WIMPS: AN OVERVIEW, CURRENT CONSTRAINTS, AND WIMP-LIKE EXTENSIONS

Debates on the Nature of Dark Matter

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OVERVIEW

We’ve learned a lot about the Universe in recent years, but there is still a lot missing.

In particular, either

• There is a huge problem with our standard theory of particle physics, or
• There is a huge problem with our standard theory of gravity,
• Or both!

• Here assume it’s particles:
  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  Normal Matter: 4% ± 0.4%
  Neutrinos: 0.2% ($\sum m_\nu/0.1\text{eV}$)
THE WEAK SCALE

Much of the attention has focused on WIMPs. Why?

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

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

• $G_F \sim 10^{-5} \text{ GeV}^{-2}$ → 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

• 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, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

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

• The WIMP Miracle is very well appreciated, and it is a quantitative feature. But its success relies on some less well-advertised qualitative features.

• First, the WIMP must be stable.

• How natural is this? A priori, not very: the only stable particles we know about are very light.

New Particle States

Stable

Standard Model Particles
LEP’S COSMOLOGICAL LEGACY

In some cases, there are even stronger reasons to exclude these 4-particle interactions (e.g., proton decay in SUSY)

• Simple solution: impose a discrete parity, so all interactions require *pairs* of new particles. This also makes the lightest new particle stable:

  LEP constraints ↔ Discrete Symmetry ↔ Stability

Cheng, Low (2003); Wudka (2003)
WIMP NEUTRALITY

- WIMPs must also be neutral
- How natural is this? Again, a priori, not very: what is the chance that the lightest one happens to be neutral?
- In fact, in many cases (SUSY, extra dims, …), masses are “proportional” to couplings, so neutral particles are the lightest

Bottom line: WIMPs, new particles that are stable and neutral with $\Omega \sim 0.1$, appear in many models of new particle physics
CURRENT CONSTRAINTS

Correct relic density $\rightarrow$ Efficient annihilation then

Efficient scattering now (Direct detection)

Efficient annihilation now (Indirect detection)

Efficient production now (Particle colliders)
DIRECT DETECTION

• WIMP properties
  – If mass is 100 GeV, local density is ~1 per liter
  – velocity $\sim 10^{-3}$ c

Look for normal matter recoiling from WIMP collisions in detectors deep underground

Dark matter elastically scatters off nuclei

Nuclear recoils detected by phonons, scintillation, ionization, …, …

Attisha
INDIRECT DETECTION

- Dark matter may pair annihilate in our galactic neighborhood to:
  - Photons
  - Neutrinos
  - Positrons
  - Antiprotons
  - Antideuterons

- The relic density provides a target annihilation cross section:
  \[ \langle \sigma_A v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \]
ROBUSTNESS OF THE TARGET CROSS SECTION

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

Roszkowski (2013);
See 1307.1567 for details
INDIRECT DETECTION: PHOTONS

Current: Veritas, Fermi-LAT, HAWC, and others
INDIRECT DETECTION: PHOTONS

Future: 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
INDIRECT DETECTION: PHOTONS

- Fermi-LAT sensitive to light WIMPs with the target annihilation cross section for certain annihilation channels
- CTA extends the reach to WIMP masses ~ 10 TeV
DARK MATTER AT COLLIDERS

Full Models (e.g., SUSY)

The LHC has not seen WIMPs, but has not yet probed the parameter space indicated by EDMs, Higgs,...: wait for LHC14 and HL-LHC
These are not mutually exclusive – multi-component DM is certainly possible
SUPERWIMPS

- An example: Gravitinos in supersymmetry with $m_{\tilde{G}} \sim m_{\text{SUSY}}$

- $\tilde{G}$ not LSP: WIMPs

- $\tilde{G}$ LSP: SuperWIMPs

- WIMP-like: TeV masses, same particle models, superWIMP inherits the right relic density

But completely different: superweakly-interacting, warm DM, BBN, long-lived charged particles at LHC, …
EXCITING DARK MATTER

- WIMP dark matter $X$ with a nearly degenerate state $X^*$

- $X^*$ created in collisions with $m_X v^2 > \Delta m \sim \text{keV to MeV}$

- WIMP-like: TeV masses, correct thermal relic density
  But completely different: dark photons to mediate up-scatter, de-excitation → INTEGRAL, 3.5 keV line, …

Finkbeiner, Weiner (2007)
HIDDEN DARK MATTER

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

  SM

  Hidden X

• A priori there are both pros and cons
  – Lots of freedom: interesting astrophysics, etc.
  – Too much freedom: no connections to known problems
  – No relation to WIMPs and the WIMP miracle

Spergel, Steinhardt (1999); Foot (2001)
WIMPNESS DARK MATTER

- The flavor problem $\rightarrow$ SUSY models with $m_X \sim g_X^2$

- If this applies also in hidden sectors, these will have DM with the correct relic density

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

- Restores
  - Particle physics motivations
  - Structure, predictivity
  - WIMP miracle without WIMPs

Feng, Kumar (2008)
**WIMPLESS SELF-INTERACTING DARK MATTER**

Feng, Shadmi (2011), Boddy, Feng, Kaplinghat, Tait (2014)

- A simple example: pure SU(N) with hidden gluons \( g \) and gluinos \( \bar{g} \)

- At early times, interaction is weak, \( \sim 1-10 \text{ TeV} \) \( \bar{g} \) freezeout with correct \( \Omega \)

  At late times, interaction is strong, glueballs (gg) and glueballinos (g\(\bar{g}\)) form and self-interact with \( \sigma_T/m \sim 0.1 \text{ cm}^2/\text{g} \sim 0.1 \text{ barn/GeV} \)

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

- WIMP-like: TeV-masses with correct thermal relic density
- But completely different: self-interacting, multi-component dark matter
CONCLUSIONS

• **Overview**
  – WIMPs, new, stable, neutral particles with the right thermal relic density, are motivated by particle physics alone
  – The fact that they might be dark matter is hard to ignore

• **Current Constraints**
  – Direct Detection: approaching the neutrino background
  – Indirect Detection: approaching the target annihilation cross section
  – Colliders: LHC probes deeper into the weak scale

• **WIMP-like Extensions**
  – SuperWIMPs, excited dark matter, WIMPIless dark matter, and many others
  – WIMP-like, but predict a rich variety of observable phenomena