Respect the ELDERs

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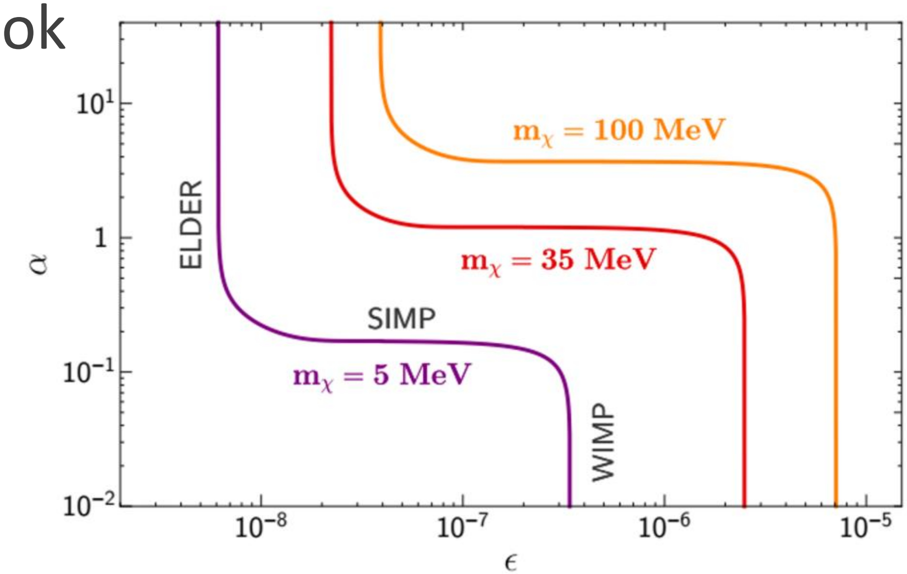
with Eric Kuflik, Maxim Perelstein and Nicolas Rey-Le Lorier
Phys. Rev. Lett. 116, 221302 (2016), 1512.04545,
arXiv:1610.xxxxx, coming up soon!

Outline

- The **Elastically Decoupling Relic** and its thermal history
- Constraints and Direct-detection Probes
- Conclusion and Outlook



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

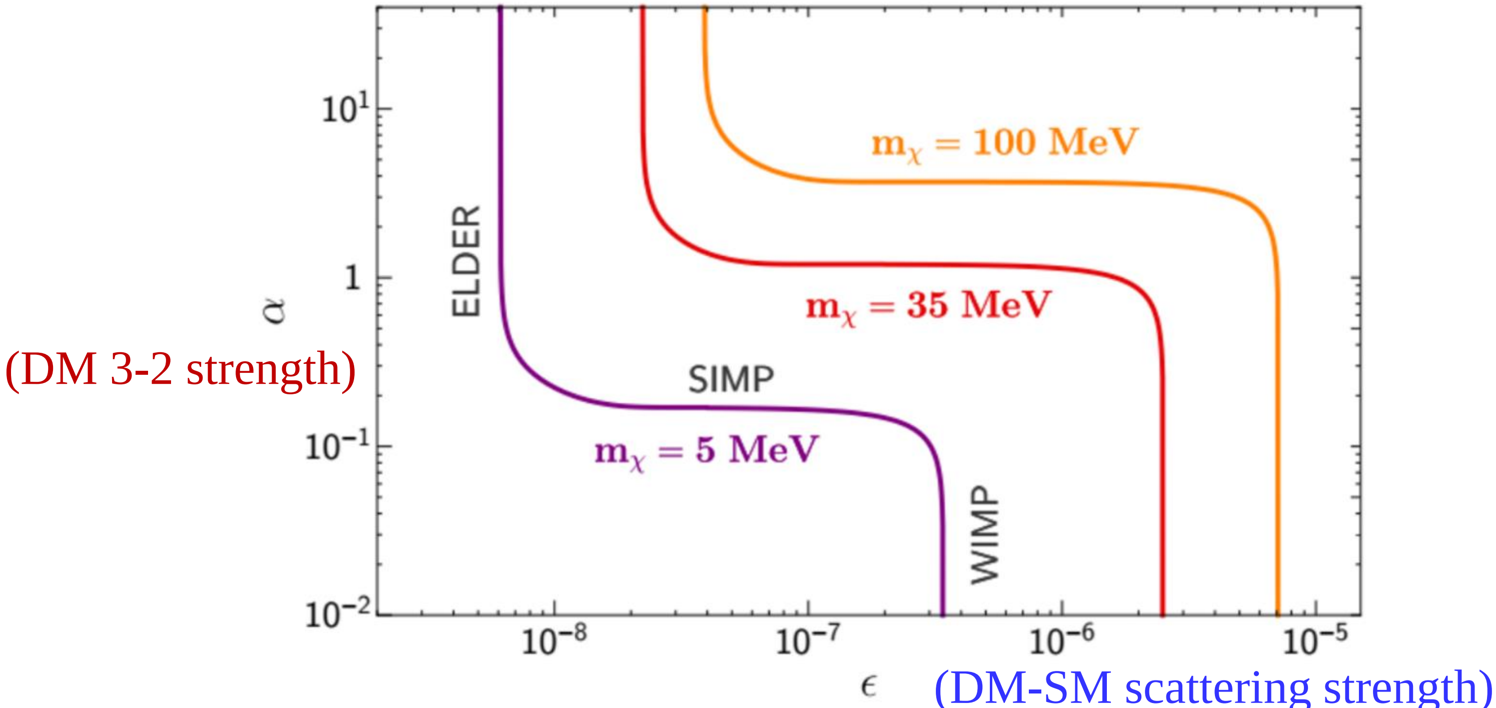
Beyond WIMP/CDM

- The exploration of **Sub-GeV Dark Matter** has begun

  Beam Dump, **Direct Detection**, …
- Collision-less CDM has small scale problems, and self-interaction has been considered to solve these issues

  What if the DM **self-interaction** changes number density?
- Can **elastic decoupling** govern the DM relic abundance**?**
- A **thermal Dark-Matter** mechanism that is new, simple but looks familiar?

The “Phase Diagram” of Different Thermal DMs



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

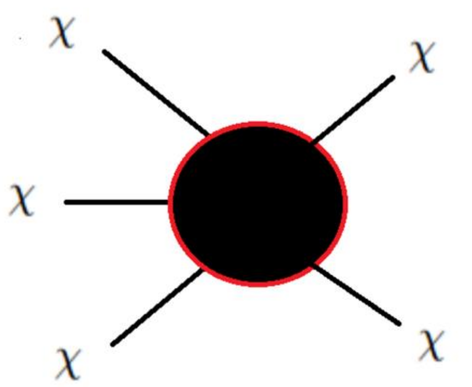
$$\frac{\partial n_\chi}{\partial t} + 3Hn_\chi = -\langle \sigma v^2 \rangle_{3\to 2}(n_\chi^3 - n_\chi^2 n_\chi^{\rm eq}) - \left(\langle \sigma v \rangle_{\chi \rm ann} n_\chi^2 - \langle \sigma v \rangle_{\gamma \rm ann}(n_\gamma^{\rm eq})^2\right).$$

$$\frac{\partial \rho_\chi}{\partial t} + 3H(\rho_\chi + P_\chi) = -\langle (E_{\rm in} - E_{\rm out})\sigma v \rangle_{\rm kin} n_\chi n_\gamma^{\rm eq}$$
$$- \left(\langle E_\chi \sigma v \rangle_{\chi \rm ann} n_\chi^2 - \langle E_\chi \sigma v \rangle_{\gamma \rm ann}(n_\gamma^{\rm eq})^2\right)$$

Important Processes for ELDER

Self-annihilation

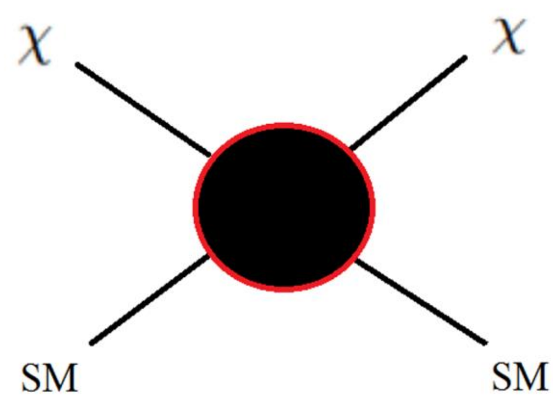
- A number changing process
- Acts to keep the DM in **chemical equilibrium** when it becomes non-relativistic



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

Elastic Scattering

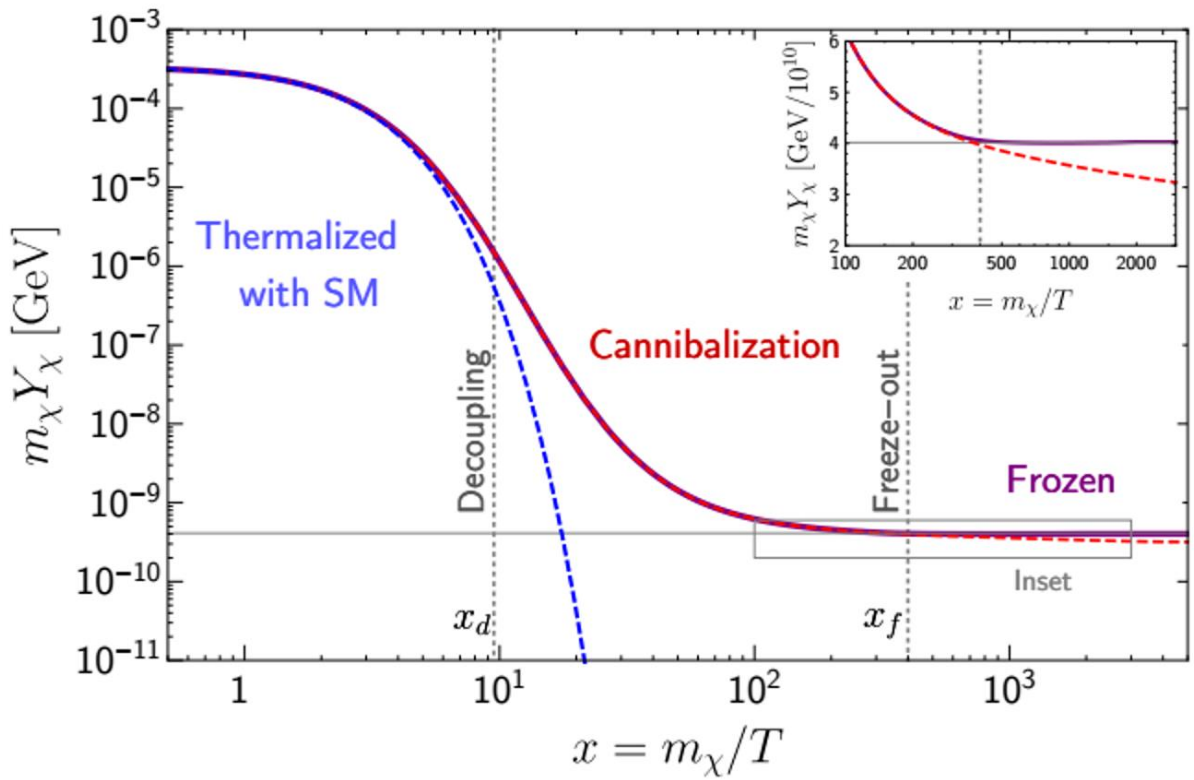
- Number conserving
- Transfers energy/entropy between DM and SM sectors.
- Acts to keep **DM/SM thermalized.**



$$\lim_{T\to 0} \langle \sigma_{\rm el} v \rangle \equiv \frac{\epsilon^2}{m_\chi^2}$$

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 $n_\chi^{\rm eq} \sim (m_\chi T)^{3/2} e^{-m_\chi/T}$

$$\dot{K}_\chi = m\, \frac{\dot{n}}{n}\bigg|_{\mu_\chi=0} \simeq -m_\chi^2 H T^{-1}.$$

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

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

- 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:

$$x_d \sim \epsilon^{1/2} m_\chi^{-1/4} M_{\rm Pl}^{1/4}.$$

- Can be done in a more rigorous/detailed fashion **analytically** by considering the energy density Boltzmann equation.

Dark Matter Cannibalization

(Carlson, Machacek and Hall, 92)

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

$$a^3 s'_\chi = a^3 \frac{m_\chi n_\chi}{T'} = \text{constant}$$
$$\Longrightarrow (T')^{1/2} e^{-m_\chi/T'} \propto T^3$$

- a is the FRW scale factor, T'/T is the DM/SM temperature
- T' depends logarithmically on T (number density drops much slower)

$$T' \approx \frac{T_d}{1 + 3x_d^{-1} \log T_d/T},$$

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

$$(n_\chi^{\rm eq})^2 \langle \sigma_{3\to 2} v_\chi \rangle \sim \dot{n}_\chi^{\rm eq} / n_\chi^{\rm eq}$$

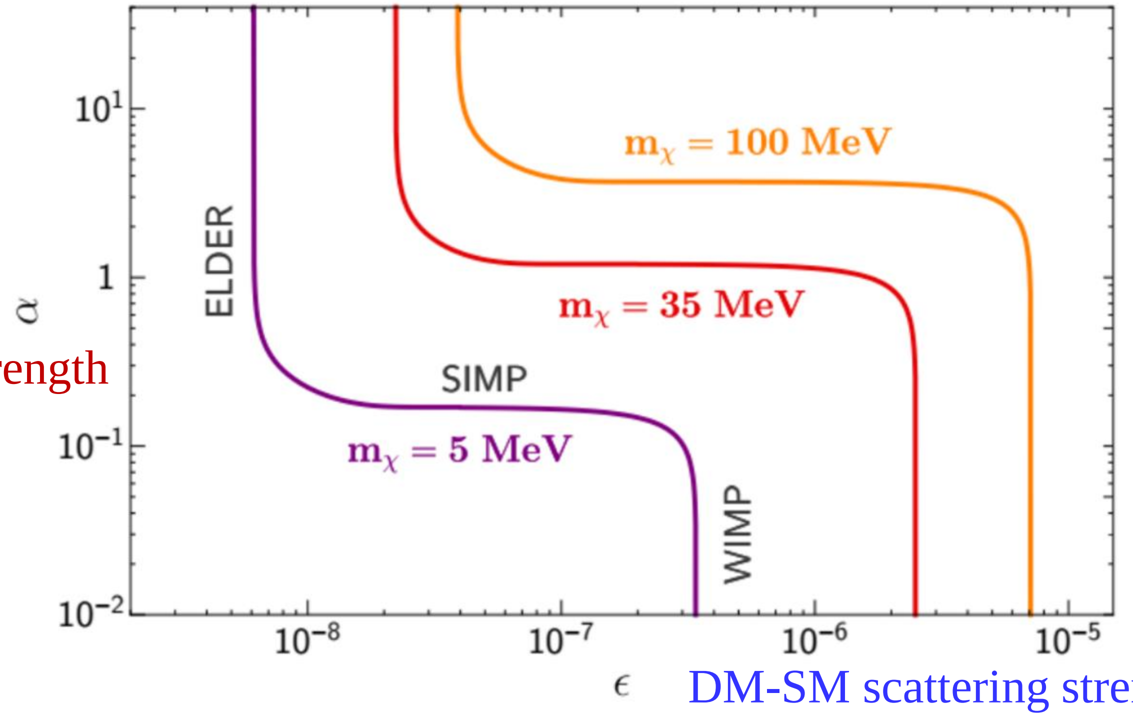
$$x'_f \sim \frac{3}{4} \log \left(\frac{M_{\rm Pl}}{m_\chi} \right) - \frac{x_d}{2} + \frac{9}{4} \log \alpha .$$

$$\Omega_\chi \sim \frac{10^6 m_{\rm MeV} \exp(-10 \epsilon_{-9}^{1/2} m_{\rm MeV}^{-1/4})}{1 + 0.07 \log \alpha}, \quad \epsilon_{-9} \equiv \epsilon / 10^{-9}$$

- Co-moving entropy is already conserved, so freeze-out does not affect much
- Ω depends logarithmically on α & exponentially on ε.
- **Elastic scattering determines the relic abundance!**

The "Phase Diagram" of Different Thermal DMs

DM 3-2 strength



DM-SM scattering strength

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

$$\frac{\partial n_\chi}{\partial t} + 3Hn_\chi = -\langle\sigma v^2\rangle_{3\to 2}(n_\chi^3 - n_\chi^2 n_\chi^{\rm eq}) - \left(\langle\sigma v\rangle_{\chi{\rm ann}} n_\chi^2 - \langle\sigma v\rangle_{\gamma{\rm ann}}(n_\gamma^{\rm eq})^2\right).$$

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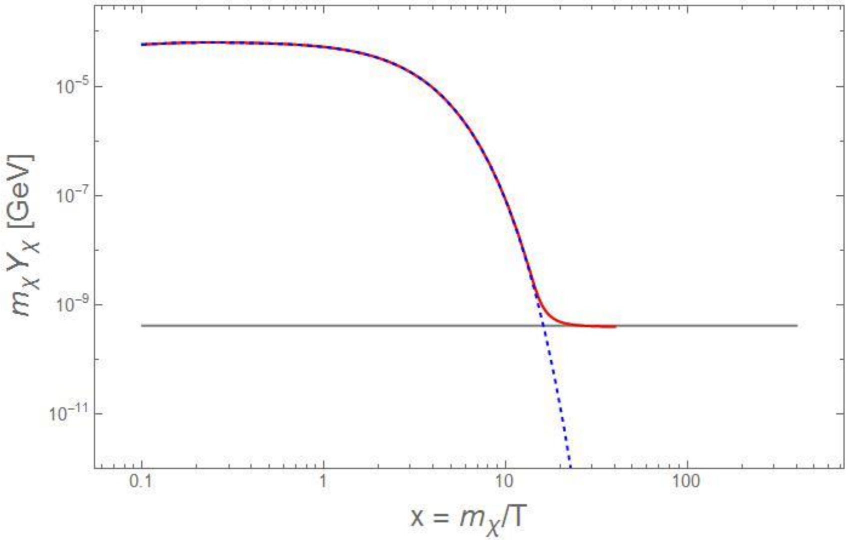
The SIMP Dark Matter

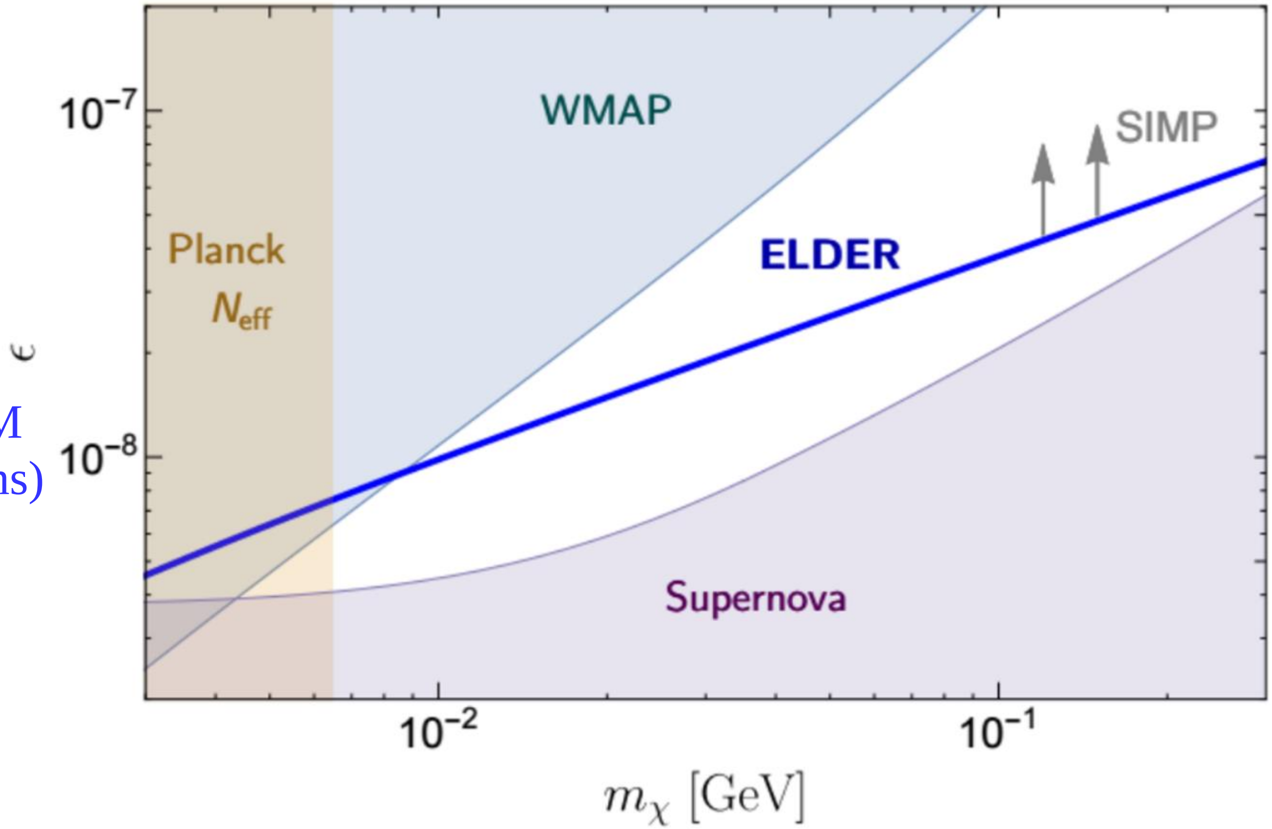
Yonit Hochberg, Eric Kuflik, Hitoshi Murayama, Tomer Volansky, Jay Wacker. arXiv:1402.5143, arXiv:1411.3727 & arXiv:1512.07917

- Strongly Interacting Massive Particles
- Always thermalized with SM before freezing out:
- The thermal history is similar to WIMP but relic governed by 3-2 freeze-out.



Constraints on the ELDER/SIMP parameter space

DM-SM
(photons)



- For ELDER/SIMP that couples to photons

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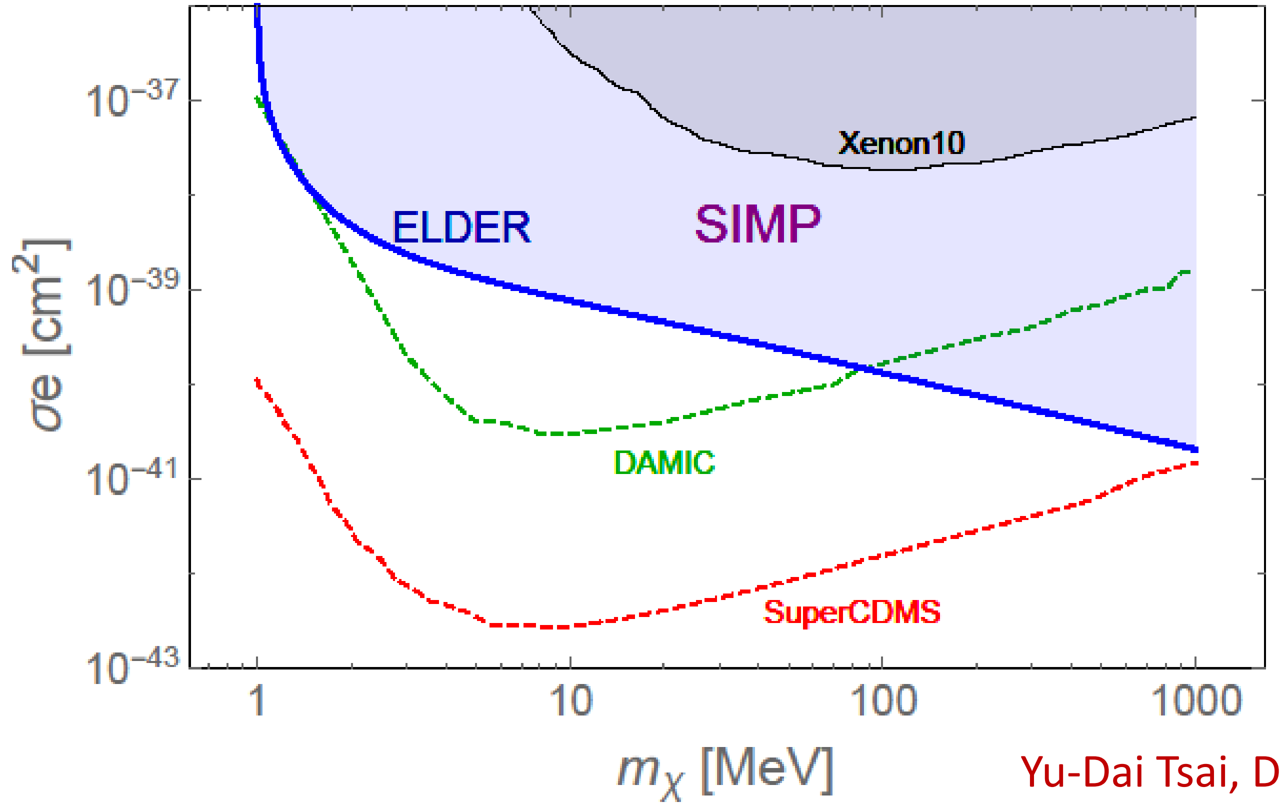
ELDER/SIMP direct detection!



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- 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 (presented by Tien-Tien on Tuesday)

Conclusion and Outlook

- New mechanism of having the right DM relic abundance governed by <u>Elastic Scattering/Decoupling</u>!

  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 DM-SM mediator is close to EW scale.

- Concrete & Interesting models are underway! Exploring other experimental/observational signatures

Thanks

Special thanks go to my collaborators Eric, Maxim and Nic
(Thank Gordan Krnjaic for the title of the talk)

Yu-Dai Tsai, DI 2016