Leptogenesis from Realistic Models

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SÃO PAULO RESEARCH FOUNDATION

Why Leptogenesis?

- Lepton & baryon numbers only accidental classical symmetries
- They are violated at the quantum level by SU(2) sphalerons. Suppressed today but large violation in the early Universe

$10^{12}\,\mathrm{GeV} \gtrsim T \gtrsim 100\,\mathrm{GeV}$ $\boxed{B - L \text{ remains conserved}}$

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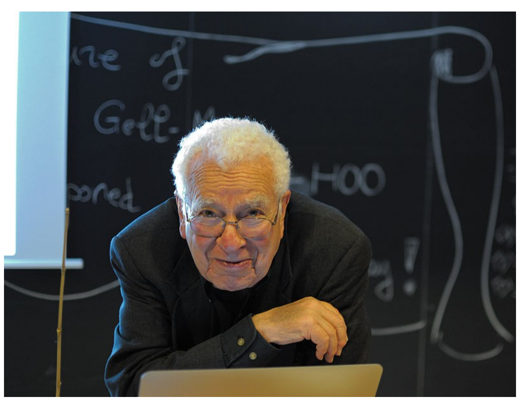
- Neutrinos (are special) being the only Majorana particles can acquire Majorana mass $m_{\alpha\beta}\overline{\nu^c_\alpha}\nu_\beta$



Everything not forbidden is compulsory

Photo: Wikimedia Commons, http://commons.wikimedia.org/wiki/File:Murray_Gell-Mann_at_Lection.JPG

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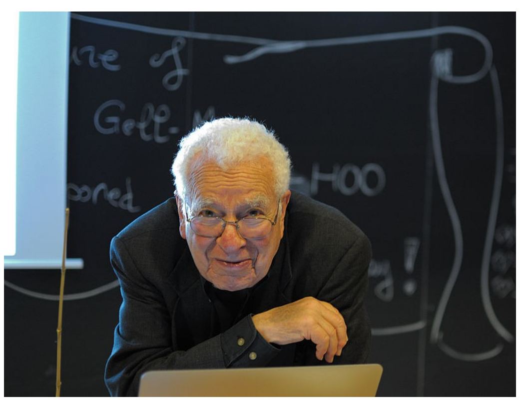
- Neutrinos (are special) being the only Majorana particles can acquire Majorana mass $m_{\alpha\beta}\overline{\nu_\alpha^c}\nu_\beta \leftarrow \frac{c^{(5)}_{\alpha\beta}}{\Lambda_L}(\overline{\ell_\alpha^c}H)(\ell_\beta H)$ [Weinberg (1979)]



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[Sakharov (1967)]

"slow" $B-L$ violation
C & CP violation
EW sphalerons
Nonzero baryon number!

[Fukugita & Yanagida (1986)]

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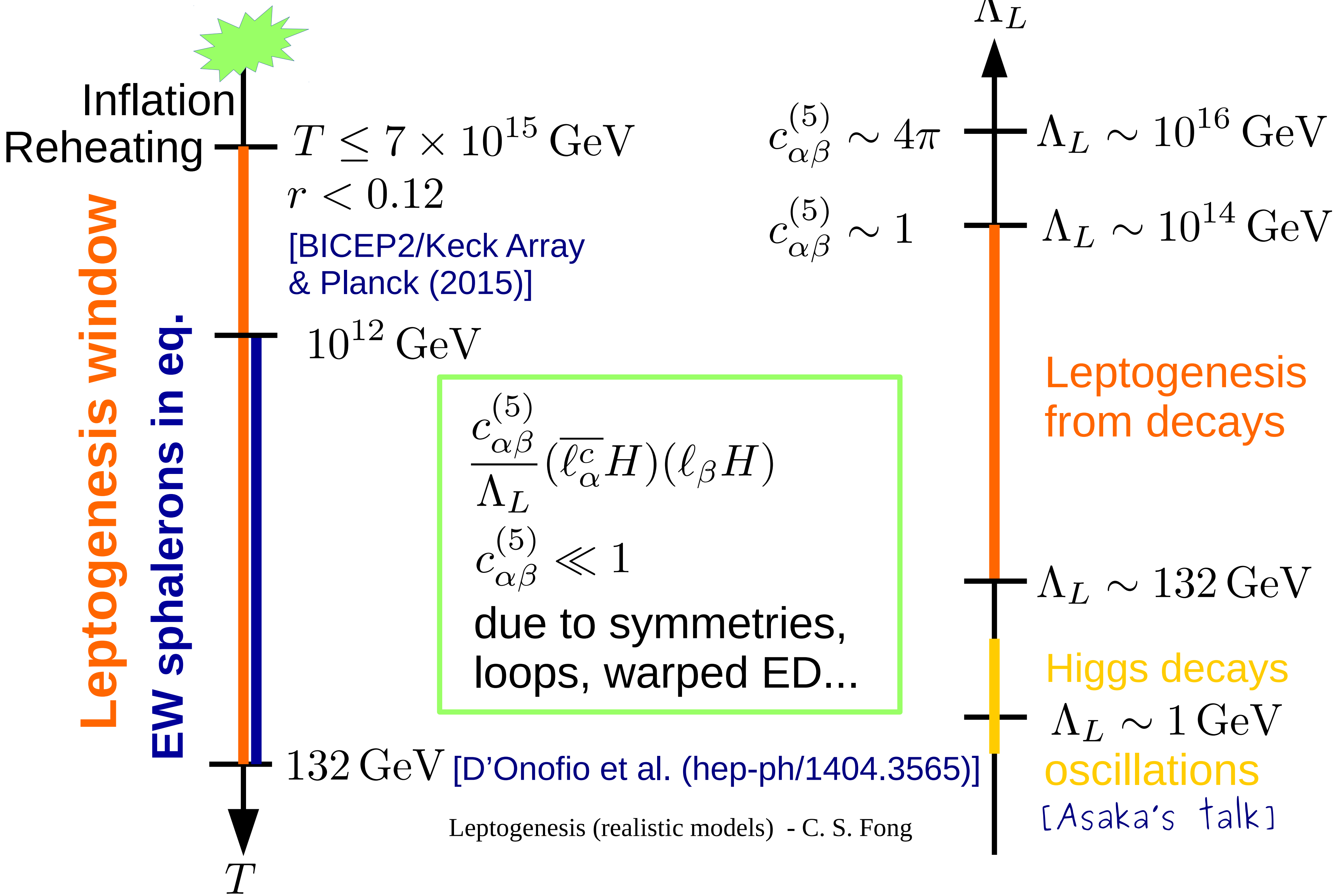
Leptogenesis Scales



Realistic Models?

- Neutrino masses and mixing through

$$\frac{c^{(5)}_{\alpha\beta}}{\Lambda_L}(\overline{\ell^c_\alpha} H)(\ell_\beta H) \longrightarrow m_{\alpha\beta} = U^*_\nu \,\mathrm{diag}(m_1, m_2, m_3)\, U^\dagger_\nu$$

- Baryon asymmetry $n_{\Delta B}/s \approx 10^{-10}$ through "slow", *B-L* and C & CP violating decays of new d.o.f of $\Lambda_L \gtrsim 132\,\mathrm{GeV}$

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- Leptogenesis "resolves" the operator: generally contains ***more*** parameters than low energy observables [3 masses, 3 mixing angles, 1 (+ 2) phase(s)] (more later)
- Define "realistic"
  - Circumstantial/supporting evidences at low energy
  - Direct probe by resolving the dim-5 operator

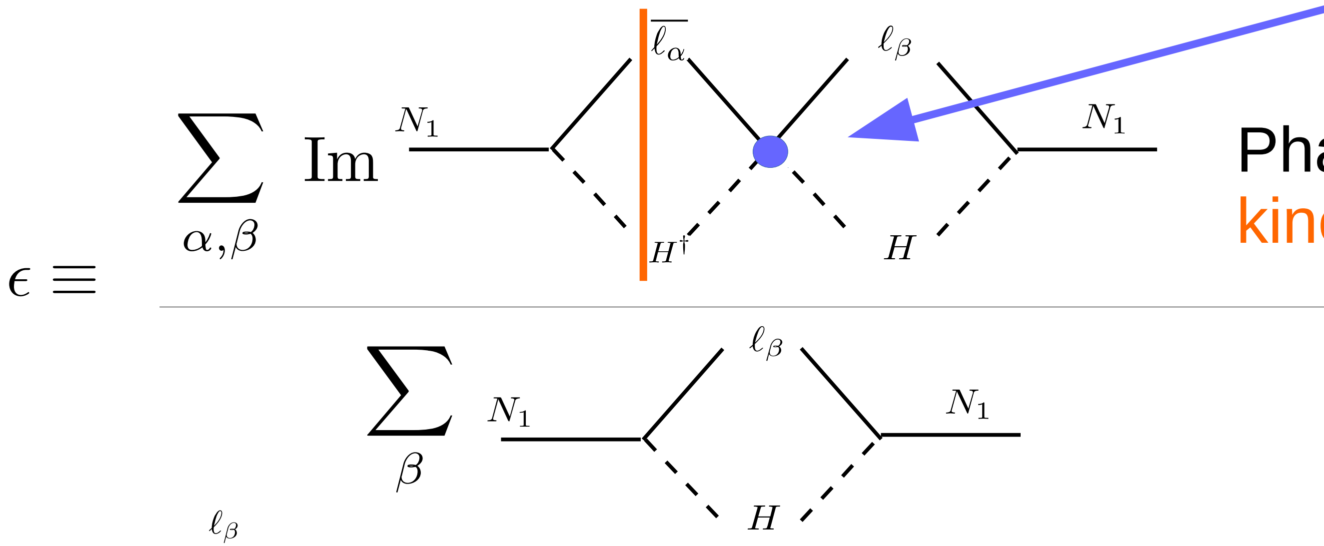
Outline

- “No-Go” on scales
- High scale models
- Low scale models
- Falsifications
- Outlook

“No-Go” on scales

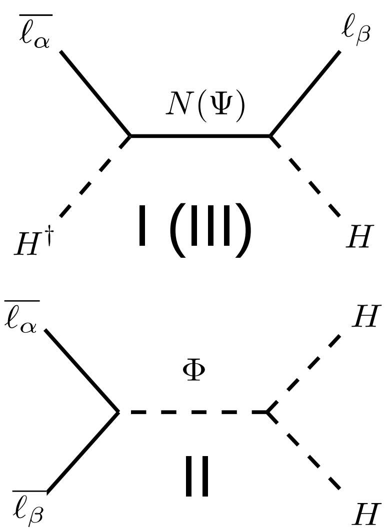
Restrictions from neutrino masses

- CP violation is tied to neutrino mass scale



Heavier states

Phases from
kinematic & couplings



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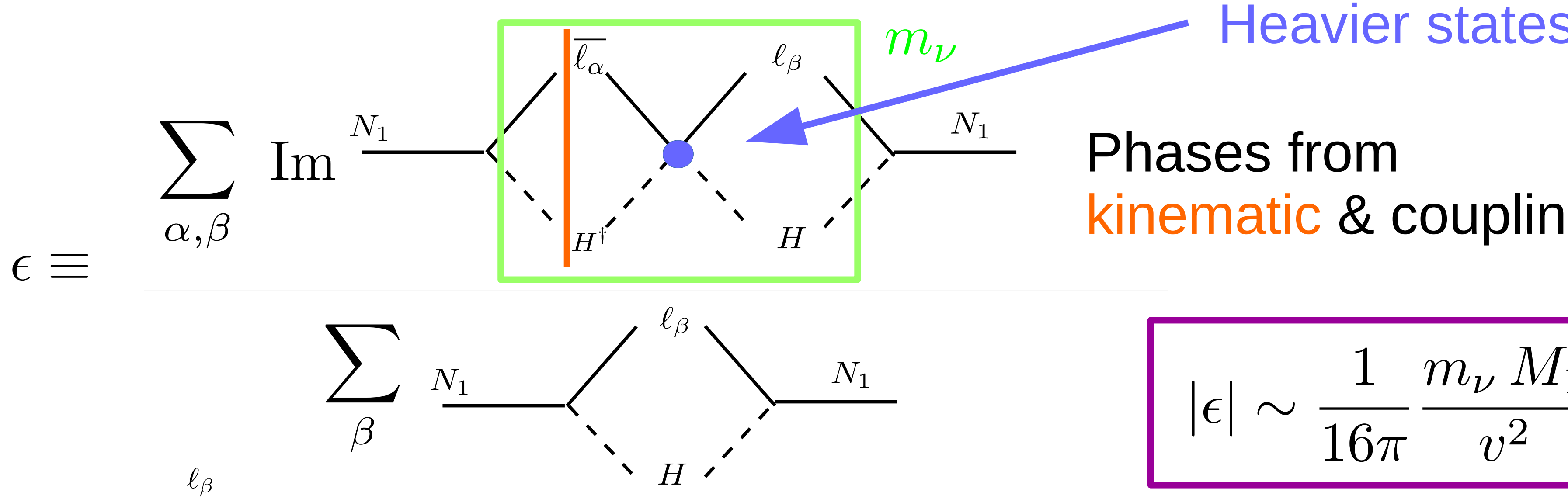
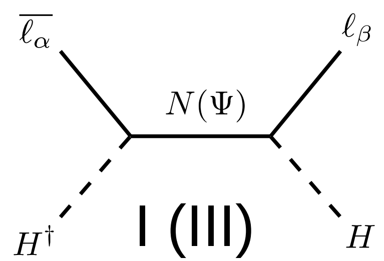


Phases from
kinematic & couplings

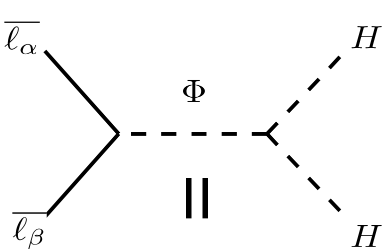
$$|\epsilon| \sim \frac{1}{16\pi}\frac{m_\nu M_1}{v^2}$$

$$|\epsilon| \gtrsim 10^{-7} \Longrightarrow M_1 \gtrsim 3 \times 10^9 \left(\frac{0.05\,\text{eV}}{m_\nu}\right) \text{GeV}$$

[Davidson & Ibarra (hep-ph/0202239)]



I (III)



II

Ways to relax from

Restrictions from neutrino masses

- Lepton number conserving (lepton flavor violating)

$$\frac{c^{(5)}_{\alpha\beta}}{\Lambda_L}(\overline{\ell^c_\alpha}H)(\ell_\beta H) \boxed{+\frac{c^{(6)}_{\alpha\beta}}{\Lambda^2_{LF}}(\overline{\ell_\alpha}H^\dagger)i\partial\!\!\!/(\ell_\beta H)}$$

Not constrained by neutrino masses!

$M_1 \gtrsim 10^6\,\mathrm{GeV}$ [Racker, Peña & Rius (hep-ph/1205.1948)]

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- Additional Higgs doublet(s) e.g.

$$\frac{c'^{(5)}_{\alpha\beta}}{\Lambda_L}(\overline{\ell^c_\alpha}H')(\ell_\beta H') \Longrightarrow |\epsilon| \sim \frac{1}{16\pi}\frac{m_\nu M_1}{v'^2}$$

[Haba & Seto (hep-ph/1102.2889)]

[Clarke, Foot & Volkas (hep-ph/1505.05744)]

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- Radiative neutrino masses i.e. from loop(s)

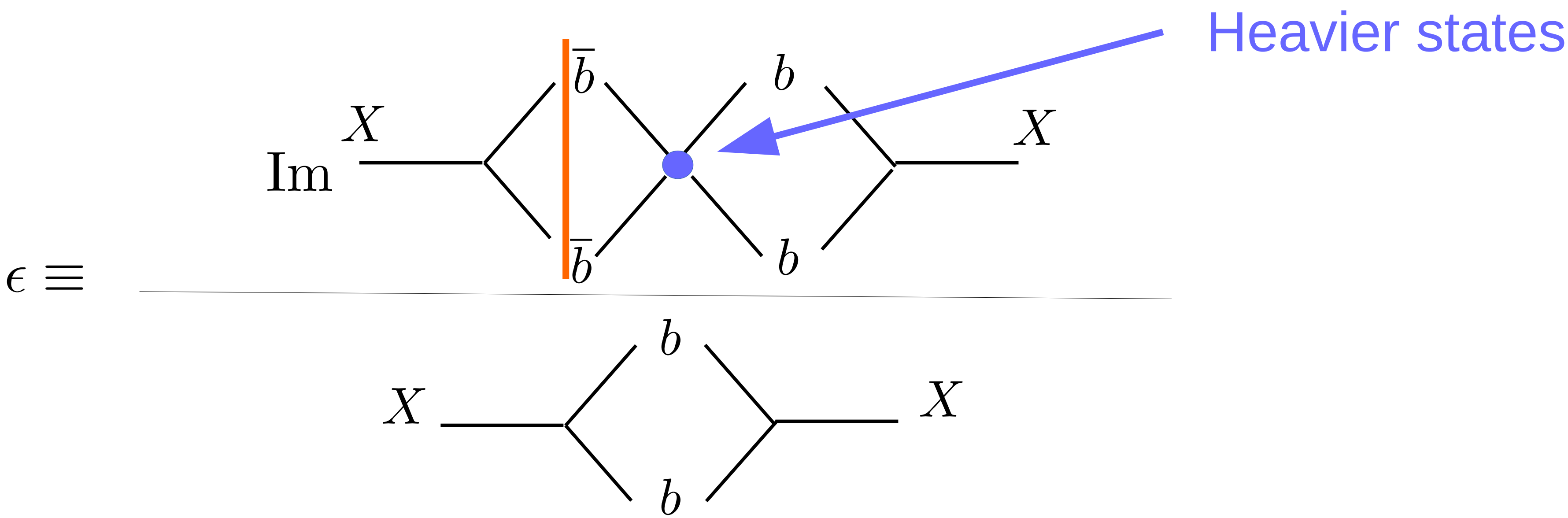
$$|\epsilon| \sim \frac{1}{16\pi}\frac{m_\nu M_1}{v'^2}(16\pi)^{\mathrm{loop}}$$

e.g. [Suematsu (hep-ph/1103.0857)]

[Clarke, Foot & Volkas (hep-ph/1505.05744)]

Model-independent

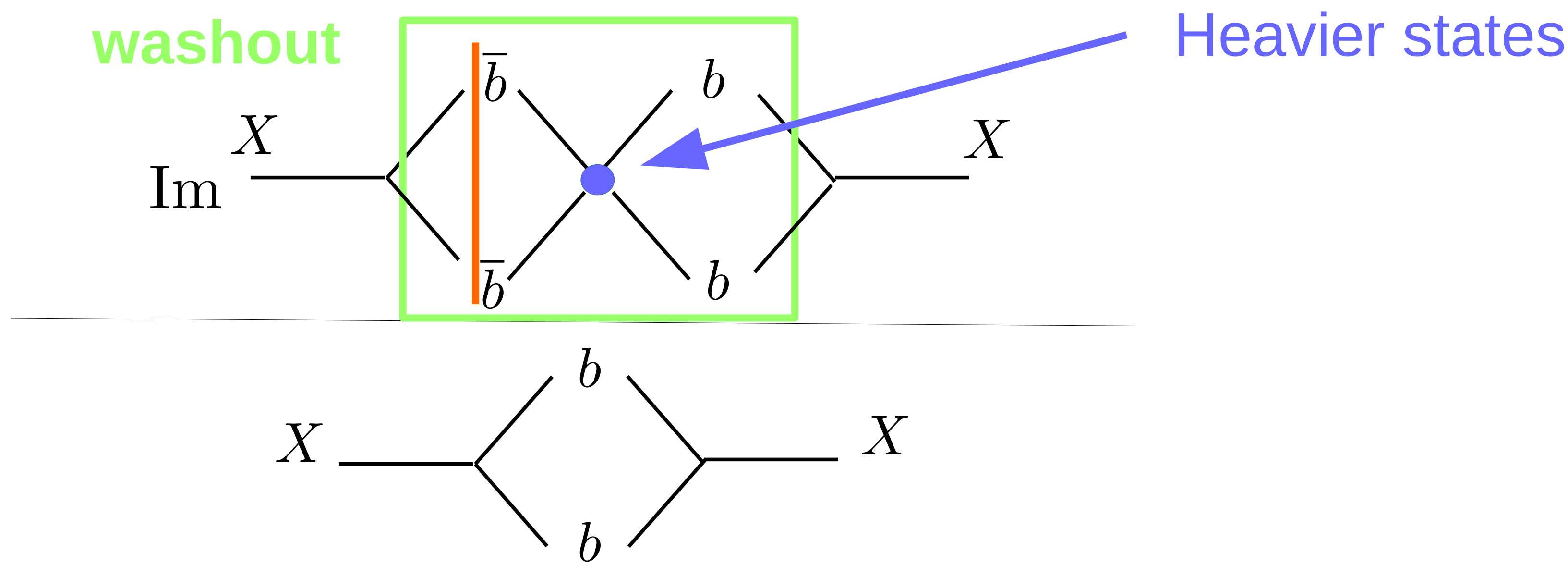
- Interplay between CP violation and washout



Model-independent

- Interplay between CP violation and washout

$\epsilon \equiv$



$$\boxed{\gamma \approx \frac{64}{\pi} M_X \, |\epsilon|^2} \lesssim 1.66\sqrt{106.75}\,\frac{M_X^2}{M_{\rm Pl}} \Longrightarrow \boxed{M_X \gtrsim 10^5\,\text{GeV}\left(\frac{\epsilon}{10^{-7}}\right)^2}$$

[Racker (hep-ph/1308.1840)] [Aristizabal, CSF, Nardi & Peinado (hep-ph/1309.4770)]
See also review in [Racker (hep-ph/1410.5482)]

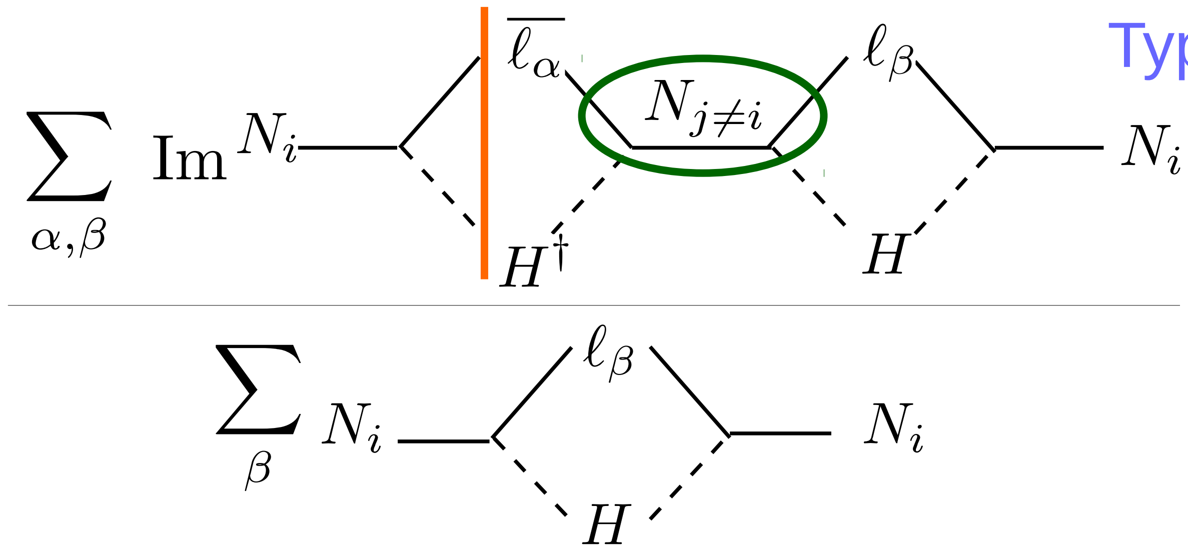
Caveats

$$M_i \sim M_j$$

- "Heavier states" not much heavier → ***resonant enhancement***

Type I seesaw

$$\epsilon_i \equiv$$



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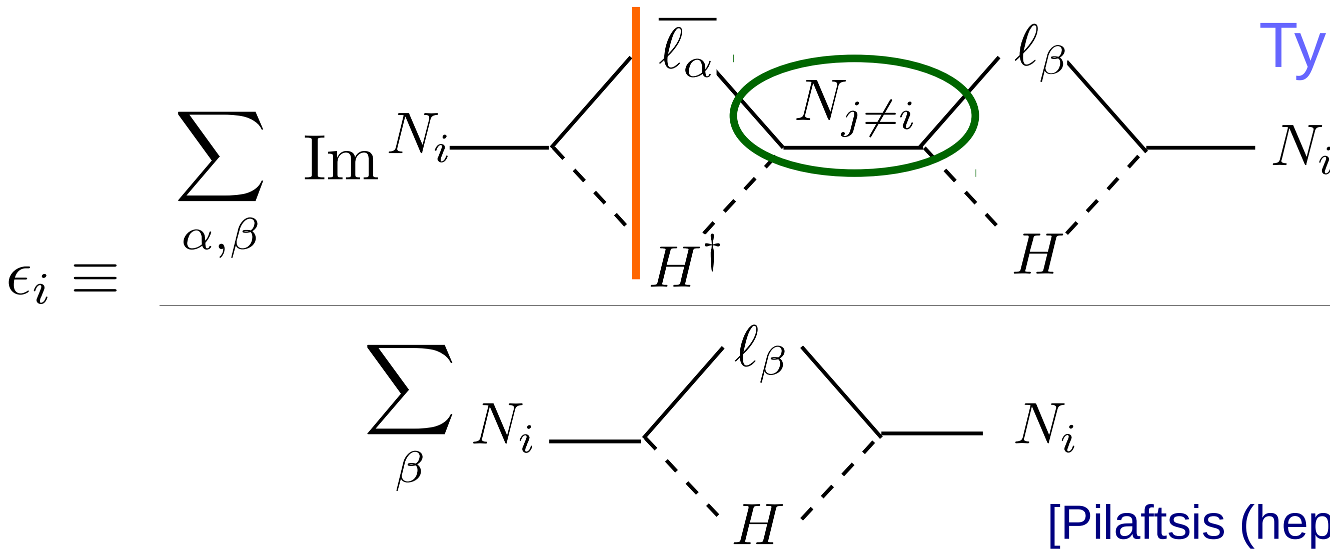

[Pilaftsis (hep-ph/9707235)]

$$\epsilon_i \sim \frac{1}{16\pi}\frac{m_\nu M_i}{v^2} \times \boxed{\sum_j \sin(\phi_i - \phi_j)\frac{(M_i^2 - M_j^2)M_j^2}{(M_i^2 - M_j^2)^2 + M_i^2\Gamma_j^2}}$$

Can go as low as possible i.e. $M_i > 132\,\mathrm{GeV}$ (more later)

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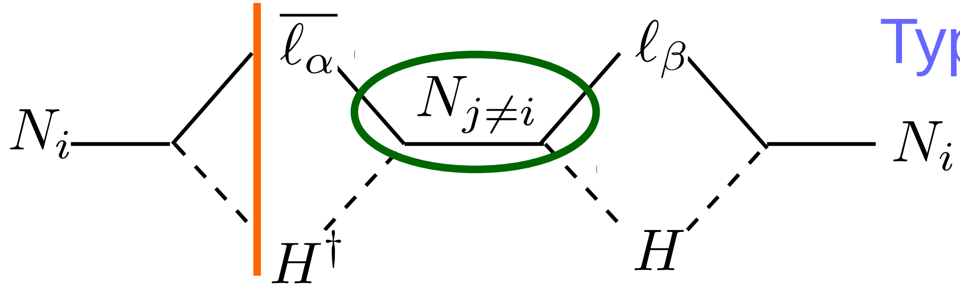
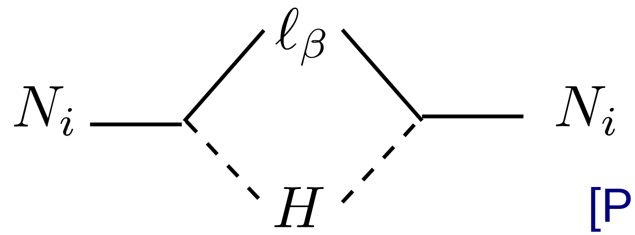
$$\epsilon_i \equiv \frac{\sum_{\alpha,\beta} \mathrm{Im}\,[\ldots]}{\sum_{\beta}[\ldots]}$$





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Can go as low as possible i.e. $M_i > 132\,\mathrm{GeV}$ (more later)

Doesn’t apply on those which rely on different physical mechanisms...

High scale models

High scale means ...

- Operator cannot be “resolved” by experiments $\Lambda_L > E_{\rm exp}$
- Circumstantial/supporting evidences
  - 1) Lepton number violation $0\nu\beta\beta$
  - 2) CP violation in leptonic sector δ
  - 3) Out-of-equilibrium + CP (upper bound on neutrino masses)

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$$y_{\alpha i} = \frac{1}{v}\left(U_\nu^* \sqrt{\hat{m}}\, \underbrace{R\sqrt{\hat{M}}}\right)_{\alpha i}, \quad R^T R = R R^T = I$$

Type I seesaw

$n = 3$

[Casas & Ibarra (hep-ph/0103065)]

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$$\epsilon(N_1 \to \ell_\alpha H) \propto {\rm Im}\left[(y^\dagger y)_{1j} y_{\alpha 1}^* y_{\alpha j}\right] = {\rm Im}\left[\left(\sqrt{\hat{M}} R^\dagger \hat{m}\, R \sqrt{\hat{M}}\right)_{1j} \underbrace{y_{\alpha 1}^* y_{\alpha j}}\right]$$

[Petcov's talk]

Depend on U_ν only if no sum over α

[Pascoli, Petcov & Riotto (hep-ph/0609125,0611338)]

$T \lesssim 10^{12}\,{\rm GeV}$

Can we probe them all?

- We have dim-5 and dim-6 which are not related a priori

$$\frac{c^{(5)}_{\alpha\beta}}{\Lambda_L}(\overline{\ell^c_\alpha}H)(\ell_\beta H) + \frac{c^{(6)}_{\alpha\beta}}{\Lambda^2_{LF}}(\overline{\ell_\alpha}H^\dagger)i\partial\!\!\!/(\ell_\beta H)$$

- In type-I seesaw

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$$\boxed{\frac{c^{(6)}_{\alpha\beta}}{\Lambda^2_{LF}}} = \left(y\hat{M}^{-2}y^\dagger\right)_{\alpha\beta} = \frac{1}{v^2}\left(U_\nu^* \hat{m} R \hat{M}^{-1} R^\dagger \hat{m} U_\nu^T\right)$$

Precisely additional 6+3 parameters that can be probed!

[Broncano, Gavela & Jenkins (hep-ph/0210271)]

Lepton nonunitarity & lepton nonuniversality $\Longrightarrow$ $|y|\, v/M \lesssim 10^{-2}$

Can we probe them all?

Yes in principle but …

- We have dim-5 and dim-6 which are not related a priori

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- In type-I seesaw $\boxed{\frac{|y|\,v}{M} \sim \sqrt{\frac{m_\nu}{M}} \sim 10^{-8}\left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)^{1/2}\left(\frac{10^6\,\mathrm{GeV}}{M}\right)^{1/2}}$

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SO(10) inspired models

- One right-handed neutrino per gen. is a prediction! $16 = 1 \oplus \bar{5} \oplus 10$
  $16 \otimes 16 = 10 \oplus 126 \oplus 120$

Type-I seesaw Type-II seesaw

- Triplet Higgs rides along $\overline{126}_H = (1 \oplus 5 \oplus \overline{10} \oplus 15 \oplus \overline{45} \oplus 50)_H$
- SO(10) inspired conditions

$$\boxed{m_u \sim m_D, V_L \sim V_{\mathrm{CKM}} \implies M_1 \sim 10^7\,\mathrm{GeV}}$$

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+ *Strong* thermal leptogenesis (no pre-existing asymmetry survives):
Tauon N_2 dominated scenario: N_2 decays generate asymmetry in tau lepton direction [Bertuzzo,Di Bari & Marzola (hep-ph/1007.1641)]

- Normal ordering
- Atmospheric mixing $< 45^\circ$
- Favor negative δ

[Di Bari & Marzola (hep-ph/1308.1107)]

[Di Bari, King & Re Florentin (hep-ph/1401.6185)]

Realistic SO(10) models

- Tuning? Just comes out from the fits – and perfect for leptogenesis – perhaps hints of underlying symmetries

Mod	Comments	$\langle m_\nu \rangle$ [meV]	δ^l_{CP} [rad]	$\sin^2\theta^l_{23}$	m_0 [meV]	M_3 [GeV]	M_2 [GeV]	M_1 [GeV]	$\chi^2_{\rm min}$
MN	no RGE, NH	0.35	0.7	0.406	3.03	5.5×10^{12}	7.2×10^{11}	1.5×10^{10}	1.10
MN	RGE, NH	0.49	6.0	0.346	2.40	3.6×10^{12}	2.0×10^{11}	1.2×10^{11}	23.0

[Dueck & Rodejohannn (hep-ph/1306.4468)]

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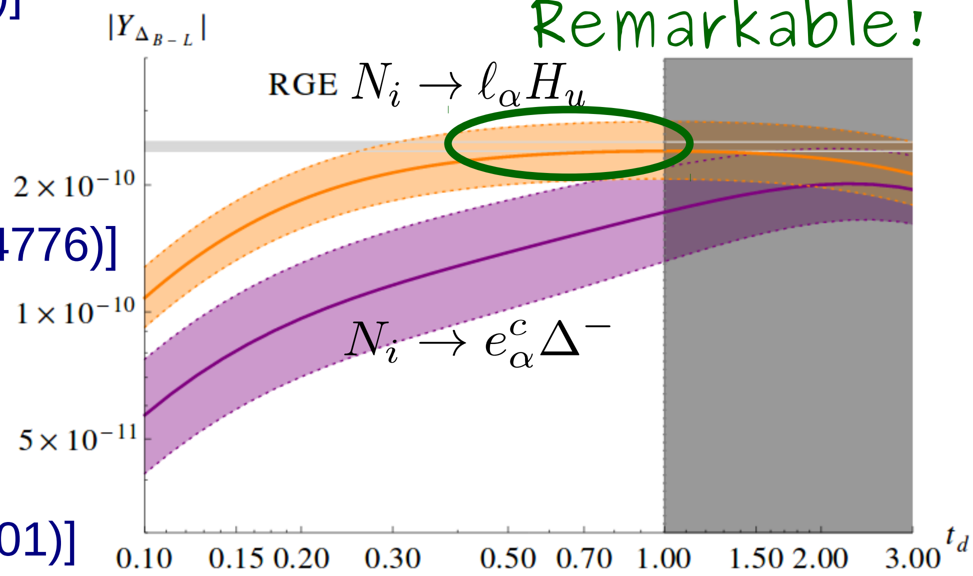
Remarkable!



[CSF, Meloni, Meroni & Nardi (hep-ph/1412.4776)]

See also [Altarelli & Meloni (hep-ph/1305.1001)]

$$t_d \equiv \frac{\langle \Sigma_d \rangle}{\langle H_d \rangle}$$

Low scale models

Resonant leptogenesis

[Pilaftsis (hep-ph/9707235)] [Pilaftsis & Underwood (hep-ph/0309342)]

- The right-handed neutrinos are quasi-degenerate to enhance the CP violation from self energy corrections
- Can be probed at LHC & CLFV [Bray, Lee & Pilaftsis (hep-ph/0702294)]
- Quasi-degeneracy $M_2 - M_1 = \mu \ll M_{1,2} \approx M$ due to
  - Approximate family symmetry (ok)
  - Soft SUSY breaking terms (ok)
  - Approximate lepton number (*difficult*)

[Grossman et al. (hep-ph/0307081)]
[D' Ambrosio et al. (hep-ph/0308031)]
[Review (hep-ph/1107.5312)]

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[Review (hep-ph/1107.5312)]

Difficult because mass degeneracy is tied to CP violation!

$$M_2 - M_1 = \mu \qquad\qquad |\epsilon| \propto \mu$$

Difficulty in details

$$M_2 - M_1 = \mu \ll M_{1,2} \approx M$$

- For generic resonant leptogenesis

$$|\epsilon| \leq \frac{1}{2} \qquad |Y_{\Delta B}| \lesssim \frac{H}{2\Gamma_2} Y_N^{\rm eq} \sim 10^{-2} \left(\frac{0.1\,{\rm eV}}{m_\nu} \right) Y_N^{\rm eq}$$

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[Blanchet, Hambye, Josse-Michaux (hep-ph/0912.3153)] Successful?

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Too small!

Discussions with Agashe, Du, Ekhterachian, Hong, Vecchi

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Regulator *<u>matters</u>* because $\Gamma_2 - \Gamma_1 \sim M_2 - M_1$

$$\frac{(M_i^2 - M_j^2) M_j^2}{(M_i^2 - M_j^2)^2 + (M_i^2 \Gamma_i^2 - M_j \Gamma_j^2)^2} \Longrightarrow \frac{H}{\mu} \propto \frac{M}{M_{\rm Pl}} \frac{M}{\mu}$$

[Buchmuller & Plumacher (hep-ph/9710460)]
[Anisimov et al. (hep-ph/0511248)]

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[Pilaftsis (hep-ph/9707235)]
Give correct physical limit

Difficulty in details

$$M_2 - M_1 = \mu \ll M_{1,2} \approx M$$

- For generic resonant leptogenesis

$$|\epsilon| \leq \frac{1}{2} \qquad |Y_{\Delta B}| \lesssim \frac{H}{2\Gamma_2} Y_N^{\rm eq} \sim 10^{-2} \left(\frac{0.1\,{\rm eV}}{m_\nu}\right) Y_N^{\rm eq}$$

- For inverse seesaw (approximate lepton number)

[Blanchet, Hambye, Josse-Michaux (hep-ph/0912.3153)] Successful?

$$|\epsilon| \lesssim \frac{\mu}{2M} \qquad |Y_{\Delta B}| \lesssim \frac{H}{M} Y_N^{\rm eq} = 17 \boxed{\frac{M}{M_{\rm Pl}}} Y_N^{\rm eq} \sim 10^{-15} \left(\frac{M}{1\,{\rm TeV}}\right) Y_N^{\rm eq}$$

Too small!

Discussions with <u>Agashe</u>, Du, Ekhterachian, Hong, Vecchi

Regulator *<u>matters</u>* because $\Gamma_2 - \Gamma_1 \sim M_2 - M_1$

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See also [Garny et al. (hep-ph/1112.6428)]

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Other interesting possibilities

GeV scale right-handed neutrinos!

- Akhemedov-Rubakov-Smirnov (hep-ph/9803255)

$$\frac{c^{(6)}_{\alpha\beta}}{\Lambda^2_{LF}}(\overline{\ell_\alpha} H^\dagger)\partial(\ell_\beta H)$$

Some recent studies: [Hernández et al. (hep-ph/1606.06719)] [Drewes et al. (hep-ph/1611.04769)] and many more

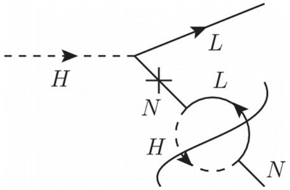
[Asaka's talk] [Drewes's poster] [Klaric's poster]

$$(B-L)^{\rm tot} = B - (L_{\rm SM} + L_A + L_B + L_C) = 0 \text{ (conserved)}$$

Lepton number violation does not play a role!

- From Higgs decay (thermal effects are crucial)

$$\frac{c^{(5)}_{\alpha\beta}}{\Lambda_L}(\overline{\ell^c_\alpha} H)(\ell_\beta H)$$



[Hambye & Teresi (hep-ph/1606.00017), (hep-ph/1705.00016)]

1) Directly produced at SHiP, FCC-ee, ILC
2) Important contributions to $0\nu\beta\beta$
3) Sensitive to delta phase from neutrino oscillations

Falsifications

Approaches

- In the Left-Right seesaw models, observation of $M_{W_R} \lesssim 10\,\mathrm{TeV}$ from $pp \to W_R \to N\ell^{\pm} \to \ell^{\pm}\ell^{\pm}jj$ would falsify leptogenesis due to large dilution from processes like

$$Ne_R \leftrightarrow d_R\bar{u}_R,\ Nu_R \leftrightarrow e_R\bar{d}_R,\ Nd_R \leftrightarrow e_R u_R,\ N \to W_R^*\ell \to \ell jj$$

[Frère, Hambye, & Vertongen (hep-ph/0806.0841)]
[Bhupal Dev, Lee & Mohapatra (hep-ph/1408.2820),(hep-ph/1503.04970)]

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- Model independent falsification of leptogenesis: observations of
  - LNV at the LHC?

Naive expectation: $\dfrac{m_\nu^2}{E^2} \sim 10^{-26}$

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But asymmetry can hide in say $B/3 - L_\tau$

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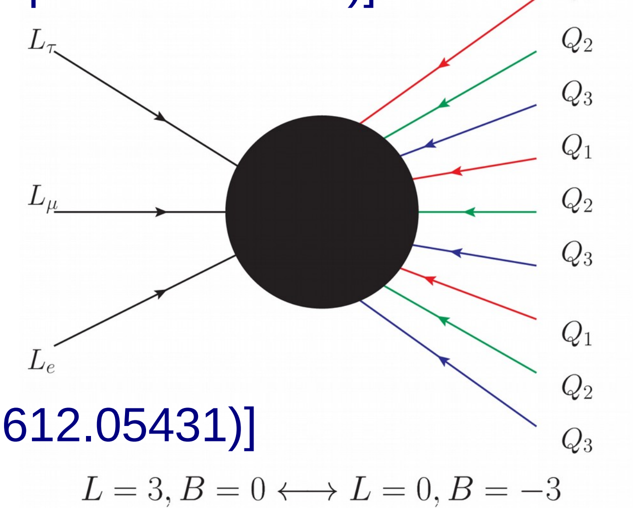
Observations hint that asymmetry *not stored* in *B-L* but other charges
e.g. [Aristizabal Sierra, CSF, Nardi & Peinado (hep-ph/1309.4770)]

One indispensable ingredient

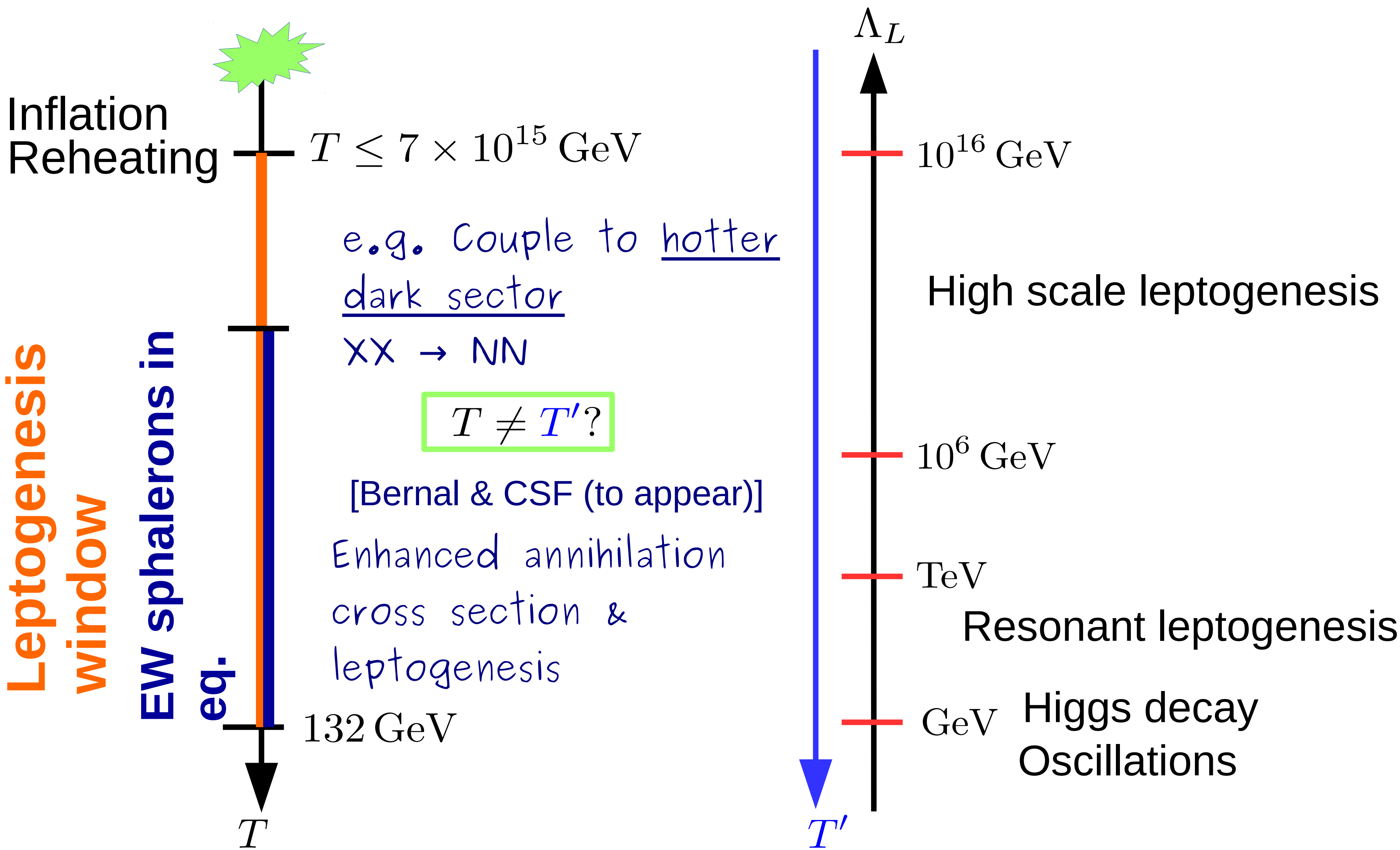
- Another <u>very important</u> ingredient (source of ***B*** violation): ***EW sphalerons*** have not been tested experimentally.
- General consensus: it is active at high T but exponentially suppressed in colliders. [Rubakov & Shaposhnikov (1996)]
- Challenged by a new calculation by Tye and Wong (hep-ph/1505.03690)]
- Based on that:
  - LHC [Ellis & Sakurai (hep-ph/1601.03654)]
  - IceCube [Ellis, Sakurai, Spannowsky (hep-ph/1603.06573)]



See comments in [Funakubo, Fuyuto & Senaha (hep-ph/1612.05431)]

Hard to probe but keep an open mind

Hot Leptogenesis?



Outlook

- Leptogenesis remains one of the most elegant neutrino mass models for baryogenesis
- Realistic models *do not* depend on whether our experiments are capable of "resolving" the Weinberg operator
- Experimentally, *crucial supporting evidences*: 1) LNV in $0\nu\beta\beta$; 2) absolute neutrino mass; 3) leptonic CP violation (+mixing)
- Theoretically, GUTs + family symmetry (+ SUSY) ((+ fun ideas))
- Discovery of large LNV (+ CLFV) could falsify leptogenesis → hints on protection mechanism from new sector?
- Low scale leptogenesis: resonant, oscillations or Higgs decays allows for direct probe of Weinberg operator