Massachusetts Institute of Technology

KINDER

KINetically DEcoupling Relic

New Pathways to the Relic Abundance of Vector-Portal DM

arXiv:2011.01240

with Hongwan Liu, Tracy Slatyer, and Yu-Dai Tsai

Patrick Fitzpatrick fitzppat@mit.edu

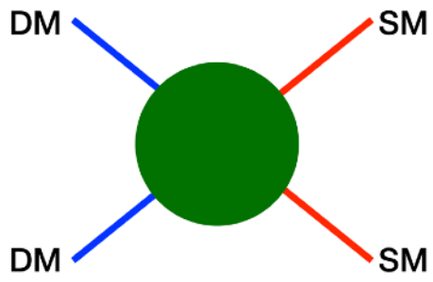
Light Thermal DM

DM Mass

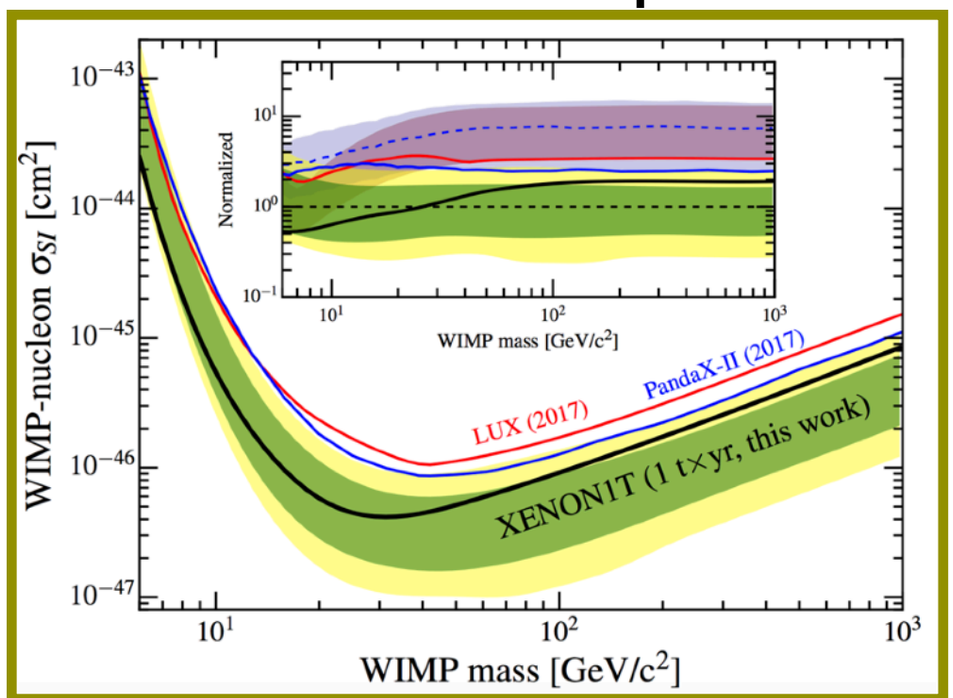
TeV

GeV

MeV



- **WIMP**
  - **Simplest thermal relic**
  - **Theoretically attractive**
  - **WIMP miracle**
- **Current direct detection constraints less sensitive < GeV**
- **Light, Thermal DM**
  - **New experiments: SENSEI, SuperCDMS, etc.**
  - **SIMP, ELDER, Co-SIMP, Forbidden DM, Not-Forbidden DM**



E. Aprile et al. (XENON Collaboration) 2017

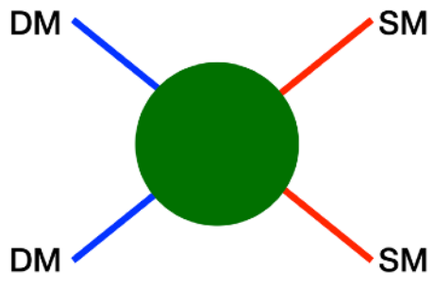
Light Thermal DM

DM Mass

TeV

GeV

MeV



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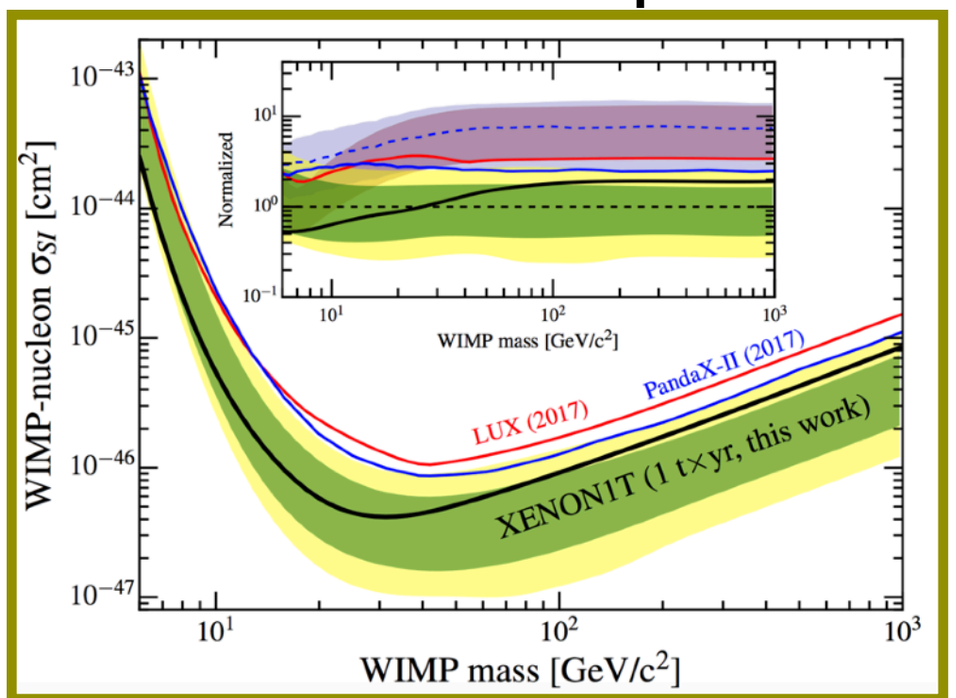
- **Current direct detection constraints less sensitive < GeV**



E. Aprile et al. (XENON Collaboration) 2017

- **Light, Thermal DM**
  - **New experiments: SENSEI, SuperCDMS, etc.**
  - **SIMP, ELDER, Co-SIMP, Forbidden DM, Not-Forbidden DM**
  - ***New Pathways to the Relic Abundance of Vector-Portal DM***
    - **KINetically DEcoupling Relic (KINDER)**

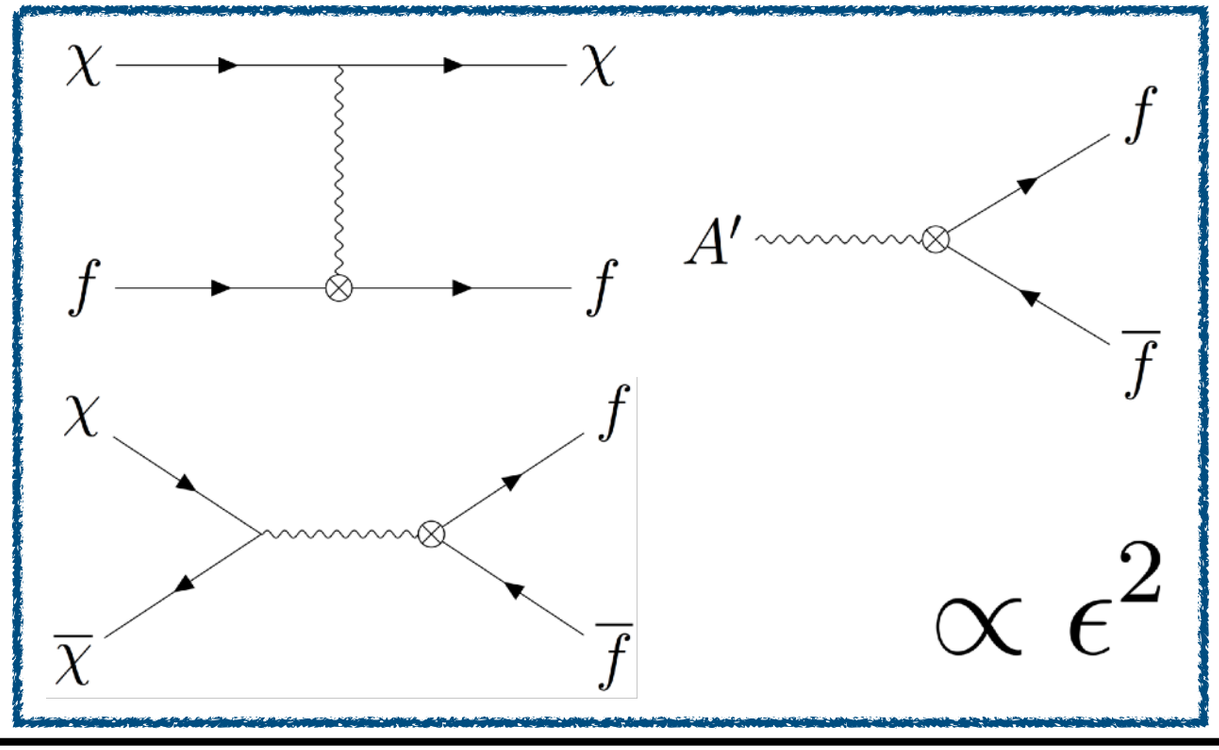
Dark Photon

- **in mass basis:**

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'^2 + \bar{\chi}\left(i\not{D} - m_\chi\right)\chi + eJ^\mu_{\mathrm{EM}}\left(A_\mu + \epsilon A'_\mu\right)$$

$$\not{D} \equiv \not{\partial} - ig_D\not{A}' \qquad \alpha_D = g_D^2/4\pi$$

- **kinetic mixing with SM:** $\mathcal{L}_{Mix} = \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$



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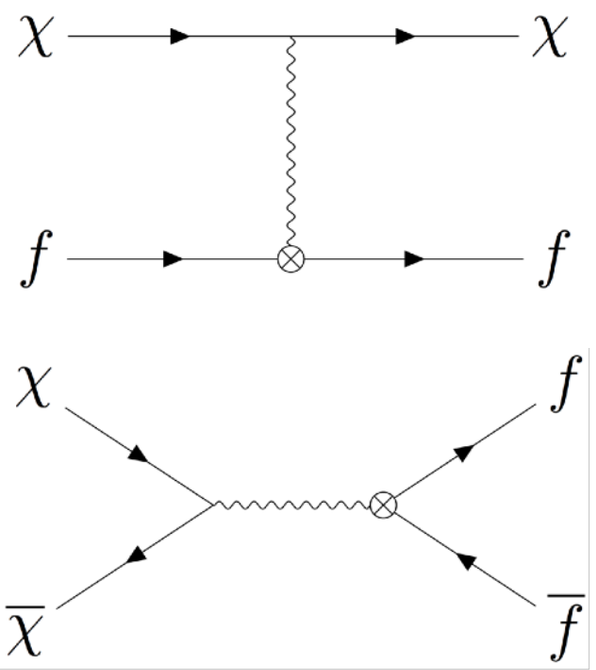
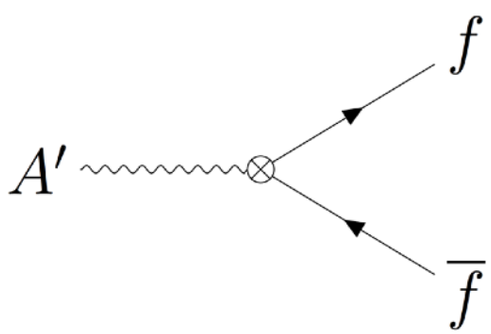
$$\not{D} \equiv \not{\partial} - ig_D\not{A}' \qquad \alpha_D = g_D^2/4\pi$$

- **Let's consider region:**

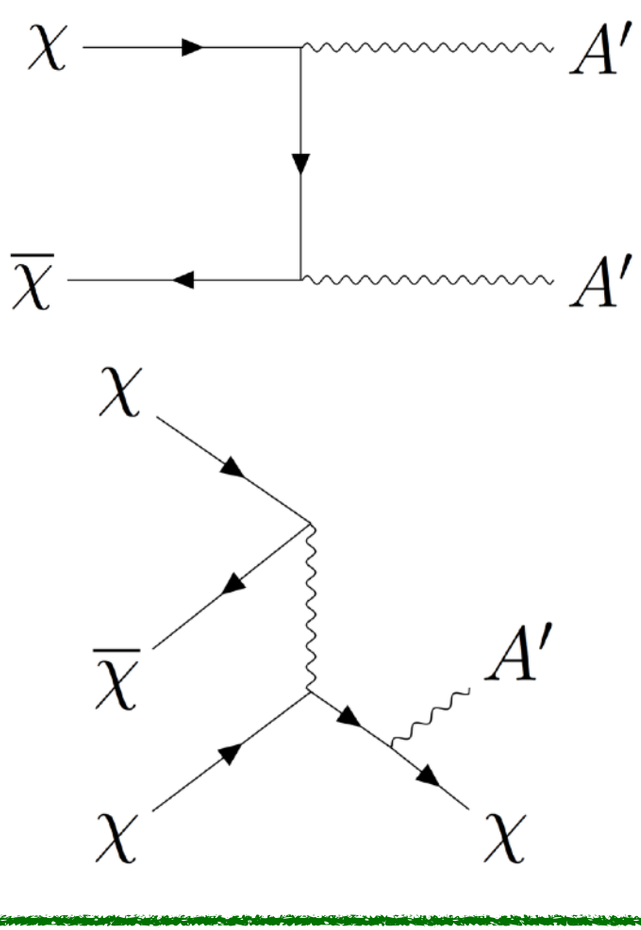
$$m_\chi \lesssim m_{A'} \lesssim 2m_\chi$$



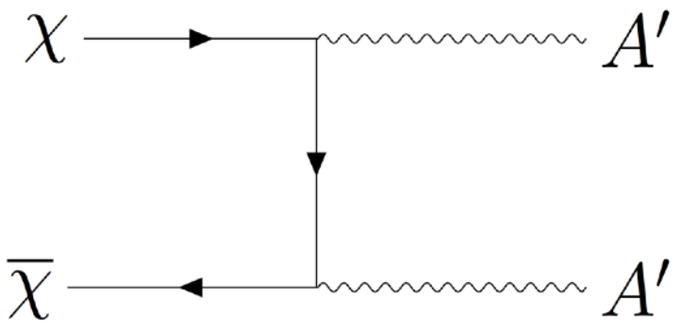


- **kinetic mixing with SM:**

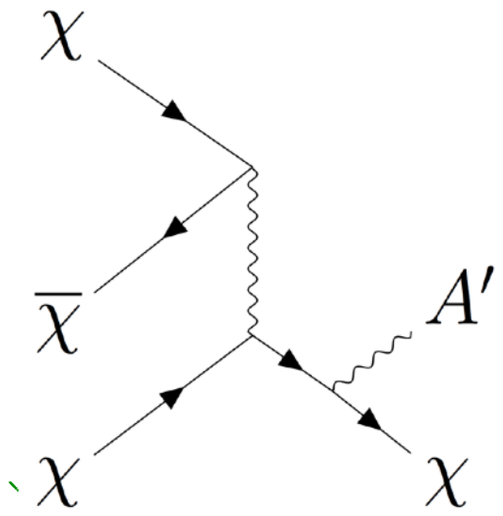
$$\propto \epsilon^2$$



Breaking Thermal Equilibrium

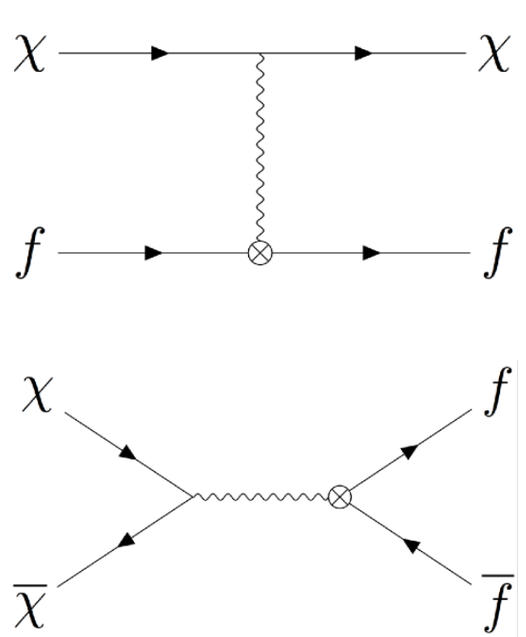


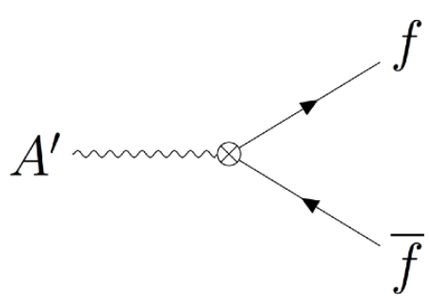
$$1 \lesssim \frac{m_{A'}}{m_\chi} \lesssim 2$$



Novel scenarios

- ϵ small but nonzero
  - DM and SM kinetically decouple
  - $T' \neq T$
- *New Pathways to the Relic Abundance*
- KINetically DEcoupling Relic





$$\propto \epsilon^2$$

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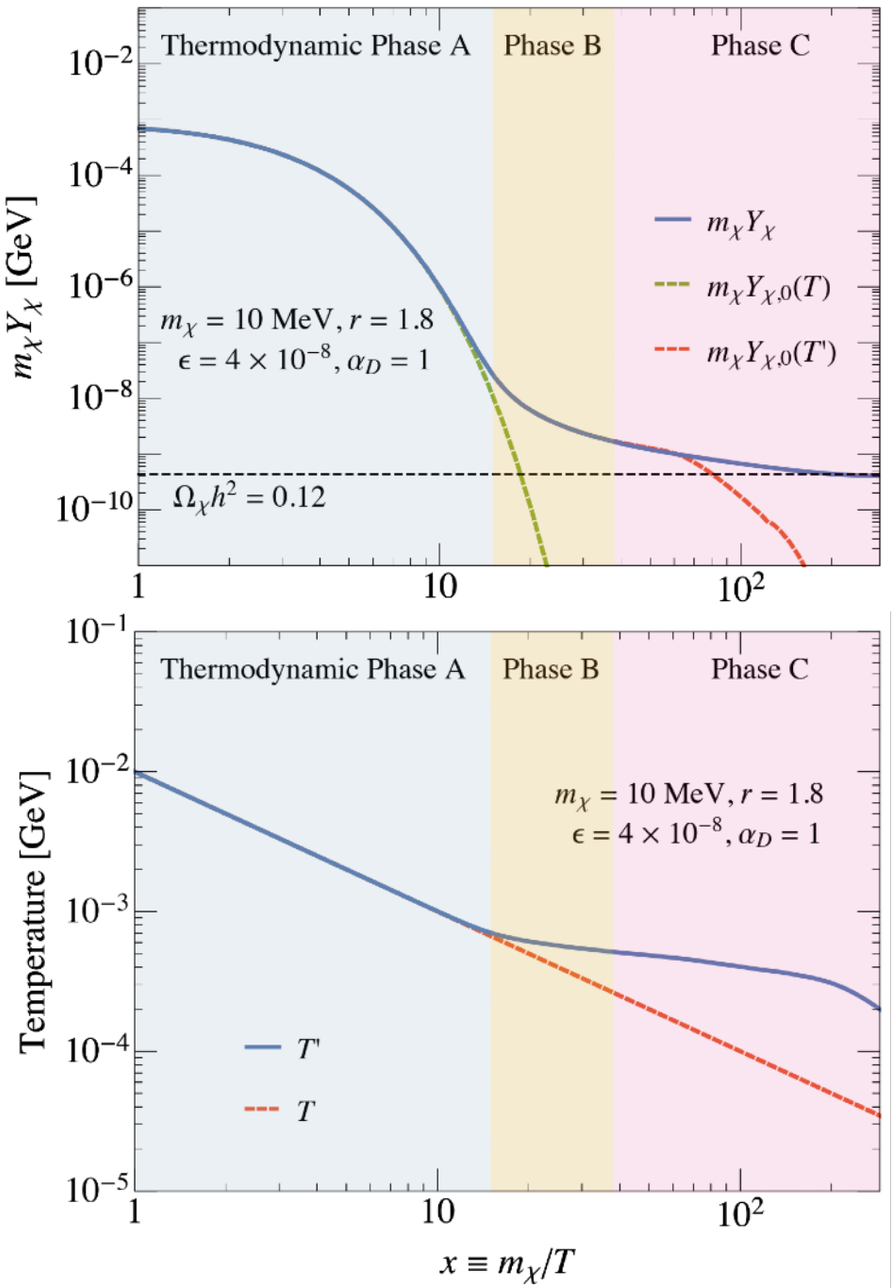
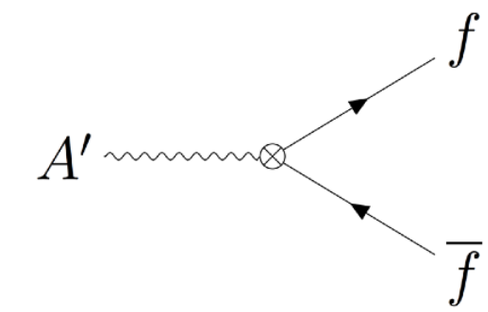
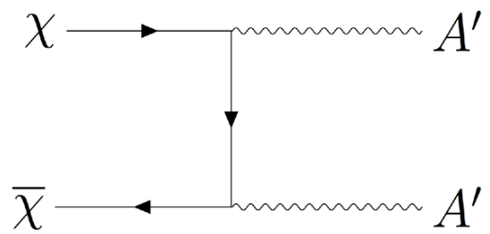
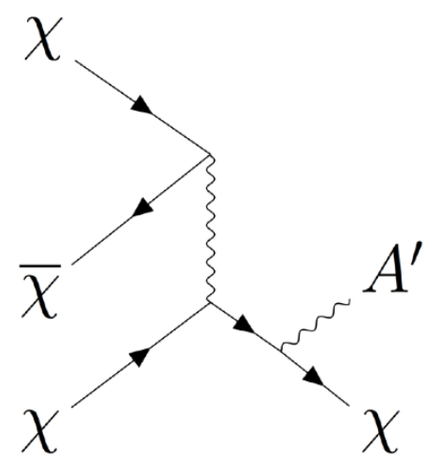


Maintains thermal equilibrium DM-SM





Maintain chemical equilibrium DM



$$r \equiv \frac{m_{A'}}{m_\chi}$$

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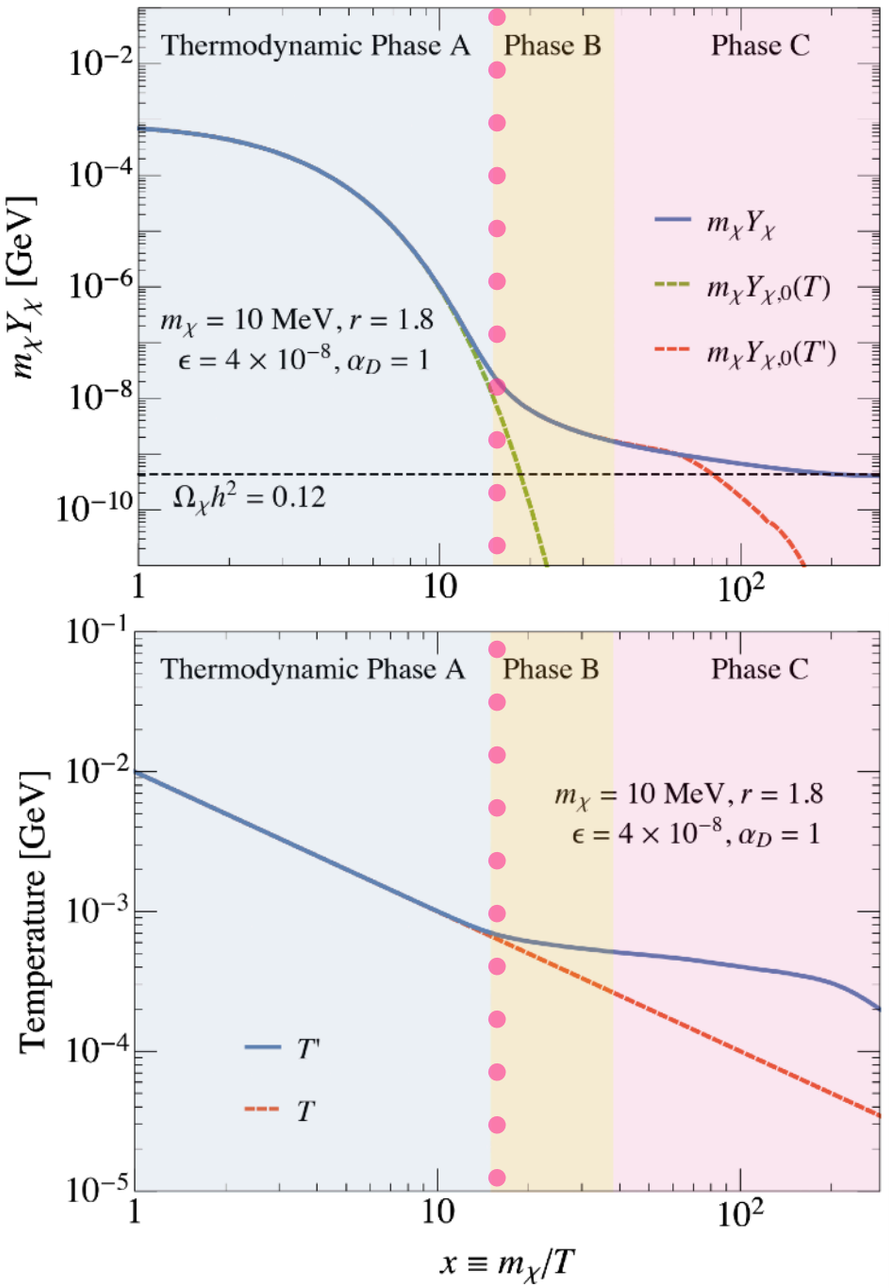
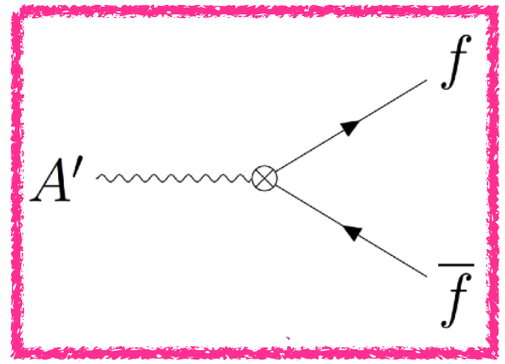
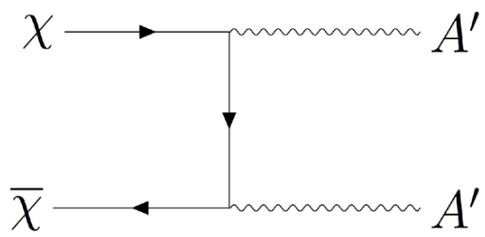


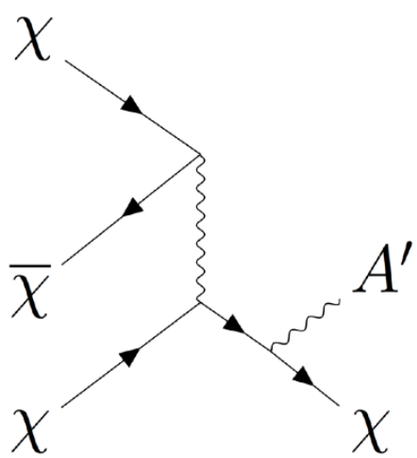
KINetic DEcoupling

$$\left(\begin{array}{c} A' \to e^+e^- \\ \text{DM-to-SM} \\ \text{Energy transfer Rate} \end{array}\right) \lesssim \left(\begin{array}{c} 3 \to 2 \\ \text{DM} \\ \text{Heating Rate} \end{array}\right)$$





Maintain chemical equilibrium DM

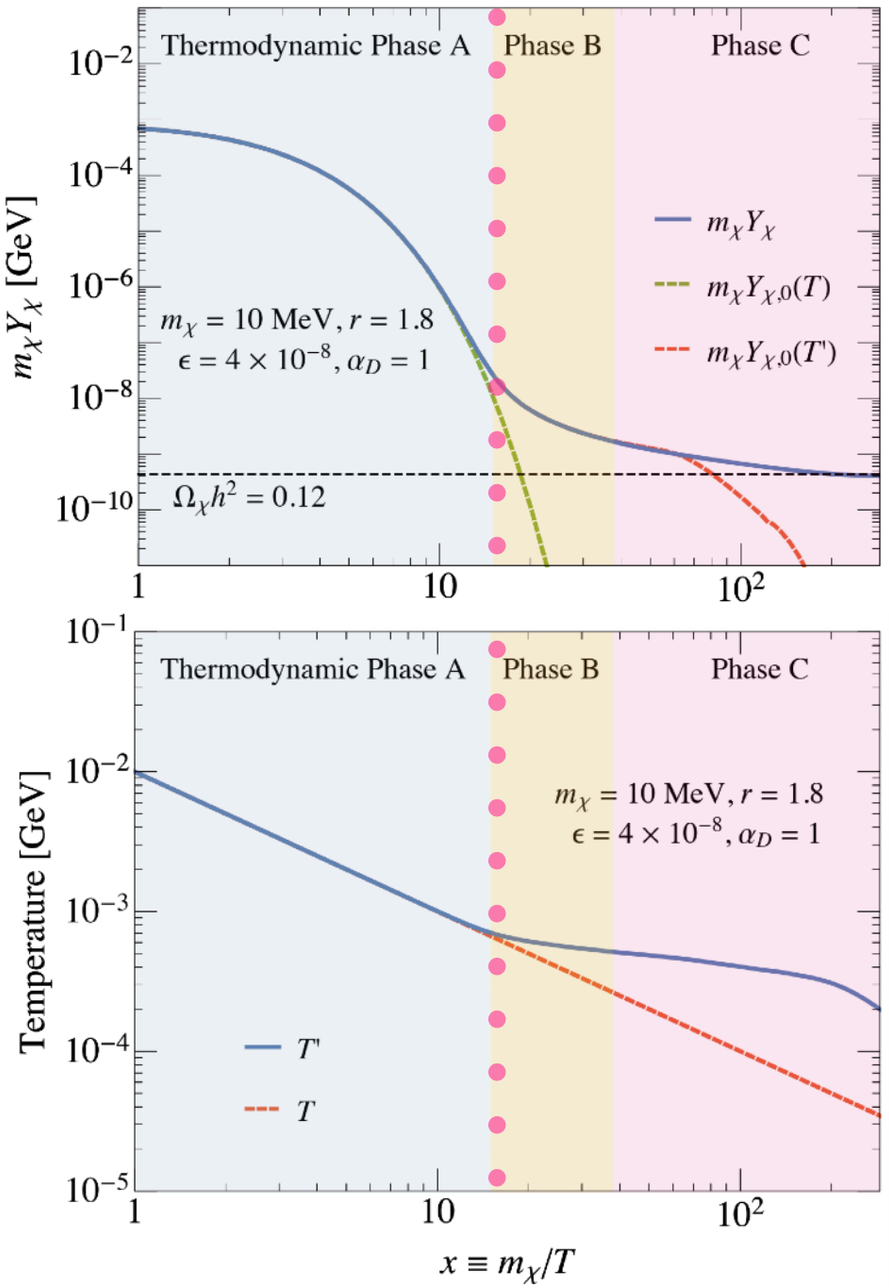


$$T' \neq T$$

T_d

$$r \equiv \frac{m_{A'}}{m_\chi}$$

KINDER



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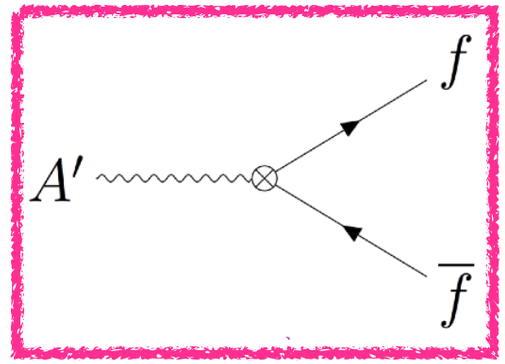
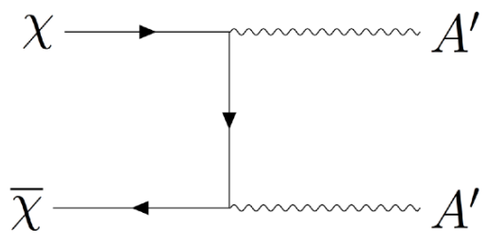
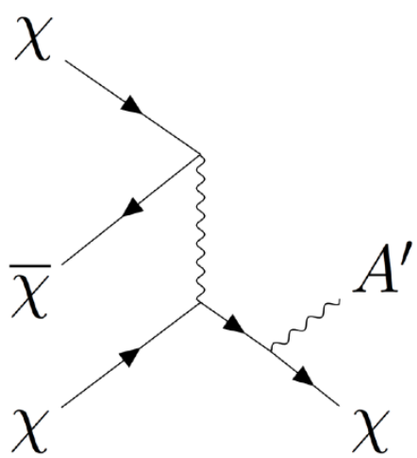




Maintain chemical equilibrium DM



$$T' \neq T$$

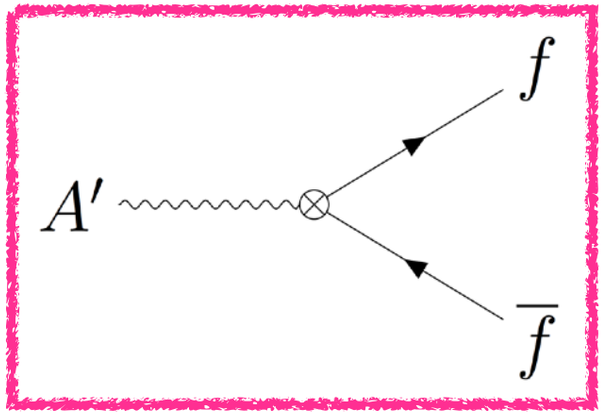
Cannibalization…

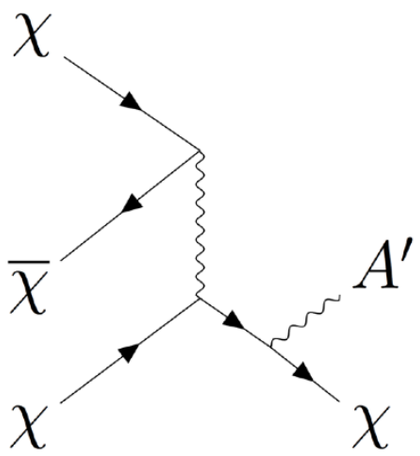
T_d

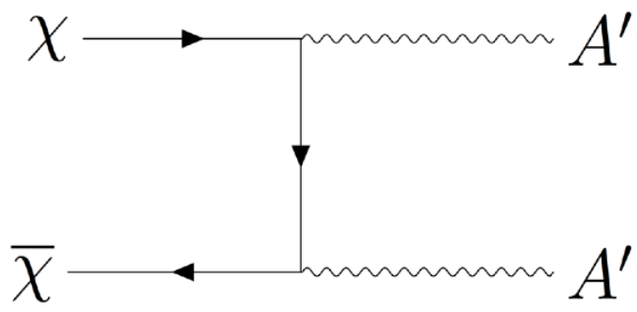
$$r \equiv \frac{m_{A'}}{m_\chi}$$

Cannibalization

- **Thermally secluded dark sector, 2—>2 and 3—>2 remain fast**







$$T' \neq T$$

$$\Gamma_{2\to 2}, \Gamma_{3\to 2} \gg H$$

$$\mu_\chi = \mu_{A'} = 0$$

- **Comoving entropy density DM conserved**

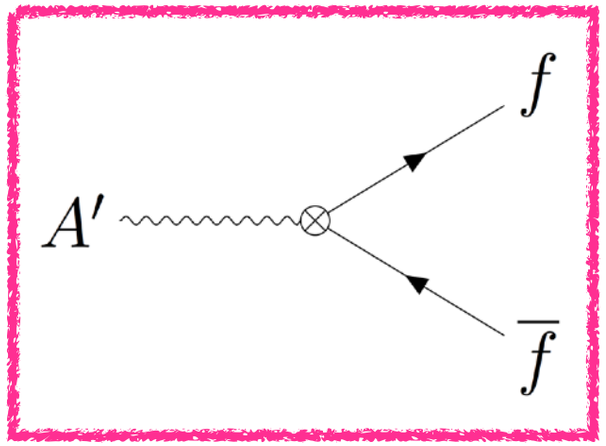
$$d\left(sa^3\right)/dT' = 0 \longrightarrow T' \simeq \frac{T_d}{1 - \frac{3T_d}{m_\chi}\ln\left(T/T_d\right)}$$

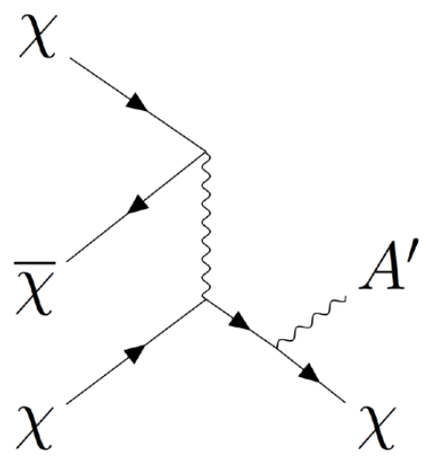
DM evolves with ~constant Temp and comoving density

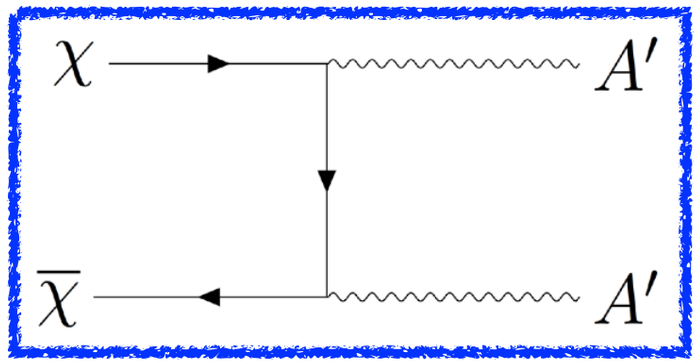
- ***Cannibalization*** **— `as the universe expands, DM cannibalizes itself to keep warm'**

2—>2 Freezeout

- **Dark sector gains nonzero μ …*cannibalization* continues**







$T' \neq T$ $\qquad$ $\Gamma_{3\to 2} \gg H$ $\qquad$ $\Gamma_{2\to 2} < H$

$$\mu_{A'} = 2\mu_\chi \neq 0$$

- **Comoving entropy density DM conserved**

$$d\left(sa^3\right)/dT' = 0 \longrightarrow T' \simeq \frac{T_2'}{1 - \frac{3}{(2-r)}\frac{T_2'}{m_\chi}\ln\frac{T}{T_2}}$$

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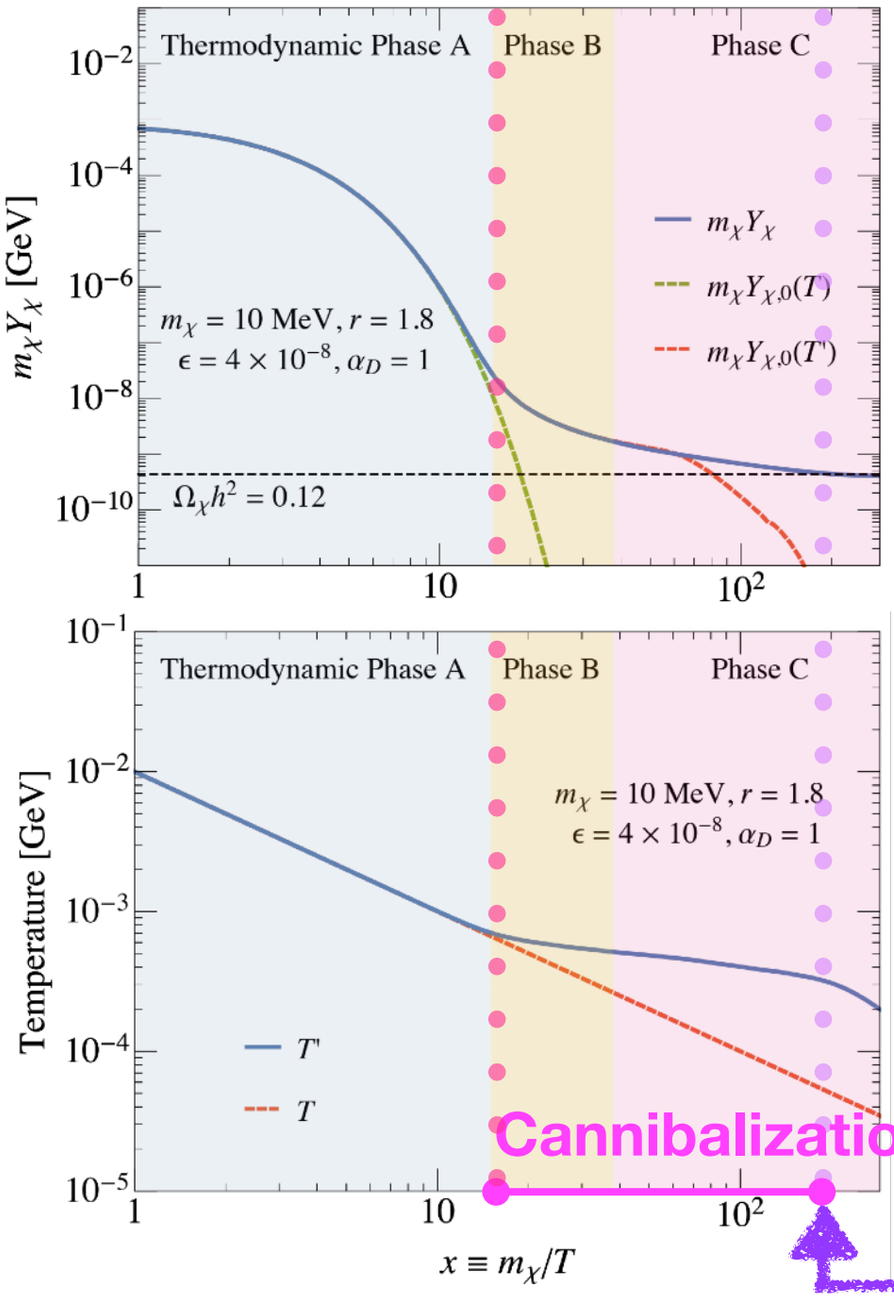
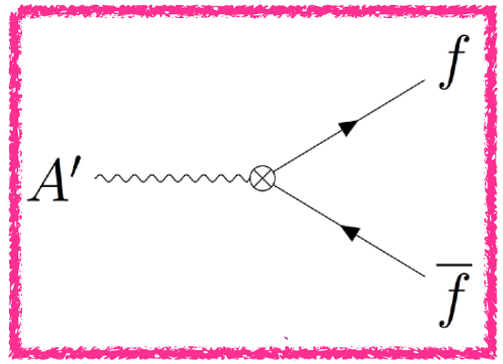
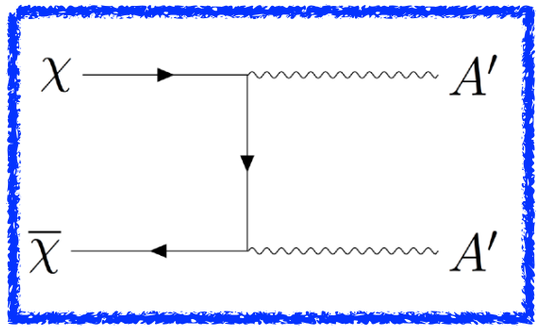
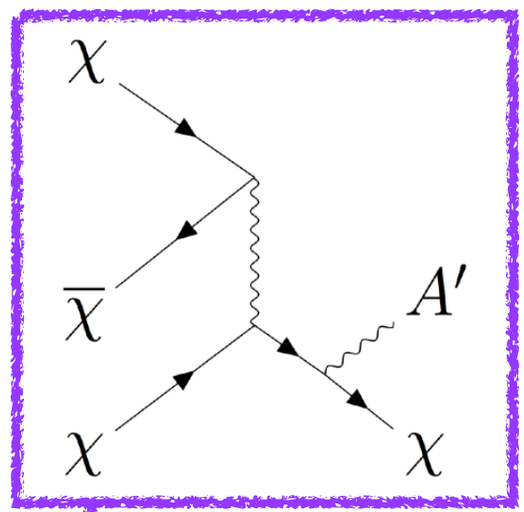


Relic abundance set by KINetic DEcoupling

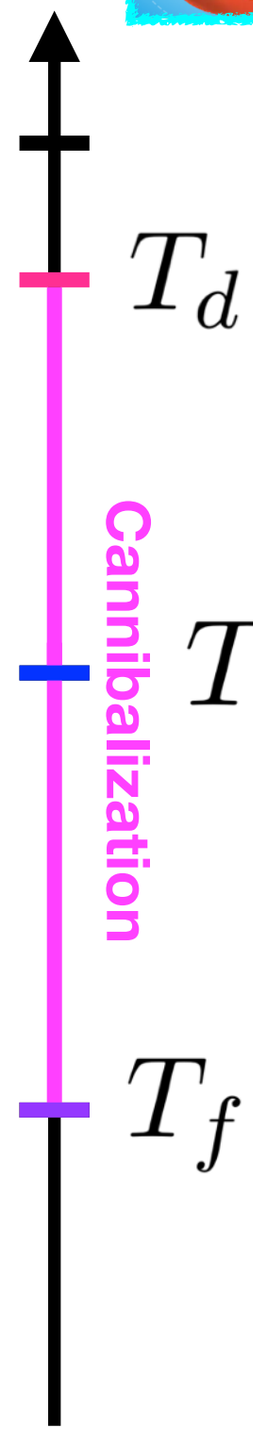
KINDER







Cannibalization $T' \propto \log T$



$$r \equiv \frac{m_{A'}}{m_\chi}$$

KINDER Relic Abundance

- **Relic abundance set by KINetic DEcoupling of A'-to-SM decays**

$$\Omega_\chi \sim Y\left(T_f\right) = \frac{n_{DM}}{s}\left(T_f\right) \sim \frac{\left(m_\chi/T_f'\right)^{-3/2} e^{-m_\chi/T_f'}}{\left(m_\chi/T_f\right)^{-3}}$$

$$\frac{m_\chi}{T_d} e^{(1-r)m_\chi/T_d} \sim \frac{m_\chi}{M_{pl}} \frac{1}{r^{7/2}\epsilon^2\alpha_{em}}$$

$$T_2' \simeq \frac{T_d}{1 - \frac{3T_d}{m_\chi}\ln\left(T_2/T_d\right)}$$

$$T_f' \simeq \frac{T_2'}{1 - \frac{3}{(2-r)}\frac{T_2'}{m_\chi}\ln\frac{T_f}{T_2}}$$

T_d

T_2

Cannibalization

T_f

KINDER Relic Abundance

- **Relic abundance set by KINetic DEcoupling of A'-to-SM decays**

$$\Omega_\chi \sim Y(T_f) = \frac{n_{DM}}{s}(T_f)$$
$$\sim \frac{\left(m_\chi/T'_f\right)^{-3/2} e^{-m_\chi/T'_f}}{(m_\chi/T_f)^{-3}}$$
$$\sim 10^8 \left(\frac{m_\chi}{\text{GeV}}\right) \frac{(m_\chi/T_d)^3}{(m_\chi/T'_3)^2} \sqrt{\frac{m_\chi}{T_d} + 3\log\frac{T_d}{T_2}} e^{-\frac{m_\chi}{T_d}}$$

$$\frac{m_\chi}{T_d} e^{(1-r)m_\chi/T_d} \sim \frac{m_\chi}{M_{pl}} \frac{1}{r^{7/2}\epsilon^2\alpha_{em}}$$

$$T'_2 \simeq \frac{T_d}{1 - \frac{3T_d}{m_\chi}\ln(T_2/T_d)}$$

$$T'_f \simeq \frac{T'_2}{1 - \frac{3}{(2-r)}\frac{T'_2}{m_\chi}\ln\frac{T_f}{T_2}}$$

T_d

T_2

T_f

Cannibalization

- **Exponentially sensitive only to the KINetic DEcoupling !**

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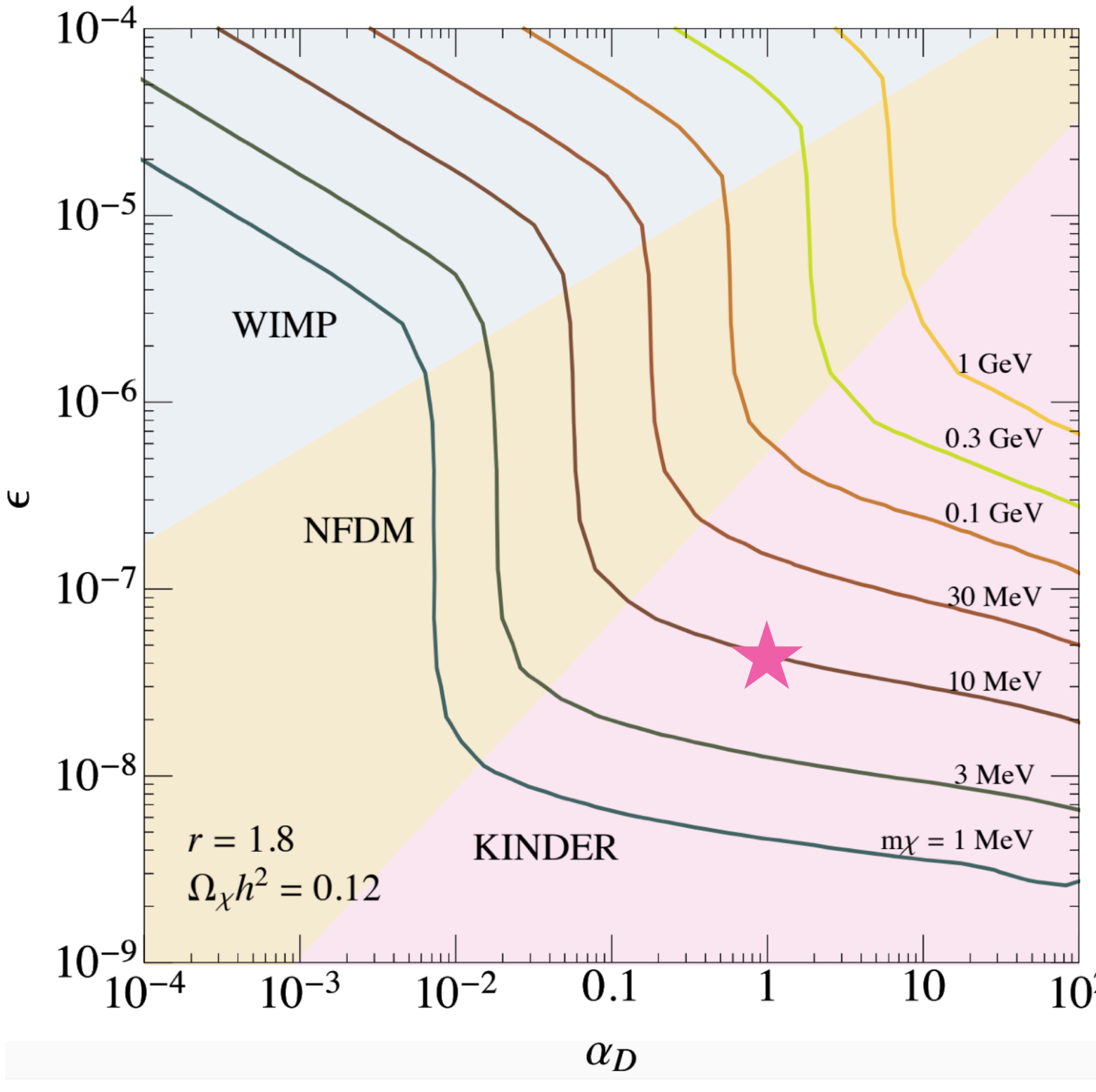
Cannibalization

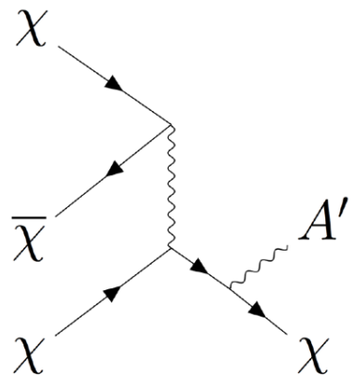
KINDER Regime



NFDM

$$\Omega_\chi \sim e^{-m_\chi/T_f}$$

$$T_f = T_f(\alpha)$$



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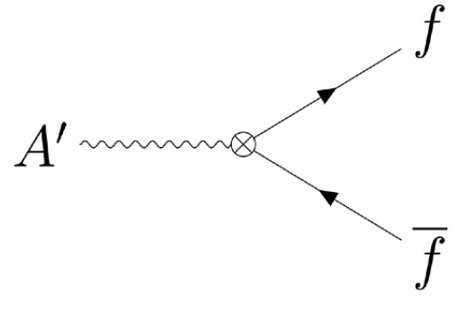
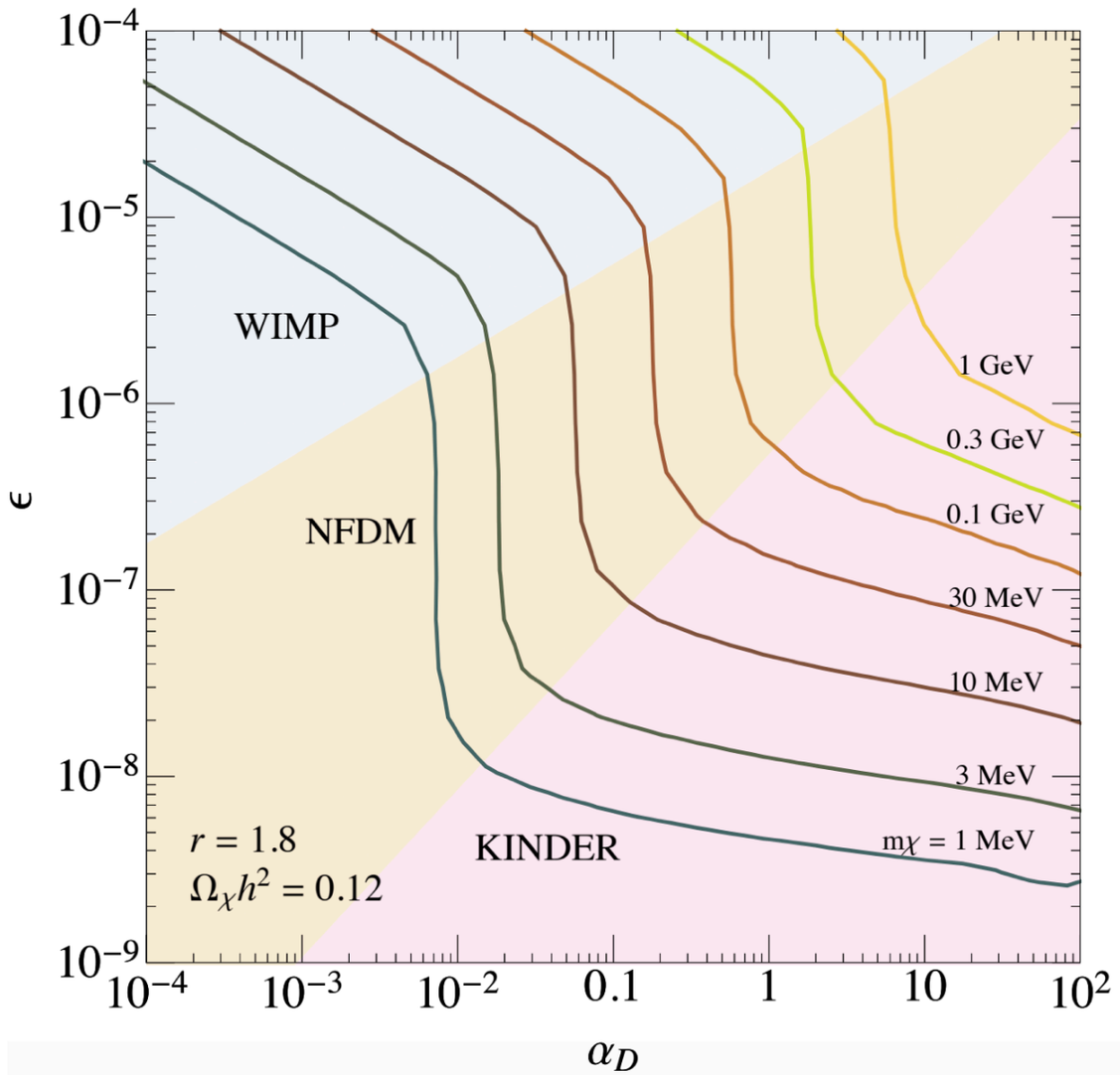
$$\Omega_\chi \sim e^{-m_\chi/T_d}$$

$$T_d = T_d(\epsilon^2)$$

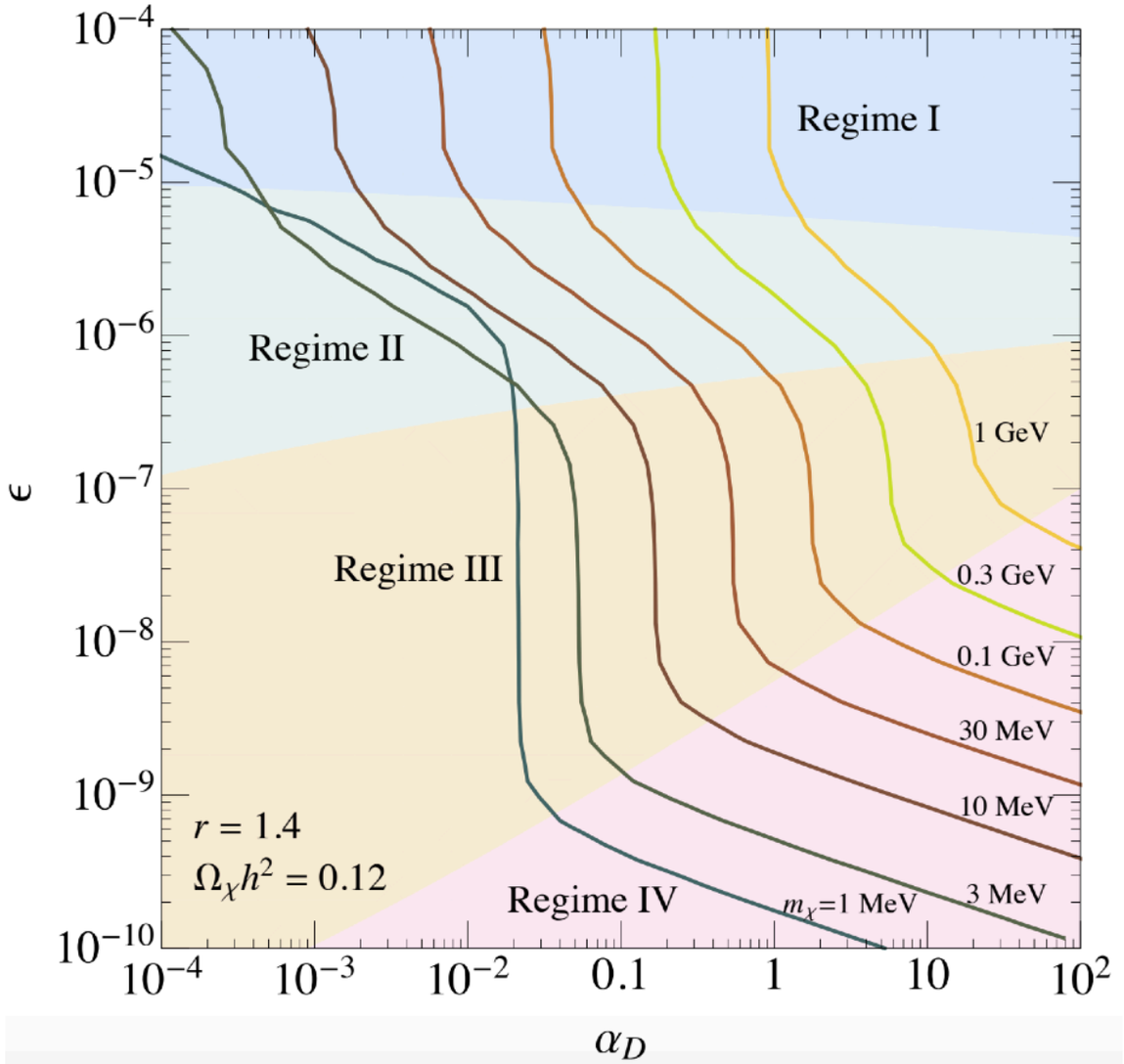


New Regimes

3—>2 freezes out last

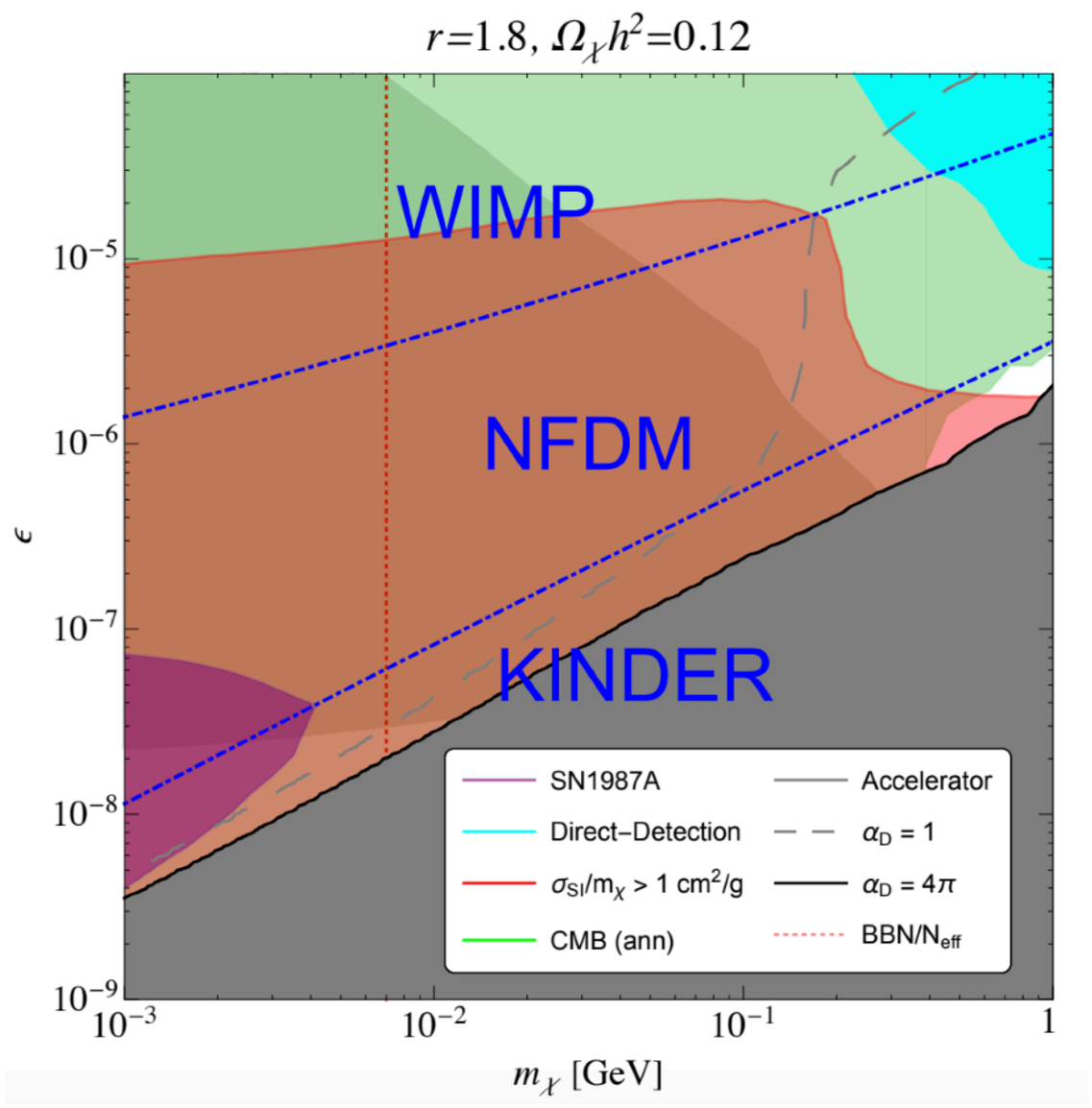


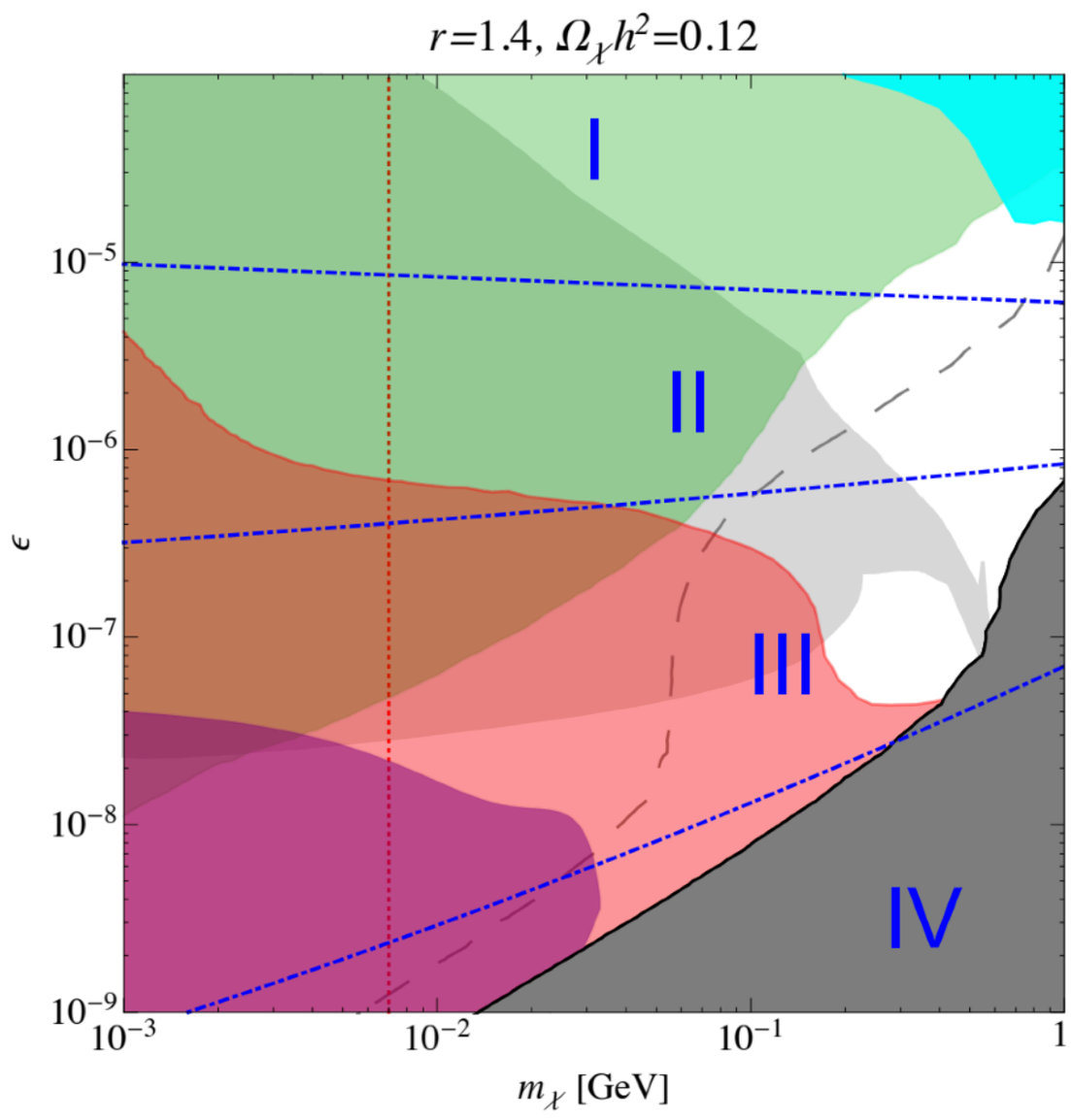
2—>2 freezes out last



- **New pathways to the relic abundance: KINDER, Regimes II, III, and IV**

Experimental Constraints





*SN constraints recast from Jae Hyeok Chang, Rouven Essig, Samuel McDermott (2018)

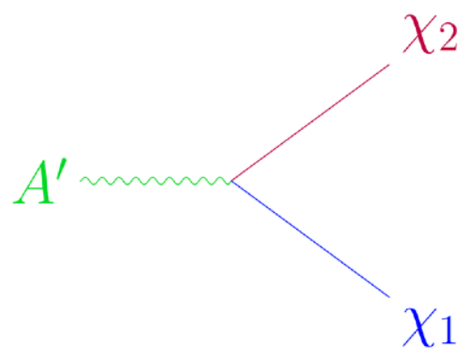
- **KINDER: small available window. Large self-interaction rates, large s-wave annihilation signal in CMB**
- **Available windows for new Regimes II, III**

Inelastic KINDER Surprise

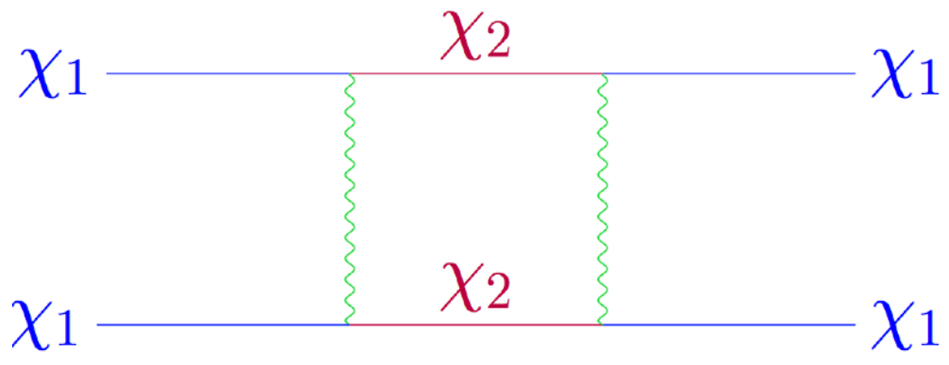
- **Alleviate CMB and Self-Interaction constraints: Inelastic DM**
- **Dark matter is a pseudo-Dirac fermion charged under dark** $U(1)_D$
- $U(1)_D$ **broken:** χ_1 χ_2 **non-degenerate Majorana fermions**

$$\delta \equiv (m_{\chi 2} - m_{\chi 1}) \lesssim T'_f$$

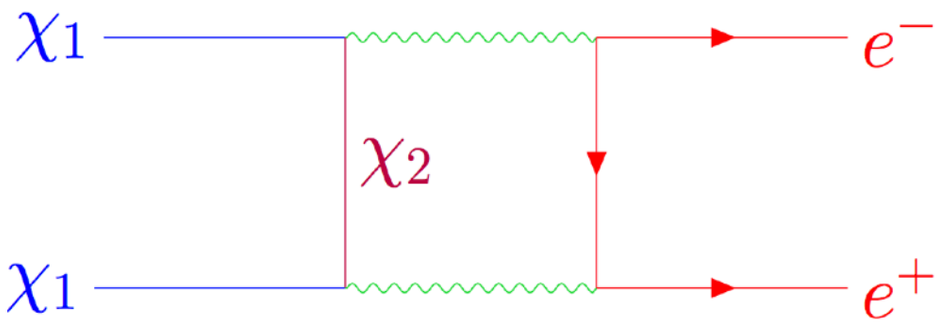
- **vector coupling off-diagonal**



- **Self-Interactions:**



- **CMB**



Conclusions

- **Fully characterized the thermal freezeout histories throughout the parameter space of the dark photon model**

- ***Rich set of novel pathways to the relic abundance which naturally produce light DM***

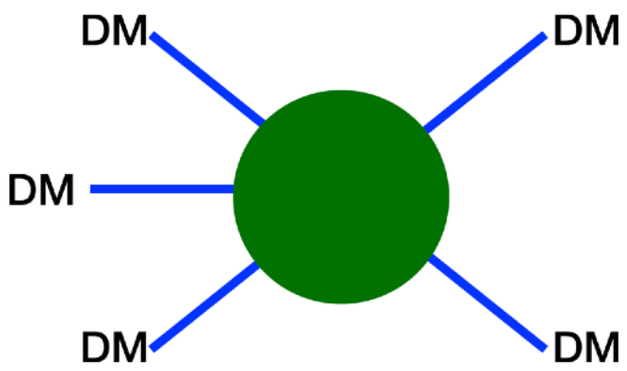
- **KINetically DEcoupling Relic:**
  - **Relic abundance set by KINetic DEcoupling of DM and SM**

- **New viable target regions for future experiments searching for light DM**

Patrick Fitzpatrick fitzppat@mit.edu

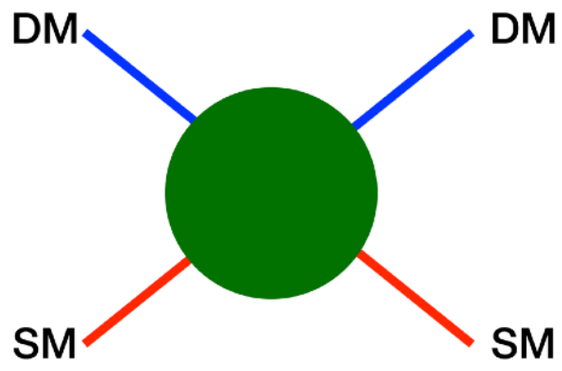
Extra Slides

SIMP Miracle



- **Maintains chemical equilibrium in dark sector**

$$\Gamma_{3\to 2} > H$$

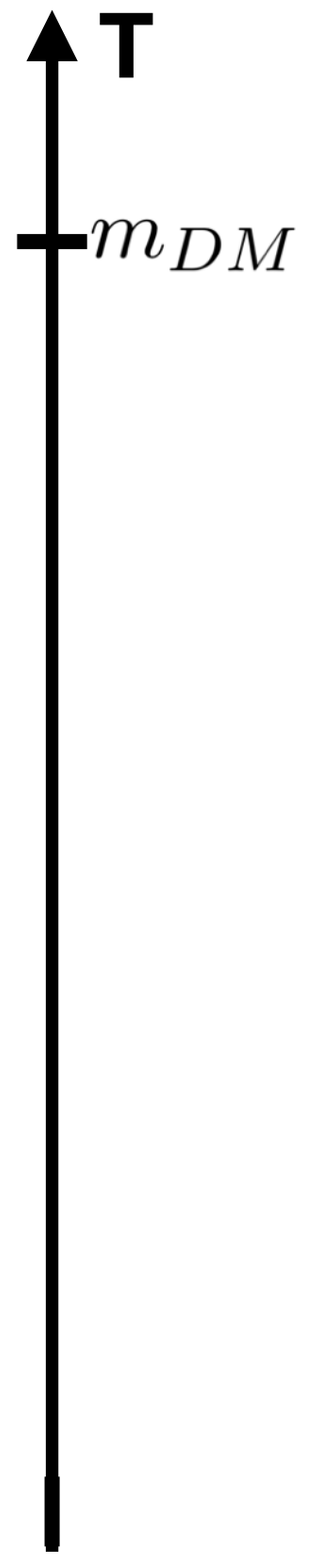


- **Maintains thermal equilibrium DM-SM**

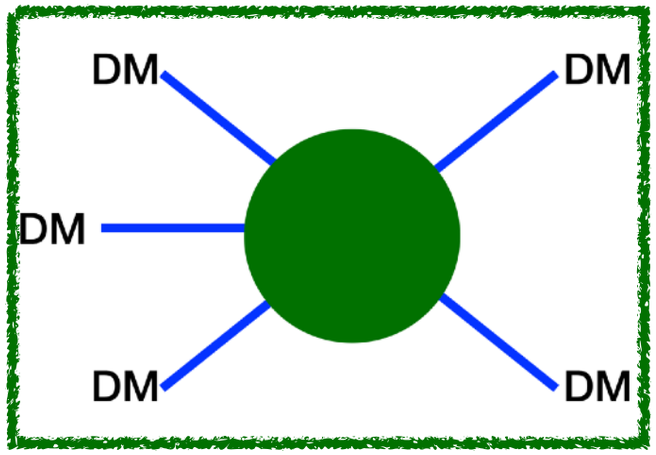
$$\Gamma_{\text{elastic}} > H$$

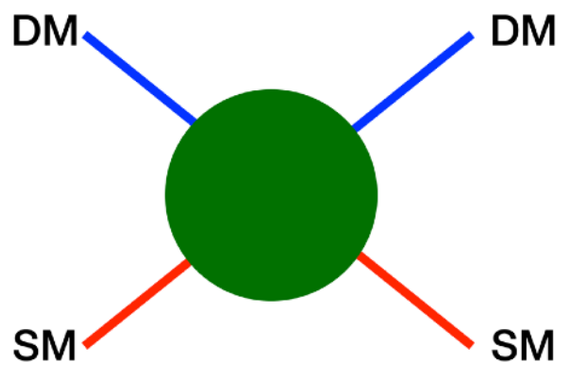
- **Strongly (Self-)Interacting Massive Particle: relic abundance set by 3—>2**

  Hochberg et al. 2014



SIMP Miracle





$$\Gamma_{\text{elastic}} > H$$

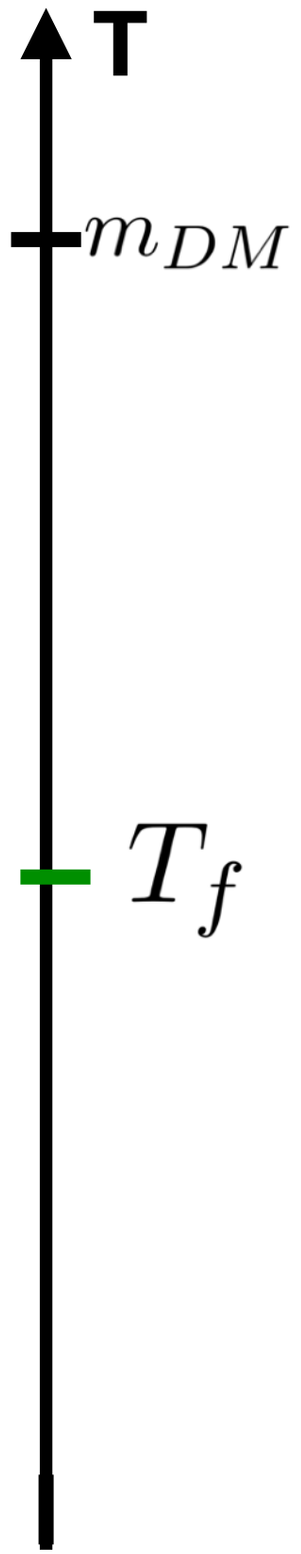
- **Strongly (Self-)Interacting Massive Particle: relic abundance set by 3—>2**

  Hochberg et al. 2014

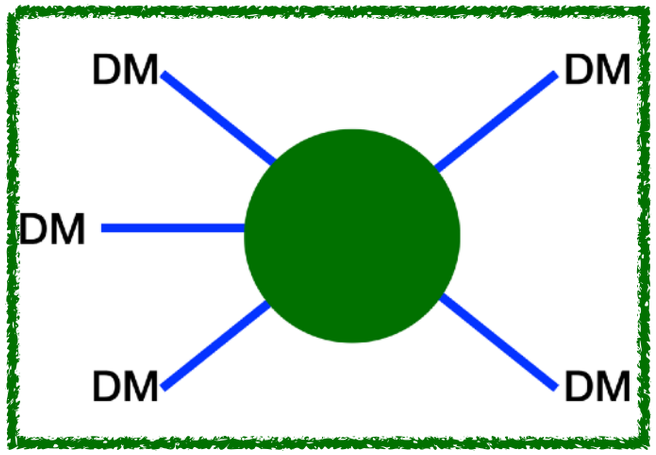
- **as Universe cools…**

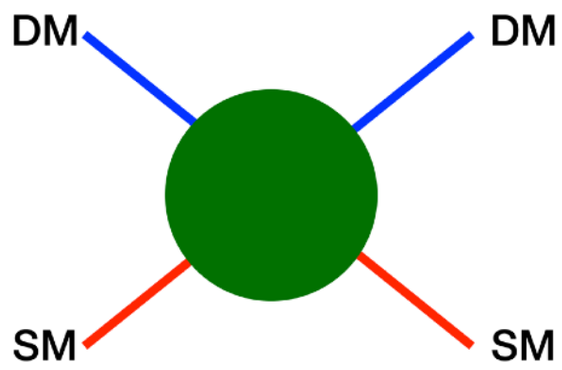
  Thermal freezeout

$$\Gamma_{3\to 2} = n_{DM}^2 \langle \sigma v^2 \rangle_{3\to 2}|_{T=T_f} = H\left(T_f\right)$$



SIMP Miracle





$$\Gamma_{\text{elastic}} > H$$

- **as Universe cools…**

  Thermal freezeout

$$\Gamma_{3\to 2} = n_{DM}^2 \langle \sigma v^2 \rangle_{3\to 2}|_{T=T_f} = H\,(T_f)$$

$$m_{DM} \sim M_{pl}^{1/3} T_{eq}^{2/3} \alpha$$

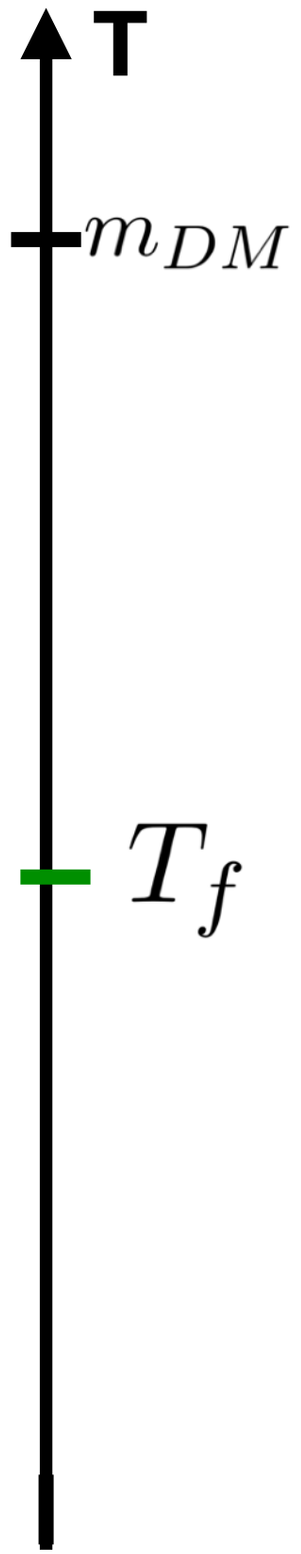
$$\Omega_\chi h^2 = 0.12 \;\rightarrow\; \sim 100\ \text{MeV} \qquad \sim 1$$

- **Strongly (Self-)Interacting Massive Particle: relic abundance set by 3—>2**

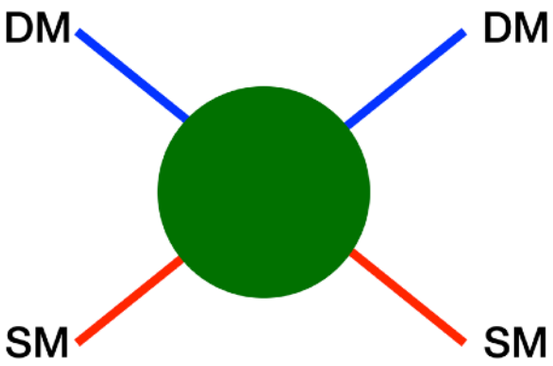
  Hochberg et al. 2014

- **Strong scale DM naturally emerges**

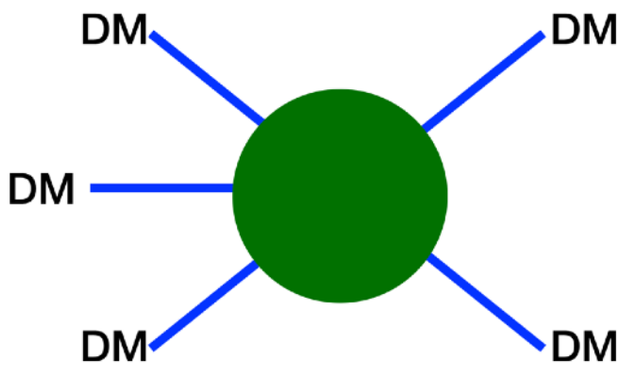
`SIMP Miracle'



Respect Your ELDERs



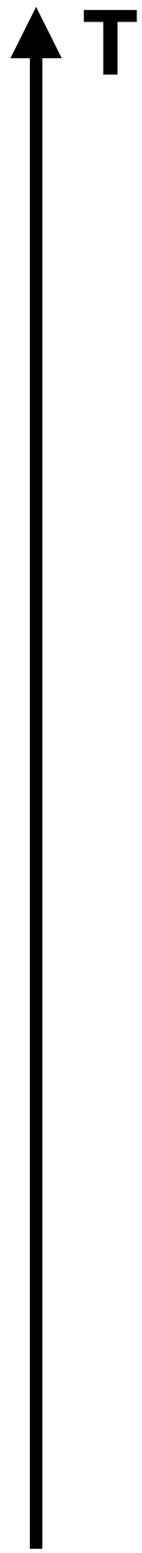
- **Maintains thermal equilibrium DM-SM**



- **Maintains chemical equilibrium DM**
- $\mu_{DM} = 0$

- **ELastically DEcoupling Relic: relic abundance set by DM-SM Elastic Scattering**

Kuflik et al. 2016



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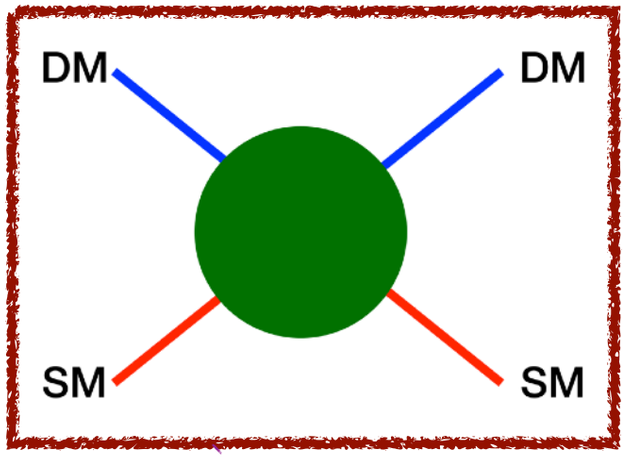
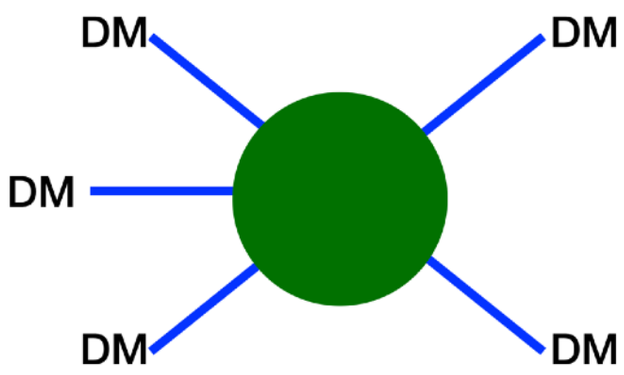




- **ELastically DEcoupling Relic: relic abundance set by DM-SM Elastic Scattering**

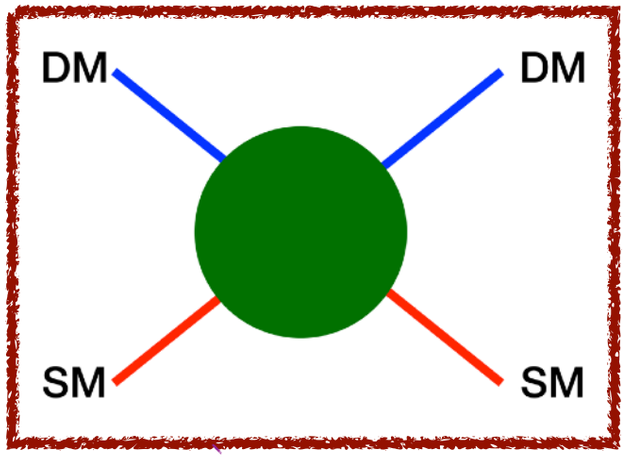
Kuflik et al. 2016

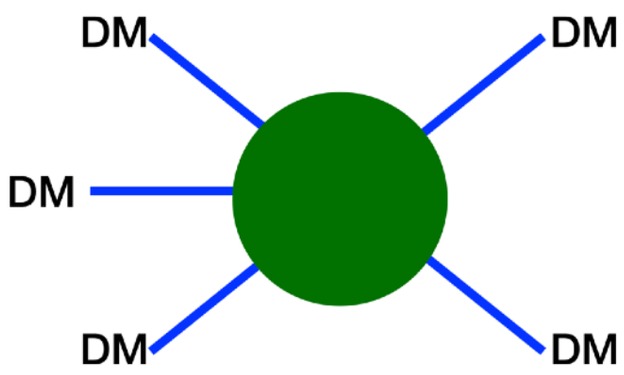
- **Maintains chemical equilibrium DM**
  - $\mu_{DM} = 0$
- **…as Universe cools…**

$$\begin{pmatrix}\text{Rate energy transfer}\\ \text{DM-to-SM}\\ \text{DM SM} \rightarrow \text{DM SM}\end{pmatrix} \lesssim \begin{pmatrix}\text{Rate mass-to-kinetic energy}\\ \text{in DM}\\ 3 \rightarrow 2\end{pmatrix}$$

Elastic Decoupling → $T' \neq T$

Respect Your ELDERs





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  Kuflik et al. 2016

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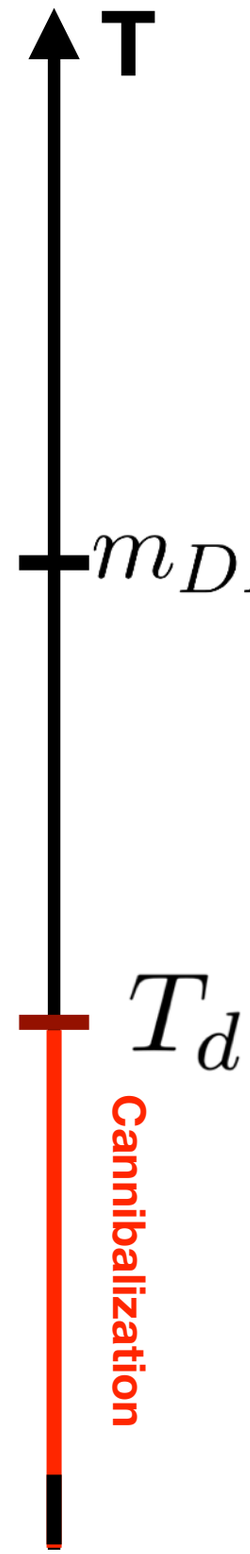
Elastic Decoupling → $T' \neq T$

- **3—>2 self-annihilations still active**
  - **convert mass to kinetic energy — heat the DM —*Cannibalization***
  - **DM evolves with ~constant Temp and comoving density**



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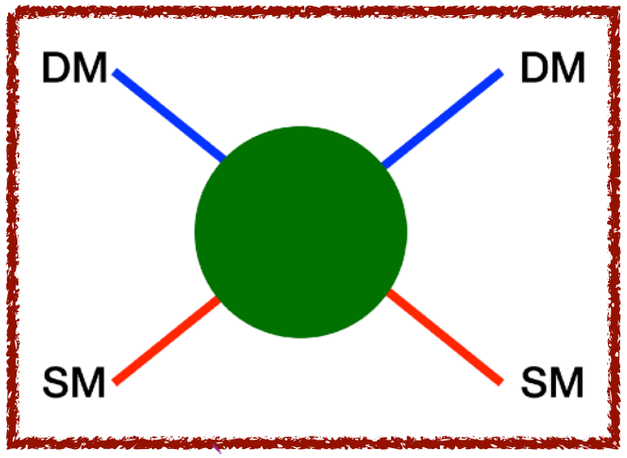

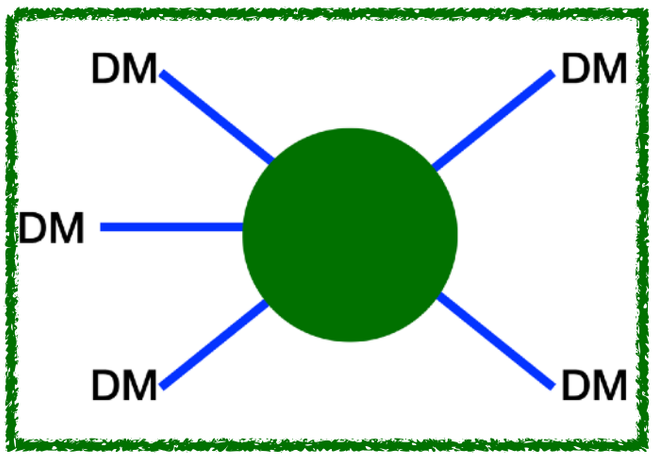

- **ELastically DEcoupling Relic: relic abundance set by DM-SM Elastic Scattering**

  Kuflik et al. 2016

- **Maintains chemical equilibrium DM**
  - $\mu_{DM} = 0$

- **…as Universe cools…**

$$\begin{pmatrix}\text{Rate energy transfer}\\ \text{DM-to-SM}\\ \text{DM SM} \rightarrow \text{DM SM}\end{pmatrix} \lesssim \begin{pmatrix}\text{Rate mass-to-kinetic energy}\\ \text{in DM}\\ 3 \rightarrow 2\end{pmatrix}$$

Elastic Decoupling → $T' \neq T$

- **3—>2 self-annihilations still active**
  - **convert mass to kinetic energy — heat the DM —*Cannibalization***
  - **DM evolves with ~constant Temp and comoving density**
- **At 3—>2 freezeout: Relic abundance set at Elastic Decoupling**