# Asymmetric Dark Matter & (Self) Interactions

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# Dark Matter Genesis?

- Dark matter

  WIMPs: Calculable thermal freeze-out with scale v

  FIMPs: Calculable thermal freeze-in with scale v

  Axions: Mis-alignment or thermal production

- Asymmetric DM & Baryons

  Sharing

  Co-genesis

# Motivation

Baryons need origin of particle-antiparticle asymmetry

$$\eta_B = Y_B - Y_{\bar{B}}$$

$$m_B \eta_B \sim \sin\phi \frac{m_\nu^2 M_R M_{Pl} \Lambda_{QCD}}{v^4}$$

CP-violating phase

- Usual, unrelated origin of baryons & DM, involving very different physics, makes it hard to understand $\Omega_{DM}/\Omega_B \simeq 4.86$

- Freeze-out dominates thinking about DM candidates, detection, and LHC phenomenology

Are we being misled?

# ADM Basics

Alternative: similar physics underlies both $\Omega_B$ and $\Omega_{DM}$

(Nussinov '85; Gelmini, Hall, Lin '87; Barr '91; Kaplan '92; Thomas '95; Hooper, JMR, West '04; explosion in last 3yrs esp work of Zurek etal; now many others...)

Baryons: $U(1)_B$ $u, d, s...$ $p$ stable $\Omega_B \propto m_B \eta_B$

DM: $U(1)_X$ $X_0, X_1, X_2...$ $X_0$ stable $\Omega_X \propto m_X \eta_X$

At some era

Interactions violate B and X to yield related values for $\eta_B$ and $\eta_X$

$$\frac{\Omega_X}{\Omega_B} = \frac{\eta_X}{\eta_B}\frac{m_X}{m_B}$$

# ADM Basics

$$\frac{\Omega_X}{\Omega_B} = \frac{\eta_X}{\eta_B}\frac{m_X}{m_B}$$

only true if X density is determined by the asymmetric part otherwise

$$\frac{\Omega_X}{\Omega_B} = \frac{Y_X + Y_{\bar{X}}}{Y_B + Y_{\bar{B}}}\frac{m_X}{m_B}$$

need $Y_X + Y_{\bar{X}} = Y_X - Y_{\bar{X}} + \text{small corrections}$

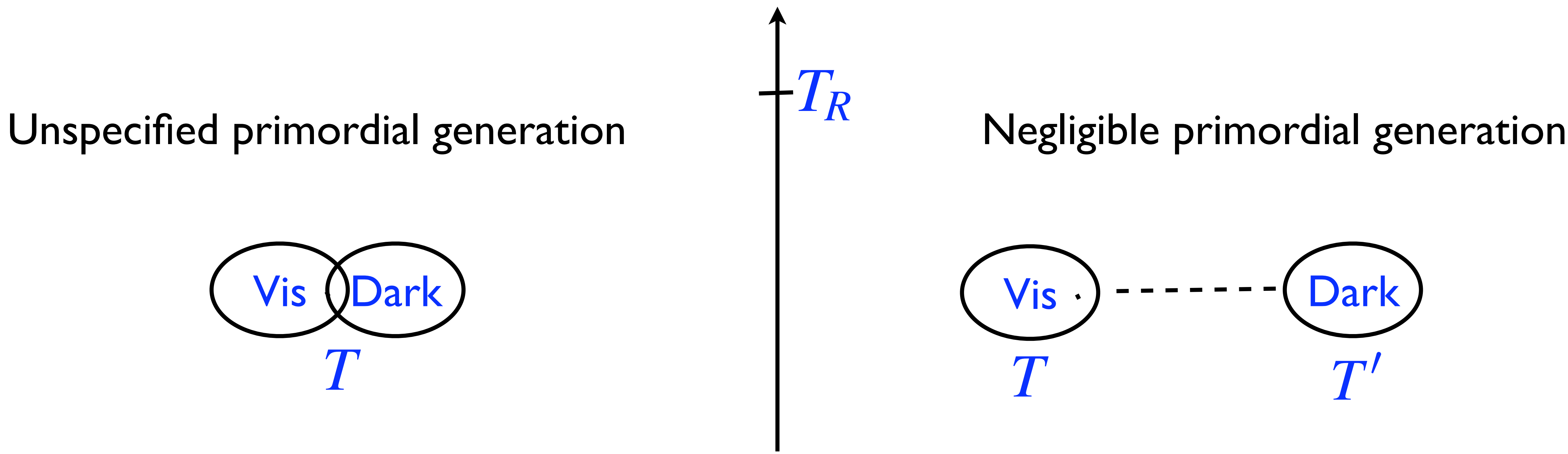
non-trivial constraint as initially

$$Y_X + Y_{\bar{X}} = \frac{Y_X - Y_{\bar{X}}}{\epsilon}$$

where $\epsilon \leq \sin(\phi_{eff}) \times \text{loop factor}$ measures CP-violation

# ADM Basics

Two general categories of theories: "sharing" & "co-generation"




$\eta_X \sim \eta_B$ by sharing

$\eta_X \sim \eta_B$ by co-generation

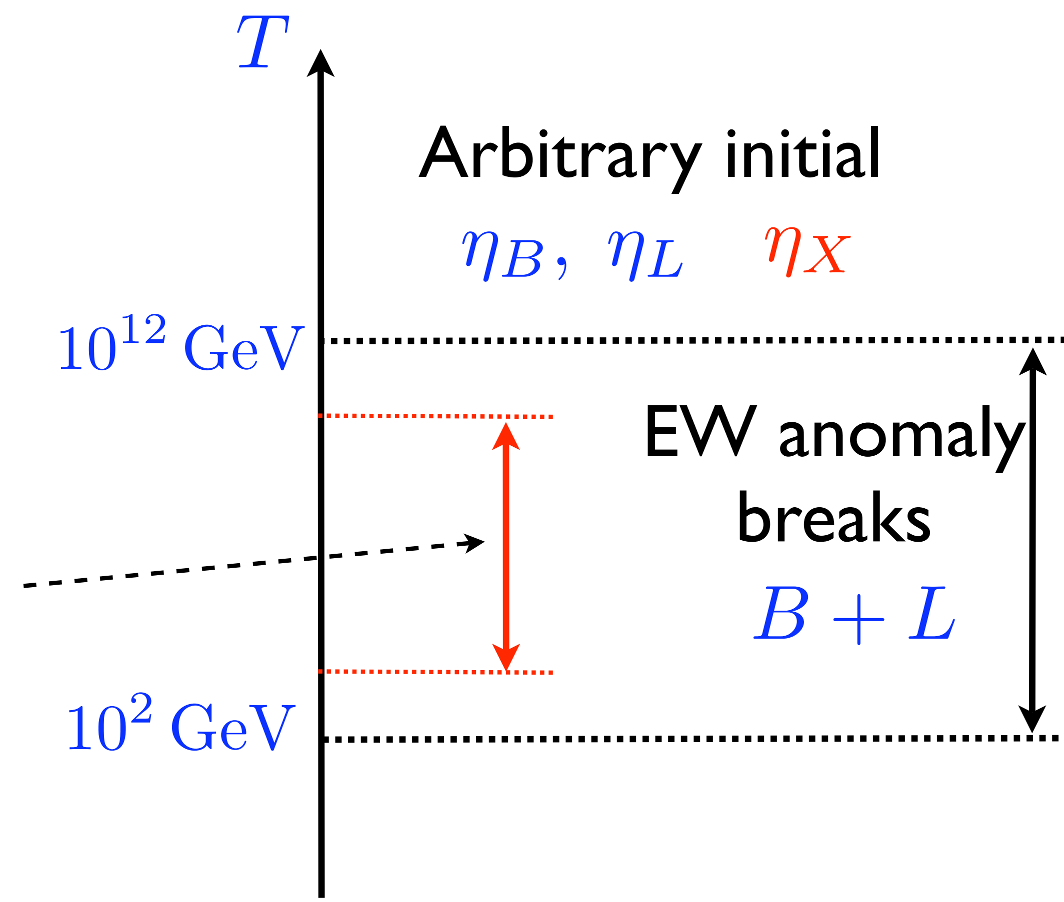
Co-generation is more ambitious: attempts to explain simultaneous origin of B & X asymmetries (if at scale ~ TeV allowing test at LHC...)

# ADM Basics

## Sharing:

Assumes presence of some initial asymmetry in (at least) one of B, L & X

A "portal interaction" breaks a combination of B/L & X, such that




there is an era when only conserved U(1) is

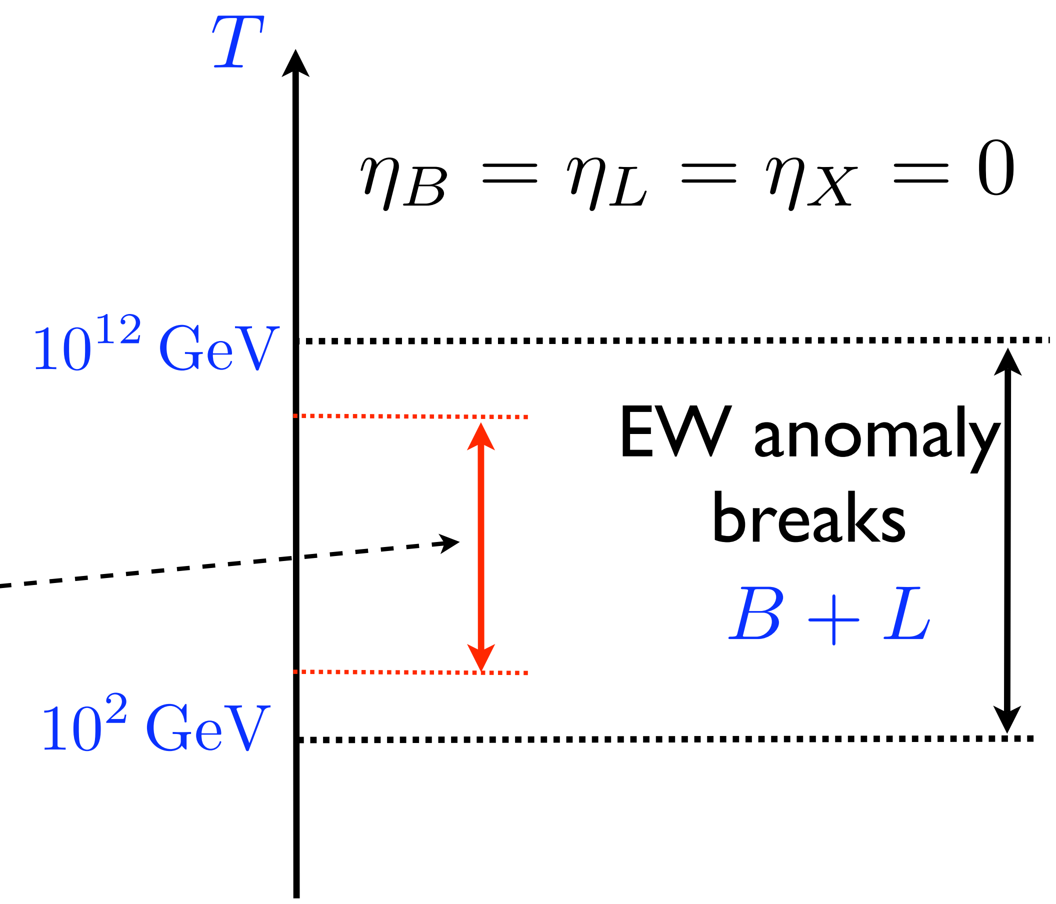
$$B - L + X \quad \Longrightarrow \quad \eta_B : \eta_L : \eta_X = N_1 : N_2 : N_3$$

# ADM Basics

## Co-generation:

zero initial asymmetry in B, L & X

"Connector interactions" both break a combination of B/L & X, and lead to generation of asymmetry which is simultaneously shared (further later sharing due to EW anomaly can occur too)



# ADM Basics

Alternative view (either sharing or co-generation):

- incompatible with standard SUSY Majorana neutralino DM
- changes one or both direct/indirect DM detection

co-generation harder as requires B, X violation & out-of-equilibrium condition (at TeV scale if testable). Requires a new theory of calculable (thermal) DM production....

# ADM Basics

$\Longrightarrow$ Must efficiently annihilate away symmetric part to light states

there has to be an efficient X-preserving freeze-out process

Three options:

- direct FO to light SM dof

  $\Longrightarrow$ operators connecting X & SM sectors with strength bounded below

- direct FO to light dark sector dof

  $\Longrightarrow$ (potentially) new long-range DM interactions

- FO to dark sector dof which then late decay to SM

  $\Longrightarrow$ late-time energy injection in early universe

# FO Portal

- direct FO of symm yield to light SM dof

  limits from direct detection experiments and monojet searches at Tevatron and LHC are very constraining

- Use effective operators to parameterise portal interactions. Some are suppressed by:

  v velocity of

  q < 0.1GeV mom'm

| $\Delta\mathscr{L}$ | | Int. | Suppression |
|---|---|---|---|
| $\mathcal{O}_s^\phi$ : | $\frac{1}{\Lambda}\phi^\dagger\phi\overline{f}f$ | SI | 1 |
| $\mathcal{O}_v^\phi$ : | $\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\overline{f}\gamma_\mu f$ | SI | 1 |
| $\mathcal{O}_{va}^\phi$ : | $\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\overline{f}\gamma_\mu\gamma^5 f$ | SD | $v^2$ |
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we shall examine

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CP-violating ops

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## m_q dep't ops

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| $\mathcal{O}_t^\psi$ : | $\frac{1}{\Lambda^2}\overline{\psi}\sigma^{\mu\nu}\psi\overline{f}\sigma_{\mu\nu}f$ | SD | 1 |
| $\mathcal{O}_p^\psi$ : | $\frac{1}{\Lambda^2}\overline{\psi}\gamma^5\psi\overline{f}\gamma^5 f$ | SD | $q^4$ |
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## direct detection constrained

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ADM relic density - removal of symmetric component:

$$\Omega_{\rm DM} h^2 \simeq 3 \times 10^8 \ (Y_{\rm sym} + Y_{\rm asym}) \left(\frac{m_{\rm DM}}{\rm GeV}\right)$$

By assumption relic density must be due to the asymmetry, so demand symmetric component <10% of asymmetric part

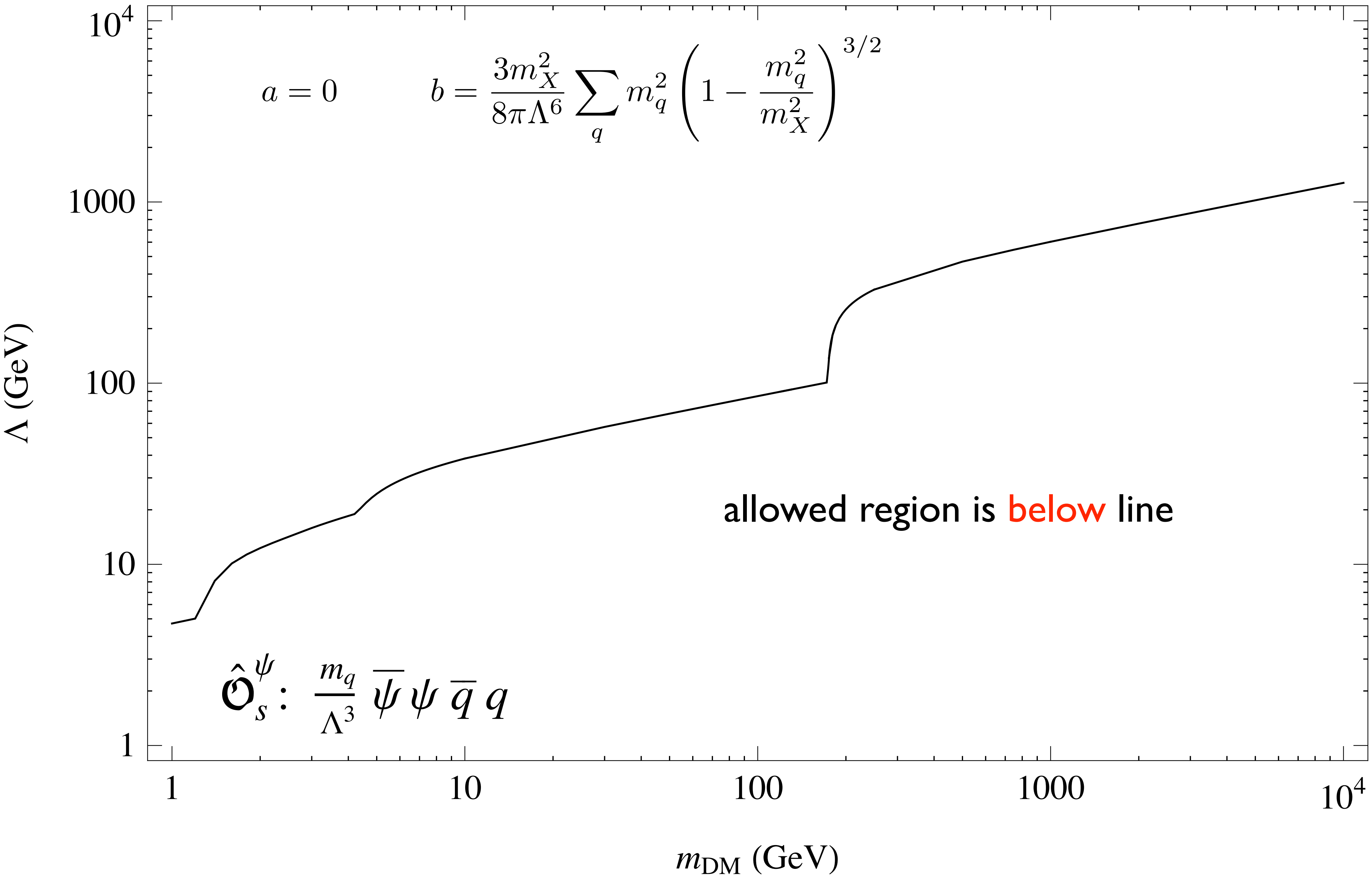
(results relatively insensitive to 0.1% vs 100%)

Yields depend on (presumed known) asymmetry and FO cross section

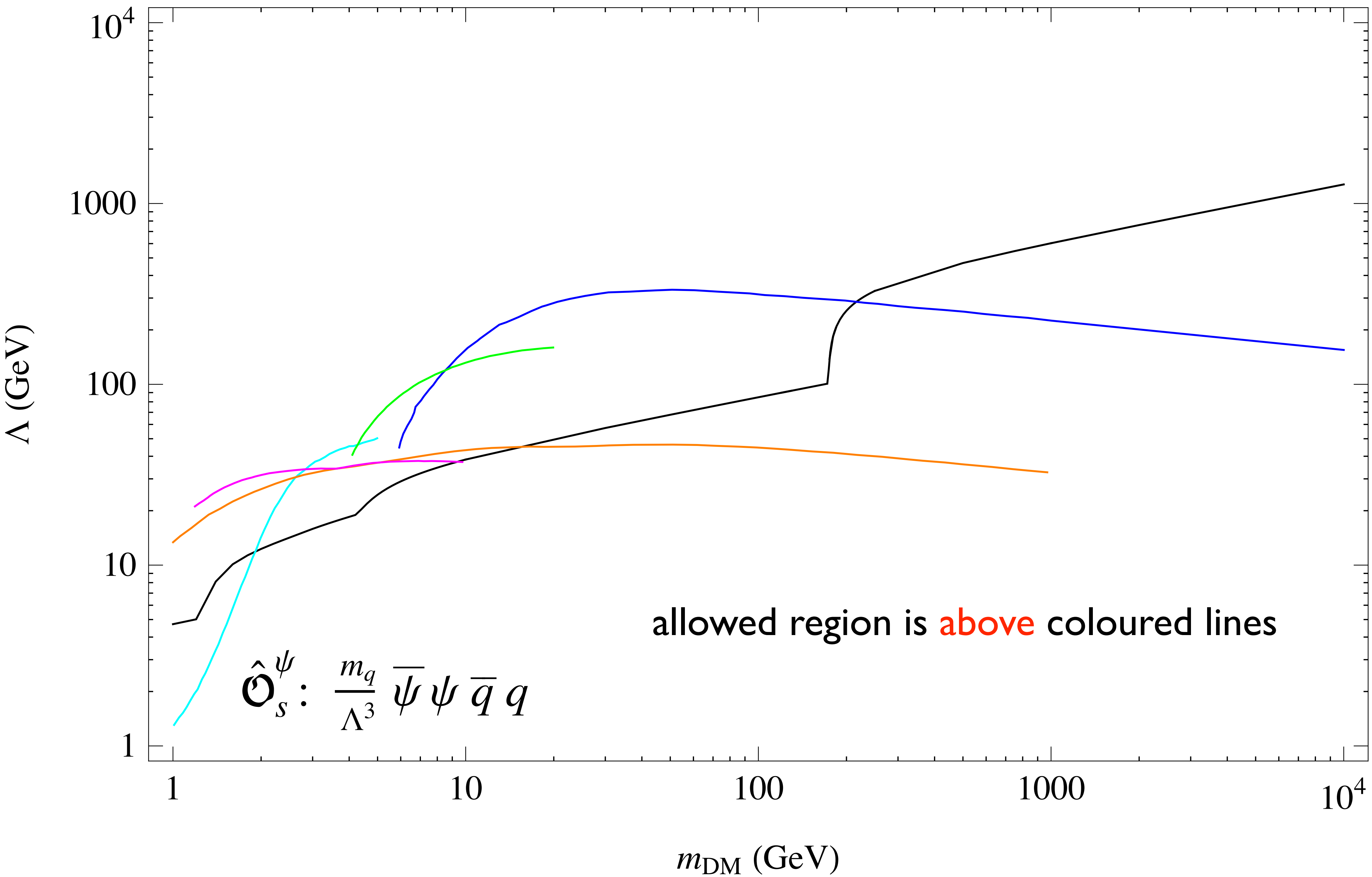
$$Y_{\rm DM} \sim \frac{\eta_X}{\exp\left[\eta_X \omega \left(\frac{a}{\bar{x}_F} + \frac{b}{\bar{x}_F^2}\right)\right] - 1} \qquad Y_{\overline{\rm DM}} \sim \frac{\eta_X}{1 - \exp\left[-\eta_X \omega \left(\frac{a}{\bar{x}_F} + \frac{b}{\bar{x}_F^2}\right)\right]}$$

where $\omega = \frac{4\pi}{\sqrt{90}} m_{\rm DM} M_{\rm Pl} \sqrt{g_*}$ and $\langle \sigma v \rangle = a + \frac{6b}{x} + \cdots$

# Example: relic density requirement on $\frac{m_q}{\Lambda^3}\overline{\psi}\psi\overline{q}q$



# Constraints from direct detection (CRESST, DAMIC, CDMS, XENON100)



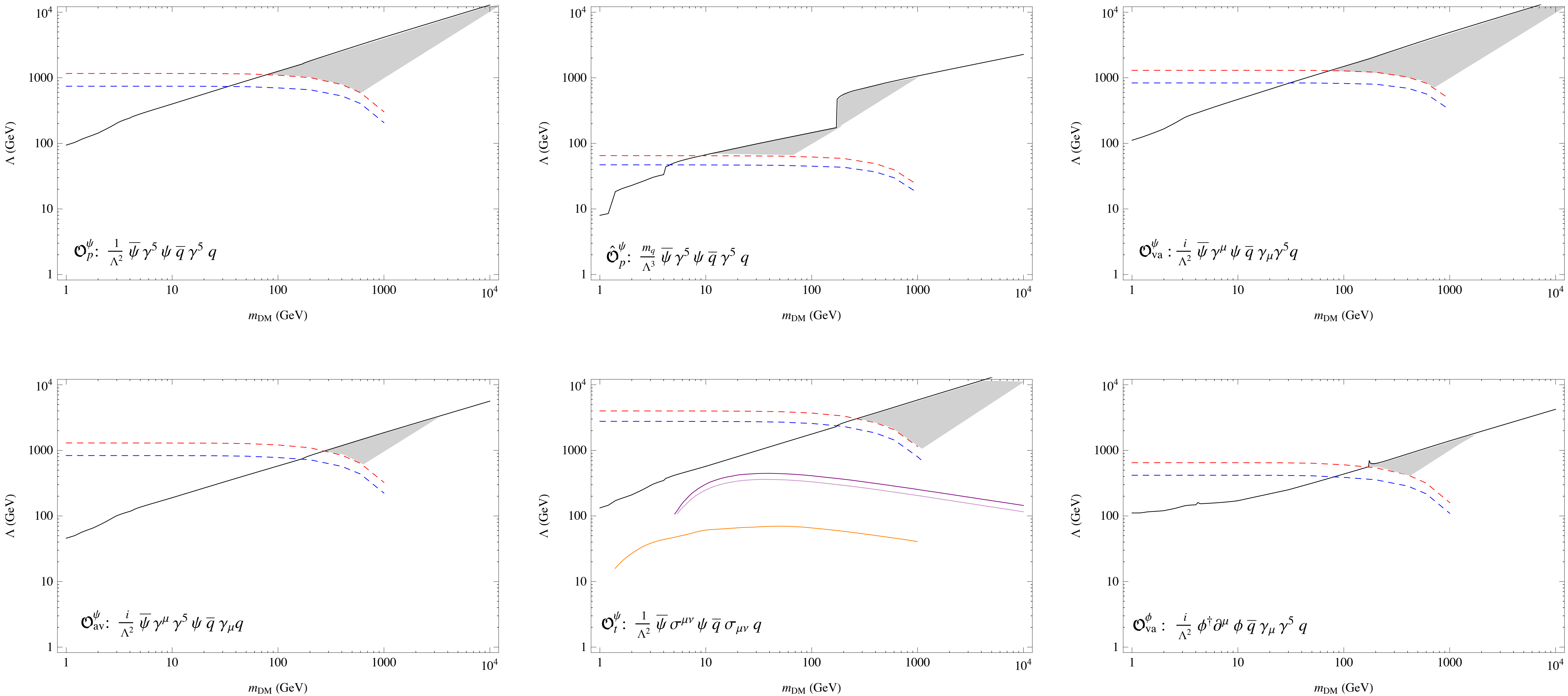

$\Longrightarrow$ ADM in preferred 1-10GeV region excluded with this op

- Portal operator $\frac{m_q}{\Lambda^3}\overline{\psi}\psi\bar{q}q$ is an easy case as direct detection not SD and not v- or q- suppressed

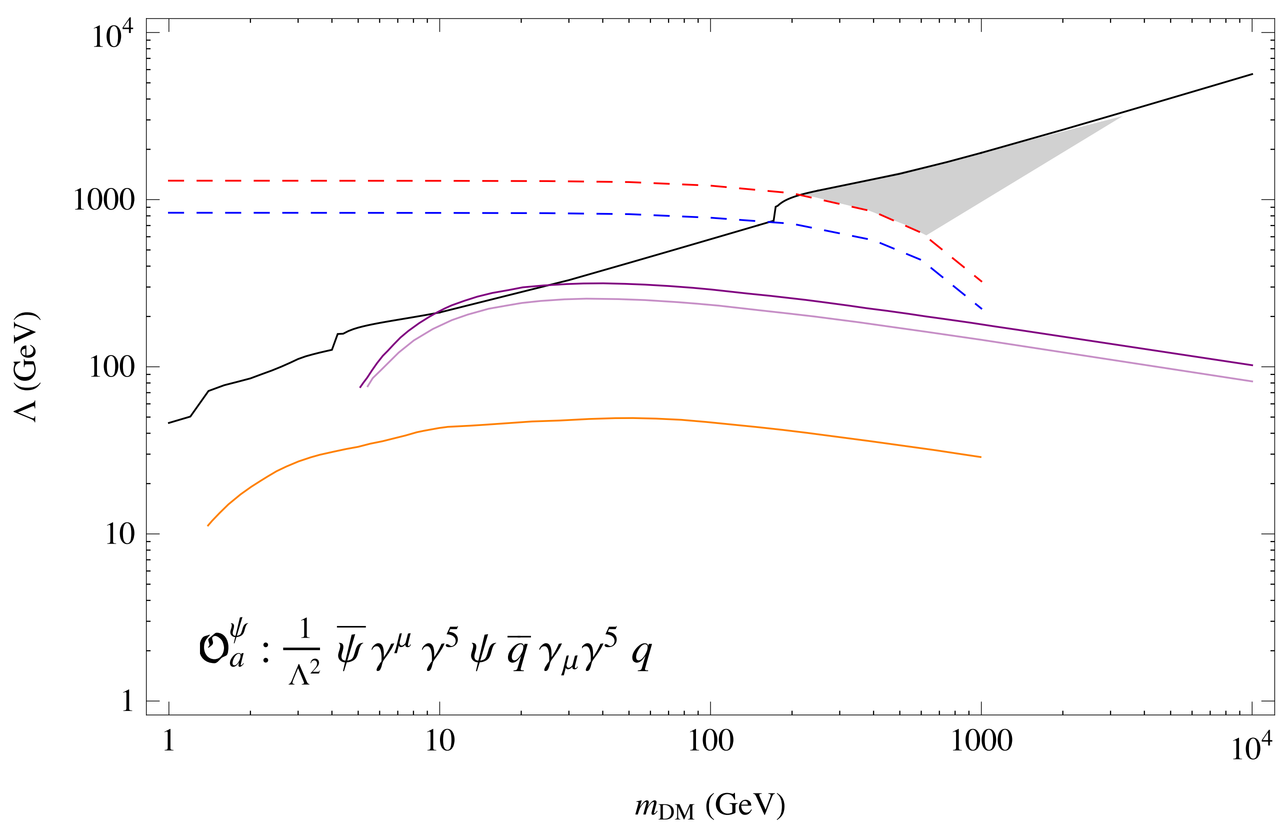
  Monojet searches provide complementary constraints on DM with interactions with quarks

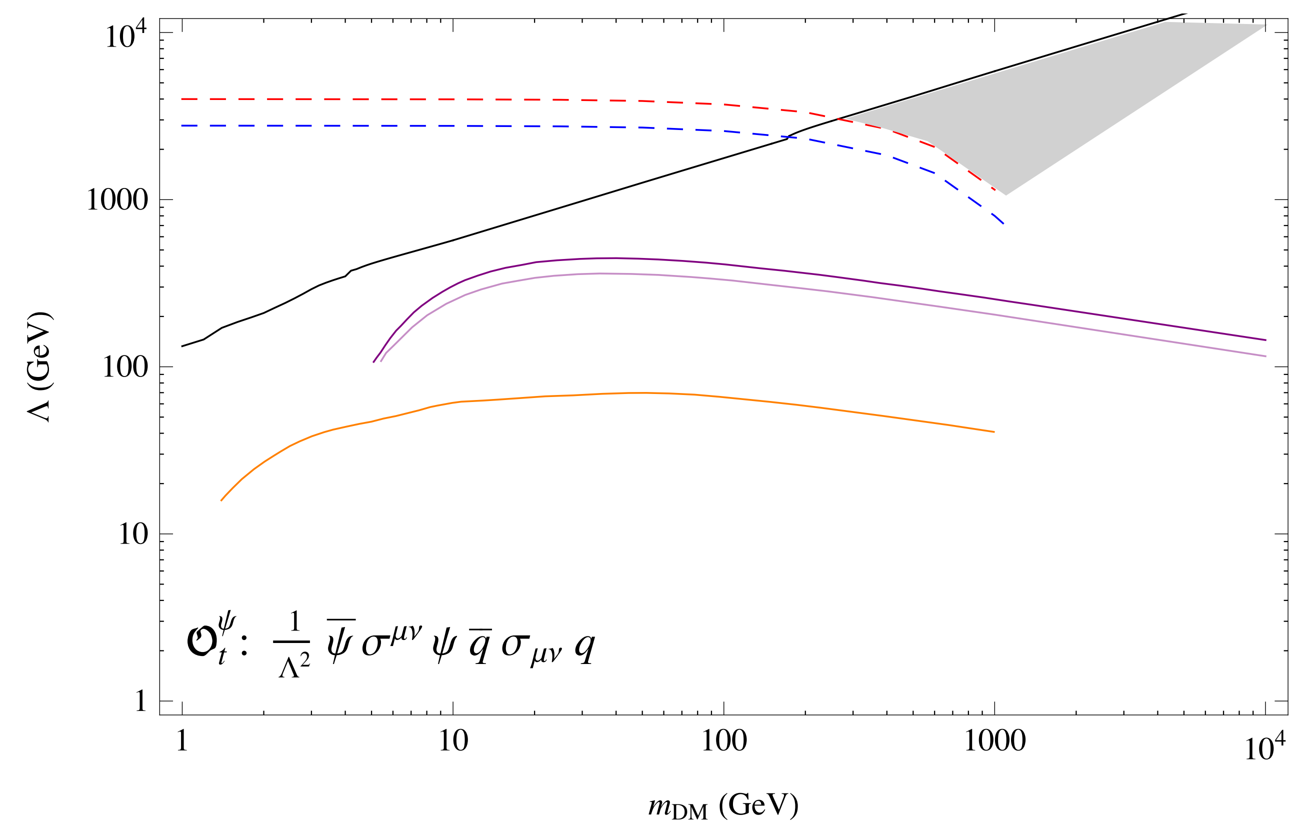
  (e.g. Bai, Fox, Harnik arXiv:1005.3797)

# Constraints on q- or v-suppressed ops

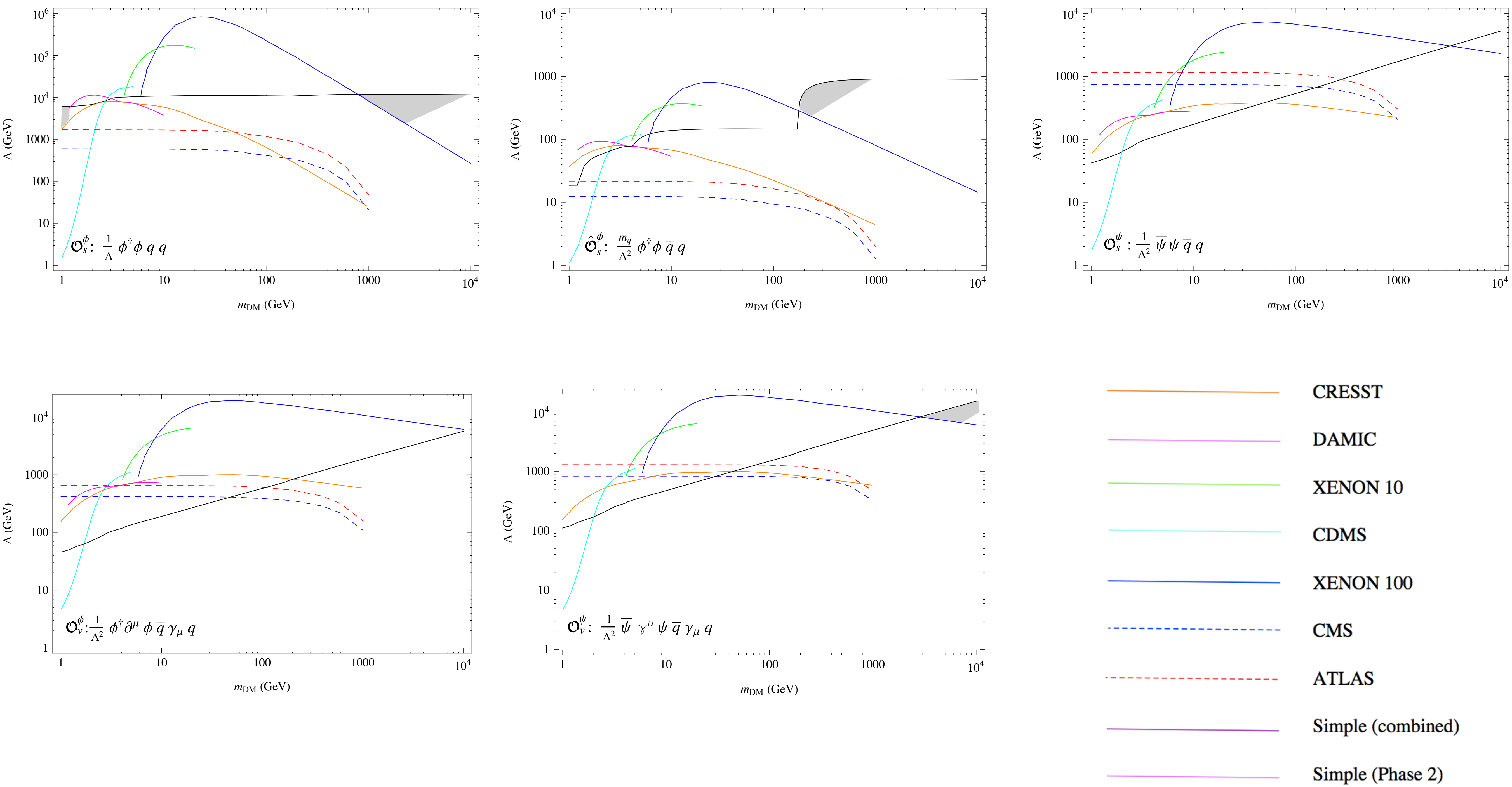


# Constraints on SD operators



# Constraints on SI operators



direct FO of symm yield to light SM dof

limits from direct detection experiments and monojet searches at Tevatron and LHC are very constraining

Main way to avoid these constraints:

Non-minimal flavour structure: e.g. isospin violating or tau-philic, or very special choice of operator...

with ugly exceptions if we want asymmetric DM in natural region $m_X < 10 \text{ GeV}$ then direct FO to SM is disfavoured

$$\Downarrow$$

eliminating symm yield likely implies new dark-sector dynamics involving further light states

Crucial question

how light?

# `Midi' Mass Mediators

- With mediators < few 100 GeV effective operator description breaks-down at LHC and previous results no longer valid

  Resonances and mass thresholds are important

  Large effects on the monojet limits and relic density calculation

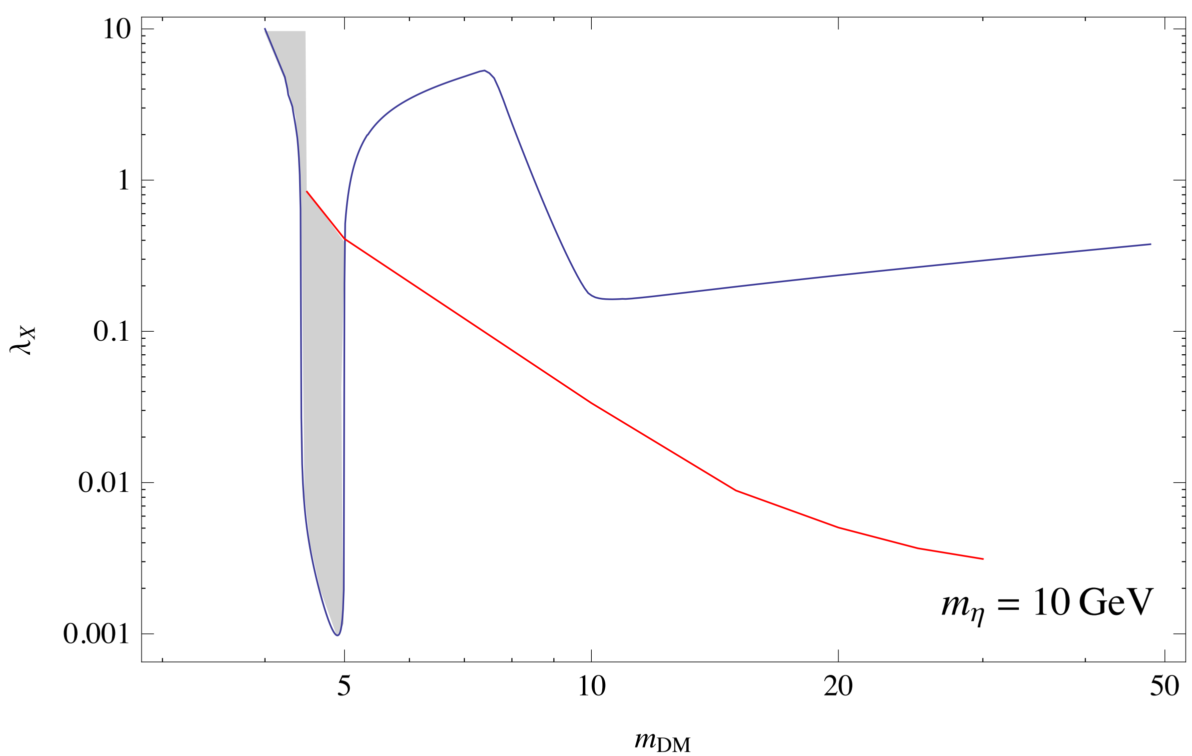
  Notably, constraints from monojet limits are greatly relaxed

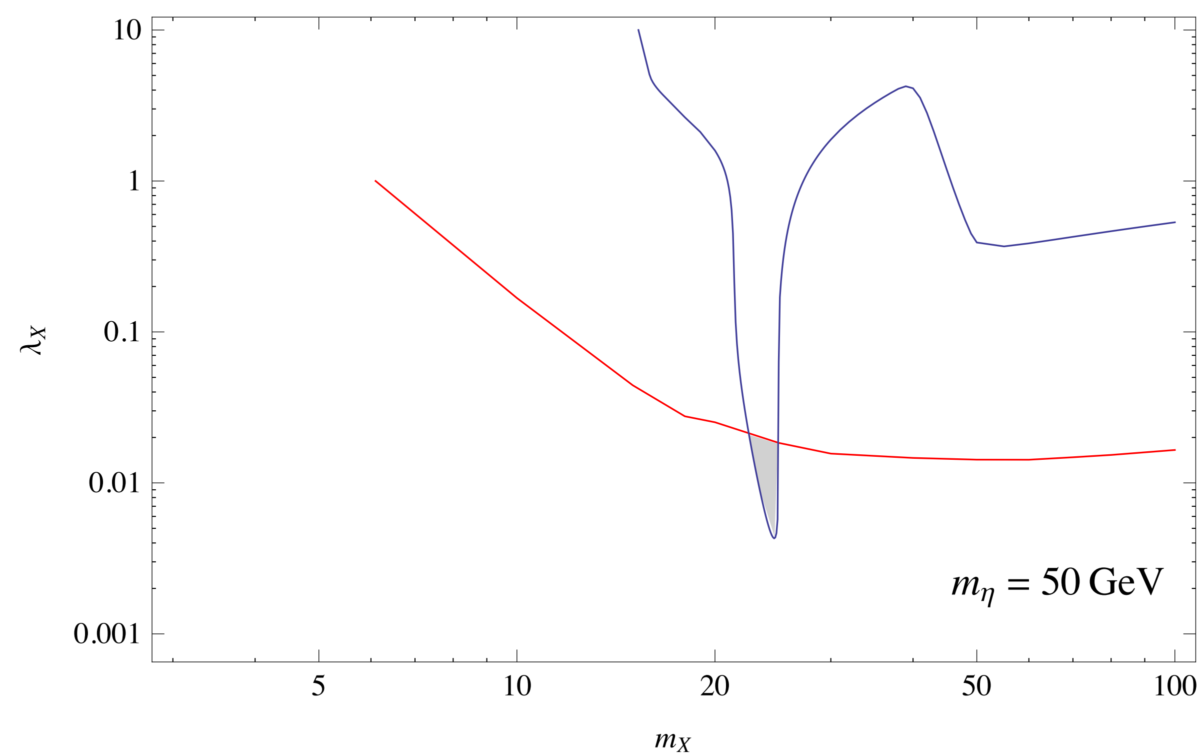
  Direct detection limits are unaffected for mediators >100 MeV as bigger than mom'm transfer & effective op is still good

## Example: scalar midi mediator

Consider a scalar mediator with couplings to quarks due to mixing with the SM Higgs $\theta \sim \frac{m_\eta}{m_H}$

$$\mathcal{L} \supset \lambda_X \eta \bar{\psi}\psi + \sum_q (\lambda' \theta y_q)\eta \bar{q} q$$




Monojet constraints relaxed, but direct detection limits remain unless in resonance region

- Such midi-mass mediating states logically possible and still marginally allow ADM with some fine-tuning (rather like traditional WIMPs)

However a much more interesting possibility in my opinion is that there are very light states in dark sector, like photon or pion/axion in our sector

$$\Downarrow$$

much richer dark-matter dynamics with astrophysical advantages (and signals)

(also potential signals in direct and indirect detection, and precision particle phys expts)

# Light Dark Sector States

- This leads to a rich and potentially extremely complicated set of possible consequences

  Here I'll discuss only the very simplest...

Suppose there exists a single v. light self-conjugate DS state Y coupling to ADM and which is stable or metastable

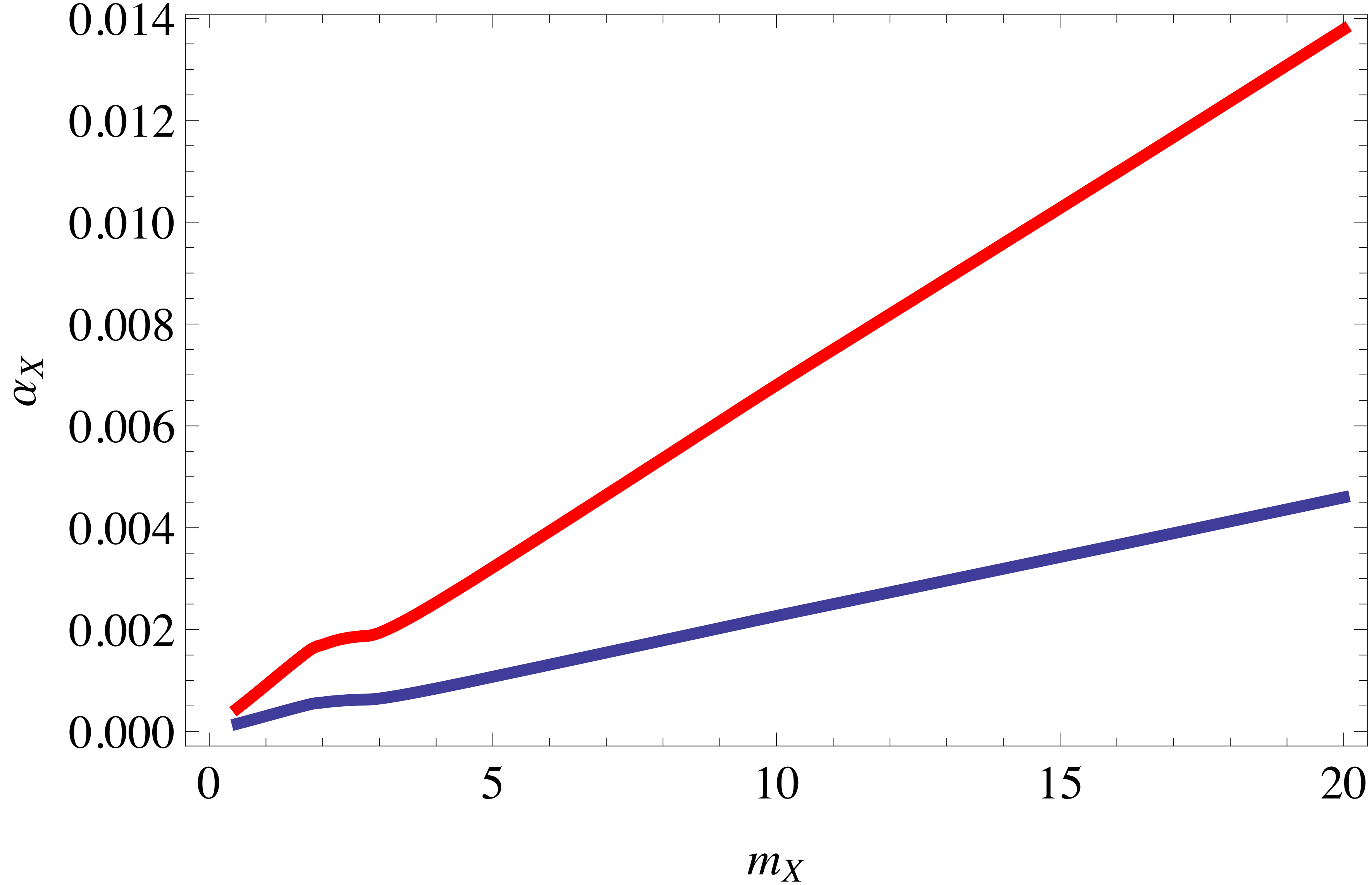
What mass should it have?

Maintaining ADM relation for DM density given symm yield $Y_X + Y_{\bar{X}} = \dfrac{Y_X - Y_{\bar{X}}}{\epsilon}$

$\Downarrow$

$$m_Y < \frac{\epsilon}{10} m_X$$

symmetric component annihilates to Y and the coupling $\alpha_X \equiv \frac{\lambda^2}{4\pi}$ must satisfy




Minimum for efficient annihilation for scalar (blue), & derivatively coupled pseudoscalar (red) mediator

(in pseudoscalar case $\lambda \equiv m_x/f$ )

## Constraints on ADM self interactions

The light state implies elastic & inelastic processes for ADM

Existence of elliptical halos implies average time for O(1) changes to DM velocity is bounded below

$$\Gamma_{\Delta v \sim v} \simeq \int d^3v_1 d^3v_2 f(v_1) f(v_2) n_X \sigma_T v_{\rm rel} \left(\frac{v_{\rm rel}^2}{v_0^2}\right)$$

Galaxy NGC720 constrains the DM momentum transfer cross-section,

$$\sigma_T \lesssim 4.4 \times 10^{-27}\ {\rm cm}^2 \left(\frac{m_X}{\rm GeV}\right)$$

Feng, Kaplinghat, Yu, arXiv:0911.0422.
Lin, Yu, Zurek, arXiv:1111.0293

# Constraints on ADM self interactions

For fermion ADM with scalar light state

$$\sigma_T \simeq \frac{32\pi}{m_\phi^2 m_X^2 v_{\rm rel}^4} \left[\alpha_X m_\phi\right]^2 \left( \ln(1+R^2) - \frac{R^2}{1+R^2} \right)$$

$$R \equiv \frac{m_X v_{\rm rel}}{m_\phi} \qquad \beta \equiv \frac{|V(r \sim m_\phi^{-1})|}{m_X v_{\rm rel}} = \frac{\alpha m_\phi}{m_X v_{\rm rel}^2}$$

upper bound for scalar case

$$\alpha_X \lesssim 2 \times 10^{-3} \left(\frac{m_\phi}{100\ {\rm MeV}}\right)^2 \left(\frac{5\ {\rm GeV}}{m_X}\right)^{1/2}$$

Pseudoscalars have similar form, but as derivatively coupled

$$\sigma_T^{(a)} \simeq 24\pi \left(\frac{27}{16}\right)^2 \frac{1}{m_a^2 m_X^2 v_{\rm rel}^4} \left[\frac{\alpha_X m_a^3}{f_a^2}\right]^2 \left(\ln(1+R^2) - \frac{R^2}{1+R^2}\left(1+\frac{R^2}{2}-\frac{R^4}{6}\right)\right)$$

leading to approximate upper bound for pseudoscalar case

$$\alpha_X \lesssim 20 \left(\frac{10^{-2}}{m_a/f_a}\right)^2 \left(\frac{m_a}{100\ \rm MeV}\right)^2 \left(\frac{5\ \rm GeV}{m_X}\right)^{1/2}$$

Significant tension with annihilation in scalar case, whereas pseudoscalar is quite free due to scattering suppression of $(m_a/f_a)^4$

## Bound states

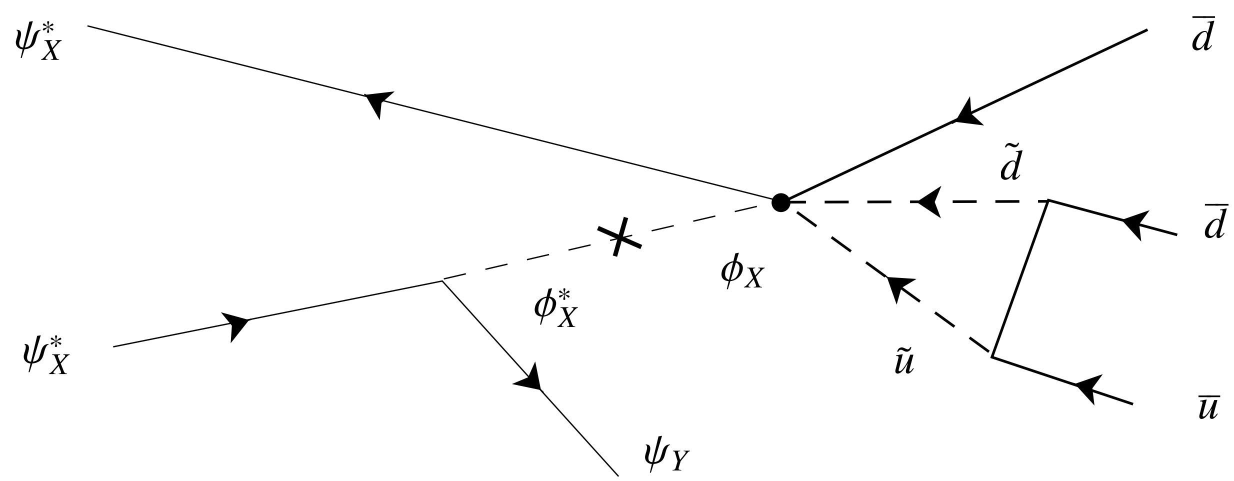
By emitting a light Y quanta the ADM can form WIMPonium bound states

$$\sigma_{\text{capture}} \sim \begin{cases} \dfrac{\pi \alpha'^2}{m_X^2 v^2} & \text{for} \quad m_X \beta^2 > m_Y \\ \dfrac{\pi \alpha'^2}{(m_X^2 m_Y v)^{2/3}} & \text{for} \quad m_X \beta^2 < m_Y \end{cases} .$$

Depending on model details there can be further transitions to deeper bound states, or even annihilation of ADM via

$$X^2 \mathcal{O}_{\mathcal{SM}}$$

# Late-time SM indirect detection signals




# with possible unusual morphology on sky

# Conclusions

ADM is an exciting, constrained, alternative to WIMPs

Requirement that symmetric component removed leads to model independent constraints

Strongly motivates an extended dark sector, with many potential signals