Elastically Decoupling Relic (ELDER) Dark Matter

Maxim Perelstein, Cornell
3rd NPKI Workshop, Seoul, Korea
June 16 2016

Kuflik, MP, Rey-Le Lorier, Tsai, 1512.04545 (PRL) + work in progress
Thermal Relic DM

- Thermal Relic: DM in thermal and chemical equilibrium with SM plasma at high temperatures (=early times)

- Predictive: DM-SM Scattering cross section \( \rightarrow \) decoupling time \( \rightarrow \) present density

- “Non-Relativistic” Decoupling: due to exponential drop in equilibrium density of DM particle once \( T < M_\chi \)

- Relic density: \( \Omega_\chi \approx \frac{10^{-26} \text{ cm}^3\text{sec}^{-1}}{\langle \sigma v \rangle} \) \( \sigma_{an} \equiv \sum_{\text{SM}} \sigma(\chi \chi \rightarrow \text{SM} + \text{SM})|_{v_\chi \sim 0.1} \)

- WIMP Miracle: \( \Omega_\chi \sim 1 \) when \( \sigma_{an} \sim \frac{\alpha^2}{M_{\text{weak}}^2} \) \( (m_\chi \sim M \sim M_{\text{weak}}) \)
“Light” Thermal Relic

- No definite discovery of weak-scale new physics so far motivates thinking about DM at different mass scales

- WIMP hypothesis makes two assumptions: DM particle and mediator masses both ~weak scale

- What if the DM particle mass is at ~QCD scale? (e.g. “dark pion” in twin Higgs-type model)

- Assume the mediator is still at the weak scale

- Relic Density: \[ \sigma_{an} \sim \frac{m_X^2}{M^4} \sim 10^{-6} \sigma_{WIMP} \rightarrow \Omega_X \sim 10^6 \]
The SIMP Miracle

• A big “WIMP assumption”: DM annihilation to SM is the only relevant process

• Obviously, only DM-number changing processes are relevant*

• What about non-DM-number-conserving self-interactions? (NB: in QCD pion number not conserved, e.g. WZW term)

• Strongly Interacting Massive Particle: $2\chi \leftrightarrow 3\chi$ process remains in equilibrium after $2\chi \leftrightarrow \text{SM + SM}$ decouples

• Relic density determined by $\langle \sigma_{\text{self-an}} v^2 \rangle |_{v\chi \sim 0.1}$, $\sigma_{\text{self-an}} \equiv \sigma(3\chi \rightarrow 2\chi)$

• SIMP Miracle: $\Omega_\chi \sim 1$ when $\sigma_{\text{self-an.}} \sim \frac{1}{(100 \text{ MeV})^5}$ [Hochberg, Kuflik, Volansky, Wacker, ’14]

• “SIMP Assumption”: Elastic SM-DM scattering maintains the two sectors at the same temperature until freeze-out
Riding Down the Hill

- Equilibrium NR number density: \( n^{\text{eq}}_\chi \sim (m_\chi T)^{3/2} e^{-m_\chi/T} \)

- SIMP follows the trajectory due to 3-to-2 self-annihilations

- This process releases kinetic energy:
  \[
  \dot{K}_\chi = m \frac{\dot{n}}{n} \approx -m_\chi^2 H T^{-1}
  \]

- Elastic SM-DM scattering must be fast enough to transfer this energy to the SM plasma, allow them to remain at same \( T \)

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

\[
\Gamma_{\text{el}} = n_{\text{SM}} \langle \sigma_{\text{el}} v \rangle
\]

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

- “Elastic Decoupling”: \( T_d \sim \epsilon^{-1/2} m_\chi^{5/4} M_{\text{Pl}}^{-1/4} \)
Beware: Cannibals!

- Self-annihilations decoupling: $n^2_x \langle \sigma_{\text{self-an}} v \rangle \sim H \quad @ \quad t_F$

- SIMP scenario: freeze-out before kinetic decoupling $t_F < t_d$

- Our work: what if $t_d < t_F$ ?

- At $t > t_d$, DM gas is in chemical equilibrium with no chemical potential (due to active self-annihilations), BUT $T_{\text{DM}} \neq T_{\text{SM}}$

- DM temperature determined by DM entropy conservation:
  \[ a^3 s_x = \text{const} \quad \Rightarrow \quad T_x^{1/2} e^{-m_x/T_x} \propto T_{\text{SM}}^3 \quad \Rightarrow \quad T_x \approx \frac{T_d}{1 + 3x_d^{-1} \log T_D/T_{\text{SM}}} \]

- “Cannibal” phase: Kinetic energy released in self-annihilations is used to “keep warm” in an expanding Universe [Carlson, Machacek, Hall, ’92]

- DM density changes as log(scale factor) during this phase!
Thermal History

- Eventually, self-annihilations decouple, DM density frozen-in

\[ x_F \approx \frac{3}{4} \log \left( \frac{M_{Pl}}{m_\chi} \right) - \frac{x_d}{2} + \frac{9}{4} \log \alpha \]
Meet the ELDER

- Relic density: \( \Omega_\chi \sim \frac{10^6 m_{\text{MeV}} \exp(-10\epsilon^{1/2} m_{\text{MeV}}^{-1/4})}{1 + 0.07 \log \alpha} \)

  - Exponential sensitivity to elastic cross section!
  - Very weak sensitivity to self-annihilation cross section

  Non-perturbative self-interactions

  Observational constraints
• Ex.: couple DM to electrons via $t$-channel vector mediator ($Z'$)

\[
\sigma_{el}(\chi e) \sim \frac{\epsilon^2}{m_{\chi}^2} \sim \frac{g^4 m_{\chi}^2}{16\pi M^4} \quad \frac{M}{g} \sim \frac{m_{\chi}}{\epsilon^{1/2}}
\]

\[
m_{\chi} \sim 10 - 100 \text{ MeV}, \epsilon \sim (1 - 5) \times 10^{-8} \quad \frac{M}{g} \sim 100 - 300 \text{ GeV}
\]

weak scale “just comes out”!
Observational Constraints

- DM coupling to photons only assumed here

- Similar constraints if DM coupling is primarily to electrons; weaker constraints if coupled to neutrinos (only 3 choices!)

CMB spectrum distortions from $\chi\chi \rightarrow \gamma\gamma$

[Similar bound from indirect detection]
• DM coupling to electrons only assumed here

• With this one assumption, ELDERs provide unambiguous prediction for direct detection cross section as a fn. of mass!
Elastic Self-Interaction

• Strong DM self-annihilation would generically be accompanied by strong DM elastic self-scattering

• Small-scale simulation “issues” possibly hint at

\[ \frac{\sigma_{XX\rightarrow XX}}{m_X} \sim 0.1 - 1 \text{ cm}^2/\text{g} \]

• Constraint (Bullet cluster, halo shapes):

\[ \frac{\sigma_{XX\rightarrow XX}}{m_X} < 1 \text{ cm}^2/\text{g} \]

• Bullet the ELDER:

\[ \sigma_{XX\rightarrow XX} = a^2 \frac{\alpha^2}{m_X^2} \rightarrow a \leq 0.01 - 0.1 \]

(just a bit) too much of a good thing…
Resonant ELDER

[a la Soo-Min Choi, Hyun Min Lee, ‘16]

• Consider a simple renormalizable model:

\[
\mathcal{L} = \lambda_1 m_\chi S^2 \chi^\dagger + \lambda_2 m_\chi S \chi^2 + \frac{1}{6} \lambda_3 S^\dagger \chi^3 + h.c.
\]

• Resonant enhancement of self-annihilation if \( m_S \approx 3m_\chi \)

• Elastic self-scattering not enhanced!

• Sample parameter set (correct relic density, Bullet, perturbative):

\[
m_\chi = 10 \text{ MeV}, \ m_S = 32 \text{ MeV}
\]

\[
\lambda_1 = \lambda_2 = 1.0, \ \lambda_3 = 0
\]

• Can be coupled to electrons e.g. via dark photon exchange
Conclusions

• Considered a thermal relic with \( \sim \text{QCD-scale mass} \), coupled to SM with a mediator of \( \sim \text{weak-scale mass} \)

• Such a particle can have correct relic abundance, if strong self-annihilation process is present

• Unusual thermal history involving “cannibalization” epoch

• Relic abundance determined dominantly by the cross section of elastic scattering of DM on SM (not a number-changing process!)

• All observational constraints are easily satisfied, mild tension with elastic self-scattering can be resolved at a price of a mild spectrum coincidence (resonance)