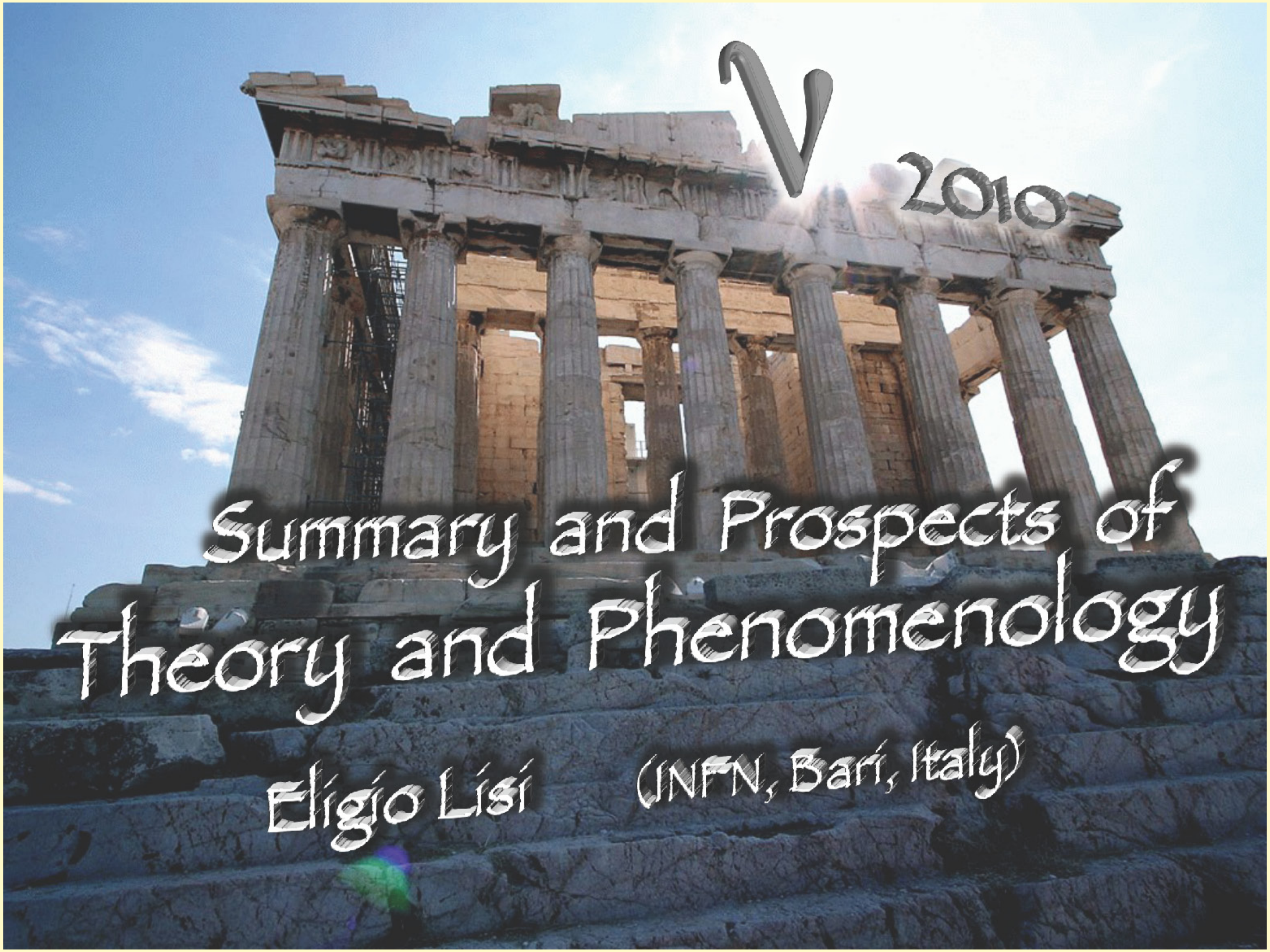
INIFA 2010 – Frascati



Eligio Lisi – Report from Neutrino 2010

Outline:

Prologue

1. Neutrino mixing and oscillations
2. Neutrino mixing and masses
3. Neutrino interactions
4. Astrophysical/cosmological neutrinos

Epilogue

~~Neutrino beams and sources~~

~~Future detectors and experiments~~

~~Neutrino technology/applications~~

PROLOGUE

Before commenting recent results... let's go back in time.
A Latin saying:

Nomen [est] Omen

"Name [is] Destiny"

Neutrino - What's in a name?

The root of the name [neutrino] … is a [kwa]stion

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!

Modern declinations of an ancient meaning:

KOTEROS … Which of the two …

Which of the two … hierarchies (normal, inverted) …

Which of the three … see-saw types (I, II, III) - if any…

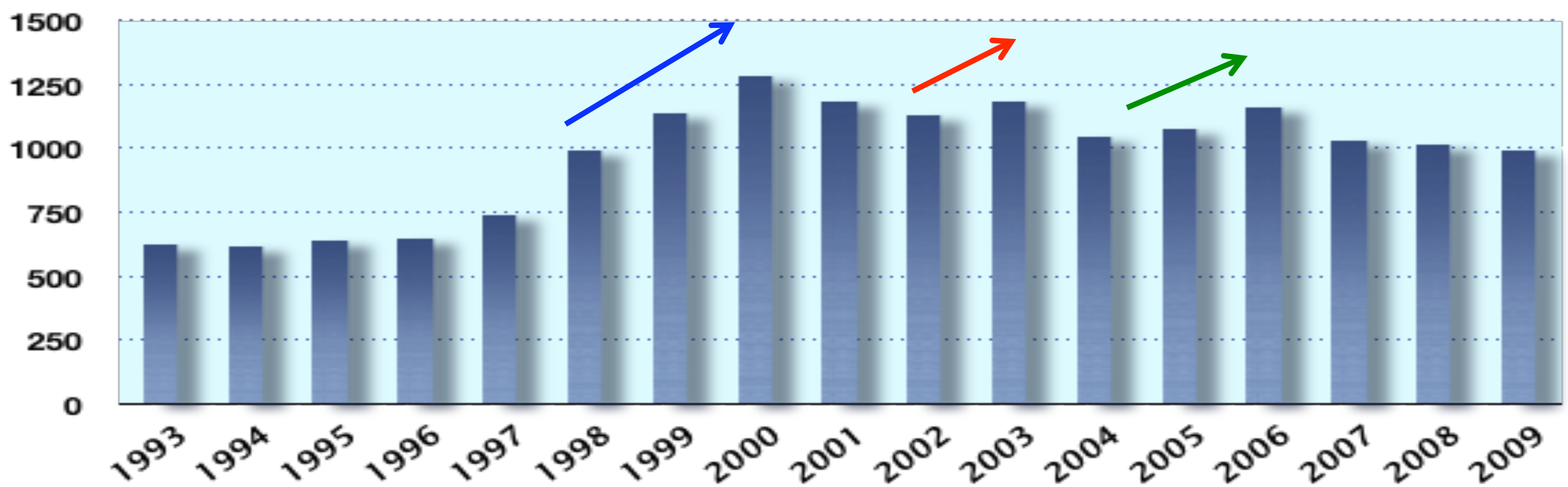
Which of the many … scales of new physics …

…………………

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!]

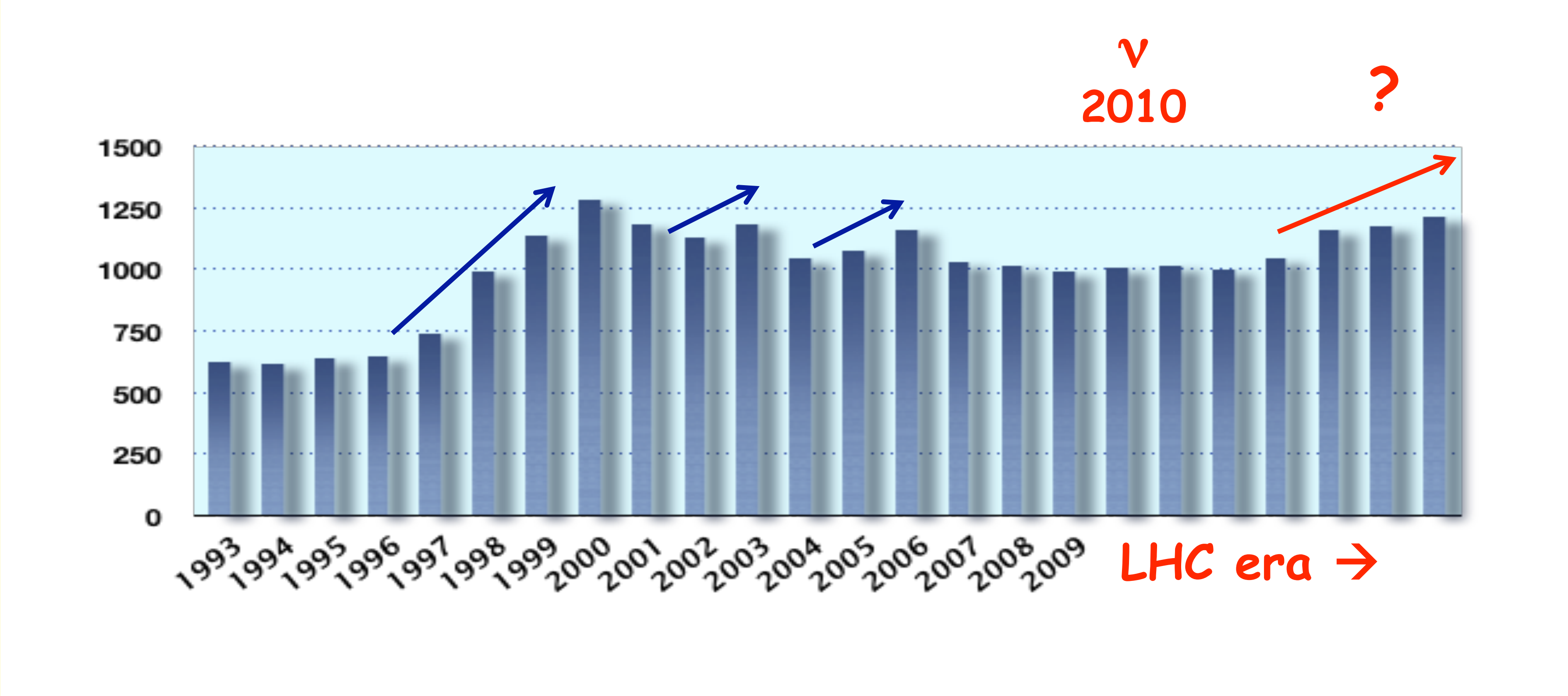


papers with "neutrino(s)" in title (from SPIRES)

New answers/questions/prospects at this Conference!

→ Current theory/pheno news & trends

→ Expectations for neutrinos in the LHC era



surprises…
surprises…
surprises… [Parke]

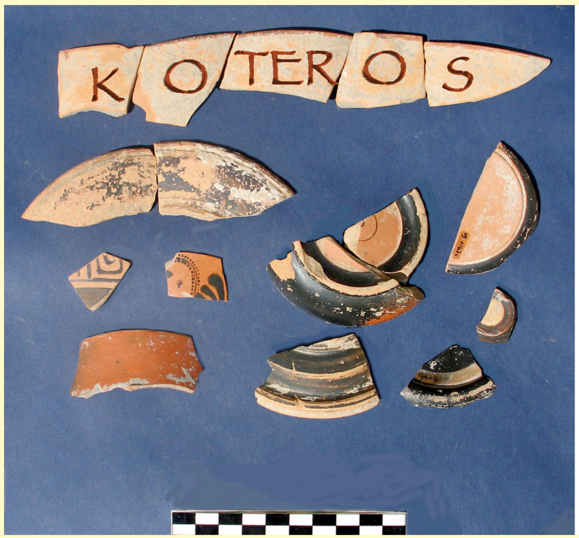
The dream:

find many fragments of new physics…

… piece them together…

… recover the picture

Usual nightmares:



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

...too many options for reconstruction
(or none of them!)

1. Neutrino mixing and oscillations

3ν parameter accuracy
[J. Valle]:

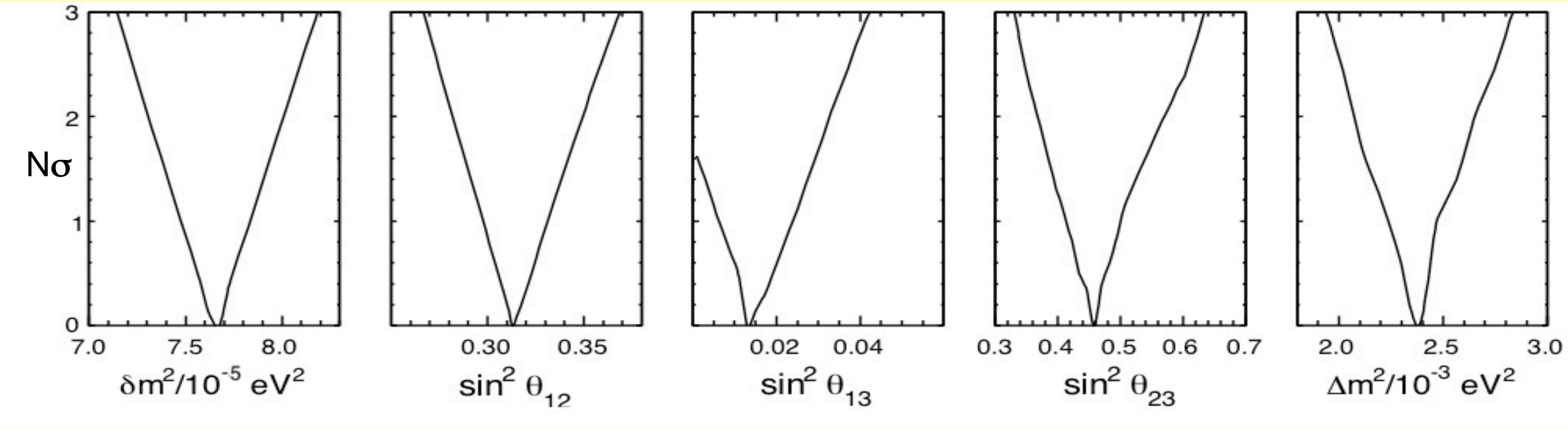
$\sigma(\delta m^2)$ ~ 2.5%
$\sigma(\Delta m^2)$ ~ 5%
$\sigma(\sin^2\theta_{12})$ ~ 6%
$\sigma(\sin^2\theta_{23})$ ~ 11%

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

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

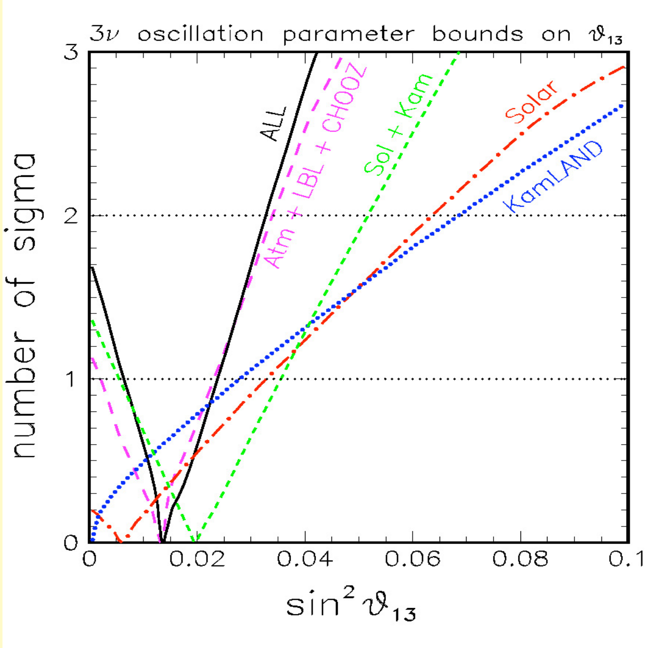
STATUS just before ν 2010… Our preliminary 2010 update*

(including MINOS app./disapp., SK-I+II+III atm, new Gallium, SNO-LETA, new SSMs):



$\sin^2\theta_{13}$: best fit 0.013; 1.7σ "hint"

This analysis is not only preliminary, but already obsolete… It needs to be revised after **new results from MINOS (disapp), Super-K,…,** as presented at this meeting!



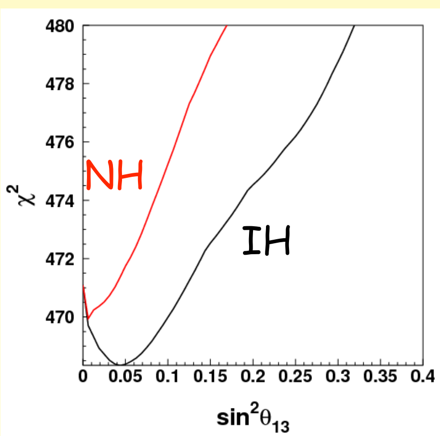
*Fogli, EL, Marrone, Palazzo, Rotunno

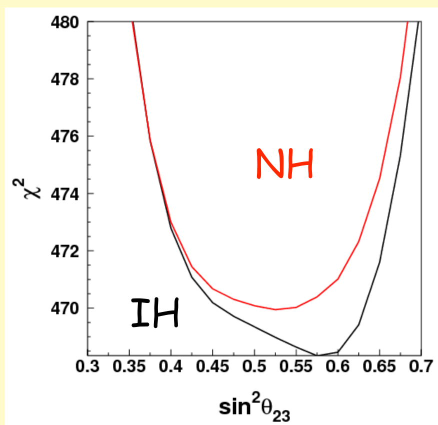
STATUS of $\theta_{13}>0$ "hints," from presentations at ν 2010:

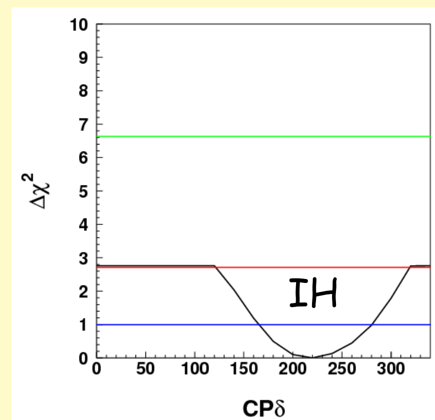
Solar+KamLAND: ~1.3σ [Valle, Klein, Takeuchi];
Note: new SK solar data! [Takeuchi];
new KamLAND data upcoming [Inoue];
final SNO analysis upcoming [Klein].

MINOS appear.: ~0.7σ [Vahle]; new MINOS data upcoming

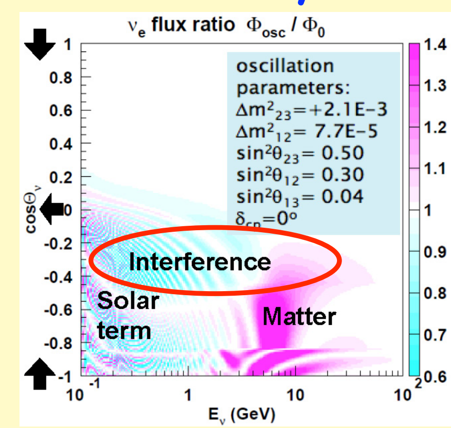
SK atmospheric: ~1.5σ [Takeuchi] from full 3ν analysis (new!),
showing also weak sensitivity (~1-1.5σ)
to **NH/IH**, δ_{CP}, θ_{23} **octant**.





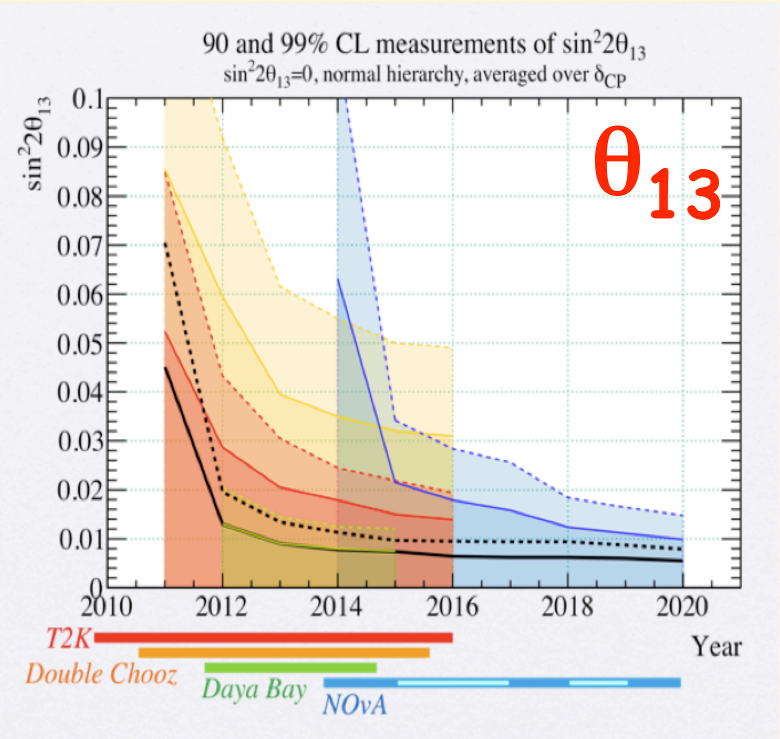


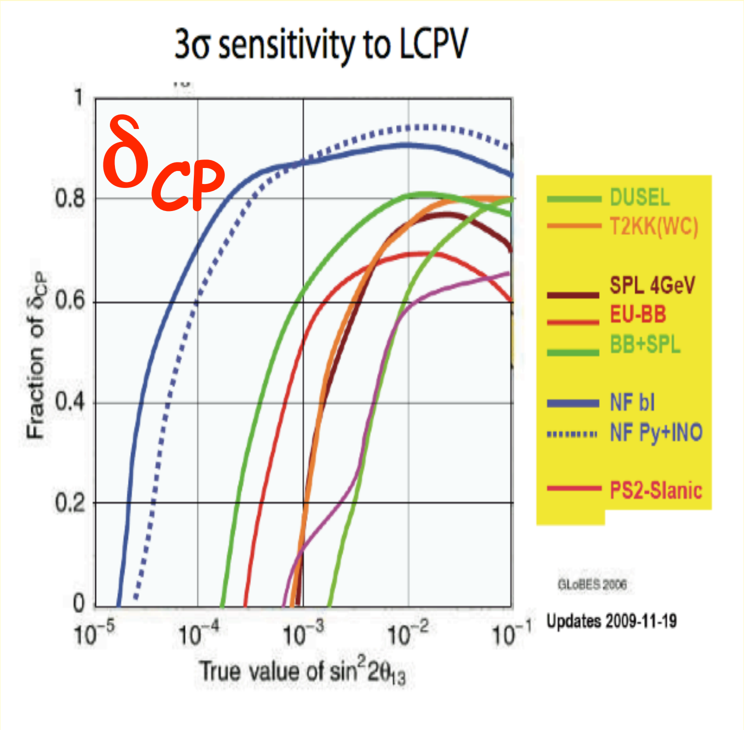
Theory



Maybe these tiny fragments are just "intriguing fluctuations"… [E. Resconi]
But they add motivations for future large-volume detectors [M. Shiozawa].

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.





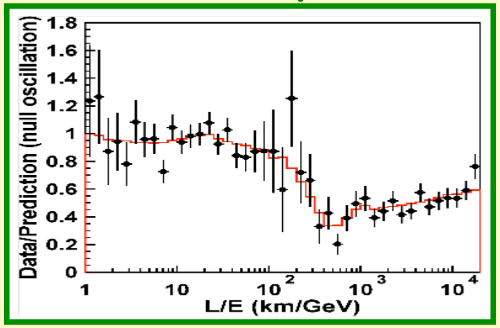
[S. Parke] + many other talks

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 might lead to **surprises** if there is new physics not far away.

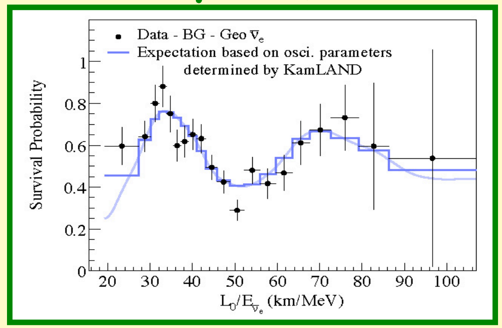
Indeed, it's not just a question of nailing down 3ν parameters…

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

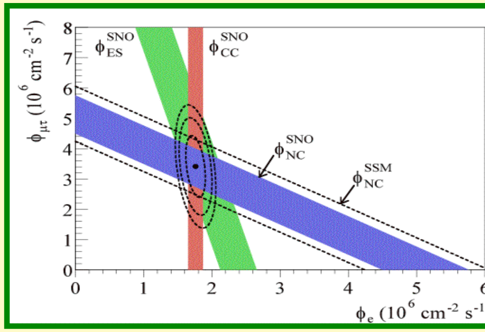
½ oscillation cycle (SK)



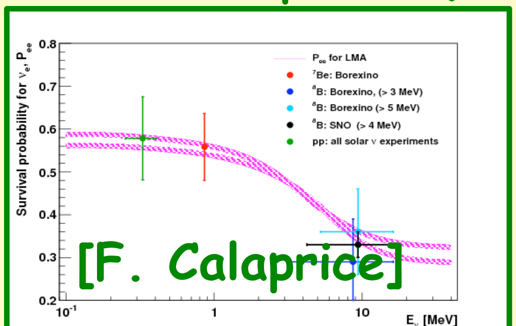
1 oscill.cycle (KamLAND)



^{8}B SSM flux test (SNO)



MSW adiab. profile (BX)



ν / anti-ν CPT (SK)

Neutrino:

$\Delta m_{23}^2 = 2.1\times10^{-3}\,eV^2$

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

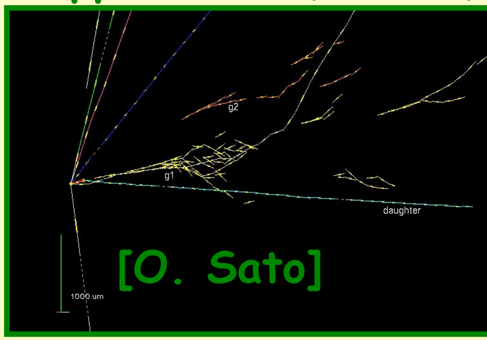
[Takeuchi]

Anti-neutrino:

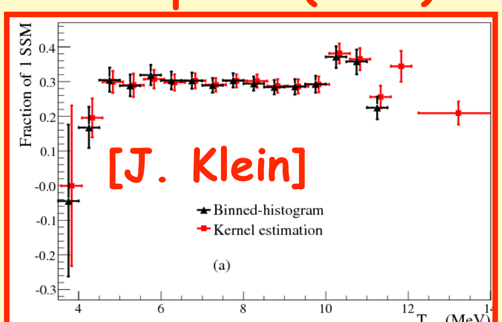
$\Delta m_{23}^2 = 2.0\times10^{-3}\,eV^2$

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

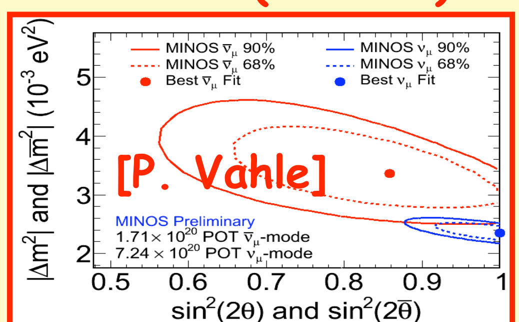
τ appearance (OPERA)



MSW upturn (SNO) ?



ν / anti-ν (MINOS) ??



???

Your favorite anomaly here

A persistent -but evolving- anomaly: LSND/MiniBooNE

ν_s oscillation interpr.: remains difficult after last results [G. Karagiorgi]

3ν? No!

3+1? Not a good fit*

3+2? Not a good fit*

*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 [Van deWater] [Guglielmi] …

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

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":

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

[Simkovic]

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

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

[Valle]
[Rodejohann]
[Simkovic]
[Mohapatra]

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

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

[Wong]

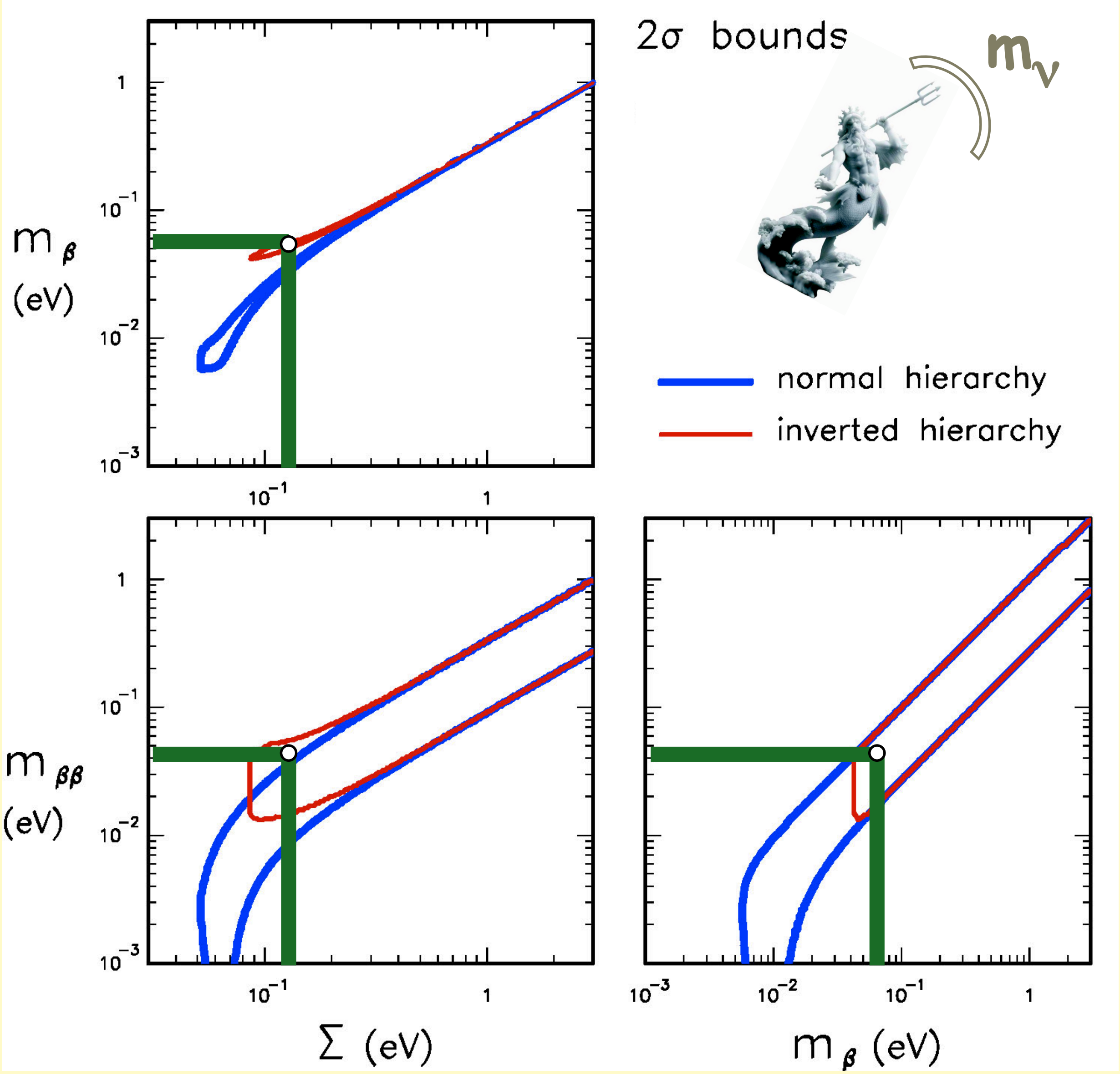
*in first approximation

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

Determine the mass scale…

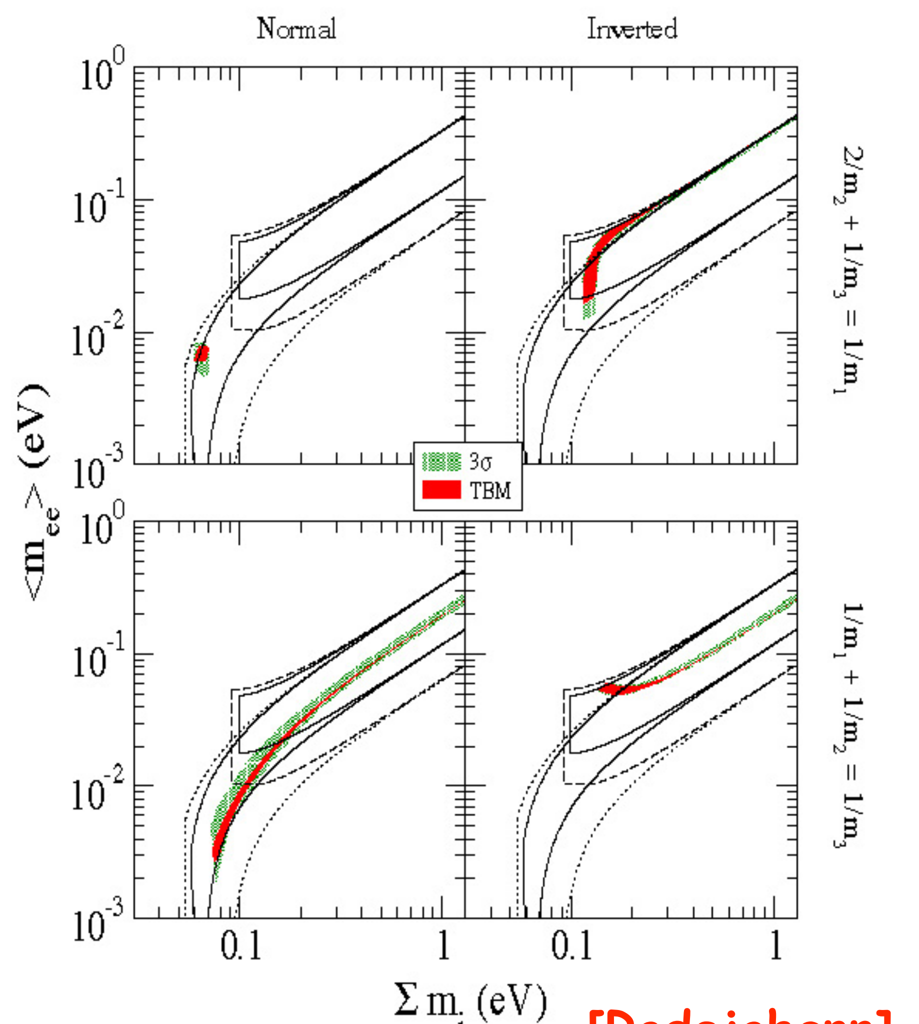
Identify the hierarchy …

Probe the Majorana nature and phase(s)…

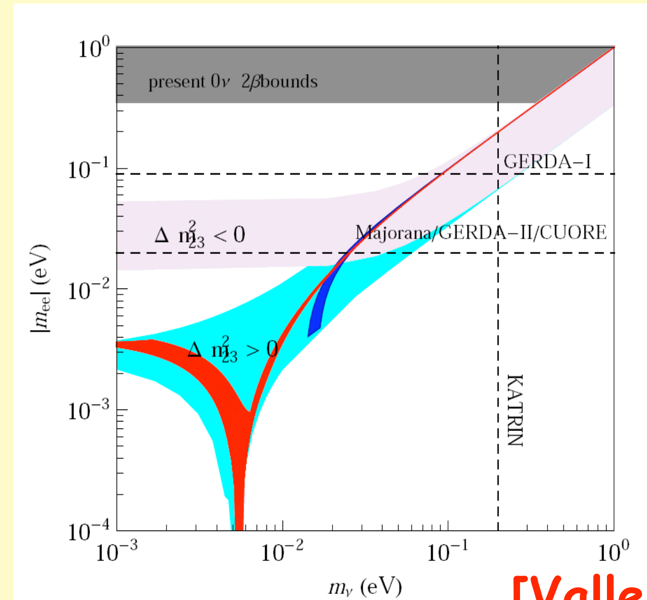


Relevant to constrain/support leptogenesis scenarios [Di Bari]

More dreams…: future, highly accurate data (+NME) might test fractions of the 3ν parameter space, as predicted by models embedding specific flavor symmetries (see later)



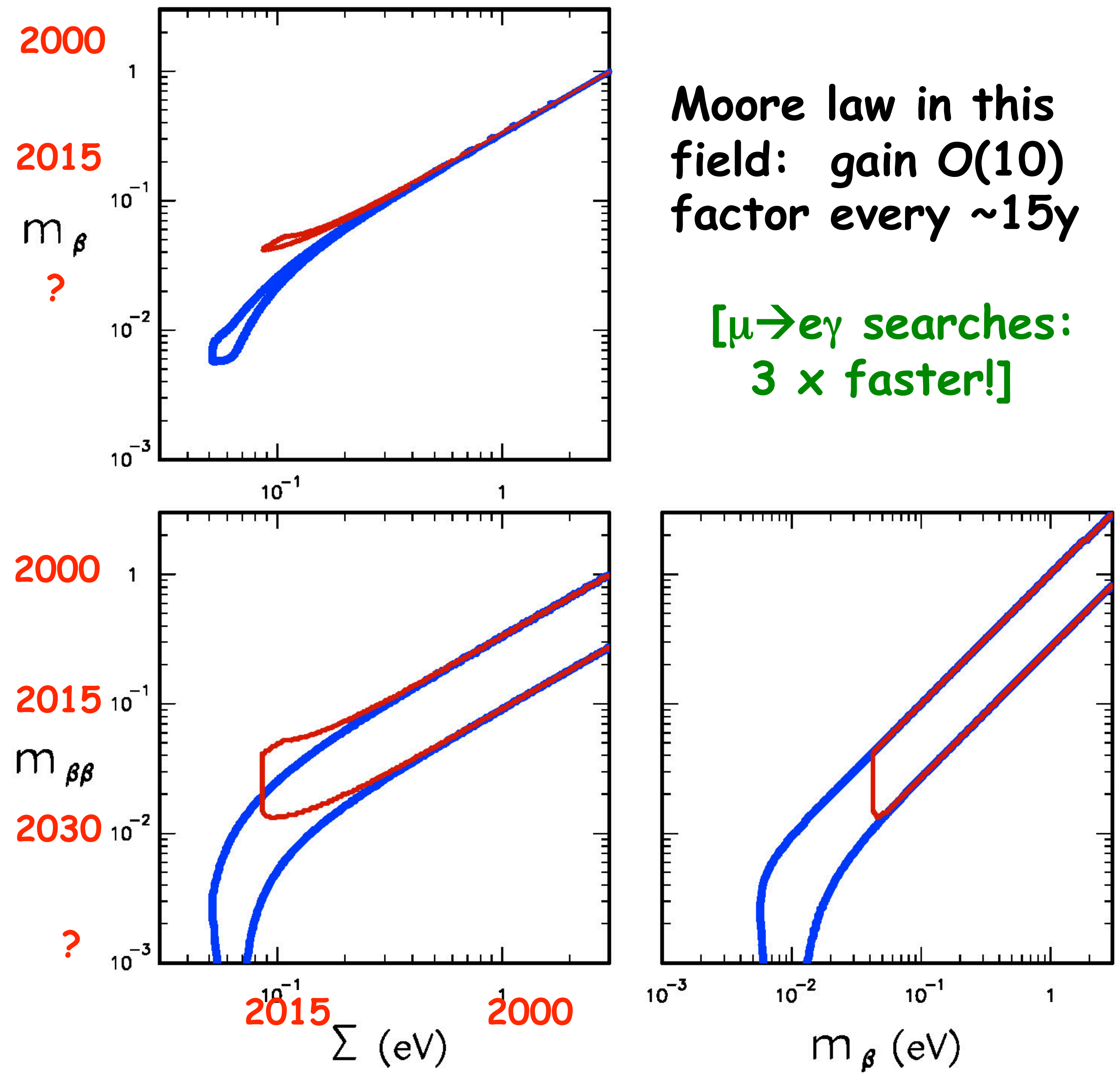
[Rodejohann]



[Valle]

Models can be tested!
(although not soon…)

Usual experimental/phenomenological nightmares …



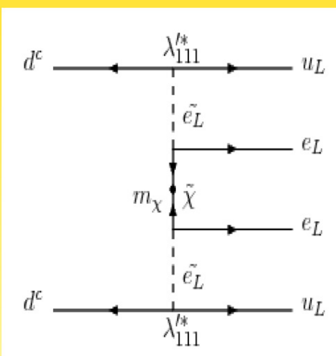
Moore law in this field: gain O(10) factor every ~15y

[$\mu \to e\gamma$ searches: 3 x faster!]

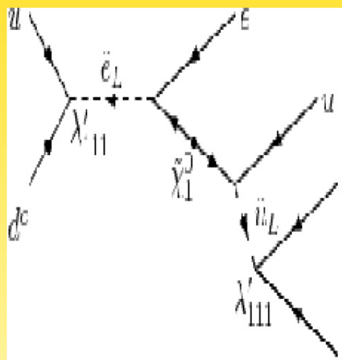
+large expt+NME error bars. But: interesting new ideas to move forward!

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) and their links/roles in other areas (new states at LHC, see-saw, leptogenesis, LFV, extraDim, MiniBoone…)

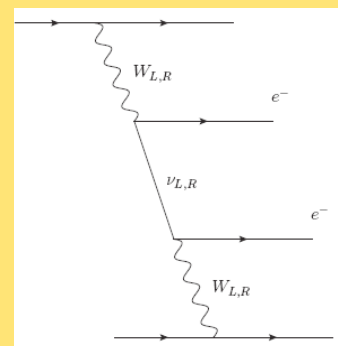


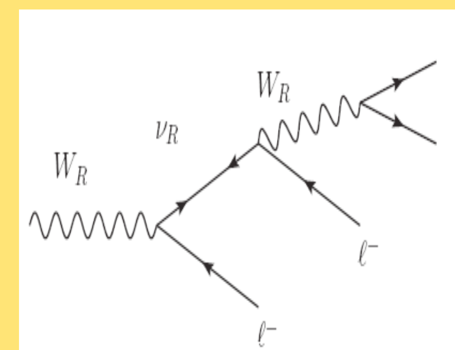
$0\nu\beta\beta$



resonant selectron production

$u\,\bar{d} \to e^+ e^+ \bar{u}\, d$





Like sign dileptons + dijets

Super-sym. [Rodejohann, Valle]   **LR-symmetry** [Mohapatra]

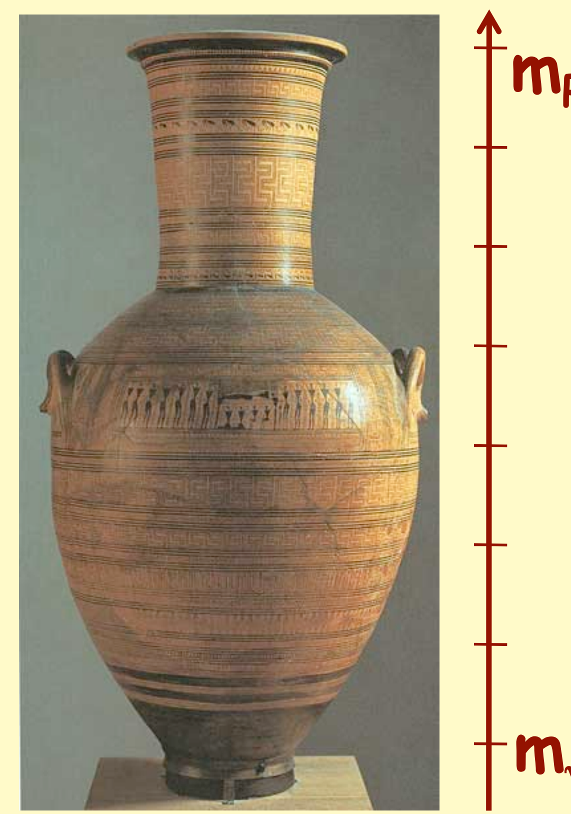
Some discrimination may be achieved via 0ν2β decay searches alone (multiple isotopes and/or final-state kinematics) [Rodejohann, Simkovic]

2. Neutrino mixing and masses:
seeking a flavor structure and a new physics scale

Symmetries?

See-saw?

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., $0\nu 2\beta$). Usual (not unique) starting points:

Tri Bi Max

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

[Parke] [Valle] [M.-C. Chen]

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. $\lambda_C \sim 0.2$ [Rodejohann]

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

Current data accuracy: $O(\lambda^2)$ for θ_{12} and θ_{13}; $O(\lambda)$ for θ_{23}
Aim at another λ factor in experimental accuracy [Parke]

Main message: Symmetry models can be predictive and testable!

E.g., TBM from T' (double A4) with CPV arising fom CG [Chen]

$$U_{\rm MNS} = V^\dagger_{e,L} U_{\rm TBM} = \begin{pmatrix} 1 & -\theta_c/3 & * \\ \theta_c/3 & 1 & * \\ * & * & 1 \end{pmatrix} \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -\sqrt{1/6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -\sqrt{1/6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

$$\theta_{13} \simeq \theta_c / 3\sqrt{2}$$

CGs of SU(5) & T′

$$\tan^2\theta_\odot \simeq \tan^2\theta_{\odot,TBM} + \frac{1}{2}\theta_c \cos\delta$$

$$\sin^2 2\theta_{atm} = 1, \quad \tan^2\theta_\odot = 0.419, \quad |U_{e3}| = 0.0583$$

neutrino mixing angle

1/2

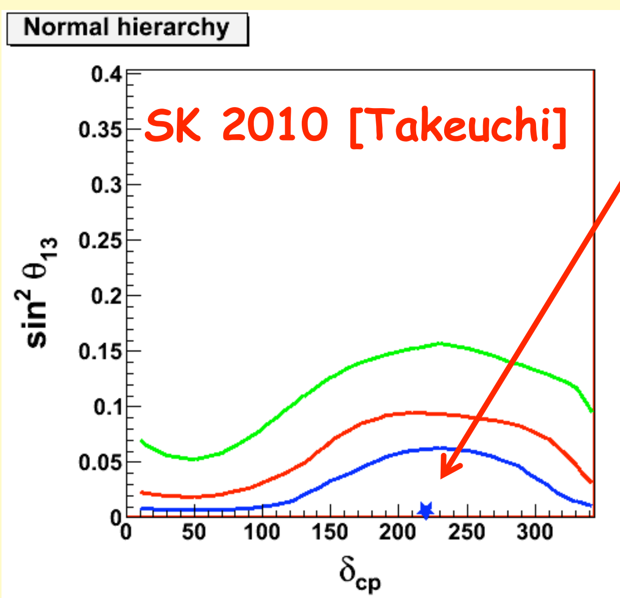
quark mixing angle

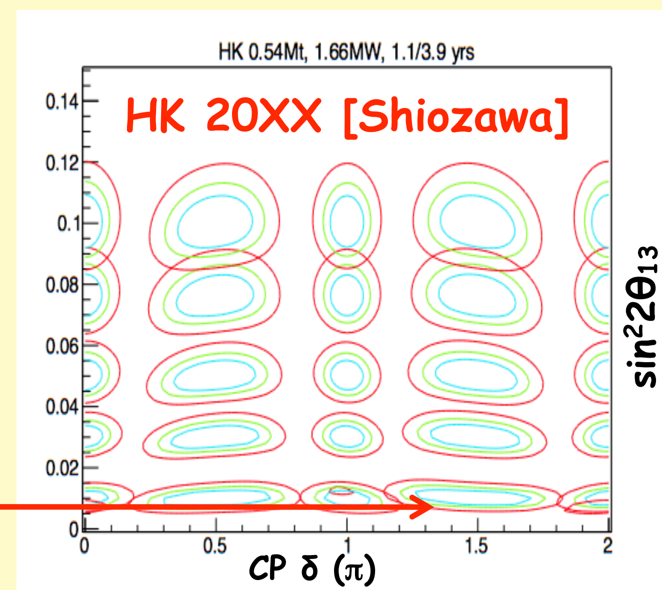
CG: leptonic Dirac CPV

prediction for Majorana phases: 0, π

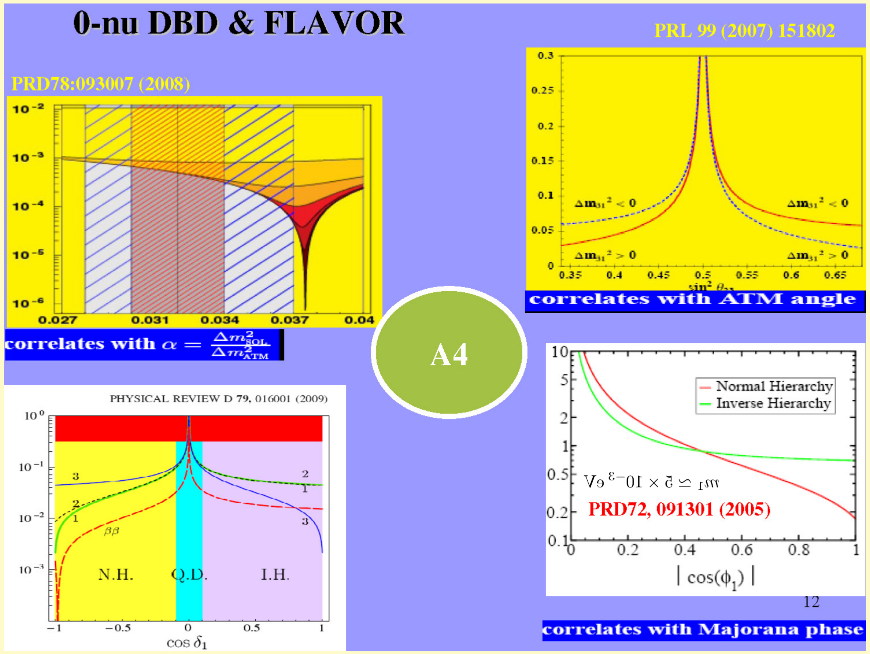
prediction for Dirac CP phase: δ = 227 degrees

⇒ connection between leptogenesis & CPV in neutrino oscillation



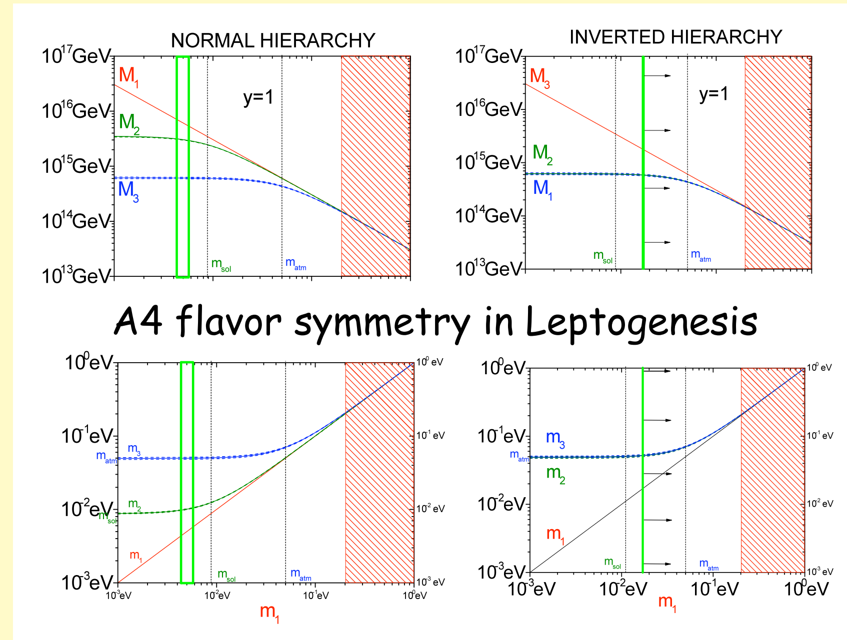


Low-energy, “direct” tests



[Valle]

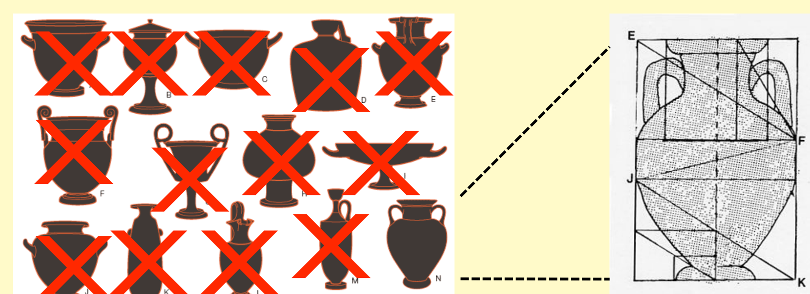
High-energy, “indirect” tests



[Di Bari]

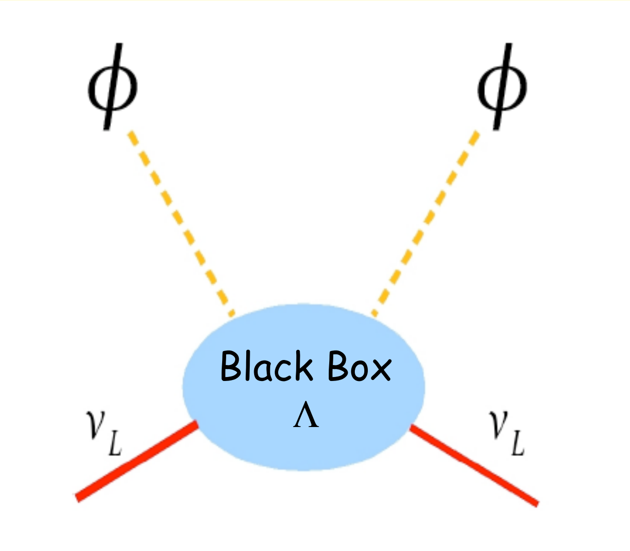
Which out of many?

… the hope …

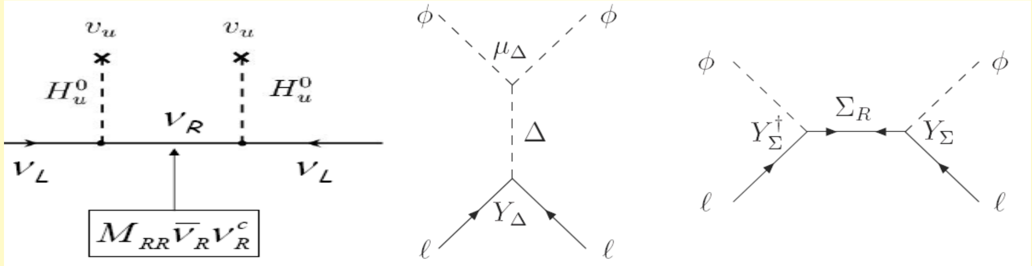


ORIGIN OF MASS

Is there a see-saw mechanism? At which scale Λ? Of which type?
[Valle], [Mohapatra]



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



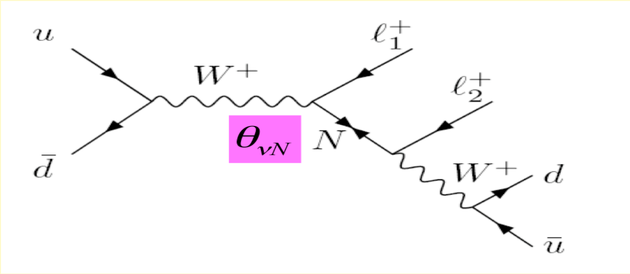
+ variants (inverse, +SUSY, +LR, +radiative,…)

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 [Mohapatra]

If the only new particles are tree-level see-saw mediators at O(TeV)…

Type I



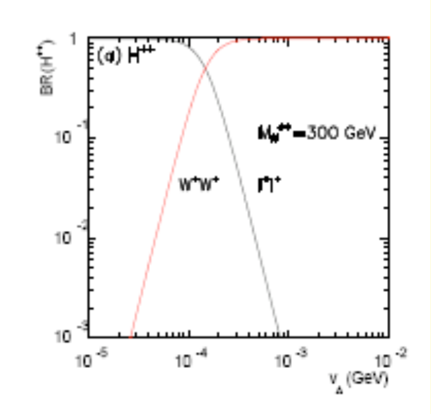
No gauge couplings (except via mixing); generally suppressed in production and decay. Situation different in type II, III:

Type II

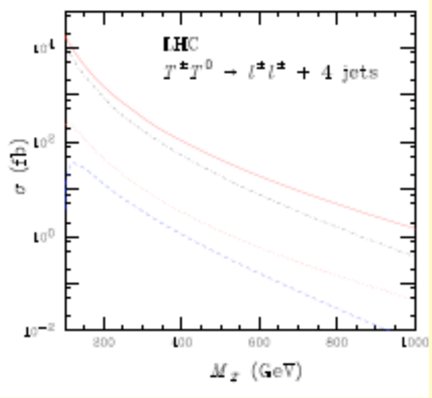
$$q\bar{q} \to Z^*/\gamma^* \to \Sigma^+\Sigma^-,\ \delta^{++}\delta^{--}$$
$$q\bar{q}' \to W^* \to \Sigma^+\Sigma^0,\ \delta^{++}\delta^{-}$$

Type III

$$\delta^{++} \to l^+l^+, W^+W^+$$
$$\delta^{+} \to l^+\bar{\nu}, W^+Z$$



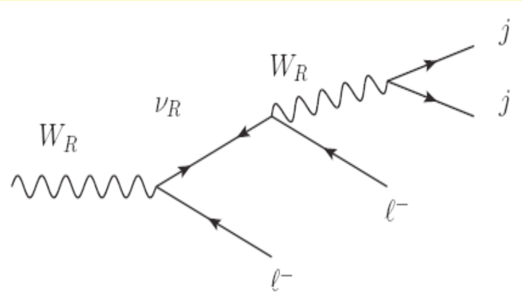
$$\Sigma^0 \to l^+W^-$$
$$\Sigma^+ \to l^+Z, ..$$



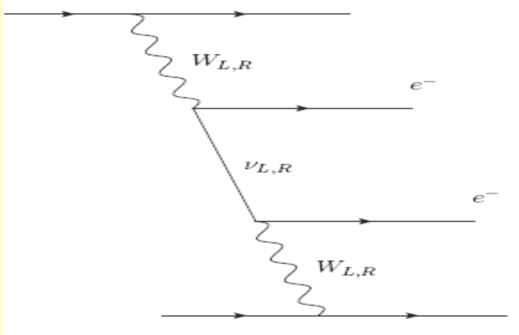
Production and decay might proceed at observable rates at the LHC [Mohapatra]

Further new physics at TeV scale (LR symmetry, Supersymmetry) may considerably enlarge the horizon, add links to other processes, and provide new, nontrivial benefits…

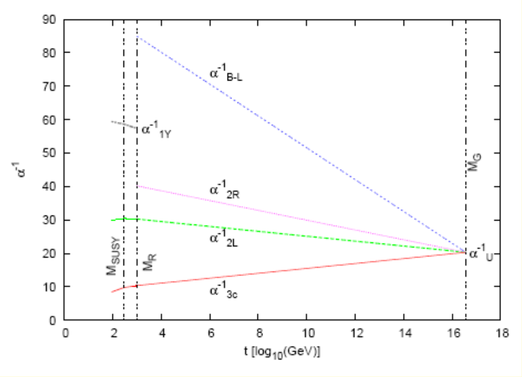
LR symmetry can rescue N production and decay via W_R …



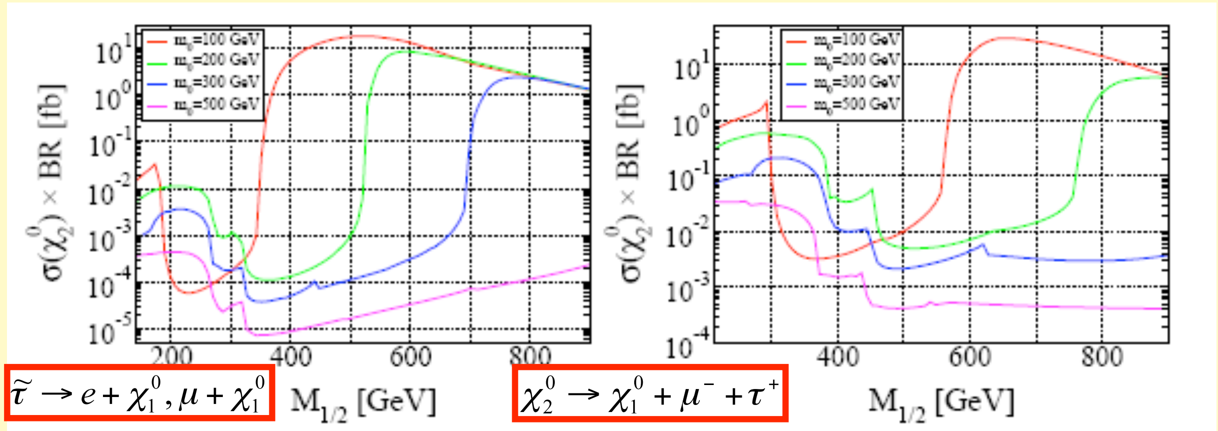
…Provide an alternative mechanism for $0\nu2\beta$ decay…



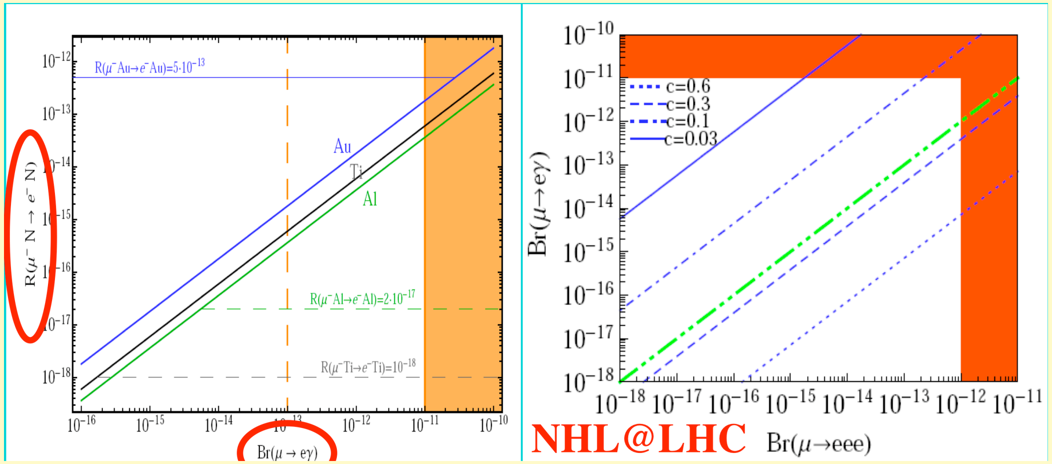
…And be consistent with coupling unification! [Mohapatra]



SUSY may provide LFV @ LHC [Valle, Mohapatra]

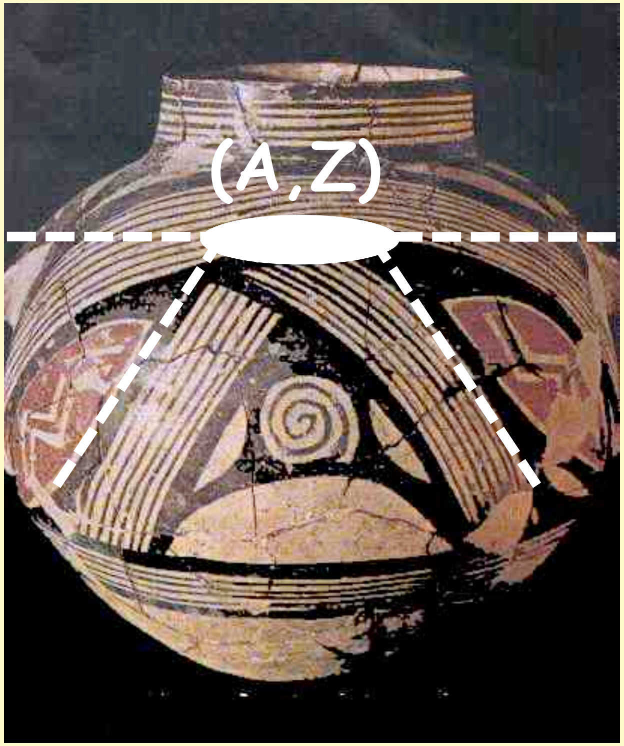


In general, models can correlate different LFV signals [Valle, Nicolo']



The hope is to find many (and matching) fragments! (Non)observation of these fragments in current experiments will be a hot topic in next ν 20XX

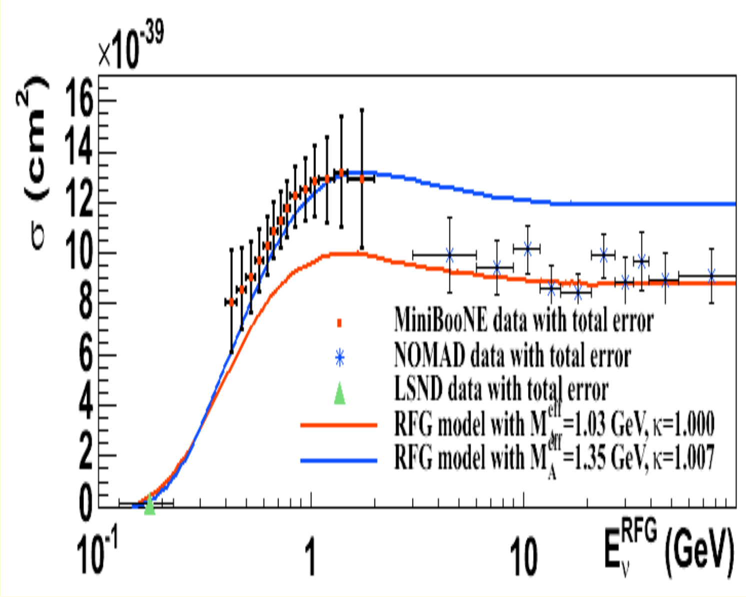
3. Neutrino interactions



Accuracy of new neutrino experiments/analyses requires a new look at "old" nuclear theory problems→

E.g., axial currents not well controlled in magnitude and/or form factors.

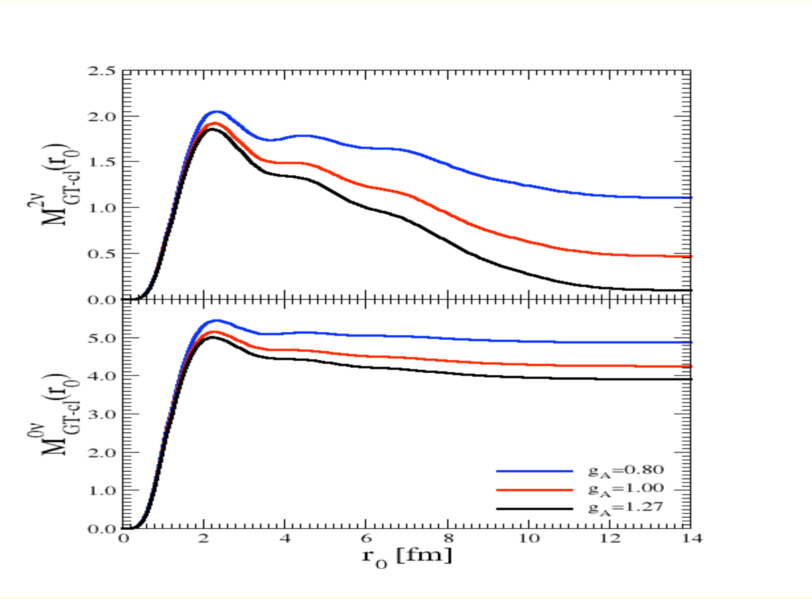
In the context of QE…



M_A → significant source of error.
Interplay with other expt. results
once MiniBooNE data are fitted

[Alvarez-Ruso]

In the context of 0ν2β…

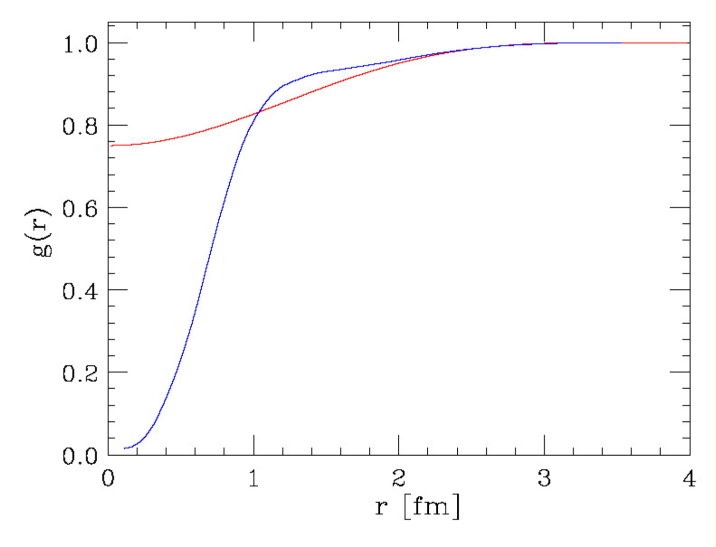


g_A → significant source of error.
Interplay with g_{pp} uncertainties
once 2ν2β data are fitted in QRPA

[Simkovic]

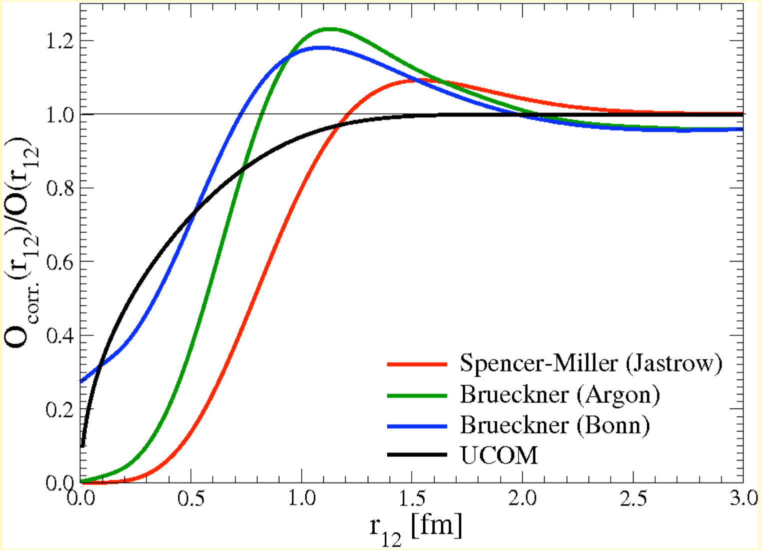
Close nucleons repel…
(short-range correlations below ~1fm)

In the context of νA …

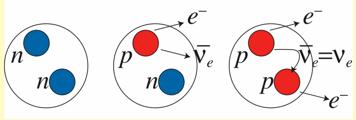


[Benhar]

In the context of 0ν2β…



[Simkovic]



Vast theory/pheno/expt program needed to build realistic nuclear models consistent with all dynamical information.

Do we need a new (nuclear theory) paradigm? [Benhar]

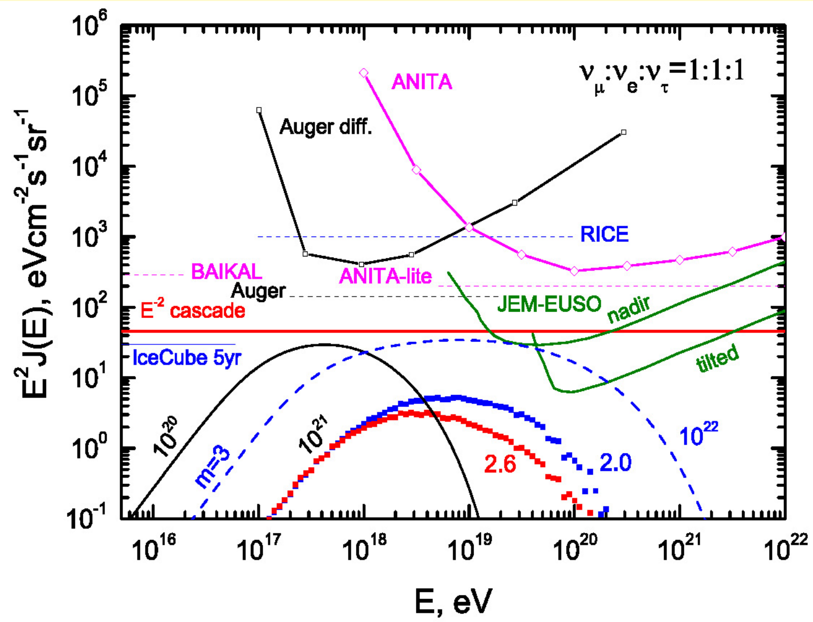
4. Astrophysics & cosmology

The ν sky is still quite dark… [Vandenbroucke]

Year	Neutrino sources	GeV gamma sources	TeV gamma sources
1966	0	0	0
1967	1	0	0
1987	2	25	0
2010	~~2~~ **3**	1451	109

… but, the Earth is an anti-ν star !
[geo-ν: Calaprice, Inoue, Tolich]

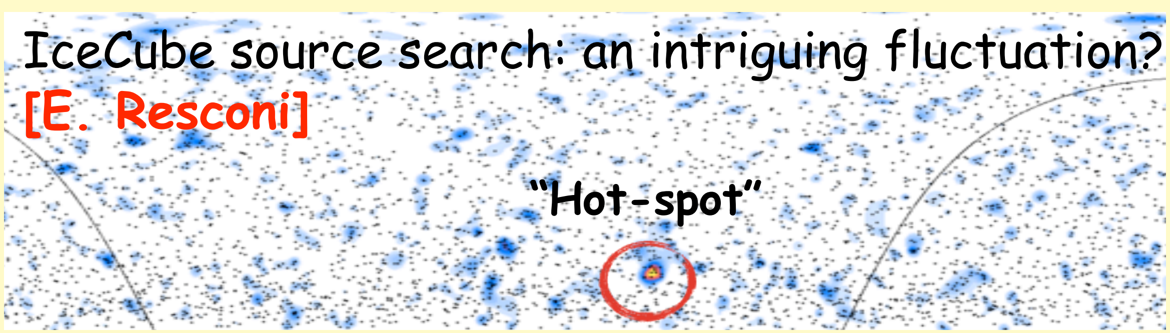
A "guaranteed" UHE source: cosmogenic ν



Recent theoretical assessment in dip model (protons) + Fermi cascade upper limit [Berezinsky]: low flux, still out of reach; even more so if protons → heavy nuclei, as suggested by Auger data [Gora].

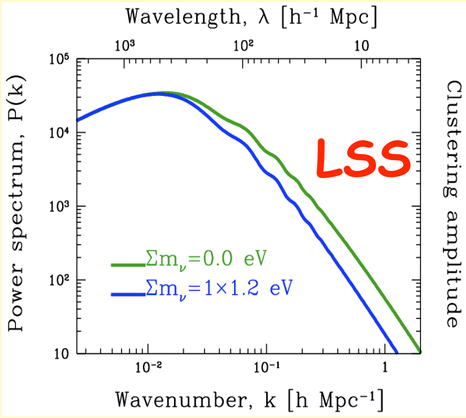
If something is found (radio-detection?), likely to be new physics (top-down)!

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 CR [Berezinsky].

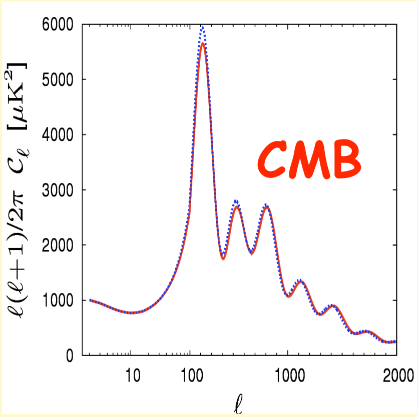


Interesting standard and nonstandard ν physics testable when sources will be discovered.

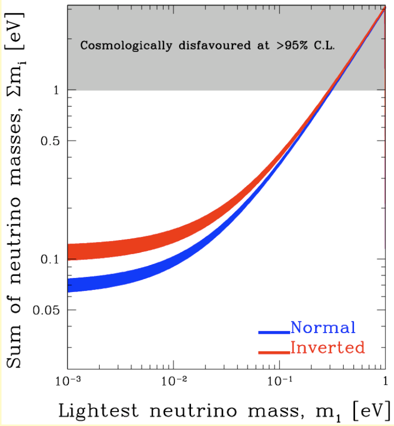
A "guaranteed" LE source: Big Bang ν [Wong]

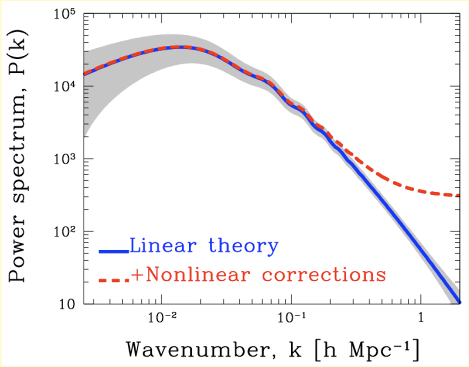


\+



\+ ... =

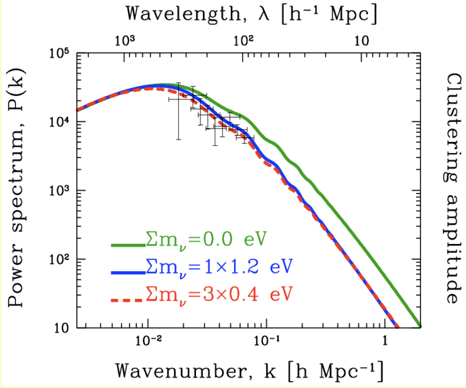




Slicing in redshift bins will allow sensitivities close to $\sqrt{\Delta m^2}$ and thus relevant to probe the hierarchy ....

... provided that numerical or semianalytical calculations can reach the 1% level of accuracy

→ next challenge for precision cosmology



Will also allow tests of nonstandard scenarios.

Ultimate goal? Go beyond $\Sigma = \mathbf{m_1 + m_2 + m_3}$ and probe mass distribution over the 3 states.

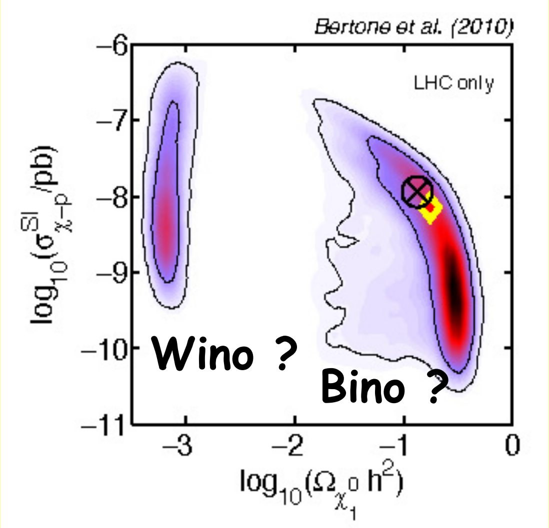
A "guaranteed" relic ν companion: DM [Bertone]

The most studied candidate - the neutralino – shares the same etimology of neutrino, and the same destiny…

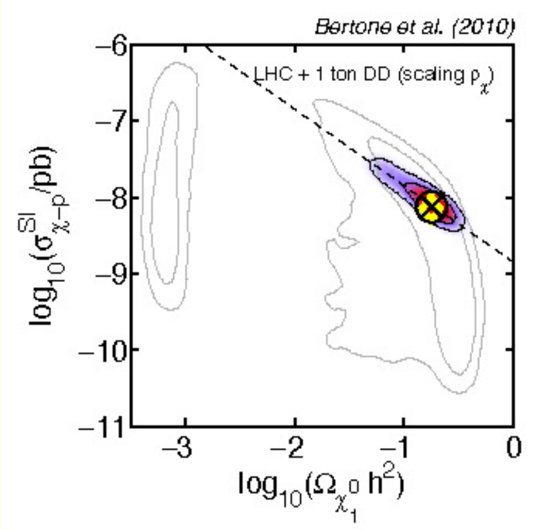
Even if SUSY spectrum reconstructed at LHC…

Mass	Benchmark value, μ	LHC error, σ
$m(\widetilde{\chi}_1^0)$	139.3	14.0
$m(\widetilde{\chi}_2^0)$	269.4	41.0
$m(\widetilde{e}_R)$	257.3	50.0
$m(\widetilde{\mu}_R)$	257.2	50.0
$m(h)$	118.50	0.25
$m(A)$	432.4	1.5
$m(\widetilde{\tau}_1) - m(\widetilde{\chi}_1^0)$	16.4	2.0
$m(\widetilde{u}_R)$	859.4	78.0
$m(\widetilde{d}_R)$	882.5	78.0
$m(\widetilde{s}_R)$	882.5	78.0
$m(\widetilde{c}_R)$	859.4	78.0
$m(\widetilde{u}_L)$	876.6	121.0
$m(\widetilde{d}_L)$	884.6	121.0
$m(\widetilde{s}_L)$	884.6	121.0
$m(\widetilde{c}_L)$	876.6	121.0
$m(\widetilde{b}_1)$	745.1	35.0
$m(\widetilde{b}_2)$	800.7	74.0
$m(\widetilde{t}_1)$	624.9	315.0
$m(\widetilde{g})$	894.6	171.0
$m(\widetilde{e}_L)$	328.9	50.0
$m(\widetilde{\mu}_L)$	228.8	50.0

… we'll still be asking: Which of the two?



Selection possible with direct detection+ansatz



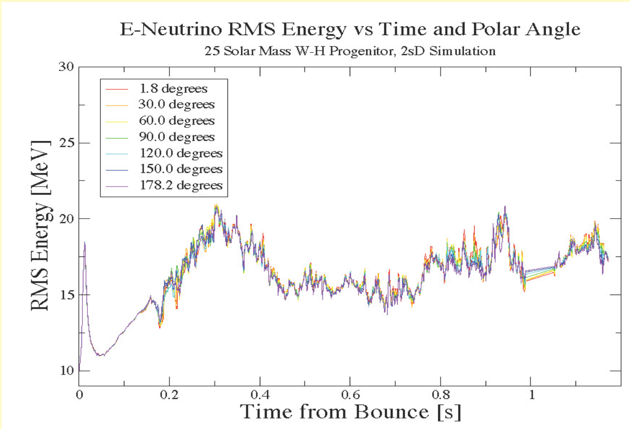
In general, many possible connections with neutrino physics, e.g.,

- Neutrinos from DM annihilation/decay, as part of a multi-messenger approach to DM searches [Bertone];
- DM SUSY see-saw → LSP decay correlation with neutrino mixing [Valle]

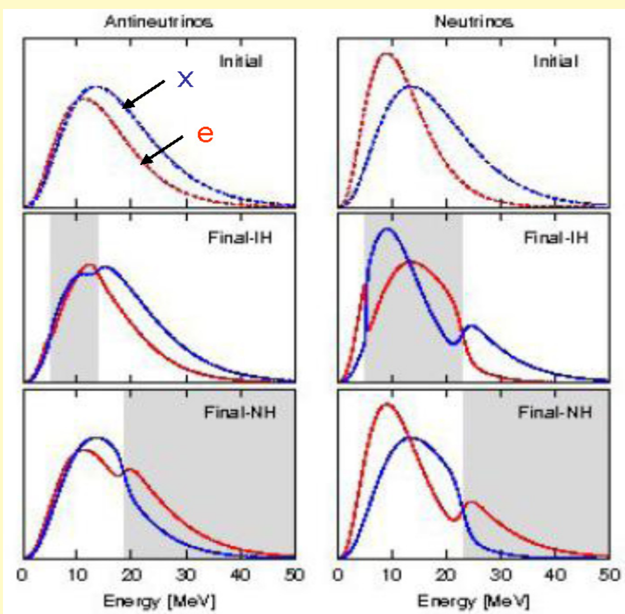
(Non)observations of DM candidates at LHC and with (in)direct detection will reshape the field → expect this to be a hot topic in next ν 20XX

"Guaranteed" (but episodic*) sources: SN

Two theoretical lines of research that should meet… but haven't yet:



Simulations: Neutrino-driven explosions are back (with exceptions). Increasing dimensionality. Neutrino transport and interactions included, but flavor mixing still ignored… Theoretical & computational challenges for many years. **[Cardall]**



Flavor evolution: Simulations taken as initial/boundary conditions. Current research activity largely focused on $\nu-\nu$ interactions →nonlinear collective flavor changes, which amplify small "instabilities"! Strong dependence on hierarchy and on energy ("splits)". Theoretical & computational challenges for many years. **[Mirizzi]**

*However, not too far from diffuse SN background detection… [Vagins]

Remark on MASS HIERARCHY via flavor transitions:

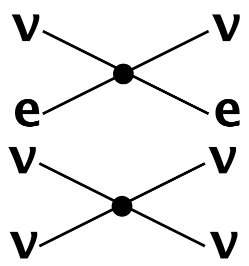
The hierarchy, namely, sign($\pm\Delta m^2$), can be probed (in principle), via <u>interference</u> of Δm^2-driven oscillations with some other Q-driven oscillations, where Q is a quantity <u>with known sign</u>.

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 SNe)

Q = Neutrino density (Collective effects in SNe)



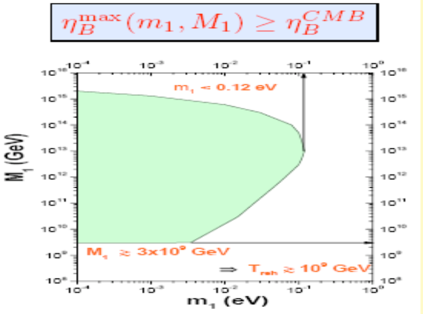
Which of the three... will succeed? Each one is very challenging, for rather different reasons. Non-oscillation observables might provide another handle. In any case: very high accuracy required.

Leptogenesis: The ultimate source of all matter? [Di Bari]

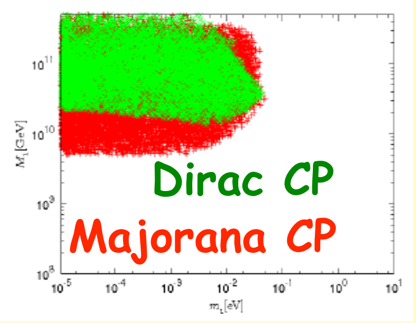
Leptogenesis aims at explaining one single number: $\eta = 6 \times 10^{-10}$

This "simple" requirement generates nontrivial constraints at LE & HE, and links between the two sectors. Progress in recent years, e.g.,

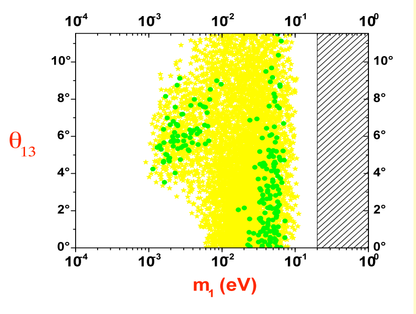
"Vanilla leptogenesis" with type-I see-saw: connects low and high mass scales (ν_1, N_1). Disconnected from LE flavor structure.



"Flavored leptogenesis" (with $M_1 < 10^{12}$ GeV): connects LE and HE flavor structure. Can work with LE CP violation phases only!



"N_2 leptogenesis" (heavy flavor effects): A new chance for SO(10)-inspired models. Constraints on LE mass/mixing parameters.



Leptogenesis

Importance of CPV constraints from successful leptogenesis motivates improved calculations…

Improved kinetic description

- Momentum dependence in Boltzmann equations
- Kadanoff-Baym equations

The asymmetry is directly calculated in terms of Green functions instead than in terms of number densities and they account for off-shell , memory and medium effects in a systematic way

Non minimal leptogenesis

Non thermal leptogenesis

The RH neutrino production is non-thermal and typically associated to inflation. They are often motivated in order to obtain successful leptogenesis with low reheating temperature.

Beyond the type I seesaw

It is motivated typically by two reasons:

- Again avoid the reheating temperature lower bound
- In order to get new phenomenological tests….the most typical motivation in this respect is quite obviously whether we can test the seesaw and leptogenesis at the LHC

Typically lowering the RH neutrino scale at TeV , the RH neutrinos decouple and they cannot be efficiently produced in colliders

Many different proposals to circumvent the problem:

… as well as exploration of many possible variants and alternatives. [Di Bari, Valle, Mohapatra]

Last, but not least:

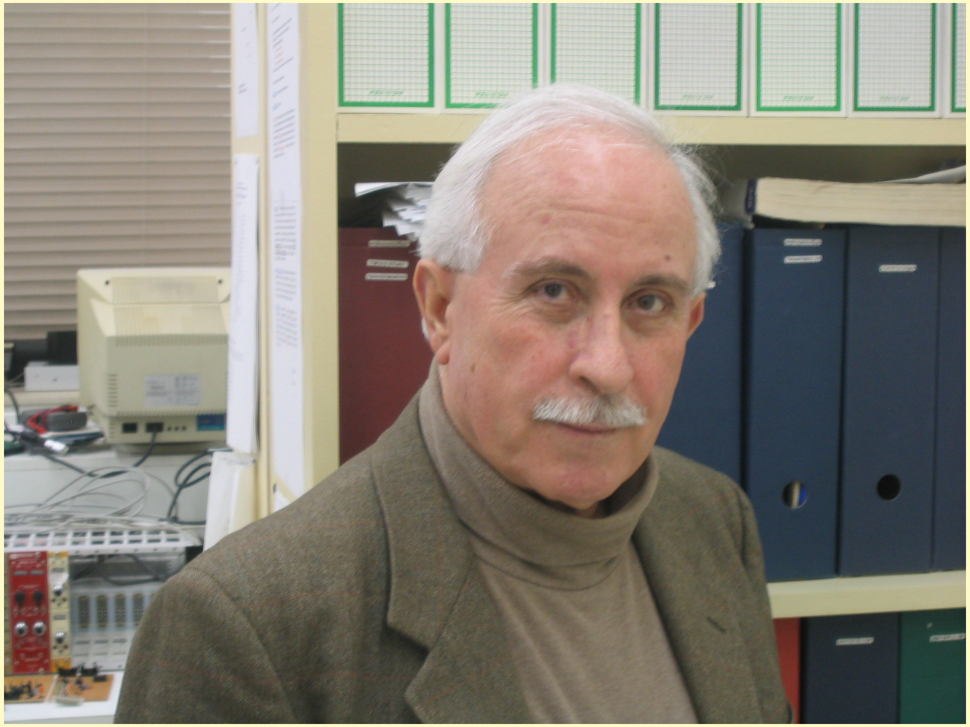
Many interesting theoretical/phenomenological topics also covered in lively poster sessions, including:

DM and neutrinos, mass/mixing models, SN neutrinos, relic neutrinos, leptogenesis, EM properties, sterile states, new interactions, neutrino and nuclear physics, UHE CR and neutrino, CPV and CPTV tests, oscillations in matter, neutrinoless double beta decay, solar and atmospheric neutrinos…

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, CLFV and collider physics,
and provide us with a beautiful new picture
of Nature... and with new questions.

THANK YOU FOR YOUR ATTENTION



... and thank you, George,
for an exciting Conference!

Grazie, Enrico… …e arrivederci a NOW 2010!