Constraining Asymmetric Dark Matter

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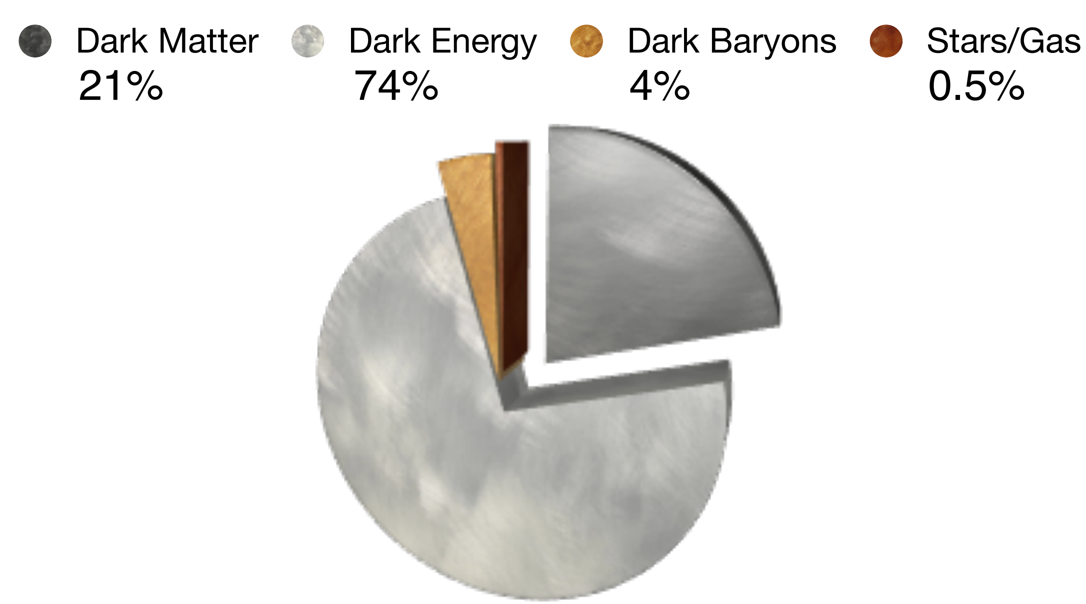
What do we know about Dark Matter?

- There's a lot of it: $\Omega_{\rm DM}/\Omega_B \approx 4.8$
- It interacts gravitationally
  - ... and not via EM/strong forces.
- It's non-relativistic.



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Aquarius Simulation

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Bullet Cluster

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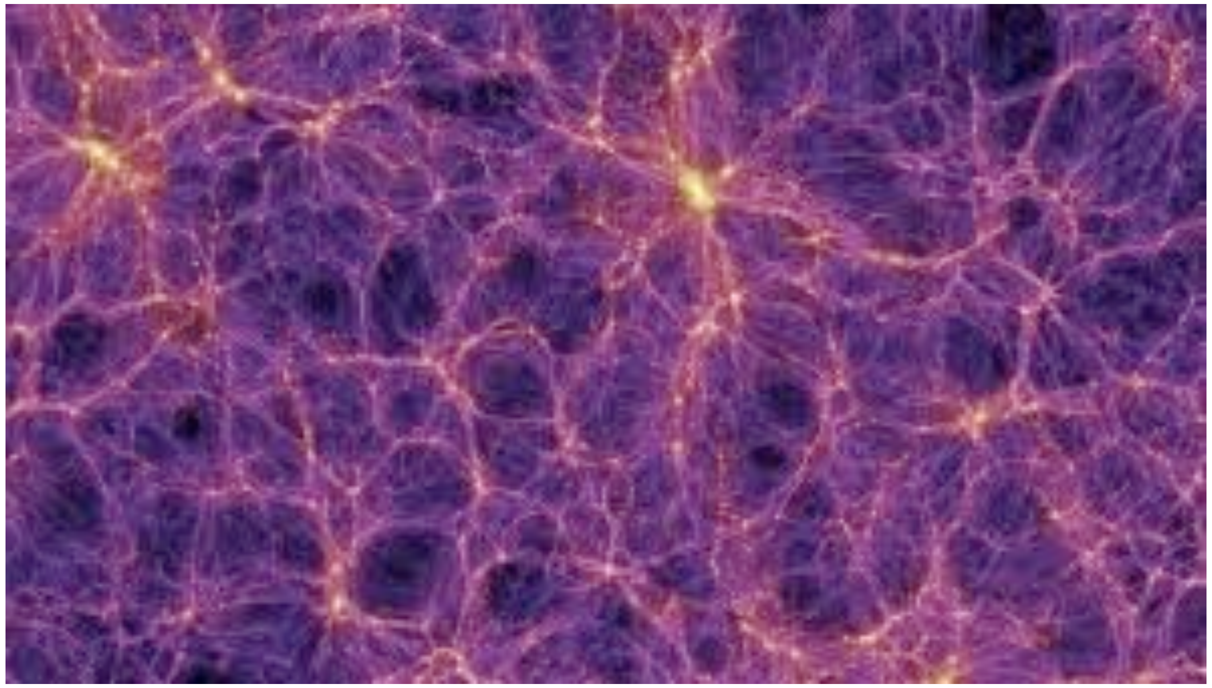

Millennium Simulation

What don't we know about DM?

- Everything else.
  - Mass?
  - Interactions beyond gravity?
  - Origin?
  - Connection to rest of particle physics?
    - Relation to Naturalness/Hierarchy problems?
    - Relation to Baryons?

- Where to start?

Assume a Connection

- Naturalness and Hierarchy problems:
- How to ensure stability of weak scale against power-law corrections

$$m_Z, m_{\text{Higgs}} \ll m_{\text{Planck}}$$

- Several solutions on the market (supersymmetry, extra dimensions)
  - All require new particles with electroweak couplings and $\mathcal{O}(100~\text{GeV})$ masses.
  - Contains an uncharged, color neutral massive particle.

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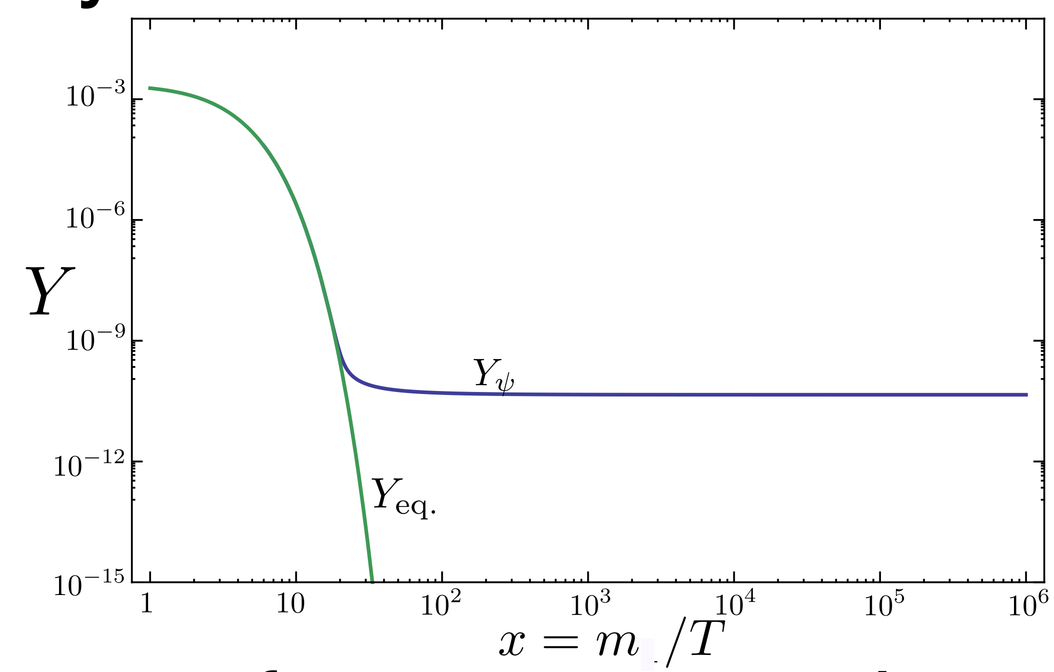
The WIMP miracle

- How would such a Weakly Interacting Massive Particle behave in the early Universe?
- 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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The WIMP miracle

- A large $\langle \sigma v \rangle$ means equilibrium lasts longer, resulting in lower $Y(\infty) \propto \langle \sigma v \rangle^{-1}$
- An intriguing coincidence:

$$\langle \sigma v \rangle \approx 3 \times 10^{-26} \text{ cm}^3/\text{s} \sim \frac{g^4}{m_W^2} \Rightarrow Y \sim 10^{-10} \Rightarrow \Omega_{\text{DM}} h^2 \sim 0.1$$

- That is, the $\langle \sigma v \rangle$ expected from a $SU(2)_L$ particle with weak-scale masses gives about the right amount of dark matter
  - *i.e.* The WIMP Miracle

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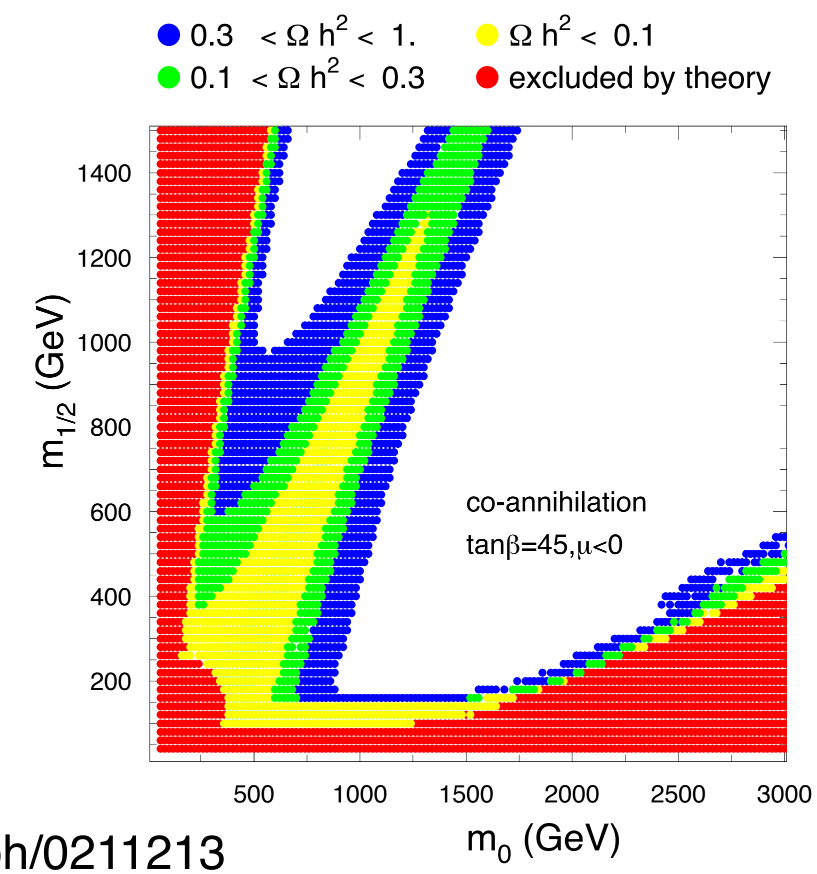
How Miraculous?

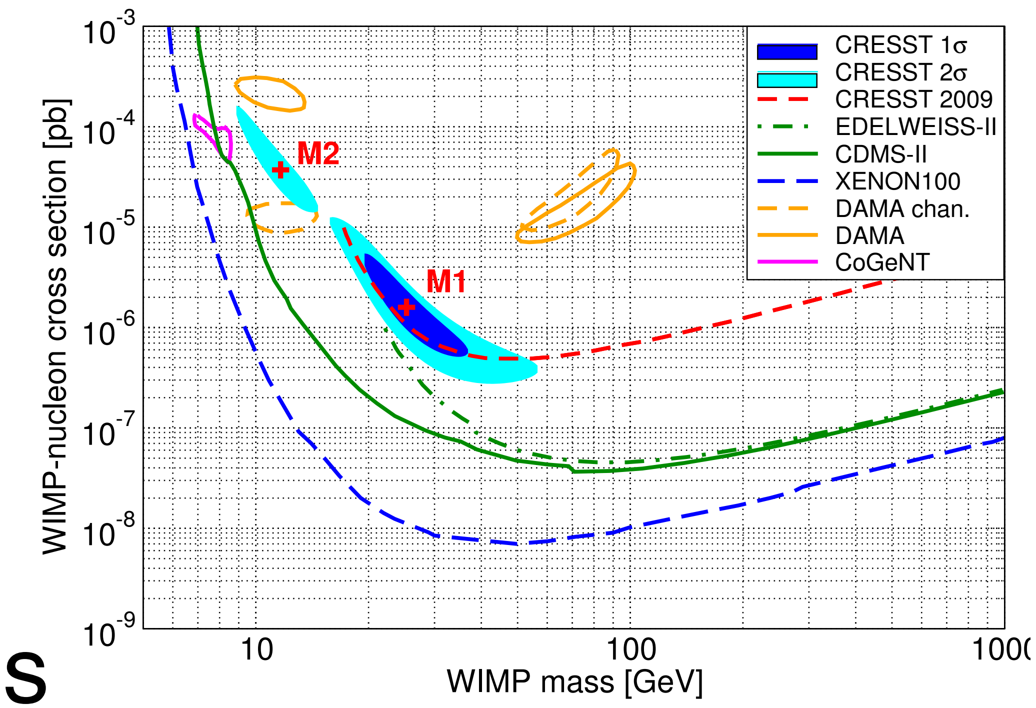
- A very fruitful idea, lots of collider phenomenology, predictions for (in)direct detection, *etc.*
  - Realized in explicit models: notably supersymmetric $\tilde{\chi}_0$
- However: not universally true that a weak-scale interaction leads to a viable dark matter candidate.
- Some degree of tuning necessary
- And obviously, no WIMP yet seen



Baer *et al* hep-ph/0211213

Anomalies

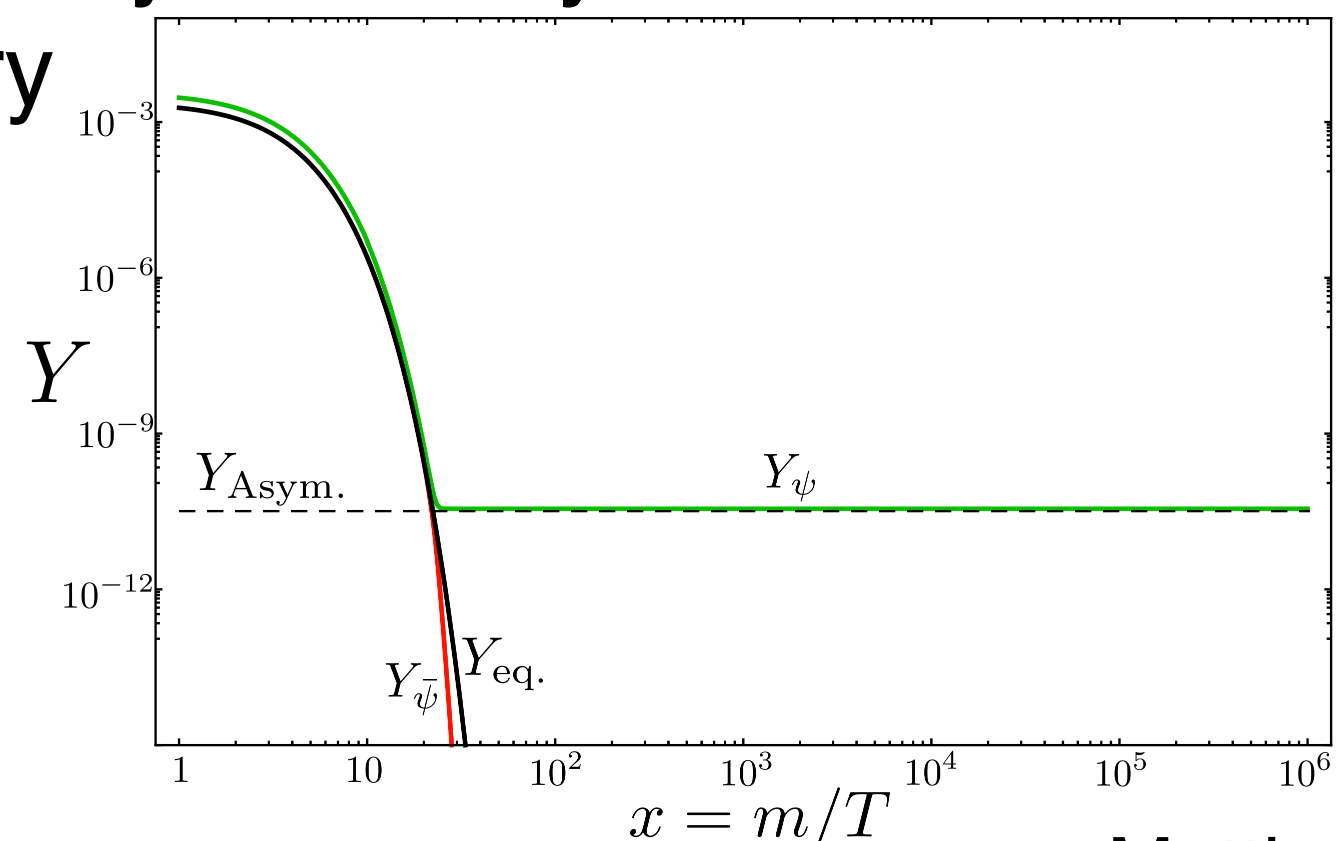
- DAMA/Libra, CoGeNT, CRESST have reported signals broadly consistent with $\sim 7 - 10\ \mathrm{GeV}$ DM
- Not impossible for WIMPs, but not the naive prediction



- Fermi/PAMELA anomalies require leptophilic DM with large annihilation cross sections
  - Possible/likely that this is astrophysics
- Regardless: A good time to look at alternatives to WIMPs

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 $\Omega_{\mathrm{DM}}/\Omega_B = \mathcal{O}(1)$, 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 $\bar{X}$

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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.

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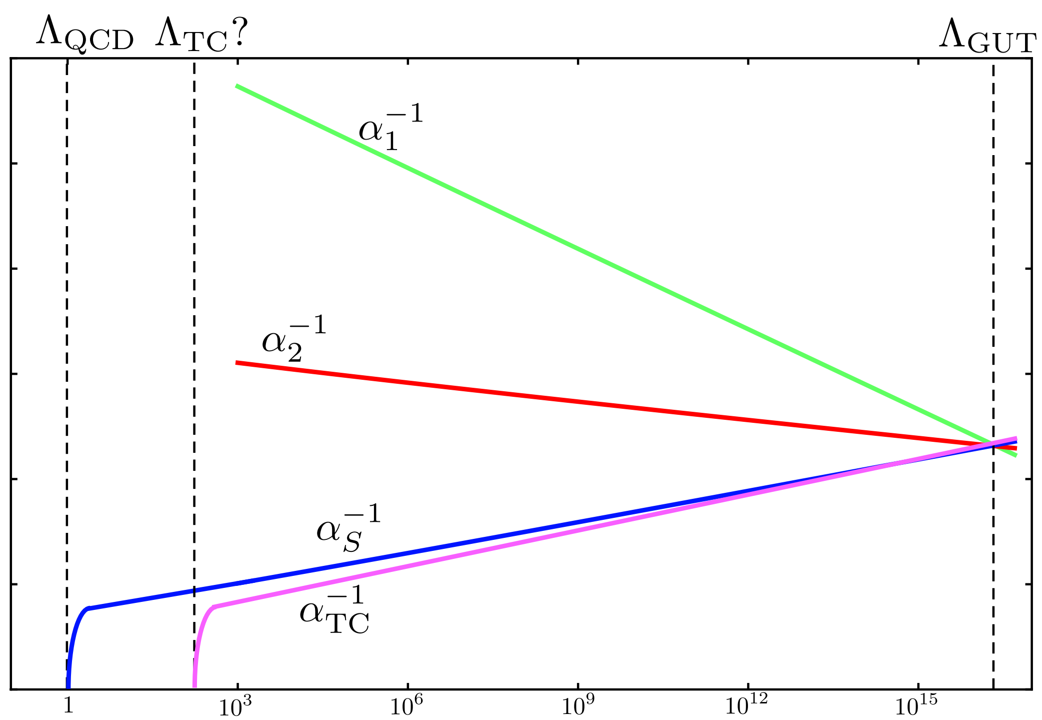
The Original ADM

- 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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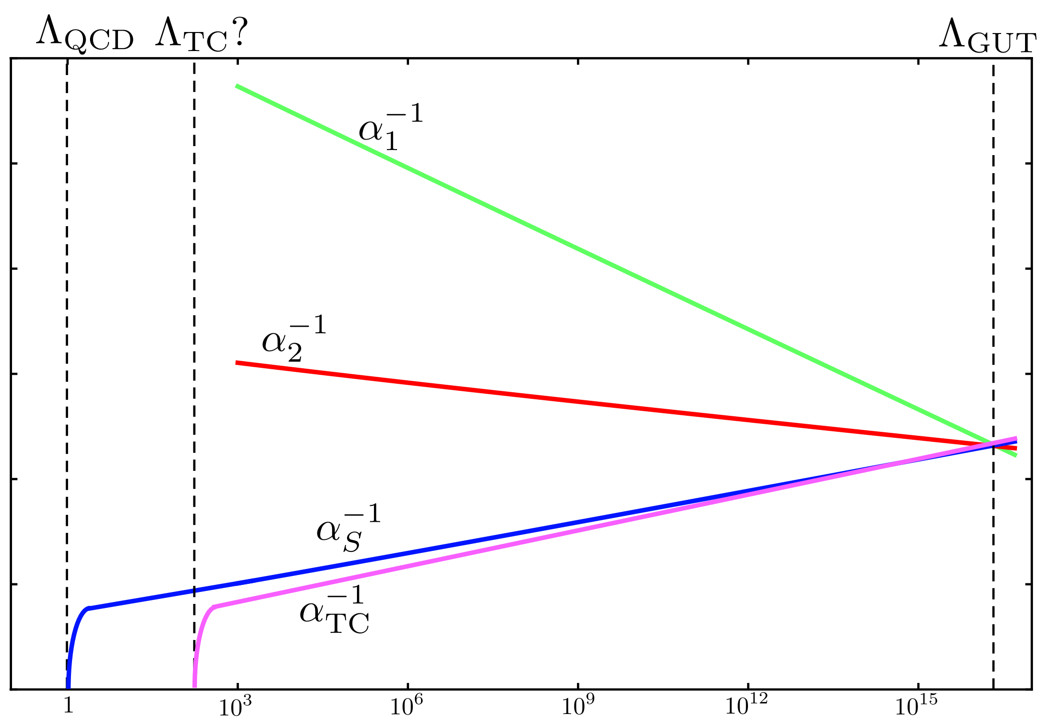
The Original ADM

- Some of these technibaryons are charged under $SU(2)_L$, results in sphaleron interactions at high temperatures ($T \gtrsim 200~\mathrm{GeV}$)
  - 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....

Predictions of ADM

- Out of the many models on the market, are there any universal statements that can be made?
  - That is, what can we say about all ADM models?
  - Mass?
  - Interactions?
  - Indirect Detection?

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First Guess

- Naive expectation is that relating these asymmetries forces $n_X = n_B$, implying

$$m_X = \frac{\Omega_{\rm DM}}{\Omega_B} m_{\rm proton} \sim 5 \text{ GeV}$$

- Which of course is very interesting if you're interested in the DAMA/CoGeNT/CRESST anomalies

  - But how solid is this conclusion?

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Transfer Mechanisms

- To determine n_X/n_B, and thus m_X, need to specify the process in which an asymmetry in one sector gets converted into the other.

- Many options:
  - Sphalerons
  - Explicit violation of global symmetries
    - Out of equilibrium decays
  - Some combination of above

- Can't look at all in detail here.

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Transfer Mechanisms

- Asymmetric number density of particle implies a non-zero chemical potential

$$n_i = g_i f(m_i/T) T^2 R(T)^3 \mu_i$$

$$f(x) = \frac{1}{4\pi^2} \int_0^\infty \frac{y^2 dy}{\cosh^2\left(\frac{1}{2}\sqrt{x^2+y^2}\right)}$$

- If an operator exists that allows $X \leftrightarrow B$, then $\mu_X = \mathcal{O}(1)\mu_B$ and

$$f(m_X/T_D) = \frac{g_B f(0)}{g_X \times (\mu_X/\mu_B)} \frac{\rho_{\rm DM}}{\rho_B} \frac{m_{\rm proton}}{m_X}$$

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Transfer Mechanisms

$$f(m_X/T_D) = \frac{g_B f(0)}{g_X \times (\mu_X/\mu_B)} \frac{\rho_{\rm DM}}{\rho_B} \frac{m_{\rm proton}}{m_X}$$

- Assume transfer operator becomes ineffective ("shuts off") at temperature T_D. Then present number density set by $n_i(T_D)$, and we have two regimes:
  - Relativistic: $m_X \ll T_D$, $m_X = \mathcal{O}(1) \times 5~\text{GeV}$
  - Non-relativistic: $m_X \gtrsim T_D$,

$$m_X = \mathcal{O}(1) \times f^{-1}(m_X/T_D) \times 5~\text{GeV}$$

- Without additional machinery in the theory, non-relativistic solutions tend to have $m_X \sim 8 - 10 T_D$

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Explicit Breaking Terms

- Can transfer asymmetry via explicit $X-B$ breaking.
- Example: in the context of supersymmetry:

$$\mathcal{L} \supseteq \frac{1}{M^2} X X \tilde{u}\tilde{d}\tilde{d}$$

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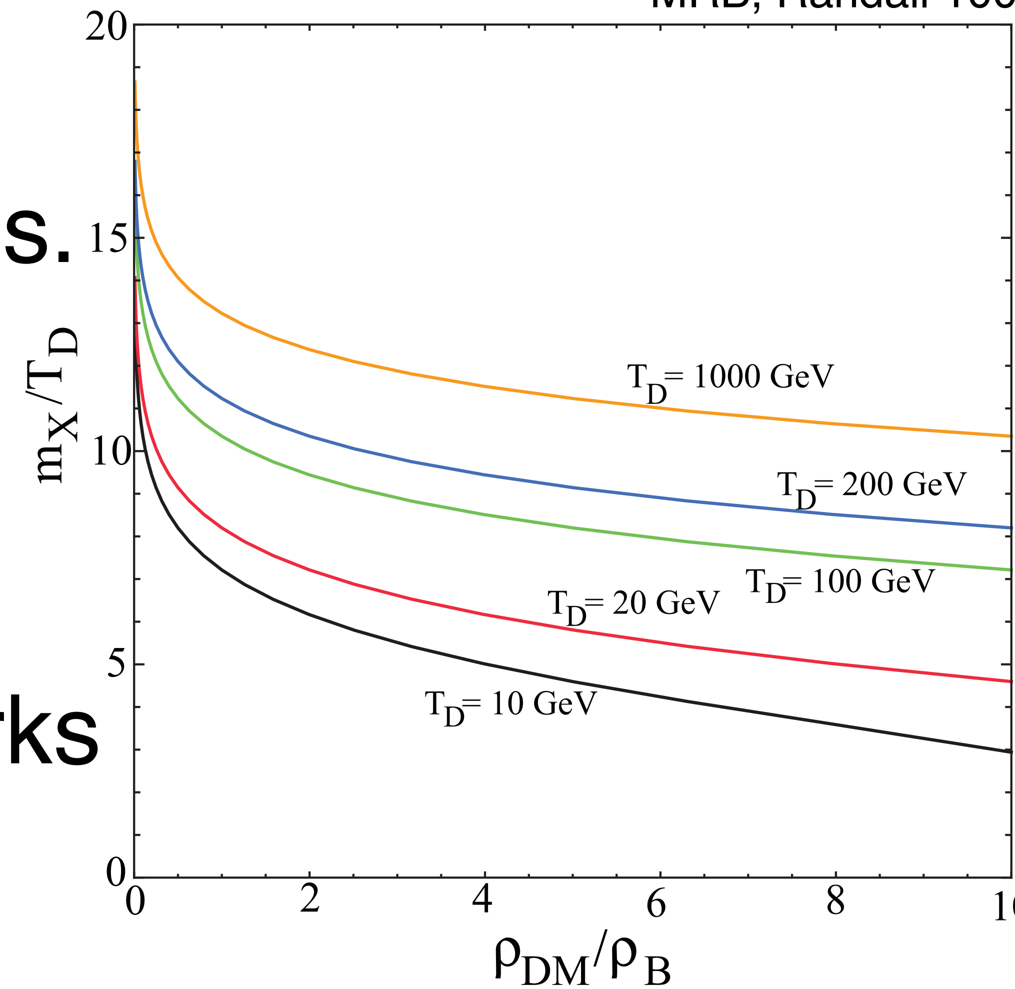
- Can have both relativistic and non-relativistic solutions.
  - T_D a free parameter
  - Non-rel. solution

$$m_X \sim 8 - 10 T_D$$

  - Collider bounds on squarks tend to push DM heavy



Sphalerons

- In the Standard Model, there is a mechanism for breaking both B and L:
  - $SU(2)_L$ sphalerons.

- A sphaleron is a non-perturbative gauge configuration, separating vacua with different numbers of fermions charged under the gauge group.
- Action of the sphaleron creates 1 of each left-handed fundamental fermion of the group, destroys 1 of each right-handed fermion.

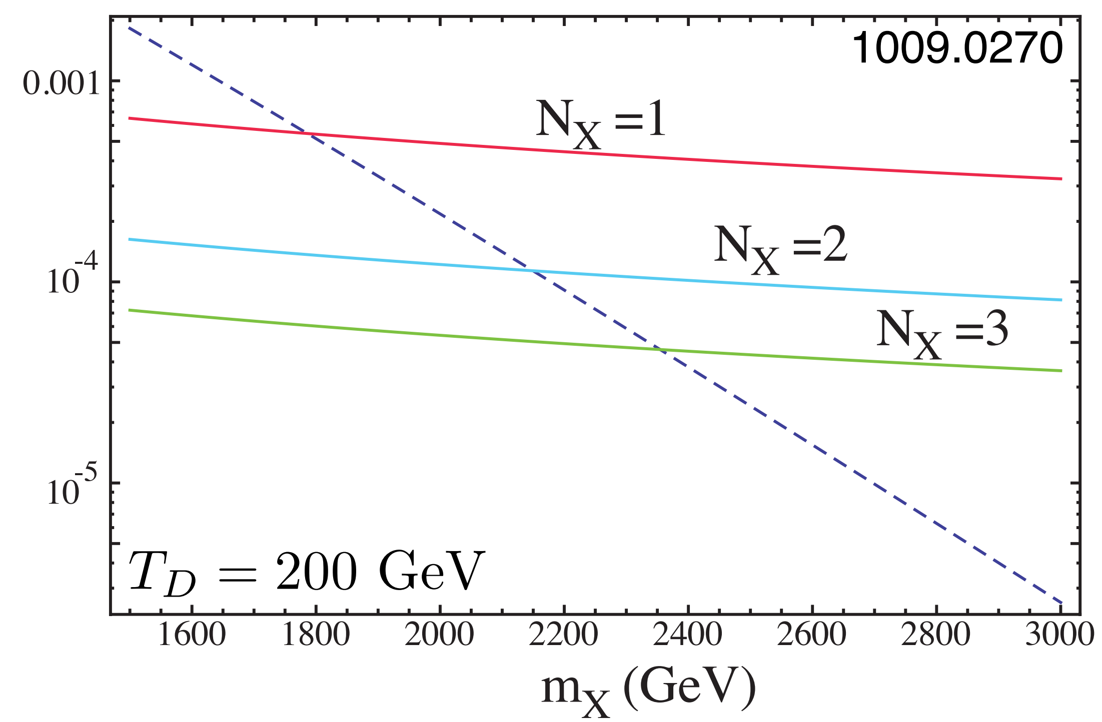
Sphalerons

- In chiral $SU(2)_L$, this creates
$$N_f \times [3(u_L + d_L) + e_L]$$
particles. Violating B and L, but not $B - L$
- Active until electroweak phase transition
$$T_D \sim v \equiv \langle H \rangle \sim 200 \text{ GeV}$$
  - Exponentially suppressed below this
- Can't create an asymmetry, but will distribute it into all sectors with chiral $SU(2)_L$ fermions

Sphalerons & ADM

- Add N_X dark matter $SU(2)_L$ doublets
- Sphaleron action would now preserve both
$$B-L, B-\frac{3}{N_X}X$$
- Obviously, new doublets at 5 GeV completely excluded by LEP, so relativistic solution out.

- Implies $2+$ TeV dark matter - ruled out by direct detection
- Can avoid this by singlet-doublet mixing



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Creating Lepton Number

- Could explicitly break X, L symmetries.

$$\mathcal{L} \supseteq \frac{1}{M} X X \tilde{L} H_u$$

  - B created via SM sphaleron processes
  - Non-relativistic solution implies heavy sneutrinos in vanilla models.
- $T_D < T_{\rm sphaleron}$ allows for interesting solutions
  - “Intermediate mass” ADM, as excess particle number “bleeds” into neutrino sector

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Predictions of ADM

- Out of the many models on the market, are there any universal statements that can be made?
  - That is, what can we say about all ADM models?
  - Mass?
  - Interactions?
  - Indirect Detection?

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A is A

- Asymmetric dark matter is asymmetric
  - Meaning that it has no significant symmetric (thermal) component
  - (definition of significant up for debate, here I'll assume $< 10\%$)

- This means that ADM must have significant annihilation cross section into *something*

$$\sigma_{\rm ADM} \gtrsim \sigma_{\rm Thermal} \sim 1~{\rm pb}$$

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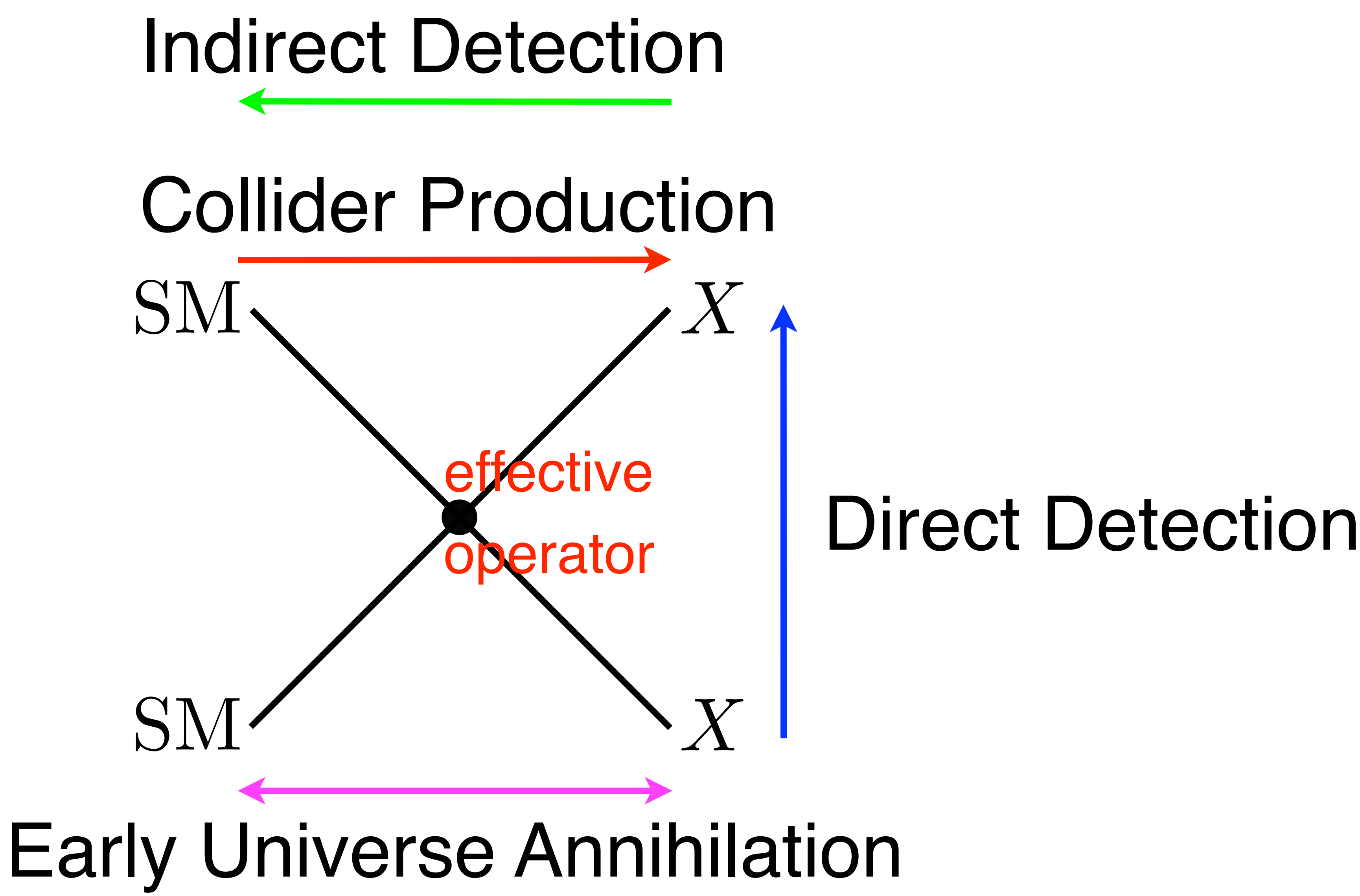
Dark Matter Interactions



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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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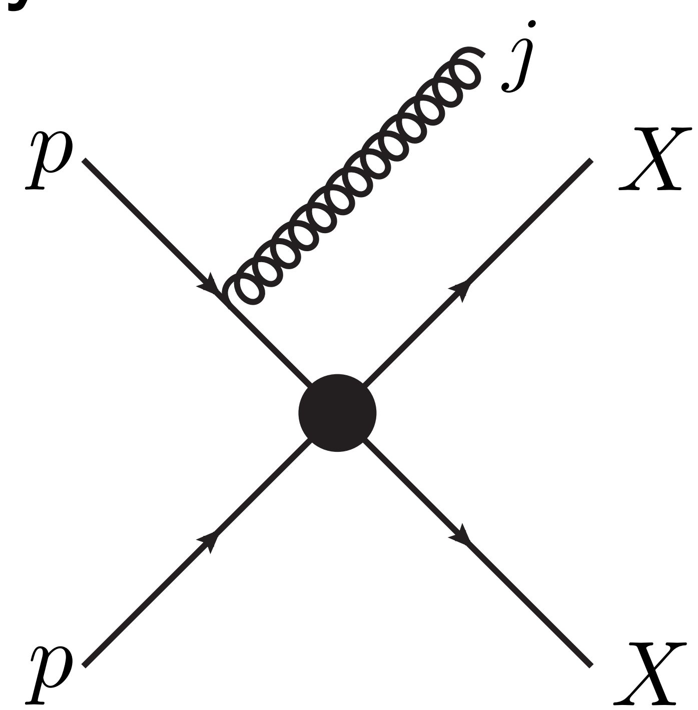
Collider Bounds

- Complete theory of dark matter often expected to have additional ($SU(3)_C$ charged) particles
- Minimal theory has only dark matter, plus some effective operator which may not be accessible at colliders.
- Only definite signal:

$$pp \to XX + \text{jets}/\gamma$$
$$\Rightarrow pp \to \not{E}_T + \text{jets}/\gamma$$

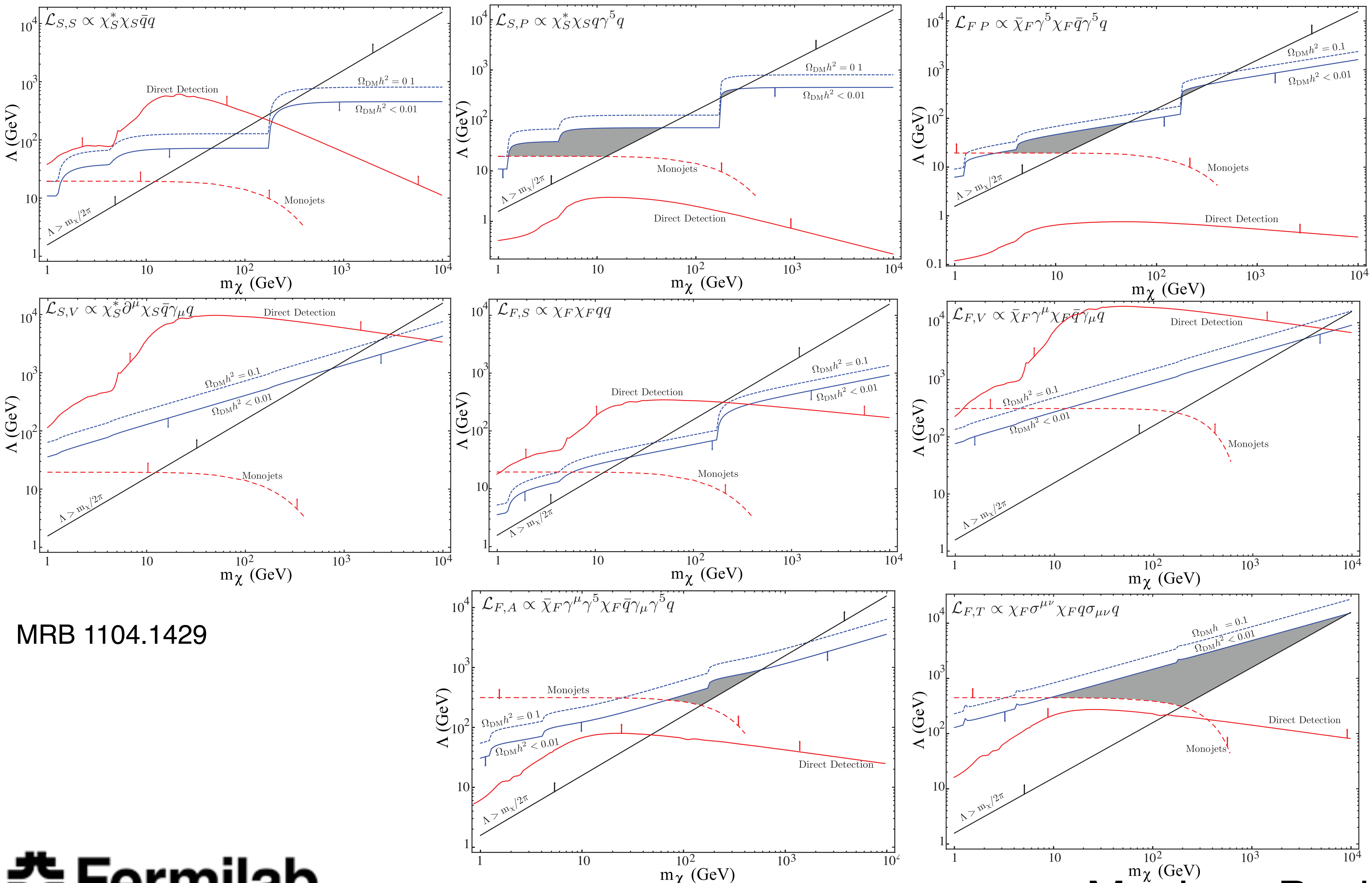


- Main background

$$pp \to (Z \to \nu\bar{\nu}) + \text{jets}/\gamma$$

- Searches using ATLAS and CMS ($1\ \text{fb}^{-1}$), and CDF results .

Effective Operators



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Effective Operators

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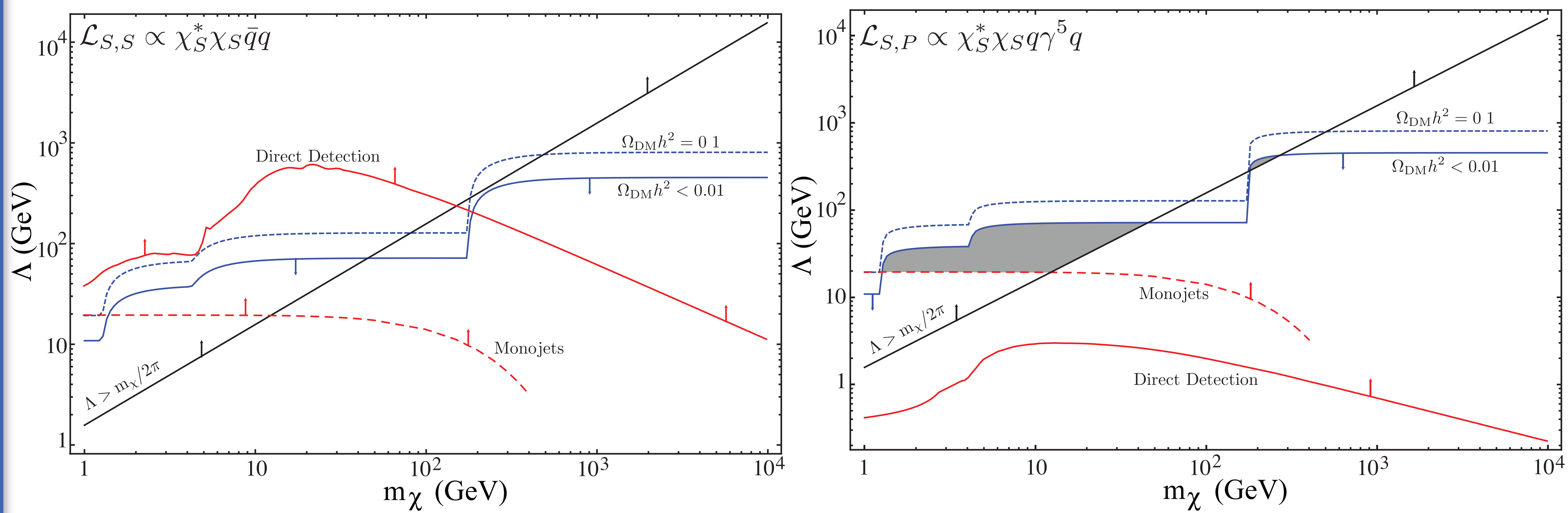

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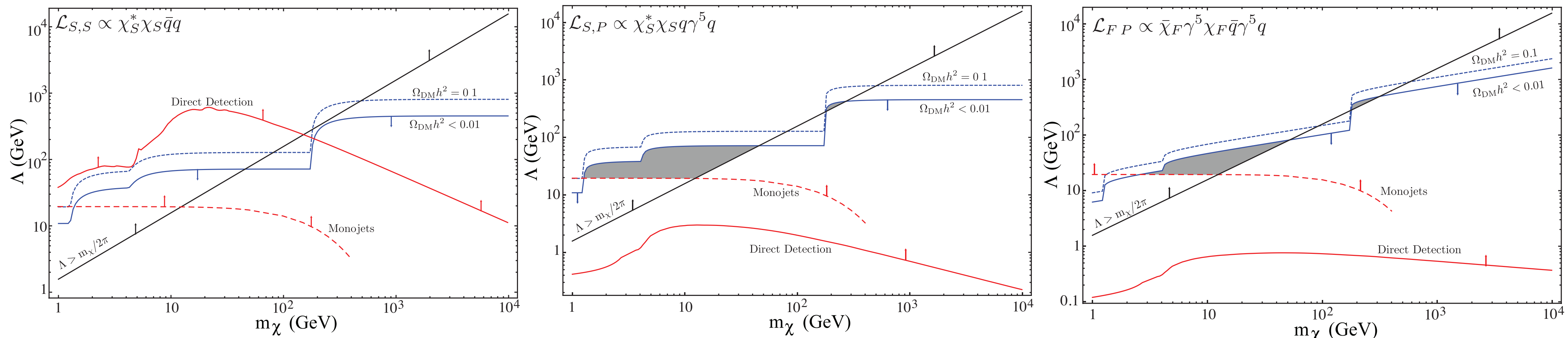
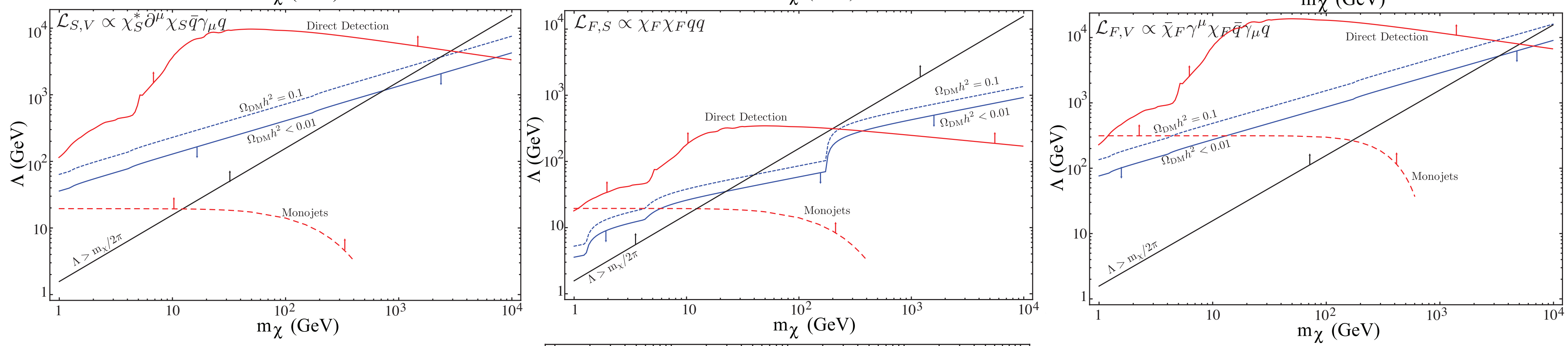
Effective Operators

Scalar/Pseudoscalar   Fermion/Pseudoscalar





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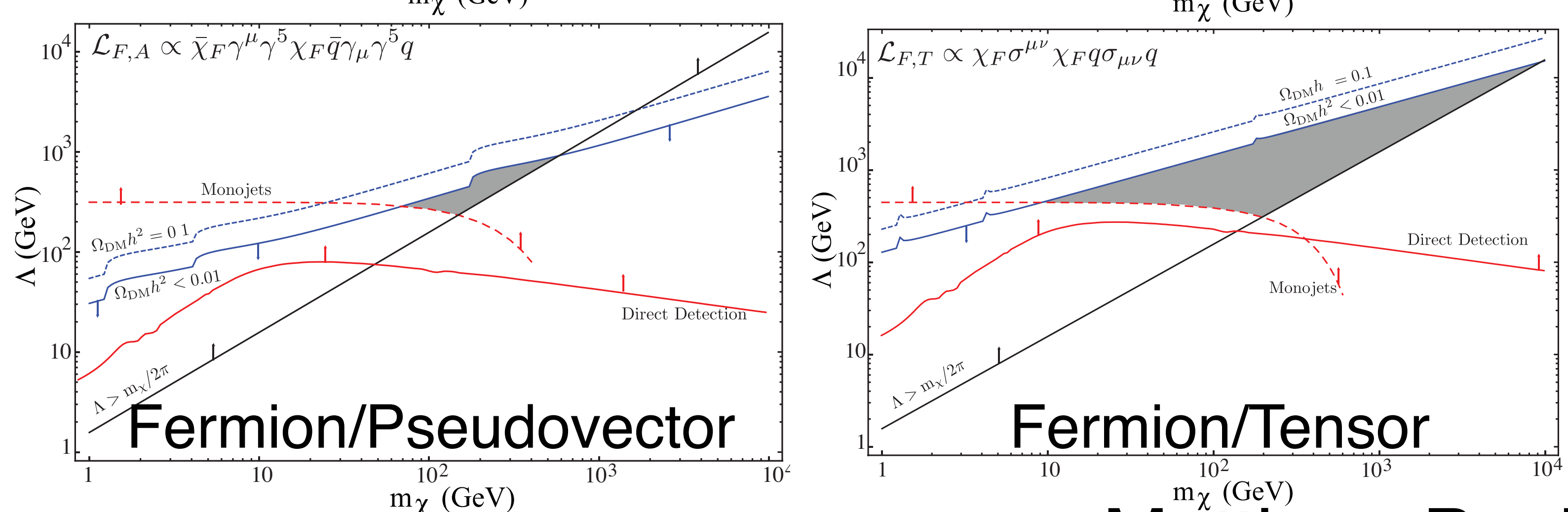

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Implications

- This parameter space is highly constrained. Can relax these constraints by
  - having ADM annihilate into leptons,
  - or annihilate into new light dark particles,
  - or the effective operator formalism doesn't apply.
    - 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.

Predictions of ADM

- Out of the many models on the market, are there any universal statements that can be made?
  - That is, what can we say about all ADM models?
  - Mass?
  - Interactions?
  - Indirect Detection?

Indirect Detection

- ADM consists of X but not $\bar{X}$
  - Naive expectation is therefore no indirect detection signals are possible

- 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

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

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 $\tau^{-1}_{\rm Universe} \sim 10^{-41}~{\rm GeV}$, possibility of extremely strict constraints on ADM mass matrix

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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

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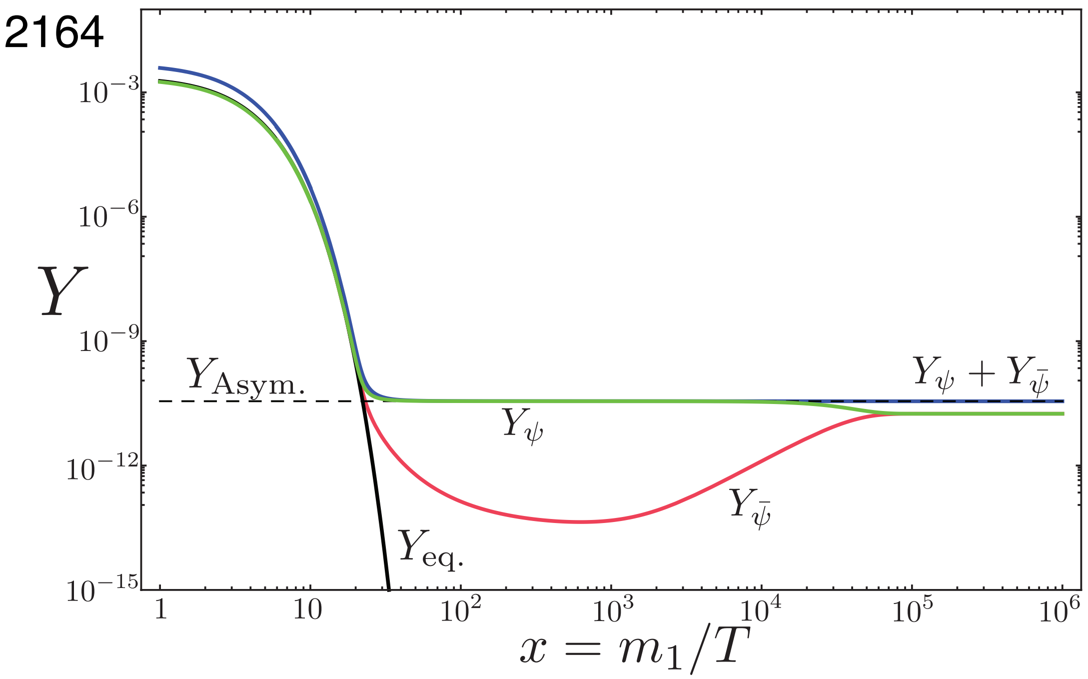

$\langle \sigma v \rangle = 1.5 \times 10^{-25}\ \mathrm{cm}^3/\mathrm{s}$
$m_1 = 10\ \mathrm{GeV}$
$\Delta m = 10^{-25}\ \mathrm{GeV}$

- 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

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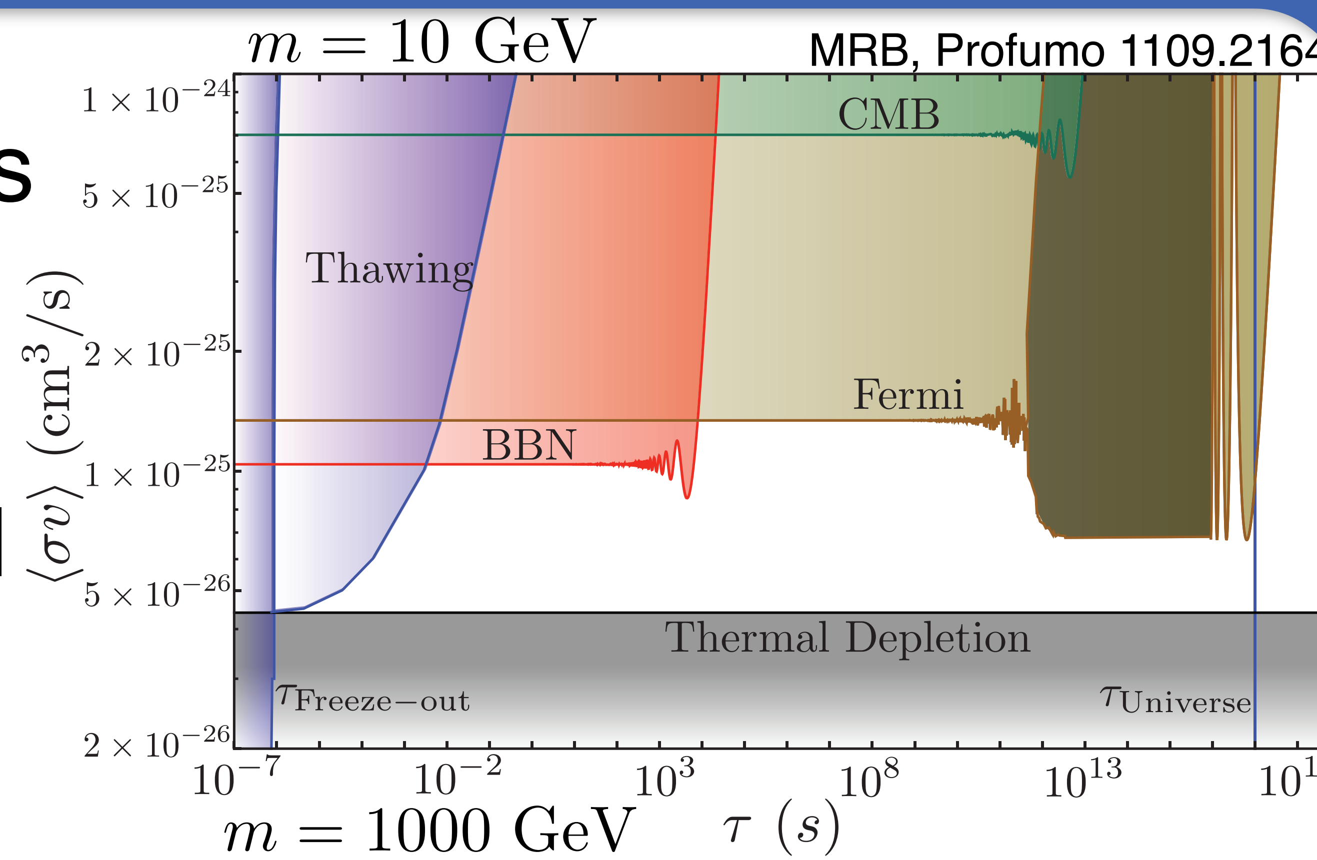

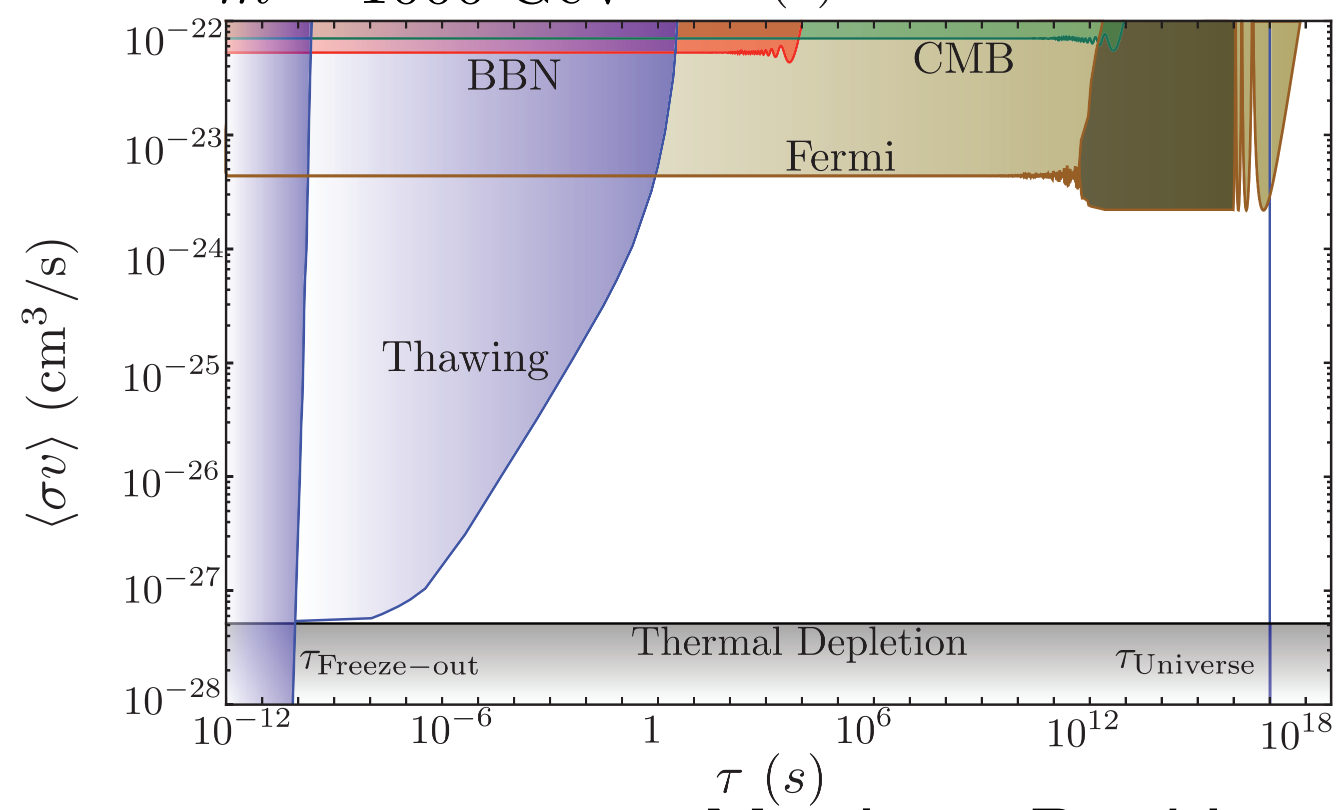

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A Note on Thawing

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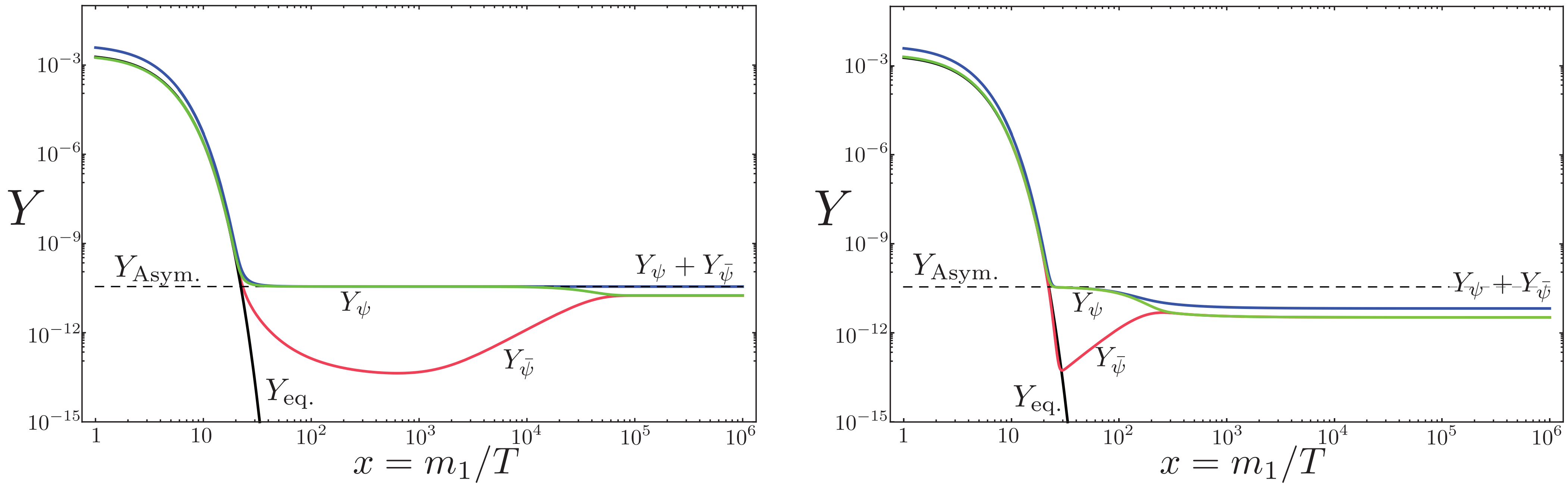
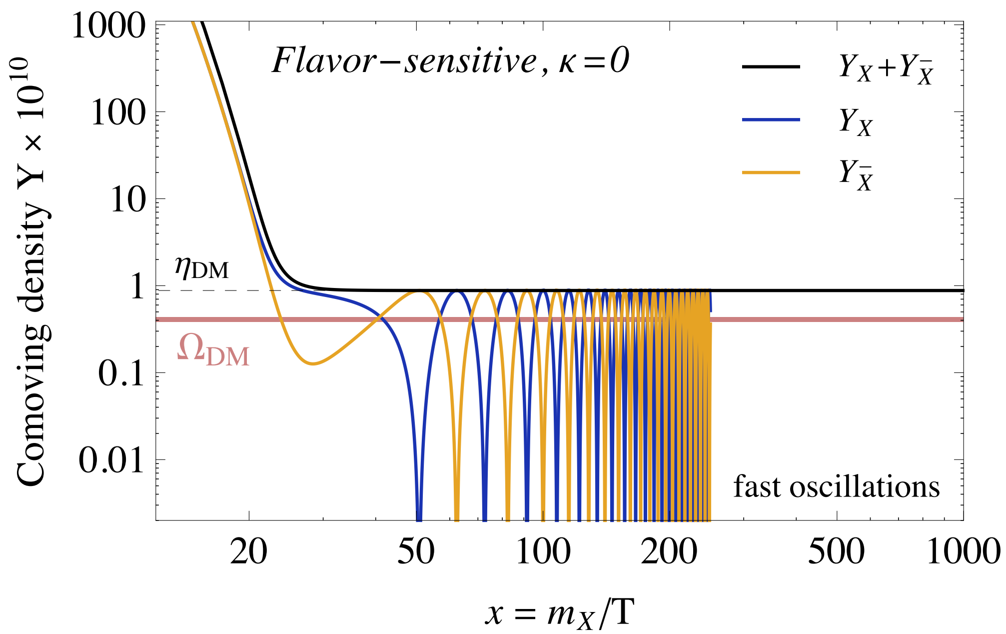
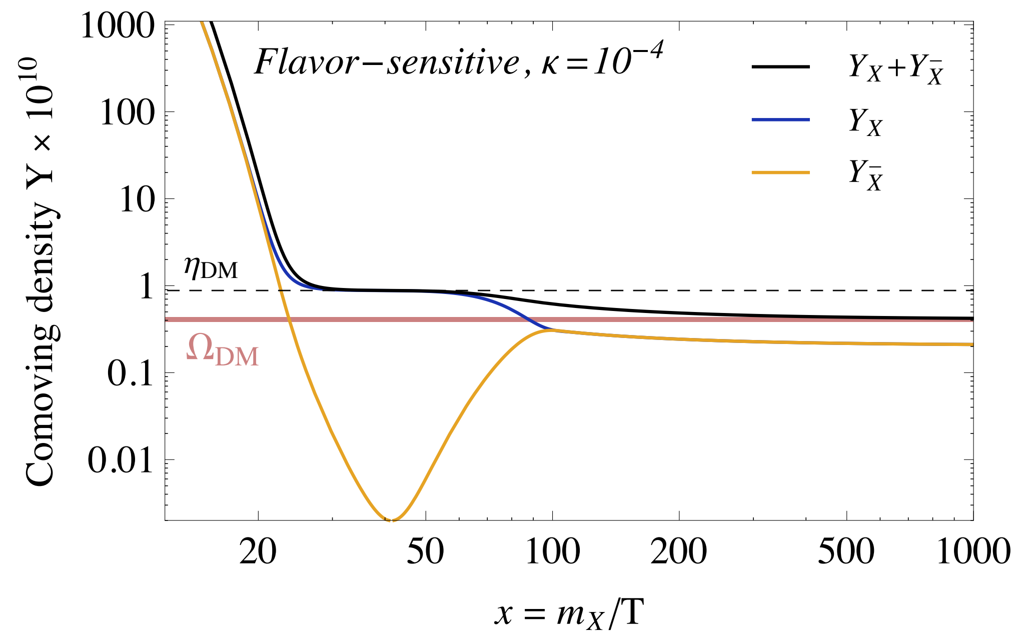


- Previous bounds derived under the assumption that ADM density $\geq 90\%$ of total
- But interesting to note that, if $\tau \gtrsim t_{\rm freeze-out}$, can drive two final abundances together
  - I'm not aware of this sort of solution to the Boltzmann Eqn. used in a cosmological context
  - Could have interesting model-building uses

Constraints & Implications

- Work by Cirelli *et al* (1110.3809) and Tulin *et al* (1202.0283) followed up in more detail.
- Found interactions that distinguish between $X \leftrightarrow X^c$ at Lagrangian level can forbid reannihilation after oscillation without scattering off of thermal bath





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Implications of Oscillation

- If Majorana mass interpreted as result of a seesaw mechanism, implies high scale $> M_{\text{Planck}}$
  - Such terms can be forbidden by simple global symmetries, but these are expected to be violated by gravitational-strength interactions

- Implies that successful ADM models require a symmetry that forbids $\Delta X = 2$ mass terms that are not violated even at extremely high energies
  - Possibly a gauge symmetry?

Conclusions

- WIMPs are a very good idea, but not the only game in town
- The coincidence between $\Omega_{\rm DM}$ and Ω_B provides an fruitful alternative for dark matter model-building.
- I've outlined the wide variety of asymmetry transfer methods potentially available
  - Leads to a wide range of potential masses for ADM
  - Not just $m_X/m_{\rm proton} = \Omega_{\rm DM}/\Omega_B$

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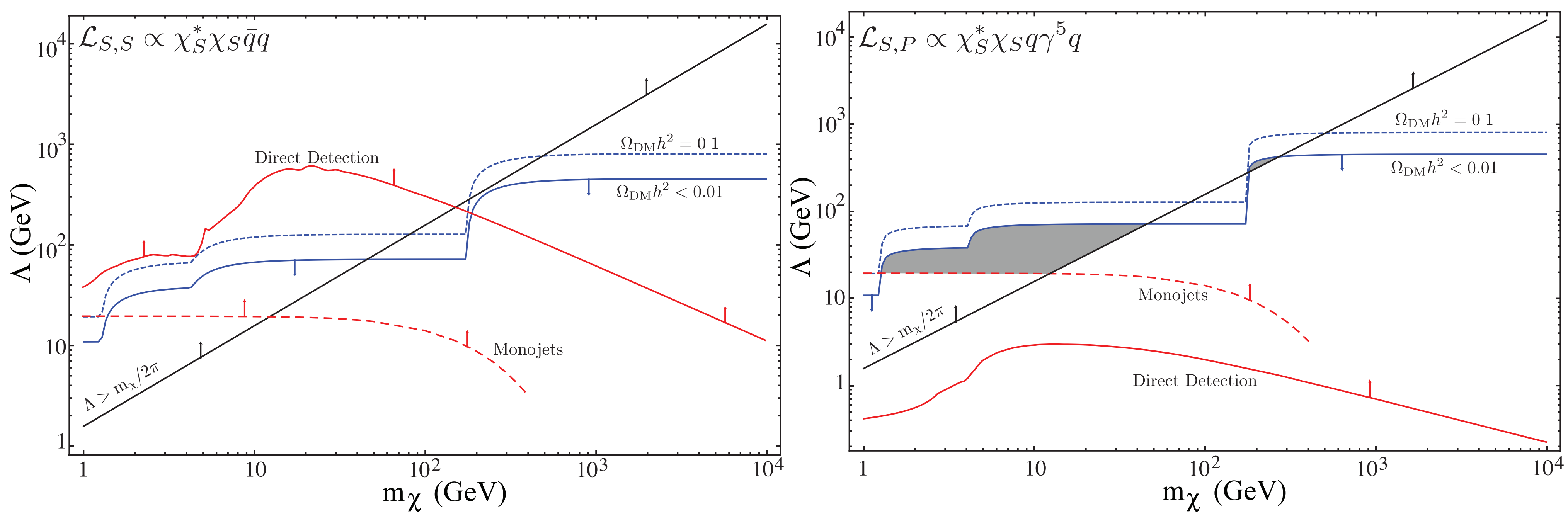
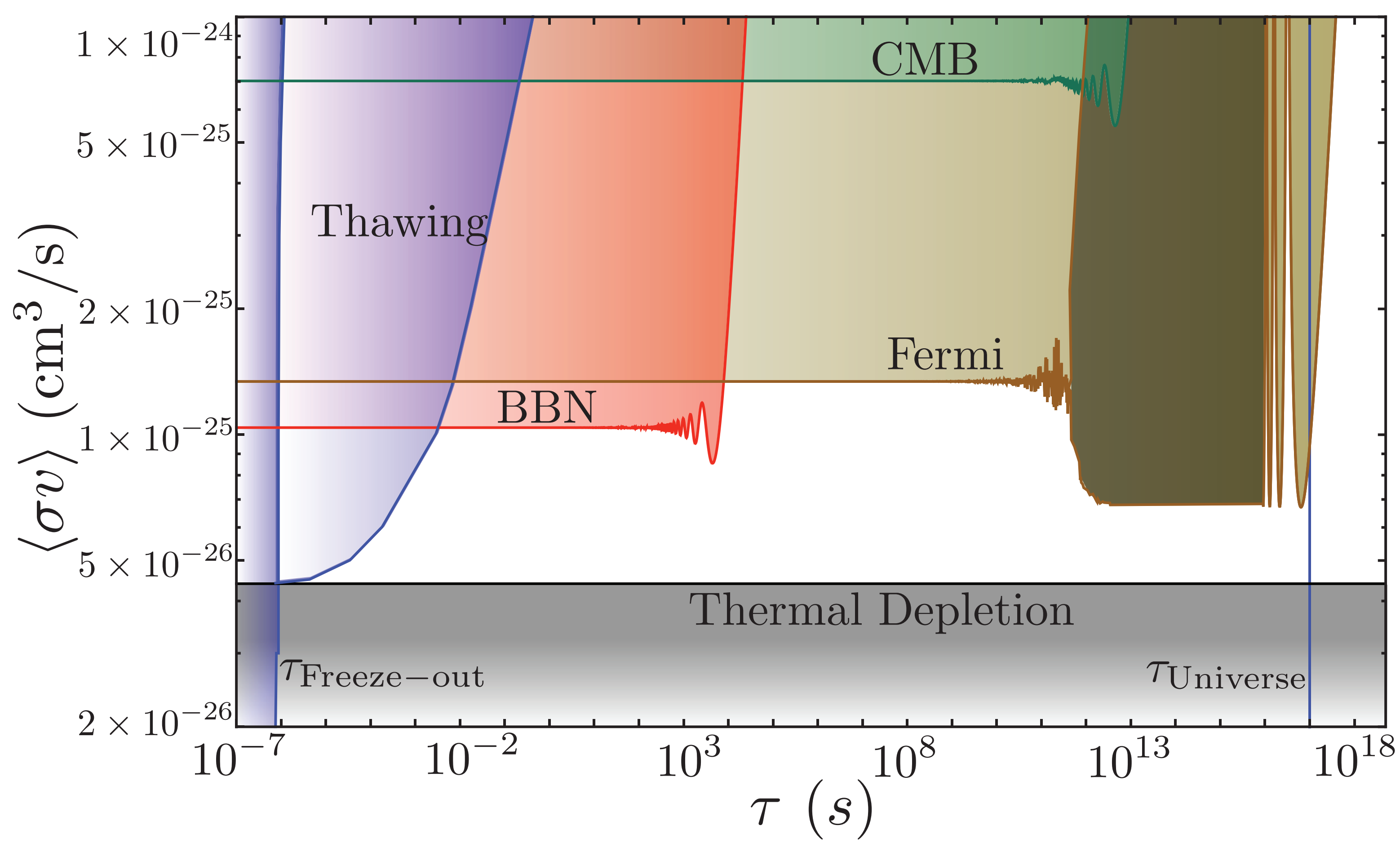
Conclusions

- Can attempt to narrow down the possible theory space:
- To be asymmetric, ADM must have:
  - Large annihilation cross section to eliminate symmetric component
  - Either affinity for leptons or new light states to annihilate into or to mediate annihilations.



Conclusions

- Either affinity for leptons or new light states to annihilate into or to mediate annihilations.
- Must forbid $\Delta X = 2$ mass-terms down to $\Delta m \sim \tau_{\rm Universe}^{-1} \sim 10^{-41}~{\rm GeV}$



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Conclusions

- Either affinity for leptons or new light states to annihilate into or to mediate annihilations.
- Must forbid $\Delta X = 2$ mass-terms down to $\Delta m \sim \tau_{\rm Universe}^{-1} \sim 10^{-41}\ {\rm GeV}$
- Implies a dark sector with a rich phenomenology:
  - New states with sizable couplings
  - New dark symmetries conserved to very high scales.
  - Perhaps pointing back to something technicolor-ish?

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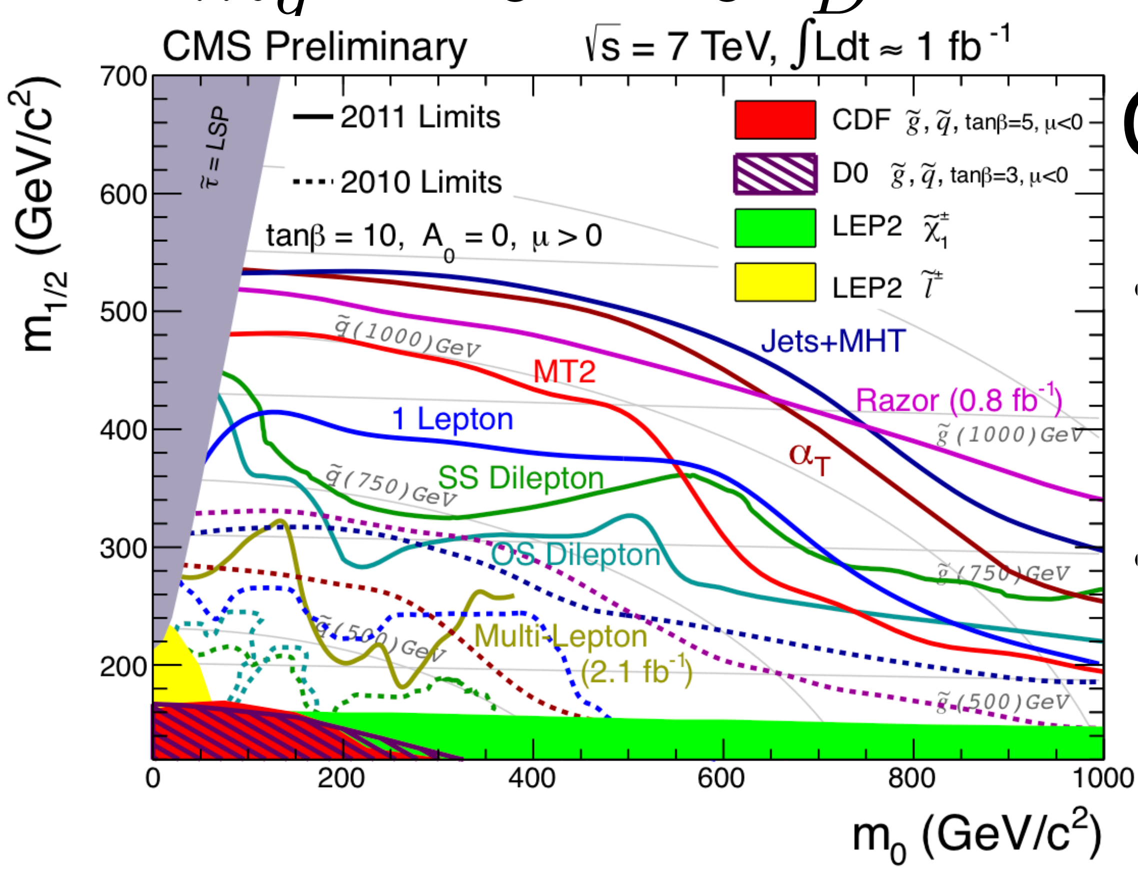
Back-Up Slides

Squark Masses in $\not{B}$

$$\Gamma = n\langle \sigma v\rangle \sim \left(\frac{m_X T}{2\pi}\right)^{3/2} \frac{\pi m_X^2}{(16\pi^2)^2 M^4} e^{-(3m_{\tilde{q}}-m_X)/T}$$

- Non-rel. solution requires $m_X \sim 10T_D$
- T_D set when $\Gamma \sim H^{-1}$, assuming M not too large, solutions when $(3m_{\tilde{q}} - m_X) \sim 45T_D$
  - Implies $m_{\tilde{q}} \sim 10 - 20T_D$



CMS

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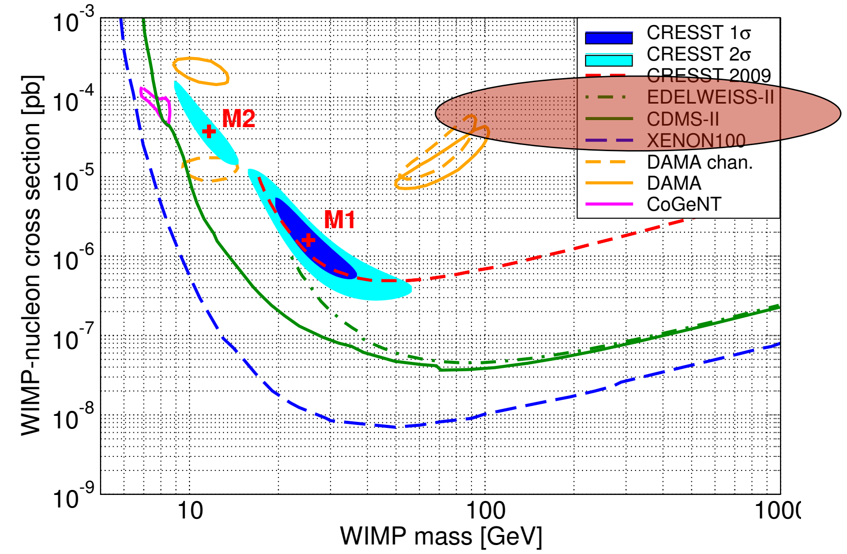
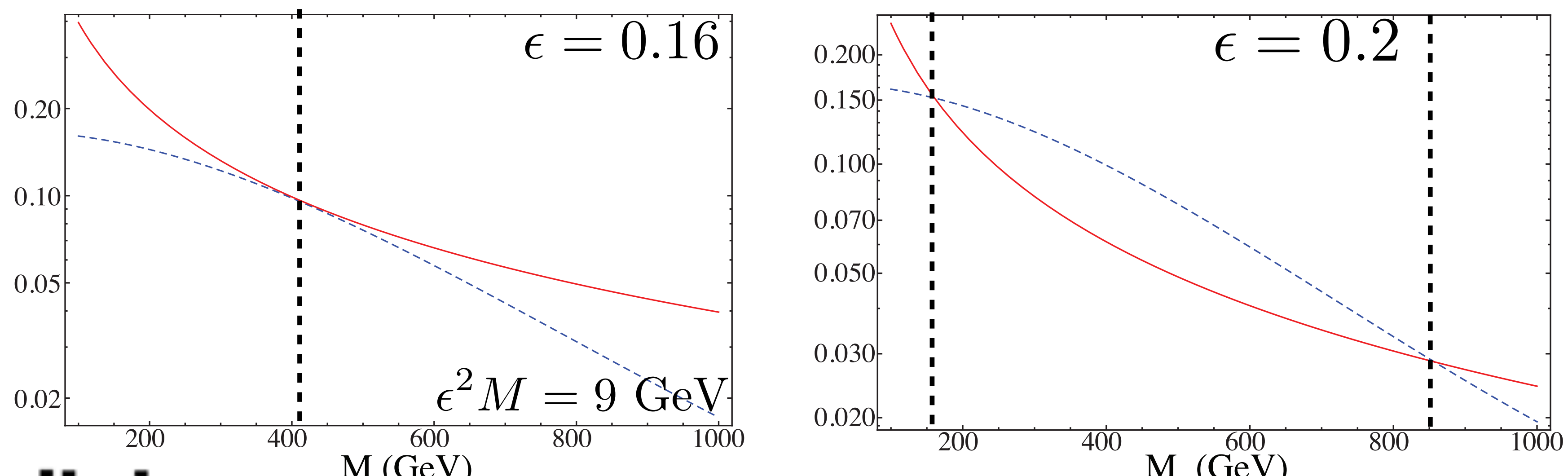
Sphalerons & ADM

- $1 - 2$ TeV chiral doublet dark matter excluded by direct detection.
- Can look at mixing doublet with $SU(2)_L$ singlets.
- Can set up system so that light state is primarily singlet: detection suppressed by ϵ^4, sphalerons create mostly heavy state (mass M), which later decays to state of mass $\epsilon^2 M$





1009.0270

Singlet-Doublet mixing

- Specific example.
- 2 “left-handed states,” singlet X_1, doublet X_L
- 2 “right-handed states,” singlets X_2, X_3
  - Form Dirac masses only

$$\mathcal{L} \supseteq v_1 v X_L \bar{X}_2 + y_2 v X_L \bar{X}_3 + m_{12} X_1 \bar{X}_2 + m_{13} X_1 \bar{X}_3$$

- Select $v_1 v = M, v_2 v \sim \epsilon M, m_{12} \sim \epsilon M, m_{13} \sim 0$
- Then action of sphaleron is to create ϵ^2 states of mass $\epsilon^2 M$ and $1-\epsilon^2$ of mass M

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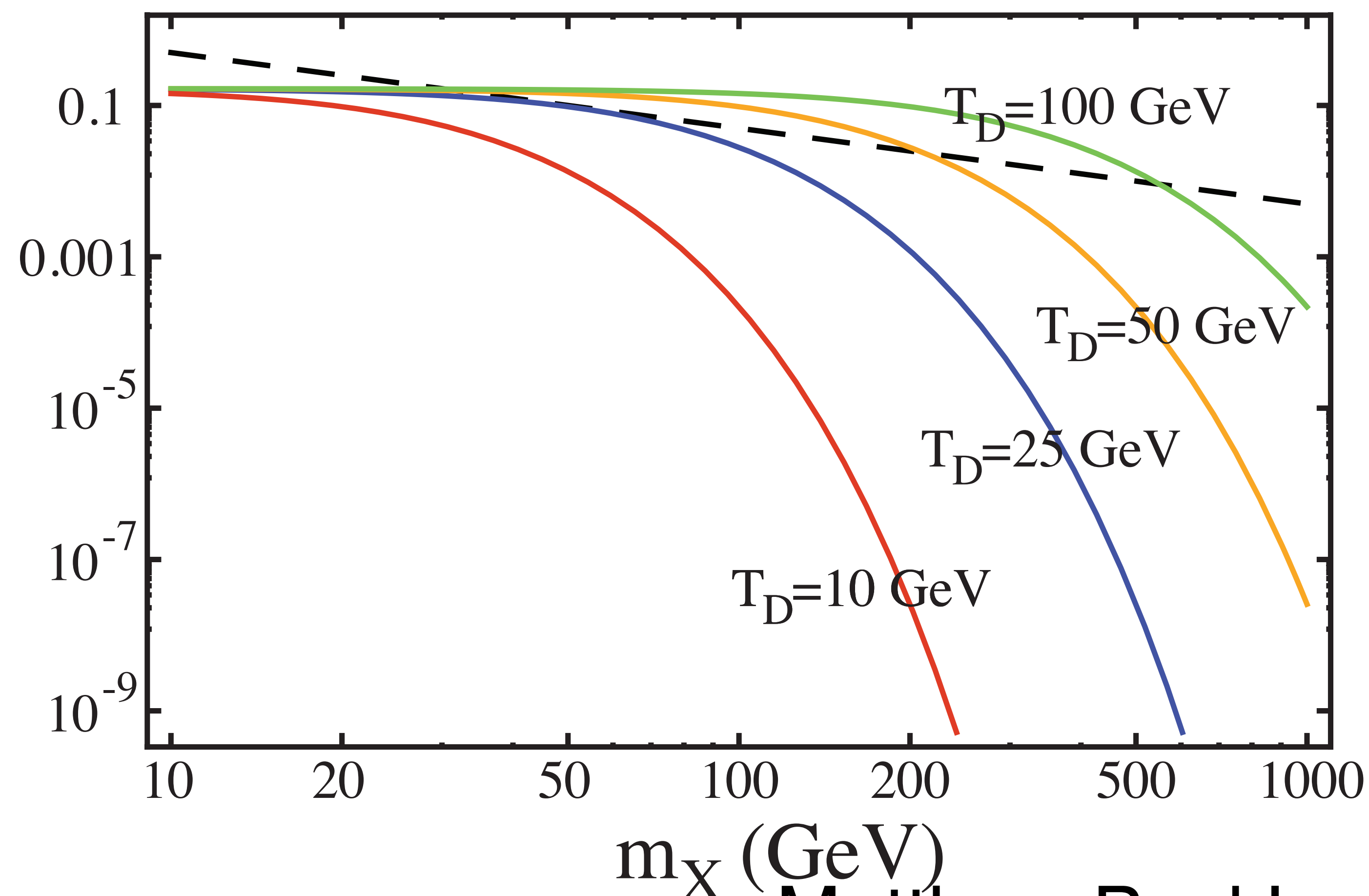
Intermediate Masses

- Lepton-violating models transfer X/L asymmetry via higher dim. operators, and transfer asymmetry via sphalerons L/B
  - If $T_D < T_{\mathrm{sphaleron}}$, then after $X \leftrightarrow L \leftrightarrow B$ stops, $X \leftrightarrow L$ continues, bleeding "excess" DM into invisible neutrinos



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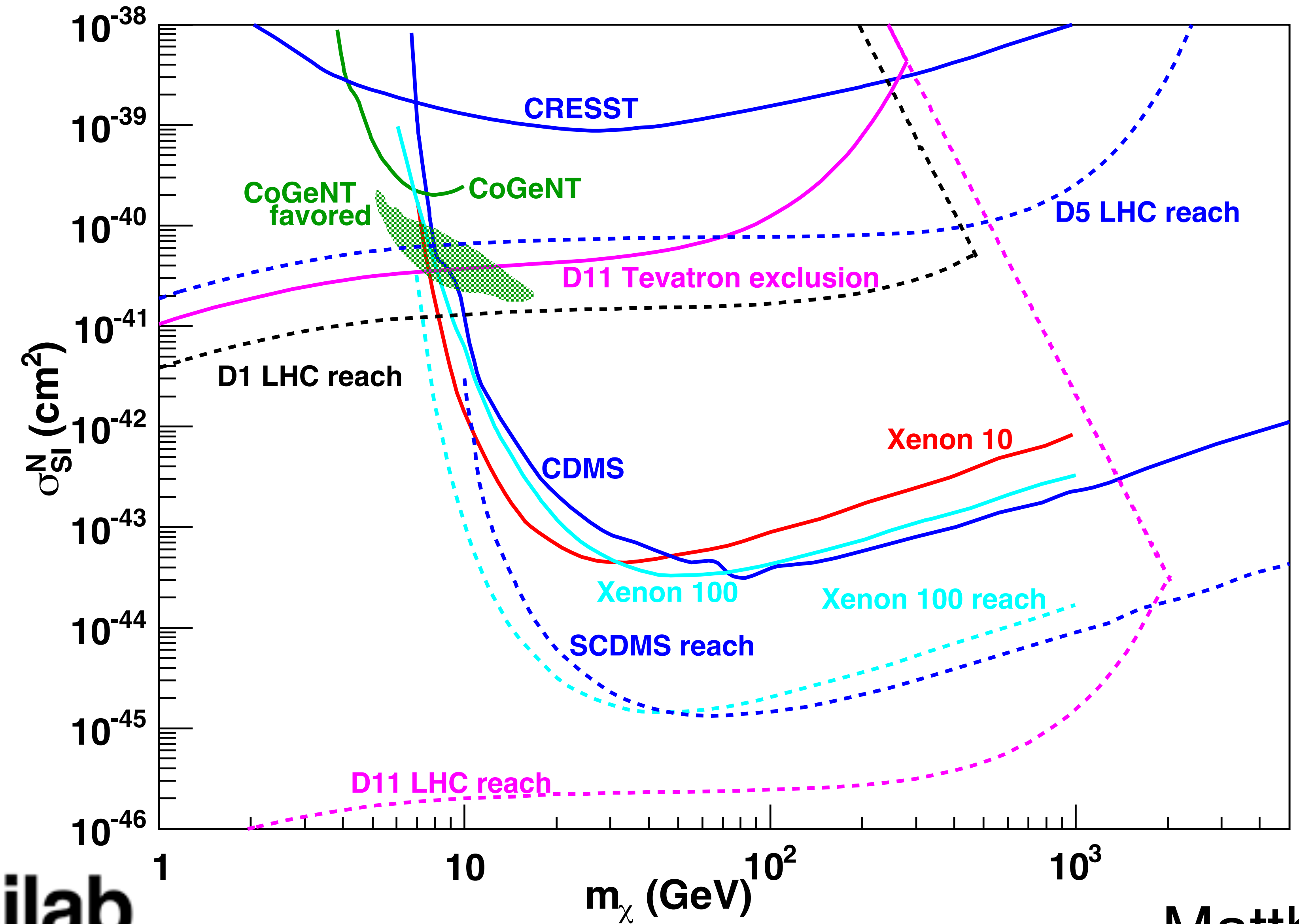
Tevatron Search

Goodman *et al* 1008.1783

- Follows CDF searches: 0807.3132
  - Require $p_{T,j} > 80\ \mathrm{GeV}$ $\not{E}_T > 80\ \mathrm{GeV}$
  - Allow $p_{T,j_2} > 30\ \mathrm{GeV}$, veto on 3+ jets



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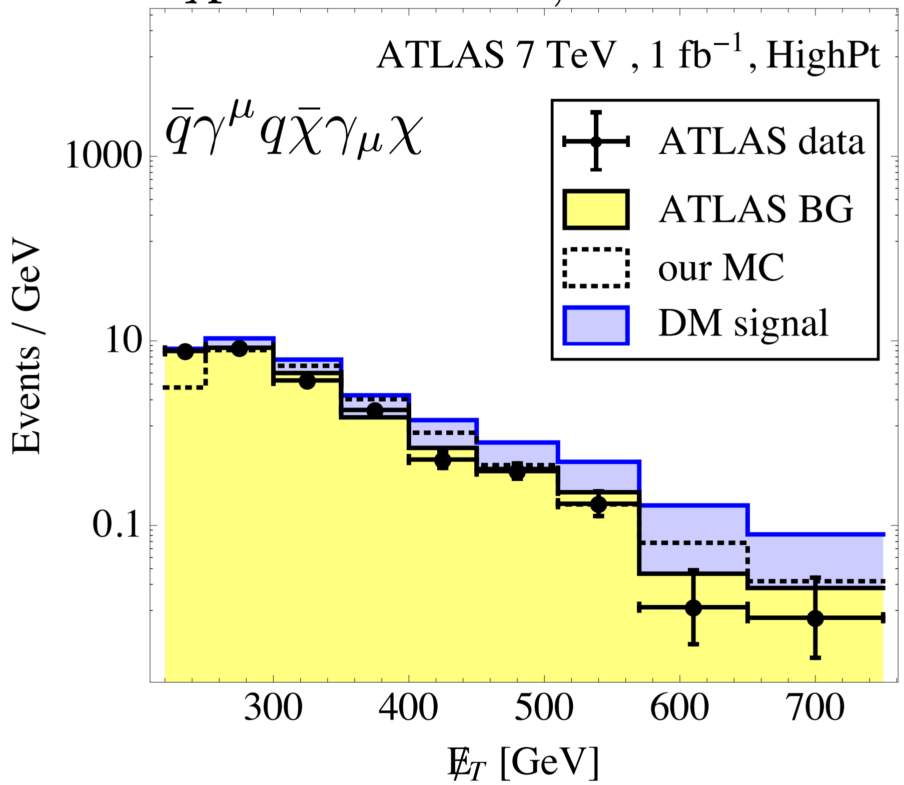
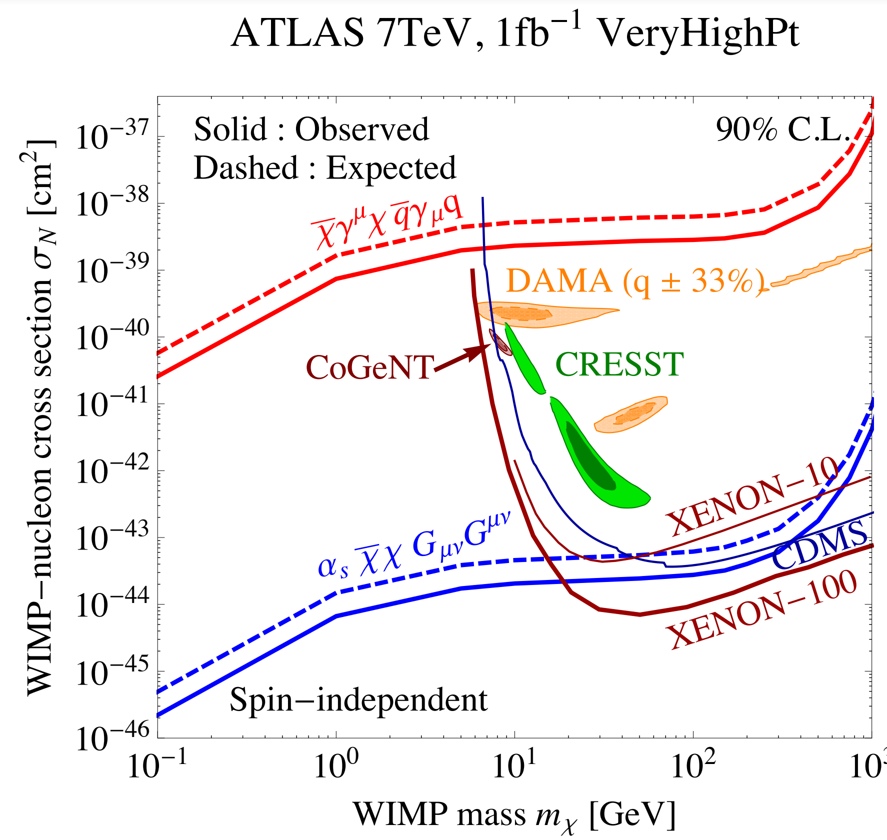
LHC Search

Fox *et al* 1109.4398

$m_X = 10$ GeV, $\Lambda = 400$ GeV





	ATLAS LowPT 1.0 fb^{-1}	ATLAS HighPT 1.0 fb^{-1}	ATLAS veryHighPT 1.0 fb^{-1}	CMS 36 pb^{-1}
Expected	15100 ± 700	1010 ± 75	193 ± 25	297 ± 45
Observed	15740	965	167	275

- Largest uncertainty is systematic error
- Pure “cut-and-count” analysis
- More sophisticated studies using event shapes going on now.

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