Mesogenesis:

Signals of Baryogenesis at *B*-Factories

Gilly Elor

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Belle-II Physics Week @ KEK

Oct 14 2024

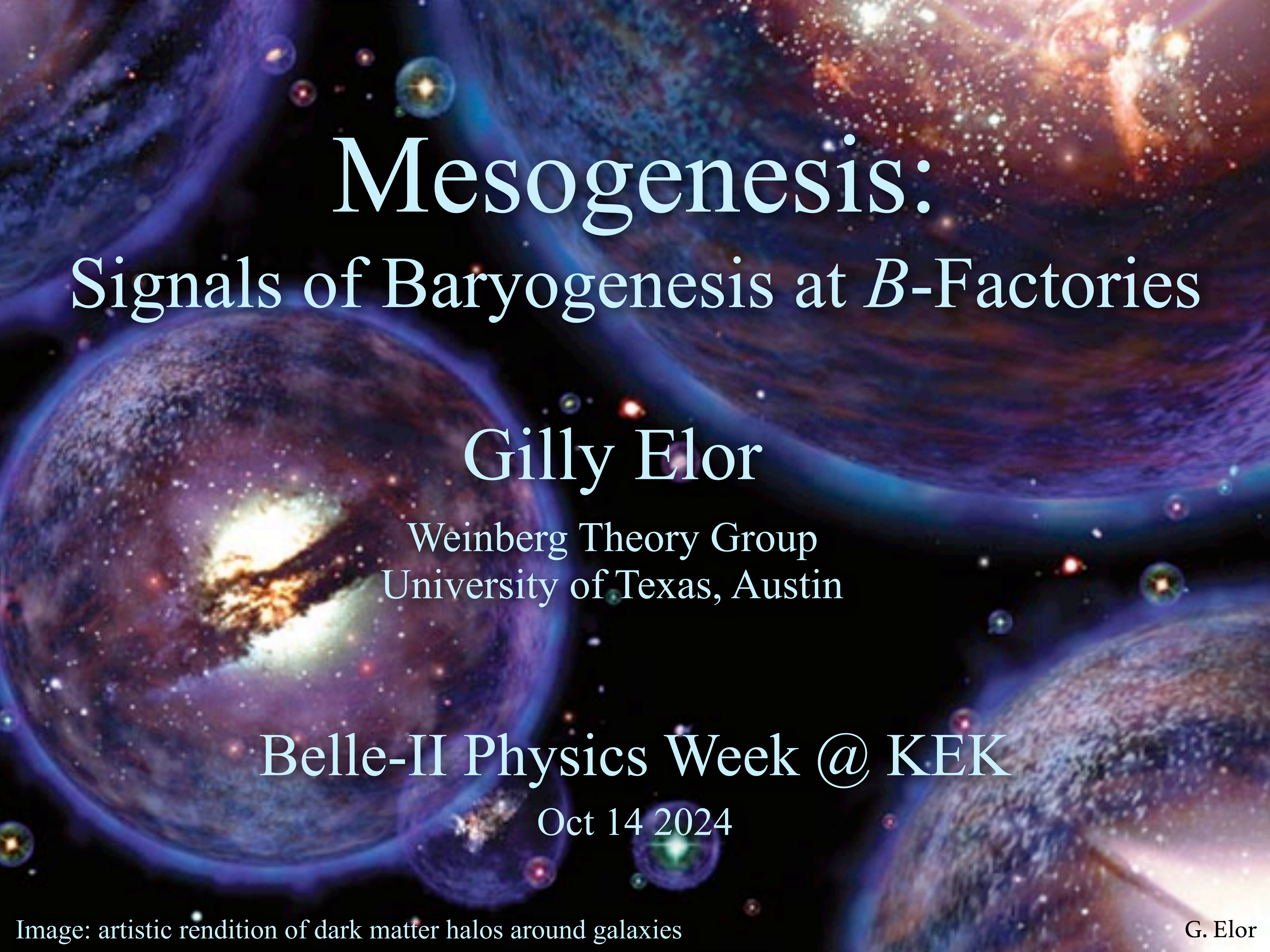
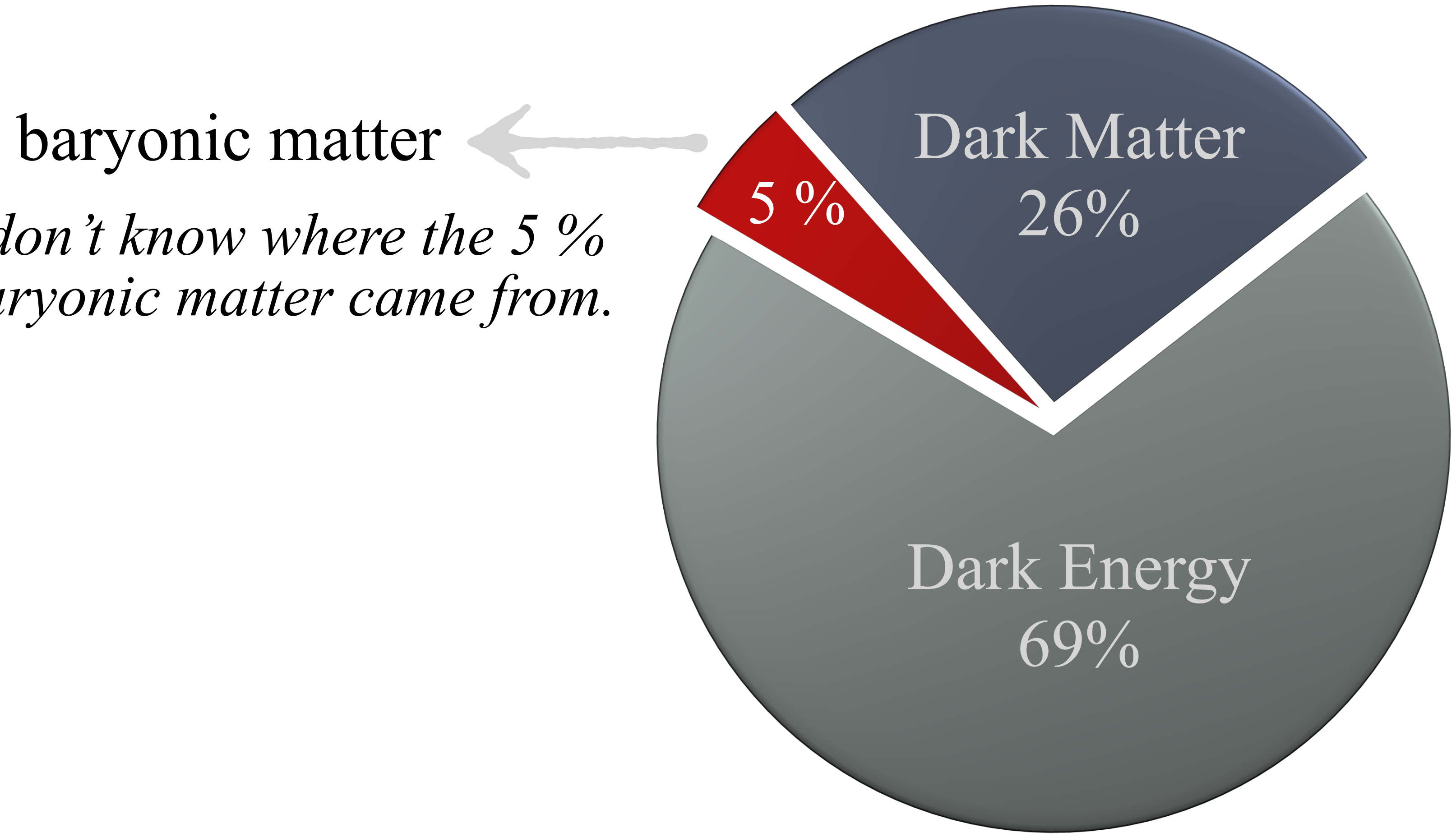


Image: artistic rendition of dark matter halos around galaxies

The Contents of the Universe

From cosmological and astrophysical measurements we know:



We don't know where the 5 % of baryonic matter came from.

Energy density today

This talk: Baryogenesis + Dark Matter

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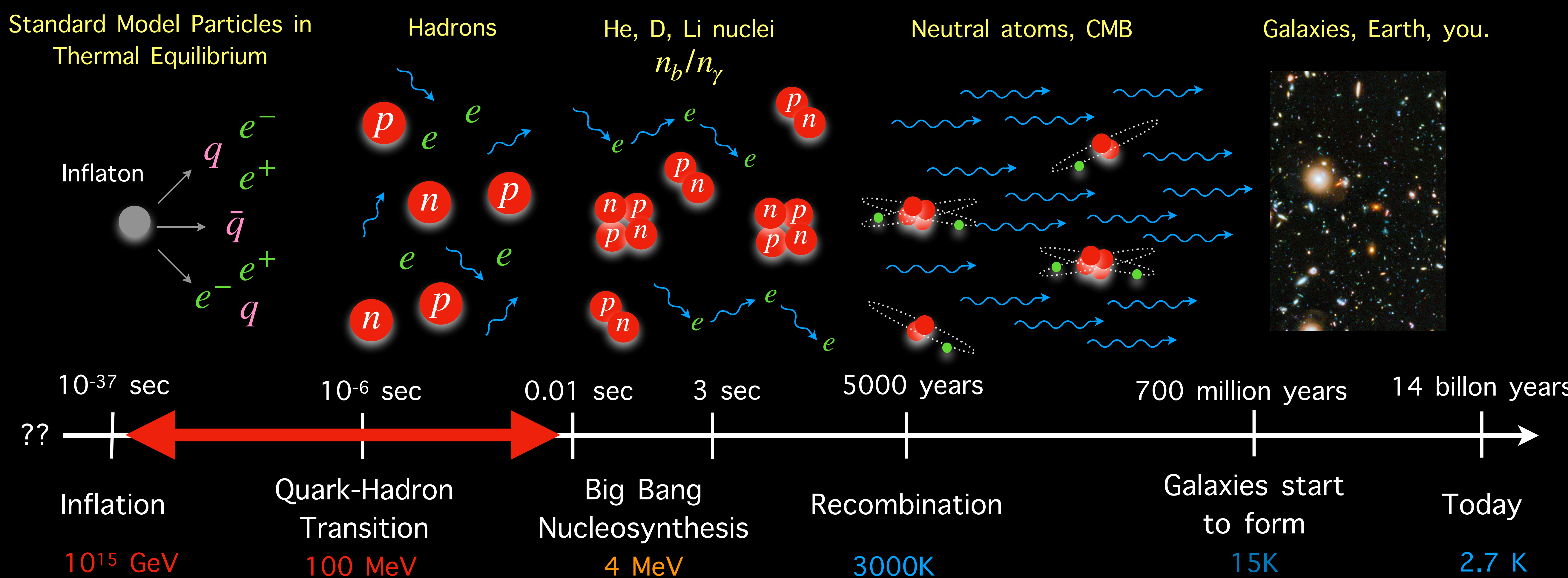
Baryogenesis



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

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

"Yield" = baryon number density / entropy density

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From the Standard Model?

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):

- 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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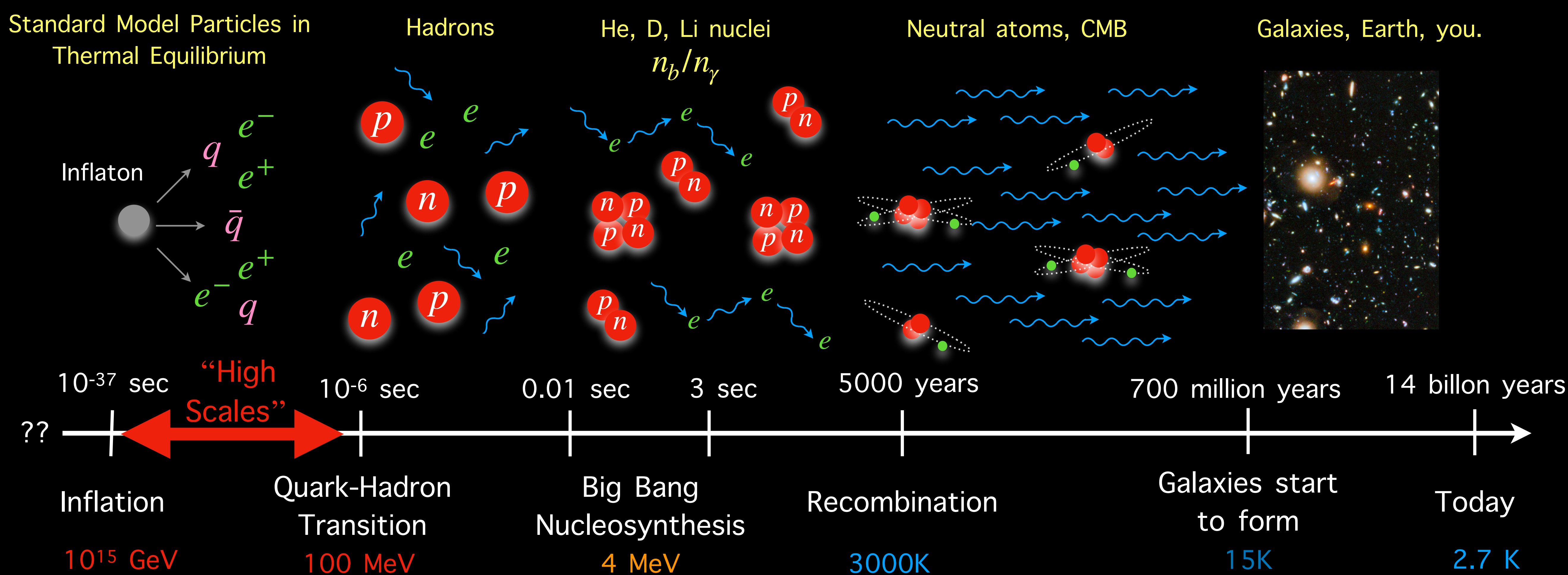
Traditional Baryogenesis Mechanisms

The Standard Model CP Violation is not Enough



- Electroweak baryogenesis. Constrained by EDMs.
- Leptogenesis. Hard to test
- GUT baryogenesis. Harder to test.
- …….

TF08 Snowmass Paper :
[Elor et. al. arXiv: 2203.05010]

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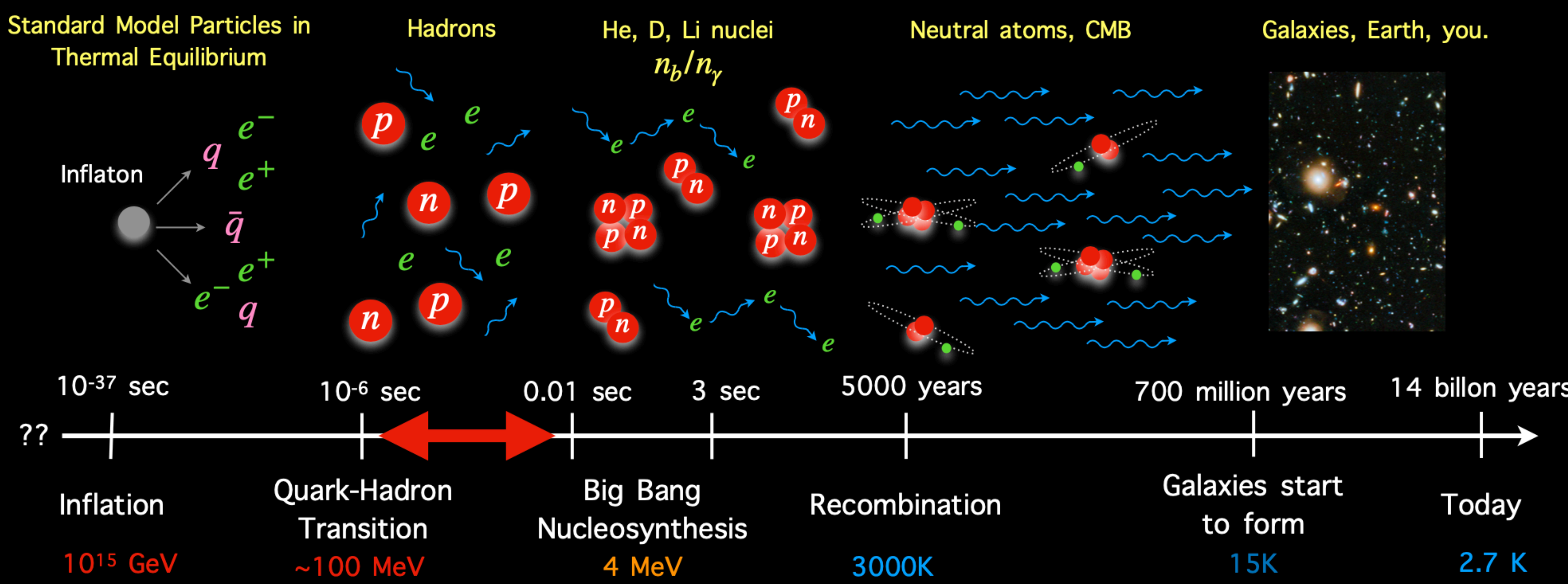
Mesogenesis



The Sakharov conditions:

- Out of thermal equilibrium: *GeV scale mesons produced when the Universe was at MeV scales.*
- CP Violation: *From SM Meson systems.*
- Baryon number violation: *SM Meson decays to dark lepton or baryon.*

Features:

- Signals!
- The SM CPV can be enough.
- Baryon asymmetry production right before BBN possible.
- Reconstructable dark matter.

Mesogenesis

Mechanisms proposed to date

Mechansim	CPV	Dark Sector	Observables	Relevant Experiments	
B^0 Mesogenesis	B_s^0 & B_d^0 oscillations	dark baryons	$A_{sl}^{s,d}$ $\mathrm{Br}(B^0 \to \mathcal{B}_{\mathrm{SM}} + X)$	LHCb B Factories, LHCb	**GE,** M. Escudero, A. Nelson **(2018)**
D^+ Mesogenesis	$D^\pm$ decays	dark leptons and dark baryons	A_{CP}^{D} Br_{D^+} $\mathrm{Br}(D^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU	**GE,** R. McGehee **(2020)**
B^+ Mesogenesis	$B^\pm$ decays	dark leptons and dark baryons	A_{CP}^{B} Br_{B^+} $\mathrm{Br}(B^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU	F. Elahi, **GE**, R. McGehee **(2021)**
B_c^+ Mesogenesis	$B_c^\pm$ decays	dark baryons	$A_{CP}^{B_c}$ $\mathrm{Br}_{B_c^+}$ $\mathrm{Br}(B^+ \to \mathcal{B}_{\mathrm{SM}}^+ + X)$	LHCb, FCC LHCb, FCC B Factories, LHCb	F. Elahi, **GE**, R. McGehee **(2021)**
Mesogenesis with a Morphing Mediator	B_s^0 & B_d^0 oscillations	dark baryons and dark phase transition	$A_{\mathrm{sl,\,SM}}^{\mathrm{s,d}}$ $\mathrm{Br}(B^0 \to \mathcal{B}_{\mathrm{SM}} + X)$ Gravitational Waves	LHCb B Factories, LHCb Pulsar Timing Arrays, CMB	**GE**, R. Houtz, S. Ipek, M. Ulloa, **(2024)**
Mesogenesis with Dark CPV	either B_d^0, B_s^0, $B^\pm$, $B_c^\pm$ decays	dark baryons and dark CP phase	$A_{\mathrm{CP}}^{\mathrm{dark}}$ $\mathrm{Br}(\mathcal{M} \to \mathcal{B}_{\mathrm{SM}} + X)$	EDMs, Flavor Observables B Factories, LHCb	**GE**, C. Kilic, S. Mathai **(2024 *targeted*)**

“Smoking Gun” Signal at *B*-Factories

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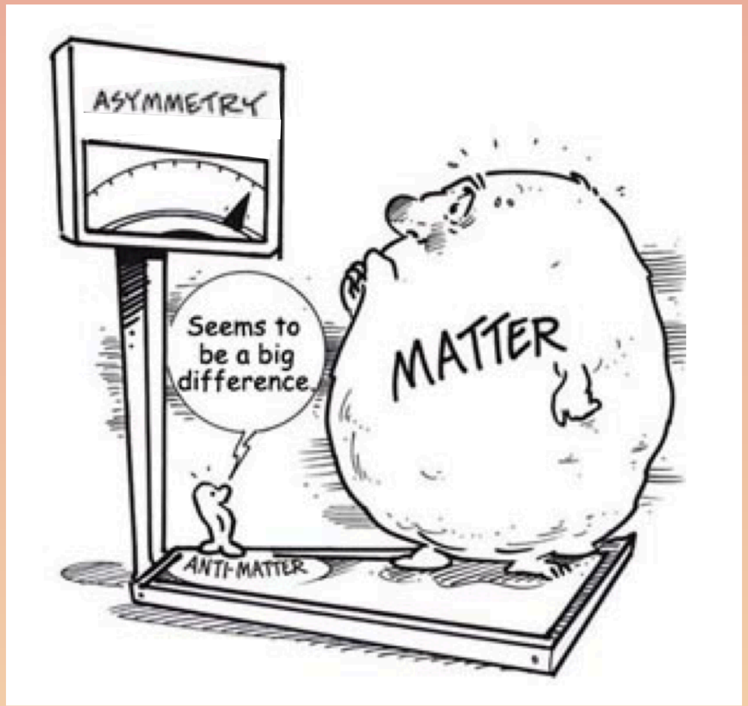
Outline

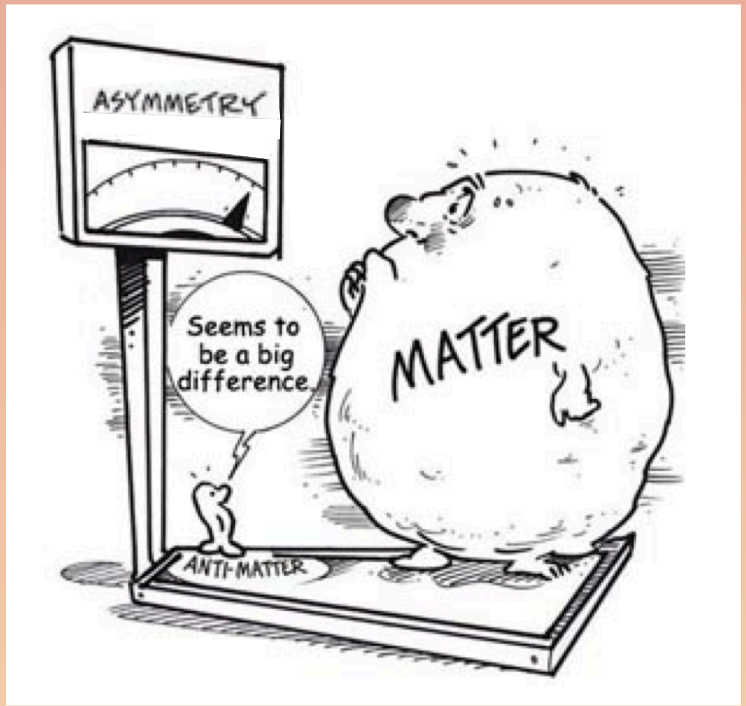


- Introduction and Neutral B Mesogenesis
- Signals!
- Bigger picture and the space of mechanisms.
- Complementarity of searches.

Based on: [**GE**, Rachel Houtz, Seyda Ipek, Martha Ulloa, Submitted to PRL, 2408.12647]
[J. Berger, **GE,** PRL, 2301.04165]
[**GE**, A. Guerrera, JHEP, 2211.10553]
[G. Alonso-Alvarez, **GE,** M. Escudero, B. Fornal, B. Grinstein, J.M. Camalich. PRD, 2111.12712]
[F. Elahi, **GE**, R. McGehee, PRD, 2109.09751]
[**GE,** R. McGehee, PRD, 2011.06115]
[G. Alonso-Alvarez, **GE**, M. Escudero, PRD, 2101.02706]
[G. Alonso-Alvarez, **GE,** E. Nelson, H. Xiao. JHEP, 1907.10612]
[**GE,** M. Escudero, A. E. Nelson, PRD, 1810.00880]

Upcoming: [**GE**, Can Kilic, Sanjay Mathai, Fall 2024 *(targeted)*]

Outline: Part 1



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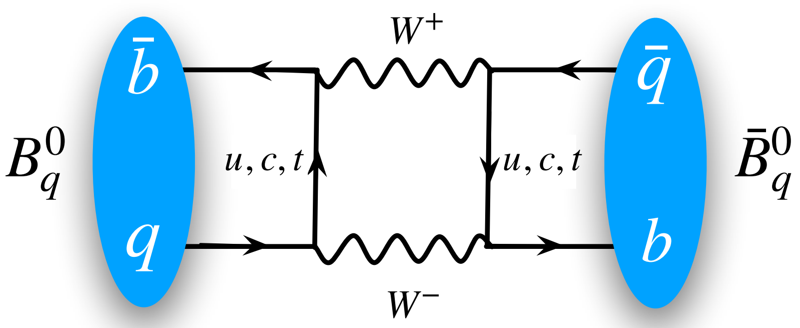
CP Violation in B Meson Oscillations

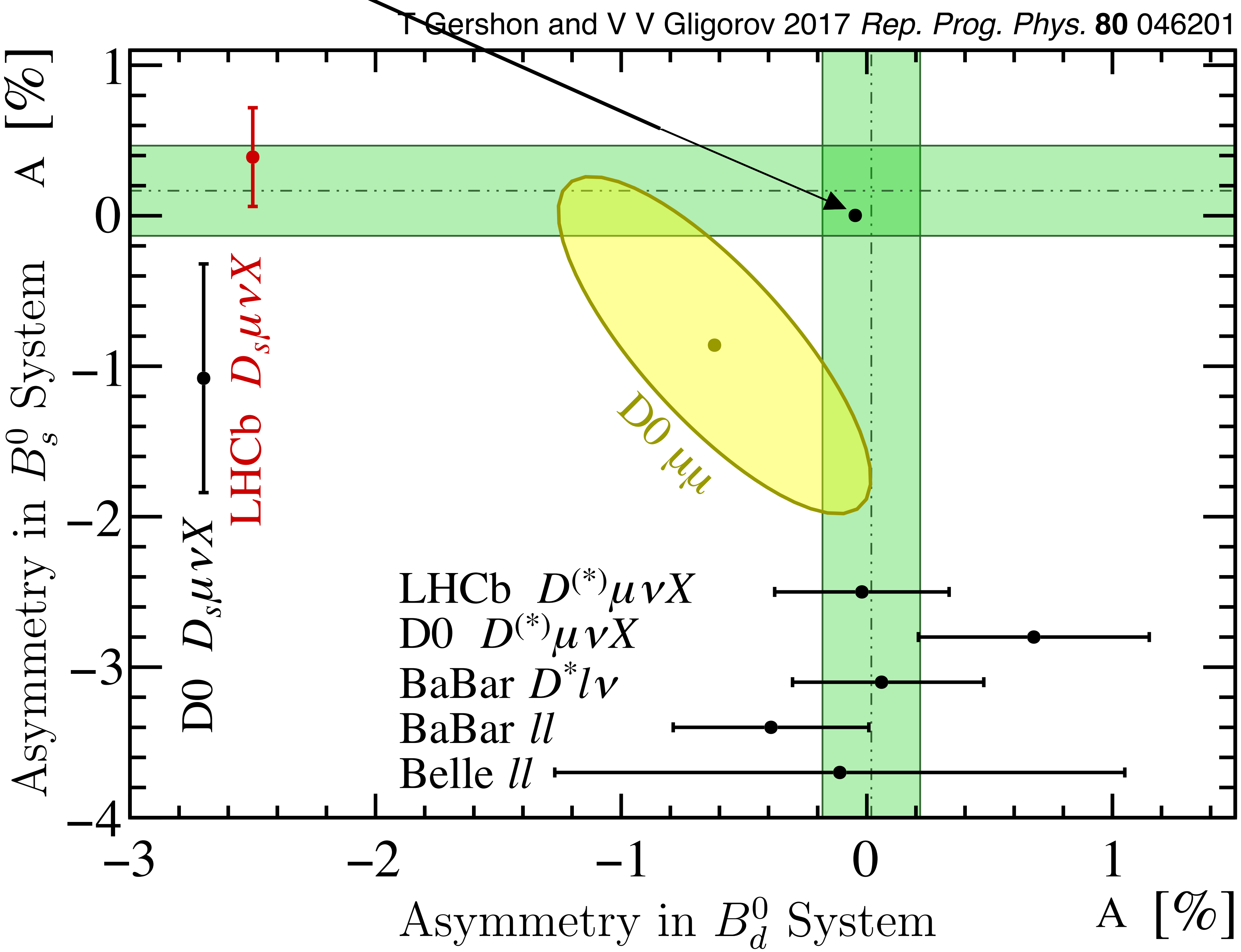
Standard Model

e.g..



$$A_{sl}^d|_{\rm SM} = (-4.7 \pm 0.4) \times 10^{-4}$$
$$A_{sl}^s|_{\rm SM} = (2.1 \pm 0.2) \times 10^{-5}$$

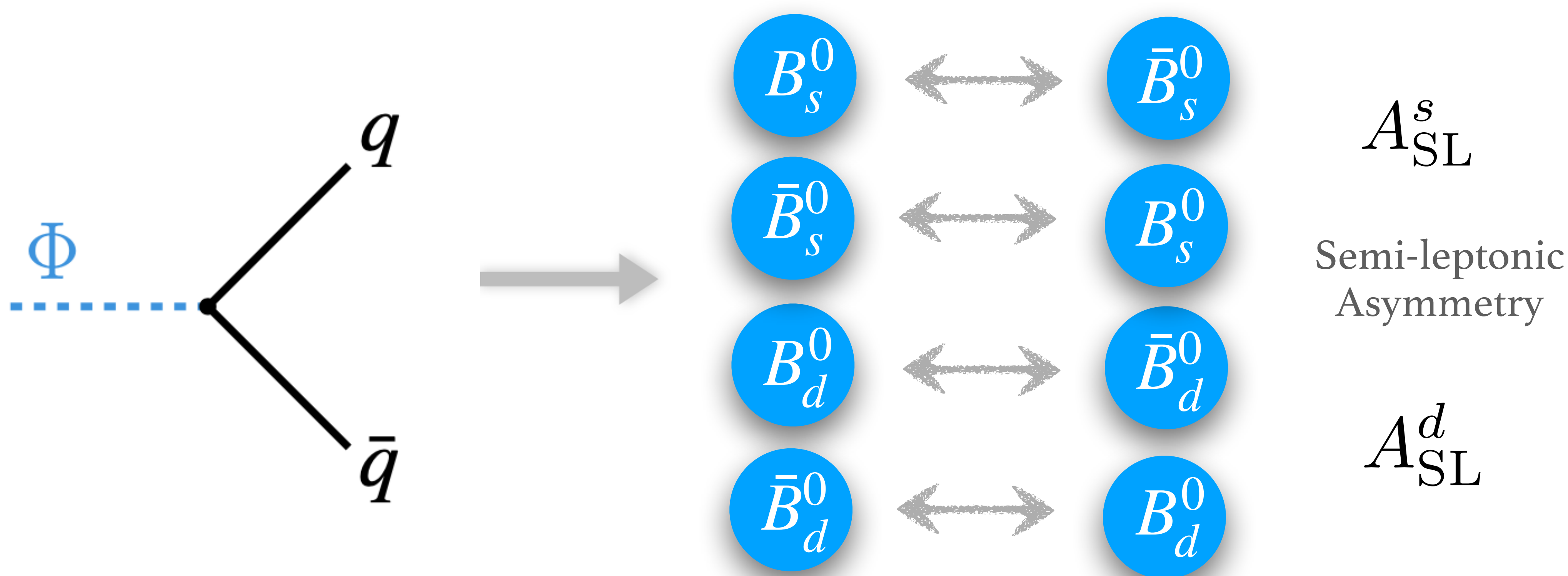
[Lenz, Tetlalmatzi, JHEP, (2020), 1912.07621]



Sakharov Conditions
Out of thermal equilibrium and CPV:

Late decay of an scalar field

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



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

Before BBN

After QCD phase transition

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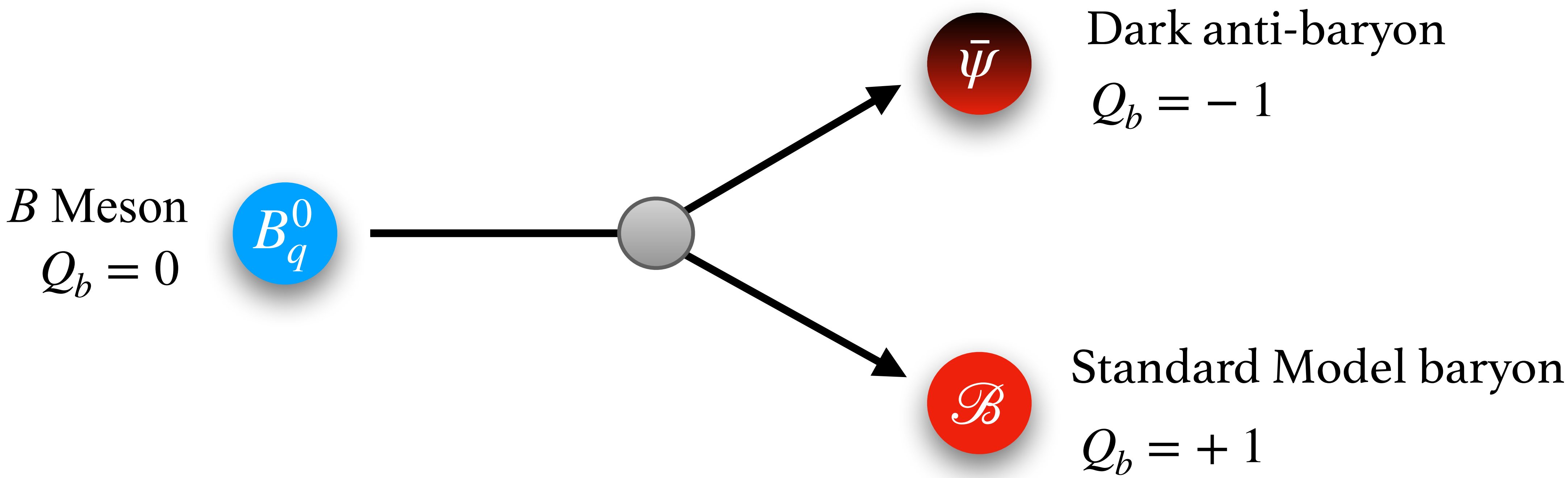
Neutral B Mesogenesis

Baryon Number Violation?

Hide baryon number in a dark sector
rather than violate it



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

Matter 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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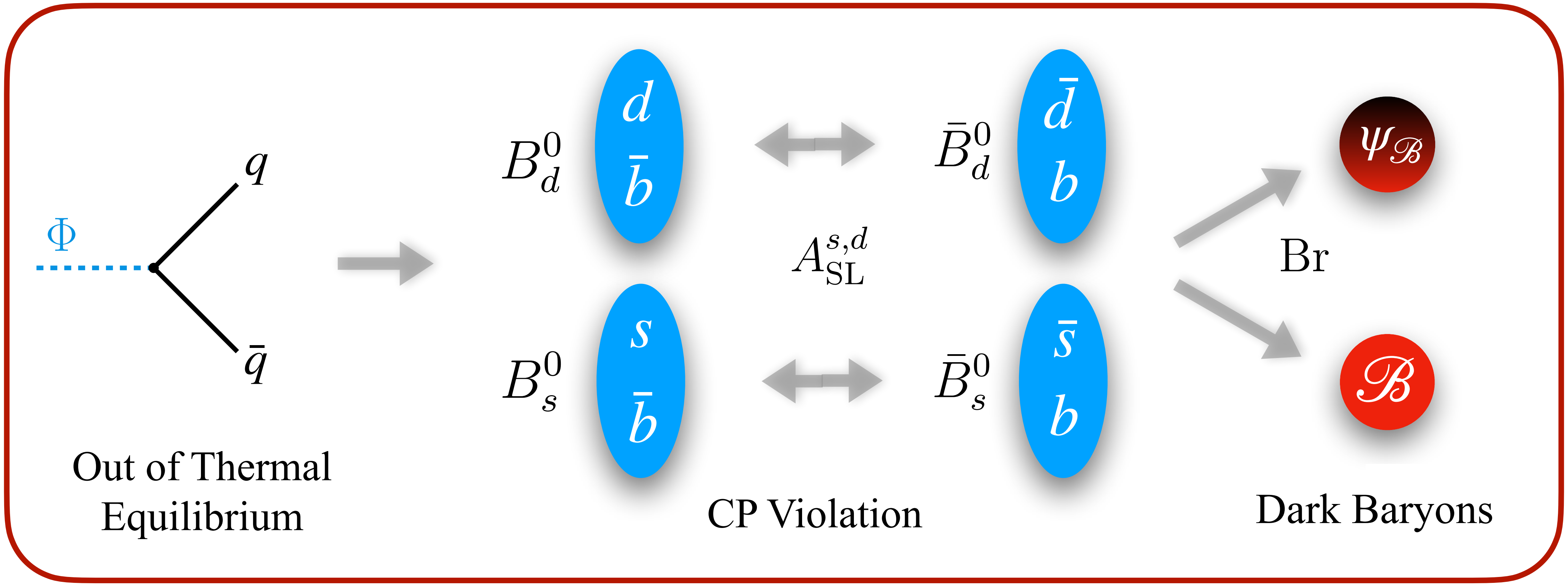
Baryon Asymmetry

Neutral B Mesogenesis [GE, M. Escudero, A. E. Nelson, PRD, 1810.00880]



Equal and opposite dark and visible baryon asymmetries generated.

$$Y_{\mathcal{B}} - Y_{\bar{\mathcal{B}}} = -\left(Y_{\psi} - Y_{\bar{\psi}}\right) \propto A_{SL}^{s,d} \times \mathrm{Br}$$

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New Particles

	Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass	
Colored Mediator:	$\mathcal{Y}$	0	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\text{TeV})$	*Could be a squark*
Dark Baryon:	$\psi_\mathcal{B}$	$1/2$	0	-1	$+1$	$\mathcal{O}(\text{GeV})$	*Kinematics forbid proton decay*

Allowed by all the symmetries: $$\mathcal{L}_\mathcal{Y} = -\sum_{i,j} y_{u_i d_j} \mathcal{Y}^\star \bar{u}_{iR} d^c_{jR} - \sum_k y_{\psi d_k} \bar{\psi}_\mathcal{B} \mathcal{Y} d^c_{kR} + \text{h.c.}$$

Effective four fermion operator at MeV scales: $$\mathcal{O}_{d_k,u_i d_j} = \mathcal{C}_{d_k,u_i d_j} \epsilon_{\alpha\beta\gamma} (\bar{\psi}_\mathcal{B} d^\alpha_k)(\bar{d}^{c\beta}_j u^\gamma_i)$$
$$\mathcal{C}_{d_k,u_i d_j} \equiv y_{\psi d_k} y_{u_i d_j} / M^2_\mathcal{Y}$$

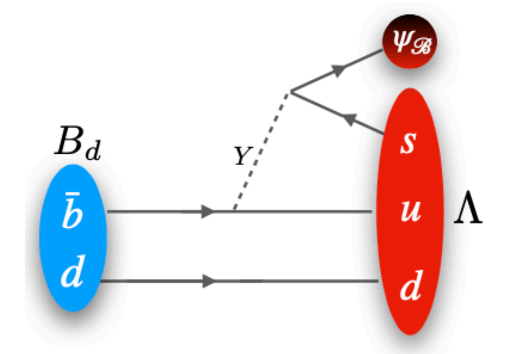
This interaction *does not* change baryon number

SUSY UV completion: [G. Alonso-Alvarez, **GE**, A. E. Nelson, H. Xiao, JHEP, 1907.10612]

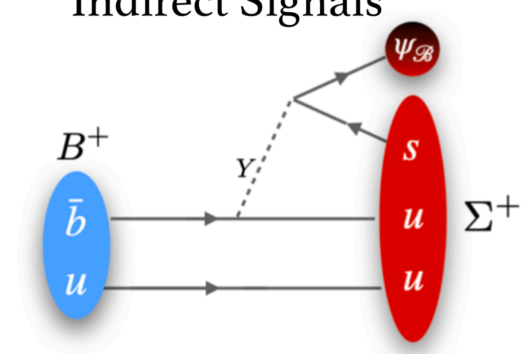
New Decays

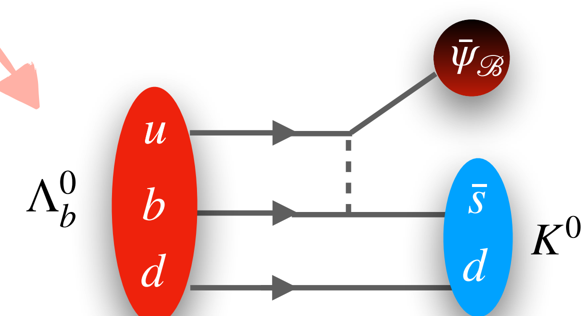
Operator/Decay	Initial State	Final state
$\mathcal{O} = \psi\, b\, u\, d$ $\bar{b} \to \psi\, u\, d$	B_d	$\psi + n\,(udd)$
	B_s	$\psi + \Lambda\,(uds)$
	B^+	$\psi + p\,(duu)$
	Λ_b	$\bar{\psi} + \pi^0$
$\mathcal{O} = \psi\, b\, u\, s$ $\bar{b} \to \psi\, u\, s$	B_d	$\psi + \Lambda\,(usd)$
	B_s	$\psi + \Xi^0\,(uss)$
	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 the baryon asymmetry



Indirect Signals





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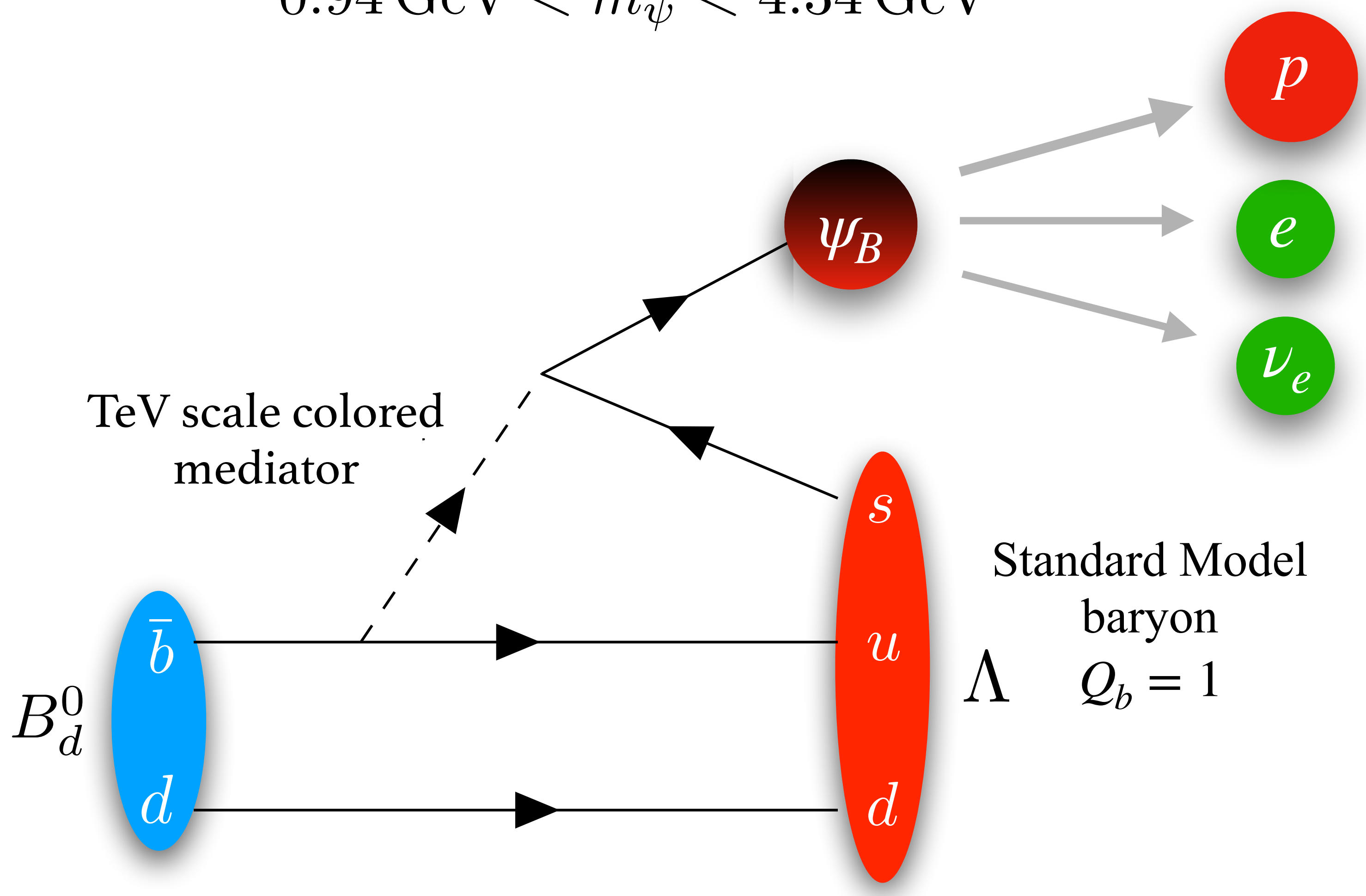
Dark Matter?

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



The dark baryon is unstable and will decay to baryonic matter, washing out the asymmetry. ψ_B *cannot be the dark matter.*

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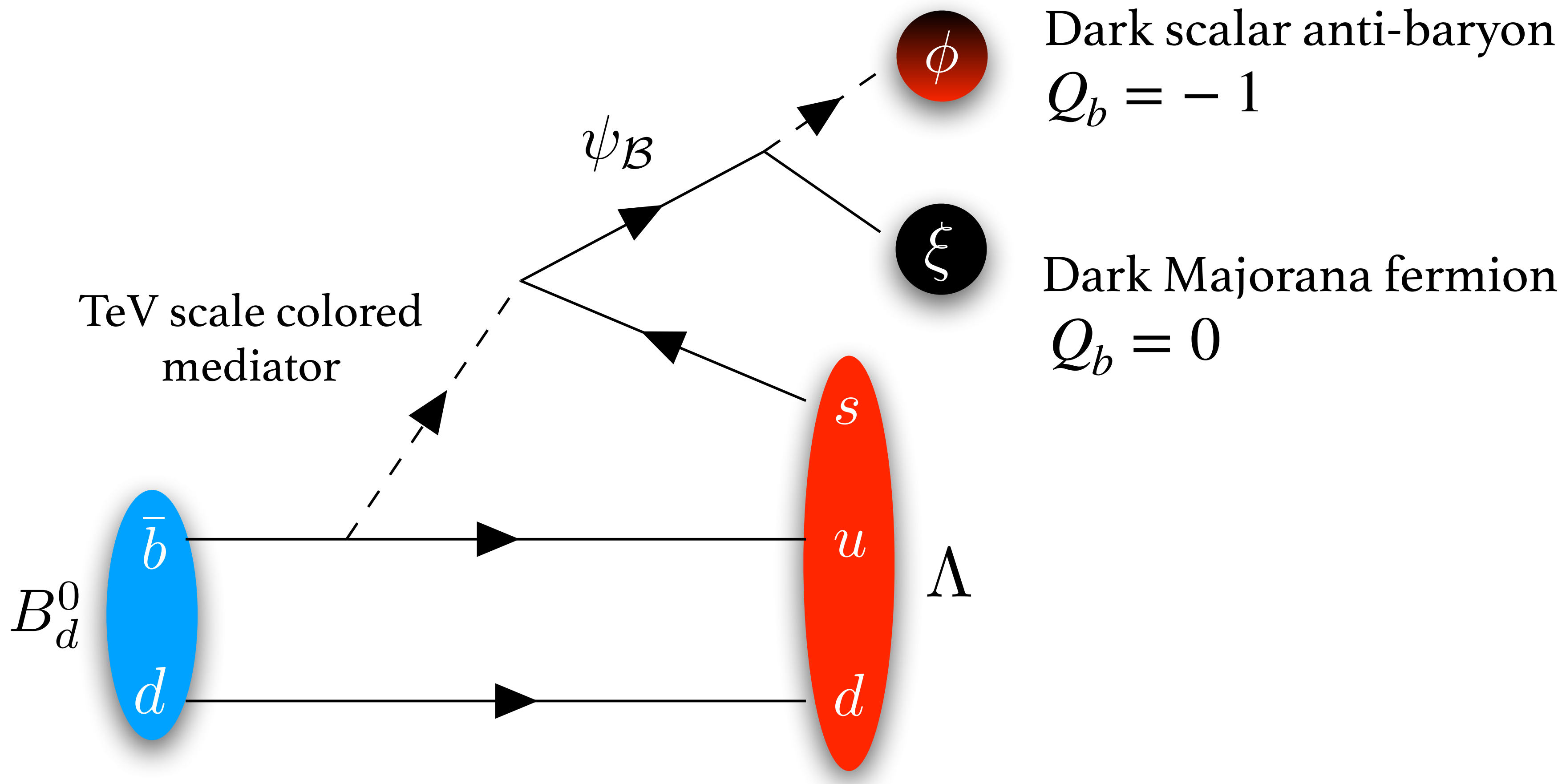
Two-Component Dark Matter

Dark fermion must quickly decay within the dark sector $\mathcal{L}_d \supset y_d \bar{\psi}_{\mathcal{B}} \xi \phi$



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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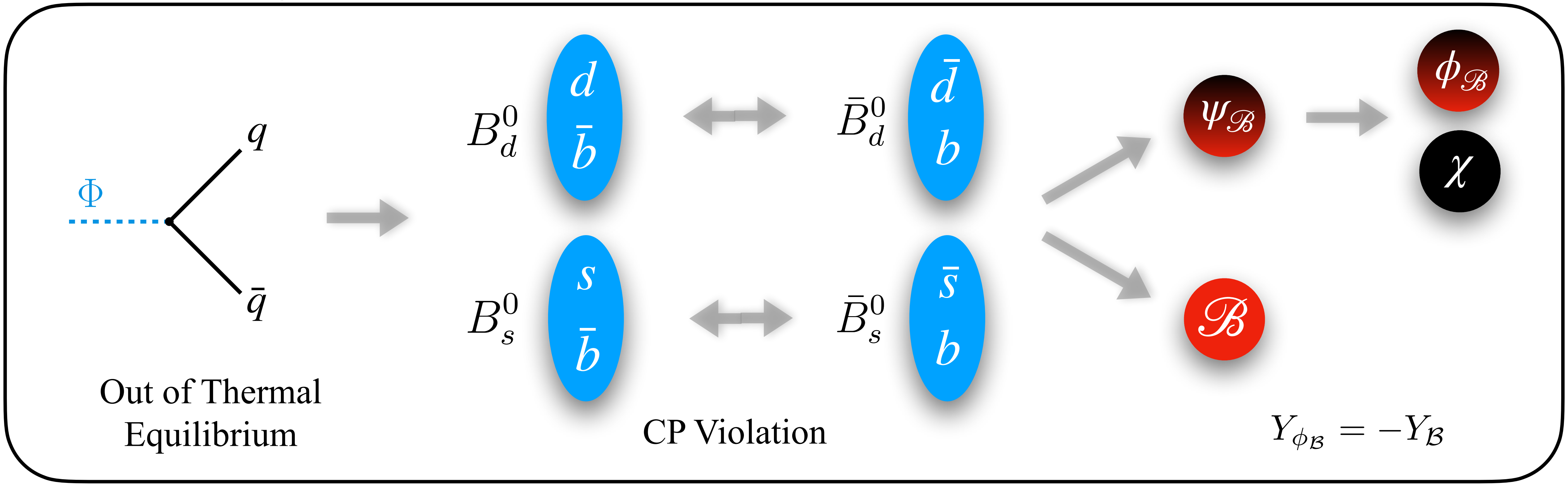
Neutral B Mesogenesis

[GE, M. Escudero, A. E. Nelson, PRD, 1810.00880]

Baryogenesis and Dark Matter from B Mesons

B^0 Mesogenesis



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Boltzmann Equations

Scalar, Radiation, Hubble:

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

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

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

Dark Matter:

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

Baryon Asymmetry:

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

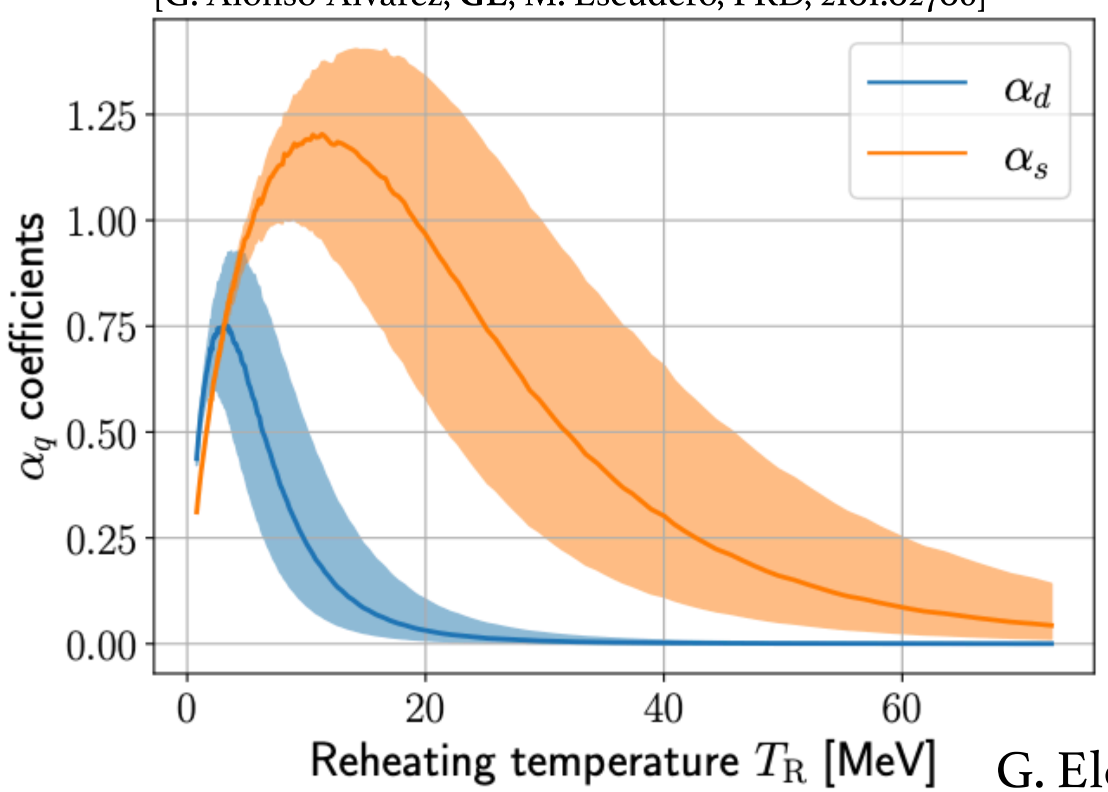
$$Y_\mathcal{B} \simeq 5\times 10^{-5} \sum_{i=d,s} \left[{\rm Br}\left(B_i^0 \to \bar\psi_\mathcal{B}\,\mathcal{B}_{\rm SM}\right) A_{sl}^i\right]\alpha_i(T_{\rm R})$$

(product of two experimental observables)

Prediction: to generated the observed baryon asymmetry

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

[G. Alonso-Alvarez, **GE**, M. Escudero, PRD, 2101.02706]



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Signals of Neutral *B*-Mesogenesis

[A. Alonso-Alvarez, **GE**, M. Escudero, PRD, 2101.02706]

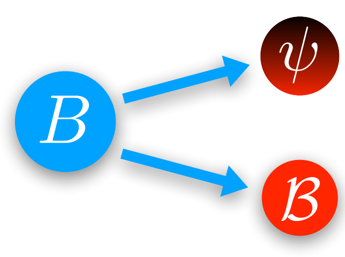
Collider Signals of Baryogenesis and Dark Matter from B Mesons (*B-Mesogenesis*)

Direct Signals

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

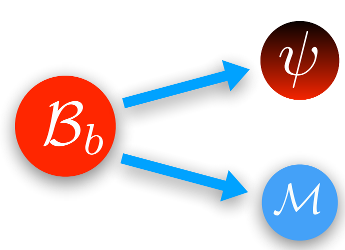
Belle II
LHCb
ATLAS
CMS

New B meson decay:



BaBar
Belle
Belle II
LHCb

New b-Baryon decay:



LHCb?
ATLAS??
CMS??

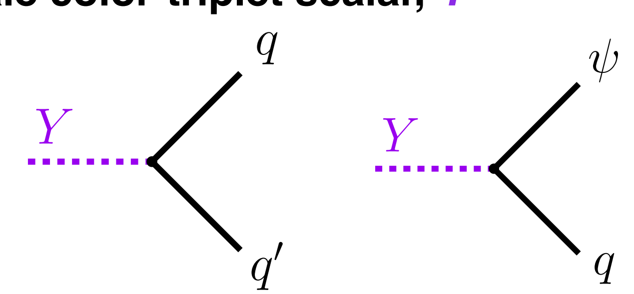
Indirect Signals

B^0 meson CPV and oscillation observables:

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

LHCb
Belle II
ATLAS
CMS

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



ATLAS
CMS

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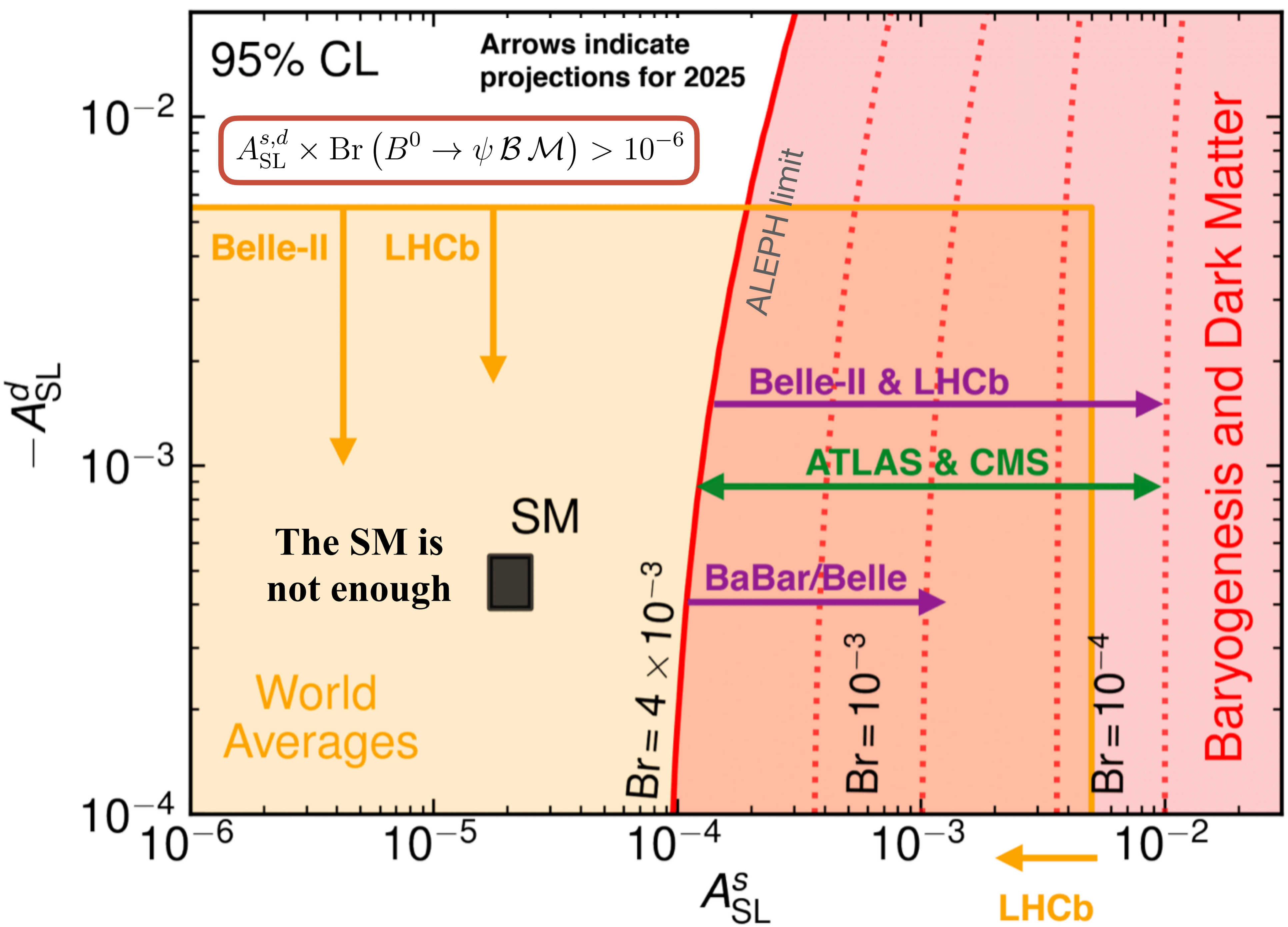
Neutral B Mesogenesis Discovery Potential

[A. Alonso-Alvarez, **GE**, M. Escudero, PRD 2101.02706]



Signals

- CP violation
- New b decays
- High pT jets and missing energy

$$A_{sl}^{d}|_{\rm SM} = (-4.7 \pm 0.4) \times 10^{-4}$$
$$A_{sl}^{s}|_{\rm SM} = (2.1 \pm 0.2) \times 10^{-5}$$

Collider Searches for B-Mesogensis

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

Operator/Decay	Initial State	Final state
$\mathcal{O} = \psi\, b\, u\, d$ $\bar{b} \to \psi\, u\, d$	B_d	$\psi + n\,(udd)$
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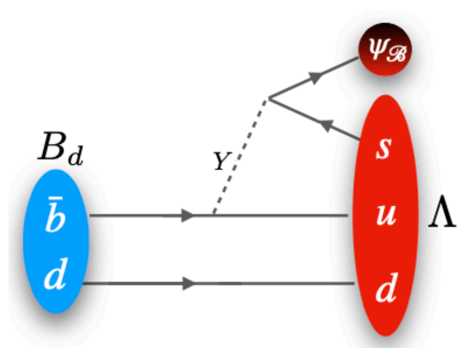
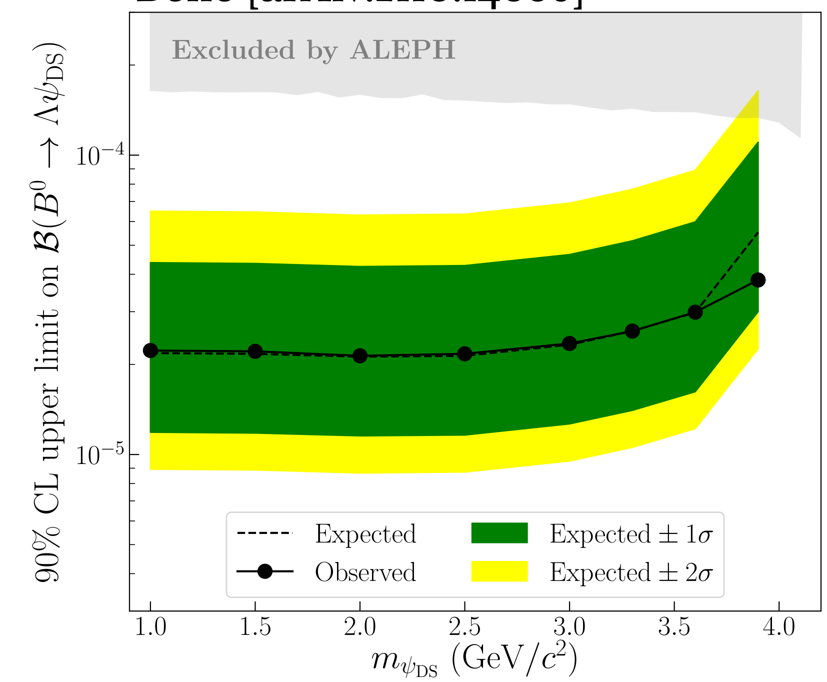
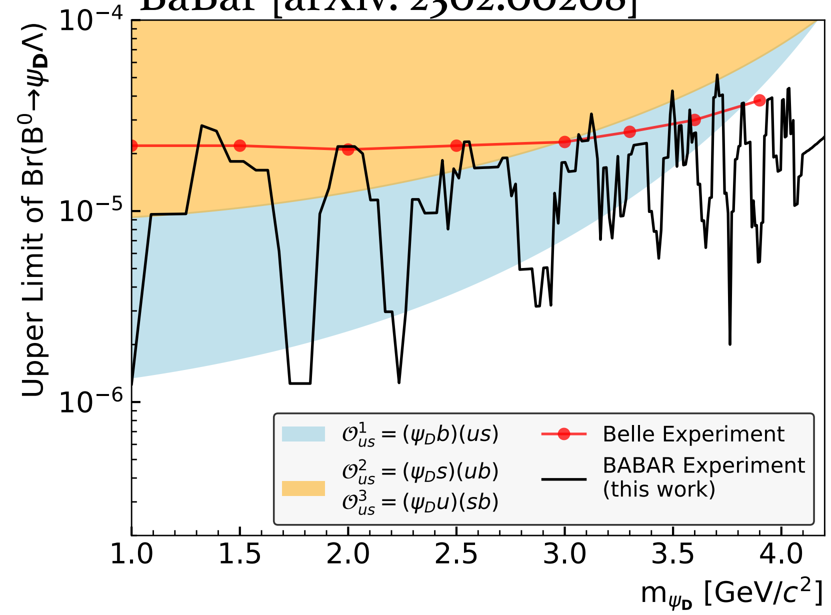


Belle [arXiv:2110.14086]



BaBar [arXiv: 2302.00208]



Designated search developed for LHCb [2106.12870]. On-going analysis.

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	B_s	$\psi + \Omega_c\,(css)$
	B^+	$\psi + \Xi_c^+\,(csu)$
	Λ_b	$\bar{\psi} + D^- + K^+$

Three other channels through which neutral B Mesogenesis can proceed. Look here!

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Collider Searches for *B*-Mesogensis

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

Should Belle improve the sensitivity?
Can we do baryogenesis with with
$\mathrm{Br} < 10^{-5}$?

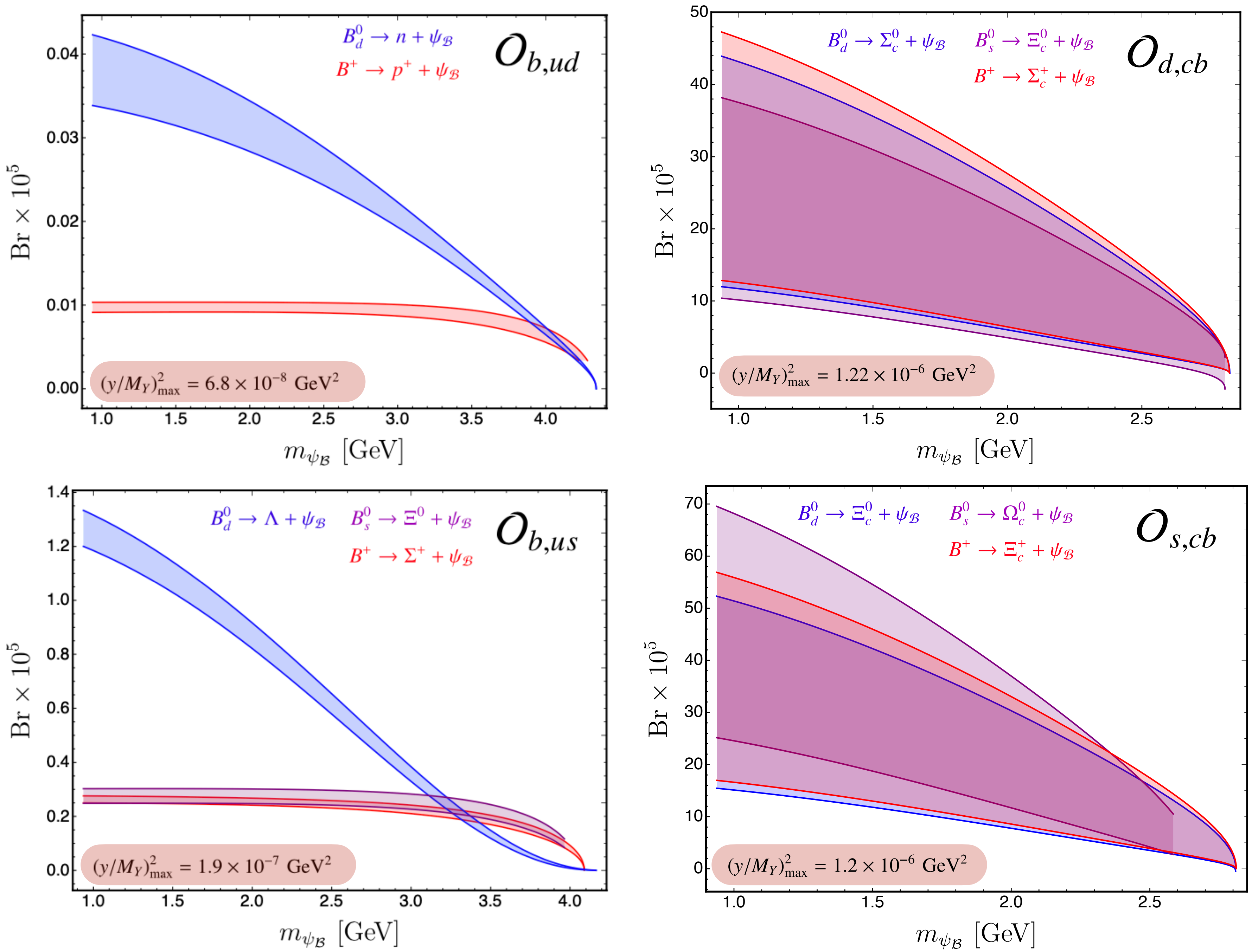
Yes!

Three other channels through which neutral B Mesogenesis can proceed. Look here!

G. Elor

Aside: Theory Support

Experimental input: exclusive rates



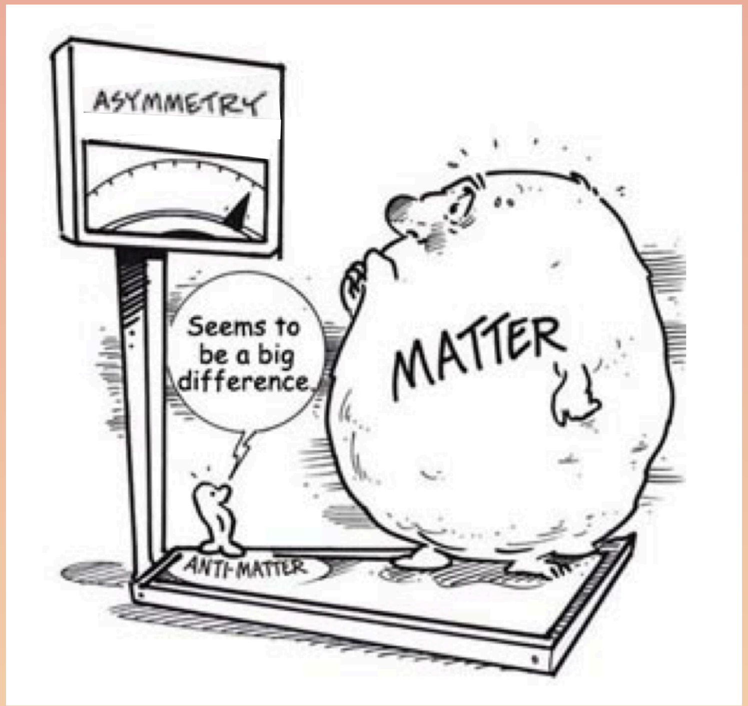
Use QCD techniques to compute meson to baryon decay rates in Mesogenesis [**GE**, A. Guerrera. JHEP, arXiv:2211.10553]

Limit on the coupling from re-casting LHC searches for squarks

[A. Alonso-Alvarez, **GE**, M. Escudero, PRD, arXiv:2101.02706]

Can theorists do more to help experimentalists? - Get in touch!

Outline: Part 2



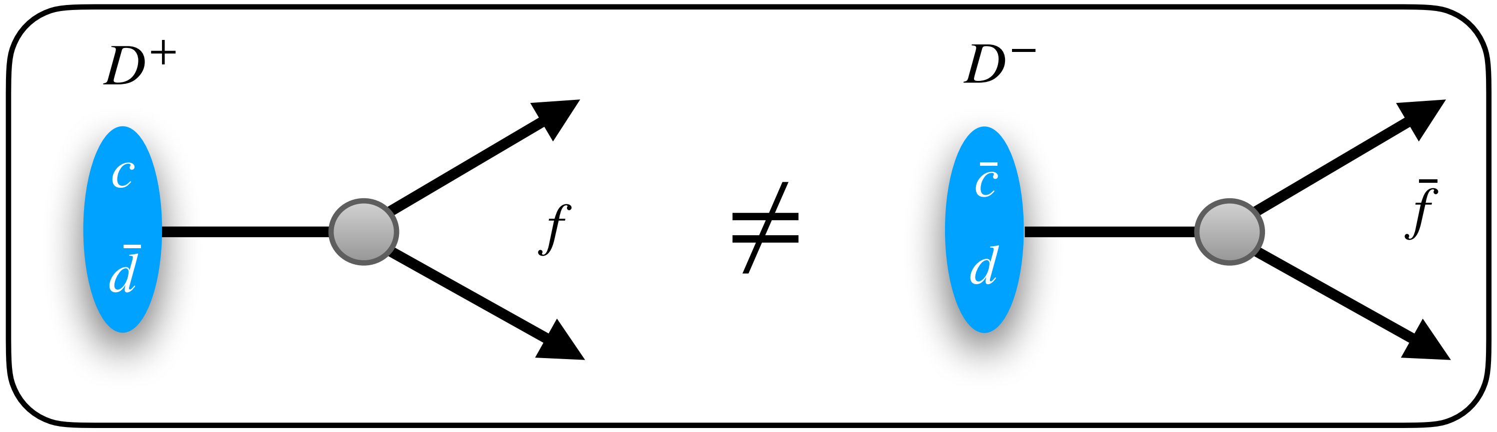
- Introduction and Neutral B Mesogenesis
- Signals!
- Bigger picture and the space of mechanisms.
- Complementarity of searches.

Based on: [**GE**, Rachel Houtz, Seyda Ipek, Martha Ulloa, Submitted to PRL, 2408.12647],
[J. Berger, **GE,** PRL, 2301.04165]
[**GE**, A. Guerrera, JHEP, 2211.10553]
[G. Alonso-Alvarez, **GE,** M. Escudero, B. Fornal, B. Grinstein, J.M. Camalich. PRD, 2111.12712]
[F. Elahi, **GE**, R. McGehee, PRD, 2109.09751]
[**GE,** R. McGehee, PRD, 2011.06115]
[G. Alonso-Alvarez, **GE**, M. Escudero, PRD, 2101.02706]
[G. Alonso-Alvarez, **GE,** E. Nelson, H. Xiao. JHEP, 1907.10612]
[**GE,** M. Escudero, A. E. Nelson, PRD, 1810.00880]

Upcoming: [**GE**, Can Kilic, Sanjay Mathai, Fall 2024 *(targeted)*]

Why Neutral *B* Mesons?

CPV in charged *D* decays:



Observable:

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

Not a small number. We want to explain: ←

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

Particle Data Group:

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
$\pi^+\eta$	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

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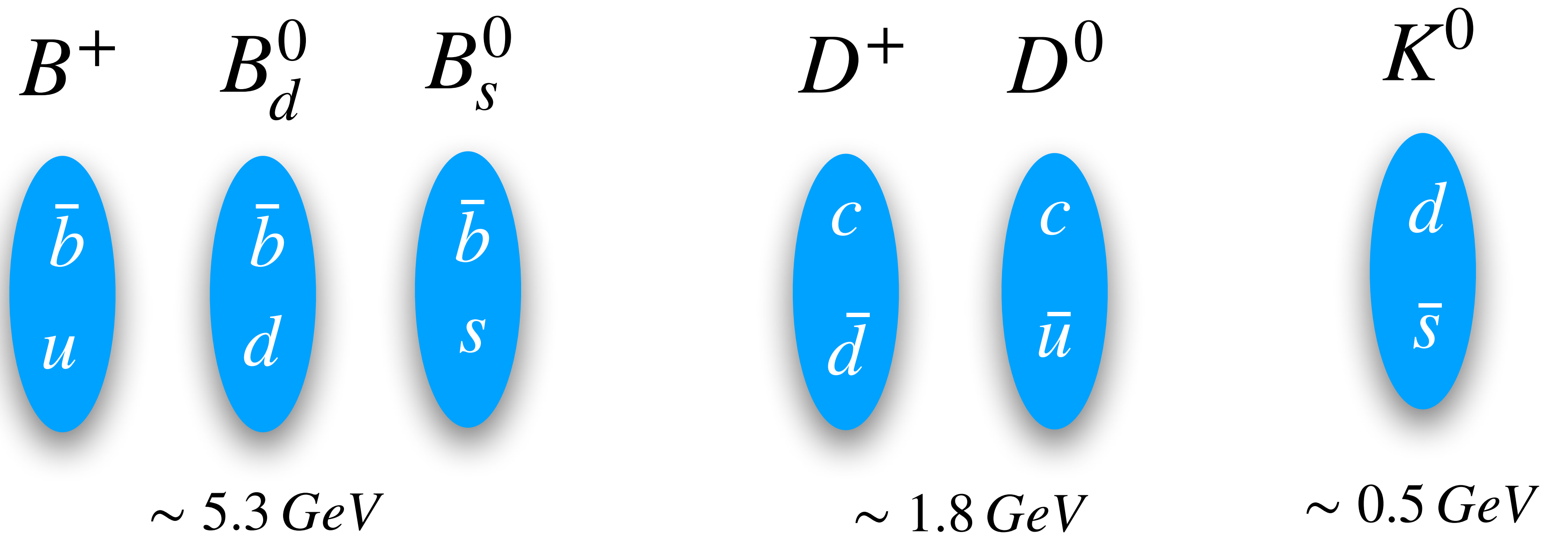
Why Neutral B Mesons?



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

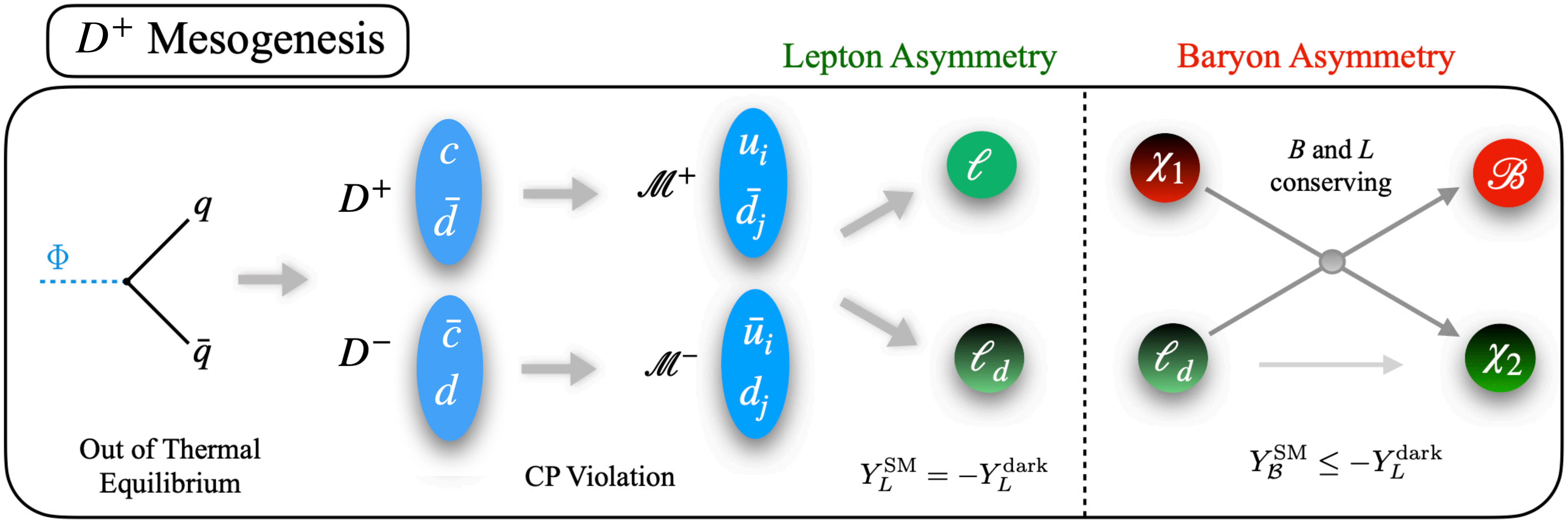
Kinematics: Dark baryons must be GeV scale. Only B mesons are heavy enough to decay into GeV scale.

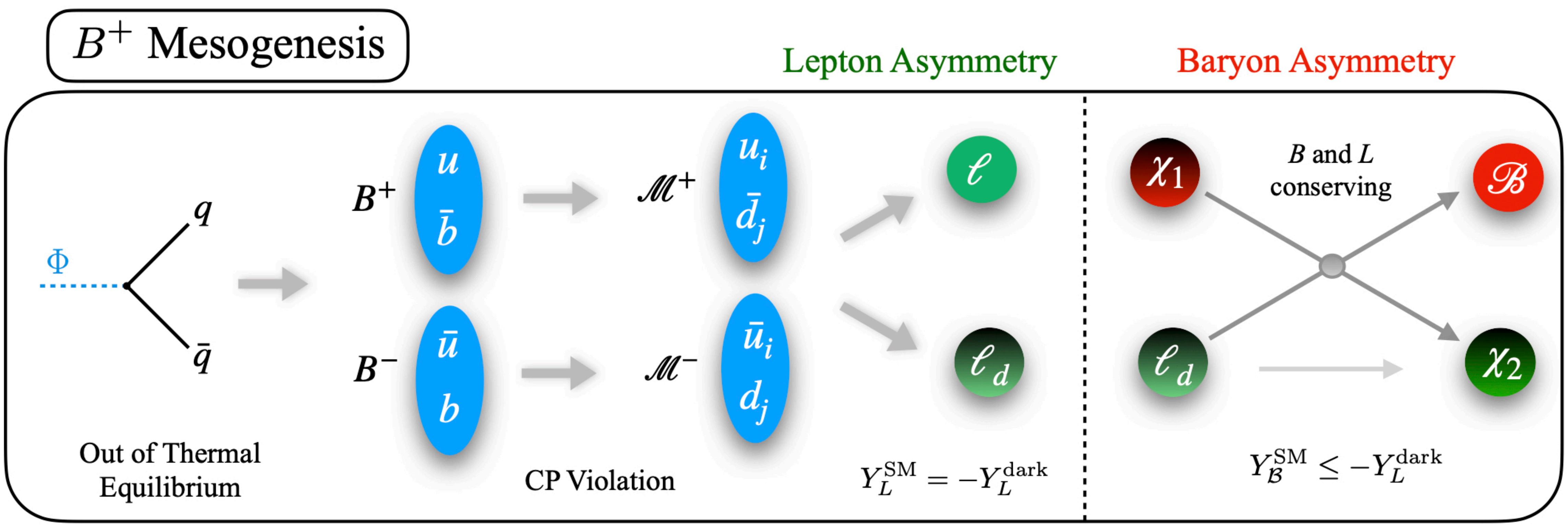
First generate a *lepton asymmetry*

G. Elor

Charged *D* and *B* Mesogenesis

[**GE**, R. McGehee, PRD, 2011.06115] and [F. Elahi, **GE**, R. McGehee, PRD, 2109.09751]





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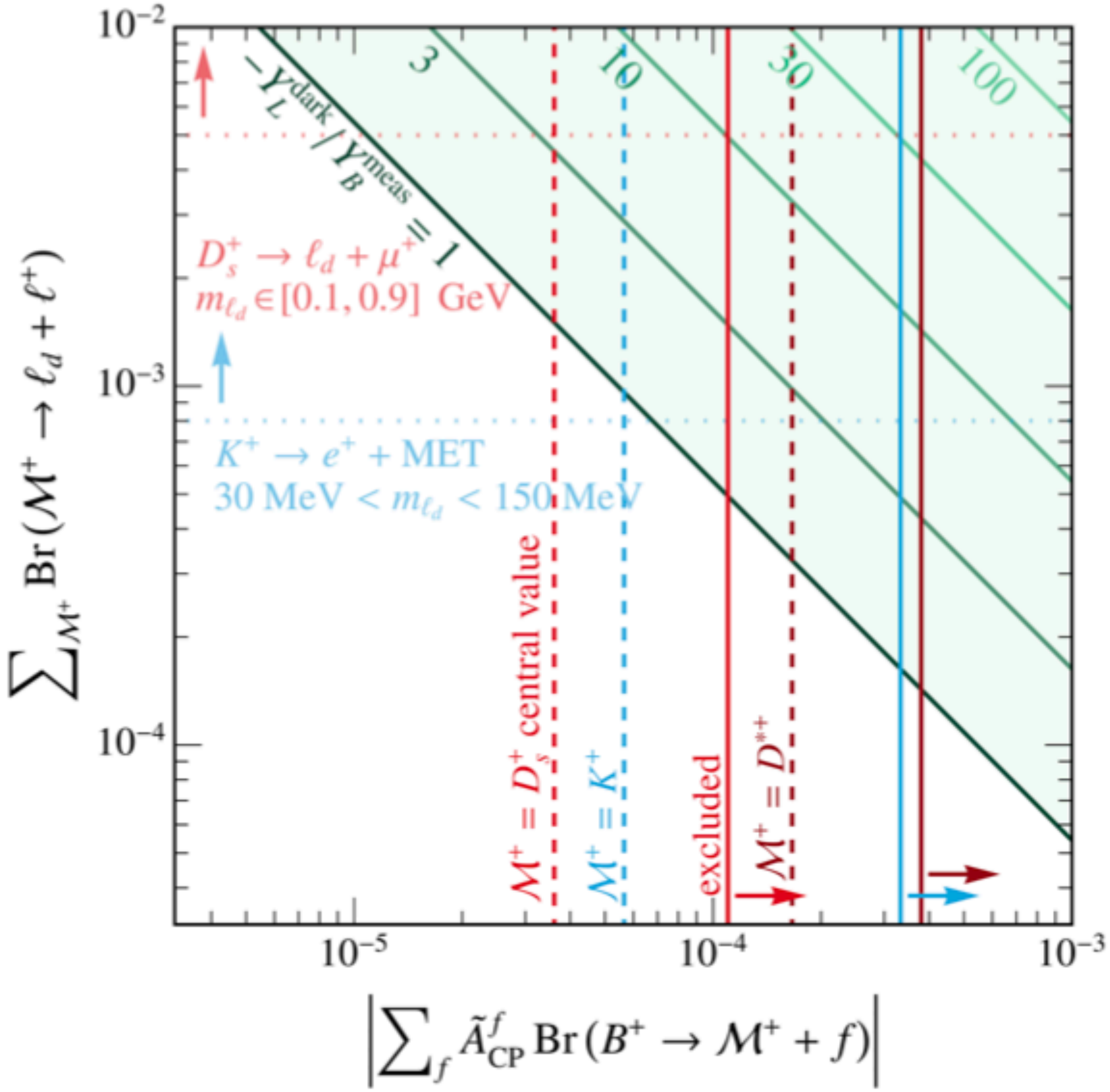
B^+ Mesogenesis

[**GE,** R. McGehee, PRD, 2011.06115] and [F. Elahi, **GE**, R. McGehee, PRD, 2109.09751]

Peak Searches



B-factories observables

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The Space of Mesogensis Mechanisms

Mechansim	CPV	Dark Sector	Observables	Relevant Experiments	
B^0 Mesogenesis	B_s^0 & B_d^0 oscillations	dark baryons	$A_{sl}^{s,d}$ $\text{Br}(B^0 \to \mathcal{B}_{\text{SM}} + X)$	LHCb B Factories, LHCb	**GE**, M. Escudero, A. Nelson **(2018)**
D^+ Mesogenesis	$D^\pm$ decays	dark leptons and dark baryons	A_{CP}^D Br_{D+} $\text{Br}(D^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU	**GE**, R. McGehee **(2020)**
B^+ Mesogenesis	$B^\pm$ decays	dark leptons and dark baryons	A_{CP}^B Br_{B+} $\text{Br}(B^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU	F. Elahi, **GE**, R. McGehee **(2021)**
B_c^+ Mesogenesis	$B_c^\pm$ decays	dark baryons	$A_{CP}^{B_c}$ $\text{Br}_{B_c^+}$ $\text{Br}(B^+ \to \mathcal{B}_{\text{SM}}^+ + X)$	LHCb, FCC LHCb, FCC B Factories, LHCb	F. Elahi, **GE**, R. McGehee **(2021)**
Mesogenesis with a Morphing Mediator	B_s^0 & B_d^0 oscillations	dark baryons and dark phase transition	$A_{\text{sl, SM}}^{\text{s,d}}$ $\text{Br}(B^0 \to \mathcal{B}_{\text{SM}} + X)$ Gravitational Waves	LHCb B Factories, LHCb Pulsar Timing Arrays, CMB	**GE**, R. Houtz, S. Ipek, M. Ulloa, **(2024)**
Mesogenesis with Dark CPV	either B_d^0, B_s^0, $B^\pm$, $B_c^\pm$ decays	dark baryons and dark CP phase	$A_{\text{CP}}^{\text{dark}}$ $\text{Br}(\mathcal{M} \to \mathcal{B}_{\text{SM}} + X)$	EDMs, Flavor Observables B Factories, LHCb	**GE**, C. Kilic, S. Mathai **(2024 *targeted*)**

Common to all mechanisms proposed to date:

colored mediator $\mathcal{L}_{\mathcal{Y}} = -\sum_{i,j} y_{u_i d_j} \mathcal{Y}^\star \bar{u}_{iR} d_{jR}^c - \sum_k y_{\psi d_k} \bar{\psi}_{\mathcal{B}} \mathcal{Y} d_{kR}^c + \text{h.c.}$ + dark sector

One mechanisms direct signal is another mechanisms indirect signal

G. Elor

The Space of Mesogensis Mechanisms

Mechansim	CPV	Dark Sector	Observables	Relevant Experiments	
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B_c^+ Mesogenesis	$B_c^\pm$ decays	dark baryons	$A_{CP}^{B_c}$ $\mathrm{Br}_{B_c^+}$ $\mathrm{Br}(B^+ \to \mathcal{B}_{\rm SM}^+ + X)$	LHCb, FCC LHCb, FCC B Factories, LHCb	F. Elahi, **GE,** R. McGehee **(2021)**
Mesogenesis with a Morphing Mediator	B_s^0 & B_d^0 oscillations	dark baryons and dark phase transition	$A_{\rm sl,\,SM}^{\rm s,d}$ $\mathrm{Br}(B^0 \to \mathcal{B}_{\rm SM} + X)$ Gravitational Waves	LHCb B Factories, LHCb Pulsar Timing Arrays, CMB	**GE,** R. Houtz, S. Ipek, M. Ulloa, **(2024)**
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Baryogenesis with only the SM CP Violation

Common to all mechanisms proposed to date:

colored mediator $$\mathcal{L}_{\mathcal{Y}} = -\sum_{i,j} y_{u_i d_j} \mathcal{Y}^\star \bar{u}_{iR} d_{jR}^c - \sum_k y_{\psi d_k} \bar{\psi}_{\mathcal{B}} \mathcal{Y} d_{kR}^c + \text{h.c.}$$ + dark sector

One mechanisms direct signal is another mechanisms indirect signal

G. Elor

Mesogensis with a Morphing Mediator

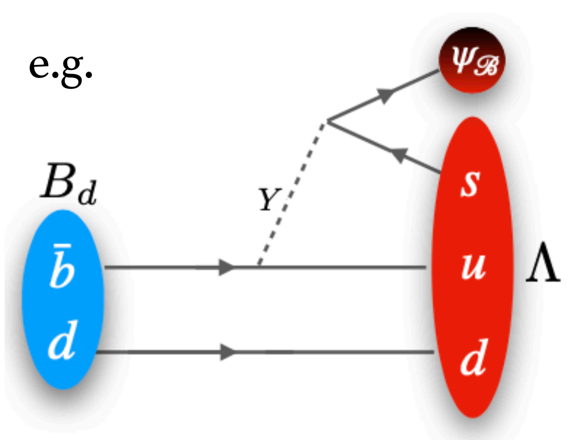
[**GE**, Rachel Houtz, Seyda Ipek, Martha Ulloa, Submitted to PRL, 2408.12647]

- Baryon asymmetry produced through decays mediated by a heavy colored particle:

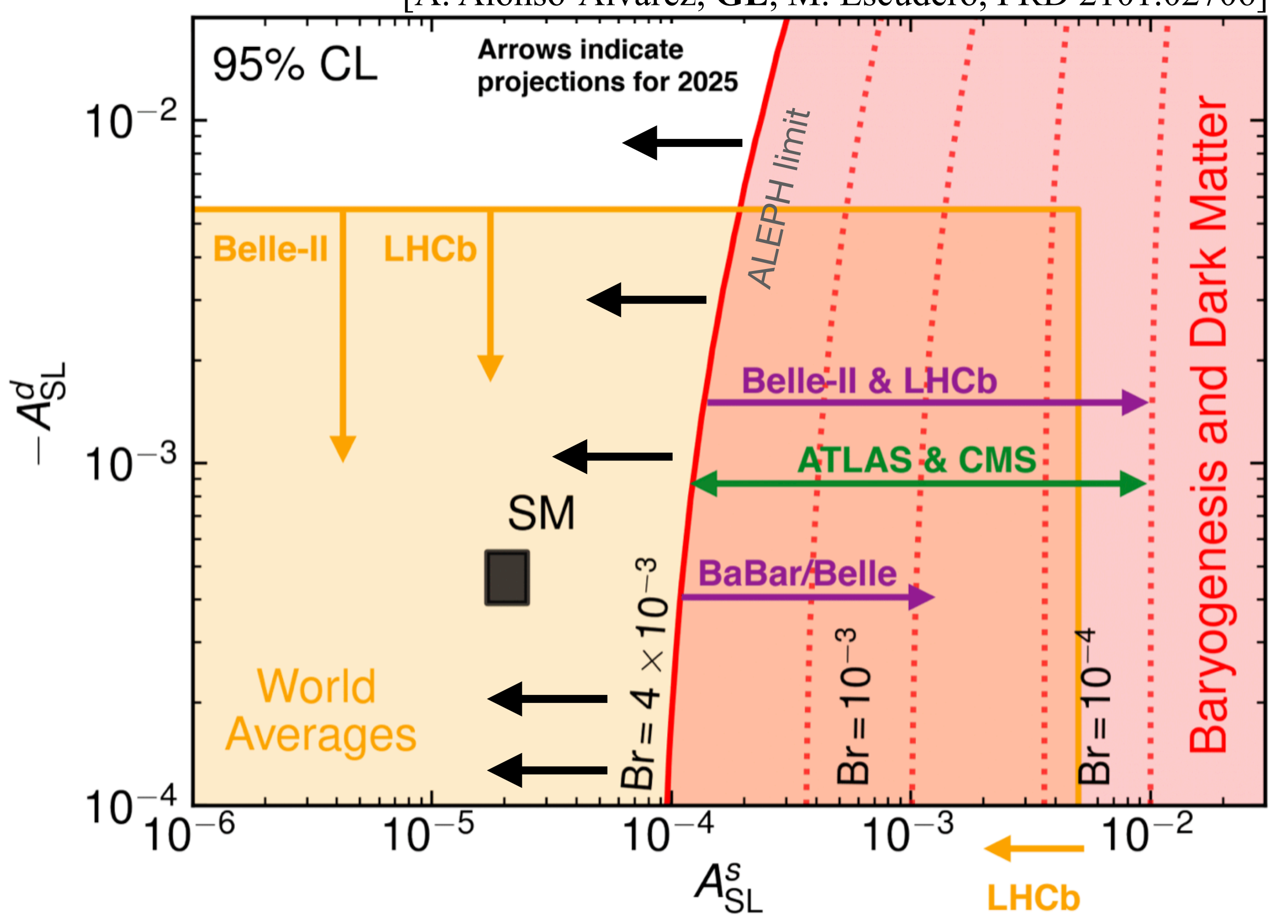
$$\mathcal{O}_{d_k,u_id_j} = \mathcal{C}_{d_k,u_id_j}\epsilon_{\alpha\beta\gamma}(\bar{\psi}_{\mathcal{B}}d_k^{\alpha})(\bar{d}_j^{c\beta}u_i^{\gamma})$$
$$\mathcal{C}_{d_k,u_id_j} \equiv y_{\psi d_k}y_{u_id_j}/M_{\mathcal{Y}}^2$$

- Collider constraints require mediator Y to have a **TeV scale mass**
- Perturbativity: $y_{\psi d_k},\ y_{u_id_j} \lesssim 4\pi$
- Branching fraction: $\text{Br} \propto 1/M_{\mathcal{Y}}^4$

e.g.



[A. Alonso-Alvarez, **GE**, M. Escudero, PRD 2101.02706]

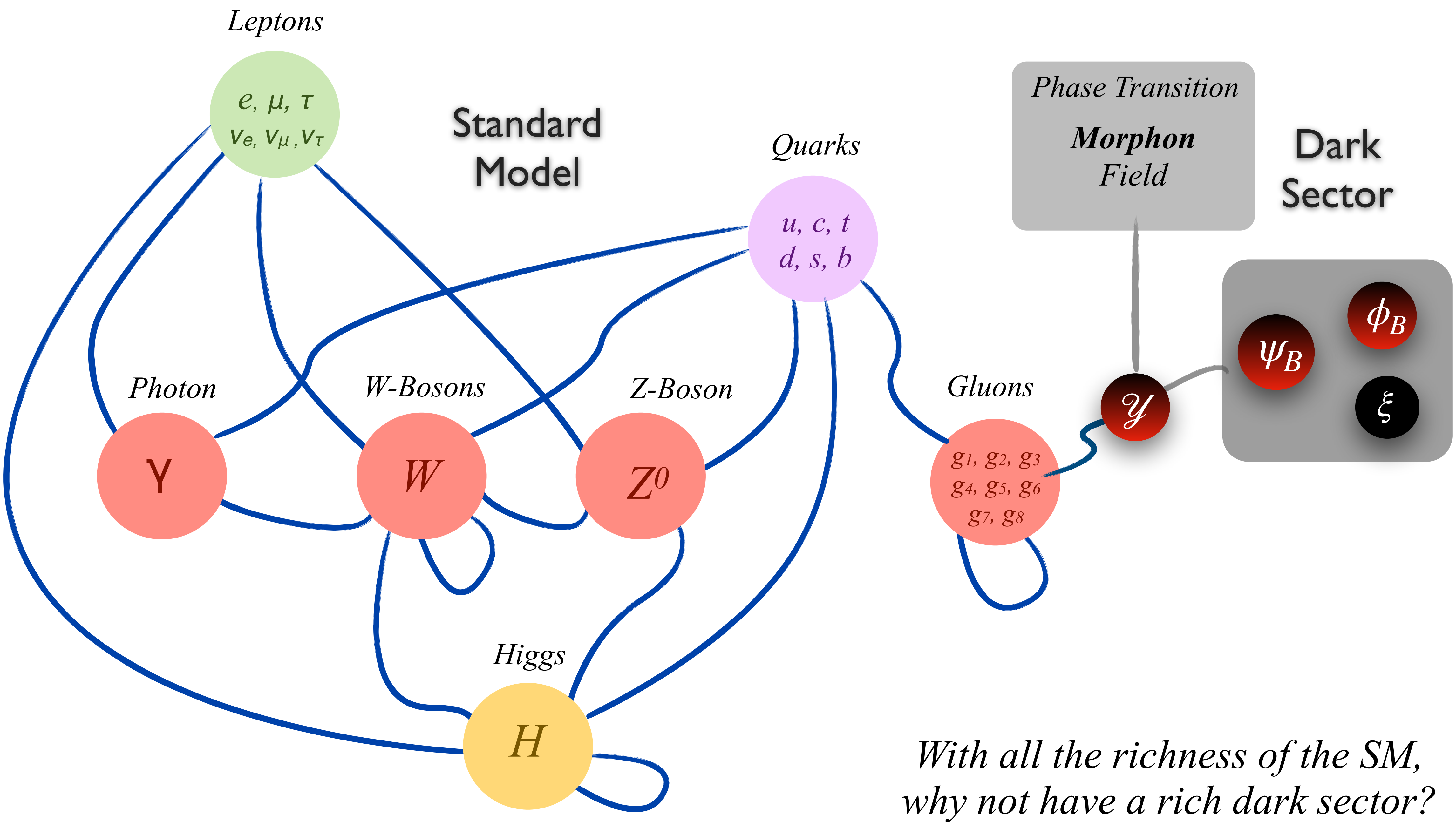


What if the mediator was lighter during the era of baryon production than it is today?

Elor

Morphing the Mediator

[**GE**, Rachel Houtz, Seyda Ipek, Martha Ulloa, Submitted to PRL, 2408.12647]



With all the richness of the SM, why not have a rich dark sector?

Morphing the Mediator

[**GE**, Rachel Houtz, Seyda Ipek, Martha Ulloa, Submitted to PRL, 2408.12647]

T_R $\sim 5 - 80$ MeV

B-Mesogenesis generates baryon asymmetry

$A_{\rm SL}^{s,d} \times {\rm Br} \ > 10^{-6}$

$M_{\mathcal{Y}}^i < {\rm TeV}$

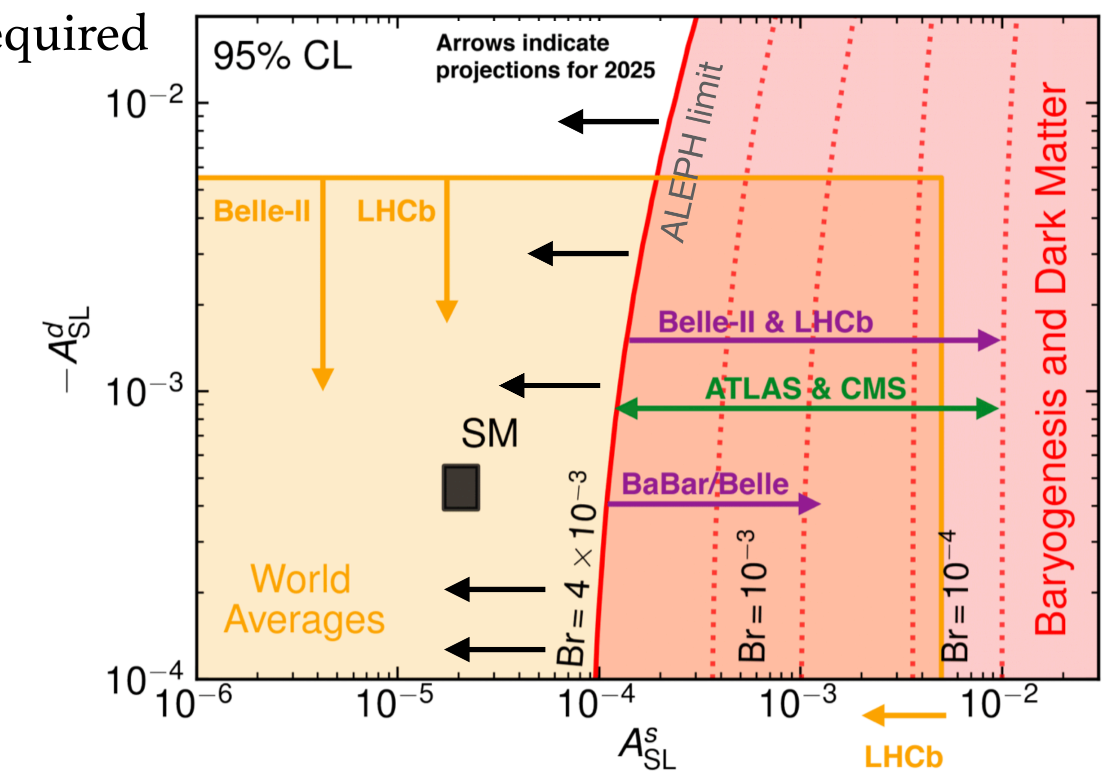
${\rm Br} \propto 1/M_{\mathcal{Y}}^4$ Enhanced relative to today by a factor $(M_{\mathcal{Y}}^f/M_{\mathcal{Y}}^i)^4$

→ Less CPV required

Can the SM be enough?

$A_{sl}^d|_{\rm SM} = (-4.7 \pm 0.4) \times 10^{-4}$

$A_{sl}^s|_{\rm SM} = (2.1 \pm 0.2) \times 10^{-5}$



T_{PT}

Dark sector phase transition *morphs* the mediator mass

$M_{\mathcal{Y}}^i \rightarrow M_{\mathcal{Y}}^f > M_{\mathcal{Y}}^i$

Today

Smaller Br expected. Collider constraints evaded.

$M_{\mathcal{Y}}^f = \mathcal{O}({\rm TeV})$

Can the SM CPV be enough? Yes!

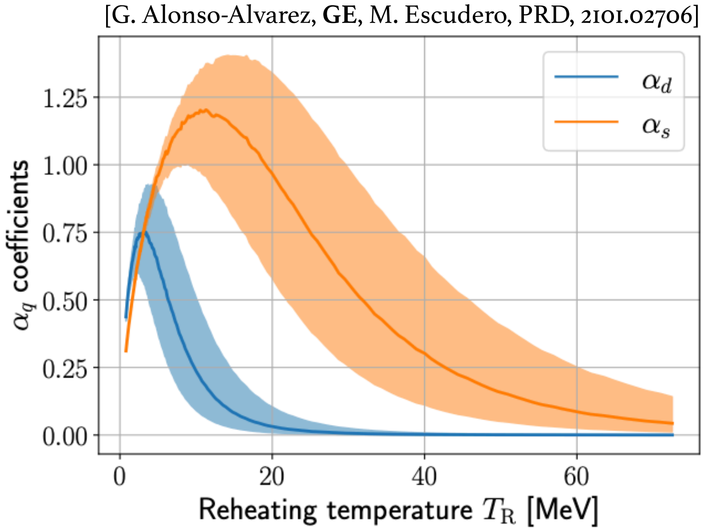
[**GE**, Rachel Houtz, Seyda Ipek, Martha Ulloa, Submitted to PRL, 2408.12647]

		$\Gamma_0 \equiv \Gamma_B\|_{m_{\psi_\mathcal{B}}=1\text{GeV}}/\mathcal{C}^2_{b,u_id_j}$	
Operator	$(M^f_y)_{\min}$ [TeV]	Decay	Γ_0 [GeV^5]
$\mathcal{O}_{b,ud}$	$\sim 1.7\sqrt{y_{\psi b}\, y_{ud}}$	$B_d \to \bar{\psi}_\mathcal{B}\, n$	$3.5_{\pm 0.4}\cdot 10^{-5}$
		$B_s \to \bar{\psi}_\mathcal{B}\, \Lambda$	n.a.
$\mathcal{O}_{b,us}$	$\sim 1.7\sqrt{y_{\psi b}\, y_{us}}$	$B_d \to \bar{\psi}_\mathcal{B}\, \Lambda$	$1.4_{\pm 0.1}\cdot 10^{-4}$
		$B_s \to \bar{\psi}_\mathcal{B}\, \Xi^0$	$3.2_{\pm 0.1}\cdot 10^{-5}$
$\mathcal{O}_{b,cd}$	$\sim 0.9\sqrt{y_{\psi b}\, y_{cd}}$	$B_d \to \bar{\psi}_\mathcal{B}\, \Sigma^0_c$	$0.7_{\pm 0.4}\cdot 10^{-6}$
		$B_s \to \bar{\psi}_\mathcal{B}\, \Xi^0_c$	$6.6_{\pm 3.3}\cdot 10^{-7}$
$\mathcal{O}_{b,cs}$	$\sim 0.9\sqrt{y_{\psi b}\, y_{cs}}$	$B_d \to \bar{\psi}_\mathcal{B}\, \Xi^0_c$	$4.7_{\pm 2.0}\cdot 10^{-6}$
		$B_s \to \bar{\psi}_\mathcal{B}\, \Omega_c$	$5.0_{\pm 3.0}\cdot 10^{-6}$

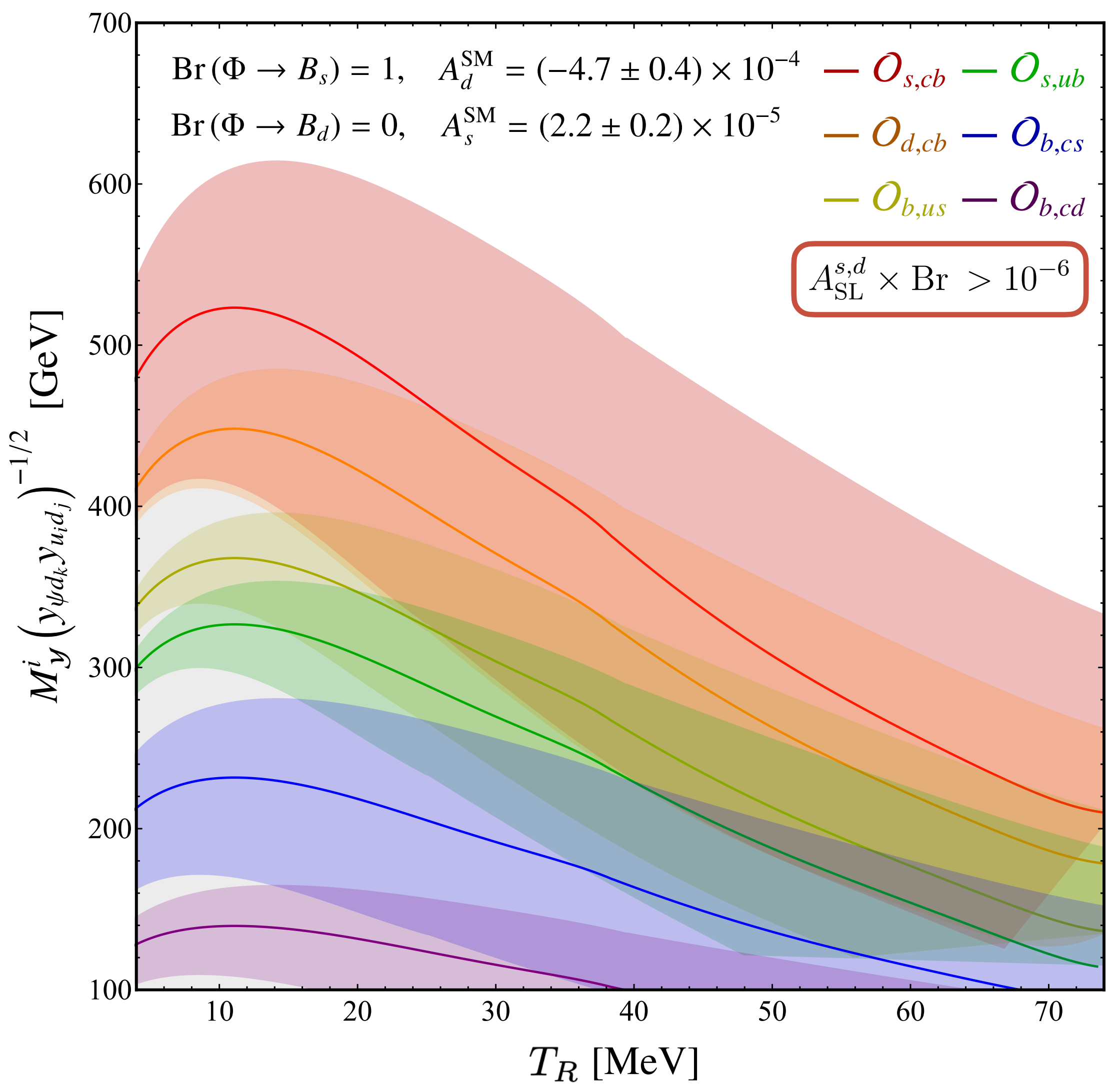
$$\mathcal{O}_{d_k,u_id_j} = \mathcal{C}_{d_k,u_id_j}\epsilon_{\alpha\beta\gamma}(\bar{\psi}_\mathcal{B} d_k^\alpha)(\bar{d}_j^{c\beta} u_i^\gamma)$$

$$Y_\mathcal{B} \simeq 5\times 10^{-5} \sum_{i=d,s}\left[A^{s,d}_{\text{SL}} \times \text{Br}\right]\alpha_i(T_{\text{R}})$$

[G. Alonso-Alvarez, **GE**, M. Escudero, PRD, 2101.02706]



Successful Baryogenesis



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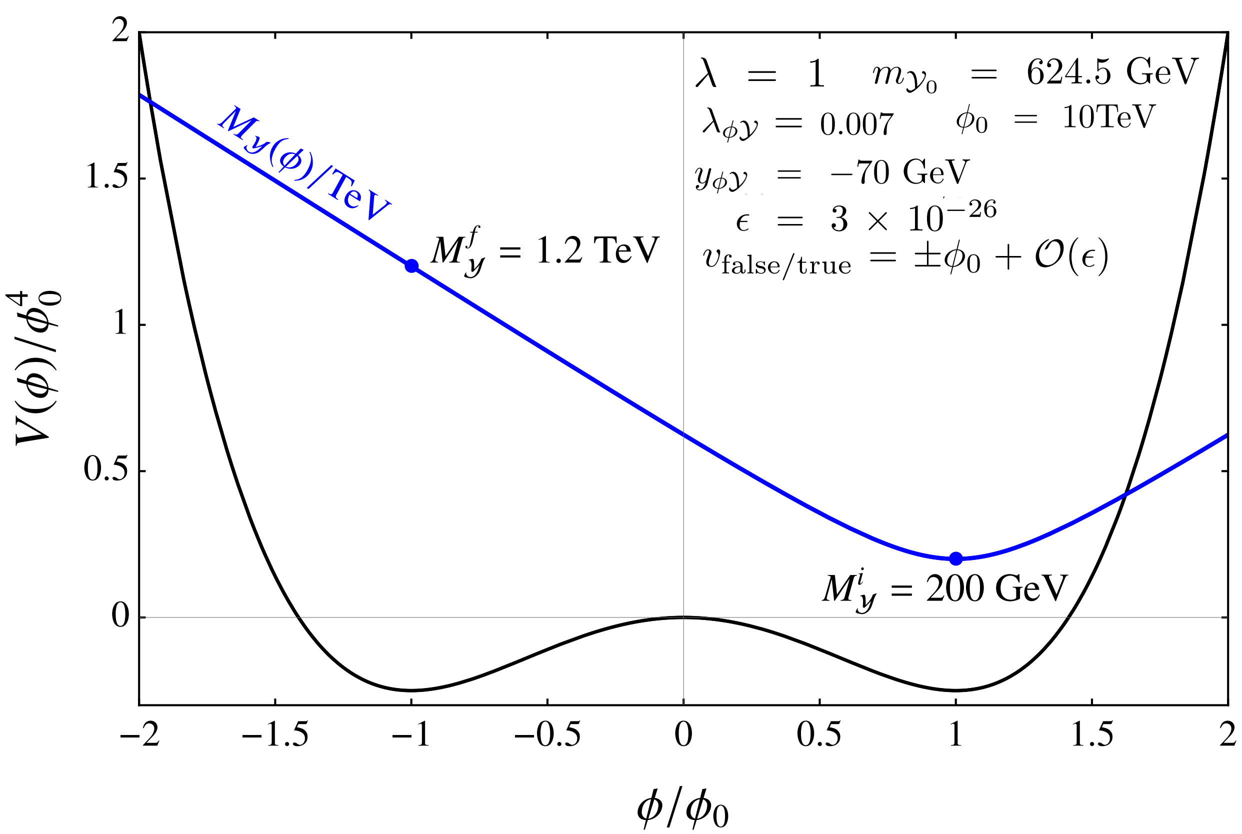
Morphing the Mediator

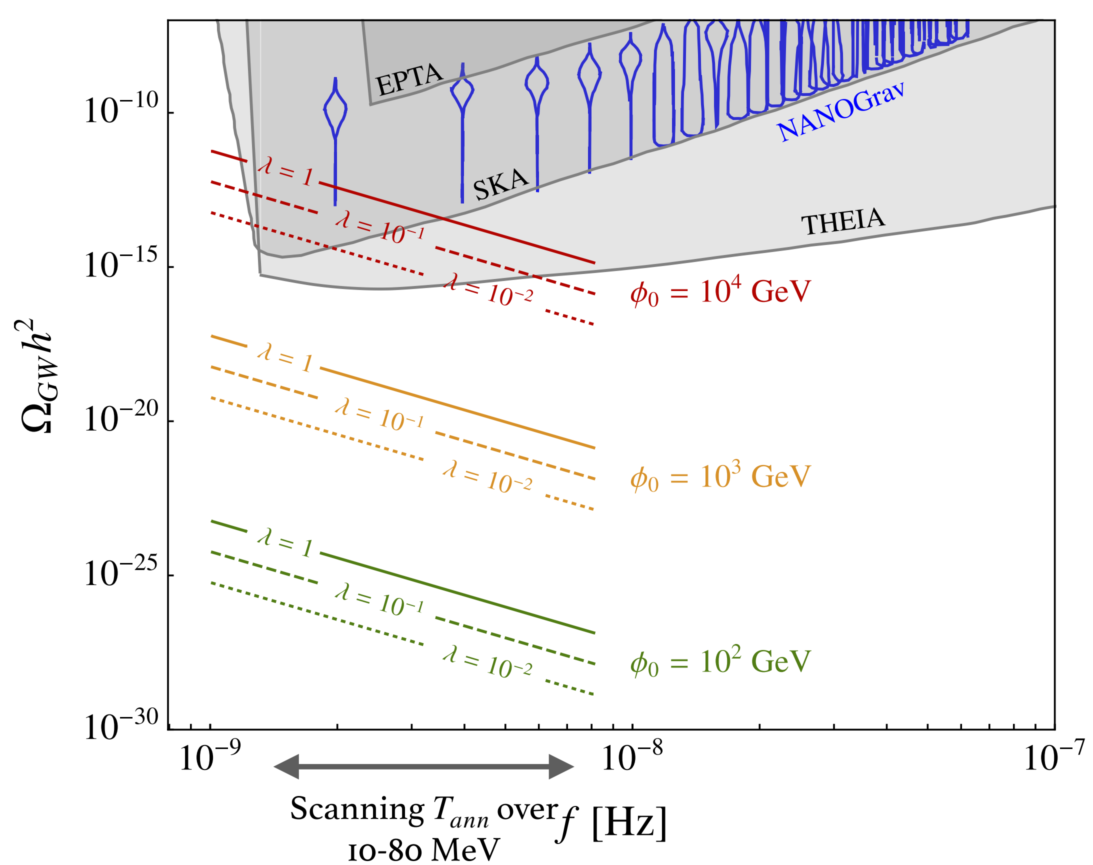
[**GE**, Rachel Houtz, Seyda Ipek, Martha Ulloa, Submitted to PRL, 2408.12647]

A mediator mass increase from ~200-500 GeV to about 1 TeV will generate the baryon asymmetry with only the SM CPV

- Toy morphon potential $V_{\rm scalar} = m_{\mathcal{Y}_0}^2|\mathcal{Y}|^2 + y_{\phi\mathcal{Y}}|\mathcal{Y}|^2\phi + \frac{1}{2}\lambda_{\phi\mathcal{Y}}|\mathcal{Y}|^2\phi^2 + \frac{1}{4}\lambda(\phi^2 - \phi_0^2)^2 + \epsilon\,\phi_0\,\phi^3$

- Domain Wall Example:





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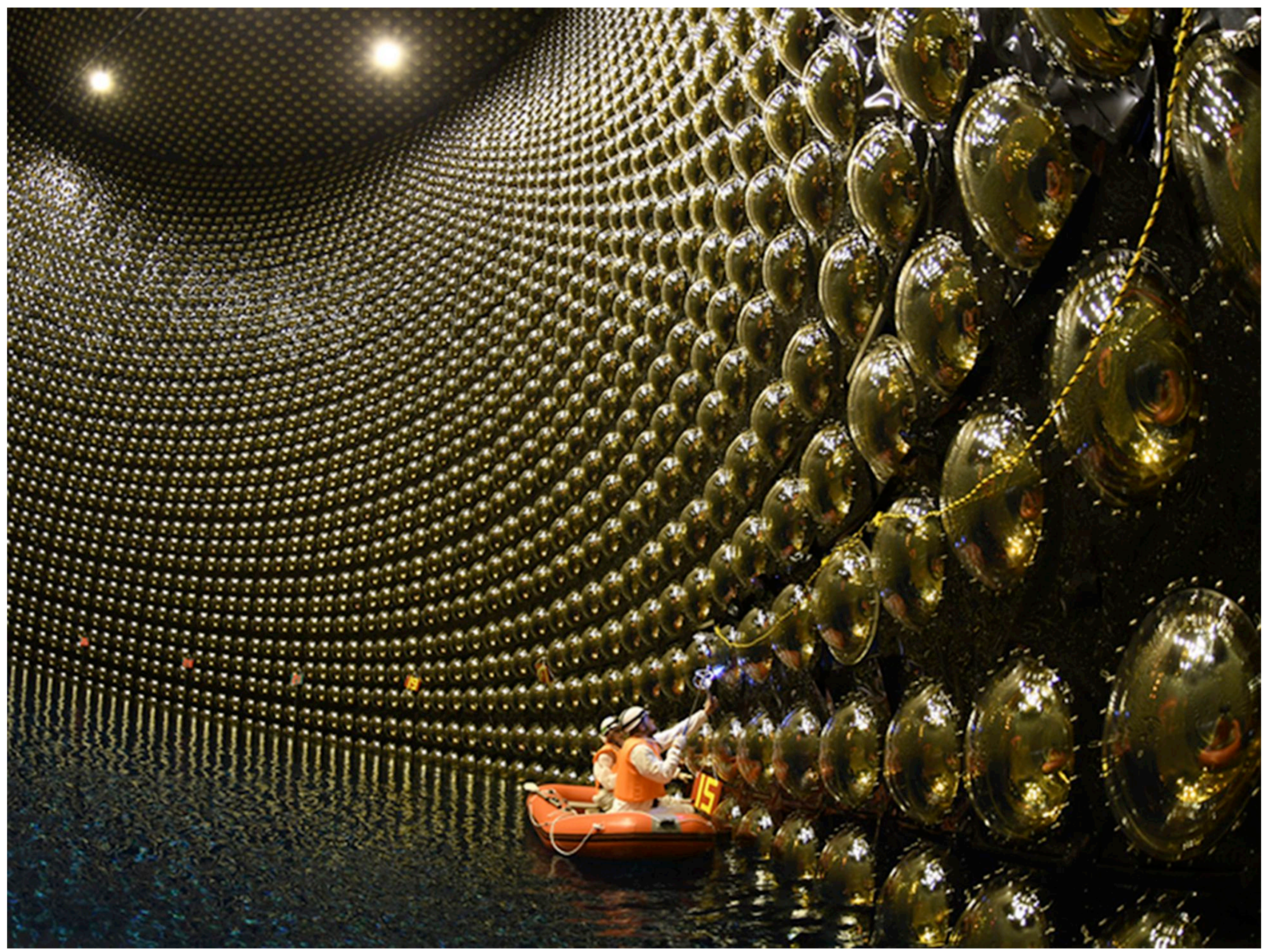
Searching for the Dark Matter

[J. Berger, **GE**. PRL. 2301.04165]

Signals at Neutrino Detectors
(for any Mesogenesis mechanisms involving decays to dark baryons)

HYPER K

JUNO



Inside the **Super-Kamiokande** water Cherenkov detector.
Credit: Kamioka Observatory, ICRR, Univ. Tokyo

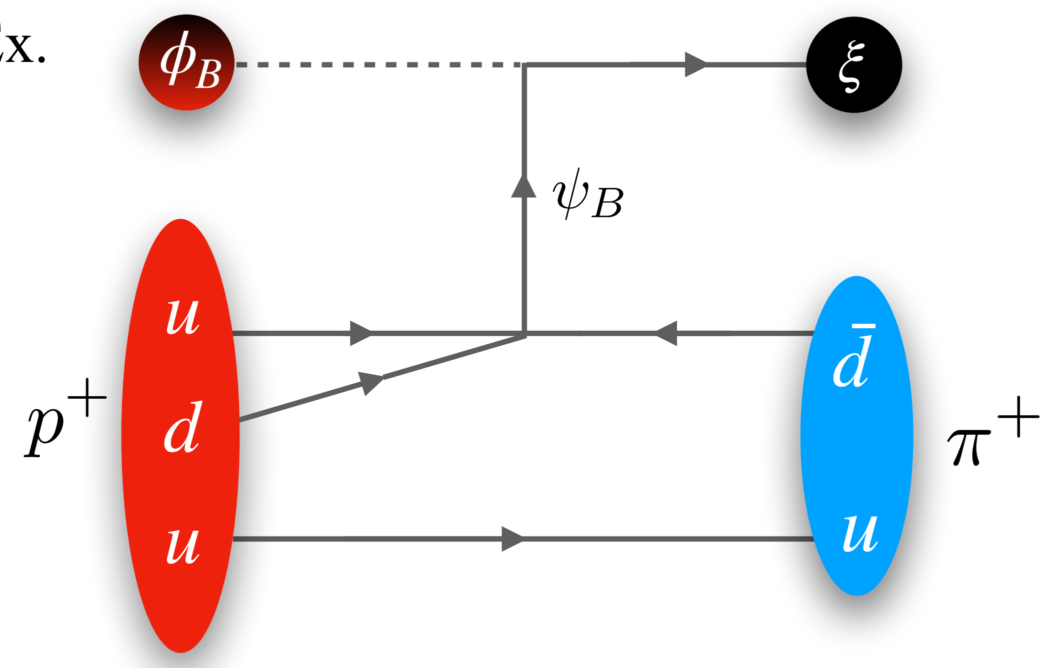
DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

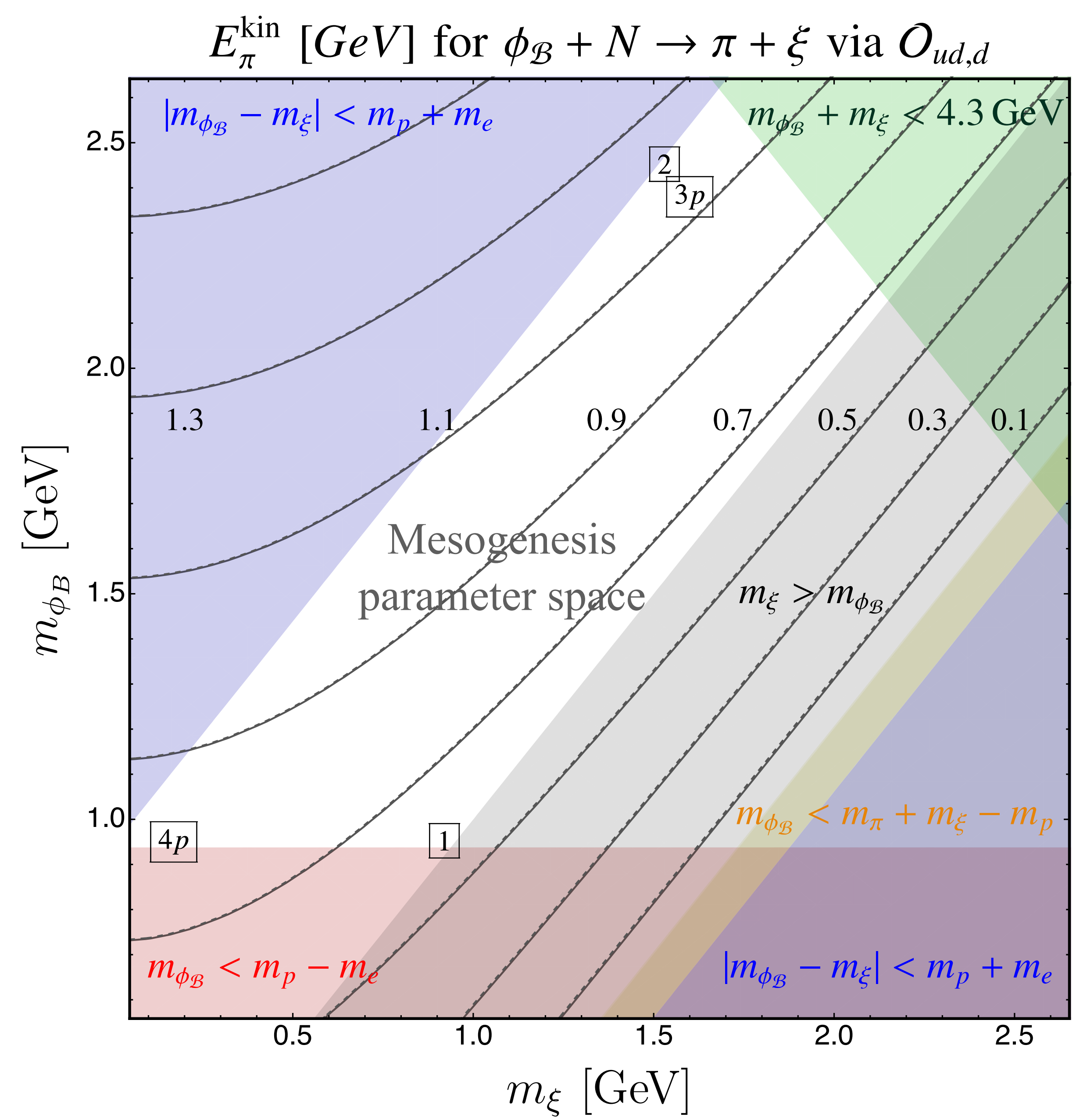
Dark Matter Induced Nucleon Decay

[J. Berger, **GE**. PRL. 2301.04165]

Incoming dark matter induces proton (or neutron decay) in nuclei of detector target material

Ex.





Mono-energetic meson (up to detector effects):

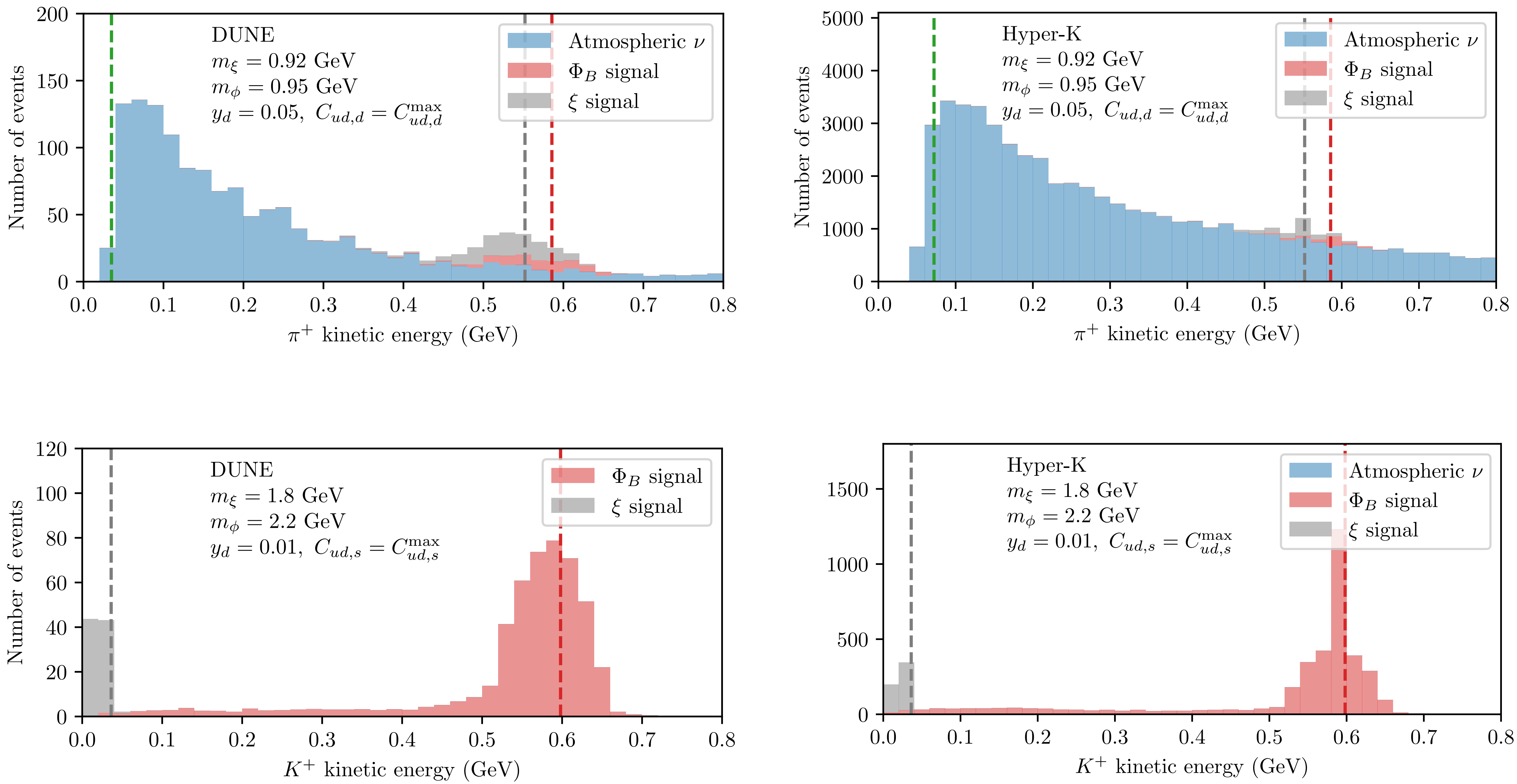
$$E^{\mathcal{M},\,\rm kin}_{\phi_{\mathcal{B}} N \to \xi \mathcal{M}} = \frac{m_{\mathcal{M}}^2 - m_\xi^2 + (m_N + m_{\phi_B})^2}{2(m_N + m_{\phi_B})} - m_{\mathcal{M}}$$

G. Elor

Signal and Background Simulation

[J. Berger, **GE**. PRL. 2301.04165]

$$\rho_{\text{total}} = \rho_\phi + \rho_\xi = 0.4\,\text{GeV/cm}^3 \quad \text{where} \quad \rho_\xi/\rho_{\phi_\mathcal{B}} = 5m_p/m_{\phi_\mathcal{B}} - 1$$



Next: Searches in astrophysics and cosmology environments

Mesogensis with a Morphing Mediator

[**GE**, Rachel Houtz, Seyda Ipek, Martha Ulloa, Submitted to PRL, 2408.12647],

"*The Standard Model CP Violation is Enough*".

A mediator mass increase from ~200-500 GeV to about 1 TeV will generate the baryon asymmetry with only the SM CPV.

- Gravitational Wave signals from dark dynamics at current and upcoming PTAs.
- Dark matter signals are still present (induced nucleon decay)
- **Motivation for collider searches to *improve branching fraction sensitivity to Br*** $< 10^{-5}$
- As measurements of the charge asymmetry improve, motivation for seeing *only* the SM CPV

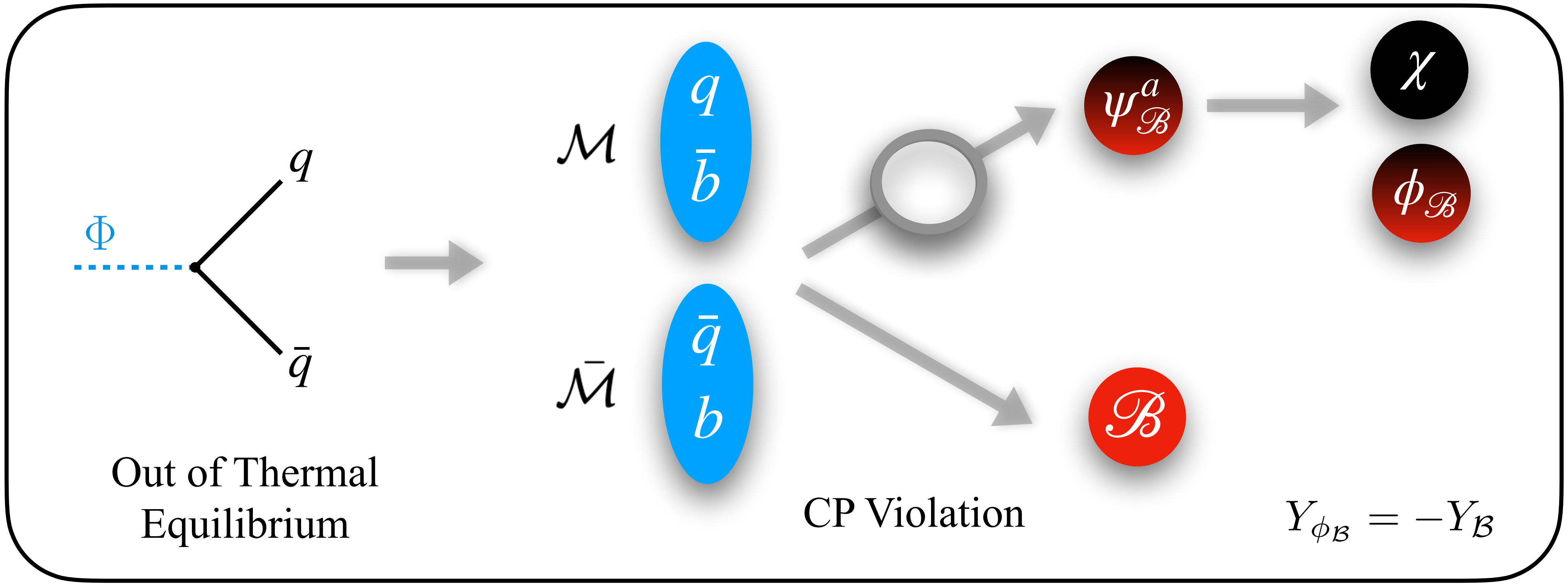
Next: dark phase transition study (models and signals) [**GE**, Rachel Houtz, Seyda Ipek, Martha Ulloa]

Mesogenesis with Dark CPV

[**GE**, Can Kilic, Sanjay Mathai, Fall 2024 *(targeted)*]

CPV entirely from the dark sector?

Mesogenesis with Dark CPV $\mathcal{M} = \{B_d^0,\, B_s^0,\, B^\pm,\, B_c^\pm\}$



$$\mathcal{L}_{mass}^{\psi} = -\sum_{ab} M_{ab} \bar{\psi}_{\mathcal{B}}^a \psi_{\mathcal{B}}^b + \text{h.c} \longrightarrow A_{CP}^{\text{dark}} \equiv \frac{\Gamma(\bar{\mathcal{M}} \to \phi_{\mathcal{B}} \xi \bar{\mathcal{B}}_{\text{SM}}) - \Gamma(\mathcal{M} \to \phi_{\mathcal{B}}^* \xi \mathcal{B}_{\text{SM}})}{\Gamma(\bar{\mathcal{M}} \to \phi_{\mathcal{B}} \xi \bar{\mathcal{B}}_{\text{SM}}) + \Gamma(\mathcal{M} \to \phi_{\mathcal{B}}^* \xi \mathcal{B}_{\text{SM}})}$$

$$\longrightarrow \boxed{Y_{\mathcal{B}} \simeq 8.7 \times 10^{-11} \left[\frac{\text{Br}(\mathcal{M} \to \mathcal{B}_{\text{SM}} + \text{MET})}{10^{-4}} \frac{A_{CP}^{\text{dark}}}{10^{-2}} \right]}$$

Br as low as 10^{-7} – 10^{-6} predicted.

Space of Mechanisms

Mechansim	CPV	Dark Sector	Observables	Relevant Experiments	
B^0 Mesogenesis	B_s^0 & B_d^0 oscillations	dark baryons	$A_{sl}^{s,d}$ $\text{Br}(B^0 \to \mathcal{B}_{\text{SM}} + X)$	LHCb B Factories, LHCb	**GE,** M. Escudero, A. Nelson **(2018)**
D^+ Mesogenesis	$D^\pm$ decays	dark leptons and dark baryons	A_{CP}^{D} Br_{D^+} $\text{Br}(D^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU	**GE,** R. McGehee **(2020)**
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One mechanisms direct signal is another mechanisms indirect signal

Space of Mechanisms

Mechansim	CPV	Dark Sector	Observables	Relevant Experiments	
B^0 Mesogenesis	B_s^0 & B_d^0 oscillations	dark baryons	$A_{sl}^{s,d}$ $\text{Br}(B^0 \to \mathcal{B}_{\text{SM}} + X)$	LHCb B Factories, LHCb	**GE**, M. Escudero, A. Nelson **(2018)**
D^+ Mesogenesis	$D^\pm$ decays	dark leptons and dark baryons	A_{CP}^{D} Br_{D^+} $\text{Br}(D^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU	**GE**, R. McGehee **(2020)**
B^+ Mesogenesis	$B^\pm$ decays	dark leptons and dark baryons	A_{CP}^{B} Br_{B^+} $\text{Br}(B^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU	F. Elahi, **GE**, R. McGehee **(2021)**
B_c^+ Mesogenesis	$B_c^\pm$ decays	dark baryons	$A_{CP}^{B_c}$ $\text{Br}_{B_c^+}$ $\text{Br}(B^+ \to \mathcal{B}_{\text{SM}}^+ + X)$	LHCb, FCC LHCb, FCC B Factories, LHCb	F. Elahi, **GE**, R. McGehee **(2021)**
Mesogenesis with a Morphing Mediator	B_s^0 & B_d^0 oscillations	dark baryons and dark phase transition	$A_{\text{sl, SM}}^{\text{s,d}}$ $\text{Br}(B^0 \to \mathcal{B}_{\text{SM}} + X)$ Gravitational Waves	LHCb B Factories, LHCb Pulsar Timing Arrays, CMB	**GE**, R. Houtz, S. Ipek, M. Ulloa, **(2024)**
Mesogenesis with Dark CPV	either B_d^0, B_s^0, $B^\pm$, $B_c^\pm$ decays	dark baryons and dark CP phase	$A_{\text{CP}}^{\text{dark}}$ $\text{Br}(\mathcal{M} \to \mathcal{B}_{\text{SM}} + X)$	EDMs, Flavor Observables B Factories, LHCb	**GE**, C. Kilic, S. Mathai **(2024 *targeted*)**

One mechanisms direct signal is another mechanisms indirect signal

My message to Belle-II experimentalists: measuring Br to 10^{-7} sensitivity could discover baryogenesis. Also, lots of indirect signals to look for. To fully exclude or discover Mesogenesis we must explore the entire parameter space.

G. Elor

What is the Universe made of?

- Mesogenesis explains both the origin of the baryon asymmetry and the dark matter of the Universe.
- Six different mechanisms of Mesogenesis exist to date. **One mechanisms direct signal is another mechanisms indirect signal.**
- Experimentalists are searching for Mesogenesis! **More searches are needed to fully explore the space of models.**
- To fully take advantage of the experimental program we must comprehensively explore all possible mechanisms, variations, and signals.

How can we exist?

Image: Galaxy cluster SMACS 0723 as seen by the James Webb Space Telescope. Credit: NASA, STScl

What is the Universe made of?

My message to Belle-II experimentalists:

- Measuring Br to 10^{-7} sensitivity could discover baryogenesis.
- Lots of indirect signals.
- Thus, to fully exclude or discover Mesogenesis, we must explore the entire parameter space.

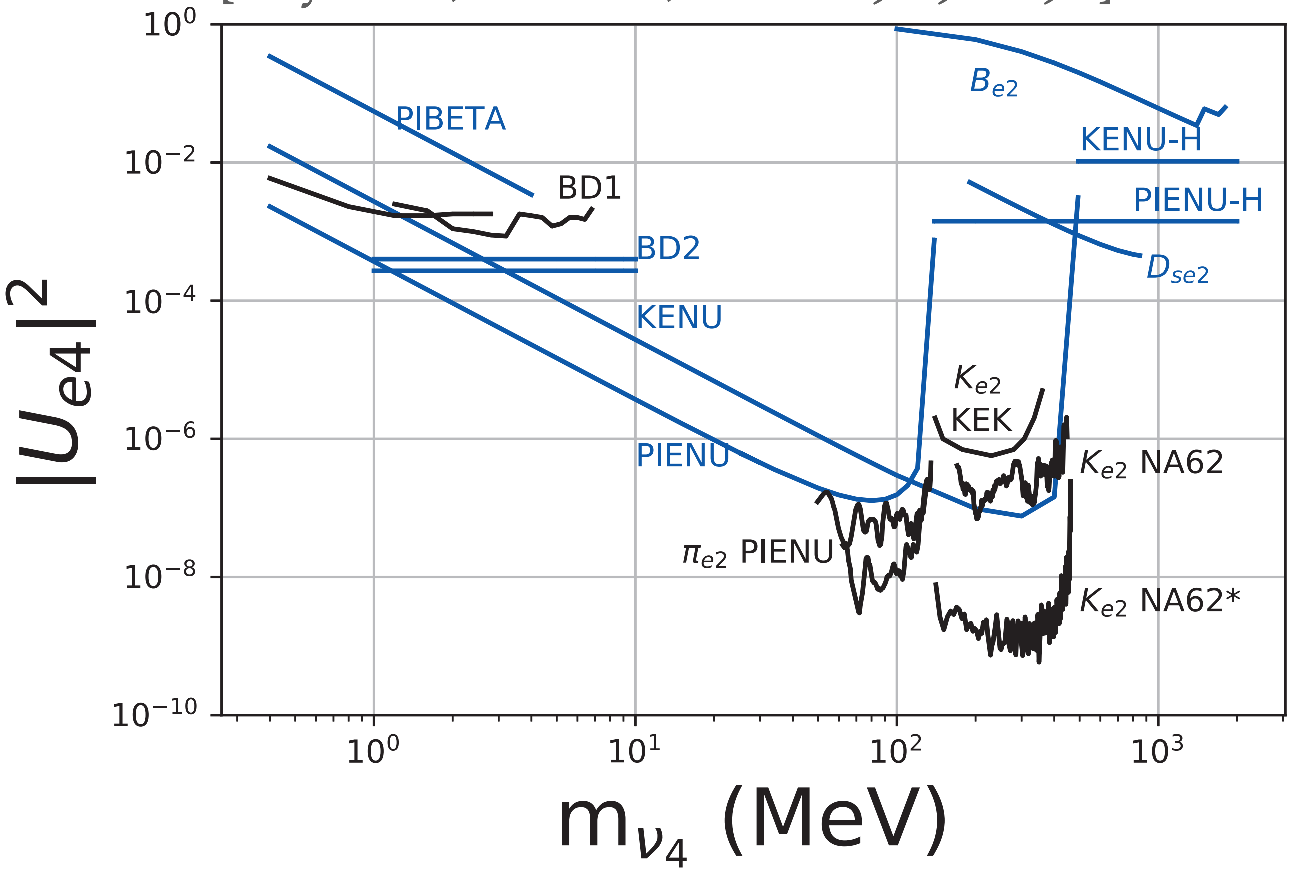
How can we exist?

Image: Galaxy cluster SMACS 0723 as seen by the James Webb Space Telescope. Credit: NASA, STScl

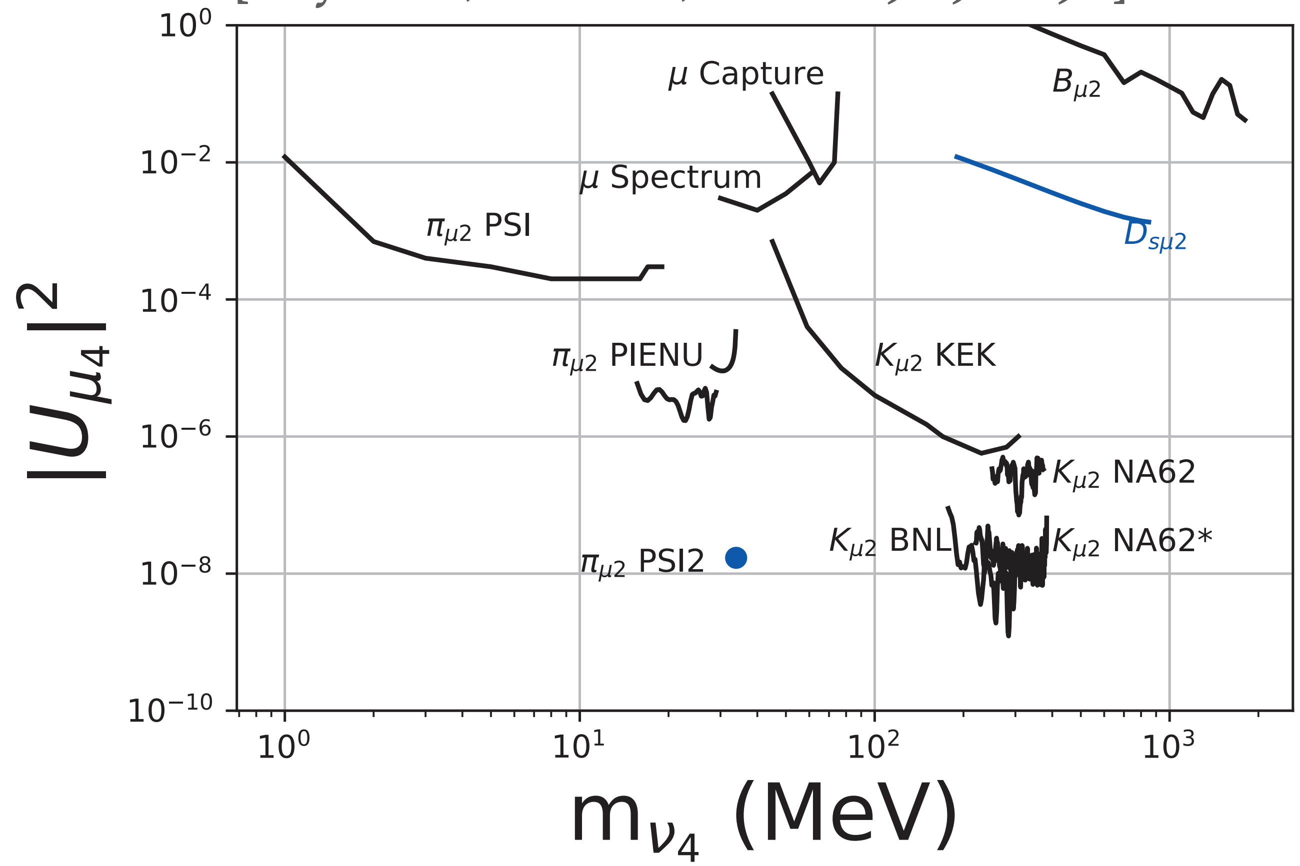
Backups

Peak Searches: 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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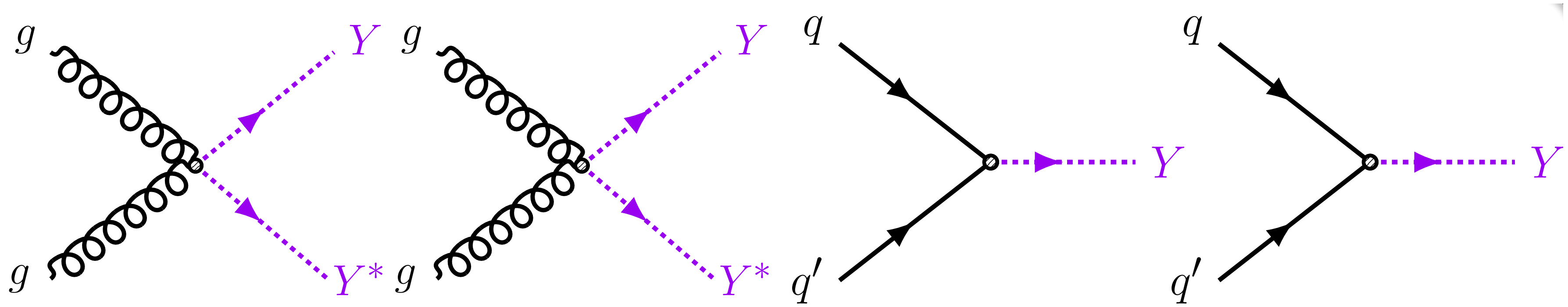
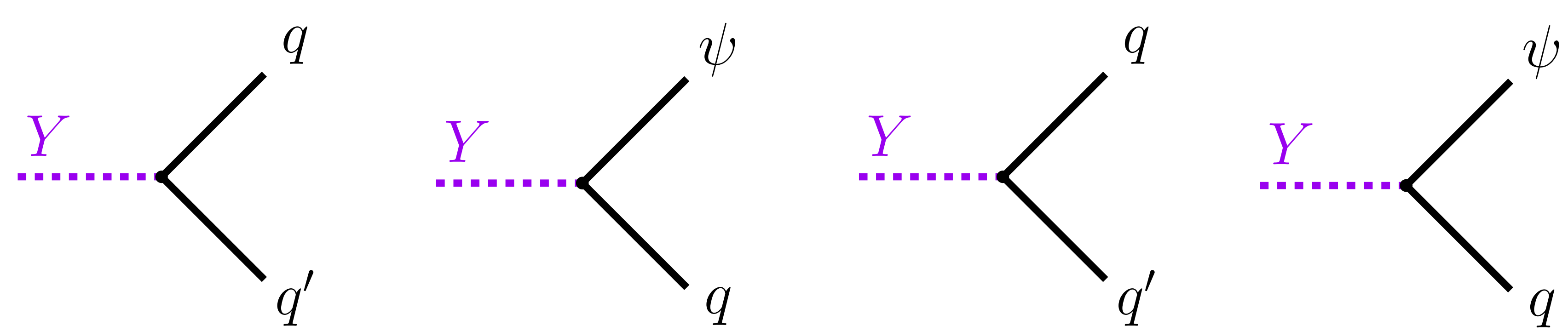
Colored Triplet Scalar

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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Boltzmann Equations

Scalar, Radiation, Hubble:

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

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

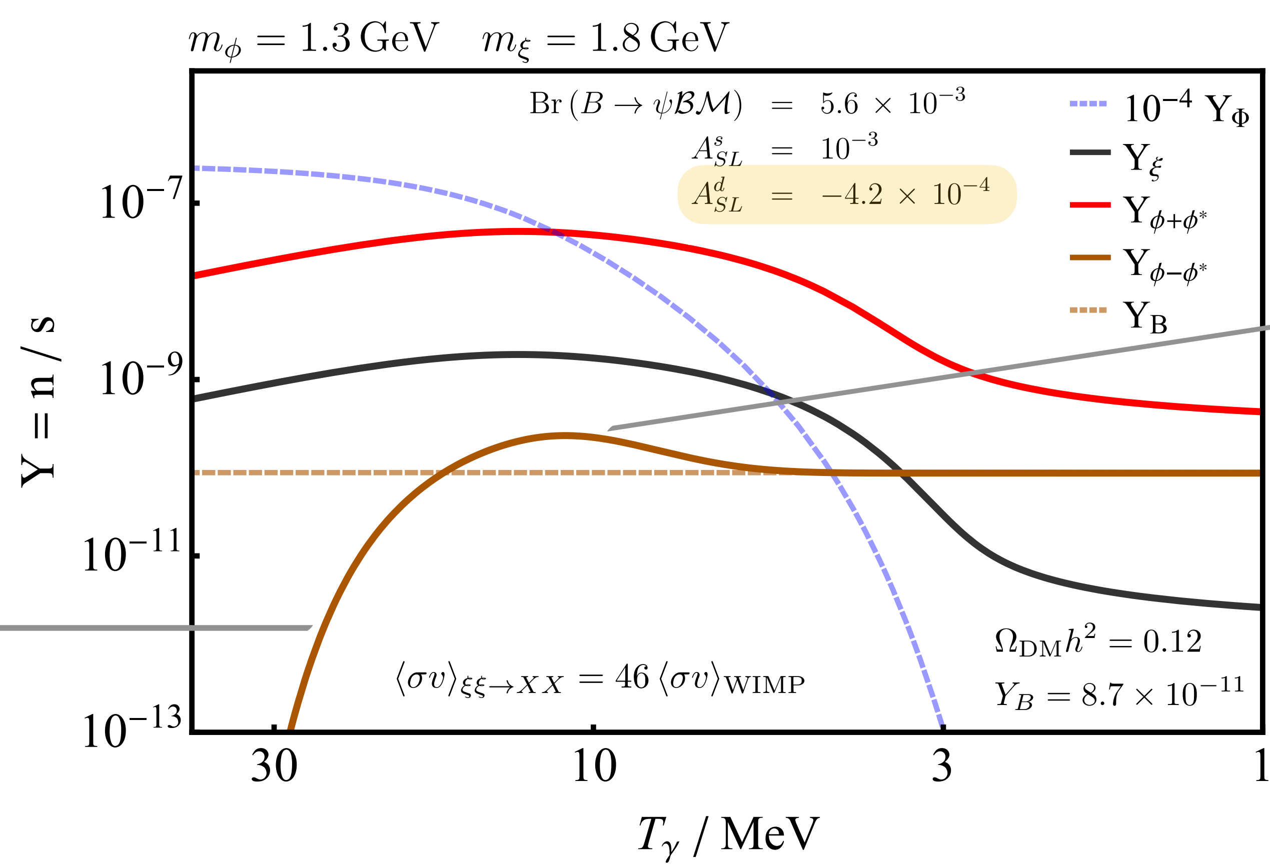
$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\left(\rho_{\rm rad} + m_\Phi n_\Phi\right)$$

Dark Matter:

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

Baryon Asymmetry:

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



$T_{B_d} \lesssim 10\,{\rm MeV}$

Coherent B_d oscillations start to deplete the asymmetry

$T_{B_s} \lesssim 20\,{\rm MeV}$

Coherent B_s oscillations start to produce an asymmetry

Need a net positive charge asymmetry

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Freezing-In a Baryon Asymmetry

Example Benchmark point:

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

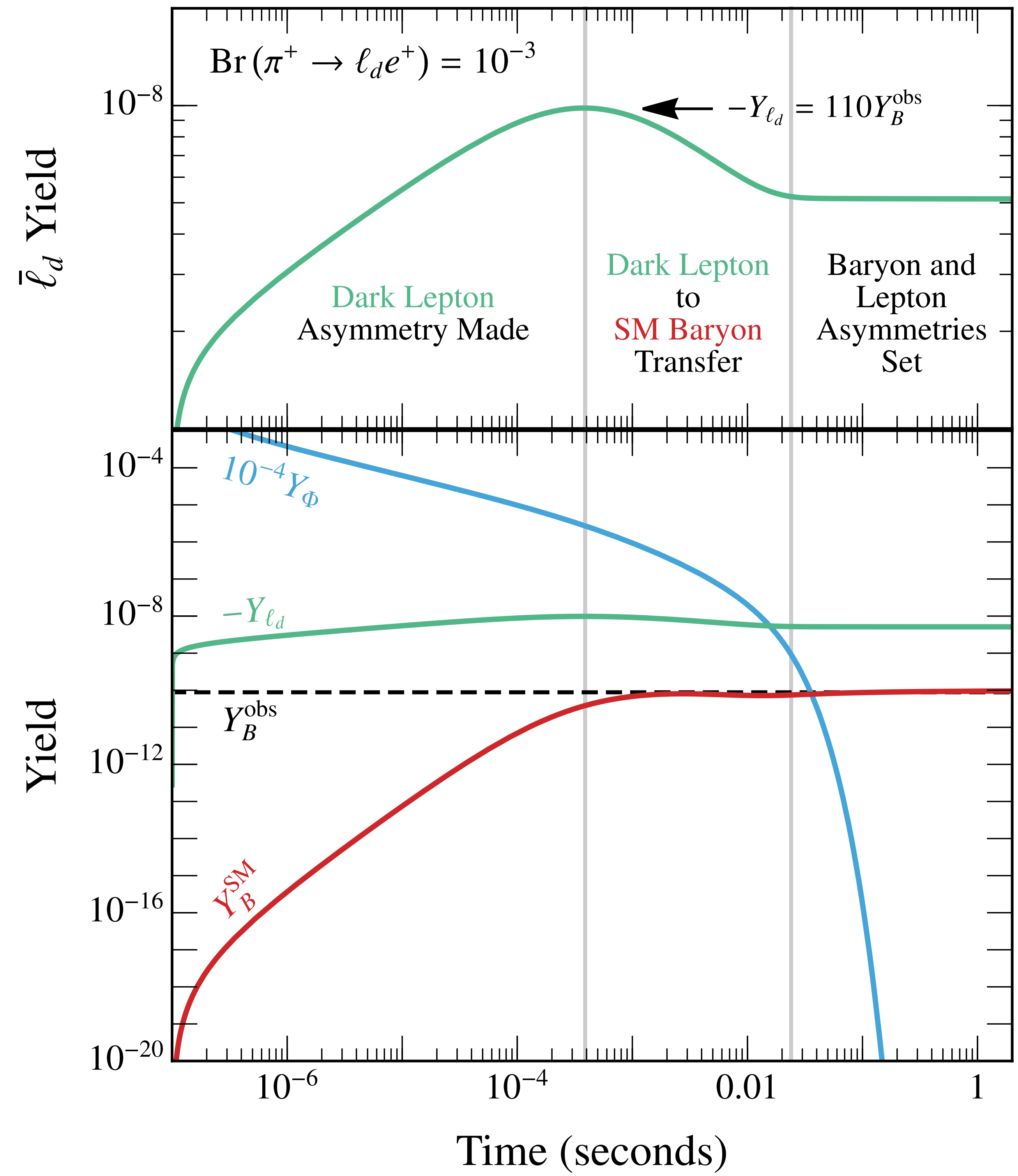
$$\langle \sigma v \rangle = 1 \times 10^{-15} \text{ GeV}^{-2}$$

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

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

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

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



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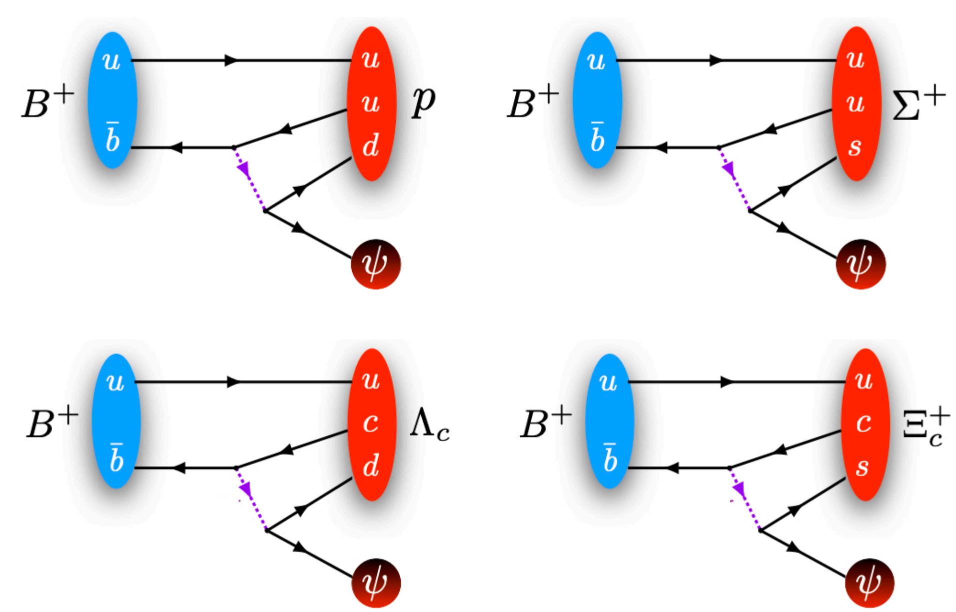
B^+ Decay

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
$\mathcal{O} = \psi\, b\, u\, d$ $\bar{b} \to \psi\, u\, d$	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	$\psi + \Xi^0_c\,(cds)$
	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	$\psi + \Xi^0_c\,(csd)$
	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 B^+ Mesogenesis.



Indirect signal of charged and neutral B Mesogenesis

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Can the SM CPV be enough?

[**GE**, Rachel Houtz, Seyda Ipek, Martha Ulloa, Submitted to PRL, 2408.12647]

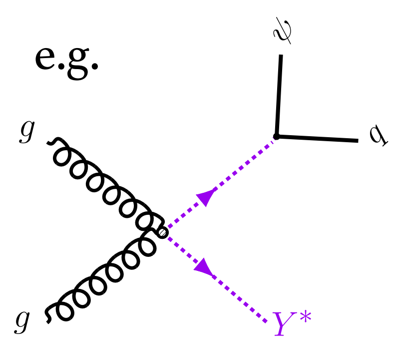
- Colored mediator ***Y*** has **TeV scale mass**:

Limits on Wilson coefficient from recasting LHC searches for squarks

$$\mathcal{C}_{d_k,u_i d_j} \equiv y_{\psi d_k} y_{u_i d_j} / M_{\mathcal{Y}}^2$$

[A. Alonso-Alvarez, **GE**, M. Escudero, PRD, 2101.02706]

e.g.



		$\Gamma_0 \equiv \Gamma_B\vert_{m_{\psi_\mathcal{B}}=1\text{GeV}}/\mathcal{C}^2_{b,u_i d_j}$	
Operator	$(M_{\mathcal{Y}}^f)_{\min}$ [TeV]	Decay	Γ_0 [GeV^5]
$\mathcal{O}_{b,ud}$	$\sim 1.7\sqrt{y_{\psi b}\, y_{ud}}$	$B_d \to \bar\psi_\mathcal{B}\, n$ $B_s \to \bar\psi_\mathcal{B}\, \Lambda$	$3.5_{\pm 0.4}\cdot 10^{-5}$ n.a.
$\mathcal{O}_{b,us}$	$\sim 1.7\sqrt{y_{\psi b}\, y_{us}}$	$B_d \to \bar\psi_\mathcal{B}\, \Lambda$ $B_s \to \bar\psi_\mathcal{B}\, \Xi^0$	$1.4_{\pm 0.1}\cdot 10^{-4}$ $3.2_{\pm 0.1}\cdot 10^{-5}$
$\mathcal{O}_{b,cd}$	$\sim 0.9\sqrt{y_{\psi b}\, y_{cd}}$	$B_d \to \bar\psi_\mathcal{B}\, \Sigma_c^0$ $B_s \to \bar\psi_\mathcal{B}\, \Xi_c^0$	$0.7_{\pm 0.4}\cdot 10^{-6}$ $6.6_{\pm 3.3}\cdot 10^{-7}$
$\mathcal{O}_{b,cs}$	$\sim 0.9\sqrt{y_{\psi b}\, y_{cs}}$	$B_d \to \bar\psi_\mathcal{B}\, \Xi_c^0$ $B_s \to \bar\psi_\mathcal{B}\, \Omega_c$	$4.7_{\pm 2.0}\cdot 10^{-6}$ $5.0_{\pm 3.0}\cdot 10^{-6}$

$$\mathcal{O}_{d_k,u_i d_j} = \mathcal{C}_{d_k,u_i d_j}\, \epsilon_{\alpha\beta\gamma} (\bar\psi_\mathcal{B} d_k^\alpha)(\bar d_j^{c\beta} u_i^\gamma)$$

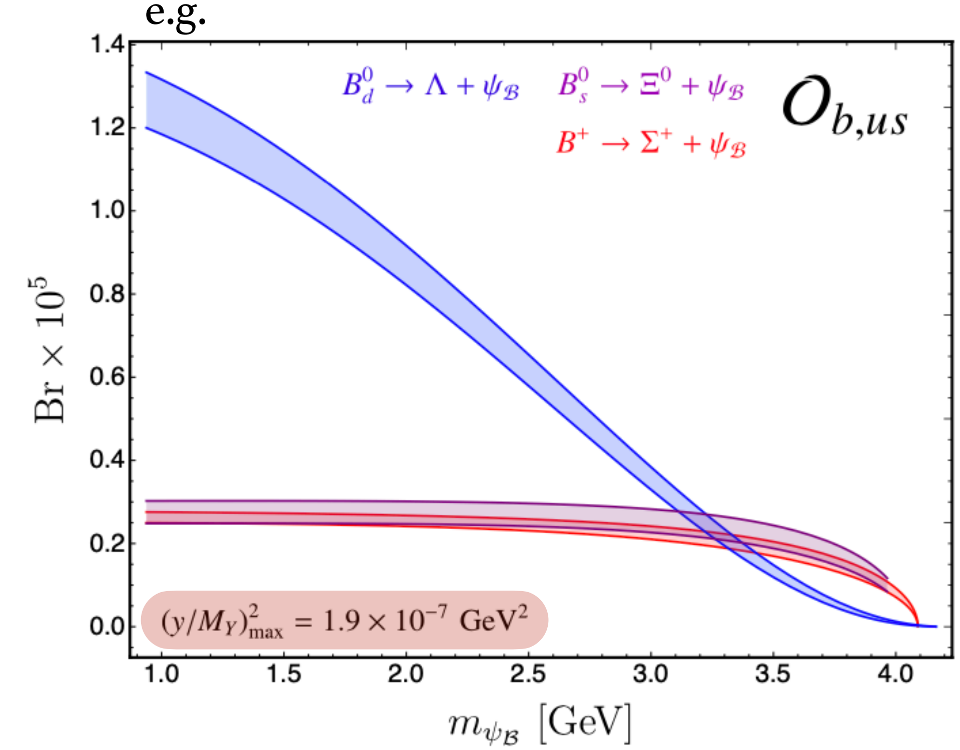
- Branching fraction:

$$\text{Br}_{B_i} = \frac{\sum_{\mathcal{B}_\text{SM}} \mathcal{C}_i^2 \Gamma_0(B_i \to \bar\psi_\mathcal{B}\, \mathcal{B}_\text{SM})}{(\tau^\text{SM}_{B_{d,s}})^{-1} + \sum_{\mathcal{B}_\text{SM}} \mathcal{C}_i^2 \Gamma_0(B_i \to \bar\psi_\mathcal{B}\, \mathcal{B}_\text{SM})} \propto \frac{1}{M_{\mathcal{Y}}^4}$$

Exact form computed using QCD light cone sum rules

[**GE**, A. Guerrera. JHEP, 2211.10553]

e.g.



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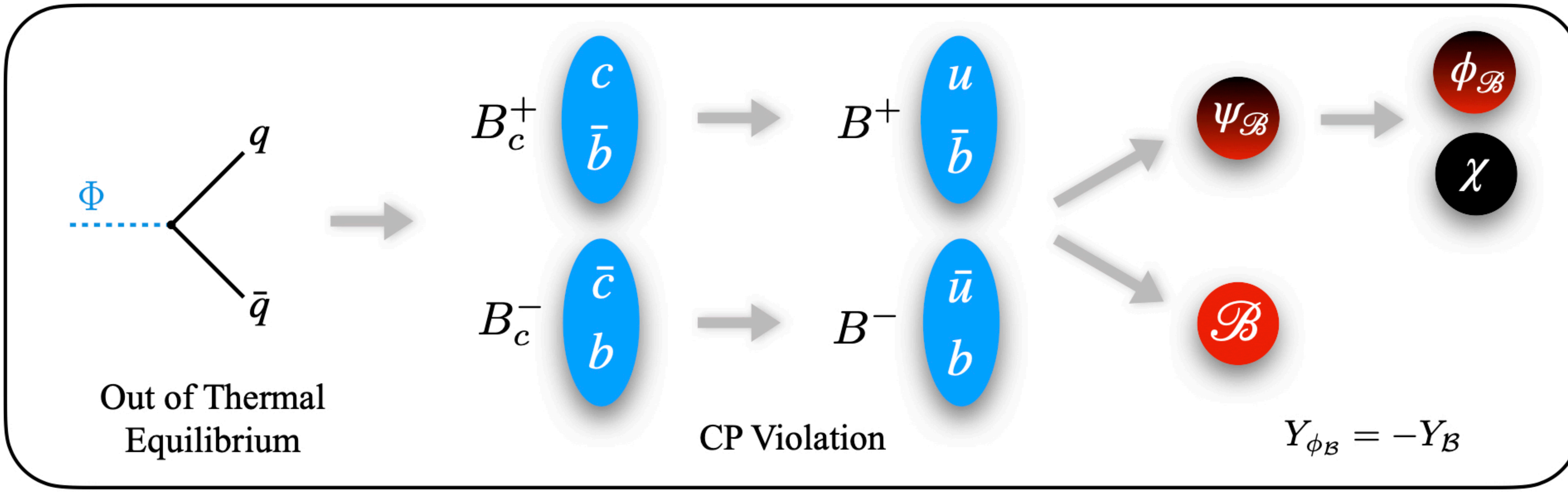
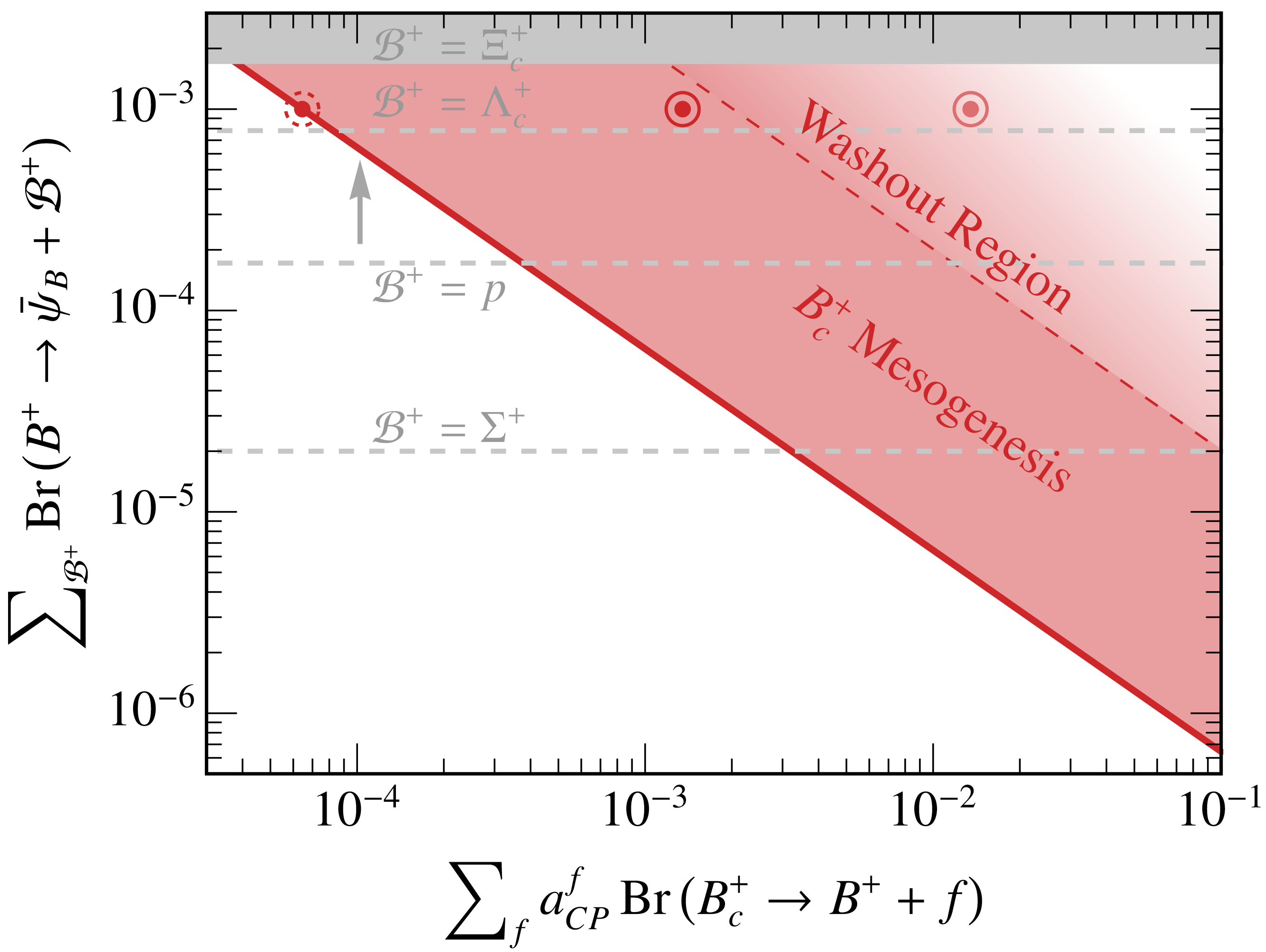
B_c^+ Mesogenesis

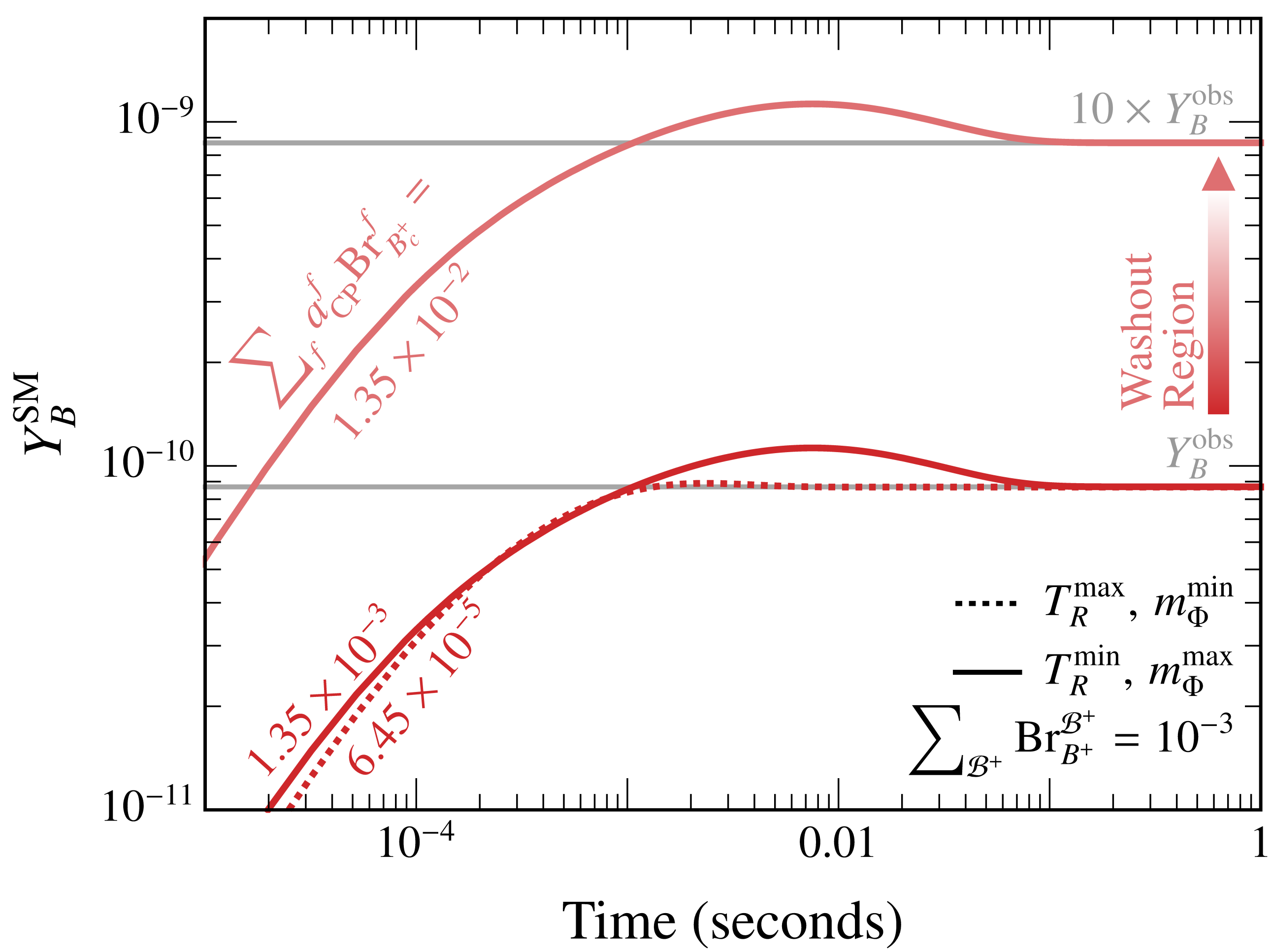
[F. Elahi, **GE**, R. McGehee, PRD, 2109.09751]



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

B_c^+ Mesogenesis





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

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A SUSY 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

A SUSY 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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