

TeV Leptogenesis and dark matter

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Cosmological coincidence

Two yet unsolved puzzles in cosmology:

- **Dark Matter:** WIMPS? Axions??
- **Baryon Asymmetry in the Universe:** Leptogenesis? ...?

Completely independent?

mass density ratio

number density ratio

$$\frac{\rho_{DM}}{\rho_B} \approx 5$$

$$\frac{n_{DM}}{n_B} \sim 5 \frac{GeV}{m_{DM}}$$

Coincidence, or **is there more behind it?**



Relating the two puzzles

Asymmetric dark matter

... Kaplan, Luty and Zurek, 2009 ...

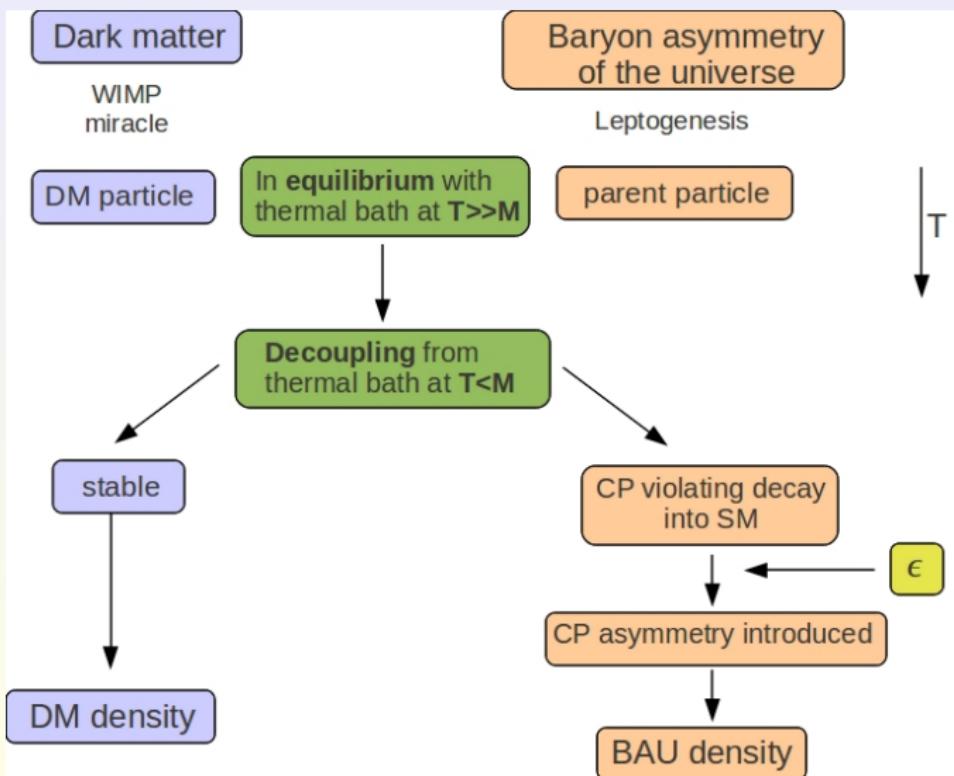
- Produce CP asymmetry which transforms into baryon asymmetry and dark matter asymmetry
- **links DM to a baryogenesis mechanism**

However: DM has a natural explanation: WIMP miracle

Idea: link baryon asymmetry to WIMP relic density

- Cui, Randall, Shuve 2011: **WIMPy Baryogenesis** (CP violation in WIMP annihilation introduces baryon asymmetry)
- McDonald 2012: **Baryomorphosis** (Modifying initial baryon asymmetry and combining with a WIMP dark matter candidate)

WIMP vs. Leptogenesis



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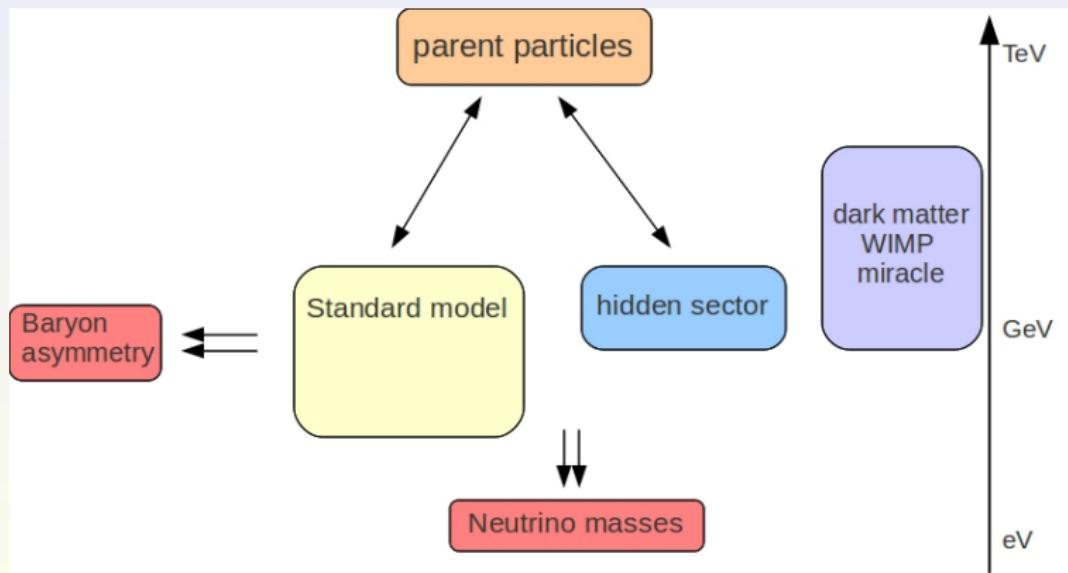
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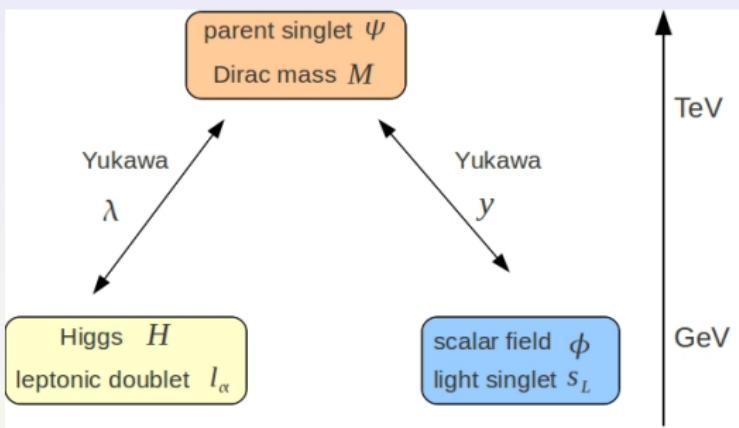
General idea

- Goal: Relate baryon asymmetry to dark matter
- DM explained by WIMP miracle
 - cross section of electroweak strength
 - mass between GeV and TeV
 - relic mass density almost independent of mass
- BAU produced by leptogenesis at TeV
 - parent particle freeze-out controlled by process of electroweak strength
 - CP asymmetry in parent decay is very big: $\epsilon = \mathcal{O}(1)$
- \Rightarrow Baryon relic density is naturally of the order of DM relic density

The model (introduction)

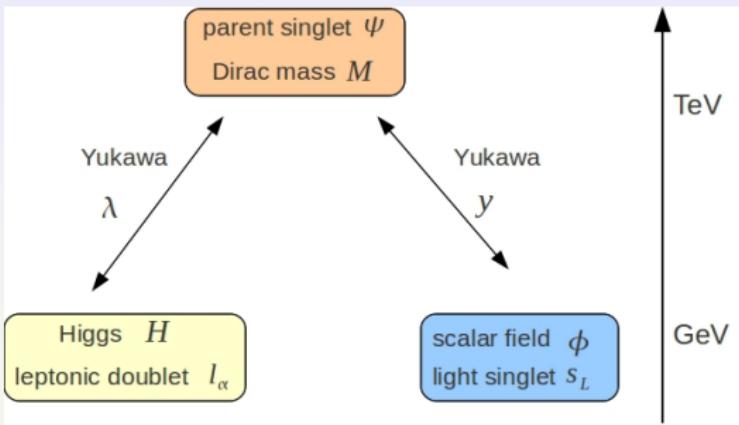


The model (details)



- Parent: Dirac field ψ_I , is gauge singlet and has mass $M = 1\text{TeV}$
- Hidden sector:
 - Light chiral field $s_{L,\alpha}$ is gauge singlet
 - scalar field ϕ

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 - scalar field ϕ
- Lepton number conserving if $L = 1$ for ψ, s_L and $L = -2$ for scalar field ϕ

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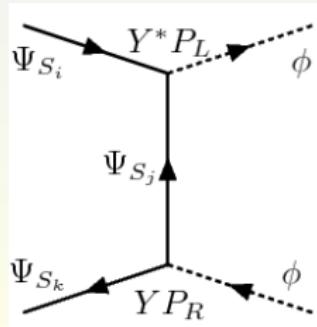
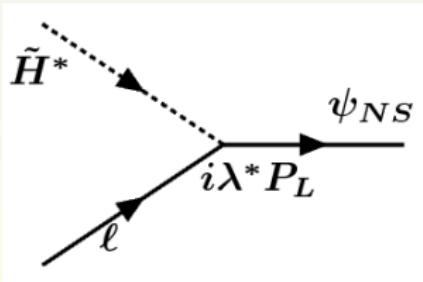
Freeze-out

At high temperature $T \gg M$

- equilibrium density of parent particles due to λ coupling to SM

Temperature dropping $T \leq M$

- parent decay starts
- for successful creation of BAU we need
 - inverse decay $\ell_\alpha H \rightarrow \psi_I$ slow compared to expansion rate of the universe (would destroy asymmetry)
 - annihilation $\psi_I \bar{\psi}_J \rightarrow \phi \bar{\phi}$ slow compared to expansion rate of the universe (would not create asymmetry)





Freeze-out

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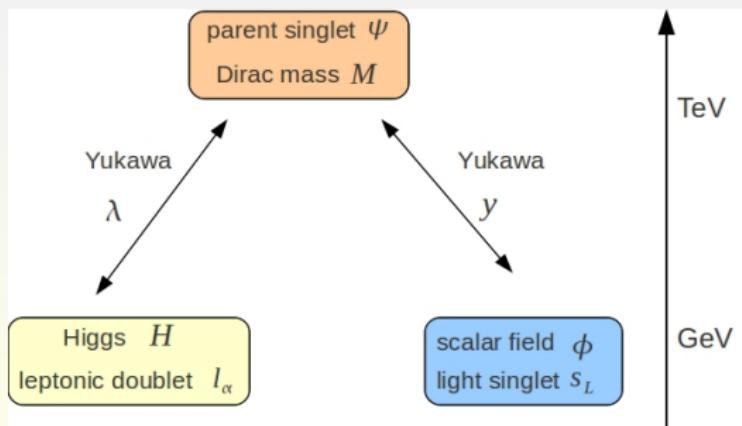
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- asymmetry washout slow
- CP violating decay can now produce asymmetry

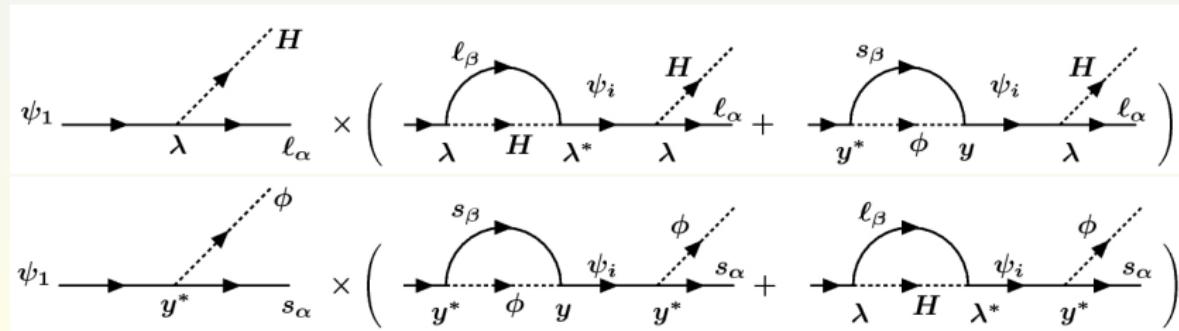
CP violation

- defined by $\epsilon = \frac{\Gamma(\psi \rightarrow f) - \Gamma(\bar{\psi} \rightarrow \bar{f})}{\Gamma(\psi \rightarrow f) + \Gamma(\bar{\psi} \rightarrow \bar{f})}$
- CP* violating phases in λ and y Yukawa couplings
- two different final states for decay of parent decays: "SM" final state and "hidden" final state



CP violation

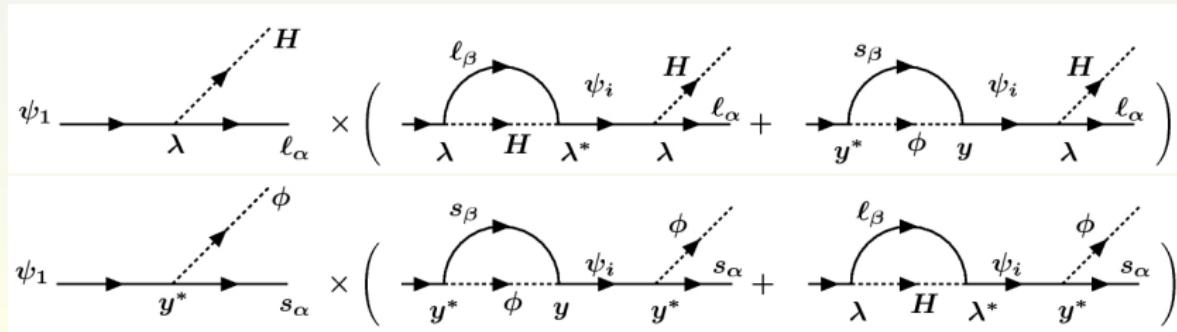
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- leading diagrams: self energy diagrams (vertex correction suppressed!)



CP violation generation

- dominating term for SM final state $\ell_\alpha H$

$$\epsilon(\psi_1 \rightarrow \ell_\alpha H) = \sum_{\beta,i} \frac{\text{Im}\{\lambda_{\alpha 1} \lambda_{\alpha i}^* y_{\beta 1} y_{\beta i}^*\}}{8\pi[2\lambda^\dagger \lambda + y^\dagger y]_{11}} \frac{\sqrt{x_i}}{1-x_i}$$



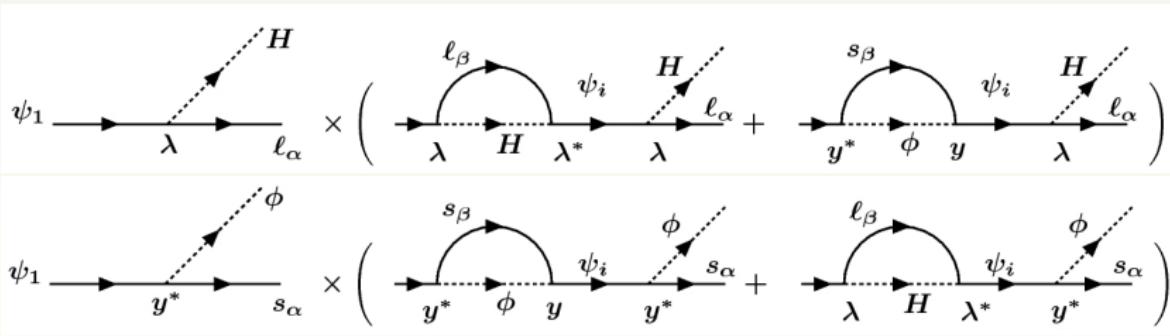
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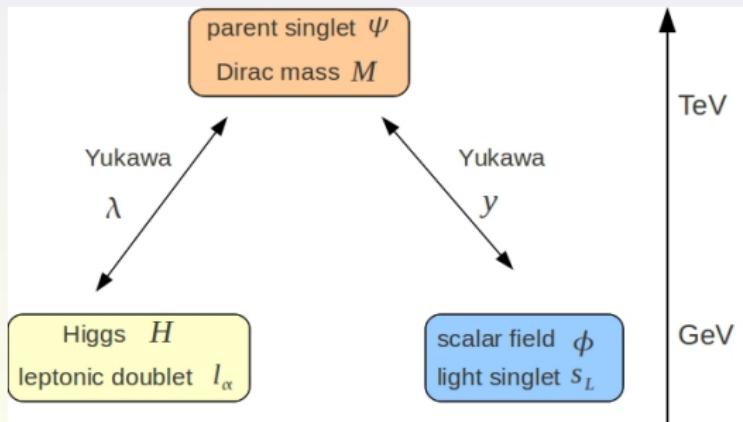
- To create enough asymmetry we need: $\epsilon \sim \mathcal{O}(1)$
- \Rightarrow degenerate parent masses: $1 - x_i \ll 1$ where $x_i = \frac{M_i^2}{M_1^2}$

Resonant Leptogenesis, Pilaftsis and Underwood 2004



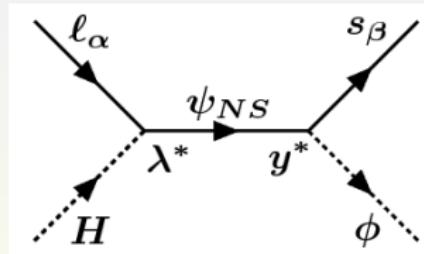
Keeping produced asymmetry

- Remember: lepton number is conserved \Rightarrow flavour sum over CP asymmetries is zero: $\sum_{\alpha} \epsilon_a = 0$
- \Rightarrow No asymmetry produced, only separated between the two different final states
- Processes from one final state to the other would erase asymmetry!



Keeping produced asymmetry

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- Processes from one final state to the other would **erase asymmetry!**



Condition: this process must be slow after parent particles freeze-out

$$\Gamma_{H\ell_a \rightarrow \phi s_\beta} < H(T_f)$$



Summary of thermal history

- parent particles **equilibrium density** produced at high temperatures
- **freeze-out:** inverse decays $\ell_\alpha H \rightarrow \psi_I$ and annihilations $\psi_I \bar{\psi}_J \rightarrow \phi \bar{\phi}$ slow
- **CP violating decays** "produce" ***CP* asymmetry** in leptonic doublet
- conversion into baryon asymmetry by **sphalerons**, with efficiency $C_{sp} = \frac{12}{37}$
- final **baryon asymmetry!**

$$Y_B = C_{sp} \epsilon Y_\psi|_{T_{\text{freeze-out}}} \quad \text{with} \quad Y = \frac{n}{s}$$



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And then?

- ϕ develops a **vacuum expectation value** $u = \langle \phi \rangle$ (after EWPT)
- **lepton number conservation is broken** by

$$\mathcal{L} = -y\phi^*\bar{S}s - \frac{Y}{2}\phi\bar{S}^cS - \frac{X}{2}\phi\bar{s}s^c - \frac{Z}{2}\phi^*\bar{N}N^c$$

where $\psi = \begin{pmatrix} S \\ N \end{pmatrix}$



Neutrino masses (extended inverse see-saw)

After EWPT and phase transition of ϕ , **mass matrix**:

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2} \left(\overline{\nu_L} \overline{(N_R)^C} \overline{S_L} \overline{(s_R)^C} \right) \begin{pmatrix} 0 & m_D & 0 & 0 \\ m_D & \mu_Z & M & 0 \\ 0 & M & \mu_Y & \mu_y \\ 0 & 0 & \mu_y & \mu_X \end{pmatrix} \begin{pmatrix} (\nu_L)^C \\ N_R \\ (S_L)^C \\ s_R \end{pmatrix}$$

- where e.g. $\mu_X = X \cdot u = X \cdot \langle \phi \rangle$

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- where e.g. $\mu_X = X \cdot u = X \cdot \langle \phi \rangle$
- interesting limit: $M \gg \text{rest}$
- light Majorana mass eigenvalue
$$m_\nu = \frac{m_D^2}{M^2} \left(\mu_Y - \frac{\mu_y^2}{\mu_X} \right)$$
- \Rightarrow no need for very heavy (see-saw type I like) singlets, $M \lesssim 1 \text{ TeV}$ enough
- for $y = X = 0$ we are in a inverse see-saw mechanism

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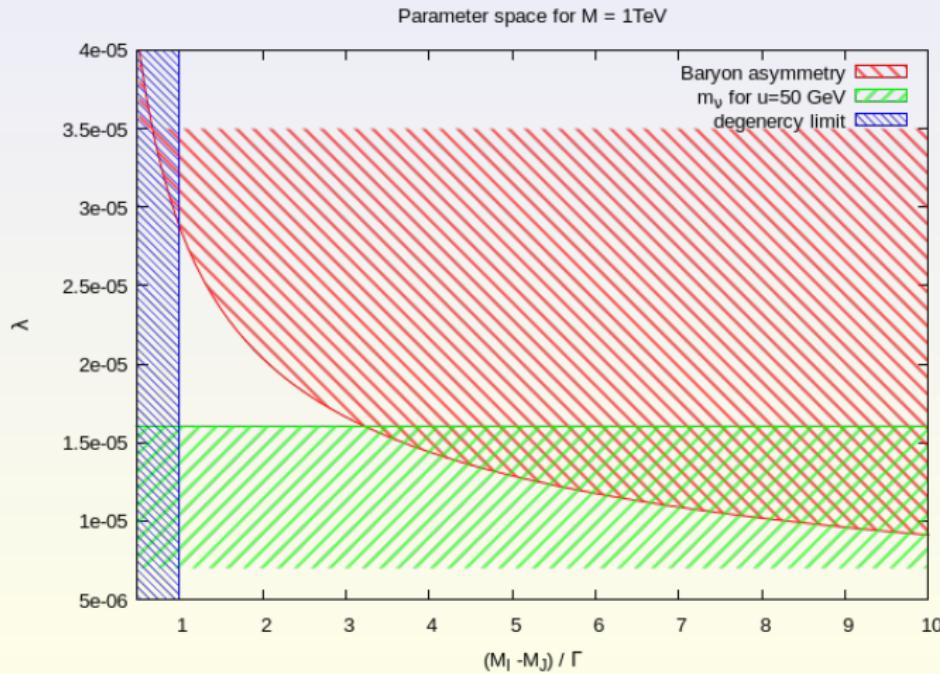
Analysis of possible parameter space

Constraints on parameters:

- produce **baryon asymmetry** $Y_{\Delta B} = 9 \cdot 10^{-11}$
 - $\epsilon \sim \mathcal{O}(1)$
 - **dangerous processes slow** after decoupling
- Parent mass scale near the **EW scale** for link to WIMP miracle
- reproduce **neutrino masses** $m_\nu \sim 0.1\text{eV}$
- ϕ **vev** not too big $u \lesssim 50\text{GeV}$

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YES, the model does work, in a very constraint parameter space

- Main problem:** ϵ is not naturally $\mathcal{O}(1)$
We have to introduce **degenerate heavy singlet masses**

$$M_I - M_J \sim \Gamma_{I,J}$$

Γ decay rate

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Conclusion

Experimental data: $\frac{Y_{DM}}{Y_B} = \mathcal{O}(1)$

Idea: linking baryon asymmetry to the dark matter

- DM by WIMP miracle
- BAU via leptogenesis model
 - parent particle with a WIMP like density at freeze-out
 - CP asymmetry of order one
 - fitting neutrino masses

Result

- self-consistent model explaining BAU by linking it to EW scale
- restricted parameter space

Outlook:

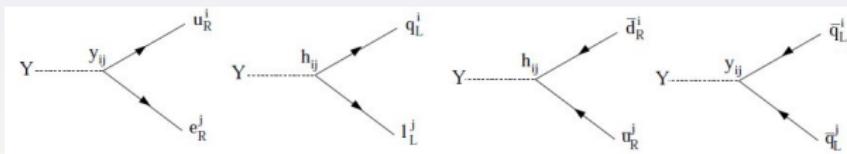
- Variation of parameter X (light singlet mass term)
- X small: light singlets s mix with SM neutrinos
- X big: s **DM candidates** \Rightarrow asymmetric dark matter

O
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MERCI!

GUT Baryogenesis

- $SU(5)$ GUT, Higgs boson with QN $(3, 1, \frac{1}{3})$
- Yukawa couplings y and h violating B



- decay out of equilibrium for small Yukawa couplings $\sim 10^{-2}$
- CP violation for complex y and h
- **BUT:** high lower limit on decaying boson masses by proton decay \Rightarrow high reheat temperature \Rightarrow too many monopoles and gravitons
- **DISFAVoured!**