Strong thermal leptogenesis:

an exploded view of the low energy neutrino parameters in the SO(10)-inspired model

by: Luca Marzola

Based on:

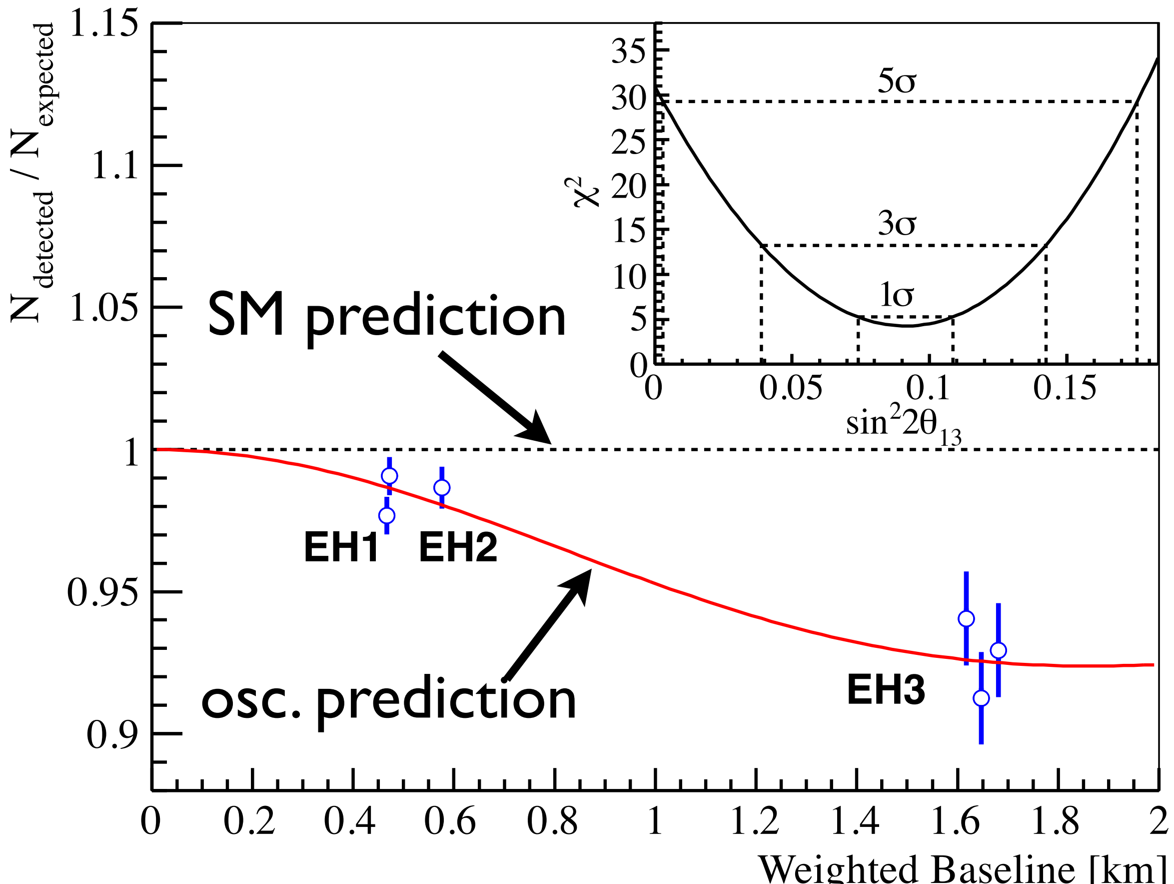
- P. Di Bari, LM: *SO(10)-inspired solution to the problem of the initial conditions in leptogenesis* - Nucl.Phys. B877 (2013)
- P. Di Bari, S.Blanchet, D.A. Jones, LM: *Leptogenesis with heavy neutrino flavours: from density matrix to Boltzmann equations* - JCAP 1301 (2013)
- P. Di Bari, E. Bertuzzo, LM: *The problem of the initial conditions in flavoured leptogenesis and the τ N_2-dominated scenario* - Nucl.Phys. B849 (2011)

XXX-th International Workshop on High Energy Physics @ IHEP, Protvino - 27/06/2014

Two Problems...

The current paradigms of Particle Physics (Standard Model) and Cosmology (Λ-CDM Model) do not explain:

- Neutrino oscillations
- Baryon asymmetry of the Universe



Daya Bay collaboration, 2012

... one solution: leptogenesis

- Minimal type I Seesaw extension of the Standard Model:

$$\mathcal{L} = \mathcal{L}_{SM} + i\overline{N_{Ri}}\partial^\mu\gamma_\mu N_{Ri} - h_{\alpha i}\overline{\ell_{L\alpha}}N_{Ri}\tilde{\Phi} - \frac{1}{2}\overline{N_{Ri}^c}D_{M_i}N_{Rj} + \text{ H.c.}$$

$(i = 1, 2, 3)$ $\quad (\alpha = e, \mu, \tau)$

  - 3 RH neutrinos with a Majorana mass term
  - Yukawa term for neutrinos

$D_X := \mathrm{diag}(X_1, X_2, X_3)$

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$(i = 1, 2, 3) \quad (\alpha = e, \mu, \tau)$

S.B. **+** Heavy R.H.N.

$-(m_D)_{\alpha i}\overline{\nu_{L\alpha}}N_{Ri}$ $\quad [M] \gg [m_D]$

$\Rightarrow$ *Type I Seesaw:*

$$M_{light} \approx -m_D M^{-1} m_D^T$$

$$M_{heavy} \approx M$$

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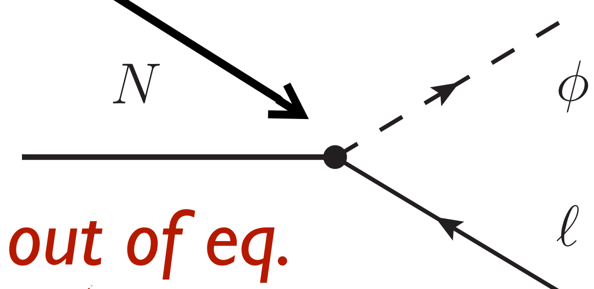
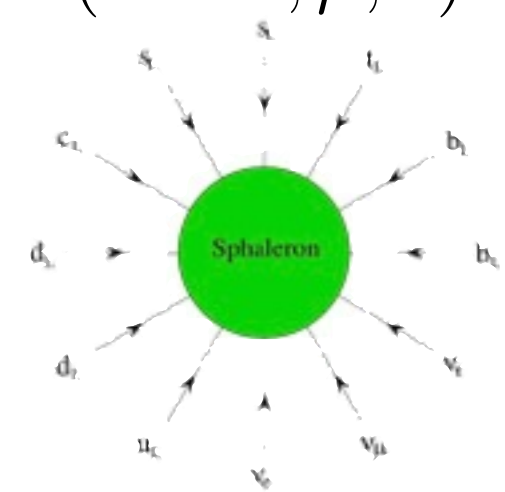


out of eq.
~~CP~~ decays

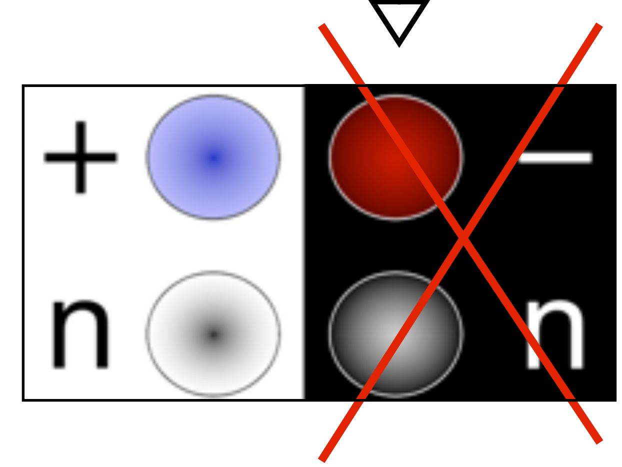
+



SM Sphaleron:

$\Delta B \neq 0 \quad \Delta L \neq 0$

$\Delta(B-L) = 0$



$$\boxed{\eta_B \simeq 10^{-2} N^f_{B-L}}$$

Sakharov's conditions

- The baryon asymmetry of the Universe, $\eta_B := (n_B - n_{\bar{B}})/n_\gamma$, cannot be set by an initial condition because of inflation.

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- A successful dynamical mechanism requires:

  1) (L and) B violation:

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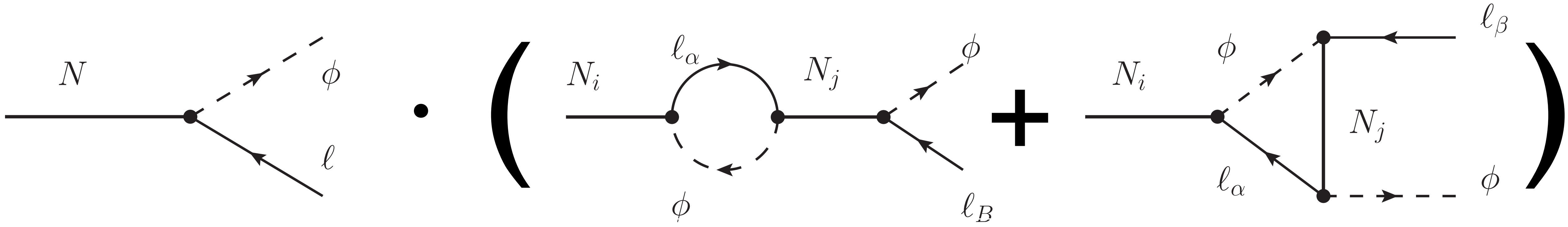
2) C and CP violation:

– C violated by weak interactions

– CP violation:

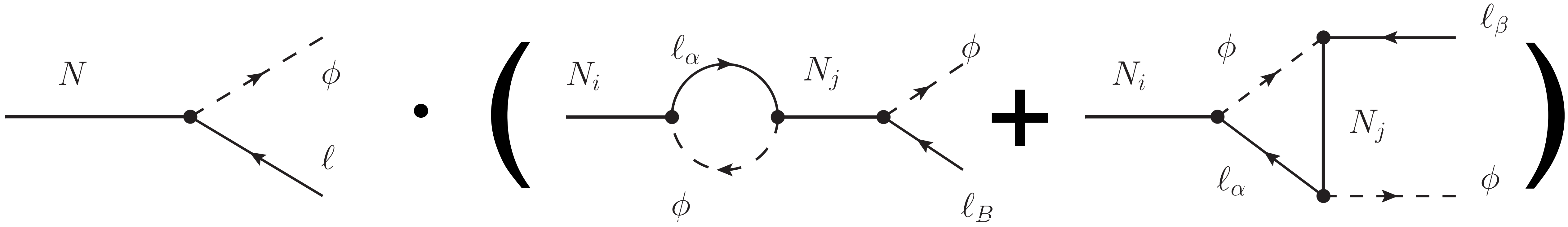
$$\epsilon_i = -\frac{\Gamma(N_i \to \ell\phi) - \Gamma(N_i \to \overline{\ell\phi})}{\Gamma(N_i \to \ell\phi) + \Gamma(N_i \to \overline{\ell\phi})}$$



$$\epsilon_i = -\frac{\int d\Pi_{\ell,\phi}\left[|h_{\alpha i}(1+\beta\mathcal{F})|^2 - |h^*_{\alpha i}(1+\beta^*\mathcal{F})|^2\right]}{\int d\Pi_{\ell,\phi}\left[|h_{\alpha i}(1+\beta\mathcal{F})|^2 + |h^*_{\alpha i}(1+\beta^*\mathcal{F})|^2\right]} \simeq 2\Im(\beta)\Im\Big(\int \mathcal{F}\, d\Pi_{\ell,\phi}\Big)$$

$\mathcal{F}$ loop factor with effective coupling $\beta = \beta(h)$

A non-vanishing CP violation imposes complex couplings $h_{\alpha i}$ *and more than one heavy neutrino.*



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3) Out-of-equilibrium dynamics:

–in thermal equilibrium: density matrix $\rho = \frac{e^{-H/T}}{Z}$

$$\langle Q(t)\rangle = \frac{\mathrm{Tr}}{Z}\left(e^{-H/T}Q(t)\right) = \frac{\mathrm{Tr}}{Z}\left(e^{-H/T}e^{-iHt}Q(t=0)e^{iHt}\right) = \langle Q(0)\rangle$$

–deviations from equilibrium arise because of the expansion of the Universe: *decoupling condition* $\Gamma/H \lesssim 1$

A taste of Leptogenesis:

A simplified scenario: N_1 Leptogenesis (no flavour effects).

- Given $z := M_1/T$, the N_1 abundance per comoving volume is:

$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N_{N_1}^{eq} \right)$$

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- The involved parameters

$$D_i(z_i) := \frac{\Gamma_{D_i}(T) + \Gamma_{\bar{D}_i}(T)}{H\ z_i} \propto K_i \qquad W_i(z_i) = \frac{1}{2} D_i(z_i) N_{N_1}^{eq}(z_i) \propto K_i$$

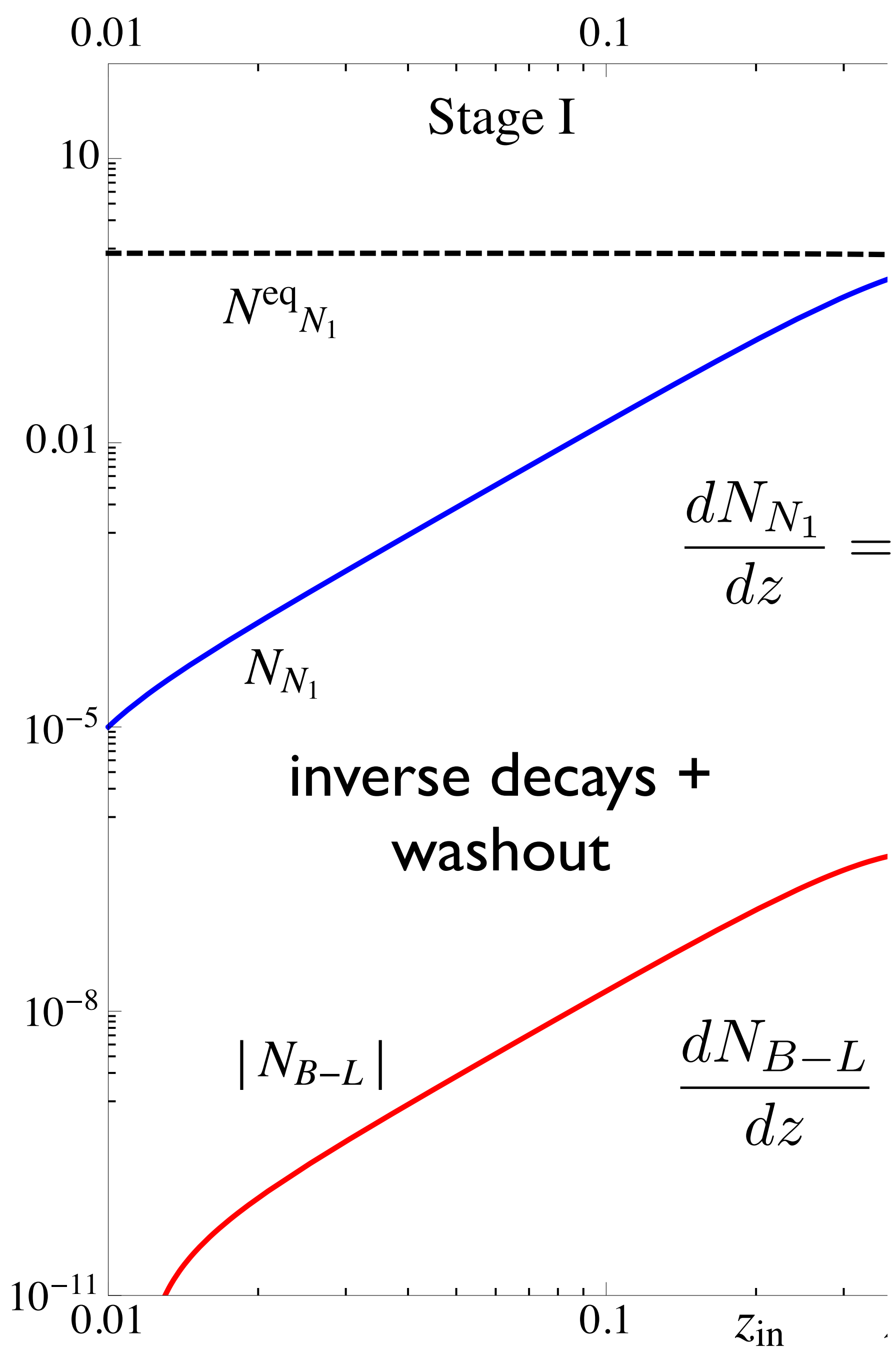
depend on the decay efficiency parameter

$$K_i := \frac{\Gamma_{D_i}(T=0) + \Gamma_{\bar{D}_i}(T=0)}{H(z_i = 1)}$$

→ *connection to low energy parameters* $\tilde{m}_i := \frac{(m_D^\dagger m_D)_{ii}}{M_i}$

$$K_i \equiv \frac{\tilde{m}_i}{m_*} \qquad m_* := \frac{16\pi^{5/2}\sqrt{g_*}}{3\sqrt{5}}\frac{v^2}{M_{Pl}} \simeq 1.08 \times 10^{-3}\ \mathrm{eV}$$

- Focus on strong washout regime: $K_1 >> 1$



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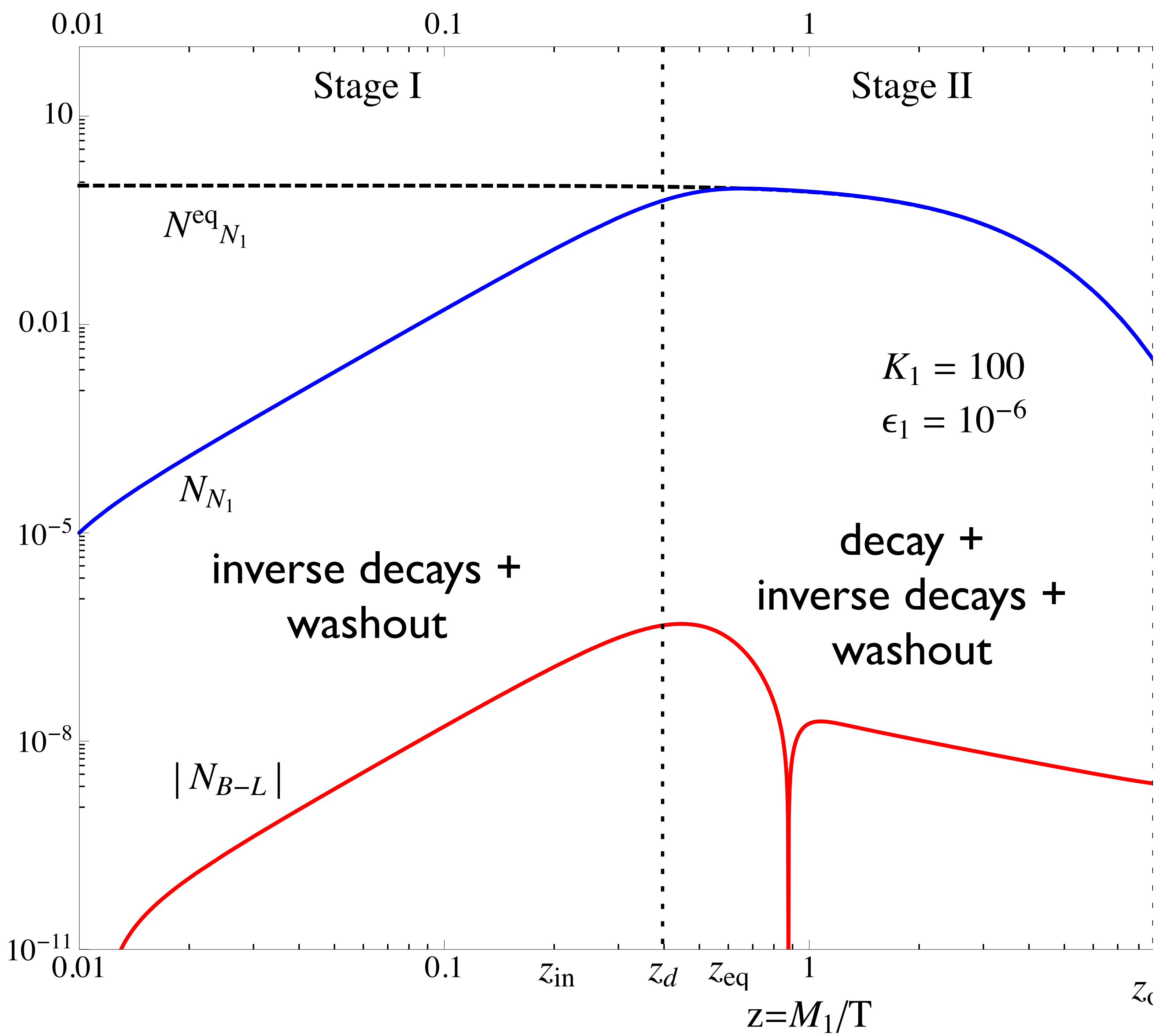

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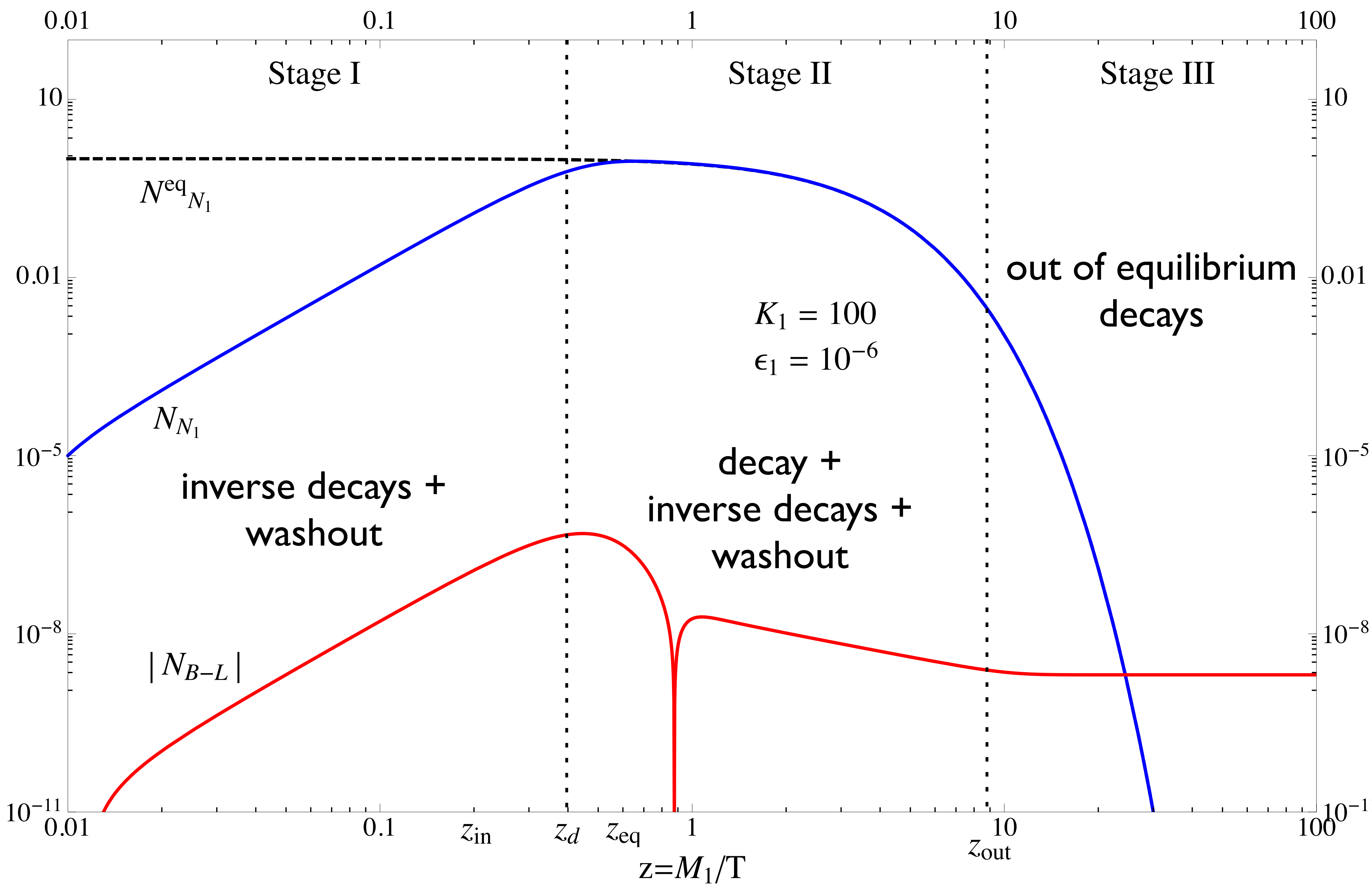

- Flavour effects complicate the picture

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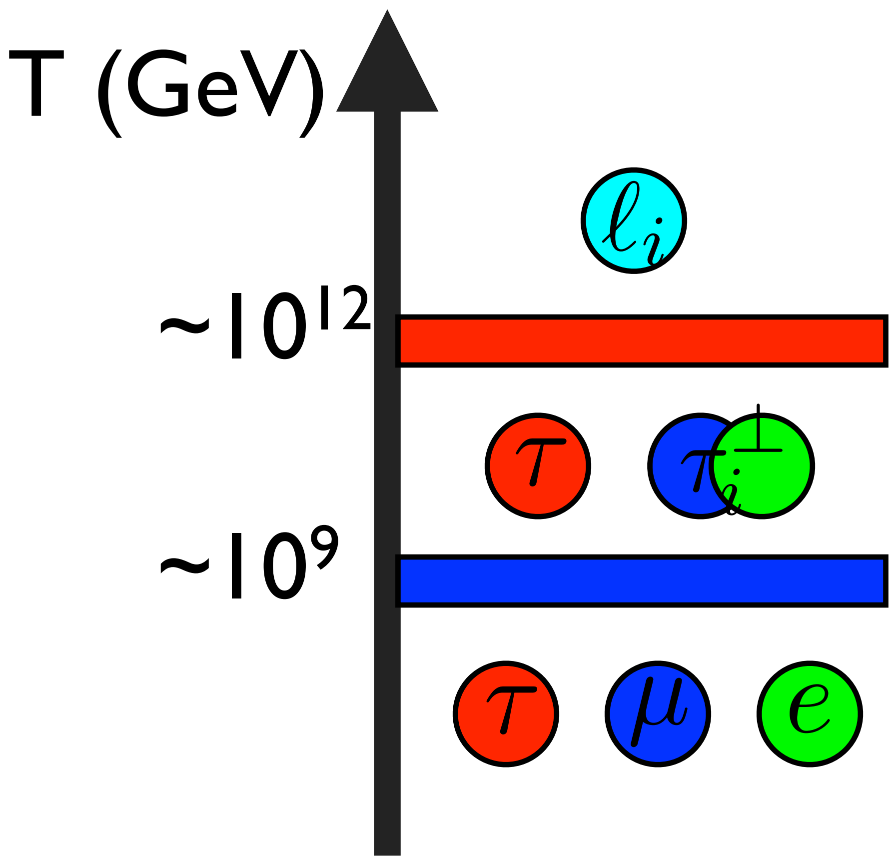

regime name:	*physical asymmetries:*
heavy flavour regime	N_{Δ_i}
two-flavour regime	$N_{\Delta\tau}\,;\,N_{\Delta\tau_i^\perp}$
three-flavour regime	$N_{\Delta e}\,;N_{\Delta\mu}\,;N_{\Delta\tau}$

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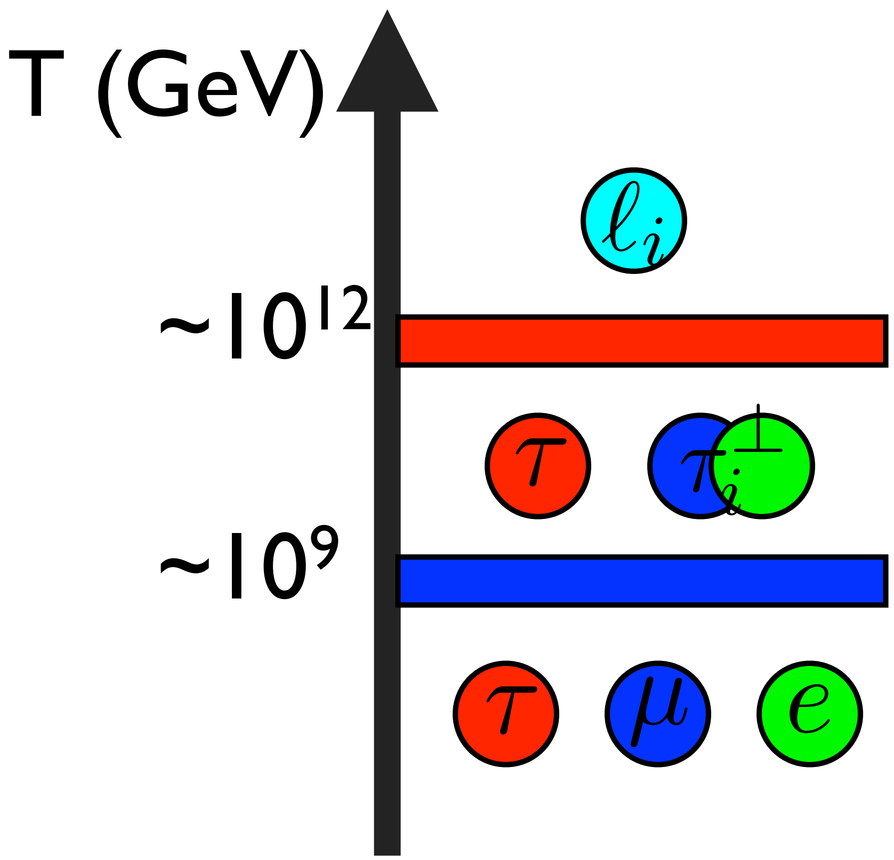

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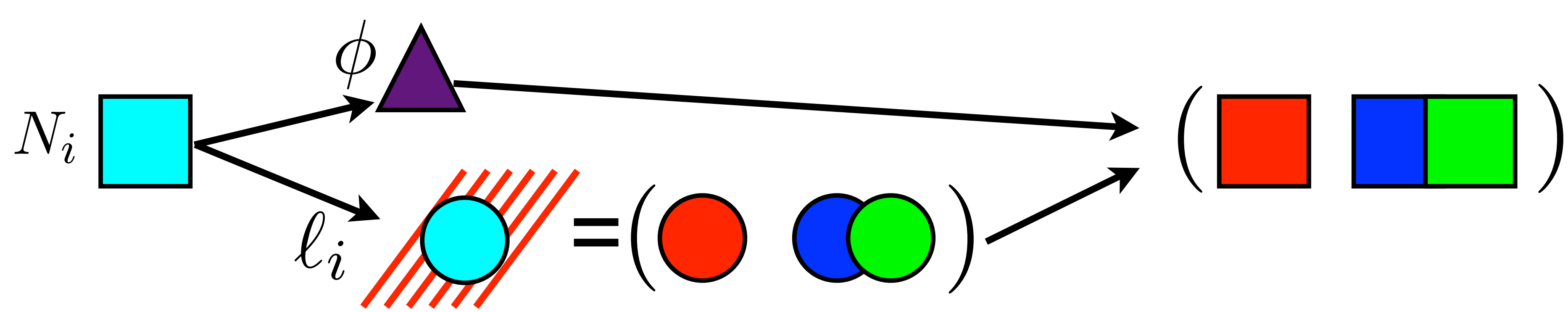
–Decoherence effects (an abstract depiction of):

for T~M_i:



SO(10)-inspired framework

- The model introduces 18 new parameters, can it be predictive?

Shift the parametrization as follows:

$$15 + 3 \rightarrow 6 + 3 + 6 + 3$$

$$h_{\alpha i}, M_i \rightarrow U, m_i, V_L, m_{Di}$$

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neutrino oscillation experiments
(info on mixing angles in U and mass splittings)

P. Di Bari, A. Riotto, 2008

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$$M_3 > 10^{12}\ \mathrm{GeV} > M_2 > 10^{9}\ \mathrm{GeV} \gg M_1$$

  - Leptogenesis is dominated by the dynamics of N_2
  - The B-L asymmetry evolves through a sequence of separated stages each described by a set of flavoured Boltzmann equations.

S. Blanchet, P. Di Bari, D.A. Jones, LM, 2013

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we can constrain the parameter space of the model by requiring $\eta_B^{lept} \approx \eta_B^0$

But which initial conditions?

- An 'ethical' problem: unknown initial conditions

Remarkably, 10^{-9} is a natural value for η_B^{lept}. However, we cannot neglect the impact of a possible preexisting B-L asymmetry ($N_{B-L}^{preex,0} \sim \mathcal{O}(1)$?) as it also would contribute into the measured baryon asymmetry:

$$\eta_B^0 \approx 10^{-2} \left(N_{B-L}^{lept,f} + N_{B-L}^{preex,f} \right) \gg 10^{-9}$$

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how to safely impose $\eta_B^{lept} \approx \eta_B^0$ *and constrain the SO(10)-inspired model?*

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$\longrightarrow$ Solution: require *strong thermal leptogenesis*

$$\eta_B^0 \approx 10^{-2} \left(N_{B-L}^{lept,f} + \cancel{N_{B-L}^{preex,f}} \right) \approx 10^{-9} \iff \text{Strong thermal Leptogenesis}$$

E. Bertuzzo, P. Di Bari, LM, 2011

as a result:

- leptogenesis is independent of its (unknown) initial conditions
- imposing $\eta_B^{lept} \approx \eta_B^0$ indeed constrains the model

The evolution of N_{B-L}^{preex}

- N_1 leptogenesis (no flavour effects)

$$\frac{dN_{B-L}^{preex}}{dz} = -W_1 N_{B-L}^{preex} \quad \Longrightarrow \quad N_{B-L}^{preex,f} = N_{B-L}^{preex} e^{-\frac{3\pi}{8}K_1}$$

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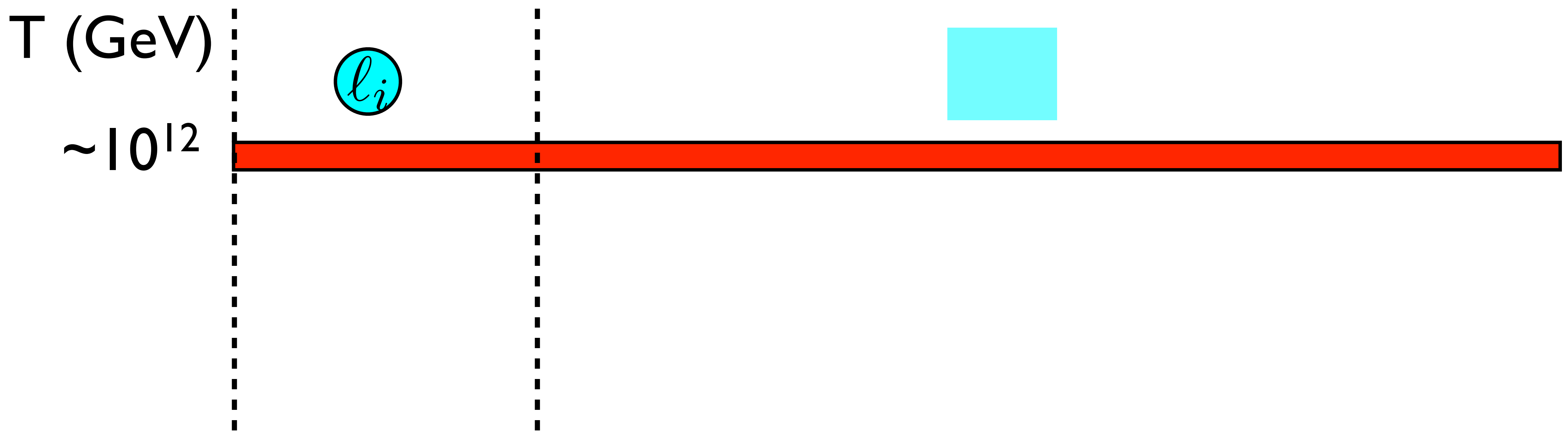

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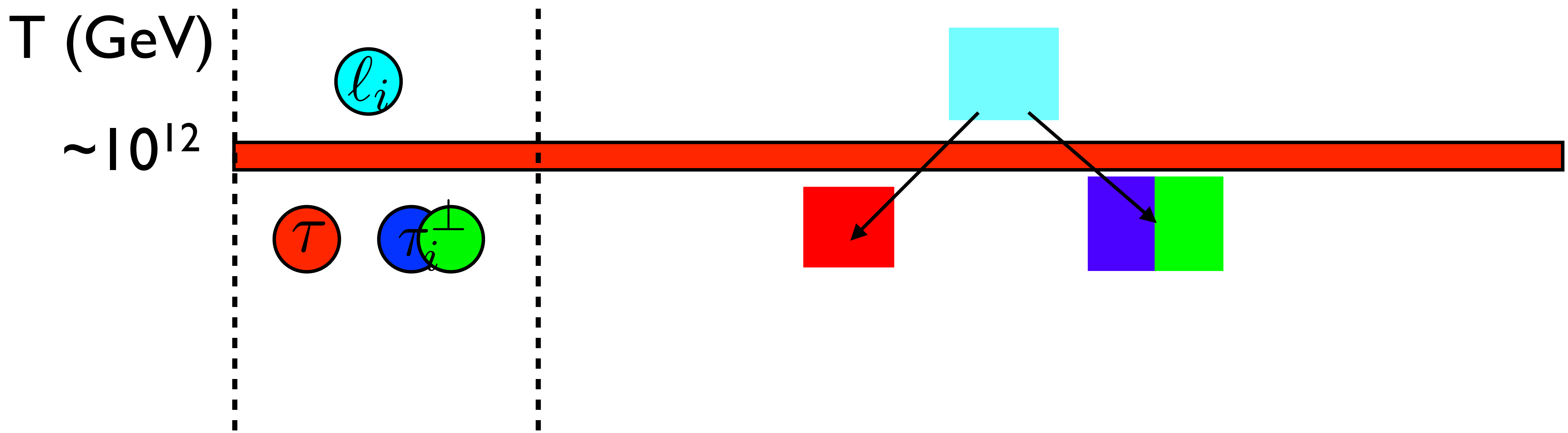

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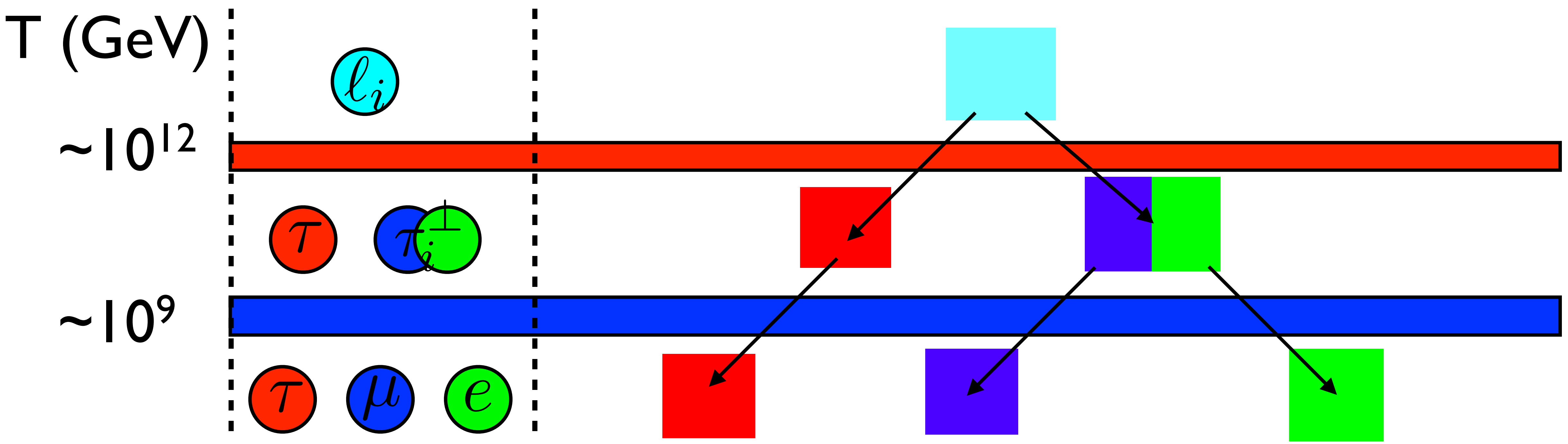
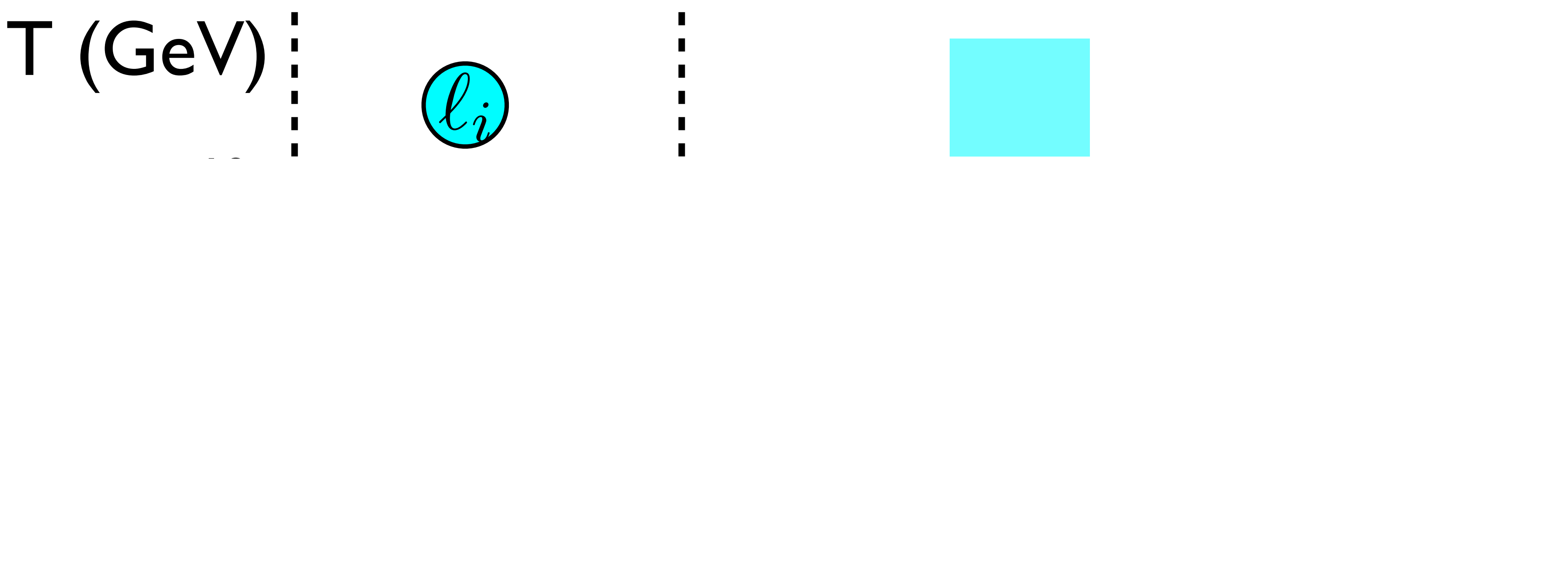


No simple criterion ensures a complete washout. Importance of the heavy neutrinos mass spectrum which selects which regimes are encountered.

The only possible solution



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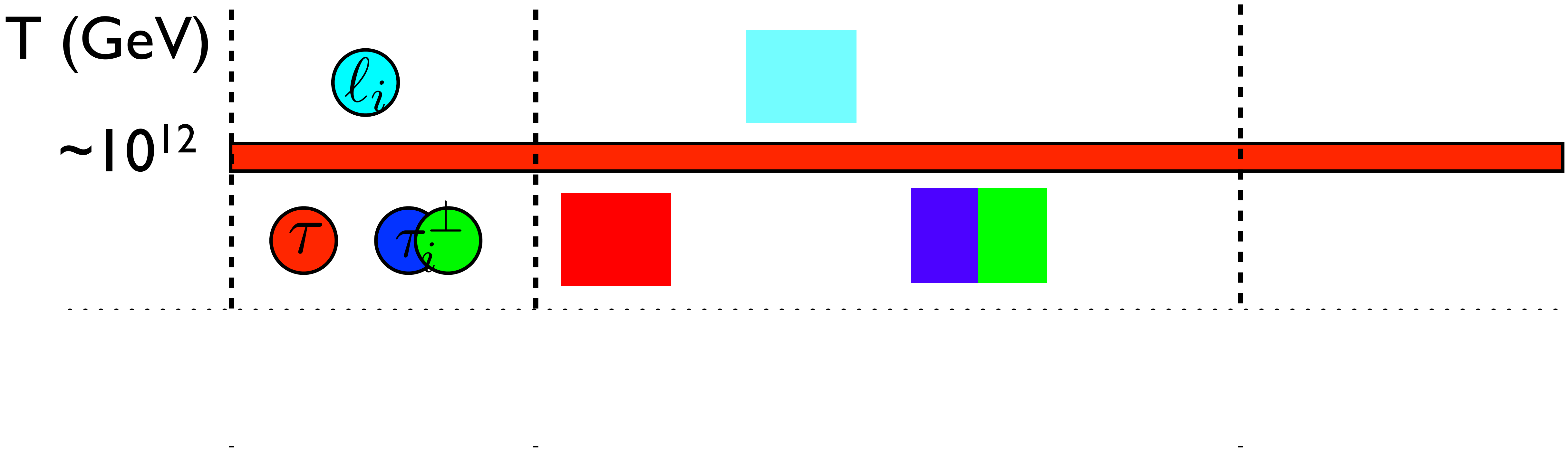

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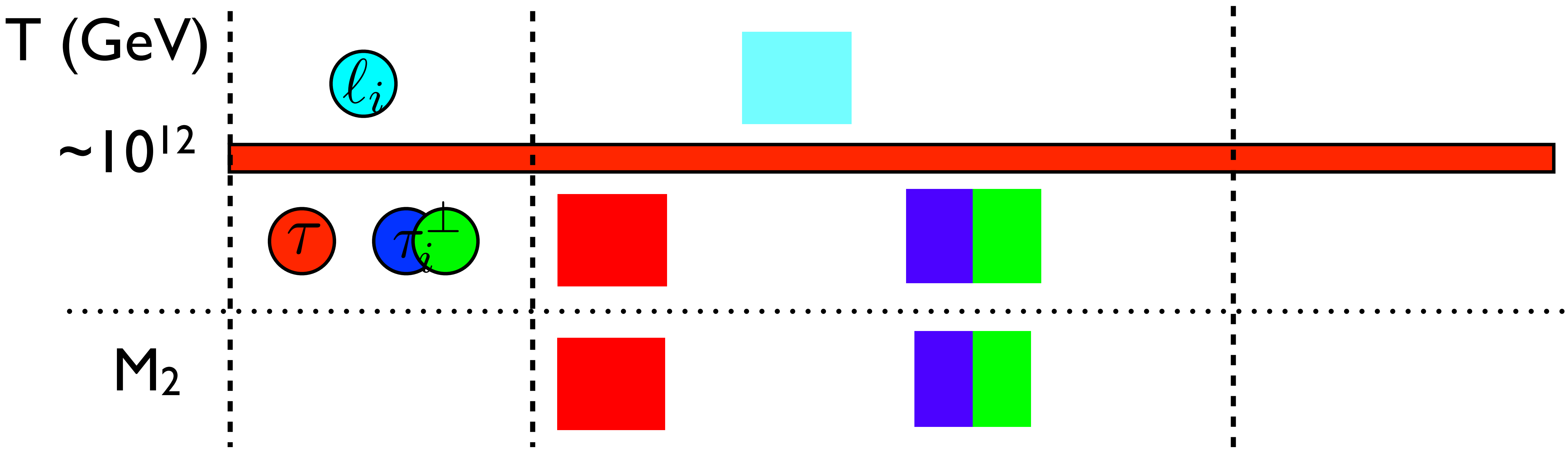

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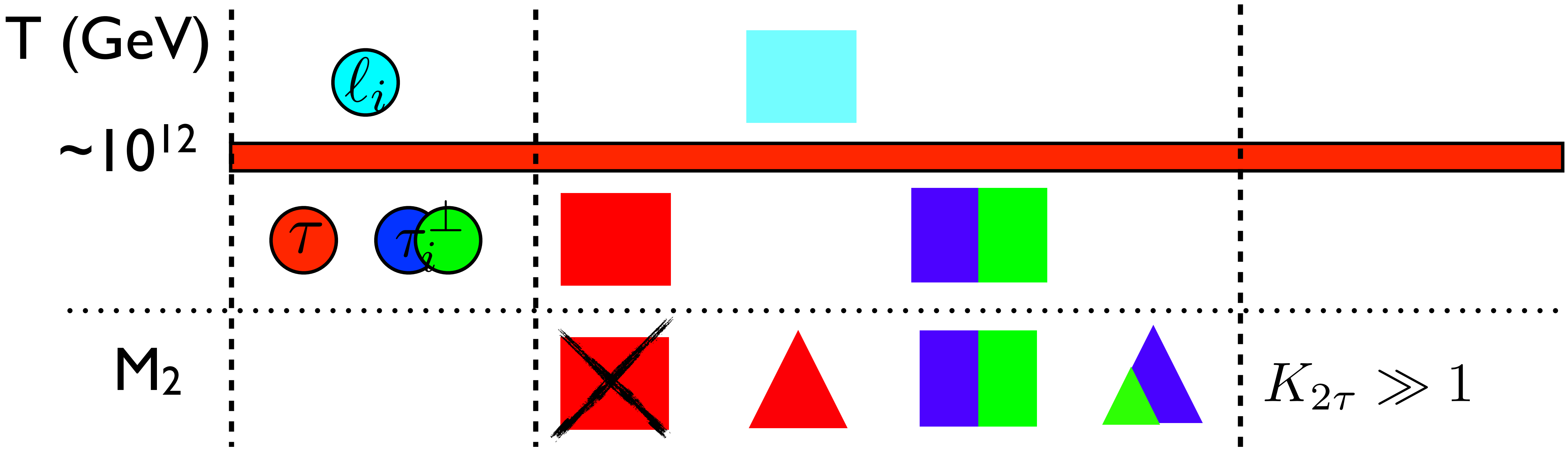

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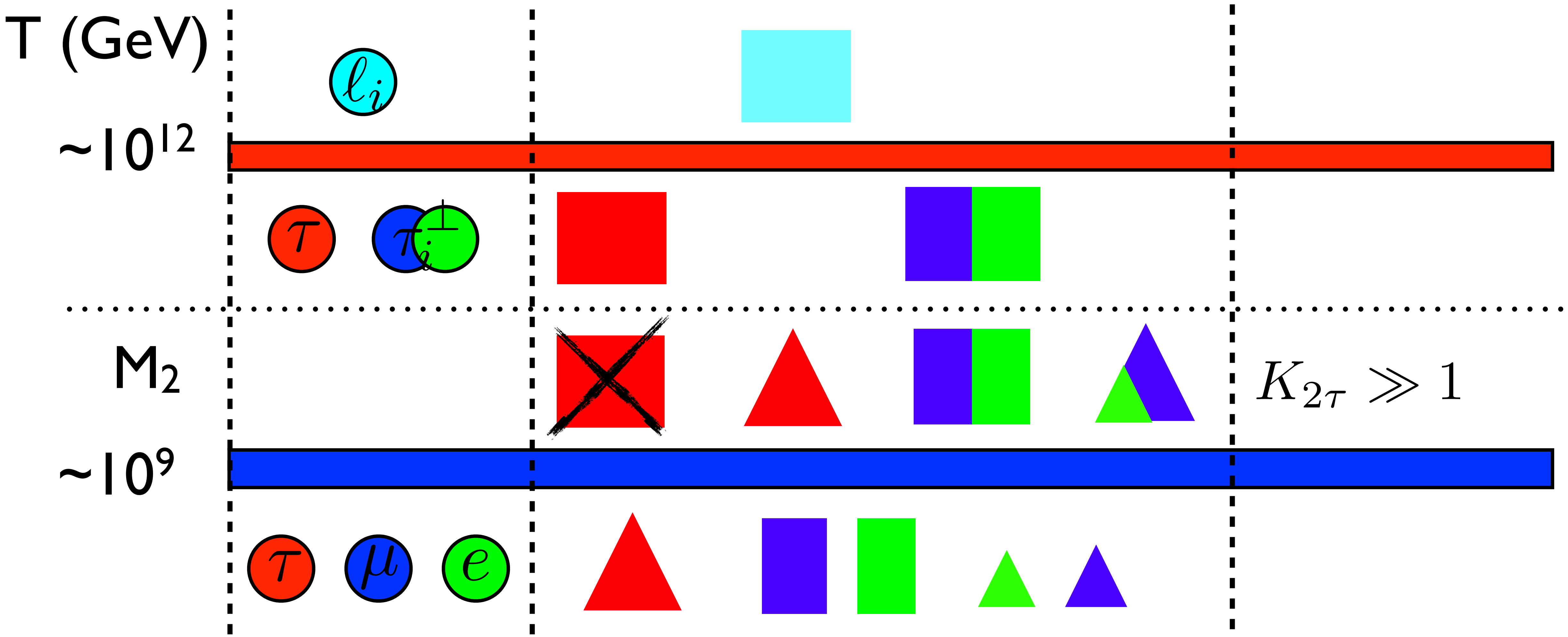

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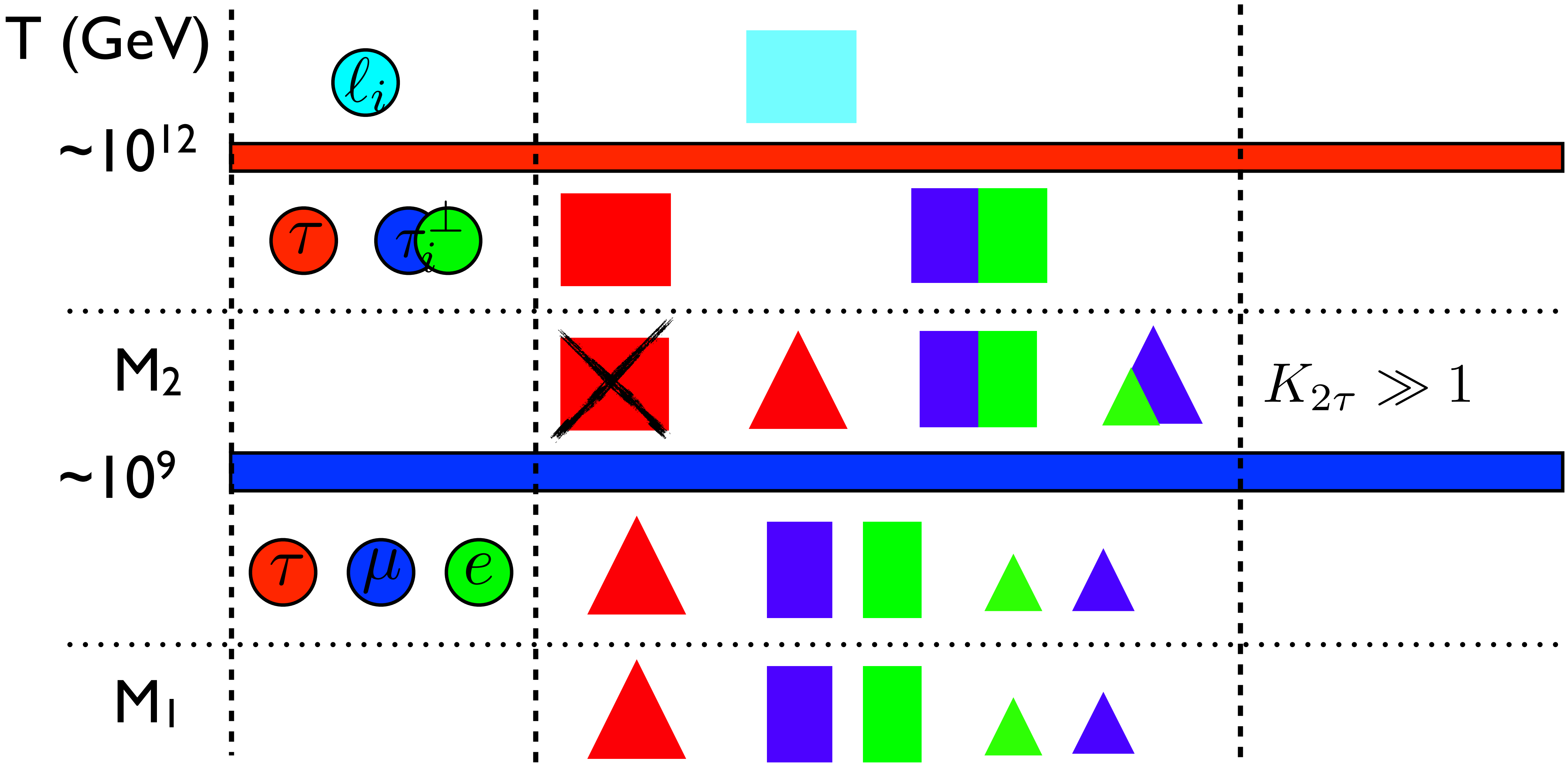

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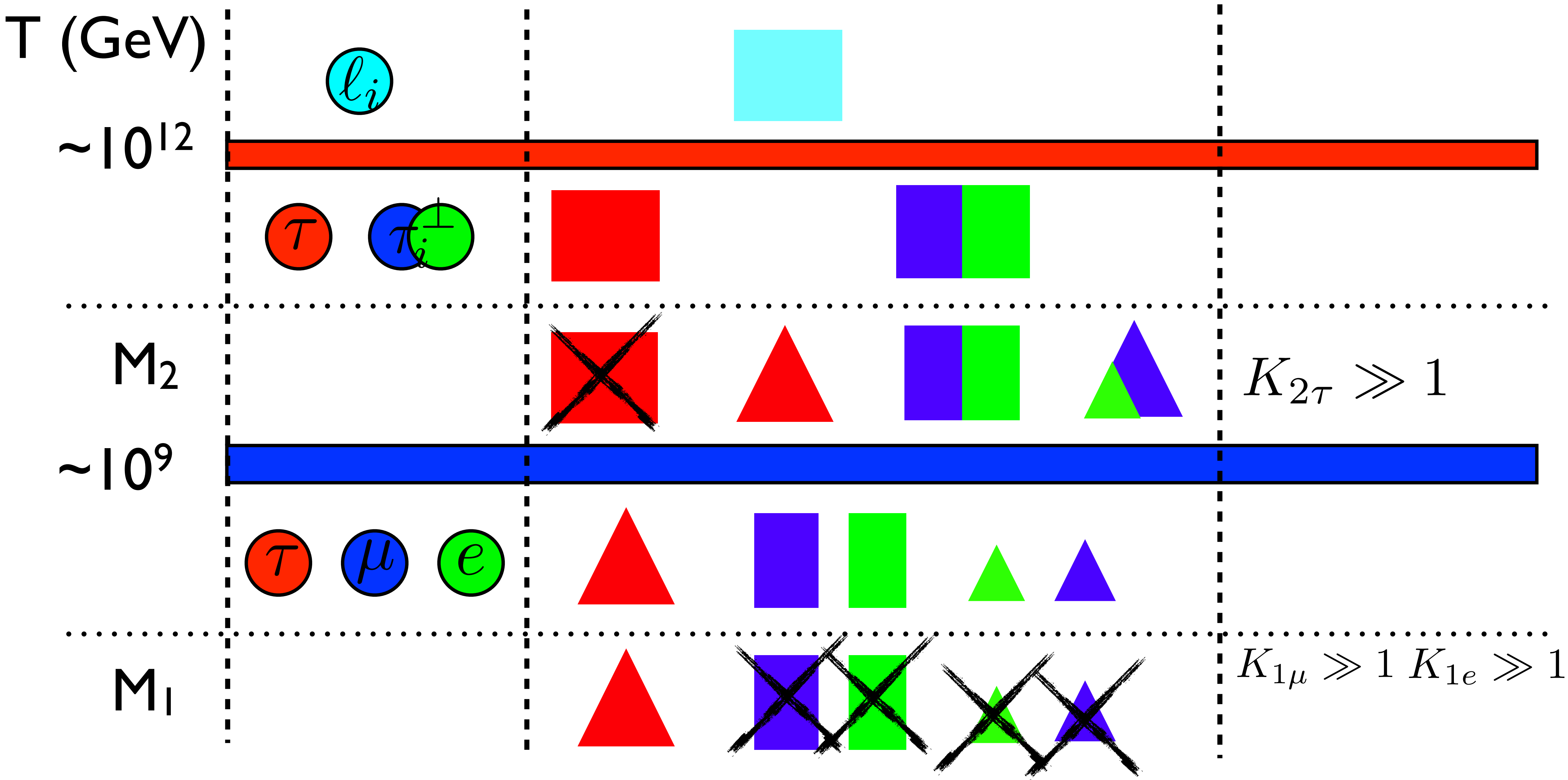

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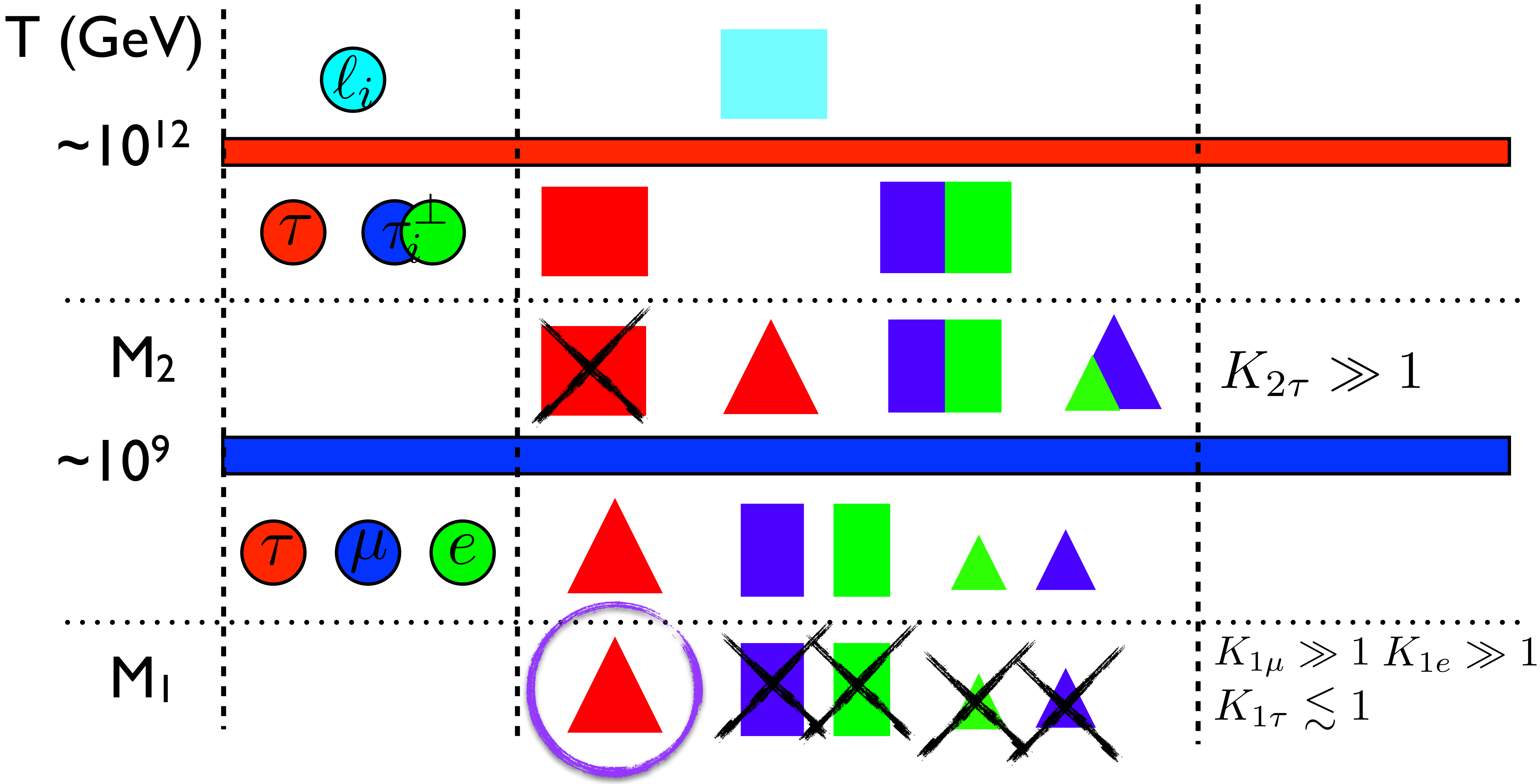

The conditions on the decay efficiency parameter and the implied mass spectrum define *the τ-N_2 dominated scenario.*

A remarkable feature:

- Due to *flavour effects*, strong thermal Leptogenesis requires non trivial conditions on key parameters that regulate the dynamics of the Leptogenesis process.

E. Bertuzzo, P. Di Bari & LM, 2011

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⟶ It is remarkable that within the SO(10)-inspired model *successful strong thermal Leptogenesis can be achieved!*

⟶ It is even more remarkable that *adopting these strong thermal Leptogenesis solutions results in sharp predictions that the SO(10)-inspired model casts on all the low energy neutrino parameters*

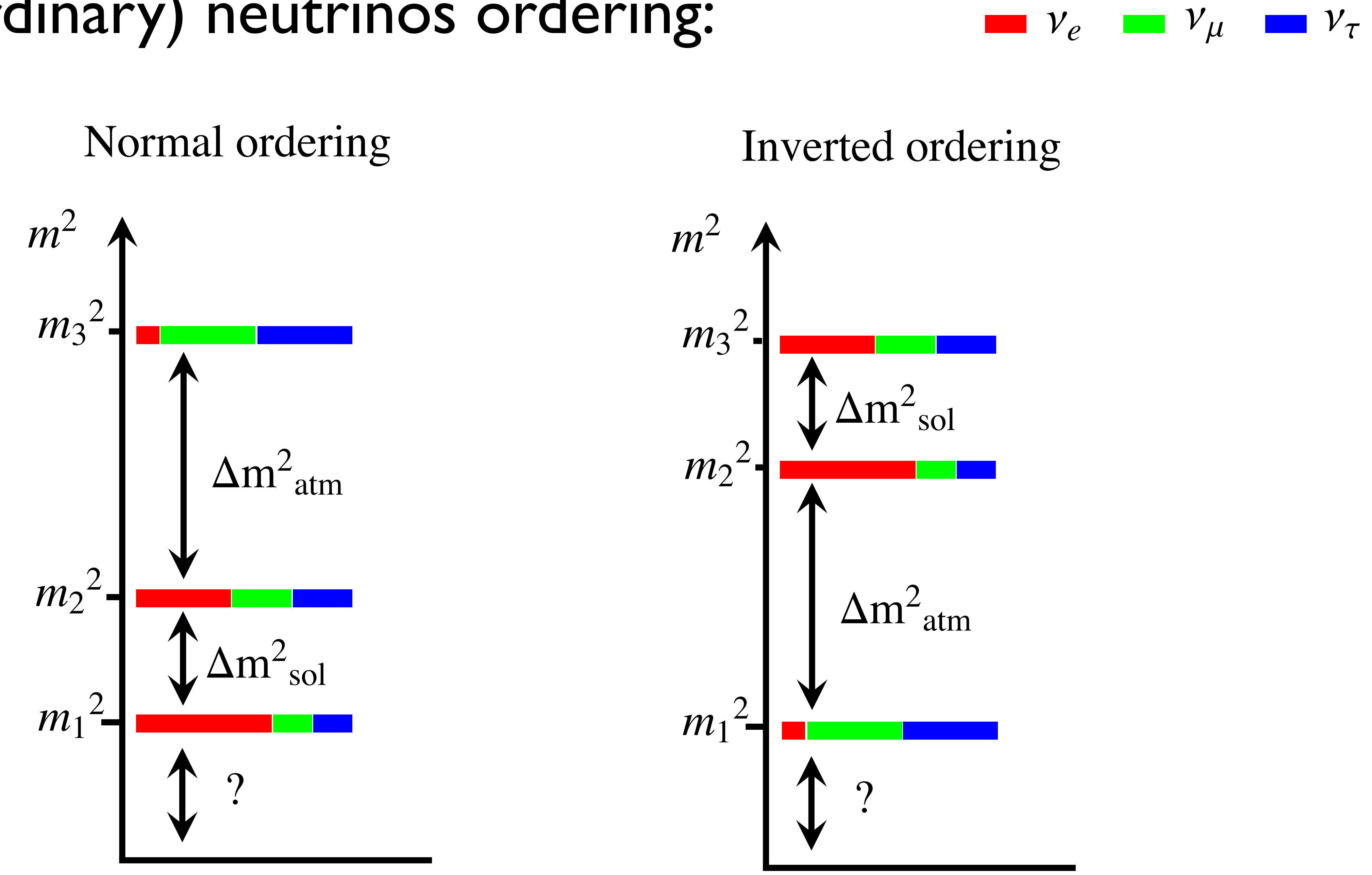
Predictions from:

SO(10)-inspired model

+

strong thermal leptogenesis

- Light (i.e. ordinary) neutrinos ordering:



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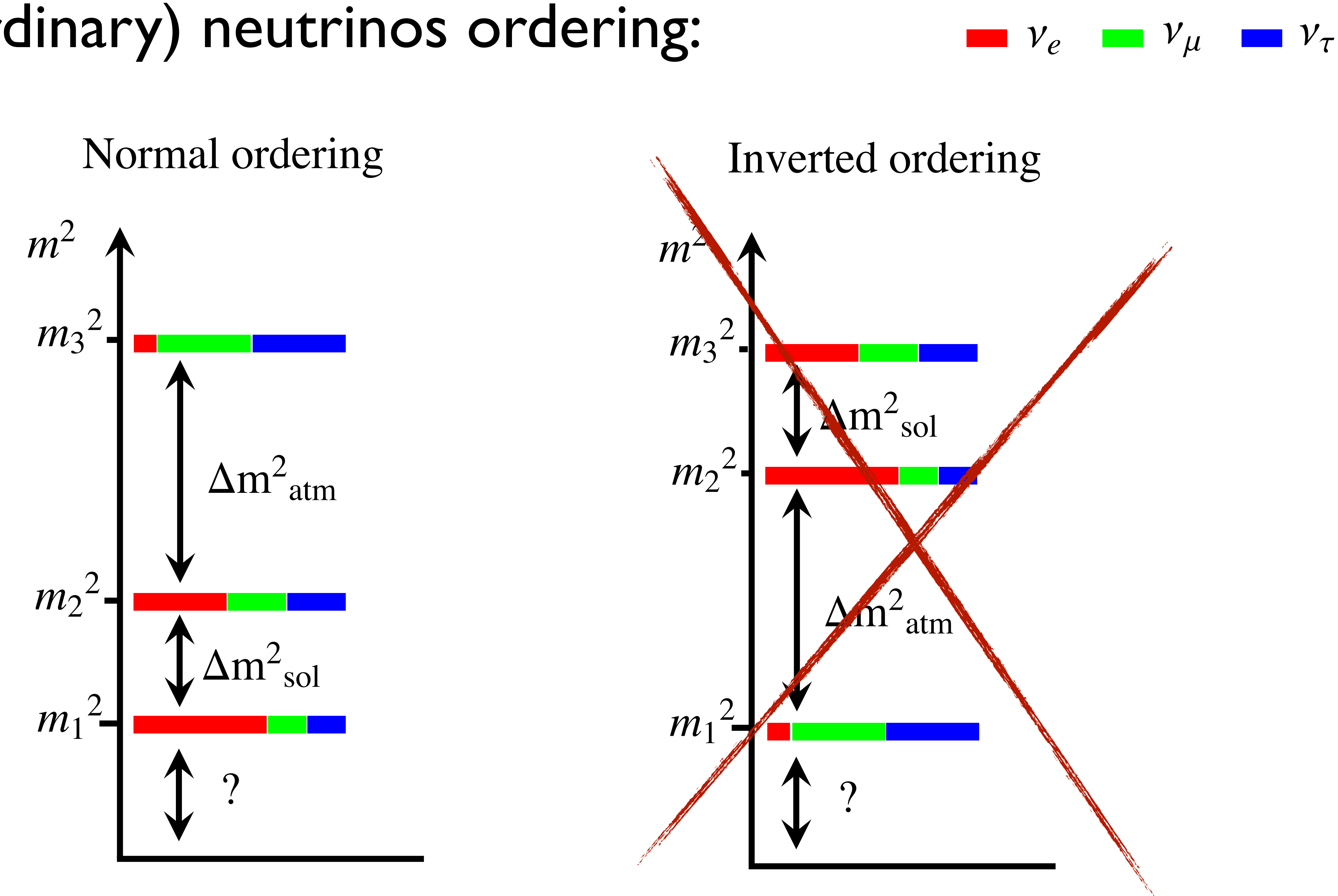


Strong SO(10)-inspired leptogenesis solutions *exclude inverted ordering* as no strong thermal solution is found in this setup

In the following plots:

- yellow regions represent successful Leptogenesis solutions:

$$N_{B-L}^{lept,f} \approx 10^{-7} \longrightarrow \eta_B^{lept} \approx \eta_B^0$$

- other colours quantify the 'strength' of the strong thermal solutions:

$$N_{B-L}^{preex,0} = 10^{-3}, 10^{-2}, 10^{-1} \longrightarrow N_{B-L}^{preex,f} < 10^{-8}$$

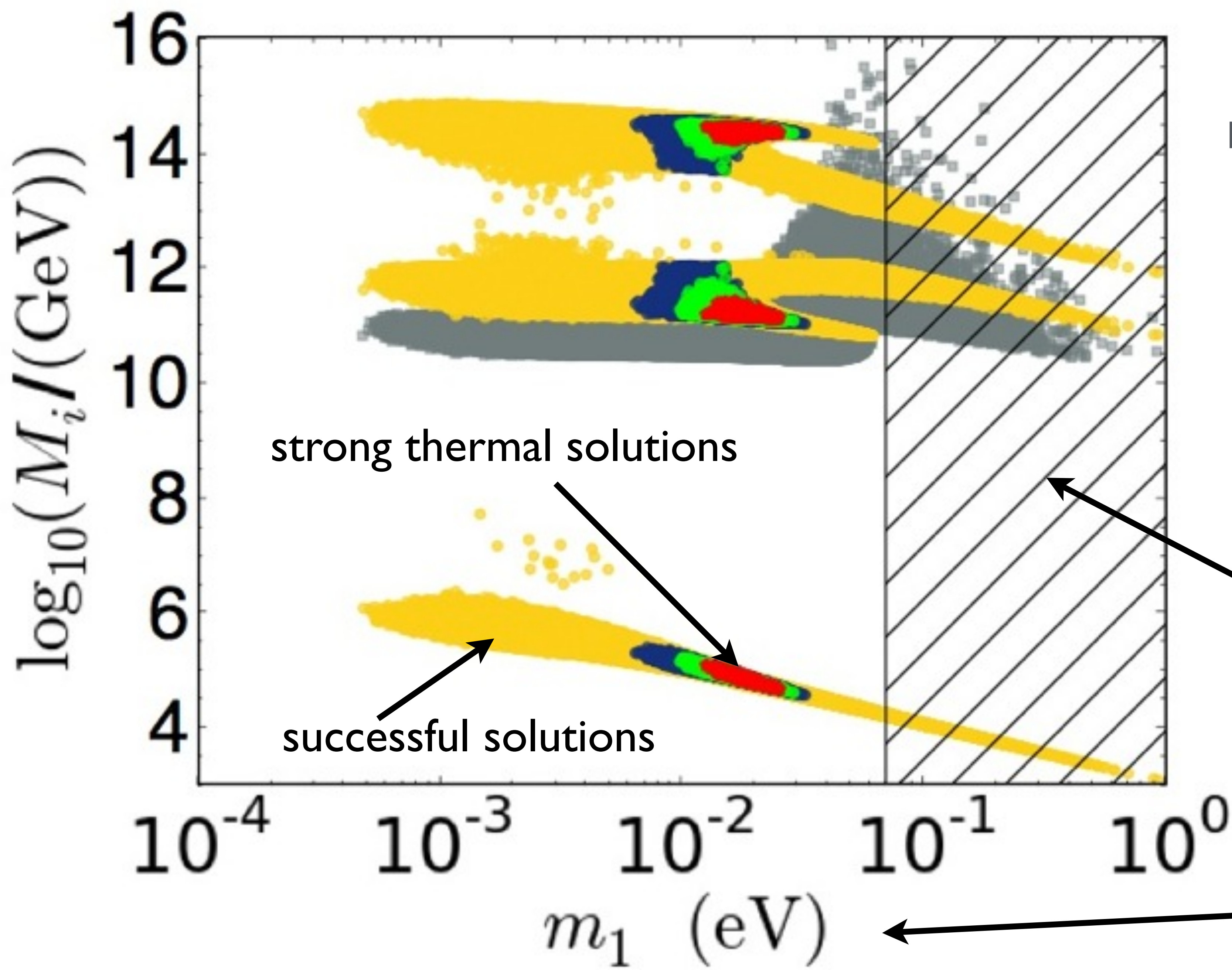
(N.B: strong thermal solutions are also successful solutions)

…and of course everything applies exclusively to normal ordering

- Heavy neutrino mass spectrum:

$$N_{B-L}^{preex,0} = 0,\ 10^{-3},\ 10^{-2},\ 10^{-1}$$

$$N_{B-L}^{preex,f} < 10^{-8}$$



Hierarchical mass spectrum of N_2-dominated scenarios, as required by the strong thermal leptogenesis conditions

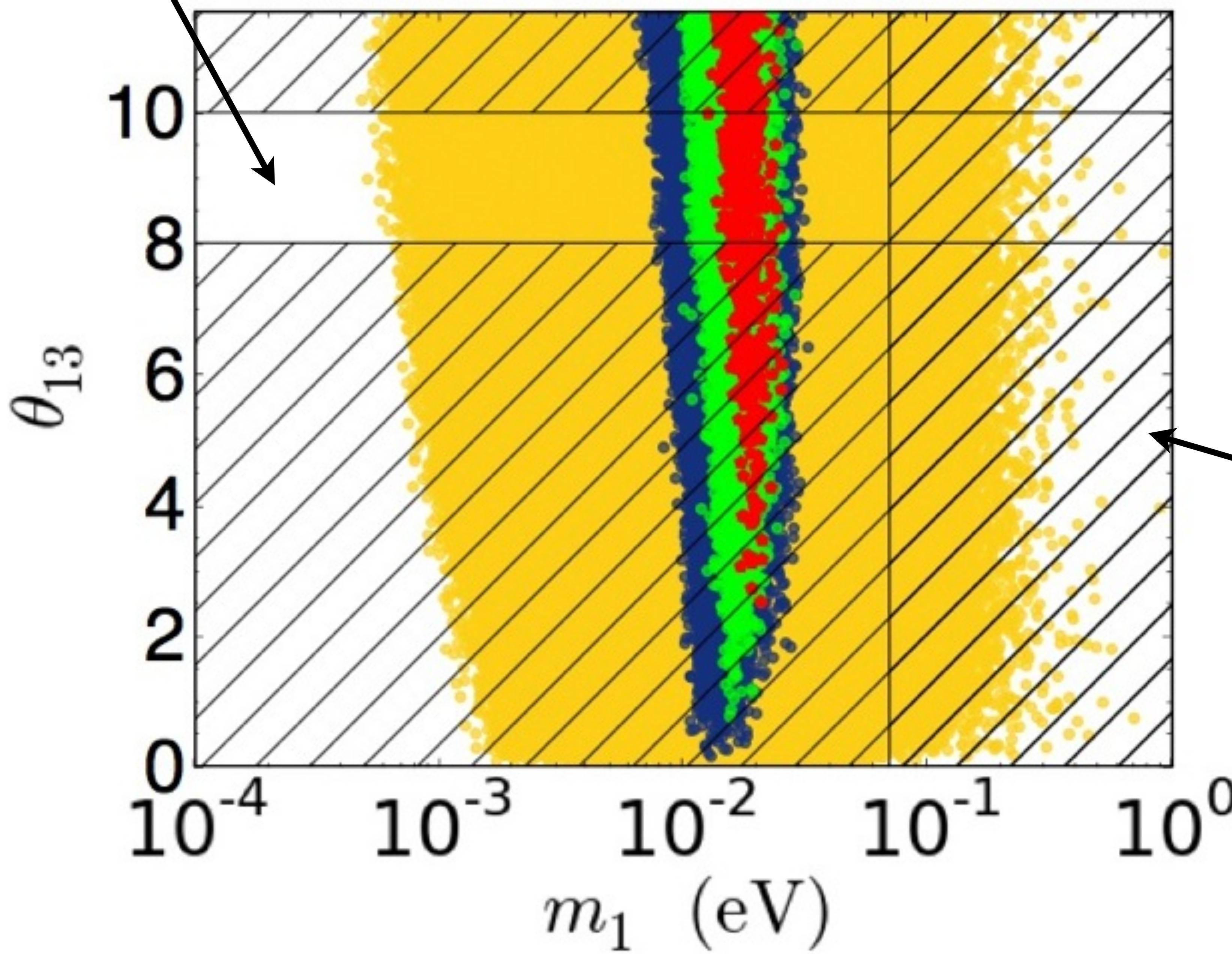
$$N_{B-L}^{preex,0} = 0, 10^{-3}, 10^{-2}, 10^{-1}$$

$$N_{B-L}^{preex,f} < 10^{-8}$$

- Reactor mixing angle θ_{13}

current 2σ range

F. Capozzi et al. 2013
M.C. Gonzalez-Garcia et al, 2012



excluded by cosmology

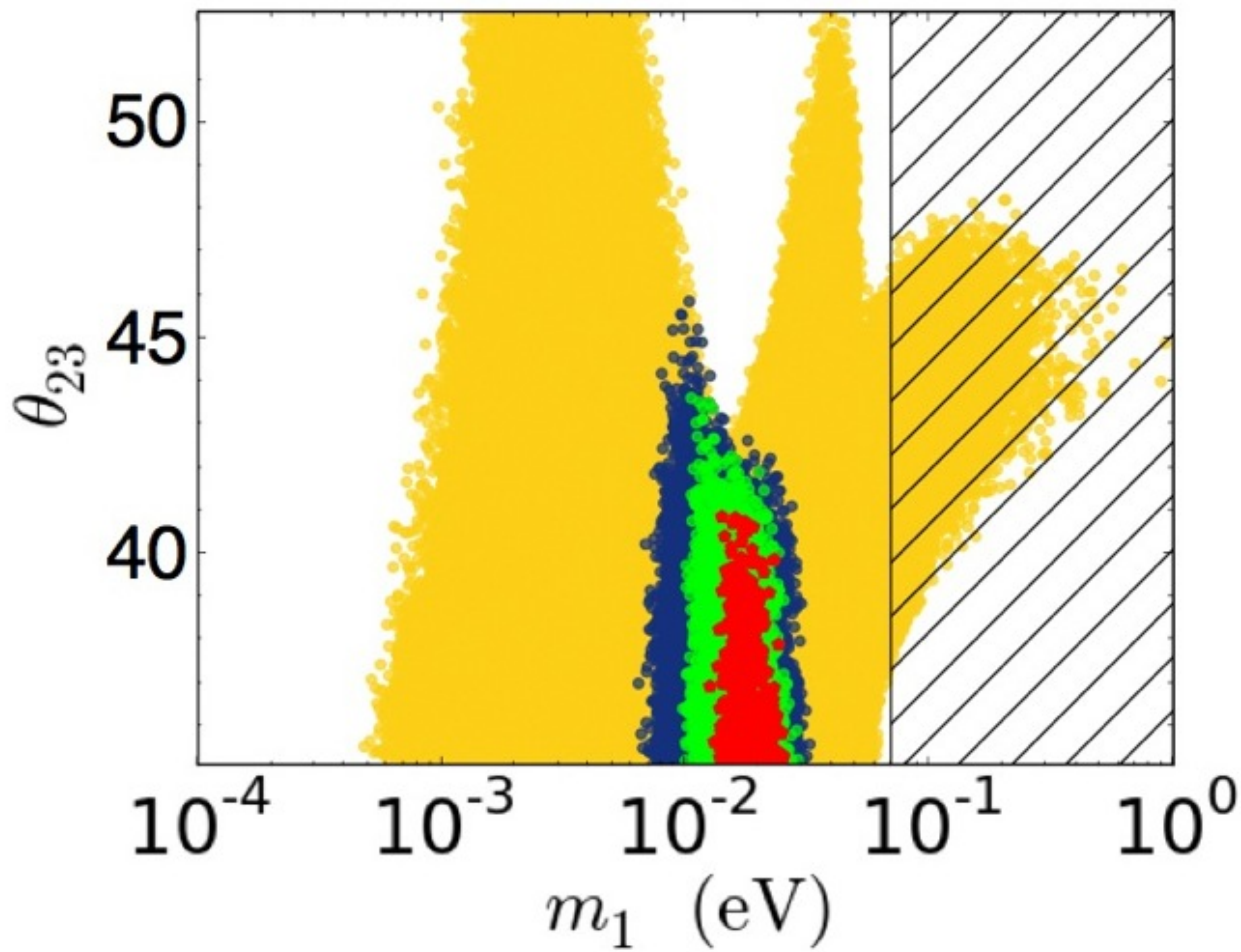
Planck collaboration, 2013

The strong SO(10)-inspired solutions point to *large values of the reactor mixing angle* (lower bound θ_{13}>2°).

- Atmospheric mixing angle θ_{23}

$N_{B-L}^{preex,0} =$ 0, 10^{-3}, 10^{-2}, 10^{-1}

$N_{B-L}^{preex,f} < 10^{-8}$



Large values of the atmospheric mixing angle are excluded.

Sharp upper bound $\theta_{23} \gtrsim 45^{o}$ gives a clear prediction on the octant.

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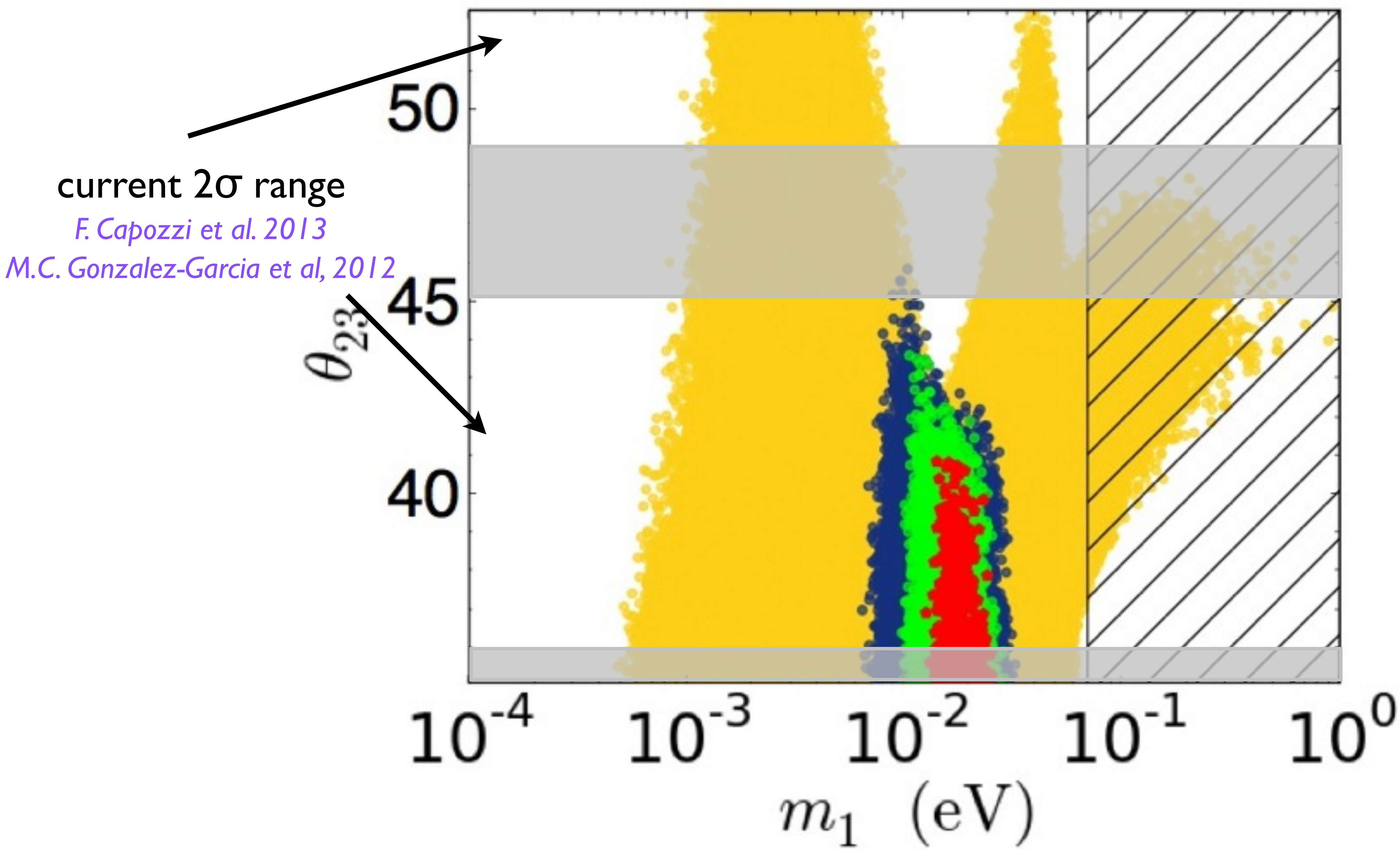
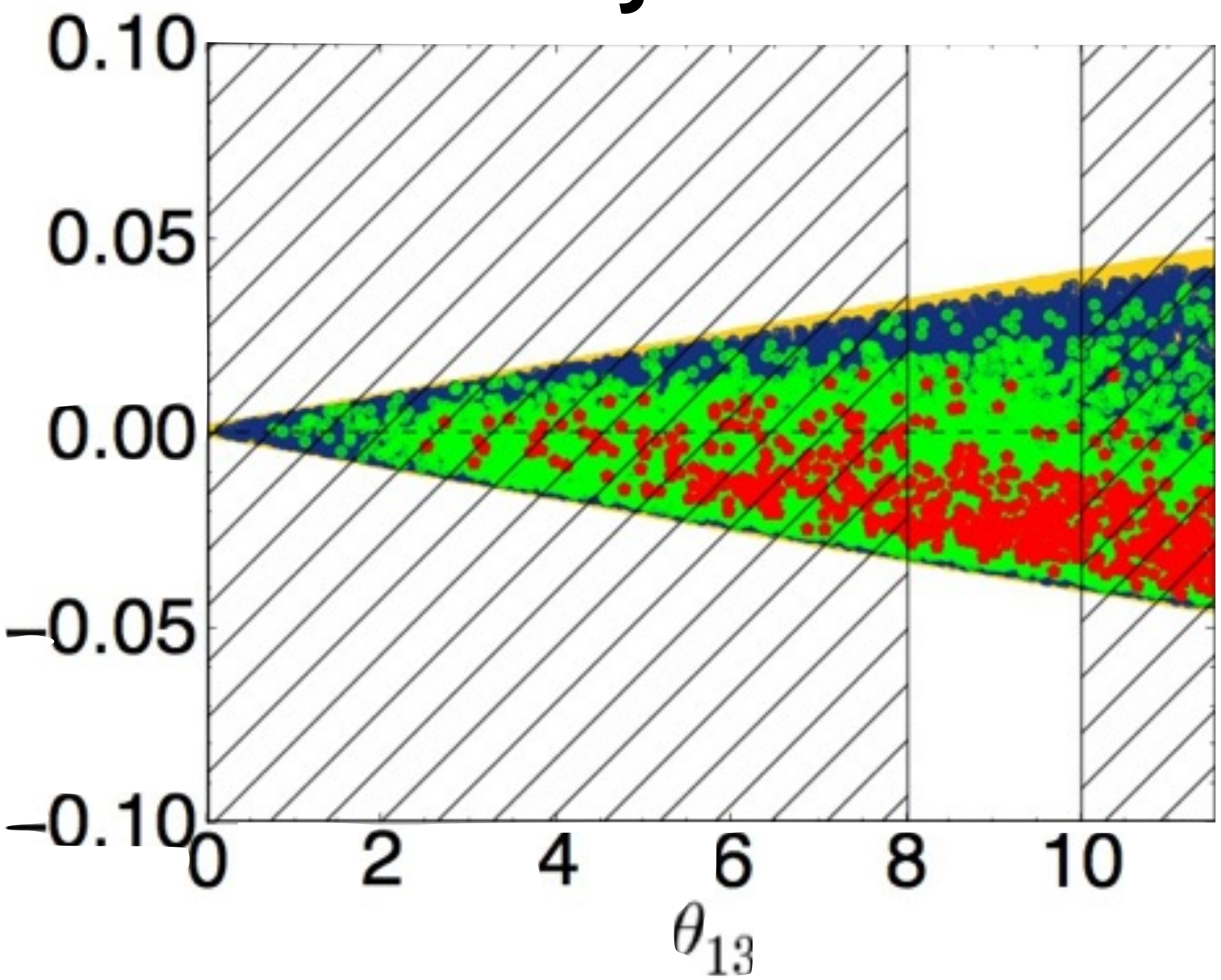
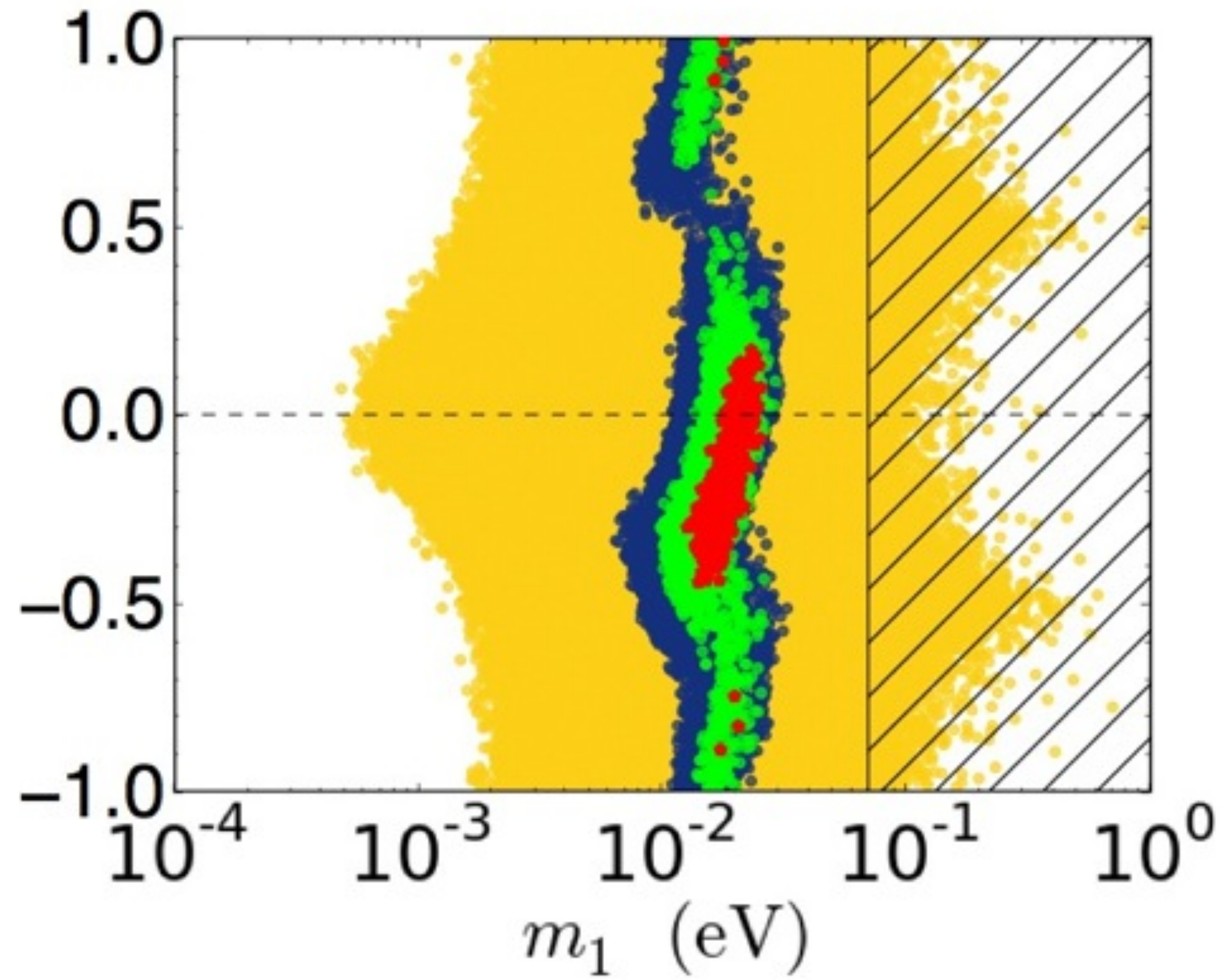


Large values of the atmospheric mixing angle are excluded.

Sharp upper bound $\theta_{23} \lessapprox 45^{\circ}$ gives a clear prediction on the octant.

- The Dirac phase and the Jarlskog invariant





Net preference for δ<0, favourite by recent global analyses for $\theta_{23} \approx 45^o$

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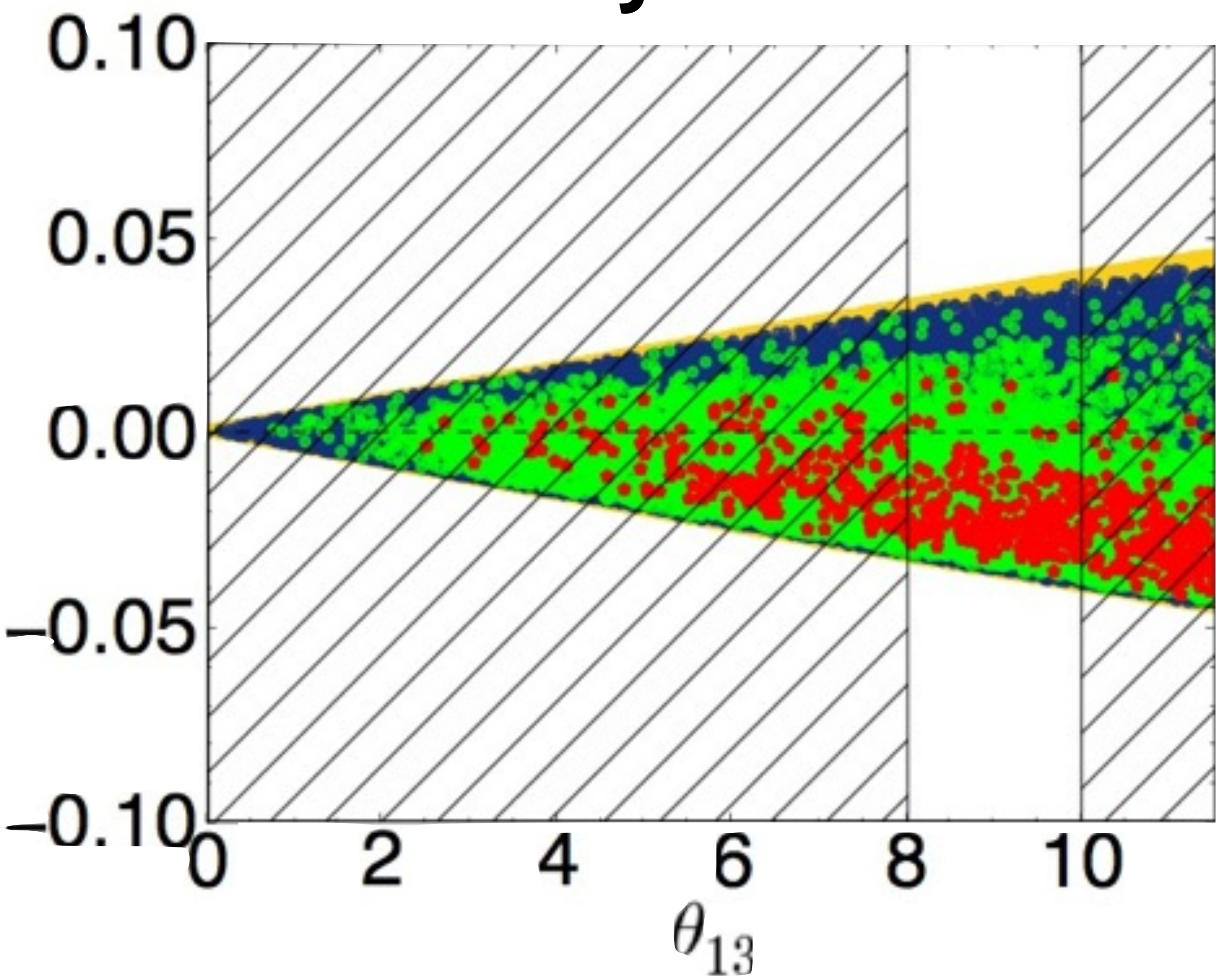
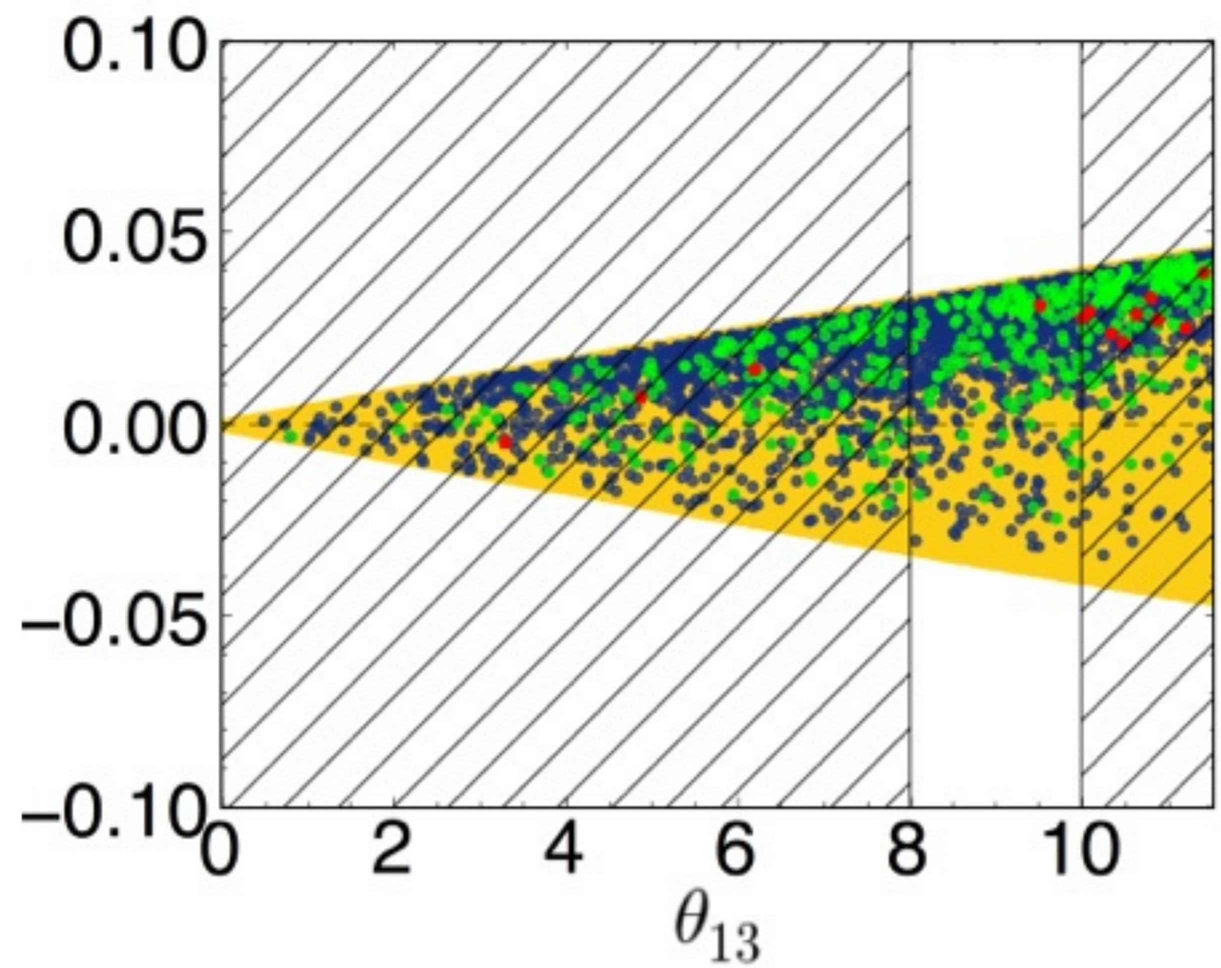
F. Capozzi et al. 2013
M.C. Gonzalez-Garcia et al, 2012

- The Dirac phase and the Jarlskog invariant

J_{CP}



$\eta_B^0 \to -\eta_B^0$



Net preference for δ<0, favourite by recent global analyses for θ_{23}≳45°

F. Capozzi et al. 2013
M.C. Gonzalez-Garcia et al, 2012

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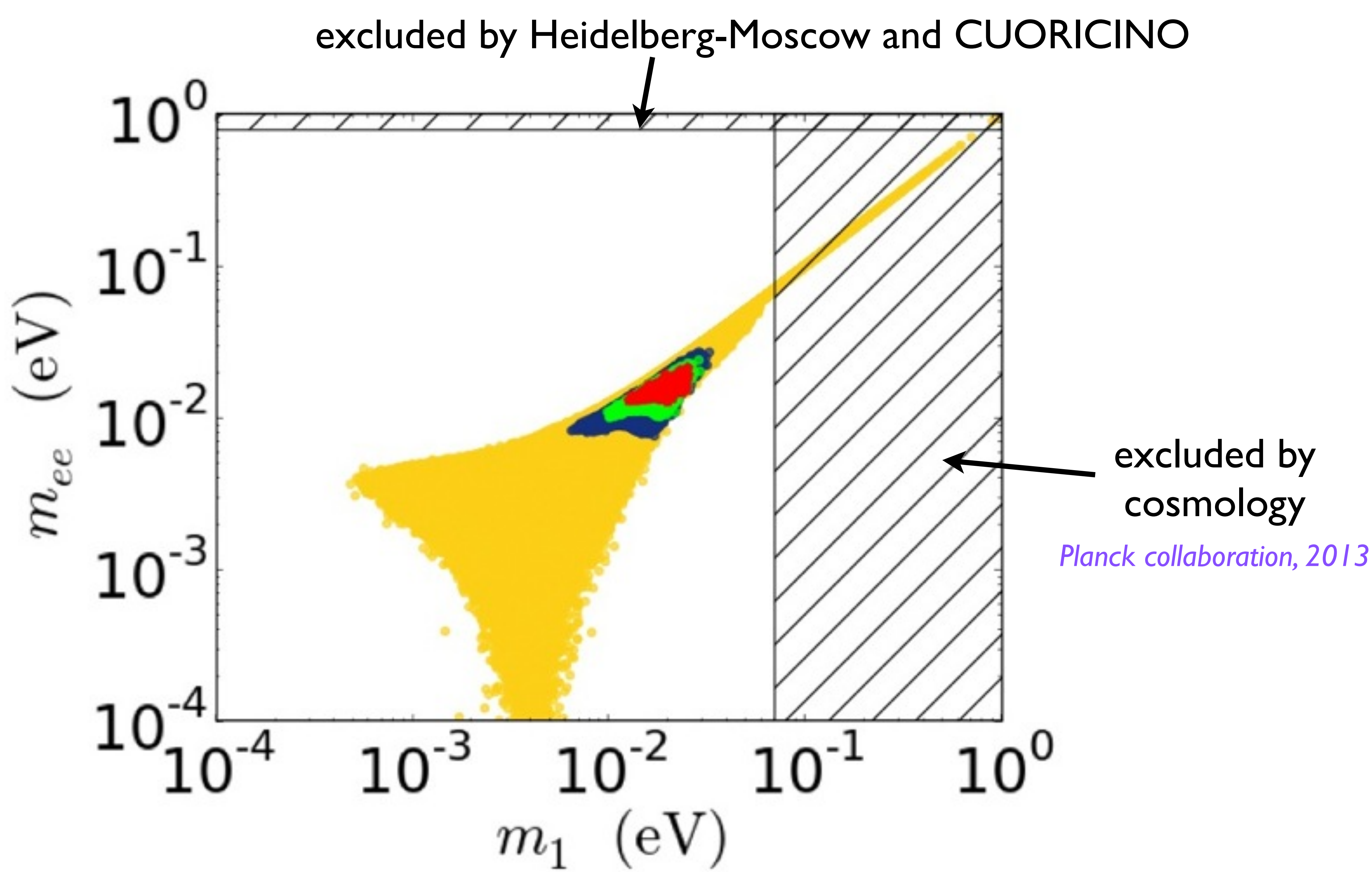
- *The signature*: light neutrino mass scales



Sharp predictions: $m_1 \simeq 10^{-2}$ eV $\quad m_{ee} \simeq 10^{-2}$ eV

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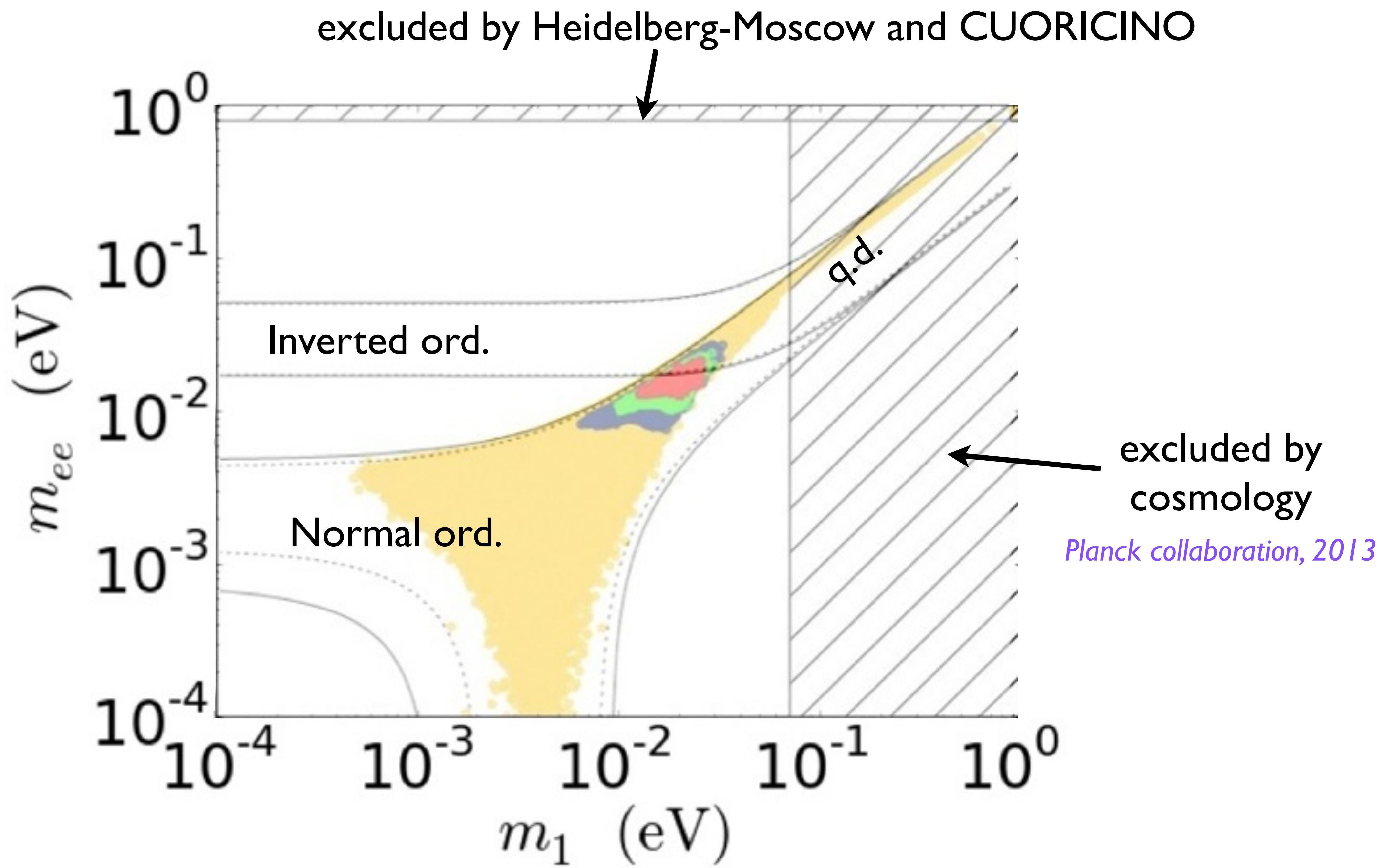

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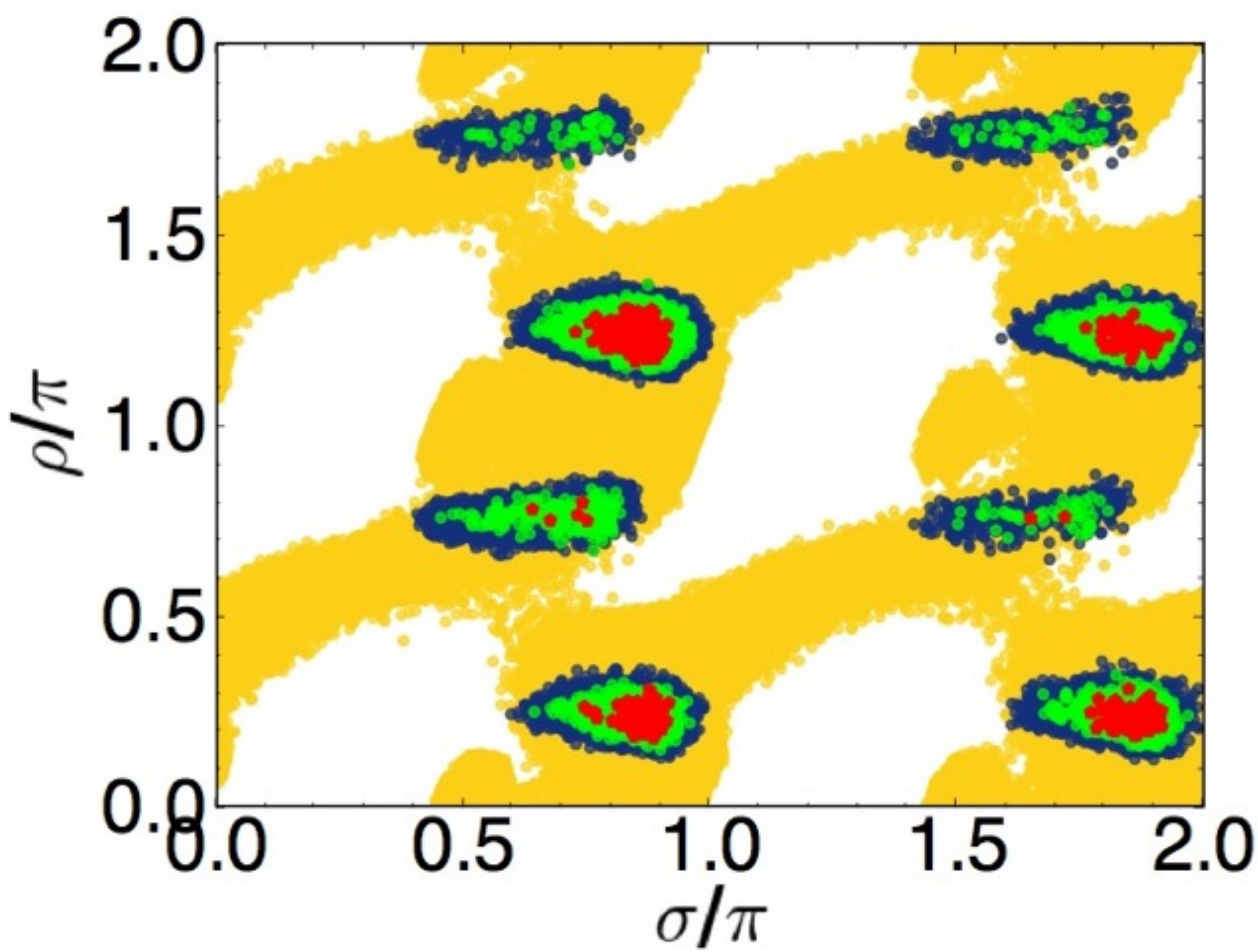
- Majorana phases



The Majorana phases are very constrained, explaining the trend

$m_{ee} \approx m_1$

Summary:

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- *Leptogenesis* is an attractive scenario that potentially *can explain the Baryon Asymmetry of the Universe and the origin of neutrino mass*
- What will happen if *strong thermal SO(10)-inspired solutions* are correct:

time

$N_{B-L}^{\rm p,i}$	10^{-1}	10^{-2}
θ_{13}	$\gtrsim 2^\circ$	$\gtrsim 0.5^\circ$
θ_{23}	$\lesssim 41^\circ$	$\lesssim 43^\circ$
ORDERING	NORMAL	NORMAL
δ	$-\pi/2 \div \pi/5$ $\simeq \pi$ (marginal, only for $\theta_{23} \lesssim 36^\circ$)	$\notin [0.4\,\pi, 0.7\,\pi]$
m_1	$(15 \div 25)$ meV	$(10 \div 30)$ meV
m_{ee}	$\simeq 0.8\, m_1 \simeq (12 \div 20)$ meV	$(8 \div 24)$ meV

✓ T2K, Daya Bay 2012

?? PINGU, T2K, NOvA

Cosmology ?

next^2 generation of $0\nu\beta\beta$ experiments

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- What happens if they are wrong:

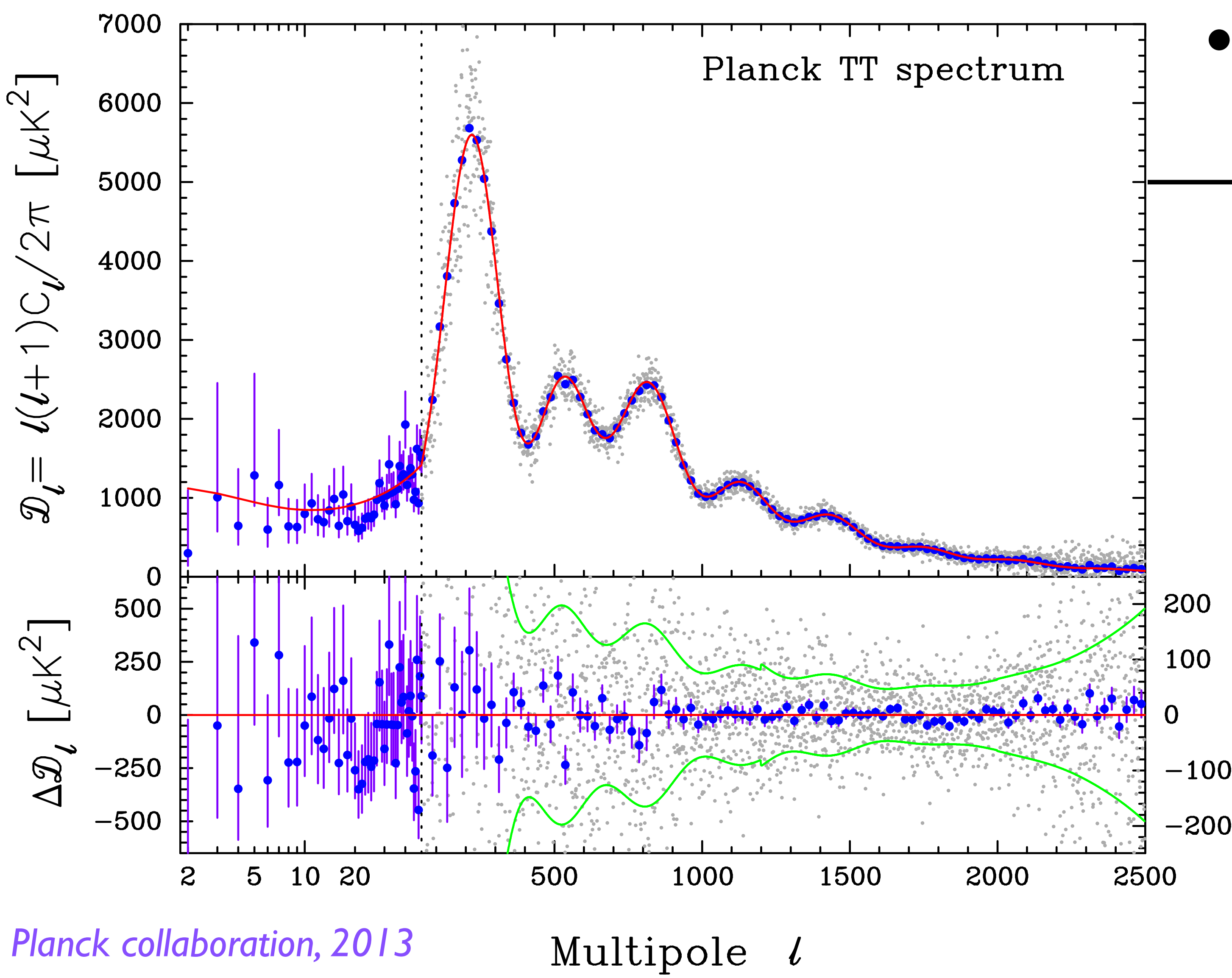
we falsified a simple, predictive and well-defined model of Leptogenesis!

Encore

The Baryon asymmetry

By analysing the Cosmic Microwave Background Radiation and the primordial abundances of elements we learn about the content of the Universe.

Fitting CMBR power spectrum:



Planck collaboration, 2013

- amount of baryons in the Universe:

$$\Omega_B h^2 \approx 0.02$$

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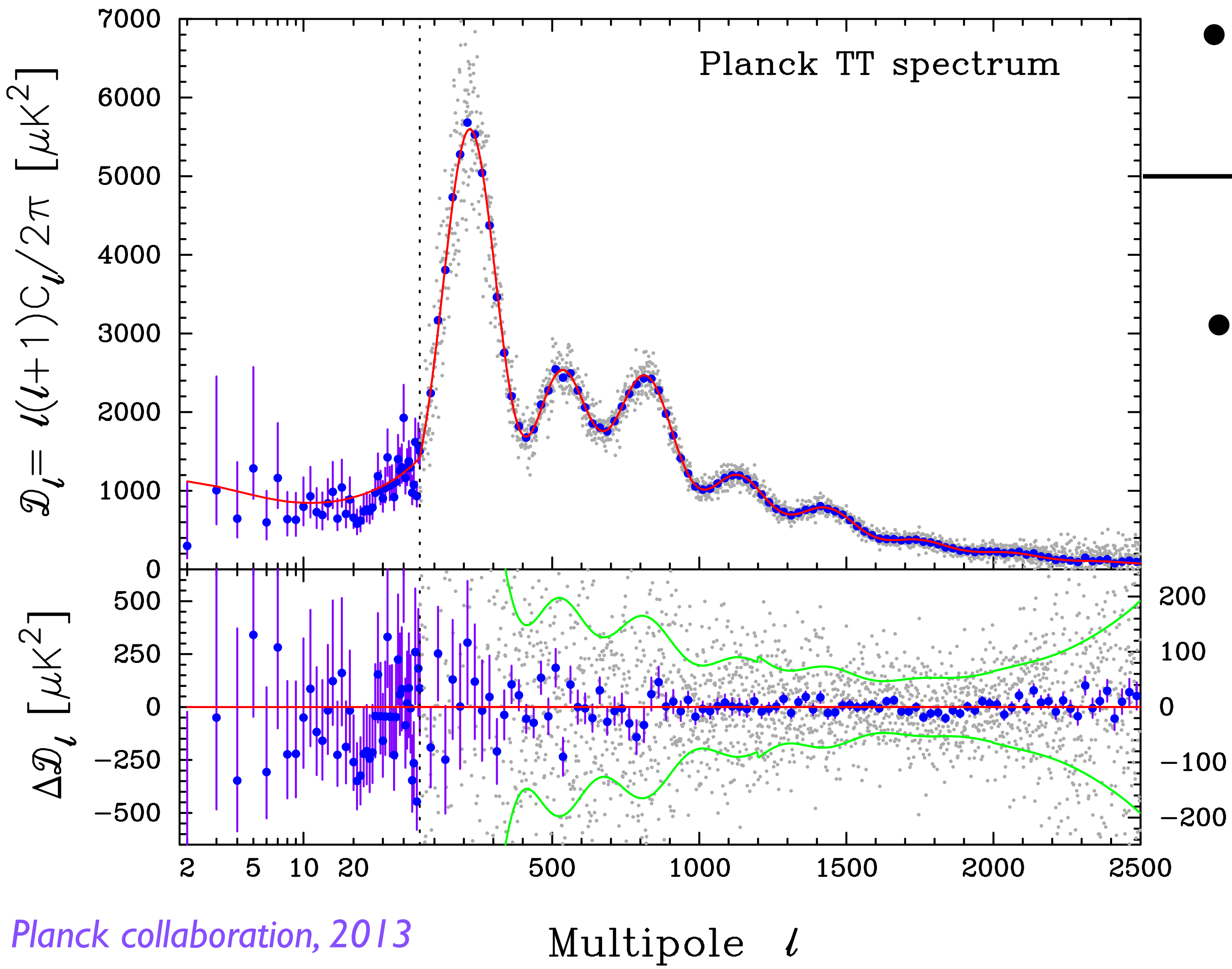


Planck collaboration, 2013

- amount of baryons in the Universe:

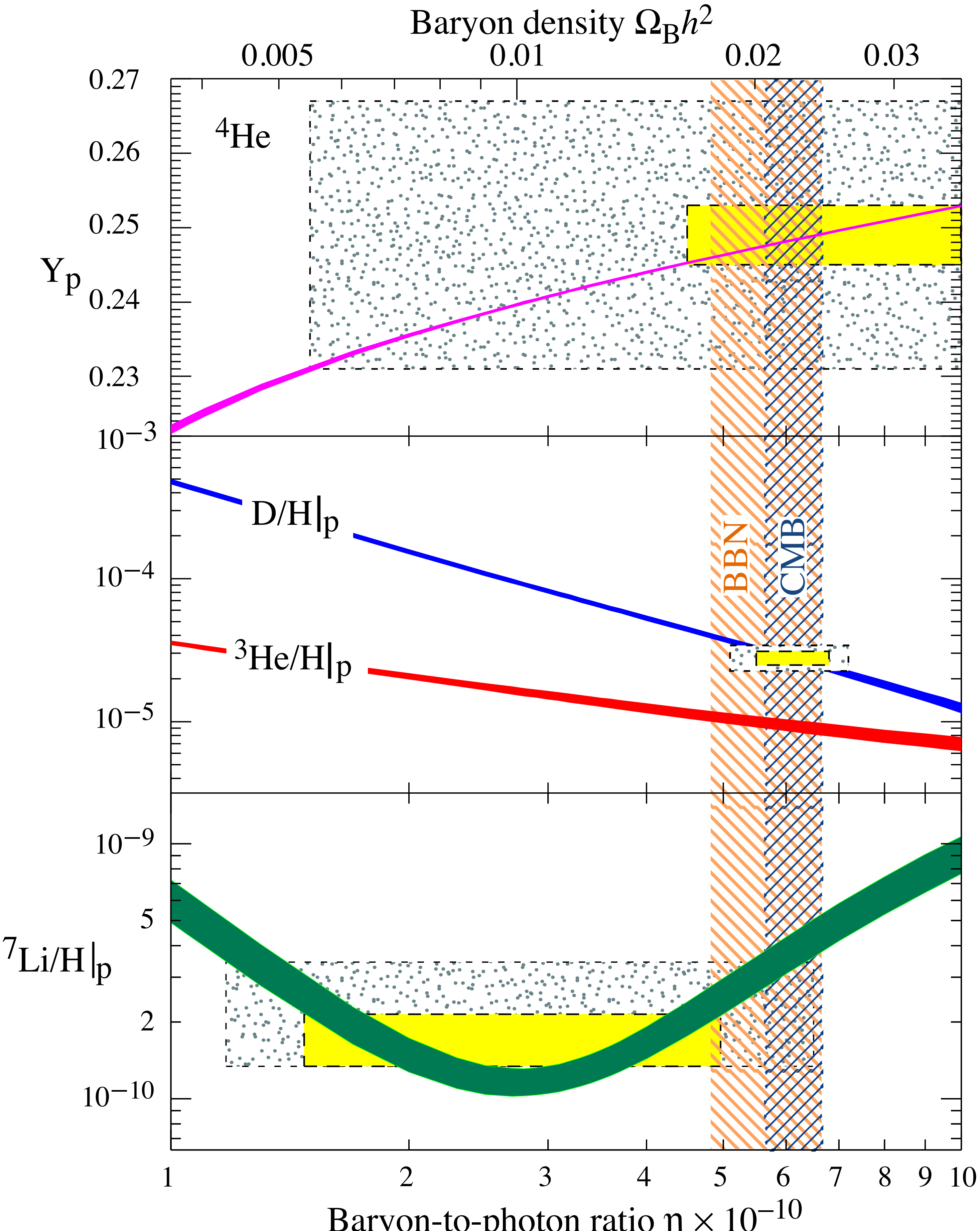
$$\Omega_B h^2 \approx 0.02$$

- No signs of primary antimatter on different scales imply $n_{\bar{B}} = 0$

(n_X = # density of X)

There is an asymmetry between matter and antimatter in our Universe

$$\eta_B := \frac{n_B - n_{\bar{B}}}{n_\gamma} \neq 0$$



PDG, 2008

Solid lines: BBN predictions

Yellow boxes: measure 2σ range

Dotted boxes: 2σ range + sys.

The agreement between BBN & CMBR is a big achievement for the Λ-CDM Model:

BBN tests BAU for $t \in \{10^{-2}, 10^{2}\}$ s

CMBR for $t \approx 10^{6}\mathrm{yrs}$

$$\eta_B = \frac{\rho_B}{m_p n_\gamma} = \frac{\Omega_B \rho_c}{m_p n_\gamma}$$

Today: $H^0 = 100h\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

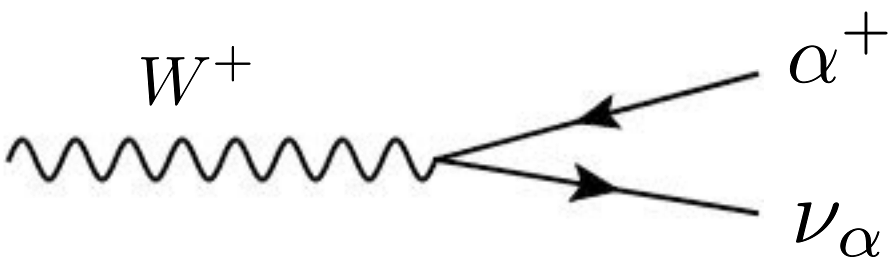
$n_\gamma^0 \approx 410\ \mathrm{cm}^{-3}$

$\rho_c^0 \approx 10.5 h^2 \mathrm{keV\ cm}^{-3}$

$$\longrightarrow\ \eta_B^0 \approx 2.7 \times 10^{-8} \Omega_B^0 h^2$$

Neutrino oscillations

Neutrinos are elusive particles that take part only in weak interactions. Up to now 3 kinds (*flavours*) of neutrino are known, named after the associated charged leptons involved in the interaction:



$\alpha \in \{e, \mu, \tau\}$, charged (anti)leptons

Suppose $\nu_\alpha \neq \nu_i$, with ν_i being the neutrino fields of the mass eigenstates, $i \in \{1,2,3\}$. Then *flavour neutrinos can be regarded as (coherent) superpositions of the latter:*

$$\nu_\alpha = U_{\alpha i}\, \nu_i \quad \longrightarrow \quad |\nu_\alpha\rangle = U^*_{\alpha i}\, |\nu_i\rangle, \qquad U \text{ unitary matrix (\textit{PMNS mixing matrix})}$$

and the Schrödinger equations for the corresponding 1-particle states allow for *flavour oscillations*:

$$P_{\nu_\alpha \to \nu_\beta}(t) := |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \sum_{i,k=1}^{3} U_{\beta i} U^*_{\alpha i} U^*_{\beta k} U_{\alpha k} e^{-\frac{\Delta m^2_{ik} t}{2E}}, \qquad \Delta m^2_{ik} := m_i^2 - m_k^2$$

- Within the Standard Model neutrinos are described as massless leptons

$$\Longrightarrow \Delta m_{ik}^2 = 0 \, \forall \, i, k \neq i \, \in \{1, 2, 3\}$$

hence our theoretical description forbids neutrino flavour oscillations!

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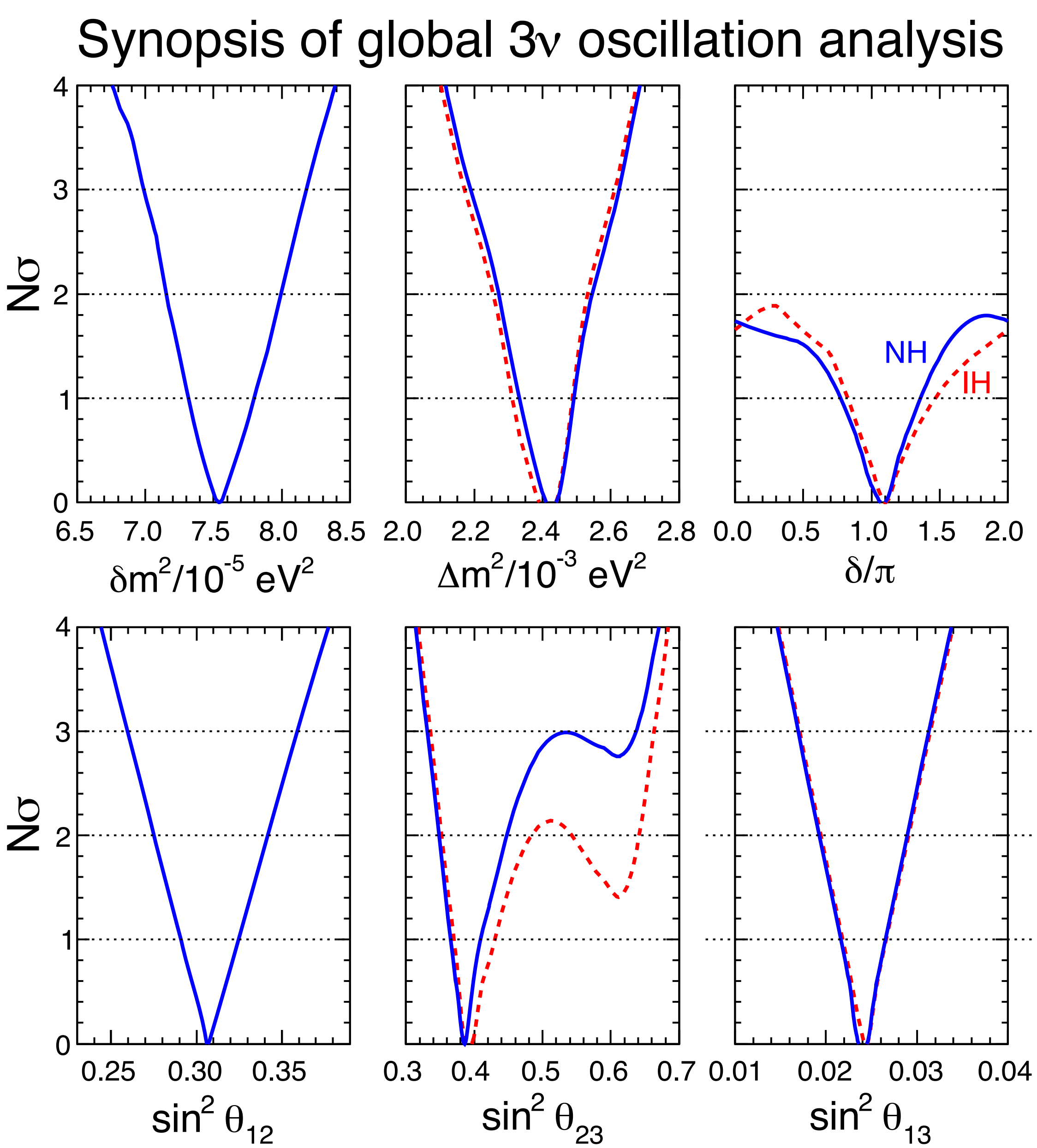
$$\longrightarrow\!\!\triangleright \quad \Delta m^2_{ik} = 0 \,\forall\, i, k \neq i \,\in \{1,2,3\}$$

hence our theoretical description forbids neutrino flavour oscillations!

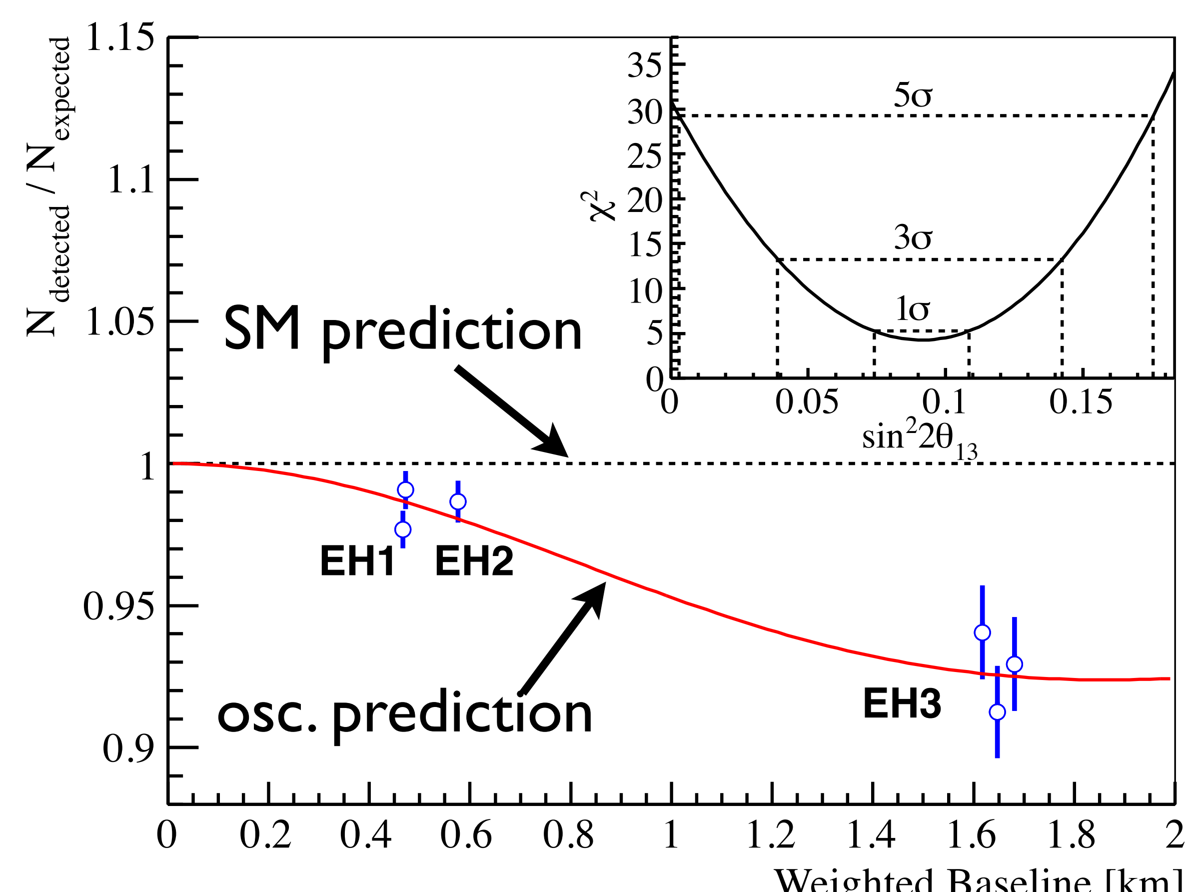
- Experimental status of neutrino oscillations: $\Delta m^2_{ik} \neq 0\,!$

$\downarrow$

Neutrino mass puzzle: unknown origin of neutrino masses and mixing



G. I. Fogli et al., 2013



Daya Bay collaboration, 2012

The Seesaw mechanism

- Neutrino masses in the type I Seesaw

$$\mathcal{L} \supset \mathcal{L}_m^\nu = - h_{\alpha i}\overline{\ell_{L\alpha}} N_{Ri}\tilde{\Phi} - \frac{1}{2}\sum_{i=1}^{3} \overline{N_{Ri}^c} D_{Mi} N_{Ri} + \text{ H.c.}$$

–Electroweak symmetry breaking:

$$-h_{\alpha i}\overline{\ell_{L\alpha}} N_{Ri}\tilde{\phi} \xrightarrow{\langle\phi\rangle \neq 0} (m_D)_{\alpha i}\overline{\nu_{L\alpha}} N_{Ri}$$

$$\boxed{m_D := \frac{\langle\phi\rangle}{\sqrt{2}} h}$$

–Seesaw mechanism: neutrinos must be Majorana particles!

$$\mathcal{L}_m^\nu = -\frac{1}{2}\left(\overline{\nu_{L\alpha}} \quad \overline{N_R^c}\right)\begin{pmatrix} 0 & m_D \\ m_D^T & D_M \end{pmatrix}\begin{pmatrix} \nu_{L\alpha}^c \\ N_R \end{pmatrix} + \text{H.c.} \equiv -\frac{1}{2}\overline{\mathbf{n_L}}\mathbb{M}_{D+M}\mathbf{n_R} + \text{H.c.}$$

Seesaw limit: light neutrino masses ~ $(M_{EW})^2/M_{GUT}$

$D_M \gg m_D$

SEE-SAW

$$\longrightarrow D_{\mathbb{M}_{D+M}} \simeq \begin{pmatrix} m_\nu & 0 \\ 0 & D_M \end{pmatrix}$$

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

N_2-dominated leptogenesis:

- Multiple-stage Boltzmann equations; vanishing initial abundance:
  - $T \sim M_3 > 10^{12}$ GeV: heavy flavour regime

    N_3 processes are active...

    $$\frac{dN_{\Delta 3}}{dz} = \epsilon_3 D_3 (N_{N_3} - N_{N_3}^{eq}) - W_3 N_{B-L}$$

    ...but CP asymmetry is negligible: $O \sim (M_2/M_3)^2$

    $$\epsilon_3 \simeq 0 \longrightarrow N_{\Delta 3} = 0$$ *no B-L asymmetry produced*

  - $T \sim M_2 < 10^{12}$ GeV $\wedge$ $M_2 > 10^9$ GeV: two-flavour regime

    N_2 processes generate a B-L asymmetry $(\beta = \tau, \tau_2^{\perp})$

    $$\frac{dN_{\Delta 2}}{dz} = \sum_{\beta} \frac{dN_{\Delta\beta}^{(2)}}{dz} \qquad \frac{dN_{\Delta\beta}^{(2)}}{dz} = \epsilon_{2\beta} D_2 (N_{N_2} - N_{N_2}^{eq}) - p_{2\beta} W_2 N_{B-L}$$

therefore:

$$\boxed{N_{\Delta 2}(T < M_2) = \epsilon_{2\tau}\kappa(K_2, K_{2\tau}) + \epsilon_{2\tau_2^\perp}\kappa(K_2, K_{2\tau_2^\perp})}$$

$$\epsilon_i = -\frac{\Gamma(N_i \to \ell\phi) - \Gamma(N_i \to \overline{\ell\phi})}{\Gamma(N_i \to \ell\phi) + \Gamma(N_i \to \overline{\ell\phi})} \qquad \epsilon_2 \propto M_2 \propto \alpha_2^2$$

$$K_i \equiv \frac{\tilde{m_i}}{m_*} \qquad K_{i\gamma} := p_{i\gamma} K_i \qquad \epsilon_{i\gamma} := p_{i\gamma}\epsilon_i \qquad p_{i\gamma} := \frac{|(m_D)_{\gamma i}|^2}{\left(m_D^\dagger m_D\right)_{ii}}$$

–$T \sim M_1 < 10^9$ GeV: three-flavour regime $(\alpha = e, \mu, \tau)$

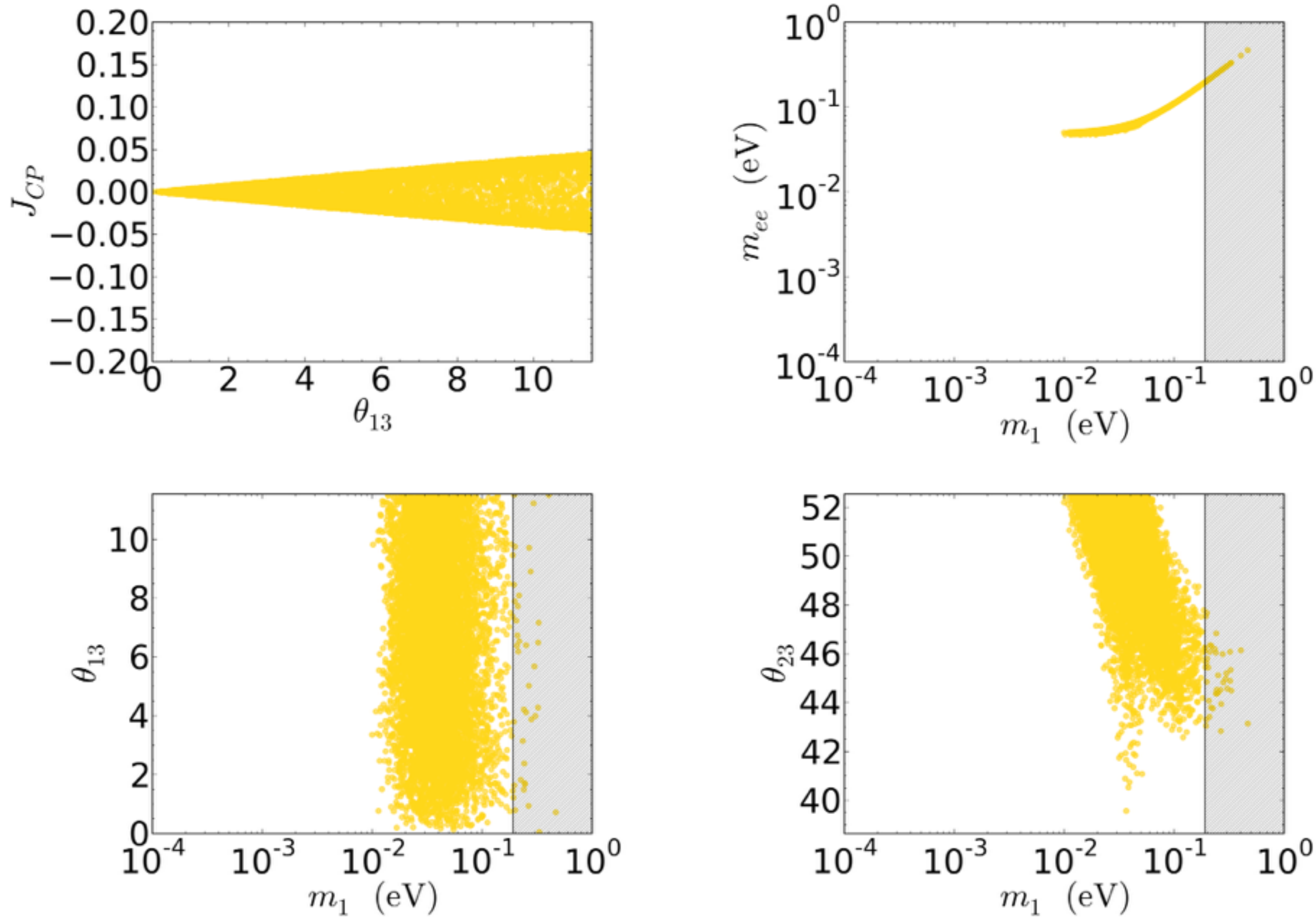
N_1 processes are active; no B-L asymmetry generated as

$M_1 < 10^9\mathrm{GeV} \quad \epsilon_1 \simeq 0$ *(Davidson - Ibarra bound)*

N_2 asymmetry is washed out: $\dfrac{dN_{\Delta\alpha}^{(1)}}{dz} = -p_{1\alpha}W_1 p_{2\alpha}N_{\Delta 2}$

$$\boxed{\begin{aligned} N_{B-L}^{lep,f} := \sum_\alpha N_{\Delta\alpha}^{(1)}(T \ll M_1) \simeq \frac{p_{2e}}{p_{2\tau_2^\perp}}\epsilon_{2\tau_2^\perp}\kappa(K_2, K_{2\tau_2^\perp})e^{-\frac{3\pi}{8}K_{1e}} + \\ + \frac{p_{2\mu}}{p_{2\tau_2^\perp}}\epsilon_{2\tau_2^\perp}\kappa(K_2, K_{2\tau_2^\perp})e^{-\frac{3\pi}{8}K_{1\mu}} + \epsilon_{2\tau}\kappa(K_2, K_{2\tau})e^{-\frac{3\pi}{8}K_{1\tau}} \end{aligned}}$$

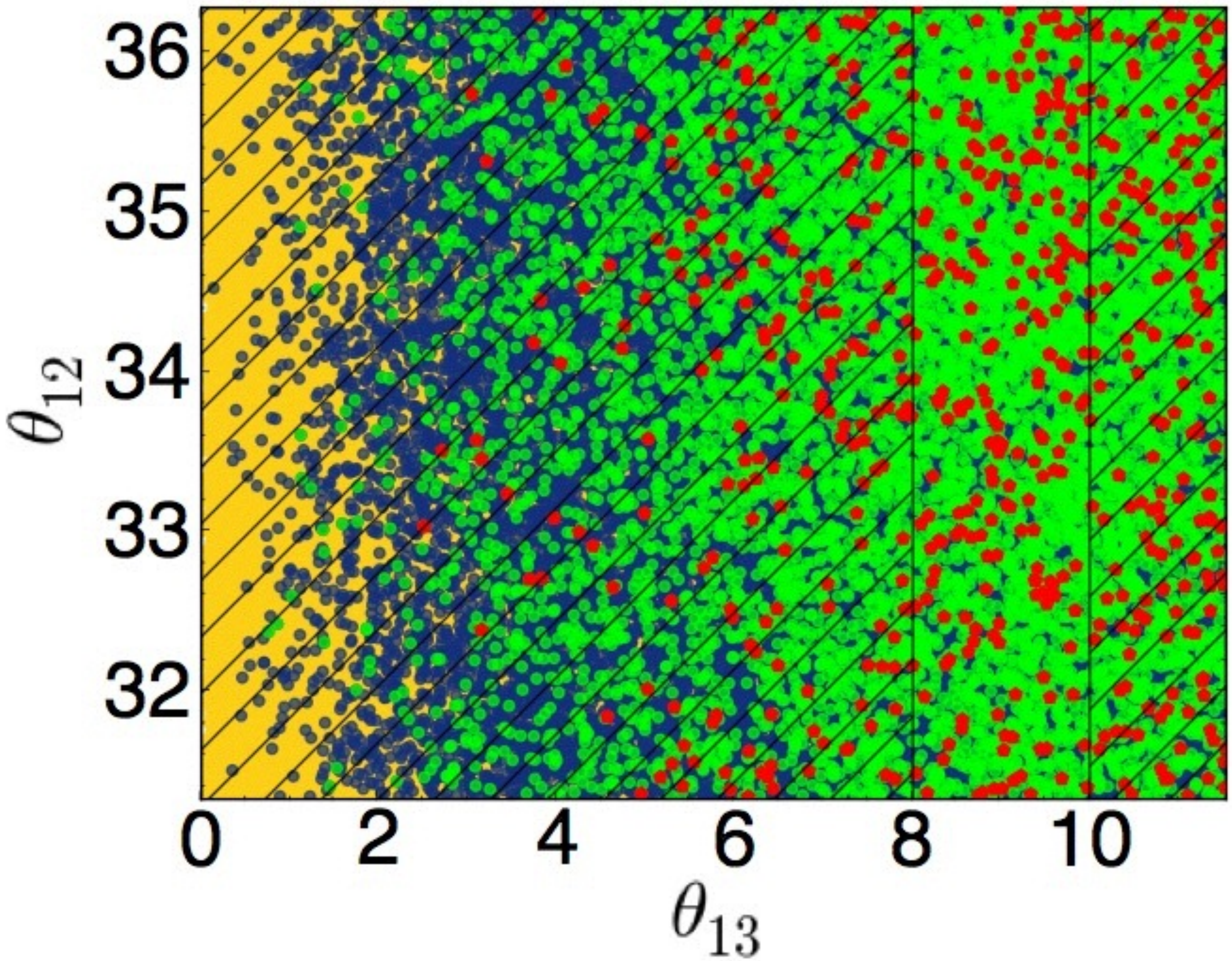
- About inverter ordering: no Strong Leptogenesis



- θ_{12} in the SO(10)-inspired models: strong thermal solutions

$N_{B-L}^{preex,0} =$ 0, 10^{-3}, 10^{-2}, 10^{-1}

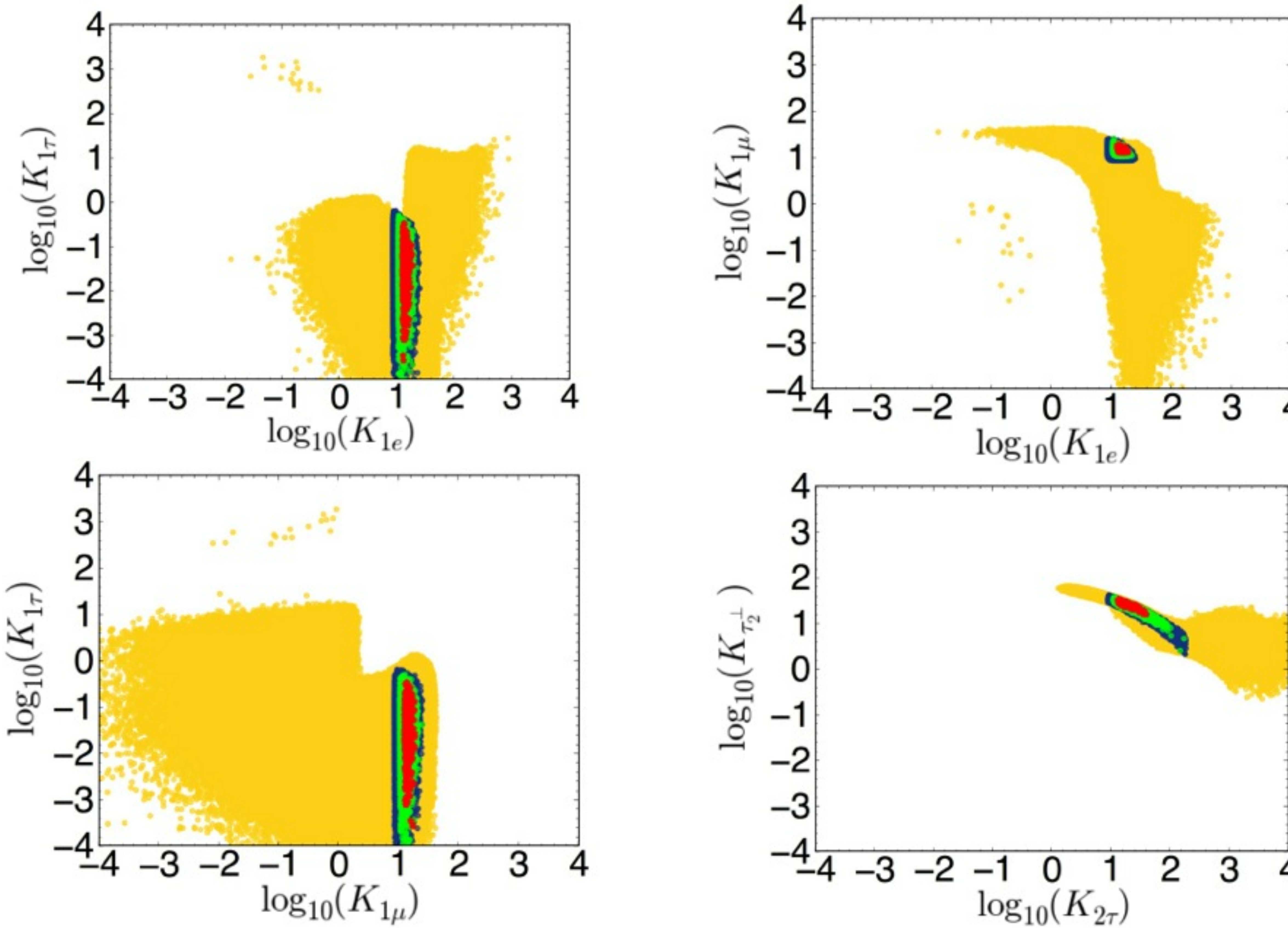
$N_{B-L}^{preex,f} < 10^{-8}$



- Decay efficiency parameters:

$N_{B-L}^{preex,0} = 0, 10^{-3}, 10^{-2}, 10^{-1}$ $\quad N_{B-L}^{preex,f} < 10^{-8}$

- N_2-*dominated Leptogenesis* in strong washout regime ($K_2 >> 1$)
- Asymmetric washout from N_1 ($K_{1e}, K_{1\mu} >> 1$; $K_{1\tau} \sim 1$)



• Status of neutrino parameters

M.C. Gonzalez-Garcia et al, 2012

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \to 0.344$	$0.311^{+0.013}_{-0.013}$	$0.273 \to 0.354$
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	$31.09 \to 35.89$	$33.87^{+0.82}_{-0.80}$	$31.52 \to 36.49$
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \to 0.667$	$0.416^{+0.036}_{-0.029} \oplus 0.600^{+0.019}_{-0.026}$	$0.341 \to 0.670$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \to 54.8$	$40.1^{+2.1}_{-1.6} \oplus 50.7^{+1.2}_{-1.5}$	$35.7 \to 55.0$
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \to 0.0299$	$0.0255^{+0.0024}_{-0.0024}$	$0.0181 \to 0.0327$
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \to 9.96$	$9.20^{+0.41}_{-0.45}$	$7.73 \to 10.42$
$\delta_{\mathrm{CP}}/^\circ$	300^{+66}_{-138}	$0 \to 360$	298^{+59}_{-145}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \to 8.09$	$7.51^{+0.21}_{-0.15}$	$7.04 \to 8.12$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \to +2.695$	$+2.489^{+0.055}_{-0.051}$	$+2.294 \to +2.715$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$	$-2.468^{+0.073}_{-0.065}$	$-2.678 \to -2.252$

Table 1. Three-flavour oscillation parameters from our fit to global data after the Neutrino 2012 conference. For "Free Fluxes + RSBL" reactor fluxes have been left free in the fit and short baseline reactor data (RSBL) with $L \lesssim 100$ m are included; for "Huber Fluxes, no RSBL" the flux prediction from [42] are adopted and RSBL data are not used in the fit.

F. Capozzi et al. 2013

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The overall χ^2 difference between IH and NH is insignificant ($\Delta\chi^2_{\mathrm{I-N}} = -0.3$).

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.37 – 2.49	2.30 – 2.55	2.23 – 2.61
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.38	2.32 – 2.44	2.25 – 2.50	2.19 – 2.56
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.15 – 2.54	1.95 – 2.74	1.76 – 2.95
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.40	2.18 – 2.59	1.98 – 2.79	1.78 – 2.98
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.37	4.14 – 4.70	3.93 – 5.52	3.74 – 6.26
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.55	4.24 – 5.94	4.00 – 6.20	3.80 – 6.41
δ/π (NH)	1.39	1.12 – 1.77	0.00 – 0.16 $\oplus$ 0.86 – 2.00	—
δ/π (IH)	1.31	0.98 – 1.60	0.00 – 0.02 $\oplus$ 0.70 – 2.00	—