

COMPOSITE MAJORANA NEUTRINOS AND LEPTOGENESIS

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27 January 2020

in collaboration with R. Leonardi, O. Panella and M. Presilla
(1707.00844 and in prep.)

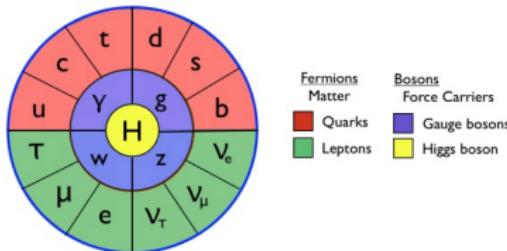
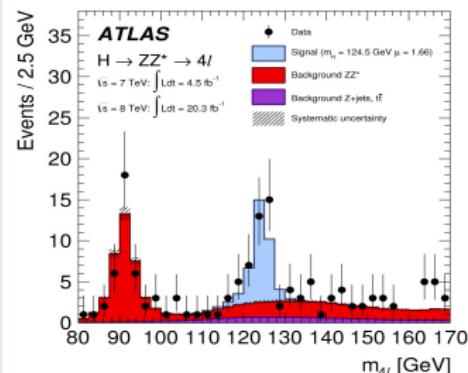
OUTLINE

- 1 BARYOGENESIS VIA LEPTOGENESIS
- 2 LEPTOGENESIS WITH COMPOSITE NEUTRINOS
- 3 CONCLUSIONS AND OUTLOOK

THE STANDARD MODEL TODAY...

- Quite a few fundamental particles
⇒ explain a lot of phenomena
- Discovery of the Higgs boson:
⇒ last great success within the SM
- The picture might appear complete...

G. Aad et al. (ATLAS coll.), Phys. Rev. D 90 052004 (2014)

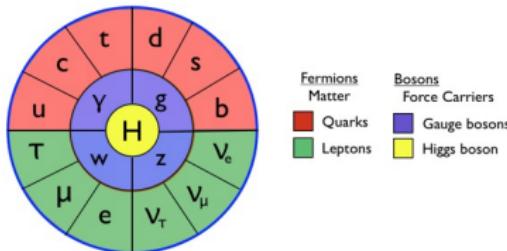
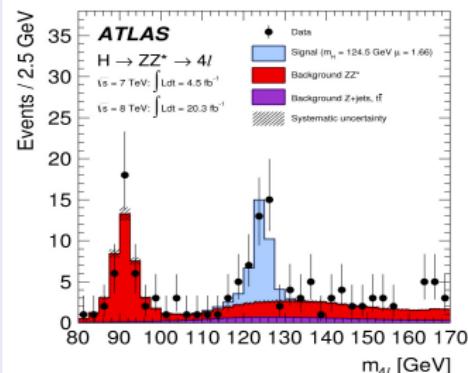


Particles of the Standard Model

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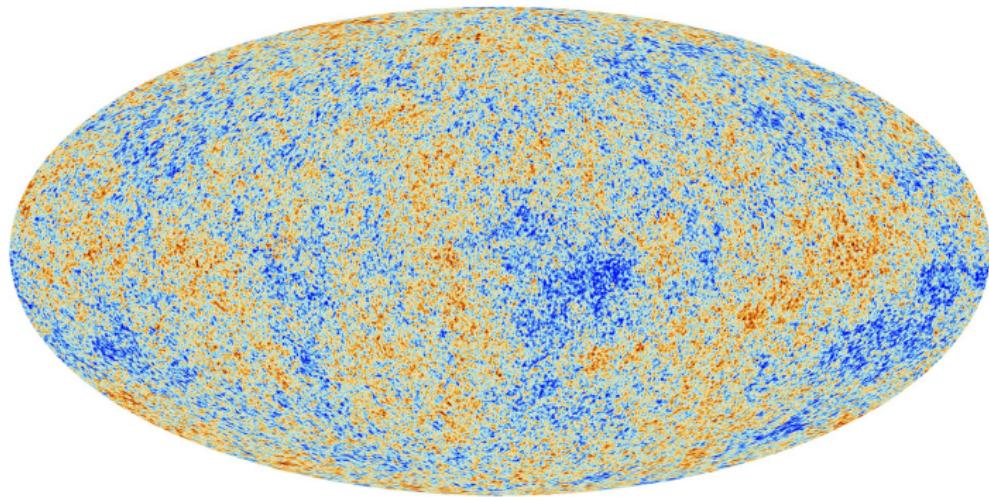
...HOWEVER

- in addition to particle physics
 - a) dark matter
 - b) baryon asymmetry in the universe...

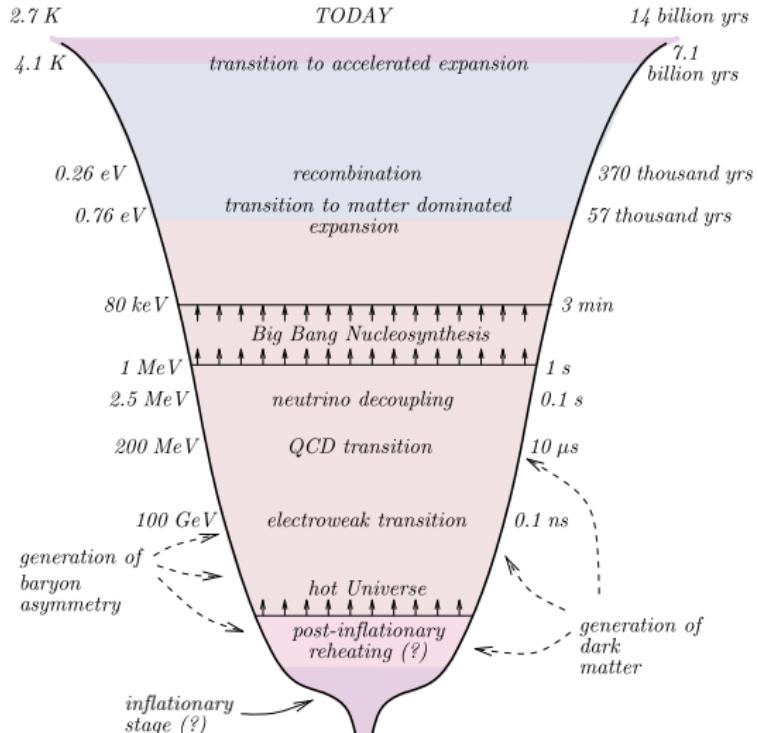
EVIDENCE FOR AN EARLY UNIVERSE

PIONEERING WORK BY GAMOW, ALPHER AND HERMAN

- nucleosynthetic processing of the H, D, ^3H ... in a dense and hot environment
Phys. Rev 70 (1946), Phys. Rev 70 (1948), Phys. Rev 74 (1948)
- transition from a plasma of baryons, electrons and γ 's \rightarrow gas of atoms and free electromagnetic radiation



AN EARLIER UNIVERSE?



Gorbunov and Rubakov (World Scientific 2011)

BARYON ASYMMETRY IN THE UNIVERSE

- The Universe shows a matter-antimatter asymmetry at many scales
- To make this statement quantitative (CMB and BBN)

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.09 \pm 0.06) \times 10^{-10}$$

Planck Collab. 2015 Results XIII (2016)

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WHEN AND HOW?

M.S. TURNER (1986), A. RIOTTO (2011)

- the asymmetry had to be there in **the early stage** (before BBN):

$$B + \bar{B} \rightarrow 2\gamma \Rightarrow \eta_B \sim 10^{-18}$$

- the observed baryon asymmetry as an **initial condition**
 ⇒ **diluted and washed-out** after the inflationary epoch

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- Dynamical generation of η_B : *Baryogenesis*
 - 1) Rigorous formulation in QFT
 - 2) Early universe: interplay with thermal field theory

BASICS OF BARYOGENESIS

SAKHAROV CONDITIONS, *A. D. Sakharov (1967)*

1) B violation: $V \rightarrow B_a + X$ and $V \rightarrow \bar{B}_a + X$

2) C and CP violation:

$$\Gamma(V \rightarrow B_a + X) \neq \Gamma(V \rightarrow \bar{B}_a + X)$$

3) Out-of-equilibrium process: an arrow in time, otherwise

$$\langle B_a(t) \rangle_T = \langle B_a(0) \rangle_T$$

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IN THE STANDARD MODEL

- CP phases are too small: Jarlskog invariant $\sim 10^{-20}$, *C. Jarlskog (1985)*
- Electroweak Baryogenesis with first order transition: $m_h < 80$ GeV

P. B. Arnold and O. Espinosa (1993), K. Kajantie, M. Laine, K. Rummukainen, and M. E. Shaposhnikov (1997)

⇒ the value $m_h \simeq 125$ GeV disfavours the model

BARYOGENESIS VIA LEPTOGENESIS

- At high temperatures, $T \geq 100$ GeV

V. A. Kuzmin, V.A. Rubakov and M. E. Shaposhnikov (1985)

⇒ **B and L are connected** by the sphalerons transitions: $\eta_B = \frac{\alpha_{\text{sph}}}{\alpha_{\text{sph}} - 1} \eta_L$

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APPEALING FRAMEWORK: LEPTOGENESIS

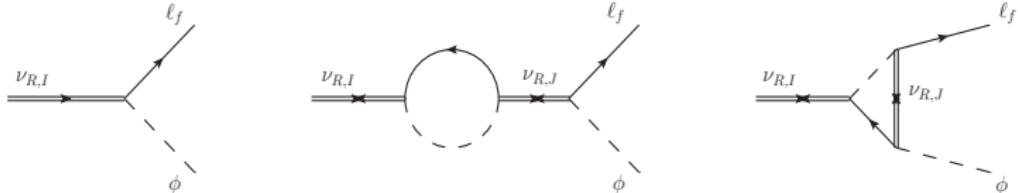
M. Fukugita and T. Yanagida (1986)

- Add right-handed neutrinos $\psi = \nu_R + \nu_R^c$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} \bar{\psi}_I (i\partial^\mu - M_I) \psi_I - F_f \bar{\psi}_I \tilde{\phi} P_R \psi_I - F_f^* \bar{\psi}_I P_L \tilde{\phi}^\dagger L_f$$

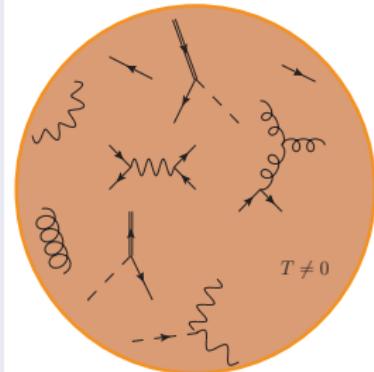
- Explain the smallness of SM neutrinos via seesaw (type-I): $m_\nu \sim v^2 \frac{|F_I|^2}{M_I}$
- Provide the ingredients for the matter-antimatter asymmetry

$$\Gamma(\nu_{R,I} \rightarrow \ell_f + X) \neq \Gamma(\nu_{R,I} \rightarrow \bar{\ell}_f + X)$$



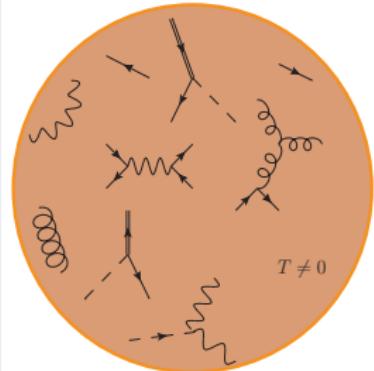
HEAVY NEUTRINOS IN A THERMAL BATH

IN-MEDIUM INTERACTIONS



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IN-MEDIUM INTERACTIONS



1) Neutrino decay width

*A. Salvio, P. Lodone and A. Strumia (2011),
M. Laine and Y. Schroder (2012), M. Laine (2013)*

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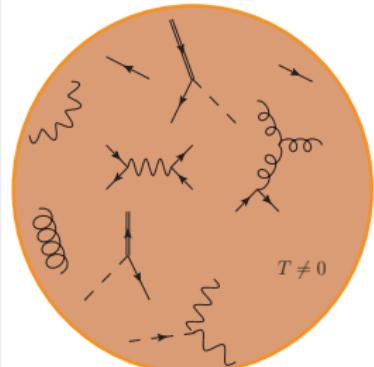
2) CP asymmetry

*M. Garny, A. Hohenegger and A. Kartavtsev (2010),
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$$\epsilon = \frac{\Gamma(\nu_{R,I} \rightarrow \ell_f + X) - \Gamma(\nu_{R,I} \rightarrow \bar{\ell}_f + X)}{\Gamma(\nu_{R,I} \rightarrow \ell_f + X) + \Gamma(\nu_{R,I} \rightarrow \bar{\ell}_f + X)}$$

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$$\frac{dn_N}{dt} + 3Hn_N = - \left(\frac{n_N}{n_N^{\text{eq}}} - 1 \right) \gamma_N, \quad \gamma_N \propto \Gamma$$

$$\frac{dn_L}{dt} + 3Hn_L = \left[\epsilon \left(\frac{n_N}{n_N^{\text{eq}}} - 1 \right) - \frac{n_L}{2n_L^{\text{eq}}} \right] \gamma_N, \quad H = \frac{T^2}{M_{\text{Pl}}} \sqrt{\frac{8\pi^3 g_{\text{eff}}}{90}}$$

STRONG WASH-OUT

- The out-of-equilibrium provided by H (universe expansion)

DECAY PARAMETER FOR THE WASH-OUT

$$K_1 = \frac{\Gamma_1^{(T=0)}}{H(T=M_1)} = \frac{M_1 (F^\dagger F)_{11}}{8\pi 1.66 \sqrt{g^*} \frac{M_1^2}{M_{Pl}}} = \frac{\tilde{m}_1}{m_*}$$

where we may define

- $\tilde{m} = (F^\dagger F)_{11} \frac{v^2}{M_1}$, effective neutrino mass
- $m_* = 8\pi 1.66 \sqrt{g^*} \frac{v^2}{M_{Pl}} \simeq 1.1 \times 10^{-3}$ eV

Cfr. P. di Bari and M. Garny

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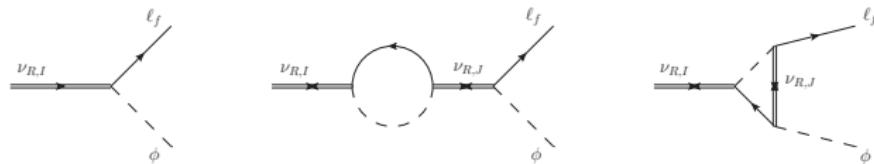
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 - Because $\tilde{m} \simeq m_{\text{sol}} = \sqrt{\Delta m_{\text{sol}}^2} \simeq 0.009 \Rightarrow K \approx 10$
- Majorana neutrinos tracks **almost** the equilibrium distribution
 - The final lepton asymmetry is produced in a **non-relativistic regime**

CP ASYMMETRIES IN HEAVY NEUTRINO DECAYS

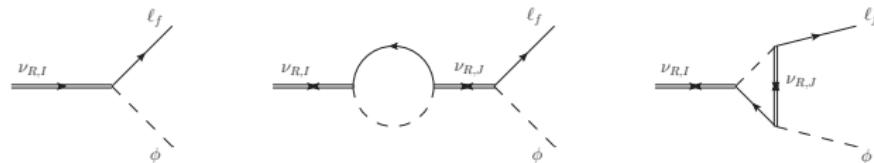
- Interference between tree and one-loop diagrams: $\sim (F_I^* F_J)^2$



$$\epsilon_I = \frac{\sum_f \Gamma(\nu_{R,I} \rightarrow \ell_f + X) - \Gamma(\nu_{R,I} \rightarrow \bar{\ell}_f + X)}{\sum_f \Gamma(\nu_{R,I} \rightarrow \ell_f + X) + \Gamma(\nu_{R,I} \rightarrow \bar{\ell}_f + X)} \propto \text{Im}(\mathcal{A}_{\text{loop}}) \text{Im} \left[(F_I^* F_J)^2 \right]$$

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CP ASYMMETRY AND HEAVY NEUTRINO MASS SPECTRUM

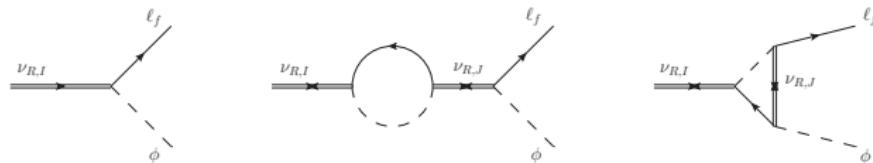
- hierarchical spectrum: $M_1 \ll M_i \Rightarrow \epsilon_{\text{indirect}} = 2\epsilon_{\text{direct}}$

$$M_1 \geq 10^9 \text{ GeV}$$

L. Covi, E. Roulet and F. Vissani (1996), S. Davidson and A. Ibarra (2002)

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- degenerate spectrum: $M_1 \approx M_2$, and if $\Delta = M_2 - M_1 \sim |\Gamma_1 - \Gamma_2|$

\Rightarrow **Resonant case:** $\epsilon_{\text{indirect}} \gg \epsilon_{\text{direct}}$

A. Pilaftsis (1997), W. Buchmüller and M. Plümacher (1998)

$$M \approx 10^3 \text{ GeV}$$

COMPOSITE HEAVY NEUTRINOS (GI)

- two options for accommodating composite neutrinos,

we choose *mirror* model $L_{R,I}^{*T} = (\nu_{R,I}^*, e_{R,I}^*)$

$$\mathcal{L}_{\text{mir}} = \frac{1}{2\Lambda} \bar{L}_{L,\alpha} \sigma^{\mu\nu} \left(f g \tau^a W_{\mu\nu}^a + f' g' \frac{Y}{2} B_{\mu\nu} \right) L_{R,I}^* + h.c.,$$

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- more explicit form with electroweak currents

$$\begin{aligned} \mathcal{L}_{\text{gauge}} &= \mathcal{L}_{\text{SM}} + \frac{1}{2} \bar{N}_I^* i\cancel{\partial} N_I^* - \frac{M_I}{2} \bar{N}_I^* N_I^* + \frac{g}{\sqrt{2}\Lambda} \left[\tilde{f}_{\alpha I} \bar{e}_\alpha \sigma^{\mu\nu} \partial_\mu W_\nu^- P_R N_I^* + h.c. \right] \\ &+ \frac{\tilde{g}}{2\Lambda} \left[\tilde{f}_{\alpha I} \bar{\nu}_\alpha \sigma^{\mu\nu} \partial_\mu Z_\nu P_R N_I^* + h.c. \right] + \dots \end{aligned}$$

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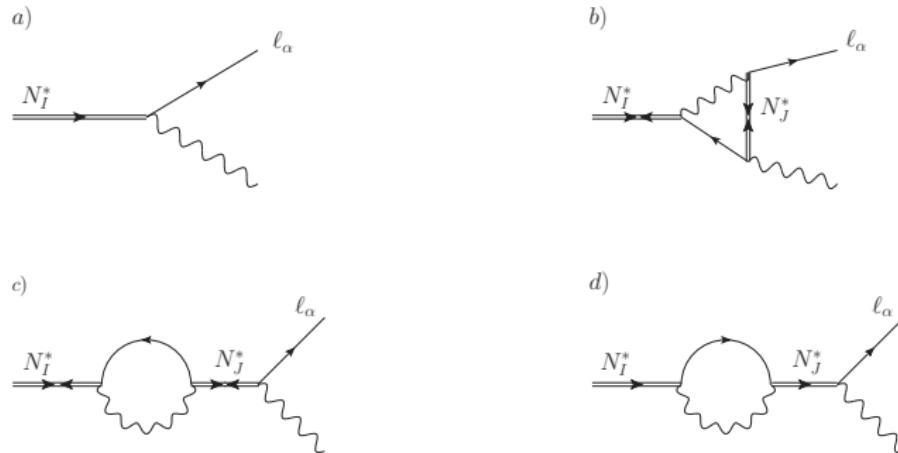
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- Our choice $f = f'$, $\tilde{g} Z_\mu \equiv g W_\mu^3 - g' B_\mu$
- Alternative choice: $f = -f'$, $\tilde{g} \bar{Z}_\mu \equiv g W_\mu^3 + g' B_\mu$ (photon)

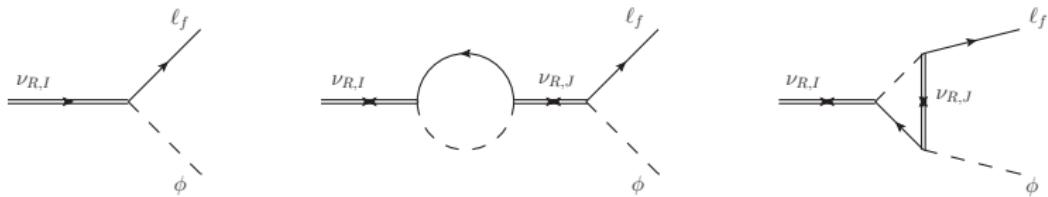
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LEPTOGENESIS WITH COMPOSITE NEUTRINOS

- use the same techniques for calculations
- **DIFFERENCE:** assume T are such that N^* is the relevant d.o.f.

⇒ no phase transition to sub-constituents

COMPOSITE HEAVY NEUTRINOS (CI)

BEFORE ZHURIDOV 1604.07740

- the contact interaction Lagrangian is ([dimension-6 operator](#))

$$\mathcal{L}_{\text{cont}} = \frac{g_*^2}{2\Lambda^2} j^\mu j_\mu ,$$

- with $g_*^2 = 4\pi$ and the vector current is

$$j^\mu = \eta_L \bar{\psi}_L \gamma^\mu \psi_L + \eta'_L \bar{\psi}_L^* \gamma^\mu \psi_L^* + \eta''_L \bar{\psi}_L^* \gamma^\mu \psi_L + h.c. + (L \rightarrow R) ,$$

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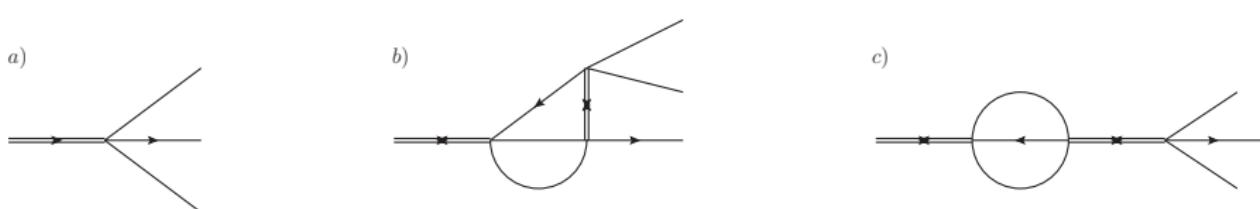
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- only one coupling can be made complex η''_L (η''_R)

$$\mathcal{L}_{\text{contact}} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \bar{N}_I^* i\partial N_I^* - \frac{M_I}{2} \bar{N}_I^* N_I^* + \frac{g_*^2}{2\Lambda^2} [\tilde{\eta}_{\alpha I} \bar{\psi} \gamma_\mu P_R \psi' \bar{\ell}_\alpha \gamma^\mu P_R N_I^* + h.c.] + \dots ,$$



WASHOUT RATES N^* LEPTOGENESIS

key ingredients K_I, ϵ_I , $Y_{\Delta B} \simeq \frac{135\zeta(3)}{4\pi^4 g_{\text{eff}}} C_{\text{sph}} \epsilon_1 \frac{2}{K_1 z_{\text{out}} J(z_{\text{out}})^2}$,

DECAY WIDTHS

$$\Gamma_{I,\alpha}^{\text{gauge}} = \frac{(g'^2 + 3g^2)}{32\pi} \left(\frac{M_I^*}{\Lambda} \right)^2 |\tilde{f}_{I\alpha}|^2 M_I^*, \quad \Gamma_{I,\alpha}^{\text{contact}} = \frac{N_f}{1536} \frac{g_*^4}{\pi^3} \left(\frac{M_I^*}{\Lambda} \right)^4 |\tilde{\eta}_{I\alpha}|^2 M_I^*$$

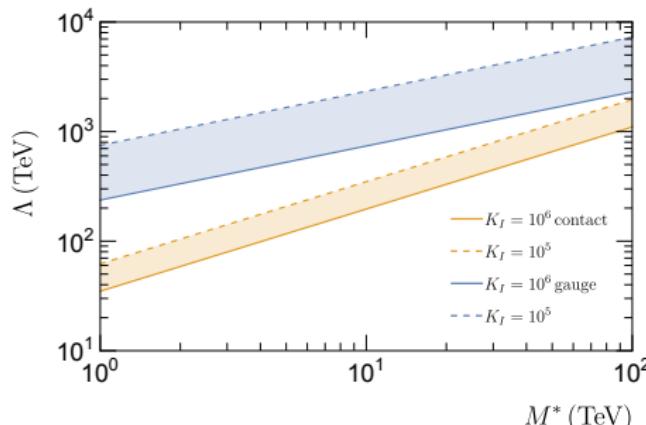
$$K_I = \frac{\Gamma_I}{H(T = M^*)} = \begin{cases} \frac{|\tilde{f}_I|^2}{1.66\sqrt{g_{\text{eff}}}} \frac{g'^2 + 3g^2}{32\pi} \frac{M_{\text{Pl}}}{M_I^*} \left(\frac{M_I^*}{\Lambda} \right)^2 \\ \frac{|\tilde{\eta}|^2}{1.66\sqrt{g_{\text{eff}}}} \frac{g_*^4 N_f}{1536\pi^3} \frac{M_{\text{Pl}}}{M_I^*} \left(\frac{M_I^*}{\Lambda} \right)^4 \end{cases}$$

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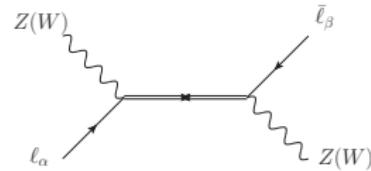
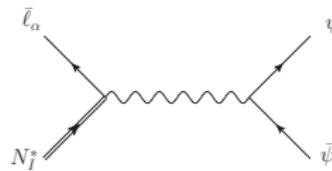
- very large washout requires large ϵ

- difference with standard leptogenesis

$|F_{I\alpha}| \text{ versus } g_*^2 |\eta_{\alpha I}|, g |f_{\alpha I}|$

RESULTS FOR GI: ROUGH ESTIMATE

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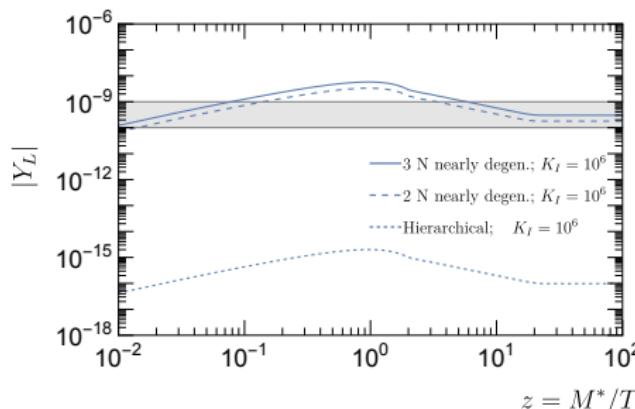
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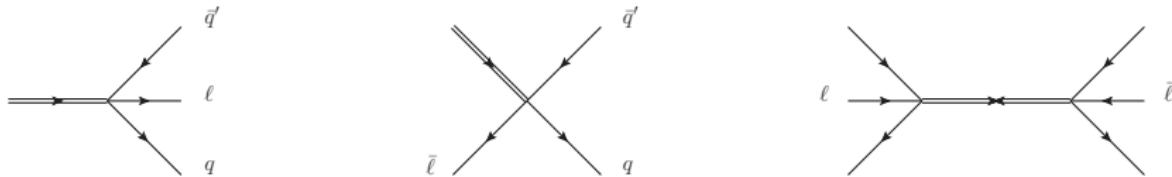


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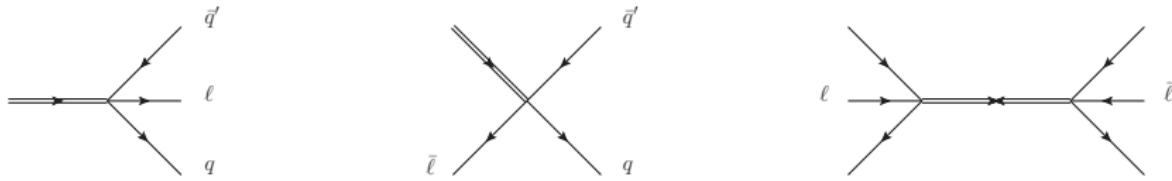
$M^* \approx 1 - 10 \text{ TeV}, \quad |\tilde{f}| \approx 0.1$
 $\Lambda > 200 - 500 \text{ TeV}$
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A CLOSER LOOK AT LEPTOGENESIS WITH CI

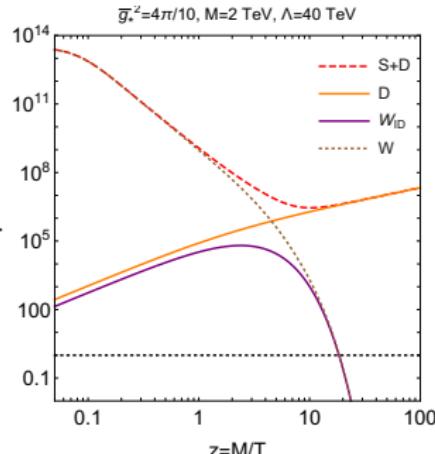


- CI preferred in experimental analyses for larger couplings/higher exclusion limits
- same (M, Λ) smaller washouts than GI [also preferred low-mass leptogenesis]

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- $M_1 \ll M_i$ with $\Delta L = 1$ scatterings and inverse decays

- absent $1/s$ scaling, cut-off in the EFT for s

$$\gamma_\sigma^i = \frac{T}{32\pi^4} g_a g_b \int_{s_{\min}}^{\bar{\Lambda}^2} ds s^{3/2} \mathcal{K}_1(\sqrt{s}/T) \sigma'(s)$$

- use the unitarity estimate $\Lambda \gtrsim \sqrt{s/3}$

HIERARCHICAL CASE

- CP asymmetry, washout and final B -asymmetry

$$\epsilon_{1,\alpha}^{\text{cont, h}} = 2 N_c \frac{g_*^4}{1536\pi^3} \left(\frac{M_1}{\Lambda} \right)^4 \sum_i \frac{M_1}{M_i} \frac{\text{Im} [(\tilde{\eta}_1^* \tilde{\eta}_i)(\tilde{\eta}_{\alpha 1}^* \tilde{\eta}_{\alpha i})]}{|\tilde{\eta}_1|^2} + \dots$$

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$$Y_{\Delta B} = (8.75 \pm 0.23) \times 10^{-11}$$

$$Y_{\Delta B} \simeq 4.34 \times 10^{-2} \frac{1}{z_{\text{out}} J(z_{\text{out}})^2} \frac{M_1}{M_{\text{Pl}}} \sum_{i=2,3} |\eta_i|^2 \sin(2\phi_i) \left(\frac{M_1}{M_i} \right)$$

- $\textcolor{red}{M_1 \approx 10^9 \text{ TeV}}$ with $M_i/M_1 = 10$, $|\eta_i|^2 = 1$, $\sin(2\phi_i) = 0.5$ and $z_{\text{out}} \approx 10 - 30$

NEARLY DEGENERATE CASE

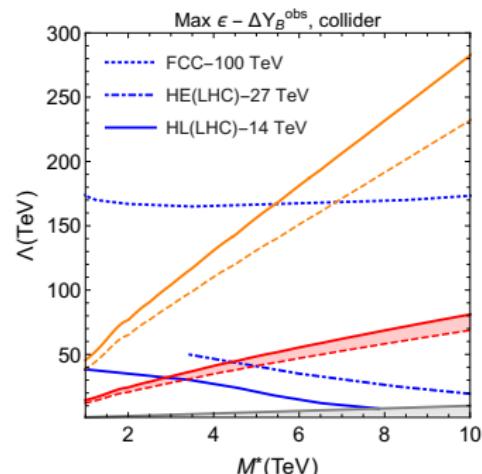
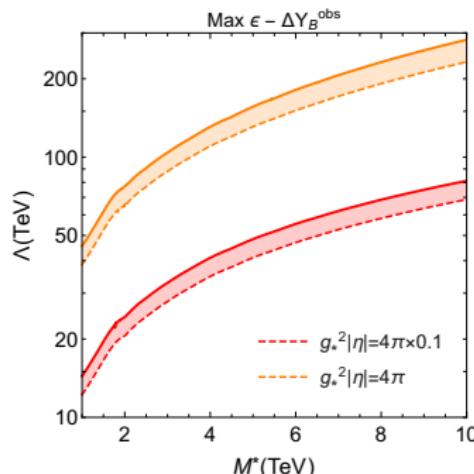
$$\epsilon_I^{\text{dege}} = \frac{N_c g_*^4}{1536\pi^3} \left(\frac{M_I}{\Lambda} \right)^4 \frac{\text{Im}(\tilde{\eta}_I^* \tilde{\eta}_J)^2}{|\eta_I|^2} \frac{M_I M_J (M_J^2 - M_I^2)}{(M_J^2 - M_I^2)^2 + A^2}$$

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CONCLUSIONS AND OUTLOOK

- Composite models for fermions are a viable BSM scenario (M^*, Λ, f, η)
- Composite Majorana neutrinos: L -violation and heavy particles

N^* good candidates for baryogenesis via leptogenesis

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- rather strong washout factors (even for $|f| = 0.1$ and $|\eta| = 0.1$)

GI : $K = 10^6 \Rightarrow \Lambda \approx 50 \text{ TeV}$ and $M \approx 3 \text{ TeV}$,

CI : $K = 10^6 \Rightarrow \Lambda \approx 450 \text{ TeV}$ and $M \approx 3 \text{ TeV}$

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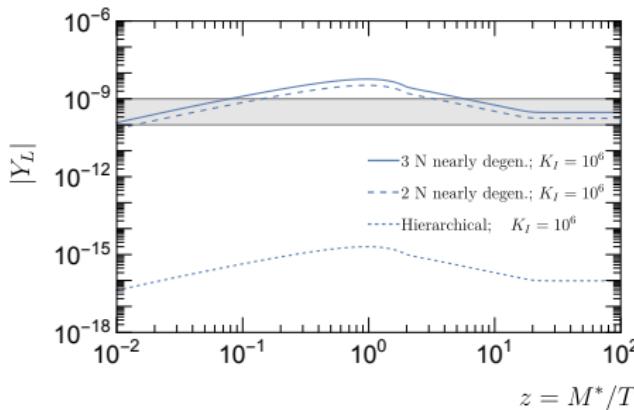
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- only resonant leptogenesis can provide

① large asymmetries $\epsilon \approx 1$

② \Rightarrow successful matter-antimatter generation at low M^*

CONCLUSION AND OUTLOOK (GI)



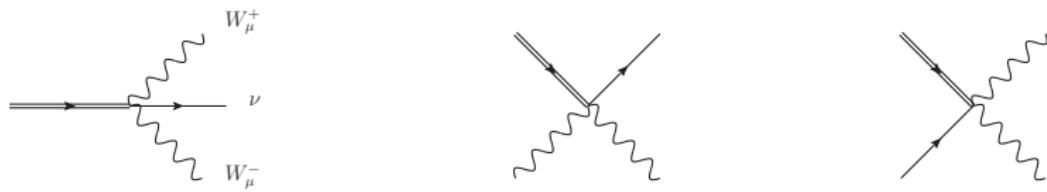
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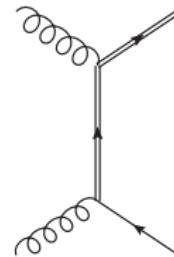
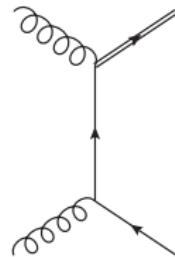
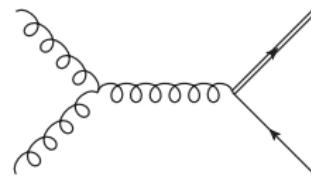
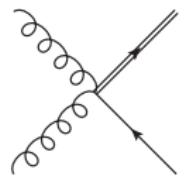
\Rightarrow most likely out from future colliders

- our study comprises only decays and inverse decays shows
- $M_1 = M_2 + \Delta$ with $\Delta \ll M_1$: successful baryogenesis



MORE ON NON ABELIAN AND GLUONS...

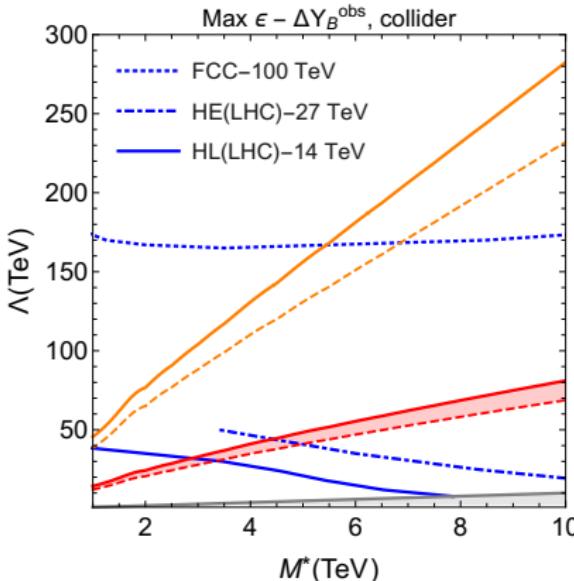
- non abelian terms for $gg \rightarrow Q^*q$
- g_s^2 is not much smaller than g_*^2
- pdf for gluons is larger than quarks!



CONCLUSION AND OUTLOOK II

CONTACT INTERACTIONS: ALSO HERE $|\eta| = 0.1$

- viable leptogenesis at low-mass scale via resonant enhancement
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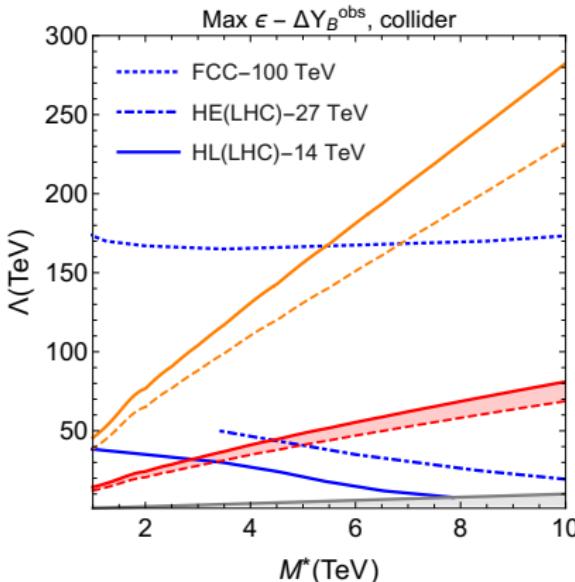


- $M \approx [1 - 10] \text{ TeV}$
- $g_*^2 = 4\pi$ ($|\tilde{\eta}| = 1$) and $\bar{g}_*^2 = 4\pi \times 10^{-1}$
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WISHES AND QUESTIONS

- sensitivity to **low M^* high Λ** (???)
- how much the exp. limits are affected by $|\eta| < 1$ (???)

MORE ON BARYO-LEPTOGENESIS

- the only source of CP violation in the SM: phase in the CKM matrix

$$B \simeq \frac{\alpha_W^4 T^3}{s} \delta_{CP} \simeq 10^{-8} \delta_{CP}$$

- The CP vanishes when two quarks with the same charge have degenerate mass

$$A_{CP} = (m_t^2 - m_c^2)(m_c^2 - m_u^2) \dots (m_s^2 - m_d^2) J$$

- By dimensional analysis ($T_C \equiv$ temperature of the electroweak phase transition)

$$\delta_{CP} \simeq \frac{A_{CP}}{T_C^{12}} \simeq 10^{-20}$$

- B and L number: not violated at tree level, anomalous at quantum level
→ changes in the vacua of the non-abelian theory

$$T < T_{EW} : \frac{\Gamma_{B+L}}{V} = \sim e^{-\frac{M_W}{\alpha k T}}$$

$$T \geq T_{EW} : \frac{\Gamma_{B+L}}{V} = \alpha^5 \ln \alpha^{-1} T^4$$

P. Arnold and L. D. McLerran (1987)

P. Arnold, D. Son and L. G. Yaffe (1997)

D. Bodeker (1999)

- the relation for baryon (B), lepton (L) and $B - L$ asymmetry is given by

$$\eta_B = \alpha_{\text{sph}} \eta_{B-L} = \frac{\alpha_{\text{sph}}}{\alpha_{\text{sph}} - 1} \eta_L$$

- In the SM with three generation of leptons and quark and one Higgs doublet

$$\alpha_{\text{sph}} = \frac{28}{79}$$