Oscillations and Baryogenesis

David McKeen
University of Pittsburgh
University of Sydney Seminar, November 3, 2017

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Formerly: Heavy Baryon Baryogenesis

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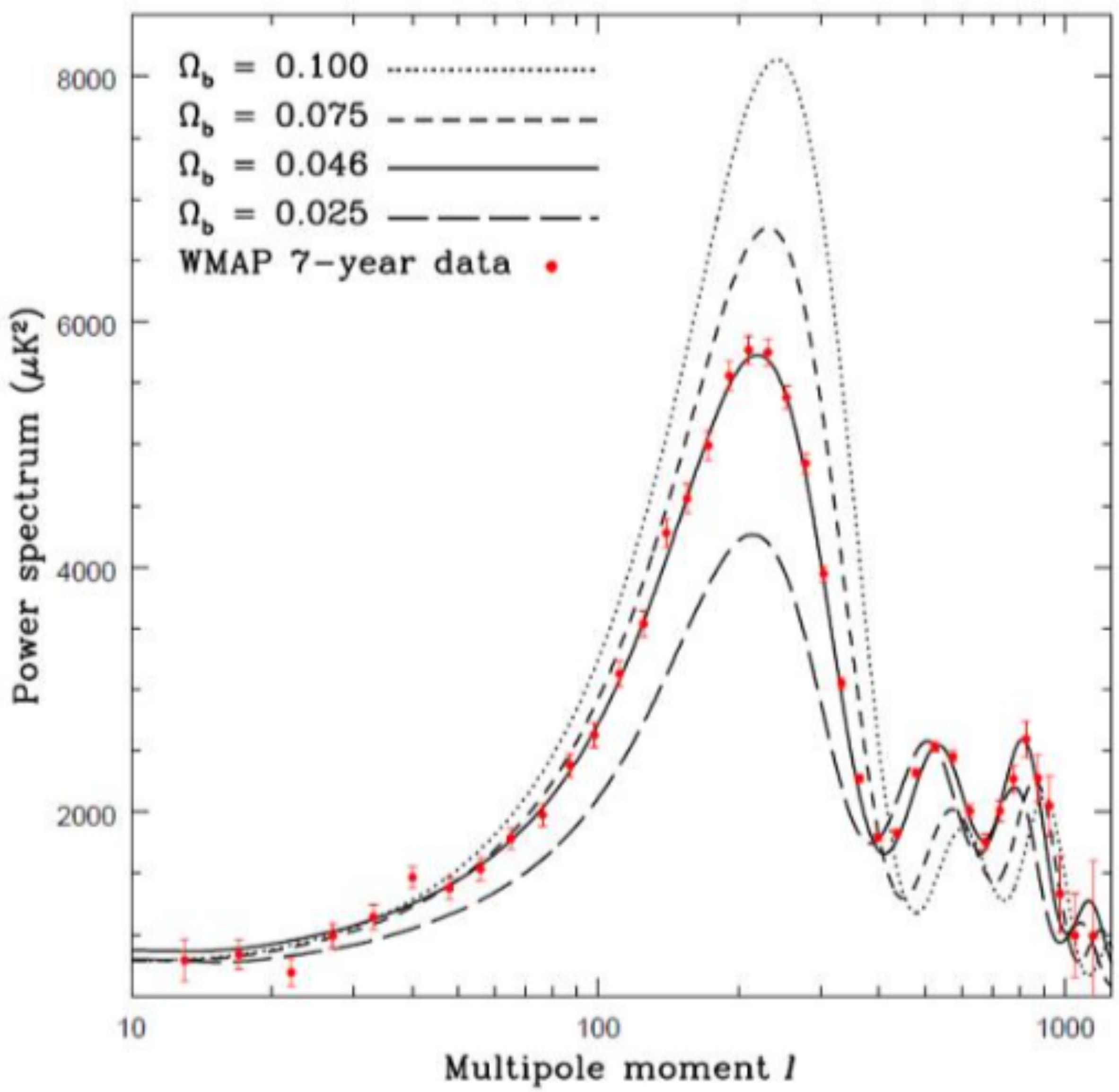
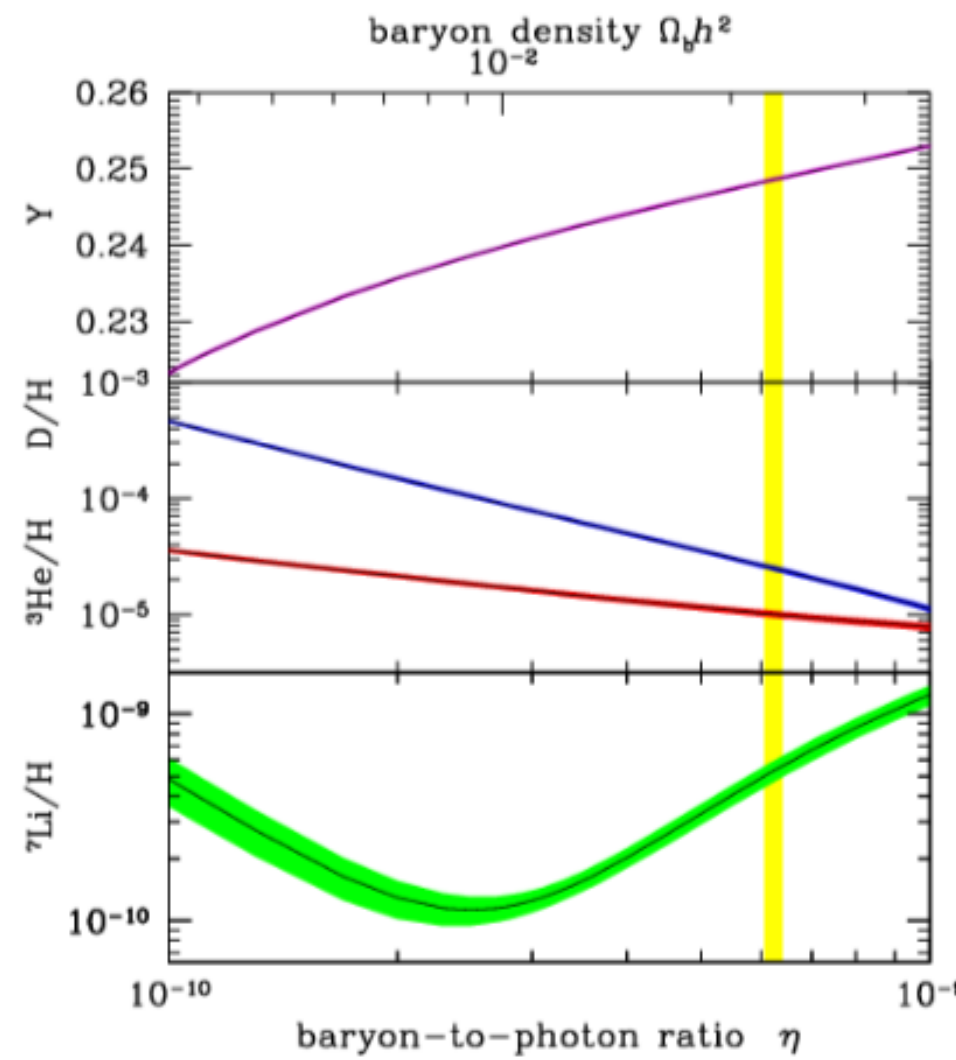
Outline

- Why Baryogenesis (matter-antimatter asymmetry)?
- Describe how oscillations of QCD bound state can explain asymmetry
- Discussion of neutron-antineutron oscillations
- Motivation for a tweak to the model
- Heavy baryon oscillations and the matter asymmetry
- Conclude

We're made of baryons





$$\Omega_B \sim 0.05$$

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

How to get baryons

Sakharov conditions:

B violation

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

q_L vs. $\bar{q}_R$

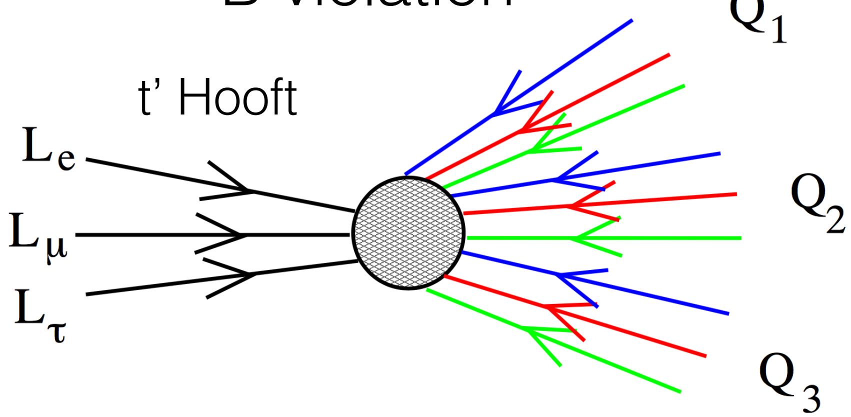
Depart from thermal eq.

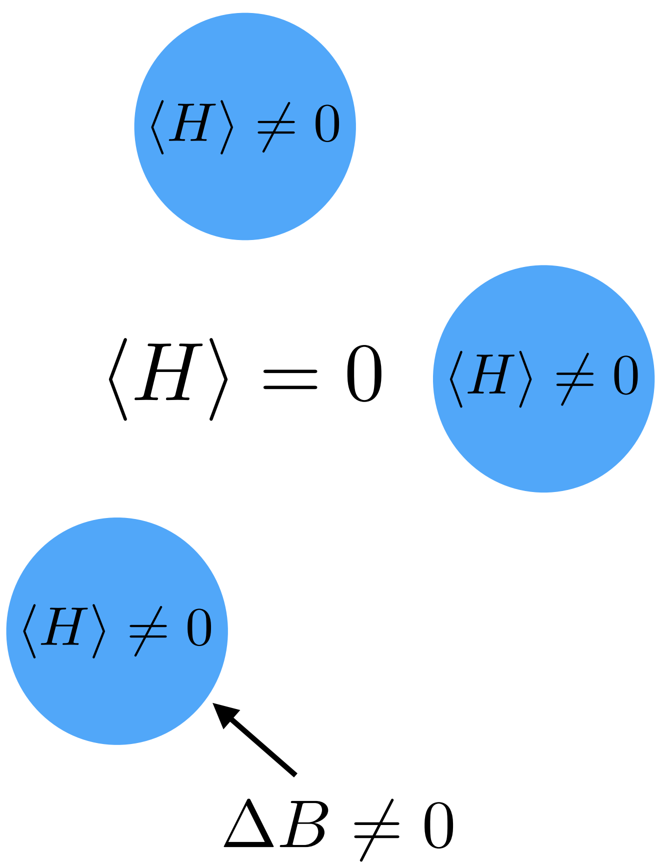
Inflation means it “must” happen dynamically

Most models of baryogenesis require a high reheat temperature which can be problematic

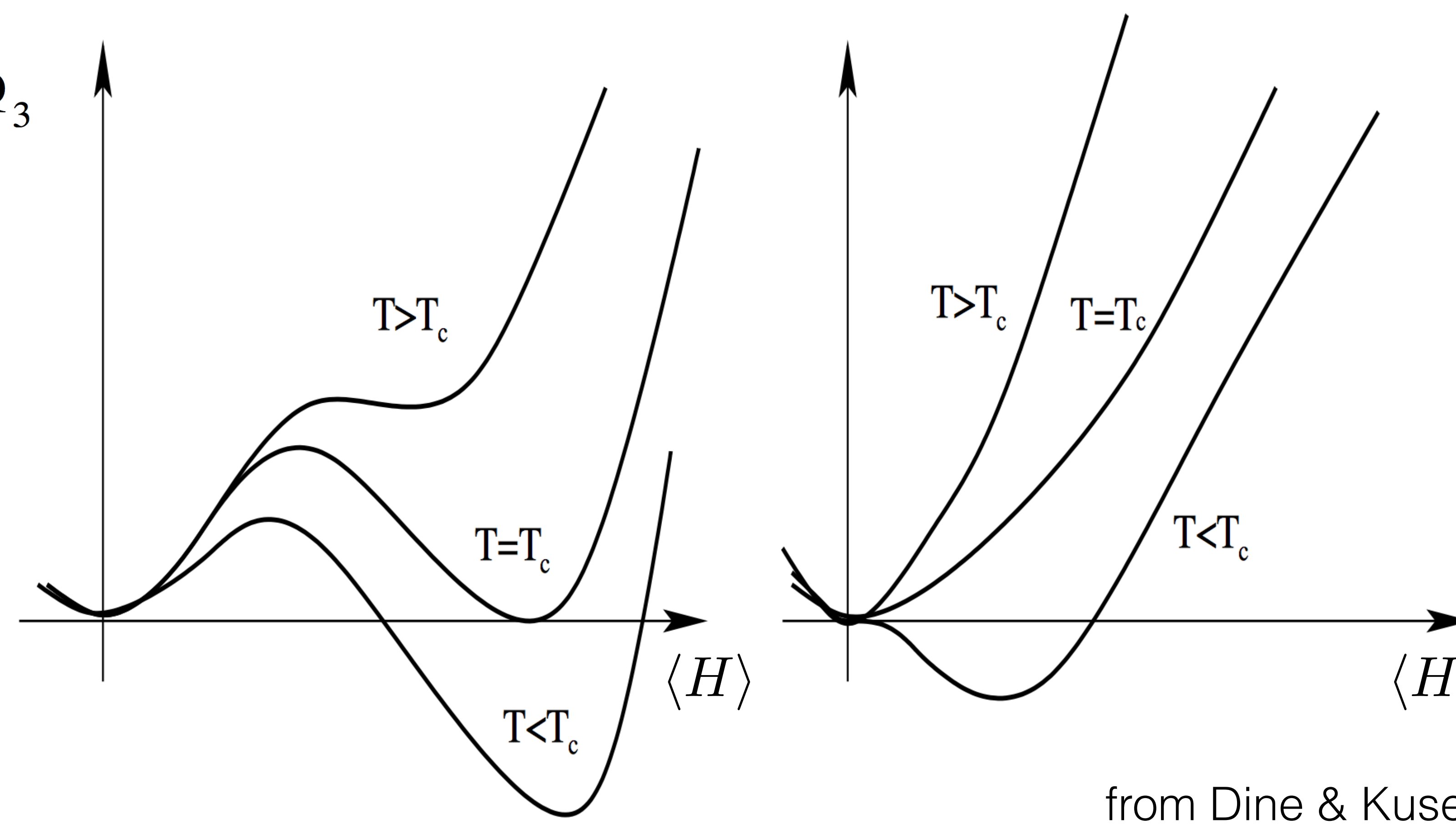
Baryon Number Violation & Thermal Equilibrium in SM

B violation





Cohen, Kaplan, Nelson



from Dine & Kusenko

requires $m_H \lesssim 80\ \mathrm{GeV}$

And, CPV small in SM: $\delta_{ms} \sim \left(\frac{g_W^2}{M_W^2}\right)^6 s_1^2 s_2 s_3 \sin\delta\, m_t^4 m_b^4 m_c^2 m_s^2 A \sim 10^{-21} A$

Shaposhnikov '86

Generating baryons requires BSM physics

Sakharov conditions:

B violation

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

Most models of baryogenesis require a high reheat temperature which can be problematic

Other possibilities

MSSM—light stops

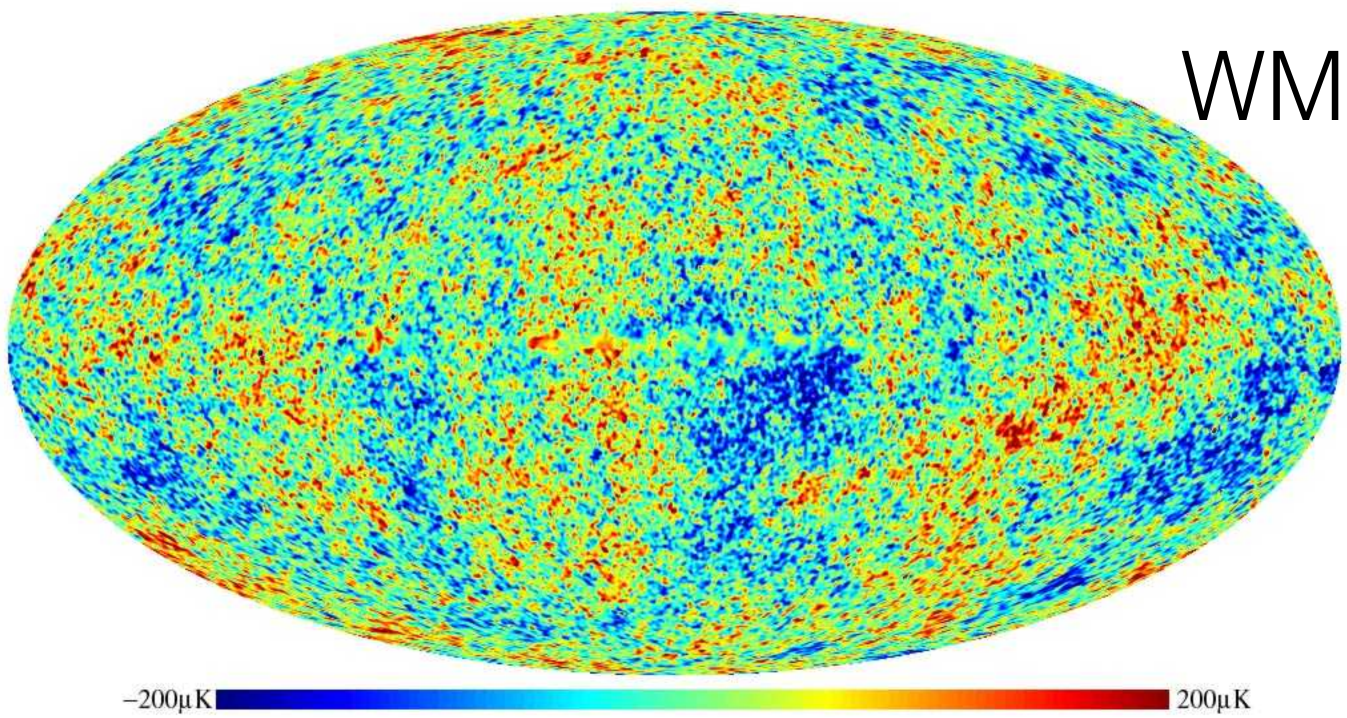
extended scalar sector, 2HDM,…

High scale: leptogenesis, GUT baryogenesis

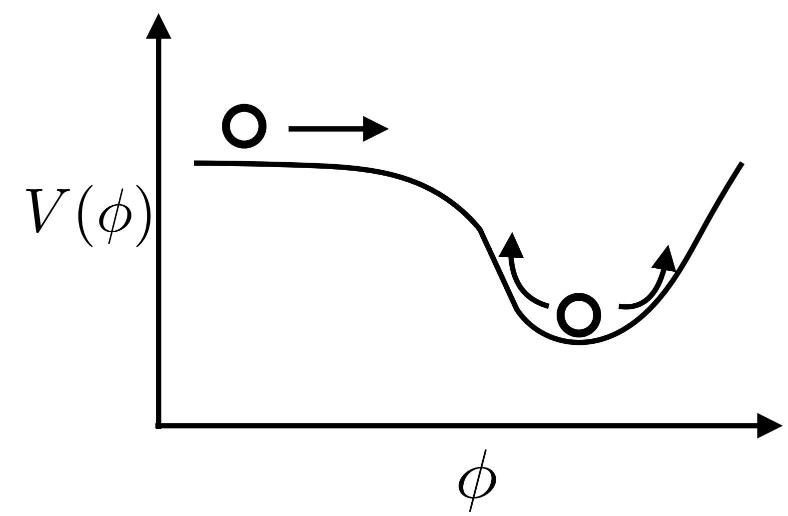
Affleck-Dine

Maybe asymmetry hidden in dark sector?

What is the reheat temp.?



WMAP



Guth, Linde, Steinhardt, …

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

Issues with high reheat T:

Gravitino production in SUSY extensions

Moroi et al. ('93)

Isocurvature perturbations

Fox et al. ('04)

Seek baryogenesis at low scales

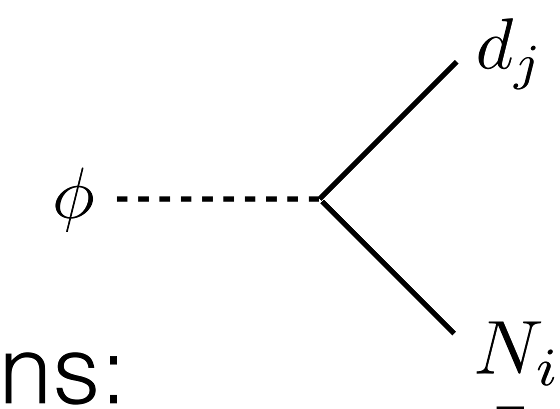
(Ghalsasi, DM, & Nelson 1508.05392)

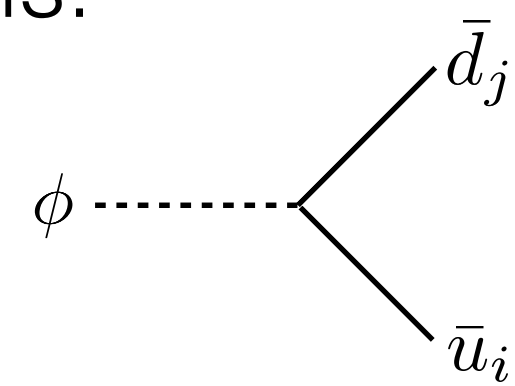
Model for low scale baryogenesis

A (colored) scalar ϕ

Neutral Majorana fermions N_i

Interactions:



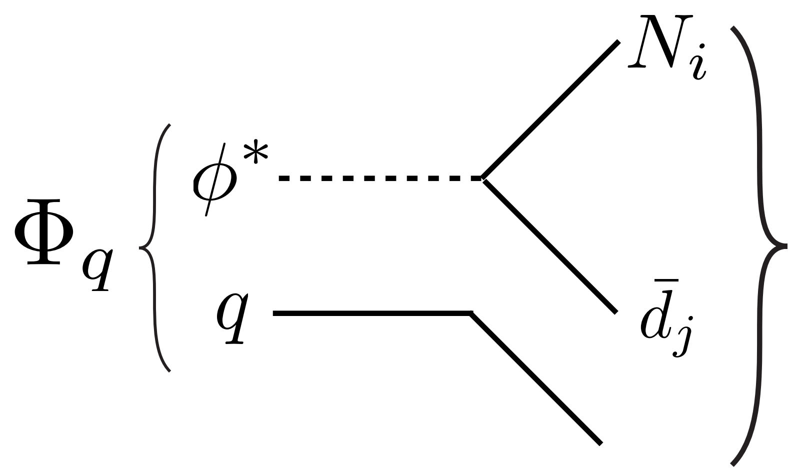


(encoded in

$$\mathcal{L} \supset y_{ij}\phi\, \bar{d}_i N_j - \frac{1}{2} m_{Nij} N_i N_j + \alpha_{ij}\phi^* \bar{d}_i \bar{u}_j + \text{c.c.})$$

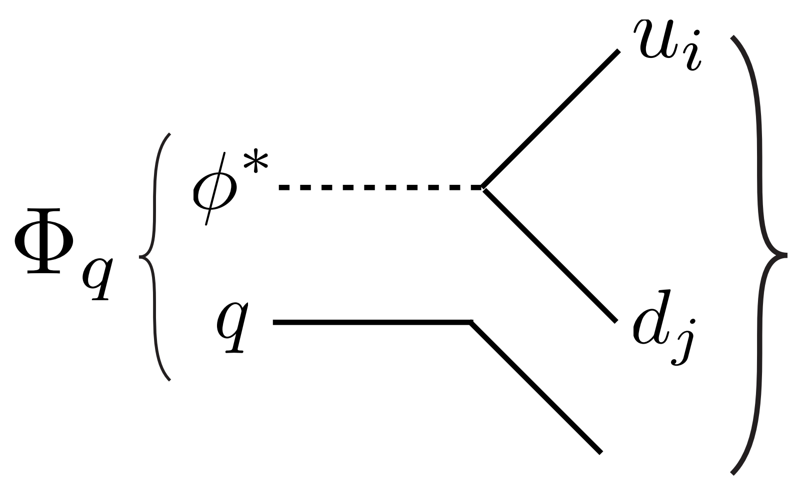
If the scalar is sufficiently long-lived it can form bound states with light quarks called "mesinos" $\Phi_q \sim \phi^* q$

Mesinos



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

Decay modes:

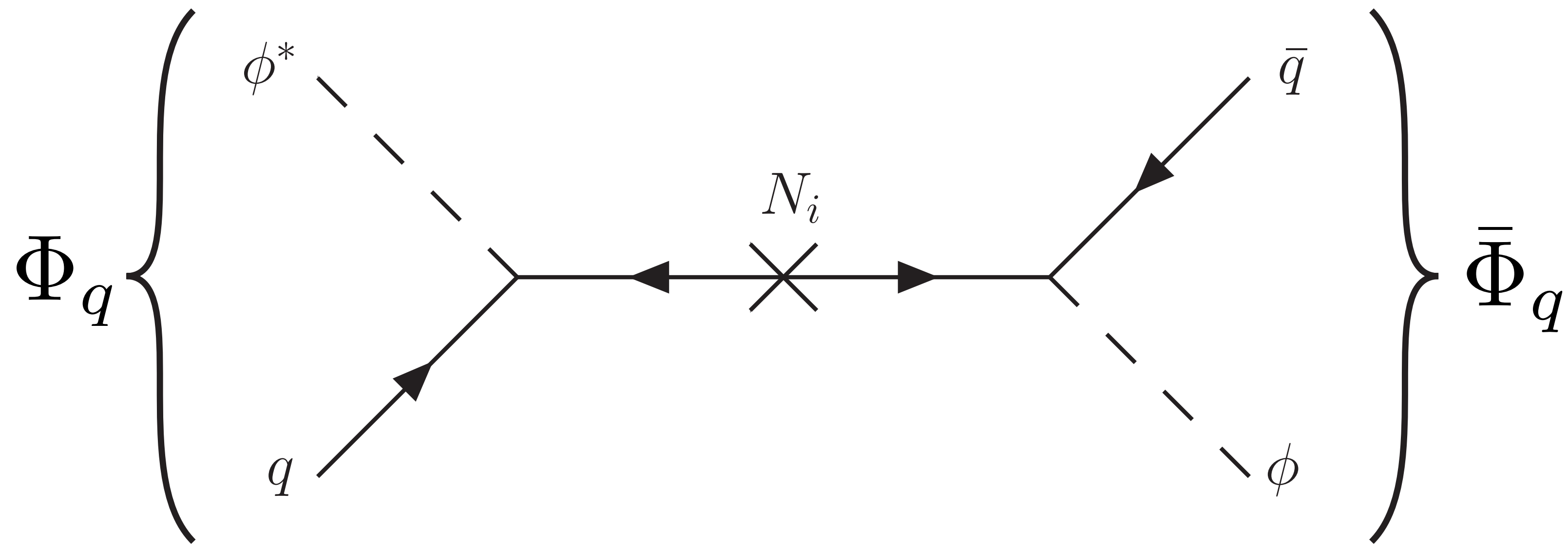


$$B = +1 + \ldots \equiv \Gamma_{\Phi_q \to B}$$

+conjugate modes

Mesinos

(Neutral) mesinos can turn into antimesinos



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

(Ipek, DM, & Nelson 1407.8193)

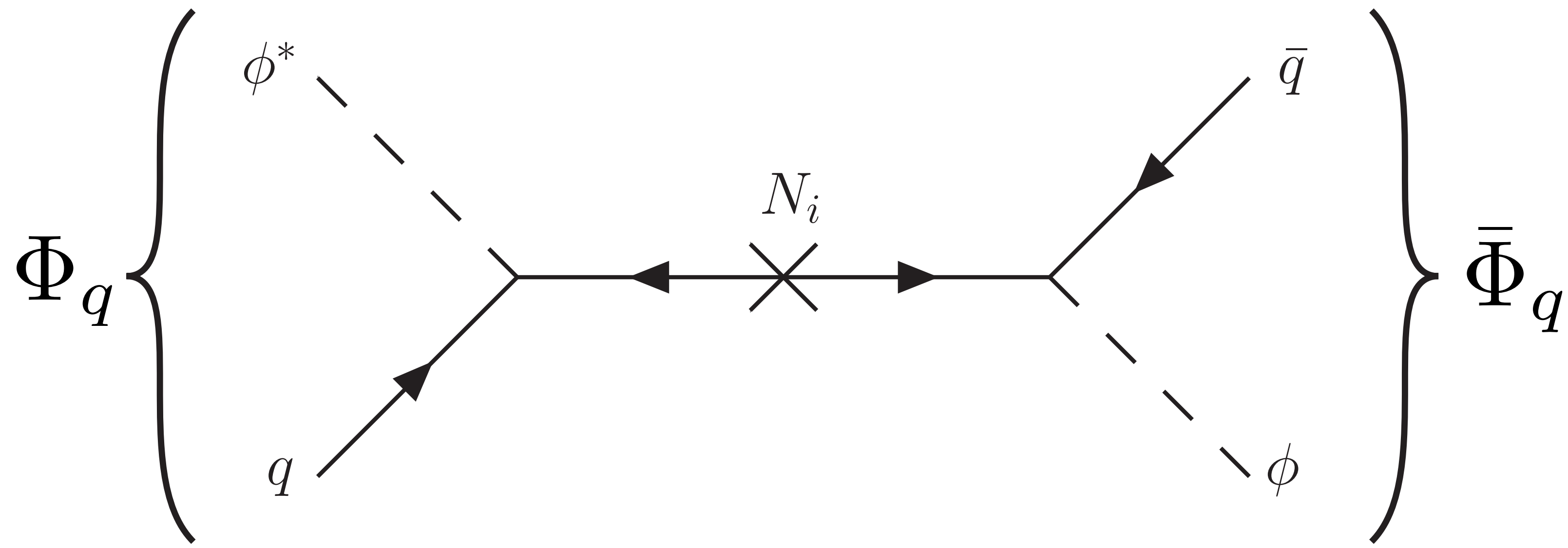
$$\mathbf{H} = \begin{pmatrix} \Phi_q \to \Phi_q & \Phi_q \to \bar{\Phi}_q \\ \bar{\Phi}_q \to \Phi_q & \bar{\Phi}_q \to \bar{\Phi}_q \end{pmatrix}$$

Mass eigenstates are an admixture of “flavor” eigenstates

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

Mesinos

(Neutral) mesinos can turn into antimesinos



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

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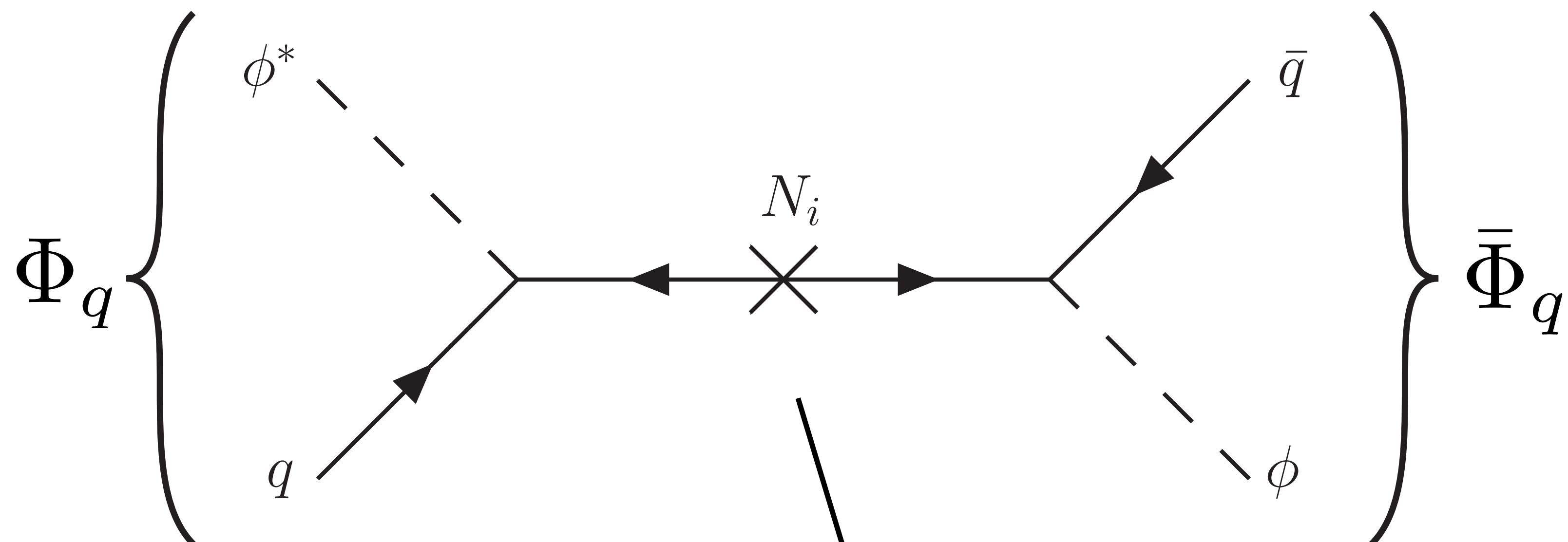
$$\mathbf{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$$

Mass eigenstates are an admixture of “flavor” eigenstates

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

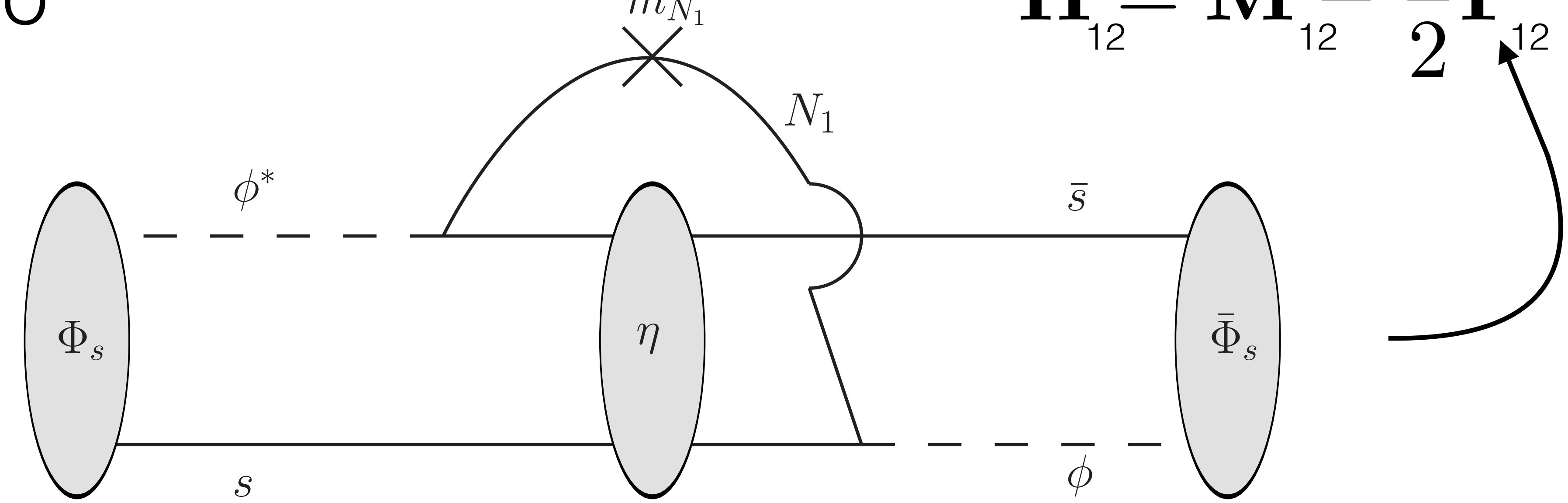
Mesinos

In addition to this



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

there is also



will take
q=s

Mesinos

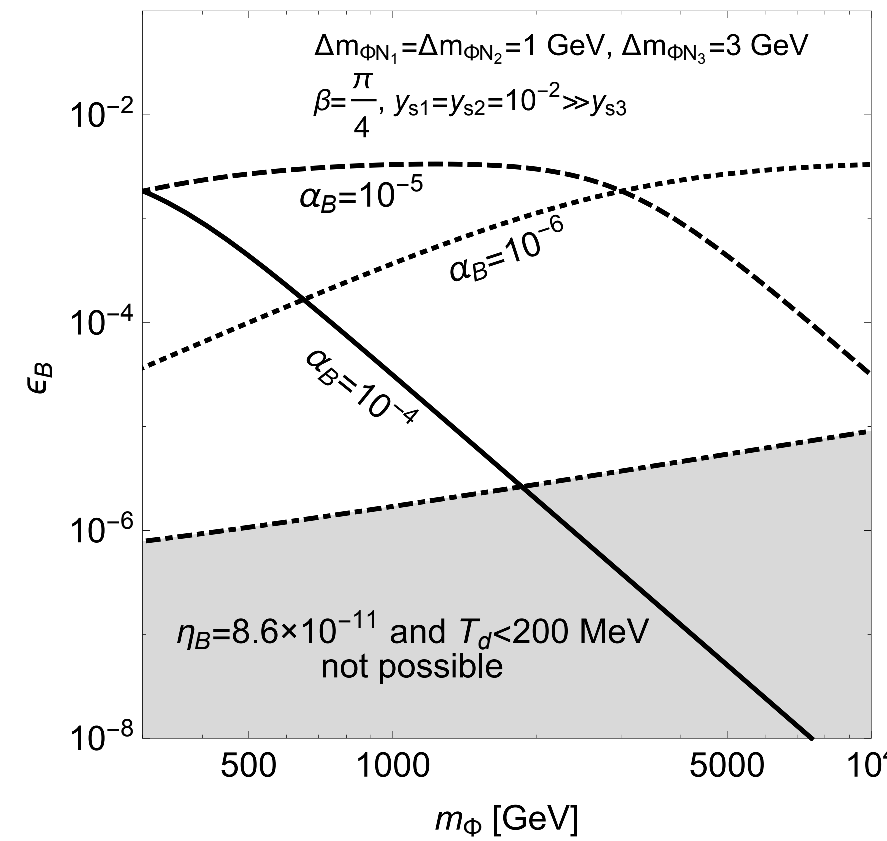
Quantity of interest is baryon asymmetry per mesino pair $\equiv \epsilon_B$

Want $m_{\Phi_s} - m_{N_1} \sim \mathrm{GeV}$

Using $|\mathbf{\Gamma}_{12}| \sim \Gamma_{\Phi_q \to N_1}$, can find

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

$$\sim \min\left(\frac{2\left|\mathbf{M}_{12}\right|}{\Gamma}, \frac{\Gamma}{2\left|\mathbf{M}_{12}\right|}\right)\sin\beta \mathrm{Br}_{\Phi_q \to N_1}\mathrm{Br}_{\Phi_q \to B}$$

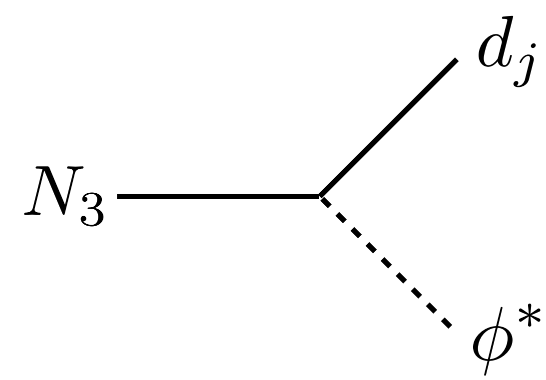


(Need >2 N's)

Typically $\epsilon_B \sim 10^{-6} - 10^{-3}$

Producing the baryon asymmetry

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



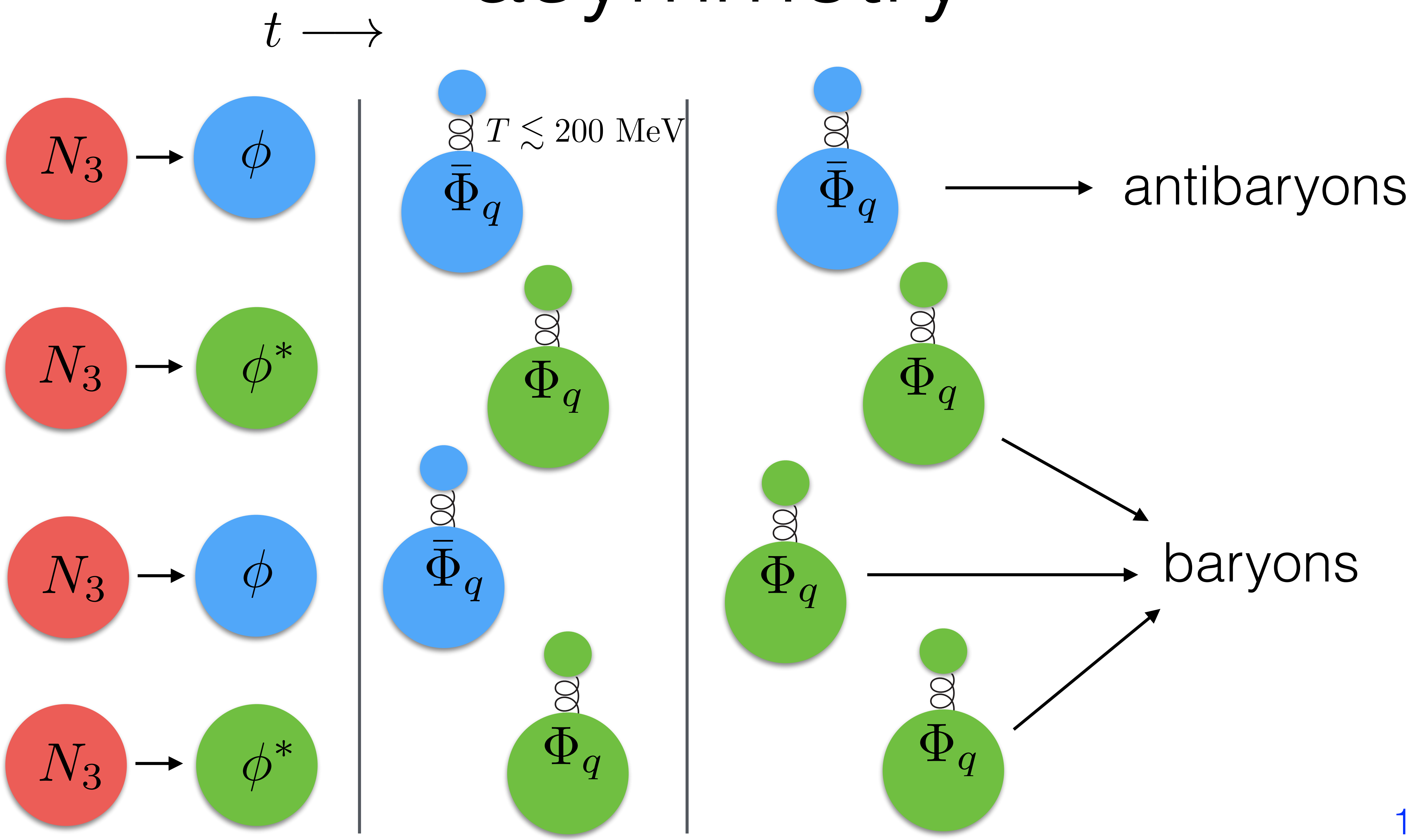
For definiteness, can use the decay of a singlet N_3

$t_{N_3} \sim 10^{-5}$ s means

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

so that mesinos form

Producing the baryon asymmetry



Cosmological evolution of the asymmetry

Evolution of relevant energy densities:

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

$$\frac{d\rho_{N_3}}{dt} = -3H\rho_{N_3} - \Gamma_{N_3} m_{N_3} n_{N_3}$$

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

Simple sudden decay approx:

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

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

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

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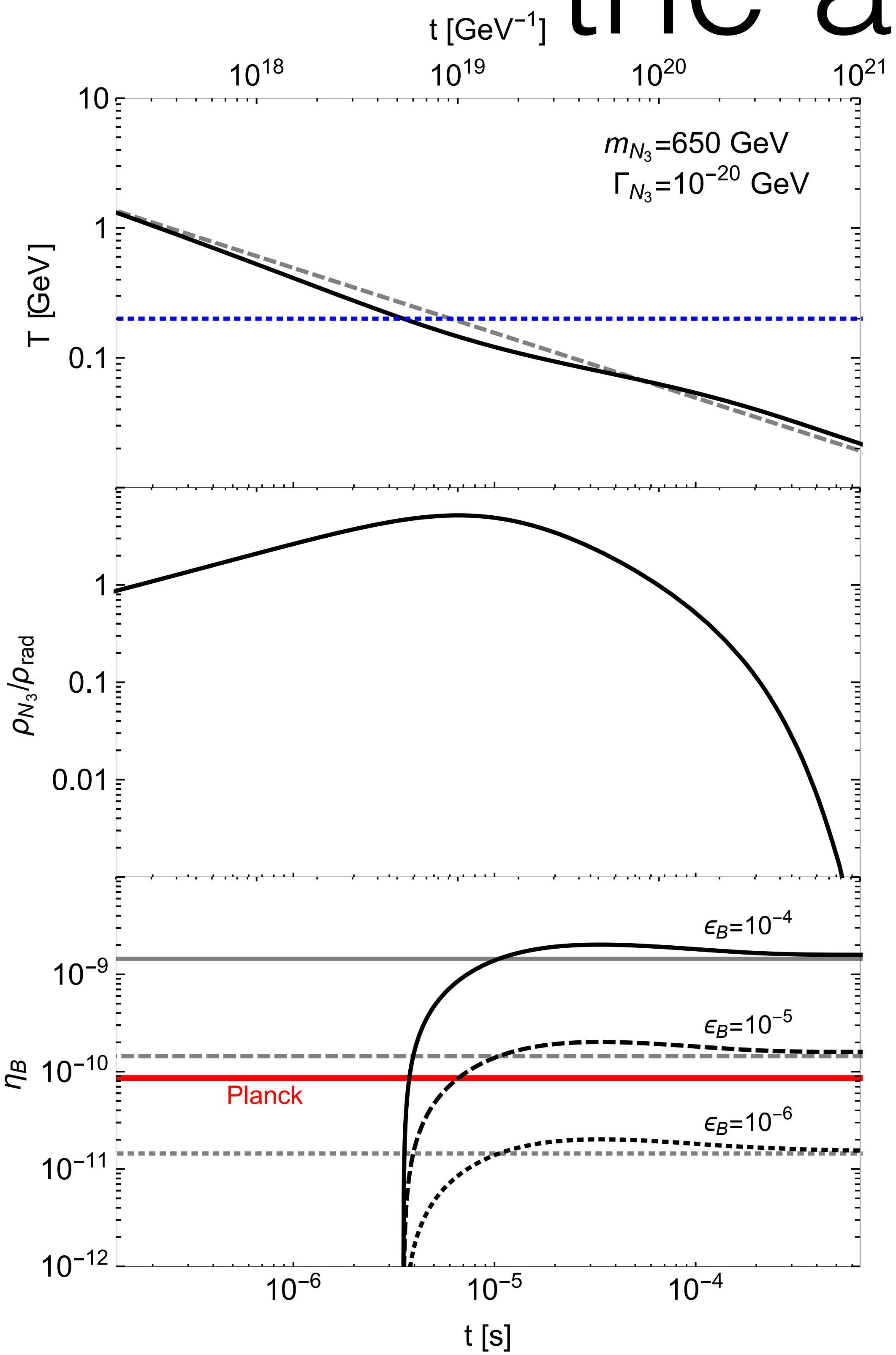
Cosmological evolution of the asymmetry



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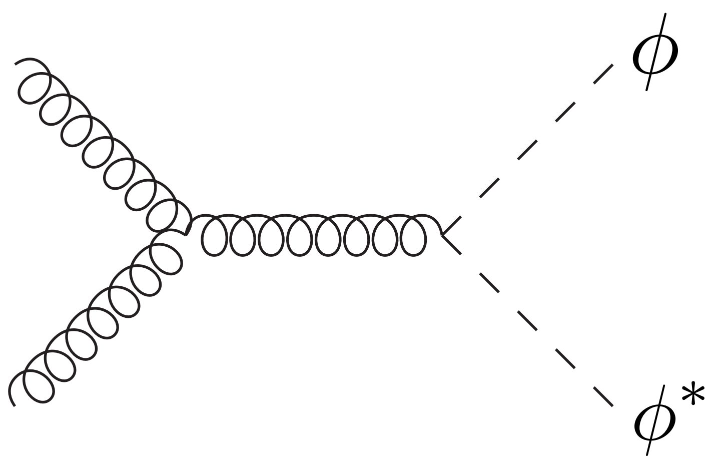
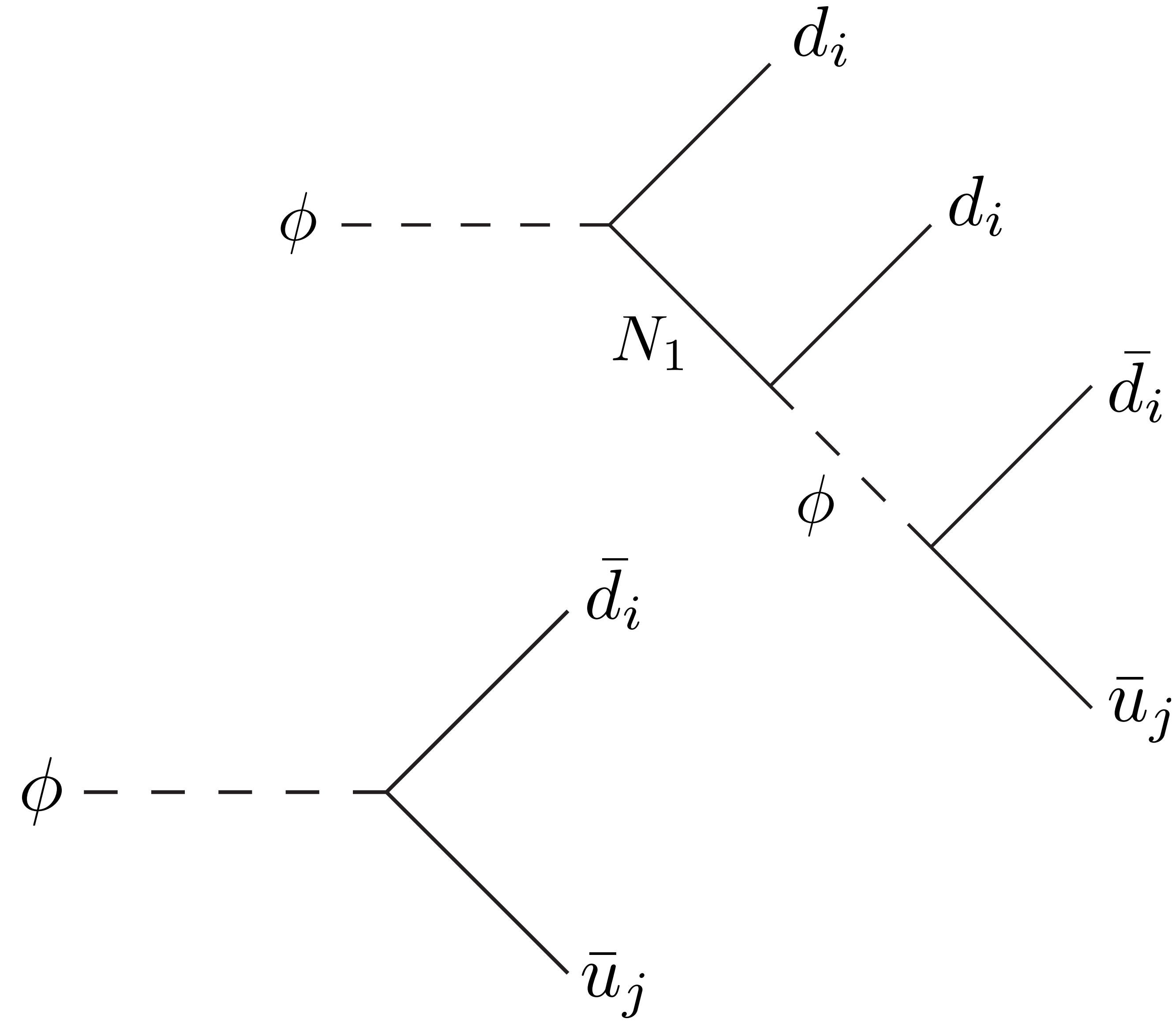
$$\frac{dn_B}{dt} = -3Hn_B + \frac{1}{2} A\,\Gamma_{N_3} \epsilon_B n_{N_3}$$

Simple sudden decay approx is not a bad estimate

Okay, so what are the constraints on/probes of such a situation?

Constraints

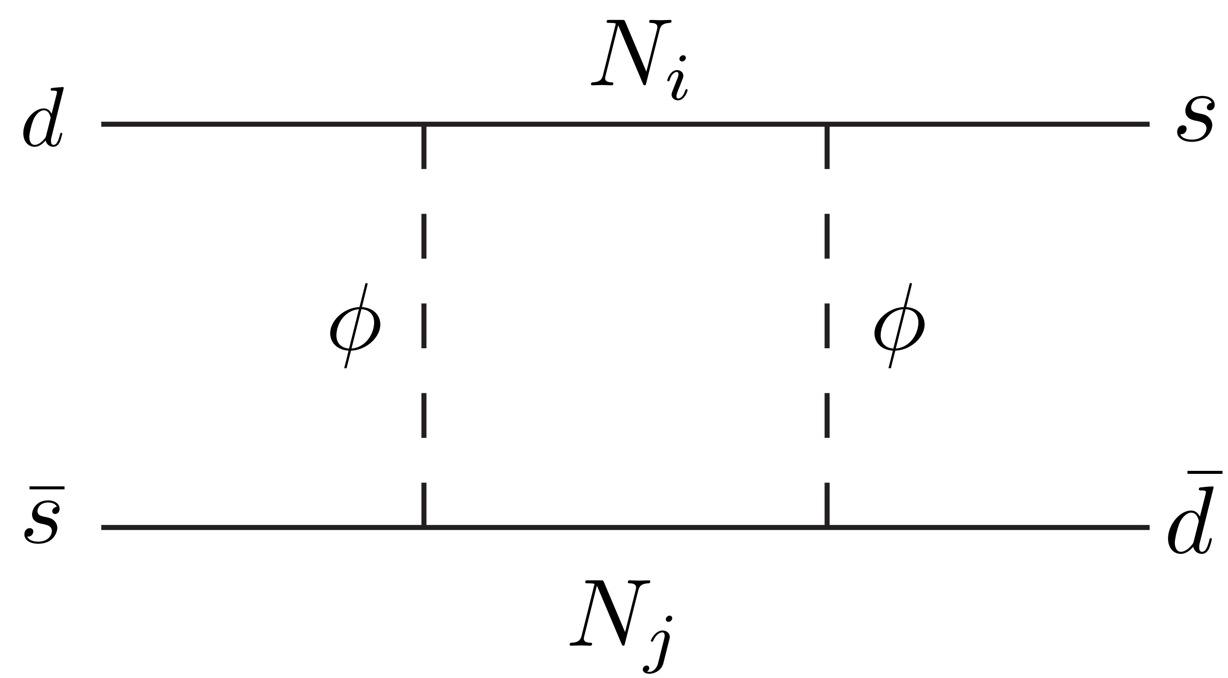




Searches for multijet final states at LHC

$$m_\phi \gtrsim 300 - 600 \ \mathrm{GeV}$$

Constraints



Kaon mixing can limit product of couplings to s, d

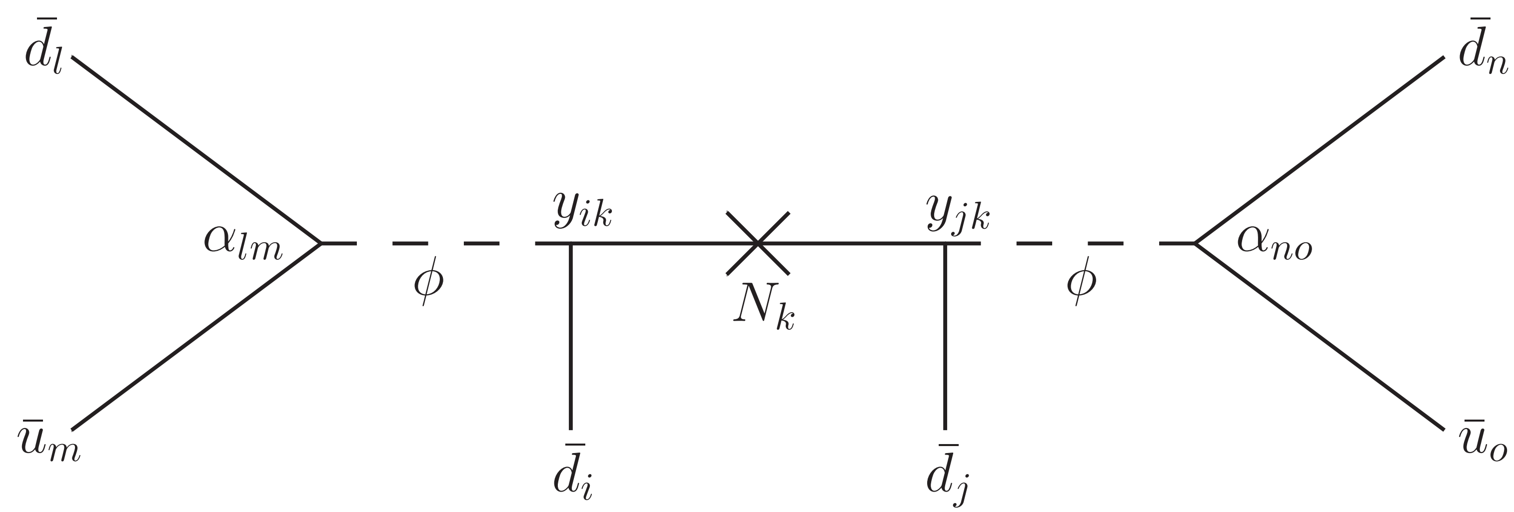
$$\left(\mathrm{Re}\sum_{i,j} y^*_{di} y_{dj} y_{si} y^*_{sj}\right)^{1/4} < 0.40\sqrt{\frac{m_\phi}{650\ \mathrm{GeV}}},$$

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

Constraints

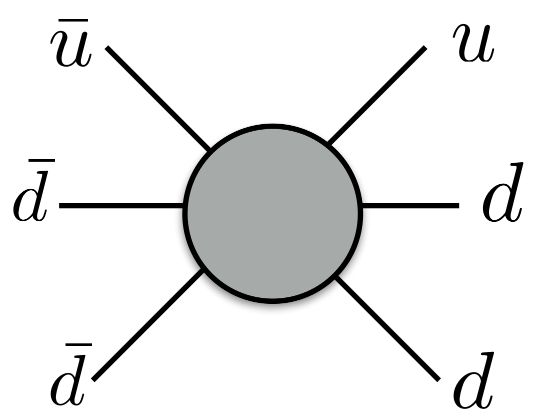
$$\Delta B = 2$$

Neutron oscillation operator suggests stronger coupling to heavy quarks



Kuzmin, Mohapatra, Marshak, …

Neutron Oscillations



generic feature of theories which violate B number (very relevant for baryogenesis!)

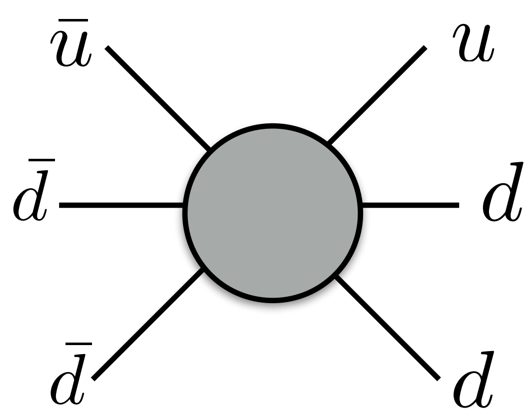
comes from dim.-9 operator $\frac{(udd)^2}{\Lambda^5}$

currently probing $\Lambda \sim 100\ \mathrm{TeV}$

to be competitive with proton decay, theory needs to allow $\Delta B = 2$ only

Arnold, Fornal, Wise, …

Neutron Oscillations



denote the $\Delta B = 2$ amplitude as

$$\langle \bar{n} | H | n \rangle \equiv \delta$$

transition prob. is

$$P_{n\to\bar{n}} = \frac{2\delta^2}{\Delta m^2}\,(1 - \cos \Delta m\, t)$$

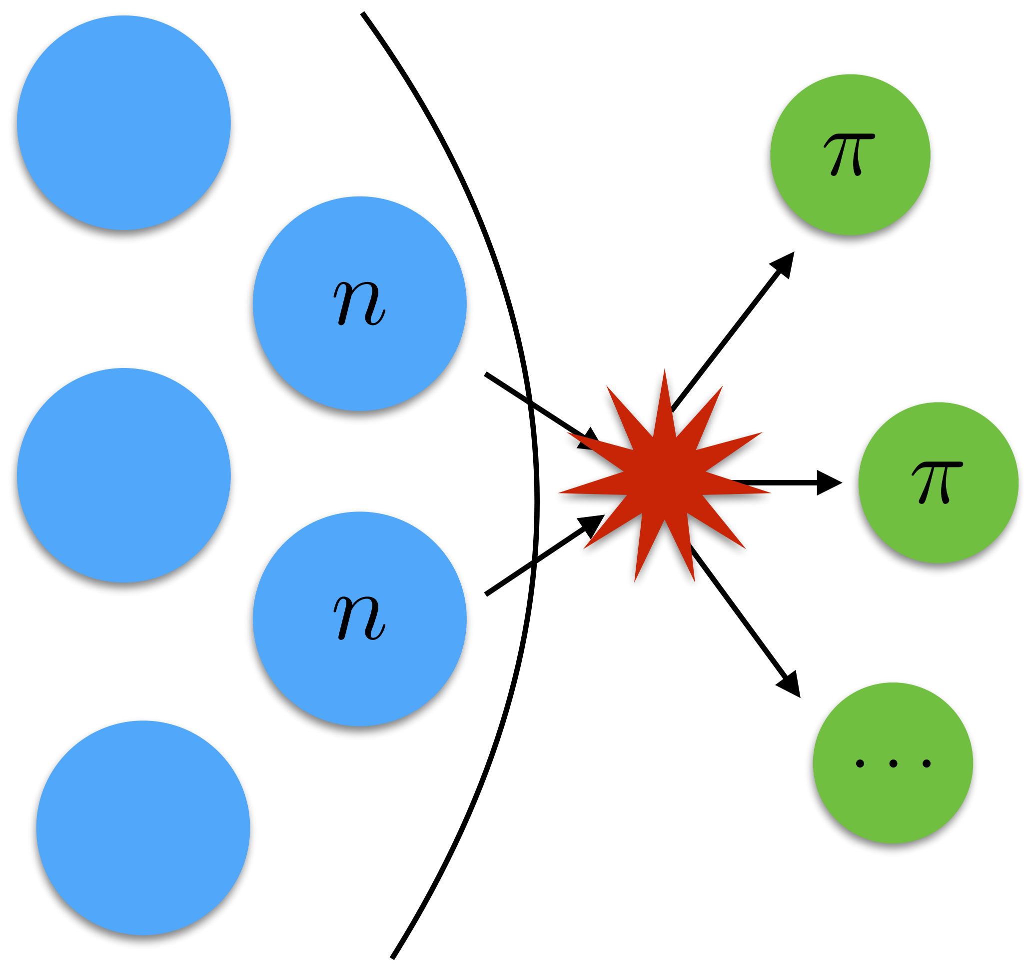
splitting due to B field, matter effects,…

Typically $\quad \Delta m\, t \ll 1 \qquad P_{n\to\bar{n}} \simeq \delta^2 t^2 \equiv (t/\tau_{n\bar{n}})^2$

Neutron Oscillations

Present best limit comes from Super-K limit on ^{16}O lifetime of

$$1.9 \times 10^{32} \ \mathrm{yr}$$



translates to

$$\tau_{n\bar{n}} > 3.5 \times 10^{8} \ \mathrm{s} \quad \text{or} \quad \delta < 1.9 \times 10^{-33} \ \mathrm{GeV}$$

see also recent limits from SNO

See also Vainshtein & Berezhiani, Gardner (& Jafari, & Yan), Tureanu & Fujikawa

(DM & Ann Nelson 1512.05359)

Neutron Oscillation Lagrangian

The general Lagrangian containing neutron bilinear

$$\mathcal{L} = \bar{n} i \gamma^\mu \partial_\mu n + \mathcal{L}_B + \mathcal{L}_{\not B}$$

$$-\mathcal{L}_B = \bar{n}\left(m_n P_L + m_n^* P_R\right) n$$

with B-preserving

$$-\mathcal{L}_{\not B} = \bar{n}^c\left(\delta_1 P_L + \delta_2^* P_R\right) n + \bar{n}\left(\delta_2 P_L + \delta_1^* P_R\right) n^c$$

and B-violating terms

In terms of 2-comp., LH Weyl spinors

$$\xi \ \ (B=+1)\,, \ \ \eta \ \ (B=-1)$$

$$n = \begin{pmatrix} \xi \\ \eta^\dagger \end{pmatrix} = \begin{pmatrix} \xi \\ i\sigma^2 \eta^* \end{pmatrix}$$

$$\mathcal{L} = \xi^\dagger i \bar{\sigma}^\mu \partial_\mu \xi + \eta^\dagger i \bar{\sigma}^\mu \partial_\mu \eta + \mathcal{L}_B + \mathcal{L}_{\not B}$$

$$-\mathcal{L}_B = m_n \eta \xi + \mathrm{h.c.}$$

$$-\mathcal{L}_{\not B} = \delta_1 \xi\xi + \delta_2 \eta\eta + \mathrm{h.c.}$$

How does this behave wrt CP?

See also Vainshtein & Berezhiani, Gardner (& Jafari, & Yan), Tureanu & Fujikawa

(DM & Ann Nelson 1512.05359)

Neutron Oscillation Lagrangian

$$\xi \xleftrightarrow[C]{} \eta$$

$$m_n \xrightarrow[C]{} m_n, \;\; \delta_1 \xleftrightarrow[C]{} \delta_2$$

$$\xi \xleftrightarrow[P]{} \eta^\dagger$$

$$m_n \xleftrightarrow[P]{} m_n^*, \;\; \delta_1 \xleftrightarrow[P]{} \delta_2^*$$

$$\xi \xleftrightarrow[CP]{} \xi^*, \;\; \eta \xleftrightarrow[CP]{} \eta^*$$

$$m_n \xleftrightarrow[CP]{} m_n^*, \;\; \delta_{1,2} \xleftrightarrow[CP]{} \delta_{1,2}^*$$

$$\mathcal{L} = \xi^\dagger i\bar{\sigma}^\mu \partial_\mu \xi + \eta^\dagger i\bar{\sigma}^\mu \partial_\mu \eta + \mathcal{L}_B + \mathcal{L}_{\not B}$$

$$-\mathcal{L}_B = m_n \eta\xi + \text{h.c.}$$

$$-\mathcal{L}_{\not B} = \delta_1 \xi\xi + \delta_2 \eta\eta + \text{h.c.}$$

3 phases, 2 fields, naively can't remove all but can rotate to remove δ_1 or δ_2

$$\xi \to \cos\theta\xi + \sin\theta\eta, \;\; \eta \to -\sin\theta\xi + \cos\theta\eta$$

(Ipek, DM, & Nelson)

Neutron Oscillation Hamiltonian

Express fields in terms of creation/annihilation operators

$$\xi_\alpha = \sum_s \int \frac{d^3p}{(2\pi)^{3/2}} \frac{1}{\sqrt{2E_p}} \left[x^s_{p\,\alpha} a^s_p e^{-ip\cdot x} + y^s_{p\,\alpha} b^{s\,\dagger}_p e^{ip\cdot x} \right]$$

$$\eta_\alpha = \sum_s \int \frac{d^3p}{(2\pi)^{3/2}} \frac{1}{\sqrt{2E_p}} \left[x^s_{p\,\alpha} b^s_p e^{-ip\cdot x} + y^s_{p\,\alpha} a^{s\,\dagger}_p e^{ip\cdot x} \right]$$

$$|n; p, s\rangle = a^{s\,\dagger}_p |0\rangle, \;\; |\bar{n}; p, s\rangle = b^{s\,\dagger}_p \| 0\rangle$$

Can then compute Hamiltonian

$$-\langle i; p, s| \int d^3x\, \mathcal{L} |j; p', s'\rangle \Big|_{p\to 0} = (2\pi)^3\, \delta^{(3)}\left(p - p'\right) H^{ss'}_{ij}$$

$$H = \begin{pmatrix} m_n & \frac{\delta_1^* + \delta_2}{2} \\ \frac{\delta_1 + \delta_2^*}{2} & m_n \end{pmatrix} \delta^{ss'}$$

Remaining phase can be removed by rephasing states

Neutron Oscillation Hamiltonian

Can easily incorporate B fields, decays in this

$$\mathcal{L} \supset (\mu_n - i d_n) F_{\mu\nu} \eta \sigma^{\mu\nu} \xi + \text{h.c.}$$

$$H = \begin{pmatrix} m_n \delta^{ss'} - (\mu_n B - d_n E) \cdot \sigma & M_{12} \delta^{ss'} \\ M_{12}^* \delta^{ss'} & m_n \delta^{ss'} + (\mu_n B - d_n E) \cdot \sigma \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_n & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_n \end{pmatrix} \delta^{ss'}$$

$$M_{12} = \delta_1^* + \delta_2$$

Gives transition probs.

$$\Delta \equiv 2\sqrt{\mu_n^2 B^2 + H_{12} H_{21}}$$

$$P_{|n\rangle \to |\bar{n}\rangle} = \frac{2 \left| H_{21} \right|^2}{\left| \Delta \right|^2} \left(\cosh \frac{\Delta \Gamma t}{2} - \cos \Delta m t \right) e^{-\Gamma_n t}$$

$$H_{12,21} = M_{12,21} - \frac{i}{2} \Gamma_{12,21}$$

CPV is, e.g.,

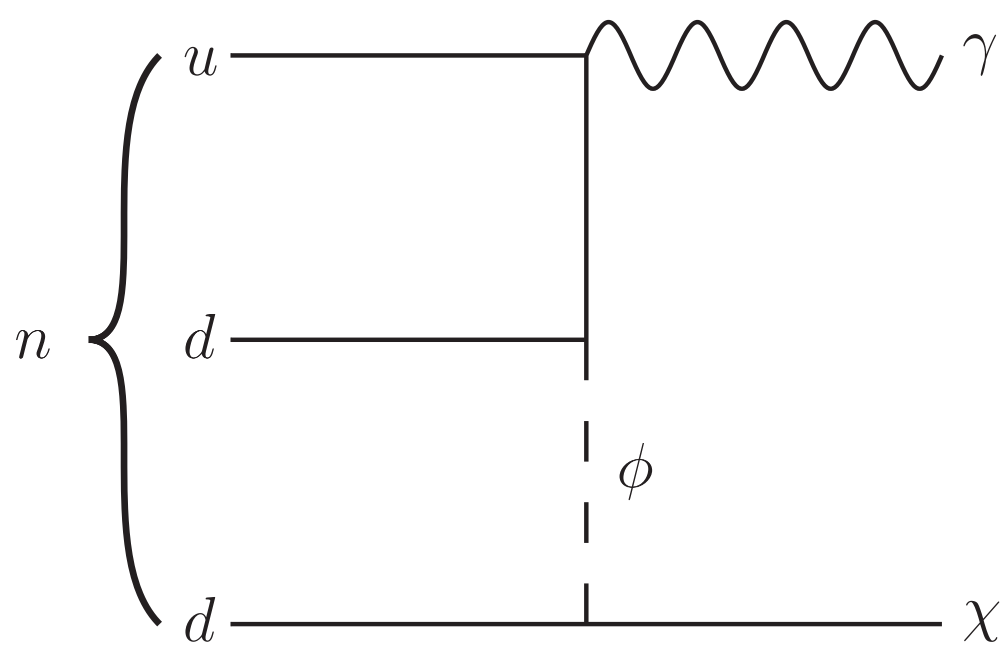
$$\frac{P_{|n\rangle \to |\bar{n}\rangle}}{P_{|\bar{n}\rangle \to |n\rangle}} - 1 = \frac{2 \mathrm{Im} \left(M_{12} \Gamma_{12}^* \right)}{\left| M_{12} \right|^2 - \left| \Gamma_{12} \right|^2 / 4 - \mathrm{Im} \left(M_{12} \Gamma_{12}^* \right)}$$

CPV in Neutron Oscillations

Is measurable CPV possible? Need Γ_{12}

$n \to \bar{p}e^+\nu_e,\ \bar{n} \to pe^-\bar{\nu}_e$ dim-12, 3 body, so extremely suppressed

Need to consider new state lighter than neutron



$$m_p - m_e < m_\chi < m_p + m_e$$

$$\mathcal{L} \supset g\phi\bar{u}\bar{d} + y\phi^*\bar{d}\chi + m_\chi\chi\chi + \text{h.c.}$$

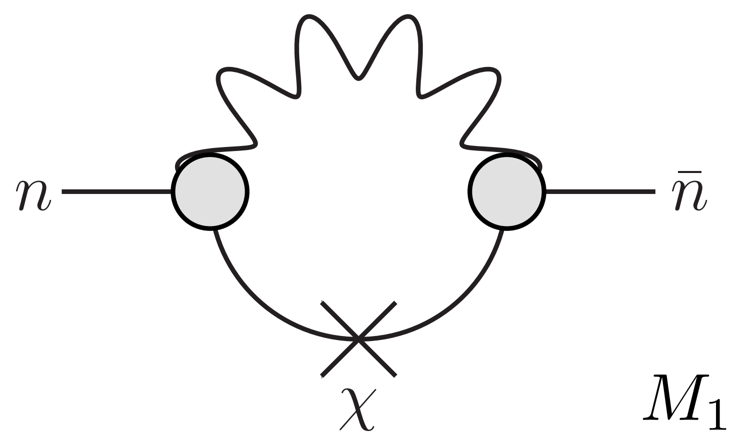
guarantees stability of $\chi,\ p$

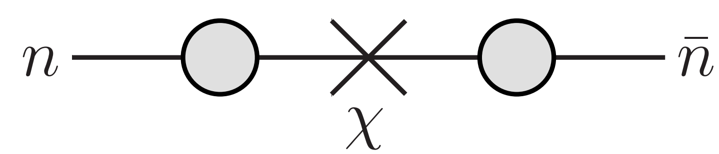
Z_2 subgroup of B number preserved

CPV in Neutron Oscillations

Is measurable CPV possible? Need Γ_{12}

$$\mathcal{L} \supset g\phi \bar{u}\bar{d} + y\phi^* \bar{d}\chi + m_\chi \chi\chi + \text{h.c.}$$





$$M_{12} \sim \left(\frac{\Lambda^3_{\rm QCD} gy}{m_\phi^2}\right)^2 \frac{m_\chi}{m_n^2 - m_\chi^2}$$

$$\sim 10^{-33}\ \text{GeV} \left(\frac{10^8\ \text{GeV}}{m_\phi/\sqrt{gy}}\right)^4 \left(\frac{1\ \text{MeV}}{\Delta M}\right)$$

$$\Gamma_{12} \sim \left(\frac{egy\Lambda^3_{\rm QCD}}{m_\phi^2 m_n^2}\right)^2 \frac{m_n^2 m_\chi}{16\pi}\left(1 - \frac{m_\chi^2}{m_n^2}\right)^3$$

$$\sim 10^{-47}\ \text{GeV} \left(\frac{10^8\ \text{GeV}}{m_\phi/\sqrt{gy}}\right)^4 \left(\frac{\Delta M}{1\ \text{MeV}}\right)^3$$

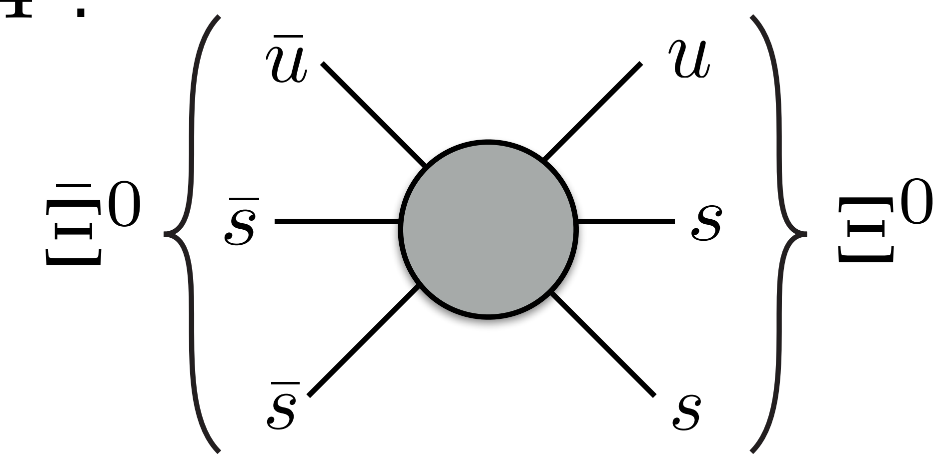
So $\dfrac{P_{n\to\bar{n}}}{P_{\bar{n}\to n}} - 1 \propto \dfrac{|\Gamma_{12}|}{|M_{12}|} \lesssim 10^{-14}\left(\dfrac{\Delta M}{1\ \text{MeV}}\right)^4$

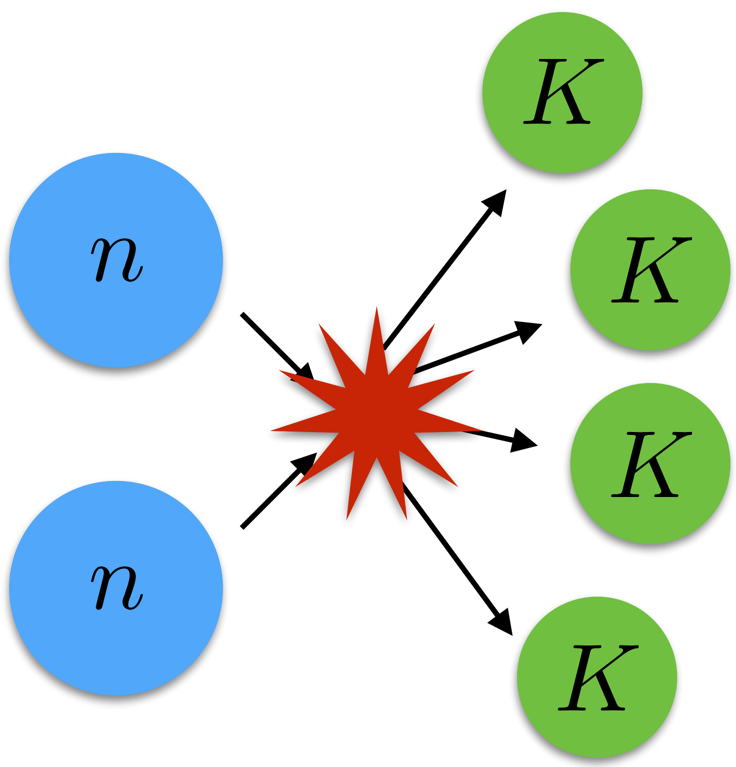
Oscillations also suppressed by $\dfrac{|M_{12}|}{\Gamma_n} \lesssim 10^{-5}$

(Aitken, DM, Neder, & Nelson)

Heavy Flavor Oscillations

What if $\Delta B = 2$ operators had $\Delta S = 4$?





is kinematically forbidden!

$$2m_N < 4m_K$$

Dominant constraints could be from colliders

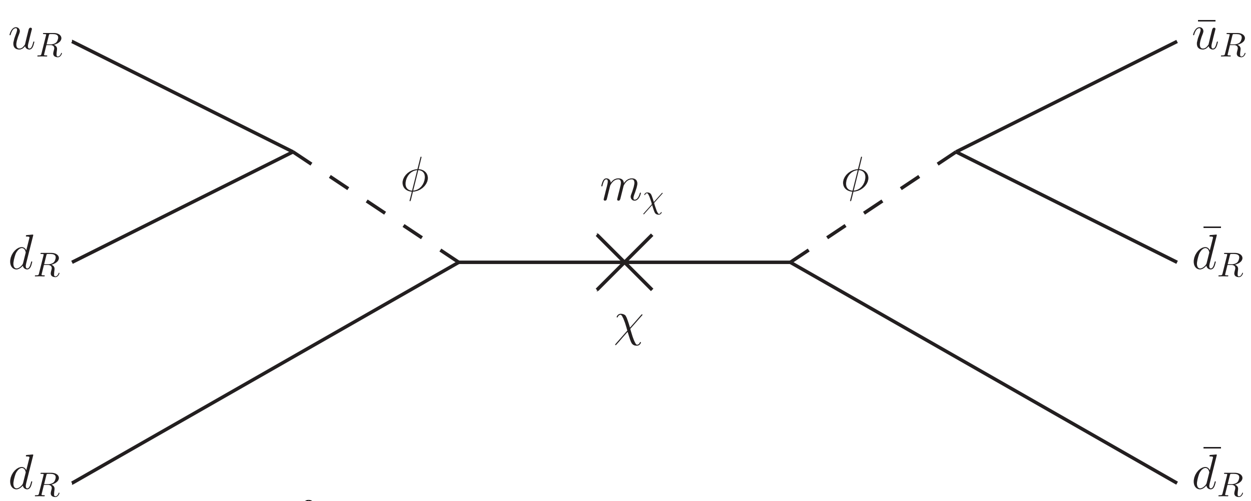
$\Gamma_{12},\ M_{12}$ could be much larger

Kuzmin ('96)

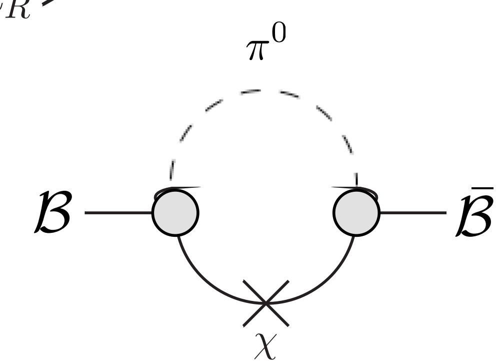
(Aitken, DM, Neder, & Nelson)

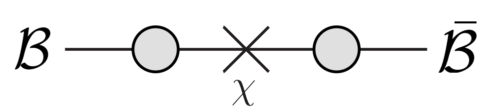
Heavy Flavor Oscillation Model

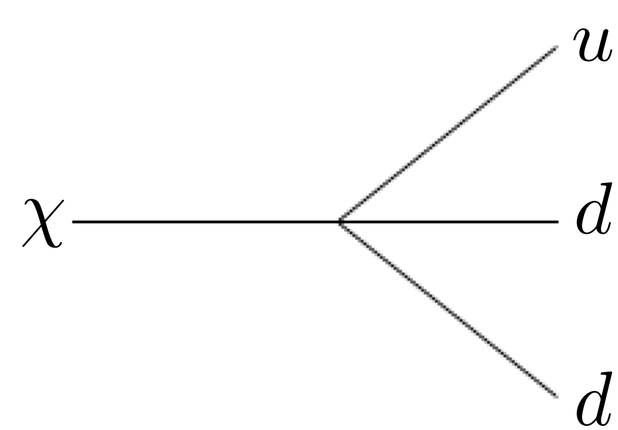
$$\mathcal{L}_{\rm int} \supset -g^*_{ud}\phi^*\bar{u}_R d^c_R - y_{id}\phi\bar{\chi}_i d^c_R + \text{H.c.}$$



Same model as described before but different regime: $m_\chi \ll m_\phi$







long-lived

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

$$\left|\frac{\Gamma_{12}}{M_{12}}\right|_1 \sim 4\pi\left(\frac{\Delta m_{\mathcal{B}1}}{m_{\mathcal{B}}}\right)^2 \simeq 0.1\left(\frac{\Delta m_{\mathcal{B}1}}{500\text{ MeV}}\right)^2\left(\frac{5\text{ GeV}}{m_{\mathcal{B}}}\right)^2$$

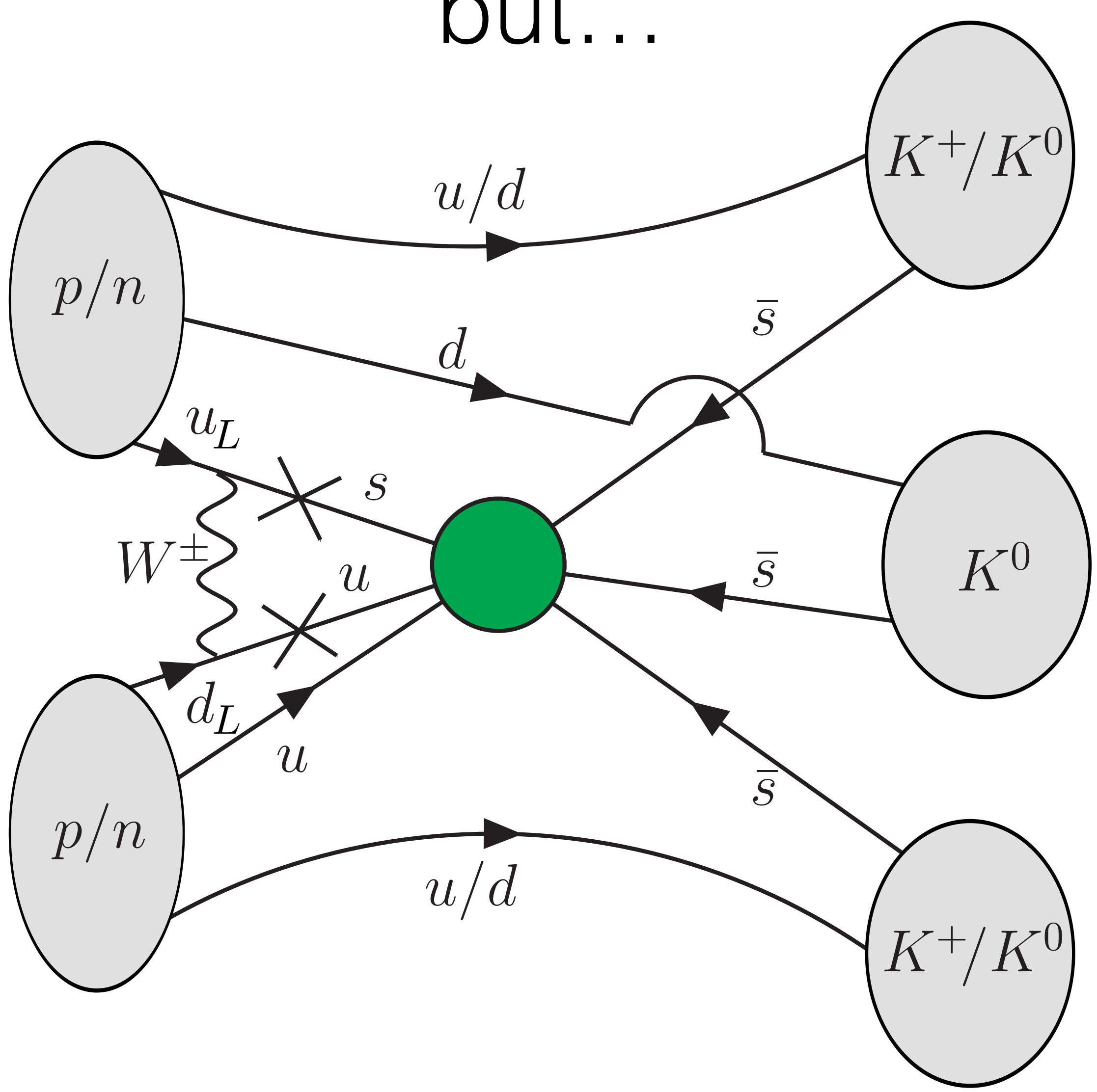
$$|M_{12}|_i \sim \frac{\kappa^2}{2\Delta m_{\mathcal{B}i}}\left|\frac{g^*_{ud}y_{id'}}{m_\phi^2}\right|^2 \simeq 8\times10^{-16}\text{ GeV}\left(\frac{500\text{ MeV}}{\Delta m_{\mathcal{B}i}}\right)\left(\frac{600\text{ GeV}}{m_\phi/\sqrt{|g^*_{ud}y_{id'}|}}\right)^4$$

Need 2 χ_i for phase diff.

Including weak interactions

What if $\Delta B = 2$ operators had $\Delta S = 4$?

but…



Chirally suppressed. Matching:

$$C_{\mathcal{BB}}(q_R q_R q_R)^2 \to \left(4\pi f_\pi^3\right)^2 \mathrm{tr} B \tilde{C}_{\mathcal{BB}} B + \ldots,$$

Combine with strangeness changing operators

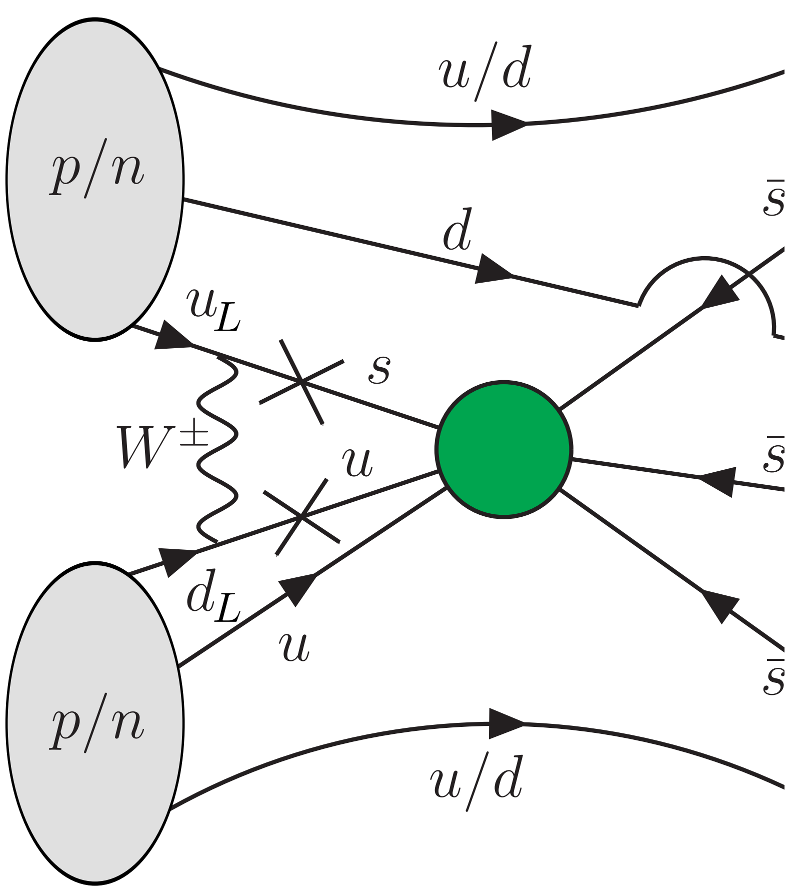
$$\underbrace{\frac{G_F}{\sqrt{2}} V_{us} V_{ud}^* f_\pi^2}_{10^{-8}} \left(4\pi f_\pi^3\right)^2 \mathrm{tr} B \tilde{C}_{\mathcal{BB}} \xi^\dagger h \xi B + \ldots$$

Can estimate constraints on heavy flavor transition amplitudes from n osc./DND

Heavy Flavor Oscillations

What if $\Delta B = 2$ operators had $\Delta S = 4$? $\quad 2m_N < 4m_K$

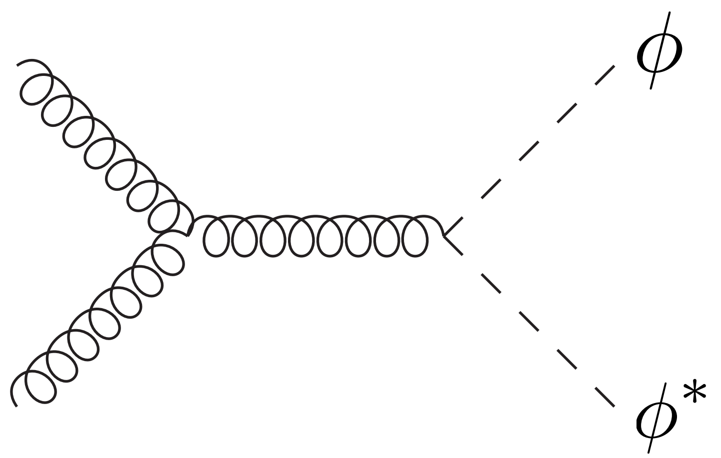
but…

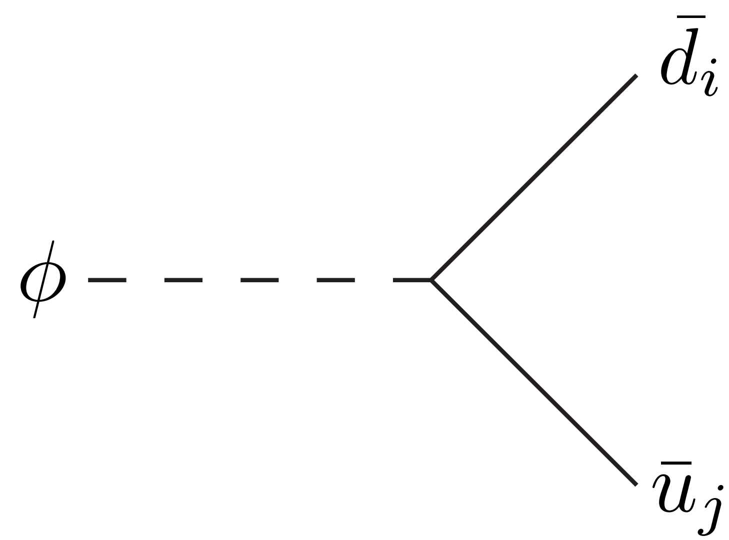


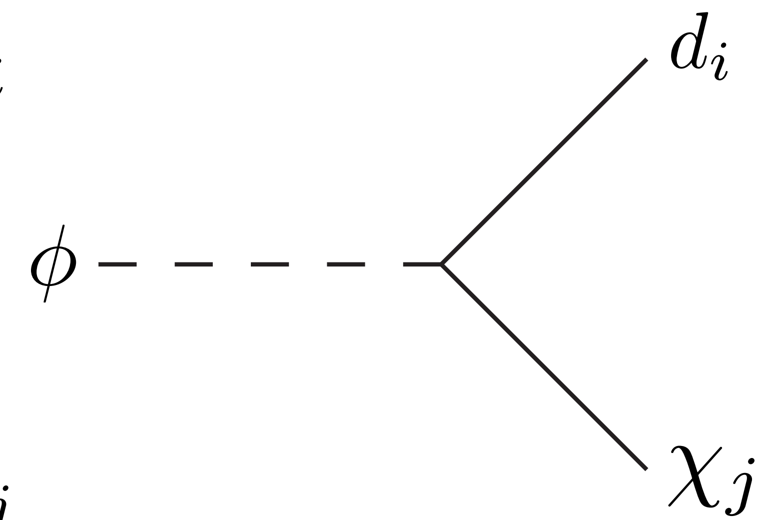
Operator	$\mathcal{B}$	Weak insertions required	Measured Γ (GeV) [22]	Limits on $\delta_{\mathcal{BB}}$ = Dinucleon decay
$(udd)^2$	n	None	$(7.477 \pm 0.009) \times 10^{-28}$	10^{-33}
$(uds)^2$	Λ	None	$(2.501 \pm 0.019) \times 10^{-15}$	10^{-30}
$(uds)^2$	Σ^0	None	$(8.9 \pm 0.8) \times 10^{-6}$	10^{-30}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

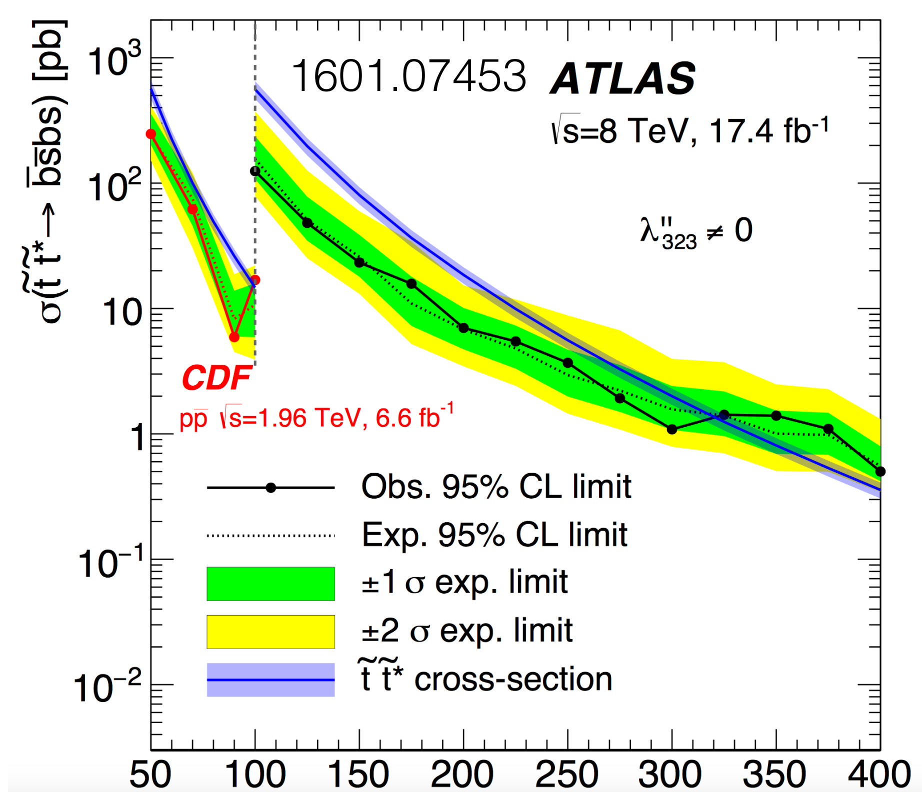
Collider constraints

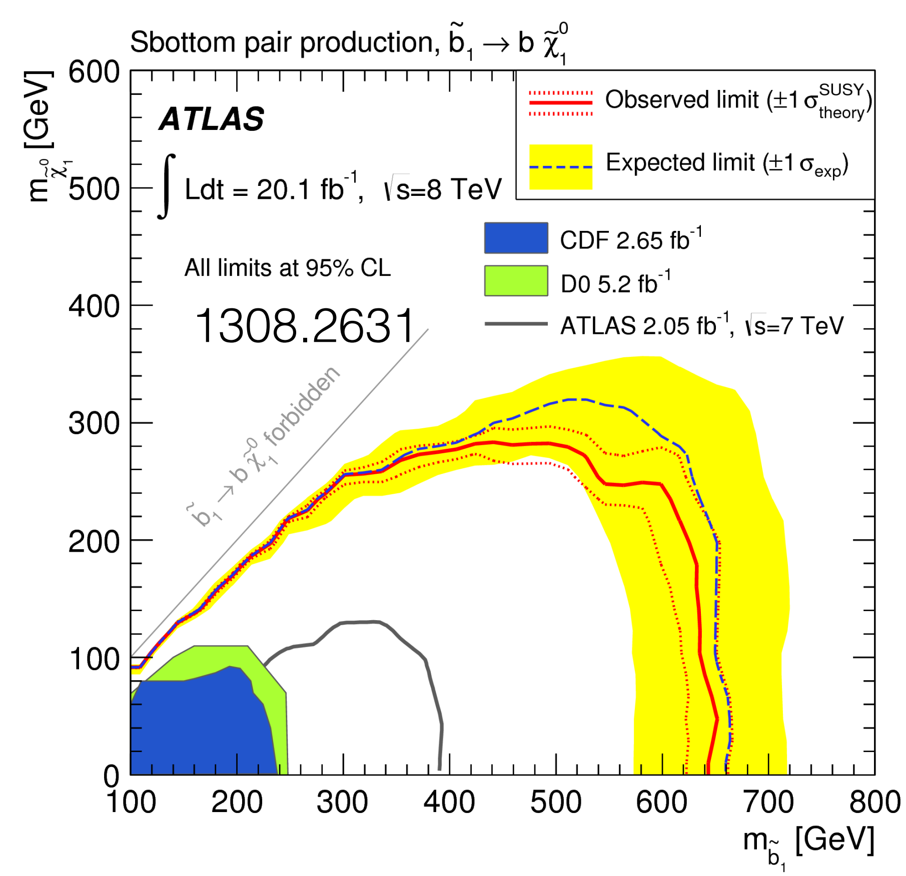
Produce color triplet scalars easily





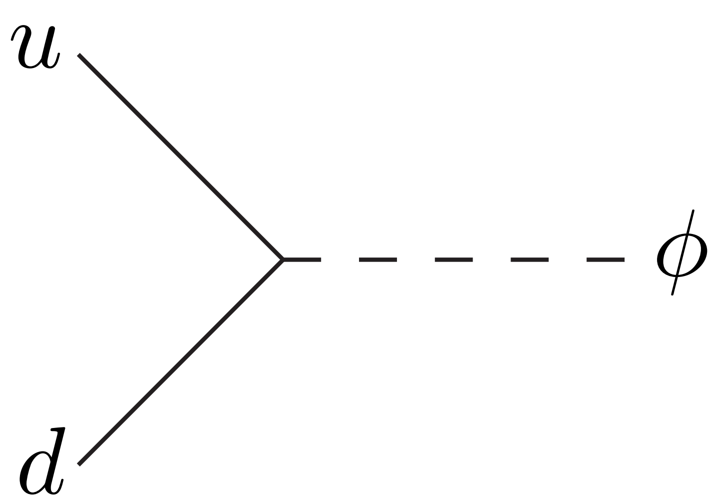


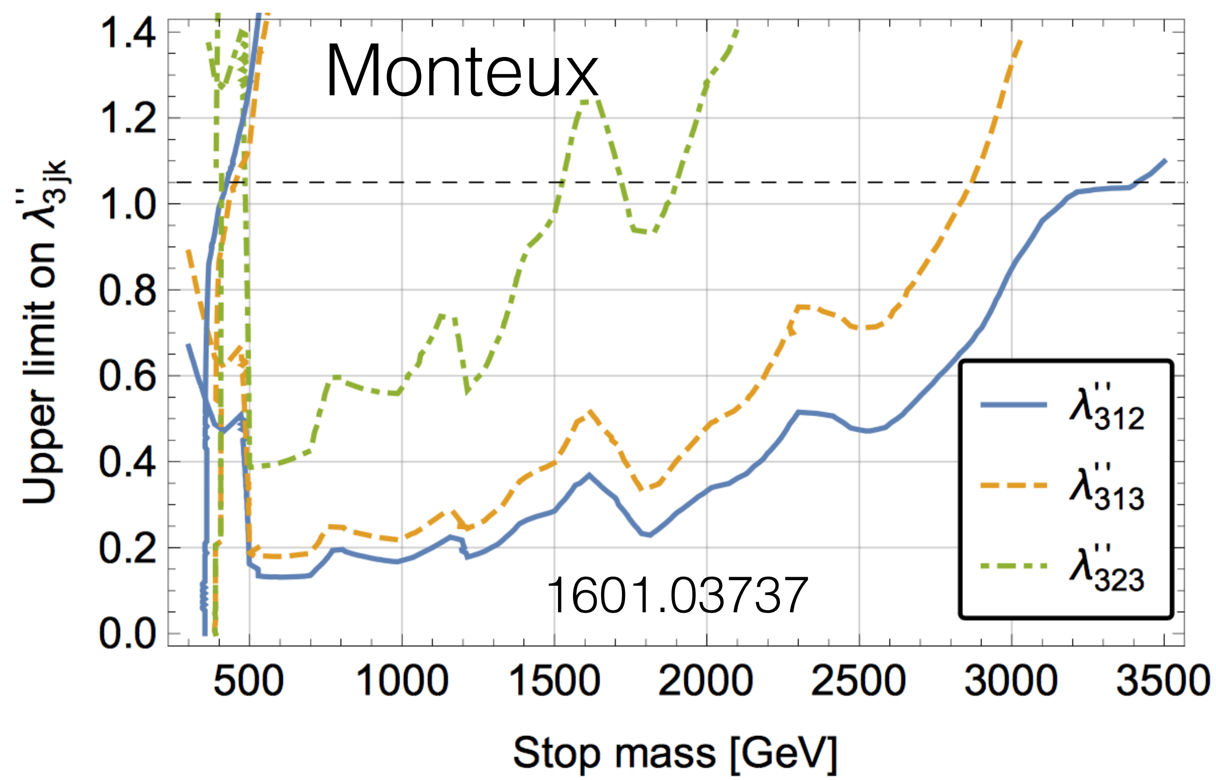




Collider constraints

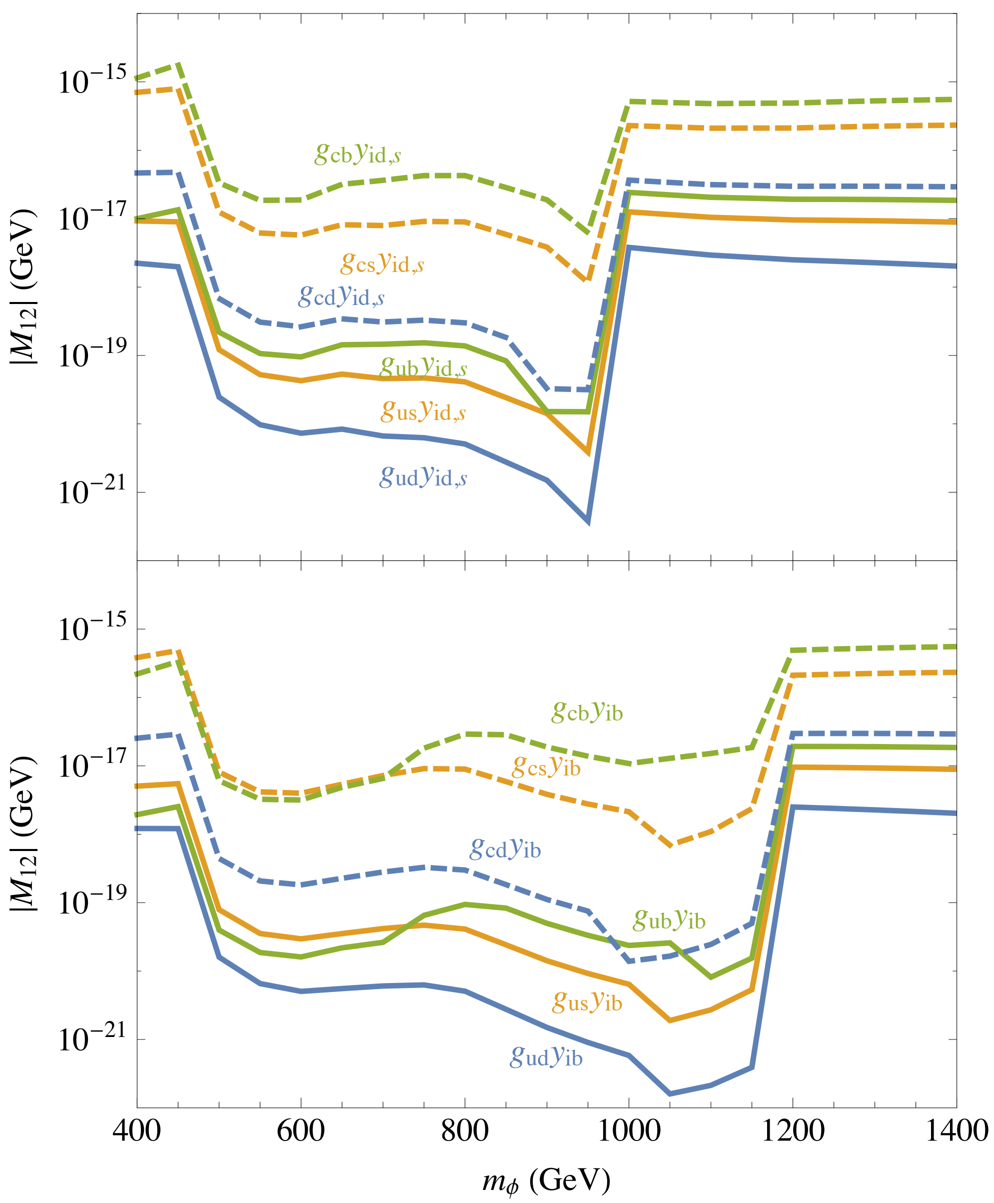
Also produced through "RPV" coupling





Resonant production is important!

Collider constraints



Scan over scalar masses

$$\Delta m = 200 \text{ MeV}$$

Operator	$\mathcal{B}$	Weak insertions required	Measured Γ (GeV) [22]	Limits on $\delta_{\mathcal{B}B} = M_{12}$ (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}
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$(udb)^2$	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}
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$(scb)^2$	$\Omega_{cb}^{0\,\dagger}$	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}

Production in the early Universe

Need a way to produce the baryons out of equilibrium

Simplest possibility is long-lived χ_3

Same as in model described by Nelson, similar to post-sphaleron scenario of Babu, Dev, Mohapatra et al.

In this case, decoherence is important

Boltzmann equations for radiation, long-lived fermion, heavy B

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

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

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

Need density matrix

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

Tulin, Yu, Zurek

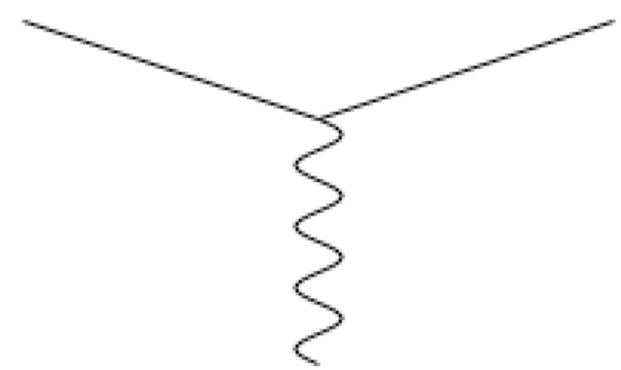
Change of variables to symmetric/asymmetric components

$$\Sigma \equiv n_{\mathcal{B}\mathcal{B}} + n_{\bar{\mathcal{B}}\bar{\mathcal{B}}}, \;\; \Delta \equiv n_{\mathcal{B}\mathcal{B}} - n_{\bar{\mathcal{B}}\bar{\mathcal{B}}}, \;\; \Xi \equiv n_{\mathcal{B}\bar{\mathcal{B}}} - n_{\bar{\mathcal{B}}\mathcal{B}}, \;\; \Pi \equiv n_{\mathcal{B}\bar{\mathcal{B}}} + n_{\bar{\mathcal{B}}\mathcal{B}}.$$

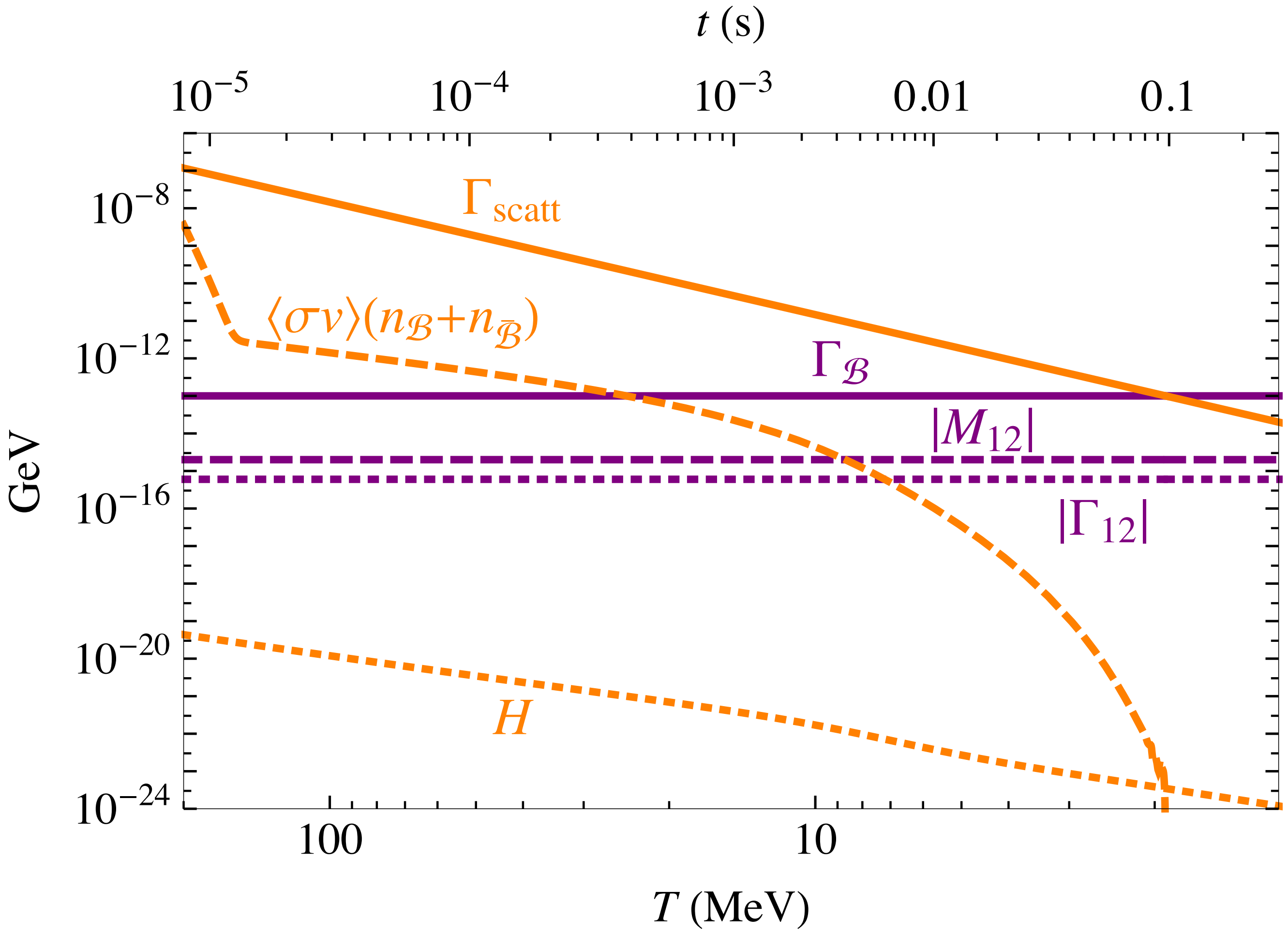
$$\begin{aligned}
\left(\frac{d}{dt} + 3H\right)\Sigma &= \frac{\Gamma_{\chi_3}\rho_{\chi_3}}{m_{\chi_3}}\mathrm{Br}_{\chi_3\to\mathcal{B}} - \Gamma_{\mathcal{B}}\Sigma - (\mathrm{Re}\,\Gamma_{12})\,\Pi + i\,(\mathrm{Im}\,\Gamma_{12})\,\Xi \\
&\quad - \frac{1}{2}\Big[\left(\langle\sigma v\rangle_+ + \langle\sigma v\rangle_-\right)\left(\Sigma^2 - \Delta^2 - 4n_{\rm eq}^2\right) \\
&\quad + \left(\langle\sigma v\rangle_+ - \langle\sigma v\rangle_-\right)\left(\Pi^2 - \Xi^2\right)\Big], \\
\left(\frac{d}{dt} + 3H\right)\Delta &= -\Gamma_{\mathcal{B}}\Delta + 2i\,(\mathrm{Re}\,M_{12})\,\Xi + 2\,(\mathrm{Im}\,M_{12})\,\Pi, \\
\left(\frac{d}{dt} + 3H\right)\Xi &= -(\Gamma_{\mathcal{B}} + 2\Gamma_- + \langle\sigma v\rangle_+\Sigma)\Xi \\
&\quad + 2i\,(\mathrm{Re}\,M_{12})\,\Delta - i\,(\mathrm{Im}\,\Gamma_{12})\,\Sigma, \\
\left(\frac{d}{dt} + 3H\right)\Pi &= -(\Gamma_{\mathcal{B}} + 2\Gamma_- + \langle\sigma v\rangle_+\Sigma)\Pi \\
&\quad - 2\,(\mathrm{Im}\,M_{12})\,\Delta - (\mathrm{Re}\,\Gamma_{12})\,\Sigma.
\end{aligned}$$

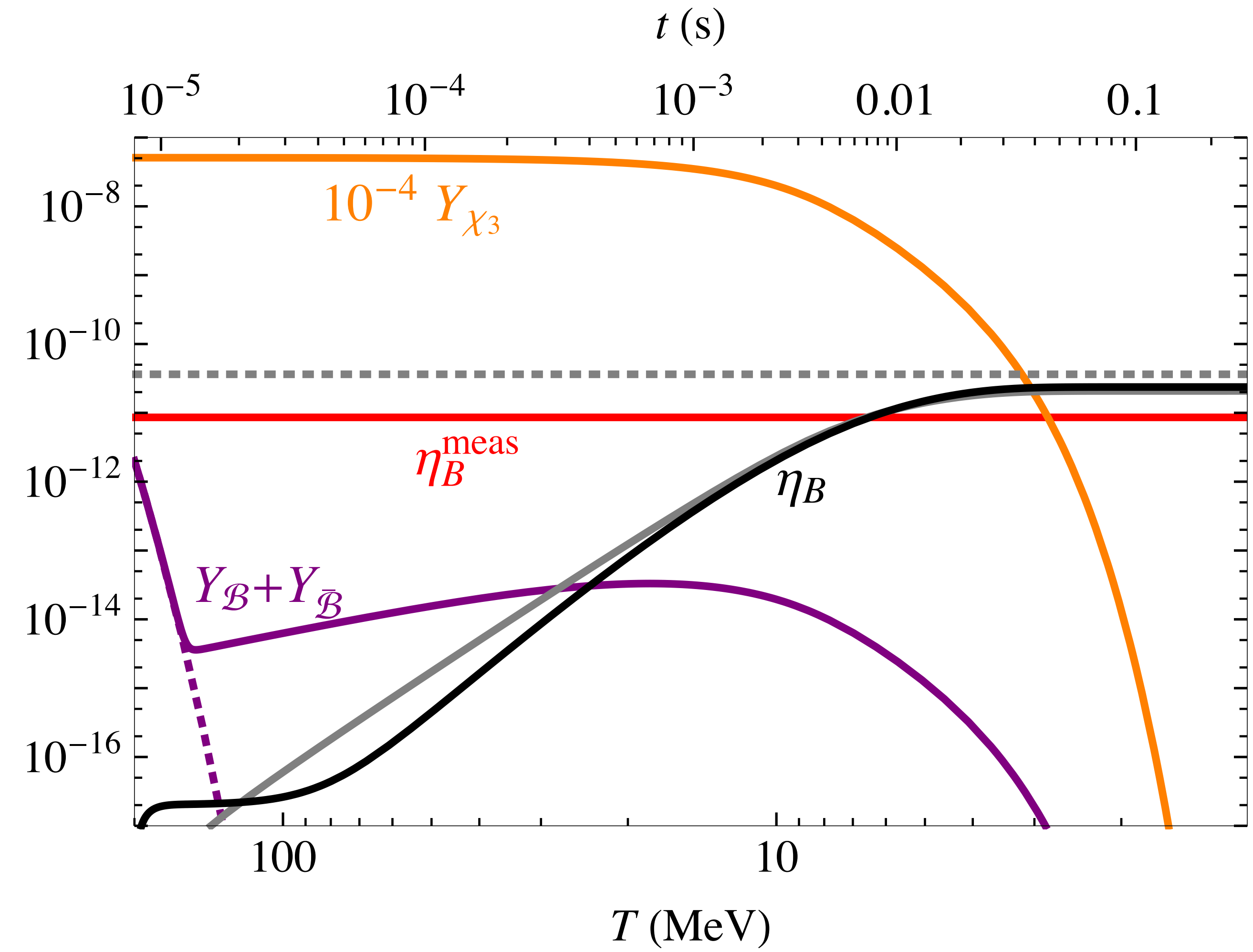
Decoherence due to

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



Baryon asymmetry calculation: Ω_{cb} $\quad \frac{|M_{12}|}{\Gamma_{\mathcal{B}}} = 10^{-2}, \quad \left|\frac{\Gamma_{12}}{M_{12}}\right| = 0.3$



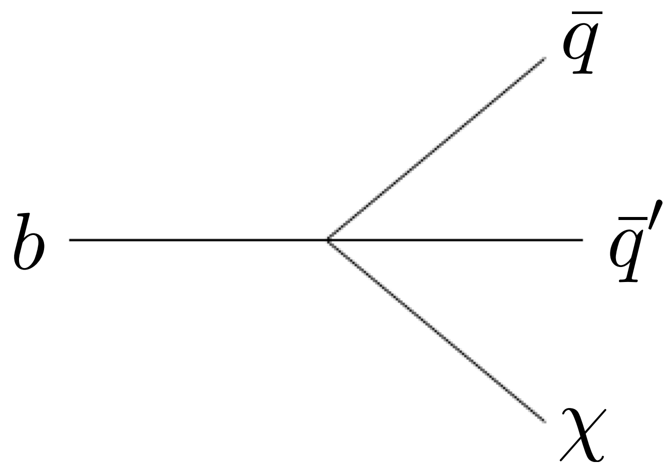


Sudden decay approx:

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

Can get observed asymmetry!

Probing this scenario



$$\Gamma_{b\to\bar{\chi}\bar{q}_i\bar{q}_j} \sim \frac{1}{60\,(2\pi)^3}\frac{m_b \Delta m^4}{\Lambda_b^4}$$

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

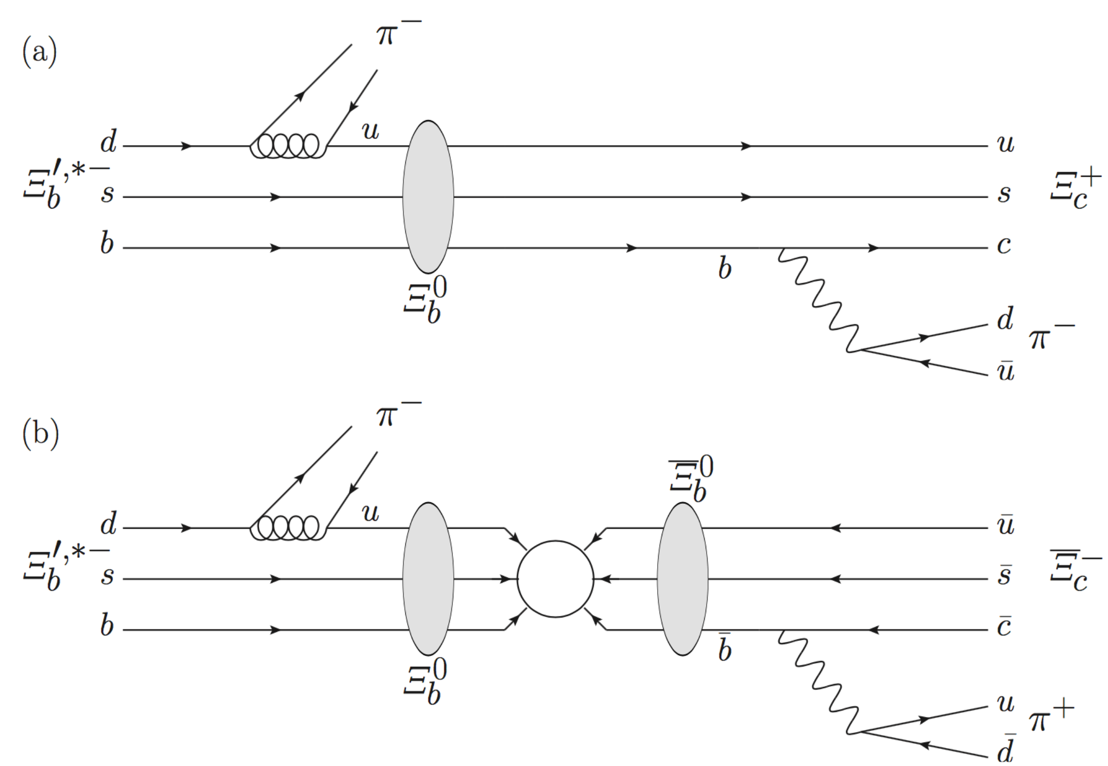
$$\text{baryon} \to \text{meson(s)} + \chi_i .$$

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

Search for baryon-number-violating Ξ_b^0 oscillations

LHCb collaboration [1708.05808]

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



Further work in progress…

Conclusions

Firm evidence that there is a baryon-antibaryon asymmetry in the Universe

Given inflation, can't be "initial condition" and must happen dynamically

Shown that this could be generated by oscillation of QCD bound state, possibly one we know already

Interesting and testable