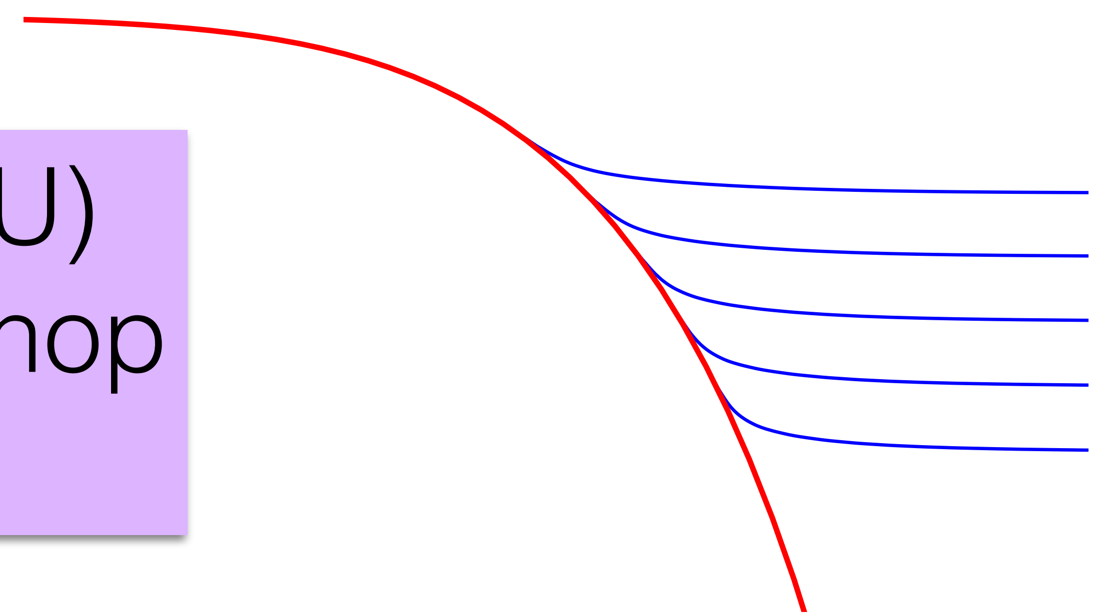
NYU

Center for Cosmology and Particle Physics

Dark Matter Targets with Exponentially Small Couplings



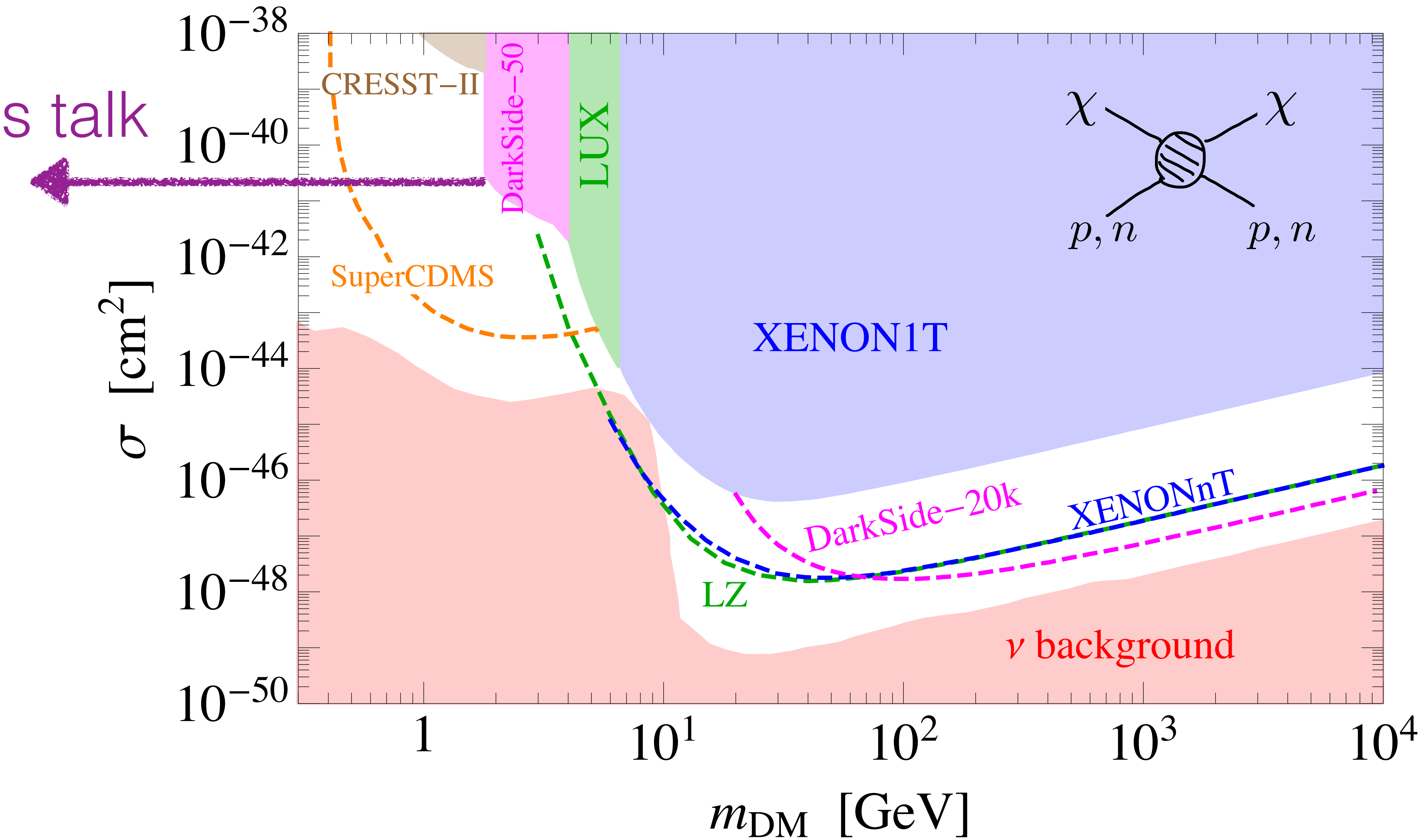
Josh Ruderman (NYU)

Johns Hopkins Workshop @IPMU, 6/7/2019

work with: Raffaele D'Agnolo, Cristina Mondino, Duccio Pappadopulo, Po-Jen Wang

Direct Detection vs. Dark Matter

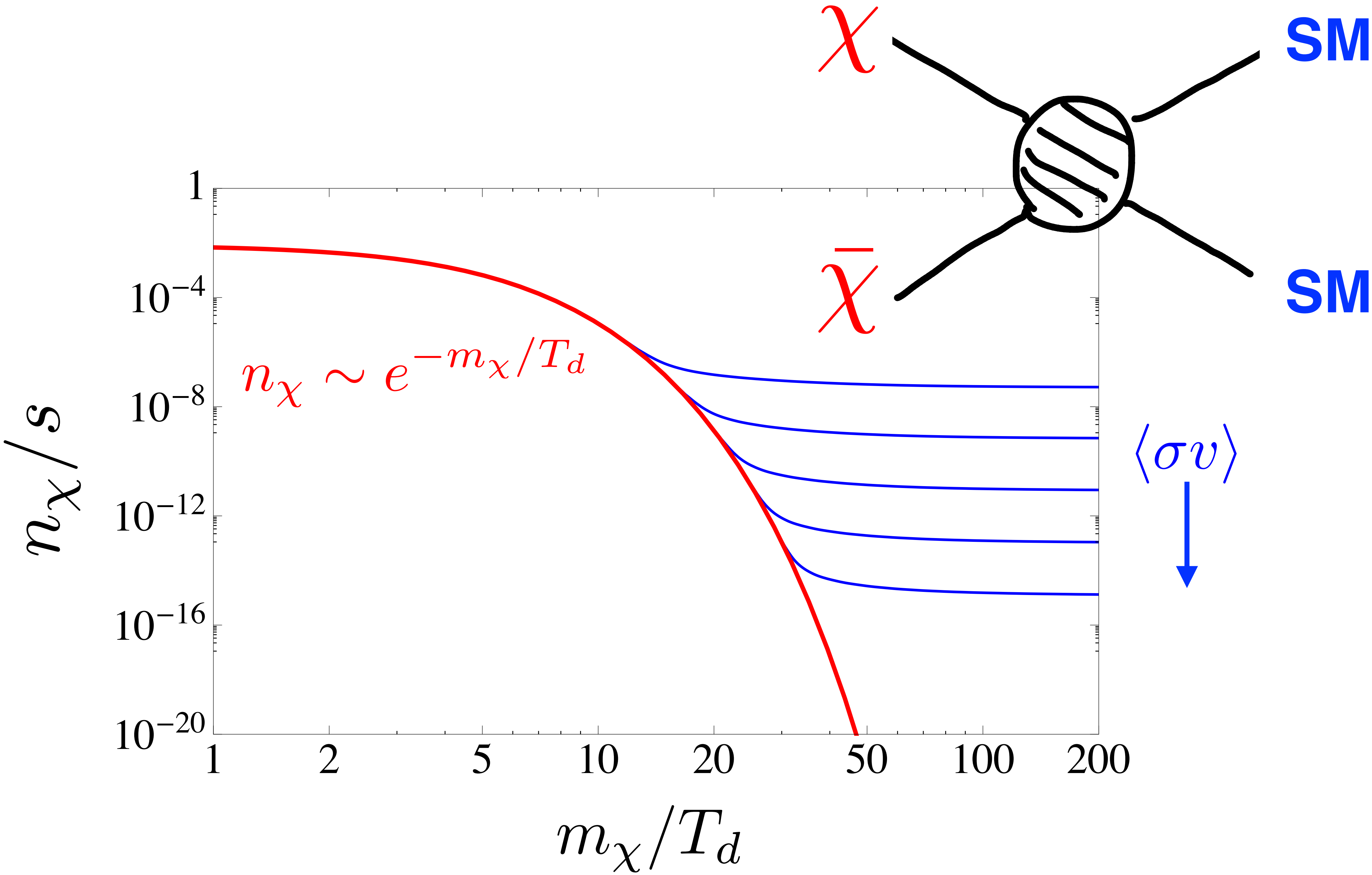
this talk



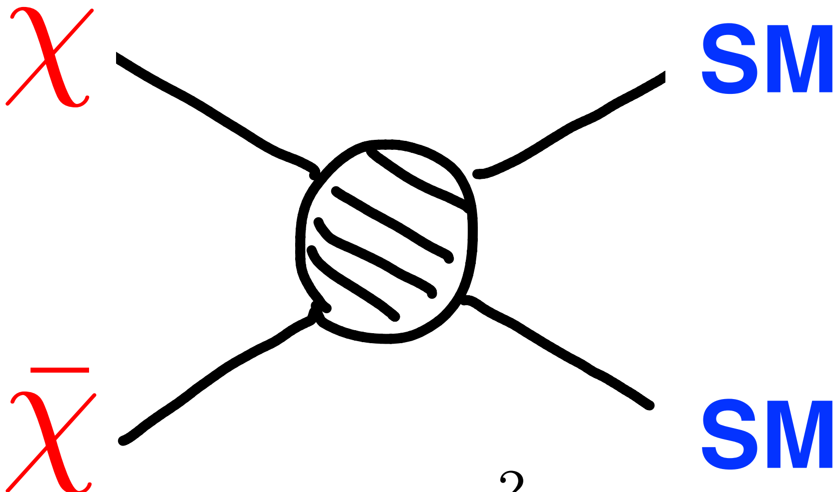
- SuperCDMS, **1610.00006**

- XENONnT, **1512.07501**
- LZ, **1802.06039**
- DarkSide-20k, **1707.08145**

WIMP "Miracle"



WIMP "Miracle"



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

- freezeout: $n_\chi \langle \sigma v \rangle \sim H$

$H \sim T^2/M_{pl}$

$s \sim T^3$

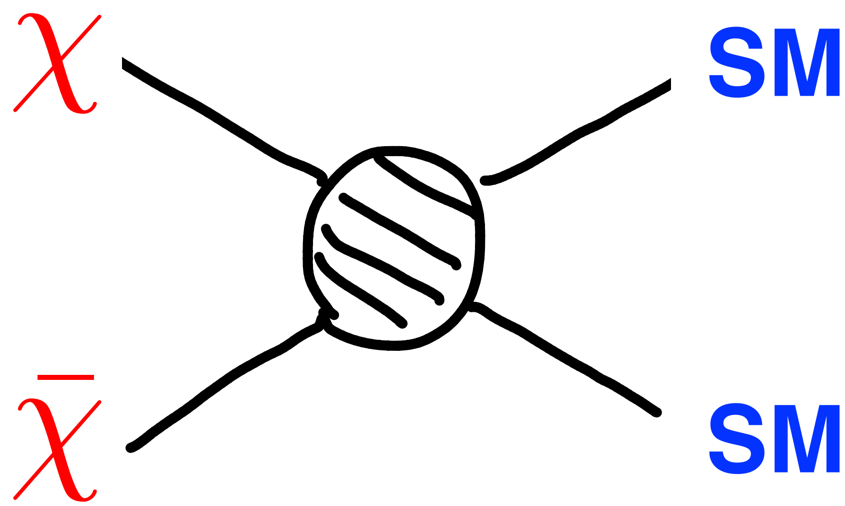
$T \sim m$

$$\Omega_\chi h^2 \sim \frac{m_\chi n_\chi}{s\, T_{eq}} \sim \frac{m_\chi H}{\langle \sigma v \rangle\, s\, T_{eq}} \sim \frac{1}{\langle \sigma v \rangle\, T_{eq} M_{pl}}$$

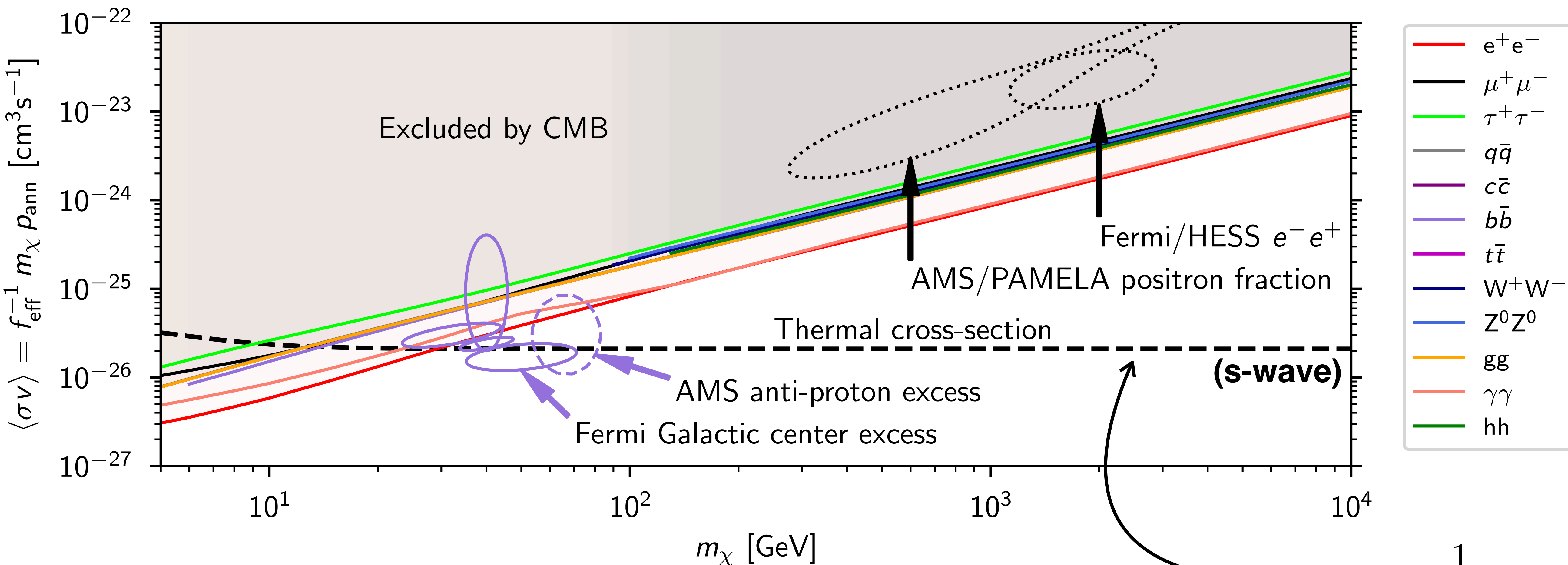
$n_\chi \langle \sigma v \rangle \sim H$

$$m_\chi \sim \alpha_d \sqrt{T_{eq} M_{pl}}$$

CMB vs. Dark Matter



power: $m_{DM}\, n_{DM}^2 \propto \dfrac{1}{m_{DM}}$

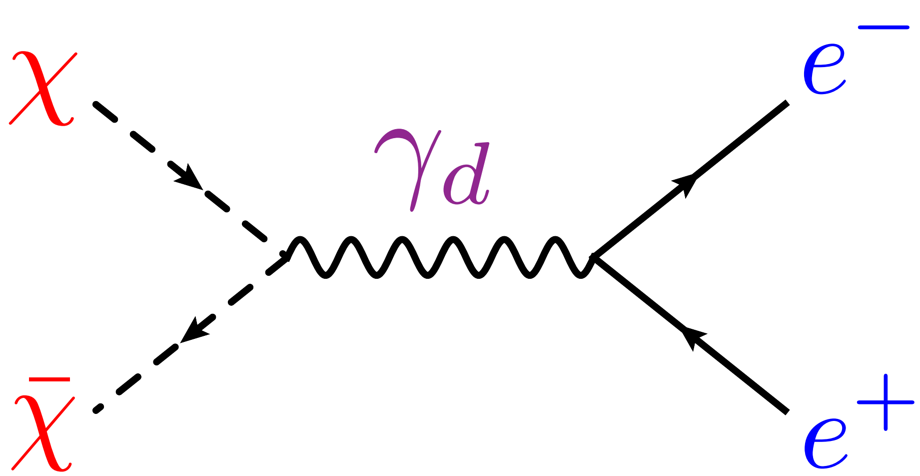


$$\langle \sigma v \rangle \sim \frac{1}{T_{eq} M_{pl}}$$

- Planck, **1807.06209**
- Slatyer, **1506.03811**, **1506.03812**

Thermal Target for Sub-GeV DM

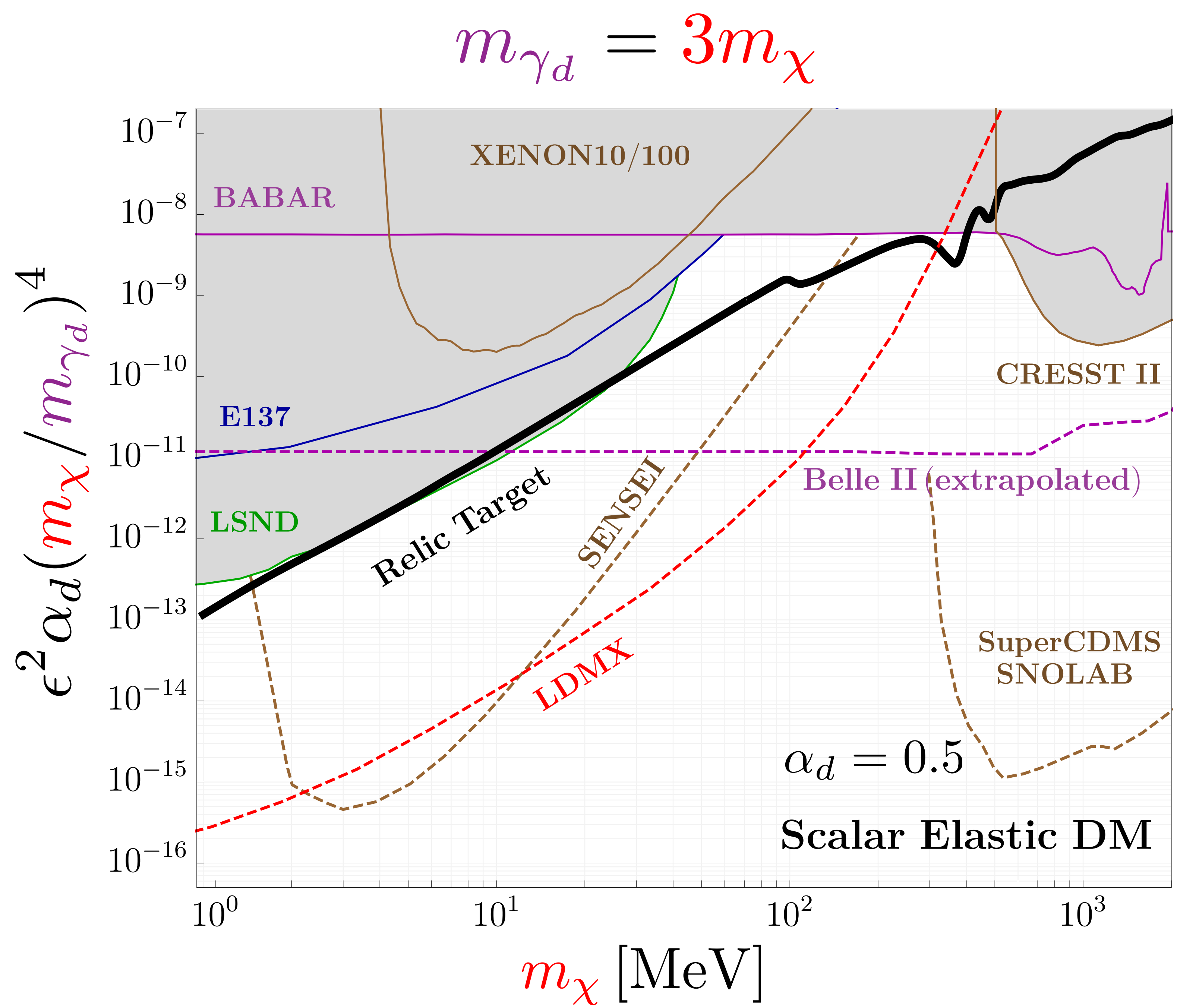
$$\frac{\epsilon}{2} F^d_{\mu\nu} F^{\mu\nu}$$



(p-wave so avoids CMB)

thermal target:

$$\frac{\epsilon^2 \alpha_d \alpha_{EM} m_\chi^2}{m_{\gamma_d}^4} \sim \frac{1}{T_{eq} M_{pl}}$$



Berlin, Blinov, Krnjaic, Schuster, Toro, **1807.01730**

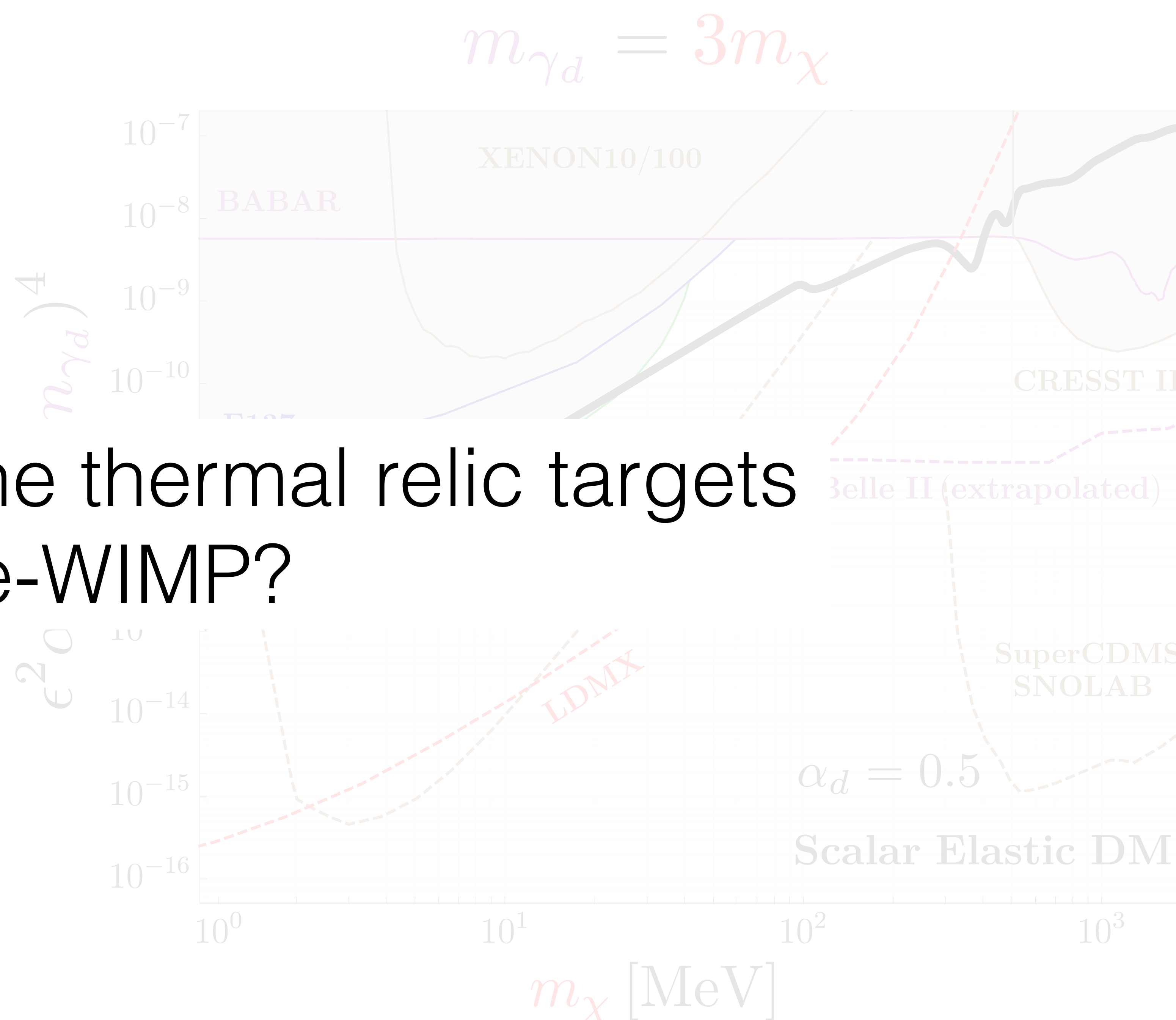
Thermal Target for Sub-GeV DM

$$\frac{\epsilon}{2} F^{d}_{\mu\nu} F^{\mu\nu}$$

(p-wave so avoids CMB)

thermal target:

$$\frac{\epsilon^2 \alpha_d \alpha_{EM} m_\chi^2}{m_{\gamma_d}^4} \sim \frac{1}{T_{eq} M_{pl}}$$



What are the thermal relic targets beyond-the-WIMP?

Berlin, Blinov, Krnjaic, Schuster, Toro, **1807.01730**

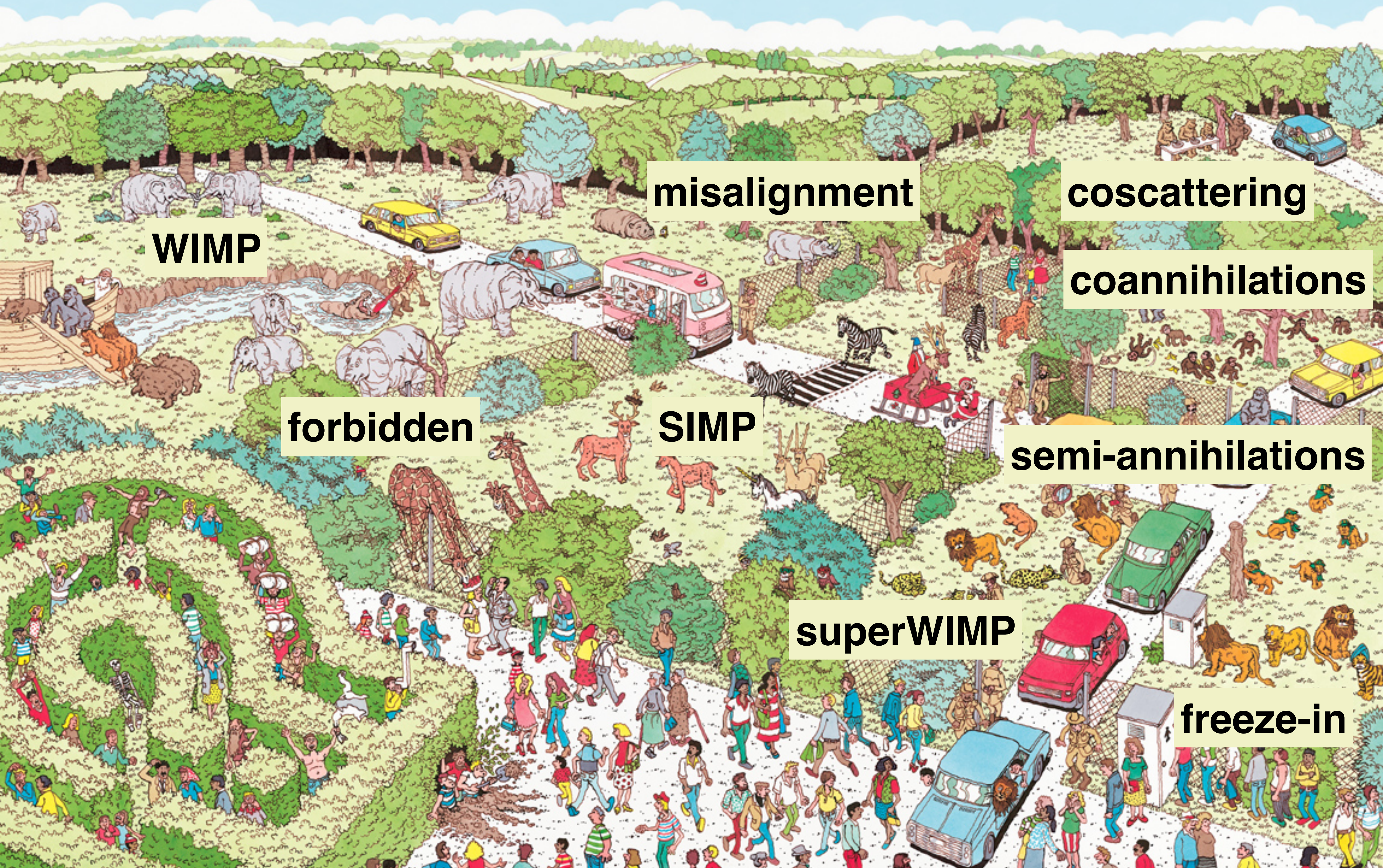
Plan

I. Freezeout Zoo

II. Coscattering

III. Thermal Relic Targets

I. Dark Freezeout Zoology



I. Dark Freezeout Zoology

WIMP

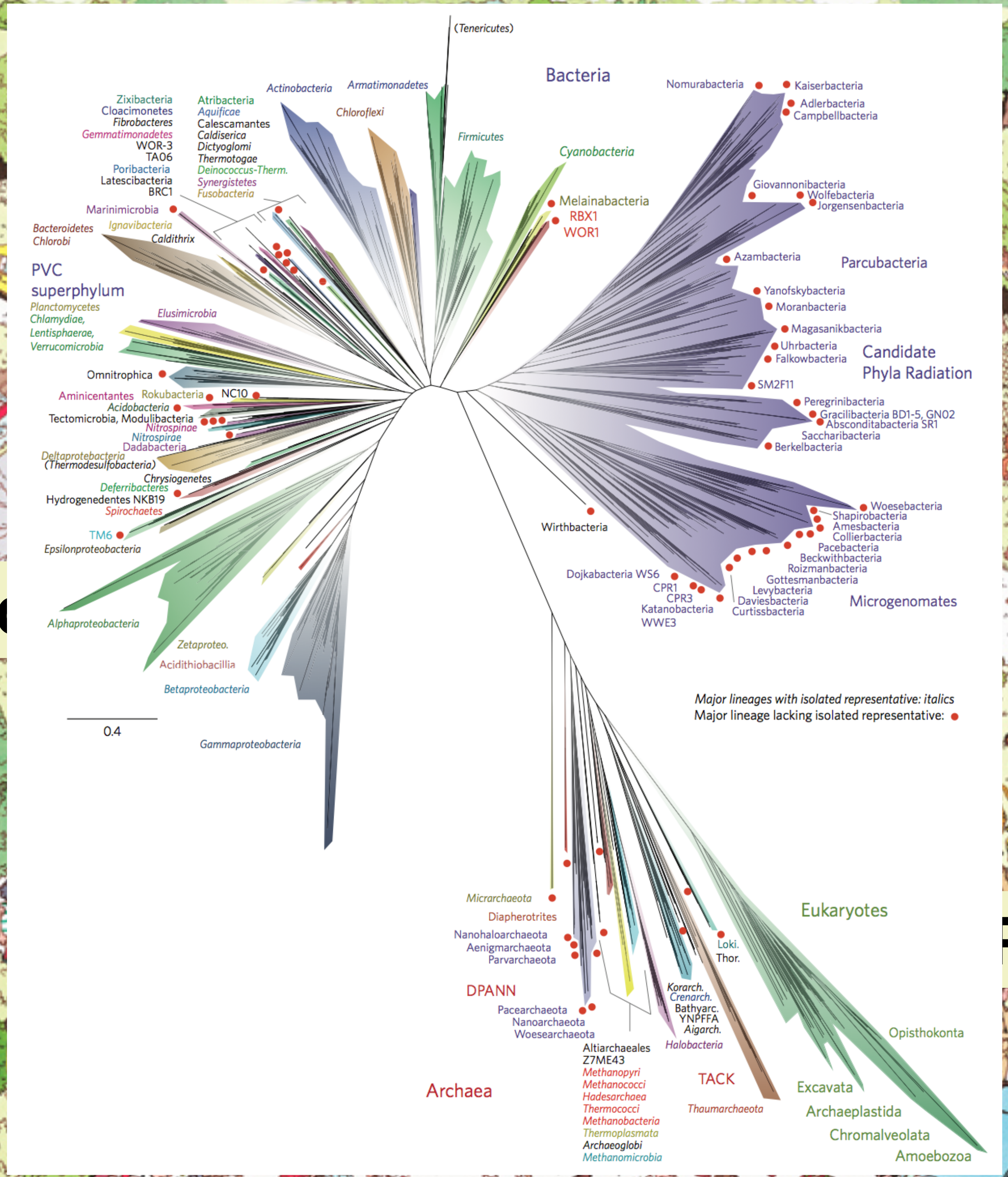
forbi

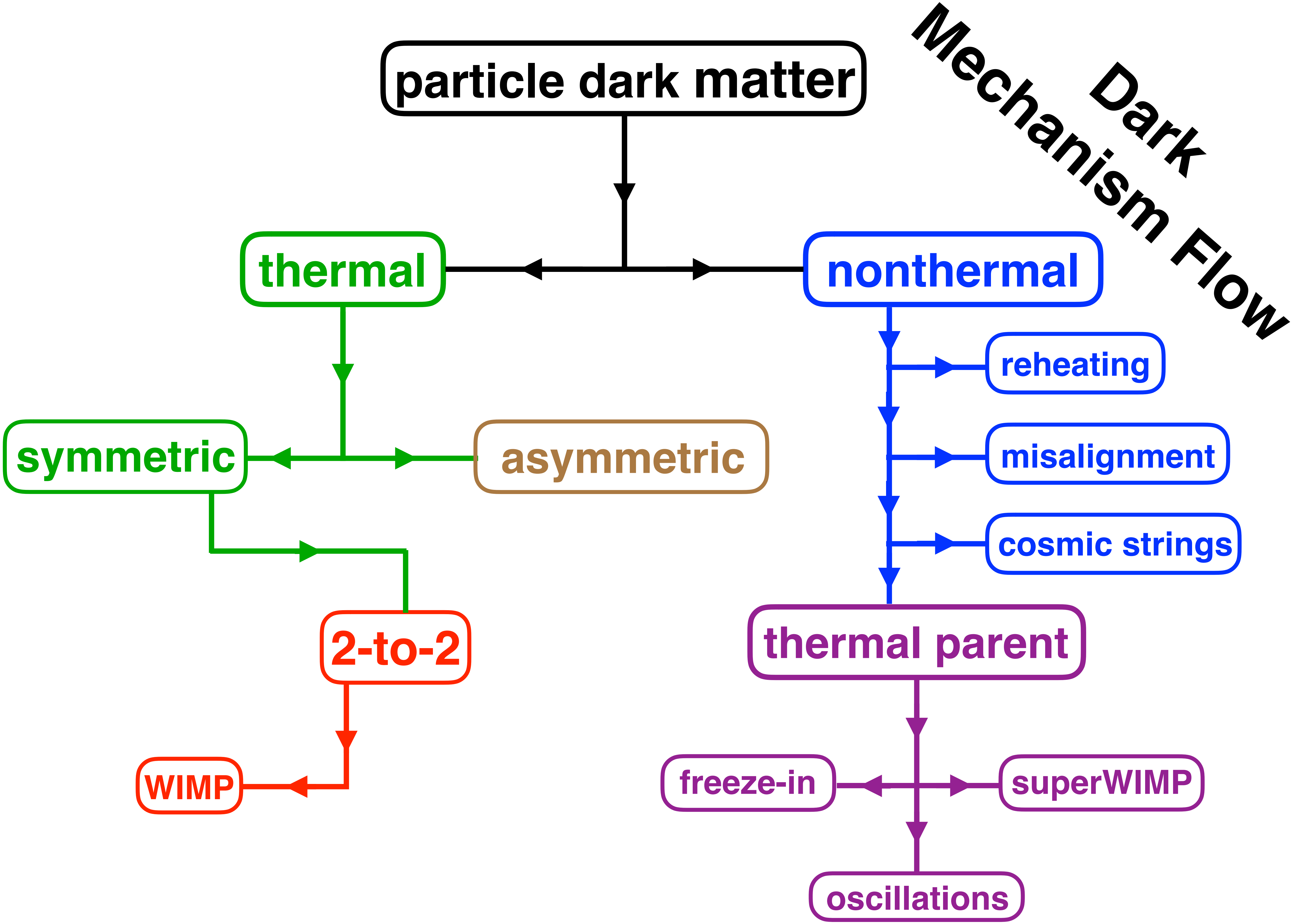
coscattering

coannihilations

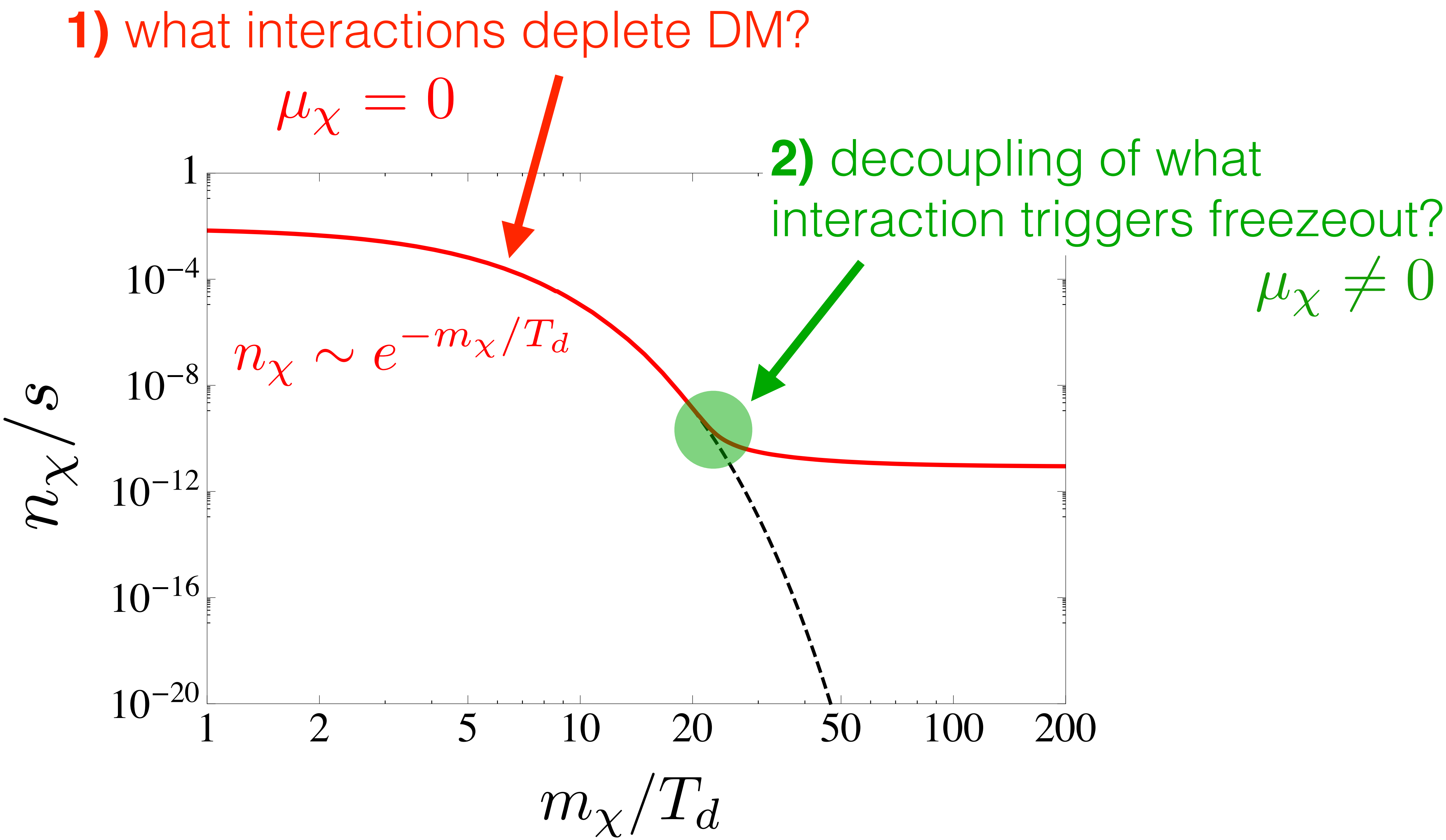
semi-annihilations

freeze-in

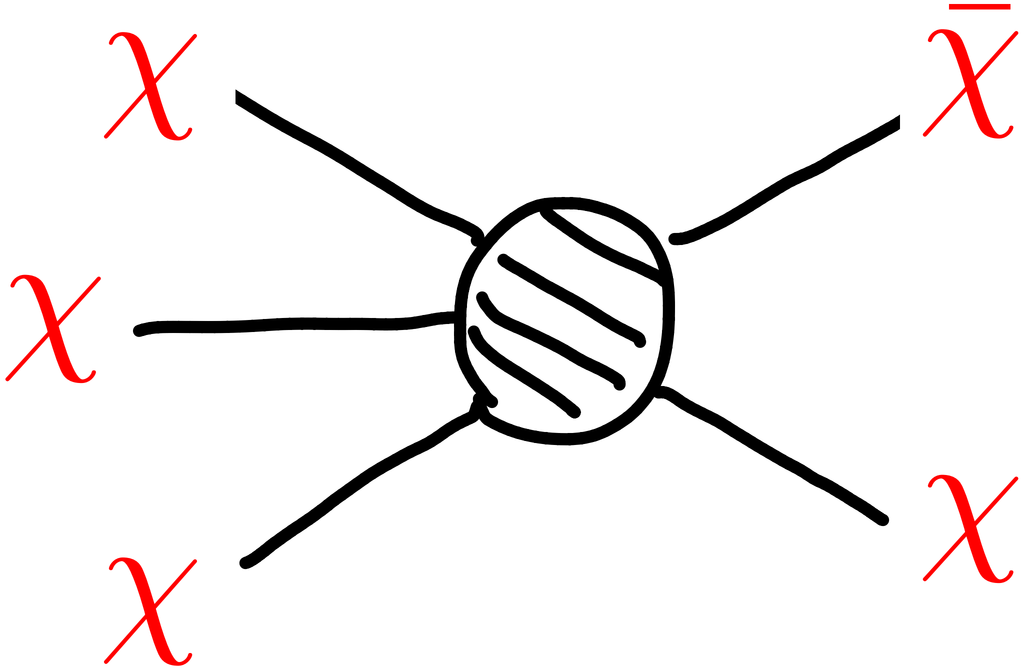



Dark
Mechanism Flow
particle dark matter
thermal
nonthermal
reheating
misalignment
cosmic strings
symmetric
asymmetric
2-to-2
WIMP
thermal parent
freeze-in
superWIMP
oscillations

Symmetric Thermal Relic



SIMP



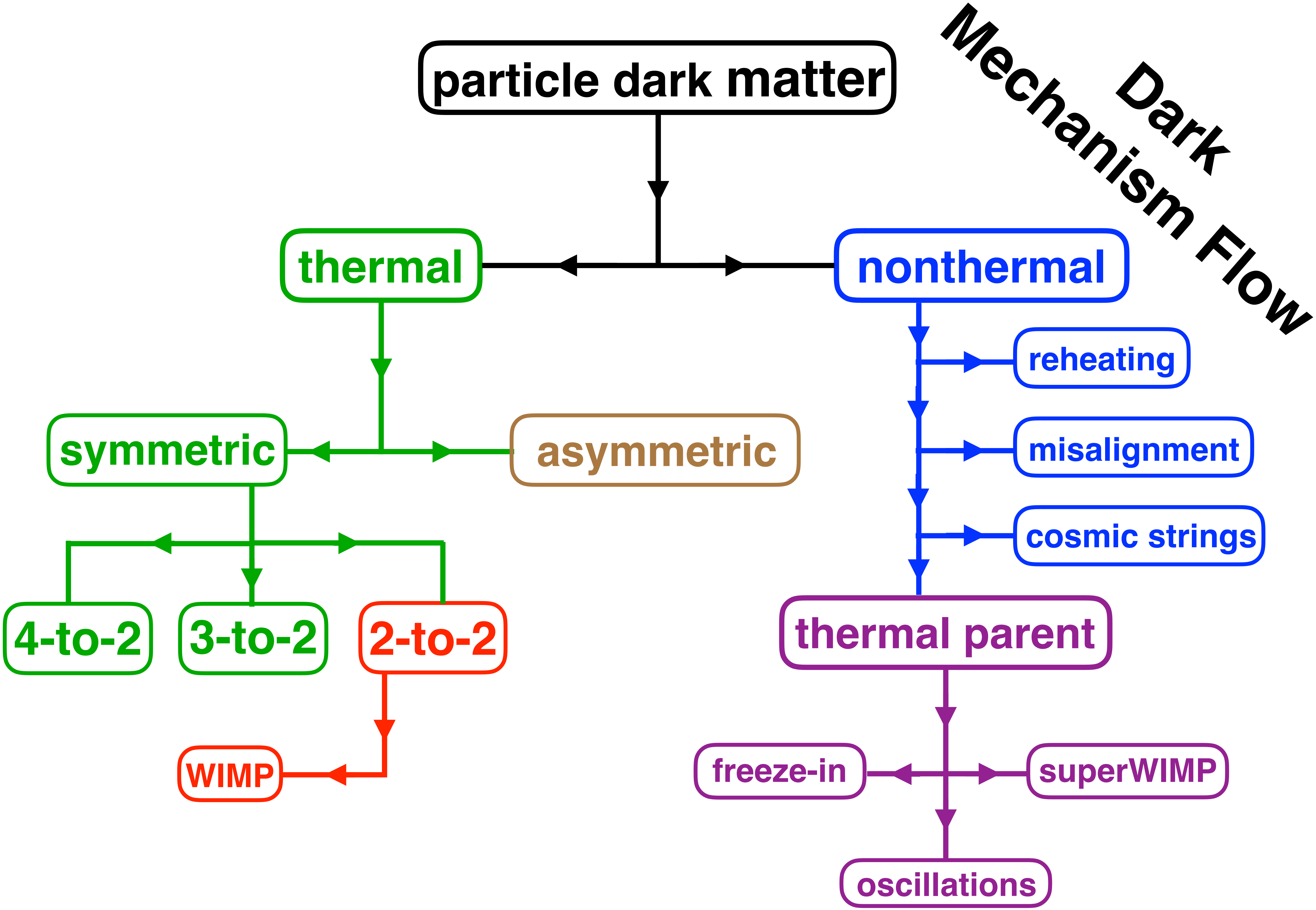
freezeout:

$$n_\chi^2 \langle \sigma v^2 \rangle \sim H$$

$$\Omega_\chi h^2 \sim \frac{m_\chi n_\chi}{s\, T_{eq}} \sim \frac{1}{m_\chi T_{eq} M_{pl}^{1/2} \langle \sigma v^2 \rangle^{1/2}}$$

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

- Hochberg, Kuflik, Volansky, Wacker, **1402.5143**
- Hochberg, Kuflik, Murayama, Volansky, Wacker, **1411.3727**


Dark Mechanism Flow
particle dark matter
thermal
nonthermal
reheating
misalignment
cosmic strings
symmetric
asymmetric
4-to-2
3-to-2
2-to-2
WIMP
thermal parent
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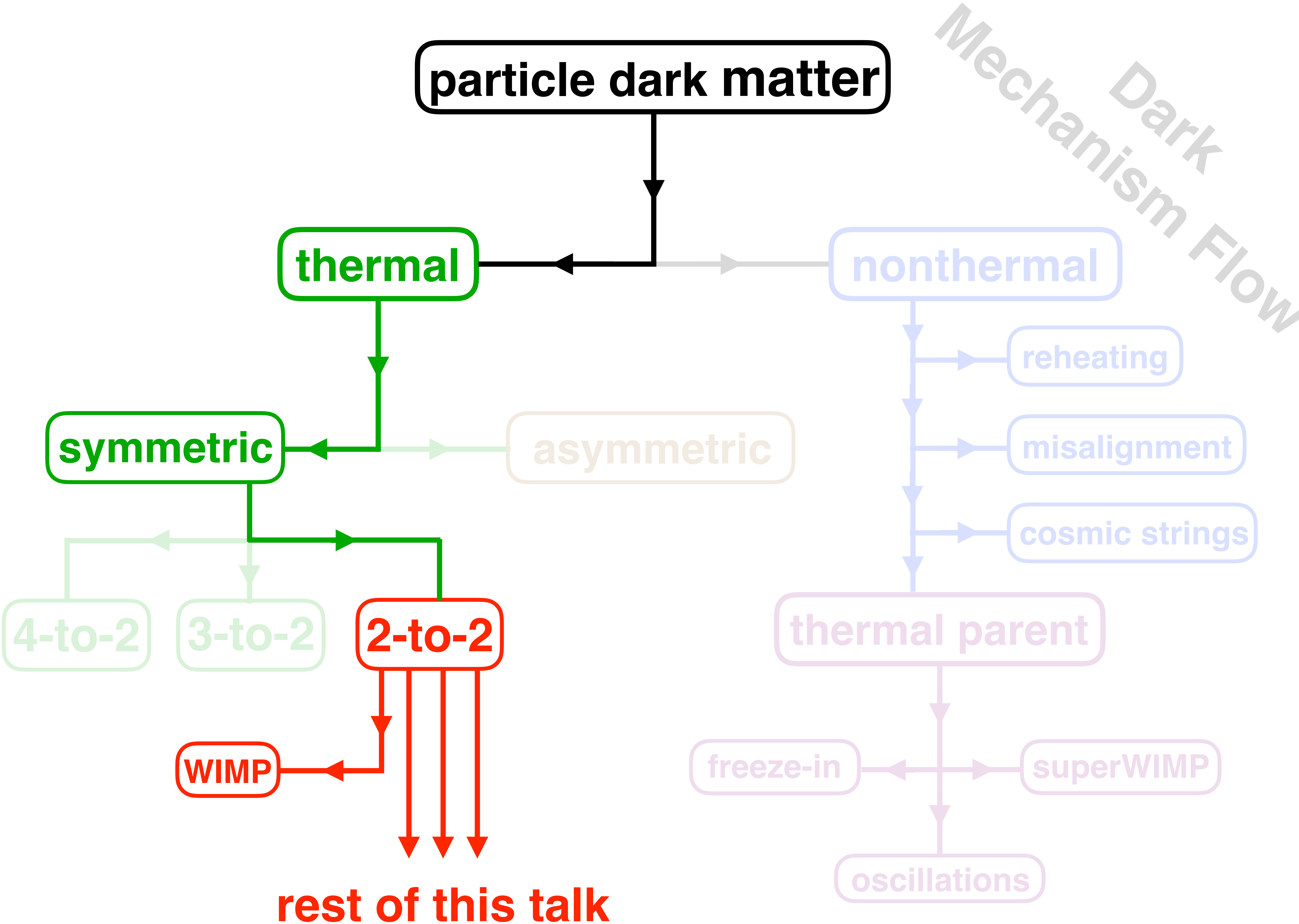
superWIMP
oscillations


Dark Mechanism Flow
particle dark matter
thermal
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reheating
misalignment
cosmic strings
4-to-2
3-to-2
2-to-2
thermal parent
WIMP
freeze-in
superWIMP
oscillations
rest of this talk

WIMP-like Assumptions

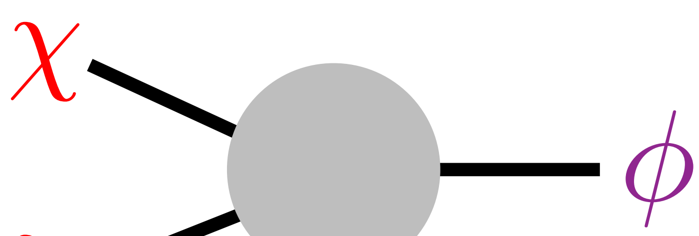
1) thermal relic with: $T_d = T_\gamma$ (kinetic equilibrium)

2) no funny cosmology (ex: no late entropy production, no cannibalism)

3) $\mathcal{Z}_2$ symmetry, 2-to-2 annihilations (2-to-2 annihilations set $\mu_{\rm DM} \to 0$)

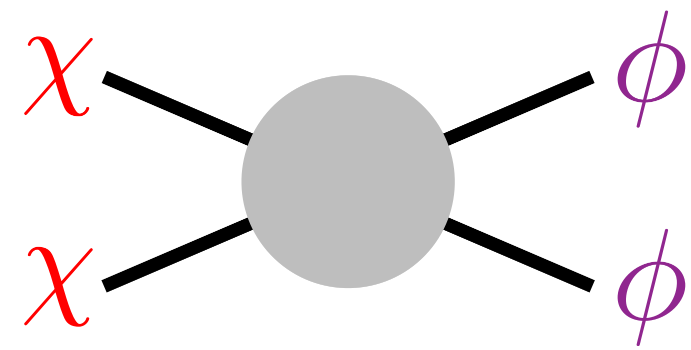
Dark Exceptions

1) pole



$2m_\chi \approx m_\phi$

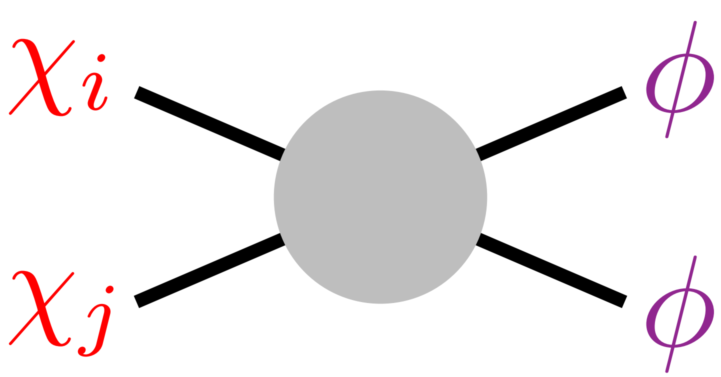
2) forbidden channels



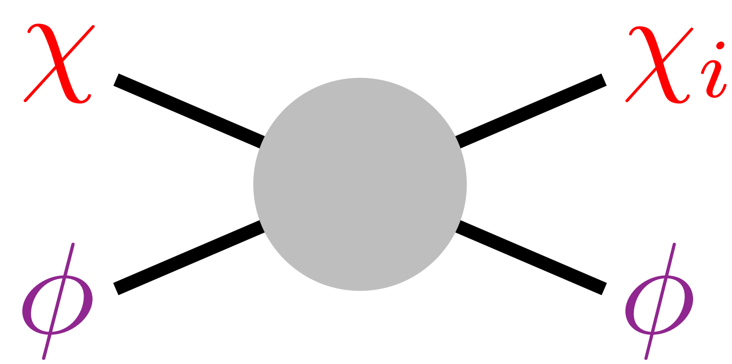
$m_\chi < m_\phi$

D'Agnolo, JTR, **1505.07107** (PRL)

3) coannihilations

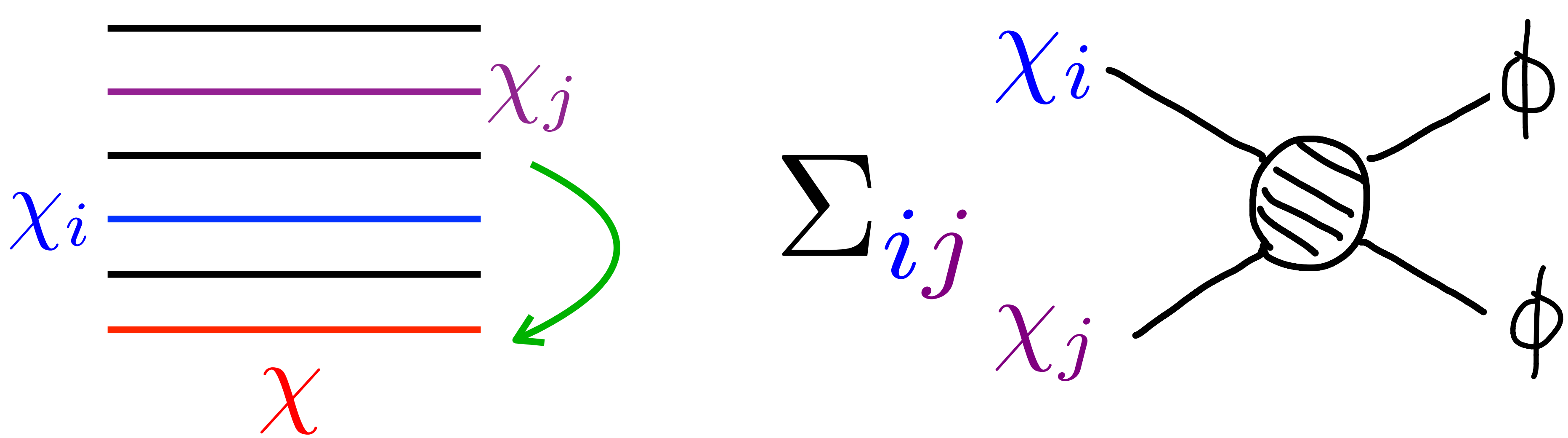


4) coscattering



- Griest, Seckel, **1991**
- D'Agnolo, Pappadopulo, JTR, **1705.08450**

Coannihilations



- heavier states decay to dark matter at late times
- *assume* chemical equilibrium among dark states: $\chi \leftrightarrow \chi_i$

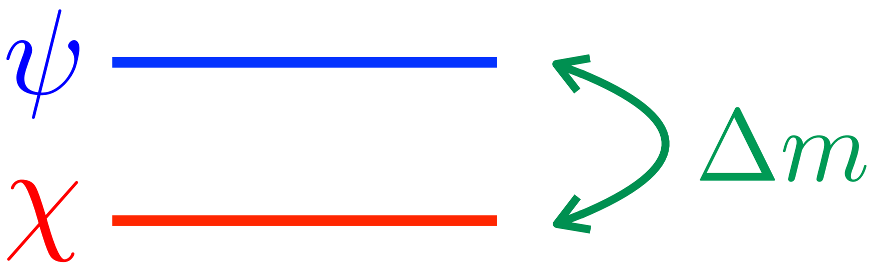
$$\Omega_\chi h^2 \sim \frac{1}{\langle \sigma v \rangle_{eff} T_{eq} M_{pl}} \qquad \langle \sigma v \rangle_{eff} = \sum_{i,j} \frac{n_i^{eq} n_j^{eq}}{(n_\chi^{eq})^2} \langle \sigma_{ij} v \rangle$$

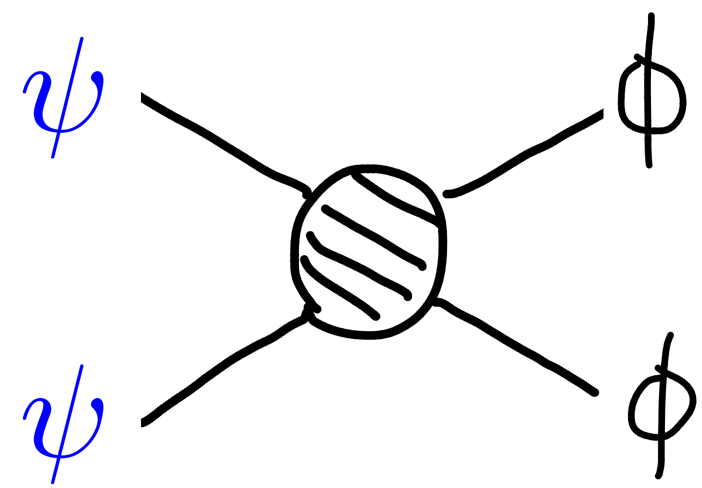
lore: only relevant for degenerate states

- Griest, Seckel, **1991**
- *well-tempered neutralino*: Arkani-Hamed, Delgado, Giudice, **hep-ph/0601041**

Light DM from Coannihilations

suppose annihilations dominated by heavy states:





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

$$\langle \sigma v \rangle_{eff} \sim \frac{\alpha_d^2}{m_\psi^2} e^{-2\Delta m/T}$$

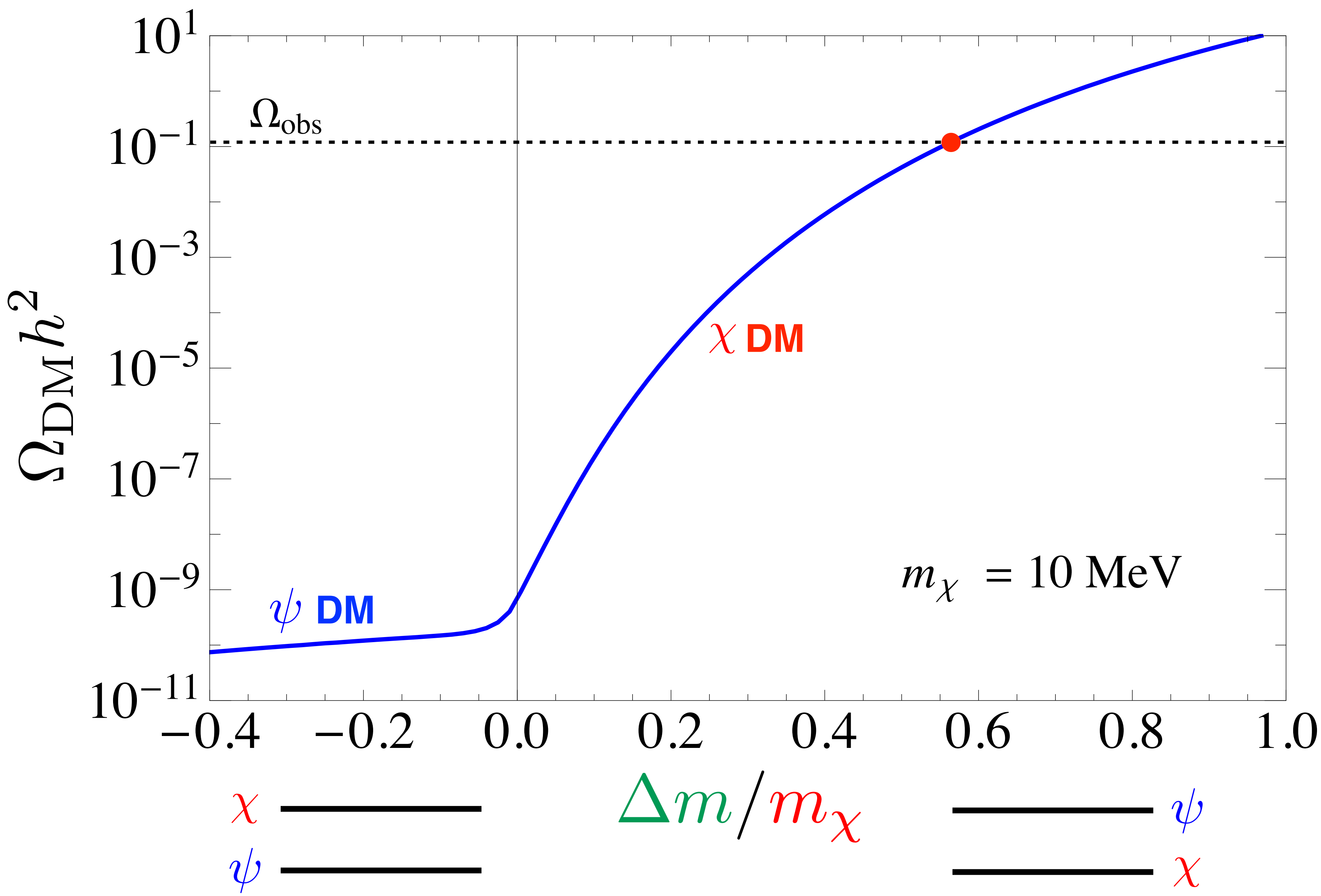
- DM mass: $m_\chi \sim \alpha_d \sqrt{T_{eq} M_{pl}}\, e^{-\Delta m/T_{FO}}$

- evades CMB: $\sigma_{\chi\chi} \ll \sigma_{\psi\psi}$

Raffaele D'Agnolo, Cristina Mondino, JTR, Po-Jen Wang, **1803.02901**

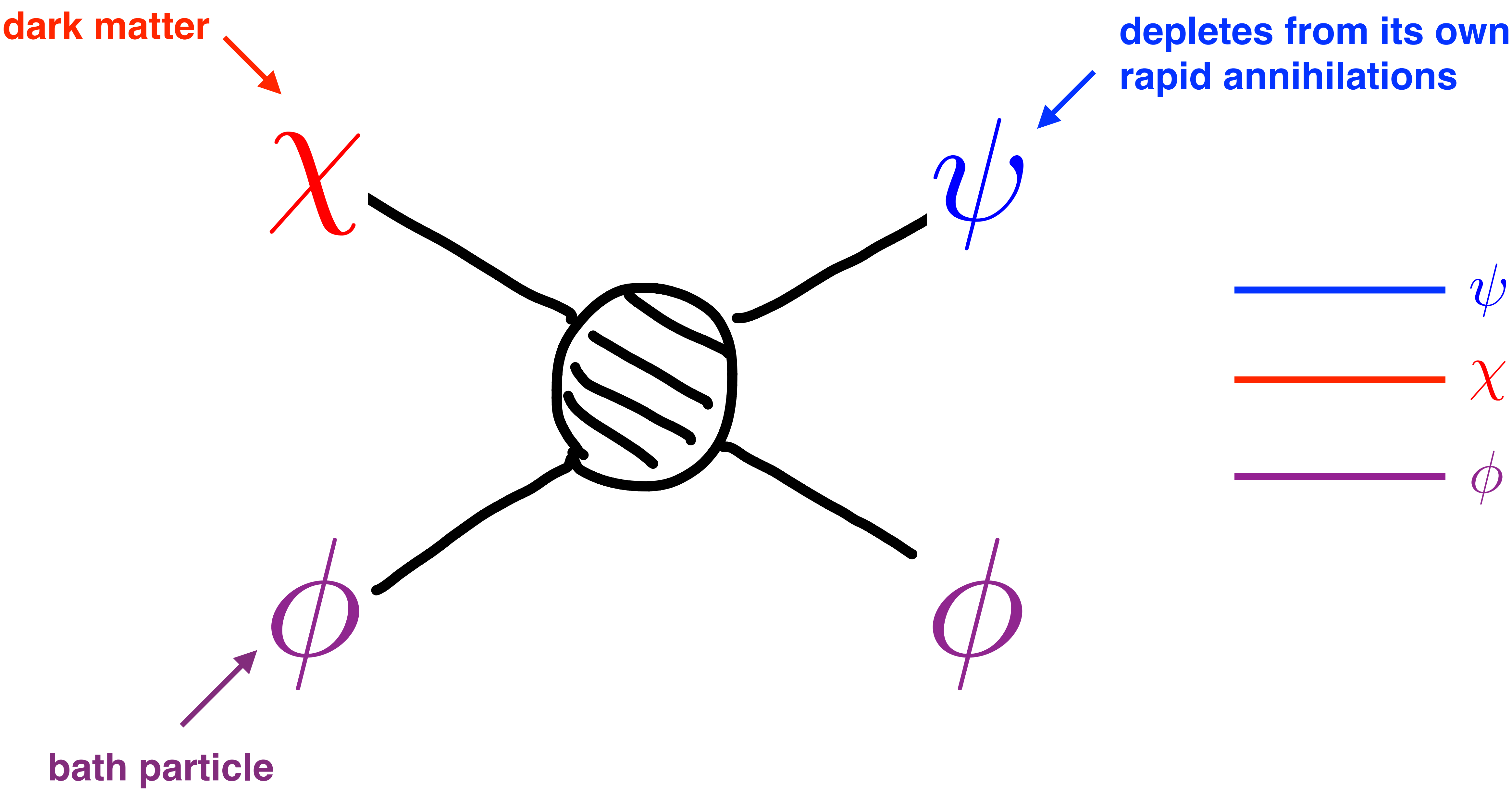
Light DM from Coannihilations

$$\Omega_\chi h^2 \sim \frac{m_\chi^2}{\alpha_d^2\, T_{eq} M_{pl}}\, e^{2\Delta m/T_{FO}}$$



Raffaele D'Agnolo, Cristina Mondino, JTR, Po-Jen Wang, **1803.02901**

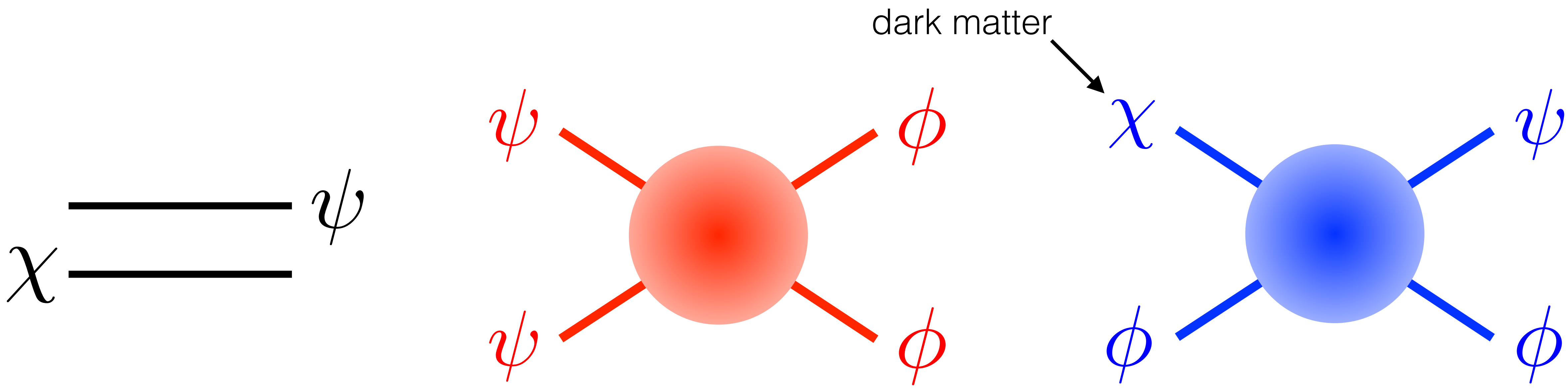
II. Coscattering



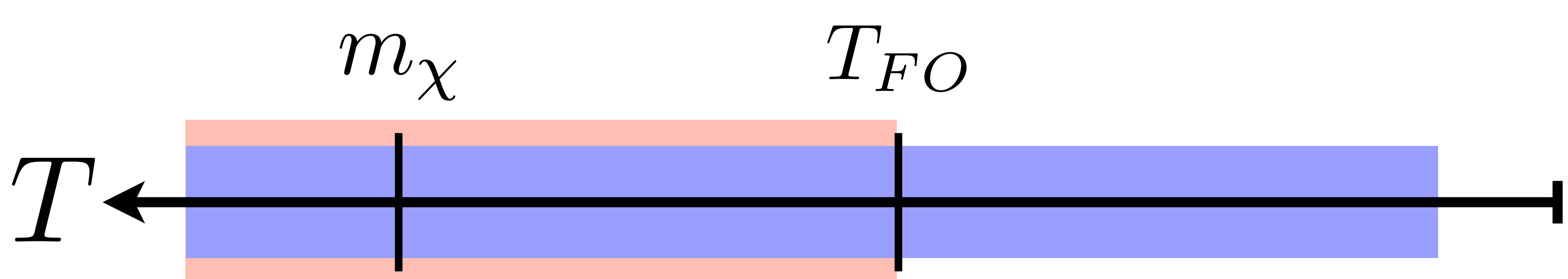
Raffaele D'Agnolo, Duccio Pappadopulo, JTR, **1705.08450**

(see also: Garny, Heisig, Lulf, Vogl, **1705.09292**)

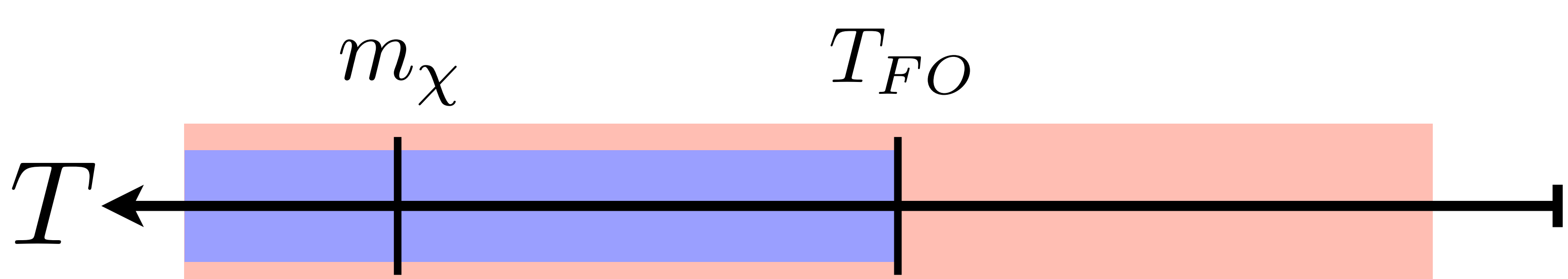
Coannihilation vs. Coscattering



- coannihilation



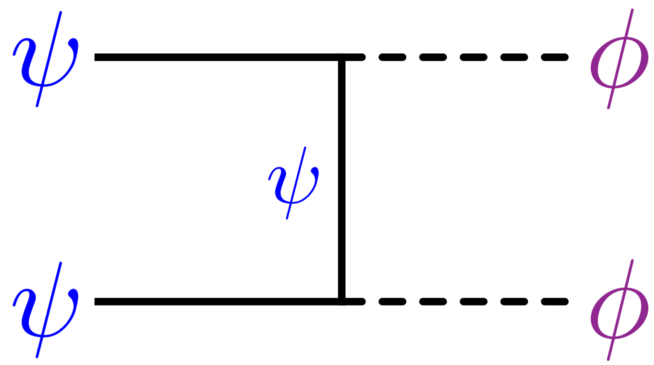
- coscattering



Mix-In Dark Matter

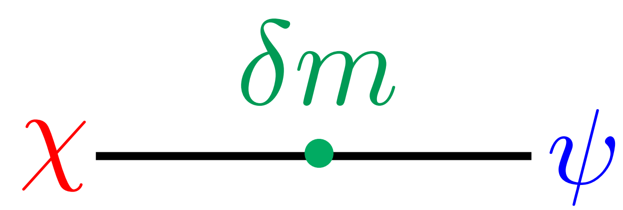
- active state

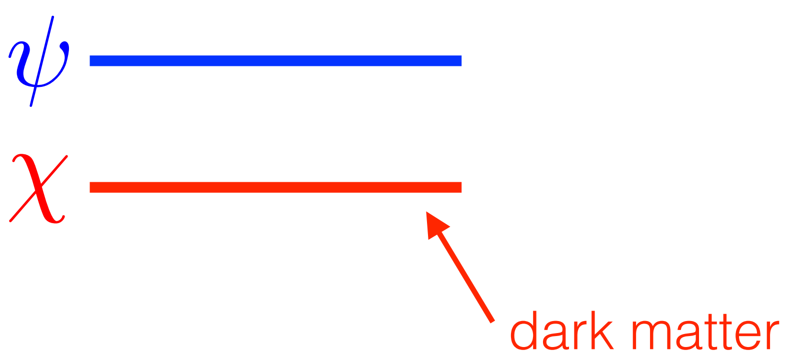
$$\frac{y}{2}\phi\psi^2$$



- sterile state (DM)

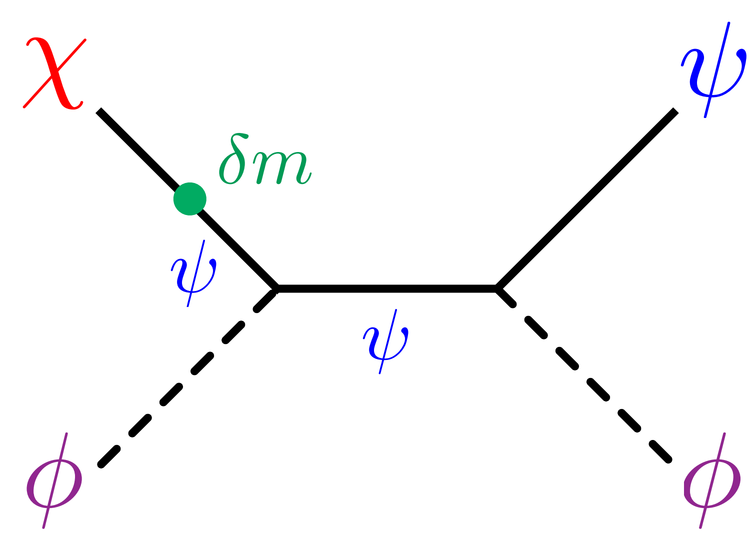
$$\delta m \chi \psi$$



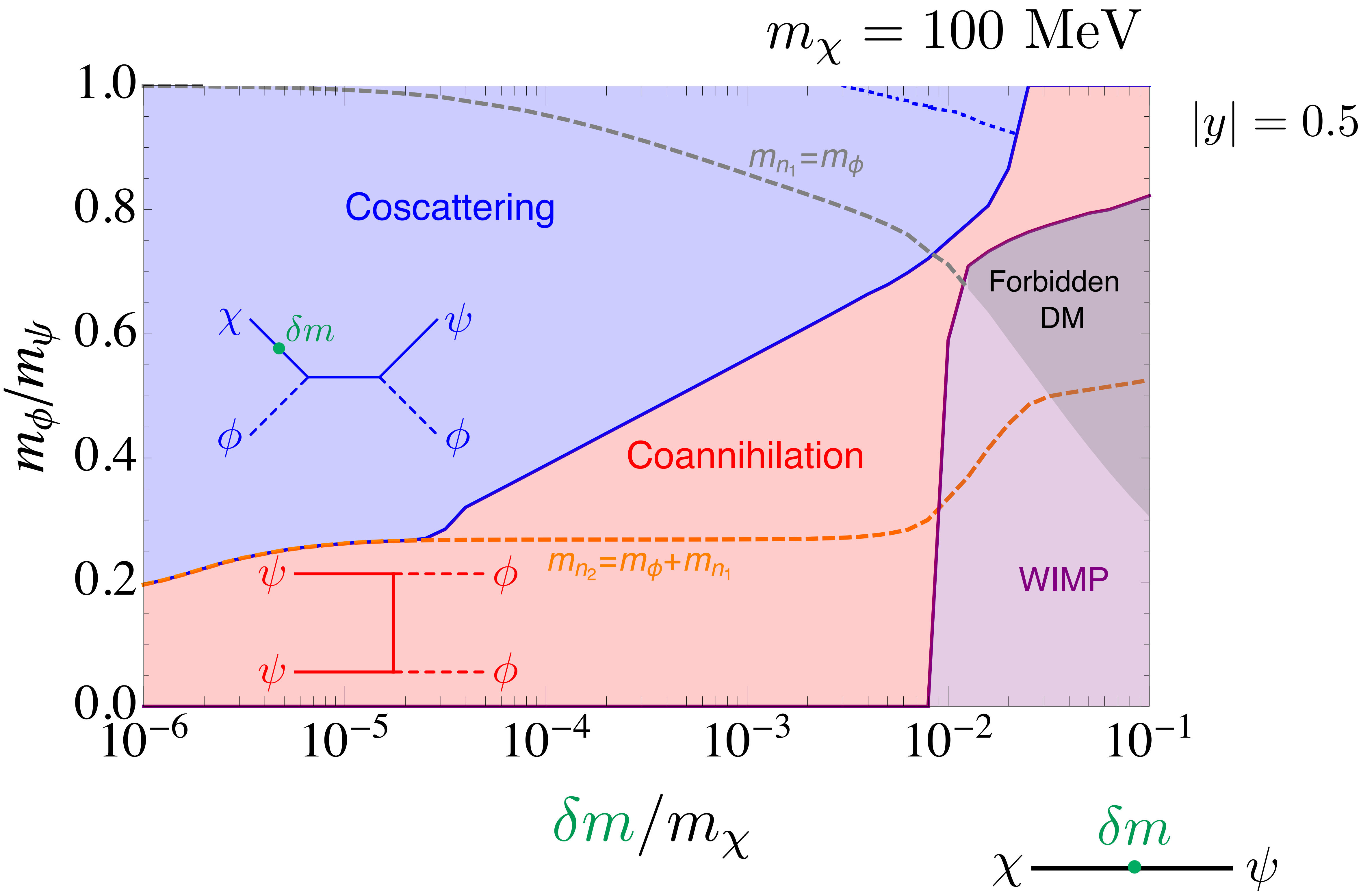


$$\delta m \ll m_\chi$$

- equilibriate: $\chi \leftrightarrow \psi$

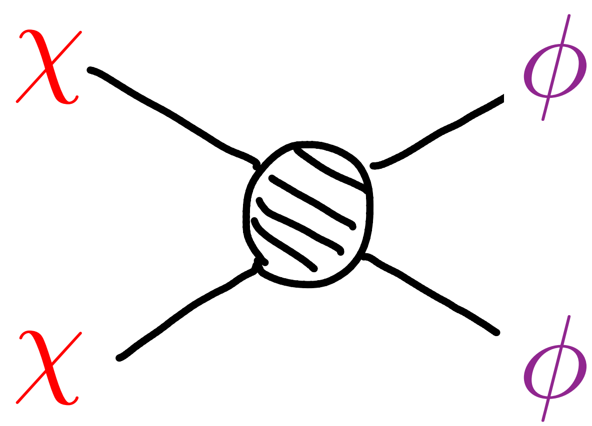


Freeze-Out Phase Diagram

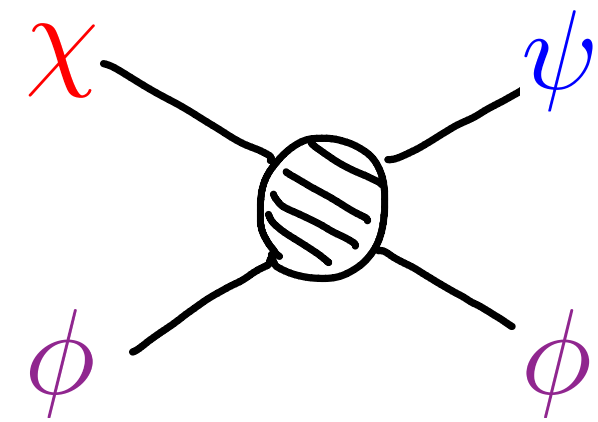


Coscattering vs. WIMP Freezeout

WIMP



coscattering



Boltzmann Equation

WIMP: $$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - (n_\chi^{eq})^2\right)$$

coscattering: $$\dot{n}_\chi + 3Hn_\chi = -n_\phi^{eq}\langle\sigma v\rangle\left(n_\chi - n_\chi^{eq}\right)$$

freezeout

WIMP: $$n_\chi^{eq}\langle\sigma v\rangle \sim H$$

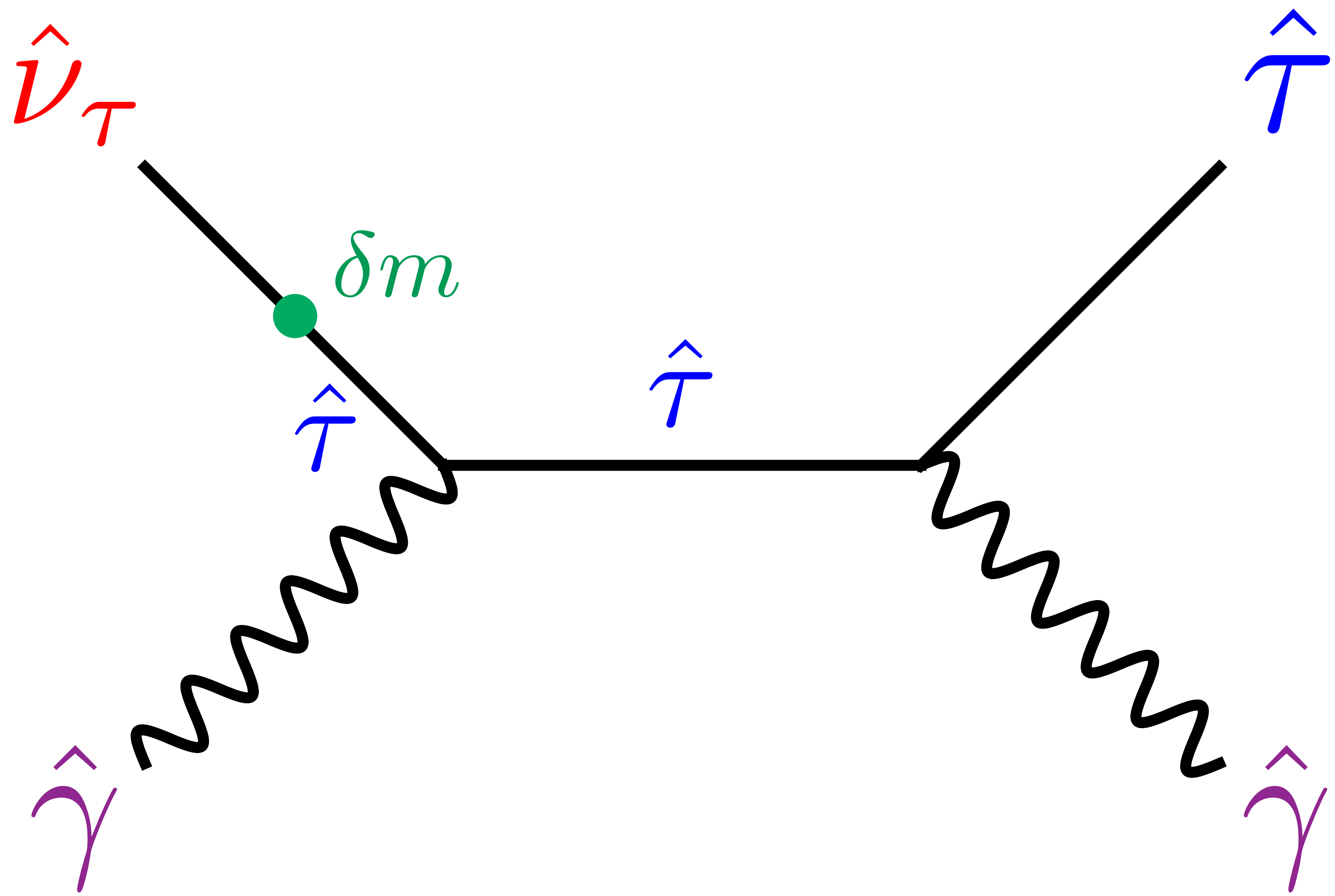
coscattering: $$n_\phi^{eq}\langle\sigma v\rangle \sim H$$

cross-section to match abundance

WIMP: $$\langle\sigma v\rangle \sim \frac{1}{T_{eq}M_{pl}}$$

coscattering: $$\langle\sigma v\rangle \sim \frac{n_\chi^{eq}}{n_\phi^{eq}}\frac{1}{T_{eq}M_{pl}} \sim \frac{e^{-(m_\chi - m_\phi)/T_{FO}}}{T_{eq}M_{pl}}$$

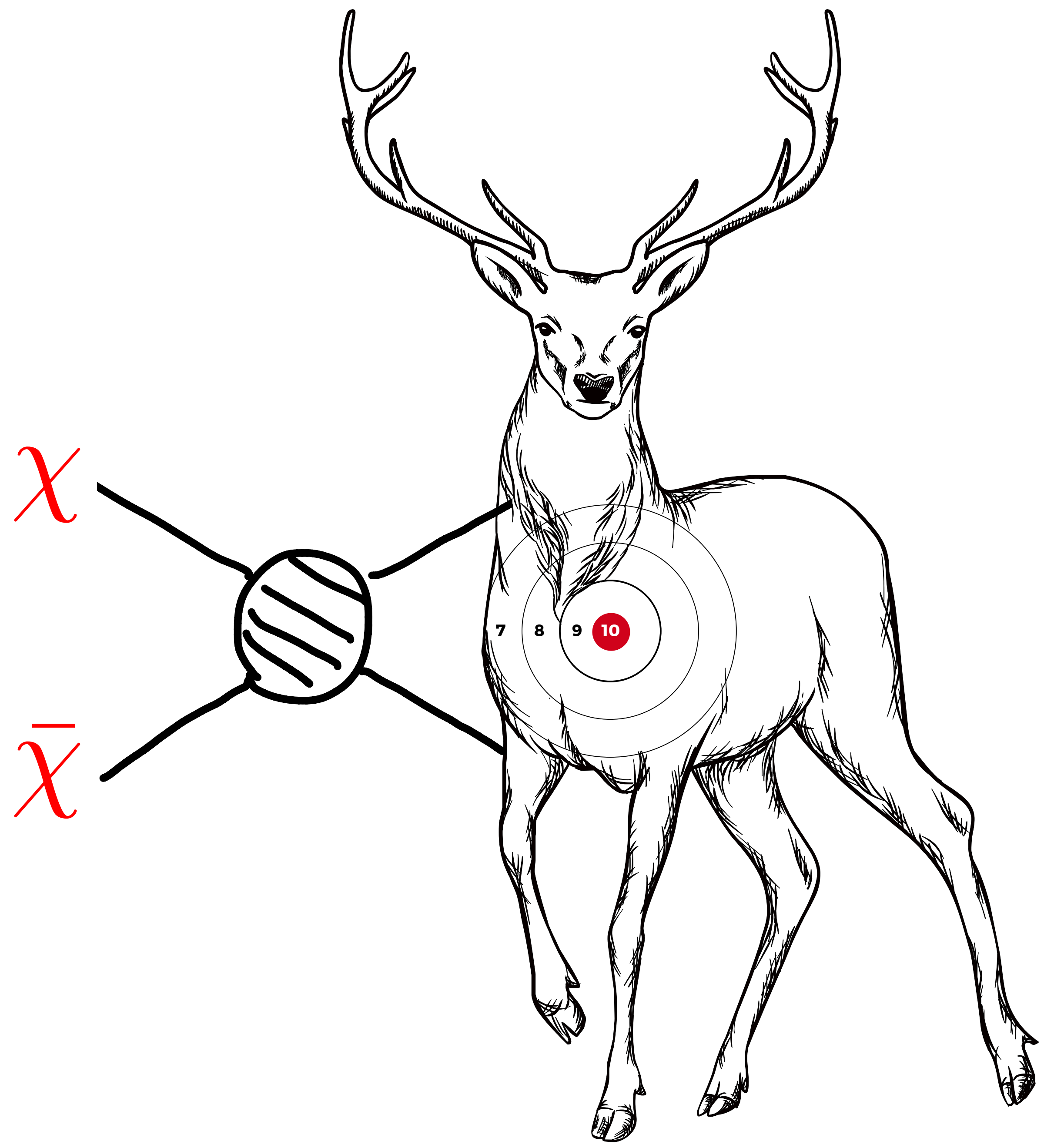
Coscattering in Twin Higgs



$$m_{\hat{\gamma}}, m_{\hat{\nu}_\tau}, m_{\hat{\tau}} \sim 0.1 - 10\,\mathrm{GeV}$$

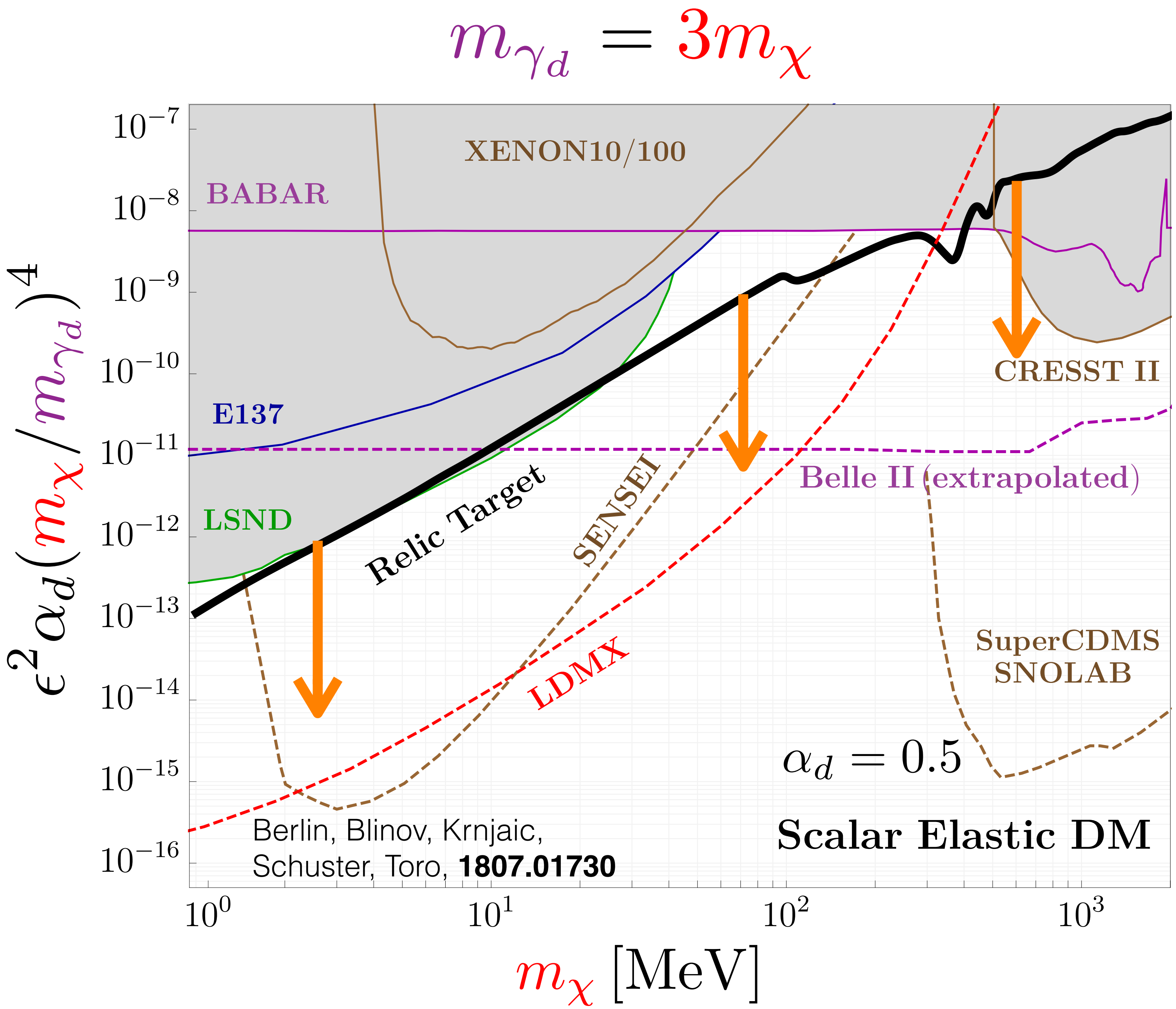
Hsin-Chia Cheng, Lingfeng Li, Rui Zheng, **1805.12139**

III. Thermal Relic Targets

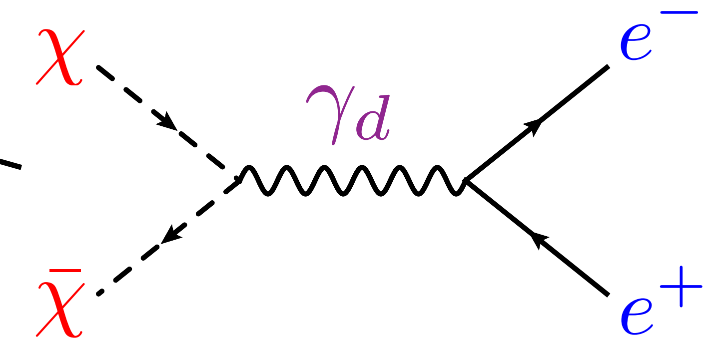


Raffaele D'Agnolo, Duccio Pappadopulo, JTR, Po-Jen Wang, *to appear.*

Thermal Target from Annihilations

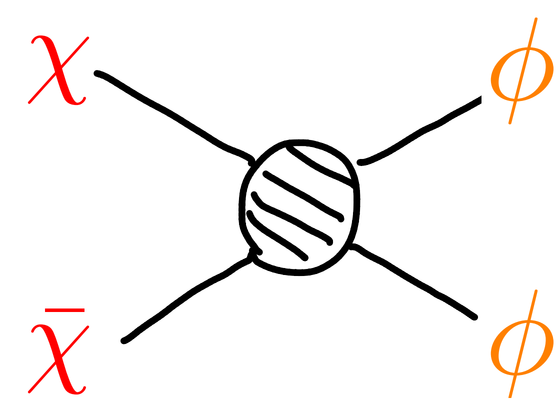


annihilations to SM:



$$\langle \sigma v \rangle_{e^+e^-} \sim \frac{1}{T_{eq} M_{pl}}$$

annihilations into the dark sector:



$$\langle \sigma v \rangle_{\phi\phi} \sim \frac{1}{T_{eq} M_{pl}}$$

- Finkbeiner, Weiner, **astro-ph/0702587**
- Pospelov, Ritz, Voloshin, **0711.4866**

WIMP-like Assumptions

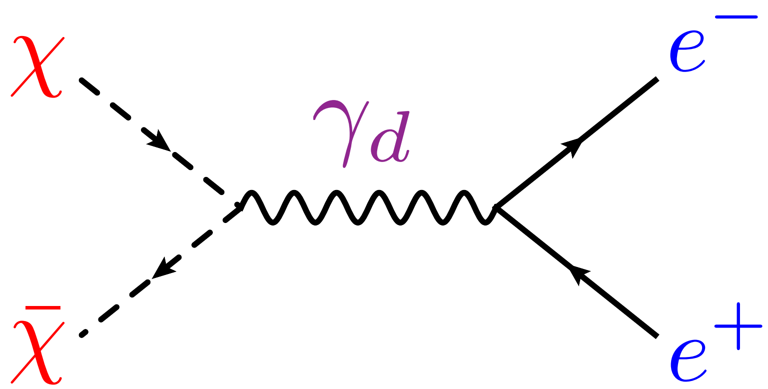
1) thermal relic with: $T_d = T_\gamma$

2) no funny cosmology

3) $\mathcal{Z}_2$ symmetry, 2-to-2 annihilations

4) freezeout triggered by decoupling of an interaction between DM and the SM

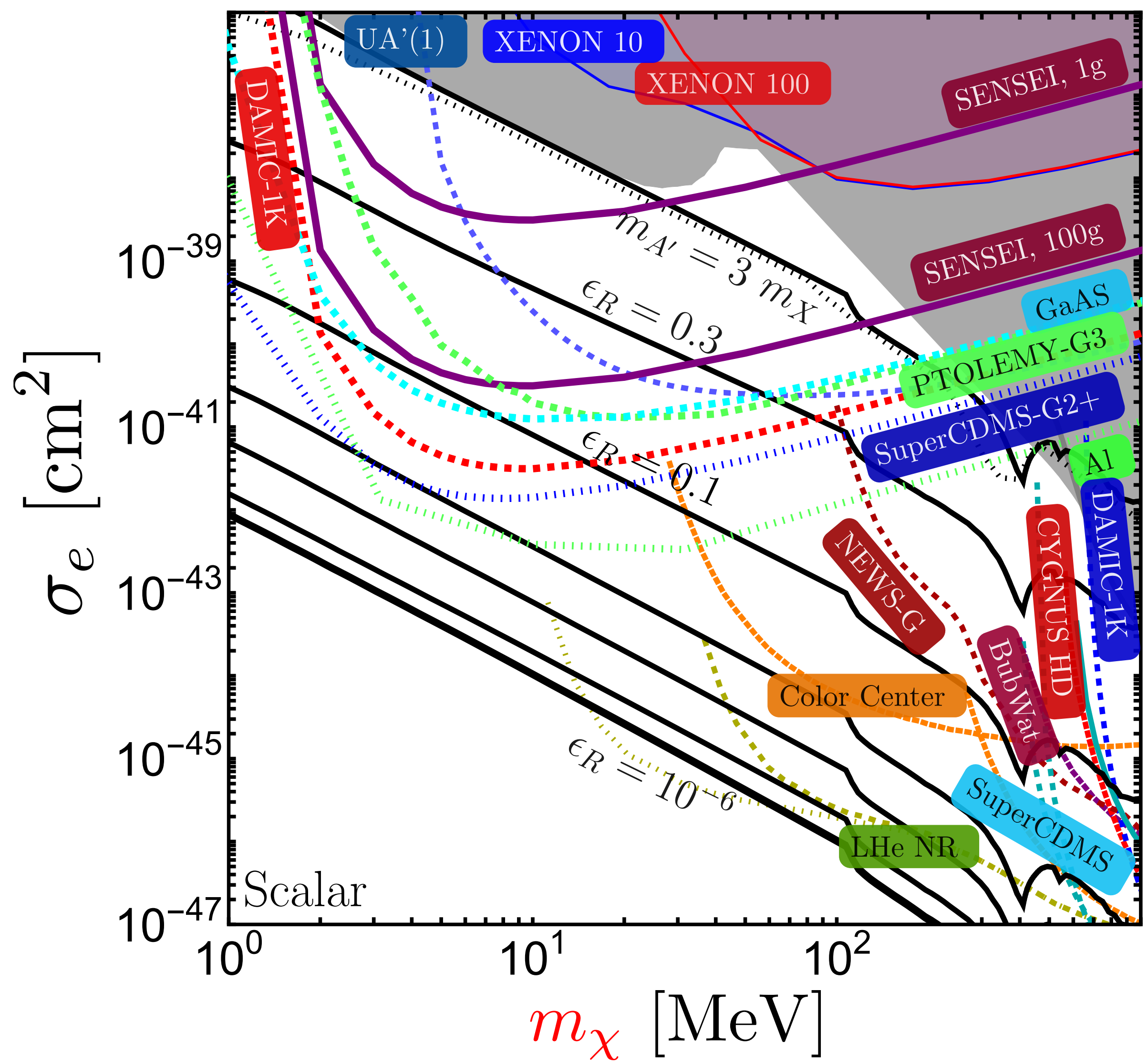
Thermal Target Near Resonance



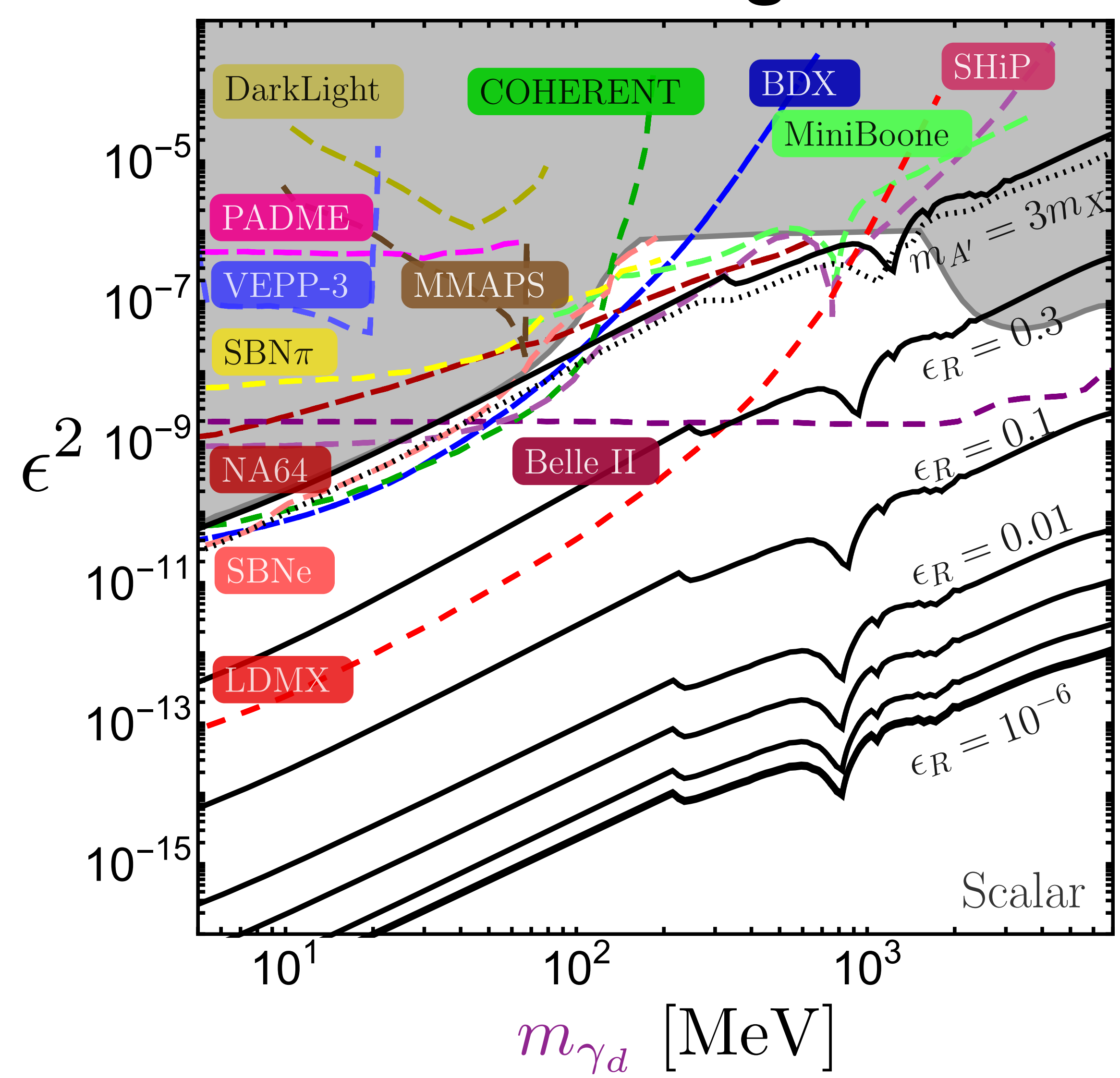
$$\epsilon_R = \frac{m_{\gamma_d}^2 - 4m_\chi^2}{4m_\chi^2}$$

pole:
$\epsilon_R \to 0$

direct detection



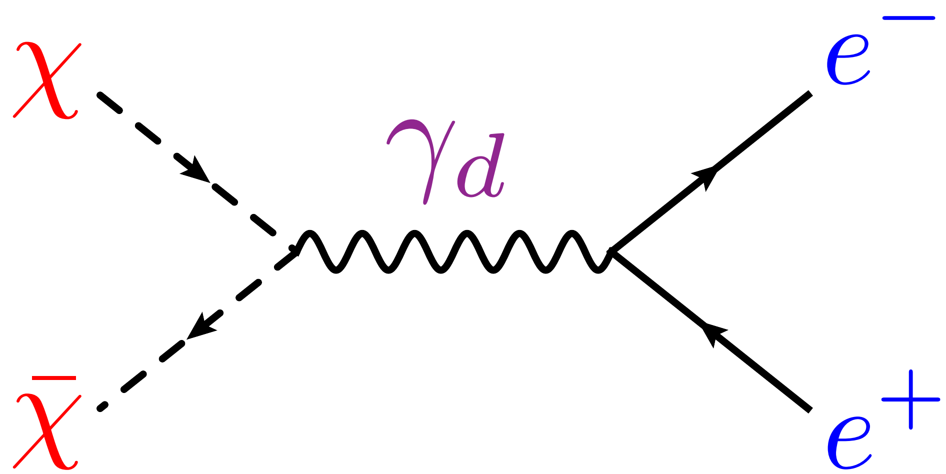
fixed target



Feng, Smolinksy, **1707.03835**

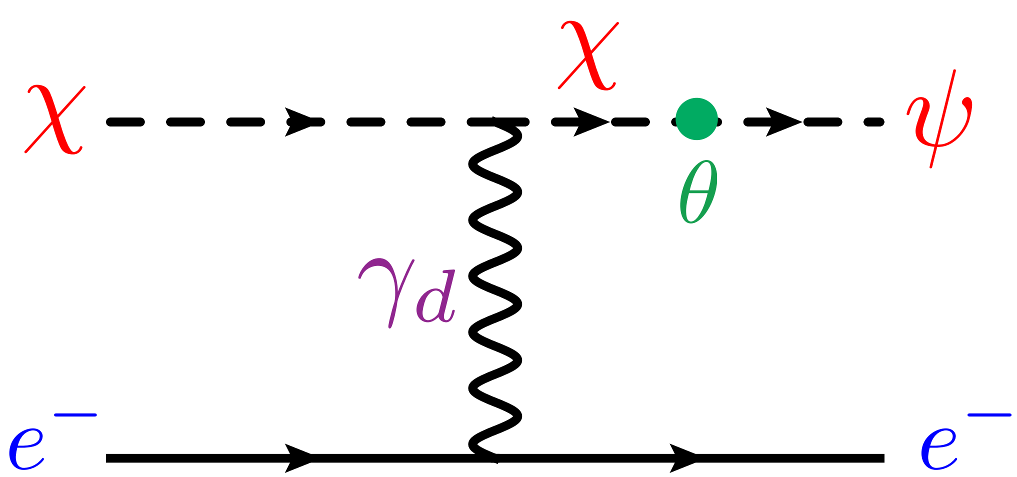
Coscattering Against the SM Bath

annihilate to SM



$$n_\chi \langle \sigma v \rangle \sim H$$

coscatter against SM

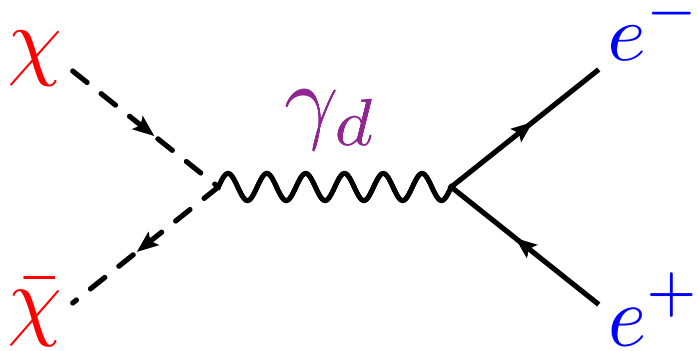


$$n_e \langle \sigma v \rangle \sim H$$

coscattering enhanced by: $\dfrac{n_e}{n_\chi} \sim e^{(m_\chi - m_e)/T} \gg 1$

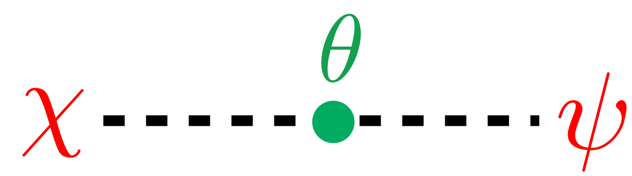
Recipe for Coscattering as a Module

1) consider any model below the thermal relic curve

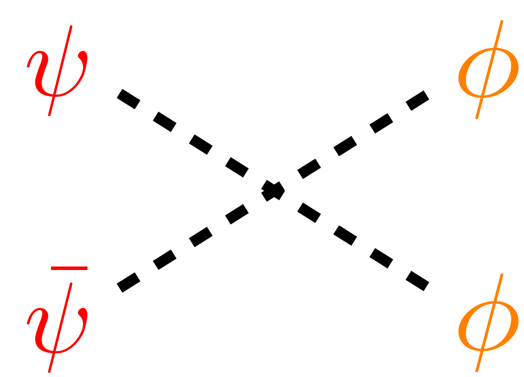


$$\langle \sigma v \rangle_{\chi\bar{\chi}} \ll \frac{1}{T_{eq} M_{pl}}$$

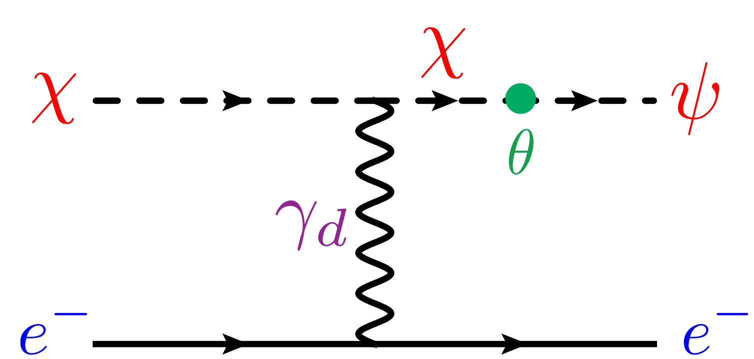
2) mix DM with a dark partner state



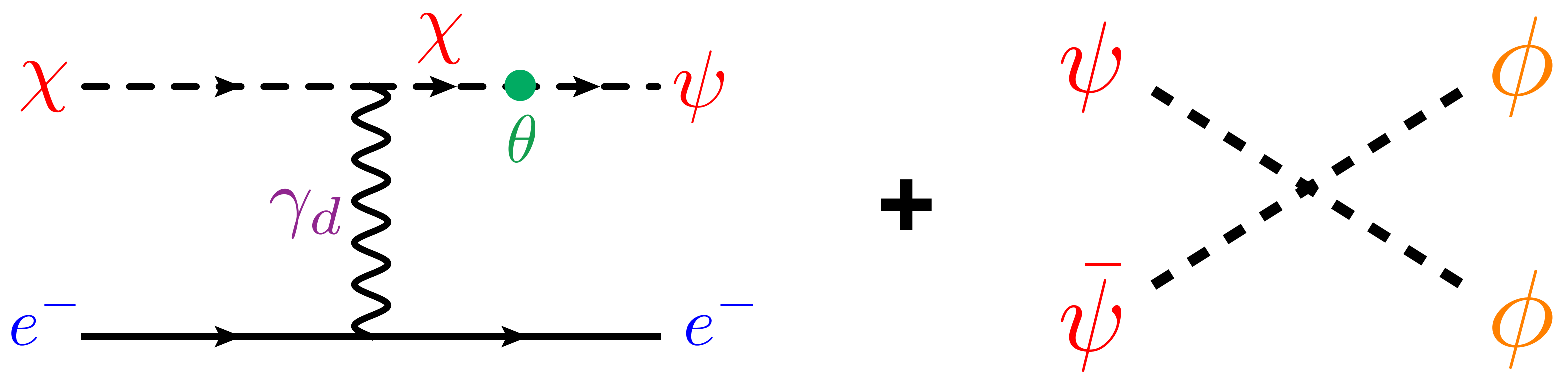
3) deplete the partner with other interactions:



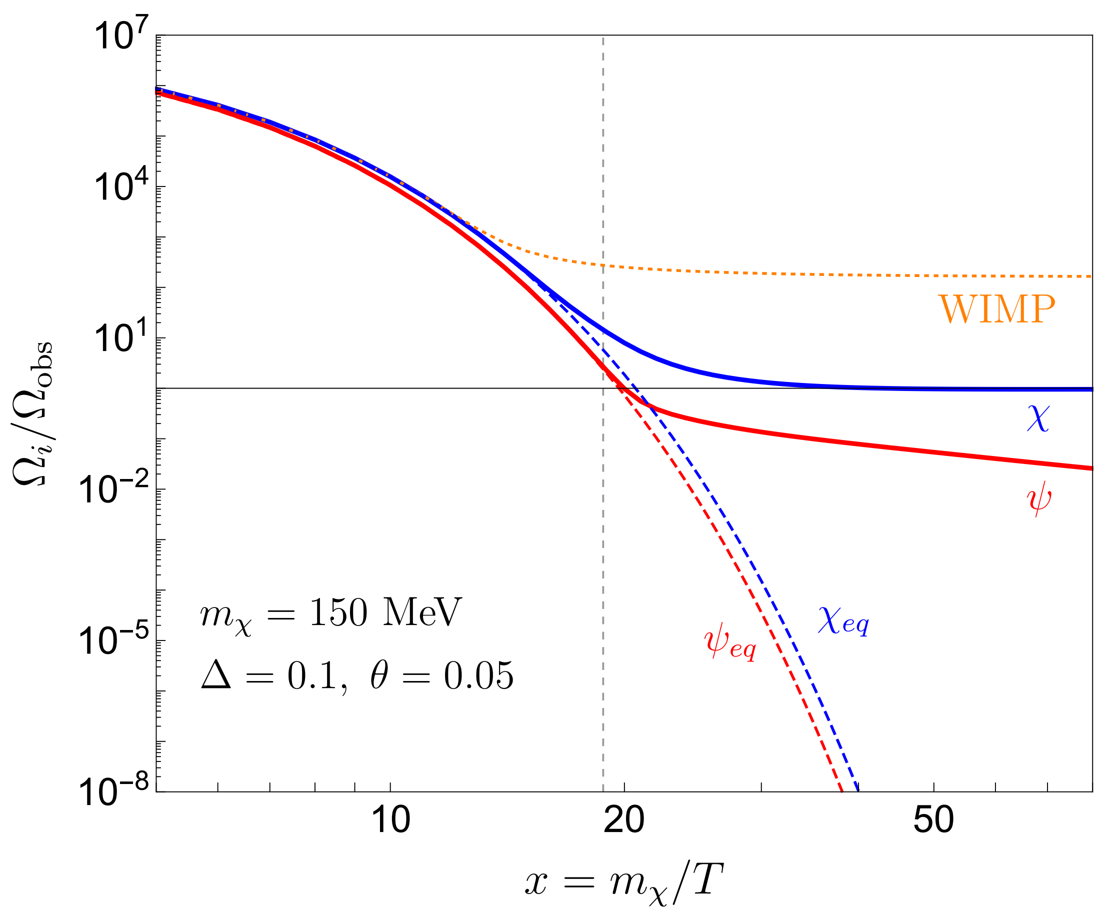
- abundance is set by coscattering:



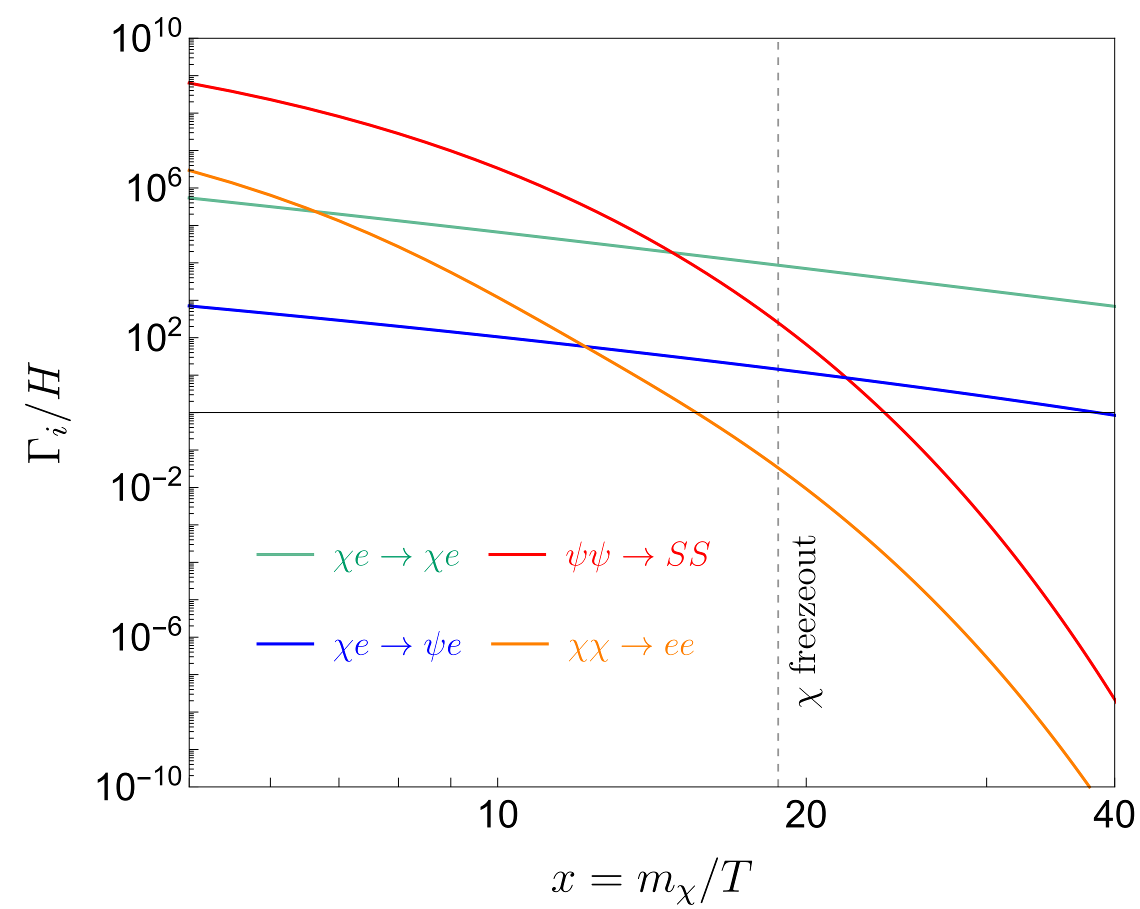
Coscattering Against the SM Bath



relic density

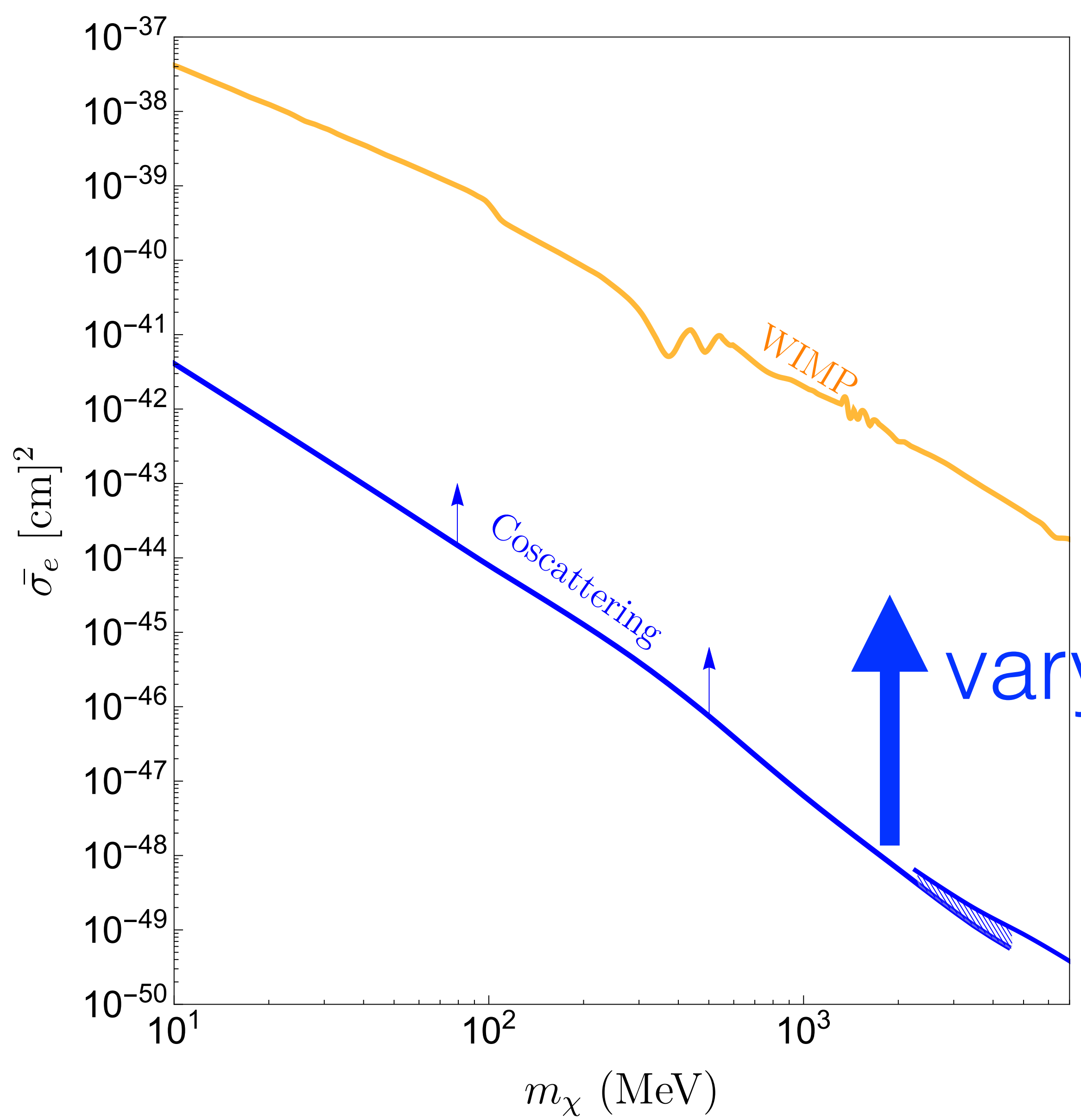


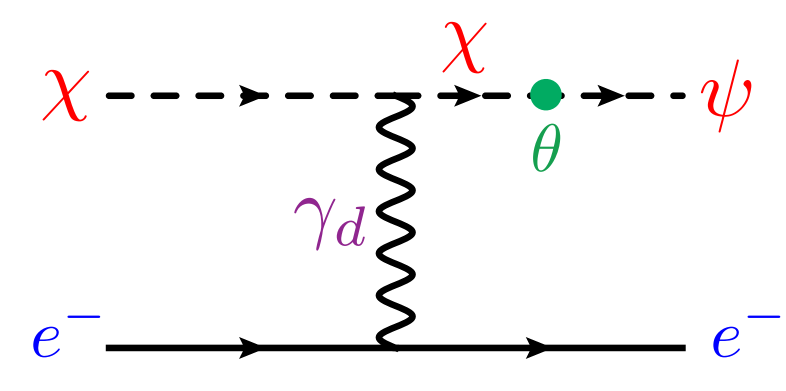
rates



Coscattering Thermal Target

rate enhancement: $$\frac{\Gamma_{\rm cosc}}{\Gamma_{\rm ann}} = \frac{n_e \langle \sigma_{\chi e} v \rangle}{n_\chi \langle \sigma_{\chi\bar{\chi}} v \rangle} \propto \frac{\theta^2 e^{-(m_\psi - m_\chi)/T}}{e^{-m_\chi/T}}$$





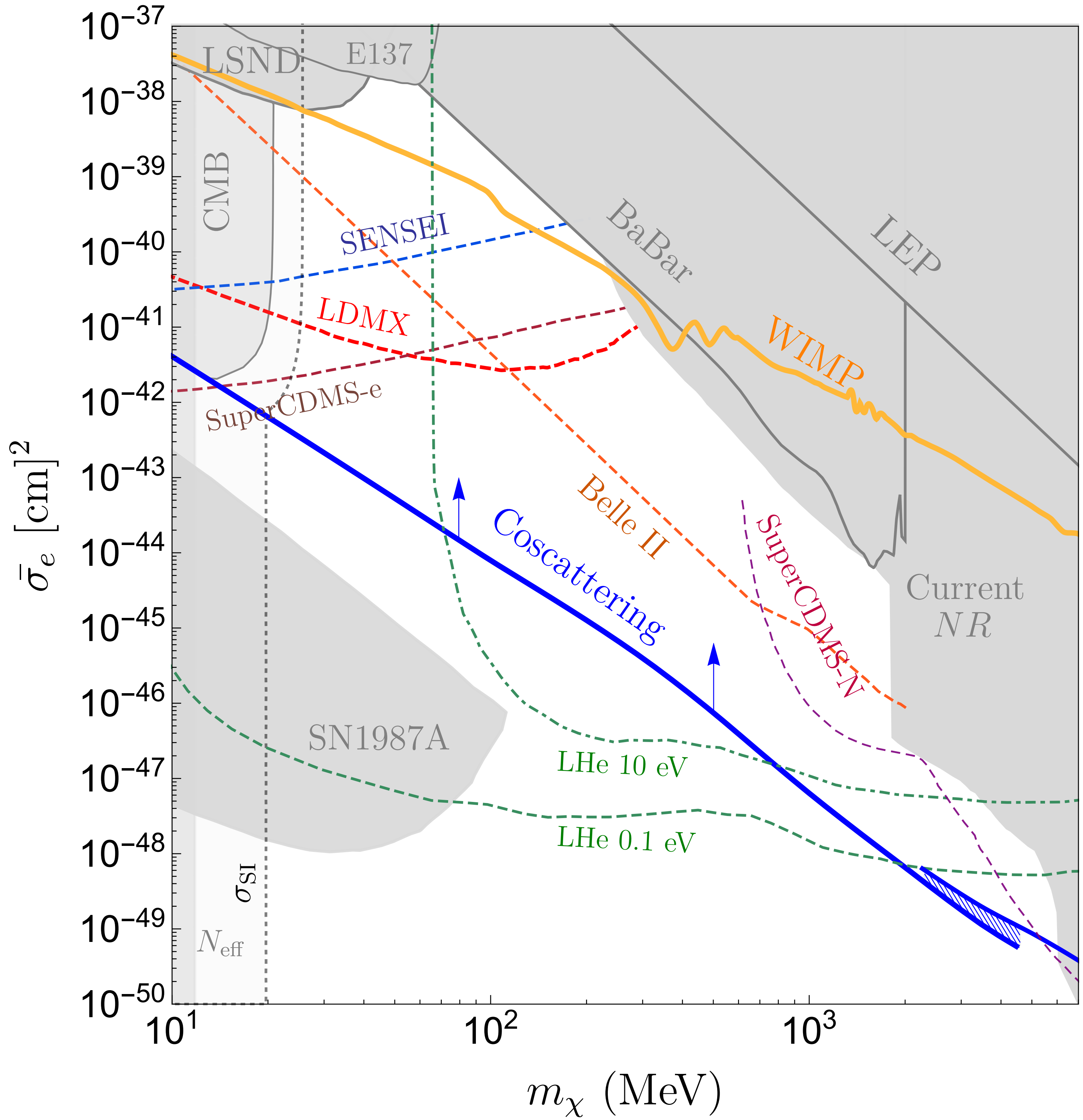
vary: θ

$m_\psi - m_\chi$

min cross section: $\theta \to \pi/4$

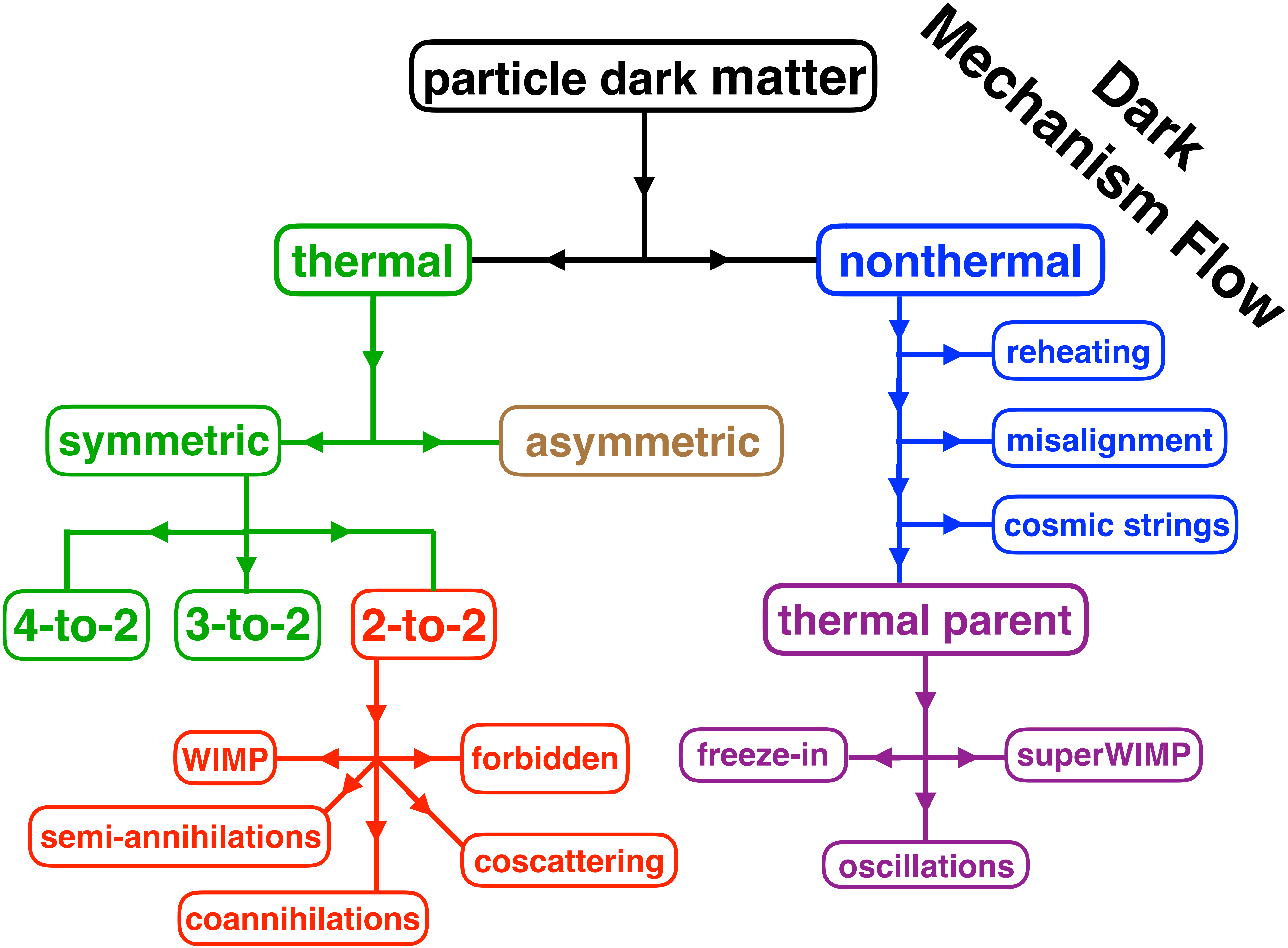
$m_\psi \to m_\chi$

Coscattering Thermal Target



$m_\psi^2 - m_\chi^2 = 0.1$

$\theta \leq 0.45$


Dark Mechanism Flow
particle dark matter
thermal
nonthermal
reheating
misalignment
cosmic strings
symmetric
asymmetric
4-to-2
3-to-2
2-to-2
thermal parent
WIMP
forbidden
semi-annihilations
coscattering
coannihilations
freeze-in
superWIMP
oscillations

Thermal Relic Targets

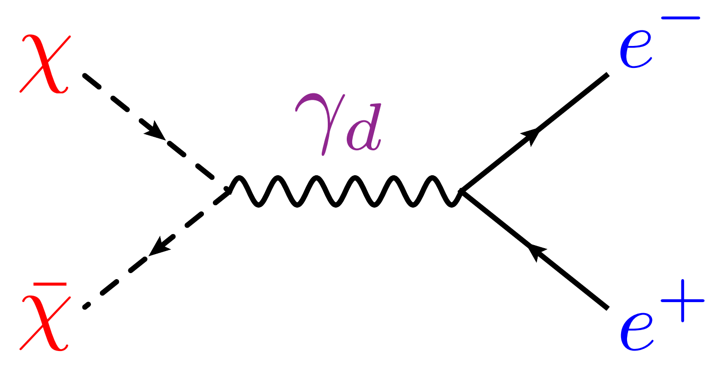
1) thermal relic with: $T_d = T_\gamma$

2) no funny cosmology

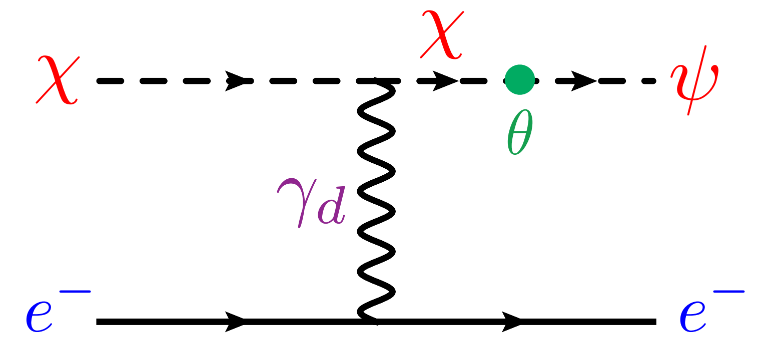
3) $\mathcal{Z}_2$, 2-to-2 annihilations

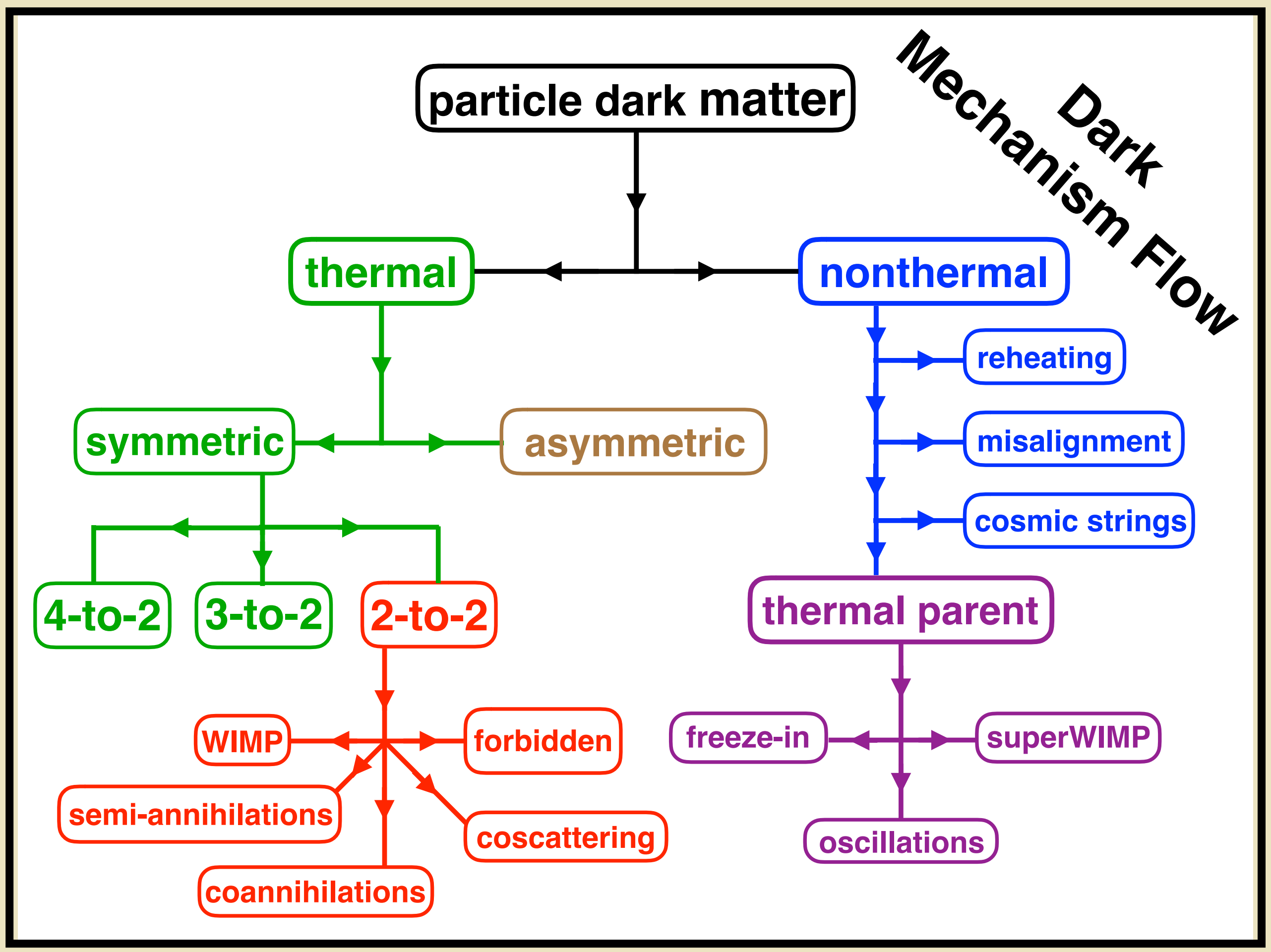
4) abundance from decoupling of interaction with SM

annihilations:



coscattering:

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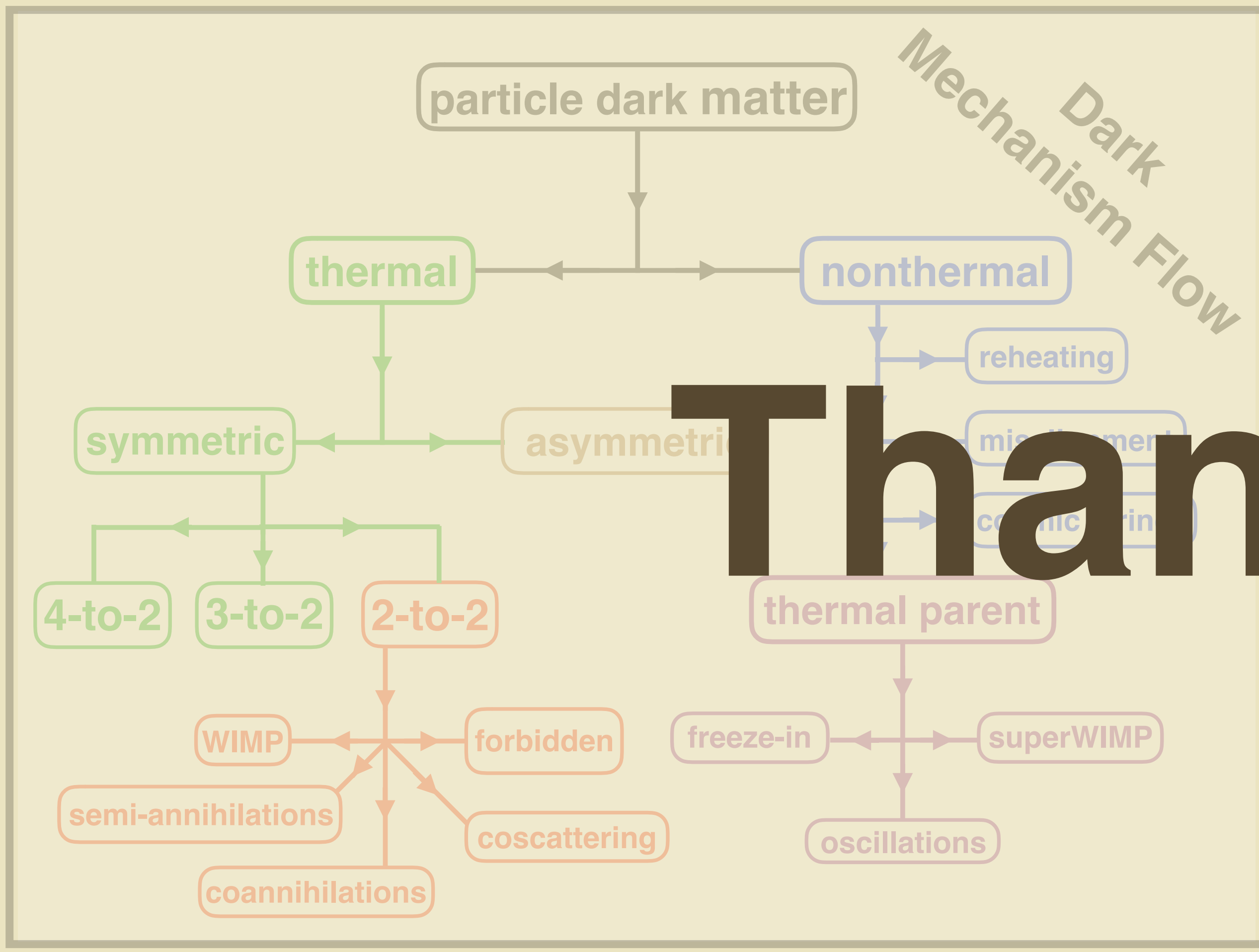
The Very, Very Many Varieties of BEER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Thanks!!!