Exploring the Co-SIMP Dark Sector

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Thermal Relic Dark Sectors

- Internally thermalized at some cosmological epoch via self-interactions and/or interactions with the Standard Model (SM).
- Plethora of mechanisms and potential observables.
- Thermal relics in particular leave imprints of high-energy processes in low-energy observables.
    - Thermal relics are dark sector species that have a present-day number density set by freeze-out or freeze-in processes which change the number of dark matter particles.
    - Generic and predictive!

Thermal Relic Zoo

- Canonical example is the WIMP where DM annihilation via $\chi\chi \to \mathrm{SM\,SM}$ sets the relic abundance.

- Various other possibilities include

  - Warm Dark Matter - decouples when relativistic, can still scatter with SM

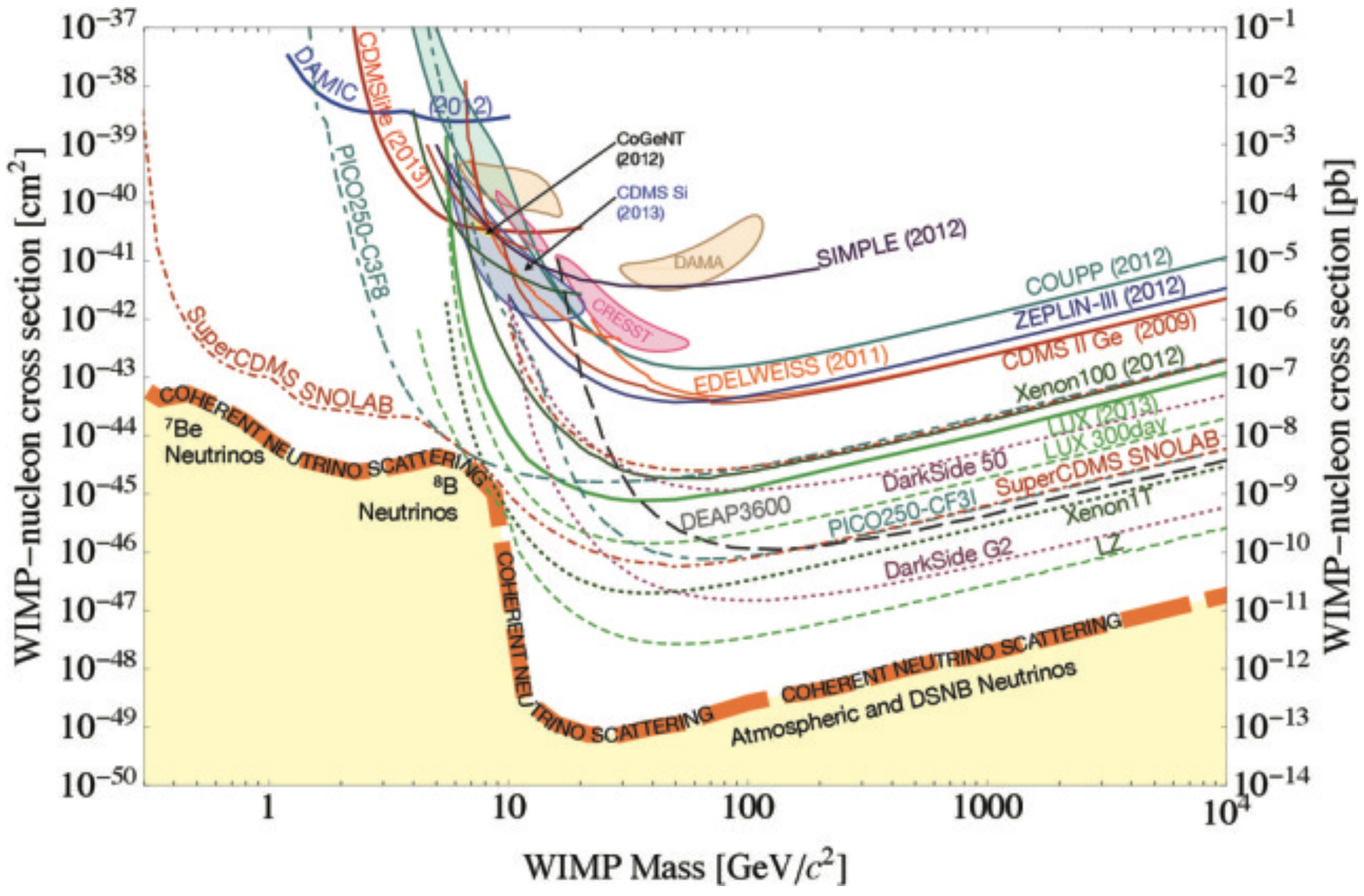
  - Decaying Dark Matter - $\chi \to \mathrm{SM\,SM}$

  - Cannibal Dark Matter - $\chi\chi\chi \to \chi\chi$ number changing self-interactions

  - SIMP, Forbidden Dark Matter, ELDER, KINDER, SIDM, …

Mass Ranges and Search Strategies

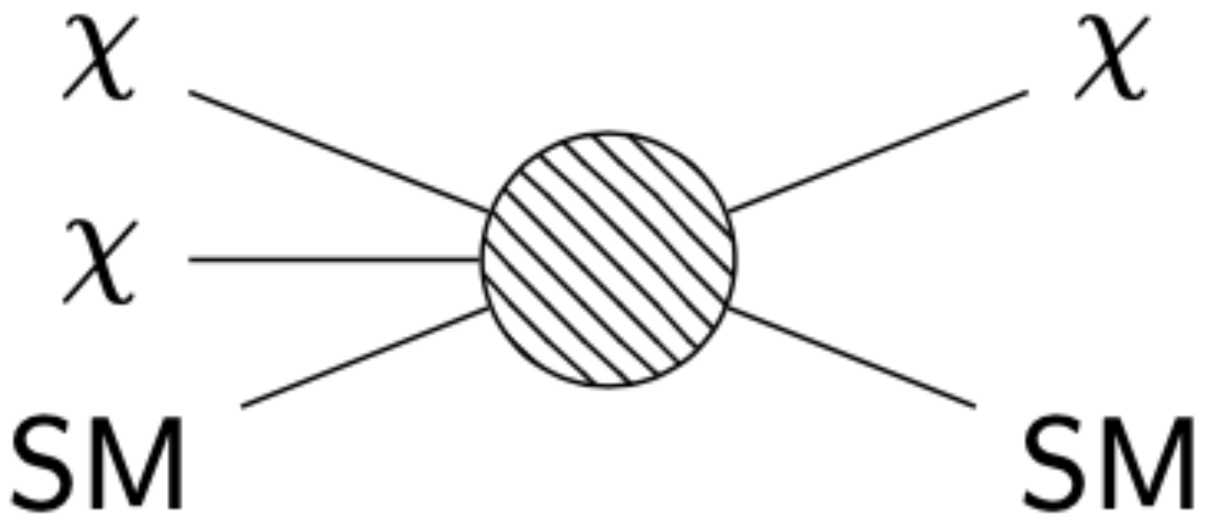
- New mechanisms open up new mass ranges
  - $3 \rightarrow 2$ cross section:
    $\langle \sigma_{3\rightarrow 2} v^2 \rangle \equiv \alpha^3 / M^5 \qquad \langle \sigma_{3\rightarrow 2} v^2 \rangle M^2 = 10^8\ \mathrm{GeV}^{-3}$
  - Natural expectation is an MeV - GeV range dark matter mass
- Standard direct detection experiments are often not the best suited to search for these new mass ranges



Cooley [1410.4960]

Co-SIMP Dark Matter

- $3 \to 2$ process involving both sectors: $\chi\chi\mathrm{SM} \to \chi\mathrm{SM}$



- Strongly interacting which leads to kinetic equilibrium with the SM
- Prevents dark sector from overheating
- Typically expect masses in the keV - MeV range

Smirnov, Beacom [2002.04038]

Co-SIMP Dark Matter EFT

- For Co-SIMP freeze out, the cross section scales as

$$\langle \sigma_{3\to 2} v_{\rm rel}^2 \rangle \approx 10^{12} \left(\frac{10^{-9}}{\eta}\right)\left(\frac{\rm MeV}{M_{\rm DM}}\right)^3 \left(\frac{0.12}{\Omega_{\rm DM} h^2}\right) \text{GeV}^{-5}$$

- If we consider a scalar χ coupled to non-relativistic electrons via $\mathcal{O} = m_e \bar{\ell}\ell\chi^3/\Lambda^3$ then the cross section scales as:

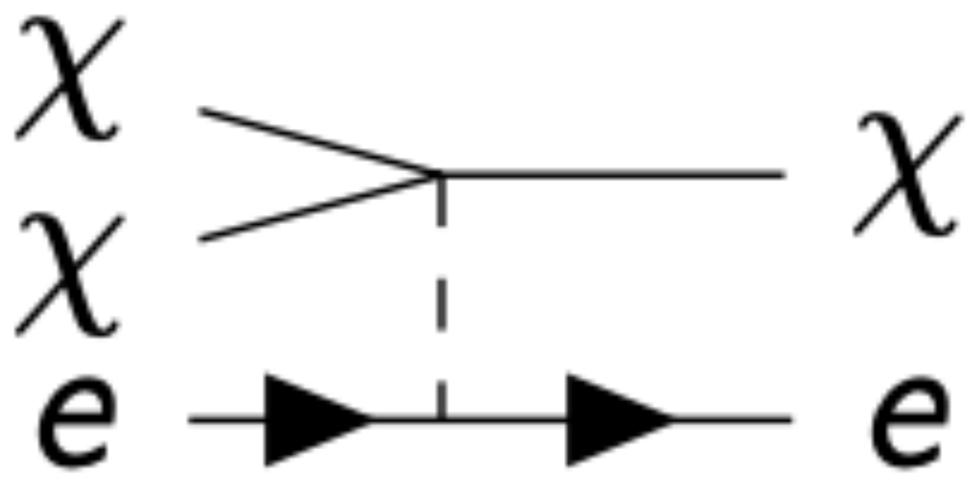
$$\langle \sigma_{3\to 2} v_{\rm rel}^2 \rangle \sim m_e^2 / M_{\rm DM} \Lambda^6$$

0.1 MeV DM implies $\Lambda \sim$ MeV

- Low cutoff!! Consider UV completions!!

Scalar Model

- Consider a scalar χ dark matter whose interactions are mediated by a scalar ϕ which also couples to leptons ℓ
  $$\mathscr{L} \supset y_{\chi\phi}\phi\chi^3 + y_{\phi\ell}\phi\bar{\ell}\ell$$



- χ is stable, ϕ is unstable since $m_\phi > m_\chi$

- Free parameters of this model are $\{m_\phi, m_\chi, y_{\chi\phi}, y_{\phi\ell}\}$

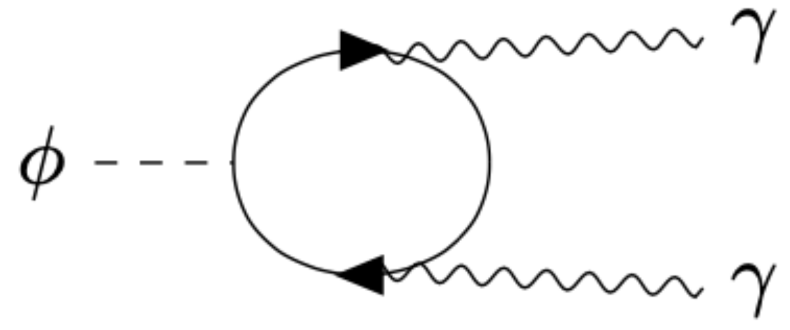
- Approximate parameter space we are interested in has small $y_{\phi\ell}$, $y_{\chi\phi} \sim \mathcal{O}(1), m_\phi, m_\chi \sim \mathcal{O}(10)$ keV

Cosmological Constraints

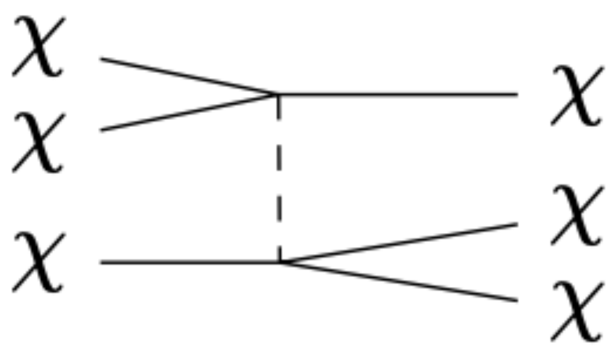
- Late thermalization and N_{eff}
  - Light dark matter contributes to radiation energy density in the early universe. N_{eff} is well-constrained at BBN and CMB.
  - Require thermal production of the dark sector to be inefficient until after BBN.
  - Require freeze out to occur before CMB.
- Relic Abundance
  - $\chi\chi \to \chi\phi$ and $\chi\chi\chi \to \bar{e}e$ kinematically shut off. Also assume that $\chi\chi\chi\chi \to \chi\chi$ is suppressed.
  - Dominant contribution from Co-SIMP processes: $\chi\chi e \to \chi e$ & $\chi\chi\gamma \to \chi\gamma$

Astrophysical & Terrestrial Constraints

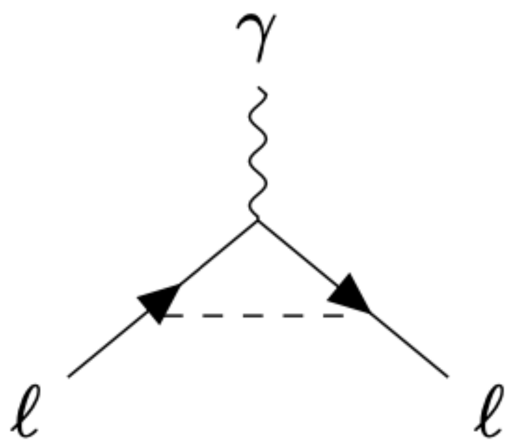
- Stellar Cooling
  - Production of dark sector particles can overcool stars. To avoid this, we require that dark sector particles are either too massive to be produced in the cores of stars or they decay before escaping.



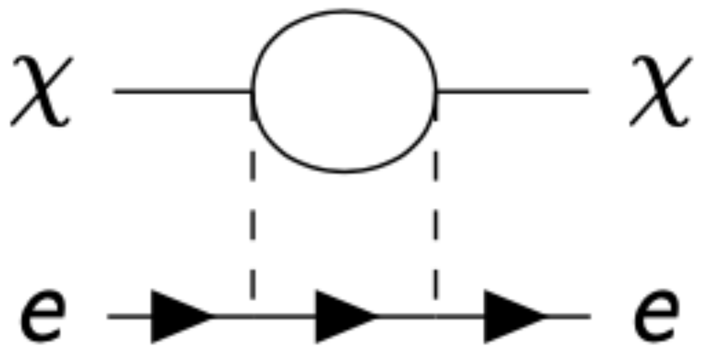
  - Red Giants: R ~ 200 s, T ~ 20 keV   Horizontal Branch Stars: R ~ 2 s, T ~ 2 keV
- Self-Interactions
  - Tree-level $\chi\chi\chi \to \chi\chi\chi$ interactions and loop-level $\chi\chi \to \chi\chi$ interactions



- Lepton g-2
  - Dominant constraint on $y_{\phi\ell}$



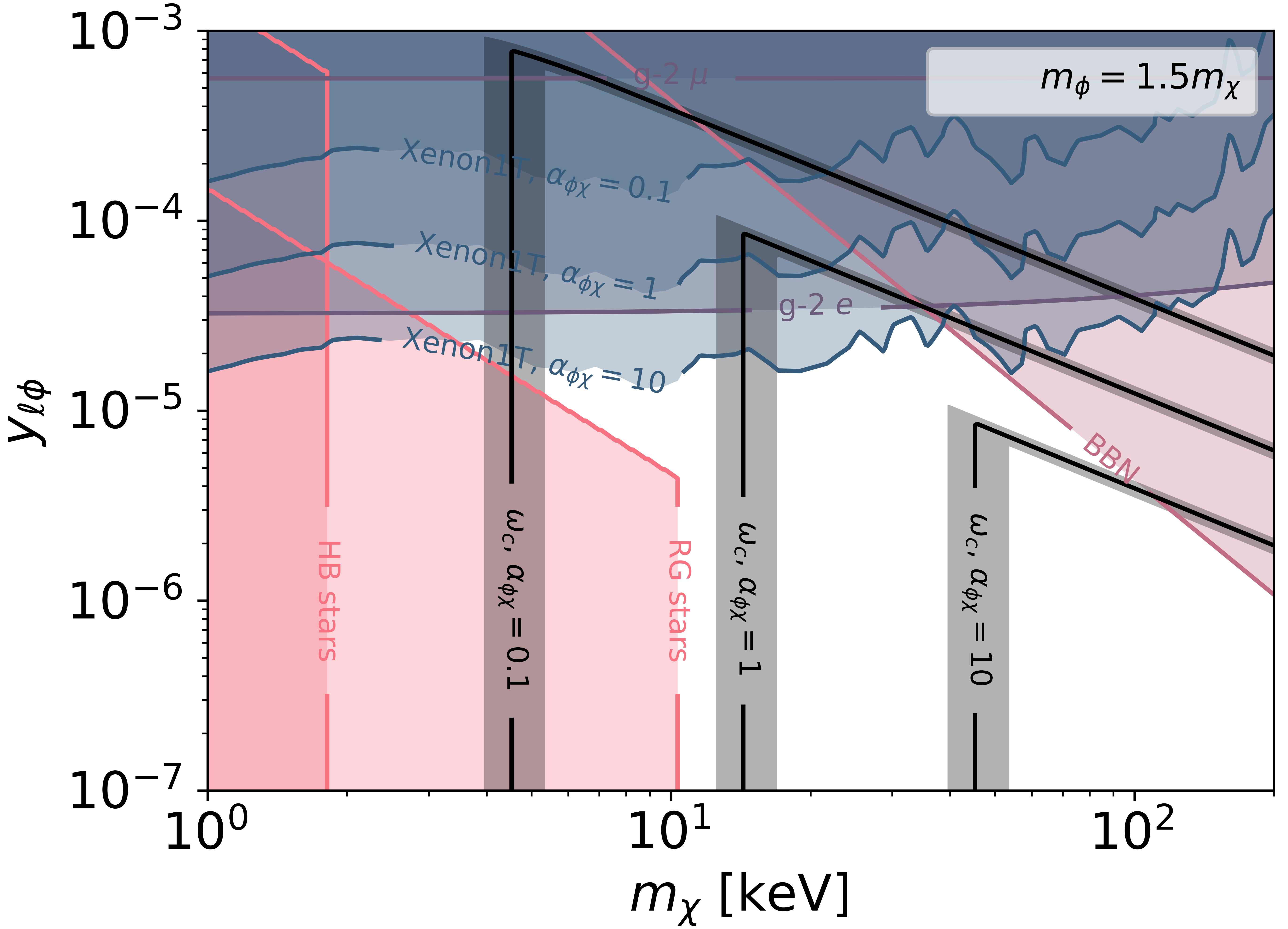
- Elastic Scattering
  - $\chi e \to \chi e$ mediated at two-loop



Constraint Plot

- Sharp corner corresponds to when the SIMP process starts to dominate over the Co-SIMP process for these parameter choices.

- Xenon1T excess can marginally be fit for $m_\chi \sim 40$ keV.



Conclusions

- We still have viable thermal relic models!
- Co-SIMPs can give us keV mass thermal relic dark matter. This mechanism also helps alleviate the problem of overheating the dark sector.
- The Co-SIMP paradigm is not restricted to just scalars. We also have a fermionic realization of this scenario.
- Rich phenomenology associated with these new mechanisms. Crucial to push direct detection towards lower masses.

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Thank You!