Direct-Detection of sub-GeV Dark Matter

Rouven Essig

Yang Institute for Theoretical Physics

An ongoing program

- “Direct Detection of sub-GeV Dark Matter”, 1108.5383, PRD
  RE, Mardon, Volansky
- “First Direct Detection Limits on sub-GeV Dark Matter from XENON10”, 1206.2644, PRL
  RE, Manalaysay, Mardon, Sorensen, Volansky
- “Direct Detection of sub-GeV Dark Matter with Semiconductor Targets”, 1509.01598, JHEP
  RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
- “Direct Detection of sub-GeV Dark Matter with Scintillating Targets”, submitted to PRL
  Derenzo, RE, Massari, Soto, Yu
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To appear:

- “Detection of Light Dark Matter and Solar Neutrinos via Chemical-Bond Breaking”,
  RE, Mardon, Oren Slone, Volansky
- “Large Dark Matter-Electron Scattering Rates In Current Direct Detection Experiments”,
  RE, Mardon, Volansky, Yu
- “Models probed by DM-electron recoil experiments”,
  RE, Tobioka, Volansky, Yu
- “Direct(ional) Detection of sub-GeV Dark Matter with Semiconductor Targets”,
  RE, Mardon, Adrian Soto, Volansky, Yu
Some related work

- An, Pospelov, Pradler, “Dark Matter Detectors as Dark Photon Helioscopes”, 1304.3461
- An, Pospelov, Pradler, Ritz, “Direct Detection Constraints on Dark Photon Dark Matter”, 1412.8378
- Dzuba, Flambaum, Pospelov, Roberts, Stadnik, “DM scattering on electrons: Accurate calculations…”, 1604.04559
Traditional Direct Detection strategy:
look for nuclear recoils from DM-nucleus scattering

targeting “WIMPs”: weakly-interacting massive particles w/ mass ~ 10-1000 GeV
Direct Detection Landscape

an active, important, and exciting program!
Beyond the WIMP Paradigm

- many other DM candidates exist
- no clear evidence for WIMPs (yet?)
- no new physics at the LHC (yet?)
- several challenges
  (“small-scale crisis of cold DM”)

Must search broadly for DM!

focus on mass ~ MeV — GeV

(an old idea, e.g. Boehm, Fayet, …)
Direct Detection below 1 GeV?

current best limit from CRESST II
Direct Detection below 1 GeV?

in future e.g. SuperCDMS: \(~300\) MeV
Difficult to probe much <100 MeV w/ Nuclear Recoils

inefficient energy transfer from DM to nucleus

\[ E_{NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v^2}{m_N} \simeq 1 \text{ eV} \times \left( \frac{m_\chi}{100 \text{ MeV}} \right)^2 \left( \frac{20 \text{ GeV}}{m_N} \right) \]
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<th>Exp</th>
<th>(E_{\text{th}}\ (\text{keV}_{\text{NR}}))</th>
<th>Ref</th>
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<tbody>
<tr>
<td>LUX</td>
<td>~3</td>
<td>1512.03506</td>
</tr>
<tr>
<td>DAMIC</td>
<td>~0.5</td>
<td>1510.00044</td>
</tr>
<tr>
<td>CDMSlite</td>
<td>~0.3</td>
<td>1509.02448</td>
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<td>CRESST-II</td>
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</table>
Can we go lower in DM mass?

and even lower??
Can we go lower in DM mass?

Yes!

and even lower??
DM-electron scattering

Signal depends on detector setup

e.g. one/a few $e^-$ or $\gamma$, phonons from drifting $e^-$…
Recoiling $e^{-}$ can access entire DM kinetic energy!

$$E_{DM} \sim \frac{1}{2} m_{DM} v_{DM}^2$$

(in principle)
DM-electron scattering can probe $\lesssim 1$ MeV
to overcome binding energy $\Delta E$

$E_{\text{DM}} \sim \frac{1}{2} m_{\text{DM}} v_{\text{DM}}^2 > \Delta E$

$v_{\text{DM}} \lesssim 800 \text{ km/s} \implies m_{\text{DM}} \gtrsim 300 \text{ keV} \left( \frac{\Delta E}{1 \text{ eV}} \right)$
Typical momentum & energy transfer

bound $e^-$ does not have definite momentum

Typical momentum transfer is set by $e^-$ not DM

\[ q_{\text{typ}} \sim \alpha m_e \sim 4 \text{ keV} \]  
(for outer shell electron)
Typical momentum & energy transfer

bound $e^-$ does not have definite momentum

Typical momentum transfer is set by $e^-$ not DM

$q_{\text{typ}} \sim \alpha m_e \sim 4 \text{ keV}$ (for outer shell electron)

transferred energy: $\Delta E_e \sim \vec{q} \cdot \vec{v}_{\text{DM}}$

$\Delta E \gtrsim 4 \text{ eV}$ requires $q$ on tail of $e^-$ wavefunction
Target materials?
### Target materials?

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**RE, Mardon, Volansky**

**RE, Manalaysay, Mardon, Sorensen, Volansky**

**RE, Mardon, Volansky, Yu (to appear)**
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<td>further R&amp;D</td>
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**Target materials?**

**Valence band**

**Conduction band**

**Band gap**

**RE, Mardon, Volansky**

**Graham, Kaplan, Rajendran, Walters**

**Lee, Lisanti, Mishra-Sharma, Safdi**

**RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu**
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Derenzo, RE, Massari, Soto, Yu
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Semiconductor & Scintillator bandgaps are near “typical” electron recoil energy — no wavefunction suppression
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*Target materials?*  

- superfluid helium
- 2D graphene
- … also possible targets

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Schutz, Zurek  
Hochberg, Kahn, Lisanti, Tully, Zurek
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XENON10 detector schematic

ran in 2006/2007, sensitive to single electrons!
Sub-GeV DM scattering off electrons
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an energetic outgoing $e^-$ can ionize other $e^-$'s
Sub-GeV DM scattering off electrons

an energetic outgoing $e^-$ can ionize other $e^-$'s
Sub-GeV DM scattering off electrons

An energetic outgoing e\(^-\) can ionize other e\(^-\)'s

One e\(^-\) produces \(\sim 27\) detected photons

("S2-signal")
Sub-GeV DM scattering off electrons

an energetic outgoing $e^-$ can ionize other $e^-$'s

one $e^-$ produces $\sim 27$ detected photons ("S2-signal")
The XENON10 data

from published “S2-only” analysis, \(1104.3088\) (15 kg-days)

90% c.l. upper bounds (counts/kg/day):

\begin{align*}
1 \text{ e}^- & : 34.5 \\
2 \text{ e}^- & : 4.5 \\
3 \text{ e}^- & : 0.83
\end{align*}

conservative limit: require DM signal < data
DD limits down to a few MeV

Excluded by XENON10 data

Hidden–Photon models

RE, Manalaysay, Mardon, Sorensen, Volansky, 2012
Comments on XENON10 results
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• Can you detect a DM event down to $m_{DM} \sim$ few MeV?
  • Yes
Comments on XENON10 results

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  • Yes

• More study needed to understand large number of observed single/few-$e^-$ events
  • Not a general “physics” background, but seems specific to dual-phase detectors (also present in XENON100, LUX), e.g.
    • $e^-$ gets trapped at liquid-gas interface & released later
    • $e^-$ gets trapped by impurities and released later
    • $e^-$ emission by cathode
Comments on XENON10 results

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    • e$^-$ gets trapped by impurities and released later
    • e$^-$ emission by cathode

• Could some events be DM?
  • Yes (more later)
Recent XENON100 S2-only data sets new limits!

RE, Mardon, Volansky, Yu (to appear)

from 1605.06262

spectrum for \( \geq 4 \) electrons
Recent XENON100 S2-only data sets new limits!

RE, Mardon, Volansky, Yu (to appear)

- Preliminary

![Graph showing recent XENON100 S2-only data sets new limits.](image)
XENON10+100 & beyond

clever cuts could significantly reduce backgrounds
XENON 10+100 & beyond

clever cuts could significantly reduce backgrounds

large exposures of LUX, XENON1t, LZ could compensate for uncertain backgrounds (e.g. look for annual modulation)
XENON10+100 & beyond

clever cuts could significantly reduce backgrounds

large exposures of LUX, XENON1t, LZ could compensate for uncertain backgrounds (e.g. look for annual modulation)

BUT: need a different detector to probe smaller DM masses & have reduced backgrounds
XENON10+100 & beyond

Clever cuts could significantly reduce backgrounds

Large exposures of LUX, XENON1t, LZ could compensate for uncertain backgrounds (e.g. look for annual modulation)

But: need a different detector to probe smaller DM masses & have reduced backgrounds

Focus here on semiconductors & scintillators, since technologies should be available over next few years
Semiconductors & Scintillators (schematic)

- Empty conduction band
- Band gap
- Filled valence band
Semiconductors & Scintillators (schematic)

<table>
<thead>
<tr>
<th>Material</th>
<th>Band Gap [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>0.67</td>
</tr>
<tr>
<td>Si</td>
<td>1.1</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.5</td>
</tr>
<tr>
<td>NaI</td>
<td>5.9</td>
</tr>
<tr>
<td>CsI</td>
<td>6.4</td>
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</table>

The diagram shows the energy bands of different materials, with the band gap indicated.
Semiconductors & Scintillators (schematic)
recoiling $e^-$ can create additional $e^-/h^+$ pairs

e.g. one pair for each 2.9 eV (3.6 eV) in Ge (Si)
Semiconductors & Scintillators (schematic)

Semiconductor:
- Apply electric field to measure electrons (ionization).

Scintillator:
- E.g. $e^-/h^+$ can recombine to produce photons (no E-field needed).
Possible advantages & challenges for scintillators

Derenzo, RE, Massari, Soto, Yu
(submitted to PRL)

• Single photons easier to detect than single electrons? (photodetectors under development by e.g. M. Pyle et.al.)

• No electric field, so no dark counts?

• A possible challenge: “afterglow”?

more R&D needed
Current best limit from a semiconductor (DAMIC, Si)

RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu

currently limited by readout noise (not backgrounds) to \( \sim 11 \) electrons
Rates increase dramatically for lower thresholds.

\[ m_\chi = 10 \text{ MeV} \]

\[ m_\chi = 1 \text{ GeV} \]

\( E_e [\text{eV}] \)

\[ \sigma_0 = 10^{-37} \text{ cm}^2 \]

\( F_{\text{DM}}(q) = 1 \)
Rates increase dramatically for lower thresholds

Current thresholds, e.g.

**CDMSlite:** $\sim 56$ eV

(1509.02448)

**DAMIC:** $\sim 40$ eV

(1105.5191)

active R&D could reduce threshold to 1 or 2 e$^-$
Prospects?

95% c.l. for zero background (i.e. 3.6 DM events)

\[ \sigma_e \text{[cm}^2] \]

\[ m_\chi \text{[MeV]} \]

RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
Derenzo, RE, Massari, Soto, Yu
Backgrounds?

- “traditional” backgrounds (radioactivity etc.) < few/kg/year/eV (likely not important)
- understanding & controlling detector & unknown backgrounds is much more important
Handles to distinguish signal from backgrounds

1. distinctive shape of recoil spectrum

\[ \sigma_e = 10^{-37} \text{ cm}^2 \]
\[ F_{DM}(q) = 1 \]

\[ m_\chi = 10 \text{ MeV} \]
\[ m_\chi = 1 \text{ GeV} \]
Handles to distinguish signal from backgrounds

2. large annual modulation

$E_e [\text{eV}]$

$F_{\text{DM}=1}$

$F_{\text{DM}\propto 1/q^2}$

$Q$

$f_{\text{mod}}$

$S_i$

$m_\chi = 1 \text{ GeV}$

$m_\chi = 10 \text{ MeV}$
Handles to distinguish signal from backgrounds

3. directional dependence of DM wrt crystal axes

RE, Mardon, Soto, Volansky, Yu (in progress)

DM “wind”
Handles to distinguish signal from backgrounds

3. directional dependence of DM wrt crystal axes

DM “wind”

RE, Mardon, Soto, Volansky, Yu (in progress)

http://butane.chem.uiuc.edu/pshapley/GenChem2/C4/1.html
Handles to distinguish signal from backgrounds

3. directional dependence of DM wrt crystal axes

RE, Mardon, Soto, Volansky, Yu (in progress)

preliminary: Si/Ge very symmetric (<1% variation);
other crystal targets (e.g. GaAs) under investigation
Handles to distinguish signal from backgrounds

4. Ptolemy setup w/ 2D graphene sheets
   (challenging to get large mass)    Hochberg, Kahn, Lisanti, Tully, Zurek

5. gravitational focusing can give energy-dependent modulation phase
   Lee, Lisanti, Mishra-Sharma, Safdi

6. other ideas?                     maybe you?
Models?

DM-\(e^-\) scattering can probe lots of models!
Models?

DM-e⁻ scattering can probe lots of models!

• DM w/ a light A′ (≈m_{DM})
• DM w/ an ultralight A′ (≪ keV)
• A′/scalar/pseudoscalar DM (≪ MeV)
• Electric or magnetic dipole moment
• SIMP, ELDER
• inelastic DM
• A′/scalar/pseudoscalar from Sun (<10 keV)
• …
DM w/ dark photon ($A'$) mediator

![Diagram](image)
DM w/ dark photon ($A'$) mediator

- light $A'$ ($\sim m_{DM}$)
- ultra-light $A'$ ($\ll$ keV)

\[ F_{DM} = 1 \]
\[ F_{DM} \propto 1/q^2 \]

simple & predictive
DM w/ dark photon (A′) mediator

- light A′ ($\sim m_{DM}$) \[ F_{DM} = 1 \]
- ultra-light A′ ($\ll$ keV) \[ F_{DM} \propto 1/q^2 \]

simple & predictive

see e.g. Arkani-Hamed et.al.; Weiner et.al.; Pospelov & Ritz; RE, Kaplan, Schuster, Toro; RE, Mardon, Volansky; Lin, Yu, Zurek; Chu, Hambye, Tytgat; Hall, Jedamzik, March-Russell, West; Boehm, Fayet; Borodatchenkova, Choudhury, Drees; Pospelov, Ritz, Voloshin; Batell, Pospelov, Ritz; Izaguirre, Krnjaic, Schuster, Toro; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu; …
Direct Detection for $m_{A'} \sim m_{\text{DM}}$

\[ \bar{\sigma}_e \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} \mu_{\chi e}^2 \quad \text{with} \quad F_{\text{DM}} = 1 \]
Thermal freeze-out

\[ m_{A'} > 2m_\chi \]

(very predictive)

see e.g. Boehm & Fayet (2003); Borodatchenkov, Choudhury, Drees (2005); Izaguirre, Krnjaic, Schuster, Toro (2015); RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu (2015)
Thermal freeze-out

\[ m_{A'} > 2m_\chi \]

(very predictive)

\[ \sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_\chi^2 v^2 \]

scalar \( \chi \):

\[ \sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_\chi^2 \]

Dirac fermion \( \chi \):

similar combination of parameters as direct detection!

see e.g. Boehm & Fayet (2003); Borodatchenkova, Choudhury, Drees (2005); Izaguirre, Krnjaic, Schuster, Toro (2015); RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu (2015)
Thermal freeze-out

![Diagram](image)

$m_{A'} > 2m_\chi$

(very predictive)

**Scalar $\chi$:**

$$\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_{\chi}^2 v^2$$

**Dirac fermion $\chi$:**

$$\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_{\chi}^2$$

similar combination of parameters as direct detection!

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see e.g. Boehm & Fayet (2003); Borodatchenko, Choudhury, Drees (2005); Izaguirre, Krnjaic, Schuster, Toro (2015); RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu (2015)
Constraints from CMB

Planck TT,TE,EE+lowP
WMAP9
CVL
Possible interpretations for:
AMS-02/Fermi/Pamela
Fermi GC

standard s-wave freeze-out disfavored <10 GeV
but p-wave or asymmetric is ok

Planck
see also e.g. Galli et.al.; Slatyer, Padmanabhan, Finkbeiner;
Madhavacheril, Sehgal, Slatyer

for γ-ray constraints see e.g. RE, Kuflik,
McDermott, Volansky, Zurek; 1309.4091
Thermal freeze-out

**Scalar \( \chi \):**

\[
\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_{\chi}^2 v^2
\]

**Dirac fermion \( \chi \):**

\[
\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_{\chi}^2
\]

- \( m_{A'} > 2m_{\chi} \)
- **p-wave unconstrained by CMB**
- **s-wave \( \Rightarrow \) asymmetric**

CMB sets **lower bound on \( \sigma v \)**

*E.g.* Kaplan, Luty, Zurek; Lin, Yu, Zurek
Thermal freeze-out

Scalar $\chi$: $\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_{\chi}^2 v^2$

Dirac fermion $\chi$: $\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_{\chi}^2$

provides nice targets for direct detection experiments!

$m_{A'} > 2m_{\chi}$

p-wave unconstrained by CMB

s-wave $\implies$ asymmetric

CMB sets lower bound on $\sigma v$

E.g. Kaplan, Luty, Zurek; Lin, Yu, Zurek
Direct Detection, complex scalar, \( m_A > 2m_{DM} \)

![Graph showing the cross-section vs mass plot for dark matter detection]

- \( \sigma_e [cm^2] \)
- \( m_\chi [MeV] \)
- Preliminary！”

RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
Direct Detection, Dirac fermion, $m_{A'}/2m_{DM}$

RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
Direct Detection, Dirac fermion, $m_{A'} > 2m_{DM}$

probably no time to discuss constraints…
Semiconductor prospects

95% c.l., assuming zero background (i.e. 3.6 events)
XENON100 events could be mostly DM…

RE, Mardon, Volansky, Yu (to appear)
LUX prospects

Event Rates LUX detector (145 kg, 2015)

1 event/minute!

1 event/hour!

RE, Mardon, Volansky, Yu (to appear)
LZ prospects

Event Rates LZ detector (6350 kg)

Message to XENON100/1t/ LUX/LZ: analyzing observed S2-only events is time well-spent! (+ annual modulation)
Other constraints?
(probably skip due to lack of time)
Self-interactions

\[ \sigma \propto \frac{\alpha_D^2}{m_{A'}^4} m_{\chi}^2 \]

sets upper bound on \( \alpha_D \)

constraint from bullet cluster etc.
e^+e^- colliders

\[ \sigma \propto \frac{\epsilon^2}{E_{CM}^2} \]

Constrained from 30/fb @BaBar

Interesting prospects @Belle-2

(need mono-photon trigger)
Proton-beam dumps

\[ \pi^0 \rightarrow \gamma A' \rightarrow XX \]

Target

Decay pipe

Shield

Detector

\[ N_{\text{obs}} \propto \epsilon^4 \alpha_D \frac{m^2_{A'}}{m^2_{A'}} \]

constrained by LSND

MiniBooNE search underway

plenty of room for future exploration, see SLAC Dark Forces workshop, 2016
Electron-beam dumps: e.g. SLAC’s E137

Electron Beam → Target → Dirt → Detector

Production: e⁻ → A' → τ̄ → e⁻

Scattering: χ → e⁻ → e⁻

~400 m

plenty of room for future exploration, see SLAC Dark Forces workshop, 2016

see Izaguirre, Krnjaic, Schuster, Toro; Diamond, Schuster; Battaglieri et.al.
End of constraints
DM w/ dark photon ($A'$) mediator

- light $A'$ ($\sim m_{DM}$)
  \[ F_{DM} = 1 \]
- ultra-light $A'$ ($\ll$ keV)
  \[ F_{DM} \propto 1/q^2 \]

simple & predictive

see e.g. RE, Mardon, Volansky; Chu, Hambye, Tytgat; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu;
Direct Detection w/ ultralight $A' (\ll \text{keV})$

$\sigma \propto \frac{16\pi\mu_{\chi e}^2\alpha\alpha_D\epsilon^2}{q^4} = \frac{16\pi\mu_{\chi e}^2\alpha\alpha_D\epsilon^2}{(\alpha^2m_e^2)^2} \times \left(\frac{\alpha^2m_e^2}{q^2}\right)^2$

assume $m_{A'} \ll \alpha m_e \sim \text{keV}$ enhanced at low $q^2$!
Direct Detection w/ ultralight $A'$ ($\ll$ keV)

\[
\sigma \propto \frac{16\pi \mu_{\chi e}^2 \alpha \alpha_D \epsilon^2}{q^4}
\]

\[
= \frac{16\pi \mu_{\chi e}^2 \alpha \alpha_D \epsilon^2}{(\alpha^2 m_e^2)^2} \times \left(\frac{\alpha^2 m_e^2}{q^2}\right)^2
\]

\[
\equiv \bar{\sigma}_e \times (F_{\text{DM}}(q))^2
\]

assume

\[m_{A'} \ll \alpha m_e \sim \text{keV}\]

enhanced at low $q^2$!
“Freeze-in”

can generate correct DM relic density by “freeze-in”

Hall et.al. (0911.1120)

build up DM abundance as Universe cools
“Freeze-in” can generate correct DM relic density by “freeze-in”

e.g. $m_X = 100$ MeV, correct relic abundance for $\alpha_D \epsilon^2 \approx 3 \times 10^{-24}$

Re, Mardon, Volansky
Chu, Hambye, Tytgat
Direct Detection w/ ultralight $A'$ ($\ll$keV)

Freeze–in, DM with Ultralight Dark Photon

DD powerful due to $\sim 1/q^4$ enhancement

note bounds on millicharged particles; accelerator-based searches very weak
Summary

- DD of DM to $\lesssim$1 MeV is possible w/ e$^-$ recoils
- noble-liquid experiments have demonstrated sensitivity & large exposures (significant improvements possible if backgrounds can be controlled or understood)
- semiconductors & scintillators (& other ideas) have great potential, but further R&D needed
- many opportunities for significant progress in next few years!