SEARCHING FOR DARK MATTER IN THE MEV SKY

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EVERYTHING WE KNOW ABOUT DARK MATTER

- CMB
- Galactic Rotation Curves
- Gravitational Lensing
- Baryonic Acoustic Oscillations
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\[ \sigma_X > R_{\text{UFD}} \]

\[ m_X > M_{\text{UFD}} \]

\[ 10^{-25} \text{ GeV} \quad \text{to} \quad 10^{62} \text{ GeV} \]
So, why look for dark matter in the MeV range?

Because we can.
Many studies have been sensitive to GeV-scale dark matter, but most observations run out of steam in the MeV range.

Fermi-LAT gamma-ray observations are sensitive to DM heavier than ~5 GeV.

A low energy mission could significantly improve this sensitivity.
Space-based cosmic-ray instruments are sensitive to signals from MeV dark matter.

However, the heliospheric potential is $\sim 1$ GV.

Significantly uncertain, prevents DM/background differentiation at low energies.
Direct detection studies are not currently sensitive to dark matter masses below the proton mass.

May be improved someday with alternative technologies.
Many studies have been sensitive to GeV-scale dark matter, but most observations run out of steam in the MeV range.

Colliders can potentially constrain very light dark matter, but their sensitivity is highly model dependent.

Beam dump experiments may soon significantly increase the sensitivity of collider experiments in the MeV range.
We need to transfer this picture of complementarity into the MeV regime.
So, why look for dark matter in the MeV range?

What is the landscape of MeV dark matter?
THE IMPETUS FOR MEV DARK MATTER - LESSONS FROM WIMPS

- CMB
- Galactic Rotation Curves
- Gravitational Lensing
- Baryonic Acoustic Oscillations

\[
\begin{align*}
10^{-25} \text{ GeV} & \quad \sigma_X > R_{\text{UFD}} \\
10^{-13} \text{ GeV} & \quad \text{QCD Axion} \\
10^2 \text{ GeV} & \quad \text{WIMP Miracle!} \\
10^{62} \text{ GeV} & \quad m_X > M_{\text{UFD}}
\end{align*}
\]

slide concept courtesy of Asher Berlin
A particle with a weak interaction cross-section and a mass on the weak scale is expected to naturally obtain the correct relic abundance through thermal freeze-out in the Earth universe.

\[
\left( \frac{\Omega_{\chi}}{0.2} \right) \sim \frac{x_{\text{f.o.}}}{20} \left( \frac{10^{-8} \text{ GeV}^{-2}}{\sigma} \right)
\]

\[
\langle \sigma v \rangle \sim 10^{-8} \text{ GeV}^{-2} \left( 3 \times 10^{-28} \text{ GeV}^2 \text{ cm}^2 \right) 10^{10} \frac{\text{cm}}{\text{s}} = 3 \times 10^{-26} \frac{\text{cm}^3}{\text{s}}
\]
At high-masses we have the unitarity bound:

- Electroweak coupling constant is proportional to $m_X^2$.
- Coupling constant must be 1, or loop contributions diverge.

$10^2 \text{ GeV}$

**WIMP Miracle!**

**Unitarity $\sim 124 \text{ TeV}$**

\[
\frac{\Omega_X}{0.2} \simeq \frac{x_{f.o.}}{20} \left( \frac{10^{-8} \text{ GeV}^{-2}}{\sigma} \right)
\]

\[
\sigma \sim \frac{g^4}{m_X^2},
\]

\[
g^2 \sim \frac{m_X}{10 \text{ TeV}}
\]
What about the lower-limit?

10^2 GeV

WIMP Miracle!

Unitarity ~124 TeV

slide concept courtesy of Asher Berlin
Lee-Weinberg bound:

\[ \Omega_X h^2 \sim 0.1 \cdot \frac{10^{-8}}{\text{GeV}^{-2}} \cdot \frac{1}{G_F^2 m_X^2} \sim 0.1 \left( \frac{10 \, \text{GeV}}{m_X} \right)^2 \]

Under the assumption that the interaction is electroweak ($G_F^2$), the dark matter mass must be larger than 10 GeV.

Two caveats:

- Dark matter may still be thermal, if the interaction that thermalizes DM is not electroweak.
- Electroweak models may still be reasonable, but only if a light scalar exists to boost the annihilation rate.
**N\textsubscript{eff} bounds:**

- If dark matter falls out of thermal equilibrium during or after neutrino decoupling, then dark matter contributes to the effective number of degrees of freedom.

- Bounds dark matter to be \( \gtrsim 3-10 \) MeV

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*Limits on MeV Dark Matter from the Effective Number of Neutrinos*

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Thermal dark matter that couples more strongly to electrons and photons than to neutrinos will heat the electron-photon plasma relative to the neutrino background if it becomes nonrelativistic after the neutrinos decouple from the thermal background. This results in a reduction in \( N_{\text{eff}} \) below the standard-model value, a result strongly disfavored by current CMB observations. Taking conservative lower bounds on \( N_{\text{eff}} \) and on the decoupling temperature of the neutrinos, we derive a bound on the dark matter particle mass of \( m_\chi > 3 - 9 \) MeV, depending on the spin and statistics of the particle. For \( p \)-wave annihilation, our limit on the dark matter particle mass is stronger than the limit derived from distortions to the CMB fluctuation spectrum produced by annihilations near the epoch of recombination.
What about the lower-limit?

- Thermal: 3-10 MeV
- Weak Force: 1 GeV
- WIMP: $10^2$ GeV
- Unitarity: ~124 TeV

slide concept courtesy of Asher Berlin
Thinking outside the standard thermal weakly interacting particle box:

- **Asymmetric Dark Matter** (e.g. Lin et al. 1111.0293)
- **Secluded Dark Matter** (e.g. Pospelov et al. 0711.4866)
- **MeV Sterile neutrinos** (Huang & Nelson, 1306.6079)
- **Strongly Interacting Massive Particles** (e.g. Hochberg et al. 1402.5143)
- **Hidden Dark Sectors** (e.g. Hufnagel et al. 1712.03972)
- **Late Decay to DM** (e.g. Choquette et al. 1604.01039)
- **Also: Mirror Dark Matter, Atomic Dark Matter, Magnetic Dark Matter, WIMPless dark matter, etc.**
Need to be careful - many of these models produce no dark matter annihilation signal.

Our dark matter models need to produce a little bit of light.
What can light dark matter annihilate into?

(i) $\gamma \gamma$: Accessible at all energies. The final state is $C$-even.
(ii) $\gamma \pi^0$: Accessible for $\sqrt{s} > m_{\pi^0}$. The final state is $C$-odd.
(iii) $\pi^0\pi^0$: Accessible for $\sqrt{s} \geq 2m_{\pi^0}$. The final state is $C$-even.
(iv) $\pi^+\pi^-$: Accessible for $\sqrt{s} \geq 2m_{\pi^\pm}$. The final state is $C$-even or $C$-odd.
(v) $\bar{\ell}\ell$ ($\ell = e, \mu, \nu$): Accessible for $\sqrt{s} \geq 2m_\ell$. The final state is either $C$-odd or is weak suppressed.

This significantly limits the possible annihilation channels, especially for masses below 135 MeV.
CMB Bounds:

- Any energy deposition during recombination affects the CMB anisotropy
- The constraint trends as $\langle \sigma v \rangle \sim 1/m$
- Small changes due to the fraction of total power which is transferred to electrons.
Moreover - the annihilation rate at low masses should exceed $3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$.

CMB bounds appear to remove most of the parameter space for thermal DM.

We can try to model build around this, for example invoking p-wave suppressed annihilations:

But these typically suppress gamma-ray emission today even more than the CMB!
CMB constraints fall between $1 \times 10^{-28}$ and $1 \times 10^{-27}$ in the 0.1-1 GeV range.

These constraints are likely to outperform future MeV gamma-ray experiments for annihilation to charged final states.
CMB constraints are typically even more sensitive than annihilation in the Galactic center.

There is allowable parameter space if the dark matter density near the galactic center is very peaked.
So the combination of

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- CMB constraints fall between $1 \times 10^{-28}$ and $1 \times 10^{-27}$ in the 0.1-1 GeV range.
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In the case of annihilation to neutral particles:

- The CMB constraints stay the same
- The gamma-ray sensitivity improves drastically.
- Gamma-Rays are the most sensitive channel!
In the Galactic center, nearly every density profile outperforms CMB constraints.

Can potentially observe the same dark matter signal in two ROIs!
- Dark Matter decay rate is not enhanced in the early universe.

- In general, the MeV scale of these models is not highly motivated (similar to GeV range).

- Analyzing these models will proceed similarly to GeV searches.

Boddy et al. (1606.07440)
Moreover, can decay at late times into annihilating component.

- Some well motivated models generate the dark matter asymmetrically, and then decay to the annihilating component.

- These models can naturally produce MeV emission.

Hardy et al. (1402.4500)
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In general - annihilation into uncharged states is better for gamma-ray observation.
If annihilation proceeds to charged particles, secondary emission becomes important.

This signal will diffuse, complicating analyses.

Must be taken into account.
PARTICLE PHYSICS CONCLUSIONS

1.) Standard Thermal Electroweak WIMP largely excluded from gamma-ray detection in the MeV range

- Can still be thermal if interaction is not electroweak

- Some exceptions, like p-wave suppressed interactions which may be observable in the Galactic center.

2.) Never fear!

- There are many models for producing MeV dark matter!

- Many models will have unique signatures:

  * Harder to use a one-size fits all approach

  * Easier to distinguish between models if you see something.
So, why look for dark matter in the MeV range?

New Techniques for looking at MeV dark matter!
EVERYTHING WE KNOW ABOUT DARK MATTER

Satellites:
Low background
and good source ID,
but low statistics

Galactic center:
Good statistics but source
confusion/diffuse background

Milky Way halo:
Large statistics but
diffuse background

Spectral lines:
No astrophysical
uncertainties, good
source ID, but low
statistics

Galaxy clusters:
Low background
but low statistics

Extragalactic:
Large statistics,
but astrophysics,
Galactic diffuse
background

slide courtesy of KIPAC
THE ANNIHILATION SPECTRA WILL UNIVERSALLY BE HARD

- Annihilation of 80 MeV DM -> e^+e^- produces gamma-rays primarily through final state radiation and bremsstrahlung.

- These spectra are brightest at the dark matter mass.

- Comparison of multiple targets becomes significantly easier at MeV energies - look for identical energy cuts!
WHAT ABOUT THE BACKGROUNDS?
Assuming Kolmogorov Diffusion in the MeV regime:

- A $\sim 10$ GeV proton which produces a 1 GeV gamma-ray travels approximately: $2.8$ kpc.
- A 100 MeV electron which produces a $\sim 1$-10 MeV gamma-ray travels approximately: $0.5$ kpc.

MeV diffuse emission will be more sensitive to local injection around 100 MeV.
In general models are not yet equipped for this detail.
WHAT ABOUT THE BACKGROUNDS?
WHAT ABOUT THE BACKGROUNDS?

The ISRF energy density is extremely smooth. Most of the substructure washes away, and you get very smooth background gamma-ray emission.

Porter et al. (1708.00816)
WHAT ABOUT THE BACKGROUNDS?

- Propagation in 10 Myr at 100 GeV:
  - Diffusion: \(~2.1\) kpc
  - Convection (20 km/s) - \(~100\) pc

- Propagation in 10 Myr at 10 MeV:
  - Diffusion: \(~466\) pc
  - Convection (20 km/s) - \(~200\) pc
DIFFICULTIES IN DIFFUSE BACKGROUND MODELING
OPPORTUNITIES IN DIFFUSE BACKGROUND MODELING!

- The MeV sky might shed significant new light on galactic cosmic-ray diffusion!

- We will soon have a diffuse sky from \(~1\) MeV to \(~100\) TeV (HAWC). Exciting potential for significant advancement.

- Cosmic-Ray Propagation Codes are rising to the challenge (e.g. PICARD; 1701.07285).
Direct gamma-rays from dark matter annihilation will have a profile that is relatively energy independent.

In the GeV range, excesses at 10 GeV are also likely to be excesses at 500 MeV

same production Mechanism

Multi-wavelength models may provide more systematic cross-checks in the MeV regime.
So, why look for dark matter in the MeV range?

Does the MeV lamppost connect to the GeV range?
COMPLEMENTARITY BETWEEN AMEGO AND FERMI

- Fermi-LAT Constraints on 100 GeV dark matter
  - 1-5 GeV most sensitive

- For 5-10 GeV dark matter?
  - Fermi already shows signs of lost sensitivity.
  - AMEGO can compete in this range of “standard” dark matter.
  - Interesting range due to asymmetries!
COMPLEMENTARITY BETWEEN AMEGO AND FERMI

- Should not forget the capability of MeV instrumentation to solve current uncertainties from Fermi-LAT observations.

- The separation of ~10-100 GeV DM from background (including $\pi^0$-decay and blazars) depends sensitively on the strength of ~100 MeV gamma-ray limits.
Another example is the observation of spatial extension in unassociated Fermi-LAT sources.

In this scenario, improved angular resolution at ~100 MeV is particularly important.

Because many of these sources are bright, instruments like AMEGO should have plenty of sensitivity.
synergy with radio telescopes, dependence on leptonic final states

Calore et al. (1409.0042)
COMPLEMENTARITY WITH TEV DARK MATTER

- Exciting dark matter is another natural model for MeV instruments to investigate.

- For many TeV -> PeV dark matter sectors, the momentum transfer in a dark matter scattering collision is in the keV to MeV range.
  - Gamma-Ray Morphology will track dark matter mass and rotation velocity.
  - MeV sensitivity is complementary for known excesses (e.g. PAMELA).
1.) Current dark matter limits in the MeV range are significantly lacking.

2.) Dark Matter model building is not as straightforward in the MeV range, compared to GeV energies.
   a.) More diversity in models -> more diversity in signals.
   b.) More diversity in models -> more diversity in techniques.

3.) MeV sensitivity is key to unlock the full power of Fermi in the GeV range.
The next decade is likely to include a significant push to MeV energies. Direct Detection will utilize electron recoils and superconductors.
The next decade is likely to include a significant push to MeV energies. Fixed-target experiments can make colliders significantly more sensitive to MeV-scale dark matter.
This vision is obtainable at MeV energies!