Phenomenology of WIMPy baryogenesis models

based on NB, François-Xavier Josse-Michaux and Lorenzo Ubaldi

To appear soon...

Nicolás BERNAL
Bethe Center for Theoretical Physics and Physikalisches Institut
Universität Bonn

Corfu Summer Institute, September 21st, 2012

Evidences for Dark Matter

Several observations indicate existence of non-luminous Dark Matter (missing force) at very different scales!

* **Galactic rotation curves**

* **Clusters of galaxies**

* **CMB anisotropies**

DM is there!
What is DM?

WIMPs

* Weakly interacting
* Neutral (electric charge & color)
* Stable or at least long-lived
* Massive enough

Baryon Asymmetry

* Observations: The lack of antimatter
  - Matter and antimatter annihilate when they meet.
  - Cannot have much antimatter 'nearby' (clusters of galaxies)

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  Difficult to separate matter & antimatter on cluster lenght scales.

  The most reasonable conclusion: **The Universe at early times possessed a (very tiny) asymmetry between baryons and antibaryons**

Motivations

* Dark Matter (DM) relic abundance

  Thermal relic density of a particle with weak scale mass and couplings

  $\Omega_{DM}h^2 = 0.1123 \pm 0.0035$

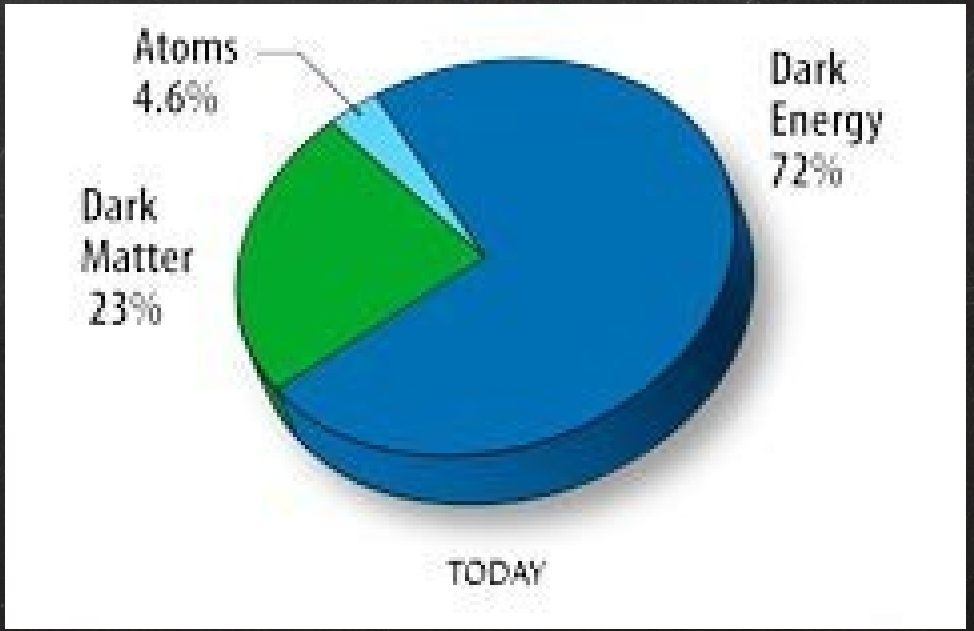
* Baryonic Mater abundance

  Baryonic matter abundance is determined by a matter-antimatter asymmetry

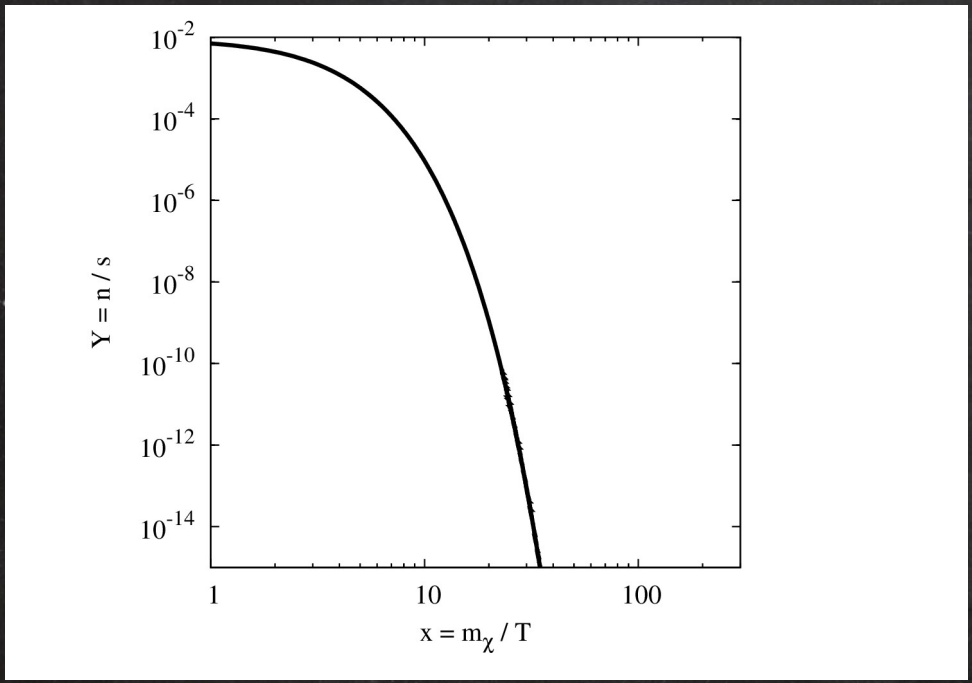
  $\Omega_{B}h^2 = 0.02260 \pm 0.00053$

* $\Omega_{DM} / \Omega_{B} \sim 5$

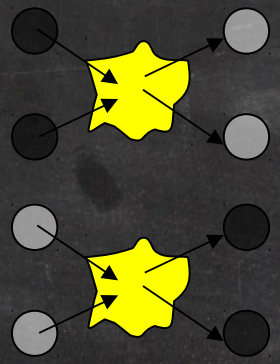
  In conventional WIMP picture, asymmetry generation and dark matter annihilation are independent processes



WIMPs: thermal production

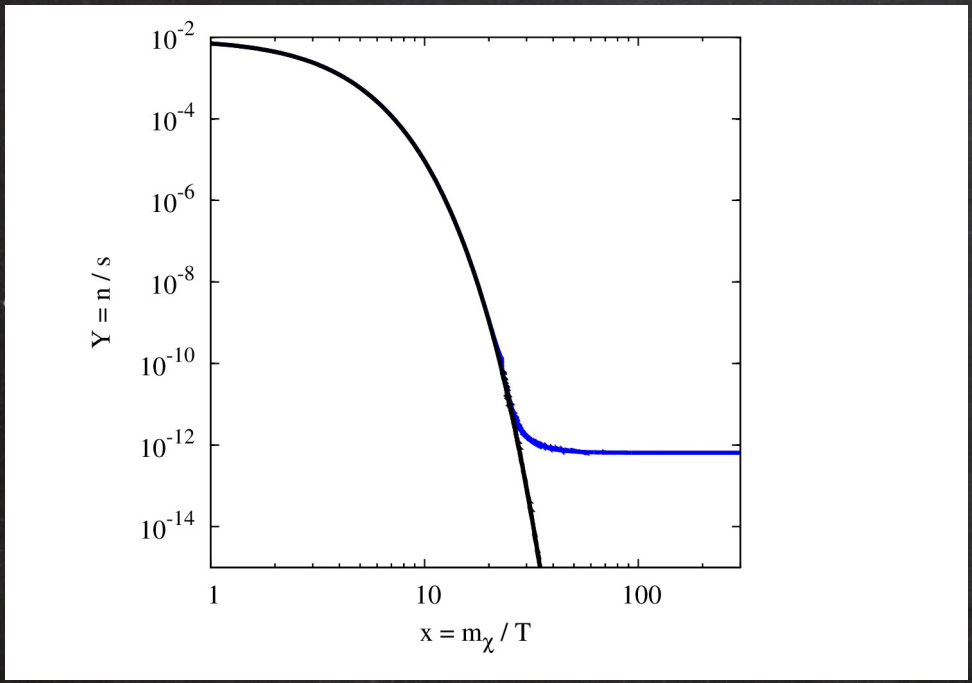


Thermal equilibrium

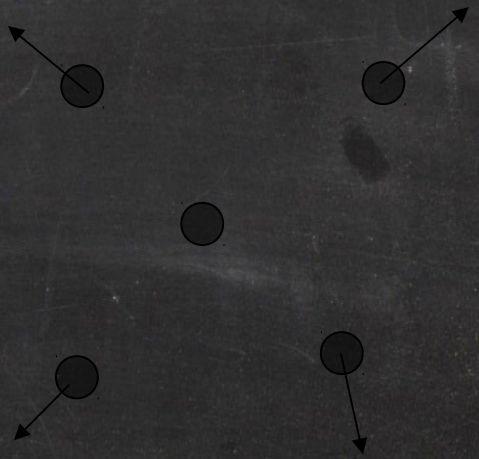


The number density of DM decreases with time.

WIMPs: thermal production

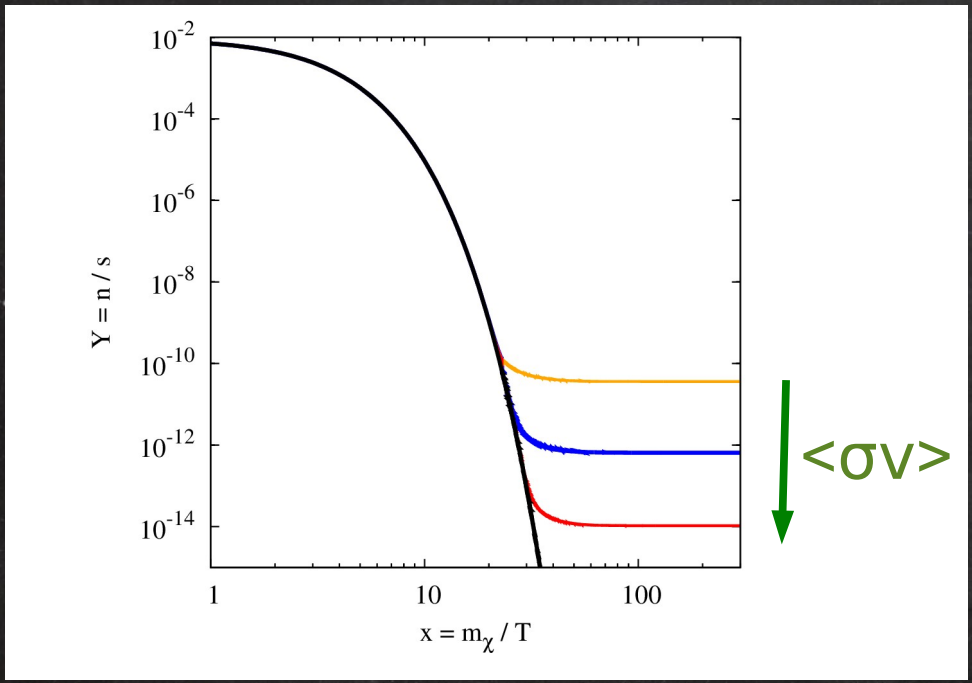


Due to the expansion of the Universe DM particles **fall out of equilibrium** and cannot annihilate any more.



A Relic Density of DM is obtained which remains constant.

WIMPs: thermal production



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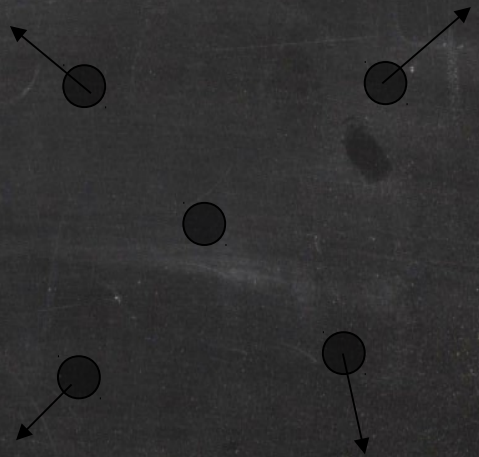

A particle with very weak interactions decouples earlier, having a larger relic density.

A Relic Density of DM is obtained which remains constant.

A particle with stronger interactions keeps in equilibrium for longer, and is more diluted.

$\langle\sigma v\rangle = 3 \cdot 10^{-26}\ \mathrm{cm}^3 / \mathrm{s}$

Generation of the Baryon Asymmetry: Sakharov conditions

* B-number violation

If baryon number is conserved, the BAU can only reflect asymmetic initial conditions.

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The interactions which produce more baryons than antibaryons will not be counterbalanced by interactions which produce more antibaryons than baryons.

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If baryon number is conserved, the BAU can only reflect asymmetic initial conditions.

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* Departure from thermal equilibrium

Otherwise compensation between processes increasing and decreasing the baryon number.

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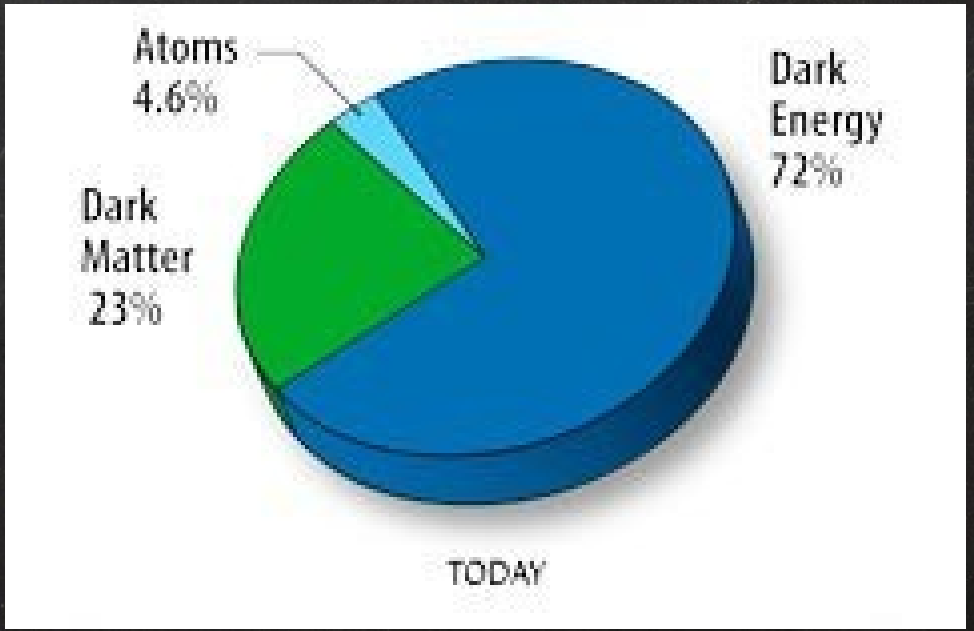

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Independently determined? Common origin?

It seems natural to consider models where the **Dark Matter** and the **Baryon Asymmetry of the Universe** (BAU) share a common origin.

Asymmetric Dark Matter...

* DM abundance is determined by a matter-antimatter asymmetry in a dark sector, which in turn is connected to the baryon asymmetry in the visible sector.

* DM relic density is set by the baryon asymmetry and not by the properties of thermal freeze-out

Hooper, March-Russel & West '04; Farrar & Zaharijas '05; Kitano, Murayama & Ratz '08; Kaplan, Luty & Zurek '09; Cohen & Zurek '09; Cai, Luty & Kaplan '09; An, Chen, Mohapatra & Zhang '09; Cohen, Phalen, Pierce & Zurek '10; Shelton & Zurek '10; Davoudiasi, Morrissey, Sigurdson & Tulin '10; Haba & Matsumoto '10; Chun '10; Gu, Lindner, Sarkar & Zhang '10; Blennow, Dasgupta, Fernández-Martínez & Rius '10; Allahverdi, Dutta & Sinha '10; Dutta & Kumar '11; Falkowski, Ruderman & Volanski '11; Buckley '11; Iminniyaz, Drees & Chen '11; March-Russel & McCullough '11; Davoudiasl, Morrisey, Sigurdson & Tulin '11; Cui, Randall & Shuve '11; Arina & Sahu '11; Blum, Efrati, Grossman, Nir & Riotto '12; Tulin, Yu & Zurek '12; Davoudiasl & Mohapatra '12, Feng, Nath & Peim '12; Ellwanger & Mitropoulos '12; Okada & Seto '12…

… but also Symmetric Dark Matter

It's also possible to have some features of **symmetric** DM while also establishing a connection between the DM and baryon abundances

DM annihilation generates a baryon asymmetry

* Baryomorphosis
  McDonald, 1009.3227 and 1108.4653

* Dark Matter Assimilation
  D'Eramo, Fei & Thaler, 1111.5615

* Wimpy Baryogenesis
  Cui, Randall & Shuve, 1112.2704

A WIMPy baryogenesis miracle

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  Conventional WIMP DM at weak-scale, thermal relic abundance

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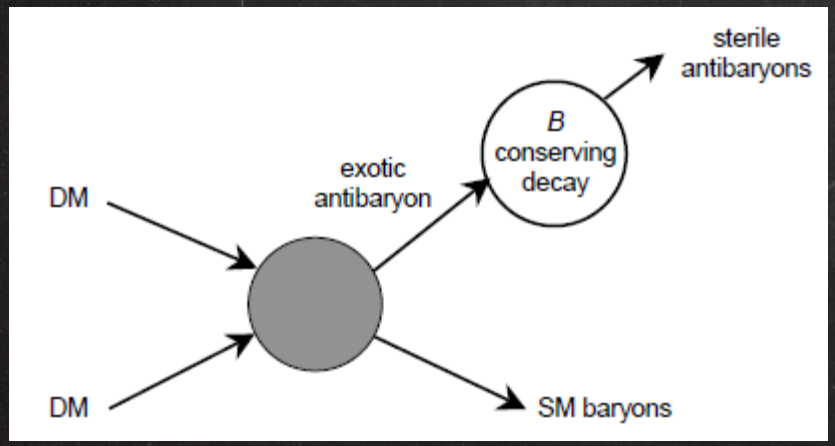

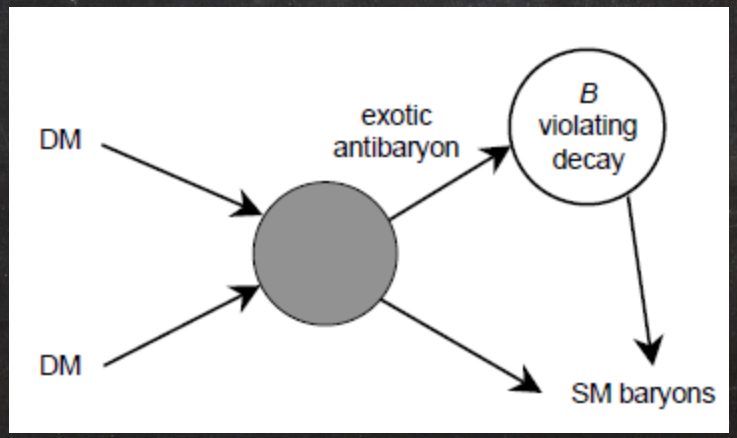

Our approach: Effective Field Theory

* WIMP 'miracle'
  Conventional WIMP DM at weak-scale, thermal relic abundance

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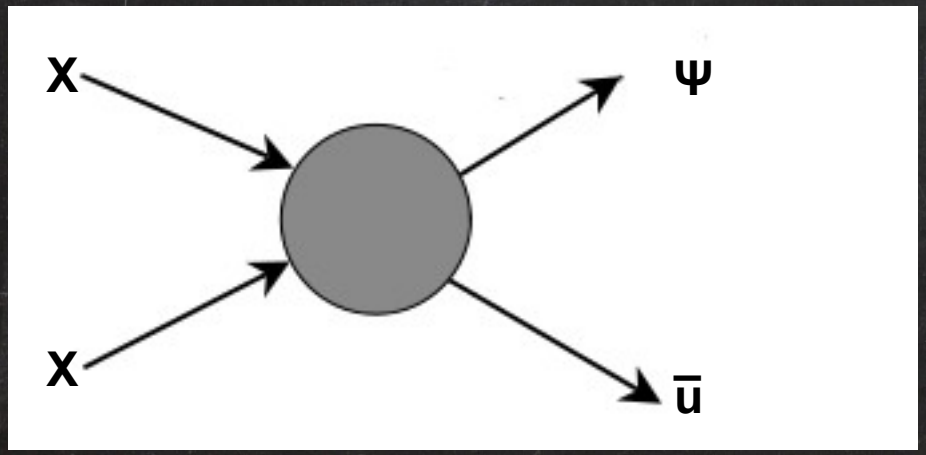

Effective Lagrangian:
dimension 6 operators

$$\mathcal{L} \supset \frac{1}{\Lambda^2} \sum_i \lambda_i^2 \mathcal{O}_i .$$

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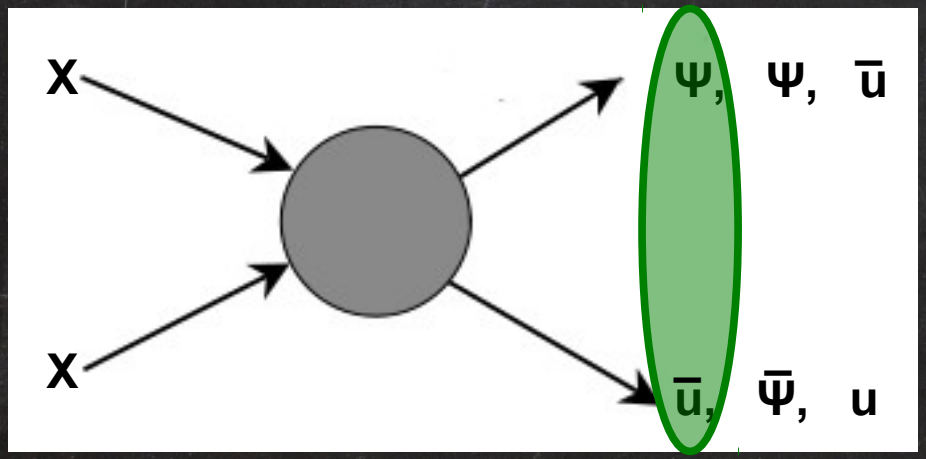

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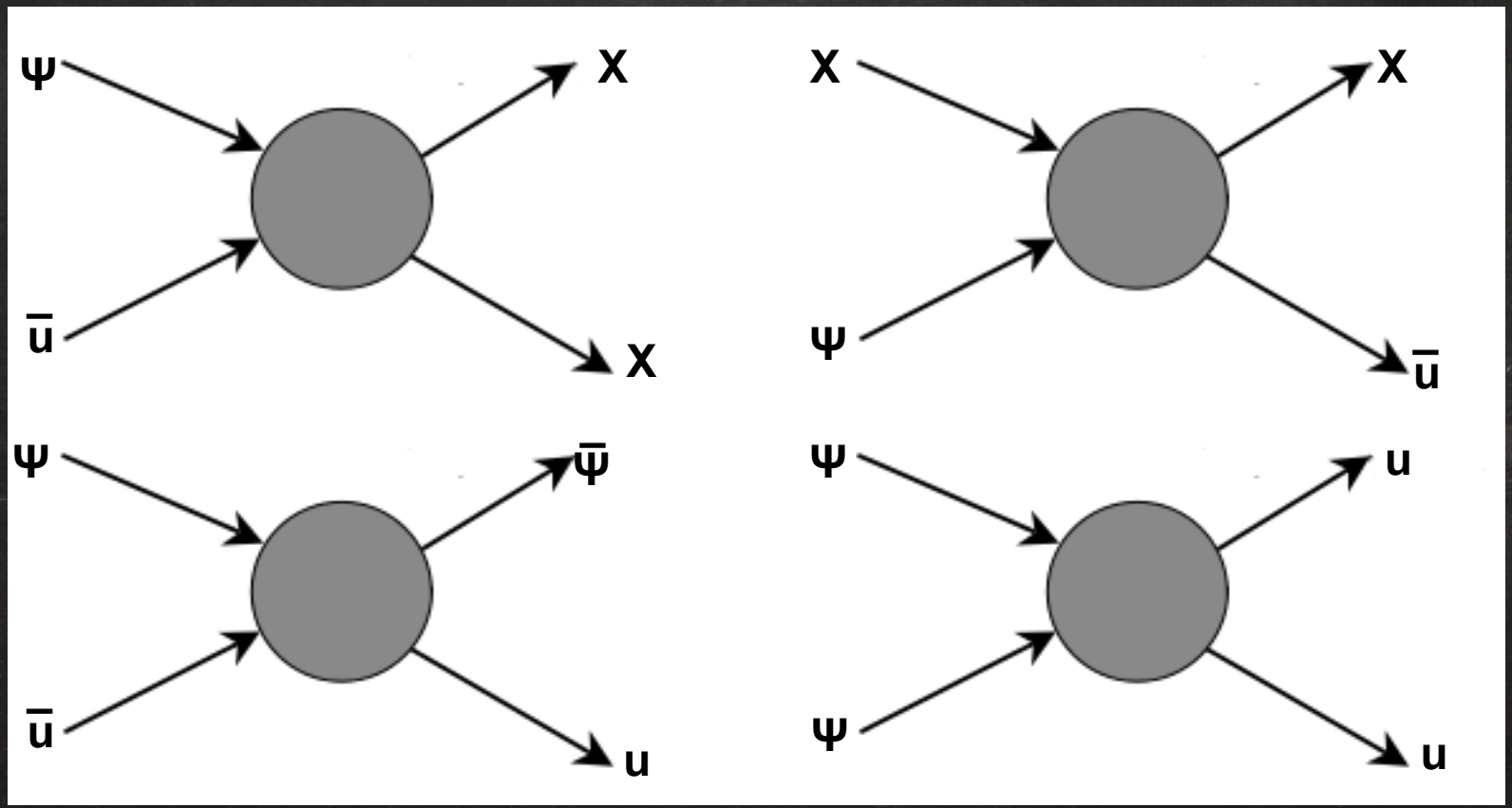
* Washout processes
  - DM annihilation are also source of washout
  - Pure washout processes



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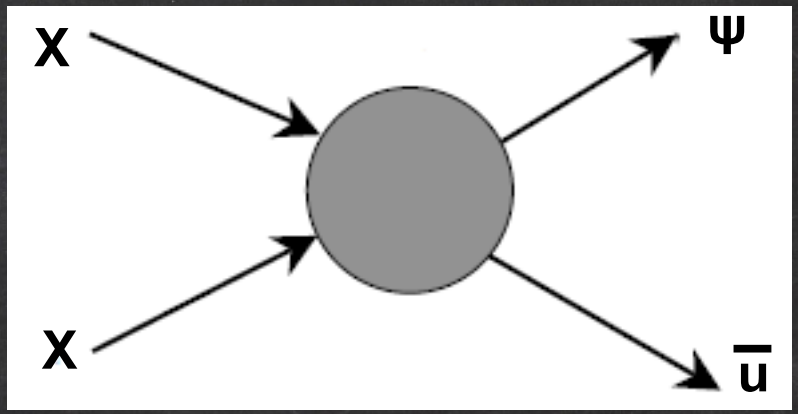
* Particle content



$\Psi \rightarrow \bar{d}\,\bar{d}\,n$

X: WIMP
Dirac fermion

Ψ: 'exotic quark'
color triplet
vector-like pair
anomaly-cancellations
$m_\psi \geq 800$ GeV

n: sterile singlet
massless

* X stable
* $XX \rightarrow \psi\,\bar{u}$

Minimal solution: **Z_4 symmetry**

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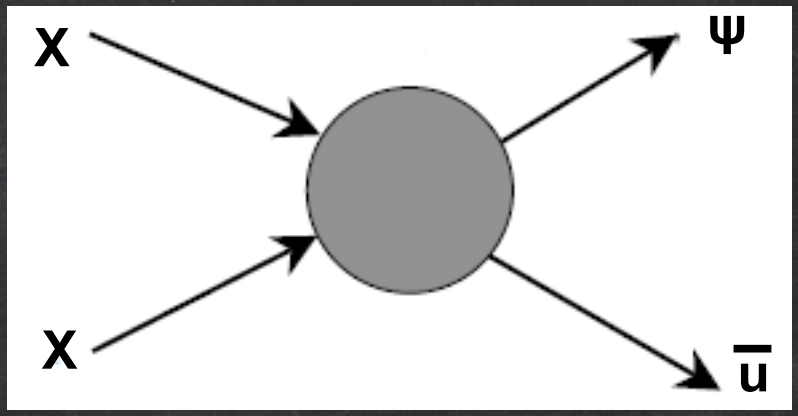

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	$SU(3)_c$	$SU(2)_L$	$Q_{U(1)_y}$	$Q_{U(1)_B}$	$\mathbb{Z}_4$
X	1	1	0	0	$+i$
$\bar{X}$	1	1	0	0	$-i$
ψ	3	1	$+2/3$	$+1/3$	-1
$\bar{\psi}$	$\bar{3}$	1	$-2/3$	$-1/3$	-1
n	1	1	0	0 or $+1$	-1
$\bar{u}$	$\bar{3}$	1	$-2/3$	$-1/3$	$+1$
$\bar{d}$	$\bar{3}$	1	$+1/3$	$-1/3$	$+1$

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* Effective Lagrangian, dim 6 operators

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DM annihilation + washout: XX → ψ ū

$$\lambda_1^2 (XX)(\psi\bar{u}) + \lambda_2^2 (\bar{X}\bar{X})(\psi\bar{u}) + \lambda_3^2 (X^\dagger X^\dagger)(\psi\bar{u}) + \lambda_4^2 (\bar{X}^\dagger \bar{X}^\dagger)(\psi\bar{u}) + \lambda_5^2 (\bar{X}^\dagger \bar{\psi}^\dagger)(X\bar{u}) + \lambda_6^2 (X^\dagger \bar{\psi}^\dagger)(\bar{X}\bar{u})$$

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DM annihilation into quarks: XX → ū u

$$\lambda_7^2 (X\bar{u})(X^\dagger \bar{u}^\dagger) + \lambda_8^2 (\bar{X}\bar{u})(\bar{X}^\dagger \bar{u}^\dagger)$$

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DM annihilation into exotic quarks: XX → ψ̄ ψ

$$\lambda_{13}^2 (X\bar{X})(\psi\bar{\psi}) + \lambda_{14}^2 (X^\dagger \bar{X}^\dagger)(\psi\bar{\psi}) + \lambda_{15}^2 (X\psi)(\bar{X}\bar{\psi}) + \lambda_{16}^2 (X^\dagger \bar{\psi}^\dagger)(X\bar{\psi}) + \lambda_{17}^2 (\bar{X}^\dagger \bar{\psi}^\dagger)(\bar{X}\bar{\psi}) + \lambda_{18}^2 (X^\dagger \psi^\dagger)(X\psi) + \lambda_{19}^2 (\bar{X}^\dagger \psi^\dagger)(\bar{X}\psi)$$

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Pure washout: ψ ψ→ u u

$$\lambda_9^2 (\psi \psi)(\bar{u} \bar{u}) + \lambda_{10}^2 (\psi \bar{u})(\psi^\dagger \bar{u}^\dagger) + \lambda_{11}^2 (\bar{\psi}^\dagger \bar{\psi}^\dagger)(\bar{u} \bar{u}) + \lambda_{12}^2 (\bar{\psi}^\dagger \bar{u}^\dagger)(\bar{\psi} \bar{u})$$

Our approach:

* Reasonable, simplifying assumptions

  λ_s coupling for all s-channel DM annihilation (into quark + exotic quark) operators

  λ_T coupling for all t-channel DM annihilation (into quark + exotic quark) operators

  λ_{wo} coupling for all pure washout operators

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λ_T coupling for all t-channel DM annihilation (into quark + exotic quark) operators

λ_{WO} coupling for all pure washout operators

and:
λ_7, λ_8 couplings for annihilation into quarks

λ_ψ coupling for annihilation into exotic quarks

Sakharov conditions

* B-number violation
  - Explicitly violated in DM annihilation

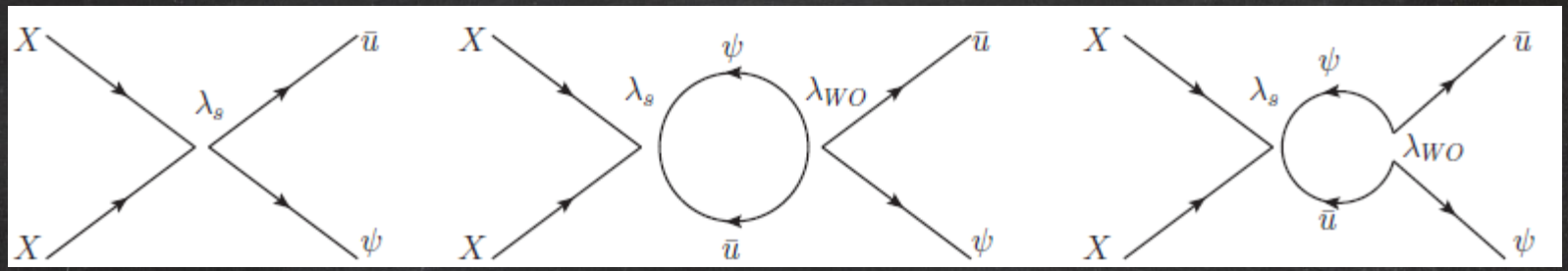
* C and CP violation
  - Physical CP phases in annihilation amplitudes
  - Interference of tree and loop diagrams

* Departure from thermal equilibrium
  - Provided by DM freeze-out

Generation of the asymmetry

$$\epsilon = \frac{\sigma(XX \to \psi\bar{u}) + \sigma(\bar{X}\bar{X} \to \psi\bar{u}) - \sigma(XX \to \psi^\dagger\bar{u}^\dagger) - \sigma(\bar{X}\bar{X} \to \psi^\dagger\bar{u}^\dagger)}{\sigma(XX \to \psi\bar{u}) + \sigma(\bar{X}\bar{X} \to \psi\bar{u}) + \sigma(XX \to \psi^\dagger\bar{u}^\dagger) + \sigma(\bar{X}\bar{X} \to \psi^\dagger\bar{u}^\dagger)}$$

For the s-channel we have:



Interference of tree and loop diagrams!
And a similar story for the s-channel operators...

$$\epsilon \propto \frac{\mathrm{Im}(\lambda_{WO}^2)}{\Lambda^2} \frac{(s - m_\psi^2)^2}{16\pi s}$$

Boltzmann equations

* DM density

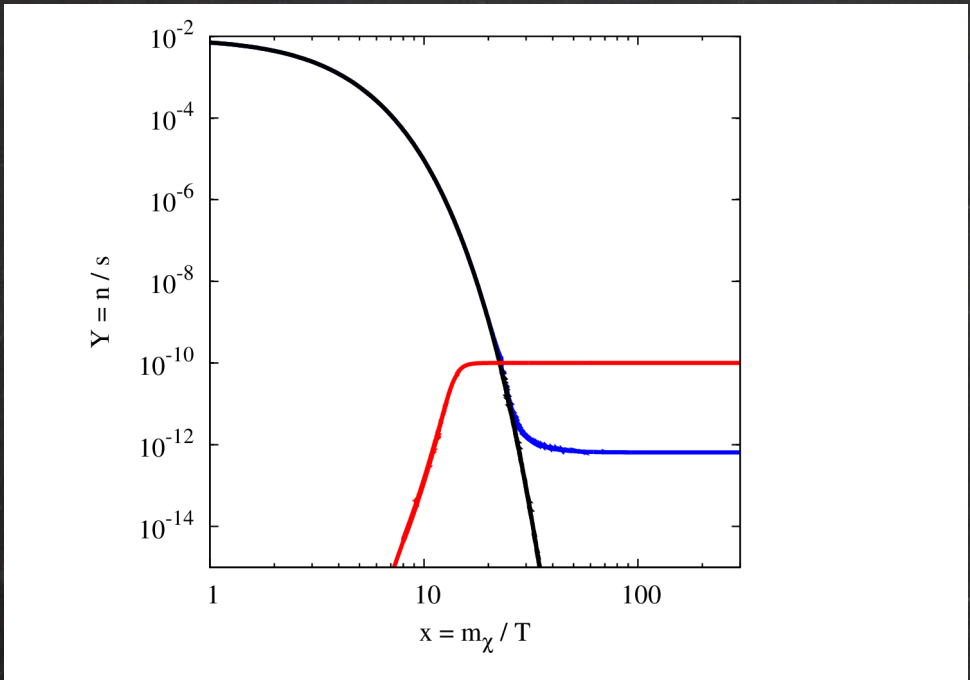
$$\frac{dY_X}{dx} = -\frac{2s(x)}{x\,H(x)}\,\langle\sigma_{\rm ann}v\rangle\,\left[Y_X^2 - (Y_X^{\rm eq})^2\right],$$

* Baryon asymmetry

$$\frac{dY_{\Delta B}}{dx} = \frac{\epsilon\,s(x)}{x\,H(x)}\,\langle\sigma_{\rm ann}v\rangle\,\left[Y_X^2 - (Y_X^{\rm eq})^2\right] - \frac{s(x)}{x\,H(x)}\,\langle\sigma_{\rm washout}v\rangle\,\frac{Y_{\Delta B}}{2Y_\gamma}\prod_i Y_i^{\rm eq}.$$

~ + ε · WIMP annihilation rate - $Y_{\Delta B}$ · washout rate

DM & BAU



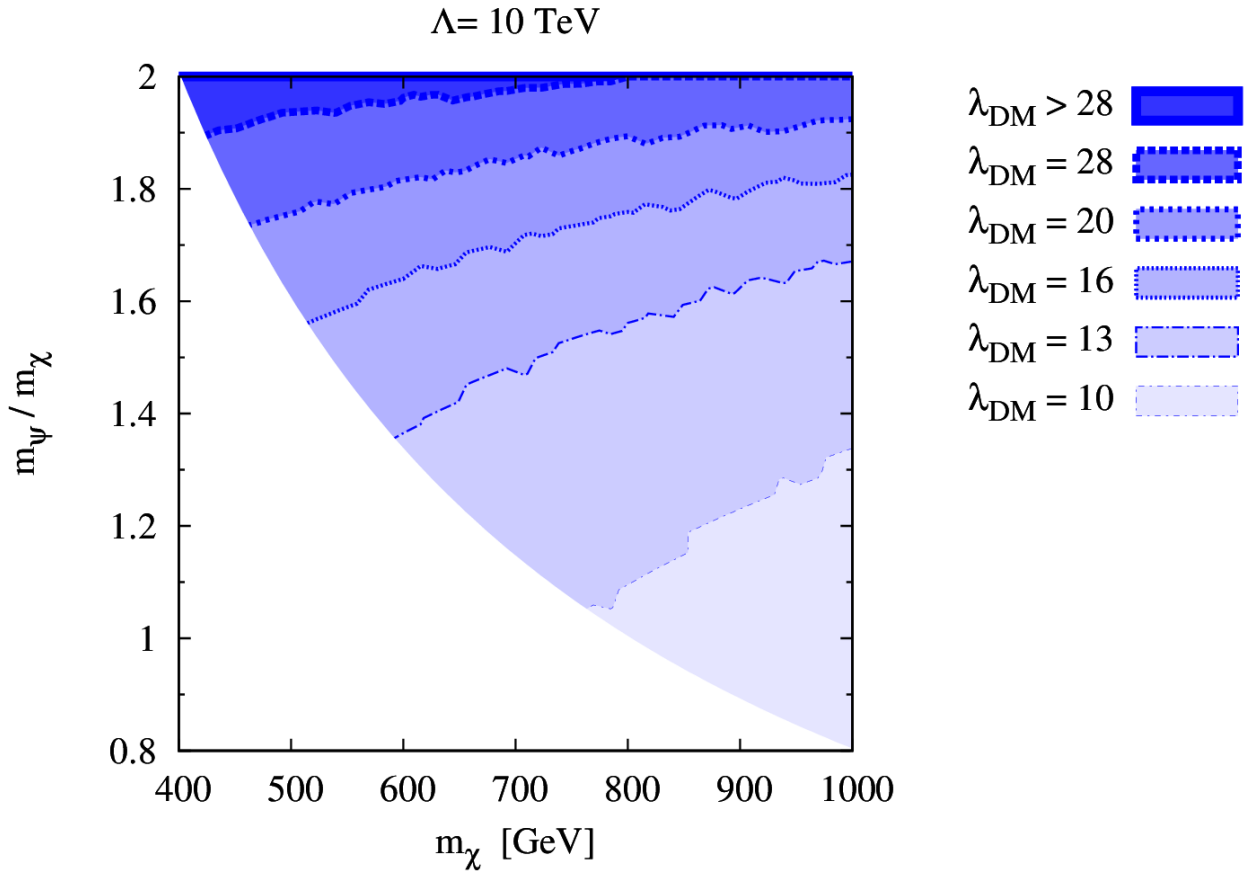
Washout plays a critical role!

"If washout processes freeze out before WIMP freezeout,
then a large baryon asymmetry may accumulate,
and its final value is proportional to the WIMP abundance
at the time that washout becomes inefficient."

$\sigma(\text{Washout}) \ll \sigma(\text{DM annihilation})$ or $m_\psi > m_\chi$

Cosmological bounds: DM

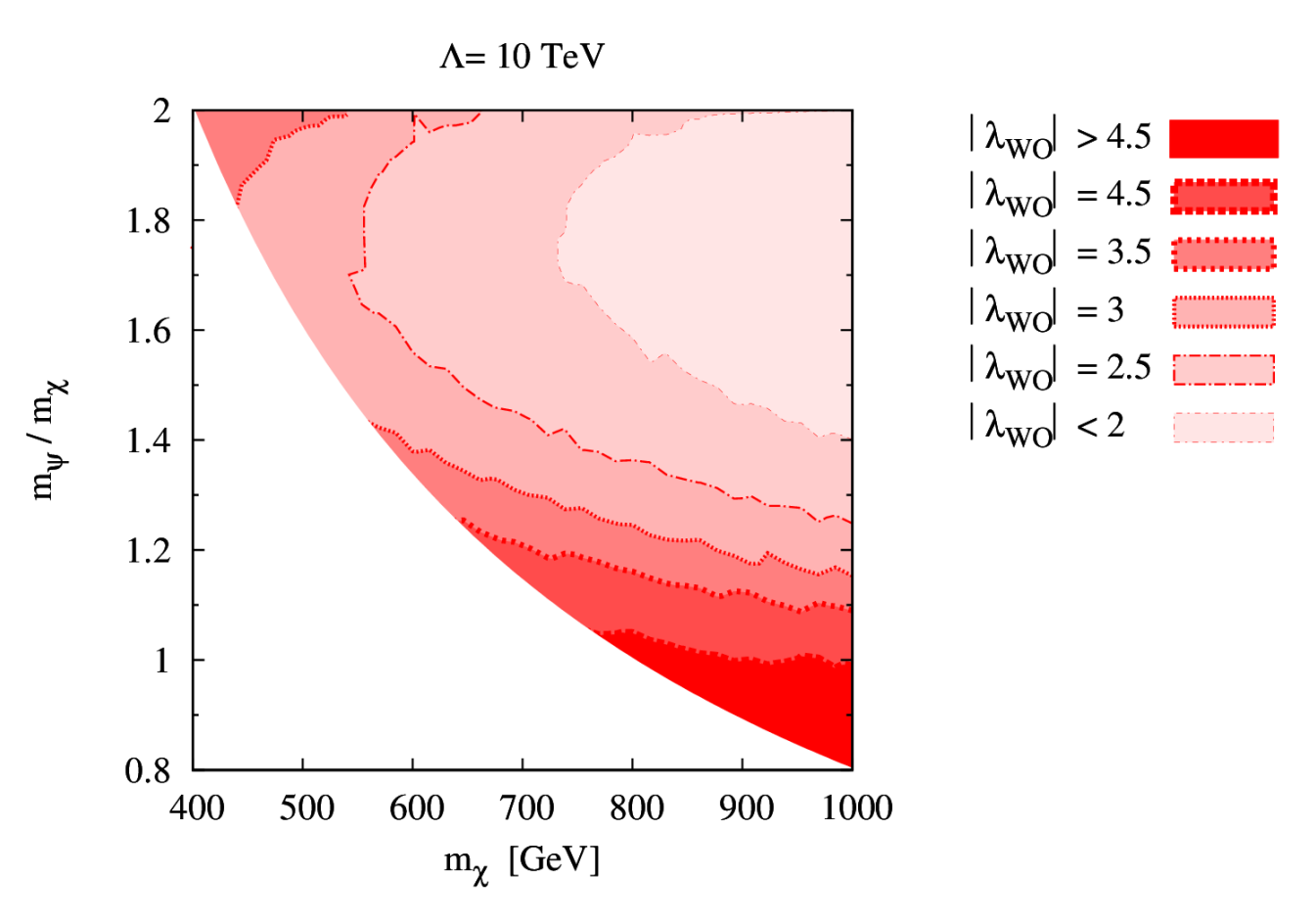
$\lambda_{DM} \equiv \lambda_S = \lambda_T$



Possible to accommodate WMAP measurements of the DM relic density...

Cosmological bounds: BAU

$\mathrm{Re}(\lambda_{WO}) = \mathrm{Im}(\lambda_{WO})$



Possible to accommodate WMAP measurements of the DM relic density...

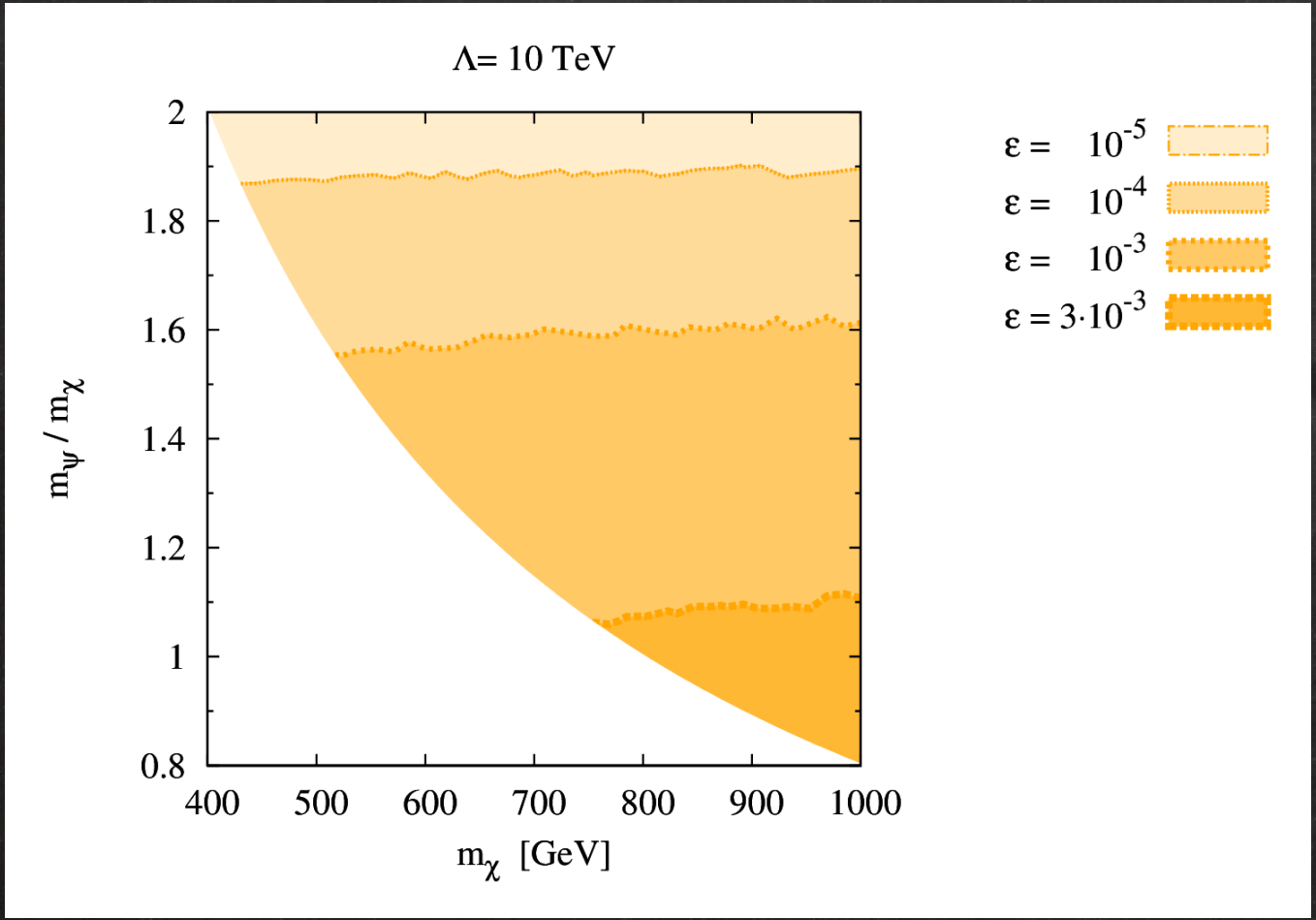
and the BAU

with order unity couplings and weak scale dark matter

with $\varepsilon \sim 10^{-3}$

Cosmological bounds: BAU

$\lambda_{WO} \equiv Re(\lambda_{WO}) = Im(\lambda_{WO})$



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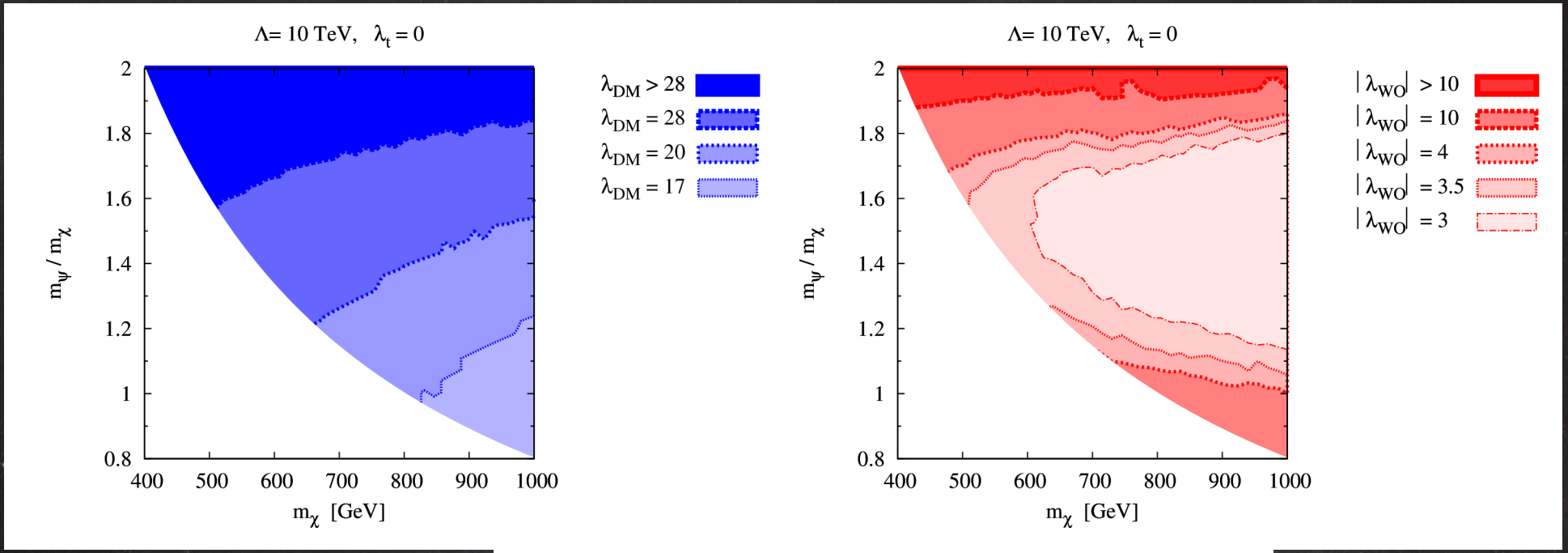
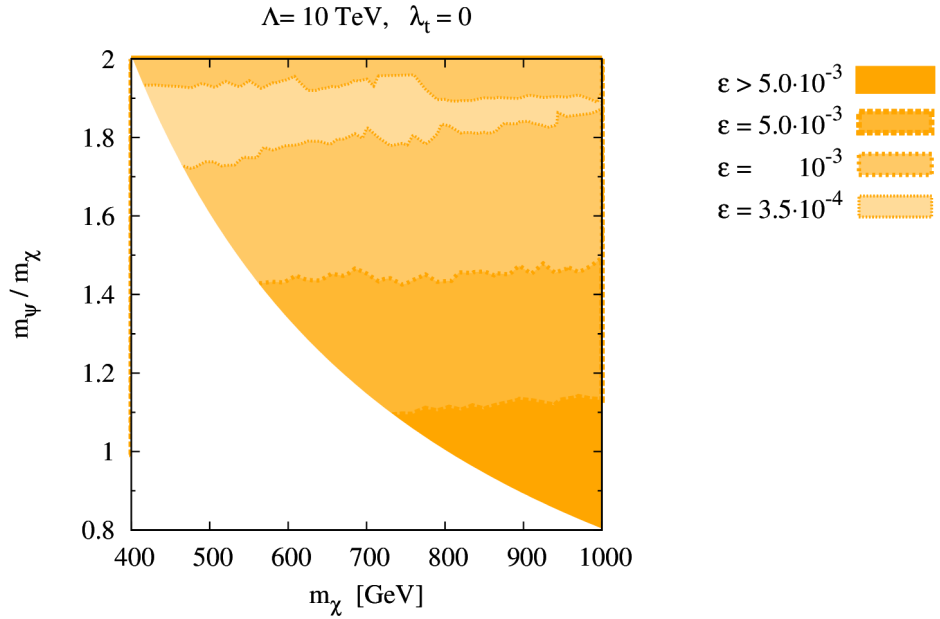
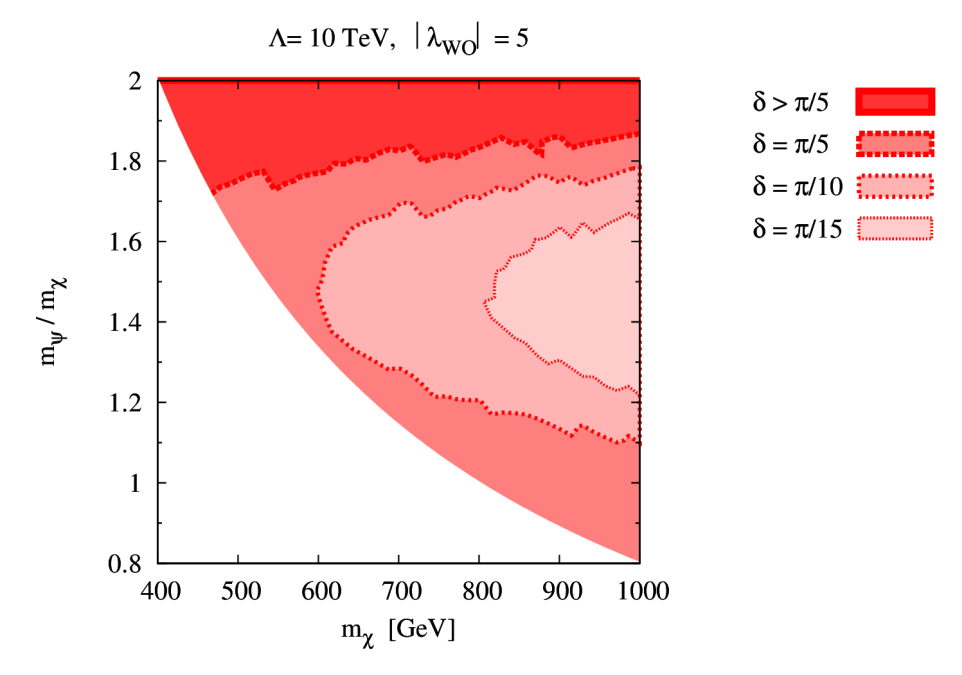
Cosmological bounds: s-channel

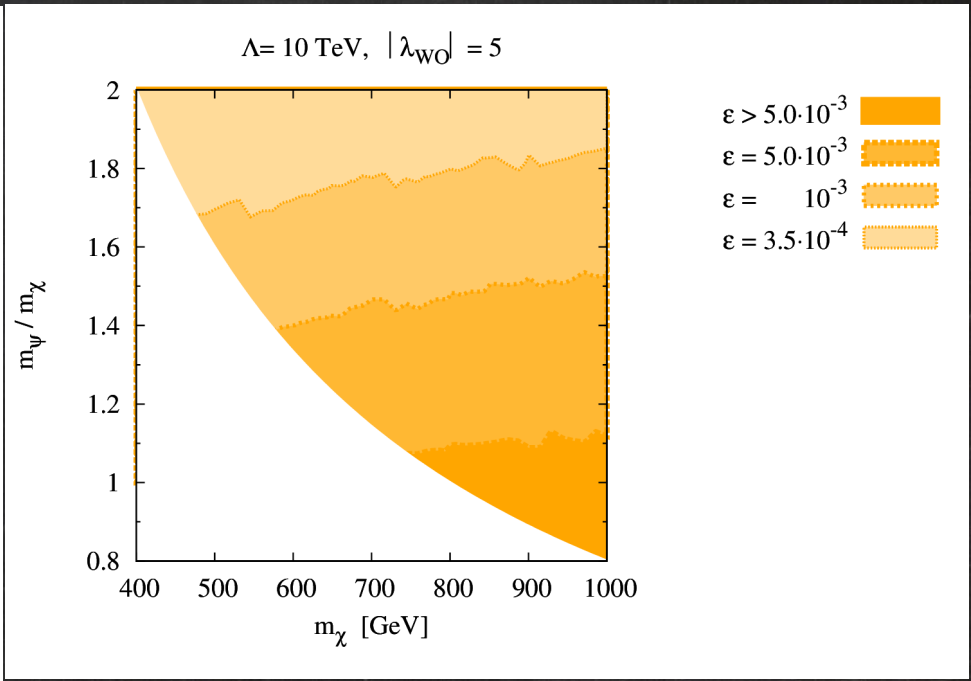




Cosmological bounds: CP-phase

$\lambda_{WO} \equiv |\lambda_{WO}| \, Exp[i\,\delta]$





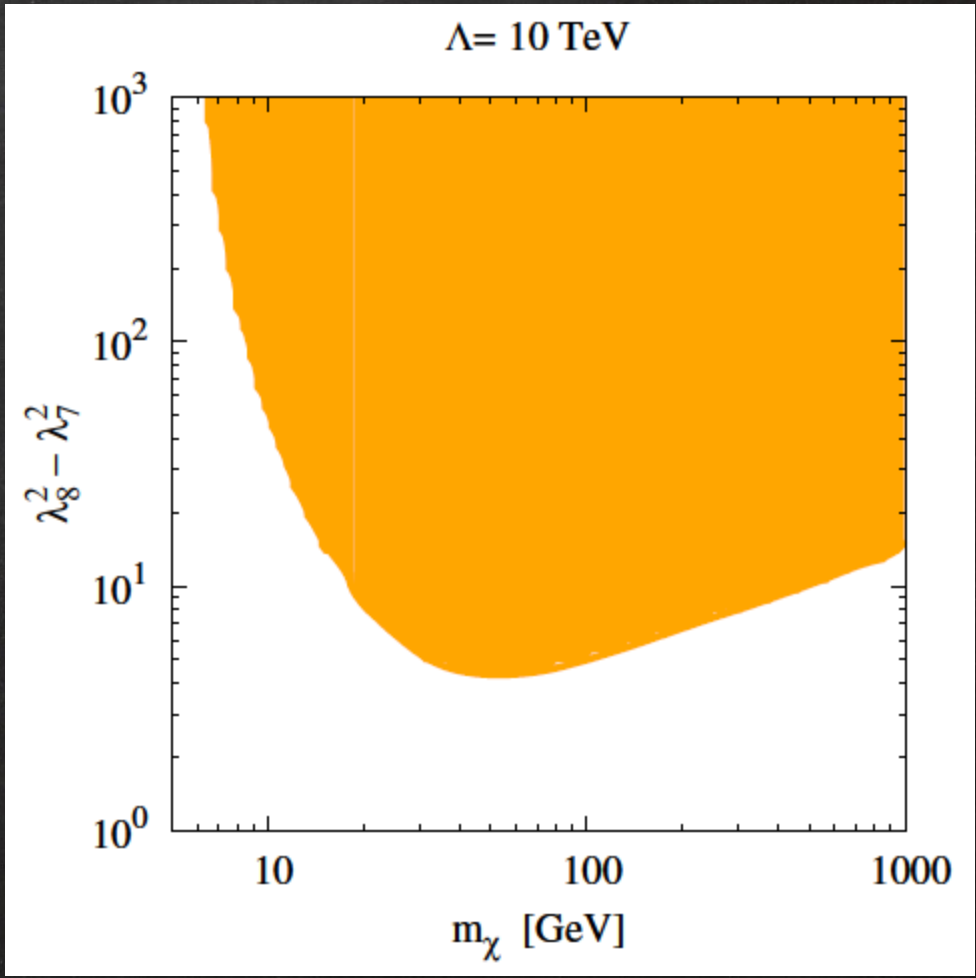
Direct detection bounds

$$\frac{1}{\Lambda^2}(\lambda_7^2(X\bar{u})(X^\dagger\bar{u}^\dagger)+\lambda_8^2(\bar{X}\bar{u})(\bar{X}^\dagger\bar{u}^\dagger)+\text{h.c.})$$

These operators contribute to
* DM annihilation into a pair of quarks
* to SI and SD direct detection already at tree level

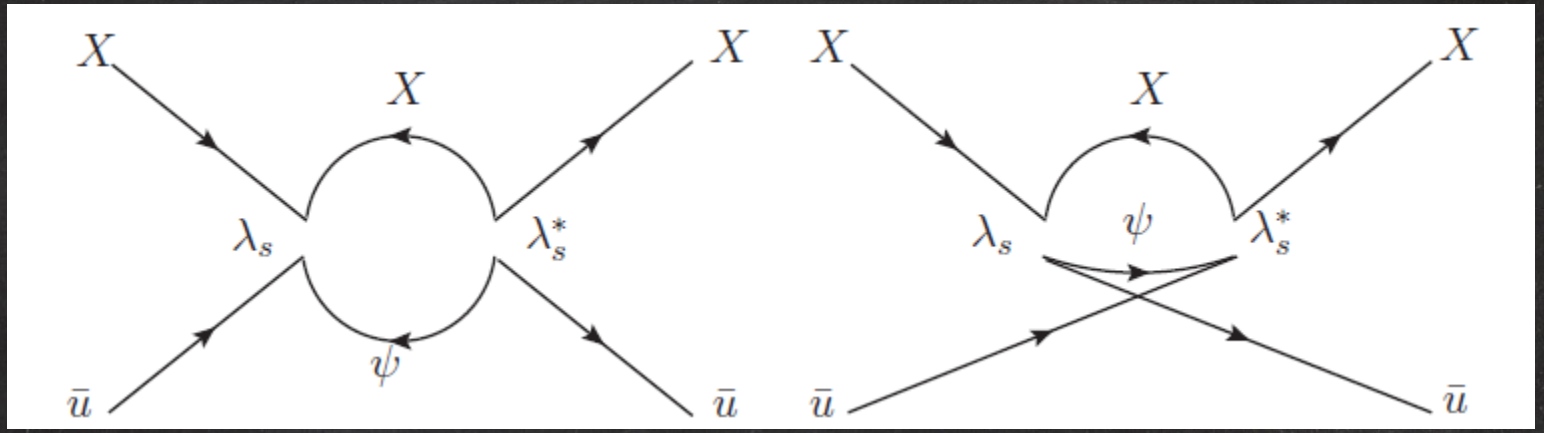
$\lambda_7, \lambda_8 < 1$

Xenon100 with 225 live days



Direct detection bounds

Can we constrain λ_s and λ_t looking at one-loop contributions to direct detection?

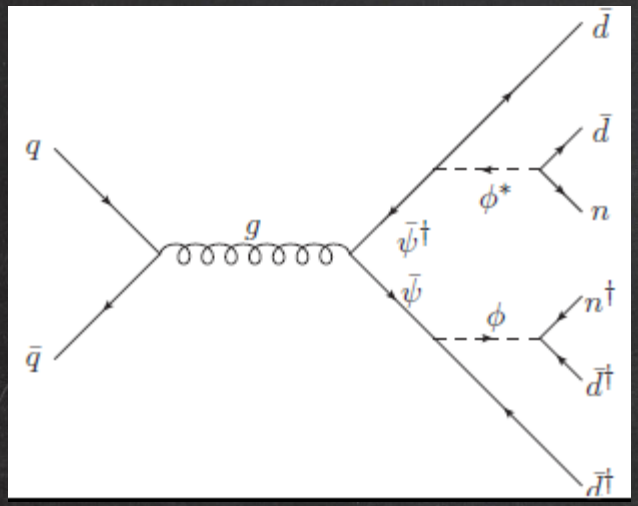


The 2 diagrams cancel!

Similar story for t-channel operators.

No bounds λ_s and λ_t from direct detection

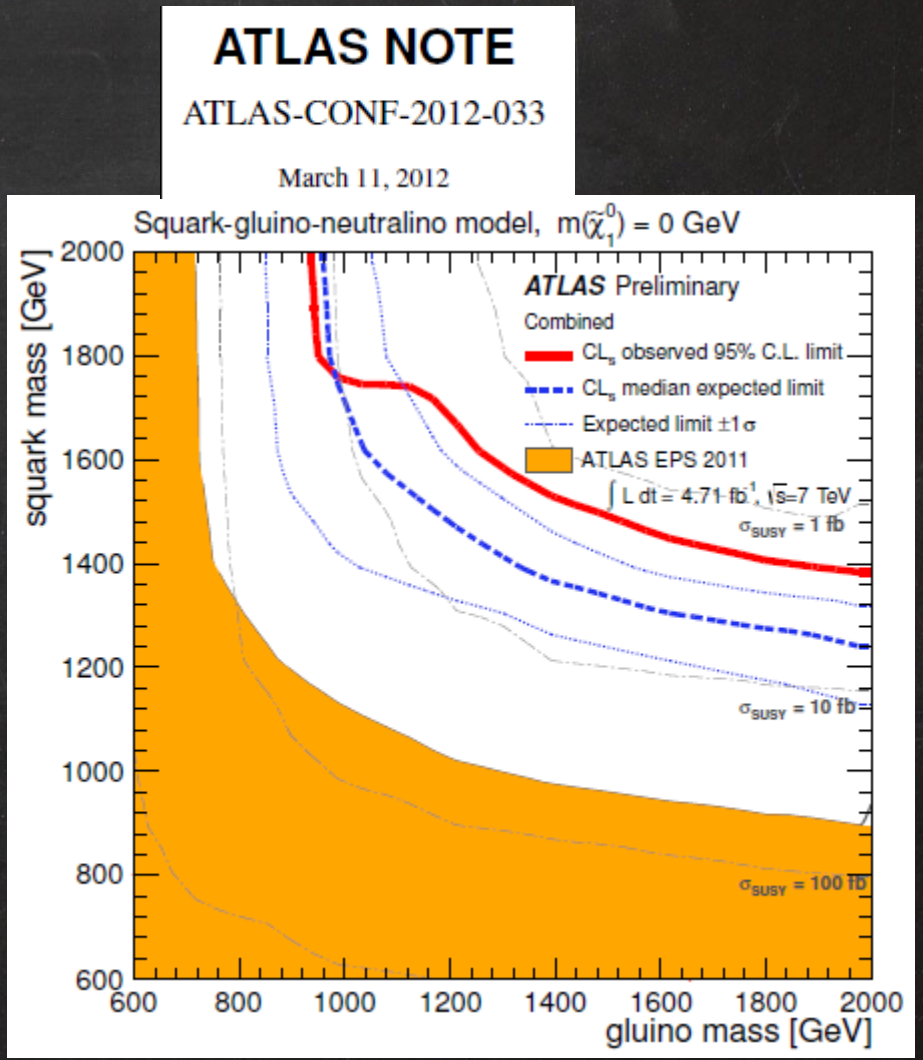
LHC bounds



* 4 jets + missing E_T

* Different group theory factors

* Current LHC bound:
  $m_\psi \geq 800$ GeV
  $m_X \geq 400$ GeV



Conclusions

* WIMPy baryogenesis is an interesting mechanism that relates the baryon asymmetry to the WIMP thermal relic density, **at the EW scale**.

* Incorporates baryogenesis by annihilation (often overlooked).

* We present a general effective model including **all** the possible dim 6 operators compatibles with the symmetries.

* For the models we considered the mechanism works in a good portion of the parameter space, with couplings of order 1.

* We studied cosmological bounds coming from the DM relic density and the Baryon Asymmetry of the Universe.

* We studied the bounds coming from the latest DM searches and from the LHC.