Dark matter and baryogenesis from *SU(2)*-lepton

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Why do we need new physics?

- **Standard Model – good description of Nature**
- **Mysteries and puzzles**
  - **dark matter**
  - **dark energy**
  - **neutrino masses**
  - **…**
  - **baryogenesis**
  - **hierarchy problem**
  - **origin of flavor**
- **Motivation for new particle and symmetries**

SU(2)-lepton SM extension

$$SU(3)_c \times SU(2)_W \times U(1)_Y \times SU(2)_\ell$$

BF, Shirman, Tait, West, arXiv:1703.00199 [hep-ph]

***SU(2)**$_l$* **doublets:**

$$\hat{l}_L \equiv \begin{pmatrix} l_L \\ \tilde{l}_L \end{pmatrix}, \quad \hat{e}_R \equiv \begin{pmatrix} e_R \\ \tilde{e}_R \end{pmatrix}, \quad \hat{\nu}_R \equiv \begin{pmatrix} \nu_R \\ \tilde{\nu}_R \end{pmatrix}$$

***SU(2)**$_l$* **singlets:**

$$l'_R, \quad e'_L, \quad \nu'_L$$

Particle content

Field	$SU(2)_\ell$	$SU(2)_W$	$U(1)_Y$
$\hat{l}_L = \begin{pmatrix} l_L \\ \tilde{l}_L \end{pmatrix}$	2	2	$-1/2$
$\hat{e}_R = \begin{pmatrix} e_R \\ \tilde{e}_R \end{pmatrix}$	2	1	-1
$\hat{\nu}_R = \begin{pmatrix} \nu_R \\ \tilde{\nu}_R \end{pmatrix}$	2	1	0
l'_R	1	2	$-1/2$
e'_L	1	1	-1
ν'_L	1	1	0
$\hat{\Phi}_\ell$	2	1	0
$\hat{\Phi}'_\ell$	2	1	0

Symmetry breaking

$$SU(3)_c \times SU(2)_W \times U(1)_Y \times SU(2)_\ell$$

$$\Big\downarrow \ \langle \hat{\Phi}_\ell \rangle$$

$$SU(3)_c \times SU(2)_W \times U(1)_Y$$

***SU(2)**$_l$* **Higgs**

$$\langle \hat{\Phi}_\ell \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_\ell \end{pmatrix}$$

Yukawa interactions

Leptonic mass terms

$$\begin{aligned}\mathcal{L}_{\mathrm{Y}} &= Y_l^{ab}\,\bar{\hat{l}}_L^a\,\hat{\Phi}_\ell\,l_R'^b + Y_e^{ab}\,\bar{\hat{e}}_R^a\,\hat{\Phi}_\ell\,e_L'^b + Y_\nu^{ab}\,\bar{\hat{\nu}}_R^a\,\hat{\Phi}_\ell\,\nu_L'^b \\ &+ y_e^{ab}\,\bar{\hat{l}}_L^a\,H\,\hat{e}_R^b + y_\nu^{ab}\,\bar{\hat{l}}_L^a\,\tilde{H}\,\hat{\nu}_R^b \\ &+ y_e'^{ab}\,\bar{l}_R'^a\,H\,e_L'^b + y_\nu'^{ab}\,\bar{l}_R'^a\,\tilde{H}\,\nu_L'^b + \mathrm{h.c.}\end{aligned}$$

$$Y\,\langle\hat{\Phi}\rangle \gg y\,\langle H\rangle$$

$$Y\,\langle\hat{\Phi}\rangle \gg y'\,\langle H\rangle$$

Lepton partners

After symmetry breaking

$$\frac{1}{\sqrt{2}}\left(\bar{\tilde{\nu}}_L \;\; \overline{\nu}'_L\right)\begin{pmatrix} Y_l\, v_\ell & y_\nu v \\ y'^{\dagger}_\nu v & Y^{\dagger}_\nu v_\ell \end{pmatrix}\begin{pmatrix} \nu'_R \\ \tilde{\nu}_R \end{pmatrix}$$

$$+\frac{1}{\sqrt{2}}\left(\bar{\tilde{e}}_L \;\; \overline{e}'_L\right)\begin{pmatrix} Y_l\, v_\ell & y_e v \\ y'^{\dagger}_e v & Y^{\dagger}_e v_\ell \end{pmatrix}\begin{pmatrix} e'_R \\ \tilde{e}_R \end{pmatrix} + \mathrm{h.c.}$$

- **6 electrically neutral states**
- **6 electrically charged states**

Dark matter

Lightest neutral combination

$$\boxed{\begin{aligned}\chi_L &= \nu'_L + \epsilon\,\tilde{\nu}_L \\ \chi_R &= \tilde{\nu}_R + \epsilon\,\nu'_R\end{aligned}}$$

Stable because of a global *U(1)* symmetry

Global symmetries

Field	$U(1)_1$	$U(1)_2$
$\hat{l}_L = \begin{pmatrix} l_L \\ \tilde{l}_L \end{pmatrix}$	0	1
$\hat{e}_R = \begin{pmatrix} e_R \\ \tilde{e}_R \end{pmatrix}$	0	1
$\hat{\nu}_R = \begin{pmatrix} \nu_R \\ \tilde{\nu}_R \end{pmatrix}$	0	1
l'_R	1	1
e'_L	1	1
ν'_L	1	1
$\hat{\Phi}_\ell$	-1	0
$\hat{\Phi}'_\ell$	-1	0

$$\begin{aligned}
\mathcal{L}_{\mathrm{Y}} \;=\;& Y_l^{ab}\,\bar{\hat{l}}_L^a\,\hat{\Phi}_\ell\,l'^b_R \\
&+ Y_e^{ab}\,\bar{\hat{e}}_R^a\,\hat{\Phi}_\ell\,e'^b_L + Y_\nu^{ab}\,\bar{\hat{\nu}}_R^a\,\hat{\Phi}_\ell\,\nu'^b_L \\
&+ y_e^{ab}\,\bar{\hat{l}}_L^a\,H\,\hat{e}_R^b + y_\nu^{ab}\,\bar{\hat{l}}_L^a\,\tilde{H}\,\hat{\nu}_R^b \\
&+ y'^{ab}_e\,\bar{l}'^a_R\,H\,e'^b_L + y'^{ab}_\nu\,\bar{l}'^a_R\,\tilde{H}\,\nu'^b_L + \mathrm{h.c.}
\end{aligned}$$

Global symmetries

Field	$U(1)_1$	$U(1)_2$	$U(1)_1$	$U(1)_L$	$U(1)_\chi$
$\hat{l}_L = \begin{pmatrix} l_L \\ \tilde{l}_L \end{pmatrix}$	0	1	0	1	0
$\hat{e}_R = \begin{pmatrix} e_R \\ \tilde{e}_R \end{pmatrix}$	0	1	0	1	0
$\hat{\nu}_R = \begin{pmatrix} \nu_R \\ \tilde{\nu}_R \end{pmatrix}$	0	1	0	0	1
l'_R	1	1	1	1	0
e'_L	1	1	1	1	0
ν'_L	1	1	1	0	1
$\hat{\Phi}_\ell$	-1	0	-1	0	0
$\hat{\Phi}'_\ell$	-1	0	-1	0	0

$\cancel{y_\nu, y_{\nu'}}$

Dark matter

Lightest neutral combination

$$\boxed{\begin{aligned}\chi_L &= \nu'_L + \epsilon\,\tilde{\nu}_L \\ \chi_R &= \tilde{\nu}_R + \epsilon\,\nu'_R\end{aligned}}$$

is stabilized by a residual *U(1)*$_\chi$ symmetry

$$\boxed{\nu_R \to e^{i\theta}\nu_R\,, \quad \tilde{\nu}_R \to e^{i\theta}\tilde{\nu}_R\,, \quad \nu'_L \to e^{i\theta}\nu'_L}$$

Dark matter mass

$$\boxed{m_\chi \approx \frac{1}{\sqrt{2}}(Y_\nu)_{ii}\,v_\ell}$$

Baryogenesis from $SU(2)_l$

Dirac leptogenesis

→

Dick, Lindner, Ratz, Wright, PRL 84, 4039 (2000),
Murayama, Pierce, PRL 89, 271601 (2002)

Asymmetric dark matter

→

Kaplan, Luty, Zurek, PRD 79, 115016 (2009),
Petraki, Volkas, IJMP A 28, 1330028 (2013), ...

→ Baryogenesis from an earlier phase transition

Shu, Tait, Wagner, PRD 75, 063510 (2007)

$SU(2)_l$ instantons

General form

$$\boxed{\epsilon_{ij}\,\hat{l}^i_L\,\hat{l}^j_L\,\bar{\hat{e}}_R\,\bar{\hat{\nu}}_R}$$

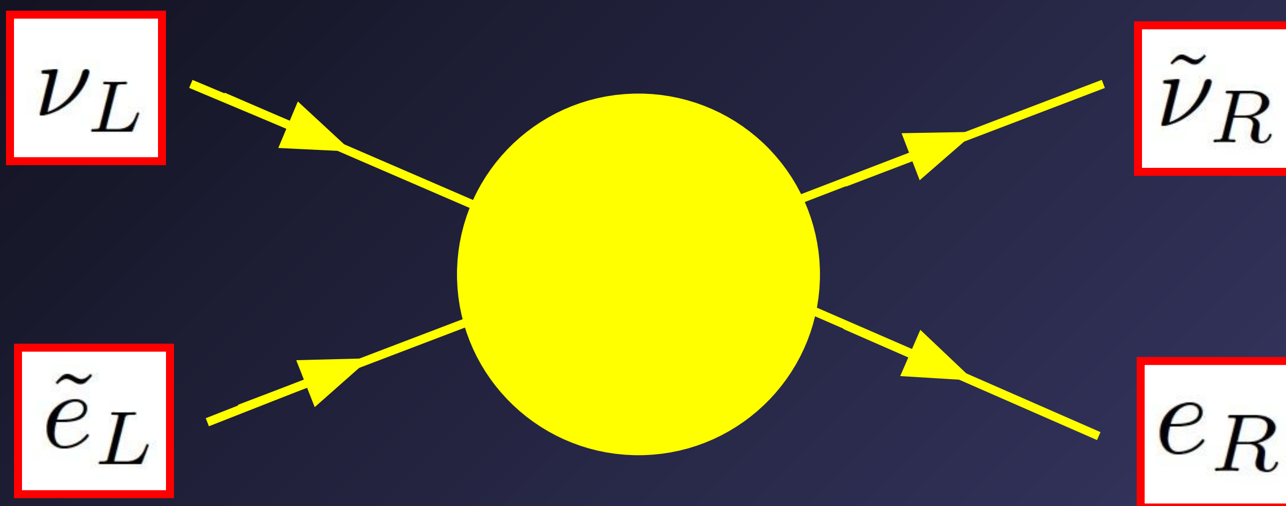
Explicit calculation yields

$$\begin{aligned}\mathcal{O}_{\rm eff} \;\sim\; \epsilon_{ij}\Big[&(l^i_L\cdot\bar{\nu}_R)(l^j_L\cdot\bar{e}_R)-(l^i_L\cdot\bar{\nu}_R)(\tilde{l}^j_L\cdot\bar{\tilde{e}}_R)\\ &+(l^i_L\cdot\tilde{l}^j_L)(\bar{\nu}_R\cdot\bar{\tilde{e}}_R)-(l^i_L\cdot\tilde{l}^j_L)(\bar{\tilde{\nu}}_R\cdot\bar{e}_R)\\ &+(\tilde{l}^i_L\cdot\bar{\tilde{\nu}}_R)(\tilde{l}^j_L\cdot\bar{\tilde{e}}_R)-(\tilde{l}^i_L\cdot\bar{\tilde{\nu}}_R)(l^j_L\cdot\bar{e}_R)\Big]\end{aligned}$$

(S1) Lepton and DM number violation

Instanton-induced interaction

$$\boxed{\nu_L\, \tilde{e}_L \to \tilde{\nu}_R\, e_R}$$



$$\boxed{\Delta L_{\mathrm{SM}} = -1 \qquad \Delta L_{\mathrm{DM}} = 1}$$

(S2) CP violation ✓

Two Higgs doublet potential

$$\begin{aligned} V(\Phi_1,\Phi_2) \;=\;& m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 + (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}) \\ &+ \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\ &+ \left[\tilde\lambda_5\Phi_1^\dagger\Phi_2|\Phi_1|^2 + \tilde\lambda_6\Phi_1^\dagger\Phi_2|\Phi_2|^2 + \tilde\lambda_7(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}\right] \end{aligned}$$

(S3) First order phase transition ✓

1. **Finite temperature effective potential**
2. **Bubble nucleation and diffusion equations**
3. **SM lepton and DM asymmetries**
4. **Baryon asymmetry**

Finite temperature effective potential

$$V(u,T) = V_{\text{tree}}(u) + V_{1\,\text{loop}}(u, v_\ell) + V_{\text{temp}}(u,T)$$

Tree level

$$V_{\text{tree}}(u) = -\frac{1}{2} m_\ell\, u^2 + \frac{1}{4}\lambda_\ell\, u^4$$

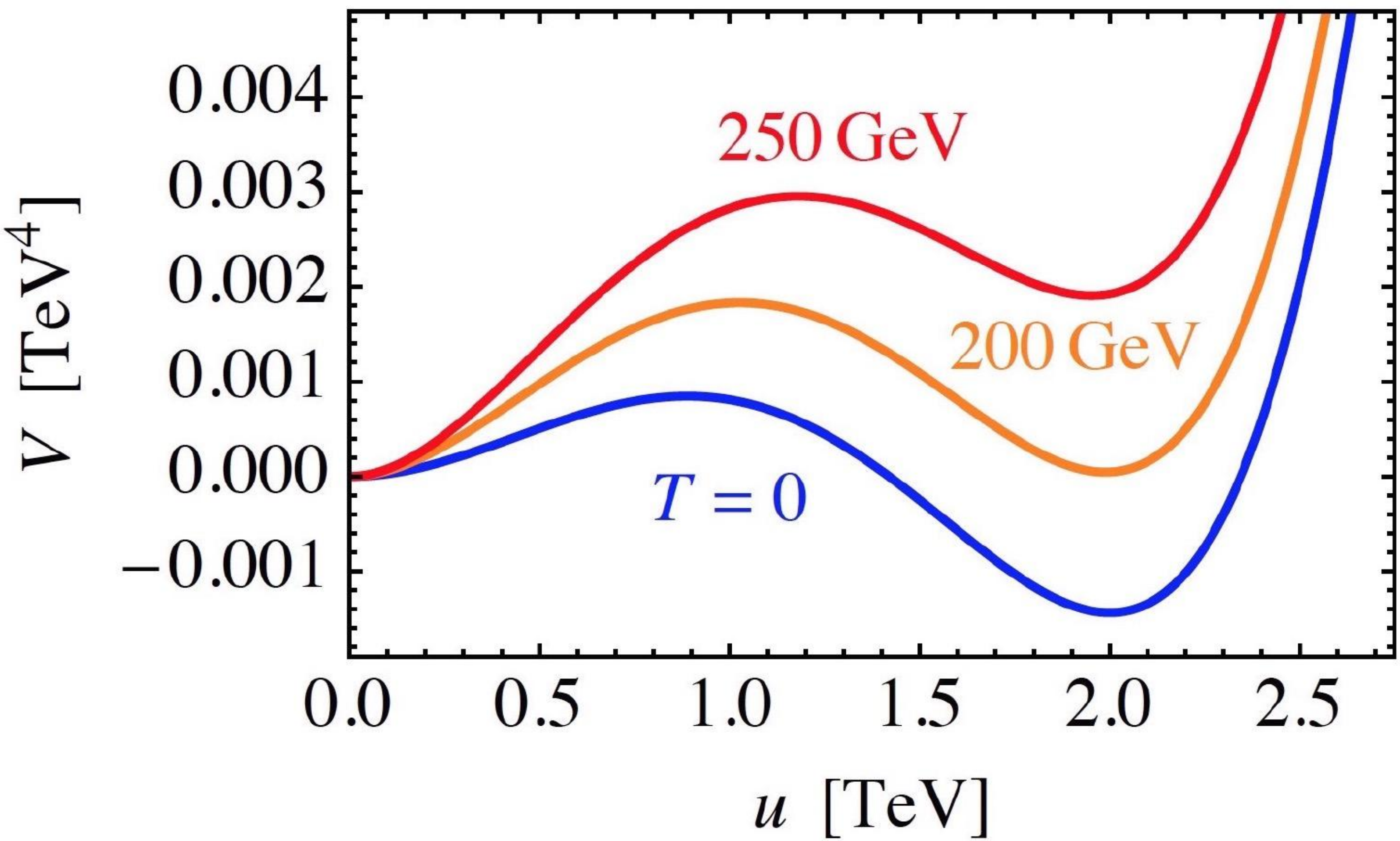
Coleman-Weinberg

$$V_{1\,\text{loop}}(u) = \frac{9}{64\pi^2}\left(\frac{g_\ell}{2}\right)^4 u^2 \left\{u^2\left[\log\left(\frac{u^2}{v_\ell^2}\right) - \frac{3}{2}\right] + 2v_\ell^2\right\}$$

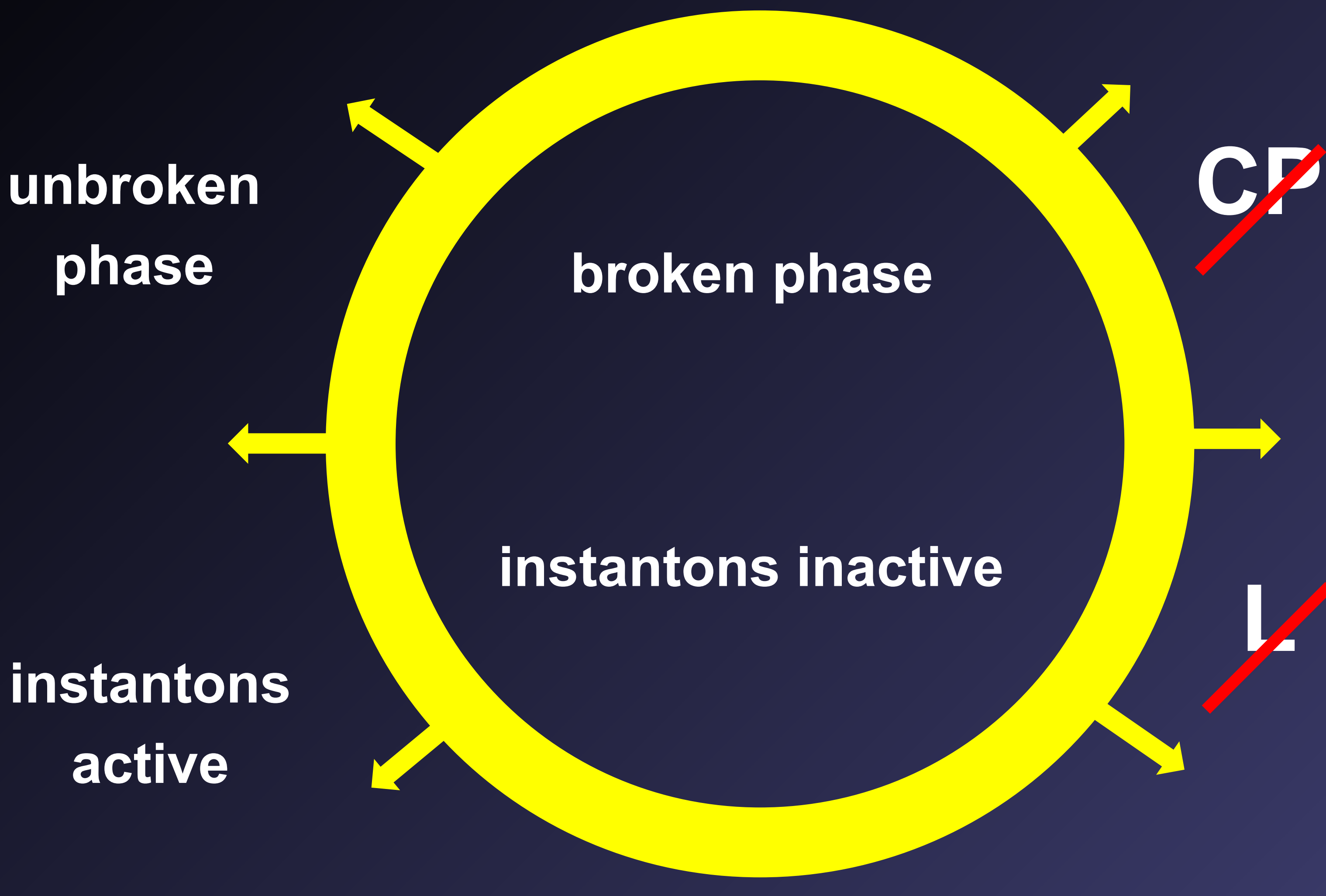
Nonzero *T*

$$V_{\text{temp}}(u,T) = \frac{9\,T^4}{2\pi^2}\int_0^\infty dx\, x^2 \times \left[\log\left(1 - e^{-\sqrt{x^2 + g_\ell^2 u^2/(4T^2)}}\right) - \log\left(1 - e^{-x}\right)\right]$$

Finite temperature effective potential



Bubble nucleation



Diffusion equations

Particle number densities

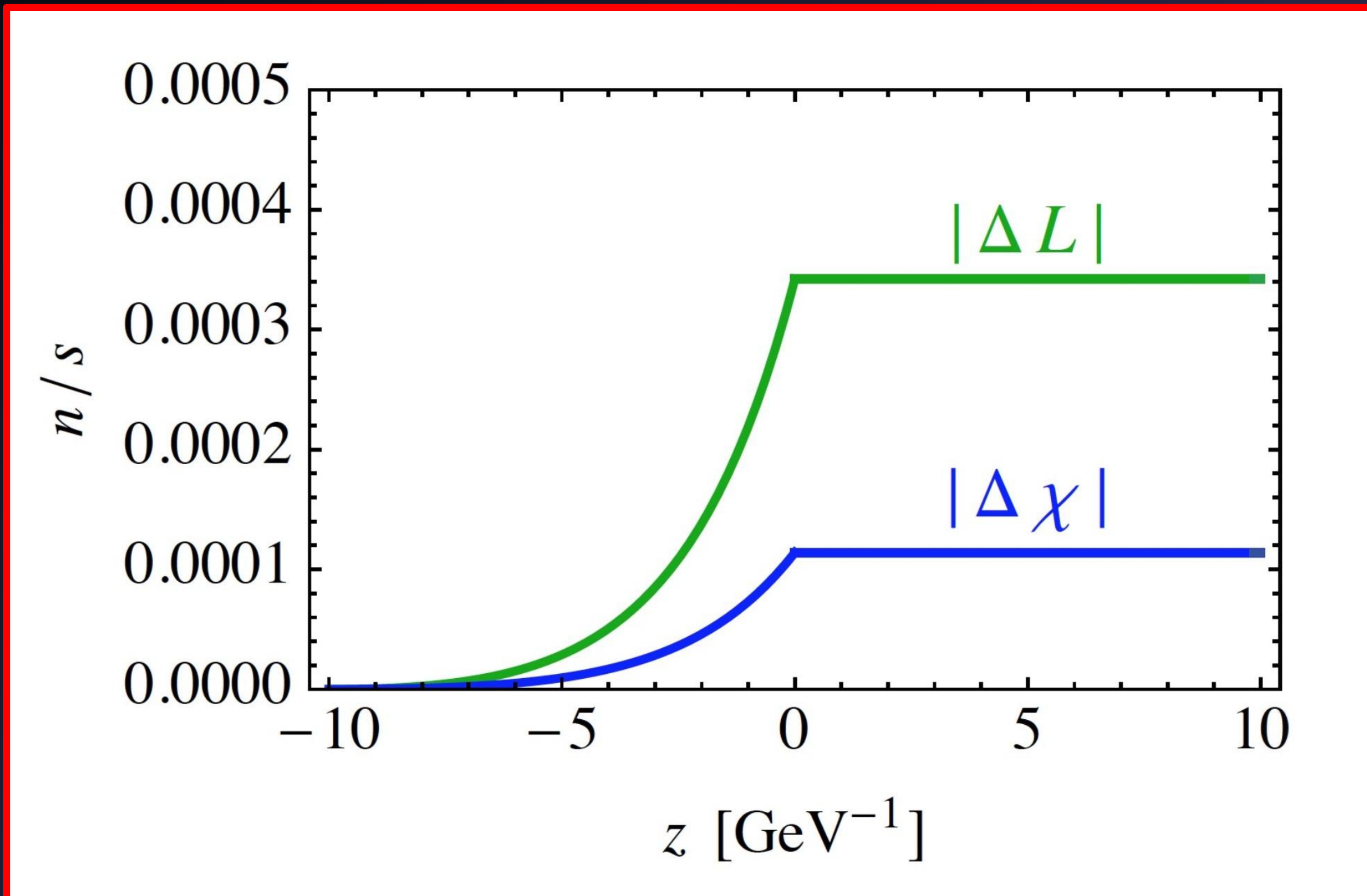
$$
\begin{array}{ccc}
l = e_L + \nu_L & e = e_R & \nu = \nu_R \\
\tilde{l} = \tilde{e}_L + \tilde{\nu}_L & \tilde{e} = \tilde{e}_R & \tilde{\nu} = \tilde{\nu}_R \\
l' = e'_R + \nu'_R & e' = e'_L & \nu' = \nu'_L \\
h = h^+ + h^0 & \Phi^u = \Phi^u_\ell & \Phi^d = \Phi^d_\ell
\end{array}
$$

To a good approximation

$$\dot{n}_i = D_i \nabla^2 n_i - \Gamma_{ij} \frac{n_j}{k_j} + \gamma_i$$

Cohen, Kaplan, Nelson, PLB 336, 41 (1994)

SM lepton and DM asymmetries



Asymmetric dark matter

Lepton and DM asymmetries

$$\boxed{\Delta L = 3\,\Delta\chi}$$

Final baryon asymmetry

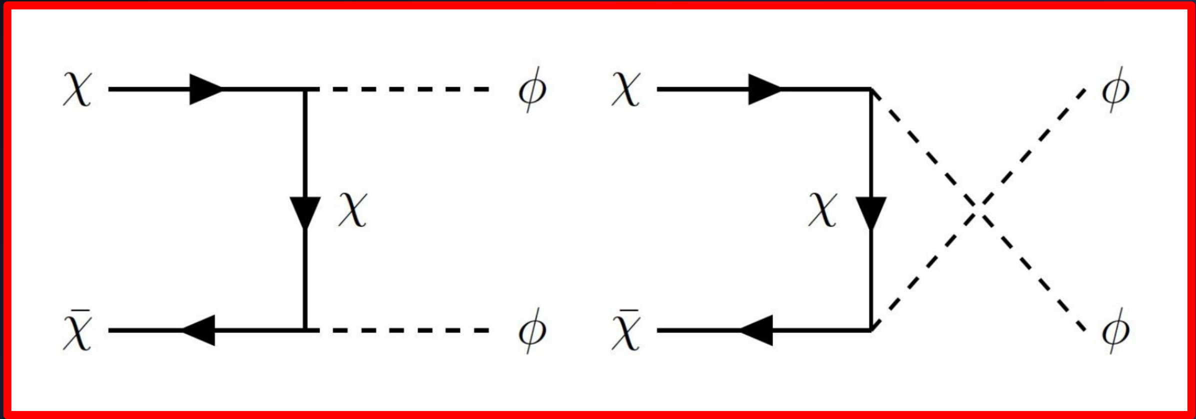
$$\boxed{\Delta B = \frac{28}{79}\,\Delta L}$$

For ADM relativistic at decoupling temperature

$$\boxed{m_\chi = m_p \frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \left| \frac{\Delta B}{\Delta\chi} \right| \approx 5 \text{ GeV}}$$

Dark matter annihilation

Annihilation to second Higgs pseudoscalar



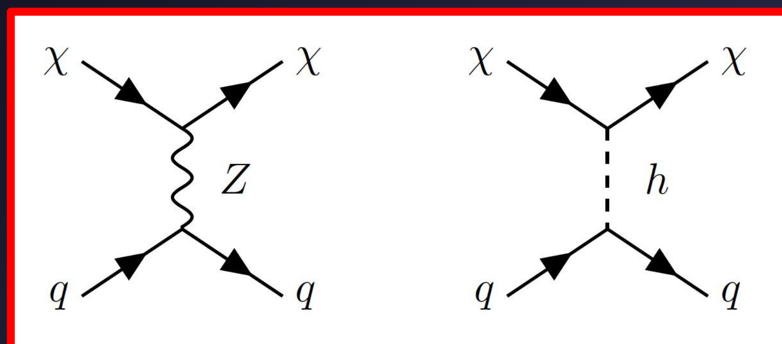
For the correct relic density $\boxed{Y_{\nu}^{\prime 11} \gtrsim 4 \times 10^{-3}}$

Experimental prospects

- LEP II constraint

$$v_\ell = \frac{2\, m_{Z'}}{g_\ell} \gtrsim 1.7 \text{ TeV}$$

- Direct detection



$$\epsilon \lesssim 0.3$$

- Hadron colliders
- Electron-positron collider

Conclusions

- Standard Model extended by *SU(2)*-lepton:
  - has a light dark matter candidate – the partner of the right-handed neutrino
  - baryon asymmetry is generated during *SU(2)*-lepton breaking by instantons
- Can one have gauge coupling unification in such a theory?


Thank you!
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UC Los Angeles
UC Irvine
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