Low-scale Baryogenesis & Baryon Number Violation

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TRIUMF

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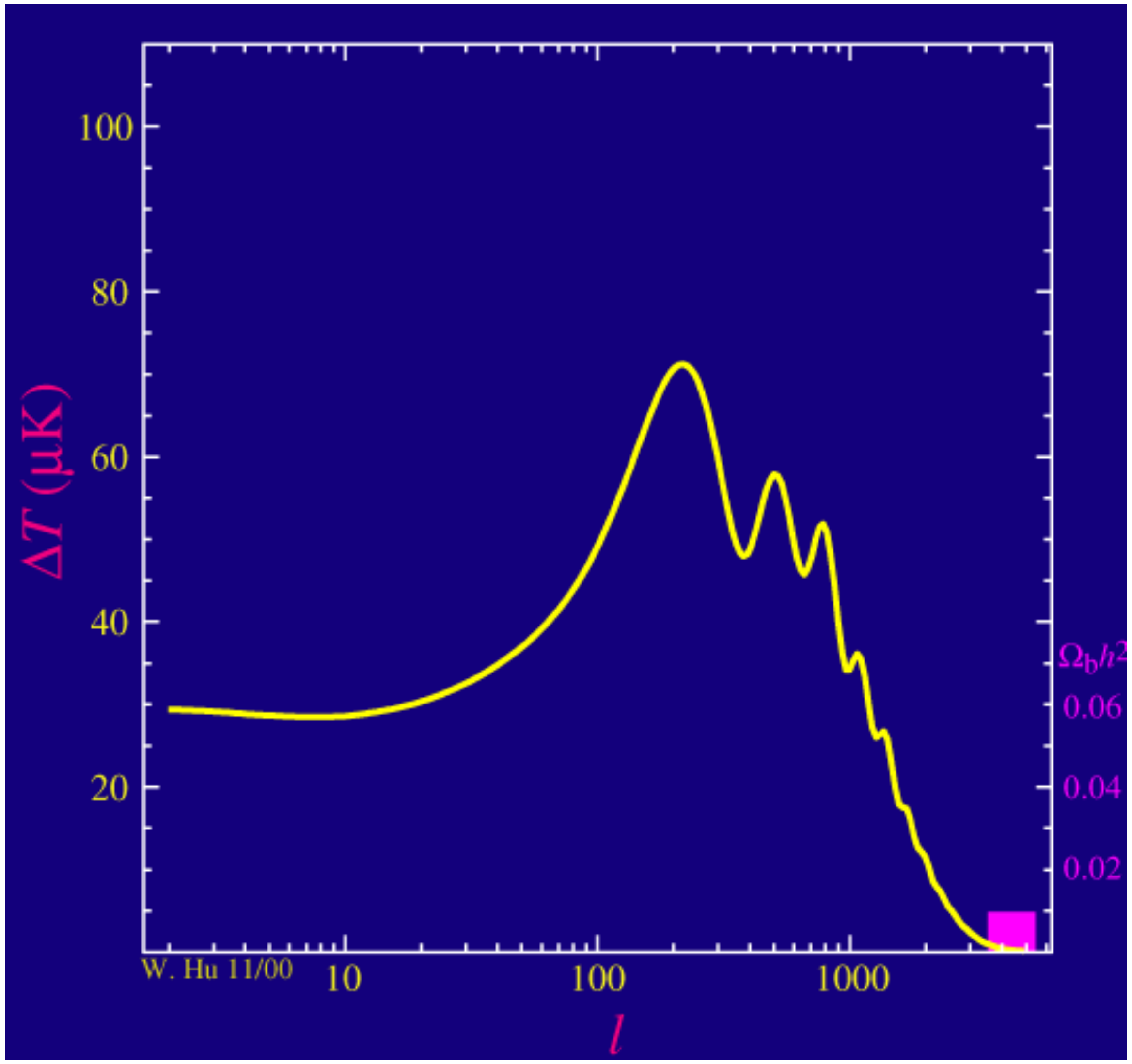
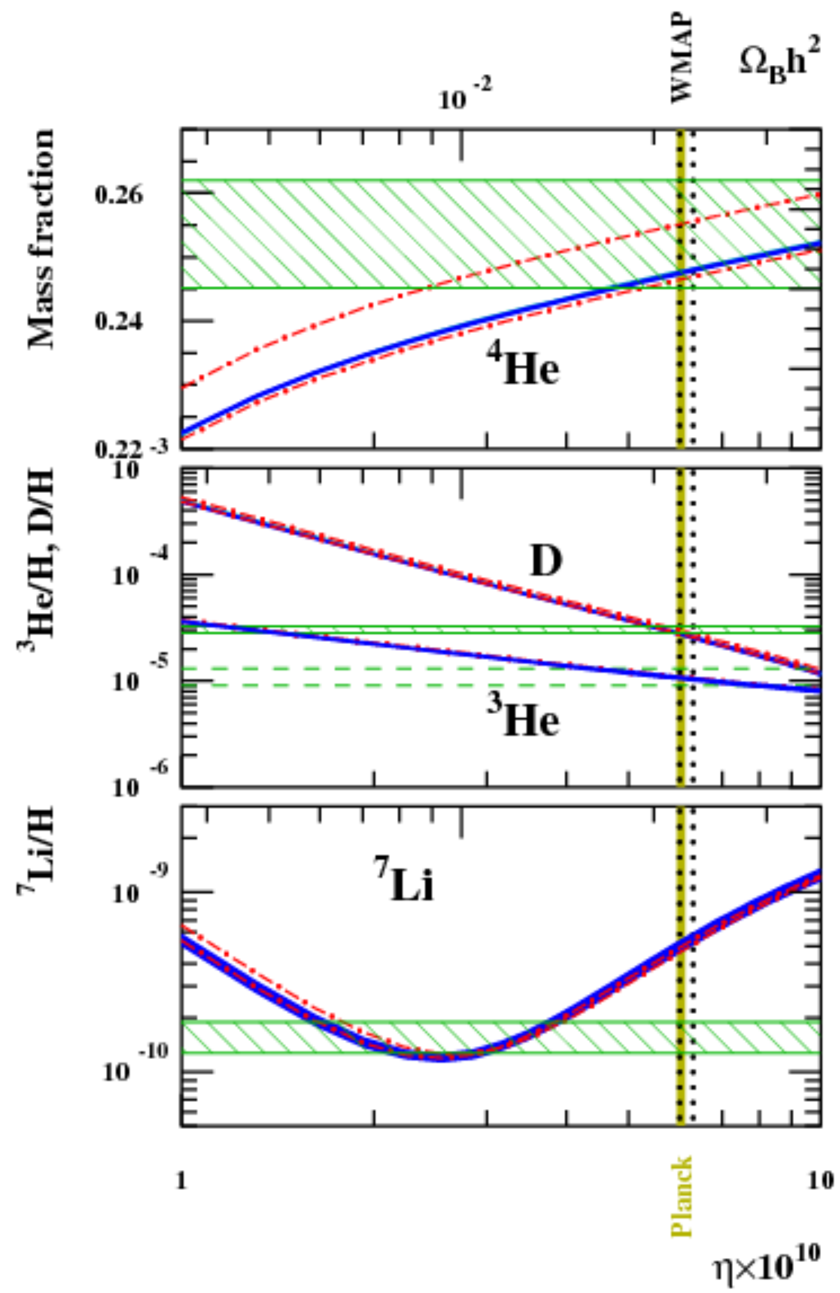
We're made of Baryons!

Wayne Hu





Coc, Uzan, Vangioni

$$\frac{\rho_B - \rho_{\bar{B}}}{\rho_{cr}} \simeq \Omega_B \simeq 0.05 \Longleftrightarrow \frac{n_B - n_{\bar{B}}}{s} \sim \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

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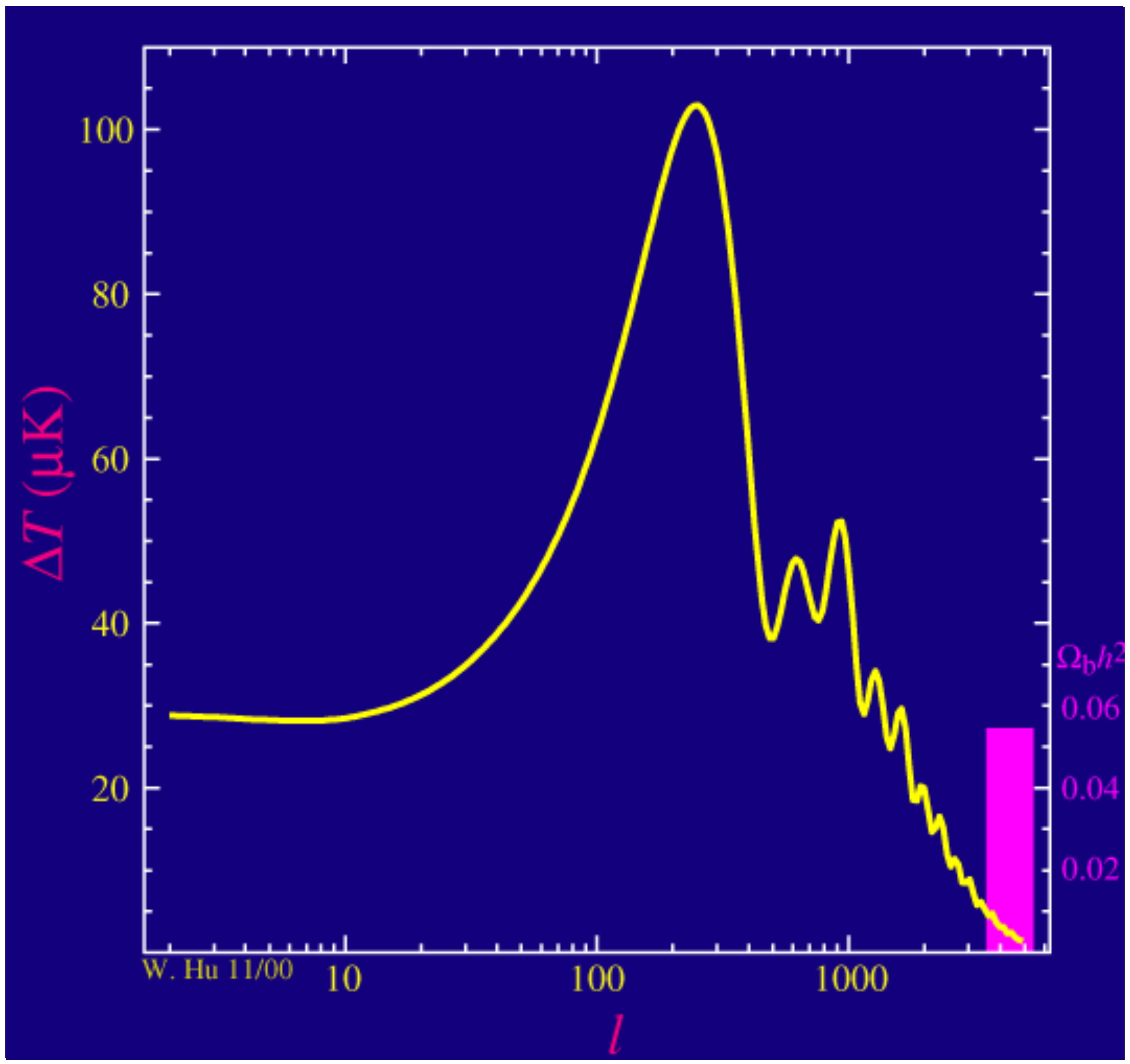

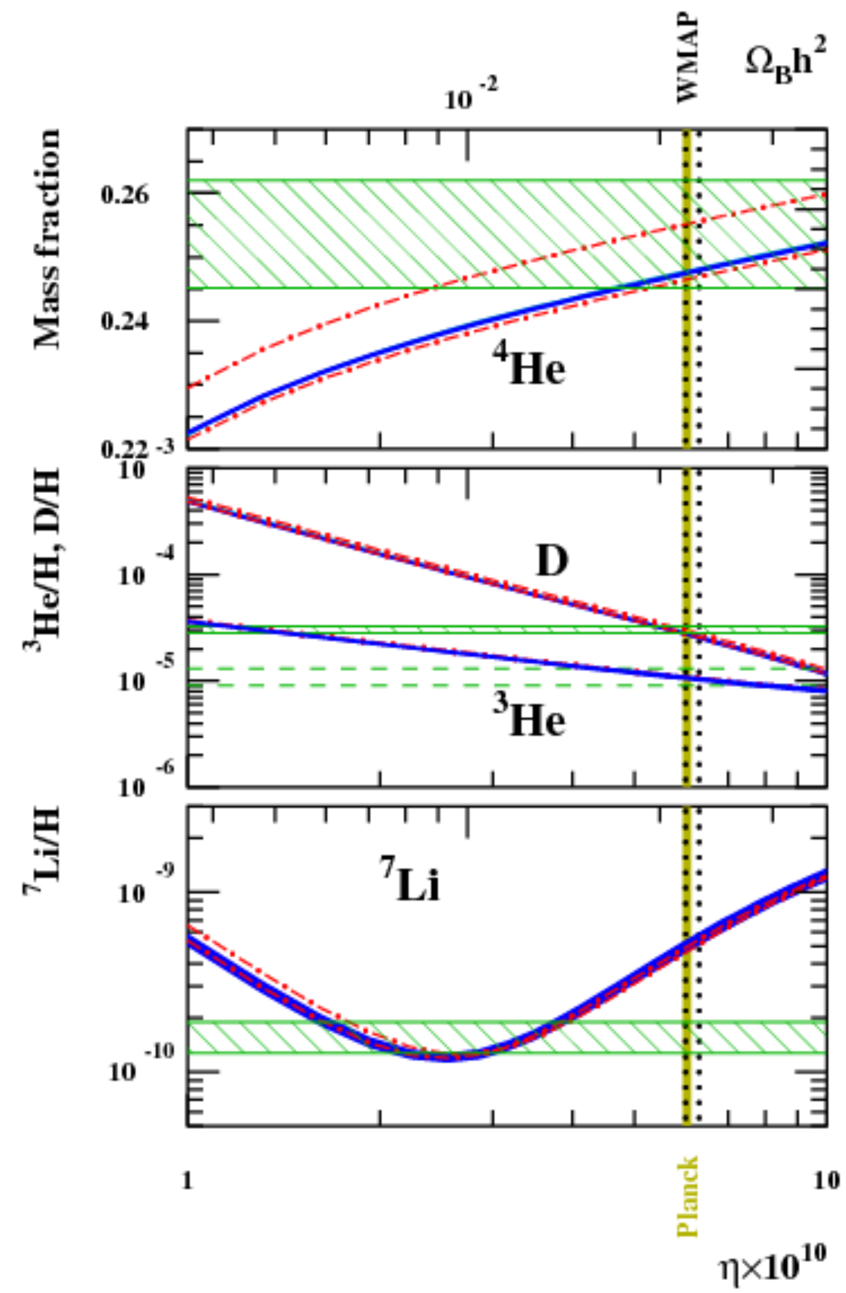

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How to make Baryons (and not $\bar{B}$...)

Sakharov:

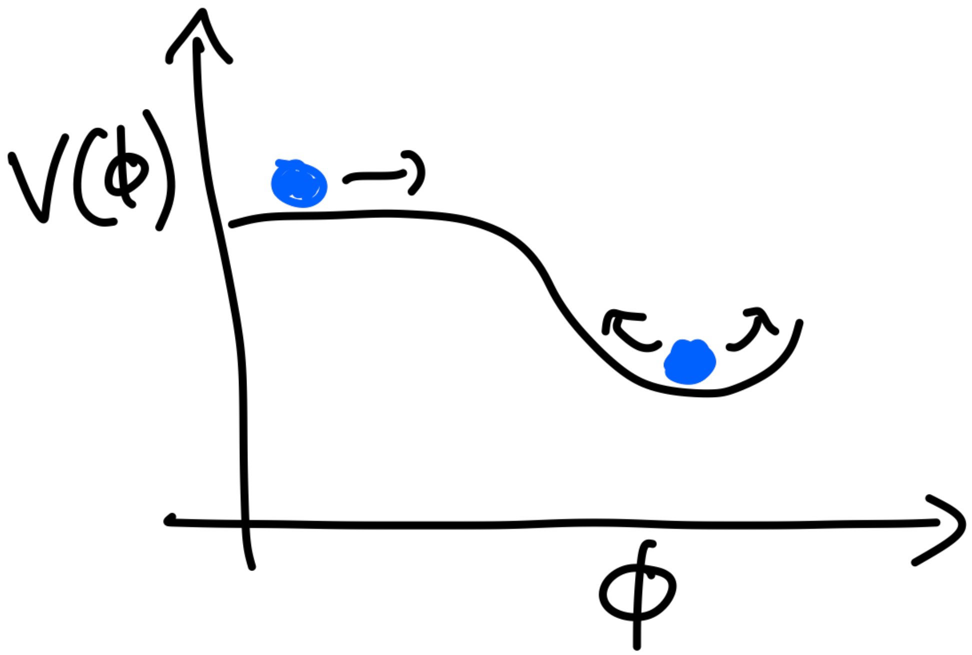
1. C & CP violation (q_L vs $\bar{q}_{L,R}$)
2. Depart from thermal eq.
3. BARYON NUMBER VIOLATION

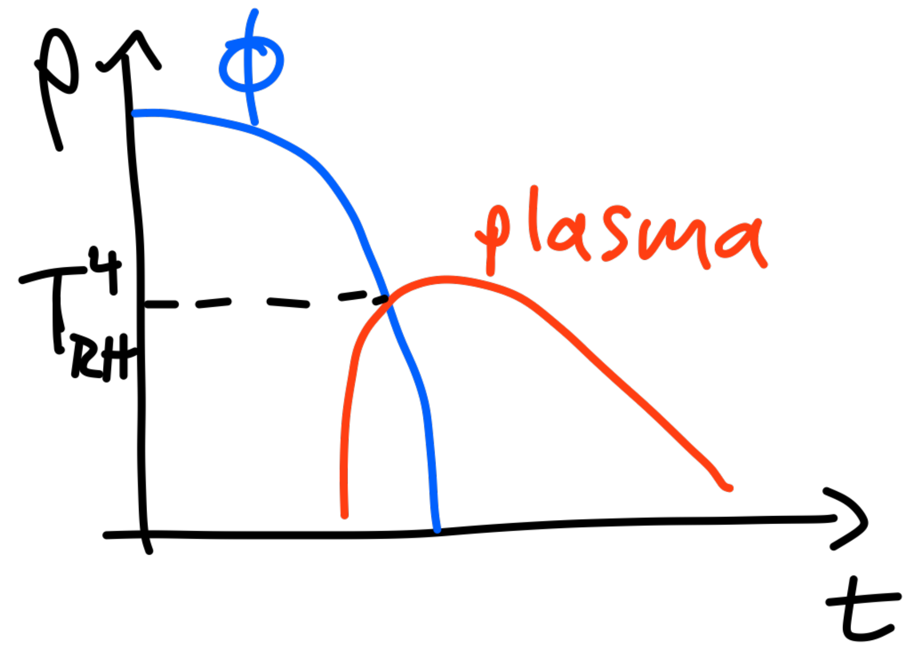
Standard Model can't quite do it

⟹ "Baryogenesis" ⟹ NEW PHYSICS

Most baryogenesis models need high "reheat temperature"

Reheat Temperature?





~ "Initial" temperature of the (radiation dominated) plasma

Most baryogenesis models need $T_{RH} > \text{TeV}$ (or $T_{RH} \gg \text{TeV}$)

Is this always the case?

Reheat Temperature?

Was $T_{RH} > \text{TeV}$? We don't know...
only know $T_{RH} \gtrsim 4\ \text{MeV}$

Problems:

1. can make bad things e.g. gravitinos
2. can induce isocurvature perturbations when ∃ axion(-like) particles
3. some EW Hierarchy Solutions (relaxion) need low T_{RH}

⇒ Let's find some models!

Basic Idea

Make neutral (QCD bound) states after QCD confines ($T \lesssim 200$ MeV)

↳ out-of-equilibrium (e.g. from decay of long lived particle)

Coherent oscillations & decays Source Baryon Asymmetry

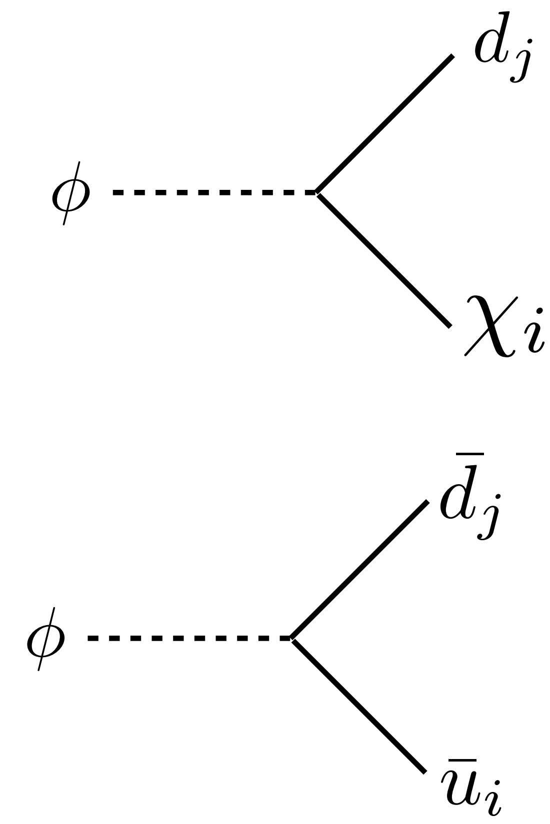
Based on work with Kyle Aitken, Seyda Ipek, Akshay Ghalsasi, Thomas Neder, & Ann Nelson

Model 1

- (colored) scalar ϕ
- Neutral Majorana fermions χ_i

$$\mathcal{L} \supset -g^*_{ud}\,\phi^*\,\bar{u}_R d_R^c - y_{id}\,\phi\,\bar{\chi}_i d_R^c - \tfrac{1}{2} m_{\chi_i}\chi_i\chi_i + h.c.$$

Interactions:

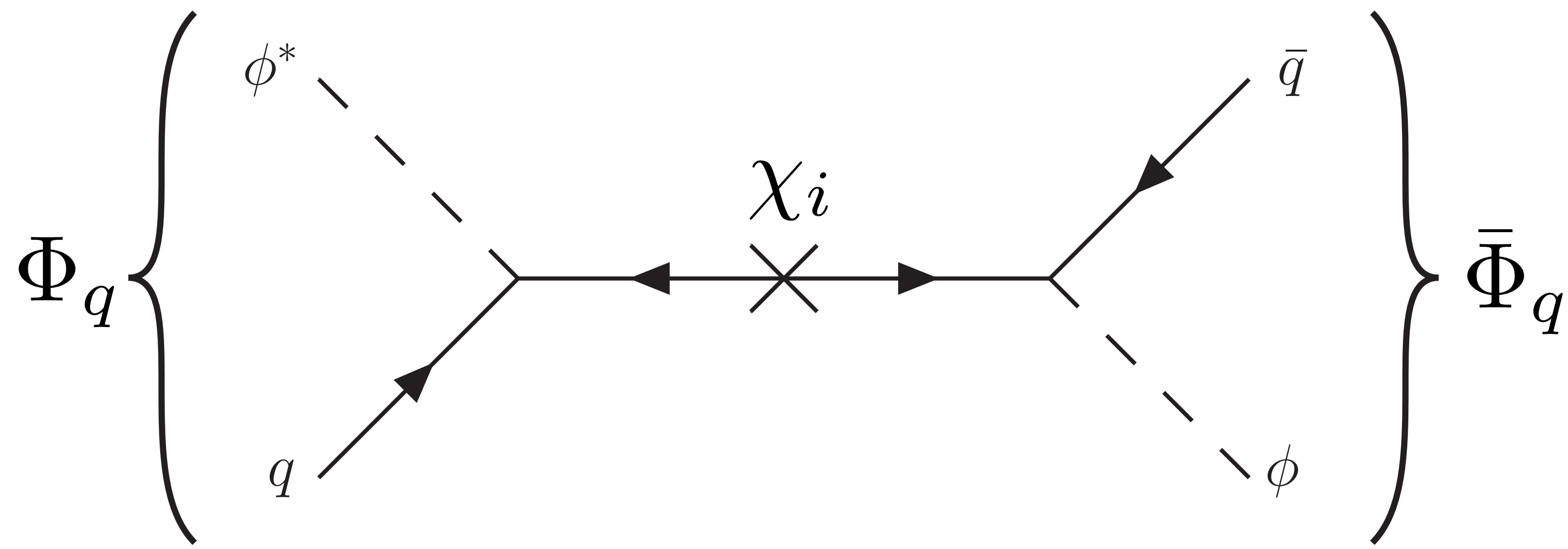


BNV

If scalar long-lived, can hadronize with quark to form a "Mesino" $\Phi_q = (\phi^* q)$

Mesino Oscillations

(Neutral) mesinos can turn into antimesinos



Just as in the case of mesons, can write down 2x2 Hamiltonian

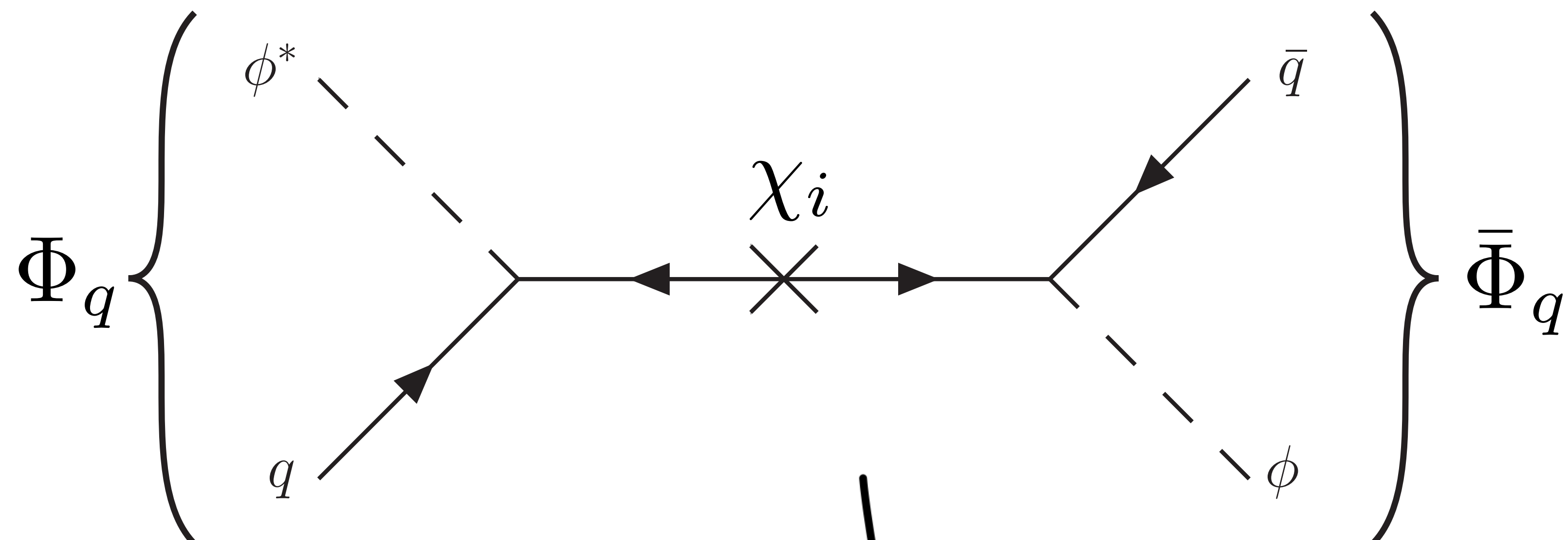
$$\mathbf{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$$

Mass eigenstates are an admixture of “flavor” eigenstates

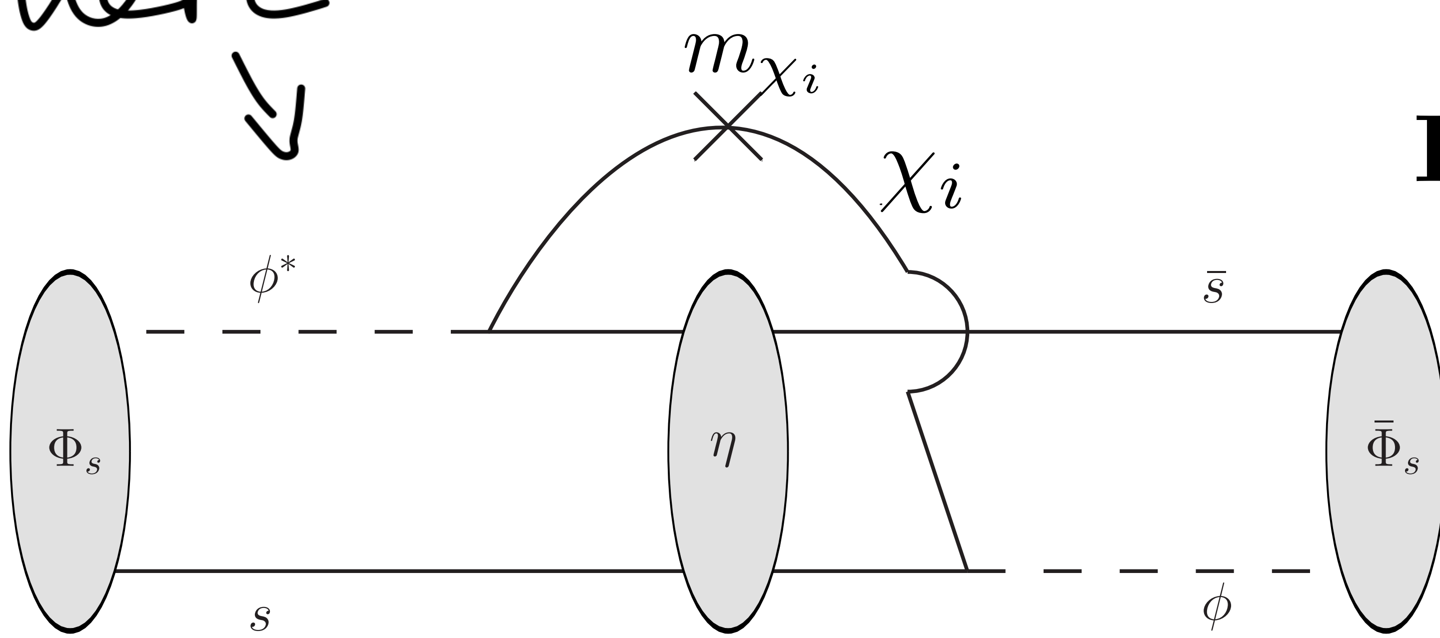
$$|\Phi_{L,H}\rangle = p|\Phi_q\rangle \pm q|\bar{\Phi}_q\rangle$$

Mesino Oscillations

In addition to →



There is

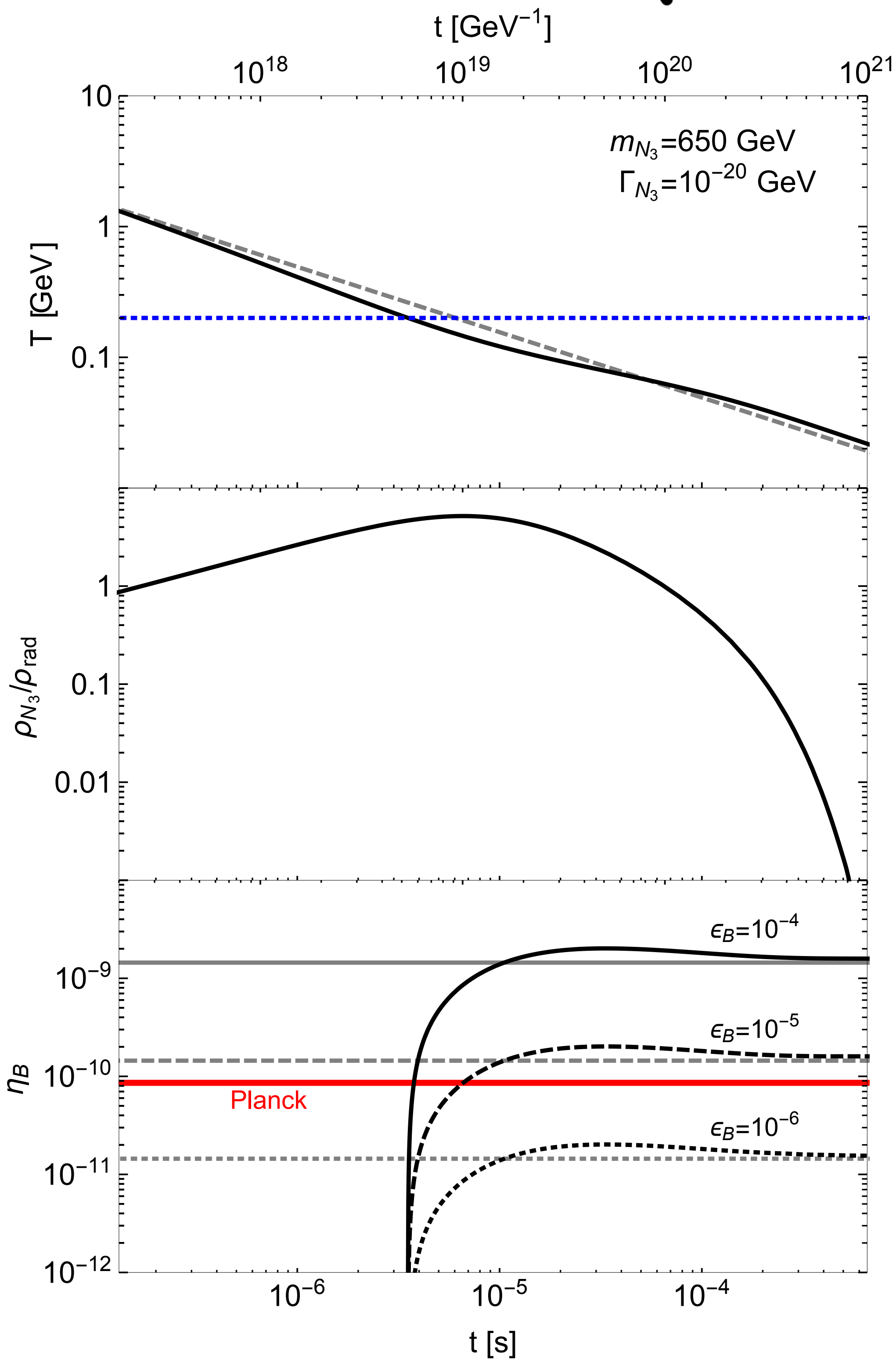


$$\mathbf{H}_{12} = \mathbf{M}_{12} - \frac{i}{2}\mathbf{\Gamma}_{12}$$

need $>1\ \chi_i$

Leads to baryon asym. $\propto \mathrm{Im}(M_{12}\Gamma_{12}^*)$

Baryon Asymmetry!



Make Φ's out-of-eq with long-lived χ_3 decays

$$\frac{d\rho_{\rm rad}}{dt} = -4H\rho_{\rm rad} + \Gamma_{N_3} m_{\chi_3} n_{\chi_3}$$

$$\frac{d\rho_{\chi_3}}{dt} = -3H\rho_{\chi_3} - \Gamma_{\chi_3} m_{\chi_3} n_{\chi_3}$$

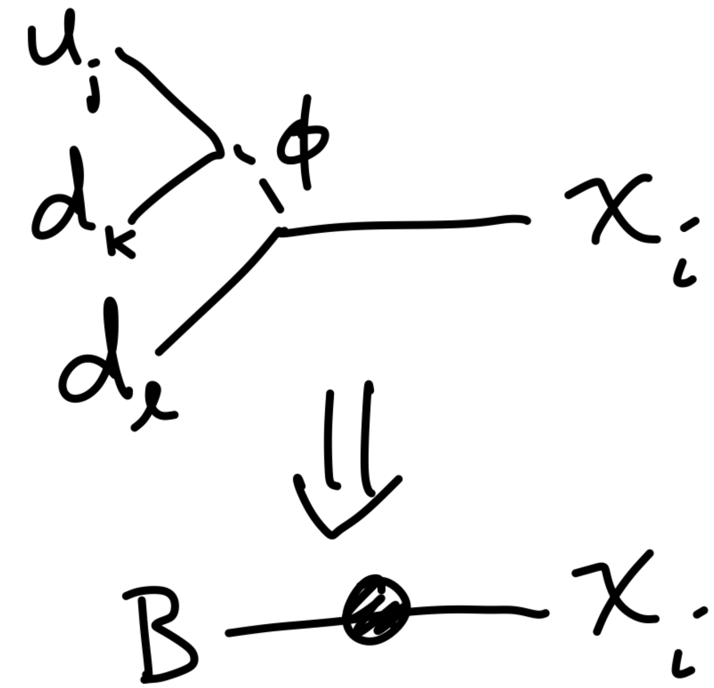
$$\frac{dn_B}{dt} = -3Hn_B + \frac{1}{2} A\,\Gamma_{N_3}\epsilon_B n_{\chi_3}$$

Can get correct asymm with $m_{\chi_2} - m_{\chi_1} \sim$ GeV $\ll m_{\chi_{1,2}}$

Can we push lower?

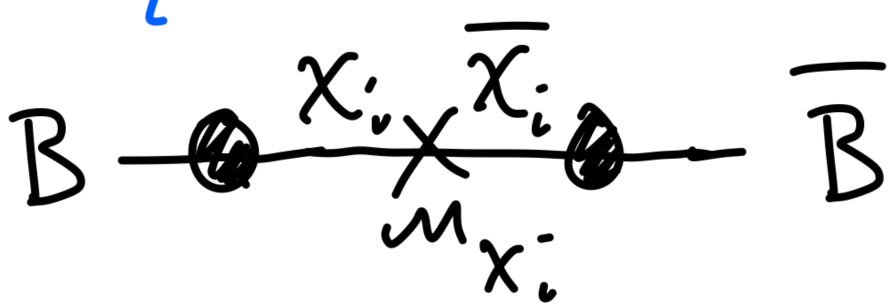
Model 2

Same model, different regime: $m_{\chi_i} \ll m_\phi$

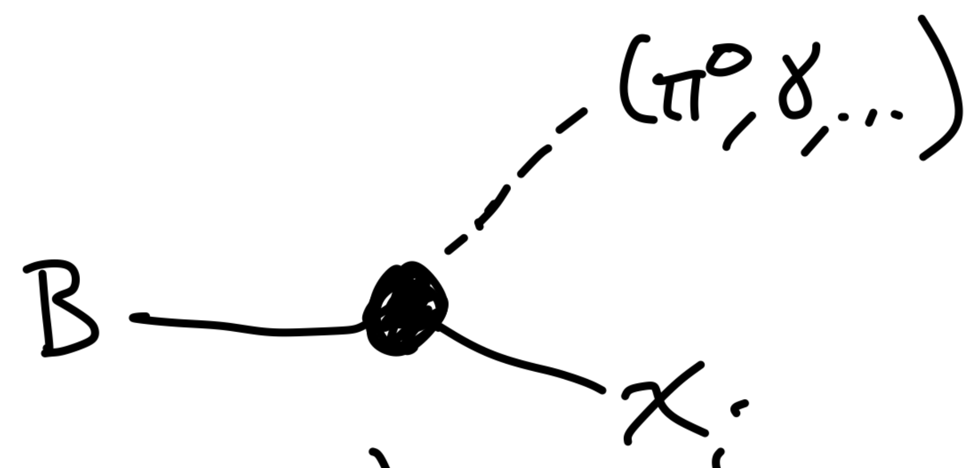


$$\mathcal{L} \supset -g^*_{ud}\,\phi^*\bar{u}_R d^c_R - y_{id}\,\phi\,\bar{\chi}_i d^c_R - \frac{1}{2} m_{\chi_i}\chi_i\chi_i + h.c.$$

Baryon Oscillations



CP Violation



(need >1 χ_i ...)

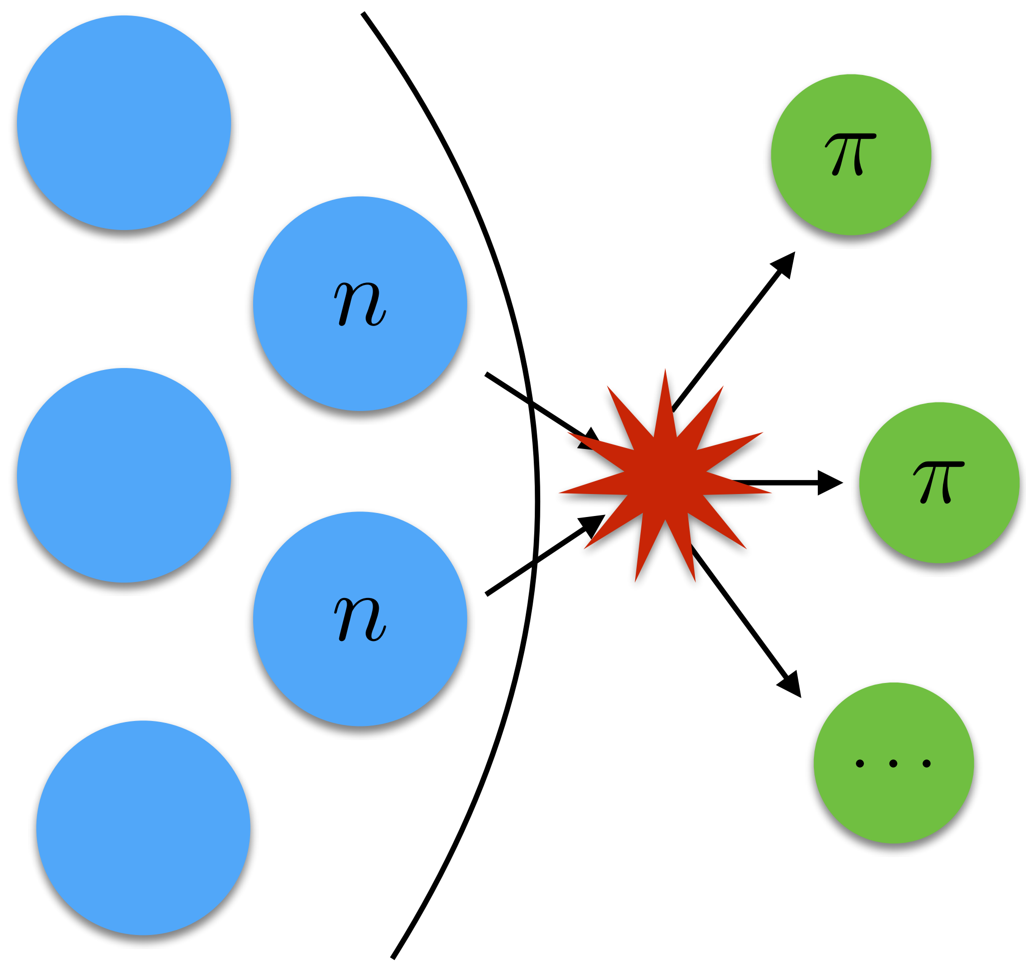
Limits: Dinucleon Decay

Along with n-$\bar{n}$ limits, dinucleon decay important. E.g. Super-K limit of

$$\tau_{^{16}\mathrm{O}} > 1.9 \times 10^{32}\ \mathrm{yr}$$

translates to

$$\tau_{n\to\bar{n}} > 3.5 \times 10^{8}\ \mathrm{s}$$



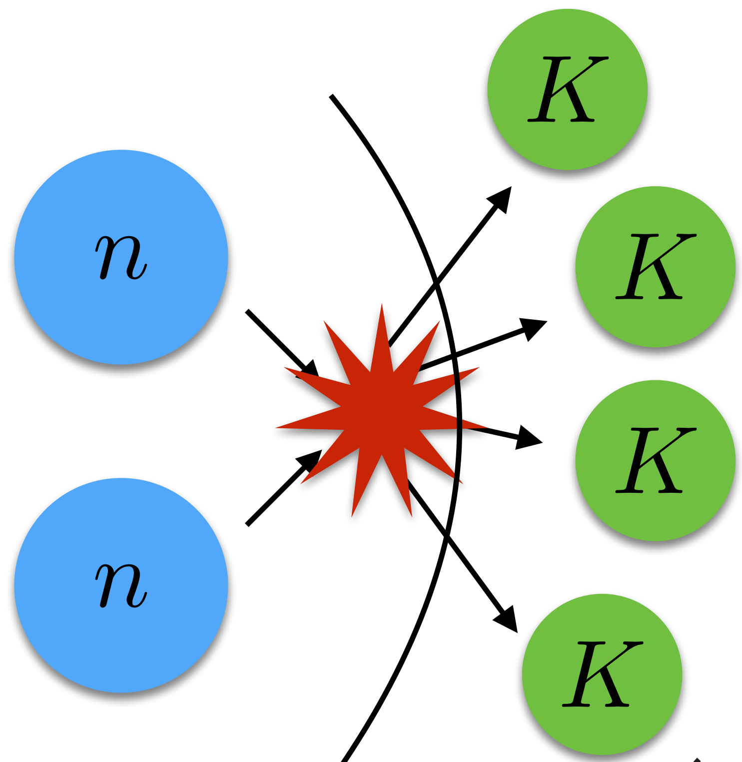
or $\left|M_{12} - \frac{i}{2}\Gamma_{12}\right| > 1.9 \times 10^{-33}\ \mathrm{GeV}$ $\left[\mathcal{L}_{\mathrm{eff}} \supset \frac{(udd)^2}{\Lambda^5} \Rightarrow M_{12}, \Gamma_{12} \propto \frac{1}{\Lambda^5},\ \Lambda \gtrsim 100\ \mathrm{TeV}\right]$

DM, & Nelson, PRD **94** 076002 [1512.05359]

(Heavy flavor) Baryon Oscillations

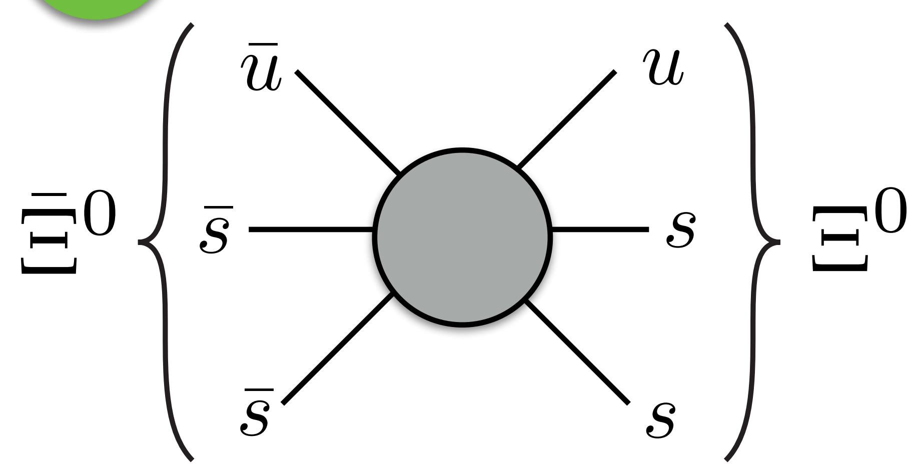
What if $\Delta B = 2$ operators had e.g. $\Delta S = 4$? $\mathcal{L}_{\text{eff}} \supset \frac{(uss)^2}{\Lambda^5}$

Then direct dinucleon decay



is kinematically forbidden!

Leads to oscillation of cascade baryons

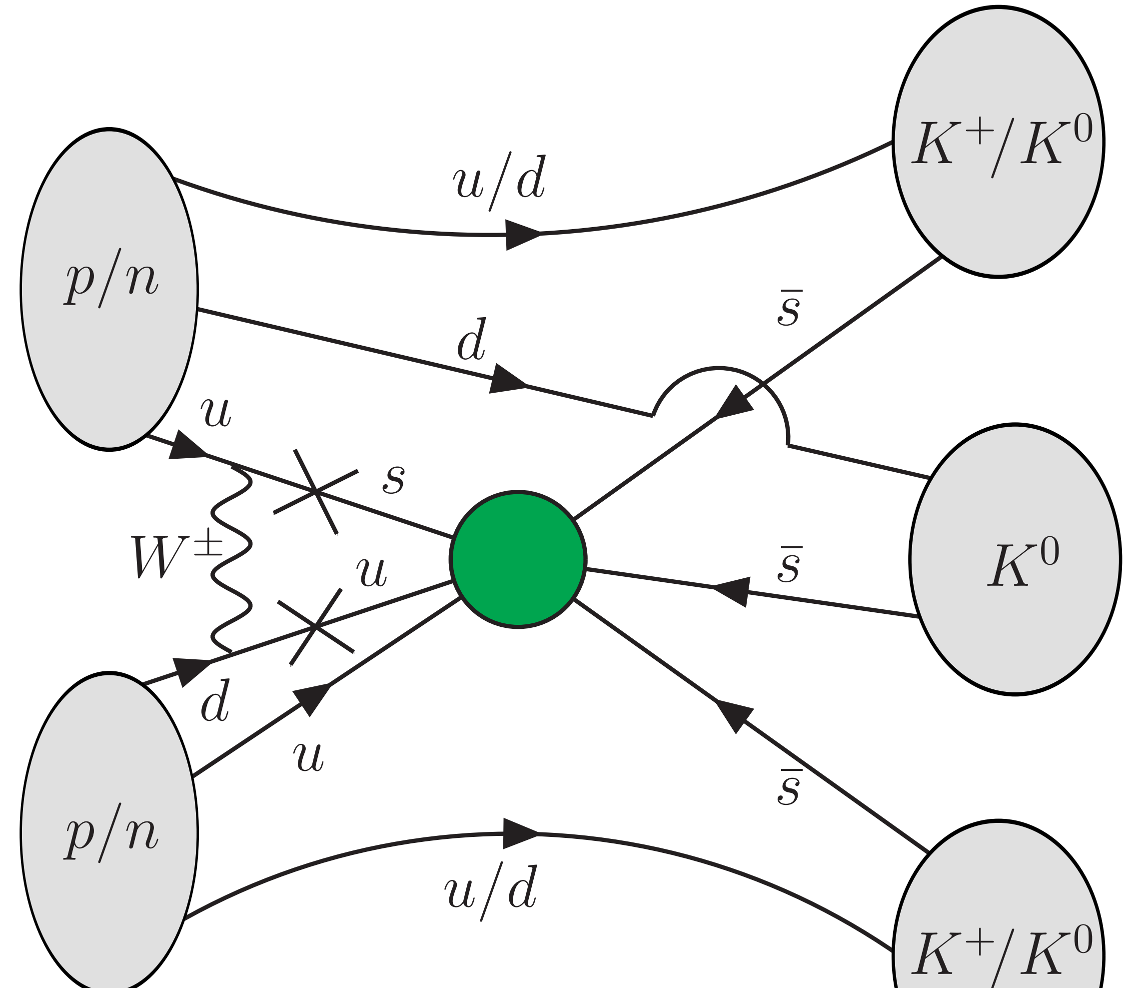


Dominant constraints could be from colliders

$\Gamma_{12},\ M_{12}$ could be much, much larger Kuzmin ('96)

(Indirect) Dinucleon Decay

There is still contribution to dinucleon decay in presence of weak interactions



Naive estimate of suppression (proper treatment involves matching onto chiral perturbation theory)

$$\frac{1}{4\pi^2}\frac{G_F}{\sqrt{2}}\,|V_{us}^*|\,|V_{ud}|\,m_u m_s \log\left(\frac{m_W^2}{\Lambda_{\rm IR}^2}\right) \sim 10^{-10}$$

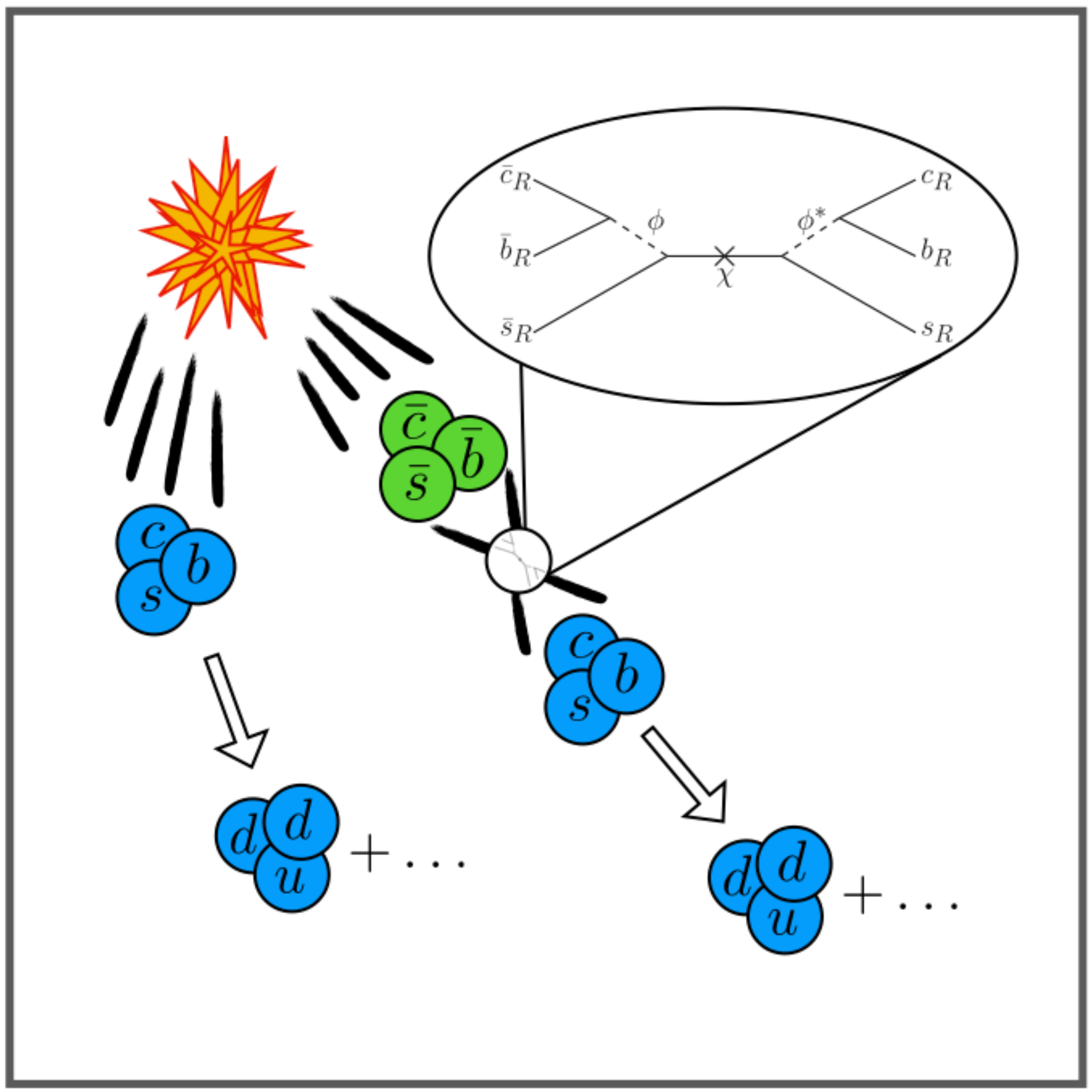
(Indirect) Dinucleon Decay

Combined limits on possible operators

Operator	$\mathcal{B}$	Weak Insertions Required	Measured Γ (GeV) [19]	Limits on $\delta_{\mathcal{B}\mathcal{B}} = M_{12}$ (GeV) Dinucleon decay	Collider
$(udd)^2$	n	None	$(7.477 \pm 0.009) \times 10^{-28}$	10^{-33}	10^{-17}
$(uds)^2$	Λ	None	$(2.501 \pm 0.019) \times 10^{-15}$	10^{-30}	10^{-17}
$(uds)^2$	Σ^0	None	$(8.9 \pm 0.8) \times 10^{-6}$	10^{-30}	10^{-17}
$(uss)^2$	Ξ^0	One	$(2.27 \pm 0.07) \times 10^{-15}$	10^{-22}	10^{-17}
$(ddc)^2$	Σ_c^0	Two	$(1.83^{+0.11}_{-0.19}) \times 10^{-3}$	10^{-17}	10^{-16}
$(dsc)^2$	Ξ_c^0	Two	$(5.87^{+0.58}_{-0.61}) \times 10^{-12}$	10^{-16}	10^{-15}
$(ssc)^2$	Ω_c^0	Two	$(9.5 \pm 1.2) \times 10^{-12}$	10^{-14}	10^{-15}
$(udb)^2$	Λ_b^0	Two	$(4.490 \pm 0.031) \times 10^{-13}$	10^{-13}	10^{-17}
$(udb)^2$	Σ_b^{0*}	Two	$\sim 10^{-3*}$	10^{-13}	10^{-17}
$(usb)^2$	Ξ_b^0	Two	$(4.496 \pm 0.095) \times 10^{-13}$	10^{-10}	10^{-17}
$(dcb)^2$	$\Xi_{cb}^{0\dagger}$	Two	$\sim 10^{-12\dagger}$	10^{-17}	10^{-15}
$(scb)^2$	$\Omega_{cb}^{0\dagger}$	Two	$\sim 10^{-12\dagger}$	10^{-14}	10^{-15}
$(ubb)^2$	$\Xi_{bb}^{0\ddagger}$	Four	$\sim 10^{-13\ddagger}$	>1	10^{-17}
$(cbb)^2$	$\Omega_{cbb}^{0\dagger}$	Four	$\sim 10^{-12\dagger}$	>1	10^{-15}

perturbation theory)

Production in the Early Universe



Heavy flavor baryons and antibaryons created out-of-equilibrium

Oscillations bias baryons over antibaryons

Calculation of Asymmetry more involved...

Again, use long-lived fermion decaying out-of-eq.

$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = \Gamma_{\chi_3}\rho_{\chi_3} \qquad \frac{d\rho_{\chi_3}}{dt} + 3H\rho_{\chi_3} = -\Gamma_{\chi_3}\rho_{\chi_3}$$

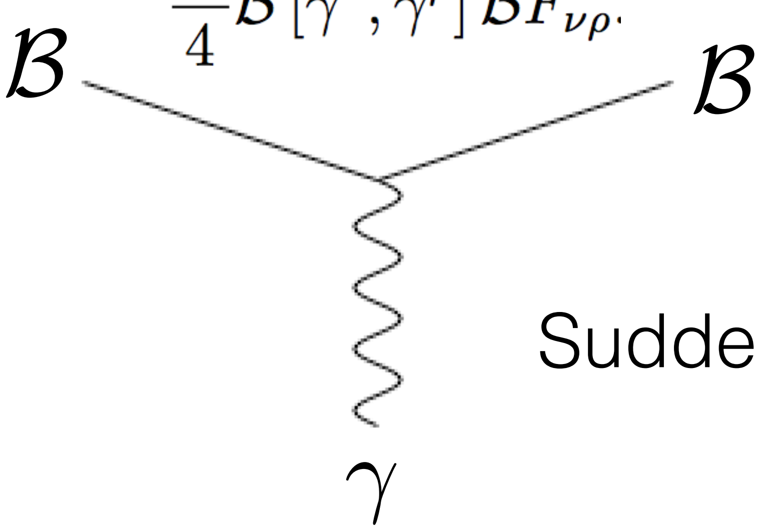
More complicated because of decoherence due to scattering on plasma

Heavy B system density matrix:

$$n = \begin{pmatrix} n_{\mathcal{B}\mathcal{B}} & n_{\mathcal{B}\bar{\mathcal{B}}} \\ n_{\bar{\mathcal{B}}\mathcal{B}} & n_{\bar{\mathcal{B}}\bar{\mathcal{B}}} \end{pmatrix}, \quad \bar{n} = \begin{pmatrix} n_{\bar{\mathcal{B}}\bar{\mathcal{B}}} & n_{\mathcal{B}\bar{\mathcal{B}}} \\ n_{\bar{\mathcal{B}}\mathcal{B}} & n_{\mathcal{B}\mathcal{B}} \end{pmatrix}$$

$$\frac{dn}{dt} + 3Hn = -i\left(\mathcal{H}n - n\mathcal{H}^\dagger\right) - \frac{\Gamma_\pm}{2}\left[O_\pm, [O_\pm, n]\right] - \langle\sigma v\rangle_\pm \left(\frac{1}{2}\{n, O_\pm \bar{n} O_\pm\} - n_{\rm eq}^2\right) + \frac{1}{2}\frac{\Gamma_{\chi_3}\rho_{\chi_3}}{m_{\chi_3}}{\rm Br}_{\chi_3\to\mathcal{B}}$$

$$\frac{i\mu}{4}\bar{\mathcal{B}}\left[\gamma^\nu, \gamma^\rho\right]\mathcal{B}F_{\nu\rho}.$$



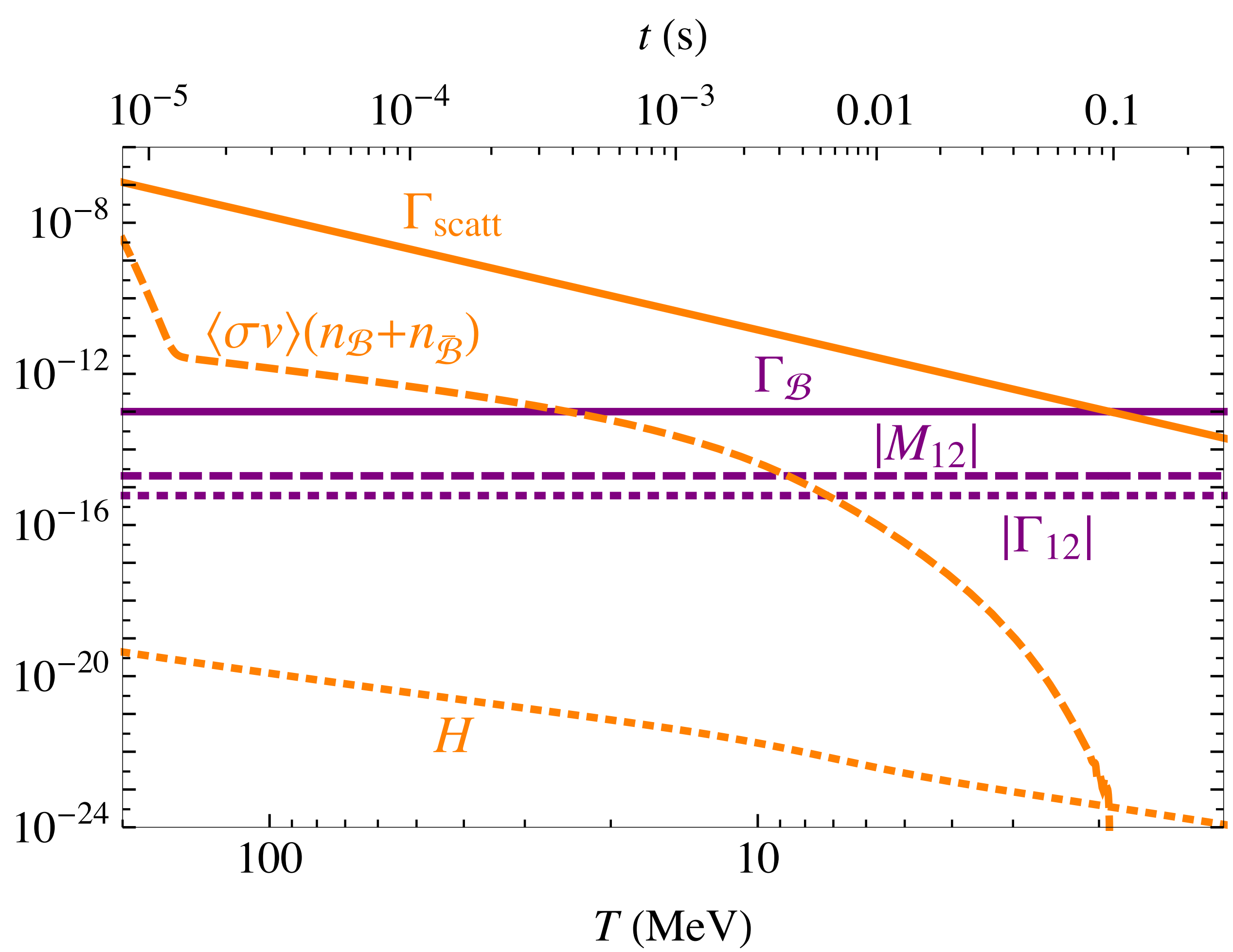
Sudden decay approx:

$$\eta_B \simeq \frac{\pi^3}{3\zeta(3)}\sqrt{\frac{\pi g_*(T_{\rm dec})}{10}}\frac{\Gamma_{\mathcal{B}}\epsilon}{\sigma m_{\chi_3}\Gamma_{\chi_3}M_{\rm Pl}}$$
$$= 9\times 10^{-11}\left[\frac{g_*(T_{\rm dec})}{50}\right]^{1/2}\left(\frac{m_{\mathcal{B}}}{5~{\rm GeV}}\right)^2\left(\frac{\Gamma_{\mathcal{B}}}{10^{-13}~{\rm GeV}}\right)$$
$$\times\left(\frac{8~{\rm GeV}}{m_{\chi_3}}\right)\left(\frac{10^{-22}~{\rm GeV}}{\Gamma_{\chi_3}}\right)\left(\frac{\epsilon}{10^{-5}}\right).$$

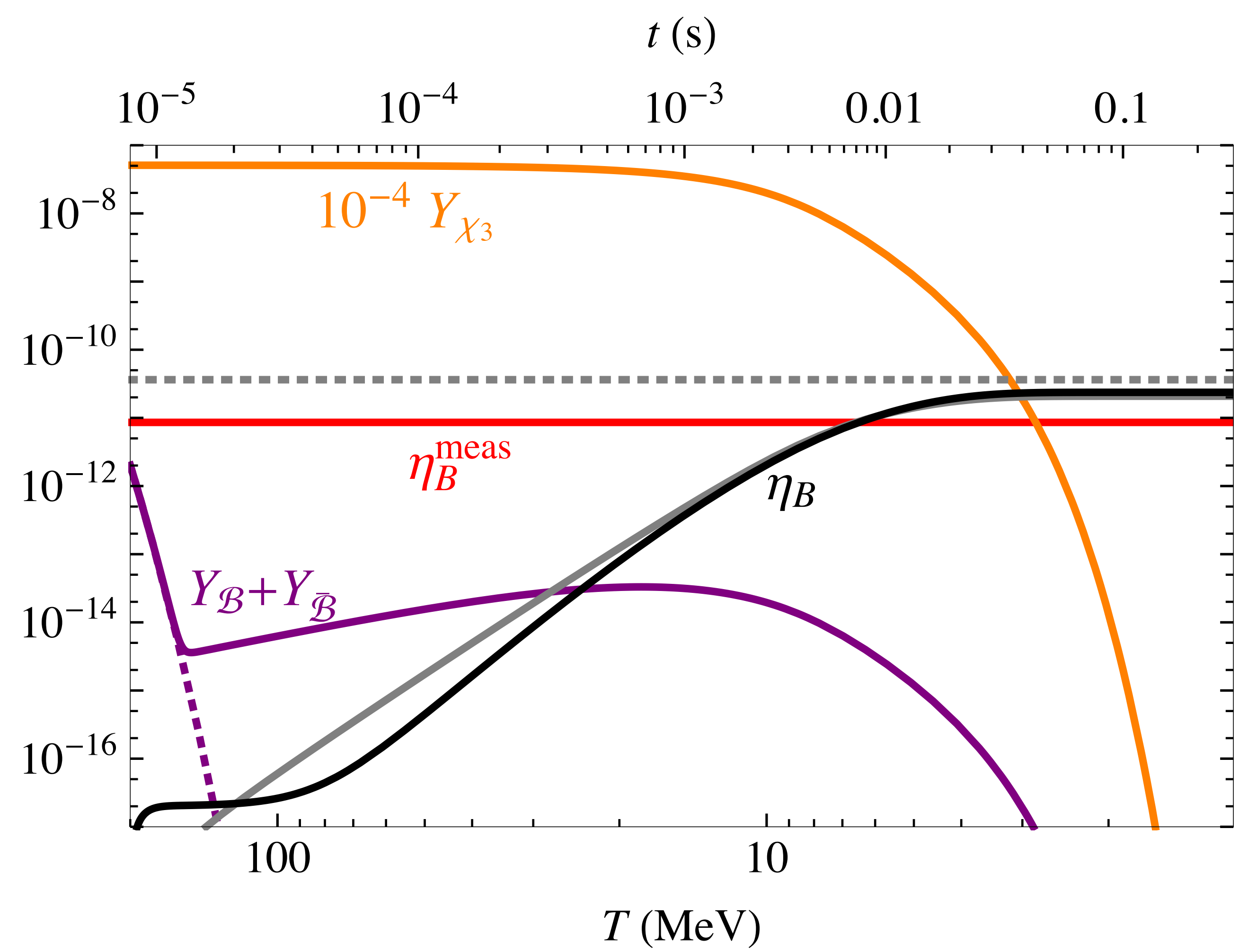
(Similar to resonant leptogenesis of Akhmedov-Rubakov-Smirnov; see also Asaka & Shaposhnikov + many others)

See also Ipek & March-Russell

Calculation of Asymmetry more involved...



Importance of decoherence due to scattering means asymmetry generated at late times, T~10 MeV



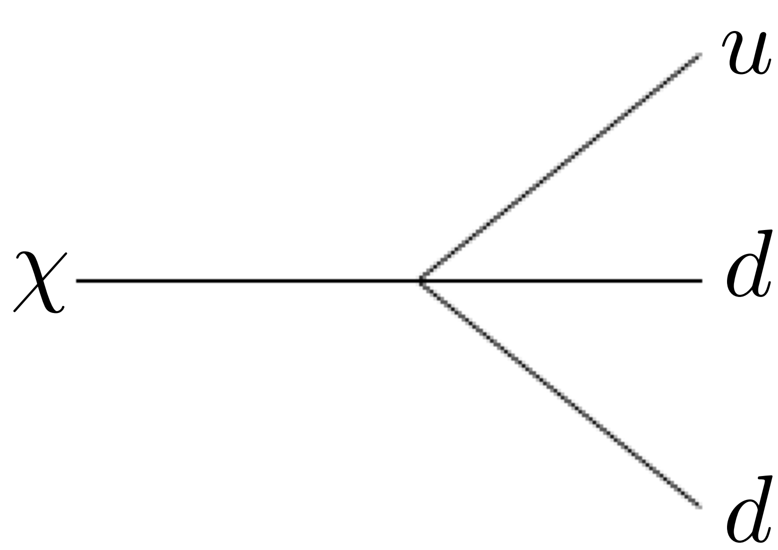
Results for $\Omega_{cb} - \bar{\Omega}_{cb}$ system

$$m_{\mathcal{B}} = 7 \text{ GeV}, \; \Gamma_{\mathcal{B}} = 3 \times 10^{-12} \text{ GeV}$$

$$|M_{12}| = 3 \times 10^{-15} \text{ GeV}, \; |\Gamma_{12}/M_{12}| = 0.3$$

$$m_{\chi_3} = 7.5 \text{ GeV}, \; \Gamma_{\chi_3} = 3 \times 10^{-23} \text{ GeV}$$

Model 2: Probes



χ_i's $(>\underline{1})$ long lived

$$\tau_{\chi_i} \sim \frac{2\,(8\pi)^3}{m_{\chi_{1,2}}^5} \left| \frac{m_\phi^2}{g_{ud}\, y_{id'}} \right|^2$$

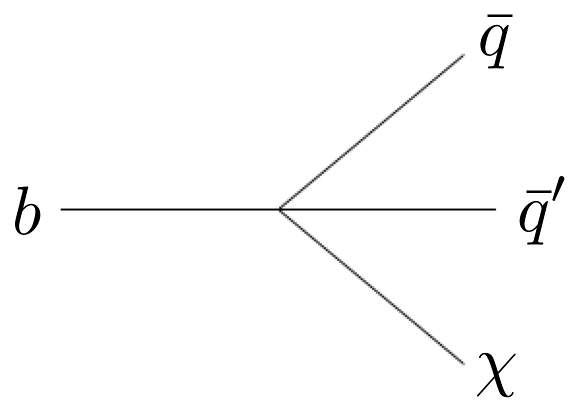
$$\simeq 10^{-6}\ \mathrm{s} \left(\frac{5\ \mathrm{GeV}}{m_{\chi_i}} \right)^5 \left(\frac{m_\phi / \sqrt{g_{ud}\, y_{id'}}}{20\ \mathrm{TeV}} \right)^4$$

$m_{\chi_i} \sim \mathcal{O}(5\ \mathrm{GeV})$

$\Rightarrow$ look at colliders

Model 2 : Probes

Exotic hadron decays



$$\Gamma_{b\to\chi_1\bar{u}\bar{d}} \sim \frac{m_b \Delta m^4}{60\,(2\pi)^3}\left(\frac{g_{ub}y_{1d}}{m_\phi^2}\right)^2 + \mathcal{O}\left(\frac{\Delta m^5}{m_b^5}\right)$$

$$\simeq 2\times 10^{-15}\ \mathrm{GeV}\left(\frac{\Delta m}{2\ \mathrm{GeV}}\right)^4\left(\frac{1.2\ \mathrm{TeV}}{m_\phi/\sqrt{g_{ub}y_{1d}}}\right)^4$$

$$\text{meson} \to \text{baryon} + \chi_i\ [+\,\text{meson(s)}]$$

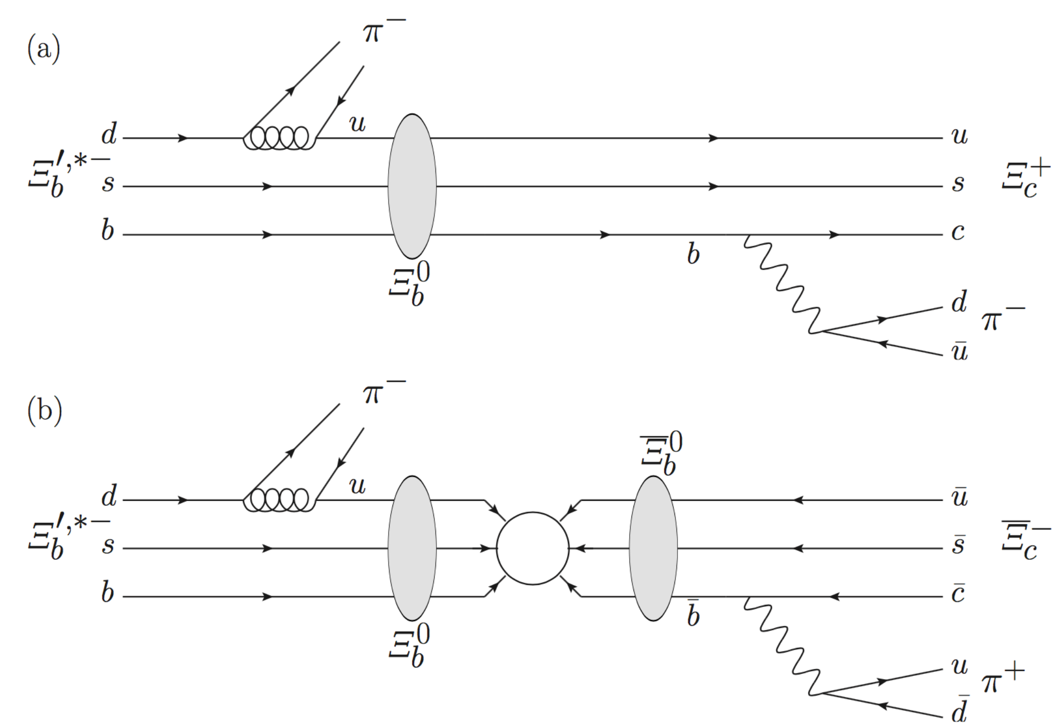
$$\text{baryon} \to \text{meson(s)} + \chi_i$$

B branchings can be $\mathcal{O}(10^{-3})$

Search for baryon-number-violating Ξ_b^0 oscillations

LHCb collaboration [1708.05808]

$$P_{\mathcal{B}\to\bar{\mathcal{B}}} \sim \frac{|M_{12}|^2}{\Gamma_{\mathcal{B}}^2} \sim 10^{-5}$$



"Wrong sign" baryon decays, displaced vertices…

Avoiding Dinucleon Decay

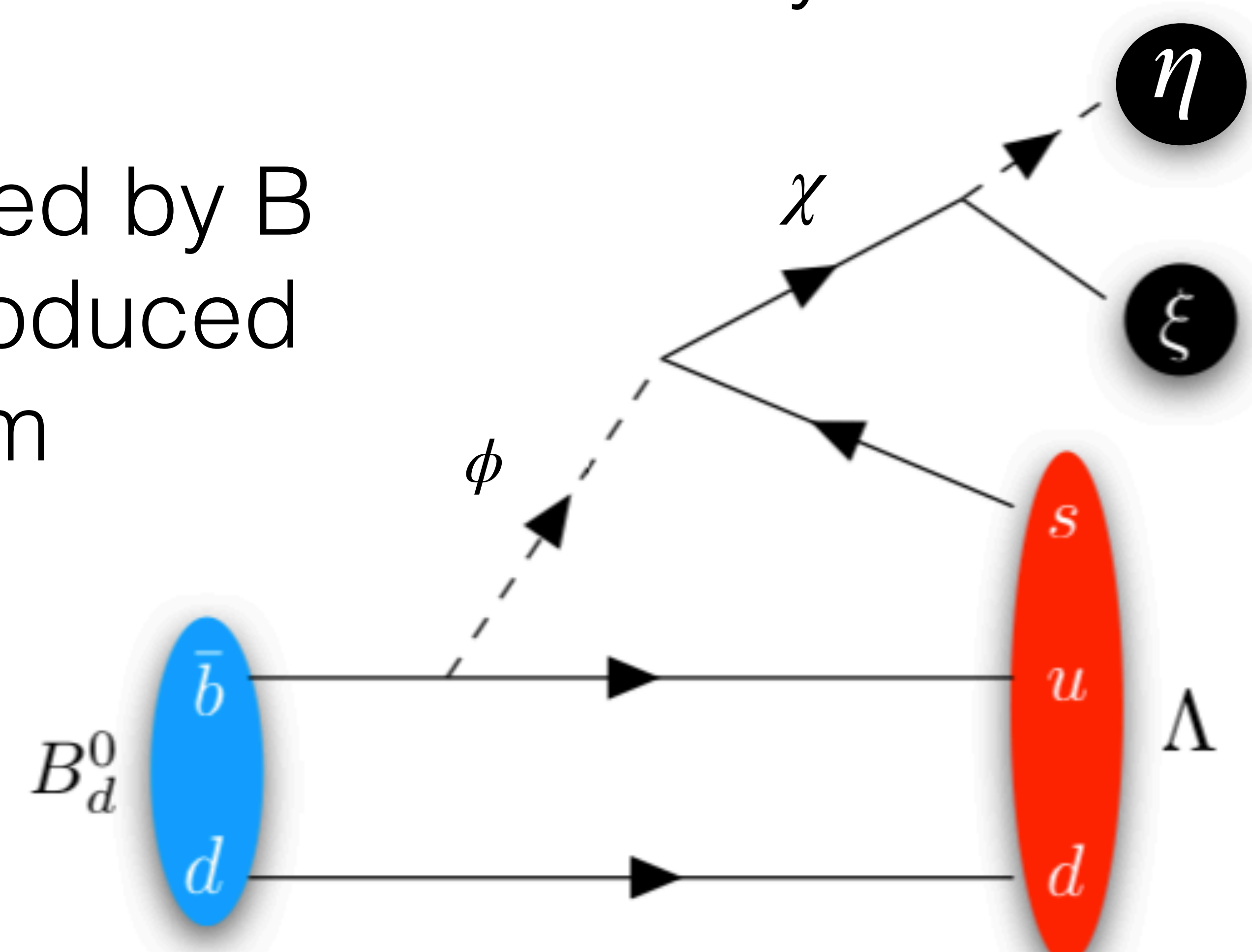
$$\mathcal{L}_{\rm int} \supset -g^*_{ud}\phi^*\bar{u}_R d^c_R - y_d\phi\bar{\chi}_L d^c_R - y'\eta\bar{\chi}_L\xi_R - m_\chi\bar{\chi}_L\chi_R + \text{h.c.}$$

χ Dirac, dark sector that carries baryon number: η, ξ

No baryon number violation⇒ no dinucleon decay constraints

Now asymmetry sourced by B meson oscillations, produced out-of-equilibrium

Exotic B meson branching must be ~0.1-10%!



Wrap Up

Baryogenesis requires new physics

Typically active above electroweak scale

Low scale scenarios generally more challenging

Described some new models involving coherent oscillations

Can lead to unique phenomenology

Testable! (In the near future!)