Baryogenesis and Dark Matter from B Mesons

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with: Gilly Elor & Ann Nelson

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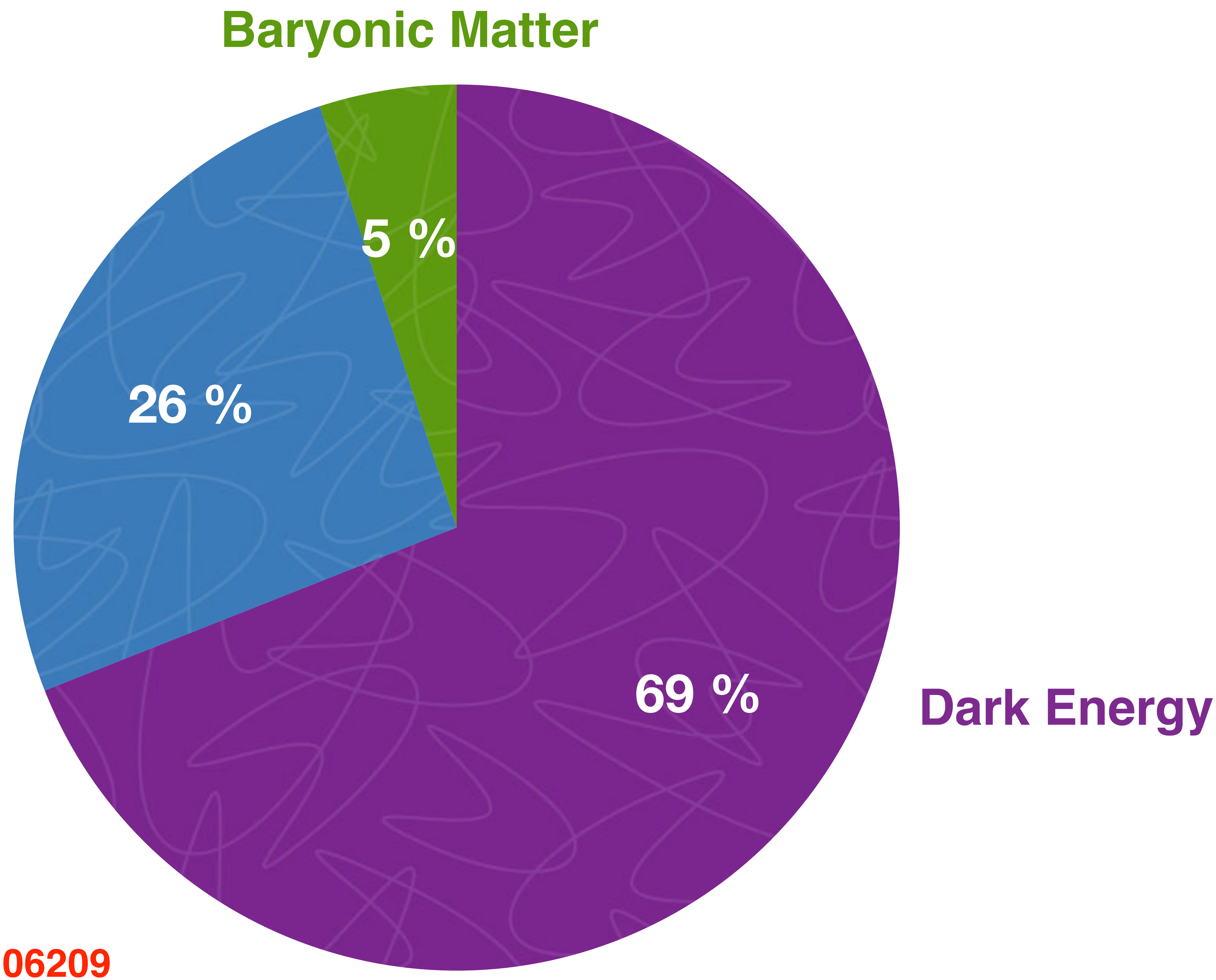
DARKHORIZONS

invisiblesPlus

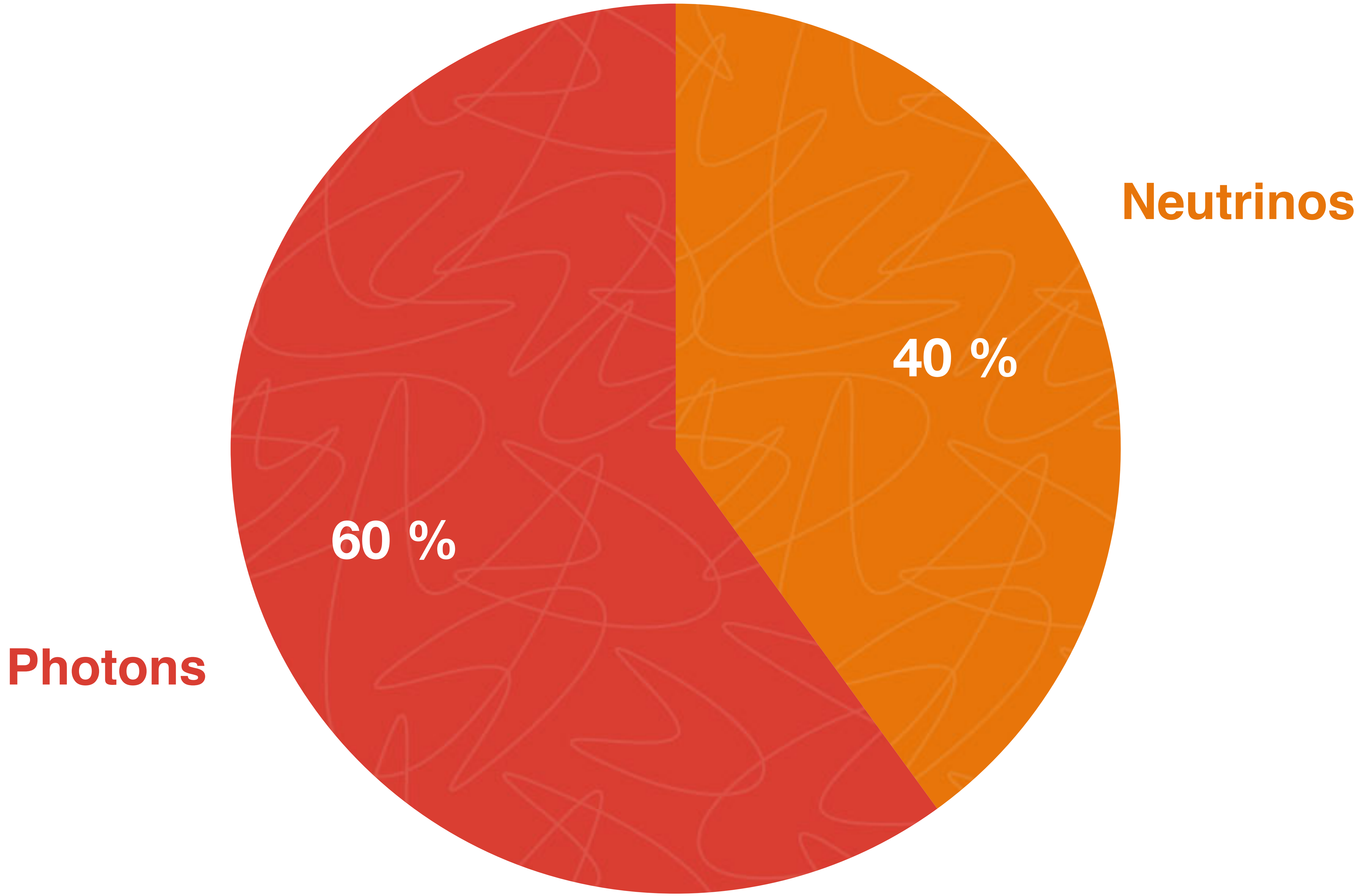
elusives
neutrinos, dark matter & dark energy physics

The Universe

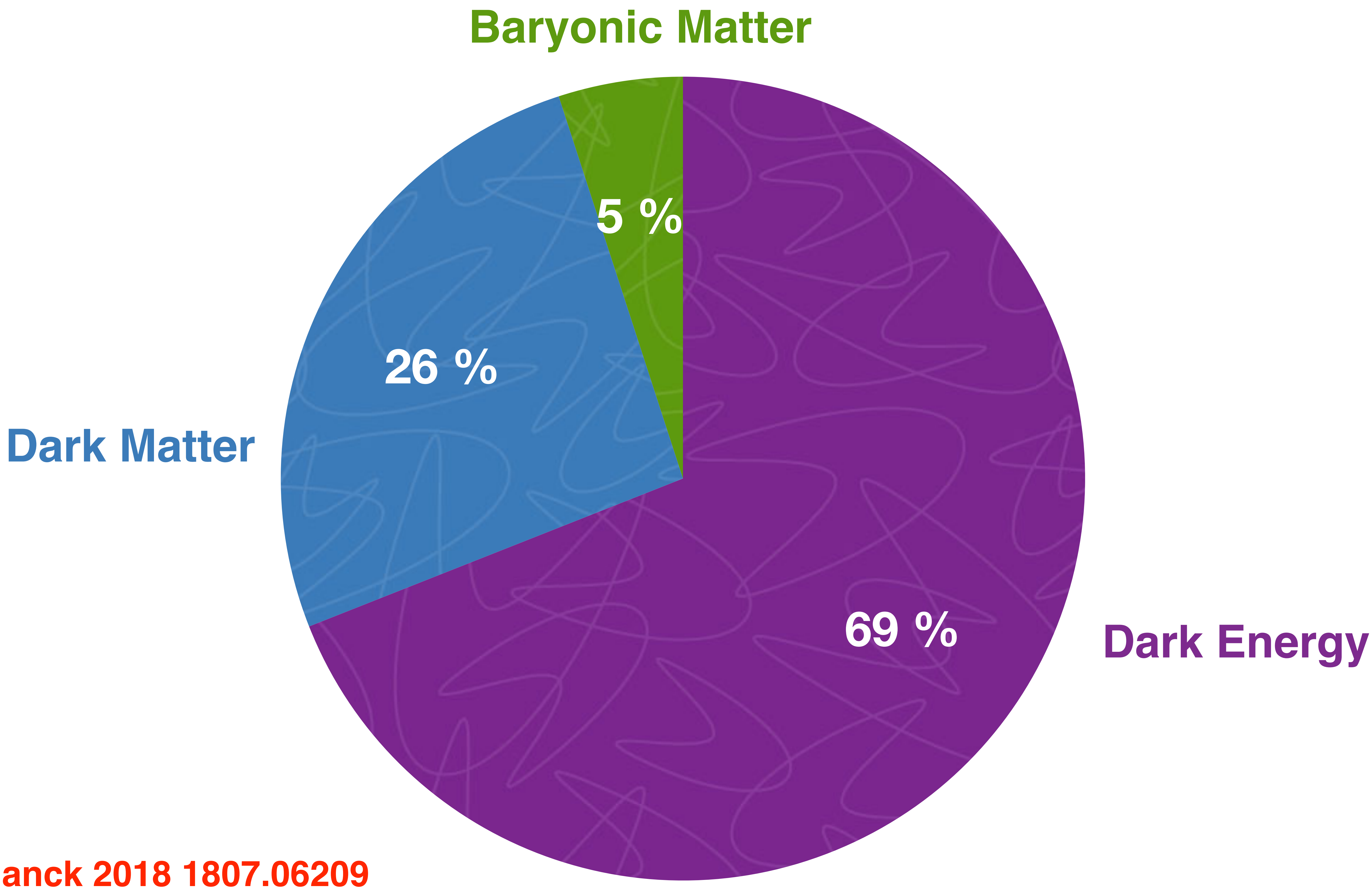


Planck 2018 1807.06209

SM Prediction:



The Universe



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Baryogenesis and Dark Matter from B Mesons

arXiv:1810.00880 Elor, Escudero & Nelson

1) Baryogenesis and Dark Matter are linked

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) Implications for Collider Experiments

4) Dark Matter phenomenology

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

The key quantity: the semileptonic asymmetry,

$$A^q_{\ell\ell} = \mathrm{Im}\left(\frac{\Gamma^q_{12}}{M^q_{12}}\right) = \frac{\Gamma\left(B^0_q \to f\right) - \Gamma\left(B^0_q \to \bar{f}\right)}{\Gamma\left(B^0_q \to f\right) + \Gamma\left(B^0_q \to \bar{f}\right)}$$

Standard Model

$$A^s_{\ell\ell}|_{\mathrm{SM}} = (2.22 \pm 0.27) \times 10^{-5}$$

$$A^d_{\ell\ell}|_{\mathrm{SM}} = (-4.7 \pm 0.6) \times 10^{-4}$$

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

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)

- **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

- **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**

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

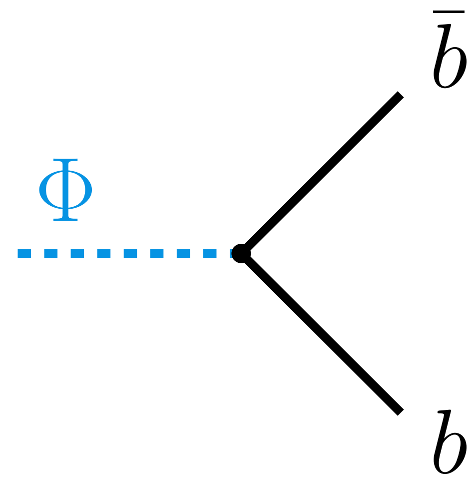
- **The decays don't spoil BBN or the CMB provided** $T_{RH} > 5\,\mathrm{MeV}$

de Salas *et al*. 1511.00672
Hasegawa *et al*. 1908.10189

Baryogenesis from B Mesons

2) Out of equilibrium and production of B Mesons

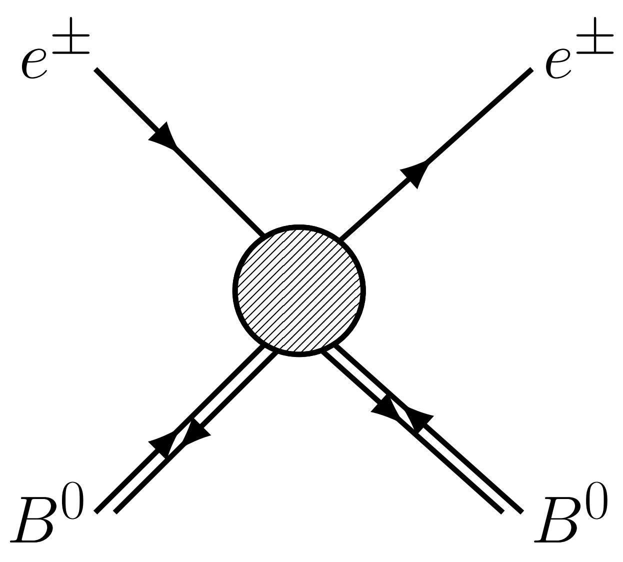
- **Scalar particle with** $m_\Phi \in 11 - 100\,\mathrm{GeV}$ **and** $\tau_\Phi = \mathcal{O}(10^{-3}\,\mathrm{s})$ **generically decays into b-quarks**



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

- **Coherent oscillations in the B⁰ system are maintained in the early Universe for Temperatures:**

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



Baryogenesis and DM from B Mesons

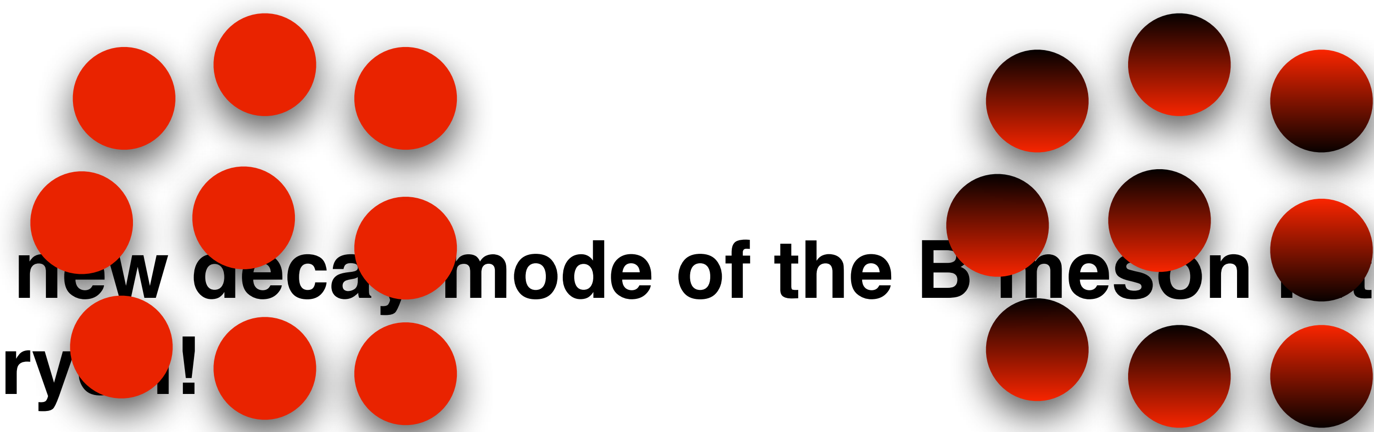
3) Baryon number violation?

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

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

- **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!**



Visible Sector (Baryons)

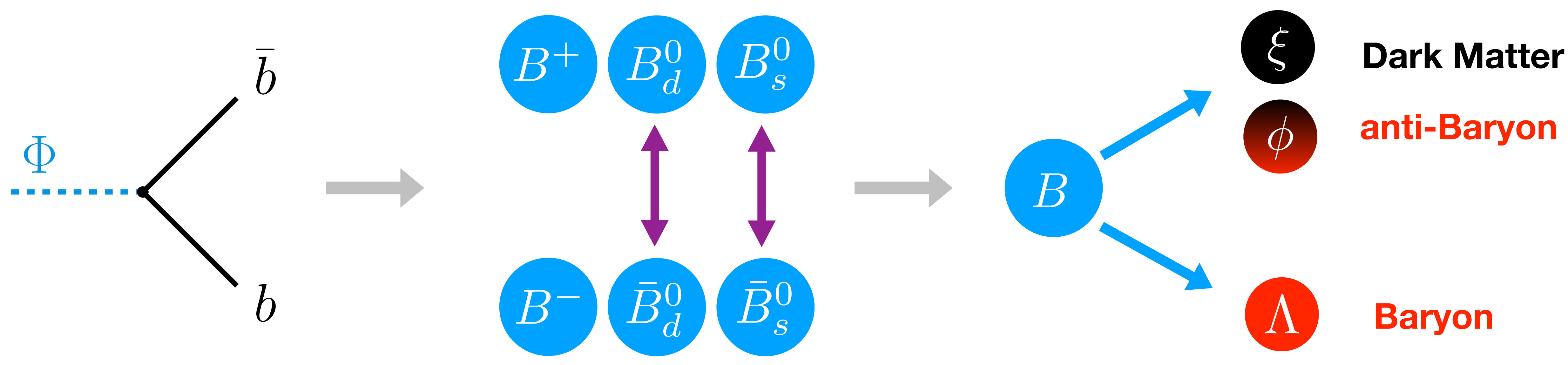
Dark Sector (anti-Baryons)

A Summary of the Mechanism

Out of equilibrium late time decay

CP violating Oscillations

B-mesons decay into Dark Matter and hadrons



$T_{\rm RH} \sim 20\,{\rm MeV}$

$A_{\ell\ell}^d \quad A_{\ell\ell}^s$

${\rm BR}(B \to \phi\xi + {\rm Baryon} + ...)$

Baryogenesis and **Dark Matter**

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

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

With the Baryon asymmetry: $Y_B \simeq 8.7 \times 10^{-11} \dfrac{A_{\ell\ell}}{5 \times 10^{-4}} \dfrac{{\rm BR}(B \to \psi + {\rm Baryon} + X)}{0.001}$

New B-Meson decay

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

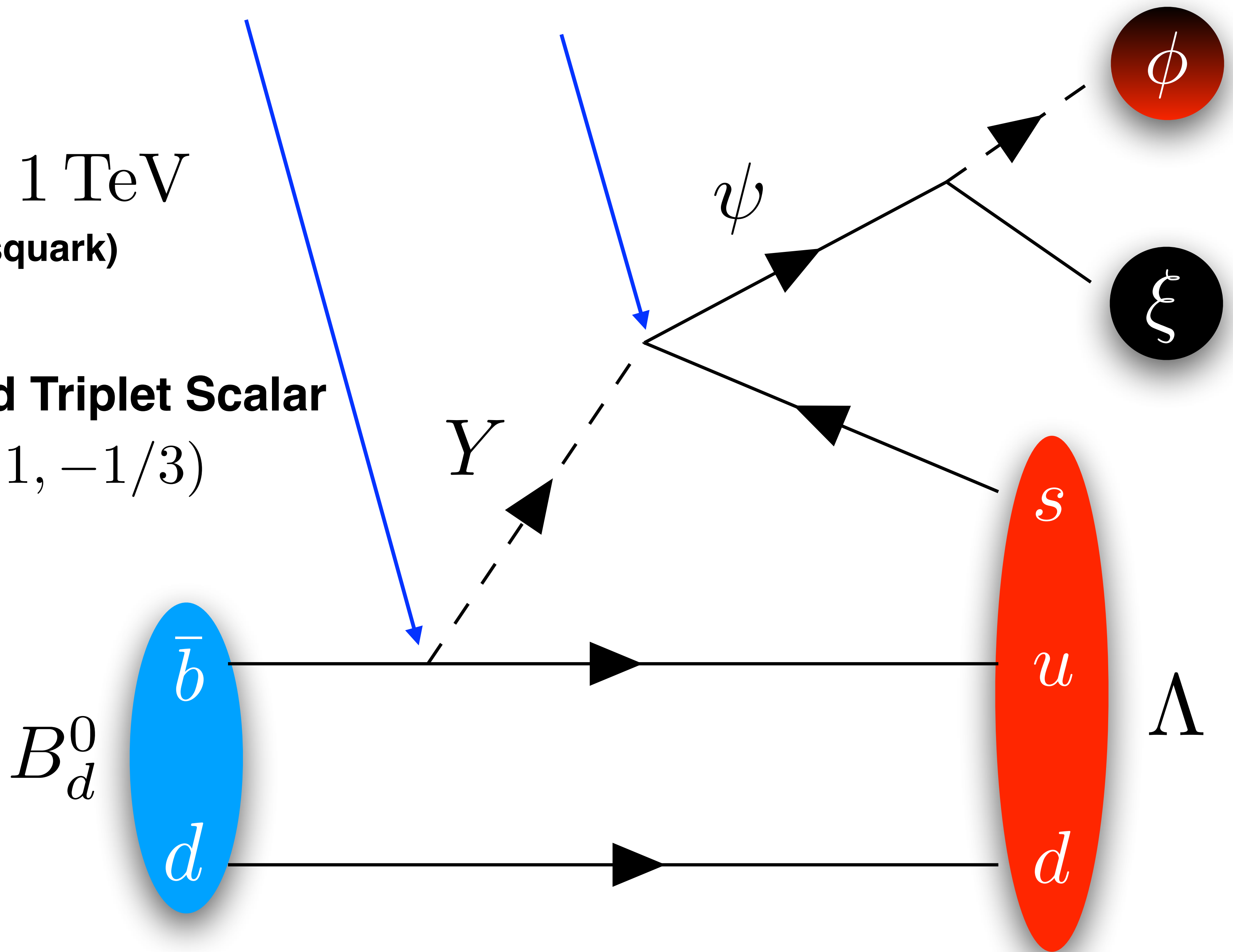
$$1.2\,\text{GeV} \lesssim m_{\phi,\,\xi} \lesssim 2.5\,\text{GeV}$$

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

(4-jet/squark)

Y: Colored Triplet Scalar

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



(anti Baryon)

Dark Matter

SM Singlets

stable via Z_2 sym

Baryon

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

Any room for a new decay mode?

Targeted decay modes are very constrained/well measured:

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

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

But our decay mode has not been targeted!

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

What about the total width of B-Mesons?

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

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

Ongoing searches with BaBar and Belle-II data!

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

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

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

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

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 B⁰ system and to the new decay of B mesons to a visible Baryon and missing energy.**
- **We take into account the decoherence of the B⁰ system in the early Universe.**

Parameter Space for Baryogenesis

Baryogenesis Requires:

$$A_{\ell\ell}^{d,\,s} \times \mathrm{Br}(B \to \psi + \mathrm{Baryon} + X) > 5 \times 10^{-7}$$

As of today we know:

$$A_{\ell\ell}^{d,\,s} \times \mathrm{Br}(B \to \psi + \mathrm{Baryon} + X) \lesssim 10^{-4}$$

Baryogenesis Requires:

$$\mathrm{Br}(B \to \psi + \mathrm{Baryon} + X) > 10^{-3} \qquad A_{\ell\ell} > 10^{-5}$$

Current collider sensitivity:

$$\mathrm{Br}(B \to \psi + \mathrm{Baryon} + X) \sim 10^{-4} \qquad A_{\ell\ell} \sim 5 \times 10^{-4}$$

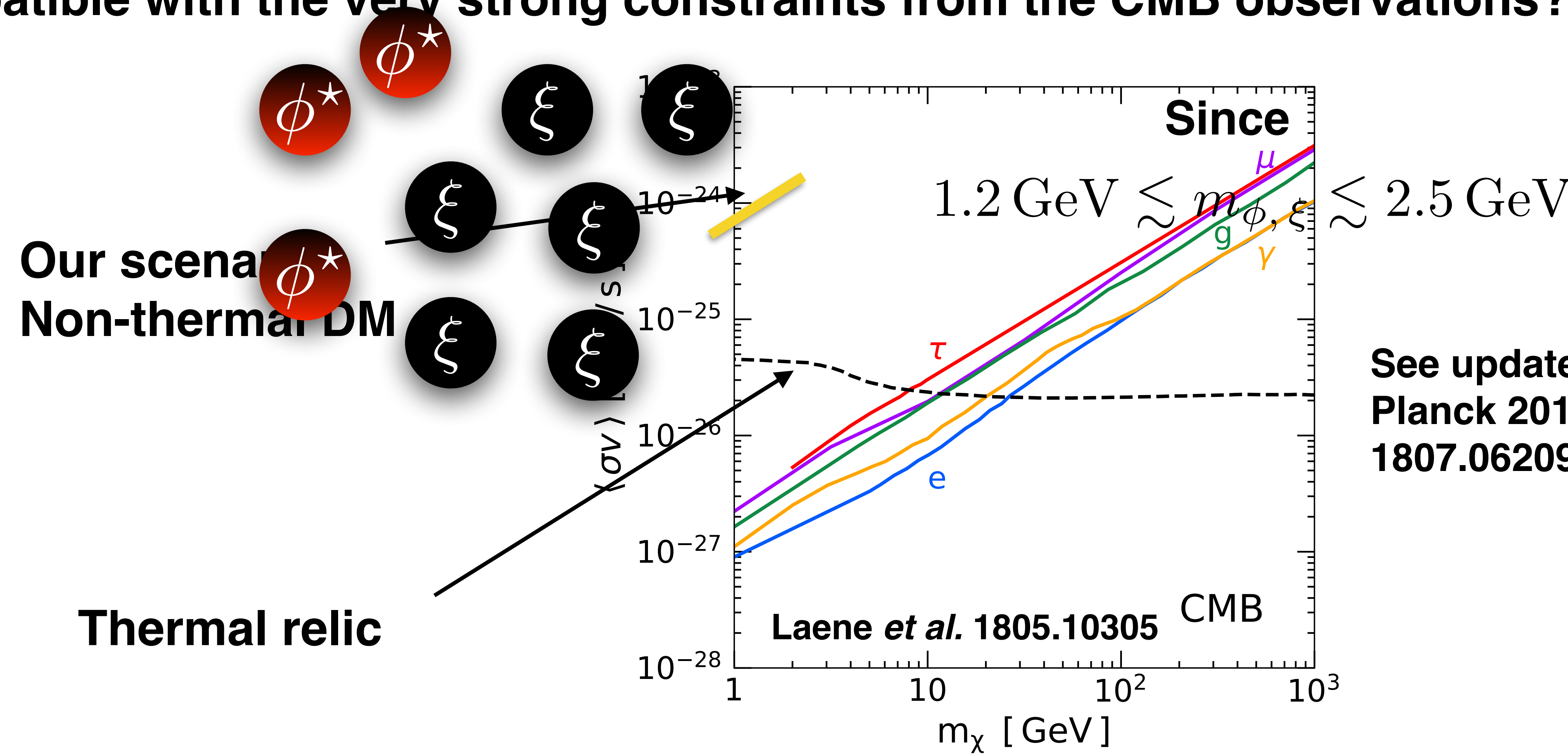
BaBar/Belle/Belle-II **LHCb/Belle-II**

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?**



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, Blennow et. al. 1903.00006

Constraints on dark matter annihilating to neutrinos are very mild:

Argüelles et. al. 1912.09486

3) Additional particles carrying baryon number

- **New scalar Baryon with B = 1/3:** $\mathcal{A}$

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

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

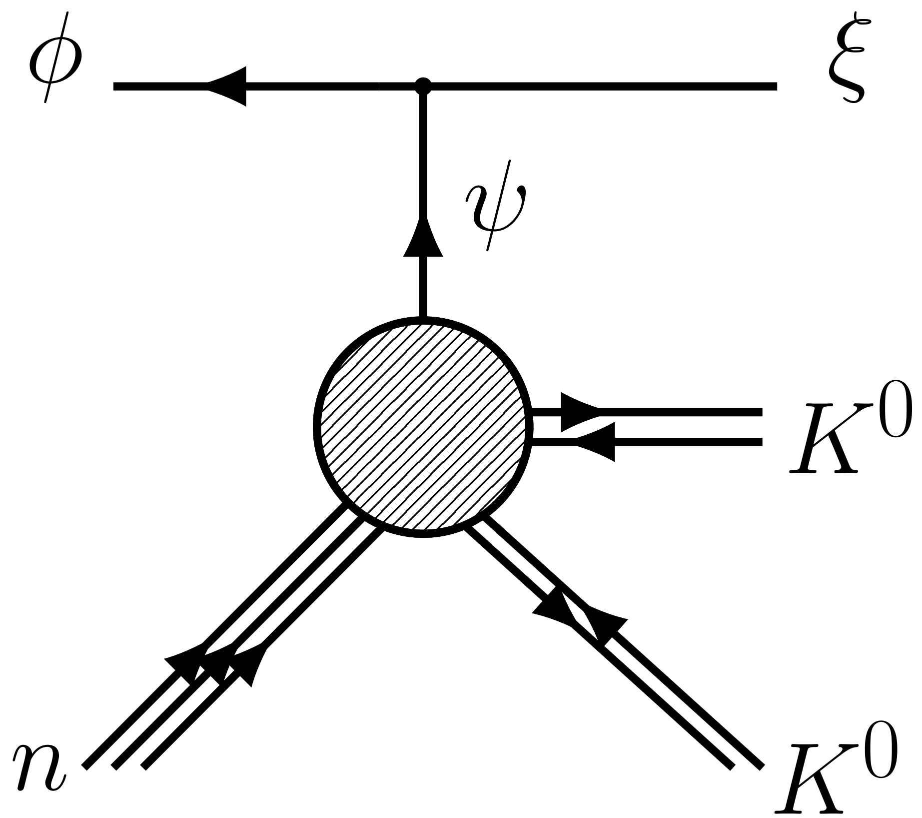
No Direct Detection Signatures

No direct coupling between the dark matter and light quarks

Coupling can be generated through weak loops:

$$u\,s\,b\,\psi \to f_\pi^2 G_F V_{tb} V_{ts}^\star\, u\,s\,s\,\psi \sim 10^{-8}\, u\,s\,s\,\psi$$

These processes are possible and could be searched for at Super-Kamiokande:



But the rate is tiny, hence unobservable
see 1008.2399

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**

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**

$$\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) > 10^{-3}$$

Ongoing search for this process at Belle-II!

B-factories should test this scenario given the constraints on other missing energy channels:

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

The mechanism is fully testable at current collider experiments!

Outlook

Theory

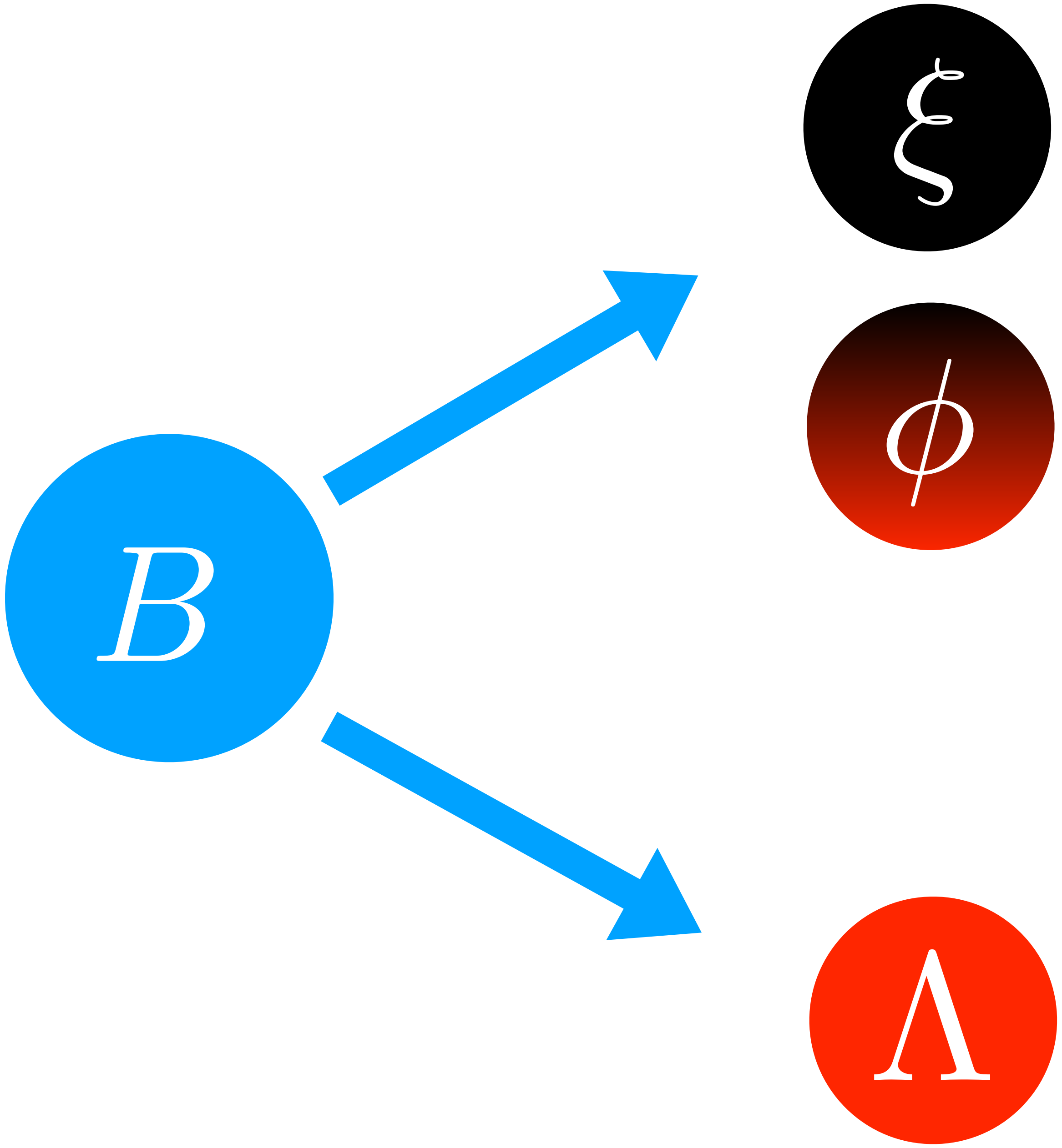
- **Are there more possibilities for the dark sector?**

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

E.g.: SUSY, 1907.10612 Alonso-Álvarez, Elor, Nelson, Xiao

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

Thank You!



Back Up

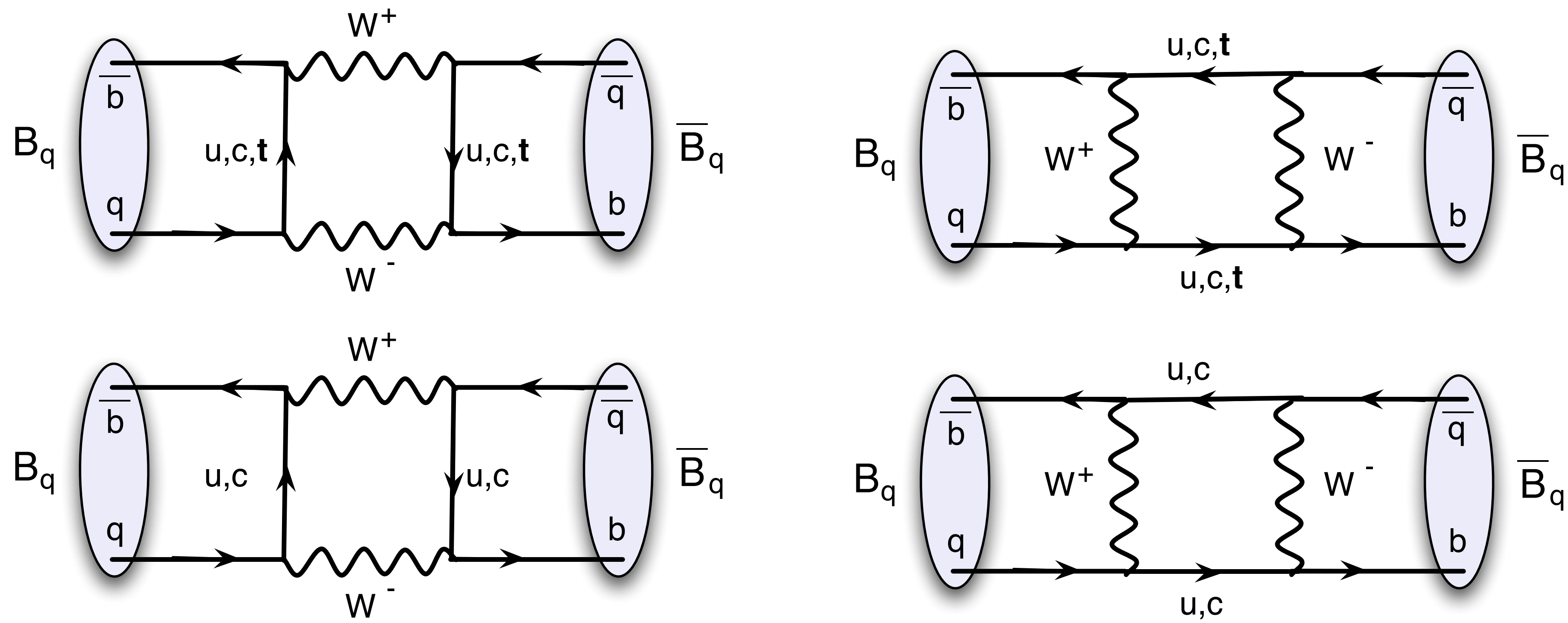
Baryogenesis from B Mesons

1) CP violation in the Meson System

SM: Box Diagrams

$M_{12} \propto$

$\Gamma_{12} \propto$



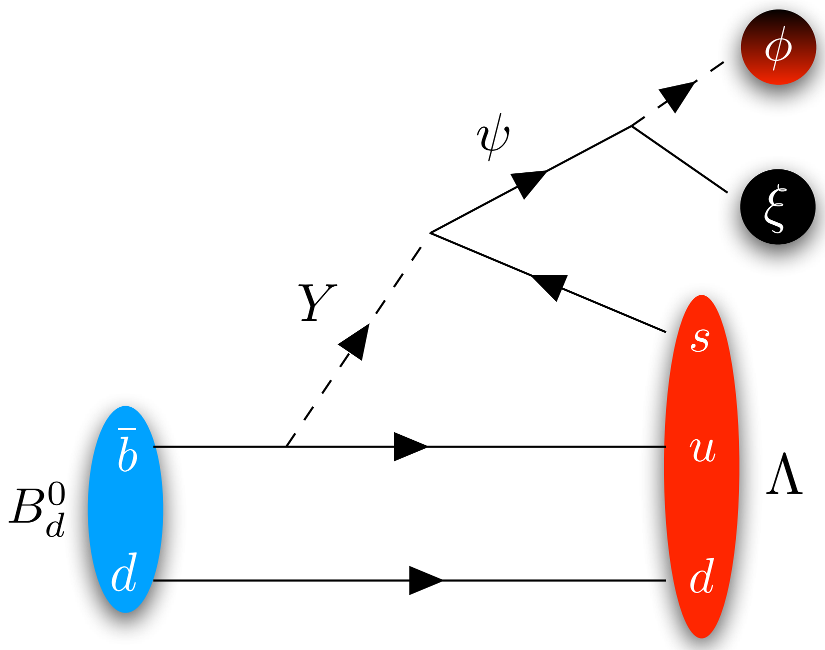
CP violating mixing requires a relative phase between Γ_{12} and M_{12}

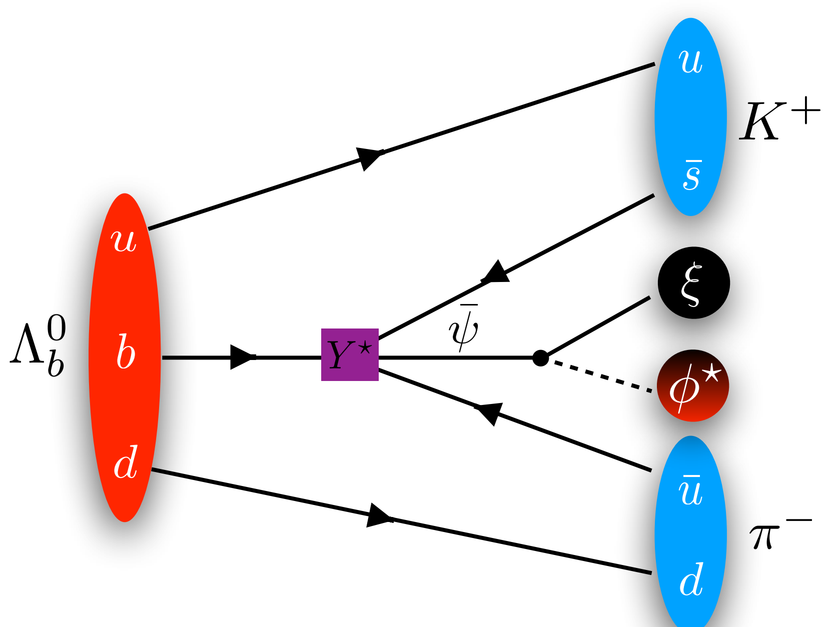
BSM?

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

see *e.g.* Nir 9911321

Back Up: Flavourful Variations





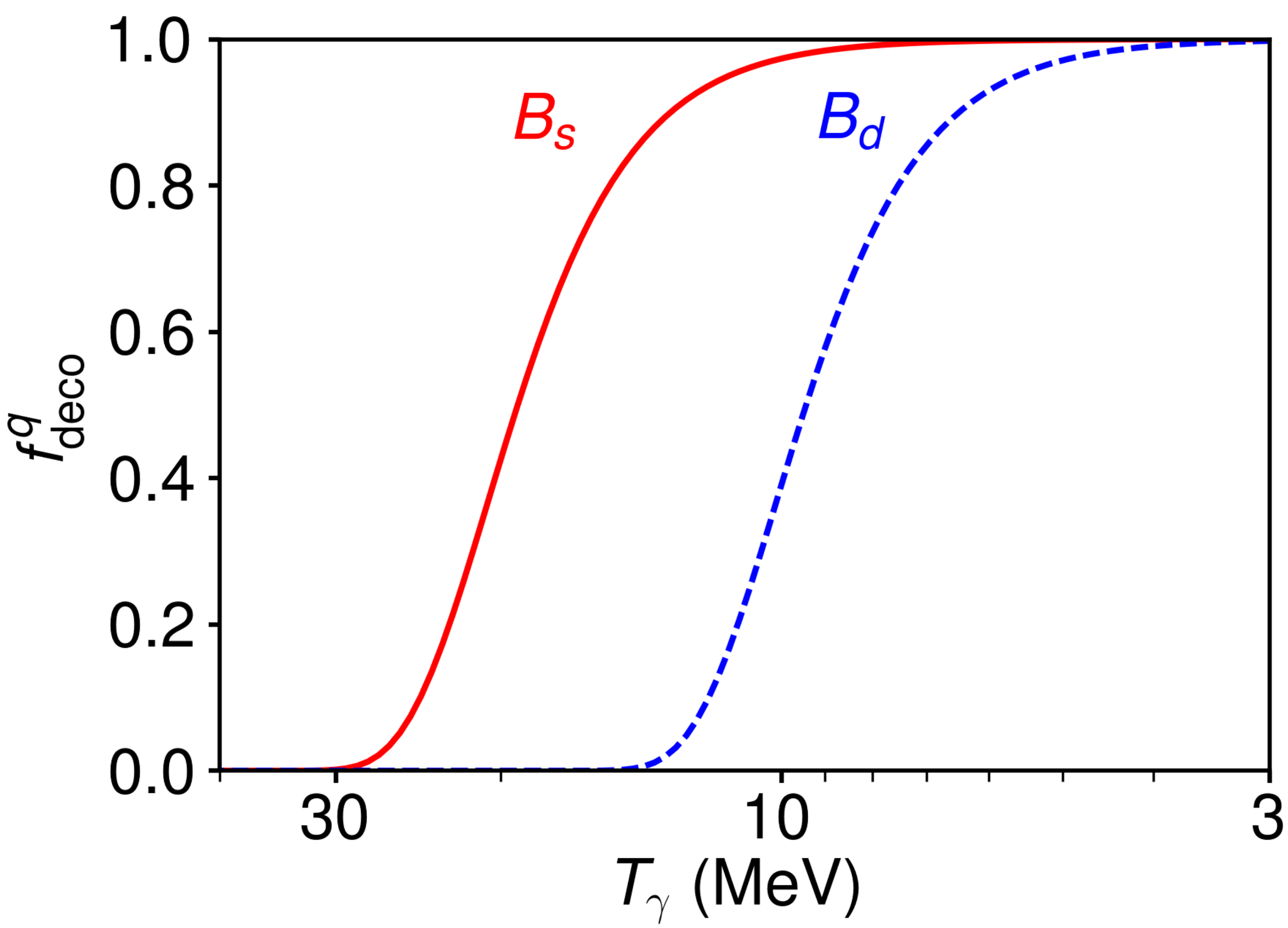
Operator	Initial State	Final state	ΔM (MeV)
$\psi\, b\, u\, s$	B_d	$\psi + \Lambda\,(usd)$	4163.95
	B_s	$\psi + \Xi^0\,(uss)$	4025.03
	B^+	$\psi + \Sigma^+\,(uus)$	4089.95
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\psi\, b\, u\, d$	B_d	$\psi + n\,(udd)$	4340.07
	B_s	$\psi + \Lambda\,(uds)$	4251.21
	B^+	$\psi + p\,(duu)$	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 $B \to$ ME + 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]

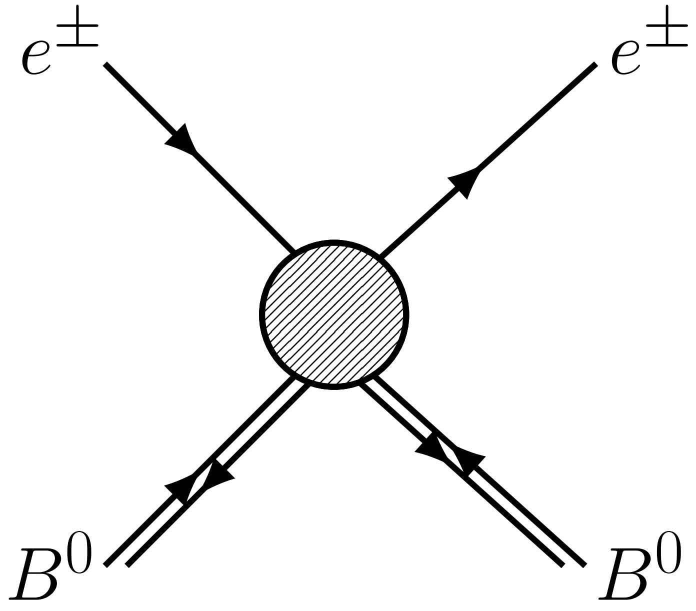
Back Up: Decoherence



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

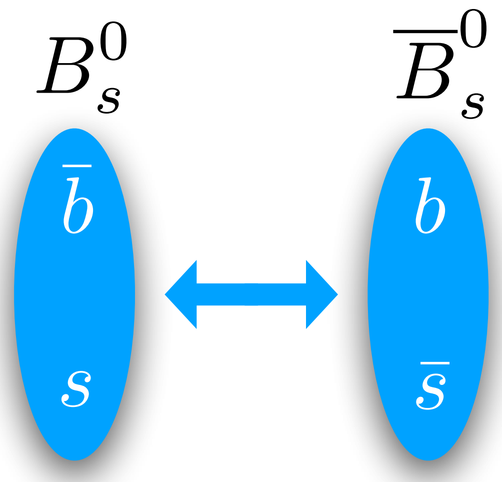
$$\Delta m_{B_s}/\Gamma_{B_s} = 26.9$$

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



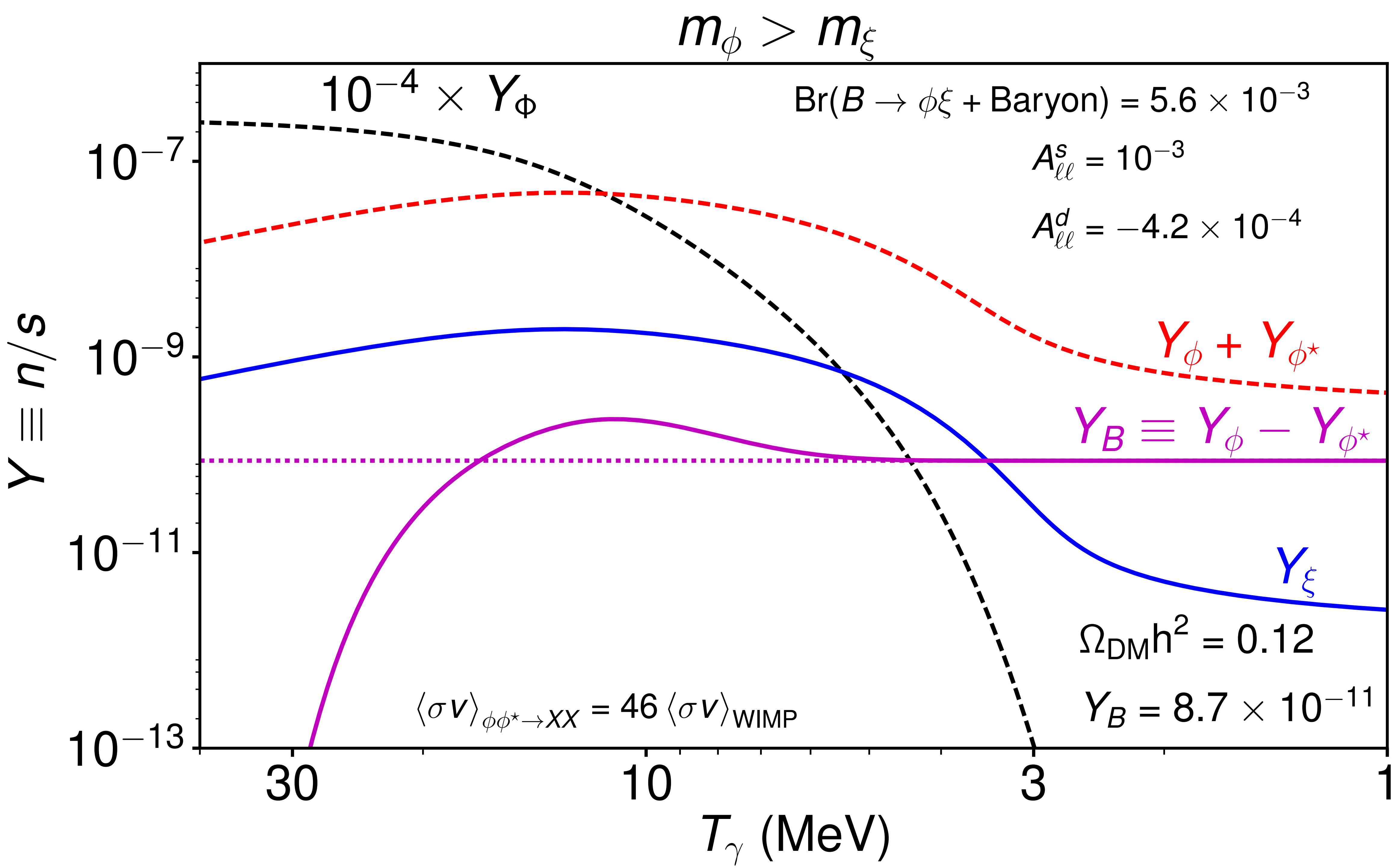
$$\Gamma(e^\pm B^0 \to e^\pm B^0) < \Delta m_{B^0}$$

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



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

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

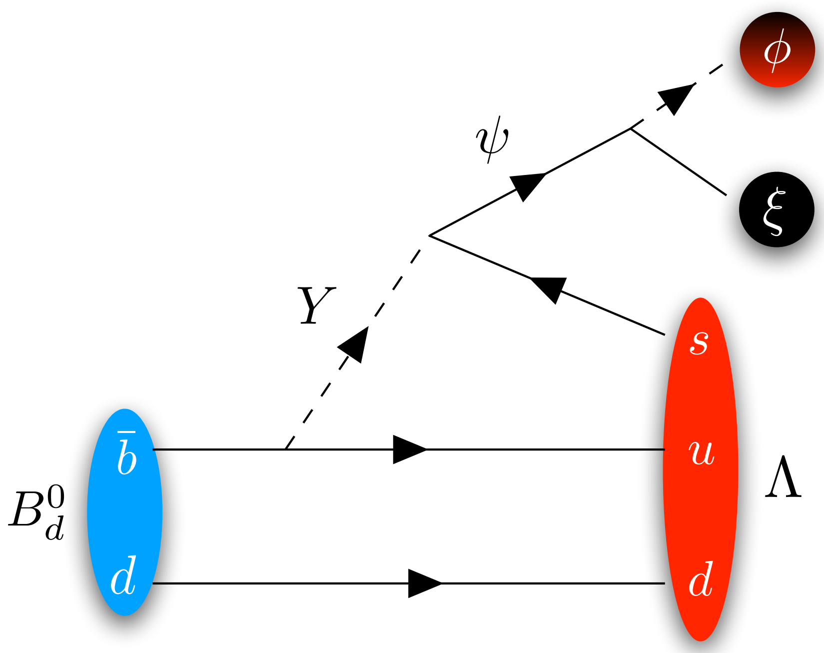


An Explicit Model

Minimal Particle Content

Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
Φ	0	0	0	+1	$11-100\,\mathrm{GeV}$
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



Heavy Colored Triplet Scalar:

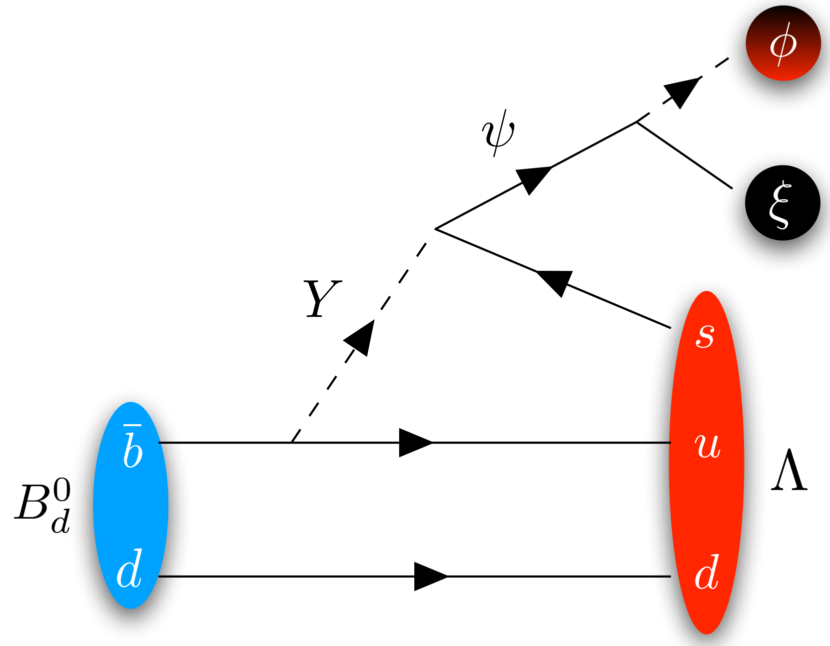
- $\mathcal{L} \supset -y_{ub}\, Y^*\, \bar{u}\, b^c - y_{\psi s}\, Y \bar{\psi}\, s^c + \mathrm{h.c}$ $\quad m_Y > 1\,\mathrm{TeV}$ **(4-jet/squark)**
- $\mathcal{H}_{eff} = \frac{y_{ub} y_{\psi s}}{m_Y^2} u\, s\, b\, \psi$ also possible $c\, s\, b\, \psi\,,\, u\, d\, b\, \psi\,,\, c\, d\, b\, \psi$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

An Explicit Model

Minimal Particle Content

Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
Φ	0	0	0	$+1$	$11 - 100\,\text{GeV}$
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



The Dark Sector:

ψ : **Dirac Dark Baryon**

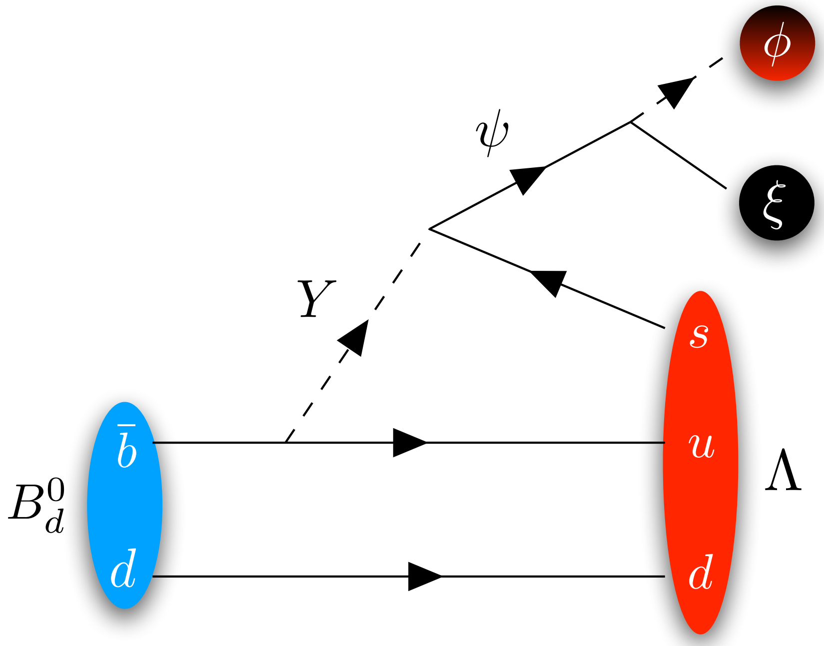
- **For the b-quark decay to happen:** $m_\psi < m_B - m_{\text{Baryon}} < 4.3\,\text{GeV}$
- ψ **needs to have decays into other dark sector particles or will decay back to visible baryons and undo the Baryogenesis** $\tau(\psi \to p + \pi^-) \sim 10^4\,\text{years}$

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**

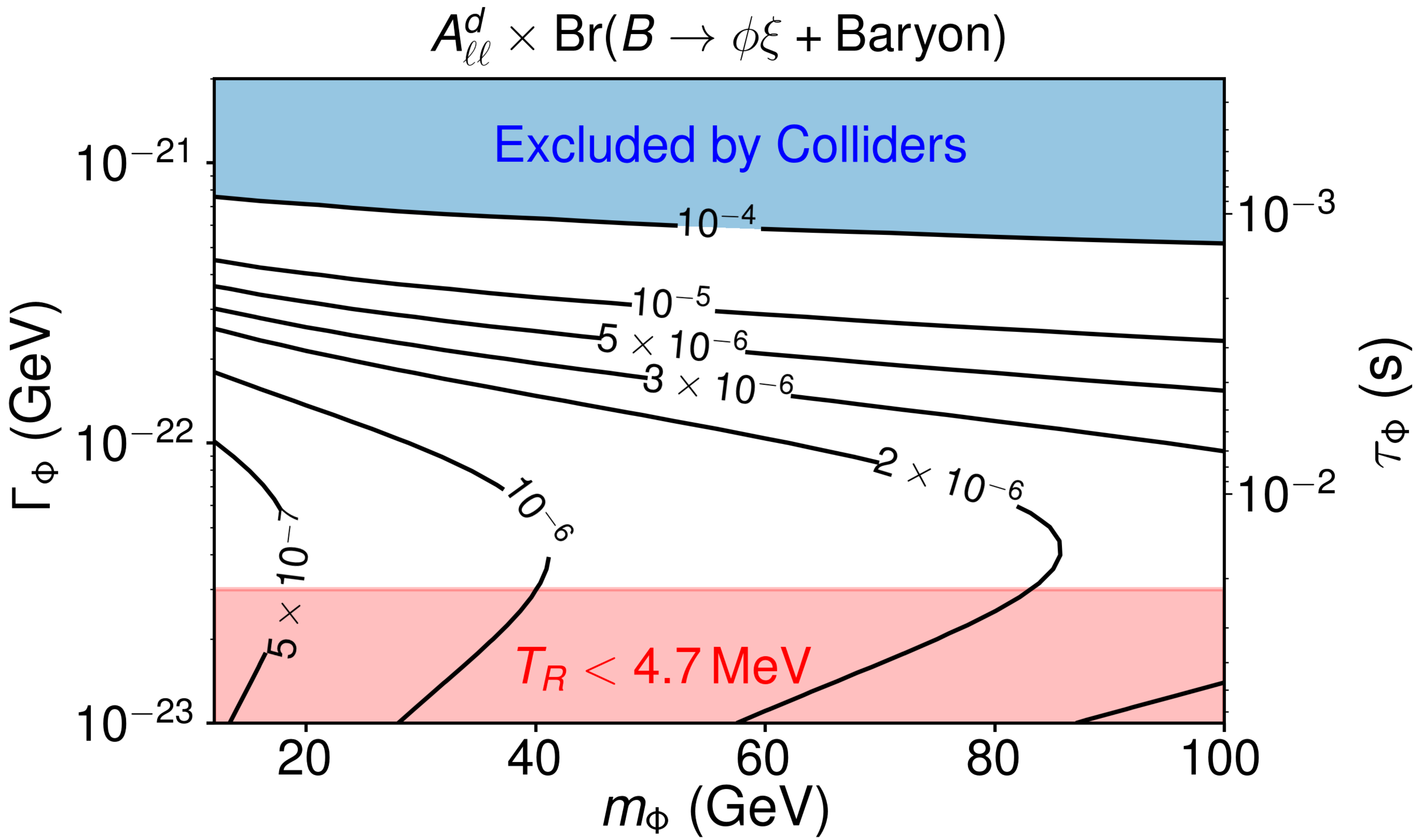
ξ : **Dark *Stable* Majorana Fermion**

- **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 $A^s_{\ell\ell} = 0$

All points correspond to the observed baryon asymmetry

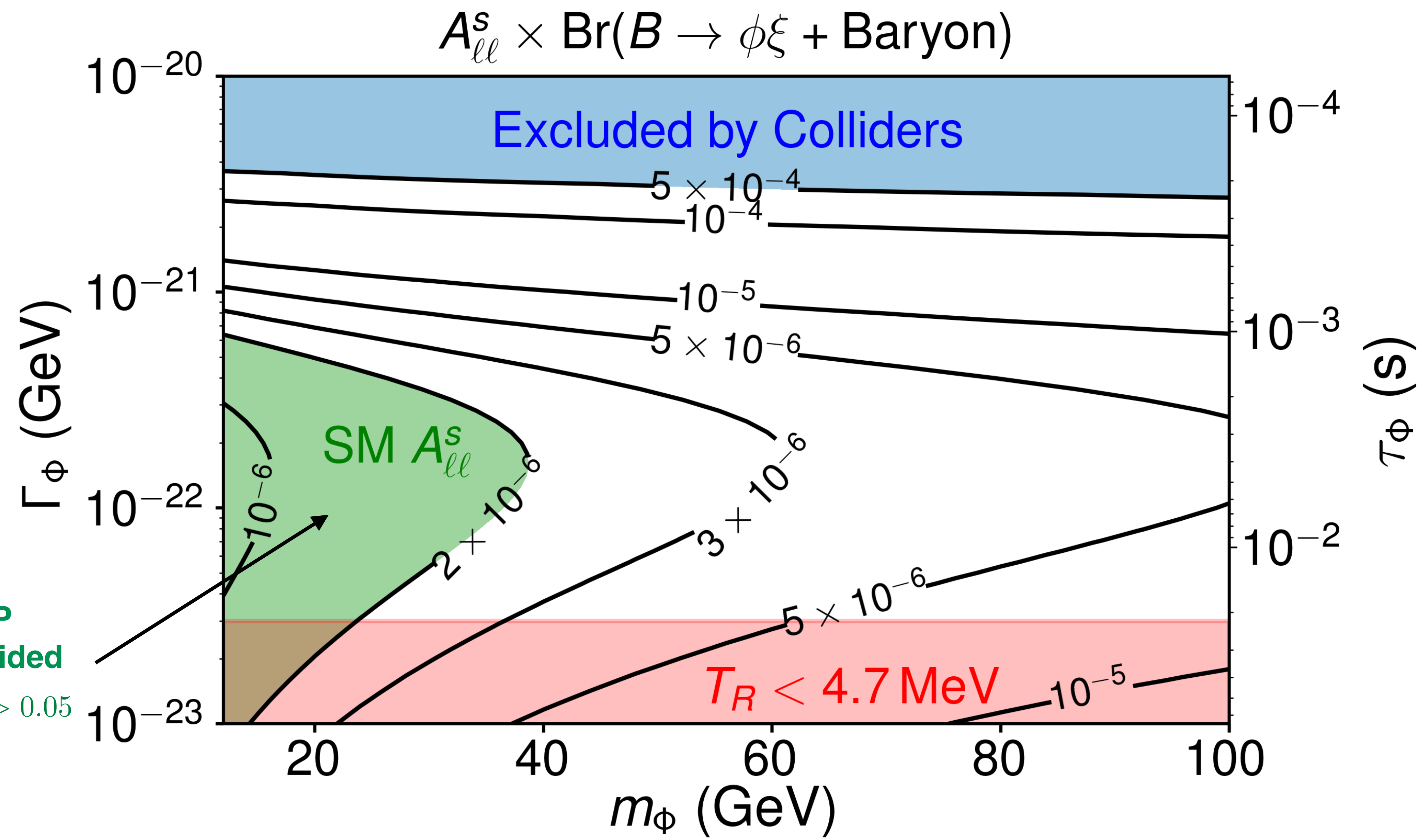


Baryogenesis requires:

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

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

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

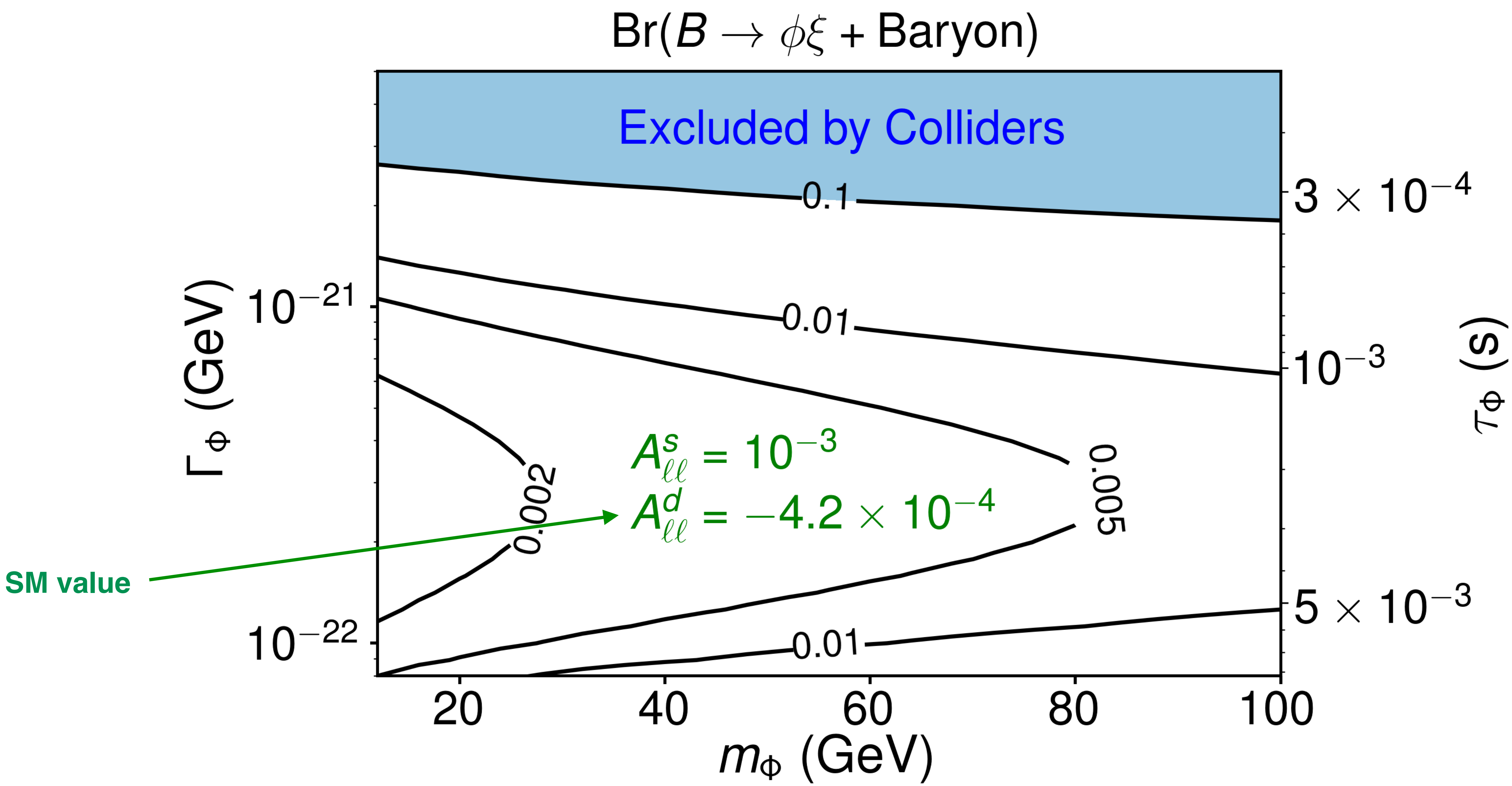


Baryogenesis can be achieved with just the CP violation in the SM! provided
$\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) > 0.05$
and $A^d_{\ell\ell} = 0$

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.**