Respect the ELDERs

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arXiv:160x.xxxxx, coming up soon!
Outline

• The Elastically Decoupling Relic and its Thermal History
• Constraints and Direct-detection Probes
• ELDER vs WIMP
• Conclusion and Outlook

Eric Kuflik, Maxim Perelstein, Nicolas Rey-Le Lorier and Yu-Dai Tsai (1512.04545)
Beyond WIMP/CDM

• The exploration of **Sub-GeV Dark Matter** has begun
  Bean Dump, **Direct Detection**, ...

• Collision-less CDM has small scale problems
  **Self-interaction** solves too-big-to-fail and core-vs-cusp issues
  What if the DM self-interaction changes number density?

• **New/simple mechanism** with familiar Physics?
The “Phase Diagram” of Different Thermal DMs

- $\Omega_{DM} h^2 = 0.1186 \pm 0.0020$.
- The elastic scattering determines the ELDER relic abundance!

$$\frac{\partial n_\chi}{\partial t} + 3H n_\chi = -\langle \sigma v^2 \rangle_{3\rightarrow2} (n_\chi^3 - n_\chi^2 n_{\chi^{eq}}) - (\langle \sigma v \rangle_{\chi \text{ann}} n_\chi^2 - \langle \sigma v \rangle_{\gamma \text{ann}} (n_\gamma^{eq})^2) .$$

$$\frac{\partial \rho_\chi}{\partial t} + 3H (\rho_\chi + P_\chi) = -\langle (E_{\text{in}} - E_{\text{out}}) \sigma v \rangle_{\text{kin}} n_\chi n_{\gamma^{eq}}$$

$$- (\langle E_\chi \sigma v \rangle_{\chi \text{ann}} n_\chi^2 - \langle E_\chi \sigma v \rangle_{\gamma \text{ann}} (n_\gamma^{eq})^2)$$
Important Processes for ELDER

Self-annihilation

- A number changing process
- Acts to keep the DM in chemical equilibrium when it becomes non-relativistic

\[
\lim_{T \to 0} \langle \sigma_{3 \to 2} v^2 \rangle \equiv \frac{\alpha^3}{m_\chi^5}
\]

Elastic Scattering

- Number conserving
- Transfers energy/entropy between DM and SM sectors.
- Acts to keep DM/SM thermalized.

\[
\lim_{T \to 0} \langle \sigma_{e1} v \rangle \equiv \frac{\epsilon^2}{m_\chi^2}
\]

DM annihilation into SM drops out before the above processes.
Thermal History of the ELDER

- **Elastic Decoupling**: Elastic Scattering becomes ineffective and SM/DM not completely thermalized (exponential change of the number density)
- **Cannibalization**: Number changing process heats up the DM sector
- **3 to 2 Freeze-out**: 3 to 2 process becomes ineffective in keeping DM in chemical equilibrium (almost no effect on number density)
Elastic Decoupling (from SM)

• The self-annihilation/number changing process maintains chemical equilibrium in the DM gas and releases kinetic energy. Consider the change of the non-relativistic number density

\[ \dot{K}_\chi = m \frac{\dot{n}}{n} \bigg|_{\mu_\chi=0} \simeq -m_\chi^2 HT^{-1}. \]

• Elastic scattering processes transfer this excess kinetic energy to the SM gas at a rate

\[ \dot{K}_\chi \sim \Gamma_{\text{el}} v_\chi^2 T \sim T^5 \epsilon^2 / m_\chi^3, \]

• **Decoupling** happens when the elastic scattering stops transferring the excess kinetic energy to the SM gas. Define \( x = m/T \) at the decoupling temperature as:

\[ x_d \sim \epsilon^{1/2} m_\chi^{-1/4} M_{\text{Pl}}^{1/4}. \]
Dark Matter Cannibalization
(Carlson, Machacek and Hall, 92)

• After decoupling, the co-moving entropy density in each sector is constant as the universe expands:

\[ a^3 s'_\chi = a^3 \frac{m_\chi n_\chi}{T'} = \text{constant} \]

\[ \implies (T')^{1/2} e^{-m_\chi/T'} \propto T^3 \]

• \( a \) is the FRW scale factor, \( T'/T \) is the DM/SM temperature

• \( T' \) depends logarithmically on \( T \) and on the scale factor \( a \)
Freeze-out (of the self-annihilation process)

- Freeze-out occurs when the number changing process is no longer sufficient to maintain chemical equilibrium.
- Less important for the relic abundance according to the plot.

\[
(n_{\chi}^{eq})^2 \langle \sigma_{3 \to 2} v_\chi \rangle \sim \frac{\dot{n}_{\chi}}{n_{\chi}^{eq}}
\]

\[
x'_f \sim \frac{3}{4} \log \left( \frac{M_{Pl}}{m_\chi} \right) - \frac{x_d}{2} + \frac{9}{4} \log \alpha.
\]

\[
\Omega_\chi \sim \frac{10^6 m_{MeV} \exp(-10^{1/2} \epsilon_{-9}^{1/4} m_{MeV}^{-1/4})}{1 + 0.07 \log \alpha}
\]

- Co-moving entropy is already conserved, so freeze-out does not affect much.
- $\Omega$ depends logarithmically on $\alpha$ & exponentially on $\epsilon$.
- Elastic scattering determines the relic abundance!
The “Phase Diagram” of Different Thermal DMs

\[ \Omega_{DM} h^2 = 0.1186 \pm 0.0020 \]

\[
\frac{\partial n_\chi}{\partial t} + 3H n_\chi = - \langle \sigma v \rangle_{3\to2} (n_\chi^3 - n_\chi^2 n_\chi^{eq}) - (\langle \sigma v \rangle_{\chi_{\text{ann}}} n_\chi^2 - \langle \sigma v \rangle_{\gamma_{\text{ann}}} (n_\gamma^{eq})^2) .
\]

\[
\frac{\partial \rho_\chi}{\partial t} + 3H (\rho_\chi + P_\chi) = - \langle (E_{\text{in}} - E_{\text{out}}) v \rangle_{\text{kin}} n_\chi n_\gamma^{eq}
\]

\[
- (\langle E_\chi v \rangle_{\chi_{\text{ann}}} n_\chi^2 - \langle E_\chi v \rangle_{\gamma_{\text{ann}}} (n_\gamma^{eq})^2)
\]
Constraints on the ELDER/SIMP parameter space

- For ELDER/SIMP that couples to photons

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ELDER/SIMP direct detection!

- For ELDER/SIMP that thermalizes through electrons
- Preliminary. Refined version to appear in a long paper
- DAMIC/SuperCDMS (silicon) curves from Essig et al arXiv:1509.01598

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Conclusion and Outlook

- New mechanism of having right DM relic abundance governed by Elastic Scattering!

- Towards a more complete understanding of thermal relics

- ELDER is predictive in terms of interaction strength with the SM sector, just like WIMP

- Projected to be probed in future direct detections

- Mass naturally linked to QCD while the mediator is close to EW scale. Detailed modeling/issues discussed in the long paper.
WIMP vs ELDER: DM miracles?

- **WIMP:**
  - Thermal relic: minimal assumptions
  - Points to a specific interaction strength with the SM sector
  - Mass & mediator given by TeV EW physics
  - Naturalness: Symmetry (still not found yet)

- **ELDER:**
  - Thermal relic: minimal assumptions
  - Points to a specific interaction strength with the SM sector
  - Mass at QCD scale & mediator at TeV EW Physics
  - Naturalness?

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Thanks

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DM Self-Interaction

- To solve small scale problems: \( \sigma/m_\chi \sim 1 \text{ cm}^2/\text{g} \approx 2 \text{ barns/GeV} \)
- Normal WIMP has like \( \sigma/m \sim 10^{-14} \) cannot achieve that
- However, constraints from merging clusters (from Sean Tulin’s slides)

Constraint: \( \sigma/m < 1.25 \text{ cm}^2/\text{g} \) (68%)
Randall et al. (2007)

- Velocity-dependent SIDM,
  Kaplinghat, Tulin and Yu, 15

Constraint: \( \sigma/m < 0.47 \text{ cm}^2/\text{g} \) (95%)
Harvey et al. (2015)
Modeling the ELDER: A resonant ELDER

- Introducing more than one species to avoid the self interaction constraint while enhancing the 3 to 2 rate (stronger than even SIMP)
- The vanilla model couple to dark photon and eventually to electrons: signatures in direct-detection experiment