Effective field theory and cosmology of sub-MeV leptophilic dark matter
1. Motivation

2. Framework

3. Deriving Constraints

4. Results

5. Conclusions
1. Motivation

2. Framework

3. Deriving constraints

4. Results

5. Conclusions
Effective theory and cosmology of sub-MeV leptophilic dark matter
Benjamin V. Lehmann

I. Motivation

Cooley 2014
Effective theory and cosmology of sub-MeV leptophilic dark matter
Benjamin V. Lehmann

Direct detection limits

Essig+ 2012
More soon!

Scattering cross section

<table>
<thead>
<tr>
<th>DM mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 GeV</td>
</tr>
</tbody>
</table>

Electron recoil?
Effective theory and cosmology of sub-MeV leptophilic dark matter

Benjamin V. Lehmann

Scattering cross section

\[ m_{\text{DM}} \ll m_{\text{target}} \]

\[ E_{\text{recoil}} \sim \left( \frac{m_{\text{DM}}}{m_{\text{target}}} \right) m_{\text{DM}} \]

Essig+ 2012
More soon!

I. Motivation 2/13
Effective theory and cosmology of sub-MeV leptophilic dark matter

Benjamin V. Lehmann

Scattering cross section

\[ m_{\text{DM}} \ll m_{\text{target}} \]

\[ E_{\text{recoil}} \sim \left( \frac{m_{\text{DM}}}{m_{\text{target}}} \right) m_{\text{DM}} \]

\[ m_{\text{DM}} \ll m_{\text{target}} \]

Essig+ 2012

More soon!

DM mass

0.1 GeV

100 GeV

Electron recoil?
Effective theory and cosmology of sub-MeV leptophilic dark matter
Benjamin V. Lehmann

\[
\begin{align*}
E_{\text{recoil}} & \sim \left( \frac{m_{\text{DM}}}{m_{\text{target}}} \right) m_{\text{DM}} \\
m_{\text{DM}} & \ll m_{\text{target}}
\end{align*}
\]

Electron recoil?

Essig+ 2012
More soon!

Direct detection limits

Scattering cross section

0.1 GeV
DM mass
100 GeV
Light DM parameter space

$10 \text{ keV}$  $1 \text{ MeV}$  $1 \text{ GeV}$

$m_{\text{DM}}$

Electron recoil

Hochberg+ 2016
Light DM parameter space

\[ m_{\text{DM}} \]

- Nuclear recoil
- Electron recoil

Hochberg+ 2016
Light DM parameter space

- **Warm DM**
- **Nuclear recoil**

- Electron recoil
  - Hochberg+ 2016
Light DM parameter space

- **Warm DM**
- **Nuclear recoil**

*M_\text{DM}*

\[ 10 \text{ keV} \quad 1 \text{ MeV} \quad 1 \text{ GeV} \]

- Many models

Electron recoil

Hochberg+ 2016

I. Motivation
Light DM parameter space

- Warm DM
- 10 keV
- 1 MeV
- 1 GeV
- Nuclear recoil
- Many models
- Electron recoil
- Hochberg+ 2016

$m_{DM}$
Light DM parameter space

- Warm DM
- Many models
- Nuclear recoil
- Cosmology?

$m_{DM}$

10 keV  1 MeV  1 GeV

Electron recoil
Hochberg+ 2016

What could electron recoil experiments see?
Sub-MeV DM

- For “vanilla” DM, **beating cosmology is hard**
Sub-MeV DM

- For “vanilla” DM, **beating cosmology is hard**
- Demonstrated by simplified models, e.g. Knapen+ 2017:
Sub-MeV DM

- For “vanilla” DM, **beating cosmology is hard**
- Demonstrated by simplified models, e.g. Knapen+ 2017:
Sub-MeV DM

- For “vanilla” DM, **beating cosmology is hard**
- Demonstrated by simplified models, e.g. Knapen+ 2017:

![Graph showing the relationship between $m_\phi = 10^{-3} \mu_{\chi e}$ and $\sigma_e [\text{cm}^2]$ for different $m_\chi [\text{MeV}]$ values.]

- For heavy mediator case, **use EFT for general bounds**
1. Motivation

2. Framework

3. Deriving constraints

4. Results

5. Conclusions
Effective theory and cosmology of sub-MeV leptophilic dark matter
Benjamin V. Lehmann

Overview

Mediators

Renormalizable, electroweak gauge-invariant coupling

SM

No renormalizable coupling

DM

Renormalizable coupling
Effective theory and cosmology of sub-MeV leptophilic dark matter

Benjamin V. Lehmann

Overview

Dark sector

Weak scale

Mediators

BBN

χ (dark matter)

Standard model

Weak scale

EFT cutoff

Cosmology

EFT is valid for both cosmology and direct detection

II. Framework
Overview

Effective theory and cosmology of sub-MeV leptophilic dark matter
Benjamin V. Lehmann

Overview

Dark sector

Standard model

Weak scale

EFT cutoff \sim Mediators

Cosmology \sim BBN

\chi (dark matter)

\begin{align*}
\zeta_1 & \quad \zeta_2 & \quad \zeta_3 \\
\text{EFT cutoff} & \sim & \text{Mediators} \\
\text{Cosmology} & \sim & \text{BBN}
\end{align*}
Overview

Effective theory and cosmology of sub-GeV leptophilic dark matter
Benjamin V. Lehmann

Overview

Dark sector

Standard model

Weak scale

EFT cutoff \sim Mediators

\begin{align*}
\zeta_1 \\
\zeta_2 \\
\zeta_3
\end{align*}

Cosmology \sim BBN

EFT is valid for both cosmology and direct detection

\chi (dark matter)
Effective field theory approach

\[ \Phi \sim \Lambda \]

UV-complete model
\((\sqrt{s} \gtrsim \Lambda)\)

Effective theory
\((\sqrt{s} \ll \Lambda)\)
Effective field theory approach

\[ \Phi \sim \Lambda \]

UV-complete model
\((\sqrt{s} \gtrsim \Lambda)\)

Enumerate effective operators to dimension 6
\[
\left\{ \frac{g}{\Lambda^2} \bar{\chi} \chi \bar{e} e, \quad \frac{g}{\Lambda^2} \bar{\chi} \gamma_\mu \chi \bar{e} \gamma^\mu e, \quad \ldots \right\}
\]

Effective theory
\((\sqrt{s} \ll \Lambda)\)

Calculate direct detection rates and cosmological limits
1. Motivation

2. Framework

3. Deriving constraints

4. Results

5. Conclusions
Observables

1. BBN
2. $N_{\text{eff}}$ (CMB)
3. DM overproduction

\{ Fixed by DM decoupling temperature \}
Observables

1. BBN
2. $N_{\text{eff}}$ (CMB)
3. DM overproduction

\[ \Gamma(\chi \chi \rightarrow e^+ e^-) \bigg|_{T_D} \approx H \bigg|_{T_D} \]

Fixed by DM decoupling temperature

$y_x$ vs $m_x/T_D$
Observables

1. BBN
2. $N_{\text{eff}}$ (CMB)
3. DM overproduction

Fixed by DM decoupling temperature

$\Gamma(\chi \chi \rightarrow e^+ e^-) |_{T_D} \simeq H |_{T_D}$
BBN constraints

- $H(T)$ well-known during and after BBN
BBN constraints

- $H(T)$ well-known during and after BBN
- Additional species in equilibrium modify energy density
BBN constraints

- $H(T)$ well-known during and after BBN
- Additional species in equilibrium modify energy density
- Observable modifications to light element abundances

requires $T_D \gtrsim 1$ MeV (except real scalar) (Pospelov & Pradler 2010)
BBN constraints

- $H(T)$ well-known during and after BBN
- Additional species in equilibrium modify energy density
- Observable modifications to light element abundances

Requires $T_D \gtrsim 1\text{ MeV}$ (except real scalar)

(Pospelov & Pradler 2010)
CMB constraints ($N_{\text{eff}}$)

$N_{\text{eff}}$ measures $T_\nu / T_\gamma$, but which sector does DM heat?
CMB constraints \((N_{\text{eff}})\)

\(N_{\text{eff}}\) measures \(T_\nu / T_\gamma\), but which sector does DM heat?

Ordering of decouplings is important
CMB constraints ($N_{\text{eff}}$)

$N_{\text{eff}}$ measures $T_{\nu}/T_\gamma$, but which sector does DM heat?

- Derive DM–$\nu_e$ decoupling $T$ from EW gauge invariance

Ordering of decouplings is important
CMB constraints ($N_{\text{eff}}$)

$N_{\text{eff}}$ measures $T_\nu / T_\gamma$, but which sector does DM heat?

- Derive DM–$\nu_e$ decoupling $T$ from EW gauge invariance
- Calculate entropy contributed to each sector

Ordering of decouplings is important
Overproduction constraints

What sets the relic abundance?
Overproduction constraints

What sets the relic abundance?

DM in equilibrium at $T_{BBN}$?
Overproduction constraints

What sets the relic abundance?

DM in equilibrium at $T_{BBN}$?

Yes

Constrained by BBN

Freeze-out
Overproduction constraints

What sets the relic abundance?

DM in equilibrium at $T_{\text{BBN}}$?

- Yes
  - Constrained by BBN
  - Freeze-out

- No
  - Unconstrained by BBN
  - Out-of-equilibrium reactions
Overproduction constraints

What sets the relic abundance?

- DM in equilibrium at $T_{\text{BBN}}$?
  - Yes
    - Constrained by BBN
      - Freeze-out
  - No
    - Unconstrained by BBN
      - Out-of-equilibrium reactions

Overproduction starting with $Y_{\text{DM}}(\infty) \sim (\text{coupling})^2$ bounds coupling above
Overproduction constraints

What sets the relic abundance?

DM in equilibrium at $T_{BBN}$?

- Yes: Constrained by BBN
  - Freeze-out
- No: Unconstrained by BBN
  - Out-of-equilibrium reactions

- Minimum relic abundance for $Y_{DM}(T_{BBN}) = 0$
Overproduction constraints

What sets the relic abundance?

DM in equilibrium at $T_{\text{BBN}}$?

- Yes
  - Constrained by BBN
  - Freeze-out
- No
  - Unconstrained by BBN
  - Out-of-equilibrium reactions

- Minimum relic abundance for $Y_{\text{DM}}(T_{\text{BBN}}) = 0$
- $Y(\infty) \sim (\text{coupling})^2$
Overproduction constraints

What sets the relic abundance?

DM in equilibrium at $T_{BBN}$?

- Yes
  - Constrained by BBN
  - Freeze-out

- No
  - Unconstrained by BBN
  - Out-of-equilibrium reactions

- Minimum relic abundance for $Y_{DM}(T_{BBN}) = 0$
- $Y(\infty) \sim (\text{coupling})^2$

Overproduction starting with $Y_{DM} = 0$ bounds coupling above
1. Motivation

2. Framework

3. Deriving constraints

4. Results

5. Conclusions
Effective theory and cosmology of sub-MeV leptophilic dark matter

Benjamin V. Lehmann

\[ \mathcal{L} \supset \frac{1}{\Lambda^2} \bar{\chi} \chi \bar{e}_L e_L \]

\[ \log_{10} \text{Scattering cross section} \ [\text{cm}^2] \]

-60
-56
-52
-48
-44
-40

\[ \Lambda \ [\text{MeV}] \]

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

Light element ratios disturbed

DM overproduced

\[ \Delta N_{\text{eff}} \]

Superconductor reach (1 kg yr, 95% CL)

D’Eramo, BVL, Profumo in prep.

IV. Results
Effective theory and cosmology of sub-MeV leptophilic dark matter

Benjamin V. Lehmann

Light element ratios disturbed

DM overproduced

$\log_{10} \left( \text{Scattering cross section} \ [\text{cm}^2] \right)$

Superconductor reach (1 kg yr, 95% CL)

Cosmology is very restrictive!

$\Delta N_{\text{eff}}$

$\mathcal{L} \supset \frac{1}{\Lambda^2} \bar{\chi} \chi \bar{e}_L e_L$

EFT suppression scale

$\Lambda$ [MeV]

$m_\chi$ [MeV]

$10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$

$10^{-2}$ $10^{-1}$ $10^0$

D’Eramo, BVL, Profumo in prep.

IV. Results
1. Motivation

2. Framework

3. Deriving constraints

4. Results

5. Conclusions
Conclusions
Conclusions

- Robust cosmological constraints dominate experimental parameter space within EFT assumptions
Conclusions

- Robust cosmological constraints dominate experimental parameter space within EFT assumptions.

- Sub-MeV DM $\leftrightarrow$ heavy mediator $\leftrightarrow$ $e^\pm$ is not a viable experimental target in our framework (real scalar may survive).
Conclusions

- Robust cosmological constraints dominate experimental parameter space within EFT assumptions

- Sub-MeV DM $\leftrightarrow$ heavy mediator $\leftrightarrow$ $e^\pm$ is not a viable experimental target in our framework (real scalar may survive)

- Electron recoil experiments may probe light mediators or more complex dark sectors