Massachusetts
Institute of
Technology

KINDER

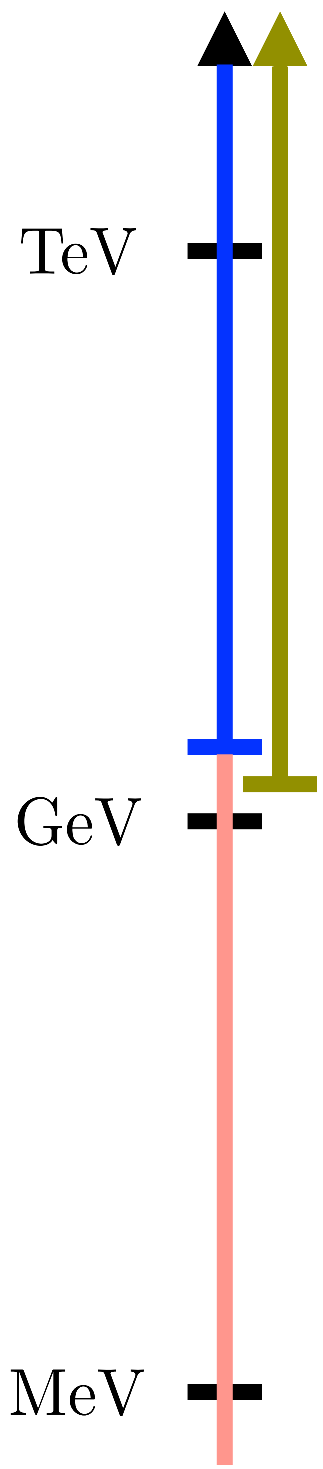
KINetically DEcoupling Relic

Patrick J. Fitzpatrick, Hongwan Liu, Tracy Slatyer, Yu-Dai Tsai

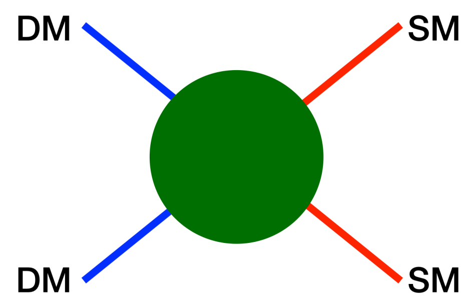
In Progress

Light Thermal DM

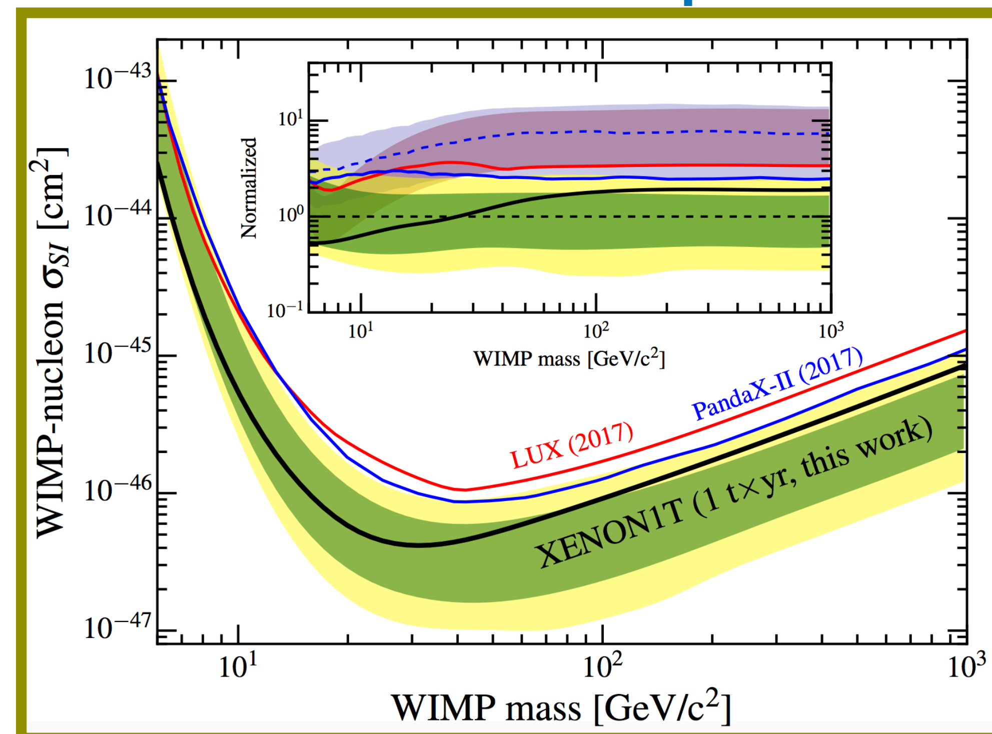
DM Mass



- **WIMP**



  - **theoretically attractive**
  - **WIMP miracle**
- **direct detection constraints**



E. Aprile et al. (XENON Collaboration) 2017

- **Light, Thermal DM**
  - **SIMP** Hochberg et al. 2014
  - **Respect your ELDERs** Kuflik et al. 2016
  - **Forbidden DM** D`Agnolo and Ruderman 2015 ; Griest and Seckel 1991
  - **Not-Forbidden DM** Cline et al. 2017
  - **…**
  - **KINetically DEcoupling Relic (KINDER)**

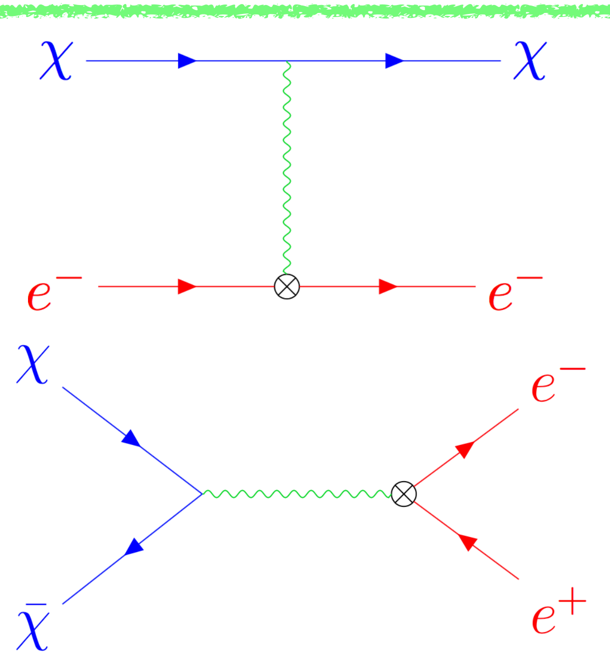
Dark Photon

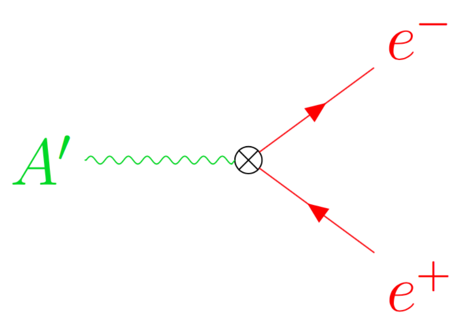
- **in mass basis:**

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

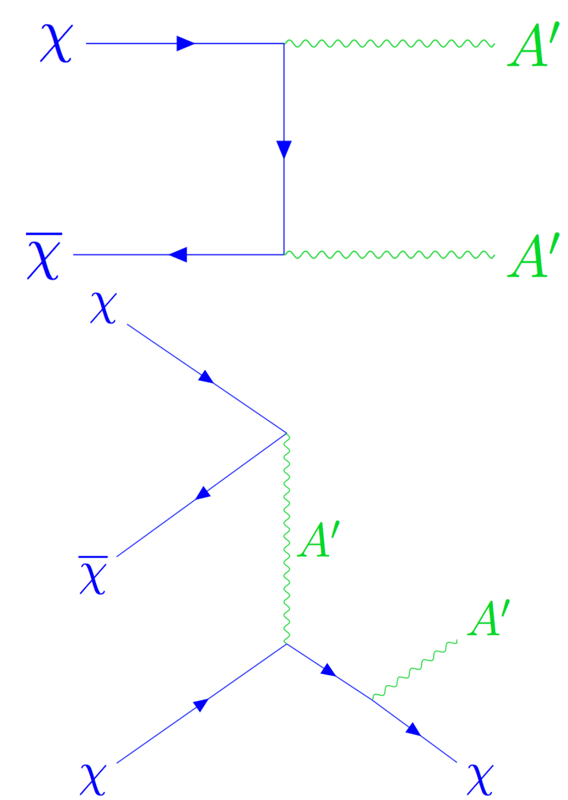
- **kinetic mixing with SM:** $\mathcal{L}_{Mix} = \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$

- **Let's consider regime:** $m_\chi \lesssim m_{A'} \lesssim 2m_\chi$

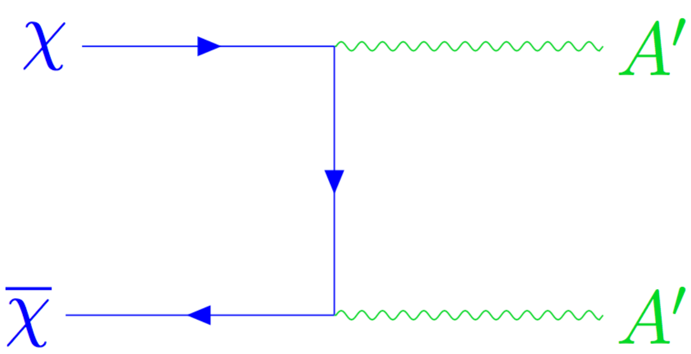




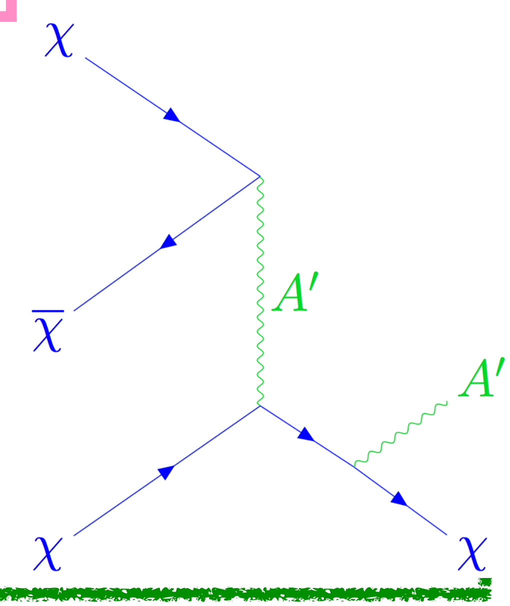
- **kinetic mixing with SM:** $\propto \epsilon^2$



(Not-) Forbidden DM



$$m_{A'} > m_\chi$$



$$\Gamma_{\chi\bar{\chi}\to A'A'} \sim \frac{\alpha_D^2}{m_\chi^2} e^{-\frac{m_\chi}{T}\left(2\frac{m_{A'}}{m_\chi}-1\right)}$$

$$\Gamma_{3\to 2} \sim \frac{\alpha_D^3}{m_\chi^5} e^{-2\frac{m_\chi}{T}}$$

kinematic suppression

$\frac{m_{A'}}{m_\chi} \gtrsim 3/2$ **3—>2 enhanced**

- "Forbidden Dark Matter"

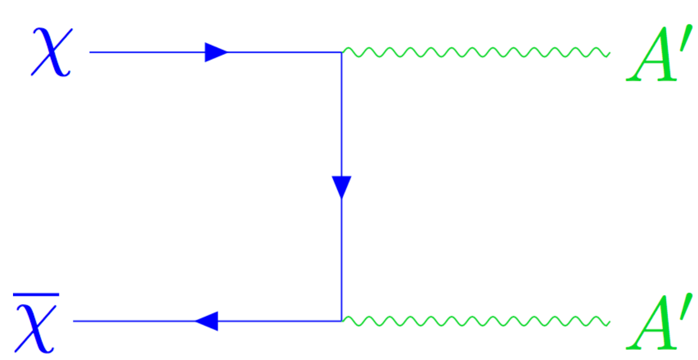
D`Agnolo and Ruderman 2015 ; Griest and Seckel 1991

- "Not-Forbidden Dark Matter"

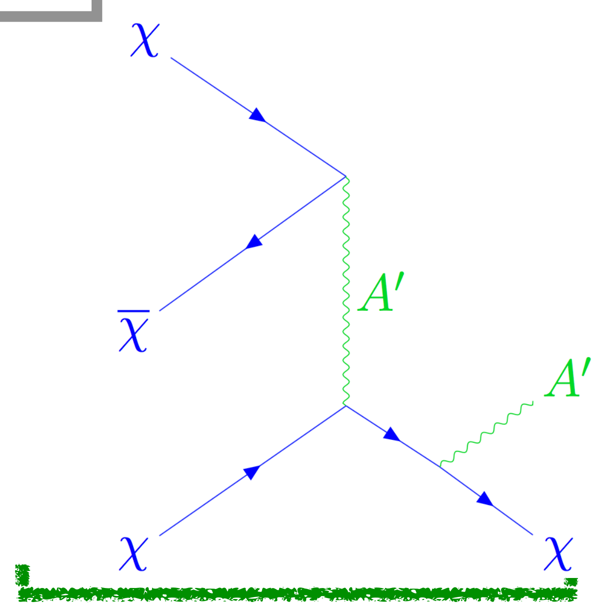
Cline et al. 2017

$\frac{m_{A'}}{m_\chi} \gtrsim 3/2$ $1 \lesssim \frac{m_{A'}}{m_\chi} \lesssim 2$

(Not-) Forbidden DM



$$m_{A'} > m_\chi$$



$$\Gamma_{\chi\bar{\chi}\to A'A'} \sim \frac{\alpha_D^2}{m_\chi^2} e^{-\frac{m_\chi}{T}\left(2\frac{m_{A'}}{m_\chi}-1\right)}$$

$$\Gamma_{3\to 2} \sim \frac{\alpha_D^3}{m_\chi^5} e^{-2\frac{m_\chi}{T}}$$

Novel scenario

- **3—>2 have important effects**
- ϵ **small but nonzero**
  - **Kinetic equilibrium not maintained between DM and SM**
  - $T' \neq T$
  - **Relic abundance fixed at KINetic DEcoupling**

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$$\frac{m_{A'}}{m_\chi} \gtrsim 3/2$$

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

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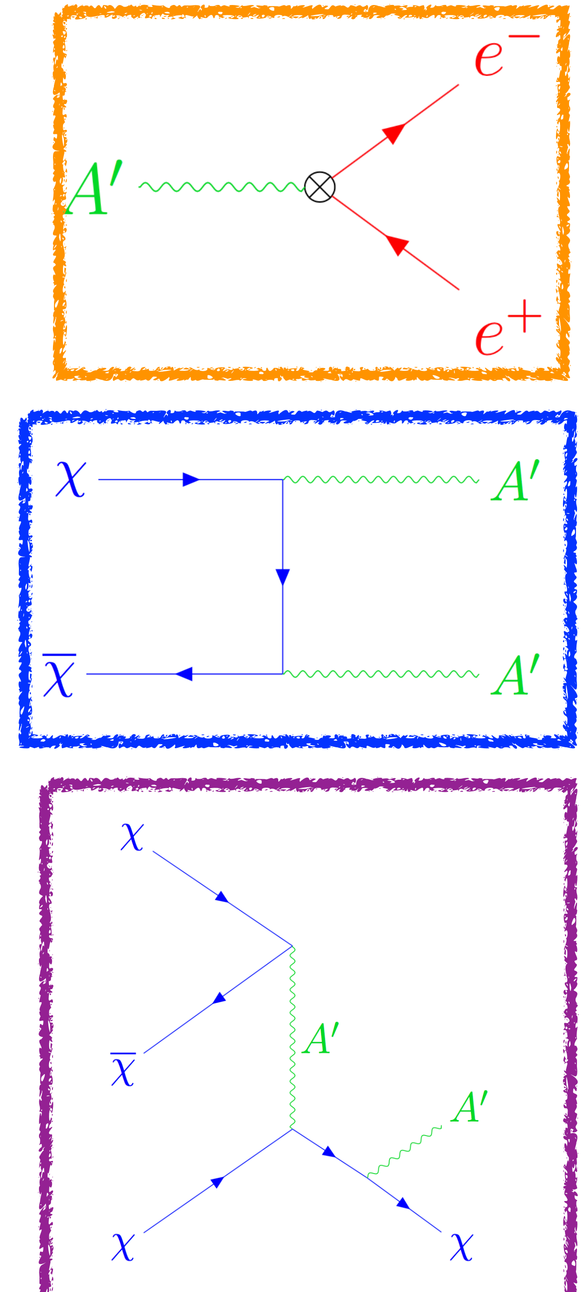
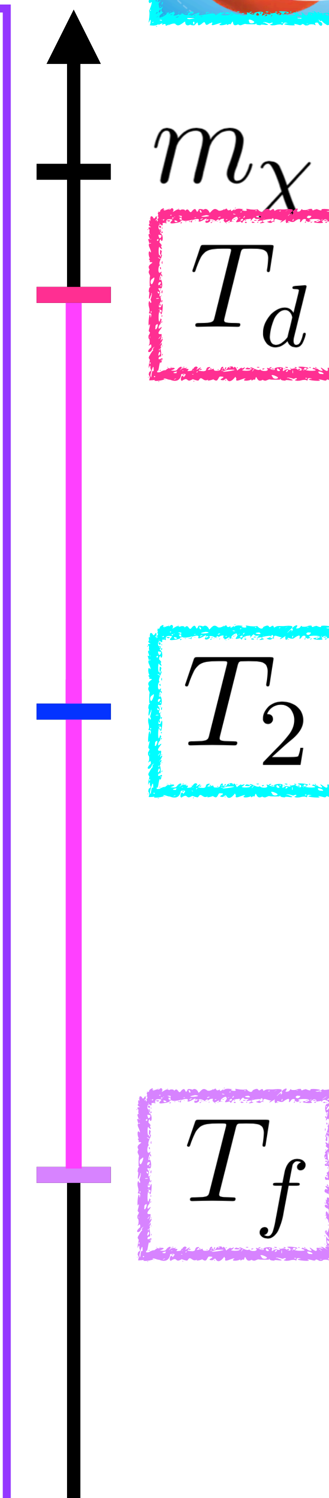
- Specific realization of **KINDER**:
- Universe expands and cools at $T < m_\chi$

1. **Kinetic Decoupling**: $T' \neq T$
   - Set by A'-to-SM **decays**
   - 3—>2 and 2—>2 still active — maintain DM chemical equilibrium
2. **2—>2 decoupling**
   - 3—>2 still active
   - DM gains chemical potential
3. **3—>2 Freezeout**
   - 3—>2 set the DM freeze-out

- **Relic density set by Kinetic Decoupling**

Cannibalization





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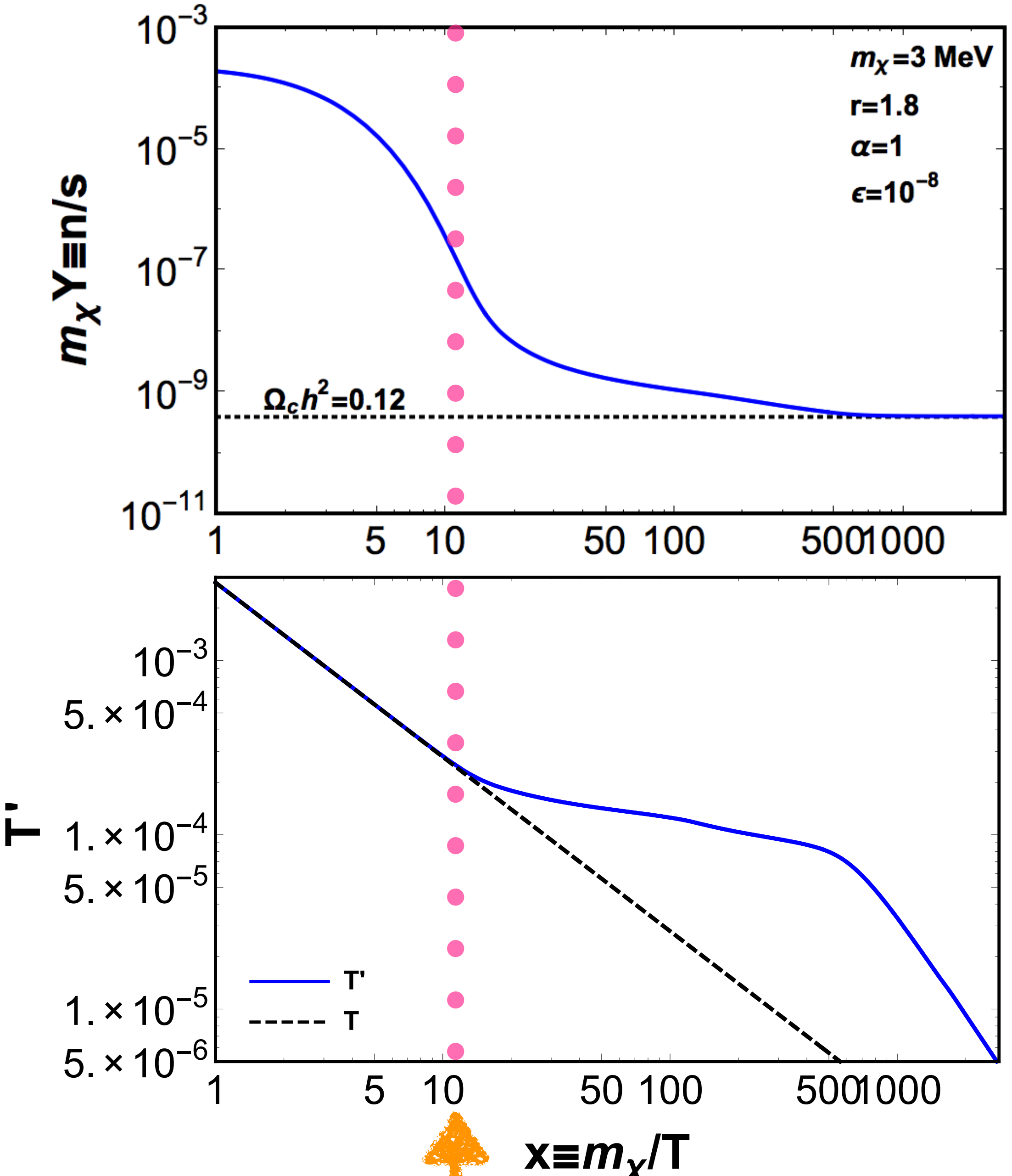
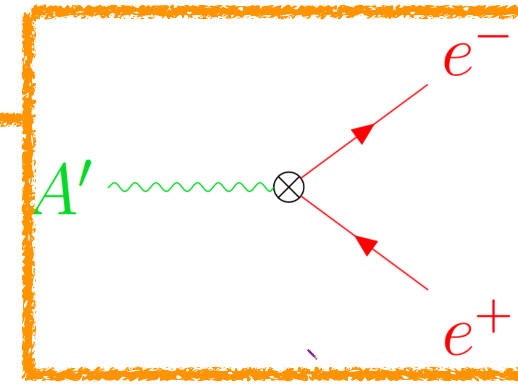
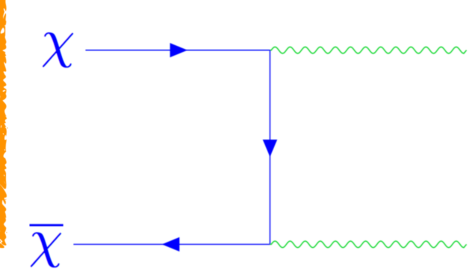
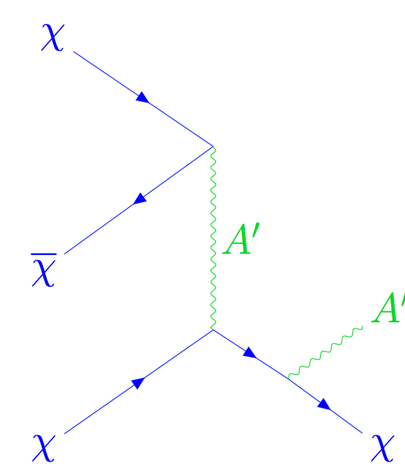
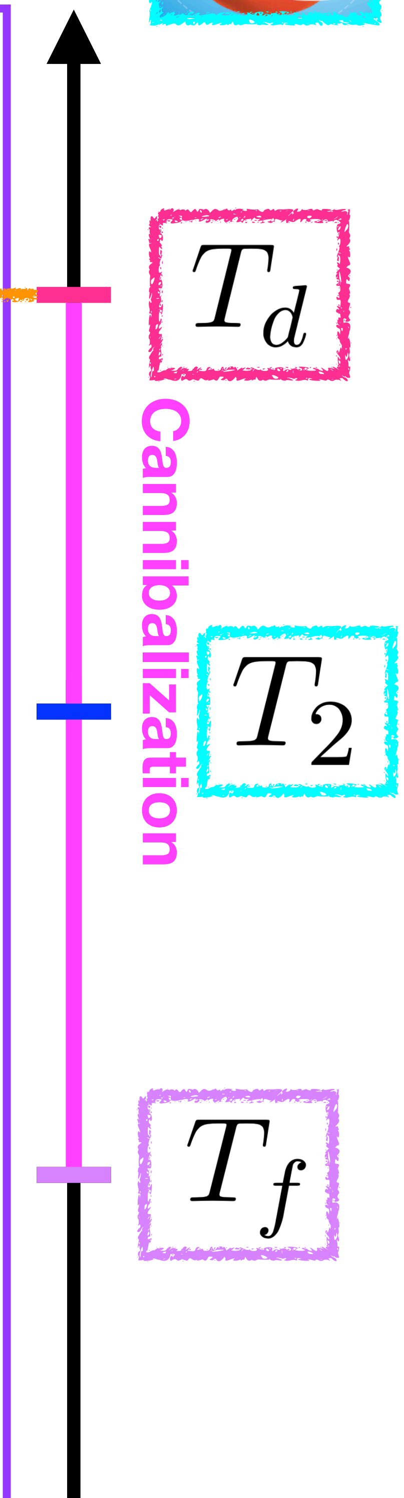




$$\begin{pmatrix} A' \to e^+e^- \\ \text{DM-to-SM} \\ \text{Energy transfer Rate} \end{pmatrix} \lesssim \begin{pmatrix} 3 \to 2 \\ \text{DM} \\ \text{Heating Rate} \end{pmatrix}$$



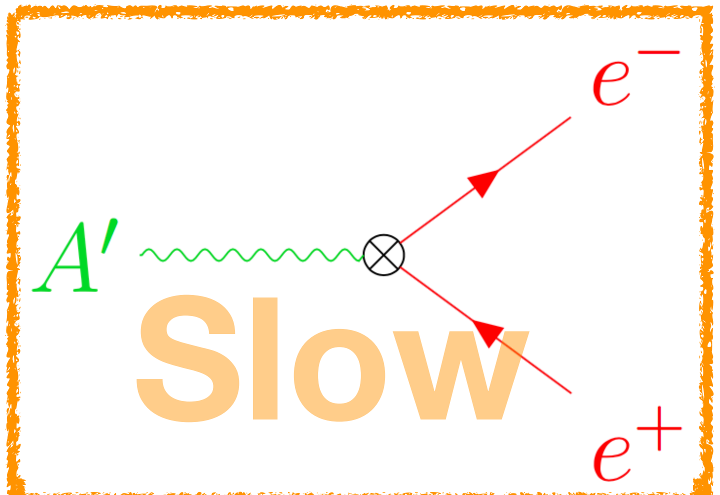




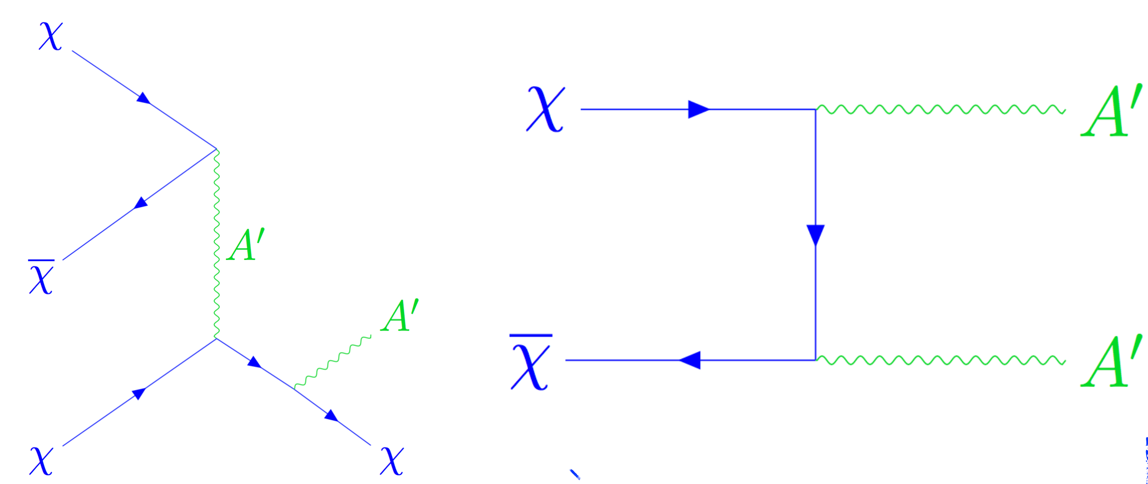
$T' \neq T$

KINetic DEcoupling…

Cannibalization



$T' \neq T$



$$\Gamma_{2\to2}, \Gamma_{3\to2} \gg H$$

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

- **Comoving entropy density DM conserved**

$$d\left(sa^3\right)/dT' = 0$$

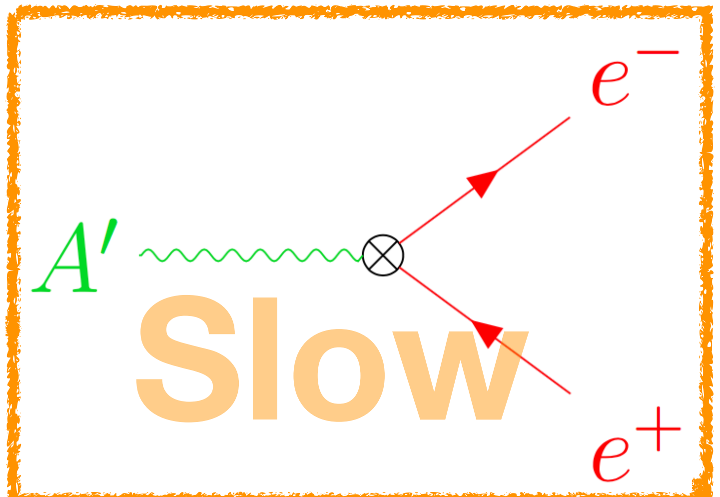
$$T' \simeq \frac{T_d}{1 - \frac{3T_d}{m_\chi}\ln\left(T/T_d\right)}$$

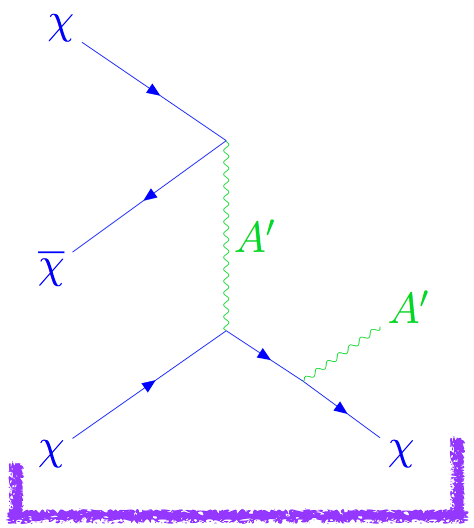
$$T' \propto \log T$$

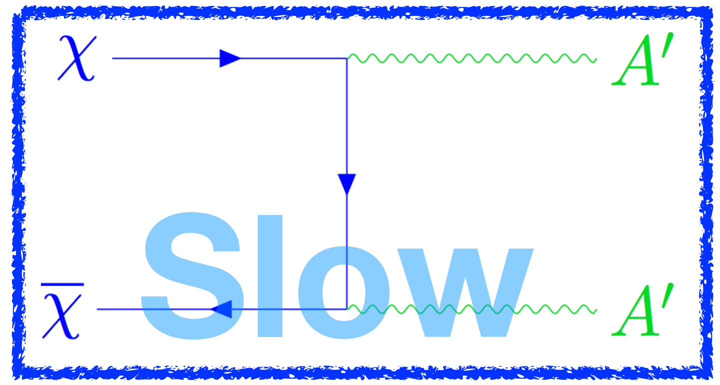
- ***Cannibalization*: `As the Universe expands, DM *cannibalizes* itself to keep warm'**

2—>2 freezeout

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







$$T' \neq T$$

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

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

- Comoving entropy density DM conserved

$$d\left(sa^3\right)/dT' = 0$$

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

$$T' \propto \log T$$

Cannibalization

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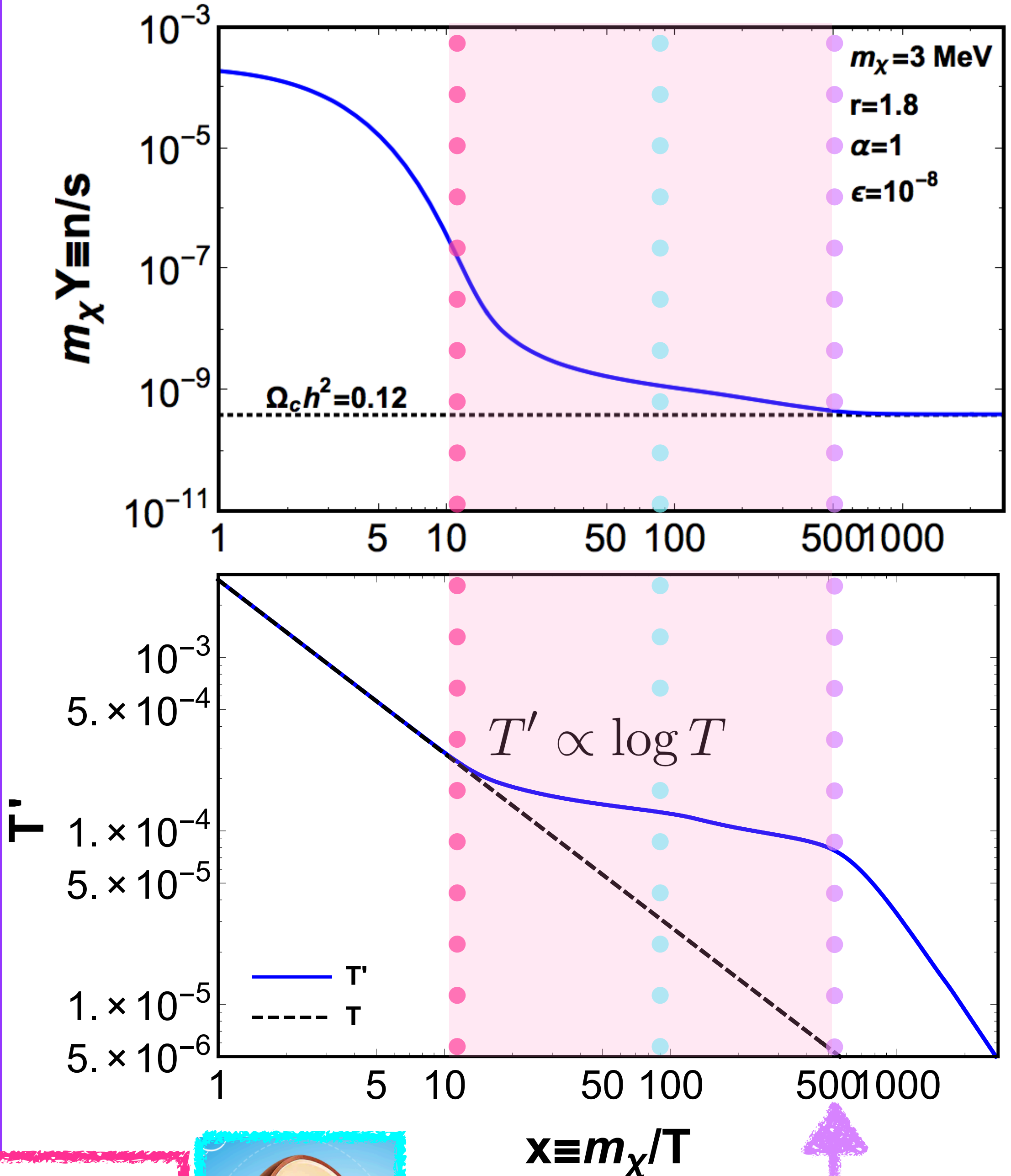

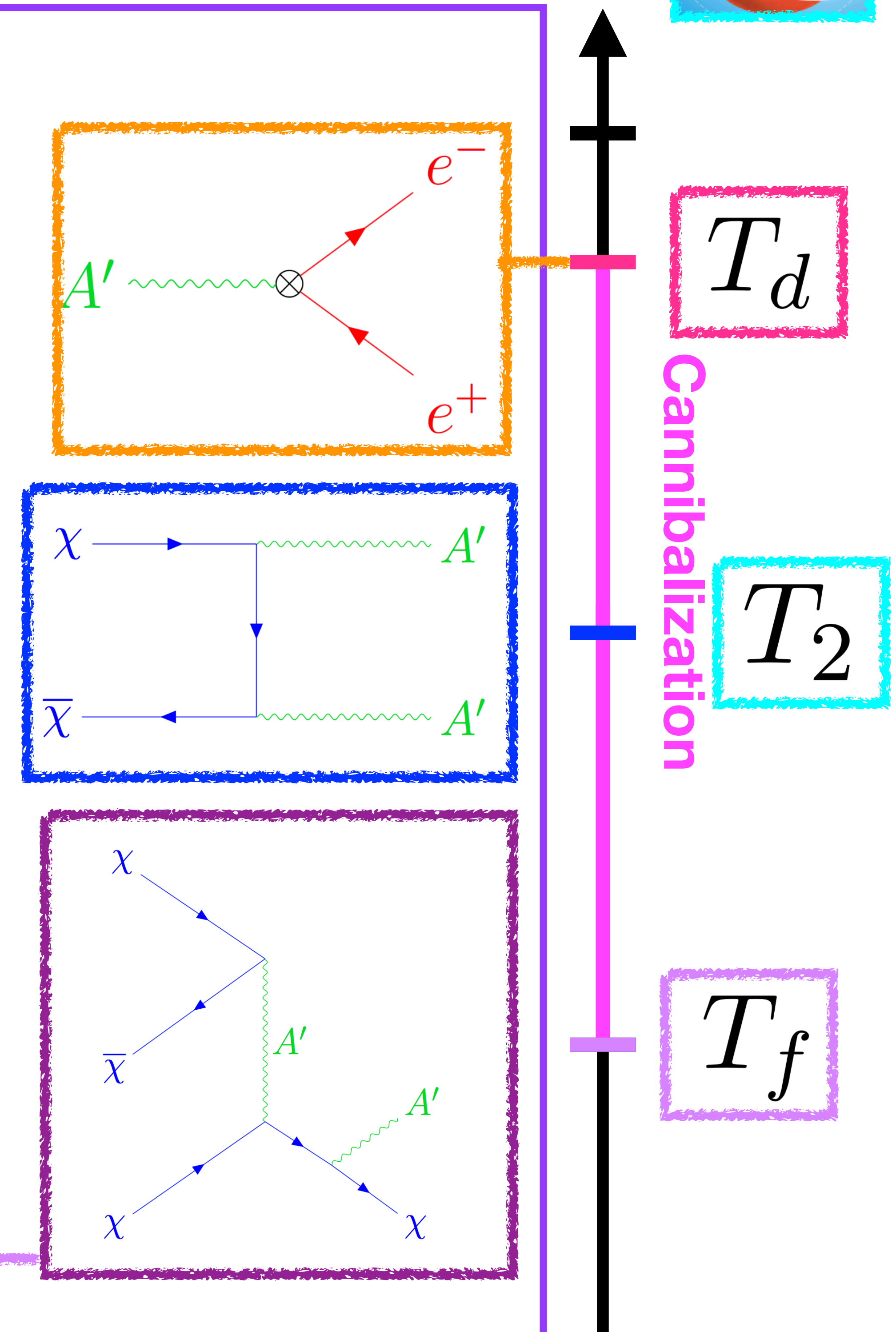

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Cannibalization

3—>2 Freezeout

KINDER Relic Abundance

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

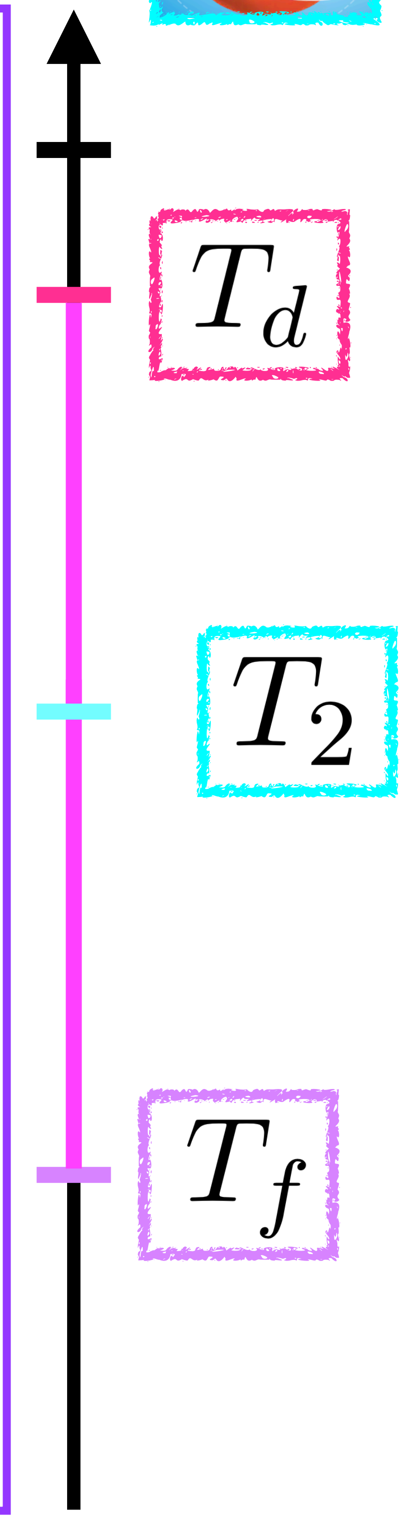
$$\frac{m_\chi}{T_d} e^{(1-r)m_\chi/T_d} \sim \frac{m_\chi}{M_{pl}} \frac{1}{r^{7/2}\epsilon^2 \alpha_{em}}$$

$$\Omega_\chi \sim Y(T_f) = \frac{n_{DM}}{s}(T_f)$$

$$\sim \frac{\left(m_\chi/T_f'\right)^{-3/2} e^{-m_\chi/T_f'}}{(m_\chi/T_f)^{-3}}$$

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

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



KINDER Relic Abundance

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

$$\Omega_\chi \sim Y(T_f) = \frac{n_{DM}}{s}(T_f)$$

$$\sim \frac{\left(m_\chi/T_f'\right)^{-3/2} e^{-m_\chi/T_f'}}{(m_\chi/T_f)^{-3}}$$

$$\sim 10^8 \left(\frac{m_\chi}{\mathrm{GeV}}\right) \frac{(m_\chi/T_d)^3}{(m_\chi/T_3')^2} \sqrt{\frac{m_\chi}{T_d} + 3\log\frac{T_d}{T_2}}\, e^{-\frac{m_\chi}{T_d}}$$

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

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

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

T_d

T_2

T_f

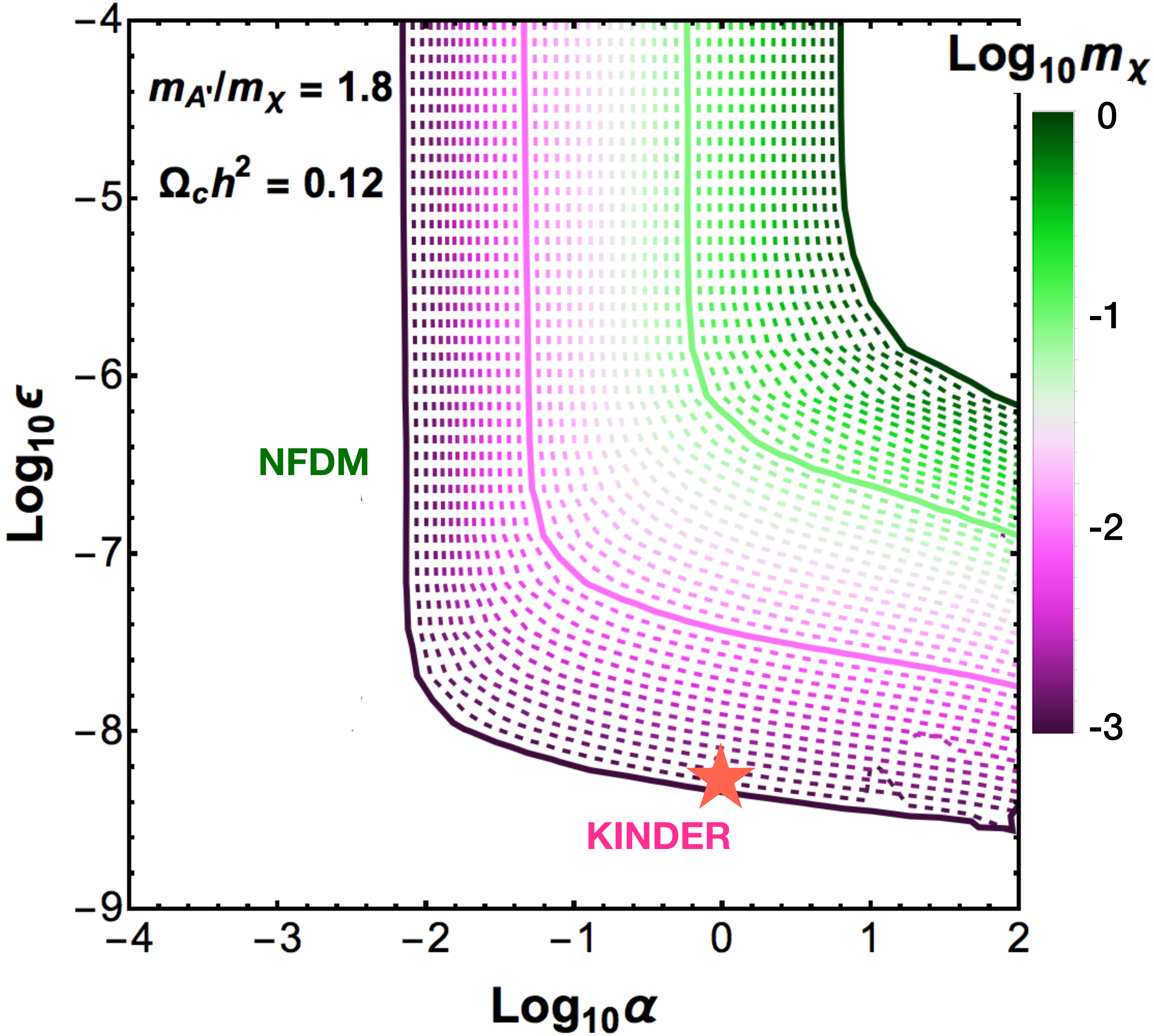
Cannibalization

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

KINDER

Cannibalization

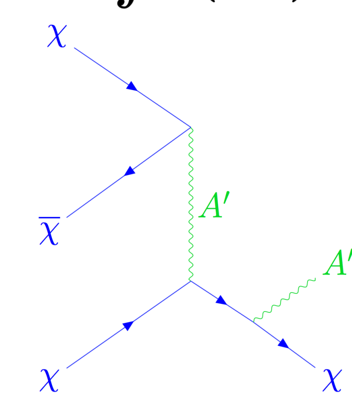
KINDER Region



NFDM

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

$$T_f = T_f(\alpha)$$



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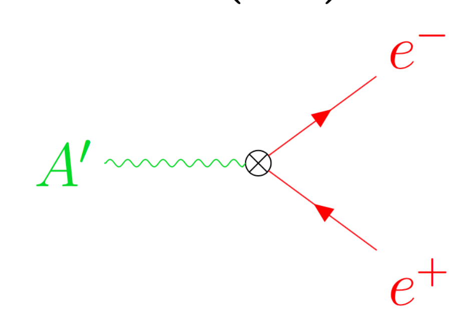
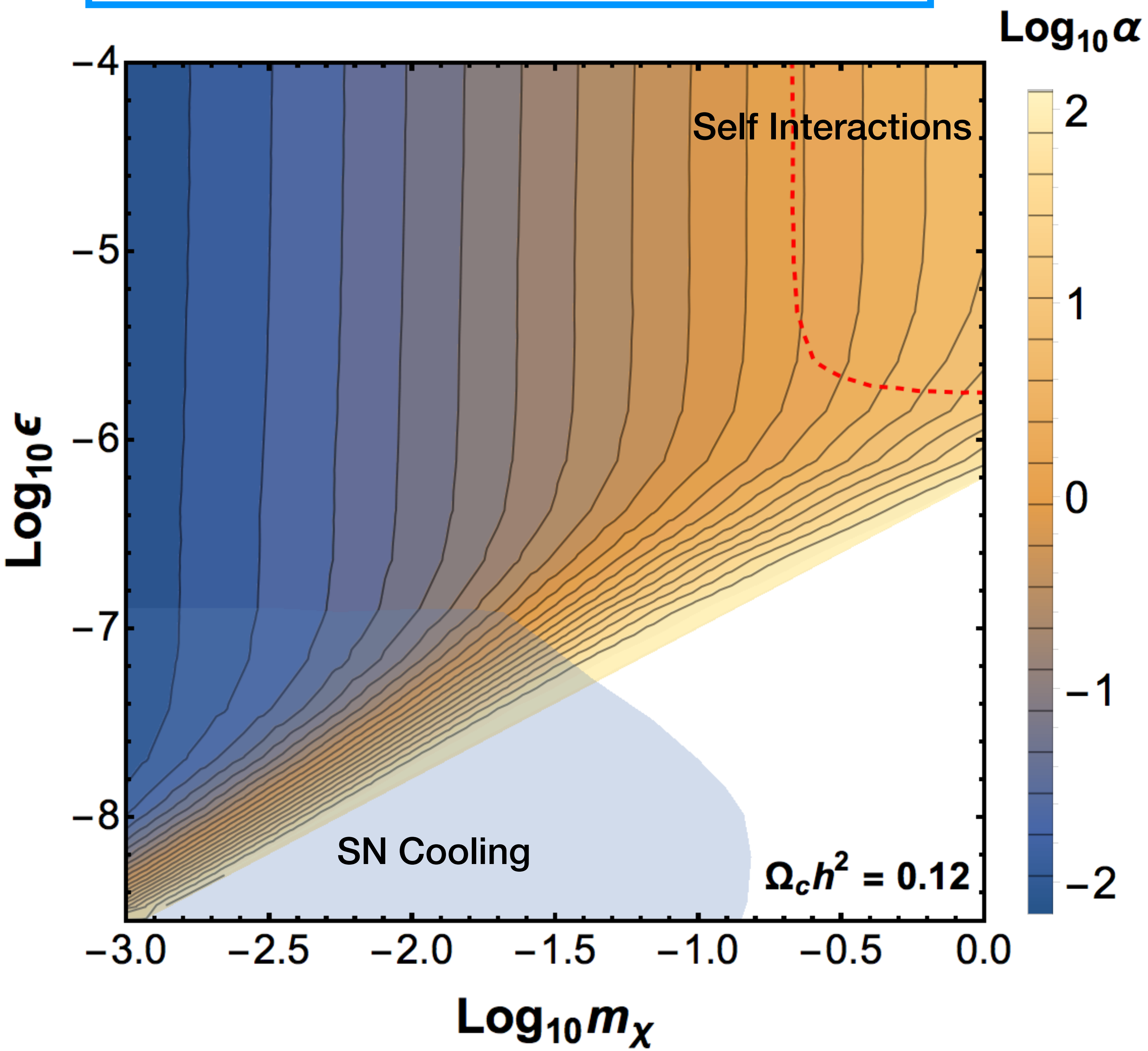
$$\Omega_\chi \sim e^{-m_\chi/T_d}$$

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



KINDER Constraints



$$\frac{\sigma_{SI}}{m_\chi} \lesssim 1\mathrm{cm}^2/\mathrm{g}$$

Conclusions

- KINetically DEcoupling Relic:
- Relic abundance set by KINetic DEcoupling of DM and SM
- Generalizes previously studied ELDER scenario
- Naturally produces light (sub-GeV) DM
- Can be realized in a simple and weakly coupled dark sector
  - dark photon model
- Self-interaction rates are large for this particular realization of KINDER