My current understanding in EFT

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Outline

1. An introduction to EFT
   - EFT V.S. SI/SD
   - EFT has been "brilliantly successfully"
   - EFT in the whole spectrum of DM models
2. Upper Limits setting with EFT for DAMIC data
3. Summary

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Theoretical models: standard SI, SD and EFT

A very naive comparison and only compare SI and EFT here. SD and EFT is similar.

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

- $\frac{dE}{dR}_{SI} = N_T \cdot \frac{\rho_\chi}{2m_\chi} \cdot \frac{A^2}{m^2_{red}(m_p)} \cdot \sigma^{SI}_{\chi p} \cdot F^2_{SI}(E) \cdot \int^{\infty}_{v_{min}} \frac{f_1(v)}{v} dv$
- $\frac{dE}{dR}_{EFT} = N_T \cdot \frac{\rho_\chi}{2m_\chi} \cdot \frac{A^2}{m^2_{red}(m_p)} \cdot \mathcal{O}s \cdot \int^{\infty}_{v_{min}} \frac{f_1(v)}{v} dv$ [~intuitively~]
- $\sigma^{SI}_{\chi p}$, cross-section of WIMPs and a proton.
  $F^2_{SI}(E)$, form factor,
  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,
  $m^2_{red}(m_p)$, reduced mass of WIMPs and a nucleon,
  v_{min}, minimum speed of WIMPs could deposit detectable energy,
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- $\mathcal{O}s$ represents the nuclear response of a detector to WIMPs.

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EFT $\mathcal{O}s$

Totally 14 $\mathcal{O}_s$ (We don't know how DM interacts with matter)

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

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

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

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

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

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

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

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

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

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

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

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

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

Others <==> S.D.

Arxiv : 1308.6288

ArxiV : 1008.1591

Arxiv : 1203.3542

ArxiV : 1503.03379

- Galilean-invariant principle (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^2LO, N^3LO.
- The Fermi interpretation on the weak interaction in 1930s is one of the most famous examples of EFT (see next slide.).

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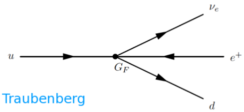
An example of EFT in particle physics

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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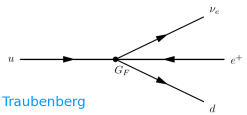

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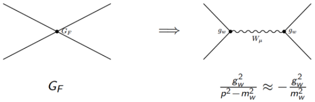
Solution: a gauge theory (Glashow, Salam, Weinberg, 60-70, [Nobel prize, 1979]).

* 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.

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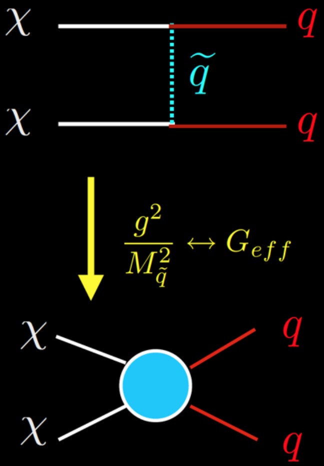
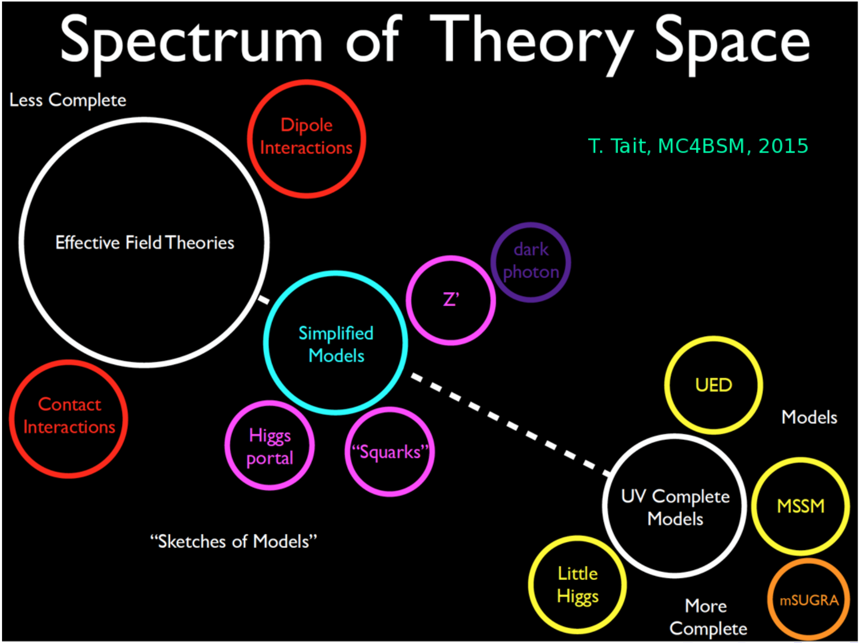
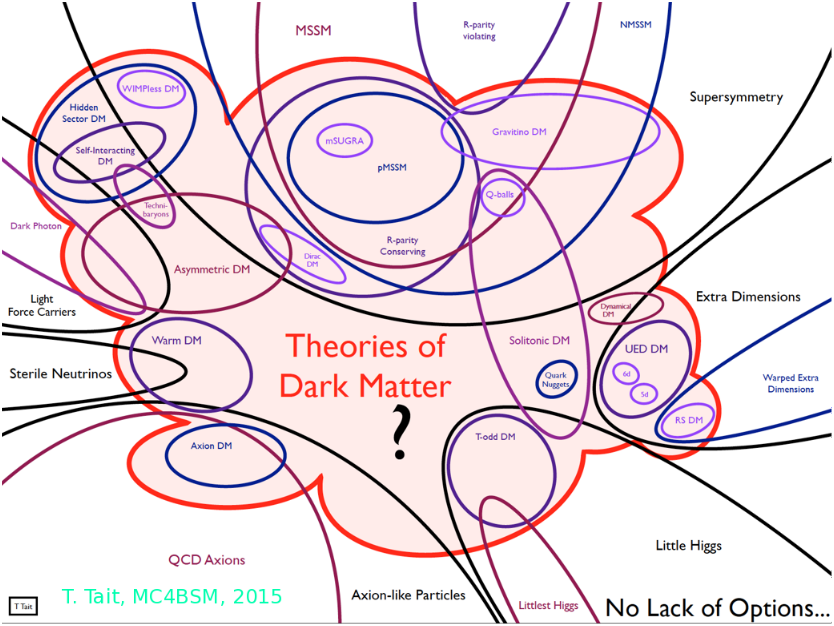
Contact Interactions

- 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.



T. Tait, MC4BSM, 2015


Spectrum of Theory Space
Less Complete
Dipole Interactions
T. Tait, MC4BSM, 2015
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
Axion DM
T-odd DM
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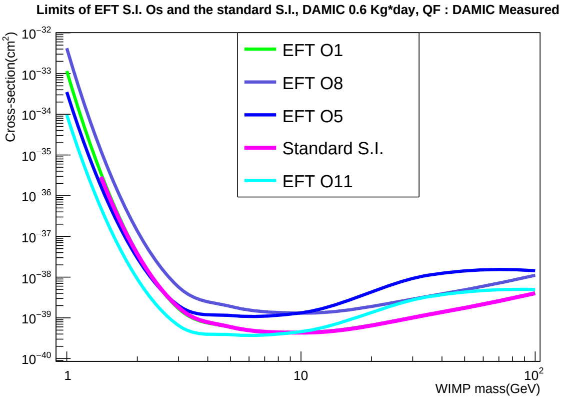
QCD Axions
T Tait
T. Tait, MC4BSM, 2015
Axion-like Particles
Littlest Higgs
No Lack of Options...

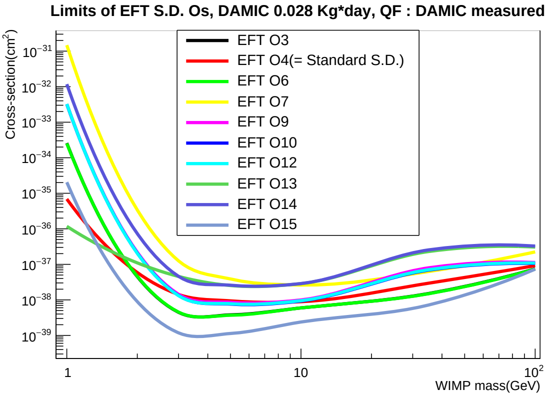
90% C.L. upper limits, all EFT S.I. $\mathcal{O}s$ and standard S.I.

- Using PRL to set limits (Asymptotic method, not Frequentist method).
- 0.6 kg*day data, QF measured by DAMIC.
- $\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$, is the most sensitive operator.



90% C.L. upper limits of all EFT S.D. $\mathcal{O}s$

- 0.6 × 5% = 0.028 kg*day data of Si-29, QF measured by DAMIC. $\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$ is the most sensitive one.



Summary

- EFT is a natural starting point to interpret possible Dark Matter signatures.
- All EFT $\mathcal{O}s$ have been studied and analyzed with DAMIC $\sim$ 0.6 kg*day data. No signal has been observed. 90% C.L. upper limits with have been set.
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