Leptogenesis

PetcovFEST, 24 April 2023

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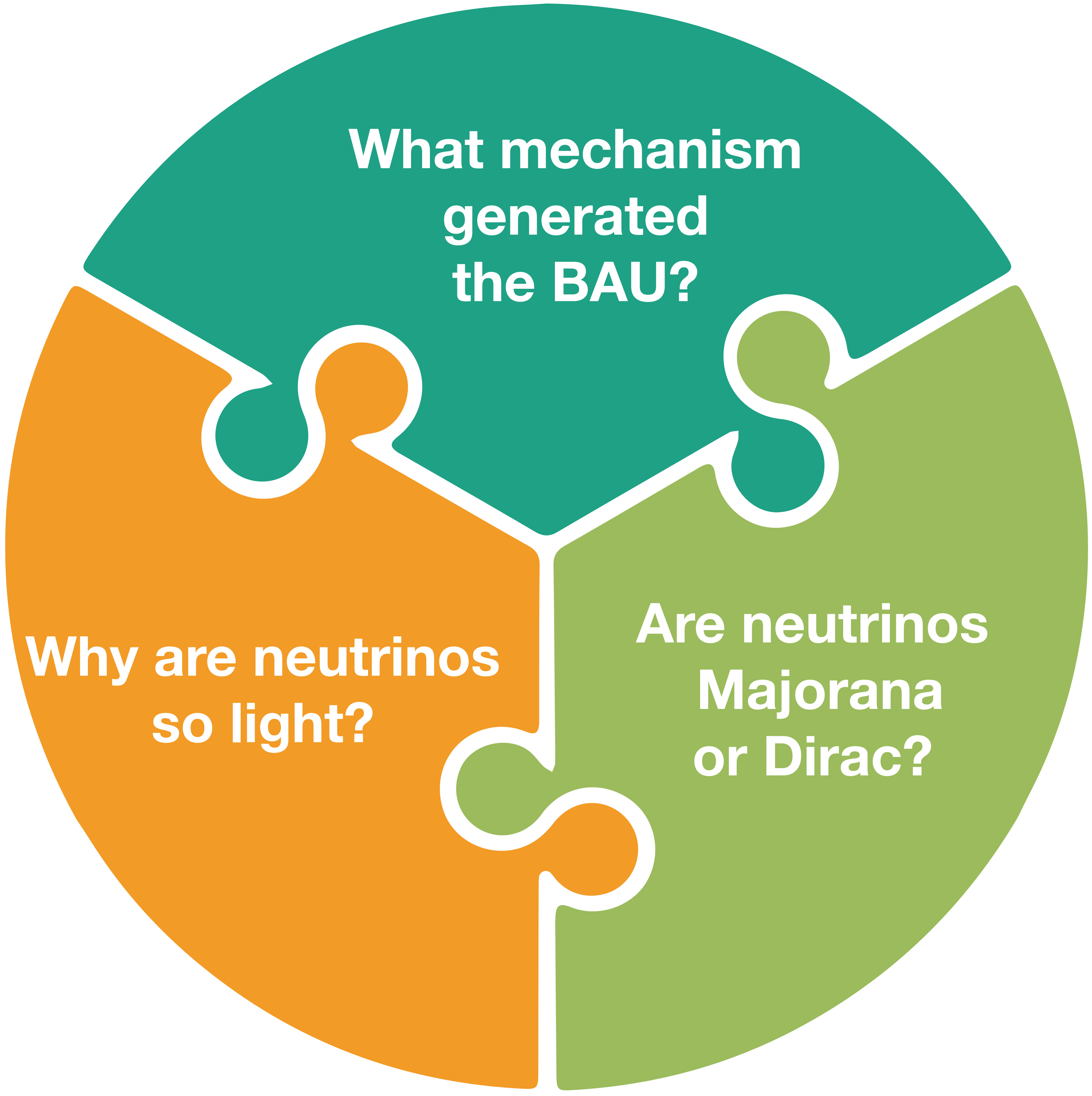
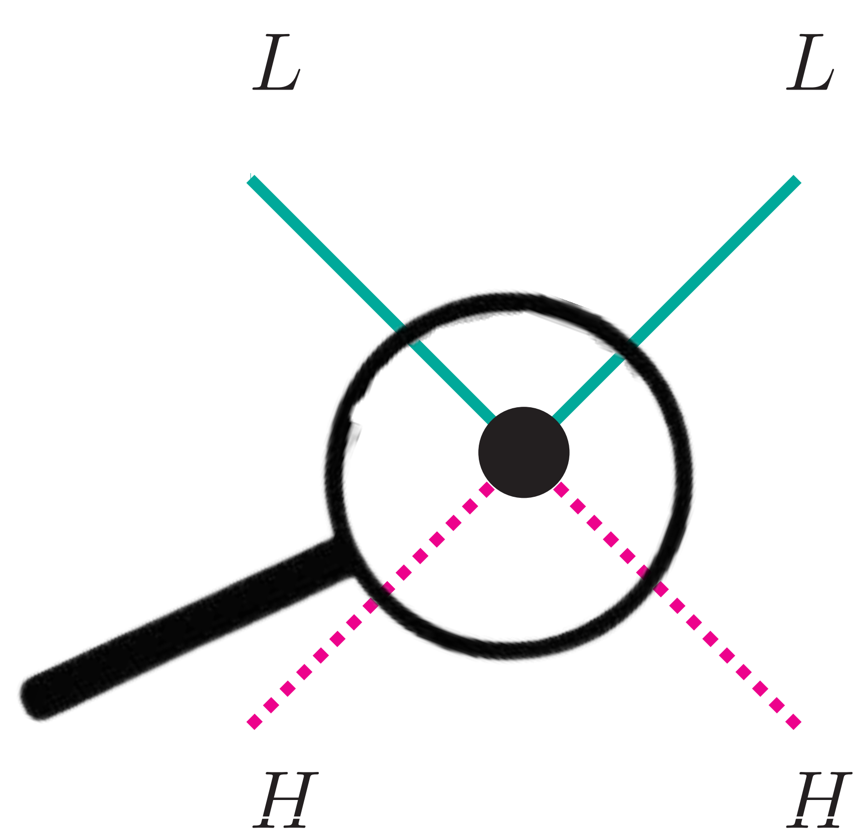
Motivation for Leptogenesis



The Seesaw Mechanism

The Standard Model is an effective theory which contains non-renormalisable operators

$$\mathcal{L}_5 = \frac{Y_\nu}{2M}\left(\overline{L^c}\tilde{H}^*\right)\left(\tilde{H}^\dagger L\right)$$



Weinberg, *Phys.Rev.Lett. 43* (1979)

The Seesaw Mechanism

After electroweak symmetry is broken a Majorana mass is produced for neutrinos

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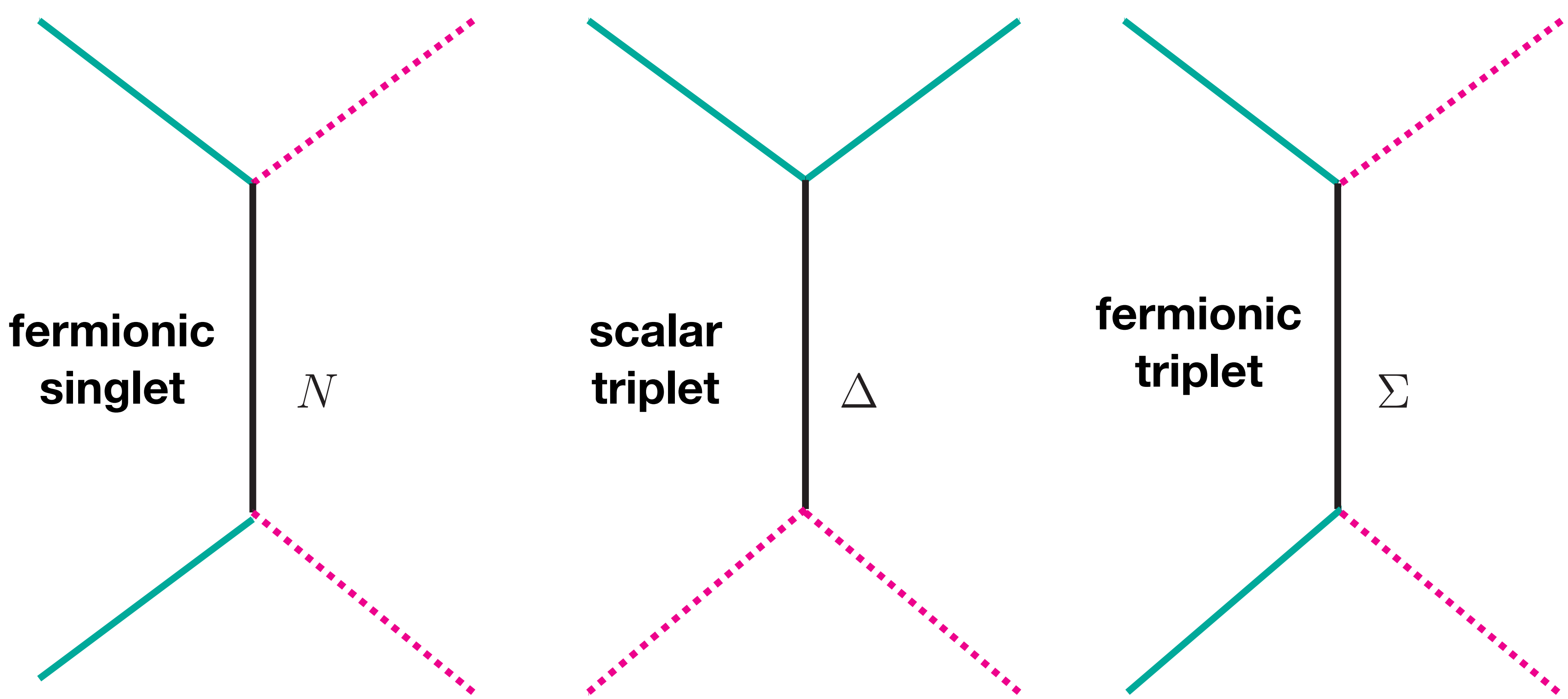

Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

Ma, Roy, Senjanovic, Hambye

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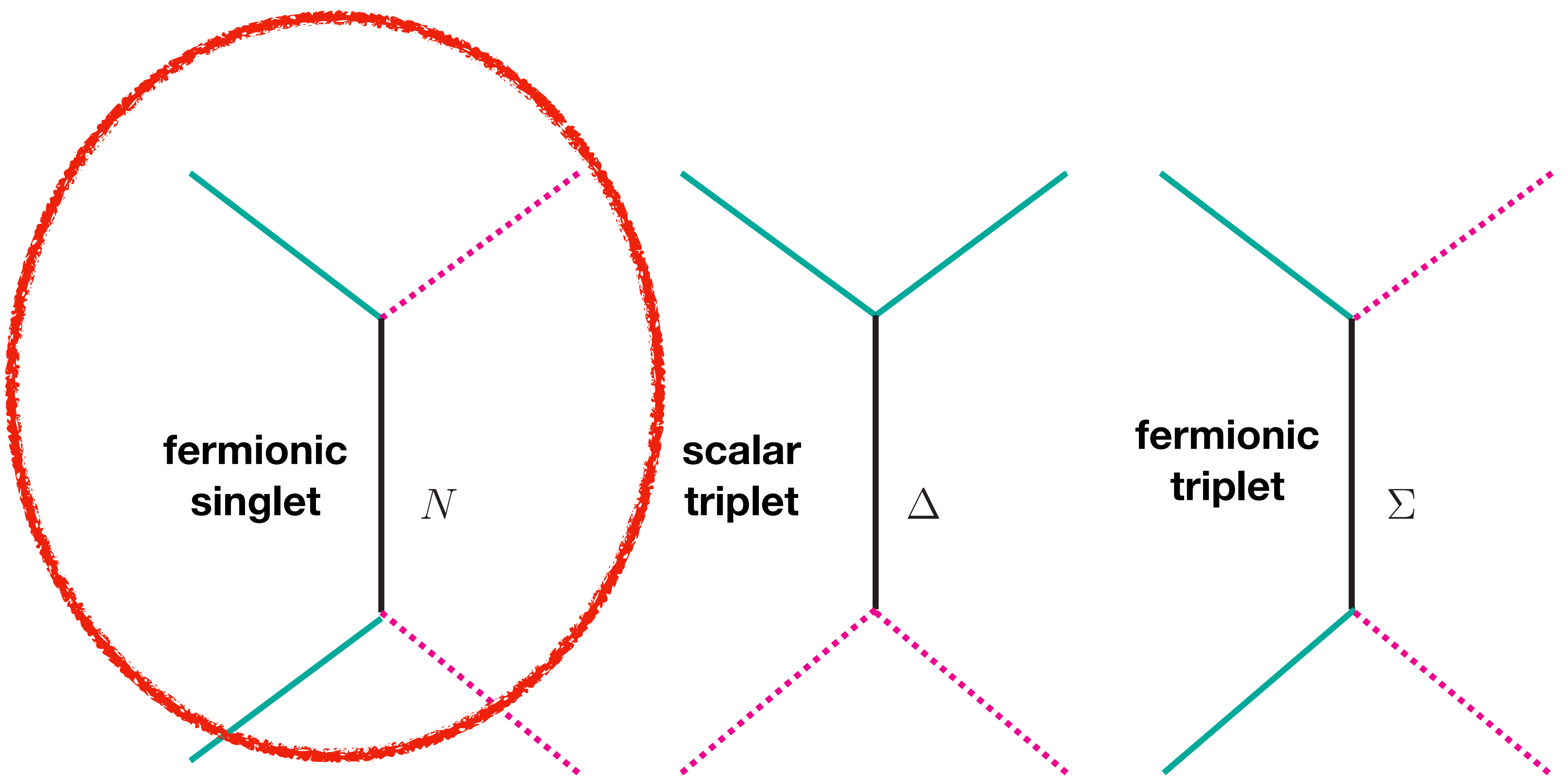

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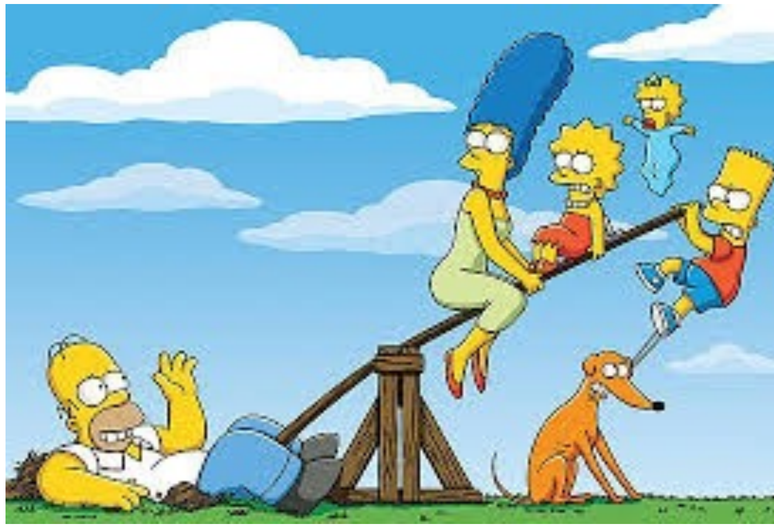
The Seesaw Mechanism



$$\mathcal{L} = Y_\nu \bar{L}\tilde{\Phi}N - \frac{1}{2}M_N\overline{N^c}N$$

$$= -\frac{1}{2}\left(\bar{\nu}_L, \overline{N^c}\right)\begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N \end{pmatrix}$$

$$m_D = \frac{Y_\nu v}{\sqrt{2}}$$

Diagonalisation

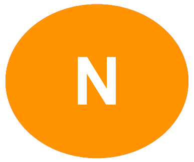
$$m_\nu = \frac{m_D m_D^T}{M_N} = \frac{Y_\nu^2 v^2}{2M_N} \sim 0.1\text{eV}$$

$$Y_\nu \sim \mathcal{O}(1) \implies M_N \sim 10^{14}\,\text{GeV}$$

Sakharov's conditions satisfied!

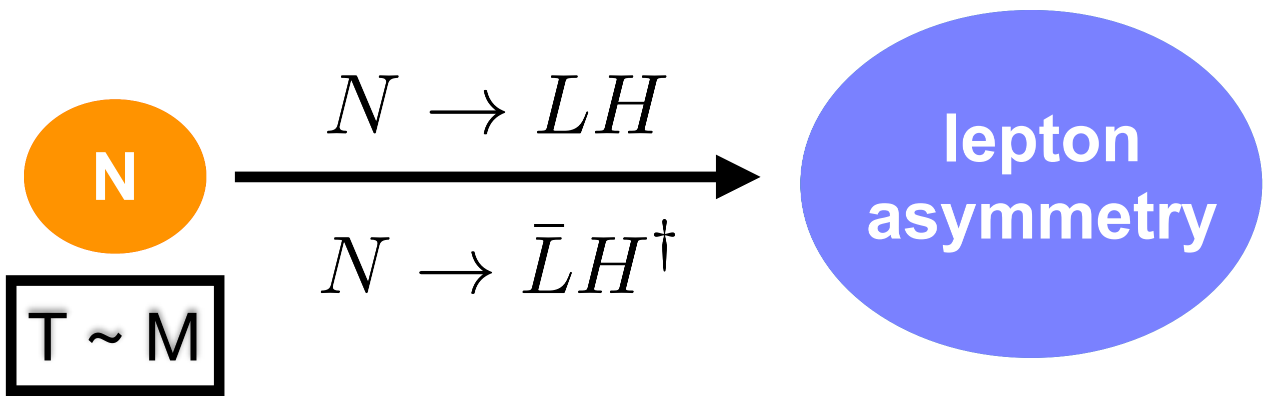
Thermal leptogenesis

Fukugida, Yanagida



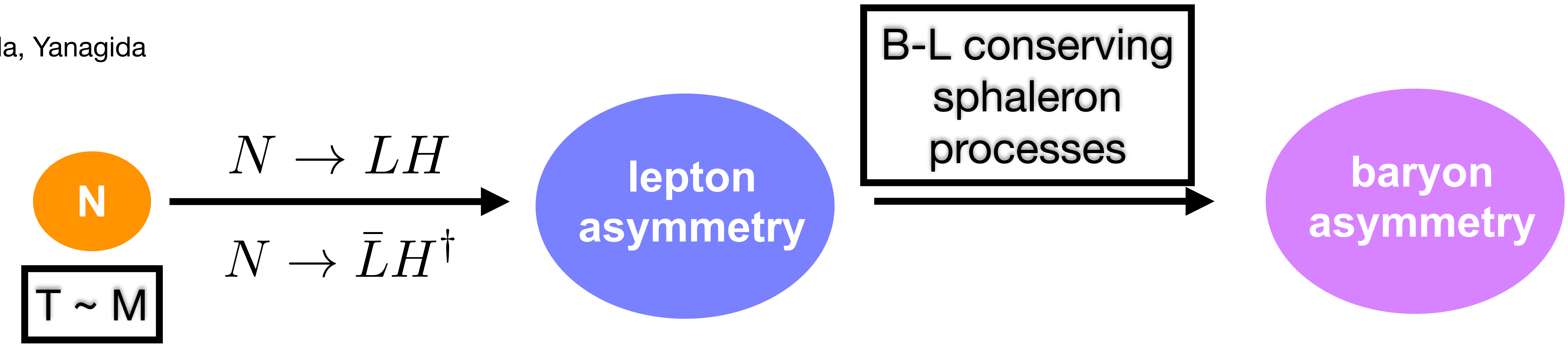
Thermal leptogenesis

Fukugida, Yanagida



Thermal leptogenesis

Fukugida, Yanagida



Thermal leptogenesis

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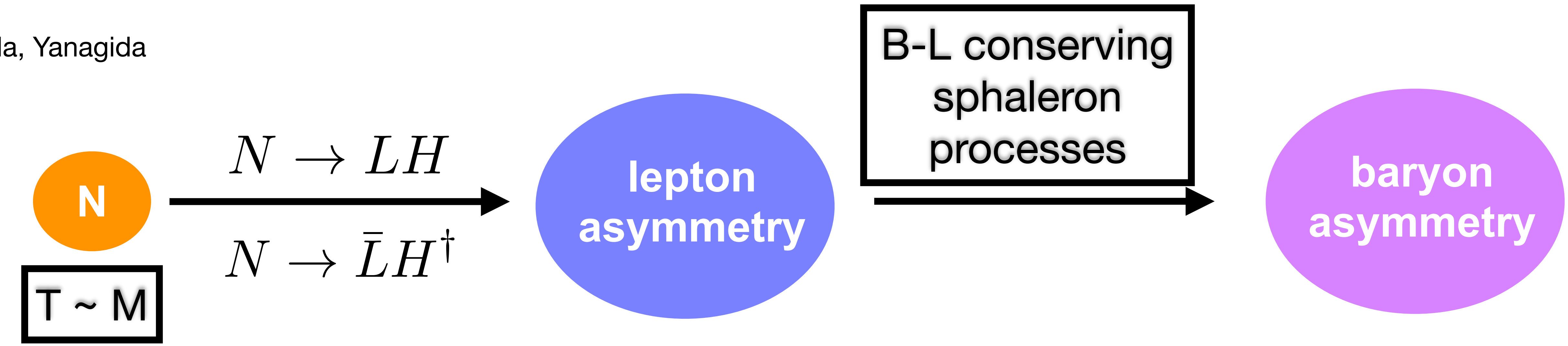
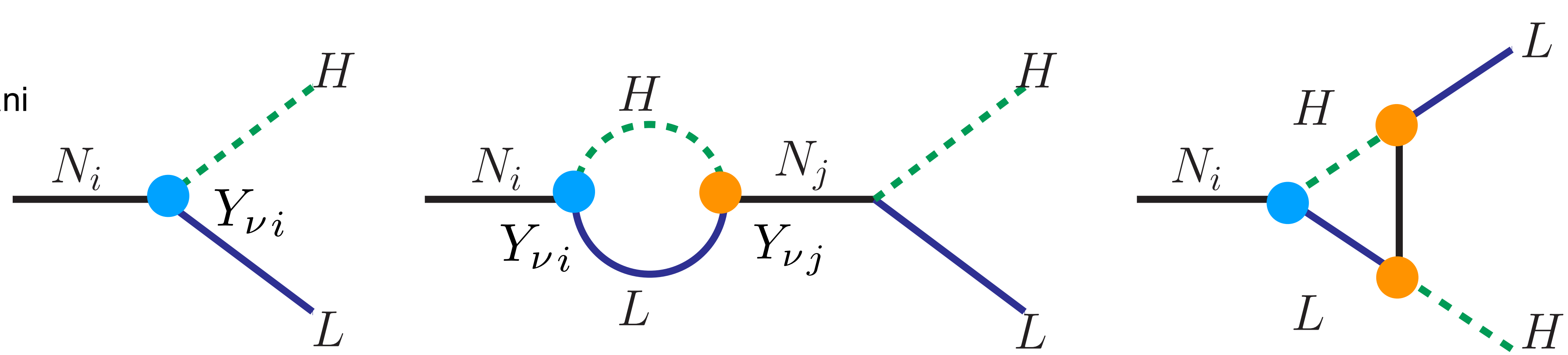


Decay asymmetry from interference between tree and loop level diagrams

Covi, Roulet, Vissani

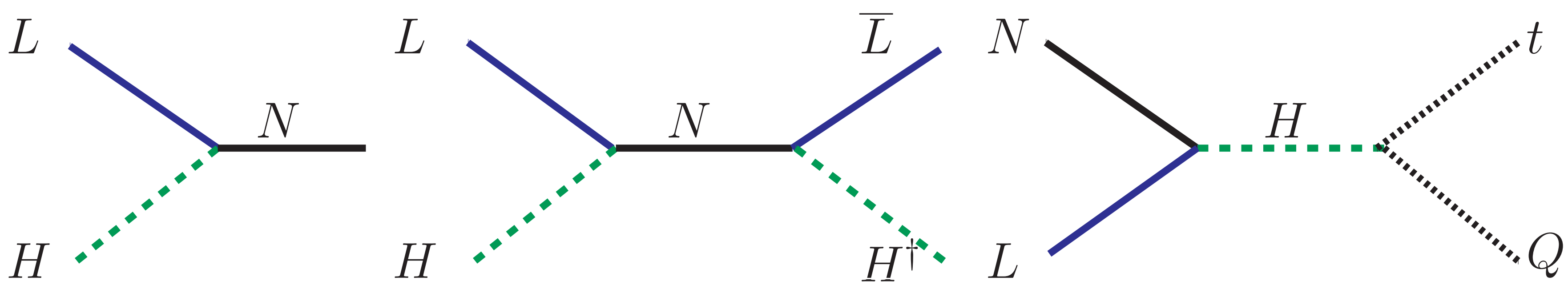


Decay Asymmetry

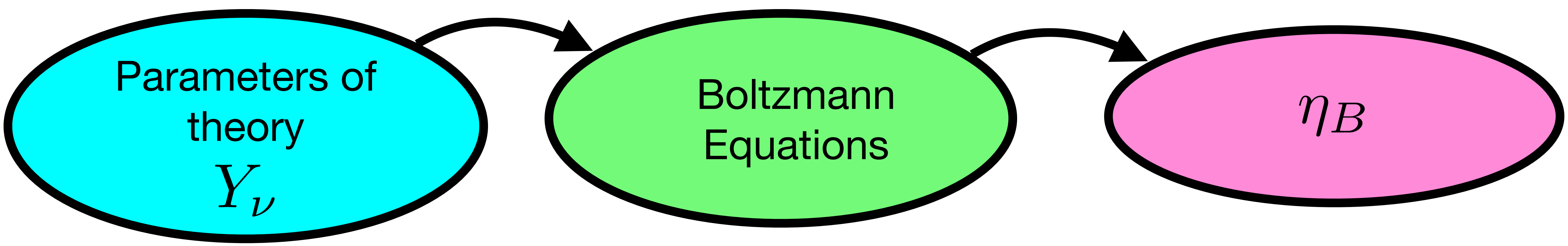
$$\epsilon_i = \frac{\Gamma_i - \overline{\Gamma}_i}{\Gamma_i + \overline{\Gamma}_i}$$

Thermal leptogenesis

Washout and scattering processes



inverse Decays $\Delta L=2$ $\Delta L=1$

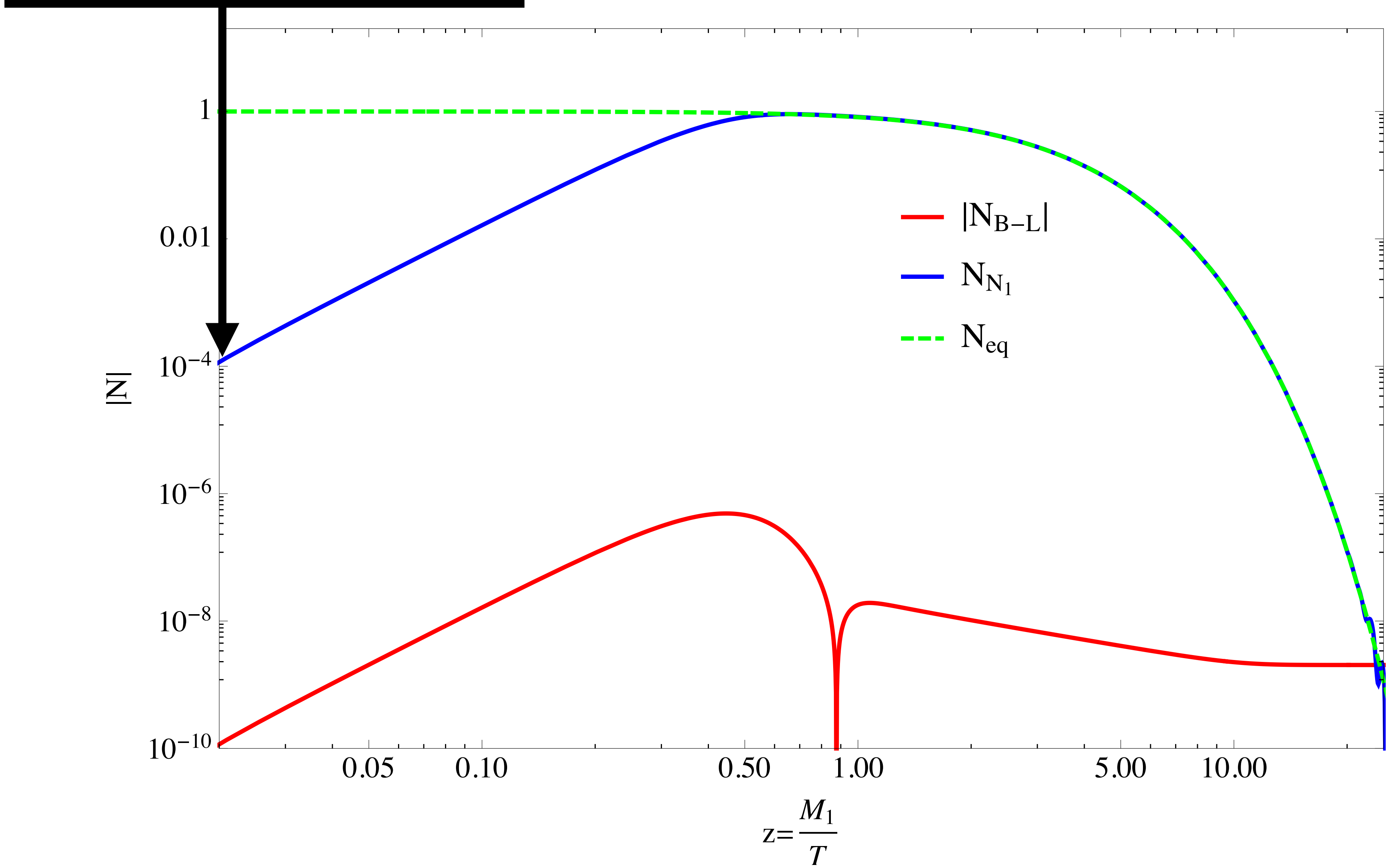


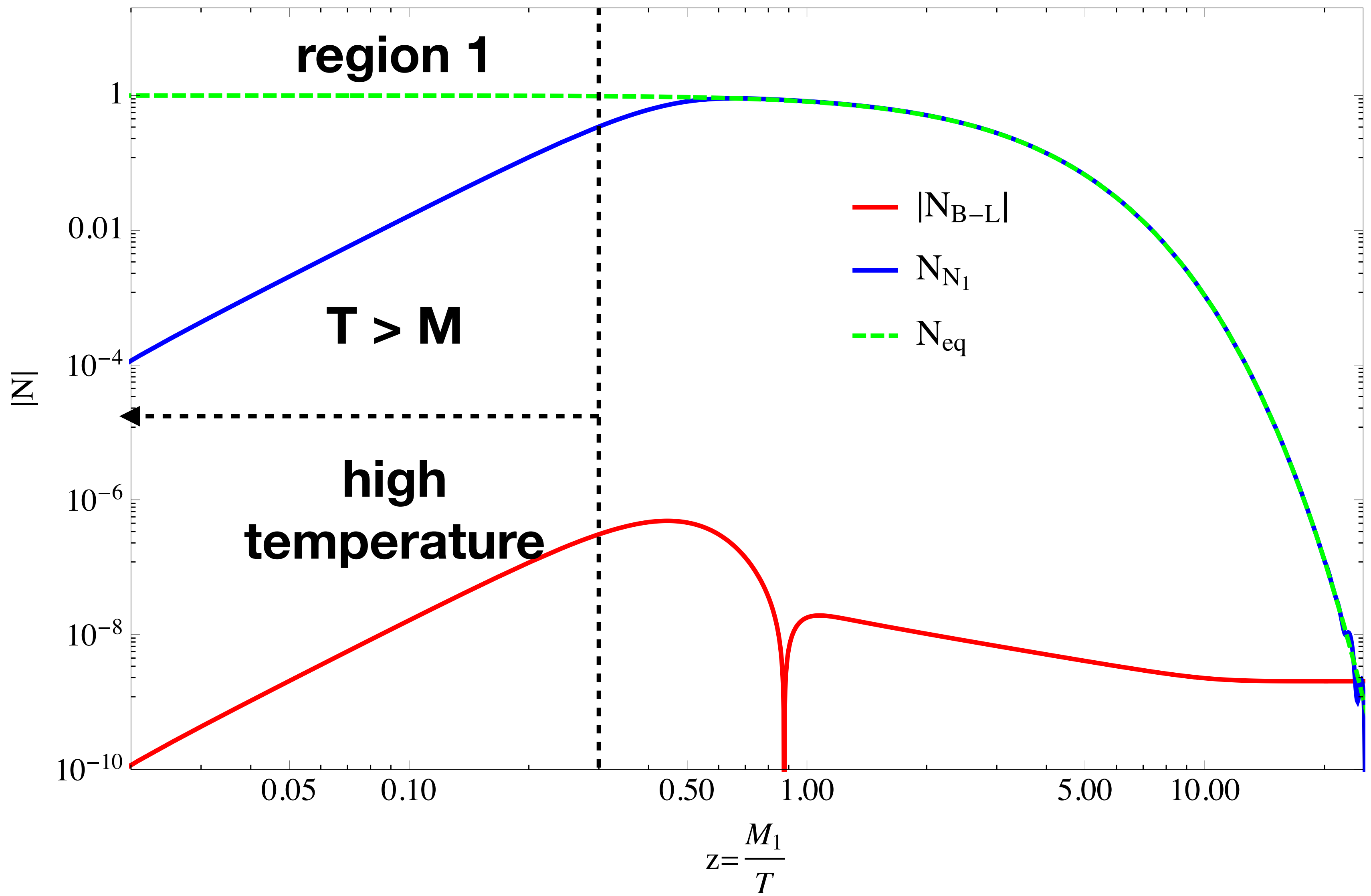
$$\frac{dN_N}{dz} = -D\left(N_N - N_N^{\rm eq}\right)$$

$$\frac{dN_{B-L}}{dz} = \epsilon\, D\left(N_N - N_N^{\rm eq}\right) - W\, N_{B-L}$$

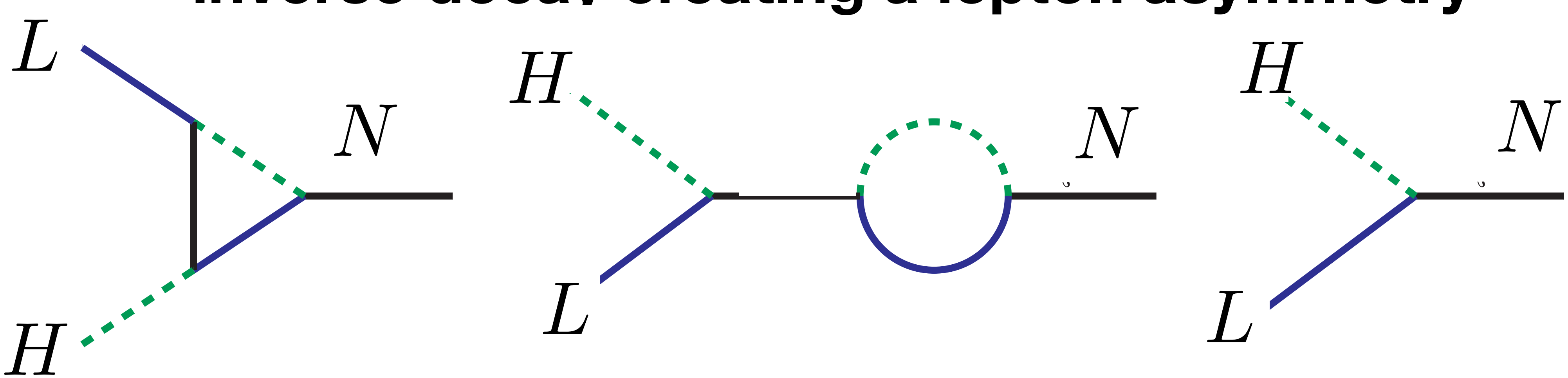
source **sink**

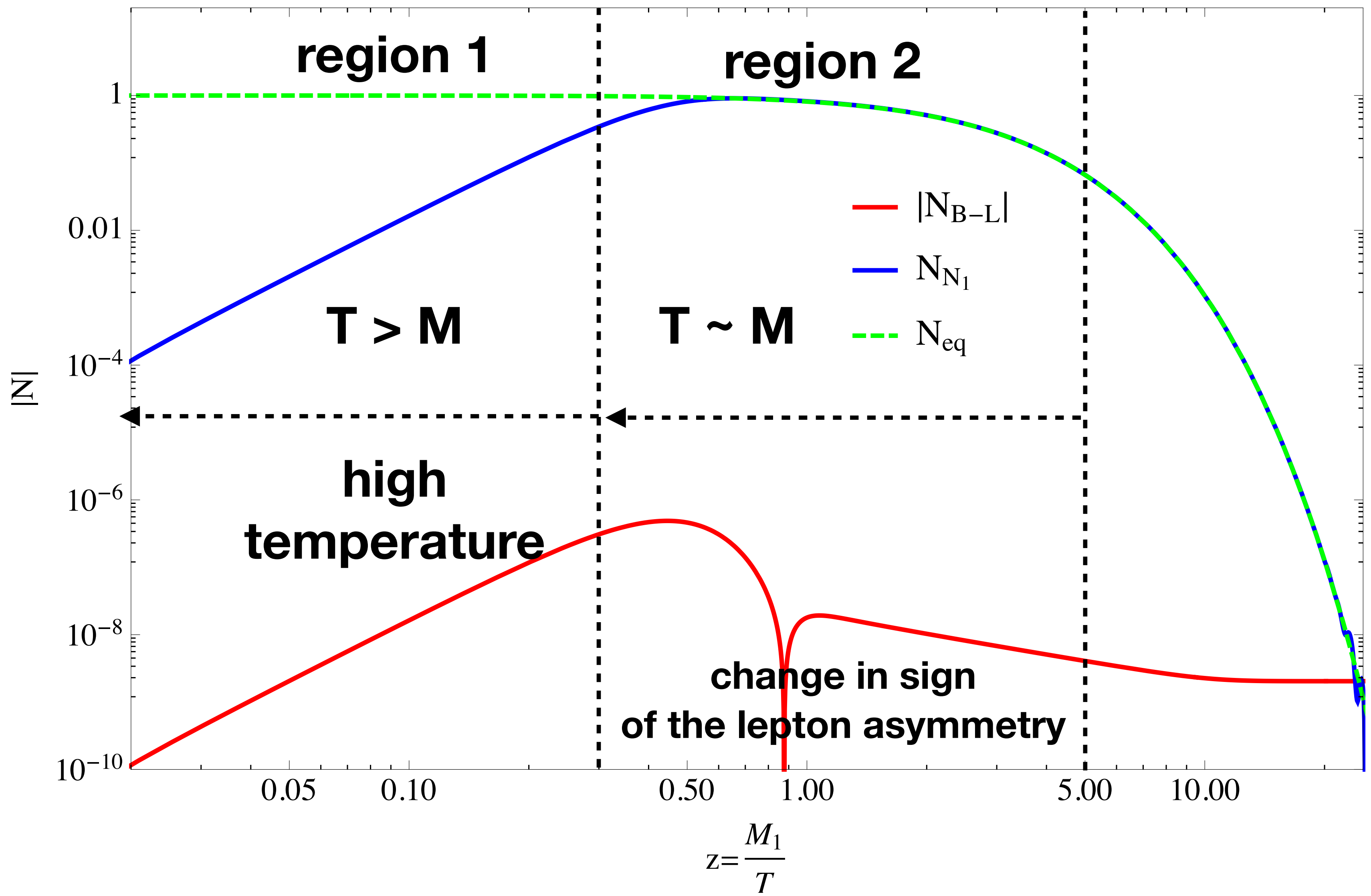
assume zero initial abundance of RHNs

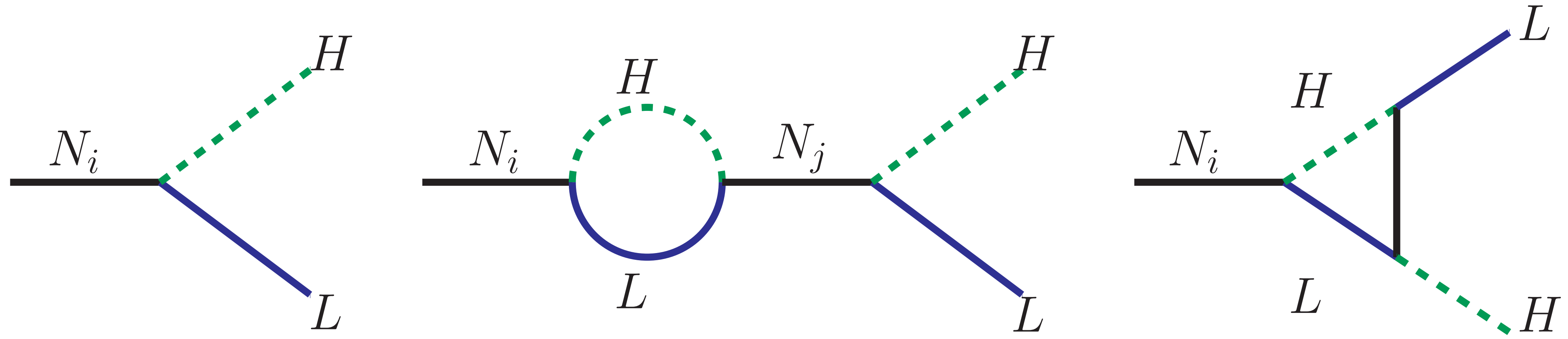


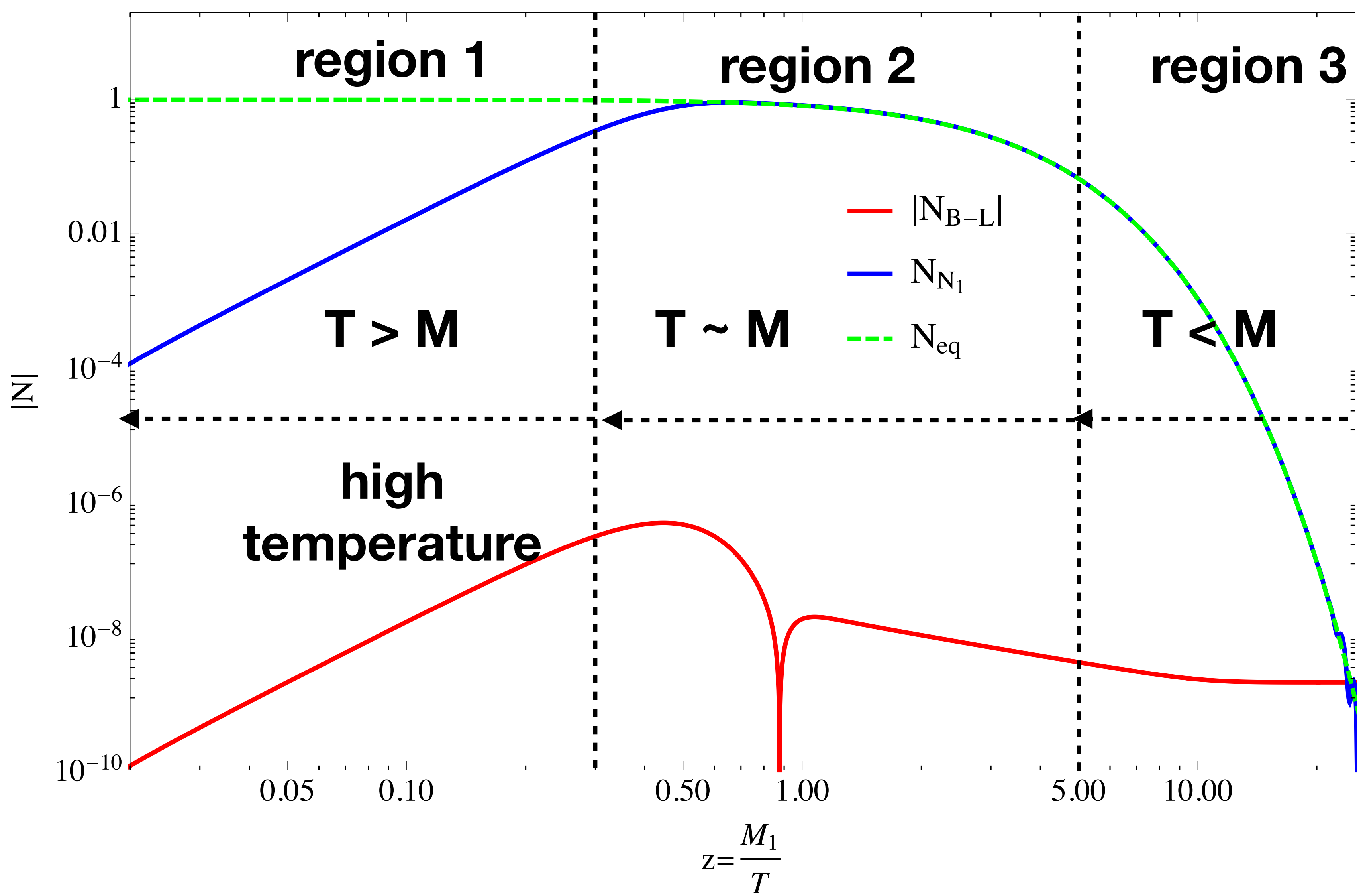


Region 1: leptons and Higgs have enough energy to inverse decay creating a lepton asymmetry




region 1
region 2
1
0.01
10^{-4}
10^{-6}
10^{-8}
10^{-10}
|N|
T > M
T ~ M
high
temperature
change in sign
of the lepton asymmetry
$|N_{B-L}|$
N_{N_1}
N_{eq}
0.05
0.10
0.50
1.00
5.00
10.00
$z=\frac{M_1}{T}$


N_i
H
L
N_i
H
L
N_j
H
L
N_i
H
L
L
H



Region 3: At T < M, RHN abundance is depleted. Lepton asymmetry freezes out.

Parameter Space

Casas, Ibarra

$$Y_\nu = \frac{1}{v} U_{\mathrm{PMNS}} \sqrt{m} R^T \sqrt{M}$$

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low-energy scale: 3 phases, 3 mixing angles and 3 masses

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low-energy scale: 3 phases, 3 mixing angles and 3 masses

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Parameter Space

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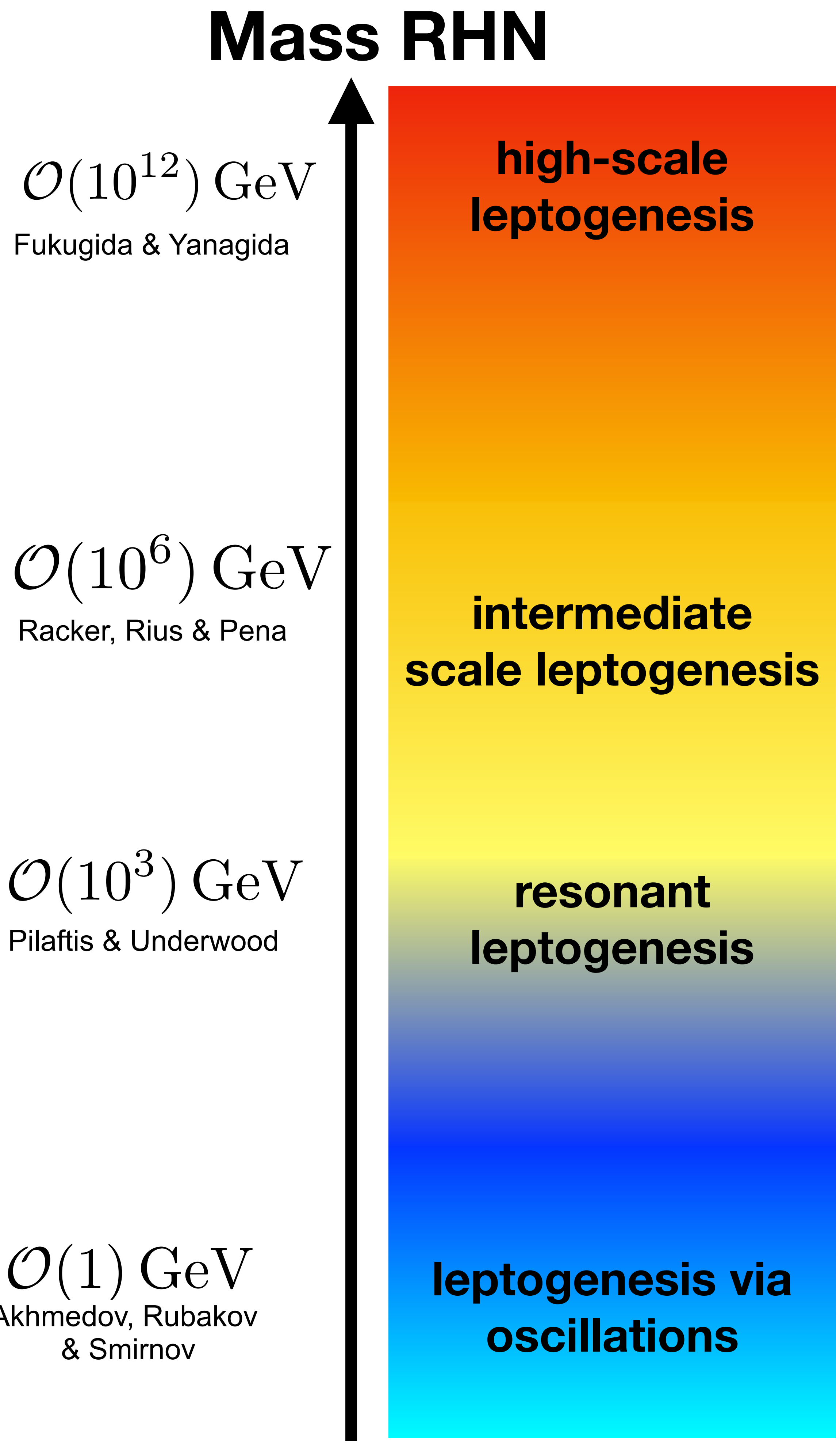
low-energy scale: 3 phases, 3 mixing angles and 3 masses

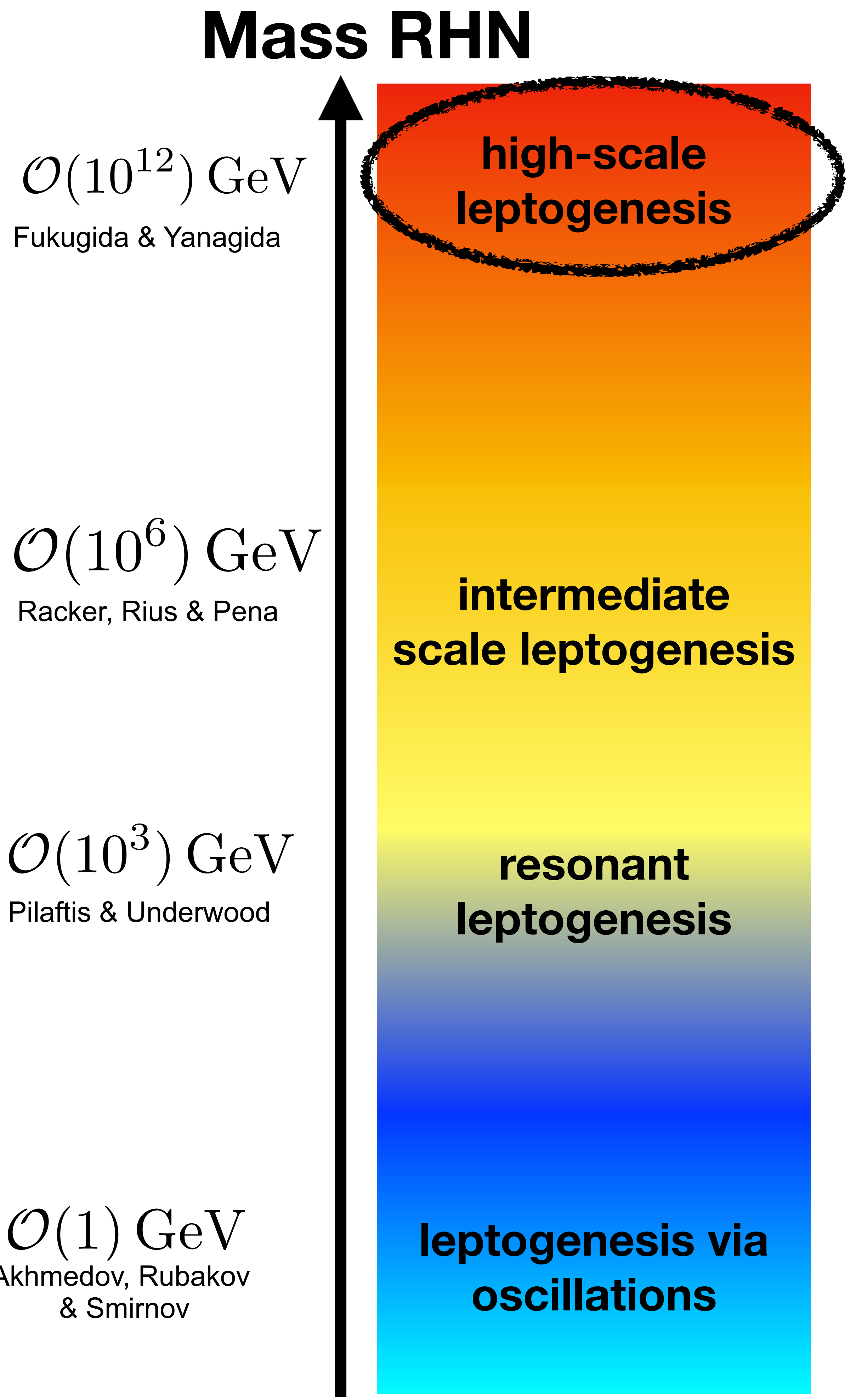
high-energy scale: 3 phases, 3 mixing angles and 3 masses

Without any symmetry constraints 18 parameters in total.

CI a model-independent way $m_\nu \leftrightarrow$ leptogenesis, if you have a model (GUT) Y_ν determined directly



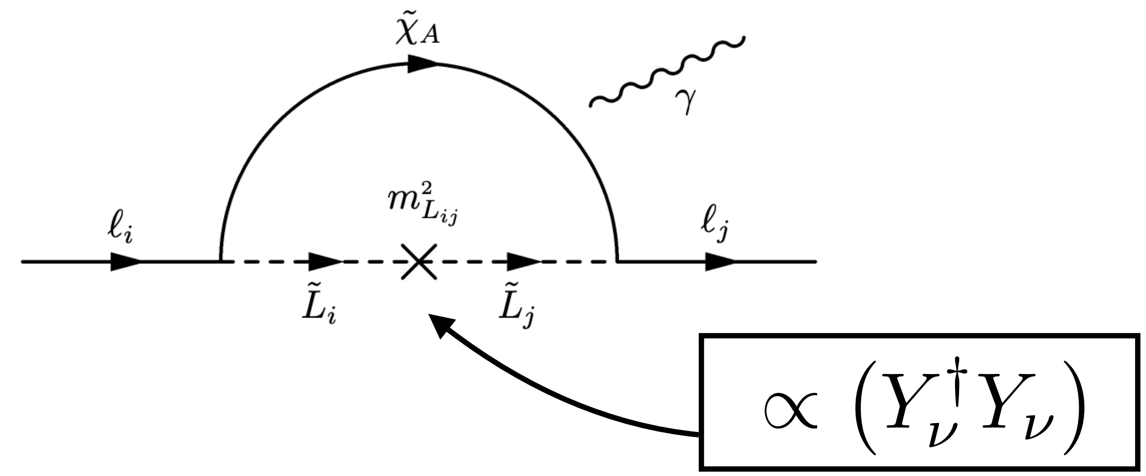
Mass RHN
$\mathcal{O}(10^{12})$ GeV
Fukugida & Yanagida
$\mathcal{O}(10^{6})$ GeV
Racker, Rius & Pena
$\mathcal{O}(10^{3})$ GeV
Pilaftis & Underwood
$\mathcal{O}(1)$ GeV
Akhmedov, Rubakov & Smirnov
high-scale leptogenesis
intermediate scale leptogenesis
resonant leptogenesis
leptogenesis via oscillations



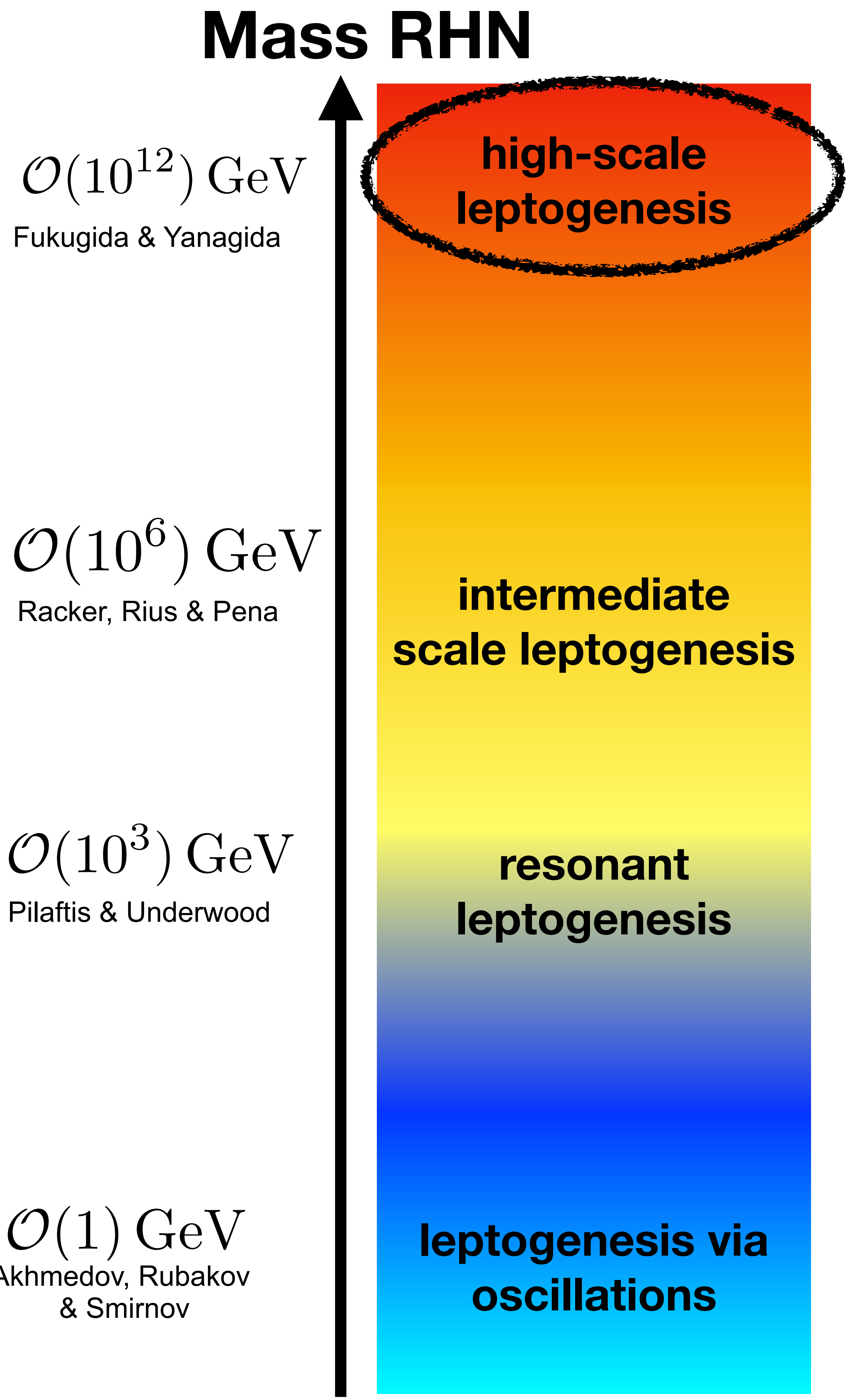


S. Pascoli, S. T Petcov, C. E. Yaguna
2003 “Quasi-Degenerate Neutrino Mass Spectrum, μ → e + γ Decay and Leptogenesis”

- SUSY GUT predicts RHNs with mass $\sim 10^{12}$ GeV



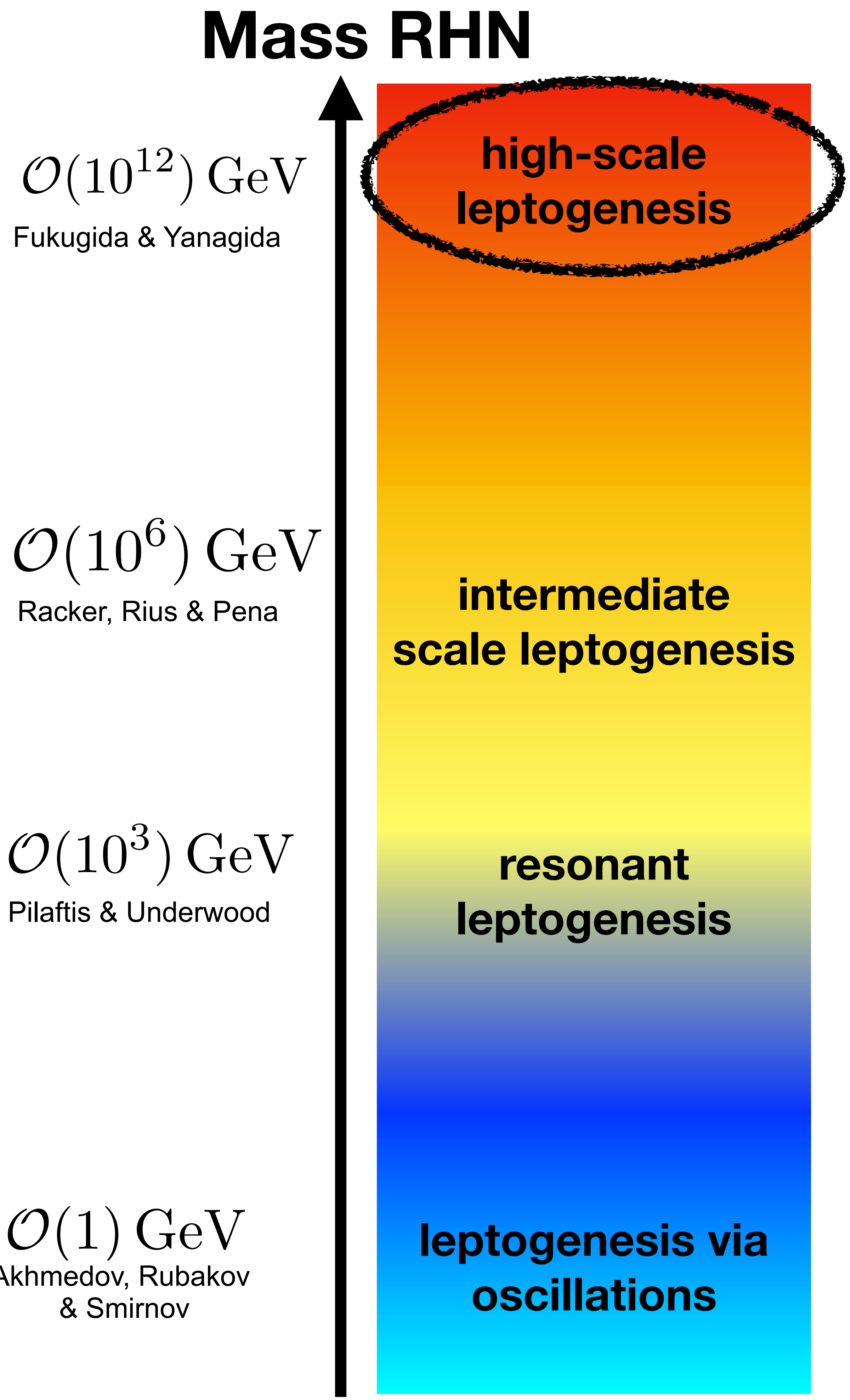
- Quasi-degenerate m_ν & showed **viable leptogenesis in context SUSY GUT** induced enhanced $\sim 10^3 - 10^6$ in Br($\mu \to e\gamma$), Br($\tau \to e\gamma$) with complex R





S. Pascoli, S. T Petcov, W. Rodejohann **2003** "On the Connection of Leptogenesis with Low Energy CP Violation and LFV Charged Lepton Decays"

- Assume hierarchical RHN masses
- Investigate "low-energy" observables connection to Leptogenesis: CLFV, $\nu 0\beta\beta$, CP-violation neutrino oscillations
- *"In general, there is no direct connection between the latter and the CP violation in leptogenesis."*



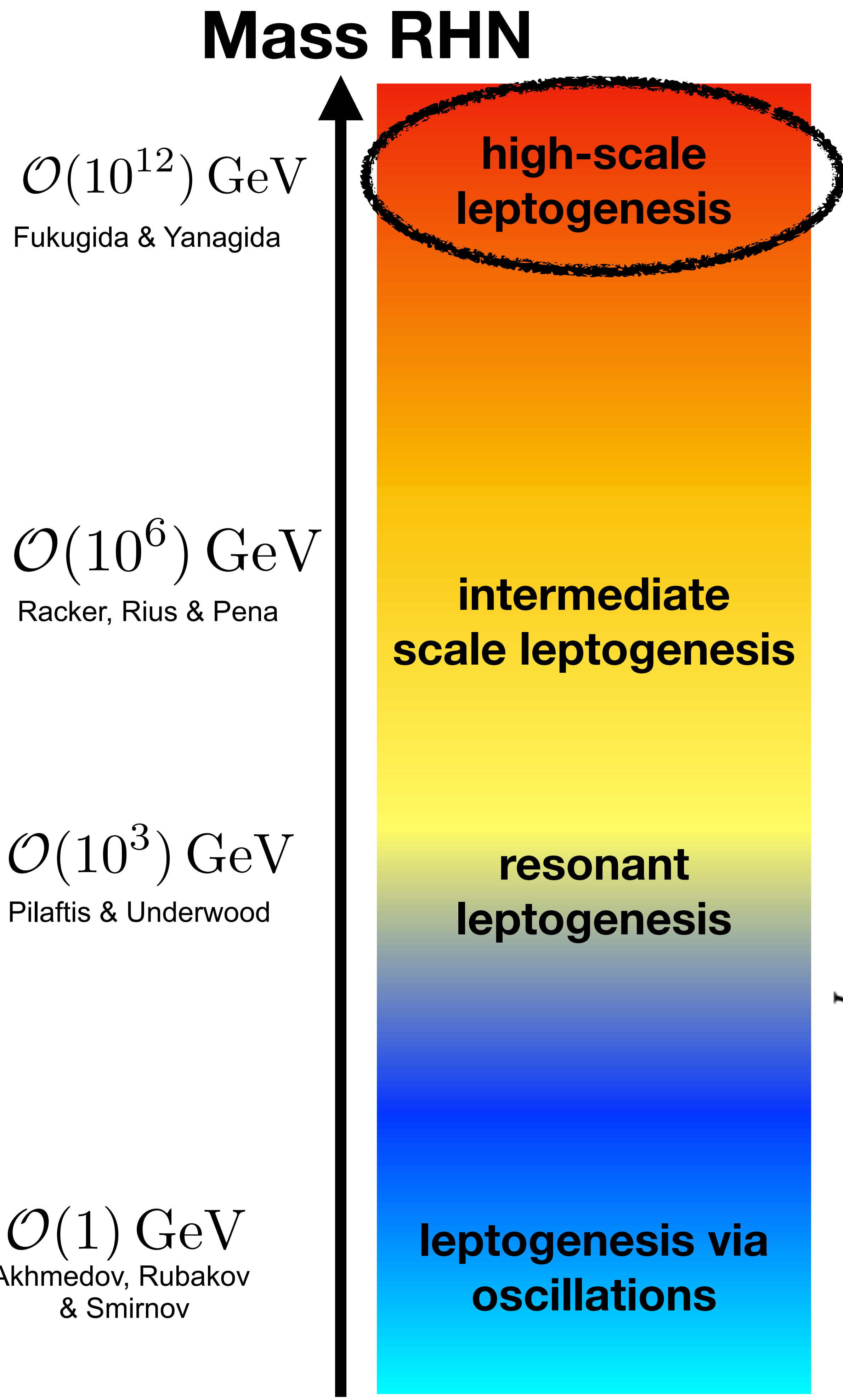


S. Pascoli, S. T Petcov, A. Riotto, **2006** **“**Connecting Low Energy Leptonic CP-violation to Leptogenesis”

- It was thought that low-scale CP-violation would not imply viable high-scale leptogenesis since $\epsilon_1 \propto \text{Im}[R^2]$

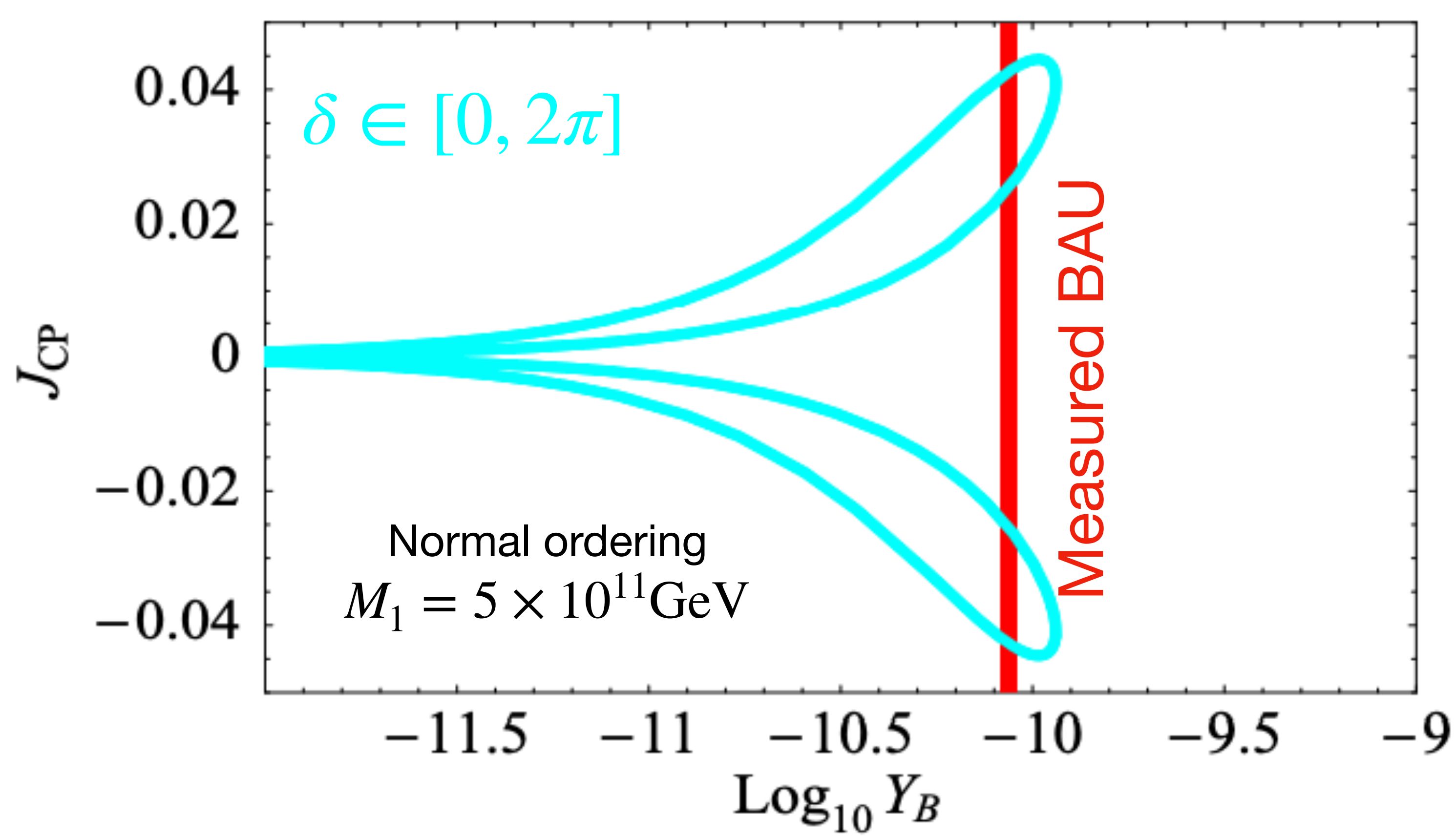
- “Flavoured Leptogenesis” Abada et al showed that
$$\epsilon_\alpha = \text{Im}\left(\sum U^*_{\alpha\beta} U_{\alpha\rho} R_{1\beta} R_{1\rho}\right) \qquad \alpha = e, \mu, \tau$$

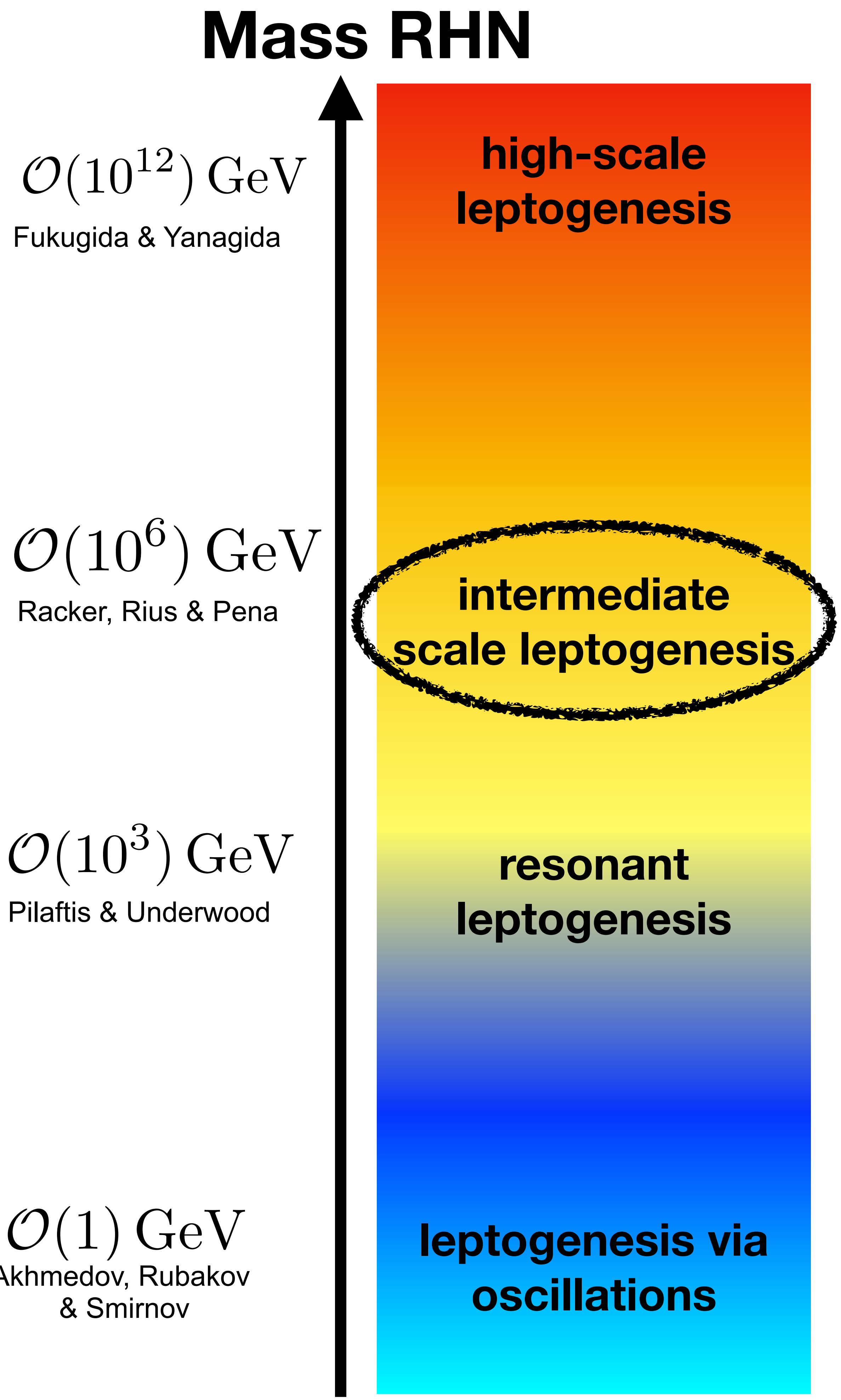
- Considered generation of BAU assuming purely real/complex R i.e. CP-violation source from low energy phases



S. Pascoli, S. T Petcov, A. Riotto, **2006** "Connecting Low Energy Leptonic CP-violation to Leptogenesis"

- Assuming real R-matrix (motivated within certain flavour symmetry model see 1602.03873)



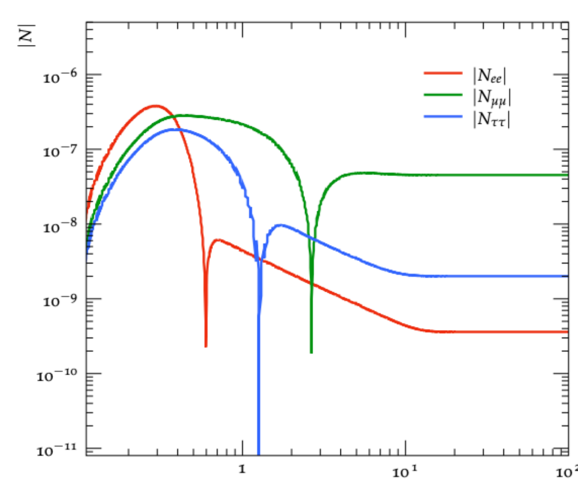


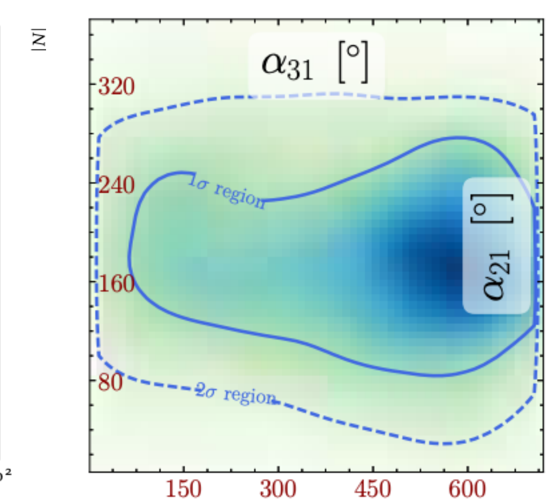


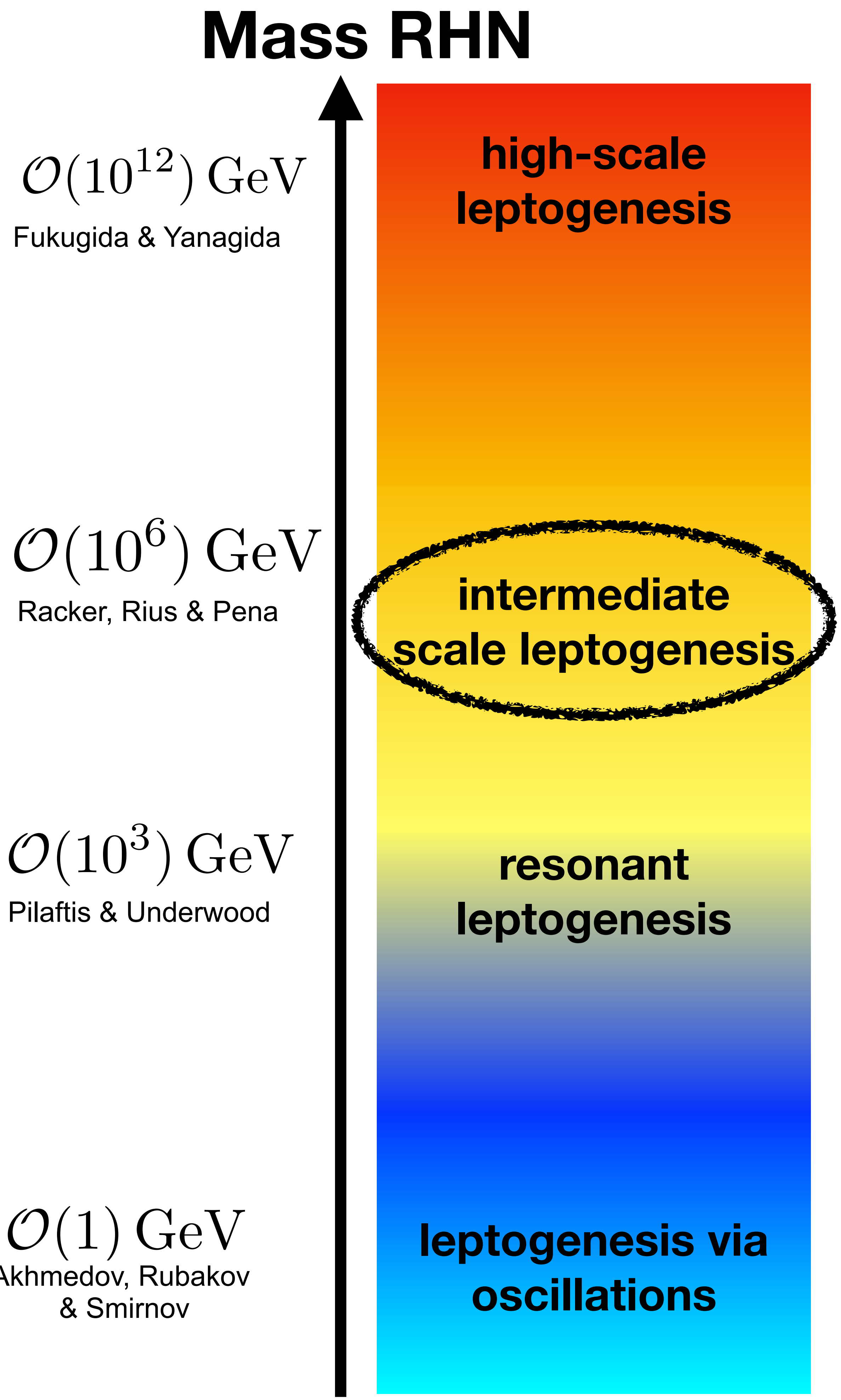


K. Moffat, S. Pascoli, S. T Petcov, H. Schulz, J. Turner, **2018** "Three-Flavoured Non-Resonant Leptogenesis at Intermediate Scales"

- Solved density matrix equations to demonstrate leptogenesis low as $M_N \sim 10^6$ GeV
- Quantified fine-tuning in m_ν & performed multi-dimensional PS exploration



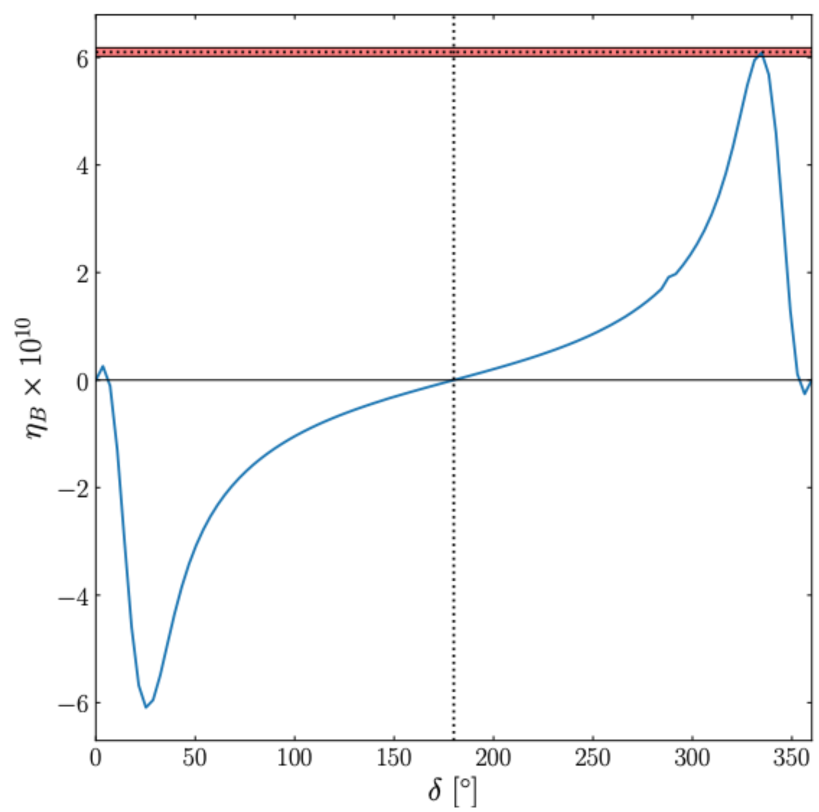




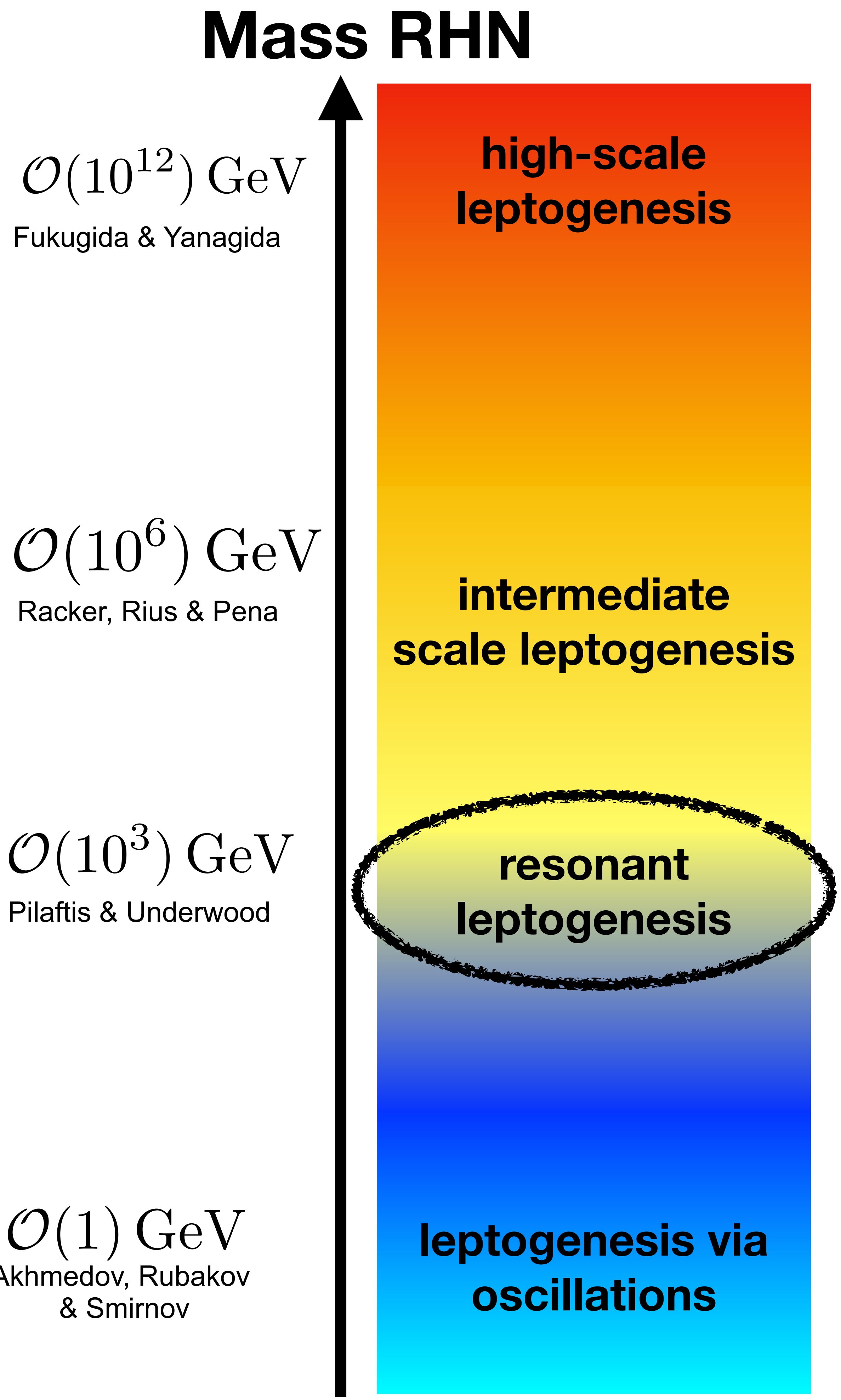



K. Moffat, S. Pascoli, S. T Petcov, J. Turner, **2018**
"Leptogenesis from Low Energy CP Violation"

- Returned to Serguey, Silvia and Antonio's initial study with new tools
- CP-violation only from low-scale sector

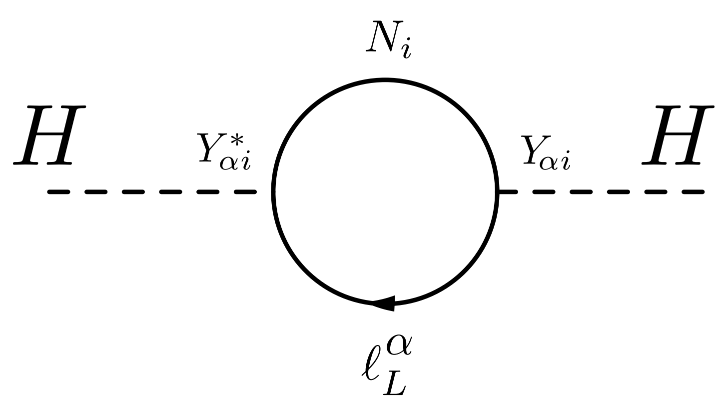


$$M_1 = 7 \times 10^8 \mathrm{GeV}$$

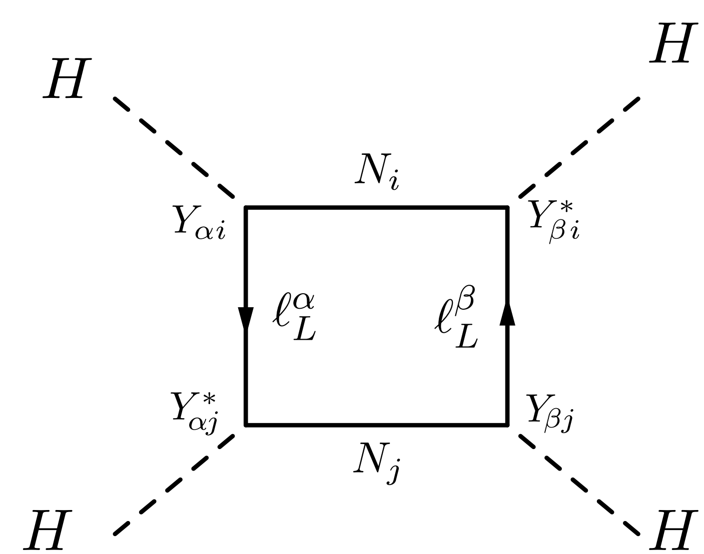


I. Brivio, K. Moffat, S. Pascoli, S. T Petcov, J. Turner, **2019 "**Leptogenesis in the Neutrino Option"

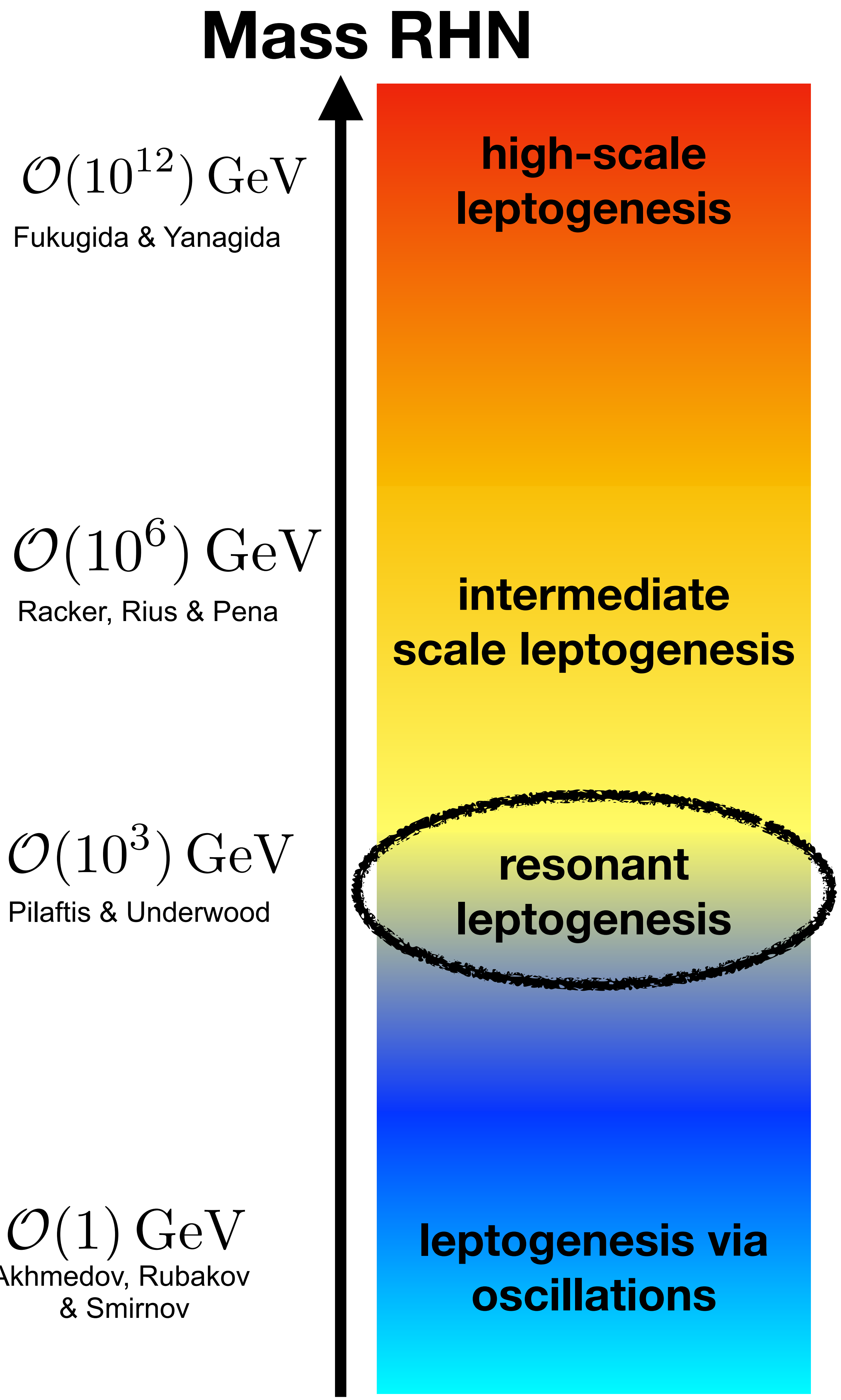
- Above EW scale, Higgs potential vanishes → generate EW scale from RHN mass "neutrino option"



$$m_H^2 \approx \frac{M^2 Y^2}{8\pi^2}$$

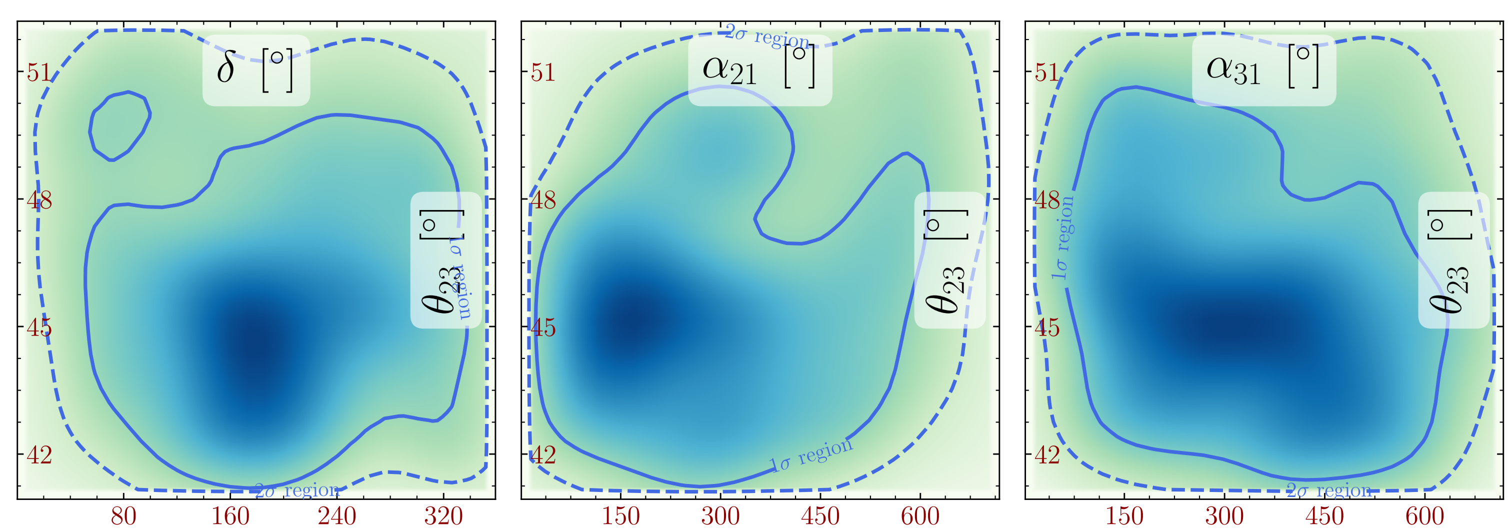


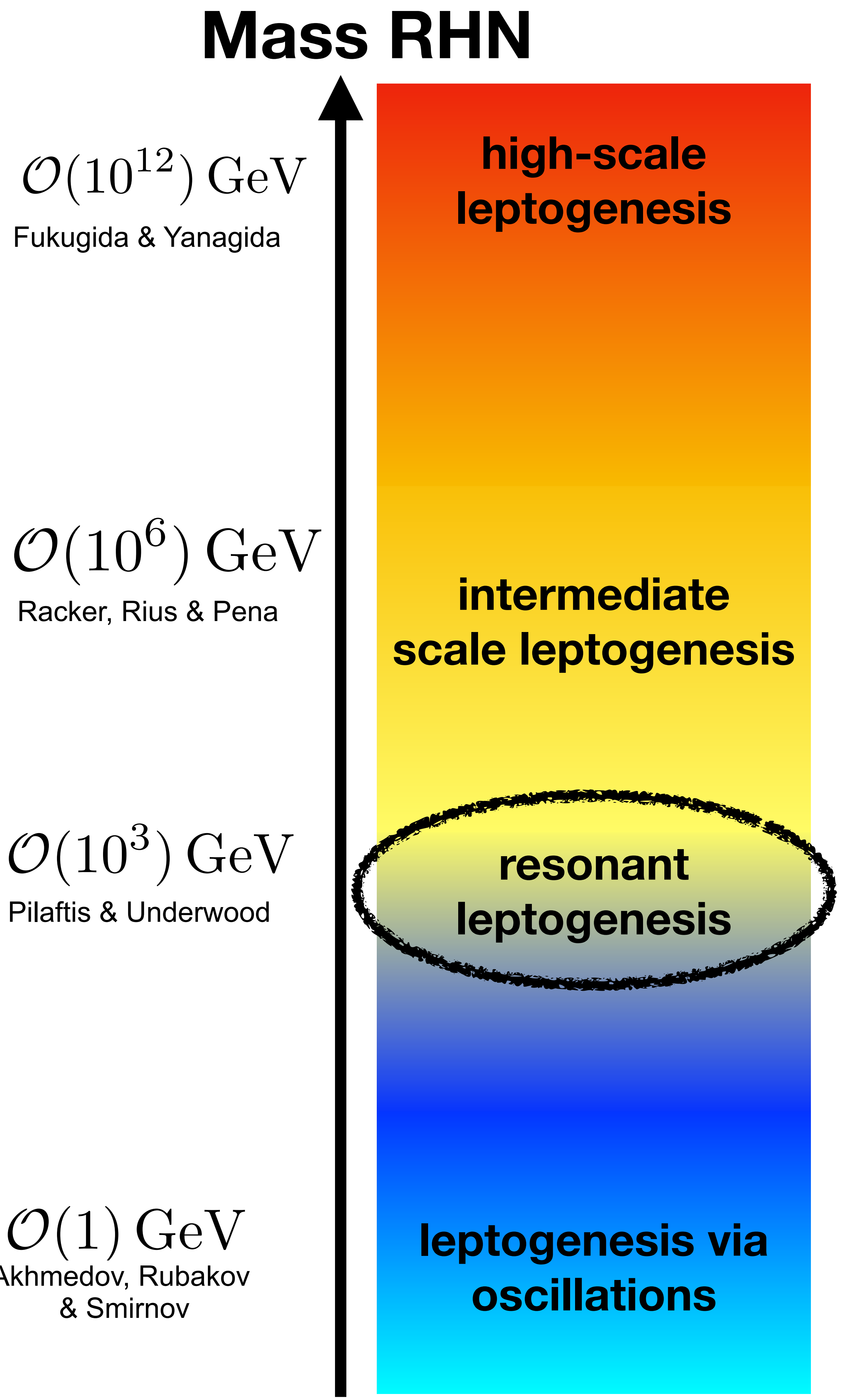
$$\lambda \approx |Y|^4$$



I. Brivio, K. Moffat, S. Pascoli, S. T Petcov, J. Turner, **2019** "Leptogenesis in the Neutrino Option"

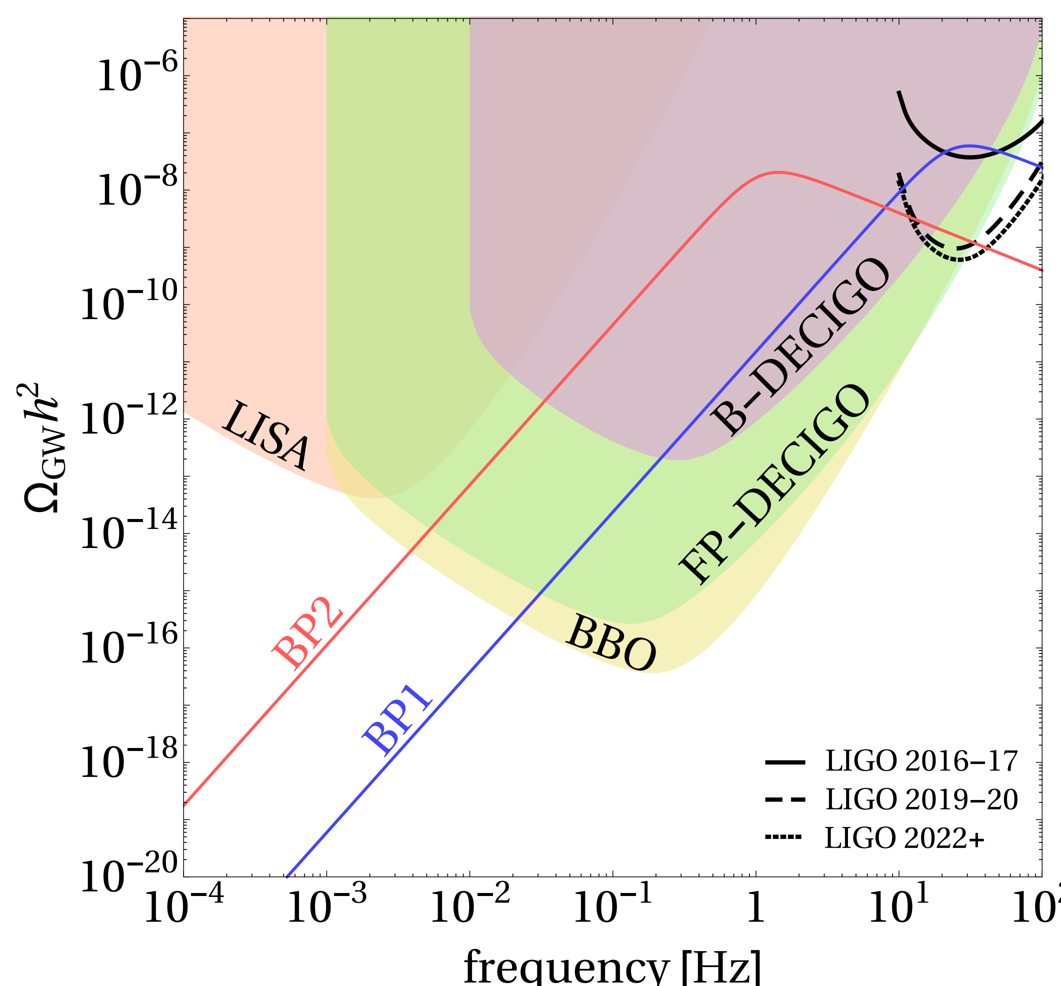
- Regions consistent with Higgs parameters & successful leptogenesis





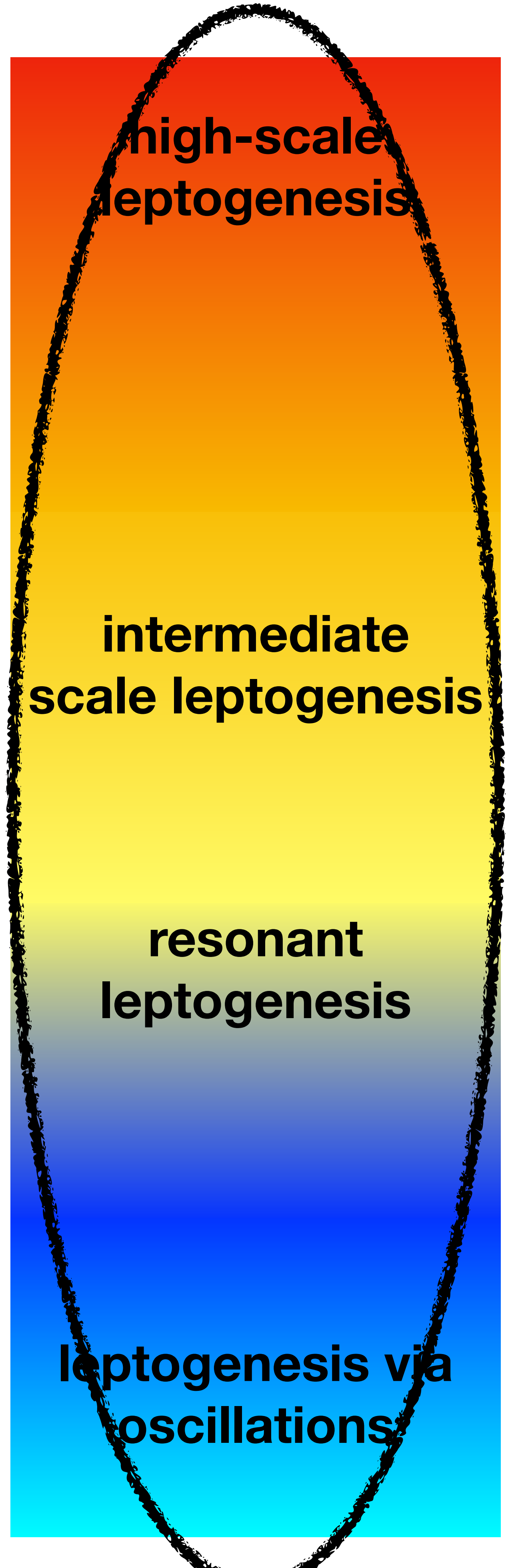
I. Brivio, K. Moffat, S. Pascoli, S. T Petcov, J. Turner, **2019** "Leptogenesis in the Neutrino Option"

- Interesting interplay with GWs



Brdar, Helmboldt, Kubo

22 papers, 18 collaborators > 1500 citations!



First Leptogenesis paper 2003, most recent 6 months ago!

Happy Belated Birthday Serguey and Thank You for your massive contributions to physics!