Asymmetry *sharing* between baryon and dark matter

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SILAFAE 2016
Antigua, Guatemala
São Paulo, Brazil
November 17, 2016

Based on hep-ph/1605.07188 [JCAP 1609,005(2016)] with Nicolás Bernal & Nayara Fonseca

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Outline

- Motivations
- Shared Asymmetry Scenarios
- Results
- Remarks

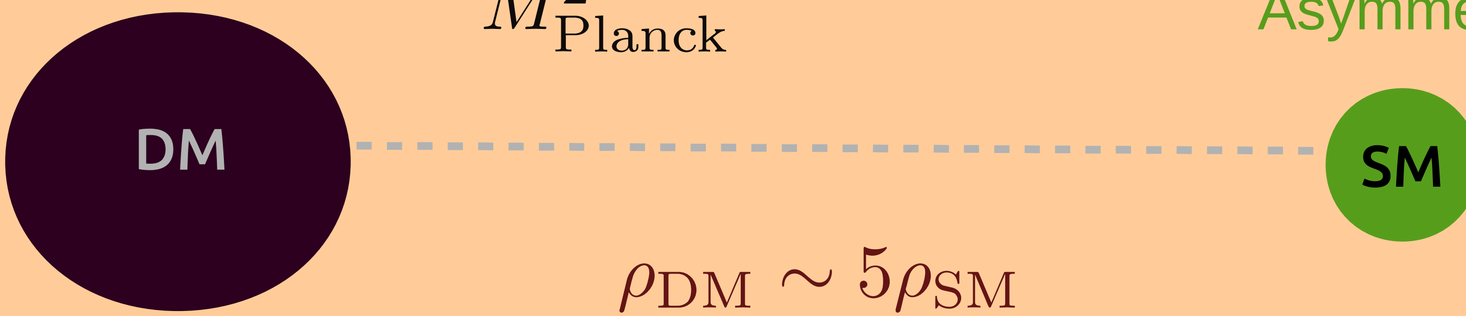
Motivations

Motivations

Particle physicists

$$\frac{1}{M_{\rm Planck}^2}$$

Maximally
Asymmetric



$$\rho_{\rm DM} \sim 5\rho_{\rm SM}$$

- Nonrelativistic, collisionless* matter
- Color, electric charged neutral
- Cosmologically stable

Motivations

what else?

Particle physicists

$\frac{1}{M_{\rm Planck}^2}$

$\frac{1}{\Lambda^n}$

Maximally Asymmetric

DM

SM

$$\rho_{\rm DM} \sim 5 \rho_{\rm SM}$$

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SU(2)$_L$ multiplet e.g. WIMP, minimal DM ...

SM singlet

Motivations

what else?

Particle physicists

Maximally Asymmetric

$$\frac{1}{M^2_{\rm Planck}} \qquad \frac{1}{\Lambda^n}$$

Maximally Asymmetric

DM

SM

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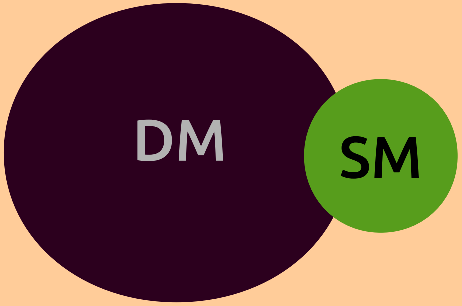
SM singlet

Asymmetric DM: 3-decade-old idea but gain renew impetus, see some recent reviews: **[Davoudiasl & Mohapatra (2012)], [Petraki & Volkas (2013)], [Zurek (2014)]**

In the early Universe

$$T \gg m_X$$

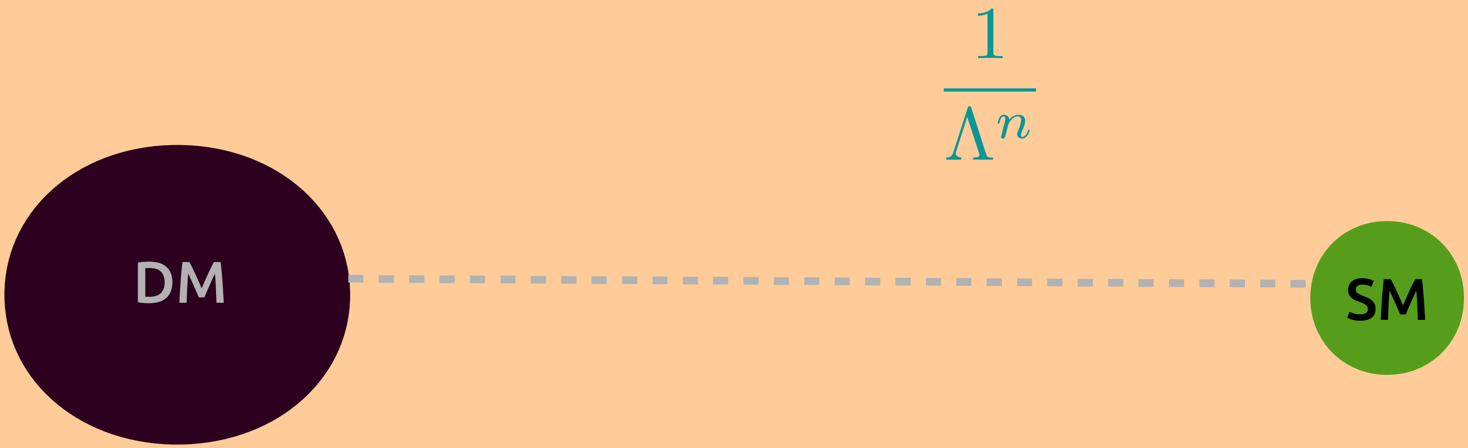
$$\frac{1}{\Lambda^n}$$



Asymmetry sharing ...

Today

$$T \ll m_X$$



Not caring ...

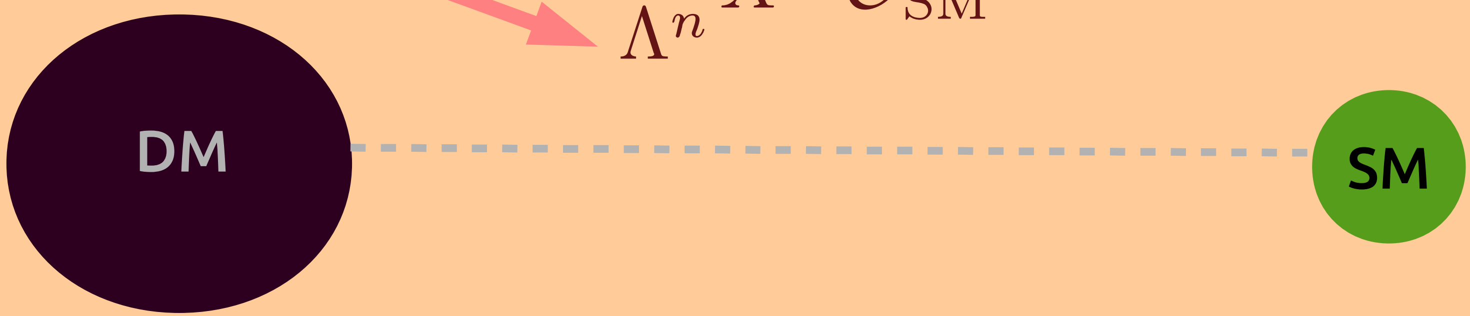
Shared Asymmetry Scenarios

Shared Asymmetry Scenarios

Our goal: Model-independent study with
Effective Operators

sharing scale

$$\frac{1}{\Lambda^n} X^N \bar{\mathcal{O}}_{\mathrm{SM}}$$



SM singlet but carries baryon B and/or lepton L number; see e.g.
[Kaplan, Luty & Zurek (2009)]

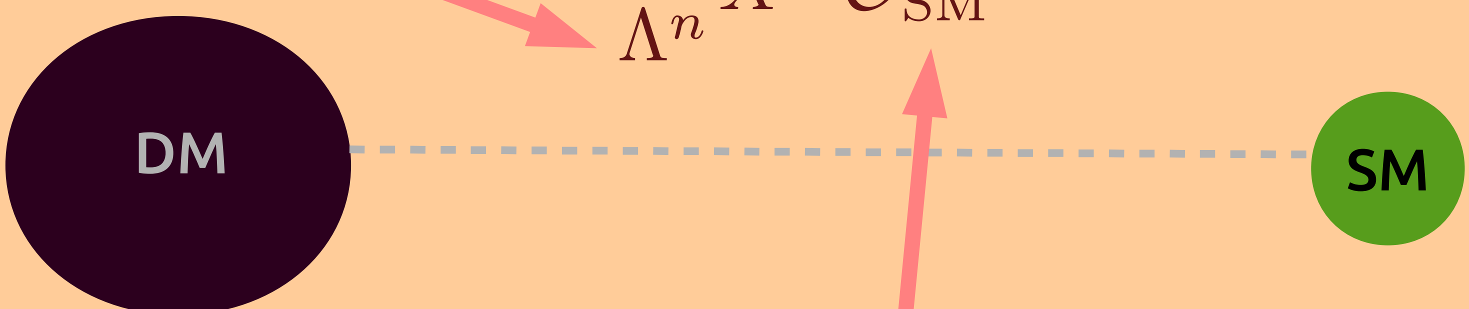
Shared Asymmetry Scenarios

Our goal: Model-independent study with
Effective Operators

N=1: decay too fast
N=2: our study

sharing scale

$$\frac{1}{\Lambda^n} X^N \bar{\mathcal{O}}_{\rm SM}$$



SM singlet but carries baryon B
and/or lepton L number; see e.g.
[Kaplan, Luty & Zurek (2009)]

A unique dim-5: (LL)HH
Four dim-6: (QL)(ud), (QQ)(ue), (QQ)(QL), (ud)(ue)

[Weinberg (1979)], [Wilczek & Zee (1979)], [Abbott & Wise (1980)]

Assumptions

- Maximally Asymmetric DM: *fast* DM-$\overline{\text{DM}}$ annihilations to remove the symmetric component
  - unitarity bound => m_X <~100 TeV **[Griest & Kamionkowski (1990)], [Hui (2001)]**
  - could give observable direct detection signatures but model-dependent
- Prior to the sharing, the B-L or B asymmetry is already *fixed* (by unspecified genesis mechanism at higher scale)
  - **B-L** = B-L(X) + B-L(SM) = $(5.4\, m_n/m_X + 78/29) Y_{\Delta B}^{obs}$
  - **B** = B(X) + B(SM) = $1/2\, |Y_{\Delta X}| + Y_{\Delta B} = (5.4/2\, m_n/m_X + 1) Y_{\Delta B}^{obs}$

Measured Unknown

Analysis

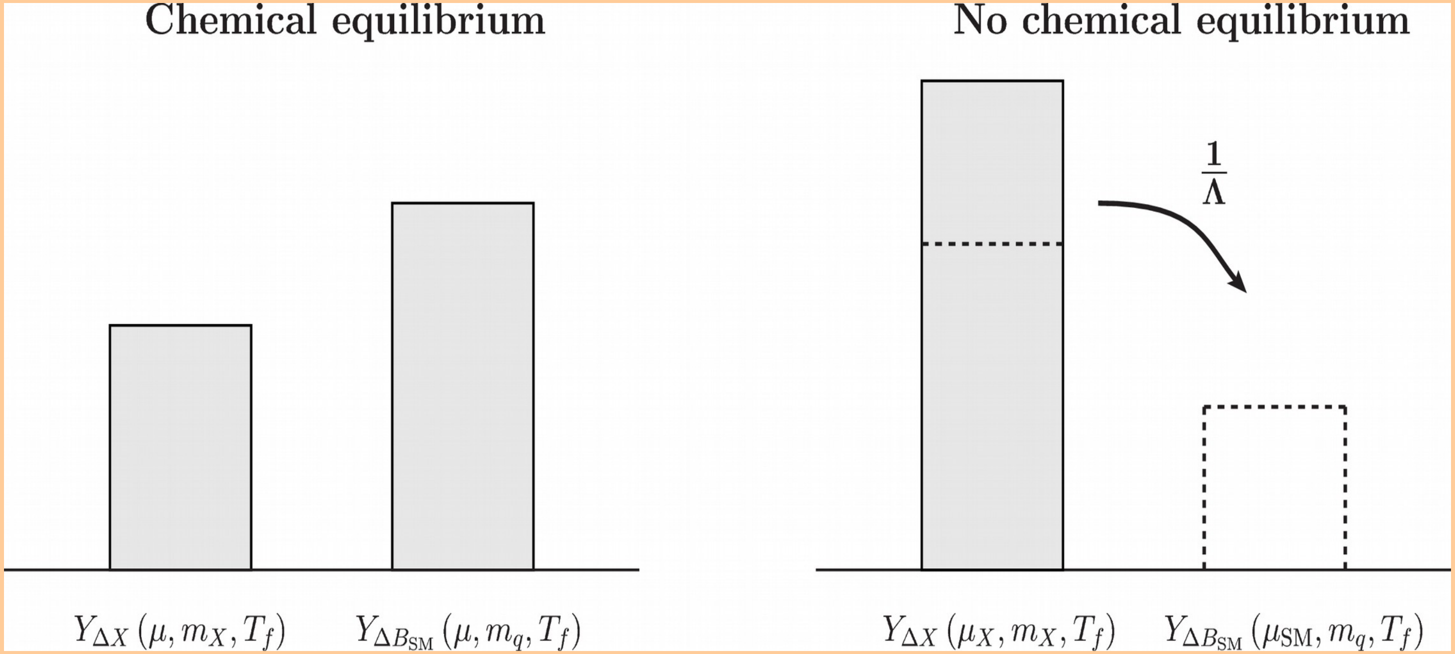
Step 1: fix m_X (total asymmetry is fixed)

$$\frac{1}{\Lambda^{d-p}} X X \bar{\mathcal{O}}^{(d)}_{\rm SM}$$

p=1: X complex scalar
p=2: X Dirac fermion

Step 2: Determine Λ for correct sharing (solving Boltzmann equations)

Step 3: Phenomenology



Assume initial asymmetry resides in X

Boltzmann equations

$$Y_{\Delta i} \equiv \frac{n_i - n_{\bar{i}}}{s}, \qquad z \equiv \frac{m_X}{T}$$

Before EW sphalerons freeze out

$$sHz\frac{Y_{\Delta X}}{dz} = -2\gamma_{\ell\ell HH}\left[2\frac{Y_{\Delta X}}{g_X \zeta_X Y_0} + \frac{22}{79}\left(\frac{Y_{\Delta(B-L)}}{Y_0} + \frac{Y_{\Delta X}}{Y_0}\right)\right]$$

After EW sphalerons freeze out

$$sHz\frac{Y_{\Delta X}}{dz} = -2\gamma_{qqq\ell}\left[2\frac{Y_{\Delta X}}{g_X \zeta_X Y_0} - \frac{1}{c_0 Y_0}\left(c_B Y_{\Delta B} + c_L Y_{\Delta L} - \frac{1}{2}(c_B + c_L)Y_{\Delta X}\right)\right]$$

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mass threshold effects: Temperature dependent

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Fixed once m_X is fixed

After EW sphalerons freeze out

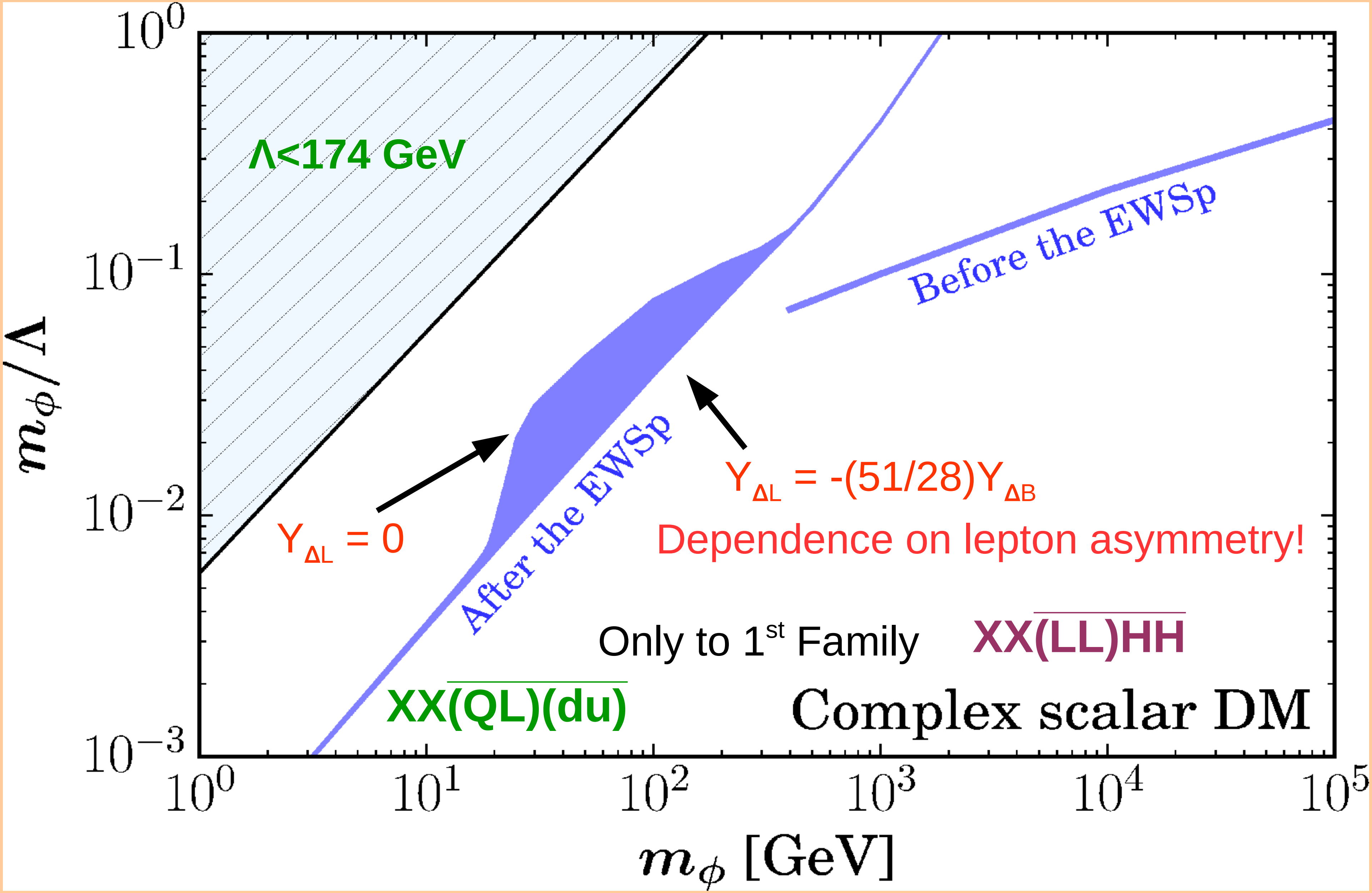
Free

$$sHz\frac{Y_{\Delta X}}{dz} = -2\gamma_{qqq\ell}\left[2\frac{Y_{\Delta X}}{g_X \zeta_X Y_0} - \frac{1}{c_0 Y_0}\left(c_B Y_{\Delta B} + c_L Y_{\Delta L} - \frac{1}{2}(c_B + c_L) Y_{\Delta X}\right)\right]$$

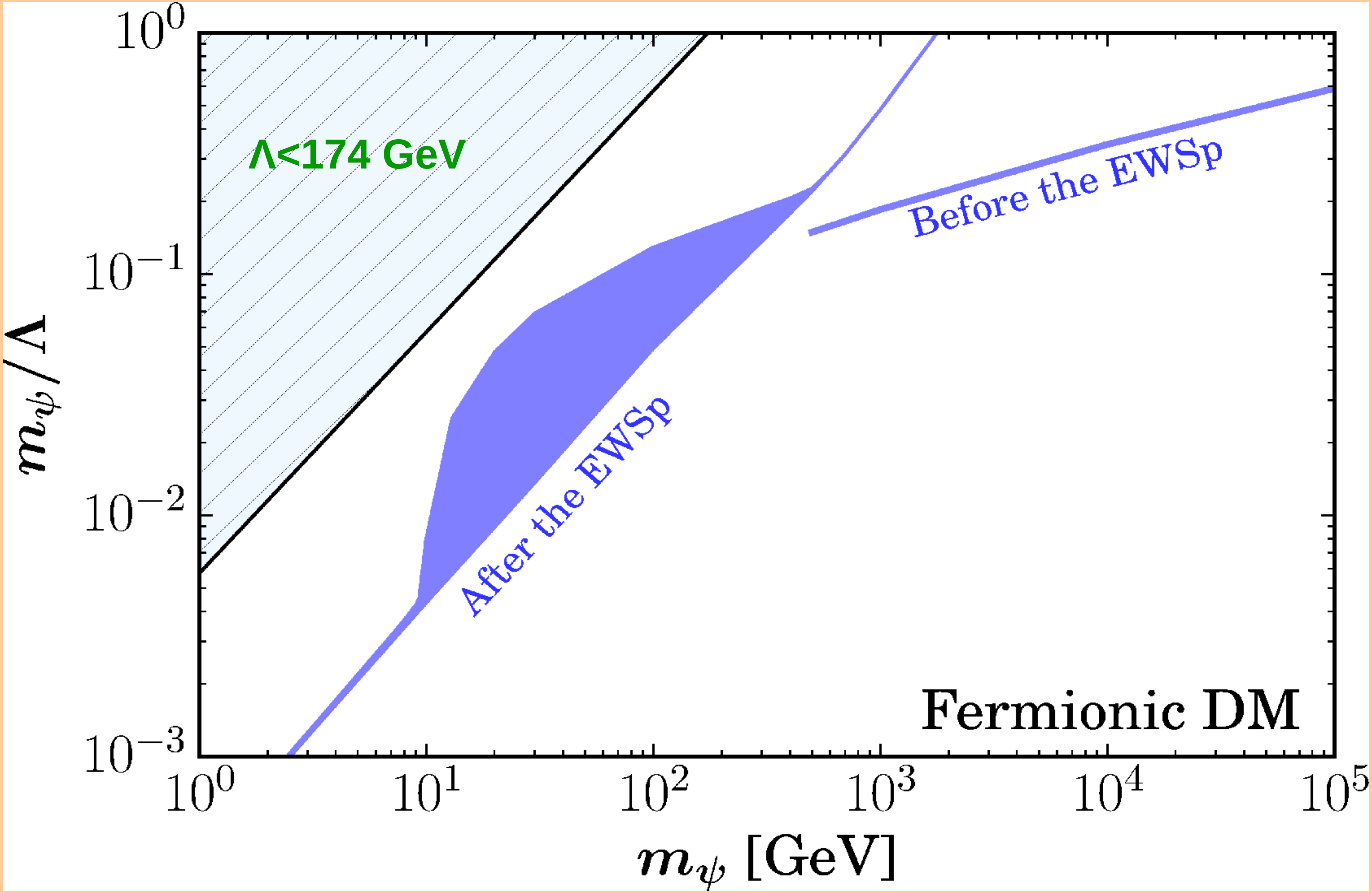
mass threshold effects: Temperature dependent

Results

Complex scalar X



Dirac fermion X



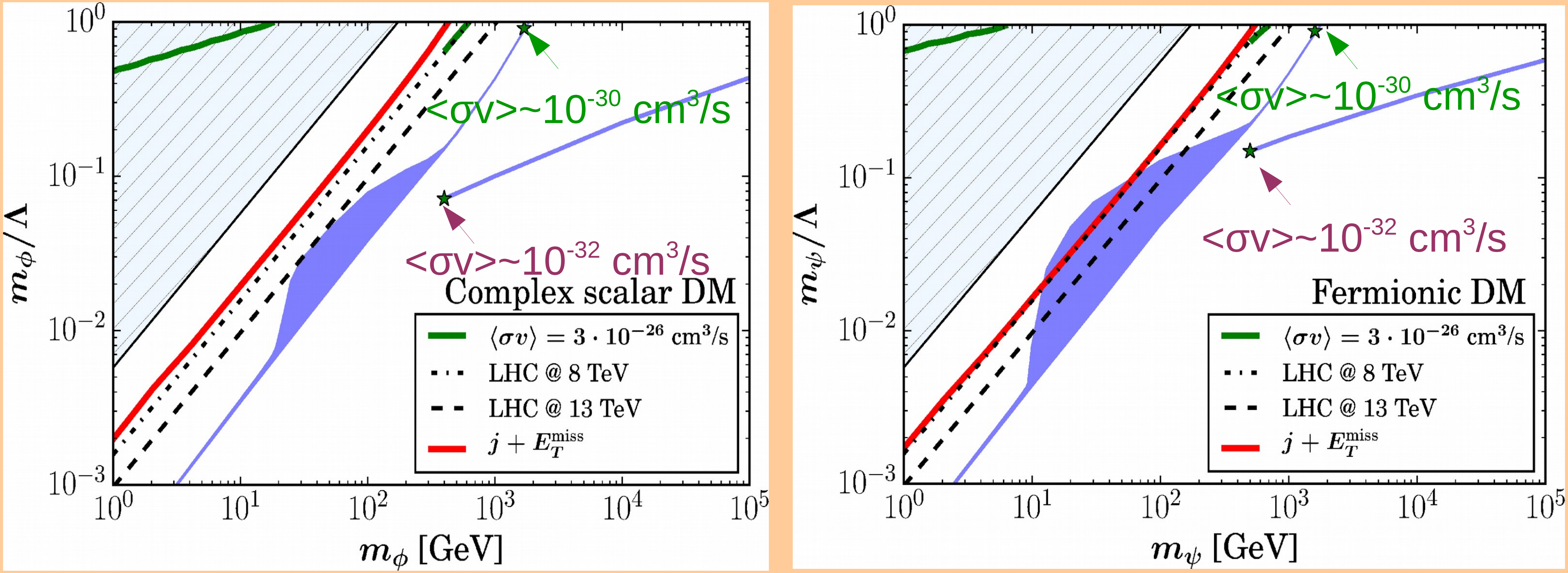
Indirect signatures

Although there are only X or $\overline{X}$ today, we can still have XX or $\overline{XX}$ annihilation signatures

$XX(ll)_L HH$ => dominant one: XX $\rightarrow \nu\nu$

$XX(ql)_L(du)_R$ => e.g. XX $\rightarrow e^+$ + hadrons ...

Still far from current experimental sensitivities



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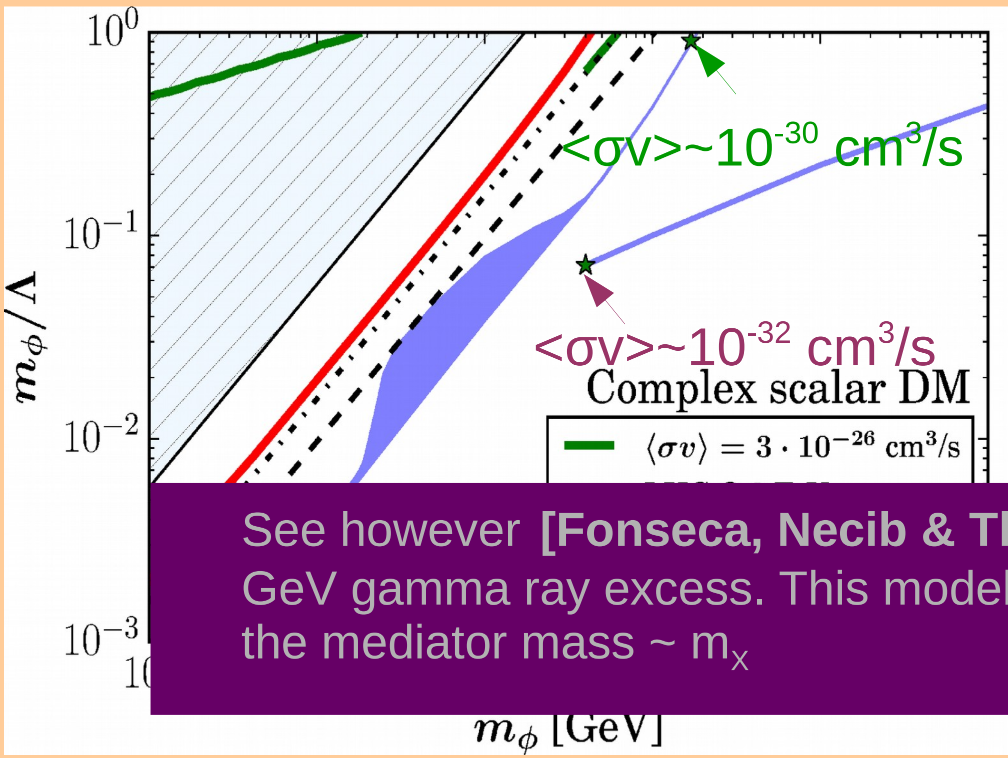
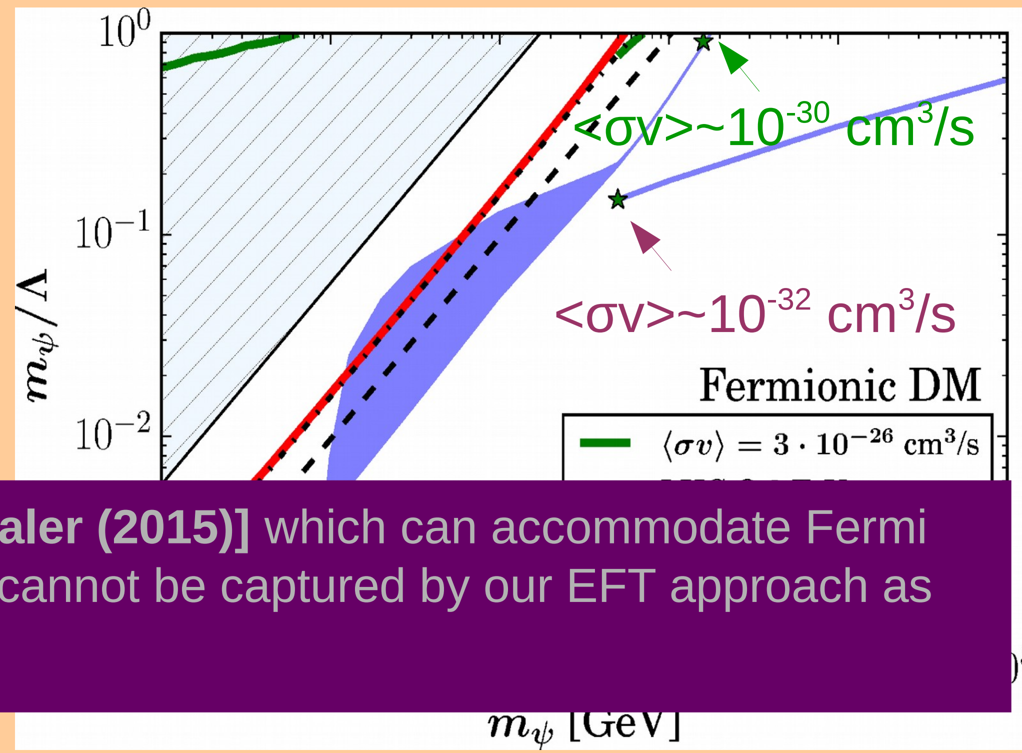




See however **[Fonseca, Necib & Thaler (2015)]** which can accommodate Fermi GeV gamma ray excess. This model cannot be captured by our EFT approach as the mediator mass ~ m_X

Direct signatures

$XX\overline{(LL)HH}$ => X + N → $\overline{X}$ + N + ν + ν through H exchange

=> Inelastic scattering: 4-body final state

NDA: $\frac{\sigma_{X-n}}{\sigma_{\rm SSDM}} \sim \frac{1}{\lambda_{\rm HP}^2}\left(\frac{m_X}{\Lambda}\right)^6 \frac{2^3\pi}{2^{11}\pi^5} \sim 10^{-8}$ for λ_{HP} = 0.01

=> Well within "neutrino floor" [Billard et al. (2014)]

$XX\overline{(QL)(du)}$ => e.g. $\overline{X}$ + p → X + e^+

Induced Nucleon Decay (IND)? [Davoudiasl et al. (2011)]

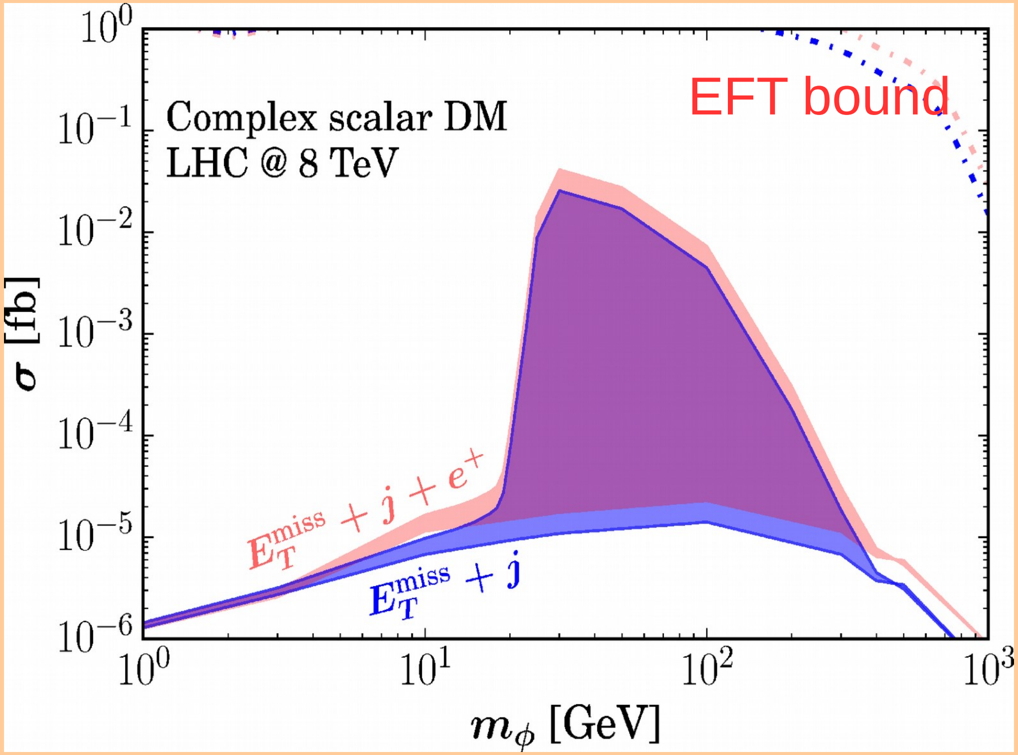
Due to baryon number conservation, in shared asymmetry scenario, only left with X(B=1/2) today, there is *no signature*!

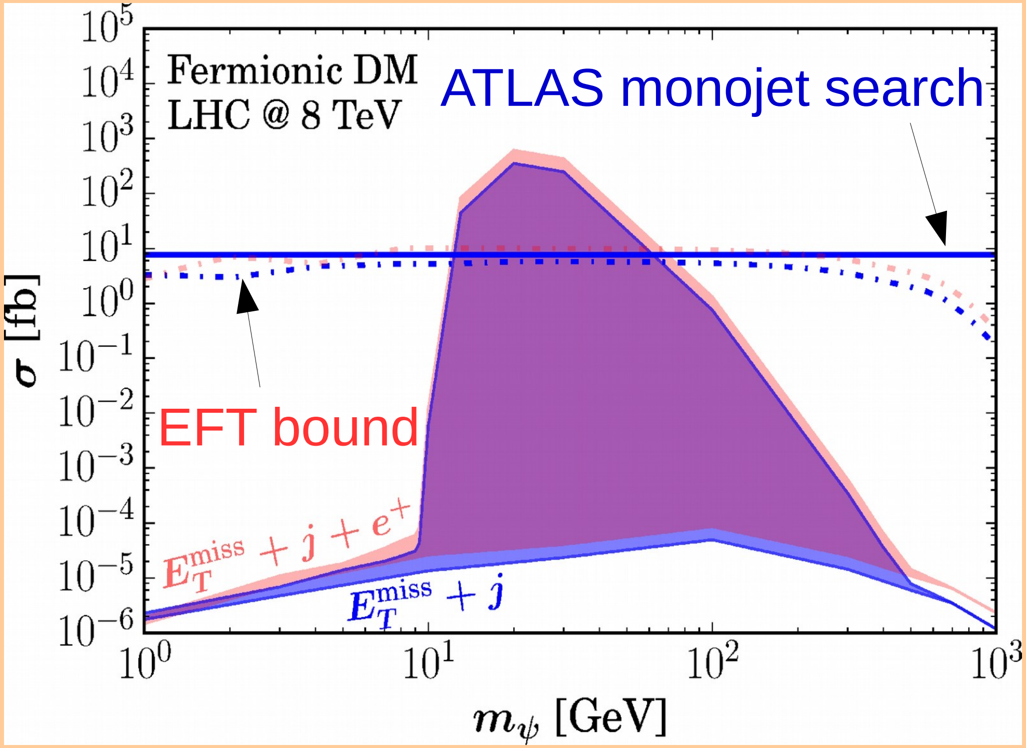
In [Davoudiasl et al. (2011)], hylogenesis generates equal in magnitude and opposite in sign asymmetry in the DM and SM sectors

- can have IND
- sharing operators cannot be in CE to avoid asymmetry washout

Collider signatures at LHC8

$XX(ql)_L(du)_R \Rightarrow pp \rightarrow j + \text{missing}$; $pp \rightarrow j + e^+ + \text{missing}$



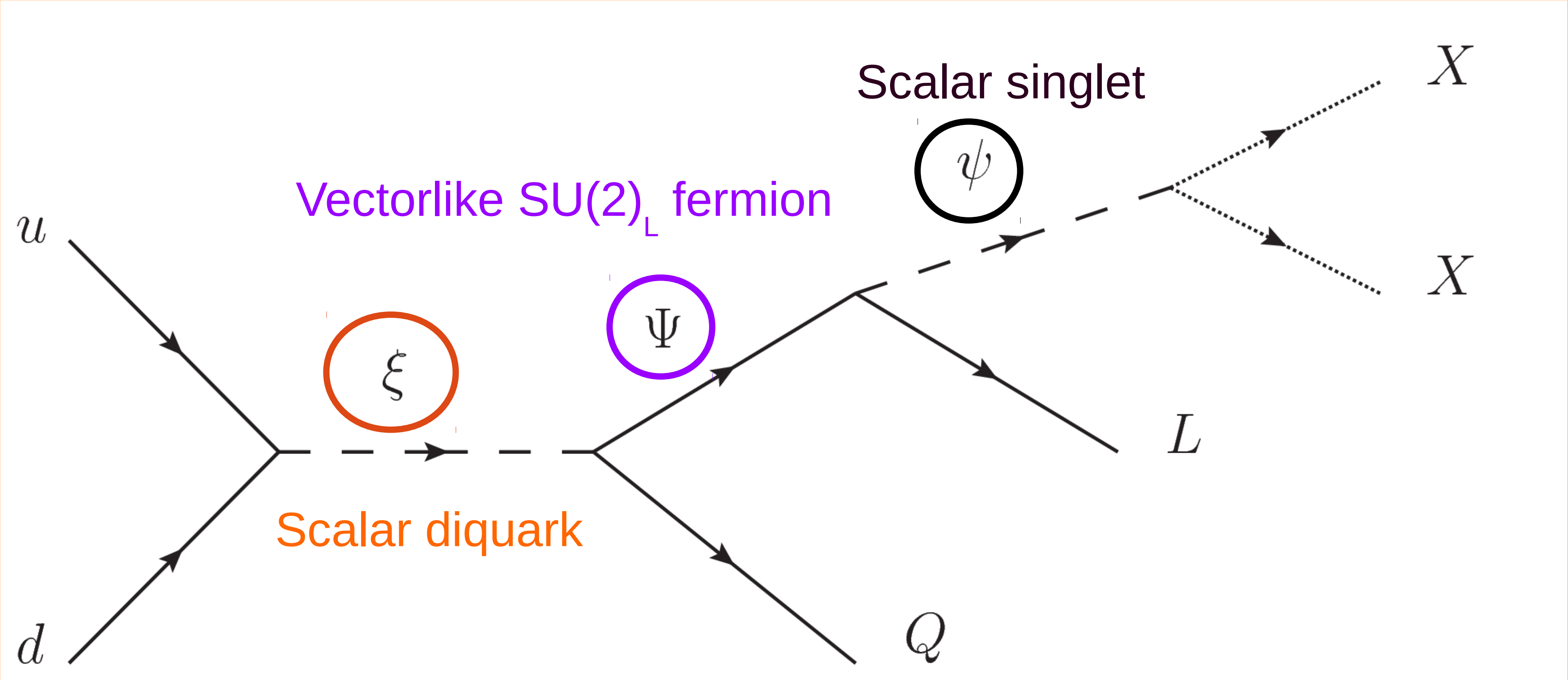


ATLAS estimated bound from monojet search cut on the quark E_T; detail analysis considering simplified models (UV models) [work in progress]

Remarks

- That the DM and the SM *share* an asymmetry in early time is an interesting possibility
- Our model-independent EFT analysis:
  - Asymmetry generation is complete prior to sharing
  - Today the DM is maximally asymmetric: unitarity bound m_X <~ 100 TeV
  - No induced nucleon decay signature
  - Due to steep energy dependence of the operators, although indirect and direct signatures are suppressed, it is not suppressed at the LHC scale
- EFT holds during the sharing period and also today but could break down at LHC energy! We need to go look at UV models ...

Simplified models (UV models)



Searches in LHC, e+e- collider

[work in progress]

Stay tuned!

Thank you for your attention!

Extra slides

Boltzmann equations

Before EW sphalerons freeze out

$$\frac{n_{\Delta i}}{g_i \zeta_i} = c_i \left[n_{\Delta(B-L)} - (B-L)_X n_{\Delta X} \right]$$

$$\zeta_i \equiv \frac{6}{\pi^2} \int_{z_i}^{\infty} dx\, x \sqrt{x^2 - z_i^2}\, \frac{e^x}{\left(e^x \pm 1\right)^2}, \qquad z \equiv \frac{m_X}{T}$$

$\boldsymbol{i}$	$\boldsymbol{q_L}$	$\boldsymbol{u_R}$	$\boldsymbol{d_R}$	$\boldsymbol{\ell_L}$	$\boldsymbol{e_R}$	$\boldsymbol{H}$
$\boldsymbol{c_i}$	$\frac{7}{237}$	$-\frac{5}{237}$	$\frac{19}{237}$	$-\frac{7}{79}$	$-\frac{3}{79}$	$-\frac{4}{79}$

Boltzmann equations

After EW sphalerons freeze out

$$\frac{n_{\Delta i}}{g_i \zeta_i} = \frac{1}{c_0}\left[c_B^i n_{\Delta B} + c_L^i n_{\Delta L} - (B_X c_B^i + L_X c_L^i) n_{\Delta X}\right]$$

$$\zeta_i \equiv \frac{6}{\pi^2}\int_{z_i}^{\infty} dx\, x \sqrt{x^2 - z_i^2}\, \frac{e^x}{(e^x \pm 1)^2}, \qquad z \equiv \frac{m_X}{T}$$

i	c_B^i	c_L^i
u	$3\left(2+\zeta_b+\zeta_s+\frac{3\zeta_W}{2}\right)$	$2\left(1+\zeta_b+\zeta_s\right)$
d	$3\left(3+2\zeta_c+\frac{3\zeta_W}{2}\right)$	$-2\left(1+\zeta_c\right)$
ν	$-2\left(1-\zeta_b+2\zeta_c-\zeta_s\right)$	$2\left[3+\left(2+\zeta_b+\zeta_c+\zeta_s\right)\frac{\zeta_W}{2}+\left(2+\zeta_c\right)\zeta_b+\left(2+\zeta_s\right)\zeta_c+2\zeta_s\right]$
e	$1-\zeta_b+2\zeta_c-\zeta_s$	$2\left[\left(2+\zeta_b+\zeta_c+\zeta_s\right)\frac{\zeta_W}{2}+\left(1+\zeta_c\right)\left(1+\zeta_b+\zeta_s\right)\right]$
W	$3\left(1-\zeta_b+2\zeta_c-\zeta_s\right)$	$-2\left(2+\zeta_b+\zeta_c+\zeta_s\right)$

Collider signatures

$XX(ll)_L HH \Rightarrow e^- e^- \rightarrow X\, X\, W^-\, W^-$ or conjugate process

- Need large center of mass energy > $2(m_X + m_W) \sim$ TeV
- No planned **e^-e^-** or **e^+e^+** collider

$XX(ll)_L HH \Rightarrow p\, p \rightarrow W^+\, W^+\, j\, j \rightarrow X\, X\, e^+ e^+\, j\, j$ or conjugate process

- Contribute to “anomalous quartic gauge coupling”
- There are searches by LHC; work in progress

400 GeV $<\sim m_X <\sim$ 100 TeV

Collider signatures

$XX(ql)_L(du)_R$ => $pp \rightarrow j$ + missing; $pp \rightarrow j + e^+$ + missing

- Both signatures are correlated
- **$pp \rightarrow j + e^-$ + missing** very suppressed due to scarcity of antiquarks in the protons
- Due to the scaling at high energy $E \gg m_X$, $\sigma \sim E^{2(5-p)}/\Lambda^{2(6-p)}$, can be quite relevant for the collider searches (compared to indirect/direct searches)
- Beware when effective operator description breaks down; conservative bound can be obtained by discarding events where $E > 4\pi\Lambda$

2 GeV <~ m_X <~ 2 TeV