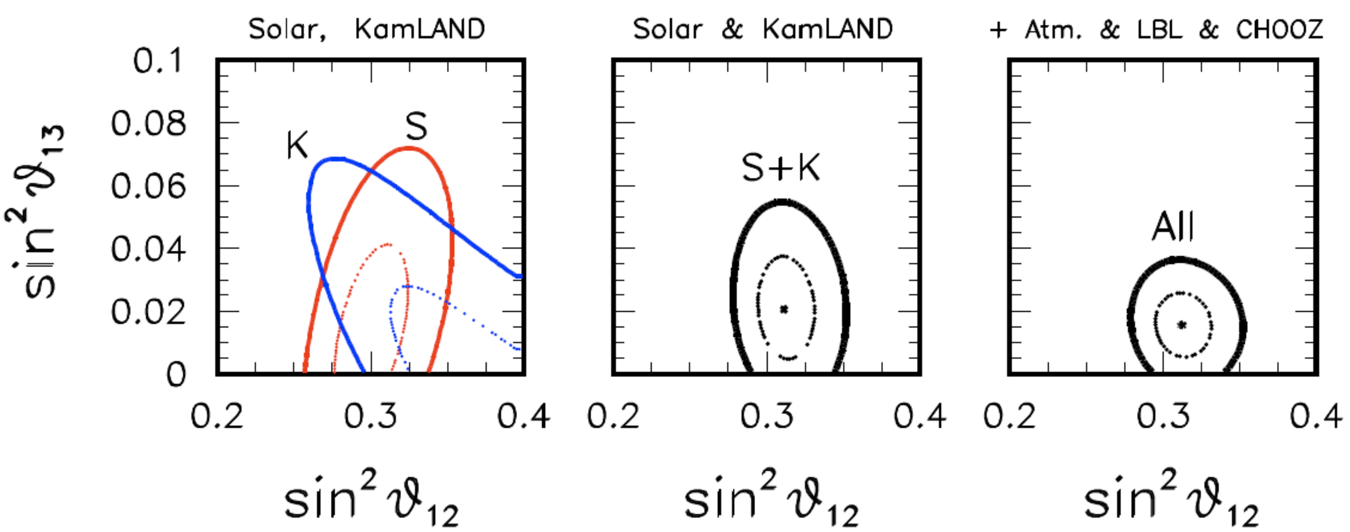
1 Dirac phase should be nonvanishing . . .

Nature has already provided us with 5 favorable conditions at **terrestrial** scales ...

Let us hope that the 6th condition is also (maximally) realized, as the hints suggest!

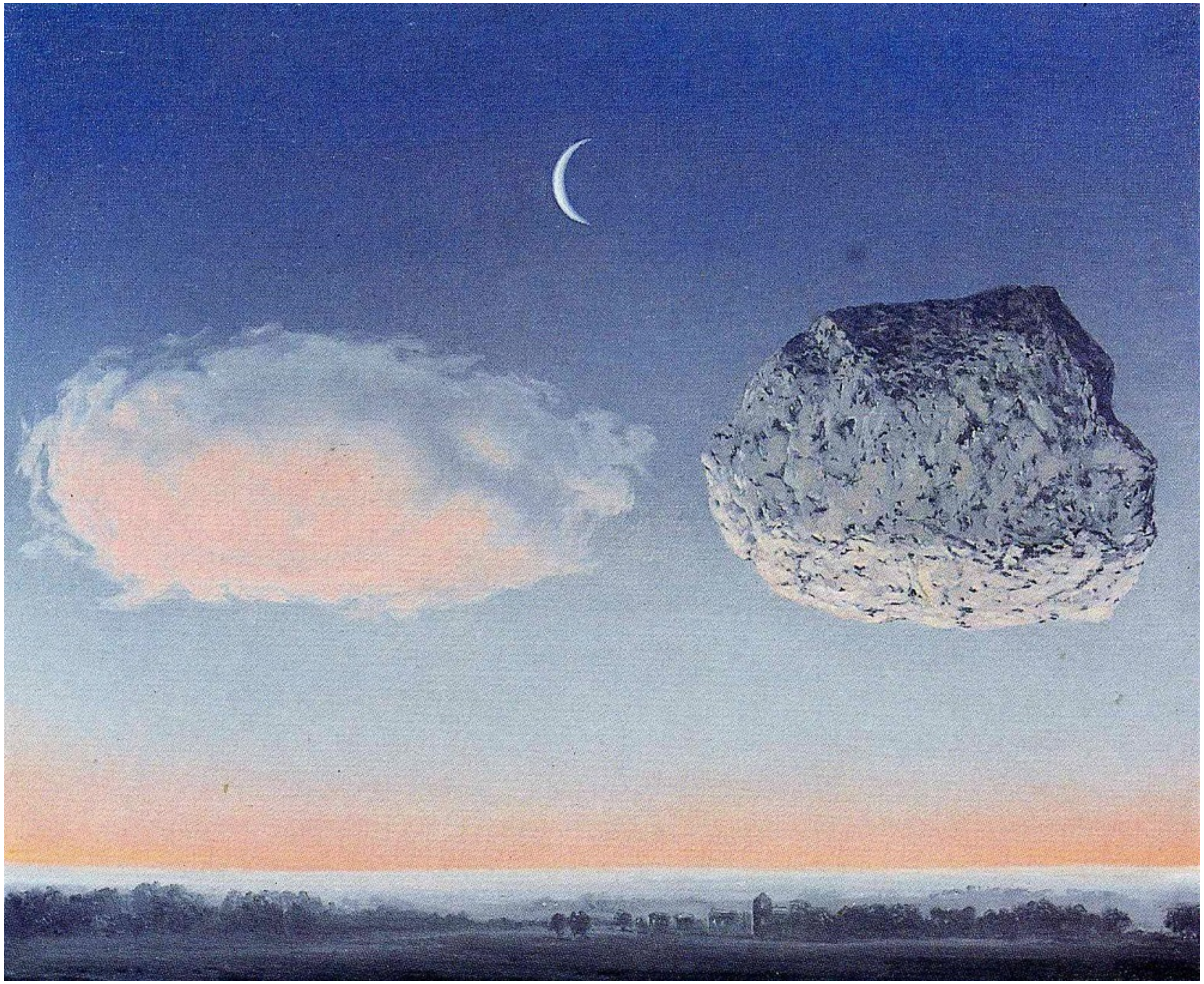
[and, if neutrinos are Majorana… we can dream of 2 more CP phases !]

A previous hint that grew up…



G.L. Fogli *et al*, arXiv:0806.2649 [hep-ph]

Absolute neutrino masses



The Battle of the Argonne (1959)

Still hiding: signals from neutrino mass observables

(m_β, $m_{\beta\beta}$, Σ)

β **decay**, sensitive to the "effective electron neutrino mass":

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

0νββ **decay**: only if Majorana. "Effective Majorana mass":

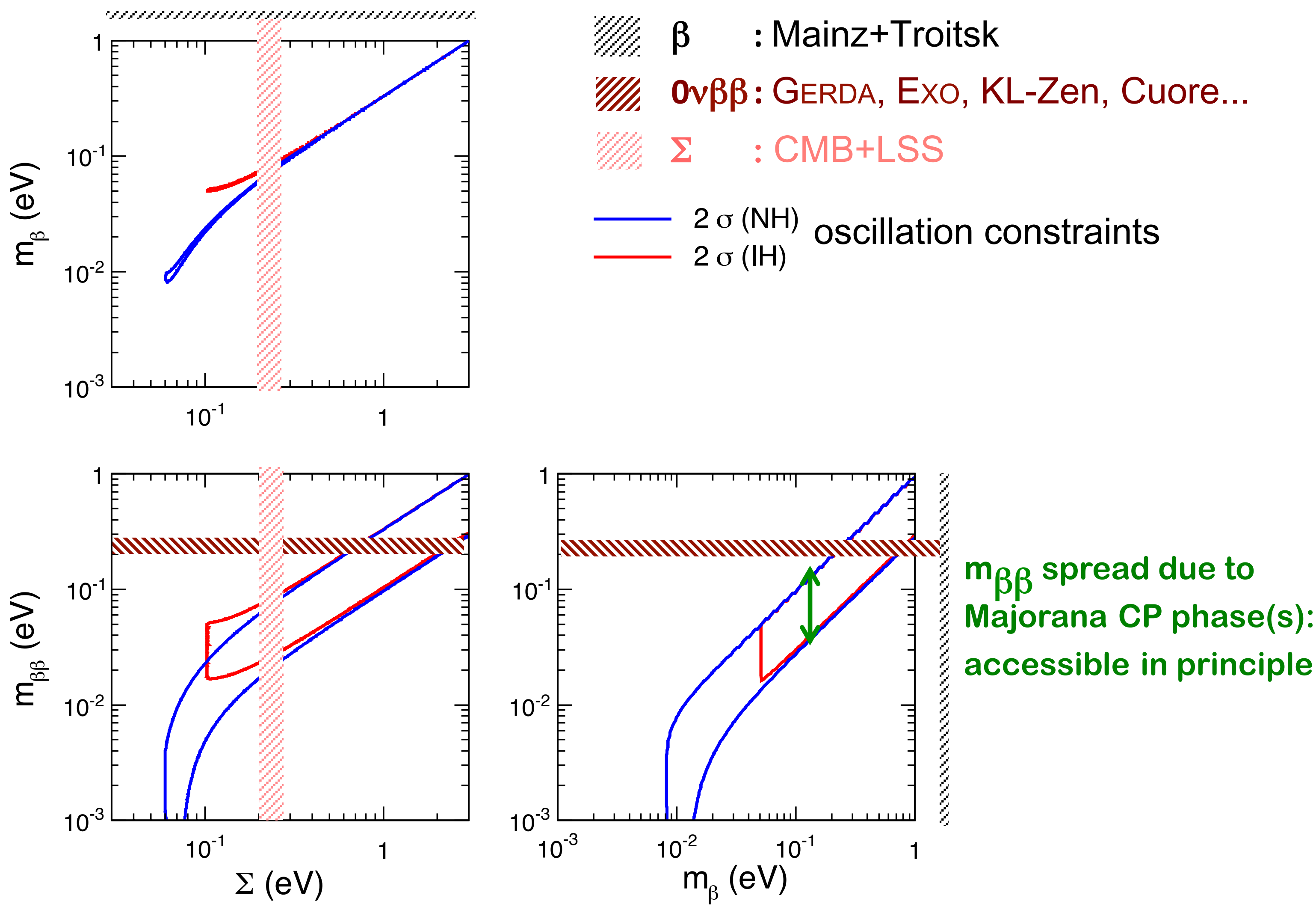
$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

Cosmology: Dominantly sensitive to sum of neutrino masses:

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

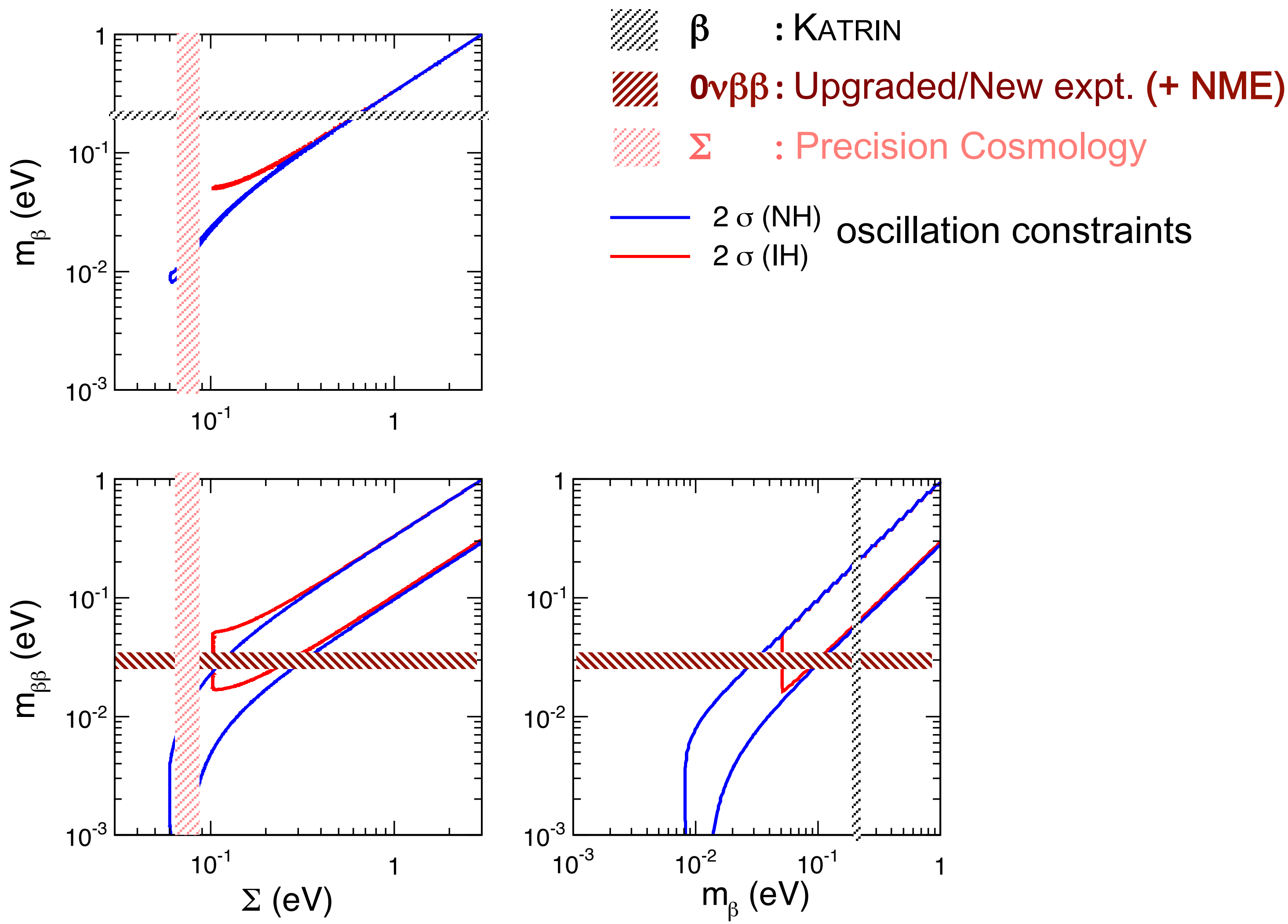
Note 1: These observables may provide handles to distinguish NH/IH.
Note 2: Majorana case gives a new source of CPV (unconstrained)
Note 2: The three observables are correlated by oscillation data→

Upper limits on m_β, $m_{\beta\beta}$, Σ (up to some syst.) + osc. constraints



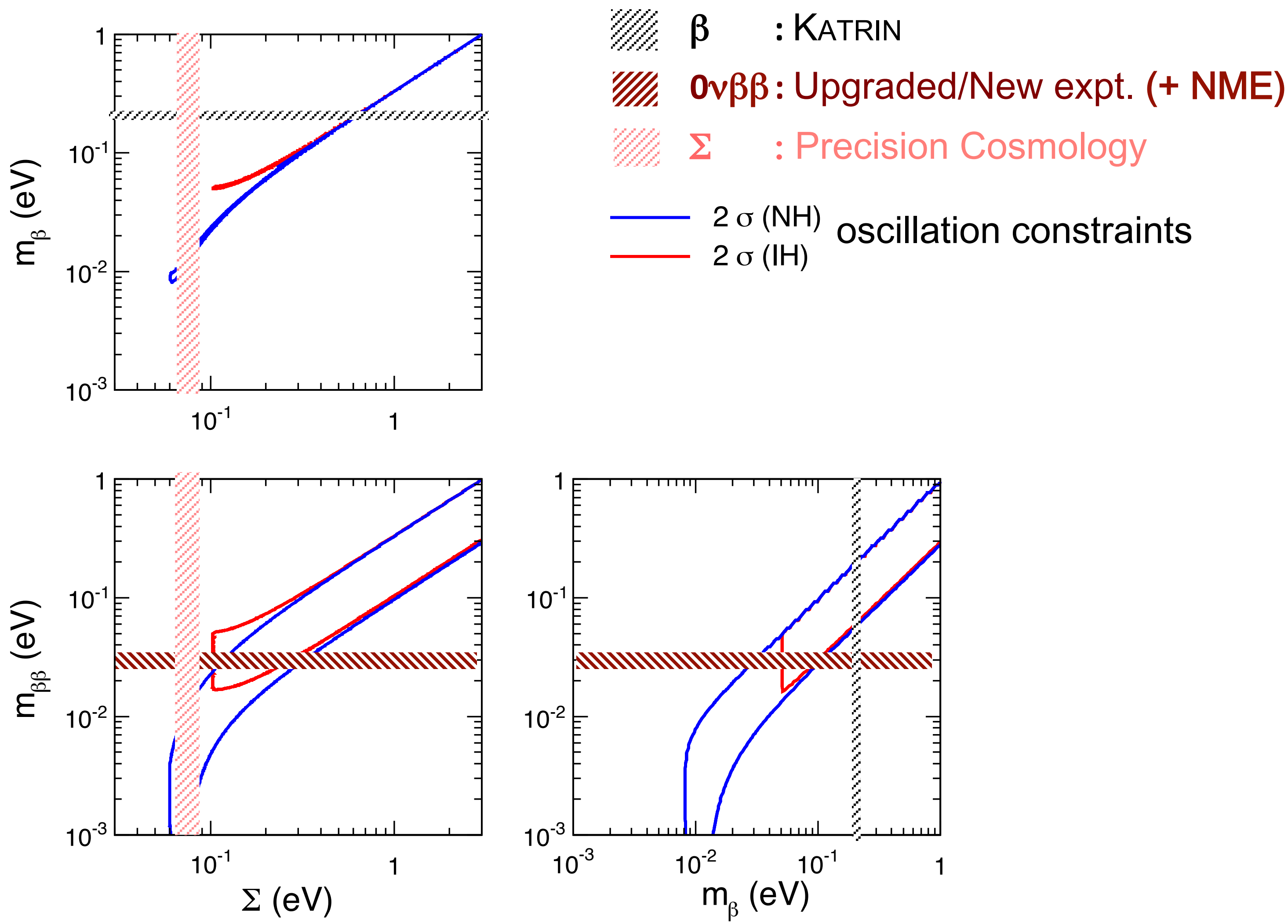
Major improvements expected in the next decade

Upper limits on m_β, $m_{\beta\beta}$, Σ in ~10 years ?



Large phase space for discoveries about ν mass and nature.

Upper limits on m_β, $m_{\beta\beta}$, Σ in ~10 years ?



Cosmology first? **Be prepared to $\Sigma>0$ (or IH rejection) claims!**

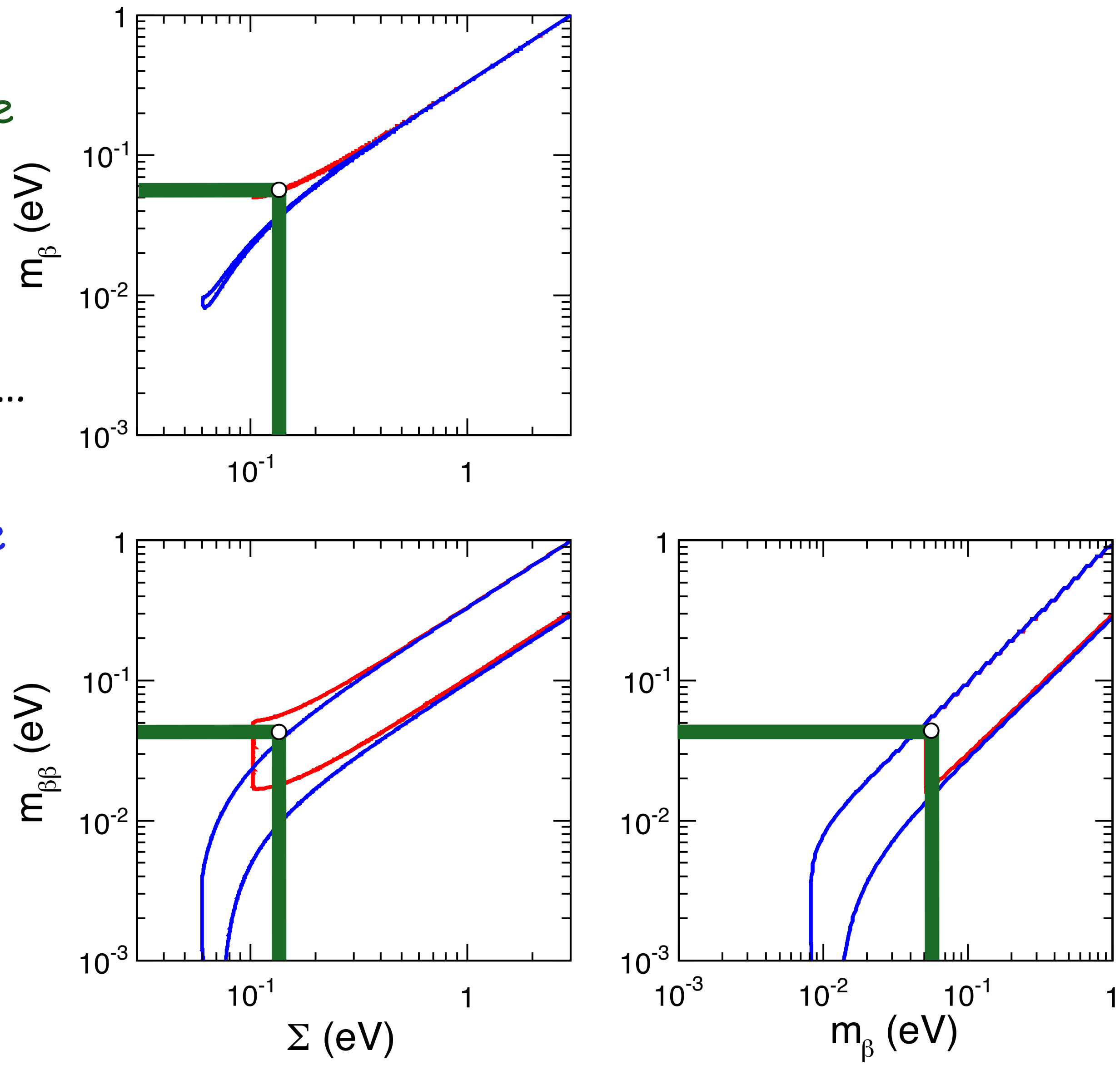
With "dreamlike" and converging data one could, e.g.

Determine the mass scale...

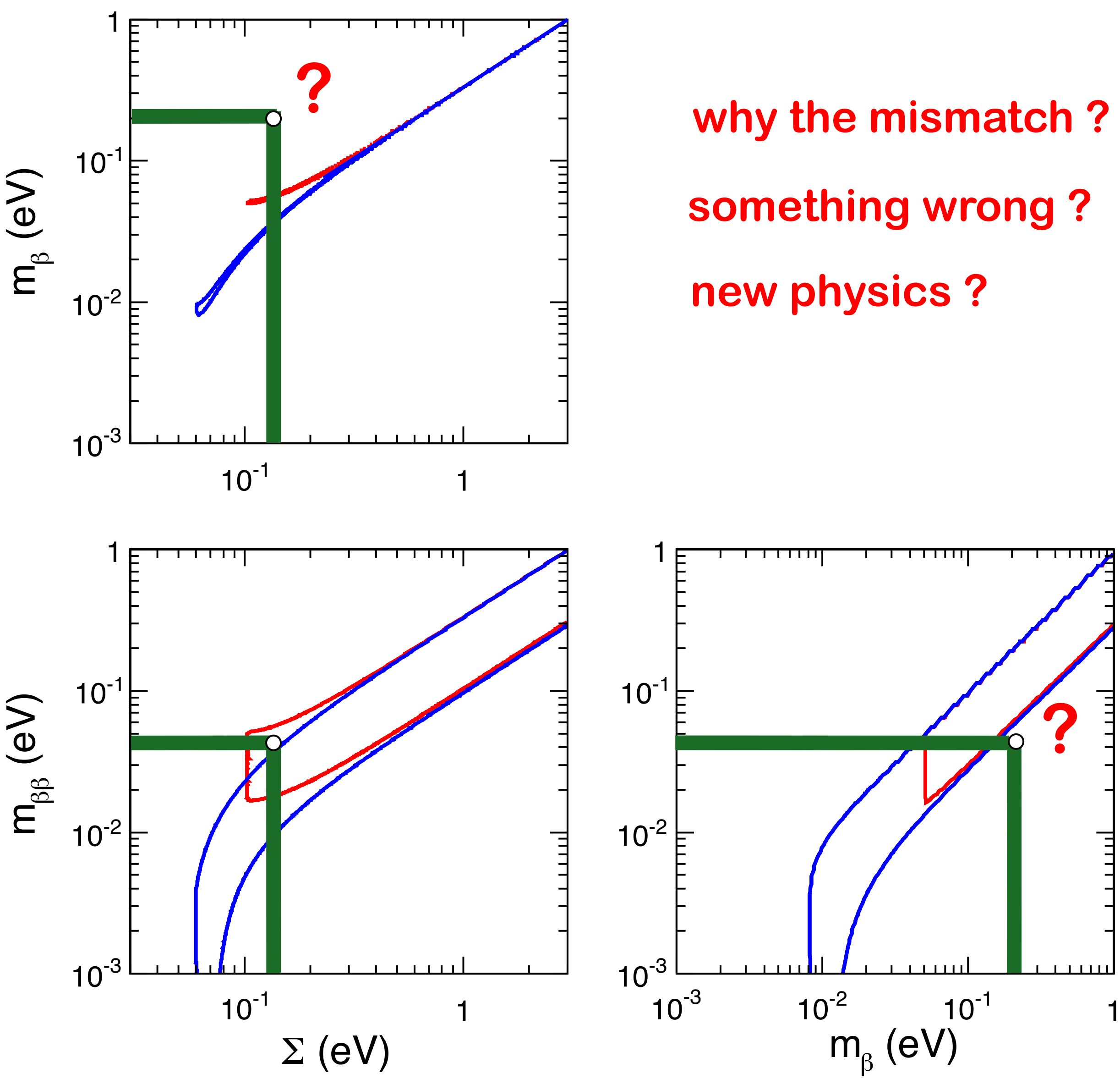
Check 3ν consistency ...

Identify the hierarchy ...

Probe the Majorana phase(s) ...



But “surreal” situations might also occur….



why the mismatch ?

something wrong ?

new physics ?

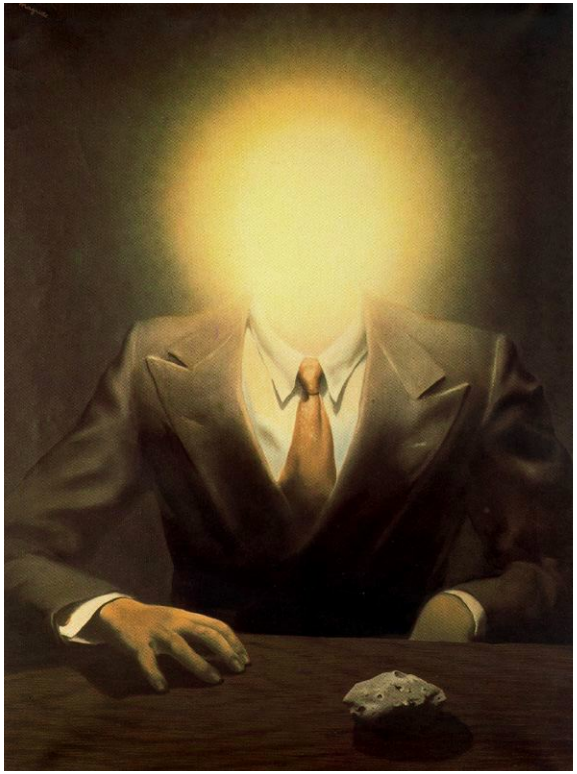
Warning: of course, a $0\nu\beta\beta$ discovery would tell us that ν=anti-ν and make us happy …

Not to be reproduced (1937)
Portrait of Edward James

Warning: of course, a 0$\nu\beta\beta$ discovery would tell us that ν=anti-ν and make us happy …

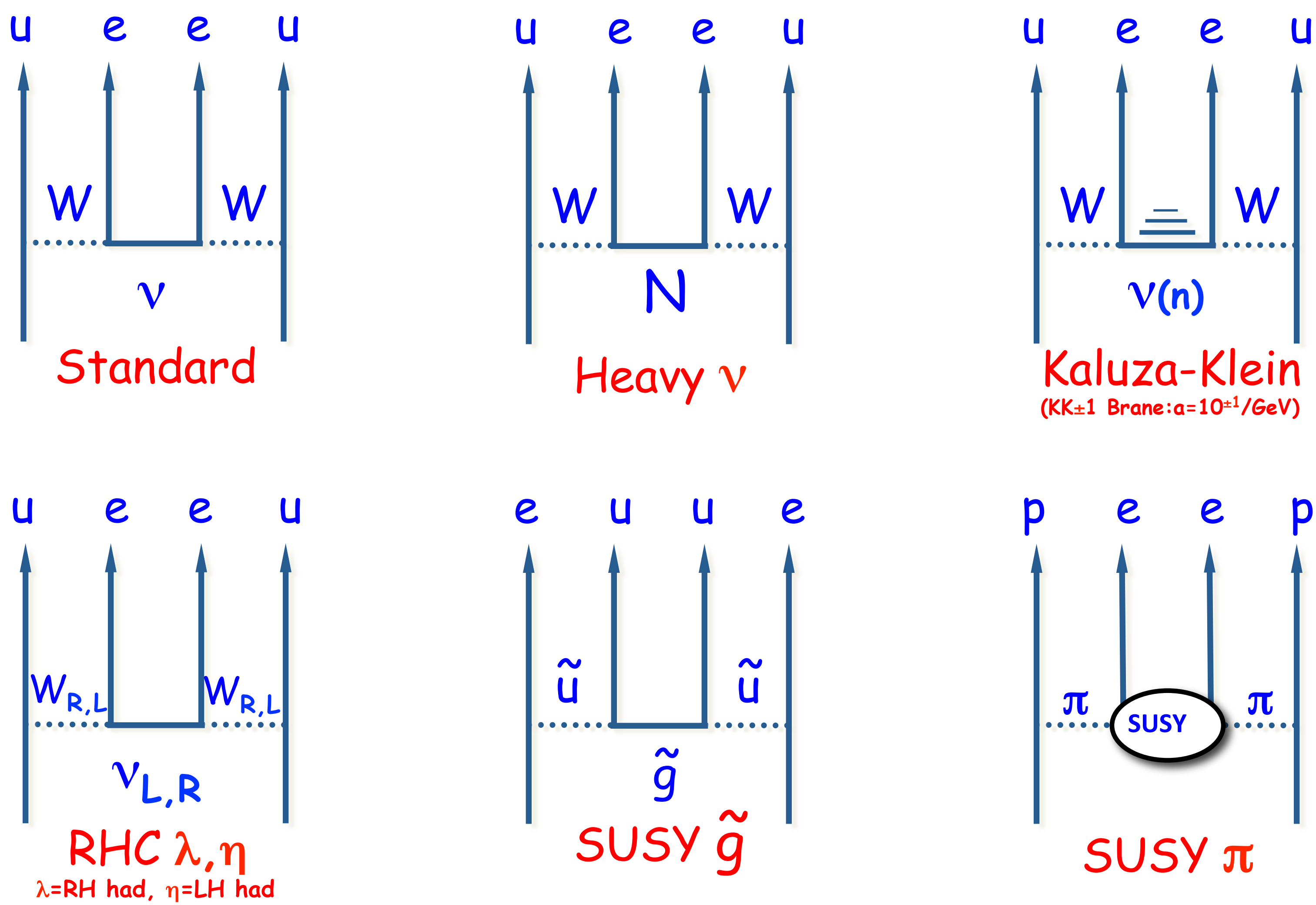
… but the identification of the underlying mechanism might be a much harder task …

Not to be reproduced (1937)
Portrait of Edward James



The pleasure principle (1937)
Portrait of Edward James

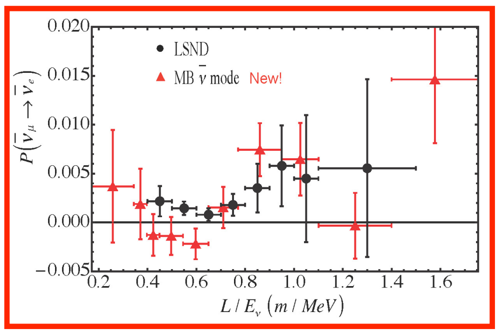
Physics beyond "3 light ν" should always be kept in mind:



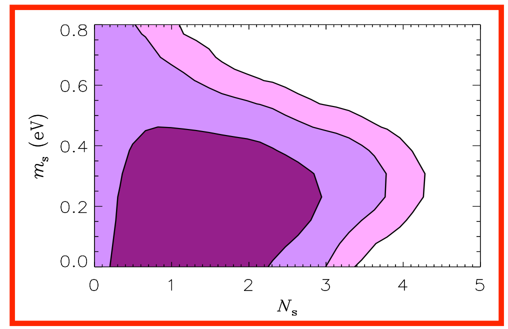
One scenario is under particular scrutiny:

Light steriles at O(1) eV scale, with small active-sterile mixing?
Prompted by some "anomalous" results still under investigation:

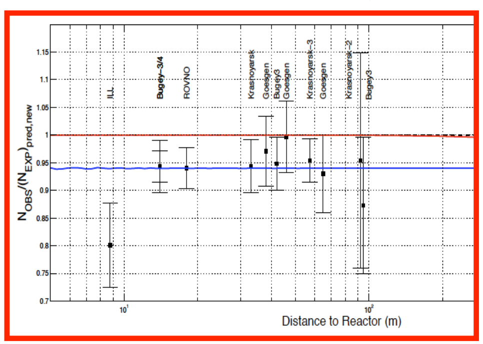
LSND/MiniBooNE (SBL)?



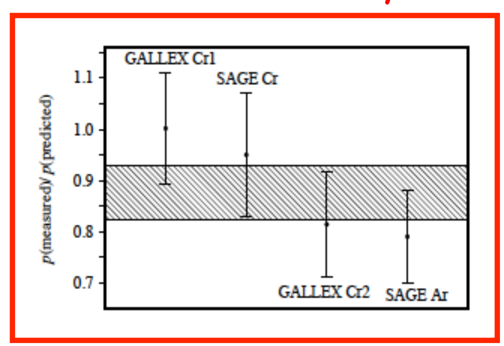
Extra cosmic radiation?



Reactor anomaly?

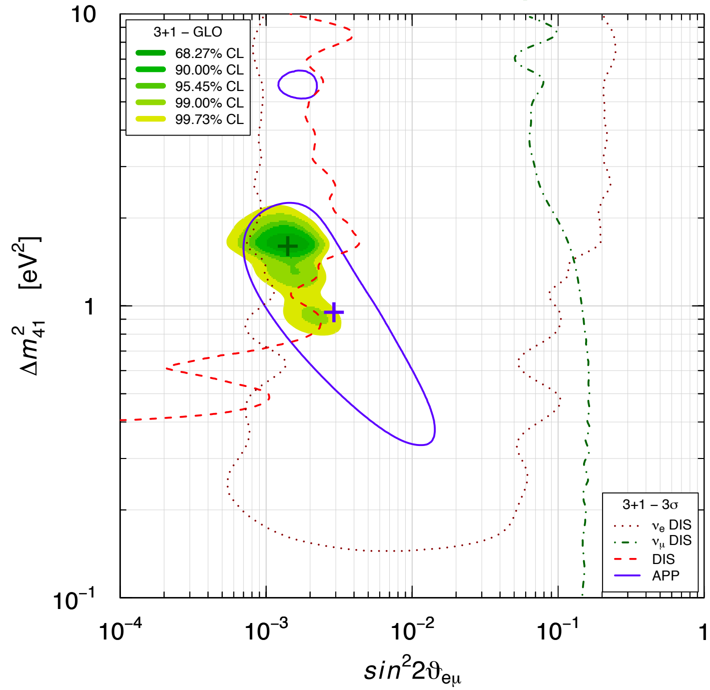


Gallium anomaly?



3+1 Global Fit

[Preliminary 2014 Update]



- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND (Y), MiniBooNE (?), OPERA (N), ICARUS (N), KARMEN (N), NOMAD (N), BNL-E776 (N)
- DIS ν_e & $\bar{\nu}_e$: Reactors (Y), Gallium (Y), ν_eC (N), Solar (N)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW (N), MINOS (N), Atmospheric (N), MiniBooNE/SciBooNE (N)

MiniBooNE $E > 475$ MeV

GoF = 26% PGoF = 7%

No Osc. excluded at 6.3σ

$\Delta\chi^2/\mathrm{NDF} = 47.7/3$

[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008]

[different approach and conclusions: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

From Giunti et al. 2014. Note: Kopp et al. 2014 find worse GOF.

In general, tension between appearance and disappearance oscillations.

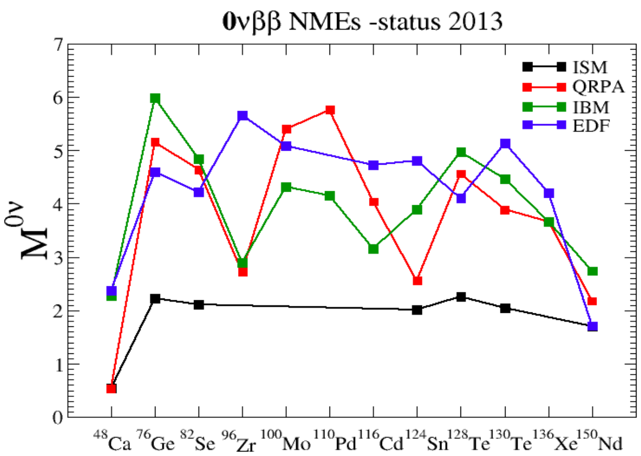
Also: some tension between oscillation and cosmology (not included above)

Several tests of sterile ν hypothesis underway.

Even within 3ν, theory will help in "seeing what is hidden by what we see"

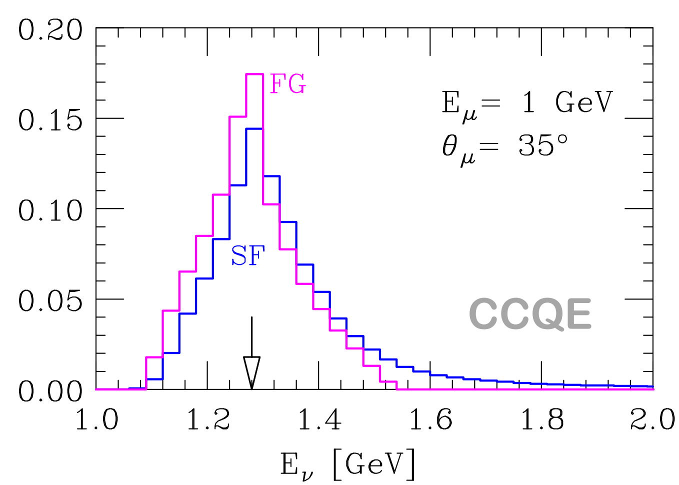
Two examples of well-defined, long-term theory programs:

Must improve modeling of nuclear structure, to understand and compare signals or limits on 0νββ decay rates and related weak/strong processes



Simkovic at NOW 2014

Must improve modeling of ν-nucleus cross sections, to understand energy spectra in accelerator and atmospheric searches for CPV and mass hierarchy



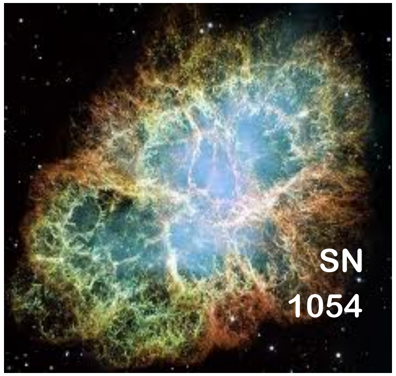
Benhar at NOW 2014

Require joint effort from nuclear and particle phys. communities

Improvements will help to refine future global data analyses

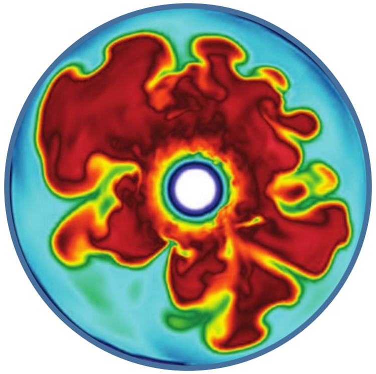
Another long-term theory program for an "unpredictable" event:

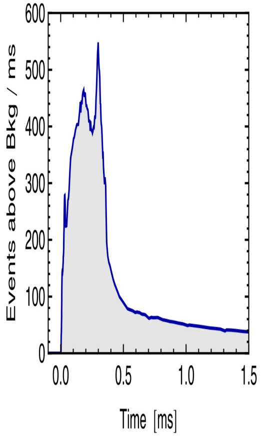
Sooner or later (say, 10±10 years ?), another galactic SN should explode... Its "autopsy" will keep us busy for decades, and teach us a lot about astrophysics and neutrino physics.



Raffelt at NOW 2014

Simulations of SN explosions, (anti)nu fluences and flavor transitions, which are already very demanding, will need to reach complexity levels comparable -probably- to QCD lattice calculations.





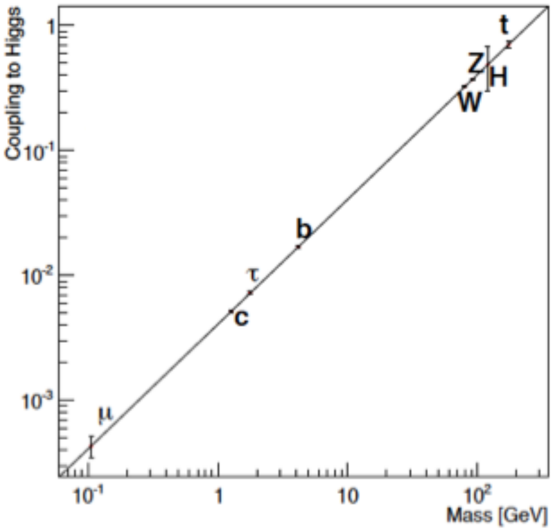
Will spark a truly interdisciplinary program from diverse communities

Long-term perspectives

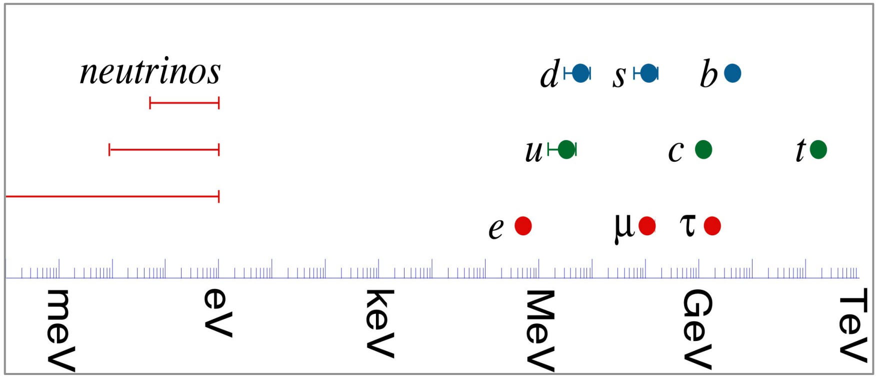
Clarvoyance (1936)

Bridging two fundamental research programs

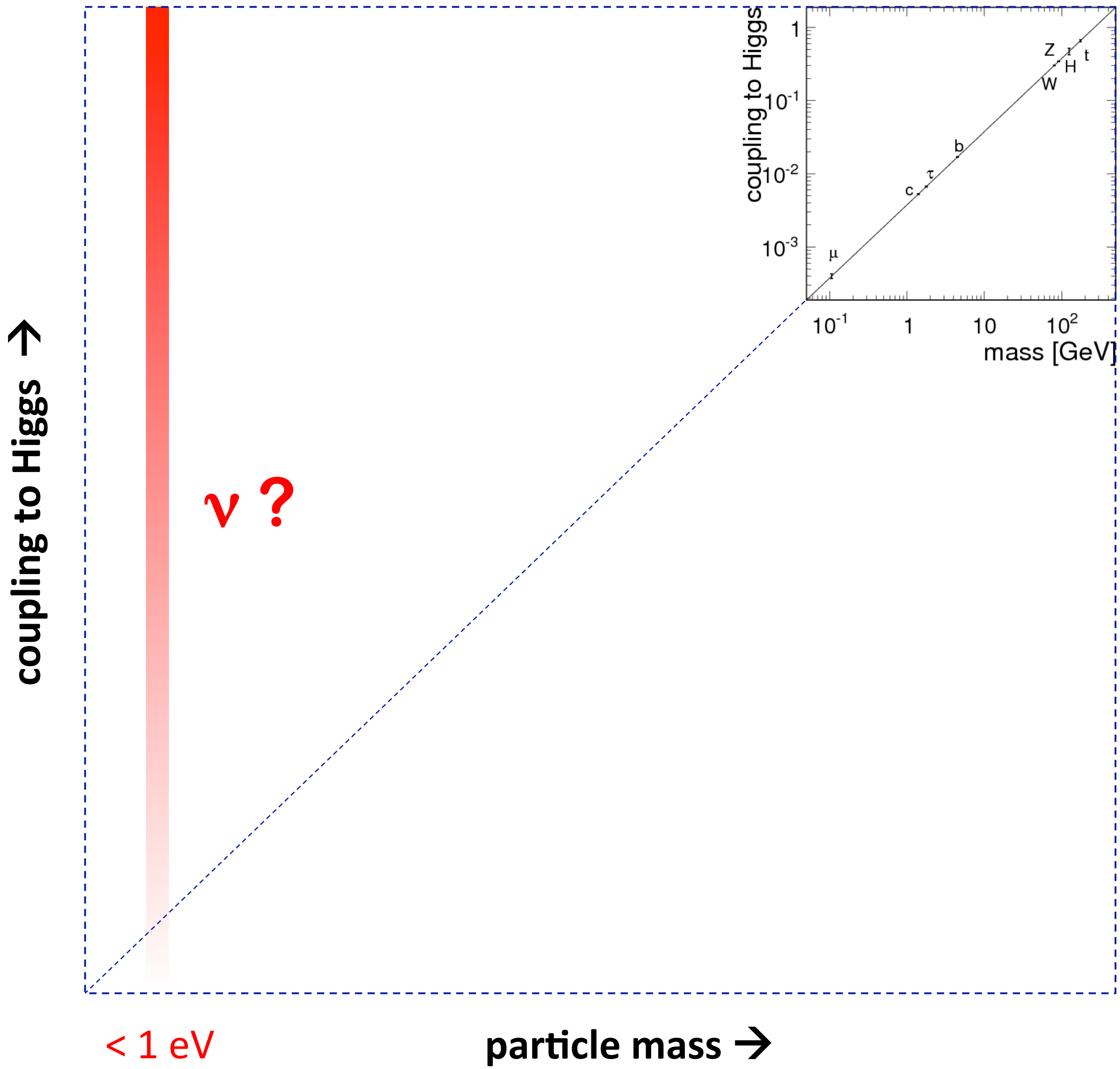
1. Test Higgs sector



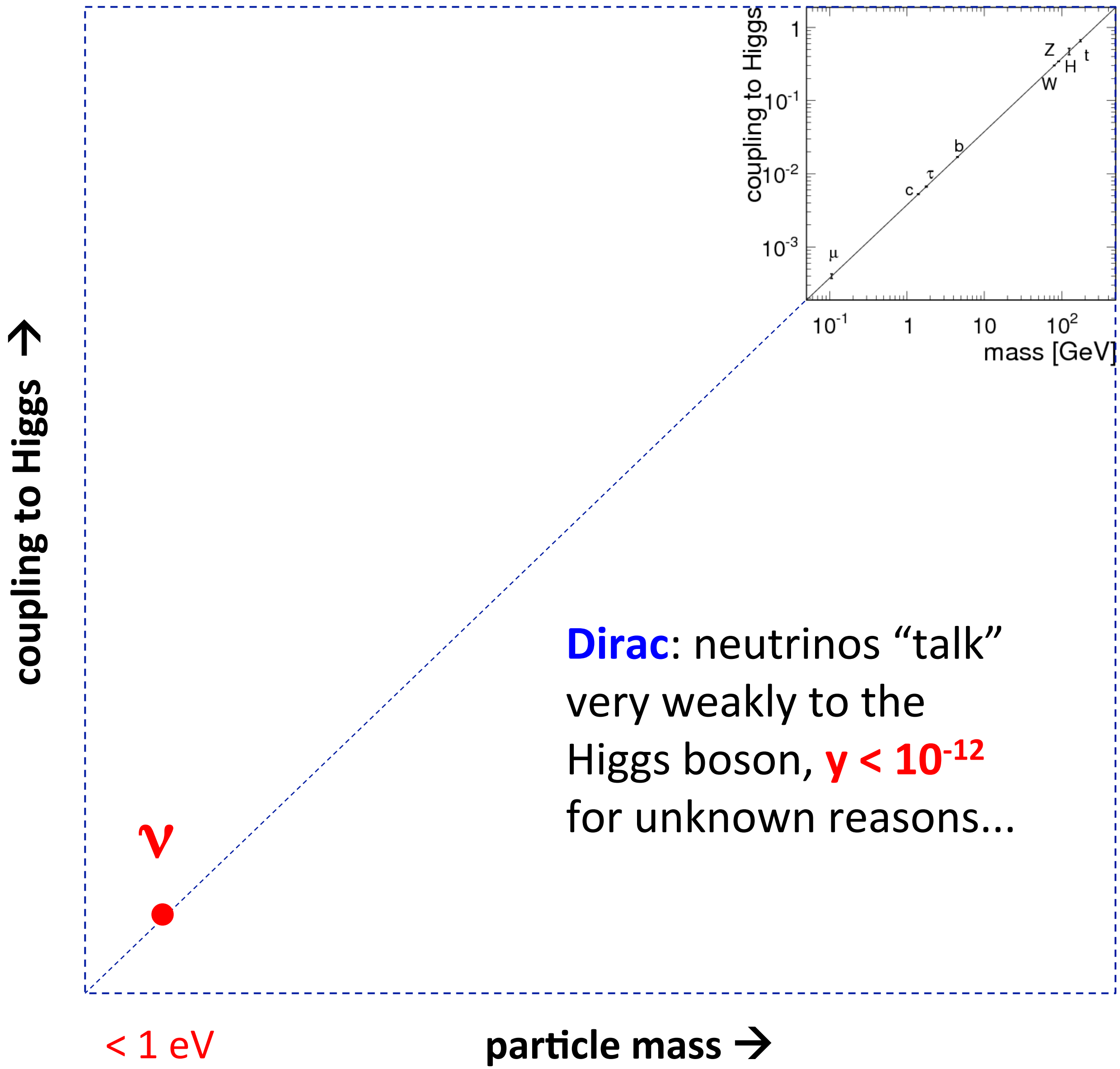
2. Find ν masses



1 + 2 Where are the ν's on this plot? Why are they so light?

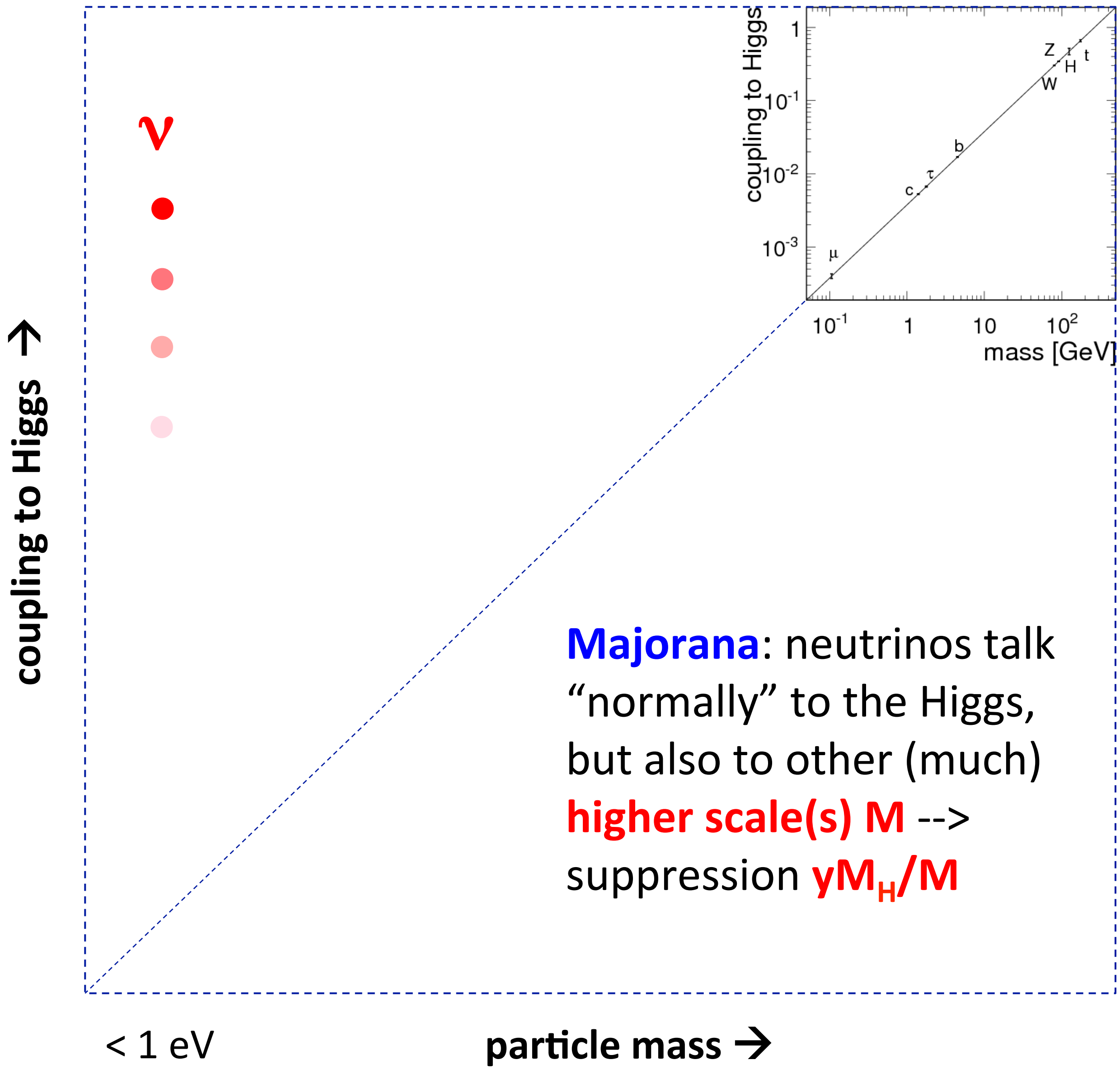


Options:



Dirac: neutrinos "talk" very weakly to the Higgs boson, **$y < 10^{-12}$** for unknown reasons...

Options:



Majorana: neutrinos talk "normally" to the Higgs, but also to other (much) **higher scale(s) M** --> suppression **yM_H/M**

Neutrinos masses may offer a great opportunity to jump beyond the EW framework via the see-saw mechanism…

… and to address fundamental physics issues, such as:

- new sources of CP violation at low and high energies
- lepton number violation and associated phenomena
- **matter-antimatter asymmetry of the universe …**

M ~ GUT scale

CP-violating decays of heavy neutrinos at scale M may generate lepton asymmetry (leptogenesis):
Discovery of leptonic CP violation and of Majorana nature (+ proton decay?) would be important steps towards this scenario.

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M ~ low scale

At the other end of the spectrum, low-scale (e.g. EW) see-saw may also generate (at the price of fine-tuning) additional interesting phenomenology: dark matter candidates, di-lepton and heavy lepton events in HEP

CP-violating decays of heavy neutrinos at scale M may generate lepton asymmetry (leptogenesis). **Discovery of leptonic CP violation and of Majorana nature (+ proton decay?) would be important steps towards this scenario.**

At the other end of the spectrum, low-scale (e.g. EW) see-saw may also generate (at the price of fine-tuning) **additional interesting phenomenology: dark matter candidates, di-lepton and heavy lepton events in HEP**

In principle, several sterile states might even be split among widely difference energy scales, and contribute to various phenomena in (astro)particle physics.
Let us remain open-minded!

EPILOGUE

"Everything
we see...

$\delta m^2 \sim 8\times10^{-5}$ eV^2
$\Delta m^2 \sim 2\times10^{-3}$ eV^2
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

EPILOGUE

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... hides another thing,
we always want to see...

$\delta(CP)$
sign(Δm^2)
octant(θ_{23})
absolute masses
Dirac/Majorana

EPILOGUE

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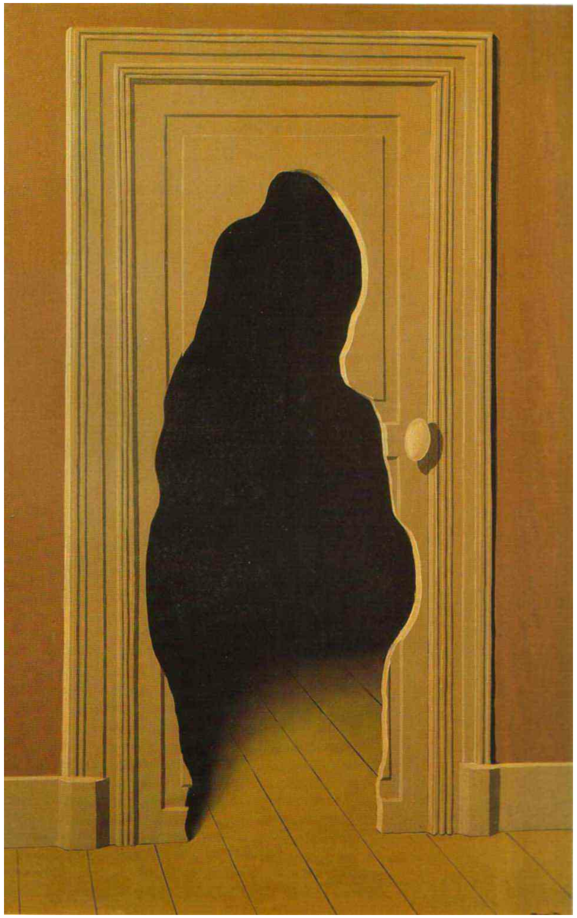
... hides another thing,
we always want to see...

δ(CP)
sign(Δm^2)
octant(θ_{23})
absolute masses
Dirac/Majorana

... what is hidden
by what we see."

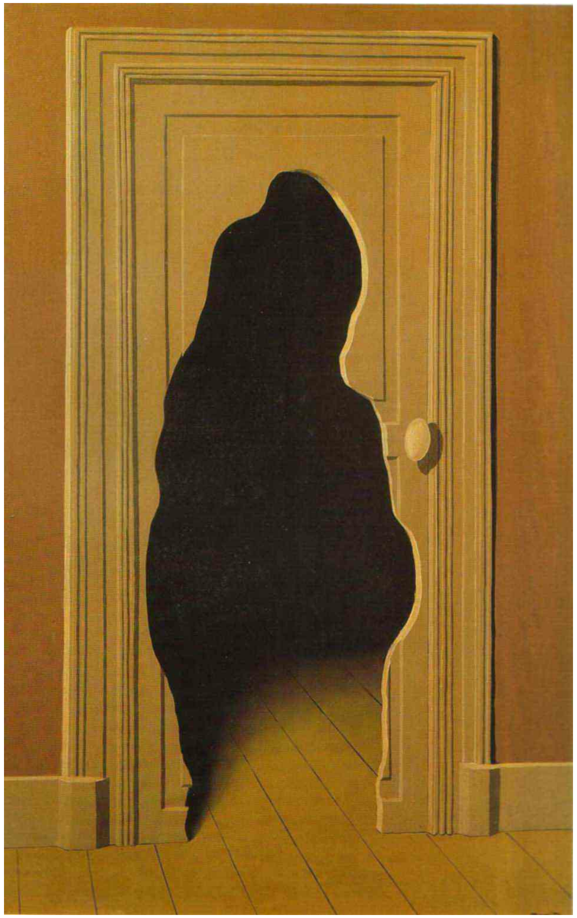
new light states
new heavy states
nonstandard inter.
flavor structure
lepton/baryon asym

ν as a door to hidden physics...



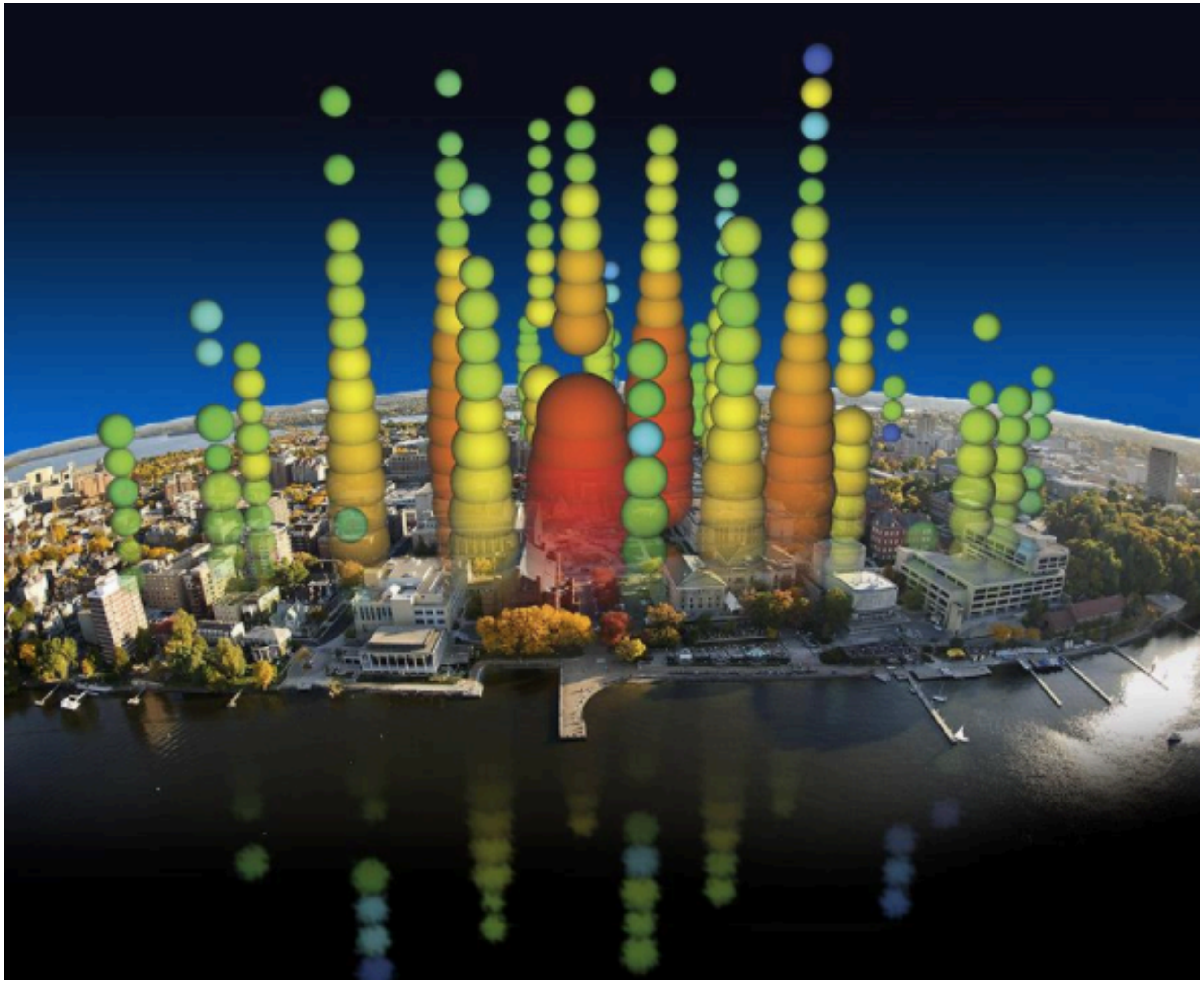
Unexpected answer (1933)

Thank you for your attention…



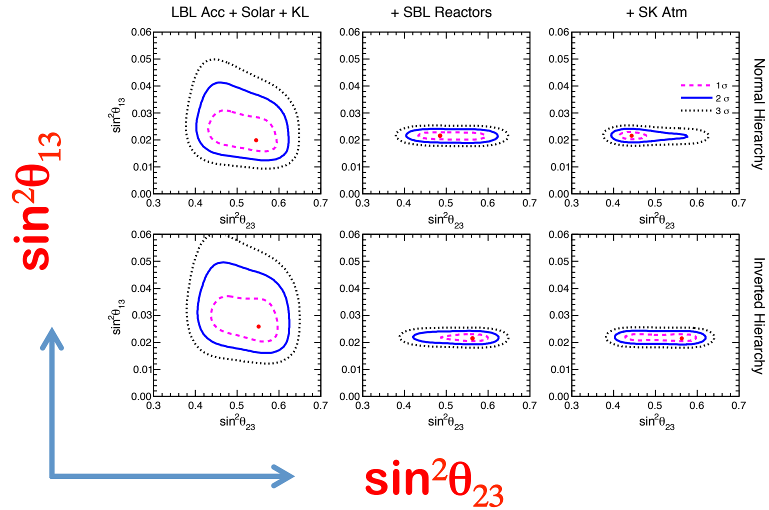
Unexpected answer (1933)

… and thank you, Francis, for surreal* neutrino events!



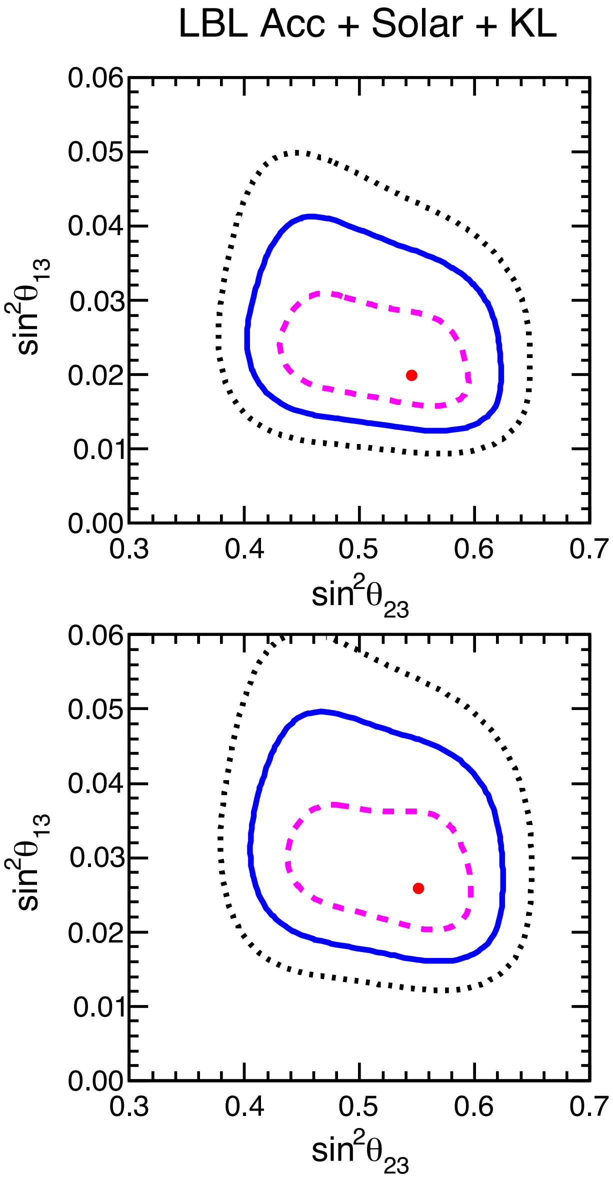
**very strange or unusual: having the quality of a dream.*

Extra slides



Leading appearance amplitude at LBL Acc. ~ $\sin^2\theta_{23}\,\sin^2(2\theta_{13})$
→ **anticorrelates** θ_{23} **and** θ_{13}

Leading disappearence amplitude at SBL Reac. ~ $\sin^2(2\theta_{13})$
Subleading disappearence effects in Solar + KL ~ $\sin^2\theta_{13}$
→ **indirectly helps in selecting** high vs low θ_{23}

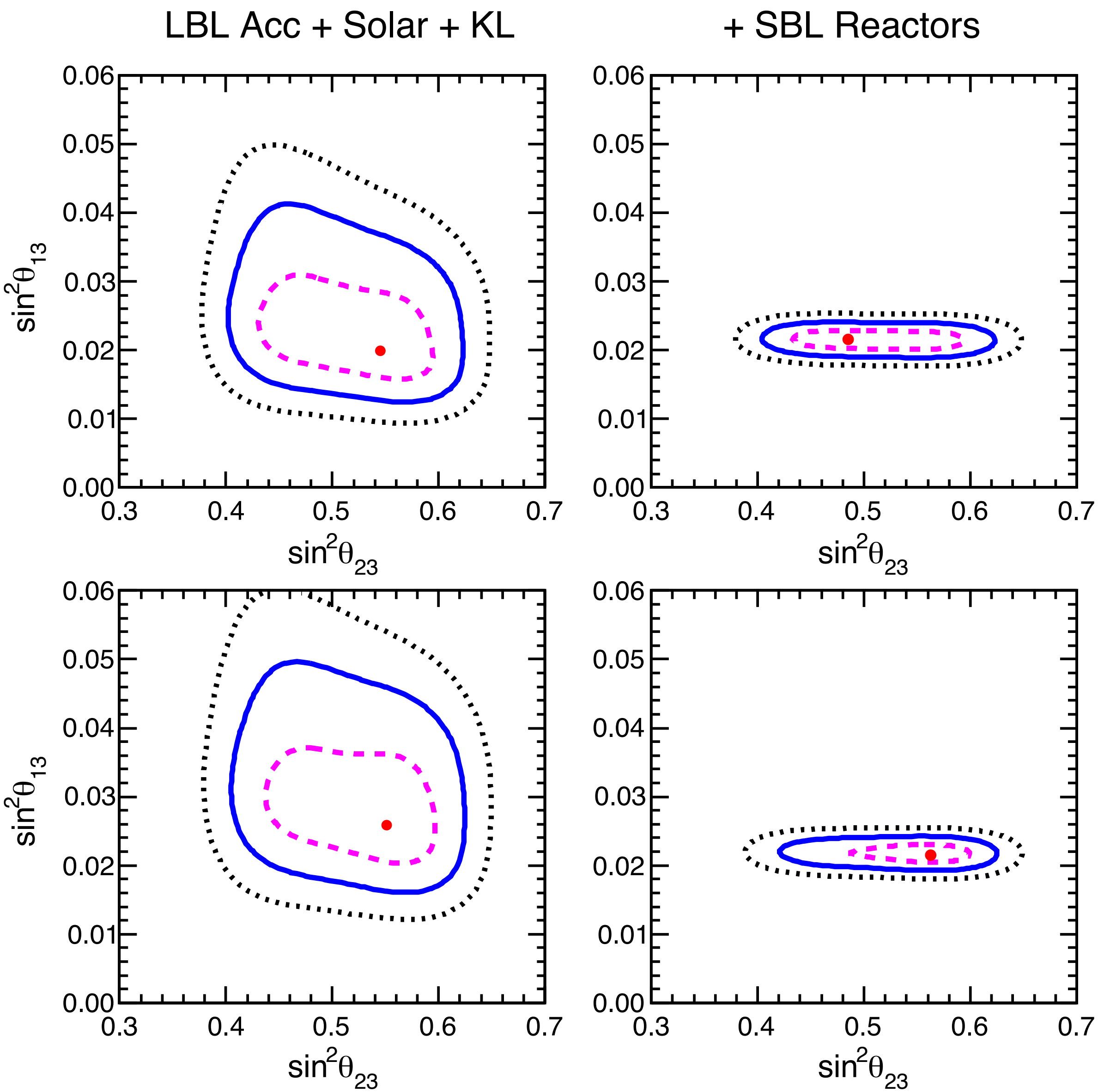


MINOS disappearance prefers nonmaximal mixing (still wins over T2K preference for ~maximal) → two degenerate minima for θ_{23}

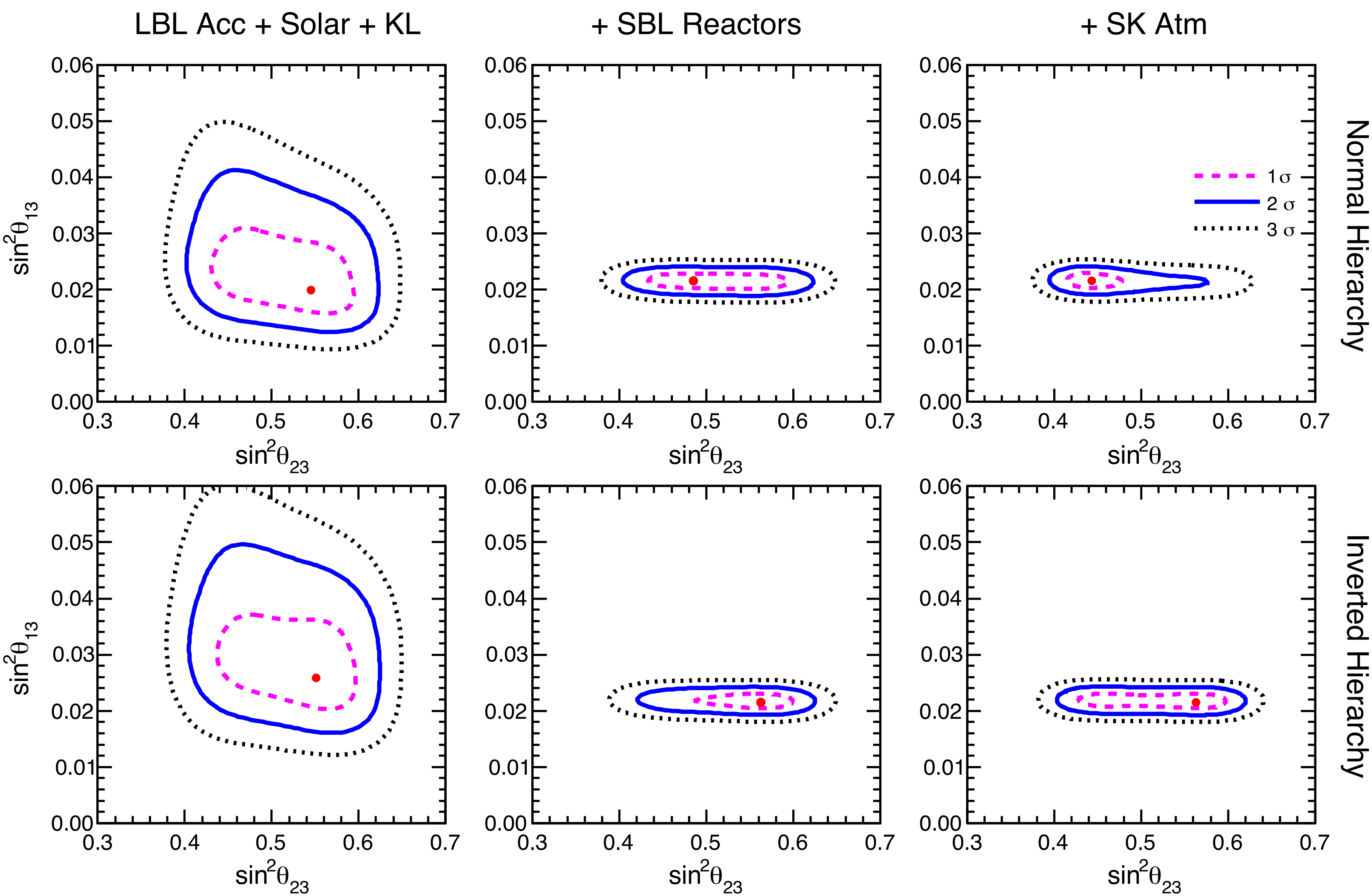
T2K + MINOS appearance anticorrelate the minima with θ_{13}: the higher θ_{23}, the lower θ_{13}

Contours extend to relatively high $\sin^2\theta_{13}$ to accommodate the relatively "strong" T2K appearance signal, especially in IH

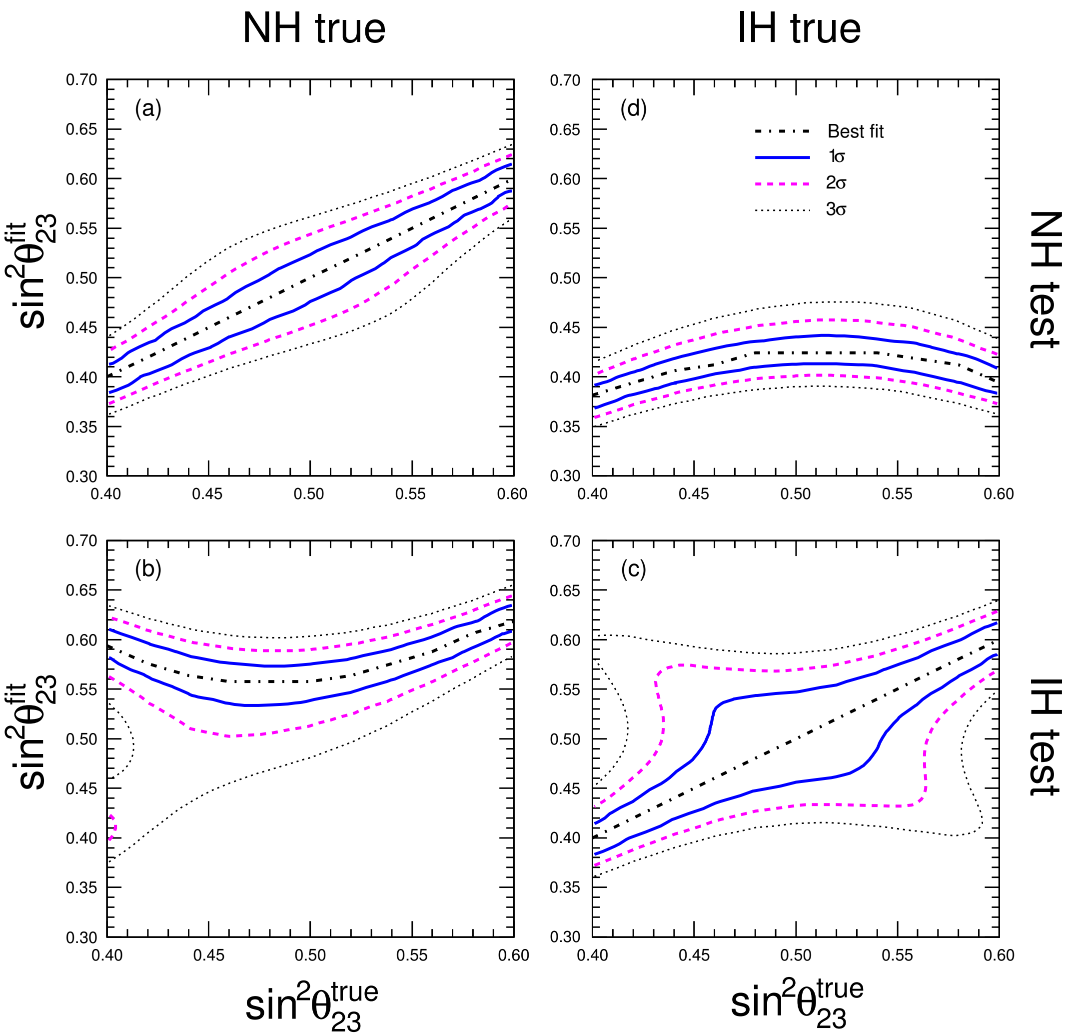
In the combination, Solar + KL data lift the degeneracy and prefer the second octant solution, associated with "low" $\sin^2\theta_{13}$~0.02



Reactor data prefer $\sin^2\theta_{13}$~0.022, slightly higher than Solar+KL: **enough to flip the octant in NH, but not enough to do so in IH.**



SK atm: In our analysis we still find an overall preference of these data for 1st octant. But, global octant balance rather fragile.



Hierarchy & octant sensitivity study for PINGU, arXiv:1503.01999