

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.



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

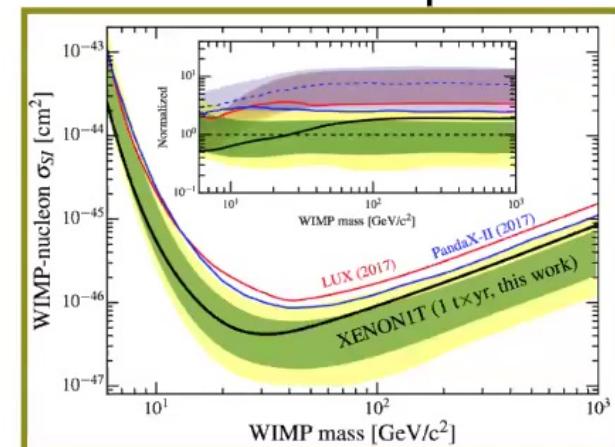
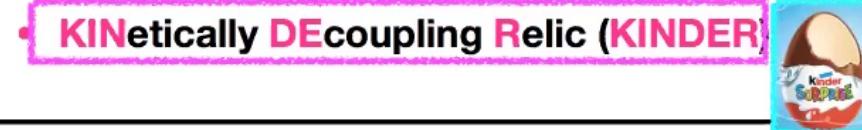
TeV

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, Forbidden DM, Not-Forbidden DM**
 - **New Pathways to the Relic Abundance of Vector-Portal DM**

• **KINetically DEcoupling Relic (KINDER)**

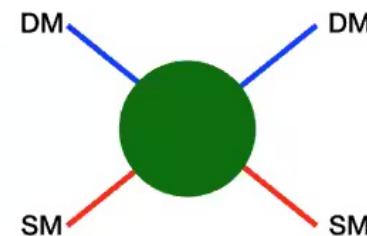
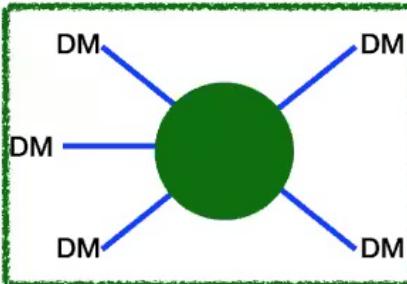


E. Aprile et al. (XENON
Collaboration) 2017

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 $3 \rightarrow 2$

Hochberg et al. 2014

- as Universe cools...

Thermal freezeout

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

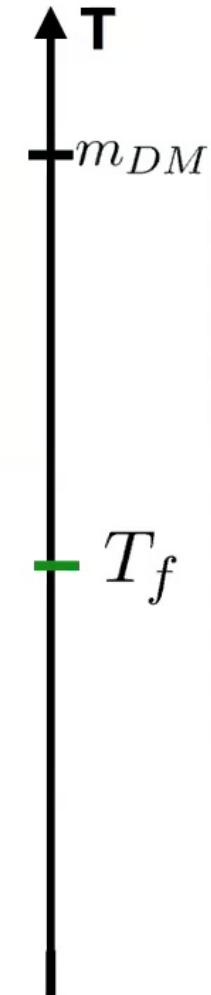
$$\sim \frac{\alpha_D^3}{m_{DM}^5} \sim \frac{T^2}{M_{pl}}$$

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

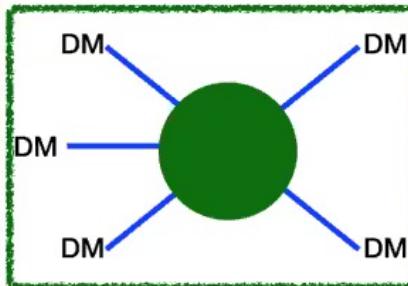
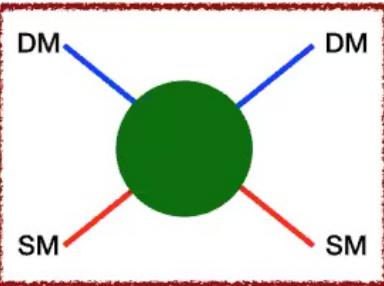
$$\Omega_\chi h^2 = 0.12 \rightarrow \sim 100 \text{ MeV}$$

- 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...

$$\left(\frac{\text{Rate energy transfer}}{\text{DM-to-SM}} \right) \gtrsim \left(\frac{\text{Rate mass-to-kinetic energy}}{\text{in DM}} \right)$$

$$3 \rightarrow 2$$
- **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

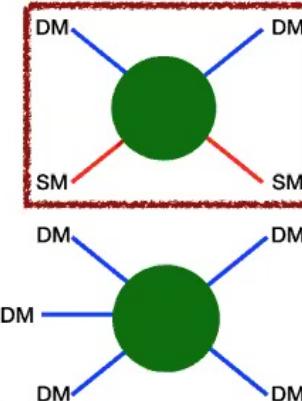
- Thermal decoupling... $T' \neq T$

$$\left(\begin{array}{c} \text{Rate energy transfer} \\ \text{DM-to-SM} \\ \text{DM SM} \rightarrow \text{DM SM} \end{array} \right) \lesssim \left(\begin{array}{c} \text{Rate mass-to-kinetic energy} \\ \text{in DM} \\ 3 \rightarrow 2 \end{array} \right)$$

- comoving entropy density conserved

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

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



- DM chemical equilibrium

$$T' \propto \log T$$

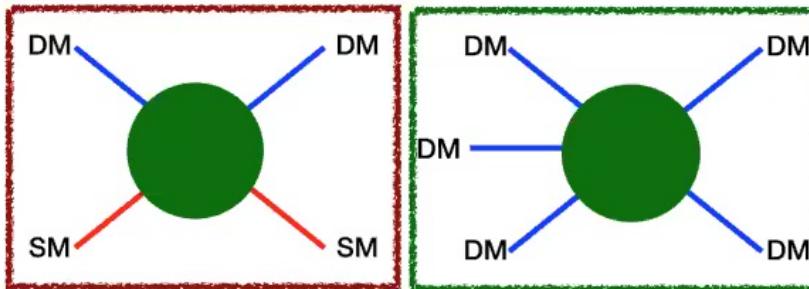
- DM evolves with ~constant Temp and comoving density

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

I

Respect Your ELDERs

Kuflik et al. 2016



- 3→2 freezeout

$$\Omega_{DM} h^2 \sim \frac{n_{DM}(T'_f)}{s(T_f)} \sim \frac{\left(T'_f/m_\chi\right)^{3/2}}{\left(T_f/m_\chi\right)^3} e^{-m_\chi/T'_f}$$

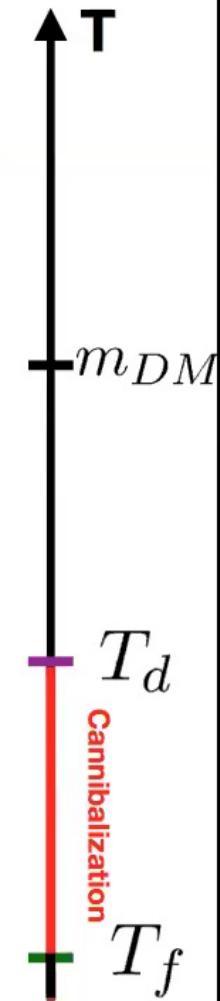
← $T'_f \simeq \frac{T_d}{1 + 3 \frac{T_d}{m_\chi} \log\left(\frac{T_d}{T_f}\right)}$

$$\sim \frac{\left(m_\chi/T_d\right)^{3/2}}{1 + 3 \frac{T_d}{m_\chi} \log\left(\frac{T_d}{T_f}\right)} e^{-m_\chi/T_d}$$

$$\sim e^{-\left(m_\chi M_{pl} \langle \sigma v \rangle\right)^{1/4}}$$

- Sub-GeV DM

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



Dark Photon

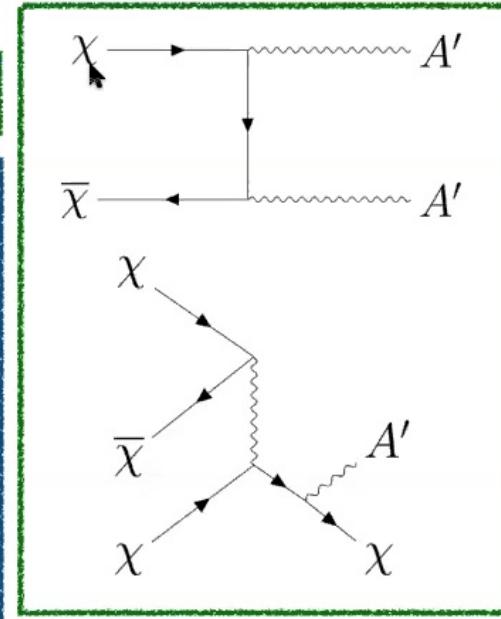
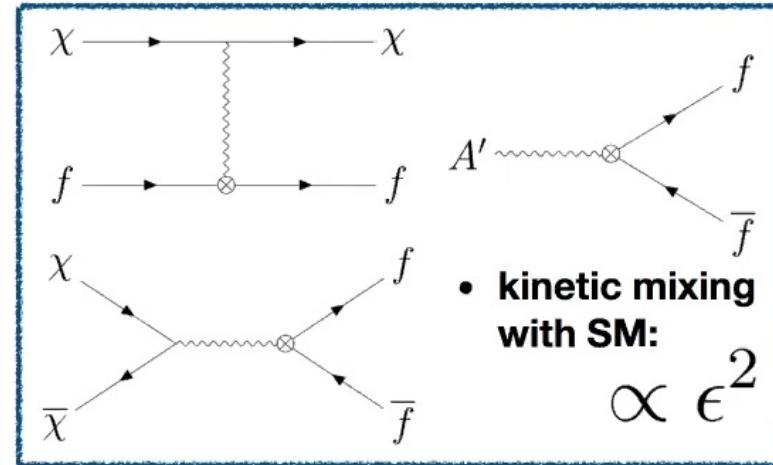
- in mass basis:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^2 + \bar{\chi}(iD\!\!\!/ - m_\chi)\chi + eJ_{\text{EM}}^\mu(A_\mu + \epsilon A'_\mu)$$

$$D\!\!\!/ \equiv \partial\!\!\!/ - ig_D A'\quad \alpha_D = g_D^2/4\pi$$

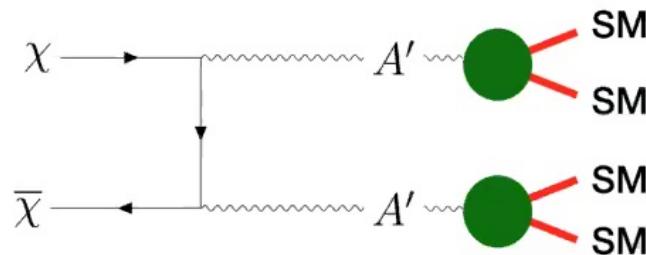
- Let's consider region:

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



Dark Photon

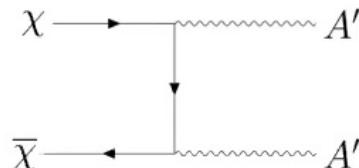
- Let's consider region: $m_\chi \lesssim m_{A'} \lesssim 2m_\chi$
- In the region $m_\chi > m'_A$ CMB constraints rule out Light DM



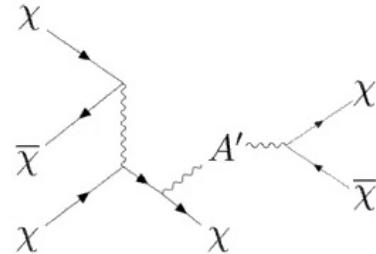
- Injects energy into SM plasma
- Ruled out by CMB for $m_\chi \lesssim 1 \text{ GeV}$

Dark Photon

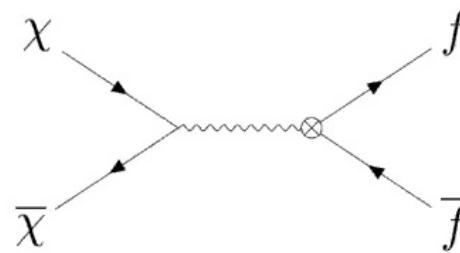
- Let's consider region: $m_\chi \lesssim m_{A'} \lesssim 2m_\chi$
- In the region $m_{A'} > 2m_\chi$ reduces to the WIMP case



Huge kinematic suppression

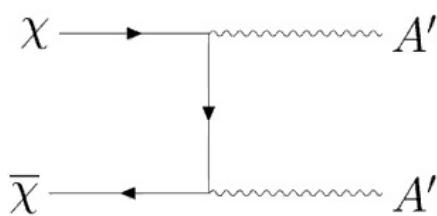


Reduces to scattering process

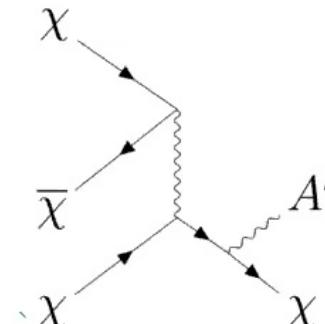


Stringent CMB constraints

(Not-) Forbidden DM



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



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

kinematic suppression

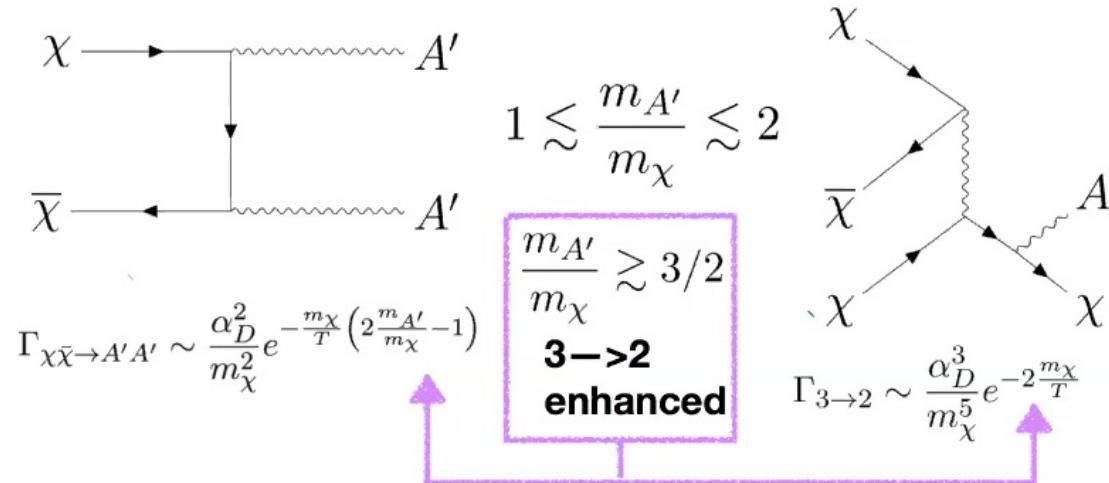
- “**Forbidden Dark Matter**”
 - DM annihilates into heavier states
 - Proceeds at finite temperature

D’Agnolo and Ruderman 2015 ;
Griest and Seckel 1991

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

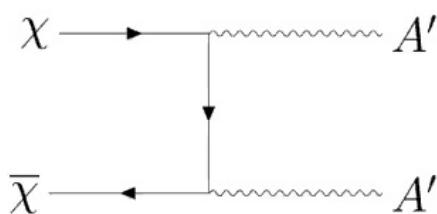
- **FDM: Naturally gives DM exponentially lighter than the weak scale — sub-GeV**

(Not-) Forbidden DM

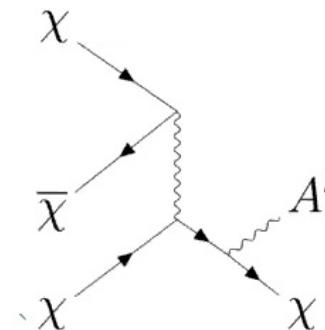


- “**Not-Forbidden Dark Matter**” Cline et al. 2017
 - $\frac{m_{A'}}{m_\chi} \gtrsim 3/2$: 3->2 can dominate in setting DM relic abundance
 - Naturally gives sub-GeV DM

(Not-) Forbidden DM

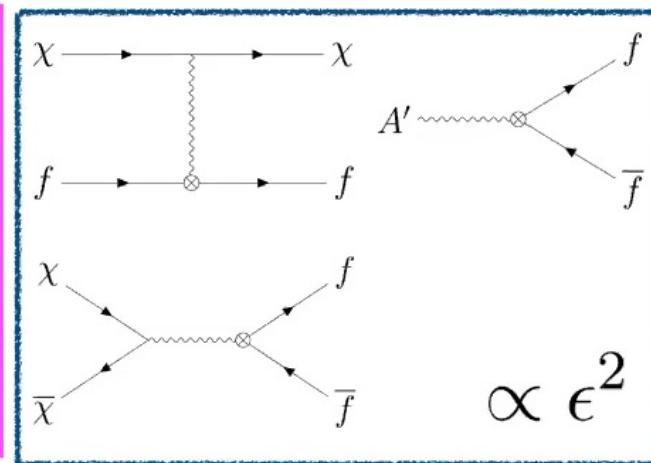


$$1 \lesssim \frac{m_{A'}}{m_\chi} \lesssim 2$$



Novel scenarios

- ϵ small but nonzero
 - DM and SM kinetically decouple
 - $T' \neq T$
- *New Pathways to the Relic Abundance*
- **KIN**etically **D**Ecoupling **R**elic

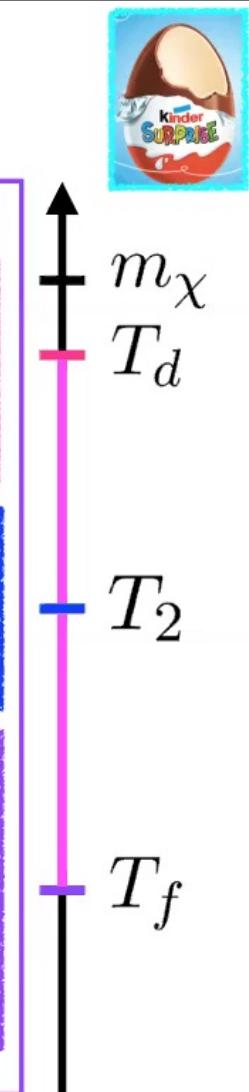
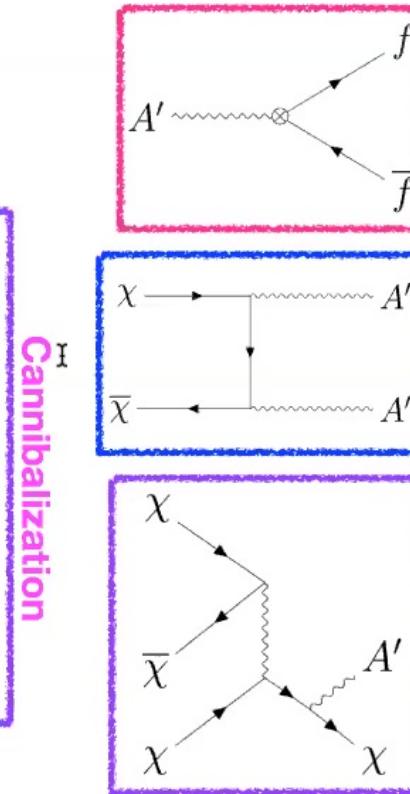


KINDER



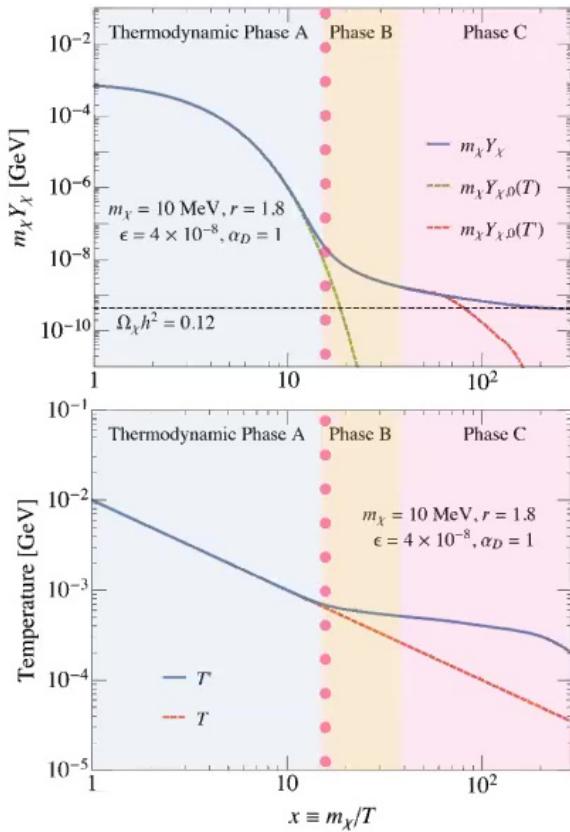
KINDER

- 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



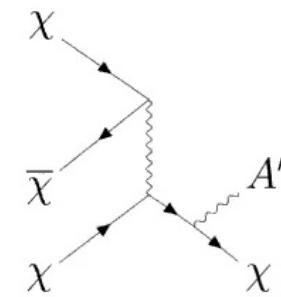
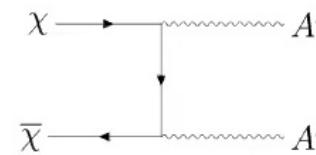
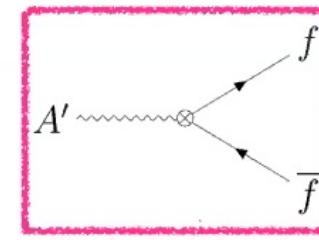
Cannibalization

KINDER



KINetic DEcoupling

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

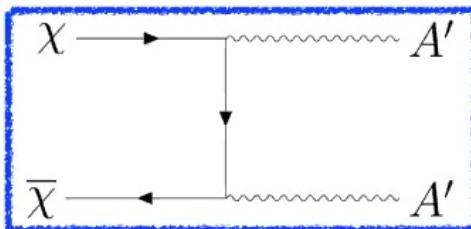


T_d

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



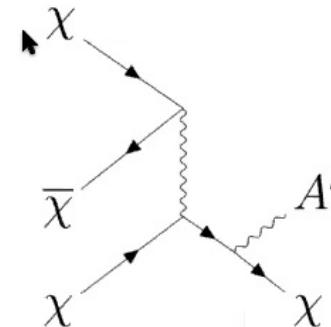
2→2 Freezeout



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

$$\xrightarrow{< H} \quad \xleftarrow{< H}$$

2→2 out of equilibrium



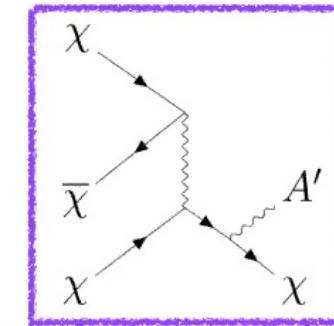
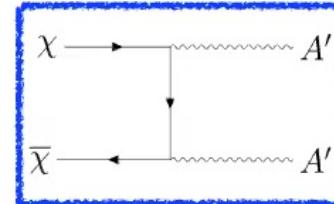
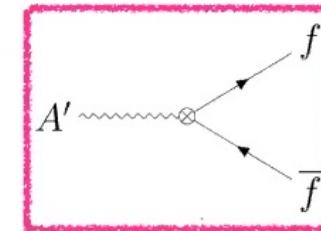
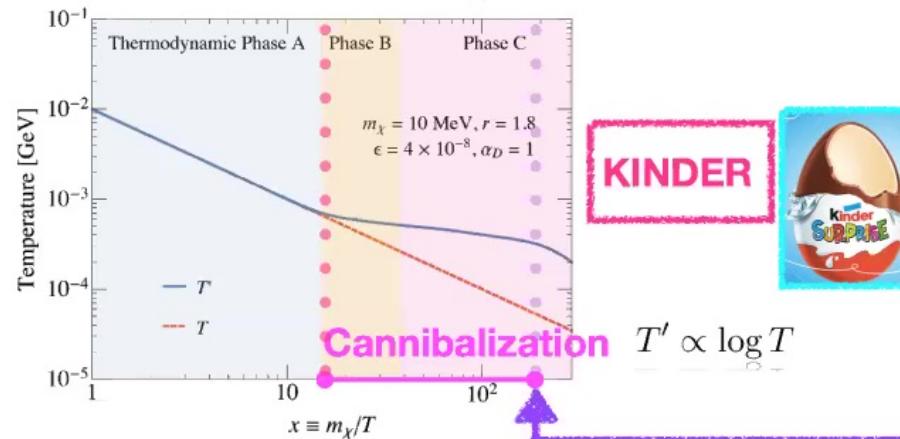
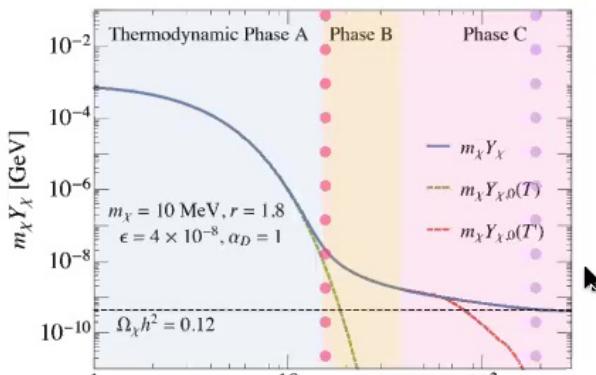
$$\Gamma_{\chi\chi\bar{\chi} \rightarrow \chi A'} \simeq \Gamma_{\chi A' \rightarrow \chi\chi\bar{\chi}}$$

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



T_d

T_2

T_f

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



KINDER Relic Abundance

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

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

$$\sim \frac{\left(m_\chi/T'_f\right)^{-3/2} e^{-m_\chi/T'_f}}{(m_\chi/T_f)^{-3}}$$

$$\sim 10^8 \left(\frac{m_\chi}{\text{GeV}}\right) \frac{(m_\chi/T_d)^3}{(m_\chi/T'_3)^2} \sqrt{\frac{m_\chi}{T_d} + 3 \log \frac{T_d}{T_2}} e^{-\frac{m_\chi}{T_d}}$$

- Exponentially sensitive only to the KINetic DECoupling !

KINDER

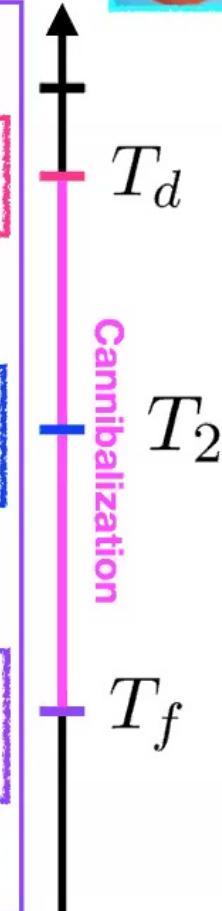


$$\frac{m_\chi}{T_d} e^{(1-r)m_\chi/T_d} \sim \frac{m_\chi}{M_{pl}} \frac{1}{r^{7/2} \epsilon^2 \alpha_{em}}$$

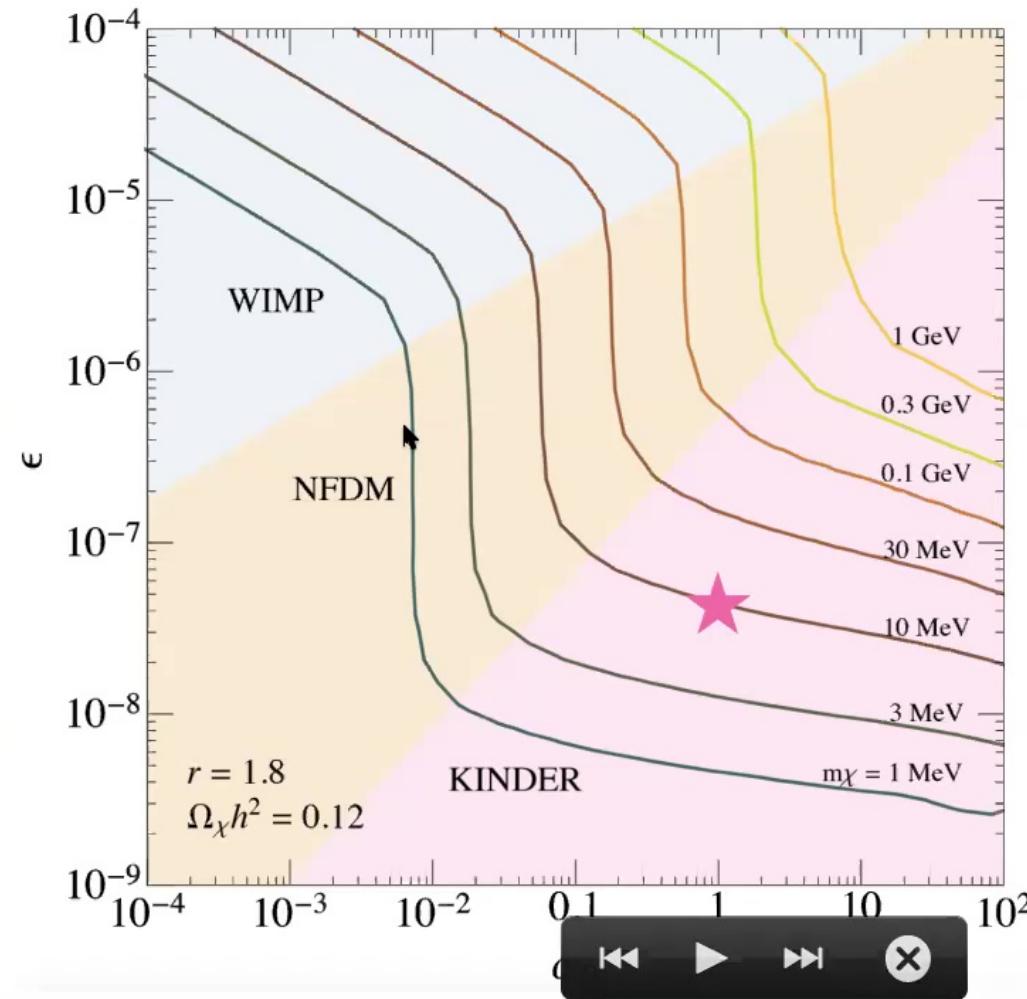
$$T'_2 \simeq \frac{T_d}{1 - \frac{3T_d}{m_\chi} \ln(T_2/T_d)}$$

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

Cannibalization



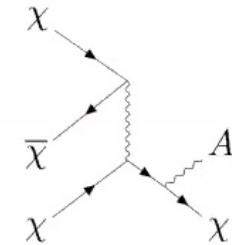
KINDER Regime



NFDM

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

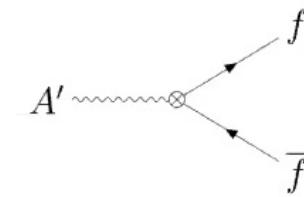
$$T_f = T_f(\alpha)$$



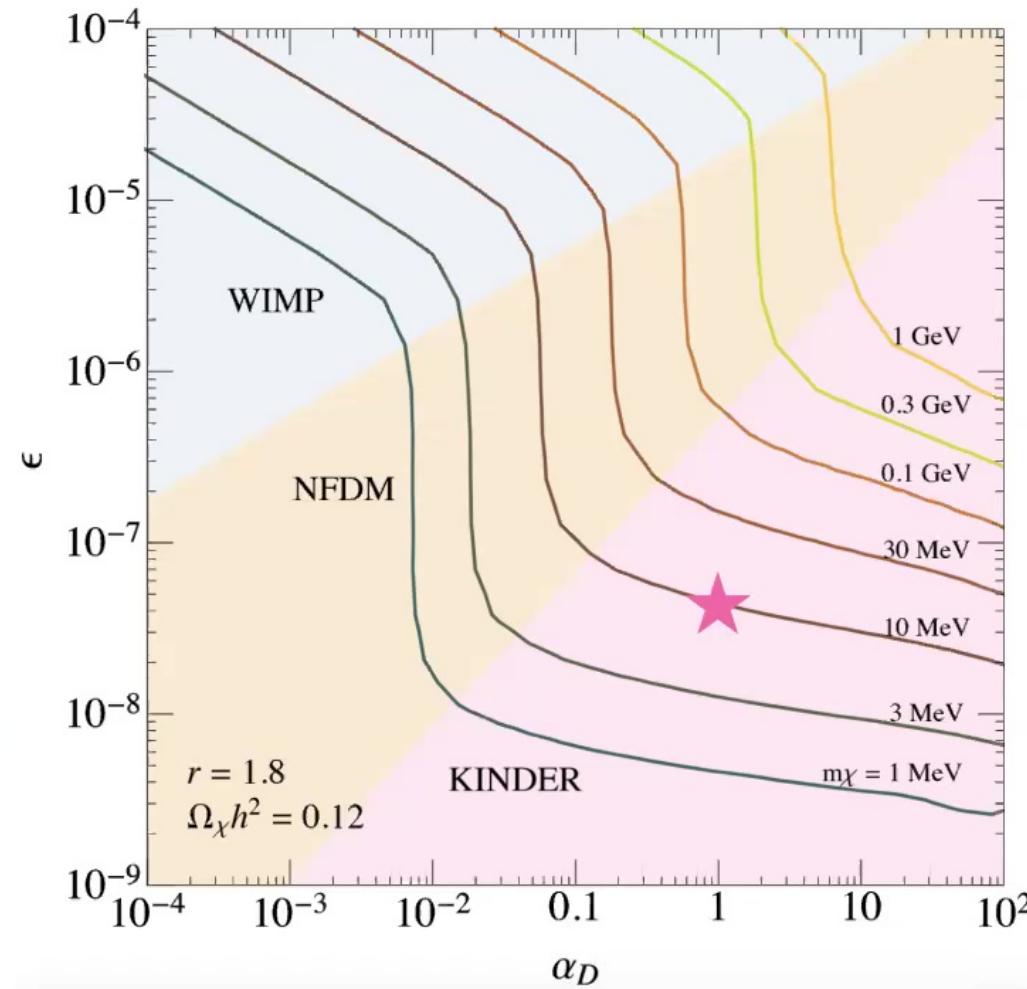
KINDER

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

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



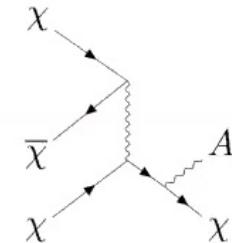
KINDER Regime



NFDM

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

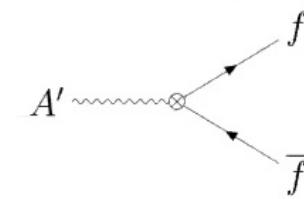
$$T_f = T_f(\alpha)$$



KINDER

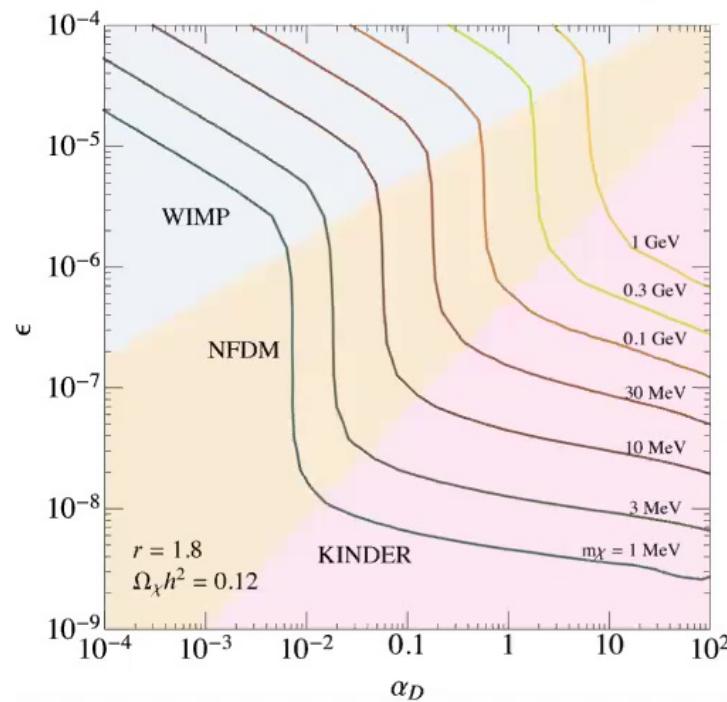
$$\Omega_\chi \sim e^{-m_\chi/T_d}$$

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

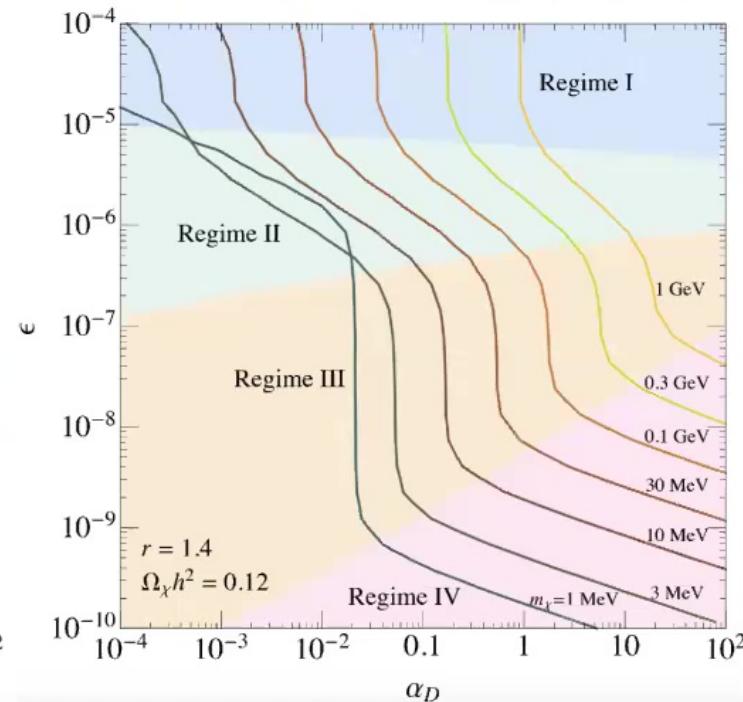


New Regimes

$r > 1.5$: $3 \rightarrow 2$ freezes out last

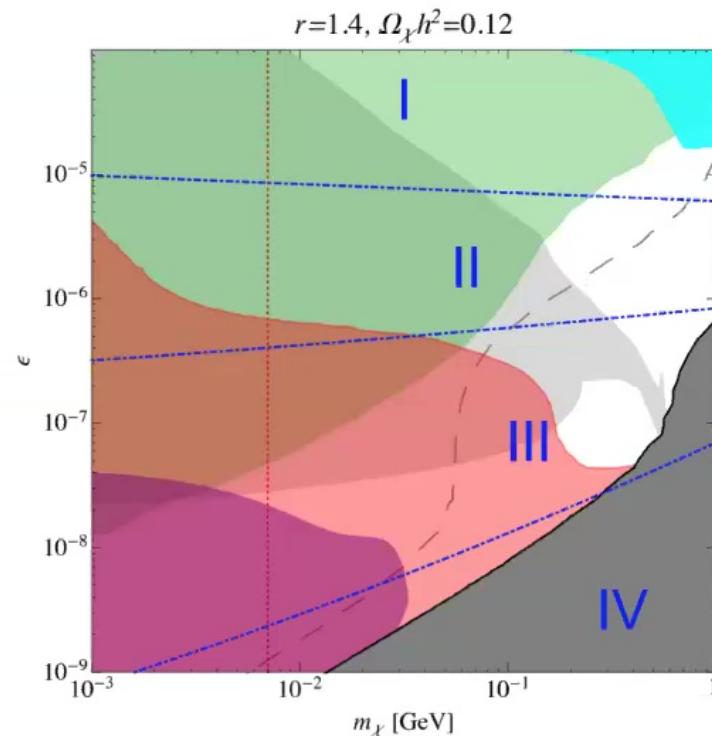
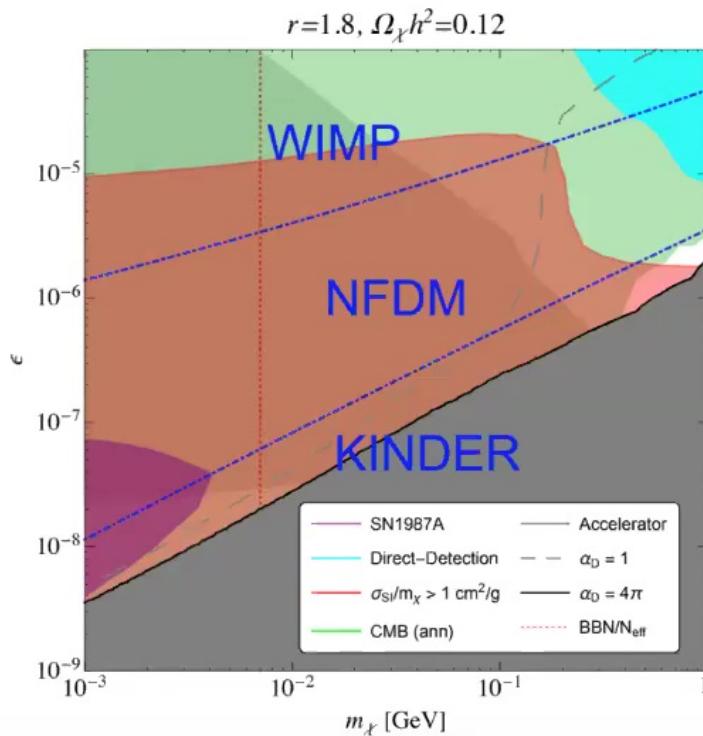


$r < 1.5$: $2 \rightarrow 2$ freezes out last



- 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**

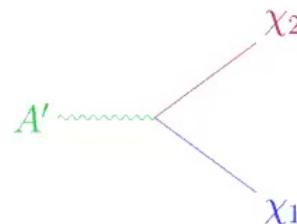
Inelastic KINDER Surprise



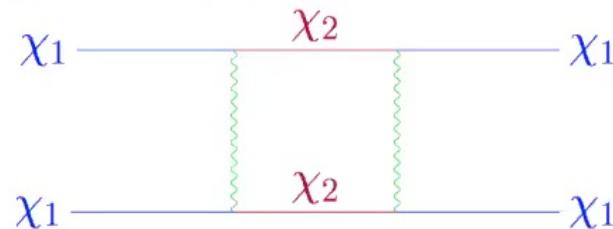
- Alleviate CMB and Self-Interaction constraints: **Inelastic DM**
- Dark matter is a pseudo-Dirac fermion charged under dark $U(1)_D$
- $U(1)_D$ broken: χ_1 χ_2 non-degenerate Majorana fermions

$$\delta \equiv (m_{\chi_2} - m_{\chi_1}) \lesssim T'_f$$

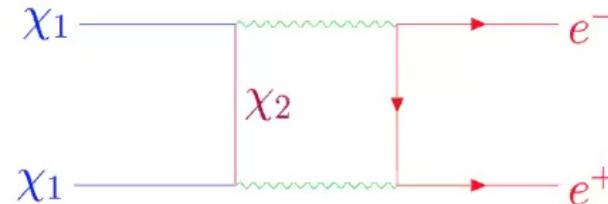
- vector coupling off-diagonal



- 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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