THE DARK SECTOR

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Jonathan Feng, UC Irvine and CERN

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DARK SECTORS AND DARK MATTER

• All evidence for dark matter is gravitational. Perhaps it’s in a hidden sector, composed of particles with no SM gauge interactions (electromagnetic, weak, strong)

• This hidden sector may have a rich structure with matter and forces of its own

• It may also have non-gauge interactions with the SM
DARK SECTOR ETHICS

• Virtues
  – Can explain anomalies (self-interactions, 3.5 keV line, direct and indirect detection signals, …)
  – Can suggest new DM searches and signals to look for
  – Playground for interesting theoretical ideas

• Sins
  – Doesn’t address known problems of the SM
  – Doesn’t make use of nice features of the SM (WIMP miracle)
  – Not predictive, a game without rules
  – Needlessly baroque

• The sins are potentially serious. (“But the SM is baroque.” Yes, but not needlessly. “What if I came up with the SM in 1895?” You wouldn’t have, and everyone would have been right to ignore you. These are poor excuses for ugly models.) WIMPs, axions, etc. are well-motivated, and a dark sector should provide elegant solutions to real problems to merit attention.
A Long History

Lee, Yang (1956); Kobsarev, Okun, Pomeranchuk (1966); Blinnikov, Khlopov (1982);
Foot, Lew, Volkas (1991); Hodges (1993); Berezhiani, Dolgov, Mohapatra (1995); …

Effective Interactions

$\phi_4$  $\phi_5$  $\phi_6$

$N$  $A'$  $\phi_h$  DM  ET

Full Models

WIMPless  SIDM  XDM

A SIMPlE Theory of DM
EFFECTIVE INTERACTIONS

• There are many ways the hidden particles could couple to us. Use effective operators as an organizing principle:

\[ \mathcal{L} = \mathcal{O}_4 + \frac{1}{M} \mathcal{O}_5 + \frac{1}{M^2} \mathcal{O}_6 + \ldots \]

where the operators are grouped by their mass dimension, with [scalar] = 1, [fermion] = 3/2, [\( F_{\mu\nu} \)] = 2

• \( M \) is a (presumably) large “mediator mass,” so start with dimension 4 operators. There are not too many:

Neutrino portal | Higgs portal | Photon portal
--- | --- | ---
\( h L N \) | \( h^\dagger h \phi^\dagger \phi_h \) | \( F_{\mu\nu} F_{\mu\nu}^h \)
One possibility is

\[ hLN \]

\( N \) is a total gauge singlet, the right-handed, or sterile, neutrino, and may be dark matter.

- If \( N \) is dark matter, its favored mass range is \( \sim \text{keV} \).
- This has received renewed attention from the 3.5 keV X-ray line seen from galaxies and galaxy clusters.

Boyarsky, Ruchayskiy, Iakubovskyi, Franse (2014)

Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall (2014)

But see also Riemer-Sorensen (2014)

see Gonzalez-Garcia, Viel, Shaposhnikov talks
Another possibility is

\[ h^+ h \phi_h^+ \phi_h \]

where the \( h \) subscript denotes “hidden”

When EW symmetry is broken, \( h \to \nu + h \), this leads to invisible Higgs decays

A leading motivation for precision Higgs studies and future colliders, such as ILC, CLIC, FCC

Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 \( \sigma \) confidence intervals for LHC at 14 TeV with 300 fb\(^{-1}\), for ILC at 250 GeV and 250 fb\(^{-1}\) ("ILC1"), for the full ILC program up to 500 GeV with 500 fb\(^{-1}\) ("ILC"), and for a program with 1000 fb\(^{-1}\) for an upgraded ILC at 1 TeV ("ILCTeV"). More details of the presentation are given in the caption of Fig. 1. The marked horizontal band represents a 5\% deviation from the Standard Model prediction for the coupling.
Another possibility is $\epsilon F_{\mu\nu} F_{\mu\nu}^h$ which leads to kinetic mixing between the SM photon and a hidden photon $A'$, which must have a mass.

Diagonalizing, one finds that SM particles have hidden charge proportional to $\epsilon$.

$\epsilon \sim 10^{-3}$ from 1-loop effects, even for arbitrarily heavy particles in the loop (non-decoupling).

$A'$ cannot be DM, but may be a portal to the dark sector, motivates searches at the “intensity frontier”.
DM EFFECTIVE THEORY

- At mass dimension 5 and higher, have 4-point interactions suppressed by heavy mediators. DM effective theory allows one to compare relic density and direct, indirect, and collider probes.

- At colliders, DM pair production is invisible, so must radiate something
  - Mono-photons at the ILC
  - Mono-jets at the LHC

Birkedal, Matchev, Perelstein (2004); Feng, Su, Takayama (2005)
DM EFFECTIVE THEORY

• This approach received a huge boost when hints of light DM motivated a hierarchy between the DM and mediator masses

  Beltran, Hooper, Kolb, Krusberg, Tait (2006)
  Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
  Bai, Fox, Harnik (2010)

• There is now a mono-\(\gamma,j,b,t,W,Z,h\) industry, probing dark sectors at the LHC one operator at a time

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
</tr>
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<tbody>
<tr>
<td>D1</td>
<td>(\bar{\chi}\chi q\bar{q})</td>
<td>(m_q/M_*^3)</td>
</tr>
<tr>
<td>D2</td>
<td>(\bar{\chi}\gamma^5\chi q\bar{q})</td>
<td>(i m_q/M_*^3)</td>
</tr>
<tr>
<td>D3</td>
<td>(\bar{\chi}\chi\gamma^5q)</td>
<td>(i m_q/M_*^3)</td>
</tr>
<tr>
<td>D4</td>
<td>(\bar{\chi}\gamma^5\chi q\bar{q})</td>
<td>(m_q/M_*^3)</td>
</tr>
<tr>
<td>D5</td>
<td>(\bar{\chi}\gamma^\mu\gamma\bar{\chi}\gamma_\mu q)</td>
<td>(1/M_*^2)</td>
</tr>
<tr>
<td>D6</td>
<td>(\bar{\chi}\gamma^\mu\gamma_\nu\chi\bar{q}\gamma_\nu q)</td>
<td>(1/M_*^2)</td>
</tr>
</tbody>
</table>

\[ L \, dt = 19.5 \, fb^{-1} \]

\[ \int_{s = 8 \, TeV} \chi - \text{Nucleon Cross Section} \, [cm^2] \]

**Spin Independent**

\[ \chi - \text{Nucleon Cross Section} \, [cm^2] \]

\[ M_\chi \, [GeV/c^2] \]
Effective interactions, taken one at a time, allow comparisons between different probes, motivate new signals. But we don’t expect just one operator. Full models allow one to address some bigger picture problems, find correlations between different interactions.

For example:

WIMP miracle: Can we preserve this?
Self-interacting DM: Can we accommodate this?
3.5 keV line: Can we explain this?
Can we do all of these in one model?
Recall the WIMP miracle: the relation between $\Omega_X$ and annihilation strength is wonderfully simple:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter:

- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$
WIMPLESS DARK MATTER

- Can dark sectors have a WIMP miracle?
- Consider SUSY, which necessarily contains different sectors
- The flavor problem $\rightarrow$ SUSY models (AMSB, GMSB) with $m_X \sim g_X^2$
- If this applies also in hidden sectors, these will have DM with the correct relic density
- Restores
  - Particle physics motivations
  - Structure, predictivity
  - WIMP miracle without WIMPs

Feng, Kumar (2008)

Feng, Tu, Yu (2010)
SELF-INTERACTING DARK MATTER

• If dark matter is completely hidden, can we learn anything about it?

• The Bullet Cluster and similar systems constrain self-interactions; DM passes through unperturbed →
  \( \sigma_T/m < 1 \text{ cm}^2/\text{g} \) (or barn/GeV)

• But there are discrepancies between CDM simulations and observations on small-scales
  – Cusps vs. cores
  – Missing satellites problem
  – Too big to fail problem
  – Cluster collisions

• These indicate need for baryons in simulations or DM self-interactions near the bounds

Rocha et al. (2012), Peter et al. (2012)
Vogelsberger et al. (2012); Zavala et al. (2012)
What sort of dark sector models can give the right self-interactions?

Assume DM X interacts through massive photon $\phi$ with coupling $\alpha_X$.

Yukawa potential produces weird trajectories: not conic sections!

Luckily, plasma physicists studying trajectories of charged particles in screened Coulomb potentials have approximated their potentials as Yukawa potentials—exactly our case! Can use their numerical results.
EXCITING DARK MATTER

Finkbeiner, Weiner (2007, 2014)

- Alternative dark sector explanation of the 3.5 keV line
- WIMP dark matter $X$ with a nearly degenerate state $X^*$
- $X^*$ created in collisions with $m_X v^2 > \Delta m$

\[
\frac{1}{M} X^* \sigma^{\mu\nu} \chi F_{\mu\nu}
\]

- Ingredients
  - $m_X \sim \text{TeV}$ to get correct relic density
  - A dark photon with small mass $\sim 100$ MeV from Higgs mechanism to get correct flux
  - A highly-degenerate state $X^*$ with even smaller mass splitting $\Delta m \sim 3.5$ keV to get correct $E_\gamma$
  - Dipole operator to give visible photon
We can put all of these together with a remarkably simple theory of dark matter: pure SUSY SU(N) with hidden gluons $g$ and gluinos $\tilde{g}$

At early times, interaction is weak, $\tilde{g}$ with $m_X \sim \text{TeV}$ freezes out with correct $\Omega$, in accord with the WIMPless miracle.

Then the Universe cools, the coupling runs, and the theory confines at $\Lambda \sim 100 \text{ MeV}$, forming glueballs ($gg$) and glueballinos ($g\tilde{g}$).

The glueballinos self-interact through glueball exchange with $\sigma_T/m \sim 1 \text{ cm}^2/\text{g}$.

* A SIMPlE THEOrY OF DARK MATTER

Boddy, Feng, Kaplinghat, Shadmi, Tait (2014, in prep)
A SIMPlE THEORY OF DARK MATTER

• The glueballino spectrum has hyperfine structure, with splitting $\Delta m \sim \alpha^4 \Lambda^2 / m_X \sim \Lambda^2 / m_X \sim \text{keV}$

\[ X \rightarrow XX^* \quad X^* \rightarrow X_\gamma \]

• A realization of XDM, where
  – $m_X \sim \text{TeV}$ to get correct relic density $\leftarrow$ set by WIMPless miracle
  – A dark photon with small mass $\sim 100$ MeV from Higgs mechanism to get correct flux $\leftarrow$ confinement replaces Higgs mechanism, mediator mass scale $\Lambda$ naturally small, set by RGEs, $m_X$, $\alpha_X$, N
  – A highly-degenerate state $X^*$ with even smaller mass splitting $\Delta m \sim 3.5 \text{keV}$ to get correct $E_\gamma$ $\leftarrow$ highly-degenerate state naturally even smaller, provided by hyperfine splitting, mass splitting set by $\Lambda^2 / m_X$
  – Dipole operator to give visible photon
A SIMPlE THEORY OF DARK MATTER

- Bottom line: hidden sector is simplest possible SUSY model: pure SU(N) with hidden gluons $g$ and gluinos $\tilde{g}$

- Preserves WIMPless miracle, explains self-interactions, 3.5 keV line energy and flux in terms of a small number of parameters

- 3.5 keV line is the “21 cm line” for DM

  Cline, Farzan, Liu, Moore, Xue (2014)

- Other important features
  - Typically requires large $N$, small $T_h/T$
  - No re-annihilation after hadronization
  - Not much cannibalization: glueballs eat their own rest mass to stay warm

  XXX $\rightarrow$ XX

  Carlson, Machacek, Hall (1992)

Boddy, Feng, Kaplinghat, Shadmi, Tait (in prep)
• Dark sectors are a logical possibility, given what we know about dark matter so far

• Lots of recent activity, resulting in novel ideas to preserve virtues, avoid problems

• Effective operators have generated ideas for signals, allow for comparison across a wide range of dark matter searches

• SIMPle Theory of Dark Matter, pure SUSY SU(N), preserves WIMP miracle, gives self-interactions, and predicts correct energy and flux for 3.5 keV line