Cosmology of Thermal Dark Sectors

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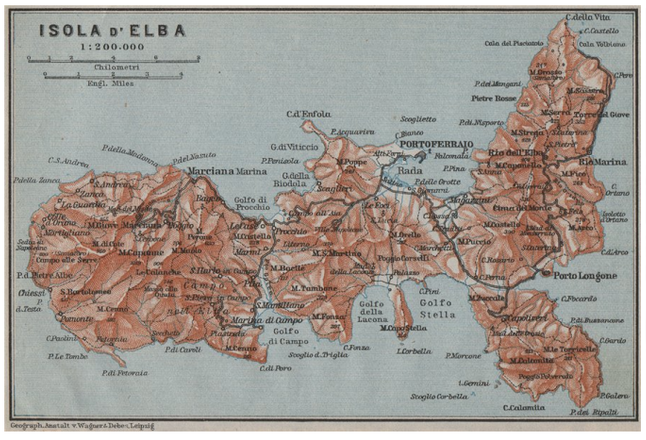
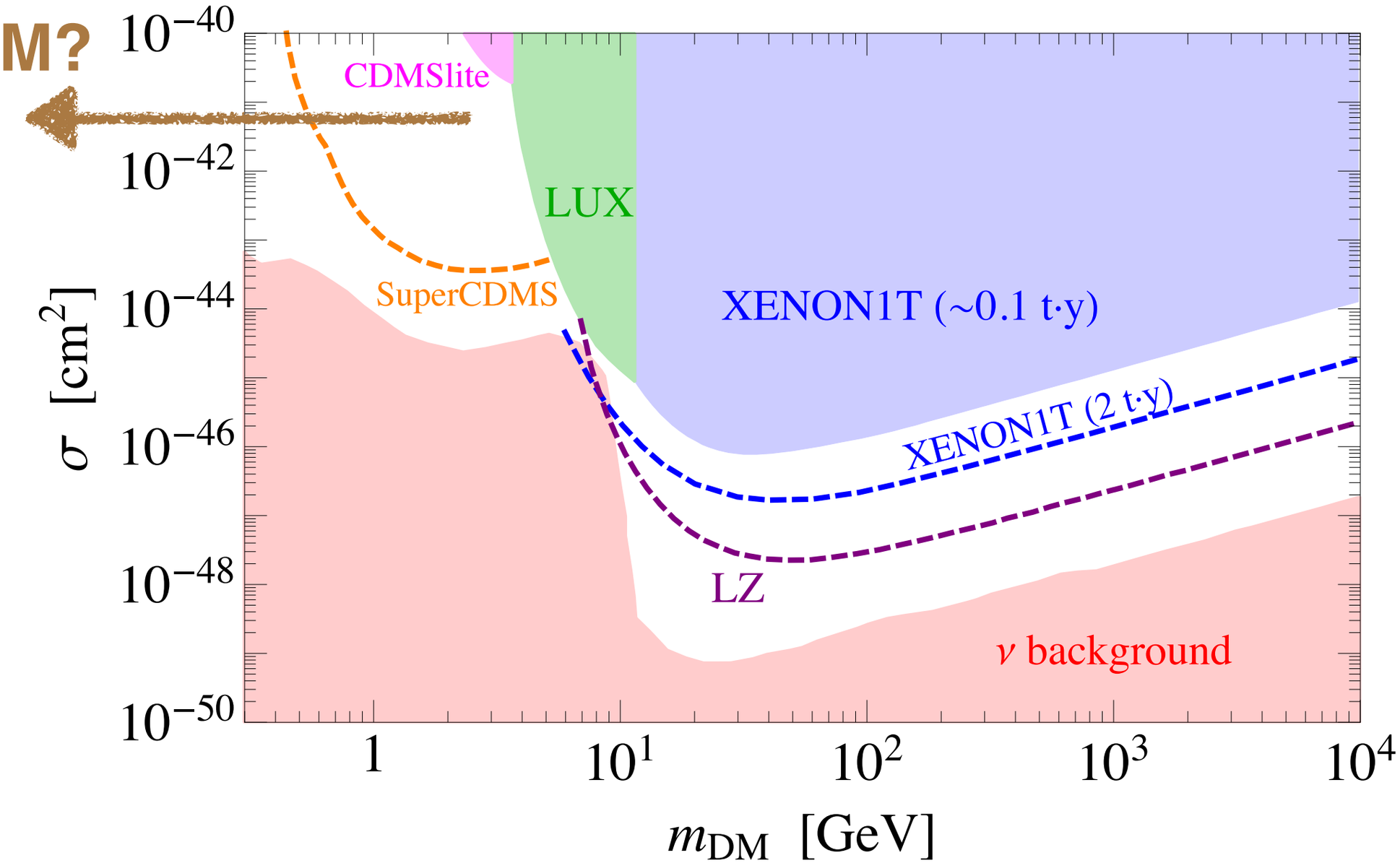
@Elba, 5/26/2017



Direct Detection vs. Dark Matter

light DM?

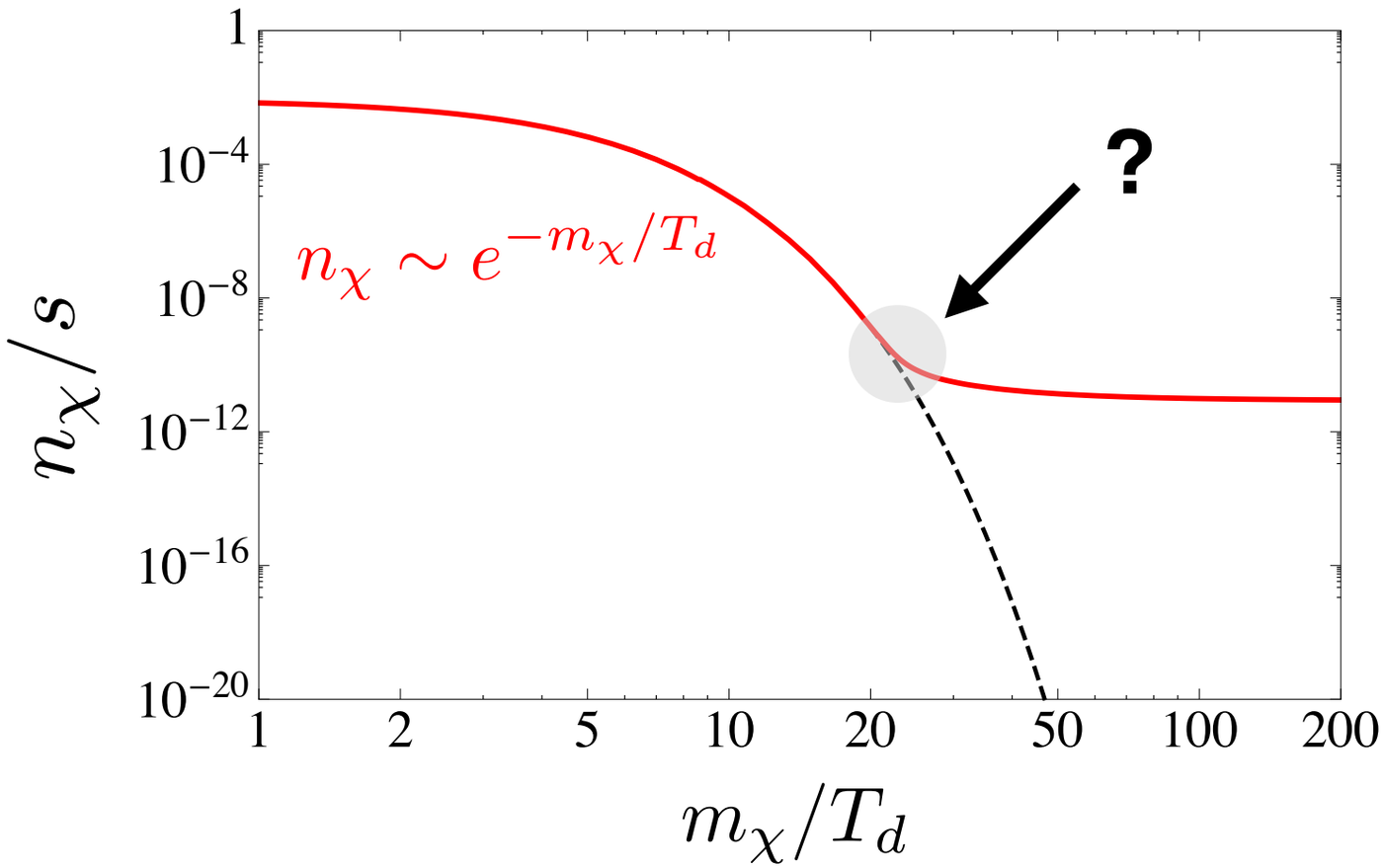


- XENON, **1512.07501**
- LZ, **1509.02910**
- SuperCDMS, **1610.00006**

Thermal Relic Dark Matter

- thermal relic:

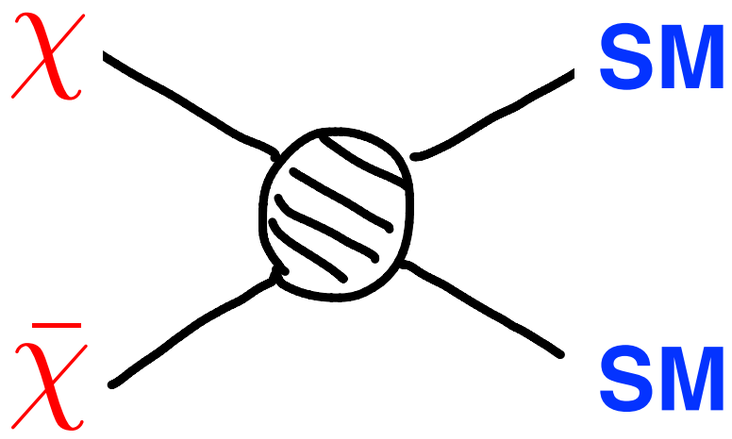
$$T_d \gtrsim m_{DM}$$



- assumptions for this talk:

1) $T_d \sim T_\gamma$
2) symmetric
3) no late entropy production

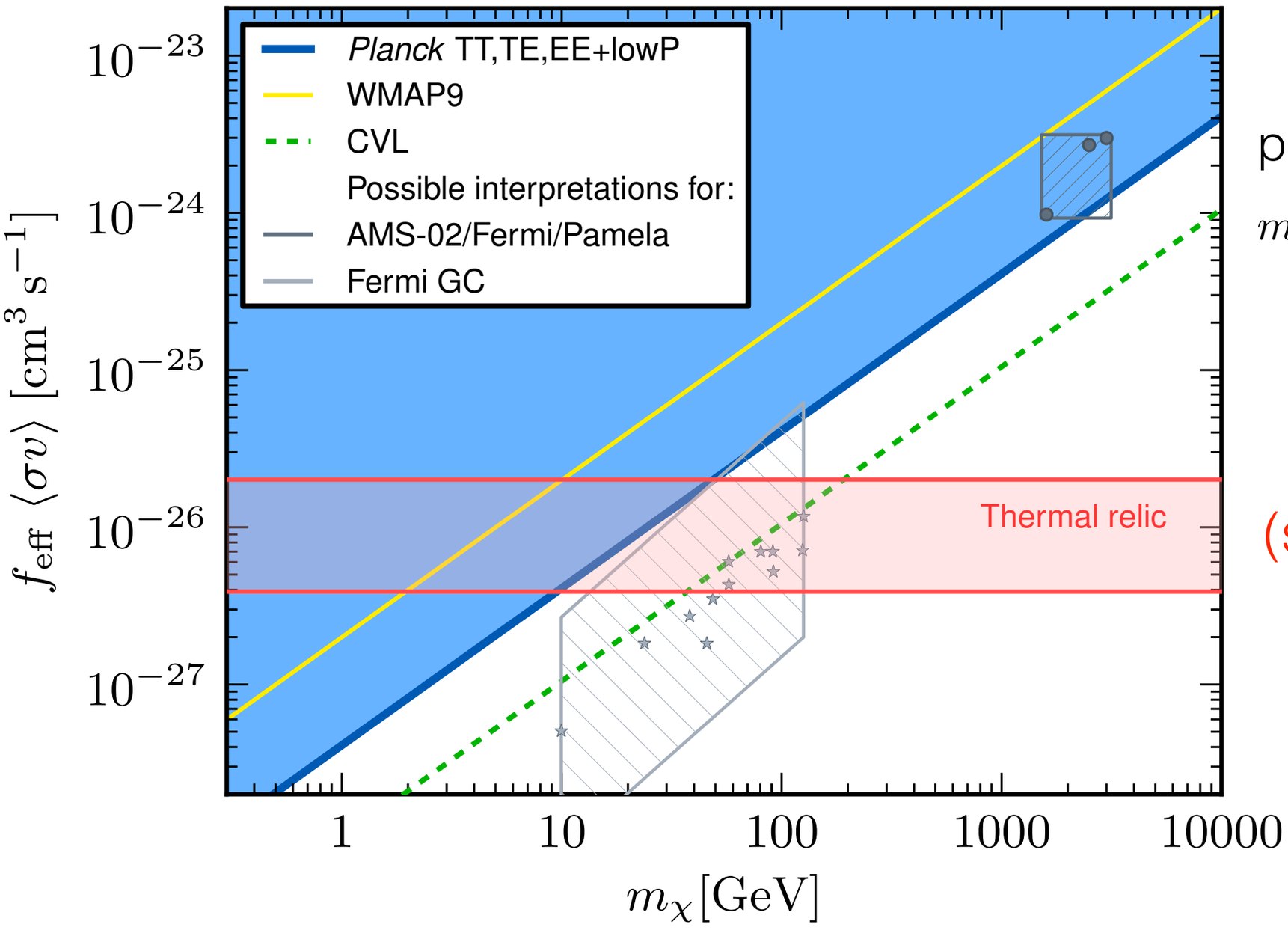
WIMP "Miracle"



$$\langle \sigma v \rangle \sim \frac{\alpha_W^2}{m_\chi^2}$$

- freezeout: $n_\chi \langle \sigma v \rangle = H$
- abundance: $\Omega_\chi h^2 \sim \frac{m_\chi n_\chi}{s\, T_{eq}} \sim \frac{1}{\langle \sigma v \rangle\, T_{eq} M_{pl}}$
- DM mass: $m_\chi \sim \alpha_W \sqrt{T_{eq} M_{pl}} \sim 1 \text{ TeV}$

CMB vs. Dark Matter



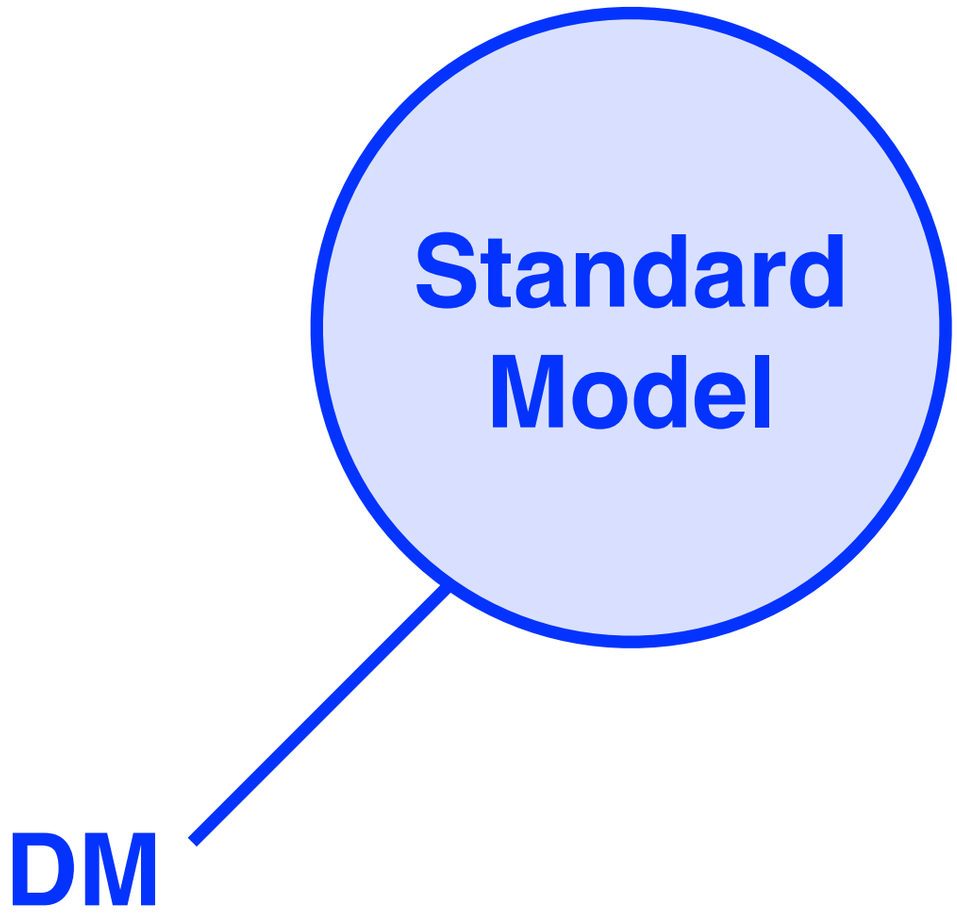
power:

$$m_{DM}\, n_{DM}^2 \propto \frac{1}{m_{DM}}$$

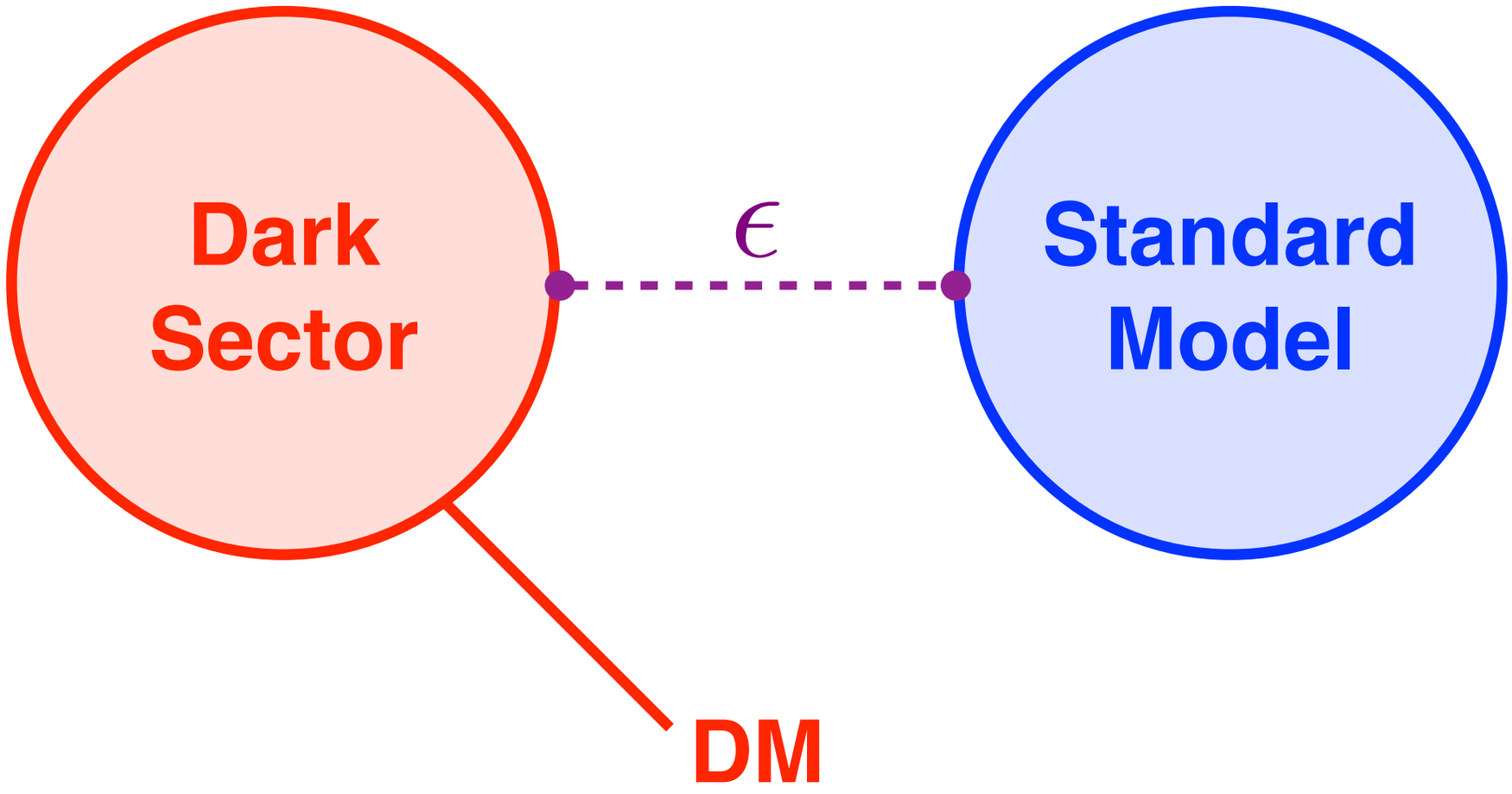
(s-wave)

- Planck, **1502.01589**
- Slatyer, **1506.03811**

Weakly Interacting Dark Matter



Hidden Sector Dark Matter



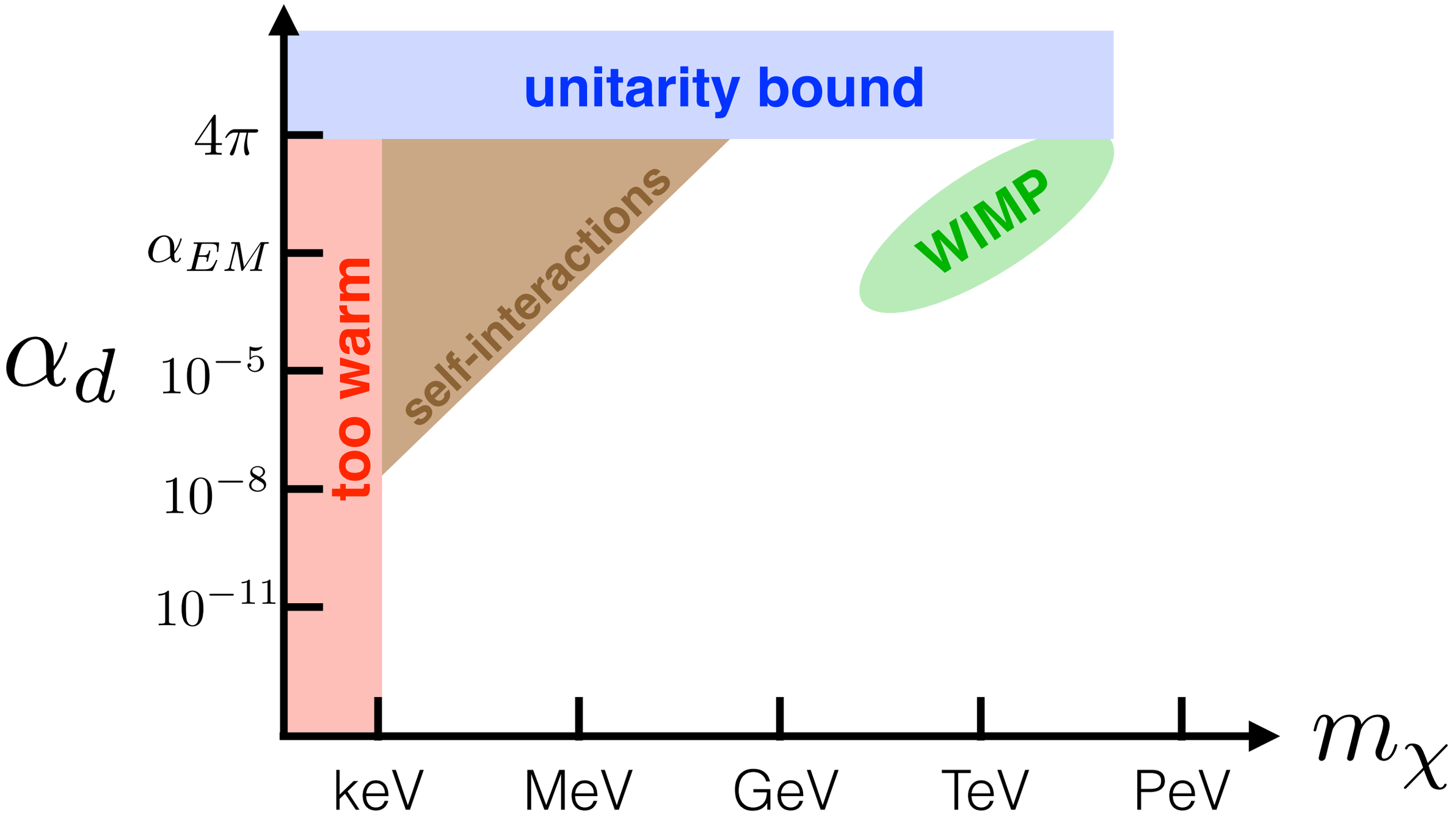
- Goldberg, Hall, **1986**
- Strassler, Zurek, **hep-ph/0604261**

plan

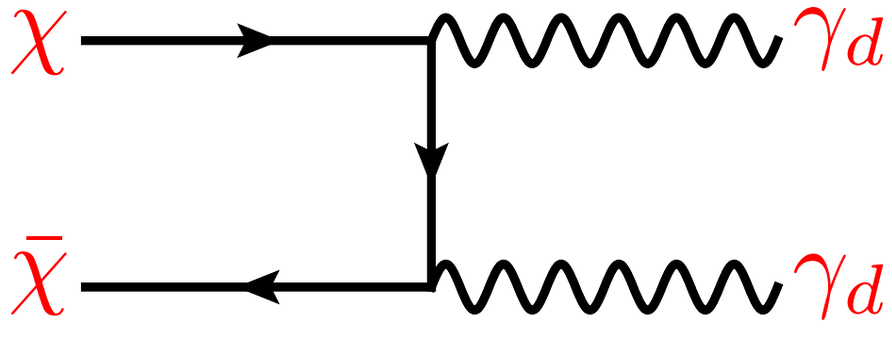
I. Dark Freezeout Map

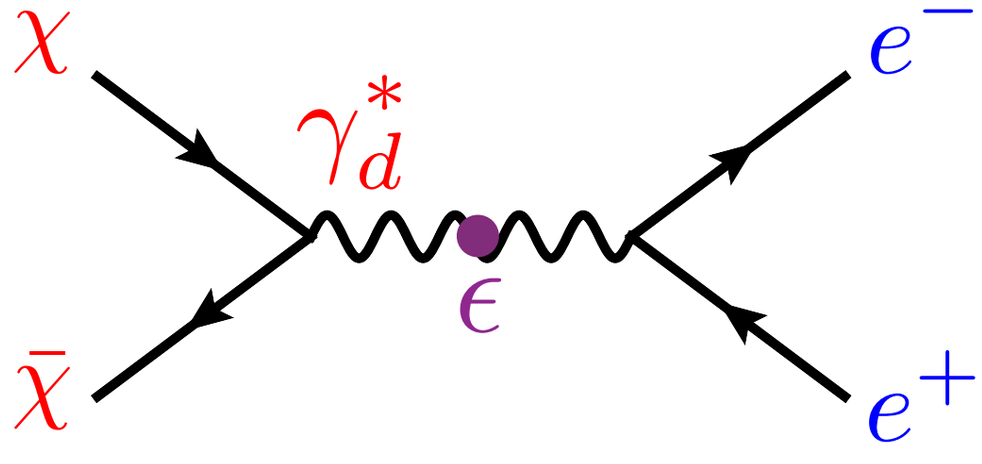
II. Annihilations with Multiple States

I. Dark Freezeout Map



Ultraweakly Interacting Dark Matter





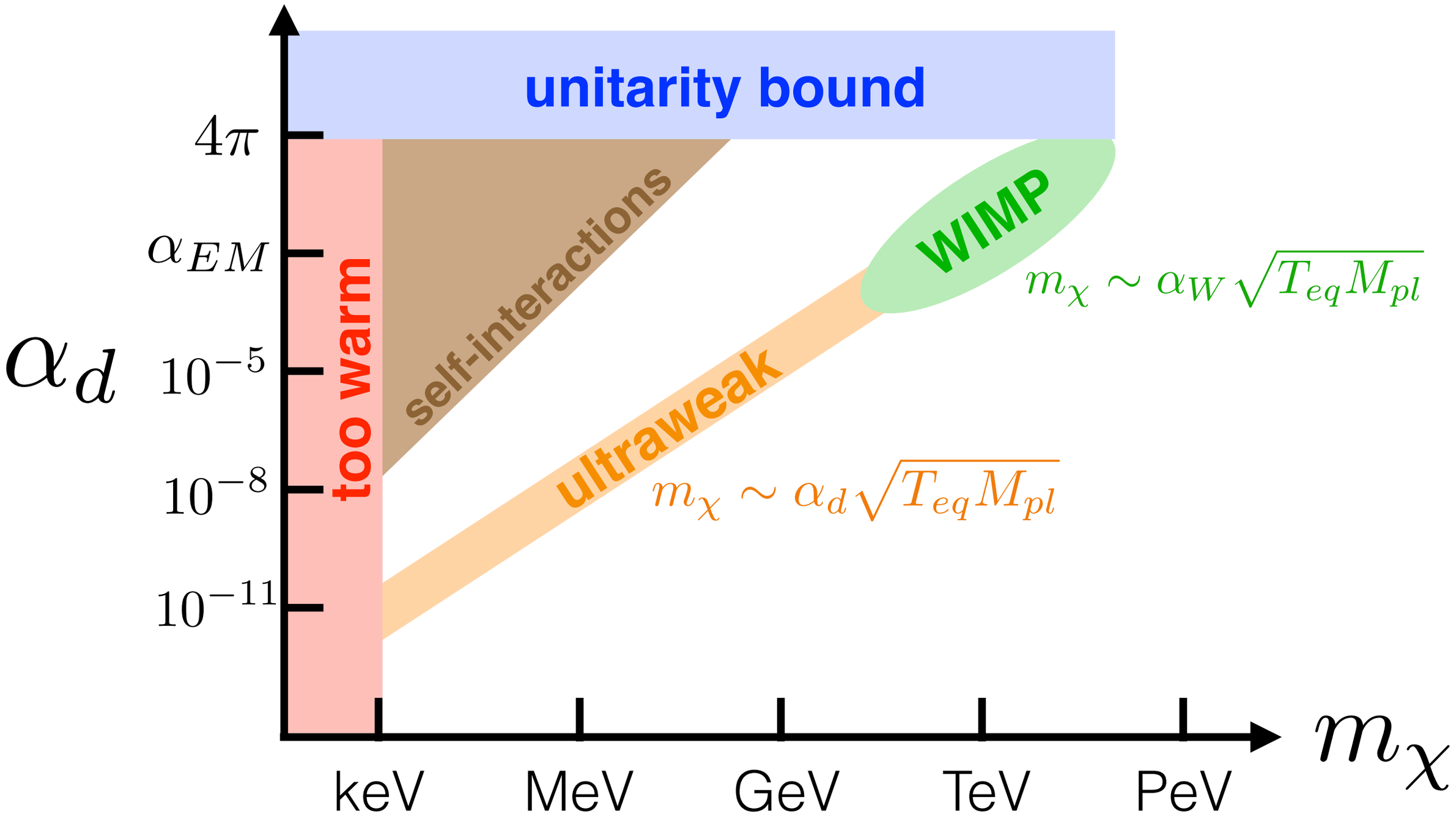
$$\langle \sigma v \rangle \sim \frac{\alpha_d^2}{m_\chi^2}$$

$$\alpha_d^{eff} = \epsilon \sqrt{\alpha_d \alpha_{EM}} \frac{m_\chi^2}{m_{\gamma_d}^2}$$

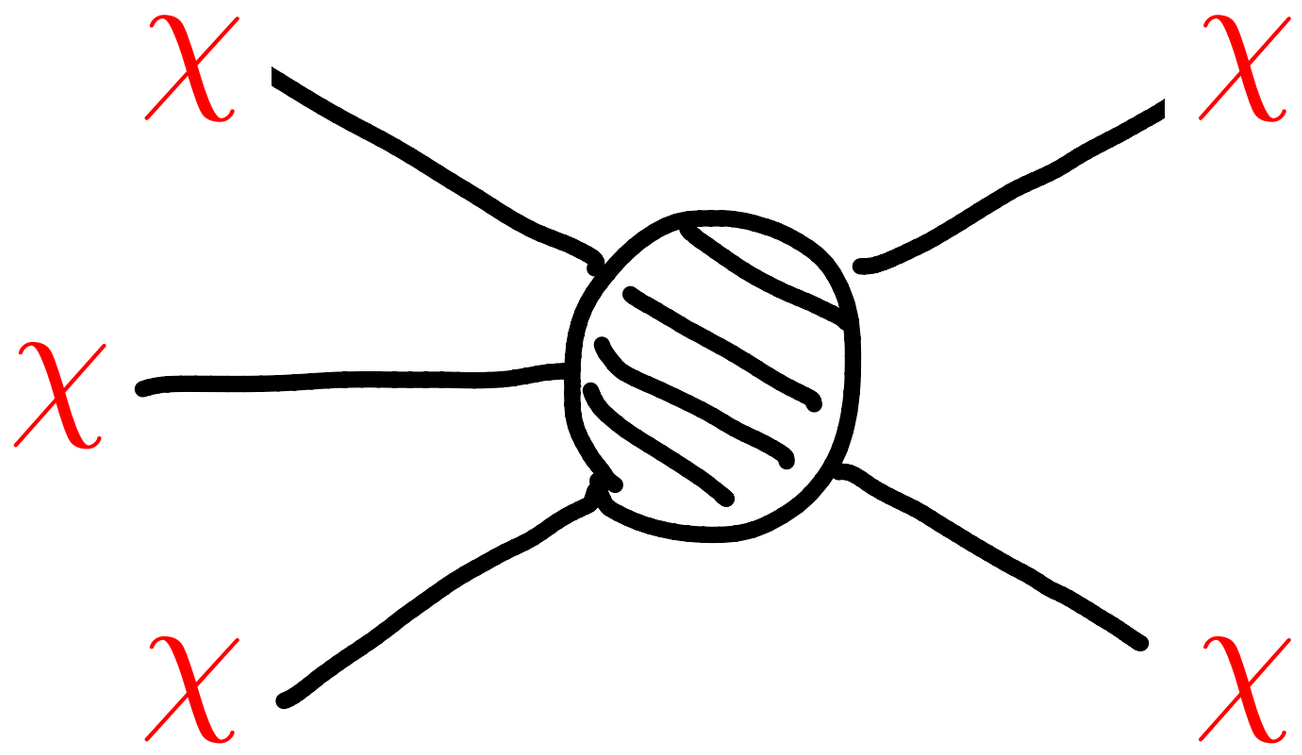
$$m_\chi \sim \alpha_d \sqrt{T_{eq} M_{pl}} \sim \left(\frac{\alpha_d}{\alpha_W} \right) \times 1 \text{ TeV}$$

- Boehm, Fayet, **hep-ph/0305261**
- Finkbeiner, Weiner, **astro-ph/0702587**
- Pospelov, Ritz, Voloshin, **0711.4866**
- Feng, Kumar **0803.4196**

Dark Freezeout Map



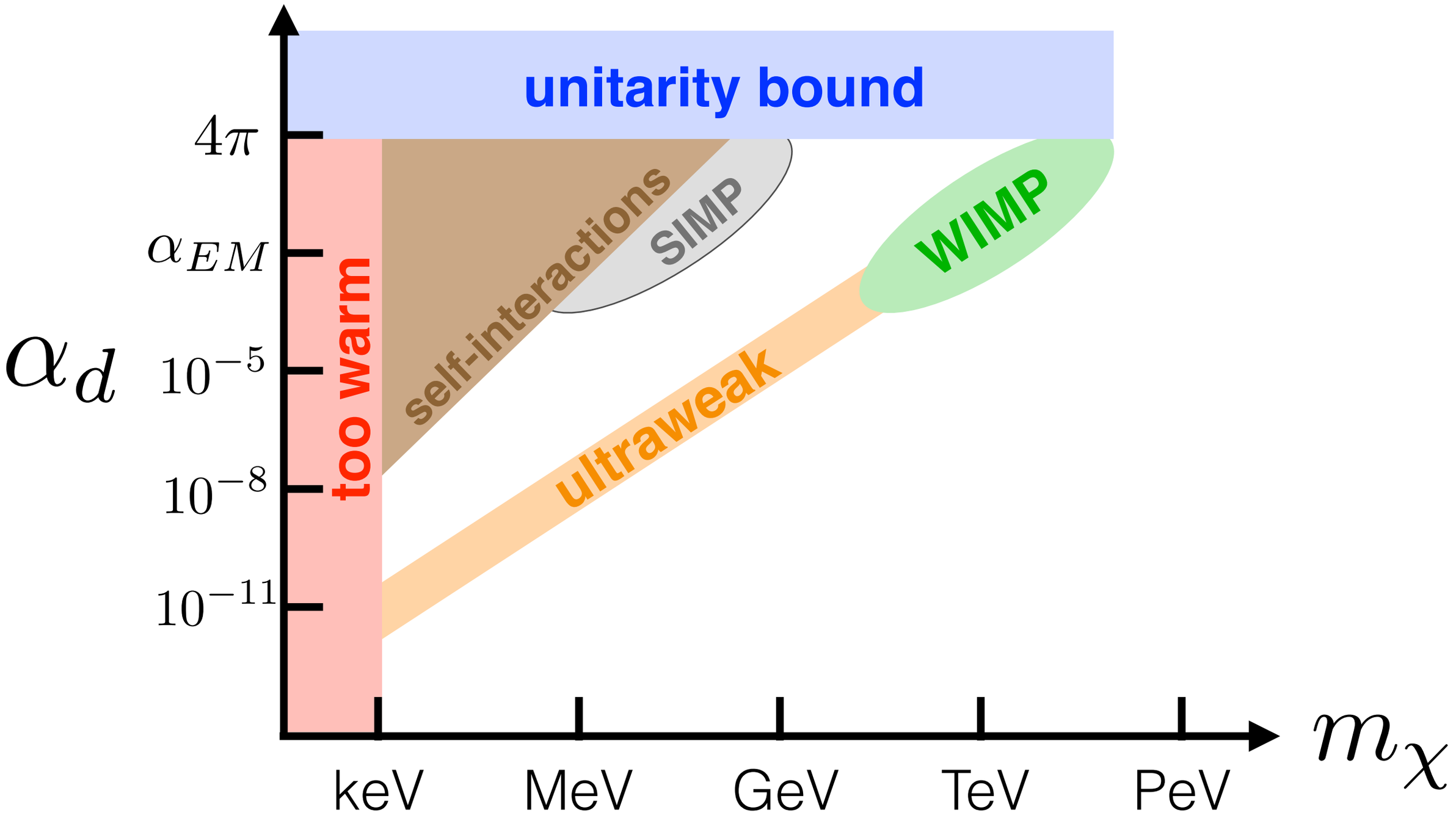
Strongly Interacting Massive Particles (SIMPs)



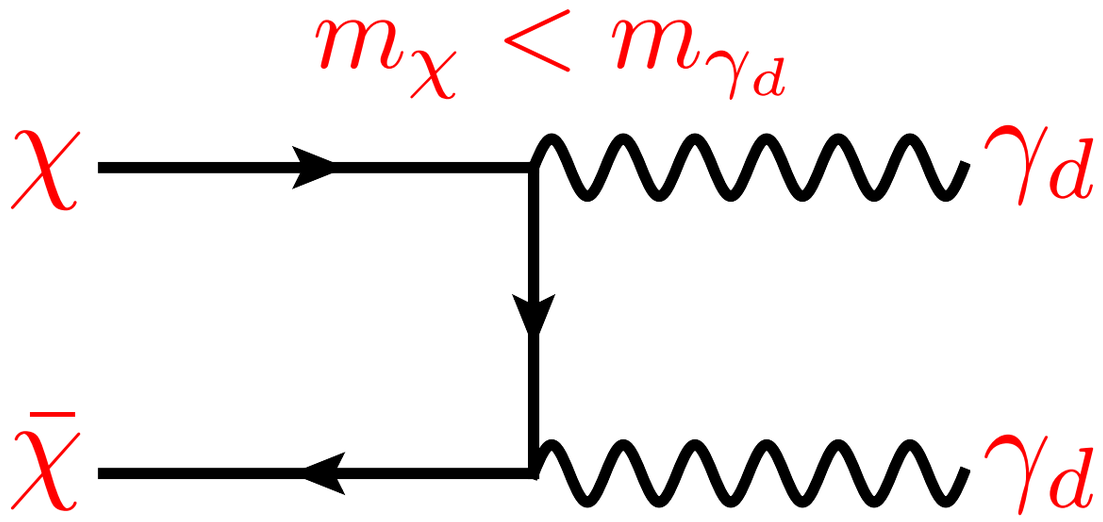
$$m_\chi \sim \alpha_{eff} \left(T_{eq}^2 M_{pl}\right)^{1/3} \sim \alpha_{eff} \times 100 \text{ MeV}$$

- Hochberg, Kuflik, Volansky, Wacker **1402.5143**

Dark Freezeout Map



Forbidden Dark Matter

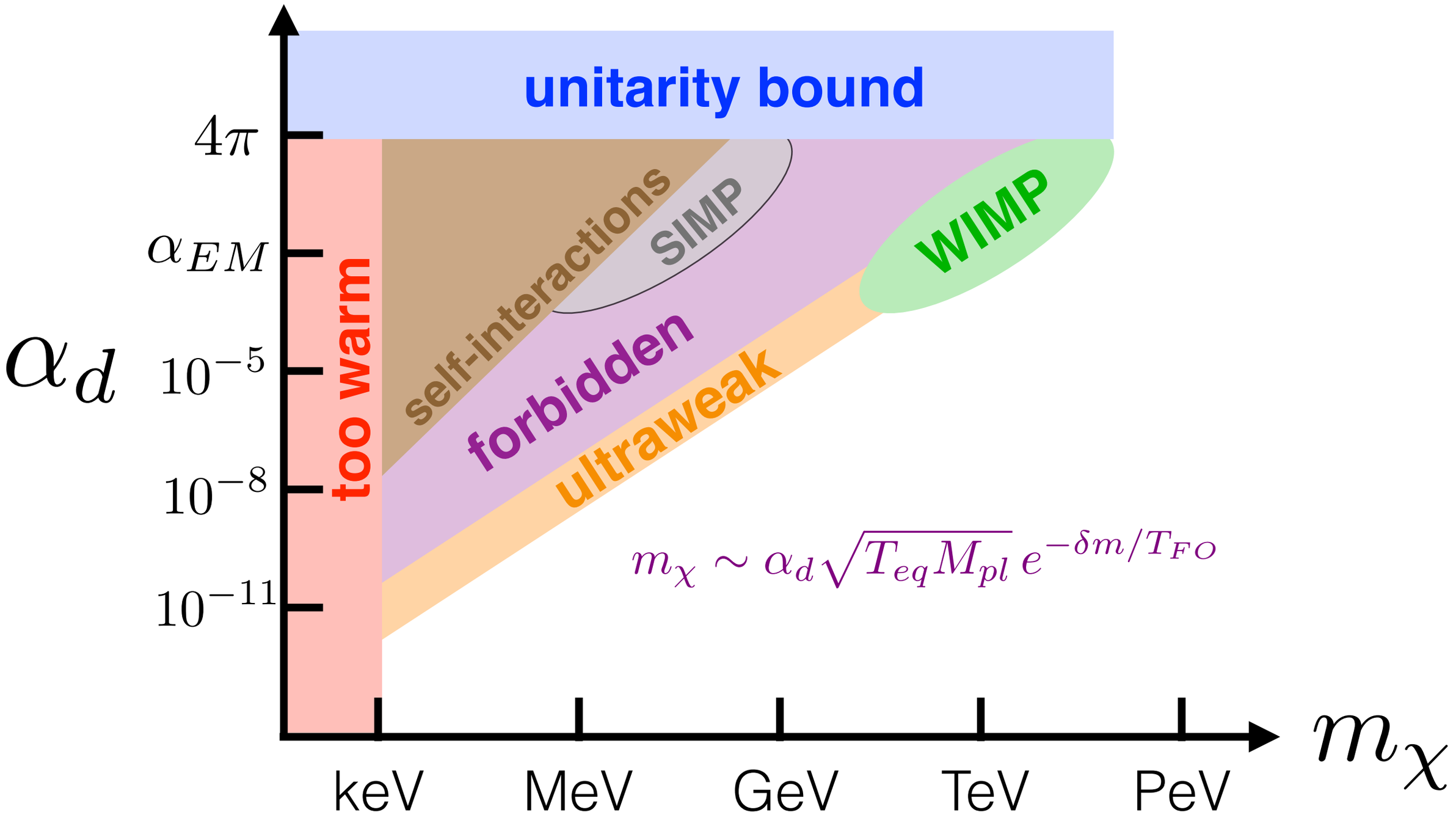


$$\delta m = m_{\gamma_d} - m_\chi$$

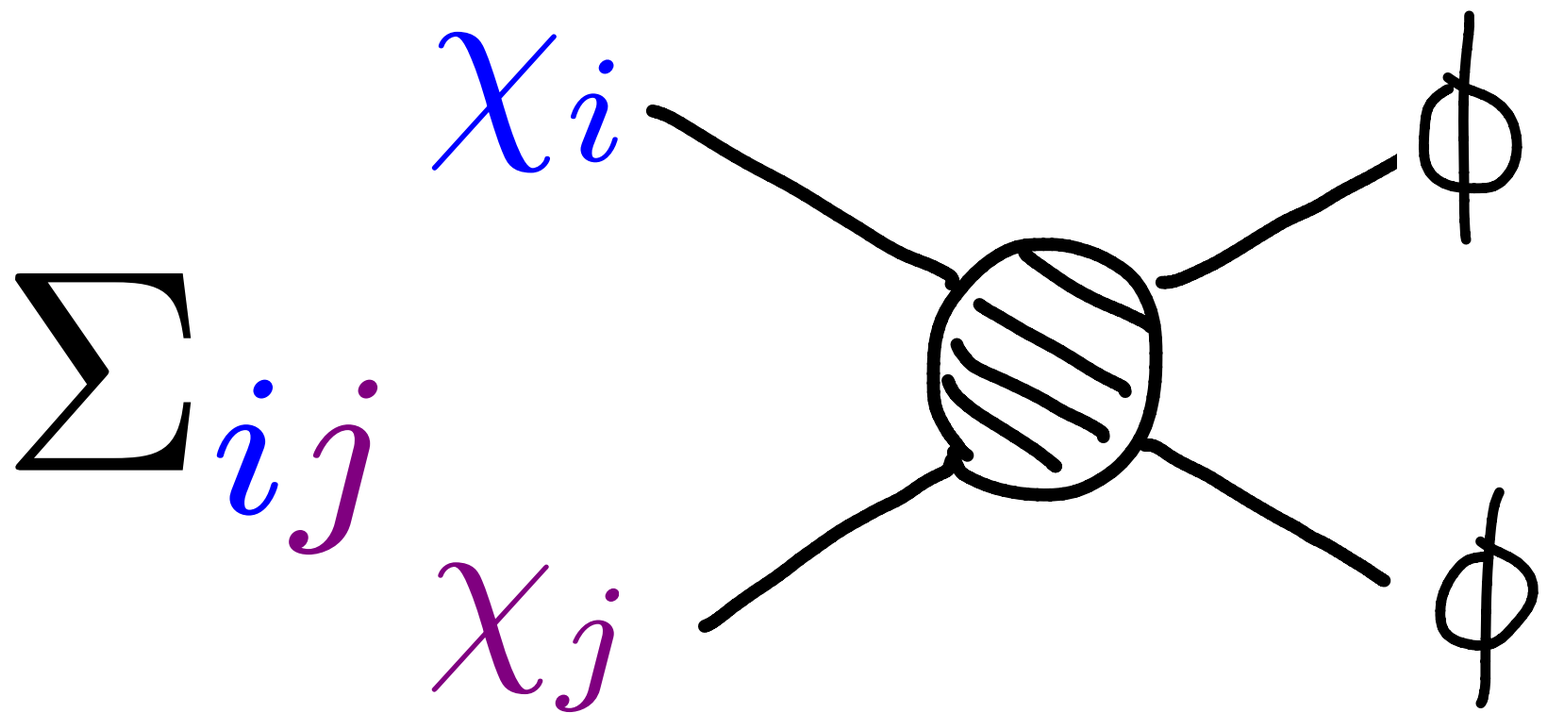
- thermal average: $\langle \sigma v \rangle \sim \frac{\alpha_d^2}{m_\chi^2} e^{-2\delta m/T}$
- dark matter mass: $m_\chi \sim \alpha_d \sqrt{T_{eq} M_{pl}}\, e^{-\delta m/T_{FO}}$
- evades CMB: $T_{CMB} \ll \delta m$

  - Griest, Seckel, **1991**
  - D'Agnolo, JTR, **1505.07107**

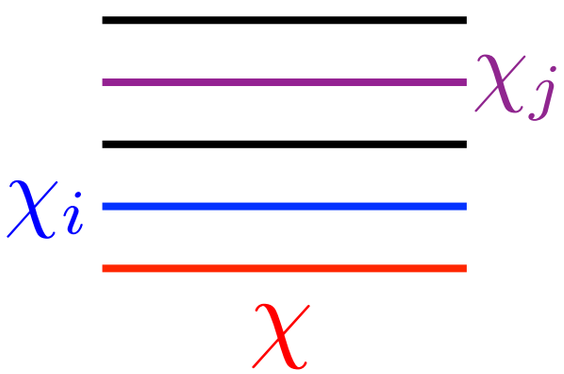
Dark Freezeout Map



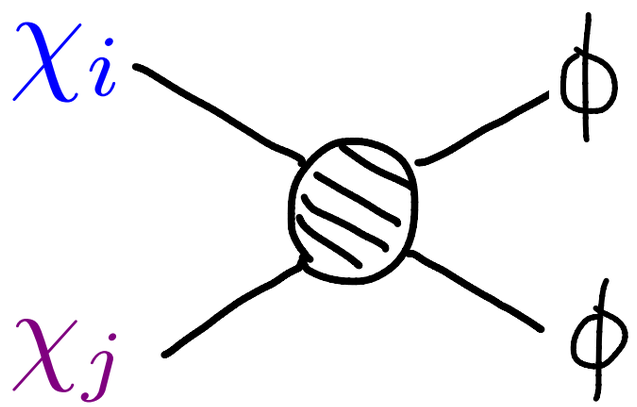
II. Annihilations with Multiple States



Coannihilations



Σ_{ij}



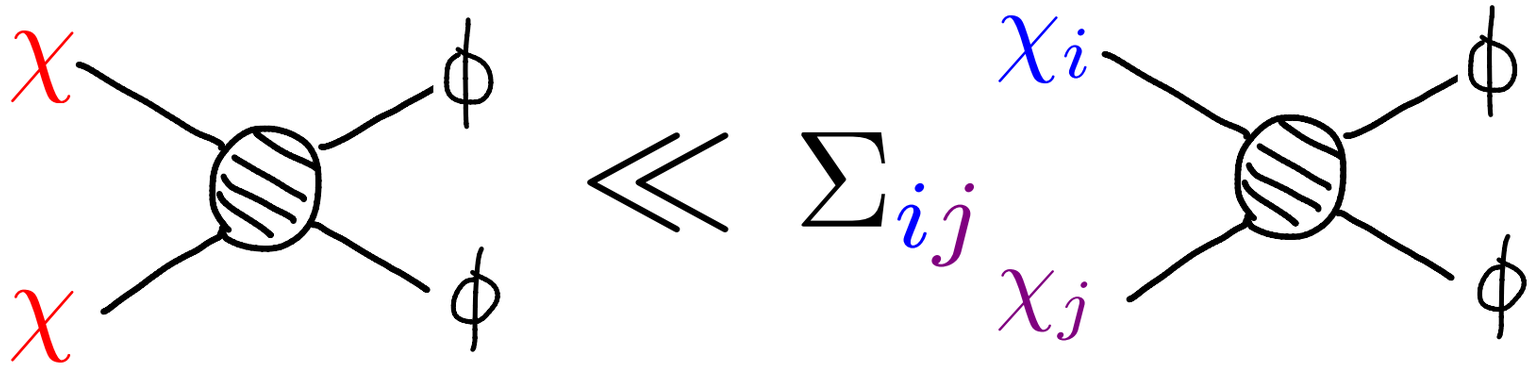
$$\langle \sigma_{eff} v \rangle = \sum_{i,j} \frac{n_i^{eq} n_j^{eq}}{(n_\chi^{eq})^2} \langle \sigma_{ij} v \rangle$$

(assume: $\chi \leftrightarrow \chi_i$ in equil.)

$$\delta m_i = m_i - m_\chi$$

- DM mass: $m_\chi \sim \alpha_d \sqrt{T_{eq} M_{pl}}\, e^{-(\delta m_i + \delta m_j)/T_{FO}}$

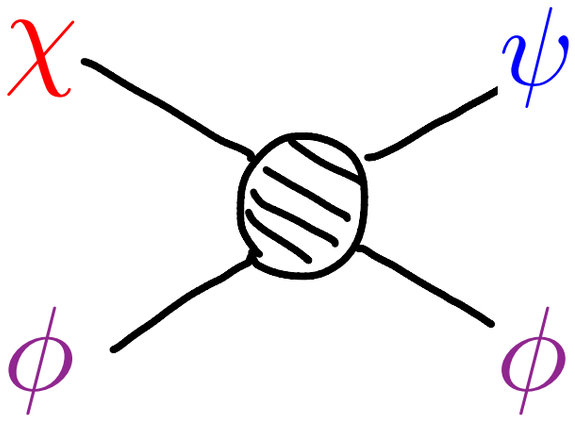
- evades CMB if:



- Griest, Seckel, **1991**

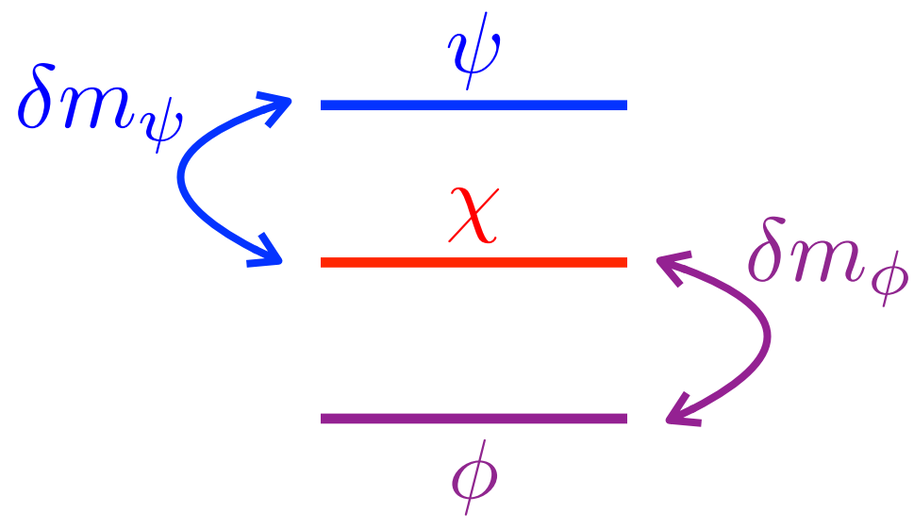
- JTR, *Beyond WIMPs*, 2015.
- D'Agnolo, Mondino, JTR, Wang, *to appear*.

Coscattering

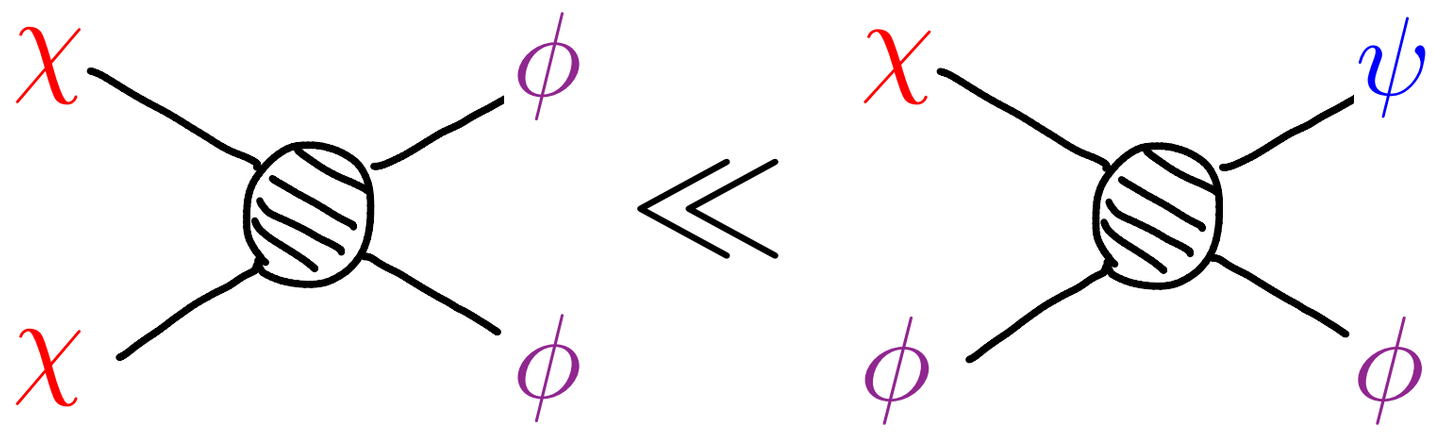


freezeout:

$$n_\phi^{eq} \langle \sigma v \rangle = H$$



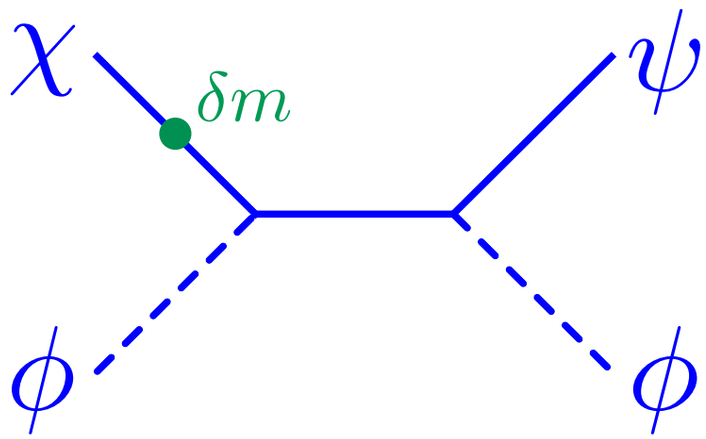
- DM mass: $m_\chi \sim \alpha_d \sqrt{T_{eq} M_{pl}}\, e^{-(\delta m_\psi - \delta m_\phi)/T_{FO}}$
- evades CMB:

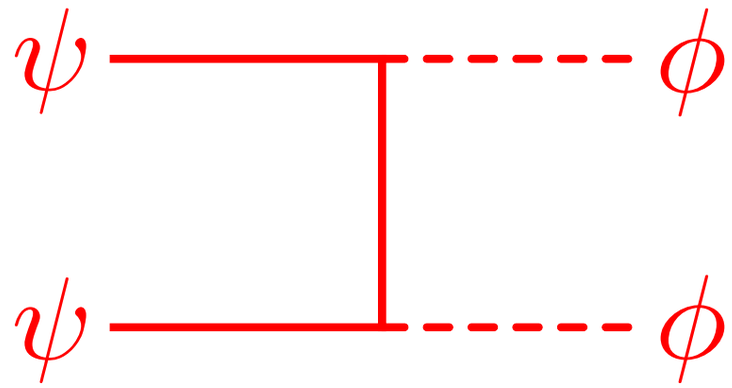


- D'Agnolo, Pappadopulo, JTR, **1705.08450**

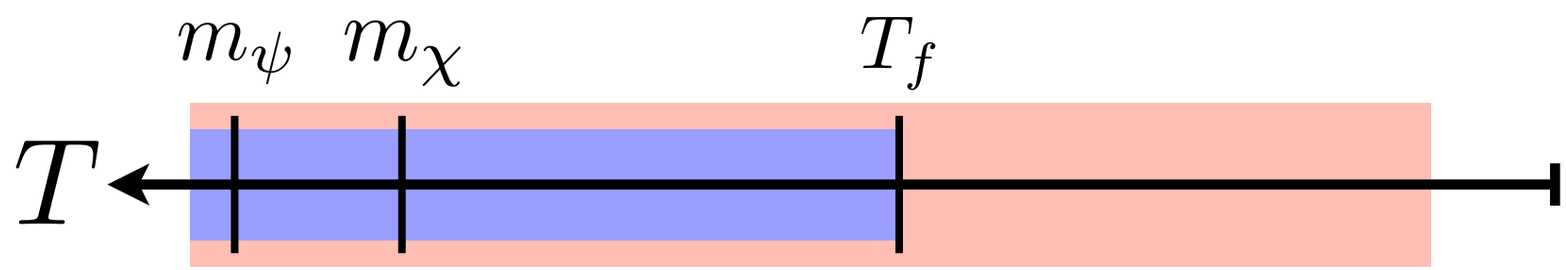
Coscattering vs. Coannihilations

$$\mathcal{L} \supset -\frac{m_\chi}{2}\chi^2 - \frac{m_\psi}{2}\psi^2 - \delta m \chi\psi - \frac{y}{2}\phi\psi^2$$

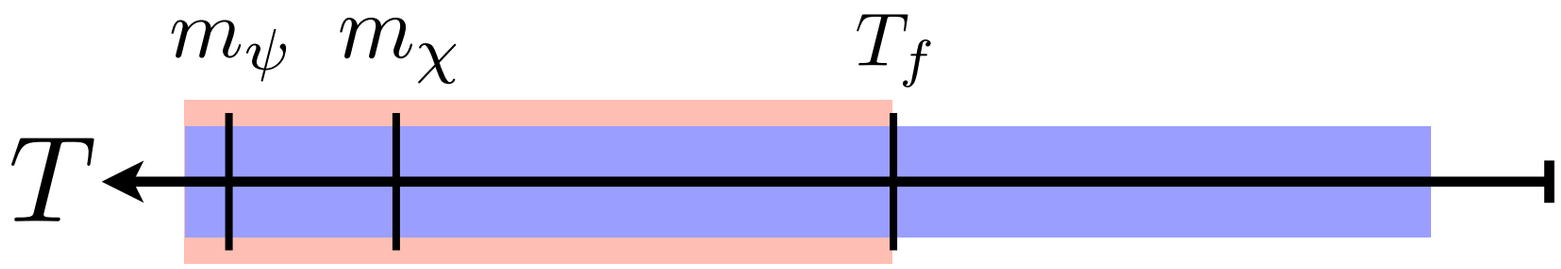




- coscattering:

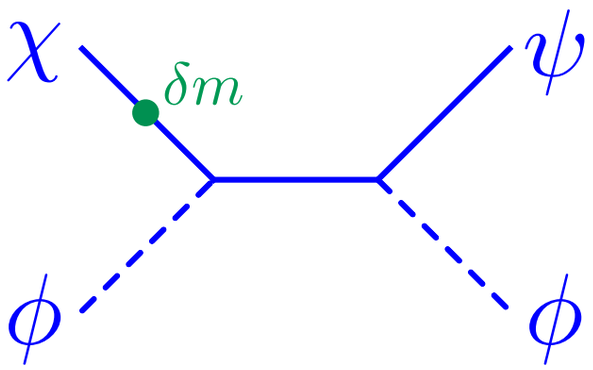


- coannihilations:

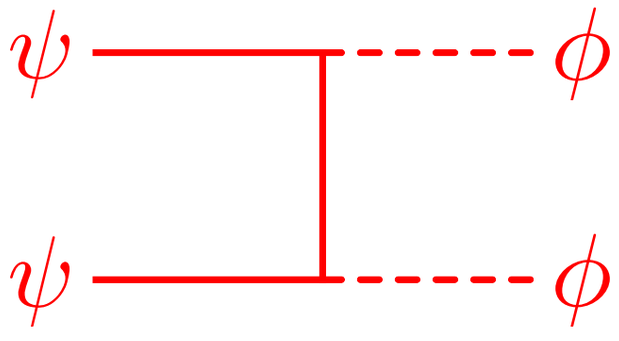


Coscattering vs. Coannihilations

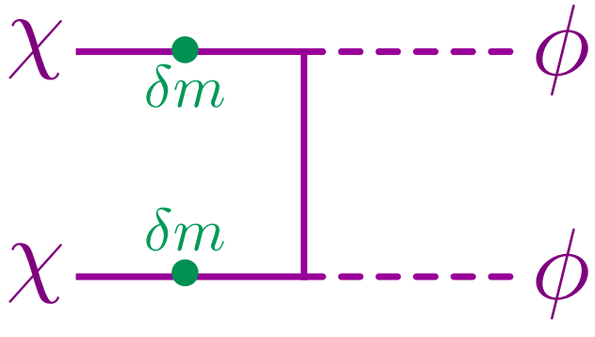
coscattering:

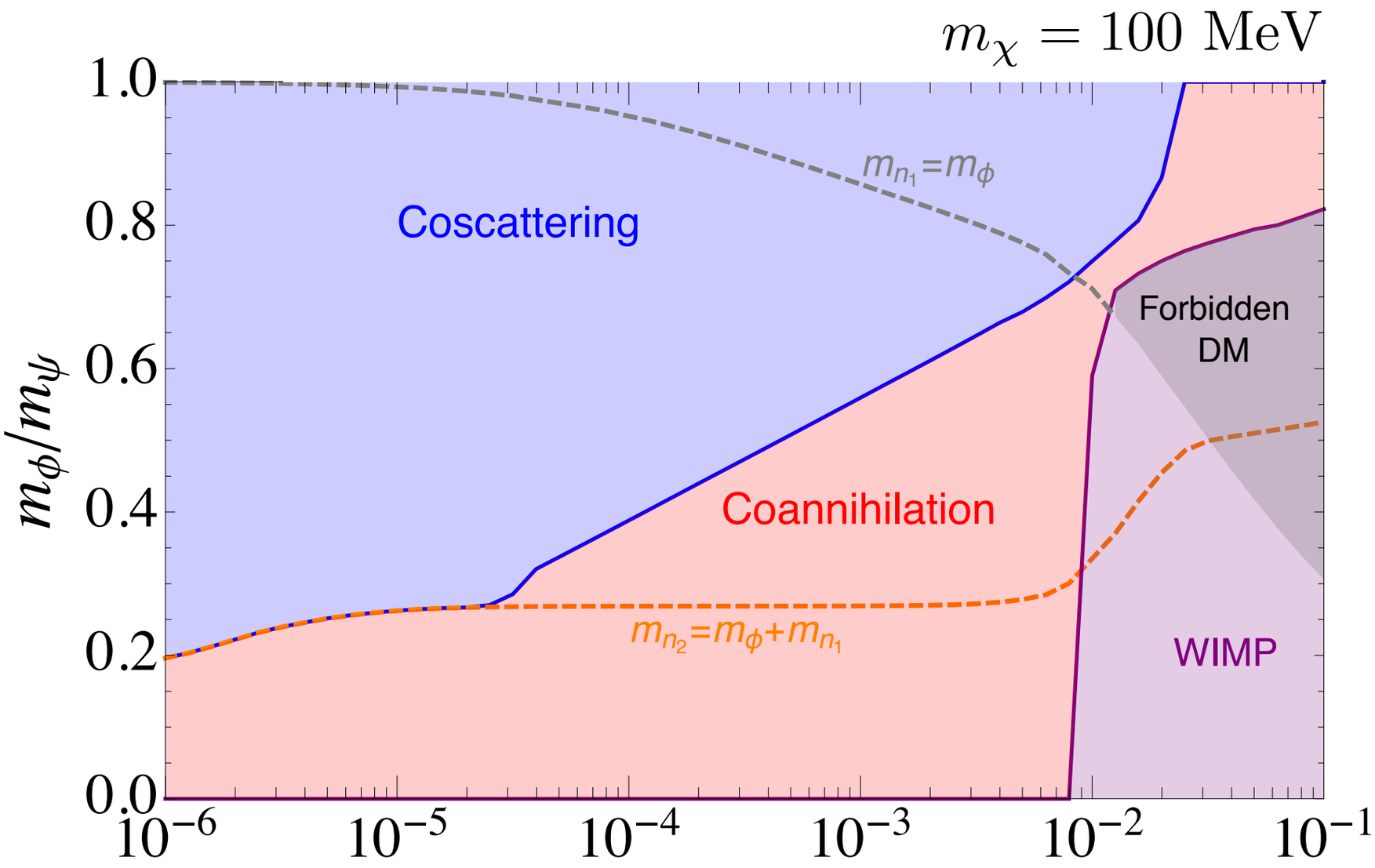


coannihilations:



WIMP:





this talk

Dark Mechanism Flow

dark matter

thermal

nonthermal

symmetric

asymmetric

inflaton decay

misalignment

3-to-2

2-to-2

thermal parent

WIMP

forbidden

freeze-in

superWIMP

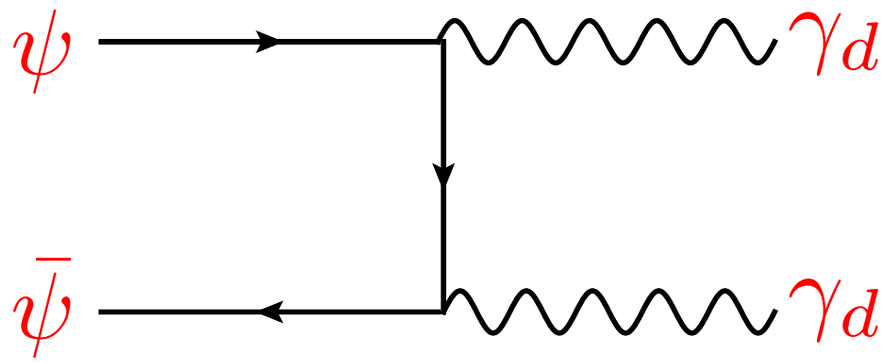
coannihilations

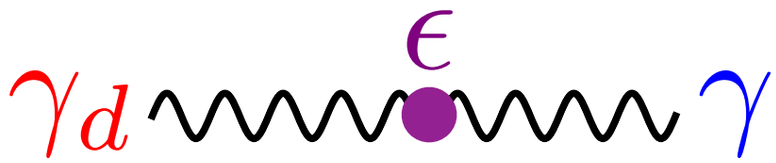
coscattering

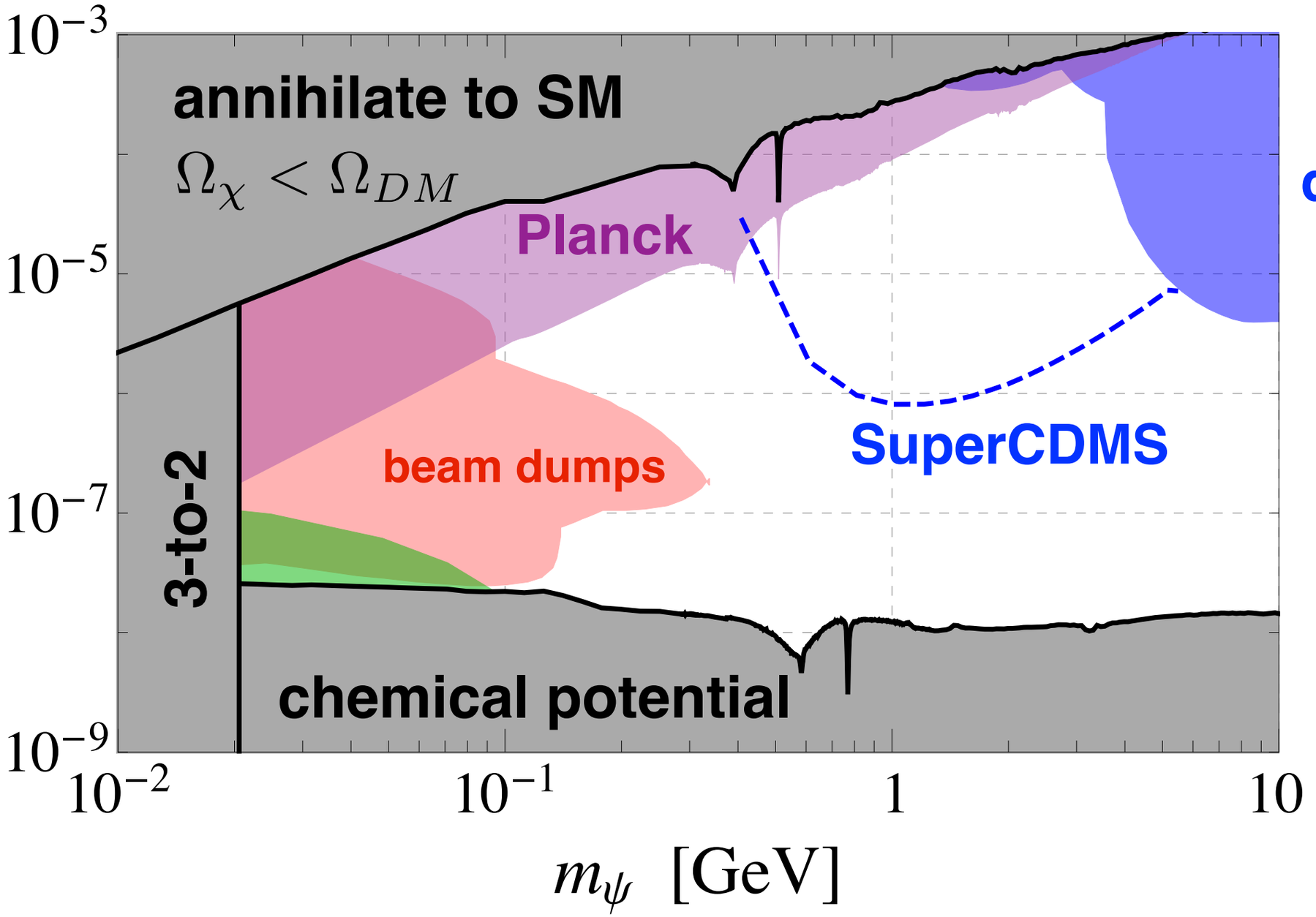
oscillations

backup

Forbidden DM Phenomenology







Coscattering Phenomenology