Update on **Dark Matter** and **Dark Forces**

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(thanks to Rouven Essig, Matt Graham, Tracy Slatyer, Neal Weiner)
Rouven’s Talk: what’s new?

Is Dark Matter still motivating the search for new GeV-scale forces?

• **DM indirect detection**
  • cosmic-rays
  • gamma-rays, neutrinos (very brief)
  • Cosmic Microwave Background
  • WMAP haze, Fermi haze

• **DM direct detection**
  • DAMA, CoGeNT, XENON-100, CDMS-02, …

Answer: Yes! But it’s complicated…
This Talk: what’s new?

Is Dark Matter still motivating the search for new GeV-scale forces?

- **DM indirect detection**
  - cosmic-ray $e^+/e^-$
    - Fermi confirms PAMELA
  - gamma-rays, neutrinos (very brief)
    - More bounds, interpretation-dependence
  - Cosmic Microwave Background
    - Planck forecasts
  - WMAP haze, Fermi haze

- **DM direct detection**
  - DAMA, CoGeNT, XENON-100, CDMS-02, …
    - CRESST signal, CoGeNT revisited, limits from Xenon and CDMS

Answer: Yes! But it’s complicated… even more
Outline

• **Indirect DM detection**
  • Recap & update on e+/e– signals
  • New gamma-ray limits – all close to the line
  • Status of ≲200 MeV mediators & substructure

• **Direct DM detection**
  • DAMA recap
  • Light-WIMP constraints: Xe100 and CDMS
  • CoGeNT: excess ↓, modulation ↑
  • CRESST anomaly & comments

• **Dark Forces updates**
  • APEX (see Bogdan’s talk)
  • Two KLOE searches
Indirect detection

PAMELA satellite

Fermi satellite, HESS

New e+ source

theory expectation

\[ m_{\text{DM}} \sim \text{TeV} \quad m_{A'} \sim \text{GeV} \]

Arkani-Hamed, Finkbeiner, Slatyer, Weiner
Pospelov & Ritz

[Meade, Papucci, Strumia, Volansky]

[Ruderman, Volansky]

[RE, Kaplan, Schuster, Toro]
Indirect detection

PAMELA satellite

Fermi 1008.3999

$\text{m}_{\text{DM}} \sim \text{TeV}$

$\text{mA}' \sim \text{GeV}$

Arkani-Hamed, Finkbeiner, Slatyer, Weiner

Pospelov & Ritz

[Ruderman, Volansky]

[RE, Kaplan, Schuster, Toro]
Cross-Checks + Extensions

Fermi checks, extends PAMELA e+ fraction

[1109.0521]

PAMELA checks Fermi/HESS e− flux

[Adriani, EPS2011]
AMS...

First events

50x PAMELA acceptance

...but no results yet

slide from Andrei Kounine
TeVPA 2010
Tests of Dark Matter Interpretations

- **Gamma rays** from DM annihilating elsewhere
  - Final-state radiation and Inverse Compton Scattering
    - Galactic center
      - Exclude DM Annihilation if halo is cuspy; borderline for cored
  
- **NEW!** Dwarf galaxies, nearby clusters (known sources)
  - Limits starting to get interesting

- **NEW!** Distant galaxies (not resolved)
  - Looks problematic, but order-of-magnitude uncertainty!
  - CMB: extra ionization *least theory uncertainty*
    - Close – Planck will be decisive

- Other implications of Sommerfeld-Enhanced models
  - Consistency with thermal history (no over-annihilation)
  - Consistency with self-interaction bounds
Annihilation in Dwarf Galaxies and Nearby Clusters

Fermi ROI (annihilation to $\mu^+\mu^-$)

1108.3546
(Limit from stacked $\gamma$ signals from 10 dwarf spheroidal galaxies)

1110.1529
(Limit from combined $\gamma$-ray signals from 8 nearby clusters)
Diffuse $\gamma$ Rays
(from outer Milky Way halo)

$\mu^+\mu^-$ decay

(note) exclusion depends on density of photons for Inverse-Compton
Black line: FSR only
Diffuse $\gamma$ Rays from DM in distant, unresolved galaxies

[Cavala et al. 1103.0776]

Caveats:
- relies on modeling of blazar and star-forming galaxies (treated as 86% of flux)
- simulation cuts off at $10^9$ M$_\odot$; constraints rely heavily on extrapolation down to $10^{-6}$ M$_\odot$ halos and subhalos (gives factor of 20-2600)
- “There but not here”: subhalos can contribute to local signal, too

FERMI flux limits

excluded by
10 (low substructure) to 1000 (high substructure)

[1103.0776] ($\gamma$ flux limit)/(Expected flux)
CMB

[small improvement from WMAP7+ACT]
CMB

[small improvement from WMAP7+ACT]
Summary of Constraints

• Extragalactic diffuse signal
  – Numerically most severe constraint
  – Order-of-magnitude theory uncertainty

• Re-ionization of CMB
  – Most robust: theory uncertainties are negligible
  – (theory uncertainties on the “target” cross-section remain, at factor-of-few level)
  – At boundary of sensitivity; Planck will improve by order of magnitude (Jan 2013)
Preferred Dark-Photon Masses?

Lore: these results (especially CMB) disfavor <200 MeV mediators as explanations of PAMELA & Fermi (strongly assumption-dependent – see next slide)

Reason: velocity-dependence of Sommerfeld effect

- Constraints on $<\sigma v>_{\text{sat}}$ imply much tighter constraints on $<\sigma v>_{\text{local}}$ if mediator is light

\[
\frac{S_{\text{now}}}{S_{\text{sat}}} \sim \frac{m_\phi}{m_\chi v} \sim \frac{m_\phi}{\text{GeV}}
\]
Preferred Dark-Photon Masses?

But….what if signals come from sub-halos in the Milky Way?

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\[
\frac{S_{\text{now}}}{S_{\text{sat}}} \sim \frac{m_\phi}{m_\chi v} \sim \frac{m_\phi}{\text{GeV}}
\]
Substructure in Milky Way

Galaxy simulations (Via Lactea II, Aquarius) resolve subhalos as small as $10^6 \text{M}_\odot$

Fraction of dark matter in subhalos is only $<\rho_{\text{sub}}>/<\rho> \sim 10^{-3}$, but what matters for annihilation is $\rho^2$.

Because subhalos are very dense, local $\Delta = <\rho^2_{\text{sub}}>/<\rho^2> \sim 1$ is possible.

Still far from calculating local substructure, but $\Delta \sim 0.3-1$ is reasonable.
Substructure in Milky Way

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$\Delta$ depends on:
- fraction of DM in subhalos
- mass distribution of subhalos
- radial distribution of subhalos
- minimum size of subhalos
- tidal disruption of subhalos

Still far from calculating local substructure, but $\Delta \sim 0.3-1$ is reasonable.
If $\Delta=1$, then the $\langle \rho^2 \rangle$ from sub-halos is as large as from the smooth Milky Way halo…

…but the Sommerfeld boost factor might be 10x larger!
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Sommerfeld DM with Substructure

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…but the Sommerfeld boost factor might be 10x larger!

\[
\frac{S_{\text{now}}}{S_{\text{sat}}} \sim \frac{m_\phi}{\text{GeV}} + \Delta
\]

For low $m_\phi$, CMB is a limit on $\Delta$

\[
\frac{S_{\text{now}}}{S_{\text{GC}}} \sim \frac{m_\phi/\text{GeV}}{m_\phi/\text{GeV}} + \Delta
\]

For low $m_\phi$, $O(1)$ $\Delta$ the GC constraints suppressed by $m_\phi/\text{GeV} \Rightarrow$ cuspy halos ok.
Parameter Space

Contours: dark-sector self-coupling required for PAMELA/Fermi (target boost factor of 100)

Assume additional processes at freeze-out and today to get correct relic abundance.

Arrows: regions excluded by
- DM self-interaction (potentially)
- CMB re-ionization by DM
(green region isn’t a constraint)

(from 1107.3546 – T. Slatyer, NT, N. Weiner)
Parameter Space

Contours: dark-sector self-coupling required for PAMELA/Fermi (target boost factor of 100)

Assume additional processes at freeze-out BUT NOT today to get correct relic abundance.

Arrows: regions excluded by

- DM self-interaction (potentially)
- CMB re-ionization by DM (green region isn’t a constraint)

PAMELA consistent with WMAP-5 for any mediator mass, if $\Delta > 0.4$

No significant constraints from self-interaction

(from 1107.3546 – T. Slatyer, NT, N. Weiner)
How do Other Constraints Change with Substructure?

• Extragalactic diffuse constraints
  – Local substructure certainly helps get away from limits
  – Still no reliable estimates: extrapolations of 2 quantities from 2 simulations. NOT precision cosmology
  – With optimistic (but reasonable) parameters, get both $\Delta \sim 1$ and low extragalactic boosts

• Inner galaxy constraints become irrelevant

• Outer galaxy remains borderline
CMB & Planck

- Planck plans to announce all cosmology results simultaneously in January 2013.
  - Present $\Delta > 0.4 \rightarrow \Delta > 5$
    - kills *most* Sommerfeld DM interpretation of PAMELA/Fermi
  - or they’ll see evidence for DM annihilation in early universe

No signal

$\Delta = 1$

$\Delta = 0.4$
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  • DAMA recap
  • Light-WIMP constraints: Xe100 and CDMS
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• **Dark Forces updates**
  • APEX (see Bogdan’s talk)
  • Two KLOE searches
Is DAMA seeing DM?

DAMA (NaI) sees annual modulation

Two popular possibilities to explain this with DM and A′s:

- \(~100\) GeV DM with \(~100\) keV splittings scattering \textit{inelastically} off Iodine

- \(5-10\) GeV DM scattering \textit{elastically} off Na

\(\text{simplest A′ models now ruled out by Xe100}\)

(modified from last year’s slide by Rouven Essig)
But inelastic DM isn’t completely dead...

DAMA has Thallium impurities (A~205) $10^{-3}$, which allows large DM splittings.

![Graphs showing DM splittings](image)

in this case, XENON-100 isn’t sensitive

(there is also “isospin violating” and “magnetic” inelastic DM)
Light Dark Matter & CoGeNT

CoGeNT (Germanium) saw excess of O(100) events

“Best-fit WIMPs” are ruled out by CDMS, Xenon10, Xenon100
CDMS-2 Low Energy Analysis

Same target material (Ge) so straightforward comparison of spectra is valid.
CoGeNT revisits

Juan Collar, TAUP

CoGeNT uncertainties (e.g., surface event rejection next to threshold)

PRELIMINARY (work in progress, not an exact science yet)

⇒ even after rise time cut, surface events aren’t negligible.
CoGeNT revisits

Juan Collar, TAUP

These events have rise time distribution inconsistent with bulk events.

Conclusion:
“Scant evidence left for a signal” \textit{or}
“Now consistent with CDMS and w/ CRESST excess”
CoGeNT modulation
CoGeNT modulation – Cautions

Modulation rate comparable to CDMS total rate ⇒ need high modulation fraction

Modulation fraction in Low-energy “DM/exponential” bin

Modulation fraction in High-energy “const. background” bin

[Fox, Kopp, Lisanti, Weiner: 1107.0717]

If it’s modulating, it’s probably highly modulating and has higher-energy & flatter ‘recoil’ spectrum than simple WIMP
CRESST

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e/\gamma$ events</td>
<td>8.00 ± 0.05</td>
<td>8.00 ± 0.05</td>
</tr>
<tr>
<td>$\alpha$ events</td>
<td>11.5$^{+2.6}_{-2.3}$</td>
<td>11.2$^{+2.5}_{-2.3}$</td>
</tr>
<tr>
<td>neutron events</td>
<td>7.5$^{+6.3}_{-5.5}$</td>
<td>9.7$^{+6.1}_{-5.1}$</td>
</tr>
<tr>
<td>Pb recoils</td>
<td>15.0$^{+5.2}_{-5.1}$</td>
<td>18.7$^{+4.9}_{-4.7}$</td>
</tr>
<tr>
<td>signal events</td>
<td>29.4$^{+8.6}_{-7.7}$</td>
<td>24.2$^{+8.1}_{-7.2}$</td>
</tr>
<tr>
<td>$m_\chi$ [GeV]</td>
<td>25.3</td>
<td>11.6</td>
</tr>
<tr>
<td>$\sigma_{WN}$ [pb]</td>
<td>1.6$\cdot 10^{-6}$</td>
<td>3.7$\cdot 10^{-5}$</td>
</tr>
</tbody>
</table>

Likelihood analysis ⇒ about 50% signal, 50% background
Is CRESST really pointing toward light WIMPs?

M1:
- 2.0 O events
- 7.3 Ca events
- 19.6 W events (67% W)
- "M3"
- 0.8 O events
- 3.8 Ca events
- 26.5 W events (85% W)

Without seeing the full data set, the presented fits and iDM limits all indicate that an excess in the W band is in better agreement
Rates

• At this point, *all* the direct detection anomalies need large cross-sections (if they have anything to do with DM)
  - Bigger than Z or h can give…

  - so new force of some kind?? Preferably light to get large rate w/o direct observation of mediator at LEP, LHC, … (other possibilities exist)
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$\phi \rightarrow \eta U, \quad \eta \rightarrow \pi^+ \pi^- \pi^0, \quad U \rightarrow e^+ e^-$

(corrected data with Dalitz decay spectrum)

Figure 5. Search for $e^+ e^- \rightarrow h'/U, \quad U \rightarrow \mu^+ \mu^-, \quad h' \rightarrow \text{"invisible"}$ events: recoil mass to the $\mu^+ \mu^-$ pair as a function of the di-muon invariant mass for data taken at the $\phi$ mass (left) and at $\sqrt{s} = 1$ GeV (right).
Fermi [1107.4272]

Proposed looking for cosmic-ray electrons from Sun, from DM annihilating into long-lived particles
– Schuster, NT, Yavin, Weiner

No significant difference in flux between real and fake suns

In this scenario, solar observation is $10^3$–$10^5$ x more sensitive than Xe100

![Graph showing energy vs. differential cross-section](image-url)
Summary

• Indirect detection:
  – Demise of light mediators has been greatly exaggerated
  – CMB (stats-limited) and Extragalactic γ-rays (theory-limited) are strongest constraints
  – Local substructure can be significant \(\Rightarrow\) true constraints fairly independent of mediator mass

• Direct detection:
  – Nobody agrees with anybody
  – CoGeNT and DAMA claim modulation
  – CRESST claims excess; CoGeNT small excess
  – If any of it is dark matter, not scattering through Standard Model mediators (Z, h)

• Dark Forces:
  – New visible & invisible search results from KLOE.
BACKUP MATERIAL
Steady-State of Pulsars?

1010.3477:

Claim excess is mostly consistent w/ steady-state injection of positrons by pulsars in the galaxy (and secondary $e^+$ from SN remnants), rather than local (DM or pulsar) sources.

Expect softer spectrum?
Tests of Dark Matter Interpretations

PAMELA and Fermi see $e^+$, $e^-$ from local sources

- **Anisotropy** a possible signal of pulsars (constrained)

  - no significant anisotropy detected

- **Gamma rays** expected from DM annihilating elsewhere

  - Galactic center
  - Dwarf galaxies
  - Distant galaxies
  - CMB

consistent relic density and self-interaction
Distribution of Substructure in the Galaxy