Leptogenesis & CP violation in the leptonic sector

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Outline

- What we know/don't know.

- Baryon asymmetry

- Leptogenesis

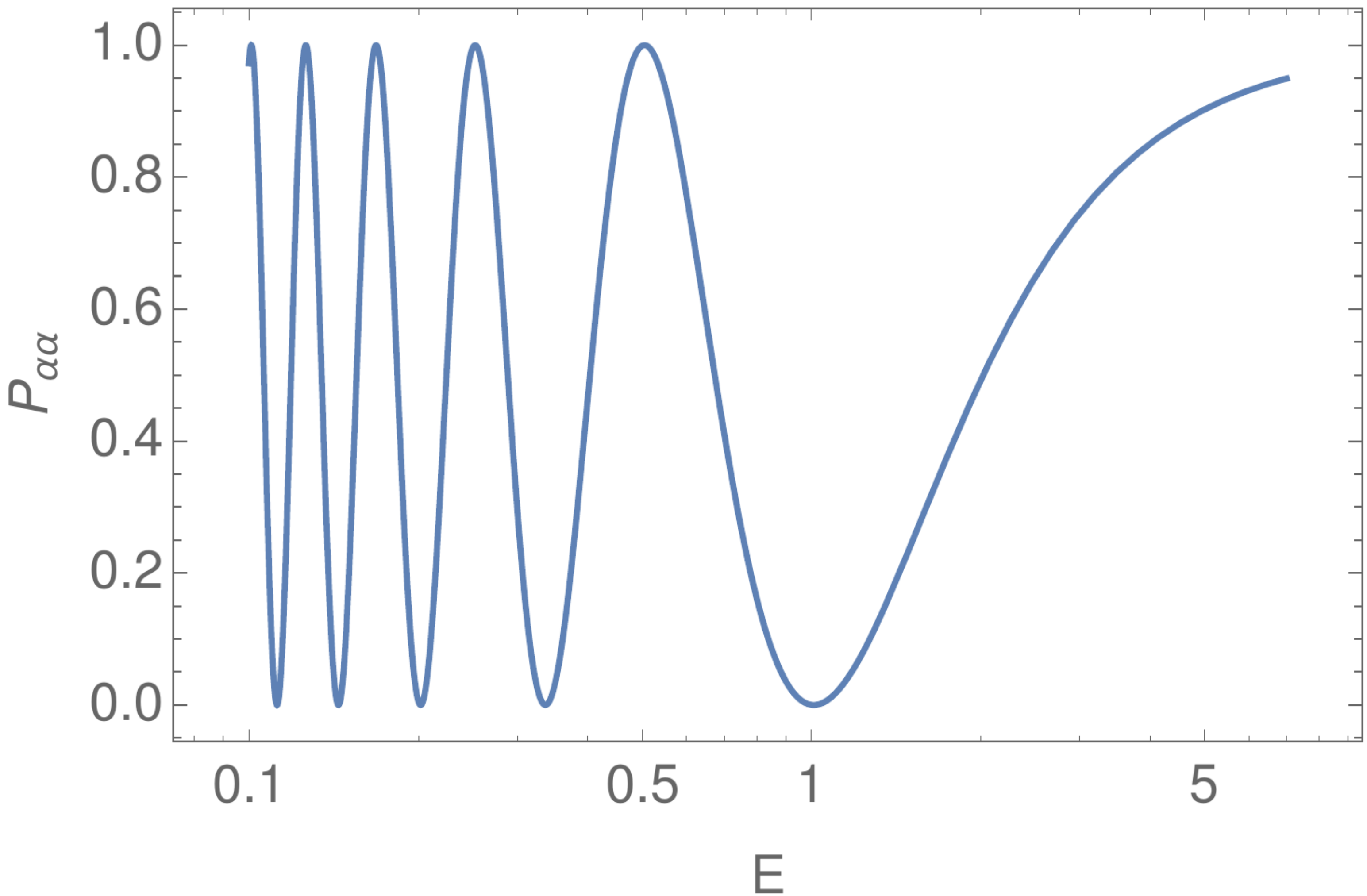
- Testable Leptogenesis.
  Hernandez, Kekic, JLP, Racker, Rius 1508.03676;
  Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

- Conclusions

What do we know from neutrino oscillation experiments?

Two family approximation

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$



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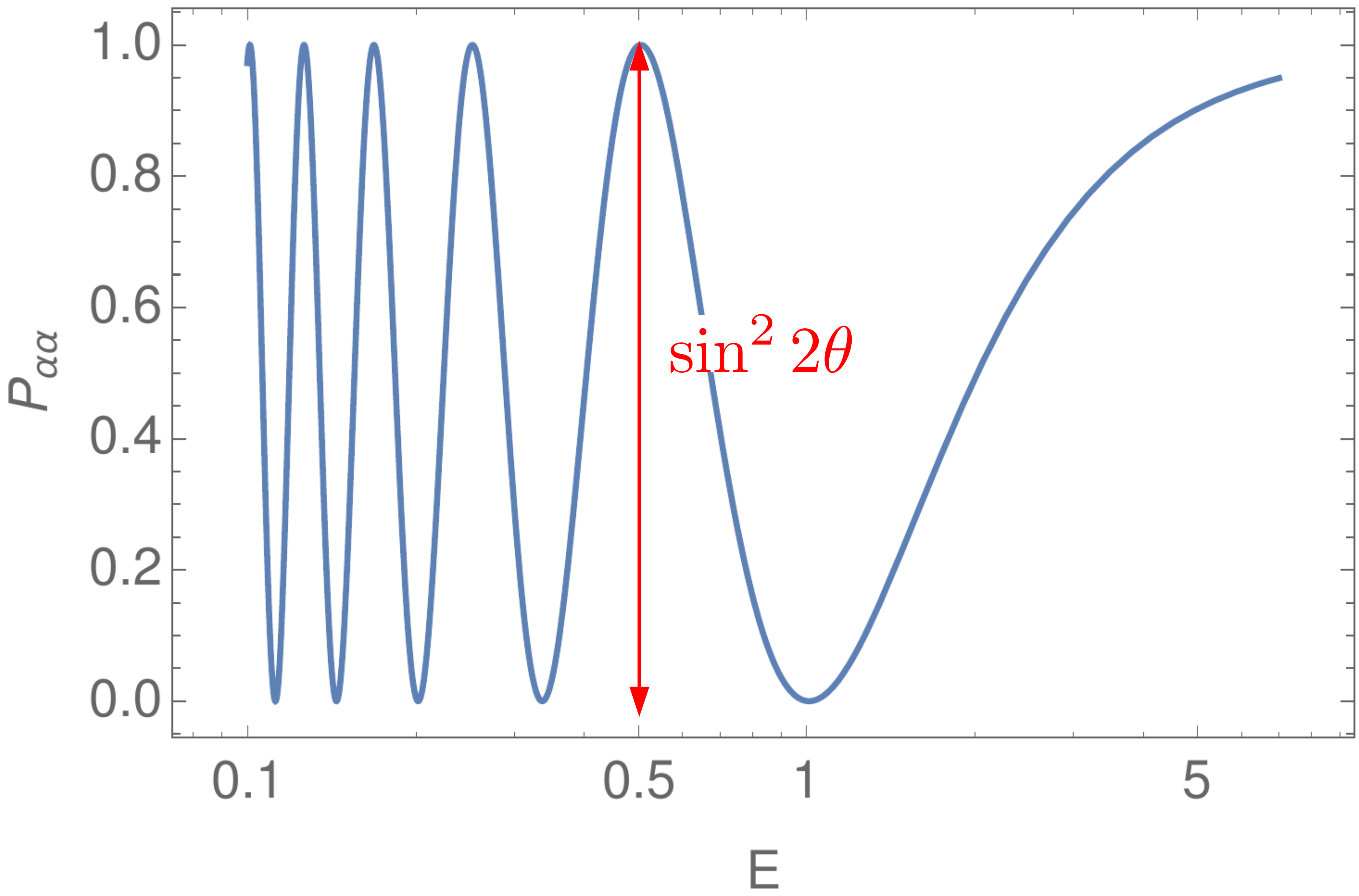

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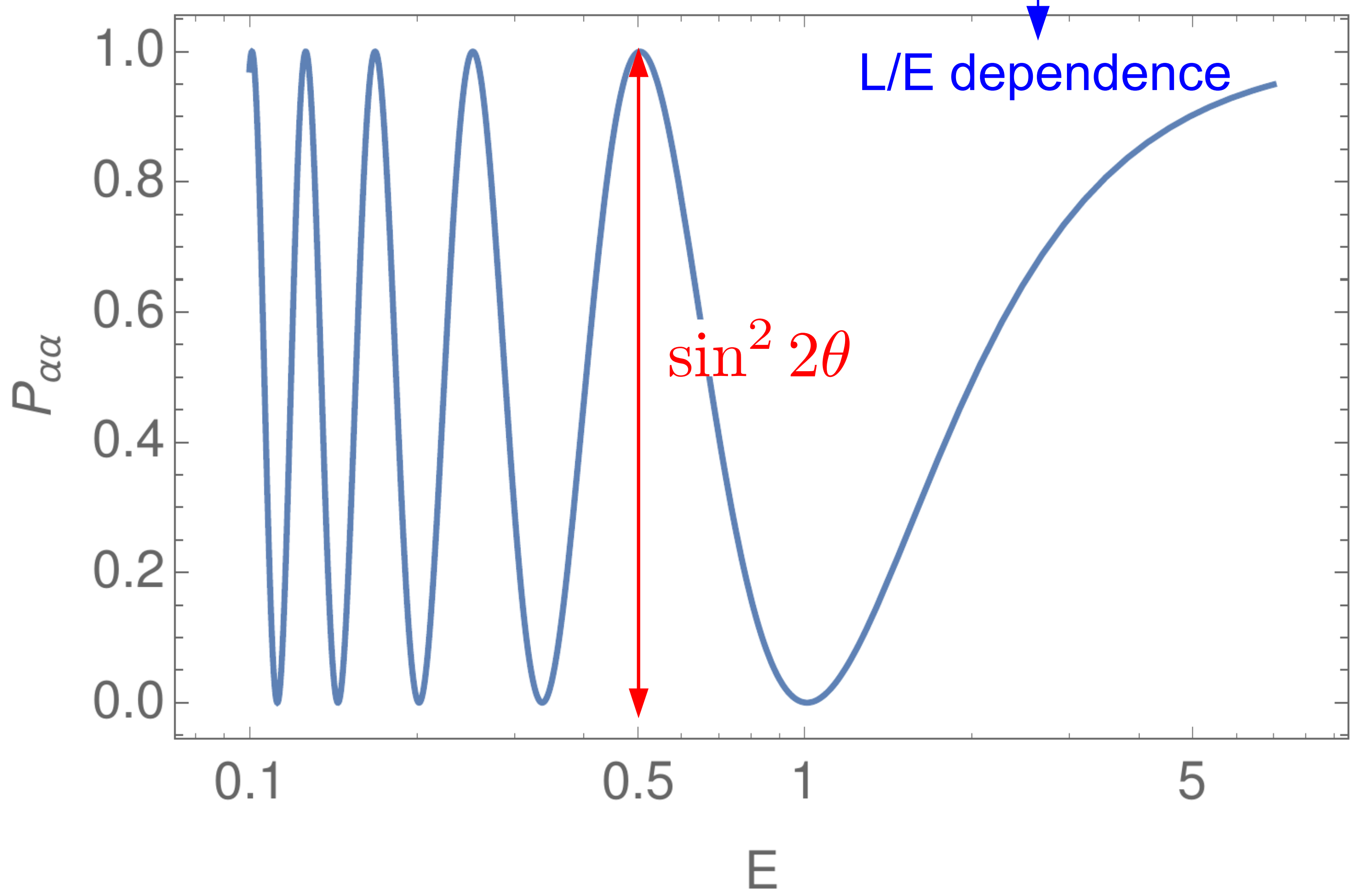

What we know...

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

Atmospheric sector — Interference/Reactor — Solar sector

$$\sin^2\theta_{12} = 0.306 \pm 0.012$$

$$\Delta m^2_{21} = (7.50^{+0.19}_{-0.17}) \times 10^{-5}\,\mathrm{eV}^2$$

(1σ)

Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Schwetz 1611.01514
See also: Capozzi, Lisi, Marrone, Montanino, Palazzo 1601.07777; de Salas, Forero, Ternes, Tortola, Valle 1708.01186

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Atmospheric sector | Interference/Reactor | Solar sector

$$\sin^2\theta_{23} = \begin{matrix} 0.440^{+0.027}_{-0.021} \\ 0.587^{+0.020}_{-0.024} \end{matrix}$$

$$\Delta m^2_{3l} = \begin{matrix} 2.524^{+0.039}_{-0.040} \\ -2.514^{+0.038}_{-0.041} \end{matrix} \times 10^{-3}\mathrm{eV}^2$$

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$$\sin^2\theta_{13} = \begin{matrix} 0.02166 \pm 0.00075 \\ 0.0217 \pm 0.00076 \end{matrix}$$

(1σ)

Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Schwetz 1611.01514
See also: Capozzi, Lisi, Marrone, Montanino, Palazzo 1601.07777; de Salas, Forero, Ternes, Tortola, Valle 1708.01186

What we still do not know in the neutrino sector

What we don't know...

See for instance: King et al 1402.4271
Altarelli et al 1205.5133, 1002.0211

① The Octant: $\theta_{23} \gtreqless 45^\circ$. *Very relevant for the flavour puzzle.*

What we don't know...

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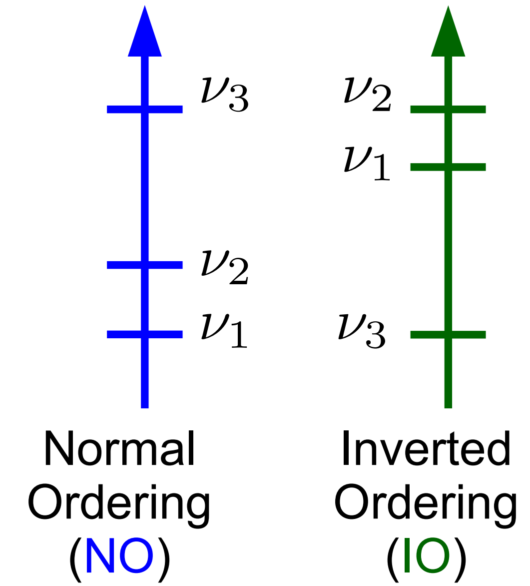
② Neutrino ordering (sign of Δm^2_{31})



What we don't know...

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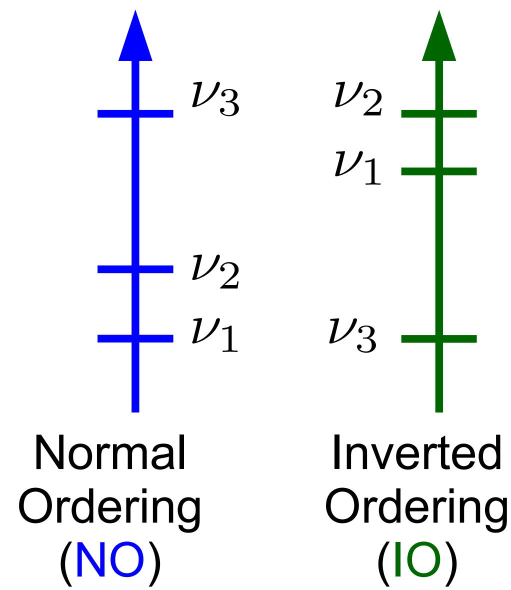
1. The Octant: $\theta_{23} \gtrless 45^\circ$. *Very relevant for the flavour puzzle.*

2. Neutrino ordering (sign of Δm^2_{31})

Extremely relevant input for other observables as $0\nu\beta\beta$ decay

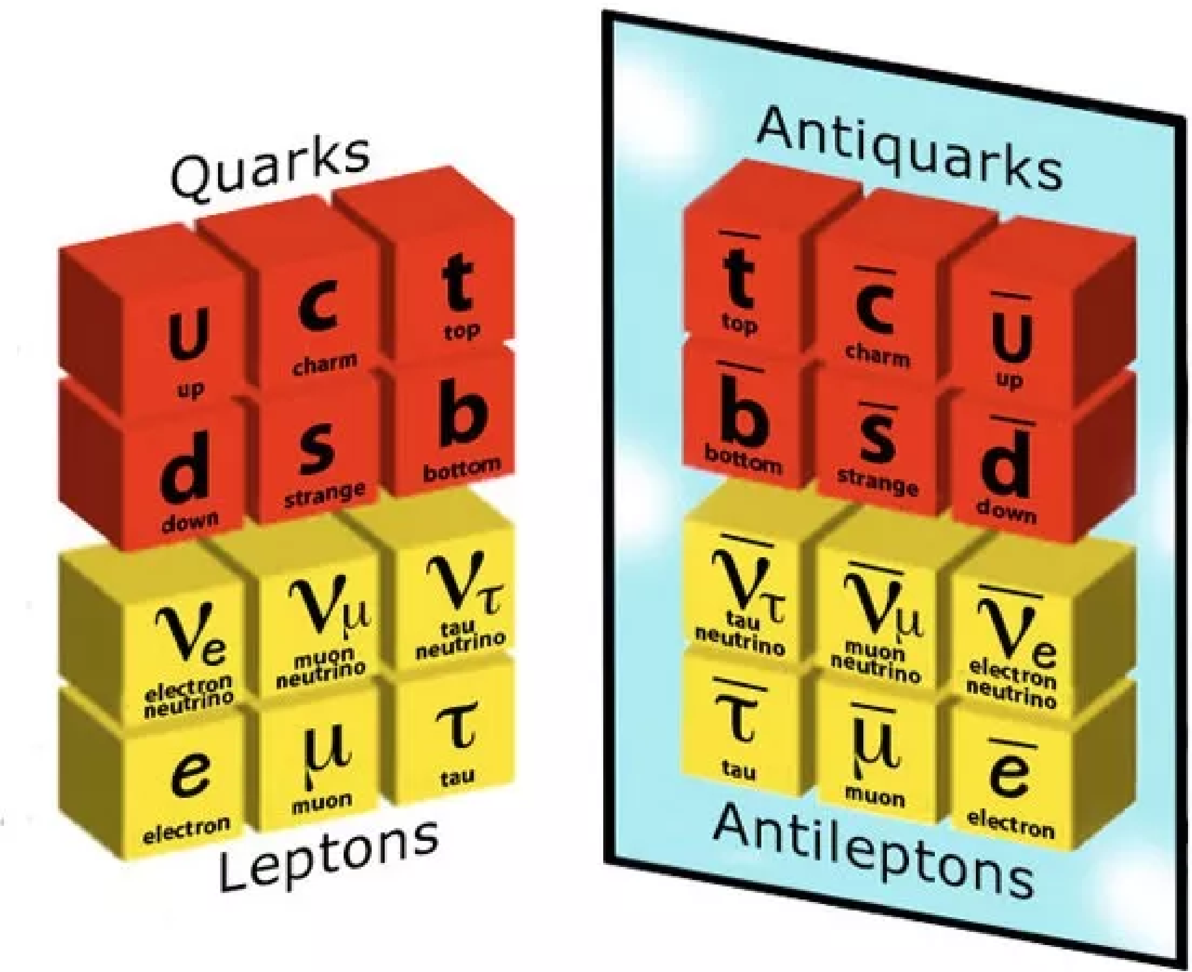


3. Absolute neutrino mass scale

Cosmological probes, Tritium beta decay (KATRIN)

(4) Dirac vs Majorana

Dirac vs Majorana



Particles

Antiparticles

- Neutrinos **can be their own antiparticles**

- *Majorana Neutrinos*

  neutrino $=$ *antineutrino*

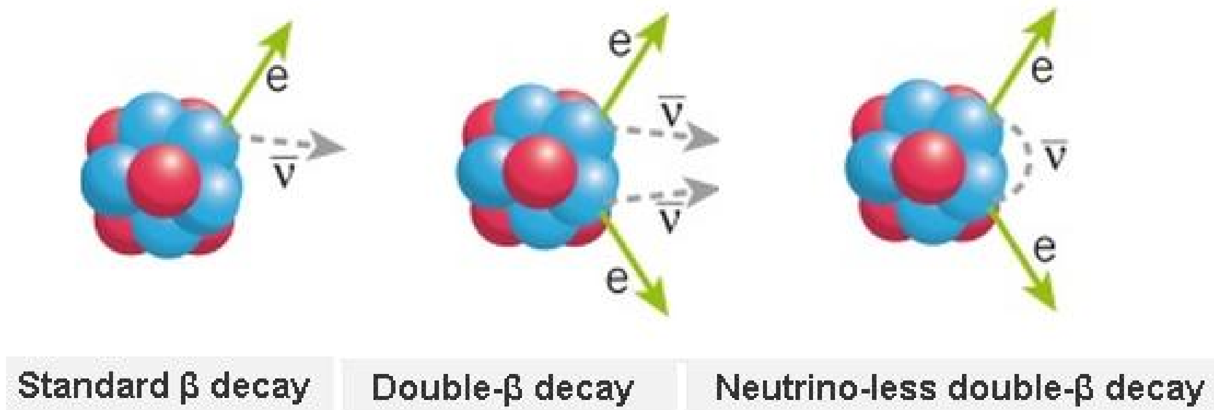
  Fundamental ingredient in order to explain the matter-antimatter asymmetry in our universe via Leptogenesis

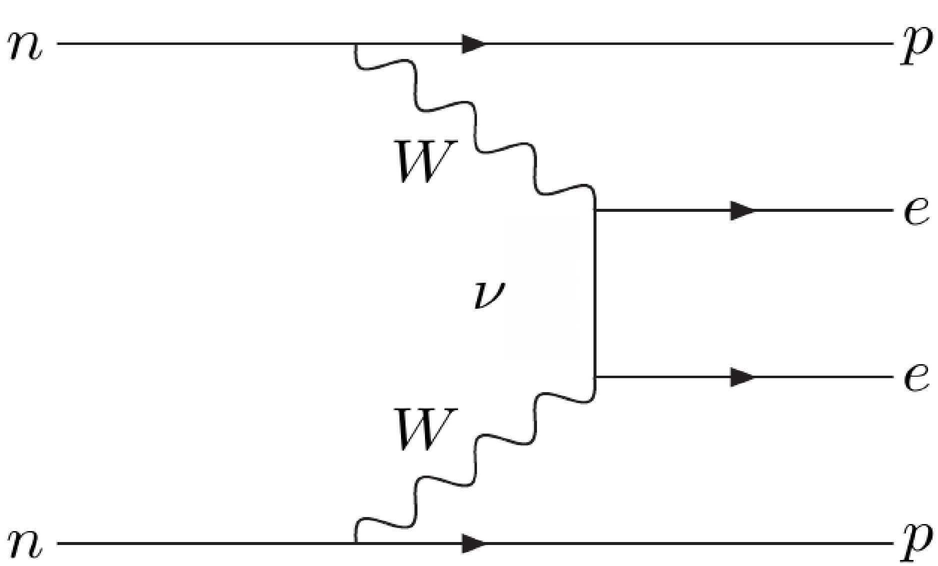
- *Dirac Neutrinos*

  neutrino $\neq$ *antineutrino*

  (as the other SM fermions)

Neutrinoless double beta decay





mixing

$$\sim m_{\beta\beta} = \sum_i m_i U_{ei}^2$$

mass of propagating neutrino

$$(Z, A) \Rightarrow (Z \pm 2, A) + 2e^{\mp}$$

⑤ CP violation

CP violation in the lepton sector?

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

Atmospheric sector — Interference/Reactor — Solar sector

Controls CP violation effects

CP violation in the lepton sector?

$$\boxed{P_{\alpha\alpha}} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

- No sensitivity to CP violation

- ***A signal of CP violation can only come from appearance channels.***

  - *CP violation only in the quark sector?*

  - *Fundamental ingredient in order to explain the matter-antimatter asymmetry in our universe via Leptogenesis*

Fukugita and Yanagida 1986

CP violation, Mass Ordering and Octant

$$P_{e\mu} - P_{\bar{e}\bar{\mu}} = \boxed{J} \cos\left(\pm\delta - \frac{\Delta_{31}L}{2}\right) \sin\left(\frac{\Delta_{21}L}{2}\right) \sin\left(\frac{\Delta_{31}L}{2}\right)$$

CP invariant

$$J \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

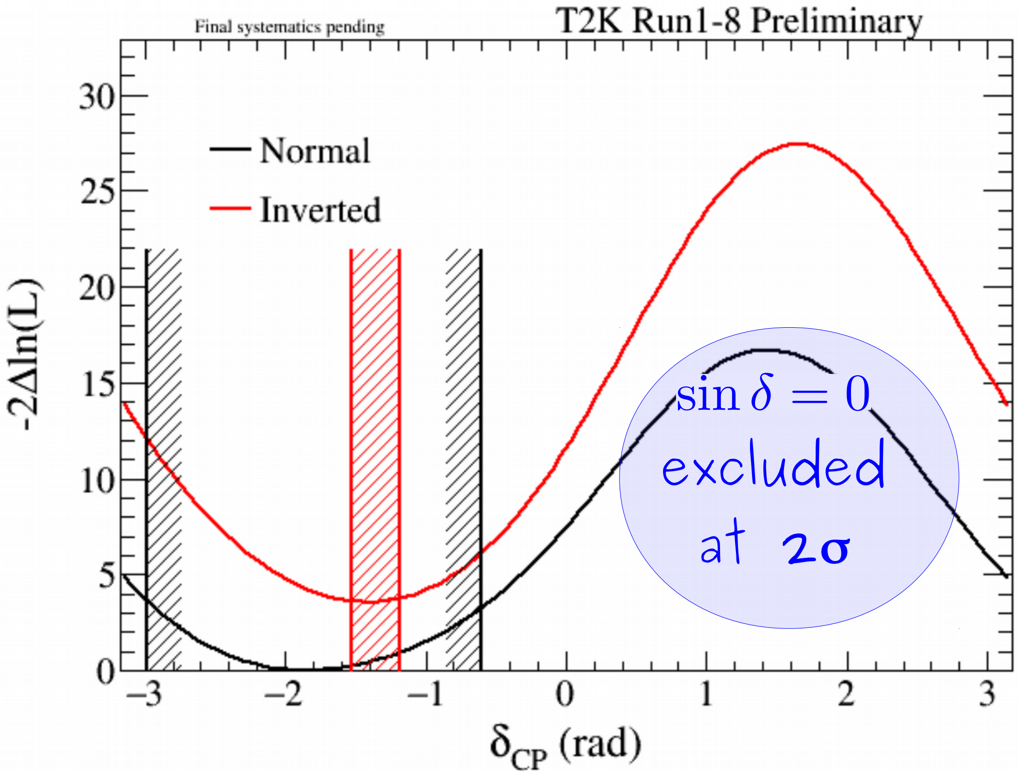
- **Present**

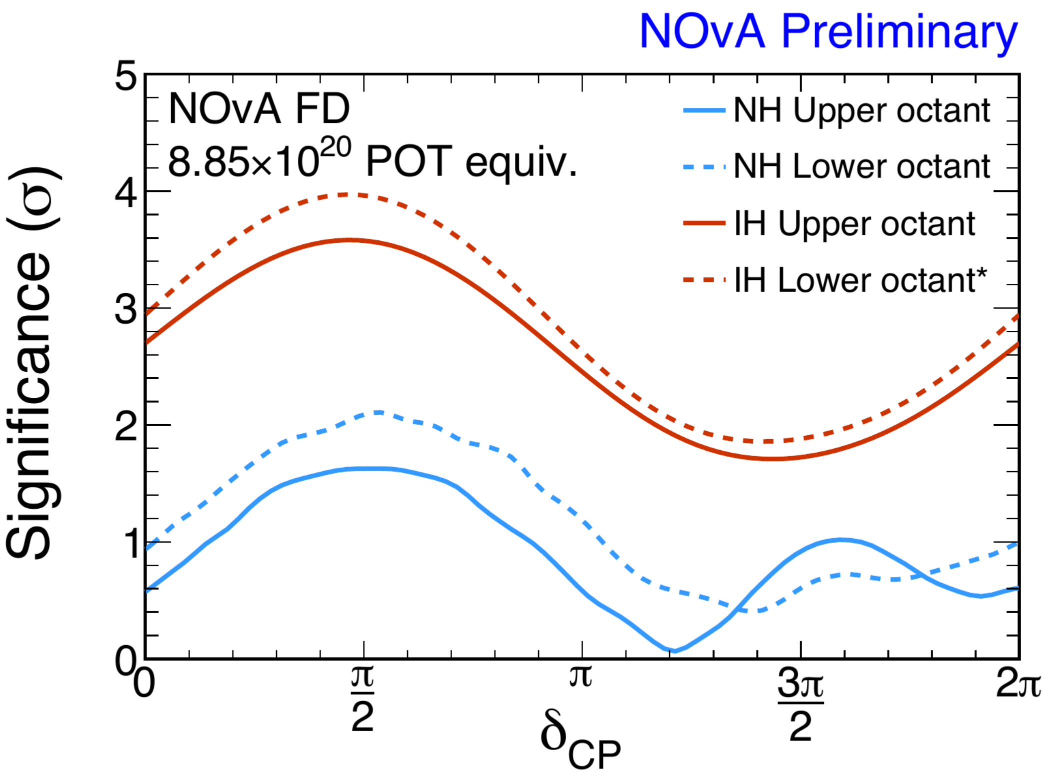
NOvA (810 km)
T2K (295 km)

- **Future**

DUNE (1300 km)
T2HK (295 km)
ESSvSB (500 km)
T2HKK (295 km, 1100 km)

New results from T2K and NOvA





Baryon asymmetry

Baryon asymmetry

- **After the Big-Bang same amount of matter and antimatter generated, but observed universe mainly made out of matter only!**

- The observed baryon asymmetry is quoted in terms of the abundance (number-density asymmetry of baryons normalized to the entropy density):

$$Y_B^{exp} = 8.65(8) \times 10^{-11}$$

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How can this matter asymmetry of our Universe be generated?

Sakharov conditions

- In order to generate the baryon asymmetry the following conditions should be satisfied:

1. Baryon number violation

If baryon asymmetry is conserved, no baryon number can be generated

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OK in the SM ⇔ Sphalerons @T ≈ 140Gev

Sakharov conditions

- In order to generate the baryon asymmetry the following conditions should be satisfied:

2 C and CP violation

If C or CP are conserved:

$$\Gamma\left(A \to B + C\right) = \Gamma\left(\overline{A} \to \overline{B} + \overline{C}\right)$$

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Exist in the SM

There is CP violation in the quark sector

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Exist in the SM ⟺ Jarlskog invariant too small

There is CP violation in the quark sector

Not enough CP violation in SM !!

Gavela, Hernandez Orloff, Pene, Quimbay 1994

Sakharov conditions

- In order to generate the baryon asymmetry the following conditions should be satisfied:

③ Departure from thermal equilibrium

Production/destruction rates of Baryons are equal in thermal equilibrium: $\Gamma\left(A \to B + C\right) = \Gamma\left(B + C \to A\right)$

Sakharov conditions

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Exist in the SM

Due to Hubble expansion of the universe

Sakharov conditions

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Exist in the SM ⟺ Deviation too small

Due to Hubble expansion of the universe

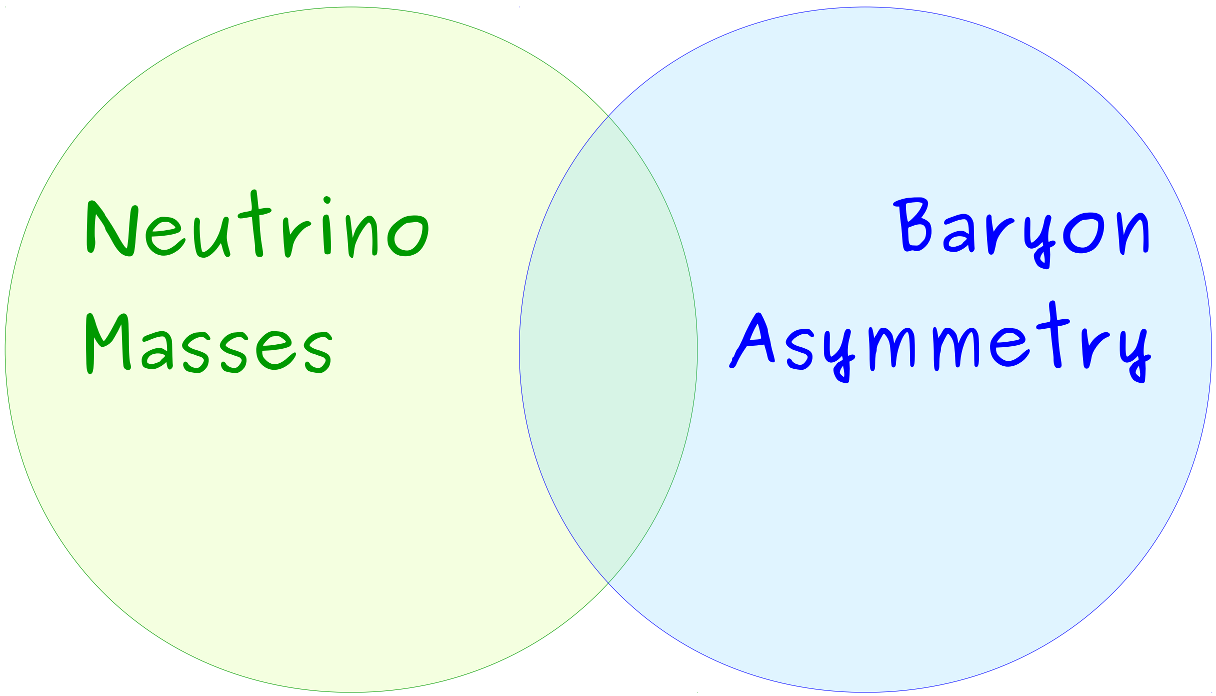
Not enough deviation from thermal equilibrium in the SM!!

Kajantie, Laine, Rummukainen, Shaposhnikov, 1996

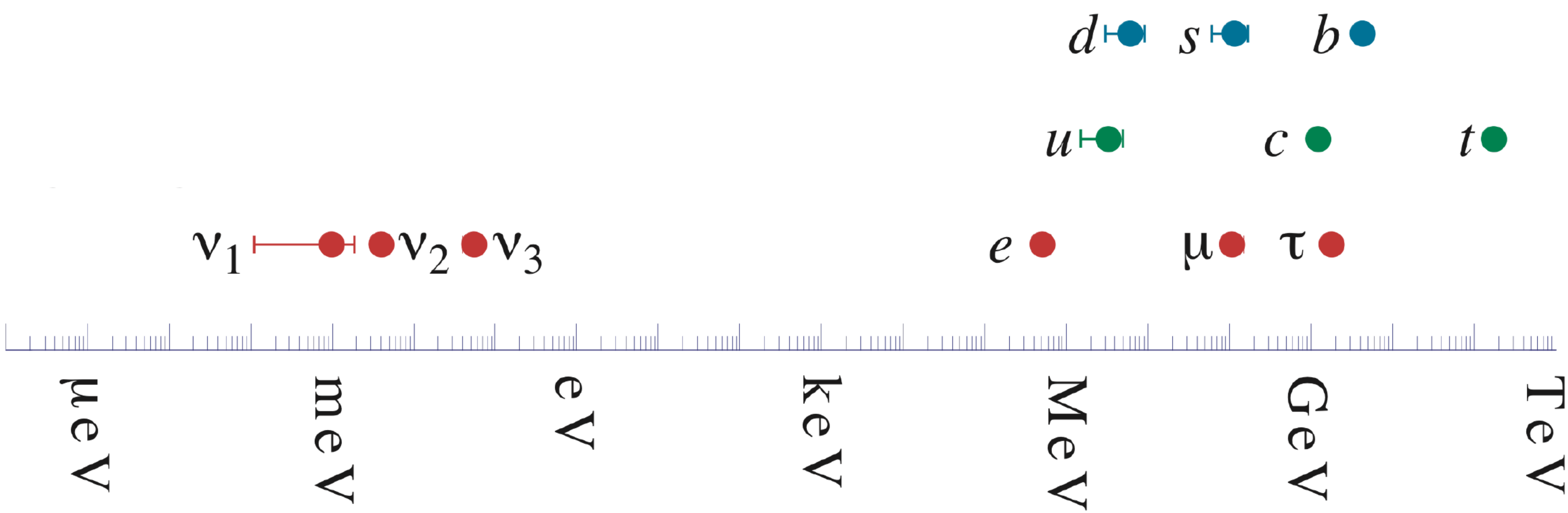
Observed
Baryon asymmetry
can not be generated
in the SM

Gavela, Hernandez Orloff, Pene, Quimbay 1994

Leptogenesis



Why are neutrinos so light?

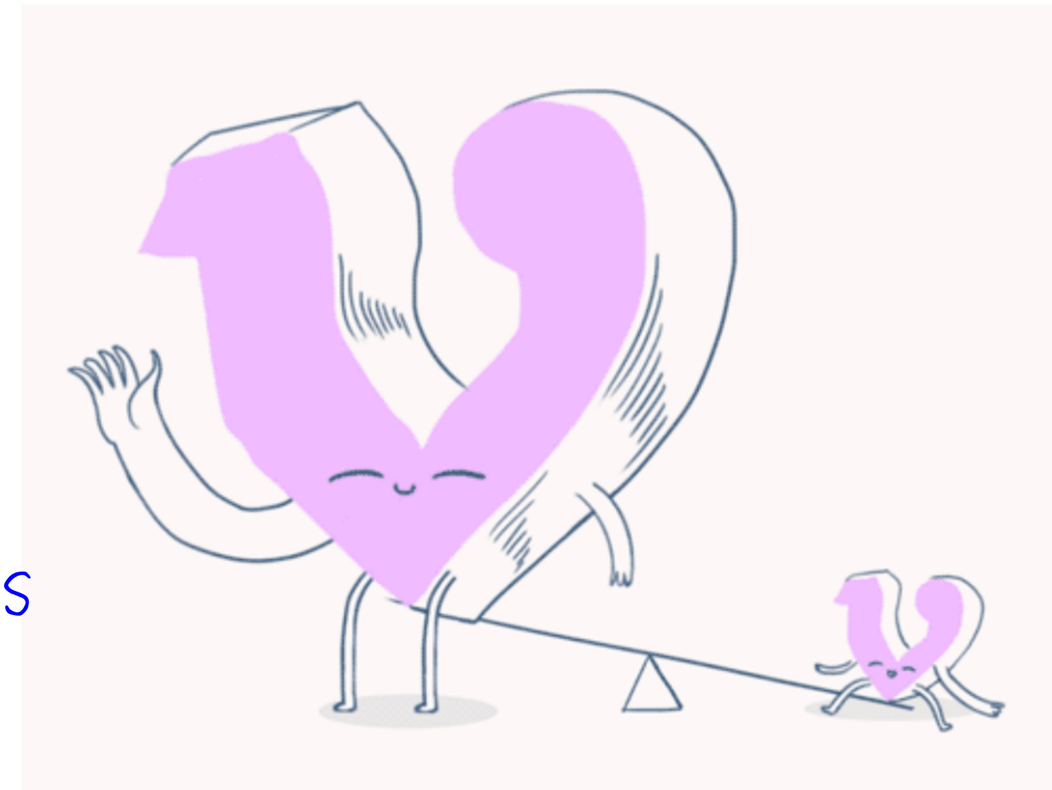


Seesaw Model

Simplest extension of SM able to account for neutrino masses. Consists in the addition of heavy fermion singlets (N_R) to the SM field content:

$$m_\nu \sim Y^2 v^2 / M$$

New Physics Scale



N_R ν_L

Minkowski 77; Gell-Mann, Ramond, Slansky 79
Yanagida 79; Mohapatra, Senjanovic 80.

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$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\mathcal{K}} - \frac{1}{2}\overline{N_i^c} M_{ij} N_j - Y_{i\alpha}\overline{N_i}\widetilde{H}^\dagger L_\alpha + h.c.$$

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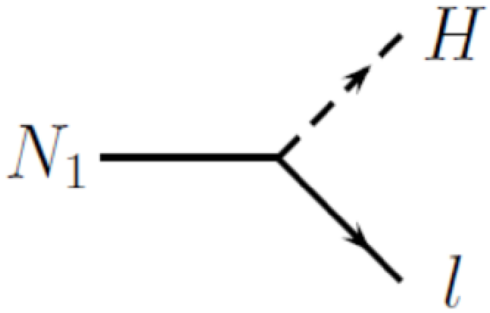
Interaction with SM particles via Yukawa coupling



$\sim Y$

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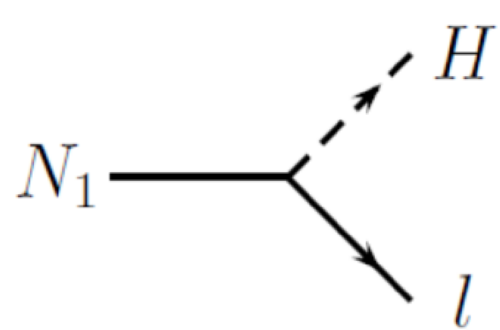
Majorana mass term

Interaction with SM particles via Yukawa coupling

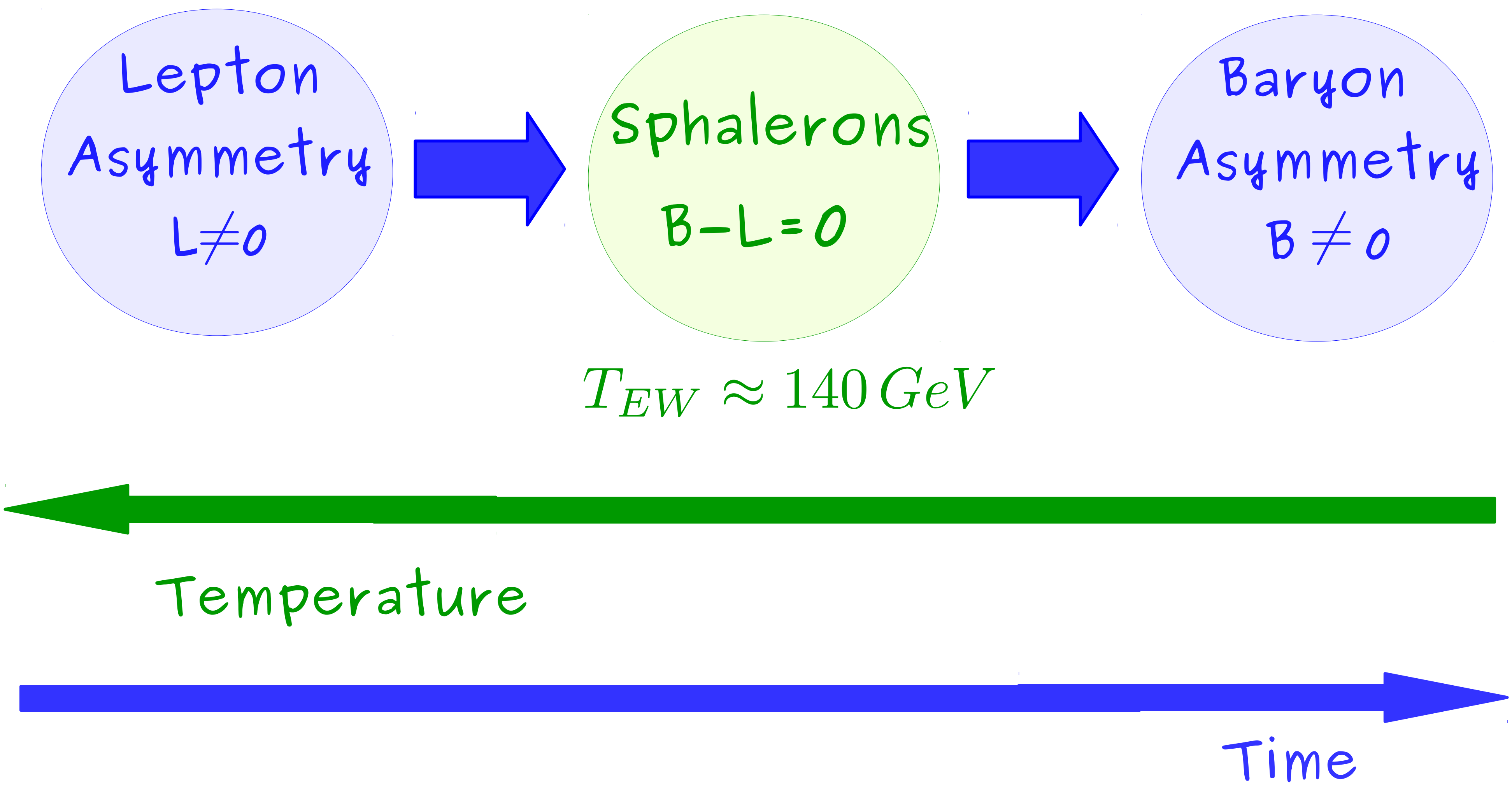
Lepton Number Violation



$\sim Y$

Standard Leptogenesis

Right-handed neutrino decays which violate CP and lepton number generate lepton asymmetry before $T_{EW} \approx 140\,GeV$



Sakharov conditions

1 Baryon number violation

If baryon asymmetry is conserved, no baryon number can be generated

OK in the SM ⟺ Sphalerons @T ≈ 140GeV

Sakharov conditions

(2) C and CP violation ✓

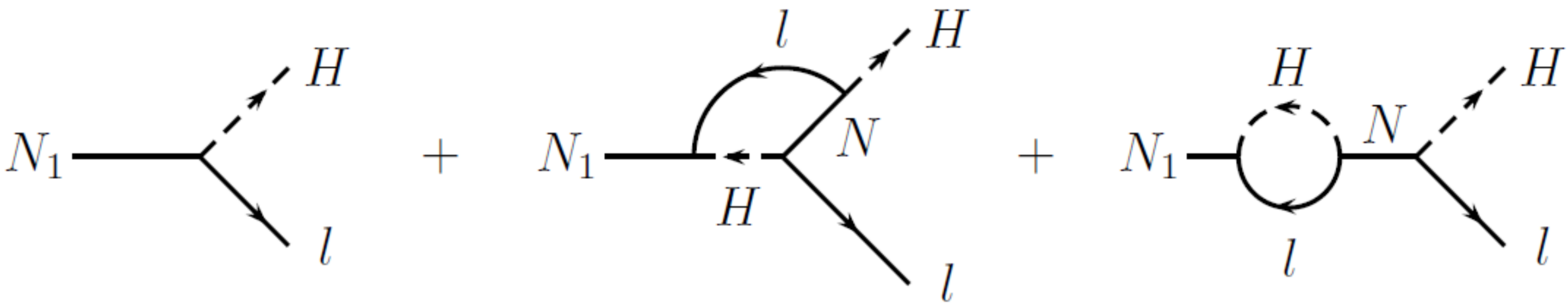
There is CP violation in the SM quark sector

Not enough CP violation in SM !!

if it also exists in lepton sector ⟺ enough CP violation

Sakharov conditions

② C and CP violation

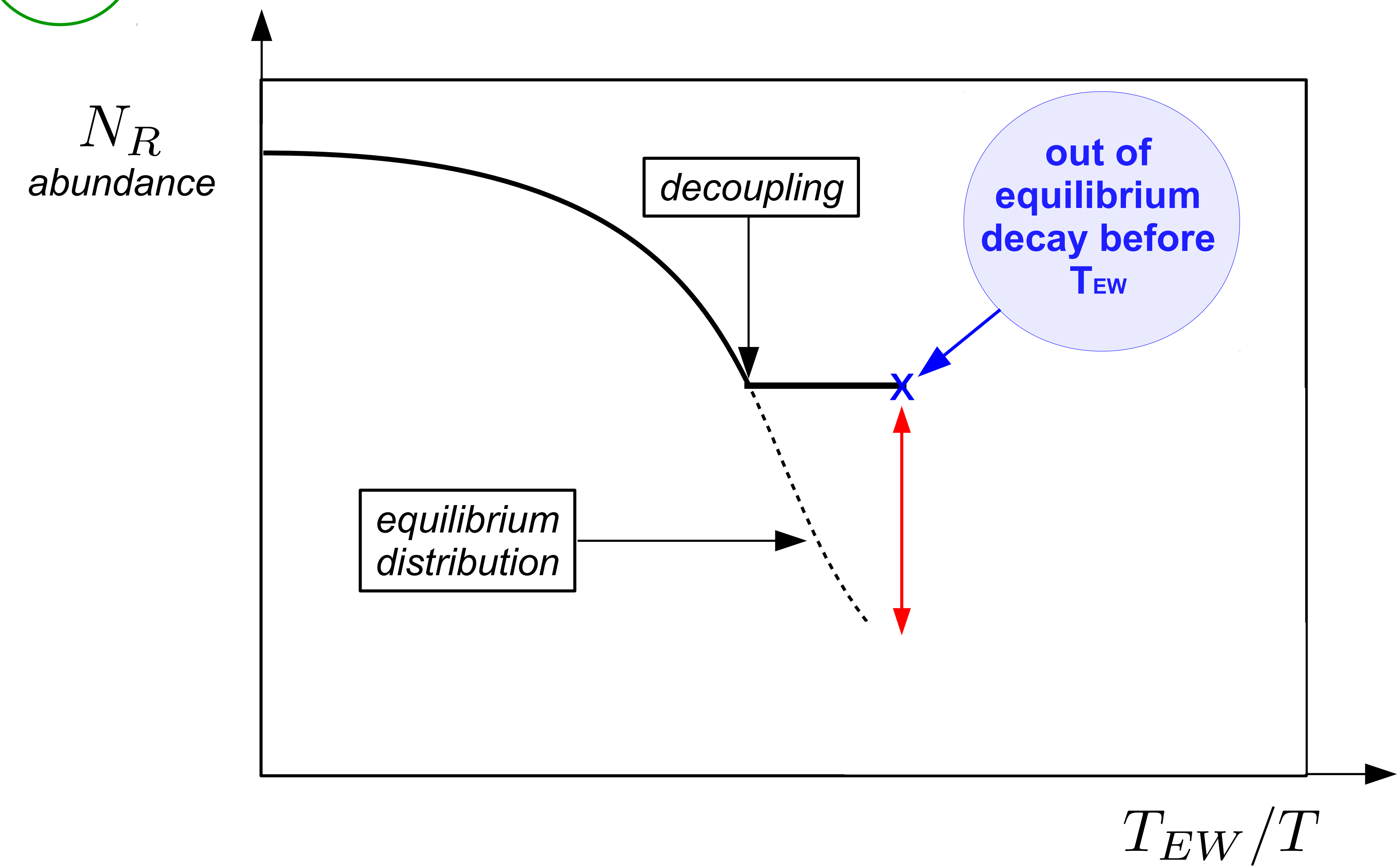


At one loop: CP asymmetry generated via interference effects

$$\epsilon = \frac{\Gamma(N \to lH) - \Gamma(N \to l^c H^c)}{\Gamma(N \to lH) + \Gamma(N \to l^c H^c)} \propto Im(Y^\dagger Y)^2_{ij}$$

Sakharov conditions

③ Departure from thermal equilibrium



Dependence on leptonic CP phases

- It is encoded in the Yukawa couplings:

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- Generation of light neutrino masses imposes constraints on Yukawa couplings from neutrino oscillation data

$$m_\nu = \frac{v^2}{2} Y M^{-1} Y^T = U_{PMNS}\, m\, U^T_{PMNS}$$

Dependence on leptonic CP phases

- It is encoded in the Yukawa couplings:

$$Y = U^*_{PMNS}\sqrt{m}\,R^T\sqrt{M}\frac{\sqrt{2}}{v}$$

Casas-Ibarra

Light Sector

- Majorana phases
  (experimentally challenging)
- Dirac CP phase δ
  (accessible via neutrino oscillations)

Heavy Sector

- Complex $3 \times n_R$ orthogonal matrix

	# of extra CP phases
$n_R = 3$	3
$n_R = 2$	1

Dependence on leptonic CP phases

- The Baryon asymmetry generated depends on both light and heavy CP phases.

Light Sector   Heavy Sector

$$Y = U^*_{PMNS}\sqrt{m}\,R^T\sqrt{M}\frac{\sqrt{2}}{v}$$

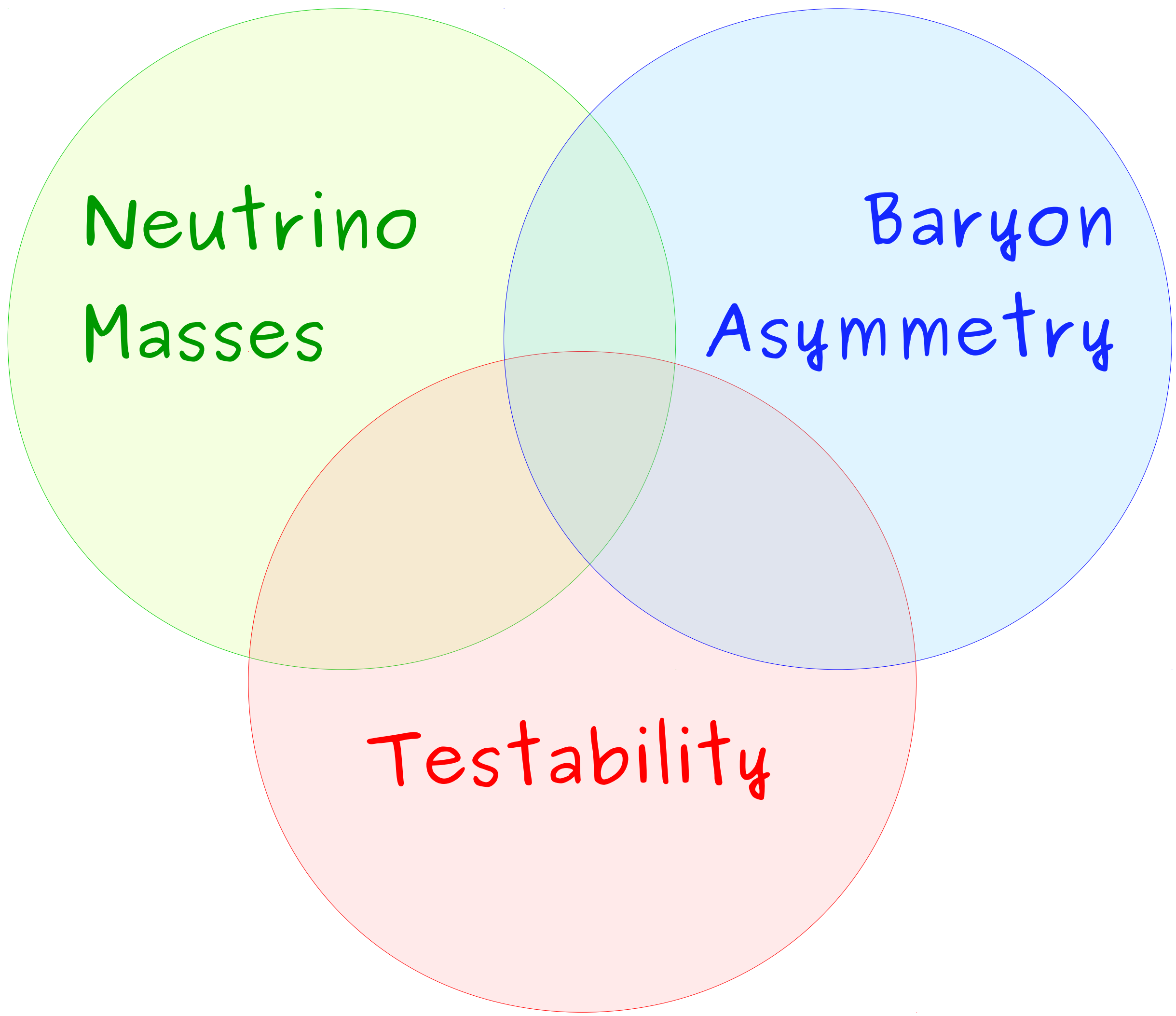
Casas-Ibarra

- The Dirac CP phase becomes particularly relevant mainly in two cases:

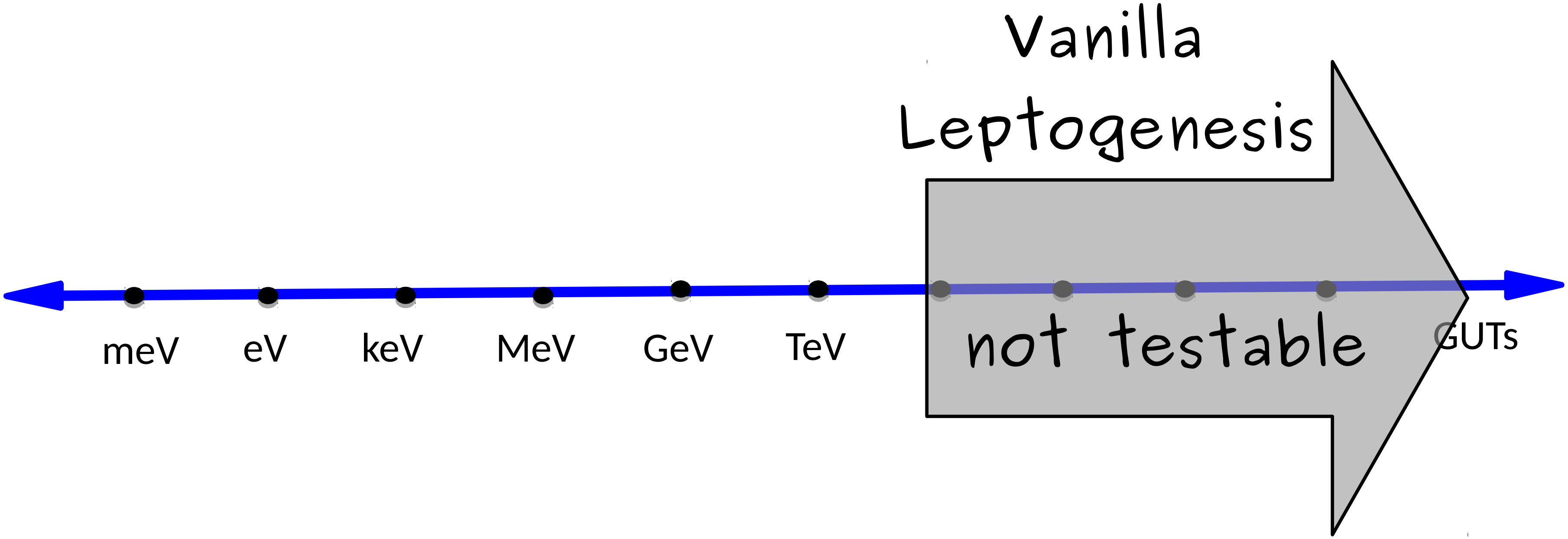
1. Flavor Models
Yukawa structure (R matrix) is constrained by flavor symmetries

2. Minimal model with 2 N_R
Small number of phases: *1 Dirac + 1 Majorana + 1 Heavy*

Testable Leptogenesis



The New Physics Scale



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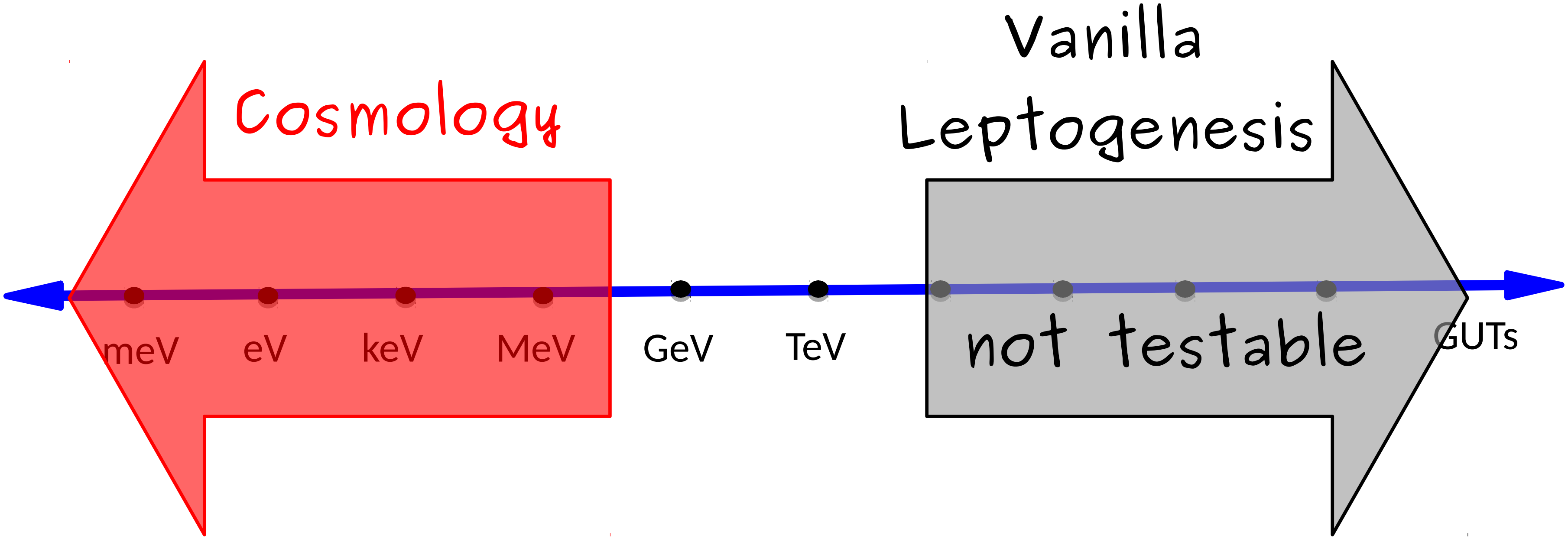
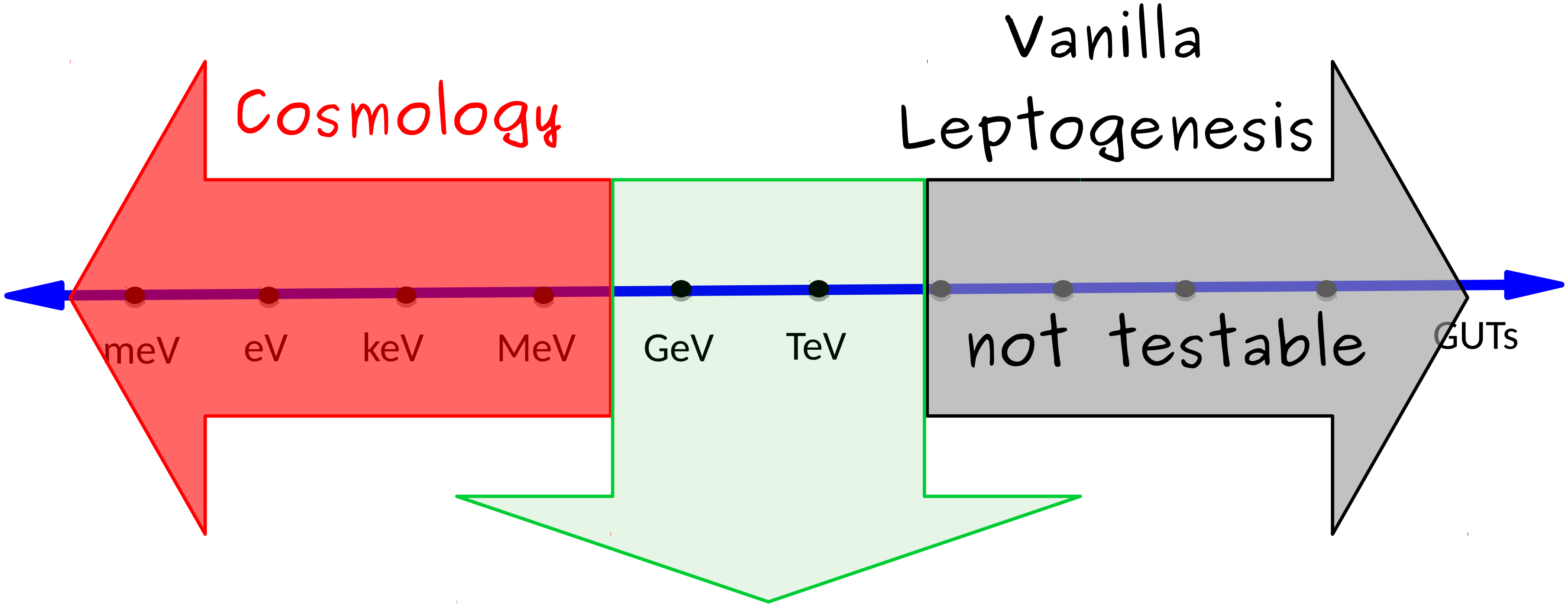


P. Hernandez, M. Kekic, JLP 1311.2614;1406.2961

The New Physics Scale

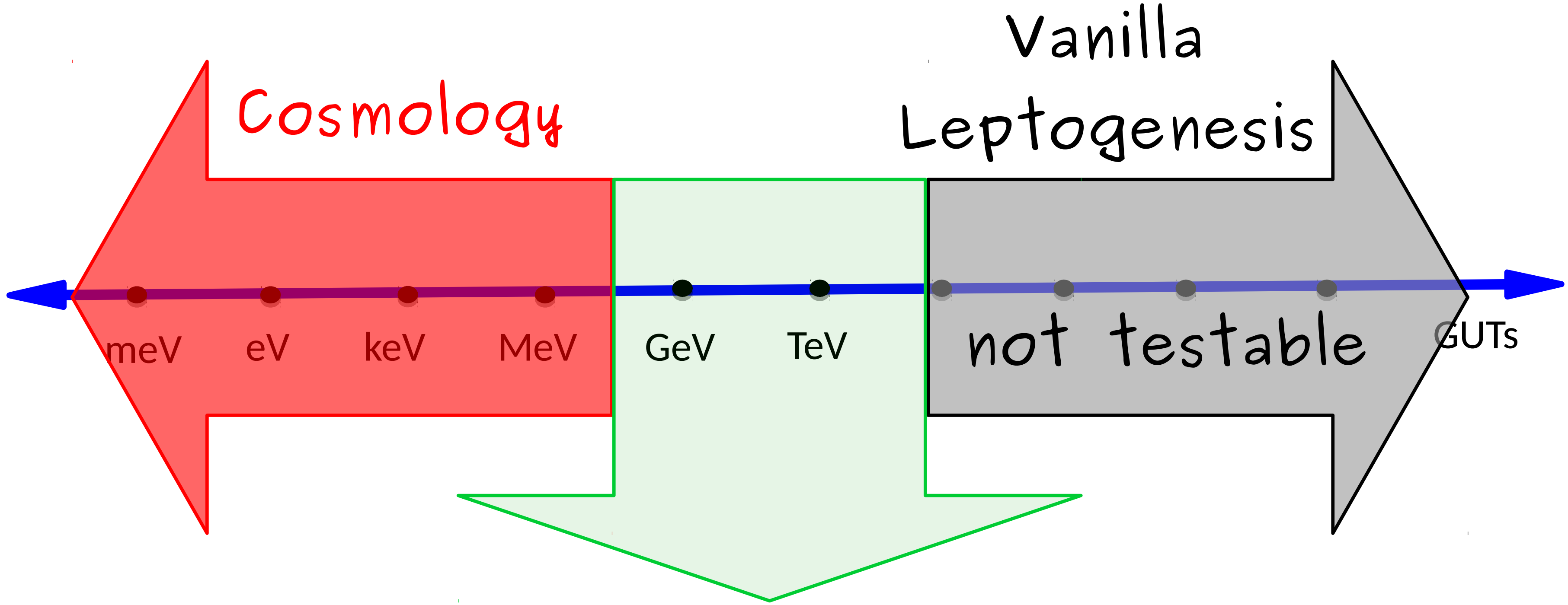


- $0\nu\beta\beta$ decay
  LFV, SHiP, LHC
  FCC…
- Leptogenesis
  via Oscillations
  M=0.1−100GeV

  Akhmedov, Rubakov, Smirnov (ARS)
  Asaka, Shaposnikov (AS)
- Resonant
  Leptogenesis
  M>100GeV

  Pilaftsis

The New Physics Scale



- $0\nu\beta\beta$ decay

LFV, SHiP, LHC
FCC...

- Leptogenesis via Oscillations

M=0.1–100GeV

Akhmedov, Rubakov, Smirnov (ARS)
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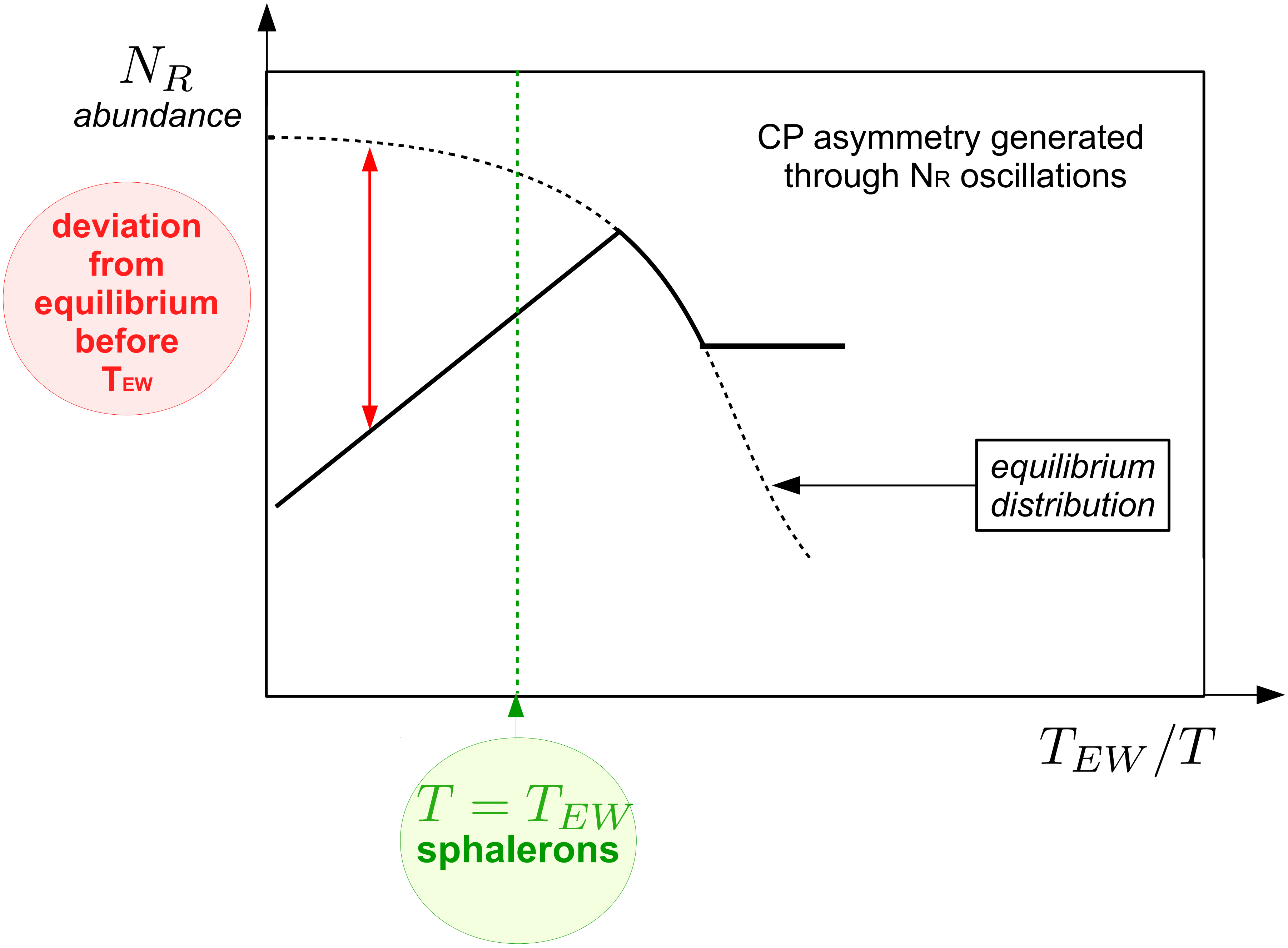
- Resonant Leptogenesis

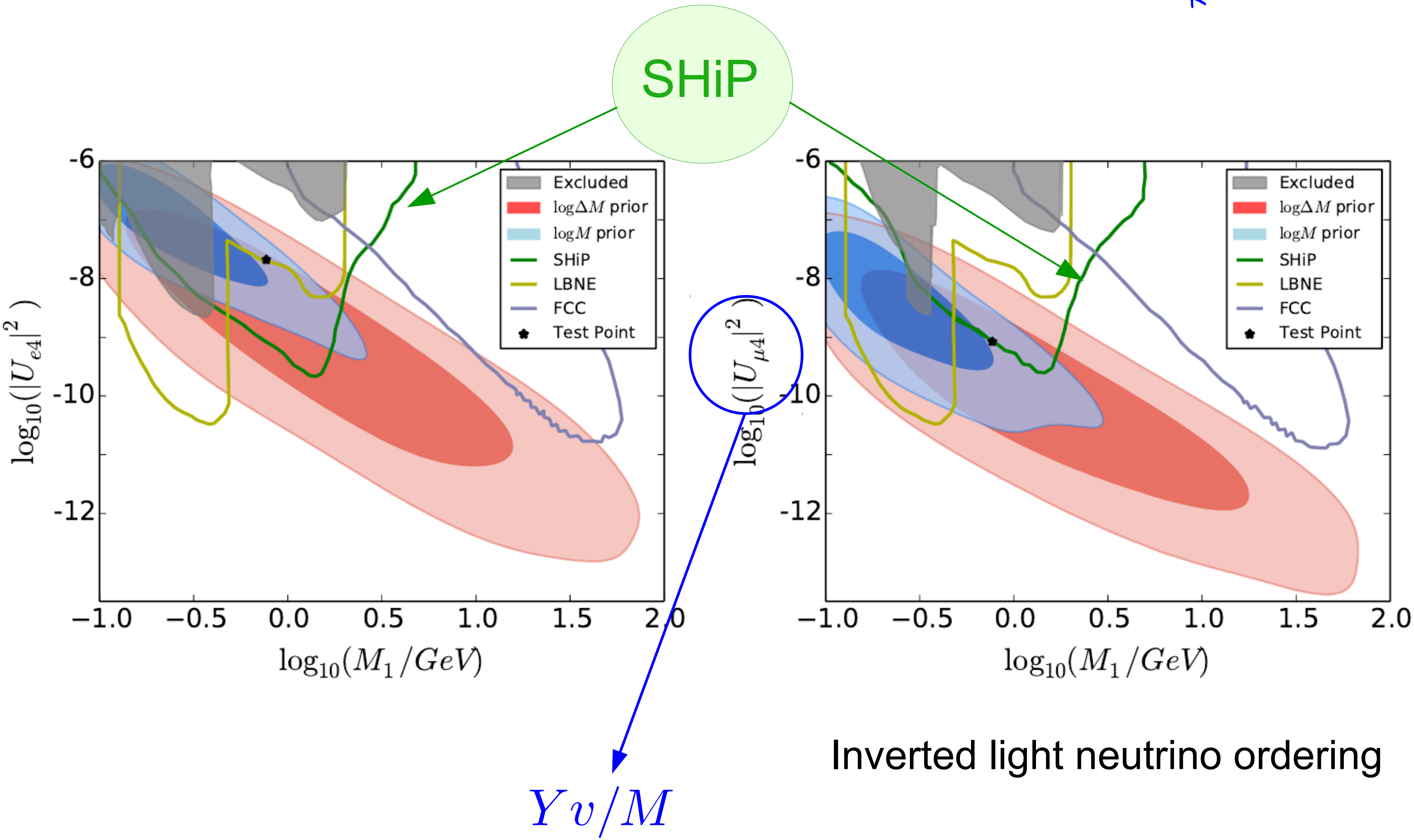
M>100GeV

Pilaftsis

Low Scale Leptogenesis (ARS)



Leptogenesis in Minimal Model $n_R=2$



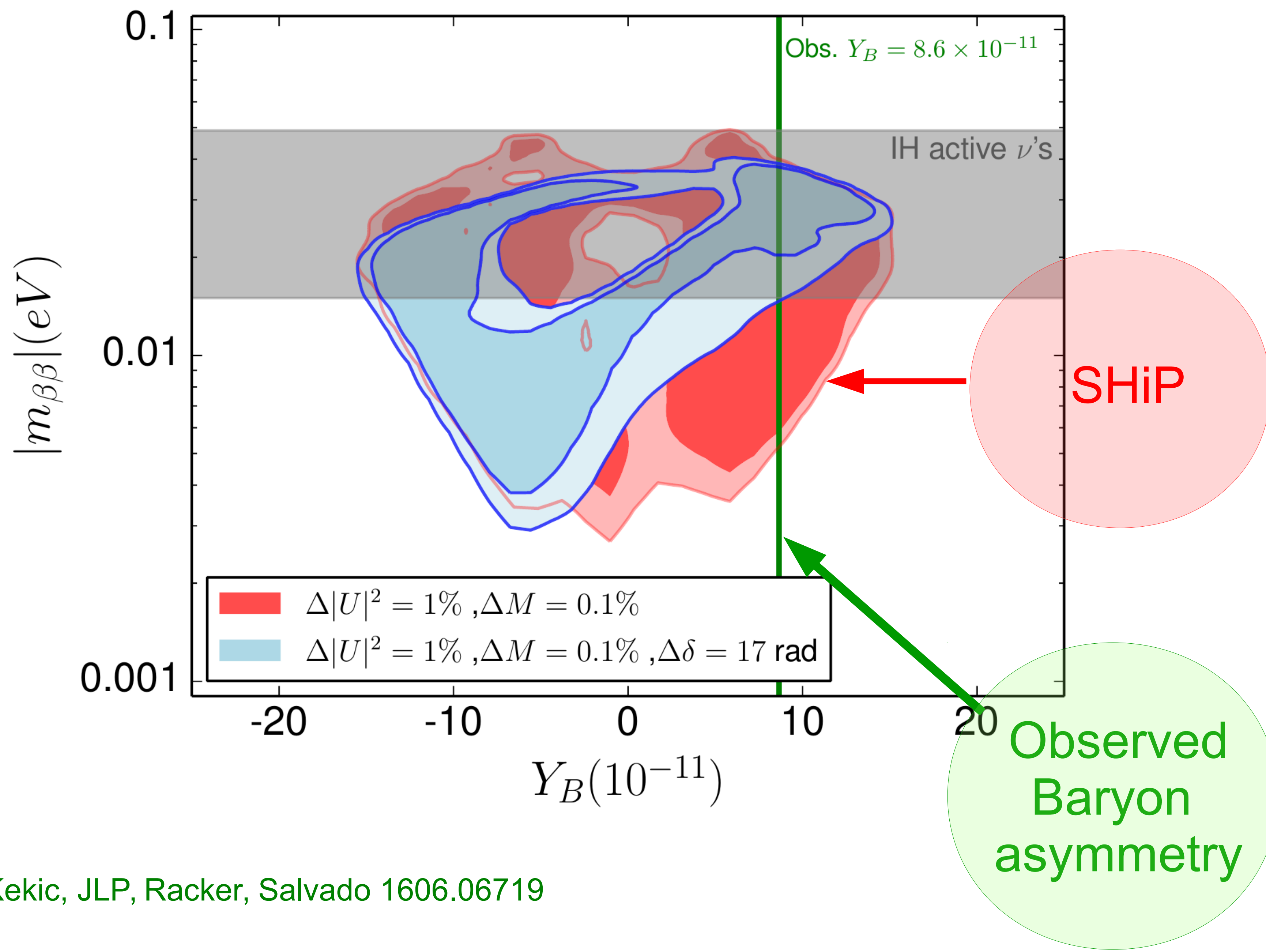
Inverted light neutrino ordering

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Can we experimentally determine Baryon asymmetry generated in minimal model

?

Determining Y_B in minimal model $n_R=2$



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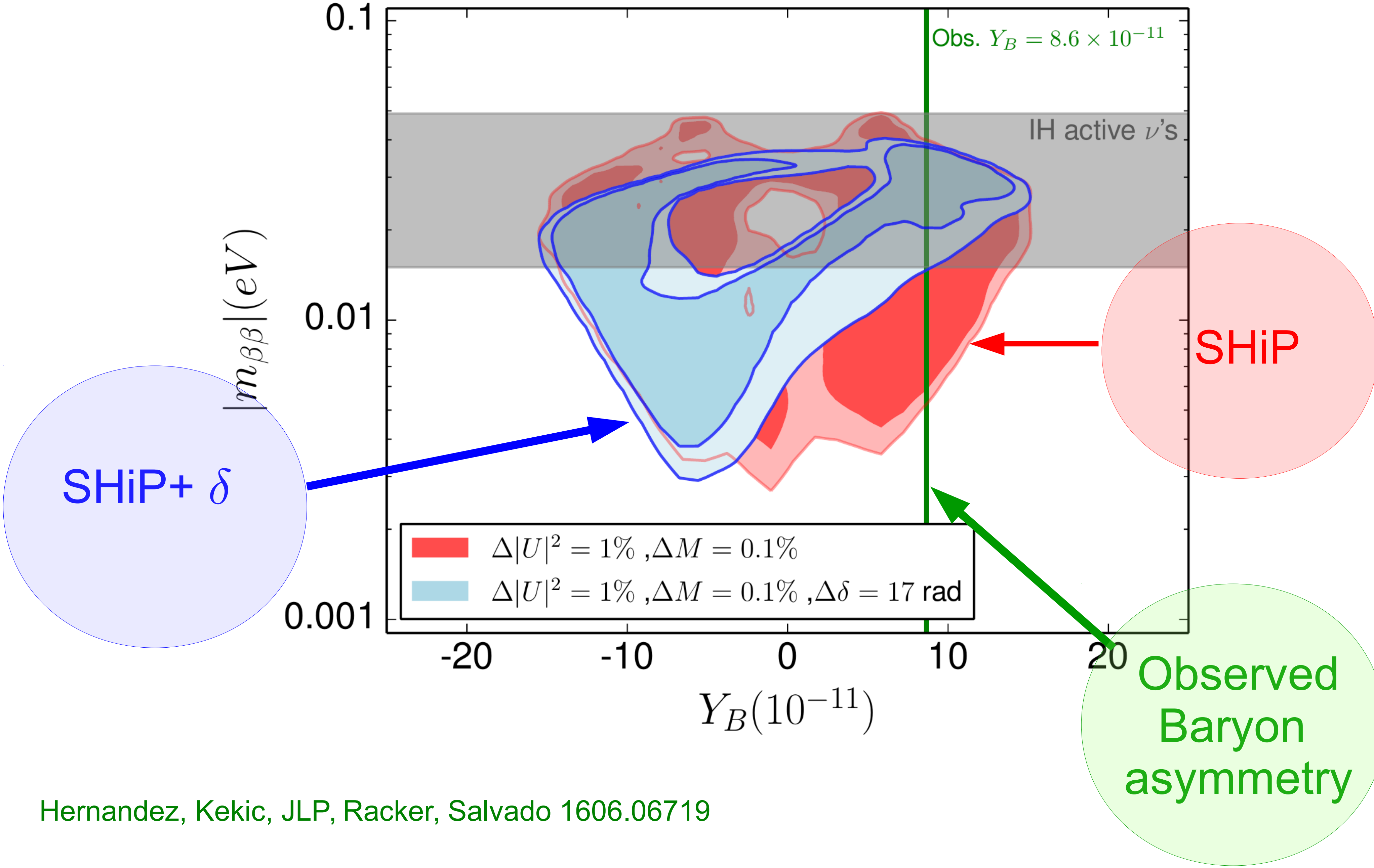

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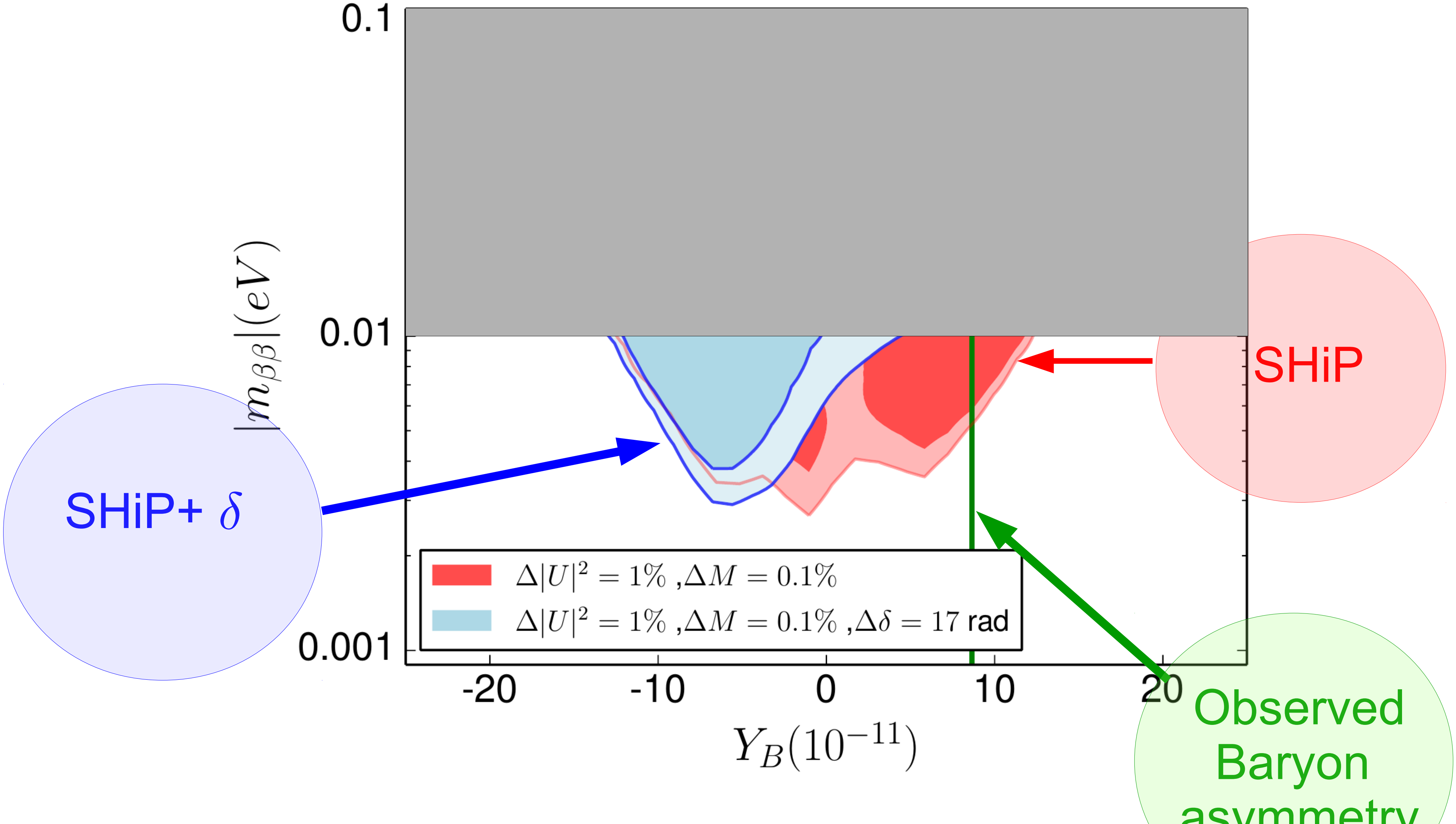

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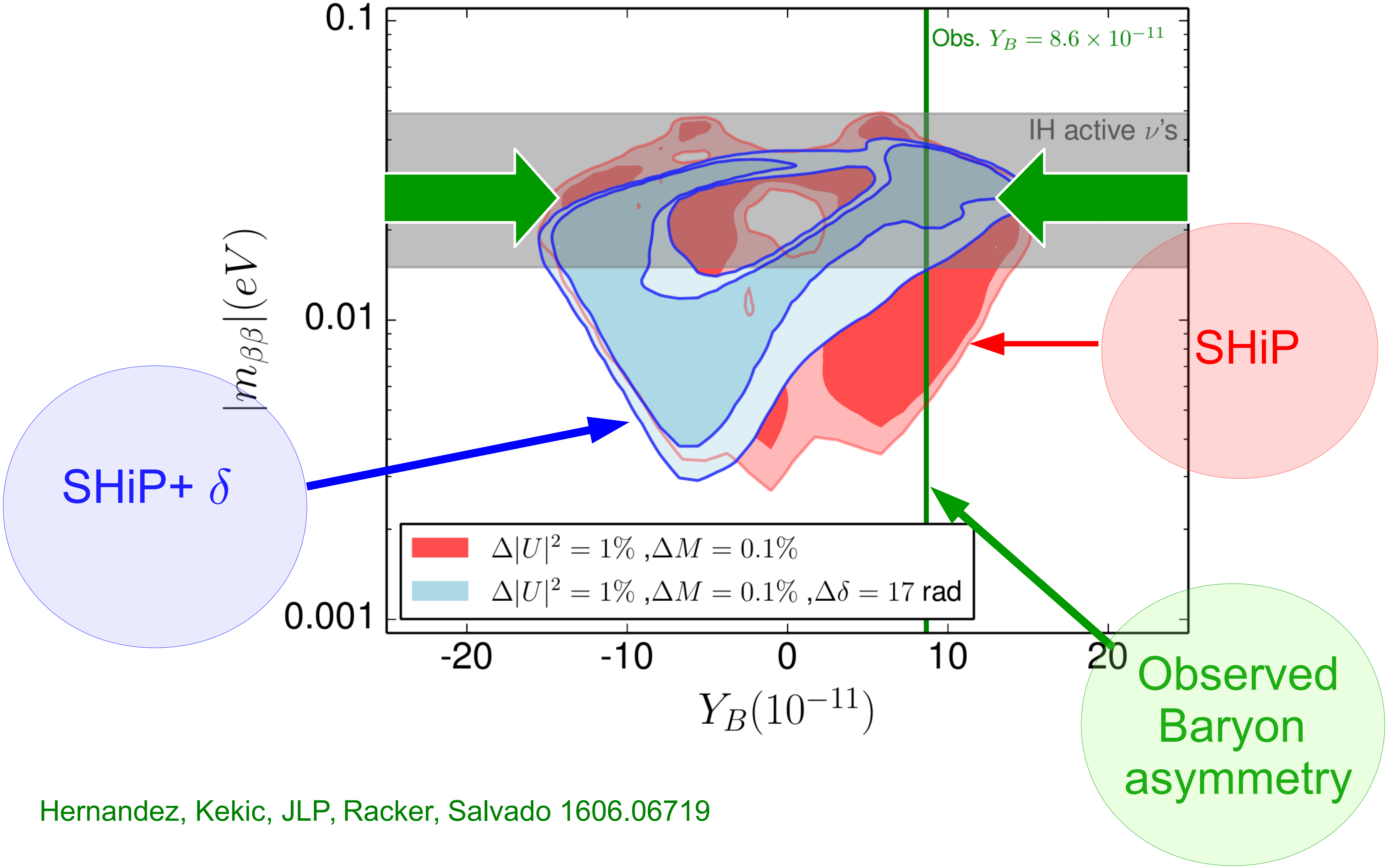

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Conclusions

- Observed universe mainly made out of only matter!
- Simplest extension of SM able to account for neutrino masses

can explain matter asymmetry of our universe via Leptogenesis

- **Leptonic CP violation required**.
- *Baryon asymmetry* generated generically *depends on CP phases from* both *light and heavy sector*.
- **Dirac CP phase particularly relevant in minimal model with two right-handed neutrinos and models including flavor symmetries.**
- Low Scale Minimal Seesaw Models are testable and highly predictive: *the mechanisms generating neutrino masses and Baryon asymmetry can be potentially tested.*

Leptogenesis in Minimal Model $n_R = 2$

$$Y_B^{\rm exp} \simeq 8.65(8) \times 10^{-11}$$

Bayesian posterior probabilities (using nested sampling Montecarlo MultiNest)

$$\log \mathcal{L} = -\frac{1}{2}\left(\frac{Y_B(t_{\rm EW}) - Y_B^{\rm exp}}{\sigma_{Y_B}}\right)^2 .$$

Casas-Ibarra $R\,(\theta + i\gamma)$

Parameters of the model	$\theta_{23}, \theta_{12}, \theta_{13}, m_2, m_3,$	$M_1, M_2, \delta, \phi_1, \theta, \gamma$

Fixed by neutrino oscillation experiments

Free parameters

Determining Y_B in minimal model $n_R=2$

- **Baryon asymmetry depends on all the unknown parameters**

- **SHiP sensitivity** ⇔ $|U^2_{\alpha j}| \gg m_\nu / M$

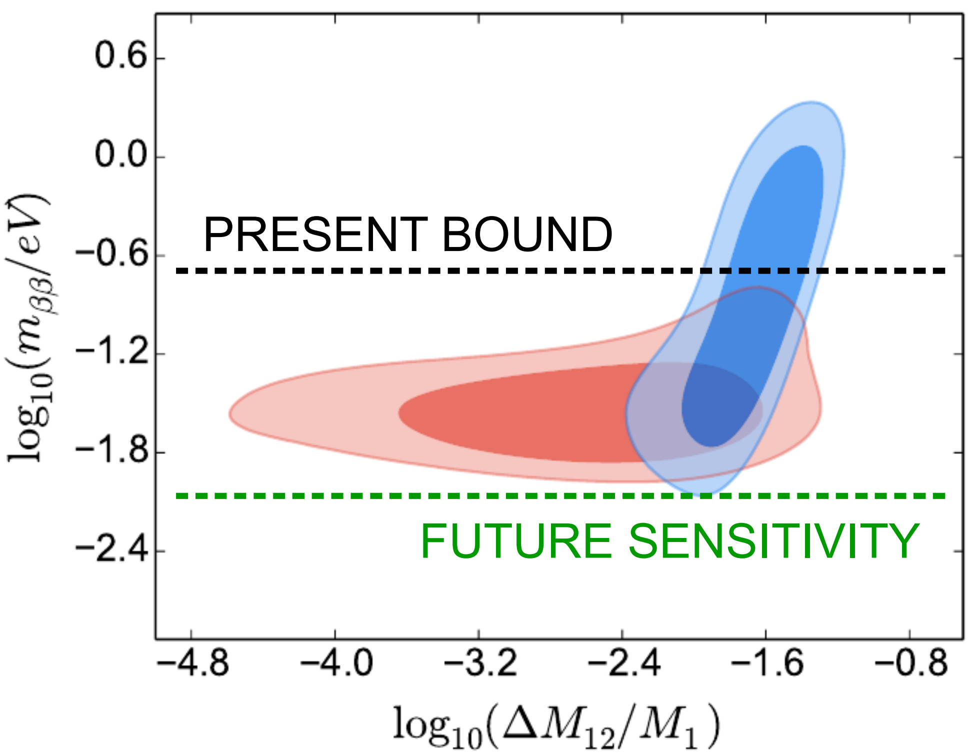
SHiP sensitive to $|U_{\alpha j}|(\delta, \phi_1, \gamma),\ M_j$

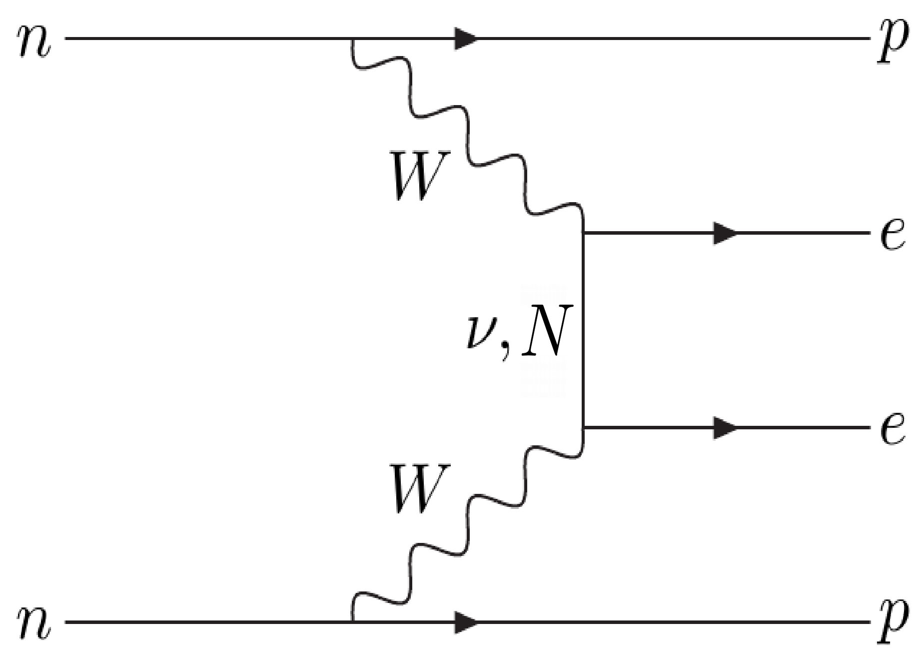
$$(U_{\alpha j})^2 \propto e^{-2\theta i}\, e^{2\gamma} f\left(\delta, \phi_1, M_j\right)$$

Neutrinoless double beta decay sensitive to θ through interference between light and heavy contribution

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Determining Y_B in minimal model $n_R=2$



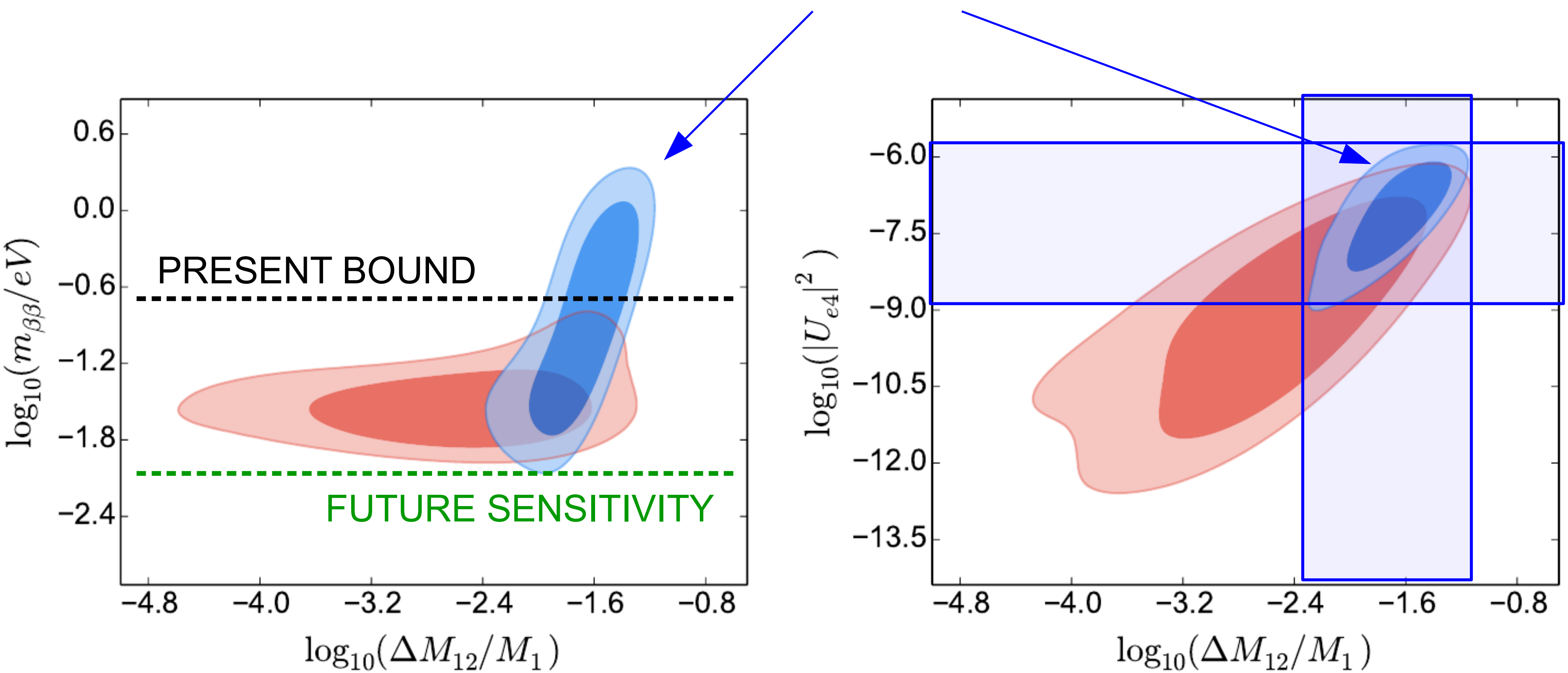


Inverted light neutrino ordering (IH)

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Leptogenesis in Minimal Model $n_R=2$

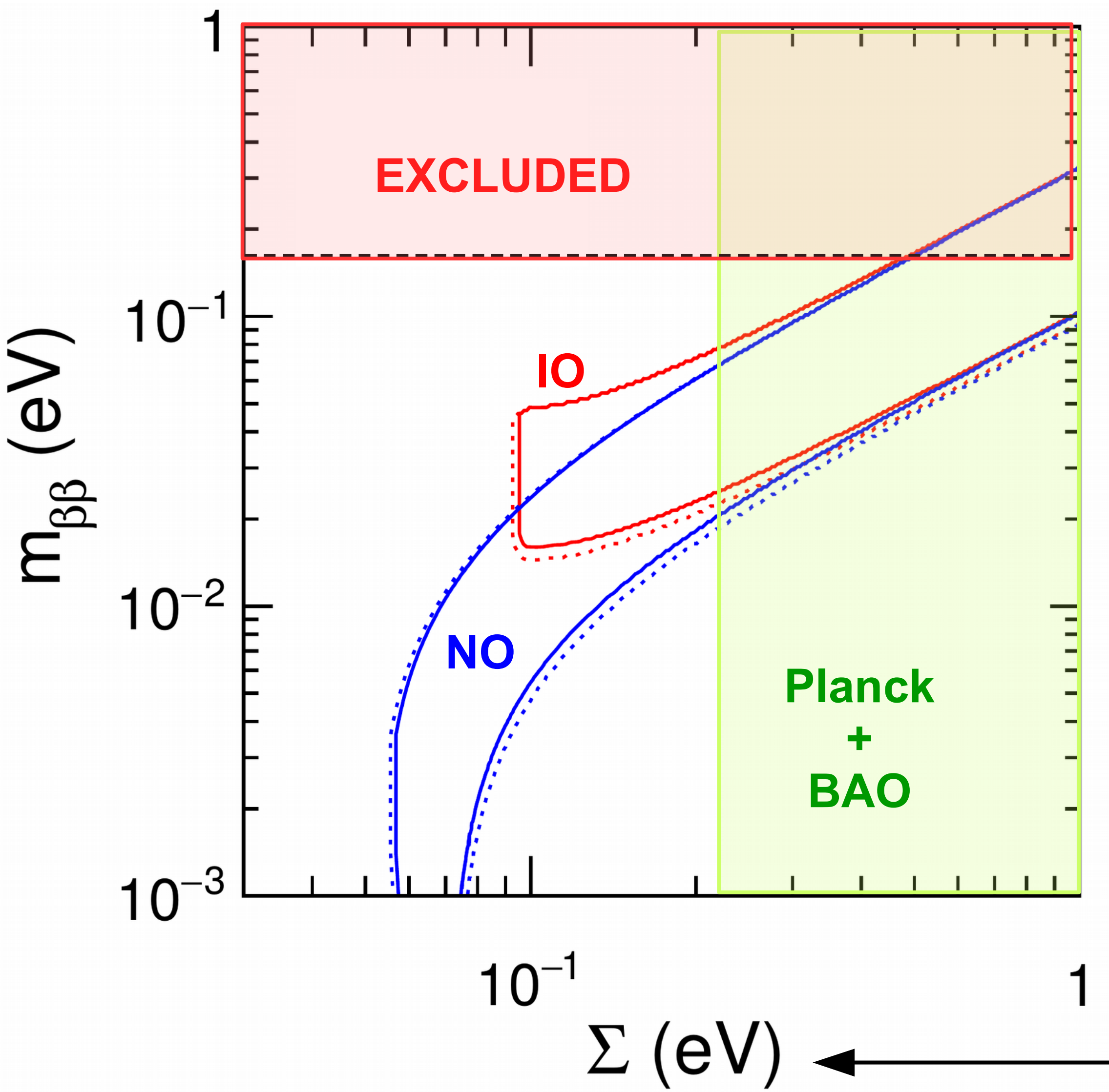
Non very degenerate solutions



Inverted light neutrino ordering (IH)

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Neutrinoless double beta decay



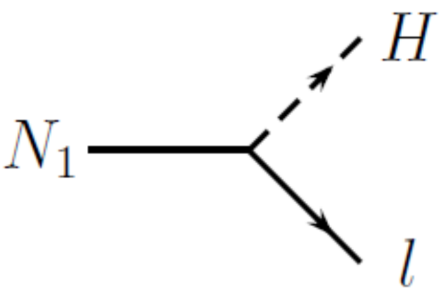
- Outstanding complementarity with ν-oscillations, Katrin and cosmology.
- *Extremely relevant input in order to probe New Physics models responsible for nu mass generation.*

Sum of three neutrino masses

Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo 1703.0447

Sakharov conditions

2 C and CP violation



At tree level the rates $\Gamma(N \to lH)$ and $\Gamma(N \to l^c H^c)$ are identical

No CP Asymmetry

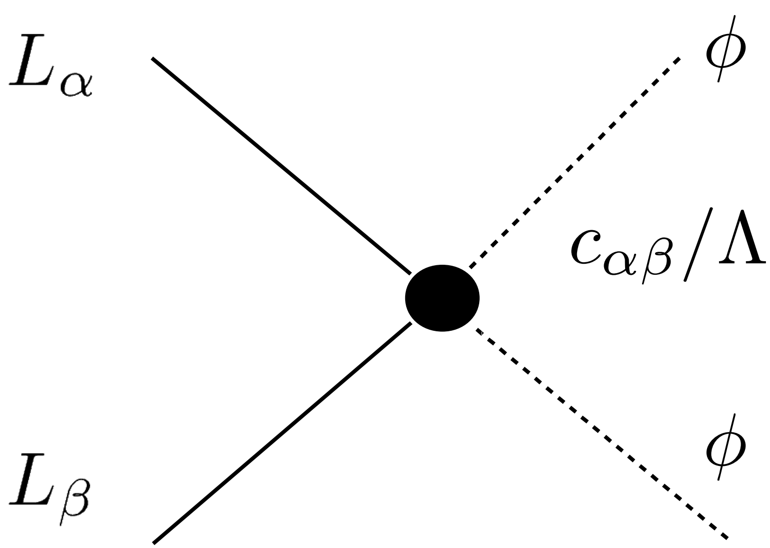
$$\epsilon = \frac{\Gamma(N \to lH) - \Gamma(N \to l^c H^c)}{\Gamma(N \to lH) + \Gamma(N \to l^c H^c)} = 0$$

The neutrino mass problem

- Consider SM as a low energy effective theory. With the SM field content, the lowest dimension effective operator is the following (d=5):

$$\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{L^c}_\alpha \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right) \xrightarrow{\text{SSB}} \frac{cv^2}{\Lambda}\overline{\nu^c_\alpha}\nu_\alpha$$

Weinberg 76

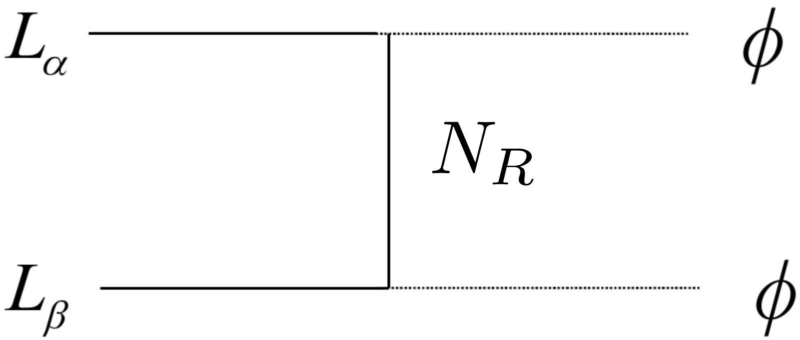


☺ Smallness of neutrino masses can be explained

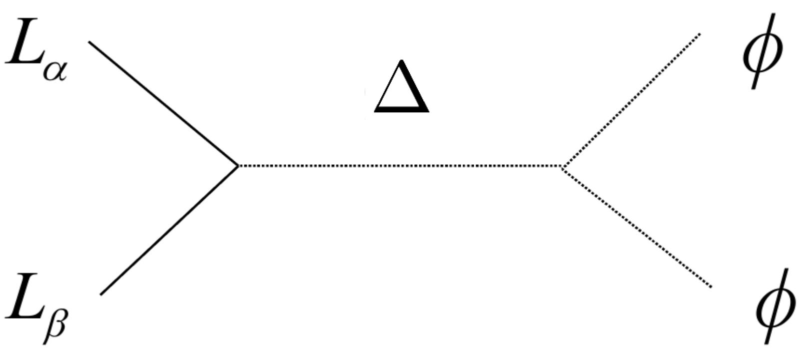
☺ Majorana masses
Neutrinos their own antiparticle

$0\nu\beta\beta$ decay

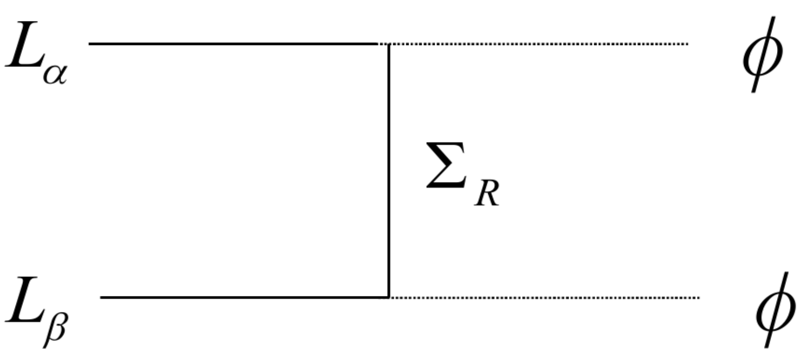
Seesaw Models



Heavy fermion singlet: N_R. Type I *seesaw.* Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.



Heavy scalar triplet: Δ. Type II *seesaw.* Magg, Wetterich 80; Schecter, Valle 80; Lazarides, Shafi, Wetterich 81; Mohapatra, Senjanovic 81.



Heavy fermion triplet: Σ
Type III *seesaw.* Foot, Lew, Joshi 89

CP violation, Mass Ordering and Octant

$$P_{e\mu} - P_{\bar{e}\bar{\mu}} = J \cos\left(\pm\delta - \frac{\Delta_{31}L}{2}\right) \sin\left(\frac{\Delta_{21}L}{2}\right) \sin\left(\frac{\Delta_{31}L}{2}\right)$$

CP invariant

Jarlskog 85

$$J \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

Bad News

The neutrino ordering and the octant are still unkown

Potential degeneracies

Minakata, Nunokawa hep-ph/0108085

Barger, Marfatia, Whisnant, hep-ph/0112119