DARK MATTER PHENOMENOLOGY

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DARK MATTER

Talks at CIPANP: Cushman, many others

- We know how much there is
  \[ \Omega_{DM} h^2 = 0.1099 \pm 0.0062 \]
  WMAP (2008)

- But what is it?

- Intimately connected to central problems in particle physics and astrophysics
  - new particles and forces
  - structure formation
CANDIDATES

- Observational constraints
  Not baryonic (≠ weakly-interacting)
  Not hot (≠ cold)
  Not short-lived (≠ stable)

- Possible masses and interaction strengths span many, many orders of magnitude

- Focus on candidates with mass around $m_{\text{weak}} \sim 100$ GeV
PARTICLE PHYSICS

• Fermi’s constant $G_F$ introduced in 1930s to describe beta decay

\[ n \to p e^{-} \bar{\nu} \]

• $G_F \approx 1.1 \times 10^5 \text{ GeV}^{-2} \rightarrow$ a new mass scale in nature

\[ m_{\text{weak}} \sim 100 \text{ GeV} \]

• We still don’t understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale
THE WIMP MIRACLE

• Assume a new (heavy) particle $X$ is initially in thermal equilibrium

• Its relic density is

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

• $m_X \sim 100$ GeV, $g_X \sim 0.6 \Rightarrow \Omega_X \sim 0.1$

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

Correct relic density $\rightarrow$ *Lower* bound on DM-SM interaction
DIRECT DETECTION 1

- **WIMP properties**
  - $v \sim 10^{-3} \text{ c}$
  - Kinetic energy $\sim 100 \text{ keV}$
  - Local density $\sim 1 / \text{ liter}$

- Detected by nuclear recoil in underground detectors; two leading methods

- Background-free detection
  - Spin-independent scattering is typically the most promising
  - Theory and experiment compared in the $(m_X, \sigma_{\text{proton}})$ plane
  - Expt: CDMS, XENON, …
  - Theory: SUSY region – WHAT ARE WE TO MAKE OF THIS?
DARK MATTER VS. FLAVOR PROBLEM

• Squark and slepton masses receive many contributions

• The gravitino mass $m_\tilde{G}$ characterizes the size of gravitational effects, which generically violate flavor and CP

$$m_\tilde{G}^2 = \begin{pmatrix} m_0^2 & 0 & 0 \\ 0 & m_0^2 & 0 \\ 0 & 0 & m_0^2 \end{pmatrix} + \begin{pmatrix} \sim m_G^2 & \sim m_G^2 & \sim m_G^2 \\ \sim m_G^2 & \sim m_G^2 & \sim m_G^2 \\ \sim m_G^2 & \sim m_G^2 & \sim m_G^2 \end{pmatrix}$$

• These violate low energy constraints (badly)
  – Flavor: Kaon mixing, $\mu \rightarrow e \gamma$
  – Flavor and CP: $\varepsilon_K$
  – CP: neutron EDM, electron EDM

• Low energy bounds: $m_\tilde{G} << m_0$
  Dark matter stability: $m_\tilde{G} > m_0$ Problem!
THE SIGNIFICANCE OF $10^{-44}$ CM$^2$

- **Possible solutions**
  - Set flavor violation to 0 by hand
  - ...
  - Make sleptons and squarks heavy (few TeV or more)

- The last eliminates many annihilation diagrams, collapses predictions

- Summary: The flavor problem $\Rightarrow \quad \sigma_{SI} \sim 10^{-44}$ cm$^2$
  (focus point SUSY, inverted hierarchy models, more minimal SUSY, 2-1 models, split SUSY,...)
DIRECT DETECTION 2

Annual modulation: Collision rate should change as Earth’s velocity adds constructively/destructively with the Sun’s.

Drukier, Freese, Spergel (1986)

DAMA: $8\sigma$ signal with $T \sim 1$ year, max $\sim$ June 2
CHANNELING

- DAMA’s result is puzzling, in part because the favored region was considered excluded by others.

- This may be ameliorated by:
  - Astrophysics
  - Channeling: in crystalline detectors, efficiency for nuclear recoil energy \(\rightarrow\) electron energy depends on direction.
    
    Gondolo, Gelmini (2005)
    Drobyshhevski (2007), DAMA (2007)

- Channeling reduces threshold, shifts allowed region to:
  - Rather low WIMP masses (~GeV)
  - Very high \(\sigma_{SI}\) (~10\(^{-39}\) cm\(^2\))
INDIRECT DETECTION

Dark Matter annihilates in _______ the halo _______ to a place

______ positrons , which are detected by ______ PAMELA/ATIC/…___.

some particles

an experiment
PAMELA AND ATIC RESULTS

Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)
ARE THESE DARK MATTER?

- Shape consistent with some dark matter candidates

- Flux is a factor of 100-1000 too big for a thermal relic; requires enhancement
  - astrophysics (very unlikely)
  - particle physics

- No enhancement seen in anti-protons

- Pulsars can explain PAMELA

  Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
  Yuksel, Kistler, Stanev (2008); Profumo (2008)
  Fermi LAT Collaboration (2009)
FERMI AND HESS

• Fermi and HESS do not confirm ATIC: no feature, consistent with background

• Pulsars can explain PAMELA
HIDDEN DARK MATTER

• The anomalies (DAMA, PAMELA, ATIC, …) are not easily explained by canonical WIMPs

• Start over: What do we really know about dark matter?
  – All solid evidence is gravitational
  – Also solid evidence against strong and EM interactions

• A reasonable 1st guess: dark matter has no SM gauge interactions, i.e., it is hidden
  
  Kobsarev, Okun, Pomeranchuk (1966); many others

• What one seemingly loses
  • Connection to central problems of particle physics
  • The WIMP miracle
  • Non-gravitaitonal signals
WIMP MIRACLE REVISITED

• Consider SUSY: Hidden sectors appear generically. Each has its own
  – mass scale $m_X$
  – gauge couplings $g_X$

• But the flavor problem motivates models with squark/slepton masses determined by gauge couplings (and so flavor-blind):
  
  \[ m_X \sim g_X^2 \]

  (e.g., gauge mediation, anomaly-mediation)

• This implies that $\Omega_X$ is constant in all sectors!
The thermal relic density constrains only one combination of $g_X$ and $m_X$

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

These models map out the remaining degree of freedom

This framework decouples the WIMP miracle from WIMPs, motivates candidates with a range of masses/couplings

Feng, Kumar (2008); Feng, Tu, Yu (2009)
HIDDEN DM SIGNALS

• Hidden DM may have only gravitational effects, but still interesting: e.g., it may have hidden charge, Rutherford scattering → self-interacting DM
  Feng, Kaplinghat, Tu, Yu (2009)

• Alternatively, hidden DM may interact with normal matter through non-gauge interactions

• Many new, related ideas
  Pospelov, Ritz (2007); Hooper, Zurek (2008)
  Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2008)
  Ackerman, Buckley, Carroll, Kamionkowski (2008)
CONCLUSIONS

• Rapid experimental progress
  – Direct detection
  – Indirect detection
  – Colliders (LHC)

• Proliferation of new classes of candidates
  – WIMP dark matter
  – Hidden dark matter
  – ...

• In the next few years, many DM models will be stringently tested; we will either see something or be forced to rethink some of our most cherished prejudices