(Almost) Minimal Dark Matter

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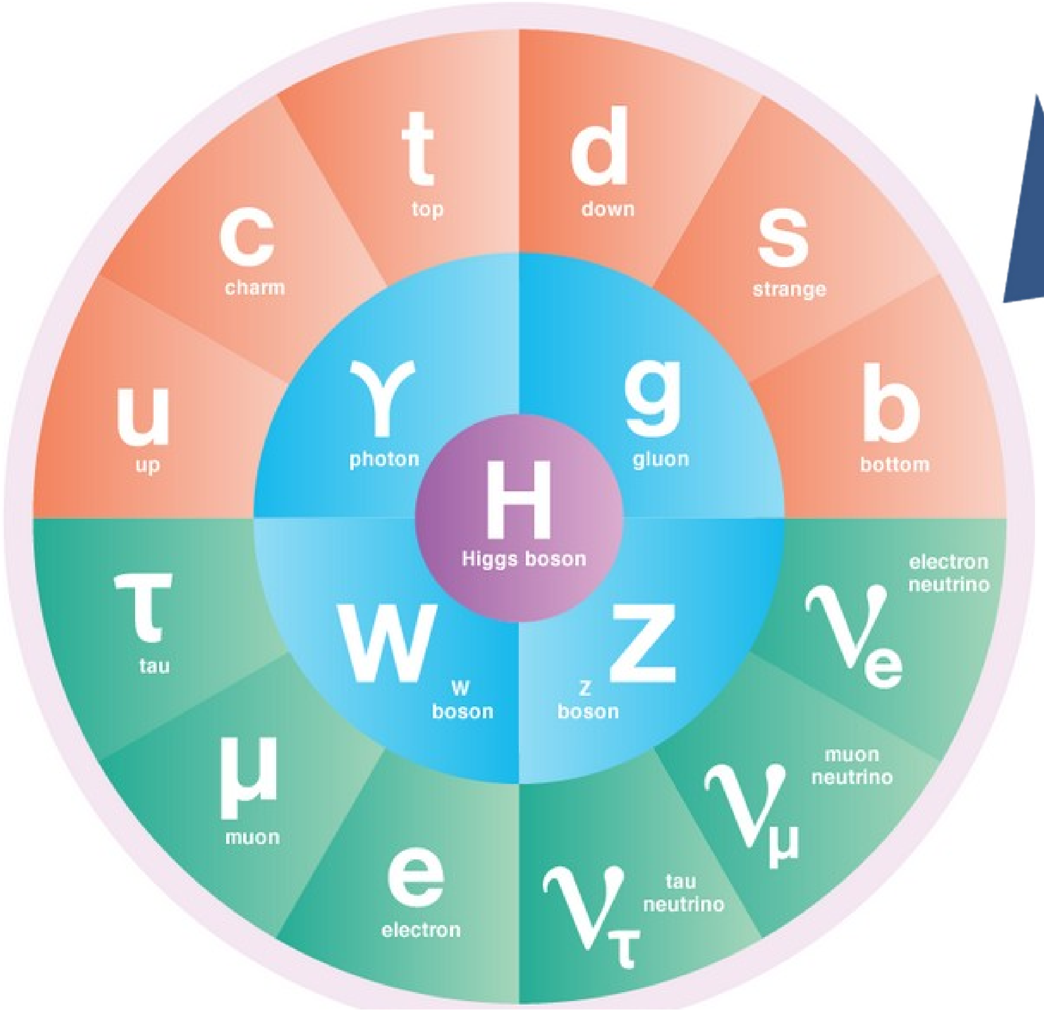
Outline

- Dark matter, what even is it?
- A very WIMP-y miracle
- Minimal dark matter (or taking WIMPs seriously)
- Minimal dark matter coupled to the Higgs

Dark matter, what even is it?

What Is Matter?

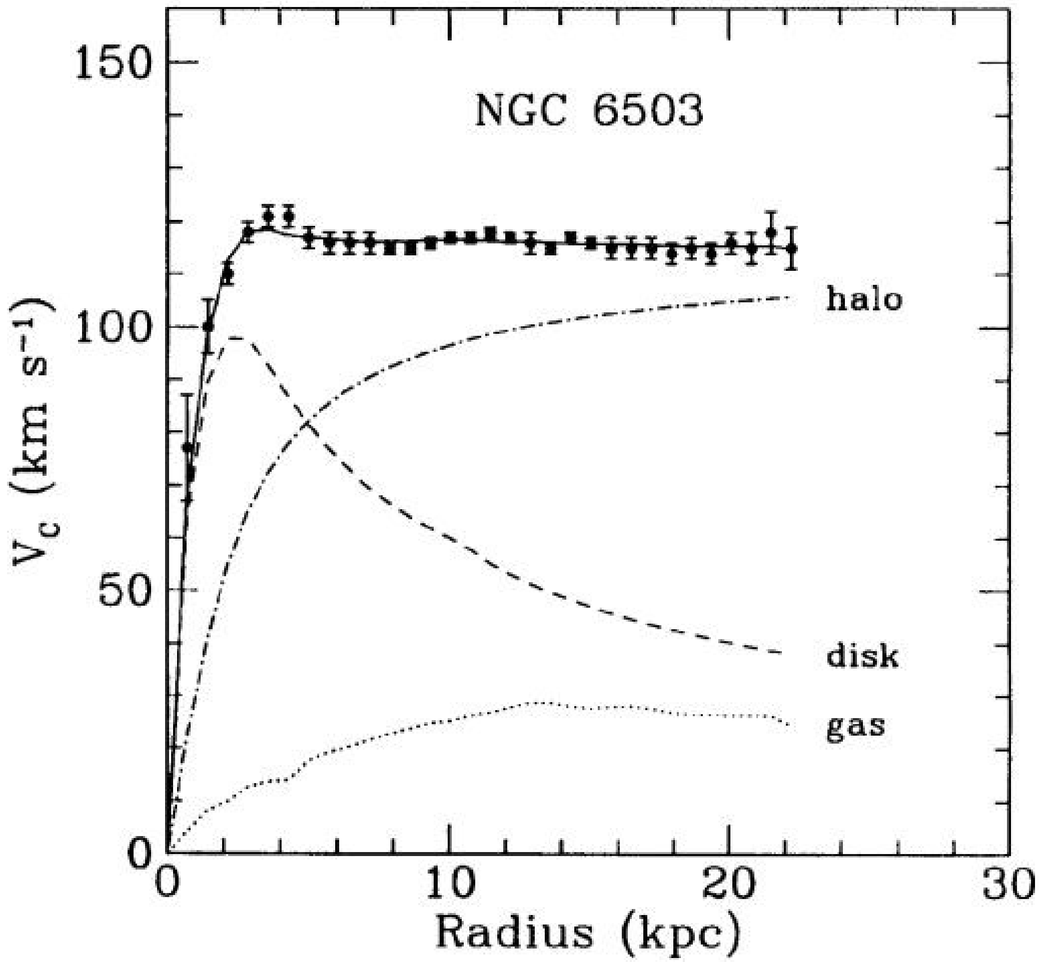


This stuff!

What Is Dark Matter?

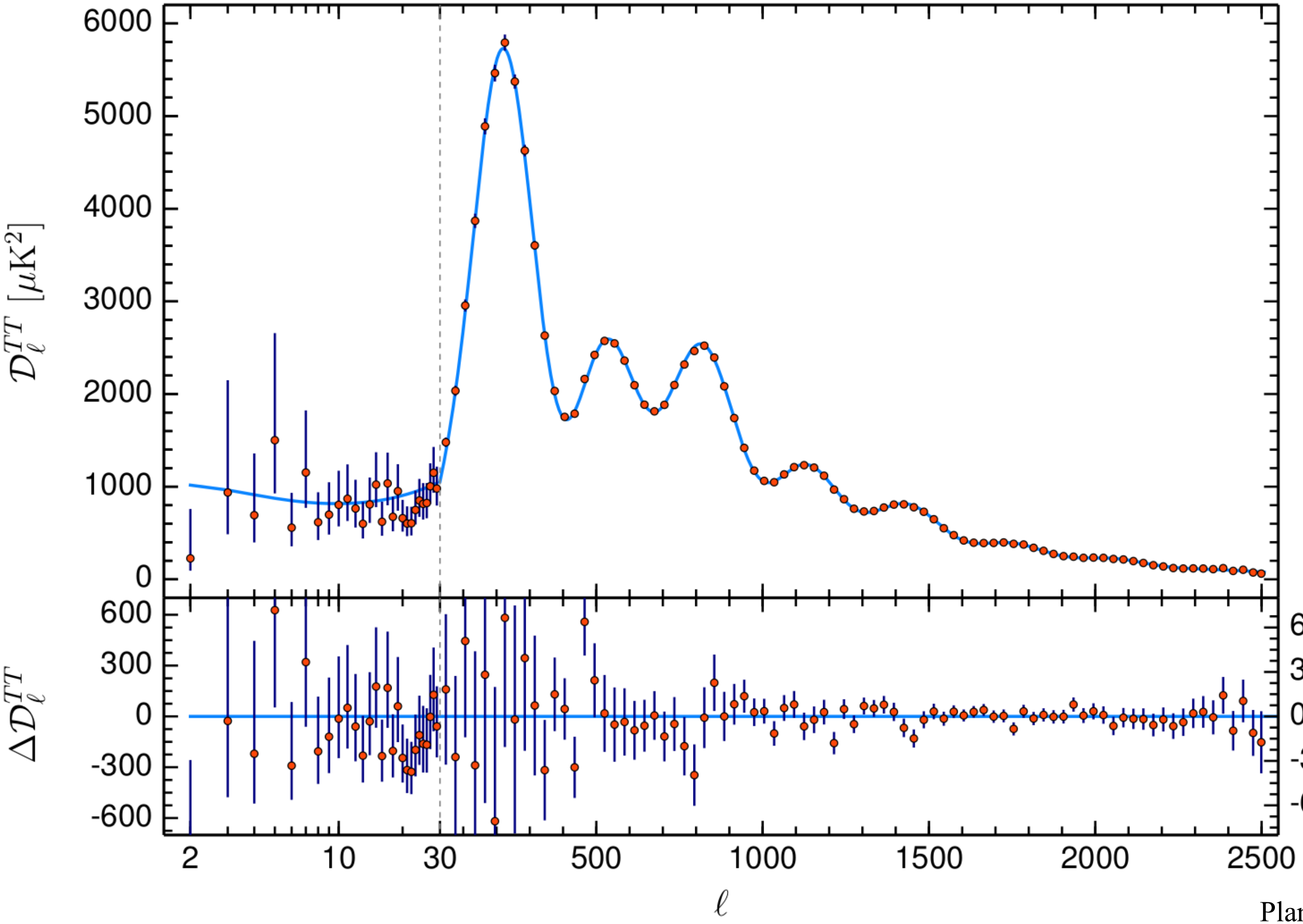
Not this stuff!

Why Is Dark Matter?



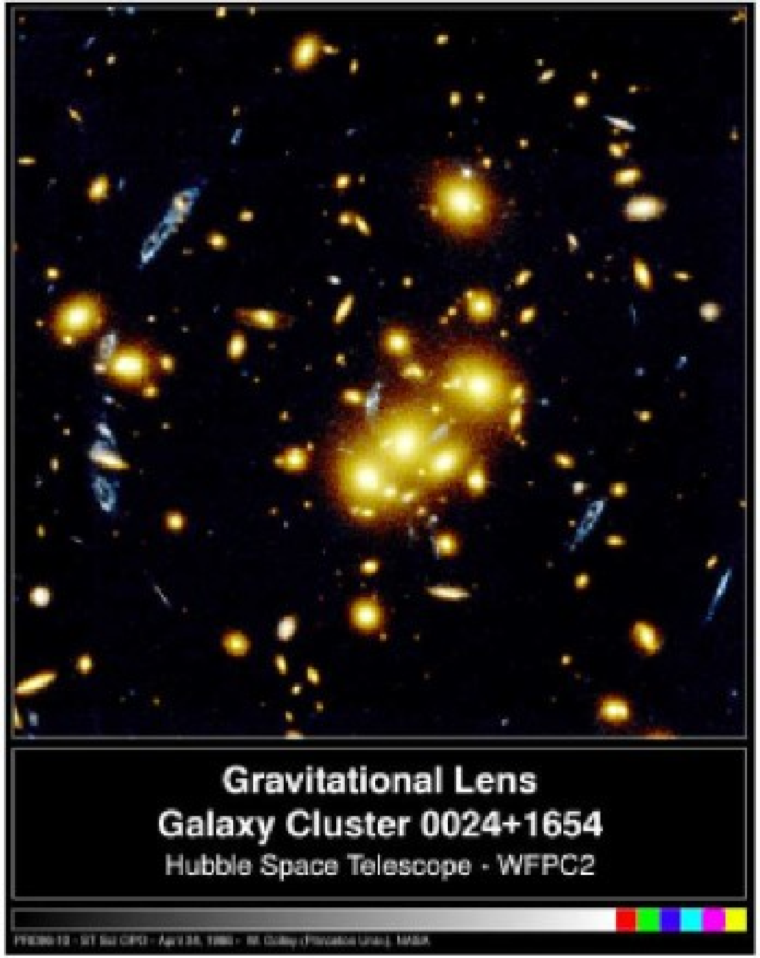
Freese (2008)

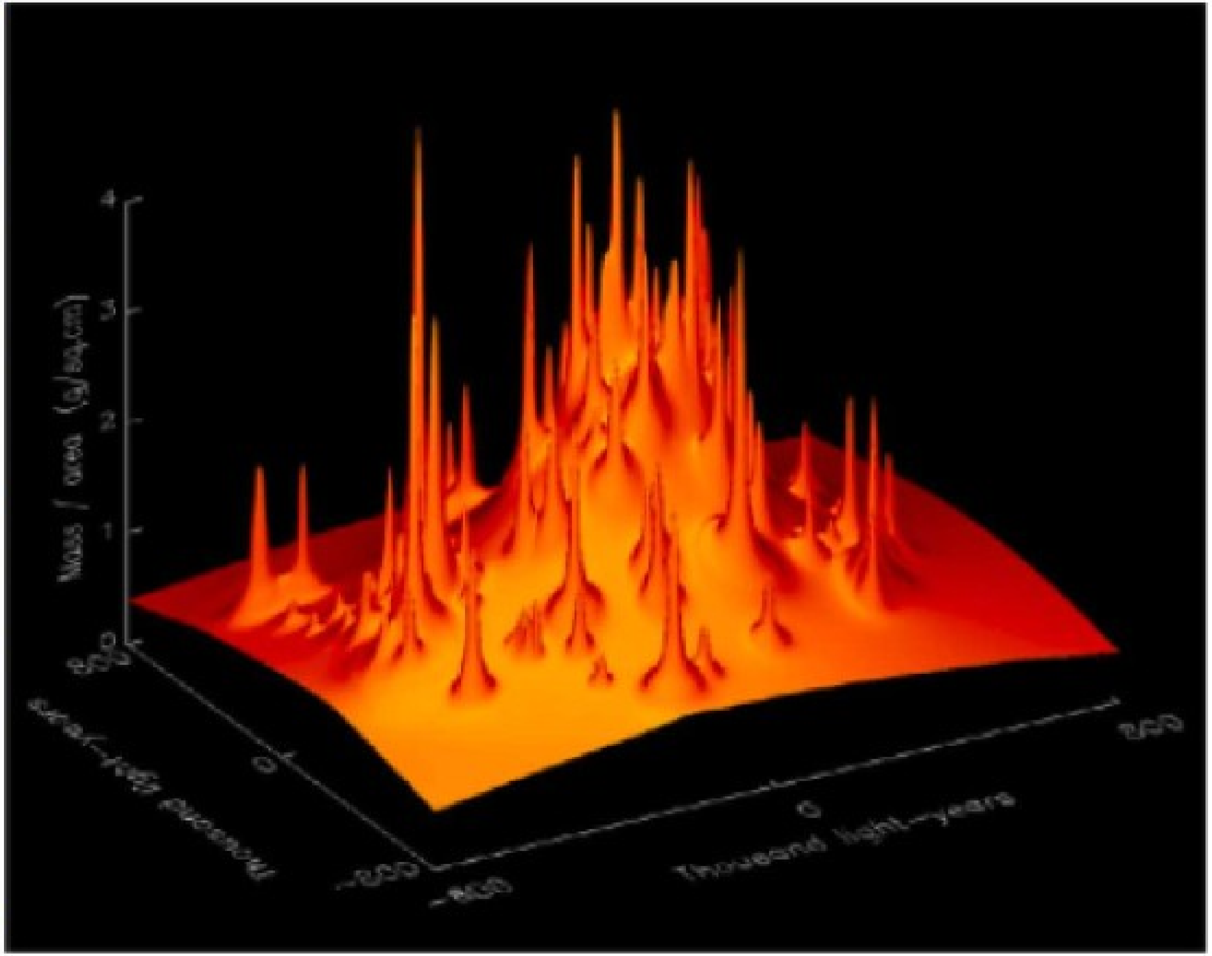
Why Is Dark Matter?



Planck Collaboration (2018)

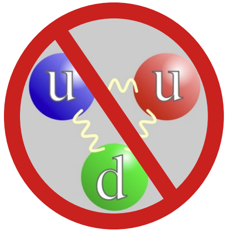
Why Is Dark Matter?



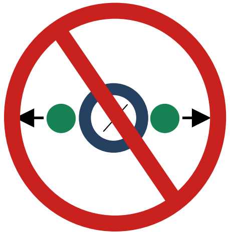


Freese (2008)

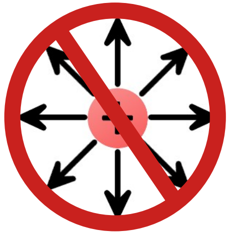
What Is Dark Matter (Again)?



Not baryonic



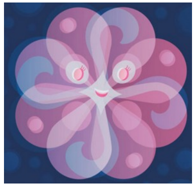
Stable (or at least very long lived)



Electrically neutral (or at least very small charge)

Cold (or at least not hot)

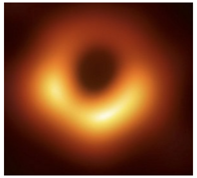
What Is Dark Matter (Last Time, I Promise)?



Weakly Interacting Massive Particles (WIMPs)

(Google says this is what these look like apparently)

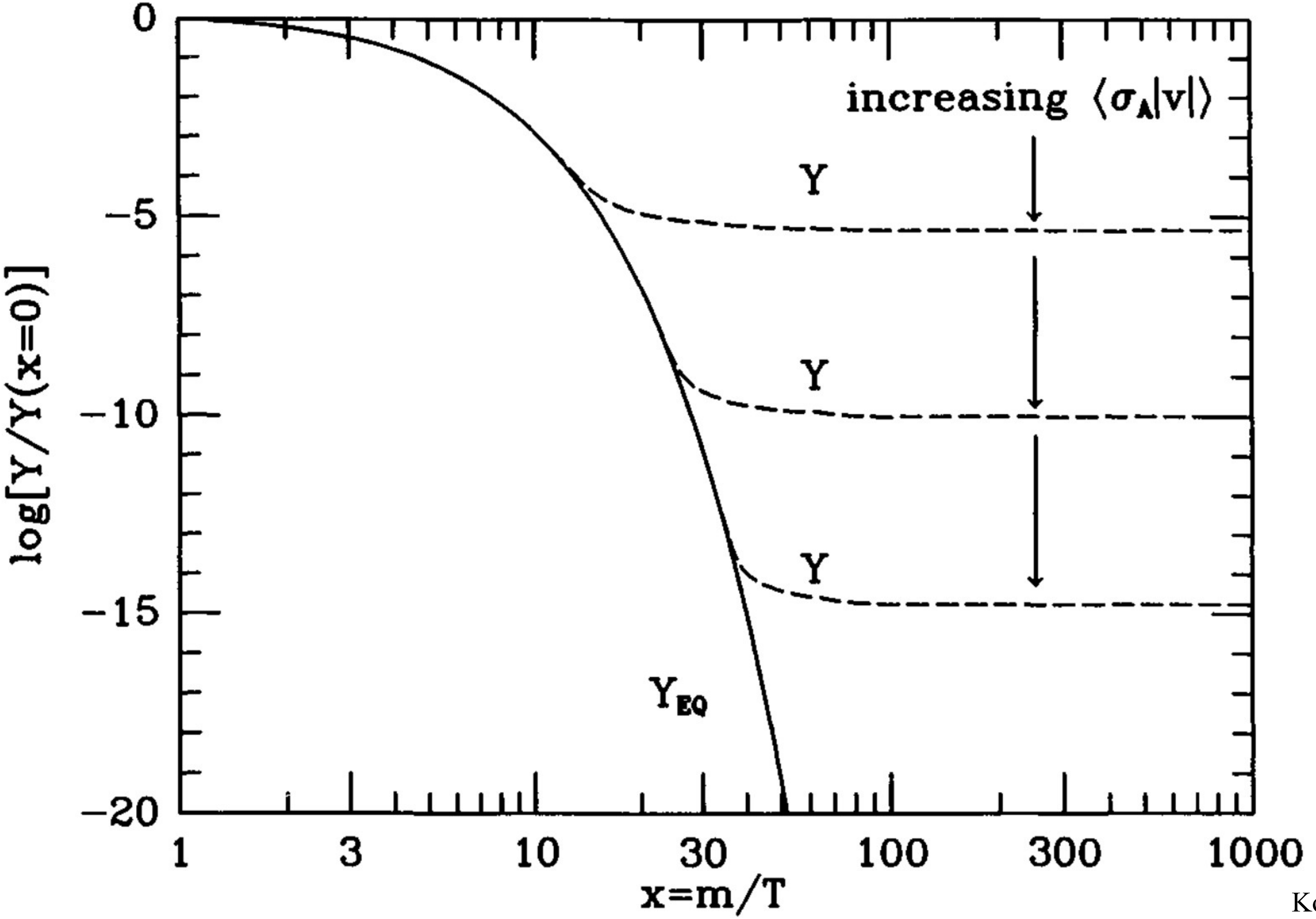
Axions & axion-like particles



Primordial black holes

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

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

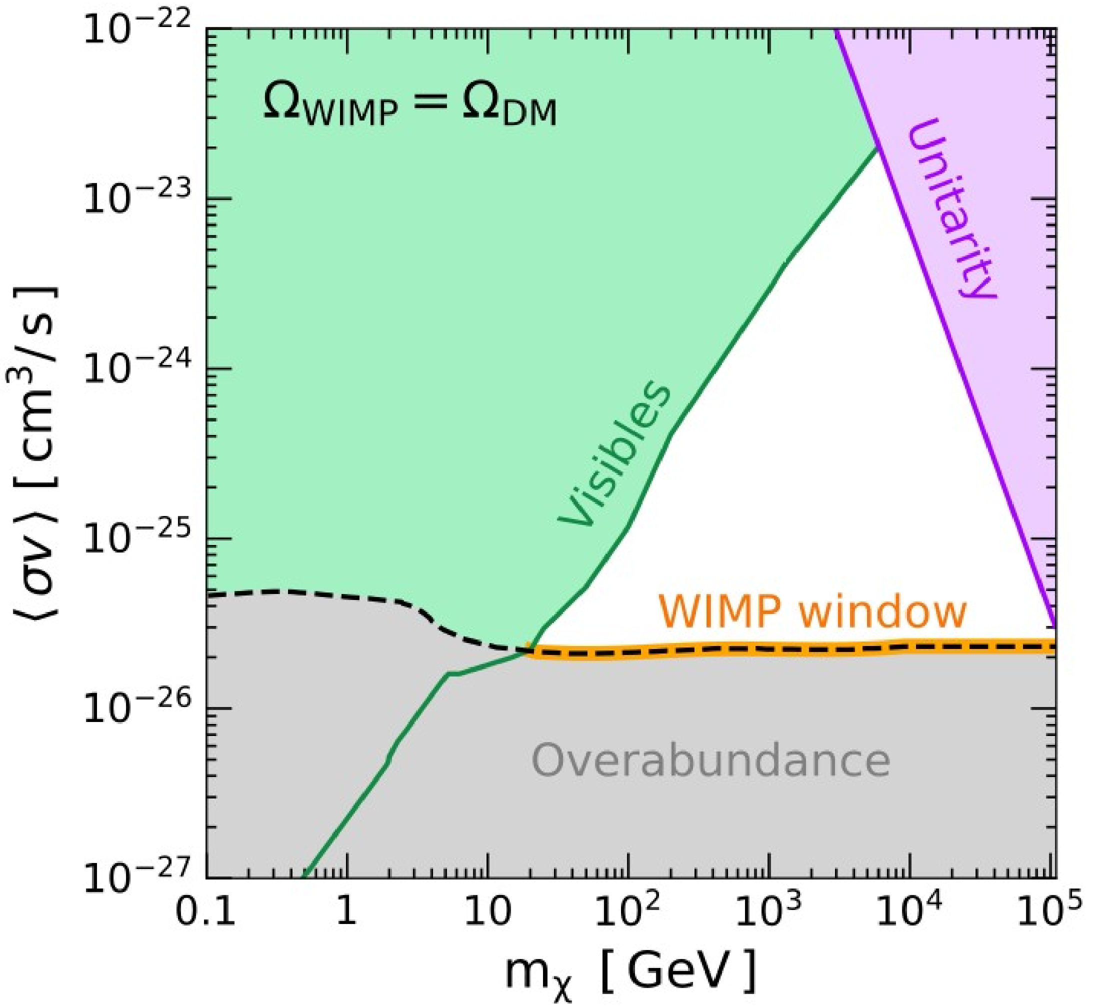
Require this

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

Stuck with this

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

The WIMP Mass



Leane, Slatyer, Beacom, Ng (2018)

Minimal Dark Matter

(or Taking WIMPs Seriously)

Building the Electroweak Lagrangian

Make up some symmetries, $SU(2)_L \times U(1)$ seem fine, and DEMAND they be enforced!

Building the Electroweak Lagrangian

Left ($\psi_{i,L}$) and right ($\psi_{e,R}$) handed particles live in different representations...because why not?

i.e. $\psi_{e,L} = (\nu_e, e_L)$, $\psi_{e,R} = e_R$

Building the Electroweak Lagrangian

Postulate Higgs (φ) doublet with $Y_h = \frac{1}{2}$ and non-zero VEV... because we didn't have enough particles before.

Building the Electroweak Lagrangian

Make a gauge invariant Lagrangian (we care about these terms, the rest are probably fine too though):

$$\mathcal{L} \supset \sum_{i,L,R} \overline{\psi_i}\gamma^\mu(i\partial_\mu - ig_2 A_\mu^a T^a - ig_1 Y_{\psi_i} B^\mu)\psi_i - \lambda_i(\overline{\psi_{i,L}}\phi\psi_{i,R} + \text{h.c.})$$

Done!

P.S. $Q_\psi = T_\psi^3 + Y_\psi$, this is important later

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!

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

SU(2)$_\mathrm{L}$ 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)

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

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

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

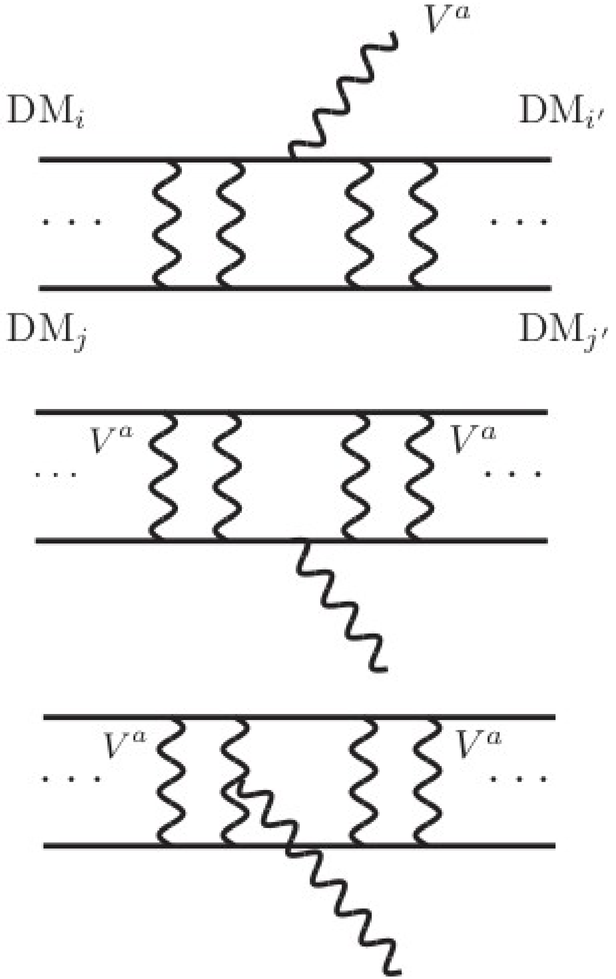
$$+$$

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

$$\downarrow$$

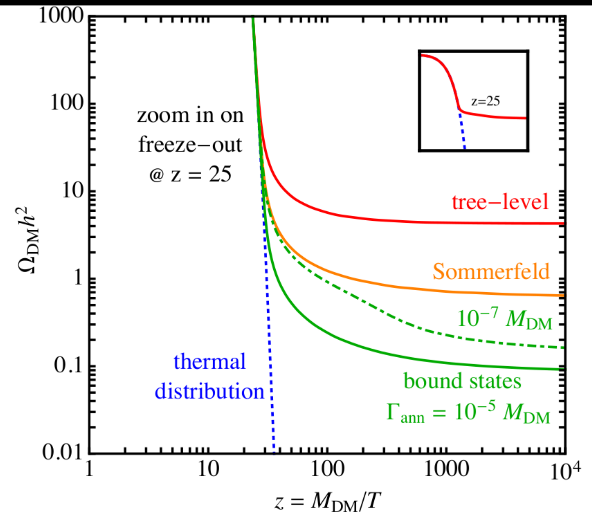
$$\boxed{\mathrm{M}_\chi \geq 500 \text{ GeV}}$$

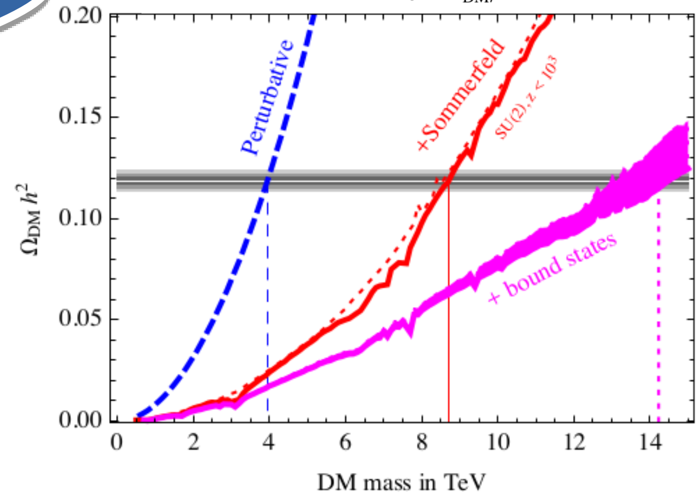
A Few Complications



Bound states

& Sommerfeld enhancement

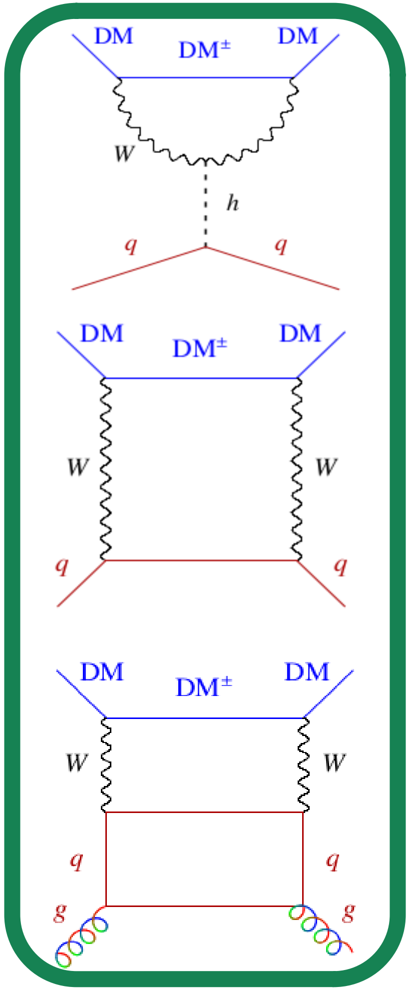




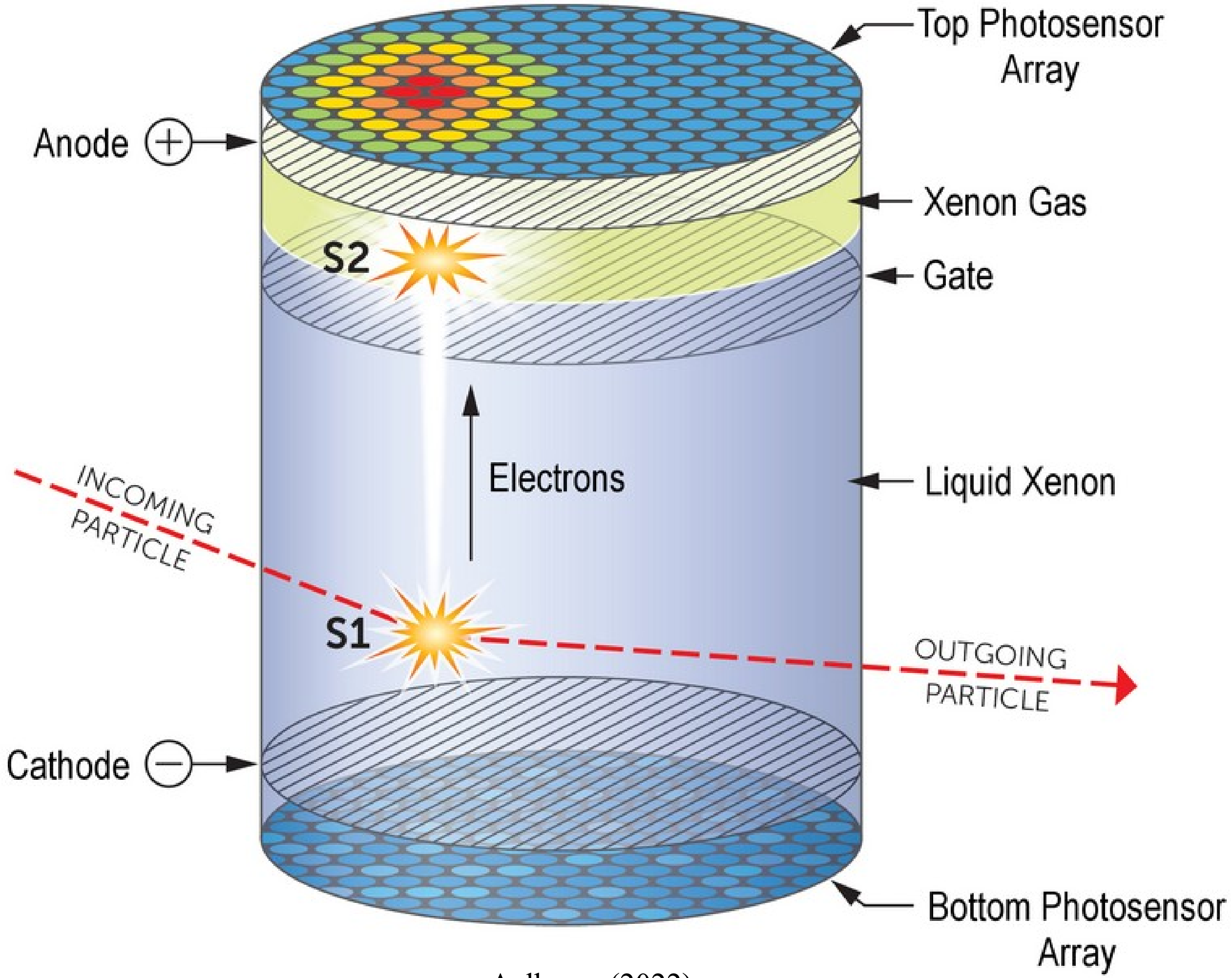
Hisano, Matsumoto, Nagai, Saito, Senami (2006)

Mitridate, Redi, Smirnov, Strumia (2018)

Finding This Stuff

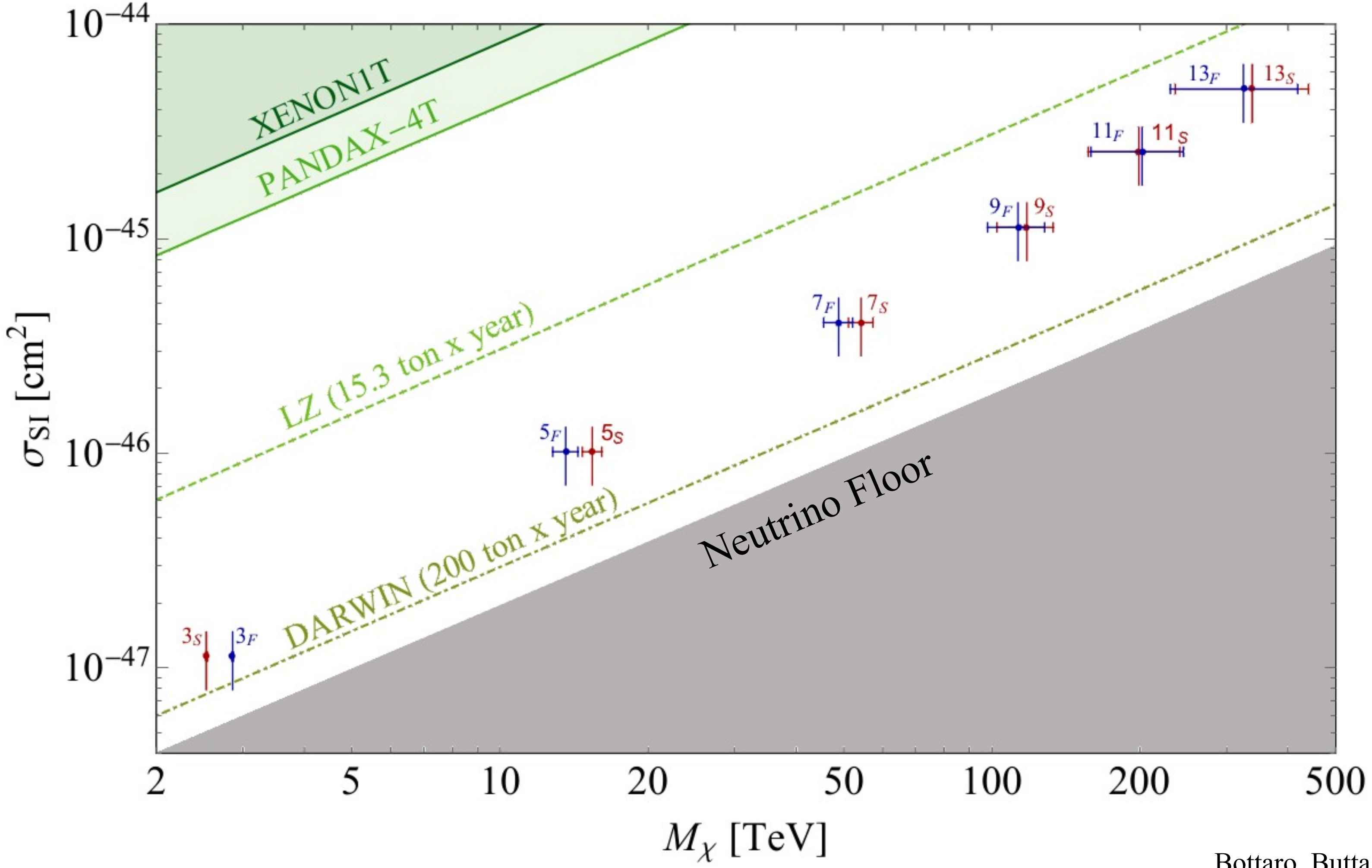


Cirelli, Strumia, Zupan (2024)



Aalbers...(2022)

Show Me That Dark Matter!



Bottaro, Buttazzo, Costa...(2022)

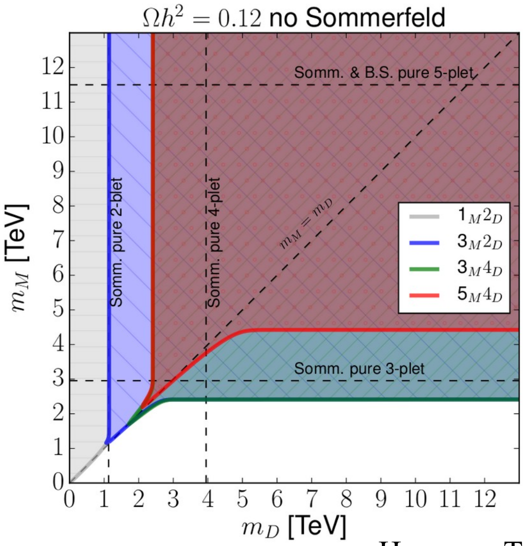
Minimal Dark Matter Coupled to the Higgs

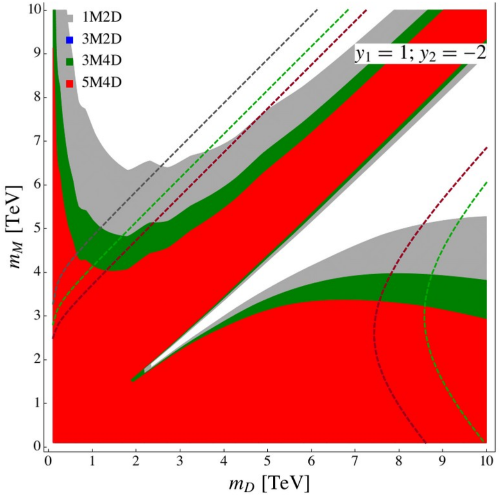
Adding a Multiplet

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

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

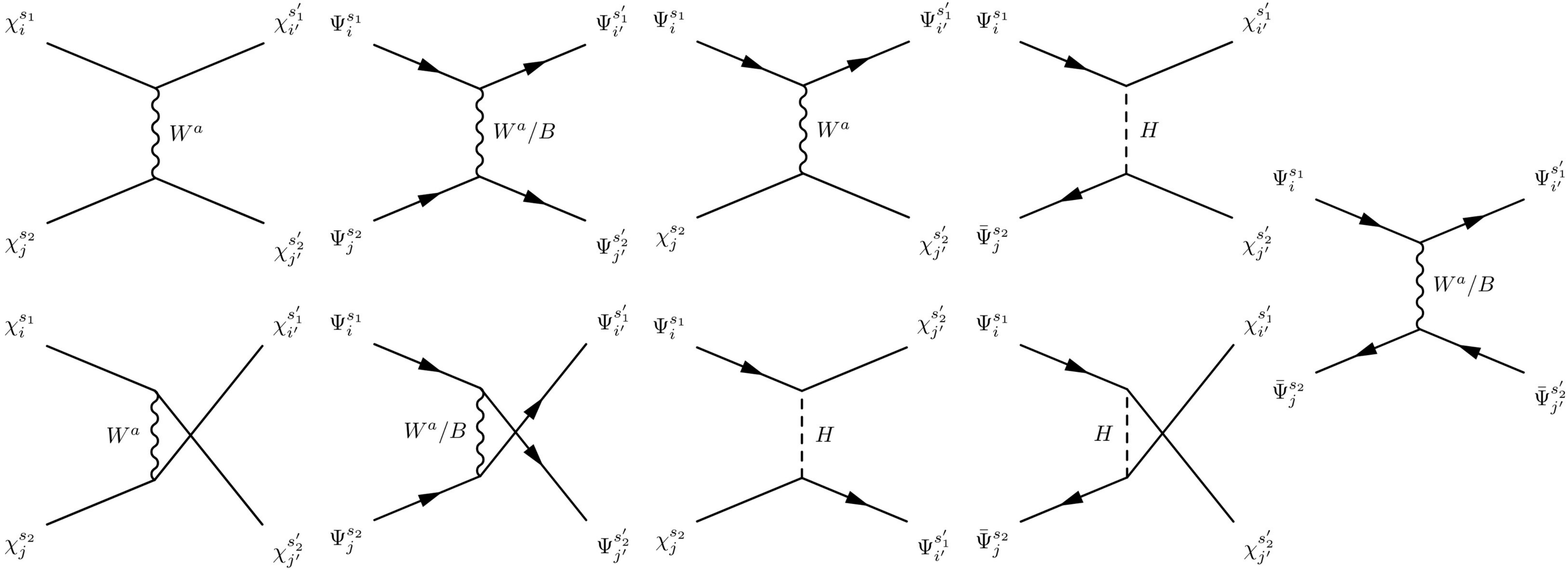
$$\chi = \begin{pmatrix} \chi \\ i\sigma_2\chi^\dagger \end{pmatrix} \qquad \Psi = \begin{pmatrix} \psi \\ i\sigma_2\tilde{\psi}^\dagger \end{pmatrix}$$





Honorez, Tytgat, Tziveloglou, Zaldivar (2017)

Long Range Potentials



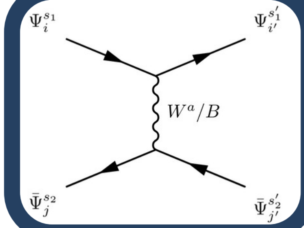
Long range potentials → **Sommerfeld enhancement** → Easy!

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

Oncala, Petraki (2021)

The Non-Relativistic Potential

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



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

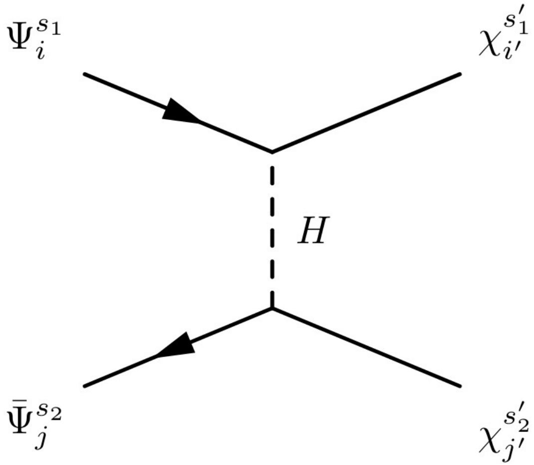
$\delta^{s_1 s_1'}\delta^{s_2 s_2'} \rightarrow 1$

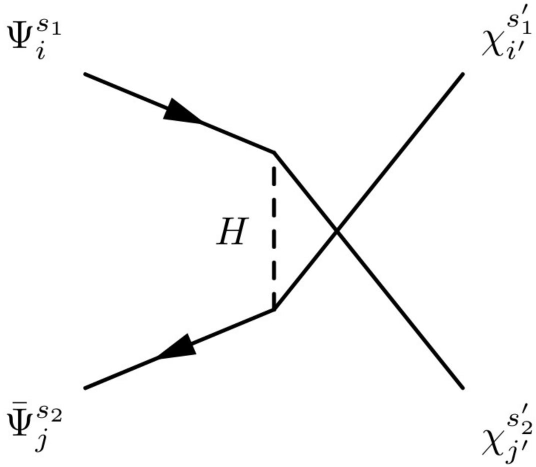
$t^a_{i'i} t^a_{jj'} \rightarrow C^{\Psi\bar{\Psi}}_{R_{\Psi\bar{\Psi}}} = \frac{1}{2}\left(C_2(R_\Psi) + C_2(R_{\bar{\Psi}}) - C_2(R_{\Psi\bar{\Psi}})\right)$

$\delta_{ii'}\delta_{jj'} \rightarrow$ selection rule

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

Mixed States





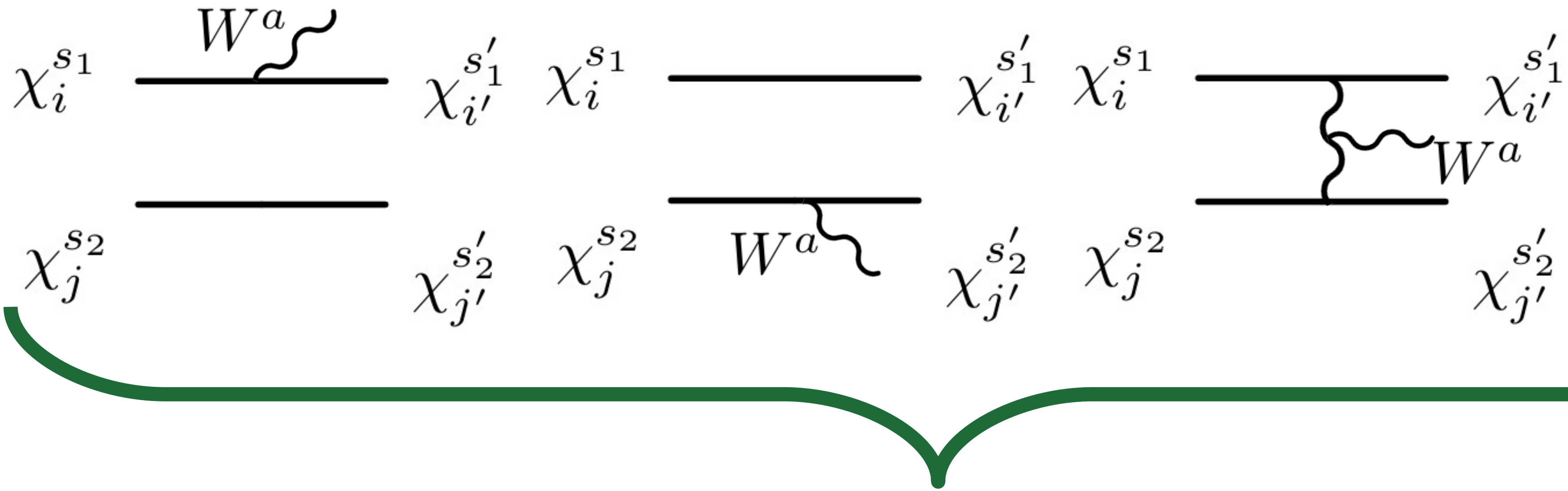
$$\boxed{\left(\frac{-\nabla^2}{2\mu} + \hat{V}(R)\right)\begin{pmatrix}\phi_{SS}(R)\\ \phi_{D\bar{D}}(R)\end{pmatrix} = E(R)\begin{pmatrix}\phi_{SS}(R)\\ \phi_{D\bar{D}}(R)\end{pmatrix}}$$

Diagonalize this

Work with eigenstates of this

Use eigenstates to find “weighted” decay rates

Bound State Formation



$+\,37$ more

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

Mitridate, Redi, Smirnov, Strumia (2018)

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

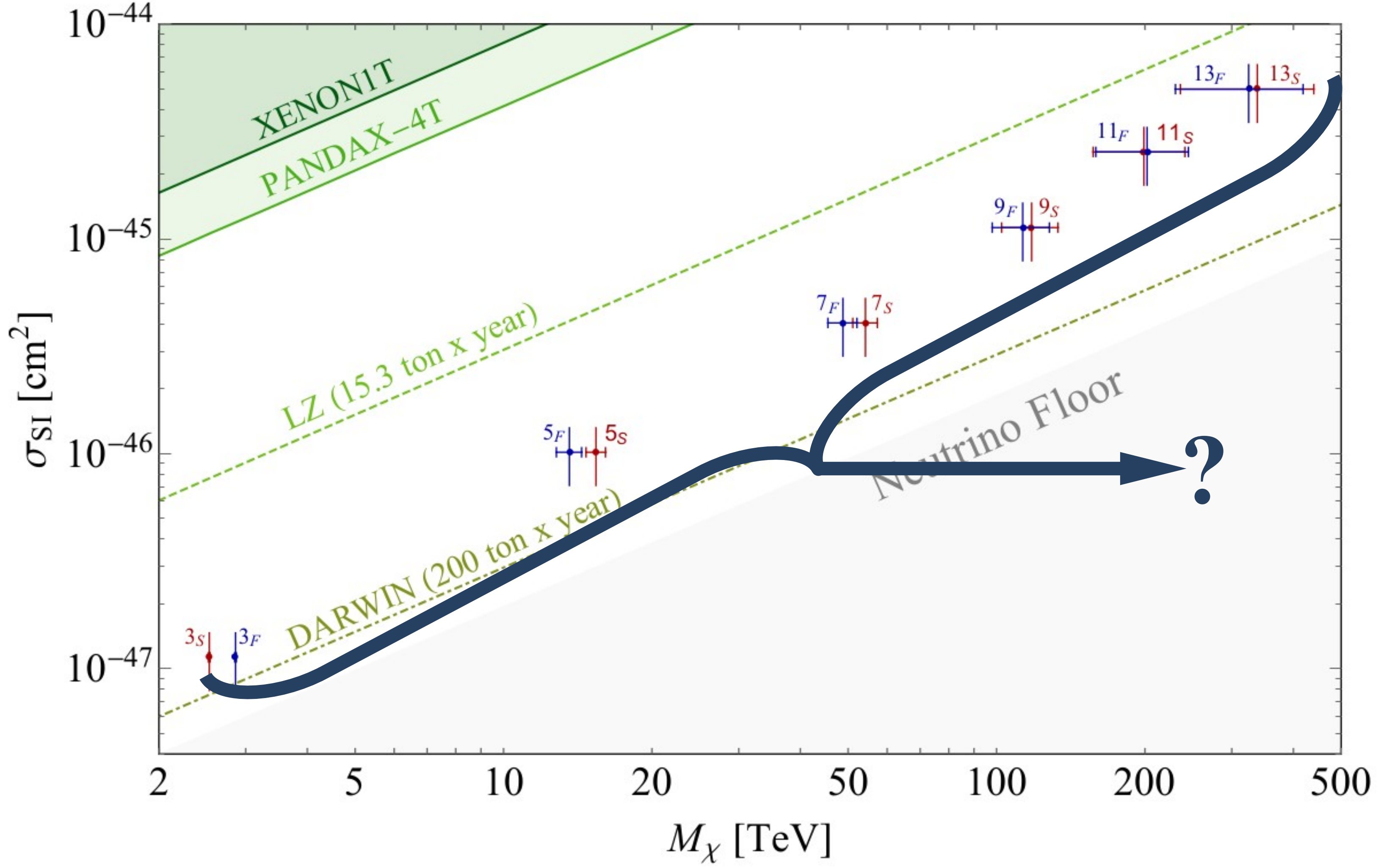
$$\boxed{< \sigma_{\chi\chi} v >}$$

Sommerfeld enhancement goes here

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

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

But What's Actually the Point?



What’s Left to Do?

Actually calculate masses

What's Left to Do?

So far we've been working in unbroken electroweak symmetry...can we?

What's Left to Do?

Thermal effects

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