(Almost) Minimal Dark Matter

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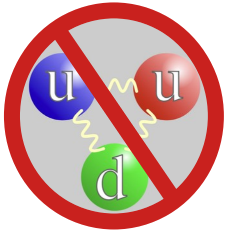
Outline

- Preliminaries
- A very WIMP-y miracle
- Minimal dark matter (or taking WIMPs seriously)
- Minimal dark matter coupled to the Higgs

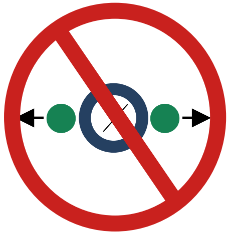
What Is Dark Matter?

Not this stuff!

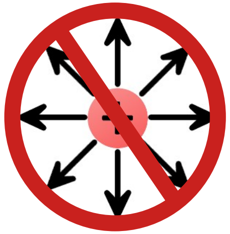
What Is Dark Matter (Again)?



Not baryonic



Stable (or at least very long lived)

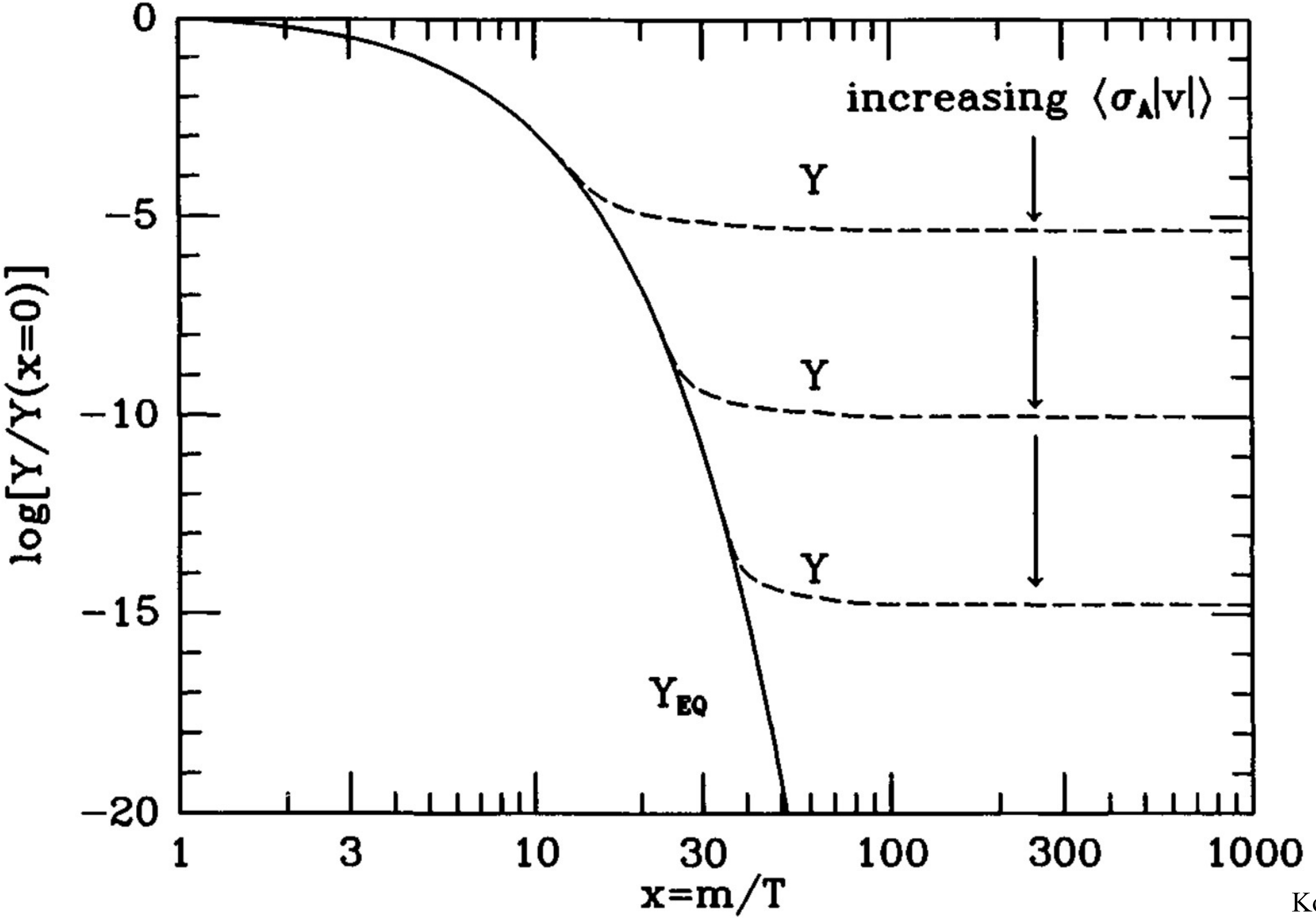


Electrically neutral (or at least very small charge)

Cold (or at least not hot)

A Very WIMP-y Miracle

Freeze Out



Kolb and Turner (1990)

The WIMP Miracle

Boltzmann Equation

$$\frac{1}{a^3}\frac{d(n_\chi a^3)}{dt} = -<\sigma_{\chi\chi} v> (n_\chi^2 - n_{\chi,\mathrm{eq}}^2)$$

Relic Abundance

$$\Omega_\chi \approx 0.1 \frac{x_f}{\sqrt{g_*(M_\chi)}} \frac{10^{-8}\mathrm{GeV}^{-2}}{<\sigma_{\chi\chi} v>}$$

Cross Section

$$\sqrt{<\sigma_{\chi\chi} v>} \approx 0.1 \sqrt{G_F}$$

The WIMP Mass

Assume this

$$< \sigma_{\chi\chi} v > \approx \frac{g^4}{16\pi^2 M_\chi^2}$$

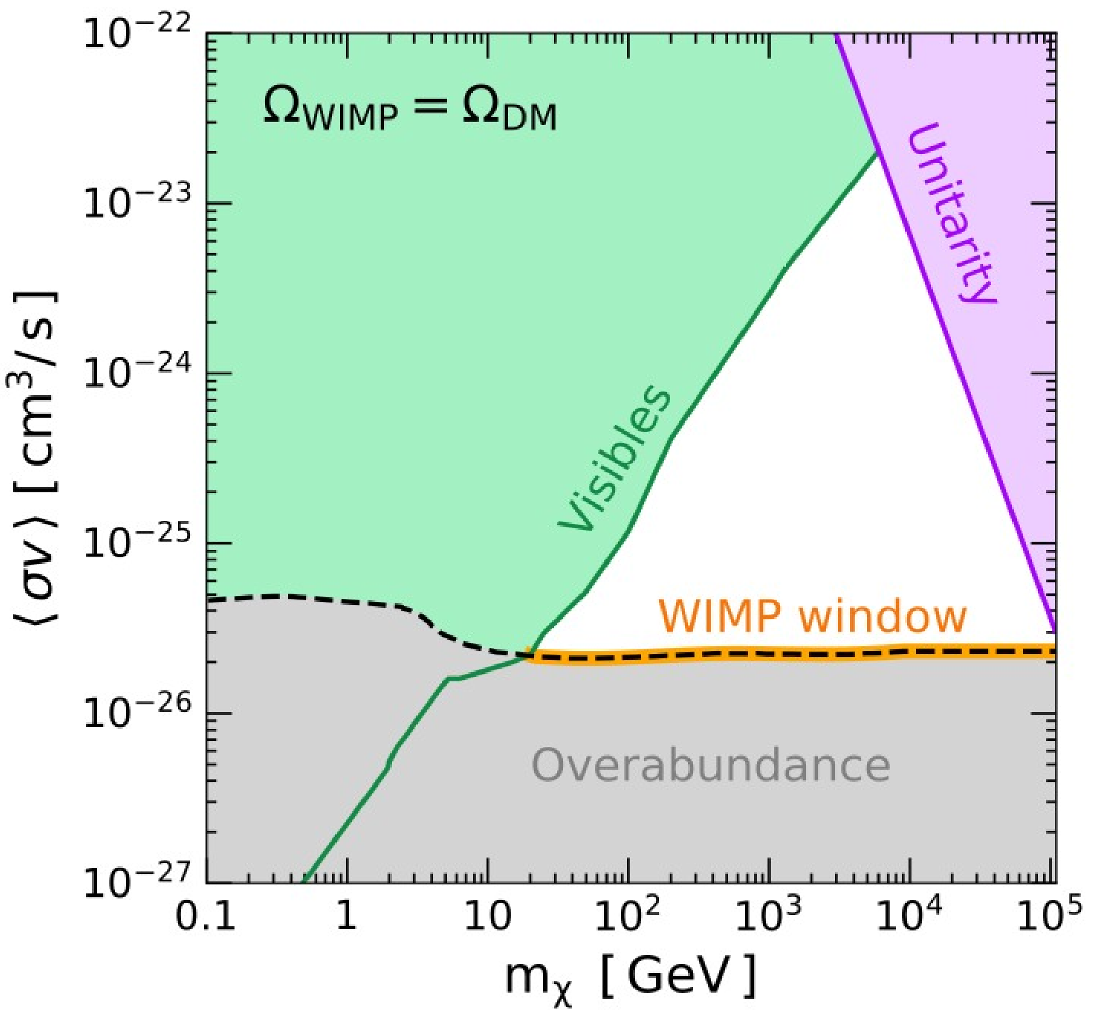
Require this

$$\mathrm{g}^2 \leq 4\pi$$

Stuck with this

$$\mathrm{M}_\chi < 54\mathrm{TeV}$$

The WIMP Mass



Leane, Slatyer, Beacom, Ng (2018)

Minimal Dark Matter

(or Taking WIMPs Seriously)

Doing the Bare Minimum

- The cross section is close to weak multiplets...
- And we know how weak multiplets work...
- Let's take the "weak" in WIMPs seriously and invent a new SU(2) multiplet!

$$\mathcal{L} \to \mathcal{L}_{\rm SM} + C \begin{cases} \bar{\chi}(i \not{D} + M_\chi)\chi \\ |D_\mu \chi|^2 - M_\chi^2 |\chi|^2 \end{cases}$$

$SU(2)_L$ n-tuplet: $\chi = \begin{pmatrix} \chi_1 \\ \vdots \\ \chi_n \end{pmatrix}$

Cirelli, Fornengo, Strumia (2006)

Example $SU(2)_L$ Multiplets

Standard Model
Y = -1/2

$$\begin{pmatrix} \nu_{e\mathrm{L}} \\ e_{\mathrm{L}} \end{pmatrix}$$

Triplet
Y = 0 (Majorana)

$$\begin{pmatrix} \chi^{+} \\ \chi^{0} \\ \chi^{-} \end{pmatrix}$$

Quadruplet
Y = 1/2 (Dirac)

$$\begin{pmatrix} \chi^{++} \\ \chi^{+} \\ \chi^{0} \\ \chi^{-} \end{pmatrix}$$

$$\mathrm{Q}_\psi = \mathrm{T}_\psi^3 + \mathrm{Y}_\psi$$

Cool Story...Does it Work?

- Not baryonic
  - Yup!
- Stable (or at least very long lived)
  - Kind of?
- Electrically neutral (or at least very small charge)
  - If we choose Y_χ correctly

Cool Story...Does it Work (Part 2)?

- Cold

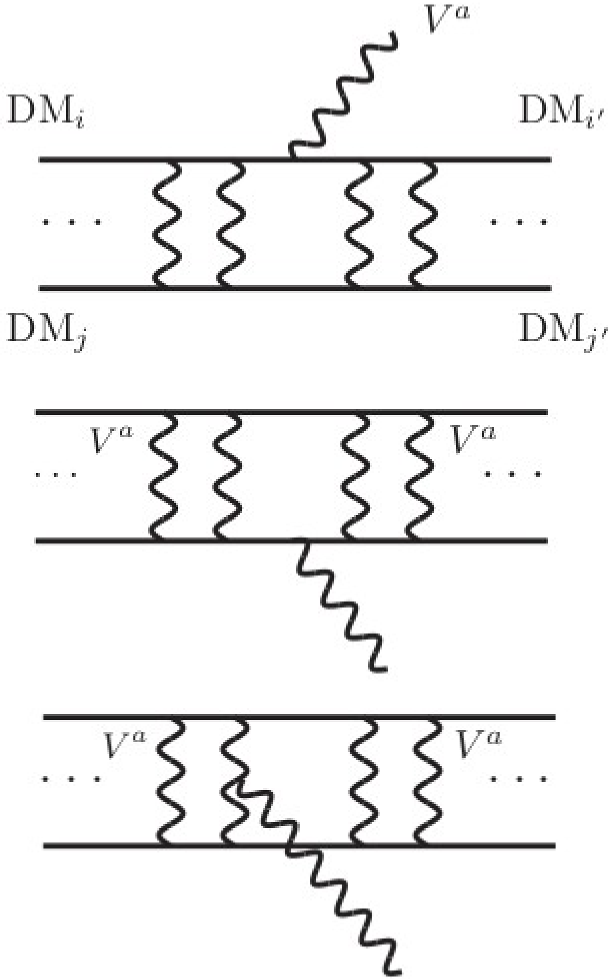
$$< \sigma_{\chi\chi} v > \approx \frac{g_2^4(2n^4 + 17n^2 - 19) + 4Y_\chi^2 g_1^4(41 + 8Y_\chi^2) + 16 g_2^2 g_1^2 Y_\chi^2 (n^2 - 1)}{128\pi M_\chi^2 g_\chi}$$

$$+$$

$$\ln \frac{g_\chi M_\chi M_{\text{Pl}} < \sigma_{\chi\chi} v >}{240\sqrt{g_{\text{SM}}}} \approx x_f \sim 20$$

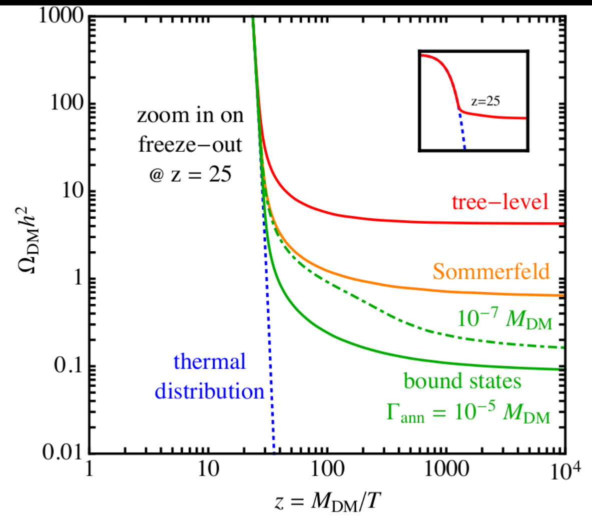
$$\text{M}_\chi \geq 500 \text{ GeV}$$

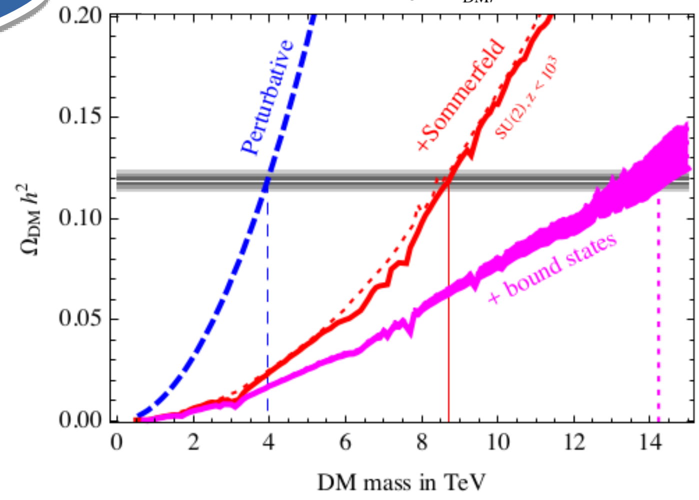
A Few Complications



Bound states

& Sommerfeld enhancement

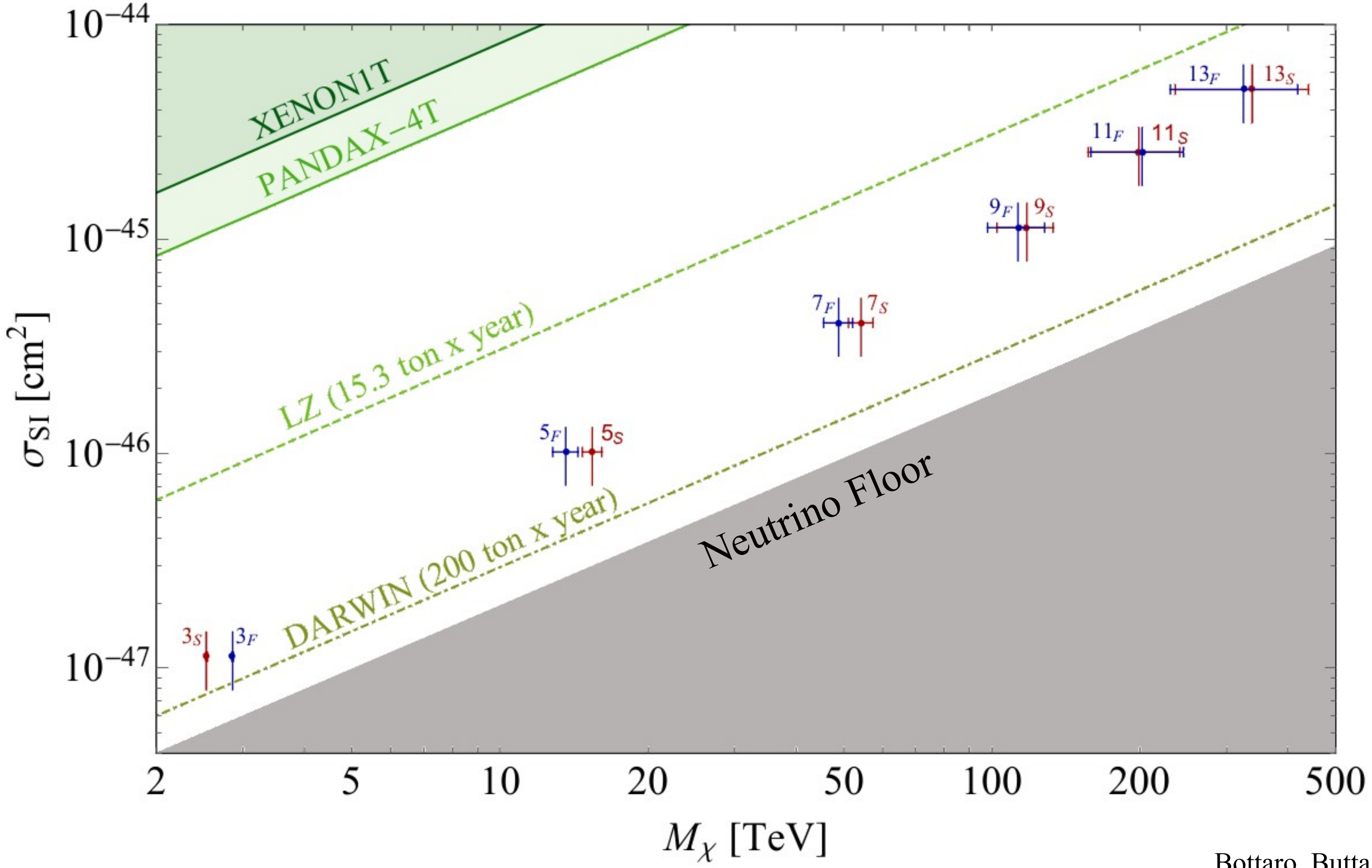




Hisano, Matsumoto, Nagai, Saito, Senami (2006)

Mitridate, Redi, Smirnov, Strumia (2018)

Show Me That Dark Matter!



Bottaro, Buttazzo, Costa...(2022)

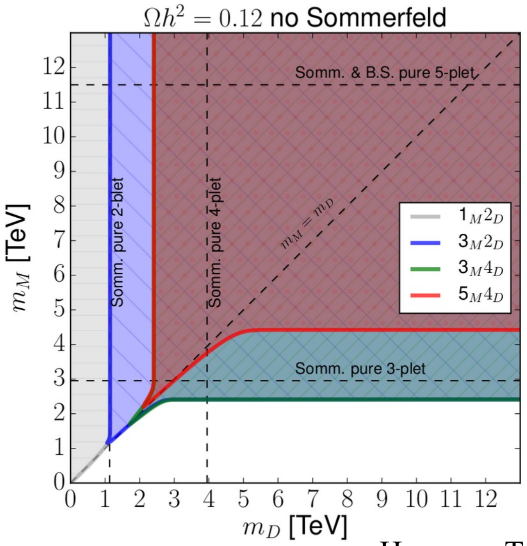
Minimal Dark Matter Coupled to the Higgs

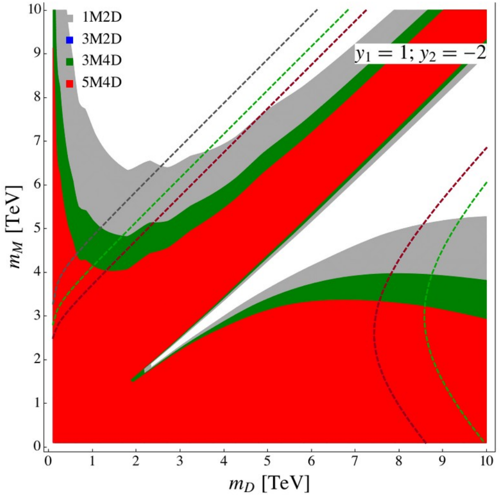
Adding a Multiplet

- If one multiplet is good, then more are better!

$$\mathcal{L} \to \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\not{D} - M_\chi)\chi + \bar{\Psi}(i\not{D} - M_\psi)\Psi - y_1\psi\chi H^* - y_2\tilde{\psi}\chi H$$

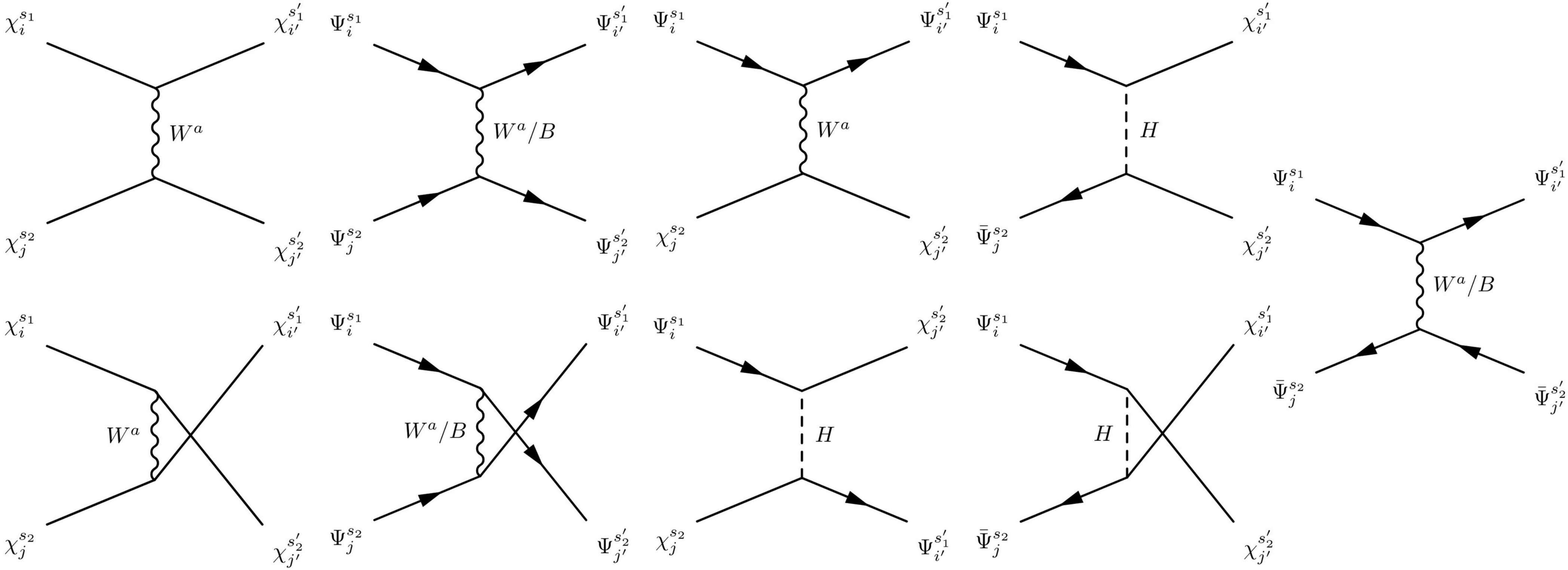
$$\chi = \begin{pmatrix} \chi \\ i\sigma_2\chi^\dagger \end{pmatrix} \qquad \Psi = \begin{pmatrix} \psi \\ i\sigma_2\tilde{\psi}^\dagger \end{pmatrix}$$





Honorez, Tytgat, Tziveloglou, Zaldivar (2017)

Long Range Potentials



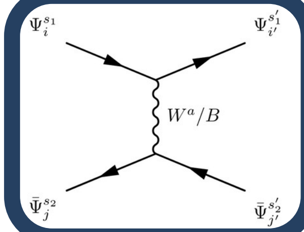
Long range potentials → **Sommerfeld enhancement** → Easy!

Long range potentials → **Bound states** → Non-trivial!

Oncala, Petraki (2021)

The Non-Relativistic Potential

Example: $\Psi\bar{\Psi} \leftrightarrow \Psi\bar{\Psi}$



$$i\mathcal{M} \approx \frac{i4M^2}{(\vec{p}-\vec{p'})^2}(g_1^2 Y_\Psi^2 \delta_{ii'}\delta_{jj'} + g_2^2 t^a_{i'i} t^a_{jj'})\delta^{s_1 s'_1}\delta^{s_2 s'_2}$$

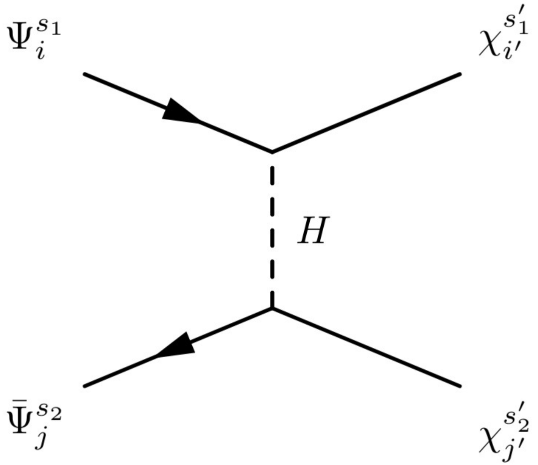
$$\delta^{s_1 s'_1}\delta^{s_2 s'_2} \to 1$$

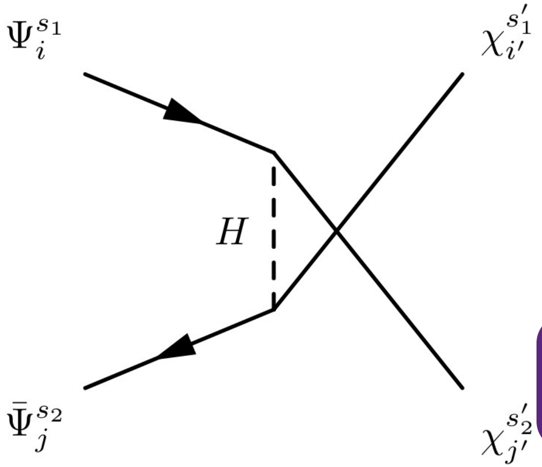
$$t^a_{i'i} t^a_{jj'} \to C^{\Psi\bar{\Psi}}_{R_{\Psi\bar{\Psi}}} = \frac{1}{2}\left(C_2(R_\Psi) + C_2(R_{\bar{\Psi}}) - C_2(R_{\Psi\bar{\Psi}})\right)$$

$$\delta_{ii'}\delta_{jj'} \to 1$$

$$V_{\Psi\bar{\Psi}\leftrightarrow\Psi\bar{\Psi}} = -\frac{1}{r}\left(\frac{\alpha_1}{4} + C^{\Psi\bar{\Psi}}_{R_{\Psi\bar{\Psi}}}\alpha_2\right)$$

Mixed States





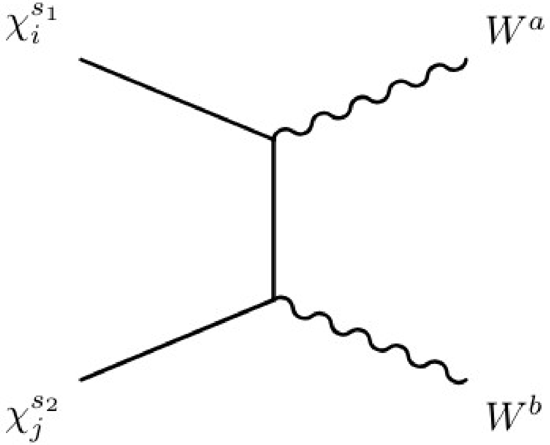
$$\left(\frac{-\nabla^2}{2\mu} + \hat{V}(R)\right)\begin{pmatrix}\phi_{\chi\chi}(R)\\ \phi_{\psi\bar{\psi}}(R)\end{pmatrix} = E(R)\begin{pmatrix}\phi_{\chi\chi}(R)\\ \phi_{\psi\bar{\psi}}(R)\end{pmatrix}$$

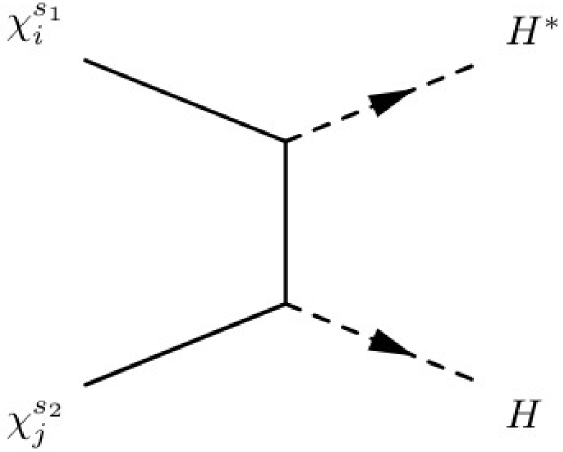
Diagonalize this

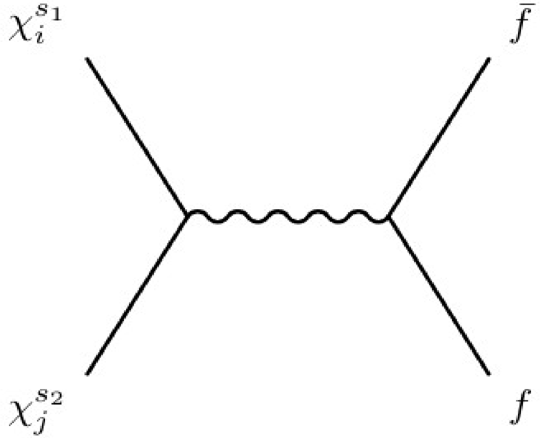
Work with eigenstates of this

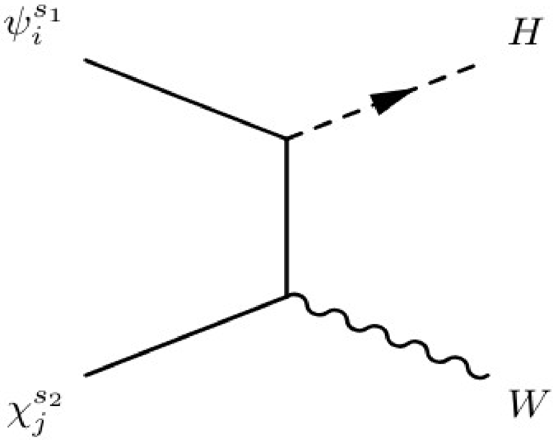
Use eigenstates to “weight” cross sections and decay rates

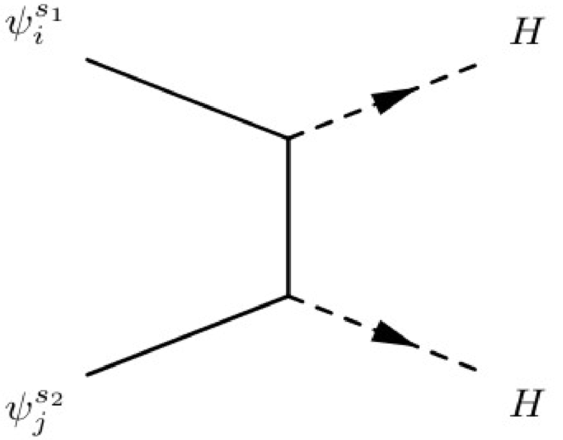
Annihilation





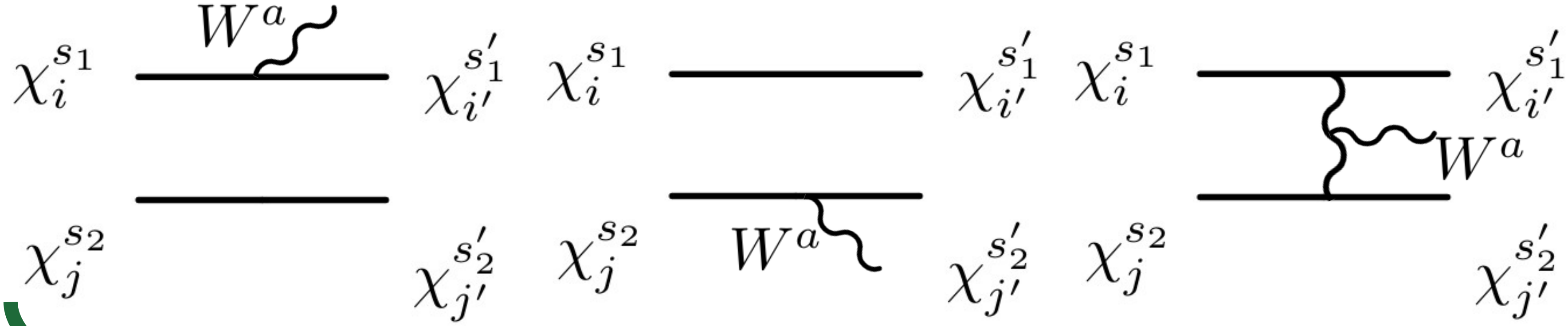






+ more

Bound State Formation



+ lots more

$$\sigma_{\rm BS}^{nlm} v$$

Mitridate, Redi, Smirnov, Strumia (2018)

This Seems Like a Lot of Work, What's the Point?

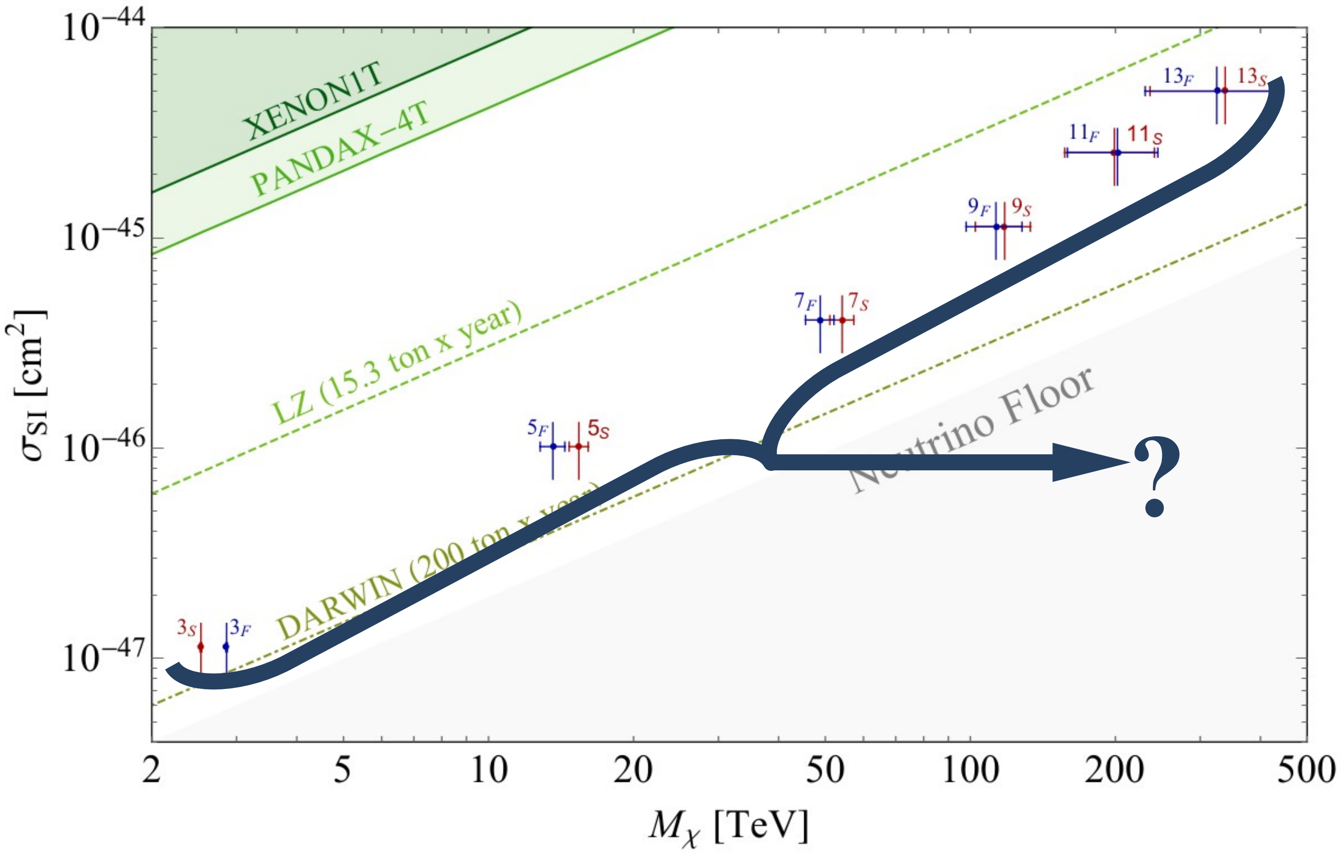
$$< \sigma_{\chi\chi} v >$$

Sommerfeld enhancement goes here

$$< \sigma_{\text{ann}} v > + \sum_{\text{BS}} < \sigma_{\text{BS}} v > \text{BR}(\text{BS} \to \text{SM})$$

$$\frac{\Gamma_{\text{ann}}}{\Gamma_{\text{ann}} + \Gamma_{\text{break}}} = \left(1 + \frac{< \sigma_{\text{BS}} v > (g_\chi + g_\psi)^2 M^3 e^{-x E_{\text{BS}}/M}}{2 g_{BS} (4\pi x)^{3/2} \Gamma_{\text{ann}}}\right)^{-1}$$

But What's Actually the Point?



Sample: 5M4D

Tree Level

$< \sigma v > \approx 1.5 \times 10^{-10} \text{GeV}^{-2}$

↓

Sommerfeld

$< \sigma v > \approx 6.7 \times 10^{-10} \text{GeV}^{-2}$

↓

Sommerfeld + Bound

$< \sigma v > \approx 9.8 \times 10^{-10} \text{GeV}^{-2}$

What's Left to Do?

Actually calculate the masses

What's Left to Do?

Repeat this for all multiplet combinations

Summary (or It's Finally Over!)

- Dark matter exists, it's a real thing!
- A minimal realization of WIMPs, adding a single weak multiplet to the SM, is close to ruled out
- Adding a second multiplet can alleviate this pressure
- Doing this is a pain because of non-perturbative effects

Backup