Baryogenesis and Dark Matter from B Mesons

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with: Gilly Elor & Ann Nelson

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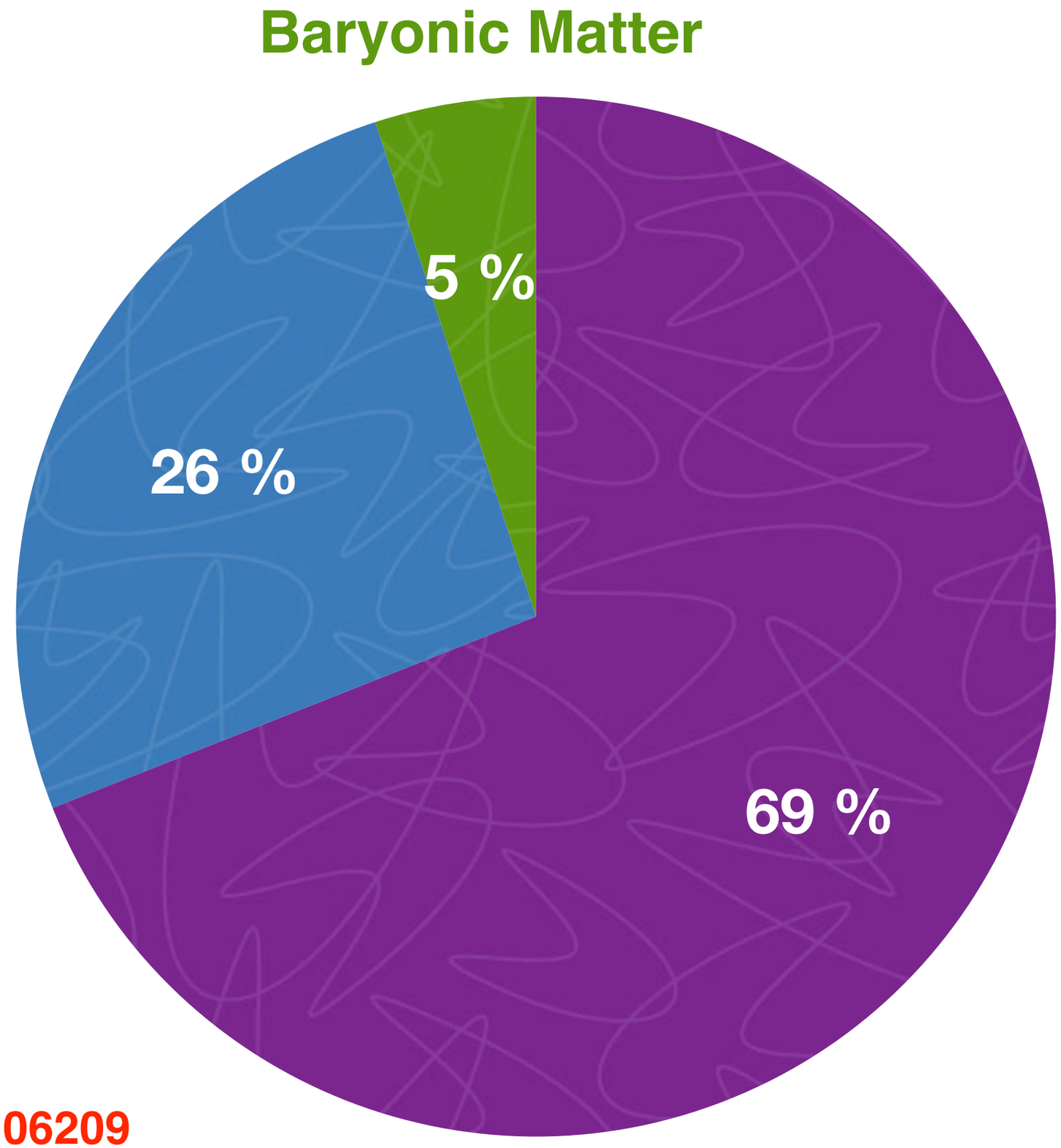
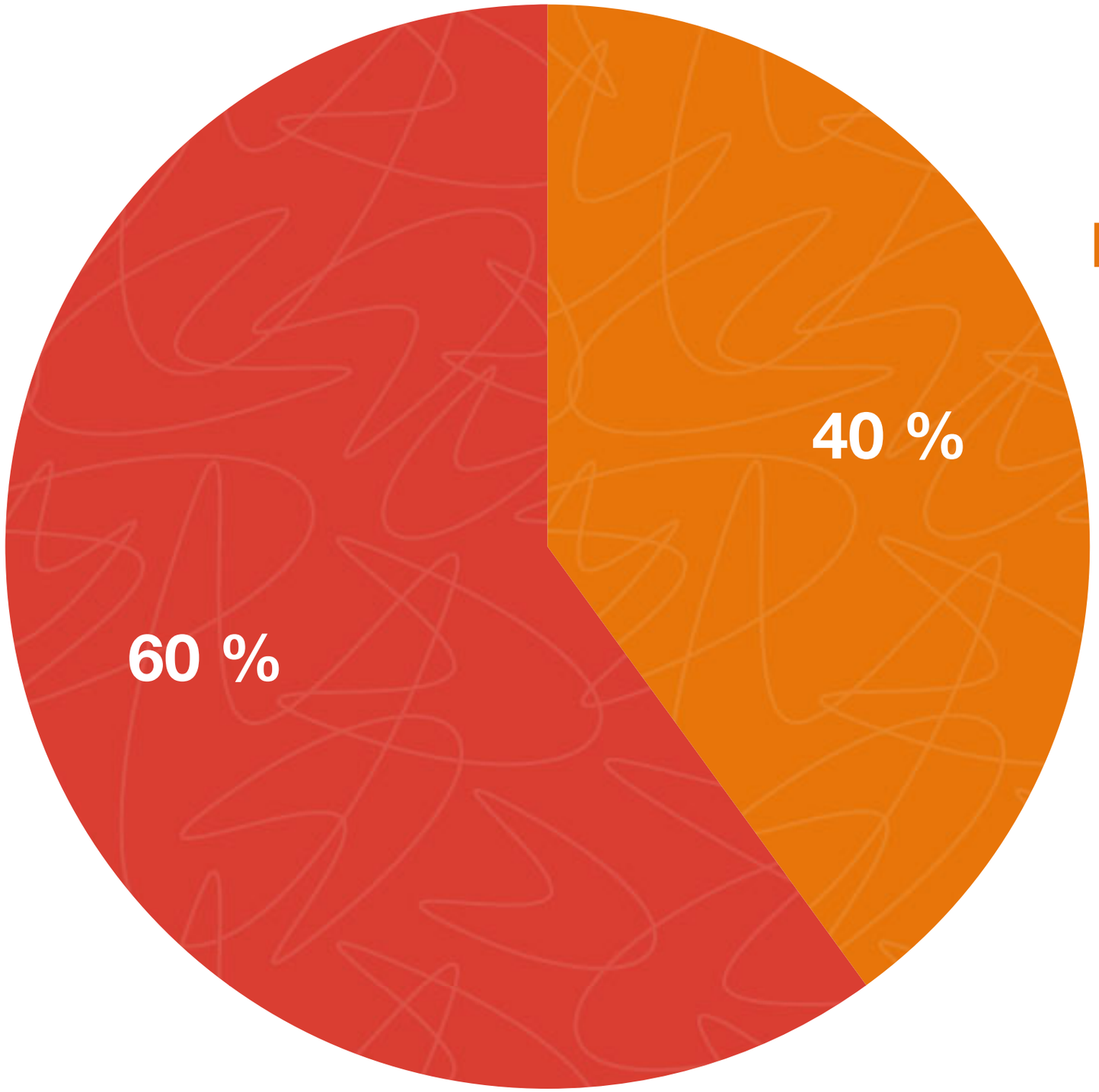
neutrinos, dark matter & dark energy physics

The Universe



Planck 2018 1807.06209

SM Prediction:



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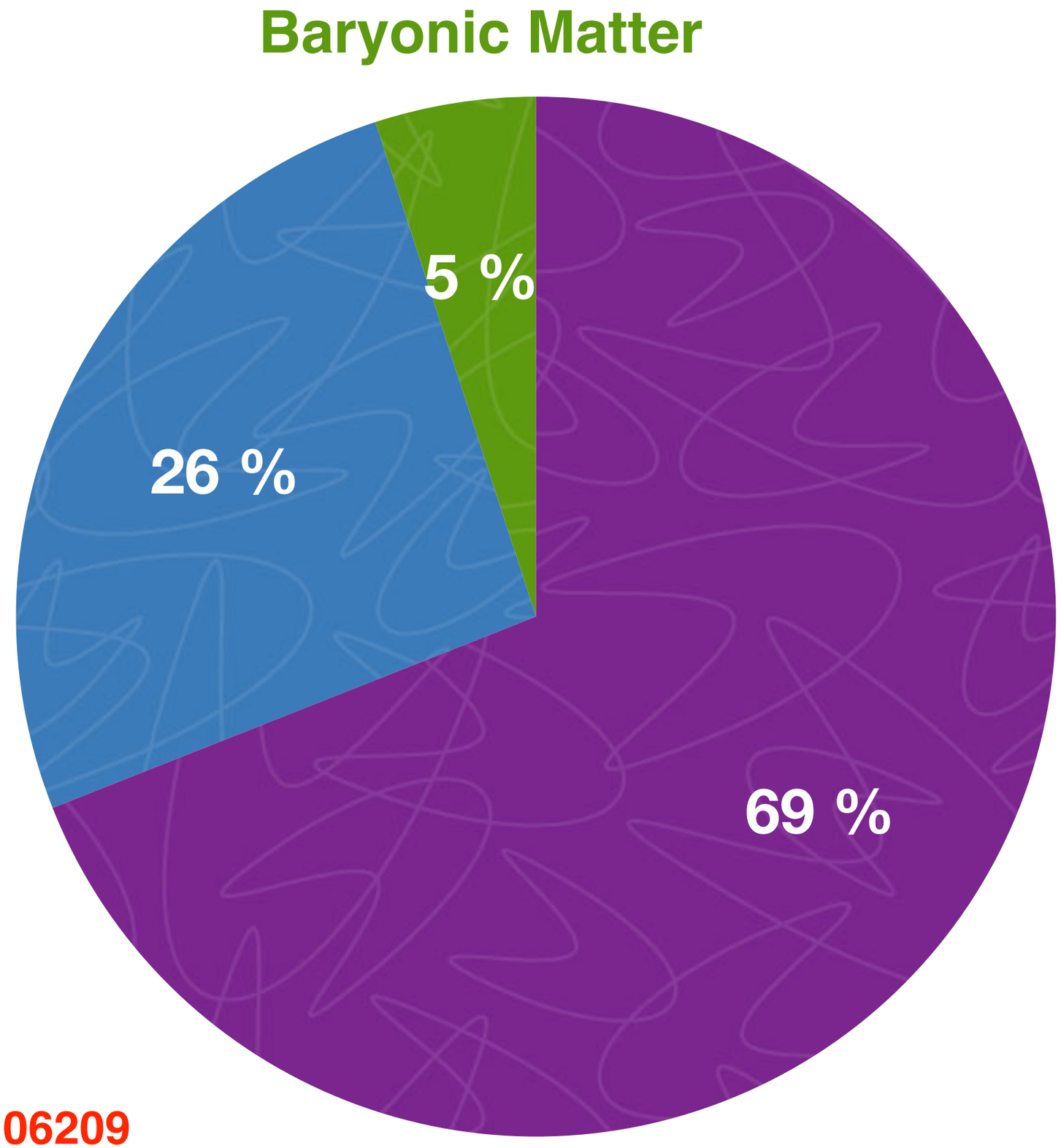

Planck 2018 1807.06209

Baryogenesis and Dark Matter from B Mesons

arXiv:1810.00880 Elor, Escudero & Nelson

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2) **Baryon asymmetry directly related to B-Meson observables**

3) **Leads to unique collider signatures**

4) **Fully testable at current collider experiments**

Outline

1) The Mechanism

1) C/CP violation
2) Out of equilibrium
3) Baryon number violation?

2) A Minimal Model

3) The Cosmology

4) Implications for Collider Experiments

5) Summary and Outlook

Baryogenesis

The three Sakharov Conditions (1967):

1) C and CP violation

2) Out of equilibrium

3) Baryon number violation

Baryogenesis from B Mesons

1) C and CP violation

Baryogenesis from B Mesons

1) C and CP violation

The key quantity: the semileptonic asymmetry,

$$A_{\ell\ell}^{q} = \mathrm{Im}\left(\frac{\Gamma_{12}^{q}}{M_{12}^{q}}\right) = \frac{\Gamma\left(B_q^0 \to f\right) - \Gamma\left(B_q^0 \to \bar{f}\right)}{\Gamma\left(B_q^0 \to f\right) + \Gamma\left(B_q^0 \to \bar{f}\right)}$$

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Standard Model

$$A_{\ell\ell}^s|_{\rm SM} = (2.22 \pm 0.27) \times 10^{-5}$$
$$A_{\ell\ell}^d|_{\rm SM} = (-4.7 \pm 0.6) \times 10^{-4}$$

small because $(m_b/m_t)^2$ is small

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Measurements

$$A^s_{\ell\ell} = (-0.6 \pm 2.8) \times 10^{-3}$$
$$A^d_{\ell\ell} = (-2.1 \pm 1.7) \times 10^{-3}$$

(World averages, HFLAV)

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(World averages, HFLAV)

- **Plenty of BSM models can enlarge the asymmetries up to 10^{-3}: SUSY, Extradim, LR, 2HDM, new generations, Leptoquarks, Z' models (see e.g. 1511.09466, 1402.1181).**

Baryogenesis from B Mesons

2) Out of equilibrium and production of B Mesons

Baryogenesis from B Mesons

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- **Require the presence of an out of equilibrium particle that dominates the energy density of the Universe and reheats it to a temperature of**

$$T_{RH} = \mathcal{O}(10\,\mathrm{MeV})$$

- **This particle should be very weakly coupled, with lifetimes**

$$\tau_\Phi = \mathcal{O}(10^{-3}\,\mathrm{s})$$

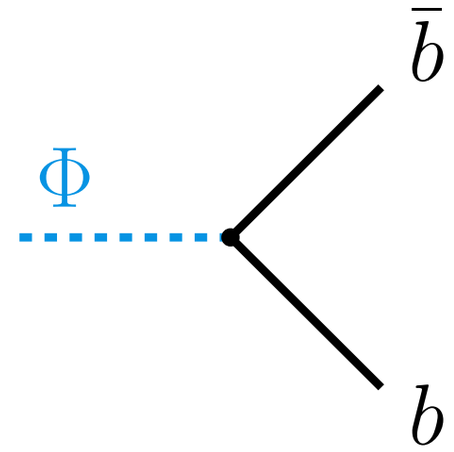
- **The decays don't spoil BBN or the CMB provided** $T_{RH} > 5\,\mathrm{MeV}$

de Salas *et al*. 1511.00672

Baryogenesis from B Mesons

2) Out of equilibrium and production of B Mesons

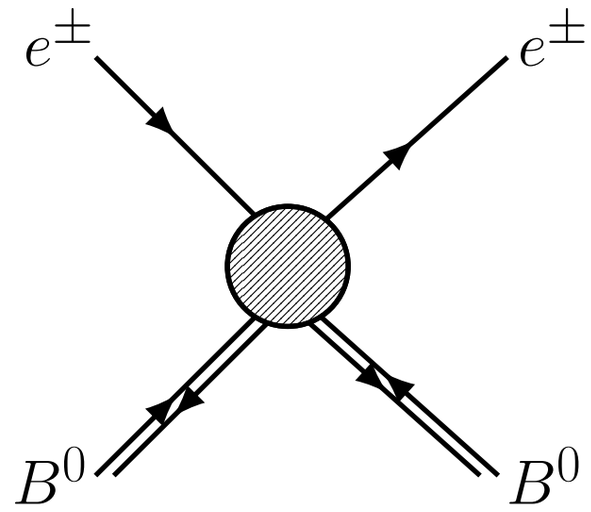
- **Scalar particle with** $m_\Phi \in 11 - 100\,\mathrm{GeV}$ **and**
  $\tau_\Phi = \mathcal{O}(10^{-3}\,\mathrm{s})$ **generically decays into b-quarks**



- **b-quarks Hadronize at** $T < T_{\mathrm{QCD}} \sim 200\,\mathrm{MeV}$

- **Coherent oscillations in the B^0 system are maintained in the early Universe for Temperatures:**

$$T \lesssim 20\,\mathrm{MeV}$$



Baryogenesis and DM from B Mesons

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- **Baryon number is conserved in our scenario:** $\Delta B = 0$

  In a similar spirit to *Hylogenesis*, Davoudiasl, Morrissey, Sigurdson, Tulin 1008.2399

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- **We make Dark Matter an anti-Baryon and generate an asymmetry between the two sectors thanks to the CP violating oscillations and subsequents decays of B-mesons.**

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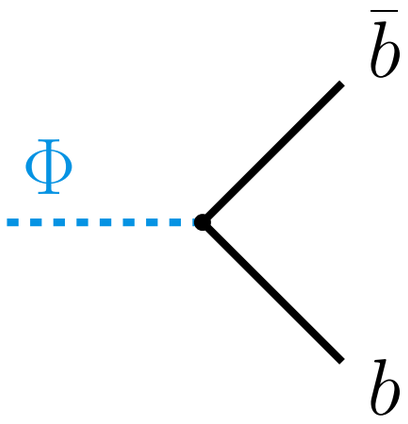
- **We make Dark Matter an anti-Baryon and generate an asymmetry between the two sectors thanks to the CP violating oscillations and subsequents decays of B-mesons.**

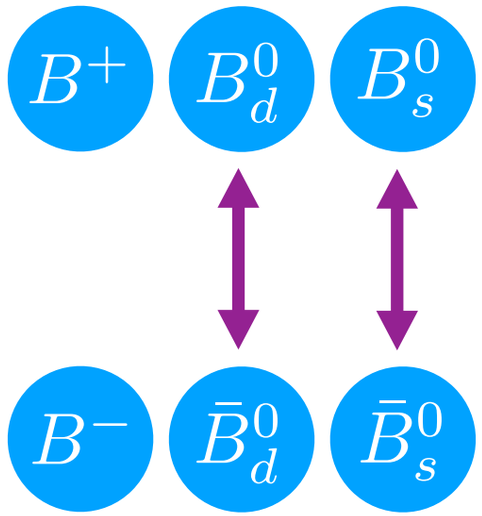
- **Require a new decay mode of the B meson into DM and a visible Baryon!**

A Summary of the Mechanism

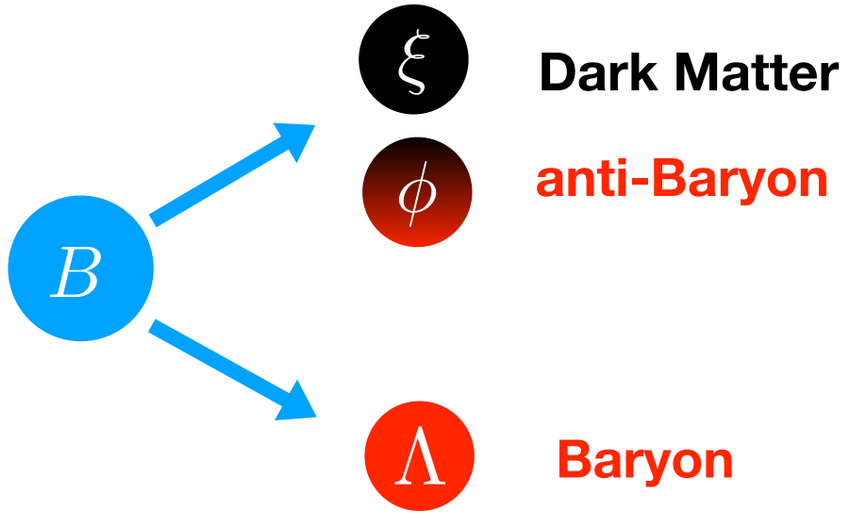
Out of equilibrium late time decay



CP violating Oscillations



B-mesons decay into Dark Matter and hadrons



$T_{\rm RH} \sim 20\,{\rm MeV}$ $\quad A_{\ell\ell}^d \quad A_{\ell\ell}^s$ $\quad {\rm BR}(B \to \phi\xi + {\rm Baryon} + ...)$

Baryogenesis

$$Y_B = 8.7 \times 10^{-11}$$

and

Dark Matter

$$\Omega_{\rm DM} h^2 = 0.12$$

With the Baryon asymmetry: $Y_B \propto \sum_{q=s,d} A_{\ell\ell}^q \times {\rm Br}(B_q^0 \to \phi\,\xi + {\rm Baryon} + X)$

New B-Meson decay

$$\mathcal{L} \supset -y_{ub}\, Y^*\, \bar{u}\, b^c - y_{\psi s}\, Y \bar{\psi}\, s^c + \text{h.c}$$

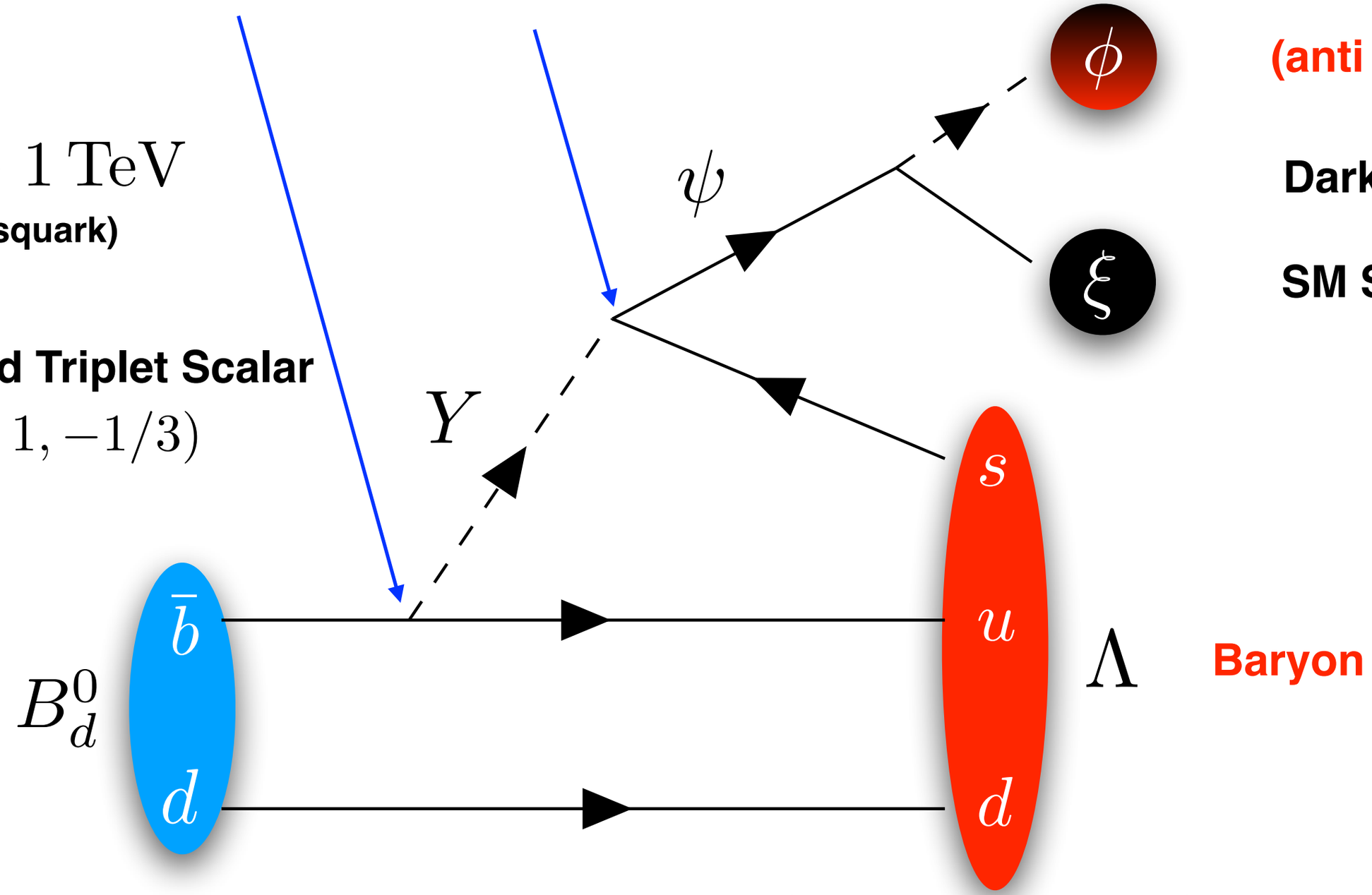
$$1.2\,\text{GeV} \lesssim m_{\phi,\,\xi} \lesssim 2.5\,\text{GeV}$$

$m_Y > 1\,\text{TeV}$

(4-jet/squark)

Y: Colored Triplet Scalar

$Y \sim (3, 1, -1/3)$



$$\text{Br}(B \to \xi\phi + \text{Baryon}) \simeq 10^{-3} \left(\frac{m_B - m_\psi}{2\ \text{GeV}}\right)^4 \left(\frac{1\ \text{TeV}}{m_Y} \frac{\sqrt{y_{ub} y_{\psi s}}}{0.53}\right)^4$$

Any room for a new decay mode?

Targeted decay modes are very constrained/well measured:

B-Factories $\mathrm{Br}(B^+ \to K^+ \bar{\nu}\nu) < 10^{-5}$

LHC $\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = (2.7 \pm 0.6) \times 10^{-9}$

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But our decay mode has not been targeted!

$$B \to \phi\xi + \mathrm{Baryon}$$

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What about the total width of B-Mesons?

Measurement: $\mathrm{Br}(B^+ \to \bar{c} + X) = (97 \pm 4)\%$

Most stringent current constraint: $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) < 10\%$

The Boltzmann Equations

Universe's Evolution

$$H^2 \equiv \left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi}{3m_{Pl}^2}\left(\rho_{\rm rad} + m_\Phi n_\Phi\right)$$

Late time Decay and Radiation

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

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

DM evolution

$$\frac{dn_\xi}{dt} + 3Hn_\xi = -\langle\sigma v\rangle_\xi\left(n_\xi^2 - n_{{\rm eq},\xi}^2\right) + 2\,\Gamma_\Phi^B\, n_\Phi \qquad \Gamma_\Phi^B \equiv \Gamma_\Phi \times {\rm Br}(B \to \phi\xi + {\rm Baryon} + X)$$

$$\frac{dn_\phi}{dt} + 3Hn_\phi = -\langle\sigma v\rangle_\phi(n_\phi n_{\phi^\star} - n_{{\rm eq},\phi} n_{{\rm eq},\phi^\star}) + \Gamma_\Phi^B\, n_\Phi \times [1 + \sum_q A_{\ell\ell}^q\, {\rm Br}(\bar{b} \to B_q^0)\, f_{\rm deco}^q]$$

$$\frac{dn_{\phi^\star}}{dt} + 3Hn_{\phi^\star} = -\langle\sigma v\rangle_\phi(n_\phi n_{\phi^\star} - n_{{\rm eq},\phi} n_{{\rm eq},\phi^\star}) + \Gamma_\Phi^B\, n_\Phi \times [1 - \sum_q A_{\ell\ell}^q\, {\rm Br}(\bar{b} \to B_q^0)\, f_{\rm deco}^q]$$

Baryon asymmetry:

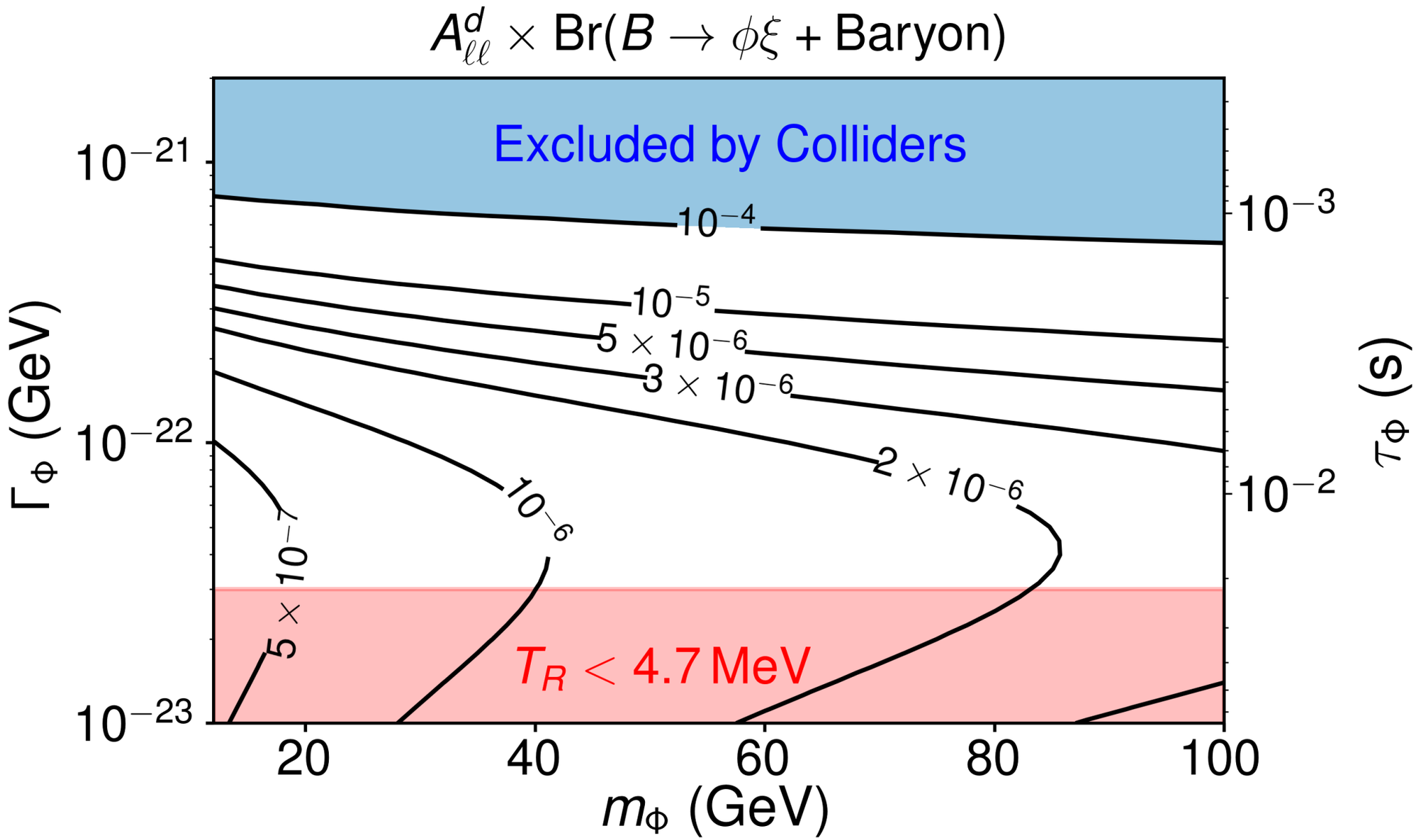
$$n_B = n_\phi - n_{\phi^\star}$$

$$\frac{dn_B}{dt} + 3\,Hn_B = 2\,\Gamma_\Phi\, n_\Phi \sum_q {\rm Br}(\bar{b} \to B_q^0)\; f_{\rm deco}^q\, A_{\ell\ell}^q\, {\rm Br}(B \to \phi\xi + {\rm Baryon} + X)$$

- **Baryon asymmetry directly related to the CP violation in the B^0 system and to the new decay of B mesons to a visible Baryon and missing energy.**
- **We take into account the decoherence of the B^0 system in the early Universe.**

Parameter Space $A^s_{\ell\ell} = 0$

All points correspond to the observed baryon asymmetry



Baryogenesis requires:

- $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) = 5 \times 10^{-4} - 0.1$
- $A^d_{\ell\ell} = 10^{-5} - 10^{-3}$

Summary

Baryogenesis and Dark Matter from B-mesons:

- **Which actually relates the CP violation in the B^0 system to Baryogenesis**
- **Baryon number is conserved and hence Dark Matter is anti-Baryonic**

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Distinct experimental signatures:

- **Positive leptonic asymmetry in B meson decays** $A_{\ell\ell}^{d\,s} > 10^{-5}$
- **Neutral and charged B mesons decay into baryons and missing energy**

$$\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) > 2 \times 10^{-4}$$

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$$\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) > 2 \times 10^{-4}$$

The mechanism is fully testable at current collider experiments!

Belle-II should test this scenario given the constraints on other missing energy channels:

$$\mathrm{Br}(B^+ \to K^+ \bar{\nu}\nu) < 10^{-5}$$

Outlook

Theory

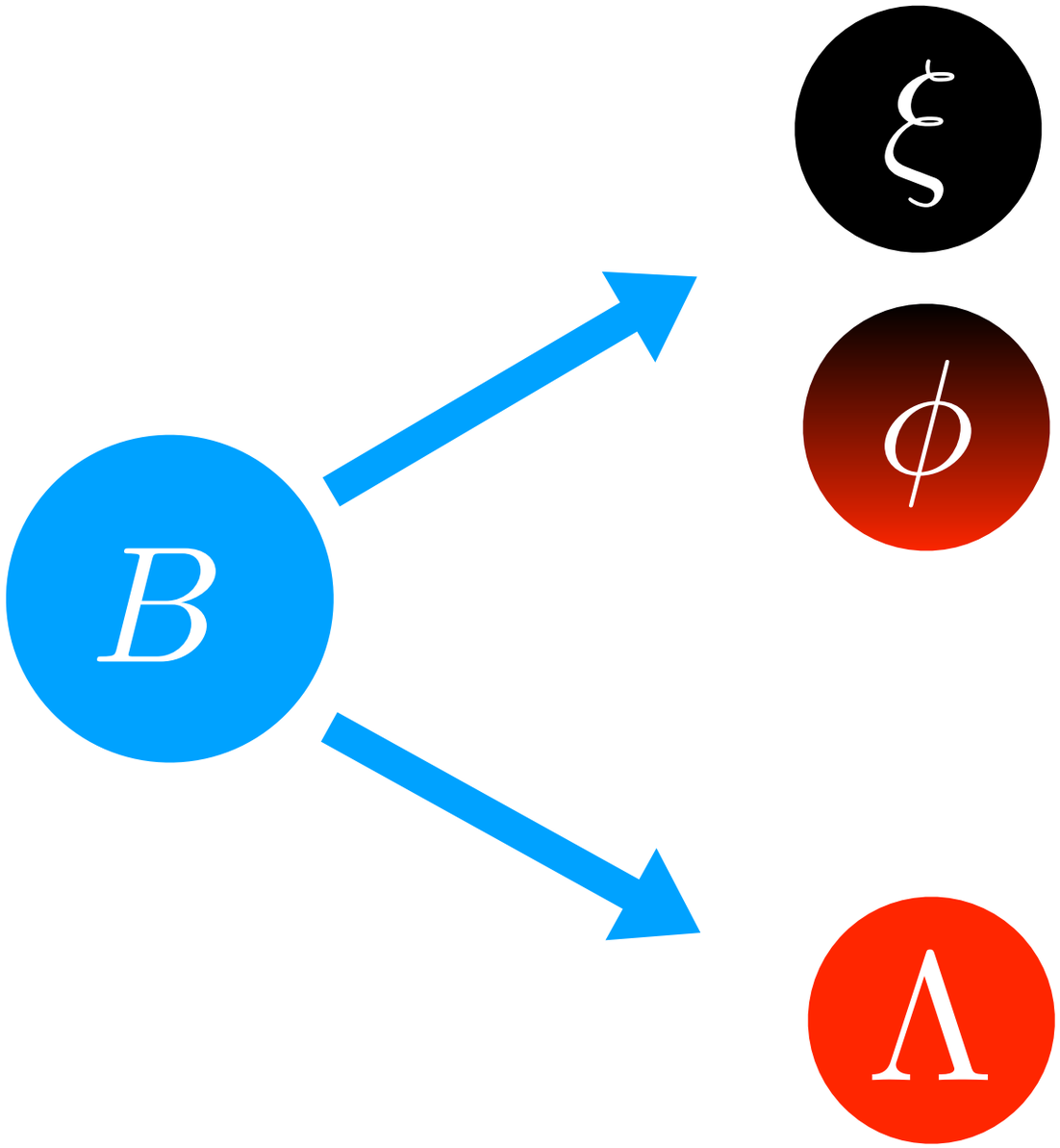
- **Are the flavor anomalies in b → s transitions related to our required positive semileptonic asymmetry?**

  Given that Leptoquarks and Z' models induce mass mixing in the Bs system and hence alter the semileptonic asymmetry.

- **What kind of UV theory contains our required heavy colored triplet scalar plus our dark matter particles at the GeV scale?**

The End

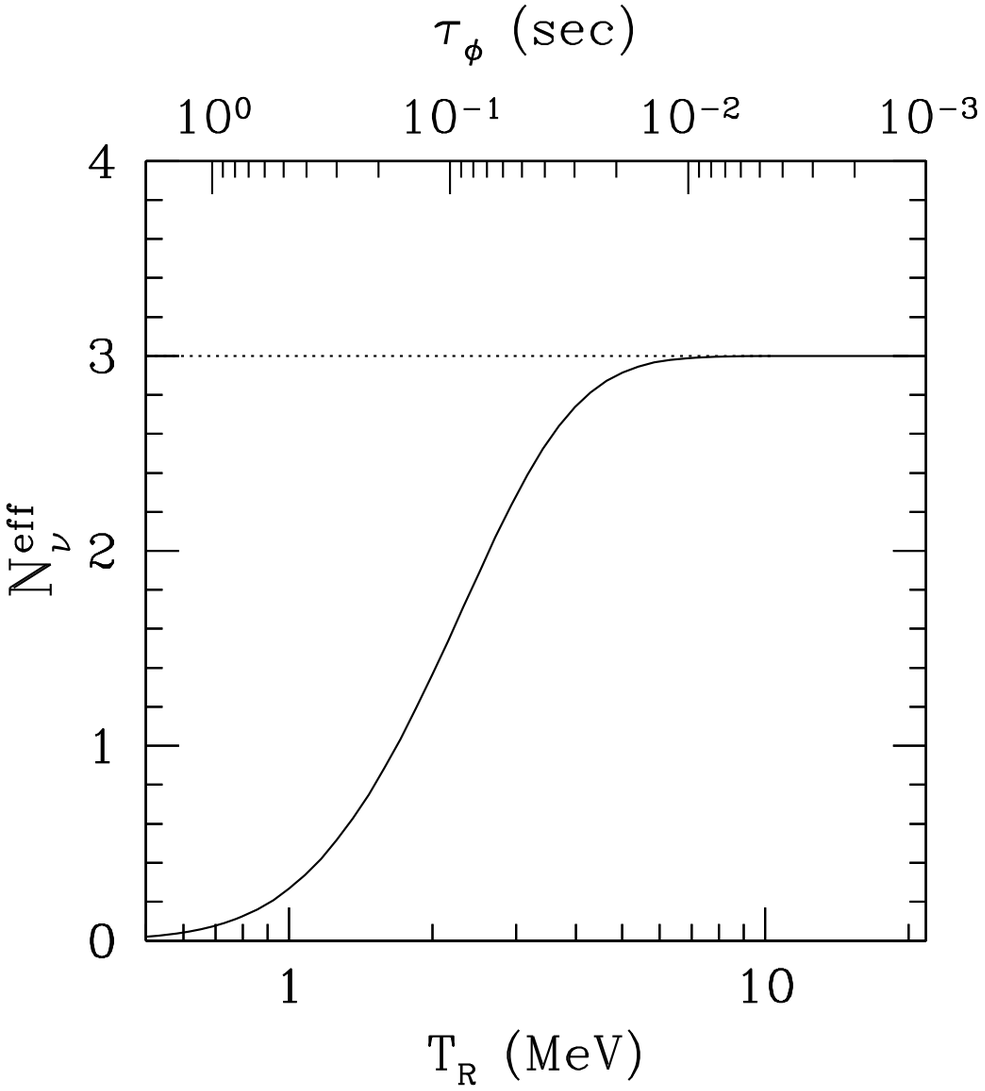
Thank You!



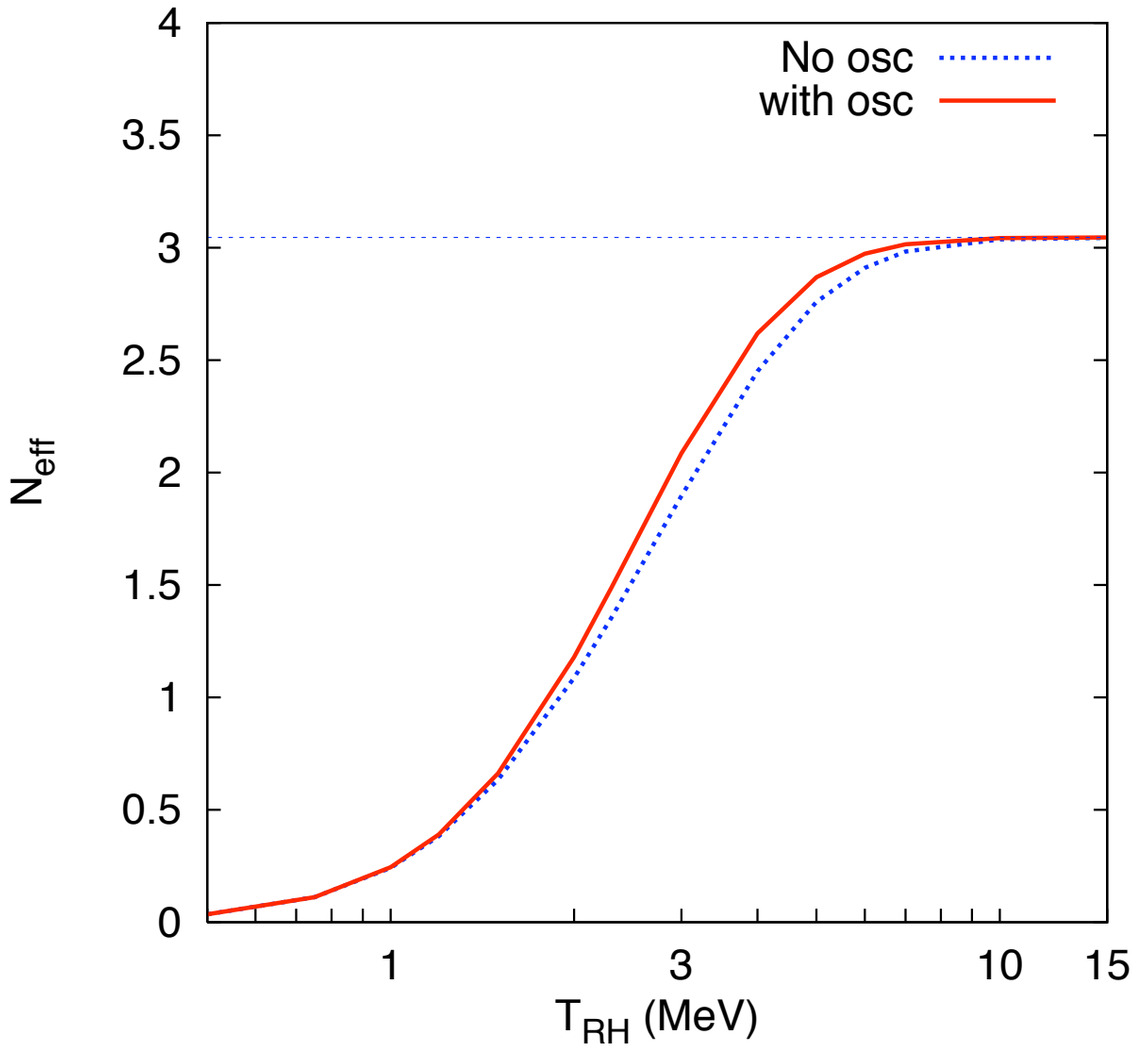
Back Up

Back Up: MeV Reheating Temperature

Kawasaki, Kohri, Sugiyama 0002127



de Salas, Lattanzi, Mangano Miele, Pastor, Pisanti 1511.00672



Current bounds 1511.00672

$$\frac{dT}{dt} = -\frac{H g_{*,s} T^4 - \frac{15}{2\pi^2} \times \Gamma_\Phi m_\Phi n_\Phi}{T^3 g_* (1 + \frac{d \log g_*}{d \log T})} .$$

$$N_{\rm eff}^{2015} > 2.74$$

$$T_{RH} > 4.7\,{\rm MeV}$$

$$\Gamma_\Phi < 3 \times 10^{-23}\,{\rm GeV} \equiv 45\,{\rm s}^{-1}$$

Planck 2018?

$$N_{\rm eff}^{2018} > 2.70$$

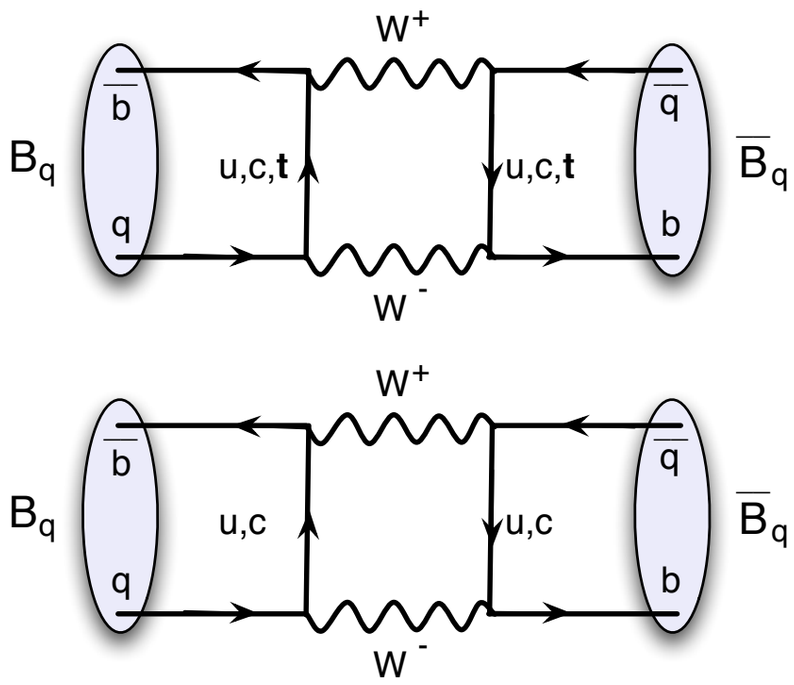
hence not expected to become more stringent

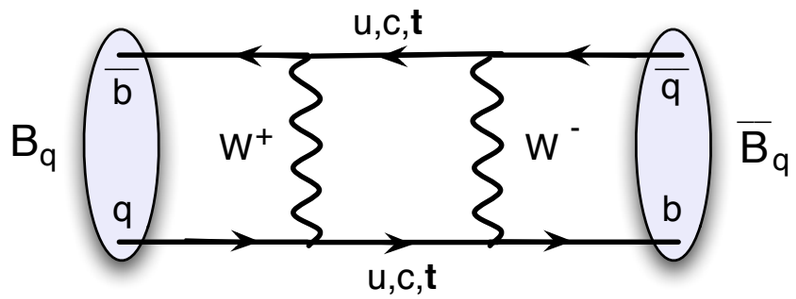
Baryogenesis from B Mesons

1) CP violation in the Meson System

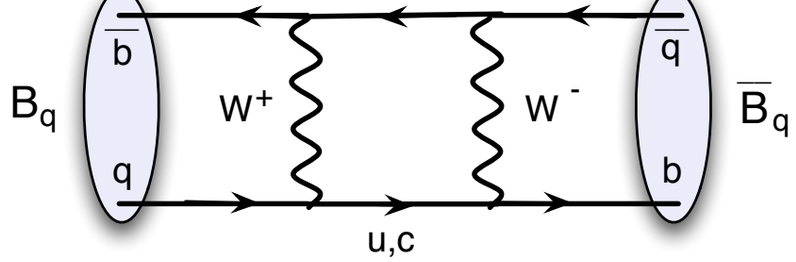
SM: Box Diagrams

$$M_{12} \propto$$





$$\Gamma_{12} \propto$$



CP violating mixing requires a relative phase between Γ_{12} and M_{12}

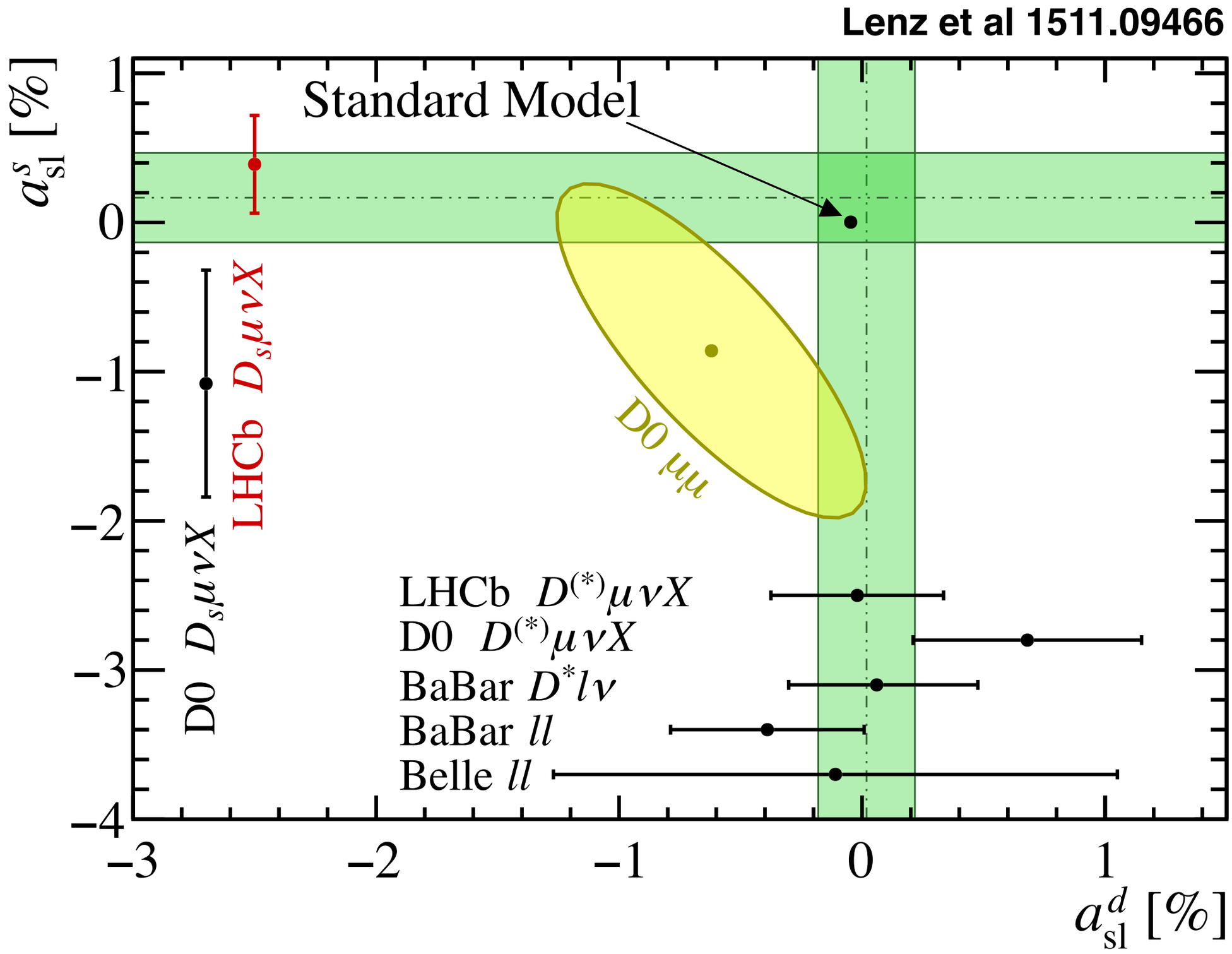
BSM?

***Z′* models (even at tree level), Leptoquarks etc ...**

see *e.g.* Nir 9911321

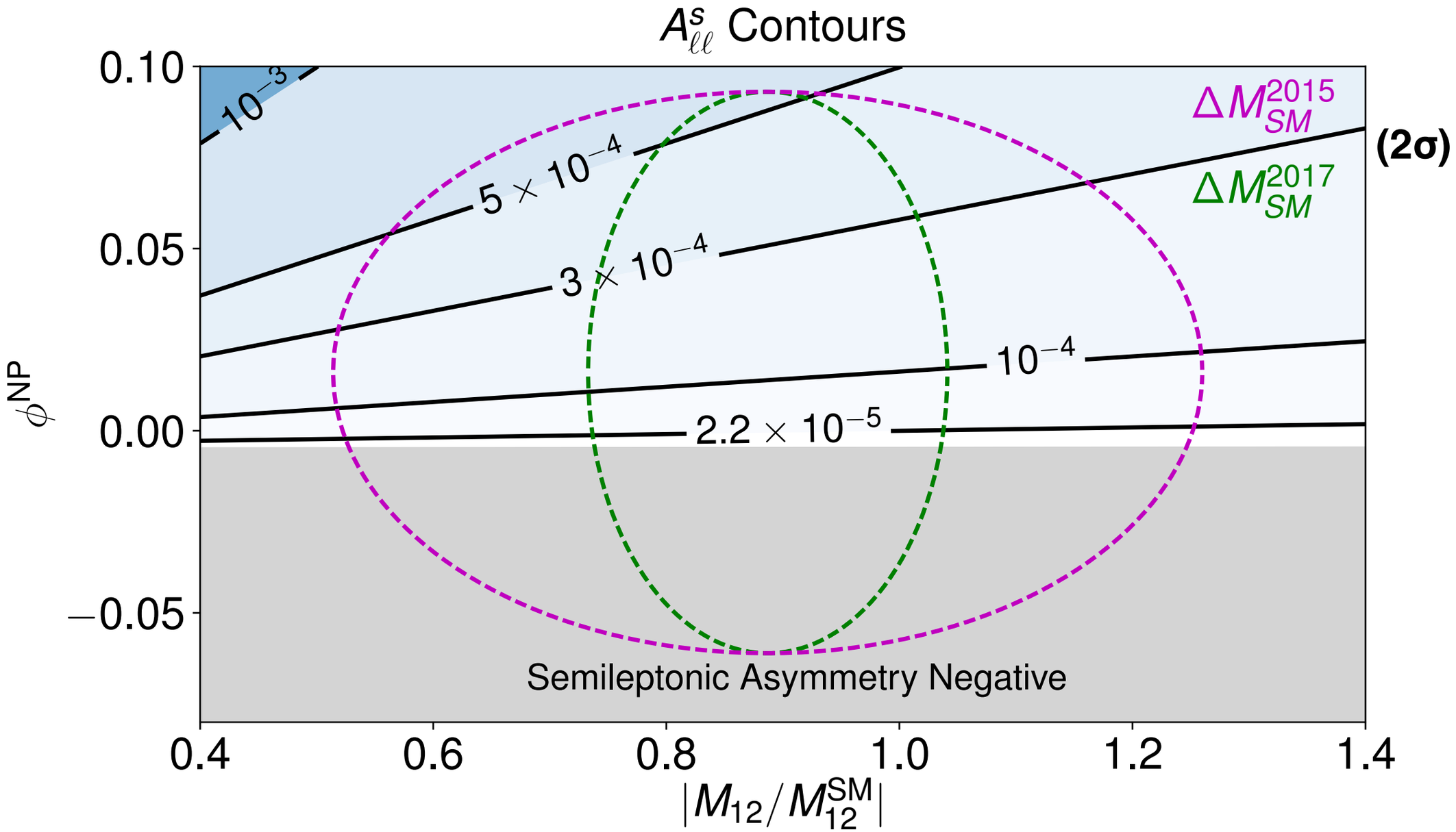
Semileptonic Asymmetry measurements

Lenz et al 1511.09466



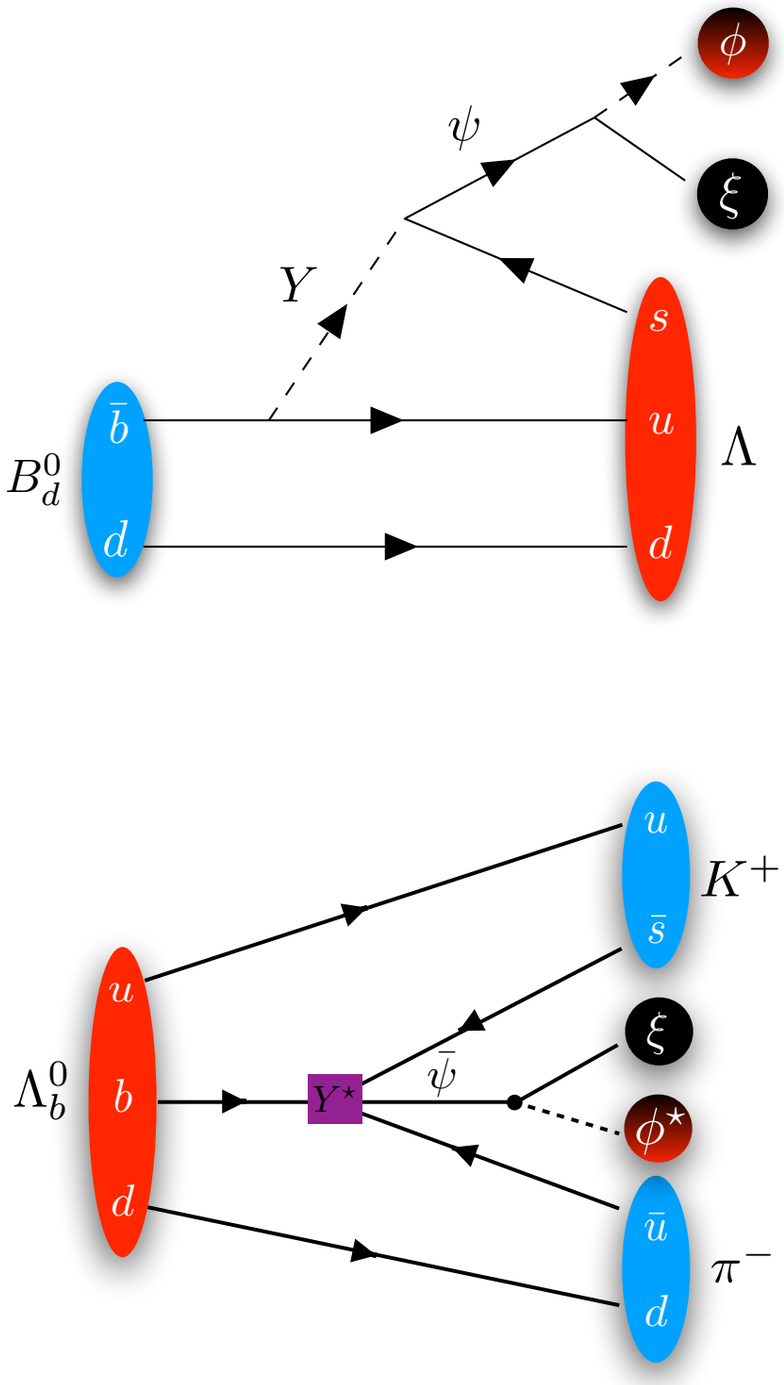
Back Up: Semileptonic asymmetry

The new physics that enhances the semileptonic asymmetry must be compatible with the measured values of Δm_B and the searches of direct CP violation given the SM prediction: Lenz et al 1511.09466, 1712.06572



Hence in the Bs system, can be enhanced up to ~ 5 x 10^{-4}

Back Up: Flavourful Variations



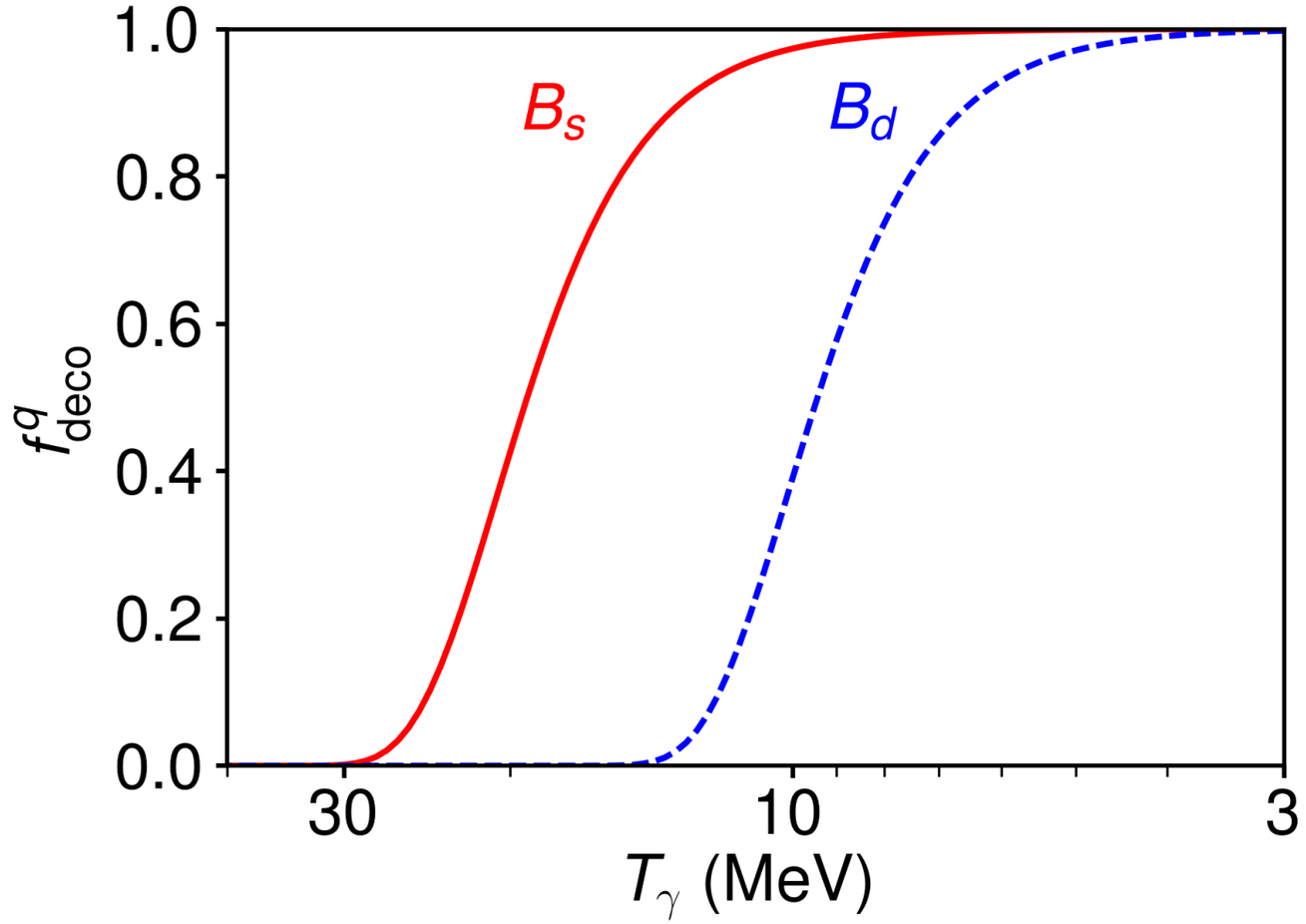
Operator	Initial State	Final state	ΔM (MeV)
$\psi\, b\, u\, s$	B_d	$\psi + \Lambda\,(usd)$	4163.95
	B_s	$\psi + \Xi^0\,(uss)$	4025.03
	B^+	$\psi + \Sigma^+\,(uus)$	4089.95
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\psi\, b\, u\, d$	B_d	$\psi + n\,(udd)$	4340.07
	B_s	$\psi + \Lambda\,(uds)$	4251.21
	B^+	$\psi + p\,(duu)$	4341.05
	Λ_b	$\bar{\psi} + \pi^0$	5484.5
$\psi\, b\, c\, s$	B_d	$\psi + \Xi_c^0\,(csd)$	2807.76
	B_s	$\psi + \Omega_c\,(css)$	2671.69
	B^+	$\psi + \Xi_c^+\,(csu)$	2810.36
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2
$\psi\, b\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$	2853.60
	B_s	$\psi + \Xi_c^0\,(cds)$	2895.02
	B^+	$\psi + \Lambda_c\,(dcu)$	2992.86
	Λ_b	$\bar{\psi} + \overline{D}^0$	3754.7

Table 1: Here we itemize the lightest possible initial and final states for the B decay process to visible and dark sector states resulting from the four possible operators. The diagram in Figure **??** corresponds to the first line. The mass difference between initial and final visible sector states corresponds to the kinematic upper bound on the mass of the dark sector ψ baryon.

Back Up: Parameters

Parameter	Description	Range	Benchmark Value	Constraint
m_Φ	Φ mass	$11 - 100$ GeV	25 GeV	-
Γ_Φ	Inflaton width	$3 \times 10^{-23} < \Gamma_\Phi/\text{GeV} < 5 \times 10^{-21}$	10^{-22} GeV	Decay between $3.5\,\text{MeV} < T < 30\,\text{MeV}$
m_ψ	Dirac fermion mediator	$1.5\,\text{GeV} < m_\psi < 4.2\,\text{GeV}$	3.3 GeV	Lower limit from $m_\psi > m_\phi + m_\xi$
m_ξ	Majorana DM	$0.3\,\text{GeV} < m_\xi < 2.7\,\text{GeV}$	1.0 and 1.8 GeV	$\lvert m_\xi - m_\phi \rvert < m_p - m_e$
m_ϕ	Scalar DM	$1.2\,\text{GeV} < m_\phi < 2.7\,\text{GeV}$	1.5 and 1.3 GeV	$\lvert m_\xi - m_\phi \rvert < m_p - m_e$, $m_\phi > 1.2\,\text{GeV}$
y_d	Yukawa for $\mathcal{L} = y_d \bar{\psi} \phi \xi$		0.3	$< \sqrt{4\pi}$
$\text{Br}(B \to \phi\xi + ..)$	Br of $B \to \text{ME} + \text{Baryon}$	$2 \times 10^{-4} - 0.1$	10^{-3}	< 0.1 [5]
$A^s_{\ell\ell}$	Lepton Asymmetry B_d	$5 \times 10^{-6} < A^d_{\ell\ell} < 8 \times 10^{-4}$	6×10^{-4}	$A^d_{\ell\ell} = -0.0021 \pm 0.0017$ [5]
$A^s_{\ell\ell}$	Lepton Asymmetry B_s	$10^{-5} < A^s_{\ell\ell} < 4 \times 10^{-3}$	10^{-3}	$A^s_{\ell\ell} = -0.0006 \pm 0.0028$ [5]
$\langle\sigma v\rangle_\phi$	Annihilation Xsec for ϕ	$(6 - 20) \times 10^{-25}\,\text{cm}^3/\text{s}$	$10^{-24}\,\text{cm}^3/\text{s}$	Depends upon the channel [3]
$\langle\sigma v\rangle_\xi$	Annihilation Xsec for ξ	$(6 - 20) \times 10^{-25}\,\text{cm}^3/\text{s}$	$10^{-24}\,\text{cm}^3/\text{s}$	Depends upon the channel [3]

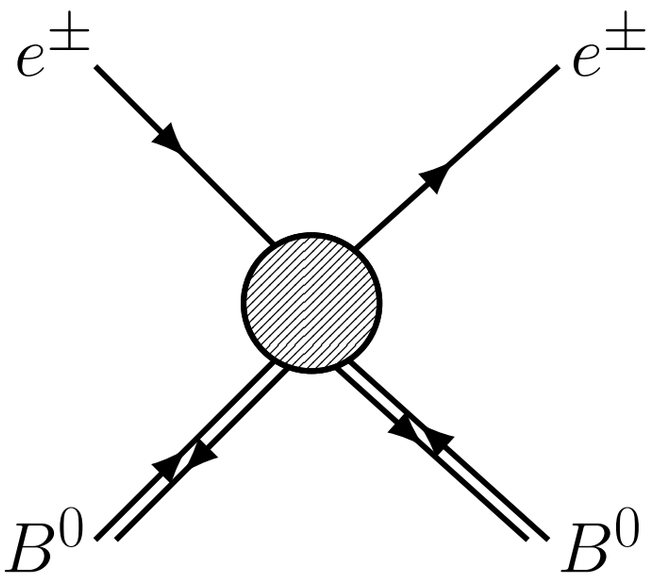
Back Up: Decoherence



$$\tau_B = 1.52\,\text{ps}$$

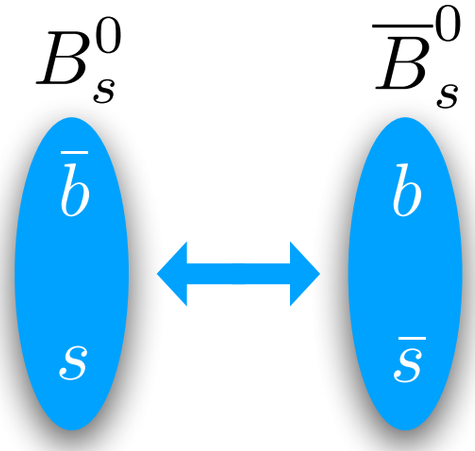
$$\Delta m_{B_s}/\Gamma_{B_s} = 26.9$$

$$\Delta m_{B_d}/\Gamma_{B_d} = 0.77$$



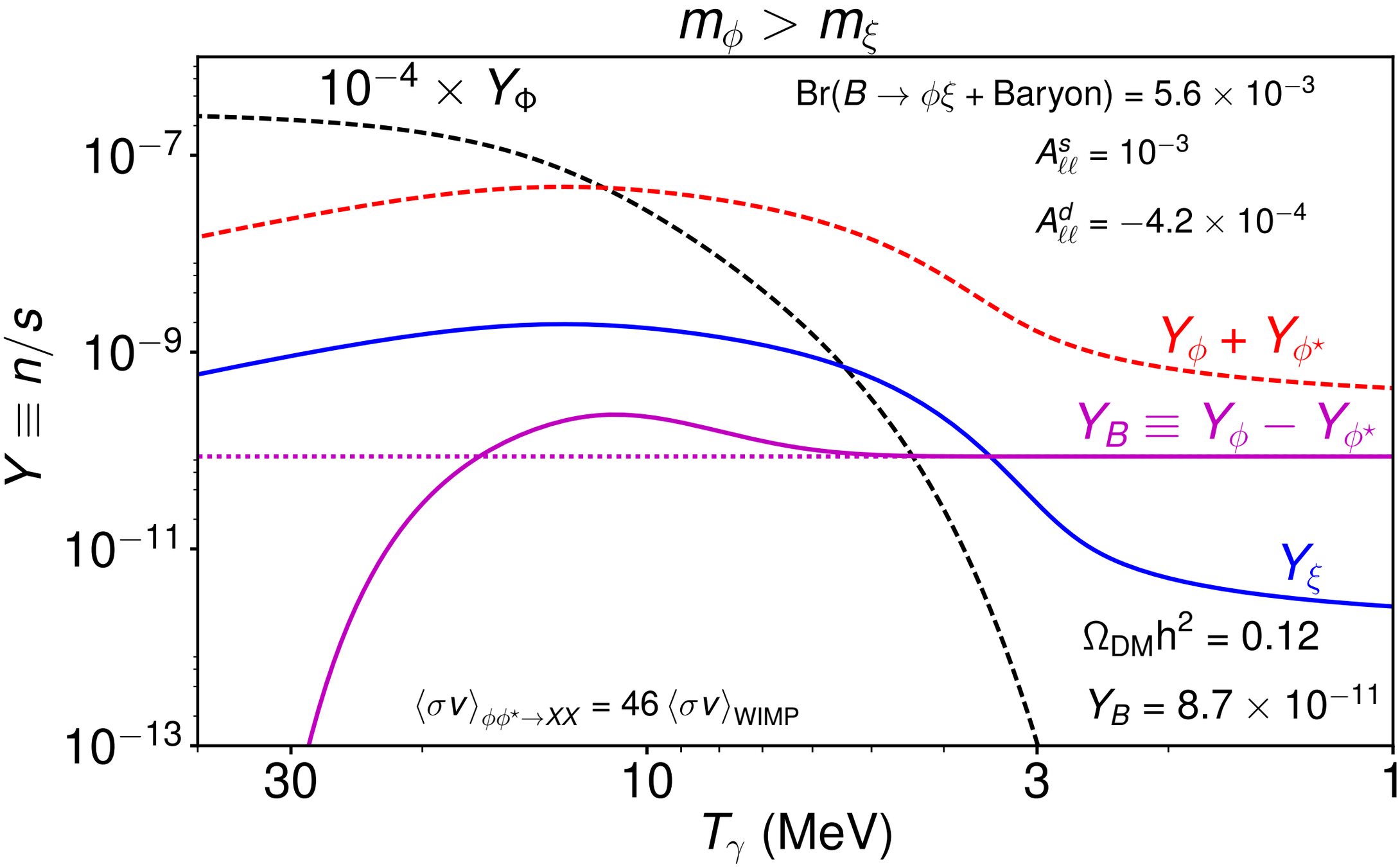
$$\Gamma(e^\pm B^0 \to e^\pm B^0) < \Delta m_{B^0}$$

$$\Gamma_{e^\pm B_0 \to e^\pm B_0} \simeq 10^{-11}\,\text{GeV} \left(\frac{T}{20\,\text{MeV}}\right)^5 \left(\frac{\langle r^2_{B_0}\rangle}{0.187}\right)^2$$



Results: $A^d < 0$ and $A^s > 0$

$m_\xi = 1.8\,\mathrm{GeV} \quad m_\phi = 1.3\,\mathrm{GeV}$

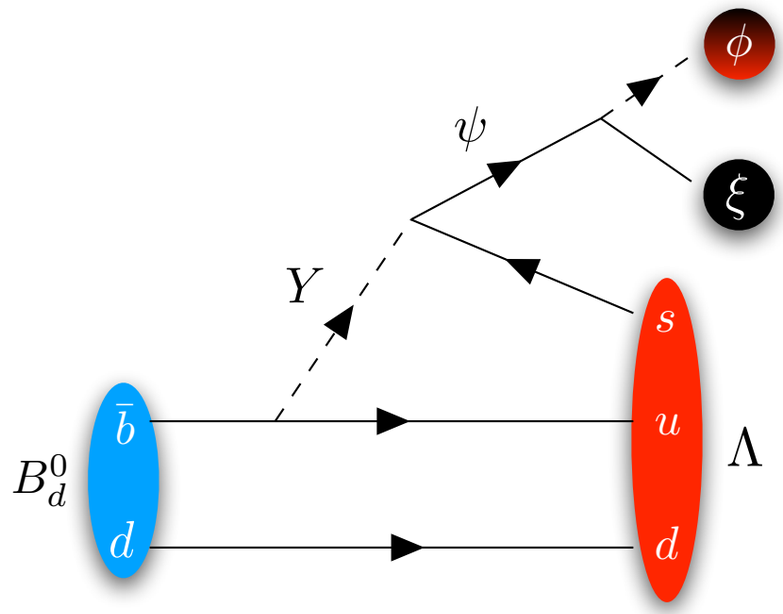


An Explicit Model

Minimal Particle Content

Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
Φ	0	0	0	+1	$11 - 100\,\text{GeV}$
Y	0	$-1/3$	$-2/3$	+1	$\mathcal{O}(\text{TeV})$
ψ	1/2	0	-1	+1	$\mathcal{O}(\text{GeV})$
ξ	1/2	0	0	-1	$\mathcal{O}(\text{GeV})$
ϕ	0	0	-1	-1	$\mathcal{O}(\text{GeV})$

B-mesons decay into DM (missing energy) and a Baryon



Heavy Colored Triplet Scalar:

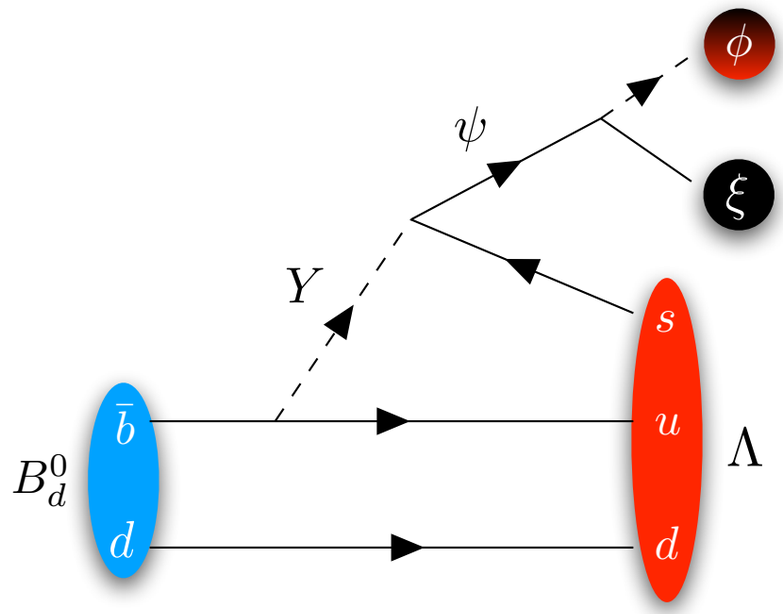
- $\mathcal{L} \supset -y_{ub}\, Y^*\, \bar{u}\, b^c - y_{\psi s}\, Y \bar{\psi}\, s^c + \text{h.c} \qquad m_Y > 1\,\text{TeV}$ **(4-jet/squark)**
- $\mathcal{H}_{eff} = \dfrac{y_{ub} y_{\psi s}}{m_Y^2} u\, s\, b\, \psi$ also possible $c\, s\, b\, \psi\,,\; u\, d\, b\, \psi\,,\; c\, d\, b\, \psi$
- $\Delta B = 0$ **operator induces new b-quark decay** $\bar{b} \to \psi u s$ **(CP and Baryon number conserving)**
- $\text{Br}(B \to \xi\phi + \text{Baryon}) \simeq 10^{-3} \left(\dfrac{m_B - m_\psi}{2\ \text{GeV}}\right)^4 \left(\dfrac{1\ \text{TeV}}{m_Y} \dfrac{\sqrt{y_{ub} y_{\psi s}}}{0.53}\right)^4$

An Explicit Model

Minimal Particle Content

Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
Φ	0	0	0	$+1$	$11 - 100\,\mathrm{GeV}$
Y	0	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\mathrm{TeV})$
ψ	1/2	0	-1	$+1$	$\mathcal{O}(\mathrm{GeV})$
ξ	1/2	0	0	-1	$\mathcal{O}(\mathrm{GeV})$
ϕ	0	0	-1	-1	$\mathcal{O}(\mathrm{GeV})$

B-mesons decay into DM (missing energy) and a Baryon



The Dark Sector:

ψ : **Dirac Dark Baryon**

- **For the b-quark decay to happen:** $m_\psi < m_B - m_{\mathrm{Baryon}} < 4.3\,\mathrm{GeV}$

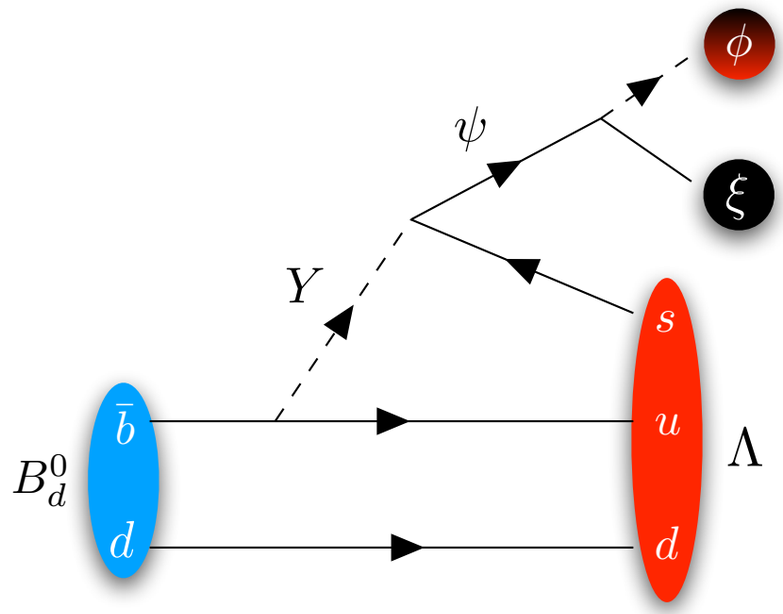
- ψ **needs to have decays into other dark sector particles or will decay back to visible baryons and undo the Baryogenesis** $\tau(\psi \to p + \pi^-) \sim 10^4\,\mathrm{years}$

An Explicit Model

Minimal Particle Content

Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
Φ	0	0	0	$+1$	$11 - 100\,\mathrm{GeV}$
Y	0	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\mathrm{TeV})$
ψ	1/2	0	-1	$+1$	$\mathcal{O}(\mathrm{GeV})$
ξ	1/2	0	0	-1	$\mathcal{O}(\mathrm{GeV})$
ϕ	0	0	-1	-1	$\mathcal{O}(\mathrm{GeV})$

B-mesons decay into DM (missing energy) and a Baryon



The Dark Sector:

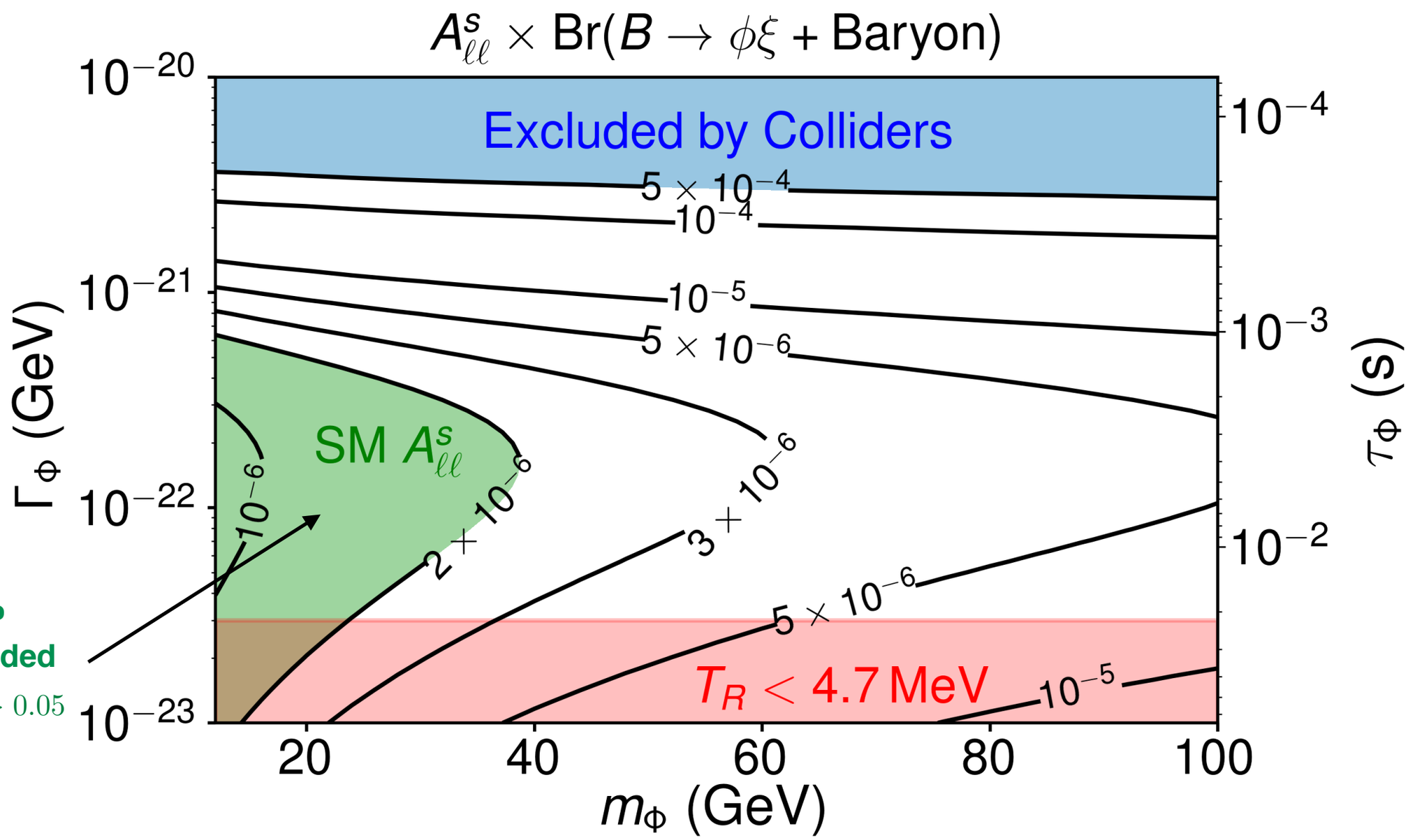
ϕ : **Charged *Stable* Scalar anti-Baryon** ξ : **Dark *Stable* Majorana Fermion**

- **Minimal Dark sector interaction** $\mathcal{L} \supset -y_d\,\bar{\psi}\,\phi\,\xi$ **with Z_2 symmetry**
- **Constraints:**
  - ***ψ -> $\phi\xi$ Decay:*** $m_\phi + m_\xi < m_\psi < 4.3\,\mathrm{GeV}$
  - **DM Stability:** $|m_\xi - m_\phi| < m_p + m_e$
  - **Neutron Star Stability:** $m_\psi > m_\phi > 1.2\,\mathrm{GeV}$

McKeen, Nelson, Reddy, Zhou 1802.08244

Parameter Space $A^d_{\ell\ell} = 0$

All points correspond to $Y_B = 8.7 \times 10^{-11}$



Baryogenesis can be achieved with just the CP violation in the SM! provided

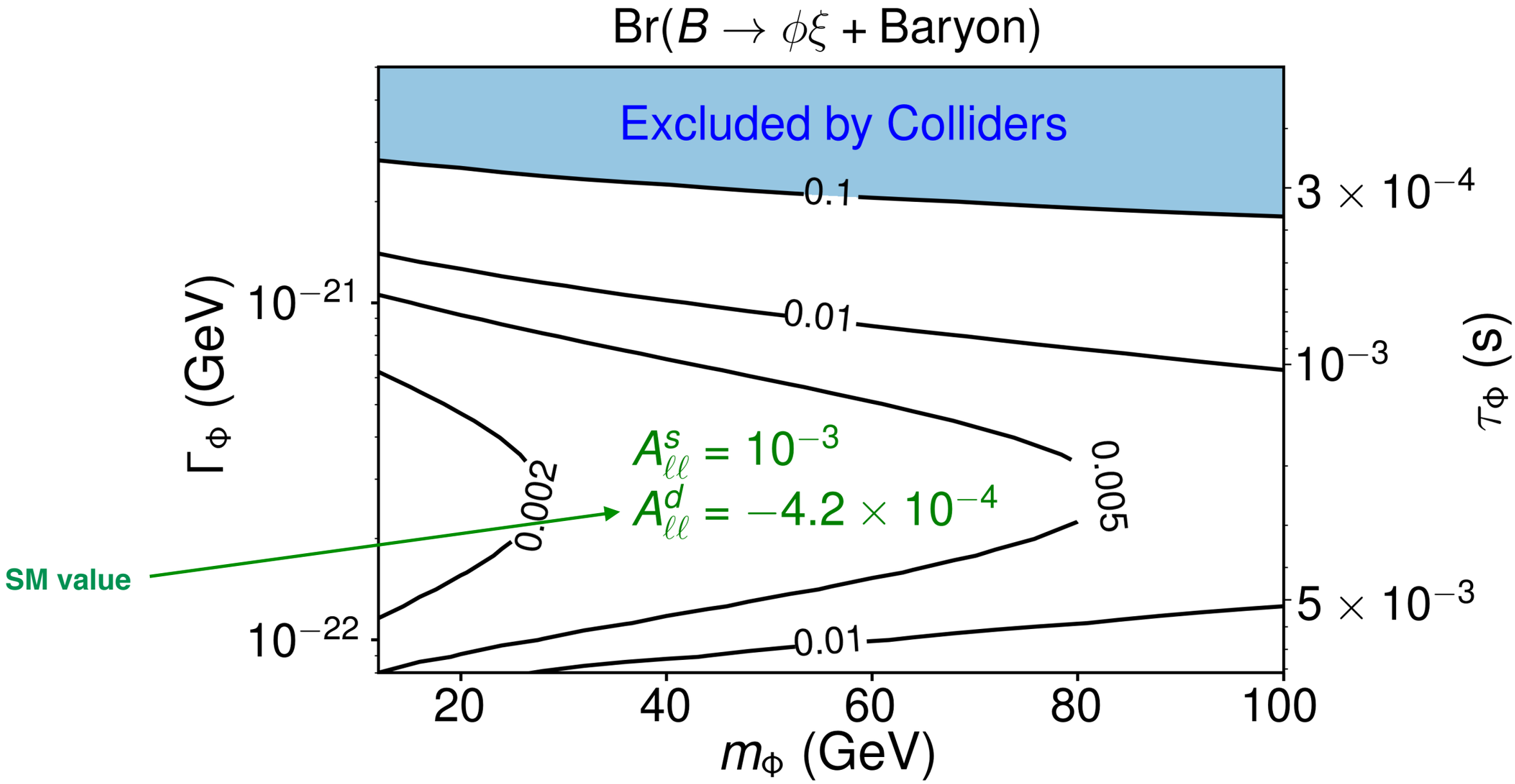
$\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) > 0.05$

and $A^d_{\ell\ell} = 0$

Baryogenesis requires:

- $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) = 2 \times 10^{-4} - 0.1$
- $A^s_{\ell\ell} = 10^{-5} - 10^{-3}$

Parameter Space $A^d_{\ell\ell} = A^d_{\ell\ell}|_{\rm SM}$



- **Baryogenesis can take place even if one asymmetry is negative provided the other is positive and large enough.**

Dark Matter Phenomenology

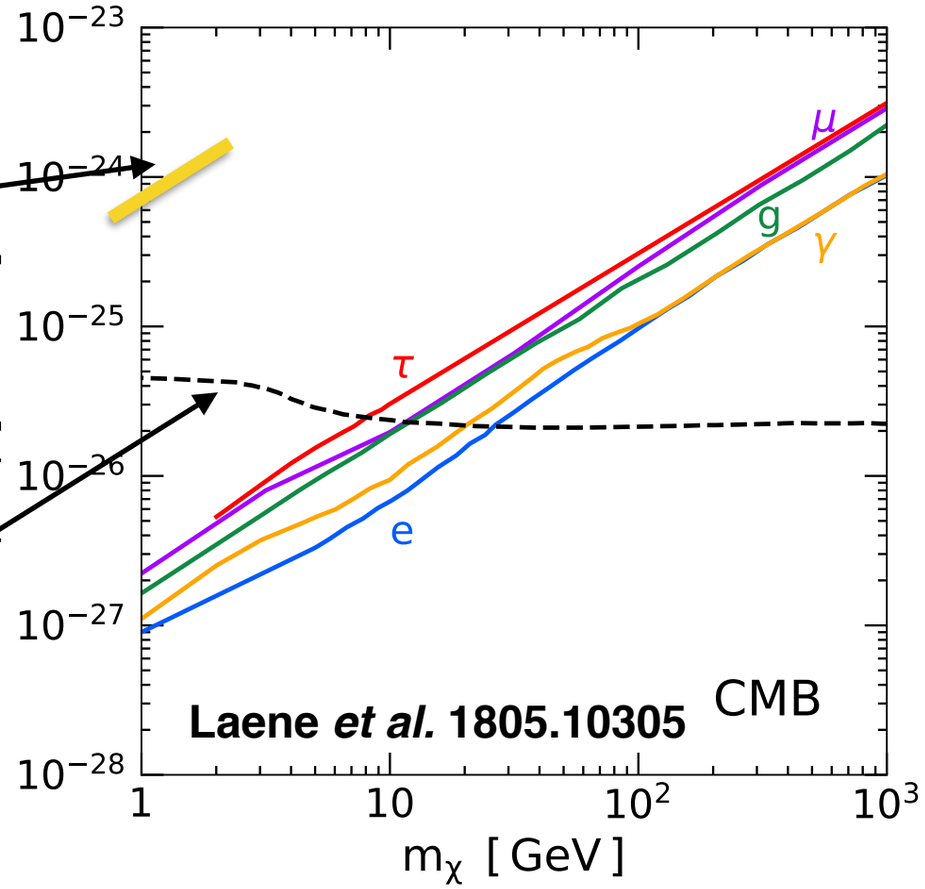
- **Relic abundance obtained with:**

$$\Omega_{\rm DM} h^2 = 0.12 \quad \longrightarrow \quad \langle \sigma v \rangle_{\rm dark} \simeq 25 \, \langle \sigma v \rangle_{\rm WIMP} \, \min[m_\phi, m_\xi]/{\rm GeV}$$

- **What kind of Dark Sector could allow for such cross sections but being compatible with the very strong constraints from the CMB observations?**

Our scenario: Non-thermal DM

Thermal relic



See update in Planck 2018 1807.06209

Possible Dark Sectors

1) Annihilation into Sterile Neutrinos

0711.4866 Pospelov, Ritz, Voloshin

The annihilation can be predominantly p-wave: 1607.02373, ME, Rius, Sanz

2) Annihilation into Active Neutrinos

González-Macias, Illana and Wudka, 1506.03825,1601.05051

Constraints on dark matter annihilating to neutrinos are very mild:

Beacom, Bell, Mack astro-ph/0608090

3) Additional particles carrying baryon number

- **New scalar Baryon with B = 1/3:**

$$\phi^\star + \phi \to \mathcal{A} + \mathcal{A}^\star$$
$$\phi + \mathcal{A} \to \mathcal{A}^\star + \mathcal{A}^\star$$

- **Which in order to get** $\Omega_{\rm DM}/\Omega_b = 5.36$ **will require** $m_{\mathcal{A}} \sim \frac{5}{3} m_p \sim 1.6\,{\rm GeV}$
- **Gives an understanding for the observed Dark Matter to Baryon energy density ratio.**

Future Searches

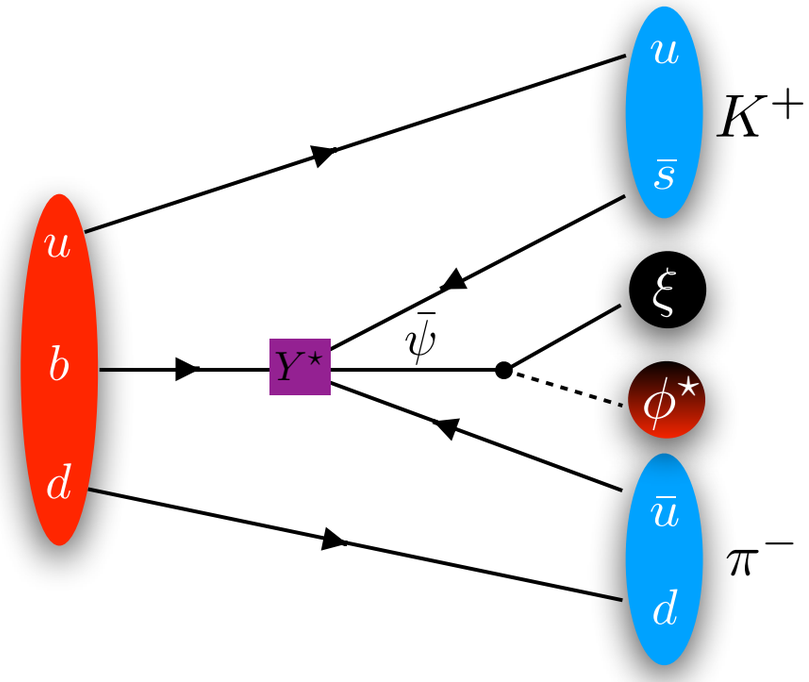
b-flavored Baryon decays into mesons and missing energy

The heavy colored scalar *Y* can also trigger such decays at the same rate as B meson decays:

$$\bar{b} \to \psi u s$$

$$\mathrm{Br}(\Lambda_b^0 \to \mathrm{Mesons} + \mathrm{DM}) \simeq \mathrm{Br}(B \to \mathrm{Baryon} + \mathrm{DM})$$

e.g.: Λ_b^0



b-flavored baryons are not produced in B-factories

This search seems considerably challenging at hadron colliders but see Stone & Zhang 1402.4205