New Ideas in Baryogenesis

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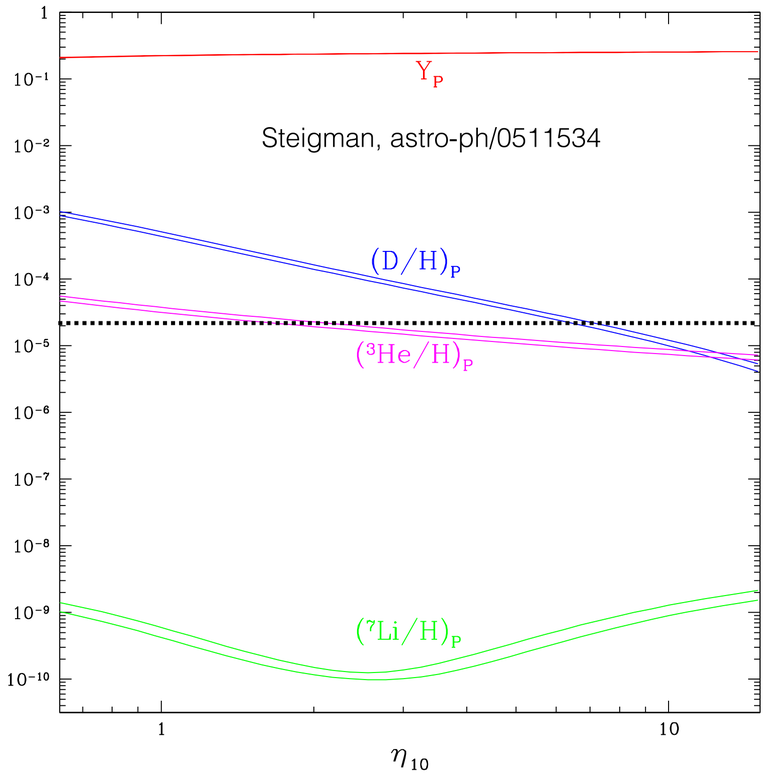
TRIUMF

Seattle Snowmass Summer Meeting
TF08 BSM Model Building
July 23, 2022

We're made of baryons



Q. How to make and excess of baryons over anti baryons?

A. [Sakharov] 3 conditions:

B violation

C (q_L vs. $\bar{q}_L$) & CP (q_L vs. $\bar{q}_R$) violation

Depart from thermal equilibrium

SM can't quite do it (does B violation at high T, C/CP violation but not enough, probably no departure from thermal equilibrium)⇒need new physics

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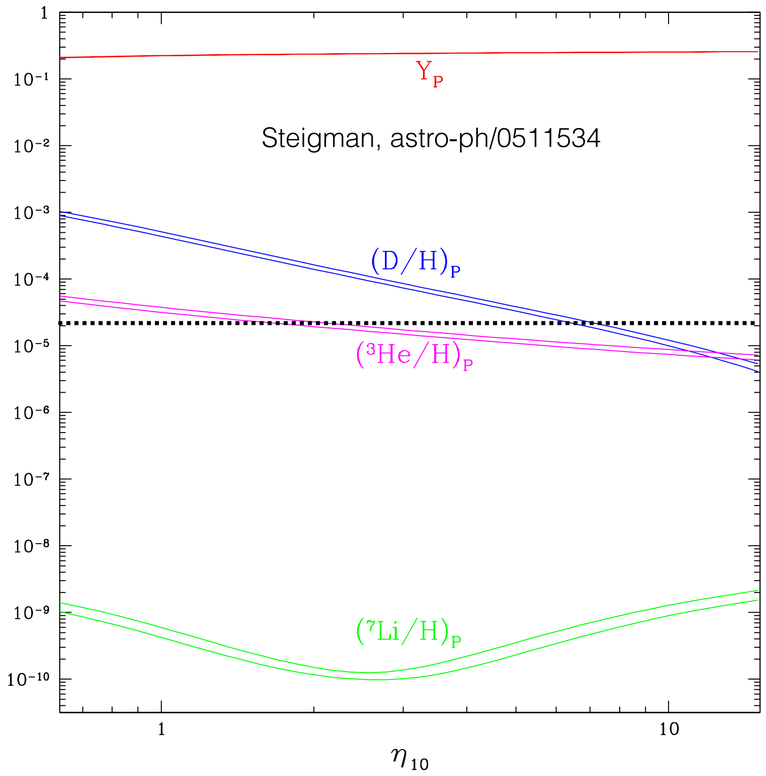

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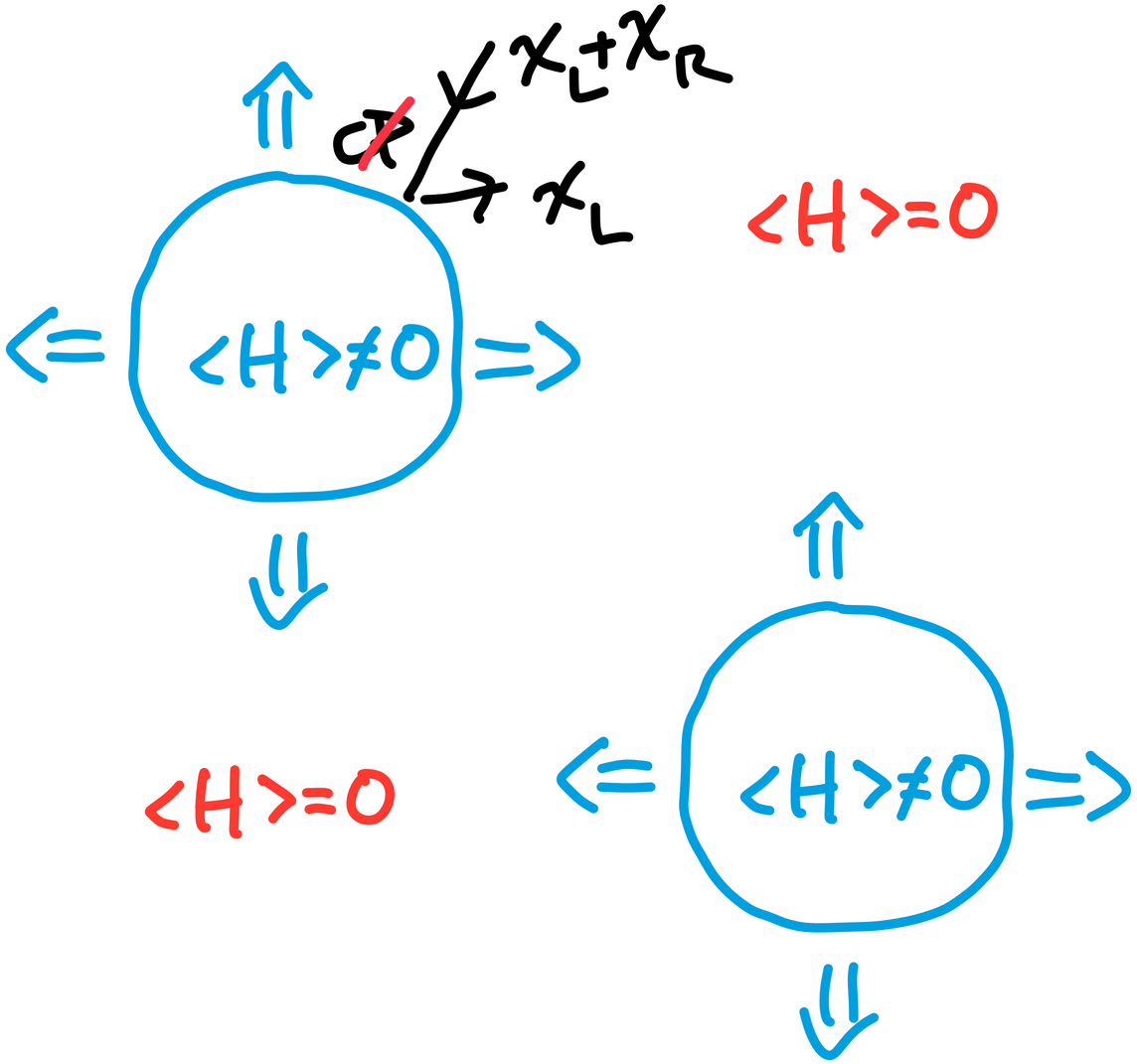
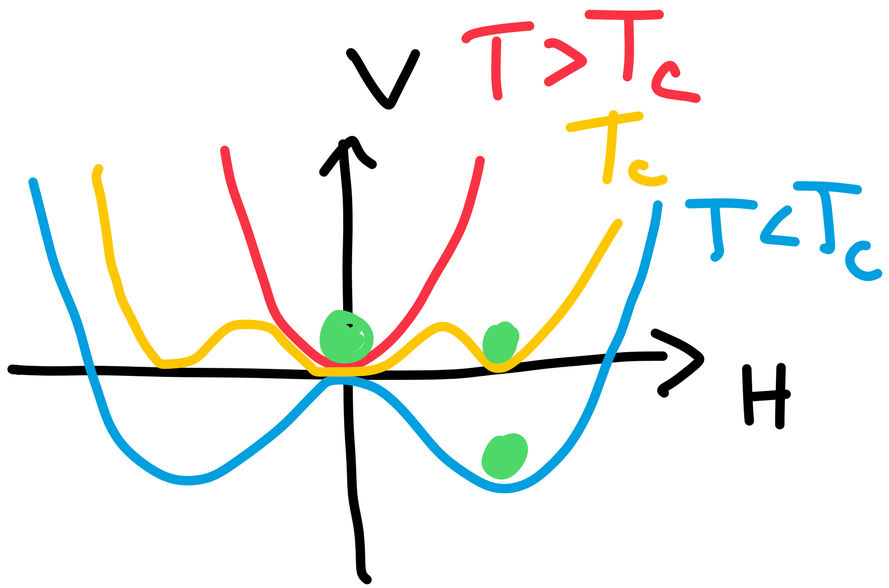
⇒Model building! (Sometimes up to "skill level 5"—cf. Murayama's previous talk)

Kuzmin, Rubakov, & Shaposhnikov, Phys. Lett. **B155** 36 (1985)

Electroweak Baryogenesis





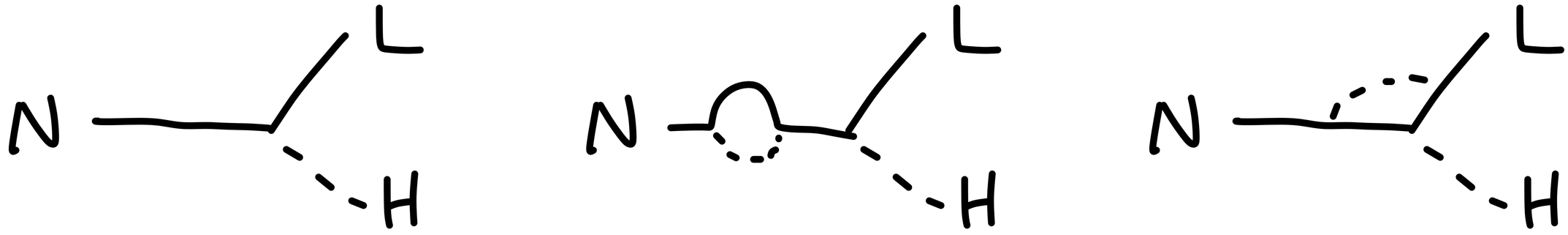
1st order PT with $m_H = 125$ GeV requires new light states coupled to Higgs…but LHC…

See e.g. Morrissey & Ramsey-Musolf, arXiv:1206.2942 for review

Fukugida & Yanagida, Phys. Lett. **B174** 45 (1986)

Vanilla Leptogenesis

Add RHN: $-\mathscr{L} \supset y_{ij}\bar{N}_i H L_j + \mathrm{h.c.}$

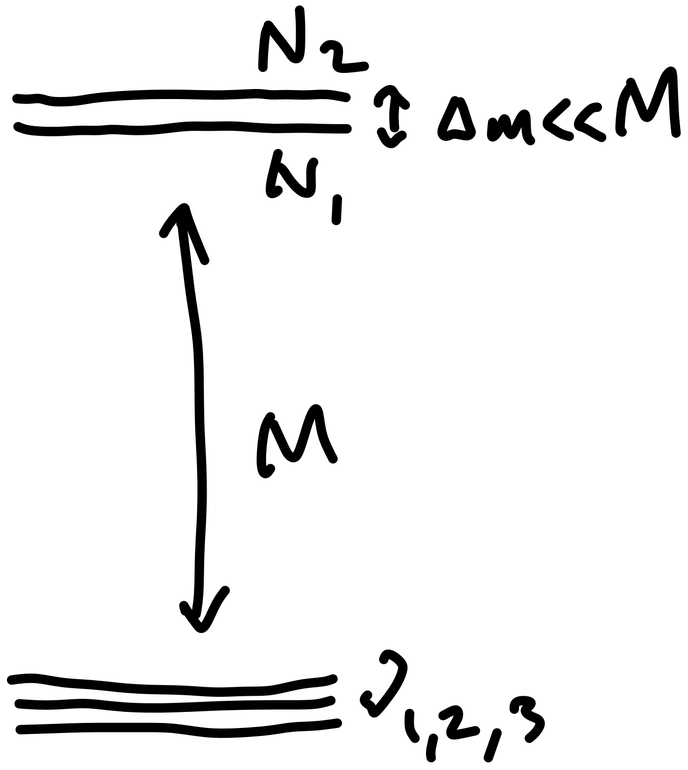


$\eta_B \propto m_N \Rightarrow m_N \gtrsim 10^9\ \mathrm{GeV}$ (Davidson-Ibarra bound)

Works “out of the box” but hard to test…(maybe LNV at LHC [Harz, …], Higgs vacuum stability [Croon, Fernandez, DM, & White])

Akhmedov, Rubakov, & Smirnov, PRL **81** 1359 (1998)
νMSM Asaka, Shaposhnikov, …

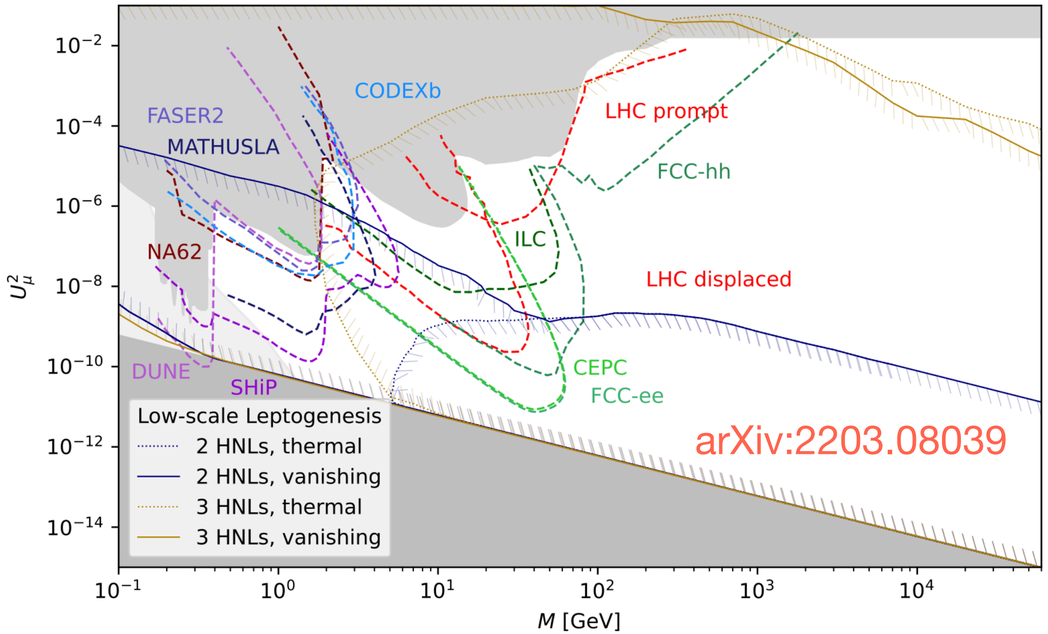
ARS Leptogenesis



Nearly degenerate RHN near $\sim \mathcal{O}(1\ \mathrm{GeV})$

CPV oscillations of heavy state create lepton flavor asymmetry

Lepton flavor asymmetry processed into baryon asymmetry by EW sphalerons

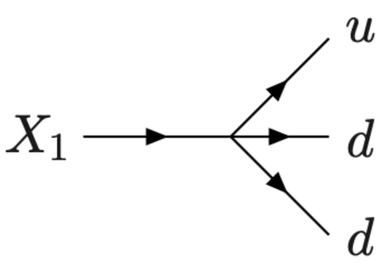


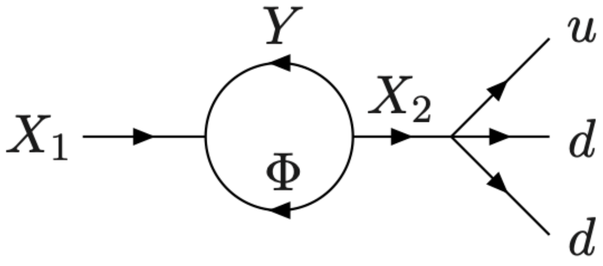
Davoudiasl, Morrissey, Sigurdson, & Tulin, PRL **105** 211304 (2010)

Hylogenesis

Add SM singlet fermions $X_{1,2}$ coupled to dark sector containing Y, Φ:

$$-\mathscr{L} \supset \frac{\lambda_a}{M^2} X_a \bar{u}\bar{d}\bar{d} + y_a X_a Y \Phi + \mathrm{h.c.}$$

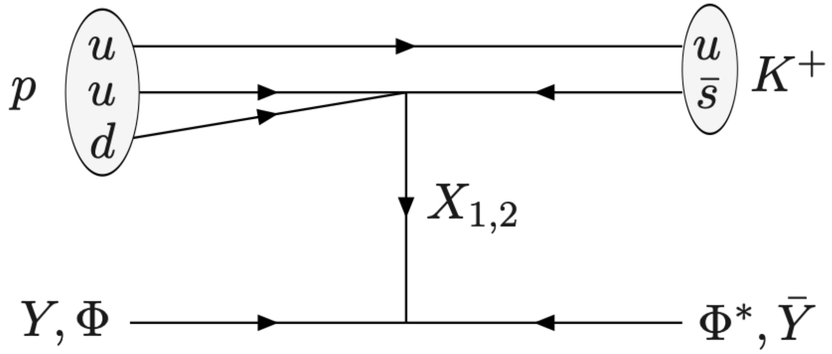




CPV makes $\Gamma_{X_1 \to B} \neq \Gamma_{\bar{X}_1 \to \bar{B}}$ and dark sector baryon number sequestered if

$$|m_Y - m_\Phi| < m_p + m_e < m_Y + m_\Phi$$

DM lives in DS and can lead to "induced nucleon decay":



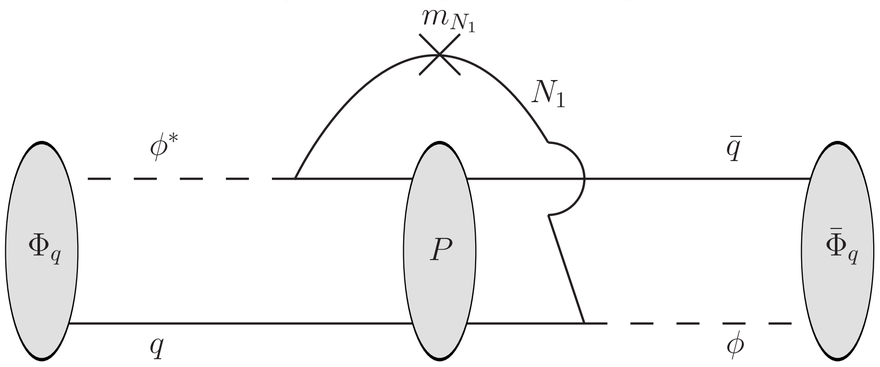
Ghalsasi, DM, & Nelson, PRD **92** 076014 (2015)
Ipek & March-Russell, PRD **93** 123528 (2016)

Mesino/Gaugino Oscillations

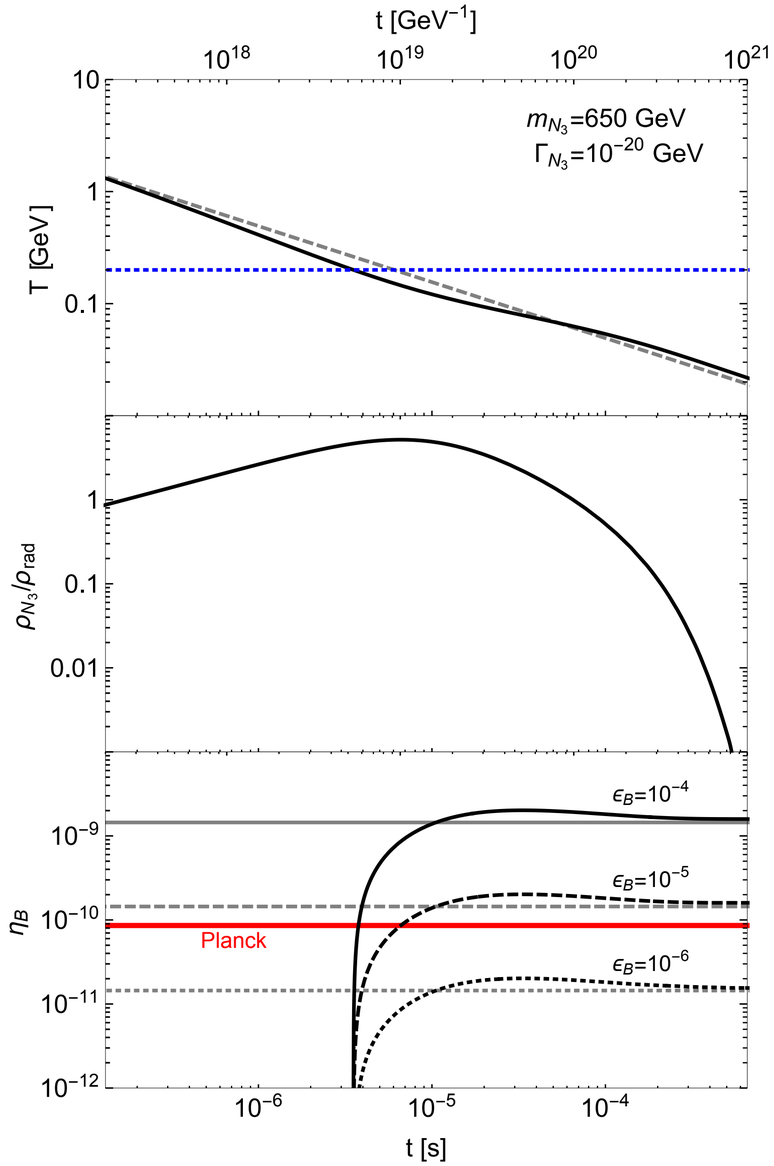
RPV/$U(1)_R$ SUSY-like model, e.g.:

$$-\mathscr{L} \supset \frac{1}{2} M_{ij} N_i N_j + y_{ij} \phi \bar{d}_i N_J + \alpha_{ij} \phi^* \bar{d}_i \bar{u}_j + \mathrm{h.c.}$$

CPV particle-antiparticle oscillations source baryon asymmetry



Generates η_B at low temperatures (below QCD confinement scale)



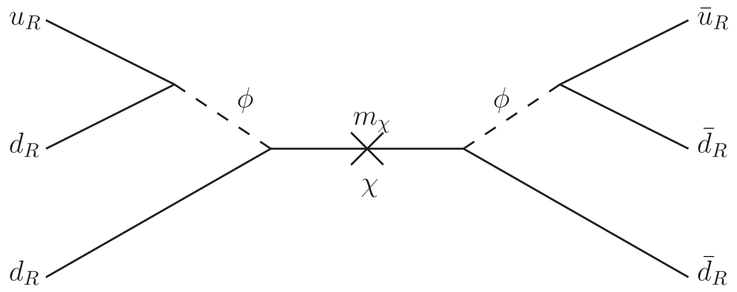
Aitken, DM, Neder, & Nelson, PRD **96** 075009 (2017)

Heavy Flavor Baryon Oscillations

Same basic RPV SUSY-like model but with χ_i at GeV scale:

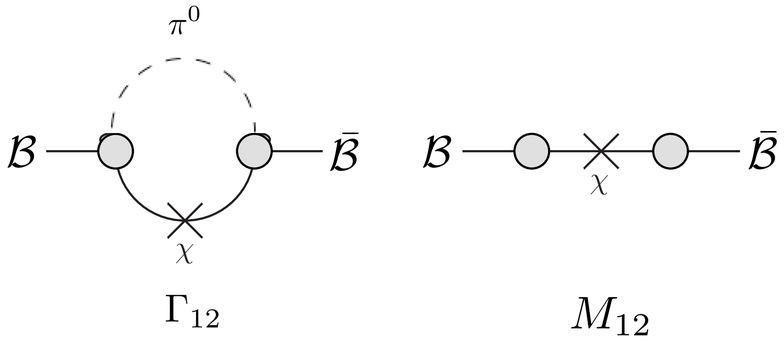
$$-\mathscr{L} \supset g_{ij}\phi u_R^i d_R^j + y_{ij}\phi\bar{\chi}_i d_R^j - \frac{1}{2}m_{ij}\chi_i\chi_j + \mathrm{h.c.}$$

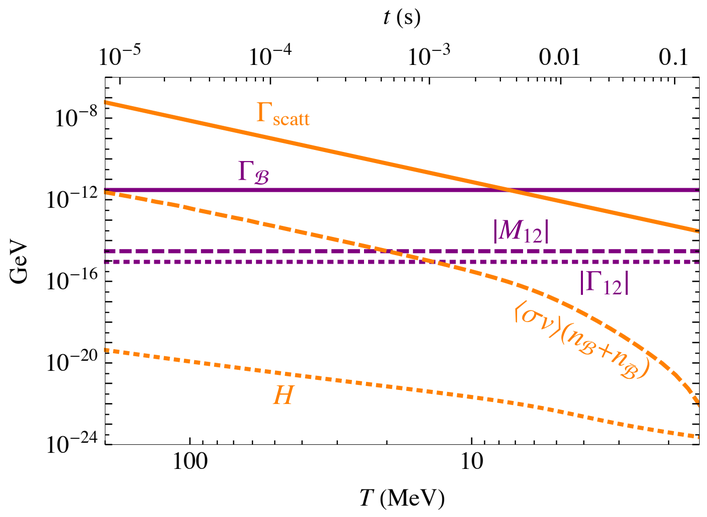
Dim-9 operator mixing B & $\bar{B}$:

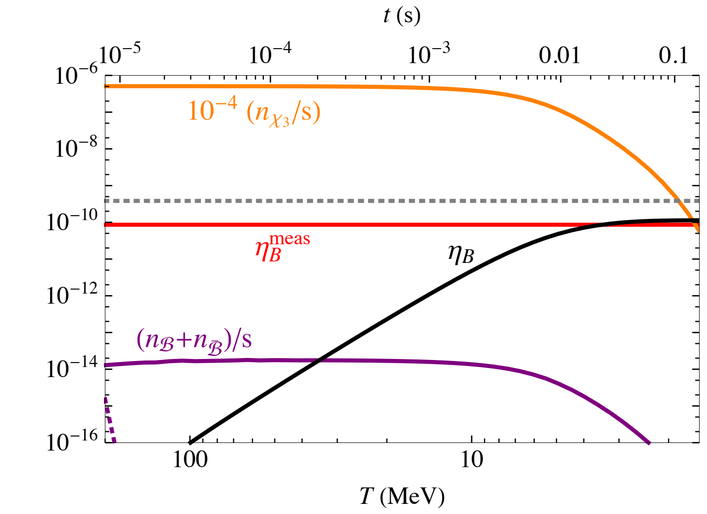


2 state hamiltonian:

$$\mathcal{H} = \begin{pmatrix} M - i\frac{\Gamma}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M - i\frac{\Gamma}{2} \end{pmatrix}$$





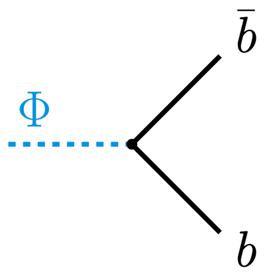


Testable with rare heavy flavor baryon decays at the $10^{-3} - 10^{-4}$ level

Alonso-Alvarez, Elor, Escudero, Hu, & Nelson

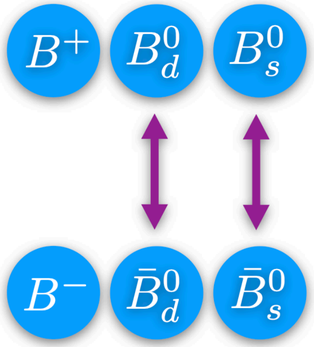
B-mesogenesis

Out of equilibrium late time decay



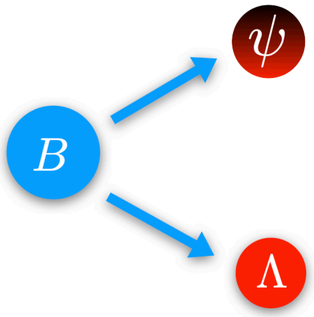
$T_R \sim 15\,\mathrm{MeV}$

CP violating oscillations



$A_{\mathrm{SL}}^d \;\; A_{\mathrm{SL}}^s$

B-mesons decay into Dark Matter and hadrons

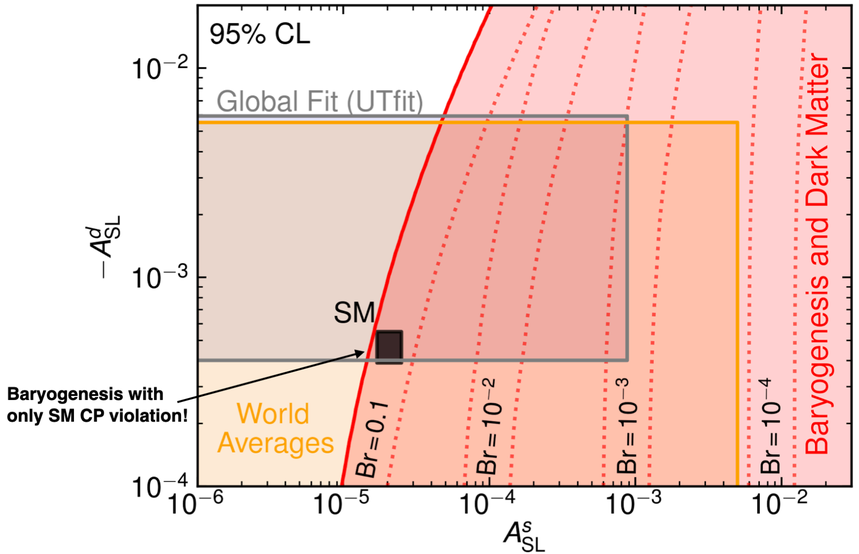


Dark Matter (anti-Baryon)

Baryon

$\mathrm{Br}\,(B \to \psi + \mathcal{B} + \mathcal{M})$

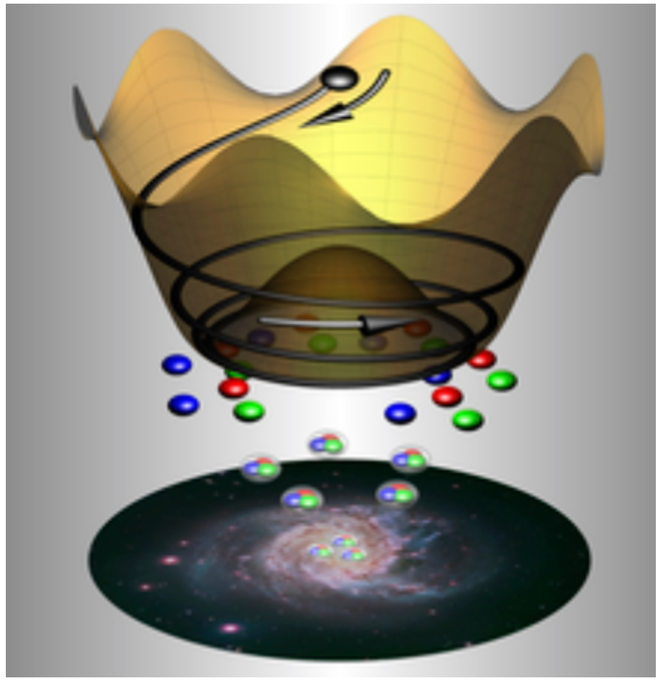
$$Y_B \simeq 8.7 \times 10^{-11}\, \frac{\mathrm{Br}(B \to \psi + \mathcal{B} + \mathcal{M})}{10^{-2}} \sum_q \alpha_q \frac{A_{\mathrm{SL}}^q}{10^{-4}}$$



Searches underway at LHCb, Belle(-II)…

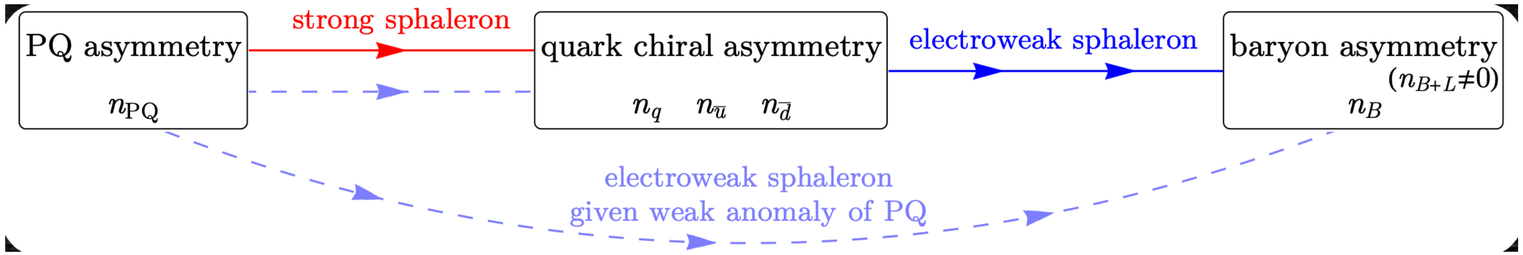
Co & Harigaya, …

Axiogenesis



Generic ALP-like particle

$$P = \frac{1}{\sqrt{2}}(S + f_a)e^{i(\phi_a/f_a)}, \qquad n_{\rm PQ} = \dot{\theta} f_a^2,$$



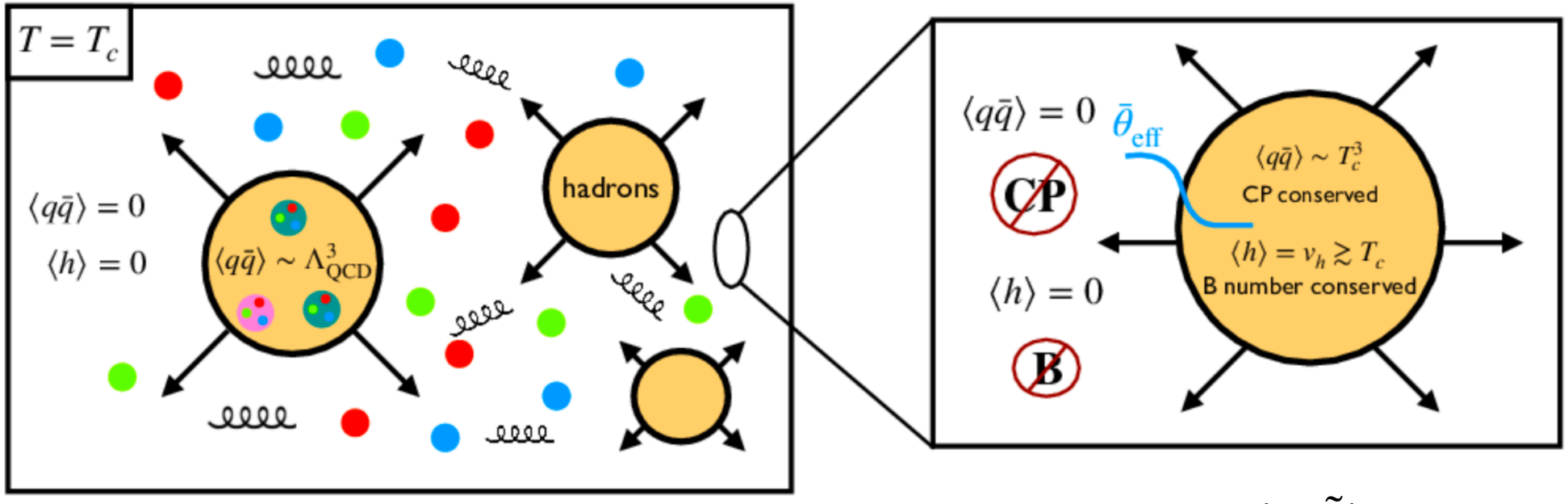
$$Y_B \simeq 10^{-10}\left(\frac{c_B}{0.1}\right)\left(\frac{T_{\rm EW}}{130\ {\rm GeV}}\right)^2\left(\frac{10^8\ {\rm GeV}}{f_a}\right)^2\left(\frac{Y_{\rm PQ}}{500}\right)$$

Croon, Howard, Ipek, & Tait, PRD **101**, 055042 (2020)

QCD Baryogenesis

$$\mathcal{L} \supset -\frac{1}{4}\left(\frac{1}{g_{s0}^2} - \frac{\phi}{M_*}\right) G^{\mu\nu} G_{\mu\nu}$$

QCD confines at high scale near electroweak



Interaction between $\langle G\tilde{G}\rangle$ and baryon current through η' which gives rise to spontaneous baryogenesis (cf. Cohen & Kaplan)

Conclusions

- The baryon asymmetry of the Universe is an old problem
- Lots of work on baryogenesis to solve it—some of the classic solutions are either under siege experimentally or too good at avoiding experimental tests
- Large amount of novel work in past 5-10 years. Lots of scenarios that operate at low temperatures/late times⇒tend to be testable, e.g. $\mathcal{O}(\mathrm{GeV})$ particles mixing with SM, particle oscillations, strange indications of baryon number violation, low f_a axions, modified QCD dynamics…
- I've given a (biased) sampling of recent work—very nice comprehensive white paper at arXiv:2203.05010