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# Neutrinos: Theory review

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# Outline:

**Introduction**

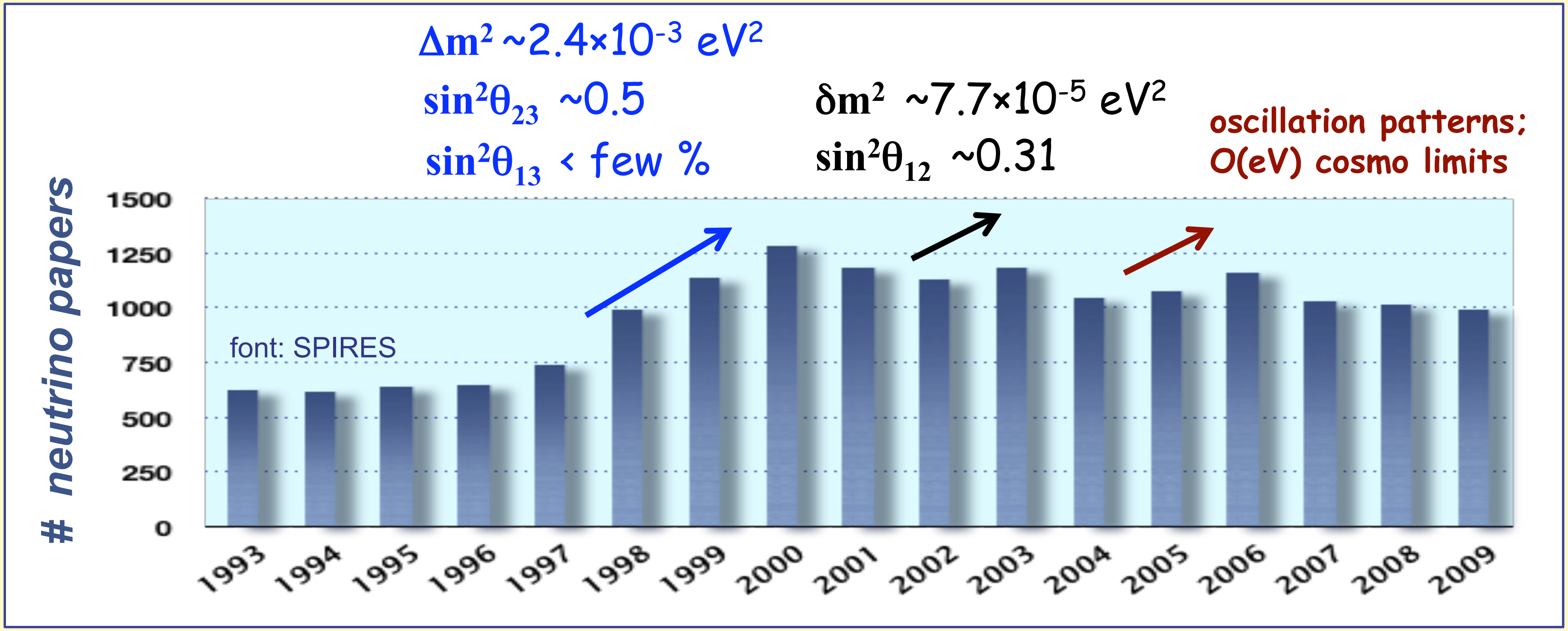
**Oscillations**
**Absolute masses**
**Mixing and symmetries**
**Towards higher energies**

**Conclusions**

Current active areas in neutrino theory: well represented in parallel talks at ICHEP 2010

# Introduction

Major HEP discovery: neutrinos are massive and mixed – like quarks.




PDG convention for mixing angle ordering – like quarks.

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

($\theta_{13}$: gateway to leptonic CPV)

## But neutrinos, unlike quarks:

- Have tiny masses and two large mixing angles
- May have a peculiar mass spectrum (normal vs inverse/degenerate)
- May be mixed with additional light partners (sterile states)
- May be their own antiparticles (Majorana)
- Majorana neutrinos can be naturally light (see-saw mechanism)
- Their heavy see-saw partners may induce $\eta \neq 0$ (leptogenesis)

## Moreover, neutrinos...

- Oscillate in flavor on macroscopic lengths (vacuum phase $\sim \Delta m^2\, L/E$)
- Feel bkgd medium through oscillation phase (matter effects $\sim G_F$)
- Can probe new interactions/states via flavor interferometry

▼

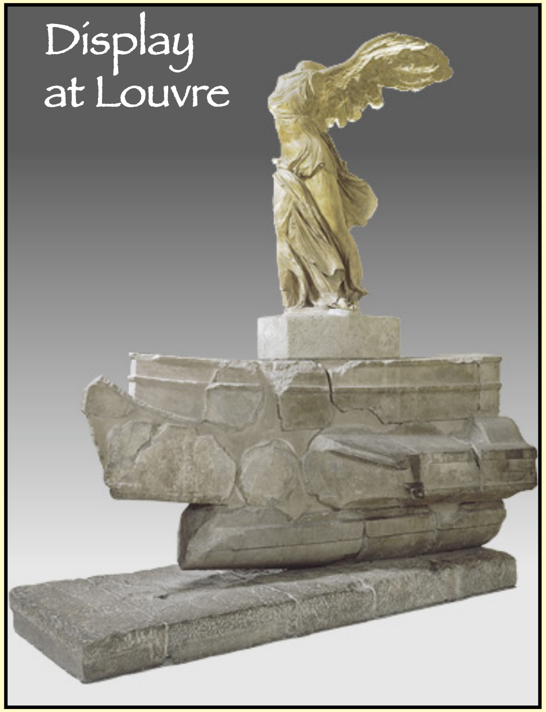
**Neutrino masses and mixing: messengers of new physics**

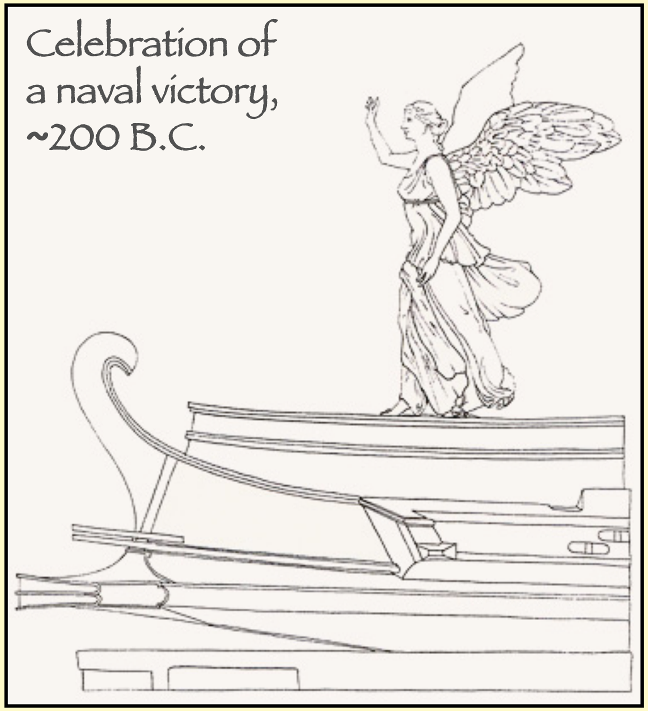
# Dreams:

find many fragments of new physics…

… link or piece them together…

… reconstruct a complete picture and its meaning


[The "Winged Victory of Samothrace," masterpiece of Greek art]

# Nightmares:

... few, disparate or unmatched fragments (or false leads!) ▶

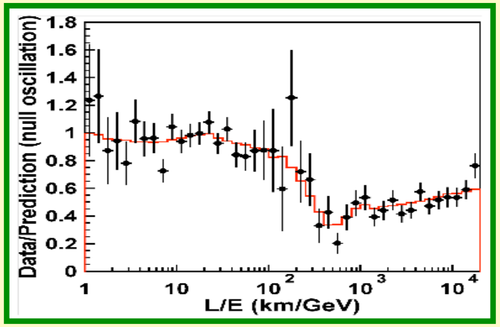
◀ ...multiple options for reconstruction (or none !)

# Neutrino oscillations: Standard 3ν scenario

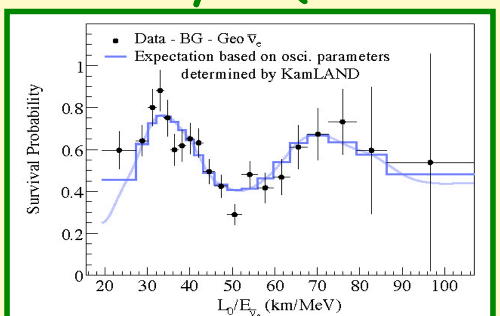
Precisely known "fragments": great success of beautiful experiments, accurate theoretical calculations, and refined statistical analyses

## Kinematics ✔

½ oscillation cycle (SK)

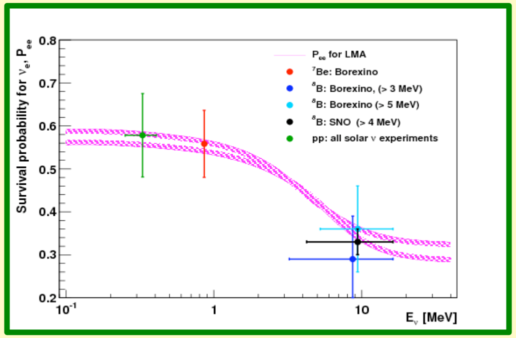



1 oscill.cycle (KamLAND)

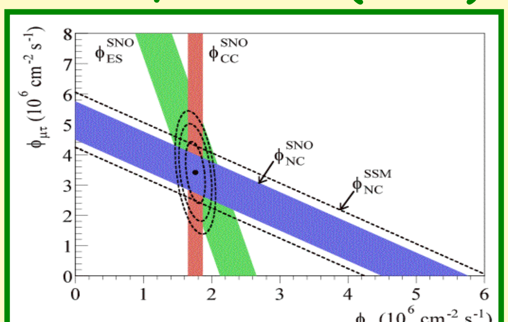



## Dynamics ✔

MSW in the Sun (Borex.)




$^8$B flux, CC/NC (SNO)




## 3ν fit accuracy:

$\sigma(\delta m^2) \sim 2.5\%$

$\sigma(\Delta m^2) \sim 5\%$

but sign($\Delta m^2$) unknown

$\sigma(\sin^2\theta_{12}) \sim 6\%$

$\sigma(\sin^2\theta_{23}) \sim 11\%$

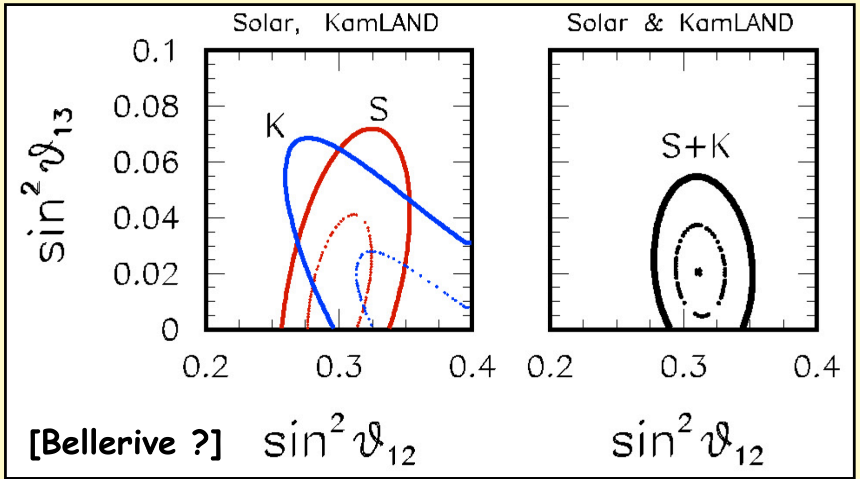
$\sigma(\sin^2\theta_{13}) \sim 0.01$

focus of attention!

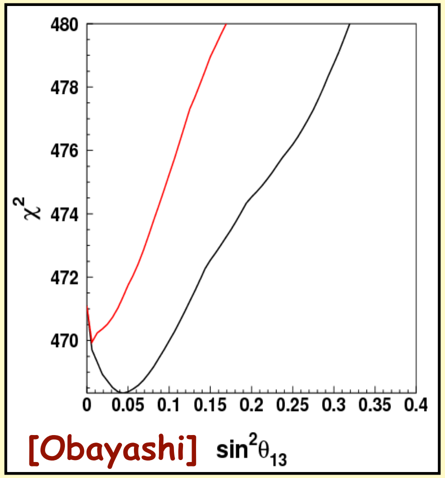
# Some theo/pheno issues in standard 3$\nu$ oscillations

**Hints of $\theta_{13}>0$?** [Fogli, EL, Marrone, Palazzo, Rotunno.] **Current status:**

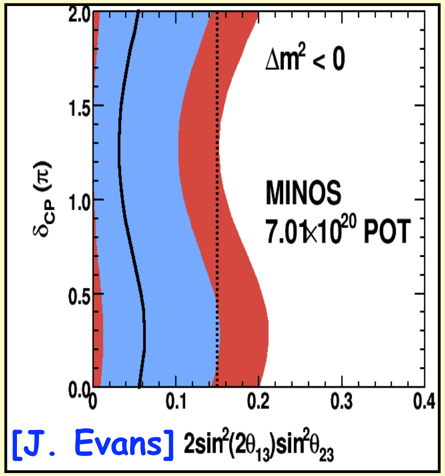
**Solar & KamLAND: ~1.5$\sigma$**




**SK atmos.: ~1.5$\sigma$**




**MINOS: ~0.7$\sigma$**




**Overall significance close to ~2$\sigma$. Intriguing, but still weak.**

Need direct $\theta_{13}$ searches at reactors/accelerators. Results will be decisive to plan next steps: The larger $\theta_{13}$, the "easier" will be to probe CPV and the mass hierarchy at future accelerator facilities.

# MASS HIERARCHY via flavor transitions:

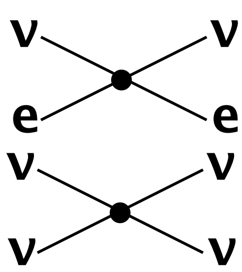
The hierarchy, namely, sign($\pm\Delta m^2$), can be probed (in principle), via interference of $\Delta m^2$-driven oscillations with some other Q-driven oscillations, where Q is a quantity with known sign.

At present, the only known possibilities are:

**Q = $\delta m^2$** (e.g., high-precision oscillometry in vacuum)

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

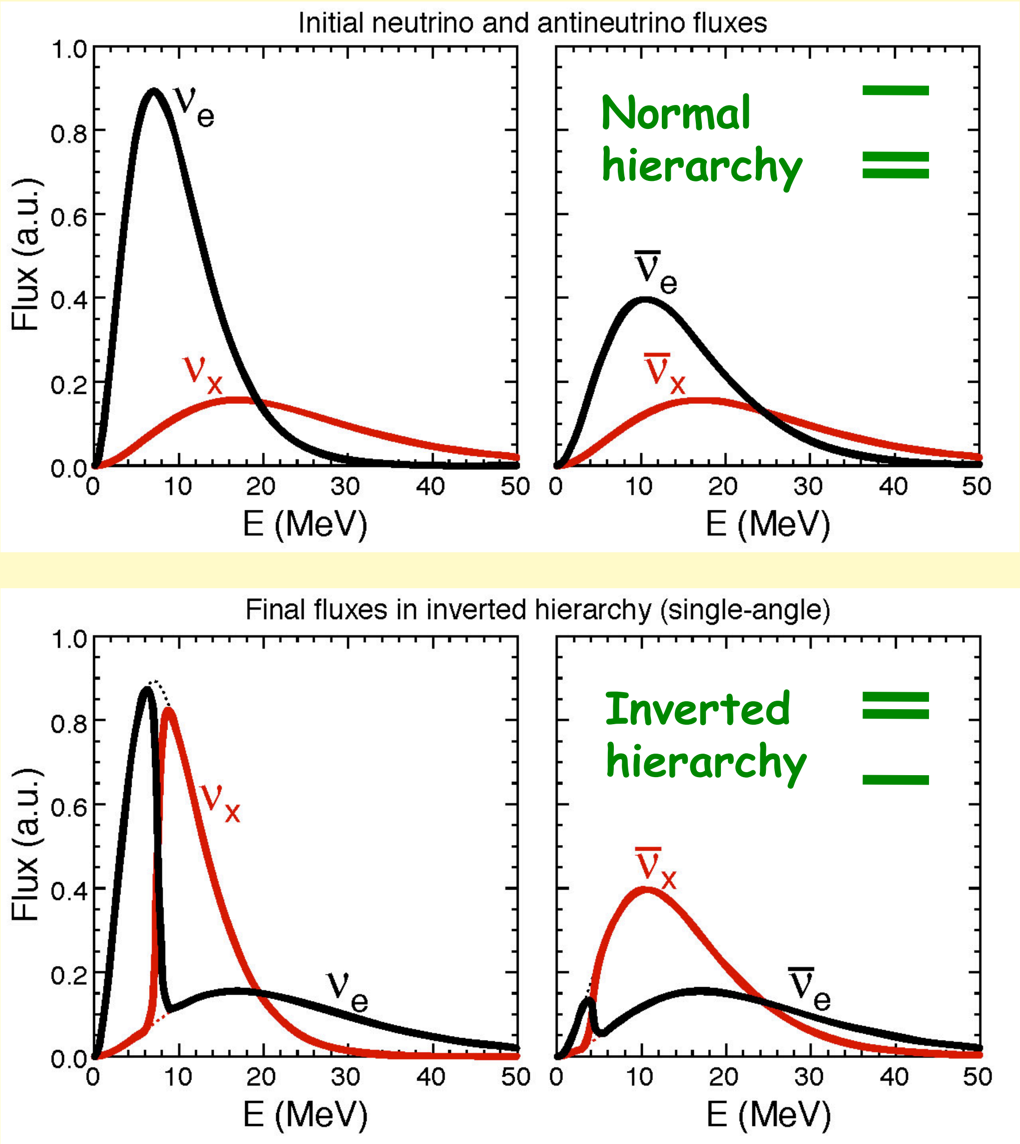
**Q = Neutrino density** (SN $\nu-\nu$ interaction effects)




Each one is very challenging, for rather different reasons.

The latter possibility has recently raised increasing interest in neutrino theory, being associated with **highly nonlinear flavor evolution effects** –for a few seconds- in core-collapse supernovae →

# SN $\nu$'s: Strong-coupling effects of weak interactions…




At very high density, $\nu-\nu$ interactions "lock" the flavor evolution among modes in some energy ranges: "collective effects."

Locking effects most evident in **inverted** hierarchy, through abrupt changes from one range to another: "spectral splits."

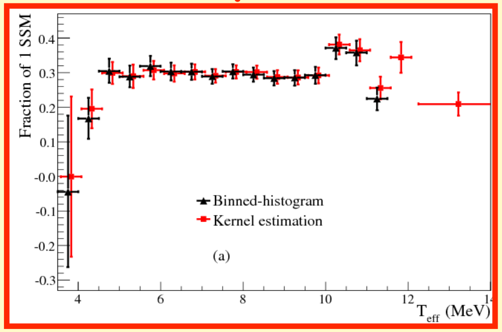
Theoretical & computational challenges for many years, since these effects have been studied only under some approximations/symmetries.

[A. Marrone, B. Dasgupta]

# Neutrino oscillations: Beyond 3ν ?

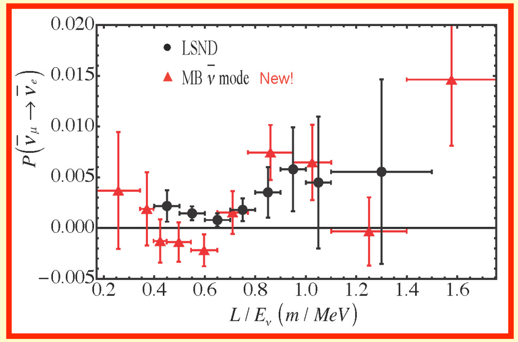
## Not all "fragments" seem to match the standard 3ν picture…

No MSW upturn (SNO)?



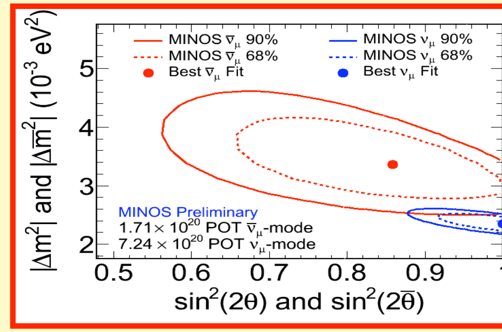

[Bellerive]

LSND/MiniBooNE osc.?




[Mills]

ν / anti-ν (MINOS) ?




[Evans]

Sterile neutrinos and/or new interactions and/or exotics (CPTV) invoked but… rather "ad hoc" solutions, difficult to match with other pieces of information

**No (convincing) theoretical interpretation emerging from these anomalies (yet). But: be open to further unexpected results and to surprises!**

E.g., large neutrino magnetic moments [Li, Egorov]

We should be prepared to face ambiguous results more and more often in the future, as experimental timescales get longer and longer …

Dispute about gesture of Samothrace Victory Goddess:

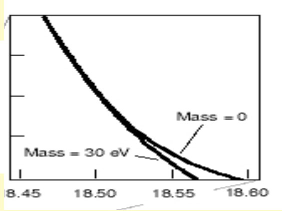
Trumpet? Wreath? Greeting?

New excavation, funded after ~90 y, discovered fragment of open-palm right hand → no trumpet, no wreath!

# Probing absolute neutrino masses: ($m_\beta$, $m_{\beta\beta}$, $\Sigma$)

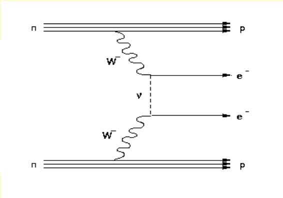
1) Single β decay: $m^2_i \neq 0$ alters the spectrum tail. Sensitive* to the so-called "effective mass of electron neutrino":

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



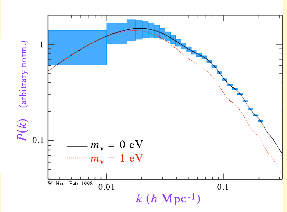

2) Double 0νββ decay: Iff $m^2_i \neq 0$ and ν=anti-ν (Majorana neutrinos). Sensitive* to the "effective Majorana mass" (and related phases):

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




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

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



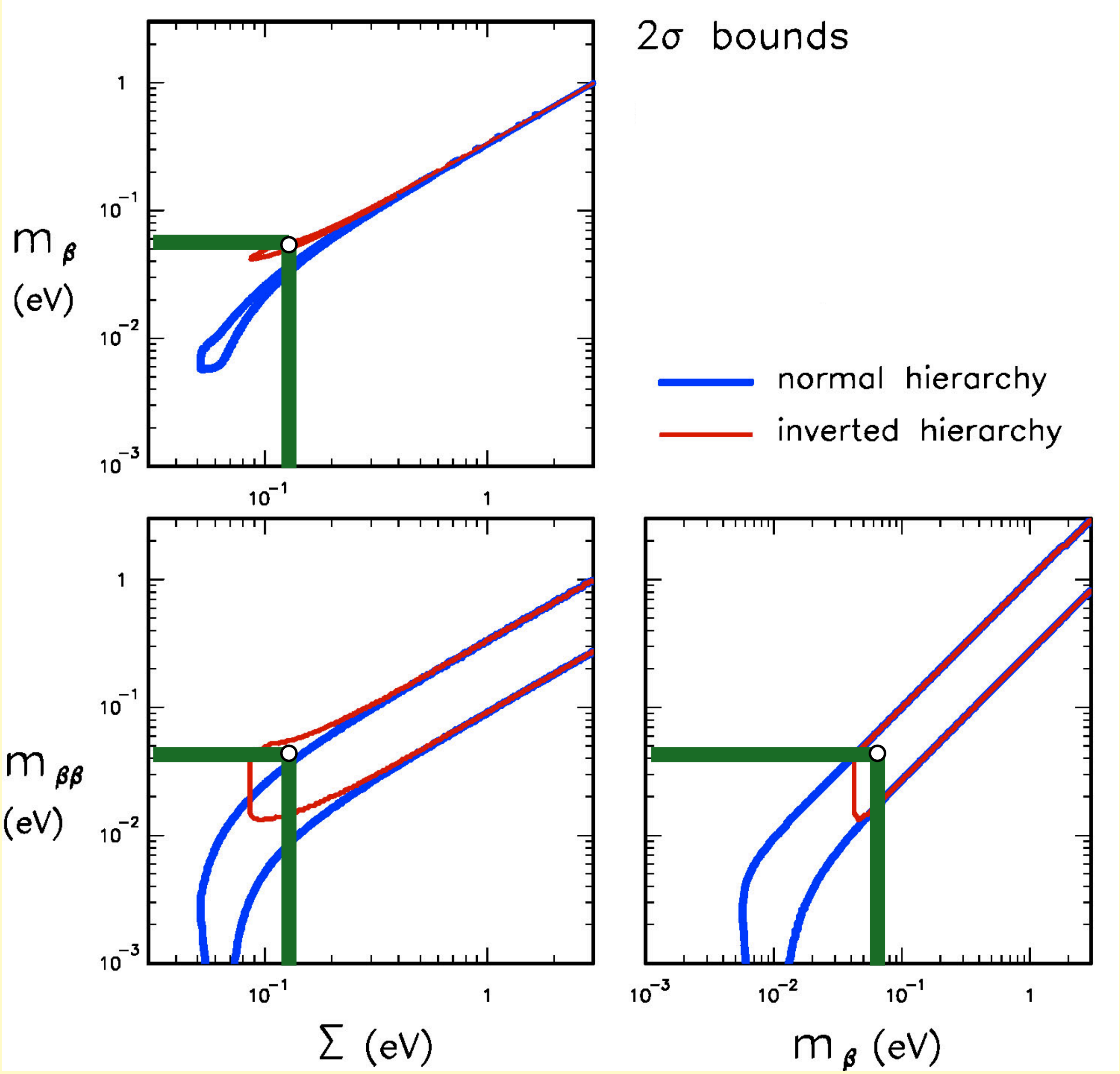

*in first approximation

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

Determine the mass scale…

Identify the hierarchy …

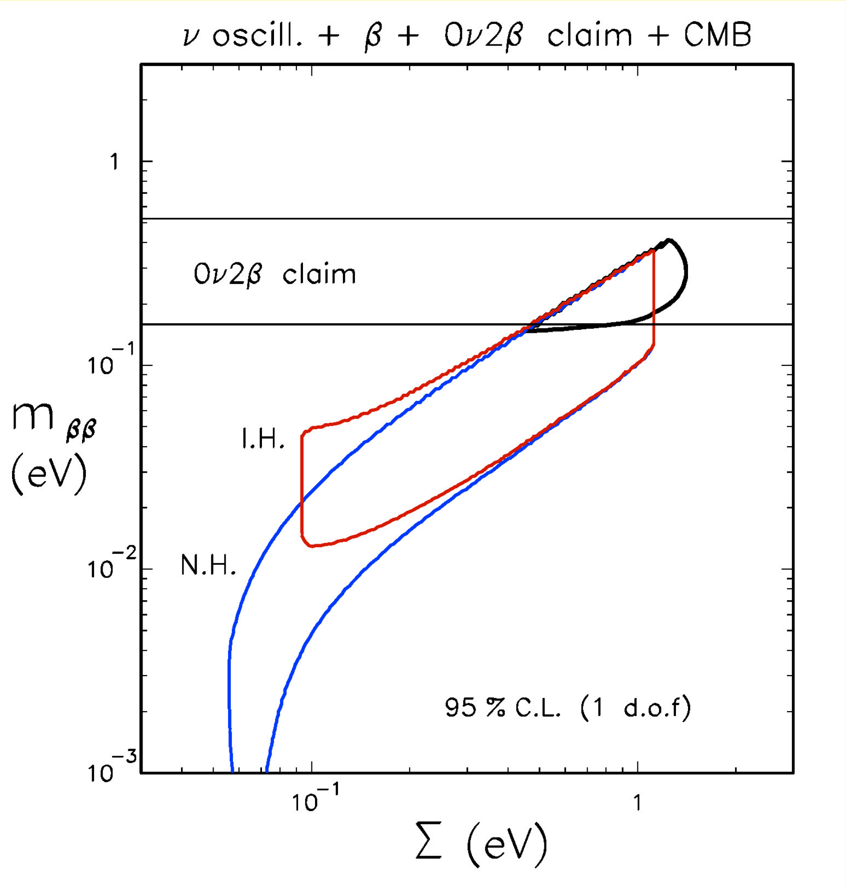
Probe the Majorana nature and phase(s)…




Relevant to constrain/support leptogenesis & flavor symmetry models

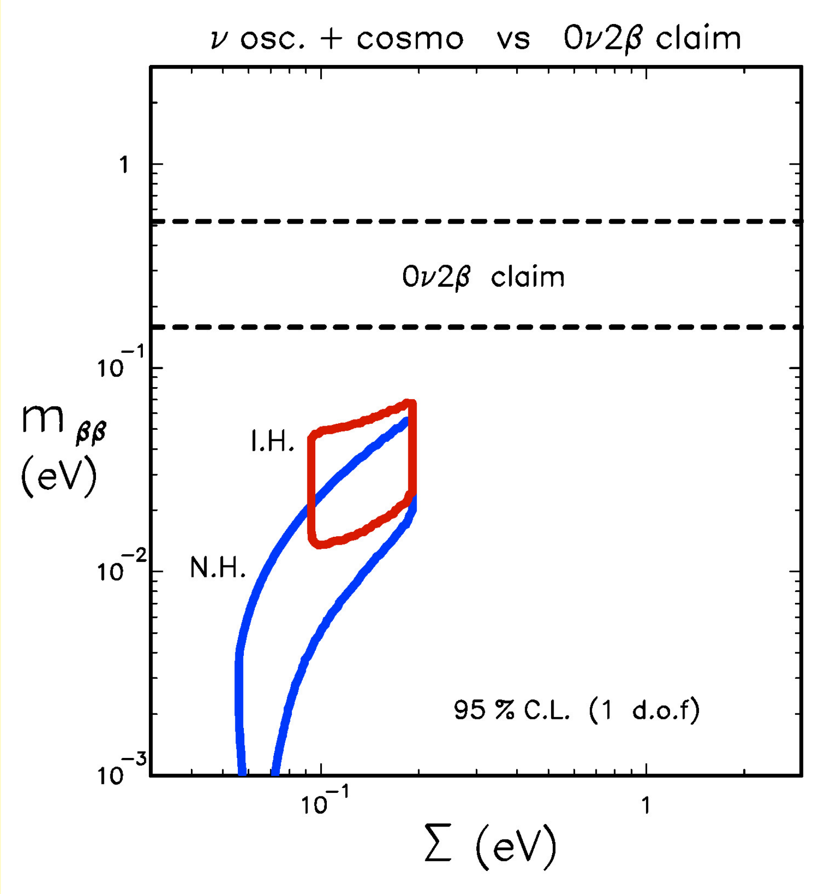
**Current situation inconclusive, e.g., wrt to disputed $0\nu2\beta$ claim**

"Conservative" cosmo limits:




fragments can match…

"Aggressive" cosmo limits:

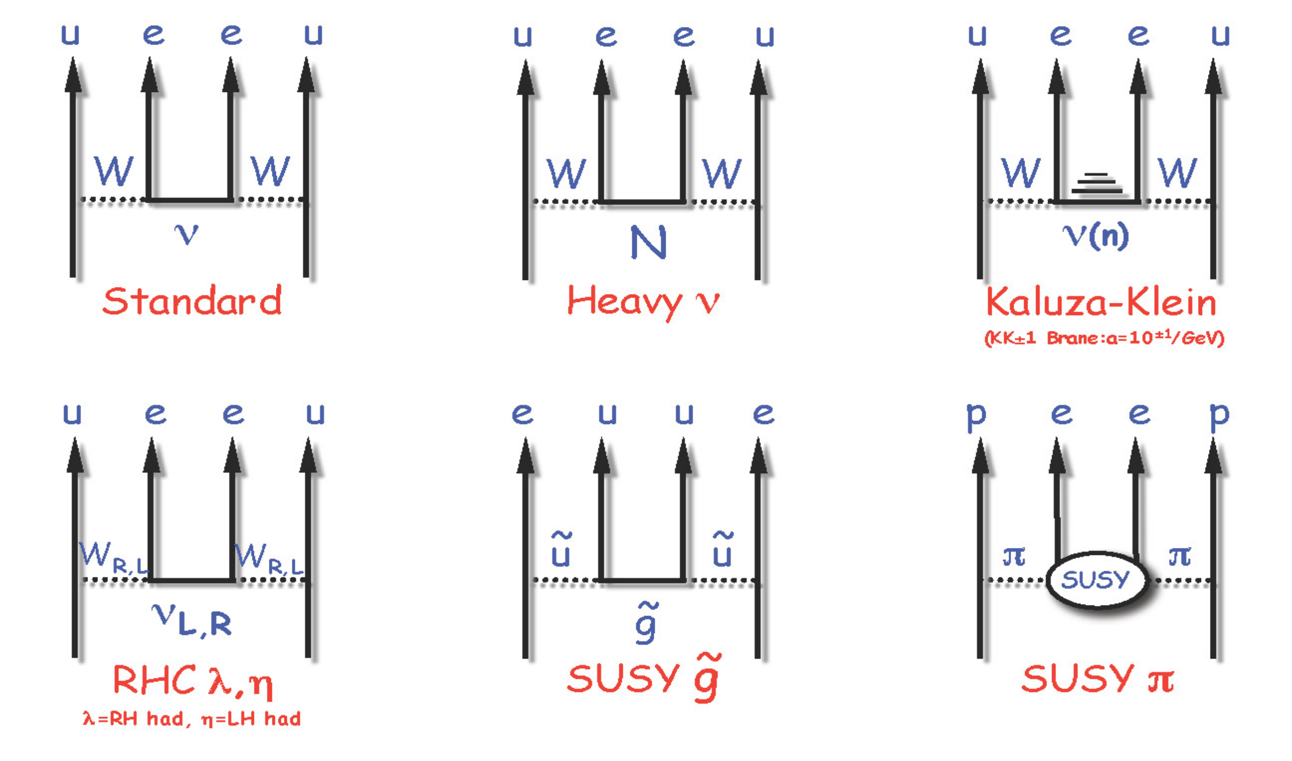



fragments don't match…

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

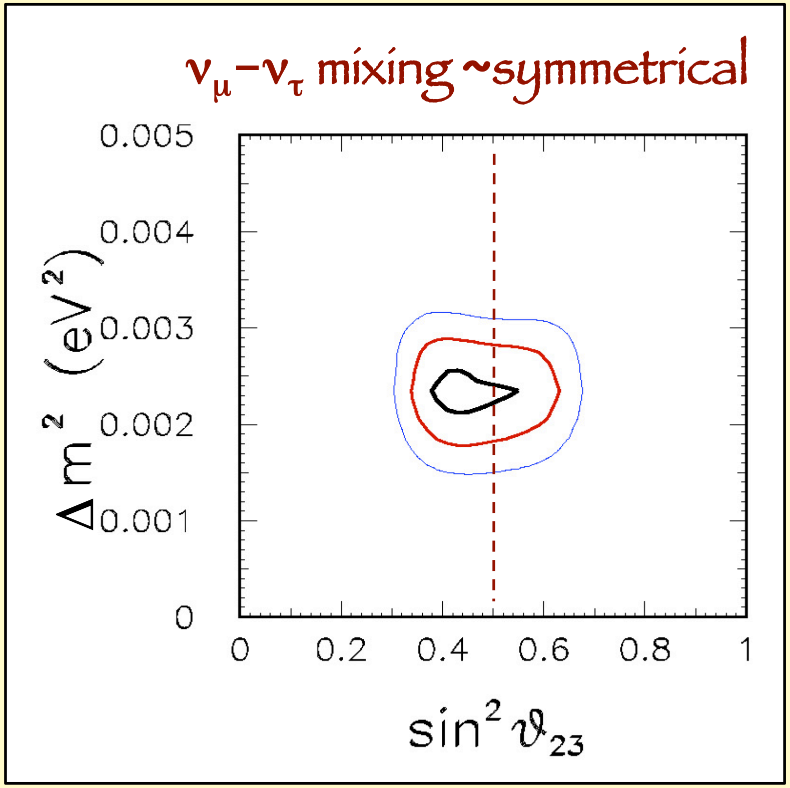
# What if no 3ν concordance? Pheno/theory nightmares …
# … or new opportunities? → New physics!

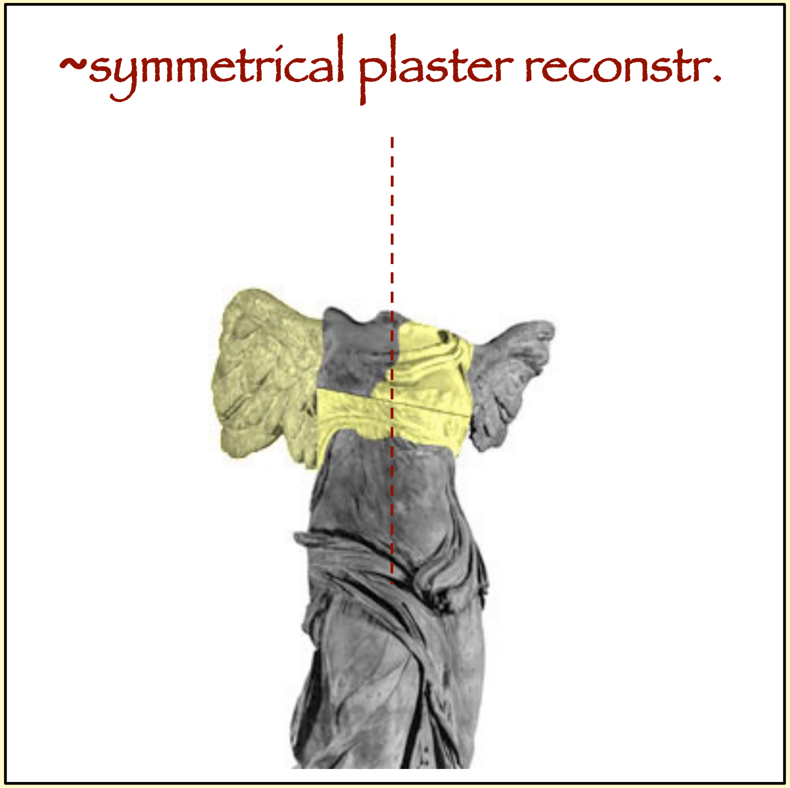
Increasing activity in studying/revisiting **alternative mechanisms** for **0ν2β** decay, their links/roles in other areas (new particles at LHC, leptogenesis, see-saw, charged LFV, extraDim…) and their **discrimination via ≥2 nuclei**.




Progress in theoretical nuclear description (0ν2β matrix elements) mandatory.
Needed also for other purposes: neutrino cross sections [Bodek]

# Neutrino mixing: Flavor symmetries?



Large mixing angles have been a surprise. Another surprise: they seem to have "special" values: $\sin^2\theta_{ij}$~ (1/2, 1/3, 0)

**Remnants of some flavor symmetry … or accidents?**

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

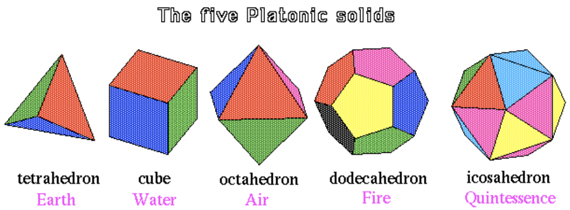
**Tri Bi Max**

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

**Bi Max**

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

Discrete groups + "Cabibbo" corrections $\lambda_C$~0.2




[Feruglio]

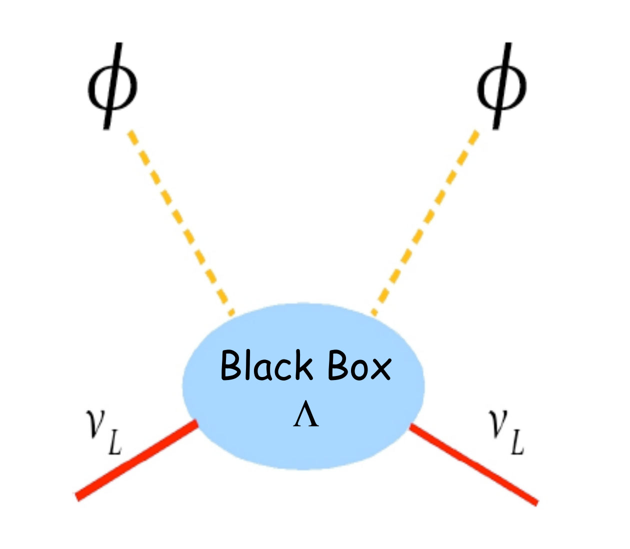
**Current data accuracy: $O(\lambda^2)$ for $\theta_{12}$ and $\theta_{13}$; $O(\lambda)$ for $\theta_{23}$**
**Aim at another $\lambda$ factor in expt accuracy to select models**

# Towards higher energy scales

# ORIGIN OF MASS

[del Aguila, Babu, Nandi]

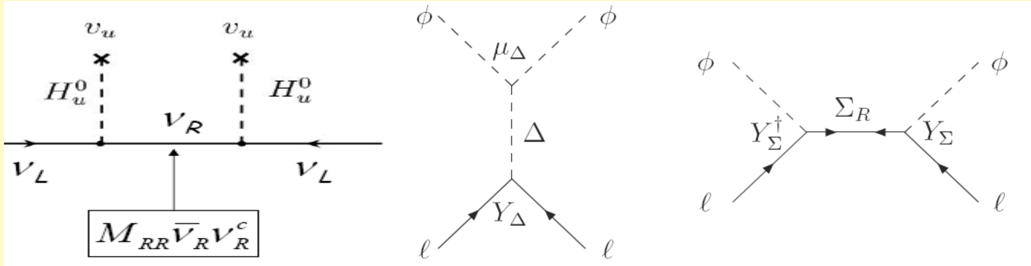
Is there a see-saw mechanism? At which scale $\Lambda$? Of which type?




Type I, fermion singlet N, charge 0

Type II, scalar triplet $\Delta$, charge 0, 1, 2

Type III, fermion triplet $\Sigma$, charge 0, 1

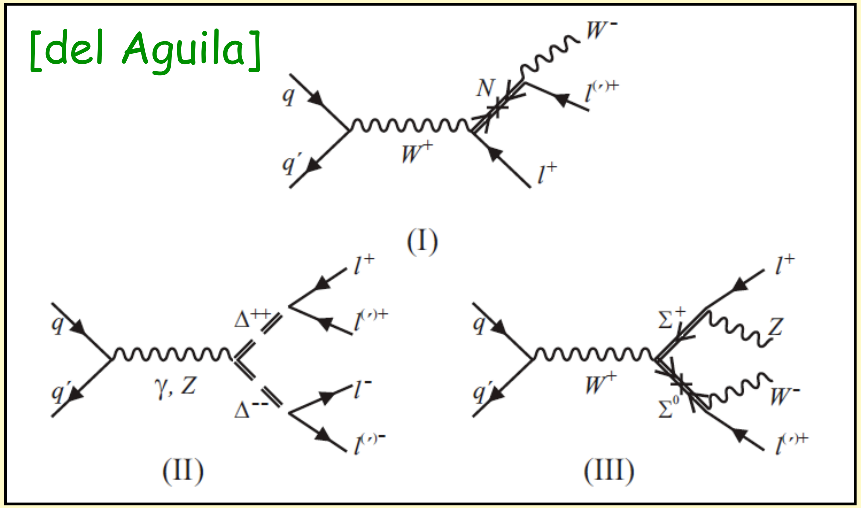



**+ variants (inverse, +SUSY, +LR, +radiative,…)**

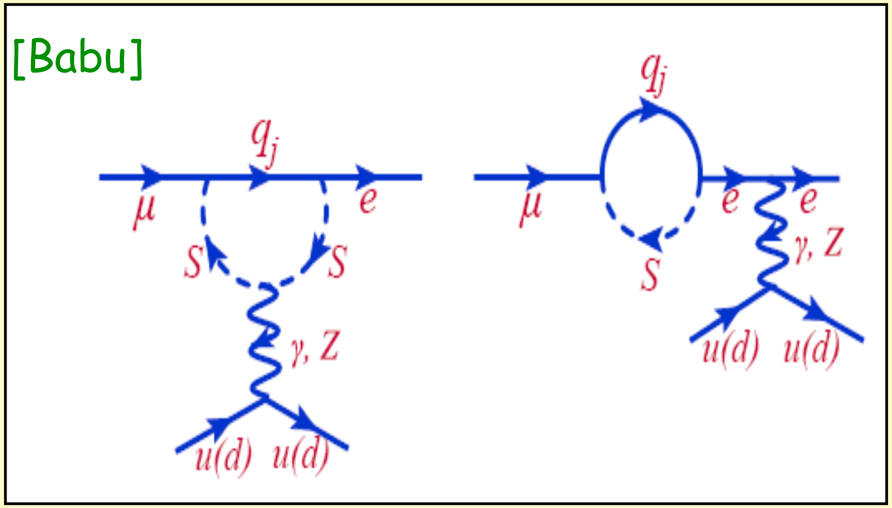
Classical arguments in favor of high-scale, type-I see-saw have their beauty (simplicity, O(1) couplings + small masses +leptogenesis at ~GUT scale, ...)

But, in the **LHC era**: $\phi$ and the black box will be directly probed at $\Lambda$~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 $\nu$ mass origin, e.g., via observable production + decay of see-saw mediators.
Also: links with **charged LFV** processes (model-dependent)

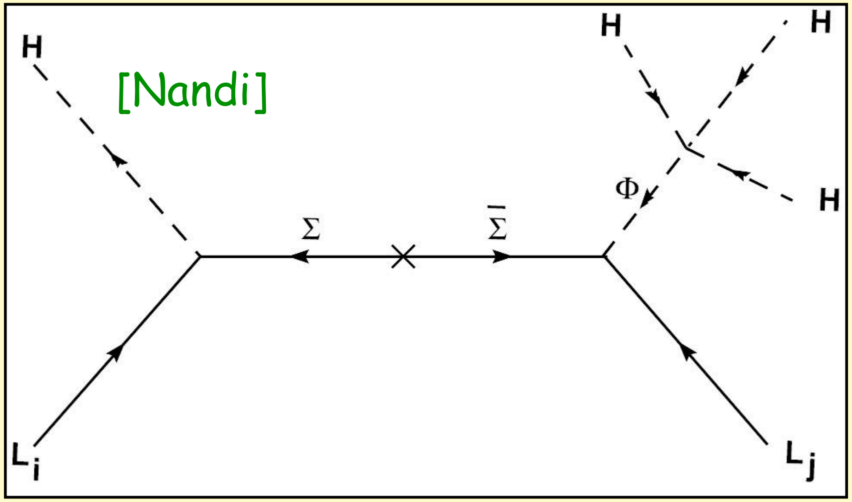
**TeV signatures of see-saw messengers: multi-lepton signals**




**LFV signatures of radiative see-saw models: $\mu$-e conversion**




**TeV signatures of new (triply charged) Higgs bosons**




With some luck, we might start finding fragments of the neutrino mass generation mechanism at the TeV scale…

# ORIGIN OF MATTER

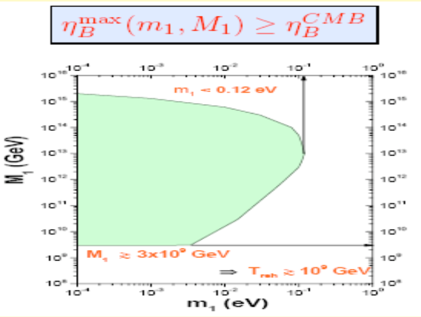
[Losada, Varzielas]

Is leptogenesis the ultimate source of all matter?

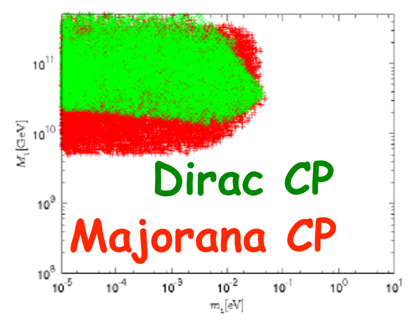
Leptogenesis aims at explaining one single number ($\eta$=6x10$^{-10}$) via CP-violating decays of heavy RH neutrinos. Difficult to test, but:

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 ($\nu_1$, $N_1$). 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!**

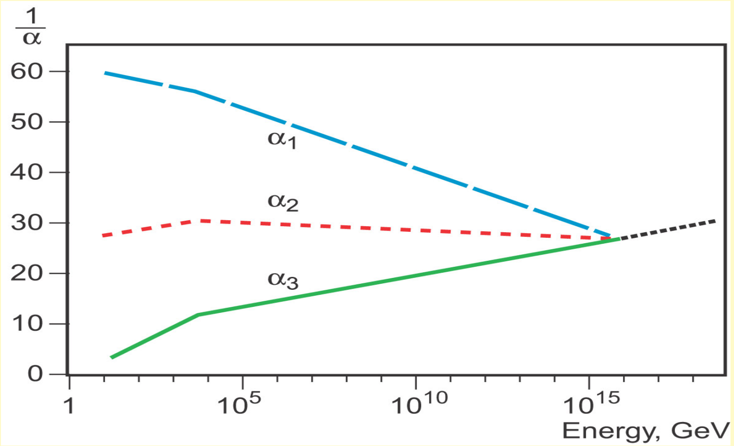


# Steps towards a bigger theoretical picture…

Leptonic CP violation + Majorana neutrinos ($0\nu2\beta$) would make it plausible that heavy $\nu_R$ at a new-physics scale $m_R$ may induce:

- Matter-antimatter asymmetry (via leptogenesis, $\nu_R \to l^+ \neq \nu_R \to l^-$)
- Small Majorana $\nu$ masses (via see-saw mechanism, $m \sim m_D^2/m_R$)

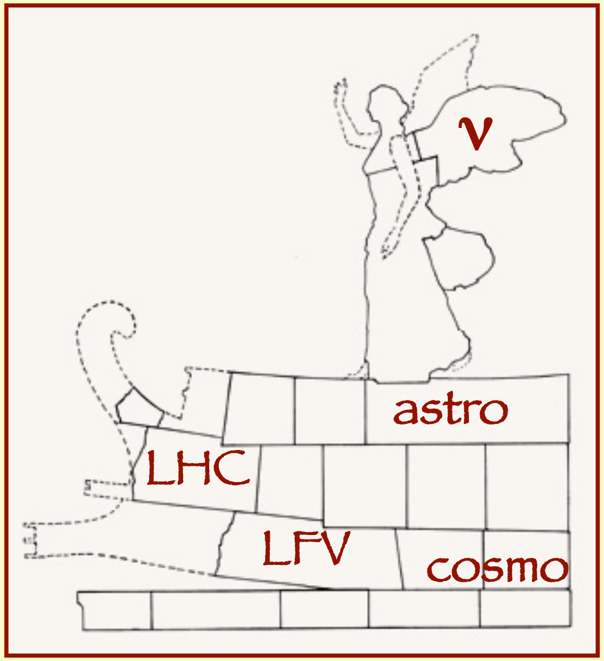
Possible $m_R$ range very large…
for $m_D \sim m_e \ldots m_{top}$:
$m_R$ from TeV to GUT scale,
models from LR to SO(10)…




TeV data will start to <u>constrain</u> the phase space of successful theories.

# CONCLUSIONS

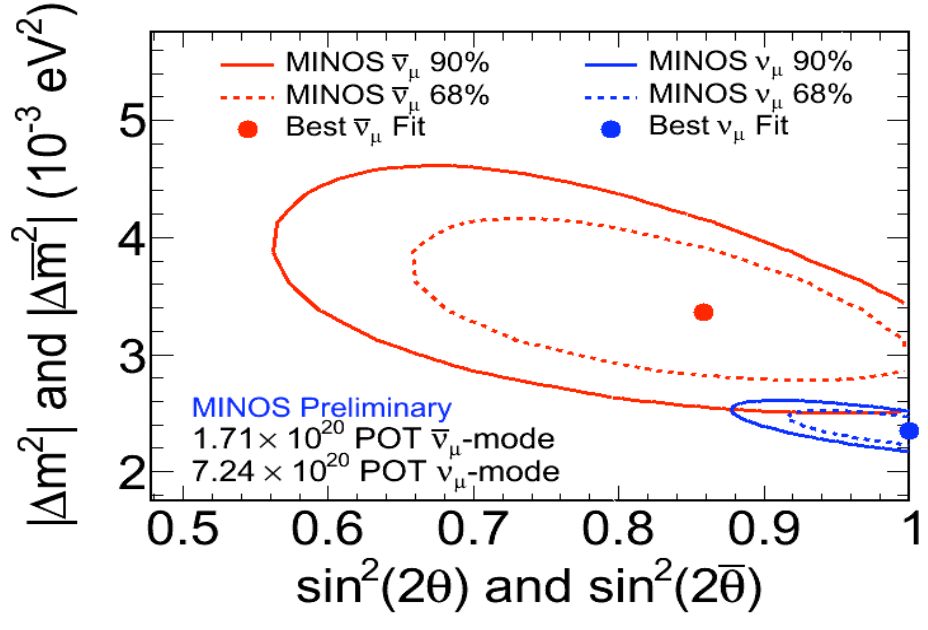
The tiny $\nu$ masses are fragments of new physics,
which will hopefully match many other fragments
from $\nu$, astroparticle, charged LFV and collider physics,
and shed light on a beautiful new picture of Nature

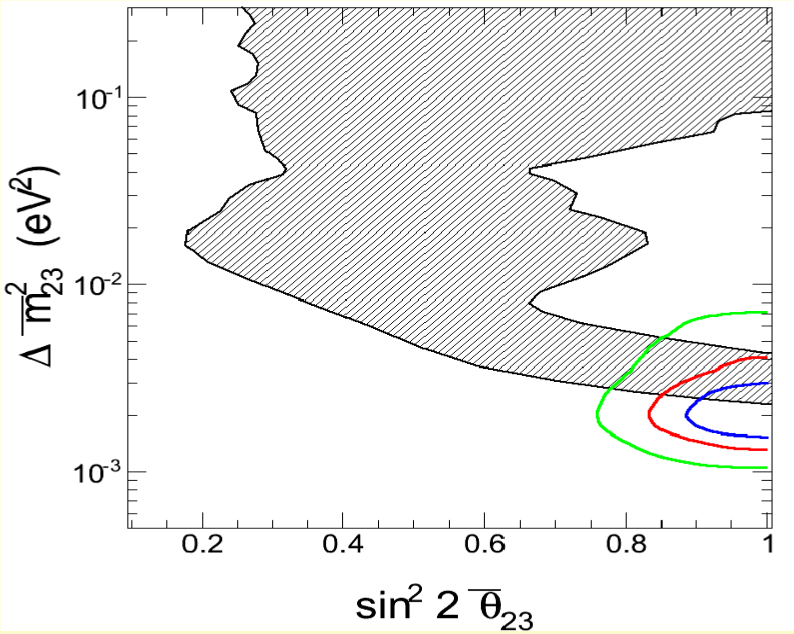



- THANK YOU FOR YOUR ATTENTION -

# Back-up slides

# A new anomalous fragment? MINOS $\nu$ vs anti-$\nu$




MINOS: some tension at $2\sigma$ level

[But: not supported by SK data]

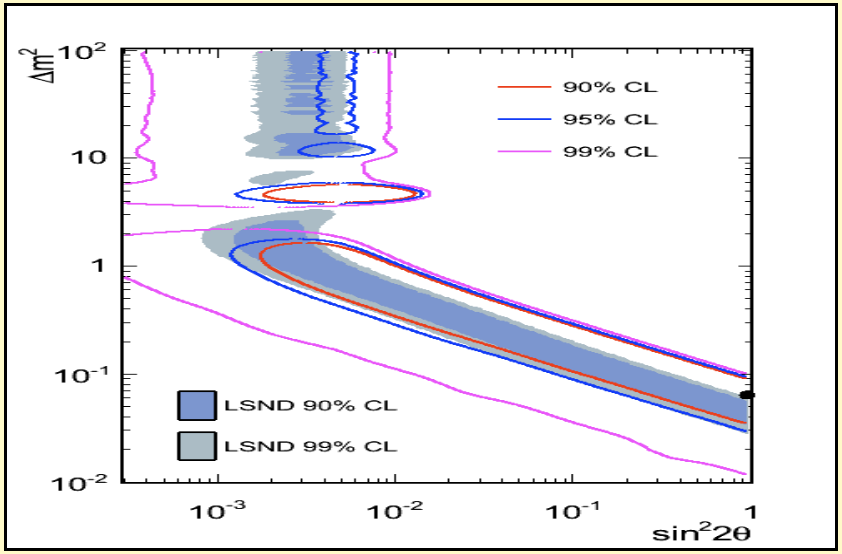
If a true signal → new $\nu$ physics in matter (FCNC) or in vacuum (CPTV) ?

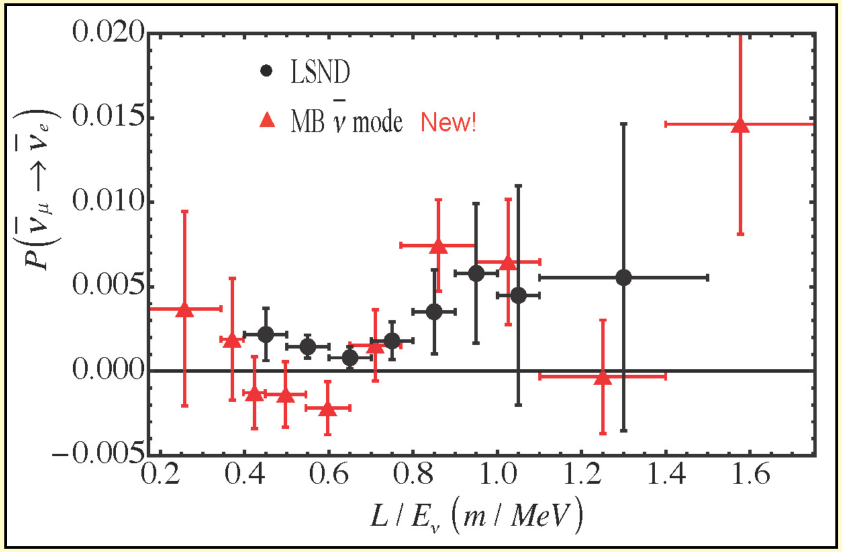
If a fluctuation → underestimated uncertainty [of Dm2] ?

No (convincing) theoretical interpretation emerging from these anomalies…

# Persistent but "evolving" anomalies: LSND & MiniBooNE

$\nu_{Sterile}$ oscillation interpr.: remains difficult after latest anti-$\nu$ results



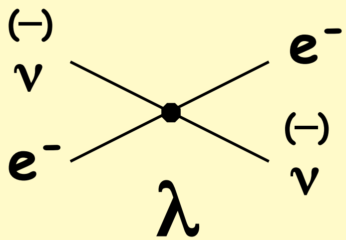



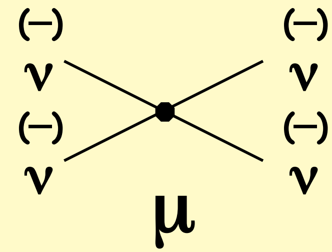

Analysis reveals tension between different datasets:
Low/high E, $\nu$/anti$\nu$, appearance/disappear., SBL/atm…
Can be mitigated by selective choice/adjustment of data sets/errors, and/or by exotic new physics (CPTV?)

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

# Supernovae and neutrino-neutrino interactions

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

besides 

(CC) one has to include 

(NC)

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

$$
\begin{aligned}
\dot{\mathbf{P}}_i &= \mathbf{V}_{\mathrm{ector}}[+\omega,\ \lambda,\ \mu,\ \mathbf{P}_j,\ \overline{\mathbf{P}}_j] \times \mathbf{P}_i \\
\dot{\overline{\mathbf{P}}}_i &= \mathbf{V}_{\mathrm{ector}}[-\omega,\ \lambda,\ \mu,\ \mathbf{P}_j,\ \overline{\mathbf{P}}_j] \times \overline{\mathbf{P}}_i
\end{aligned}
$$

Vacuum frequency

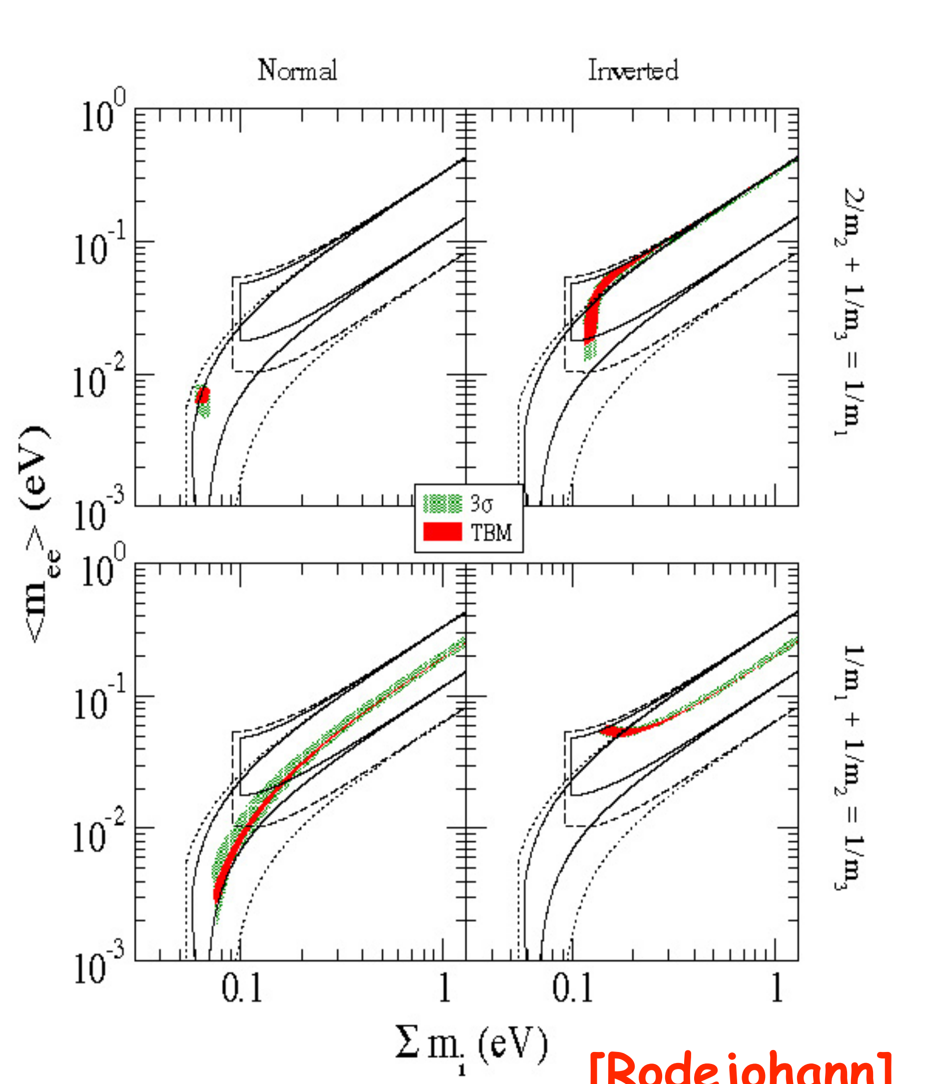
matter

self-interaction

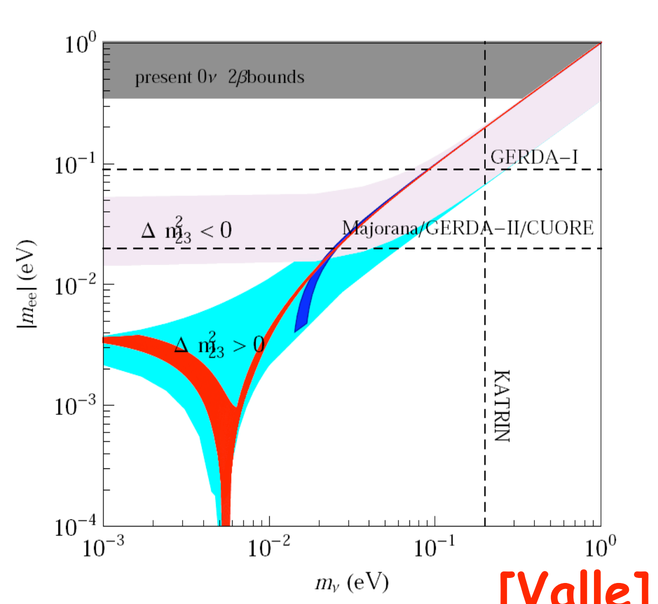
ij couplings

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

**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…)**

# Main message: Symmetry models can be predictive and testable!

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

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

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

CGs of SU(5) & T′

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

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

neutrino mixing angle

1/2

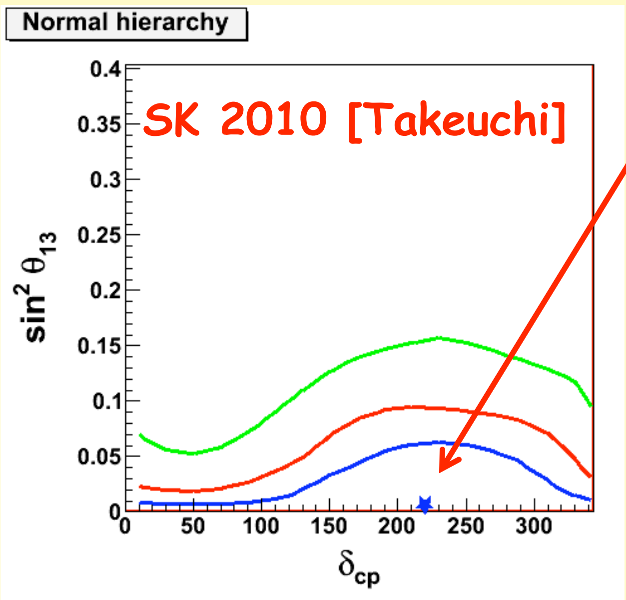
quark mixing angle

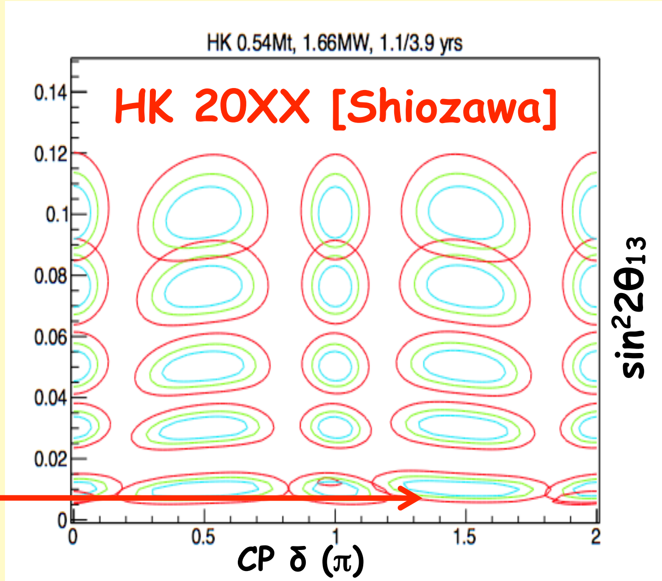
CG: leptonic Dirac CPV

prediction for Majorana phases: 0, π

prediction for Dirac CP phase: δ = 227 degrees

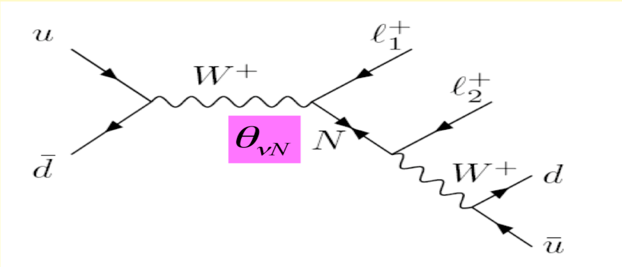
⇒ connection between leptogenesis & CPV in neutrino oscillation



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

### Type I



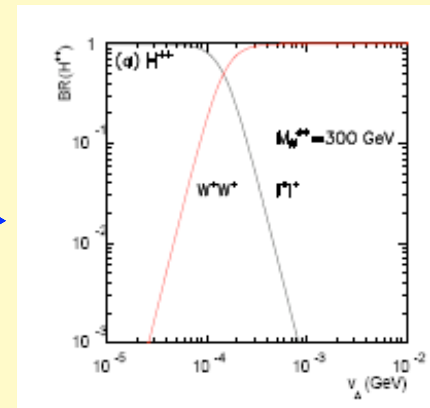

No gauge couplings (except via mixing); generally suppressed in production and decay. Situation different in type II, III:

### Type II

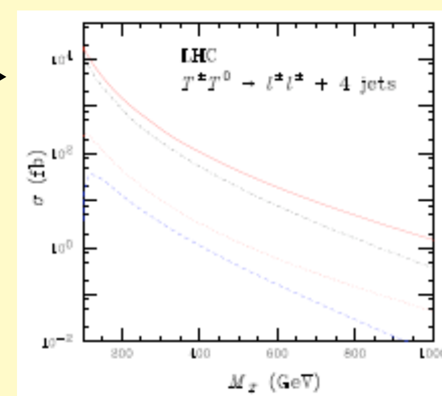
$$q\bar{q} \to Z^*/\gamma^* \to \Sigma^+\Sigma^-, \quad \delta^{++}\delta^{--}$$
$$q\bar{q}' \to W^* \to \Sigma^+\Sigma^0, \quad \delta^{++}\delta^{-}$$

### Type III

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



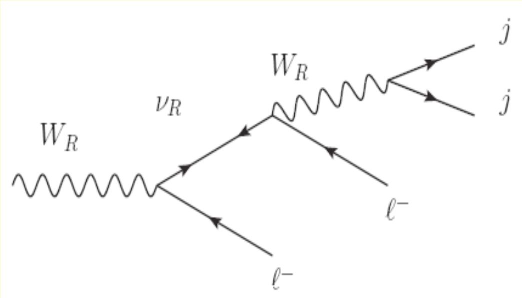

$$\Sigma^0 \to l^+W^-$$
$$\Sigma^+ \to l^+Z, ..$$



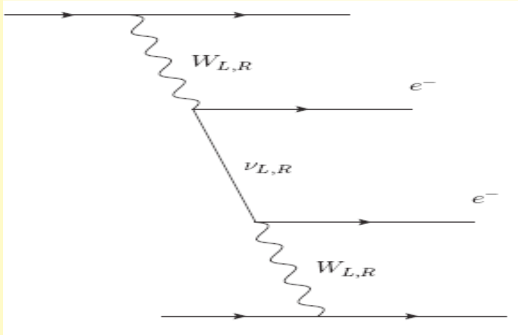

Production and decay might proceed at observable rates at the LHC [Mohapatra]

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

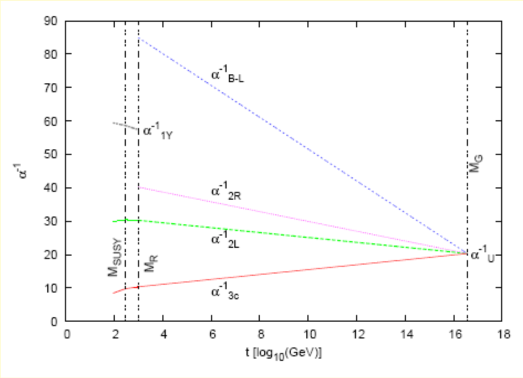
LR symmetry can rescue N production and decay via $W_R$ …



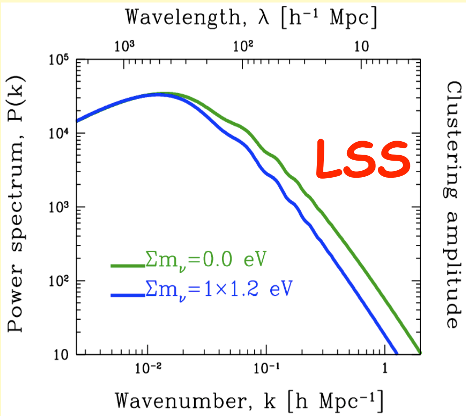

…Provide an alternative mechanism for $0\nu2\beta$ decay…




…And be consistent with coupling unification! [Mohapatra]



# A “guaranteed” LE source: Big Bang ν [Wong]

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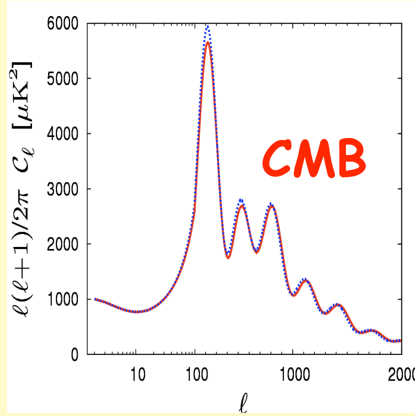
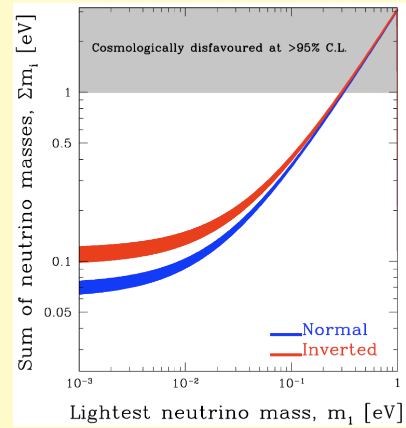


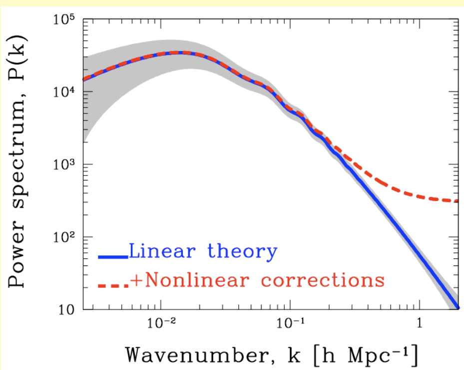

+ ... =




← Now

← Planck

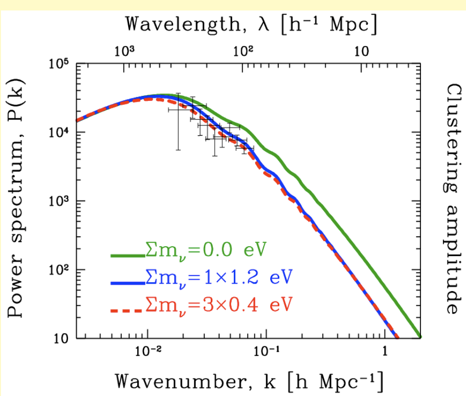
← Lensing




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 $\Sigma=m_1+m_2+m_3$ and probe mass distribution over the 3 states.

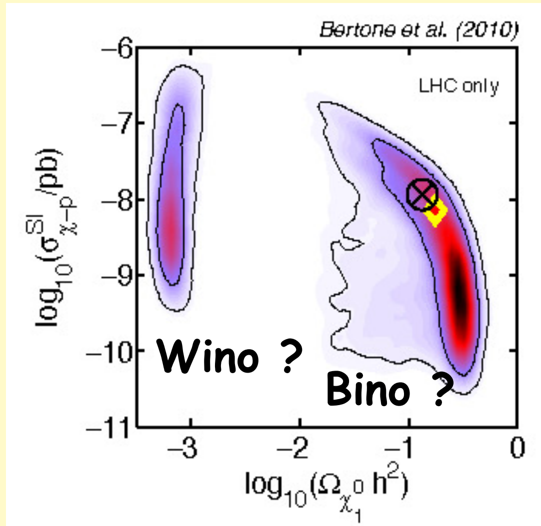
# A "guaranteed" relic ν companion: DM [Bertone]

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

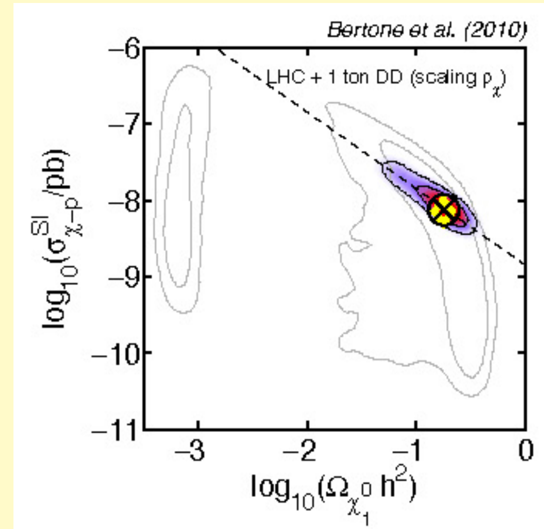
**Even if SUSY spectrum reconstructed at LHC…**

| Mass | Benchmark value, $\mu$ | LHC error, $\sigma$ |
|---|---|---|
| $m(\widetilde{\chi}_1^0)$ | 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**

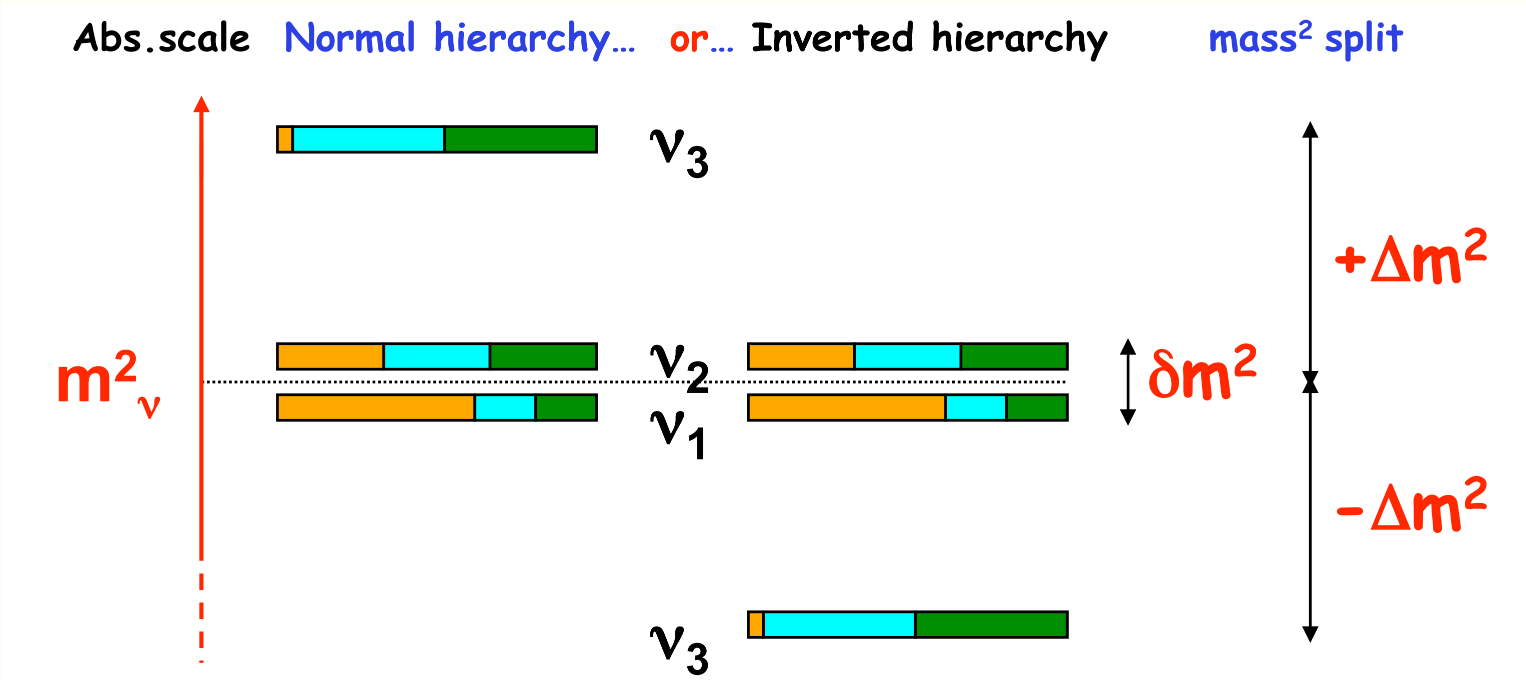



In general, many possible connections with neutrino physics, e.g.,

- 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**

In recent years, $\nu$ masses and mixings have provided important (but incomplete) fragments of new physics. **Flavor = e $\mu$ $\tau$ is not conserved** (transitions observed in vacuum & matter). **3$\nu$ scenario:**




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

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

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

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

# 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:

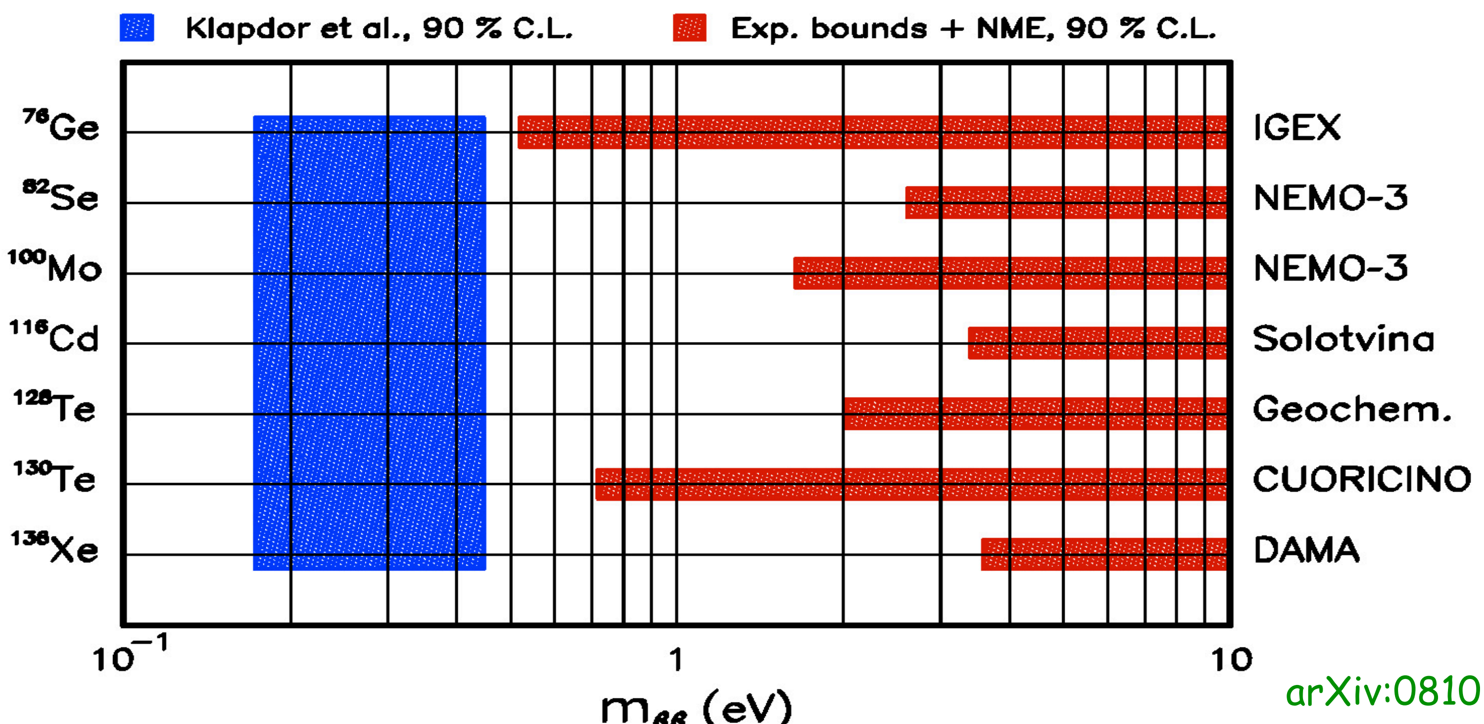
**… as well as exploration of many possible variants and alternatives.** [Di Bari, Valle, Mohapatra]

# Status [and prospects]

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

$\Sigma$ < ~1 eV ("conservative") down to
< ~0.2 eV ("aggressive")
[< ~0.6 eV: "consensus value", aim at x10 improvement]

$m_{\beta\beta}$




arXiv:0810.5733

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