

New Thermal Decoupling Windows to the Dark Sector



Patrick J. Fitzpatrick

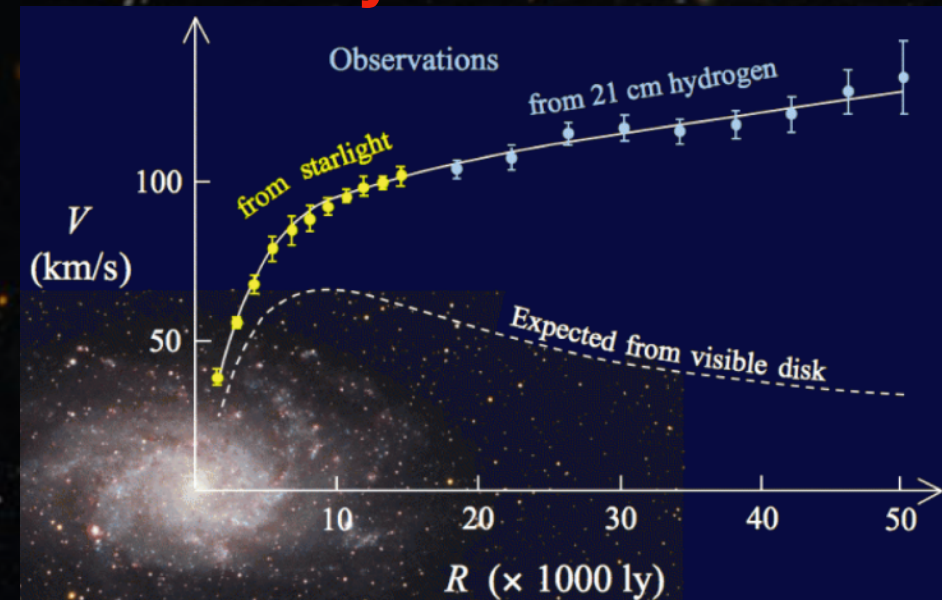
Más allá del Model Estándar y Astropartículas, IFUNAM, 2025

Mystery of the Missing Matter

Coma Cluster

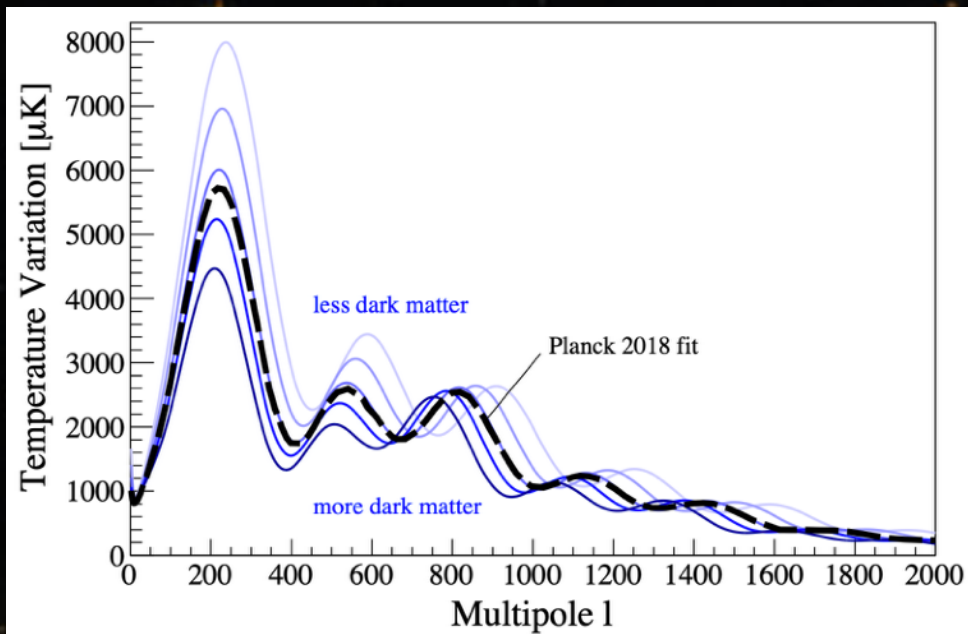


Galaxy rotation curves



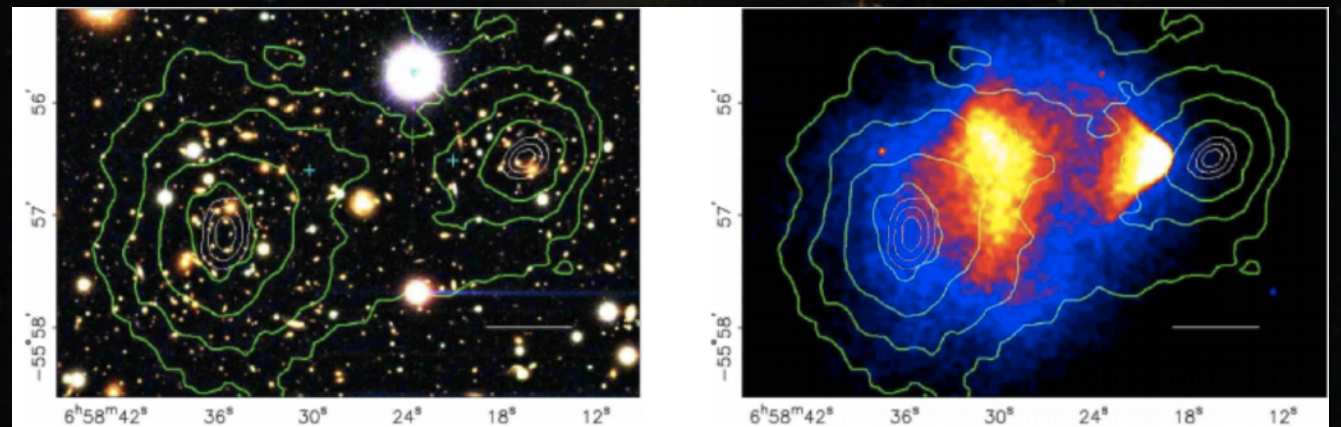
Rubin & Ford (1970), from Penoyre for Astrobitis

CMB Temperature Anisotropies



from Schumann (2019)

Merging galaxy clusters (Bullet cluster)



Clowe, Bradač, Gonzalez et al. (2006), from Khullar for Astrobitis

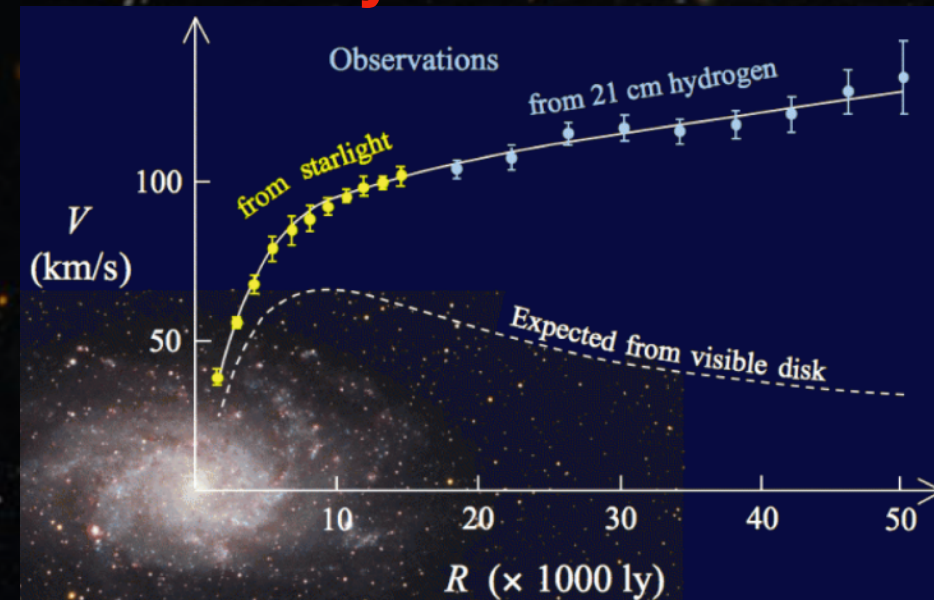
- **DM: No (detectable) E&M interaction**
Gravitational Interaction
85 +/- 2%

Mystery of the Missing Matter

Coma Cluster

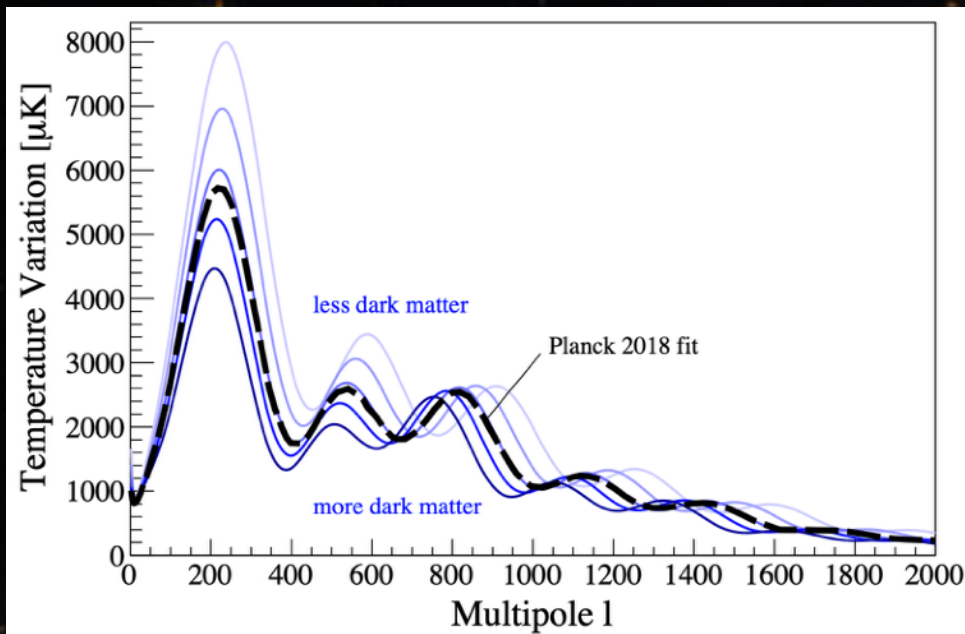


Galaxy rotation curves



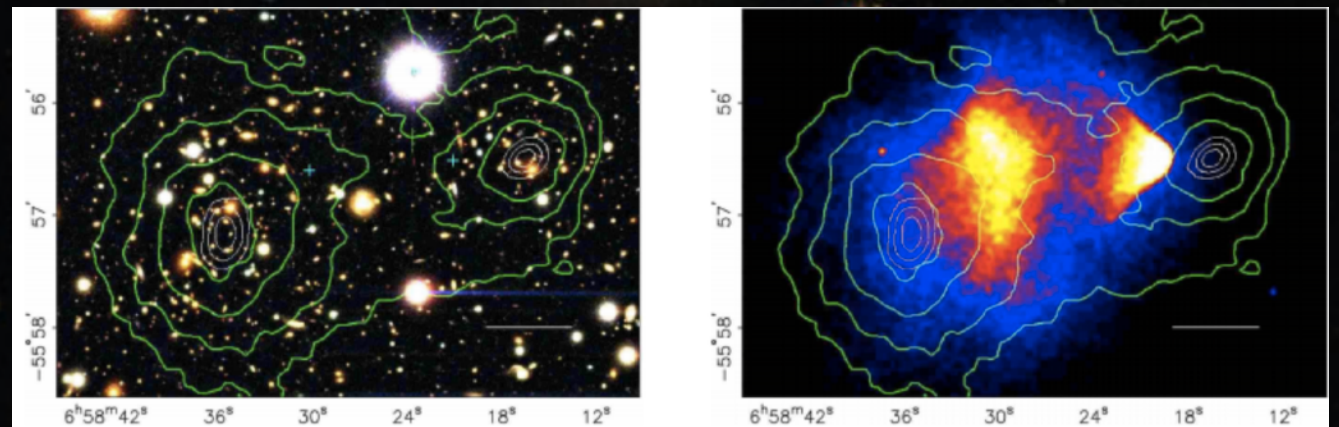
Rubin & Ford (1970), from Penoyre for Astrobitis

CMB Temperature Anisotropies



from Schumann (2019)

Merging galaxy clusters (Bullet cluster)

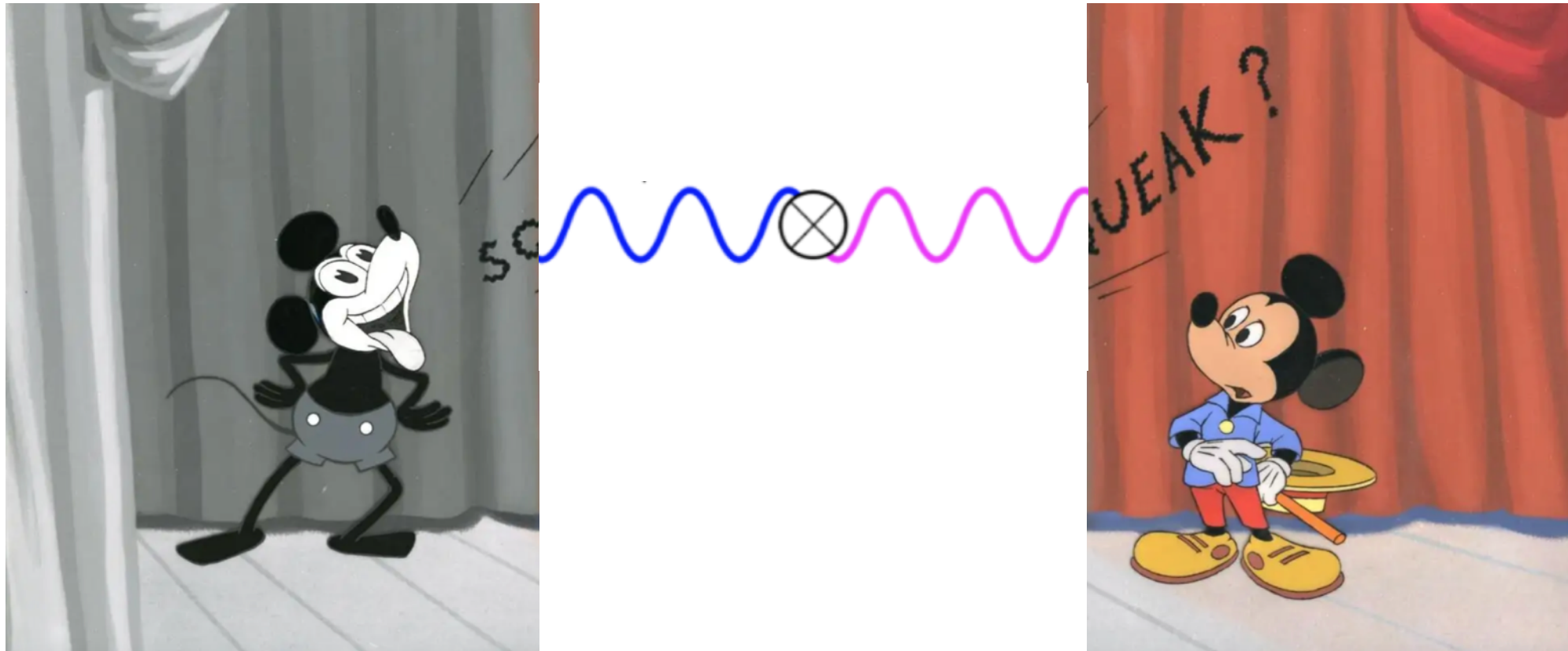


Clowe, Bradač, Gonzalez et al. (2006), from Khullar for Astrobitis

• DM:

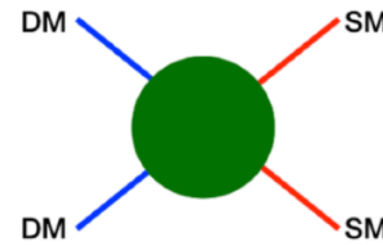
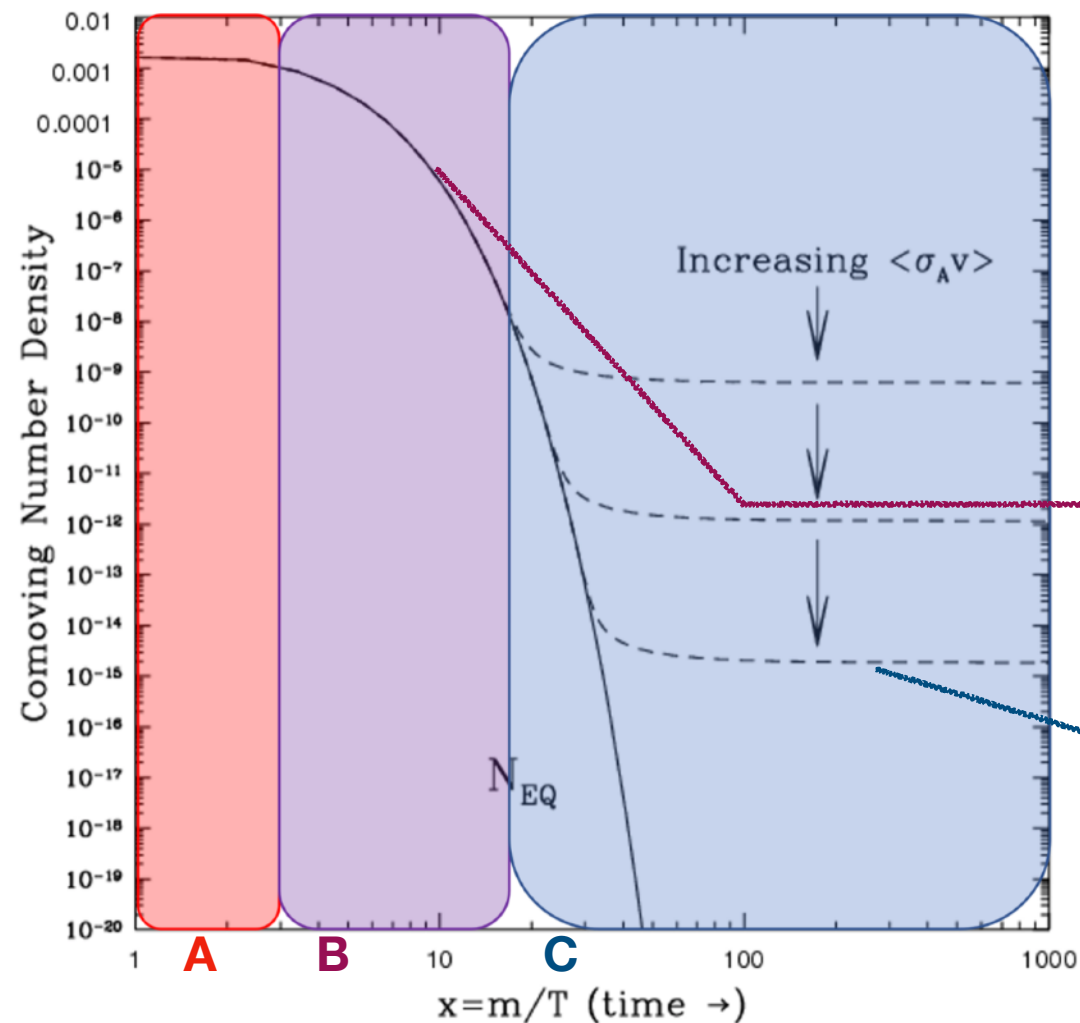
??????????

Portal to the Dark Side?



- Leading hypothesis: **non-gravitational interactions between dark and visible matter**
 - Generic in BSM theories
 - Coincidence problem
 - **Shared thermal (or non-thermal) history with SM**

WIMP Miracle



A) $\Gamma_{\text{DM} \rightarrow \text{SM}} \simeq \Gamma_{\text{SM} \rightarrow \text{DM}}$ **Equilibrium**

B) $\Gamma_{\text{DM} \rightarrow \text{SM}} \gtrsim \Gamma_{\text{SM} \rightarrow \text{DM}}$
 $n_{\text{DM}} \sim e^{-m_{\text{DM}}/T}$ **Dilution in Equilibrium**

C) $\Gamma_{\text{DM} \rightarrow \text{SM}} = n_{\text{DM}} \langle \sigma v \rangle_{\text{DM} \rightarrow \text{SM}} \lesssim H$ **Freeze-out**

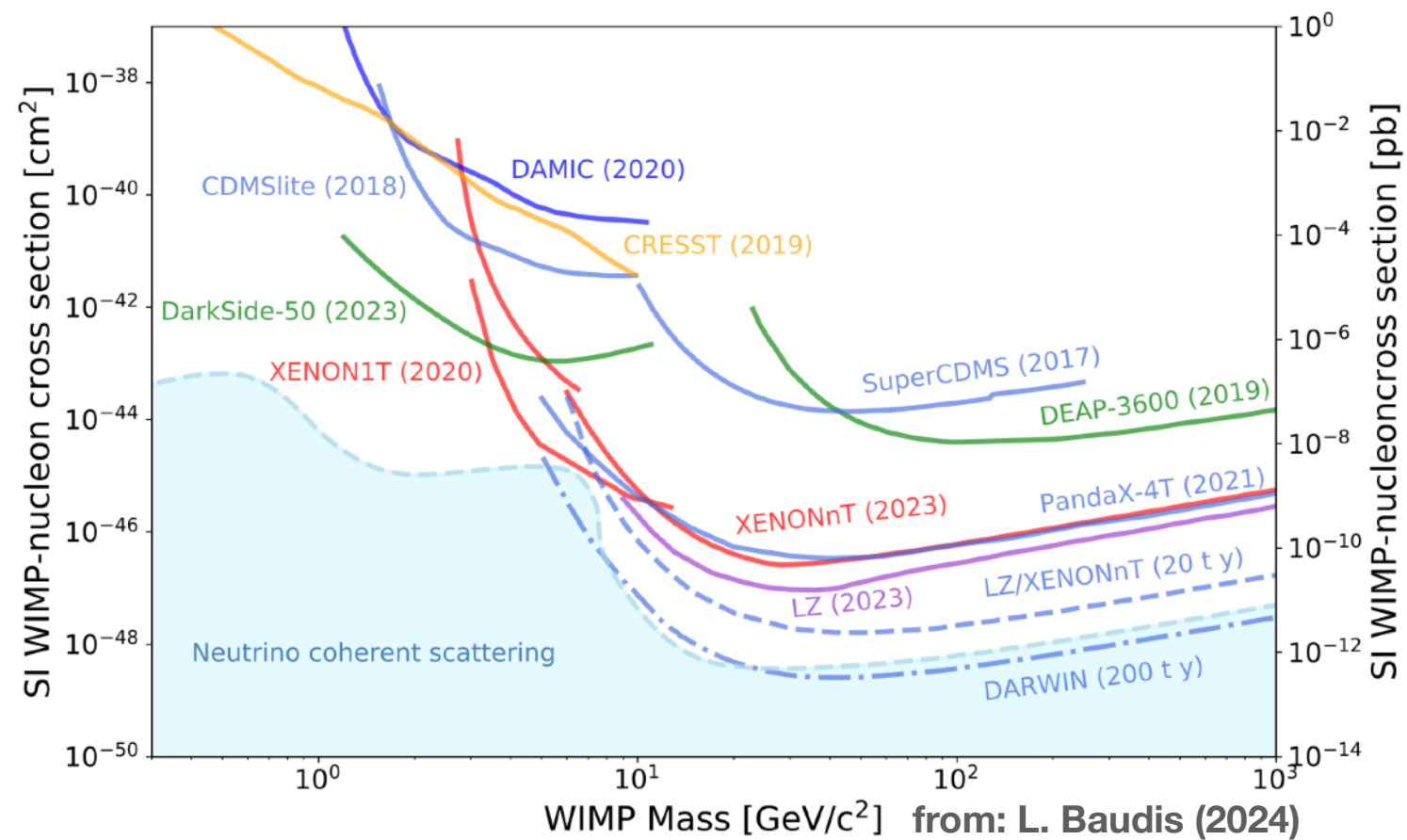
$$\langle \sigma v \rangle_{\text{DM} \rightarrow \text{SM}} \equiv 10^{-9} \text{ GeV}^{-2}$$

$$\alpha_D \sim 0.01 \longleftrightarrow m_{\text{DM}} \sim 10^3 \text{ GeV}$$

Weak scale naturally emerges
WIMP Miracle

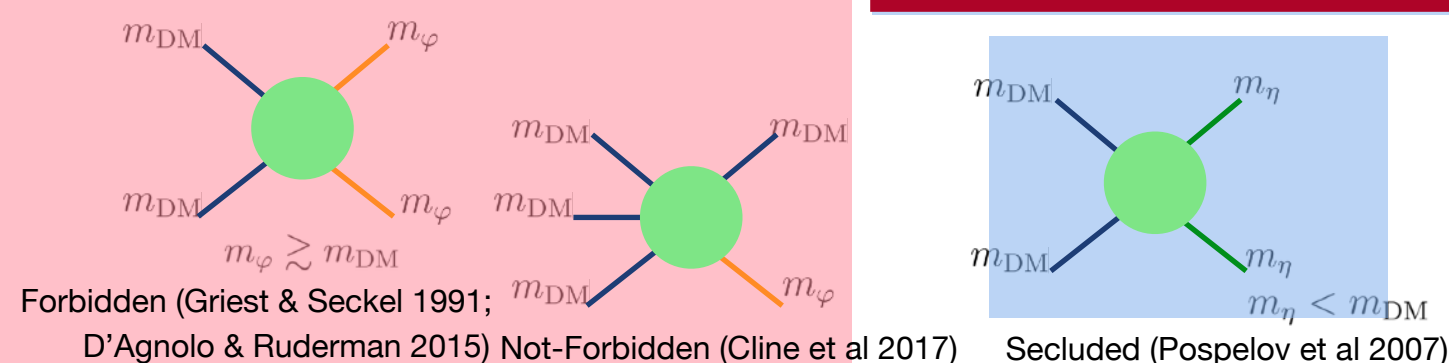
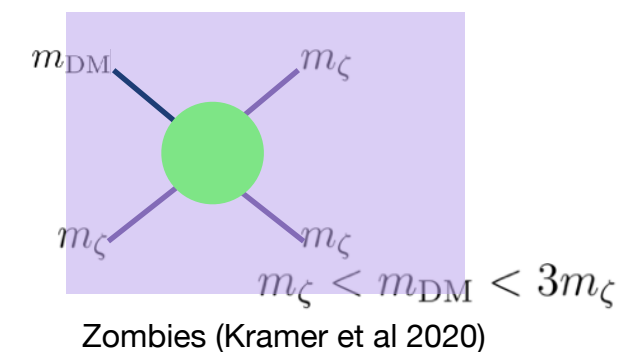
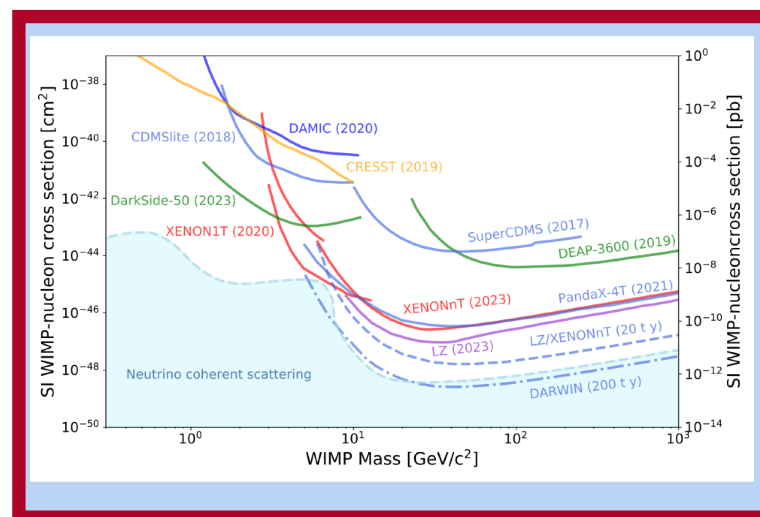
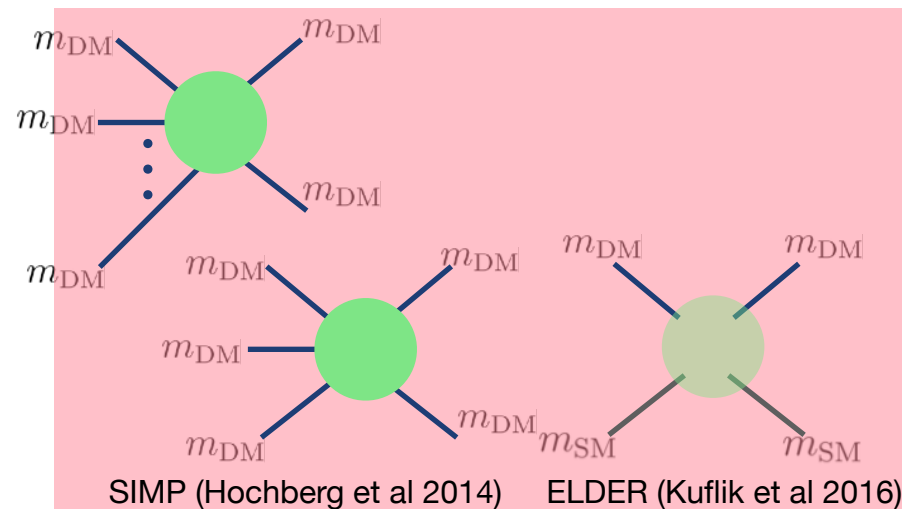
Beyond the WIMP Paradigm

Electroweak-scale window to the dark sector is closing



Beyond the WIMP Paradigm

Electroweak-scale window to the dark sector is closing

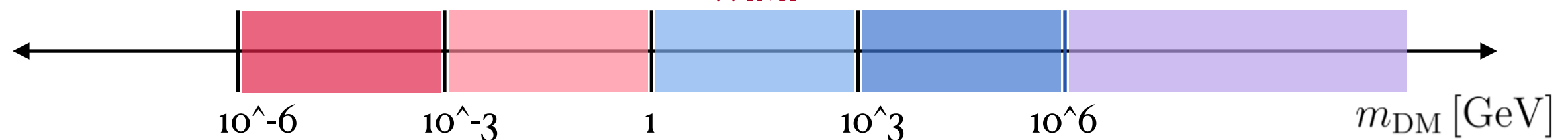


Warm
DM

BBN

Unitarity

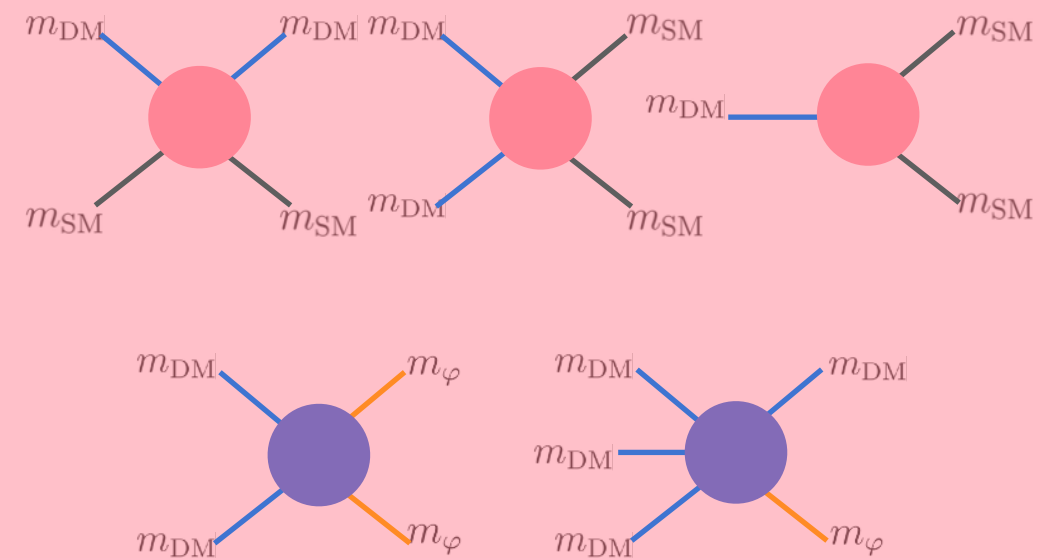
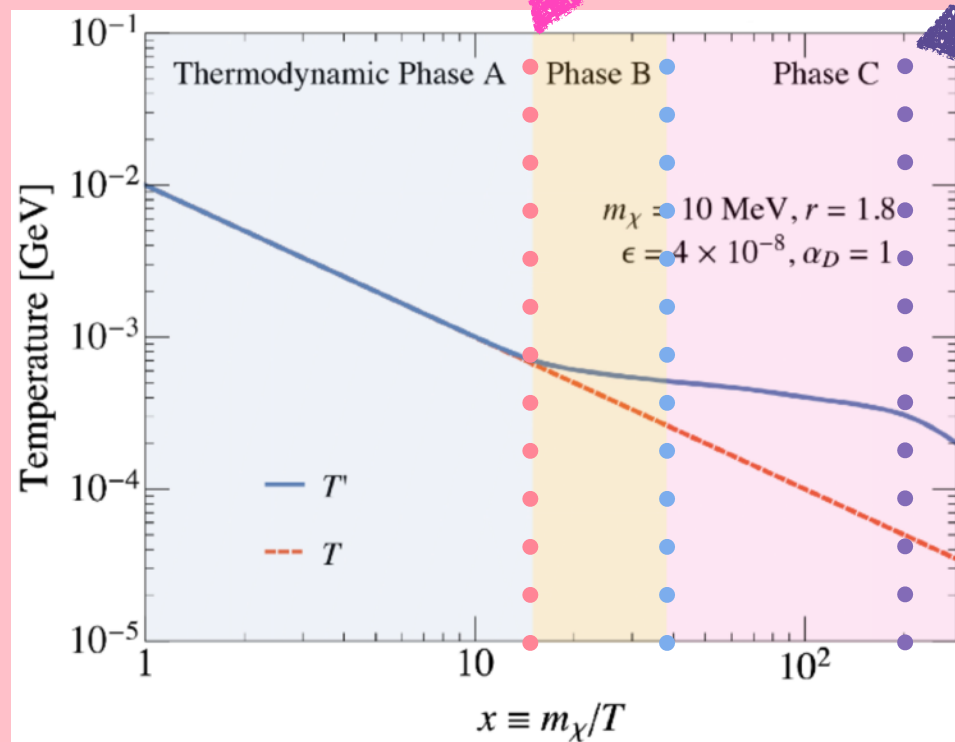
WIMP



New Thermal Relic Scenarios

Beyond the WIMP Paradigm

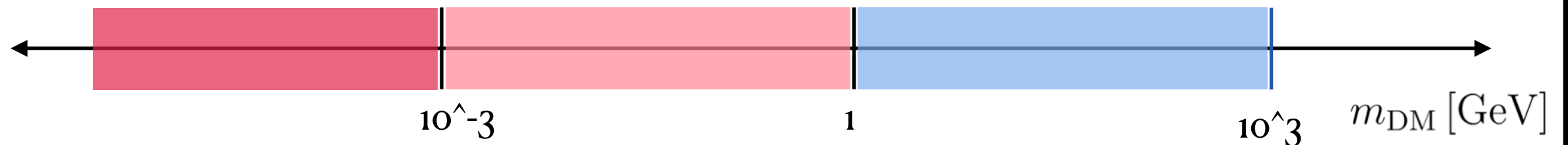
KINetically DEcoupling Freezeout



BBN

Unitarity

WIMP

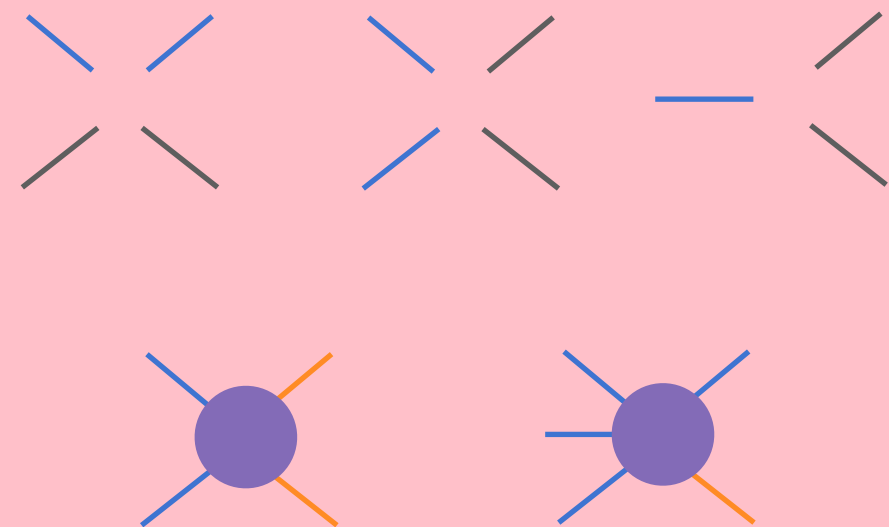
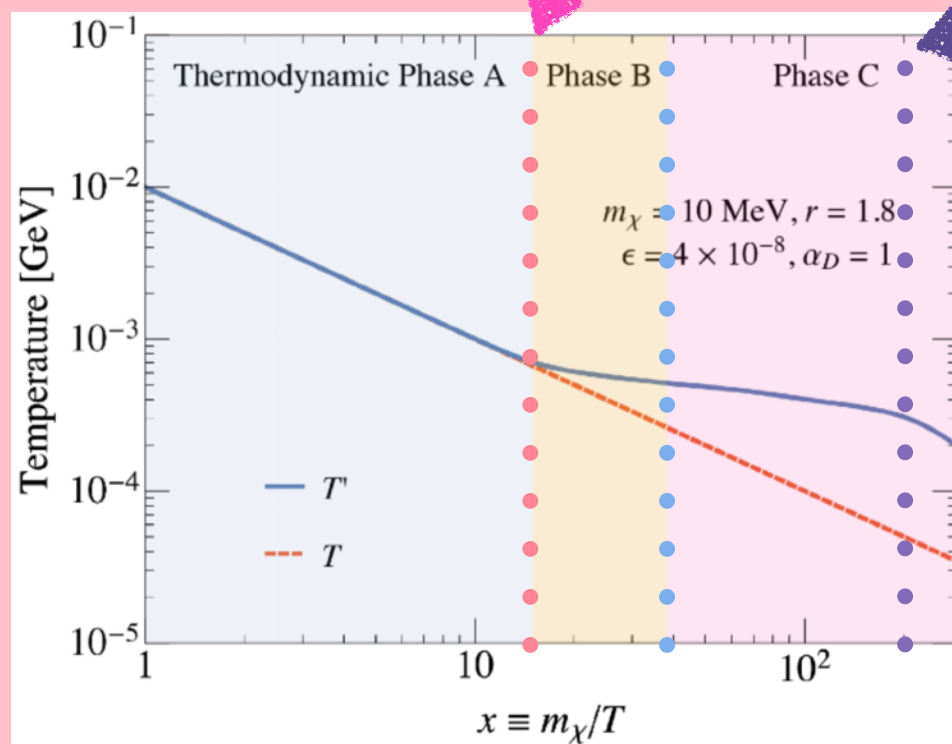


New Thermal Decoupling Relic Scenarios

Beyond the WIMP Paradigm



KINetically DEcoupling Freezeout

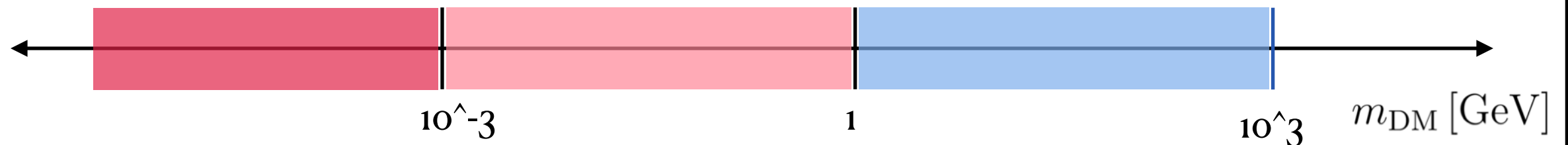


*Multitude of New Pathways
to the Relic Abundance of DM*

BBN

Unitarity

WIMP



New Thermal Decoupling Relic Scenarios

Dark Photon

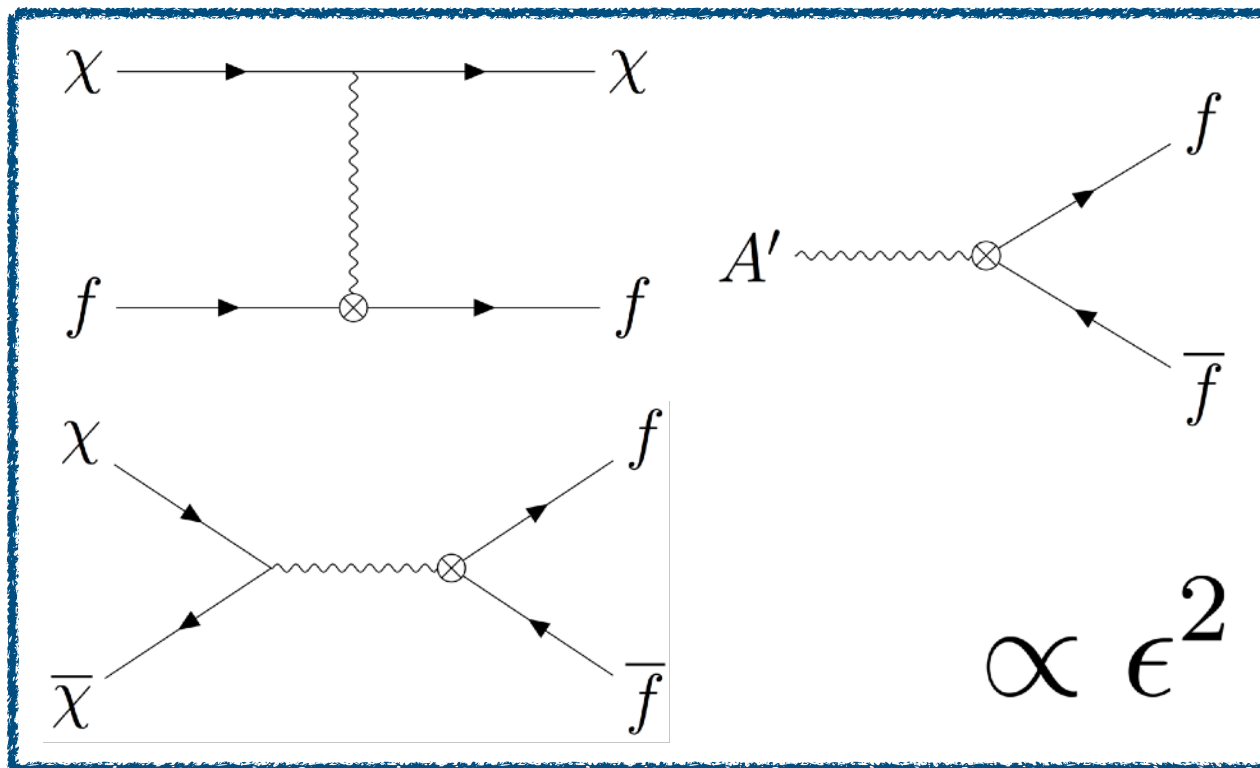
- in mass basis:

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

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

- kinetic mixing with SM:

$$\mathcal{L}_{Mix} = \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$



Dark Photon

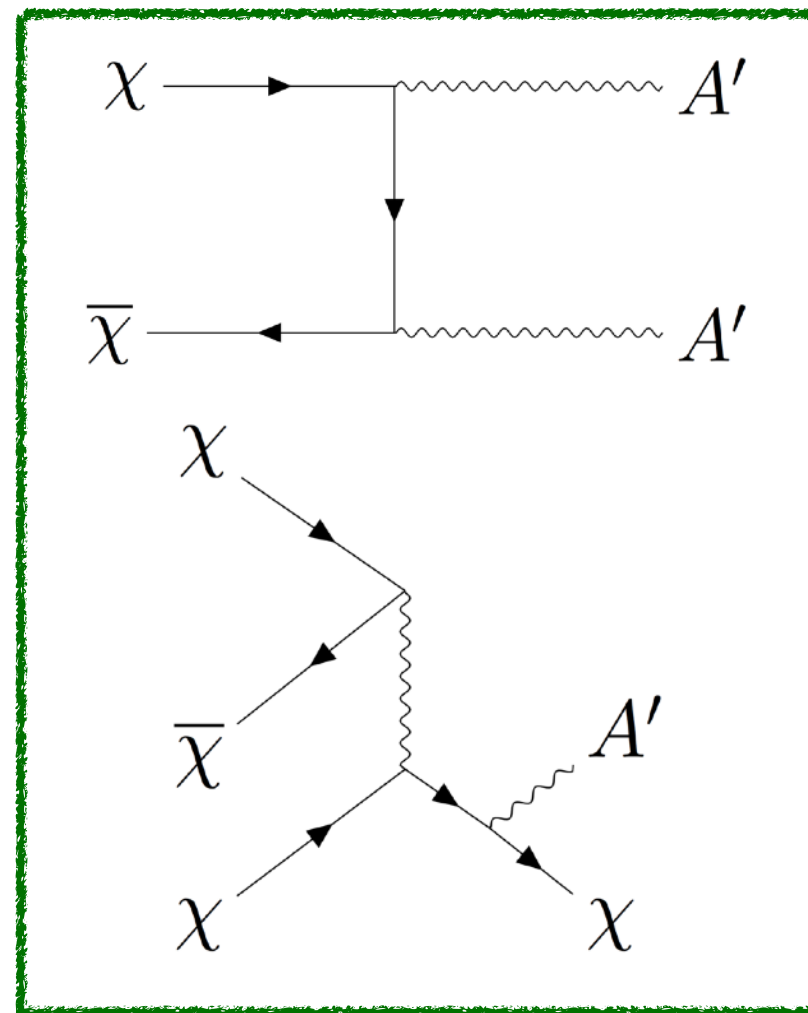
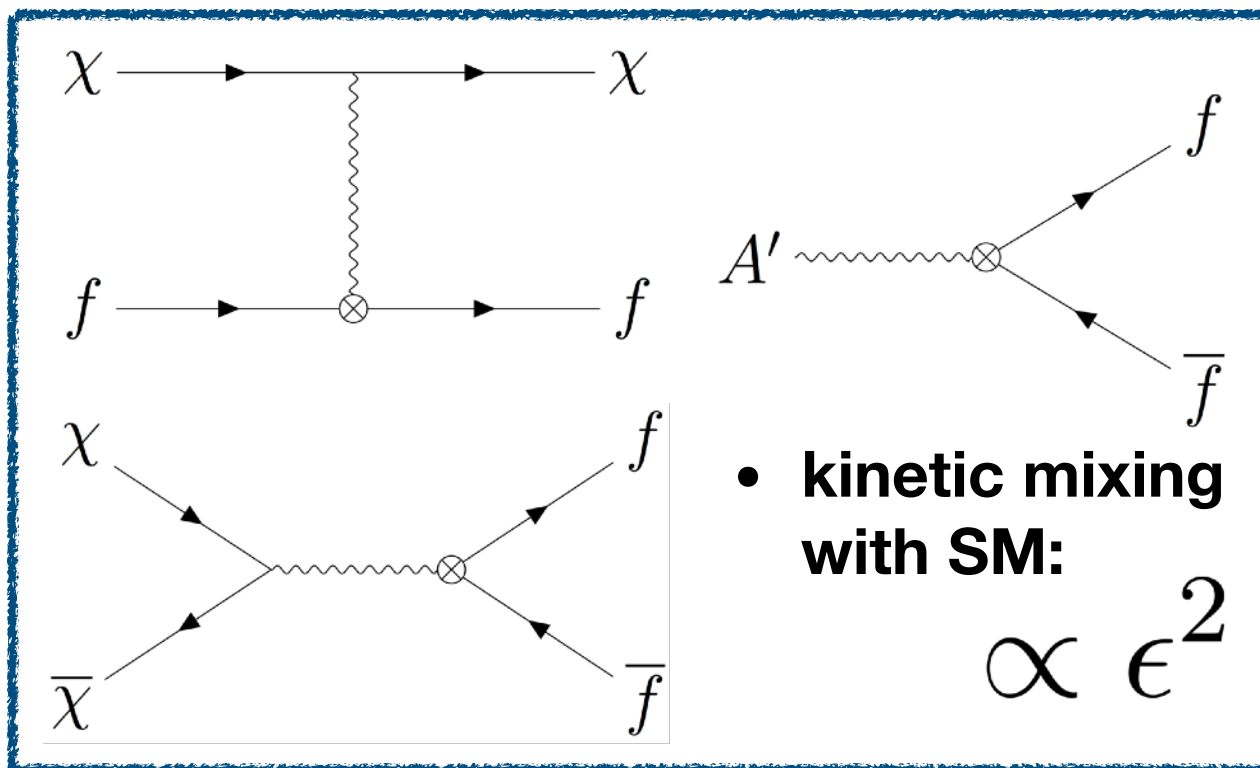
- in mass basis:

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

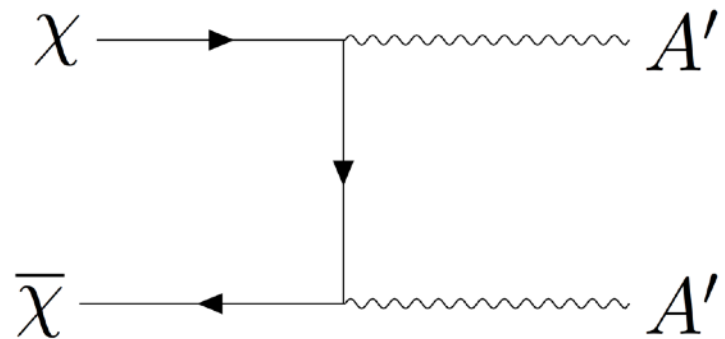
$$\not{D} \equiv \not{\partial} - ig_D \not{A}' \quad \alpha_D = g_D^2/4\pi$$

- Let's consider region:

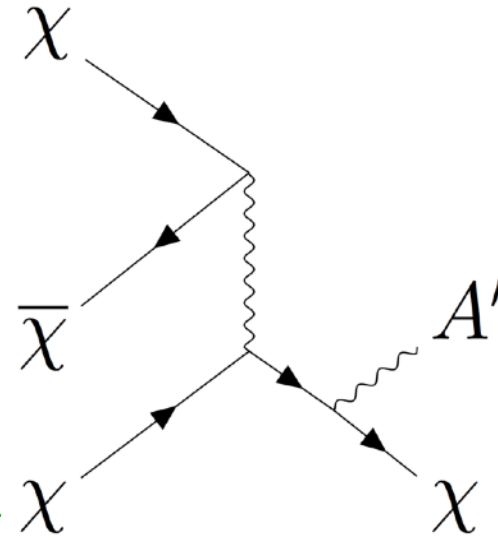
$$m_\chi \lesssim m_{A'} \lesssim 2m_\chi$$



Breaking Equilibrium

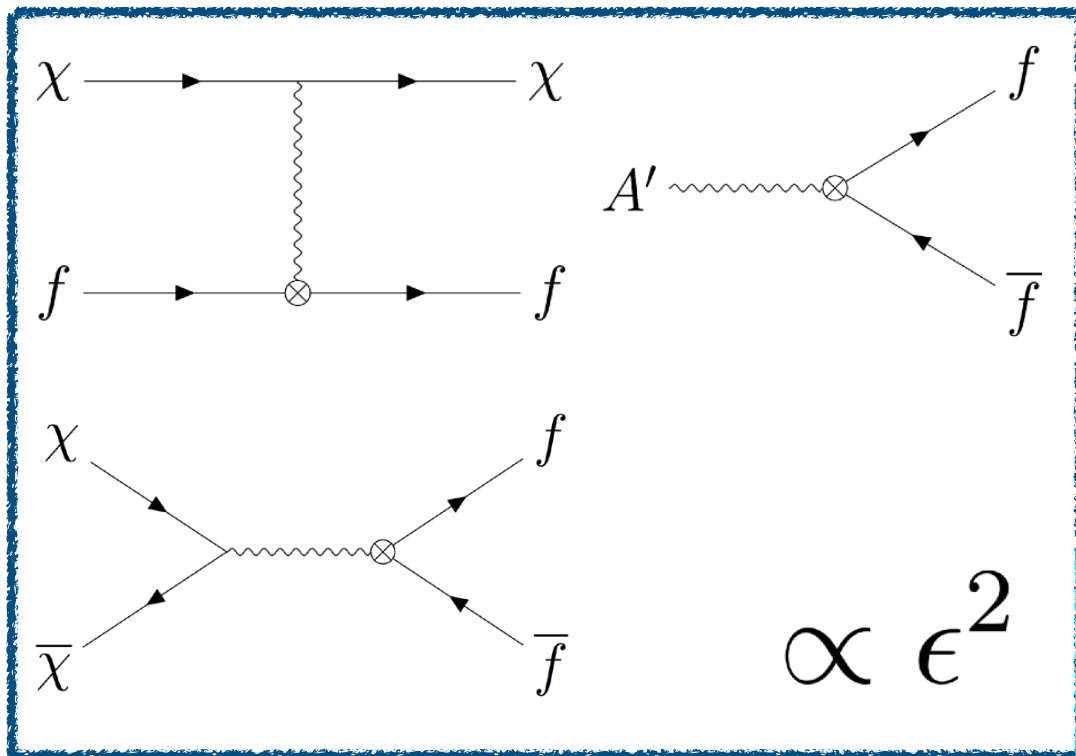


$$1 \lesssim \frac{m_{A'}}{m_\chi} \lesssim 2$$



Novel scenarios

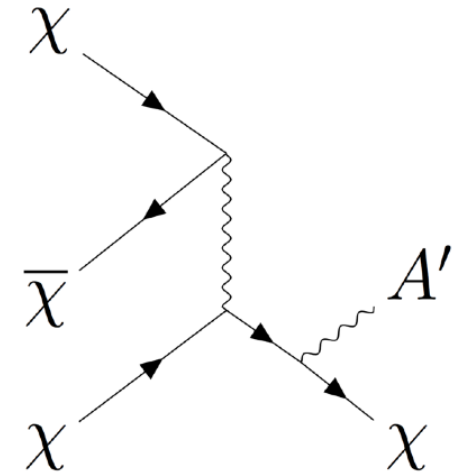
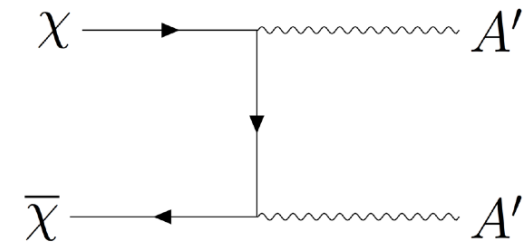
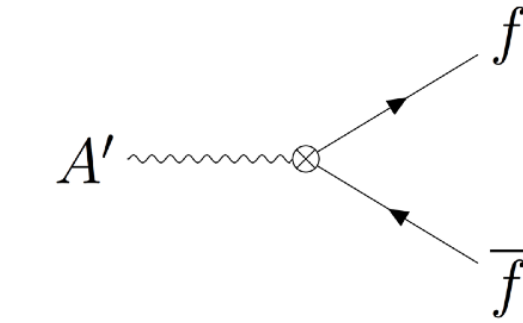
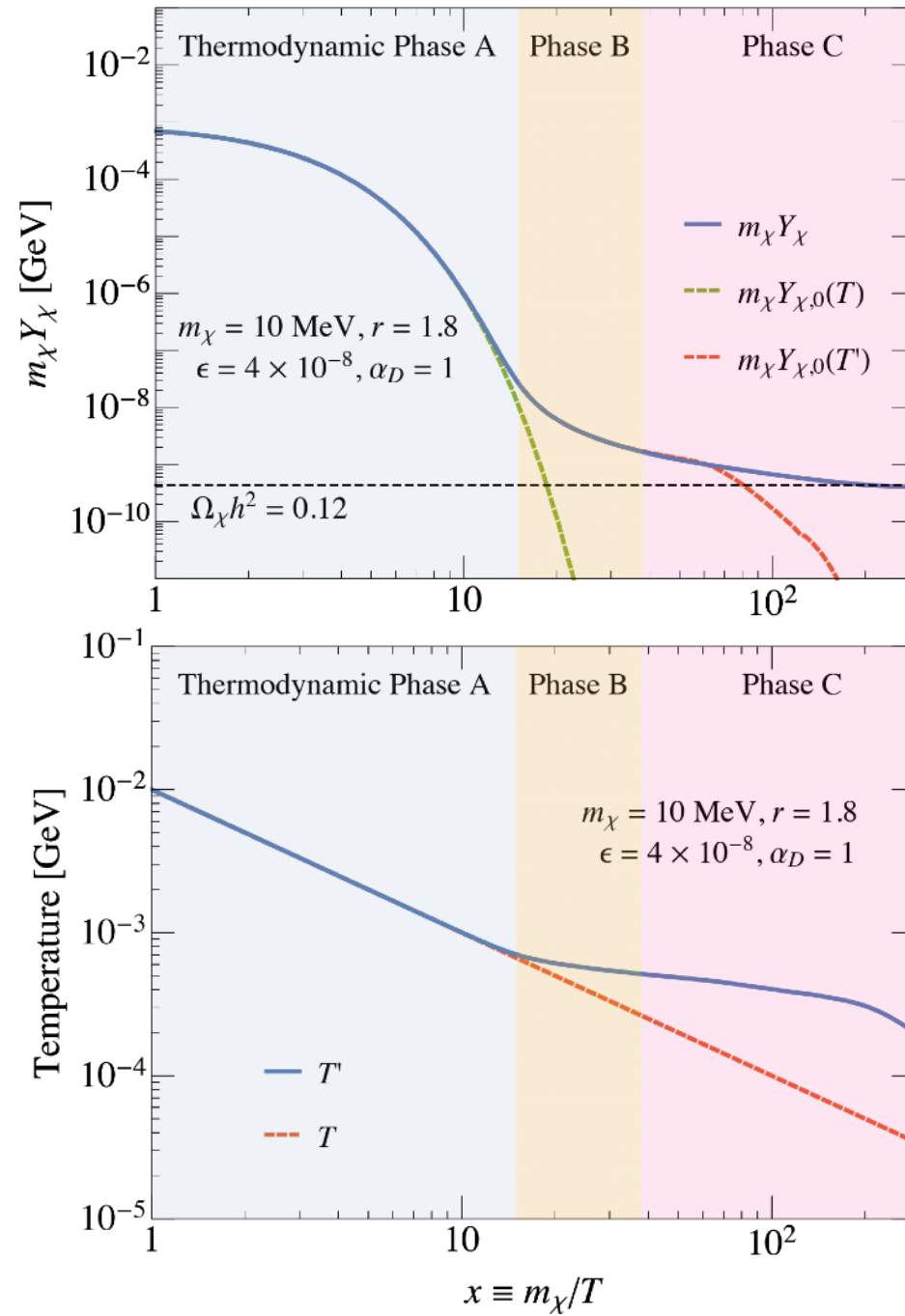
- ϵ small but nonzero
 - DM and SM kinetically decouple
 - $T' \neq T$
- *New Pathways to the Relic Abundance*
- **KIN**etically **DE**coupling **RE**lic



KINDER

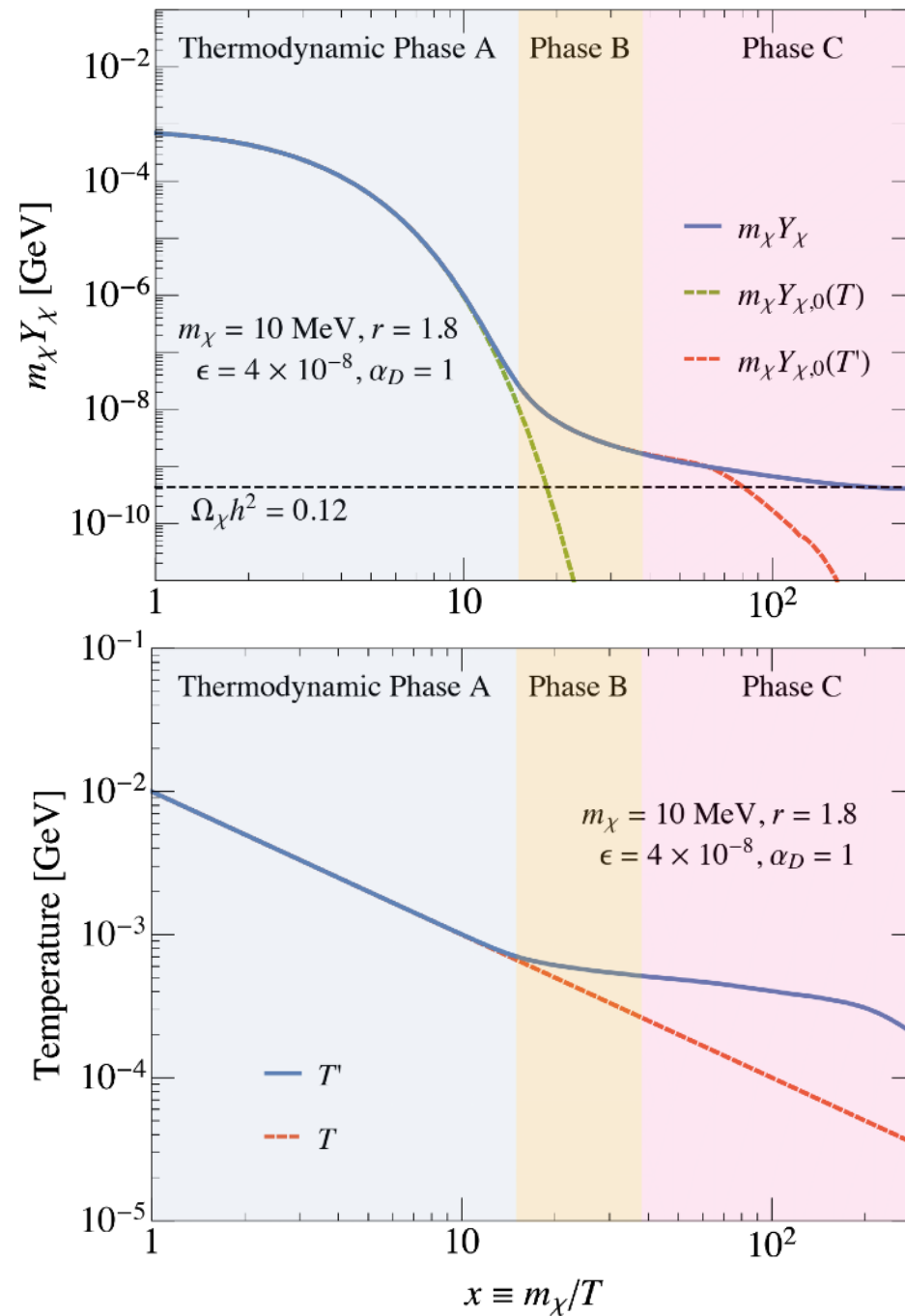


KINDER

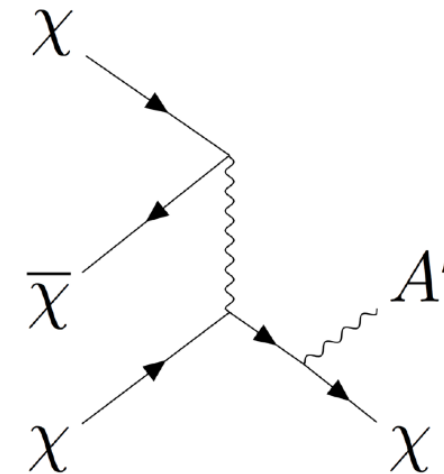
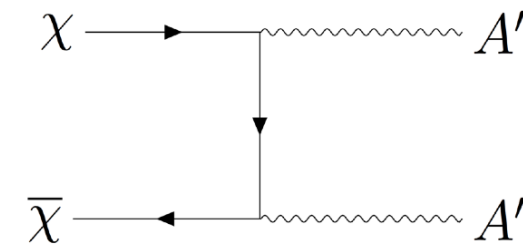
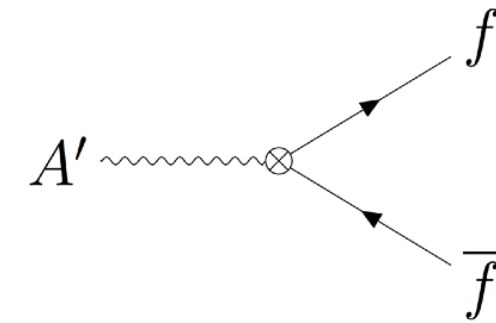


$$r \equiv \frac{m_{A'}}{m_\chi}$$

KINDER

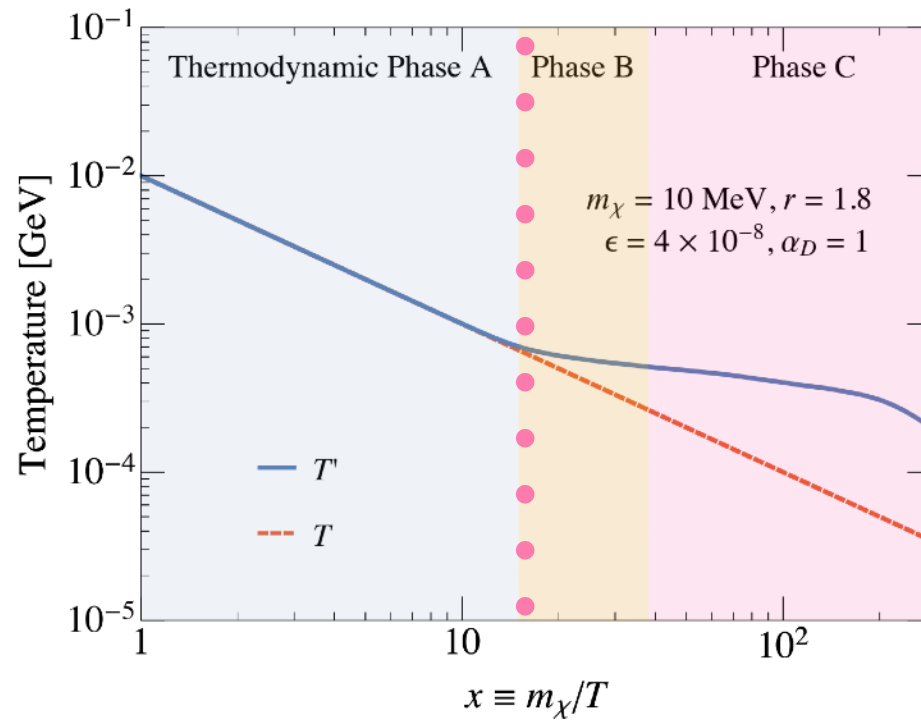
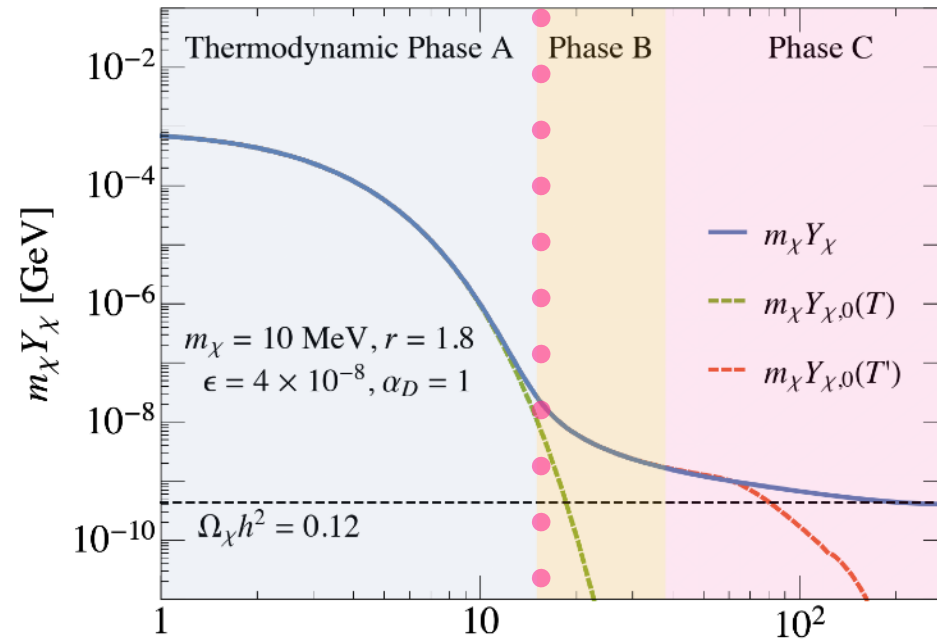


**High
Temperatures:
DM-SM
Equilibrium**



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

KINDER

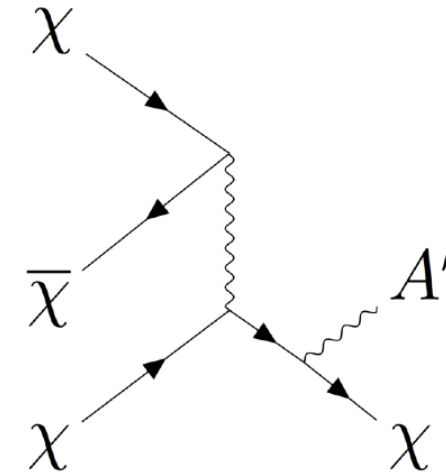
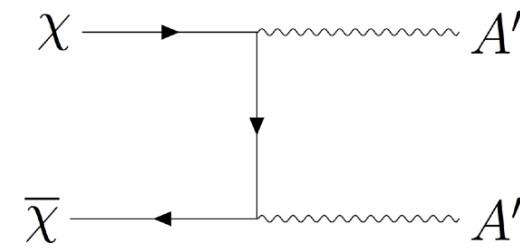
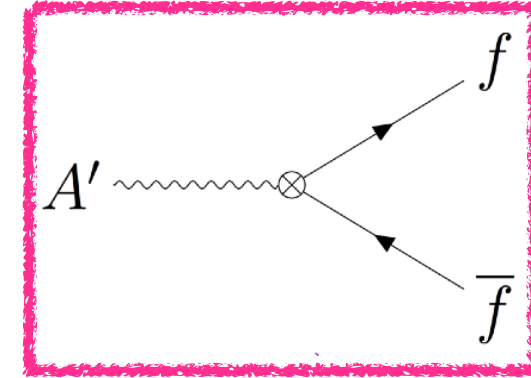


KINetic DEcoupling

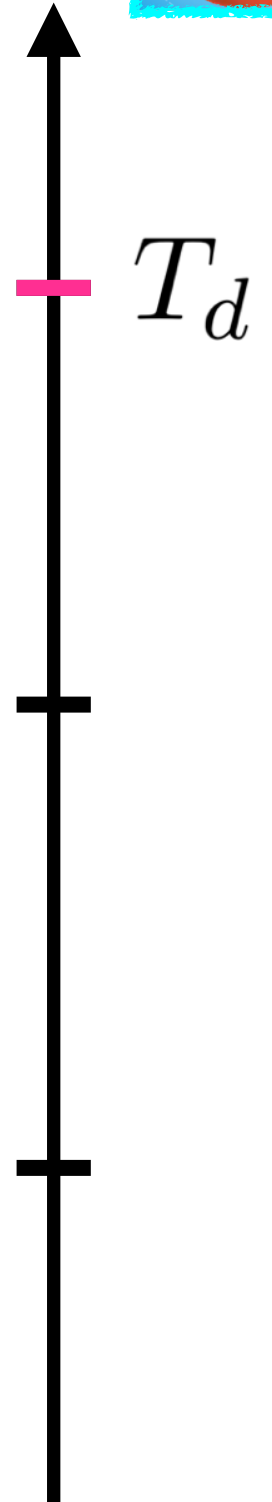
$$\left(\begin{array}{c} A' \rightarrow e^+ e^- \\ \text{DM-to-SM} \\ \text{Energy transfer Rate} \end{array} \right)$$

$\lesssim$

$$\left(\begin{array}{c} 3 \rightarrow 2 \\ \text{DM} \\ \text{Heating Rate} \end{array} \right)$$

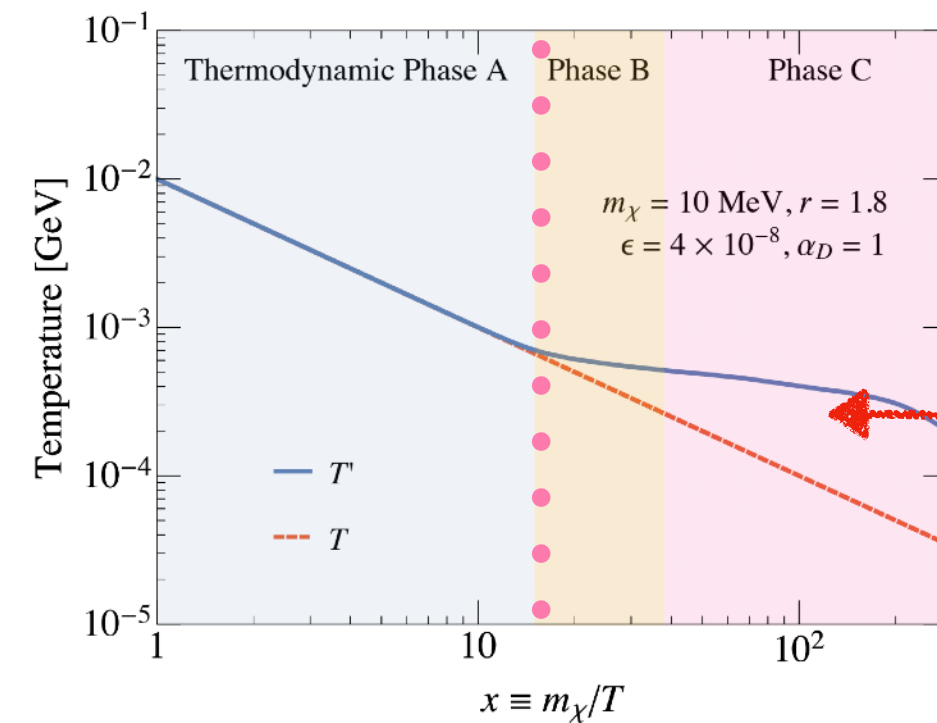
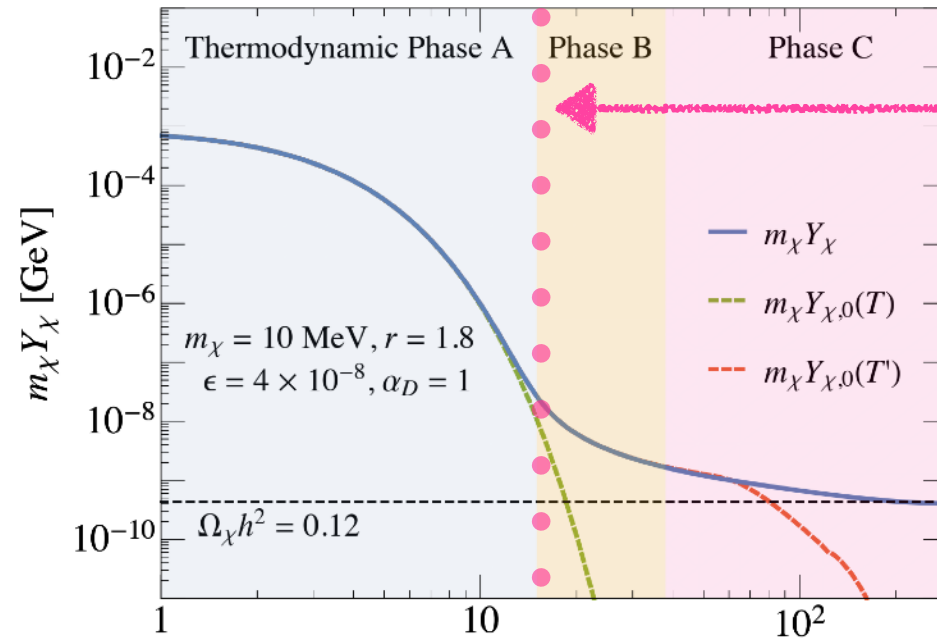


$$T' \neq T$$



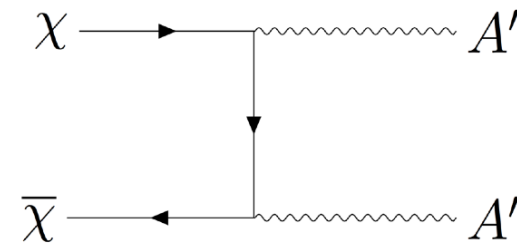
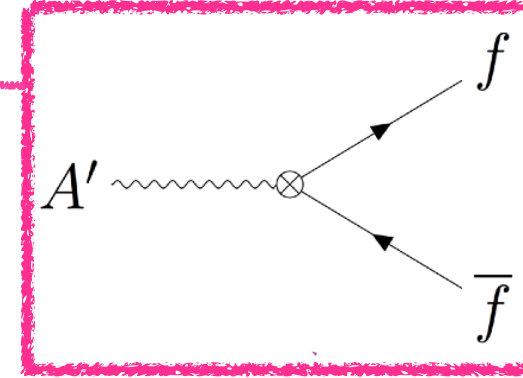
$$r \equiv \frac{m_{A'}}{m_{\chi}}$$

KINDER



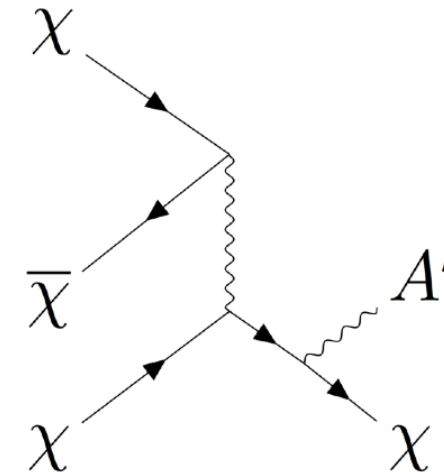
KINetic DEcoupling

Dark Sector Thermally secluded

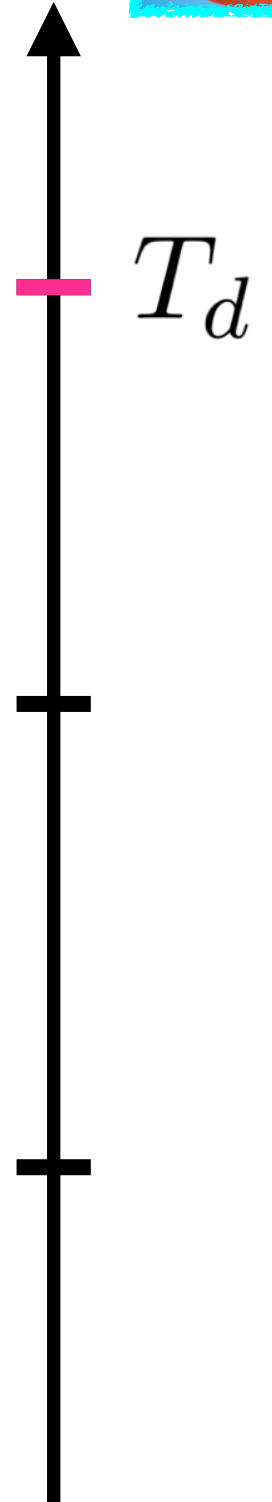


Equilibrium Dark Sector

Dark Sector Heating



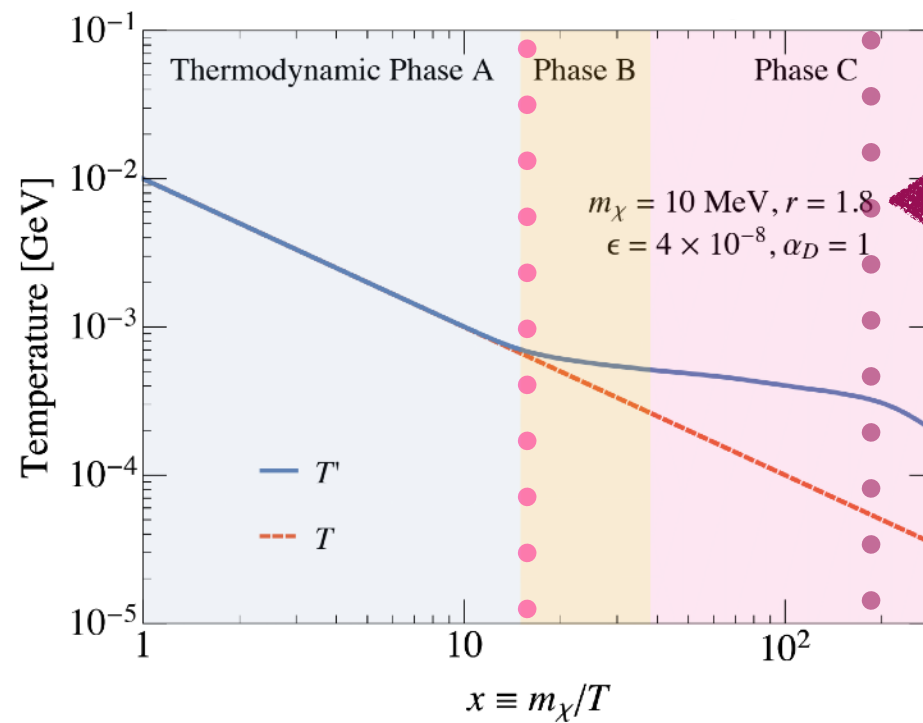
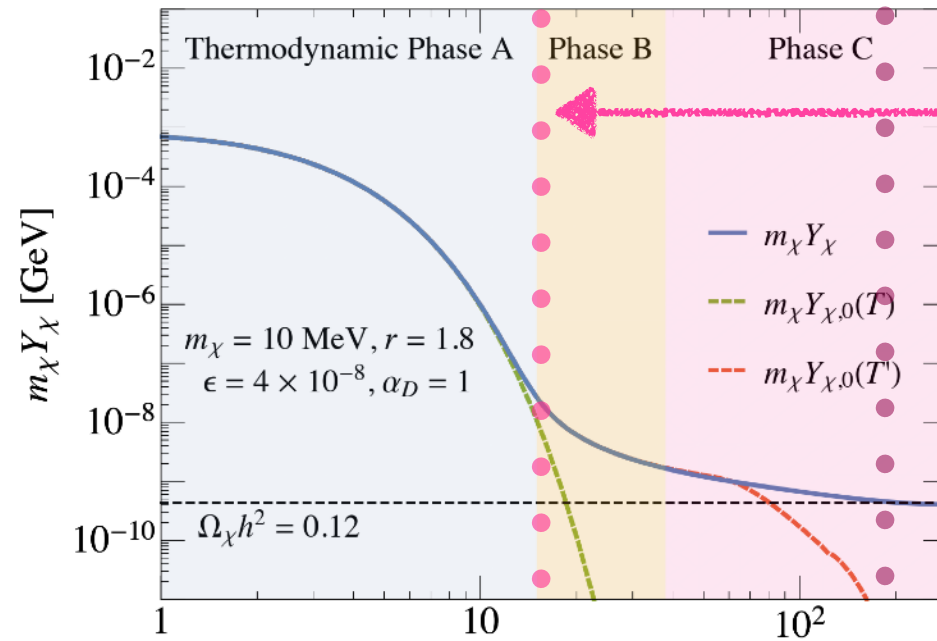
$$T' \neq T$$



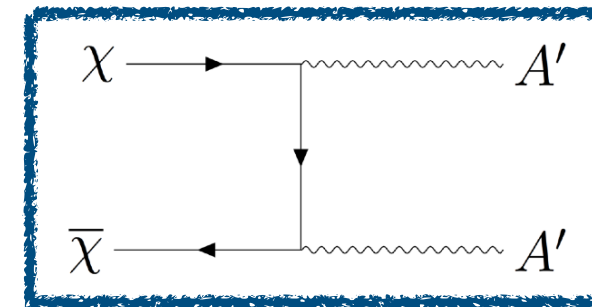
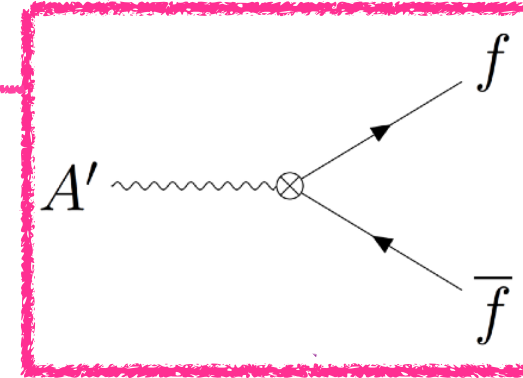
T_d

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

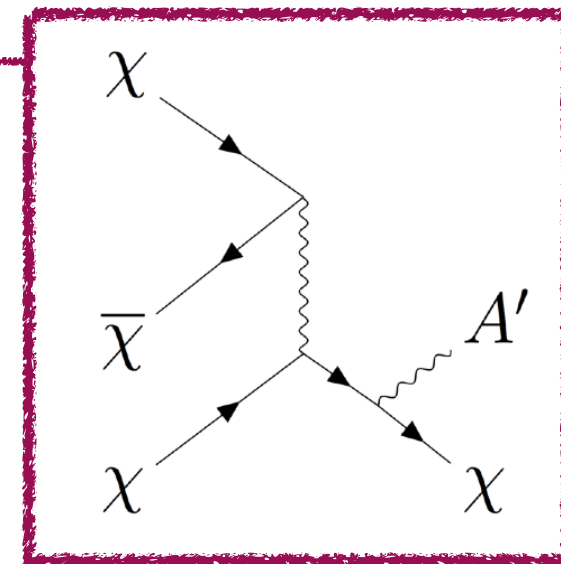
KINDER



KINetic DEcoupling



DM freezeout

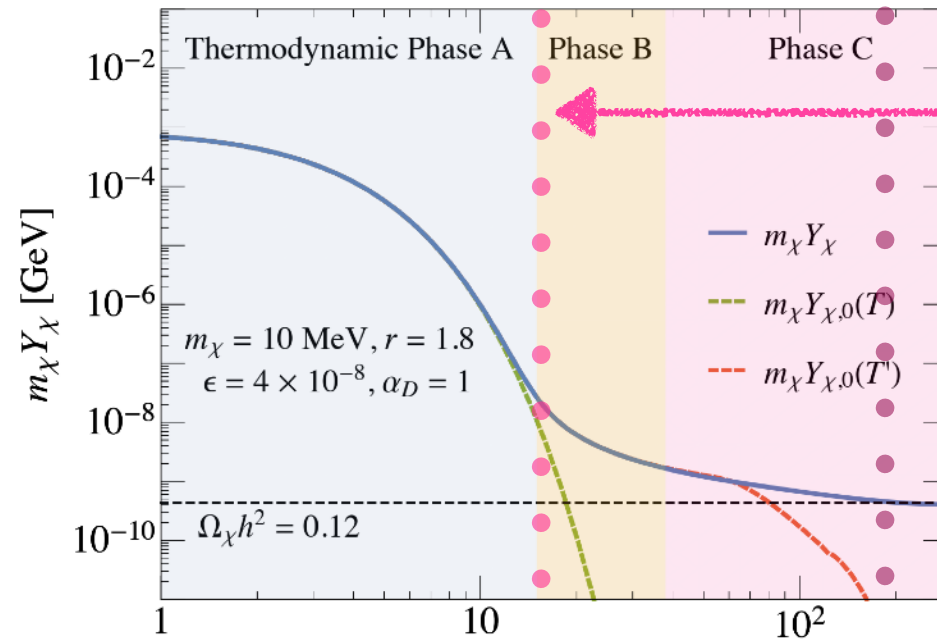


$$T' \neq T$$

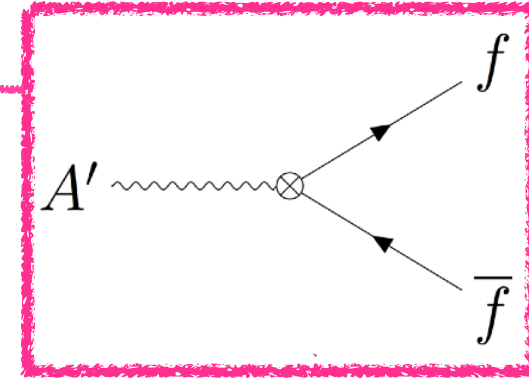
T_d

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

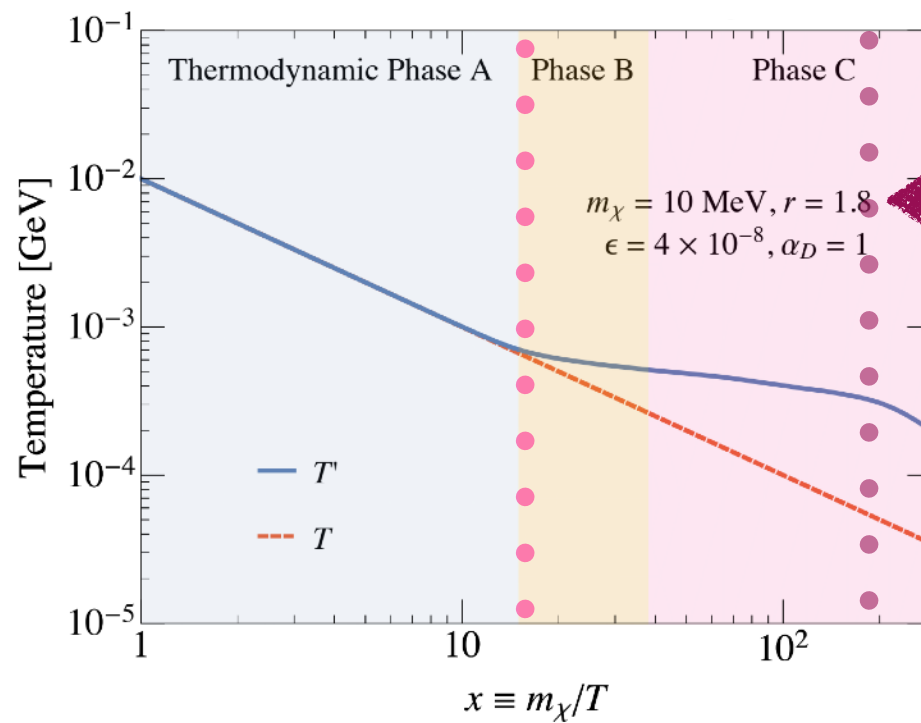
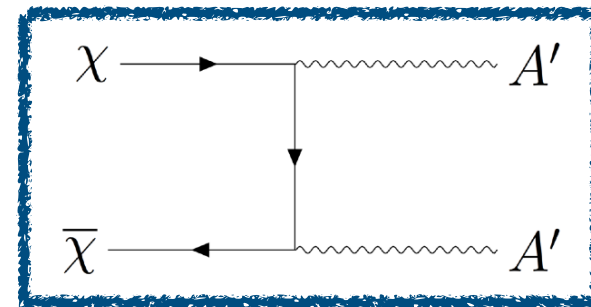
KINDER



KINetic DEcoupling

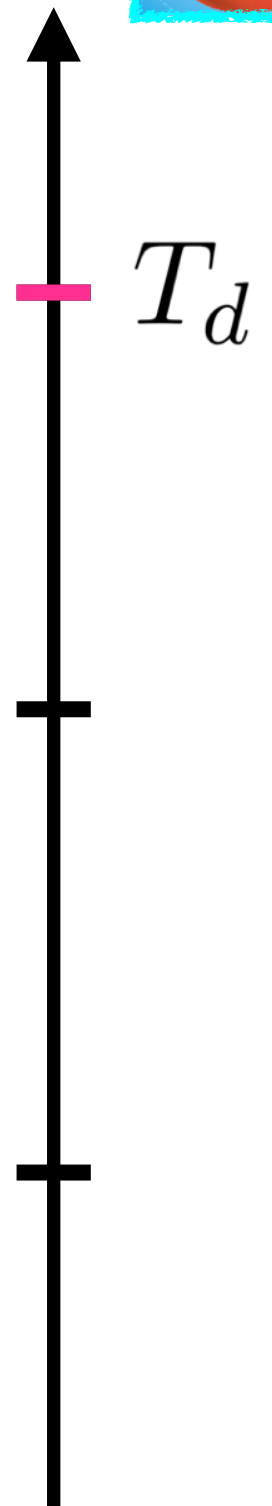
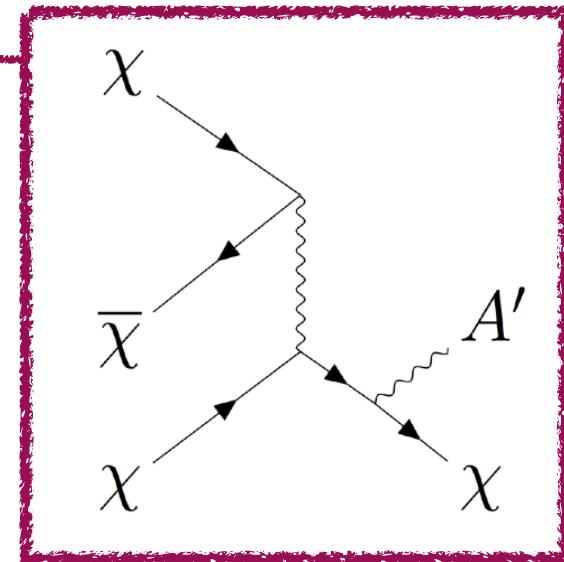


KINDER



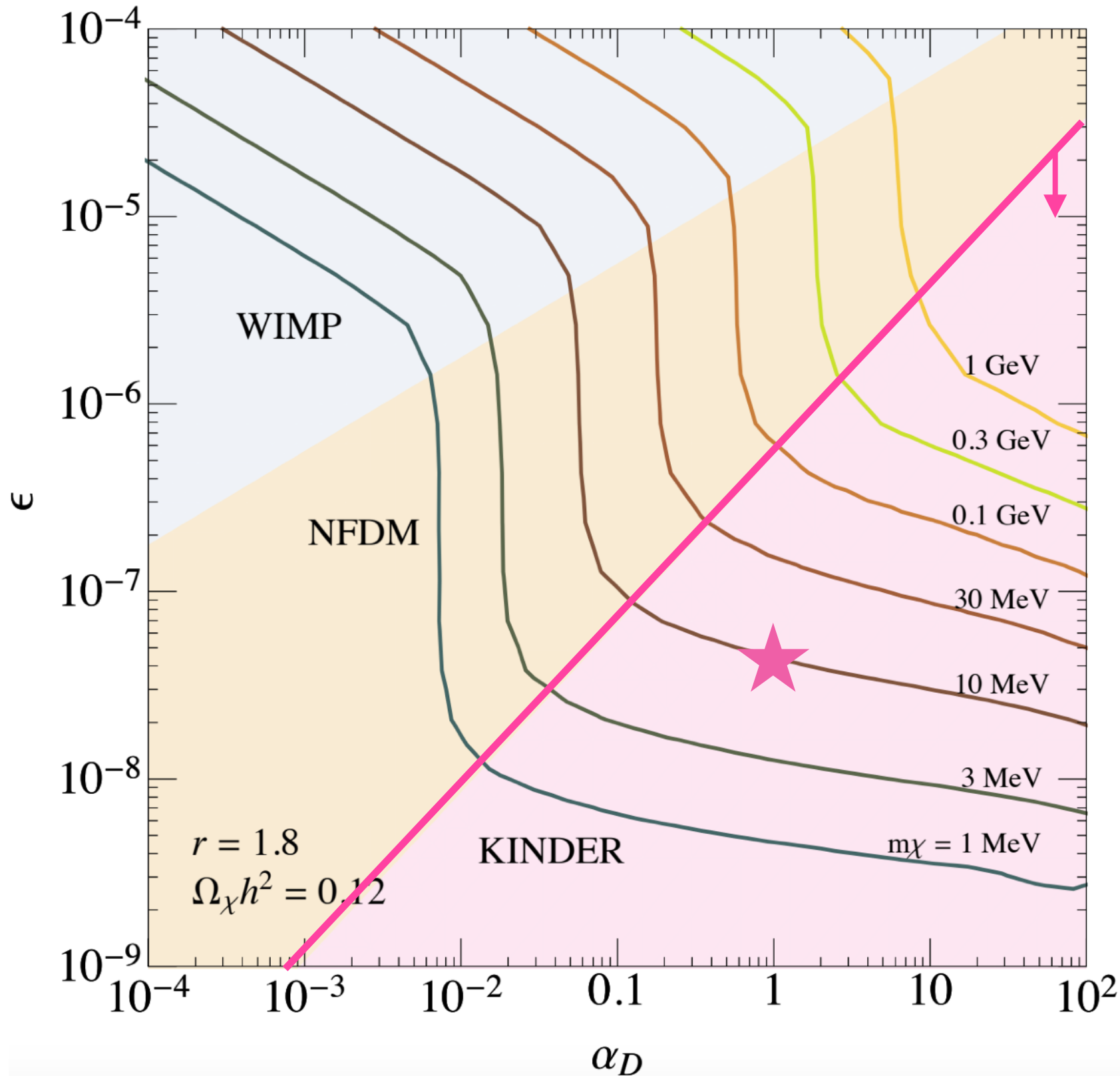
DM freezeout

$$T' \neq T$$



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

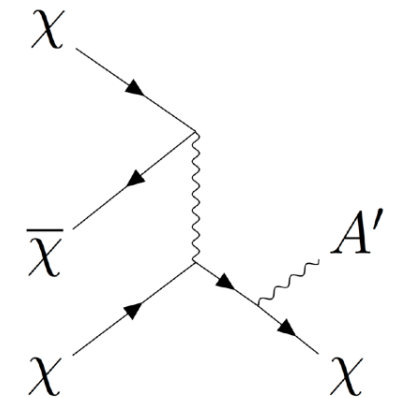
KINDER Regime



NFDM

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

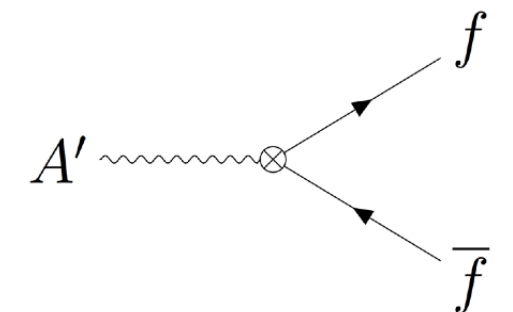
$$T_f = T_f(\alpha)$$



KINDER

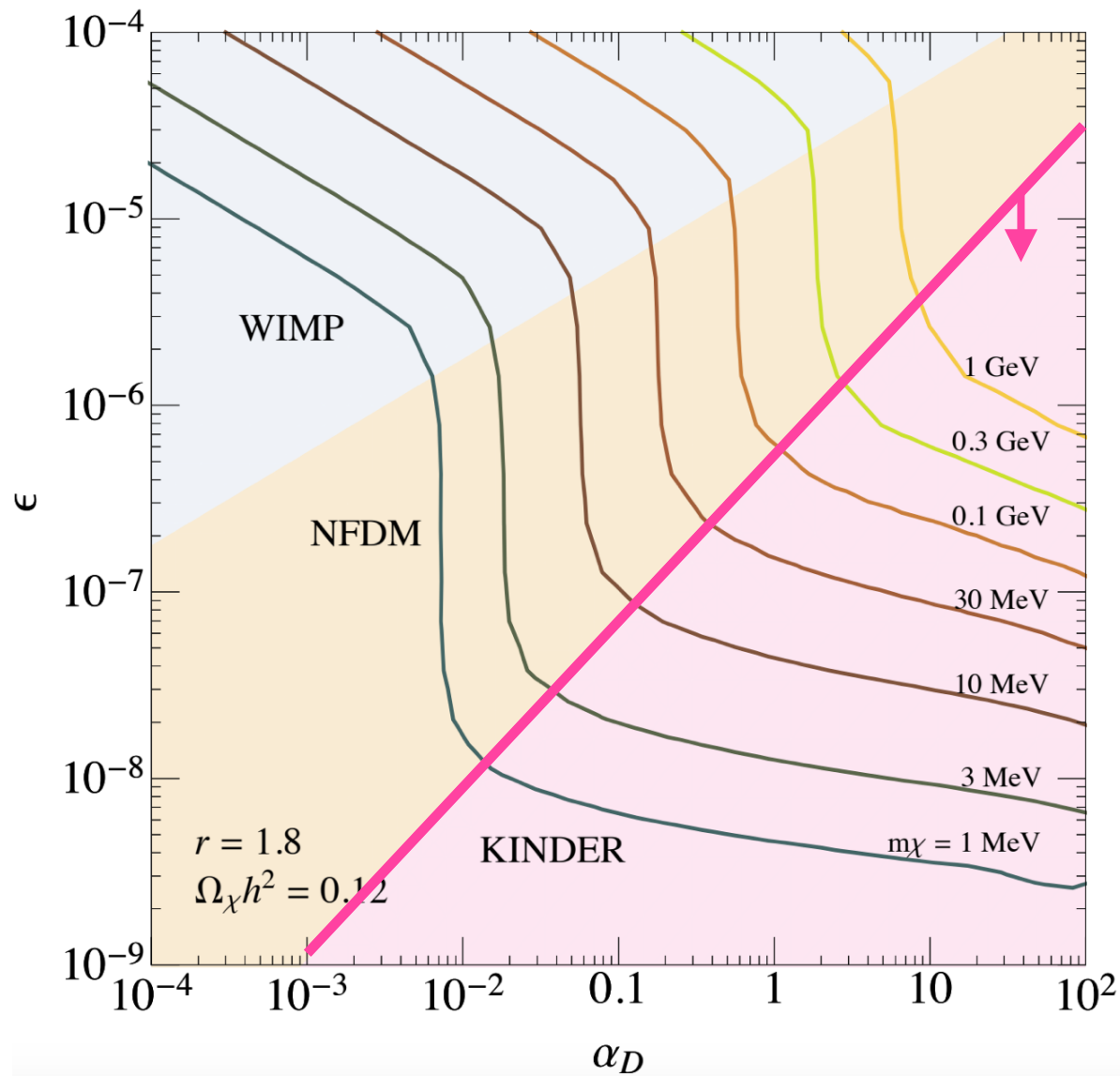
$$\Omega_\chi \sim e^{-m_\chi/T_d}$$

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

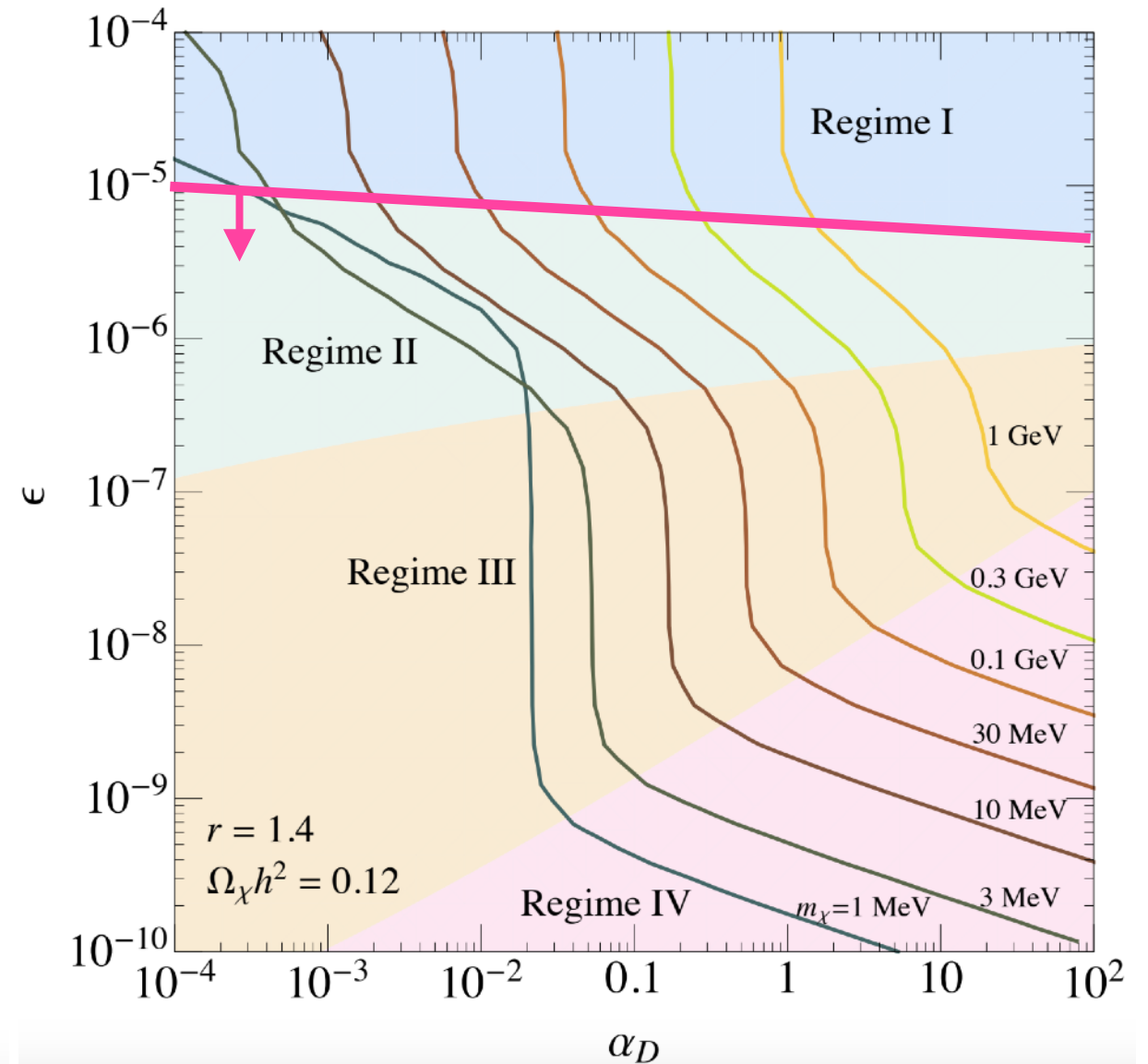


New Regimes

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



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



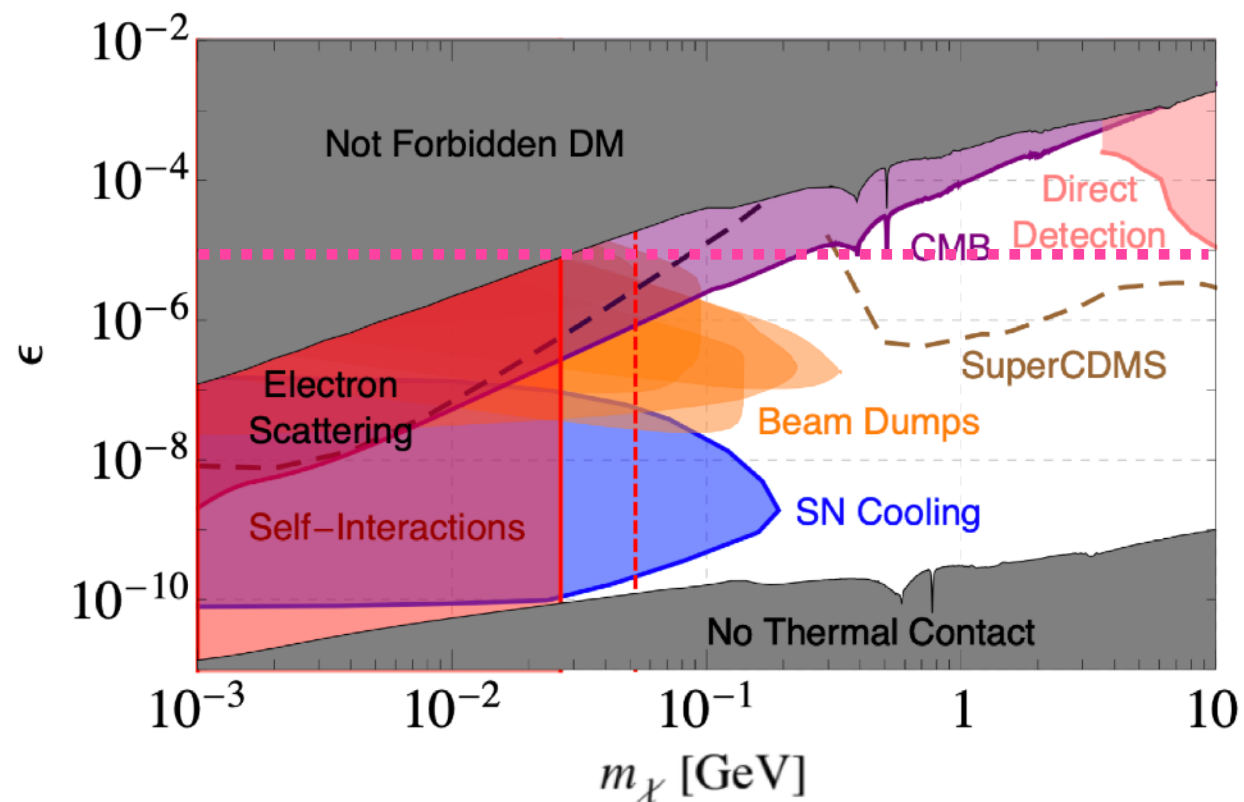
from Fitzpatrick, Liu, Slatyer, Tsai (2022)

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

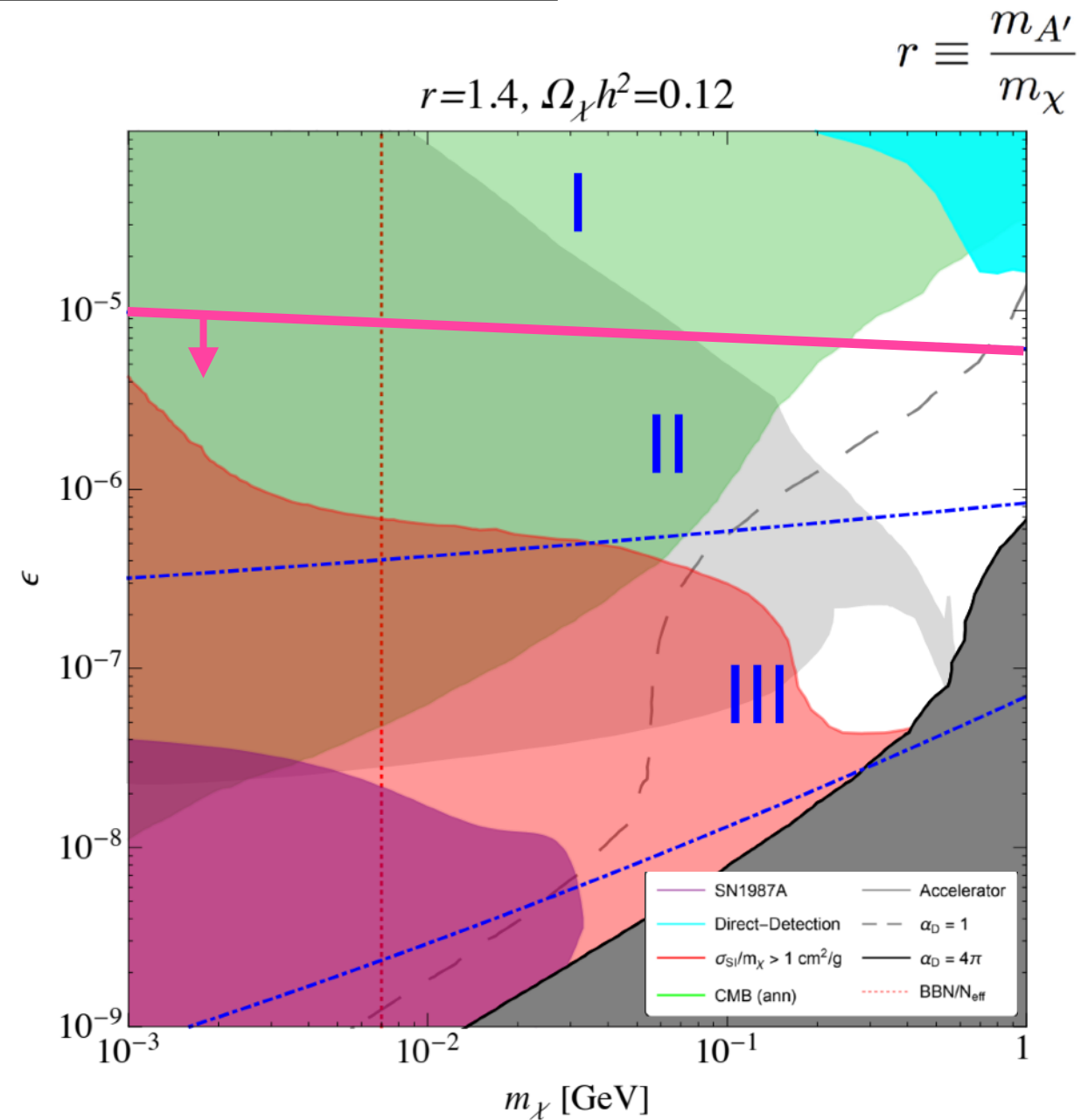
Experimental Constraints

Assuming Thermal Production

Signals from Kinetic Mixing ($\alpha_d=0.1$)



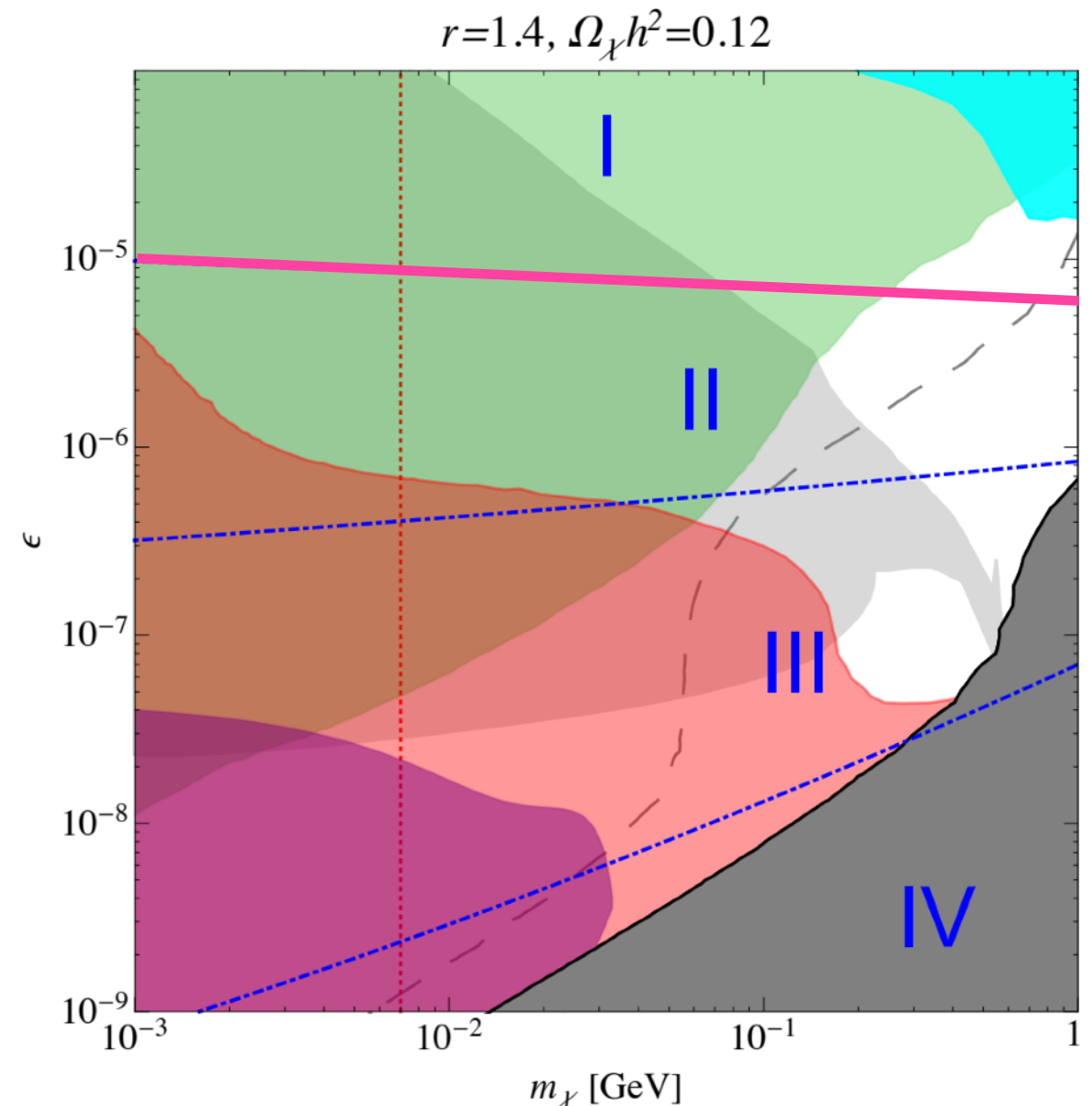
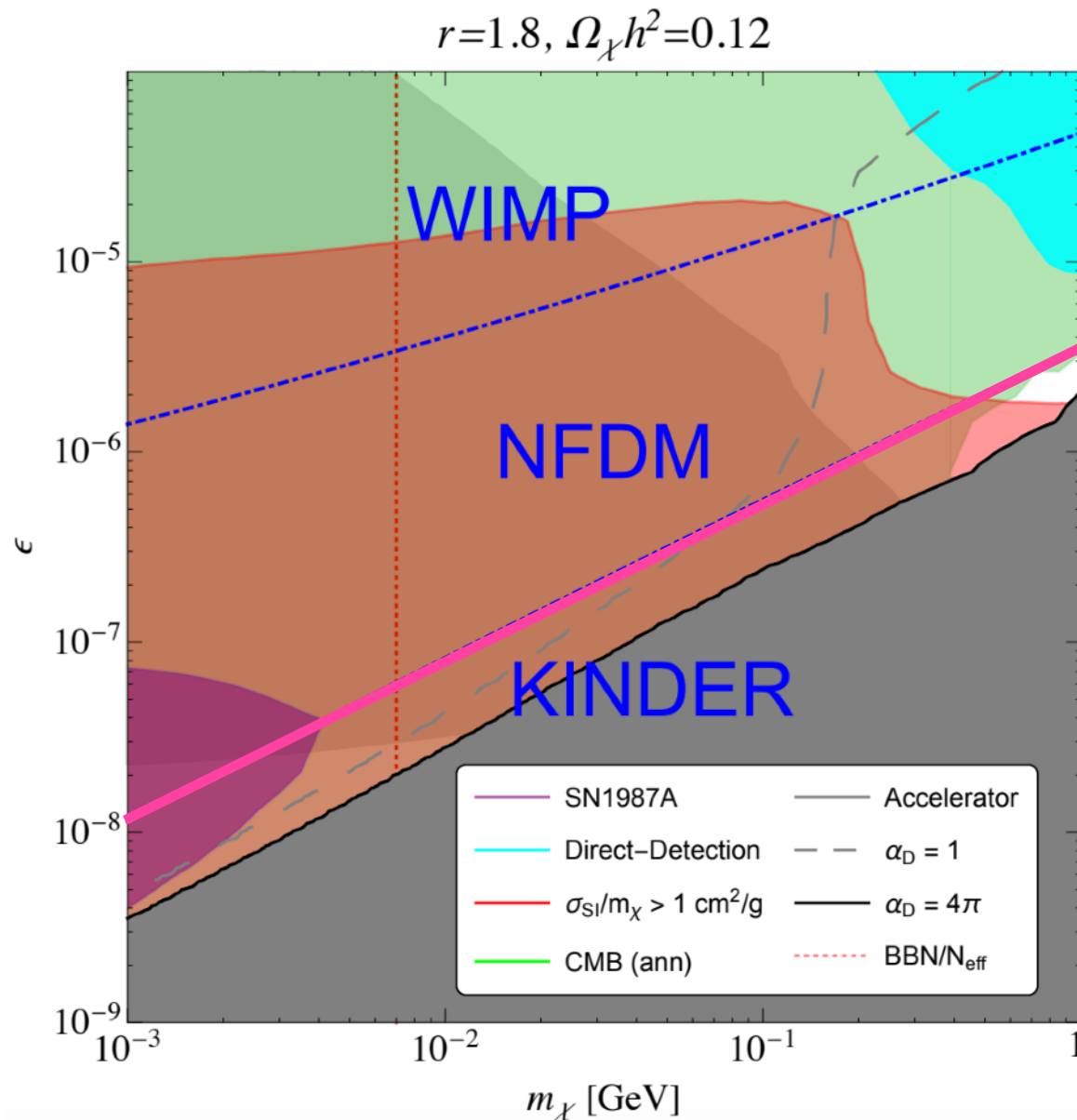
from D'Agnolo and Ruderman (2015)



from Fitzpatrick, Liu, Slatyer, Tsai (2022)

Kinetic decoupling essential for accurate experimental projections

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**

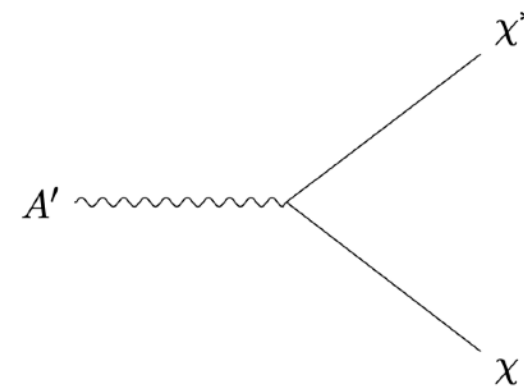
Inelastic Vector-Portal DM

DM pseudo-Dirac fermion charged under hidden $U(1)_D$

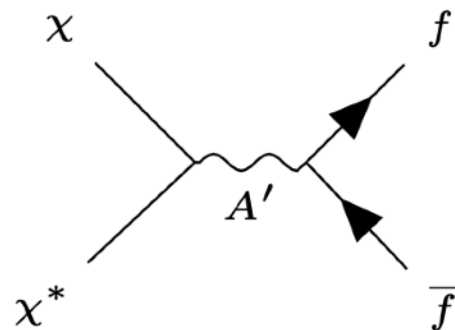
$U(1)_D$ broken: $\chi \chi^*$ Non-degenerate Majorana fermions

$$\delta m_\chi = m_{\chi^*} - m_\chi < T'_f$$

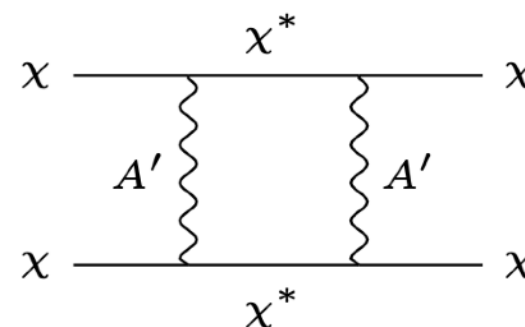
Vector coupling off-diagonal



CMB

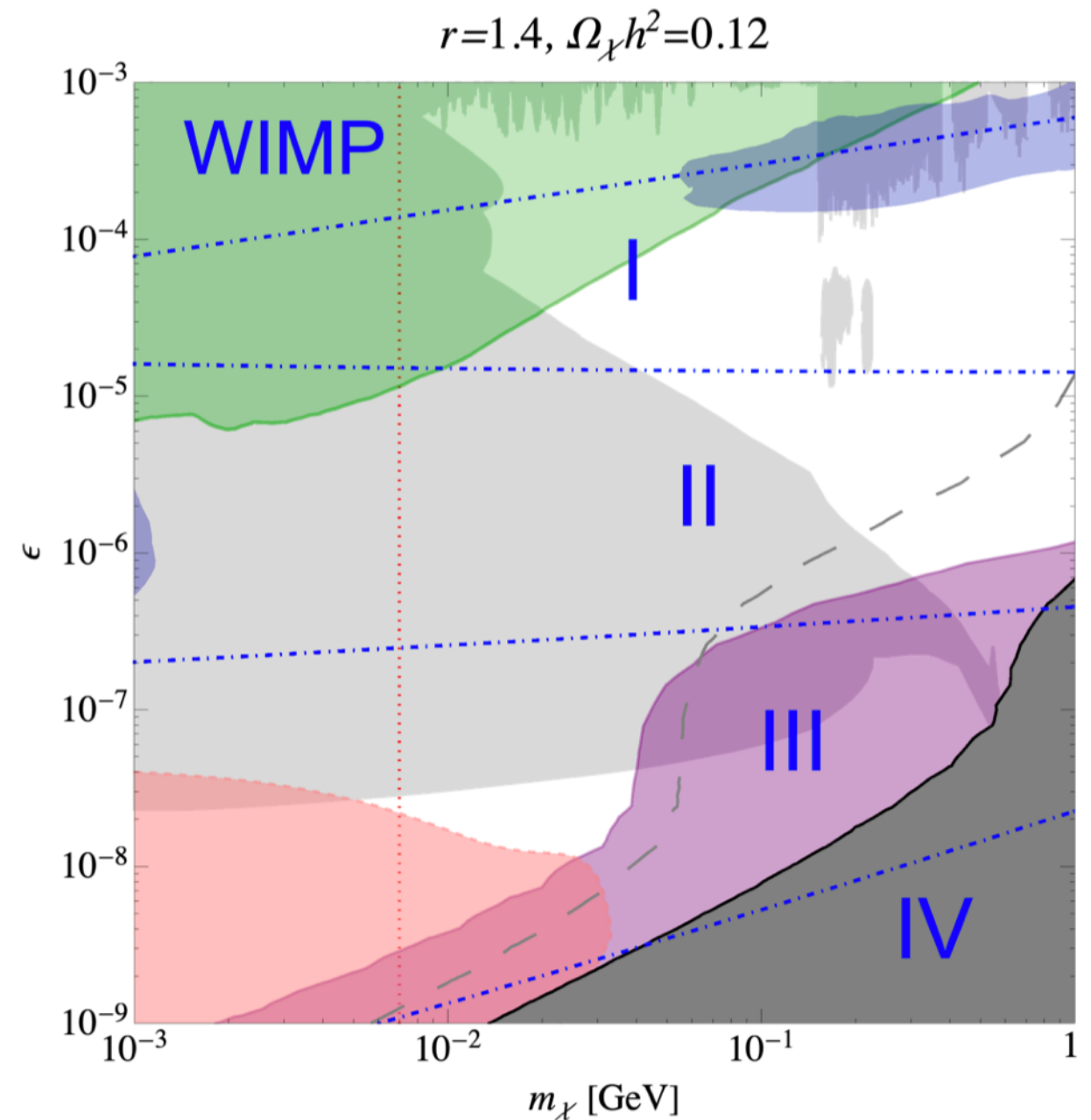
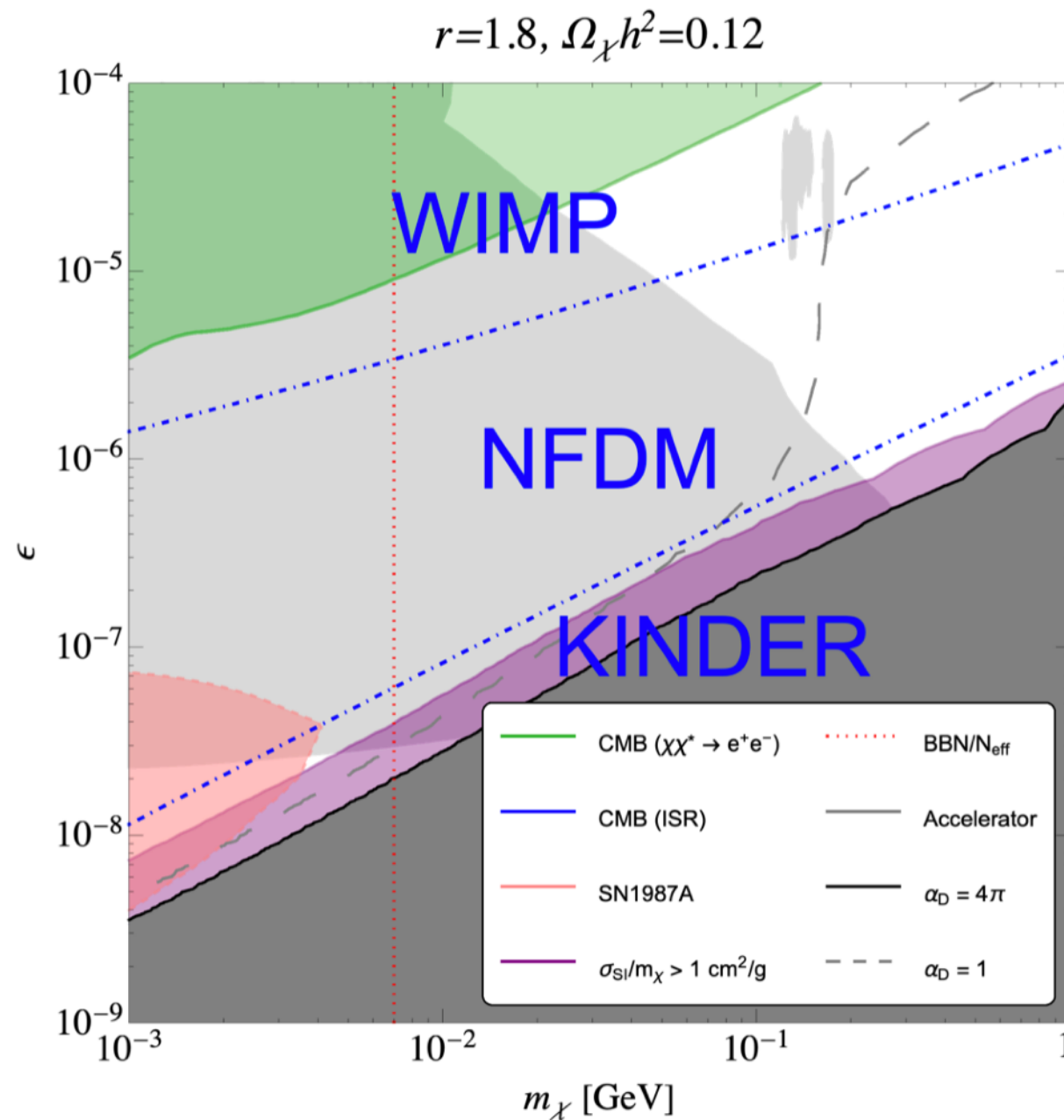


Self-interaction



Constraints alleviated

Inelastic KINDER Constraints



- CMB and Self-Interaction constraints alleviated
- Available windows for new Regimes KINDER, II, III

Conclusions

- **KIN**etically **DE**coupling freeze-out production of DM
- Rich set of novel pathways to the relic abundance of DM
- Necessary for accurate experimental targets
- New viable target regions for future experiments searching for light DM
- Carefully explore even benchmark dark sector models in search of new cosmological histories
- More to come...