Baryogenesis and Dark Matter from B Mesons

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Based on:

arXiv:1810.00880, PRD 99, 035031 (2019)
with: Gilly Elor & Ann Nelson
arXiv:2006.XXXXX
with: Gilly Elor, Gonzalo Alonso-Álvarez, David McKeen

Spring Meeting LHC DM WG: 28-04-2020

European Research Council
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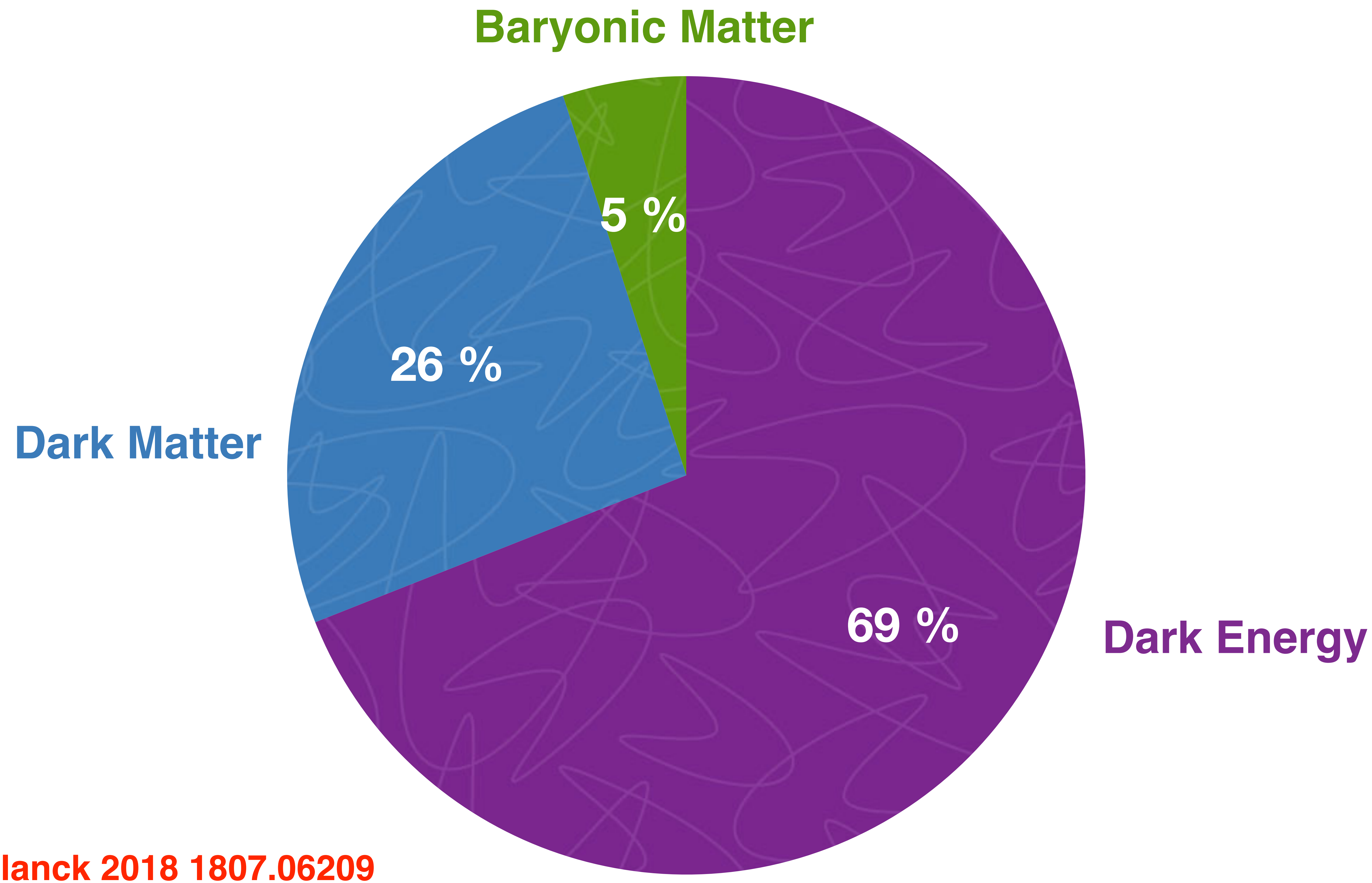
DARKHORIZONS

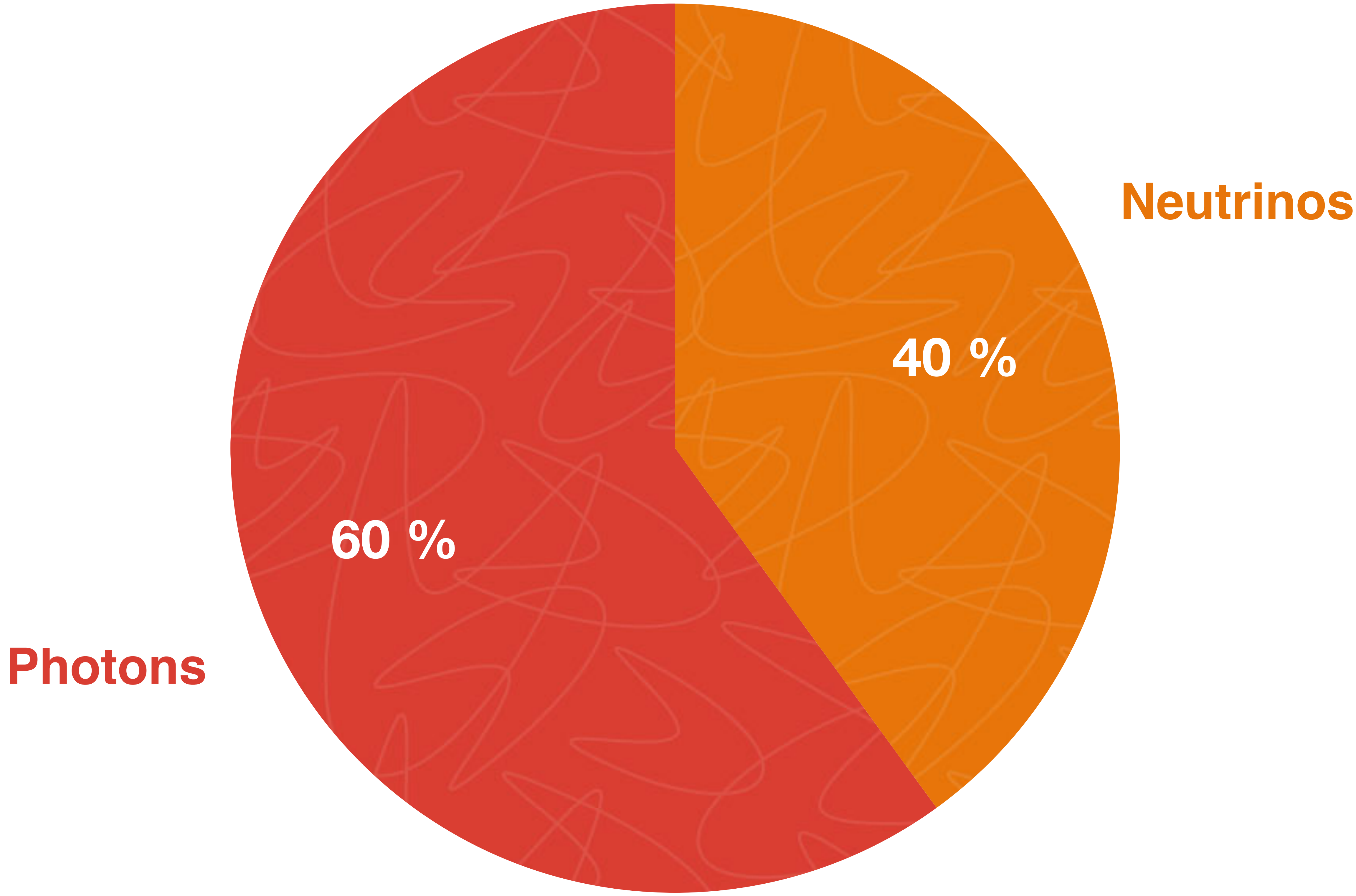
neutrinos, dark matter & dark energy physics

The Universe

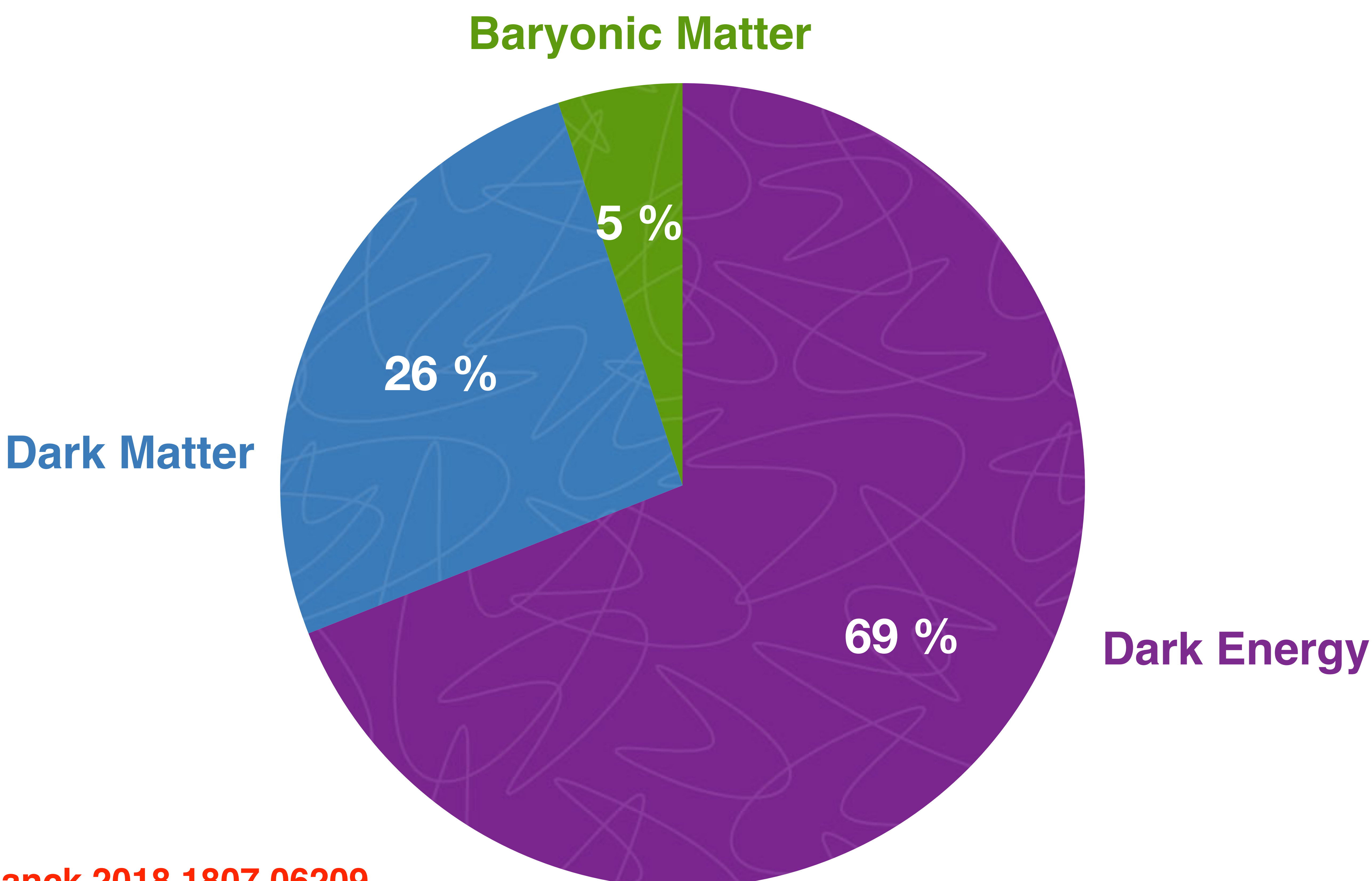


Planck 2018 1807.06209

SM Prediction:



The Universe



Planck 2018 1807.06209

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) **Baryogenesis and DM from B Mesons**

2) **Collider implications**

3) **Summary and Conclusions**

Baryogenesis

The three Sakharov Conditions (1967):

1) C and CP violation

2) Out of equilibrium

3) Baryon number violation

Baryogenesis from B Mesons

The three Sakharov Conditions (1967):

1) C and CP violation

Neutral B-Meson system

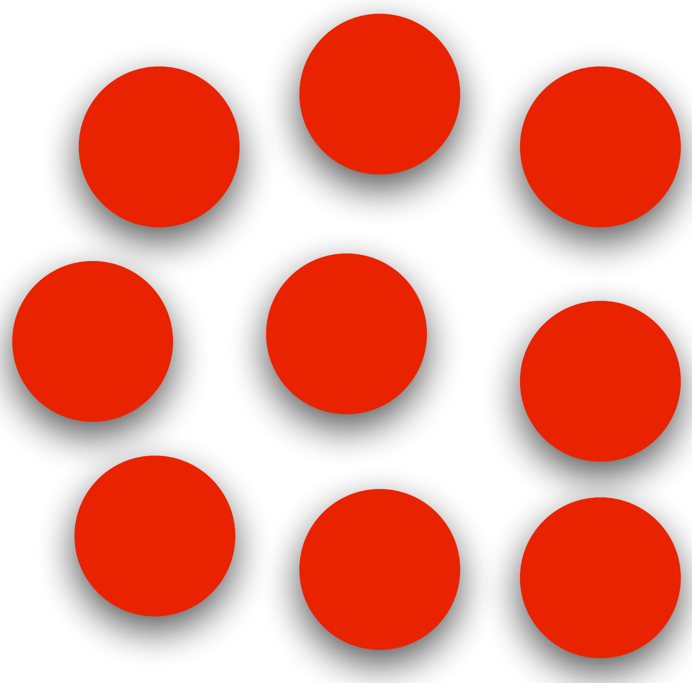
2) Out of equilibrium and B meson production

Late time ($\tau \sim 0.01$ s) decaying particle into b-quarks

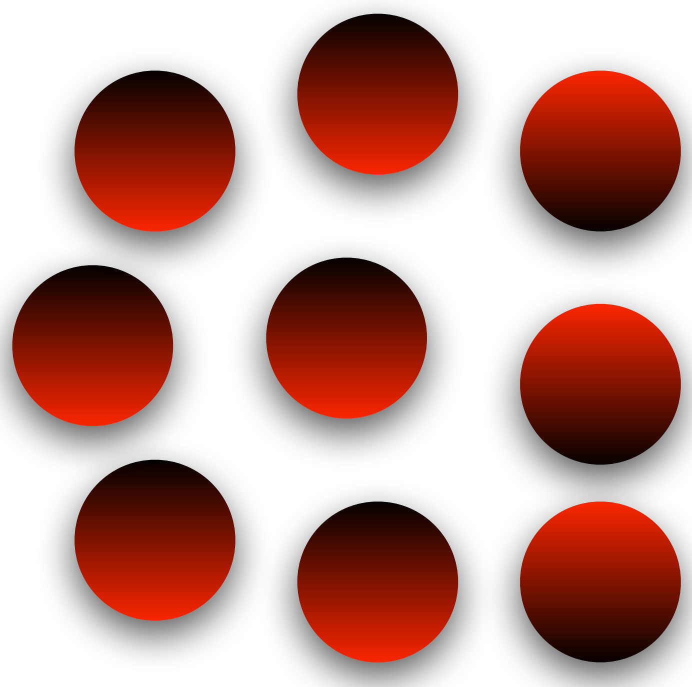
3) Baryon number violation

Baryon number is conserved! Dark Matter is antibaryonic

Baryogenesis and DM from B Mesons



Visible Sector
(Baryons)



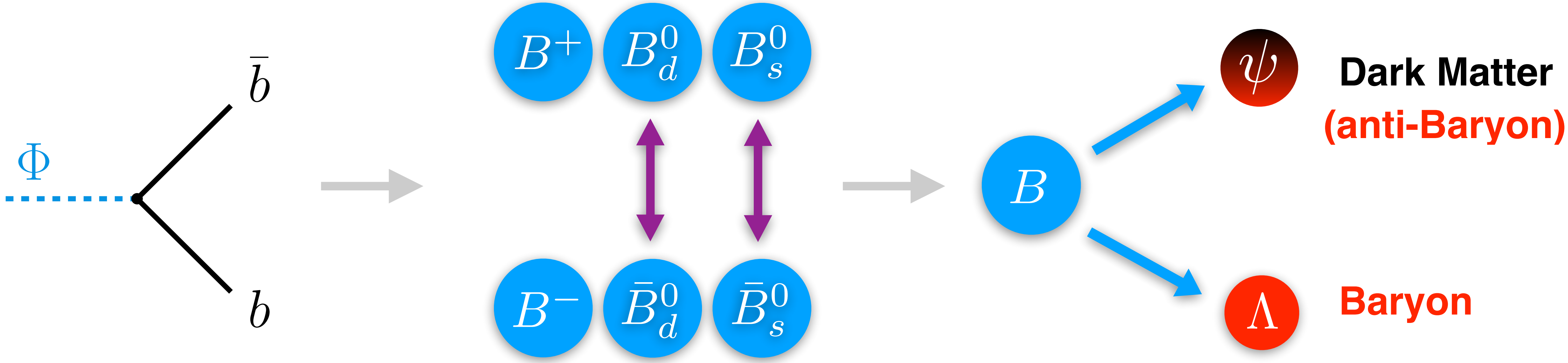
Dark Sector
(anti-Baryons)

The Mechanism in a Nutshell

Out of equilibrium late time decay

CP violating oscillations

B-mesons decay into Dark Matter and hadrons



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

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

${\rm BR}(B \to \psi + {\rm Baryon} + X)$

Baryogenesis

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

and

Dark Matter

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

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

Collider Signatures

1) Extra CP violation in B Meson decays

2) New B Meson decay into ME and a Baryon

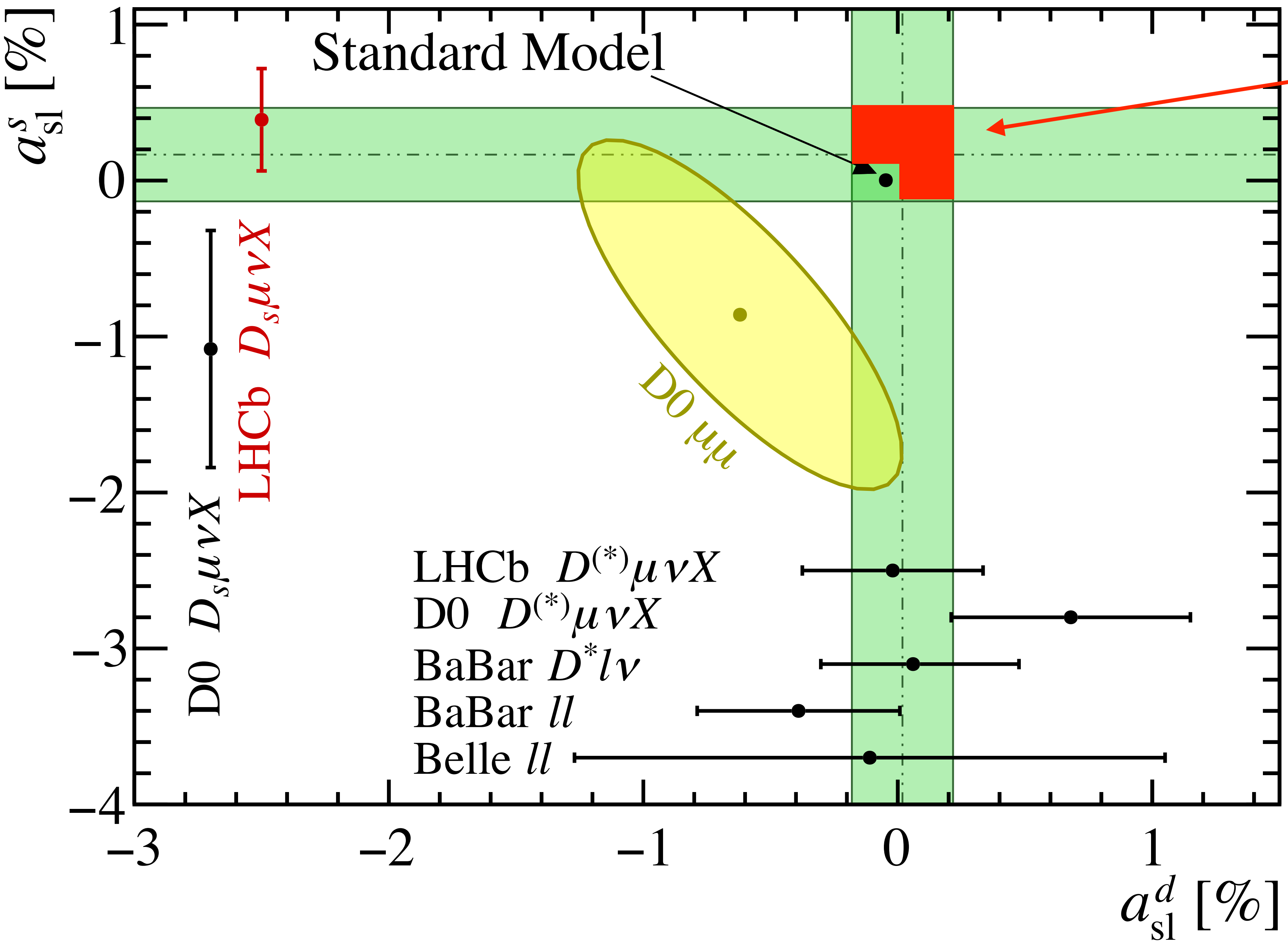
3) New TeV t-channel DM mediator

Indirect CP violation Searches

Key Quantity:
(Semileptonic Asymmetry)

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

Lenz et al 1511.09466



Baryogenesis

$A^{s,d}_{\ell\ell} > 10^{-5}$

Expected sensitivity:

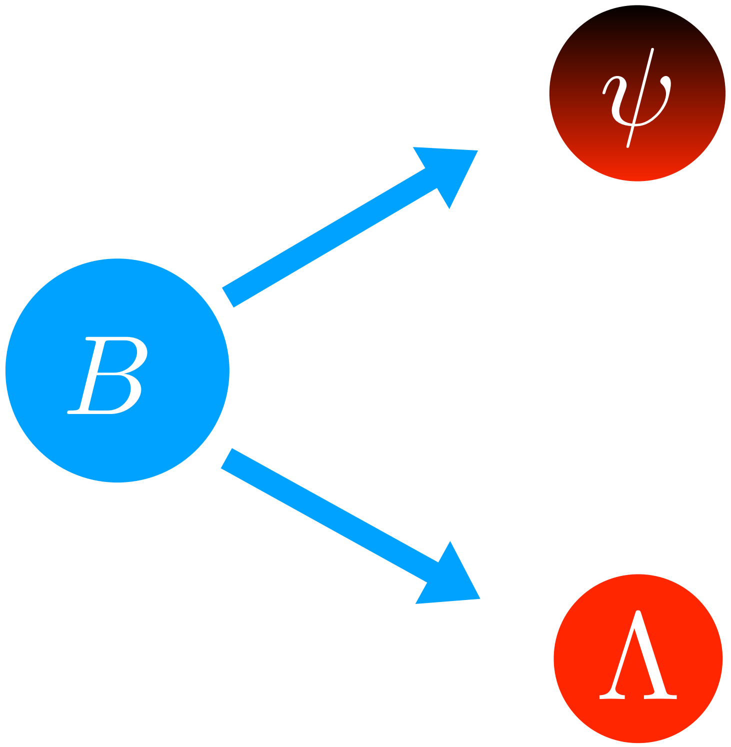
LHCb (50 fb⁻¹)

$A^s_{\ell\ell} \sim 5\times 10^{-4}$
$A^d_{\ell\ell} \sim 5\times 10^{-4}$

Belle-II (50 ab⁻¹)

$A^d_{\ell\ell} \sim 5\times 10^{-4}$

New B-Meson decay



Baryogenesis requires:

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

Best current constraint:

$$\mathrm{BR}(B \to \psi + \mathrm{Baryon} + X) \lesssim 10\%$$

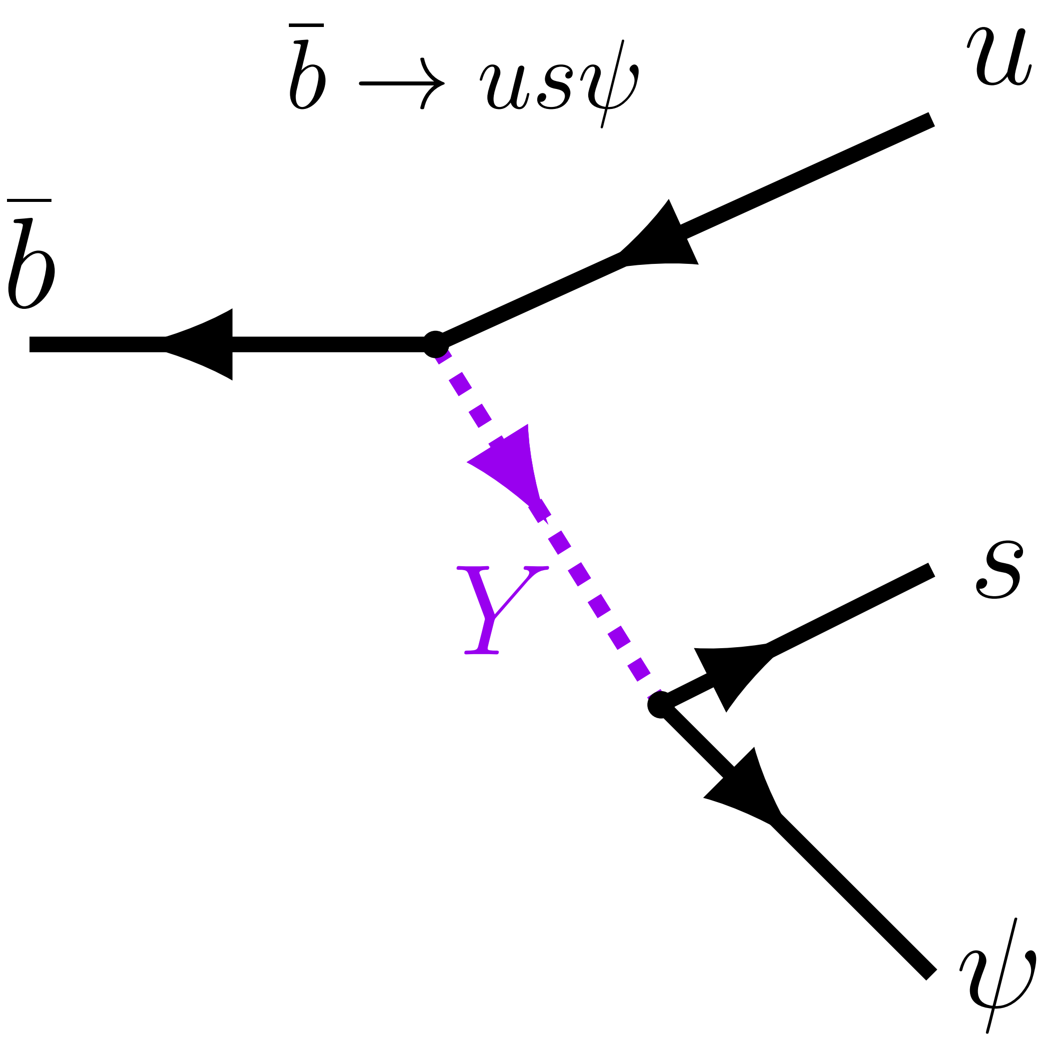
(from the total width of B mesons)

There is no available search for this process

Ongoing searches at Belle-II will test the scenario $\mathrm{BR}(B \to K \bar{\nu} \nu) \sim 10^{-6}$

LHCb will also be able to contribute, likely also ATLAS&CMS $N_B \sim 10^{12}$

New Force Carrier



Y: Colored Triplet Scalar

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

Same Quantum Numbers as a SUSY squark!

t-channel DM mediator

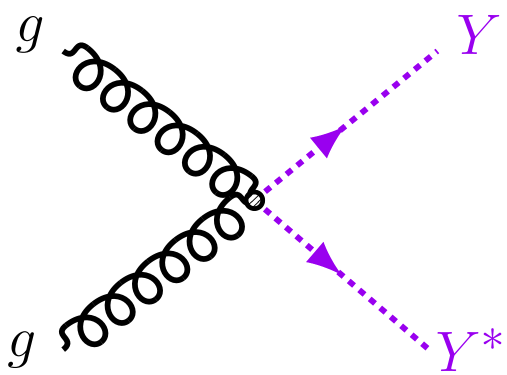
Benchmark for searches?

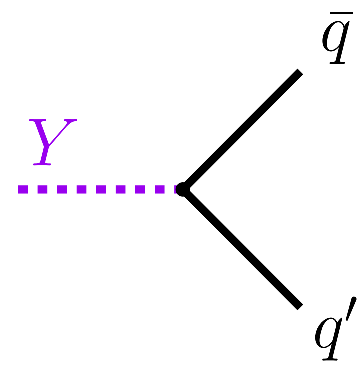
$$\mathrm{Br}(B \to \psi + \mathrm{Baryon} + X) \simeq 10^{-3} \left(\frac{m_B - m_\psi}{2\ \mathrm{GeV}}\right)^4 \boxed{\left(\frac{1.6\ \mathrm{TeV}}{m_Y} \frac{\sqrt{y_{ub} y_{\psi s}}}{0.6}\right)^4}$$

Flavorful Variations: $\mathcal{H}_{eff} = \frac{y_{ub} y_{\psi s}}{m_Y^2} u\, s\, b\, \psi \qquad c\, s\, b\, \psi\,,\ u\, d\, b\, \psi\,,\ c\, d\, b\, \psi$

Squark Searches

Production | **Decay** | **Signature** | **Constraint**

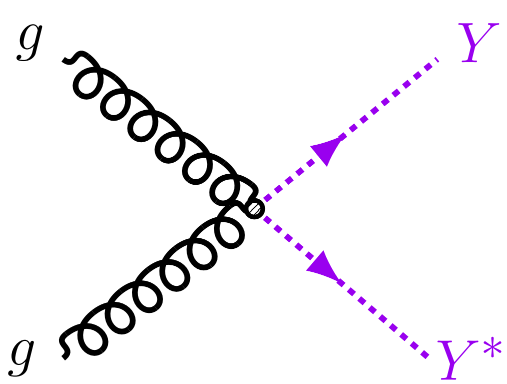


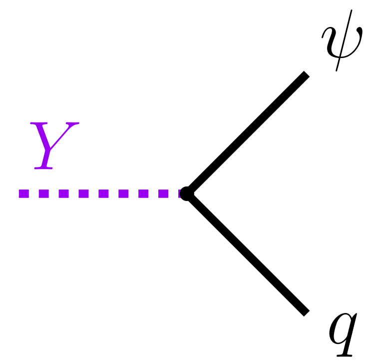


4 jets

$m_Y >$ **0.5 TeV**

1710.07171 (ATLAS)

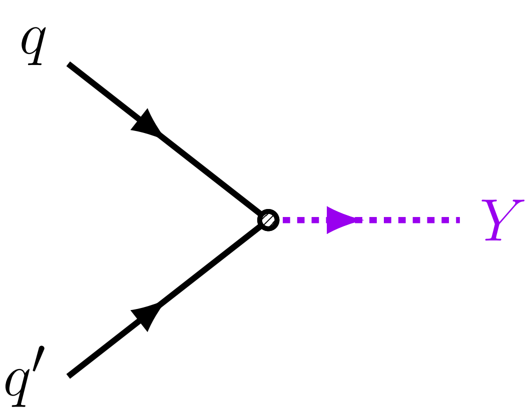


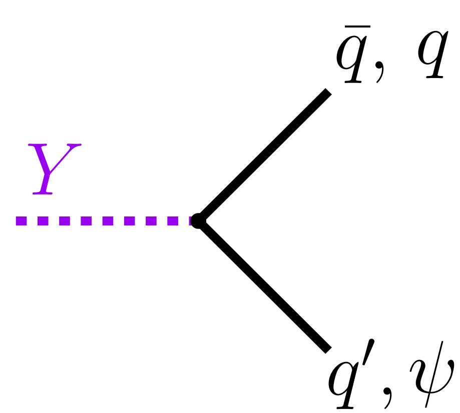


2 jets+ME

$m_Y >$ **1.1 TeV**

1908.04722 (CMS)





2 jets

$m_Y >$ **1-7 TeV**

1611.03568 (CMS)

Monojet

$m_Y >$ **1-2 TeV**

1708.01259 (CMS+ATLAS recast)

Bounds depend upon combinations of y_{ub} $y_{s\psi}$

Work in progress: 2006.XXXXX Alonso-Álvarez, Elor, Escudero, McKeen

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^0 meson decays** $A_{\ell\ell}^{d\,s} > 10^{-5}$
- **Neutral and charged B mesons decay into baryons and missing energy**

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

Ongoing search for B → Baryon + ME at BaBar&Belle-II!

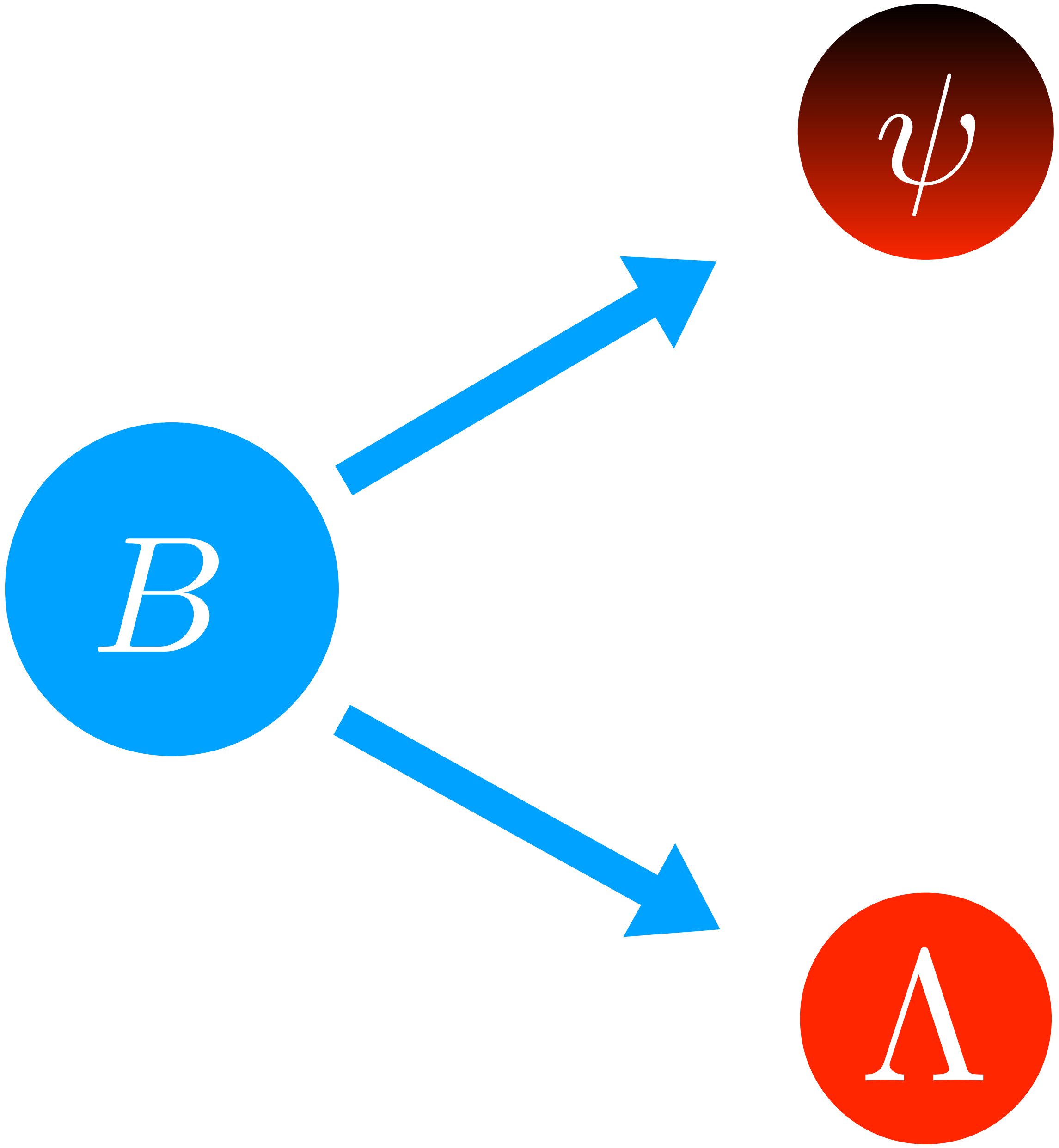
B-factories should test this scenario given the constraints on other missing energy channels:

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

The mechanism requires for a t-channel DM mediator!

- **But parameter space is not the same as for a Thermal WIMP**
- **There is a diquark coupling:** $y_{ub}\, Y^*\, \bar{u}\, b^c$

Thank You!



Back Up

New B-Meson decay

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

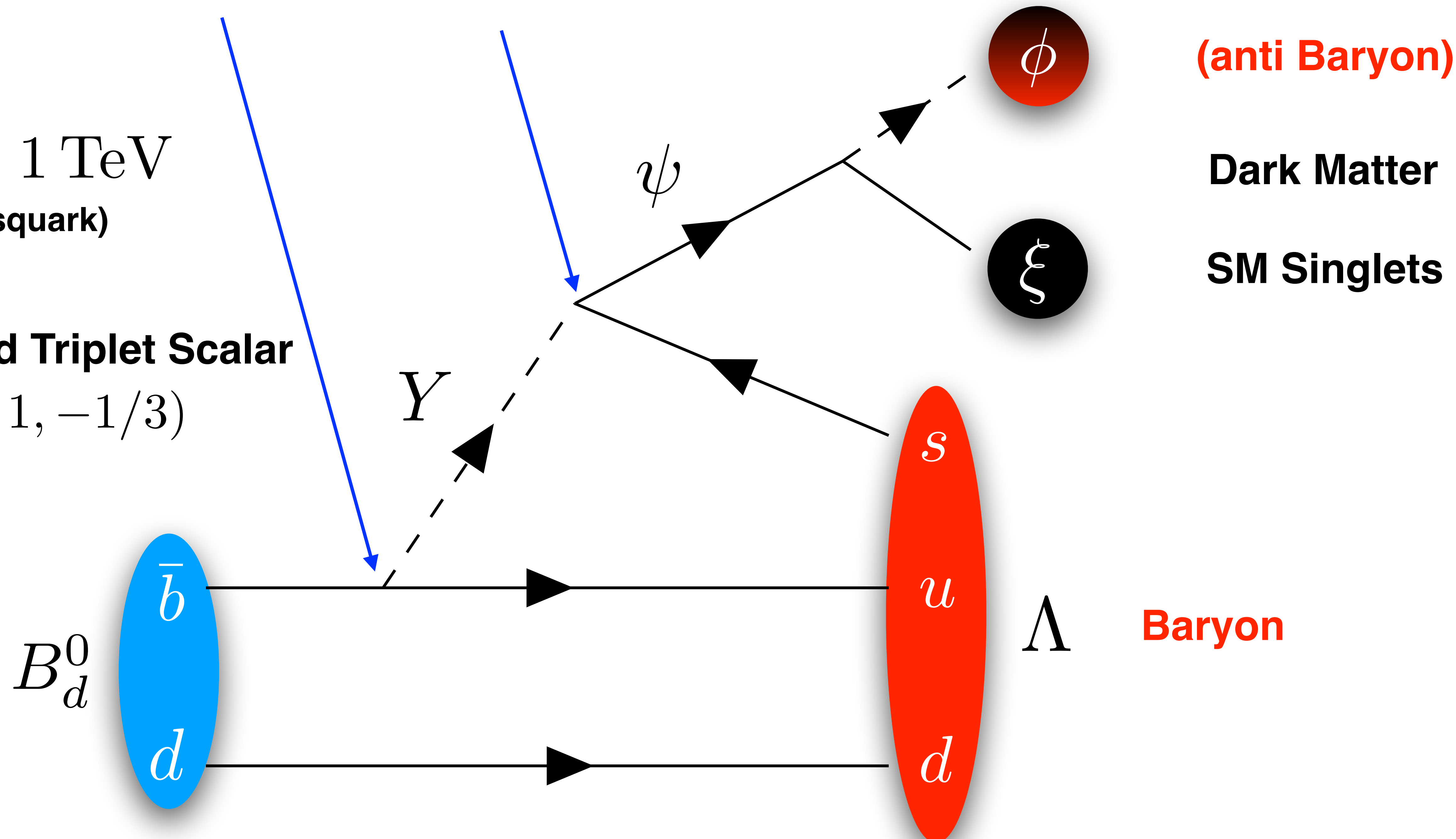
$1.2\,\text{GeV} \lesssim m_{\phi,\,\xi} \lesssim 2.5\,\text{GeV}$

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

(4-jet/squark)

Y: Colored Triplet Scalar

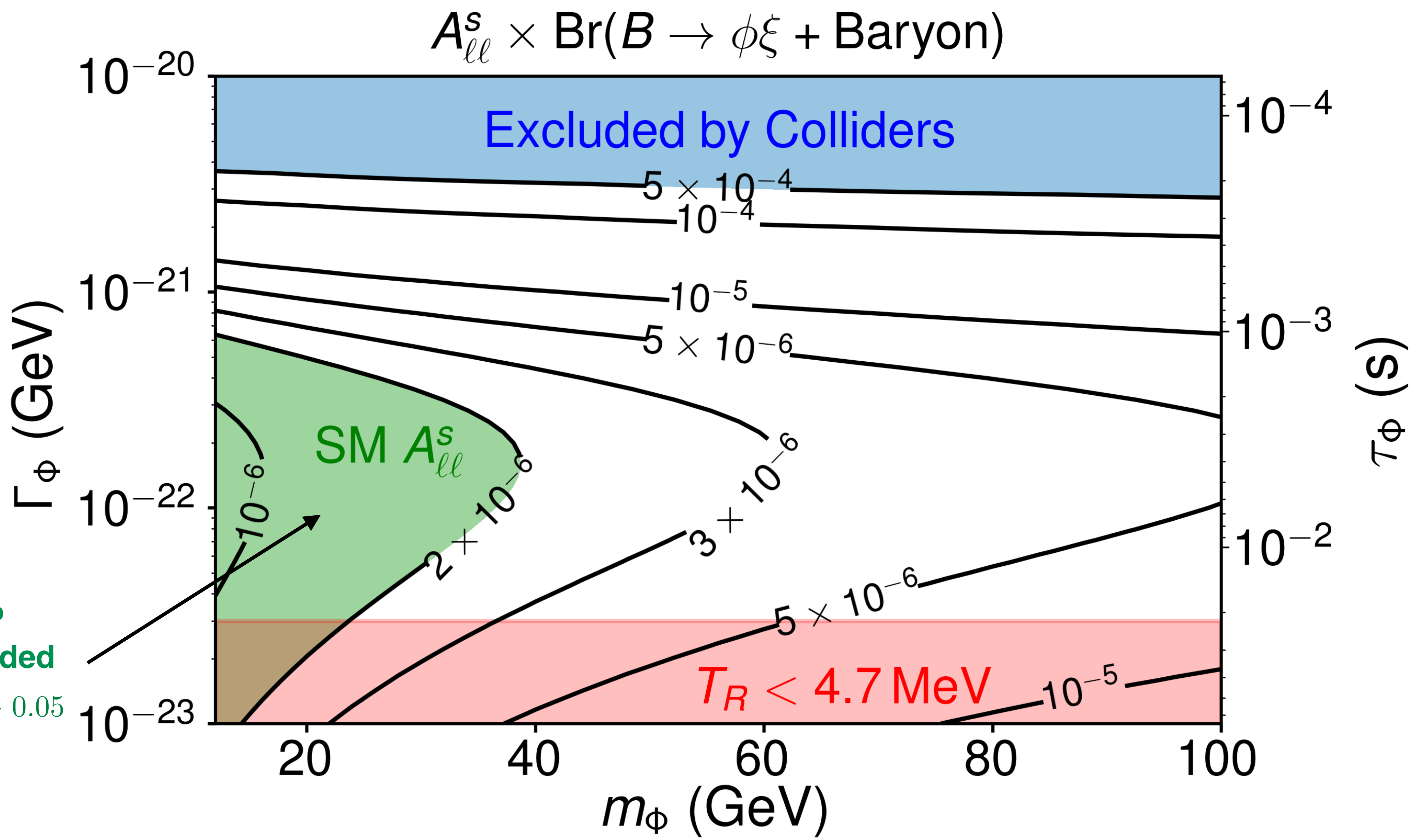
$Y \sim (3, 1, -1/3)$



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

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

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

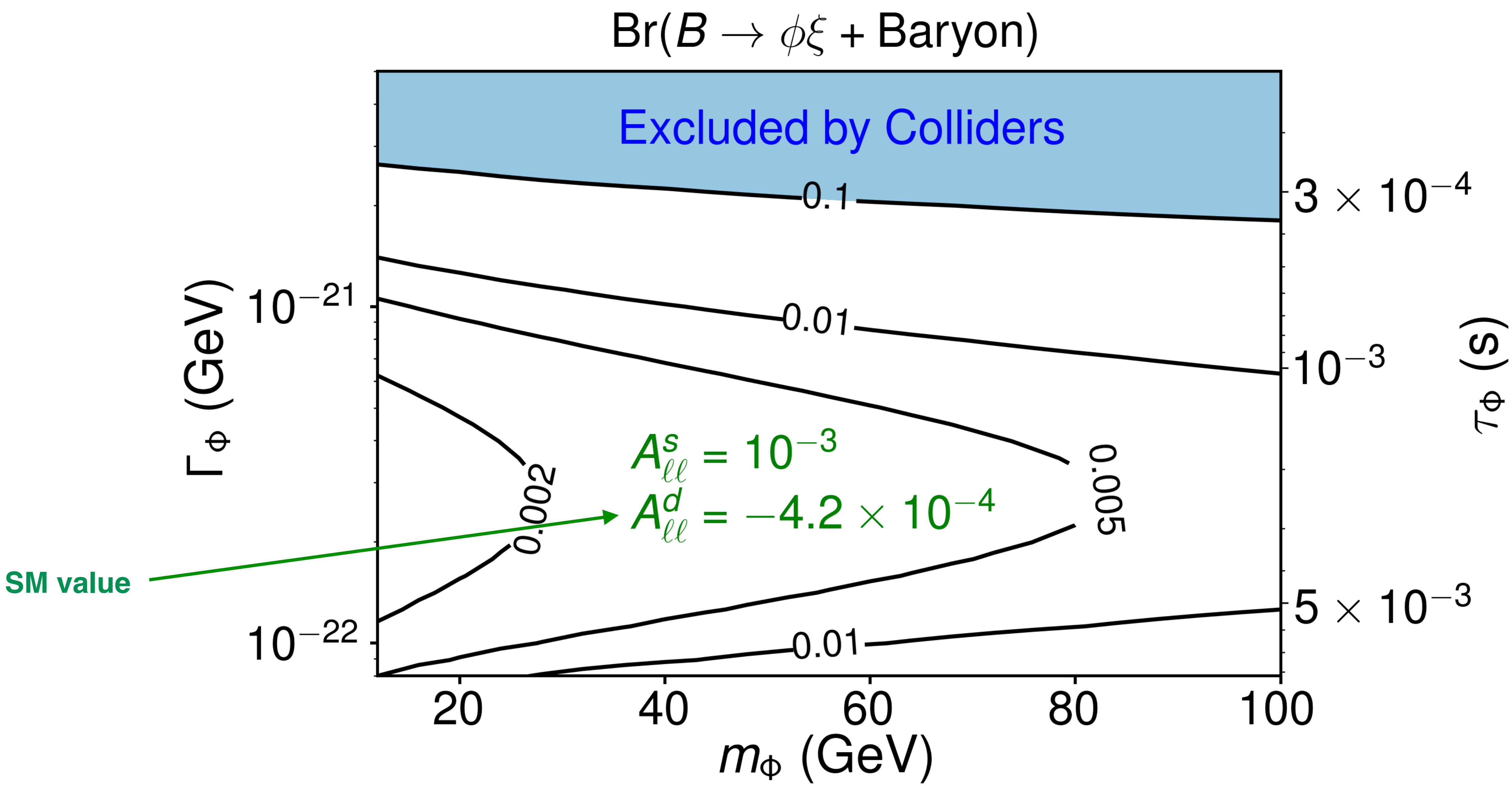


Baryogenesis can be achieved with just the CP violation in the SM! provided $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) > 0.05$ **and** $A^d_{\ell\ell} = 0$

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 $A_{\ell\ell}^d = A_{\ell\ell}^d|_{\rm SM}$



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

Back Up: Parameters

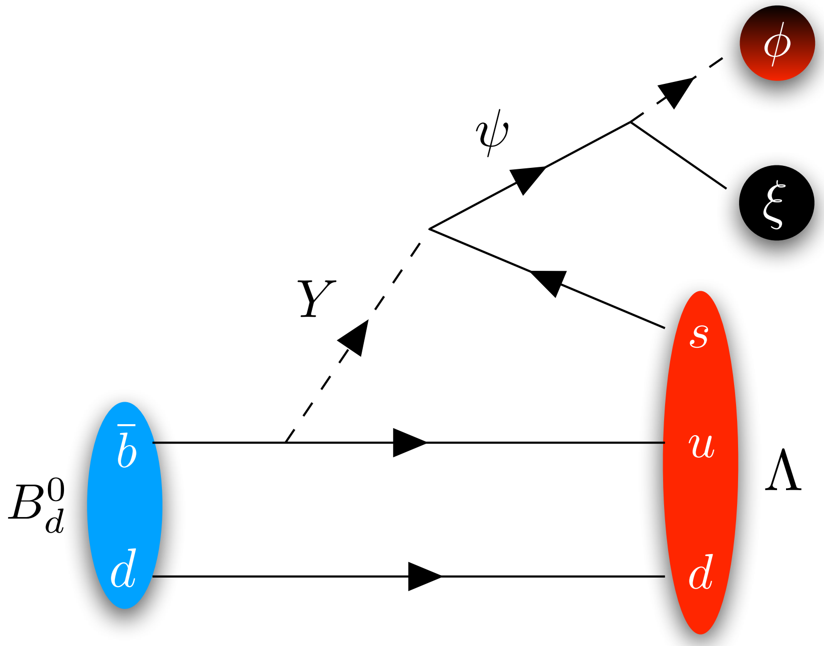
Parameter	Description	Range	Benchmark Value	Constraint
m_Φ	Φ mass	$11-100$ GeV	25 GeV	-
Γ_Φ	Inflaton width	$3\times10^{-23} < \Gamma_\Phi/\text{GeV} < 5\times10^{-21}$	10^{-22} GeV	Decay between $3.5\,\text{MeV} < T < 30\,\text{MeV}$
m_ψ	Dirac fermion mediator	$1.5\,\text{GeV} < m_\psi < 4.2\,\text{GeV}$	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	$2\times10^{-4} - 0.1$	10^{-3}	< 0.1 [5]
$A^s_{\ell\ell}$	Lepton Asymmetry B_d	$5\times10^{-6} < A^d_{\ell\ell} < 8\times10^{-4}$	6×10^{-4}	$A^d_{\ell\ell} = -0.0021\pm0.0017$ [5]
$A^s_{\ell\ell}$	Lepton Asymmetry B_s	$10^{-5} < A^s_{\ell\ell} < 4\times10^{-3}$	10^{-3}	$A^s_{\ell\ell} = -0.0006\pm0.0028$ [5]
$\langle\sigma v\rangle_\phi$	Annihilation Xsec for ϕ	$(6-20)\times10^{-25}\,\text{cm}^3/\text{s}$	$10^{-24}\,\text{cm}^3/\text{s}$	Depends upon the channel [3]
$\langle\sigma v\rangle_\xi$	Annihilation Xsec for ξ	$(6-20)\times10^{-25}\,\text{cm}^3/\text{s}$	$10^{-24}\,\text{cm}^3/\text{s}$	Depends upon the channel [3]

An Explicit Model

Minimal Particle Content

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

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



Heavy Colored Triplet Scalar:

- $\mathcal{L} \supset -y_{ub}\, Y^*\, \bar{u}\, b^c - y_{\psi s}\, Y \bar{\psi}\, s^c + \text{h.c}$ $\quad m_Y > 1\,\text{TeV}$ **(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)**
- $\text{Br}(B \to \xi\phi + \text{Baryon}) \simeq 10^{-3} \left(\dfrac{m_B - m_\psi}{2\ \text{GeV}}\right)^4 \left(\dfrac{1\ \text{TeV}}{m_Y} \dfrac{\sqrt{y_{ub} y_{\psi s}}}{0.53}\right)^4$

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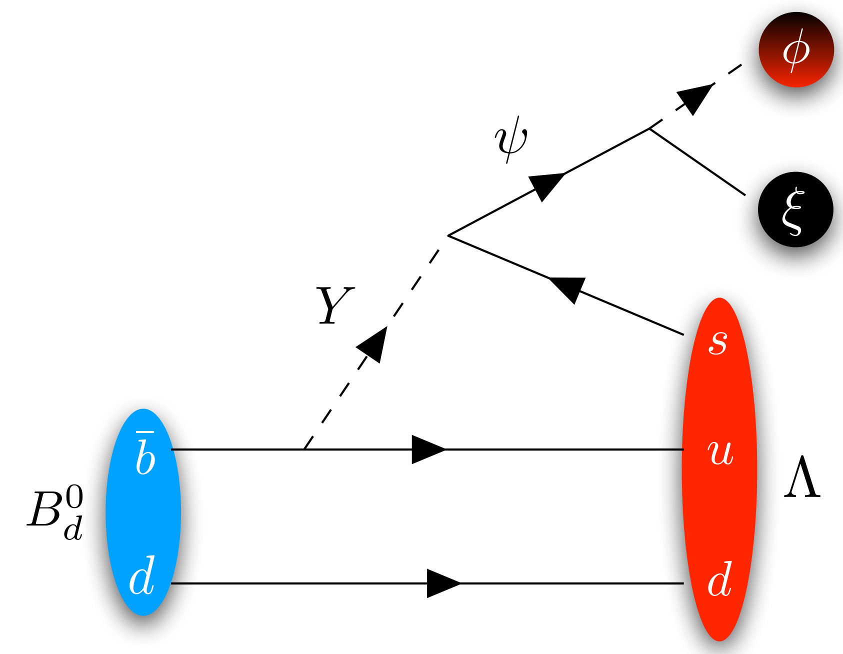
Φ	0	0	0	+1	$11 - 100\,\text{GeV}$
Y	0	$-1/3$	$-2/3$	+1	$\mathcal{O}(\text{TeV})$
ψ	1/2	0	-1	+1	$\mathcal{O}(\text{GeV})$
ξ	1/2	0	0	-1	$\mathcal{O}(\text{GeV})$
ϕ	0	0	-1	-1	$\mathcal{O}(\text{GeV})$

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



The Dark Sector:

ψ : **Dirac Dark Baryon**

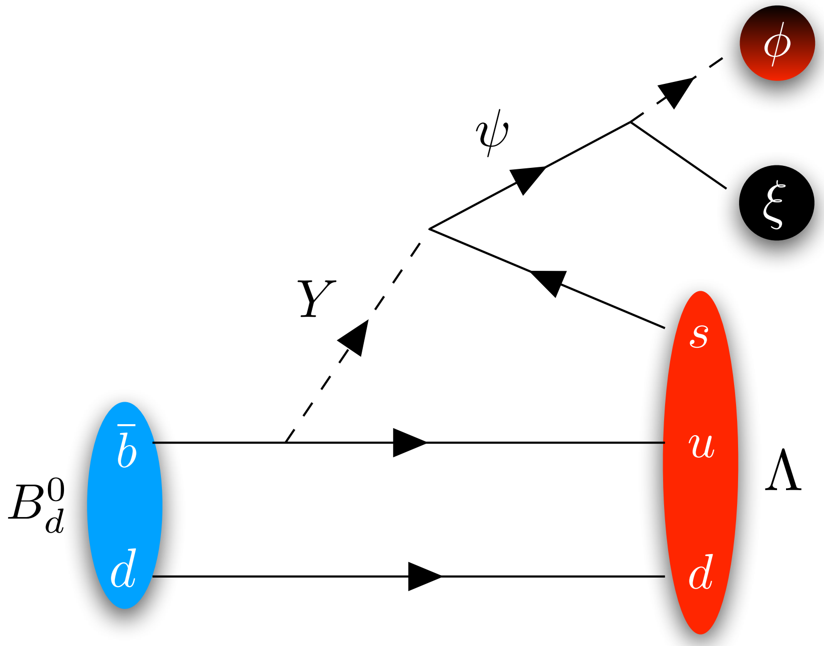
- **For the b-quark decay to happen:** $m_\psi < m_B - m_{\text{Baryon}} < 4.3\,\text{GeV}$
- ψ **needs to have decays into other dark sector particles or will decay back to visible baryons and undo the Baryogenesis** $\tau(\psi \to p + \pi^-) \sim 10^4\,\text{years}$

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