ELDER (and SIMP) Dark Matter

Maxim Perelstein, Cornell
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Eric Kuflik, MP, Nic Rey-Le Lorier, Yu-Dai Tsai,
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• Observations firmly establish existence of Dark Matter, and it must involve physics beyond the SM

- Dark Matter: powerful evidence for New Physics

  - galaxy rotation curves: something’s missing!
  - cosmic microwave background: precision measurement of baryonic & non-baryonic density
  - Bullet cluster: mapping matter & light

- Dark Energy 73%
  - Dark Matter 23%
  - Light 0.005%
  - Neutrinos 0.0034%

- BBN: fix baryon density
WIMP Dark Matter

- Introduce a new particle, $\chi$
- Thermal Relic: $\chi$ is in equilibrium with SM plasma at high $T$ (=early times)
- Chemical equilibrium:
  $$\chi + \chi \leftrightarrow \text{SM} + \text{SM}$$
- Kinetic equilibrium:
  $$\chi + \text{SM} \leftrightarrow \chi + \text{SM}$$

- Equilibrium density
  $$n_\chi \propto e^{-m_\chi/T}$$
  drops quickly when $T < M_\chi$
- “Freeze-out”: $n_\chi \sigma_{\text{an}} \nu \sim H$ annihilation decouples
- After freeze-out, DM and SM still in kinetic equilibrium, but DM number cannot change $\rightarrow$ DM chemical potential
Freeze-Out vs. Kinetic Decoupling

- Kinetic decoupling always occurs after freeze-out:

\[ \Gamma_{\text{an}} \sim n_\chi \sigma v, \quad \Gamma_{\text{el}} \sim n_{\text{SM}} \sigma v \quad n_\chi \propto e^{-m_\chi/T} \]

- Between FO and KD, \( \chi \) is in thermal equilibrium with non-zero chemical potential

- Kinetic decoupling plays no role in determining relic density
WIMP Miracle

- Leftover WIMP density estimate:

\[ n_{f-o} \approx \frac{H_{f-o}}{\sigma_{an} v} \approx \frac{T_{f-o}^2}{M_{Pl} \sigma_{an} v} \]

\[ T_{f-o} \approx m_{\chi}/20 \]

- DM density:

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

- WIMP Miracle: \( \Omega_{\chi} \sim 1 \) when \( \sigma_{an} \sim \frac{\alpha^2}{M_{\text{weak}}^2} \) (\( m_{\chi} \sim M \sim M_{\text{weak}} \))
WIMP Hypothesis Under Attack

- Direct detection searches and LHC searches are deep into the territory where WIMPs and their cousins are expected

- Not “ruled out”… but lack of discovery so far motivates thinking about DM at different mass scales
“Dark Sector” Dark Matter

- “Dark Sector”: particles with no SM gauge charges
- May interact with SM through a “mediator” particle, generally a very weak interaction ($\epsilon \ll 1$)
- If DM particle is in the dark sector, annihilation to SM $2\chi \leftrightarrow SM + SM$ is “weaker than weak”
- Annihilation process decouples too early, leaving too much DM behind - “overclosure”
**SIMP Dark Matter**

[Hochberg, Kuflik, Volansky, Wacker, '14]

- What if there are strong, number-changing DM self-interactions, e.g.

$$3\chi \leftrightarrow 2\chi$$

- Continue to reduce DM density after annihilations to SM decouple

- Relic density estimate:

$$n_{\text{DM}}^2 \langle \sigma v^2 \rangle_{3\rightarrow 2} |_{T=T_F} = 0.33 \sqrt{g_*} \frac{T_F^2}{M_{\text{Pl}}}$$

- Parametrize \( \langle \sigma v^2 \rangle_{3\rightarrow 2} \equiv \frac{\alpha_{\text{eff}}^3}{m_{\text{DM}}^5} \), take \( \alpha_{\text{eff}} \sim 1 \)

- Correct relic density for \( m_{\text{DM}} \sim 100 \text{ MeV} \) - QCD scale!
Evidence for Self-Interacting DM?

- Inner cores are less dense than expected from CDM simulations, in dwarfs and galaxies and galaxy clusters

- Many astrophysical uncertainties, but self-interactions with $\frac{\sigma_{\chi\chi \rightarrow \chi\chi}}{m_\chi} \sim 0.1 - 1 \text{ cm}^2/\text{g}$ could be a simple explanation

[Kaplinghat, Tulin, Yu, '15]
Freeze-Out vs. Kinetic Decoupling

- This is only true if kinetic decoupling occurs after freeze-out.
- Unlike WIMP case, this may or may not be true, depending on model parameters:
  \[ \Gamma_{an} \propto \epsilon^2 n_\chi, \quad \Gamma_{3\rightarrow 2} \propto \alpha_{\text{eff}}^3 n_\chi^2, \quad \Gamma_{el} \propto \epsilon^2 n_{\text{SM}} \]

- SIMP relic density estimate assumes same temperature for DM and SM at freeze-out:
  \[ n_{DM}^2 \langle \sigma_3 \rightarrow 2v^2 \rangle |_{T=T_F} = 0.33 \sqrt{g_* F} \frac{T_F^2}{M_{Pl}} \]
What If KD Occurs Before FO?

- After KD, before FO: DM gas is in thermal equilibrium, at zero chemical potential, but not at the same temperature as SM!

- DM is warmer than SM during this period

![Graph showing decoupling and freezeout](image)
Boltzmann Equations

- DM density/distribution \( f_\chi(p, t) \) is controlled by
  \[
  \frac{\partial f_\chi}{\partial t} - H \frac{p^2}{E} \frac{\partial f_\chi}{\partial E} = C[f_\chi]
  \]

- In our problem, \( 2\chi \leftrightarrow 2\chi \) is always fast enough to maintain LTE, so
  \[
  f_\chi = \frac{1}{e(E-\mu_\chi)/T' - 1}
  \]

- Then BE reduces to 2 ODEs:
  \[
  \frac{\partial n_\chi}{\partial t} + 3Hn_\chi = -\langle \sigma_{3\rightarrow 2}v^2 \rangle (n_\chi^3 - n_\chi^2 n_{\chi}^{\text{eq}}),
  \]
  \[
  \frac{\partial \rho_\chi}{\partial t} + 3H (\rho_\chi + P_\chi) = -\langle \sigma_{elv}\delta E \rangle n_\chi n_{\psi},
  \]

- Before freeze-out, \( \mu_\chi = 0 \) and kinetic decoupling is described by
  \[
  \frac{\partial T'}{\partial T} = 3 \frac{T'^2}{m_\chi T} + a \left( \frac{T}{m_\chi} \right)^{1+n} \frac{T'^2}{m_\chi^2} \frac{(T' - T)}{m_\chi}
  \]

- Approximate analytic solution:
  \[
  x' = e^t \left( \left( \frac{a}{n+4} \right)^{n+4} \Gamma \left( \frac{n+3}{n+4}, t \right) - \frac{3 \text{Ei}(-t)}{n+4} \right), \quad \text{where} \; t \equiv \frac{ax-n-4}{n+4}
  \]
Beware: Cannibals!

- Each $3\chi \rightarrow 2\chi$ annihilation converts mass of 1 DM particle into kinetic energy: $E_f = 1.5m_\chi$

- This kinetic energy quickly thermalizes by $2\chi \leftrightarrow 2\chi$ leading to increase in DM temperature ("cannibalization")

- DM temperature determined by DM entropy conservation:

$$a^3 s_\chi = \text{const} \quad \rightarrow \quad T_\chi^{1/2} e^{-m_\chi/T_\chi} \propto T_{SM}^3 \quad \rightarrow \quad T_\chi \approx \frac{T_d}{1 + 3x_d^{-1} \log T_D/T_{SM}}$$

- DM temperature decreases very slowly (log, not power) with scale factor

[Carlson, Machacek, Hall, ’92]
Thermal History

- Coming DM density decreases slowly between KD and FO ("cannibalization epoch"), then stays constant after FO

- Relic density depends mainly on when the KD occurred, which is controlled by Elastic Scattering cross section!
Meet the ELDER

- Relic density: \( \Omega_\chi \sim \frac{10^6 m_{\text{MeV}} \exp\left(-10\epsilon\frac{1/2}{9} m^{-1/4}_{\text{MeV}}\right)}{1 + 0.07 \log \alpha} \)

Very weak sensitivity to self-annihilation cross section

ELastically DEcoupling Relic (ELDER)
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!)

Entropy ejected into photons/electrons after neutrinos decouple
[Similar bound from BBN]

CMB spectrum distortions from $\chi \chi \rightarrow \gamma \gamma$
[Similar bound from indirect detection]

Entropy ejected into photons/electrons after neutrinos decouple
[Similar bound from BBN]
**SIMP/ELDER Coupling to SM**

- **“Vector”** \( \epsilon F^{Y,\mu\nu} F'_{\mu\nu} \) dark photon \( A' \)

- **“Axion”** \( \frac{1}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} a \) axions & axion-like particles (ALPs)

- **“Higgs”** \( \lambda H^2 S^2 + \mu H^2 S \) exotic Higgs decays?

- **“Neutrino”** \( \kappa (HL) N \) sterile neutrinos?

- **Vector portal** is most suitable to couple SIMP/ELDER to SM; only coupling to **electrons** is relevant for most of the SIMP/ELDER allowed mass range

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- See e.g. review 1312.4992, Curtin, RE, Gori, Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong
ELDER in Direct Detection

Nuclear Recoil experiments not sensitive to dark matter in the 10-100 MeV mass range...

Many experiments recently proposed to search for DM scattering on electrons instead...

Precisely the same process that sets ELDER relic density!
ELDER in Direct Detection

- Relic density constraint **completely fixes** direct detection cross section as a fn. of mass! Interesting target for future experiments.

- The ELDER curve is the **lower boundary** of the SIMP region.
ELDER in Dark Photon Searches

- As long as $m_V > 2m_\chi$, the Dark Photon decays invisibly to DM pairs
Dark Sector: Toy Model

- Start with a $U(1)_D$ gauge theory with 2 complex scalars:

$$Q(\Phi) = +3, \quad Q(\chi) = +1$$

- Scalar potential:

$$V = V(\Phi) + V(\chi) + \frac{g}{3!} (\Phi^* \chi^3 + \Phi \chi^* 3) + \lambda_{\Phi \chi} |\Phi|^2 |\chi|^2,$$

- $\Phi$ vev breaks the gauge symmetry, preserves a discrete $\mathbb{Z}_3$

- $A_D$ becomes the Dark Photon, has kinetic mixing with SM EM

- $\chi$ is the “L3P”, stable DM candidate

$$V_{\text{eff}} = V(\chi) + \frac{R}{3!} m_\chi (\chi^3 + \chi^* 3) \quad \begin{array}{r} R = \frac{g w}{\sqrt{2} m_\chi} \end{array}$$
DS Toy Model

- Unbroken $Z_3$ allows 3-to-2 self-annihilations:

![Diagram of 3-to-2 self-annihilation processes]

- SIMP condition: $R_{\text{SIMP}} \approx 2.6 \left( \frac{m_\chi}{10 \text{ MeV}} \right)^{1/2} \left( \frac{\Omega_\chi h^2}{0.1} \right)^{1/2}$

- Elastic scattering cross section:

$$\frac{\bar{\sigma}_{\text{SIMP}}}{m_\chi} \approx \left( \frac{m_\chi}{10 \text{ MeV}} \right)^{-1} \cdot \left( 30 \frac{\text{cm}^2}{\text{g}} \right)$$

- Conflict with cluster data
Toy Model 2

[Choi, Lee, 1601.0356]

- Start with a $U(1)_D$ gauge theory with 3 complex scalars:

\[ q(\phi) = +5, \quad q(S) = +3, \quad q(\chi) = +1 \]

- Scalar potential: $< 0!$

\[
V_d = m_\phi^2 |\phi|^2 + \lambda_{\phi} |\phi|^4 + m_S^2 |S|^2 + \lambda_S |S|^4 + m_\chi^2 |\chi|^2 + \lambda_\chi |\chi|^4 \\
+ \lambda_{\phi_S} |\phi|^2 |S|^2 + \lambda_{\phi_\chi} |\phi|^2 |\chi|^2 + \lambda_{S_\chi} |S|^2 |\chi|^2 + \\
+ \frac{1}{\sqrt{2}} \lambda_1 \phi^\dagger S^2 \chi^\dagger + \frac{1}{\sqrt{2}} \lambda_2 \phi^\dagger S \chi^2 + \frac{1}{6} \lambda_3 S^\dagger \chi^3 + \text{h.c.}
\]

- Phi vev breaks the gauge symmetry, preserves a discrete $Z_5$

- Assume $\chi$ is the “L5P”, and $\phi$ is too heavy to matter

\[
V_d = \frac{m_\chi}{\sqrt{2}} R_1 S^2 \chi^\dagger + \frac{m_\chi}{\sqrt{2}} R_2 S \chi^2 + \frac{1}{6} \lambda_3 S^\dagger \chi^3 + \text{h.c.} \\
+ \lambda_S |S|^4 + \lambda_\chi |\chi|^4 + \lambda_{S_\chi} |S|^2 |\chi|^2,
\]

\[
R_i = \frac{v_D \lambda_i}{\sqrt{2} m_\chi}
\]
Resonance!

- Enhancement over the “naive” (3->2)/(2->2) ratio by up to 3 orders of magnitude!
- Broad resonance - no strong fine-tuning of masses is necessary
- Avoids tension between SIMP/ELDER strong 3->2, and cluster bounds
• Viable SIMP/ELDER DM for very reasonable parameters:

\[ m_\chi \sim 10 - 30 \text{ MeV} \quad R_i \sim 1 - 5 \]

\[ \epsilon \sim 10^{-4}, m_D \sim 100 \text{ MeV} \]
Dreaming of Dark Pions I

- In toy models, 100 MeV scale was put in by hand - not really a "miracle"

- Can Dark Matter mass be tied to QCD confinement scale?

- Dark Sector may contain confining gauge group(s), e.g. $SU(3)_D$

- In the deep UV, there may be a "mirror symmetry" between SM and DS gauge interactions, e.g. $Z_2 : SU(3)_{SM} \leftrightarrow SU(3)_D$ [ex.: Twin Higgs]

- In this setup, $SU(3)_D$ confinement scale is naturally $\sim \Lambda_{QCD}$

expect dark mesons and dark baryons around 100 MeV!
QCD-Like Realization?

- Consider dark sector: $SU(N_c)$ with $N_f$ quarks
- Confinement/chiral symmetry breaking $\rightarrow$ pions!
- Chiral Perturbation Theory:
  \[ U = \exp \left( \frac{2i\pi}{f_\pi} \right), \quad \mathcal{L} = \frac{f_\pi^2}{8} \text{Tr} \left[ \partial_\mu U \partial^\mu U^\dagger \right] \]
- Wess-Zumino-Witten term induces a 5-pion vertex:
  \[ \mathcal{L}_{WZW} = \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\alpha\beta} \text{Tr} \left[ \pi \partial_\mu \pi \partial_\nu \pi \partial_\alpha \pi \partial_\beta \pi \right] \]
- Gauged $U(1)_D$, spontaneously broken, kinetically mixed with SM hyper charge $\rightarrow$ elastic scattering off electrons
- Caution: need to forbid $\pi^0 \rightarrow V^*V^* \rightarrow e^+e^-e^+e^-$

[Hochberg, Kuflik, Murayama, Volansky, Wacker, ’14]
Viable SIMP/ELDER DM is possible, but requires $m_{\pi} \approx 500$ MeV, $m_V = 10m_{\pi}$, $\alpha_D = 1/(4\pi)$

- Viable SIMP/ELDER DM is possible, but requires $\frac{m_{\pi}}{f_{\pi}} \approx 5$
Constraints

- Rho-mass problem: \( m_\rho \sim \frac{2\pi f_\pi}{\sqrt{N_c}} \) so \( m_\rho \sim m_\pi \) in the SIMP/ELDER region

- No overlap between SIMP/ELDER and regime of validity of chiral perturbation theory ☹️
Conclusions

- Considered a thermal relic with ~QCD-scale mass, number-changing self-annihilation process

- Two regimes: SIMP and ELDER (with unusual thermal history involving “cannibalization” epoch)

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

- Dark photon is the preferred mediator of DM/SM interactions

- Interesting, robust predictions for DM direct detection and dark photon searches

- Viable renormalizable, perturbative model of dark matter self-interactions exists; QCD-like models?