WIMP and EFT

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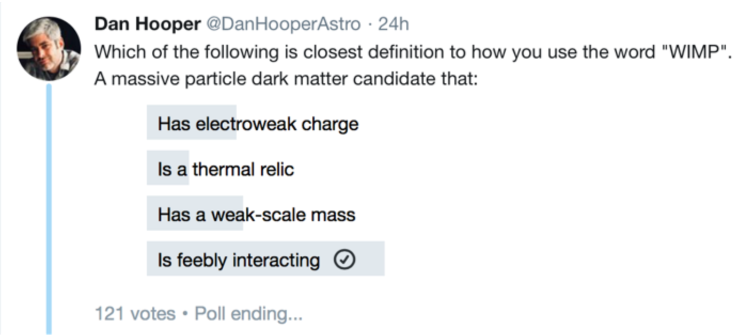
Outline

1. WIMP
   - A “stupid” question: what’s WIMP
   - WIMP miracle V.S. SUSY WIMP (Neutralinos)
2. An introduction to EFT
   - EFT successfully described a weak-interaction, beta decay
   - EFT V.S. SI/SD
   - EFT in the whole spectrum of DM models
3. Summary

Outline

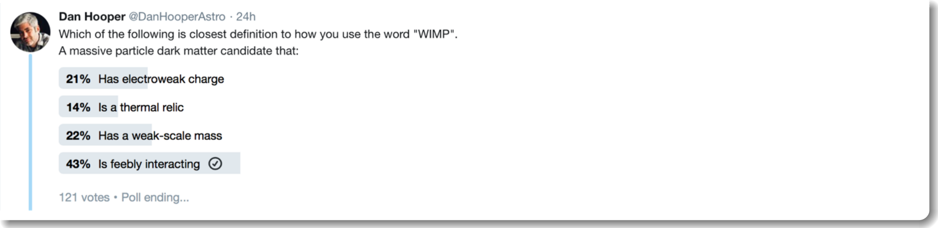
An interesting survey by Prof. Dan Hooper on Twitter

WIMP = Weakly Interactive Massive Particles



- The (very likely but can’t guarantee) back story of this survey: I asked Dan how to link the “WIMP miracle motivated” WIMP and “Higgs hierarchy problem motivated” WIMP when he visited at Brown for a colloquium.

Surprising survey results



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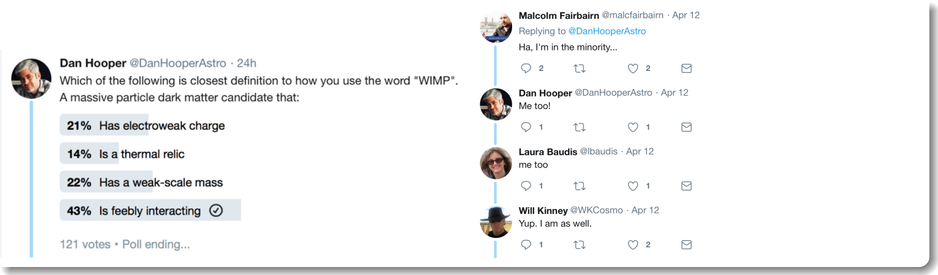

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WIMP miracle and Neutralinos come from totally different scenarios

- Difference: WIMP miracle is a simple model; Neutralinos based on very well built and complicated model, SUSY.
- Common : Neither of these two scenarios have been verified.

WIMPs

G.Bertone, Nature09509

In the simplest WIMP models, dark matter particles are kept in thermal and chemical equilibrium in the early Universe with all other particles, by virtue of their self-annihilation into particles of the standard model and vice versa. Their density rapidly decreases as the Universe expands, until it becomes so low that WIMPs cannot self-annihilate any more and they freeze-out from equilibrium, that is, their co-moving number density remains fixed. Under some simplifying assumptions[23], the relic abundance of WIMPs in the Universe Ω_χ (that is, the number density of WIMPs in the local Universe in units of the critical density (see ref. 12 for further details)) can be simply expressed in terms of the self-annihilation cross-section, σv:

$$\Omega_\chi h^2 \approx \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\sigma v} \qquad (1)$$

where h is the Hubble parameter, which encodes the expansion rate of the Universe, in units of 100 km s^{-1} Mpc^{-1}. As the measured value of $\Omega_\chi h^2$ is around 0.1 (ref. 12), the self-annihilation cross-section required in order to achieve the appropriate relic density is $\sigma v \approx 3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$, a cross-section typical of weak interactions in the standard model, hence the name WIMPs. Although in this

3.2.1. Neutralinos. The gauge hierarchy problem is most elegantly solved by supersymmetry. In supersymmetric extensions of the SM, every SM particle has a new, as-yet-undiscovered partner particle, which has the same quantum numbers and gauge interactions, but differs in spin by 1/2. The introduction of new particles with opposite spin-statistics from the known ones supplements the SM quantum corrections to the Higgs boson mass with opposite sign contributions, modifying Equation 4 to

$$\Delta m_h^2 \sim \frac{\lambda^2}{16\pi^2}\int^\Lambda \frac{d^4p}{p^2}\bigg|_{\mathrm{SM}} - \frac{\lambda^2}{16\pi^2}\int^\Lambda \frac{d^4p}{p^2}\bigg|_{\mathrm{SUSY}} \sim \frac{\lambda^2}{16\pi^2}(m_{\mathrm{SUSY}}^2 - m_{\mathrm{SM}}^2)\ln\frac{\Lambda}{m_{\mathrm{SUSY}}}, \qquad (11)$$

where m_{SM} and m_{SUSY} are the masses of the SM particles and their superpartners. For $m_{\mathrm{SUSY}} \sim m_{\mathrm{weak}}$, this is at most an $\mathcal{O}(1)$ correction, even for $\Lambda \sim M_{\mathrm{Pl}}$. This by itself stabilizes, but does not solve, the gauge hierarchy problem; one must also understand why $m_{\mathrm{SUSY}} \sim m_{\mathrm{weak}} \ll M_{\mathrm{Pl}}$. There are, however, a number of ways to generate such a hierarchy; for a review, see Shadmi & Shirman (2000). Given such a mechanism, the relation of Equation 11 implies that quantum effects will not destroy the hierarchy, and the gauge hierarchy problem may be considered truly solved.

Not surprisingly, the doubling of the SM particle spectrum has many implications for cosmology. For dark matter, it is natural to begin by listing all the new particles that are electrically neutral. For technical reasons, supersymmetric models require two Higgs bosons. The neutral supersymmetric particles are then

J. Feng, Annu. Rev. Astron. Astrophys. 2010. 48:495-545

Outline

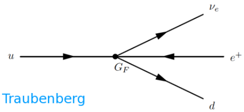
An example of EFT in particle physics

The Fermi model of weak interaction is an EFT

- In the experiments of nuclear beta decay, physicists observed the energy spectrum of the electron is continuous. To interpret it, Pauli introduced the neutrino.
- Fermi proposed the Lagrangian to describe the beta decay.
- It has been widely considered as a "brilliantly successful" theory until 1960s the weak interaction theory arose.

Phenomenological model based on four-point interactions (Fermi, 1932).

$$\mathcal{L}_{\rm Fermi} = -2\sqrt{2} G_F \left[\bar\Psi_d \, \gamma_\mu \frac{1-\gamma^5}{2} \, \Psi_u\right] \left[\bar\Psi_{\nu_e} \, \gamma^\mu \frac{1-\gamma^5}{2} \, \Psi_e\right] + \text{h.c.}\ .$$



B. Fuks & M. Traubenberg

- Does this indicate we can understand DM only until 2040s ? Since 2040s - 2010s $\sim$ = 30 years = 1960s - 1930s , $\ddot\smile$.

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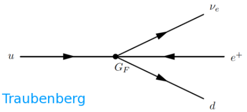
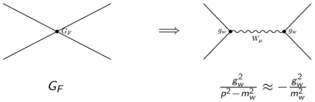


B. Fuks & M. Traubenberg

Solution: a gauge theory (Glashow, Salam, Weinberg, 60-70, [Nobel prize, 1979]).

* Four fermion interactions can be seen as a *s*-channel diagram.
* Introduction of a **new gauge boson** W_μ.
* This boson couples to fermions with a **strength** g_w.



* Prediction: $g_w \sim \mathcal{O}(1) \Rightarrow m_w \sim 100$ GeV.

B. Fuks & M. Traubenberg

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Outline

EFT $\mathcal{O}s$

A talk can't miss EFT presentation, Prof. W. Haxton in LUX analysis workshop.

$\mathcal{O}_1 = 1_\chi 1_N$ (Standard Spin Independent)

$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$

$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$ (Standard Spin Dependent)

$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$

$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$

$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$

$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$

$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$

$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$

$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$

$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$

$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$

$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$

$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$

$\mathcal{O}_{\mathcal{U}}$ <==> S.I.

Others <==> S.D.

Arxiv : 1308.6288

ArxiV : 1008.1591

Arxiv : 1203.3542

ArxiV : 1503.03379

- The first paper listed all of the $\mathcal{O}_s$ for F-F interactions. (JHEP11(2006) 005).
- The first paper applying “JHEP11(2006) 005” into DM, arXiv: 1308.6288.
- Galilean-invariant (NR). Elastic scattering.
- Four parameters:
  DM velocity, $\vec{v} \sim 10^{-3}c$;
  momentum transfer, $\vec{q}$;
  DM spin, $\vec{S}_\chi$;
  nucleon spin; $\vec{S}_N$.
- $\mathcal{O}_1$ and $\mathcal{O}_4$, tree level;
  $\mathcal{O}_1$ = standard S.I. ; $\mathcal{O}_4$ = standard S.D.
  others $\mathcal{O}_s$, LO, NLO, N^{2}LO, N^{3}LO.
- The Fermi interpretation on the weak interaction in 1930s is one of the most famous examples of EFT (see next slide.).

Wrap interactions into event rate: EFT and standard SI/SD

Event rate, standard Spin Independent (SI) and EFT, (Kg day keV)$^{-1}$

- $\frac{dE}{dR}_{\text{SI}} = N_T \cdot \frac{\rho_\chi}{2m_\chi} \cdot \frac{A^2}{m_{red}^2(m_p)} \cdot \sigma^{\text{SI}}{}_{\chi p} \cdot F_{\text{SI}}^2(E) \cdot \int_{v_{min}}^{\infty} \frac{f_1(v)}{v} dv$
- $\frac{dE}{dR}_{\text{EFT}} = N_T \cdot \frac{\rho_\chi}{2m_\chi} \cdot \frac{A^2}{m_{red}^2(m_p)} \cdot \mathcal{O}s \cdot \int_{v_{min}}^{\infty} \frac{f_1(v)}{v} dv$ [∼intuitively∼]
- $\sigma^{\text{SI}}_{\chi p}$, cross-section of WIMPs and a nucleon.
  $F_{\text{SI}}^2(E)$, form factor.
- $\mathcal{O}s$ represents the nuclear response of a detector to WIMPs.
- N_T, # of target nucleon per kg detector,
  ρ_χ, WIMP mass density,
  m_χ, mass of dark matter,
  A, atomic number of target nucleus,
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The key difference between EFT and standard SI / SD (intuitive)

Whether or not considered the transferred momentum of a DM-detector scattering

- Left picture: a long wavelength corresponds to a small momentum transferred scattering; EFT and Standard SI/SD is the same for this kind of scattering.
- Right picture: a short wavelength corresponds to big momentum transferred scattering; standard SI/SD uses a form factor to characterize the “reduced” recoil energy to the hit nuclei while ignore the interactions caused by the transferred momentum; EFT fully characterizes all of possible interactions with operators.

The key difference between EFT and standard SI / SD

- Left picture: the interactions between DM and detector by considering the transferred momentum under EFT.
- Right picture: as a result, by considering the "extra" interactions caused by EFT operators, the recoil energy of EFT operators are higher than standard SI/SD.

The point-nucleus world is what we thought we could probe
But the derivative coupling world is is easy to see, with the right target

$$
\begin{aligned}
R_M^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) &= c_1^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^2}{m_N^2}\vec{v}_T^{\perp 2} c_5^\tau c_5^{\tau'} + \vec{v}_T^{\perp 2} c_8^\tau c_8^{\tau'} + \frac{\vec{q}^2}{m_N^2} c_{11}^\tau c_{11}^{\tau'}\right] \\
R_{\Phi''}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) &= \frac{\vec{q}^2}{4m_N^2} c_3^\tau c_3^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left(c_{12}^\tau - \frac{\vec{q}^2}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^2}{m_N^2} c_{15}^{\tau'}\right) \\
R_{\Phi'' M}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) &= c_3^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left(c_{12}^\tau - \frac{\vec{q}^2}{m_N^2} c_{15}^\tau\right) c_{11}^{\tau'} \\
R_{\tilde{\Phi}'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) &= \frac{j_\chi(j_\chi+1)}{12}\left[c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^2}{m_N^2} c_{13}^\tau c_{13}^{\tau'}\right] \\
R_{\Sigma''}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) &= \frac{\vec{q}^2}{4m_N^2} c_{10}^\tau c_{10}^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \right. \\
&\left. \frac{\vec{q}^2}{m_N^2}(c_4^\tau c_6^{\tau'} + c_6^\tau c_4^{\tau'}) + \frac{\vec{q}^4}{m_N^4} c_6^\tau c_6^{\tau'} + \vec{v}_T^{\perp 2} c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^2}{m_N^2}\vec{v}_T^{\perp 2} c_{13}^\tau c_{13}^{\tau'}\right] \\
R_{\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) &= \frac{1}{8}\left[\frac{\vec{q}^2}{m_N^2}\vec{v}_T^{\perp 2} c_3^\tau c_3^{\tau'} + \vec{v}_T^{\perp 2} c_7^\tau c_7^{\tau'}\right] + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \right. \\
&\left. \frac{\vec{q}^2}{m_N^2} c_9^\tau c_9^{\tau'} + \frac{\vec{v}_T^{\perp 2}}{2}\left(c_{12}^\tau - \frac{\vec{q}^2}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^2}{m_N^2} c_{15}^{\tau'}\right) + \frac{\vec{q}^2}{2m_N^2}\vec{v}_T^{\perp 2} c_{14}^\tau c_{14}^{\tau'}\right] \\
R_{\Delta}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) &= \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^2}{m_N^2} c_5^\tau c_5^{\tau'} + c_8^\tau c_8^{\tau'}\right] \\
R_{\Delta\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) &= \frac{j_\chi(j_\chi+1)}{3}\left[c_5^\tau c_4^{\tau'} - c_8^\tau c_9^{\tau'}\right].
\end{aligned}
$$

W. Haxton

TABLE I. The upper energy threshold E_{max} (in keV$_{\rm nr}$) for each of the effective field theory operators, such that an energy window from 0 to E_{max} captures either 50% or 90% of WIMP-neutron recoil events for the given operator and WIMP mass.

Nicole Larson's EFT draft paper

Operator	50-GeV WIMP $E^{50\%}_{max}$ (keV$_{\rm nr}$)	50-GeV WIMP $E^{90\%}_{max}$ (keV$_{\rm nr}$)	500-GeV WIMP $E^{50\%}_{max}$ (keV$_{\rm nr}$)	500-GeV WIMP $E^{90\%}_{max}$ (keV$_{\rm nr}$)
SI	10.8	27.3	16.6	44.7
$\mathcal{O}_1$	6.8	21.7	11.8	43.8
$\mathcal{O}_3$	26.4	49.1	148.1	344.4
SD	8.6	21.6	11.9	37.5
$\mathcal{O}_4$	7.0	24.0	32.8	299.6
$\mathcal{O}_5$	16.2	38.6	65.5	328.9
$\mathcal{O}_6$	33.6	64.0	267.3	433.7
$\mathcal{O}_7$	5.0	16.2	25.2	279.9
$\mathcal{O}_8$	6.8	22.2	14.5	64.8
$\mathcal{O}_9$	13.7	37.2	276.7	464.7
$\mathcal{O}_{10}$	21.7	48.6	112.6	340.4
$\mathcal{O}_{11}$	15.5	34.4	39.0	279.9
$\mathcal{O}_{12}$	17.4	38.1	34.8	176.5
$\mathcal{O}_{13}$	28.2	53.2	54.5	219.7
$\mathcal{O}_{14}$	11.9	27.9	240.9	400.0
$\mathcal{O}_{15}$	34.3	59.1	261.2	433.7

The EFT interactions in the space of particle physics (relativistic)

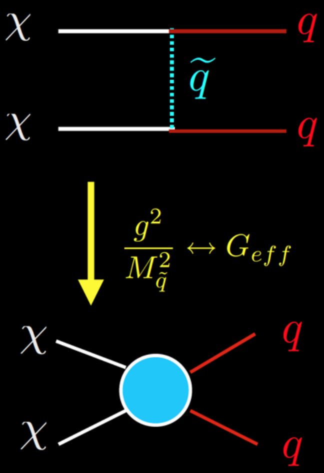
N. Anard etc, arXiv: 1308.6288

j	$\mathcal{L}^j_{\rm int}$	Nonrelativistic reduction	$\sum_i c_i \mathcal{O}_i$	P/T
1	$\bar\chi\chi\bar N N$	$1_\chi 1_N$	$\mathcal{O}_1$	E/E
2	$i\bar\chi\chi\bar N\gamma^5 N$	$i\frac{\vec q}{m_N}\cdot\vec S_N$	$\mathcal{O}_{10}$	O/O
3	$i\bar\chi\gamma^5\chi\bar N N$	$-i\frac{\vec q}{m_\chi}\cdot\vec S_\chi$	$-\frac{m_N}{m_\chi}\mathcal{O}_{11}$	O/O
4	$\bar\chi\gamma^5\chi\bar N\gamma^5 N$	$-\frac{\vec q}{m_\chi}\cdot\vec S_\chi\frac{\vec q}{m_N}\cdot\vec S_N$	$-\frac{m_N}{m_\chi}\mathcal{O}_6$	E/E
5	$\bar\chi\gamma^\mu\chi\bar N\gamma_\mu N$	$1_\chi 1_N$	$\mathcal{O}_1$	E/E
6	$\bar\chi\gamma^\mu\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$\frac{\vec q^{\,2}}{2m_N m_M}1_\chi 1_N + 2(\frac{\vec q}{m_\chi}\times\vec S_\chi + i\vec v^\perp)\cdot(\frac{\vec q}{m_M}\times\vec S_N)$	$\frac{\vec q^{\,2}}{2m_N m_M}\mathcal{O}_1 - 2\frac{m_N}{m_M}\mathcal{O}_3 + 2\frac{m_N^2}{m_M m_\chi}\left(\frac{q^2}{m_N^2}\mathcal{O}_4 - \mathcal{O}_6\right)$	E/E
7	$\bar\chi\gamma^\mu\chi\bar N\gamma_\mu\gamma^5 N$	$-2\vec S_N\cdot\vec v^\perp + \frac{2}{m_\chi}i\vec S_\chi\cdot(\vec S_N\times\vec q)$	$-2\mathcal{O}_7 + 2\frac{m_N}{m_\chi}\mathcal{O}_9$	O/E
8	$i\bar\chi\gamma^\mu\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$2i\frac{\vec q}{m_M}\cdot\vec S_N$	$2\frac{m_N}{m_M}\mathcal{O}_{10}$	O/O
9	$\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar N\gamma_\mu N$	$-\frac{\vec q^{\,2}}{2m_\chi m_M}1_\chi 1_N - 2(\frac{\vec q}{m_N}\times\vec S_N + i\vec v^\perp)\cdot(\frac{\vec q}{m_M}\times\vec S_\chi)$	$-\frac{\vec q^{\,2}}{2m_\chi m_M}\mathcal{O}_1 + \frac{2m_N}{m_M}\mathcal{O}_5 - 2\frac{m_N}{m_M}\left(\frac{\vec q^{\,2}}{m_N^2}\mathcal{O}_4 - \mathcal{O}_6\right)$	E/E
10	$\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$4(\frac{\vec q}{m_M}\times\vec S_\chi)\cdot(\frac{\vec q}{m_M}\times\vec S_N)$	$4(\frac{\vec q^{\,2}}{m_M^2}\mathcal{O}_4 - \frac{m_N^2}{m_M^2}\mathcal{O}_6)$	E/E
11	$\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar N\gamma^\mu\gamma^5 N$	$4i(\frac{\vec q}{m_M}\times\vec S_\chi)\cdot\vec S_N$	$4\frac{m_N}{m_M}\mathcal{O}_9$	O/E
12	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$-[i\frac{\vec q^{\,2}}{m_\chi m_M} - 4\vec v^\perp\cdot(\frac{\vec q}{m_M}\times\vec S_\chi)]\frac{\vec q}{m_M}\cdot\vec S_N$	$-\frac{m_N}{m_\chi}\frac{\vec q^{\,2}}{m_M^2}\mathcal{O}_{10} - 4\frac{\vec q^{\,2}}{m_M^2}\mathcal{O}_{12} - 4\frac{m_N^2}{m_M^2}\mathcal{O}_{15}$	O/O
13	$\bar\chi\gamma^\mu\gamma^5\chi\bar N\gamma_\mu N$	$2\vec v^\perp\cdot\vec S_\chi + 2i\vec S_\chi\cdot(\vec S_N\times\frac{\vec q}{m_N})$	$2\mathcal{O}_8 + 2\mathcal{O}_9$	O/E
14	$\bar\chi\gamma^\mu\gamma^5\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$4i\vec S_\chi\cdot(\frac{\vec q}{m_M}\times\vec S_N)$	$-4\frac{m_N}{m_M}\mathcal{O}_9$	O/E
15	$\bar\chi\gamma^\mu\gamma^5\chi\bar N\gamma^\mu\gamma^5 N$	$-4\vec S_\chi\cdot\vec S_N$	$-4\mathcal{O}_4$	E/E
16	$i\bar\chi\gamma^\mu\gamma^5\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$4i\vec v^\perp\cdot\vec S_\chi\frac{\vec q}{m_M}\cdot\vec S_N$	$4\frac{m_N}{m_M}\mathcal{O}_{13}$	E/O
17	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar N\gamma_\mu N$	$2i\frac{\vec q}{m_M}\cdot\vec S_\chi$	$2\frac{m_N}{m_M}\mathcal{O}_{11}$	O/O
18	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$\frac{\vec q}{m_M}\cdot\vec S_\chi[i\frac{\vec q^{\,2}}{m_N m_M} - 4\vec v^\perp\cdot(\frac{\vec q}{m_M}\times\vec S_N)]$	$\frac{\vec q^{\,2}}{m_M^2}\mathcal{O}_{11} + 4\frac{m_N^2}{m_M^2}\mathcal{O}_{15}$	O/O
19	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar N\gamma_\mu\gamma^5 N$	$-4i\frac{\vec q}{m_M}\cdot\vec S_\chi\vec v_\perp\cdot\vec S_N$	$-4\frac{m_N}{m_M}\mathcal{O}_{14}$	E/O
20	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$4\frac{\vec q}{m_M}\cdot\vec S_\chi\frac{\vec q}{m_M}\cdot\vec S_N$	$4\frac{m_N^2}{m_M^2}\mathcal{O}_6$	E/E

Outline

Contact Interactions

- On the "simple" end of the spectrum are theories where the dark matter is the only state accessible to our experiments.
- This is a natural place to start, since effective field theory tells us that many theories will show common low energy behavior when the mediating particles are heavy compared to the energies involved.
- The drawback to a less complete theory is such a simplified description will undoubtably miss out on correlations between quantities which are obvious in a complete theory.
- And it will break down at high energies, where one can produce more of the new particles directly.



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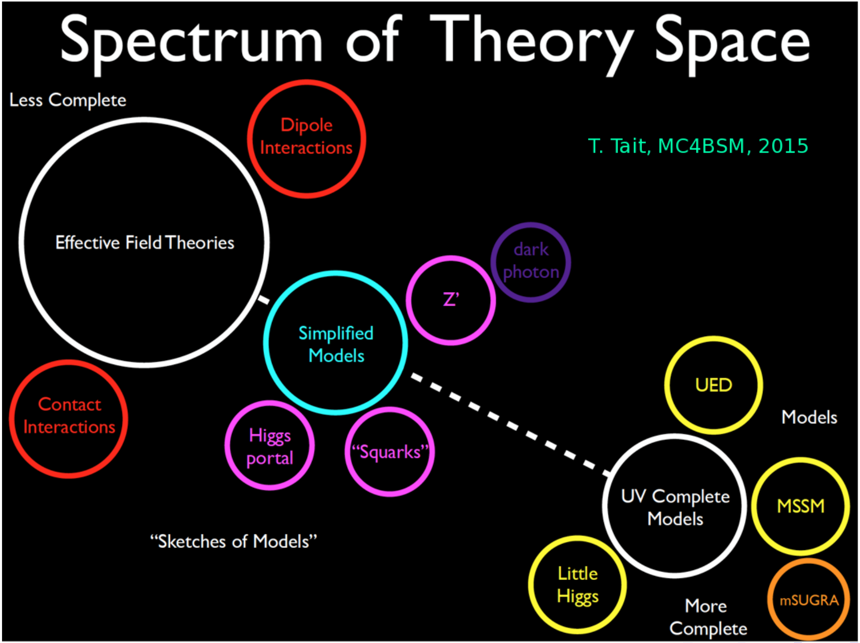
Spectrum of Theory Space
Less Complete
Dipole Interactions
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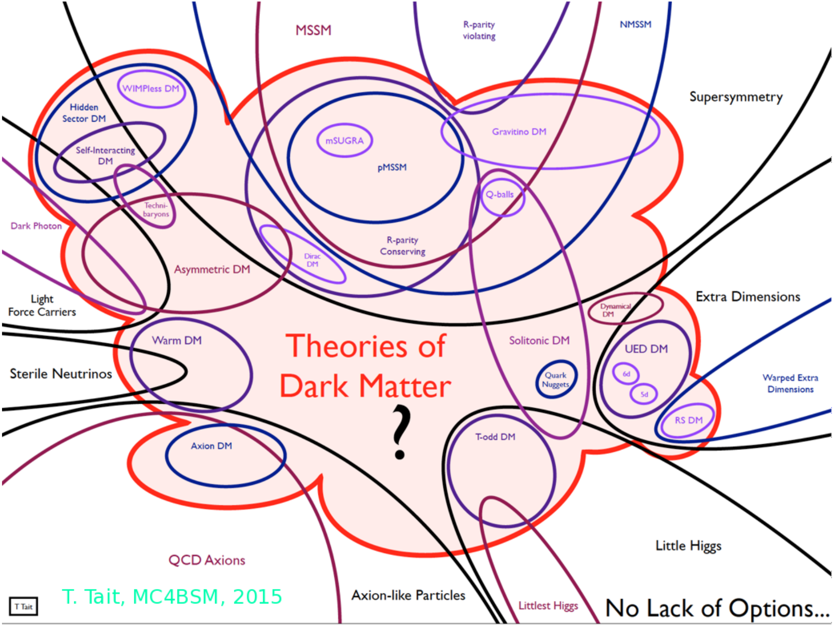
Effective Field Theories
dark photon
Z'
Simplified Models
UED
Models
Contact Interactions
Higgs portal
"Squarks"
UV Complete Models
MSSM
"Sketches of Models"
Little Higgs
More Complete
mSUGRA


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
Dirac DM
R-parity Conserving
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
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Axion-like Particles
Littlest Higgs
No Lack of Options...

Summary

- There are two WIMP scenarios.
- EFT is a natural starting point to characterize possible WIMP signatures.

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