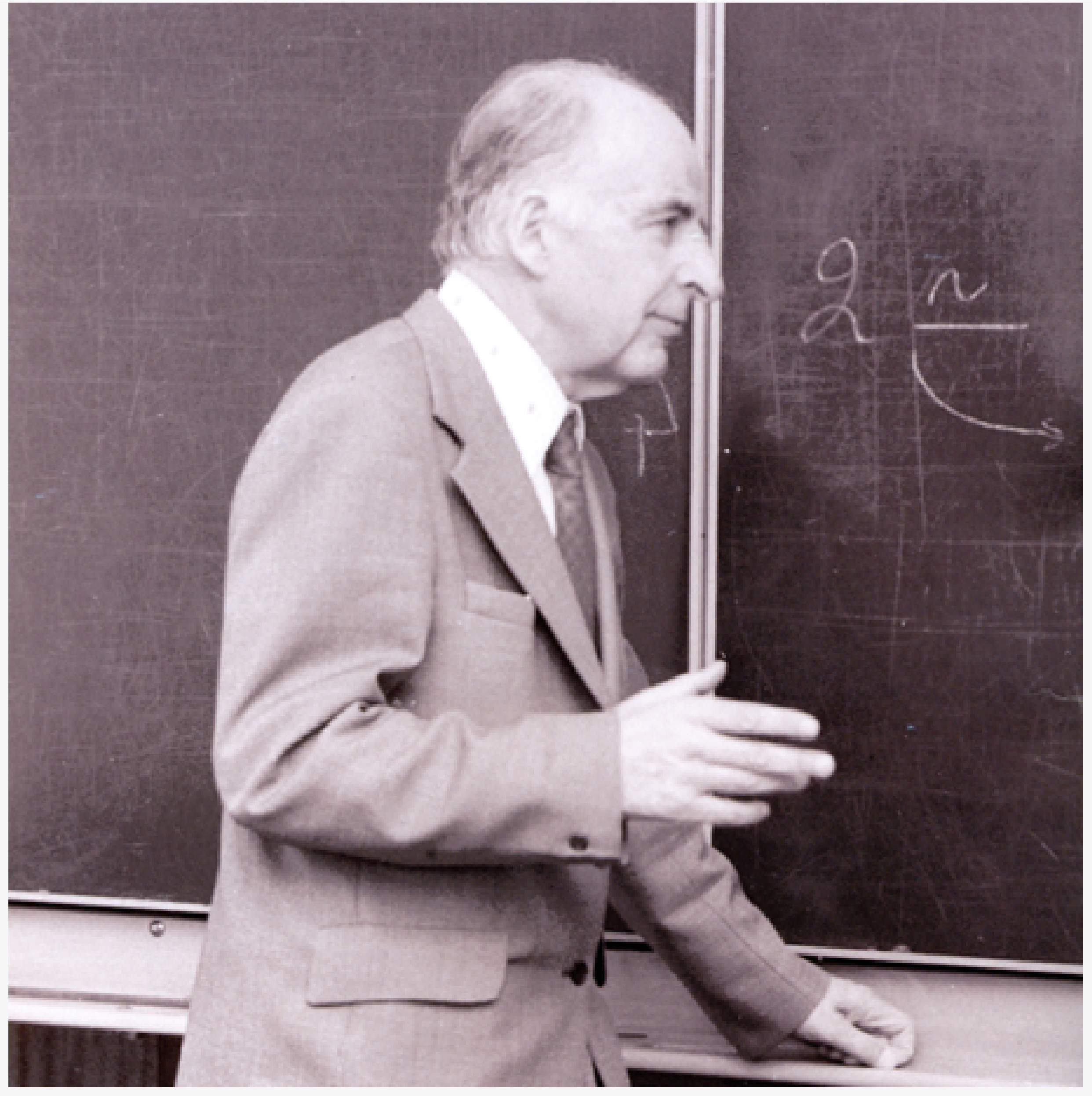
Pontecorvo100, Pisa, 20 September '13

Concluding Talk: Fundamental Lessons and Challenges from Neutrinos

G. Altarelli
Universita' di Roma Tre/CERN

Bruno at the age when I met him several times



Bruno Pontecorvo has pioneered the physics of neutrinos in many different aspects

Mitselmakher
Steinberger
Bilenky

In the last two decades experiments have established neutrino oscillations and the most important related parameters have been measured

These results represented a major progress of great importance for particle physics and cosmology

Neutrino physics is at present a vital domain of particle physics and the remaining open qestions are of crucial importance

In the last ~15 years we have learnt that

- ν's are massive (at least two of them)
- their masses are very small
- ν's oscillate (no separate lepton number cons.)
- Δm^2_{ij} and mixing angles are measured with fair precision
- probably ν's are Majorana particles [can explain small masses and large mixing (see-saw, O_5)]
- an appealing picture: ν's as probes of GUT's, baryogenesis thru leptogenesis....
- open questions: absolute scale of m^2? inverse or normal hierarchy? CP viol? flavour symmetry? sterile ν's?....

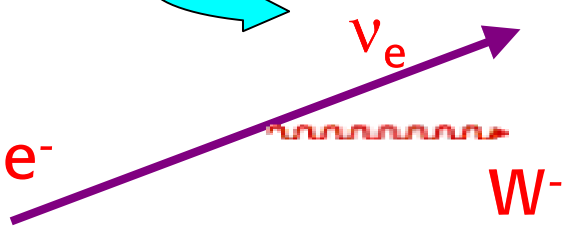
ν Oscillations Imply Different ν Masses

ν_e: same weak isospin doublet as e^-

flavour mass

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

U: mixing matrix



$U = U_e^{+} U_\nu$

e.g 2 flav.

$$\nu_e = \cos\theta\,\nu_1 + \sin\theta\,\nu_2$$
$$\nu_\mu = -\sin\theta\,\nu_1 + \cos\theta\,\nu_2$$

$\nu_{1,2}$: eigenstates of different masses $m_{1,2}$ with $\Delta m^2 = m_2^2 - m_1^2$

In vacuum:

$$P(\nu_e <-> \nu_\mu) = |< \nu_\mu(L)|\ \nu_e>|^2 = \sin^2(2\theta)\cdot\sin^2(\Delta m^2 L/4E)$$

In matter the MSW effect

At a distance L, ν_μ from μ^- decay can produce e^- via charged weak interact's

ν oscillations measure Δm^2. What is m^2?

$\Delta m^2_{atm} \sim 2.5\ 10^{-3}\ eV^2$; $\Delta m^2_{sun} \sim 8\ 10^{-5}\ eV^2$

- Direct limits

$m_{"\nu e"} < 2.2$ eV

$m_{"\nu\mu"} < 170$ KeV

$m_{"\nu\tau"} < 18.2$ MeV

End-point tritium βdecay (Mainz, Troitsk, future: Katrin)

- Cosmology $\Omega_\nu h^2 \sim \Sigma_i m_i\ /94eV$ $(h^2 \sim 1/2)$

$\Sigma_i m_i < 0.23 - 0.8$ eV 95% Planck +BAO+WMAPPol+HighL

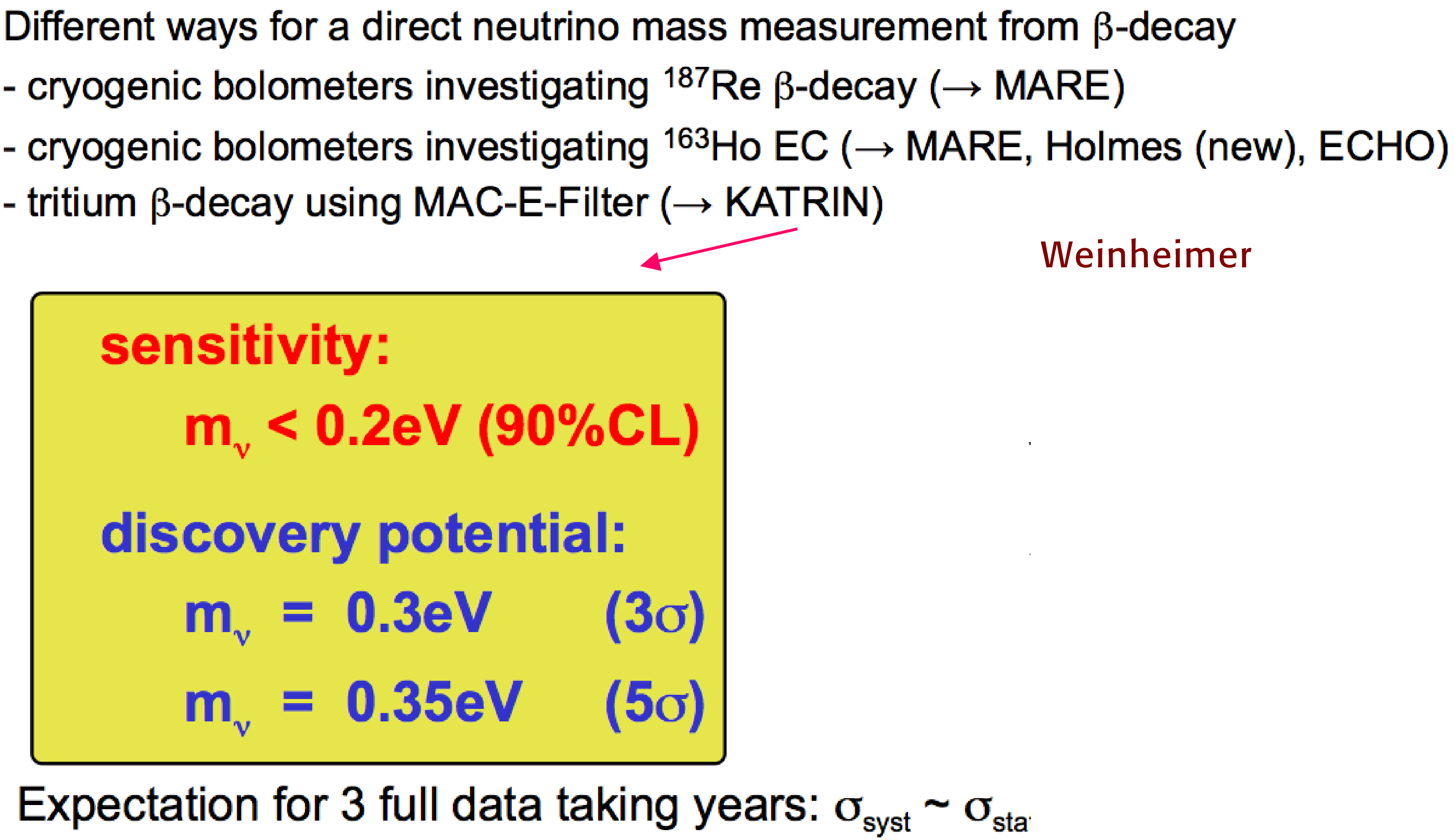
Any ν mass $< 0.08 - 0.27$ eV

depends on cosmology priors

Hannested

$m_{ee} = |\Sigma\, U_{ei}^2\, m_i|$

- $0\nu\beta\beta$ $m_{ee} < 0.2 - 0.7 - ?$ eV (nucl. matrix elmnts)



Different ways for a direct neutrino mass measurement from β-decay

- cryogenic bolometers investigating ^{187}Re β-decay (→ MARE)
- cryogenic bolometers investigating ^{163}Ho EC (→ MARE, Holmes (new), ECHO)
- tritium β-decay using MAC-E-Filter (→ KATRIN)

Weinheimer

sensitivity:

$m_\nu < 0.2$eV (90%CL)

discovery potential:

$m_\nu = 0.3$eV (3σ)

$m_\nu = 0.35$eV (5σ)

Expectation for 3 full data taking years: $\sigma_{syst} \sim \sigma_{sta}$

Expect start of tritium data taking in 2015

ν oscillations measure Δm^2. What is m^2?

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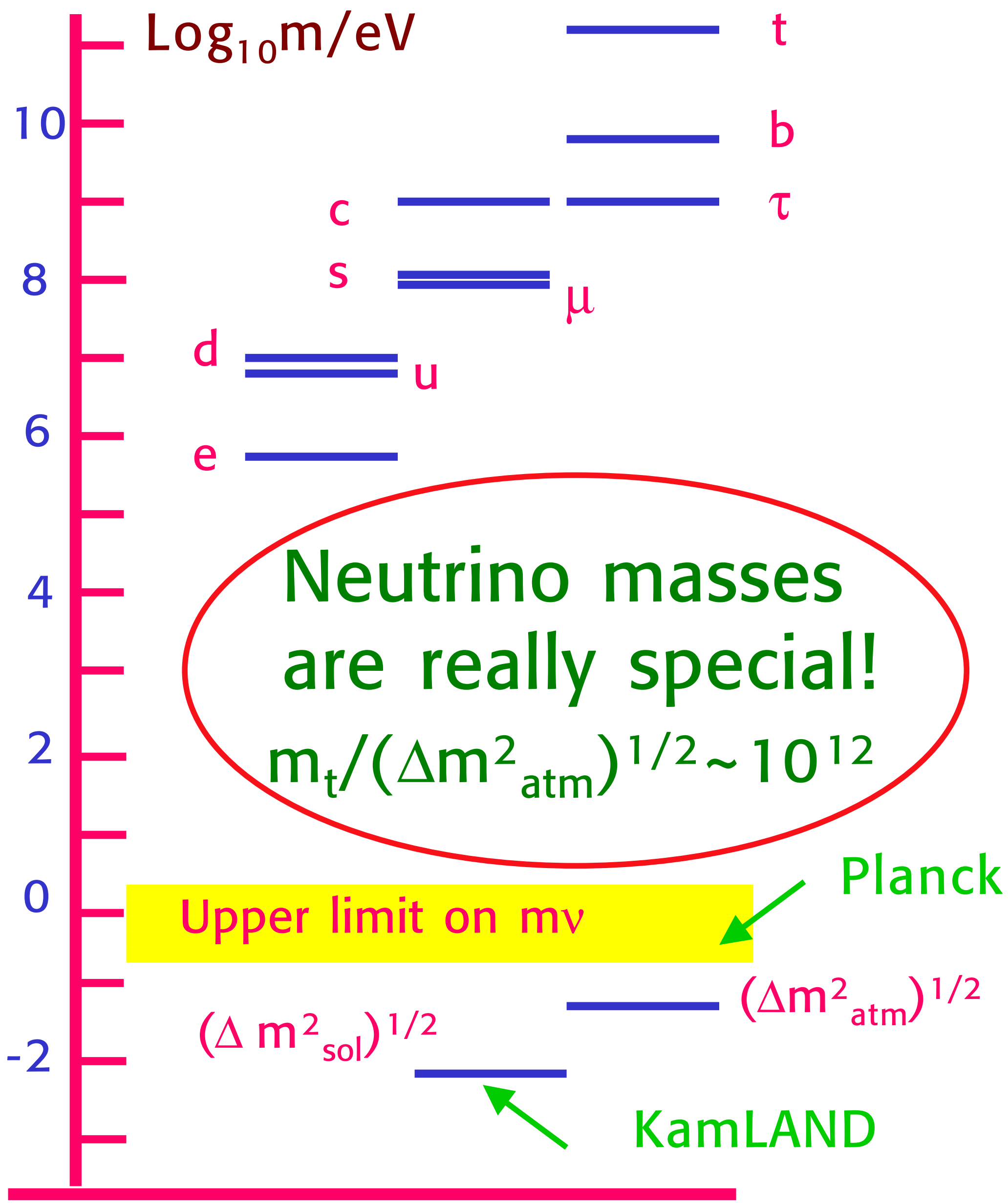


Neutrino masses are really special!

$m_t/(\Delta m^2_{atm})^{1/2} \sim 10^{12}$

It is often said that ν masses are physics beyond the SM

Massless ν's?

- no ν_R
- L conserved

But ν_R can well exist and we really have no reason to expect that B and L are exactly conserved

Small ν masses?

- ν_R very heavy
- L not exactly cons.

Completing the SM

It is sufficient to introduce 3 RH gauge singlets ν_R
[each completing a 16 of SO(10) for one generation]
and not artificially impose that L is conserved

In the SM, in the absence of ν_R, B and L are “accidental” symmetries
[no renormalizable gauge invariant B and/or L non-conserving vertices can be built from the fields of the theory]

But we know that non perturbative terms (instantons) break B and L and also non renormalizable operators

With ν_R Majorana renormalizable mass terms are allowed by gauge symmetries and break L

How to guarantee a massless neutrino?

1) ν_R does not exist

→ No Dirac mass

$$\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L$$

and

2) Lepton Number is conserved

→ No Majorana mass

$$\nu^T_R \, \nu_R \ \text{or} \ \nu^T_L \, \nu_L$$

Are there Majorana fermions?

Neutrinos are probably Majorana fermions

Under charge conjugation C: particle <--> antiparticle

For bosons there are many cases of particles that coincide (up to a phase) with their antiparticle:

$$\pi^0, \rho^0, \omega, \gamma, Z^0.....$$

A fermion that coincides with its antiparticle is called a Majorana fermion

The fundamental fermions of the Standard Model:

$$\begin{bmatrix} uuu\nu_e \\ ddde \end{bmatrix} \quad \begin{bmatrix} ccc\nu_\mu \\ sss\mu \end{bmatrix} \quad \begin{bmatrix} ttt\nu_\tau \\ bbb\tau \end{bmatrix}$$

- Of all fundamental fermions only ν's are neutral

  If lepton number L conservation is violated then no conserved charge distinguishes neutrinos from antineutrinos ⟶

  Majorana ν's : each mass eigenstate of definite helicity coincides with its own antiparticle.
  Neutrinos are their own antiparticles

- ν's have very small masses

  The two facts are probably related

The field of an electron (massive, charged) has 4 components

In fact there are 4 dof: $e^-, e^+, h = +, -$
(h is the helicity: component of spin along momentum)

$$\begin{tikzcd} |e^{--}, h = + > \arrow[r, "\text{Lorentz boost}"] \arrow[d, "\text{TCP}"'] & |e^{--}, h = - > \arrow[d, "\text{TCP}"'] \\ |e^{+}, h = - > \arrow[r, "\text{Lorentz boost}"] & |e^{+}, h = + > \end{tikzcd}$$

For a massless neutrino $|\nu_L > = |\nu, h = --1 >$ and $|\overline{\nu}_R > = |\overline{\nu}, h = +1 >$ can be enough because massless particles go at the speed of light (no boost can flip h)

For a massive Majorana neutrino only two states are enough

ν's have no electric charge. Their only charge is L.

IF L is not conserved (not a good quantum number)

ν and $\bar{\nu}$ are not really different

Majorana Neutrino

$$|\,\nu,\, h = -1/2 \,\rangle \xrightarrow{\text{TCP, "Lorentz"}} |\,\bar{\nu},\, h = +1/2 \rangle$$

For a Majorana neutrino each mass eigenstate of definite helicity coincides with its own antiparticle

Weak isospin I

$\nu_L \Rightarrow I = 1/2,\ I_3 = 1/2$

$\nu_R \Rightarrow I = 0,\ I_3 = 0$

Dirac Mass:

$\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L$ $|\Delta I| = 1/2$

Can be obtained from Higgs doublets: $\bar{\nu}_L \nu_R H$

For Dirac ν's no explanation of small masses

Majorana Mass:

- $\nu^T_L \nu_L$ $|\Delta I| = 1$

needs 2 Higgs $\nu^T_L \nu_L HH$

- $\nu^T_R \nu_R$ $|\Delta I| = 0$ →

Non ren., dim. 5 operator:

$$O_5 = \frac{(Hl)_i^T \lambda_{ij} (Hl)_j}{\Lambda} + h.c.$$

Directly compatible with SU(2)xU(1)!

See-Saw Mechanism

Minkowski; Glashow; Yanagida;
Gell-Mann, Ramond , Slansky;
Mohapatra, Senjanovic…..

$M\nu^T{}_R\nu_R$ allowed by SU(2)xU(1)

Large Majorana mass M (as large as the cut-off)

$m_D\bar{\nu}_L\nu_R$

Dirac mass m_D from Higgs doublet(s)

$$\begin{array}{c|cc} & \nu_L & \nu_R \\ \hline \nu_L & 0 & m_D \\ \nu_R & m_D & M \end{array}$$

$M \gg m_D$

Eigenvalues

$$|\nu_{light}| = \frac{m_D{}^2}{M} \quad , \quad \nu_{heavy} = M$$

A very natural and appealing explanation:

ν's are nearly massless because they are Majorana particles and get masses through L non conserving interactions suppressed by a large scale $M \sim M_{GUT}$

$$m_\nu \sim \frac{m^2}{M}$$

$m: \leq m_t \sim v \sim 200$ GeV
M: scale of L non cons.

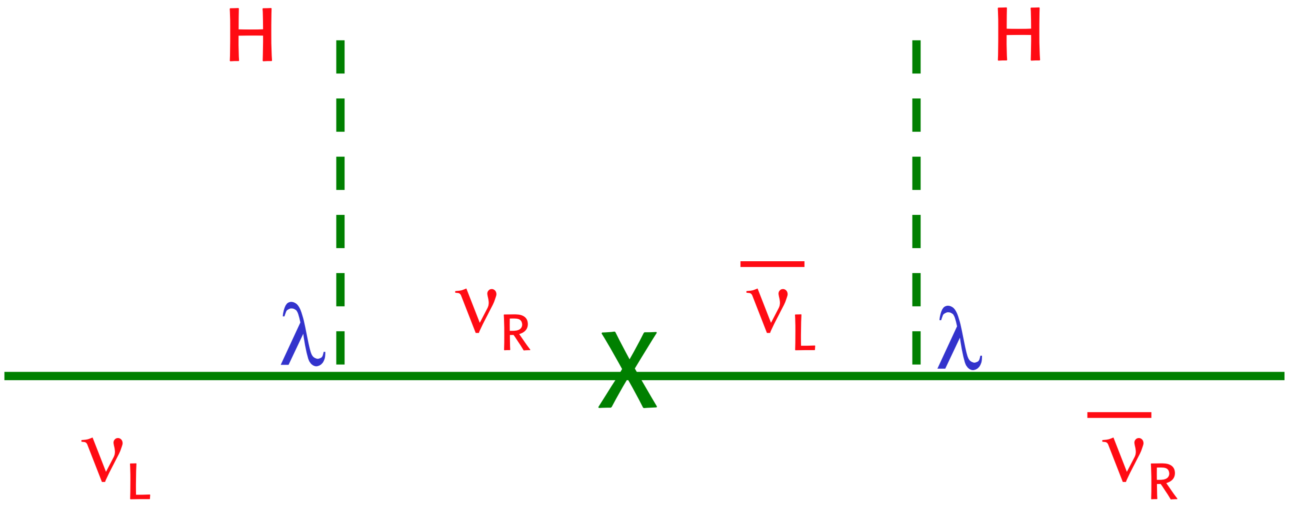
Note:

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05$ eV
$m \sim v \sim 200$ GeV

$M \sim 10^{14} - 10^{15}$ GeV

Neutrino masses are a probe of physics at M_{GUT} !

A different way to look at the see-saw mechanism



An effective operator for a LL Majorana mass

$$\lambda^2/M \ \nu_L^T \nu_L HH$$

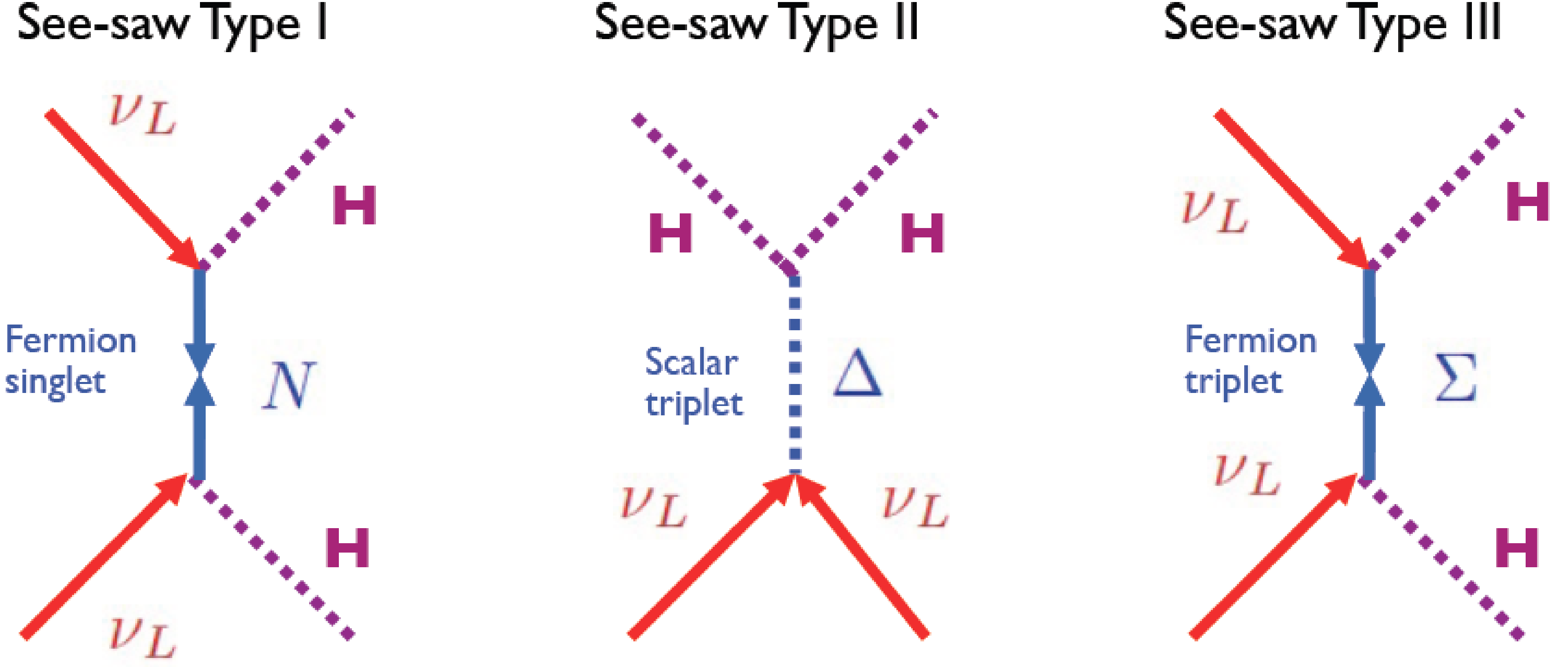
can arise from the exchange of a heavy ν_R

$$\lambda^2 v^2/M \sim m^2/M$$

[v is the H vacuum expectation value]

Different possible intermediate heavy particles (see-saw types)

Pascoli



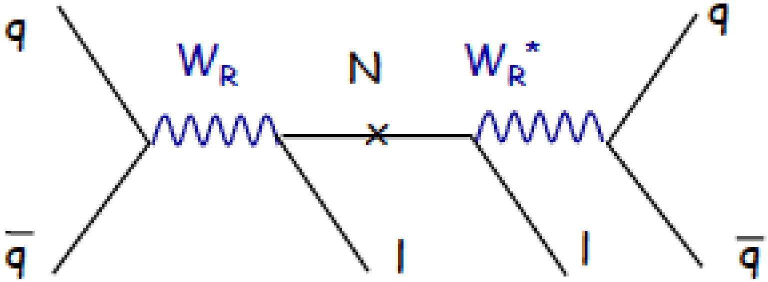
All correspond to the same effective operator

$$O_5 = \frac{(Hl)_i^T \lambda_{ij} (Hl)_j}{\Lambda} + \ h.c.$$

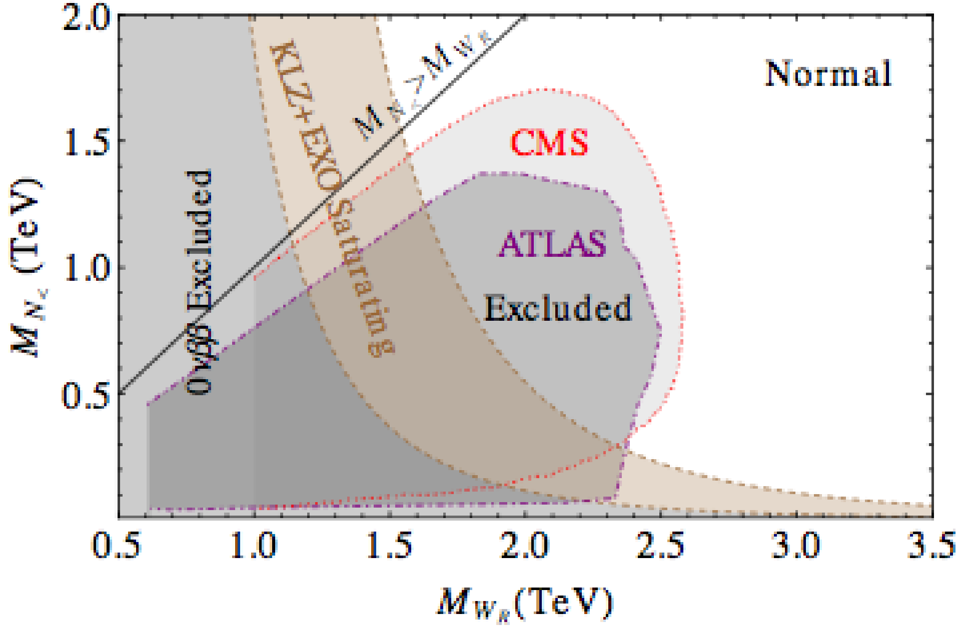
Alternatively can one see signals at the LHC of the ν mass generation?

Senjanovic
Keung

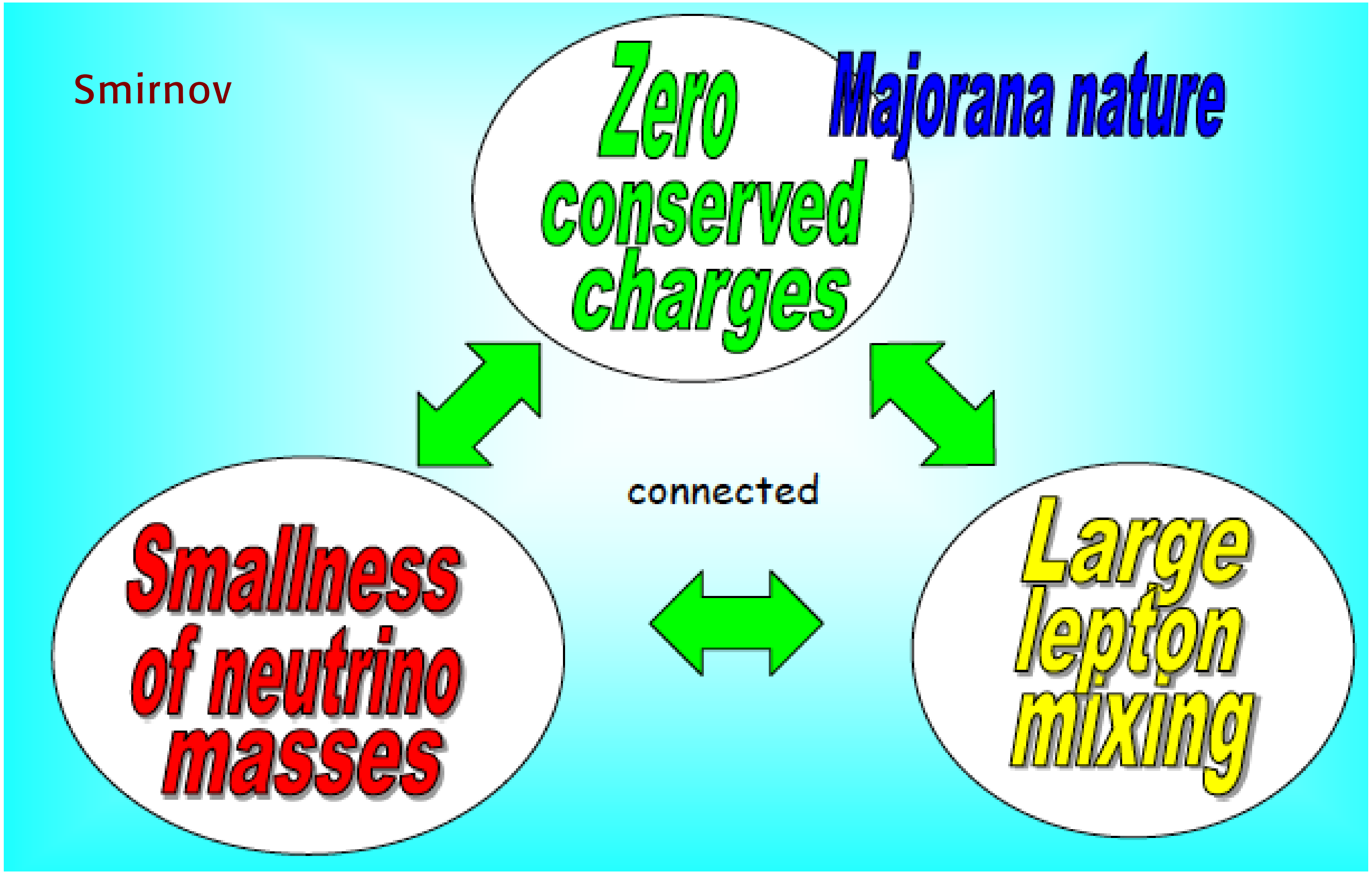
Example: Low energy L-R symmetry



Smirnov

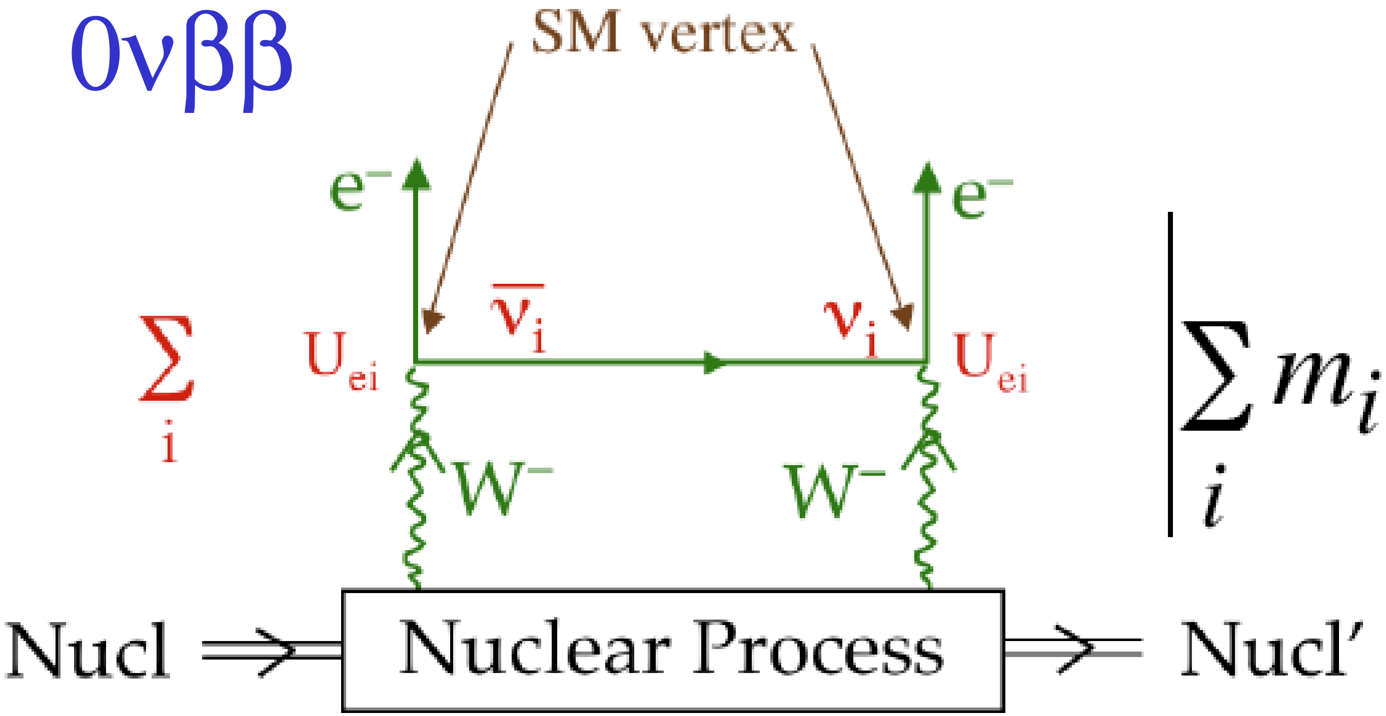


Limits from LHC
and 0νββ

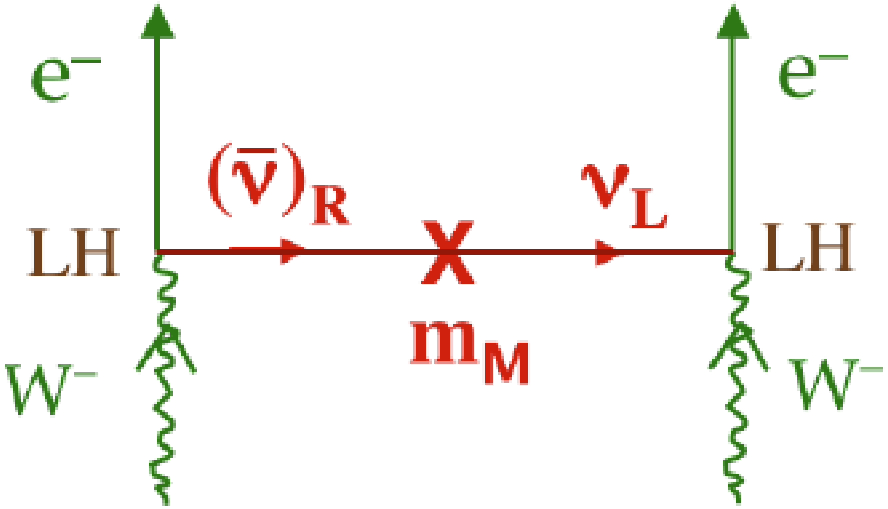


Observation of $0\nu\beta\beta$ would prove that ν's are Majorana fermions

0νββ



$$\left|\sum_i m_i U_{ei}^2\right| \equiv m_{\beta\beta}$$



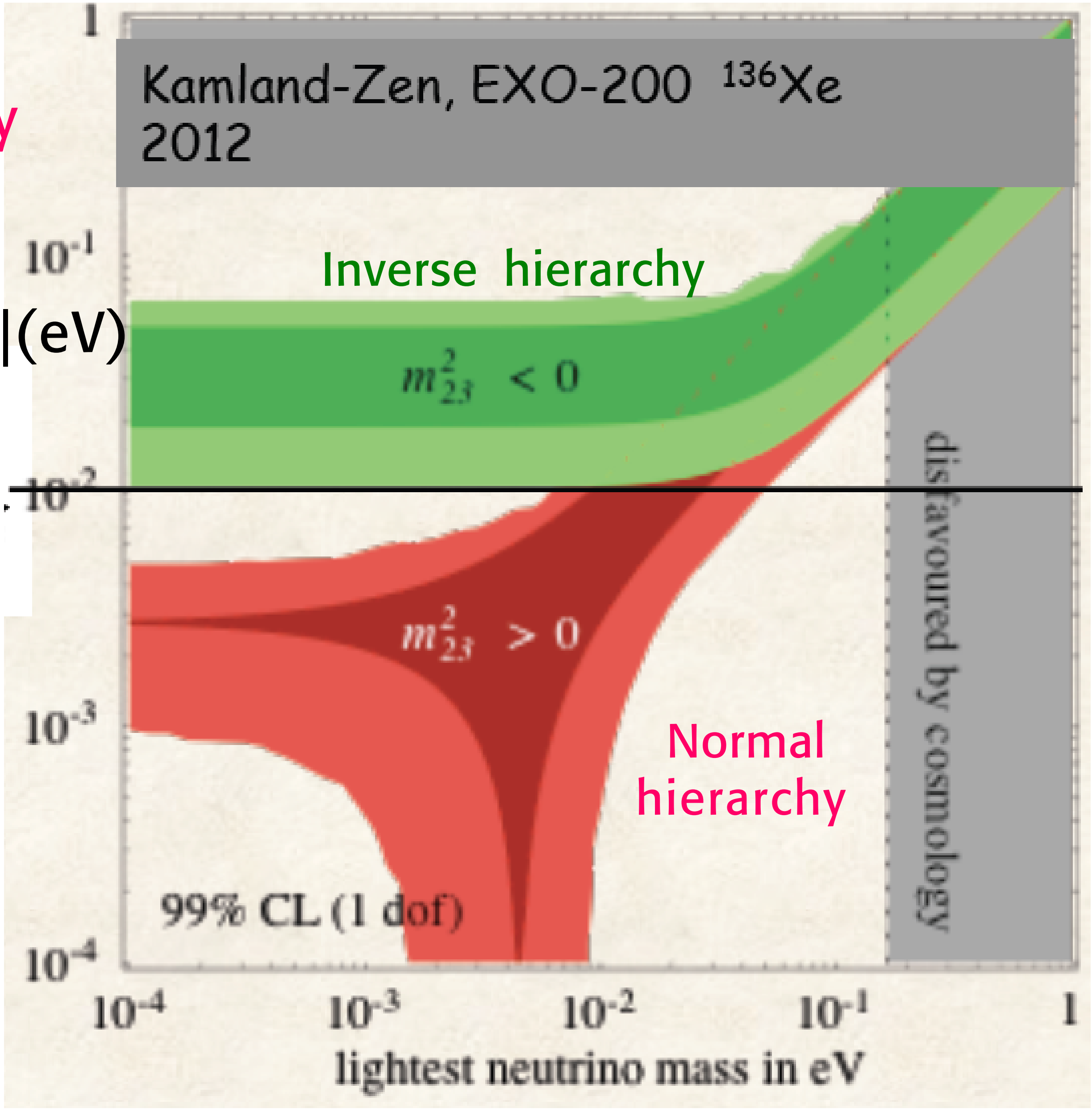
0νββ signal would establish Majorana ν's

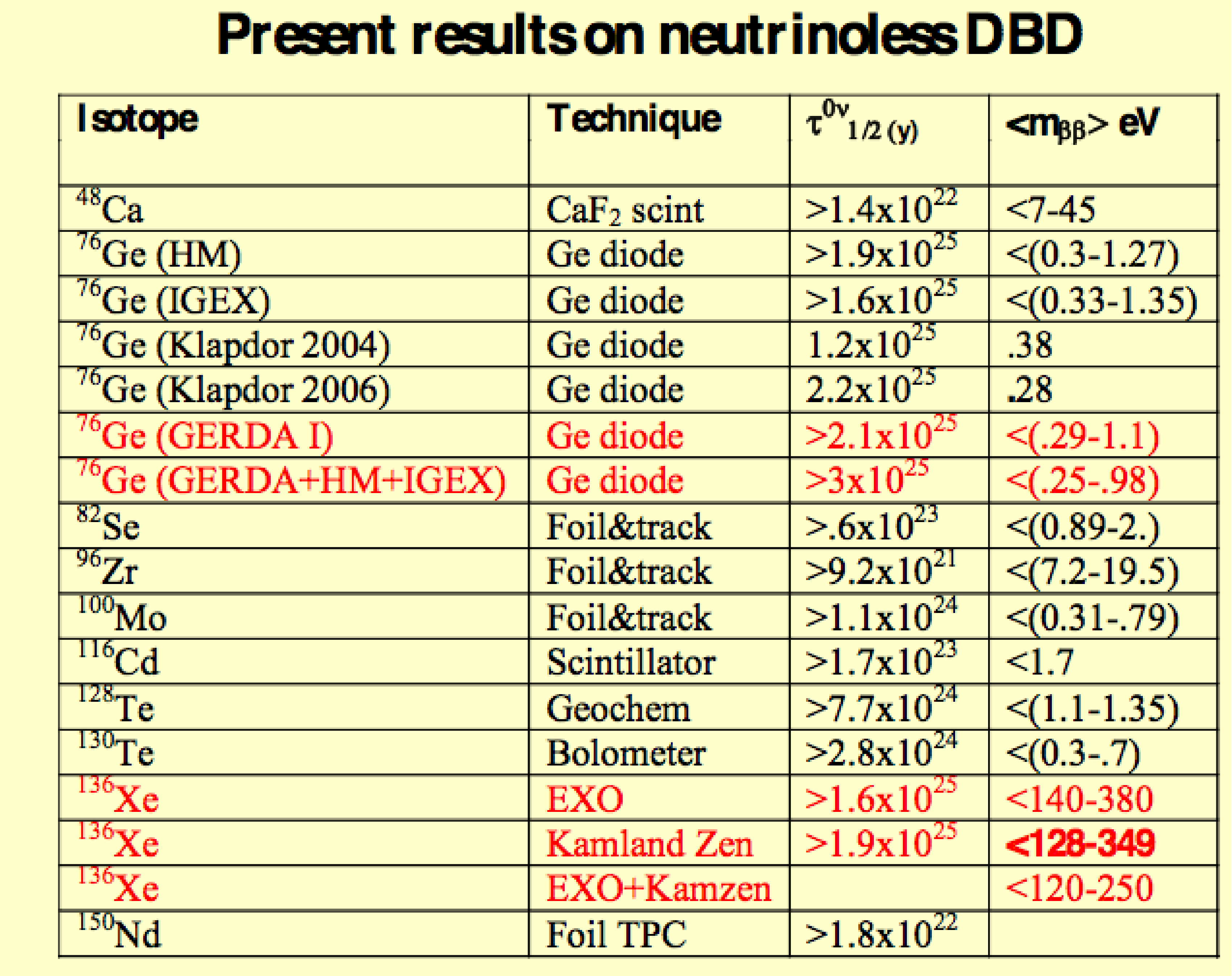
0νββ experiments

present sensitivity

$m_{ee} = |\Sigma U_{ej}^2 \, m_j \, e^{i\alpha_j}|$

next generation
10 meV





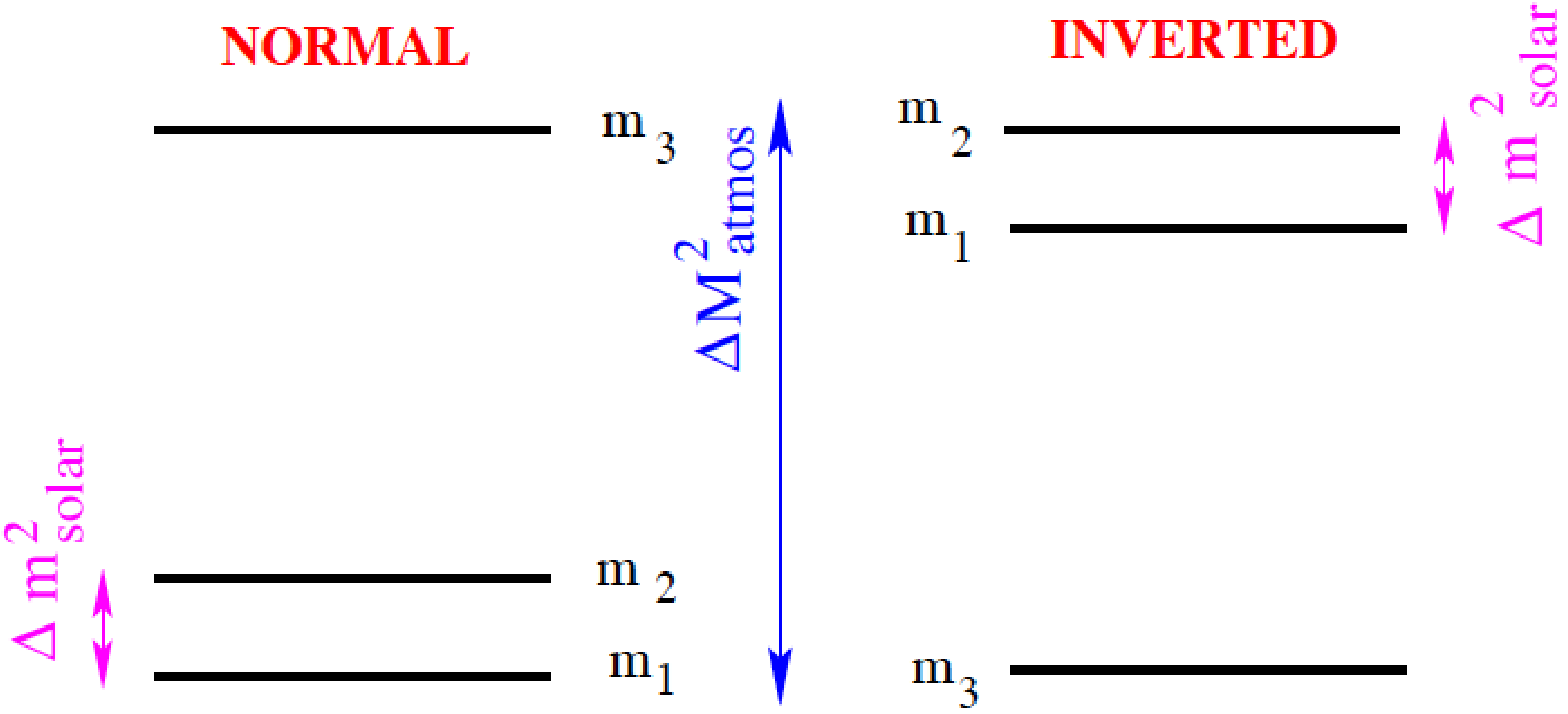
Present results on neutrinoless DBD

Isotope	Technique	$\tau^{0\nu}_{1/2}$ (y)	$<m_{\beta\beta}>$ eV
^{48}Ca	CaF_2 scint	$>1.4\times10^{22}$	<7-45
^{76}Ge (HM)	Ge diode	$>1.9\times10^{25}$	<(0.3-1.27)
^{76}Ge (IGEX)	Ge diode	$>1.6\times10^{25}$	<(0.33-1.35)
^{76}Ge (Klapdor 2004)	Ge diode	1.2×10^{25}	.38
^{76}Ge (Klapdor 2006)	Ge diode	2.2×10^{25}	.28
^{76}Ge (GERDA I)	Ge diode	$>2.1\times10^{25}$	<(.29-1.1)
^{76}Ge (GERDA+HM+IGEX)	Ge diode	$>3\times10^{25}$	<(.25-.98)
^{82}Se	Foil&track	$>.6\times10^{23}$	<(0.89-2.)
^{96}Zr	Foil&track	$>9.2\times10^{21}$	<(7.2-19.5)
^{100}Mo	Foil&track	$>1.1\times10^{24}$	<(0.31-.79)
^{116}Cd	Scintillator	$>1.7\times10^{23}$	<1.7
^{128}Te	Geochem	$>7.7\times10^{24}$	<(1.1-1.35)
^{130}Te	Bolometer	$>2.8\times10^{24}$	<(0.3-.7)
^{136}Xe	EXO	$>1.6\times10^{25}$	<140-380
^{136}Xe	Kamland Zen	$>1.9\times10^{25}$	**<128-349**
^{136}Xe	EXO+Kamzen		<120-250
^{150}Nd	Foil TPC	$>1.8\times10^{22}$	

Fiorini

here Ettore forgot the dot: 0.140 etc

Determining the type of spectrum is still an open problem



Better outlook now that θ_{13} has been measured and is large

Wang, Suzuki, Nishikawa, Geer

MATTER-ANTIMATTER ASYMMETRY ↔ NEUTRINO MASSES CONNECTION: BARYOGENESIS THROUGH LEPTOGENESIS

Masiero

- Key-ingredient of the SEE-SAW mechanism for neutrino masses: **large Majorana mass for RIGHT-HANDED neutrino**
- In the early Universe the heavy RH neutrino decays with Lepton Number violatiion; if these decays are accompanied by a new source of CP violation in the leptonic sector, then

→ it is possible to create a lepton-antilepton asymmetry at the moment RH neutrinos decay. Since SM interactions preserve Baryon and Lepton numbers at all orders in perturbation theory, but violate them at the quantum level, such **LEPTON ASYMMETRY** can be converted by these purely quantum effects into a BARYON-ANTIBARYON ASYMMETRY (**Fukugita-Yanagida mechanism for leptogenesis**)

Recent issues in neutrino mass and mixing

- Are sterile neutrinos coming back?

  A White Paper: K.N. Abazajian et al, ArXiv:1204.5789

- θ_{13} measured (~ 8 -10 σ from zero, rather large: $\theta_{13} \sim 9^{o}$)

  T2K, MINOS, DoubleCHOOZ, Daya Bay, RENO

- Indication of θ_{23} non maximal,

  Indication of $\cos\delta_{CP} < 0$

  Related to θ_{13} large, from MINOS and T2K

  Fogli et al '12, Forero et al '12, Gonzalez-Garcia et al '12

Sterile ν's? A number of "hints" with some "tensions"

(they do not make an evidence but pose an important experimental problem that needs clarification)

Giunti

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- LSND and MiniBoone (appearance)
- Reactor anomaly ($\bar{\nu}_e$ disappearance)
- Gallium ν_e disappearance

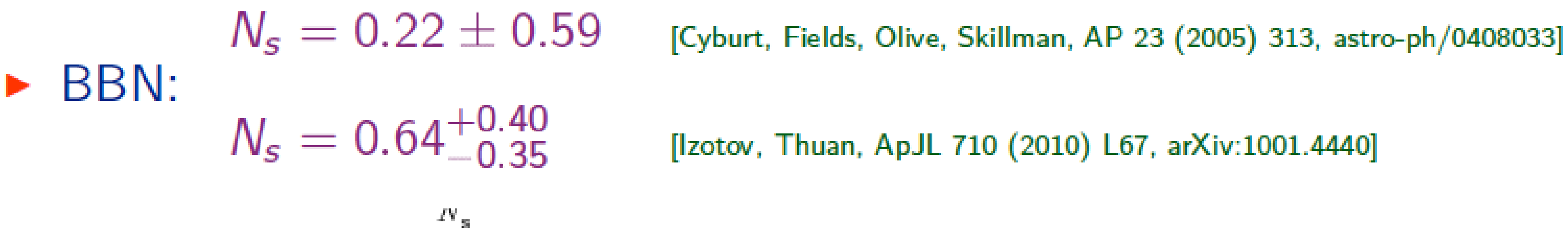
These data hint at sterile neutrinos at ~ 1 eV which would represent a major discovery in particle physics

Important information also from

- Neutrino counting from cosmology

Cosmology is fully compatible with N_{eff} ~3 but could accept one sterile neutrino

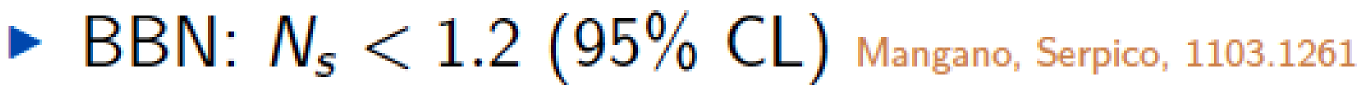
The bound from nucleosynthesis is the most stringent (assuming thermal properties at decoupling)



- BBN: $N_s = 0.22 \pm 0.59$ [Cyburt, Fields, Olive, Skillman, AP 23 (2005) 313, astro-ph/0408033]

  $N_s = 0.64^{+0.40}_{-0.35}$ [Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]

N_s



- BBN: $N_s < 1.2$ (95% CL) Mangano, Serpico, 1103.1261

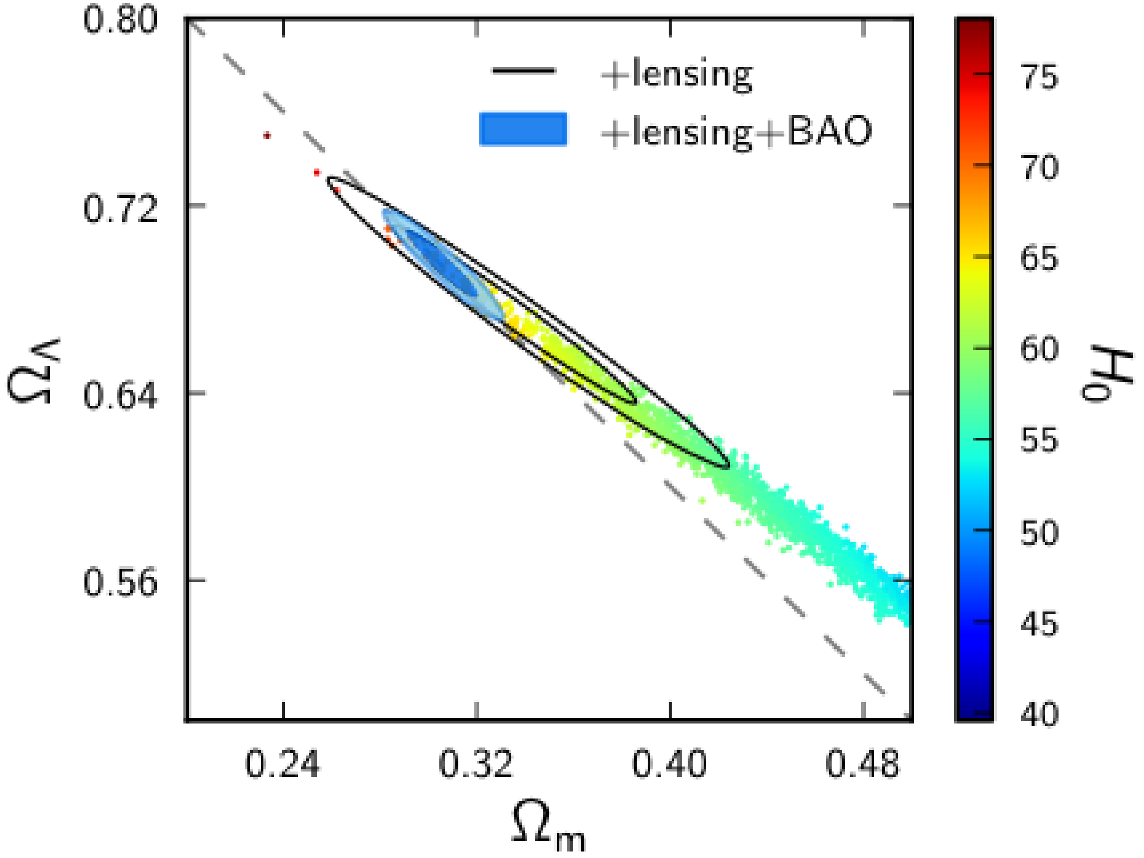
- BBN: $N_s < 1.54$ (95% CL) [M. Pettini, et al, arXiv:0805.0594]

A “simple” cosmology emerges from Planck

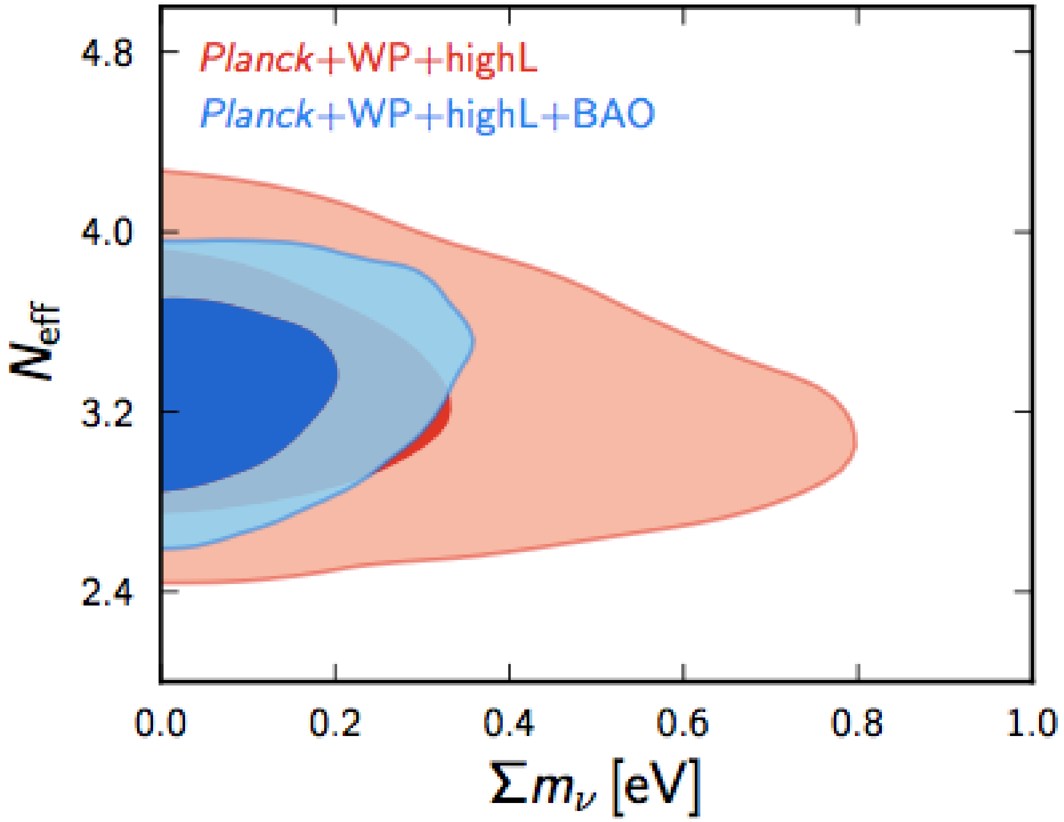
More precise values of cosmological parameters

$\Omega_\Lambda = 0.686 \pm 0.020$
$\Omega_m = 0.314 \pm 0.020$
$\Omega_b h^2 = 0.02207 \pm 0.00033$
$h = 0.674 \pm 0.014$

ΛCDM confirmed



No evidence for sterile neutrinos N_{eff}=3.36±0.34

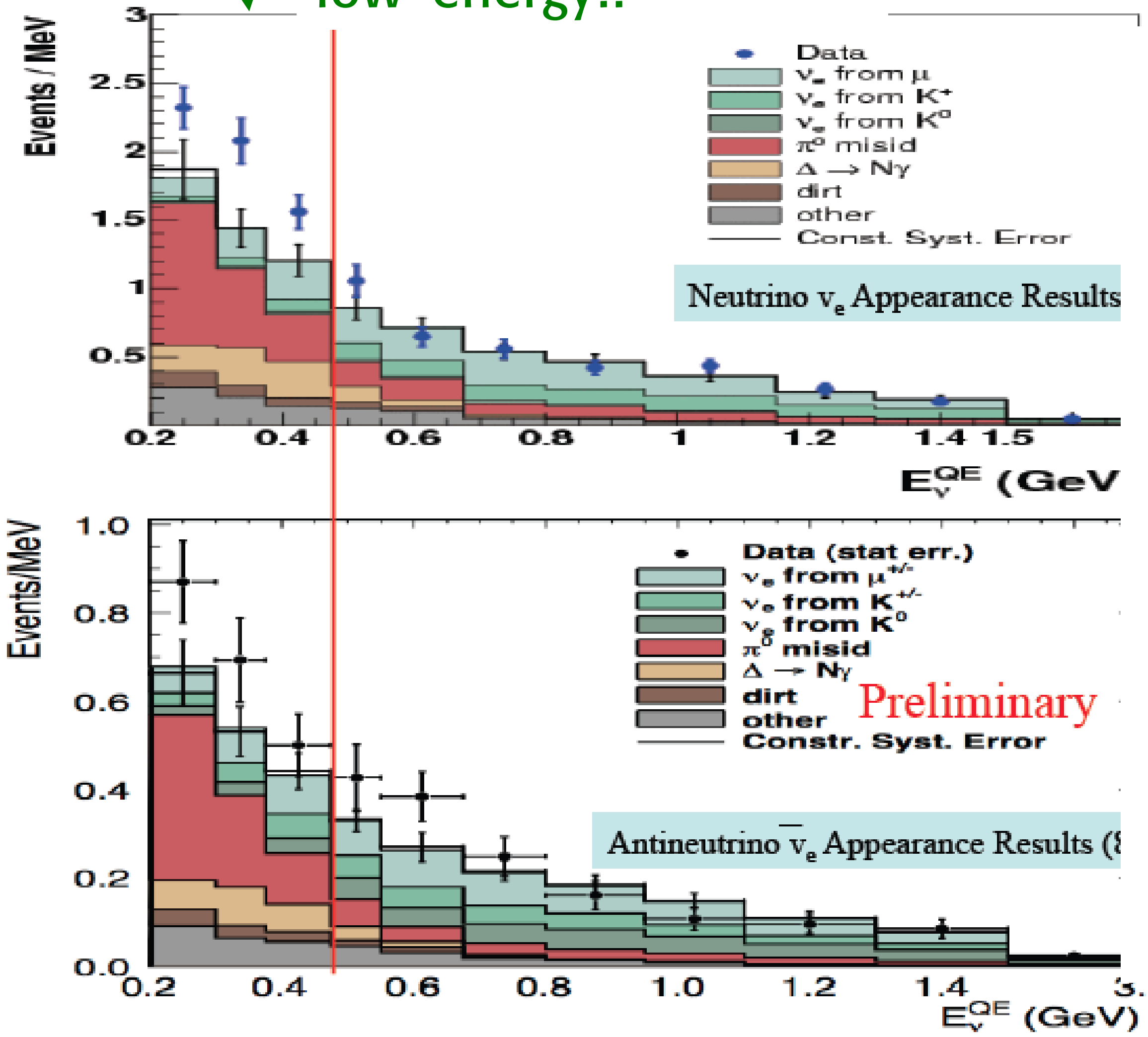


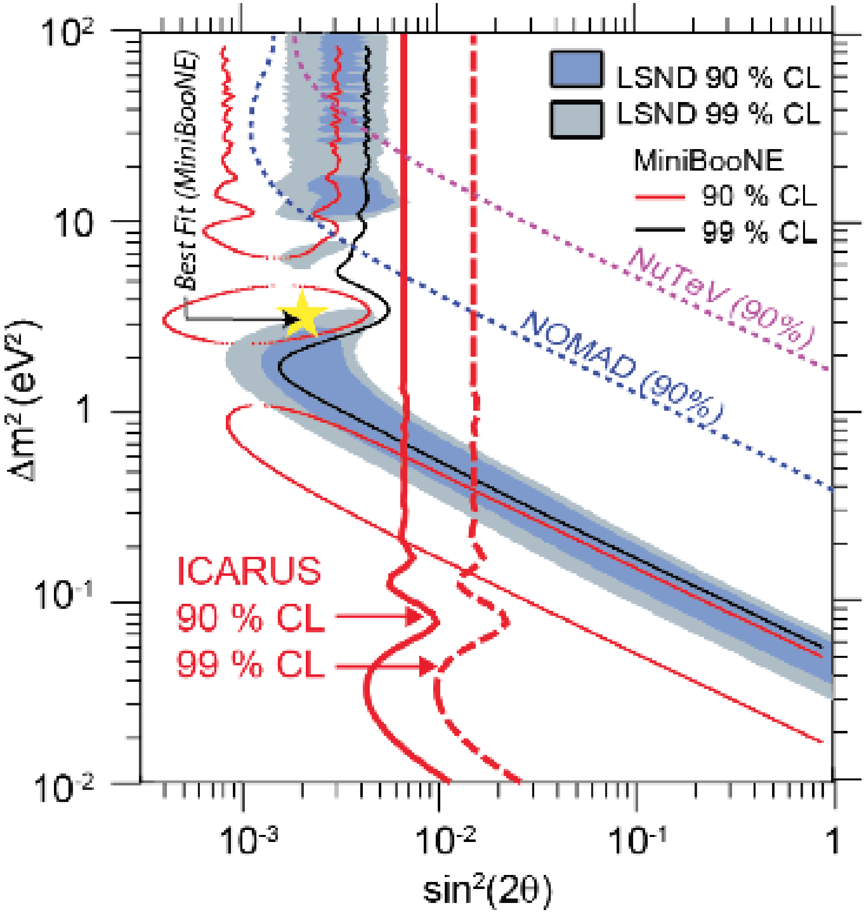
$\Sigma m_\nu <$ 0.23- 0.8 eV

LSND, KARMEN, MiniBooNE

MiniBooNE supports LSND in $\bar{\nu}_\mu$
but not in ν_μ (or CP viol.?)

Unidentified excess at low energy!!

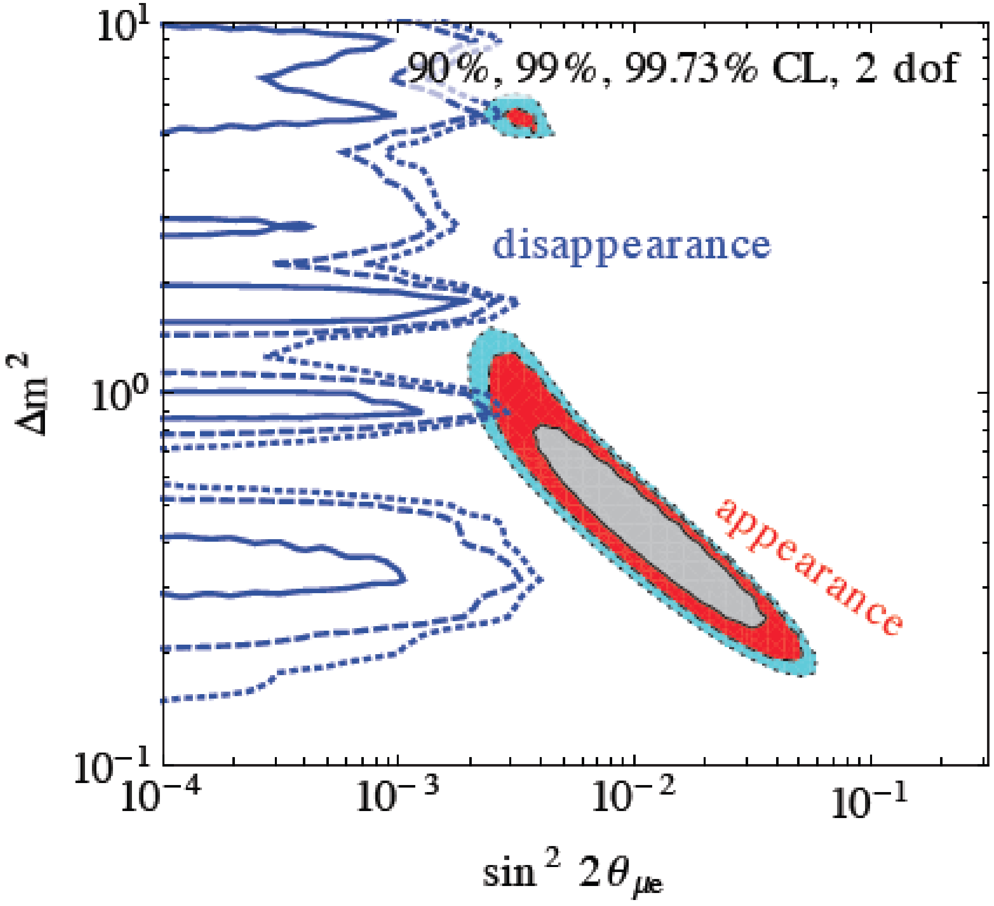




ICARUS Coll,1307.4699

No signal in ν_μ disappearance in accelerator experiments (CDHSW, MINOS, CCFR, MiniBooNE-SciBooNE) creates a tension with LSND (if no CP viol.)

Kopp et al '13



For example, in 3+1 models here is the clash between appearance (LSND, MiniBoone.....) and disappearance (MINOS...)

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

app. wants this large

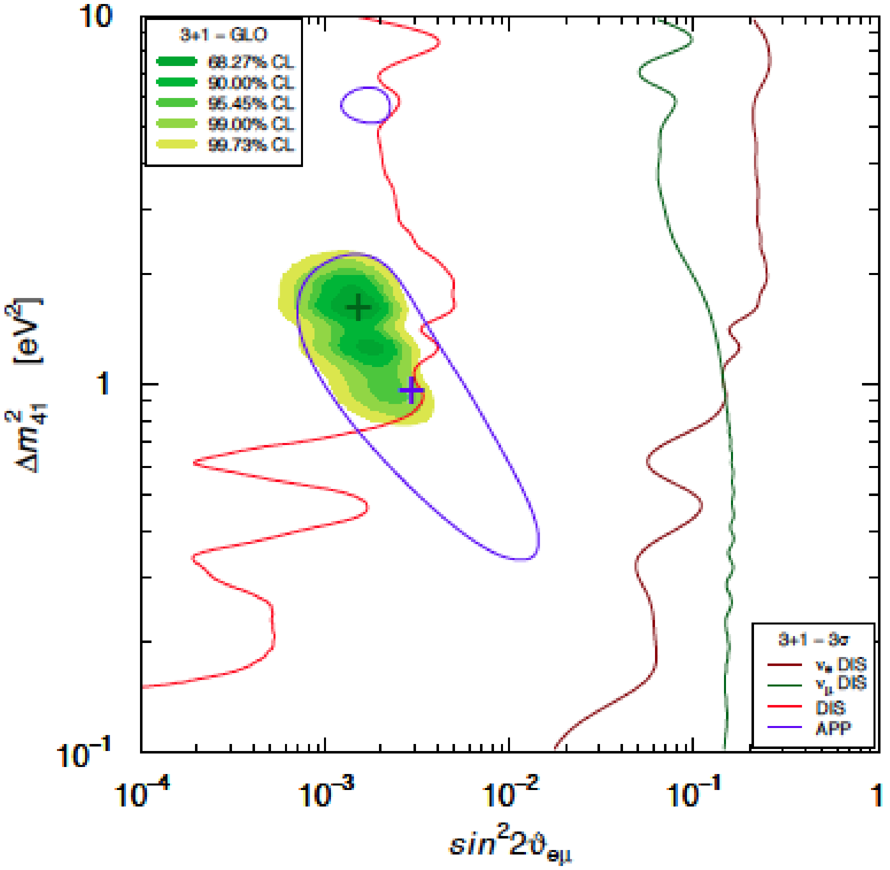
disapp. wants this small

Giunti et al are more positive on the 3+1 fit

The difference comes from the low energy MiniBooNe data (not included here)

3+1 Global Fit

[Giunti, Laveder, Y.F. Li, H.W. Long, arXiv:1308.5288]



- 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

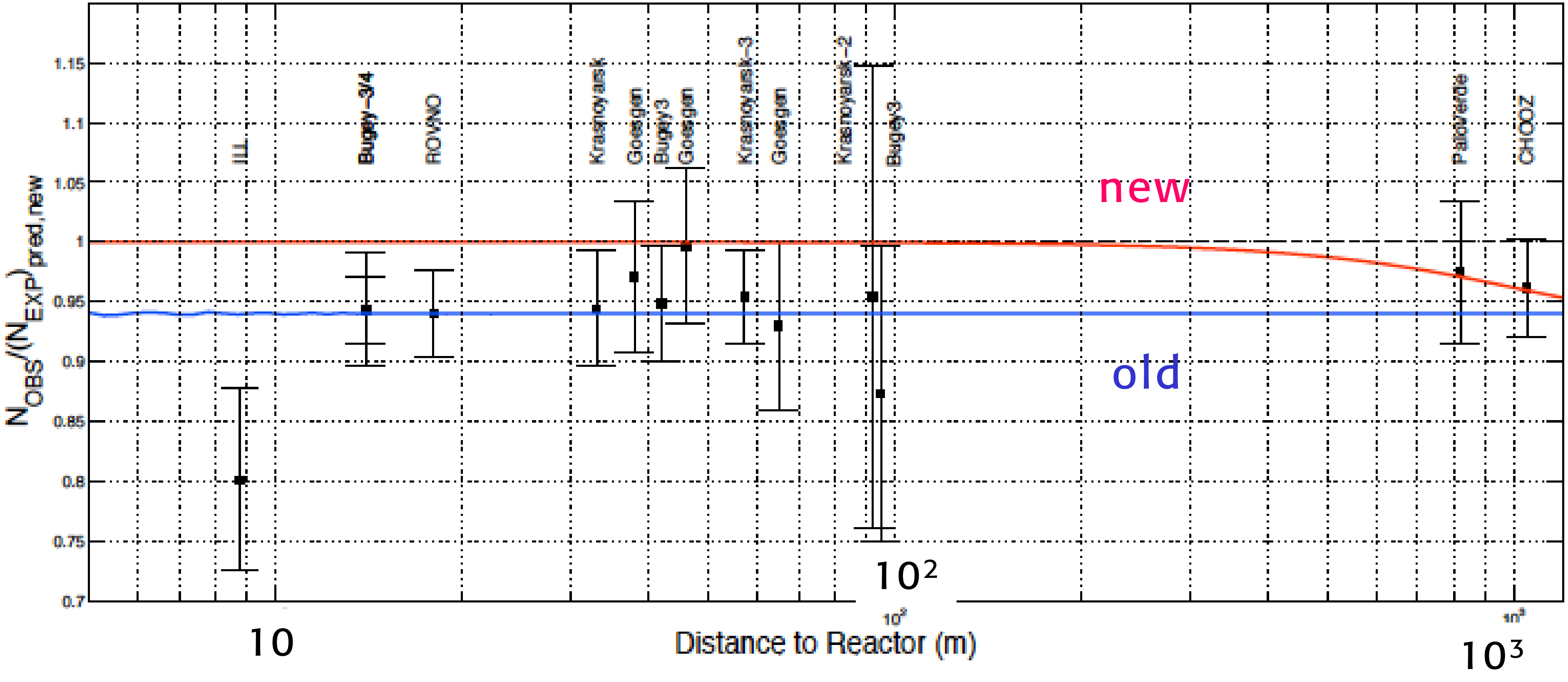
GoF = 29%   PGoF = 9%

No Osc. excluded at 6.2σ

$\Delta\chi^2/\text{NDF} = 46.2/3$

The reactor anomaly (below 100m baseline)
(after a revision of the theoretical flux and of crosssections)

Lasserre

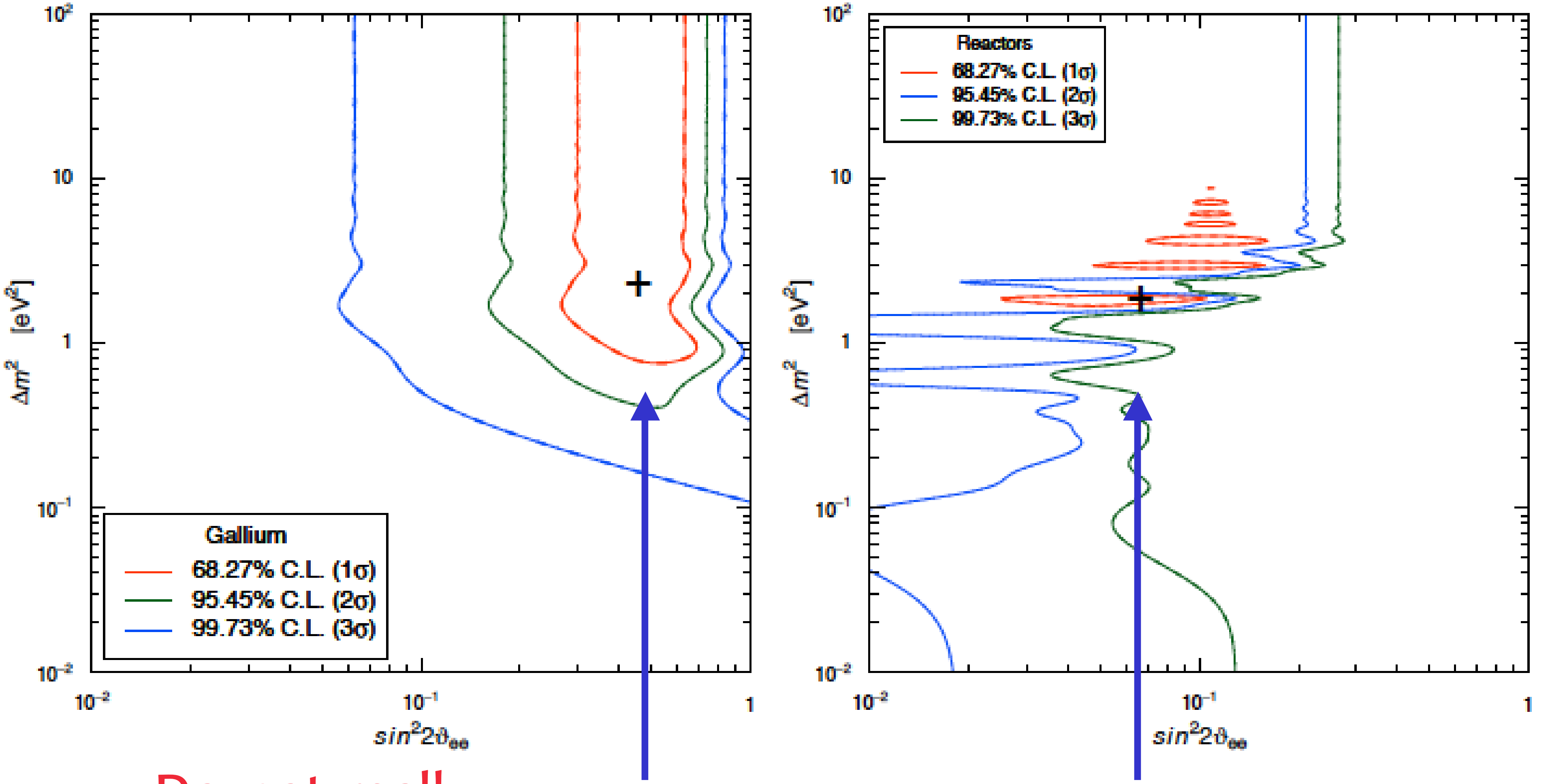


Systematic errors not shown in this figure (estimated in paper)!
Certainly of the same order of the shift.
They could well be larger than estimated

Depends on assumed cross section! Recently new measurements appear to confirm

Gallium Anomaly

Reactor Anomaly

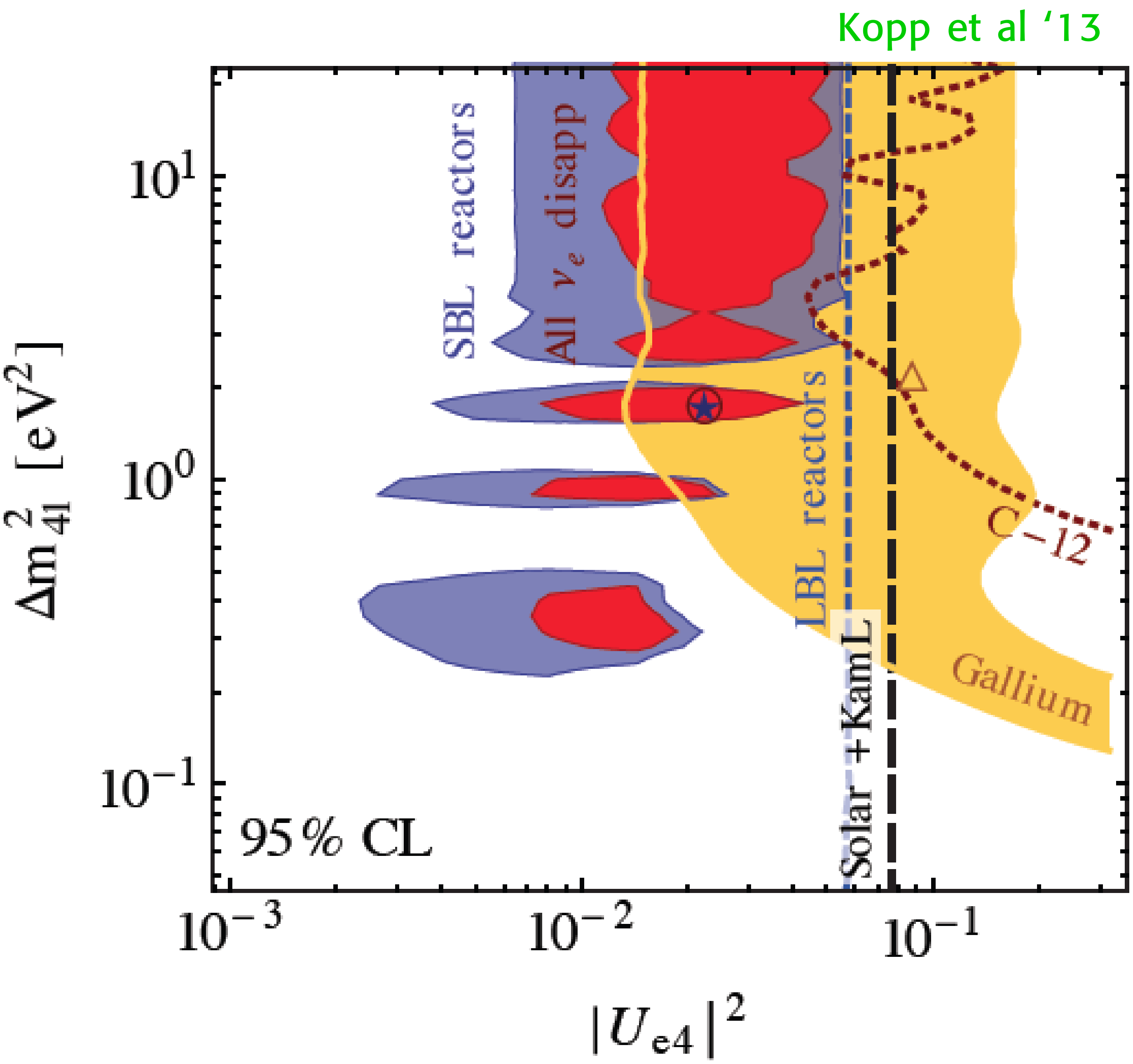


Do not really coincide!

large angle

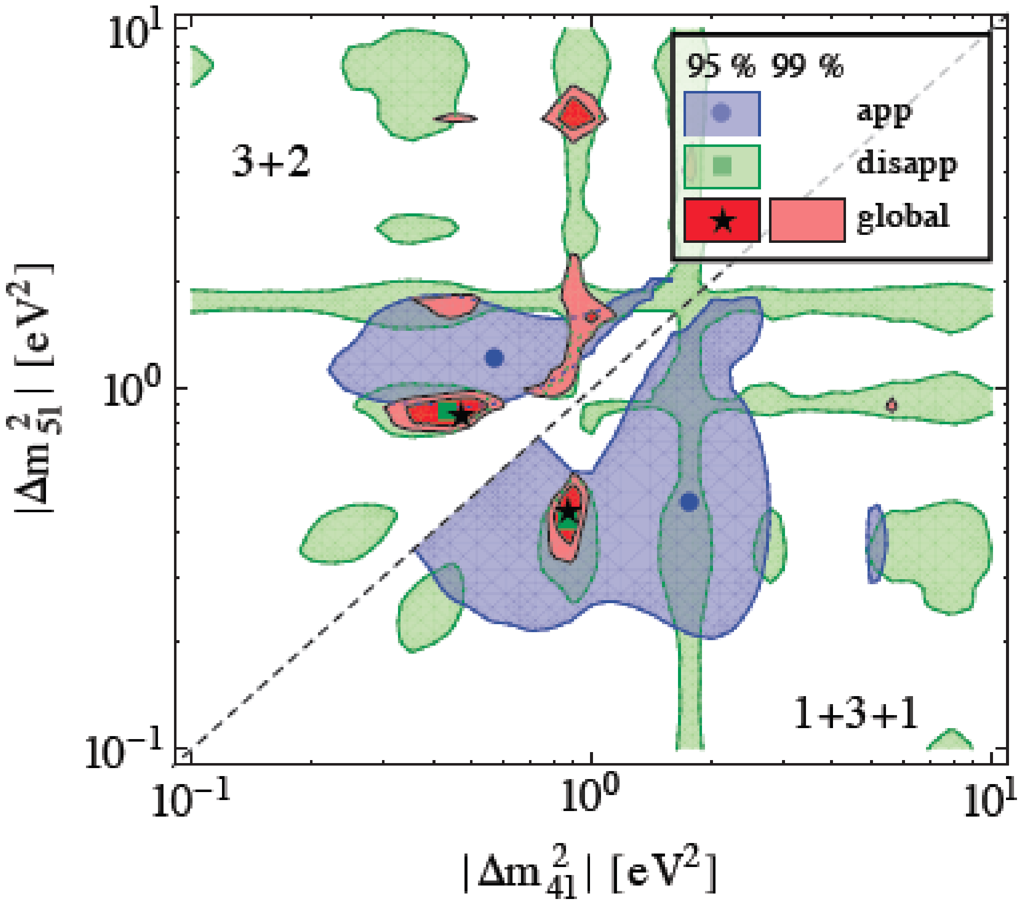
small angle

SBL reactors
and gallium
in 3+1 models



These data are
not in tension
with other
measurements

Global fit to all data (2 sterile neutrinos)



Kopp et al '13
Conrad et al '12

The Δm^2 values are in tension with the cosmology mass bound

$\Sigma m_\nu <$ 0.23 - 0.8 eV

Many Exciting New Experiments and Projects

Giunti

- Reactor $\bar{\nu}_e$ Disappearance:
  - Nucifer (OSIRIS, Saclay), Stereo (ILL, Grenoble) [arXiv:1204.5379]
  - DANSS (Kalinin Nuclear Power Plant, Russia) [arXiv:1304.3696], POSEIDON (PIK, Gatchina, Russia) [arXiv:1204.2449]
  - SCRAAM (San Onofre, California) [arXiv:1204.5379]
  - CARR (China Advanced Research Reactor) [arXiv:1303.0607]
  - Neutrino-4 (SM-3, Dimitrovgrad, Russia), SOLID (BR2, Belgium), Hanaro (Korea) [D. Lhuillier, EPSHEP 2013]
- Radioactive Source ν_e and $\bar{\nu}_e$ Disappearance:
  - SOX (Borexino, Gran Sasso, Italy) [arXiv:1304.7721]
  - CeLAND (^{144}Ce@KamLAND, Japan) [arXiv:1107.2335]
  - SAGE (Baksan, Russia) [arXiv:1006.2103]
  - IsoDAR (DAEδALUS, USA) [arXiv:1210.4454, arXiv:1307.2949]
  - SNO+, Daya Bay, RENO [T. Lasserre, Neutrino 2012]
- Accelerator $\overset{(-)}{\nu}_{\mu} \to \overset{(-)}{\nu}_{e}$ Appearance:
  - ICARUS/NESSIE (CERN) [arXiv:1304.2047, arXiv:1306.3455]
  - nuSTORM [arXiv:1308.0494]
  - OscSNS (Oak Ridge, USA) [arXiv:1305.4189, arXiv:1307.7097]

A drastic conjecture

No new thresholds from m_W to M_{Pl}?

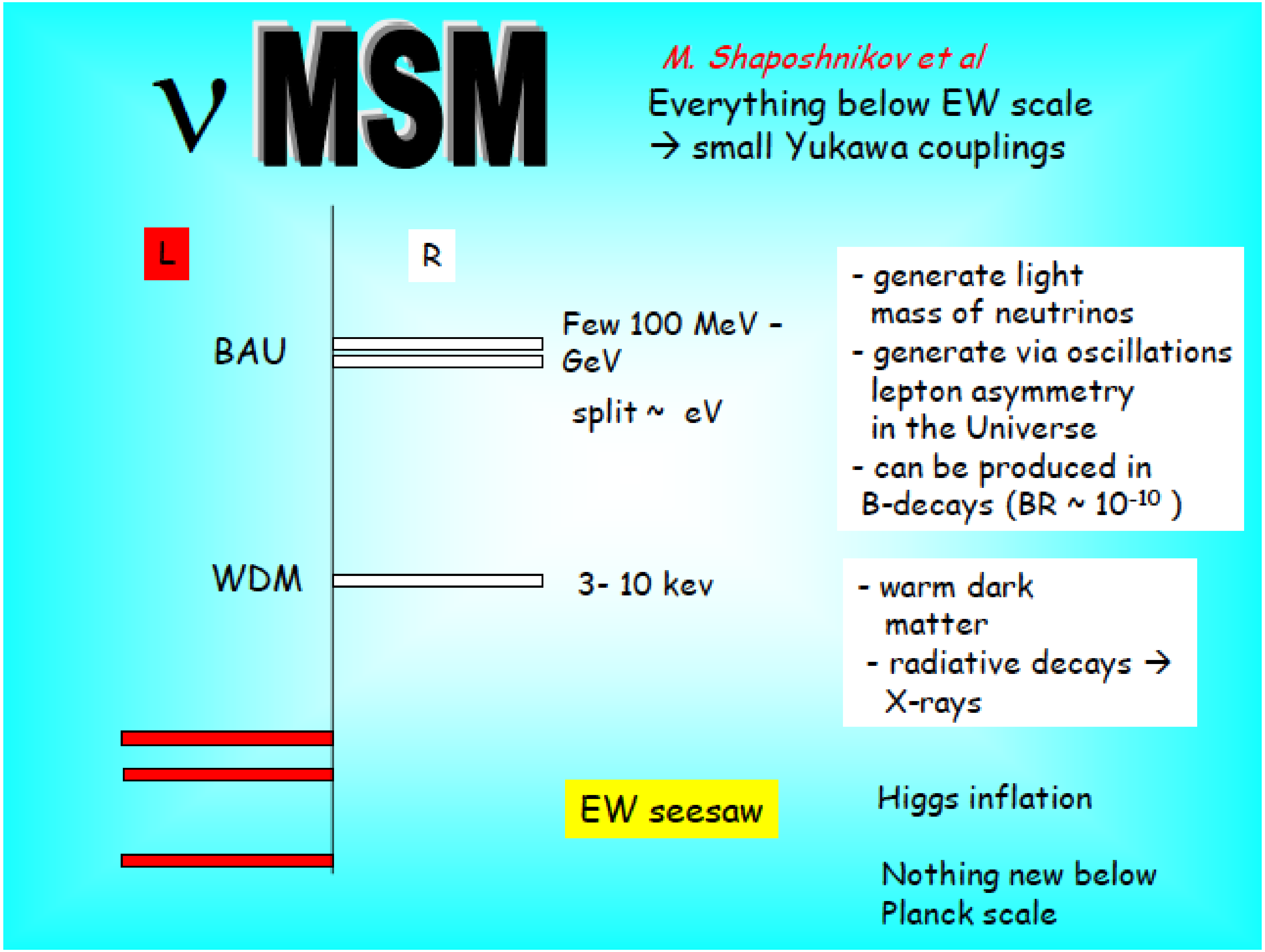
Shaposhnikov

In particular no GUT's

And hope that gravity will somehow fix the problem of fine tuning (with many thresholds it would be more difficult for gravity to arrange the fine tuning)

For this one would need to solve all problems like Dark Matter, neutrino masses, baryogenesis.... at the EW scale

Smirnov



ν MSM

M. Shaposhnikov et al

Everything below EW scale
→ small Yukawa couplings

L

R

BAU

Few 100 MeV - GeV

split ~ eV

- generate light mass of neutrinos
- generate via oscillations lepton asymmetry in the Universe
- can be produced in B-decays (BR ~ 10^{-10})

WDM

3- 10 kev

- warm dark matter
- radiative decays → X-rays

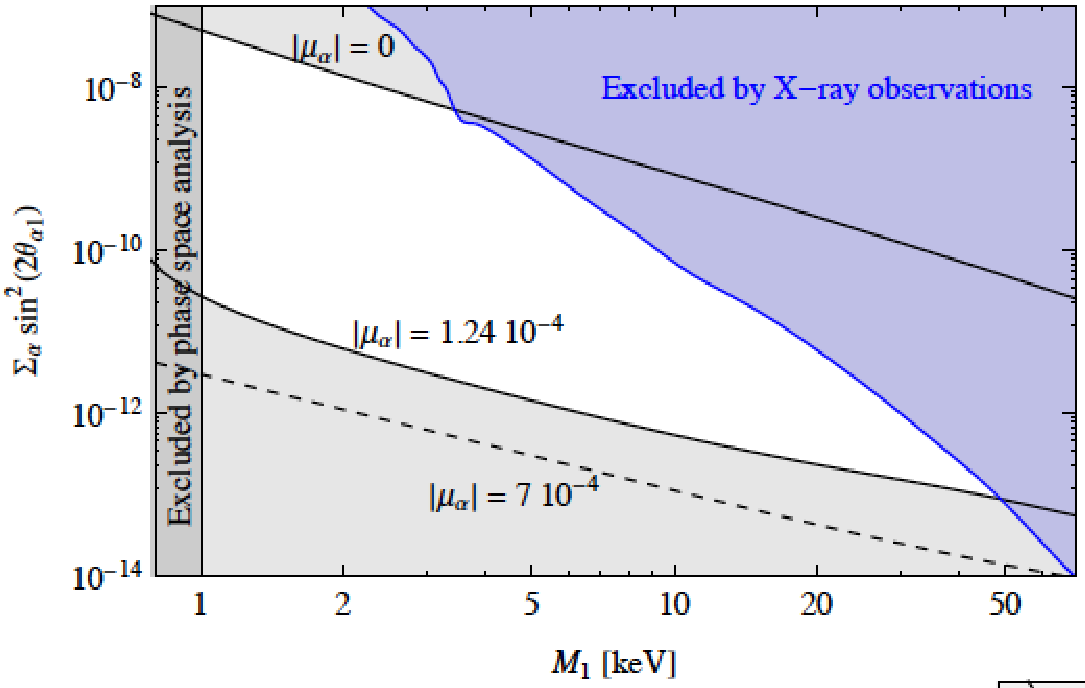
EW seesaw

Higgs inflation

Nothing new below Planck scale

Canetti et al ‘12

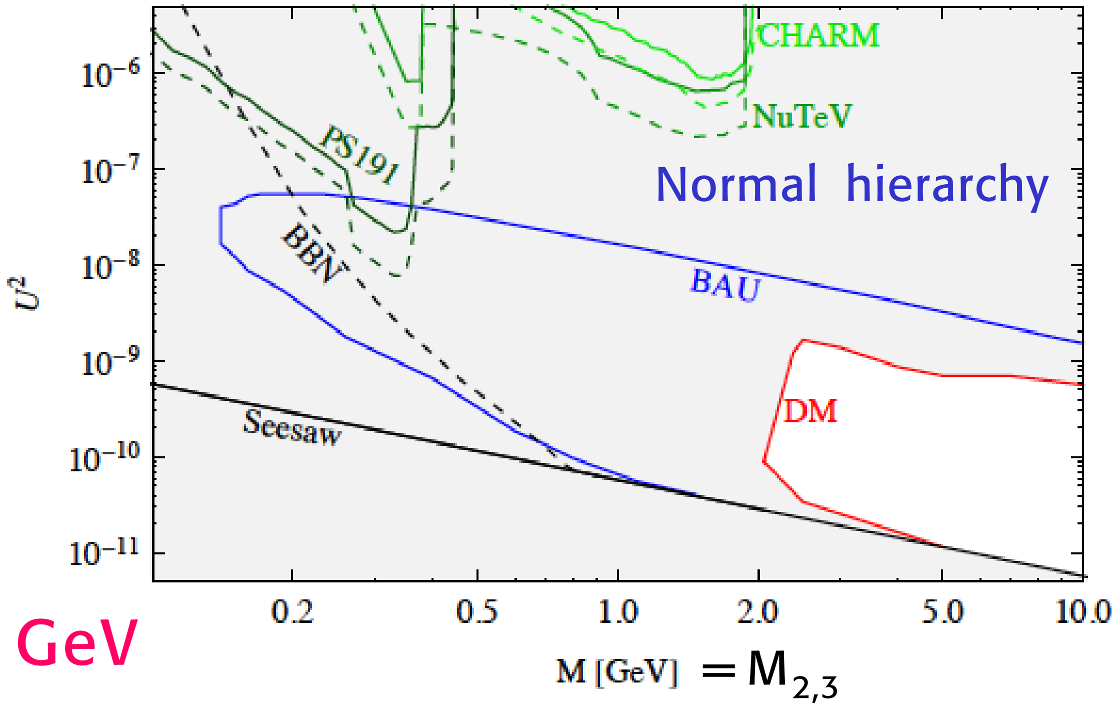
The claim is that all constraints can be satisfied



keV

No explanation of the mass splitting

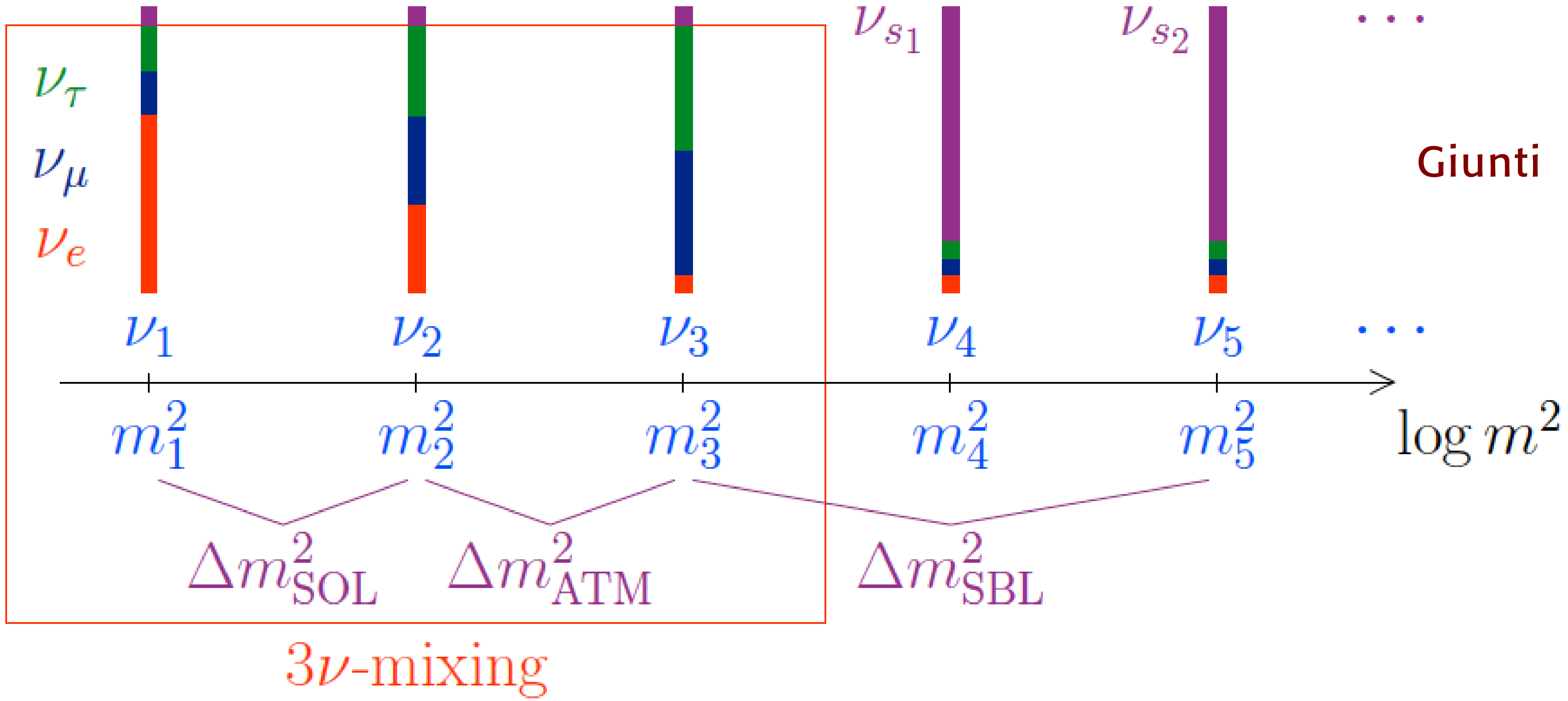
GeV



Normal hierarchy

$= M_{2,3}$

In any case only a small leakage from active to sterile neutrinos is allowed by present data



Thus 3-ν's are still the main framework for ν mass and mixing

Models of ν masses and mixings

$$m_\ell \to \bar{R} m_\ell L$$

An interplay of different matrices:

$$m_\ell' = V_\ell^\dagger m_\ell U_\ell$$

$$m_\ell^{\dagger\prime} m_\ell' = U_\ell^\dagger m_\ell^\dagger m_\ell U_\ell$$

$$U_{PMNS} = U_\ell^\dagger U_\nu$$

neutrino diagonalisat'n

charged lepton diagonalisat'n

$$O_5 = \ell^T \frac{\lambda^2}{M} \ell HH \to \nu_L^T m_\nu \nu_L$$

See-saw

$$m_\nu = m_D^T M^{-1} m_D$$

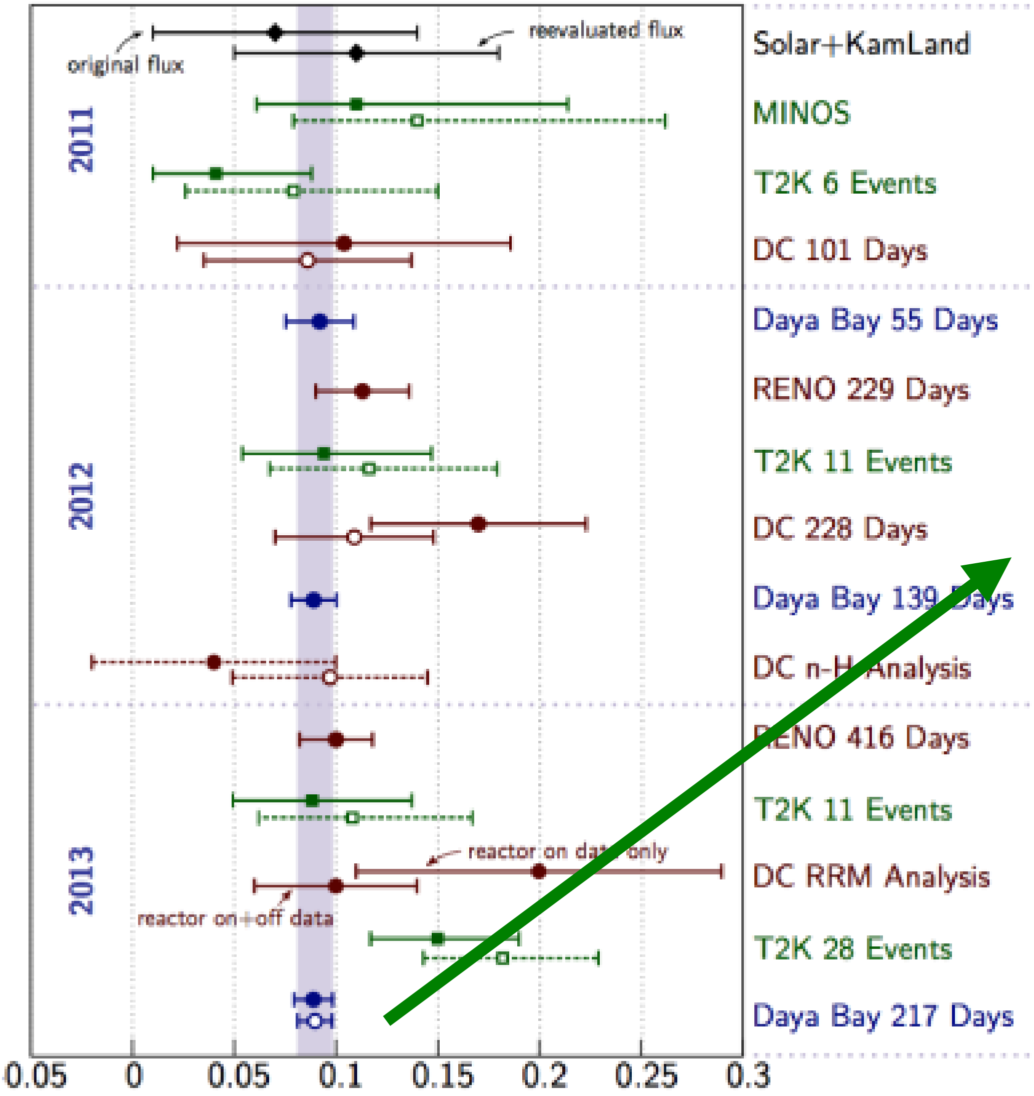
neutrino Dirac mass

neutrino Majorana mass

The large ν mixing versus the small q mixing can be due to the Majorana nature of ν's

$$m_\nu' = U_\nu^T m_\nu U_\nu$$

Now we have a good measurement of θ_{13}!!



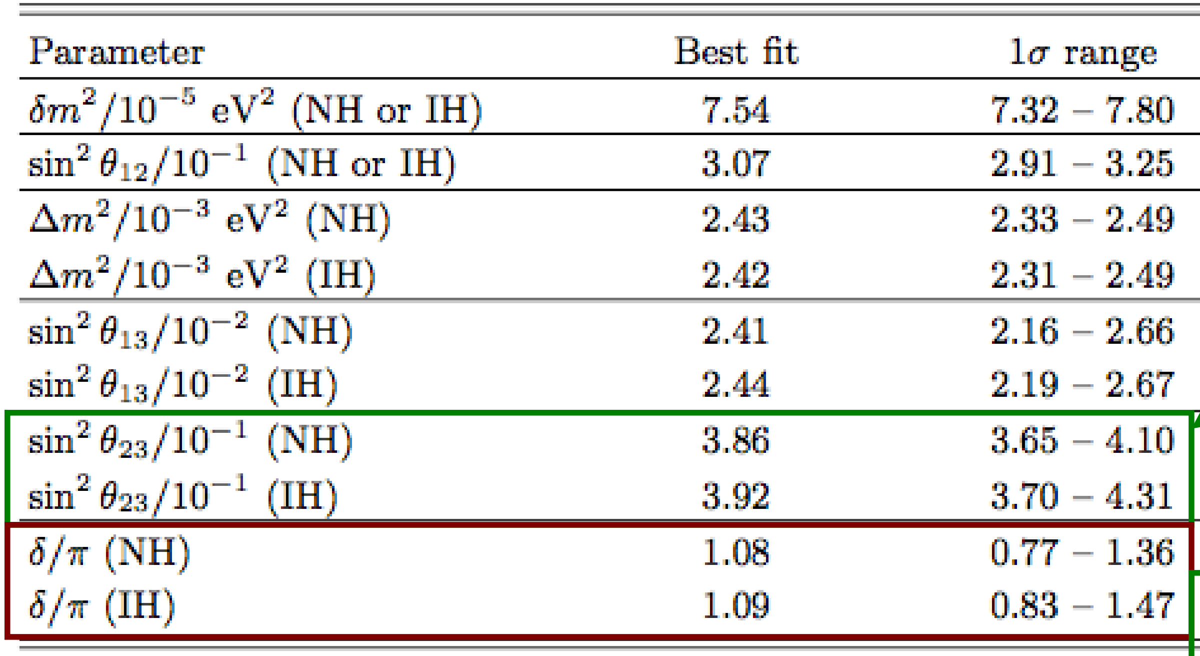
~10 σ from zero

Daya Bay

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

Wang

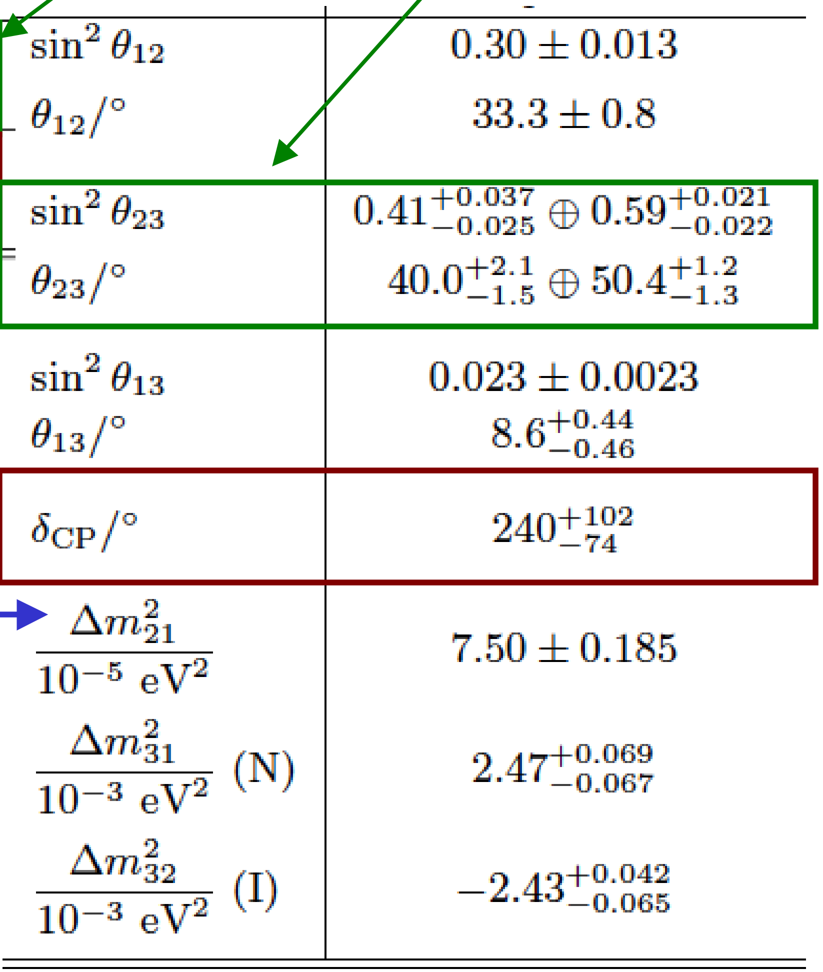
A large impact on model building and on designing new experiments!
(hierarchy, δ_{CP}...)



Parameter	Best fit	1σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31
δ/π (NH)	1.08	0.77 – 1.36
δ/π (IH)	1.09	0.83 – 1.47

Fogli et al '12

θ_{23} non maximal



$\sin^2\theta_{12}$	0.30 ± 0.013
$\theta_{12}/^\circ$	33.3 ± 0.8
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$
$\sin^2\theta_{13}$	0.023 ± 0.0023
$\theta_{13}/^\circ$	$8.6^{+0.44}_{-0.46}$
$\delta_{\mathrm{CP}}/^\circ$	240^{+102}_{-74}
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	7.50 ± 0.185
$\dfrac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$2.47^{+0.069}_{-0.067}$
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.43^{+0.042}_{-0.065}$

$\cos\delta < 0$?

Gonzalez-Garcia et al '12

By now all mixing angles are fairly well known!

In spite of this progress viable models still span a wide range that goes from very little structure to a lot of symmetry

At one extreme are models dominated by chance
Some examples:

Anarchy
$U(1)_{\text{Froggatt-Nielsen}}$ charges
••••••

On the other hand the range for each mixing angle has narrowed and precise special patterns can be tentatively identified as starting approximations that, if significant, would lead to specified discrete symmetries:

TriBimaximal (TB), BiMaximal (BM),.......
Discrete non abelian flavour groups A4, S4, T′, $\Delta(96)$.....

θ_{13} near the previous bound and θ_{23} non maximal both go in the direction of Anarchy (a great success for Anarchy!)

Anarchy: no order for lepton mixing

In the neutrino sector no symmetry, no dynamics is needed; only chance

Hall, Murayama, Weiner ’00

.....

de Gouvea, Murayama ‘12

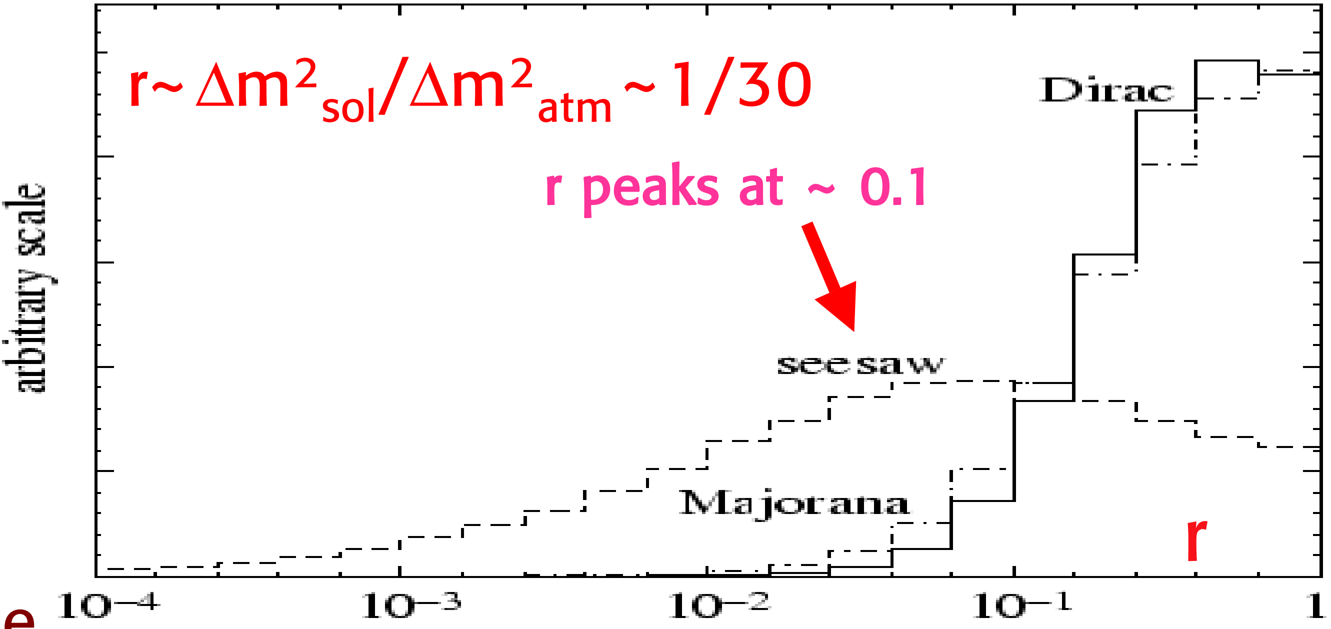
$\theta_{12}, \theta_{13}, \theta_{23}$ are just 3 random angles, the value of $r = \Delta m^2_{sun} / \Delta m^2_{atm} \sim 1/30$ is also determined by chance

Anarchy: No structure in the neutrino sector

Hall, Murayama, Weiner ‘00

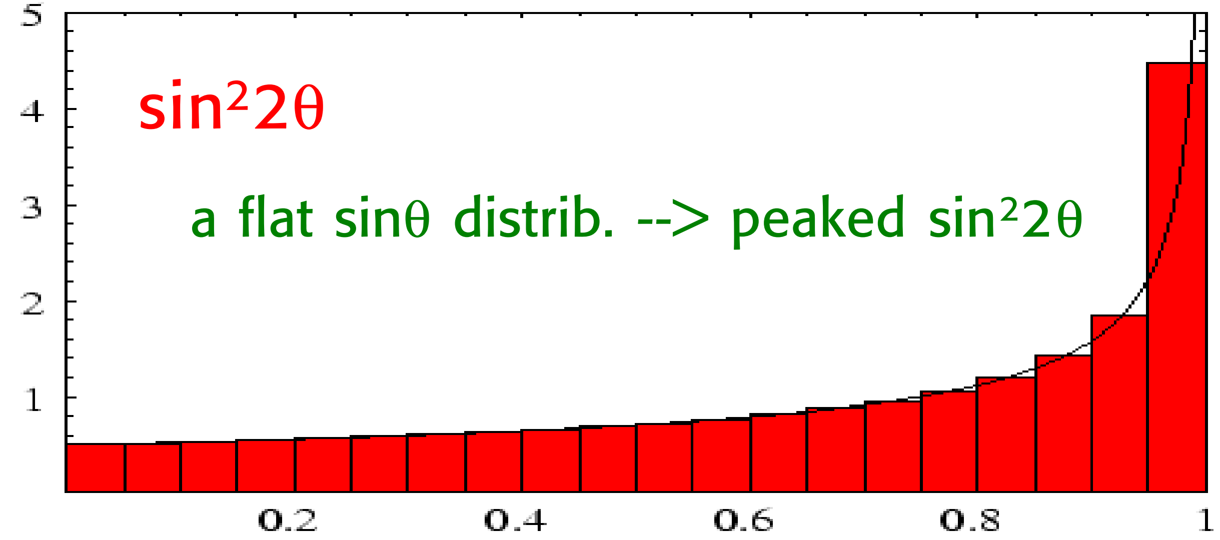
See-Saw:
$m_\nu \sim m^T M^{-1} m$
produces hierarchy
from random m, M

could fit the data on r


$r \sim \Delta m^2_{sol}/\Delta m^2_{atm} \sim 1/30$

r peaks at ~ 0.1

All mixing angles
should be not too large,
not too small


$\sin^2 2\theta$

a flat $\sin\theta$ distrib. --> peaked $\sin^2 2\theta$

Predicts θ_{13} near old
bound and
θ_{23} sizably non maximal

successful!

Anarchy and its variants can be embedded in a simple GUT context based on

$SU(5)xU(1)_{flavour}$

Froggatt Nielsen ‘79

Offers a simple description of hierarchies for quarks and leptons, but only orders of magnitude are predicted (large number of undetermined o(1) parameters c_{ab})

The typical order parameter is $o(\lambda_C)$ and the entries of mass matrices are suppressed by $m_{ab} \sim c_{ab} (\lambda_C)^{nab}$

The exponents n_{ab} are fixed by the charge imbalance

Anarchy can be realised in SU(5) by putting all the flavour structure in $T \sim 10$ and not in $F^{bar} \sim 5^{bar}$

$m_u \sim 10\,.10$ strong hierarchy $m_u : m_c : m_t$

$m_d \sim 5^{bar}\,.10 \;\sim m_e^T$ milder hierarchy $m_d : m_s : m_b$

or $m_e : m_\mu : m_\tau$

Experiment supports that down quark & charged lepton hierarchy is roughly the square root of up quark hierarchy

$m_\nu \sim \nu_L^T m_\nu \nu_L \sim 5^{barT}\,.5^{bar}$ or for see saw $(5^{bar}.1)^T\,(1.1)\,(1.5^{bar})$

For example, for the simplest flavour group, $U(1)_F$

1st fam. 2nd 3rd

Anarchy

$$\begin{cases} T : & (3, 2, 0) \\ F^{bar} : & (0, 0, 0) \\ 1 : & (0, 0, 0) \end{cases}$$

SU(5)xU(1)

One can try different charge assignments

1st fam. 2nd 3rd

Ψ_{10}: (5, 3, 0)
Ψ_5: (2, 0, 0)
Ψ_1: (1,-1, 0)

Equal 2,3 ch. for lopsided

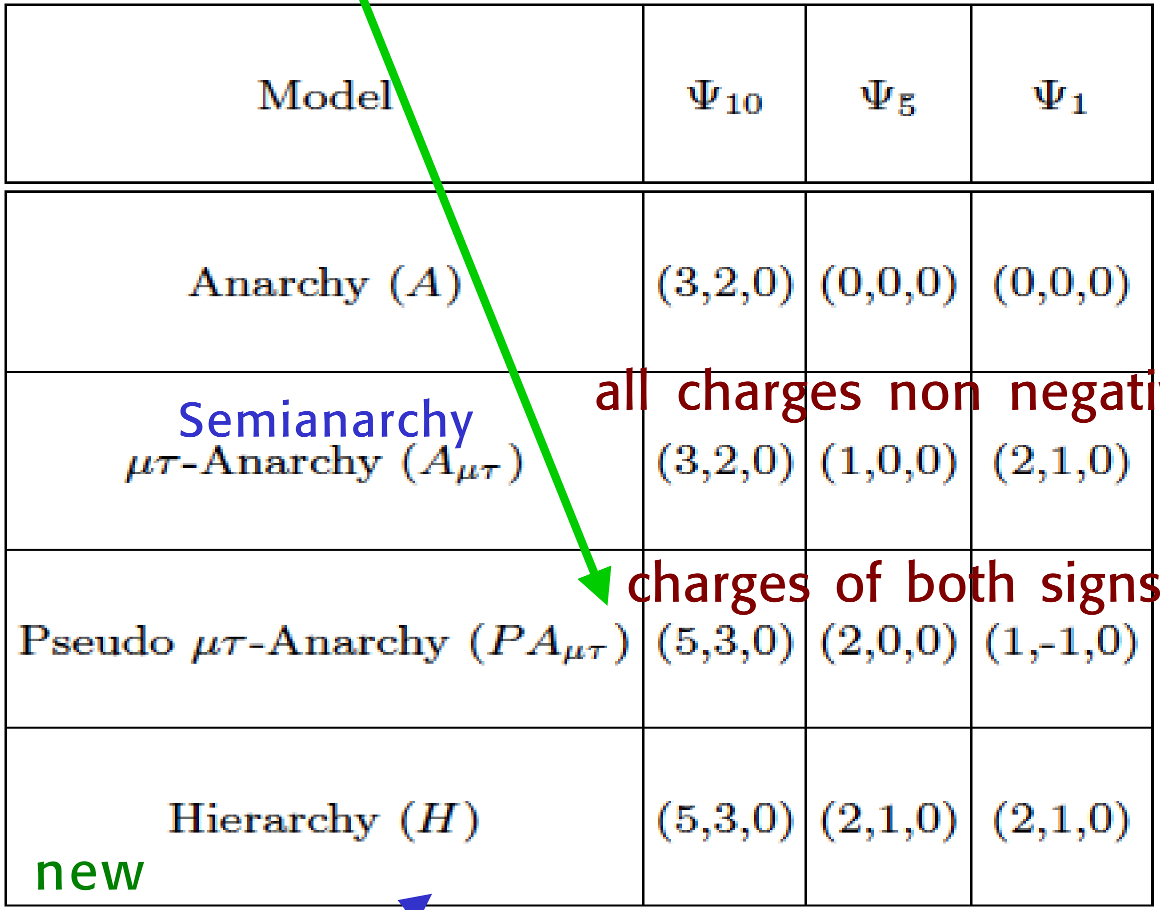
Recall: $m_u \sim 10\ 10$
$m_d = m_e^T \sim 5^{bar}\ 10$
$m_{\nu D} \sim 5^{bar}\ 1$; $M_{RR} \sim 1\ 1$

No structure for leptons

No automatic det23 = 0

Automatic det23 = 0

With suitable charge assignments many relevant patterns can be obtained



Model	Ψ_{10}	Ψ_5	Ψ_1
Anarchy (A)	(3,2,0)	(0,0,0)	(0,0,0)
$\mu\tau$-Anarchy ($A_{\mu\tau}$)	(3,2,0)	(1,0,0)	(2,1,0)
Pseudo $\mu\tau$-Anarchy ($PA_{\mu\tau}$)	(5,3,0)	(2,0,0)	(1,-1,0)
Hierarchy (H)	(5,3,0)	(2,1,0)	(2,1,0)

Semianarchy

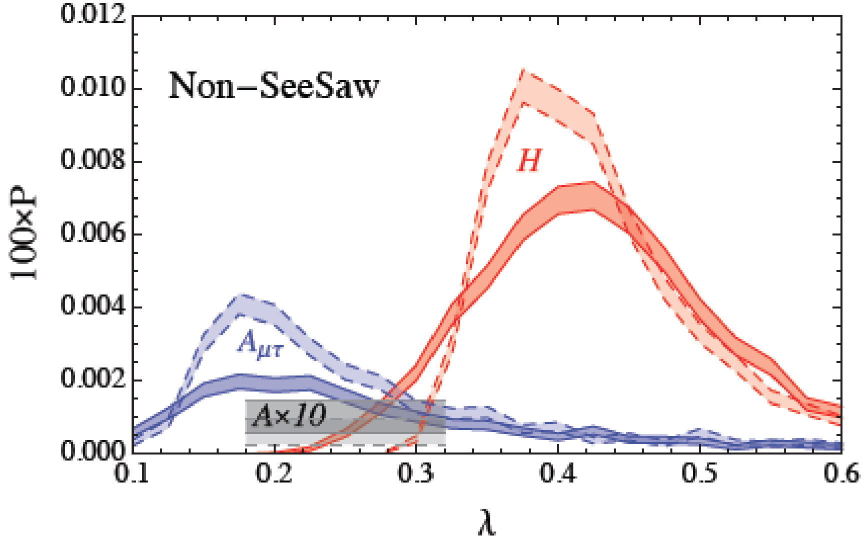
all charges non negative

charges of both signs

new

here r, θ_{23} are suppressed

If we embed anarchy in GUT's and explain quark hierarchies in terms of FN charges, then more effective variants of anarchy can be built, where chance is somewhat mitigated



Anarchy (A): both r and θ_{13} small by accident

$\mu\tau$-anarchy ($A_{\mu\tau}$): only r small by accident

H, $PA_{\mu\tau}$: no accidents

extraction range:
solid [0.5-2.0] dashed [0.8-1.2]

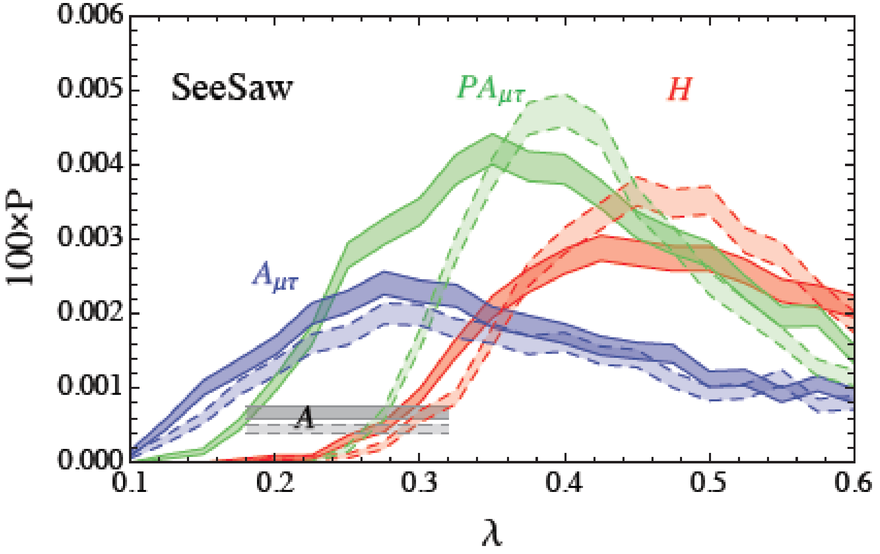
GA, Feruglio, Masina '02,'06
GA, Feruglio, Masina, Merlo '12

Optimal values of $\lambda \sim o(\lambda_C)$

$A_{\mu\tau}$: $\lambda \sim 0.2$ (non SS), 0.3 (SS)

$PA_{\mu\tau}$: $\lambda \sim 0.35\text{-}0.4$

H: $\lambda \sim 0.4$ (non SS), 0.45 (SS)

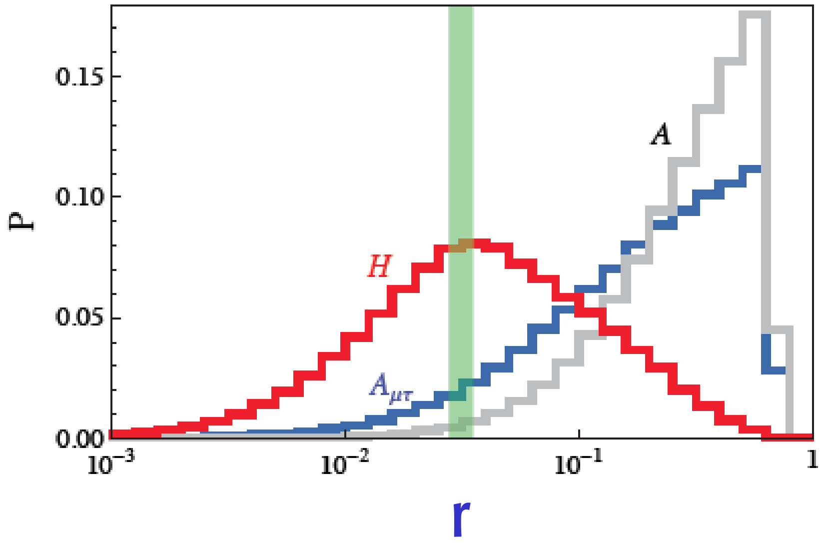


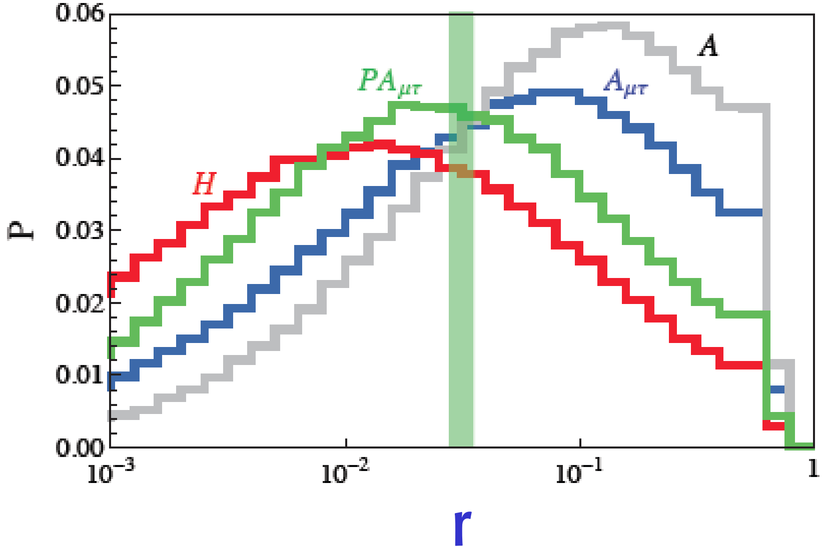
no see-saw

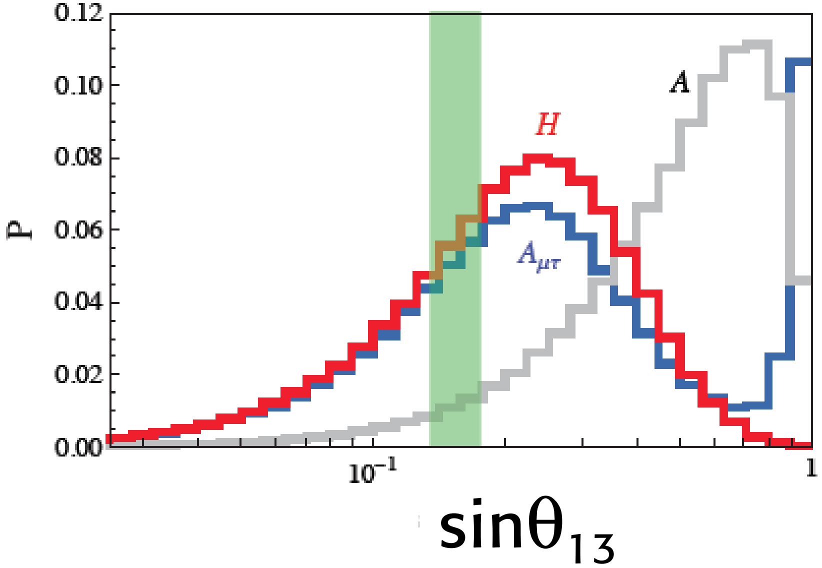
$$O_5 = \ell^T \frac{\lambda^2}{M} \ell HH \to \nu_L{}^T m_\nu \nu_L$$

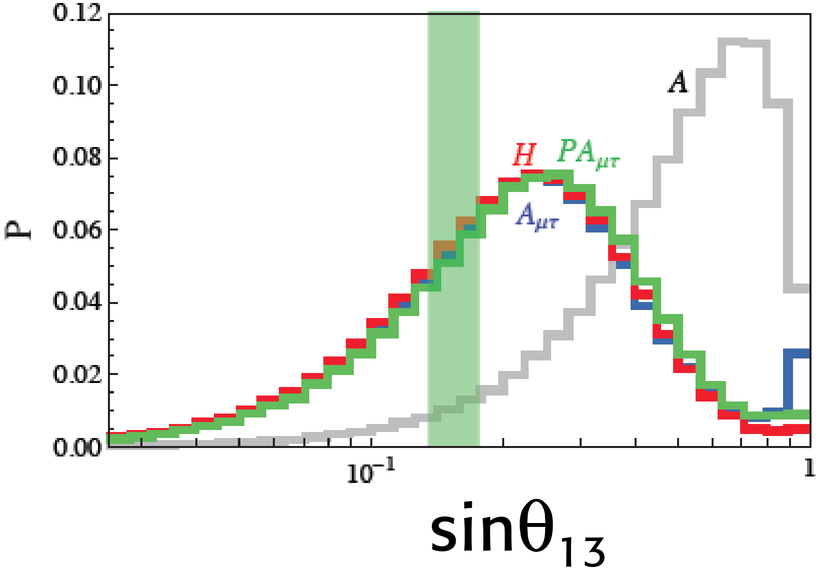
when all charges are positive see-saw only affects r

see-saw









From Anarchy to more symmetry

Larger than U(1) continuous symmetries:

e.g $U(3)_l x U(3)_e$ ----> $U(2)_l x U(2)_e$

Blankenburg, Isidori, Jones-Perez '12
Alonso, Gavela, isidori, Maiani'13

At the other extreme from Anarchy

models with a maximum of order:
based on non abelian discrete flavour groups

(reviews: G.A., Feruglio, Rev.Mod.Phys. 82 (2010) 2701;
G.A., Feruglio, Merlo'12 ;
King, Luhn'13)

A number of "coincidences" could be hints pointing to the underlying dynamics

TB Mixing

TB mixing is close to the data:
θ_{12}, θ_{23} agree within ~ 2σ
θ_{13} is the smallest angle

$$U = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

At 1σ:

Fogli et al '12

$\sin^2\theta_{12} = 1/3$: 0.291- 0.325
$\sin^2\theta_{23} = 1/2$: 0.36 - 0.41
$\sin\theta_{13} = 0$: 0.14 - 0.16

A coincidence or a hint?

Called:
Tri-Bimaximal mixing

Harrison, Perkins, Scott '02

$$\nu_3 = \frac{1}{\sqrt{2}}(-\nu_\mu + \nu_\tau)$$

$$\nu_2 = \frac{1}{\sqrt{3}}(\nu_e + \nu_\mu + \nu_\tau)$$

θ_{13} largish and θ_{23} non maximal tend to move away from TB

LQC: Lepton Quark Complementarity

$\theta_{12} + \theta_C = (46.4 \pm 0.8)^o \sim \pi/4$ ← Gonzalez-Garcia et al '12

Suggests Bimaximal mixing corrected by diagonalisation of charged leptons

$$U_{BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

A coincidence or a hint?

Golden Ratio

$$\sin^2\theta_{12} = \frac{1}{\sqrt{5}\phi} = \frac{2}{5+\sqrt{5}} \approx 0.276$$

$$U_{GR} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ \frac{\sin\theta_{12}}{\sqrt{2}} & -\frac{\cos\theta_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{\sin\theta_{12}}{\sqrt{2}} & -\frac{\cos\theta_{12}}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

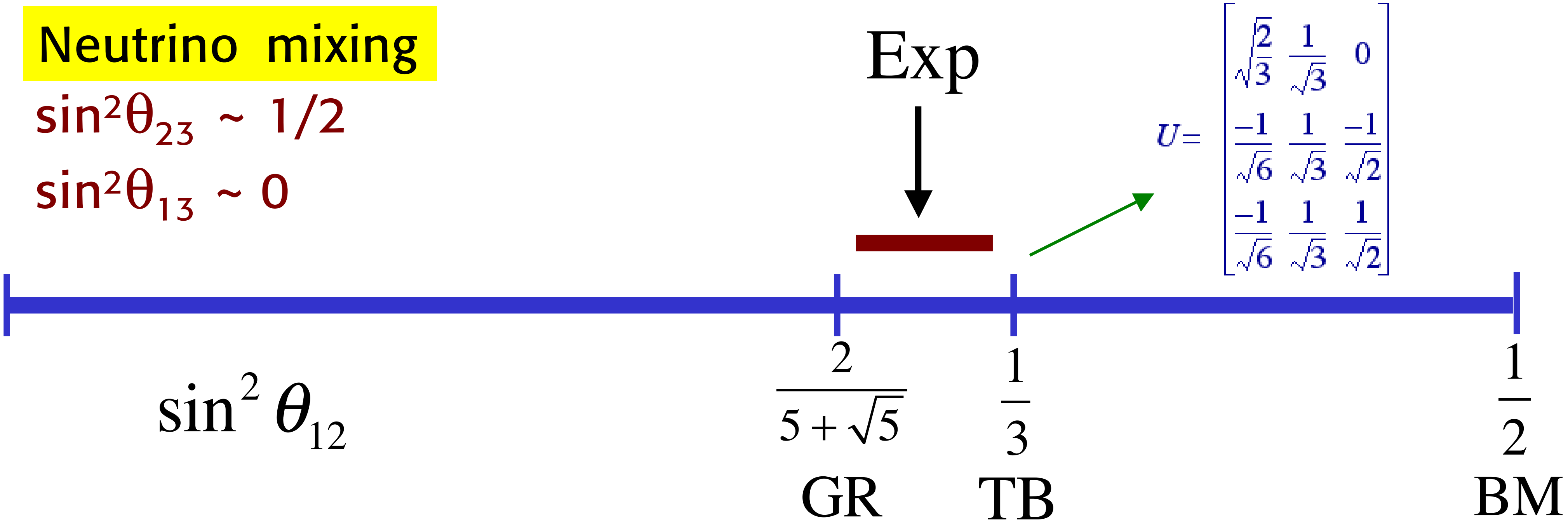
A coincidence or a hint?

Cannot all be true hints, perhaps none

Neutrino mixing

$\sin^2\theta_{23} \sim 1/2$

$\sin^2\theta_{13} \sim 0$



$$U = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

TB: Group A4, S4..... A vast literature (Ma, Rajasekaran ‘01.....)

GR: Golden Ratio - Group A5 Feruglio, Paris ’11; G. J. Jing et al ‘11
Cooper et al ’12

BM: Group S4 GA, Feruglio, Merlo ’09

TB Mixing naturally leads to discrete flavour groups (similarly for GR, BM....)

TB Mixing: $$U = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

This is a particular rotation matrix with specified fixed angles

At LO in A4 models TB mixing is exact

When NLO corrections are included from operators of higher dimension in the superpotential each mixing angle generically receives corrections of the same order $\delta\theta_{ij} \sim o(VEV/\Lambda) \sim o(\xi)$

Typical predicted pattern

$$\sin^2\theta_{12} = \frac{1}{3} + o(\xi)$$ ← ~ -0.03

$$\sin^2\theta_{23} = \frac{1}{2} + o(\xi)$$ ← ~ - 0.1

$$\sin\theta_{13} = o(\xi)$$ ← ~ 0.15

exp values of $o(\xi)$

As the maximum allowed corrections to θ_{12} are numerically $o(\lambda_C^2)$, one typically expected $\theta_{13} \sim o(\lambda_C^2)$

This generic prediction can be altered in special versions e.g. Lin '09 discussed a A4 model where $\theta_{13} \sim o(\lambda_C)$

Bimaximal Mixing

Taking the “complementarity” relation seriously:

$$\theta_{12} + \theta_C = (46.4 \pm 0.8)^\circ \sim \pi/4$$ Raidal’04

leads to consider models that give $\theta_{12} = \pi/4$ but for corrections from the diag’tion of charged leptons

$$U_{PMNS} = U_\ell^\dagger U_\nu$$

Recall:

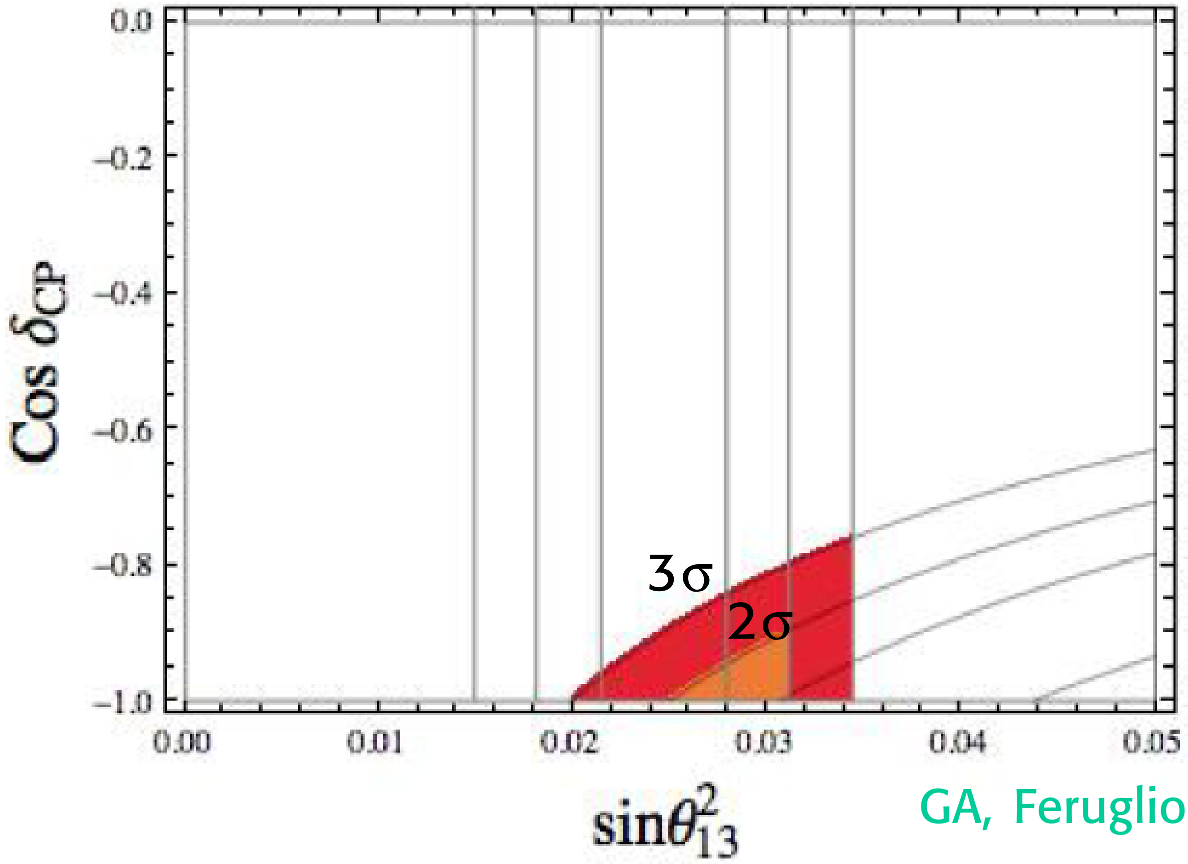
$$\lambda_C \approx 0.22 \text{ or } \sqrt{\frac{m_\mu}{m_\tau}} \approx 0.24$$

Normally one obtains $\theta_{12} + o(\theta_C) \sim \pi/4$ “weak compl.” rather than $\theta_{12} + \theta_C \sim \pi/4$

$$\begin{aligned}\delta_{CP} &= \pi + \arg\left(c^e_{12} - c^e_{13}\right)\\ \sin\theta_{13} &= \frac{1}{\sqrt{2}}\left|c^e_{12} - c^e_{13}\right|\xi\\ \sin^2\theta_{12} &= \frac{1}{2} - \frac{1}{\sqrt{2}}\mathcal{R}e\left(c^e_{12} + c^e_{13}\right)\xi\\ \sin^2\theta_{23} &= \frac{1}{2}\,.\end{aligned}$$

For dominance of a single c^e, e.g. $c^e_{13}=0$ we have a sum rule

$$\sin^2\theta_{12} = \frac{1}{2} + \sin\theta_{13}\cos\delta_{CP}$$

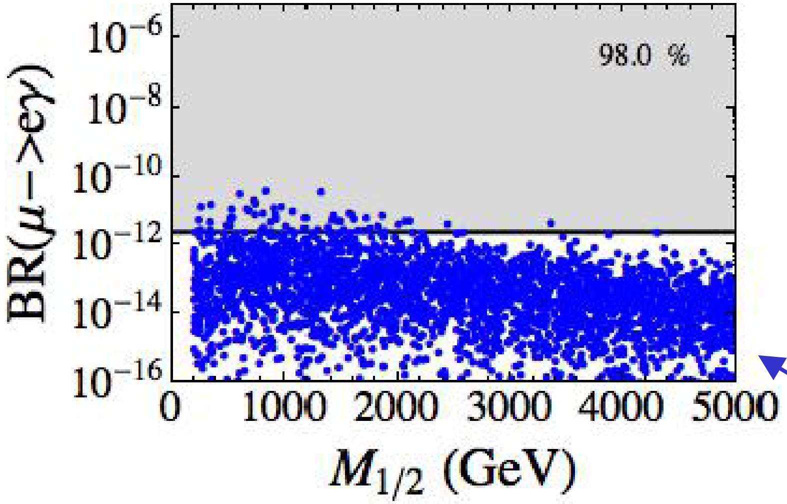


Then $\cos\delta_{CP} \sim -1$ is predicted

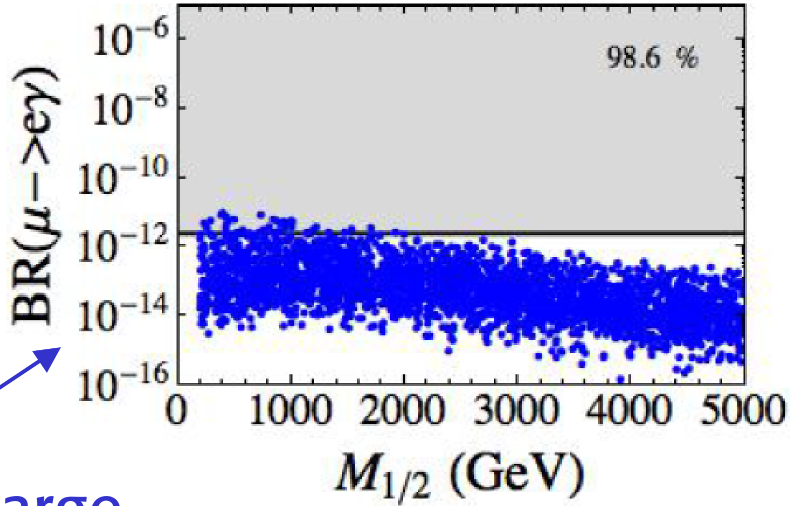
GA, Feruglio, Merlo, Stamou '12

$Br(\mu \to e\,\gamma) < 5.7\ 10^{-13}$: a serious constraint

CMSSM



Typical A4, $\xi = 0.076$

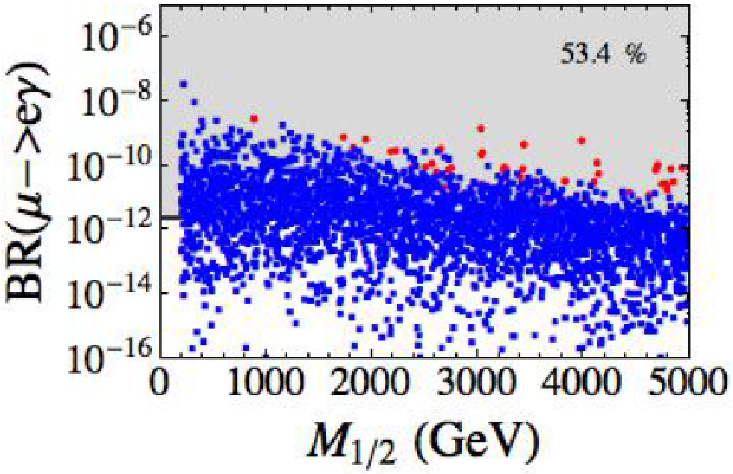


Lin-type A4, $\xi' = 0.184$

[main effect $o(\xi'^2)$]

m_0 ~ 5 TeV large

$\tan\beta$ ~ 2



S4, $\xi = 0.172$

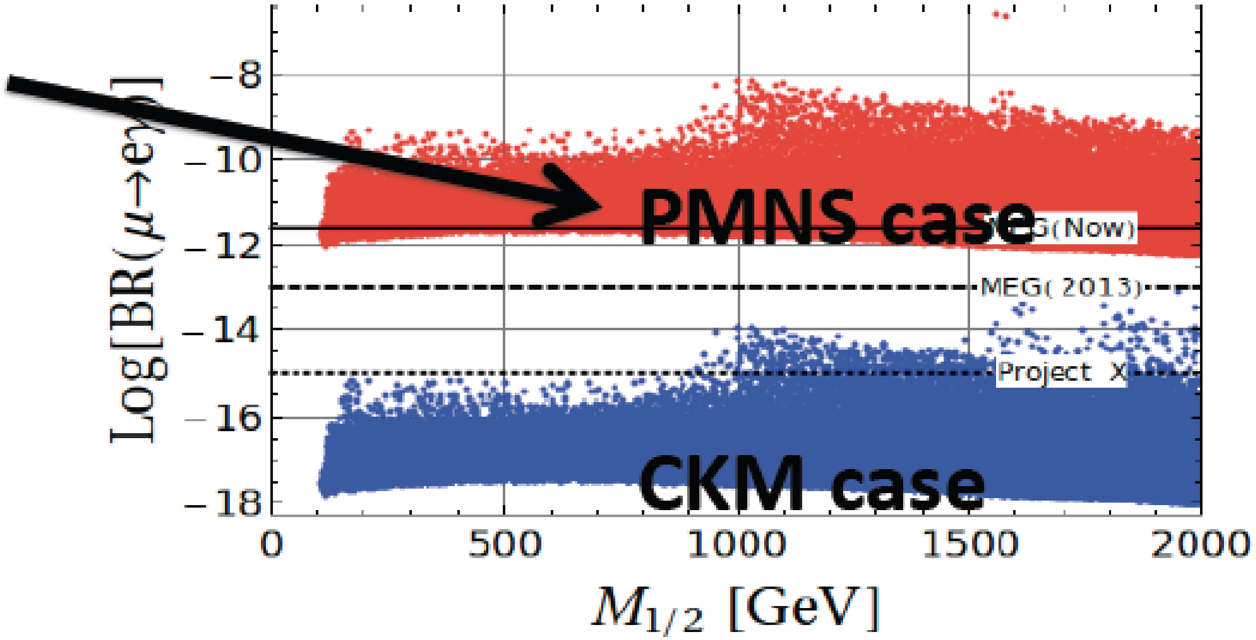
S4 is disadvantaged as large off diagonal ch. lepton mass terms are needed (of $o(\lambda_C)$)

Needs either m_0 or $M_{1/2}$ heavy

GA, Feruglio, Merlo, Stamou '12

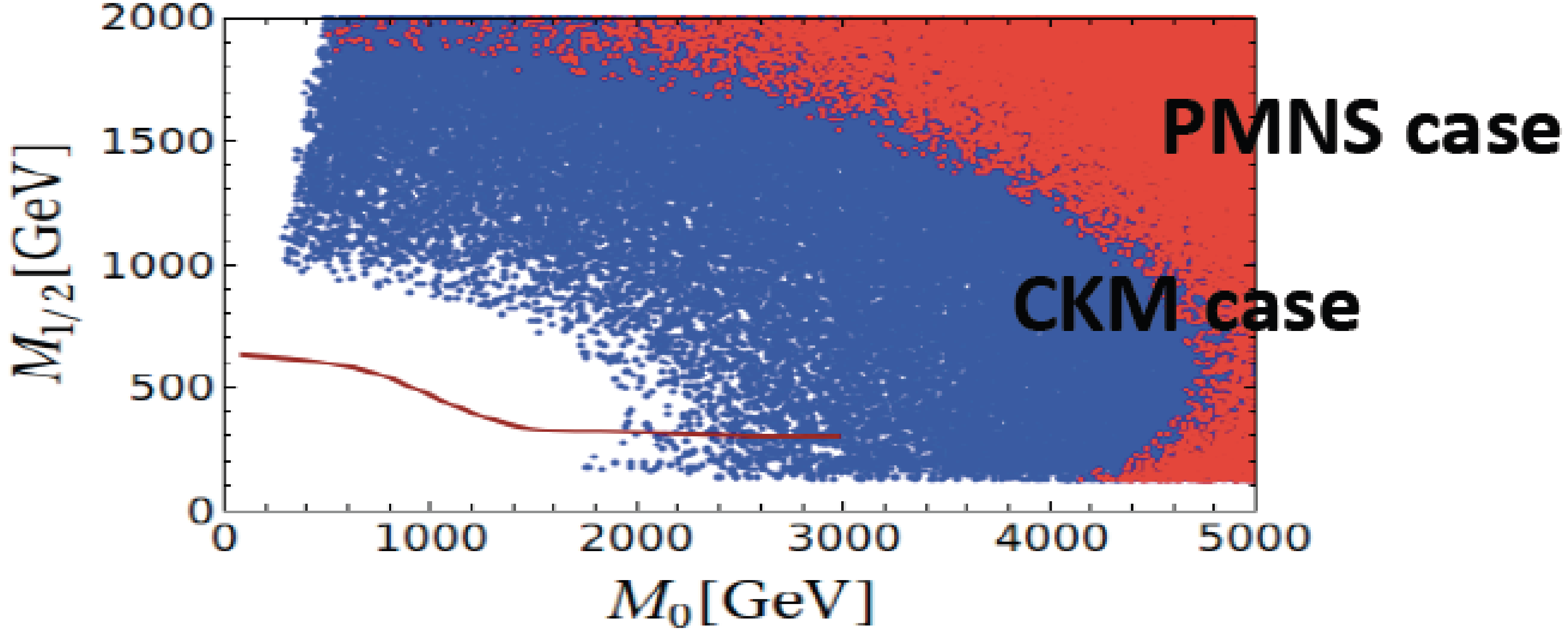
Br(μ -> e γ) < 5.7 10^{-13}: a serious constraint for SUSY models

PMNS case in mSUGRA with tanβ = 10



Masiero

Calibbi et al. 2012



Models based on discrete flavour groups are less favoured now

Some selected versions are still perfectly viable

GA, Feruglio, Merlo, Stamou ‘12

Larger groups have been studied

de A. Toorop, Feruglio, Hagedorn’11
Lam ‘12 - ‘13,
Holthauser, Lim, Lindner ‘12
Neder, King, Stuart ‘13....

CP violation has been included in the symmetry breaking pattern

Feruglio, Hagedorn, Ziegler‘12 - ‘13,
Ding, King, Luhn, Stuart ‘13

Symmetry requirements have been relaxed

Hernandez, Smirnov ‘12

Data on mixing angles are much better now but models of neutrino mixing still span a wide range from anarchy to discrete flavour groups

In the near future it will not be easy to decide from the data which ideas are right

So far no real illumination came from leptons to be combined with the quark sector for a more complete theory of flavour

Conclusion

Pontecorvo made seminal contributions to neutrino physics

This domain of physics deals with fundamental issues,
is being vigorously studied and our knowledge has much
increased in the last 15 years

But many crucial problems are still open

Conclusion

Pontecorvo made seminal contributions to neutrino physics

This domain of physics deals with fundamental issues, is being vigorously studied and our knowledge has much increased in the last 15 years

But many crucial problems are still open

As a last speaker, on behalf of all of you, I warmly thank the Organisers of this very stimulating Conference in a pleasant environment