Constraining Asymmetric Dark Matter

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What we've been talking about

- A: statistical
- B: astrophysical
- C: theoretical

- ....D: even more theoretical

The WIMP miracle

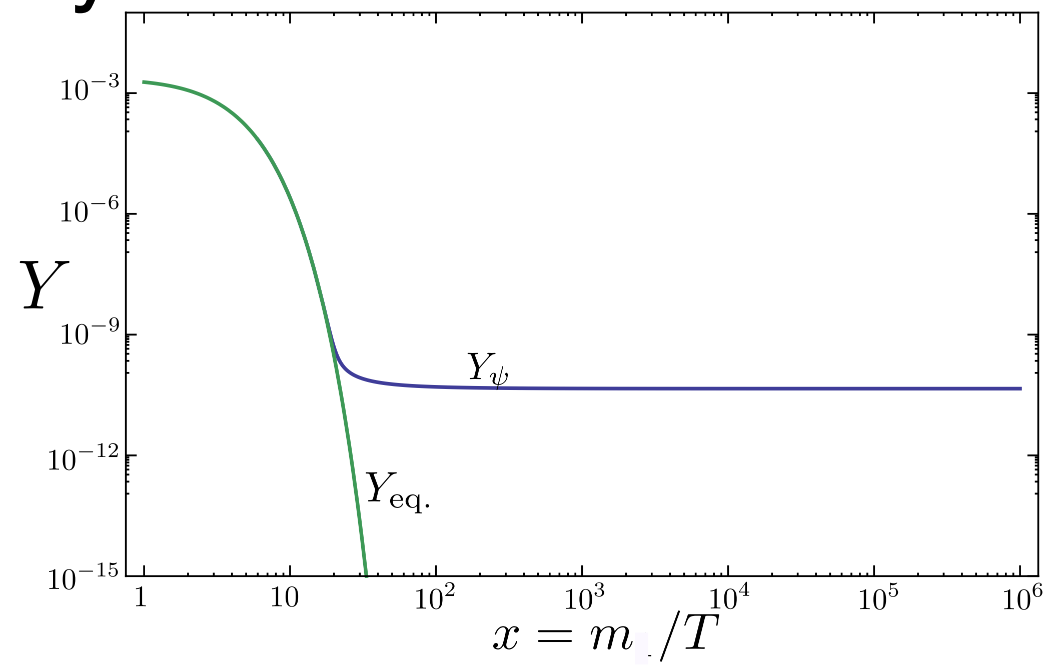
- The Standard Dark Matter story:

- All particles present in thermal bath,continual annihilation/production processes allow n to follow equilibrium density:

$$\frac{dY}{dx} = \frac{-x\langle\sigma v\rangle s}{H(m)}\left(Y^2 - Y_{\rm EQ}^2\right)$$

$$Y \equiv n/s,\ \ x \equiv m/T$$

$$Y_{\rm EQ} \sim x^{3/2} e^{-x}$$



- Eventually these processes freeze out, and Y becomes constant: a thermal relic.

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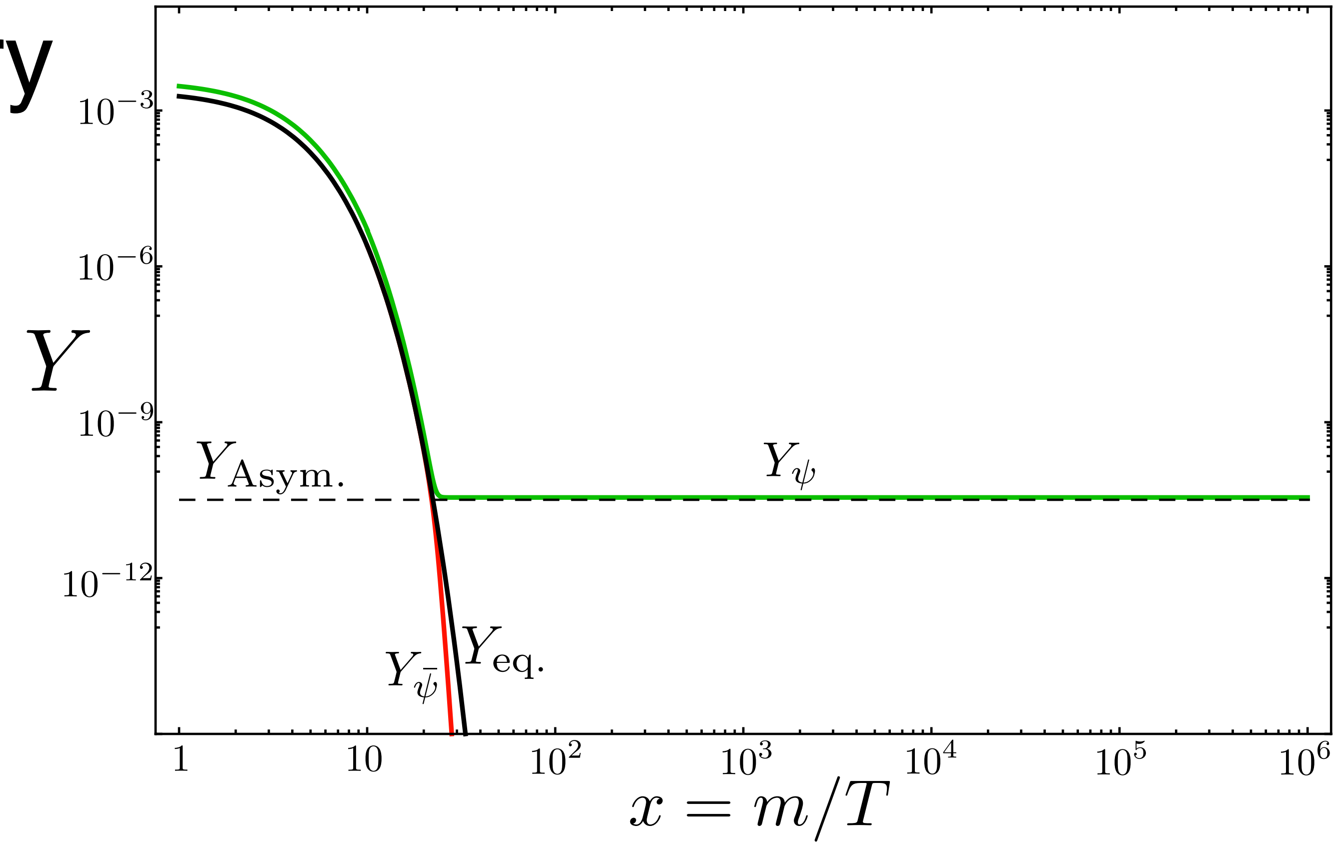
Beyond WIMPs

- If not the WIMP miracle, then what?
- Take inspiration from the one component of the Universe we (mostly) understand.
  - Baryons are *not* a thermal relic. QCD cross-section too large by a factor of $\sim 10^9$
  - We have baryons today because of an initial asymmetry



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Asymmetric Dark Matter

- If asymmetry explains baryons, why not dark matter as well?
- Take guidance from $\Omega_{\rm DM}/\Omega_B = \mathcal{O}(1)$, rather than from the WIMP miracle.
- Assume this relation is not a coincidence, but a hint of deeper physics. Then:
  - DM not a thermal relic.
  - Production of DM related to the production of baryons
  - Baryons - and thus DM (X) - contains an asymmetry: X but not $\bar{X}$

Asymmetric Dark Matter

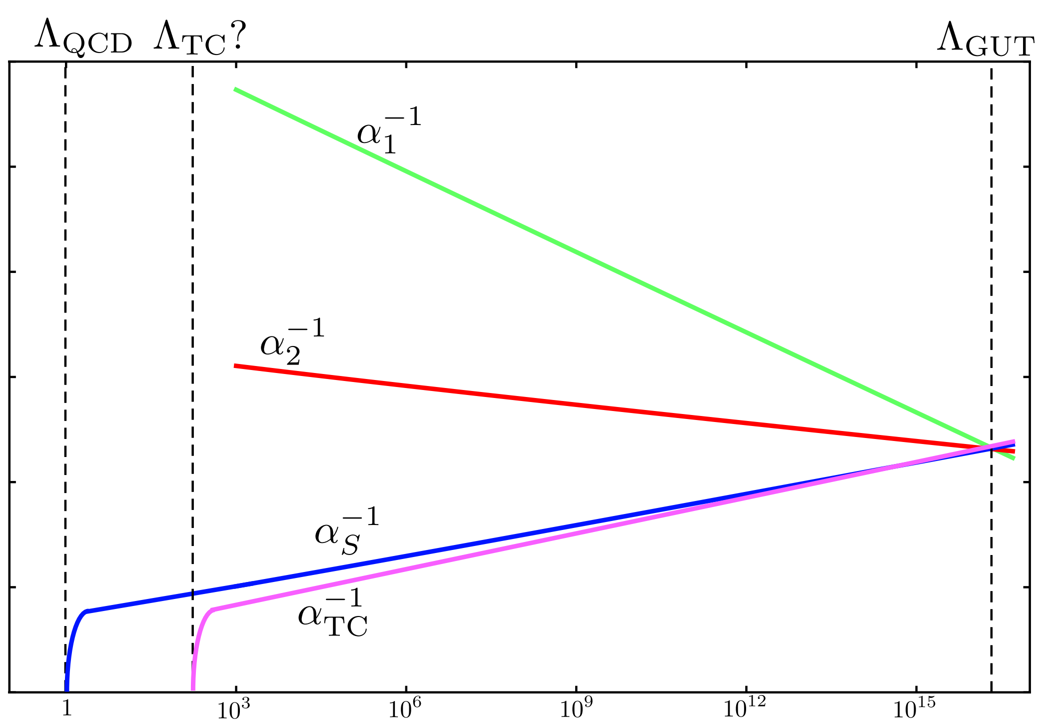
- "Dark" Sakharov conditions:
  - CP violation
  - Departure from thermal equilibrium
  - X-symmetry violation

- Additional sector to "hide" CP violation that can seed a B-asymmetry opens the door for many new solutions for baryogenesis.
- Here, I will remain agnostic as to the initial source of the asymmetry.

The Original ADM

- An idea with a lengthy history
  - Originally postulated in technicolor models

    Nussinov (1985), Barr, Chivukula, Farhi (1990)
  - Electroweak symmetry broken by condensate of a new strongly interacting force with confinement at low energies (analogous to strong nuclear force)
  - Leads to “technibaryons,” very similar to baryons



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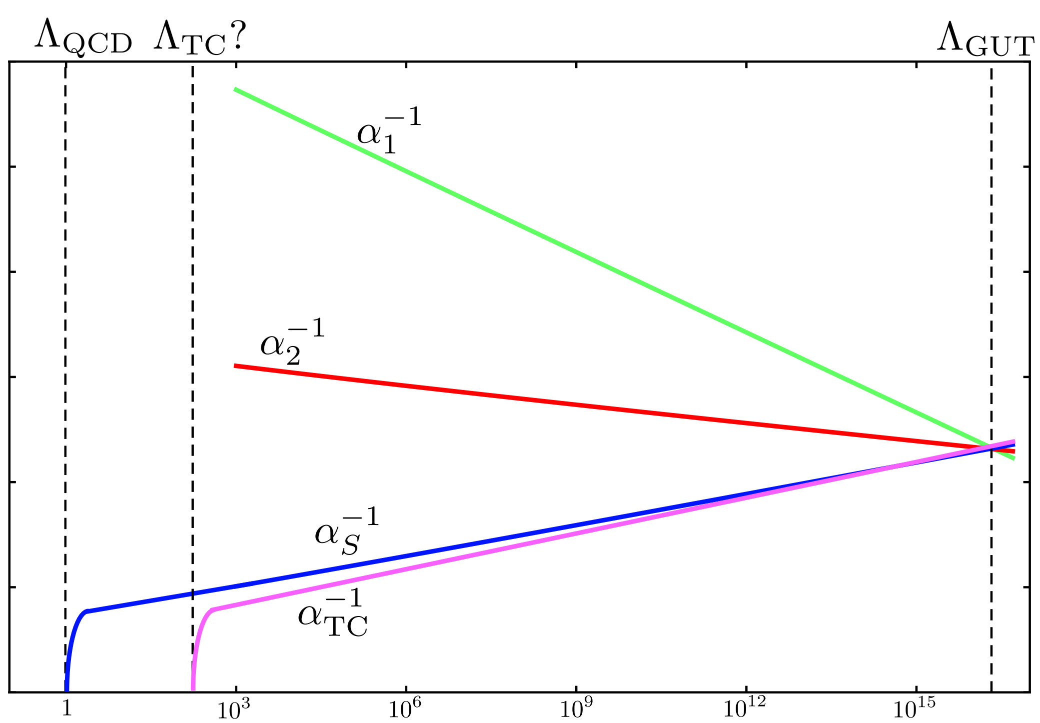
The Original ADM

- Some of these technibaryons are charged under $SU(2)_L$, results in sphaleron interactions at high temperatures ($T \gtrsim 200 \text{ GeV}$)
  - These interactions would transfer any asymmetry from baryons into technibaryons (or vice versa)
  - LEP put strong constraints on most technicolor models.



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The New ADM

- Spurred by light DM signals and general interest in non-supersymmetry-like models:

  D.E. Kaplan *et al* 0901.4117
  Cohen & Zurek 0909.2035
  MRB & Randall 1009.0270
  .... (see Refs. [1-2] of 1109.2164)

- Phenomenological: bottom-up, don't require solutions to hierarchy/naturalness

- Plenty of names to choose from: Xogenesis, aidnogenesis, darkogenesis, hylogenesis....

The New ADM

- Lots of freedom in how asymmetry in visible/dark sectors related:
    - Explicit Baryon/Lepton # violating operators
    - Electroweak Sphalerons
    - Sphalerons of new gauge groups

- Can lead to a wide range of masses:
    - From ~5 GeV to ~TeV

What is different about ADM?

- What does every ADM model need?
  - Needs to be *asymmetric*
  - So no symmetric (thermal) component
    - (I’ll assume $< 10\%$ of total)

- Requires $\sigma_{\rm ADM} \gtrsim \sigma_{\rm Thermal} \sim 1 \text{ pb}$

  - So: large interactions with *something*

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Effective Operators

- Assume ADM annihilates into SM quarks, parametrized by an effective operator with scale

$$
\begin{aligned}
\mathcal{L}_{S,S} &= \frac{m_q}{\Lambda^2}\chi_S^*\chi_S\bar{q}q \\
\mathcal{L}_{S,P} &= \frac{m_q}{\Lambda^2}\chi_S^*\chi_S\bar{q}\gamma^5 q \\
\mathcal{L}_{S,V} &= \frac{1}{\Lambda^2}\chi_S^*\partial_\mu\chi_S\bar{q}\gamma^\mu q
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{F,S} &= \frac{m_q}{\Lambda^3}\bar{\chi}_F\chi_F\bar{q}q \\
\mathcal{L}_{F,P} &= \frac{m_q}{\Lambda^3}\bar{\chi}_F\gamma^5\chi_F\bar{q}\gamma^5 q \\
\mathcal{L}_{F,V} &= \frac{1}{\Lambda^2}\bar{\chi}^F\gamma_\mu\chi_F\bar{q}\gamma^\mu q \\
\mathcal{L}_{F,A} &= \frac{1}{\Lambda^2}\bar{\chi}^F\gamma^5\gamma_\mu\chi_F\bar{q}\gamma^5\gamma^\mu q \\
\mathcal{L}_{F,T} &= \frac{1}{\Lambda^2}\bar{\chi}^F\sigma_{\mu\nu}\chi_F\bar{q}\sigma^{\mu\nu} q
\end{aligned}
$$

- Lower limits on Λ from direct detection, collider searches, applicability of formalism ($m_\chi < 2\pi\Lambda$)
- Upper limits from over-annihilation of ADM

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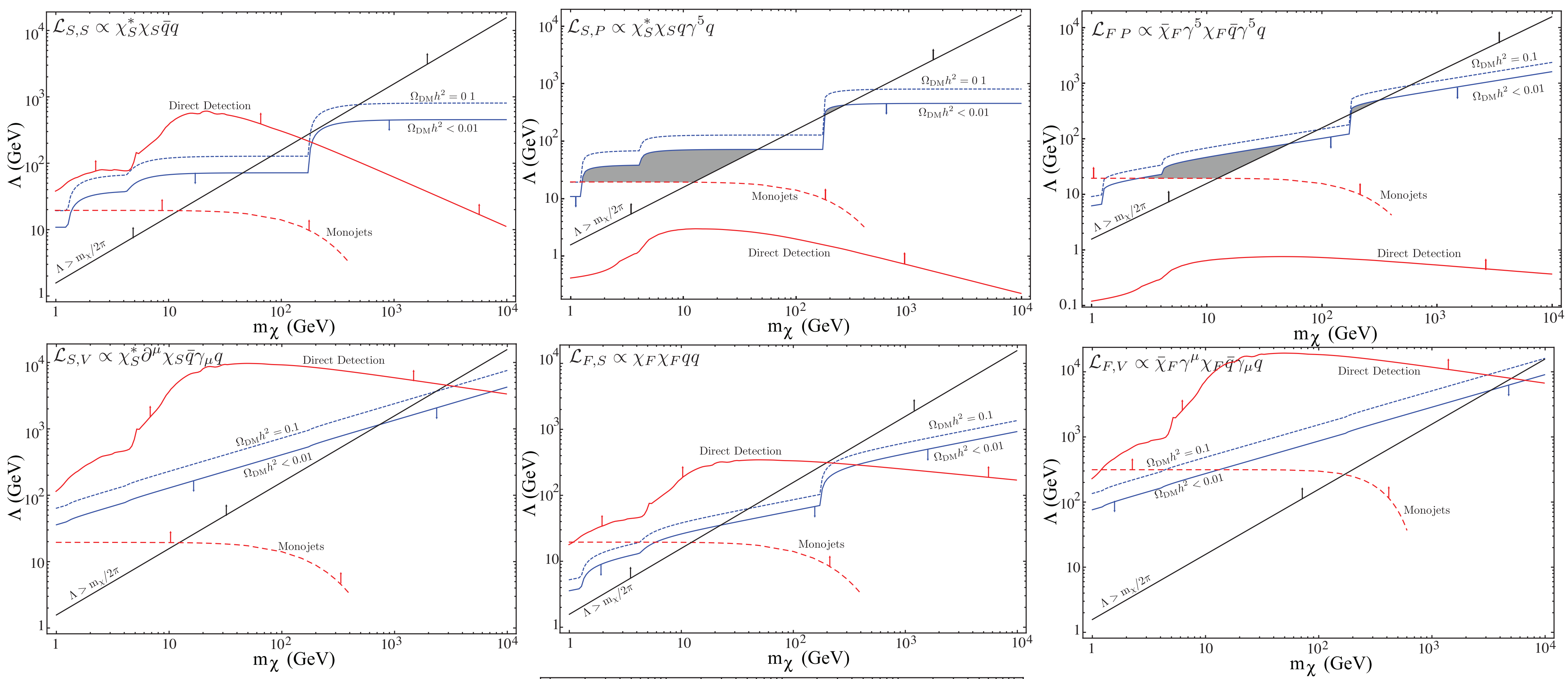
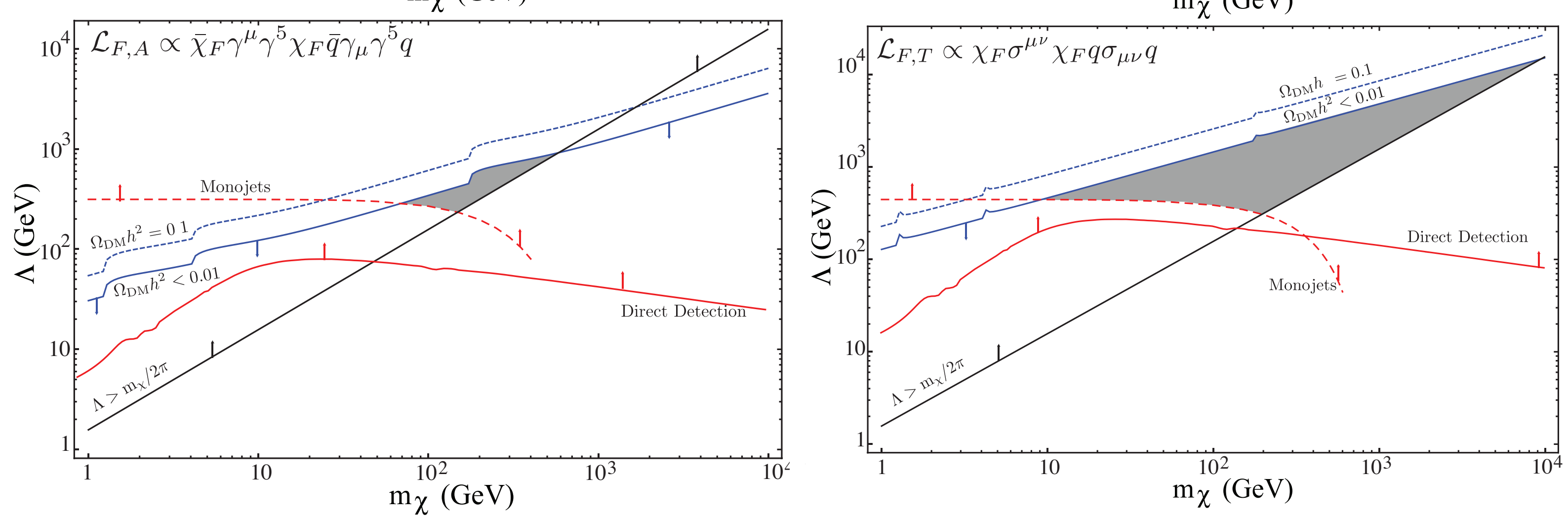
Effective Operators



MRB 1104.1429



Effective Operators

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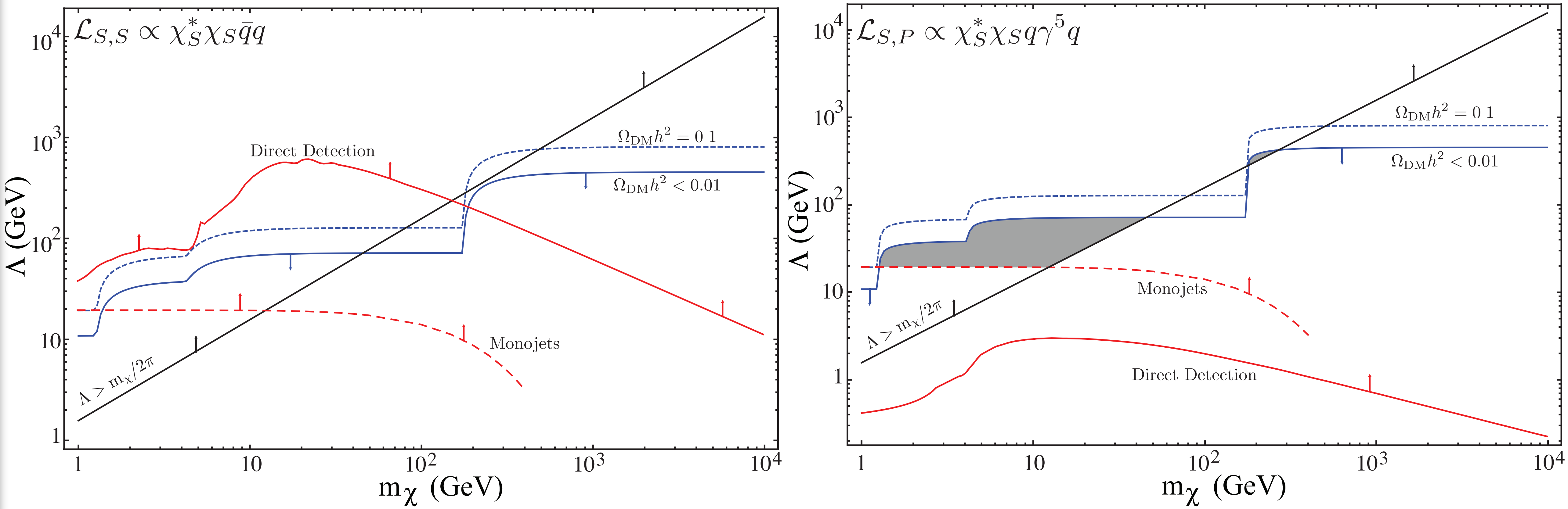
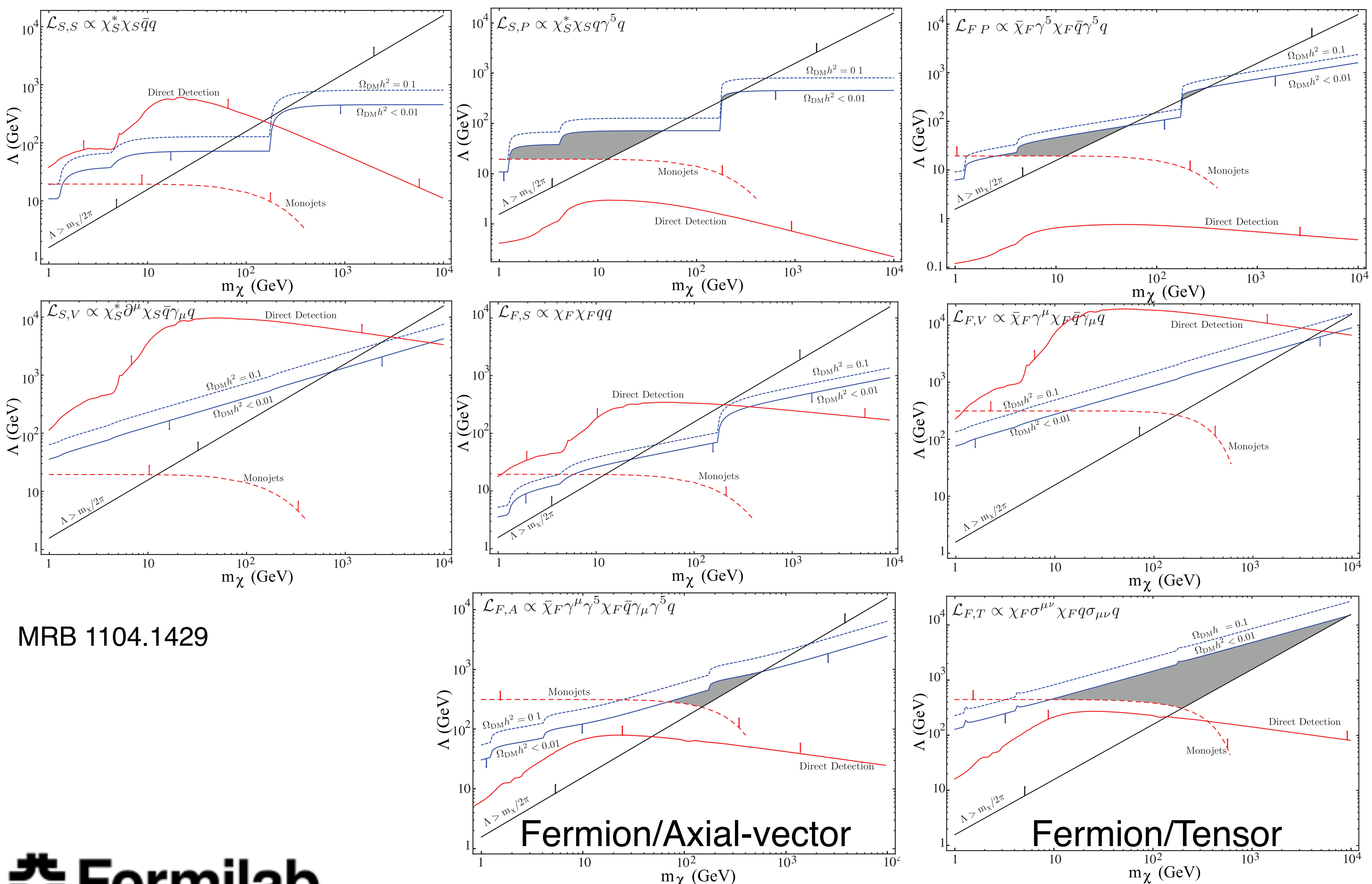


Effective Operators

Scalar/Pseudoscalar

Fermion/Pseudoscalar



MRB 1104.1429

Implications

- This parameter space is highly constrained. Can relax these constraints by
  - having ADM annihilate into leptons,
  - or annihilate into new light dark particles,
  - or if the effective operator formalism doesn't apply.
    - New light vector bosons?
    - Requires new particles close in mass to DM
- All of these interesting avenues for ADM model building. The last especially is suggestive of technicolor-like dark matter.

Indirect Detection

- ADM consists of X but not $\bar{X}$
  - Naive expectation is therefore no indirect detection signals are possible
    - (Bad news for this workshop)

- However, DM is a singlet under the unbroken SM gauge groups $SU(3)_C \times U(1)_{\rm EM}$
  - Like with neutrinos, it is therefore generically possible to write Lagrangians containing "Majorana" $\Delta X = 2$ mass terms

$$\mathcal{L} \supseteq m_D X\bar{X} + m_M(XX + \bar{X}\bar{X})$$

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Oscillating Dark Matter

- Combination of Dirac and Majorana mass terms leads to split mass eigenvalues:

$$m_1 = m_D - m_M, \; m_2 = m_D + m_M$$

- DM produced as X will oscillate into $\bar{X}$ with a timescale of $\tau = \Delta m^{-1}$
- Combined with large annihilation cross-section, can lead to significant energy injection at late times

- With $\tau_{\text{Universe}}^{-1} \sim 10^{-41}\ \text{GeV}$, possibility of extremely strict constraints on ADM mass matrix
  - Alternatively, a positive signal could probe extremely high scale physics

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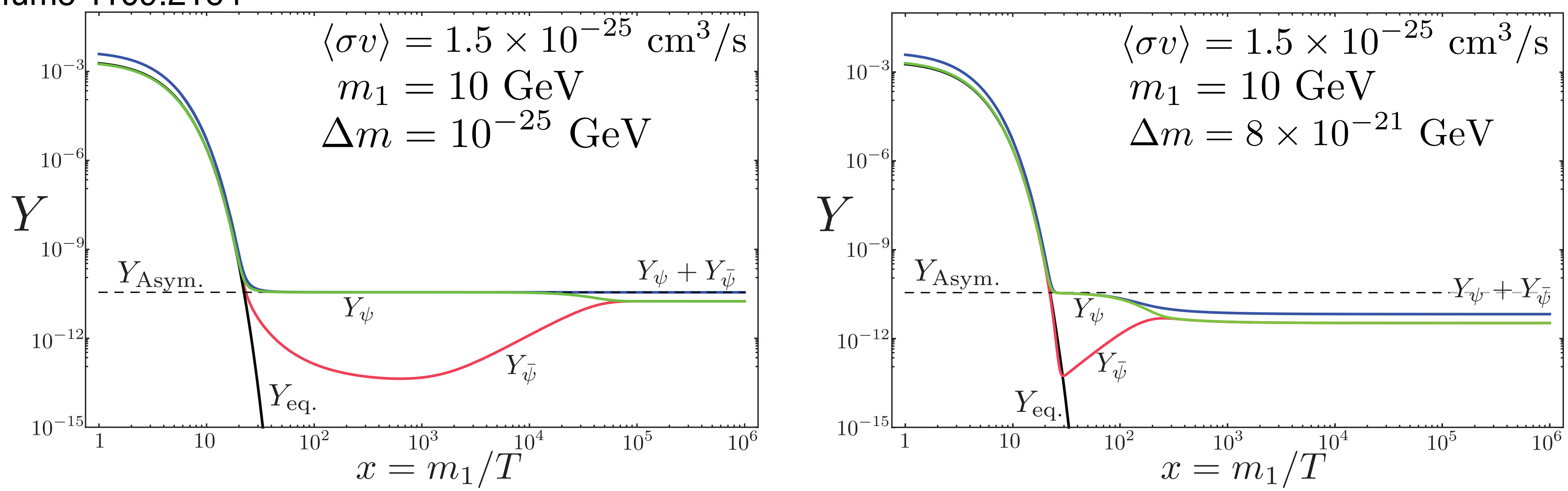
Oscillating Dark Matter

- Oscillation time τ must be longer than $t_{\mathrm{freeze-out}}$
- If $\tau \sim t_{\mathrm{freeze-out}}$, annihilation can re-start (“thaw”) and resymmetrize the ADM

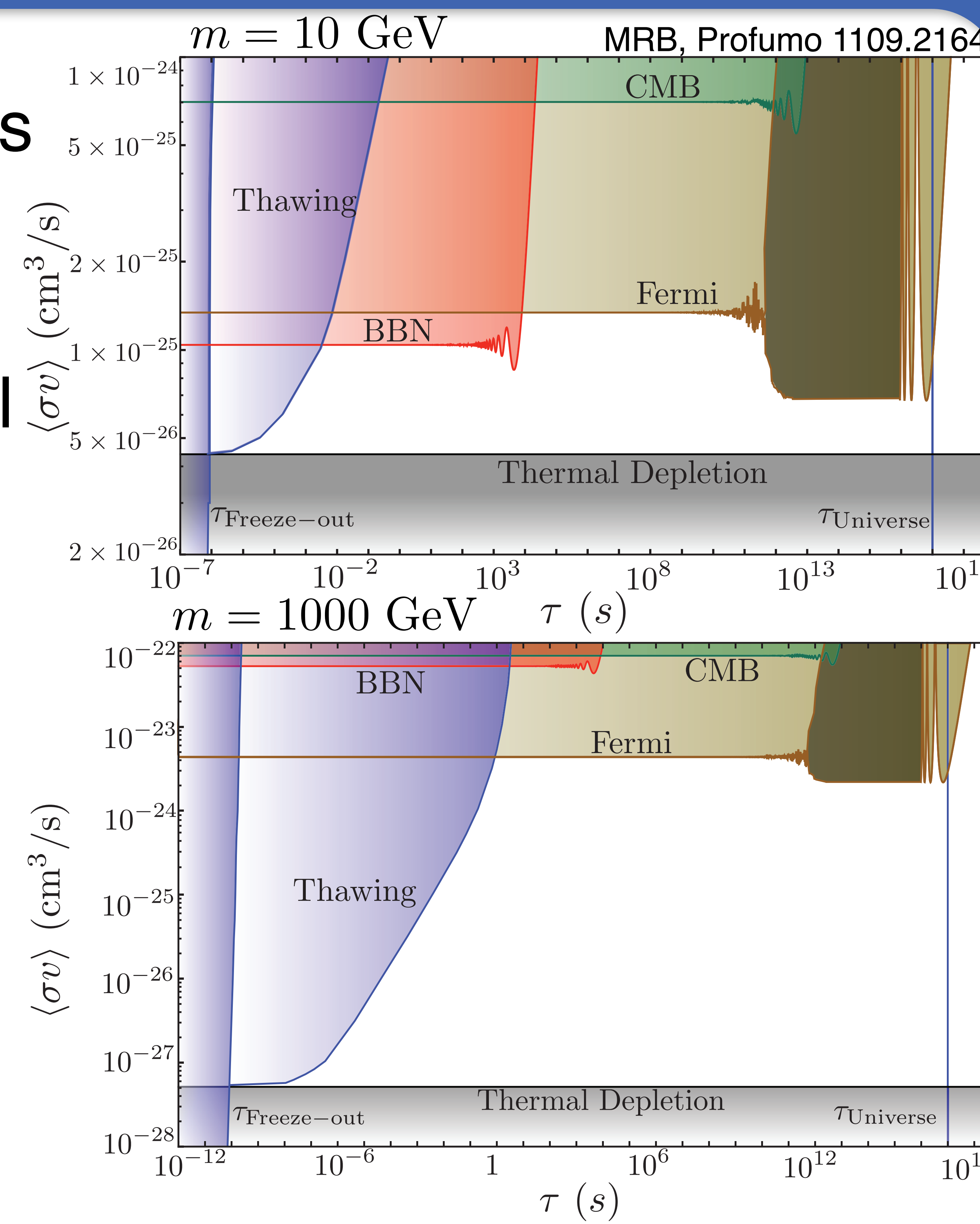
MRB, Profumo 1109.2164



- Constraints (for large $\langle\sigma v\rangle$) when oscillation time characteristic timescale of BBN, CMB, and $\leq$ annihilation in dwarf galaxies in the present day (Fermi dwarf stacking)

Constraints & Implications

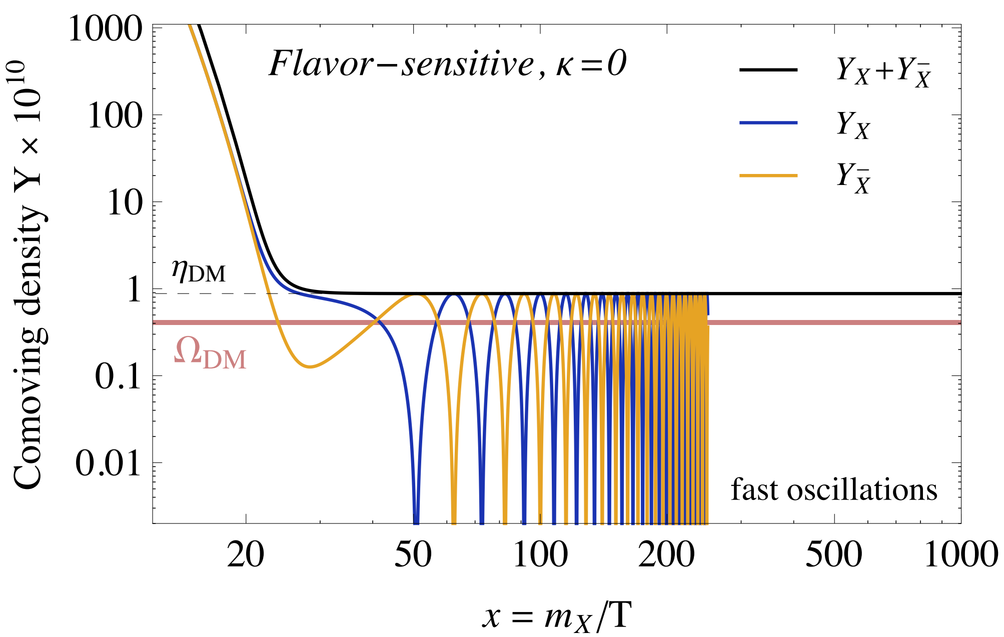
- Fairly stringent constraints on oscillation time $\tau = \Delta m^{-1}$
- Outside of relatively small window of allowed $\langle\sigma v\rangle$, find $m_M \lesssim 10^{-41}$ GeV
  - (Derived for fermions)
- Implies some symmetry absolute forbids $\Delta X = 2$ mass terms



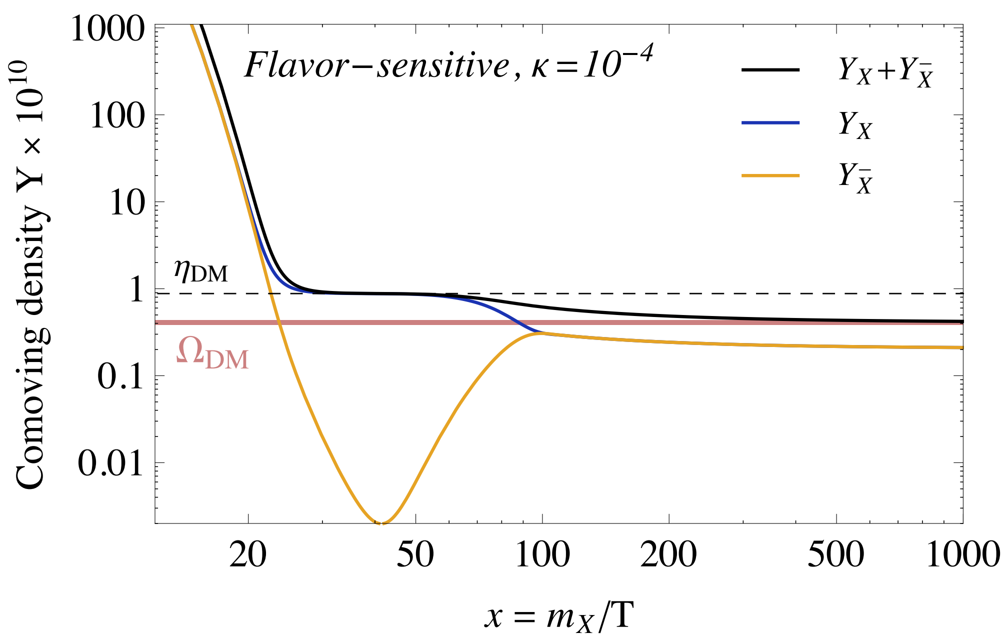
Constraints & Implications

- Work by Cirelli *et al* (1110.3809) and Tulin *et al* (1202.0283) followed up in more detail.
- "Flavor" ($X/\bar{X}$)-sensitive interactions need scattering off of thermal bath to break coherence in oscillations

Tullin *et al* 1202.0283



Oscillation but no annihilation



"washout"/"thawing"

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What does it all mean?

- This is a conference on gamma rays
- Naive prediction of ADM is that no annihilation should occur in the sky today.
  - Bad news for indirect detection

- But non-observation (combined with direct detection/collider results) has potential to probe physics up to Planck scale

- Depending on interactions in early Universe, could have very large cross sections today
  - More (type D) theory work to be done here

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