COMPLEMENTARITY OF INDIRECT DARK MATTER DETECTION

AMS Days at CERN

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CONGRATULATIONS TO AMS

RECENT PROGRESS
IN SUPERSYMMETRY
AND
IMPLICATIONS FOR
DARK MATTER

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AMS Workshop, Erice
9 May 2000
Complementarity permeates dark matter: diverse approaches are required to search for different candidates, probe various regions of parameter space for a given candidate, confirm and study a signal, find the particle properties of dark matter, and determine if there’s more than one kind of dark matter.
DARK MATTER AT THE WEAK SCALE

- The weak scale ~10 GeV – 1 TeV remains an excellent place to look for dark matter

- This case has not been diminished much by null results from the LHC

- Consider supersymmetry
**Flavor Problem**

\[ \Delta m_K \Rightarrow \left[ \frac{10 \text{ TeV}}{m_q} \right]^2 \left[ \frac{\Delta m_{q_{12}}^2}{m_q^2} \right]^{\frac{2}{0.1}} < 1 \]

Requires squark degeneracy (superGIM mechanism) or extremely heavy squarks.

Also \( \mu \rightarrow e\gamma \).

**CP Problem**

\[ \text{EDM}_e \Rightarrow \left( \frac{2 \text{ TeV}}{m_{\tilde{e}}} \right)^2 \left( \frac{\mu M_1}{m_{\tilde{e}}^2} \right) \tan \beta \sin \phi_{CP} < 1 \]

Moroi, etc.

Requires heavy selectrons or \( \phi_{CP} \ll 1 \).

Note: flavor-conserving, so cannot be suppressed by degeneracy.

Also EDM$_{n}$.
**Proton Decay**

Gauge coupling unification $\rightarrow$ proton unstable

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\begin{align*}
\begin{array}{c}
u_R \\
1/M_c \begin{pmatrix} p_1 & p \alpha & \tau \beta & \tau \beta \gamma \end{pmatrix}
\end{array}
\end{align*}
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"New" $\tan^2 \beta$-enhanced operator.
Goto, Nihei

Proton decay in minimal SU(5) is generally too fast:

$$
\frac{\tau(p \rightarrow K^+ \bar{\nu})}{5.5 \times 10^{32} \text{ years}} \lesssim \left[ \frac{m_q^4}{1 \text{ TeV}^2 \mu^2} \right] \left[ \frac{5}{\tan \beta} \right]^4 \times \left[ \frac{M_c}{10^{17} \text{ GeV}} \right]^2
$$

Requires heavy superpartners (or no GUT).

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**FOCUS POINT SUSY**

JF, Matchev, Moroi, 1999

Experiment suggests $m_f \gtrsim 2$ TeV.

The only possible objection is naturalness.

Supersymmetric theories are natural if the weak scale is not unusually sensitive to small variations in the fundamental parameters.

't Hooft
Susskind/Wilson

How do we implement this, quantify fine-tuning? Several proposals in the literature. Adopt the following prescription:
BOTTOM LINE

• Those who were optimistic about SUSY before the LHC began should remain optimistic about SUSY

• Those who were pessimistic about SUSY before the LHC began should remain pessimistic about SUSY

• Those who were optimistic about SUSY before the LHC began and are now pessimistic: why?

• LHC Run 2 and dark matter searches for SUSY and other new weak-scale physics are as promising as ever
INDIRECT DETECTION

- Dark matter may pair annihilate or decay in our galactic neighborhood to
  - Photons
  - Neutrinos
  - Positrons
  - Antiprotons
  - Antideuterons
  - …
INDIRECT DETECTION BASIC FEATURES

- Energy: high, provided by the Big Bang (or reheating)
- Rate: relic density provides a target $\langle \sigma_A v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$
ROBUSTNESS OF TARGET CROSS SECTION

Relative to direct, indirect rates typically have smaller particle physics uncertainties (but larger astrophysical uncertainties)

Roszkowski (2013);
See 1306.1567 for details
CONTRAST WITH DIRECT DETECTION
Dark Matter annihilates in the GC / dwarf galaxies to a place photons, which are detected by Fermi, HESS, ... an experiment

The flux factorizes:

\[
\frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \frac{dN^i_\gamma}{dE} \sigma_i v \frac{1}{4\pi m^2_\chi} \int_\psi \rho^2 dl
\]

Particle physics: two kinds of signals
- Lines from XX → γγ, γZ: loop-suppressed rates, but distinctive signal
- Continuum from XX → ff → γ: tree-level rates, but a broad signal

Astrophysics: two kinds of sources
- Galactic Center: close and large signal, but high backgrounds
- Dwarf galaxies: farther and smaller, but low backgrounds
PHOTONS: CURRENT EXPERIMENTS

Veritas, HESS, Fermi-LAT, HAWC, many others
PHOTONS: FUTURE EXPERIMENTS

Cerenkov Telescope Array

Low-energy section:
4 x 23 m tel. (LST)
(FOV: 4-5 degrees)
energy threshold
of some 10s of GeV

Core-energy array:
23 x 12 m tel. (MST)
FOV: 7-8 degrees
best sensitivity
in the 100 GeV–10 TeV domain

High-energy section:
30-70 x 4-6 m tel. (SST)
- FOV: ~10 degrees
10 km² area at
multi-TeV energies

First Science: ~2016
Completion: ~2019
PHOTONS: STATUS AND PROSPECTS

- Fermi-LAT has excluded a light WIMP with the target annihilation cross section for certain annihilation channels
- CTA will extend the reach to masses $\sim 10$ TeV
INDIRECT DETECTION: NEUTRINOS

Dark Matter annihilates in **the center of the Sun** to a place **neutrinos**, which are detected by **IceCube, ANTARES,...** some particles an experiment
NEUTRINOS: EXPERIMENTS

Current: IceCube/DeepCore, superK, ANTARES

Future: KM3NeT, PINGU
NEUTRINOS: STATUS AND PROSPECTS

- The Sun is typically in equilibrium
- Spin-dependent scattering off hydrogen $\rightarrow$ capture rate $\rightarrow$ annihilation rate
- Results are typically plotted in the $(m_X, \sigma_{SD})$ plane and compared with spin-dependent direct detection experiments

Future experiments may discover the smoking-gun signal of HE neutrinos from the Sun, or set stringent $\sigma_{SD}$ limits
INDIRECT DETECTION: ANTI-MATTER

| Dark Matter annihilates in \( \text{the halo} \) to \( \text{a place} \) \( \text{positrons} \), which are detected by \( \text{AMS, PAMELA, …} \). some particles an experiment |

In contrast to photons and neutrinos, anti-matter does not travel in straight lines

- bumps around the local halo before arriving in our detectors
- for example, positrons, created with energy \( E_0 \), detected with energy \( E \)

\[
\frac{d\Phi_{e^+}}{d\Omega dE} = \frac{\rho^2}{m^2} \sum_i \sigma_i v B^i_{e^+} \int dE_0 \, f_i(E_0) \, G(E_0, E)
\]
BUT SHARP FEATURES ARE PRESERVED

- For example, KKDM with large $B^1B^1 \rightarrow e^+e^-$

- Note: In SUSY, $\chi\chi \rightarrow e^+e^-$ is suppressed because neutralinos are Majorana fermions, and so the feature is not as sharp (but still prominent)

- Precise measurements can provide evidence for DM, distinguish SUSY and extra dims, measure DM mass
ANTI-MATTER: EXPERIMENTS

- Positrons (PAMELA, Fermi-LAT, AMS, CALET, …)
- Anti-Protons (PAMELA, AMS, …)
- Anti-Deuterons (AMS, GAPS, …)
Large excesses were reported previously, but required DM signals with boost factors of $B \sim 100$-$1000$ over target cross sections.
POSITRONS: PRESENT AND FUTURE

• With the new, precise AMS-02 data, we have entered a new era of looking for signals based not on fluxes, but on spectral features.
COMPLEMENTARITY: FULL MODELS

pMSSM 19-parameter scan of SUSY parameter space

- Complementarity for SUSY models; also for DM effective theories
- Many promising approaches to dark matter, and any compelling signal will have far-reaching implications

Cahill-Rowley et al. (2013)
INDIRECT DETECTION OF DARK SECTORS

• All evidence for dark matter is gravitational. Perhaps it’s in a hidden sector, composed of particles without EM, weak, strong interactions

• *A priori* this seems pretty unmotivated
  – No WIMP miracle
  – No connection to known problems
THE WIMPLESS MIRACLE

• Can we recover the WIMP miracle in a hidden sector?

• In many SUSY models (GMSB, AMSB), to avoid unseen flavor effects, superpartner masses satisfy

\[ m_X \sim g_X^2 \]

• If this holds in a hidden sector, we have a “WIMPless Miracle”: hidden sectors of these theories automatically have DM with the right \( \Omega \) (but they aren’t WIMPs)
SELF-INTERACTING DARK MATTER

• The Bullet Cluster provided evidence for DM. Since it passed through unperturbed → $\sigma_T/m < 1 \text{ cm}^2/\text{g} (~1 \text{ barn/GeV})$

• But there are indications that the self-interactions may be near this limit
  – Cusps vs. cores
  – Number of visible dwarf galaxies

Rocha et al. (2012), Peter et al. (2012) 
Vogelsberger et al. (2012); Zavala et al. (2012)
3.5 KEV LINE

- There is evidence of a 3.5 keV X-ray line being emitted from galaxies and galaxy clusters.

- The default DM explanation is sterile neutrino decay: $N \rightarrow \nu \gamma$.

Boyarsky, Ruchayskiy, Iakubovskyi, Franse (2014)
Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall (2014)
but see also Riemer-Sorensen (2014), others
• None of the indications for exotic DM is completely compelling on its own. But can we find a simple model where dark matter:

Has the right relic density through the WIMPIless miracle?

Self-interacts with the right cross section?

Explains the 3.5 keV line?
• In fact, we can put all of these together in a simple theory: a pure SU(N) SUSY hidden sector with only hidden gluons $g$ and gluinos $\tilde{g}$

• At early times, the interaction is weak, the gluinos with $m \sim \text{TeV}$ freeze out with correct $\Omega$, in accord with the WIMPless miracle

• Then the Universe cools, 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 $\sigma_T/m \sim 1 \text{ cm}^2/\text{g}$
SIMPe DARK MATTER

- Such a system has a glueballino spectrum with hyperfine splitting $\Lambda^2/m \sim 10$ keV (cf. $\alpha^4 m_e^2/m_p$ for Hydrogen)

- $X^*$ created in collisions with $m_X v^2 > \Delta m$

- Adding a dipole operator, the excited state can decay to the ground state and a 3.5 keV photon; the 3.5 keV line is the “21 cm line” for DM

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

Finkbeiner, Weiner (2007, 2014)
CONCLUSIONS

• WIMPs remain interesting and there has also been a recent proliferation of other dark matter ideas

• Indirect detection plays an essential role in probing these dark matter candidates

• With AMS, other indirect searches, direct detection, and cosmological probes improving rapidly, and the LHC coming back on-line, these are exciting times for dark matter