

# Oscillations and Baryogenesis

David McKeen

March 23, 2017

Seyda Ipek, DM, & Ann Nelson 1407.8193

Akshay Ghalsasi, DM, & Ann Nelson 1508.05392

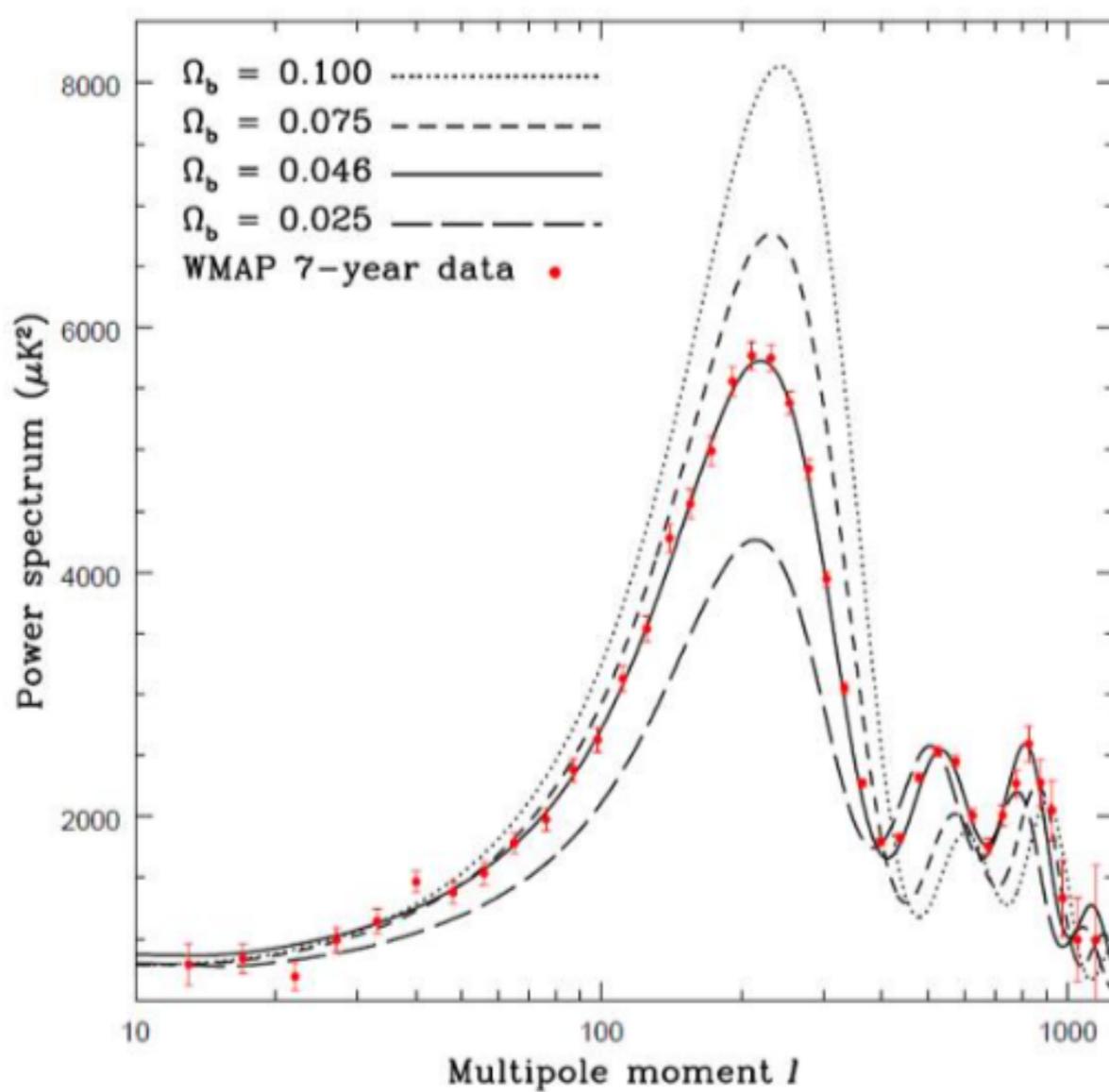
DM & Ann Nelson 1512.05359

Kyle Aitken, DM, Thomas Neder, & Ann Nelson in prep.

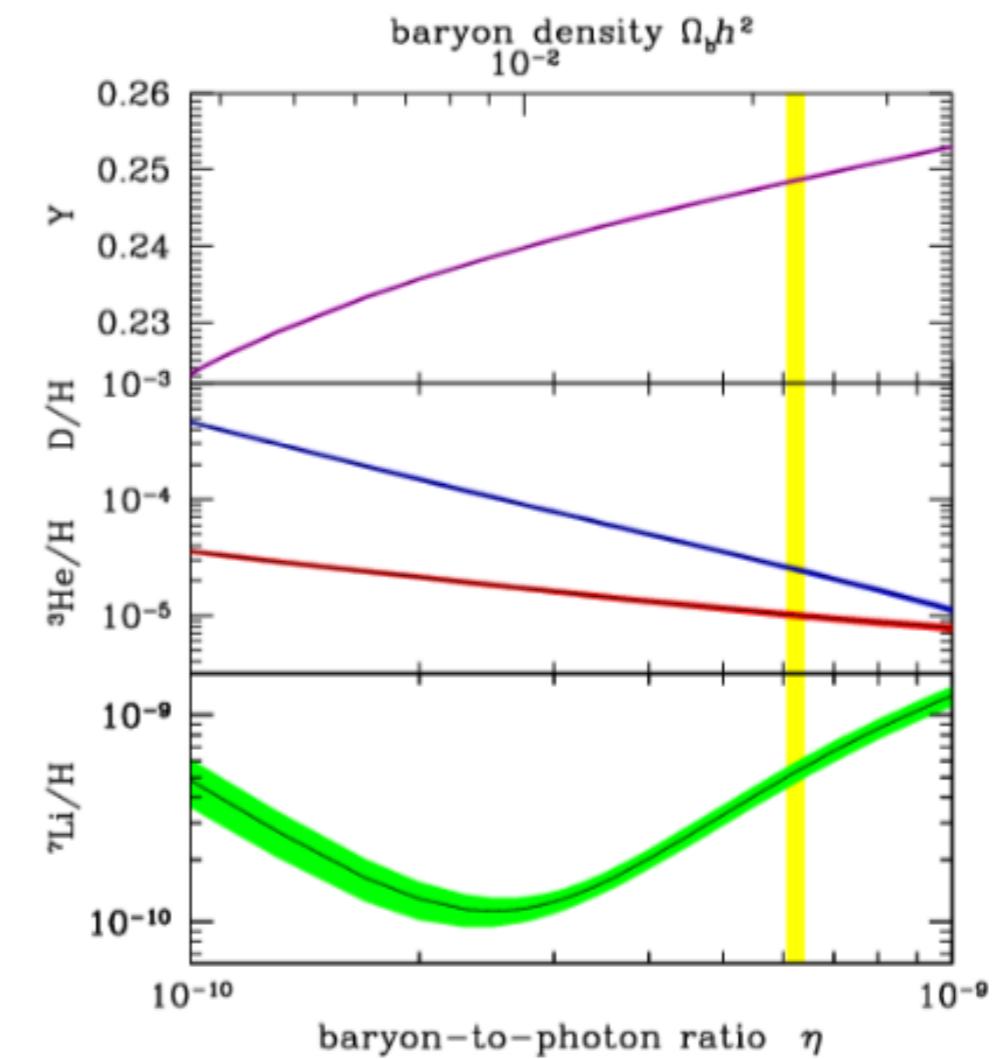
# Outline

- Why Baryogenesis (matter-antimatter asymmetry)?
- Describe a model where oscillations of QCD bound state can explain asymmetry
- Discussion of baryon-antibaryon oscillations
- Motivation for a tweak to the model
- 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 (sphalerons in SM)
- 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

# Generating baryons requires BSM physics

Sakharov conditions:

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

but 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.?

No direct evidence reheating T was high

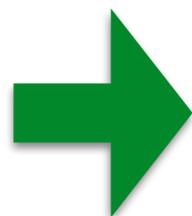
Issues with high reheat T:

Gravitino production in SUSY extensions

Moroi et al. ('93)

Isocurvature perturbations

Fox et al. ('04)



Seek baryogenesis at low scales

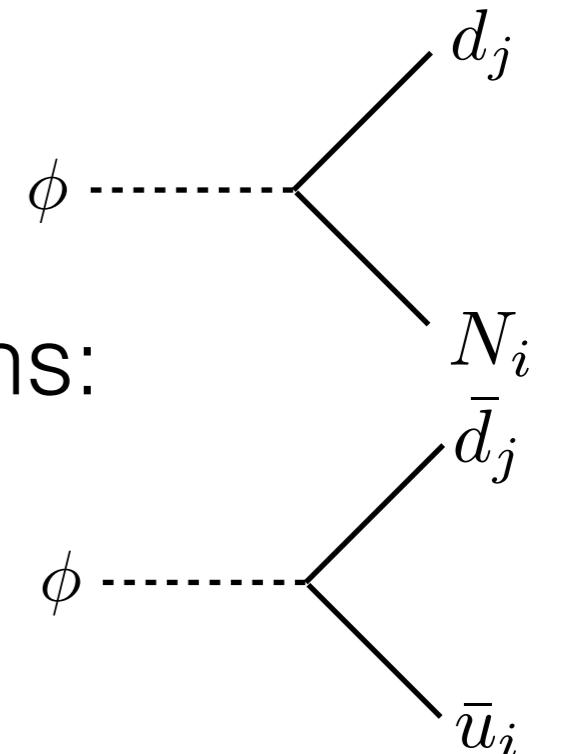
# Model for low scale baryogenesis

A (colored) scalar  $\phi$

Neutral Majorana fermions  $N_i$

(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

$$\Phi_q \left\{ \begin{array}{c} \phi^* \cdots \\ q \end{array} \right. \left. \begin{array}{c} N_i \\ \bar{d}_j \end{array} \right\} N_i + \dots \equiv \Gamma_{\Phi_q \rightarrow N_i}$$

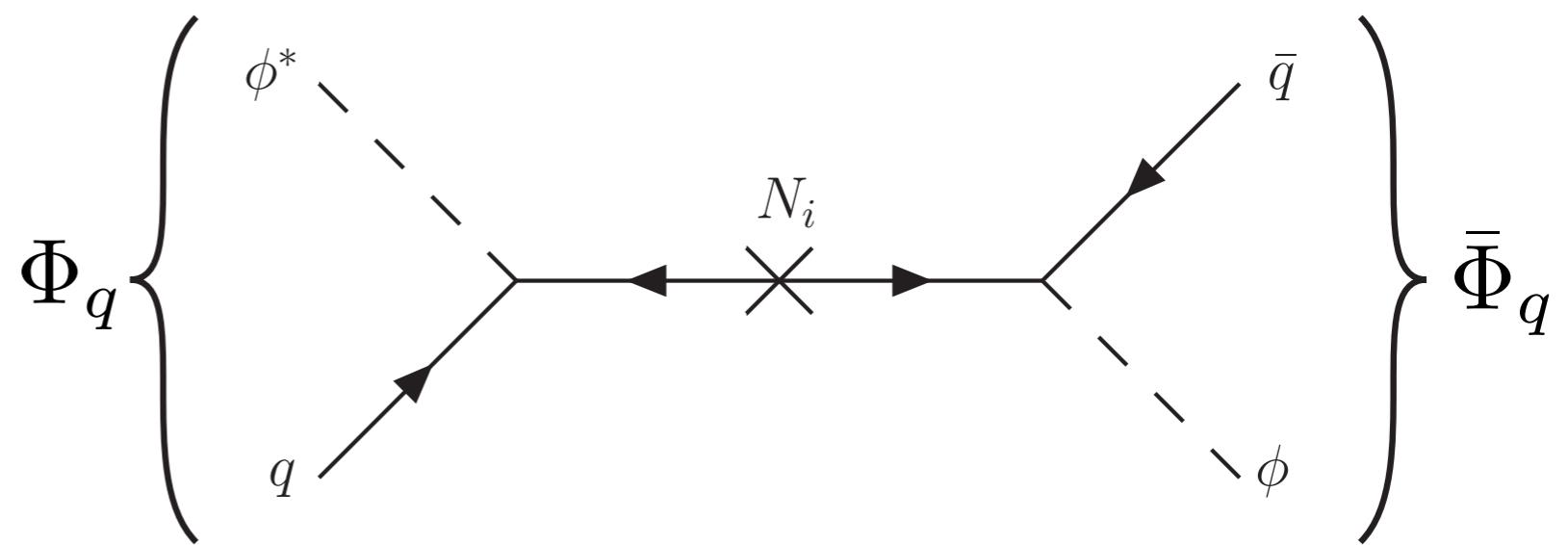
Decay modes:

$$\Phi_q \left\{ \begin{array}{c} \phi^* \cdots \\ q \end{array} \right. \left. \begin{array}{c} u_i \\ d_j \end{array} \right\} B = +1 + \dots \equiv \Gamma_{\Phi_q \rightarrow B}$$

+conjugate modes

# Mesinos

(Neutral) mesinos can turn into antimesinos



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

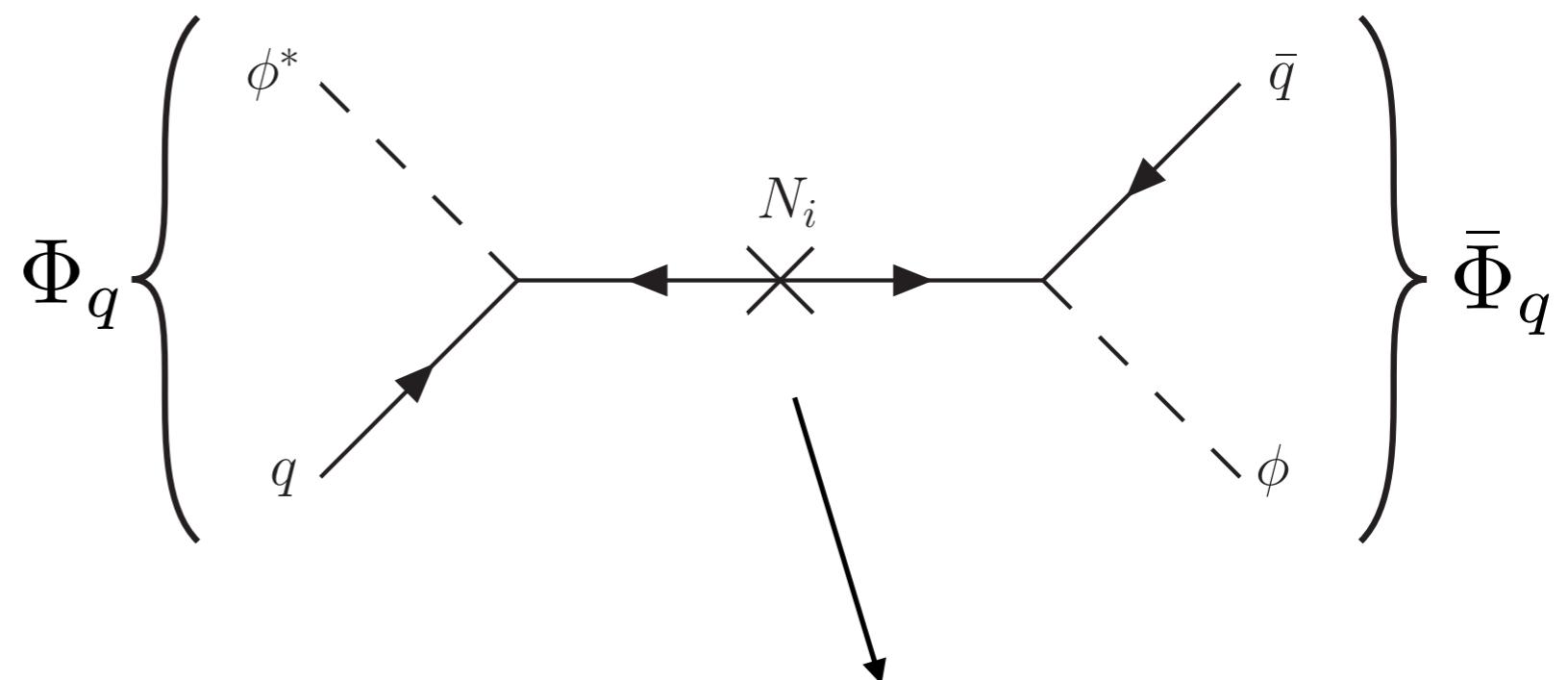
$$H = M - \frac{i}{2}\Gamma$$

Mass eigenstates are an admixture of “flavor” eigenstates

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

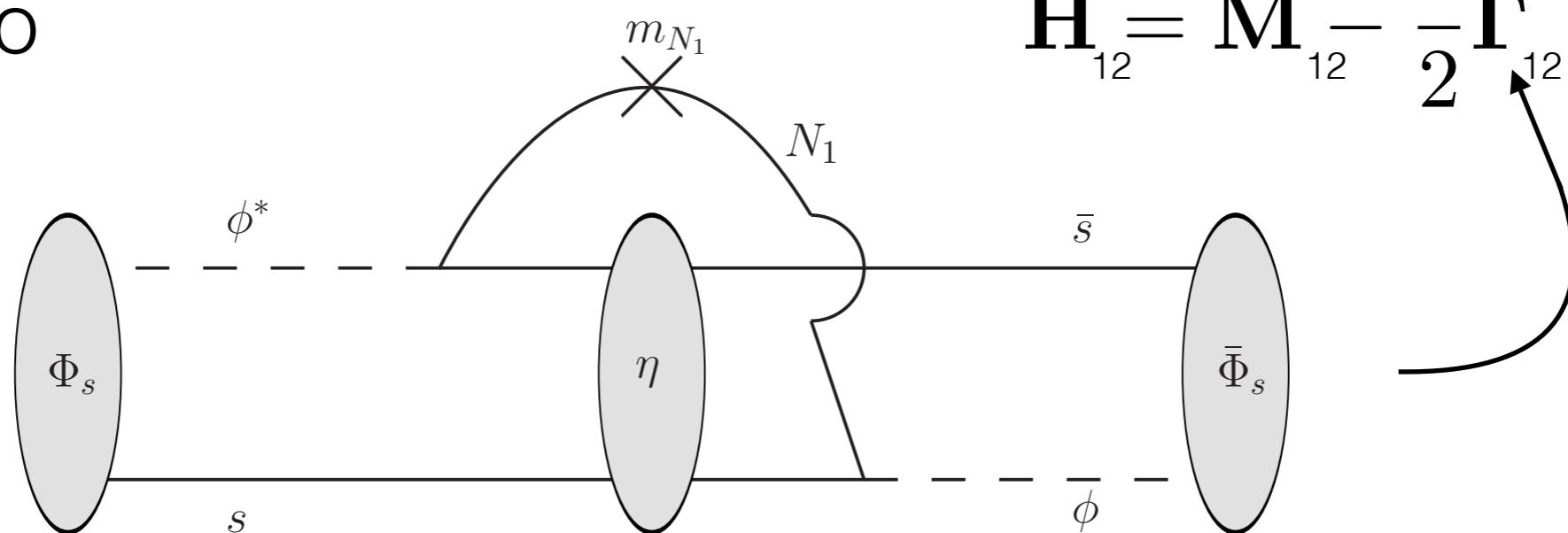
# Mesinos

In addition to this



there is also

will take  
 $q=s$



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

# Mesinos

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

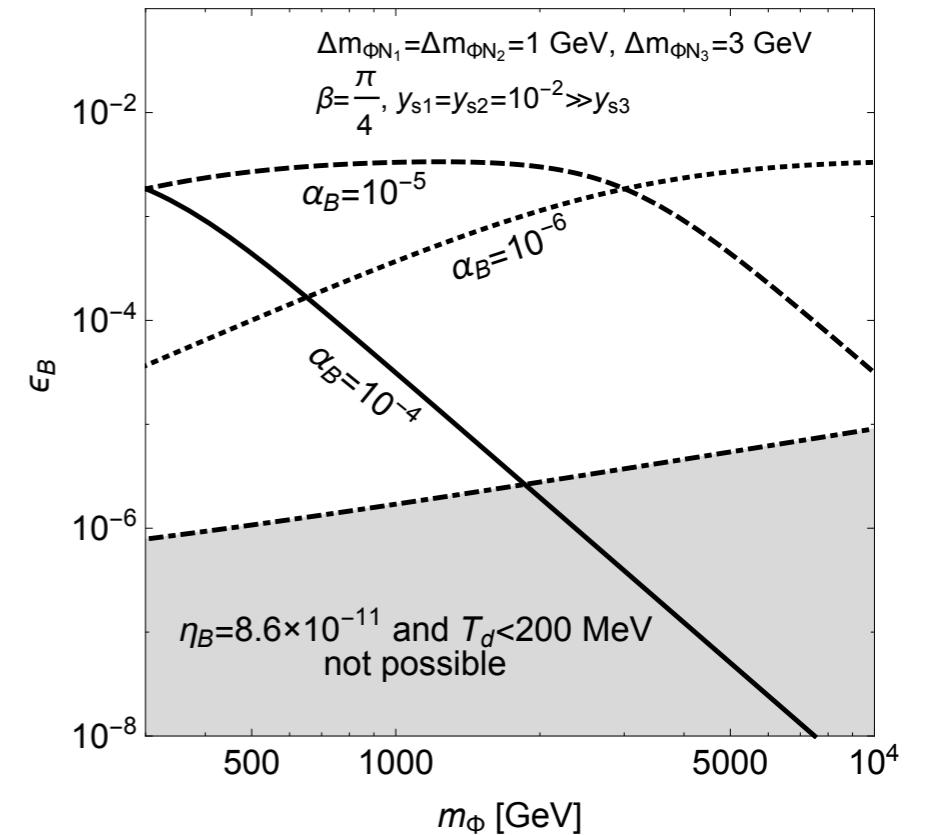
Want  $m_{\Phi_s} - m_{N_1} \sim \text{GeV}$

Using  $|\Gamma_{12}| \sim \Gamma_{\Phi_q \rightarrow N_1}$ , can find

$$\begin{aligned} \epsilon_B &= \frac{2 \text{Im} \mathbf{M}_{12}^* \Gamma_{12}}{\Gamma^2 + 4 |\mathbf{M}_{12}|^2} \text{Br}_{\Phi_q \rightarrow B} \\ &\sim \min \left( \frac{2 |\mathbf{M}_{12}|}{\Gamma}, \frac{\Gamma}{2 |\mathbf{M}_{12}|} \right) \sin \beta \text{Br}_{\Phi_q \rightarrow N_1} \text{Br}_{\Phi_q \rightarrow B} \end{aligned}$$

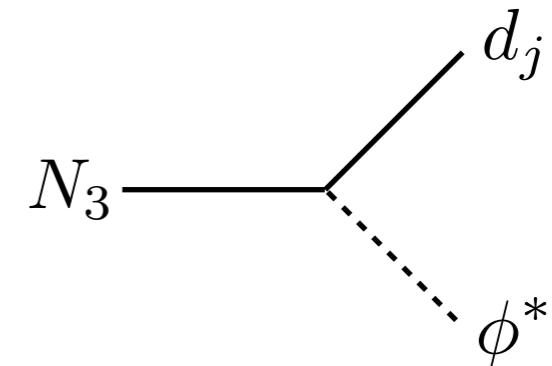
(Need >2 N's)

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



# Producing the baryon asymmetry

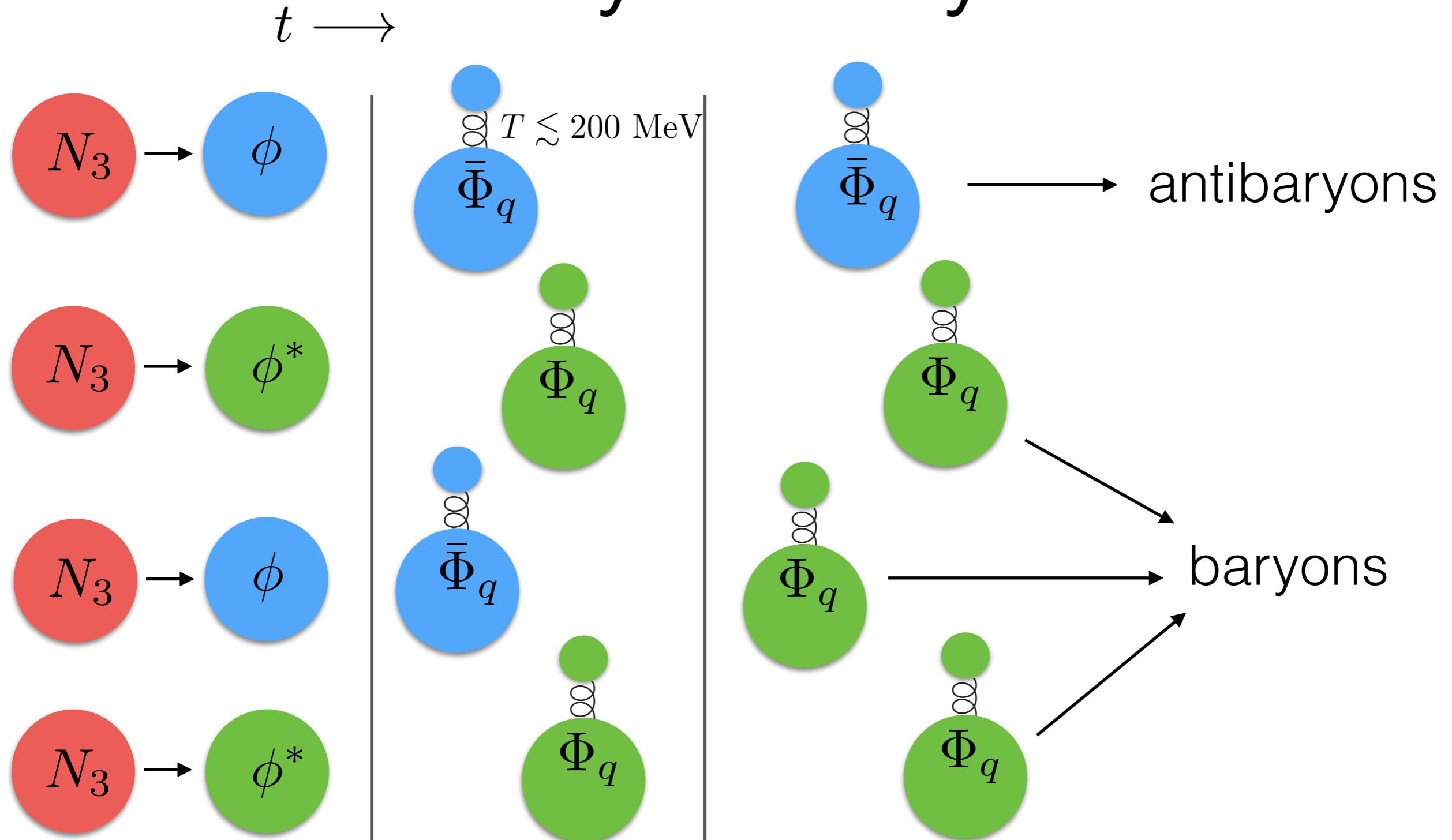
Need a source of scalars/  
mesinos out of thermal  
equilibrium (i.e. distinct from  
strong interactions)



For definiteness, can use the  
decay of a singlet  $N_3$

$t_{N_3} \sim 10^{-5}$  s means  
 $T \lesssim T_{\text{QCD}} \sim 200$  MeV  
so that mesinos form

# Producing the baryon asymmetry



# Calculating the asymmetry

Evolution of relevant energy densities:

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

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

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

Simple sudden decay approx:

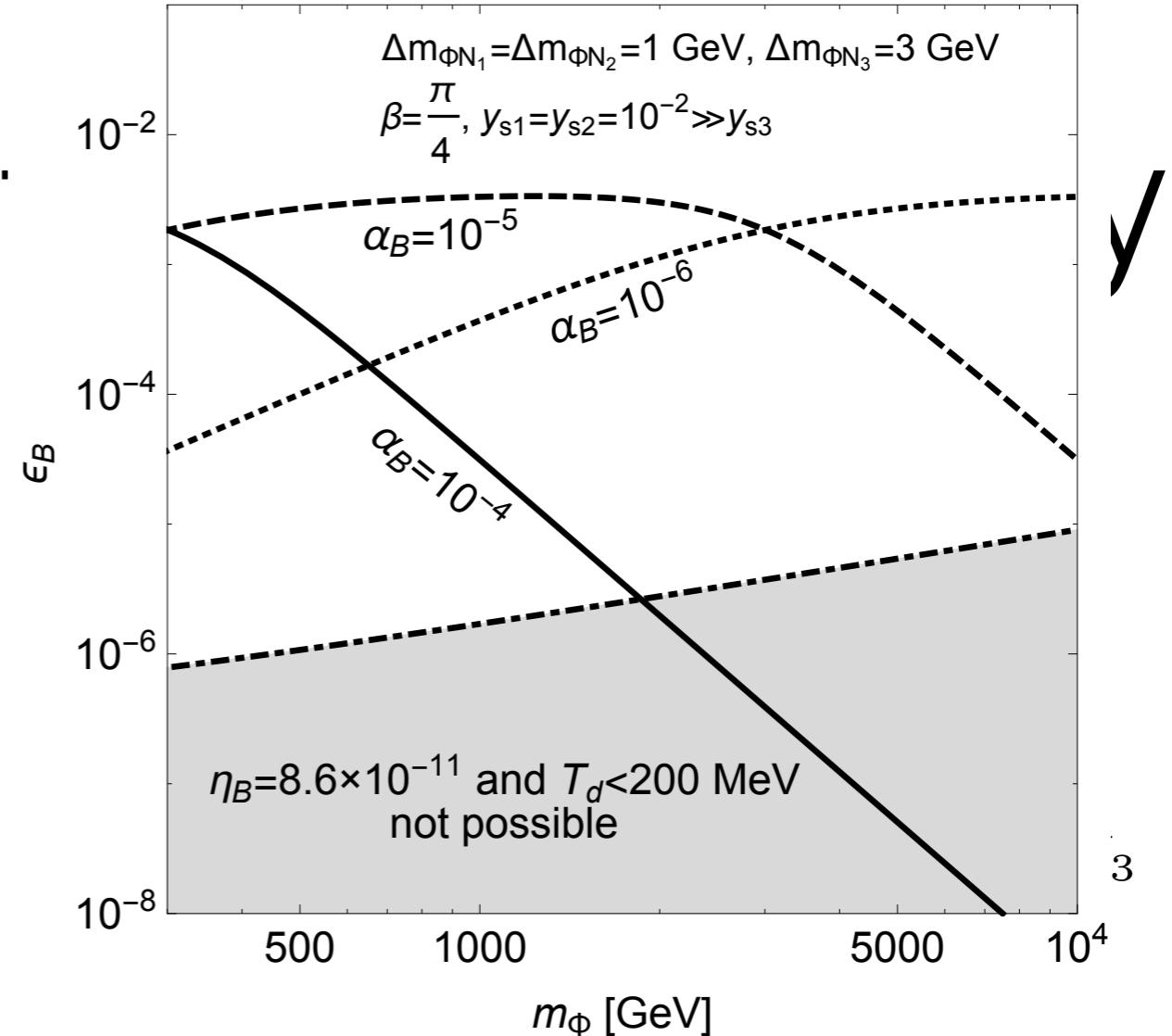
$$\begin{aligned}\eta_B &= \frac{n_B(t = t_{\text{decay}}^+)}{s_{\text{rad}}(t = t_{\text{decay}}^+)} = \frac{n_{N_3}(t = t_{\text{decay}}^-)}{s_{\text{rad}}(t = t_{\text{decay}}^+)} \times \frac{1}{2}A\epsilon_B \\ &\simeq 6.1 \times 10^{-10} \left( \frac{116.25}{g_*(T_i)} \right) \left( \frac{10}{1+\xi} \right)^{3/4} \left( \frac{A}{1/3} \right) \left( \frac{\epsilon_B}{10^{-5}} \right).\end{aligned}$$

$\xi \propto (m_{N_3}^2 t_{N_3})^{2/3}$  is an “entropy dilution” factor

# Calculating

Evolution of relevant energy densities:

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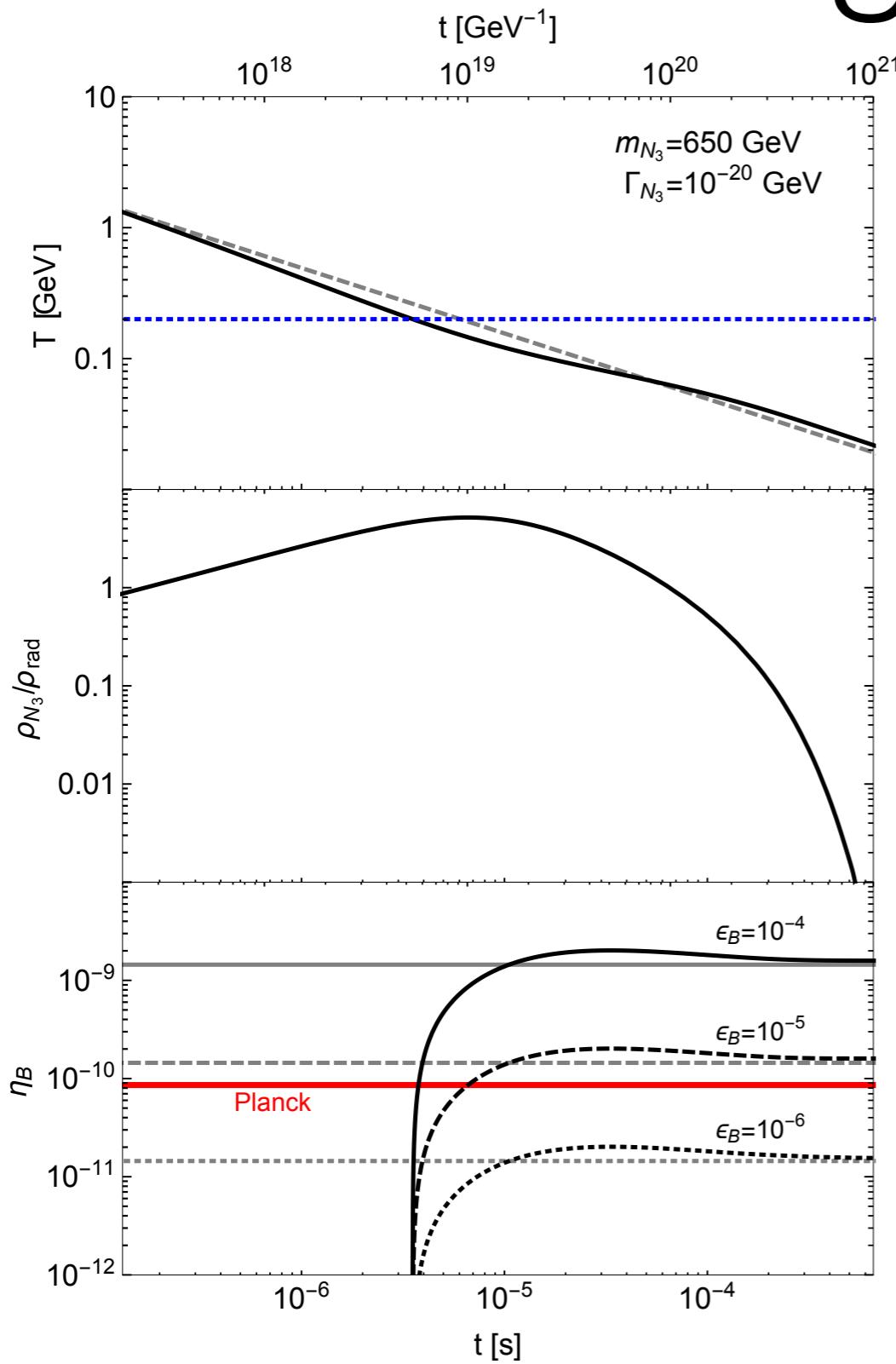


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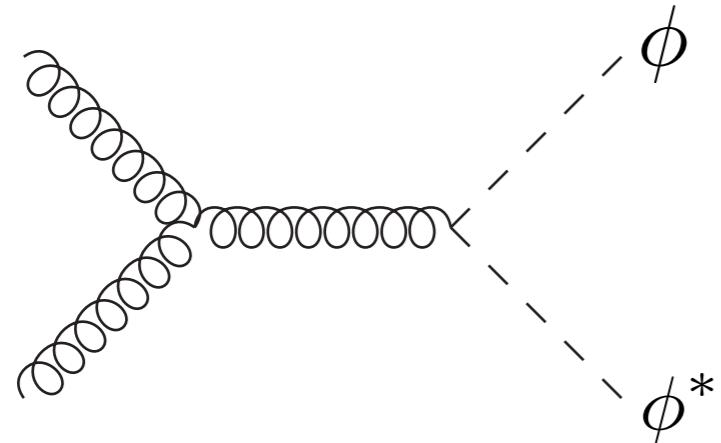
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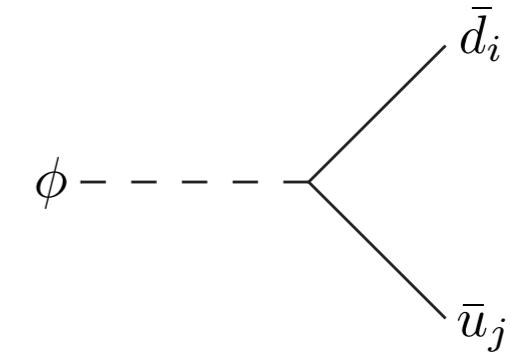
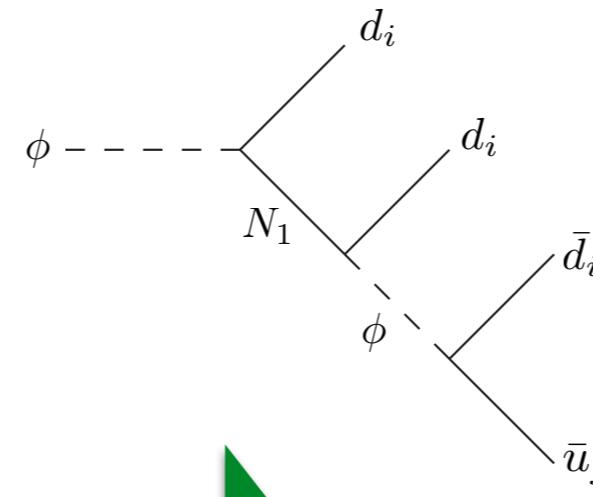
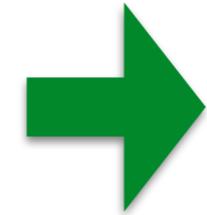
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Simple sudden  
decay approx is not  
a bad estimate

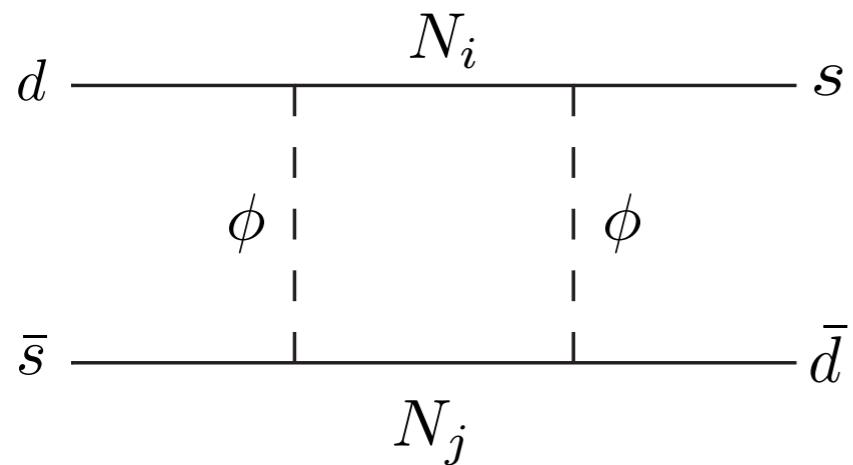
# Constraints



Searches for multijet  
final states at LHC

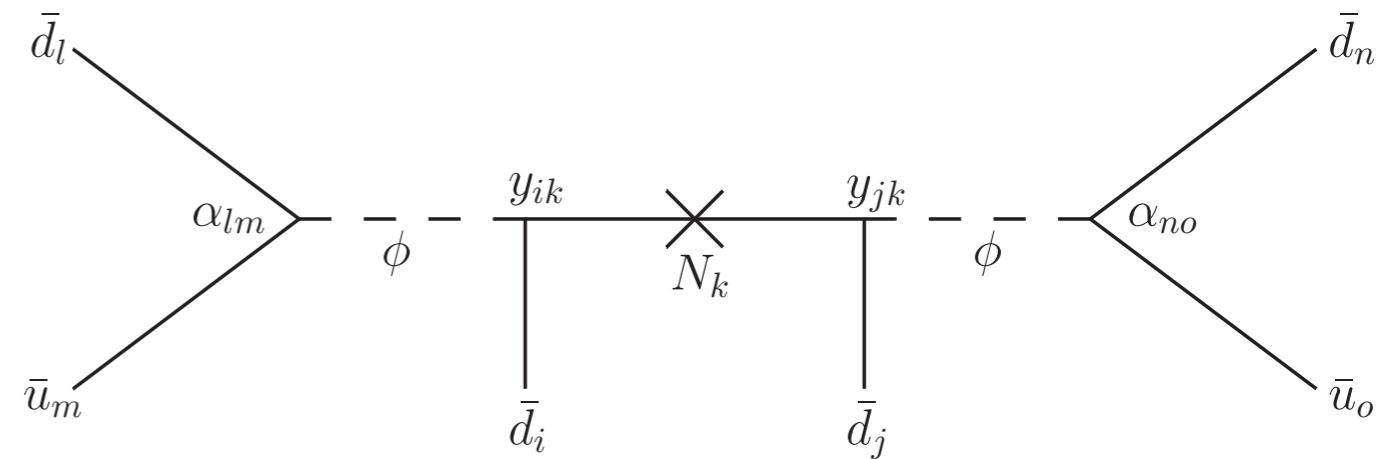


$$m_\phi \gtrsim 300 - 600 \text{ GeV}$$



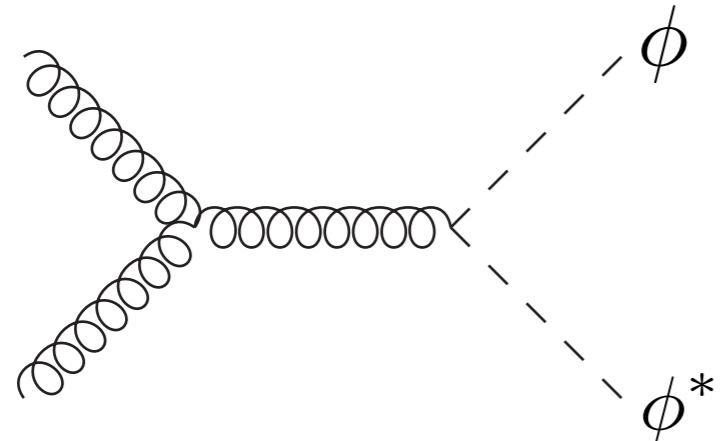
$$\left( \operatorname{Re} \sum_{i,j} y_{di}^* y_{dj} y_{si} y_{sj}^* \right)^{1/4} < 0.40 \sqrt{\frac{m_\phi}{650 \text{ GeV}}},$$

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

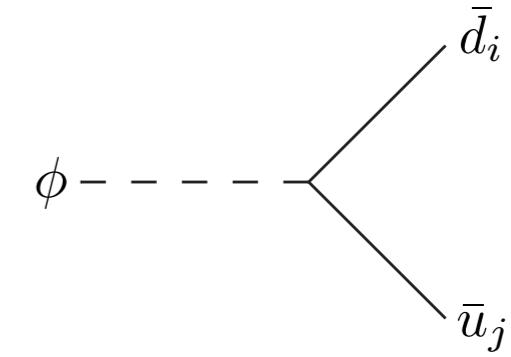
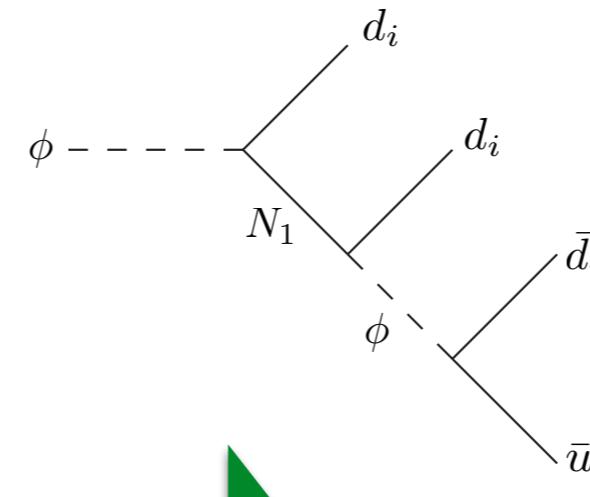
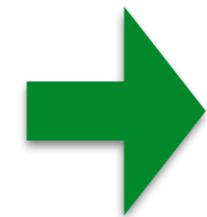


$$\Delta B = 2$$

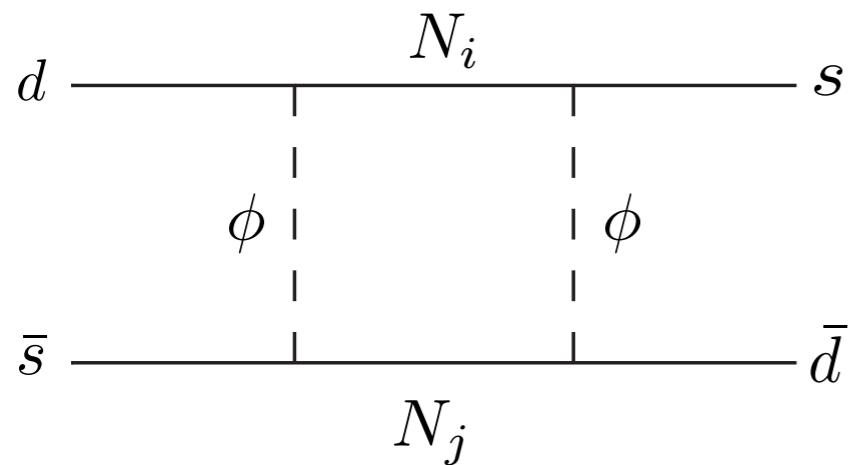
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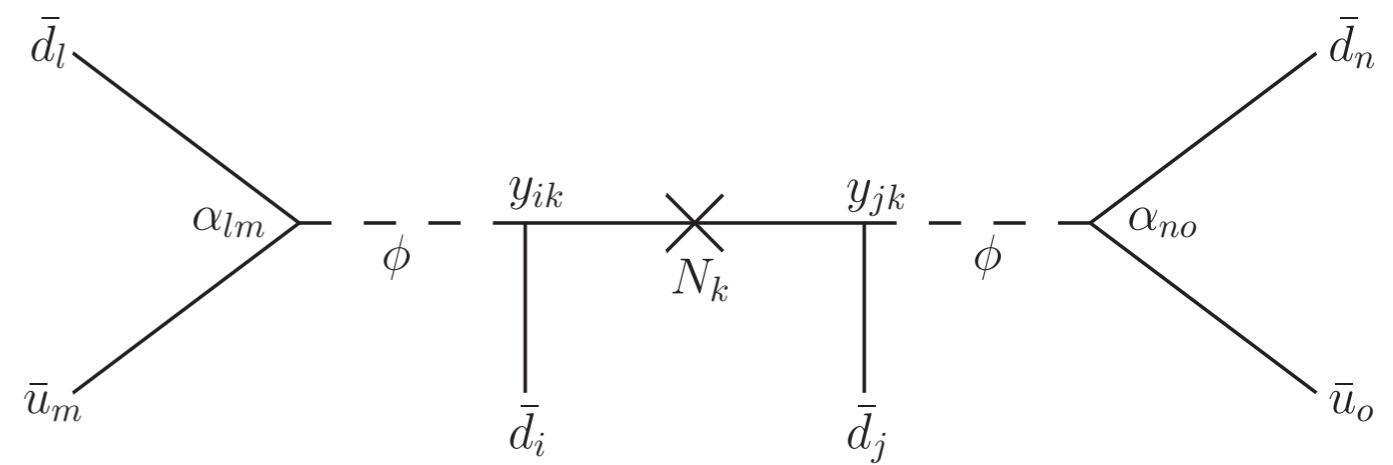


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$$\Delta B = 2$$

Will return to this

Instead of mesinos, could  
oscillations of baryons we  
know source BAU?

# Neutron Oscillations

Developed formalism to compute  
nonrelativistic 4x4 Hamiltonian

Ipek, McKeen, Nelson ('14)

$$H = \begin{pmatrix} m_n \times \mathbb{1} - \mu_n \mathbf{B} \cdot \boldsymbol{\sigma} & M_{12} \times \mathbb{1} \\ M_{12}^* \times \mathbb{1} & m_n \times \mathbb{1} + \mu_n \mathbf{B} \cdot \boldsymbol{\sigma} \end{pmatrix} + \frac{i}{2} \begin{pmatrix} \Gamma_n \times \mathbb{1} & \Gamma_{12} \times \mathbb{1} \\ \Gamma_{12}^* \times \mathbb{1} & \Gamma_n \times \mathbb{1} \end{pmatrix}$$

Can rotate so that spin quant. axis  
parallel to B field, 2x2 description  
sufficient, standard formulae correct

See Gardner & Jafari ('14)

CP violation is

$$\frac{P_{n \rightarrow \bar{n}}}{P_{\bar{n} \rightarrow n}} = \left| \frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}} \right|^2 \neq 1$$

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new physics

Can rotate so that spin quant. axis parallel to B field, 2x2 description sufficient, standard formulae correct

CP violation is

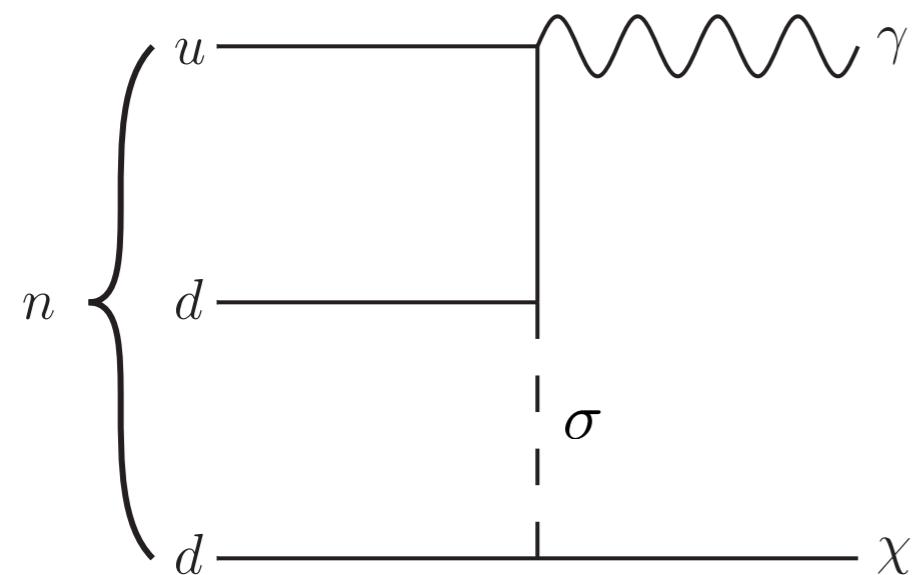
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# Neutron Oscillations

Is appreciable CPV possible?

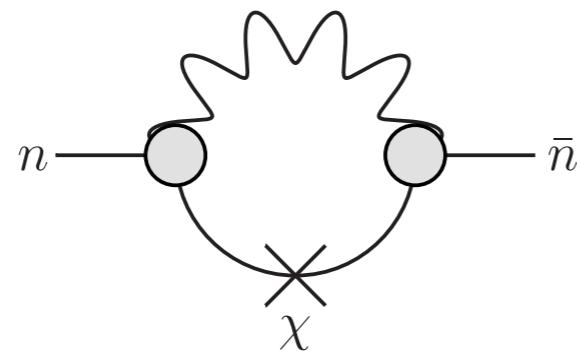
$n \rightarrow \bar{p}e^+\nu_e, \bar{n} \rightarrow p e^-\bar{\nu}_e$  dim-12, \*extremely\* suppressed

Need to consider new state lighter than neutron



$m_p - m_e < m_\chi < m_p + m_e$   
guarantees stability of  $\chi, p$   
 $Z_2$  subgroup of B  
number preserved

# Neutron Oscillations



$$\Gamma_{12} \sim 10^{-47} \text{ GeV} \left( \frac{10^8 \text{ GeV}}{M} \right)^4 \left( \frac{\Delta m}{1 \text{ MeV}} \right)^3$$

$$M_{12} \sim 10^{-33} \text{ GeV} \left( \frac{10^8 \text{ GeV}}{M} \right)^4 \left( \frac{1 \text{ MeV}}{\Delta m} \right)$$

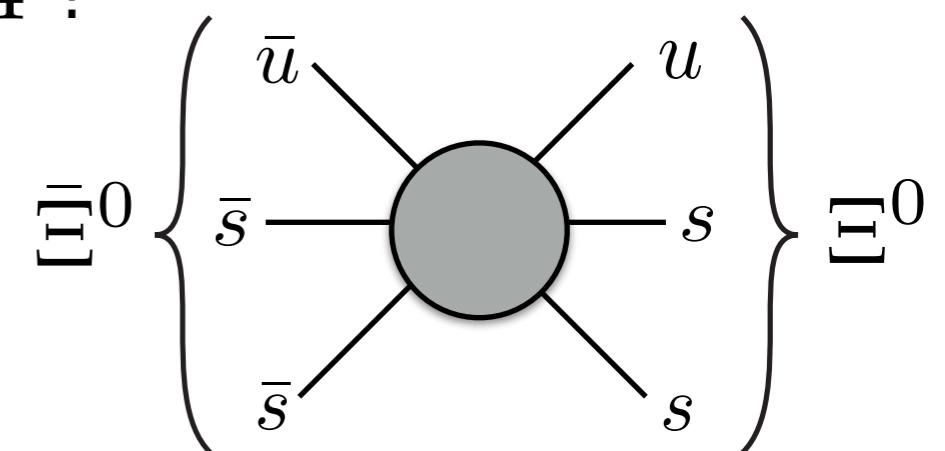
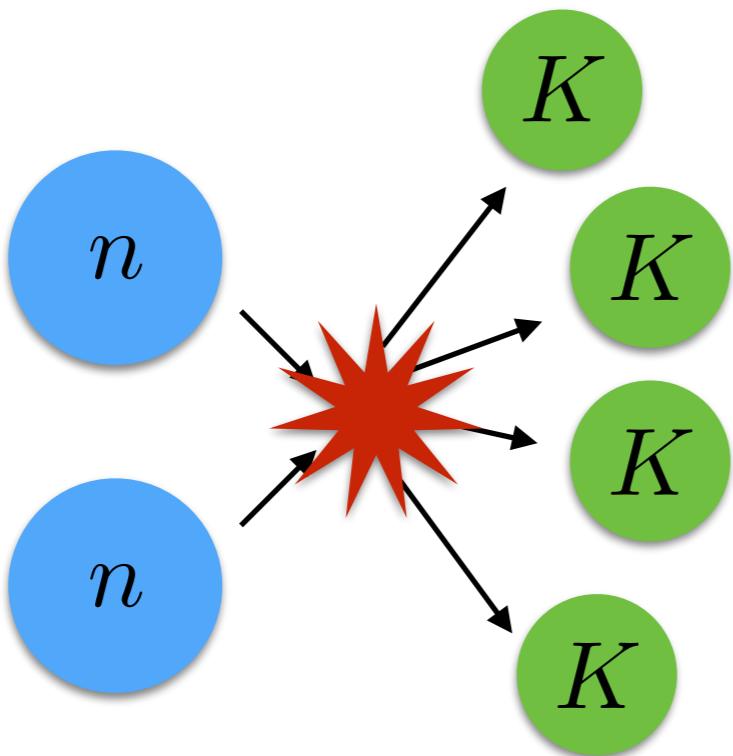
dinucleon decay/free n osc.

or 
$$\frac{P_{n \rightarrow \bar{n}}}{P_{\bar{n} \rightarrow n}} - 1 \propto \frac{|\Gamma_{12}|}{|M_{12}|} \lesssim 10^{-14} \left( \frac{\Delta m}{1 \text{ MeV}} \right)^4$$

$$\frac{P_{n \rightarrow \bar{n}}}{P_{n \rightarrow p e^- \bar{\nu}}} \propto \frac{|M_{12}|^2}{\Gamma_n^2} \sim 10^{-12} \left( \frac{|M_{12}|}{10^{-33} \text{ GeV}} \right)^2 \quad \text{tiny! but...}$$

# Heavy Flavor Oscillations

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



is kinematically forbidden!

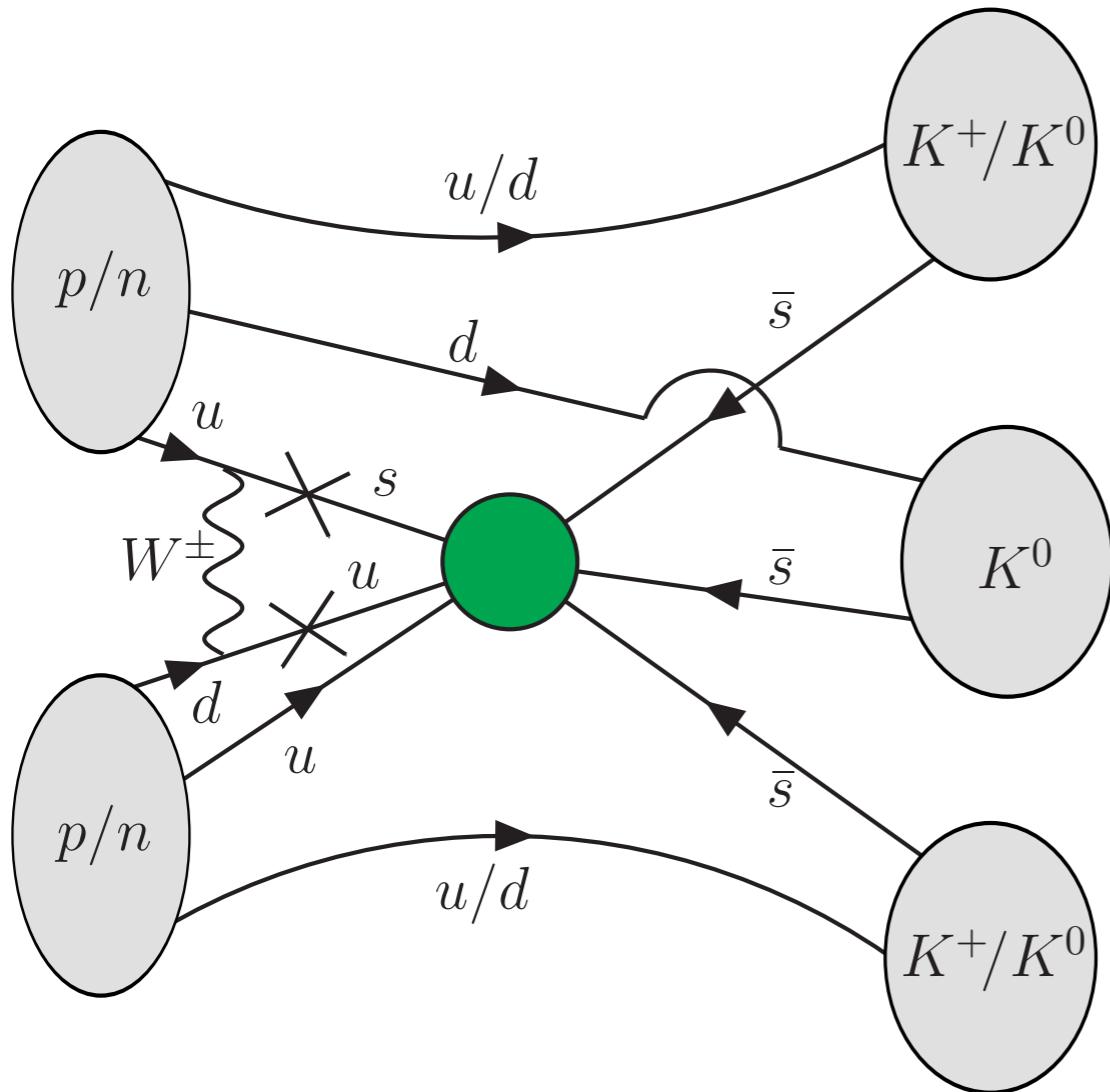
Dominant constraints could be from colliders

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

Kuzmin ('94)

# Heavy Flavor Oscillations

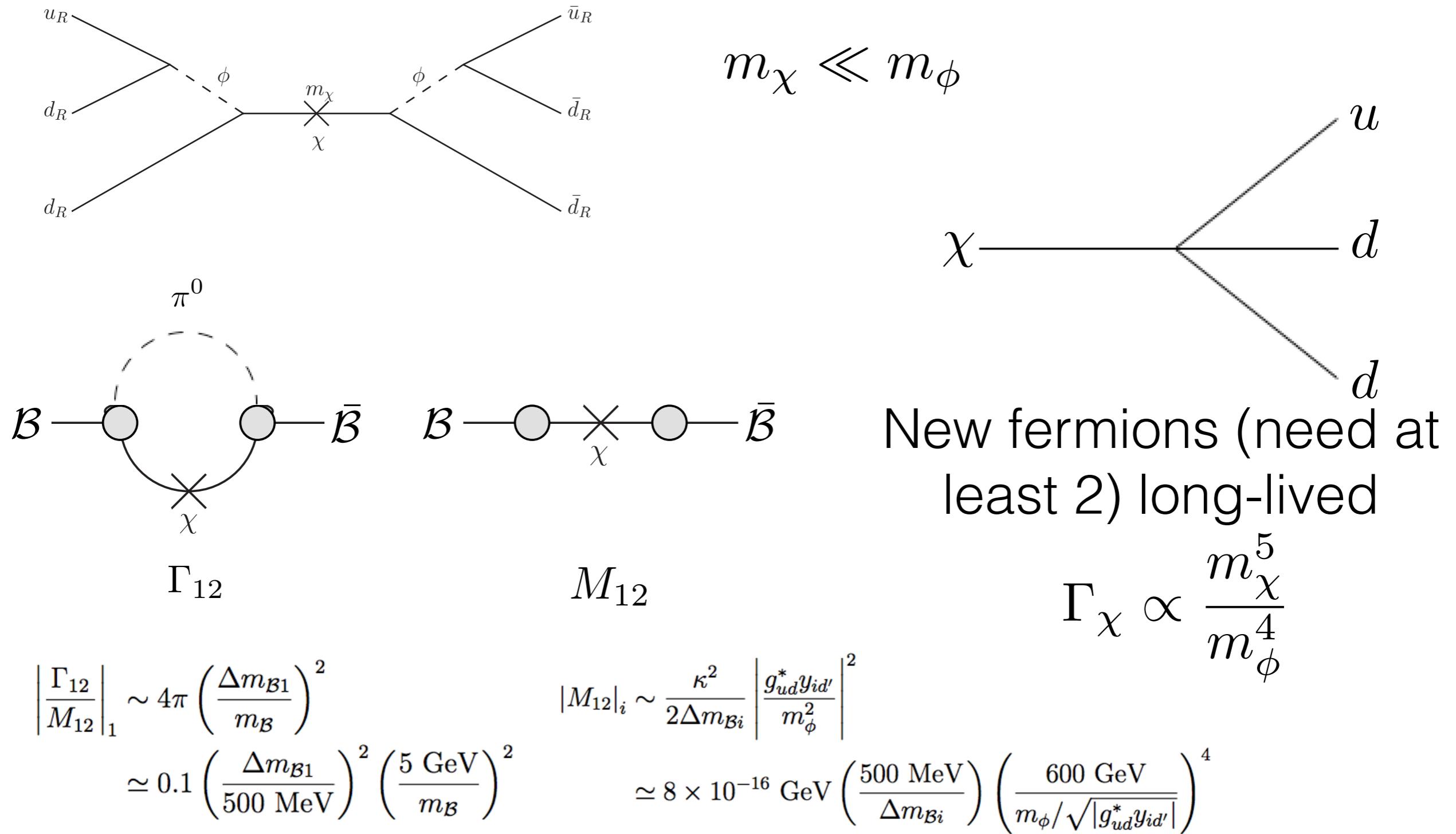
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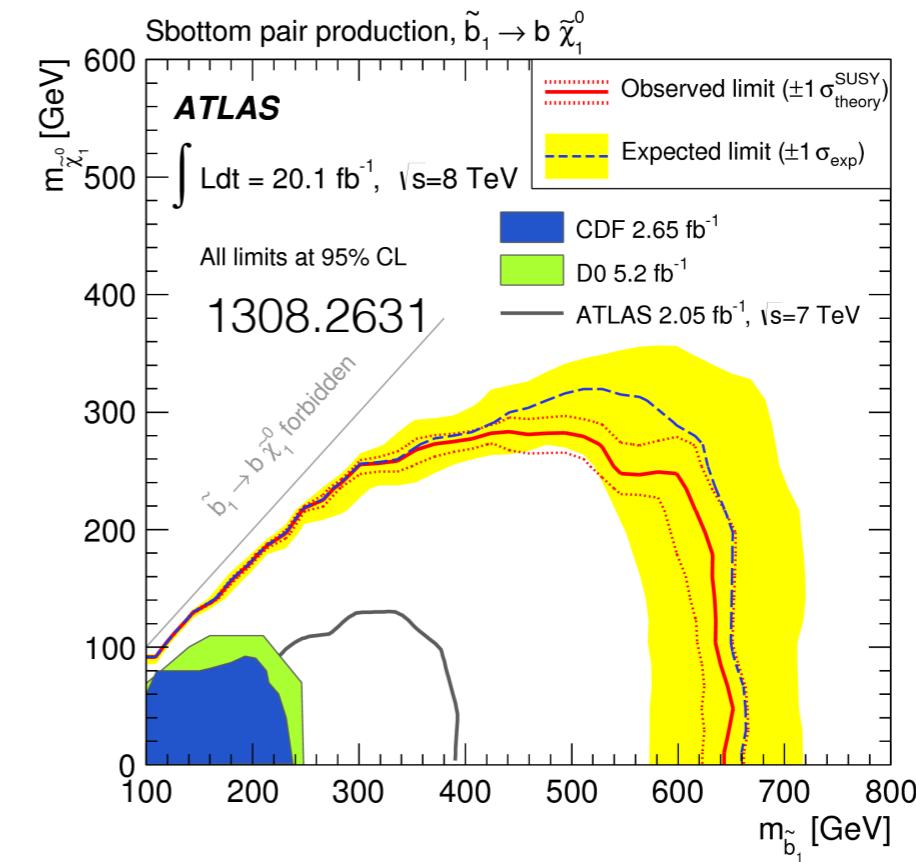
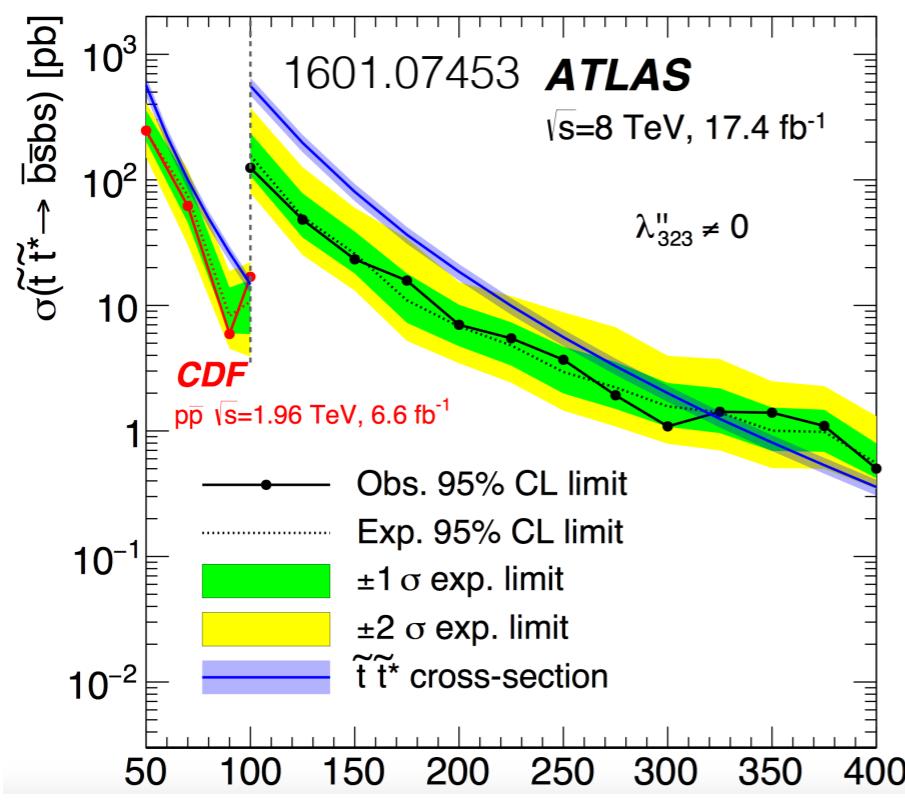
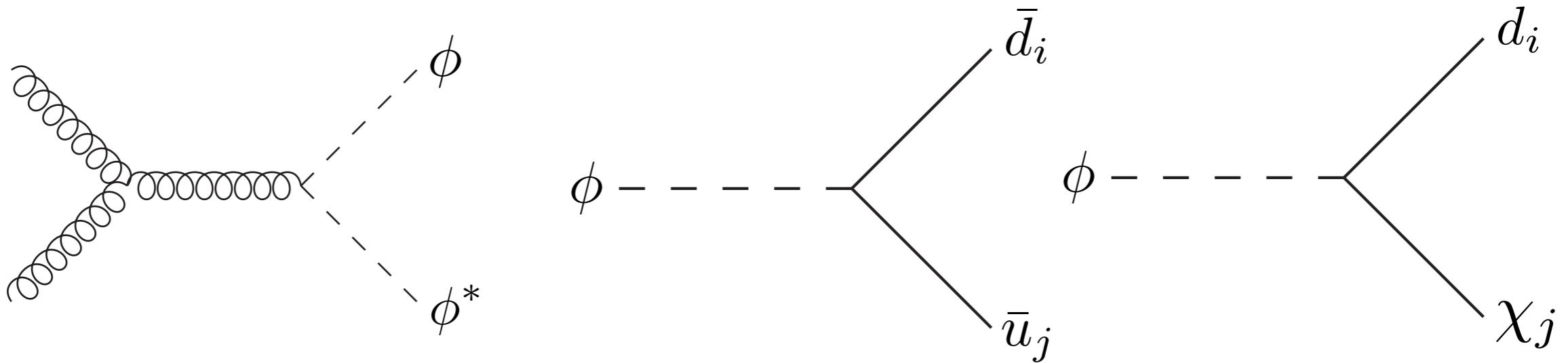
$$\frac{1}{4\pi^2} \frac{G_F}{\sqrt{2}} |V_{us}^*| |V_{ud}| m_u m_s \log \left( \frac{m_W^2}{\Lambda_{\text{IR}}^2} \right) \sim 10^{-10}$$

Operator	$\mathcal{B}$	Weak Loops Required	Measured $\Gamma$ (GeV) [32]	Limits on $\delta_{\mathcal{B}\mathcal{B}} = M_{12}$ (GeV) Dinucleon decay
$(udd)^2$	$n$	None	$(7.477 \pm 0.009) \times 10^{-28}$	$10^{-33}$
$(uds)^2$	$\Lambda$	None	$(2.501 \pm 0.019) \times 10^{-15}$	$10^{-30}$
$(uds)^2$	$\Sigma^0$	None	$(8.9 \pm 0.8) \times 10^{-6}$	$10^{-30}$
$(uss)^2$	$\Xi^0$	One	$(2.27 \pm 0.07) \times 10^{-15}$	$10^{-20}$
$(ddc)^2$	$\Sigma_c^0$	Two	$(1.83^{+0.11}_{-0.19}) \times 10^{-3}$	$10^{-16}$
$(dsc)^2$	$\Xi_c^0$	Two	$(5.88^{+0.68}_{-0.52}) \times 10^{-12}$	$10^{-17}$
$(ssc)^2$	$\Omega_c^0$	Two	$(9.5 \pm 1.7) \times 10^{-12}$	$10^{-15}$
$(udb)^2$	$\Lambda_b^0$	Two	$(4.490 \pm 0.031) \times 10^{-13}$	$10^{-13}$
$(udb)^2$	$\Sigma_b^{0\dagger}$	Two	$\sim 10^{-3\dagger}$	$10^{-13}$
$(usb)^2$	$\Xi_b^0$	Two	$(4.496 \pm 0.095) \times 10^{-13}$	$10^{-10}$
$(dcb)^2$	$\Xi_{cb}^{0\dagger}$	Two	Unknown	$10^{-17}$
$(scb)^2$	$\Omega_{cb}^{0\dagger}$	Two	Unknown	$10^{-14}$
$(ubb)^2$	$\Xi_{bb}^{0\dagger}$	Four	Unknown	$>1$
$(ccb)^2$	$\Omega_{ccb}^{0\dagger}$	Four	Unknown	$>1$

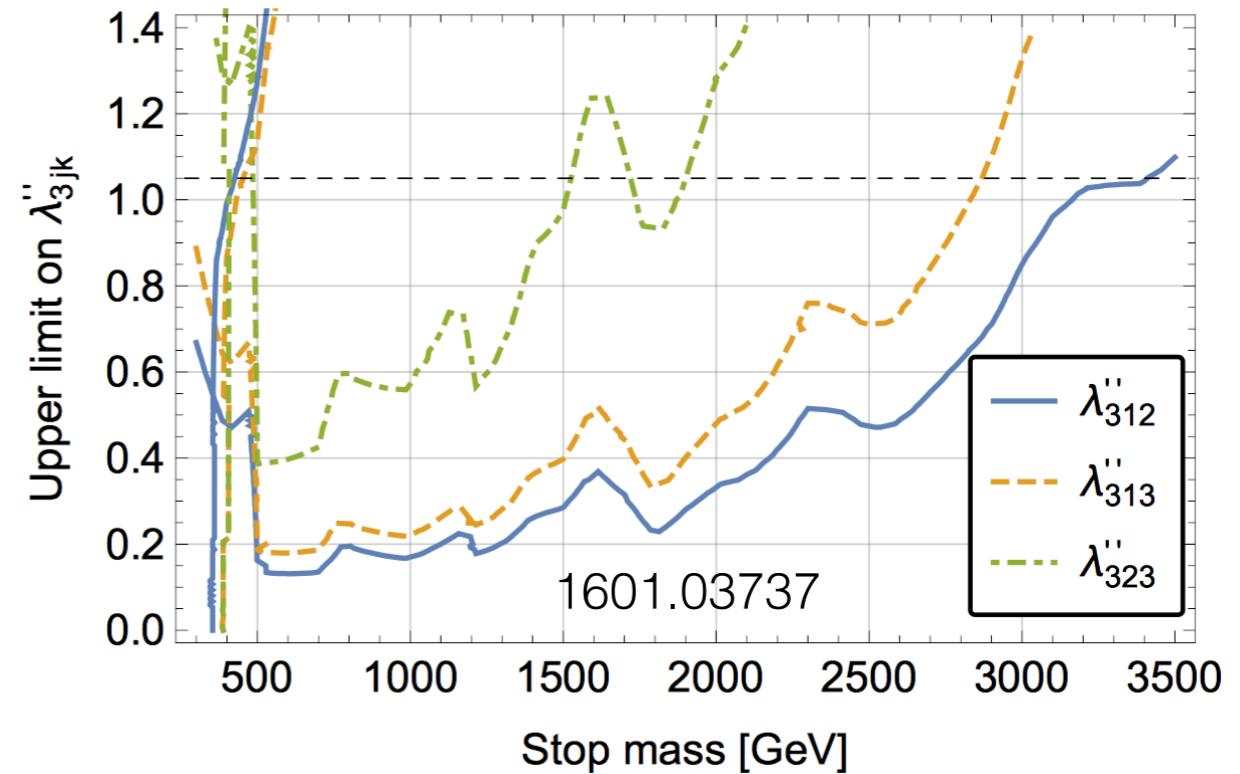
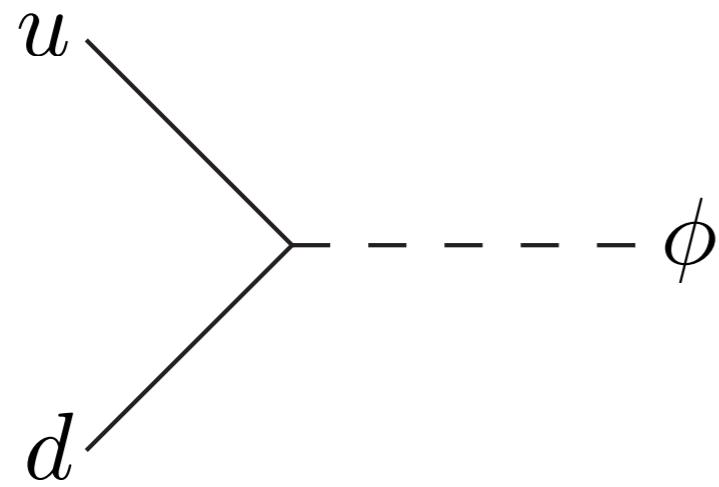
# Same model, different regime



# Collider constraints

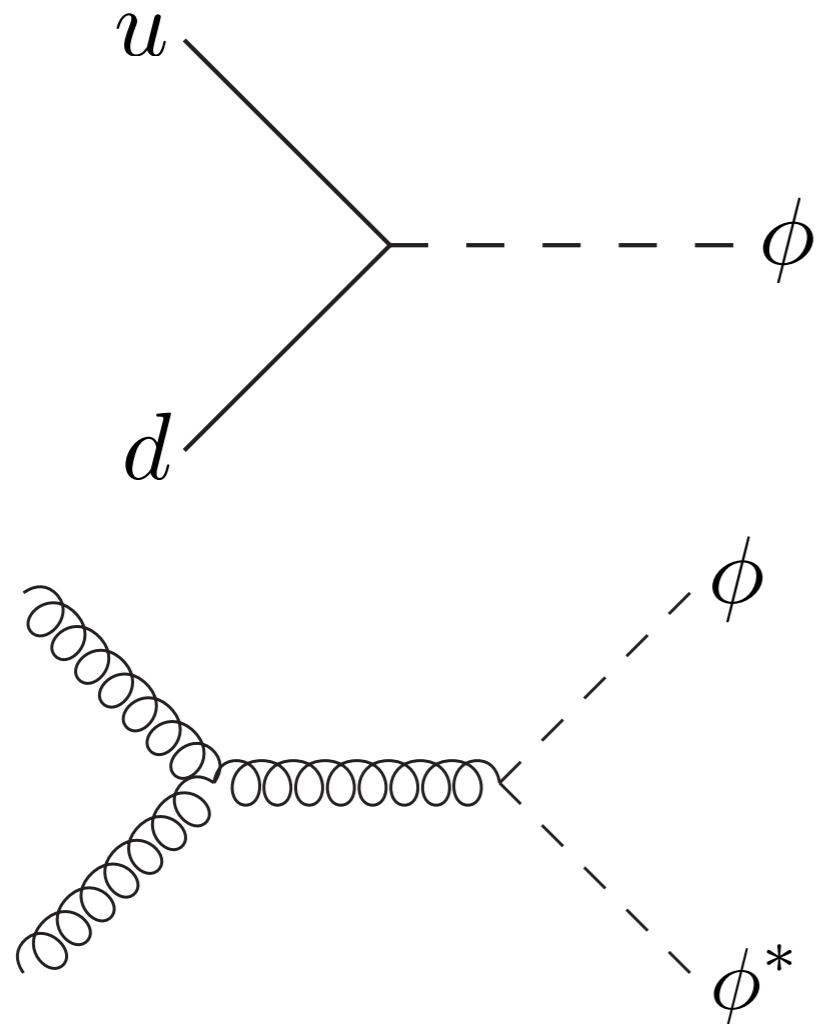


# Collider constraints



Resonant production is important!

# Collider constraints



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$(scb)^2$	$\Omega_{cb}^{0\dagger}$	Two	Unknown	$10^{-14}$	$10^{-14}$	
$(ubb)^2$	$\Xi_{bb}^{0\dagger}$	Four	Unknown	$>1$	$10^{-15}$	
$(ccb)^2$	$\Omega_{ccb}^{0\dagger}$	Four	Unknown	$>1$	$10^{-14}$	

Cosmology is a little bit more complicated  
 (Again, production out-of-eq. through decays)

$$\begin{aligned} \frac{d\rho_{\text{rad}}}{dt} + 4H\rho_{\text{rad}} &= \Gamma_{\chi_3}\rho_{\chi_3} & \frac{d\rho_{\chi_3}}{dt} + 3H\rho_{\chi_3} &= -\Gamma_{\chi_3}\rho_{\chi_3} \\ \frac{dn}{dt} + 3Hn &= -i(\mathcal{H}n - n\mathcal{H}^\dagger) - \frac{\Gamma_\pm}{2}[O_\pm, [O_\pm, n]] \\ &\quad - \langle\sigma v\rangle_\pm \left( \frac{1}{2} \{n, O_\pm \bar{n} O_\pm\} - n_{\text{eq}}^2 \right) + \frac{1}{2} \frac{\Gamma_{\chi_3}\rho_{\chi_3}}{m_{\chi_3}} \text{Br}_{\chi_3 \rightarrow \mathcal{B}}, \end{aligned} \quad \text{Tulin, Yu, Zurek}$$

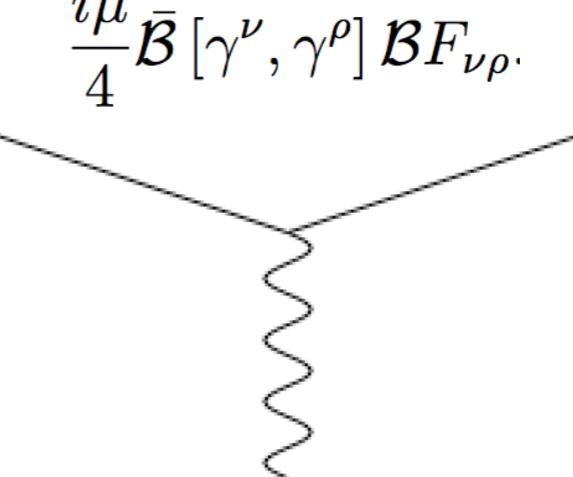
Heavy B system:

Change of variables

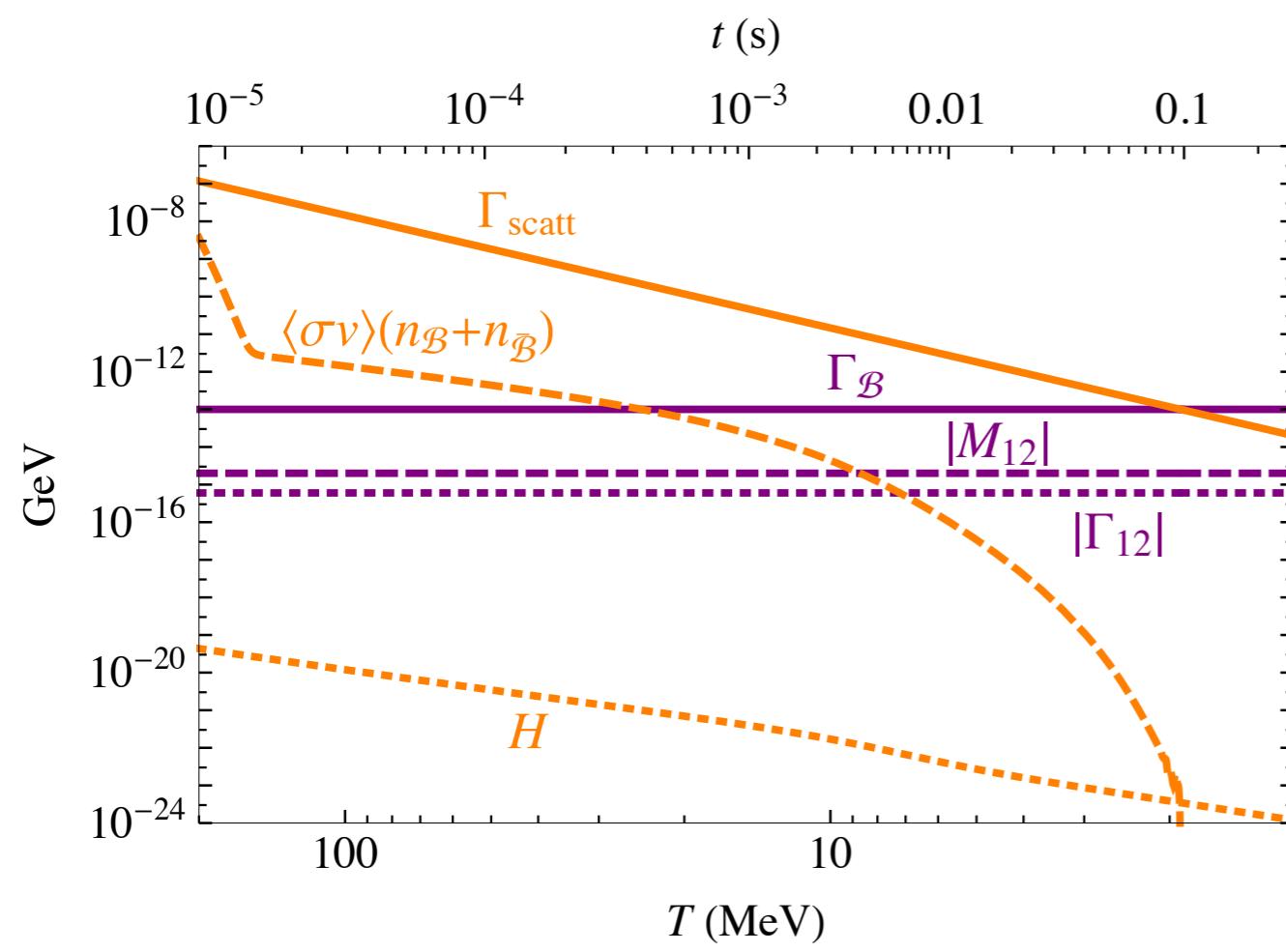
$$n = \begin{pmatrix} n_{\mathcal{B}\mathcal{B}} & n_{\mathcal{B}\bar{\mathcal{B}}} \\ n_{\bar{\mathcal{B}}\mathcal{B}} & n_{\bar{\mathcal{B}}\bar{\mathcal{B}}} \end{pmatrix}, \quad \bar{n} = \begin{pmatrix} n_{\bar{\mathcal{B}}\bar{\mathcal{B}}} & n_{\mathcal{B}\bar{\mathcal{B}}} \\ n_{\mathcal{B}\bar{\mathcal{B}}}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

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

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



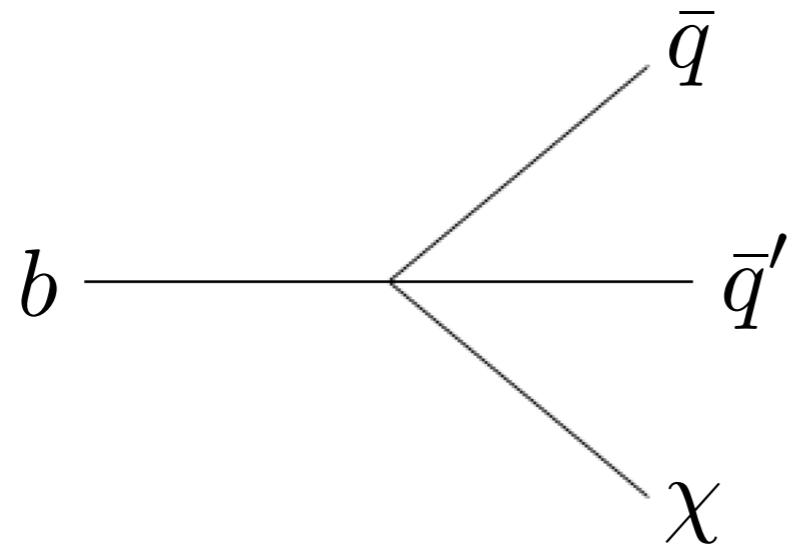
# Numerical Solution



Sudden decay approx.

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

# Hadron decays



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

branchings can be  $\mathcal{O}(10^{-5})$

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

A search for baryon- and lepton-number violating decays of  $\Lambda$  hyperons using the CLAS detector at Jefferson Laboratory

1507.03859

$\Lambda \rightarrow \bar{p}\pi^+$	$5.00 \times 10^{-4}$	0.0425	4.98	0	0	2.44	$9 \times 10^{-7}$
$\Lambda \rightarrow K_S^0 \nu$	0.01875	0.0600	2.23	239.25	-3.88	14.1	$2 \times 10^{-5}$

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**