Cosmological Constraints on Light (but Massive) Relics

UW Institute for Nuclear Theory 2022

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[2006.09395, 2006.09380 & 2107.09664]
Light but Massive Relics

Particles that were in thermal contact with SM at early universe, were relativistic at decoupling, but behaves like matter today.
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Two categories:

- Neutrinos
- Not Neutrinos
Light but Massive Relics

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- **Neutrinos**
  - Last piece of the SM
  - Massive, but unresolved

- **Not Neutrinos**

New particles! Ubiquitous in SM Extensions
Light but Massive Relics

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Particles that were in thermal contact with SM at early universe, were relativistic at decoupling, but behaves like matter today.

Two categories:

- Neutrinos
  - Last piece of the SM
  - Massive, but unresolved
- Not Neutrinos (LiMRs)
  - New particles!
  - Ubiquitous in SM Extensions
Light but Massive Relics (LiMRs)

- Mass $m_X$
- (present-day) Temperature $T_X^{(0)}$
- Thermalized dofs $g_X$
LiMRs: but why?

- They could exist
LiMRs : but why?

- They could exist
- We could find them
LiMRs: the Light part

\[ g_{*S}^{(dec)} \propto (T_X^0)^{-3} \]

[Deporzio, WLX, Münoz, Dvorkin 2006.09380]
LiMRs: the Light part

\[ g^{(\text{dec})}_{*S} \propto (T^0_X)^{-3} \]

Minimal extensions \( \implies T^0_X \geq 0.91 \, \text{K}. \)

[Deporzo, WLX, Múnoz, Dvorkin 2006.09380]
LiMRs: the Light part

$$\Delta N_{\text{eff}} \propto g_X (T_X^0)^4$$

[Deporzio, WLX, Múnoz, Dvorkin 2006.09380]
LiMRs: the Light part

$$\Delta N_{\text{eff}} \propto g_X (T_X^0)^4$$

Planck $\Delta N_{\text{eff}} \leq 0.36 \implies T^0_{\text{Weyl}} \leq 1.5$ K
CMB-S4 $\Delta N_{\text{eff}} \leq 0.06 \implies T^0_{\text{Weyl}} \leq 0.96$ K

[95% CL]

[Deporzio, WLX, Múnoz, Dvorkin 2006.09380]
LiMRs : the Massive part

Stuff that clusters ↔ Stuff that expands

Neutrinos & LiMRs
LiMRs: the Massive part

Galaxies are biased tracers

\[ P_g \propto b P_m(k, z) \]

\[ \delta_m = \delta_{cb} + \delta_\nu + \delta_X \]
Galaxies are biased tracers of clustering matter

\[ P_g \propto b \frac{P_m}{P_{cb}(k, z)} \]

\[ \delta_m = \delta_{cb} + \delta_\nu + \delta_X \]
LiMRs : the Massive part

\[ \omega_X \propto g_X m_X (T_X^{(0)})^3 \]
LiMRs : the Massive part

$$\omega_X \propto g_X m_X (T_X^{(0)})^3$$

$$k_{fs,X} \propto \frac{m_X / T_X^{(0)}}{\sqrt{1 + z}}$$
LiMRs: the Massive part

$$\omega_X \propto g_X m_X (T_{X}^{(0)})^3$$

$$k_{fs,X} \propto \frac{m_X/T_{X}^{(0)}}{\sqrt{1 + z}}$$

[WLX, Műnoz, Dvorkin 2107.09664]
LiMRs : the Massive part

\[ \delta_g \equiv b_1 \delta_{cb} + b_2 \delta_{cb}^2 + b_3 G_2 \]

\[ \delta_{cb} = (1 - f_\nu - f_X) \delta_m \]
LiMRs: one caveat

\[ N_{\text{eff}} \propto g_X(T_X^0)^4 \quad k_{f_{s,X}} \propto m_X/T_X^{(0)} \quad \omega_X \propto g_X m_X (T_X^{(0)})^3 \]
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\[ N_{\text{eff}} \propto g_X (T_X^0)^4 \quad k_{f s, X} \propto m_X / T_X^{(0)} \quad \omega_X \propto g_X m_X (T_X^{(0)})^3 \]

\[ \omega_X \propto N_{\text{eff}} k_{f s, X} \]

\[ \implies 1 \text{ axis of degeneracy within } \{ g_X, m_X, T_X^{(0)} \} \]
LiMRs: one caveat

\[ N_{\text{eff}} \propto g_X (T^0_X)^4 \quad k_{f s, X} \propto m_X / T^0_X \quad \omega_X \propto g_X m_X (T^0_X)^3 \]

\[ \implies 1 \text{ axis of degeneracy within} \{ g_X, m_X, T^0_X \} \]

Cast to equivalent “neutrinos” \( \{ m_X, T^0_X, g_X \} \rightarrow \{ m_{eq}, T_{eq}^0, 2 \} \)

\[ m_{eq} = m_X \left( \frac{g_X}{2} \right)^{1/4} c_1^{\gamma/4} c_2^\gamma \quad T_{eq}^0 = T^0_X \left( \frac{g_X}{2} \right)^{1/4} c_1^{\gamma/4} \]

\[ c_1 = \frac{8}{7}, \quad c_2 = \frac{7}{6}, \quad \gamma = \begin{cases} 0 & \text{fermion} \\ 1 & \text{boson} \end{cases} \]
Data/Experiments

- Markov Chain Monte Carlo
  \[ \{ \omega_b, \omega_{cdm}, h, n_s, A_s, \tau, \sum m_\nu \} + \{ m_X, T_X^{(0)} \} \]

- \{ Scalar, Weyl, Vector, Dirac \}

- Planck 2018 TT+TE+EE +Lensing
- CFHTLens
- BOSS DR 12 (CLASS-PT)

[Chudaykin, Ivanov, Philcox, Simonović, 2004.10607]
Results

So, have we found anything?
Results

So, have we found anything?
No(t yet), but...

![Graph showing $T_{X}^{(0)}$ at fixed $m_X$ (95% CL)]

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Cosmological Constraints on Light (but Massive) Relics 2107.09664

[WLX, Múnoz, Dvorkin 2107.09664]
### Results: what we know now

\[ T_X = 0.91 \, \text{K} \]

<table>
<thead>
<tr>
<th>( m_X ) (95% CL)</th>
<th>Scalar</th>
<th>11.2 eV</th>
<th>Weyl</th>
<th>2.26 eV</th>
<th>Vector</th>
<th>1.58 eV</th>
<th>Dirac</th>
<th>1.06 eV</th>
</tr>
</thead>
</table>

[WLX, Múnoz, Dvorkin 2107.09664]
Or equivalently...

<table>
<thead>
<tr>
<th>$m_X$ (95% CL)</th>
<th>Scalar</th>
<th>Weyl</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.91 K</td>
<td>11.2 eV</td>
<td>0.79 K</td>
</tr>
<tr>
<td>1.04 K</td>
<td>2.65 eV</td>
<td>0.91 K</td>
</tr>
<tr>
<td>1.08 K</td>
<td>2.23 eV</td>
<td>0.94 K</td>
</tr>
<tr>
<td>1.22 K</td>
<td>1.76 eV</td>
<td>1.08 K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_X$ (95% CL)</th>
<th>Vector</th>
<th>Dirac</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.77 K</td>
<td>7.91 eV</td>
<td>0.67 K</td>
</tr>
<tr>
<td>0.88 K</td>
<td>1.87 eV</td>
<td>0.76 K</td>
</tr>
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Results: what we know now

Scalar
- 11.2 eV
- Weyl [Viel et al. '05]
- Weyl [Osato et al. '16]
- Weyl [P18+BOSS-BAO+WLens]
- Weyl [P18+BOSS-FS+WLens]

Vector
- Dirac

Prior results

This work

[WLX, Mūnoz, Dvorkin 2107.09664]
Results: what we know now & what we can learn from it

Light gravitinos in gauge-mediated SUSY breaking

\[ m_{3/2} = \frac{\langle F \rangle}{\sqrt{3}M_{pl}}, \quad T_{3/2} \approx 0.95 \text{ K}, \quad g_{3/2,\text{eff}} = 2 \]

\[ m_{3/2} \leq 1.91 \text{ eV} \implies \sqrt{\langle F \rangle} \leq 63.5 \text{ TeV} \]
Results: where we’re going next

Better data coming soon!
Data/Experiments: Round 2

- Fisher Forecasts
Data/Experiments: Round 2

- Fisher Forecasts
- Planck, CMB-S4 + $\tau$
- LSS Single Tracers:
  - BOSS
    $\mathcal{O}(100)/\Delta z/\text{deg}^2$ LRGs
  - DESI
    $\mathcal{O}(1000)/\Delta z/\text{deg}^2$ ELGs
  - Euclid
    $\mathcal{O}(5000)/\Delta z/\text{deg}^2$ H$_\alpha$s
Results

[Weyl Fermion, $g_X = 2$

DESI+Planck

Planck Only

DESI Only

[Deporzio, WLX, Múnoz, Dvorkin 2006.09380, Minimal temperature $T_X = 0.91$ K]
Results

$N_{\text{eff}}$

$\sigma_{g_X}$

$\omega_{cdm}$

$[\text{Deporzio, WLX, Muñoz, Dvorkin 2006.09380, Minimal temperature } T_X \text{ = 0.91 K}]$
Results

Detectible at $3\sigma$

$N_{\text{eff}}$

$\omega_{\text{cdm}}$

$\sigma_{g_X}$

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

$m_X$ [eV]

$10^2$ $10^1$ $10^0$

$g_X = 2$

Weyl Fermion,

DESI+Planck

Planck Only

DESI Only

3$\sigma$ Threshold

[Deporzio, WLX, Múnoz, Dvorkin 2006.09380, Minimal temperature $T_X = 0.91$ K]
Results: what we can look forward to

Scalar, \( g_X = 1 \)

Weyl Fermion, \( g_X = 2 \)

Vector, \( g_X = 2 \)

Dirac Fermion, \( g_X = 4 \)

[Deporzio, WLX, Mţuoz, Dvorkin 2006.09380]
Results: what we can look forward to

\[ T_X = 0.91 \text{ K} \]

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<th>( m_X ) (95% CL)</th>
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<th>Forecast</th>
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<tr>
<td>Scalar</td>
<td>11.2 eV</td>
<td>9.6 eV</td>
</tr>
<tr>
<td>Weyl</td>
<td>2.26 eV</td>
<td>1.90 eV</td>
</tr>
<tr>
<td>Vector</td>
<td>1.58 eV</td>
<td>1.37 eV</td>
</tr>
<tr>
<td>Dirac</td>
<td>1.06 eV</td>
<td>0.86 eV</td>
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Results: what we can look forward to

\[ T_X = 0.91 \, \text{K} \]

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<tr>
<td>Scalar</td>
<td>1.96 eV</td>
<td>1.14 eV</td>
</tr>
<tr>
<td>Weyl</td>
<td>1.20 eV</td>
<td>0.78 eV</td>
</tr>
<tr>
<td>Vector</td>
<td>0.90 eV</td>
<td>0.58 eV</td>
</tr>
<tr>
<td>Dirac</td>
<td>0.61 eV</td>
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Also: 3σ discovery potential for GMSB gravitinos at

\[ m_{3/2} \geq 0.77 \text{ eV or } \sqrt{F} \geq 40 \text{ TeV} \]

2σ at all masses
Results: what we can look forward to

[Deporzio, WLX, Múnoz, Dvorkin 2006.09380]

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Cosmological Constraints on Light (but Massive) Relics
Results & where we’ve landed

Dark sectors are worth studying, in whole or in part

- Compelling reasons to care about LiMRs
- If so, cosmological data is uniquely powerful
- The first set of comprehensive constraints
  + better things to come
Results & where we’ve landed

Dark sectors are worth studying, in whole or in part

What’s next?

- Generalize the framework (+ annihilations, decays...)
- Develop model applications + follow-up plans
  - what are the compelling targets to search for?
  - how do we identify them if we detect something?
Thank you!