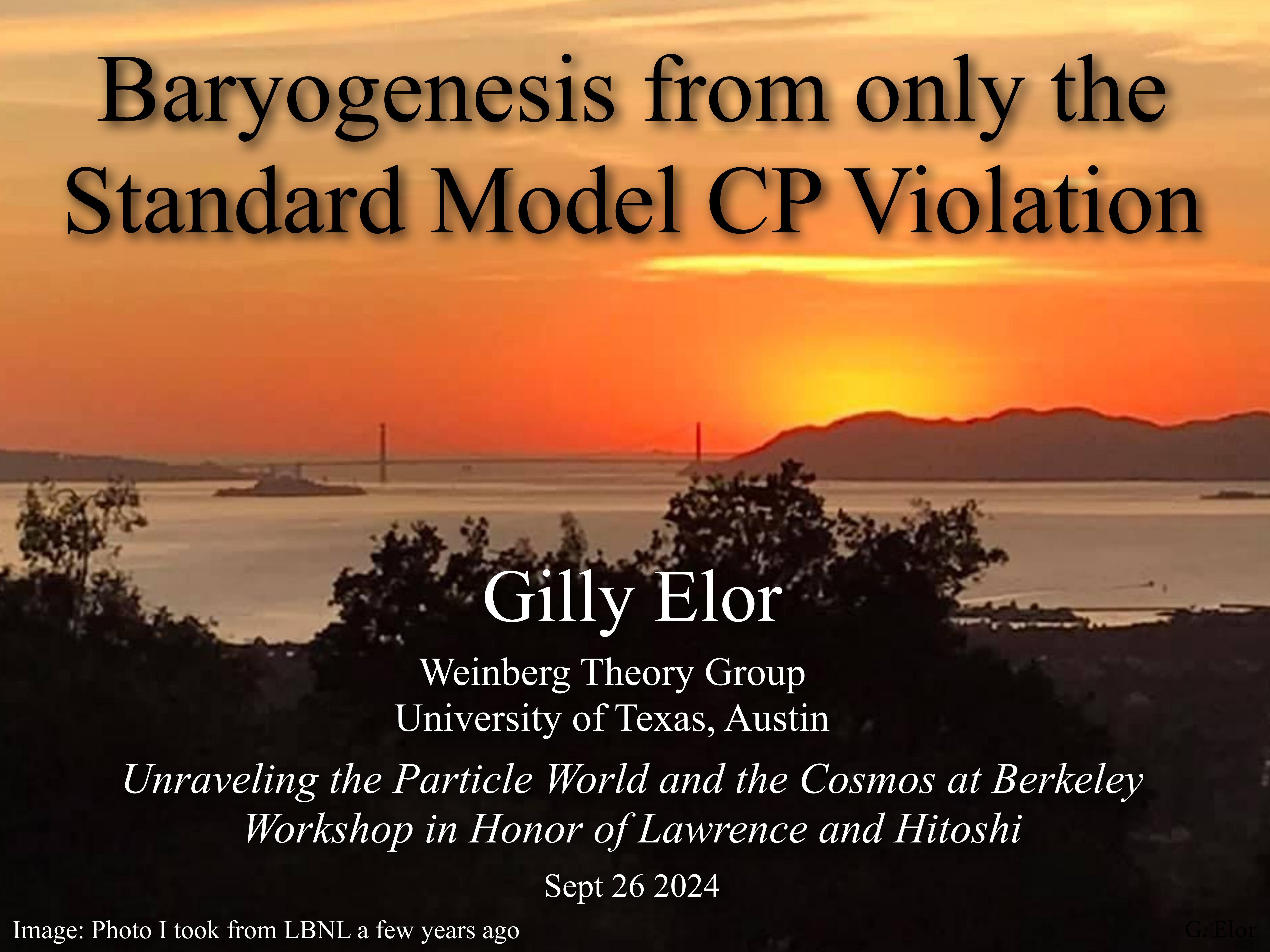
Baryogenesis from only the Standard Model CP Violation



Gilly Elor

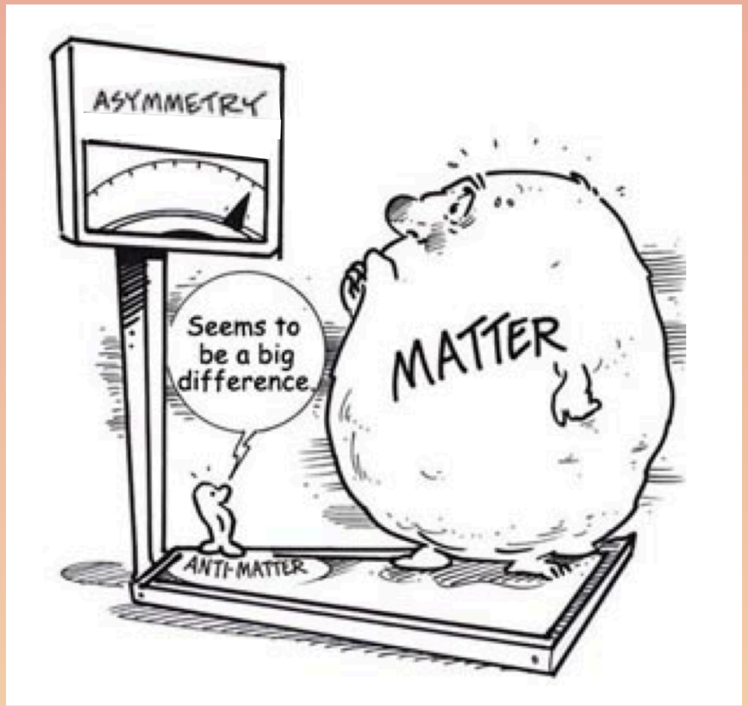
Weinberg Theory Group
University of Texas, Austin

Unraveling the Particle World and the Cosmos at Berkeley
Workshop in Honor of Lawrence and Hitoshi

Sept 26 2024

Image: Photo I took from LBNL a few years ago

Outline



- Background on Mesogenesis.
- Bigger picture and the space of mechanisms.
- Mesogenesis with a Morphing Mediator.
- Outlook (bigger picture, again)

Based on: [**GE**, Rachel Houtz, Seyda Ipek, Martha Ulloa, Submitted to PRL, 2408.12647], "*The Standard Model CP Violation is Enough*".

As well as: [J. Berger, **GE,** PRL, 2301.04165]
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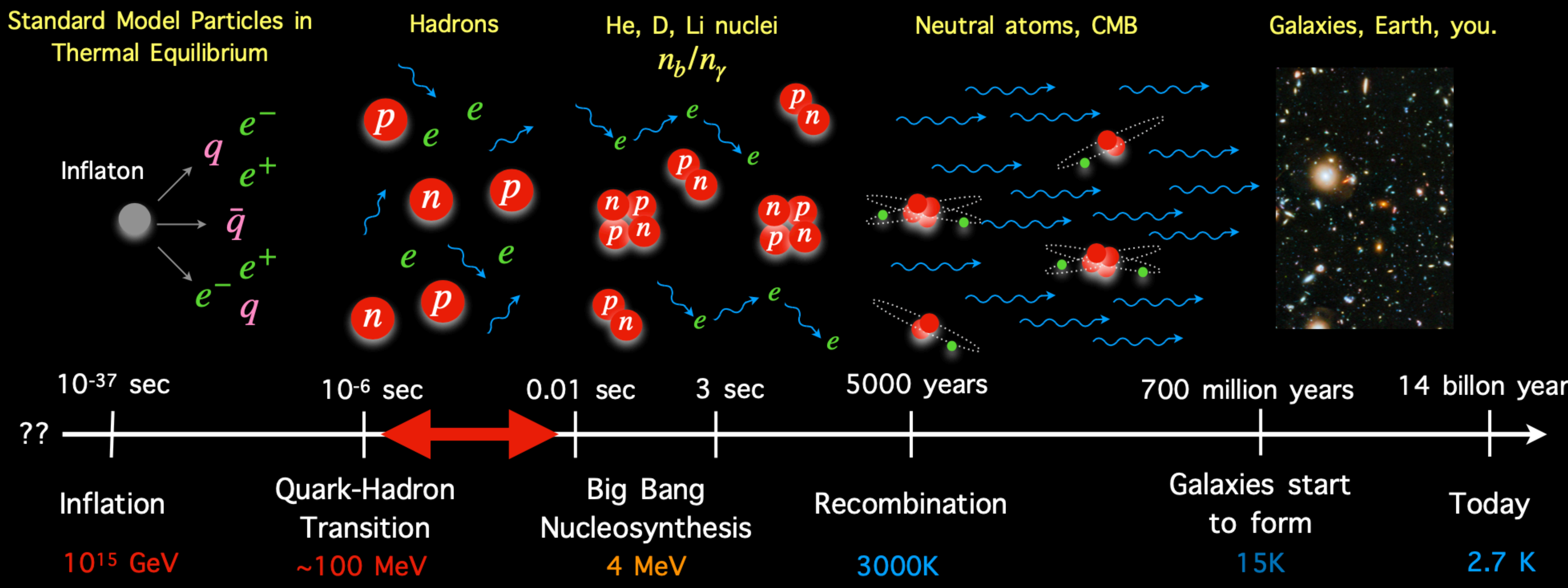
Upcoming: [**GE**, Can Kilic, Sanjay Mathai, Fall 2024 *(targeted)*]

Mesogenesis

Baryogenesis and Dark Matter from Mesons



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 baryons (or leptons).*

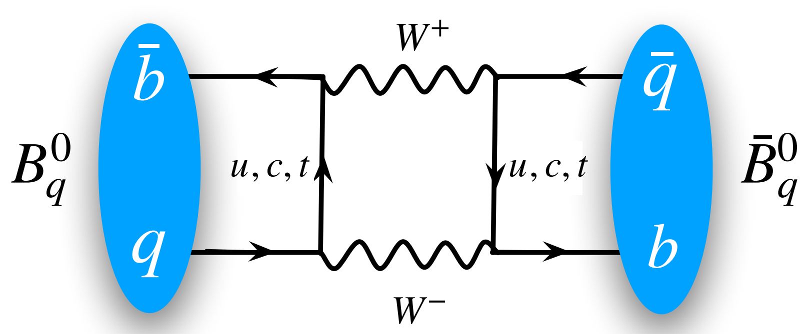
Features:

- Signals!
- The SM CPV can be enough!
- Baryon asymmetry production right up to the era of BBN possible.
- Reconstructable dark matter.

CP Violation in B Meson Oscillations

Standard Model

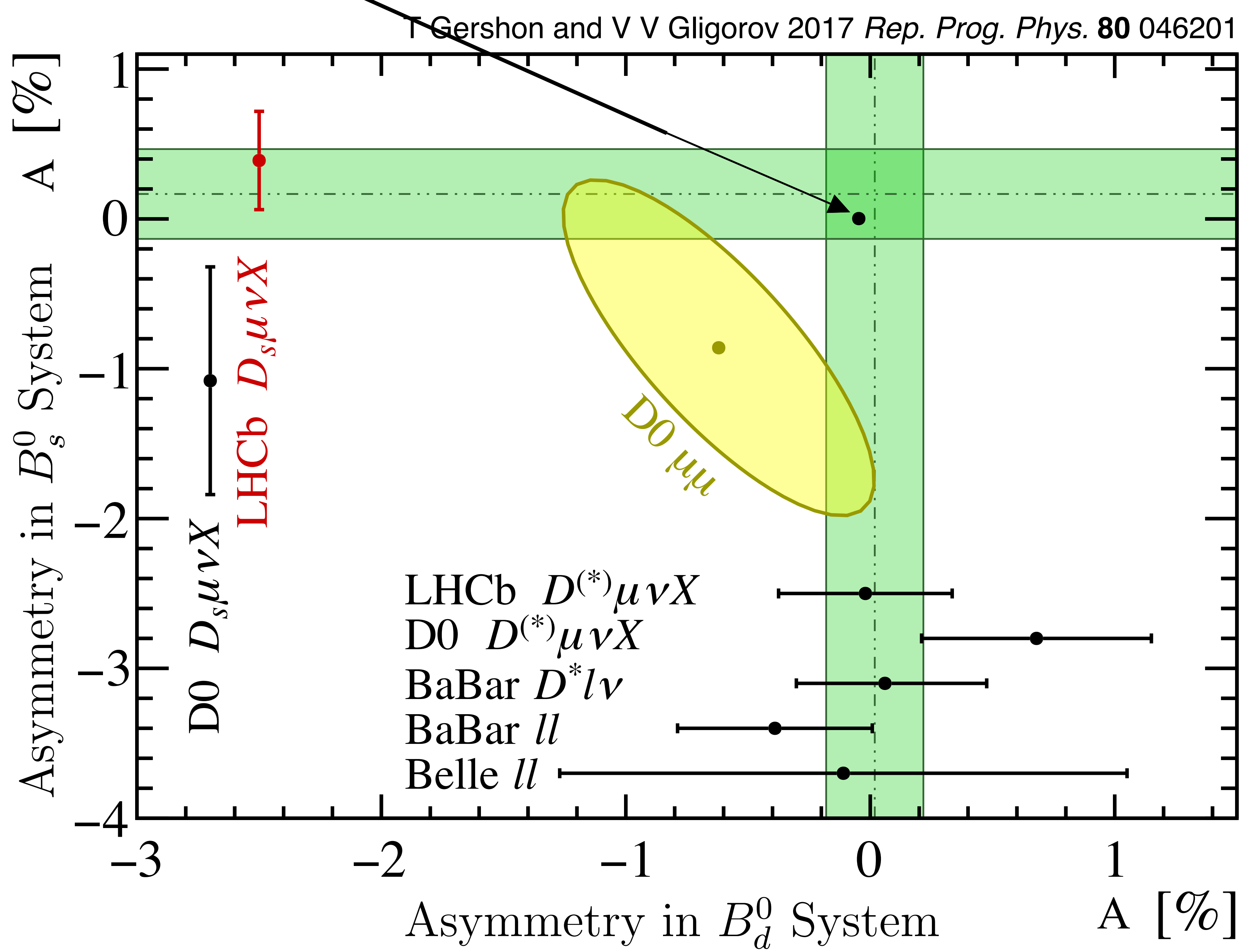
e.g..



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

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

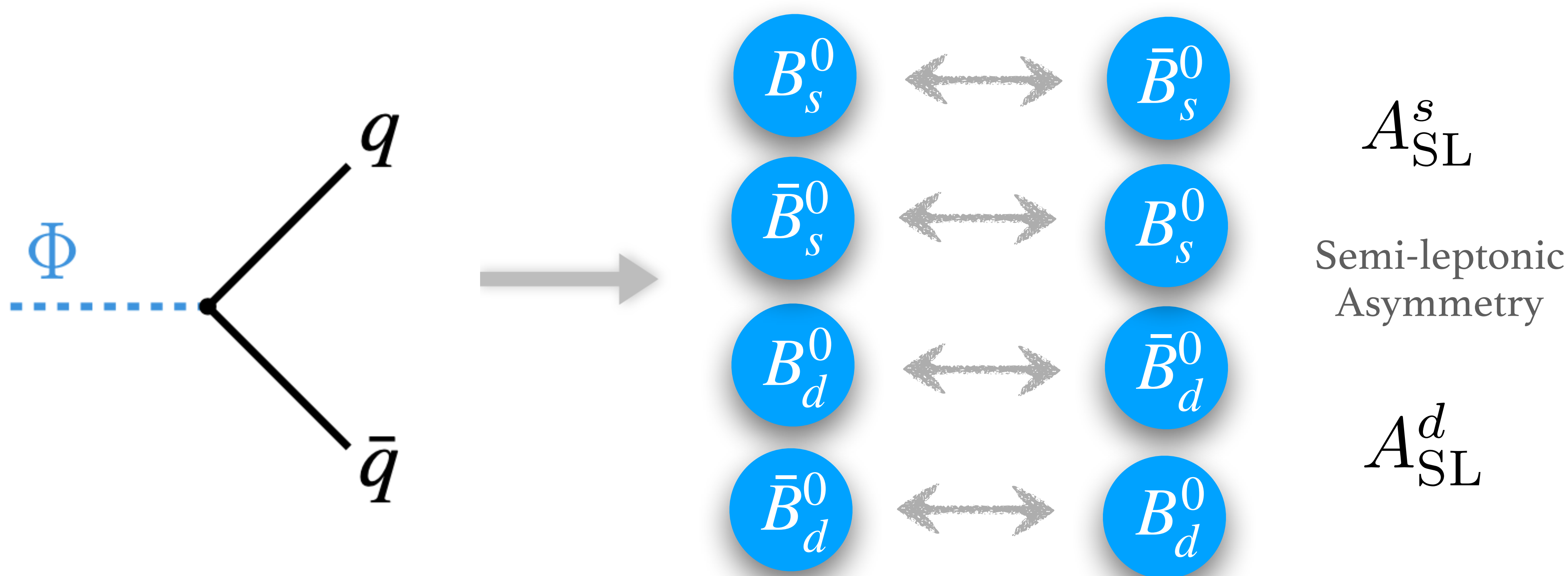
$$A_{\rm SL}^q = \frac{\Gamma\left(\bar{B}_q^0 \to B_q^0 \to f\right) - \Gamma\left(B_q^0 \to \bar{B}_q^0 \to \bar{f}\right)}{\Gamma\left(\bar{B}_q^0 \to B_q^0 \to f\right) + \Gamma\left(B_q^0 \to \bar{B}_q^0 \to \bar{f}\right)}$$



Neutral B Mesogenesis
Out of thermal equilibrium and CPV:

Late decay of an scalar field

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



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

Before BBN ↑ After QCD phase transition ↑

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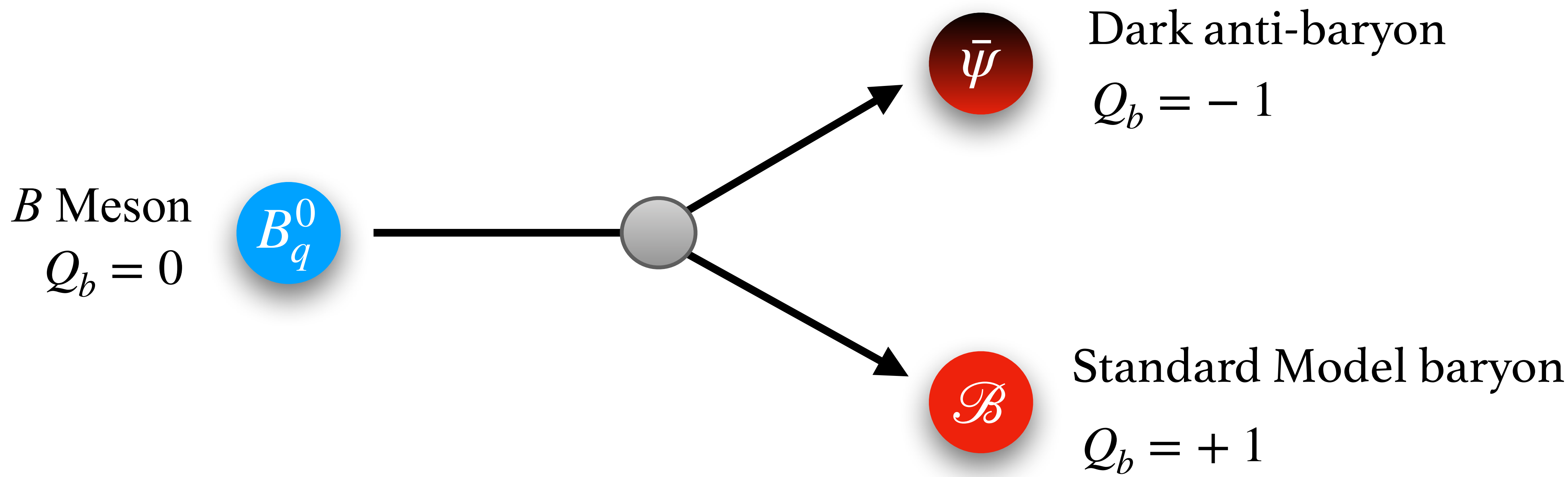
Neutral *B* Mesogenesis

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.

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

G. Elor

Neutral B Mesogenesis

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

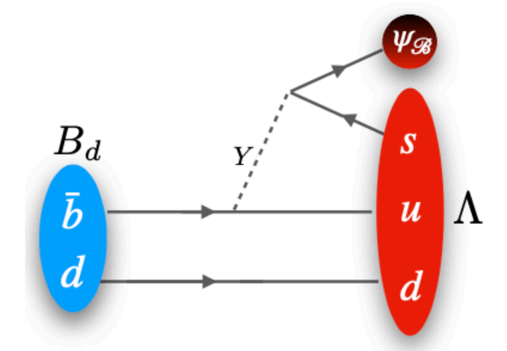
SUSY UV completion: [G. Alonso-Alvarez, **GE**, A. E. Nelson, H. Xiao, JHEP, 1907.10612]

Neutral B Mesogenesis

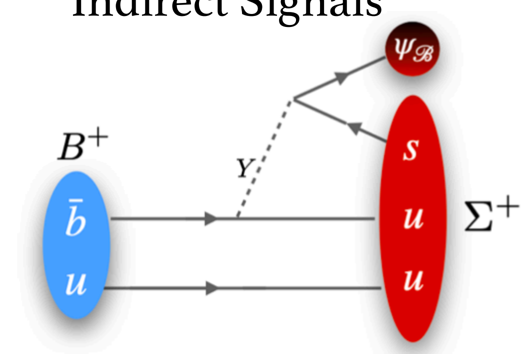
New Decays

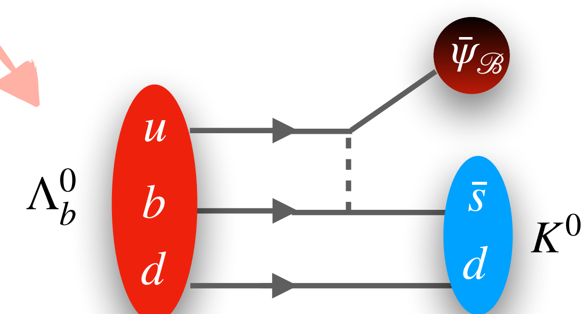
Operator/Decay	Initial State	Final state
$\mathcal{O} = \psi\, b\, u\, d$ $\bar{b} \to \psi\, u\, d$	B_d	$\psi + n\,(udd)$
	B_s	$\psi + \Lambda\,(uds)$
	B^+	$\psi + p\,(duu)$
	Λ_b	$\bar{\psi} + \pi^0$
$\mathcal{O} = \psi\, b\, u\, s$ $\bar{b} \to \psi\, u\, s$	B_d	$\psi + \Lambda\,(usd)$
	B_s	$\psi +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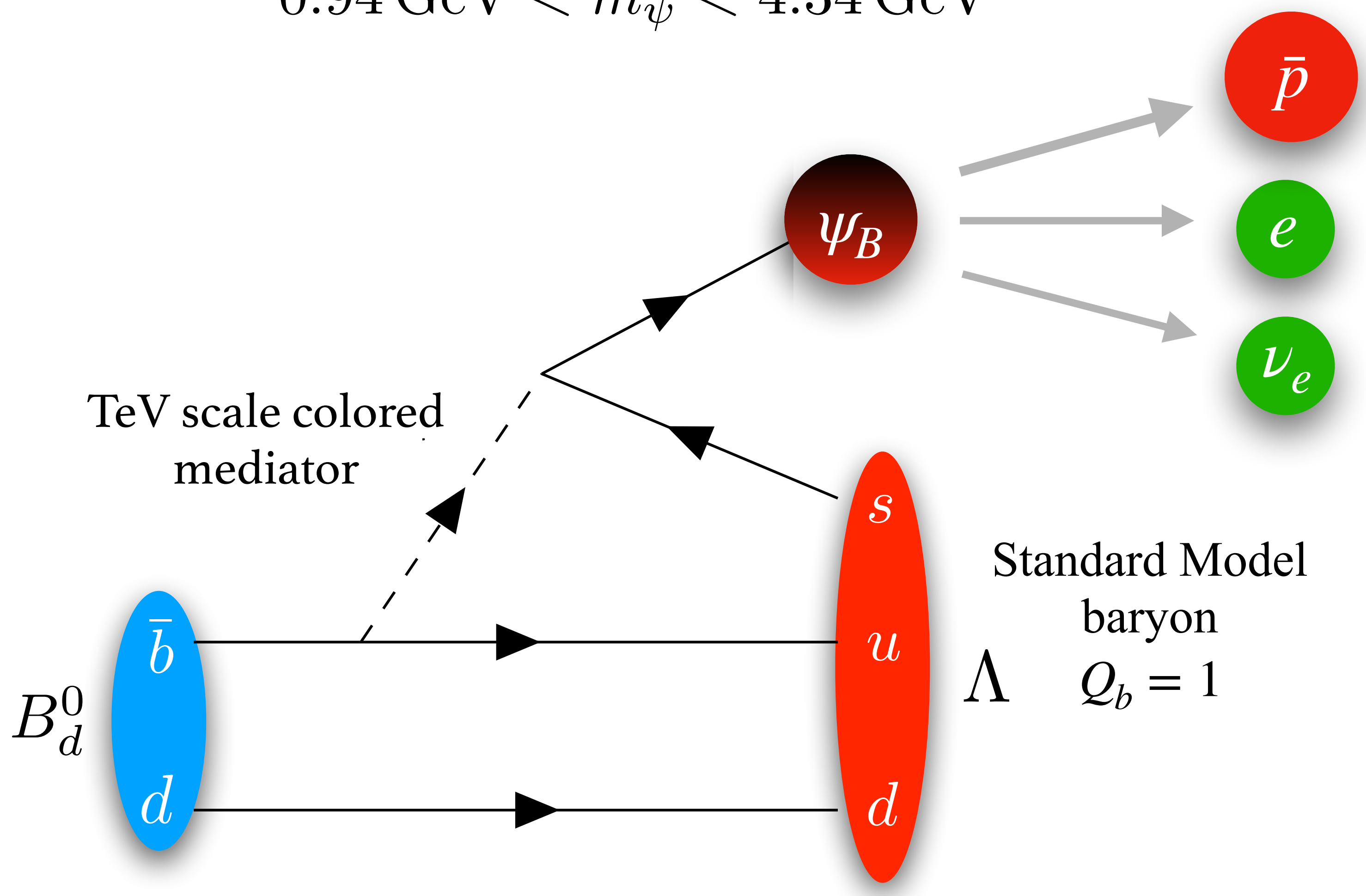
Neutral *B* Mesogenesis
Dark Matter?

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



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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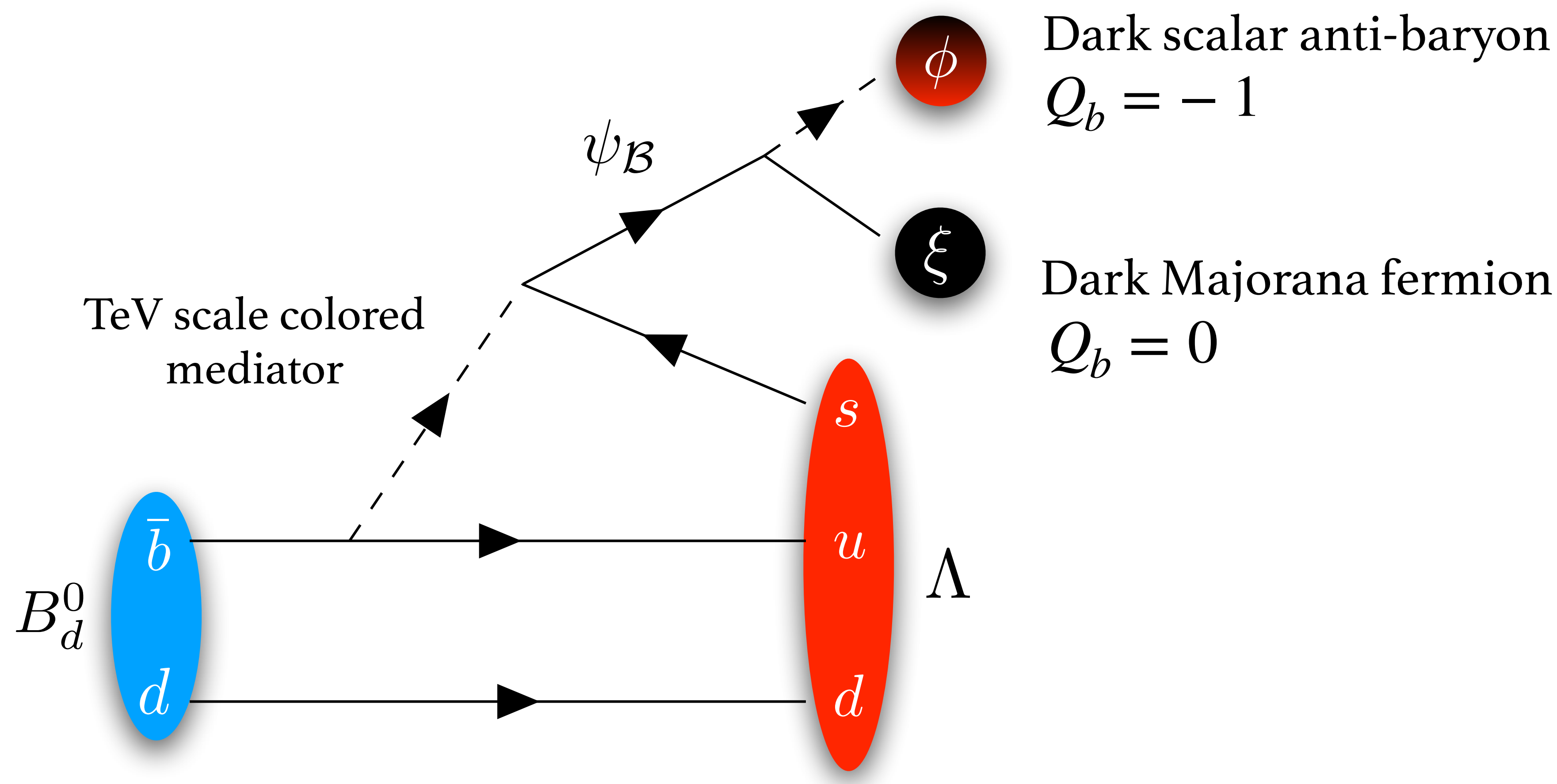
Neutral B Mesogenesis
Two-Component Dark Matter

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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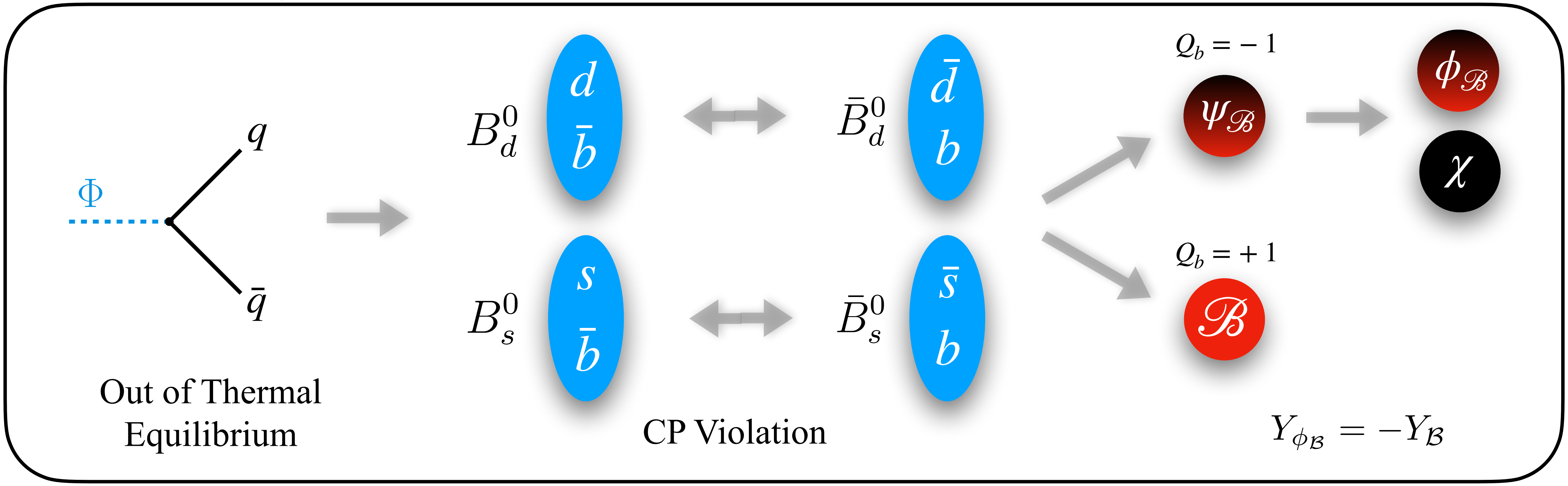
Neutral B Mesogenesis

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

Baryogenesis and Dark Matter from B Mesons

B^0 Mesogenesis



Neutral B Mesogenesis
Boltzmann Equations

Scalar, Radiation, Hubble:

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

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

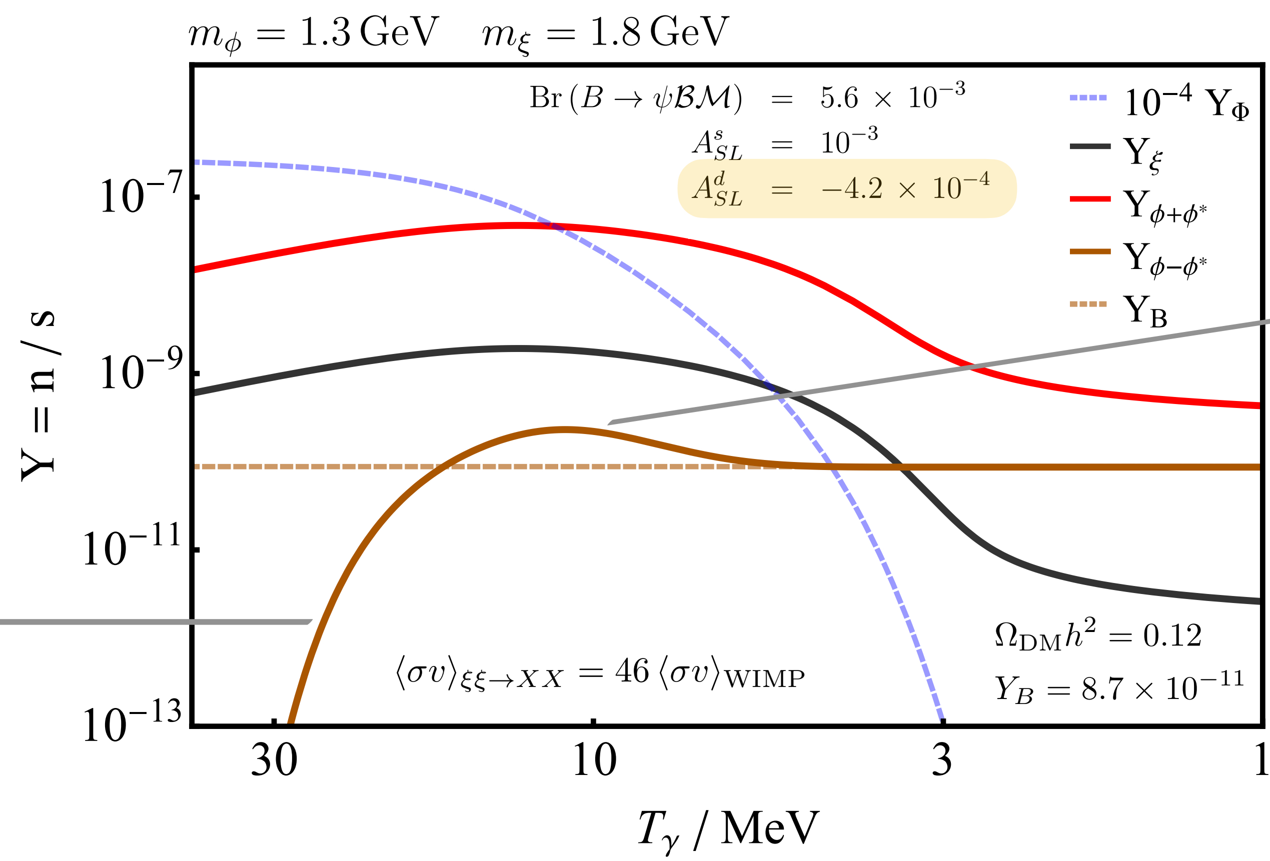
$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\left(\rho_{\rm rad} + m_\Phi n_\Phi\right)$$

Dark Matter:

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

Baryon Asymmetry:

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



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

Coherent B_s oscillations start to produce an asymmetry

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

Coherent B_d oscillations start to deplete the asymmetry

Need a net positive charge asymmetry

G. Elor

Neutral B Mesogenesis
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:

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

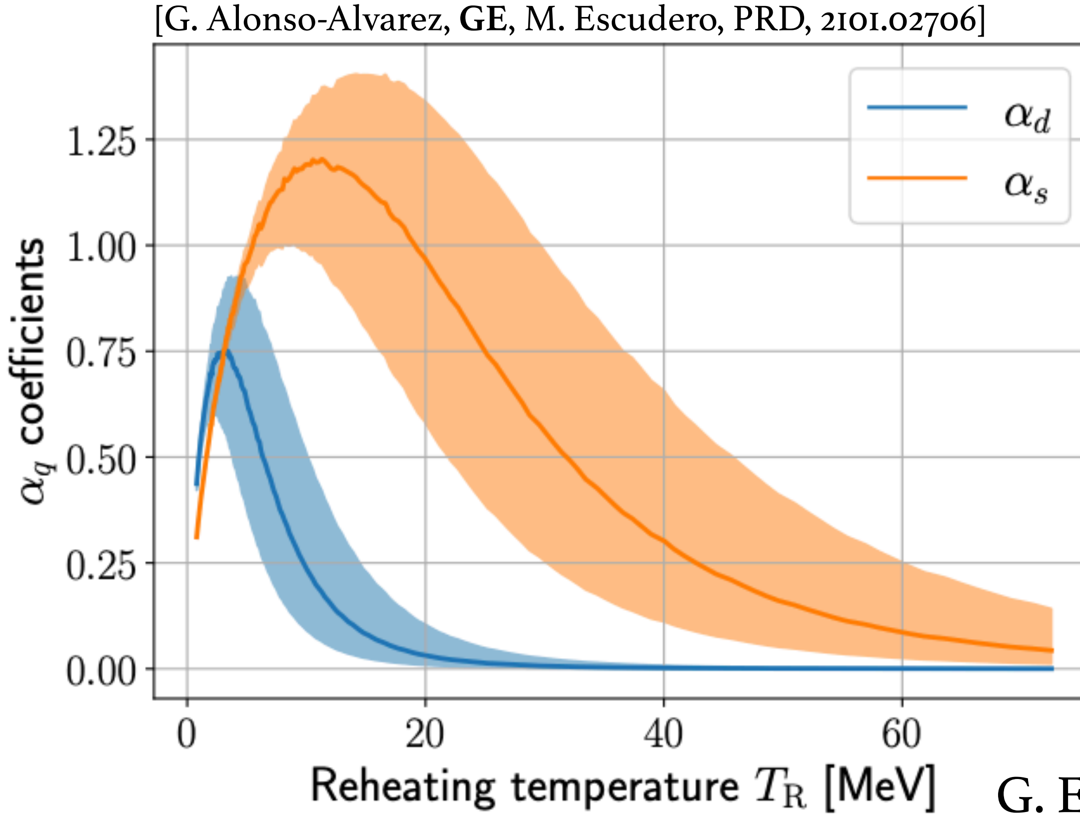
$$Y_\mathcal{B} \simeq 5\times 10^{-5} \sum_{i=d,s}\left[{\rm Br}\left(B_i^0 \to \bar\psi_\mathcal{B}\,\mathcal{B}_{\rm SM}\right) A_{sl}^i\right]\alpha_i(T_{\rm R})$$

(product of two experimental observables)

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]

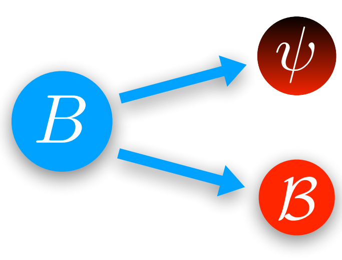
Collider Signals of Baryogenesis and Dark Matter from B Mesons (*B-Mesogenesis*)

Direct Signals

Semileptonic asymmetry: $A^q_{\mathrm{SL}} > 10^{-5}$

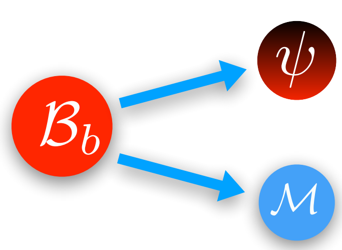
Belle II
LHCb
ATLAS
CMS

New B meson decay:



BaBar
Belle
Belle II
LHCb

New b-Baryon decay:



LHCb?
ATLAS??
CMS??

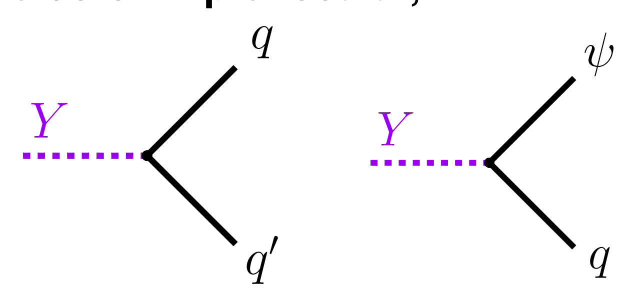
Indirect Signals

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*

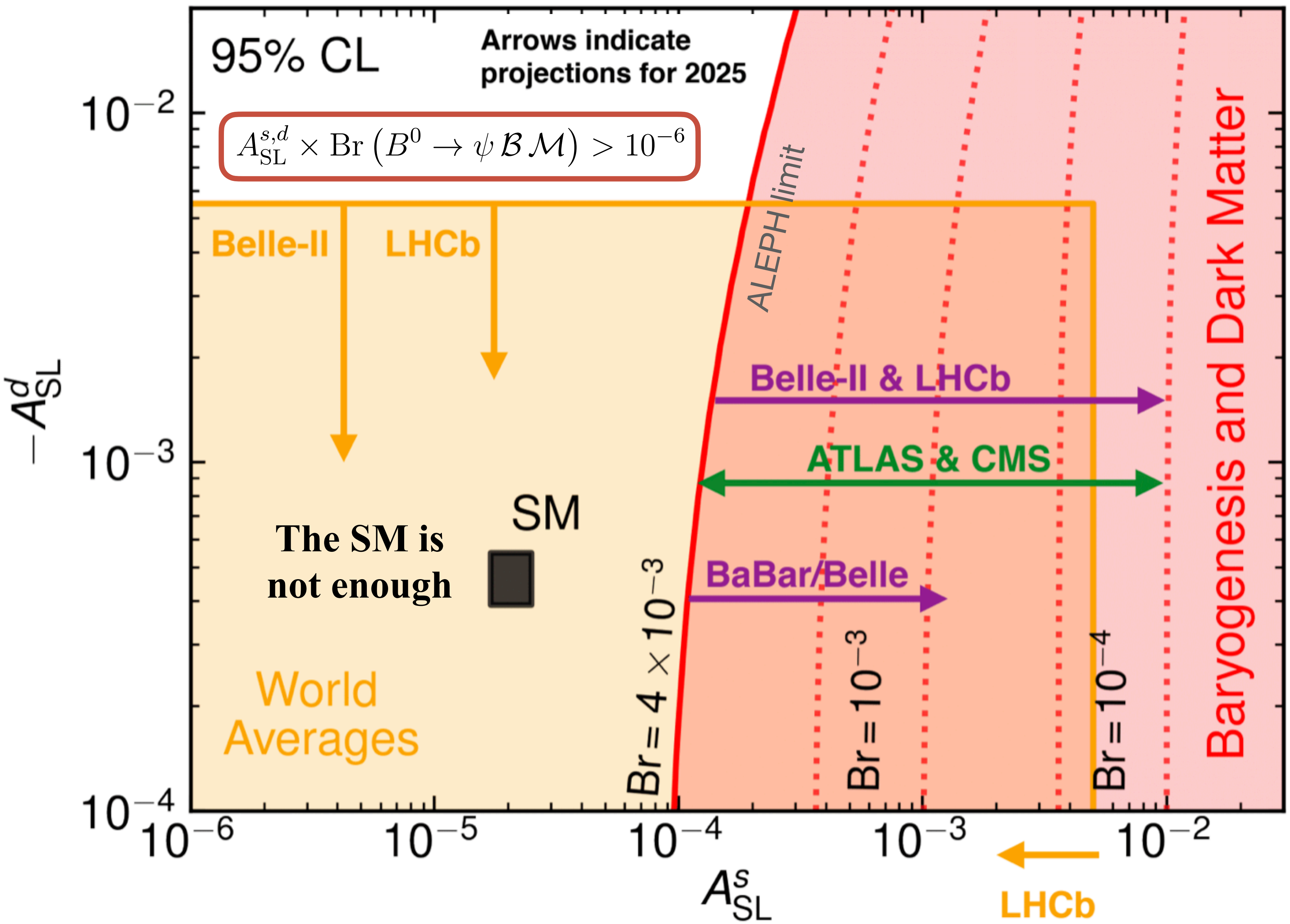


ATLAS
CMS

G. Elor

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

$$A^d_{sl}|_{\rm SM} = (-4.7 \pm 0.4) \times 10^{-4}$$
$$A^s_{sl}|_{\rm SM} = (2.1 \pm 0.2) \times 10^{-5}$$

G. Elor

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
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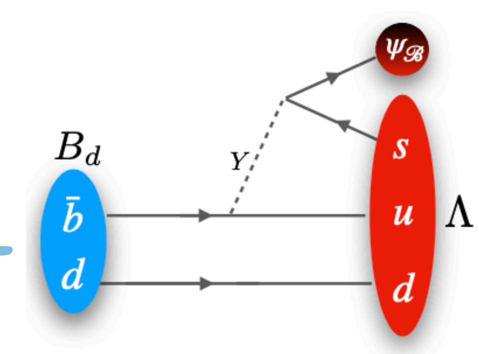
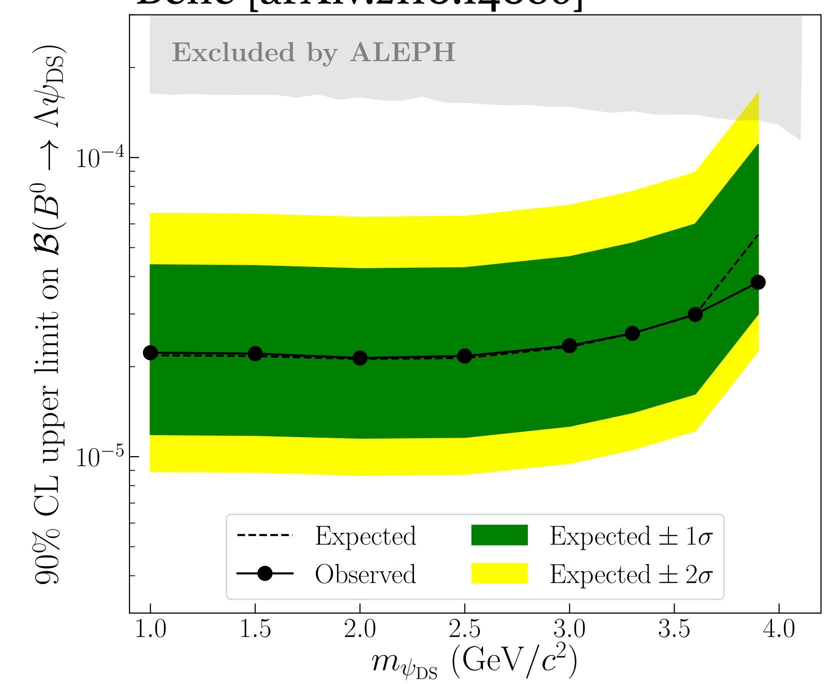
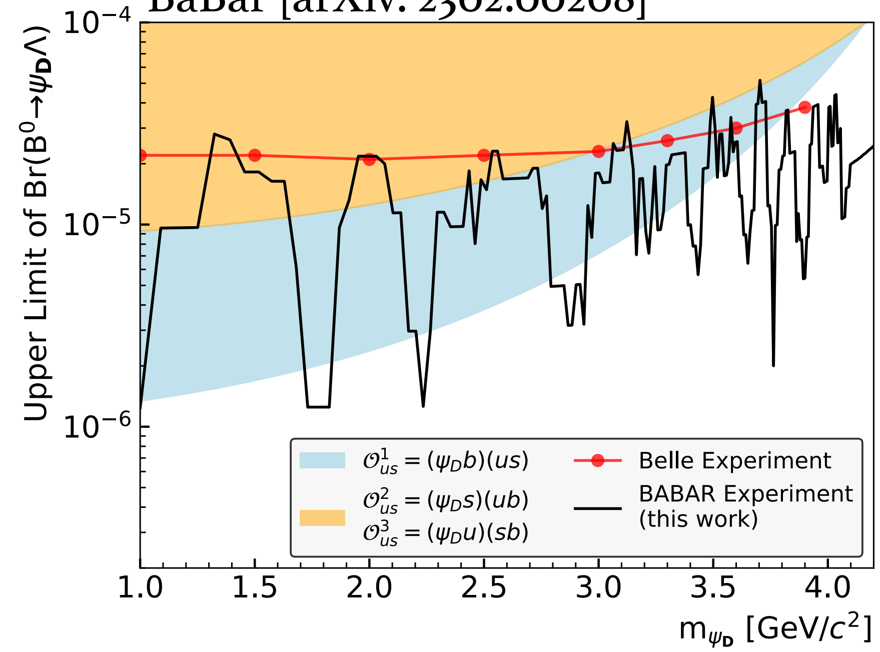


Belle [arXiv:2110.14086]



BaBar [arXiv: 2302.00208]



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

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

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

Yes!

Three other channels through which neutral B Mesogenesis can proceed.

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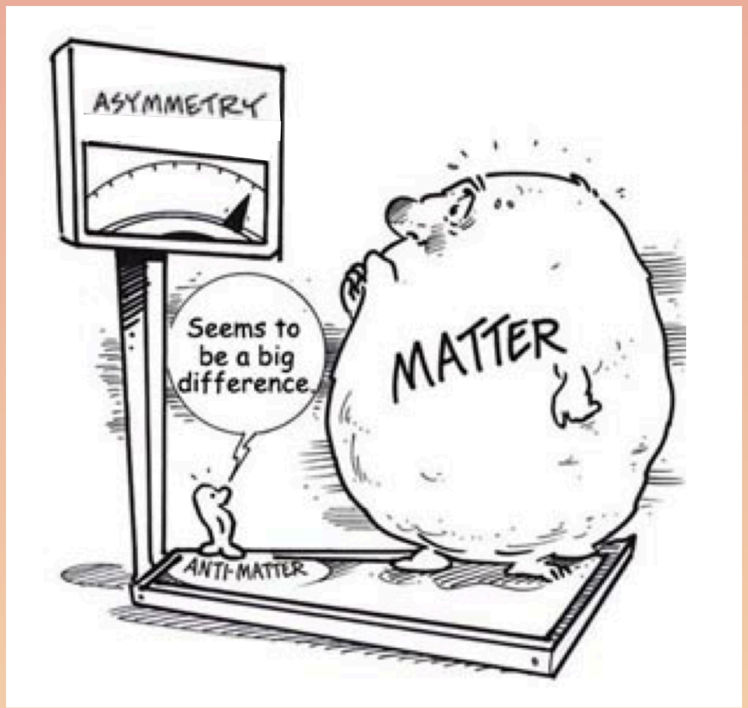
Outline



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

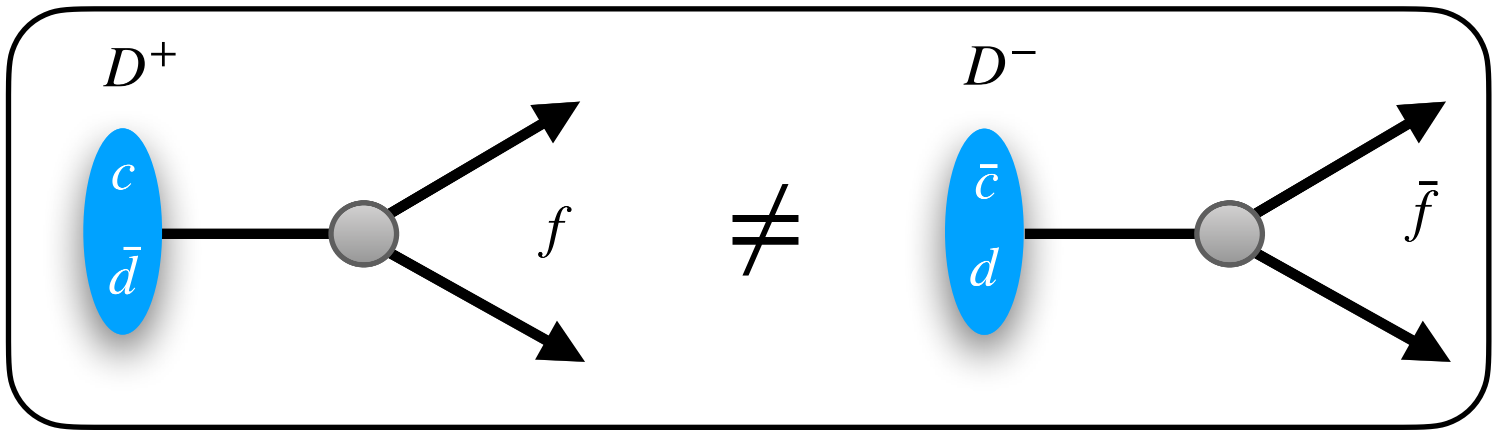
Upcoming: [**GE**, Can Kilic, Sanjay Mathai, Fall 2024 *(targeted)*]

Why Neutral B Mesons?

Particle Data Group:

D^+ decay mode	$A^f_{CP}/10^{-2}$
$K^0_S\pi^+$	-0.41 ± 0.09
$K^-\pi^+\pi^+$	-0.18 ± 0.16
$K^-\pi^+\pi^+\pi^0$	$-0.3 \pm 0.6 \pm 0.4$
$K^0_S\pi^+\pi^0$	$-0.1 \pm 0.7 \pm 0.2$
$K^0_S\pi^+\pi^+\pi^-$	$0.0 \pm 1.2 \pm 0.3$
$\pi^+\pi^0$	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

CPV in charged D decays:



Observable:

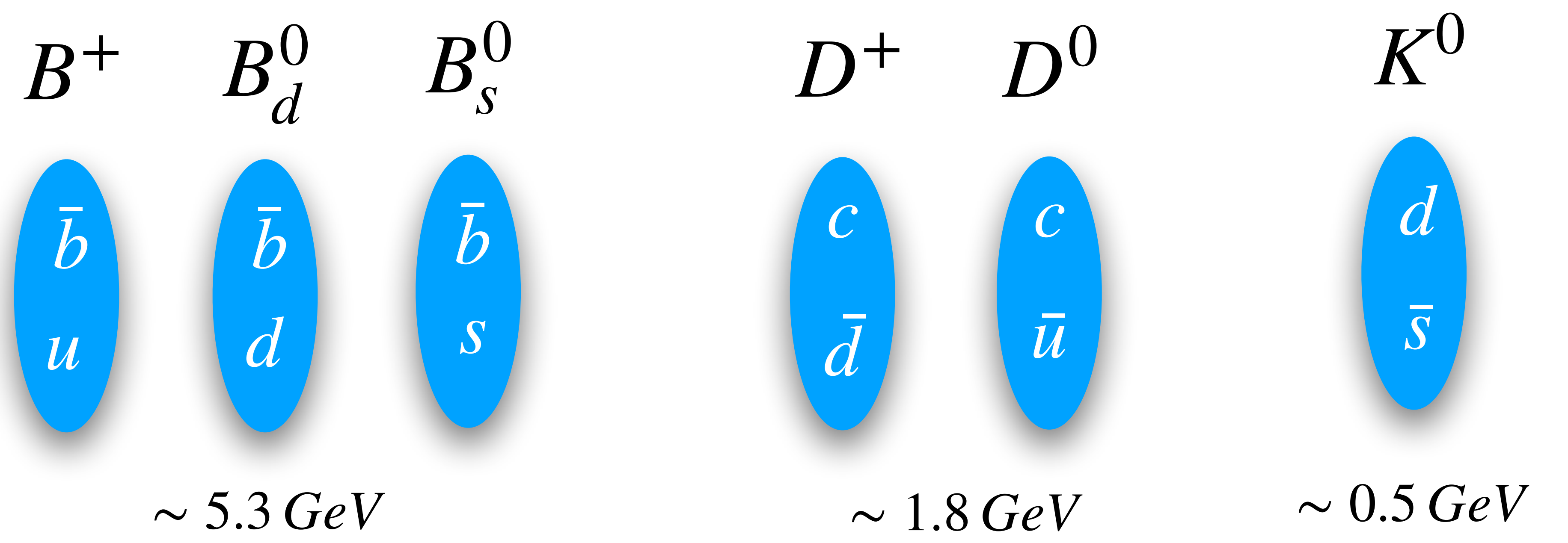
$$A^f_{CP} = \frac{\Gamma(D^+ \to f) - \Gamma(D^- \to \bar{f})}{\Gamma(D^+ \to f) + \Gamma(D^- \to \bar{f})}$$

Not a small number. We want to explain: ←

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

G. Elor

Why Neutral B Mesons?



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

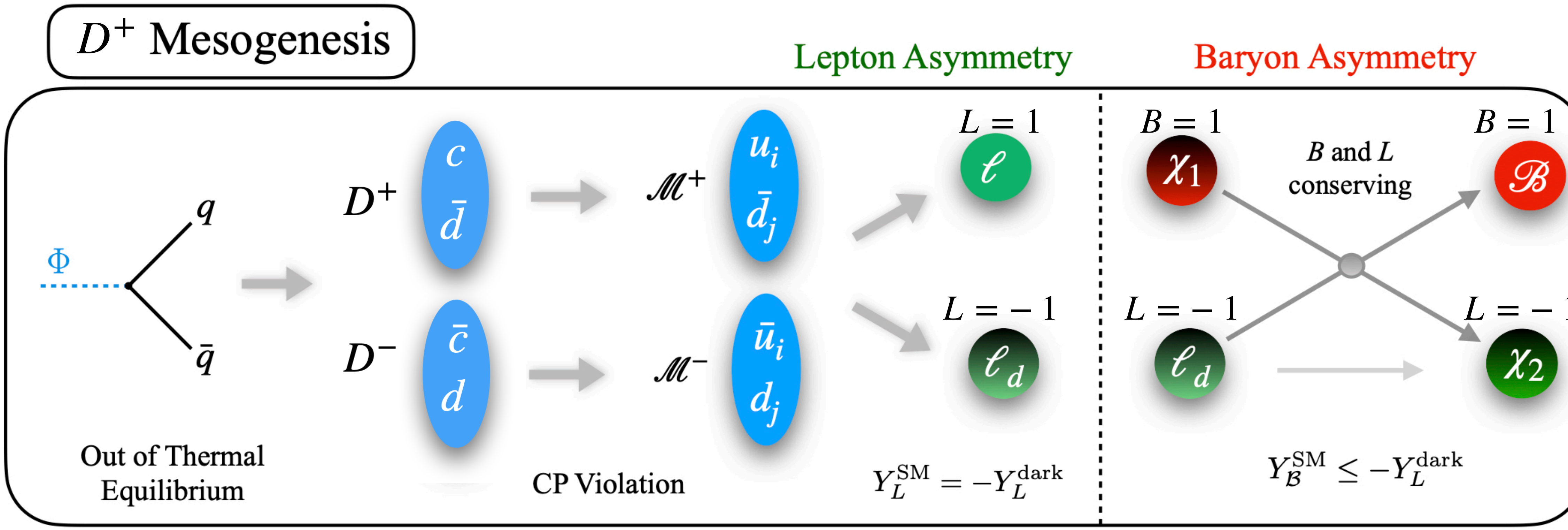
Kinematics: Dark baryons must be GeV scale. Only B mesons are heavy enough to decay into GeV scale.

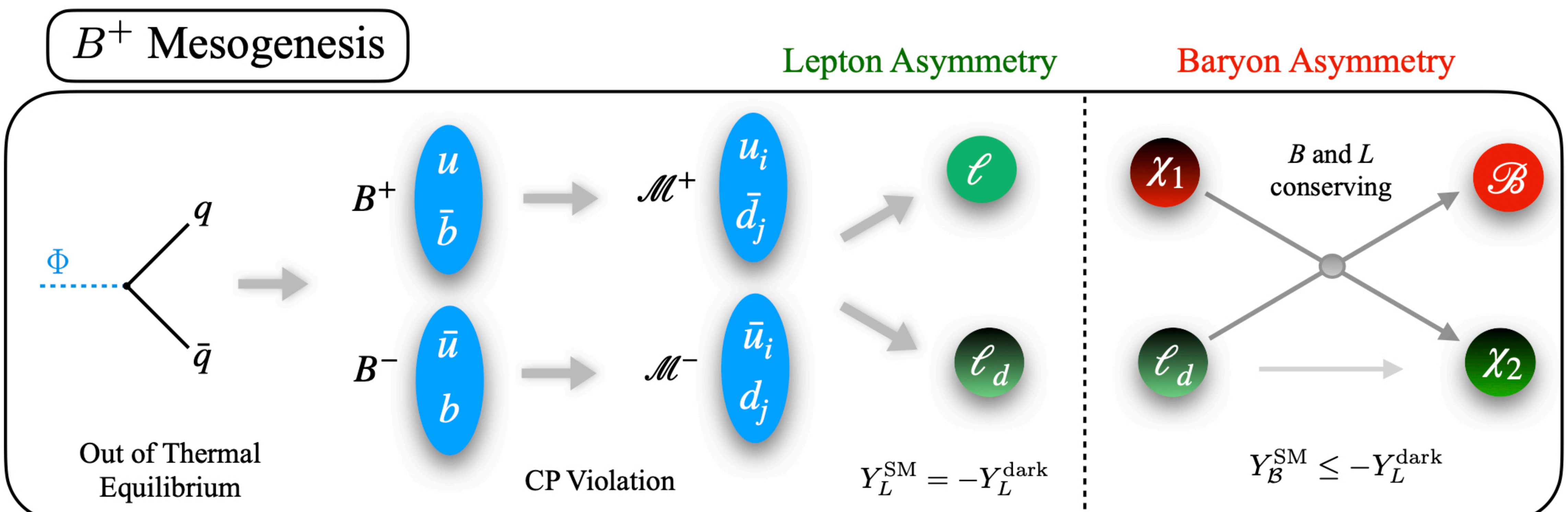
First generate a *lepton asymmetry*

G. Elor

Charged D and B Mesogenesis

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





G. Elor

Mesogenesis

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*)**

Common to all mechanisms proposed to date:

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

One mechanisms direct signal is another mechanisms indirect signal

G. Elor

Mesogenesis

Mechansim	CPV	Dark Sector	Observables	Relevant Experiments	
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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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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)**
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Baryogenesis with only the SM CP Violation

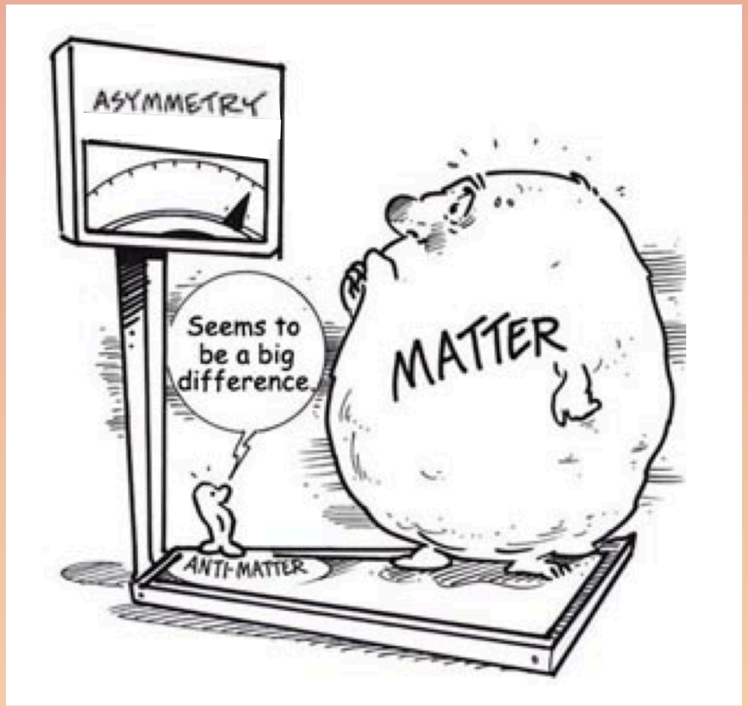
Common to all mechanisms proposed to date:

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

Outline



- Background on Mesogenesis.
- Bigger picture and the space of mechanisms.
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- Outlook (bigger picture, again).

Based on: [**GE**, Rachel Houtz, Seyda Ipek, Martha Ulloa, Submitted to PRL, 2408.12647], "*The Standard Model CP Violation is Enough*".

As well as:
[J. Berger, **GE,** PRL, 2301.04165]
[**GE**, A. Guerrera, JHEP, 2211.10553]
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[F. Elahi, **GE**, R. McGehee, PRD, 2109.09751]
[**GE,** R. McGehee, PRD, 2011.06115]
[G. Alonso-Alvarez, **GE**, M. Escudero, PRD, 2101.02706]
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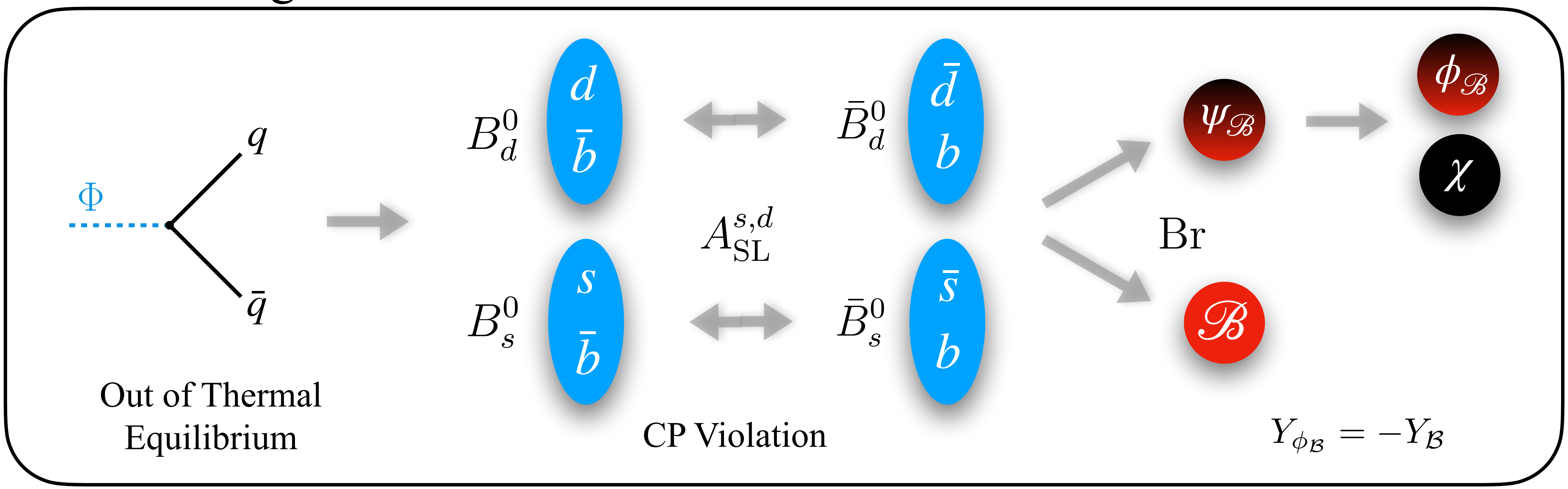
Upcoming: [**GE**, Can Kilic, Sanjay Mathai, Fall 2024 *(targeted)*]

Based on Neutral B Mesogenesis

B^0 Mesogenesis



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

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

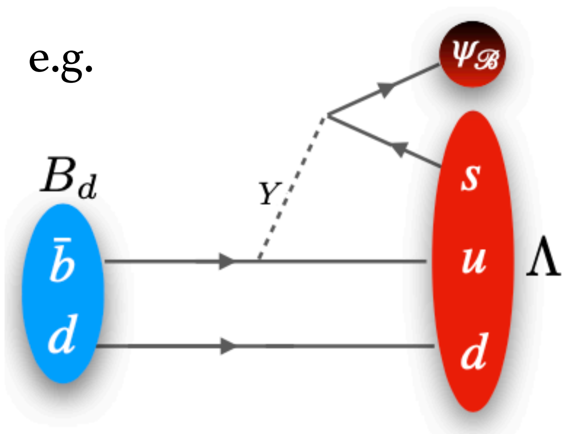
G. Elor

Based on Neutral B Mesogenesis

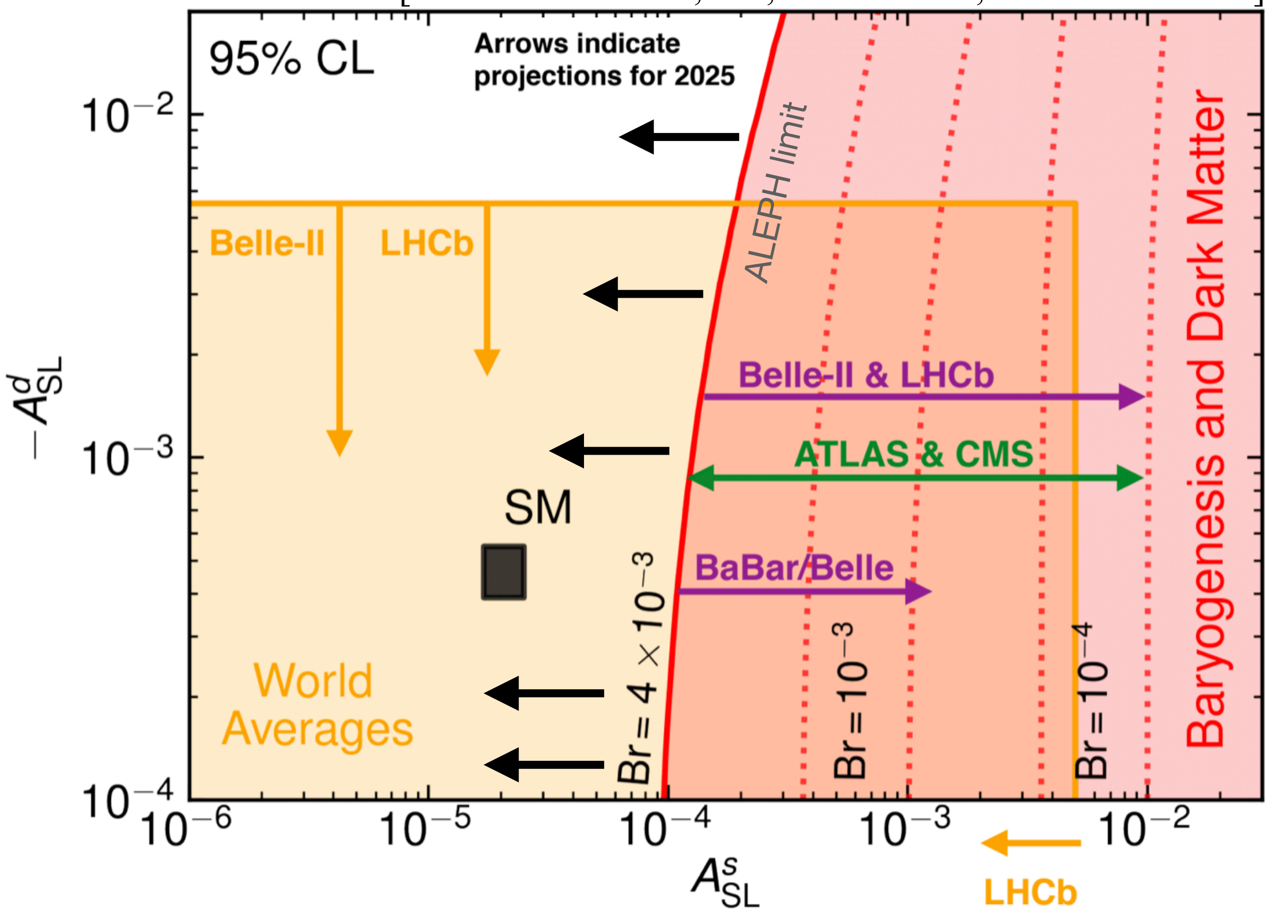
- Baryon asymmetry produced through decays mediated by a heavy colored particle:

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

- 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: $\mathrm{Br} \propto 1/M_{\mathcal{Y}}^4$



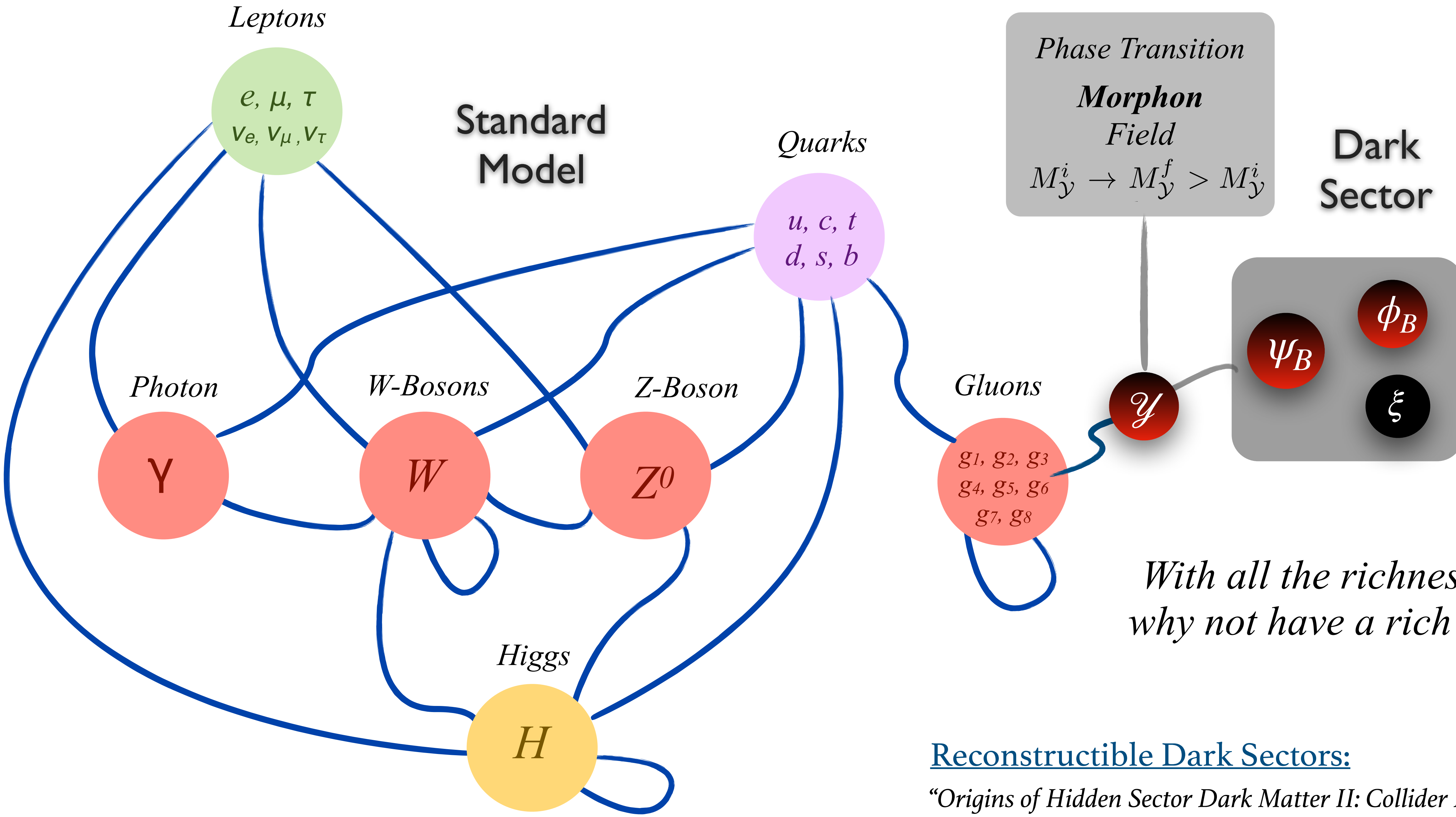
[A. Alonso-Alvarez, **GE**, M. Escudero, PRD 2101.02706]



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

Elor

Morphing the Mediator



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

Reconstructible Dark Sectors:

"Origins of Hidden Sector Dark Matter II: Collider Physics"
Cliff Cheung, GE, **Lawrence Hall**, Piyush Kumar
JHEP (2011) 1010.0024

"Origins of Hidden Sector Dark Matter I: Cosmology"
Cliff Cheung, GE, **Lawrence Hall**, Piyush Kumar
JHEP (2011) 1010.0022

Tricks with Dark Sector Phase Transitions:

"Light Dark Matter through Resonance Scanning"
Djuna Croon, GE, Rachel Houtz, **Hitoshi Murayama**, Graham White, PRD (2020) 2012.15284

Morphing the Mediator

T_R

$\sim 5 - 80$ MeV

B-Mesogenesis generates baryon asymmetry

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

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

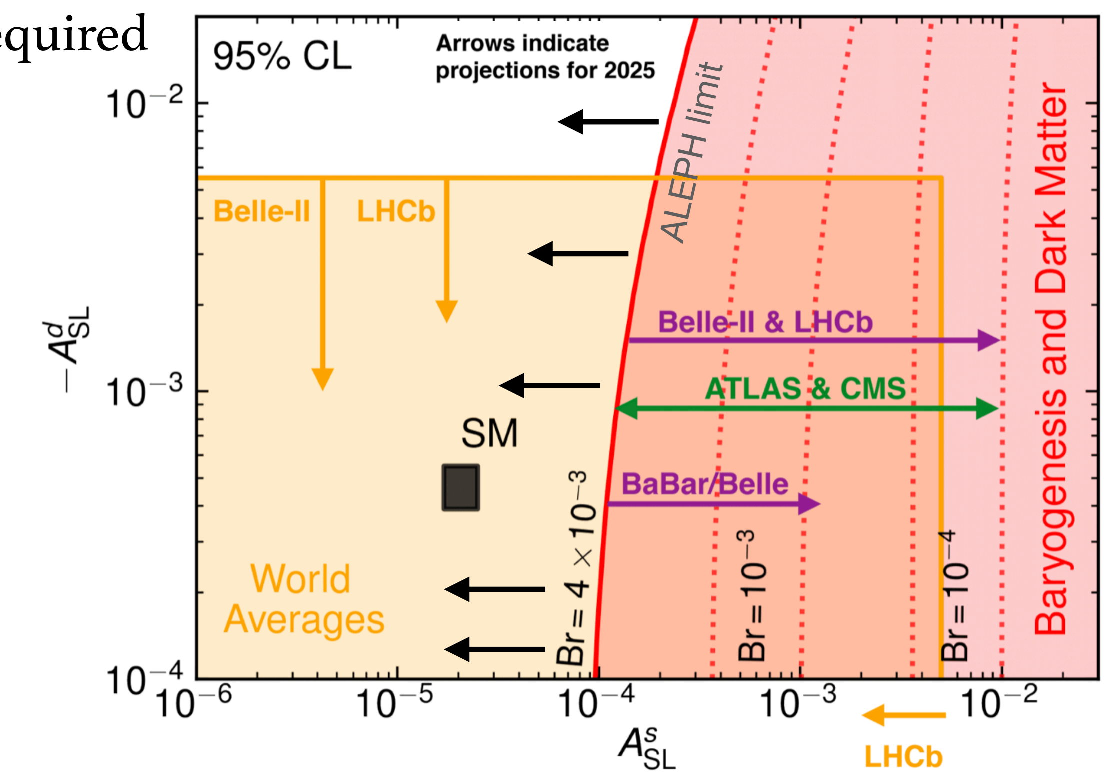
${\rm Br} \propto 1/M_{\mathcal{Y}}^4$ Enhanced relative to today by a factor $(M_{\mathcal{Y}}^f/M_{\mathcal{Y}}^i)^4$

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

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

Today

Smaller Br expected. Collider constraints evaded.

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

G. Elor

Can the SM CPV be enough?

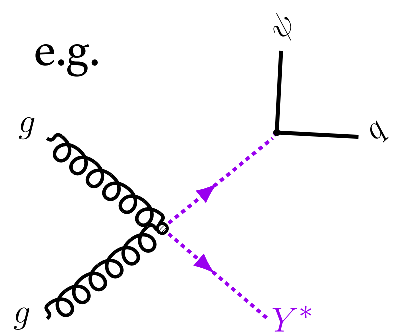
- Colored mediator ***Y*** has **TeV scale mass**:

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.



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

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

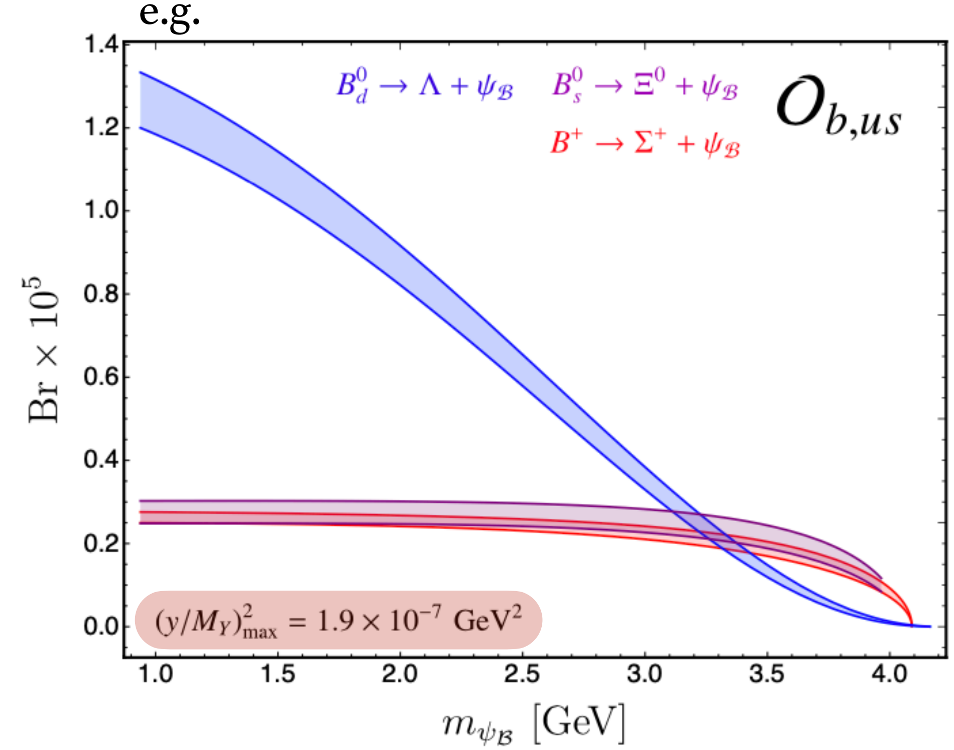
- Branching fraction:

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

Exact form computed using QCD light cone sum rules

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

e.g.



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Can the SM CPV be enough?

Yes!

		$\Gamma_0 \equiv \Gamma_{\mathcal{B}}\vert_{m_{\psi_\mathcal{B}}=1\text{GeV}}/\mathcal{C}^2_{b,u_i d_j}$	
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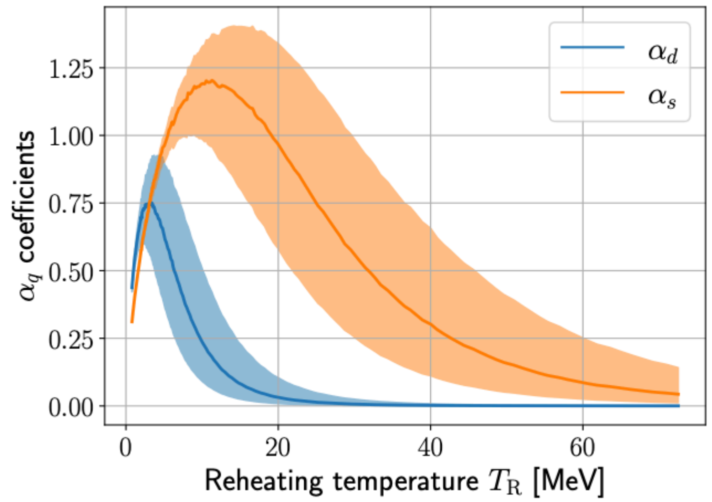
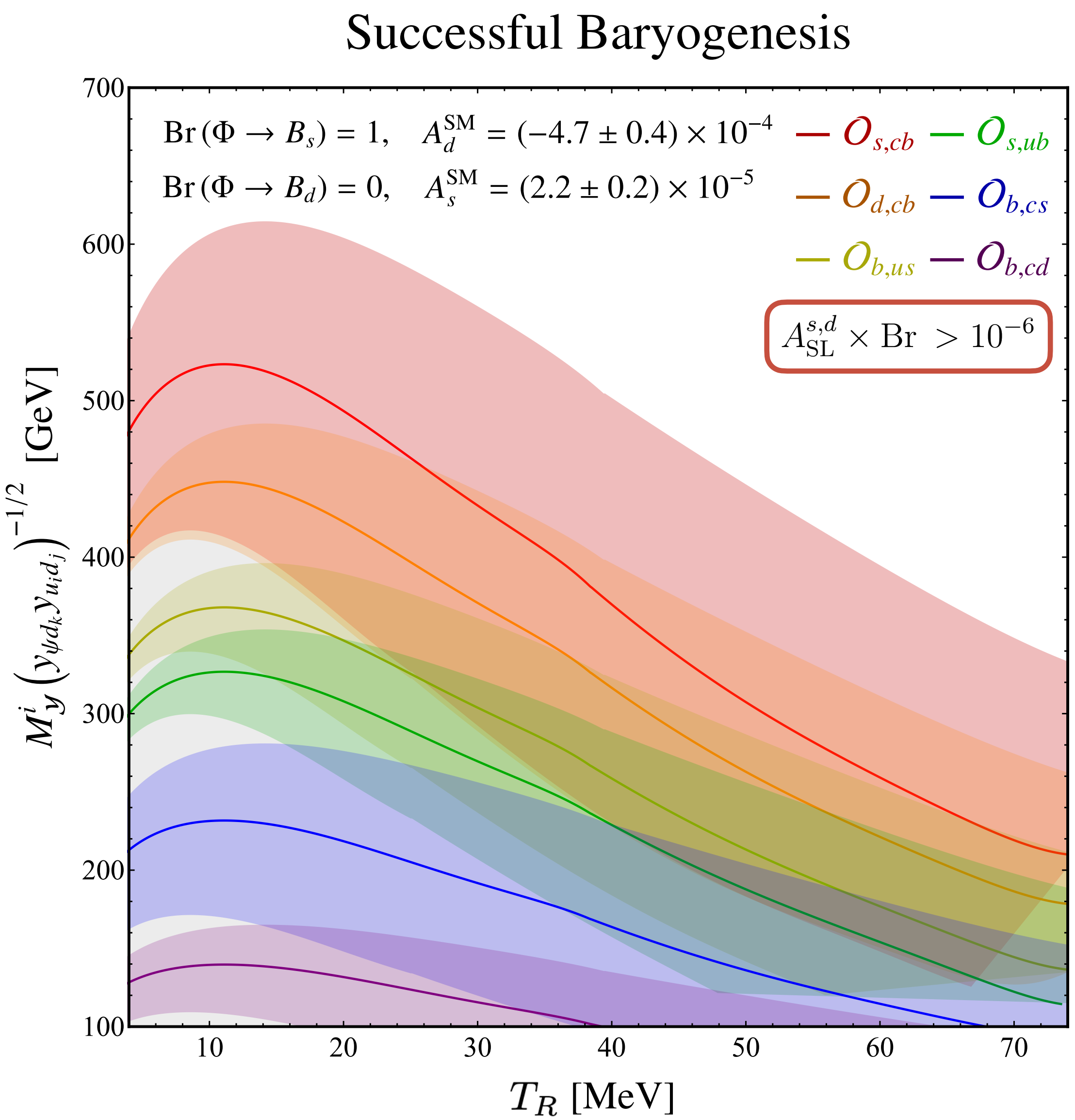
$$Y_\mathcal{B} \simeq 5\times 10^{-5} \sum_{i=d,s}\left[A_{\rm SL}^{s,d}\times \text{Br}\right]\alpha_i(T_R)$$

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





G. Elor

Morphing the Mediator

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

- Seems like a reasonable phase transition ? Scalar *morphon* gets a vev.

  1) Nucleation: The mass shift must occur after the BAU is generated.
  2) Percolation: The Universe must effectively transit from the false to the true morphon vacuum.
  3) Avoid Inflation: To avoid triggering inflation after the BAU is generated or during BBN, the scalar morphon must not dominate the energy density of the Universe.

Can we find an example?

- Did this "trick" cost us a signal??

Morphing with Dark Dynamics

- Toy morphon potential $V_{\rm scalar} = m_{\mathcal{Y}0}^2|\mathcal{Y}|^2 + y_{\phi\mathcal{Y}}|\mathcal{Y}|^2\phi + \frac{1}{2}\lambda_{\phi\mathcal{Y}}|\mathcal{Y}|^2\phi^2 + \frac{1}{4}\lambda(\phi^2-\phi_0^2)^2 + \epsilon\,\phi_0\,\phi^3$

$$M_{\mathcal{Y}}^2(\phi) = m_{\mathcal{Y}_0}^2 + y_{\phi\mathcal{Y}}\phi + \tfrac{1}{2}\lambda_{\phi\mathcal{Y}}\phi^2 \qquad v_{\rm false/true} = \pm\phi_0 + \mathcal{O}(\epsilon)$$

- Find example such that $M_{\mathcal{Y}}^i = M_{\mathcal{Y}}(v_{\rm false}) = \mathcal{O}(100\ \text{GeV})$

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

Domain Wall (DW) example

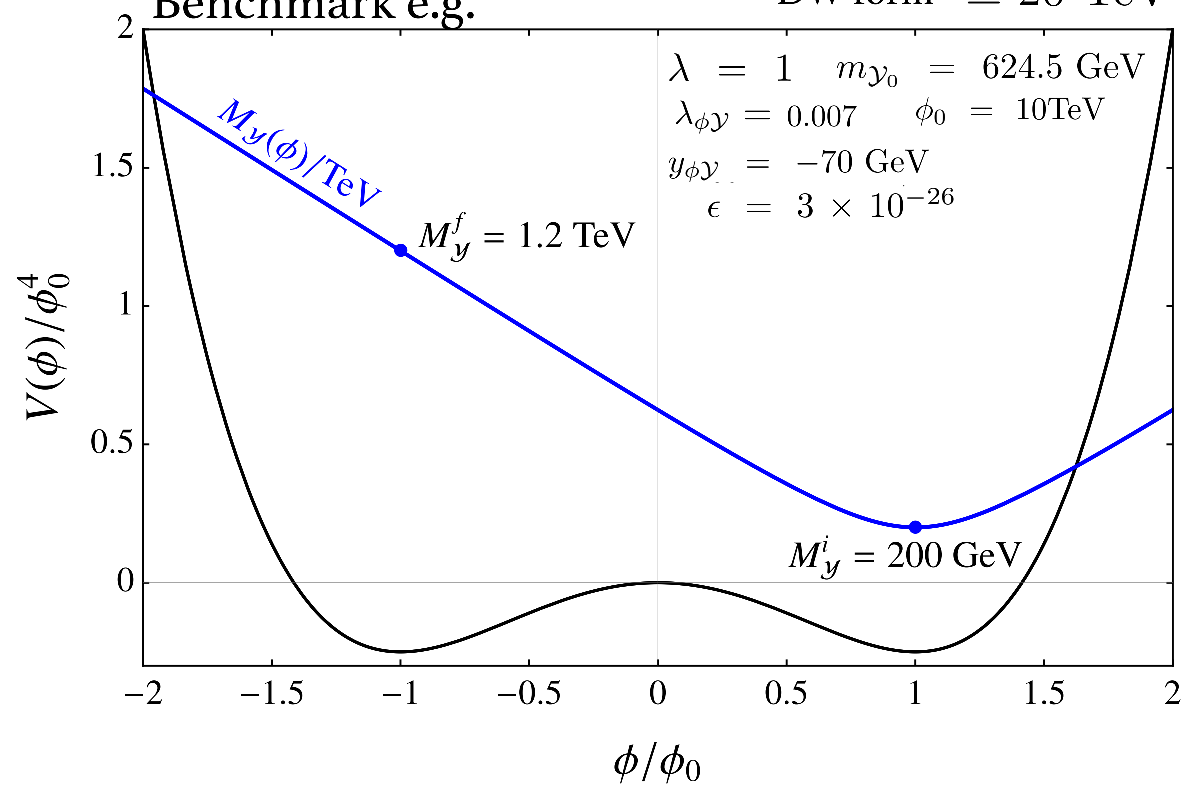
DWs percolate:	$\epsilon \lesssim 0.2\lambda$
DWs grow to horizon size:	$\epsilon < \frac{2\sqrt{2}}{3}\sqrt{\frac{8\pi^3 g_{\rm eff}}{90}}\frac{T^2}{M_{Pl}}\frac{\sqrt{\lambda}}{\phi_0}\Big\rvert_{T=T_c=2\phi_0}$
DW annihilate at 10MeV (after BAU, before BBN):	$\epsilon > \frac{2\sqrt{2}}{3}\sqrt{\frac{8\pi^3 g_{\rm eff}}{90}}\frac{T^2}{M_{Pl}}\frac{\sqrt{\lambda}}{\phi_0}\Big\rvert_{T=10\ \text{MeV}}$
DW annihilate before they trigger inflation:	$\epsilon > \left(\frac{4}{3}\right)^3\frac{4\pi\lambda\phi_0^2}{M_{Pl}^2}$

See [G. B.Gelmini, et. al. JCAP 02, 032, 2009,01903]

DW pressure and surface tension: $p_T = \sigma/R,\ \ \sigma = (2\sqrt{2}/3)\sqrt{\lambda}\phi_0^3$

DW annihilate when: $p_T > p_{\rm vac} = \epsilon\phi_0^4 \longrightarrow t_{\rm ann} \sim \sigma/\epsilon\phi_0^4$

Benchmark e.g. DW form $\simeq 20$ TeV



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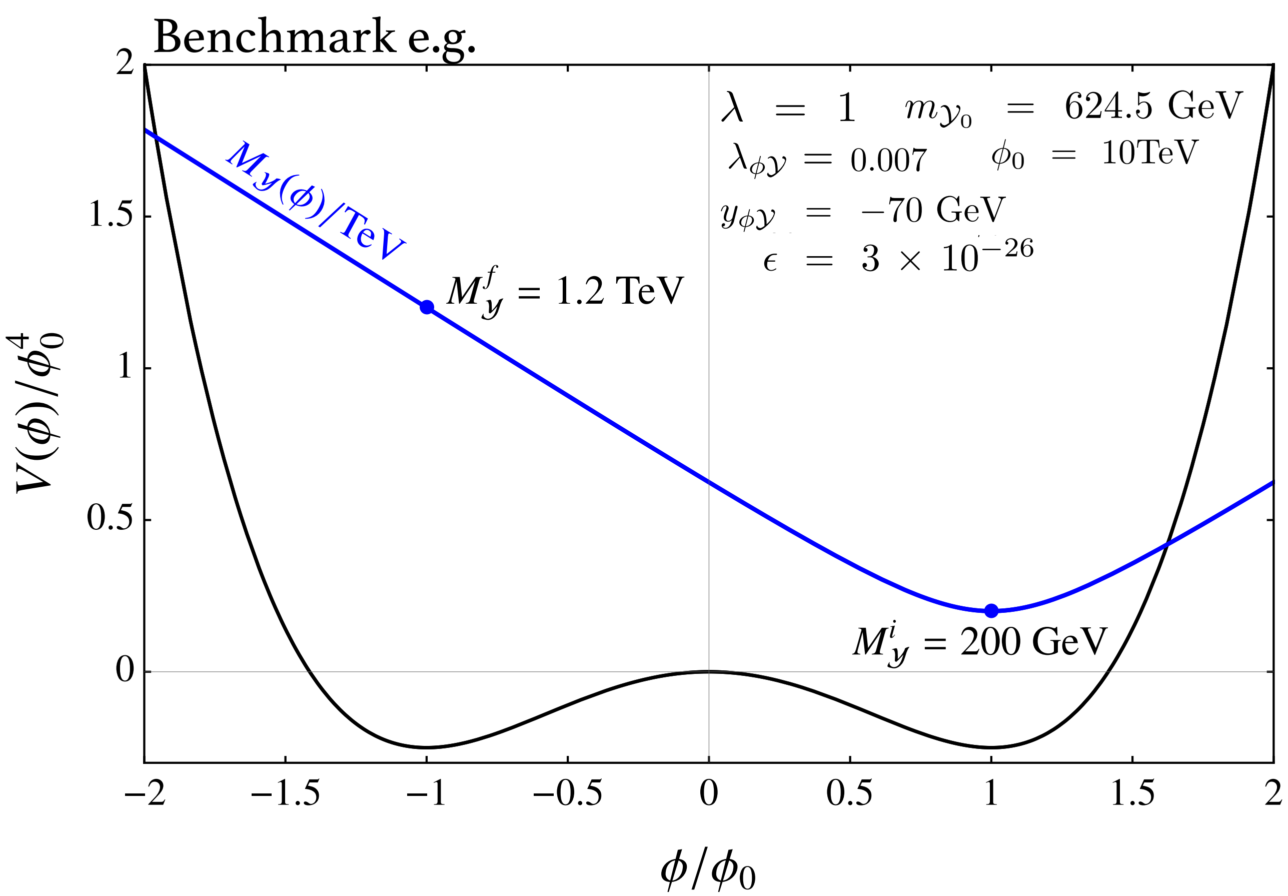
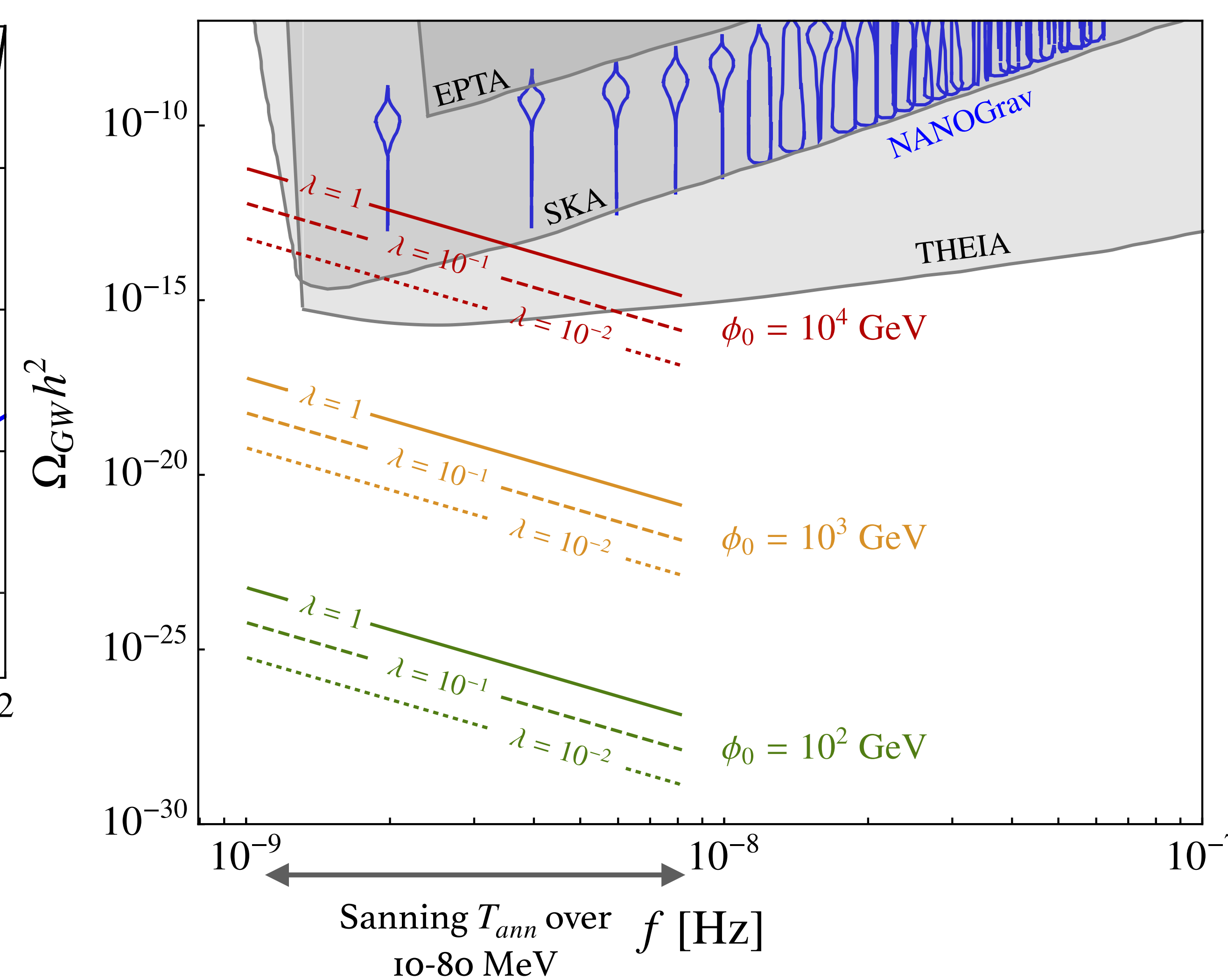
Gravitational Wave Signal

The annihilation of the DW network can leave behind a stochastic gravitational wave background.

Benchmark e.g.



Standard expressions
e.g. from G. B.Gelmini et. al, JCAP, 032, 2009,01903:



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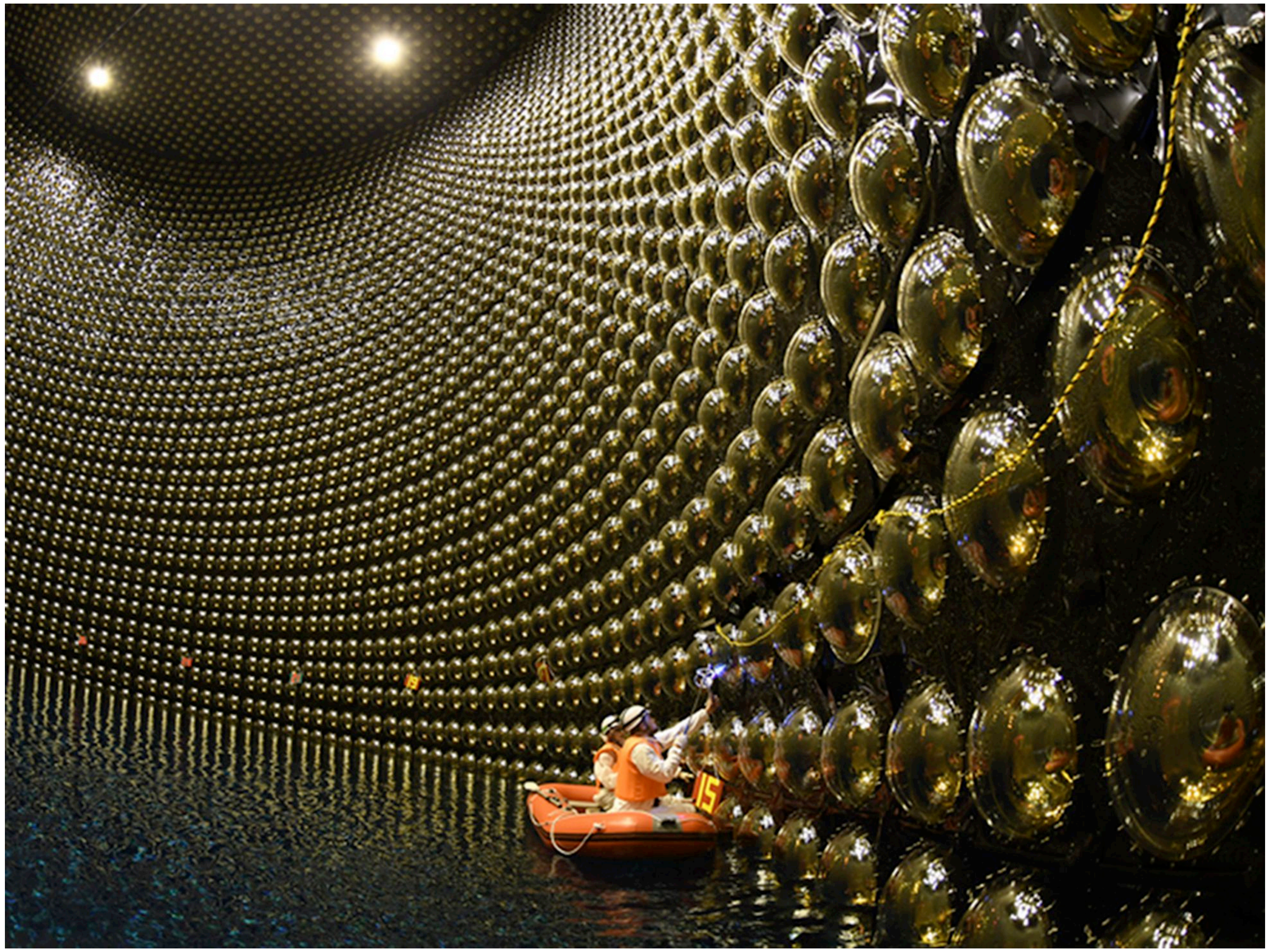
Searching for the Dark Matter

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

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



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

HYPER K

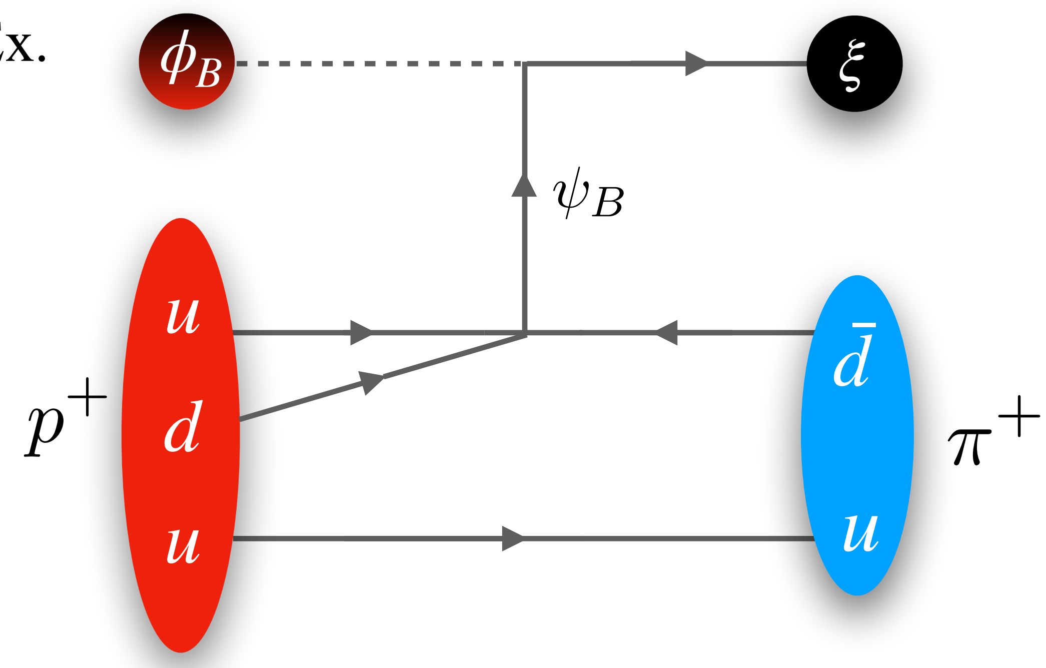
JUNO

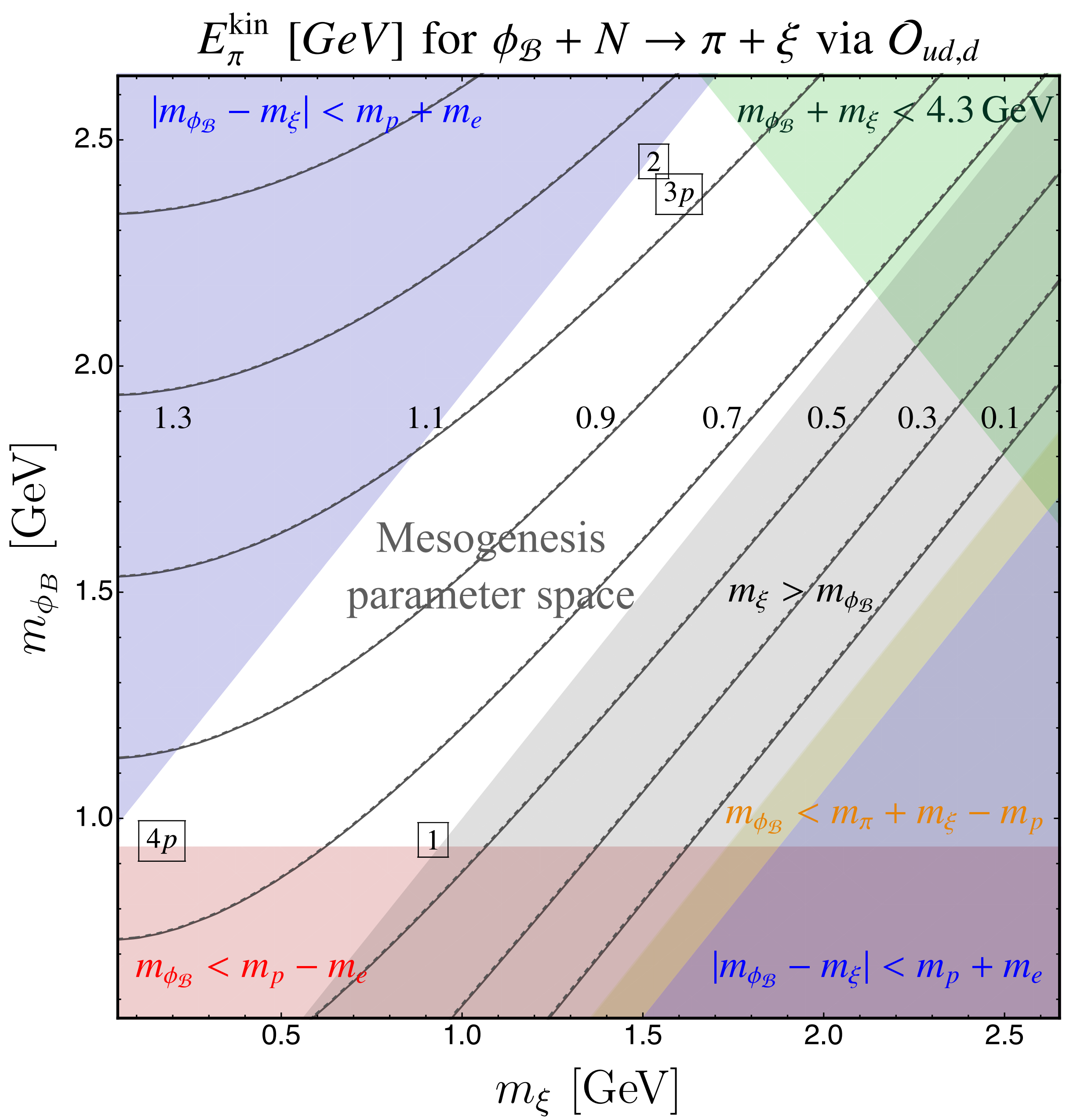
DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Dark Matter Induced Nucleon Decay

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

Ex.





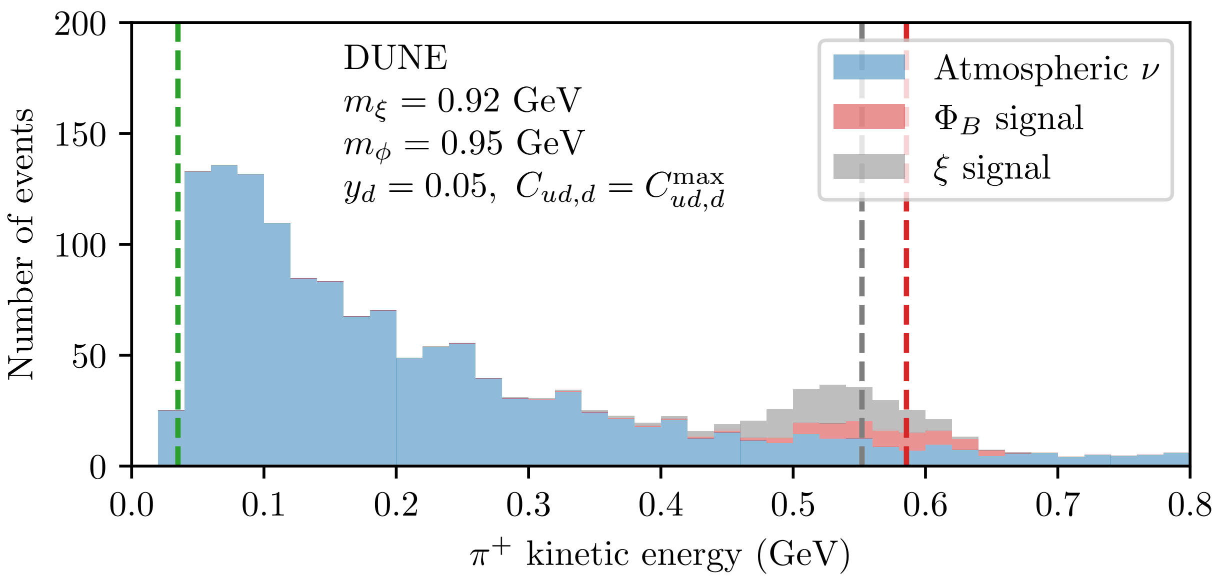
Mono-energetic meson (up to detector effects):

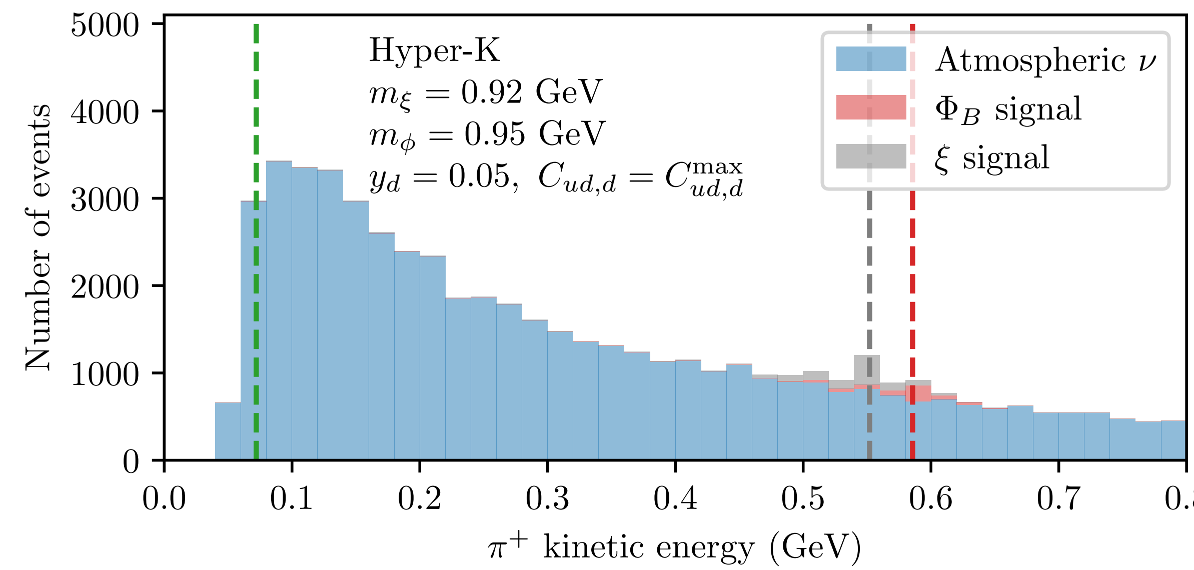
$$E^{\mathcal{M},\,\rm kin}_{\phi_{\mathcal{B}} N \to \xi \mathcal{M}} = \frac{m_{\mathcal{M}}^2 - m_\xi^2 + (m_N + m_{\phi_B})^2}{2(m_N + m_{\phi_B})} - m_{\mathcal{M}}$$

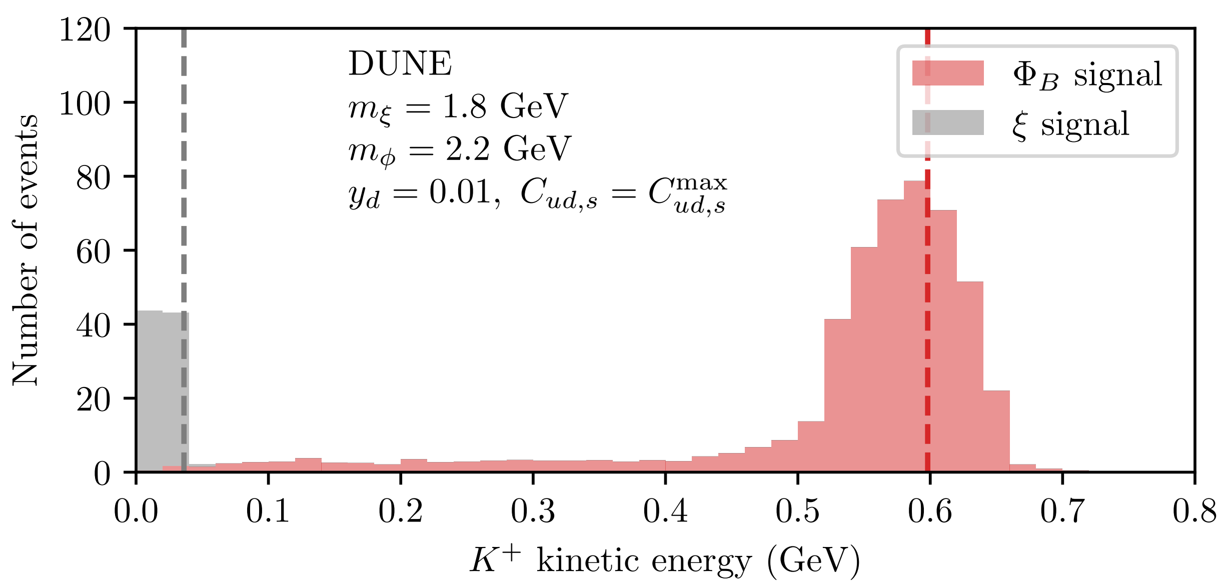
[J. Berger, G. Elor. Submitted to PRL. arXiv:2301.04165]

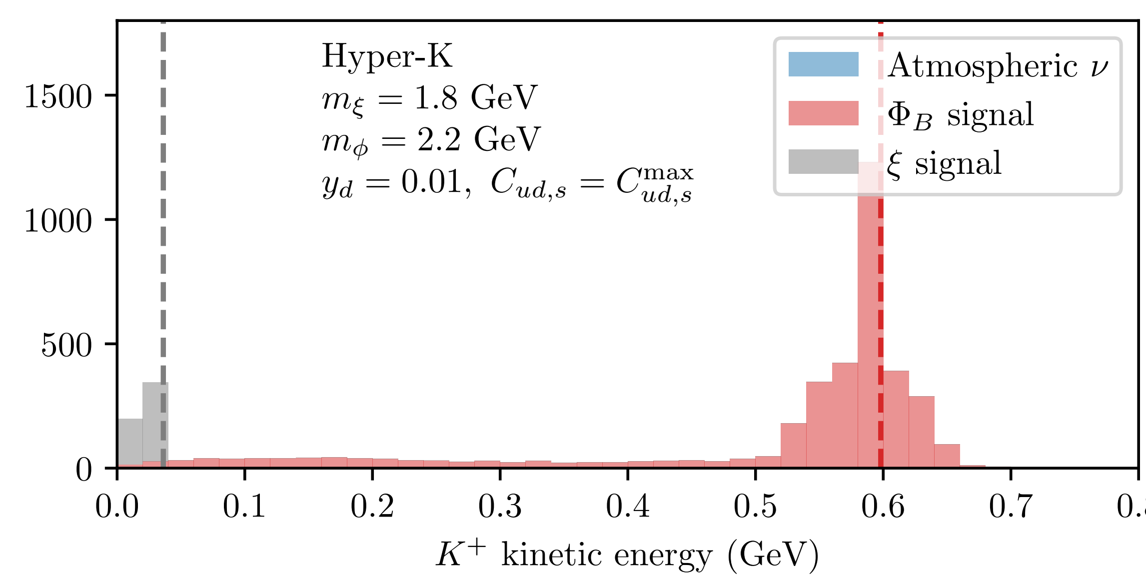
Signal and Background Simulation

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









Next: Searches in astrophysics and cosmology environments

Mesogensis with a Morphing Mediator

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

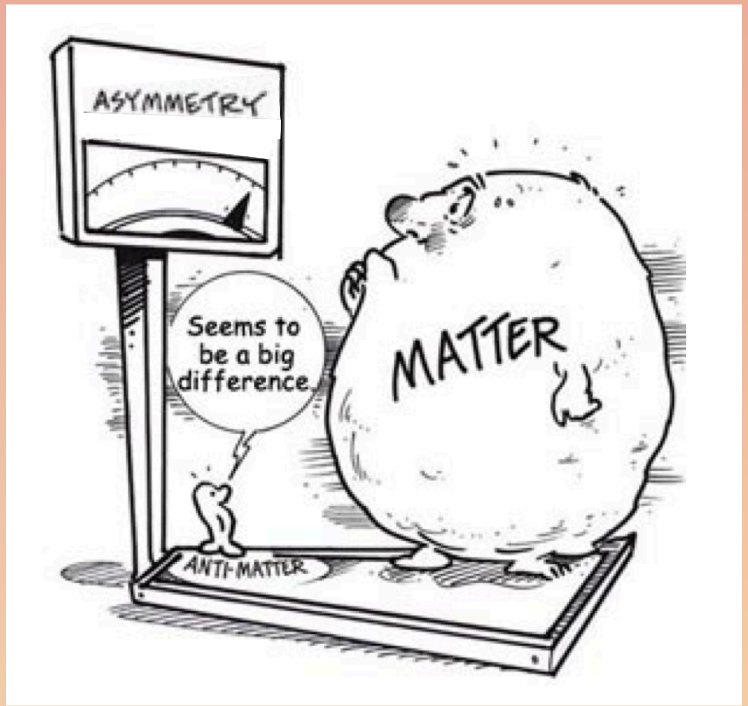
"*The Standard Model CP Violation is Enough*".

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]

Outline



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

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)***

CPV from entirely from the dark sector?

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

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

Br as low as $10^{-7} - 10^{-6}$ expected.

<u>My message to experimentalists:</u> measuring Br to better sensitivity could discover baryogenesis.

<u>My message to theorists:</u> it is experimentally motivated to fully explore the space of Meso mechanisms.

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!
- To fully take advantage of the experimental program we must comprehensively explore all possible mechanisms, variations, and signals.

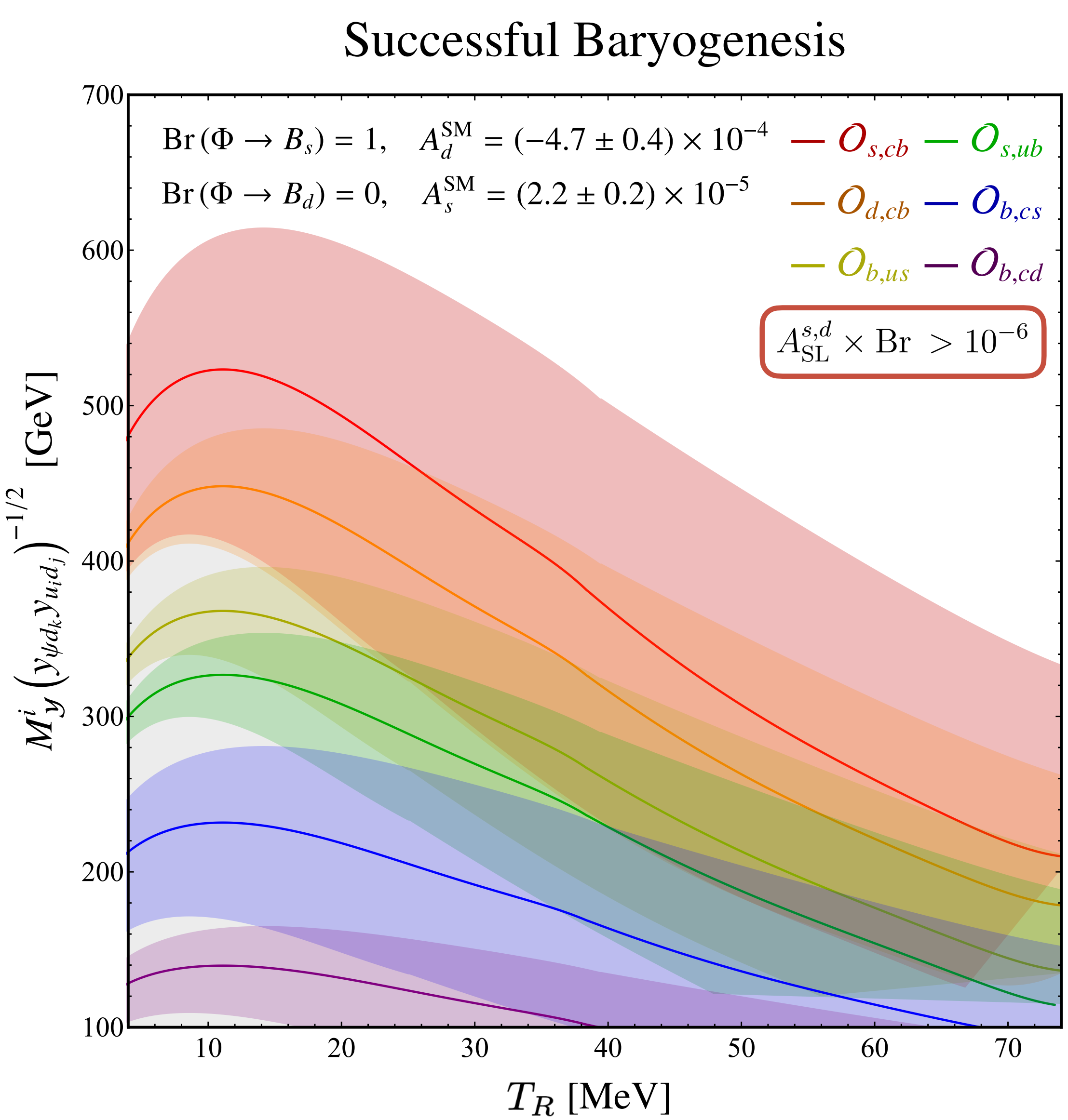
How can we exist?

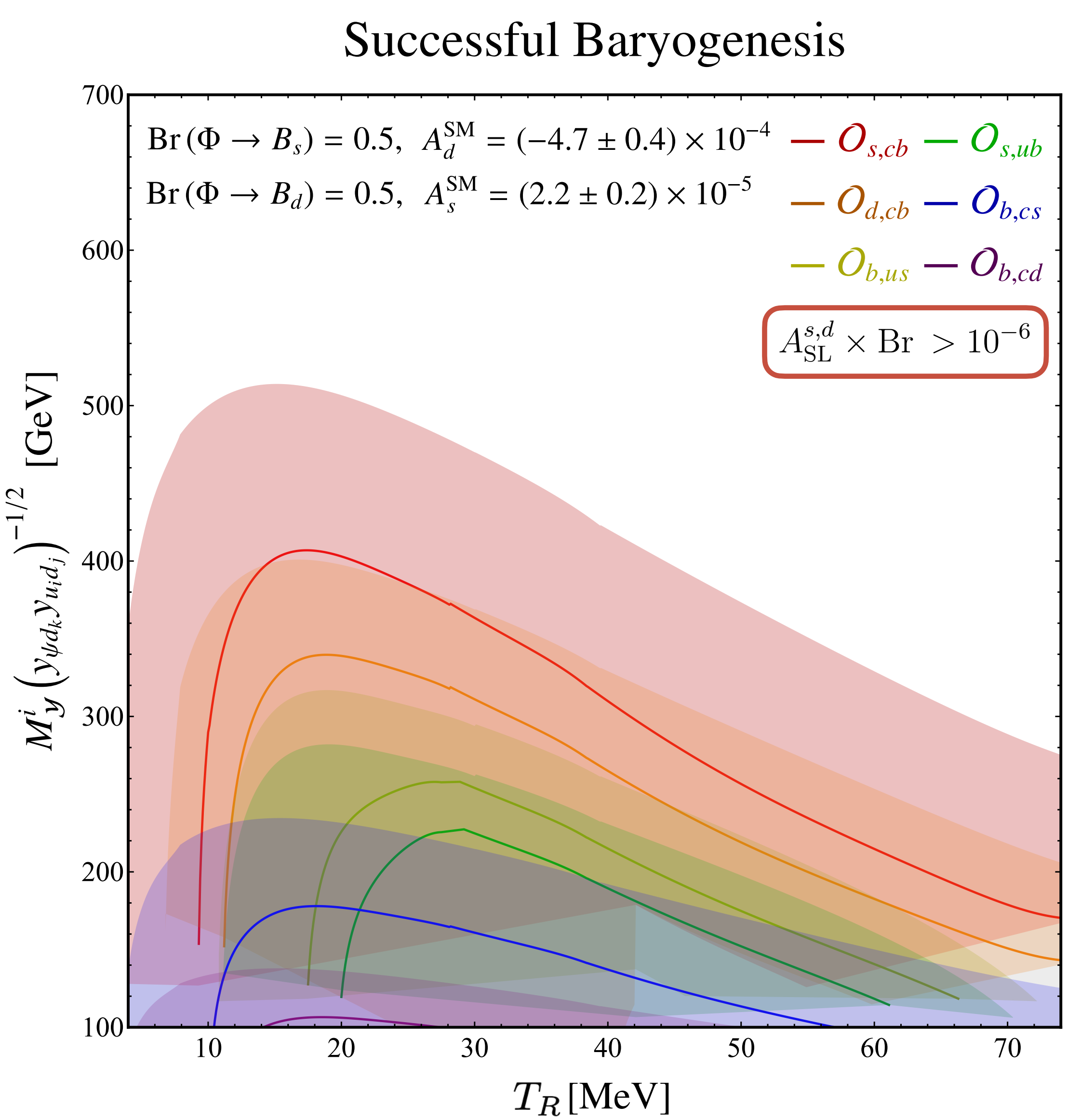
Image: Galaxy cluster SMACS 0723 as seen by the James Webb Space Telescope. Credit: NASA, STScl

Backups

Can the SM CPV be enough?

Yes!





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

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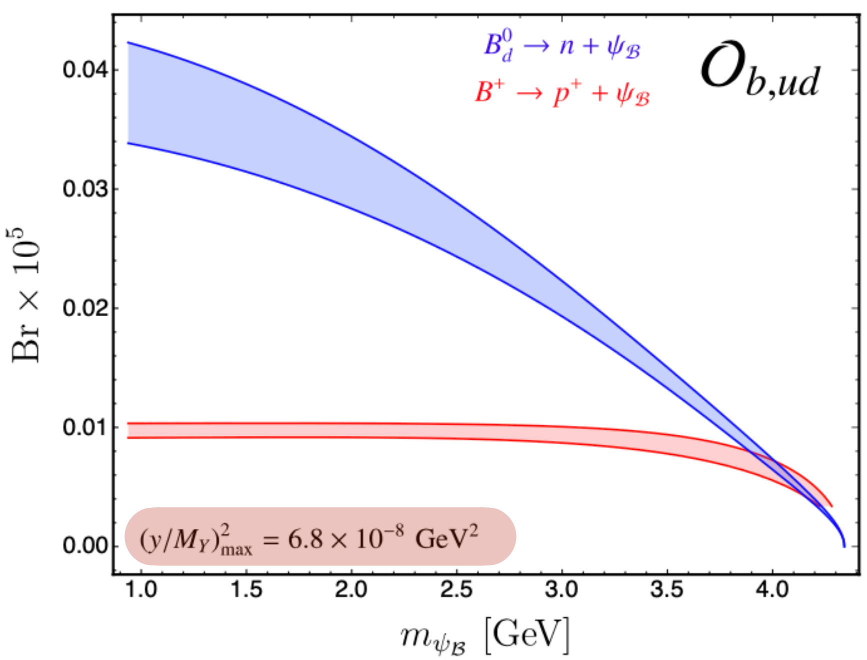
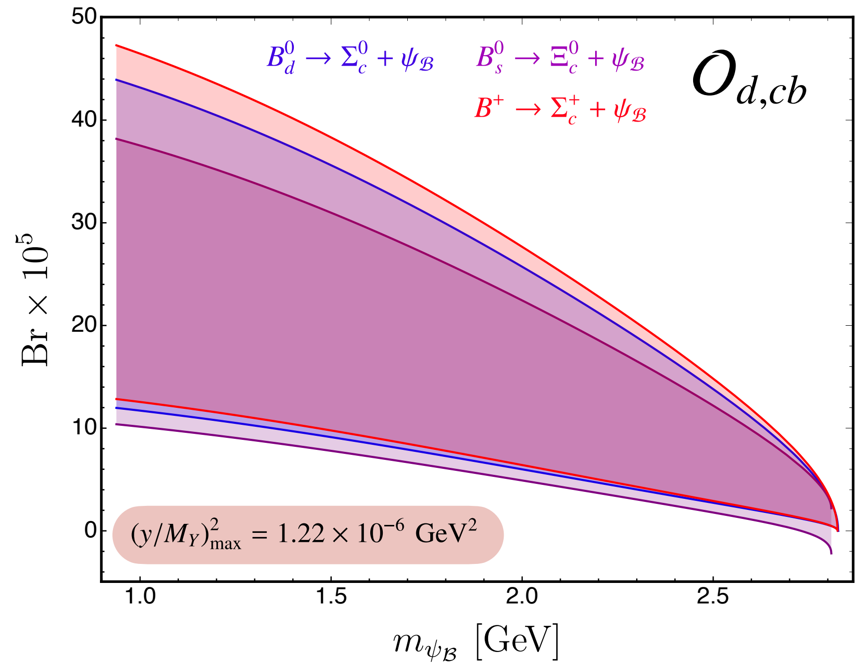
Baryon Asymmetry: Exotic *B* Meson Decays

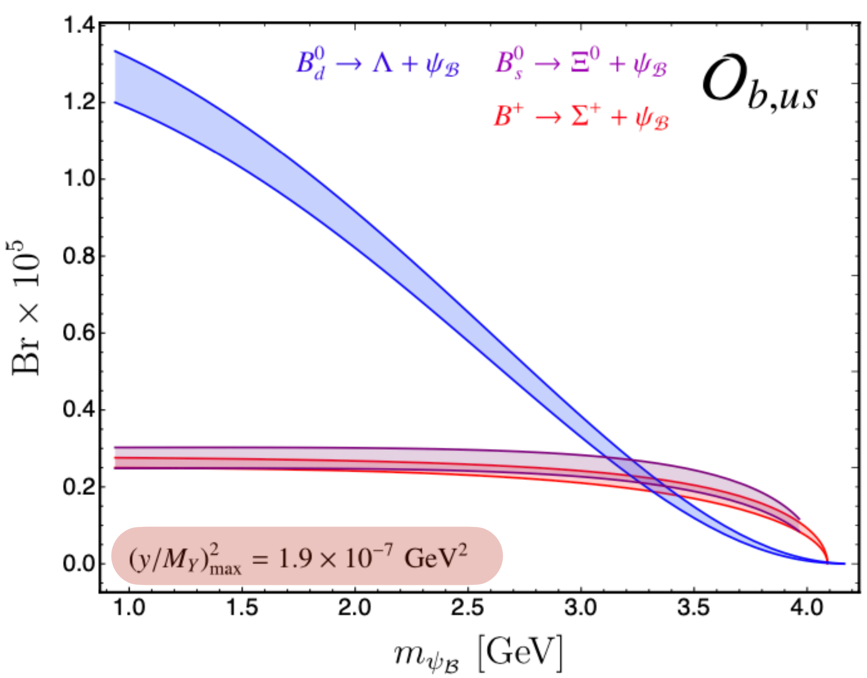
Experimental input: exclusive rates

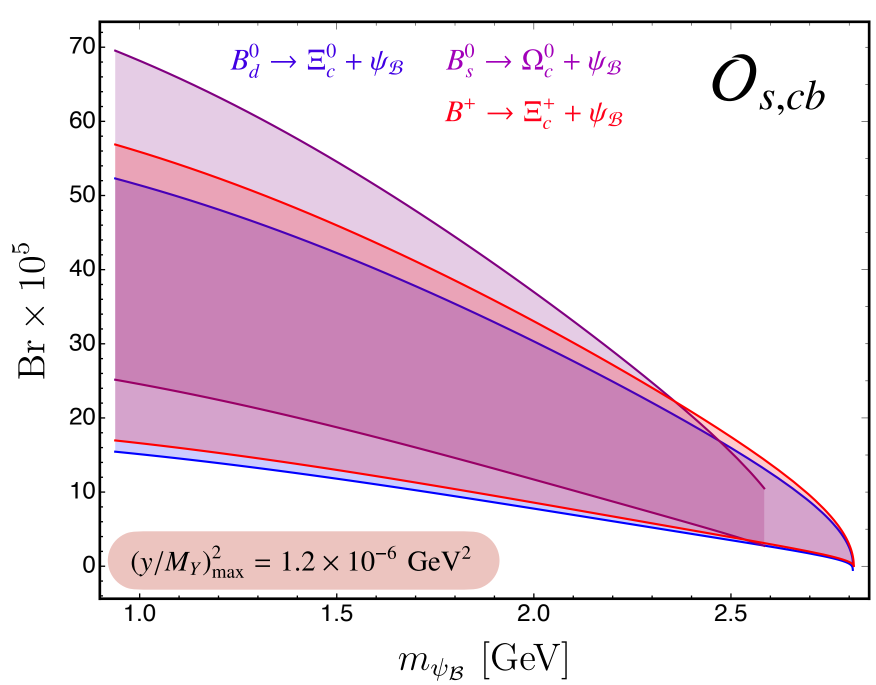




Use QCD techniques to compute meson to baryon decay rates in Mesogenesis

[G. Elor, A. Guerrera. JHEP, arXiv:2211.10553]





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

[A. Alonso-Alvarez, G. Elor, M. Escudero, PRD arXiv:2101.02706]

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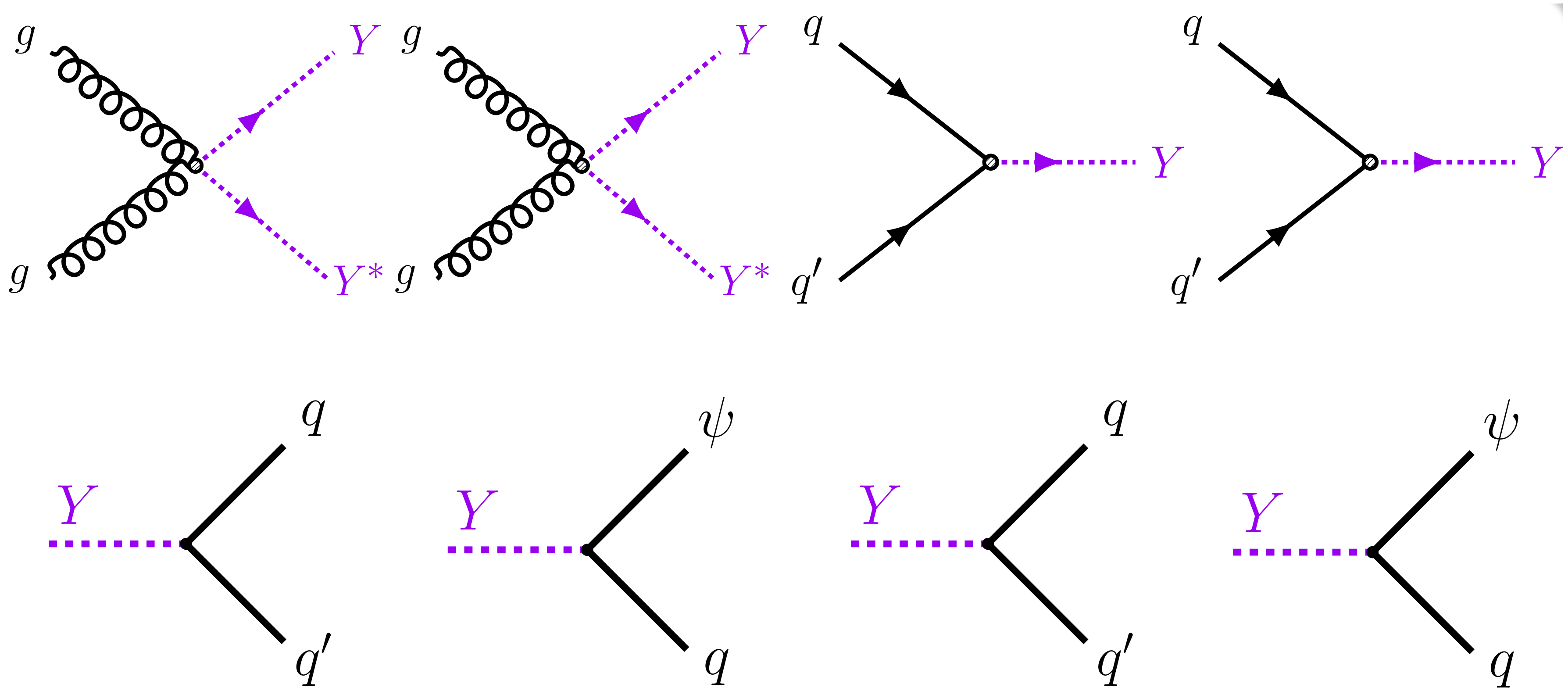
Colored Triplet Scalar

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

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

G. Elor

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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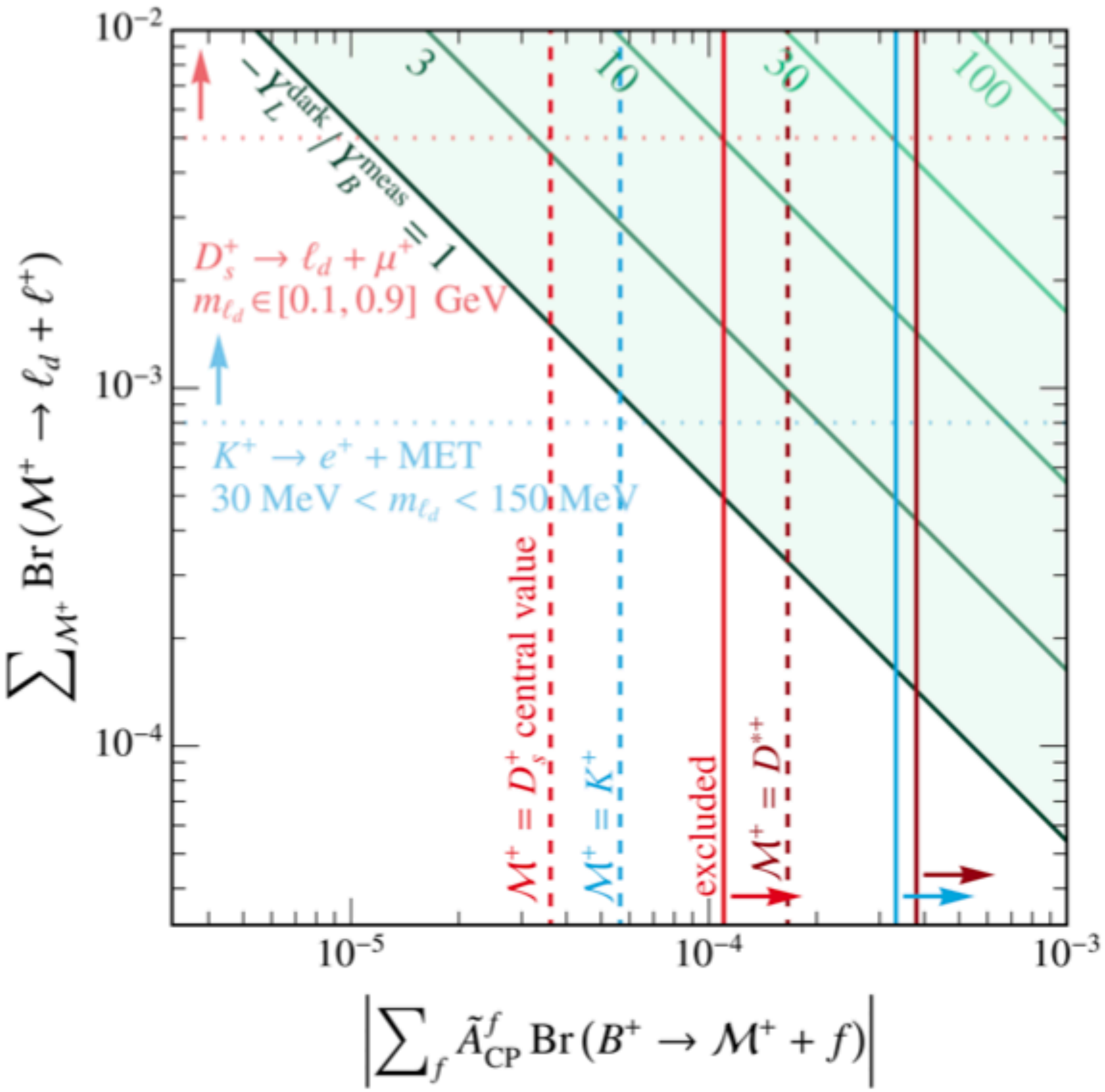
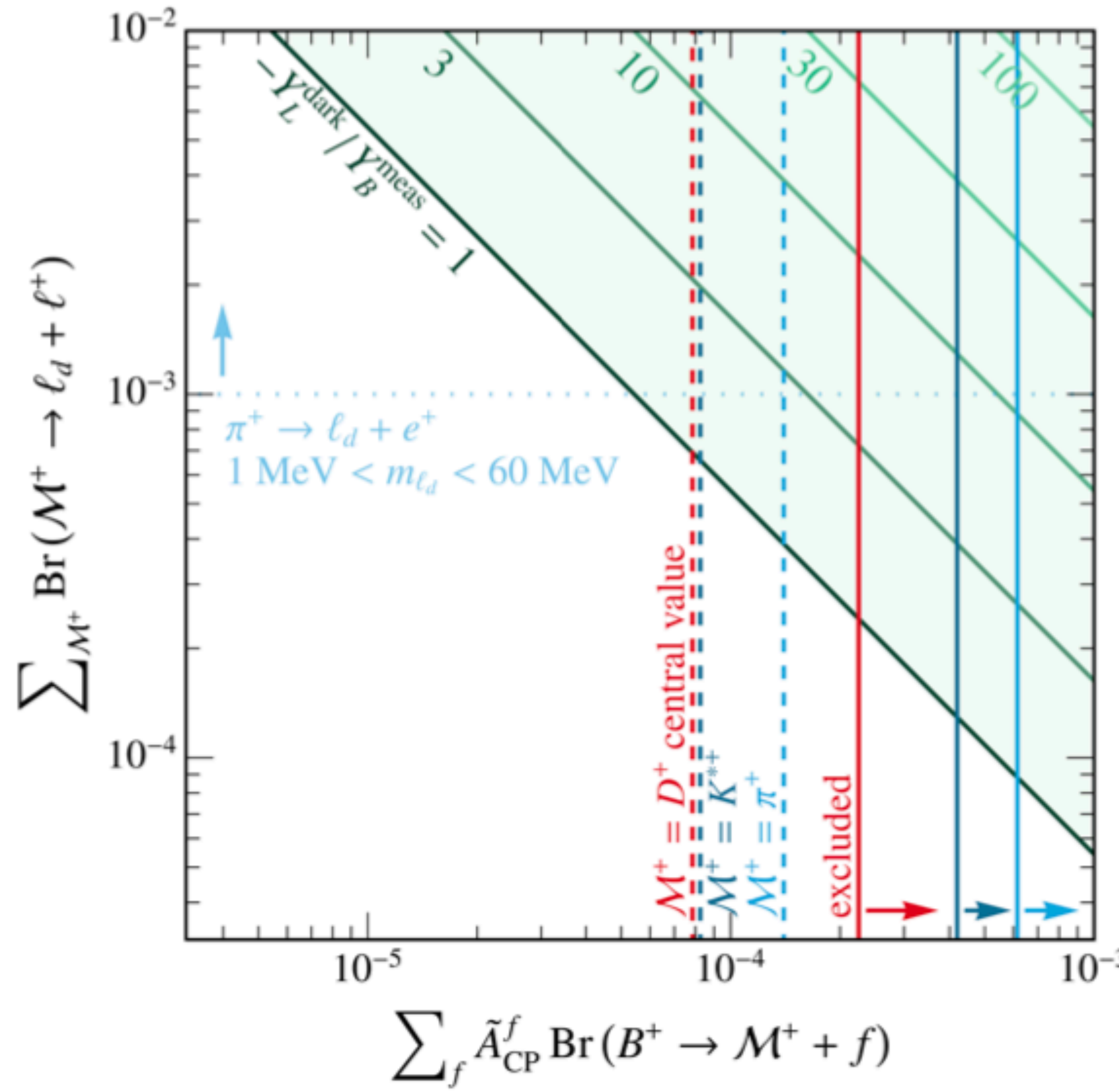
B^+ Mesogenesis





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Freezing-In a Baryon Asymmetry

Example Benchmark point:

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

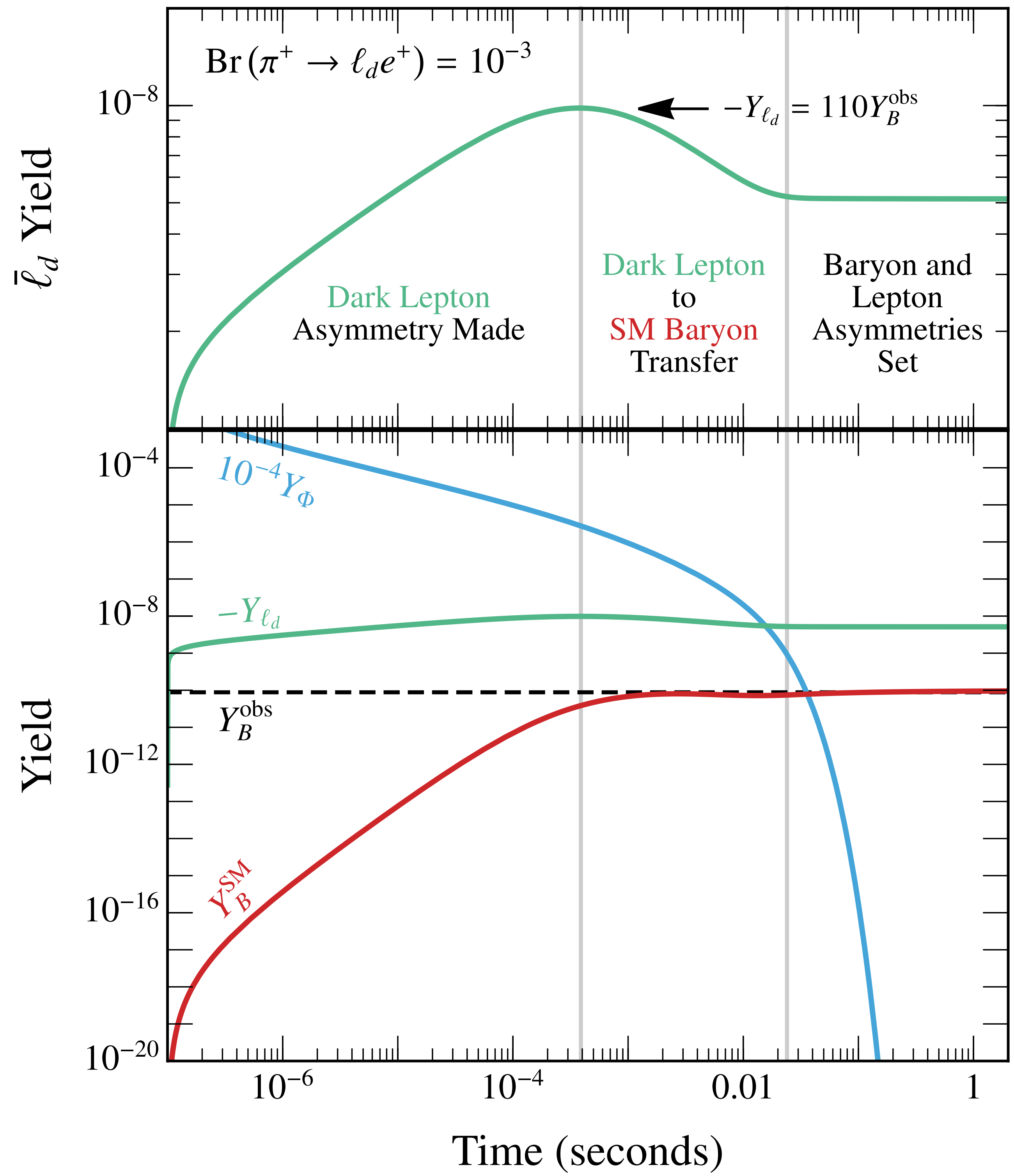
$$\langle\sigma v\rangle = 1\times 10^{-15}\text{ GeV}^{-2}$$

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

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

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

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



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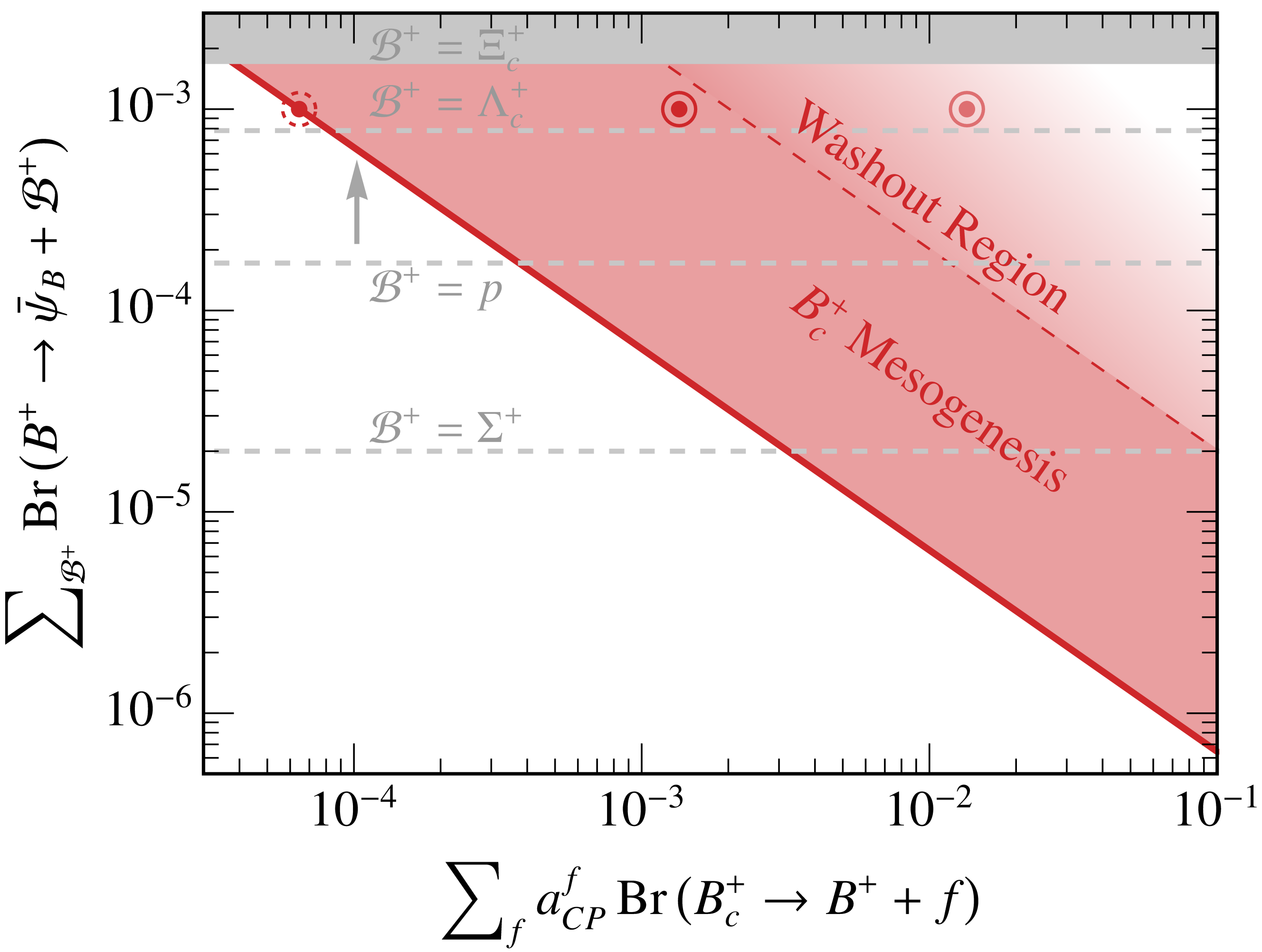
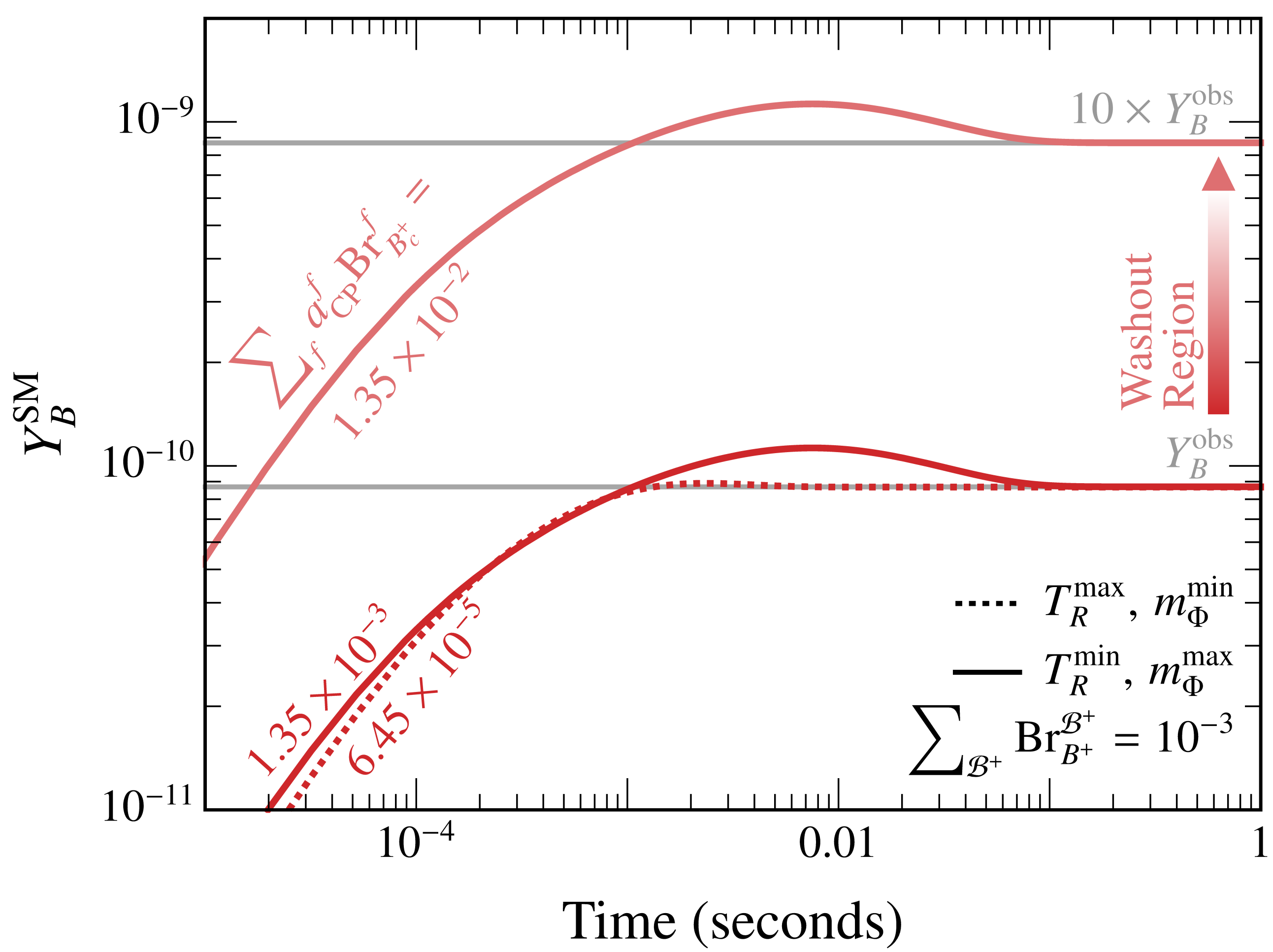
B_c^+ Mesogenesis





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

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