Séminaire du groupe de physique théorique: “On baryogenesis from dark matter annihilation (BarDaMA)”

[N.Bernal, F.X.Josse-Michaux, J.D.Racker, L.Ubaldi, SC, JCAP10(2013)035]

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Outline

1. DM + BAU : a common origin ?
2. Some ways (among which ours) to BarDaMA.
3. Our toolkit (BEs, freeze-out mechanism, sphaleron processes).
4. The original idea.
5. A first unsuccessful implementation.
6. Let the things work !
7. Numerical results and costraints.
8. Outlook.

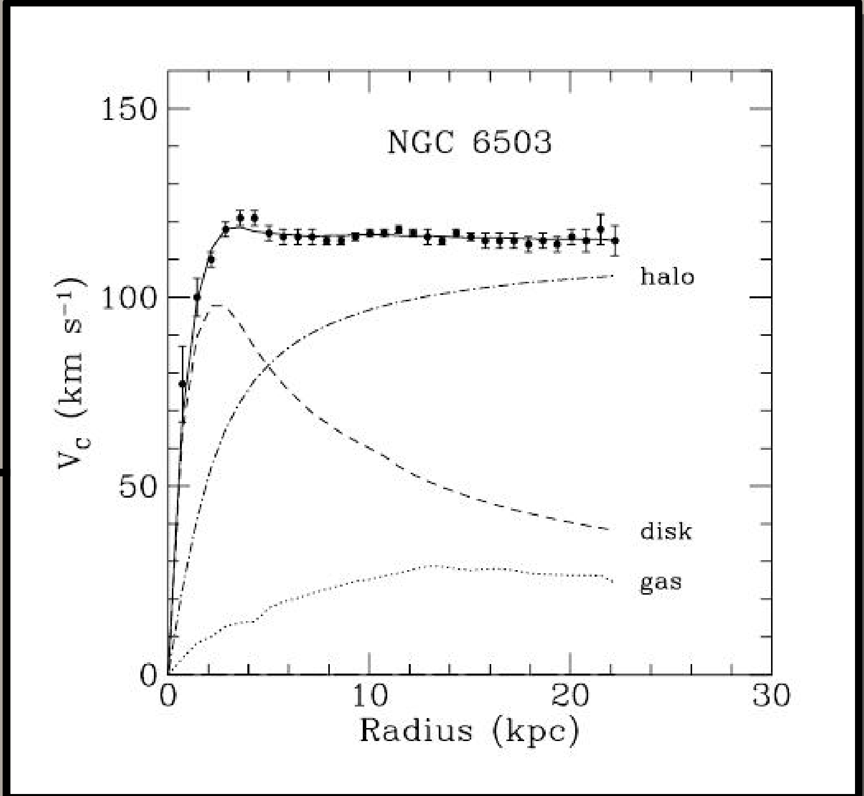
Will I make it ?

Dark matter (DM)

Rotation curves of galaxies usually show flatness at large radius . Expected Newtonian velocity:

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

with $M(r) = 4\pi \int \rho(r) r^2 dr$



The mass density should follow $\rho(r) \sim 1/\sqrt{r}$, but:

$$\Omega_i = \frac{\rho_i}{\rho_c}$$

$$v(r) \sim c \Rightarrow M(r) \sim r \Rightarrow \rho(r) \sim r^{-2}$$

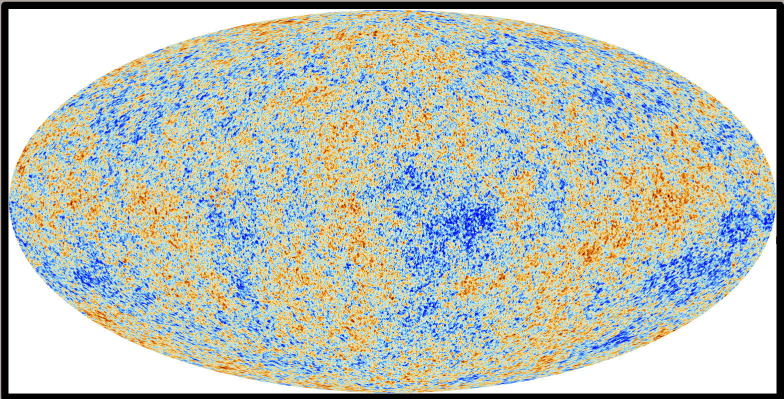
→ Dominant halo of non detectable matter: $\Omega_{DM} h^2 \simeq 0.11$

Baryon asymmetry of the universe (BAU)

Why our universe contains more matter than antimatter ?

- ✗ Produced at collider experiment (@ LHC: $\bar{p}p$).
- ✗ Not seen on earth or in our solar system.
- ✗ Cosmic rays: antiprotons to proton ratio $\sim 10^{-4}$.
- ✗ Absence of γ-ray flux from galaxy clusters.

$$\eta \equiv \left.\frac{n_b - n_{\bar{b}}}{n_\gamma}\right|_0 \simeq 6 \times 10^{-10}$$



Ade et al. , PLANCK 2013 results

Agreement with:

- ✓ Big Bang Nucleosynthesis.
- ✓ CMB measure of $\Omega_b h^2 \simeq 0.02$

$(\eta = 2.74 \times 10^{-8}\ \Omega_b h^2)$

$$\frac{\Omega_{DM}}{\Omega_b} \sim \mathcal{O}(1)$$

Only a coincidence ?

Hopefully a chance to relate **DM** and **BAU** ! (But no ADM)

DM

- MACHOs
- Light neutrinos
- Axions
- WIMPs
- Kaluza-Klein states
- Light Scalar DM
- WIMPzillas
- ...

BAU

- Planck scale baryogenesis
- GUT baryogenesis
- Electroweak baryogenesis:
  - in SM
  - in SUSY
- Leptogenesis
- Affleck-Dine mechanism
- ...

WIMPs + Leptogenesis → WIMPy baryogenesis

"WIMP miracle"

Get the right relic abundance with a typical cross section for a weak interacting particle, independently from its mass :

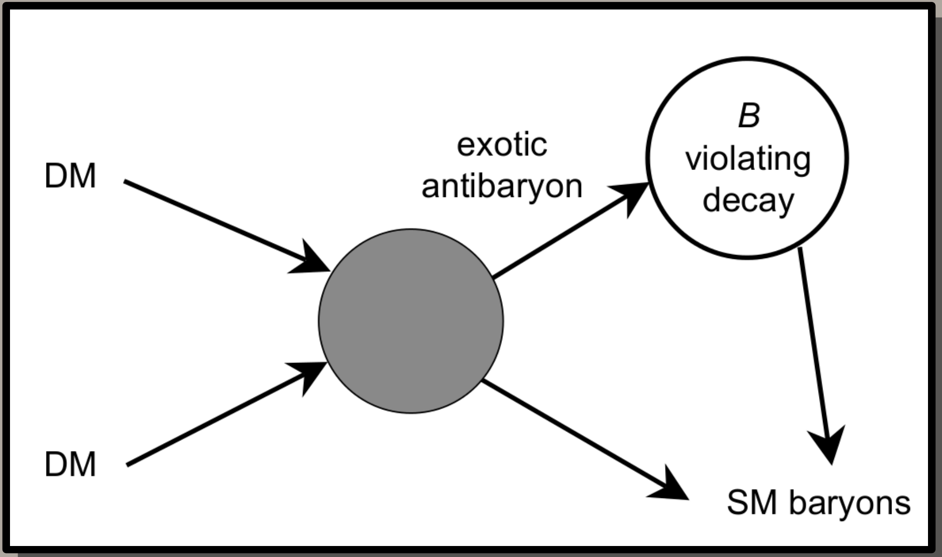
$$\Omega_{DM} h^2 \approx \frac{3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma v \rangle_{ann}}$$

"WIMPy miracle"

Sakharov conditions:

1. Baryon number violation
2. CP violation
3. Departure from thermal equilibrium

Cui, Randall and Shuve, JHEP 1204 (2012) 075



Exploring ways for **BarDaMA**

1. For temperatures above 100 TeV it is possible to generate the BAU from CP-violating annihilations of heavy particles into SM particles. → DM relic density too high !

2. Generate the BAU in the three-body decay of a heavy particle ? Washout processes involving three particles in the in. or fin. state are naturally phase-space suppressed. But: 2→3 too suppressed.

3. Resonant baryogenesis: CP asymmetry induced by a pair of particles almost degenerate in mass, it can be enhanced up to O(1) values. → Suppressing the washouts by taking the relative couplings small enough, too much DM relic density again.

4. Include a massive field, ψ, in the annihilation products, $m_\psi > m_\chi$ → Proven successful in EFT in N.Bernal, L.Ubaldi *et al.* JCAP1301(2013)124

Boltzmann equations (1)

Distribution functions of the particles obey

Liouville operator ← $\mathbf{L}[f] = \mathbf{C}[f]$ → Collision operator

Number density for massive particles, i.e. non-rel. limit:

$$n_{i,MB}^{eq}(p) = \frac{g_i}{(2\pi)^3}\int d^3p f_{i,MB}^{eq}(p) = \frac{g_i T^3}{2\pi^2} z_i^2 K_2(z_i)$$

The comoving number density $Y_x = n_x/s$ evolution:

$$\frac{dY_x}{dt} = -\sum_{int}\Big[\frac{Y_x Y_a \ldots}{(sY_x^{eq})(sY_a^{eq})\ldots}\gamma(X+a+\ldots \to i+j+\ldots) - \frac{Y_i Y_j \ldots}{(sY_i^{eq})(sY_j^{eq})\ldots}\gamma(i+j+\ldots \to X+a+\ldots)\Big]$$

Boltzmann equations (2)

The interaction density:

$$\gamma(X+a+\ldots \to i+j+\ldots) = \int d\Pi_X f_x^{eq} d\Pi_a f_a^{eq} \ldots |\mathcal{M}(X+a+\ldots \to i+j+\ldots)|^2 \tilde{\delta} d\Pi_i d\Pi_j$$

2→2 scattering:

$$z = \frac{m_\chi}{T}$$

$$\gamma_{ij}^{mn} = \frac{g_i g_j}{32\pi^4} \int ds s^{\frac{3}{2}} K_1\left(\frac{\sqrt{s}}{T}\right) \lambda\left(1, \frac{m_i^2}{s}, \frac{m_j^2}{s}\right) \sigma(s)$$

$$\Gamma(T) \equiv n_x^{eq} \langle \sigma v \rangle$$

Assumptions:

- $X\bar{X} \to \psi\bar{\psi}$
- CP invariance
- no asymmetry
- thermal eq. of ψ
- $\mu = 0$

Boltzmann eq. controlled by the effectiveness of annihilations:

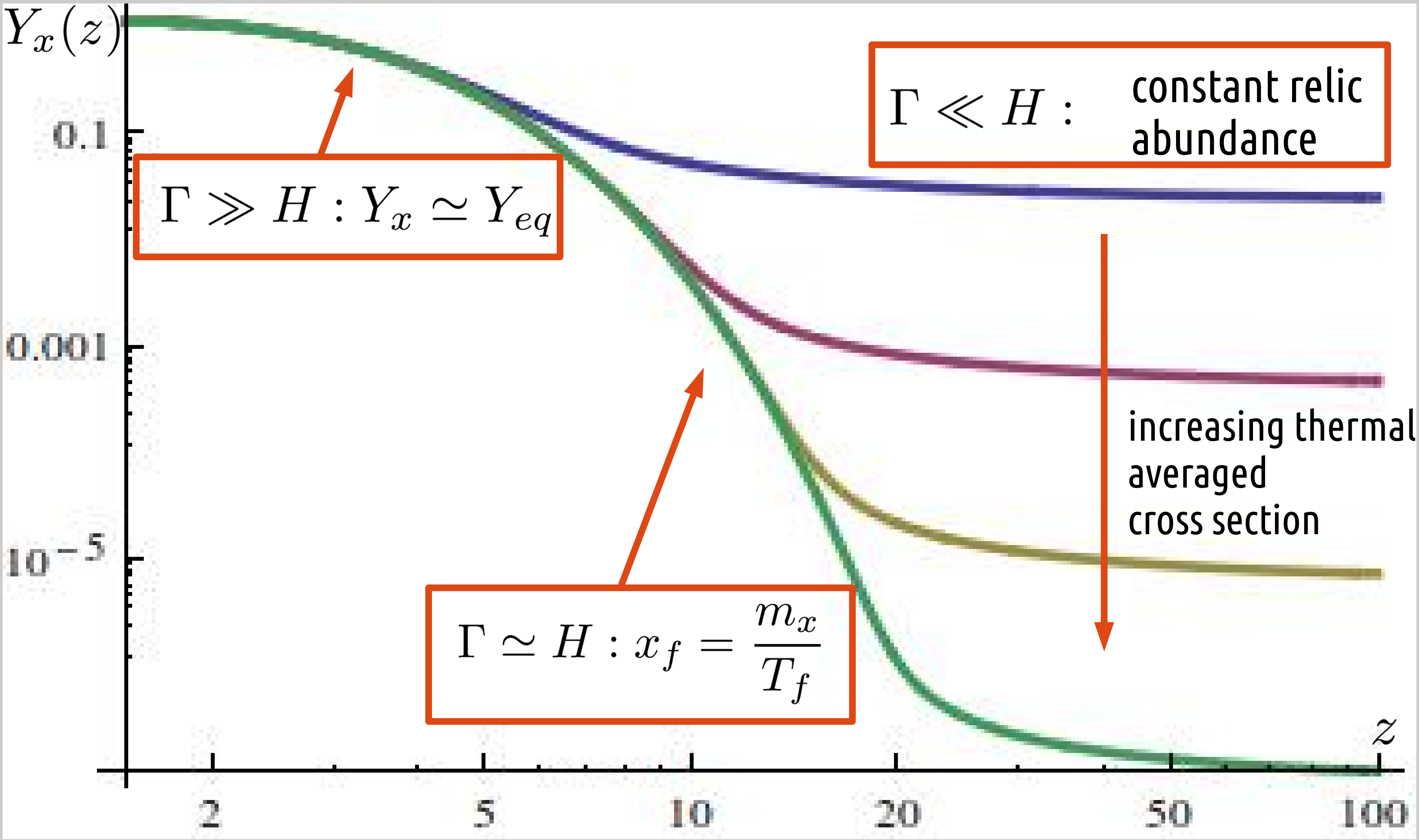
$$\frac{z}{Y_x^{eq}} \frac{dY_x}{dz} = -\frac{\Gamma}{H} \left[\left(\frac{Y_x}{Y_x^{eq}} \right)^2 - 1 \right]$$

Hubble expansion rate:

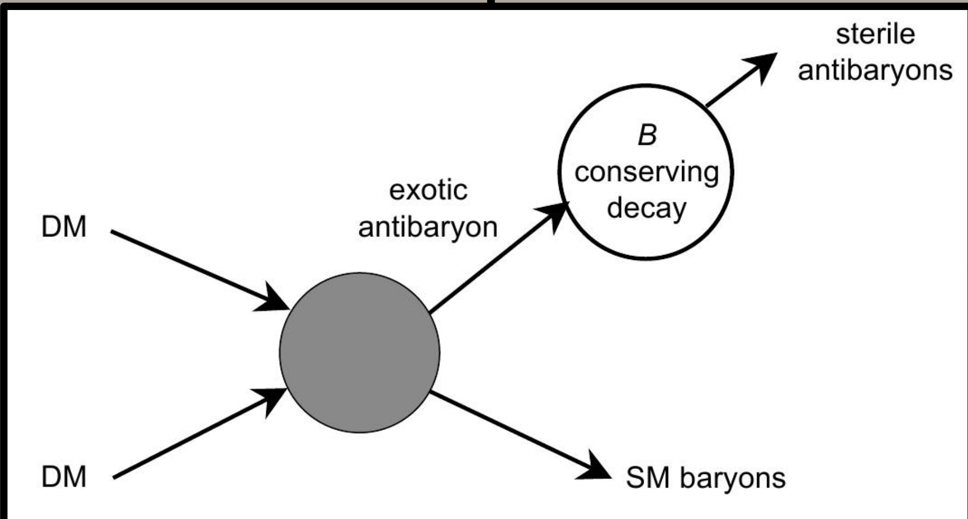
$$H = \sqrt{\frac{4\pi^3 g_*}{45}} \frac{T^2}{m_{pl}}$$

Freeze-out

Freeze-out of X abundance occurs when the annihilation rate of the particle specie is not efficient enough against the expansion of the universe:



Randall's idea



* Dirac vector-like gauge singlet dark matter X
* Pseudoscalars S
* Vectorlike exotic quark color triplets ψ

$$L = -\frac{i}{2}\left(\lambda_{X\alpha} X^2 + \lambda'_{X\alpha}\bar{X}^2\right) S_\alpha + i\lambda_{B\,\alpha}\, S_\alpha \bar{u}\psi.$$

* "Sequestered" sector required.
* $\mathbb{Z}_4$ symmetry needed.

Sure ?

	X	$\bar{X}$	ψ	$\bar{\psi}$	S	$\bar{u}$	$\bar{d}$	$\phi/\tilde{d}$	Q	H	n	leptons
Z_4	$+i$	$-i$	$+1$	$+1$	-1	-1	-1	-1	-1	$+1$	$+1$	$+1$

Sphalerons

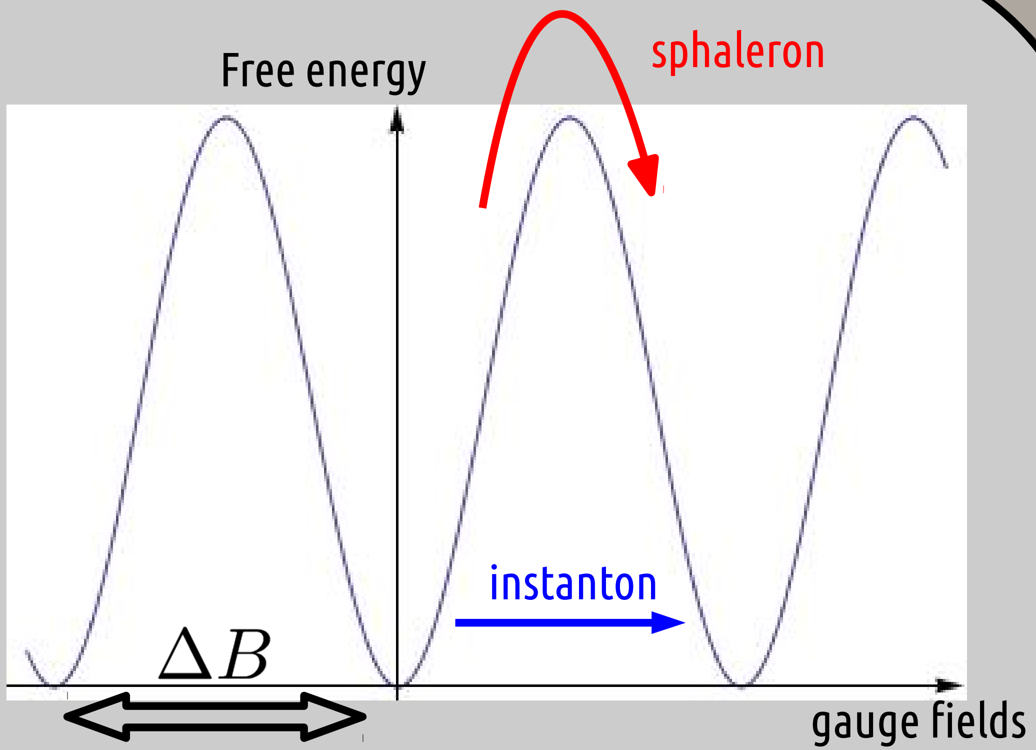
- Tunneling effects (*instantons*) among different vacua of a gauge theory at zero T unimportant.

$$\text{rate} \sim e^{-4\pi/\alpha_W}$$

- Non-perturbative thermal transitions (*sphalerons*) can overcome potential barriers, with a B-violation rate:

$$\frac{dB}{dt} = -cBTe^{-\frac{F}{T}}$$

- violating B+L , conserving B-L



Can move the asymmetry from baryons to leptons (or the other way round).

Simplest implementation

Majorana DM

Exotic heavy quark

Heavy pseudo-scalars

	$SU(3)$	$SU(2)_L$	$Q_{U(1)_y}$	$Q_{U(1)_B}$	Z_2
χ	1	1	0	0	-1
Ψ	3	1	$+2/3$	$+1/3$	$+1$
~~Ψ_2~~	~~3~~	~~1~~	~~$+2/3$~~	~~$+1/3$~~	~~$+1$~~
$P_L Q$	3	2	$+1/6$	$+1/3$	$+1$
$P_R U$	3	1	$+2/3$	$+1/3$	$+1$
$S_{1,2,3}$	1	1	0	0	$+1$
H	1	2	$+1/2$	0	$+1$

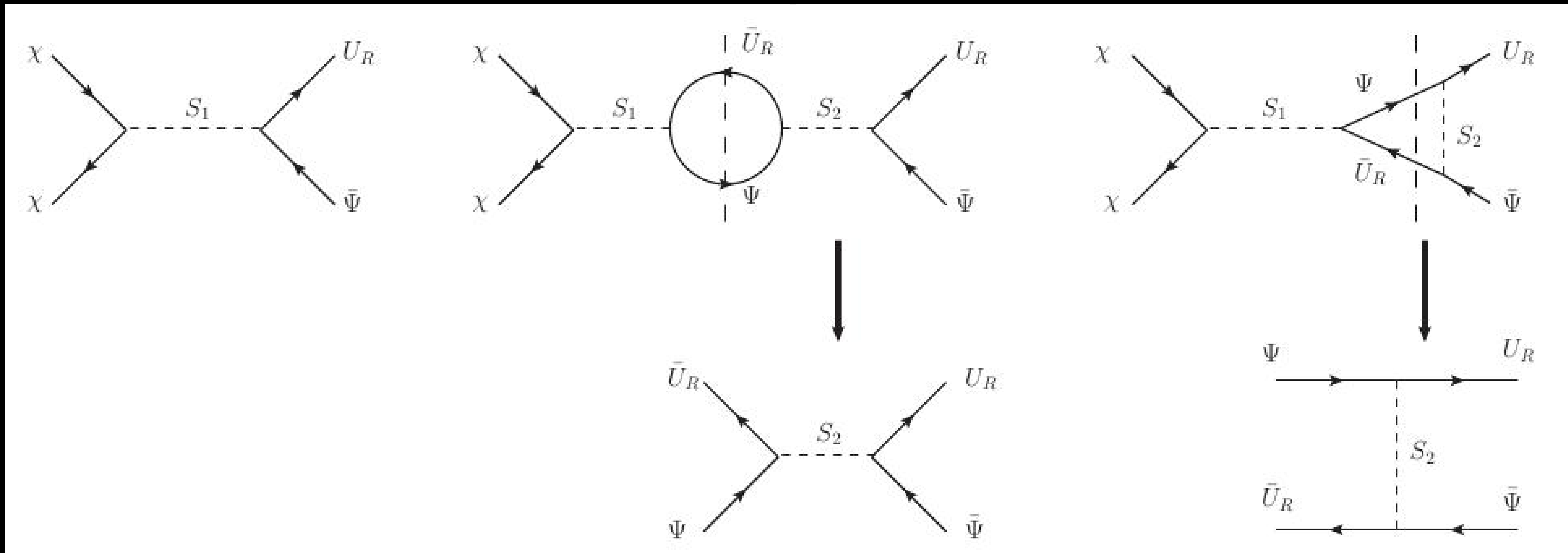
$$\mathcal{L} \supset i\lambda_{X_\alpha} S_\alpha \bar{\chi}\gamma_5\chi + iS_\alpha(\lambda_{B_\alpha}\bar{u}P_L\psi - \lambda^*_{B_\alpha}\bar{\psi}P_R u) + y_\psi \tilde{H}\bar{Q}P_R\psi + \lambda_3 S_3\bar{\psi}\psi_2 + y_{\psi_2}\tilde{H}\bar{Q}P_R\psi_2$$

Mass hierarchy: $2m_\chi > m_\psi > 1TeV$

→ negligible mixing effect with SM.

[N.Bernal, F.X.Josse-Michaux, J.D.Racker, L.Ubaldi, SC, hep-ph\1307.6878]

The asymmetry



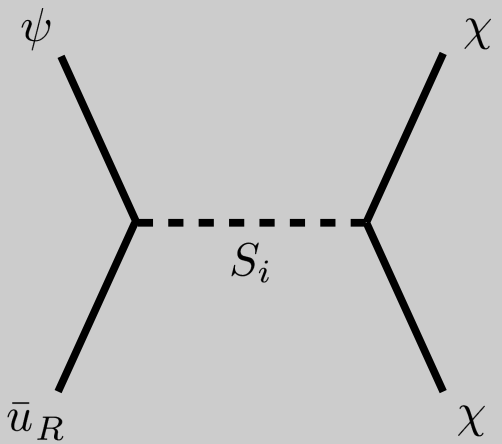
$$\epsilon = \frac{\int d\Pi_{out}\tilde{\delta}\left(|c_0\mathcal{A}_0 + c_1\mathcal{A}_1|^2 - |c_0^*\mathcal{A}_0 + c_1^*\mathcal{A}_1|^2\right)}{2\int d\Pi_{out}\tilde{\delta}|c_0\mathcal{A}_0|^2} = \frac{2\mathrm{Im}(c_0c_1^*)\int d\Pi_{out}\tilde{\delta}\mathrm{Im}(\mathcal{A}_0\mathcal{A}_1^*)}{|c_0|^2\int d\Pi_{out}\tilde{\delta}|\mathcal{A}_0|^2}$$

- The imaginary part of the interference has to be calculated with the **Cutkoski rules**, i.e. put particles in the loop on-shell.

Wash-outs

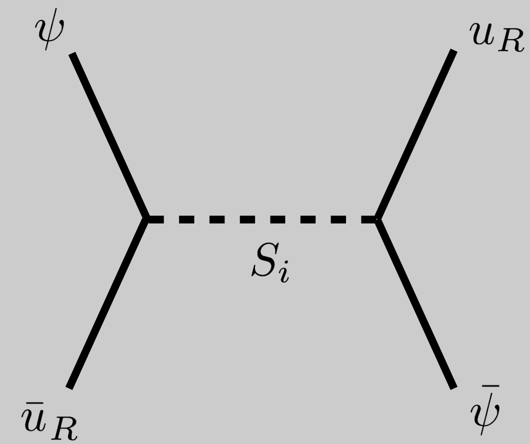
"If wash-out processes freeze out before WIMP freeze-out, then a large baryon asymmetry may accumulate."

Inverse annihilations



Boltzmann suppressed for $T < m_\chi$

Baryon-antibaryon scattering



Need exotic quark with $m_\psi > m_\chi$

DM annihilations kinematics

$m_\chi < m_\psi < 2m_\chi$

A closer look at our BE

The evolution of $B_{SM} - L$ is sphaleron-independent:

$$
\begin{aligned}
3szH\frac{dY_{B_{SM}-L}}{dz} \supset\ & \frac{Y_{S_1}}{Y^{eq}_{S_1}}\gamma(S_1 \to \bar\psi u_i) - \frac{Y_{\bar\psi}}{Y^{eq}_{\bar\psi}}\frac{Y_{u_1}}{Y^{eq}_{u_1}}\gamma(\bar\psi u_i \to S_1) \\
& -\frac{Y_{S_1}}{Y^{eq}_{S_1}}\gamma(S_1 \to \psi\bar u_i) + \frac{Y_{\psi}}{Y^{eq}_{\psi}}\frac{Y_{\bar u_1}}{Y^{eq}_{\bar u_1}}\gamma(\psi\bar u_i \to S_1) \\
& +2\frac{Y_{\bar u_i}}{Y^{eq}_{\bar u_i}}\frac{Y_{\psi}}{Y^{eq}_{\psi}}\gamma'(\bar u_i\psi \to \bar\psi u_i) - 2\frac{Y_{\psi}}{Y^{eq}_{\psi}}\frac{Y_{u_i}}{Y^{eq}_{u_i}}\gamma'(\bar\psi u_i \to \bar u_i\psi) \\
& +\left(\frac{Y_\chi}{Y^{eq}_\chi}\right)^2[\gamma'(\chi\chi \to \bar\psi u_i) - \gamma'(\chi\chi \to \psi\bar u_i)] \\
& -\frac{Y_{\bar\psi}}{Y^{eq}_{\bar\psi}}\frac{Y_{u_i}}{Y^{eq}_{u_i}}\gamma'(\bar\psi u_i \to \chi\chi) + \frac{Y_{\psi}}{Y^{eq}_{\psi}}\frac{Y_{\bar u_i}}{Y^{eq}_{\bar u_i}}\gamma'(\psi\bar u_i \to \chi\chi)
\end{aligned}
$$

1) $m_{S_2} \gg m_{S_1}$ → only S_1 can be produced on-shell.

2) S_1 is coupled only to one flavour of quarks.

3) Introduce γ' = total rates with the **on-shell part subtracted**.

$$\gamma'(\bar{u}_i\psi \to \bar{\psi}u_i) = \gamma(\bar{u}_i\psi \to \bar{\psi}u_i) - \gamma(\bar{u}_i\psi \to S_1)Br(S_1 \to \bar{\psi}u_i)$$
$$\gamma'(\chi\chi \to \bar{\psi}u_i) = \gamma(\chi\chi \to \bar{\psi}u_i) - \gamma(\chi\chi \to S_1)Br(S_1 \to \bar{\psi}u_i)$$

4) Switch to "orthogonal" basis:

$$y_x = \frac{Y_x - Y_{\bar{x}}}{Y_x^{eq}}$$ → first order in the asymmetry

$$x_x = \frac{Y_x + Y_{\bar{x}}}{Y_x^{eq}}$$ → =2 if particle in equilibrium

5)

CPT invariance

$$\mathcal{M}(i \to j) = \mathcal{M}(\bar{j} \to \bar{i})$$

Unitarity

$$\sum_j |\mathcal{M}(i \to j)|^2 = \sum_j |\mathcal{M}(j \to i)|^2$$

$$\Delta\gamma(u_i\bar{\psi} \to \bar{u}_i\psi) + \Delta\gamma(u_i\bar{\psi} \to \chi\chi) = 0$$
$$\Delta\gamma(\chi\chi \to \bar{\psi}u_i) = \Delta\gamma(u_i\bar{\psi} \to \bar{u}_i\psi)$$

6) Further simplifications:
- 3-body decays neglected;
- processes with 2 heavy particles subdominant in the WOs;
- $m_{S_1} \gg m_\chi$ → neglect rates with external S.

$$3szH\frac{dY_{B_{SM-L}}}{dz} = [(\frac{Y_\chi}{Y_\chi^{eq}})^2 - x_\psi]\Delta\gamma(\chi\chi \to \bar{\psi}u_i) - (y_{Q_i} + y_H - y_\psi)\gamma(\psi \to HQ_i)$$
$$-(x_\psi y_{u_i} - y_\psi)[2\gamma(\bar{u}_i\psi \to \bar{\psi}u_i) + \gamma(\chi\chi \to \bar{\psi}u_i)]$$
$$-(\frac{Y_x}{Y_x^{eq}}y_{u_i} - \frac{Y_\chi}{Y_\chi^{eq}}y_\psi)\gamma(\chi u_i \to \chi\psi)$$

$$szH\frac{dY_\chi}{dz} = -4[(\frac{Y_\chi}{Y_\chi^{eq}})^2 - x_\psi]\gamma(\chi\chi \to \bar{\psi}u_i)$$

$$\frac{1}{2}szH\frac{dY_{\psi+\bar{\psi}}}{dz} = -[x_\psi - (\frac{Y_\chi}{Y_\chi^{eq}})^2]\gamma(\chi\chi \to \psi\bar{u}_i) - 2(x_\psi^2 - 1)\gamma(u_iu_i \to \psi\psi)$$
$$-(x_\psi - 1)[\gamma(\psi \to HQ_i) + \frac{Y_\chi}{Y_\chi^{eq}}\gamma(\chi u_i \to \chi\psi)]$$

Issue: back to our BE for $B_{SM} - L$

$$szH\frac{dY_{B_{SM}-L}}{dz} \supset 2\frac{Y_\psi - Y_{\bar\psi}}{Y_\psi^{eq}}\gamma(\bar u_i\psi \to \bar\psi u_i)$$

Since $B_{SM} + B_\psi - L$ is conserved:

$$Y_\psi - Y_{\bar\psi} = -Y_{B_{SM}-L}$$

$$szH\frac{dY_{B_{SM}-L}}{dz} \supset -\frac{Y_{B_{SM}-L}}{Y_\psi^{eq}}\gamma(\bar u_i\psi \to \bar\psi u_i)$$

No Boltzmann suppression
→ asymmetry washed-out
(independently of how heavy is ψ)

The actual model

New features:

2nd vector quark

Third scalar quark

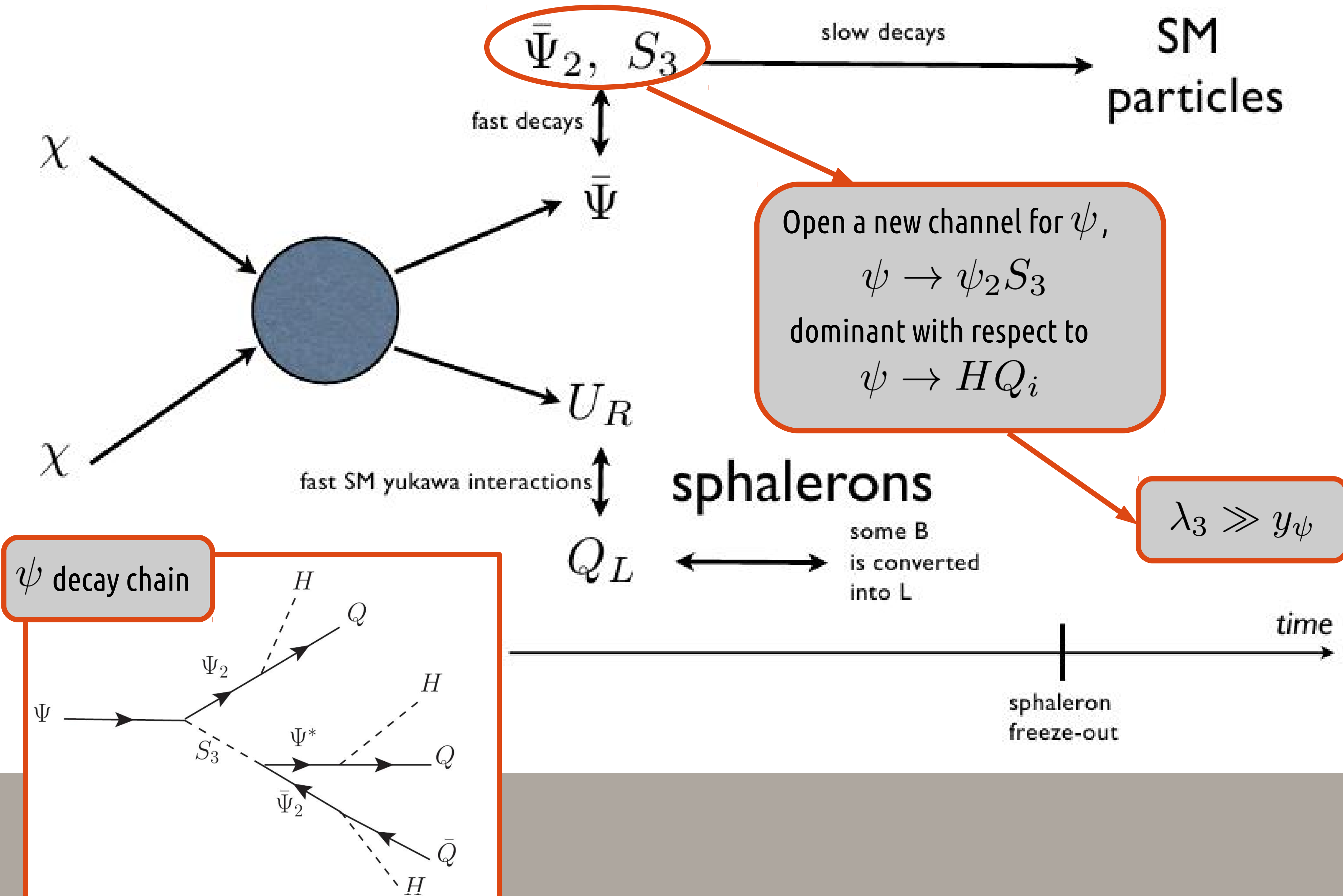
	$SU(3)$	$SU(2)_L$	$Q_{U(1)_y}$	$Q_{U(1)_B}$	Z_2
χ	1	1	0	0	-1
Ψ	3	1	$+2/3$	$+1/3$	$+1$
Ψ_2	3	1	$+2/3$	$+1/3$	$+1$
$P_L Q$	3	2	$+1/6$	$+1/3$	$+1$
$P_R U$	3	1	$+2/3$	$+1/3$	$+1$
$S_{1,2,3}$	1	1	0	0	$+1$
H	1	2	$+1/2$	0	$+1$

→ Additional terms in the Lagrangian:

$$\mathcal{L} \supset \lambda_3 S_3 \bar{\psi}\psi_2 + y_{\psi_2}\tilde{H}\bar{Q}P_R\psi_2$$

Why bother ?

Some pictorial might help...



Thanks to the new conservation law

$$(Y_\psi - Y_{\bar\psi}) + (Y_{\psi_2} - Y_{\bar\psi_2}) + Y_{B_{SM}-L} = 0$$

the wash-out is now Boltzmann suppressed:

$$szH\frac{dY_{B_{SM}-L}}{dz} \supset -\frac{1}{(m_{\psi_2}/m_\psi)^{\frac{3}{2}}e^{(m_\psi - m_{\psi_2})/T}+1}\frac{Y_{B_{SM}}}{Y_\psi^{eq}}\gamma(\bar{u}_i\psi \to \bar\psi u_i)$$

→ Wash-out freeze-out happens before DM freeze-out.

Restriction: kinematics for annihilation and decays require the **mass hierarchy**

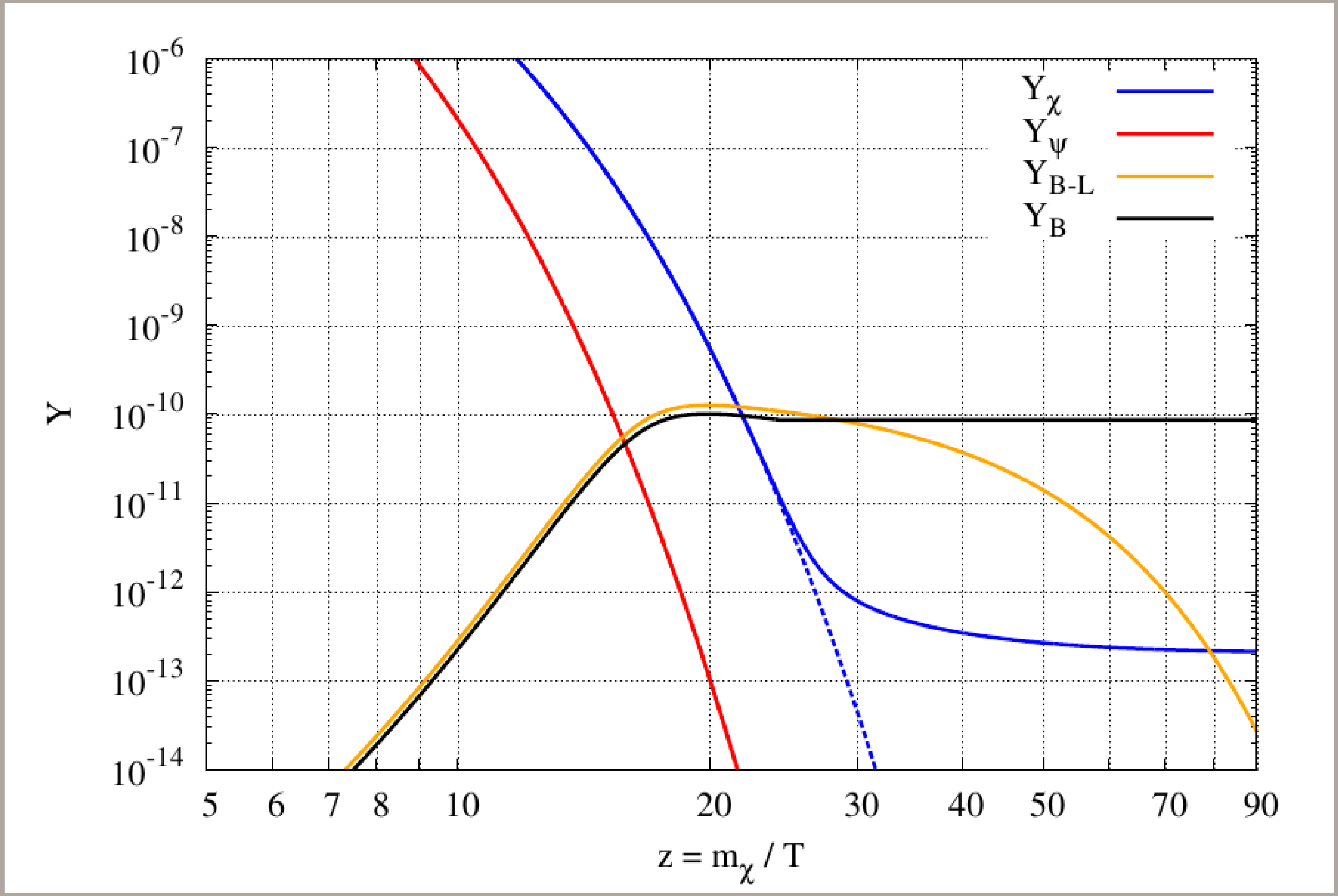
$$2m_\chi > m_\psi > m_{S_3} > m_{\psi_2} > 0.8\ (\mathrm{TeV})$$

Numerical results

1) We find some benchmark points for successful baryogenesis in the parameter space for masses and couplings. Here:

$$m_\chi = 2\ ,\ m_\psi = 3.1\ ,\ m_{S_1} = 5\ ,\ m_{S_2} = 5 \quad \text{(TeV)}$$

$$\lambda_{X_1} = 0.48\ ,\ \lambda_{X_2} = 0.48\ ,\ \lambda_{B_1} = 0.7\ ,\ \lambda_{B_2} = 0.7\ ,\ y_\psi = 5 \times 10^{-4}$$



Costraints

Collider searches: bounds on vector-like quarks from LHC require
(F.J.Botella, G.C.Branco, M.Nebot 1207.4440)

$$m_{\psi_2} > 800 \text{ GeV}$$

Direct detection: to achieve BAU, the resulting costraints on couplings are too mild.

Indirect detection: apparently nothing stringent, we're still thinking about it.

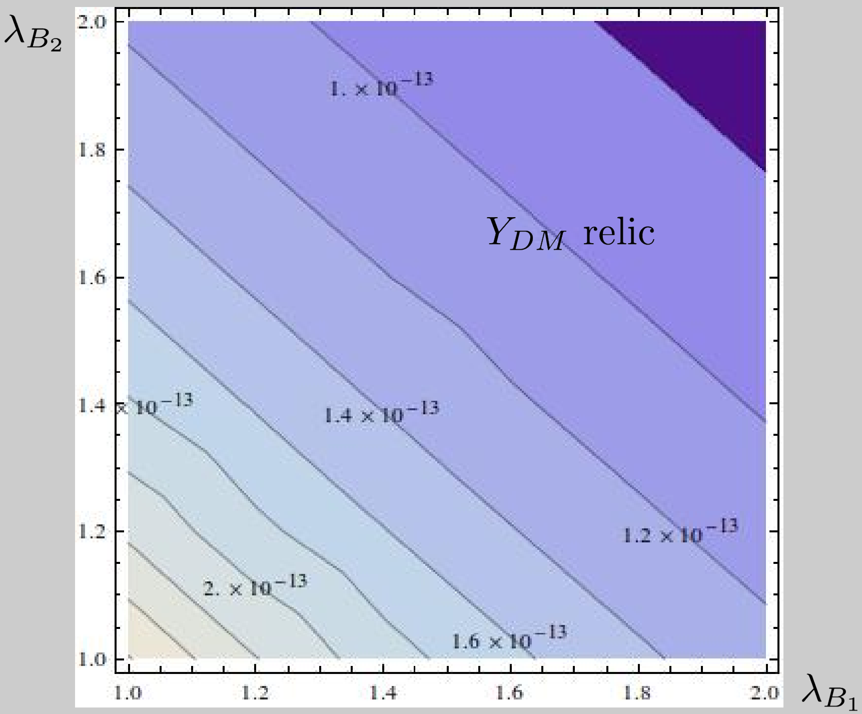
EDM: Loops contributing to EDMs are helicity preserving with an even number of Yukawa → 1L diagrams are complex conjugates of one another.

Outlook

1) Perform scans in the parameter space in a wider range of values.
2) Analysis of the **resonant case** , where $m_{S_1} - m_{S_2} = \Gamma/2$ the asymmetry is enhanced:

$$|\epsilon| \simeq |\mathrm{Im}(\lambda^*_{B_1}\lambda_{B_2})|/(2\lambda^2_{B_1}\lambda^2_{B_2})$$

3) Indirect detection constraints.



Merci de votre attention !