Mesogenesis

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MITP Mega Dark Matter Workshop

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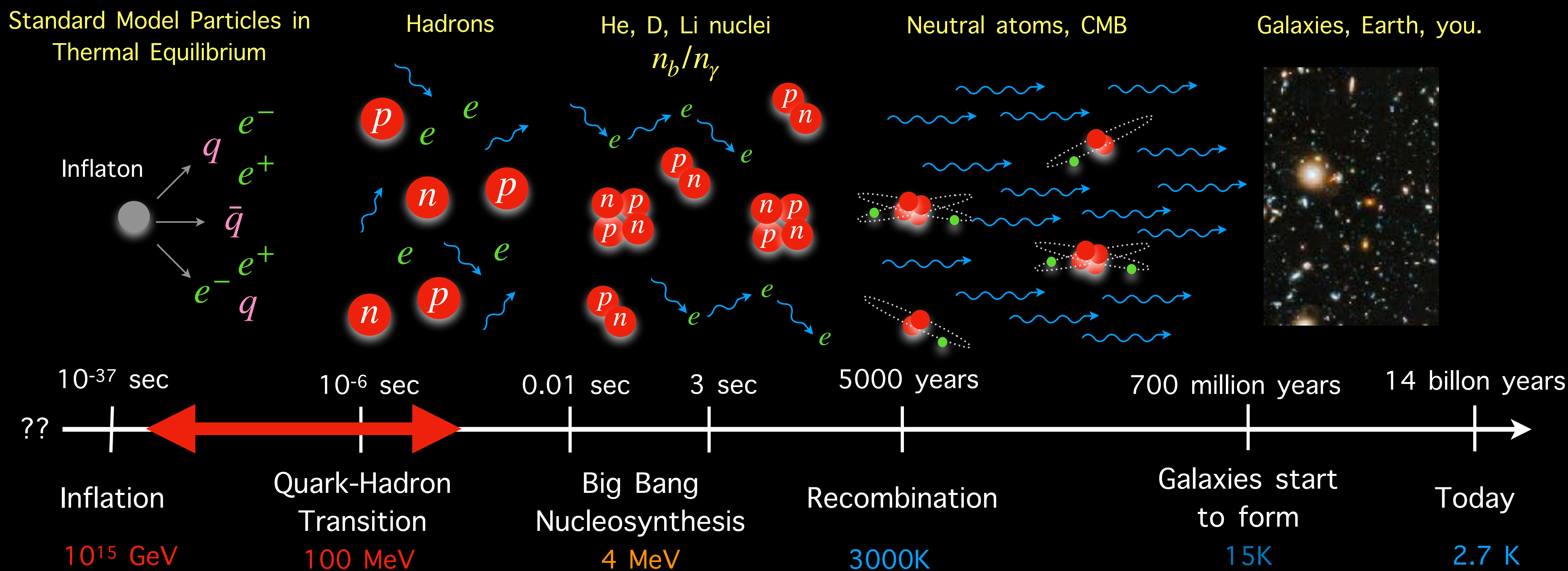
Yet another none Mega Dark Matter talk

The History of the Universe



Baryogenesis?

What mechanism generated the initial asymmetry? Observed to be (BBN, CMB):

$$Y_B^{obs} \equiv \frac{n_{\mathcal{B}} - n_{\bar{\mathcal{B}}}}{s} \sim 8 \times 10^{-11}$$

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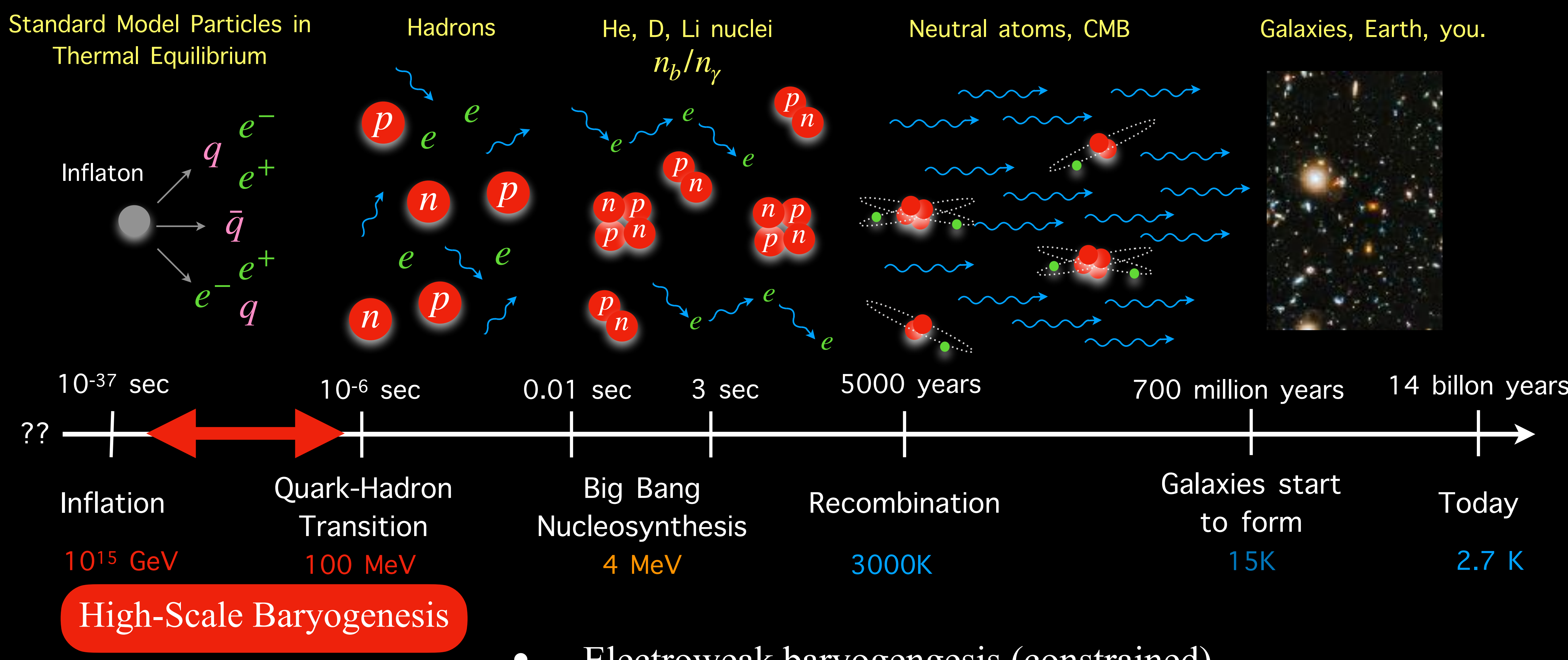
“Traditional” Baryogenesis



- Electroweak baryogengesis (constrained)
- Leptogenesis (hard to test)
- Affleck-Dine (very hard to test)
- ……

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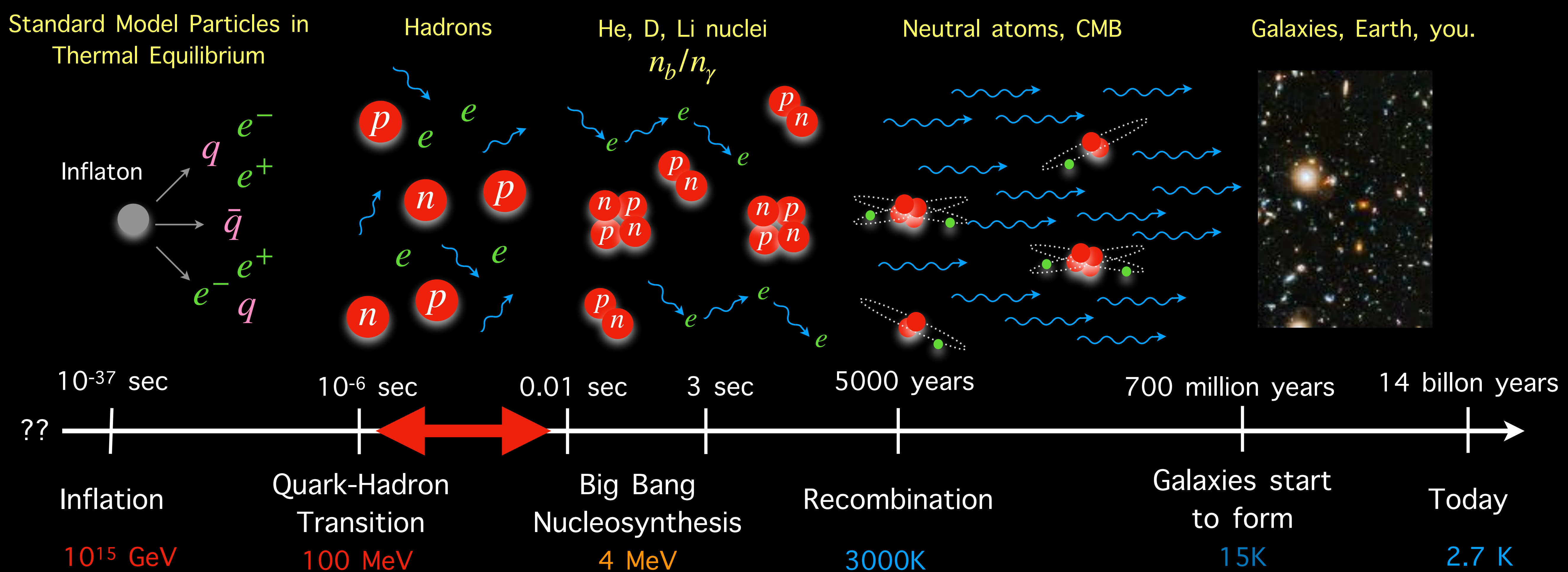
Making the Universe at 20MeV



Mesogenesis:
baryon asymmetry + dark matter

- Controlled by experimental observables. Signals!
- Theoretically appealing e.g. Relaxion and Nnaturalness require low scale baryogenesis.

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Mesogenesis

How to generate a matter/antimatter asymmetry

$$Y_B^{obs} \equiv \frac{n_{\mathcal{B}} - n_{\bar{\mathcal{B}}}}{s} \sim 8 \times 10^{-11} \quad \text{(CMB, BBN)}$$

The Sakharov conditions (1967):

- Out of thermal equilibrium: Late decays of "inflaton" field to SM Mesons.
- CP Violation: In SM Meson systems.
- "Baryon number violation": SM Meson decays to dark leptons or baryons.

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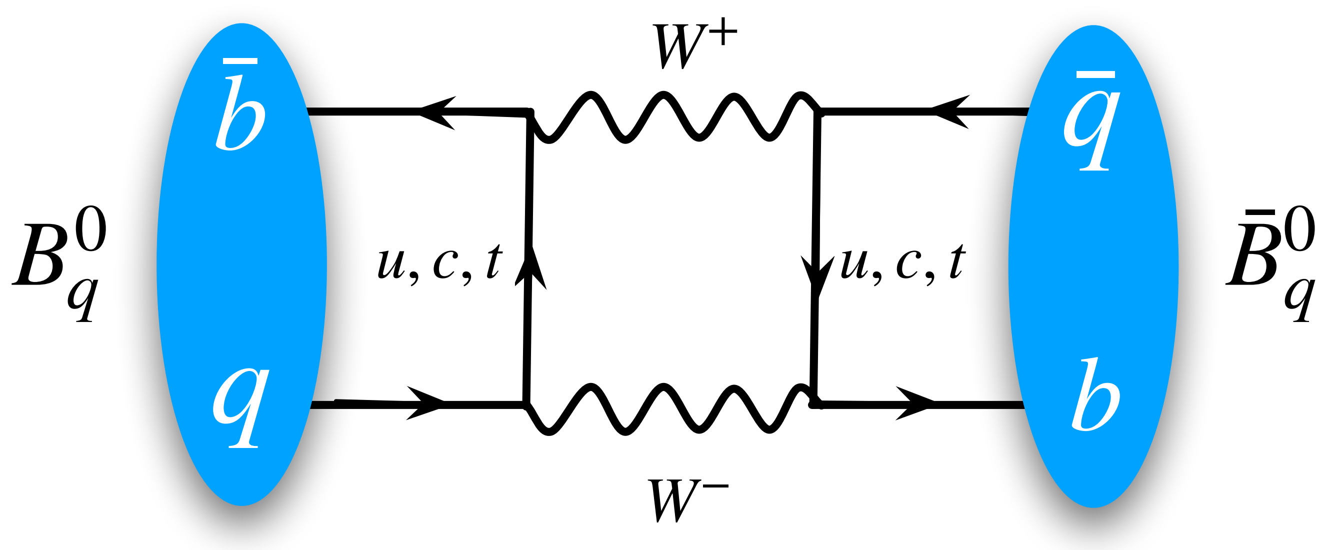
The Many Flavors of Mesogenesis

Mechanism	CPV	Dark Sector	Observables	Relevant Experiments
B^0 Mesogenesis	B_s^0 & B_d^0 oscillations	Dark baryons	$A_{sl}^{s,d}$ $\text{Br}(B \to \mathcal{B} + X)$	LHCb B Factories, LHCb
D^+ Mesogenesis	$D^\pm$ decays	Dark leptons and/or baryons	A_{CP}^D Br_{D^+} $\text{Br}(\mathcal{M}^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU
B^+ Mesogenesis	$B^\pm$ decays	Dark leptons and/or baryons	A_{CP}^B Br_{B^+} $\text{Br}(\mathcal{M}^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU
B_c^+ Mesogenesis	$B_c^\pm$ decays	Dark baryons	$A_{CP}^{B_c}$ $\text{Br}_{B_c^+}$ $\text{Br}_{B^+ \to \mathcal{B}^+ + X}$	LHCb, FCC LHCb, FCC B Factories, LHCb

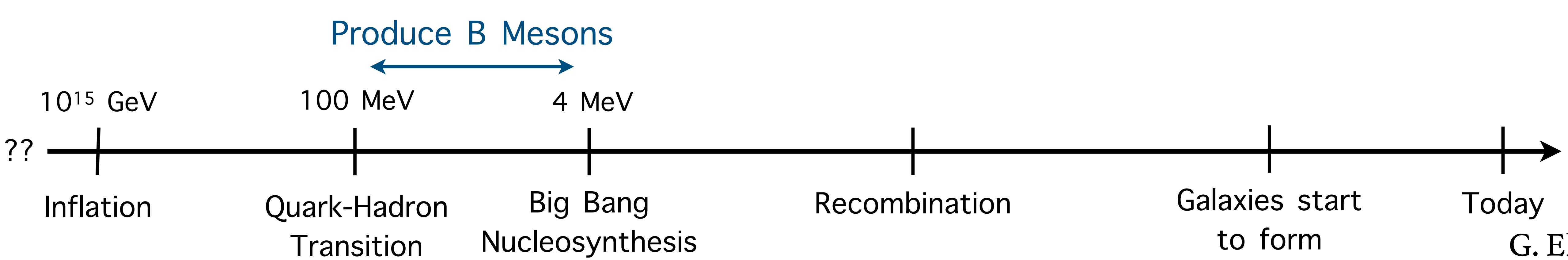
GE, M. Escudero, A. E. Nelson, PRD, [1810.00880]
G. Alonso-Alvarez, GE, A. E. Nelson, H. Xiao, JHEP, [1907.10612]
GE, R. McGehee, PRD [2011.06115]
G. Alonso-Alvarez, GE. M. Escudero, PRD, [2101.02706]
F. Elahi, GE, R. McGehee, [2109.09751]
G. Alonso-Alvarez, GE, M. Escudero, B. Fornal, B. Grinstein, J.M. Camalich [arXiv:2111.12712]

Neutral *B* Meson Oscillations

At low energies we can use CPV in *B* meson mixing
e.g. from CKM phases in the case of the Standard Model
(but new physics contributions are also not excluded)



$$\propto \quad (V_{tb} V_{tq}^*)^2$$



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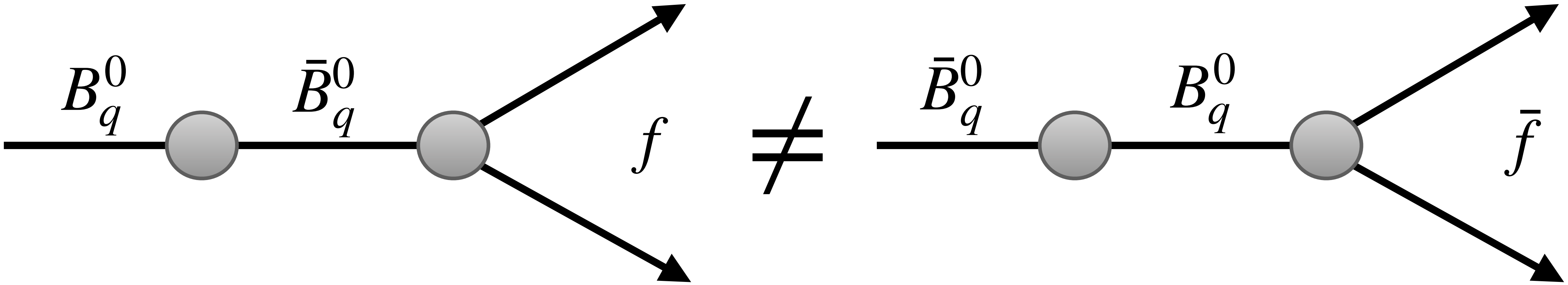
CP Violation

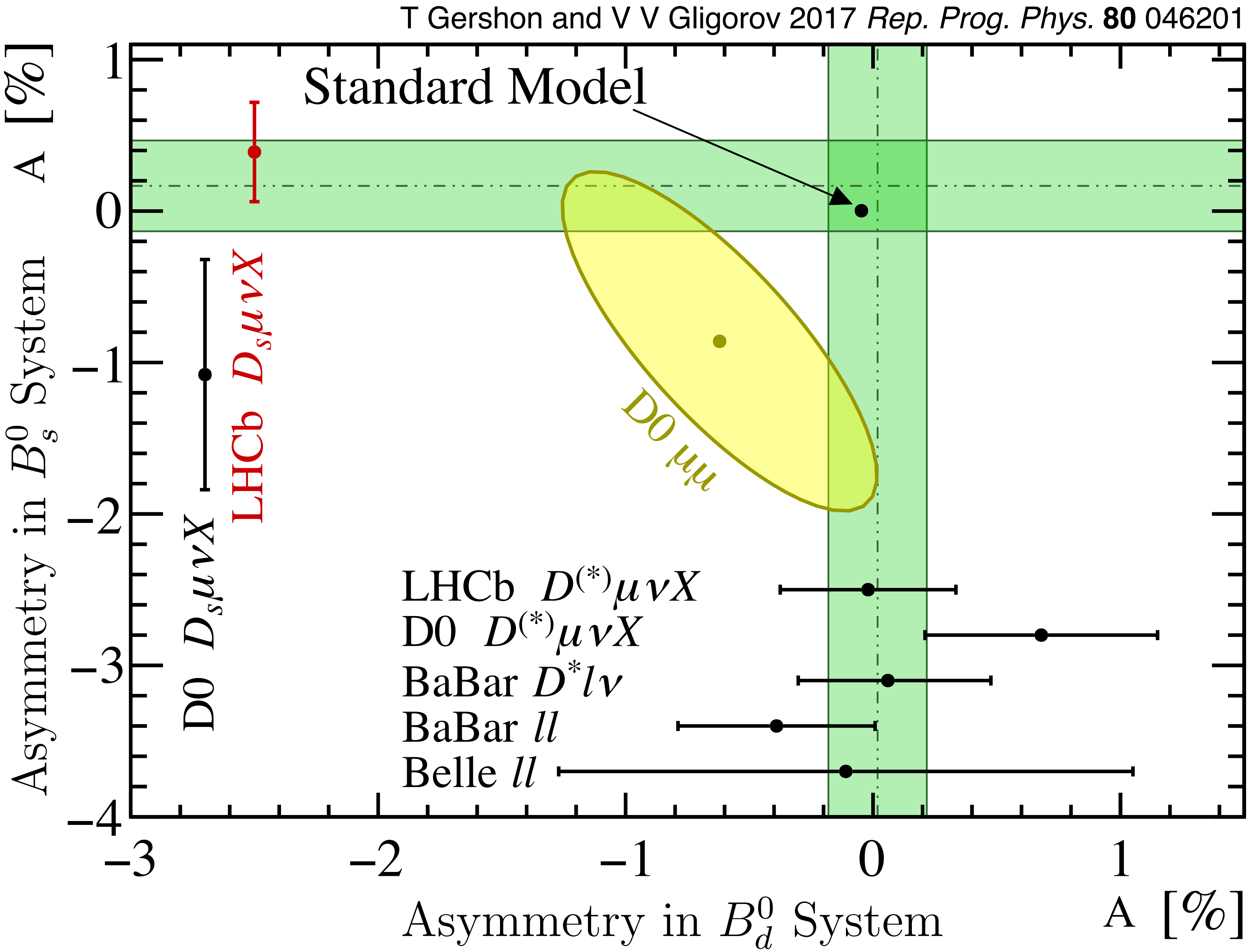
B meson/anti-meson mixing has sizable CP violation



Observable: $$A_{\rm SL}^q = \frac{\Gamma\left(\bar{B}_q^0 \to B_q^0 \to f\right) - \Gamma\left(B_q^0 \to \bar{B}_q^0 \to \bar{f}\right)}{\Gamma\left(\bar{B}_q^0 \to B_q^0 \to f\right) + \Gamma\left(B_q^0 \to \bar{B}_q^0 \to \bar{f}\right)}$$

CP Violation

Can accommodate contributions from new physics



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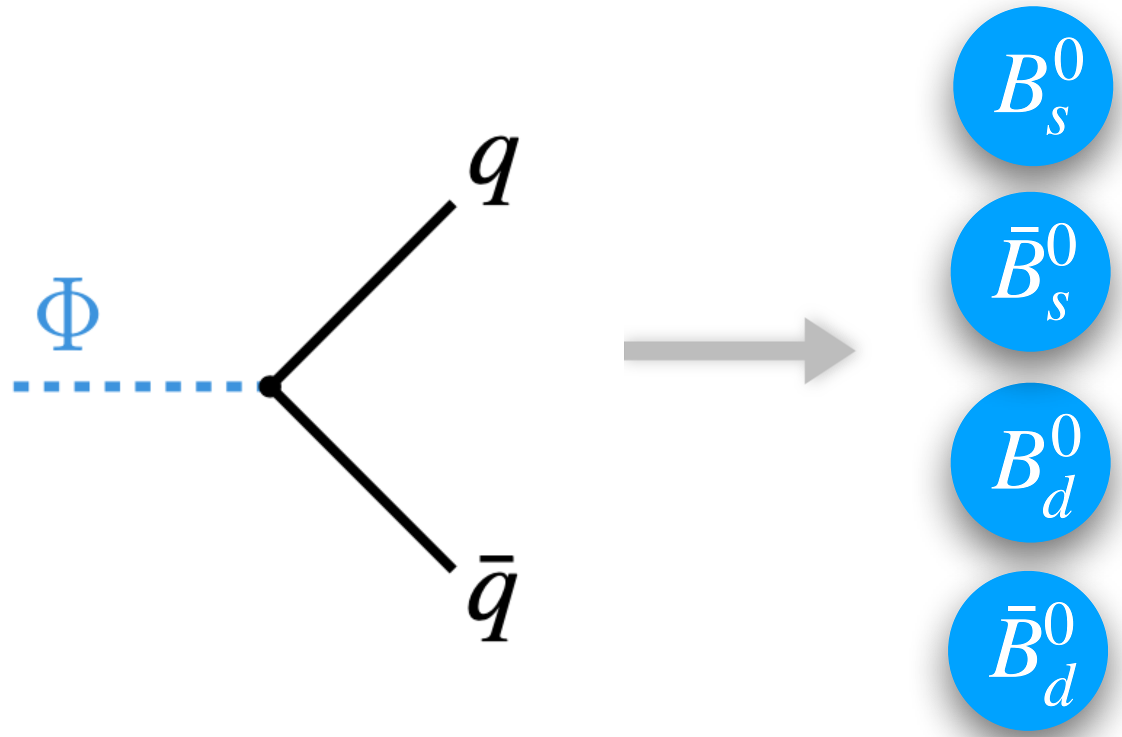
Sakharov I. Out of Equilibrium

Late decay of an "inflaton-like" field

Decays at: $\Gamma_\Phi = 4H(T_R)$ to quarks $m_\Phi \in [5\,\text{GeV}\,,\ 100\,\text{GeV}]$



$$3.5\,\text{MeV} \lesssim T_\text{R} \lesssim 100\,\text{MeV}$$

Before BBN — After QCD phase transition

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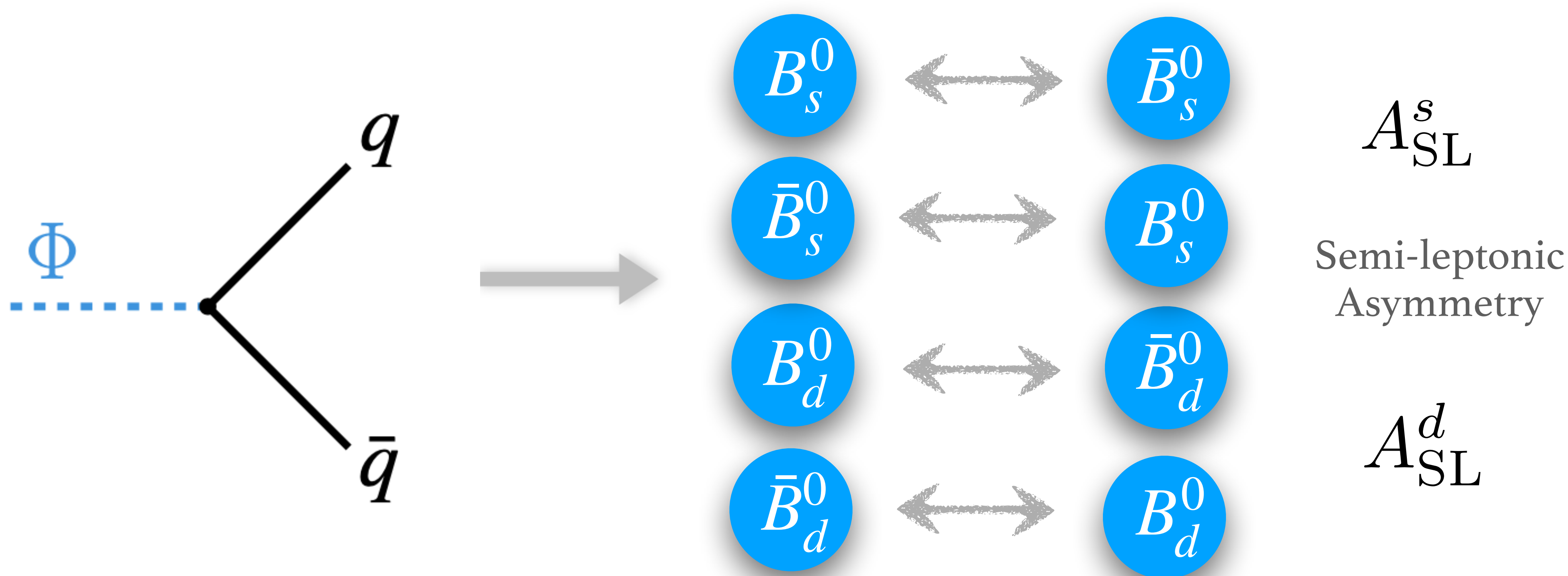
Sakharov II. CP Violation

Late decay of an "inflaton-like" field

Decays at: $\Gamma_\Phi = 4H(T_R)$ to quarks $m_\Phi \in [5\,\text{GeV}\,,\ 100\,\text{GeV}]$



$$3.5\,\text{MeV} \lesssim T_{\text{R}} \lesssim 100\,\text{MeV}$$

↑ Before BBN ↑ After QCD phase transition

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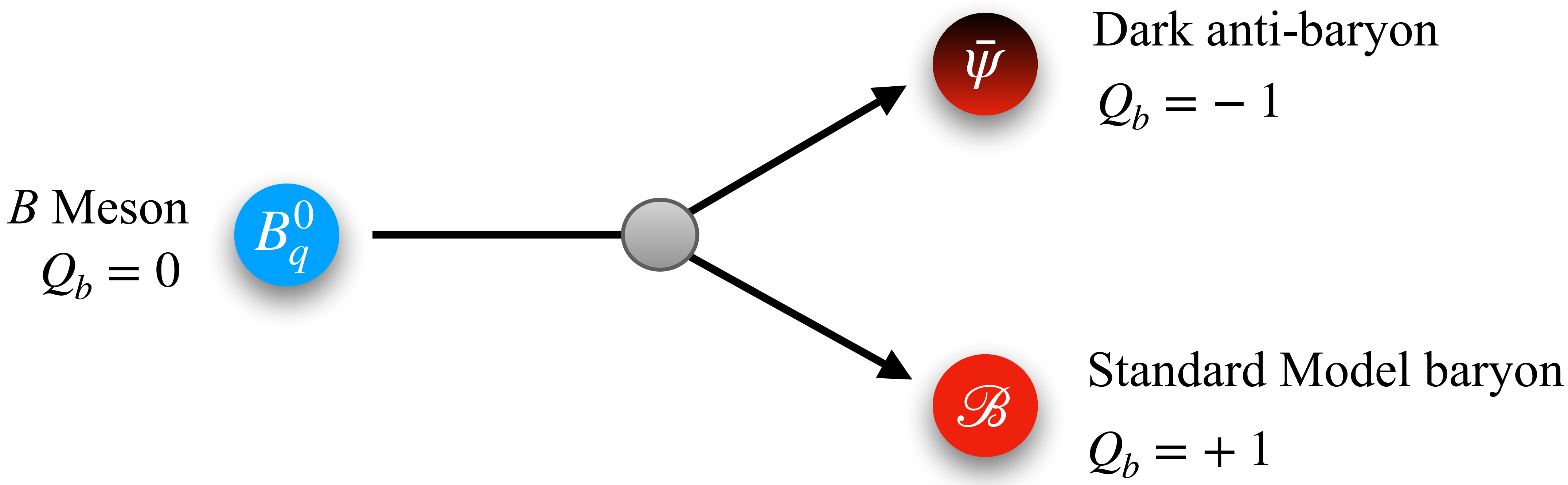
Sakharov III. *B* Violation?

Need a way to change baryon number

Hide baryon number in a dark sector
rather than violate it

Dark Sector Baryon

Hide baryon number in a dark sector



Kinematics: $m_\psi < m_B - m_{\text{Baryon}} < 4.3\,\text{GeV}$

Proton stability: $m_\psi > m_p - m_e \simeq 937.8\,\text{MeV}$

Equal and opposite dark and visible baryon asymmetries generated.

$$Y_{\mathcal{B}} - Y_{\bar{\mathcal{B}}} = -\left(Y_\psi - Y_{\bar{\psi}}\right)$$

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New Fields

Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
Y	0	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\text{TeV})$
$\psi_\mathcal{B}$	$1/2$	0	-1	$+1$	$\mathcal{O}(\text{GeV})$

SUSY Squark

Kinematics, forbid proton decay

Allowed by all the symmetries:

$$\mathcal{L}_{-1/3} = -\sum_{i,j} y_{u_i d_j} Y^\star \bar{u}_{iR} d^c_{jR} - \sum_k y_{\psi d_k} Y d^c_{kR} \bar{\psi}_\mathcal{B} + \text{h.c.}$$

Effective four fermion operator at MeV scales:

$$\mathcal{H}_{eff} = \frac{\kappa}{m_Y^2} b\, u\, s\, \psi_\mathcal{B}$$

This interaction *does not* change baryon number

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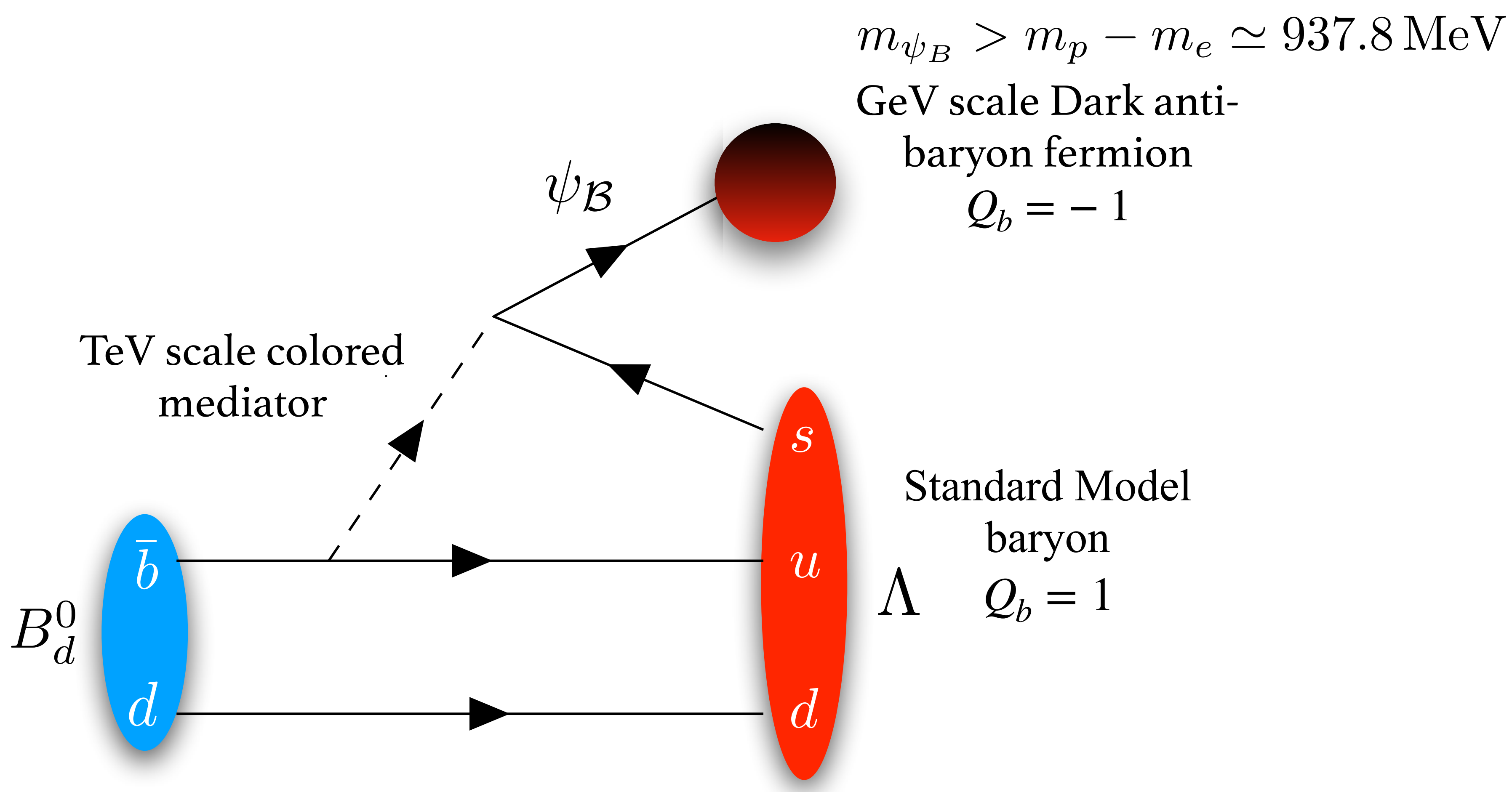
New decay of the B Meson



Equal and opposite dark and visible baryon asymmetries generated.

$$Y_{\mathcal{B}} - Y_{\bar{\mathcal{B}}} = -\left(Y_\psi - Y_{\bar{\psi}}\right)$$

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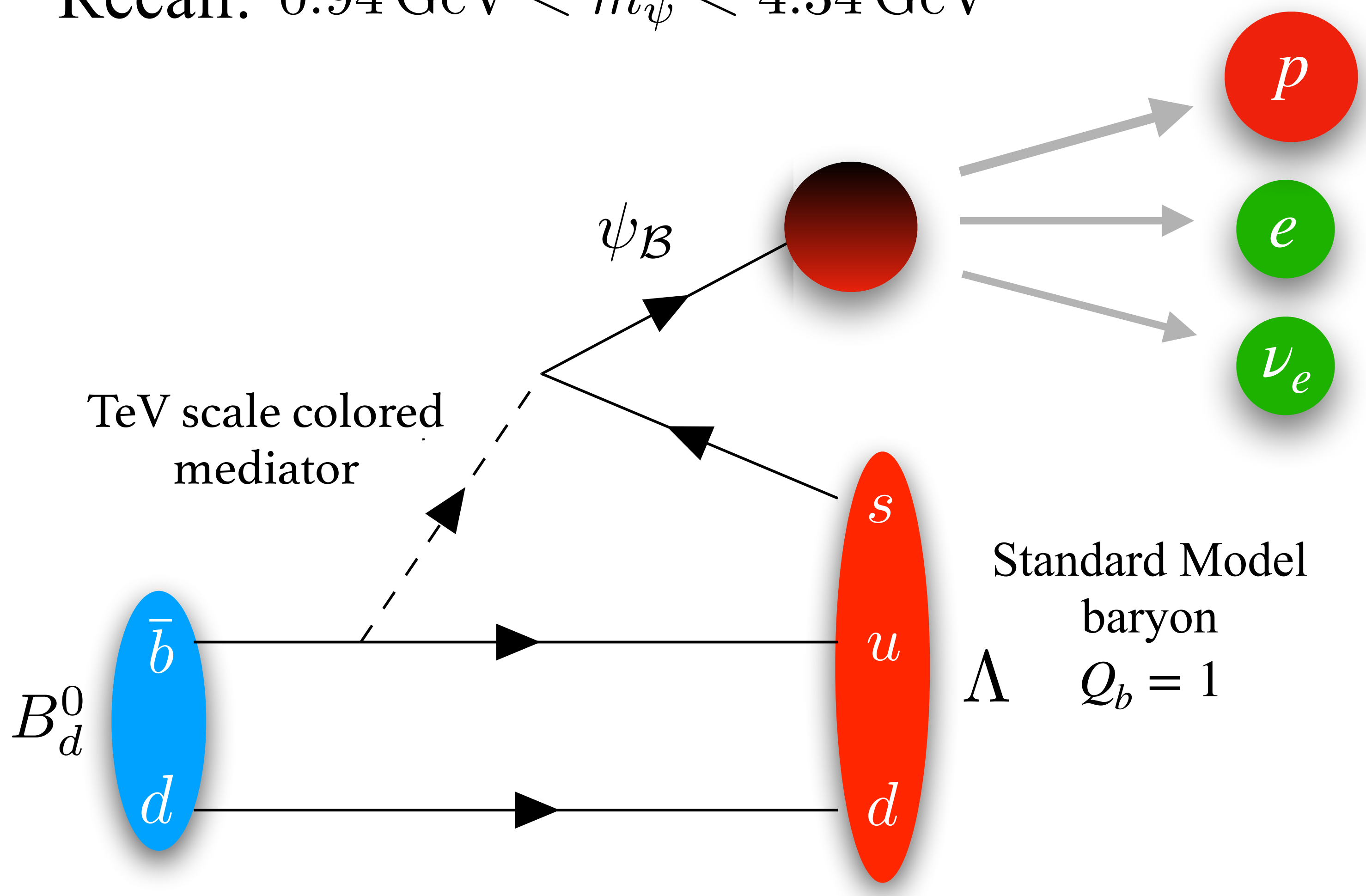
Dark Matter?

Recall: $0.94\,\text{GeV} < m_\psi < 4.34\,\text{GeV}$



New dark baryon is unstable and will decay to baryonic matter, washing out the asymmetry in the process. It cannot be the dark matter.

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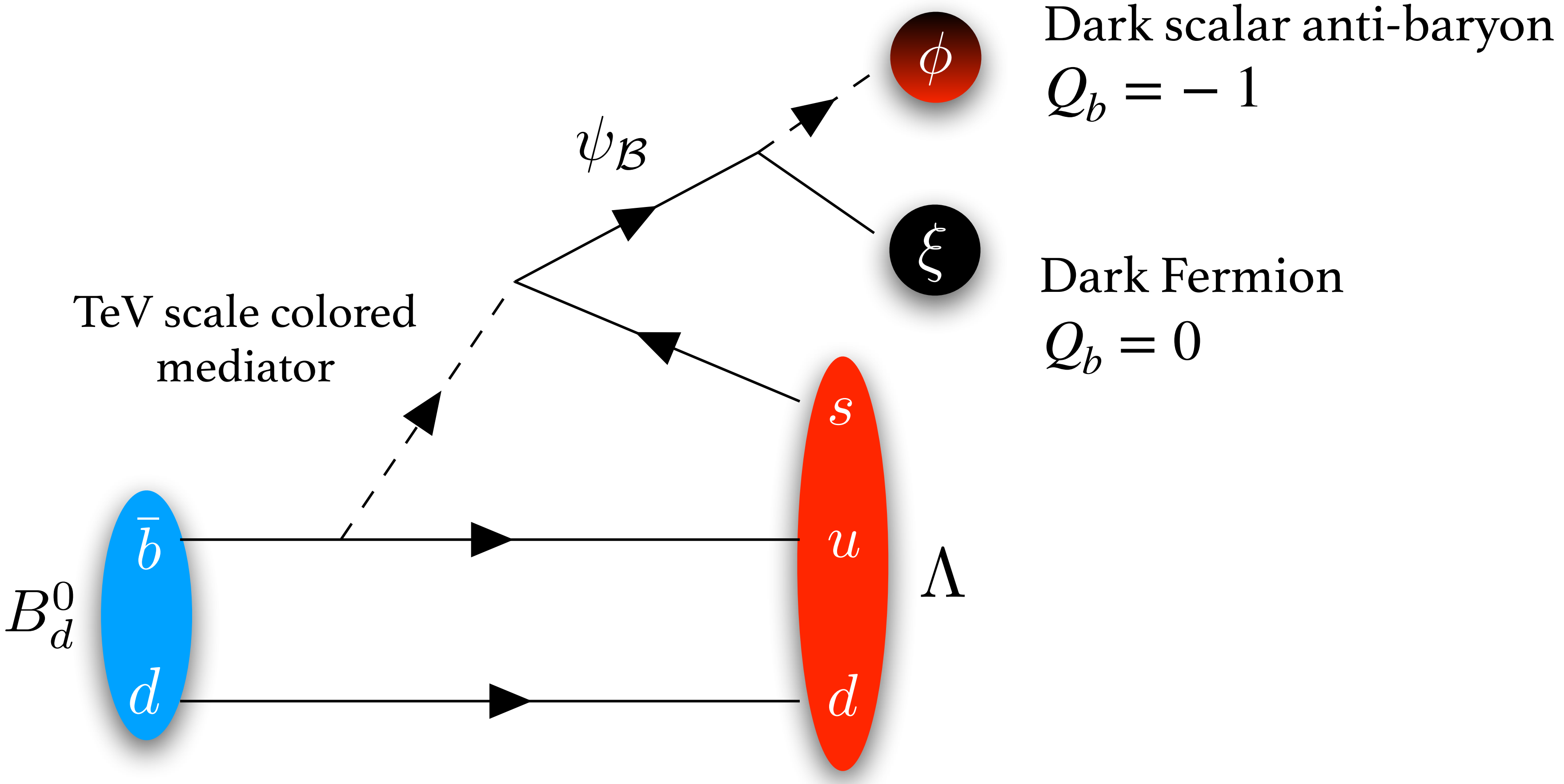
Dark Matter

Dark fermion must quickly decay within the dark sector.



DM stability/asymmetry preserved if : $m_\phi < m_p + m_e + m_\xi$

Generated asymmetry: $Y_{\mathcal{B}} - Y_{\bar{\mathcal{B}}} = -(Y_\phi - Y_{\phi^\star})$

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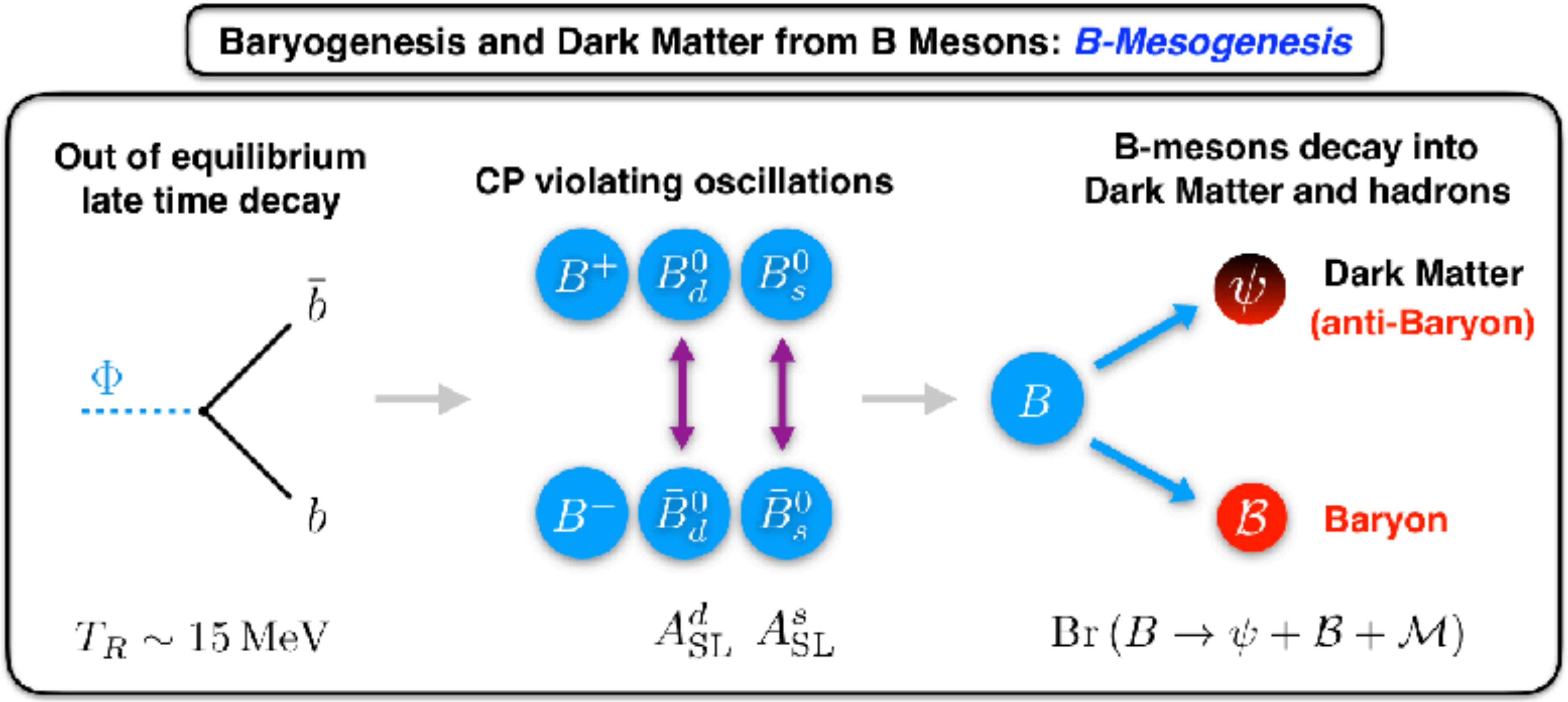
Neutral *B* Mesogenesis



Asymmetry is related to observables:

$$Y_{\mathcal{B}} \simeq 8.7 \times 10^{-11} \frac{\mathrm{Br}\left(B \to \psi \mathcal{B} \mathcal{M}\right)}{10^{-2}} \sum_{q=s,d} \alpha_q \frac{A_{\rm SL}^q}{10^{-4}}$$

succesful *B* Mesogenesis requires:

$$A_{\rm SL}^{s,d} \times \mathrm{Br}\left(B^0 \to \psi\, \mathcal{B}\, \mathcal{M}\right) > 10^{-6}$$

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Boltzmann Equations

- Inflaton:

$$\frac{dn_\Phi}{dt} + 3Hn_\Phi = -\Gamma_\Phi n_\Phi$$

- Radiation:

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

- Hubble:

$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\left(\rho_{\rm rad} + m_\Phi n_\Phi\right)$$

$$\Gamma_\Phi = 4H\left(T_R\right)$$

- Symmetric component of the dark scalar baryon

$$\frac{dn_{\phi+\phi^*}}{dt} + 3\,H\,n_{\phi+\phi^*} = 2\,\Gamma_\Phi^B\,n_\Phi - 2\,\langle\sigma v\rangle_\phi\left(n_{\phi+\phi^*}^2 - n_{{\rm eq},\,\phi+\phi^*}^2\right)$$

- Anti-symmetric dark sector baryon makes up the baryon asymmetry

$$\frac{dn_{\phi-\phi^*}}{dt} + 3Hn_{\phi-\phi^*} = 2\Gamma_\Phi^B \sum_q {\rm Br}\left(\bar{b} \to B_q^0\right) A_{\rm SL}^q f_{\rm deco}^q n_\Phi$$

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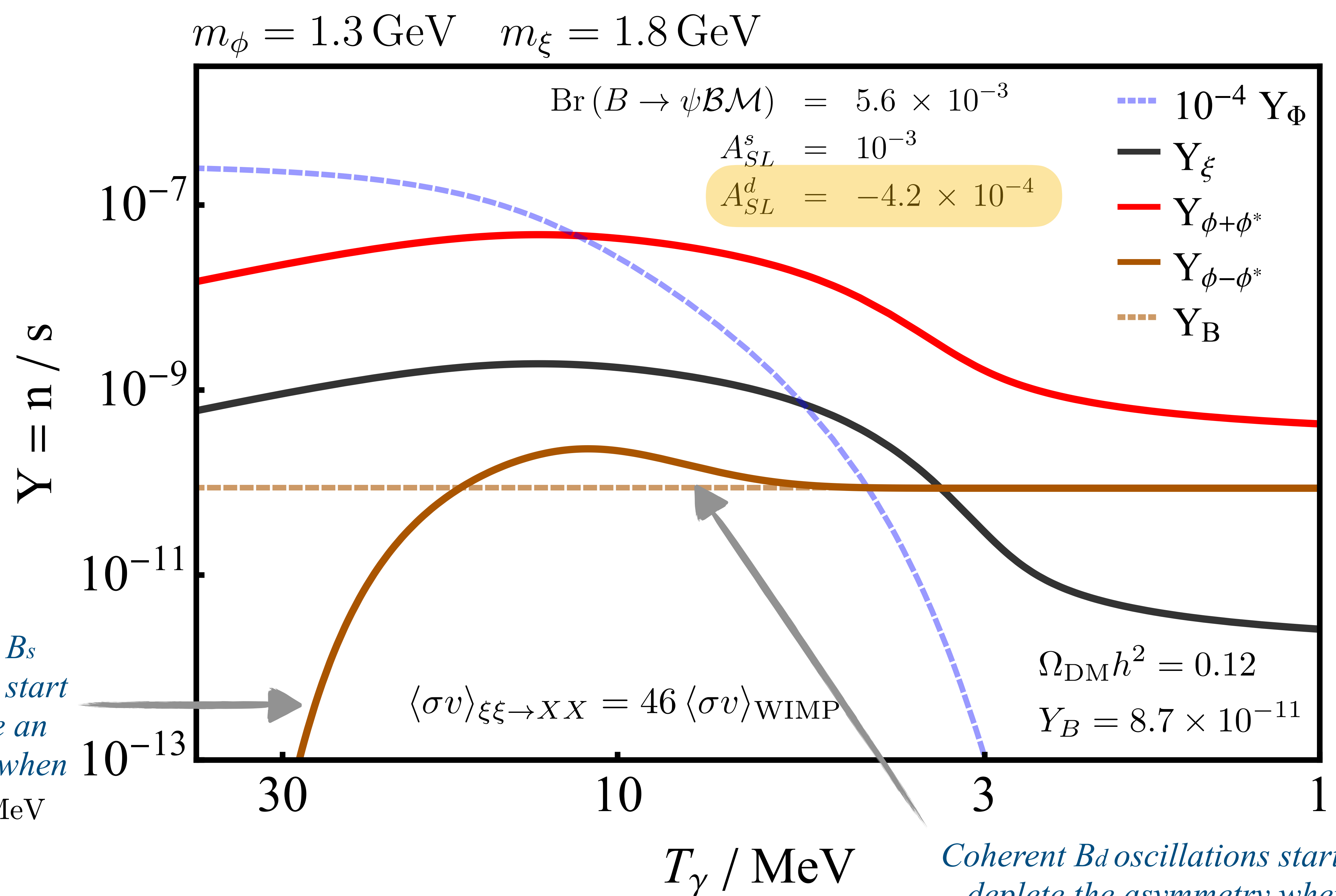
Example Benchmark Point



Coherent Bs oscillations start to produce an asymmetry when $T_{B_s} \lesssim 20\,\text{MeV}$

Need a net positive asymmetry

Coherent Bd oscillations start to deplete the asymmetry when $T_{B_d} \lesssim 10\,\text{MeV}$

Numerical Result

$$Y_{\mathcal{B}} \simeq 8.7 \times 10^{-11} \frac{\text{Br}\left(B \to \psi \mathcal{B} \mathcal{M}\right)}{10^{-2}} \sum_{q=s,d} \alpha_q \frac{A_{\text{SL}}^q}{10^{-4}}$$

Successful
neutral B-Mesogenesis

$$A_{\text{SL}}^{s,d} \times \text{Br}\left(B^0 \to \psi\, \mathcal{B}\, \mathcal{M}\right) > 10^{-6}$$

Experimental Observables

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Signals of Neutral *B*-Mesogenesis

For successful baryogenesis: $A_{\rm SL}^{s,d} \times {\rm Br}\left(B^0 \to \psi\, \mathcal{B}\, \mathcal{M}\right) > 10^{-6}$

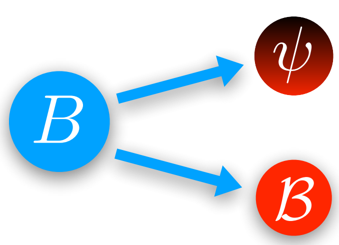
Collider Signals of Baryogenesis and Dark Matter from B Mesons (*B-Mesogenesis*)

Direct Signals

Semileptonic asymmetry: $A_{\rm SL}^{q} > 10^{-5}$

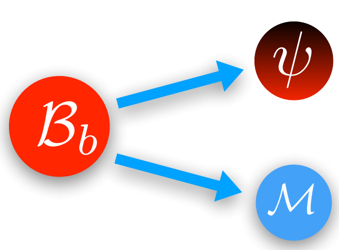
Belle II
LHCb
ATLAS
CMS

New B meson decay:



BaBar
Belle
Belle II
LHCb

New b-Baryon decay:



LHCb?
ATLAS??
CMS??

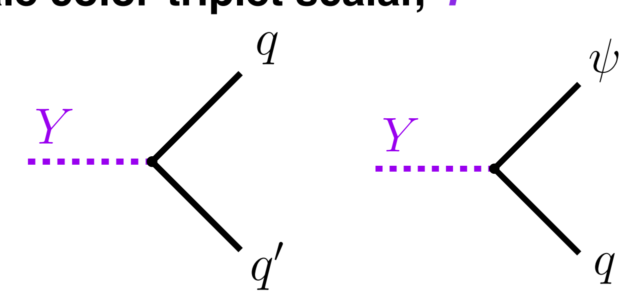
Indirect Signals

B^0 meson CPV and oscillation observables:

$\phi_{12}^{d,s} \quad \Delta M_{d,s} \quad \Delta\Gamma_{d,s}$

LHCb
Belle II
ATLAS
CMS

New TeV-scale color-triplet scalar, *Y*



ATLAS
CMS

Independent of UV model. Given a UV model there will be even more signals!

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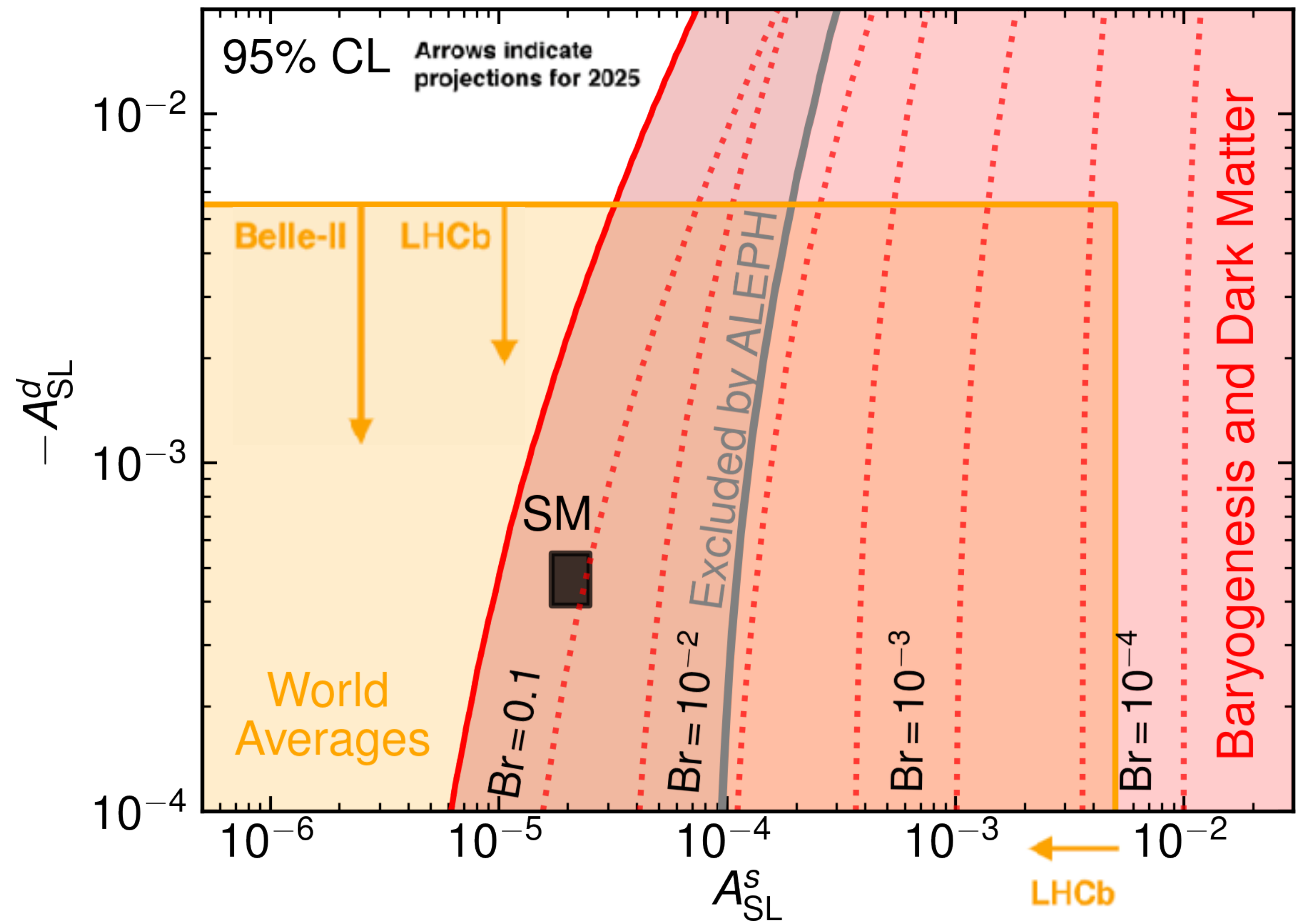
The Semi-Leptonic Asymmetry



$\lesssim 10^{-3}$

$$Y_{\mathcal{B}} \simeq 8.7 \times 10^{-11} \frac{\mathrm{Br}\left(B \to \psi \mathcal{B} \mathcal{M}\right)}{10^{-2}} \sum_{q=s,d} \alpha_q \frac{A_{\mathrm{SL}}^{q}}{10^{-4}}$$

for baryogenesis

$$\mathrm{Br}(B \to \psi\, \mathcal{B}\, \mathcal{M}) \gtrsim 10^{-4}$$

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Flavorful Variations

No a priori reason to expect a particular flavor structure.

Most general interactions:

$$\mathcal{L}_{-1/3} = -\sum_{i,j} y_{u_i d_j} Y^\star \bar{u}_{iR} d^c_{jR} - \sum_k y_{\psi d_k} Y d^c_{kR} \bar{\psi} + \text{h.c.}$$

Possible operators:

$$\mathcal{O}_{ud} = \psi\, b\, u\, d$$
$$\mathcal{O}_{us} = \psi\, b\, u\, s$$
$$\mathcal{O}_{cd} = \psi\, b\, c\, d$$
$$\mathcal{O}_{cs} = \psi\, b\, c\, s$$

B-Mesogenesis requires: $\text{Br}(B \to \psi\, \mathcal{B}\, \mathcal{M}) \gtrsim 10^{-4}$

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Searching for new b-Hadron Decays

Can be searched for at Belle, BaBar and LHCb

Flavorful variations:

Operator/Decay	Initial State	Final state
$\mathcal{O} = \psi\, b\, u\, d$ $\bar{b} \to \psi\, u\, d$	B_d	$\psi + n\,(udd)$
	B_s	$\psi + \Lambda\,(uds)$
	B^+	$\psi + p\,(duu)$
	Λ_b	$\bar{\psi} + \pi^0$
$\mathcal{O} = \psi\, b\, u\, s$ $\bar{b} \to \psi\, u\, s$	B_d	$\psi + \Lambda\,(usd)$
	B_s	$\psi + \Xi^0\,(uss)$
	B^+	$\psi + \Sigma^+\,(uus)$
	Λ_b	$\bar{\psi} + K^0$
$\mathcal{O} = \psi\, b\, c\, d$ $\bar{b} \to \psi\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$
	B_s	$\psi + \Xi_c^0\,(cds)$
	B^+	$\psi + \Lambda_c\,(dcu)$
	Λ_b	$\bar{\psi} + \overline{D}^0$
$\mathcal{O} = \psi\, b\, c\, s$ $\bar{b} \to \psi\, c\, s$	B_d	$\psi + \Xi_c^0\,(csd)$
	B_s	$\psi + \Omega_c\,(css)$
	B^+	$\psi + \Xi_c^+\,(csu)$
	Λ_b	$\bar{\psi} + D^- + K^+$

← Directly related to baryon asymmetry

← Indirectly constrains B-Mesogenesis. Charged track is an advantage for searches

← b-flavored baryon decays can yield indirect constraints.

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Targeted Searches at Colliders

UV Model: $\mathcal{L}_{-1/3} = -\sum_{i,j} y_{u_i d_j} Y^\star \bar{u}_{iR} d^c_{jR} - \sum_k y_{\psi d_k} Y d^c_{kR} \bar{\psi}_B + \text{h.c.}$

Operator/Decay	Initial State	Final state
$\mathcal{O} = \psi\, b\, u\, d$ $\bar{b} \to \psi\, u\, d$	B_d	$\psi + n\,(udd)$
	B_s	$\psi + \Lambda\,(uds)$
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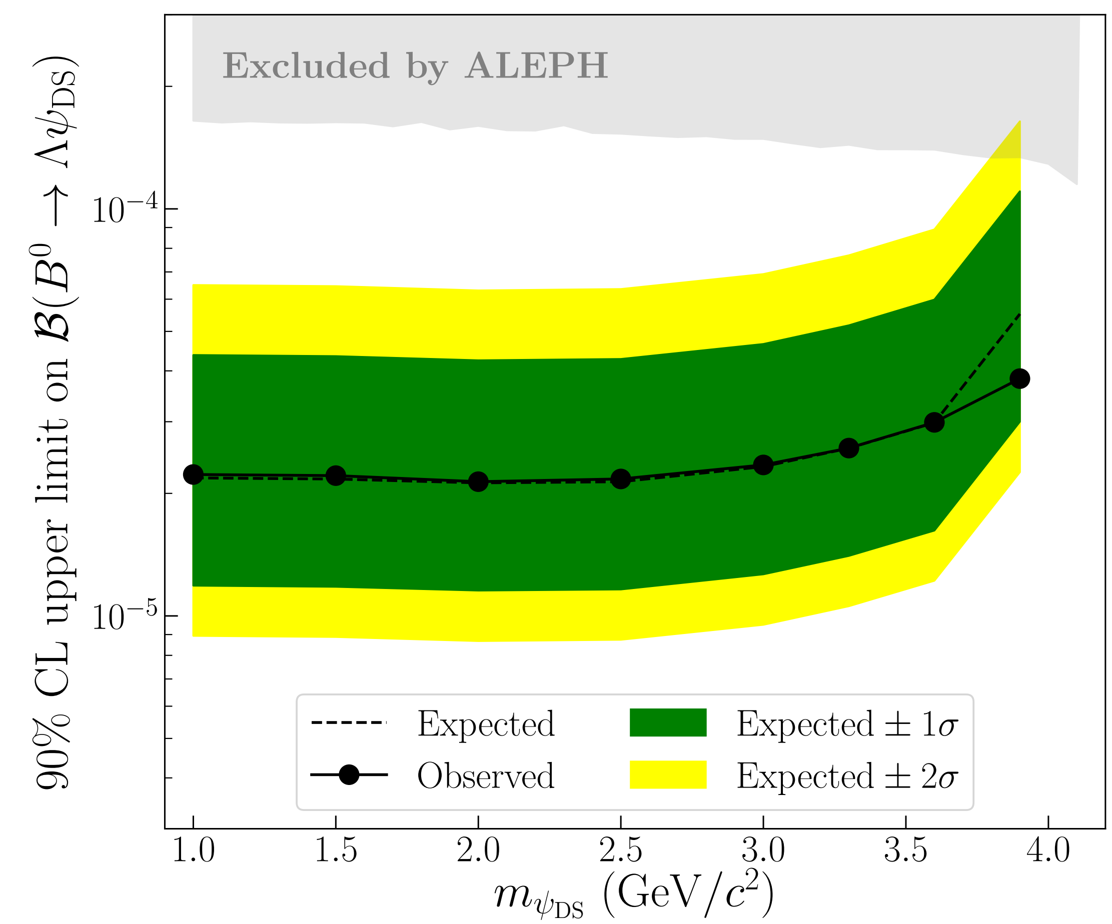
	B^+	$\psi + \Lambda_c\,(dcu)$
	Λ_b	$\bar{\psi} + \overline{D}^0$
$\mathcal{O} = \psi\, b\, c\, s$ $\bar{b} \to \psi\, c\, s$	B_d	$\psi + \Xi_c^0\,(csd)$
	B_s	$\psi + \Omega_c\,(css)$
	B^+	$\psi + \Xi_c^+\,(csu)$
	Λ_b	$\bar{\psi} + D^- + K^+$

Belle collaboration [arXiv:2110.14086]



Proposed searches for all modes at LHCb [2106.12870]

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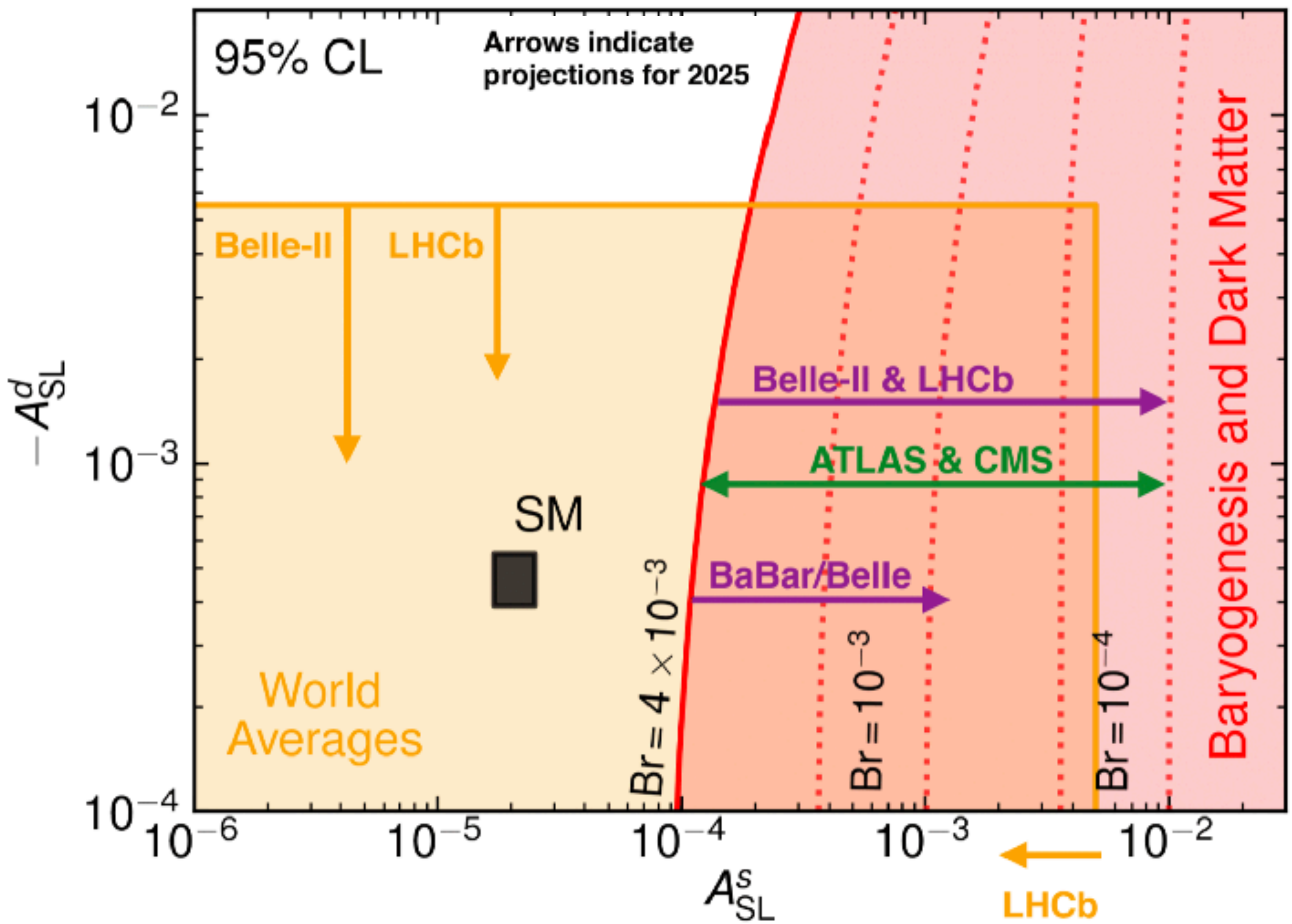
Discovering Neutral B-Mesogenesis

Could be fully tested in but a few years.



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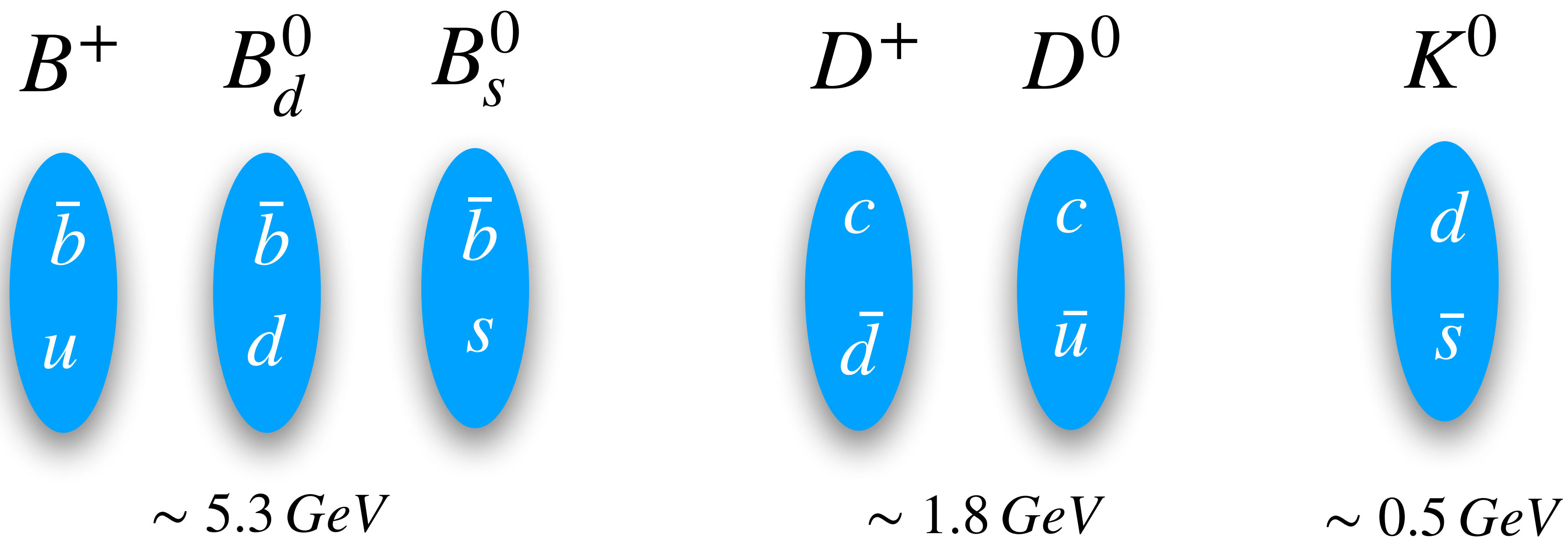
Why Neutral B Mesons?



$$m_{\psi_B} > m_p - m_e \simeq 937.8\,\mathrm{MeV}$$

- Kinematics: Dark baryons must be GeV scale. Only B mesons are heavy enough to decay into GeV scale. Charge dark particle under lepton number instead, then it can be light.

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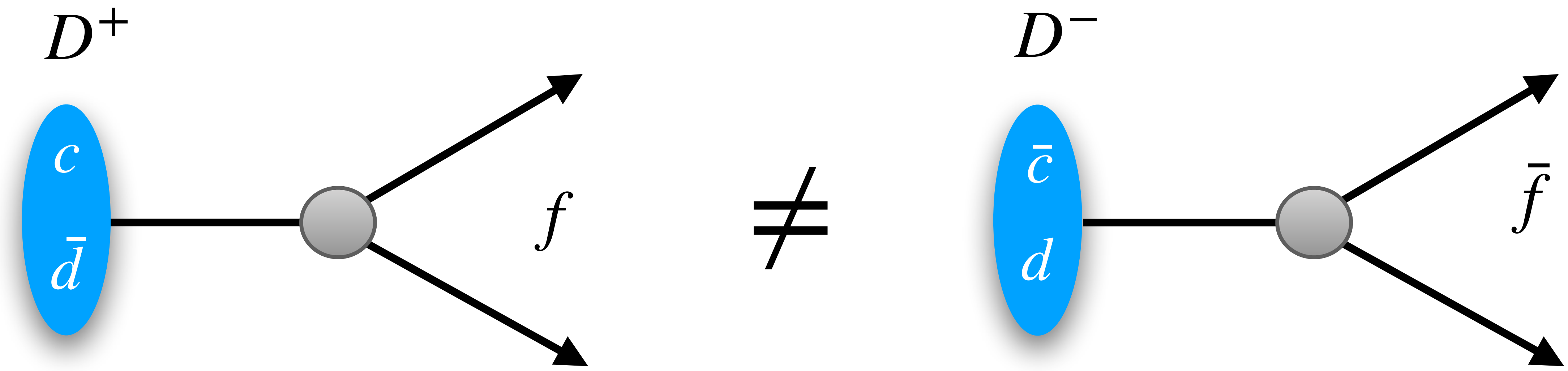
Charged D Mesogenesis



Observable: $$A_{CP}^{f} = \frac{\Gamma(D^+ \to f) - \Gamma(D^- \to \bar{f})}{\Gamma(D^+ \to f) + \Gamma(D^- \to \bar{f})}$$

CPV in Charged D Decays

Example: Standard Model decays to an odd number of charged pions

D^+ decay mode	$A_{CP}^f/10^{-2}$
$K_S^0\pi^+$	-0.41 ± 0.09
$K^-\pi^+\pi^+$	-0.18 ± 0.16
$K^-\pi^+\pi^+\pi^0$	$-0.3 \pm 0.6 \pm 0.4$
$K_S^0\pi^+\pi^0$	$-0.1 \pm 0.7 \pm 0.2$
$K_S^0\pi^+\pi^+\pi^-$	$0.0 \pm 1.2 \pm 0.3$
$\pi^+\pi^0$	2.4 ± 1.2
$\pi^+\eta$	1.0 ± 1.5

D^+ decay mode	$A_{CP}^f/10^{-2}$
$\pi^+\eta$	1.0 ± 1.5
$\pi^+\eta'(958)$	-0.6 ± 0.7
$K^+K^-\pi^+$	0.37 ± 0.29
$\phi\pi^+$	0.01 ± 0.09
$a_0(1450)^0\pi^+$	$-19 \pm 12^{+8}_{-11}$
$\phi(1680)\pi^+$	$-9 \pm 22 \pm 14$
$\pi^+\pi^+\pi^-$	-1.7 ± 4.2

Not a small number if we want to explain $Y_B^{\rm obs} = (8.718 \pm 0.004) \times 10^{-11}$

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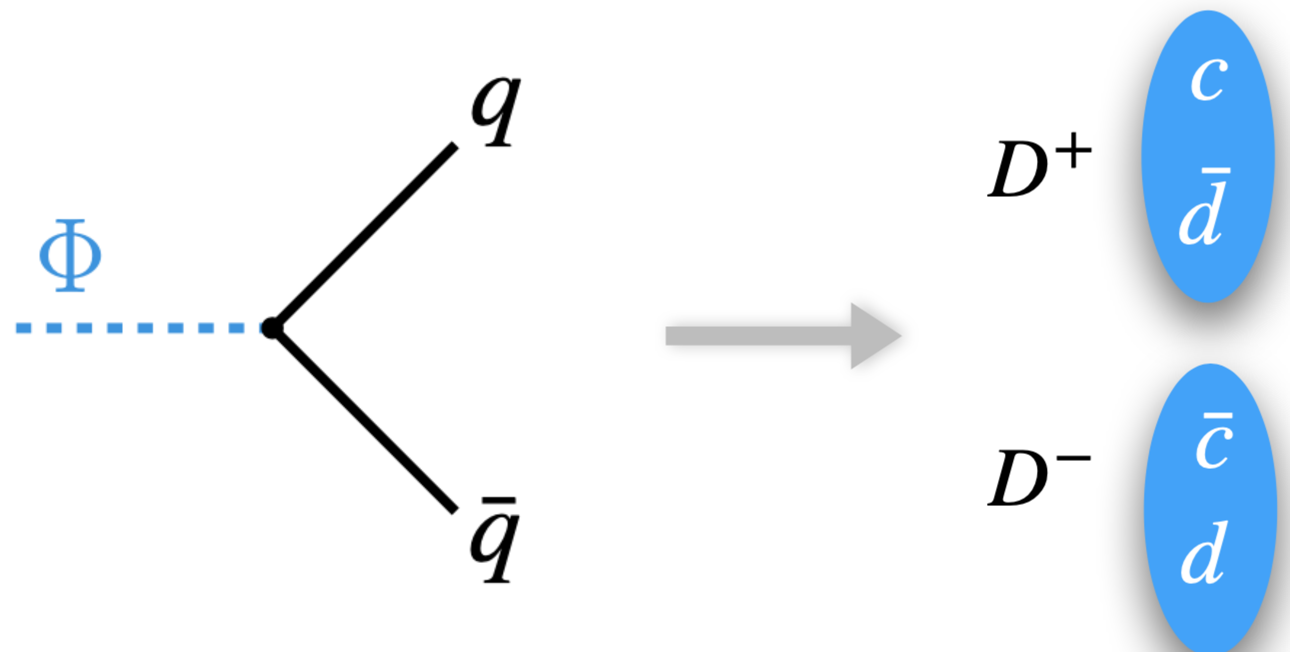
Sakharov I. Out of Equilibrium

Late decay of an "inflaton-like" field

Decays at: $\Gamma_\Phi = 4H\,(T_R)$ to quarks $m_\Phi \in [5\,\mathrm{GeV}\,,\ 100\,\mathrm{GeV}]$



$$3.5\,\mathrm{MeV} \lesssim T_\mathrm{R} \lesssim 20\,\mathrm{MeV}$$

Before BBN

After QCD phase transition

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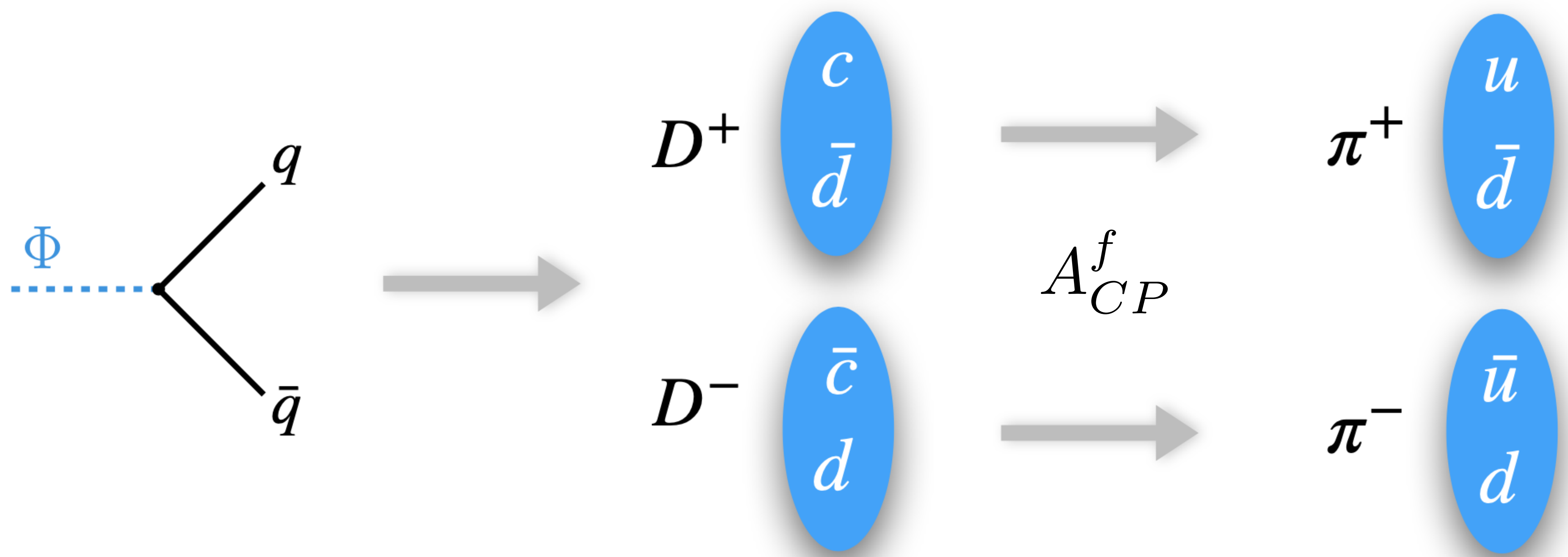
Sakharov II. CP Violation

D mesons quickly undergo Standard Model decays to pions



Decays at: $3.5\,\mathrm{MeV} \lesssim T_\mathrm{R} \lesssim 20\,\mathrm{MeV}$

Asymmetry in charged pions

Before BBN

D mesons decay rather than scatter

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Sakharov III. *B* Violation?

Need a way to change baryon number

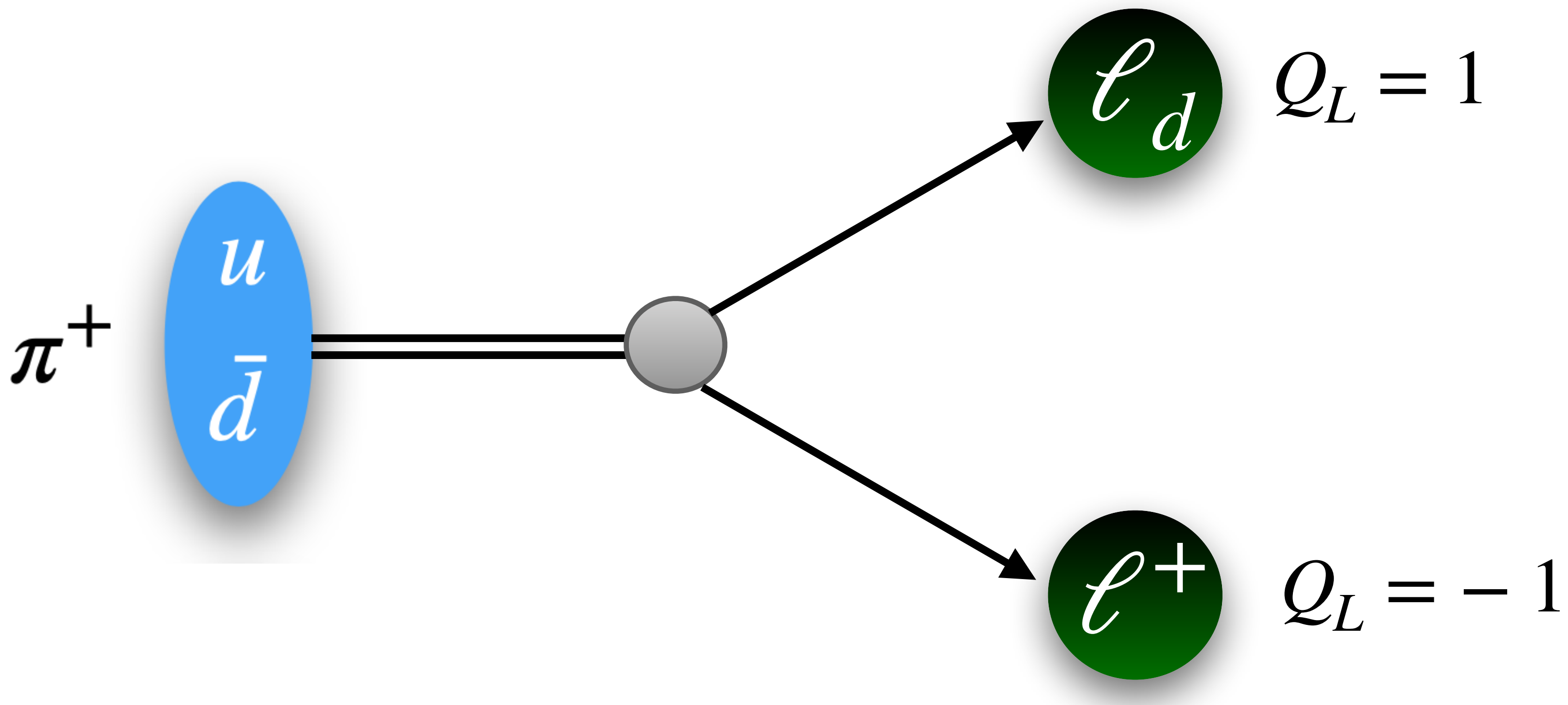
Hide baryon *and lepton* number in a dark sector without violating either.

First generate a *lepton asymmetry*

Dark Sector Lepton

Portal Operator: $\mathcal{O} = \frac{1}{\Lambda^2}\left[\bar{d}\Gamma^\mu u\right]\left[\bar{\ell}_d \Gamma_\mu \ell\right] + \text{h.c.}$

Pion Decays: $\pi^+ \to \ell_d + \ell^+\,, \quad m_{\ell_d} < m_{\pi^+} - m_\ell$ Can be light



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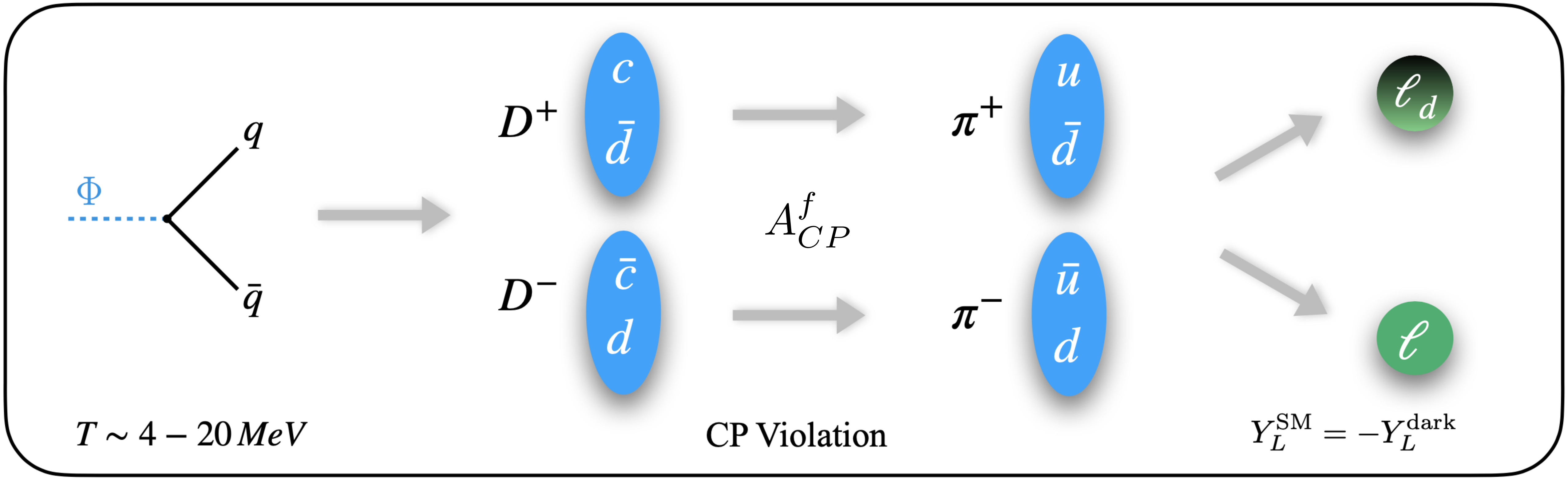
Generating a Lepton Asymmetry

Equal and opposite dark/visible sector lepton asymmetry



$$Y_L^{\text{dark}} \equiv \left(\frac{n_{\ell_d} - n_{\bar{\ell}_d}}{s}\right) \propto \text{Br}\left(\pi^+ \to \ell_d + \ell^+\right) \sum_f A^f_{\text{CP}} \times \text{Br}\left(D^+ \to f\right)$$

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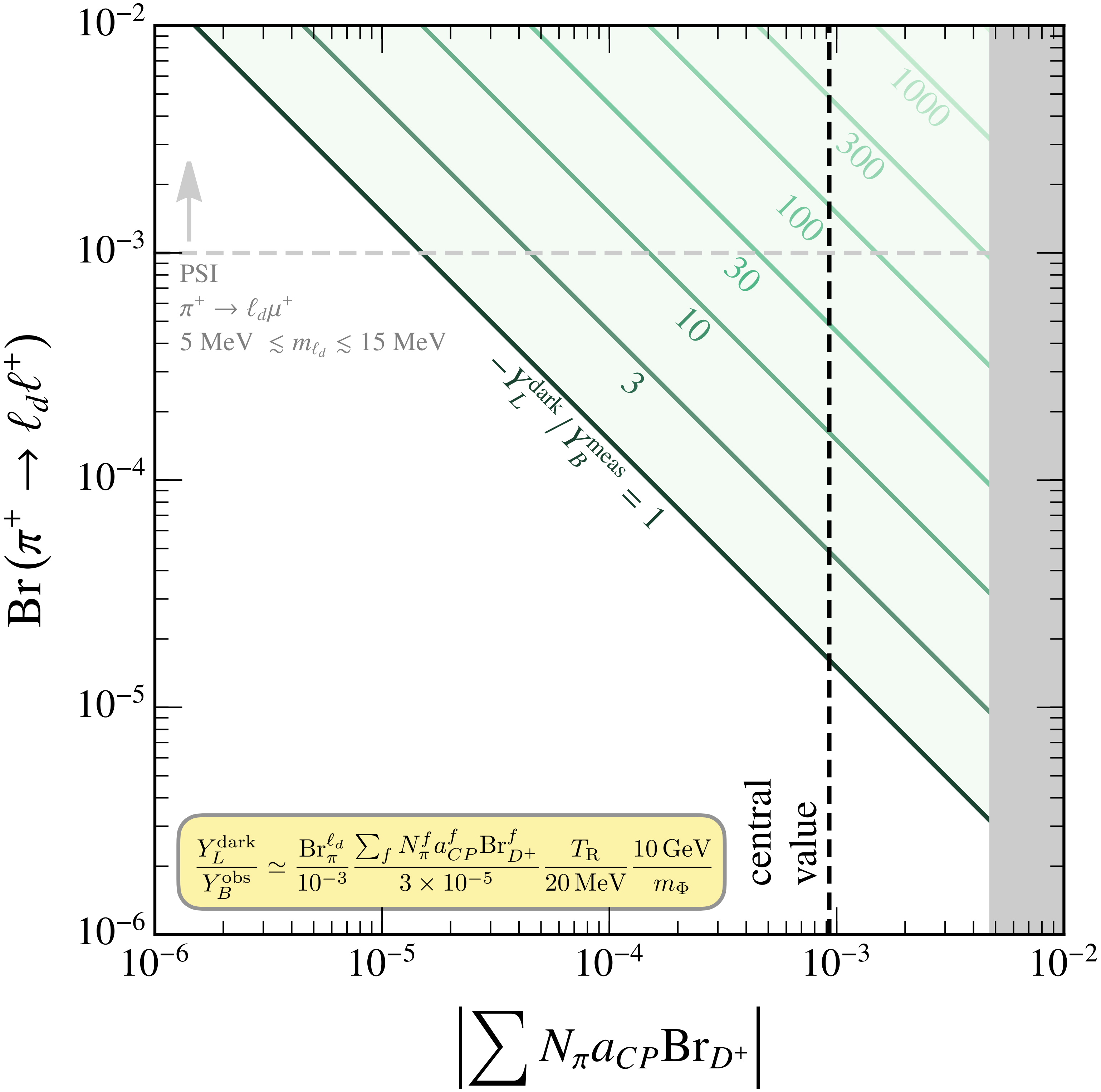
Generating a Lepton Asymmetry



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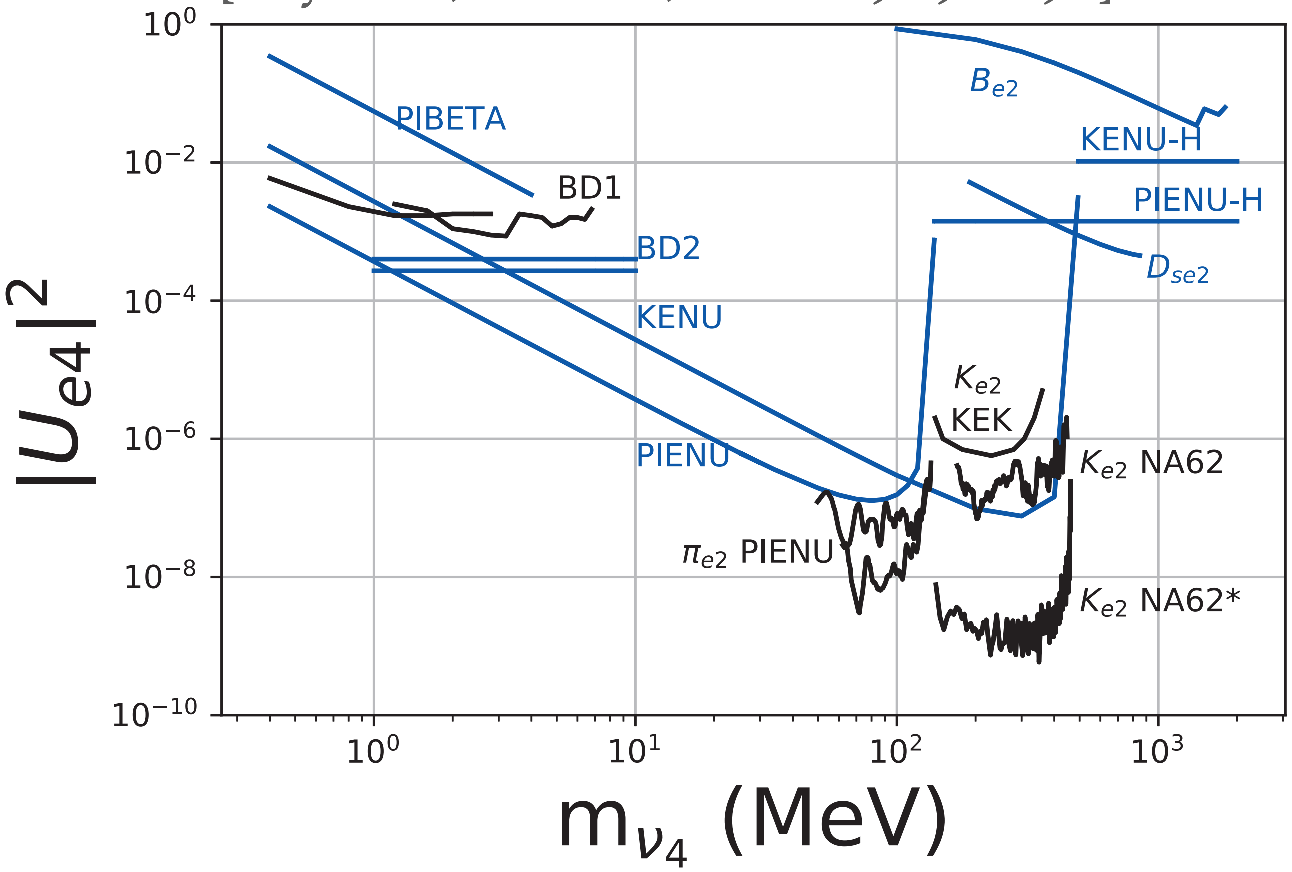
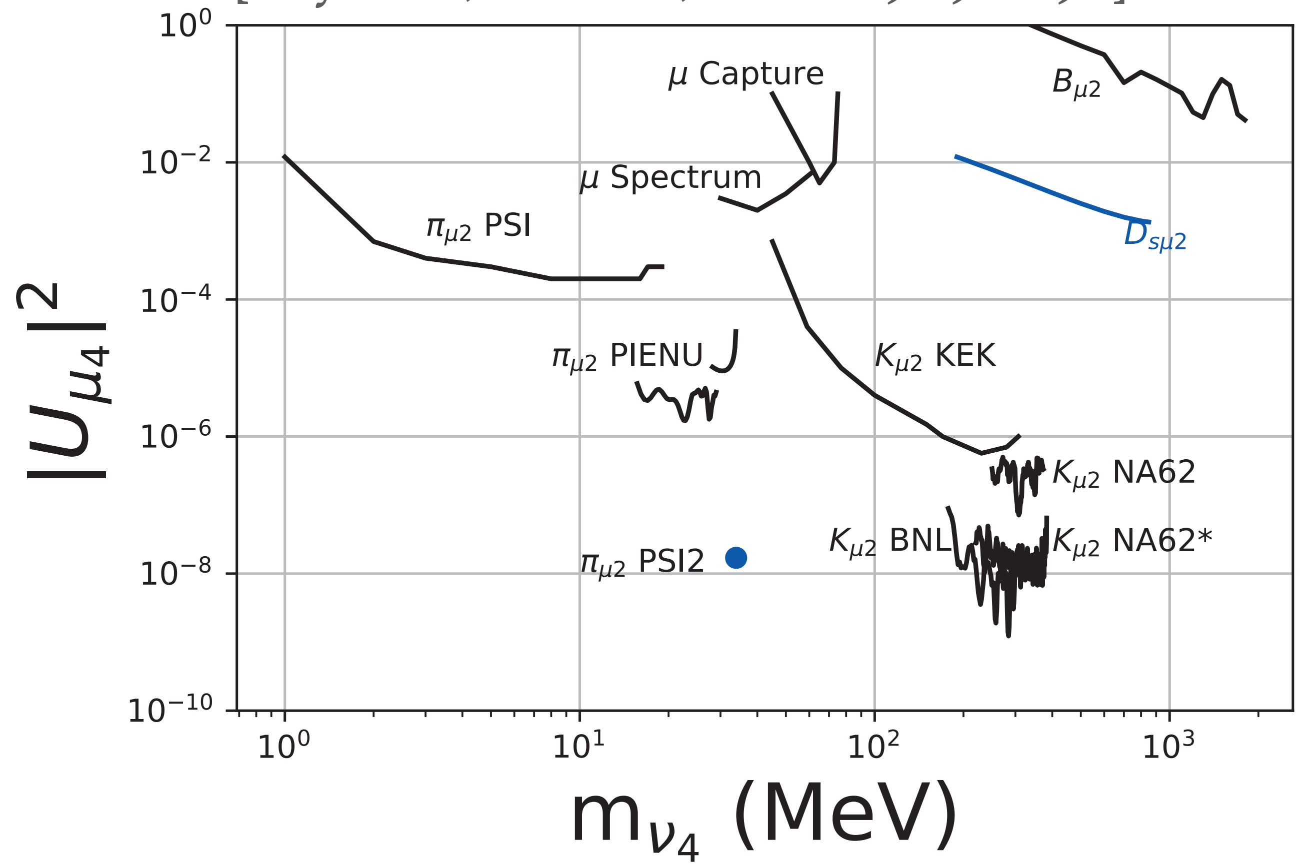
Limits on Pion Decays

[Bryman, Shrock, arXiv:1909.11198]



[Bryman, Shrock, arXiv:1909.11198]



$$\text{Limit on } |U_{\ell N}|^2 \quad \Rightarrow \quad \text{limit on } \frac{\Gamma(\pi^\pm \to \ell^\pm + \ell_d)}{\Gamma(\pi^\pm \to \ell^\pm + \nu_{\rm SM})}$$

[Shrock, Phys. Rev. D24, 1232 (1981)]

$$\text{Br}(\pi^\pm \to \mu^\pm + \text{MET}) \lesssim 10^{-3}\,, \quad \text{for } 5\,\text{MeV} < m_{\ell_d} < 15\,\text{MeV}\,.$$

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Generating a Baryon Asymmetry

When you make the Universe at 20 MeV, you (of course) can not use Electroweak Sphalerons to transfer a lepton into a baryon asymmetry.

You also don't need them...

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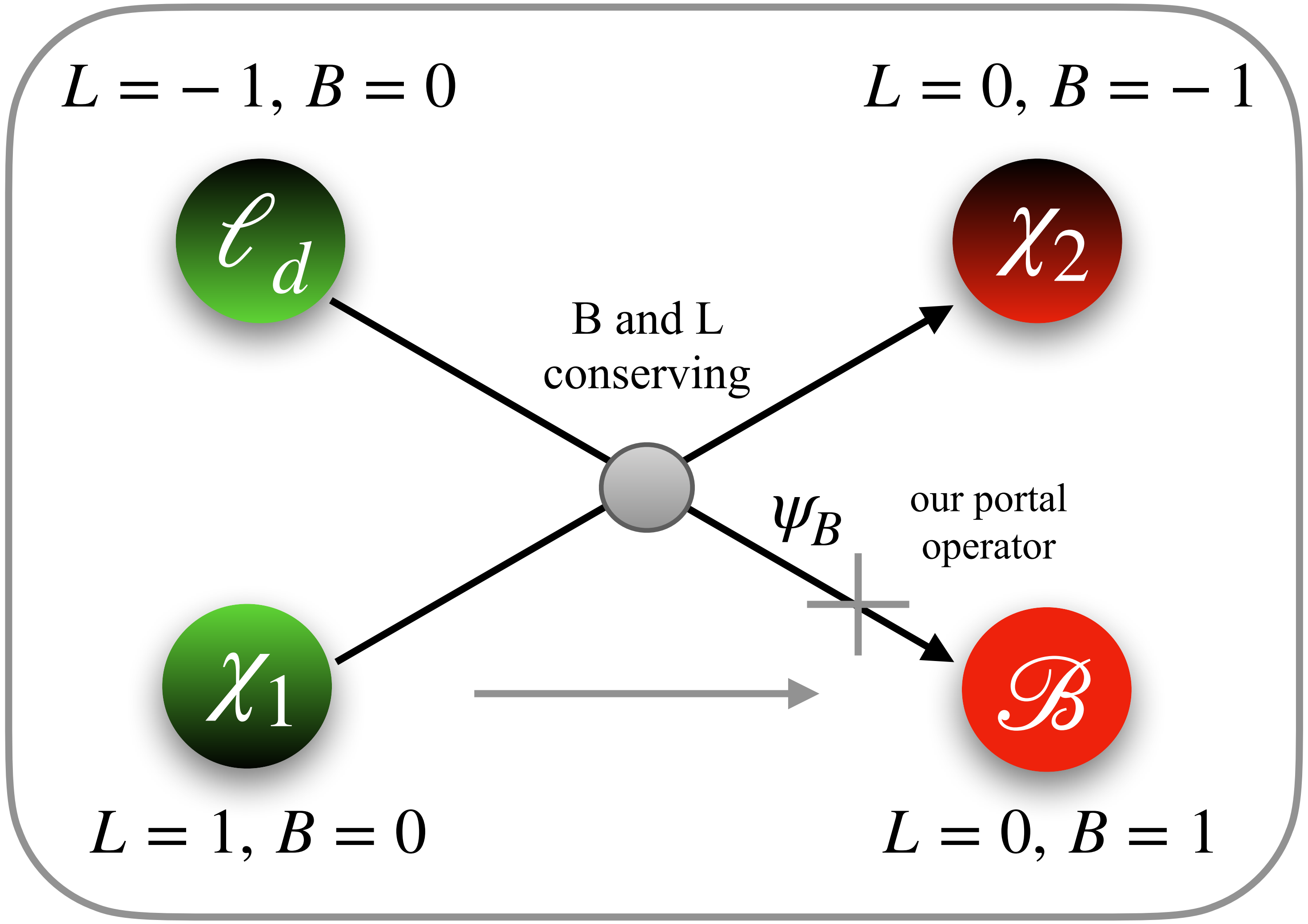
Dark Scatterings

Dark Leptons



Dark Baryon

SM Baryon

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Freezing-In a Baryon Asymmetry

Example Benchmark point:

$$T_R = 10 \text{ MeV}, \; m_\Phi = 6 \text{ GeV}$$

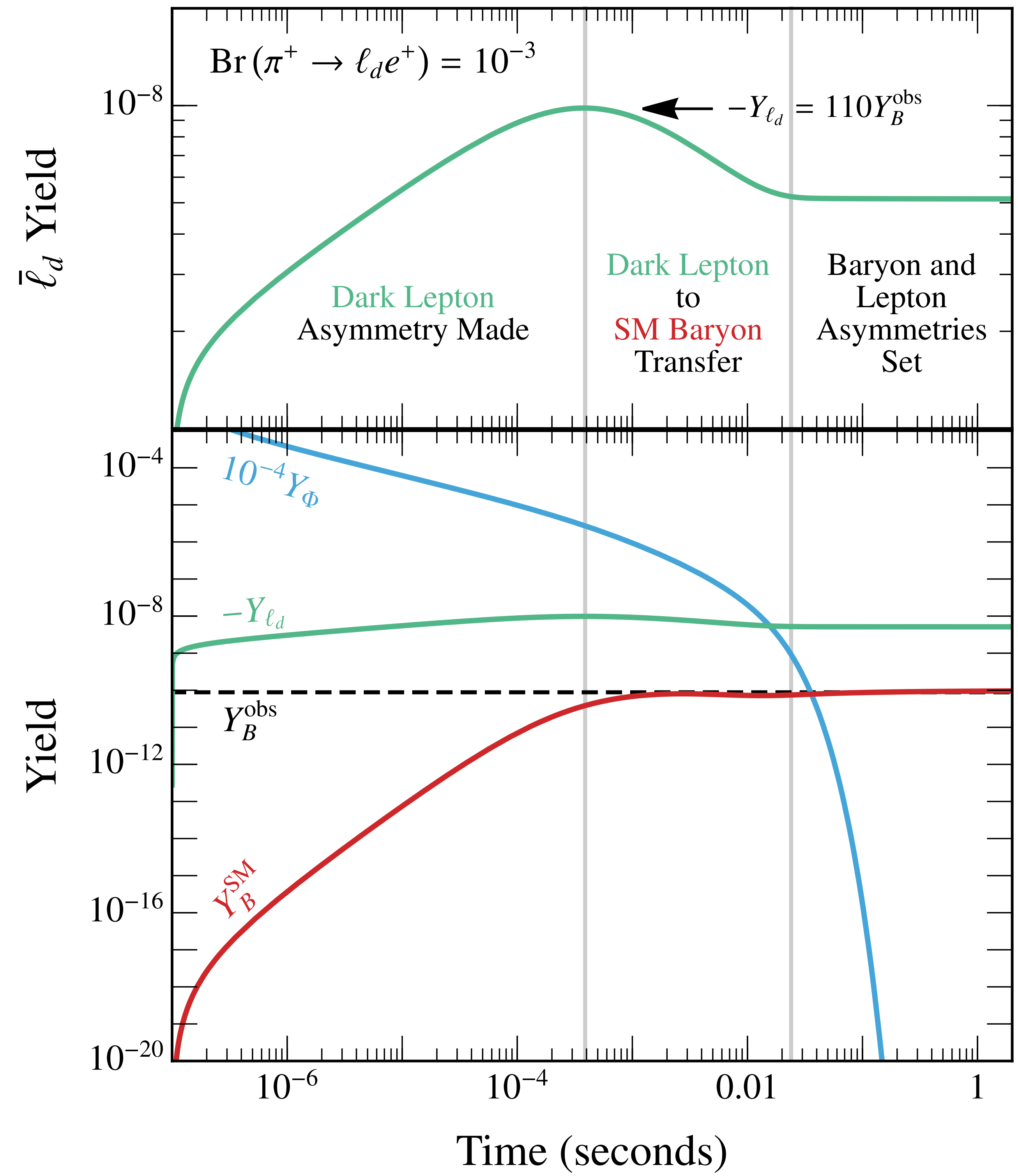
$$\langle \sigma v \rangle = 1 \times 10^{-15} \text{ GeV}^{-2}$$

$$\text{Br}(\Phi \to \chi_1 \bar{\chi}_1) = 0.1$$

$$\sum_f N_\pi^f a_{CP}^f \text{Br}_{D^+}^f = (-9.3 \times 10^{-4})$$

$$\frac{d}{dt}(n_\mathcal{B} - n_{\overline{\mathcal{B}}}) + 3H(n_\mathcal{B} - n_{\overline{\mathcal{B}}}) = - \langle \sigma v \rangle n_{\chi_1} (n_{\ell_d} - n_{\bar{\ell}_d})$$

$$\left. \frac{n_{\chi_1} \langle \sigma v \rangle}{H(T)} \right|_{T=T_R} \gtrsim \frac{Y_B^{\text{obs}}}{Y_L^{\text{dark}}} \, .$$



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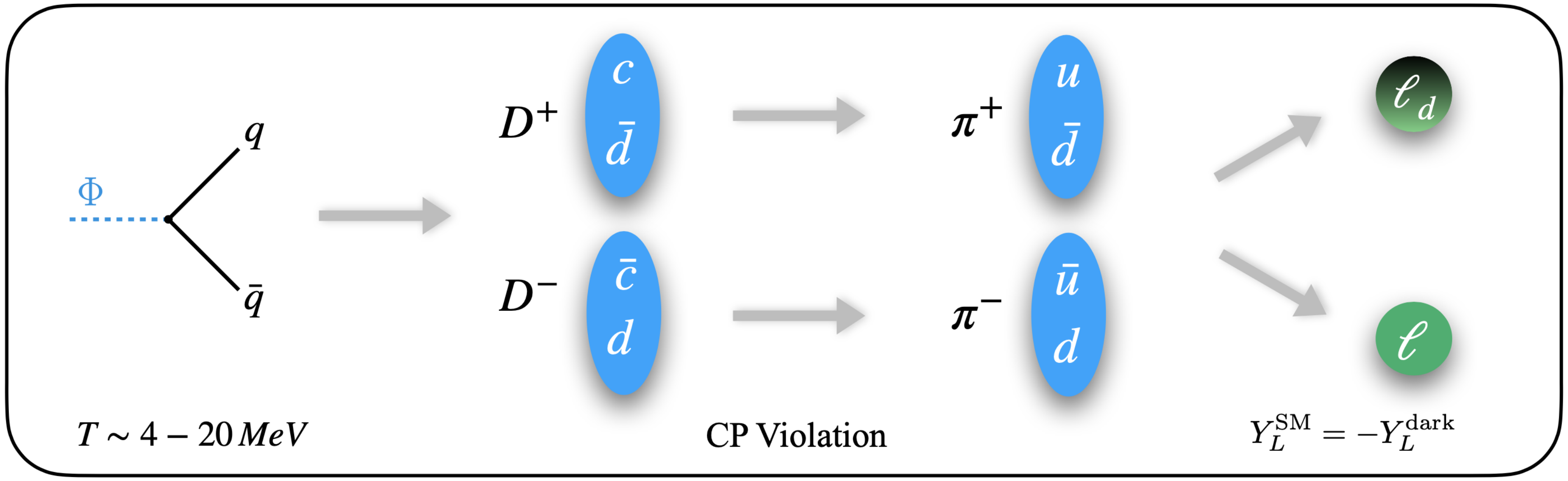
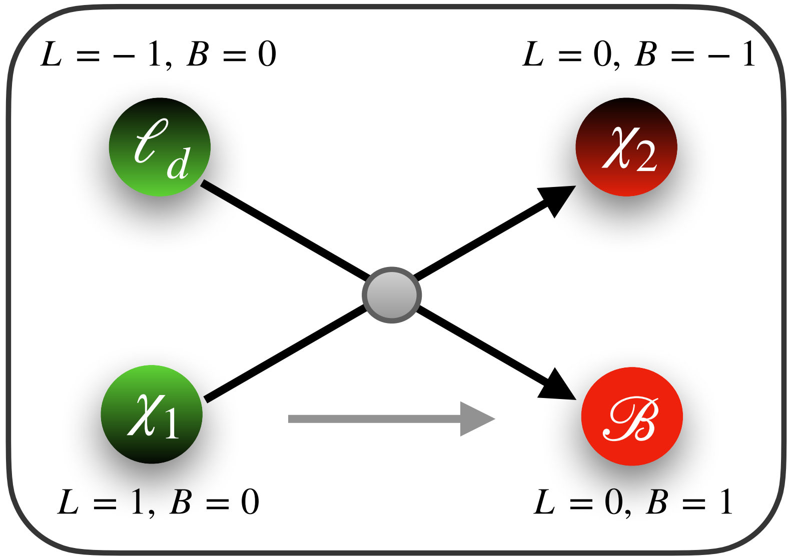
D^+ Mesogenesis





- First generates a lepton asymmetry and then freezes in a baryon asymmetry through dark sector scatterings.
- Baryogenesis and dark matter production are controlled by experimental observables of the charged *D* Mesons system.

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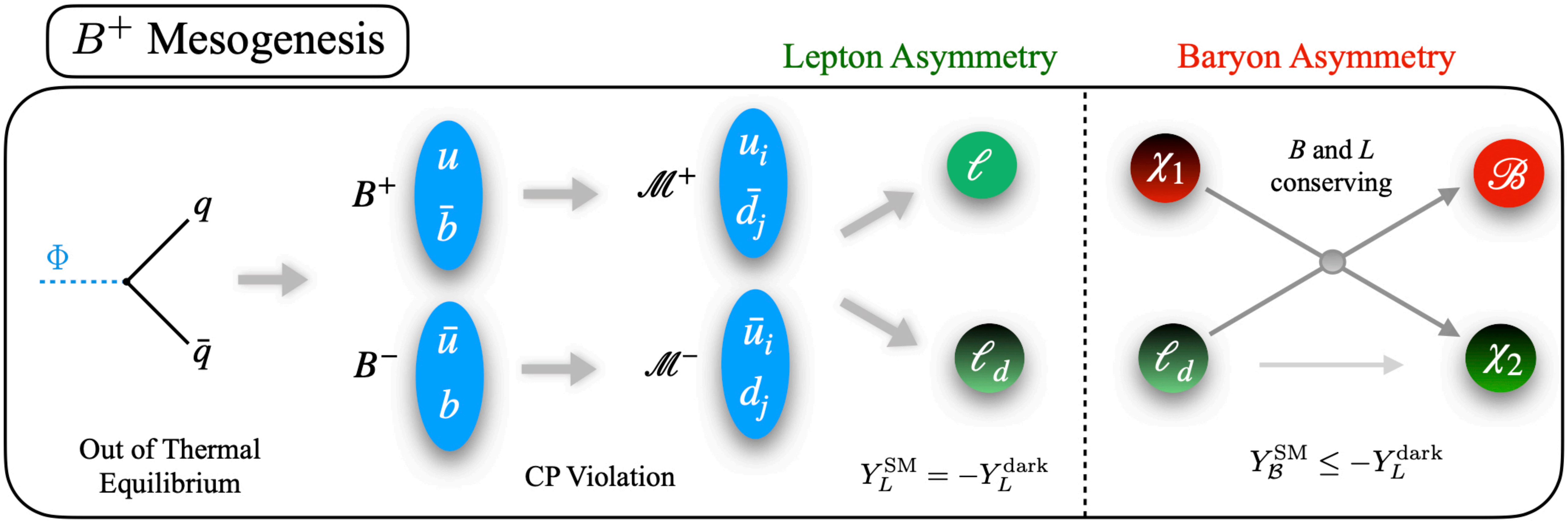
B^+ Mesogenesis

GE with Fatemeh Elahi and Robert McGehee [arXiv:2109.09751]



$$Y_{\ell_d} \propto \sum_{\mathcal{M}^+} {\rm Br}^{\ell_d}_{\mathcal{M}^+} \sum_f \tilde{A}^f_{\rm CP}\, {\rm Br}^f_{B^+}$$

$$\tilde{A}^f_{\rm CP} = \frac{\Gamma\left(B^+ \to f\right) - \Gamma\left(B^- \to f\right)}{\Gamma\left(B^+ \to f\right) + \Gamma\left(B^- \to f\right)}$$

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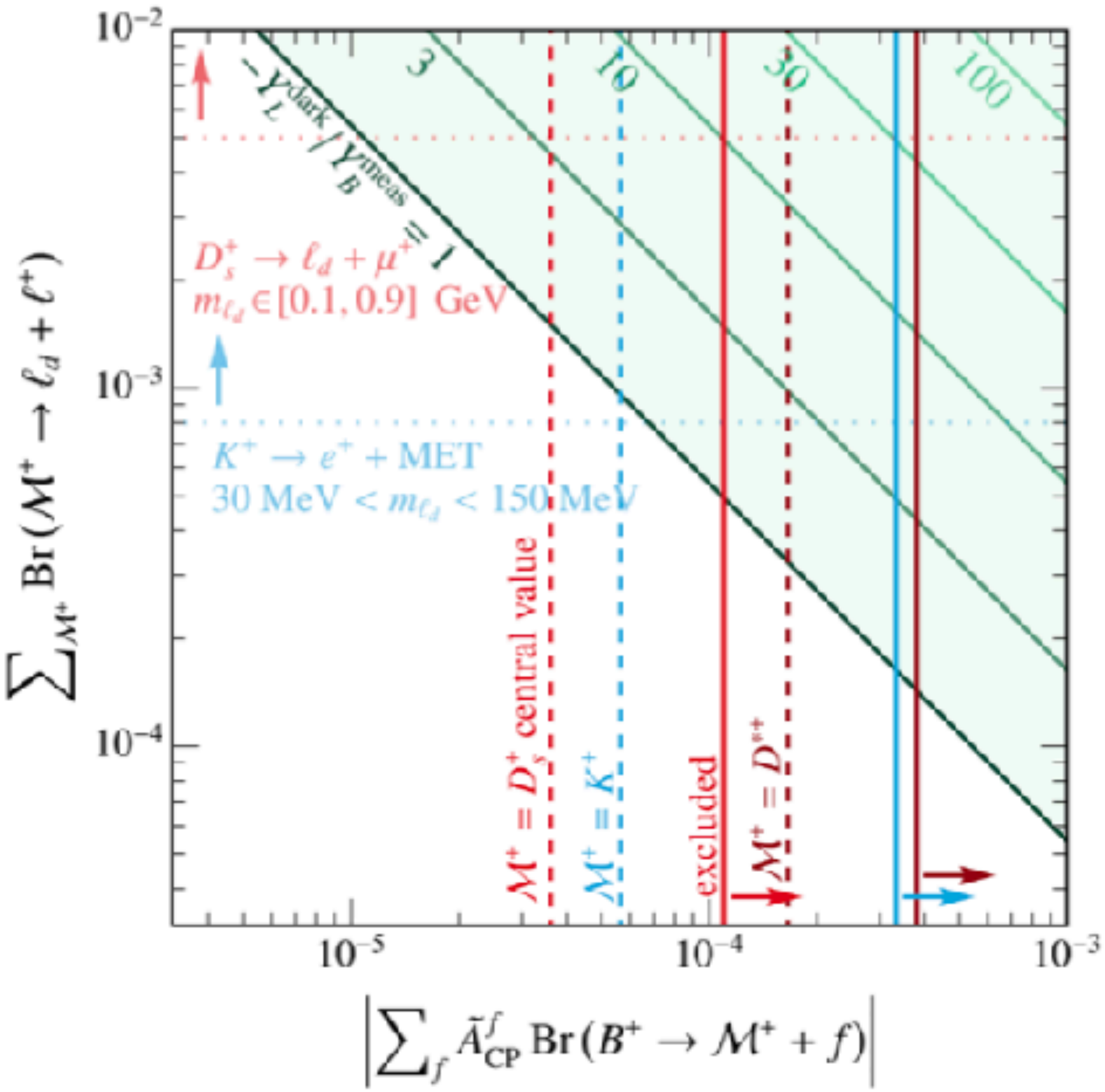
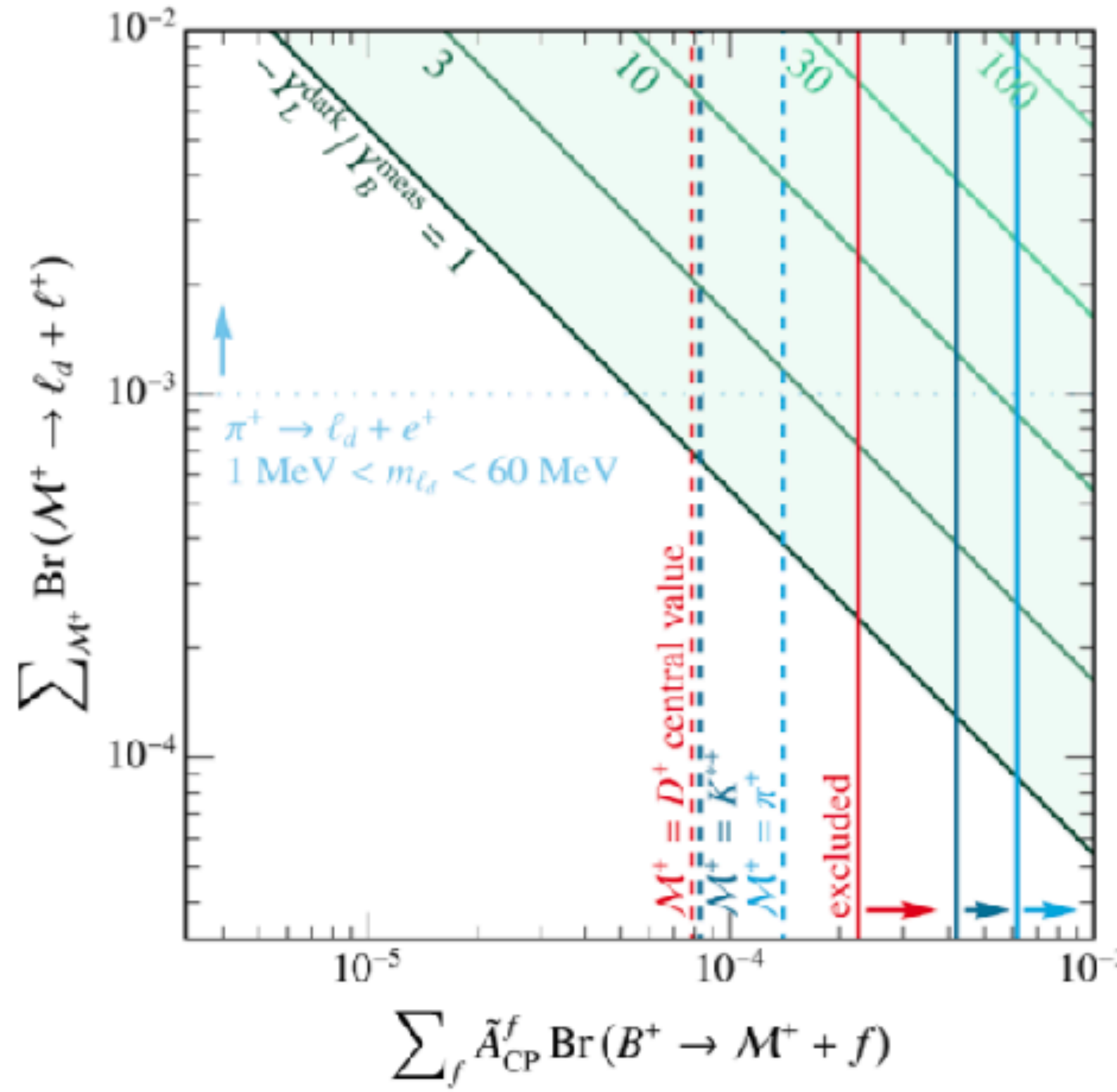
B^+ Mesogenesis

GE with Fatemeh Elahi and Robert McGehee [arXiv:2109.09751]





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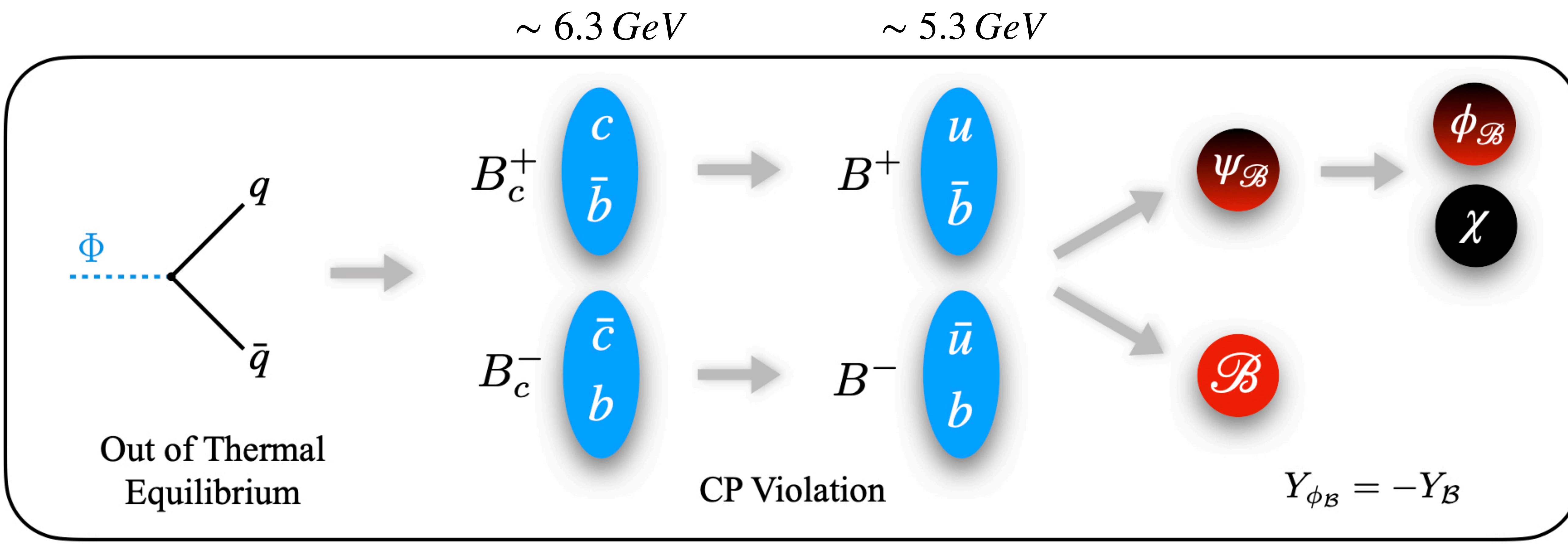
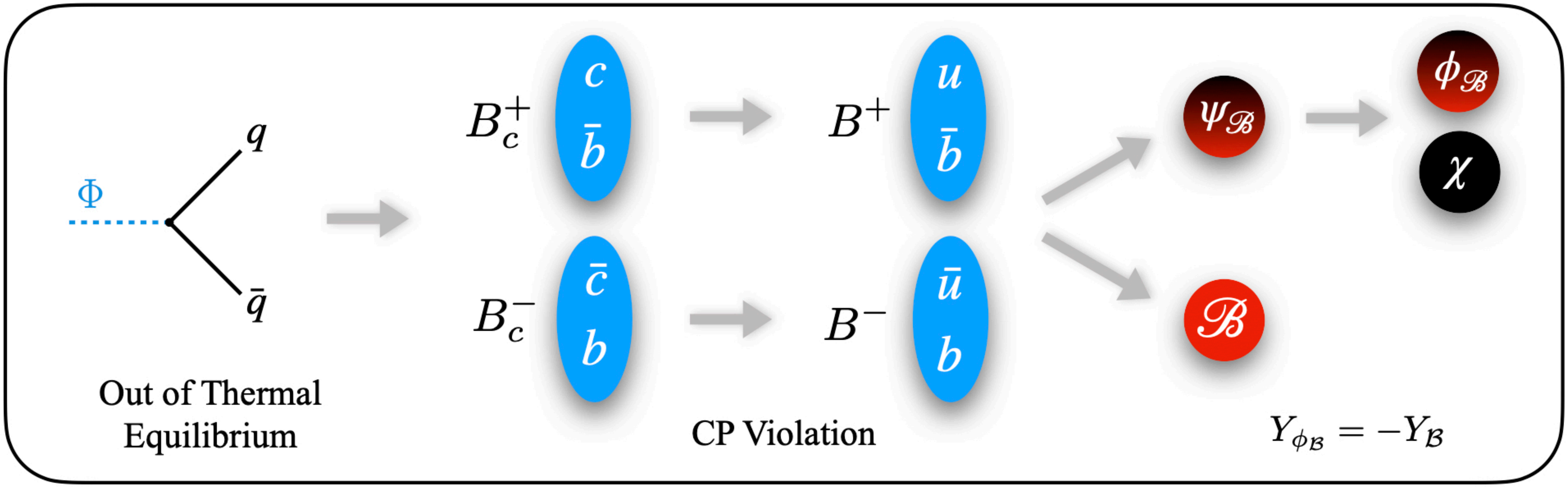
B_c^+ Mesogenesis

GE with Fatemeh Elahi and Robert McGehee [arXiv:2109.09751]



B_c^+ Mesogenesis

GE with Fatemeh Elahi and Robert McGehee [arXiv:2109.09751]



$$A_{\rm CP}^f = \frac{\Gamma(B_c^+ \to f) - \Gamma(B_c^- \to \bar{f})}{\Gamma(B_c^+ \to f) + \Gamma(B_c^- \to \bar{f})}$$

$$\mathcal{O} = \frac{y^2}{M_\phi^2} \bar{\psi}_{\mathcal{B}} b \bar{u}_i^c d_j + \text{h.c.}\,,$$

$$m_{\psi_B} > m_p - m_e \simeq 937.8\,\text{MeV}$$

G. Elor

B^+ Decay

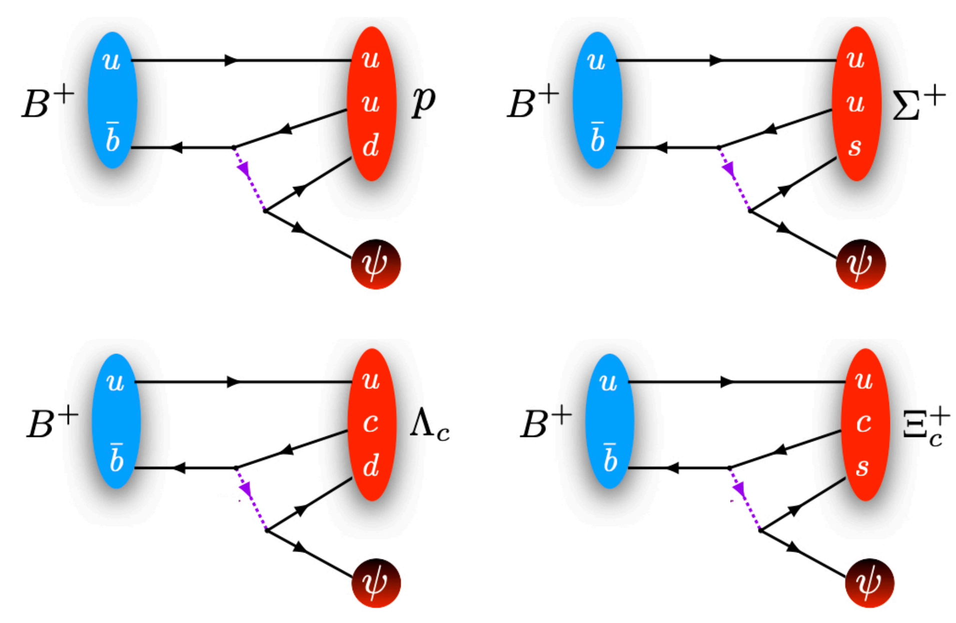
GE with Fatemeh Elahi and Robert McGehee [arXiv:2109.09751]

UV Model: $\mathcal{L}_{-1/3} = -\sum_{i,j} y_{u_i d_j} Y^\star \bar{u}_{iR} d^c_{jR} - \sum_k y_{\psi d_k} Y d^c_{kR} \bar{\psi} + \text{h.c.}$

Operator/Decay	Initial State	Final state
$\mathcal{O} = \psi\, b\, u\, d$ $\bar{b} \to \psi\, u\, d$	B_d	$\psi + n\,(udd)$
	B_s	$\psi + \Lambda\,(uds)$
	B^+	$\psi + p\,(duu)$
	Λ_b	$\bar{\psi} + \pi^0$
$\mathcal{O} = \psi\, b\, u\, s$ $\bar{b} \to \psi\, u\, s$	B_d	$\psi + \Lambda\,(usd)$
	B_s	$\psi + \Xi^0\,(uss)$
	B^+	$\psi + \Sigma^+\,(uus)$
	Λ_b	$\bar{\psi} + K^0$
$\mathcal{O} = \psi\, b\, c\, d$ $\bar{b} \to \psi\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$
	B_s	$\psi + \Xi_c^0\,(cds)$
	B^+	$\psi + \Lambda_c\,(dcu)$
	Λ_b	$\bar{\psi} + \overline{D}^0$
$\mathcal{O} = \psi\, b\, c\, s$ $\bar{b} \to \psi\, c\, s$	B_d	$\psi + \Xi_c^0\,(csd)$
	B_s	$\psi + \Omega_c\,(css)$
	B^+	$\psi + \Xi_c^+\,(csu)$
	Λ_b	$\bar{\psi} + D^- + K^+$

Directly related to neutral B Mesogenesis, and indirectly related B^+ Mesogenesis.

Directly related to charged B Mesogenesis



Indirect signal of charged and neutral B Mesogenesis

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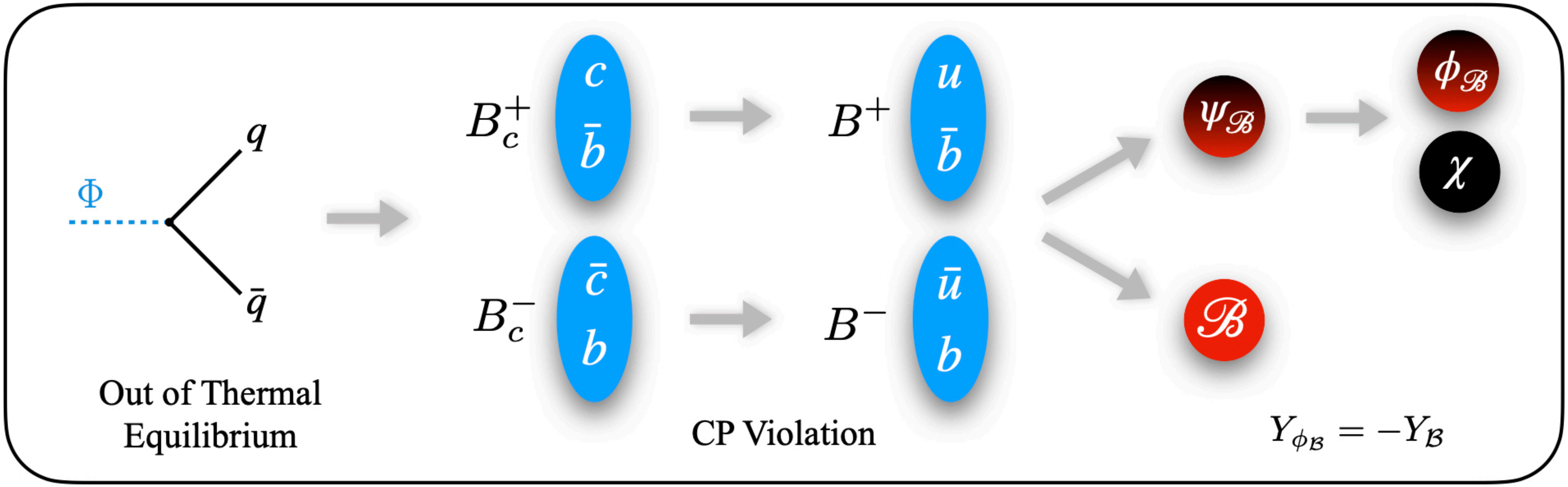
B_c^+ Mesogenesis

Same UV model as Neutral B Mesogenesis: $\mathcal{O} = \frac{y^2}{M_\phi^2} \bar{\psi}_{\mathcal{B}} b \bar{u}_i^c d_j + \mathrm{h.c.}\,,$

$m_{\psi_B} > m_p - m_e \simeq 937.8\,\mathrm{MeV}$



$$Y_{\mathcal{B}} \equiv \frac{n_{\mathcal{B}} - n_{\bar{\mathcal{B}}}}{s} \propto \sum_f A_{\mathrm{CP}}^f \,\mathrm{Br}\left(B_c^+ \to B^+ + f\right) \times \sum_{\mathcal{B}^+} \mathrm{Br}\left(B^+ \to \bar{\psi}_{\mathcal{B}} + \mathcal{B}^+\right)$$

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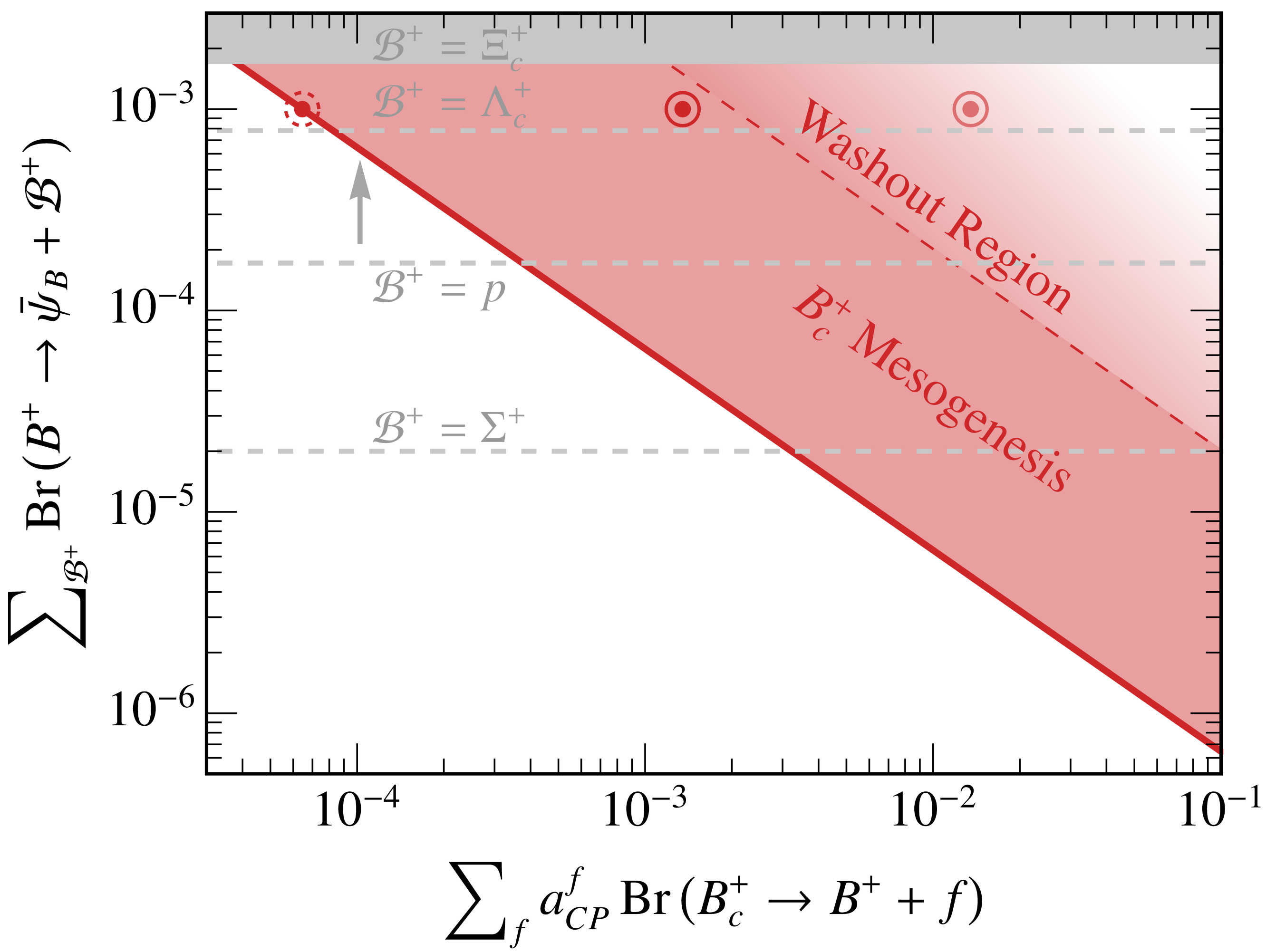
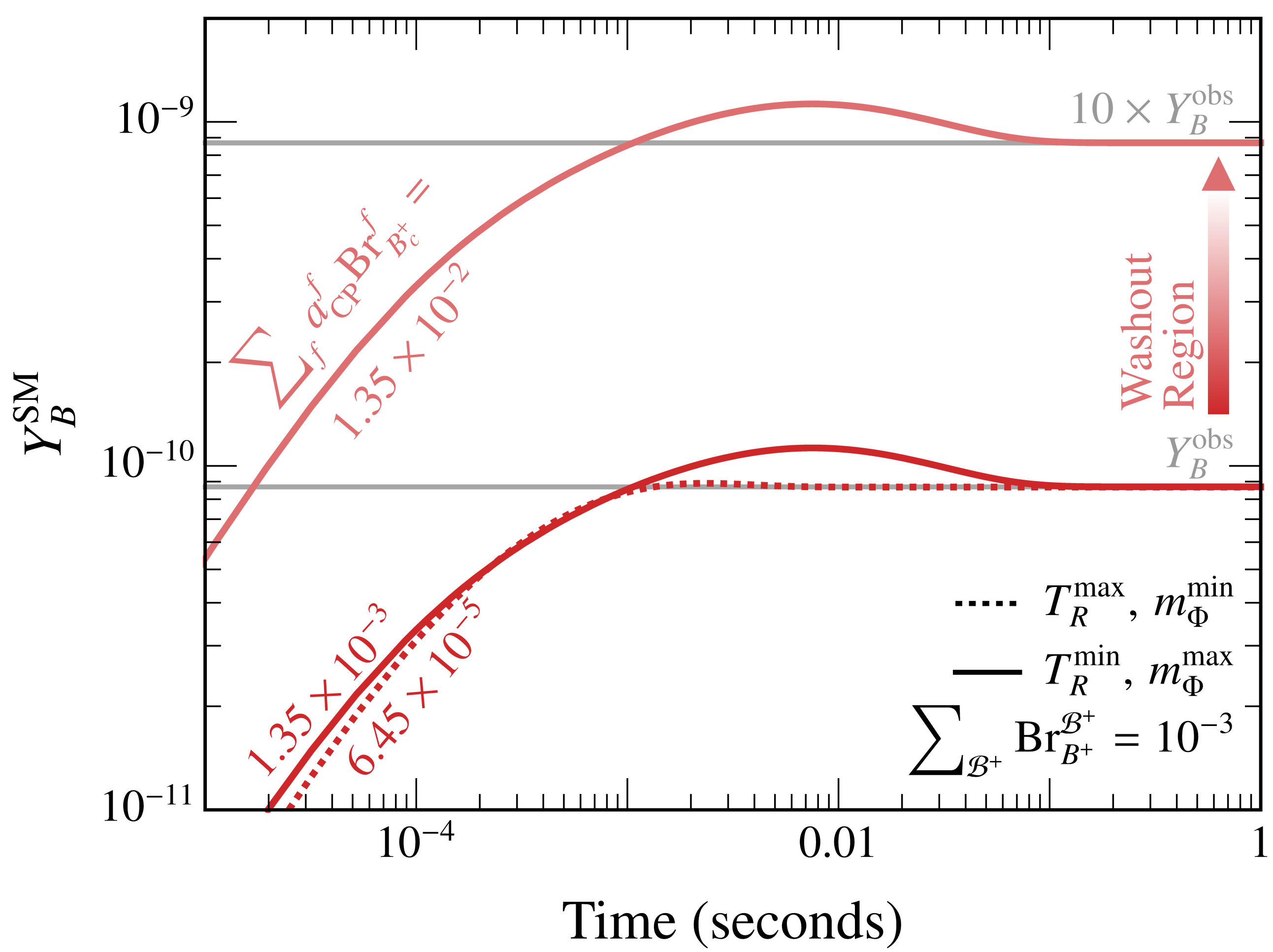
B_c^+ Mesogenesis

GE with Fatemeh Elahi and Robert McGehee [arXiv:2109.09751]





$$\frac{Y_\mathcal{B}}{Y_\mathcal{B}^{\rm obs}} \simeq \frac{\sum_{\mathcal{B}^+} \mathrm{Br}_{B^+}^{\mathcal{B}^+}}{10^{-3}} \frac{\sum_f a_{\rm CP}^f \mathrm{Br}_{B_c^+}^f}{6.45 \times 10^{-5}} \frac{T_R}{20 \ \mathrm{MeV}} \frac{2 m_{B_c^+}}{m_\Phi}$$

The Many *Flavors* of Mesogenesis

Mechanism	CPV	Dark Sector	Observables	Relevant Experiments
B^0 Mesogenesis	B_s^0 & B_d^0 oscillations	Dark baryons	$A_{sl}^{s,d}$ $\text{Br}(B \to \mathcal{B} + X)$	LHCb B Factories, LHCb
D^+ Mesogenesis	$D^\pm$ decays	Dark leptons and/or baryons	A_{CP}^D Br_{D^+} $\text{Br}(\mathcal{M}^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU
B^+ Mesogenesis	$B^\pm$ decays	Dark leptons and/or baryons	A_{CP}^B Br_{B^+} $\text{Br}(\mathcal{M}^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU
B_c^+ Mesogenesis	$B_c^\pm$ decays	Dark baryons	$A_{CP}^{B_c}$ $\text{Br}_{B_c^+}$ $\text{Br}_{B^+ \to \mathcal{B}^+ + X}$	LHCb, FCC LHCb, FCC B Factories, LHCb

Outlook:

- Continued support of experimental efforts.
- Even more flavors of Mesogenesis?
- Making the Universe above 20 MeV?
- Theory of inflation?
- Explore UV embedding and dark sector models.

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The Many *Flavors* of Mesogenesis

Mechanism	CPV	Dark Sector	Observables	Relevant Experiments
B^0 Mesogenesis	B^0_s & B^0_d oscillations	Dark baryons	$A^{s,d}_{sl}$ $\text{Br}(B \to \mathcal{B} + X)$	LHCb B Factories, LHCb
D^+ Mesogenesis	$D^\pm$ decays	Dark leptons and/or baryons	A^D_{CP} Br_{D^+} $\text{Br}(\mathcal{M}^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU
B^+ Mesogenesis	$B^\pm$ decays	Dark leptons and/or baryons	A^B_{CP} Br_{B^+} $\text{Br}(\mathcal{M}^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU
B^+_c Mesogenesis	$B^\pm_c$ decays	Dark baryons	$A^{B_c}_{CP}$ $\text{Br}_{B^+_c}$ $\text{Br}_{B^+ \to \mathcal{B}^+ + X}$	LHCb, FCC LHCb, FCC B Factories, LHCb

Outlook:

- Continued support of experimental efforts.
- Even more flavors of Mesogenesis?
- Making the Universe above 20 MeV?
- Theory of inflation?
- Explore UV embedding and dark sector models.

Thanks!

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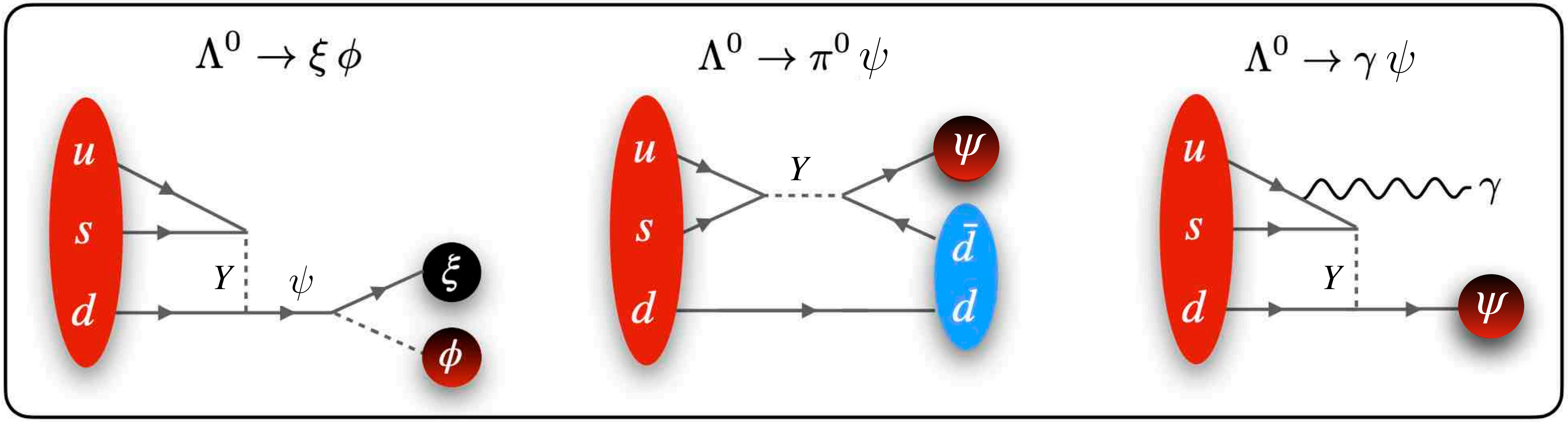
Backups

New Hyperon Decays

Another indirect probe of *B*-Mesogenesis that can be searched for at BESIII, Belle-II, and LHCb



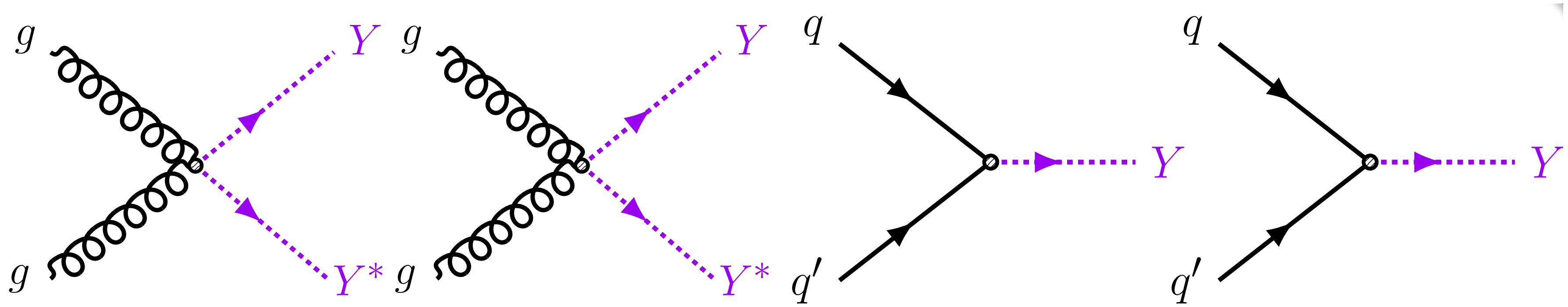
Light hadrons: we can compute form factors by matching onto chiral EFT.

[arXiv:2111.12712] GE with Gonzalo Alonso-Alvarez, Miguel Escudero, Bartosz Fornal, Benjamin Grinstein, Jorge Martin Camalich

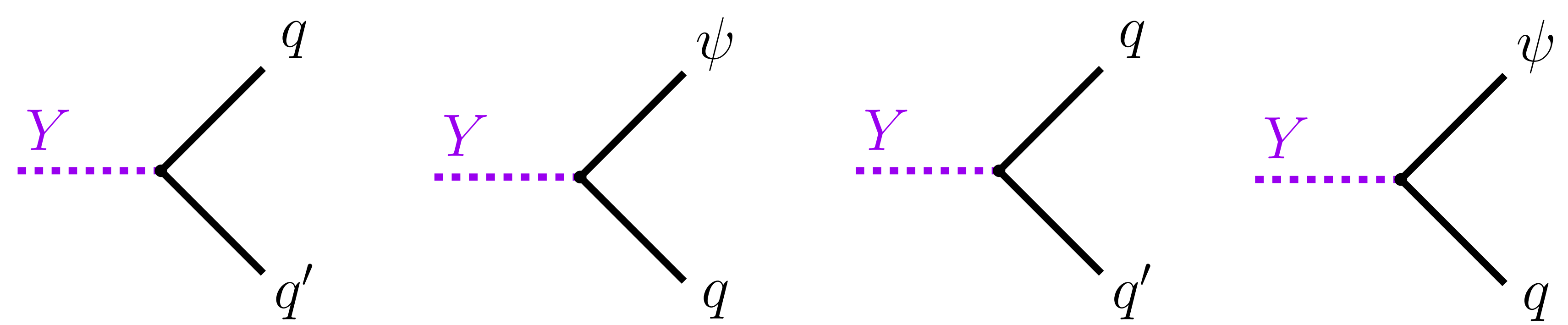
Colored Triplet Scalar

Constraints from LHC squark searches

Production:



Decay:



Signature:	4 jets	2 jets + MET	dijet	jet + MET
Search:	ATLAS [1710.07171]	ATLAS [2010.14293] CMS [1908.04293]	CMS [1806.00843]	ATLAS [1711.03301]
Constraint:	$M_Y > 0.5\,\text{TeV}$	$M_Y > 1.2\,\text{TeV}$	$M_Y > 1 - 7\,\text{TeV}$	$M_Y > 1 - 7\,\text{TeV}$

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Colored Triplet Scalar

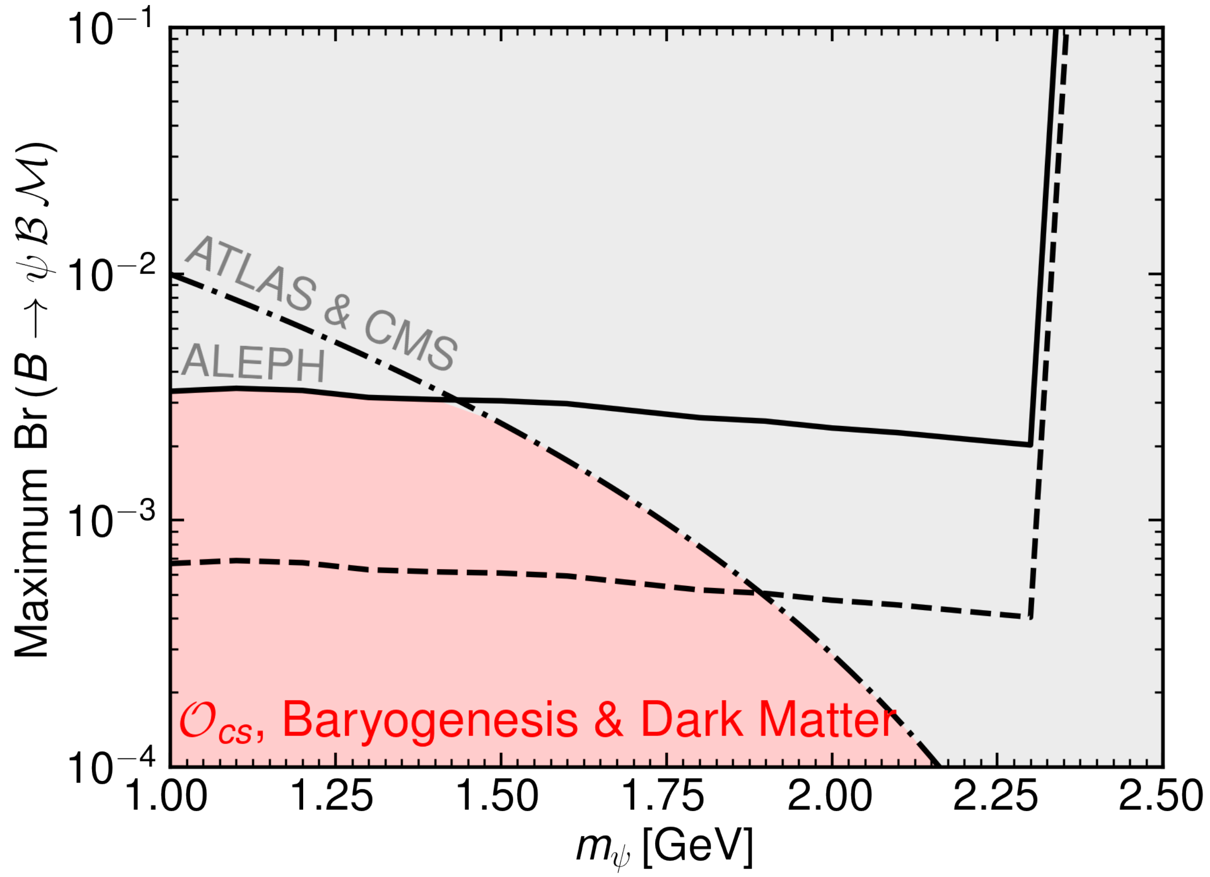
Constraints from LHC squark searches

B-Mesogenesis requires: $\mathrm{Br}(B \to \psi\, \mathcal{B}\, \mathcal{M}) \simeq 10^{-3} \left(\frac{\Delta m}{3\ \mathrm{GeV}}\right)^4 \left(\frac{1.5\ \mathrm{TeV}}{M_Y}\frac{\sqrt{y_{ub} y_{\psi d}}}{0.53}\right)^4 \gtrsim 10^{-4}$

$\Delta m = m_B - m_\psi - m_{\mathcal{B}} - m_{\mathcal{M}}$

Since collider bounds depend on the ratio $\frac{\sqrt{y_{u_i d_j} y_{\psi d_k}}}{M_Y}$ they will in turn constrain the branching fraction.

e.g.



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A Roadmap for Discovering Neutral *B*-Mesogenesis

GE with Gonzalo Alonso-Alvarez, Miguel Escudero, [arXiv:2101.02706, PRD]

Paper out last month: *"The Strange Physics of Dark Baryons"*
GE with Gonzalo Alonso-Alvarez, Miguel Escudero, Bartosz Fornal, Benjamin Grinstein, Jorge Martin Camalich [arXiv:2111.12712]

Recent searches by the Belle collaboration [arXiv:2110.14086]
Proposed searches at LHCb, see [arXiv:2105.12668] and [arXiv:2106.12870]

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Searching for new *b*-Hadron Decays

Possibilities at LHCb

[See our white paper on "Stealth Physics at LHCb" 2105.12668]

- No handle on initial energy of decaying *B* meson so measuring missing energy is non-trivial.
- But, LHCb has advantages: larger number of *B* mesons produced than at Belle, excellent vertex resolution, and good particle reconstruction efficiencies.
- Some possibilities for searches do exist. e.g. new paper just last week!

Prospects on searches for baryonic Dark Matter produced in *b*-hadron decays at LHCb

[2106.12870]

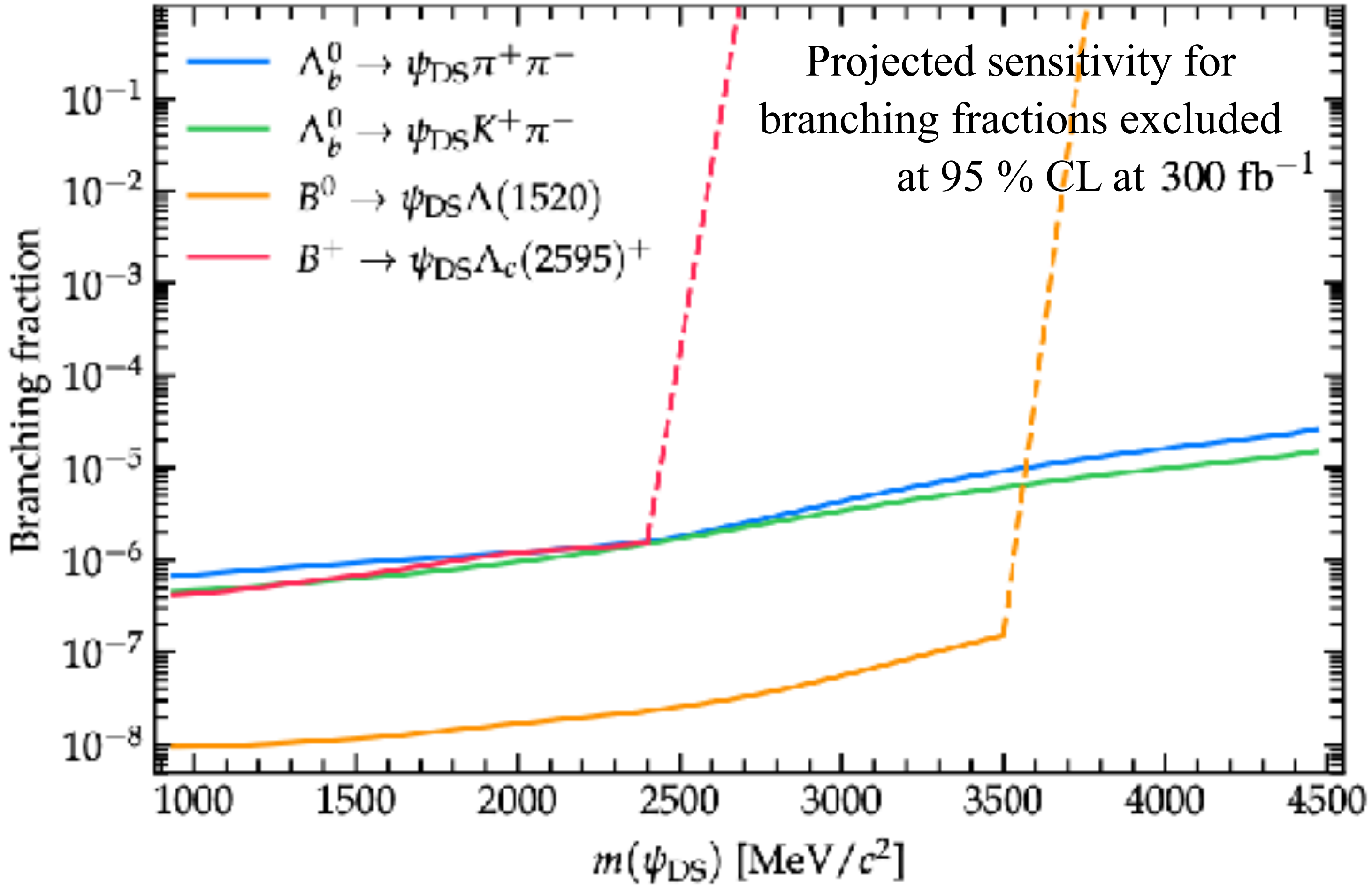
Alexandre Brea Rodríguez [a,1], **Veronika Chobanova** [b,1], **Xabier Cid Vidal** [c,1], **Saúl López Soliño** [d,1], **Diego Martínez Santos** [e,1], **Titus Mombächer** [f,1], **Claire Prouvé** [g,1], **Emilio Xosé Rodríguez Fernández** [h,1], **Carlos Vázquez Sierra** [i,2]

[1]Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain
[2]European Organization for Nuclear Research (CERN), Geneva, Switzerland

Searching for new b-Hadron Decays

Proposed Search at LHCb [2106.12870]

- Search for decays of B mesons and b-Flavored baryons into an excited baryon in the final state $B \to \psi \mathcal{B}^\star$
- The excited baryon promptly decay at the same decay point as original decay, allowing one to trigger on this decay.



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Boltzmann Equations

Late time decay of Inflaton

$$\Gamma_\Phi = 4H(T_R)$$

- Inflaton: $$\frac{dn_\Phi}{dt} + 3Hn_\Phi = -\Gamma_\Phi n_\Phi$$
- Radiation: $$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = +\Gamma_\Phi m_\Phi n_\Phi$$
- Hubble: $$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\left(\rho_{\rm rad} + m_\Phi n_\Phi\right)$$

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Boltzmann Equations

Dark Sector

- Symmetric component of the dark scalar baryon

$$\frac{dn_{\phi+\phi^*}}{dt} + 3\,H\,n_{\phi+\phi^*} = 2\,\Gamma^B_\Phi\,n_\Phi - 2\,\langle\sigma v\rangle_\phi\left(n^2_{\phi+\phi^*} - n^2_{\text{eq},\,\phi+\phi^*}\right)$$

Overproduced particle must be depleted by additional dark interactions.

- The dark Majorana fermion

$$\frac{dn_\xi}{dt} + 3Hn_\xi = 2\Gamma^B_\Phi n_\Phi - \langle\sigma v\rangle_\xi\left(n^2_\xi - n^2_{\text{eq},\xi}\right)$$

$$\Gamma^B_\Phi \equiv \Gamma_\Phi \times \text{Br}\left(B \to \psi\,\mathcal{B}\,\mathcal{M}\right)$$

Simplification: For the (low) temperature range of interest we can check that the *B* mesons decay more quickly than they annihilate

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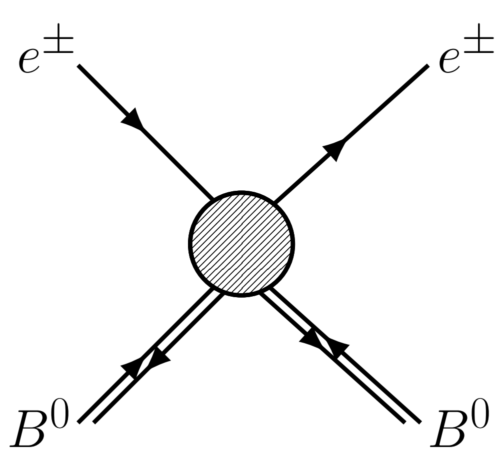
Boltzmann Equations

The Baryon Asymmetry

- Anti-symmetric dark sector baryon makes up the baryon asymmetry

$$\frac{dn_{\phi-\phi^*}}{dt} + 3Hn_{\phi-\phi^*} = 2\Gamma_\Phi^B \sum_q \mathrm{Br}\left(\bar{b} \to B_q^0\right) A_{\mathrm{SL}}^q f_{\mathrm{deco}}^q n_\Phi$$

Coherent *B* meson oscillations maintained for 20 MeV scales and below



$$\Gamma\left(e^\pm B_q^0 \to e^\pm B_q^0\right) = 10^{-11}\mathrm{GeV}\left(\frac{T}{20\mathrm{MeV}}\right)^5$$

$$f_{\mathrm{deco}}^q = e^{-\Gamma\left(e^\pm B_q^0 \to e^\pm B_q^0\right)/\Delta m_{B_q}}$$

$$T_{B_s} \leq 20\,\mathrm{MeV} \text{ and } T_{B_d} \leq 10\,\mathrm{MeV}$$

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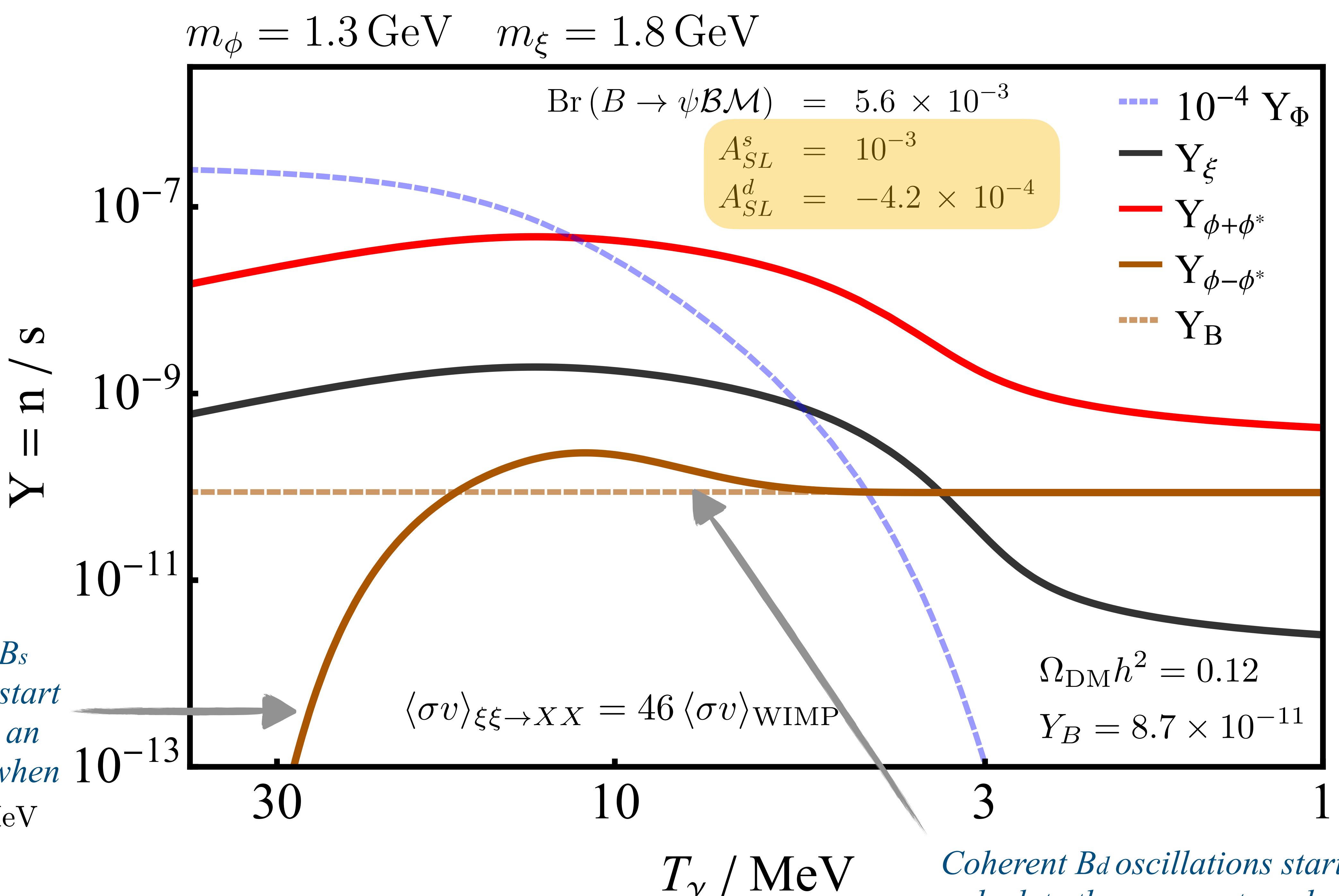
Example Benchmark Point



Coherent Bs oscillations start to produce an asymmetry when $T_{B_s} \lesssim 20\,\mathrm{MeV}$

Need a net positive asymmetry

Coherent Bd oscillations start to deplete the asymmetry when $T_{B_d} \lesssim 10\,\mathrm{MeV}$

Searching for new b-Hadron Decays

Caution: Inclusive vs. Exclusive Rates

- All decays (and their searches) discussed thus far have been *exclusive*. But, the observable controlling the baryon asymmetry is an *inclusive* rate.

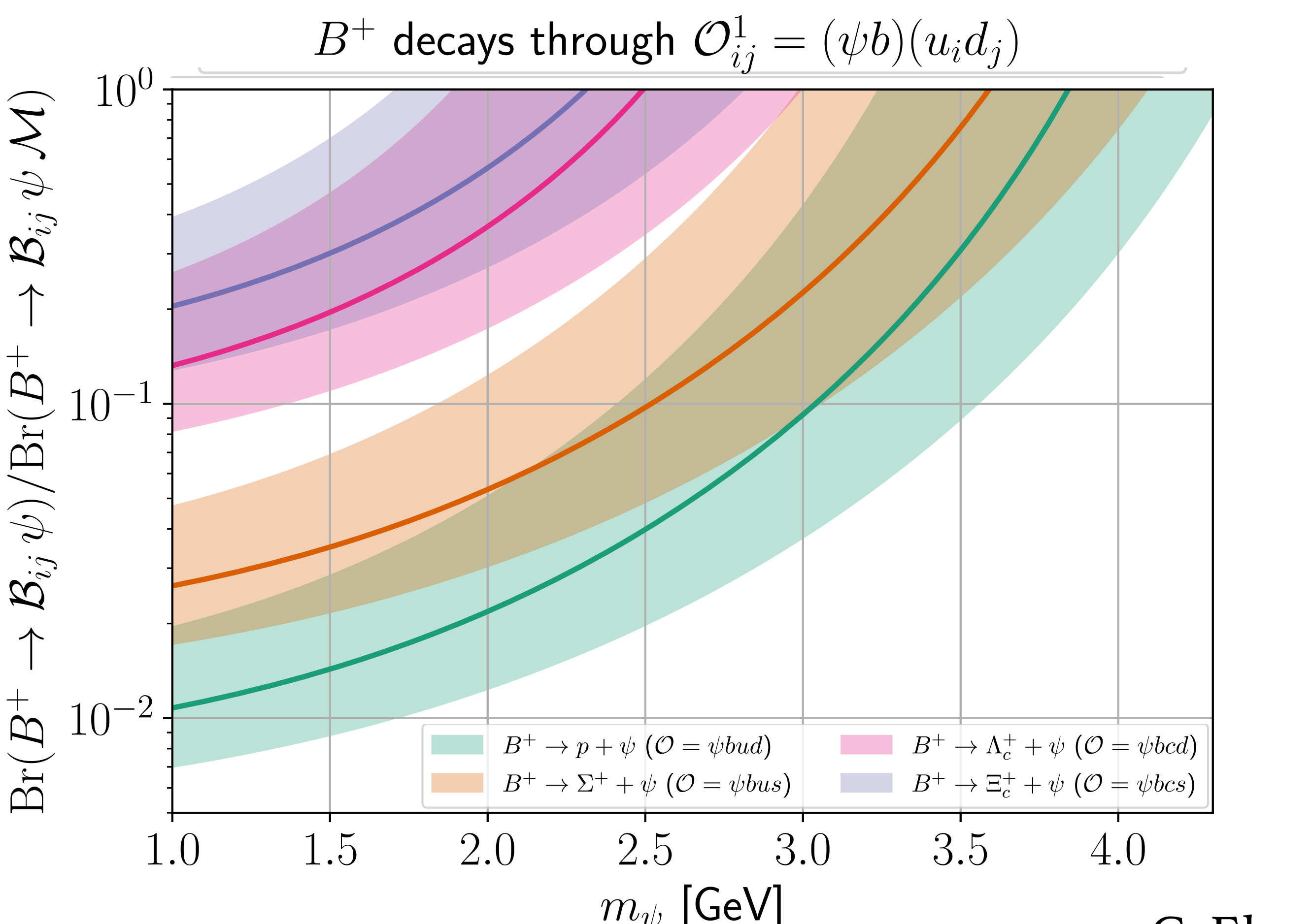
$$\mathrm{Br}(B \to \psi\, \mathcal{B}\, \mathcal{M}) \gtrsim 10^{-4}$$

- Need a dedicated calculation using QCD sum rules or lattice techniques etc. to calculate form factors. Beyond my current expertise….

- Phase space method

  [Bigi, Phys.Lett.B 106, 510 (1981)]

$$\frac{\mathrm{Br}\,(B \to \psi\, \mathcal{B})}{\mathrm{Br}(B \to \psi\, \mathcal{B}\, \mathcal{M})} \gtrsim (1-10)\,\%\,.$$



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Freezing-In a Baryon Asymmetry

Boltzmann Equations with scattering: $\bar{\ell}_d + \chi_1 \to \chi_2 + \mathcal{B}$

- New dark lepton/lepto-baryon: $m_\Phi \gtrsim m_{\chi_1} \quad m_\Phi \gtrsim m_{\chi_2} + m_{\mathcal{B}}$

$$\frac{dn_{\chi_1}}{dt} + 3Hn_{\chi_1} = \Gamma_\Phi n_\Phi \mathrm{Br}\left(\Phi \to \chi_1 \bar{\chi}_1\right) - \langle \sigma v \rangle n_{\bar{\ell}_d} n_{\chi_1}$$

- Dark lepton:

$$\frac{d}{dt}\left(n_{\ell_d} - n_{\bar{\ell}_d}\right) + 3H\left(n_{\ell_d} - n_{\bar{\ell}_d}\right) = 2\Gamma_\Phi^D n_\Phi \mathrm{Br}_\pi^{\ell_d} \sum_f N_\pi^f a_{CP}^f \mathrm{Br}_{D^+}^f - \langle \sigma v \rangle n_{\chi_1}\left(n_{\ell_d} - n_{\bar{\ell}_d}\right)$$

- Baryon asymmetry:

$$\frac{d}{dt}\left(n_{\mathcal{B}} - n_{\overline{\mathcal{B}}}\right) + 3H\left(n_{\mathcal{B}} - n_{\overline{\mathcal{B}}}\right) = -\langle \sigma v \rangle n_{\chi_1}\left(n_{\ell_d} - n_{\bar{\ell}_d}\right)$$

To efficiently transfer the asymmetry $\left.\frac{n_{\chi_1}\langle \sigma v \rangle}{H(T)}\right|_{T=T_R} \gtrsim \frac{Y_B^{\mathrm{obs}}}{Y_L^{\mathrm{dark}}}$

G. Elor

Boltzmann Equations: Lepton Asymmetry

- Inflaton: $$\frac{dn_\Phi}{dt} + 3Hn_\Phi = -\Gamma_\Phi n_\Phi$$
- Radiation: $$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = +\Gamma_\Phi m_\Phi n_\Phi$$
- Hubble: $$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\left(\rho_{\rm rad} + m_\Phi n_\Phi\right) \qquad \Gamma_\Phi = 4H\left(T_R\right)$$
- The dark lepton asymmetry: $\Gamma_\Phi^D \equiv \Gamma_\Phi {\rm Br}(\Phi \to c){\rm Br}(c \to D)$

$$\frac{d}{dt}\left(n_{\ell_d} - n_{\bar{\ell}_d}\right) + 3H\left(n_{\ell_d} - n_{\bar{\ell}_d}\right) = 2\,\Gamma_\Phi^D n_\Phi {\rm Br}_\pi^{\ell_d} \sum_f N_\pi^f a_{CP}^f {\rm Br}_{D^+}^f$$

Experimental Observables:

- SM charged D decays: $a_{CP}^f \equiv A_{CP}^f/(1 + A_{CP}^f) \approx A_{CP}^f$ *LHCb, B factories*

  ${\rm Br}_{D^+}^f \equiv {\rm Br}\left(D^+ \to f\right)$
- Charged pion decays: ${\rm Br}_\pi^{\ell_d} \equiv {\rm Br}\left(\pi^+ \to \ell_d + \ell^+\right)$ *PIENU, PSI, etc.*

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Dark Possibilities

$$\bar{\ell}_d + \chi_1 \to \chi_2 + \bar{\psi}_B$$

Field	L	B	Field	L	B
χ_1	1	0	χ_1	1	1
χ_2	0	-1	χ_2	0	0
χ_1	0	1	χ_1	0	0
χ_2	1	0	χ_2	-1	-1

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Models

Proof of concept that what I have told you thus far is not (too) crazy.

- Some example models/dark sector charge assignments.

$$\bar{\ell}_d + \chi_1 \to \chi_2 + \mathcal{B}$$

- Estimation of the scattering cross section to confirm it can be large enough to transfer the asymmetry given current constraints.

$$\langle \sigma v \rangle \gtrsim 10^{-16}\,\mathrm{GeV}^{-2}\,\frac{Y_B^{\mathrm{obs}}}{Y_L^{\mathrm{dark}}} \times \frac{10\,\mathrm{GeV}}{m_\Phi}\frac{20\,\mathrm{MeV}}{T_R}\frac{10^{-1}}{\mathrm{Br}(\Phi \to \chi_1 \bar{\chi_1})}$$

Portal to the Dark Sector

Model Build for: $\bar{\ell}_d + \chi_1 \to \chi_2 + \mathcal{B}$

New fields: (Same model as for *B*-Mesogenesis[arXiv:1810.00880])

	Field	Spin	L	B	$\mathbb{Z}_2$	Mass	
Color triplet scalar mediator	Y	0	0	$-2/3$	$+1$	$\gtrsim 1\,\text{TeV}$	Collider bounds (as just discussed)
	ℓ_d	$1/2$	1	0	$+1$	$\mathcal{O}(10-140\,\text{MeV})$	
Dark Baryon	ψ_B	$1/2$	0	-1	$+1$	$\gtrsim 1.2\,\text{GeV}$	Stability of matter, neutron star bounds

Allowed Interactions: $\mathcal{L} \supset y_{u_i d_j} Y^* \bar{u}_i d_j^c + y_{\psi d_k} Y \bar{\psi}_B d_k^c + h.c.$

$$\mathcal{L}_{\text{eff}} = \frac{y^2}{M_Y^2} \bar{u}_i^c d_j d_k^c \psi_B$$

dark baryon-SM baryon "mixing"

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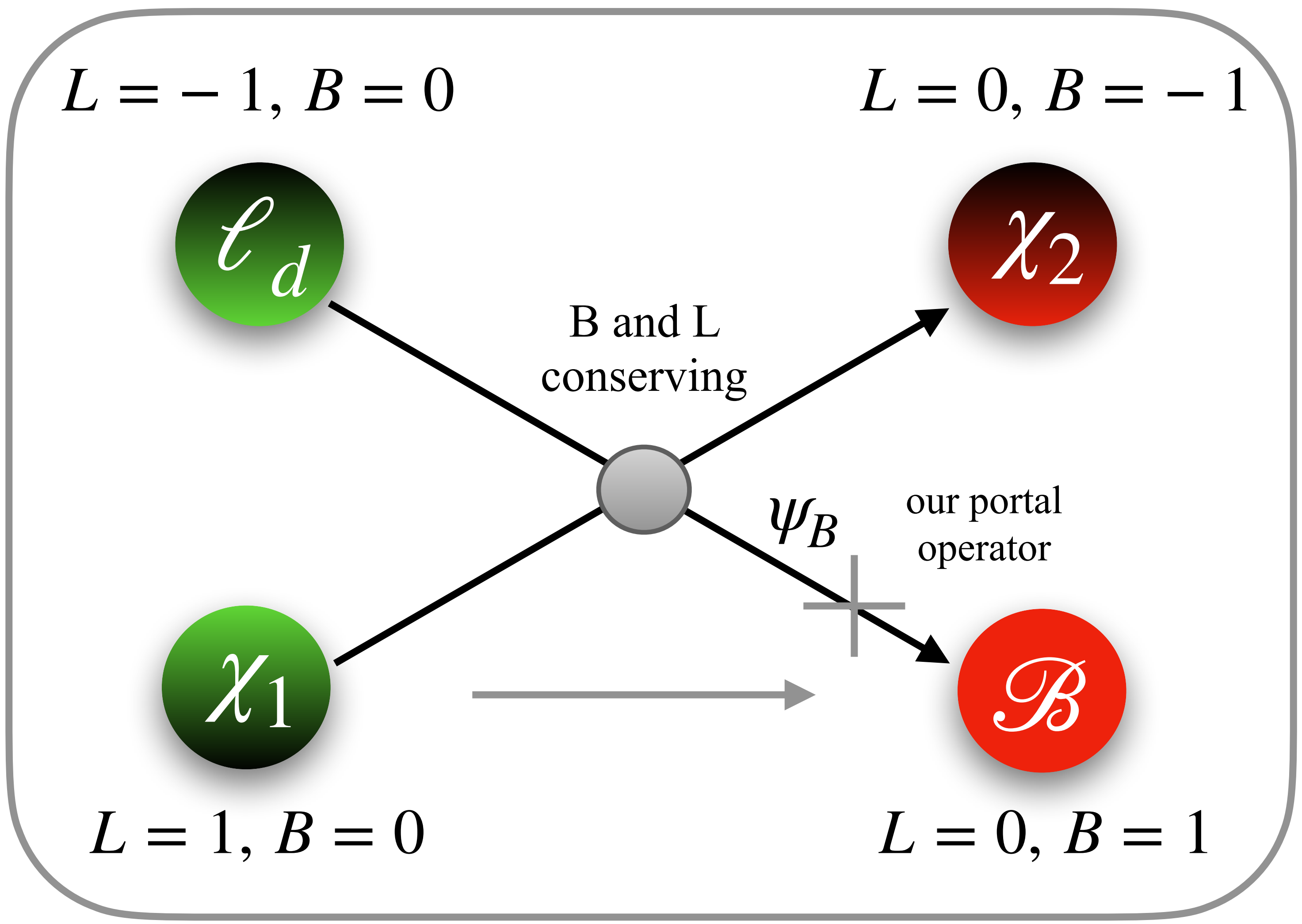
Example Charge Assignment

$m_{\chi_2} + m_\xi > m_{\psi_B} > m_{\mathcal{B}}$

Dark Leptons



Dark Baryons

$$\mathcal{L} \supset y_b\, \bar{\psi}_B \xi \chi_2 + y_l\, \bar{\ell}_d \xi \chi_1 + \text{h.c.}\,.$$

MeV scale Dirac Fermion mediator

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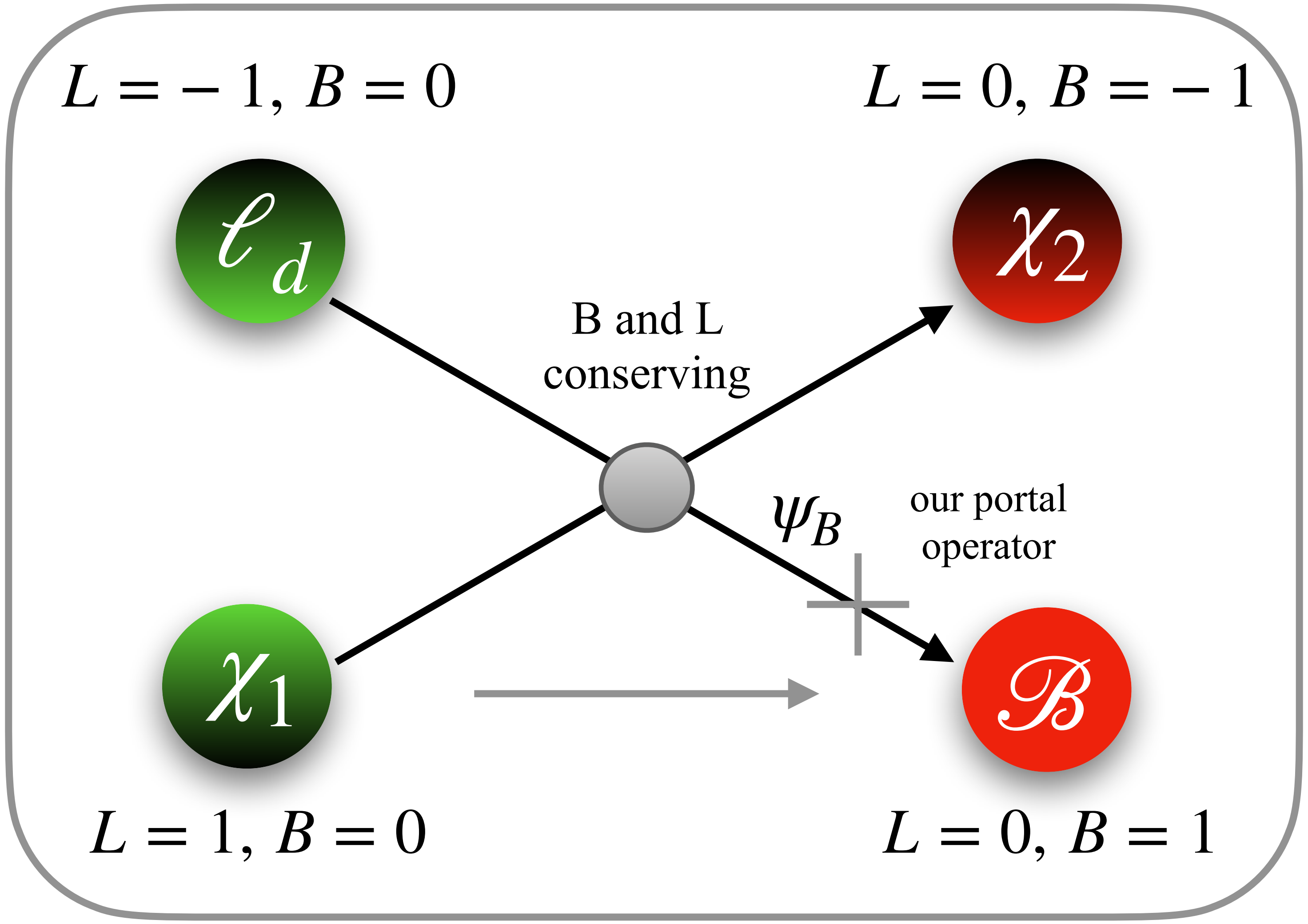
Example Charge Assignment

$m_{\chi_2} + m_\xi > m_{\psi_B} > m_{\mathcal{B}}$

Dark Leptons



Dark Baryons

$$\langle \sigma v \rangle \simeq 10^{-15}\,\mathrm{GeV}^{-2}\,(y_l\, y_b)^2 \times \left(\frac{10\,\mathrm{MeV}}{m_{\ell_d}}\right)\left(\frac{20\,\mathrm{GeV}}{m_{\chi_1}}\right)\left(\frac{10\,\mathrm{GeV}}{m_{\chi_2}}\right)$$

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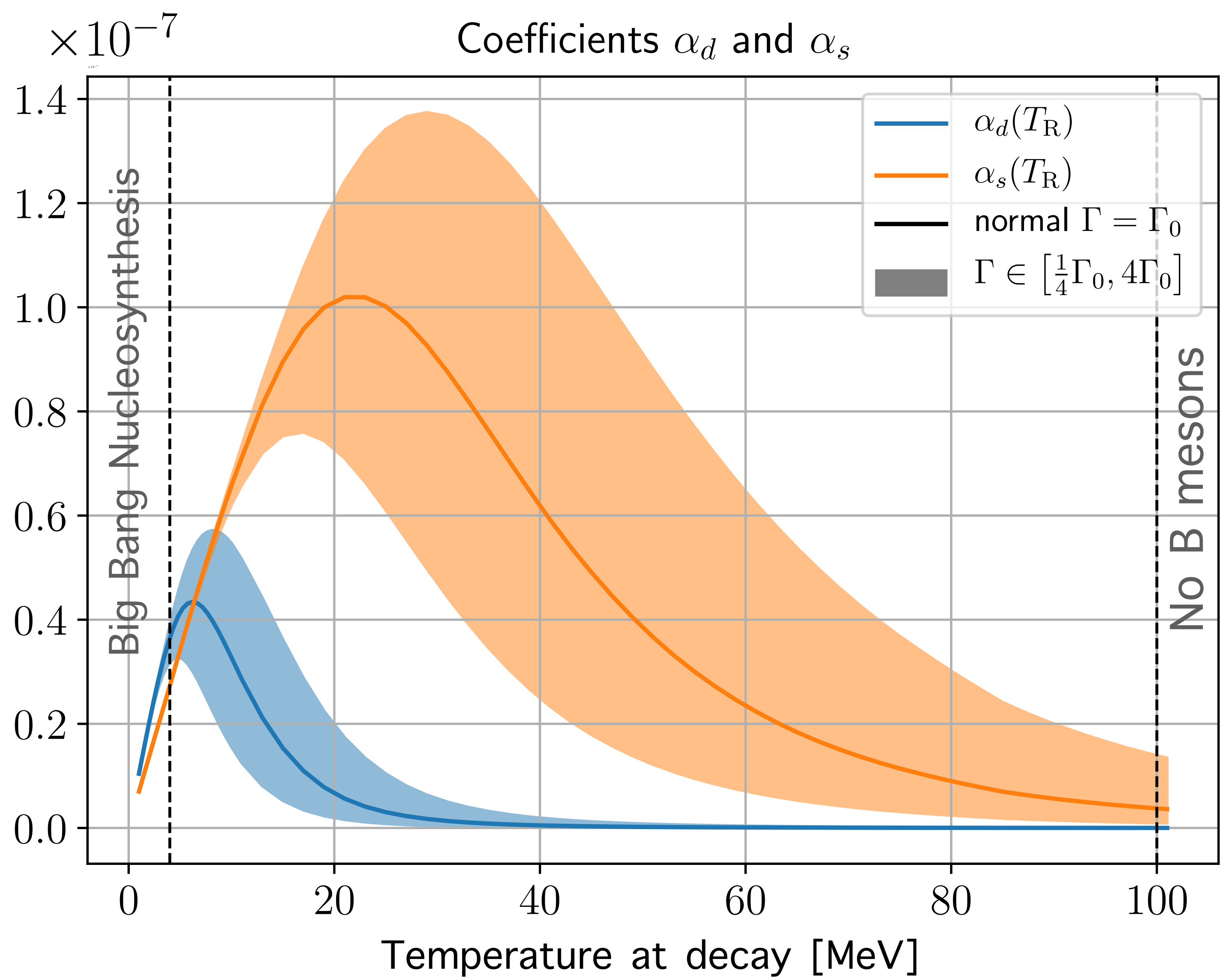
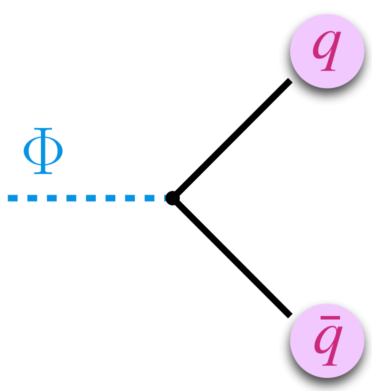
Baryogenesis and Dark Matter from B Mesons





$$Y_b - Y_{\bar{b}} = \left(\frac{\text{Br}}{10^{-2}}\right)\left(\frac{100\text{GeV}}{m_\Phi}\right)(\alpha_d(T)A_d + \alpha_s(T)A_s)$$

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A Supersymmetric Theory

MSSM, R Symmetry, and Dirac Gauginos and Sterile Neutrios

Superfield	R-Charge	L no.
$\mathbf{U}^c, \mathbf{D}^c$	$2/3$	0
$\mathbf{Q}$	$4/3$	0
$\mathbf{H}_u, \mathbf{H}_d$	0	0
$\mathbf{R}_u, \mathbf{R}_d$	2	0
$\mathbf{S}$	0	0
$\mathbf{L}$	1	1
$\mathbf{E}^c$	1	-1
$\mathbf{N}_R^c$	1	-1

"RPV" $$\mathbf{W} = y_u \mathbf{Q}\mathbf{H}_u\mathbf{U}^c - y_d \mathbf{Q}\mathbf{H}_d\mathbf{D}^c - y_e \mathbf{L}\mathbf{H}_d\mathbf{E}^c + \frac{1}{2}\lambda''_{ijk}\mathbf{U}_i^c\mathbf{D}_j^c\mathbf{D}_k^c + \mu_u \mathbf{H}_u\mathbf{R}_d + \mu_d \mathbf{R}_u\mathbf{H}_d + \lambda_u^t \mathbf{H}_u\mathbf{T}\mathbf{R}_d + \lambda_d^t \mathbf{R}_u\mathbf{T}\mathbf{H}_d + \lambda_d^s \mathbf{S}\mathbf{R}_u\mathbf{H}_d \,.$$

$$\rightarrow \quad \mathcal{L} = \lambda''_{113}\left(\tilde{d}_R^* u_R^\dagger b_R^\dagger + \tilde{u}_R^* d_R^\dagger b_R^\dagger + \tilde{b}_R^* u_R^\dagger d_R^\dagger\right) ,$$

Gauge:

$$\mathcal{L}_{\text{gauge}} = -\sqrt{2}g(\phi T^a \psi^\dagger)\lambda^{a\dagger} + \text{h.c.}$$
$$\Rightarrow \quad -\sqrt{2}g(\tilde{d}_R^* d_R \tilde{B}^\dagger) - \sqrt{2}g(\tilde{d}_L d_L^\dagger \tilde{B}^\dagger) + \text{h.c.}$$

Neutrio:

$$\mathbf{W} = \frac{\lambda_N}{4}\mathbf{S}\mathbf{N}_R^c\mathbf{N}_R^c + \mathbf{H}_u\mathbf{L}^i y_N^{ij}\mathbf{N}_R^{c,j} + \frac{1}{2}\mathbf{N}_R^c M_M \mathbf{N}_R^c + \text{h.c.} ,$$

$$\rightarrow \quad 4\lambda_N\left(\lambda_s \nu_R^\dagger \tilde{\nu}_R^* + \phi_s \nu_R^\dagger \nu_R^\dagger\right) + \text{h.c.}$$

Parameter space: "RPV" couplings and squark mass mixing

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A Supersymmetric Theory

Superpartners and SM particles have different charge under an unbroken R-symmetry. We can identify this with Baryon number.

→ Superpartners as dark baryons.

	Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
	Φ	0	0	0	$+1$	$11 - 100\,\text{GeV}$
MSSM Squark	$\tilde{d}_R$	0	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\text{TeV})$
Dirac Bino	$\begin{bmatrix}\tilde{B} \\ \lambda_s^\dagger\end{bmatrix}$	$1/2$	0	-1	$+1$	$\mathcal{O}(\text{GeV})$
Right handed neutrino multiplet	ν_R	$1/2$	0	0	-1	$\mathcal{O}(\text{GeV})$
	$\tilde{\nu}_R$	0	0	-1	-1	$\mathcal{O}(\text{GeV})$

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