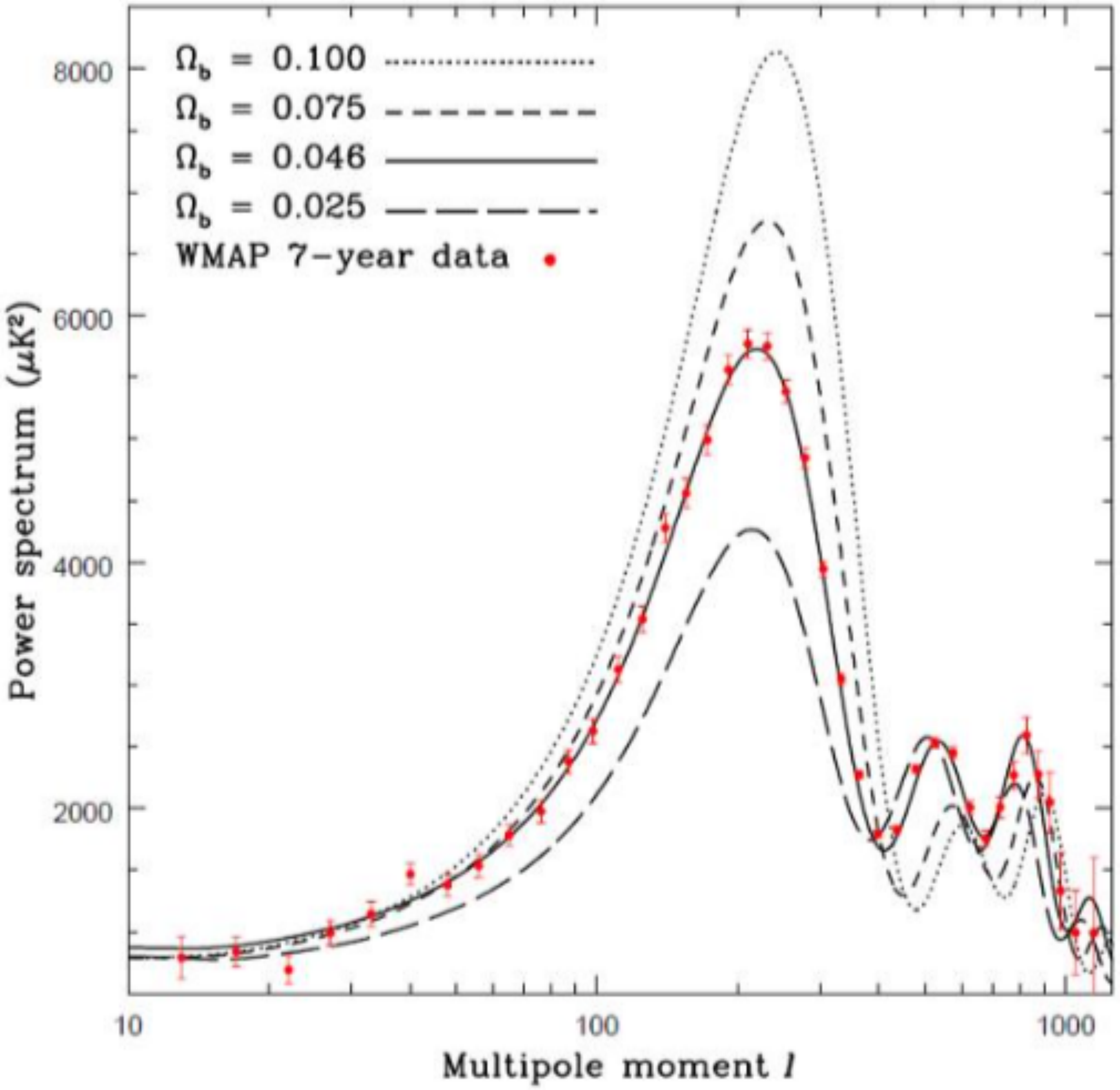
New Low Scale Baryogenesis Models

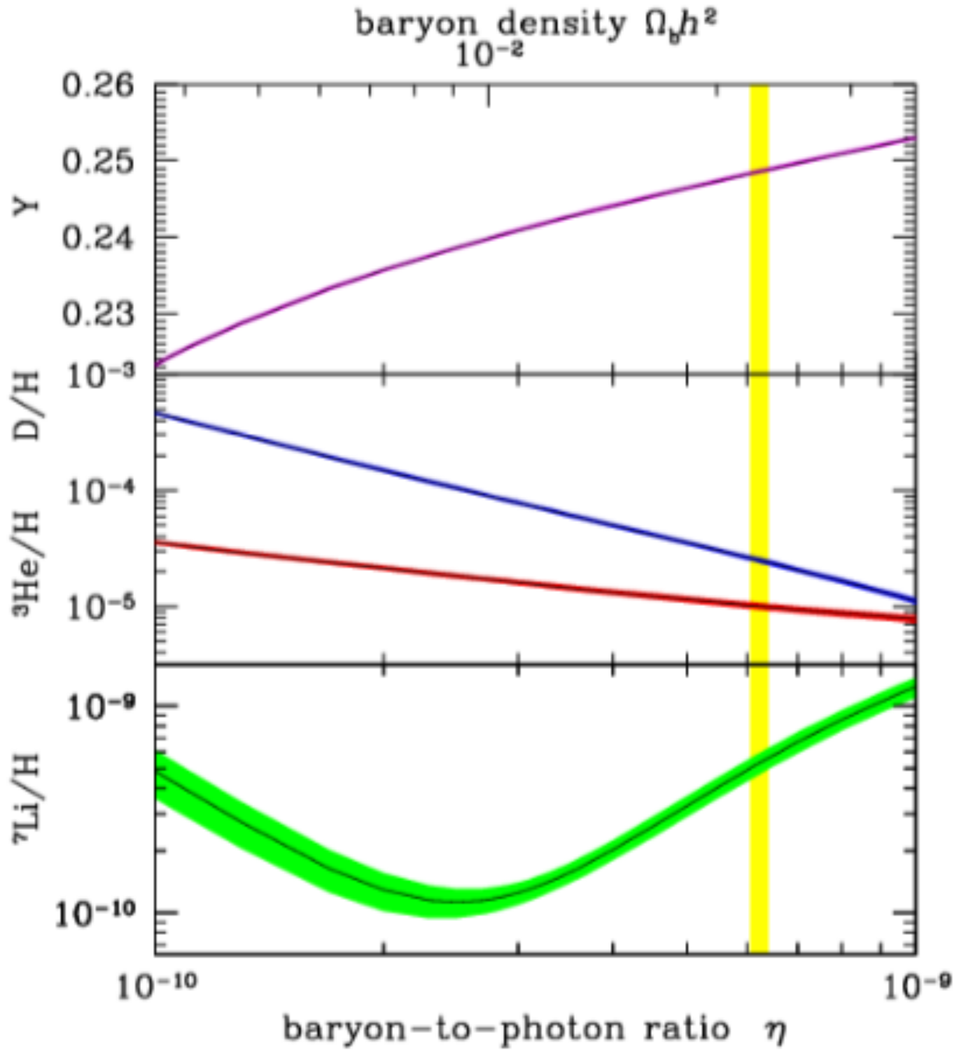
David McKeen

TRIUMF

IPA 2018
October 10, 2018

We’re made of baryons





$$\frac{\rho_B - \rho_{\bar{B}}}{\rho_{\rm cr}} = \Omega_B \sim 0.05$$

or

$$\frac{n_B - n_{\bar{B}}}{s} \sim \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

How to get baryons

Sakharov conditions:

- B violation
- C & CP violation q_L vs. $\bar{q}_L$
 q_L vs. $\bar{q}_R$
- Depart from thermal eq.

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SM can't quite do it

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SM can't quite do it

Inflation means it "must" happen dynamically: "baryogenesis"

How to get baryons

Sakharov conditions:

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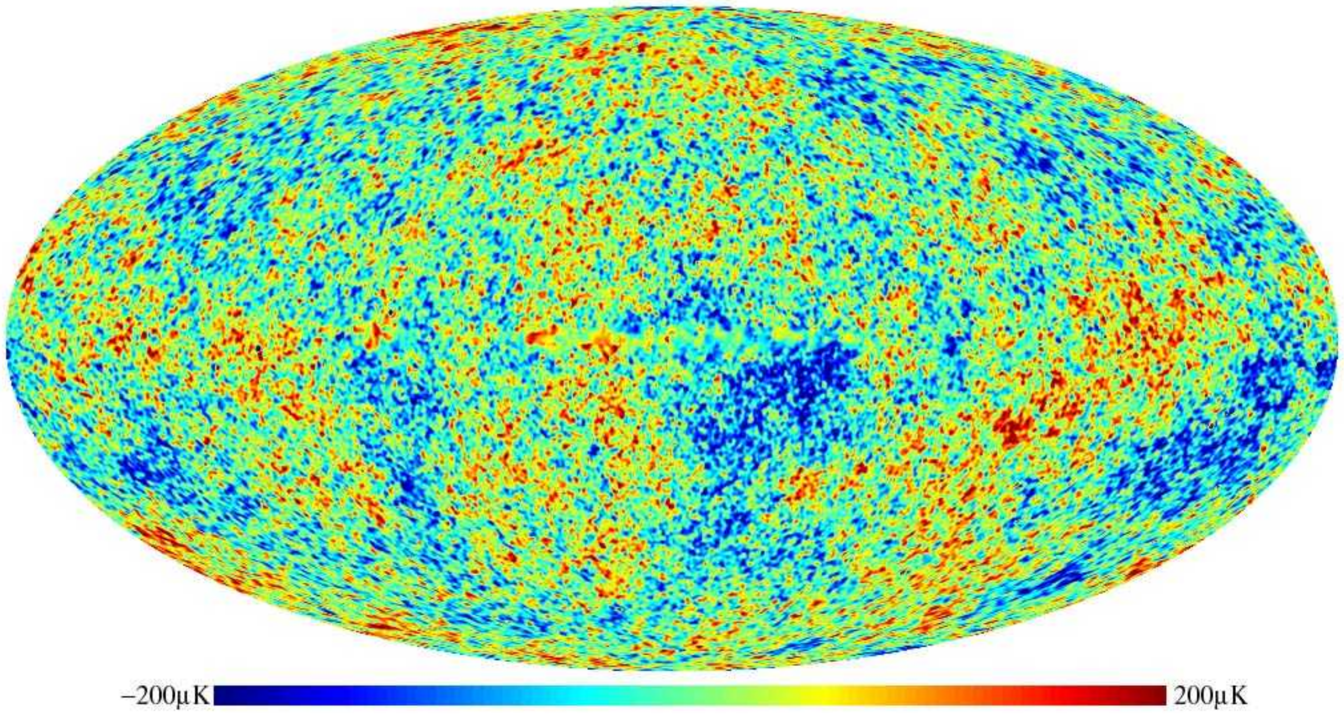
- C & CP violation
  - q_L vs. $\bar{q}_L$
  - q_L vs. $\bar{q}_R$
- Depart from thermal eq.

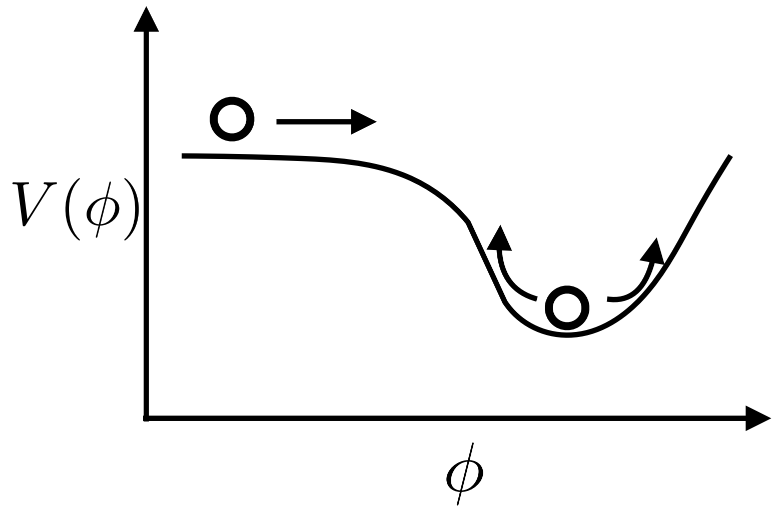
SM can't quite do it

Inflation means it "must" happen dynamically: "baryogenesis"

Most models of baryogenesis require a high reheat temperature (above EW) which can be problematic

What is the reheat temp.?





Inflation…
- smooths and flattens Universe
- gets rid of "problematic" things (e.g. monopoles)
- can explain pattern of CMB anisotropies

After inflation Universe cold and dominated by inflaton
Coupling to SM reheats Universe

What is the reheat temp.?

No direct evidence reheating T was high (compared to, say, electroweak), could have been low

Issues with high reheat T:

Gravitino production in SUSY extensions

Moroi, Murayama, Yamaguchi, Kawasaki, Yanagida;
Bolz, Brandenburg, Buchmuller;+ others

Isocurvature perturbations from axion(-like particles)

Turner, Wilczek, Zee, Seckel; Fox, Pierce, Thomas; + others

Relaxion models require low inflation scale

Graham, Kaplan, Rajendran

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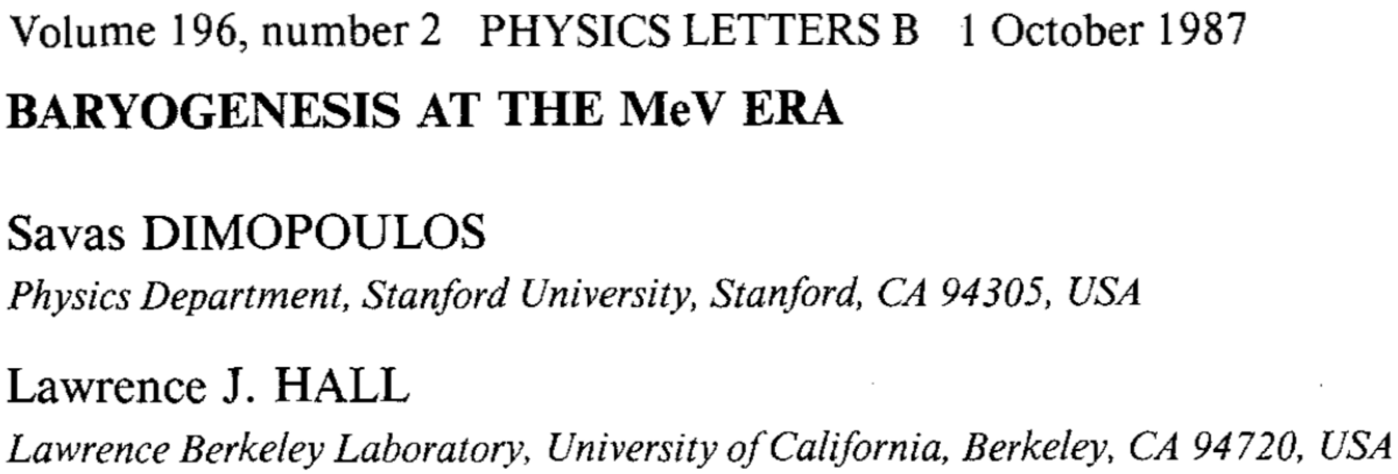
Seek baryogenesis at low scales

An Early Low Scale Baryogenesis Model



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BARYOGENESIS AT THE MeV ERA

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Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA

Baryonic RPV SUSY

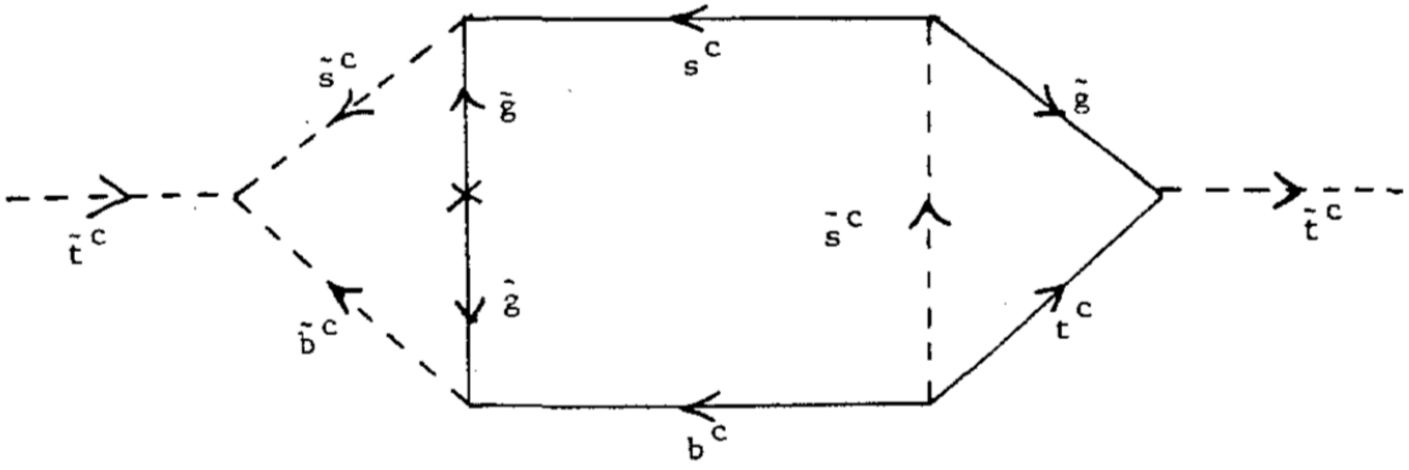
$$W \supset \lambda''_{ijk} u_i d_j d_k$$

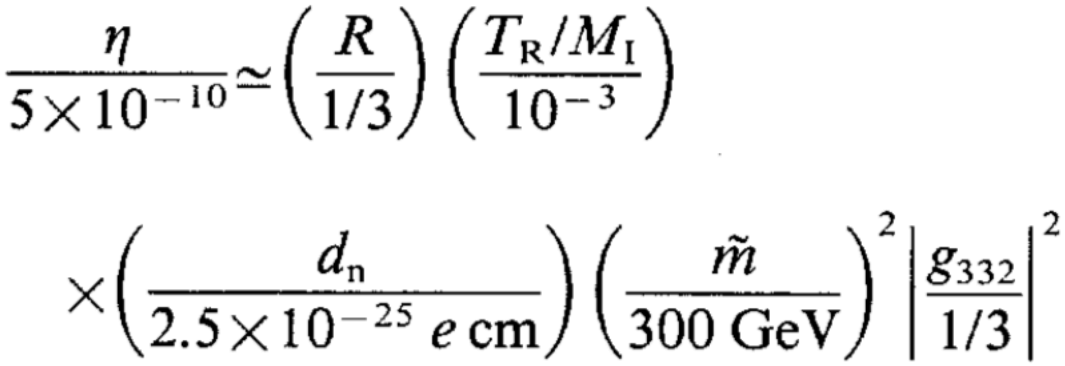
(this will come up again)

Stop decays source asymmetry

Low reheat T prevents wash out

but…





$$\frac{\eta}{5\times10^{-10}} \simeq \left(\frac{R}{1/3}\right)\left(\frac{T_{\mathrm{R}}/M_{\mathrm{I}}}{10^{-3}}\right) \times\left(\frac{d_{\mathrm{n}}}{2.5\times10^{-25}\ e\ \mathrm{cm}}\right)\left(\frac{\tilde{m}}{300\ \mathrm{GeV}}\right)^2\left|\frac{g_{332}}{1/3}\right|^2$$

Too large neutron EDM

New Models for Low Scale Baryogenesis

Basic idea: make neutral (QCD bound) states after QCD confines

Coherent oscillations and decays source baryon asymmetry

Out of equilibrium condition provided by long-lived particle that decays to the states that oscillate

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

+new work by Gilly Elor, Miguel Escudero, & Ann Nelson

Ghalsasi, DM, & Nelson, PRD **92** 076014 [1508.05392]

Low Scale Baryogenesis: Model I

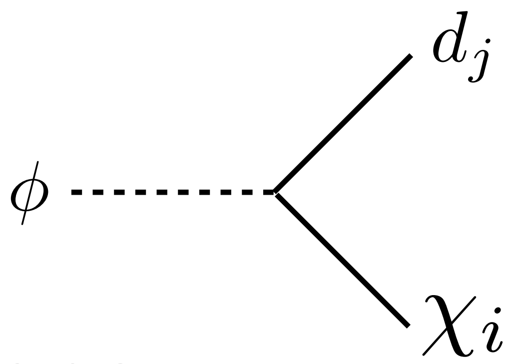
A (colored) scalar ϕ

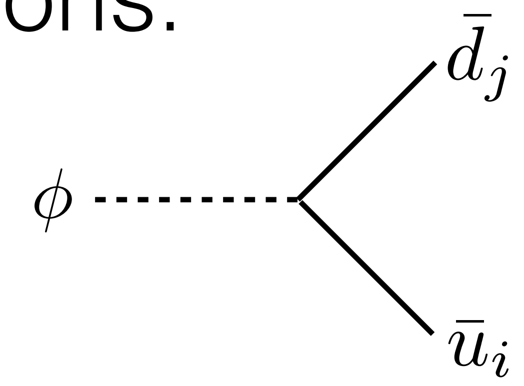
Neutral Majorana fermions χ_i

(encoded in

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

Interactions:





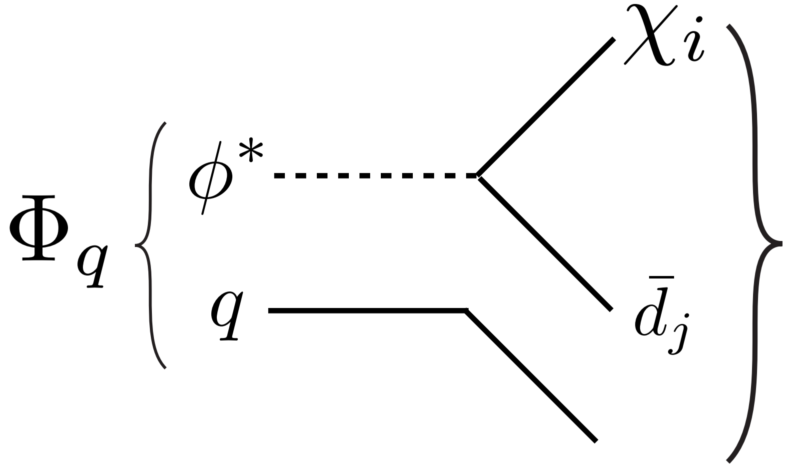
If the scalar is sufficiently long-lived it can form bound states with light quarks called “mesinos”

$$\Phi_q \sim \phi^* q$$

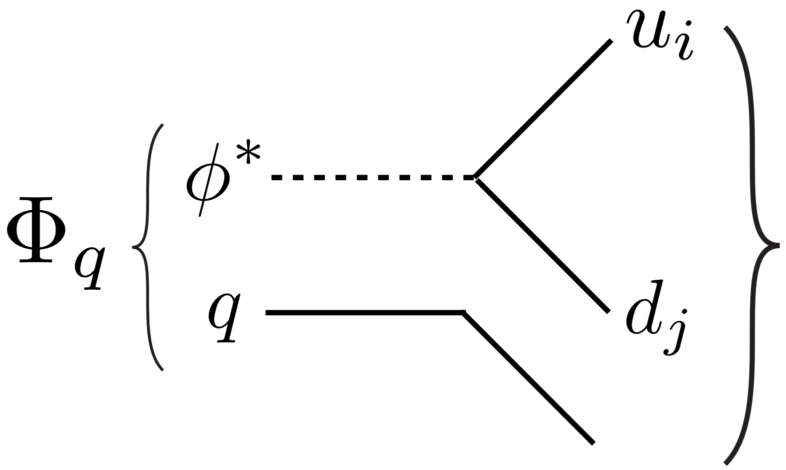
What are Mesinos?

Take quark→squark inside a meson
“superpartner” of a meson

Decay modes:



$$\chi_i + \ldots \quad \equiv \Gamma_{\Phi_q \to \chi_i}$$

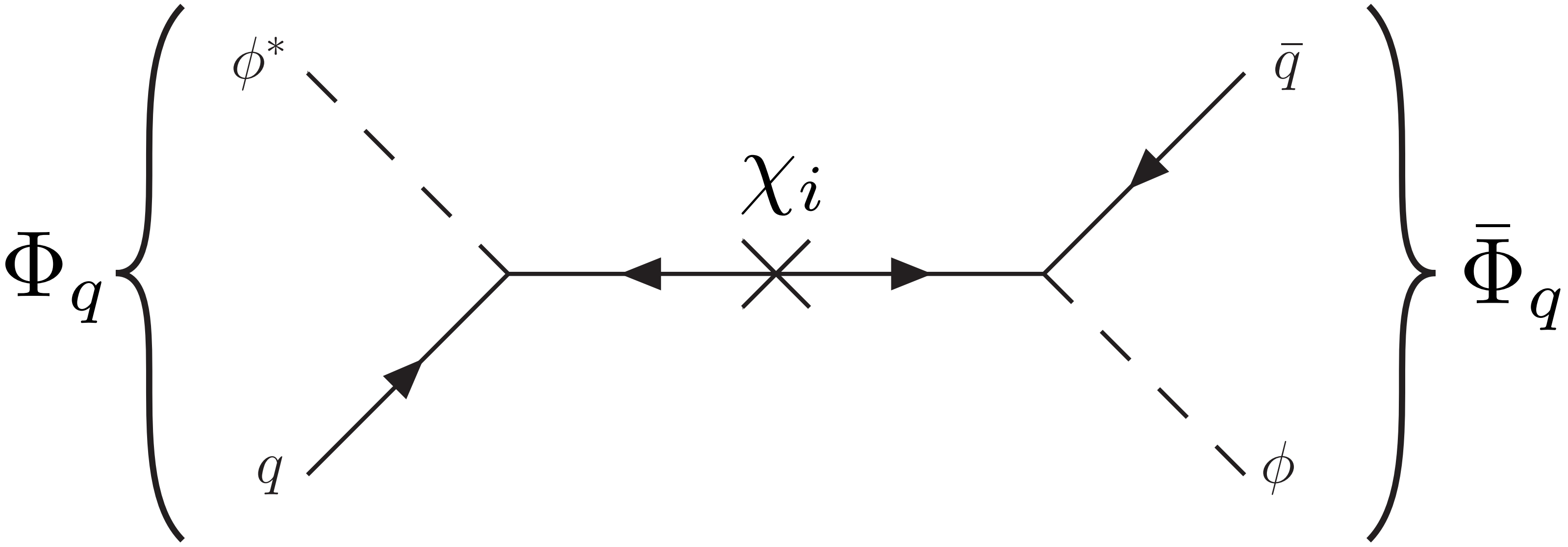


$$B = +1 + \ldots \equiv \Gamma_{\Phi_q \to B}$$

+conjugate modes for antimesinos

What do Mesinos do?

(Neutral) mesinos can turn into antimesinos



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

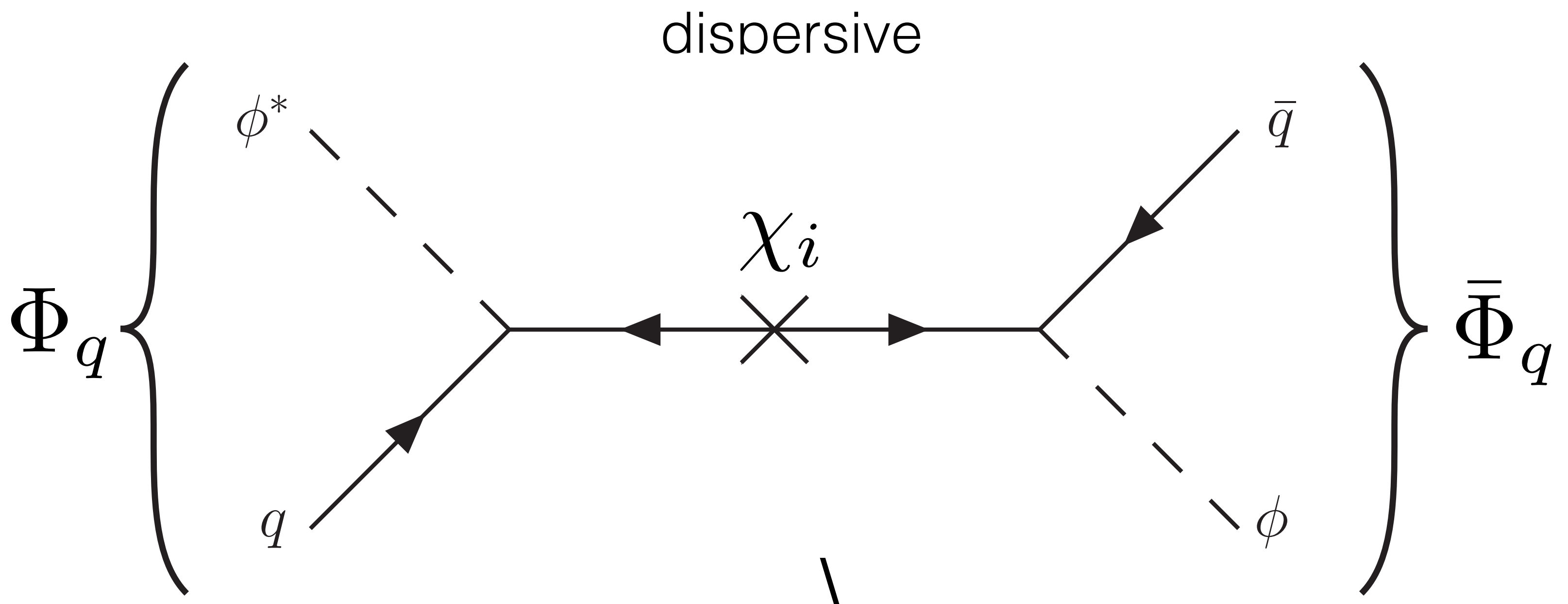
$$\mathbf{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$$

Mass eigenstates are an admixture of “flavor” eigenstates

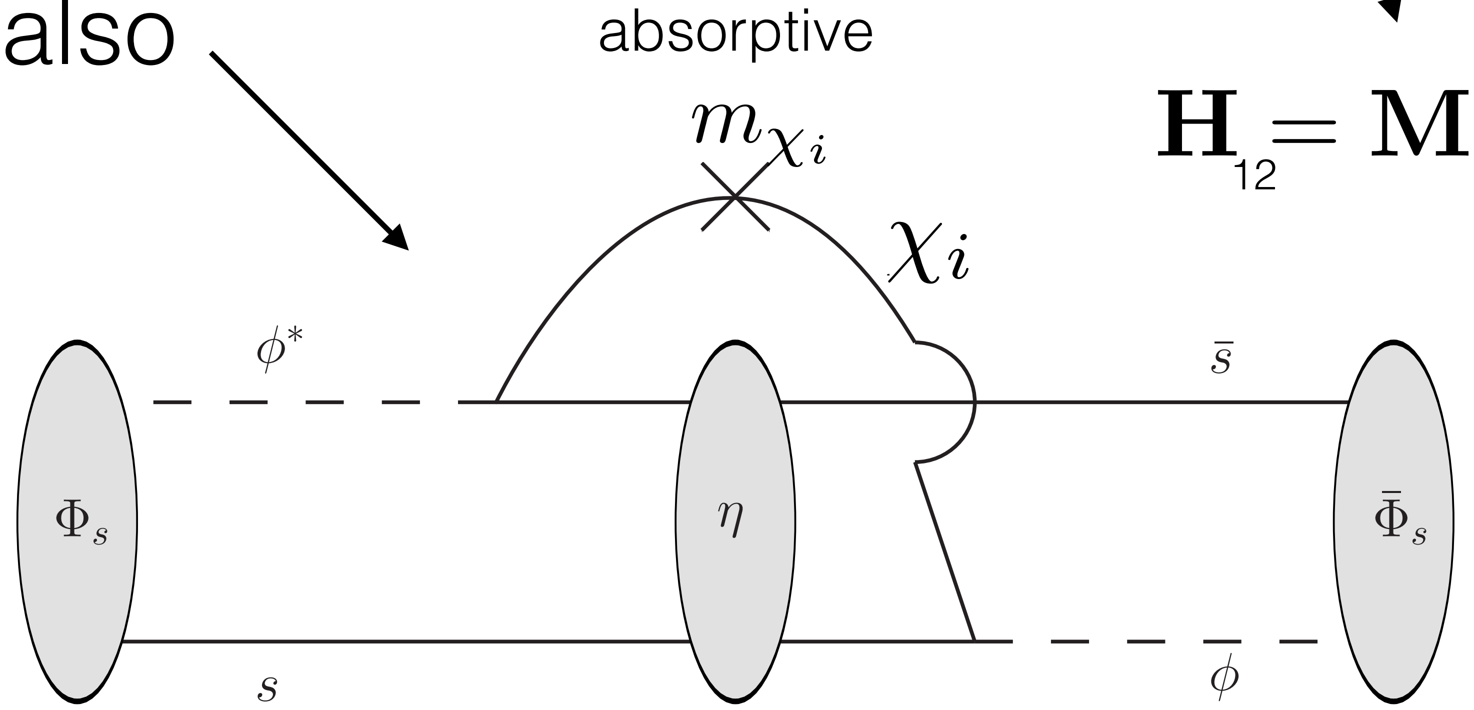
$$|\Phi_{L,H}\rangle = p|\Phi_q\rangle \pm q|\bar{\Phi}_q\rangle$$

What do Mesinos do?

In addition to this →



There is also

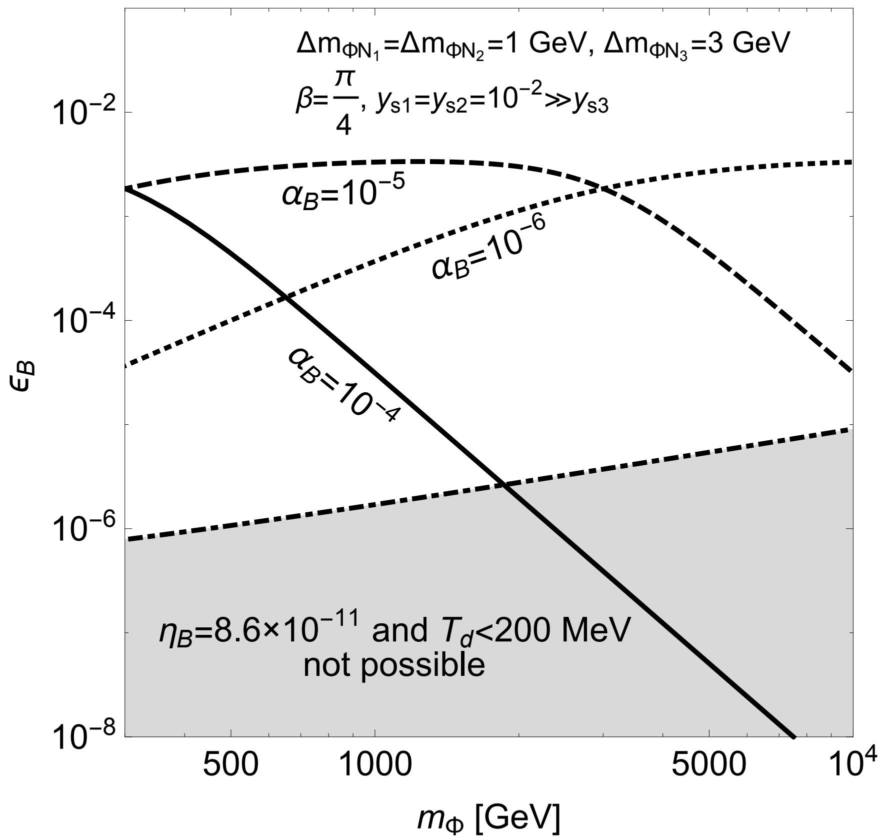


$$\mathbf{H}_{12} = \mathbf{M}_{12} - \frac{i}{2}\mathbf{\Gamma}_{12}$$

(Note: taking
strange quarks
for definiteness)

Baryon asymmetry per mesino-antimesino pair

$$\epsilon_B \equiv \frac{\Gamma(\Phi\bar{\Phi} \to BB) - \Gamma(\Phi\bar{\Phi} \to \bar{B}\bar{B})}{\Gamma_\Phi + \Gamma_{\bar{\Phi}}}$$



Want $m_{\Phi_s} - m_{\chi_1} \sim \mathrm{GeV}$

Using $|\mathbf{\Gamma}_{12}| \sim \Gamma_{\Phi_s \to \chi_1}$, can find

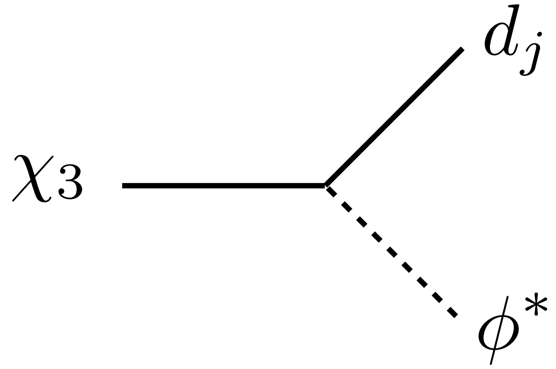
$$\epsilon_B = \frac{2\mathrm{Im}\mathbf{M}_{12}^*\mathbf{\Gamma}_{12}}{\Gamma^2 + 4\left|\mathbf{M}_{12}\right|^2}\mathrm{Br}_{\Phi_q \to B}$$

$$\sim \min\left(\frac{2\left|\mathbf{M}_{12}\right|}{\Gamma}, \frac{\Gamma}{2\left|\mathbf{M}_{12}\right|}\right) \sin\beta \mathrm{Br}_{\Phi_q \to \chi_1}\mathrm{Br}_{\Phi_q \to B}$$

(Need 2 χ_i for phase diff.) Typically $\epsilon_B \sim 10^{-6} - 10^{-3}$

Out of equilibrium condition

Need a source of scalars/ mesinos out of thermal equilibrium (i.e. distinct from strong interactions)



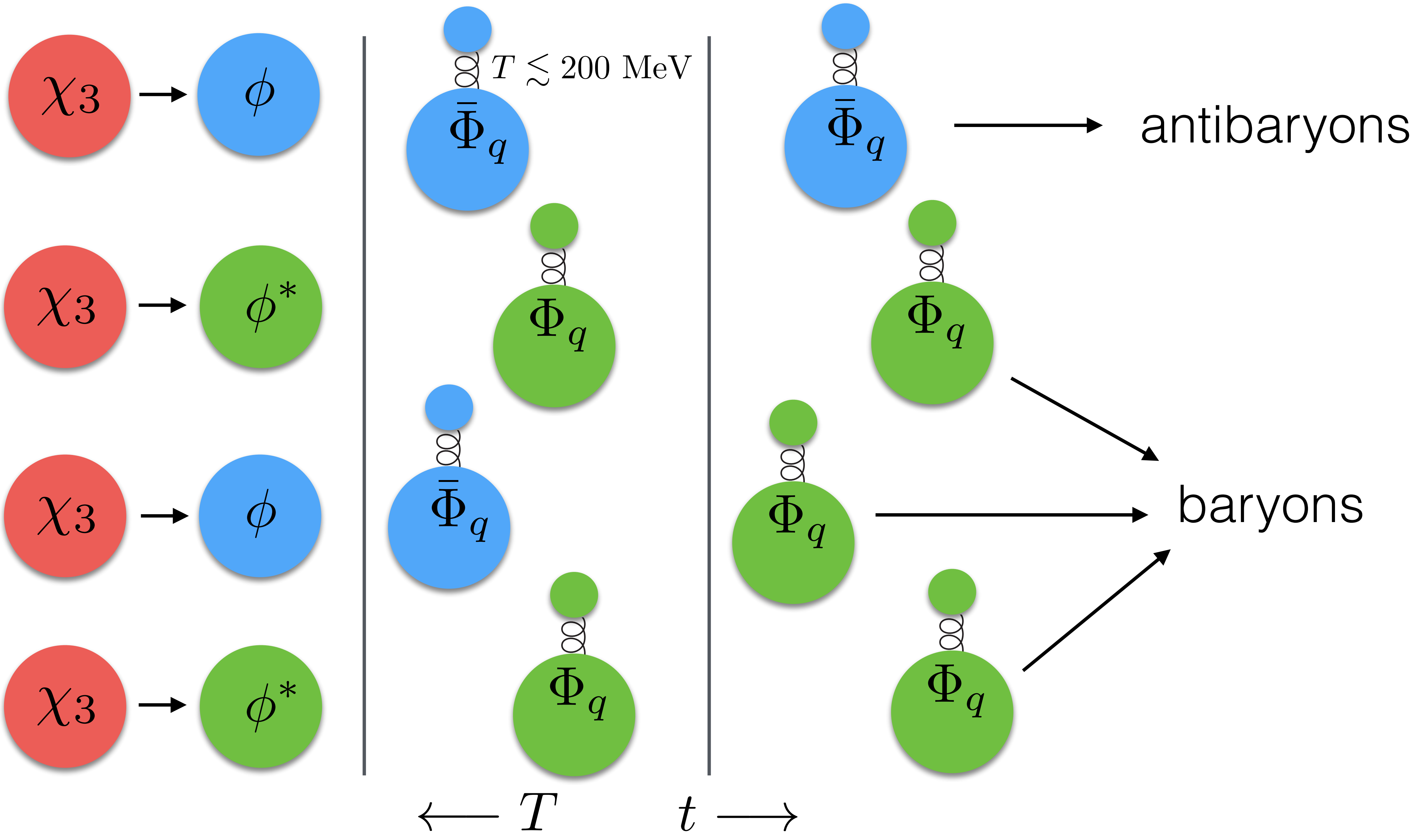
For definiteness, can use the decay of a singlet χ_3

$t_{\chi_3} \sim 10^{-5}\ \mathrm{s}$ means

$T \lesssim T_{\mathrm{QCD}} \sim 200\ \mathrm{MeV}$

so that mesinos form

Cosmic history of the asymmetry



antibaryons

baryons

Calculating the asymmetry

Boltzmann equations:

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

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

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

Simple sudden decay approx:

$$\eta_B = \frac{n_B\left(t=t^+_{\rm decay}\right)}{s_{\rm rad}\left(t=t^+_{\rm decay}\right)} = \frac{n_{N_3}\left(t=t^-_{\rm decay}\right)}{s_{\rm rad}\left(t=t^+_{\rm decay}\right)} \times \frac{1}{2}A\,\epsilon_B$$

$$\simeq 6.1\times 10^{-10}\left(\frac{116.25}{g_*\left(T_i\right)}\right)\left(\frac{10}{1+\xi}\right)^{3/4}\left(\frac{A}{1/3}\right)\left(\frac{\epsilon_B}{10^{-5}}\right).$$

$\xi \propto \left(m^2_{\chi_3}\,t_{N_3}\right)^{2/3}$ is an "entropy dilution" factor

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in the right ballpark

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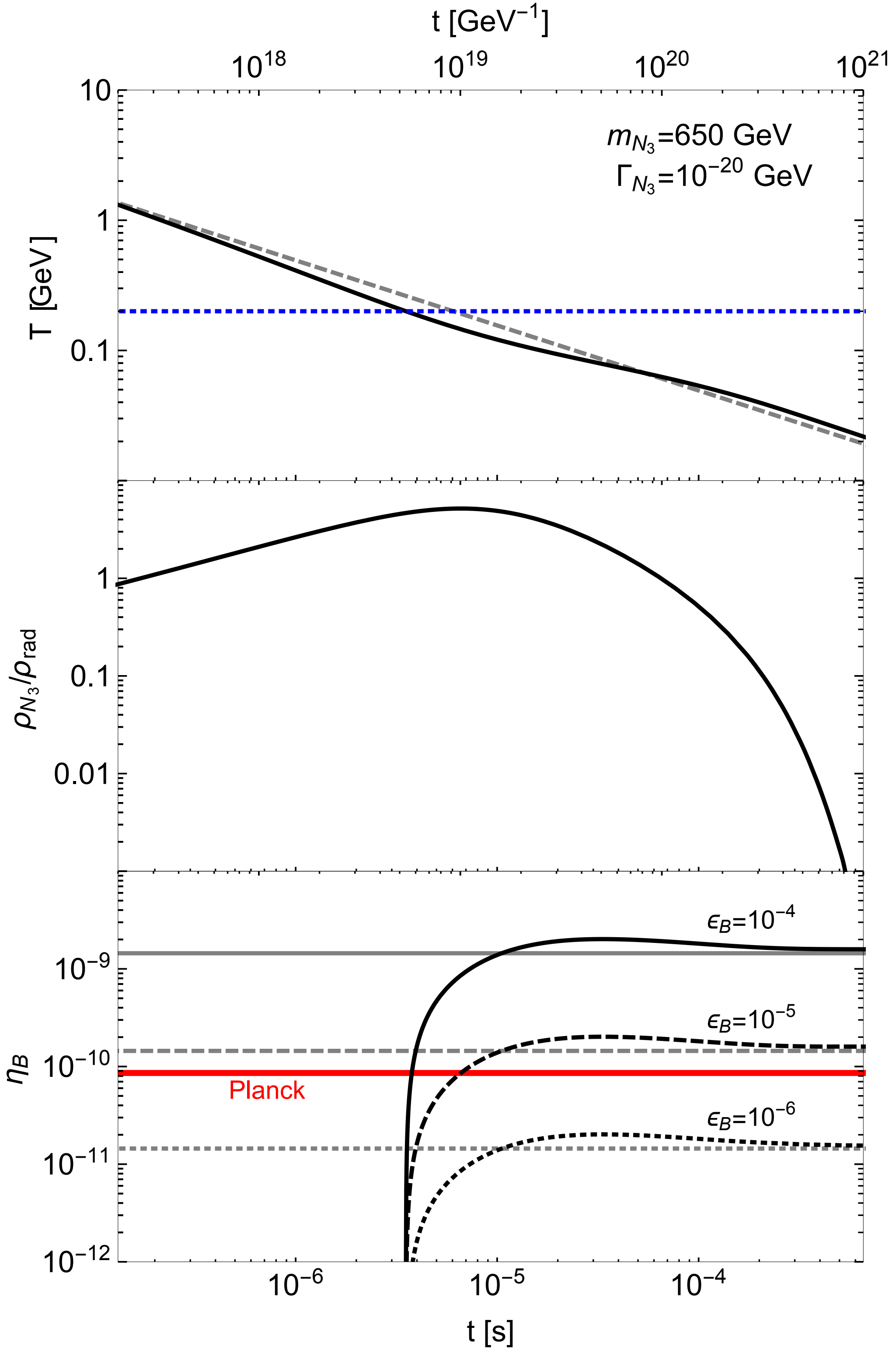

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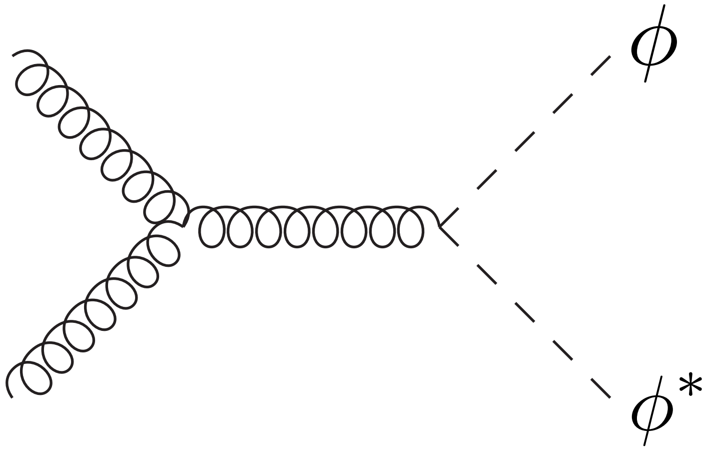
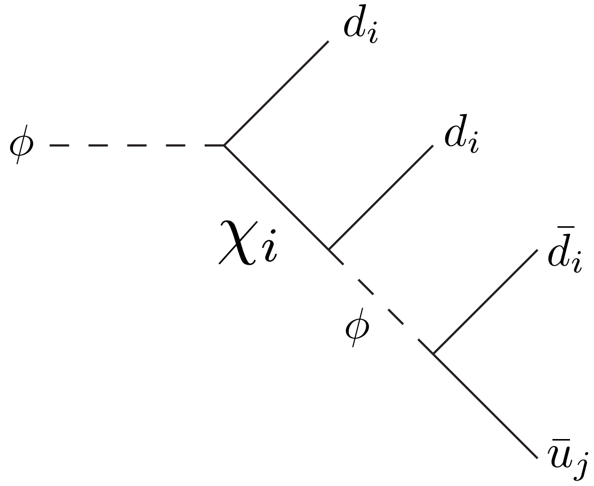
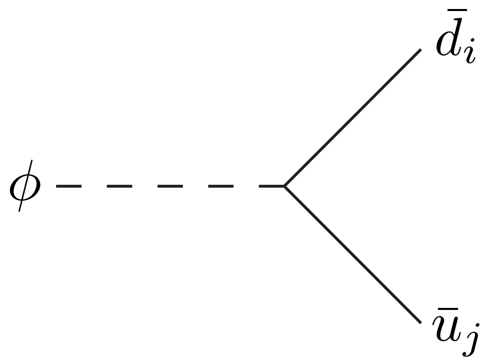
$$\frac{dn_B}{dt} = -3Hn_B + \frac{1}{2} A\,\Gamma_{N_3}\epsilon_B n_{\chi_3}$$

Simple sudden decay approx. works well

Constraints on this model

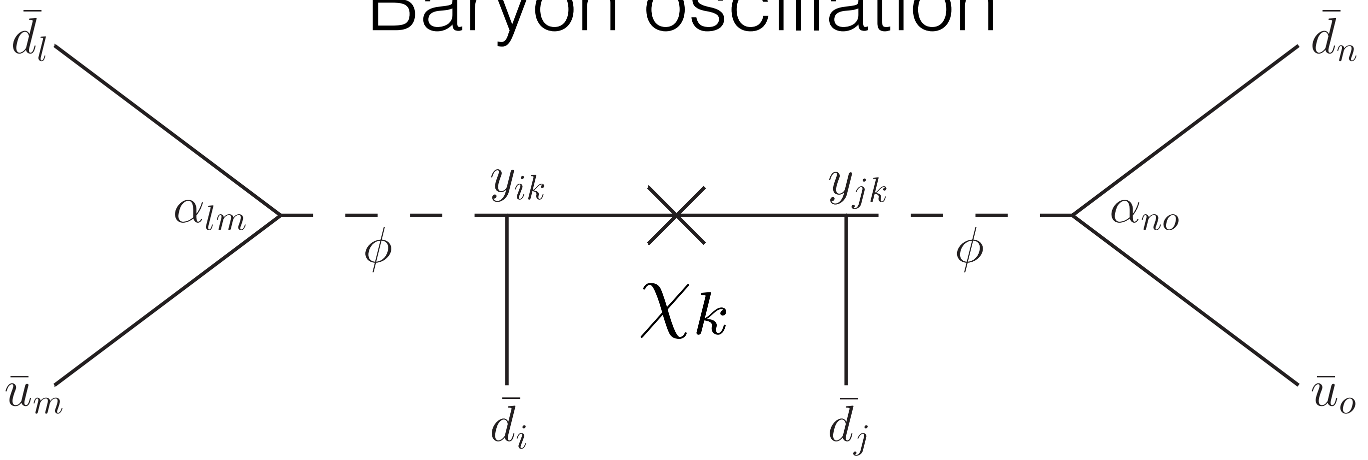






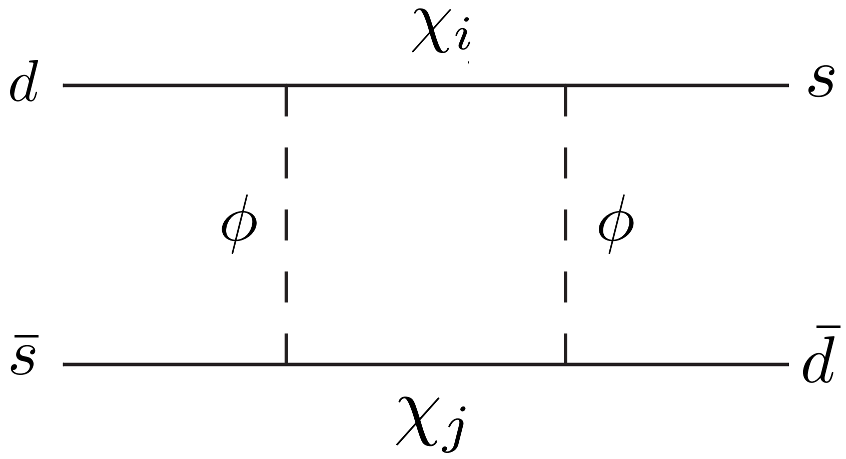
Searches for multijet final states at LHC $\Rightarrow m_\phi \gtrsim 600 - 800\ \mathrm{GeV}$

Baryon oscillation



$\Delta B = 2 \qquad \Lambda \gtrsim 100\ \mathrm{TeV}$

Meson oscillation



$$\left(\mathrm{Im}\sum_{i,j} y^*_{di} y_{dj} y_{si} y^*_{sj}\right)^{1/4} < 0.11\sqrt{\frac{m_\phi}{650\ \mathrm{GeV}}}.$$

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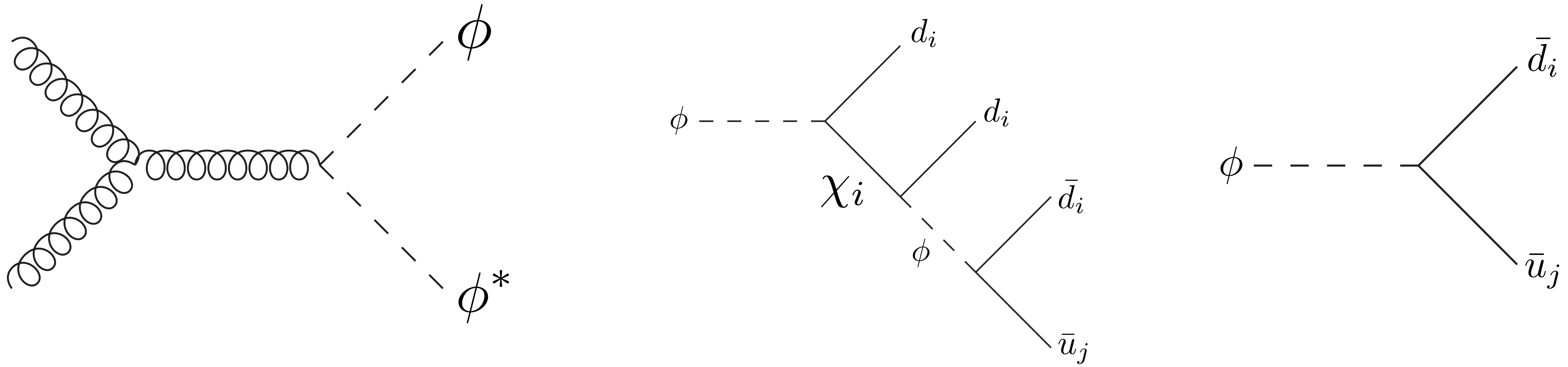

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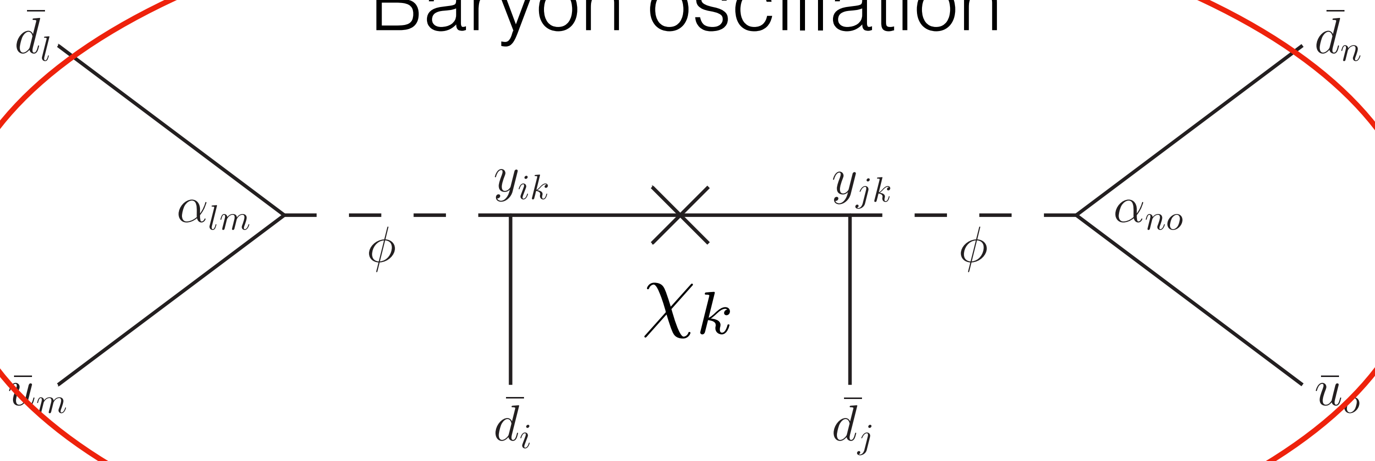

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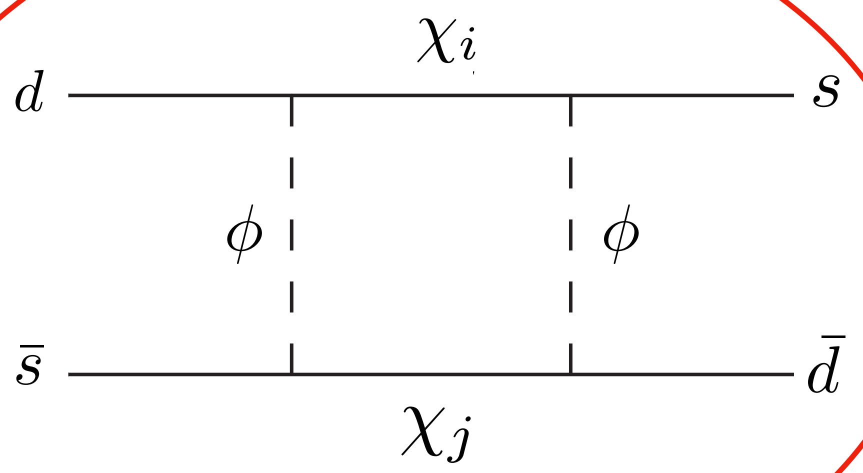
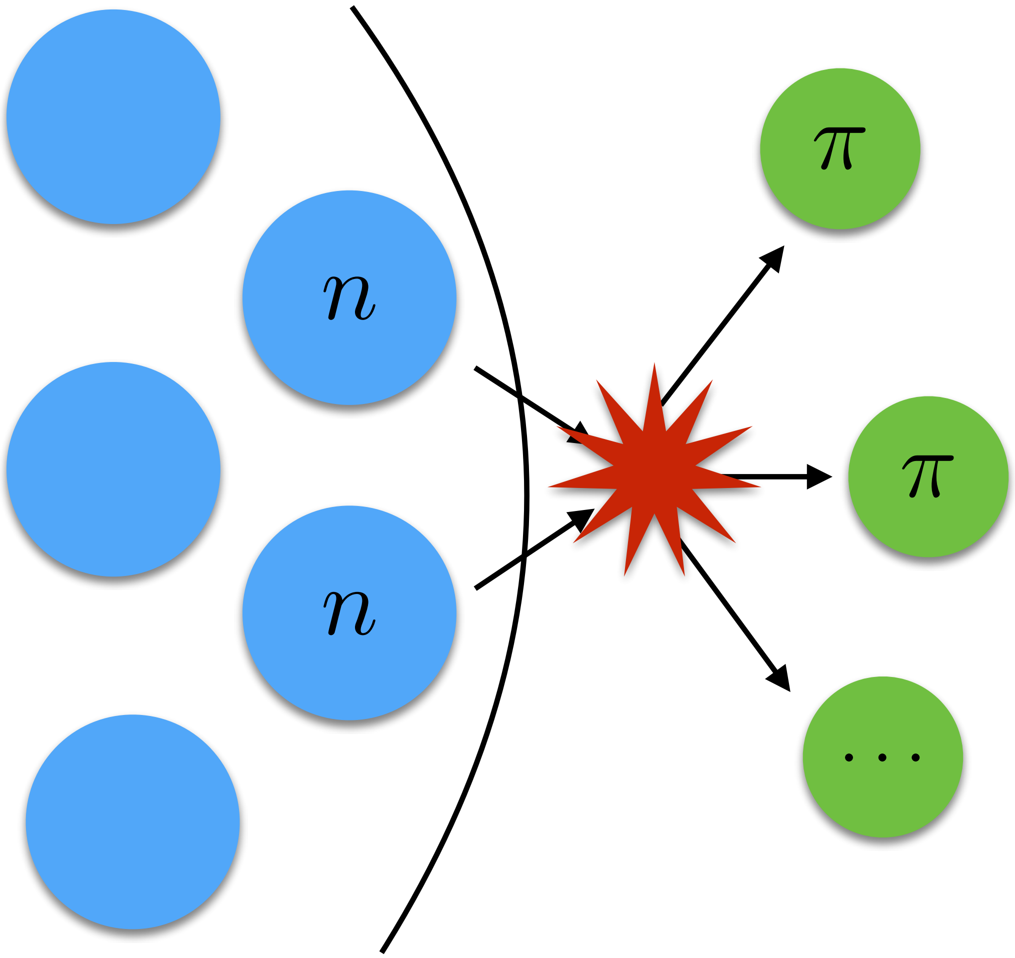


$$\left(\text{Im}\sum_{i,j} y^*_{di} y_{dj} y_{si} y^*_{sj}\right)^{1/4} < 0.11\sqrt{\frac{m_\phi}{650 \text{ GeV}}}.$$

What about these? Can we use them instead of mesinos?

Baryon (neutron) oscillations

Present best limit on $\Delta B = 2$ processes comes from Super-K limit on lifetime of ${}^{16}\mathrm{O}$



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

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]

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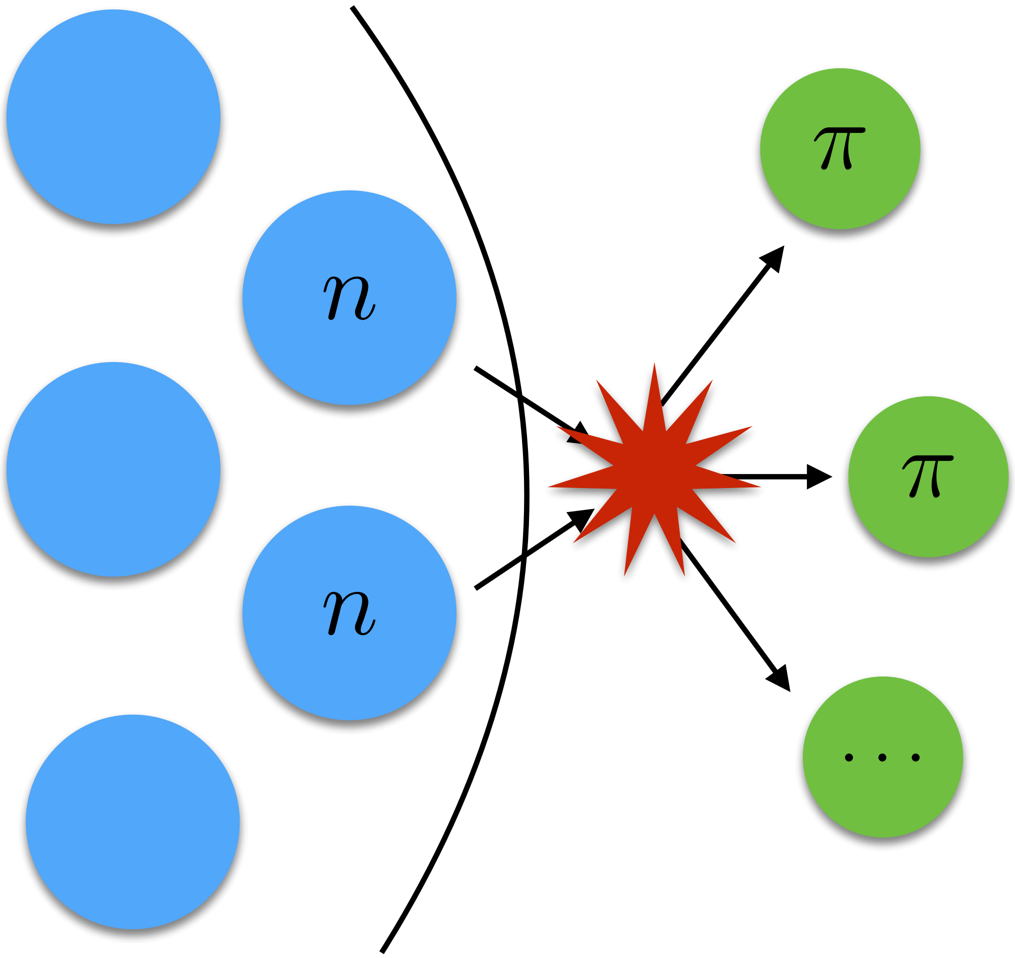

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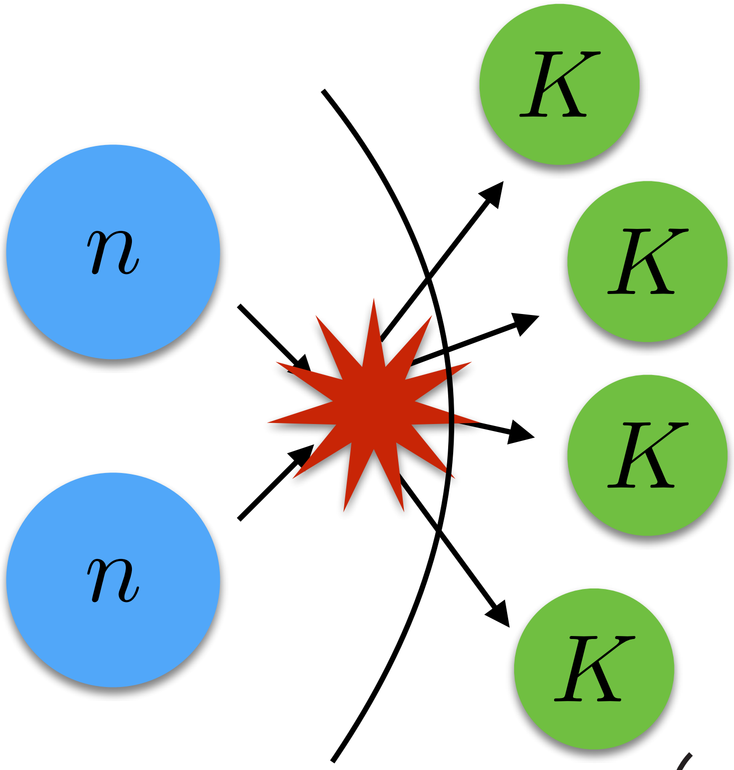
⇒hard to implement asymmetry with neutron oscillations

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

(Heavy flavor) Baryon oscillations

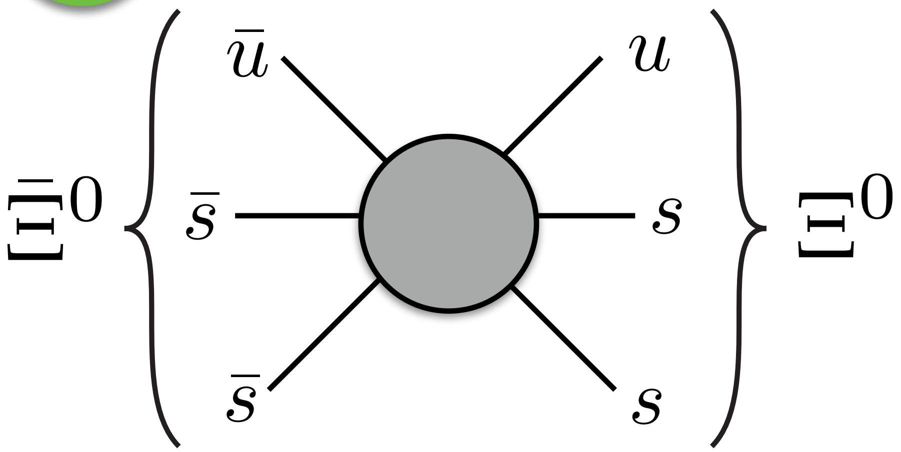
What if $\Delta B = 2$ operators had e.g. $\Delta S = 4$? $\mathcal{L}_{\text{eff}} \supset \dfrac{(uss)^2}{\Lambda^5}$



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 ('94)

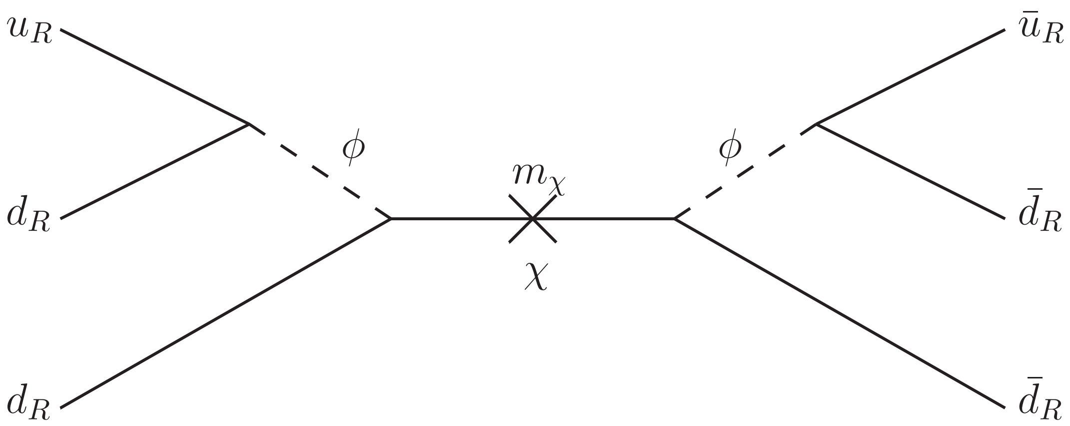
Aitken, DM, Neder, & Nelson, PRD **96** 075009 [1708.01259]

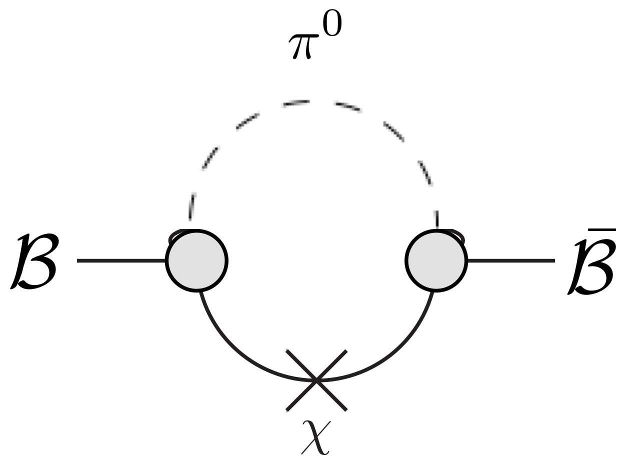
Low Scale Baryogenesis: Model II

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

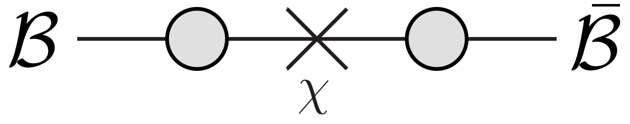
Same model but different regime: $m_{\chi_{1,2}} \ll m_\phi$

Relevant operator for oscillations:





Γ_{12}



M_{12}

$$|M_{12}|_i \sim \frac{\kappa^2}{2\Delta m_{\mathcal{B}i}}\left|\frac{g^*_{ud}y_{id'}}{m^2_\phi}\right|^2$$

$$\simeq 8\times 10^{-16}\ \text{GeV}\left(\frac{500\ \text{MeV}}{\Delta m_{\mathcal{B}i}}\right)\left(\frac{600\ \text{GeV}}{m_\phi/\sqrt{|g^*_{ud}y_{id'}|}}\right)^4$$

$$\left|\frac{\Gamma_{12}}{M_{12}}\right|_1 \sim 4\pi\left(\frac{\Delta m_{\mathcal{B}1}}{m_{\mathcal{B}}}\right)^2$$

$$\simeq 0.1\left(\frac{\Delta m_{\mathcal{B}1}}{500\ \text{MeV}}\right)^2\left(\frac{5\ \text{GeV}}{m_{\mathcal{B}}}\right)^2$$

$$M_{12}, \Gamma_{12} \gg 10^{-33}\ \text{GeV}$$

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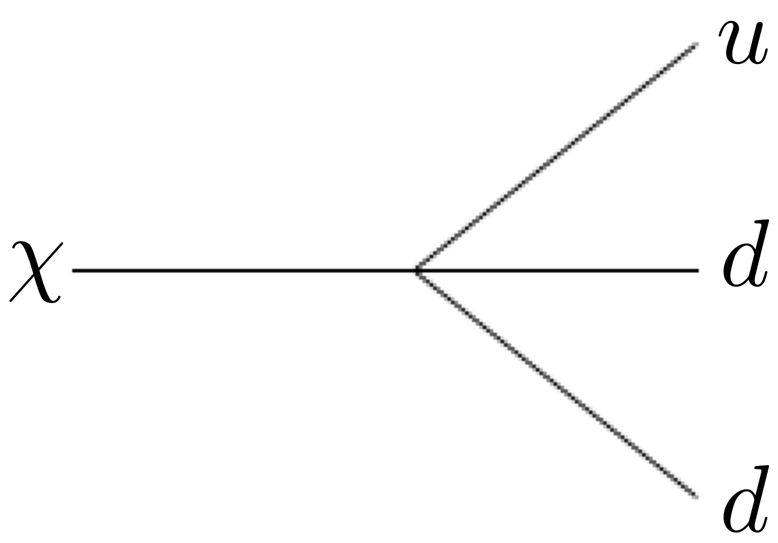


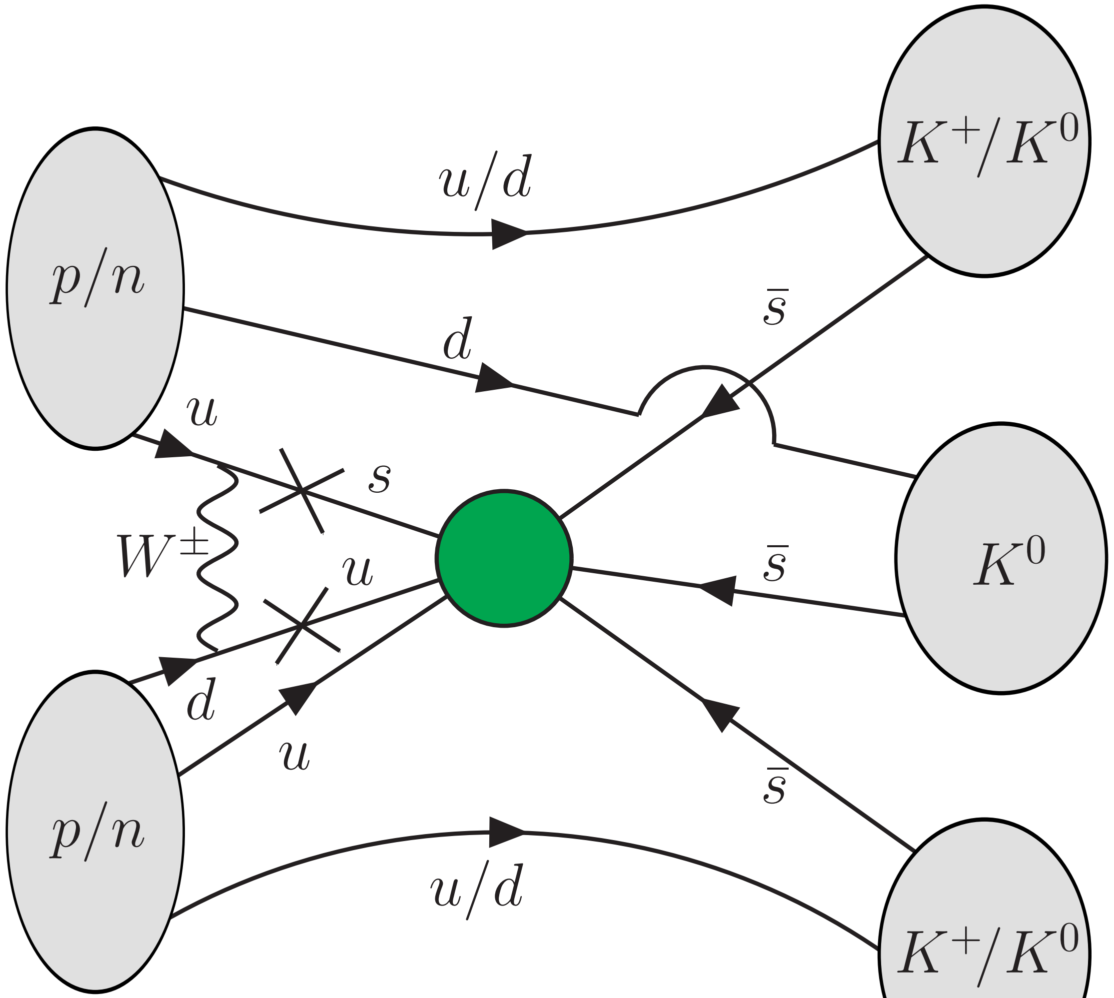
New fermions (again, need at least 2) long-lived

$$\Gamma_\chi \propto \frac{m_\chi^5}{m_\phi^4}$$

Collider constraints (on colored scalars) similar

(Indirect) dinucleon decay

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

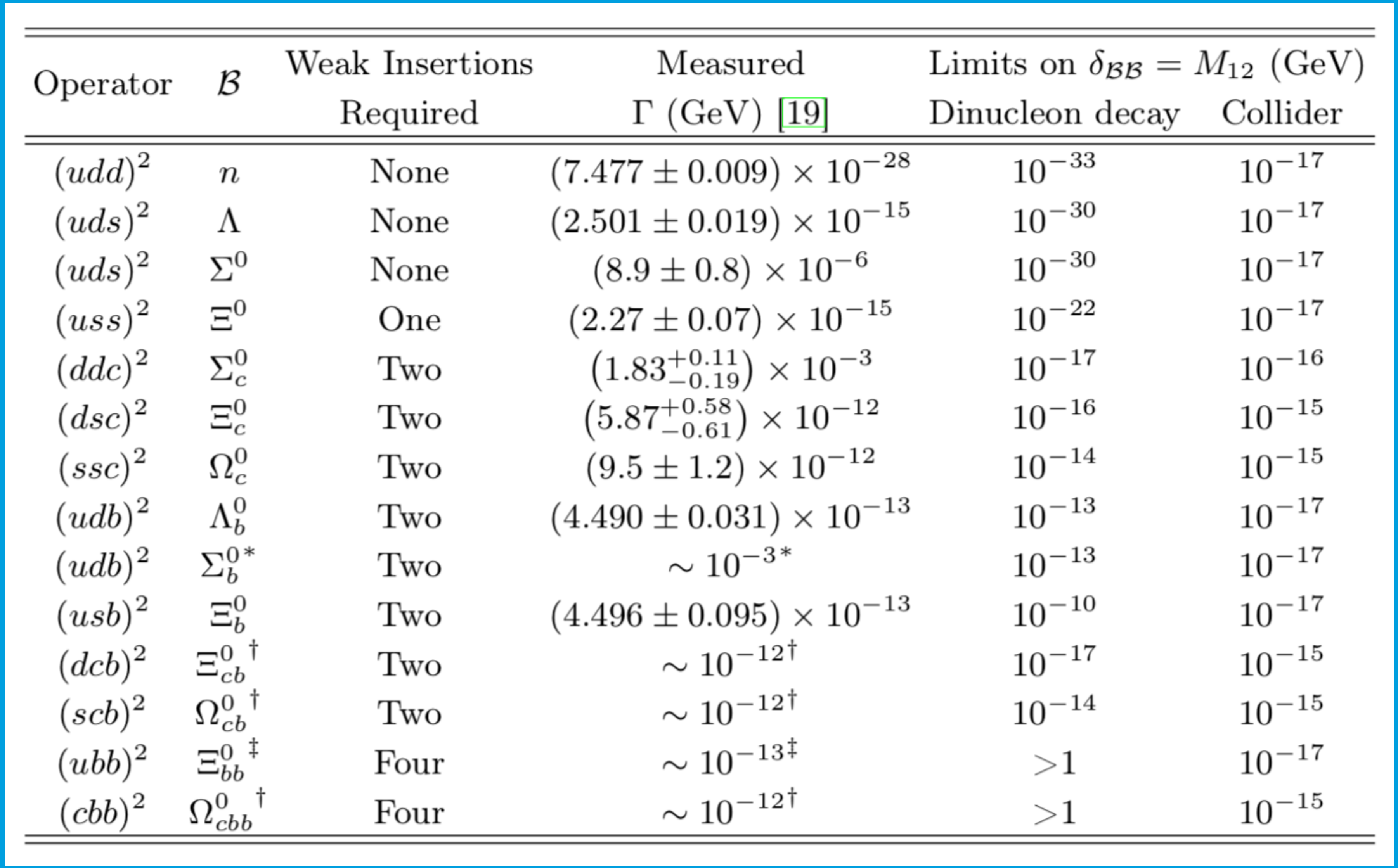


Naive estimate of suppression (proper treatment involves matching onto chiral perturbation theory)

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

(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	Limits on $\delta_{\mathcal{B}\mathcal{B}} = M_{12}$ (GeV) 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) $4\pi^2\sqrt{2}$ $\left(\Lambda_{\text{IR}}\right)$

Calculating the asymmetry

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

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

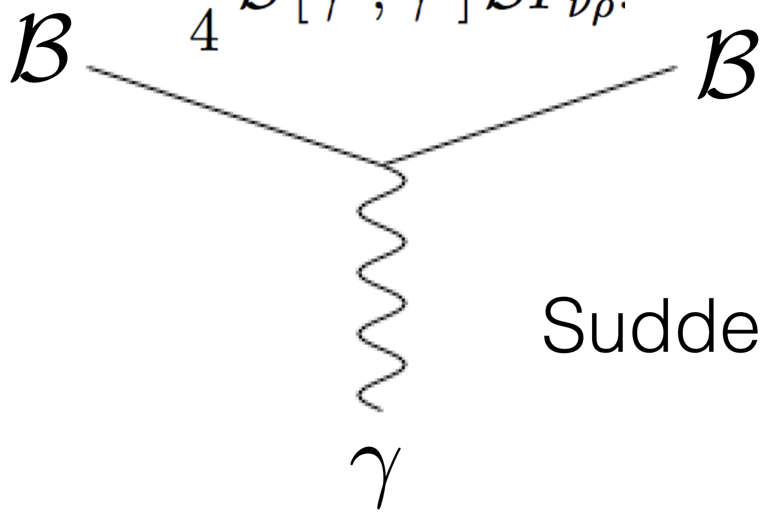
More complicated because of decoherence due to scattering on plasma

Heavy B system density matrix:

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

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

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

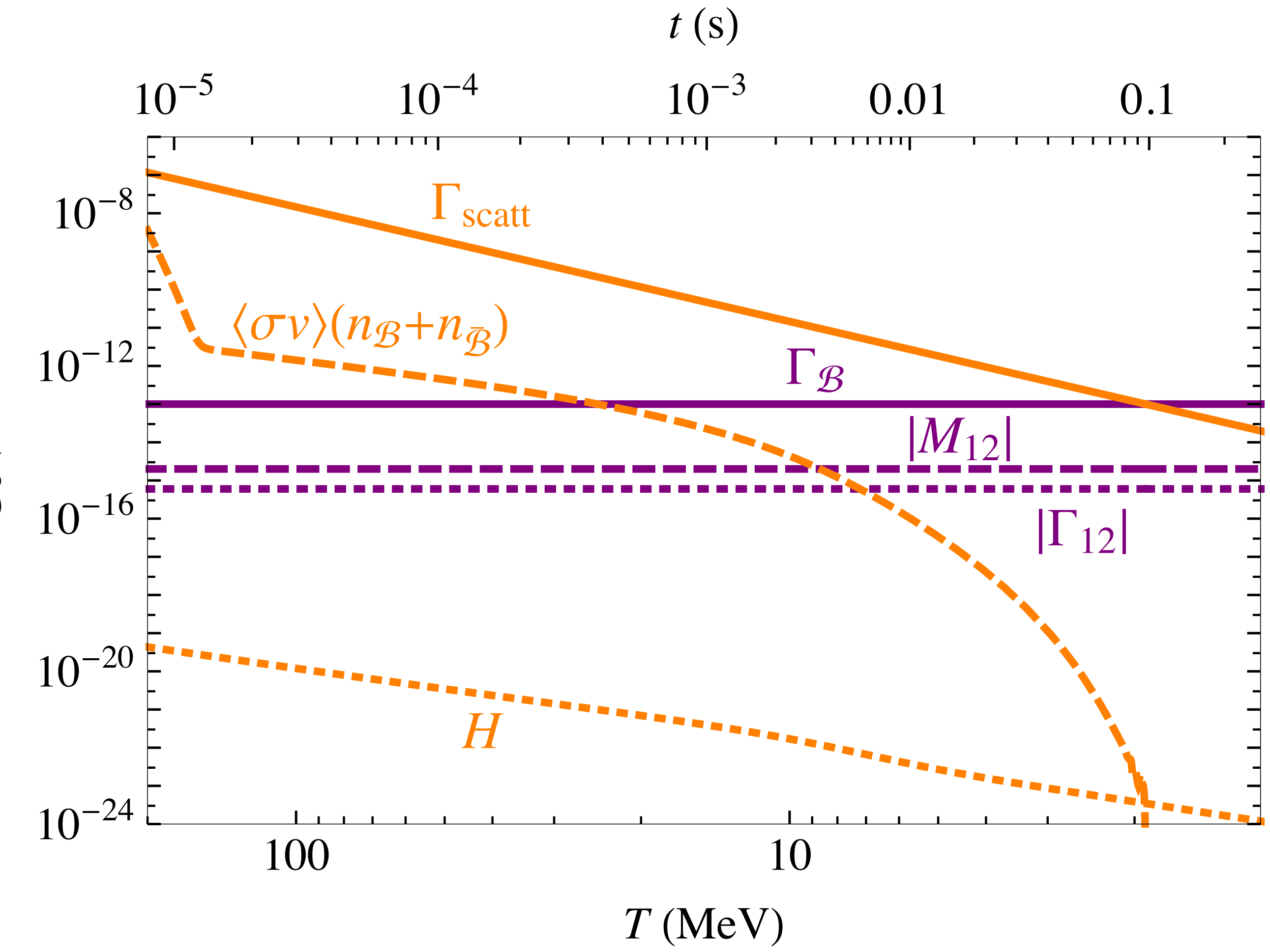


Sudden decay approx:

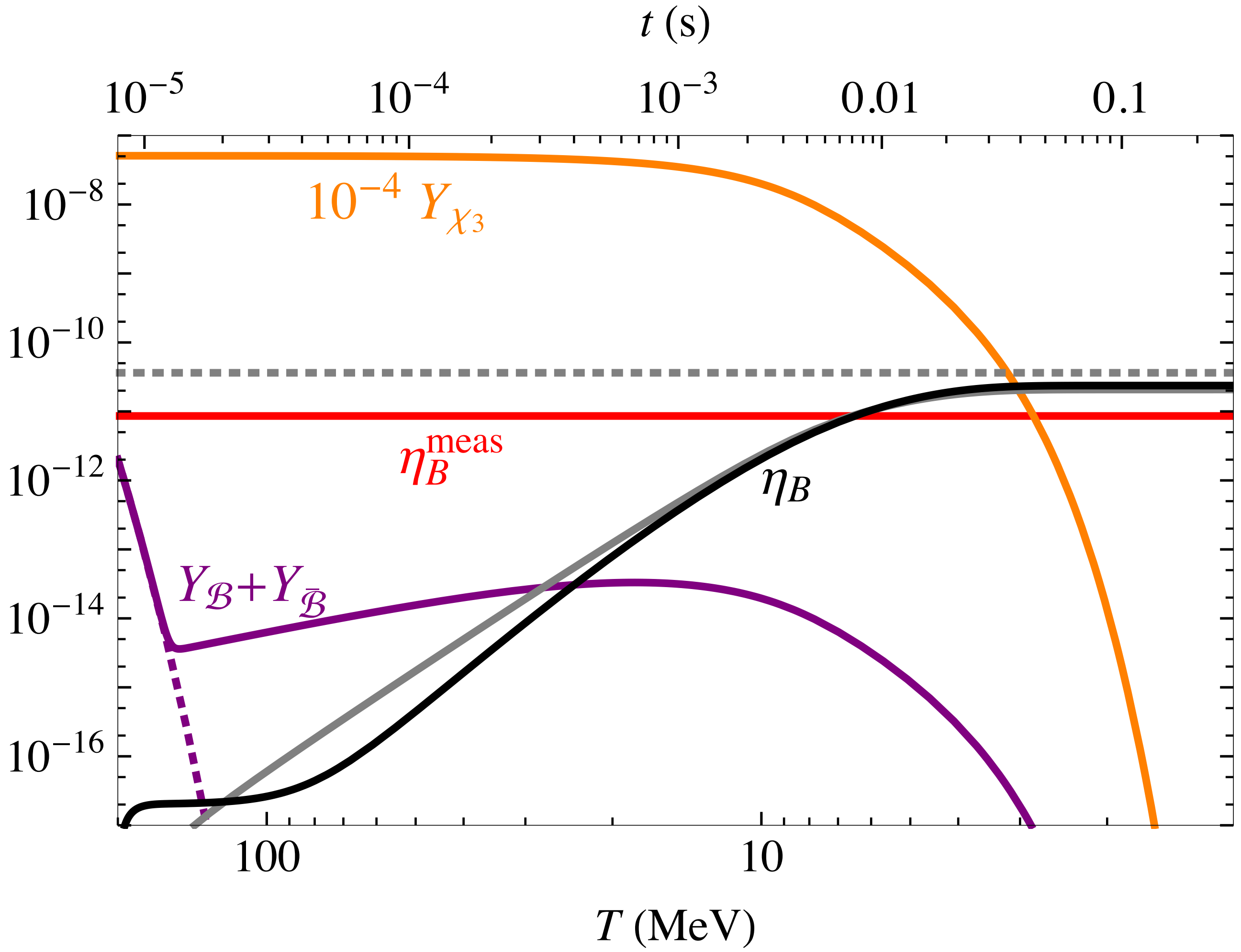
$$\eta_B \simeq \frac{\pi^3}{3\zeta(3)}\sqrt{\frac{\pi g_*(T_{\rm dec})}{10}}\frac{\Gamma_{\mathcal{B}}\epsilon}{\sigma m_{\chi_3}\Gamma_{\chi_3}M_{\rm Pl}}$$
$$= 9\times 10^{-11}\left[\frac{g_*(T_{\rm dec})}{50}\right]^{1/2}\left(\frac{m_{\mathcal{B}}}{5~{\rm GeV}}\right)^2\left(\frac{\Gamma_{\mathcal{B}}}{10^{-13}~{\rm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

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

Calculating the asymmetry



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



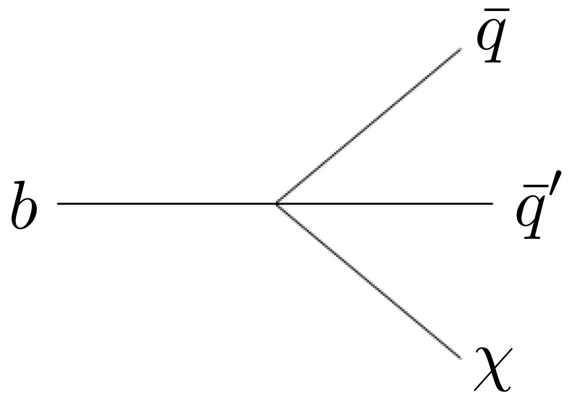
Results for $\Omega_{cb} - \bar{\Omega}_{cb}$ system

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

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

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

Low Scale Baryogenesis: Model II, Probes



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

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

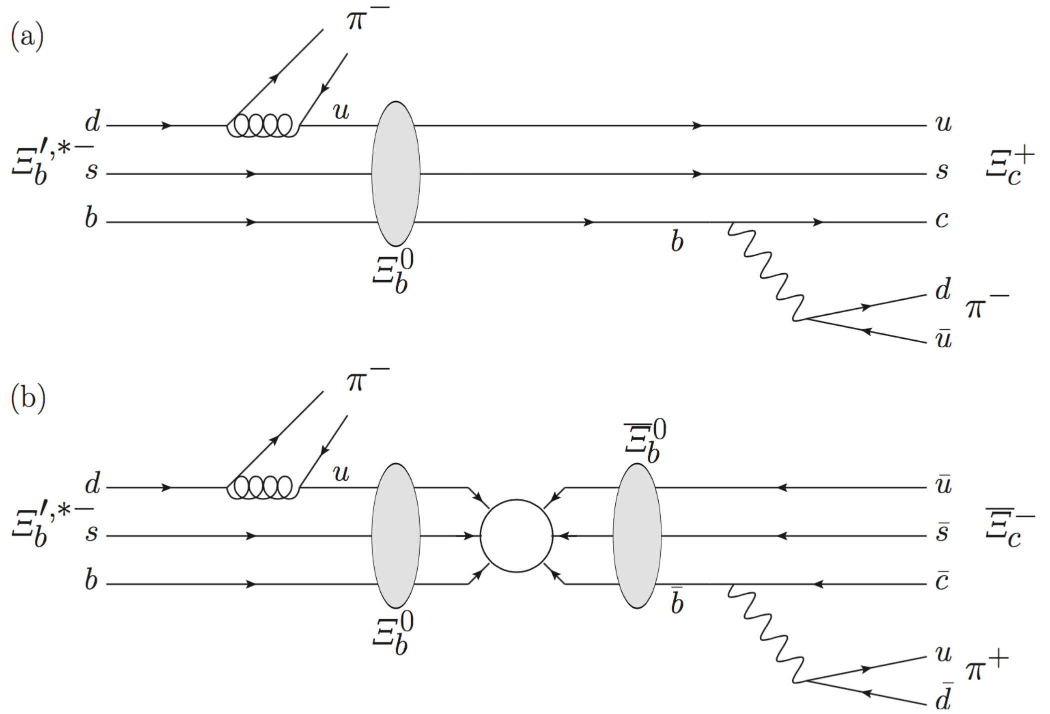
$$\text{meson} \to \text{baryon} + \chi_i\ [+\,\text{meson(s)}]$$
$$\text{baryon} \to \text{meson(s)} + \chi_i$$

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…

Elor, Escudero, & Nelson arXiv:1810.00880

Low Scale Baryogenesis: Model III

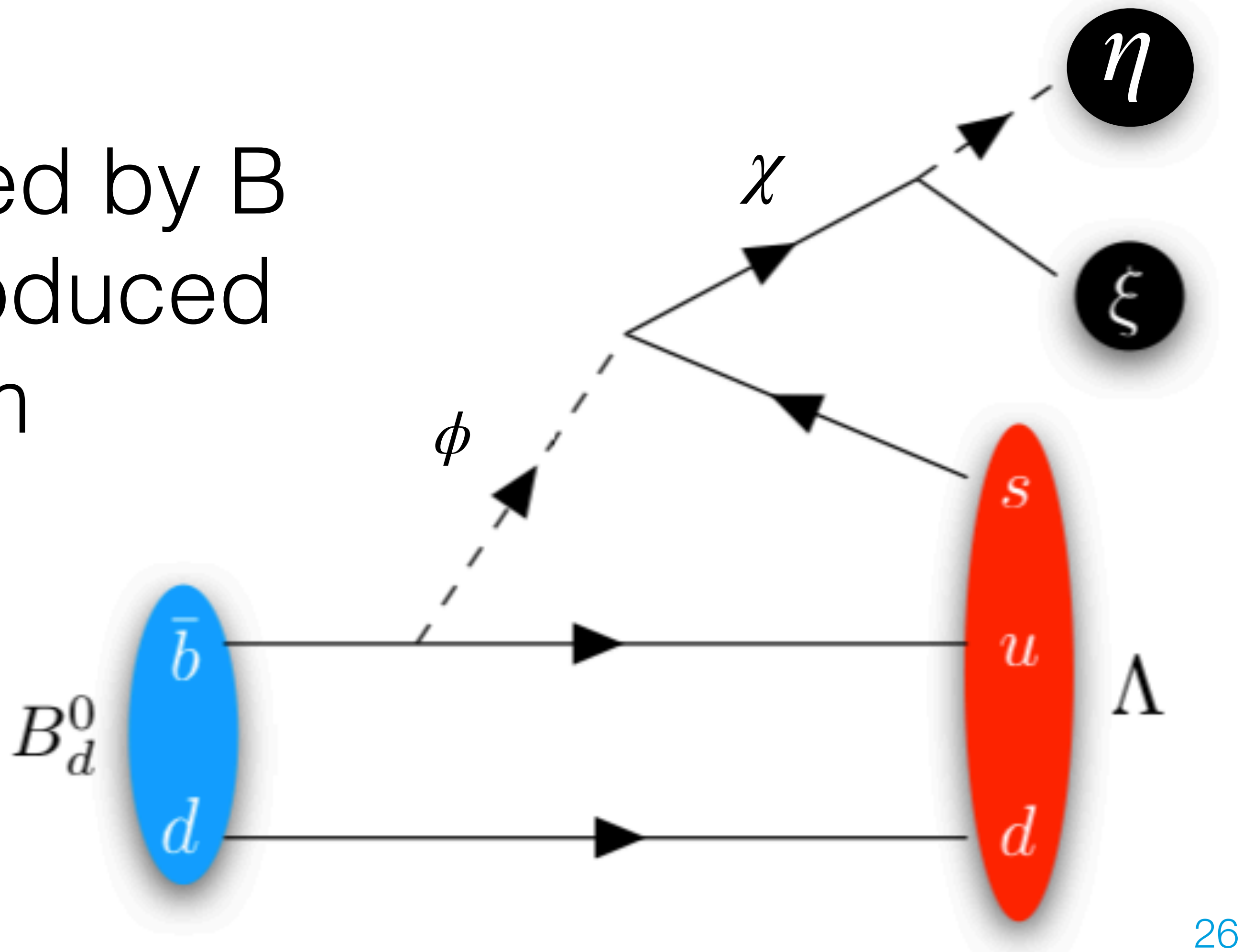
$$\mathcal{L}_{\rm int} \supset -g_{ud}^{*}\phi^{*}\bar{u}_R d_R^c - y_d \phi \bar{\chi}_L d_R^c - y' \eta \bar{\chi}_L \xi_R - m_\chi \bar{\chi}_L \chi_R + \text{h.c.}$$

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 ~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!)