Baryogenesis and Dark Matter from B Mesons

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Based on arXiv:1810.00880 with Gilly Elor & Ann Nelson

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DARKHORIZONS

invisiblesPlus

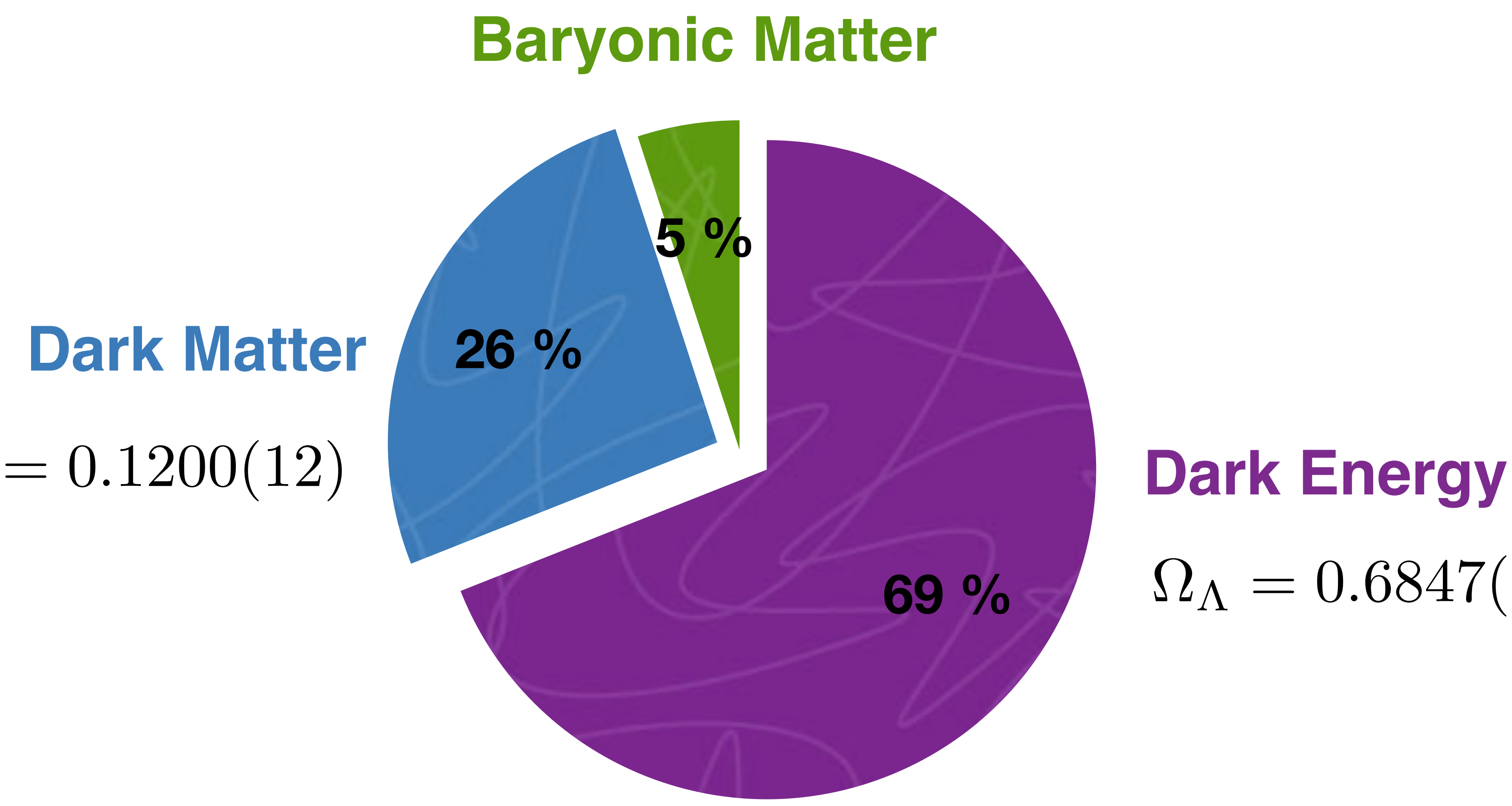
elusives
neutrinos, dark matter & dark energy physics

Cosmology

Experiment   Planck 2018 1807.06209

- **Outstanding precision in the cosmological parameters.**
- **ΛCDM firmly stablished as the cosmological paradigm.**
- **Baryonic, Dark Matter and Dark Energy energy densities known at the percent and sub-percent level:**

$$\Omega_b h^2 = 0.02237(15)$$



$$\Omega_{\rm cdm} h^2 = 0.1200(12)$$

$$\Omega_\Lambda = 0.6847(73)$$

Cosmology

Theoretical Understanding?

Motivating Question:

What fraction of the Energy Density of the Universe comes from Physics Beyond the Standard Model?[1]

99.85%!

[1]Ann Nelson, Sakurai Prize Lecture 2018

Cosmology

Theoretical Understanding?

Dark Energy Little to nothing

Dark Matter

The CMB anisotropies clearly motivate a particle description

Many candidates: WIMPS, Axions, Sterile Neutrinos ...

Existing experimental constraints on the various possibilities

Baryons

Prediction The SM predicts a Universe with only photons and neutrinos. With very small and equal parts of matter and antimatter $\Omega_b h^2 = \Omega_{\bar{b}} h^2 \sim 10^{-11}$

Observation The Universe (we) is made out of only Baryons:

$$\Omega_b h^2 = 0.02237(15) \qquad \frac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$$

Baryogenesis and DM from B Mesons

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

2) A minimal Model which leads to:
   1) Positive charge asymmetries in B meson decays
   2) B-meson decays into a Baryon and missing energy
   3) b-flavored baryons decay into mesons and missing energy

3) The Boltzmann equations

4) Results

5) Searches and prospects at collider experiments

6) Summary and Outlook

Baryogenesis

The three Sakharov Conditions (1967):

1) C and CP violation

2) Out of equilibrium

3) Baryon number violation

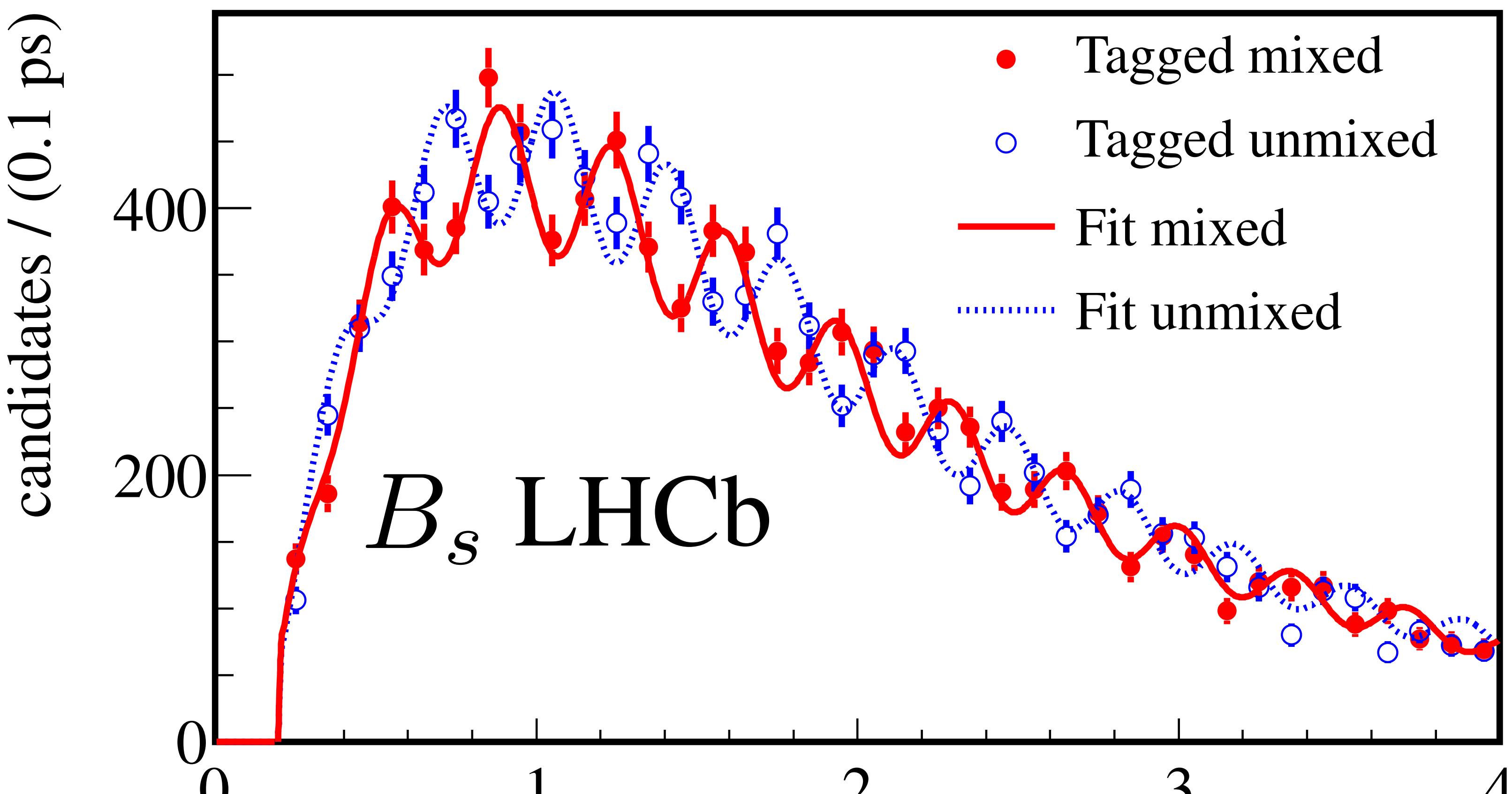
Baryogenesis from B Mesons

1) C and CP violation

Neutral and CP violating oscillation systems in the SM:

Kaons cannot decay into baryons $m_K < m_p$

Neutral B Mesons are the perfect system: $m_B \simeq 5.3\,\mathrm{GeV}$



1304.4741

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

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

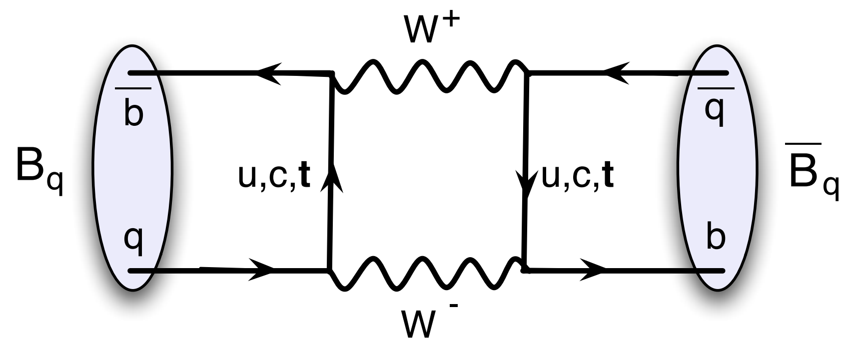
$$\Delta m_{B_d}/\Gamma_{B_d} = 0.77$$

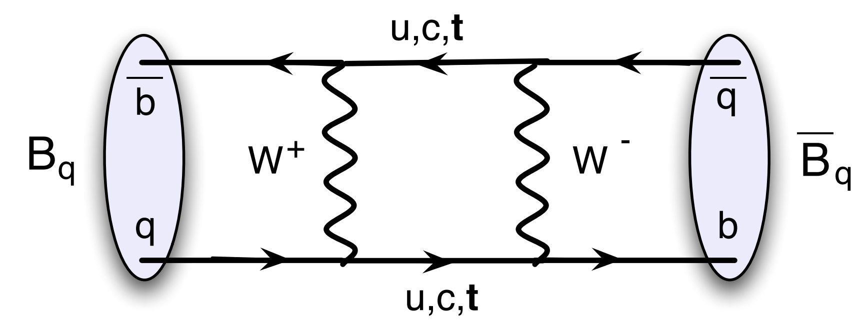
Baryogenesis from B Mesons

1) CP violation in the Meson System

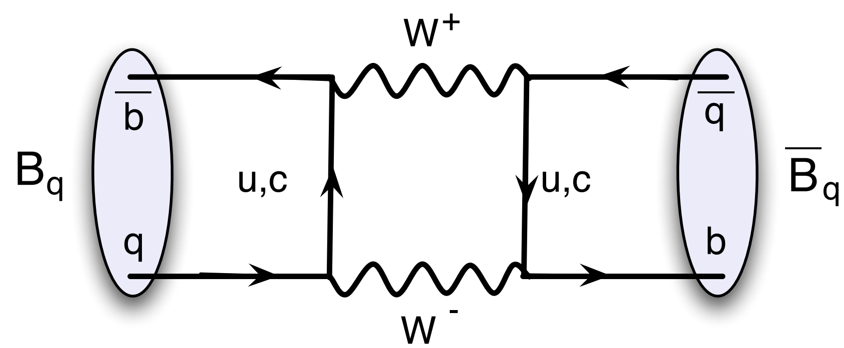
SM: Box Diagrams

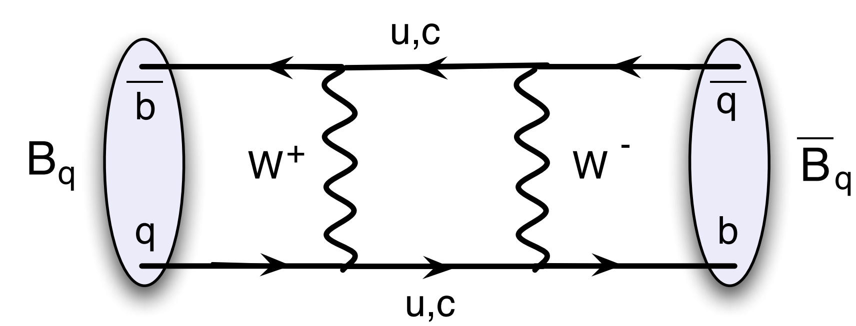
$M_{12} \propto$





$\Gamma_{12} \propto$





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

Baryogenesis from B Mesons

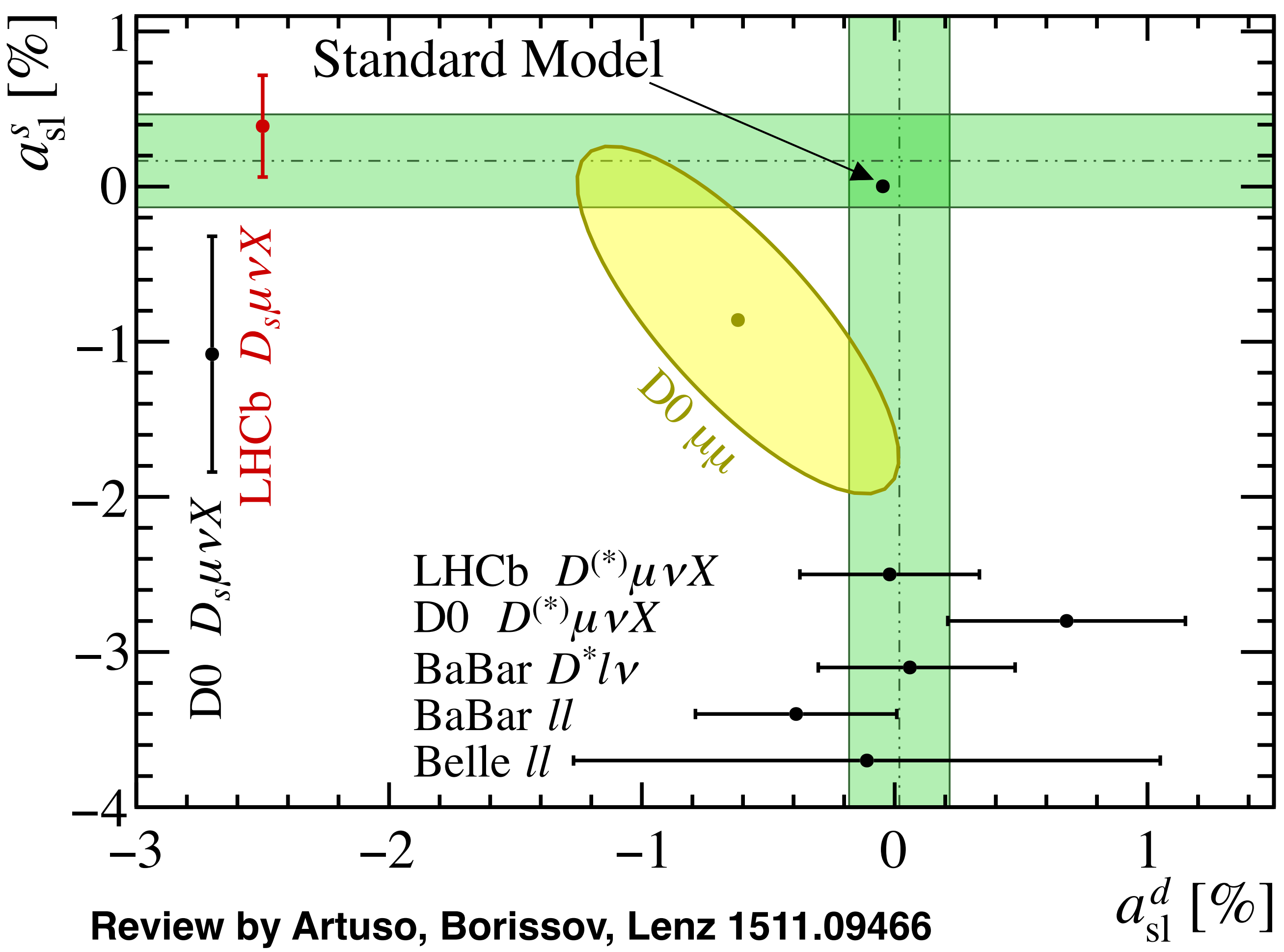
CP violation in the neutral B-meson system

The key quantity: the semileptonic asymmetry

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

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

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



Review by Artuso, Borissov, Lenz 1511.09466

Measured

$$A_{\ell\ell}^s = (-0.6 \pm 2.8) \times 10^{-3}$$
$$A_{\ell\ell}^d = (-2.1 \pm 1.7) \times 10^{-3}$$

- **Plenty of BSM models that can enlarge the asymmetries up to 10^{-3}: SUSY, Extradim, LR, 2HDM, new generations, Leptoquarks, *Z'* models ... (see e.g. 1511.09466, 1402.11811).**
- **Including the BSM models that are invoked to explain the recent anomalies at LHCb.**

Baryogenesis from B Mesons

2) Out of equilibrium and production of B Mesons

- We require the presence of an out of equilibrium particle that dominates the energy density of the Universe and reheats the Universe to a temperature of $T_{RH} = \mathcal{O}(10\,\mathrm{MeV})$.

- This particle should be very weakly coupled, with lifetimes $\tau_\Phi = \mathcal{O}(10^{-3}\,\mathrm{s})$. It could be the Inflaton, a particle produced during reheating, or any very weakly coupled particle that falls out of equilibrium while relativistic. For instance, a string modulus.

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

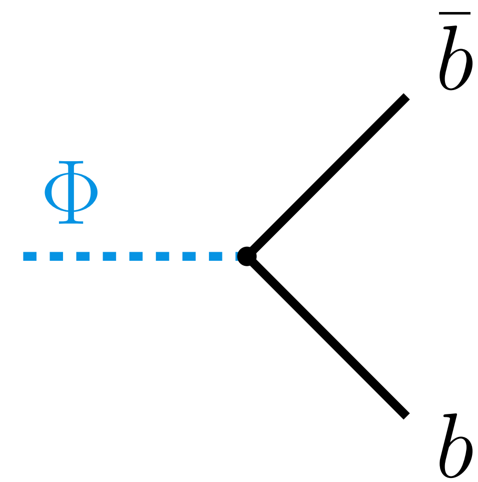
- Having a low reheat temperature solves the unwanted relic problems i.e. over abundance of gravitino etc.

Baryogenesis from B Mesons

2) Out of equilibrium and production of B Mesons

- **Scalar particle with** $m_\Phi \in 11 - 100\,\mathrm{GeV}$ **generically decays into b-quarks.**

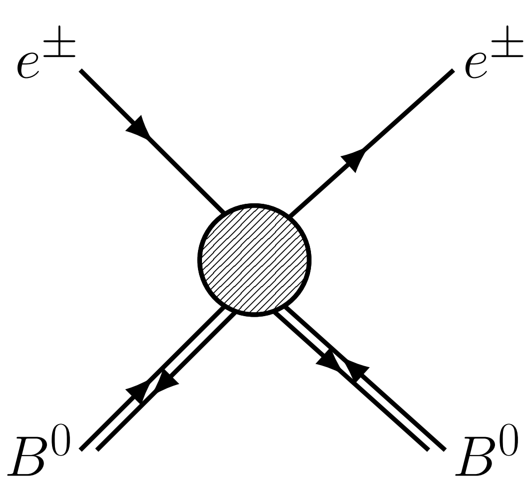
$$T_{RH} = \mathcal{O}(10\,\mathrm{MeV}) \qquad \tau_\Phi = \mathcal{O}(10^{-3}\,\mathrm{s})$$



- **b-quarks Hadronize at** $T < T_{\mathrm{QCD}}$

- **Coherent oscillations in the B⁰ system are maintained in the early Universe for Temperatures:** $T \lesssim 20\,\mathrm{MeV}$

The electrons/positrons present in the thermal plasma can interact as to measure the flavor eigenstates and to damp the (CPV) oscillations if the scattering rate is higher than the oscillation rate.



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

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

Baryogenesis 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

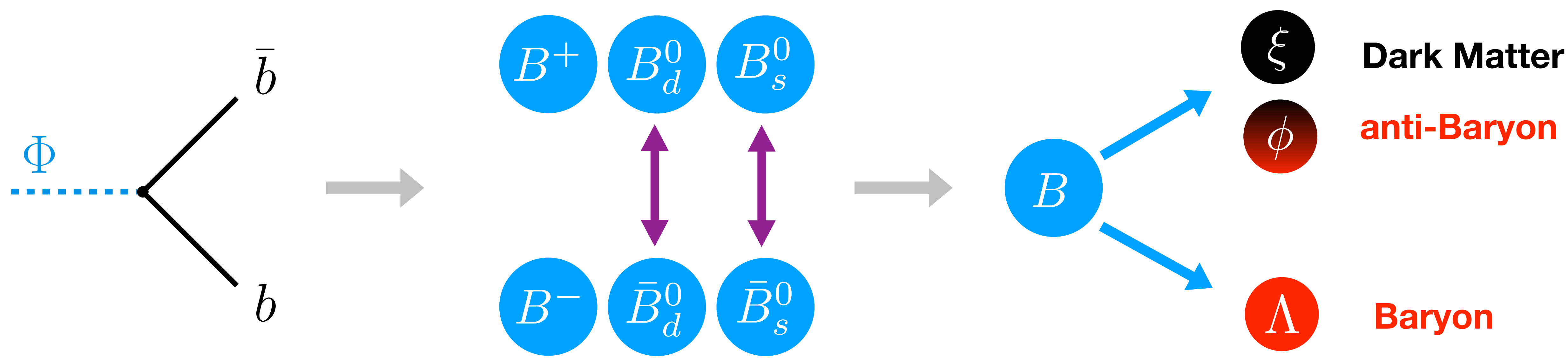
- **We make Dark Matter an anti-Baryon and generate an asymmetry between the two sectors thanks to the CP violating oscillations and subsequents decays of B-mesons.**

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

- **This evades the very strong bounds from proton decay and dinucleon decay and links DM to Baryogenesis.**

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 and **Dark Matter**

$$Y_B = 8.7 \times 10^{-11} \qquad \Omega_{\rm DM} h^2 = 0.12$$

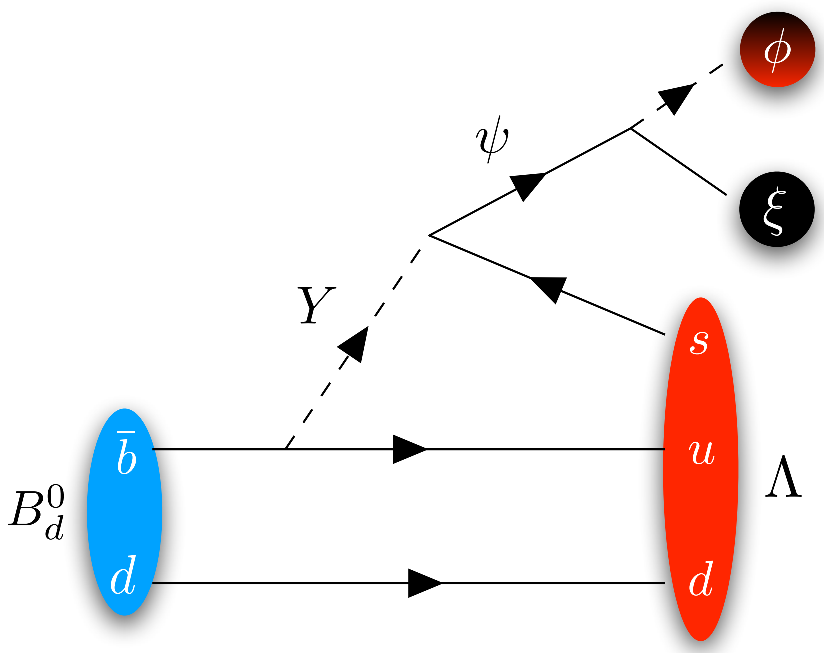
With the Baryon asymmetry: $$Y_B \propto \sum_{q=s,d} A_{\ell\ell}^q \times {\rm Br}(B_q^0 \to \phi\,\xi + {\rm Baryon} + X)$$

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



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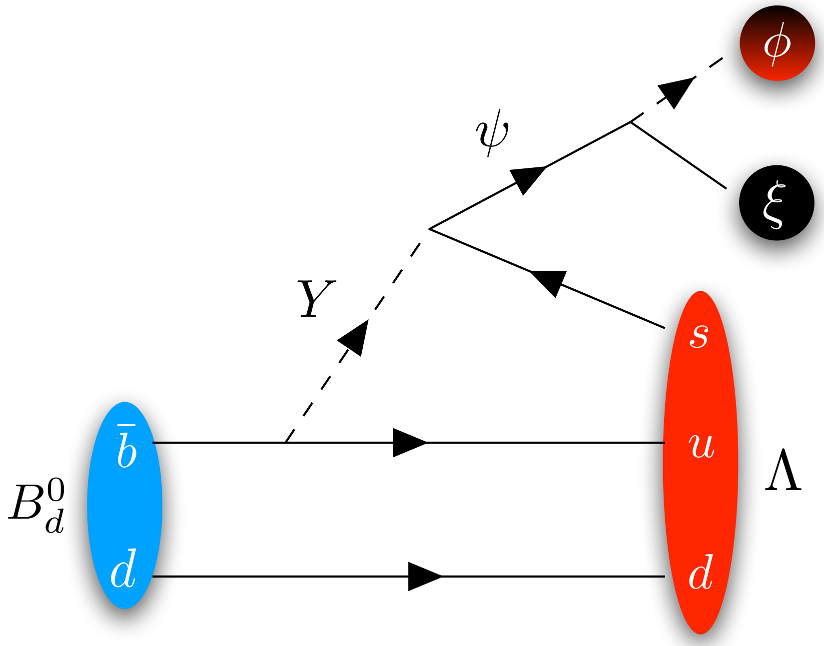

Heavy Colored Triplet Scalar:

- $\mathcal{L} \supset -y_{ub}\, Y^*\, \bar{u}\, b^c - y_{\psi s}\, Y \bar{\psi}\, s^c + \text{h.c}$ $\quad m_Y > 0.5 - 1\,\text{TeV}$ **(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
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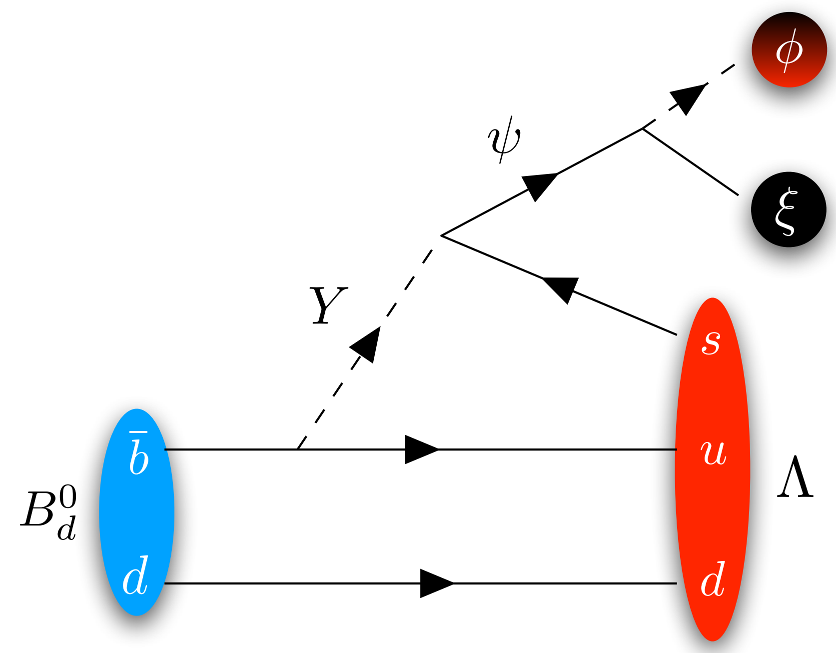
B-mesons decay into DM (missing energy) and a Baryon



The Dark Sector:

ψ : **Dirac Dark Baryon**

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

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	$\mathcal{O}(\mathrm{GeV})$
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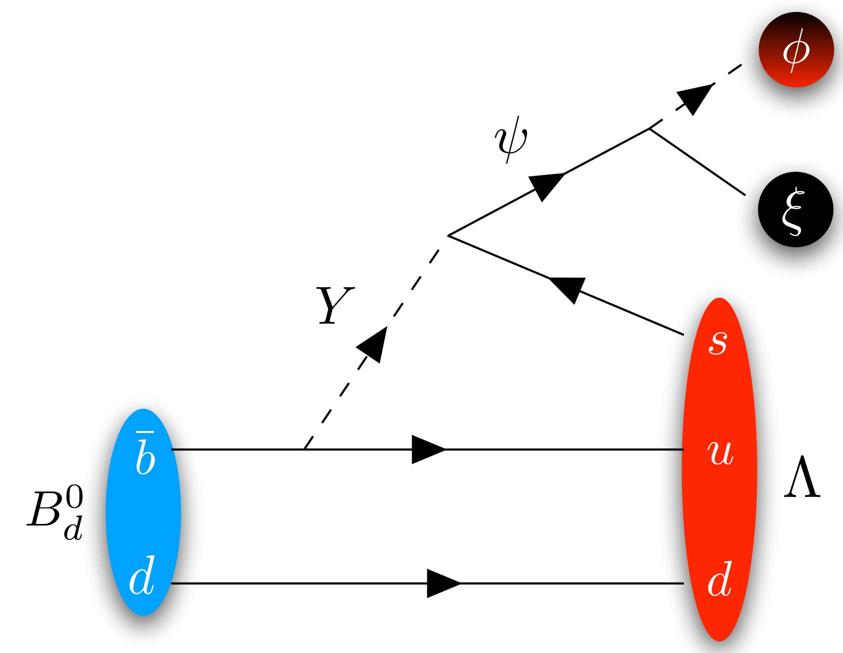
B-mesons decay into DM (missing energy) and a Baryon



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*:*** $m_\phi + m_\xi < m_\psi$
  - **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

The Boltzmann Equations

Universe's Evolution

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

Inflaton 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 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.**

The Dark Sector in depth

- **In our set up the DM would be generically overproduced unless additional interactions are present because the B-mesons produce ~1000 (1/A$_{ll}$) times more symmetric DM than asymmetric.**

- **Therefore additional interactions between DM and additional light states are required, which we parametrize with $\langle \sigma v \rangle$.**

- **In addition, the DM cannot be purely asymmetric because** $\Omega_{\rm DM}/\Omega_b = 5.36$ **would imply** $m_\phi \simeq 5.36\, m_p$ **but** $m_\phi < m_B - m_p = 4.3\,\text{GeV}$ **so DM contains a symmetric and an antisymmetric component:**

if $m_\xi > m_\phi$ **then** $\xi\xi \to \phi\phi^\star$

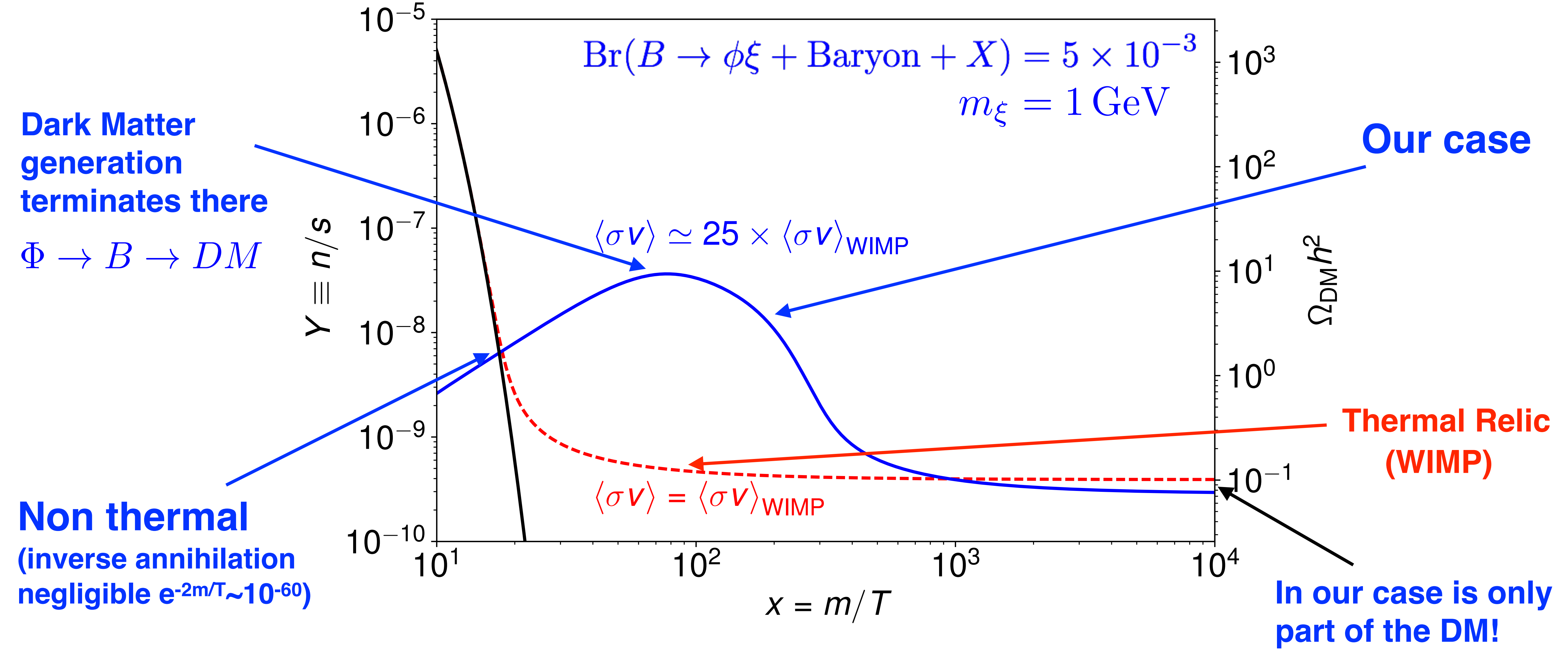
and ϕ,ϕ^* **form the DM**

if $m_\phi > m_\xi$ **then** $\phi\phi^\star \to \xi\xi$

and ξ ***is the primary DM*** **component**

The Dark Sector in depth

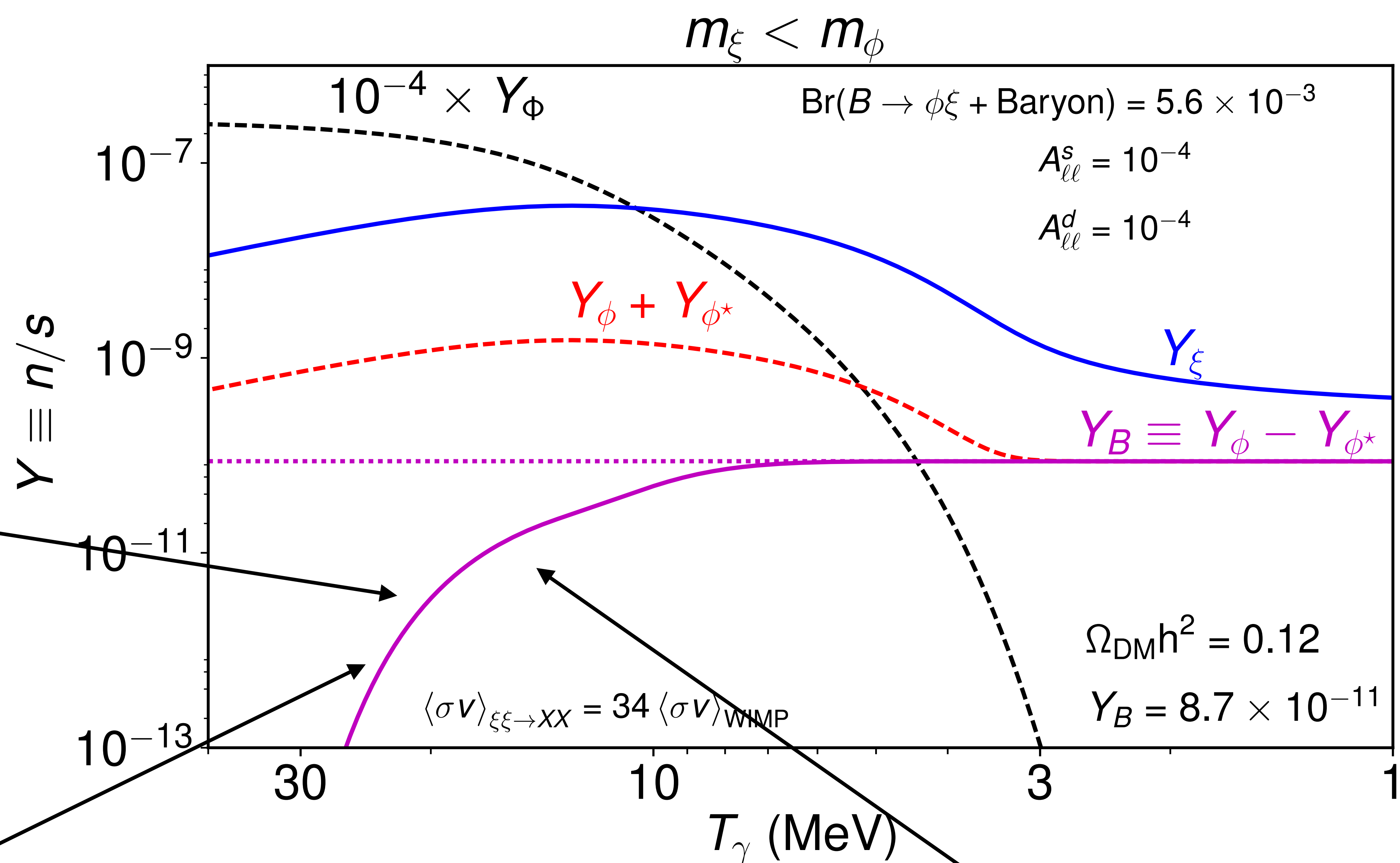
Dark Matter Abundance: Baryon Symmetric Component



- $\langle \sigma v \rangle$ **in our scenario is about one order of magnitude larger than for WIMPS because** $\Omega h^2 \propto x_{\mathrm{FO}} / \langle \sigma v \rangle$ **and for WIMPS** $x = m/T \simeq 20$ **but in our case** $x = m/T \simeq 2\,\mathrm{GeV}/10\,\mathrm{MeV} \simeq 200$.

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

$m_\xi = 1\,\mathrm{GeV} \qquad m_\phi = 1.5\,\mathrm{GeV}$



B_s produces the asymmetry

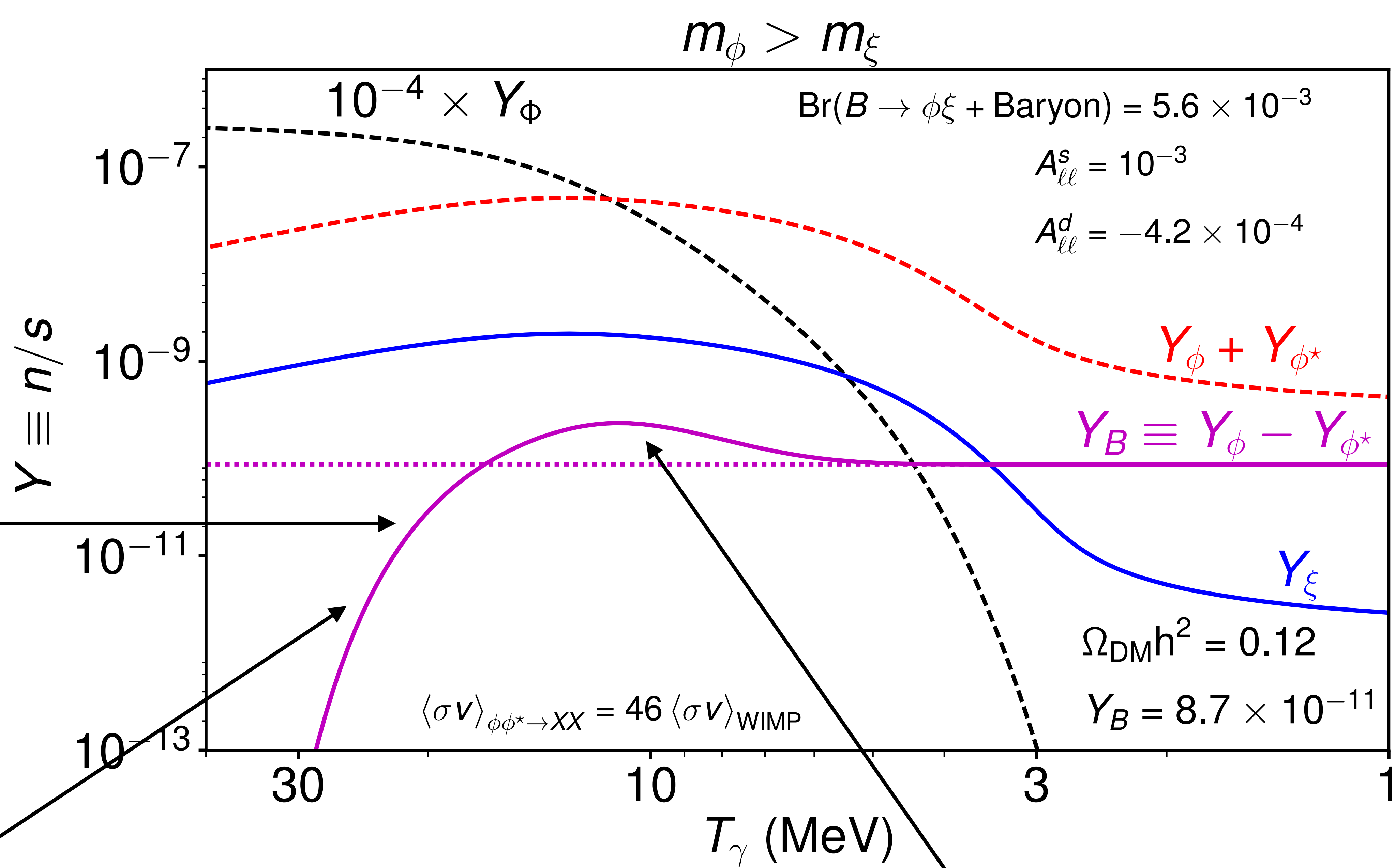
Asymmetric component only begins to form when there is coherence in the B^0 system

$T_{B_s} \lesssim 20\,\mathrm{MeV} \quad T_{B_d} \lesssim 10\,\mathrm{MeV}$

The B_d contributes to it too

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

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



In this case the B_s produces the asymmetry.

Asymmetric component only begins to form when there is coherence in the B^0 system

$T_{B_s} \lesssim 20\,\mathrm{MeV} \quad T_{B_d} \lesssim 10\,\mathrm{MeV}$

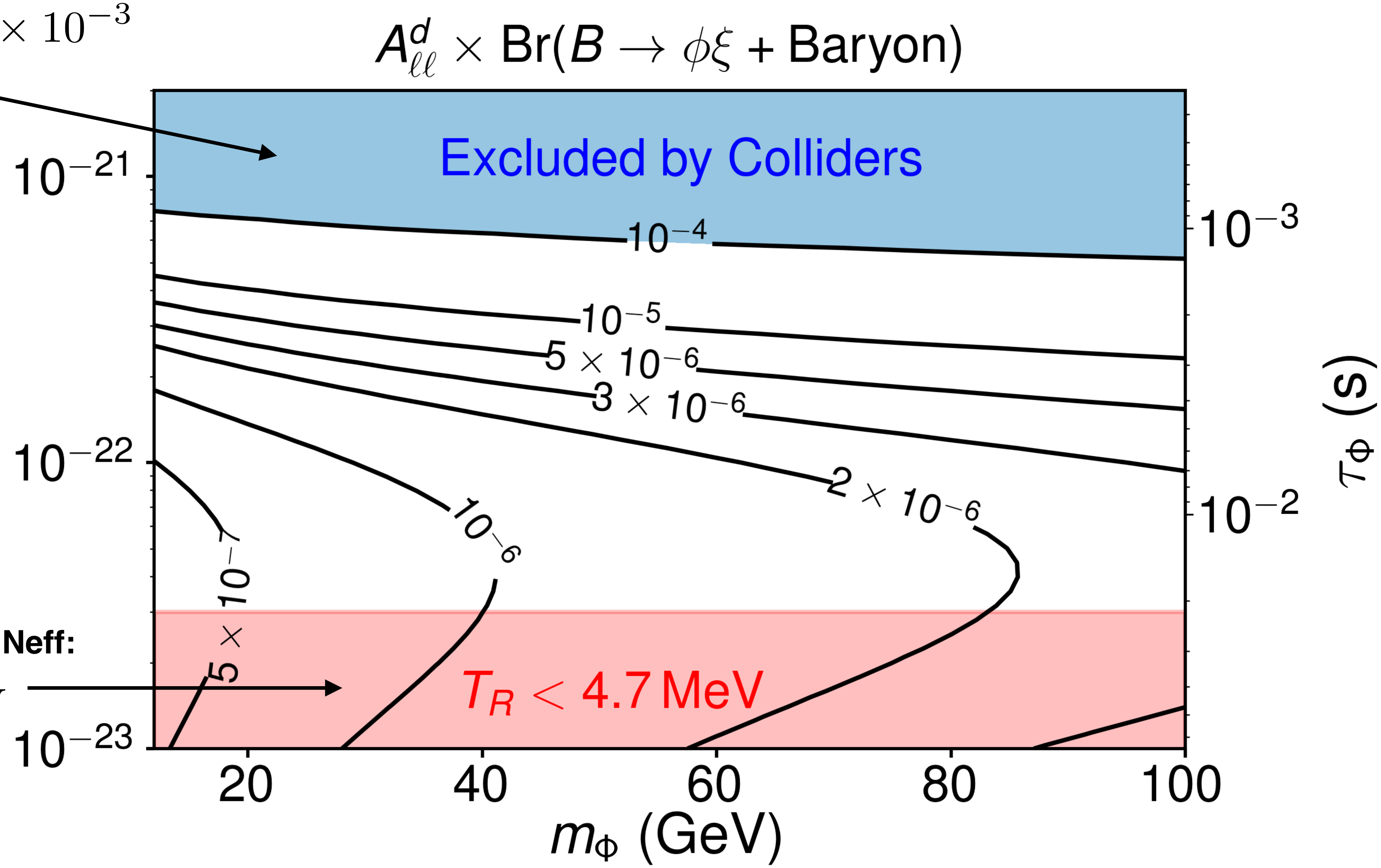
While the B_d erases part of it ($A_d < 0$).

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

$\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) < 0.1$

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

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



CMB and BBN agreement on Neff:

$\Gamma_\Phi > 3 \times 10^{-23}\,\mathrm{GeV}$

de Salas *et al.* 1511.00672

Baryogenesis requires:

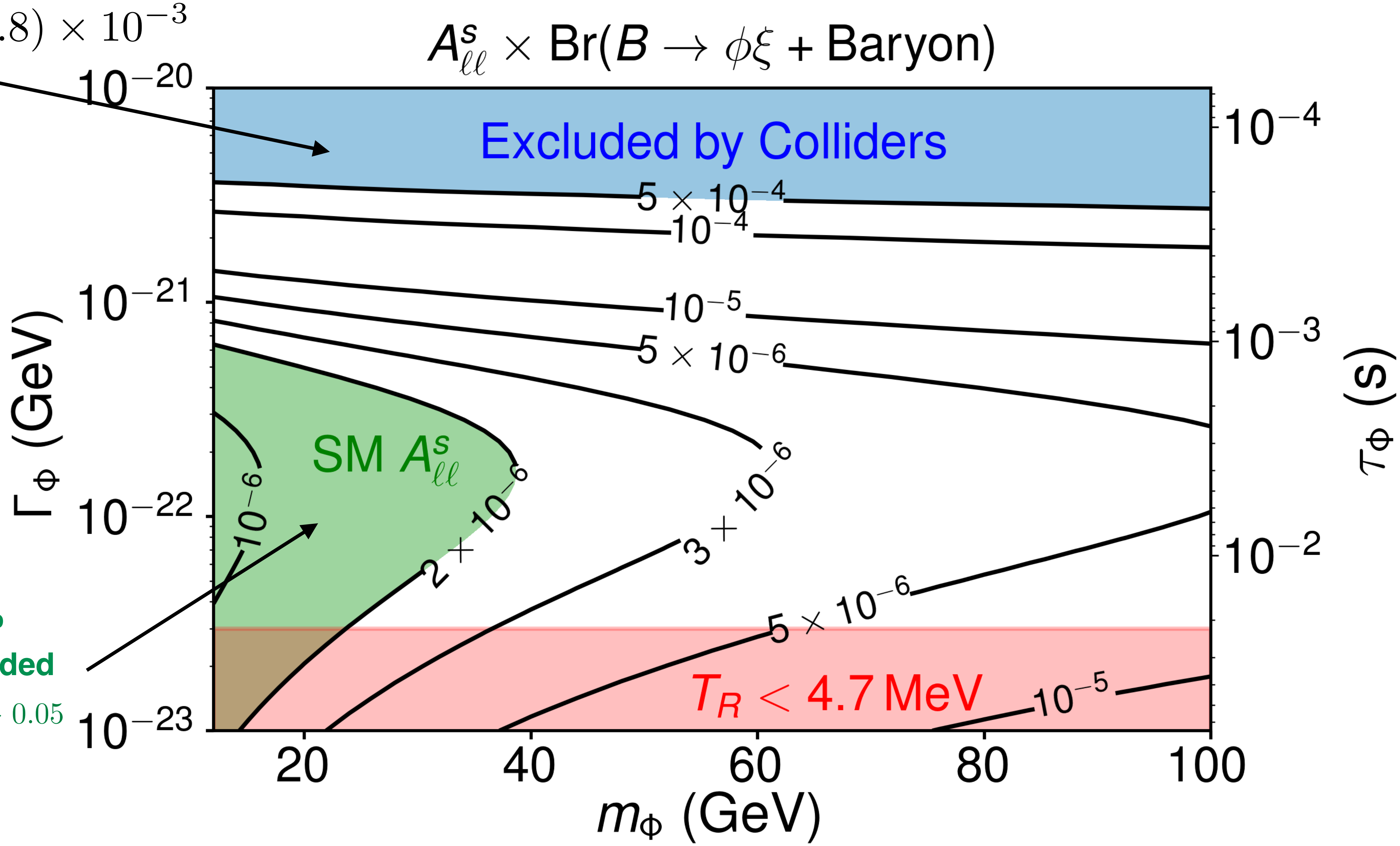
- $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) = 5 \times 10^{-4} - 0.1$
- $A^d_{\ell\ell} = 10^{-5} - 10^{-3}$

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

$\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) < 0.1$

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

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



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

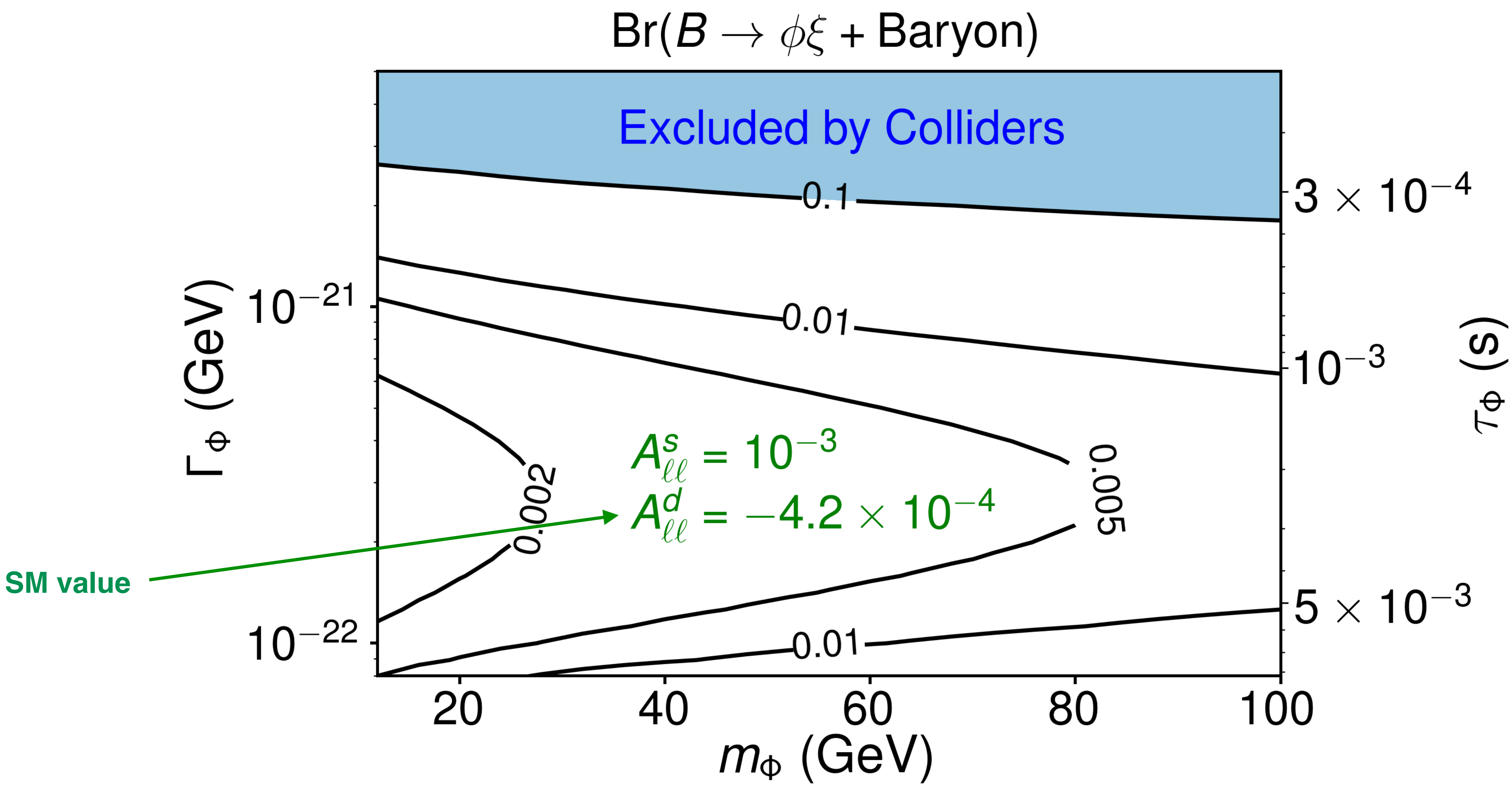
$\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) > 0.05$

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.**

Prospects on the observables

Leptonic charge asymmetry in B meson decays

- **Baryogenesis requires:** $A_{\ell\ell} = 10^{-5} - 10^{-3}$
- **Current bounds:** $A^s_{\ell\ell} = (-0.6 \pm 2.8) \times 10^{-3}$ $A^d_{\ell\ell} = (-2.1 \pm 1.7) \times 10^{-3}$ **from various hadron colliders and B-factories (PDG)**

The semileptonic asymmetry can be measured at:

- **Hadron Colliders:**
  both for the $A^d_{\ell\ell}$ **and** $A^s_{\ell\ell}$
  50 fb^{-1} LHCb sensitivity $\simeq 5 \times 10^{-4}$ **(1511.09466)**
  ATLAS and CMS could search for it too, but sensitivity not studied.

- **B-factories:**
  Only B_d mesons are produced at the nominal energy.
  Sensitivity not addressed in the Belle-II physics book 1808.10567
  but it should be $\mathcal{O}(10^{-4})$ **for** $A^d_{\ell\ell}$
  Belle-II will take 5ab^{-1} of data at $E = m_{\Upsilon(5S)}$ **and could also potentially allow for a measurement of** $A^s_{\ell\ell}$

Prospects on the observables

B meson decays into missing energy and a Baryon

- **Baryogenesis requires:** $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) = 2 \times 10^{-4} - 0.1$
- **Current bounds are very mild:**

  $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) < 0.3$ **from the predicted vs measured decay width of b-hadrons 1412.1446**

  $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) < 0.1$ **from the absence of a charm quark in the final state (PDG)**

The branching fraction can be constrained by:

- **Direct searches on** $B \to \phi\xi + \mathrm{Baryon} + X$ **(both charged and neutral)**

  B-factories have a good handle on missing energy *e.g.*: $\mathrm{Br}(B \to K\nu\nu) < 10^{-5}$

  Constraints from old BaBar and Belle data are possible, Belle-II will be able too.

- **Inclusive measurement of** $\mathrm{Br}(B \to \mathrm{Baryon} + X)$

  That would indirectly constrain the model, and could be searched for at both hadron colliders and B-factories. LHCb, ATLAS, CMS, Belle-II ...

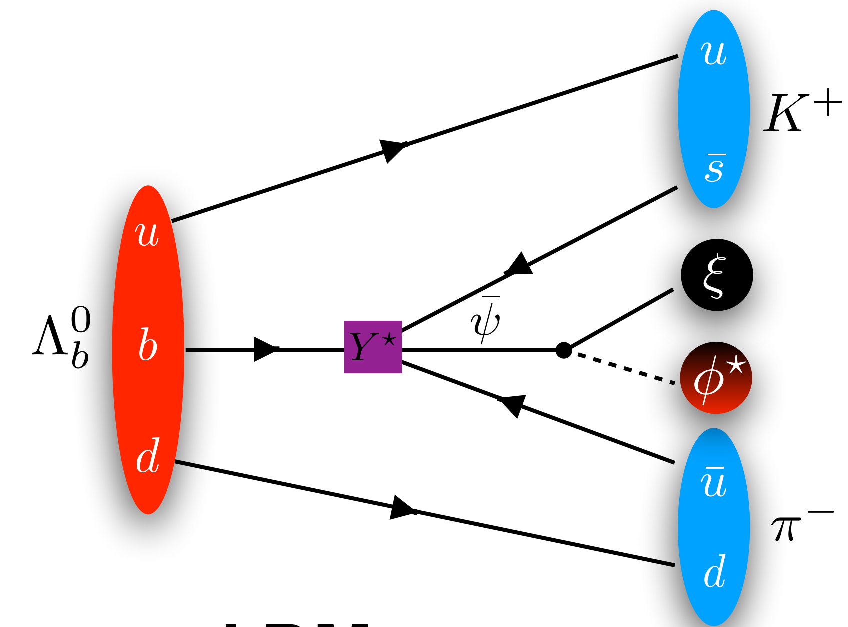
Prospects on the observables

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:**

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

***e.g.*:**

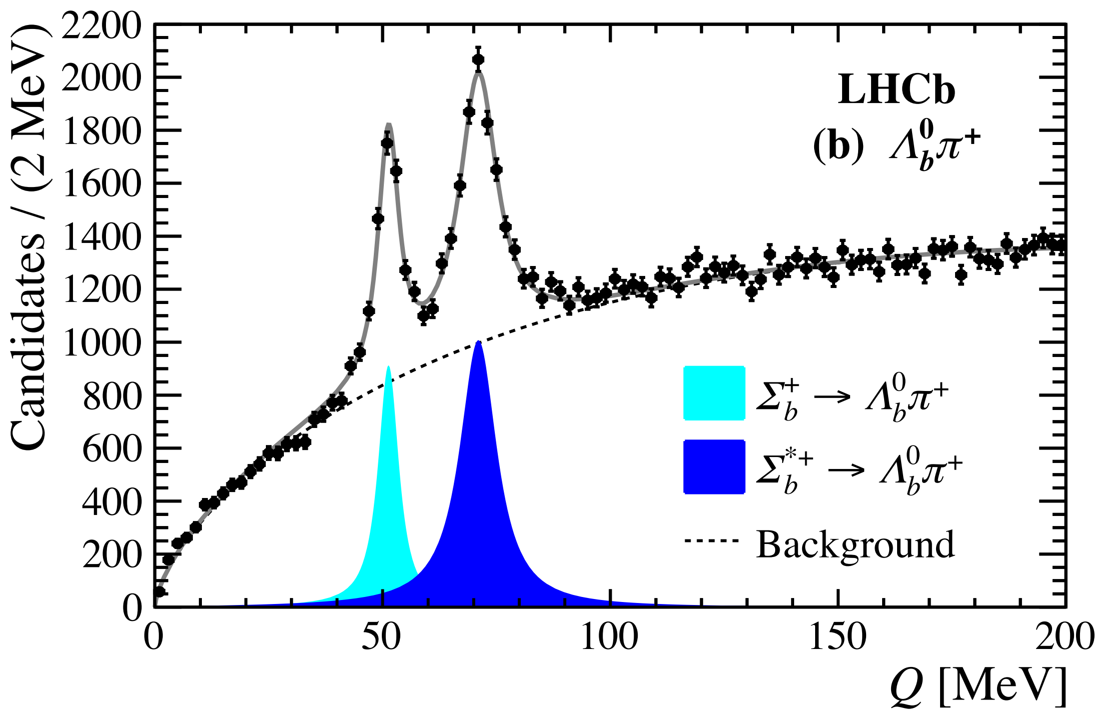


- **Search for b-flavored baryon decays into mesons and DM:**

b-flavored baryons are not produced at B-factories

Missing energy is difficult at hadron colliders but Stone & Zhang 1402.4205 pointed out that by tagging the pion in the process $\Sigma_b^\pm,\ \Sigma_b^{\pm\star} \to \Lambda_b + \pi^\pm$ one could hope to measure the initial energy.

Very recently the LHCb collaboration (1809.07752) has identified ~23000 candidates in this channel. It should also be possible to search for it in ALTAS and CMS.



Dark Matter Phenomenology

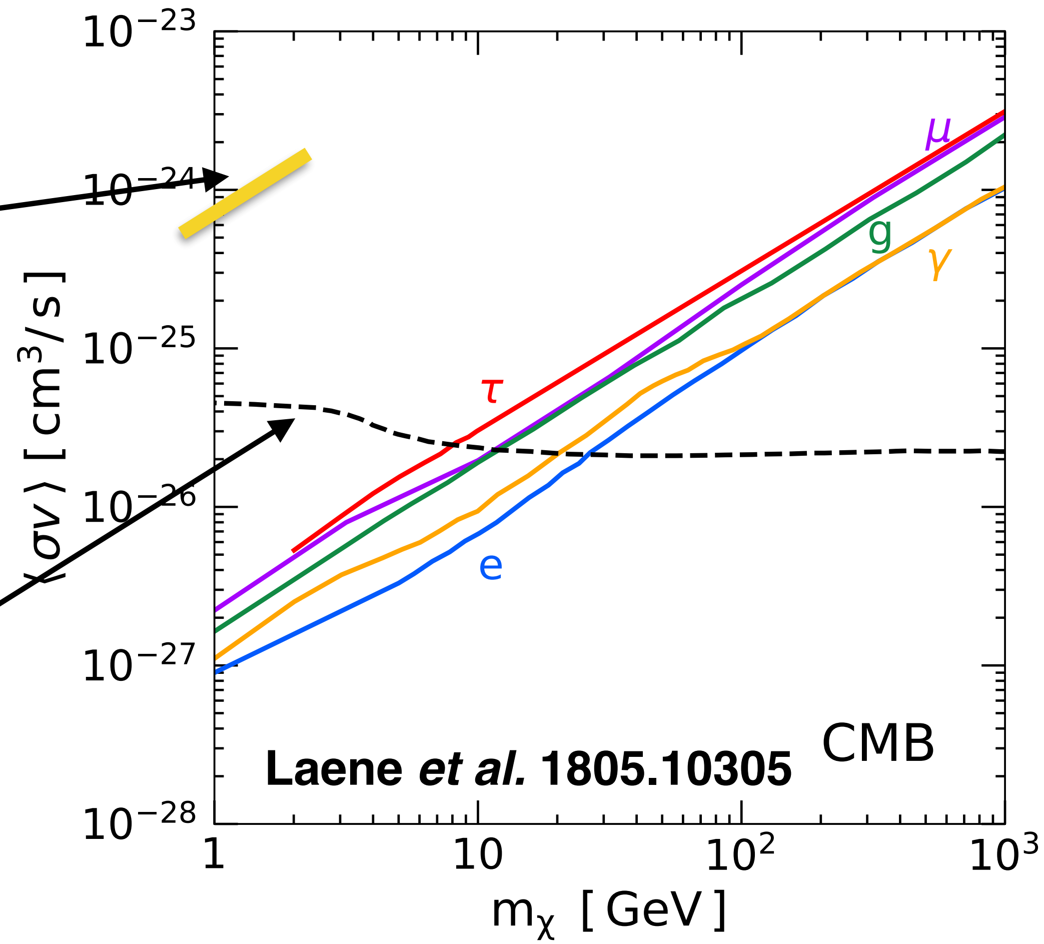
- **Relic abundance obtained with:**

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

- **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

- **Sterile neutrinos being singlets under the SM gauge group represent a simple possibility for a depletion mechanism in hidden sectors (Pospelov, Ritz, Voloshin 0711.4866) and in particular with our global symmetries (Escudero, Rius, Sanz 1607.02373).**

- **Can be minimally achieved by adding one additional state:**

$$m_\xi > m_\phi \qquad\qquad\qquad m_\phi > m_\xi$$

$$\mathcal{L} \subset y_N\, \phi \bar{\Psi} N_R + \text{h.c.} \qquad\qquad \mathcal{L} \subset y_N\, \xi \Phi^{'} N_R + \text{h.c.}$$

- **The *s*-wave contribution to the annihilation cross section is quirality suppressed. Which means that the annihilation can be predominantly *p*-wave (ME, Rius, Sanz) and therefore relaxes the CMB constraints.**

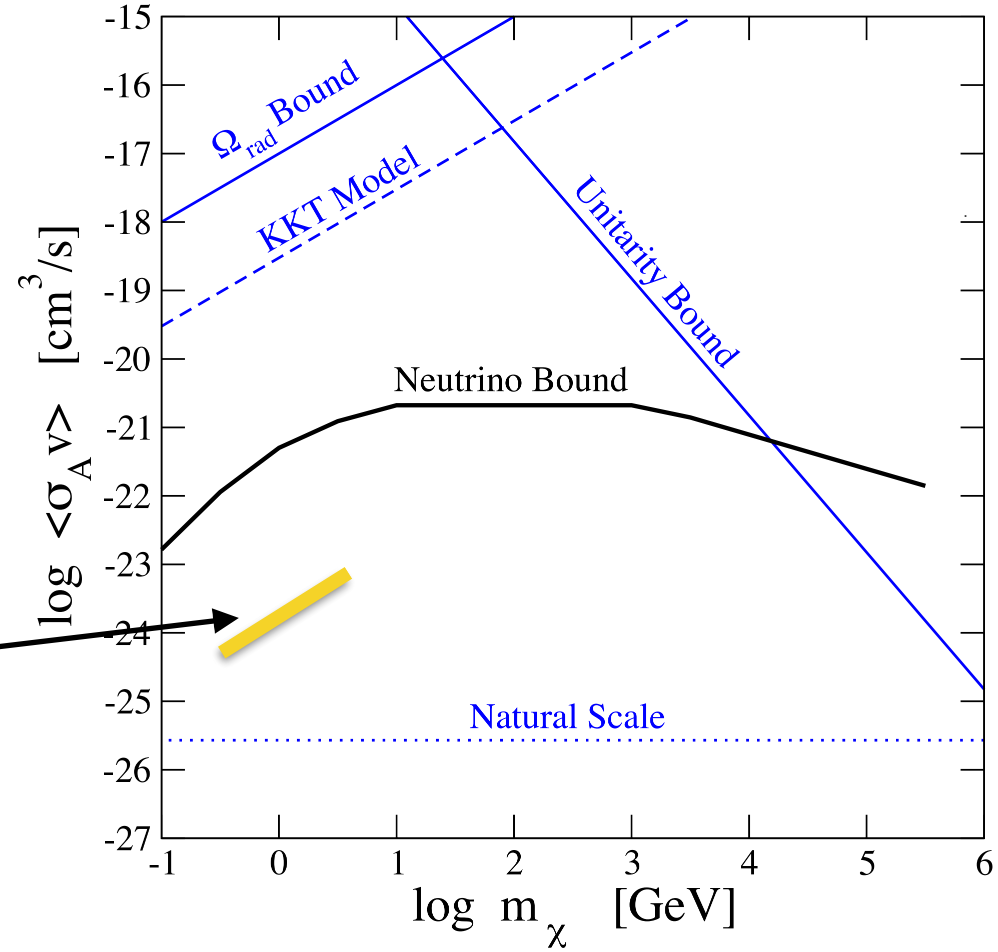
- **Furthermore, if $m_N < m_\pi$ and mixing is only with ν_τ then the final state is composed out of only active neutrinos. And therefore Planck constraints would be fully evaded.**

Possible Dark Sectors

2) Annihilation into Active Neutrinos

- If the sterile neutrinos are not kinematically accessible, then annihilation can proceed to active neutrinos via mixing (see González-Macias, Illana and Wudka, 1506.03825,1601.05051).
- Constraints on dark matter annihilating into neutrinos are mild due to the very small neutrino cross sections, and even our large annihilation cross section is two orders of magnitude below the current bounds.

Our scenario: Non-thermal DM



Beacom, Bell, Mack astro-ph/0608090

Possible Dark Sectors

3) Additional Dark Sector states

- **Additional states carrying baryon number could lead to the dark sector being composed by just anti baryons.**

- **Example:**
  - **New scalar Baryon with B = 1/3:** $\mathcal{A}$
  - **Interactions can convert the excess of ϕ particles into 3 excesses of $\mathcal{A}$ particles:**

$$\mathcal{L} \supset \kappa\, \phi \mathcal{A}^3 + \kappa'\, \phi\phi^* \mathcal{A}\mathcal{A}^* \ + \ \mathrm{h.c.} \longrightarrow \begin{array}{c} \phi^\star + \phi \to \mathcal{A} + \mathcal{A}^\star \\ \phi + \mathcal{A} \to \mathcal{A}^\star + \mathcal{A}^\star \end{array} \ \textbf{etc}$$

  - **Which in order to get $\Omega_{\rm DM}/\Omega_b = 5.36$ will require $m_{\mathcal{A}} \sim \frac{5}{3} m_p \sim 1.6\,\mathrm{GeV}$**

Summary

- **New mechanism for 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 antibaryonic**
  - **Testable!**
- **Baryon asymmetry directly related to two observables at collider experiments:**

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

- **Distinct experimental signatures:**
  - **Positive leptonic asymmetry in B meson decays** $10^{-5} < A_{\ell\ell}^{d,\,s} < 10^{-3}$
  - **New decay mode of neutral and charged B mesons into baryons and missing energy** $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) > 2 \times 10^{-4}$
  - **New decay mode of b-flavored baryons into mesons and missing energy**
- **Dark Matter abundance requires:**

$$\langle \sigma v \rangle_{\mathrm{dark}} \simeq 25\, \langle \sigma v \rangle_{\mathrm{WIMP}}\; \min[m_\phi, m_\xi]/\mathrm{GeV}$$

Outlook

- **Are the flavor anomalies ($b \to s\mu^+\mu^-$) in B-decays related to our required positive semileptonic asymmetry given the fact that Leptoquarks and Z' flavorful models induce substantial mixing in the B_s system?**

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

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

- **Additional dark sector states with baryon number?**

- **How well can current collider experiments measure**

$$\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X)\,\textbf{?}$$

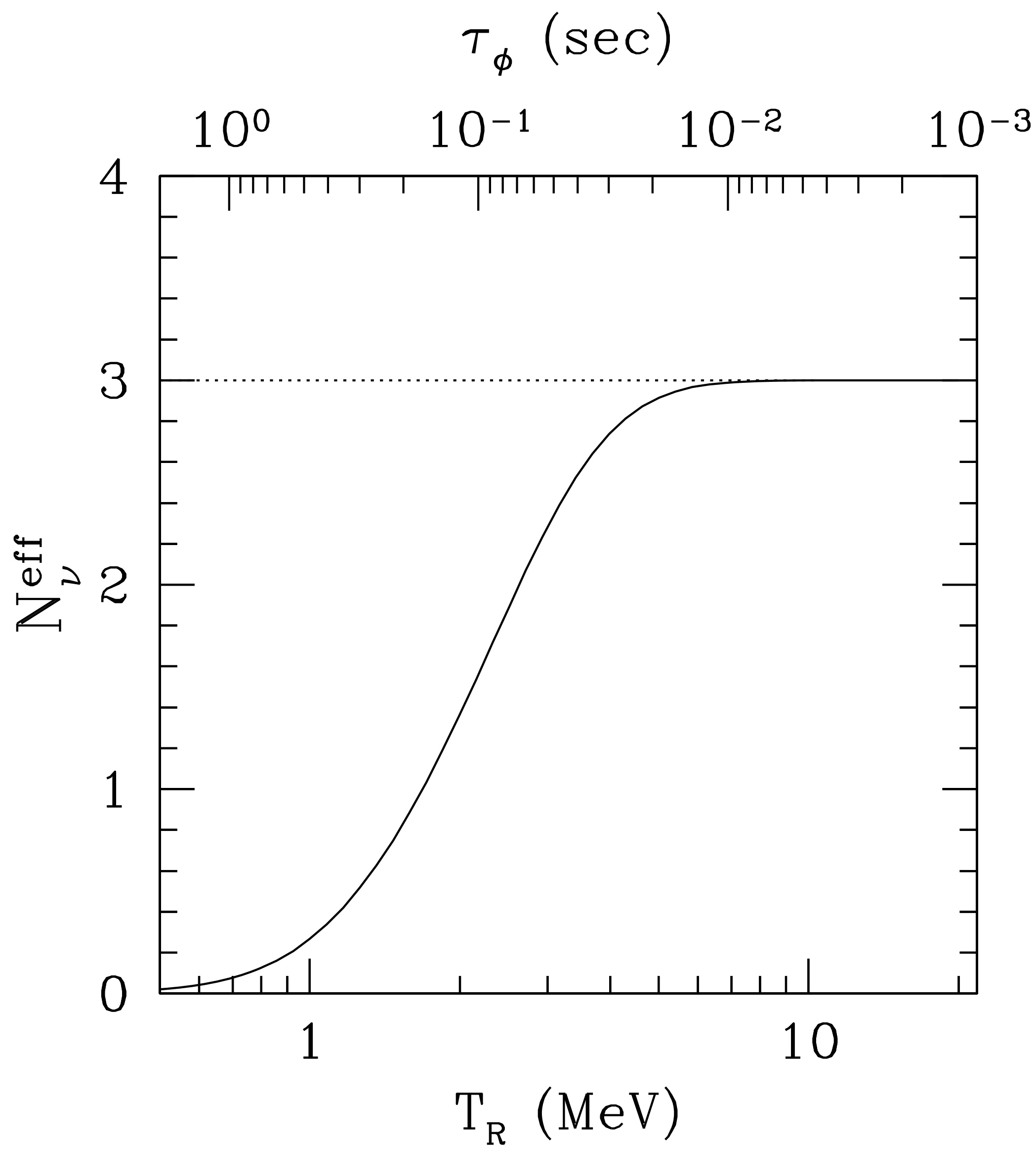
THE END

Thank you very much for your attention!

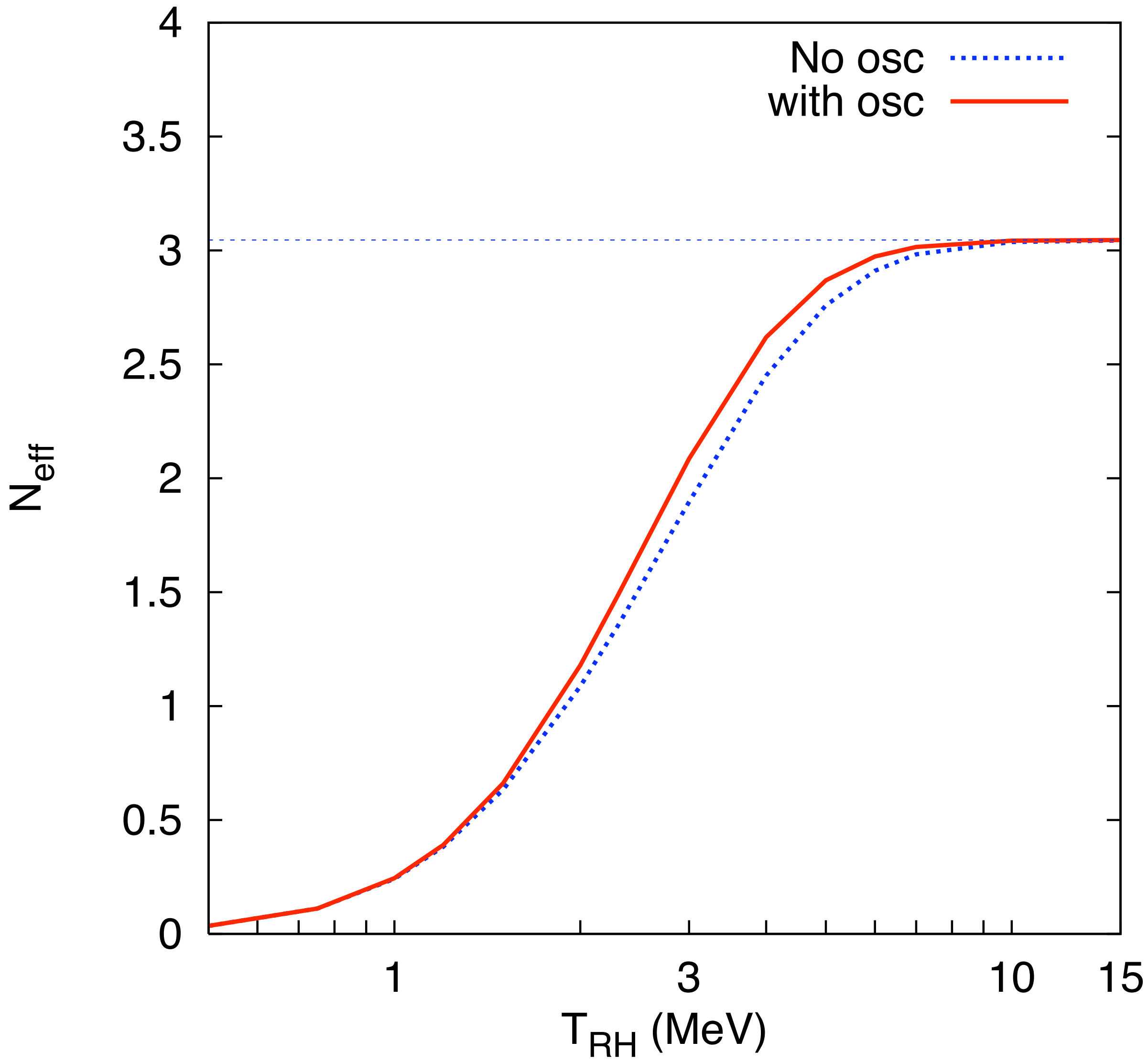
Time for Questions and Comments!

Back Up: MeV Reheating Temperature

Kawasaki, Kohri, Sugiyama 0002127



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



Current bounds 1511.00672

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

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

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

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

Planck 2018?

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

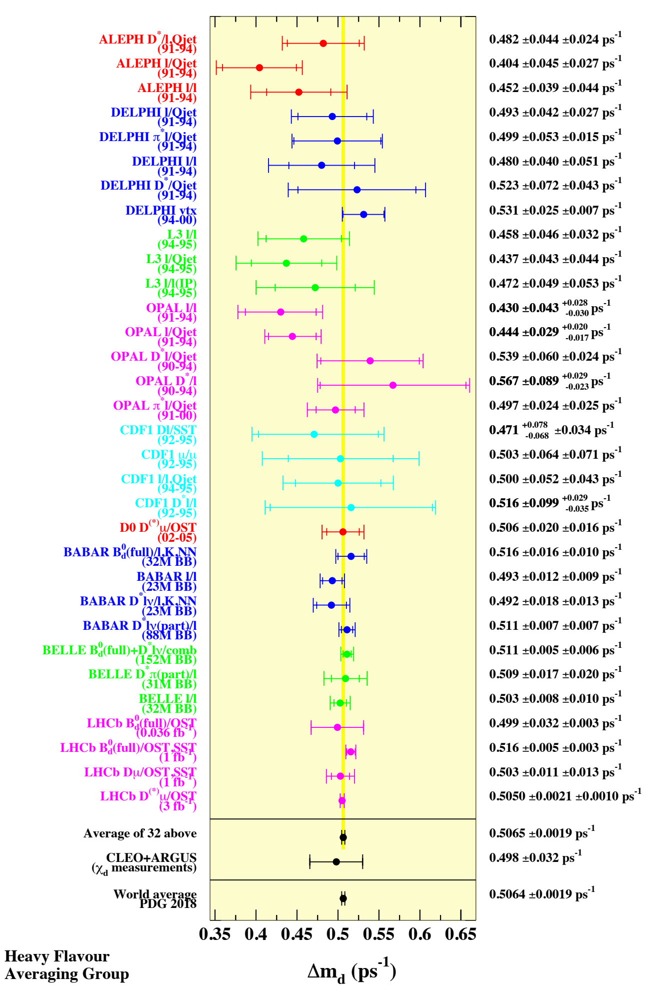
hence not expected to become more stringent

Back Up: Modifications to masses and decays

$$A^q_{SL} = \mathrm{Im}\left(\frac{\Gamma^q_{12}}{M^q_{12}}\right).$$

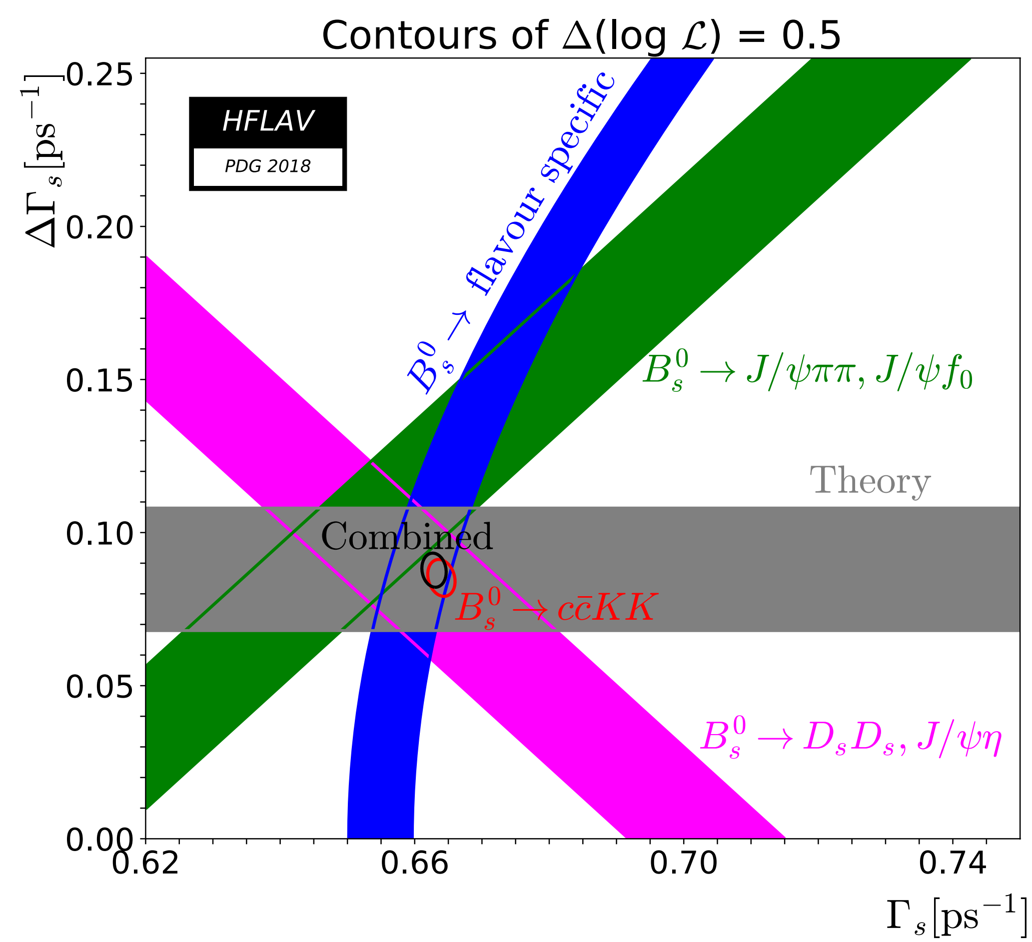
$$\Delta m_B = 2|M_{12}| \quad \text{and} \quad \Delta\Gamma_B = -\frac{2\mathrm{Re}(M^*_{12}\Gamma_{12})}{|M_{12}|}$$

The new physics that alters M_{12} and Γ_{12} should be compatible with the observed values of Δm_B and $\Delta\Gamma_B$

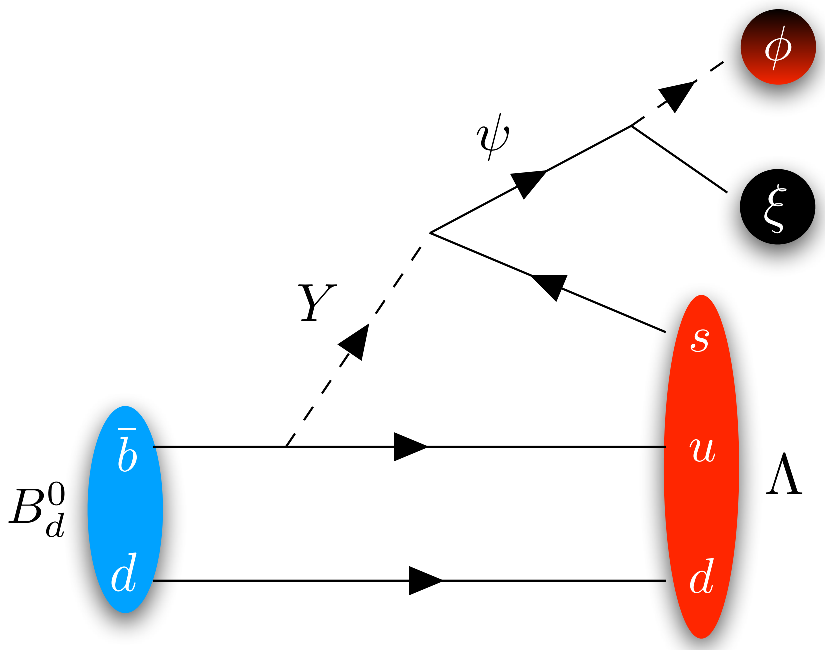


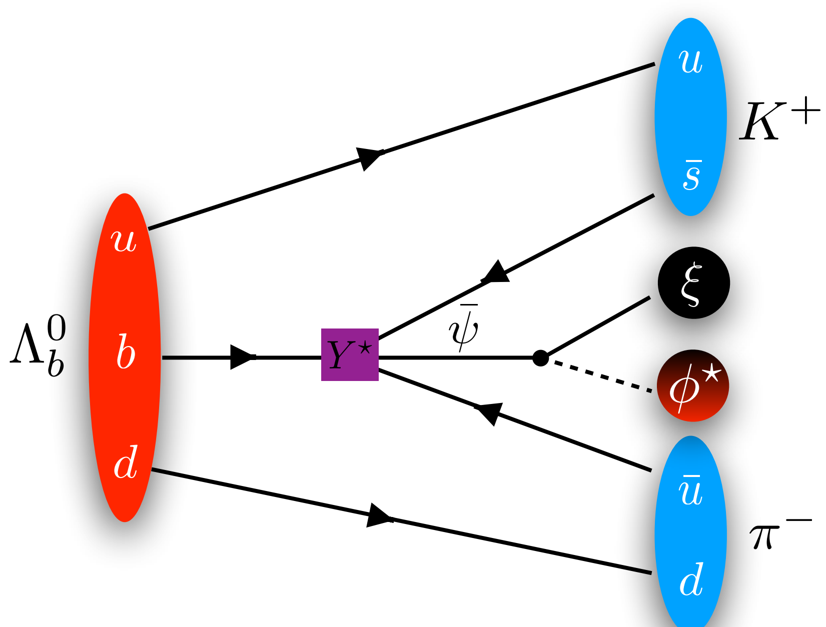
$$\Delta m_{B_d} = 0.5064 \pm 0.0019\,\mathrm{ps}^{-1}$$

$$\Delta m_{B_s} = 17.757 \pm 0.021\,\mathrm{ps}^{-1}$$



Back Up: Lowest decay final states





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.

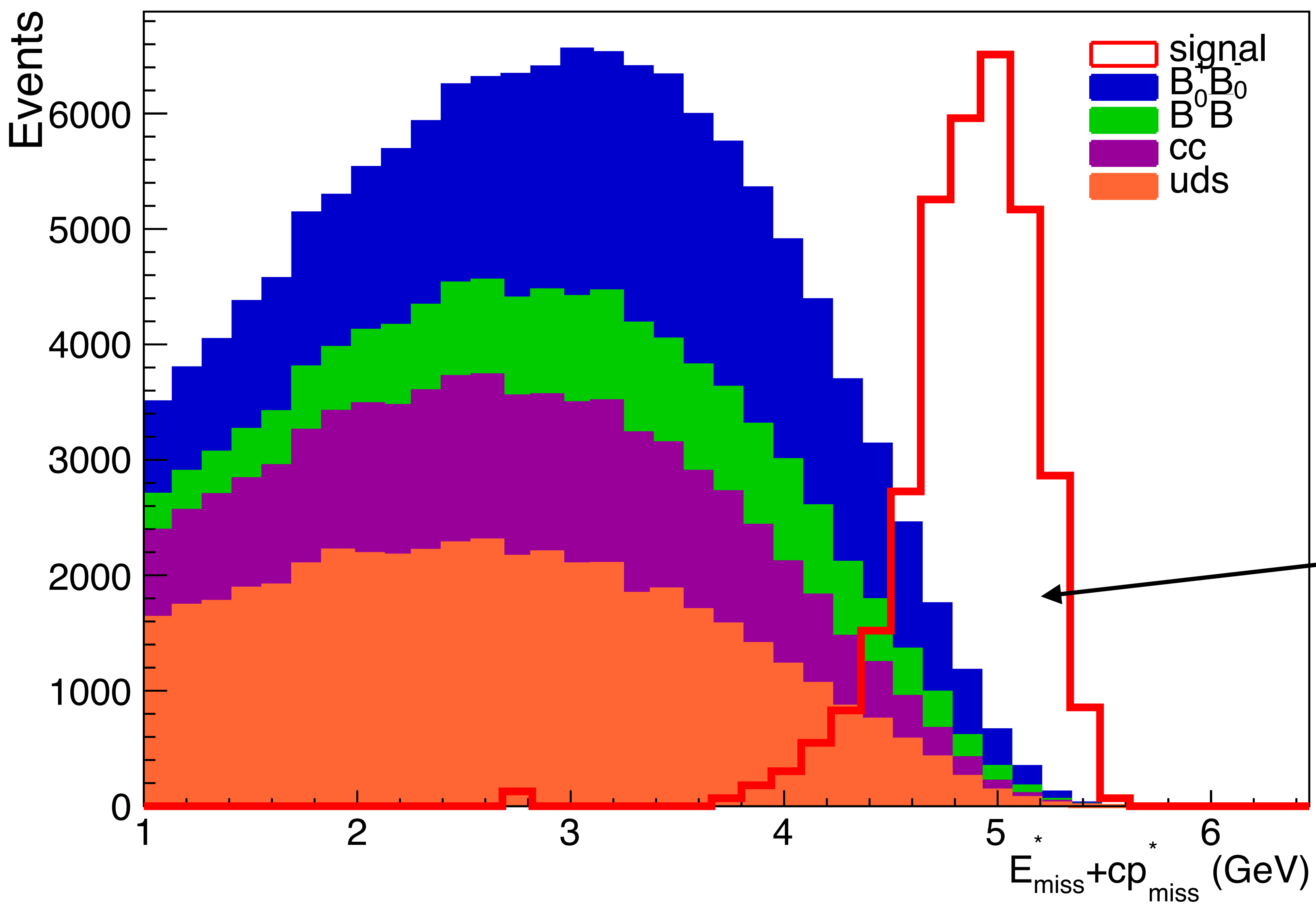
Back Up: Parameters

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

Back Up: Belle-II?

Belle-II physics book 1808.10567

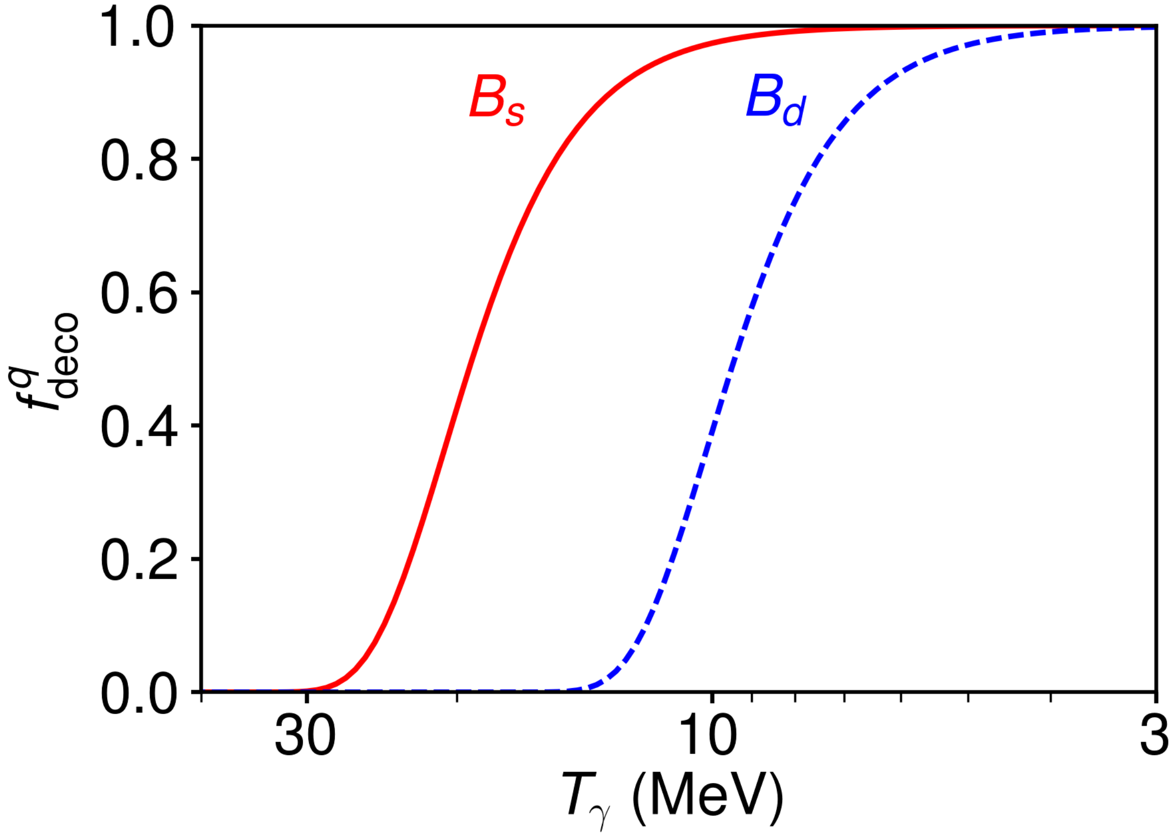
$$B \to \phi\xi + \mathrm{Baryon}$$ **?**



SM

$$B \to K\bar{\nu}\nu$$

Back Up: Decoherence



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

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