Dark Matter

The Future of Cosmological Physics

2015/10/14
Michael Turner
The Big Picture
Wendy Freedman
Observational Cosmology
John Carlstrom
Cosmic Microwave Background
Angela Quinto
Ultra-High Energy Particles

2016/1/6
Rocky Kolb
Dark Matter
Wayne Hu
Dark Energy

2016/3/30
Josh Frieman
Cosmic Surveys
Andrey Kravtsov
Structure Formation

2016/6/1
Scott Odegard
Cosmic Cosm

Chicago scientists brought together the fields of particle physics and cosmology. This mirror of the very big and the very small now underscores both disciplines. A series of special Kavli Institute for Cosmological Physics colloquia addresses the future of cosmology and celebrates the opening of the Eckhart Research Center and the 125th anniversary of The University of Chicago.

All talks will take place in the Eckhart Auditorium, 2:00 - 5:00 PM, with discussion and reception to follow.

Rocky Kolb, KICP
Why You Should Care About Dark Matter

...it’s most of the mass in the Universe (kind of important)

Dark Matter: 25%
Dark Energy: 70%
Stars: 0.8%
H & He: 4%
Chemical Elements: (other than H & He) 0.025%
Neutrinos: 0.17%
Radiation: 0.005%
WIMP?
... the dinosaurs didn’t care, and look what happened to them!

Why You Should Care About Dark Matter

LISA RANDALL

NEW YORK TIMES BESTSELLING AUTHOR OF
WARPED PASSAGES

DARK MATTER
AND THE DINOSAURS

THE ASTOUNDING
INTERCONNECTEDNESS OF THE UNIVERSE
Far Future of Dark Matter

• **Particle Physics:**
  Understand the nature of dark matter (DM) and how it is embedded into a deeper theoretical framework:
  • If DM is a particle, want to know more than just mass, spin, and couplings, want to know how it fits into a model or theory
  • Want to know *why* DM exists
  • Want to understand its contribution to the mass budget

• **Astrophysics:**
  Understand the role of DM in the evolution of the universe and structure formation:
  • Is the DM completely cold?
  • Is there only one DM component?
  • Does DM have interactions that affect structure formation?
<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>(M/L)⊙</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1932</td>
<td>Oort: Local Neighborhood a Little Dim</td>
<td>~2–3</td>
<td></td>
</tr>
<tr>
<td>1937</td>
<td>Zwicky: Galaxy Clusters Really Dark</td>
<td>~500</td>
<td></td>
</tr>
<tr>
<td>1970s</td>
<td>Rubin &amp; Ford: Individual Galaxy Halos Also Dark</td>
<td>~60</td>
<td></td>
</tr>
<tr>
<td>1990s</td>
<td>Dwarf Observers: Dwarfs Really, Really Dark</td>
<td>~3000</td>
<td></td>
</tr>
</tbody>
</table>

While at ETH Zwicky lived in Spiegelgasse 17, Zurich, Switzerland.

Varna, Bulgaria

While at ETH Zwicky lived in Spiegelgasse 17, Zurich, Switzerland.
cluster dynamics

galactic rotation curves

dwarf galaxies

gravitational lensing

nucleosynthesis

cluster gas in x-rays

background radiation

structure formation

cluster collisions
1. It exists!!! Thank you astronomy!
2. What is the local DM phase-space velocity distribution?
3. What is the local value of $\rho_{DM}$?
4. Are there nearby DM subclumps?
5. What is the background for $\gamma$-ray emission from the galactic center?

6. What is $\rho_{DM}(r)$
   \begin{align*}
   &\text{very near the galactic center?} \\
   &\text{in dwarf spheroidals?} \\
   &\text{in DM subclumps?}
   \end{align*}

7. Is DM multi-component like visible matter?
8. Does DM have self-interactions?
9. Does DM have normal gravitational interactions?

(a complete theory containing dark matter could answer the last three)
Einstein or Newton didn’t have the last word

Modified Gravity

Modified Newtonian Dynamics, i.e., $F \neq ma$

- Rocky Rogue Planets
- Mass Challenged Stars
- Black Holes
- Unknown Particle Species

Massive Compact Halo Objects (MACHOs)
Known Particle Species

Quarks
- up
- down
- top
- bottom
- strange
- charm

Antiquarks
- $\bar{u}$
- $\bar{d}$
- $\bar{t}$
- $\bar{b}$
- $\bar{s}$
- $\bar{c}$

Leptons
- electron
- muon
- tau
- electron neutrino
- muon neutrino
- tau neutrino

Antileptons
- $e^+$
- $\mu^+$
- $\tau^+$
- $\bar{\nu}_e$
- $\bar{\nu}_\mu$
- $\bar{\nu}_\tau$

Force Carriers
- photon
- gluon
- $W$
- $Z$
- graviton

and now the HIGGS!

Dark particle must be **stable** and **massive** and interact **weakly**

Dark particle must be “Beyond the Standard Model” (BSM)
Theories of Dark Matter
Some Possible Origins of Dark Matter

Cosmological Phase Transitions (axions, mass ca. $10^{-15}$ GeV)
Asymmetric Relics (name needed, mass ca. 6 GeV)
Cold Thermal Relics (WIMPs, mass ca. $10^2$ GeV)
Gravitational (Inflation) Production (WIMPZILLAs, mass ca. $10^{12}$ GeV)
### Particle Dark Matter Bestiary

- (sub-) eV mass neutrinos (WIMPs exist!)  
  - (hot)  
  - thermal relics, or decay of or oscillation from thermal relics
- sterile neutrinos, gravitini  
  - (warm)  
- lightest supersymmetric particle  
  - (cold)
- lightest Kaluza-Klein particle  
  - (cold)
- Bose-Einstein condensates  
- axions, axion miniclusters  
- solitons (Q-balls, B-balls, …)  
- supermassive WIMPZILLAs  
- from phase transitions  
- from inflation  
- nonthermal relics

### Mass

<table>
<thead>
<tr>
<th>Mass</th>
<th>Interaction Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-22}$ eV ($10^{-56}$ g) Bose-Einstein</td>
<td>only gravitational: WIMPZILLAs</td>
</tr>
<tr>
<td>$10^{-8} M_\odot$ ($10^{+25}$ g) axion miniclusters</td>
<td>strongly interacting: B balls</td>
</tr>
</tbody>
</table>
Relative abundance $\frac{M}{T}$

Equilibrium $e^{-\frac{M}{T}}$

Increasing $\sigma_A$

Decreasing abundance

Cold Thermal Relics*

* An object of particular veneration.
Cosmological Lower Bound on Heavy Neutrino Masses

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AND

STEVEN WEINBERG**
Stanford University, Physics Department, Stanford, California 94305

ABSTRACT

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of $2 \times 10^{-29} \text{g/cm}^3$, the lepton mass would have to be greater than a lower bound of the order of 2 GeV.

** On leave 1976-7 from Harvard University.
Motivated by an *incorrect* experimental result (high-µ anomaly)

**Model**
- effective field theory
- excluded by direct detection
- LEP ν counting
\[\langle \sigma v \rangle = \text{NR annihilation cross section} \times \text{Møller flux} \langle \text{thermal average} \rangle \]

\[\Omega h^2 \approx 0.11 \times \frac{10^{-36} \text{ cm}^2}{\langle \sigma v \rangle} \]

Not quite so clean:
- velocity dependence
- resonances
- co-annihilation
- log dependence on \( M \)
- decay production
- spin-dependence
- asymmetries
  
\[\sigma = 10^{-36} \text{ cm}^2 = \frac{\alpha^2}{(150 \text{ GeV})^2}\]

weak scale!
DM Has “Weak-Scale” Interactions
Weakly-Interacting Massive Particle:

A WIMP!
Michael Turner
(actual size)

If I have seen further, it is by sitting on the shoulders....
The WIMP “Miracle”

Miracle
From Wikipedia, the free encyclopedia

... often used to give an impression of great and unusual value in a trivial context ...

mir·a·cle
\ˈmir-i-kəl\
noun

1: an extraordinary event manifesting divine intervention in human affairs
WIMPs: Social or Maverick Species?

Social WIMP
Friended by many like-mass particles
Pals around with new un-WIMPy particles
Part of a larger theoretical framework
Top down
Generally UV complete
Find the WIMP by finding its friends
Example: SUSY

Maverick WIMP
Not friended by any new particles
Any un-WIMPy pals beyond reach
Part of a larger theoretical framework
Theory framework: Don’t ask/Don’t tell
Bottom up
Generally UV complete: Effective Field Theory
Find the WIMP through what is not seen
Example: Neutrinos before late 1960s
Developed in the early 70’s
Every known particle has an undiscovered superpartner.
Superpartners are massive.
Lightest superpartner should be stable!
In many realizations, lightest superpartner is weakly interacting.

Lightest Supersymmetric Particle is a candidate WIMP
SWIMPs

gravitinos, sneutrinos, axinos, ... neutralinos

Lightest neutralino: linear combination of SUSY partners of $\gamma$, $Z$, and 2 Higgs bosons

- Mass and gaugino/Higgsino fractions depend on about 100 SUSY parameters
- Reduce to a manageable number of parameters (pMSSM, CMSSM, mSUGRA, …)
- Many processes/diagrams contribute to annihilation into many channels
  - $W^+W^-$, $ZZ$, $Zh$, $ZH$, $ZA$, $W^+H^-$, $HH$, $Hh$, $Ah$, $AH$, $f\bar{f}$
  - Annihilation into $f\bar{f}$ proportional to fermion mass
  - No two-body final state with a photon (at lowest order)
- LHC & other experiments have pushed SUSY scale high, usually too large $\Omega h^2$, unless some chicanery increases $\sigma_A$:

“Focus Point” SUSY

Resonant Annihilation

Coannihilation
SWIMPs

gravitinos, sneutrinos, axinos, … neutralinos

Lightest neutralino: linear combination of SUSY partners of $\gamma$, $Z$, and 2 Higgs bosons

• Choose a model framework to reduce from about 100 SUSY parameters
• Require consistent low-energy model
  – with neutralino DM candidate
  – that satisfies all experimental constraints
• Low-energy annihilation cross section depends on neutralino composition, mass, and coupling and possibly other masses; all of these depend on about 100 SUSY parameters
• Generally $\sigma_A v = a + b v^2$ (velocity-independent part plus velocity-suppressed part)

SUSY DM phenomenology very interesting and very rich.

SUSY/DM Relationship:
Maverick Effective Field Theory (EFT)

- WIMP is the only state accessible to experiments: other states too massive (Maverick)

- Many theories have common low-energy behavior when mediating particles are heavy compared to energies involved

- EFT not as desirable as a UV-complete theory:
  - can miss relations between quantities
  - can’t describe high-energy behavior (possibly like LHC)

- One example (DM fermionic & couples to quarks)

\[
\mathcal{L} = \frac{\Lambda^{-2}}{\Gamma_1 \Gamma_2} \bar{\chi} \Gamma_1 \chi \bar{q} \Gamma_2 q
\]

\[
\mathcal{L} = m_q \frac{\Lambda^{-3}}{\Gamma_1 \Gamma_2} \bar{\chi} \Gamma_1 \chi \bar{q} \Gamma_2 q \quad \text{Minimal Flavor Violation}
\]
Maverick WIMPs

\[ \Omega h^2 \rightarrow \Lambda_{\Gamma_1 \Gamma_2} (M) \]

\[ \sigma_A v = a + b v^2 \]

\[ \Omega_{DM}: \, v^2 \sim 1/20 \]

\[ \overline{\chi} \chi \rightarrow q q \quad \text{unsuppressed} \]
\[ \overline{\chi} \chi \rightarrow q \gamma^5 q \quad \text{unsuppressed} \]
\[ \overline{\chi \gamma^5 \chi} \rightarrow q q \quad \text{unsuppressed} \]
\[ \overline{\chi \gamma^5 \chi} \rightarrow q \gamma^5 q \quad \text{unsuppressed} \]
\[ \overline{\chi \gamma^\mu \chi} \rightarrow q \gamma_\mu q \quad \text{unsuppressed} \]
\[ \overline{\chi \gamma^\mu \chi} \rightarrow q \gamma_{\mu5} q \quad \text{unsuppressed} \]
\[ \overline{\chi \gamma_{\mu5} \chi} \rightarrow q \gamma_\mu q \quad \text{unsuppressed} \]
\[ \overline{\chi \gamma_{\mu5} \chi} \rightarrow q \gamma_{\mu5} q \quad \text{unsuppressed} \]
\[ \overline{\chi \gamma^{\mu \nu} \chi} \rightarrow q \gamma_{\mu \nu} q \quad \text{unsuppressed} \]
\[ \overline{\chi \gamma^{\mu \nu 5} \chi} \rightarrow q \gamma_{\mu \nu} q \quad \text{unsuppressed} \]
Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^5$ GeV; or strongly interacting particles of masses $1-10^3$ GeV.

Dark galactic halos may be clouds of elementary particles so weakly interacting or so few and massive that they are not conspicuous. Many dark-matter candidates have been proposed. Magnetic monopoles are one dark-matter candidate accessible to experimental search, and the same seems to be true for axions. On the other hand, massive neutrinos are a popular dark-matter candidate which seems very difficult to detect except under very favorable conditions. For many other dark-matter candidates considered in the literature, no practical experiments have been proposed.

Recently, Drukier and Stodolsky proposed a new way of detecting solar and reactor neutrinos. The idea is to exploit the fact that these neutrinos are produced in the Sun and have a large number of interactions on their way to Earth.

Let us first discuss the lower limit on detectable masses. If a halo particle of mass $m$ and velocity $v$ scatters from a target nucleus of mass $M$, the recoil momentum is at most $2mv$ and the recoil kinetic energy is at most $\epsilon = (2mv)^2/2M$. A reasonable value of $v$ is $v = 200$ km/sec. The lightest nucleus considered in Ref. 5 is aluminum, with $A = 27$ and $M \approx 27$ GeV. There seems to be a reasonable chance of building a detector sensitive to $\epsilon \sim 50-100$ eV (considerably more optimistic possibilities are discussed in Ref. 5). For $\epsilon \geq 50-100$ eV, we need $m \geq 1-2$ GeV, and this is the lower limit on the mass of detectable halo particles. It is important to note, though, that the lower limit of $50-100$ GeV, made in Ref. 5,
Direct Detection

- \( f(v) \) local WIMP phase-space density
  - Assume: \( \rho_{DM} = 0.4 \text{ GeV cm}^{-3} \)
    (subclumps, streams, ...?)
  - Assume: Maxwellian velocity distribution
    \( \langle v^2 \rangle^{1/2} = 220 \text{ km s}^{-1} \)

- Spin dependent or independent?
  \[
  \sigma_{\chi N} \text{ (axial)} = \frac{8}{\pi} \frac{m_{\chi}^2 m_N^2}{m_{\chi} + m_N} \Lambda^2 J(J+1)
  \]

- Same coupling to \( p \) and \( n \)?
  \[
  \sigma_{\chi N} \text{ (scalar)} = \frac{1}{\pi} \frac{m_{\chi}^2 m_N^2}{(m_{\chi} + m_N)^2} \left[ (A - Z) f_n + Z f_p \right]^2
  \]
Direct Detection

Recoil energies few to few dozen keV

Astrophysics: \( \rho_{\text{WIMP}} f(v) \)

Particle physics: \( \frac{M_{\text{WIMP}}}{d\sigma/dE_R} \)

Detector Mass

Nuclear Target(s) \( (M_{\text{Nucleus}} \text{ and } J_{\text{Nucleus}}) \)

\[ E_{\text{Threshold}} = 2\mu_{\chi N}^2 \nu_{\text{MIN}}^2 / M_{\text{Nucleus}} \]

\[ d\sigma/dE_R \]
Direct Detection
Nuclear Recoil $\rightarrow$ Signal

SUPERHEATED BUBBLES
COUPP, PICASSO, PICO

IONIZATION
CoGeNT, CDMSlite, MALBEK

PHONONS
CDMS, Edelweiss

LIGHT
XENON, LUX, DarkSide, ZEPLIN

CRESST

CUORE

DAMA/LIBRA, KIMS, ANAIAS, SABRE

After Jodi Cooley
LIMITS ON COLD DARK MATTER CANDIDATES
FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN a, F.T. AVIGNONE III b, R.L. BRODZINSKI c, A.K. DRUKIER d,e, G. GELMINI f,g,h and D.N. SPERGEL d,h

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c Pacific Northwest Laboratory, Richland, WA 99352, USA
d Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
e Applied Research Corp., 8201 Corporate Dr., Landover MD 20785, USA
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Received 5 May 1987

An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy. Using a realistic model for the galactic halo, large regions of the mass-cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken as an example of particles with spin-independent Z0 exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is <0.4 GeV/cm^3 for masses between 17.5 GeV and 2.5 TeV, at the 68% confidence level.
Direct Detection

COUPP

CDMS

PICO

CoGeNT

( + EDELWEISS, DAMA, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, LUX, ARDM, ANAIS, CDEX PandaX, DarkSide, DAMA/LIBRA …)
Maverick WIMPs

\[ \Omega h^2_{\Gamma_1 \Gamma_2} \rightarrow \Lambda (M) \]
\[ \rightarrow \sigma_S (M) \]

EFT operator

- \( \bar{\chi} \chi \) \( \bar{q} q \)
- \( \bar{\chi} \chi \) \( \bar{q} \gamma^5 q \)
- \( \bar{\chi} \gamma^5 \chi \) \( \bar{q} q \)
- \( \bar{\chi} \gamma^5 \chi \) \( \bar{q} \gamma^5 q \)
- \( \bar{\chi} \gamma^\mu \chi \) \( \bar{q} \gamma_\mu q \)
- \( \bar{\chi} \gamma^\mu \chi \) \( \bar{q} \gamma_{\mu 5} q \)
- \( \bar{\chi} \gamma^\mu_5 \chi \) \( \bar{q} \gamma_\mu q \)
- \( \bar{\chi} \gamma^\mu_5 \chi \) \( \bar{q} \gamma_{\mu 5} q \)
- \( \bar{\chi} \gamma^{\mu \nu} \chi \) \( \bar{q} \gamma_{\mu \nu} q \)
- \( \bar{\chi} \gamma^{\mu \nu 5} \chi \) \( \bar{q} \gamma_{\mu \nu} q \)

Spin independent

- \( v^2, Q^2 \) suppressed

Spin dependent

- \( v^2, Q^2 \) suppressed

\[ \sigma_S = c + d (v + Q)^2 \]

Spin-independent/-dependent

\[ \sigma = \frac{1}{M} \]

DM \rightarrow SM

DM \rightarrow SM
Direct Detection

Spin-Independent Scattering

$10^{-36} \text{ cm}^2 = 1 \text{ picobarn}$

$10^{-39} \text{ cm}^2 = 1 \text{ femtobarn}$

$10^{-42} \text{ cm}^2 = 1 \text{ attobarn}$

$10^{-45} \text{ cm}^2 = 1 \text{ zeptobarn}$

$10^{-48} \text{ cm}^2 = 1 \text{ yoctobarn}$

$\sigma_{0,\text{SI}}$ (per nucleon) $[\text{cm}^2]$

$M$ $[\text{GeV}]$
Direct Detection

Spin-Dependent Scattering

\[ \sigma_{0,SD} \text{ (per nucleon)} \text{ [cm}^2\text{]} \]

\[ M \text{ [GeV]} \]

\[ 10^{10} \quad 10^{12} \quad 10^{14} \]

M. Fedderke

Graph showing the spin-dependent scattering cross-section for different experiments as a function of mass.
Direct Detection

Spin-Independent Scattering

EFT: $m_f \Lambda^{-3} \bar{\chi} \chi \bar{f} f$

Minimal Flavor Violation

-$\sigma_{0,SI}$ (per nucleon) [cm$^2$]

$M$ [GeV]

Coherent neutrino scattering
Direct Detection

Spin-Dependent Scattering

EFT: $\Lambda^{-2} \bar{\chi} \gamma^5 \chi \bar{f} \gamma_{\mu_5} f$
**SWIMPs/Direct-Detection Relationship**

- Spin-independent/dependent ratio depends on model parameters.
- Cross section depends on model parameters, can vary many, many orders of magnitude.

![Diagram showing spin-independent and spin-dependent interactions](image-url)
Direct Detection

One analysis of one of many possible SUSY frameworks

\begin{figure}
\centering
\includegraphics[width=\textwidth]{plot.png}
\caption{Graph showing the direct detection cross-section for neutralino dark matter in the context of the pMSSM10 framework with and without LHC8 data.}
\end{figure}
Direct Detection: The Present

Maverick WIMPs (for given $M$, choose $\Lambda \rightarrow$ relic abundance):

- Vector couplings excluded in range 10 GeV to 2000 GeV
- Scalar couplings excluded in range 10 GeV to 200 GeV
- Axial & Tensor couplings spin-dependent, weak or no limits
- Pseudoscalar couplings velocity suppressed $\rightarrow$ no limits

SWIMPs (choose 100 or so SUSY parameters):

- Any limits very model dependent
- Direct detection limits constraining
- LHC+ pushing SUSY scale high $\rightarrow$ pushing to higher-mass SWIMPs
Direct Detection: The Future

New Techniques

Excluded Region

Also:
Directionality
Different mass targets
Spin-dependent $\sigma$

Supersize

$\sigma_{\chi N}$

mass
Direct Detection: The Future

The path is clear (at least to me) (Goal is to discover WIMP or kill a 39-year old idea.)

• Push spin-independent limits down to neutrino background – no more than 2 orders-of-magnitude below proposed experiments
• Lot of white space for spin-dependent limits
• Push sensitivity to lower WIMP mass (new techniques?)
• If see a signal:
  – Seasonal variations
  – Different targets
  – Directional sensitivity
• If don’t see a signal:
  – Think beyond nuclear recoil
  – Work on 21cm astrophysics
Indirect Detection

THE COSMIC $\gamma$-RAY BACKGROUND FROM THE ANNIHILATION OF PRIMORDIAL STABLE NEUTRAL HEAVY LEPTONS

F. W. STECKER

Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center

Received 1977 December 12; accepted 1978 February 14

ABSTRACT

In light of the recent work on the astrophysical implications of the possible existence of stable neutral heavy leptons and the suggestion that continuing annihilation of heavy leptons produced in the big bang might produce a substantial cosmic $\gamma$-ray background radiation, we examine in detail the spectra and intensities of such radiation from (1) a homogeneous cosmic lepton background, (2) a possible lepton halo around the Galaxy, and (3) integrated background radiation from possible lepton halos around other galaxies and from rich galaxy clusters. In the case of our own galactic halo, $\gamma$-radiation from heavy-lepton annihilation appears to be able to account for the intensity of the observed background only if there are $\sim 100$ $\gamma$-rays produced per annihilation. However, in that case both the energy spectrum and isotropy would be inconsistent with the observations. More likely lepton annihilation fluxes from a galactic halo would be confused with cosmic-ray-produced radiation and therefore would be difficult to observe. Heavy-lepton annihilation radiation from the halos of other galaxies accounts for at most $5 \times 10^{-9}$ of the background intensity, and those from rich clusters account for at most $5 \times 10^{-8}$ of the background intensity. Those from a homogeneous cosmological lepton background appear to be able to account for $\lesssim 10^{-9}$ of the observed cosmic $\gamma$-ray background, although the spectrum and isotropy in this case would be consistent with the data.

Subject headings: cosmic rays: general — cosmology — elementary particles — gamma rays: general

$$\sigma v \sim 10^{-36} \text{ cm}^2 \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$
Indirect Detection

Galactic Center
Dwarf spheroidals
DM clumps, Sun

Wimps

Quarks
Low-energy photons

Positrons

Electrons

Neutrinos

Antiprotons

Protons

Leptons
Medium-energy gamma rays

Bosons
Indirect Detection

\[ \frac{d\Phi(E)}{dE} = \frac{dN_{\gamma,\nu}}{dE} \frac{\langle \sigma_A \nu \rangle}{4\pi} \int_{\text{line of sight}} \int_{\text{region of interest}} \rho^2 [r(s,l,b)] \frac{1}{2M_{WIMP}^2} ds \cos b \, db \, dl \]

What to look for

- Charged particles: $\bar{p}$, high-energy $e^-e^+$
  easy to detect
  astronomical backgrounds
  bent by magnetic field

- Continuum photons, neutrinos
  $\gamma$ easy to detect
  astronomical backgrounds
  $\nu$ hard to detect/often not dominant

- Monoenergetic photon line ($\tilde{\chi}\tilde{\chi} \rightarrow \gamma\gamma$)
  low background
  (probably) low signal
  “golden” detection channel

Where to look for it

- Galactic Center
  know where to look
  largest signal
  largest backgrounds

- Nearby subclumps
  clean: no baryons
  don’t know where to look
  signal down $10^{-3}$

- Dwarf spheroidals ($\mathcal{M}/\mathcal{L}_\odot > 3000$)
  know where to look (about 20)
  clean: very few baryons
  signal down another $10^{-3}$
Indirect Detection

ATIC

MAGIC

Fermi/GLAST

PAMELA

Veritas

IceCube

H.E.S.S.

AMS-02

PAMELA

Veritas

IceCube
Indirect Detection: Maverick WIMPs

$$\Omega h^2 \rightarrow \Lambda_{\Gamma_1 \Gamma_2}(M)$$

**EFT operator**

<table>
<thead>
<tr>
<th>Operator</th>
<th>SM</th>
<th>DM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\overline{\chi}\chi$</td>
<td>$q\bar{q}$</td>
<td>suppressed</td>
</tr>
<tr>
<td>$\overline{\chi}\chi$</td>
<td>$q\gamma^5q$</td>
<td>suppressed</td>
</tr>
<tr>
<td>$\overline{\chi}\gamma^5\chi$</td>
<td>$q\bar{q}$</td>
<td>unsuppressed</td>
</tr>
<tr>
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<td>unsuppressed</td>
</tr>
<tr>
<td>$\overline{\chi}\gamma^\mu\chi$</td>
<td>$q\gamma_\mu q$</td>
<td>unsuppressed</td>
</tr>
<tr>
<td>$\overline{\chi}\gamma^\mu\chi$</td>
<td>$q\gamma_\mu\gamma^5 q$</td>
<td>suppressed*</td>
</tr>
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<td>suppressed*</td>
</tr>
<tr>
<td>$\overline{\chi}\gamma^\rho\chi$</td>
<td>$q\gamma_\rho q$</td>
<td>unsuppressed</td>
</tr>
<tr>
<td>$\overline{\chi}\gamma^\rho\chi$</td>
<td>$q\gamma_\rho\gamma^5 q$</td>
<td>unsuppressed</td>
</tr>
</tbody>
</table>

**Indirect Detection:**

$$\sigma_A v = a + b v^2$$

$$\Omega_{DM}: v^2 \sim 1/20$$

indirect detection: $v^2 \sim 10^{-6}$

**Direct Detection:**

$$\sigma_S = c + d (v + Q)^2$$

spin-independent/-dependent
direct detection: $v^2, Q^2 \sim 10^{-6}$
# Maverick WIMPs

<table>
<thead>
<tr>
<th>Signal or lack thereof</th>
<th>WIMP \cdot FERMION operator(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIRECT (SI) + INDIRECT</td>
<td>V \cdot V</td>
</tr>
<tr>
<td>DIRECT (SD) + INDIRECT</td>
<td>T \cdot T</td>
</tr>
<tr>
<td>DIRECT (SI) + INDIRECT</td>
<td>S \cdot S</td>
</tr>
<tr>
<td>DIRECT (SD) + INDIRECT</td>
<td>A \cdot A</td>
</tr>
<tr>
<td>DIRECT + INDIRECT</td>
<td>P \cdot P, P \cdot S, V \cdot A</td>
</tr>
<tr>
<td>DIRECT + INDIRECT</td>
<td>S \cdot P, A \cdot V</td>
</tr>
</tbody>
</table>
SWIMPs/Indirect-Detection Relationship

• Low-energy annihilation cross section depends on neutralino composition, mass, and coupling and possibly other masses; all of these depend on about 100 SUSY parameters
• Generally both velocity-independent & velocity-suppressed parts
• Relative size depends on model parameters
• Many possible final states depending on model parameters
• Many possible diagrams depending on model parameters
• Branching fractions depending on model parameters
• Annihilation to fermions \( \propto m_f^2 \)
• No two-body final state with a photon (at lowest order)—no \( \gamma \)-ray “lines”
Diffuse $\gamma$-Rays from the Galactic Center

Goodenough, Hooper, Dalyan, Portillo, Rood, Boyarsky, Malyshev, Ruchayskiy, Linden, Abazajian, Kaplinghat, Gordon, Macias, Canac, Horiuichi, Slatyer, Berlin, Cholis, McDermott, Lin, Finkbeiner, Calore, Cholis, Weniger, ...

- Start with FERMI public data and tools
- Pick search region of interest (around galactic center)
- Remove point sources and model and remove every non-DM astrophysical source
- Fit excess (if any) to cross section & annihilation channel(s)

$M = 32.25$ GeV
annihilation to $\bar{b}b$
$\sigma v = 1.7 \times 10^{-26}$ cm$^3$/s

\[
\begin{array}{cccccc}
\text{Model} & \alpha_1 & \alpha_1 & E_B & \chi^2/\text{dof} & p\text{-value} \\
\text{BPL} & 1.42^{+0.22}_{-0.31} & 2.63^{+0.13}_{-0.095} & 2.06^{+0.23}_{-0.17} \text{GeV} & 1.06 & 0.39 \\
\bar{b}b & M = 49^{+6.4}_{-5.4} \text{ GeV} & \sigma v = 1.76^{+0.28}_{-0.27} \times 10^{-26} \text{ cm}^2 & 1.08 & 0.36 \\
\bar{c}c & M = 38.2^{+4.6}_{-3.9} \text{ GeV} & \sigma v = 1.25^{+0.2}_{-0.18} \times 10^{-26} \text{ cm}^2 & 1.07 & 0.37 \\
\bar{\tau}\tau & M = 0.337^{+0.047}_{-0.039} \text{ GeV} & \sigma v = 1.25^{+0.2}_{-0.18} \times 10^{-26} \text{ cm}^2 & 1.52 & 0.06 \\
\end{array}
\]
Indirect Detection: The Future

The path is clear (at least to me) (Goal is to discover WIMP or kill a 39-year old idea.)

- Have an overwhelmingly statistically significant $\gamma$-ray excess from GC
- Why aren’t we all as excited as Dan Hooper?
- Possible background contamination (thousands of millisecond pulsars, …)
- Better astrophysical understanding of galactic center
- Better understanding of dark-matter density profile
- Better observations
  - Better angular resolution
    (resolve background sources, remove emission correlated with gas, …)
  - Better spectral resolution
  - More collecting area—look for signals elsewhere, stacked dwarfs, etc.
  - Ground observations, e.g., CTA will teach us about backgrounds
Looking for an *invisible* needle in a haystack
Maverick WIMPs at the LHC

\[ \Omega h^2 \rightarrow \Lambda_{\Gamma_1, \Gamma_2}(M) \]

\[ \rightarrow \sigma_P(M) \]

EFT operator

\[ \begin{align*}
\bar{\chi}\chi & \rightarrow \bar{q}q \\
\bar{\chi}\chi & \rightarrow \bar{q}\gamma^5q \\
\bar{\chi}\gamma^5\chi & \rightarrow \bar{q}q \\
\bar{\chi}\gamma^5\chi & \rightarrow \bar{q}\gamma^5q \\
\bar{\chi}\gamma^{\mu}\chi & \rightarrow \bar{q}\gamma^{\mu}q \\
\bar{\chi}\gamma^{\mu}\chi & \rightarrow \bar{q}\gamma_{\mu5}q \\
\bar{\chi}\gamma^{\mu5}\chi & \rightarrow \bar{q}\gamma^{\mu}q \\
\bar{\chi}\gamma^{\mu5}\chi & \rightarrow \bar{q}\gamma_{\mu5}q \\
\bar{\chi}\gamma^{\mu\nu}\chi & \rightarrow \bar{q}\gamma^{\mu\nu}q \\
\bar{\chi}\gamma^{\mu\nu5}\chi & \rightarrow \bar{q}\gamma_{\mu\nu}q
\end{align*} \]

Same for all operators

\( \sigma_P \) in relativistic limit
Maverick WIMPs at the LHC

- Look for “monojets”
- Monojets are Nature’s garbage can
- Also mono-$\gamma$'s & mono-$Z$'s, inclusive $b$ jets
- SM background extremely well modeled and understood
- Neutrino background can be removed
- Couplings irrelevant in relativistic limit
- Validity of EFT?

Beltran, Hooper, Kolb, Krusberg, Tait 2009; Goodman, Ibe, Rajaraman, Shepard, Tait, Yu; Rajaraman, Shepherd, Tait, Wijangco; Bai, Fox, Harnik; Fox, Harnik, Kopp, Tsai; CDF, CMS, ATLAS, …
SWIMPs at the LHC
Most popular cold thermal relic: the neutralino

- Gluinos, squarks, charginos will be discovered first
- Analysis model dependent
- LHC chewing away allowed region
- Can swiggle out … but it is getting harder
- Don’t throw in towelino just yet
- Stay tuned for results from 13 TeV run
- Eventually will see WIMP in missing energy signals
Complicated decay chain—very model dependent
Collider Searches: The Future

• LHC has just started running at 13 TeV
• LHC will eventually accumulate a tremendous amount of data
• If DM is a SUSY relic, some indication of SUSY will be discovered at LHC
  – gluinos, squarks, charginos, will be seen first
  – search strategies well developed
• If DM is a Maverick particle
  – only hope is missing-energy searches
  – most effective for low masses
  – no guarantee EFT valid at LHC
Dark Matter: If Not a WIMP

• If DM not a WIMP, many other possibilities:
  - Axions
  - Asymmetric DM
  - Sterile neutrino DM (e.g., 7 keV sterile neutrino producing 3.5 keV X-ray line which may, or may not, be observed)
  - Axino (7 keV axino) DM
  - Self-interacting DM
  - Inelastic DM
  - $Q$-balls or other solitonic DM
  - Quark nuggets
  - Hidden-sector DM
  - WIMPZILLA
Dark Matter: The Future

• We are in the eighth decade of Dark Matter!

• 2010s is the Decade of the WIMP
  – LHC
  – Direct detection
  – Indirect detection

Have to run to ground the WIMP (cold thermal relic) hypothesis.

• Indirect/Direct/LHC confusion not an issue

• WIMPs may be more complicated than discussed: Leptophilic, Leptophobic, Flavorful, Self-Interacting, Dynamical, Inelastic, …

• My predictions:
  – We will know the answer before a century of dark matter
  – Dark matter discovery will be unanticipated
  – Dark matter will be “none of the above”
  – Dark matter will be multicomponent
  – Dark matter will be part of a dark sector
Dark Matter
Rocky Kolb, KICP