Lepton flavour - a brief review

Michele Frigerio
Laboratoire Charles Coulomb, CNRS & Université de Montpellier

Rencontre de Physique des Particules - January 2015

Outline

- Experimental data: present status, perspectives
- Theoretical framework: neutrino mass origin, flavour structure
- Connections with baryogenesis, dark matter, Higgs

A model of leptons

Weinberg '67

$$\mathcal{L}_{lep} = \sum_{\alpha=e,\mu,\tau} \left[\overline{l_{L\alpha}} i\gamma^\mu D_\mu l_{L\alpha} + \overline{e_{R\alpha}} i\gamma^\mu D_\mu e_{R\alpha} - (y_\alpha \overline{l_{L\alpha}} H e_{R\alpha} + h.c.)\right]$$

- Standard Model symmetries:
  - ✳ $U(1)_e \times U(1)_\mu \times U(1)_\tau = U(1)_L \times$ orthogonal combinations
  - ✳ CP invariance
- Yet, neutrino flavour eigenstates oscillate into one another

  Super-Kamiokande '98
  - ✳ a striking effect, but induced by tiny masses: due to new physics very weakly mixed with the SM !
  - ✳ $U(1)_L$ and CP resist, for the nonce

Lepton mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad U = R(\theta_{23})R(\theta_{13},\delta)R(\theta_{12})$$

Pontecorvo ’57
Maki-Nakagawa-Sakata ’62

U relates the neutrino mass eigenstates $\nu_{1,2,3}$ to the charged lepton mass eigenstates e,μ,τ

$$\mathcal{L}_{lep} \supset -m_\alpha \overline{e_{L\alpha}} e_{R\alpha} - \boxed{\frac{1}{2} e^{i\phi_i}}^{*} m_i \overline{\nu_{Li}} \nu_{Ri} + \frac{g}{\sqrt{2}} \overline{e_{L\alpha}} \gamma^\mu W_\mu^- U_{\alpha i} \nu_{Li}$$

Oscillation probabilities are sensitive to
m_i^2-m_j^2 (frequencies), θ_{ij} (amplitudes), and δ (odd under CP)

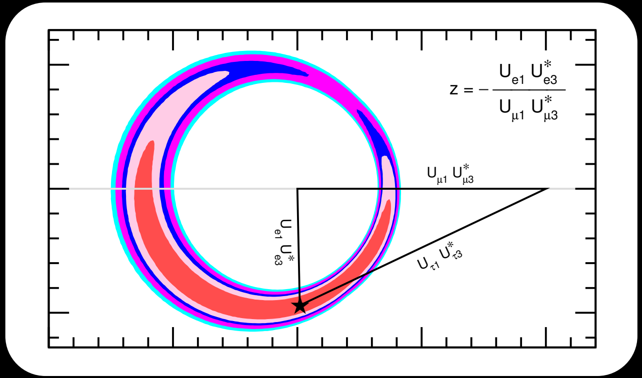
* in the case of Majorana neutrinos $\nu_R \equiv (\nu_L)^c$

Neutrino oscillation data

Mass squared differences known precisely, up to one sign: $m_3 > m_{1,2}$ (Normal Ordering) or $m_3 < m_{1,2}$ (Inverted Ordering)

θ_{13} measured (in 2012, from reactor ν's) almost as precisely as θ_{12} (solar ν's), θ_{23} (atmospheric ν's) is not precisely determined yet (slight preference for non-maximal value, from accelerator ν's)

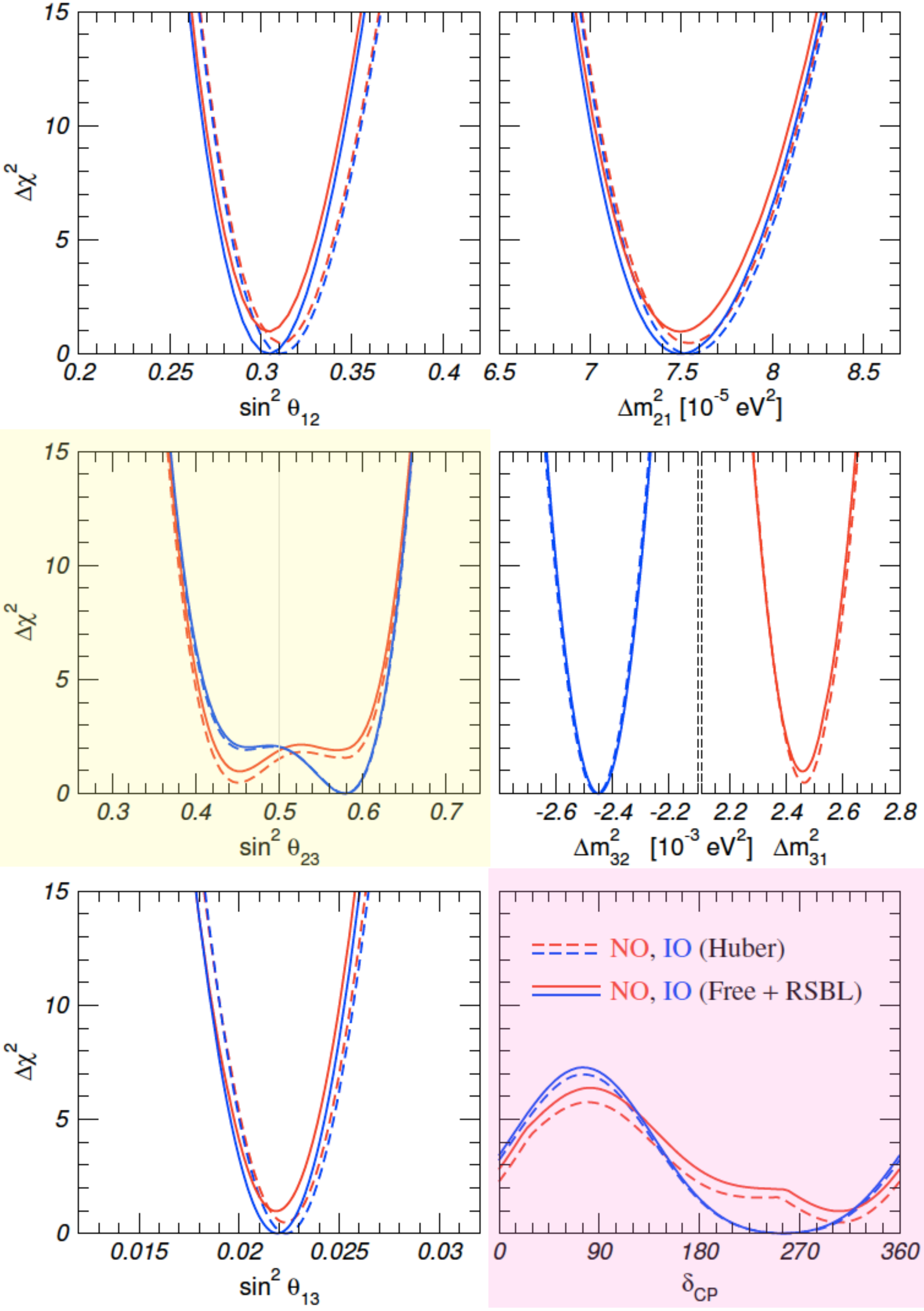
Leptonic CP-violation is around the corner ? Some values of δ already disfavoured at 2σ !



See also analog fits by
Forero,Tortola,Valle '14
Capozzi,Fogli,Lisi,Marrone,Montanino,Palazzo '13

Gonzalez-Garcia,Maltoni,Schwetz '14

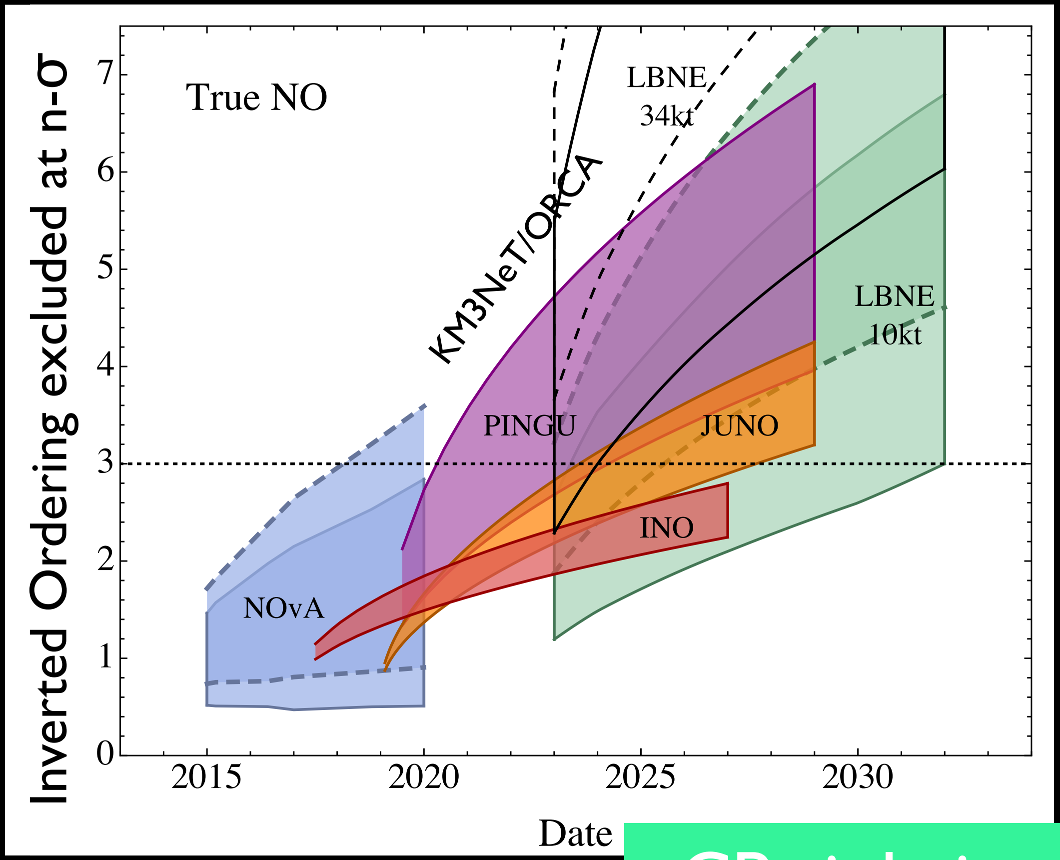
NuFIT 2.0 (2014)

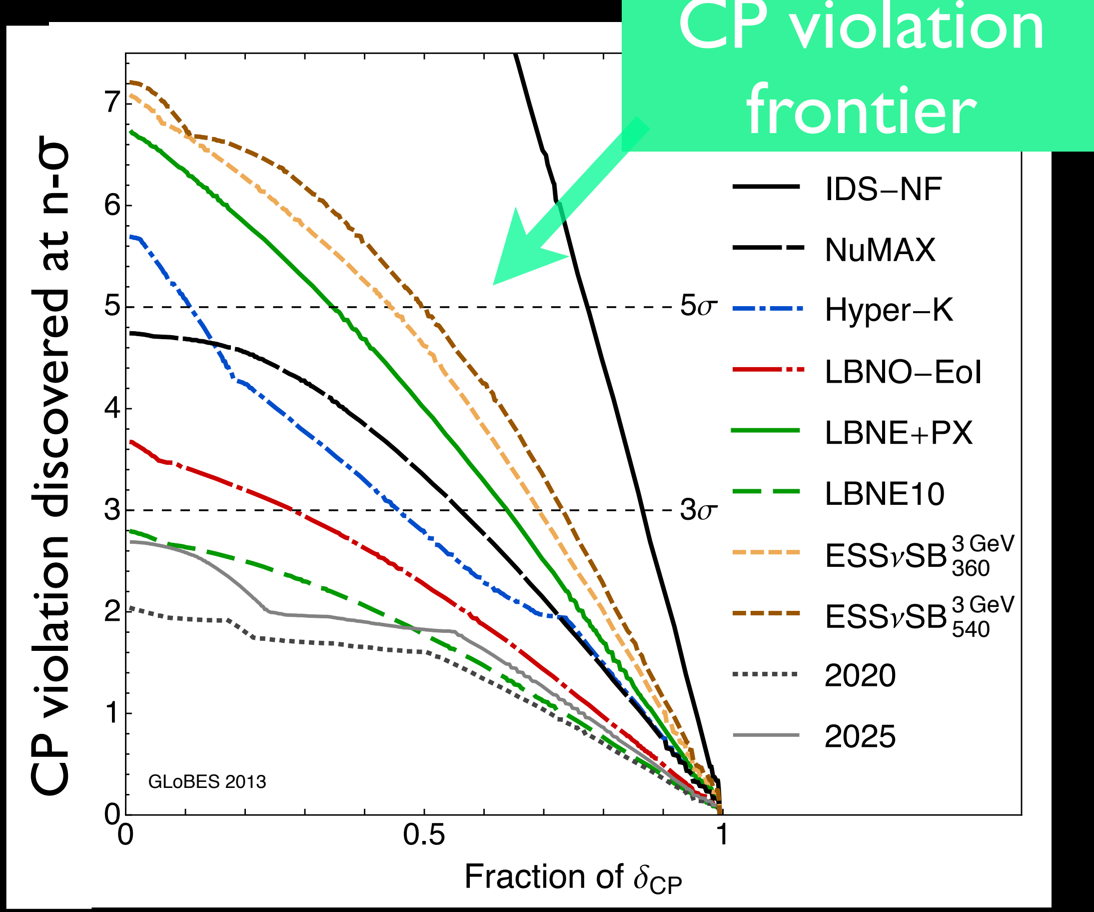


Next experimental challenges

- Precision oscillation experiments needed
    - to tell the mass ordering: normal or inverted
    - to explore CP violating values of δ (away from $\delta = 0$ or π)
    - to pinpoint $0.38 < \sin^2\theta_{23} < 0.64$ (3σ)
- What is the absolute value of the ν mass ? The lightest ν mass lies in the range $0 \leq m_{\text{light}} < 0.1$ eV (conservative 95% C.L. upper bound from cosmology, Planck 2014). The kinematic measurement by KATRIN will be sensitive to 0.2 eV.

Blennow,Coloma,Huber,Schwetz '11





CP violation frontier

ESSνSB '13

Effective neutrino mass

The SM is an effective theory valid up to scale Λ

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_{D=5} + \frac{1}{\Lambda^2}\mathcal{L}_{D=6} + \ldots$$

Weinberg '79

$$\boxed{\frac{1}{\Lambda}\mathcal{L}_{D=5} = \frac{c_{\alpha\beta}}{\Lambda} l_{L\alpha} l_{L\beta} H H + h.c.}$$

$$(m_\nu)_{\alpha\beta} = c_{\alpha\beta}\frac{v^2}{\Lambda}$$

The D=5 operator breaks all global symmetries: lepton flavour numbers, CP (if $c_{\alpha\beta}$ are complex), as well as the lepton number $U(1)_L$

Such description is appropriate as long as new degrees of freedom are heavier than the electroweak scale

$$\frac{\Lambda}{c_{\alpha\beta}} = 10^{15}\ \mathrm{GeV}\ \frac{0.03\ \mathrm{eV}}{(m_\nu)_{\alpha\beta}}$$

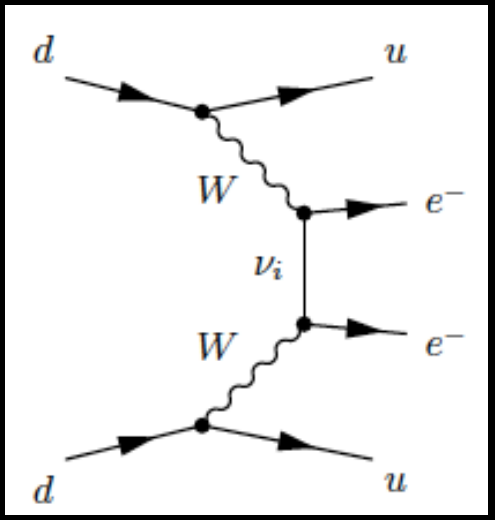
GUT scale states for $c \sim 1$

TeV scale states for $c \sim y_e^2 \sim 10^{-12}$

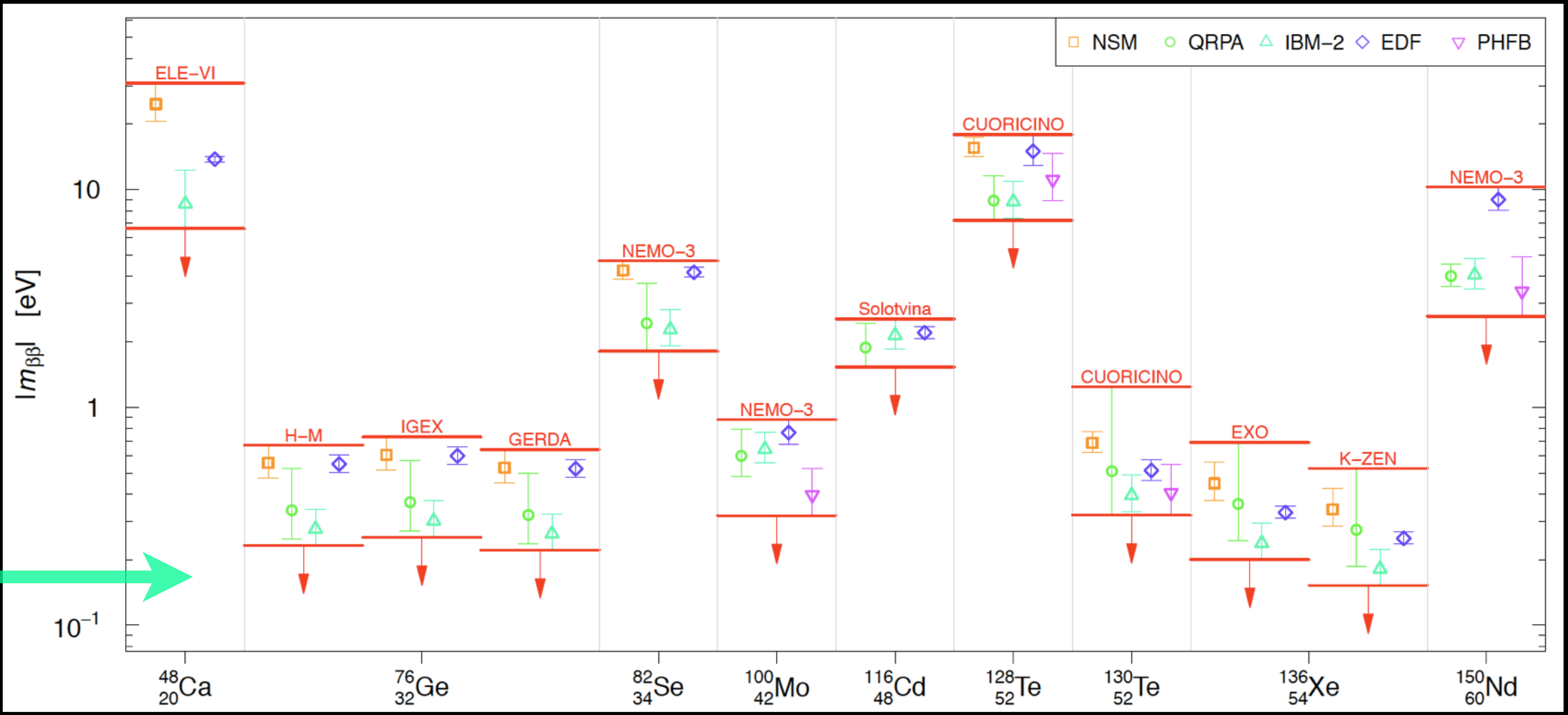
Neutrino-less double-β decay

- If $U(1)_L$ is broken, several heavy nuclei can undergo double-β decay with no neutrino emission: the only accessible observable to probe the Majorana nature of neutrinos

- Rate is proportional to $|(m_\nu)_{ee}|^2$. Depending on nuclear matrix elements, $0 < |(m_\nu)_{ee}| < 0.2 - 0.5$ eV (90% C.L. mostly Xe / Ge)



Bilenky, Giunti '14



lepton number violation frontier

New particles in the lepton sector?

- Extra degrees of freedom coupled to the SM leptons: several possibilities to induce m_ν (fermions/scalars, tree-level / n-loop level, ...)
- Below the electroweak scale, a few particles may have escaped detection if sufficiently weakly coupled (Goldstone scalars as the Majoron, light sterile neutrinos, a B-L vector boson with a tiny gauge coupling, ...)
- Above the electroweak scale, well-motivated theories often include a vast collection of new states
- We focus on sterile neutrinos only: a surprisingly rich phenomenology

One sterile neutrino

$$\mathcal{L}_N = -\frac{1}{2}\overline{(N_R)^c} M_N N_R - \sum_{\alpha=e,\mu,\tau} y^\nu_\alpha \overline{l_{L\alpha}} \tilde{H} N_R + h.c.$$

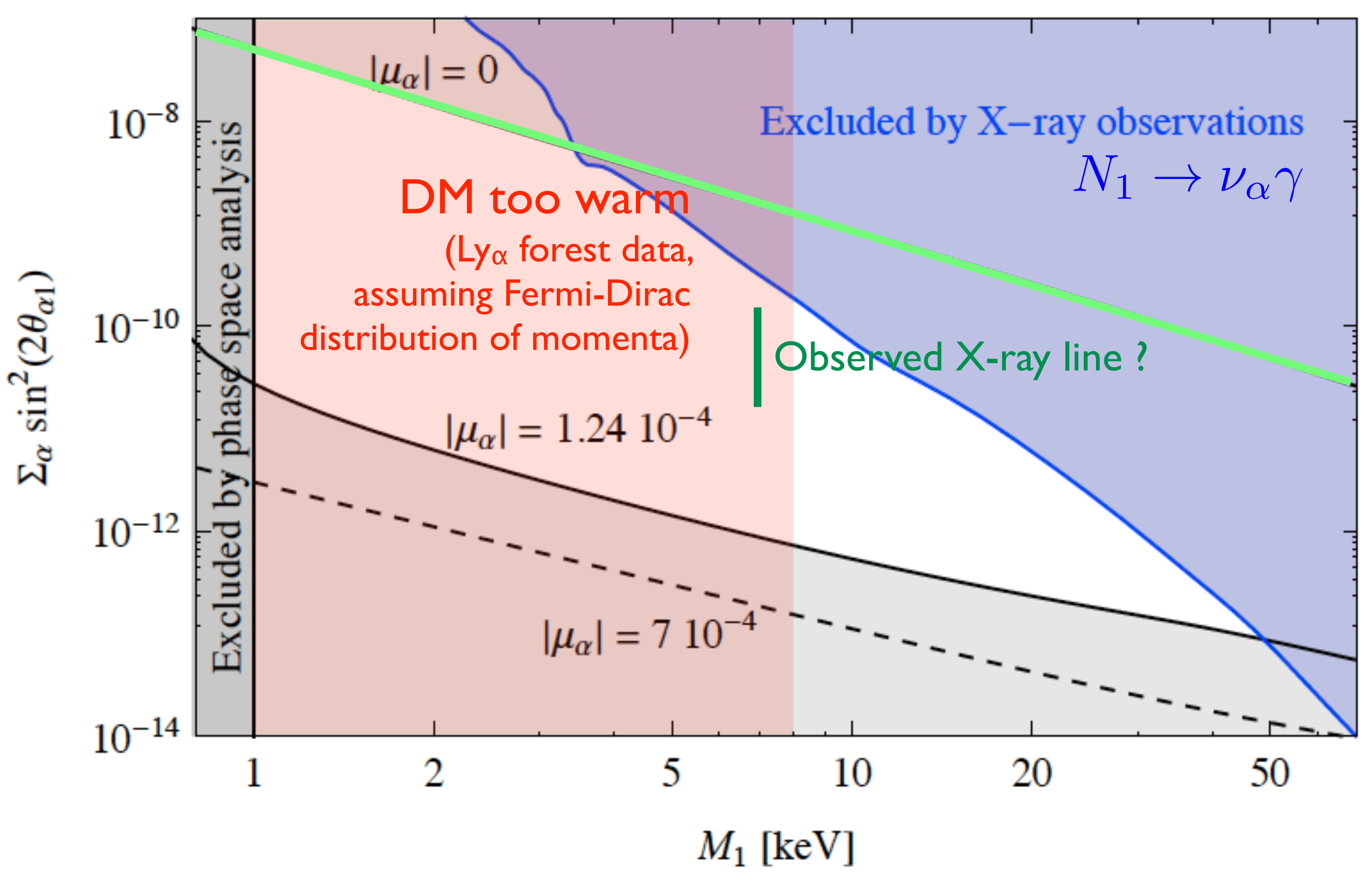
- U(1)$_L$ broken but CP preserved and two active neutrinos remain massless
- For $M_N \sim$ eV, active-sterile mixing relevant to explain various oscillations anomalies: viable explanation in some cases, but not compelling at present
- For $M_N \sim$ 10 keV, the sterile neutrino N produced via active-sterile mixing is a good dark matter candidate *(next slide)*
- For $M_N \sim$ 100 GeV, the Yukawa couplings must be tiny, $y^\nu_\alpha < 10^{-6}$: no detection possible

Giunti et al. '13
Kopp et al. '13

Dodelson-Widrow '93

Sterile neutrino dark matter

Along the green line $\Omega_N = \Omega_{DM}$



adapted from Canetti-Drewes-Frossard-Shaposhnikov '12

Non-minimal production mechanism for N is needed: resonant oscillations, freeze-in, ...

Unidentified X-ray line at 3.5 keV from some galaxy clusters plus Andromeda (the signal significance was questioned, and no signal was observed from other clusters/galaxies, in several recent papers)

Bulbul et al. '14
Boyarsky et al. '14

Two sterile neutrinos

$$\mathcal{L}_N = -\sum_{i=1,2}\left[\frac{1}{2}\overline{(N_{Ri})^c}M_{Ni}N_{Ri} + \sum_{\alpha=e,\mu,\tau} y^{\nu}_{\alpha i}\overline{l_{L\alpha}}\tilde{H}N_{Ri} + h.c.\right]$$

- All oscillation data can be successfully accommodated: only one active neutrino remains massless

- CP can be violated by 3 physical complex phases:
  a matter-antimatter asymmetry arises from out-of-equilibrium interactions of the sterile neutrinos;
  successful baryogenesis via leptogenesis is possible
  in a huge energy window, GeV < M_{N1} < 10^{15} GeV *(next slides)*

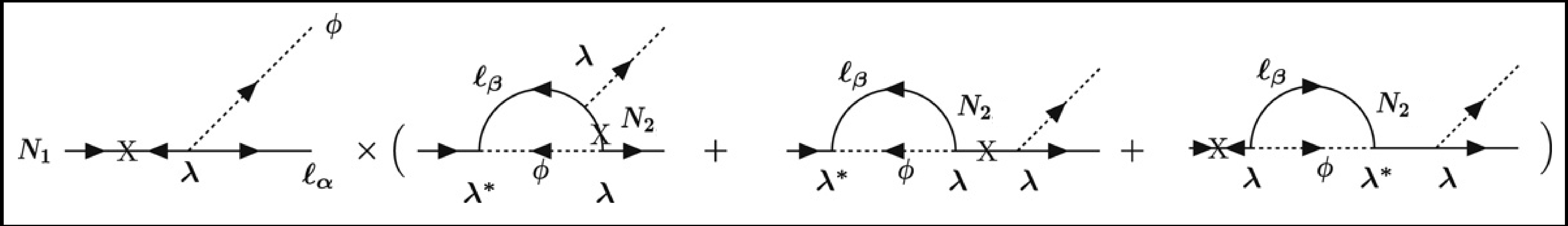
- $m_\nu = \theta_1^2 M_{N1} + \theta_2^2 M_{N2}$: if one accepts fine-tuning the mixing angles can be much larger than $(m_\nu / M_N)^{1/2}$ and N-detection may become possible at colliders; large mixing is more natural in extended models such as the inverse seesaw.

talk by Cedric Weiland, poster by Valentina De Romeri

Leptogenesis from decays

Fukugita-Yanagida ‘86

Decays of N_1 at temperatures just below its mass:



Davidson, Nardi, Nir ’08

A sufficient CP asymmetry requires $M_{N1} > 10^9$ GeV (because m_ν is tiny); one can go down to the TeV scale if M_{N1} is very close to M_{N2} (resonant enhancement of the asymmetry).

A few recent developments:

- flavour effects: $y_{e,\mu,\tau}$ go to equilibrium at very different temperatures (e.g. m_ν can be as raised from 0.2 eV to ~ 1 eV)

e.g. Abada et al. ’06
Nardi et al. ’06

- quantum corrections due to non-equilibrium dynamics, not accounted for by Boltzmann equations (e.g. resonant enhancement is reduced)

e.g. Anisimov et al. ’09
Garny et al. ’09

- the lepton / antilepton asymmetry may be related to a dark matter / dark antimatter asymmetry (asymmetric dark matter scenarios)

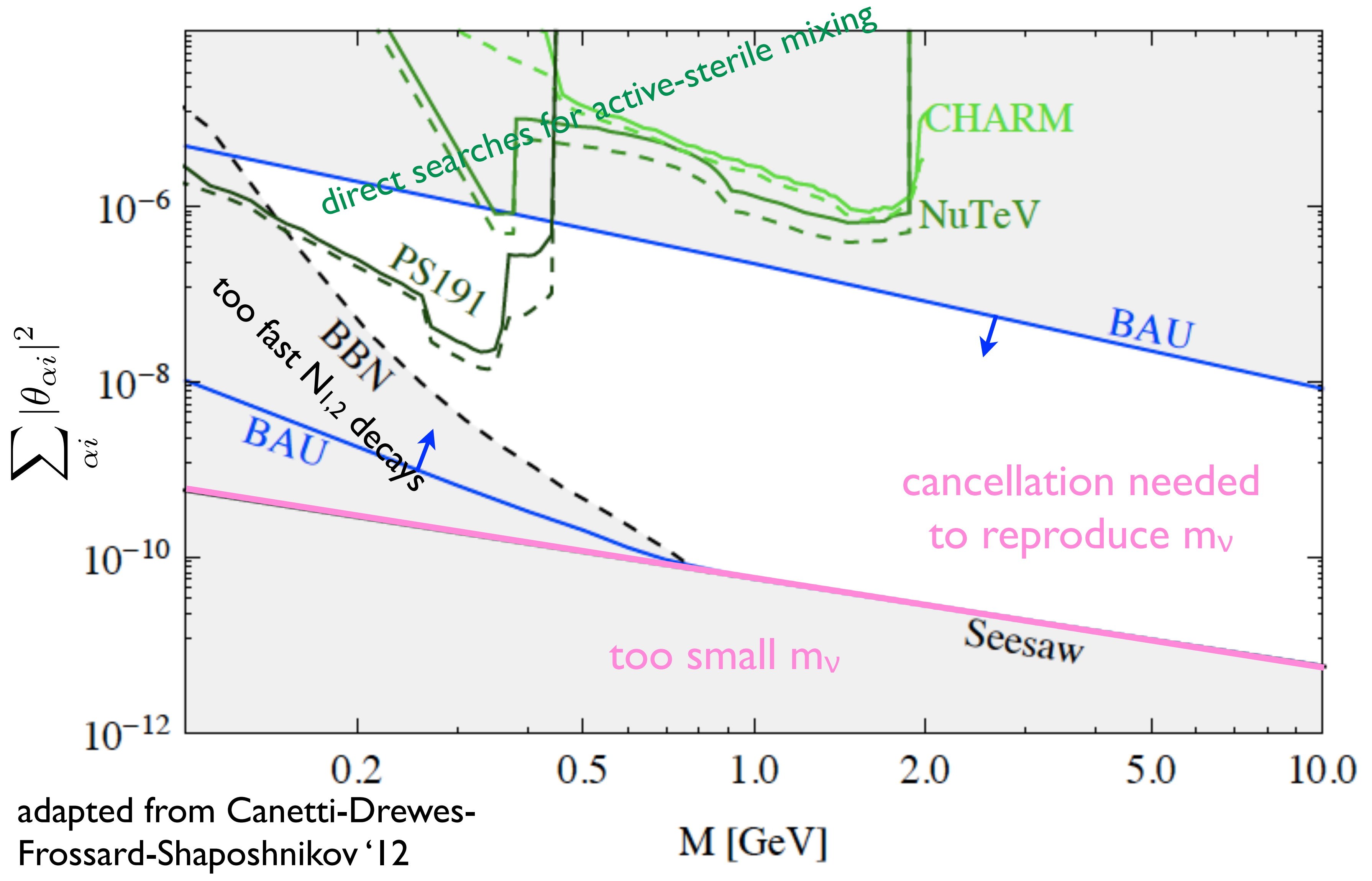
e.g. Blennow et al. ’10
Falkowski et al. ’11

Leptogenesis from oscillations

Akhmedov-Rubakov-Smirnov '98
Asaka-Shaposhnikov '05

- At T >> M_N flavour eigenstates N_α are produced coherently and oscillate ($\alpha = e,\mu,\tau$)
- Flavour asymmetries Δ_α appear between N_α of opposite helicities
- $\Sigma_\alpha\Delta_\alpha=0$, but a net lepton asymmetry can be transferred to baryons, if only some flavour α goes into equilibrium before T_{EW} ($y^\nu_\alpha > 10^{-7}$)

- To reduce washout $M_N < 100$ GeV
- To preserve coherence $y^\nu_\alpha < 10^{-5}$
- To preserve BBN $M_N > 0.1$ GeV
- With $N_{1,2}$ only, a strong tuning needed to enhance the asymmetry; not the case in extended models



adapted from Canetti-Drewes-Frossard-Shaposhnikov '12

Three sterile neutrinos

- No neutrino is left massless: quasi-degenerate spectrum possible
- Strong theoretical motivations:
  - ✳ $U(1)_{B-L}$ can be gauged and left-right symmetry becomes possible (spontaneous P breaking)
  - ✳ SO(10) grand unification: tailor-suited theory for neutrino masses
- Extensions of the SM gauge group make the flavour sector predictive: (i) interconnected Yukawa matrices; (ii) correlations between low energy parameters and high energy physics (e.g. leptogenesis, flavour violation)
- Extra, generic contribution to m_ν from a weak triplet scalar T : this is the truly Minimal Flavour Violation for the lepton sector (when all other new physics is flavour blind)

talk by Luiz Henrique Vale Silva

e.g.
Hosteins,Lavignac,Savoy '06
Bertolini,Malinsky,Schwetz '06
Abada,Hosteins, Josse-Michaux, Lavignac '08
Fong,Meloni,Meroni,Nardi '14

Joaquim,Rossi '06

$$c_{\alpha\beta} l_{L\alpha} l_{L\beta} T \quad \Rightarrow \quad (m_\nu)_{\alpha\beta} = c_{\alpha\beta} v_T \sim c_{\alpha\beta} \frac{v^2}{M_T}$$

Flavour violation other than in m_ν

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_{D=5} + \frac{1}{\Lambda^2}\mathcal{L}_{D=6} + \ldots$$

- Flavour violation processes involving charged leptons are induced by the D=5 operator, but with a tiny rated suppressed by $(m_\nu/m_W)^4$

- $\Lambda_{D=6}$ can be naturally much smaller than the scale Λ_L where lepton number is broken (this is the only hope to observe new physics!)

- Indeed TeV scale new physics addressing the hierarchy problem generically violates flavour at variance with data.
  Even when one imposes flavour blindness at some scale, sizable flavour violations are induced radiatively by SM and neutrino Yukawa couplings.

- Flavour-violating charged lepton processes are potentially sensitive to new states much heavier than the LHC reach

Rates and correlations of various channels strongly depend on the new physics model...

for the case of sterile neutrinos see
de Gouvêa '07, Dihn, Ibarra, Molinaro, Petcov '12
Abada, De Romeri, Teixeira, Vicente, Weiland, '12-'14

talk by Cedric Weiland,
poster by Valentina De Romeri

Charged lepton flavour violation

$$\frac{y_\mu}{(1+k)\Lambda^2}\overline{l_{Le}}H\sigma^{\mu\nu}F_{\mu\nu}\mu_R$$

$$BR(\mu^+ \to e^+\gamma) < 5.7 \times 10^{-13} \ (90\%\text{C.L.})$$

MEG data 2009-2011, PRL 2013

upgrade to approach the ultimate sensitivity ~ 10^{-14}

$$+\frac{k}{(1+k)\Lambda^2}(\overline{l_{Le}}\gamma^\mu l_{R\mu})(\overline{q_L}\gamma_\mu q_L)$$

$$CR(\mu^- \text{Au} \to e^- \text{Au}) < 7 \times 10^{-13} \ (90\%\text{C.L.})$$

SINDRUM II, EJPC 2006

improvement by a factor 10^4 to 10^6

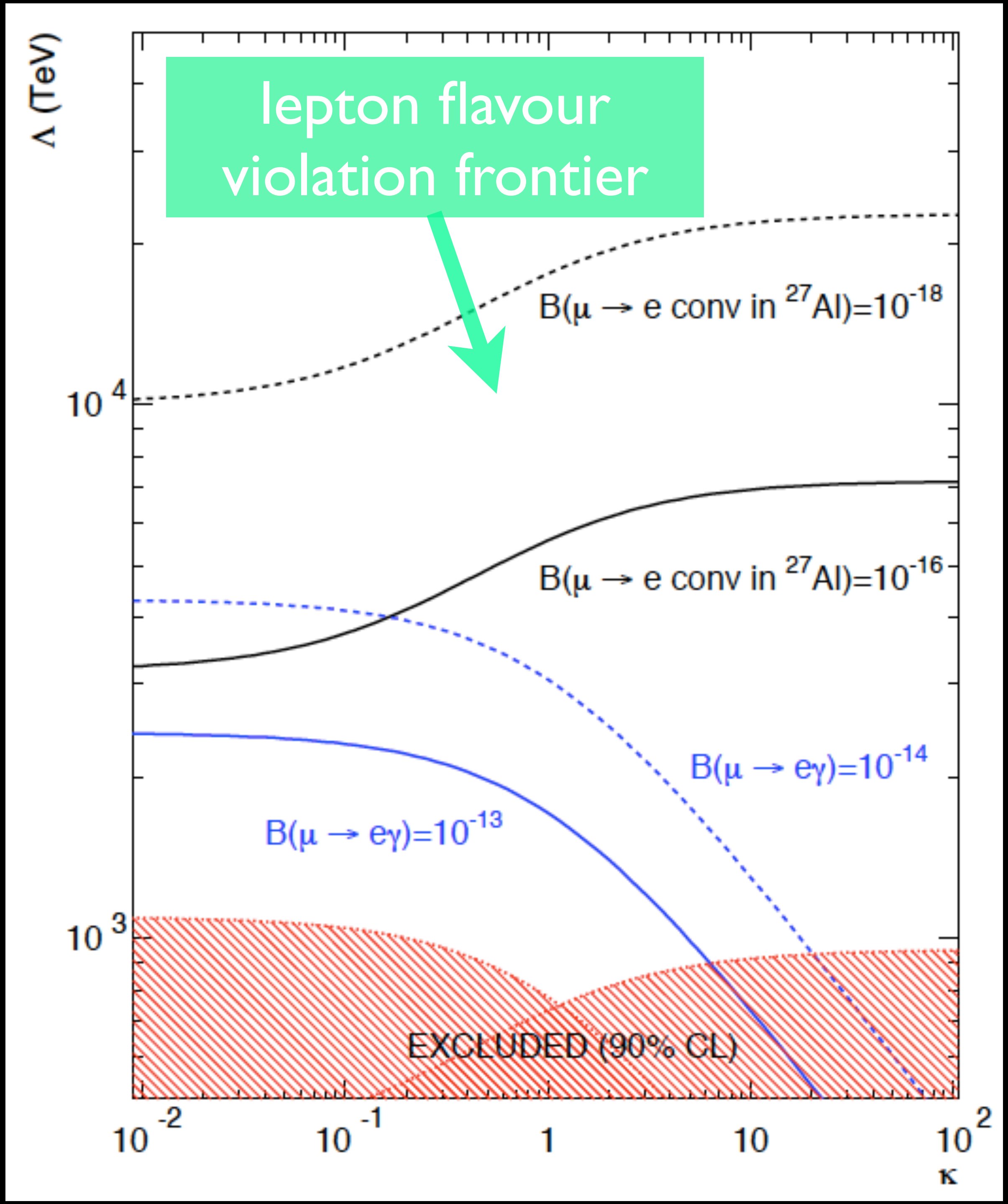
(for various nuclei: Al, Ti, ...)

expected with COMET (J-PARC)

and Mu2e (Fermilab)

dipole >> 4 fermions

dipole << 4 fermions


lepton flavour violation frontier

de Gouvêa, Vogel '13

Muon anomalous magnetic moment

- 3σ discrepancy: $a_\mu^{exp} - a_\mu^{SM} \simeq (25 \pm 8)\ 10^{-10}$

reviewed e.g. by Knecht ’14

- Intense activity to improve on the SM theoretical uncertainty, but the estimated size of the corrections is much smaller than the discrepancy

Passera,Marciano,Sirlin ’08-’10

- One experiment only dominates the measurements; two new projects aim to reduce by 4 the experimental uncertainty

E821 (Brookhaven) ’06
E989 (Fermilab proposal) ’10
g-2 (J-PARC proposal) ’10

- The discrepancy can be explained by (flavour-conserving) new physics at scale 8 TeV ~ $\Lambda_{g-2} = \varepsilon_{e\mu}\,\Lambda_{e\mu} \ \Rightarrow\ \varepsilon_{e\mu} < 10^{-2}$

$$\frac{y_\mu}{\Lambda^2}\overline{l_{L\mu}}H\sigma^{\mu\nu}F_{\mu\nu}\mu_R$$

- Such new physics typically within the LHC reach, with exceptions, e.g. a multi-TeV leptoquark

Chakraverty,Choudhury,Datta ’01
Biggio,Bordone ’14

- A chance for new physics also in a_e (with exp. progress)

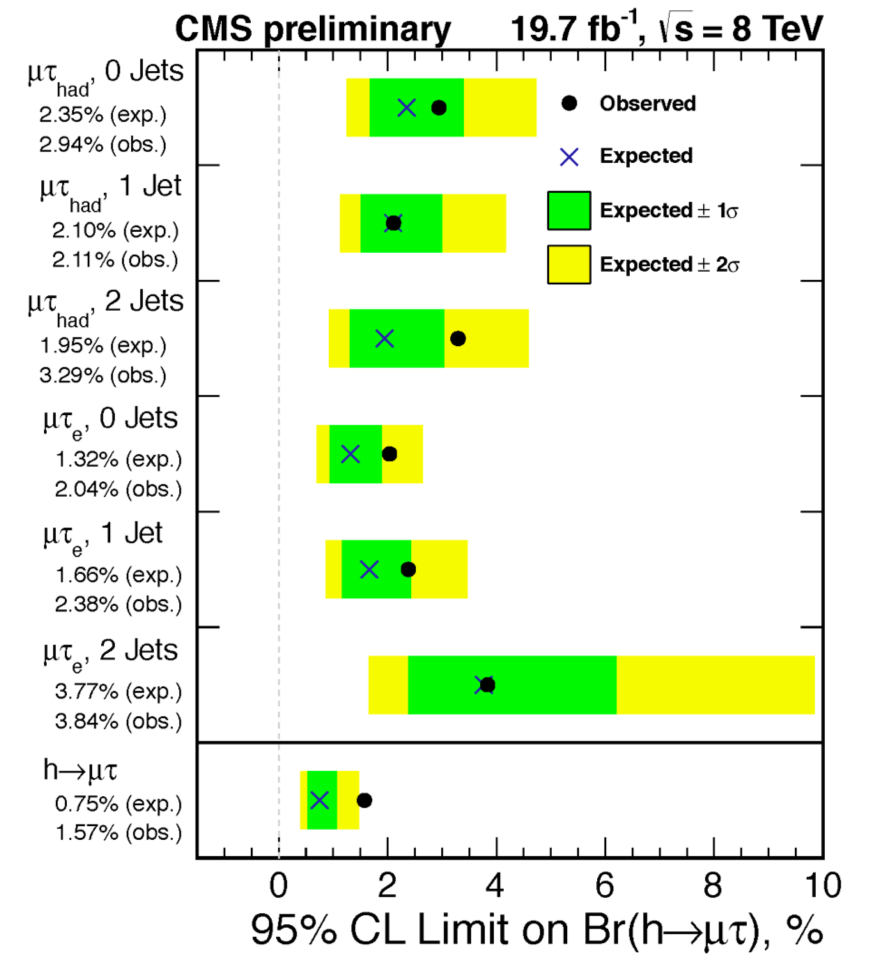
Giudice,Paradisi,Passera ’12

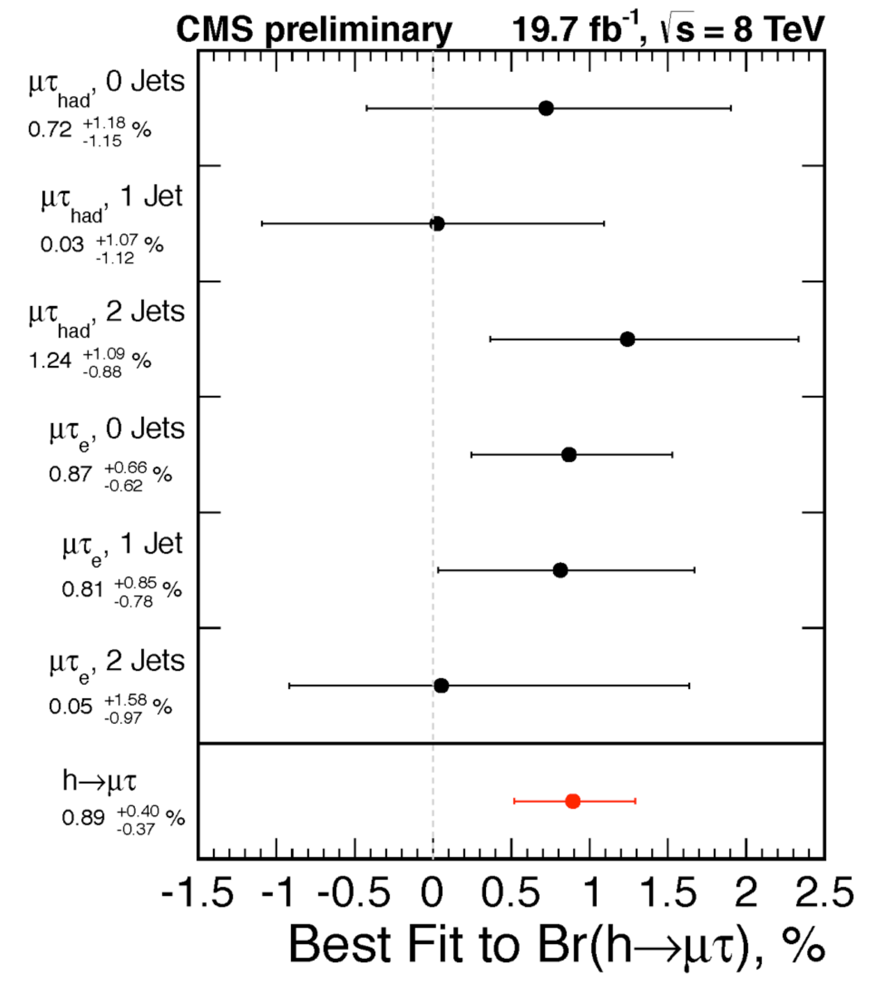
Flavour violating Higgs couplings

- Bounds on τ flavour-violating decays are weaker w.r.t. μ (branchings ~ 10^{-8}): Higgs couplings $y_{\tau\mu}$, $y_{\tau e}$ ~ 10^{-1} still allowed
- The Higgs is very narrow (relatively e.g. to the Z boson), therefore on-shell Higgs decays may constrain small coupling better than low-energy Higgs-mediated processes

Blankenburg,Ellis,Isidori ’12
Harnik,Kopp,Zupan ’12
Davidson,Verdier ’12

$$\frac{1}{\Lambda^2}(H^\dagger H)(\overline{l_{L\mu}}H)\tau_R$$





CMS searched for Higgs into μτ with τ decaying to hadrons or to eνν
(CMS-PAG-HIG-14-005)

$$BR(H \to \mu\tau) < 1.6\% \quad (95\%\ \text{C.L.})$$

$$BR = (0.9 \pm 0.4)\% \quad (2.5\sigma\ \text{excess})$$

Quest for flavour dynamics

- Search for a theory of fermion masses and mixing
- In the lepton sector the Yukawa couplings break the flavour symmetry $U(3)_{lL} \times U(3)_{eR}$ to nothing (when $m^{\nu}_{\text{lightest}} \neq 0$)
- Is (part of) the flavour group a fundamental symmetry broken dynamically? A variety of continuous/discrete subgroups
- Do data point to a hierarchical symmetry breaking sequence?
  How to identify the order parameters?
  What is the energy scale of symmetry breaking?

Structure of the mass matrices

The flavour dynamics determines the Yukawa couplings:
symmetries should be looked for in the matrix structures, NOT in the value of the observables (masses, mixing angles, CP phases)

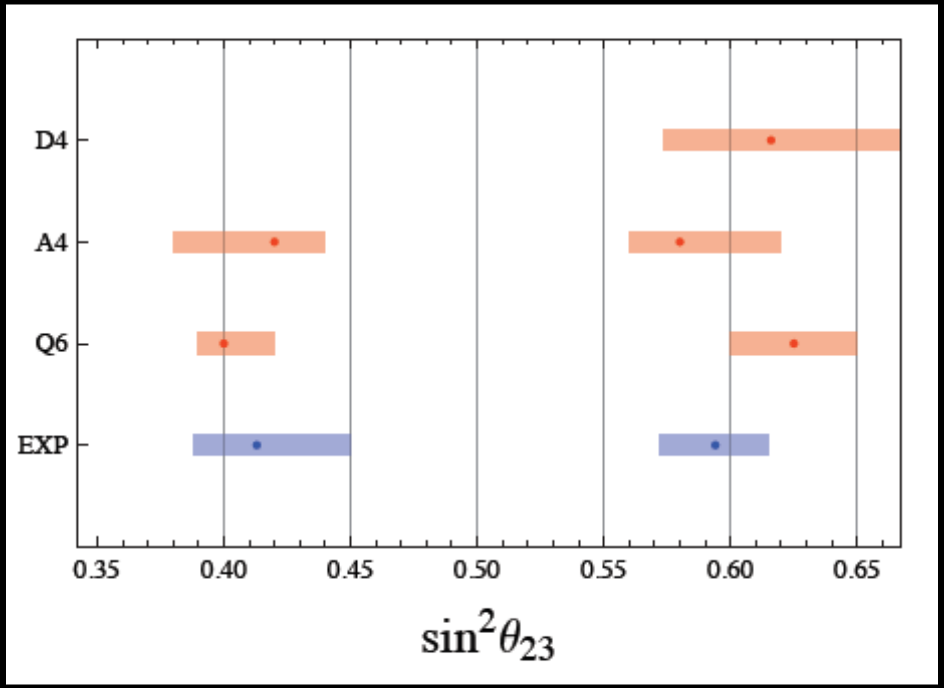
$$M_e = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} U_{e_R} \qquad M_\nu = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & m_{\mu\mu} & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & m_{\tau\tau} \end{pmatrix}$$

assuming
three
Majorana
neutrinos

The structures are basis-dependent, but less ambiguity than for quarks

M_ν strongly depend on the neutrino mass eigenvalues, that are largely undetermined at present: absolute value, ordering, relative phases

Even if mixing angles do not take extreme values (zero or π/4), the matrix structures can carry the clear footprint of a symmetry



minimal (predictive) flavour models with a discrete symmetry

global 3ν fit at 1σ

Directions in modeling flavour

- A few recent, promising approaches to the lepton flavour problem:
  - ✳ Residual symmetries of M_e and M_ν separately can be used to build systematically possible flavour groups: model-independent correlations emerge among mixing angles
  - ✳ Models which combine the breaking of the flavour group and of the CP symmetry, making predictions for the CP phases
  - ✳ The same flavour symmetry that accounts for the structure of lepton mass matrices can address/ alleviate the flavour problem of 'natural' TeV scale theories (supersymmetry / compositeness)

C.S.Lam '08
Hernandez,Smirnov '12

De Medeiros Varzielas,
Emmanuel-Costa '11
Babu,Kawashima,Kubo '11
Feruglio,Hagedorn,Ziegler '12
Holthausen,Lindner,Schmidt '12

Feruglio,Hagedorn,Lin,Merlo '09
Calibbi,Paradisi,Ziegler '14 /
Csaki,Delaunay,Grojean,Grossman '08
Del Aguila,Carmona,Santiago '10
Hagedorn,Serone '11

Summary

the talk was already a summary summary