Astrophysical Motivations for Dark Forces

Jefferson Lab
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Neal Weiner
Center for Cosmology and Particle Physics
New York University
 Era of data

Cosmics: PAMELA, Fermi, ATIC, HESS, AMS, ACTs, WMAP, Planck...

Direct: CDMS, DMTPC, XENON, LUX, CRESST, COUPP, PICASSO, KIMS...

Production: LHC/Tevatron, Fixed Target, Beam dump
Era of anomalies
Era of anomalies

Indications of high energy electron or positron production
Anomalies and anomalies

- High Energy Electrons/Positrons: PAMELA (HEAT, AMS-01), ATIC, EGRET, WMAP
- Low energy positrons: INTEGRAL
- Direct detection: DAMA/LIBRA
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multiple indications
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\[\text{"classic" WIMP} \quad \text{new, improved, WIMP}\]
Dark Matter
what is it?
The WIMP “miracle”

Assume thermal equilibrium

\[ \chi \chi \leftrightarrow \bar{f} f \]

\[ \chi \quad \text{time} \quad f \]

\[ \chi \quad \bar{f} \]
The WIMP “miracle”

assume thermal equilibrium

\[ \chi \leftrightarrow \bar{f} \]

\[ \chi \leftrightarrow f \leftarrow \text{time} \rightarrow \bar{f} \]

**miracle** |ˈmirəkl|
noun
a surprising and welcome event that is not explicable by natural or scientific laws and is therefore considered to be the work of a divine agency: the miracle of rising from the grave.
- a highly improbable or extraordinary event, development, or accomplishment that brings very welcome consequences: it was a miracle that more people hadn’t been killed or injured [as adj.]: a miracle drug.
- an amazing product or achievement, or an outstanding example of something: a machine which was a miracle of design.

ORIGIN Middle English: via Old French from Latin *miraculum* ‘object of wonder,’ from *mirari* ‘to wonder,’ from *mirus* ‘wonderful.’
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When \( T \ll M_{\text{WIMP}} \), number density falls as \( e^{-M/T} \)
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\[ \Omega h^2 \approx 0.1 \times \left( \frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]

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When \( T < M_{\text{WIMP}} \), number density falls as \( e^{-M/T} \)

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Any weak-scale particle naturally freezes out within a few orders of magnitude of the correct cross section.
Signals of thermal DM
- Production (accelerators)
- Cosmic rays/indirect detection (PAMELA/Fermi/WMAP...)
- Direct detection (DAMA/XENON/CDMS...)
Signals of thermal dark matter

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The step-child of dark matter anomalies: INTEGRAL

INTEGRAL/ SPI: (spectrometer)
Energy range: 20 keV - 8 MeV
Field of view: 16 deg
Angular resolution: 2.5 deg FWHM
Launched: 2002 Oct 17
Still operating...
distribution of the INTEGRAL 511 keV line
The step-child of dark matter anomalies: INTEGRAL

**Fig. 2.** A fit of the SPI result for the diffuse emission from the GC region (|l|, |b| ≤ 16°) obtained with a spatial model consisting of an 8° FWHM Gaussian bulge and a CO disk. In the fit a diagonal response was assumed. The spectral components are: 511 keV line (dotted), Ps continuum (dashes), and power-law continuum (dash-dots). The summed models are indicated by the solid line. Details of the fitting procedure are given in the text.
Suppose TeV mass dark matter has an excited state \( \sim \) MeV above the ground state, and a new force \( \phi \) with mass \( \sim \) GeV through which DM can scatter into the excited state, then decay back by emitting e+e-.
Need cross section near the geometric cross section, i.e.

\[ \sigma \sim \frac{1}{q^2} \]

Only possible if new force with mass

\[ m_\phi < \text{GeV}^2 \] is in the theory
The NKOTB of dark matter anomalies: PAMELA
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PAMELA

Positron to Electron Fraction

End 2007:
~20 000 positrons total
~2000 > 5 GeV

Energy (GeV)

Mirko Boezio, IDM2008, 2008/08/20

Preliminary!!!
PAMELA
Fermi, HESS, ATIC, PPB-BETS

- **Harder** spectrum than expected - no break until $\sim$ TeV
Positrons expected from secondary production
How do electrons propagate?

\[
\frac{\partial}{\partial t} \frac{dn_e}{dE_e} = \nabla \cdot \left[ K(E_e, \vec{x}) \nabla \frac{dn_e}{dE_e} \right] + \frac{\partial}{\partial E_e} \left[ b(E_e, \vec{x}) \frac{dn_e}{dE_e} \right] + Q(E_e, \vec{x}),
\]

- **ICS and synchrotron energy losses (fairly well understood)**
- **Diffusion (not well understood)**
- **what we want to know**

Sunday, February 28, 2010
Astrophysics?

Malyshev, Cholis, Gelfand, ’09

Aharonian, Atoyan, Volk ’95; Hooper, Blasi, Serpico ’08; Profumo ’09...
DM or Astrophysics?
(look in the inner galaxy)
Interstellar Dust from IRAS, DIRBE (Finkbeiner et al. 1999)
Map extrapolated from 3 THz (100 micron) with FIRAS.
Ionized Gas from WHAM, SHASSA, VTSS (Finkbeiner 2003)
H-alpha emission measure goes as thermal bremsstrahlung.
Synchrotron at 408 MHz  (Haslam et al. 1982)
Fig. 1.— The WMAP foreground grid; see detailed discussion in §2.7.
Dobler and Finkbeiner '08
A “Haze”

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Dobler and Finkbeiner ‘08

electrons spiraling in magnetic field create microwaves
pulsars

WMAP Haze (Finkbeiner 2004; Dobler & Finkbeiner 2008)

plots courtesy G. Dobler

dark matter
Natural interpretation is of new source of 10+ GeV e+e-in galactic center, but with larger amplitude than locally.

pulsars

good fit for DM explanation

dark matter

plots courtesy G. Dobler

W. M. P. Haze (Finkbeiner 2004; Dobler & Finkbeiner 2008)
Fermi ICS

In the inner galaxy, high energy e+e- convert energy to synchrotron radiation (WMAP haze) and inverse-compton scattered photons

Same electrons should upscatter starlight into gamma rays
Fig. 2.— GALPROP model illustrating the three primary gamma-ray emission mechanisms (see §3) and their relative amplitudes in the Galactic plane ($|\ell| \leq 30$, $|b| \leq 5$).
Hints of high energy $e^+e^-$

- PAMELA tells us that there is a primary source of 10-100 GeV positrons within 1kpc

- Fermi indicates an excess of $e^+e^-$ up to ~ 1 TeV (ATIC as well)

- The WMAP Haze suggests us that there is a new population of 10-100 GeV positrons in the galactic center (5°-15°)

- Fermi gamma rays seem also to indicate high energy electron production in galactic center

NB: Hard analyses!
WIMP annihilations? Not so fast!
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The three ingredients to explain PAMELA/Fermi
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Wide range of models all share similar structure (Pospelov and Ritz, ’08; Fox and Poppitz ’08; Nomura and Thaler ’08; Nelson and Spitzer ’08; Katz and Sundrum ’08...)

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New forces = new annihilation modes

Arkani-Hamed, Finkbeiner, Slatyer, NW, '08

Finkbeiner, NW PRD '07; Pospelov, Ritz, Voloshin PLB '08
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No antiprotons comes from kinematics
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Cholis, Goodenough, NW, arxiv:0802.2922

Pre-PAMELA

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-Cholis, Goodenough, NW, arxiv:0802.2922

Pre-PAMELA

“WIMP Miracle” works as before ($\sigma \sim 1/M^2$)

Post-PAMELA

Arkani-Hamed, Finkbeiner, Slatyer, NW, ‘08

Cholis, et al, arxiv:0810.5344

Finkbeiner, NW PRD ‘07; Pospelov, Ritz, Voloshin PLB ‘08

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Sommerfeld Enhancement
High velocity

Hisano, Nojiri, Matsumoto ’04; Cirelli & Strumia ’07; Arkani-Hamed, Finkbeiner, Slatyer, NW, ’08
Sommerfeld Enhancement

High velocity

Low velocity

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Low velocity

\[ \sigma = \sigma_0 \left( 1 + \frac{v_{\text{esc}}^2}{v^2} \right) \]

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If these signals arise from thermal dark matter, dark matter must have a long range force.

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If particles interact via a “long range” force, cross sections can be much larger than the perturbative cross section.

If these signals arise from thermal dark matter, dark matter must have a long range force:

$$m_{\phi}^{-1} \gtrsim (\alpha M_{DM})^{-1} \text{ (fm)}$$

Hisano, Nojiri, Matsumoto ‘04; Cirelli & Strumia ‘07; Arkani-Hamed, Finkbeiner, Slatyer, NW, ’08
How natural the GeV scale?

Interactions with standard model generate scales

Works most naturally with new physics models (SUSY, Randall-Sundrum, etc)
Searching for WIMPs
Searching for WIMPs

How to detect a WIMP?
Searching for WIMPs

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Step 1: Build big detector
Searching for WIMPs

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rate \approx \frac{\text{few events}}{\text{kg} \cdot \text{year}} \times \frac{\sigma}{10^{-36}\text{cm}^2} \times \frac{v}{300\text{km/s}}
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Step II: Go deep underground to shield from cosmic rays
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Step II: Go deep underground to shield from cosmic rays

Step III: Have no other background
seasonal variation

as galaxy rotates, we experience a WIMP "wind"

seasonal variation

in the summer, moving against wind

WIMP "wind"

expect an annual modulation in signal!

in the winter, moving against wind

DAMA experiment

- 8.3 sigma signal for modulation
- only in “single hit” events
- proper phase

Dark matter?

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DAMA experiment


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Dark matter?


CDMS: 2004+2005 (reanalysis) +2008 Ge
ZEPLIN III (Dec 2008) result
CRESST 2007 60 kg-day CaWO4
WARP 2.3L, 96.5 kg-days 55 keV threshold
DAMA 2000 58k kg-days NaI Ann. Mod. 3sigma w/DAMA 1996
Edelweiss I final limit, 62 kg-days Ge 2000+2002+2003 limit
KIMS 2007 - 3409 kg-days CsI
CDMS (Soudan) 2005 Si (7 keV threshold)

Sunday, February 28, 2010
Consider vector interaction

\[ \chi_1 \sigma_\mu \chi_1 A^\mu \]
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\[ \chi_1 \sigma_\mu \chi_1 A^\mu \]
Consider vector interaction

\[ \chi_1 \sigma_{\mu} \chi_1 A^\mu \]

\[ \chi_1 \sigma_{\mu} \chi_2 A^\mu \]
Consider vector interaction

\[ \chi_1 \sigma_\mu \chi_1 A^\mu \]

\[ \chi_2 \sigma_\mu \chi_2 A^\mu \]

Vector interactions for massive WIMPs \((M_{\text{DM}} > M_{\text{force}})\) **always** require multiple states

interaction is off-diagonal
Question:
Question:

What is the splitting between those states?
Question:

What is the splitting between those states? δ

Tiny?
Question:

- What is the splitting between those states? \( \delta \)
- Tiny?
- Comparable to WIMP kinetic energy?
Question:

What is the splitting between those states? $\delta$

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Comparable to WIMP kinetic energy?

Huge?
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- For Sommerfeld Enhancement (i.e., PAMELA), states must be small
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- Tiny?
- Comparable to WIMP kinetic energy?
- Huge?

For Sommerfeld Enhancement (i.e., PAMELA), states must be small

$$\frac{\delta}{M} \lesssim \frac{\alpha^2}{4}$$

For $\alpha \sim 10^{-2}$, $M \sim TeV$

$\delta \sim 100\text{MeV} \sim \text{kinetic energy of a WIMP}$
“Inelastic” dark matter

- DM-nucleus scattering must be inelastic
- If dark matter can only scatter off of a nucleus by transitioning to an excited state (100 keV), the kinematics are changed dramatically


\[ \chi N \rightarrow \chi^* N \]
“Inelastic” dark matter

- DM-nucleus scattering must be inelastic
- If dark matter can only scatter off of a nucleus by transitioning to an excited state (100 keV), the kinematics are changed dramatically

\[ \frac{v^2 \mu_{\chi N}}{2} > \delta \]

Favors heavier targets

visible to DAMA

visible to DAMA and CDMS

Disfavors CDMS
Enhanced modulation

Favors modulation experiments
Together, these three effects allow a positive DAMA signal consistent with XENON/CDMS/CRESST/KIMS...
A new force in the dark sector

- Outputs > Inputs
  - GeV mediator gives all aspects of the anomalies (size, leptons, no antiprotons)
  - Non-Abelian or multi-state models give natural explanation for all anomalies (INTEGRAL, DAMA, and e+e-)

Sunday, February 28, 2010
NEUTRINO MOMENTS, MASSES AND CUSTODIAL SU(2) SYMMETRY

Howard GEORGI and Michael LUKE

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Received 17 April 1990

We identify and exemplify a new mechanism which leads to a nonzero magnetic moment for a neutrino, while suppressing the neutrino’s mass. The mechanism requires that the contribution to the neutrino mass of the new particles that are responsible for its magnetic moment is approximately canceled by a contribution from neutral particles, related by a custodial SU(2) symmetry.

1. The problem

Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B\(^8\) neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the solar neutrino data, the apparent modulation of the flux of solar neutrinos with the sun-spot cycle, is certainly intriguing [3]. It is, of course, possible that this is an astrophysical problem rather than a particle physics problem. But that would require a synchronization of cycles of the interior of the sun with those of the convective layer, both in frequency and in phase. Thus it seems particularly interesting that there may be a particle physics explanation of this effect [4], involving a magnetic moment of the electron neutrino
“Unreliable” astrophysical signals can be the first sign of new physics
The future of beyond the standard model physics?

\[ m \sim \alpha' \]

\[ m \sim \alpha'^{1/2} \]
The future of beyond the standard model physics?

New physics (SUSY, etc)

Standard model → Dark sector

energy frontier

luminosity frontier
Motivating dark forces
Motivating dark forces

A wealth of anomalies can be explained by the presence of a new, dark force
Motivating dark forces

- A wealth of anomalies can be explained by the presence of a new, dark force
- Single ingredient: new dark force at ~ GeV addresses key issues
  - Large excitation cross section for INTEGRAL
  - Hard leptons/no antiprotons for PAMELA/Fermi
  - Large Annihilation cross section
  - Excited states for DAMA/INTEGRAL
Motivating dark forces

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Testable
Thank you very much!
Spectra in “realistic” halos

Kuhlen & NW, in prep

Yellin techniques (optimum interval, maximum gap, pmax) **unreliable** for inelastic models in experiments with good energy resolution
Limits from galactic center

Interesting limits from bremsmed photons (Beacom, Bell, Bertone, ‘04; Bell & Jacques ‘08; Bertone, Cirelli, Strumia, Taoso, ‘08; Bergstrom, Bertone, Bringmann, Edsjo, Taoso, ‘08; Meade, Papucci, Volansky, ‘09; Mardon, Nomura, Stolarski, Thaler, ‘09)

Limits rely on knowing density and velocity in GC – can change a lot with baryons!

Governato et al, 2006

Romano-Diaz, Schlosman, Hoffman, Heller, ‘08

NB: Many simulation uncertainties (matching bulge with MW, other numerical issues involving baryons)
GOING FORWARD

Planck

Padmanabhan & Finkbeiner ’04; Bertone, Galli, Iocco, Melchiorri, ’09; Slatyer, Finkbeiner, Padmanabhan ’09

DM annihilation injects high-energy particles into the IGM [71], which heat and ionize neutral hydrogen as they cool. This ionizing energy does not generally change the redshift of recombination, but does alter the residual ionization after recombination. The increased ionization fraction leads to a broadening of the last scattering surface, attenuating correlations between temperature fluctuations. The low-\ell correlations between polarization fluctuations, on the other hand, are enhanced by the thicker scattering surface.

Should definitively test DM electronic production