Title: New Pathways to the Relic Abundance of Vector-Portal Dark Matter

Speakers: Patrick Fitzpatrick

Series: Particle Physics

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Abstract: In the conventional weakly-interacting massive particle (WIMP) paradigm the late-time density of dark matter (DM) is set by the rate of two-body annihilations, but there has been considerable recent interest in exploring alternative DM scenarios where other interactions control the final abundance. I will show that by fully exploring the parameter space of a simple, weakly-coupled dark sector, we can find a rich set of novel pathways which lead to the observed relic density of DM. In particular, we can identify and characterize a general class of mechanisms in which the DM relic abundance is determined by processes controlling the thermal coupling of the DM and Standard Model (dubbed the KINetically DEcoupling Relic -- KINDER), generalizing previously-studied special cases of this behavior.

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

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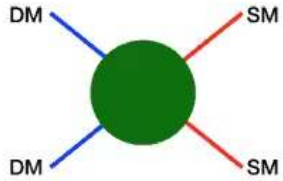
Light Thermal DM

DM Mass

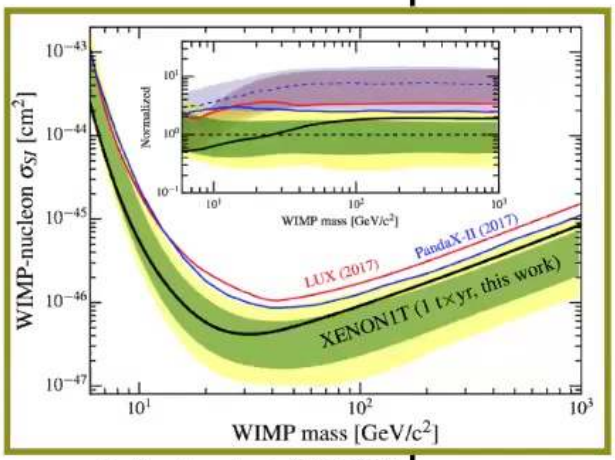
TeV

GeV

MeV



- **WIMP**
  - **Simplest thermal relic**
  - **Theoretically attractive**
  - **WIMP miracle**
- **Current direct detection constraints less sensitive < GeV**



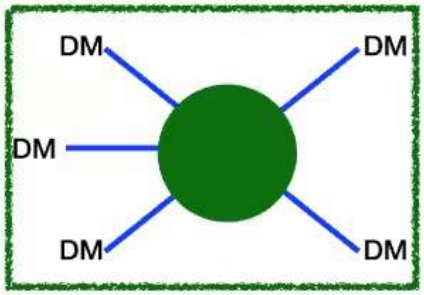
E. Aprile et al. (XENON Collaboration) 2017

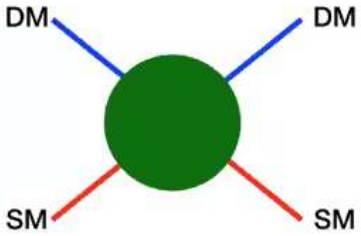
- **Light, Thermal DM**
  - **New experiments: SENSEI, SuperCDMS, etc.**
  - **SIMP, ELDER, Forbidden DM, Not-Forbidden DM**
  - ***New Pathways to the Relic Abundance of Vector-Portal DM***
- **KINetically DEcoupling Relic (KINDER)**

Outline

- Light (sub-GeV) thermal relics
  - SIMP, ELDER
- Vector-Portal DM
  - More light thermal relics: Forbidden DM, and Not-Forbidden DM
- New Pathways to the Relic Abundance of Vector Portal DM
  - KINetically DEcoupling Relic (KINDER)
  - Thermal history of KINDER
  - Where KINDER lives in parameter space (regimes of vector-portal DM)
  - Experimental constraints

SIMP Miracle





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

  Hochberg et al. 2014

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

- **as Universe cools…**

  Thermal freezeout

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

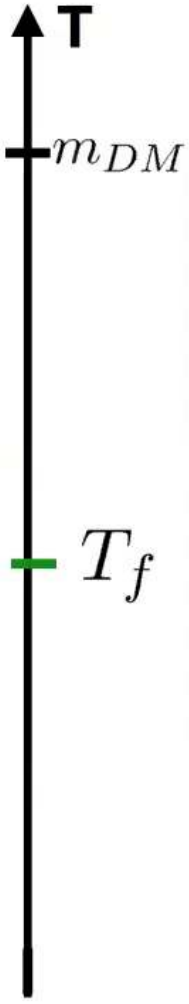
$$\sim \frac{\alpha_D^3}{m_{DM}^5} \qquad \sim \frac{T^2}{M_{pl}}$$

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

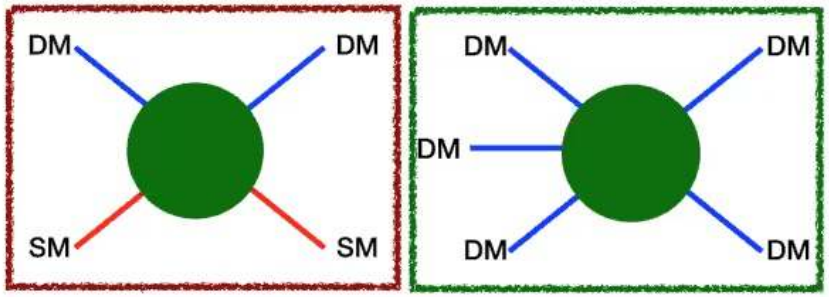
$$\Omega_\chi h^2 = 0.12 \rightarrow \sim 100\ \text{MeV} \qquad \sim 1$$

- **Strong scale DM naturally emerges**

`SIMP Miracle'



Respect Your ELDERs



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

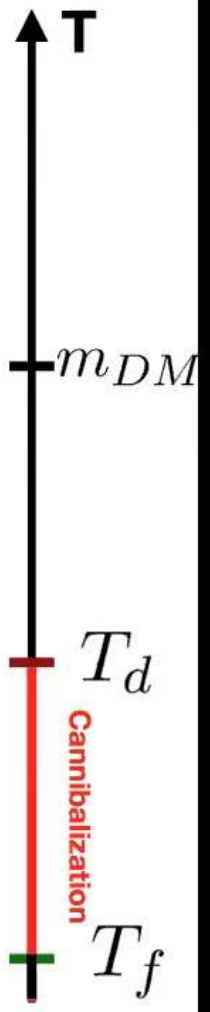
  Kuflik et al. 2016

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

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

Elastic Decoupling → $T' \neq T$

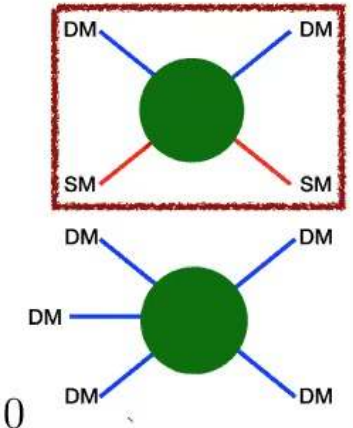
- **3—>2 self-annihilations still active**
  - **convert mass to kinetic energy — heat the DM —*Cannibalization***
  - **DM evolves with ~constant Temp and comoving density**
- **At 3—>2 freezeout: Relic abundance set at Elastic Decoupling**



Cannibalization

- **Thermal decoupling…** $T' \neq T$

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



- **comoving entropy density conserved**

$$\frac{d\left(sa^3\right)}{dT'} = 0 \quad \longrightarrow \quad \mu_{DM} = 0$$

- **DM chemical equilibrium**

$$T' \simeq \frac{T_d}{1 + 3\frac{T_d}{m_\chi}\log\left(\frac{T_d}{T}\right)}$$

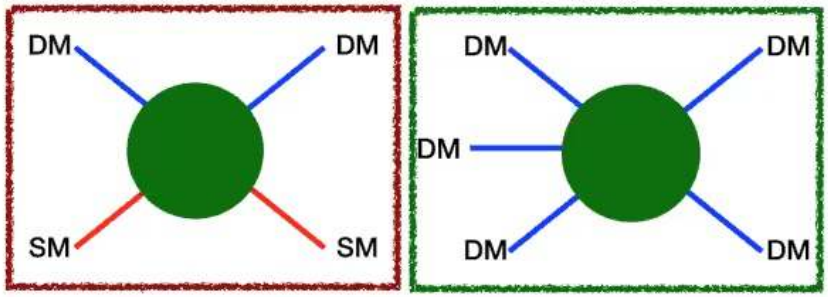
$$T' \propto \log T$$

- **DM evolves with ~constant Temp and comoving density**

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

Respect Your ELDERs

Kuflik et al. 2016



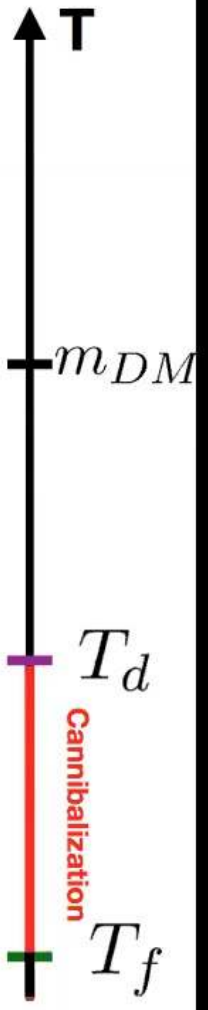
- **3—>2 freezeout**

$$\Omega_{DM}h^2 \sim \frac{n_{DM}\left(T_f'\right)}{s\left(T_f\right)} \sim \frac{\left(T_f'/m_\chi\right)^{3/2}}{\left(T_f/m_\chi\right)^3} e^{-m_\chi/T_f'} \sim \frac{\left(m_\chi/T_d\right)^{3/2}}{1+3\frac{T_d}{m_\chi}\log\left(\frac{T_d}{T_f}\right)} e^{-m_\chi/T_d} \sim e^{-\left(m_\chi M_{pl}\langle\sigma v\rangle\right)^{1/4}}$$

$$T_f' \simeq \frac{T_d}{1+3\frac{T_d}{m_\chi}\log\left(\frac{T_d}{T_f}\right)}$$

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

- **Sub-GeV DM**



Dark Photon

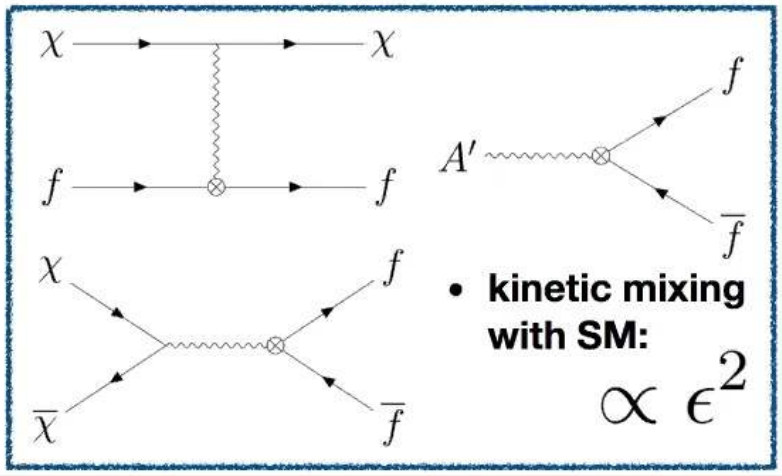
- **in mass basis:**

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

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

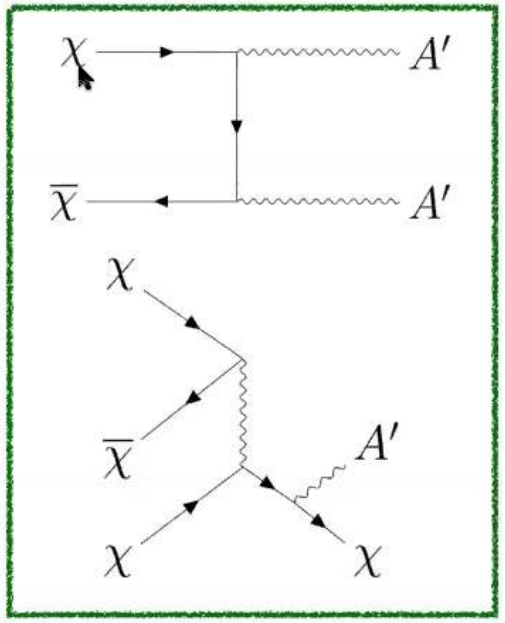
- **Let's consider region:**

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



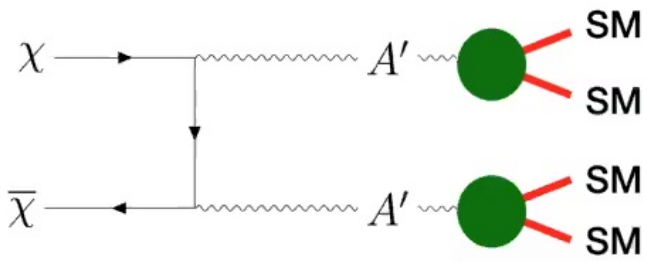
- **kinetic mixing with SM:**

$$\propto \epsilon^2$$



Dark Photon

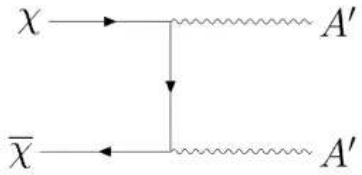
- Let's consider region: $m_\chi \lesssim m_{A'} \lesssim 2m_\chi$
- In the region $m_\chi > m'_A$ CMB constraints rule out Light DM



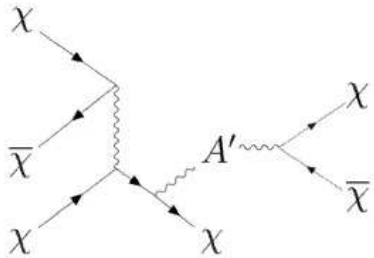
- Injects energy into SM plasma
- Ruled out by CMB for $m_\chi \lesssim 1\,\mathrm{GeV}$

Dark Photon

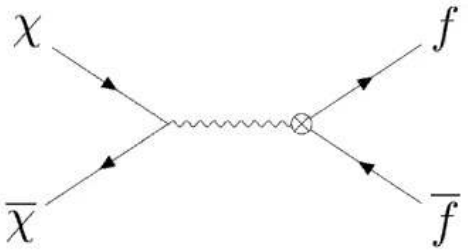
- Let's consider region: $m_\chi \lesssim m_{A'} \lesssim 2m_\chi$
- In the region $m_{A'} > 2m_\chi$ reduces to the WIMP case



Huge kinematic suppression

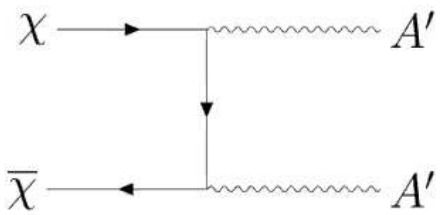


Reduces to scattering process

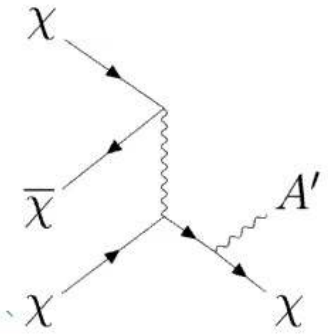


Stringent CMB constraints

(Not-) Forbidden DM



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



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

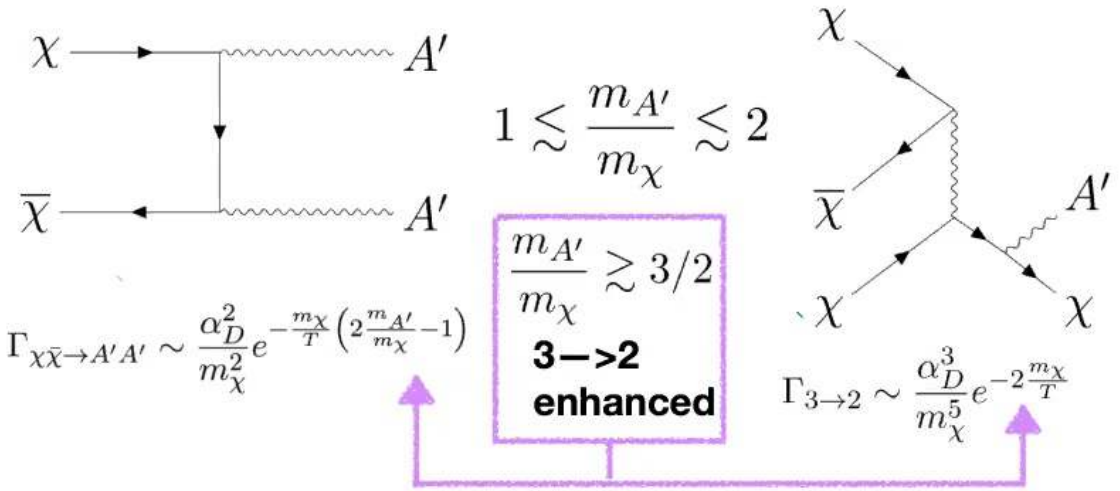
- **"Forbidden Dark Matter"**
  - **DM annihilates into heavier states**
  - **Proceeds at finite temperature**

D`Agnolo and Ruderman 2015 ; Griest and Seckel 1991

$$\Omega_{DM}h^2 \sim 0.1 \frac{(20\ \mathrm{TeV})^{-2}}{\alpha_D^2/m_{DM}^2} e^{2\frac{m_\chi}{T}(r-1)}$$

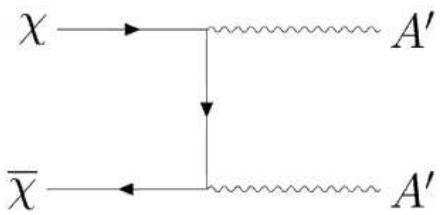
- **FDM: Naturally gives DM exponentially lighter than the weak scale — sub-GeV**

(Not-) Forbidden DM

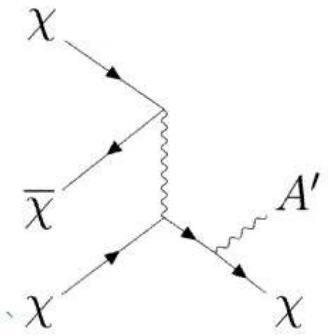


- **"Not-Forbidden Dark Matter"** Cline et al. 2017
  - $\frac{m_{A'}}{m_\chi} \gtrsim 3/2$ **: 3—>2 can dominate in setting DM relic abundance**
  - **Naturally gives sub-GeV DM**

(Not-) Forbidden DM

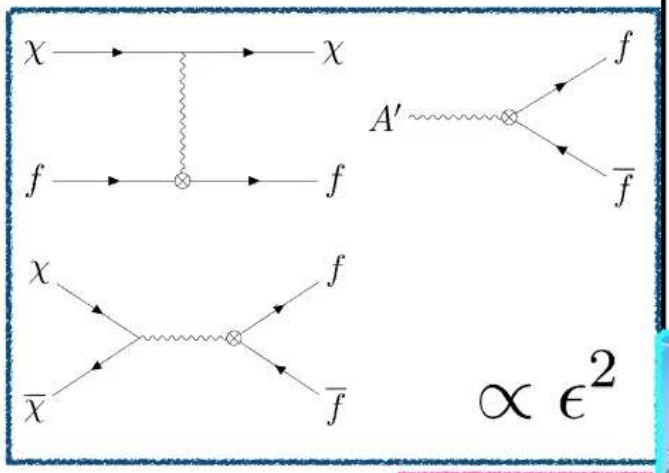


$$1 \lesssim \frac{m_{A'}}{m_\chi} \lesssim 2$$



Novel scenarios

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



KINDER

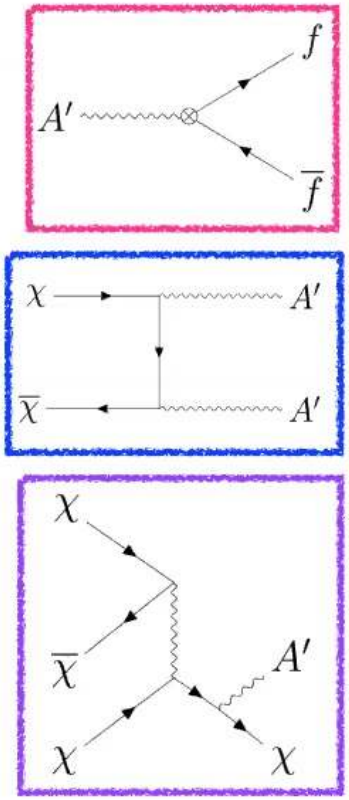
KINDER

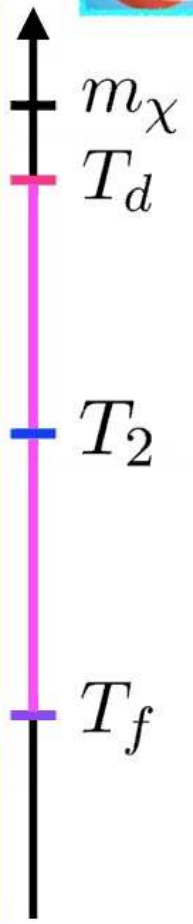
- **Specific realization of KINDER:**
- **Universe expands and cools at** $T < m_\chi$

1. **Kinetic Decoupling:** $T' \neq T$
   - **Set by** A'**-to-SM decays**
   - **3—>2 and 2—>2 still active — maintain DM chemical equilibrium**
   - $\mu = 0$
2. **2—>2 Freezeout**
   - **3—>2 still active**
   - **DM gains** $\mu \neq 0$
3. **3—>2 Freezeout**
   - **3—>2 set the DM freeze-out**

- **Relic density set by Kinetic Decoupling**

Cannibalization





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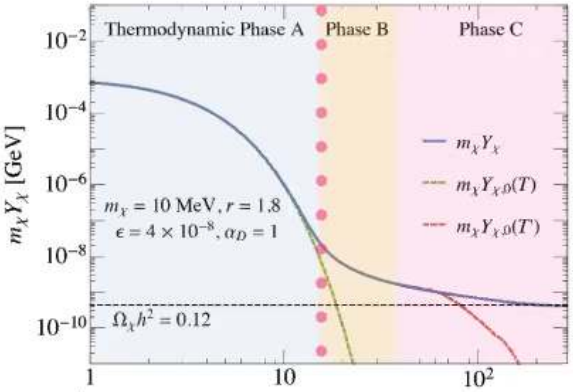
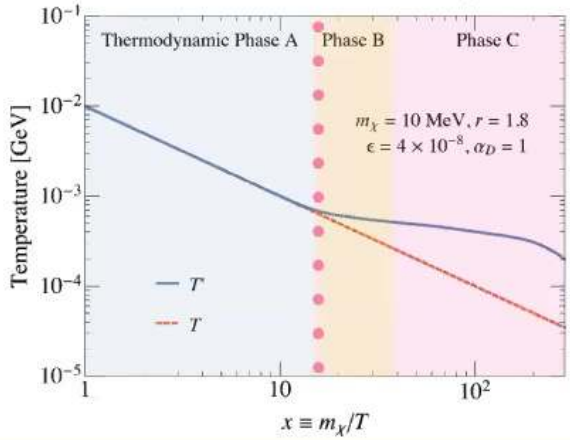
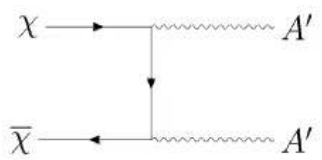


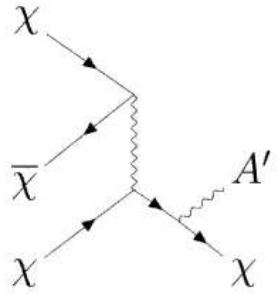


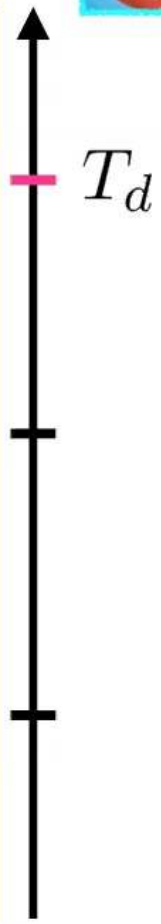
KINetic DEcoupling

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

$$T' \neq T$$

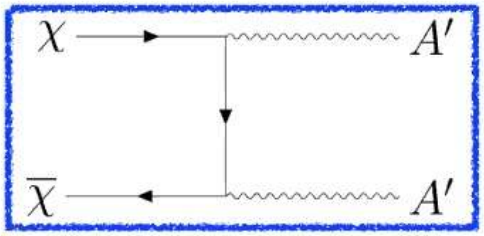






$$r \equiv \frac{m_{A'}}{m_\chi}$$

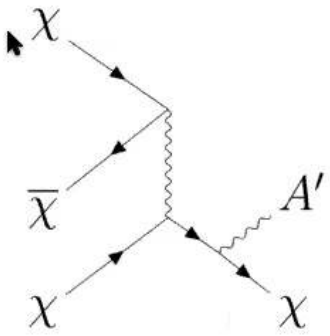
2—>2 Freezeout



$$\Gamma_{\chi\bar{\chi}\to A'A'} \neq \Gamma_{A'A'\to\chi\bar{\chi}}$$

$$< H \qquad < H$$

2—>2 out of equilibrium



$$\Gamma_{\chi\chi\bar{\chi}\to\chi A'} \simeq \Gamma_{\chi A'\to\chi\chi\bar{\chi}}$$

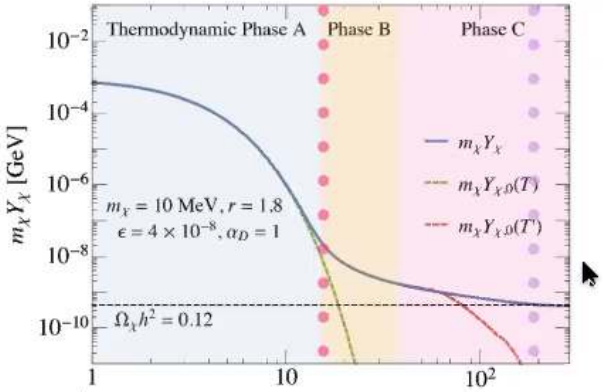
$$> H \qquad > H$$

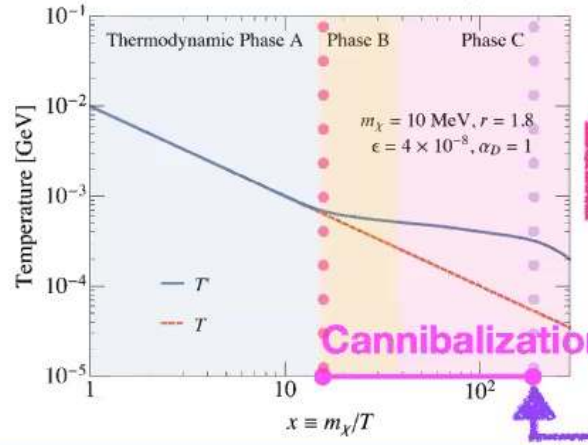
3—>2 in equilibrium

One process, Two species

- **DM gains nonzero chemical potential** $n_\chi = n_{\chi(0)} e^{\mu/T'} = n_{\chi(0)} \sqrt{\frac{n_{A'}}{n_{A'(0)}}}$

KINDER





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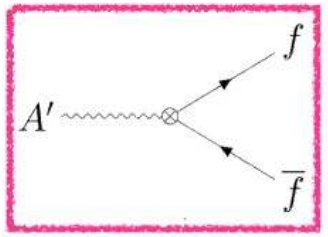
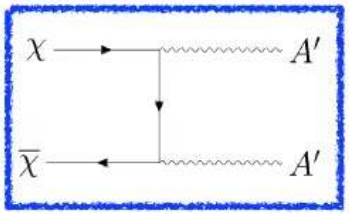
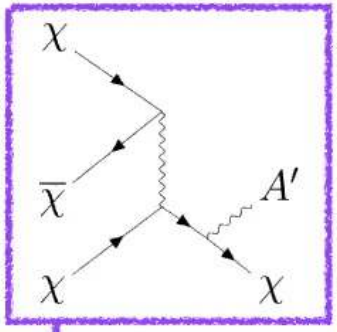
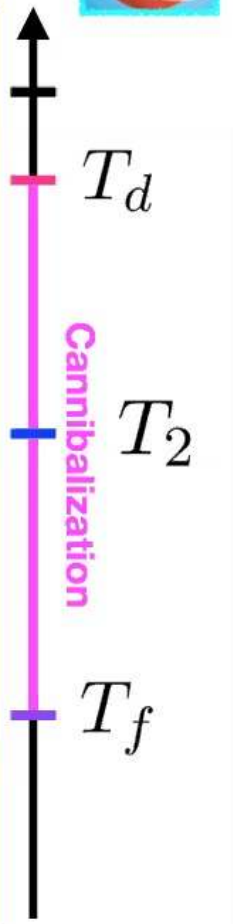
Cannibalization $T' \propto \log T$









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

KINDER Relic Abundance

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

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

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

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

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

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

KINDER

Cannibalization

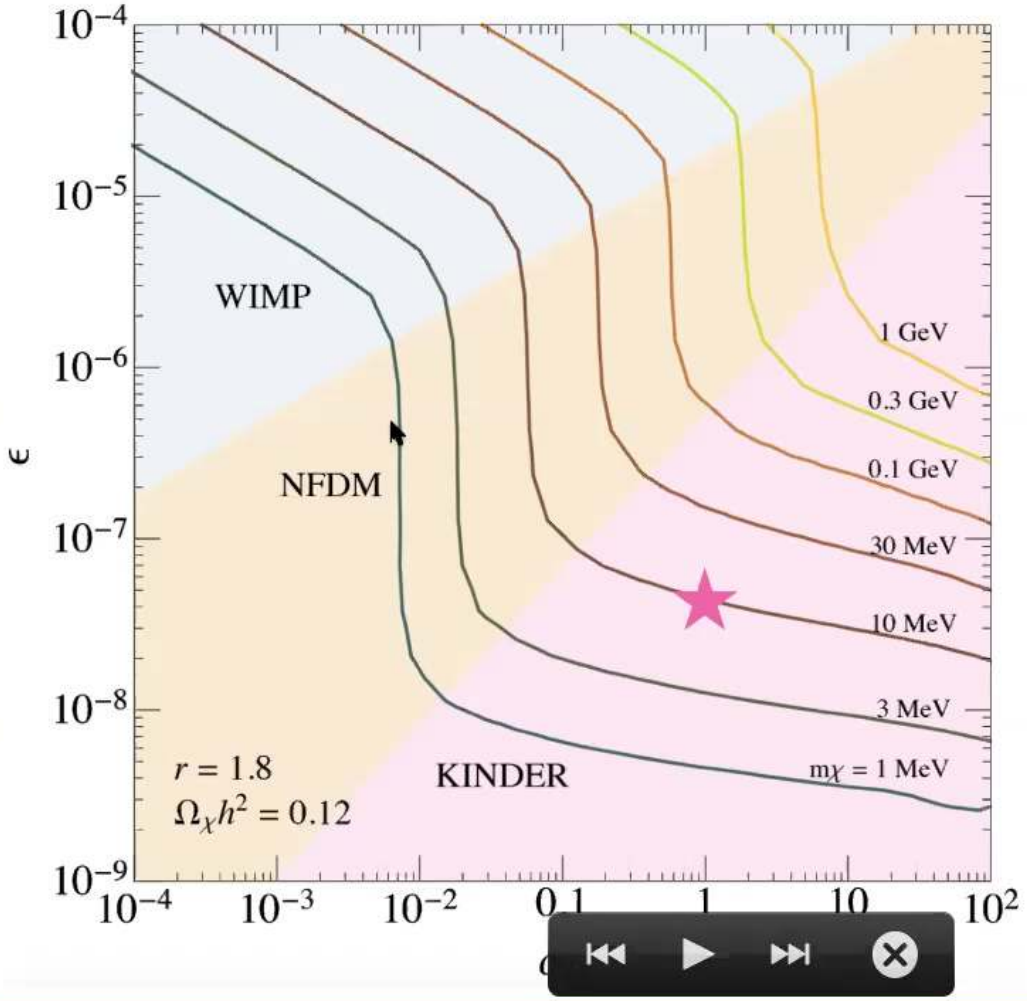
T_d

Cannibalization

T_2

T_f

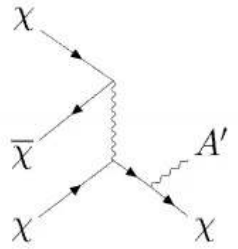
KINDER Regime



NFDM

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

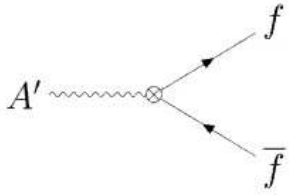
$$T_f = T_f(\alpha)$$



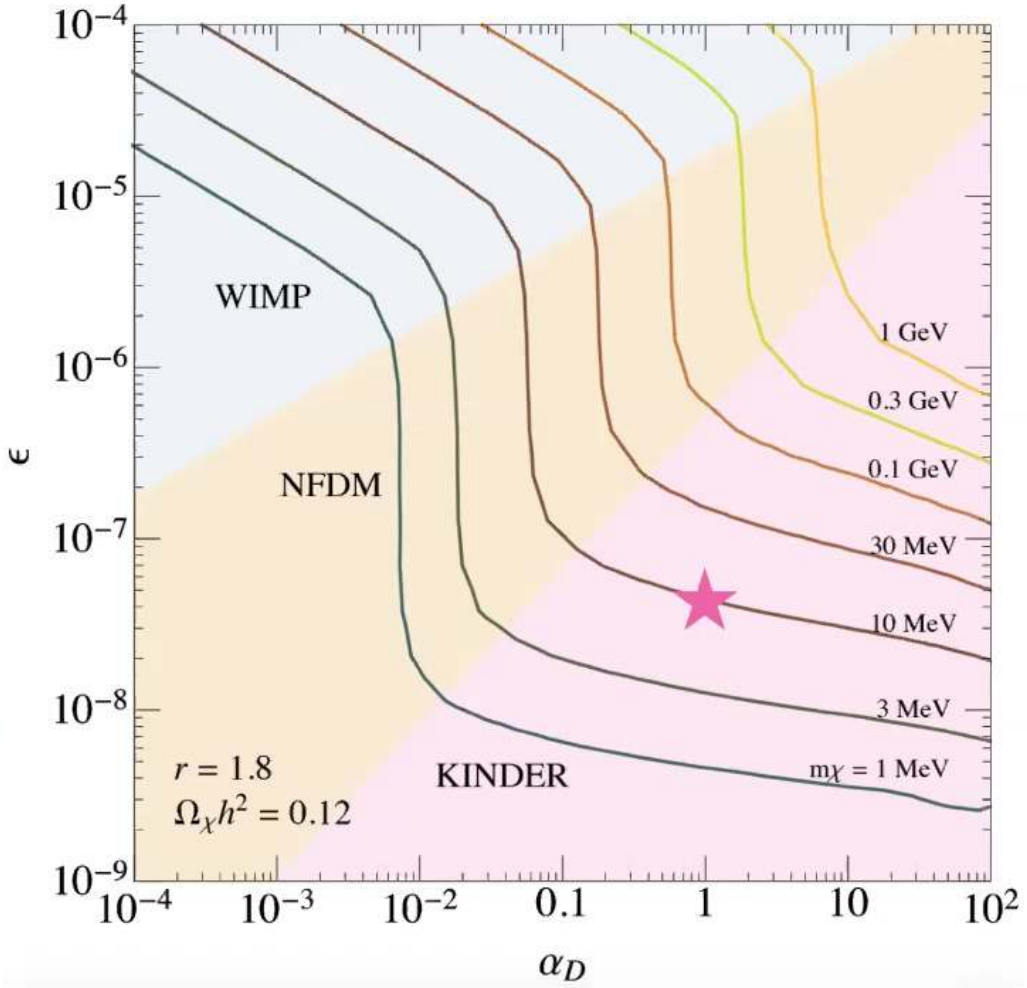
KINDER

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

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



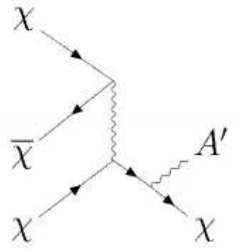
KINDER Regime



NFDM

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

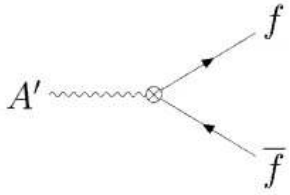
$$T_f = T_f(\alpha)$$



KINDER

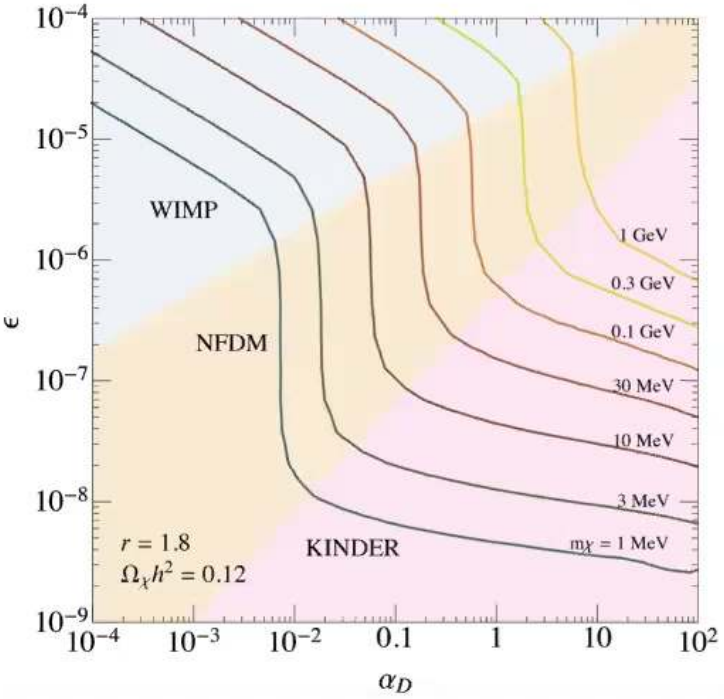
$$\Omega_\chi \sim e^{-m_\chi/T_d}$$

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

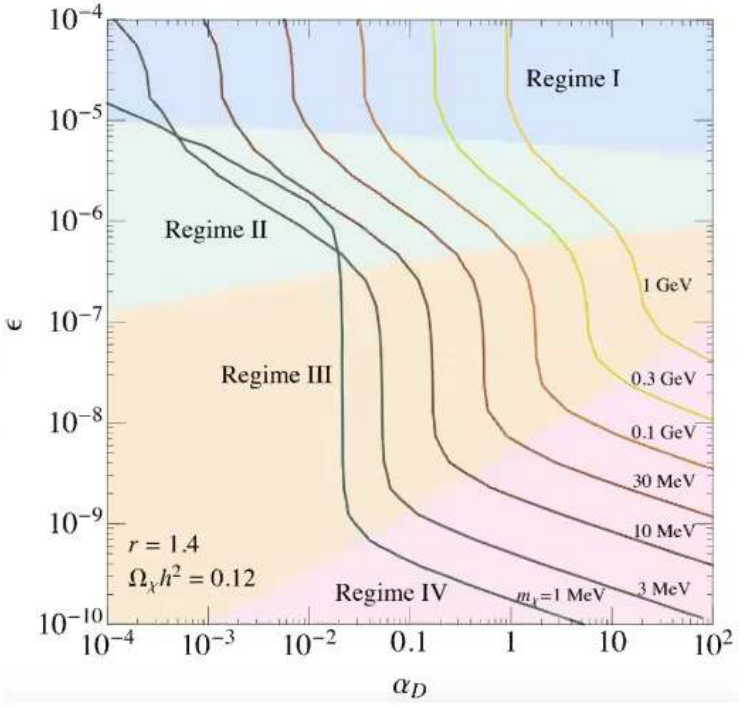


New Regimes

r >1.5: 3—>2 freezes out last

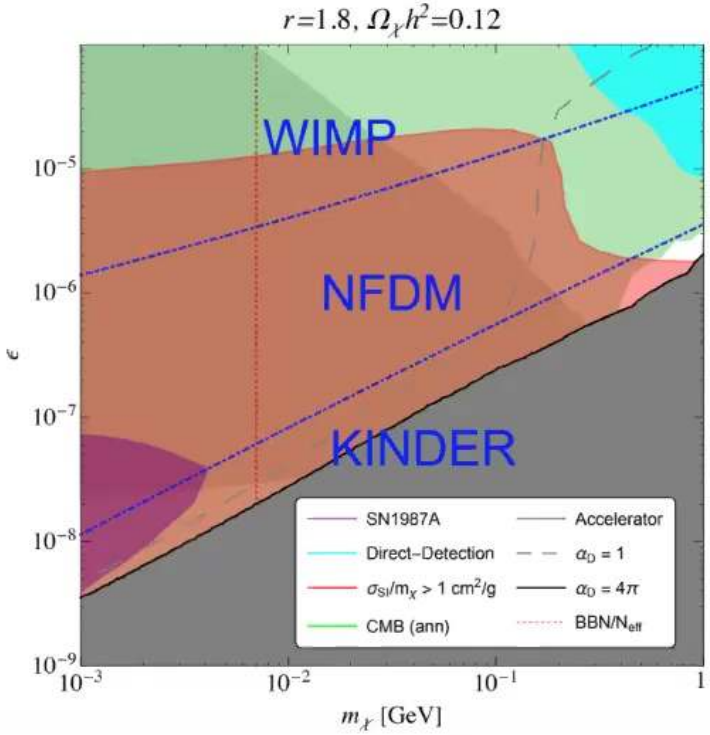


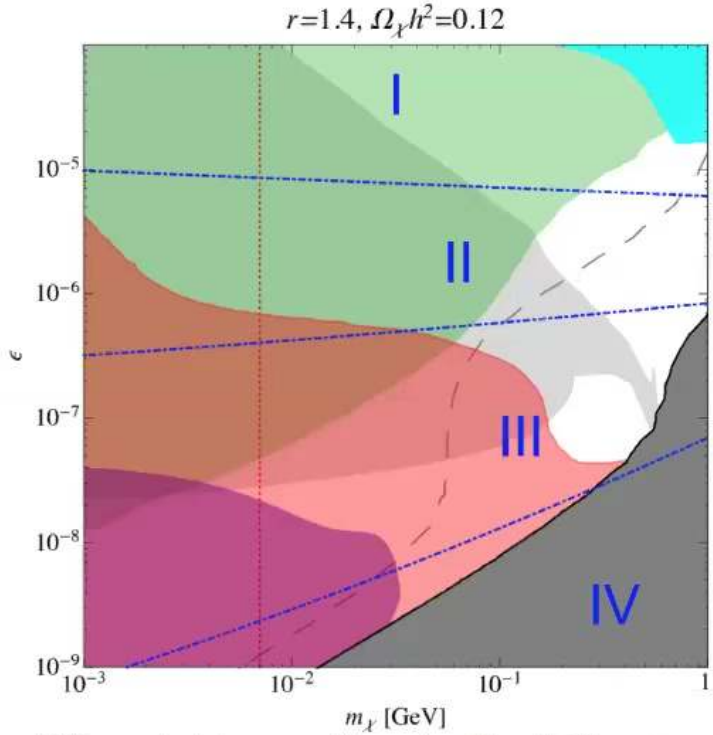
r <1.5: 2—>2 freezes out last



- **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)

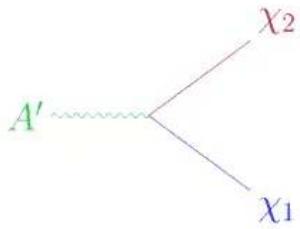
- **KINDER: small available window. Large self-interaction rates, large s-wave annihilation signal in CMB**
- **Available windows for new Regimes II, III**

Inelastic KINDER Surprise

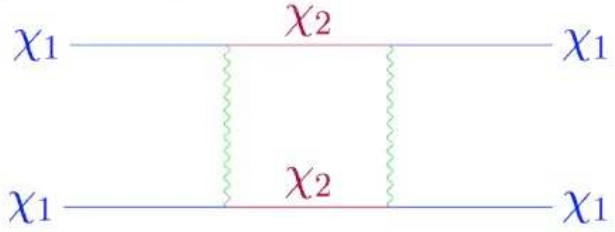
- **Alleviate CMB and Self-Interaction constraints: Inelastic DM**
- **Dark matter is a pseudo-Dirac fermion charged under dark** $U(1)_D$
- $U(1)_D$ **broken:** χ_1 χ_2 **non-degenerate Majorana fermions**

$$\delta \equiv (m_{\chi 2} - m_{\chi 1}) \lesssim T_f'$$

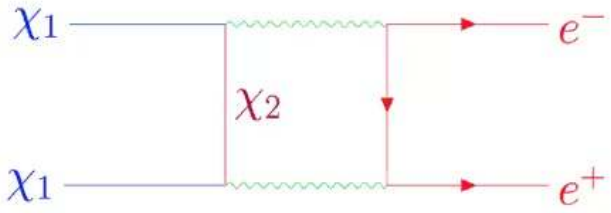
- **vector coupling off-diagonal**



- **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

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