Mesogenesis

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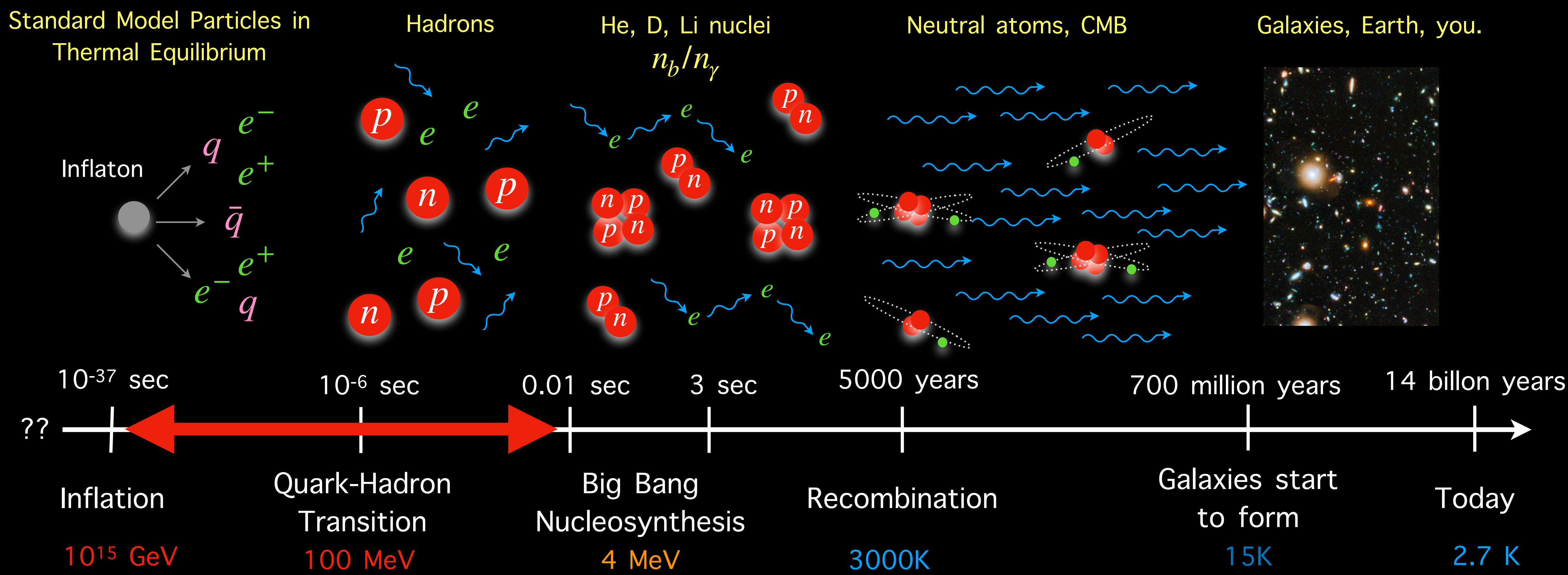
Baryogenesis



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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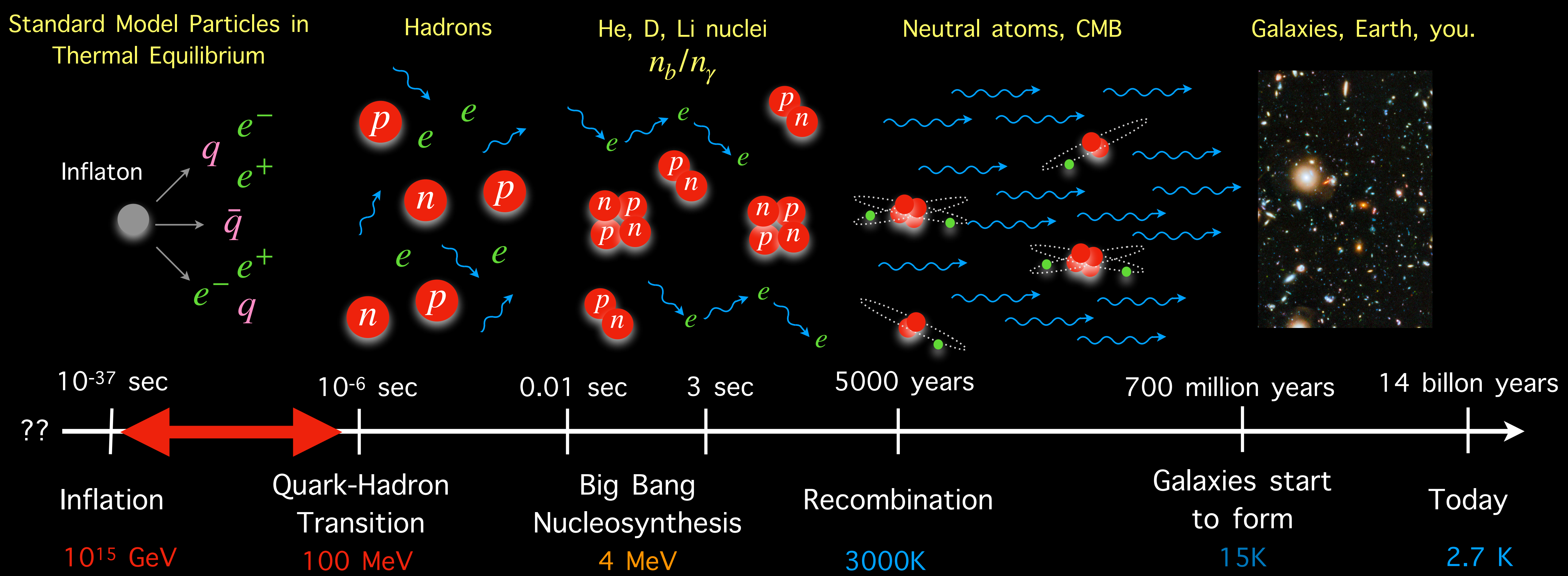
Traditional Baryogenesis Mechanisms

are traditionally hard to test



- GUT baryogenesis
- Electroweak baryogenesis
- Leptogenesis
- ....

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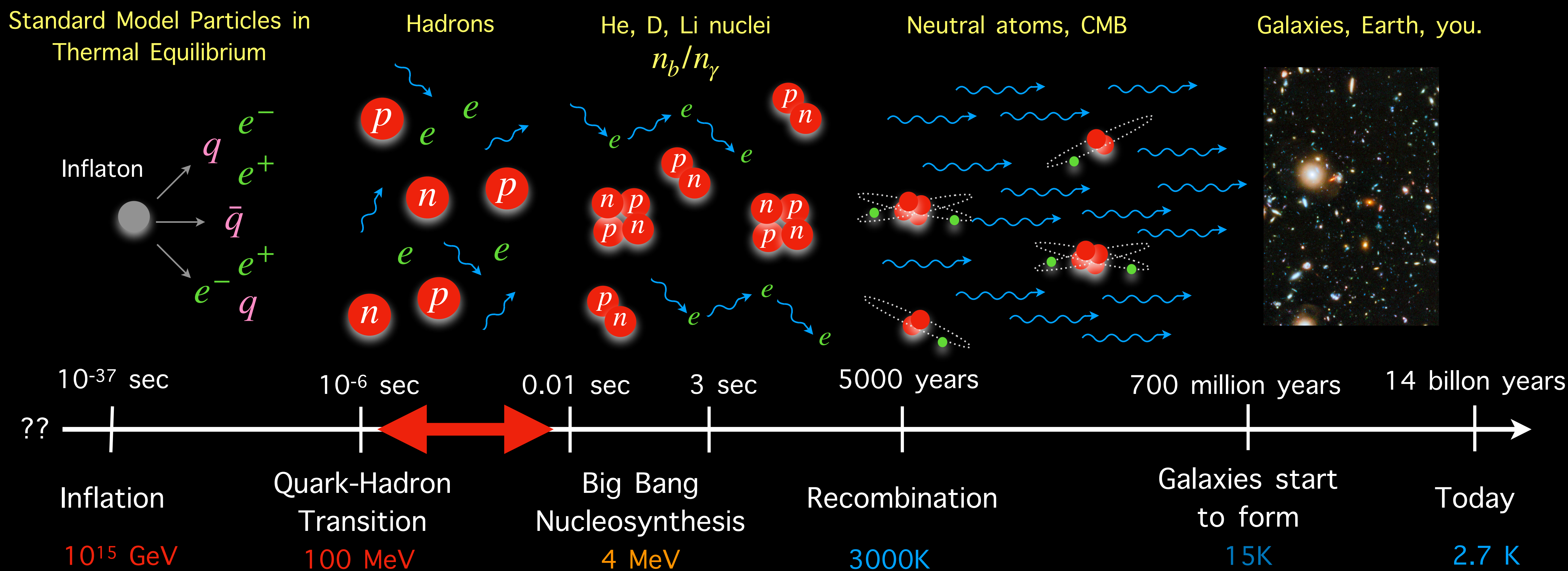
Making the Universe at 20MeV



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

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

Image: Stolen from the Internet

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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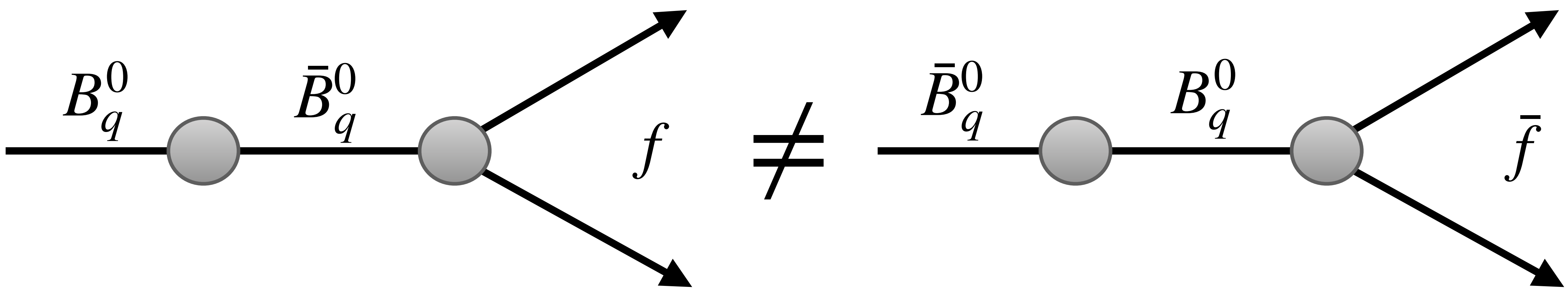
The Many Flavors of Mesogenesis

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]

CP Violation in B Meson Oscillations

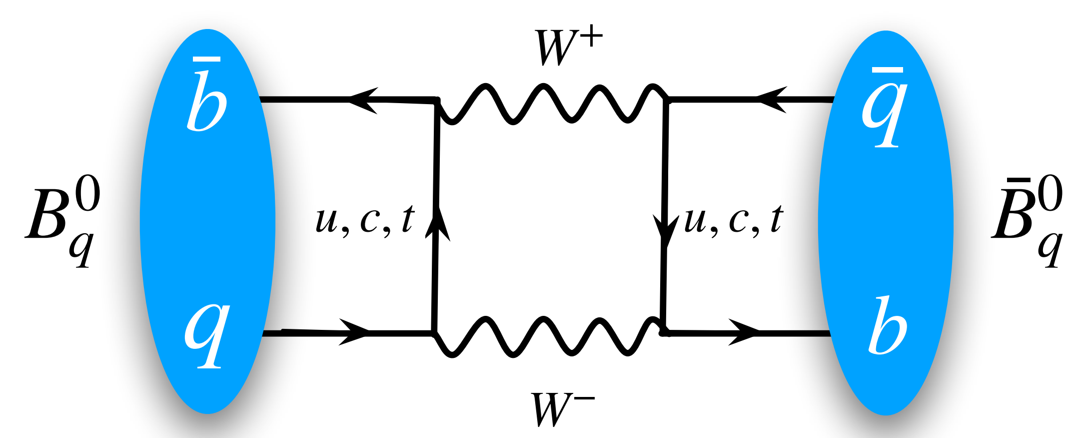
B meson/anti-meson mixing has sizable CP violation



Experimental Observable:

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

e.g. in Standard Model



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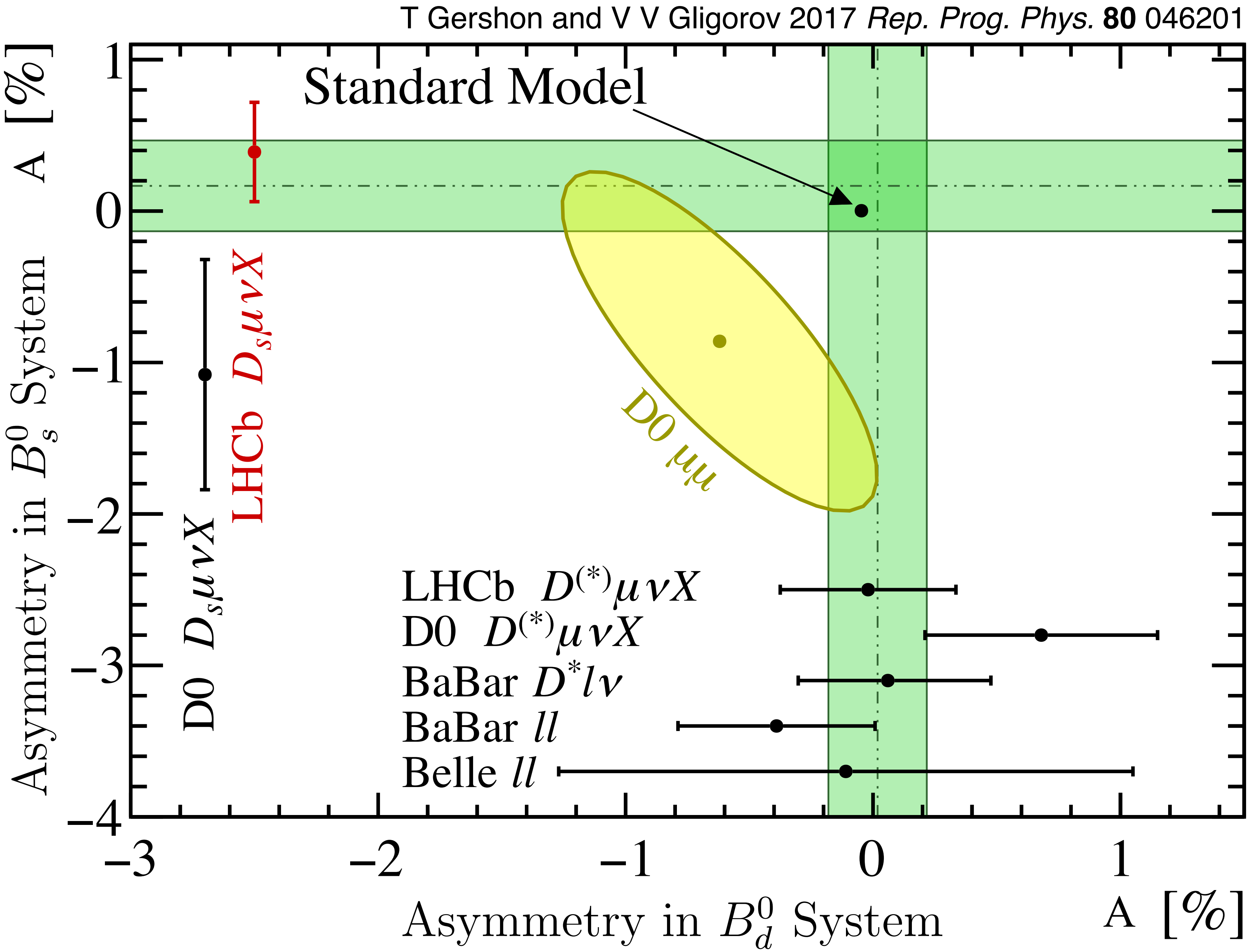
CP Violation in *B* Meson Oscillations

Can accommodate contributions from new physics



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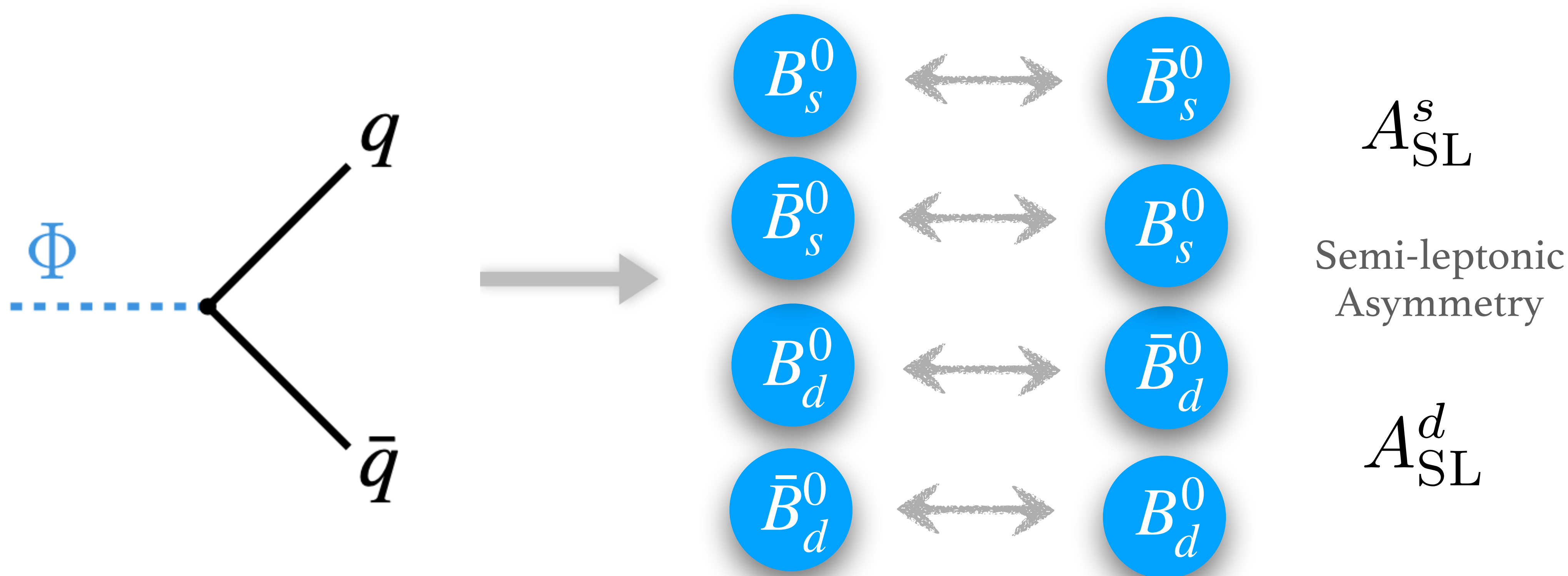
Sakharov I & II: Out of thermal equilibrium and CPV

Late decay of an “inflaton-like” field

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



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

Before BBN

After QCD phase transition

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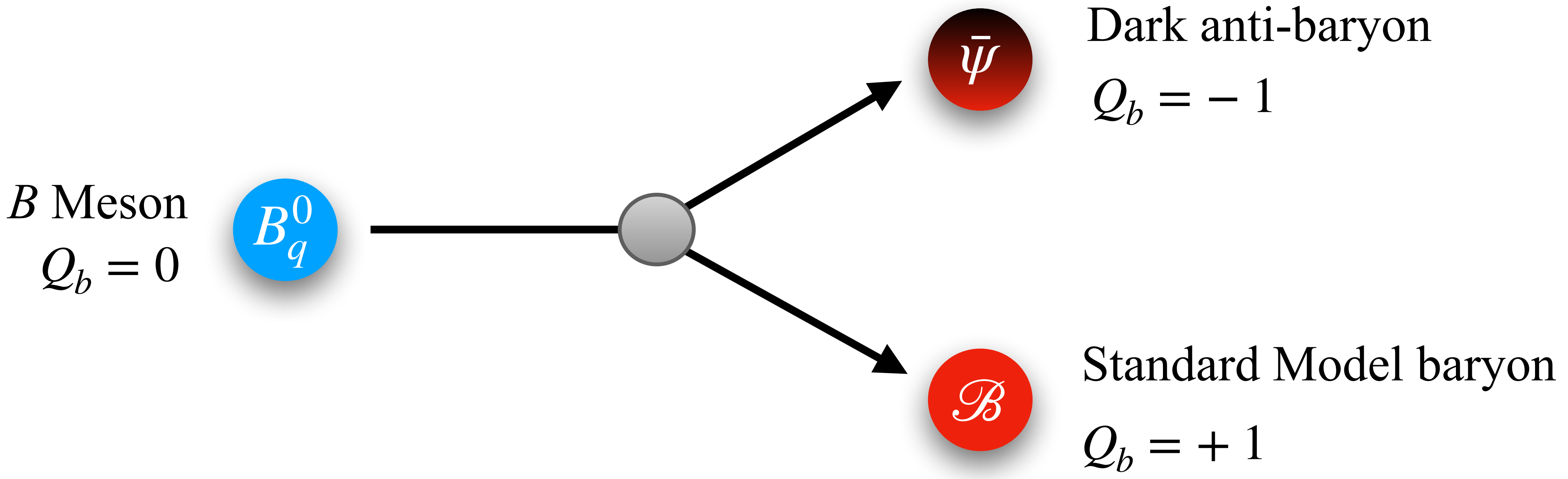
Sakharov III. *B* Violation?

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	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\mathrm{TeV})$	SUSY Squark
$\psi_{\mathcal{B}}$	$1/2$	0	-1	$+1$	$\mathcal{O}(\mathrm{GeV})$	Kinematics, forbid proton decay

Allowed by all the symmetries:

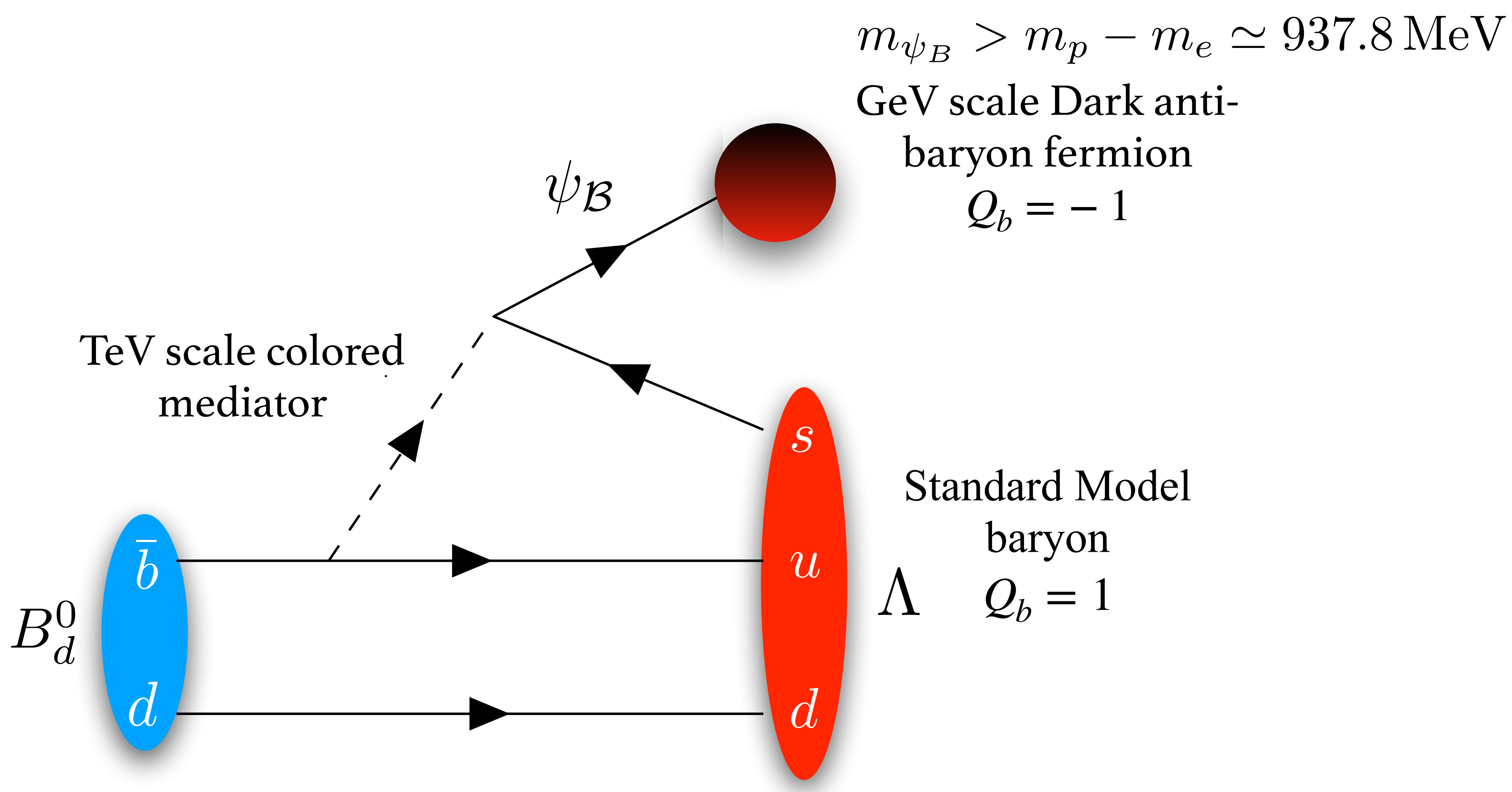
$$\mathcal{L}_{-1/3} = -\sum_{i,j} y_{u_i d_j} Y^\star \bar{u}_{iR} d^c_{jR} - \sum_k y_{\psi d_k} Y d^c_{kR} \bar{\psi}_{\mathcal{B}} + \text{h.c.}$$

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

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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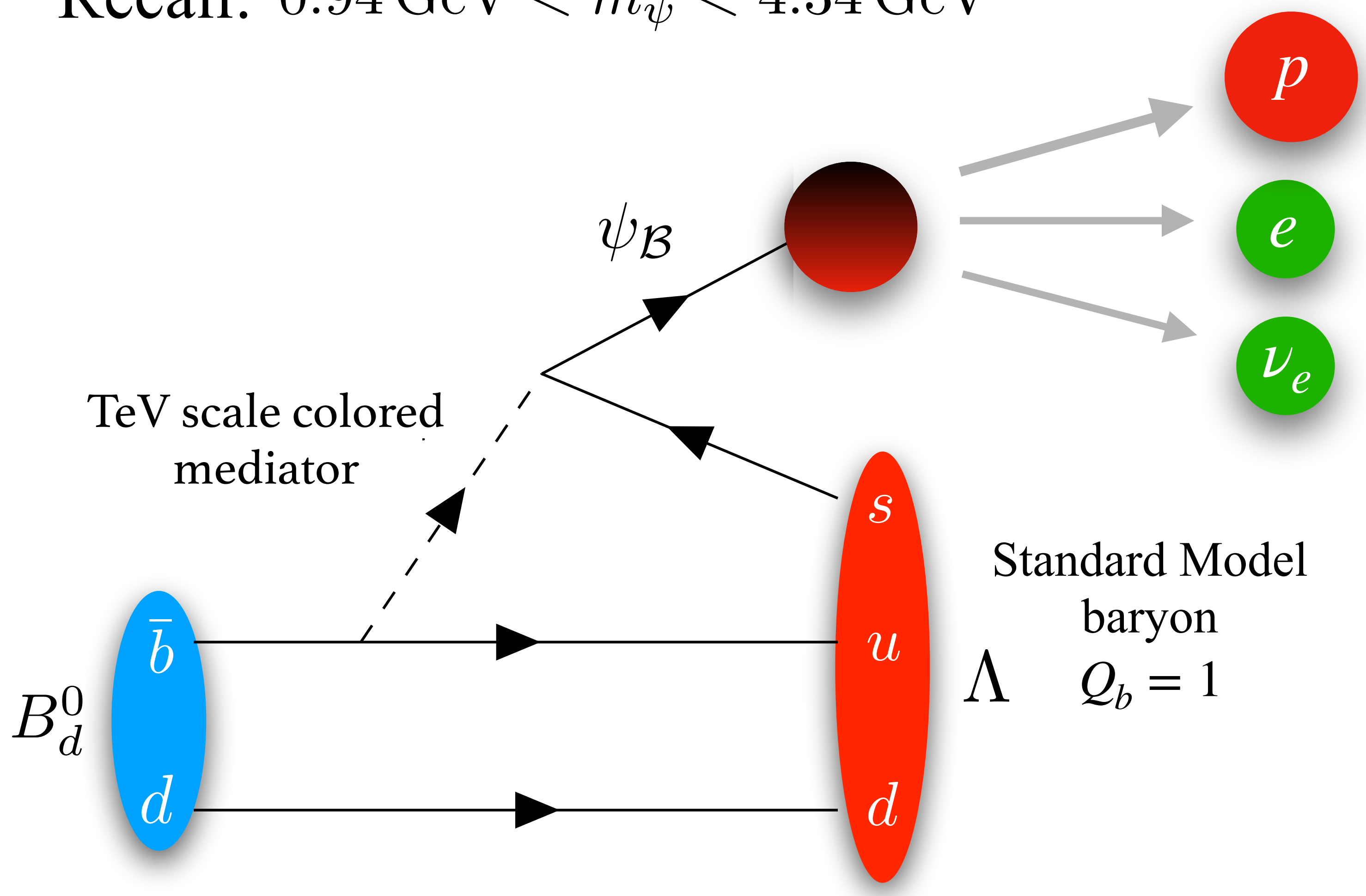
Dark Matter?

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



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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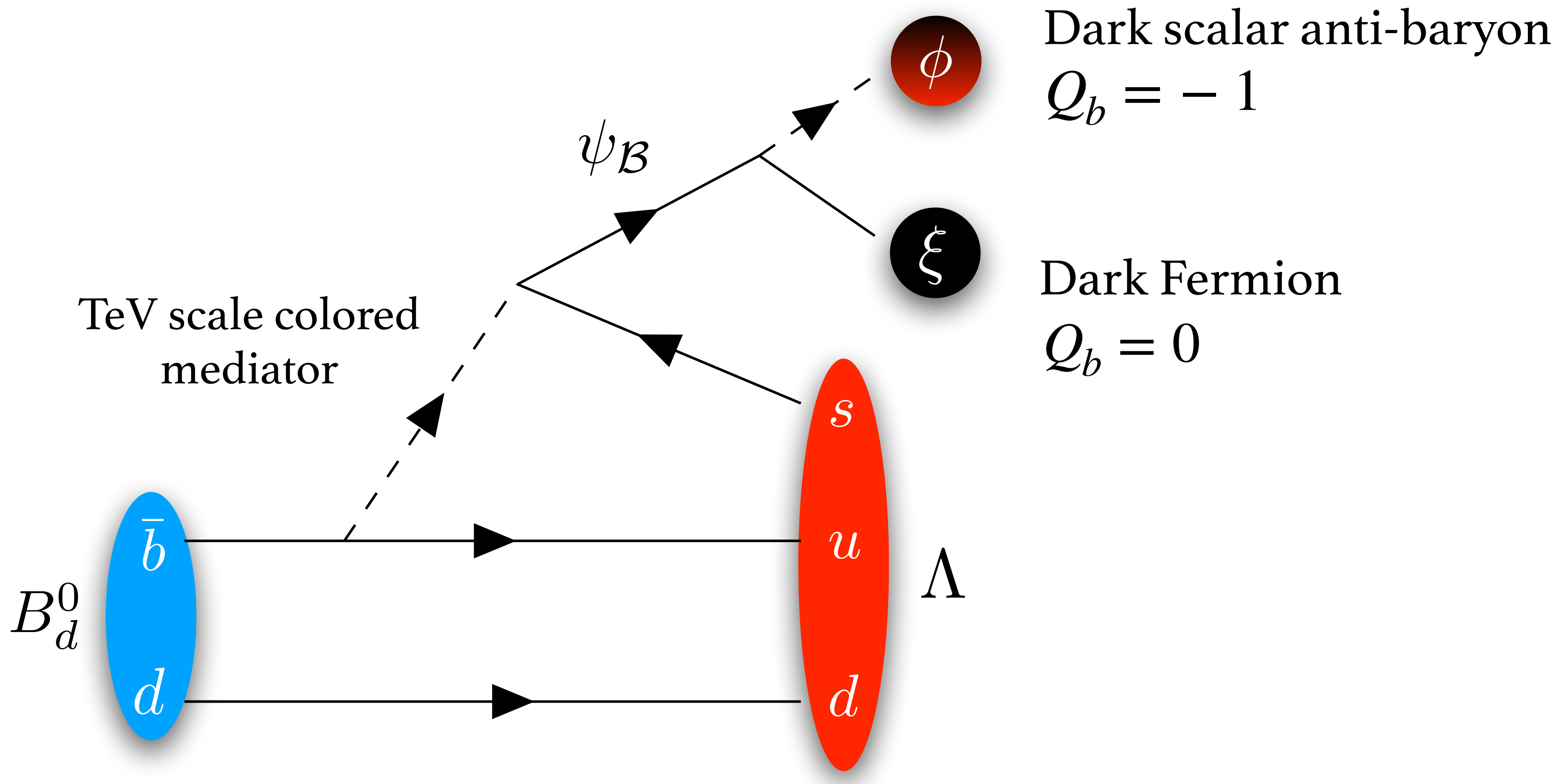
Dark Matter

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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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:

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

- 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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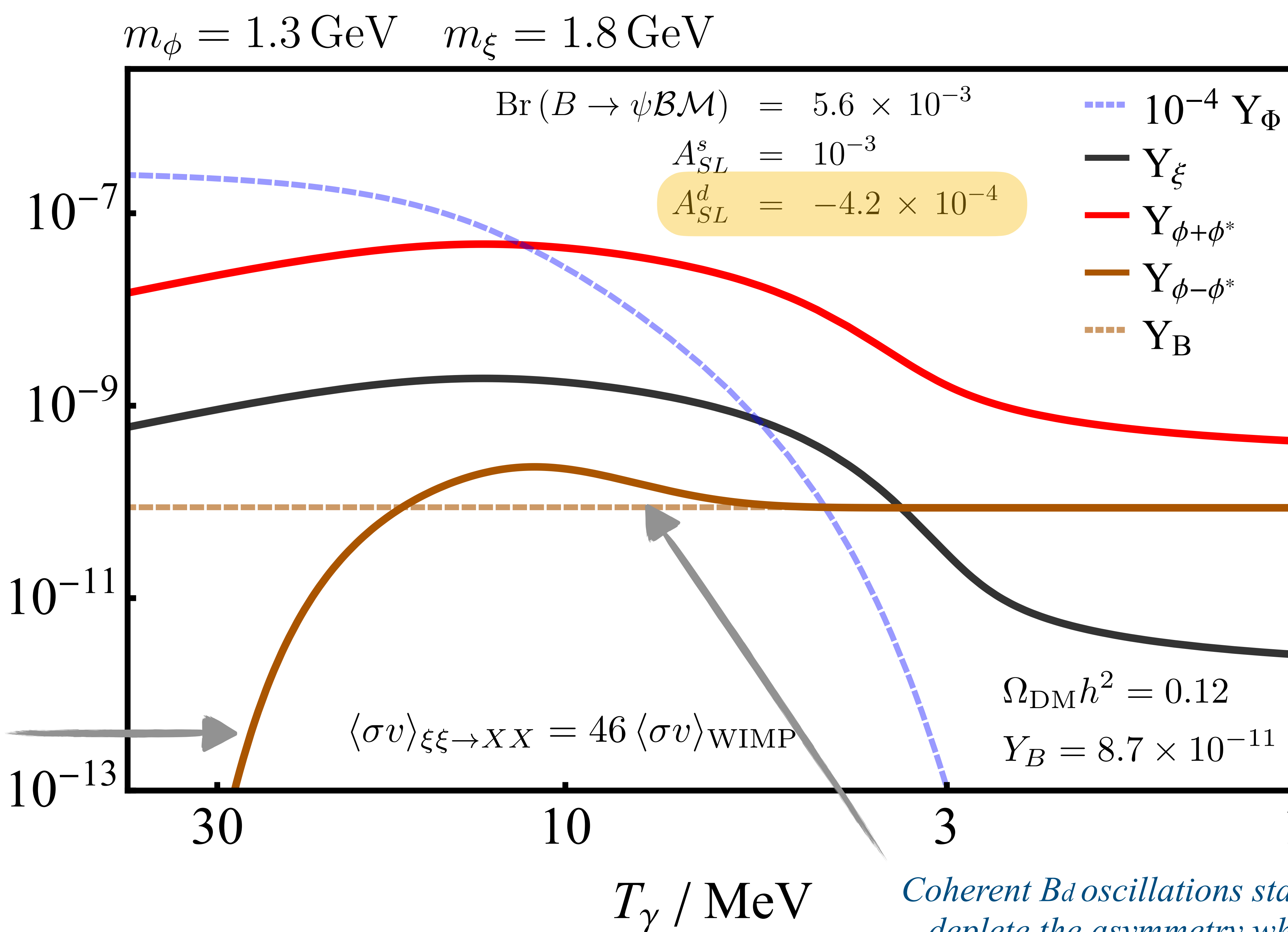
Example Benchmark Point



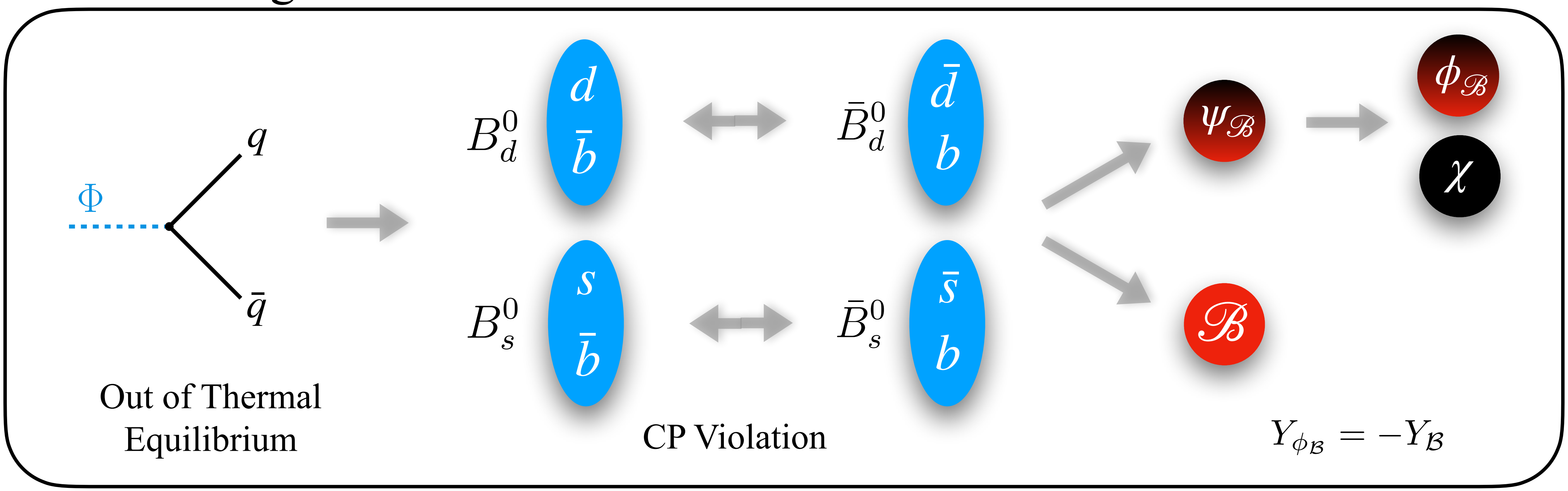
Coherent Bs oscillations start to produce an asymmetry when $T_{B_s} \lesssim 20\,\mathrm{MeV}$

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

Need a net positive asymmetry

Neutral B Mesogenesis

B^0 Mesogenesis



Asymmetry is related to observables:

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

succesful B Mesogenesis requires:

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

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Signals of Neutral *B*-Mesogenesis

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

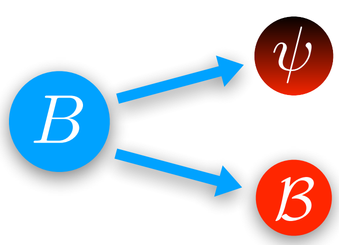
Collider Signals of Baryogenesis and Dark Matter from B Mesons (*B-Mesogenesis*)

Direct Signals

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

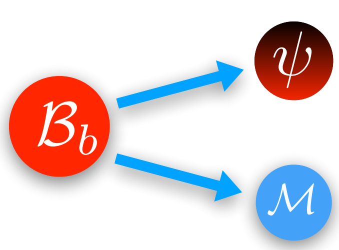
Belle II
LHCb
ATLAS
CMS

New B meson decay:



BaBar
Belle
Belle II
LHCb

New b-Baryon decay:



LHCb?
ATLAS??
CMS??

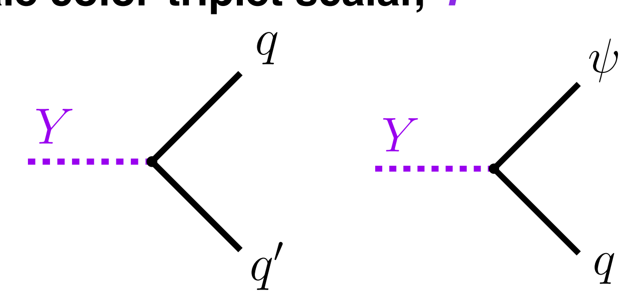
Indirect Signals

B⁰ 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

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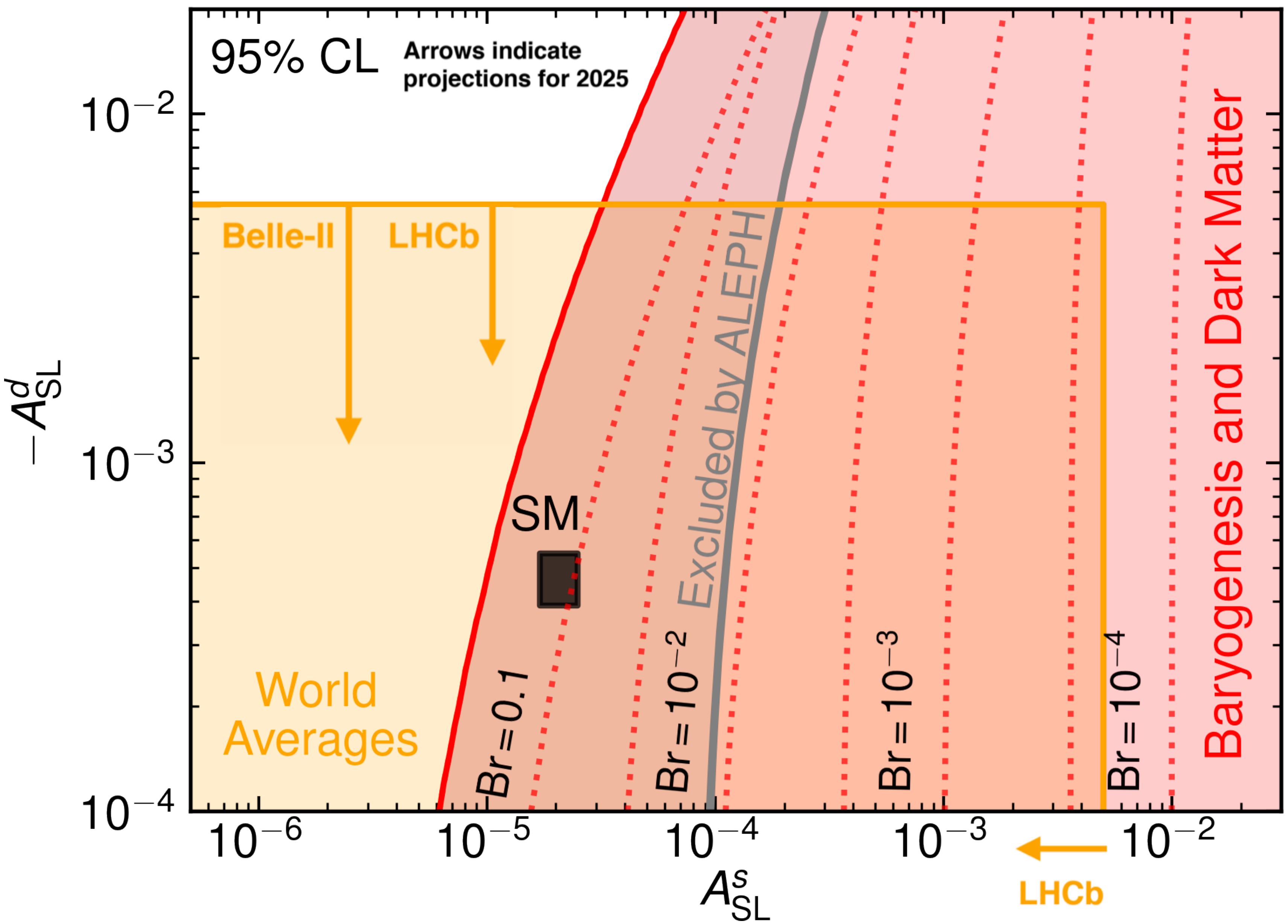
The Semi-Leptonic Asymmetry



$\lesssim 10^{-3}$

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

for baryogenesis

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

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New b-Hadron Decays

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

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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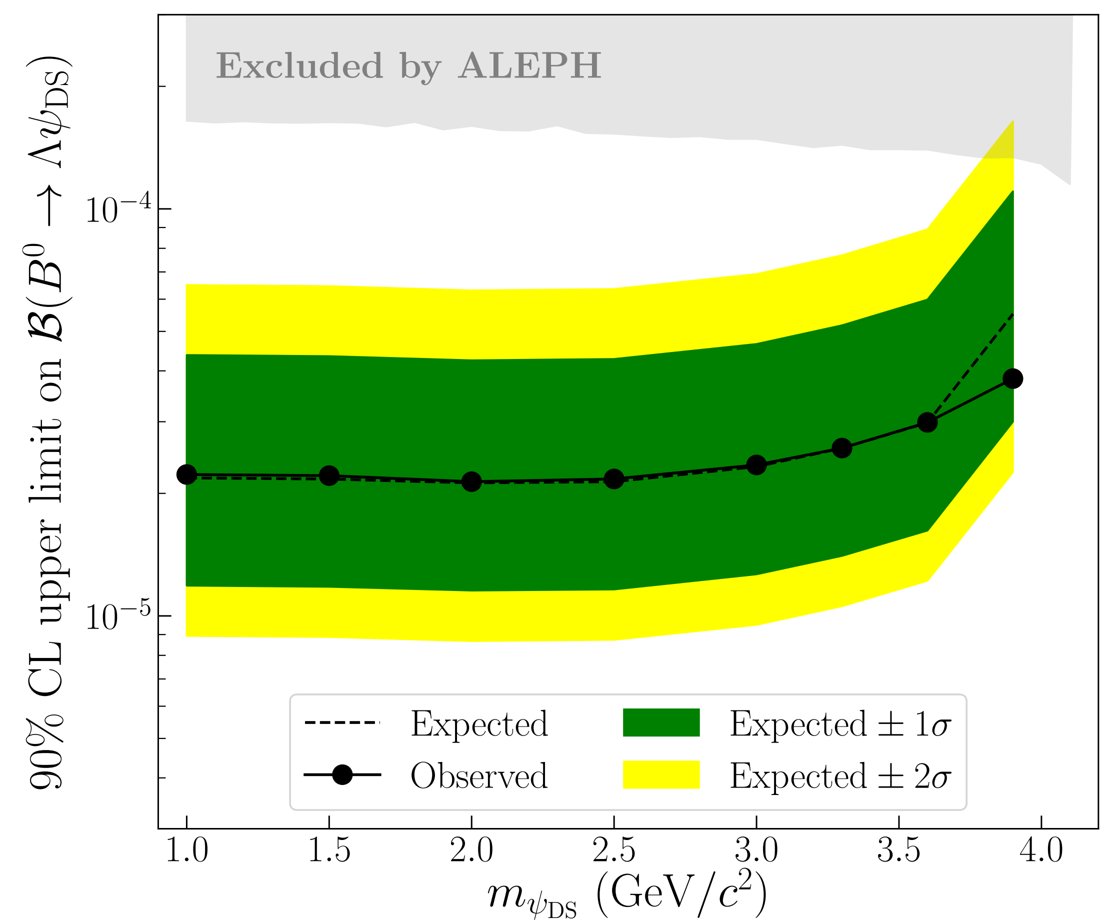
New b-Hadron Decays

Targeted Searches at Colliders!

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	$\bar{\psi} + D^- + K^+$

Belle collaboration [arXiv:2110.14086]



Proposed searches for all modes at LHCb [2106.12870]

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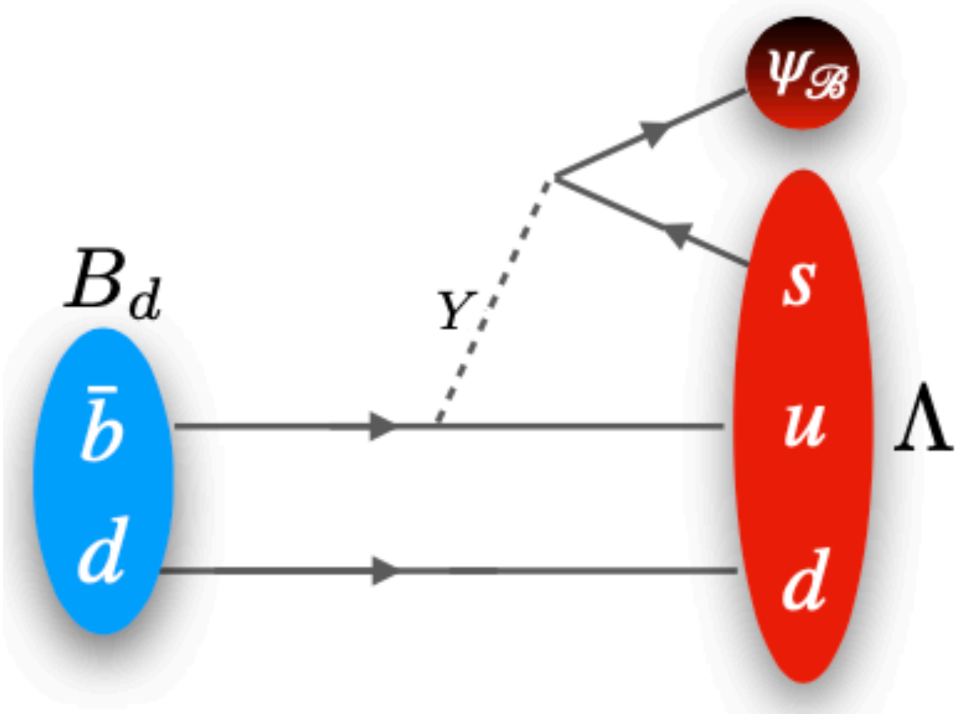
New b-Hadron Decays

Form Factor Calculation from Light Cone QCD Sum Rules

[arXiv:22xx.xxxx] GE with Alfredo Guerrera

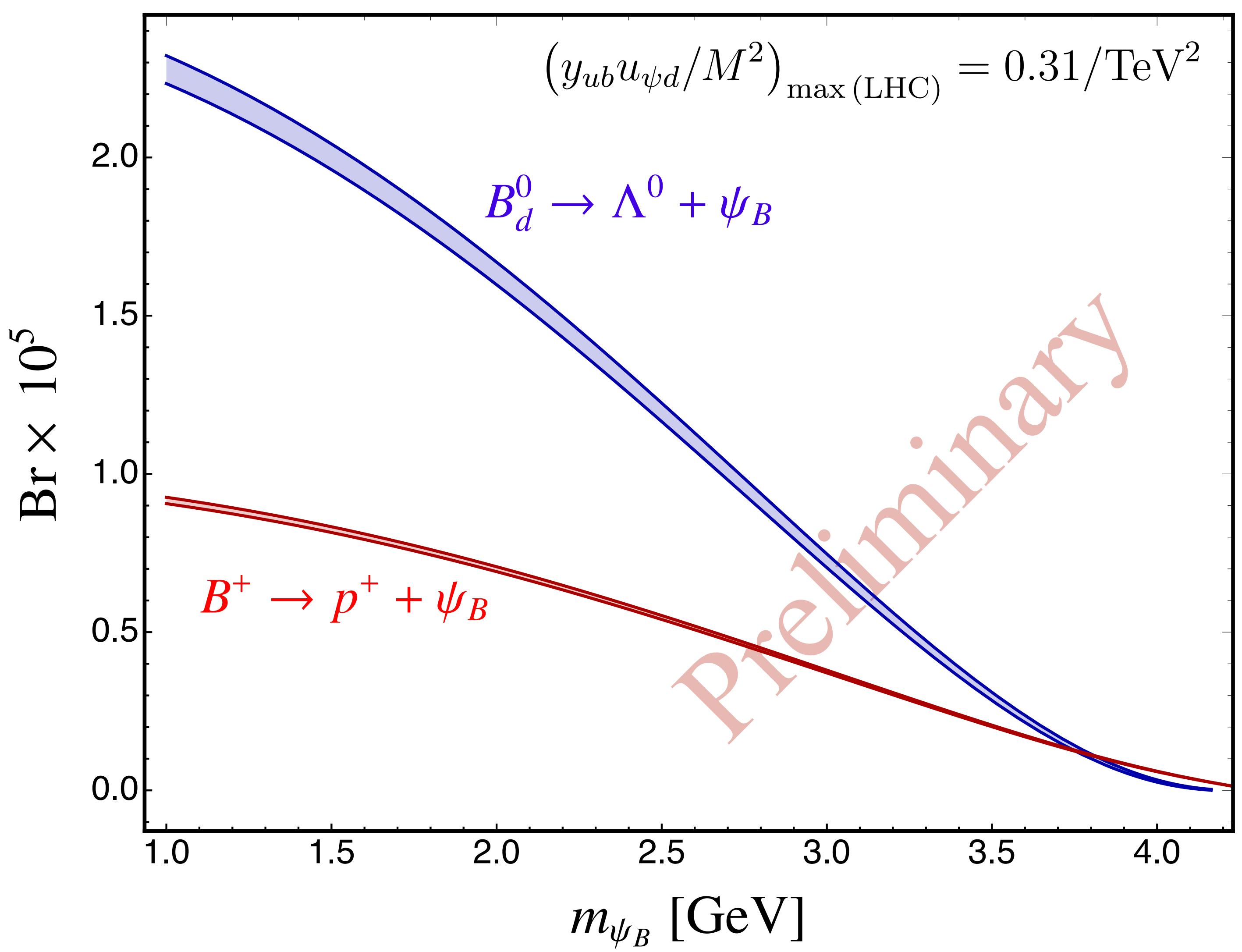
example: $\mathcal{A}\left(B_s^0 \to \Lambda^0 \psi_B\right) = \frac{y_{ub} u_{\psi d}}{M^2} \left(b_R u_R\right) \langle \Lambda^0(P) | \mathcal{O}_{ub,d} | B_s^0(P+q) \rangle u_\psi^c(q)$



$$\mathcal{O}_{ub,d} = \frac{y_{ub} u_{\psi d}}{M^2} \left(b_R u_R\right) \left(\psi_{B,R} d_R\right)$$

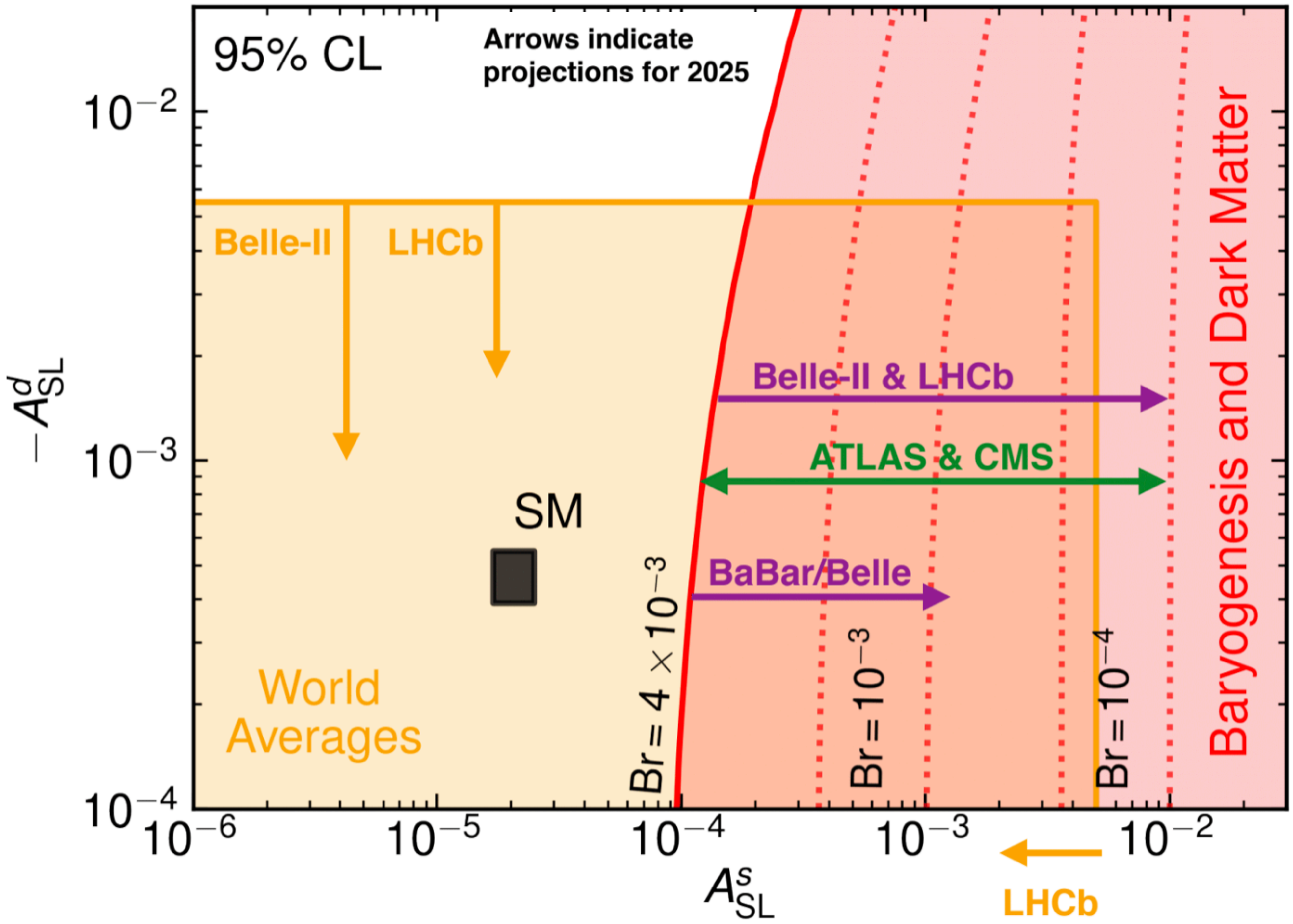
Recall for B-Mesogenesis:

$$\mathrm{Br}\left(B \to \psi_B + \mathcal{B}_{\mathrm{SM}}\right) \gtrsim 10^{-4}$$



Recent paper A. Khodjamirian and M. Wald [arXiv:2206.11601] (proton form factor only)

Discovering Neutral B-Mesogenesis



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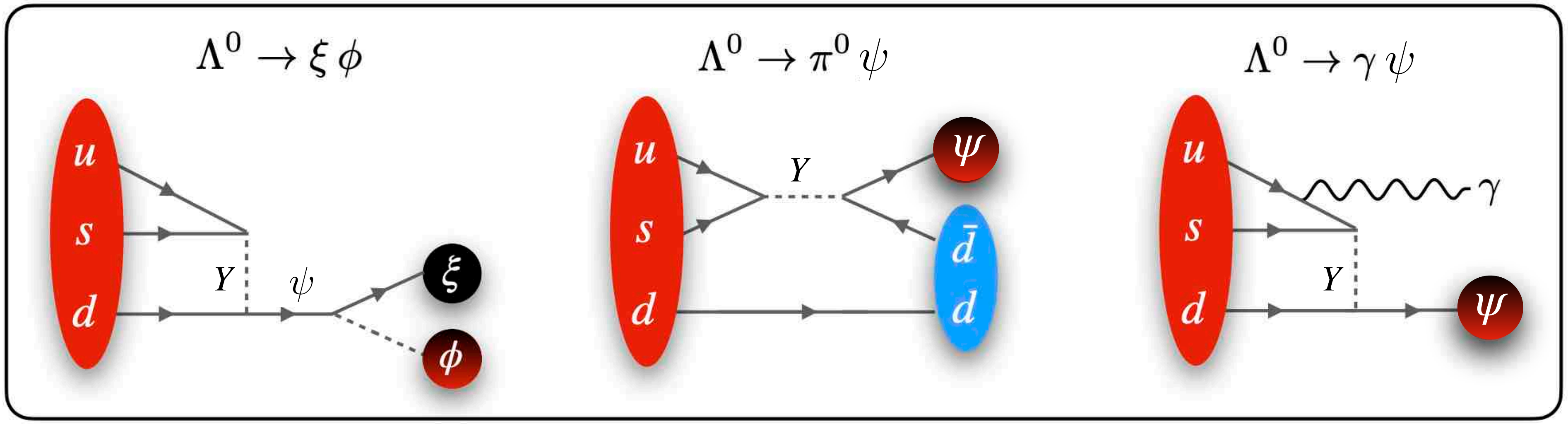
Indirect Signals: New Hyperon Decays

$$\mathcal{O}^{L,R}_{u_a d_b, d_c} = \frac{y_{u_a d_b} y_{\psi d_c}}{M^2} (u_a d_b)_{L,R} (\psi_B d_c)_R$$



Initial State	Final State	Max$[m_\chi]$ (MeV)	Operator	Br $\times \left[\frac{C^{L/R}_{ud_a,d_b}}{0.5\,\text{TeV}^{-2}}\right]^2$ (LHC)	SN 1987A Limit	BESIII
$\Lambda\,(uds)$	$\chi + \gamma$	1116	$\mathcal{O}^{L/R}_{us,d}$	3.5×10^{-6}	$\sim 10^{-7}$	–
	$\xi + \phi$	1116	$\mathcal{O}^{L/R}_{ud,s}$	$5.0 \times 10^{-4}\,\lvert y_{\xi\phi}\rvert^2$	$\sim 10^{-8}$	7×10^{-5} [50]
	$\chi + \pi^0$	981	$\mathcal{O}^{L}_{us,d}$	1.1×10^{-3}	$\sim 10^{-7}$	–
$\Sigma^+\,(uus)$	$\chi + \pi^+$	1050	$\mathcal{O}^{L/R}_{us,d}$	1.6×10^{-3}	$\sim 10^{-4}$	–
$\Sigma^-\,(dds)$	$\chi + \pi^-$	1058	$\mathcal{O}^{L/R}_{ud,s}$	1.2×10^{-3}	$\sim 10^{-4}$	–
$\Xi^0\,(uss)$	$\chi + \gamma$	1315	$\mathcal{O}^{L/R}_{us,s}$	1.5×10^{-5}	–	–
	$\xi + \phi$	1315	$\mathcal{O}^{L/R}_{us,s}$	$3.7 \times 10^{-4}\,\lvert y_{\xi\phi}\rvert^2$	–	–
	$\chi + \pi^0$	1180	$\mathcal{O}^{R}_{us,s}$	6.2×10^{-3}	–	–
$\Xi^-\,(dss)$	$\chi + \pi^-$	1182	$\mathcal{O}^{R}_{us,s}$	7.1×10^{-3}	–	–

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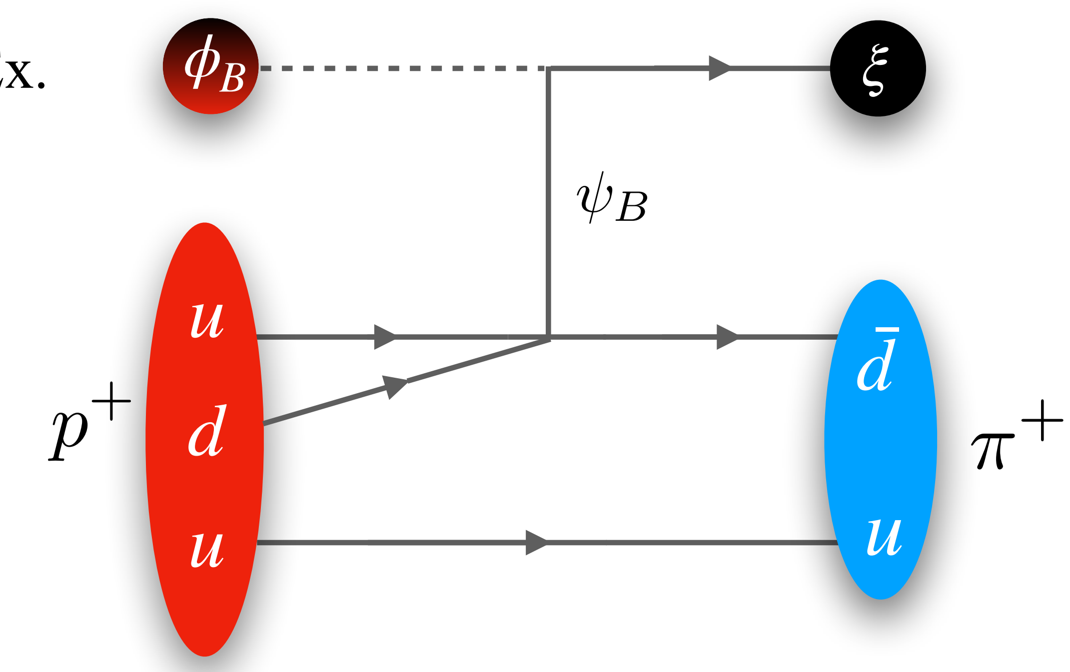
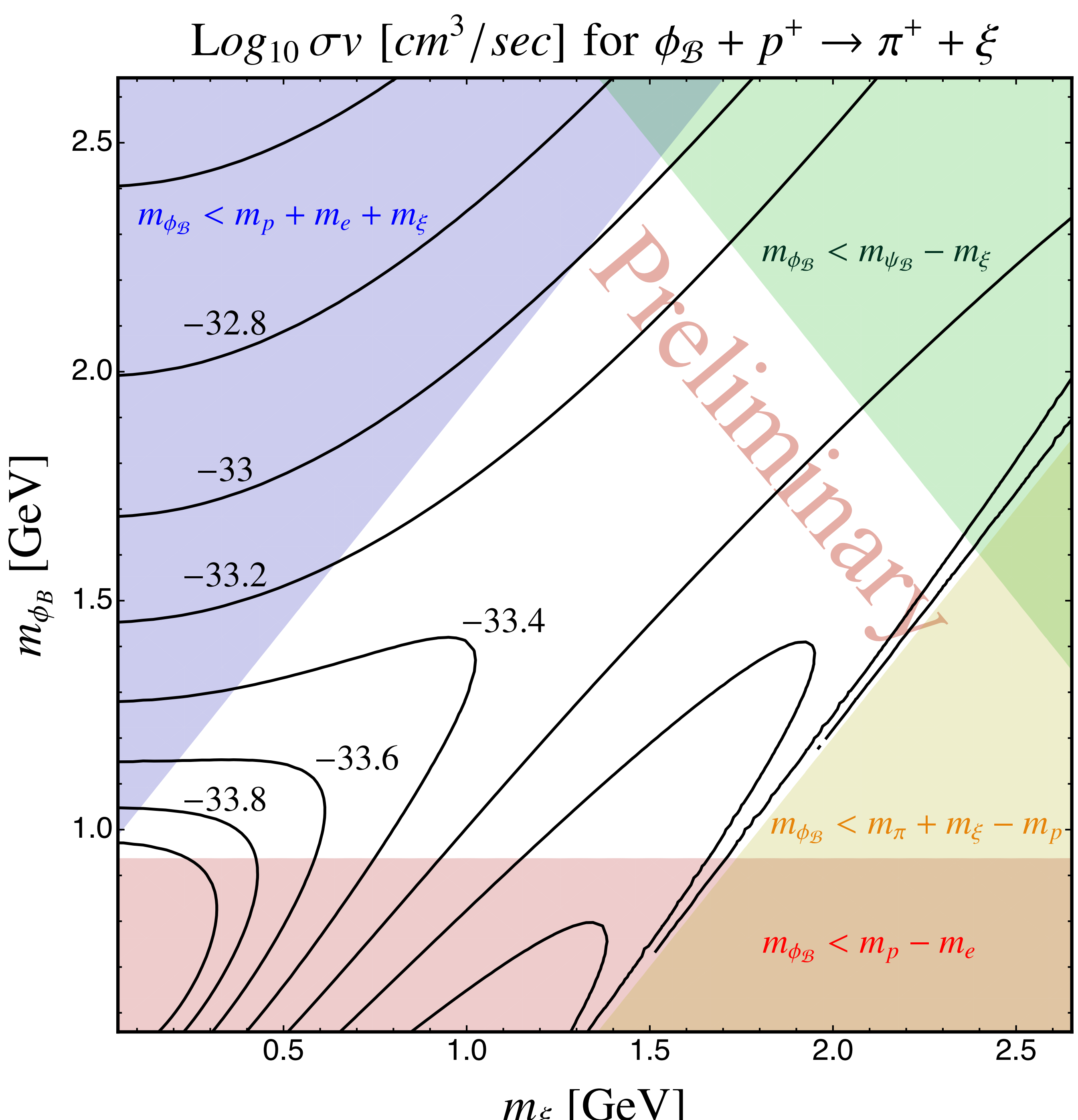
Indirect Signals:
Induced Nucleon Decay at DUNE

[arXiv:22xx.xxxx] GE with Josh Berger

Ex.





Mono-energetic meson:

$$E_{\mathcal{M}} = \frac{m_{\mathcal{M}}^2 - m_\xi^2}{2(m_N + m_{\phi_B})} + \frac{1}{2}(m_N + m_{\phi_B}) + \mathcal{O}(v_{\phi_B})$$

DUNE: 40 kiloton liquid argon detector.
Expect sensitivity down to $\sigma v \sim 10^{-40}\mathrm{cm}^3/\mathrm{sec}$
after one year of running.

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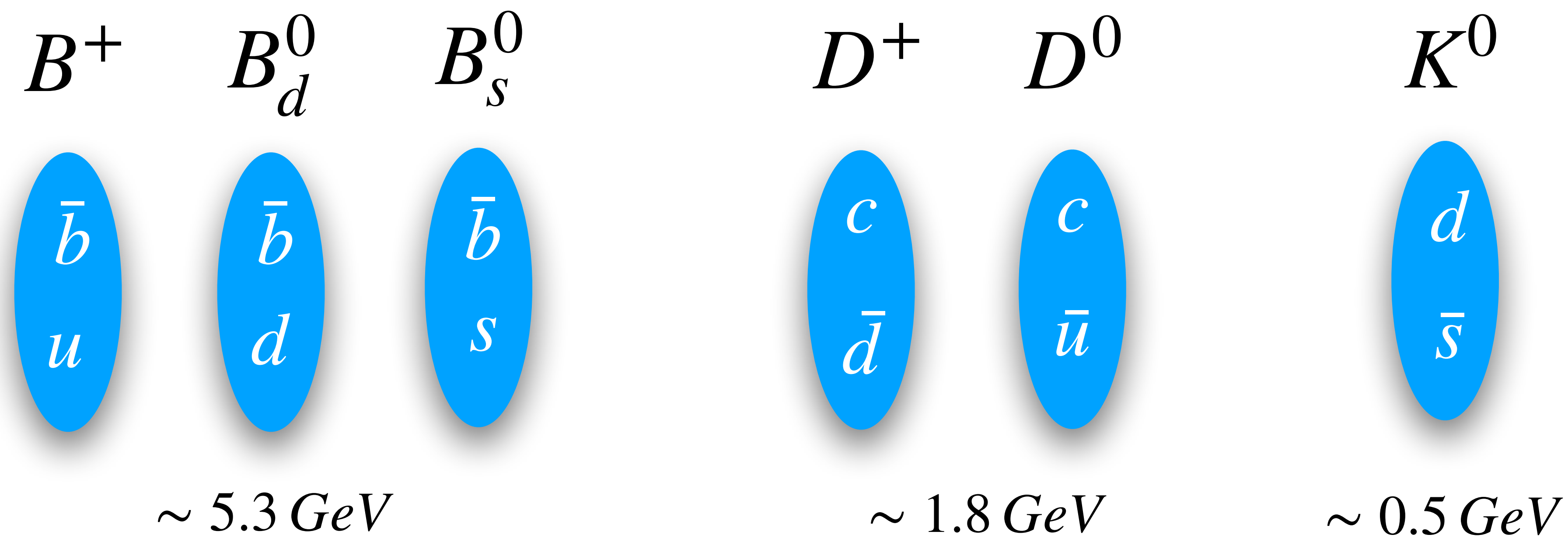
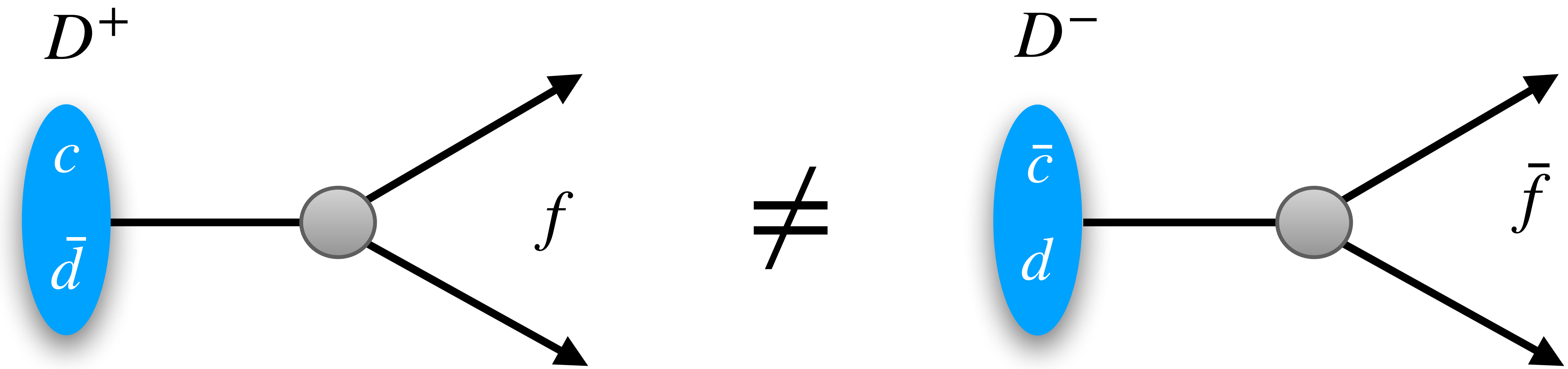
Why Neutral B Mesons?



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

- 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.

Charged D Mesogenesis



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

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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 $Y_B^{\text{obs}} = (8.718 \pm 0.004) \times 10^{-11}$

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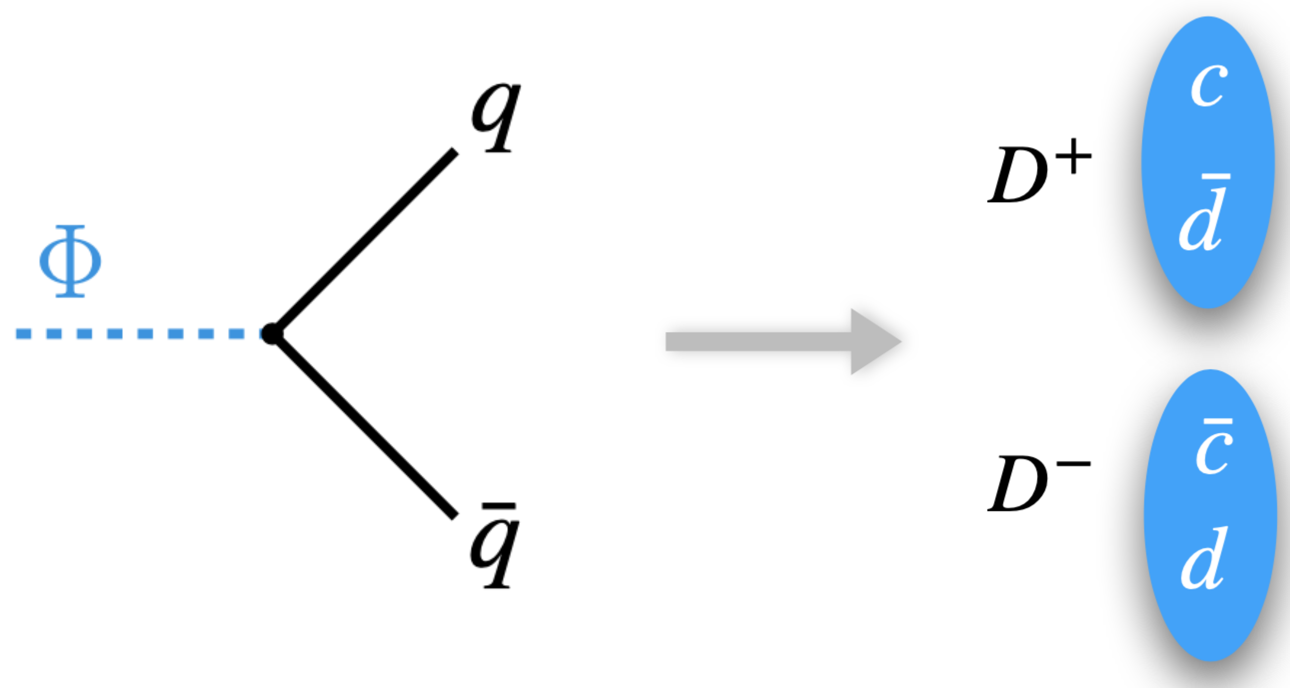
Sakharov I. Out of Equilibrium

Late decay of an "inflaton-like" field

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



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

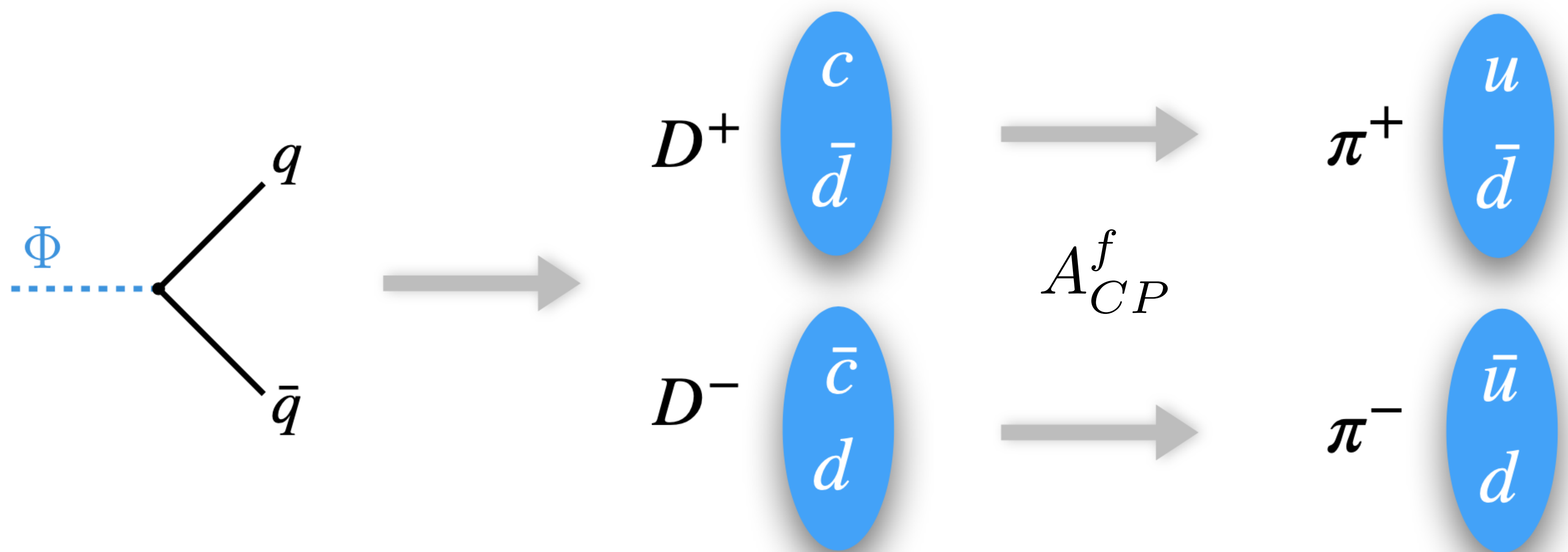
Before BBN

After QCD phase transition

G. Elor

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

G. Elor

Sakharov III. *B* Violation?

Need a way to change baryon number

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

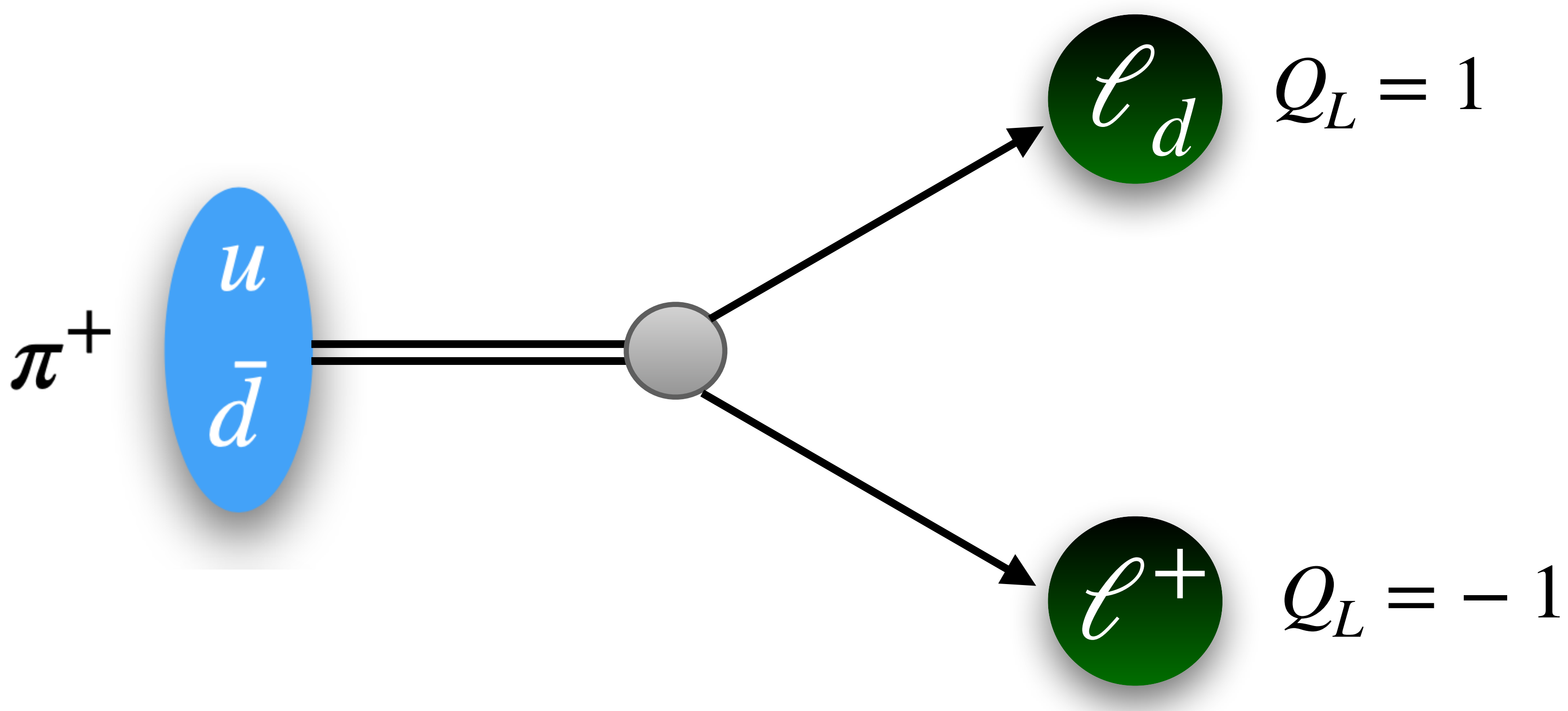
First generate a *lepton asymmetry*

G. Elor

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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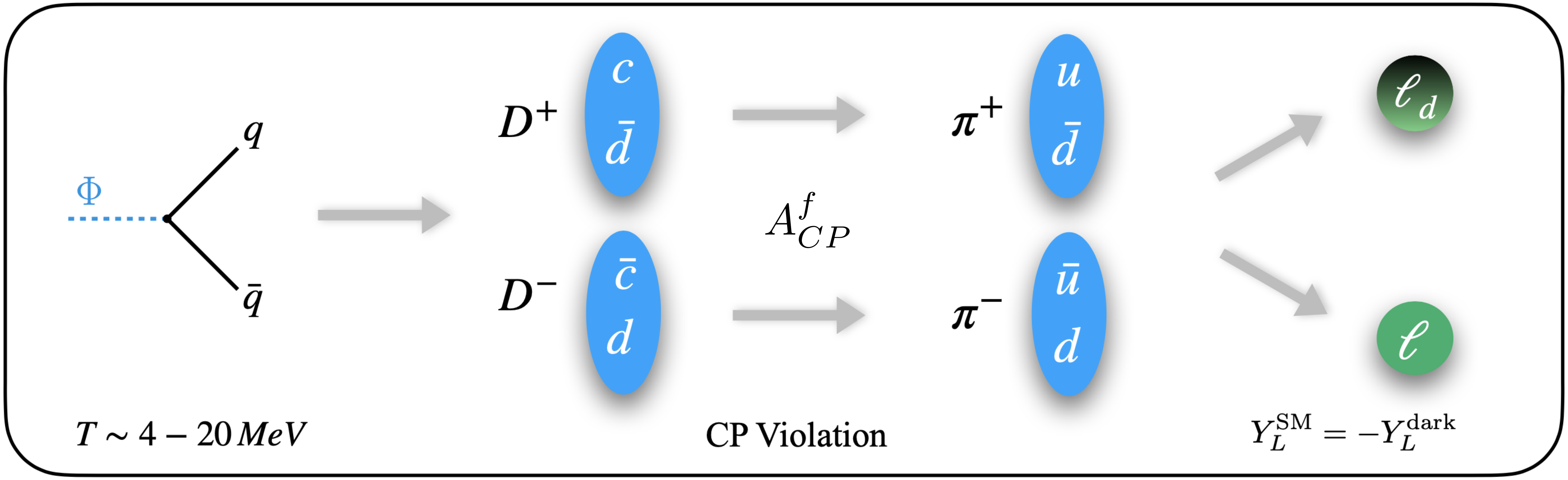
Generating a Lepton Asymmetry

Equal and opposite dark/visible sector lepton asymmetry



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

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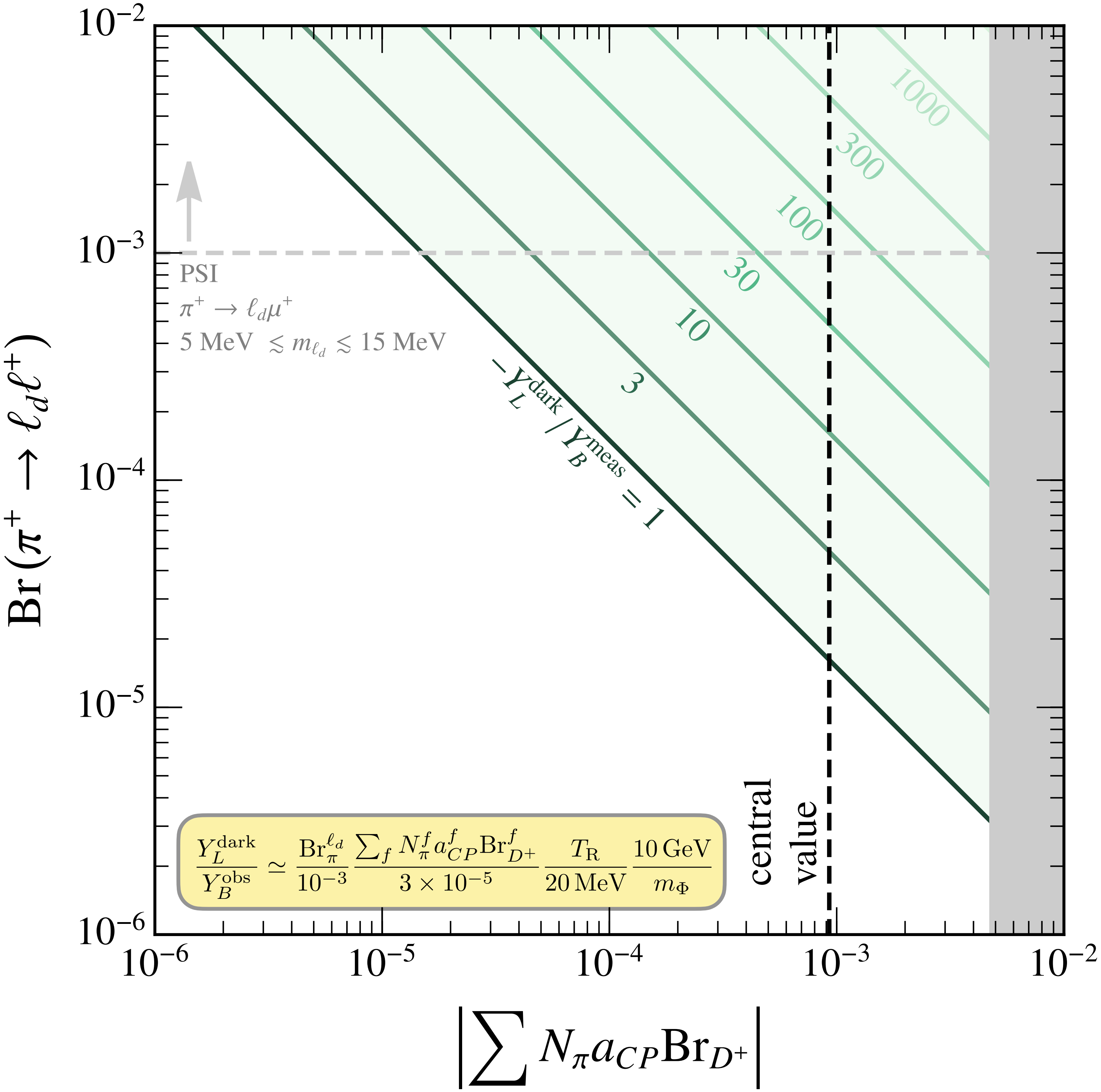
Generating a Lepton Asymmetry



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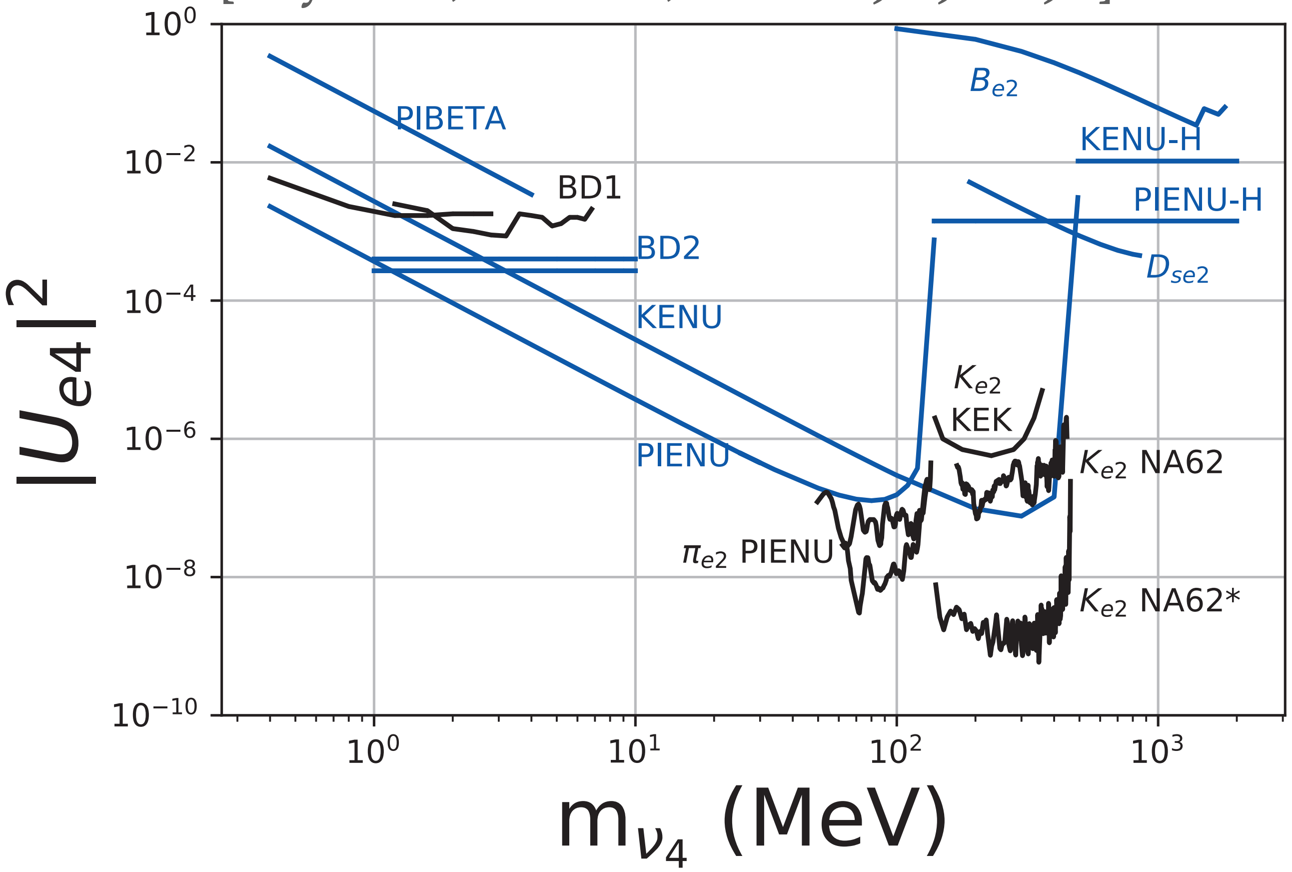
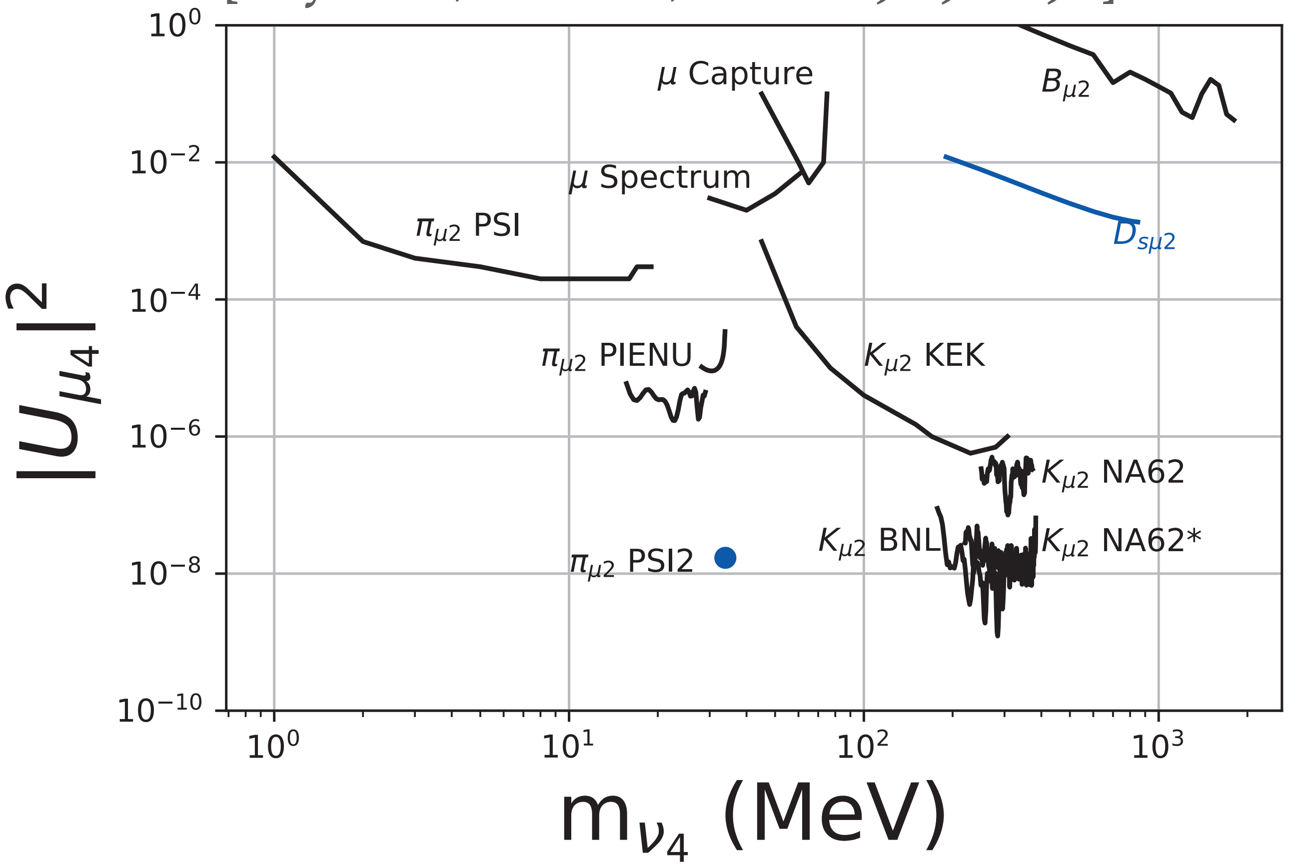
Limits on Pion Decays

[Bryman, Shrock, arXiv:1909.11198]



[Bryman, Shrock, arXiv:1909.11198]



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

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

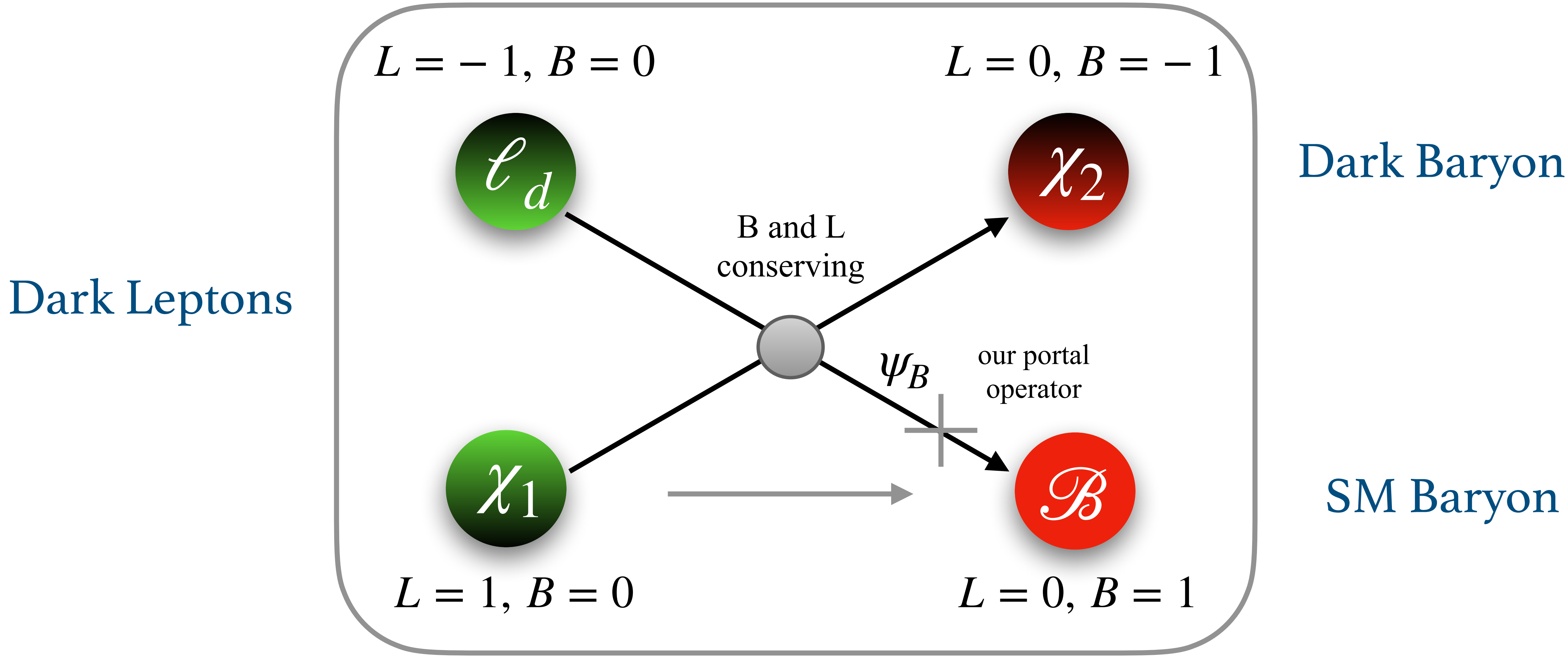
$$\text{Br}(\pi^\pm \to \mu^\pm + \text{MET}) \lesssim 10^{-3}, \quad \text{for } 5\,\text{MeV} < m_{\ell_d} < 15\,\text{MeV}.$$

G. Elor

Generating a Baryon Asymmetry?

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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Freezing-In a Baryon Asymmetry

Example Benchmark point:

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

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

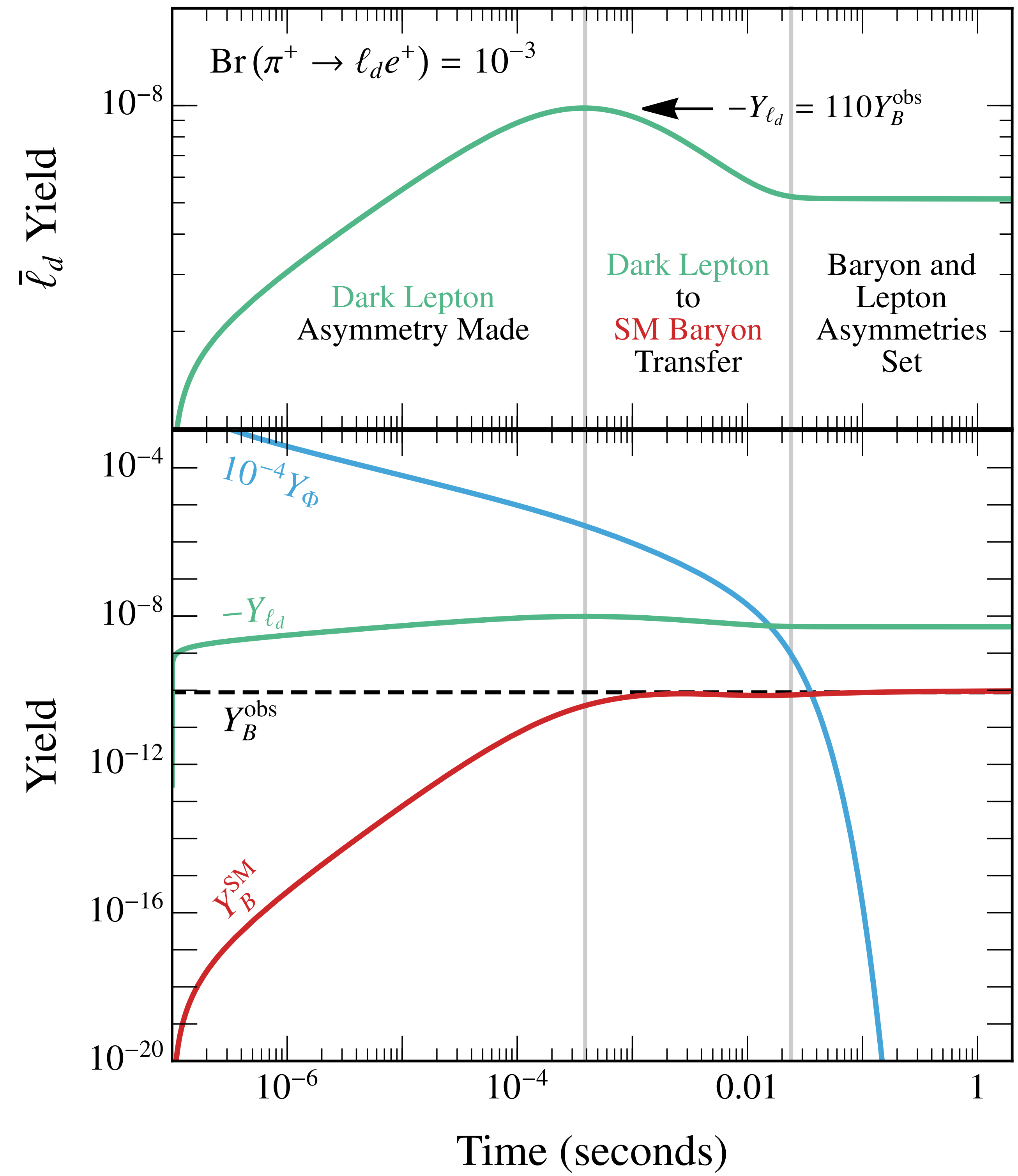
$$\text{Br}(\Phi \to \chi_1 \bar{\chi}_1) = 0.1$$

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

$$\frac{d}{dt}\left(n_\mathcal{B} - n_{\overline{\mathcal{B}}}\right) + 3H\left(n_\mathcal{B} - n_{\overline{\mathcal{B}}}\right) =$$

$$- \langle \sigma v \rangle n_{\chi_1} \left(n_{\ell_d} - n_{\bar{\ell}_d}\right)$$

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



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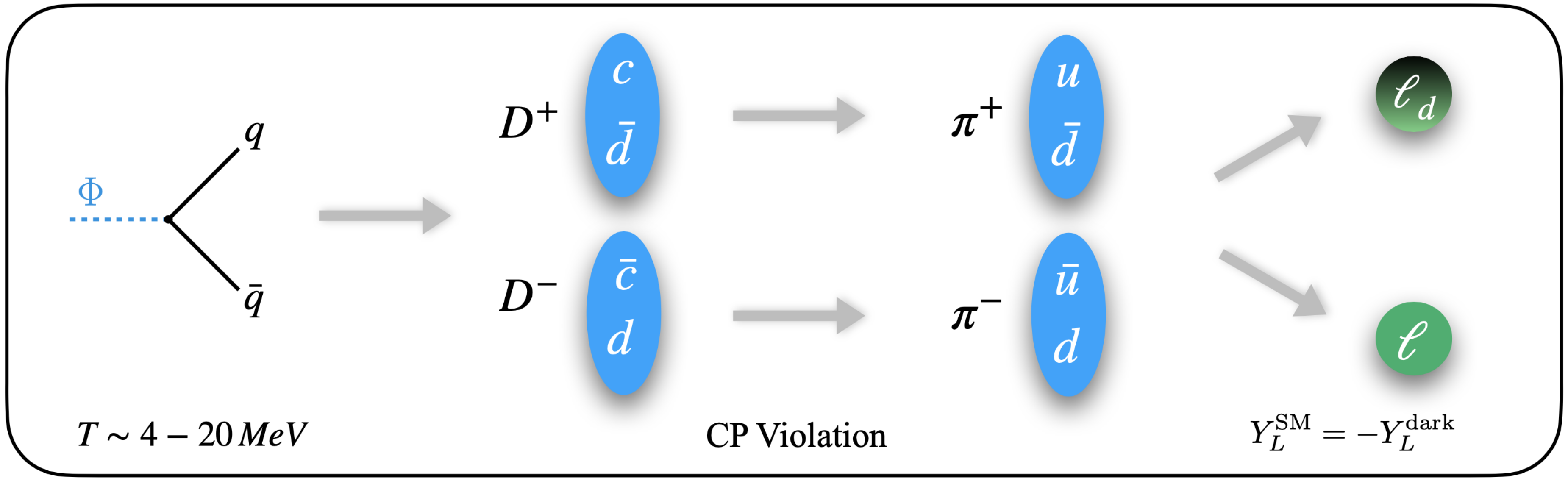
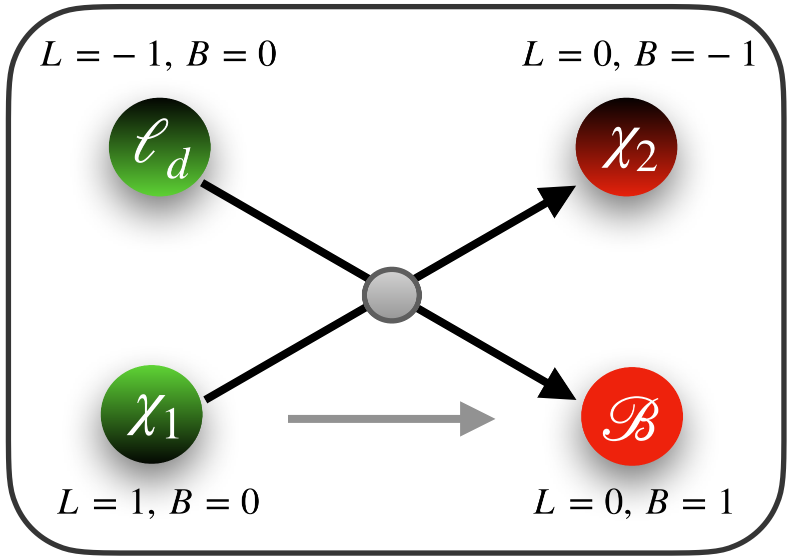
D^+ Mesogenesis

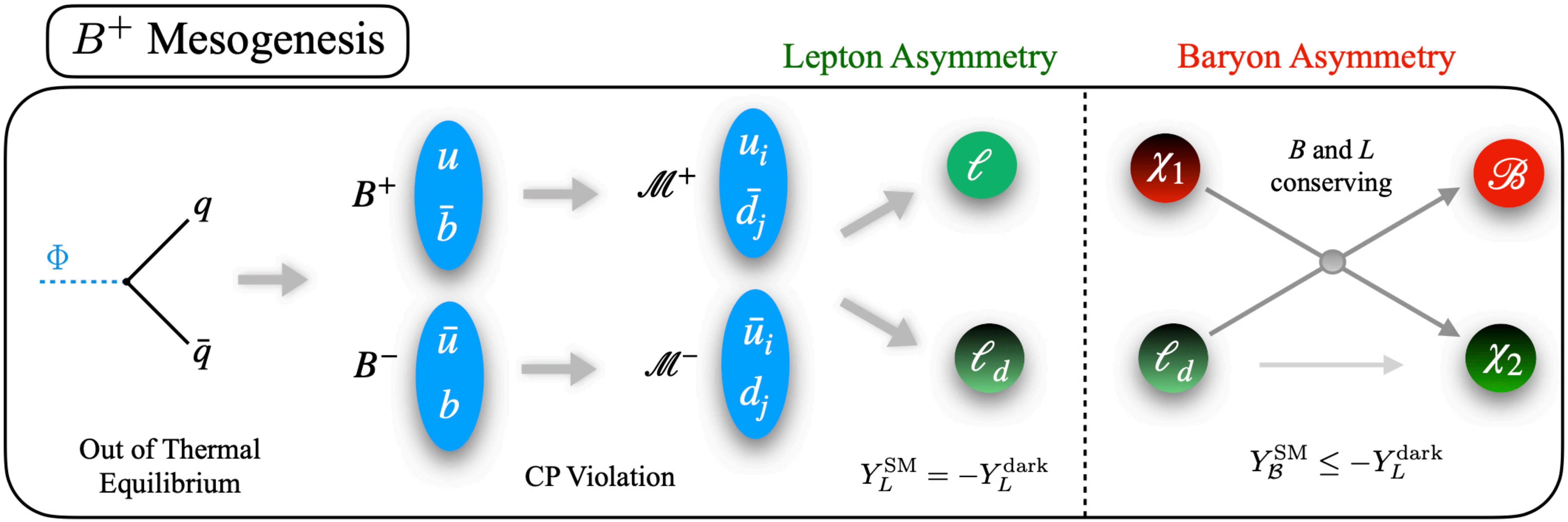




- First generates a lepton asymmetry and then freezes in a baryon asymmetry through dark sector scatterings.
- Baryogenesis and dark matter production are controlled by experimental observables of the charged *D* Mesons system.

G. Elor

B^+ Mesogenesis



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

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

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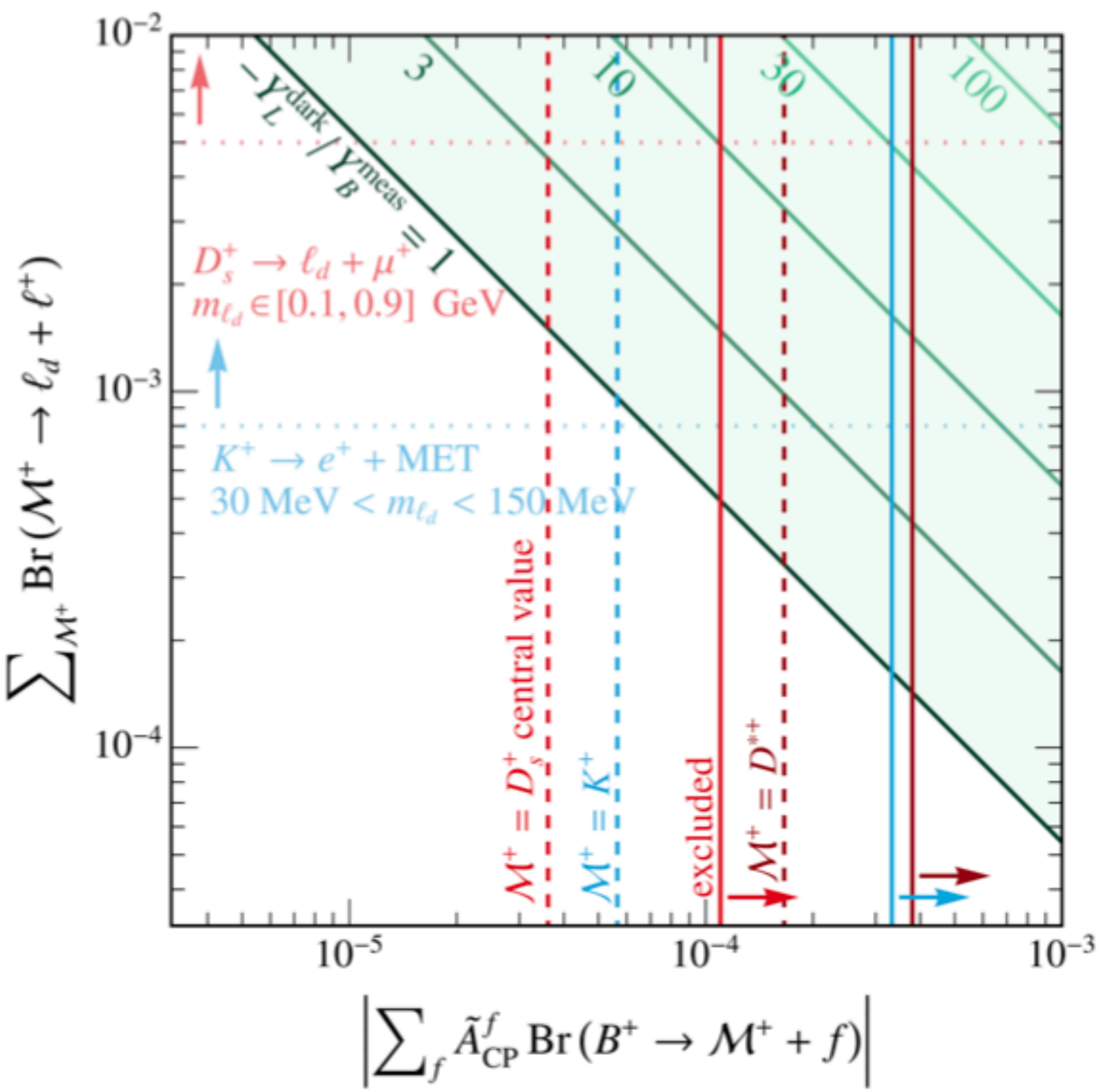
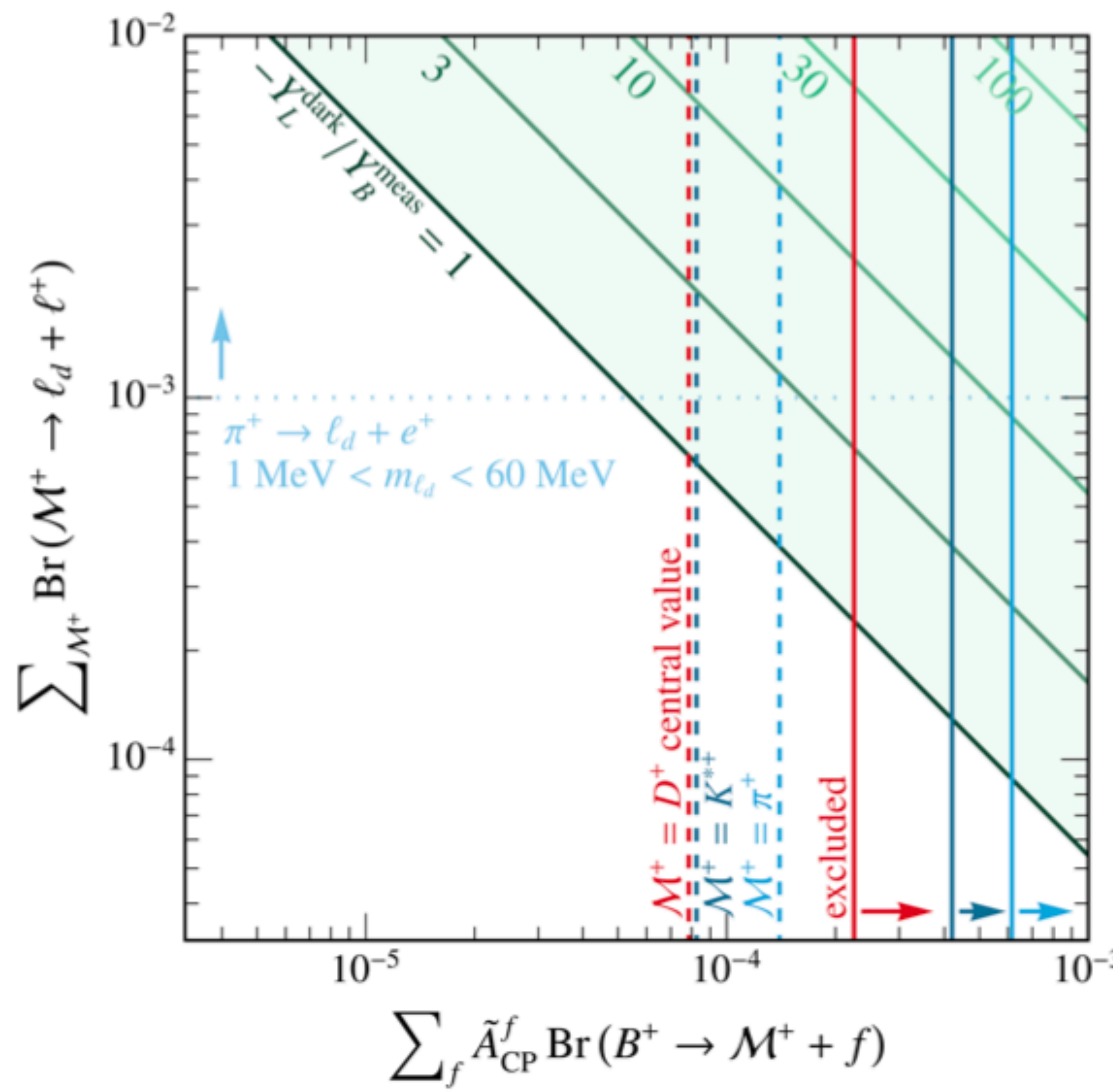
B^+ Mesogenesis





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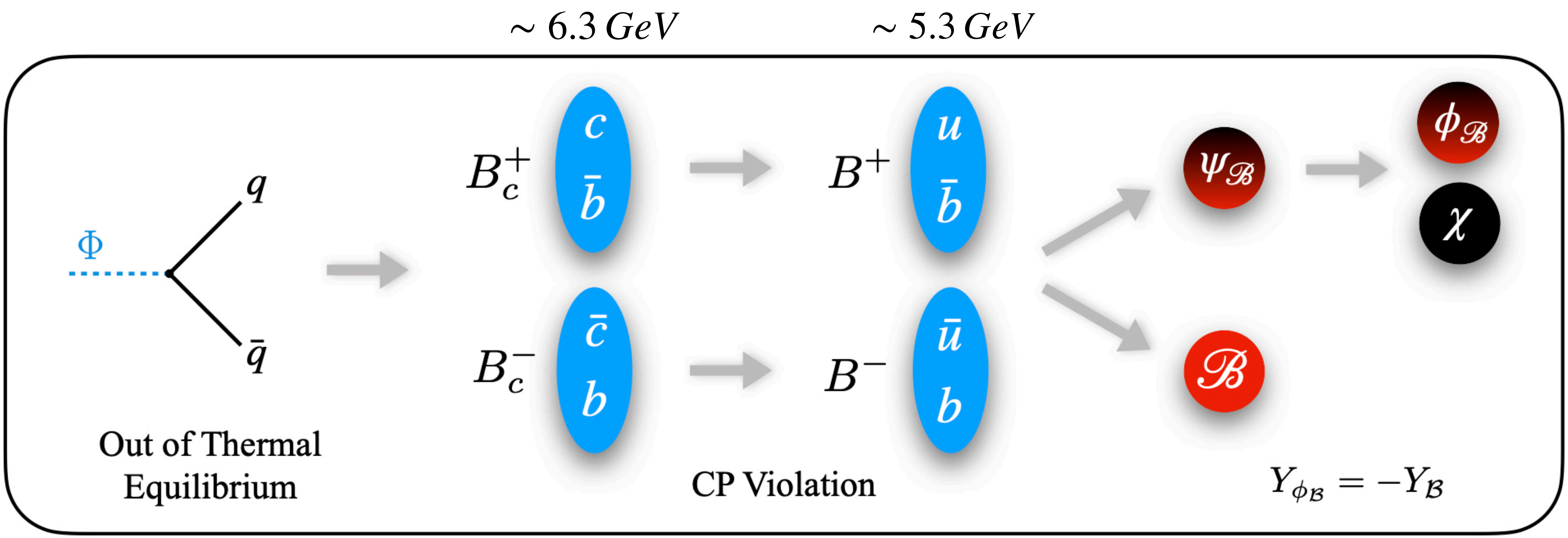
B_c^+ Mesogenesis



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

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

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

G. Elor

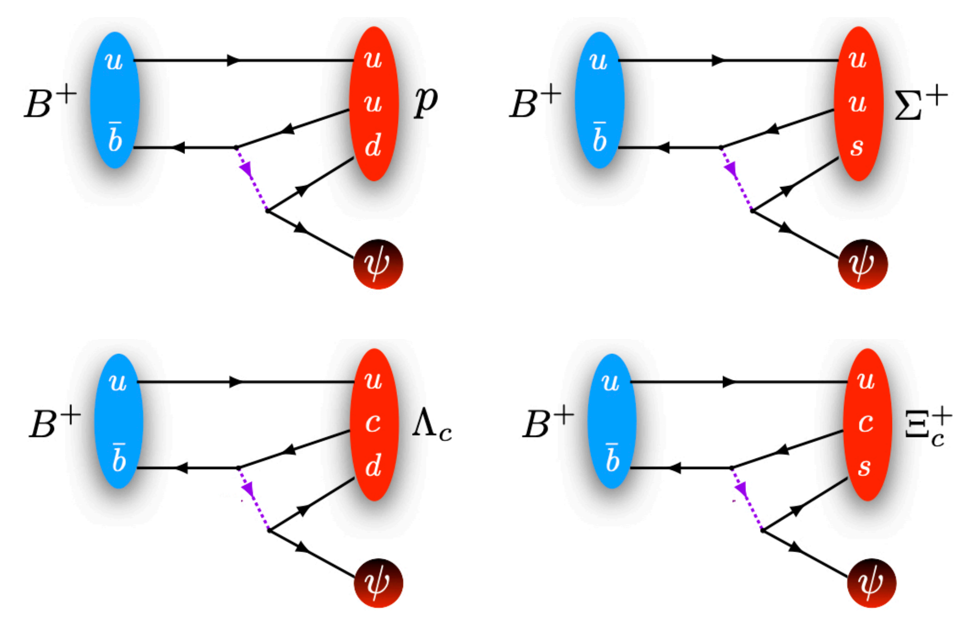
B^+ Decay

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
$\mathcal{O} = \psi\, b\, u\, d$	B_d	$\psi + n\,(udd)$
$\bar{b} \to \psi\, u\, d$	B_s	$\psi + \Lambda\,(uds)$
	B^+	$\psi + p\,(duu)$
	Λ_b	$\bar{\psi} + \pi^0$
$\mathcal{O} = \psi\, b\, u\, s$	B_d	$\psi + \Lambda\,(usd)$
$\bar{b} \to \psi\, u\, s$	B_s	$\psi + \Xi^0\,(uss)$
	B^+	$\psi + \Sigma^+\,(uus)$
	Λ_b	$\bar{\psi} + K^0$
$\mathcal{O} = \psi\, b\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$
$\bar{b} \to \psi\, c\, d$	B_s	$\psi + \Xi_c^0\,(cds)$
	B^+	$\psi + \Lambda_c\,(dcu)$
	Λ_b	$\bar{\psi} + \overline{D}^0$
$\mathcal{O} = \psi\, b\, c\, s$	B_d	$\psi + \Xi_c^0\,(csd)$
$\bar{b} \to \psi\, c\, s$	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 B^+ Mesogenesis.



Indirect signal of charged and neutral B Mesogenesis

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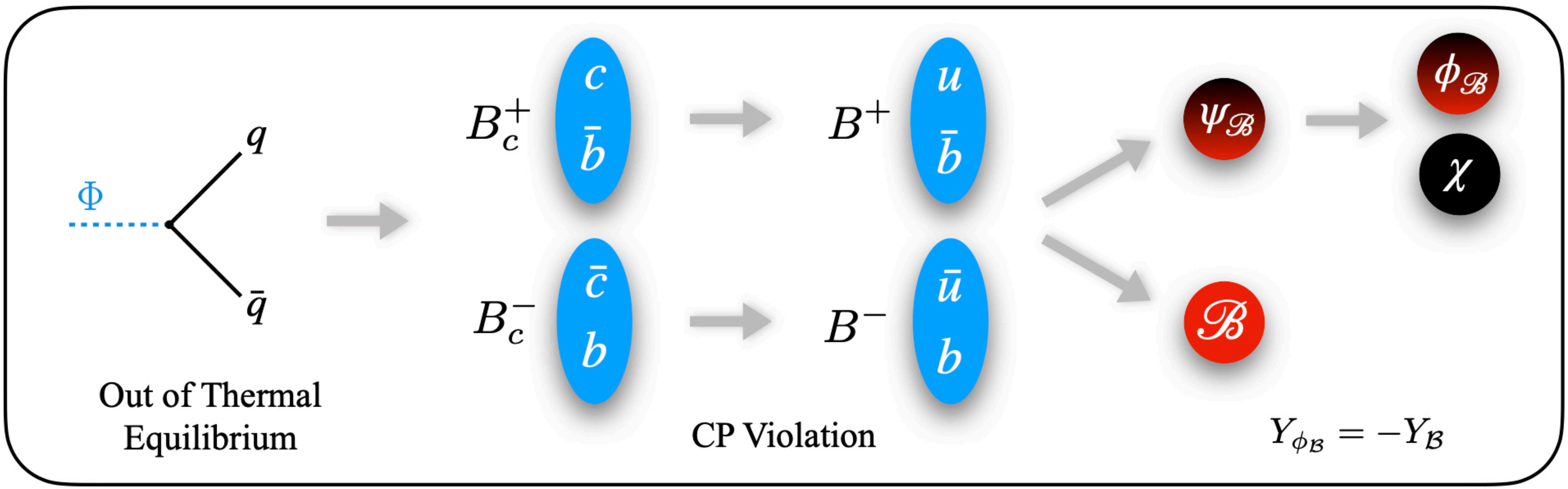
B_c^+ Mesogenesis



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

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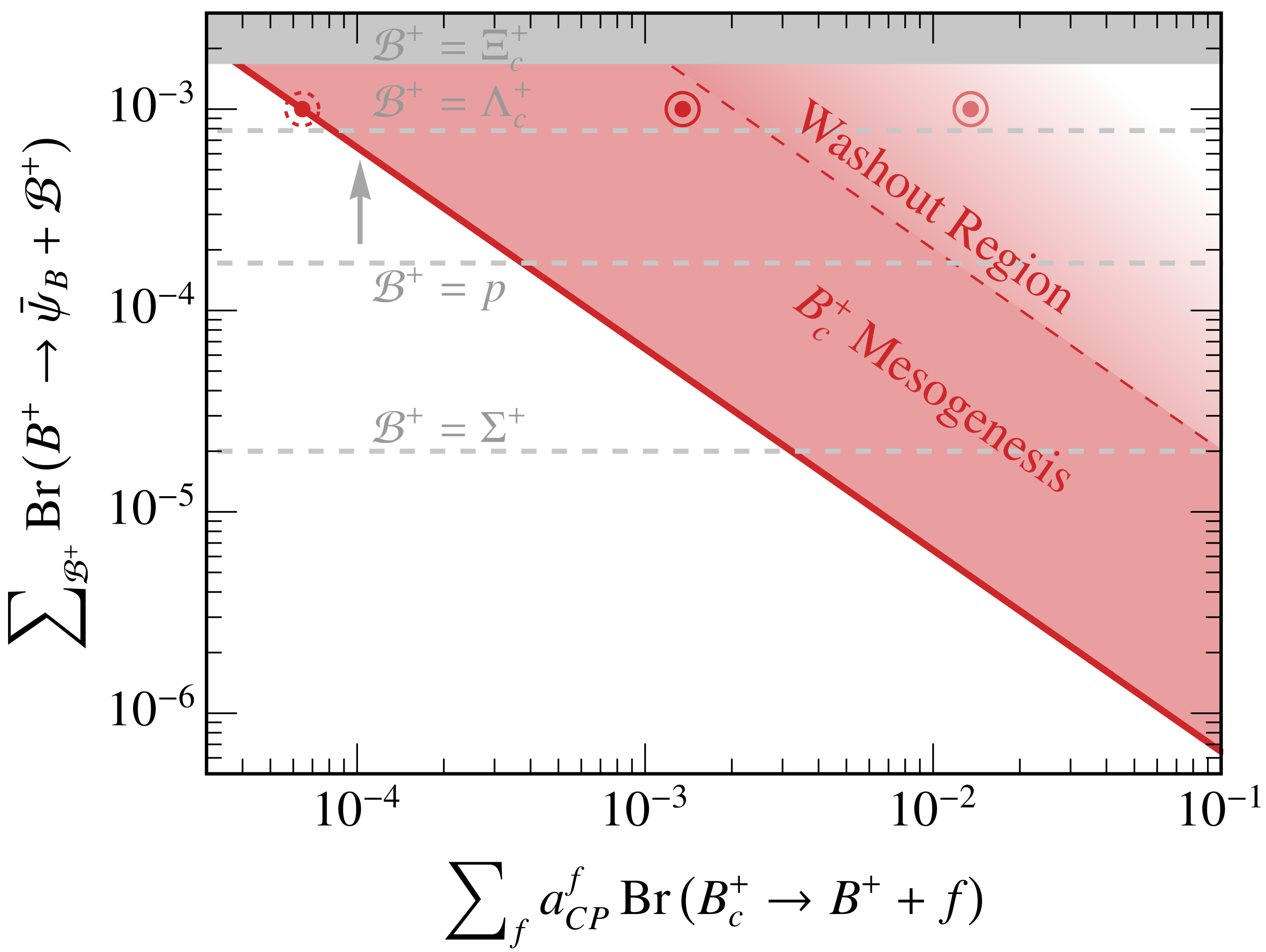
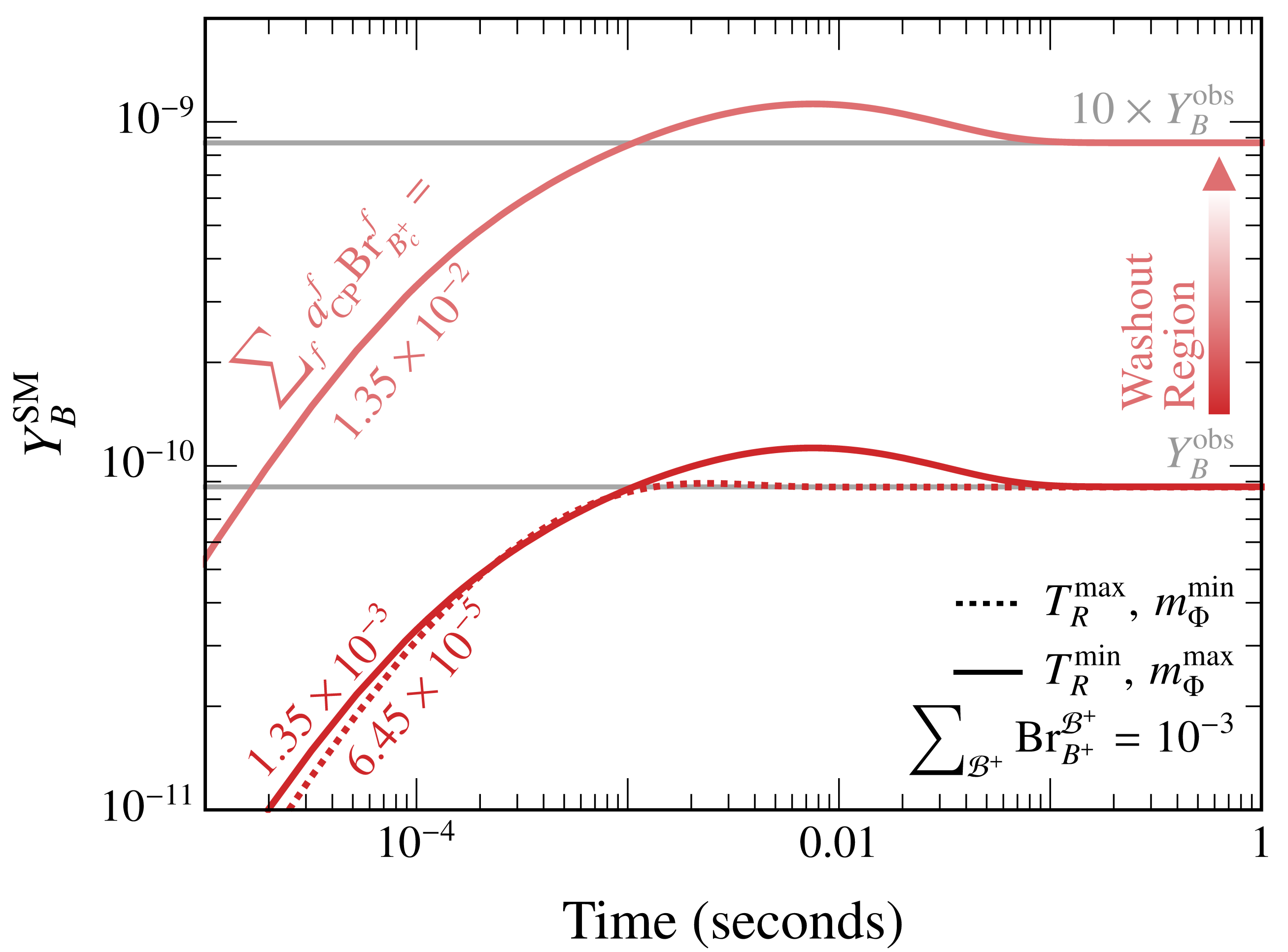
B_c^+ Mesogenesis





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

G. Elor

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]

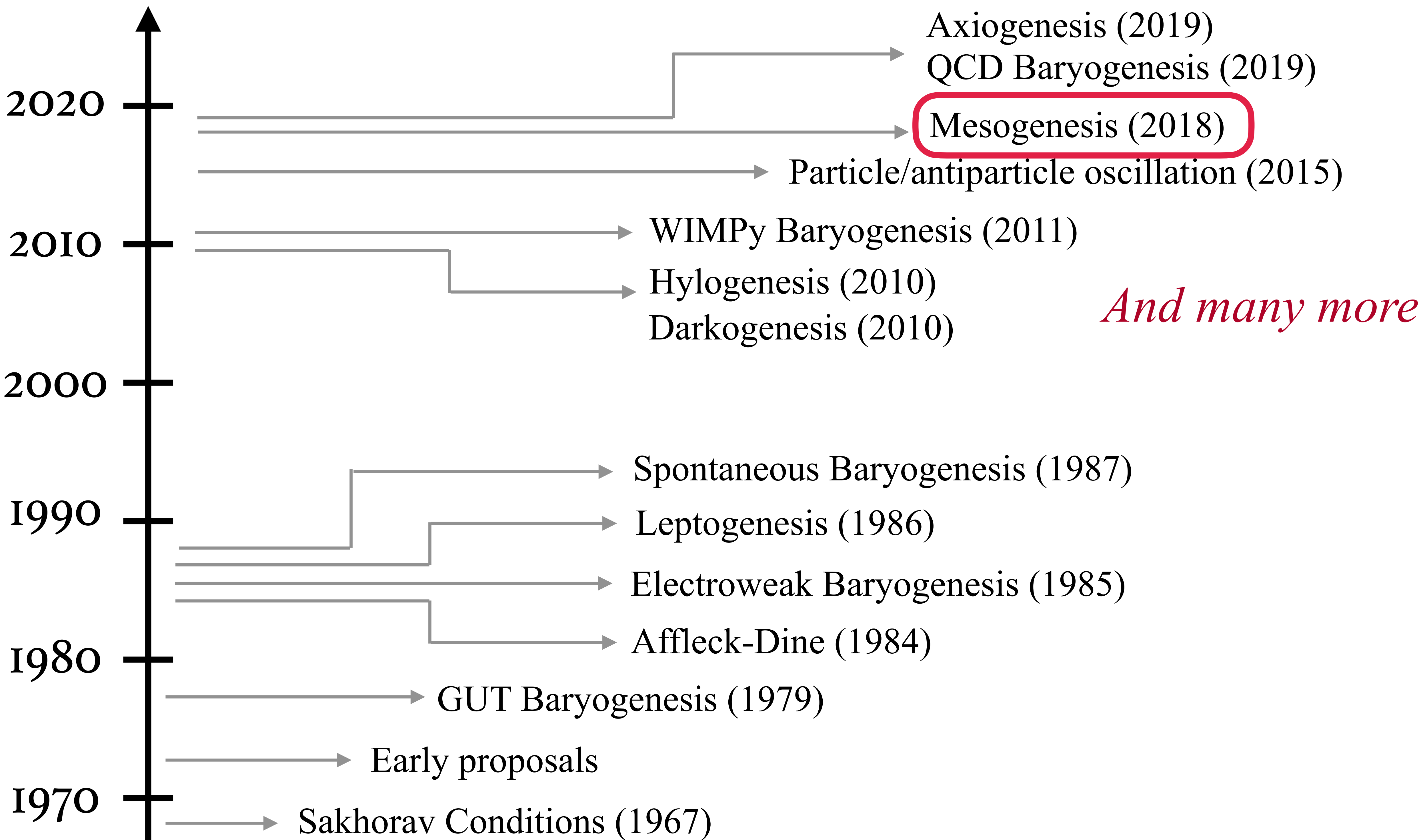
GE, R. McGehee, PRD [2011.06115]

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]

New Ideas Baryogenesis



[TF08 Snowmass White Paper: 2203.05010]

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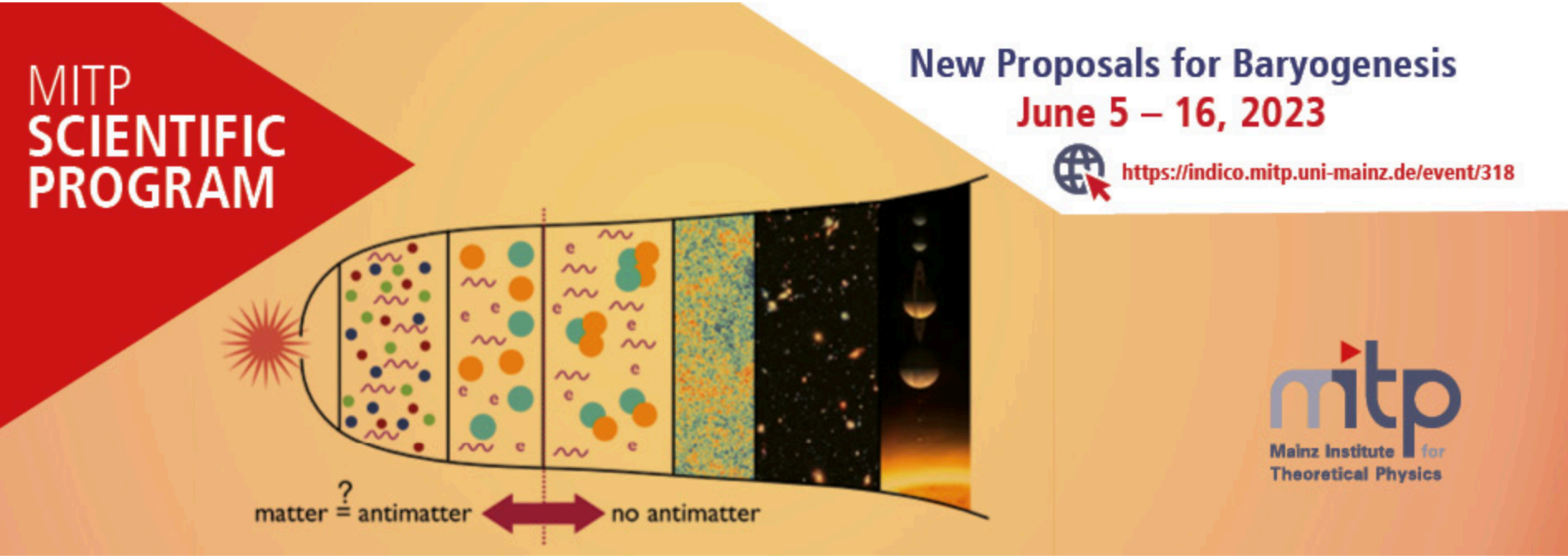
MITP Program 2023

Join us in Mainz in 2023!



Organizing with Seyda Ipek and Bibhushan Shakya

The Many Flavors of Mesogenesis

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

Thanks!

Backups

Emphasis on Testability

New Ideas in Baryogenesis: A Snowmass White Paper

Editors: Gilly Elor,[1] Julia Harz,[2] Seyda Ipek,[3] Bibhushan Shakya.[4]

Authors: Nikita Blinov,[5] Raymond T. Co,[6] Yanou Cui,[7] Arnab Dasgupta,[8] Hooman Davoudiasl,[9] Fatemeh Elahi,[1] Gilly Elor,[1] Kåre Fridell,[2] Akshay Ghalsasi,[8] Keisuke Harigaya,[10] Julia Harz,[2] Chandan Hati,[2] Peisi Huang,[11] Seyda Ipek,[3] Azadeh Maleknejad,[10] Robert McGehee,[12] David E. Morrissey,[13] Kai Schmitz,[10] Bibhushan Shakya,[4] Michael Shamma,[13] Brian Shuve,[14] David Tucker-Smith,[15] Jorinde van de Vis,[4] Graham White.[16]

Model	Key Ingredients	Observable scale	Observables
Axiogenesis	Axion misalignment, sphalerons	axion scale ~ O($10^{8\text{-}11}$ GeV) axion mass ~ μeV	Gravitational waves
W_R baryogenesis	axion inflation, W_R interactions with the inflaton	LR symmetry breaking ~ O(10^{10} GeV)	Gravitational waves
QCD Baryogenesis	Singlet scalar coupled to the gluon field strength, axion, sphalerons	masses ~ O(10 GeV) temperature ~ O(TeV)	Scalar field mixing with the Higgs Graviational waves
Wash-in Leptogenesis	Charge asymmetry instead of *B-L*, out of equilibrium decays	Right-handed neutrino masses ~ O(100 TeV)	Charged lepton flavor violation
Hylogenesis	Long-lived dark baryons	GeV-TeV	Induced nucleon decay collider signatures
WIMPy Baryogenesis	Metastable WIMPs	O(100 GeV)	Long-lived particles
Gaugino Portal Baryogenesis	hidden sector gaugino-bino mixing, R-parity violation	masses ~ O(10 - 10^8 GeV)	Neutron-antineutron oscillation, LLP (RPV decays) at colliders
Freeze-in Baryogenesis	DM oscillations	masses ~ O(TeV), O(10 keV)	missing momentum searches structure formation, X-ray signals
Pseudogenesis	Pseudo-Dirac fermions, particle-antiparticle oscillations	O(100 GeV - TeV)	LLPs, dilepton asymmetry
Mesino-genesis	Mesino-antimesino oscillations, SU(3)-charged scalars	masses ~ O(TeV) temperature ~ O(100 MeV)	LLPs, same-sign top quark decays, mullti-jet signals
Mesogenesis	CPV from SM Meson systems, dark states charged under SM B and L number	masses ~ O(1-100 GeV) temperature ~ O(5-100 MeV)	CPV observables at B factories, LHC, decays of hadrons to dark baryons, peak searches at colliders
Baryogenesis from Quantum Statistics	dark matter chemical potential	—	—

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:

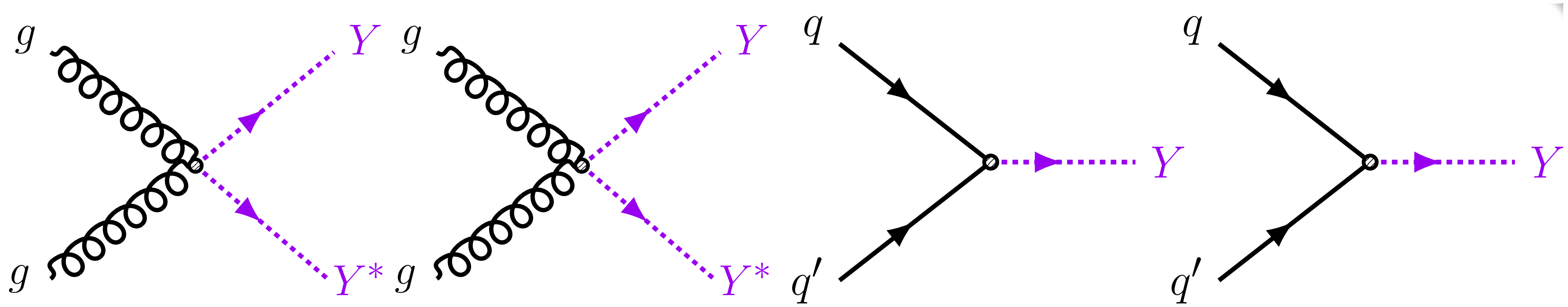
$$\text{Br}(B \to \psi\, \mathcal{B}\, \mathcal{M}) \gtrsim 10^{-4}$$

G. Elor

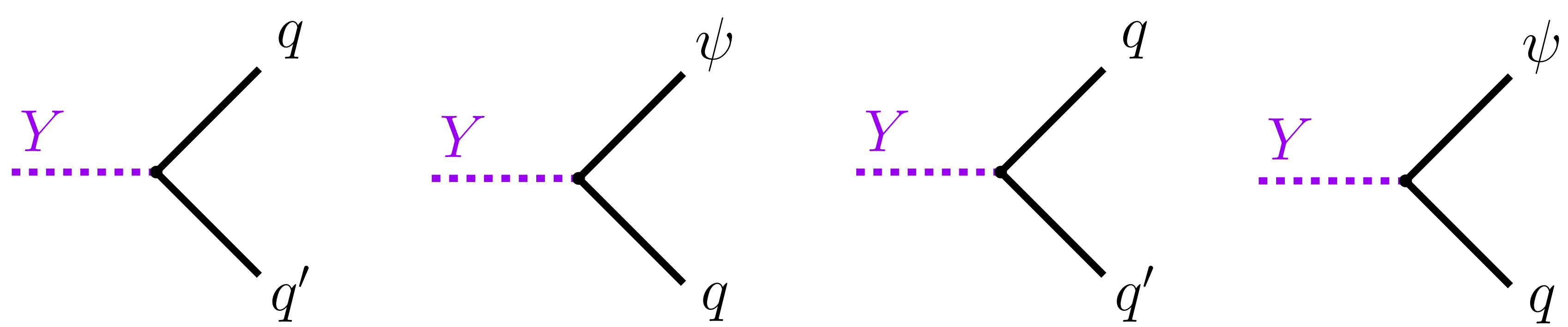
Colored Triplet Scalar

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:	$M_Y > 0.5\,\text{TeV}$	$M_Y > 1.2\,\text{TeV}$	$M_Y > 1-7\,\text{TeV}$	$M_Y > 1-7\,\text{TeV}$

G. Elor

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]

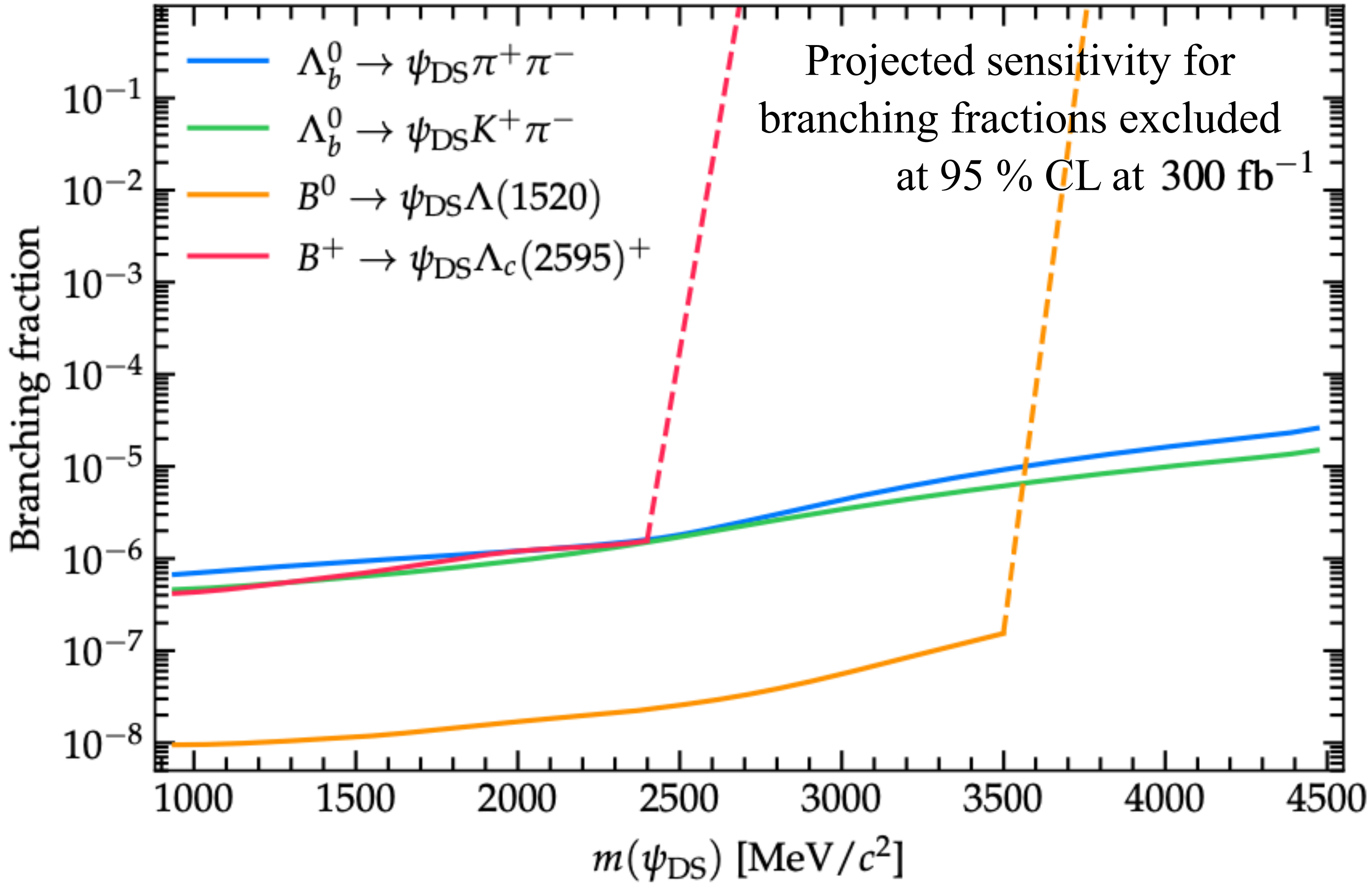
Alexandre Brea Rodríguez [a,1], Veronika Chobanova [b,1], Xabier Cid Vidal [c,1], Saúl López Soliño [d,1], Diego Martínez Santos [e,1], Titus Mombächer [f,1], Claire Prouvé [g,1], Emilio Xosé Rodríguez Fernández [h,1], Carlos Vázquez Sierra [i,2]

[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.



G. Elor

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: $$a_{CP}^f \equiv A_{CP}^f/(1 + A_{CP}^f) \approx A_{CP}^f$$ $${\rm Br}_{D^+}^f \equiv {\rm Br}\left(D^+ \to f\right)$$ *LHCb, B factories*
- Charged pion decays: $${\rm Br}_\pi^{\ell_d} \equiv {\rm Br}\left(\pi^+ \to \ell_d + \ell^+\right)$$ *PIENU, PSI, etc.*

G. Elor

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.

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

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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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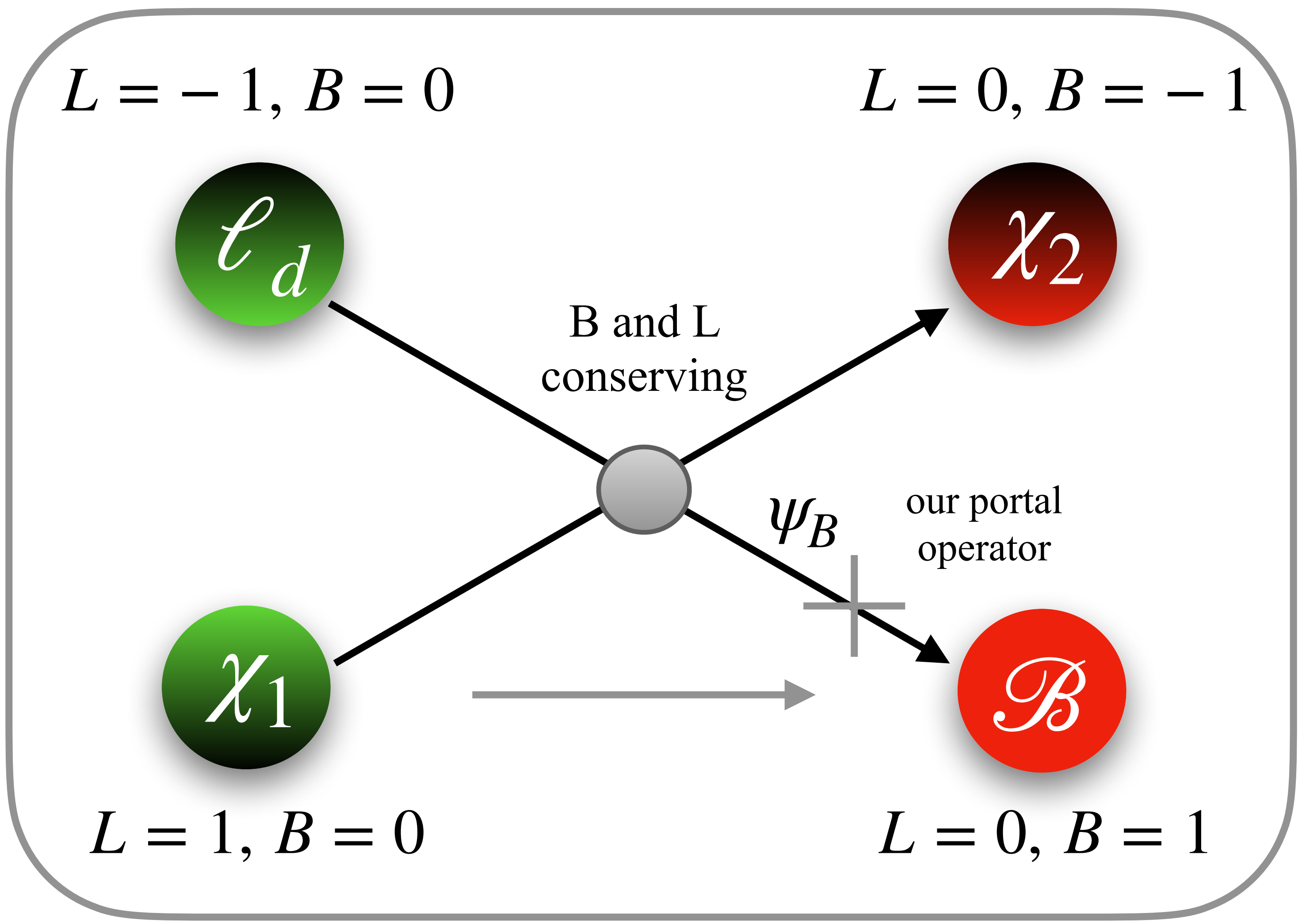
Example Charge Assignment

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

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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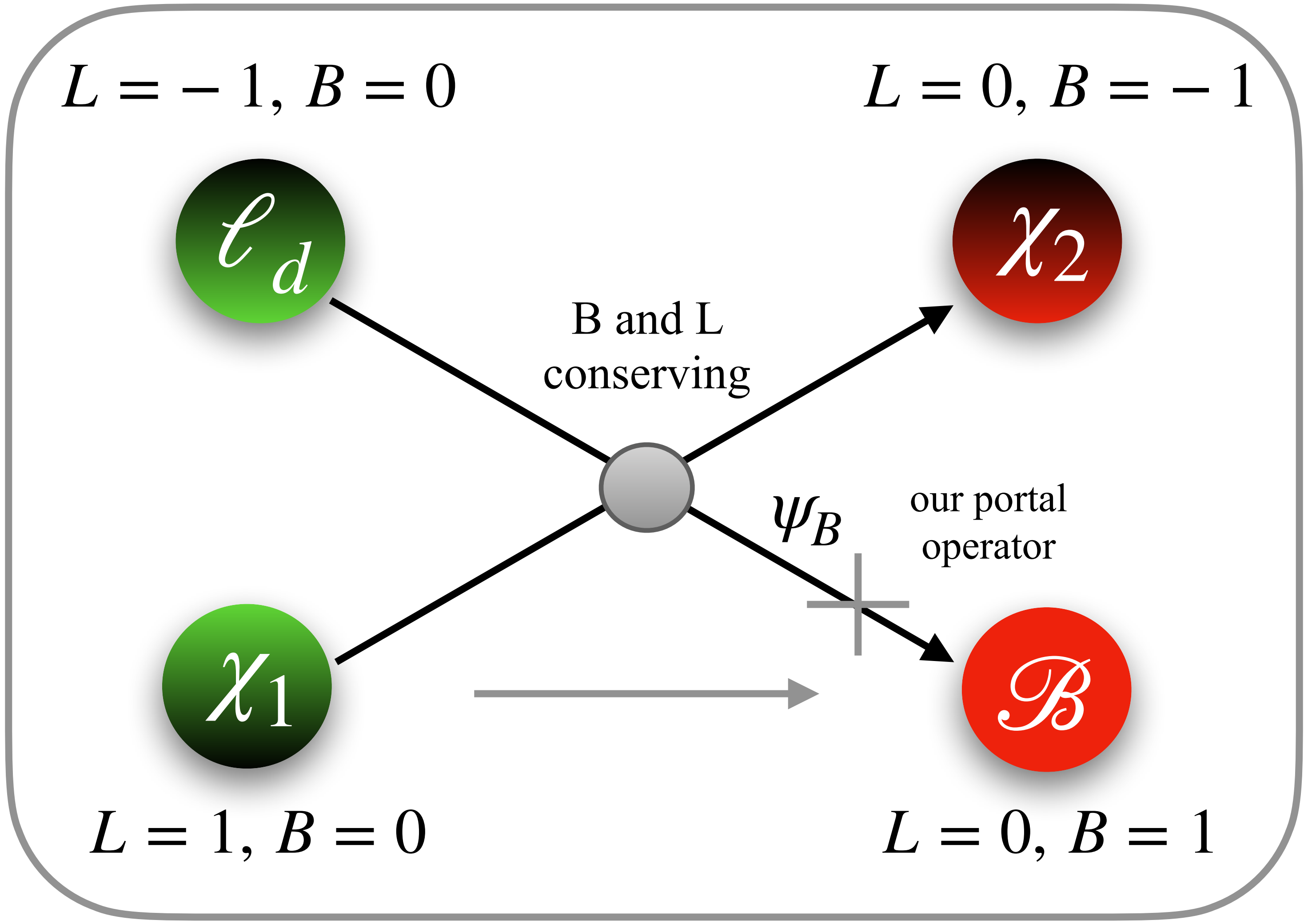
Example Charge Assignment

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

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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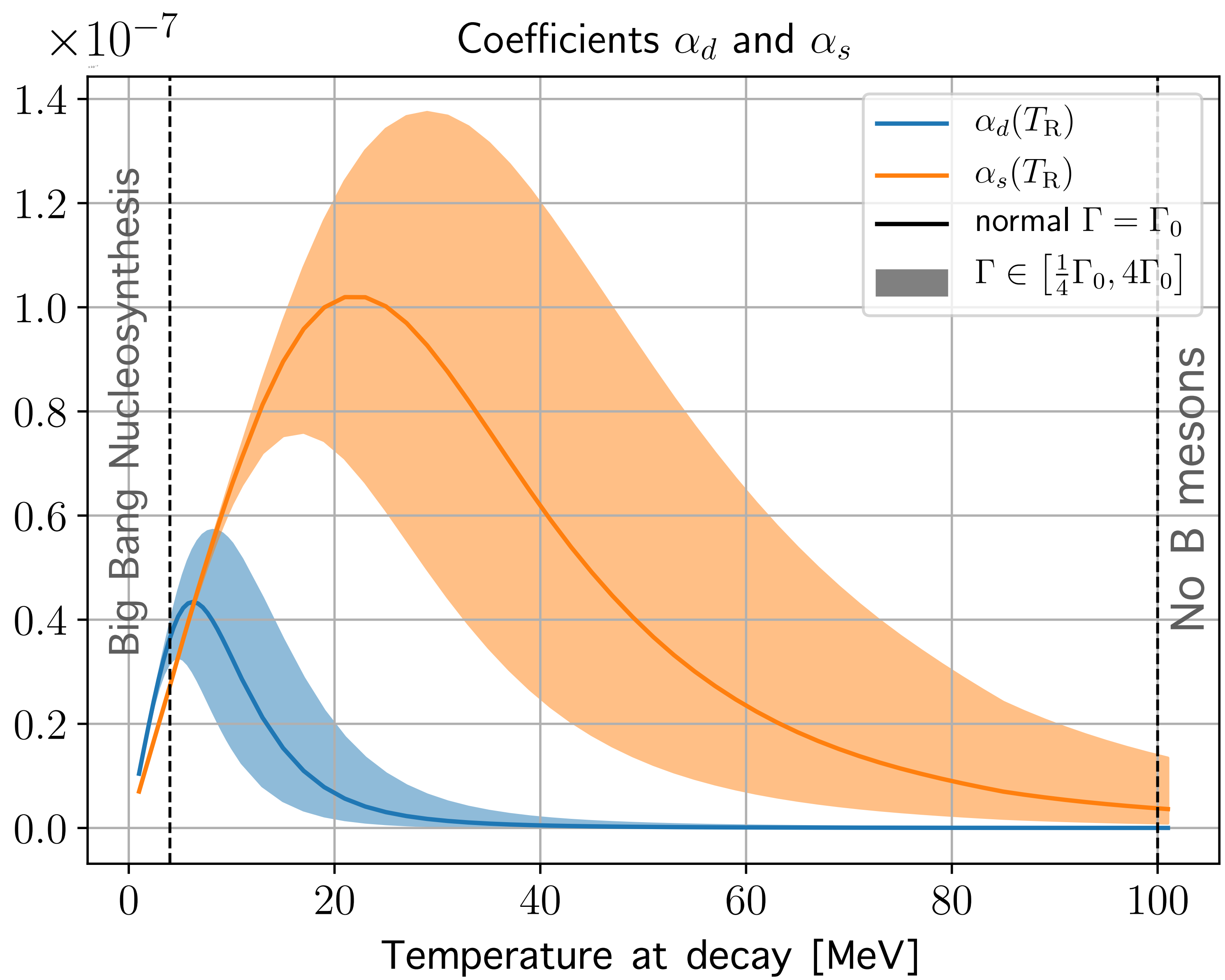
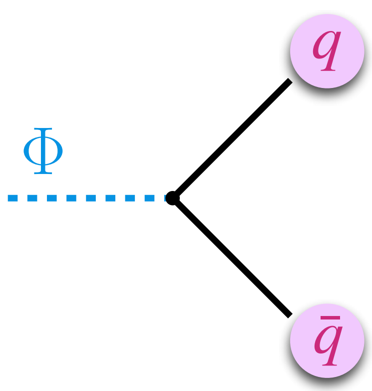
Baryogenesis and Dark Matter from B Mesons





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

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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
$\mathbf{N}^c_R$	1	-1

"RPV"

$$\mathbf{W} = y_u \mathbf{Q}\mathbf{H}_u\mathbf{U}^c - y_d \mathbf{Q}\mathbf{H}_d\mathbf{D}^c - y_e \mathbf{L}\mathbf{H}_d\mathbf{E}^c + \frac{1}{2}\lambda''_{ijk}\mathbf{U}^c_i\mathbf{D}^c_j\mathbf{D}^c_k + \mu_u \mathbf{H}_u\mathbf{R}_d + \mu_d \mathbf{R}_u\mathbf{H}_d + \lambda^t_u \mathbf{H}_u\mathbf{T}\mathbf{R}_d + \lambda^t_d \mathbf{R}_u\mathbf{T}\mathbf{H}_d + \lambda^s_d \mathbf{S}\mathbf{R}_u\mathbf{H}_d\,.$$

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

Gauge:

$$\mathcal{L}_{\text{gauge}} = -\sqrt{2}g(\phi T^a \psi^\dagger)\lambda^{a\dagger} + \text{h.c.}$$

$$\Rightarrow \quad -\sqrt{2}g(\tilde{d}^*_R d_R \tilde{B}^\dagger) - \sqrt{2}g(\tilde{d}_L d^\dagger_L \tilde{B}^\dagger) + \text{h.c.}$$

Neutrio:

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

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

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	$+1$	$11-100\,\mathrm{GeV}$
MSSM Squark	$\tilde{d}_R$	0	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\mathrm{TeV})$
Dirac Bino	$\begin{bmatrix} \tilde{B} \\ \lambda_s^\dagger \end{bmatrix}$	$1/2$	0	-1	$+1$	$\mathcal{O}(\mathrm{GeV})$
Right handed neutrino multiplet	ν_R	$1/2$	0	0	-1	$\mathcal{O}(\mathrm{GeV})$
Right handed neutrino multiplet	$\tilde{\nu}_R$	0	0	-1	-1	$\mathcal{O}(\mathrm{GeV})$

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Baryogenesis from the SM?

How to generate a matter/antimatter asymmetry

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

Image: Stolen from the Internet

The Sakharov conditions (1967):

- Interactions that violate Baryon number. Yes. Electroweak Sphalerons.
- Conjugate rates must be different. CPV CKM phases are not large enough.
- Out of thermal equilibrium. Need to add new physics to the Higgs sector to make EWPT first order.

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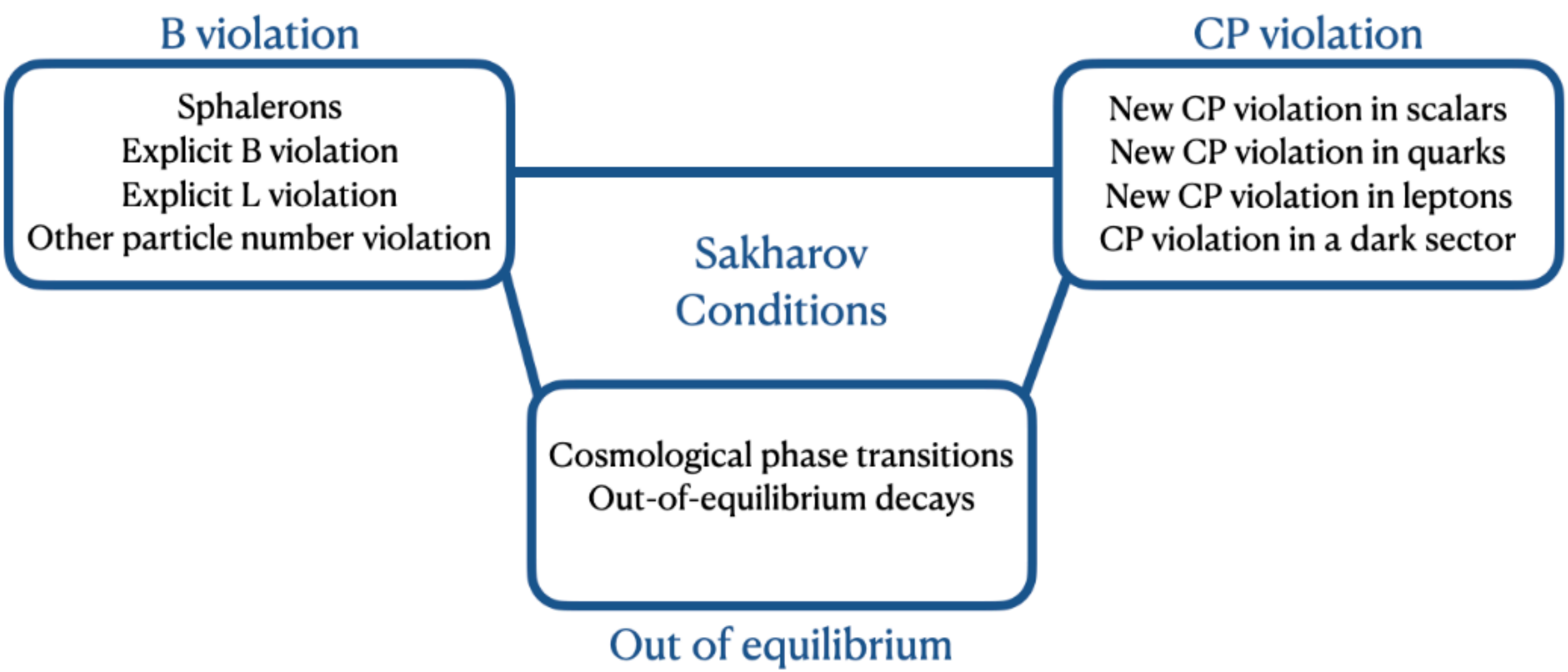
A Need for BSM Physics

How to generate a matter/antimatter asymmetry



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