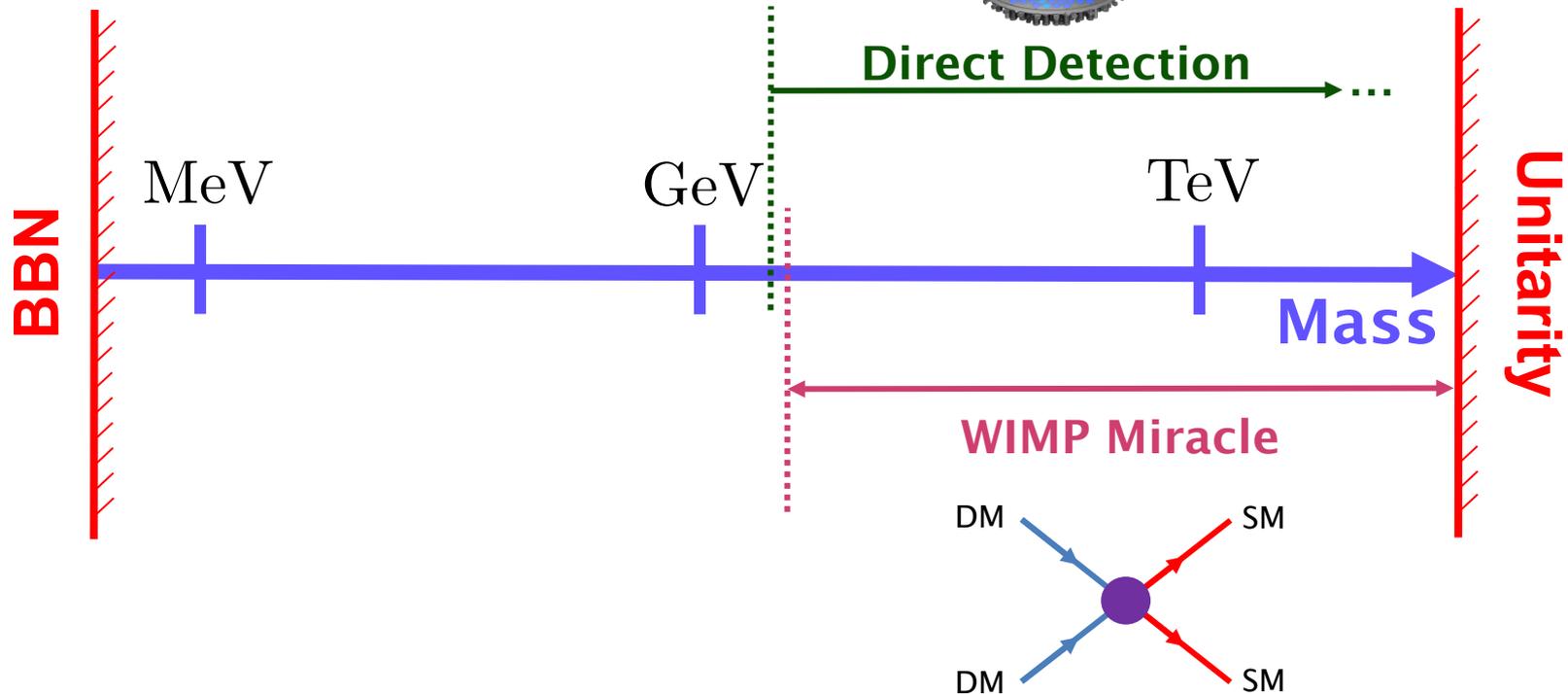
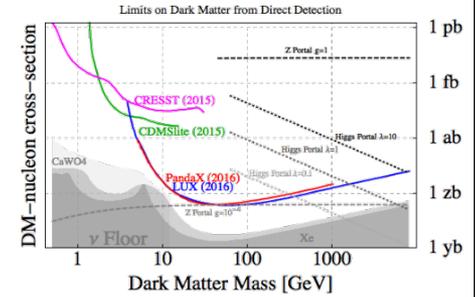
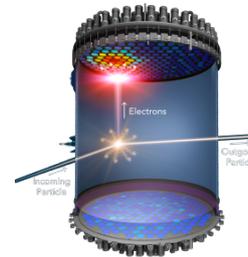




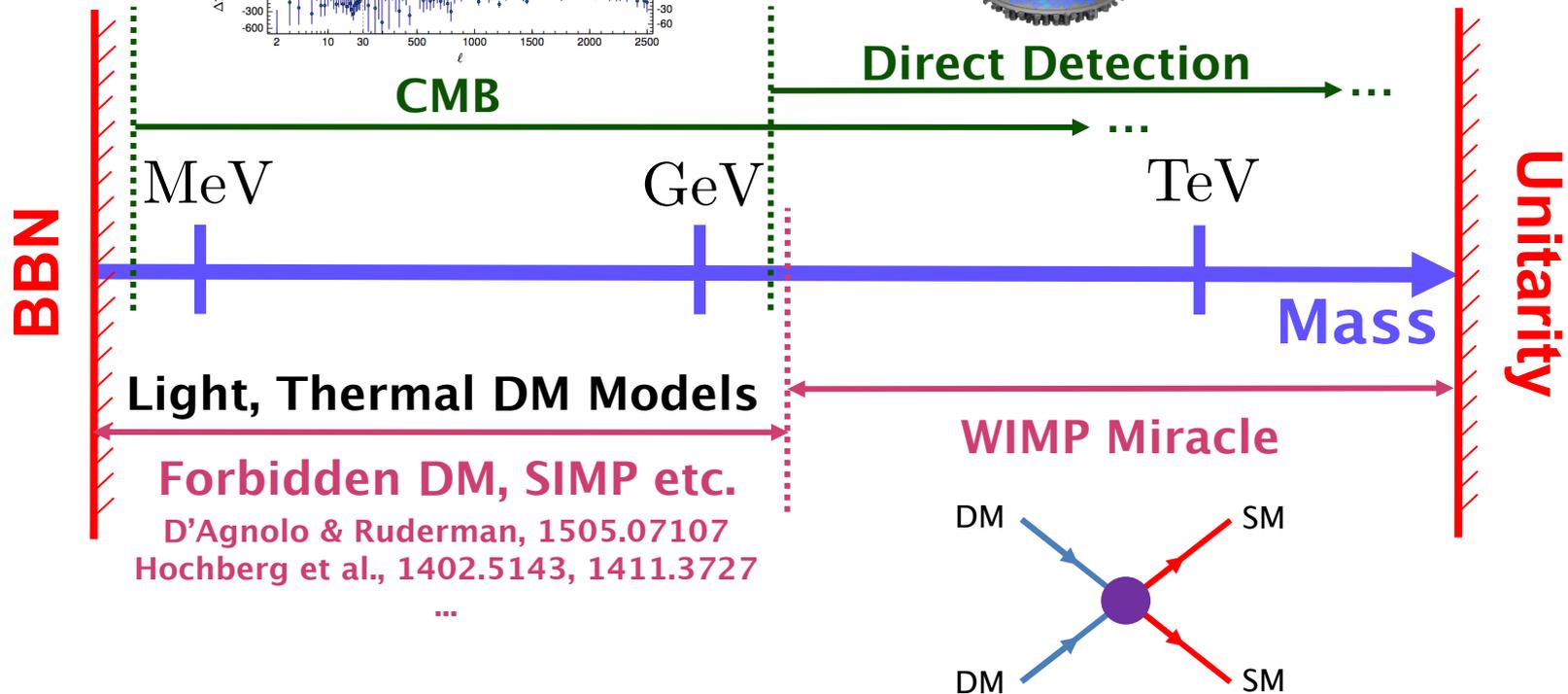
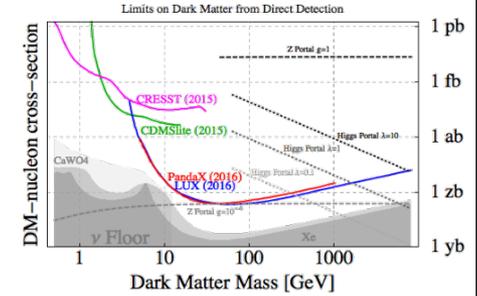
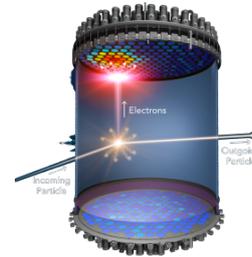
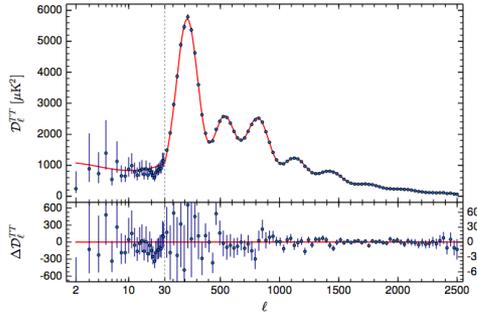
Enabling Forbidden Dark Matter

James M. Cline, Hongwan Liu, Tracy Slatyer, Wei Xue
1702.07716

● ● ● ● **Light Thermal DM**



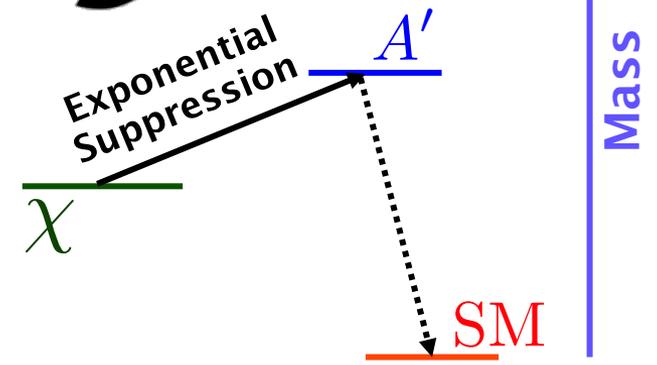
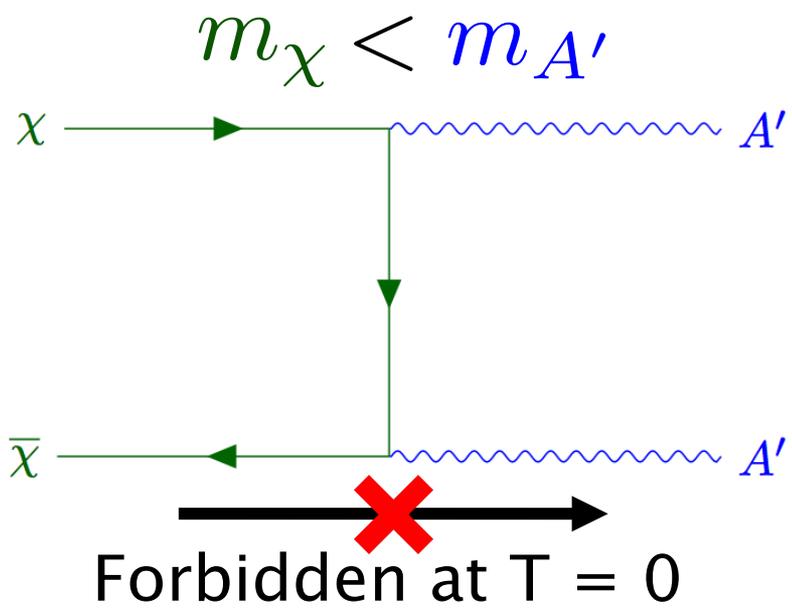
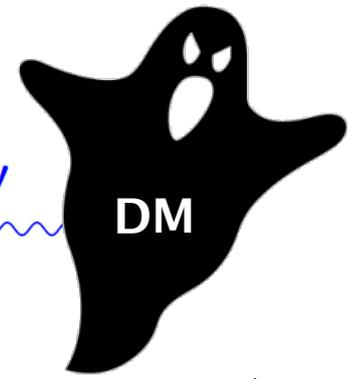
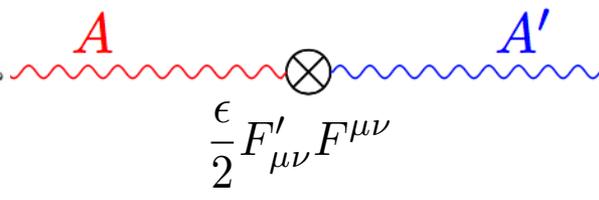
● ● ● ● **Light Thermal DM**



Forbidden DM, SIMP etc.
 D'Agnolo & Ruderman, 1505.07107
 Hochberg et al., 1402.5143, 1411.3727

●●●● **Forbidden DM**

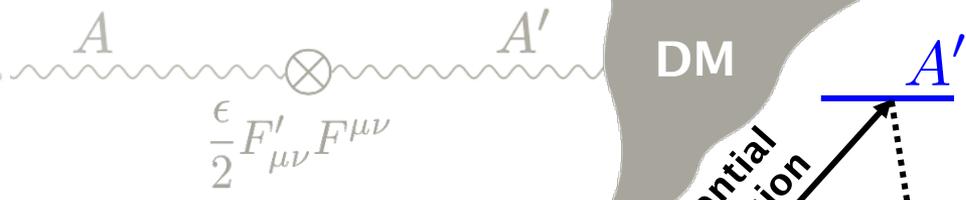
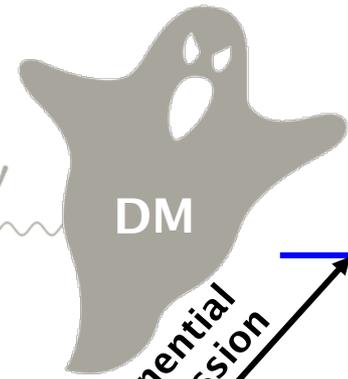
D'Agnolo & Ruderman, 1505.07107



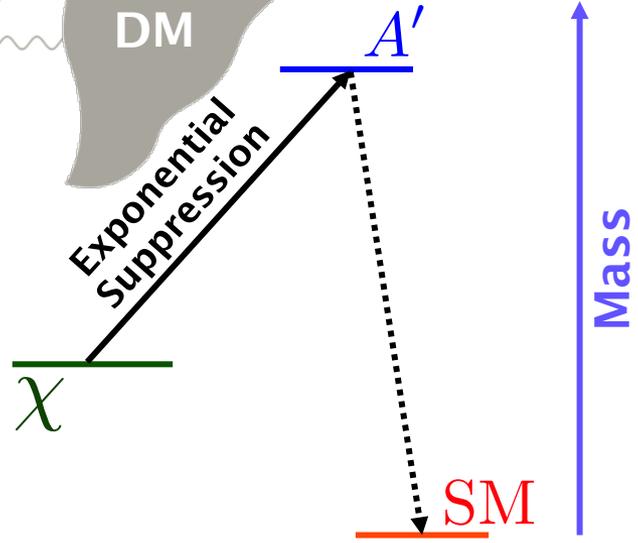
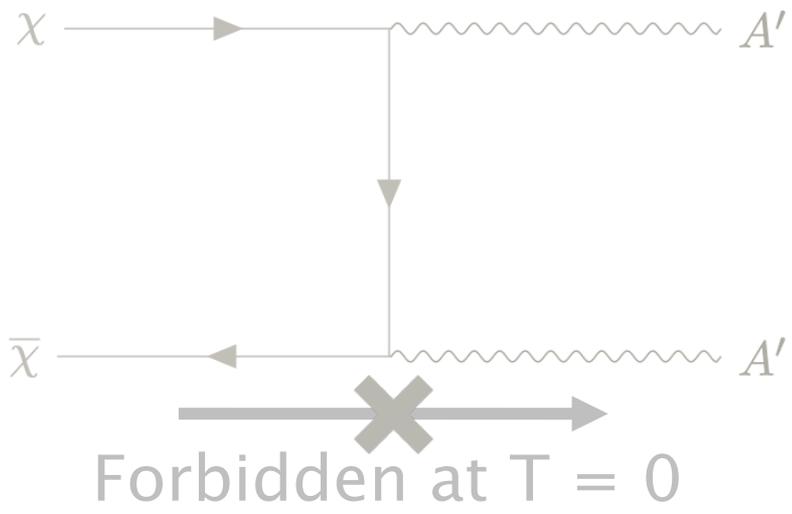
●●● For correct relic density, suppression in $\langle\sigma v\rangle$ means lighter DM is preferred.

●●●● **Forbidden DM**

D'Agnolo & Ruderman, 1505.07107



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



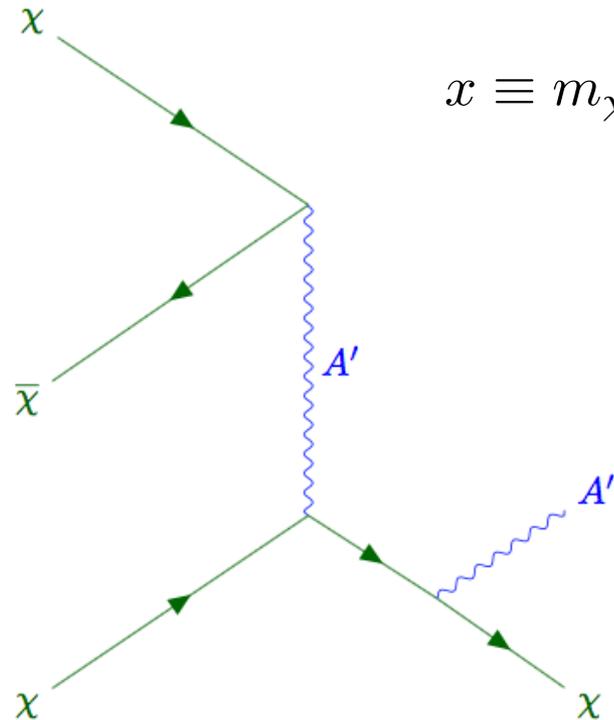
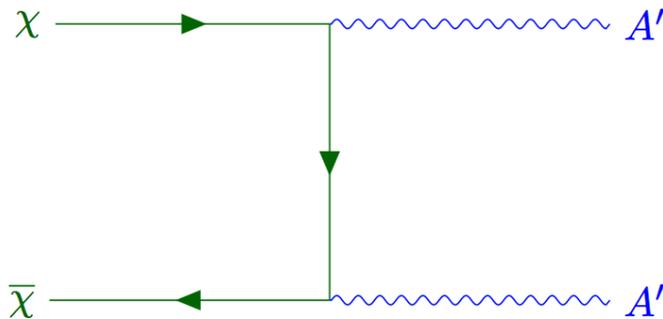
●●● As $m_{A'}$ increases, are there other processes that become important?

●●●● **Not-Forbidden DM**

$$\Gamma_{2 \rightarrow 2} = n_\chi \langle \sigma v \rangle \propto e^{(1-2r)x}$$

$$\Gamma_{3 \rightarrow 2} = n_\chi^2 \langle \sigma v^2 \rangle \propto e^{-2x}$$

$$x \equiv m_\chi / T$$

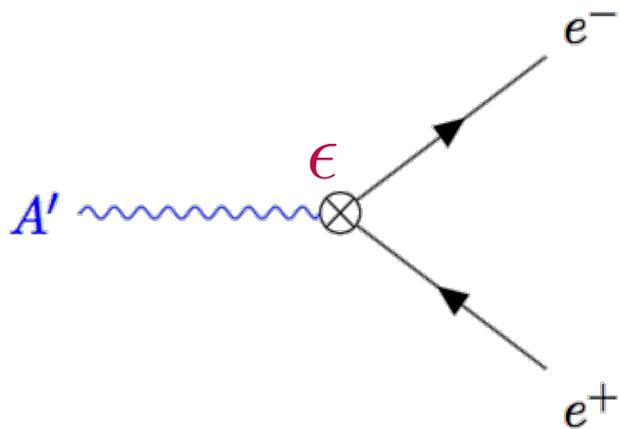
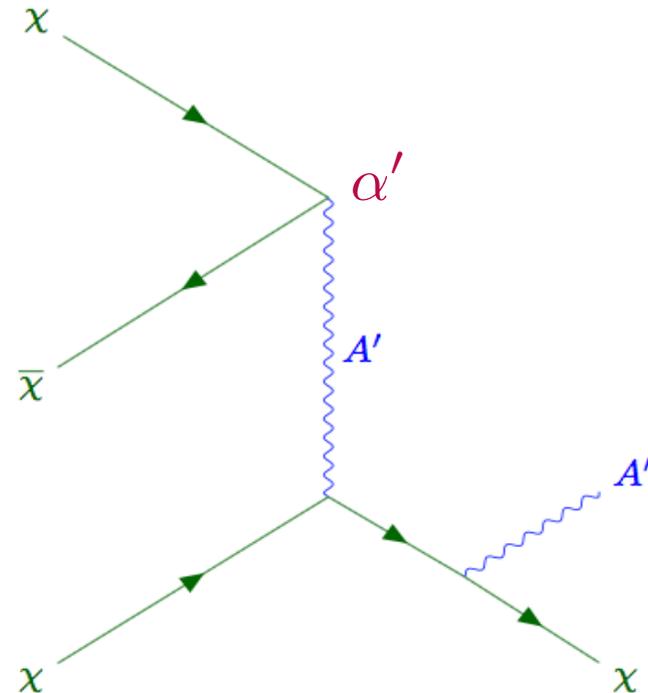
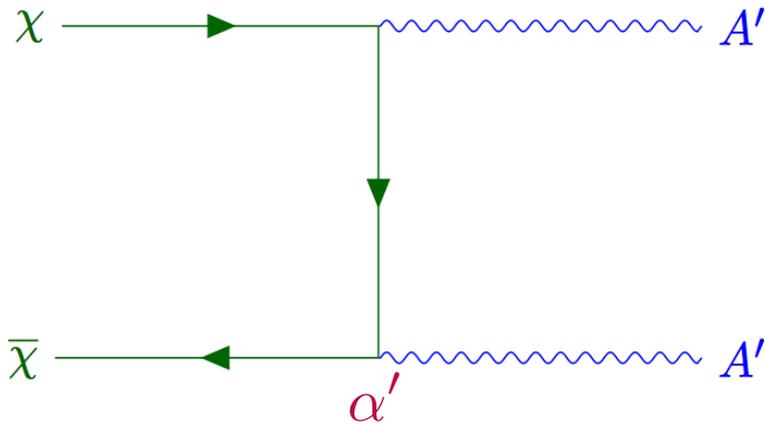


Importance of Process

$$r \equiv m_{A'} / m_\chi = 1$$

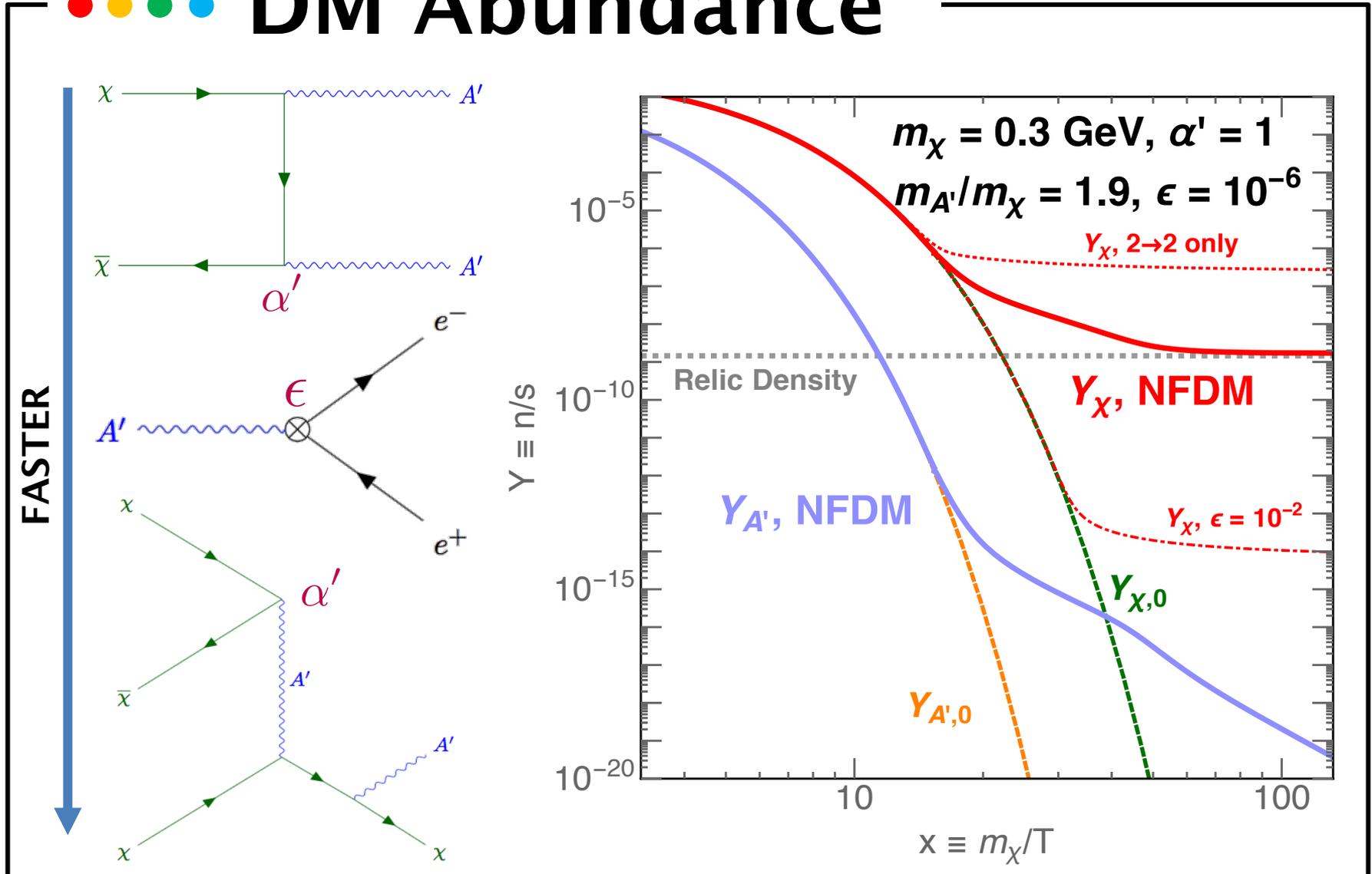
$$r \equiv m_{A'} / m_\chi = 2$$

● ● ● ● **Relevant Processes**

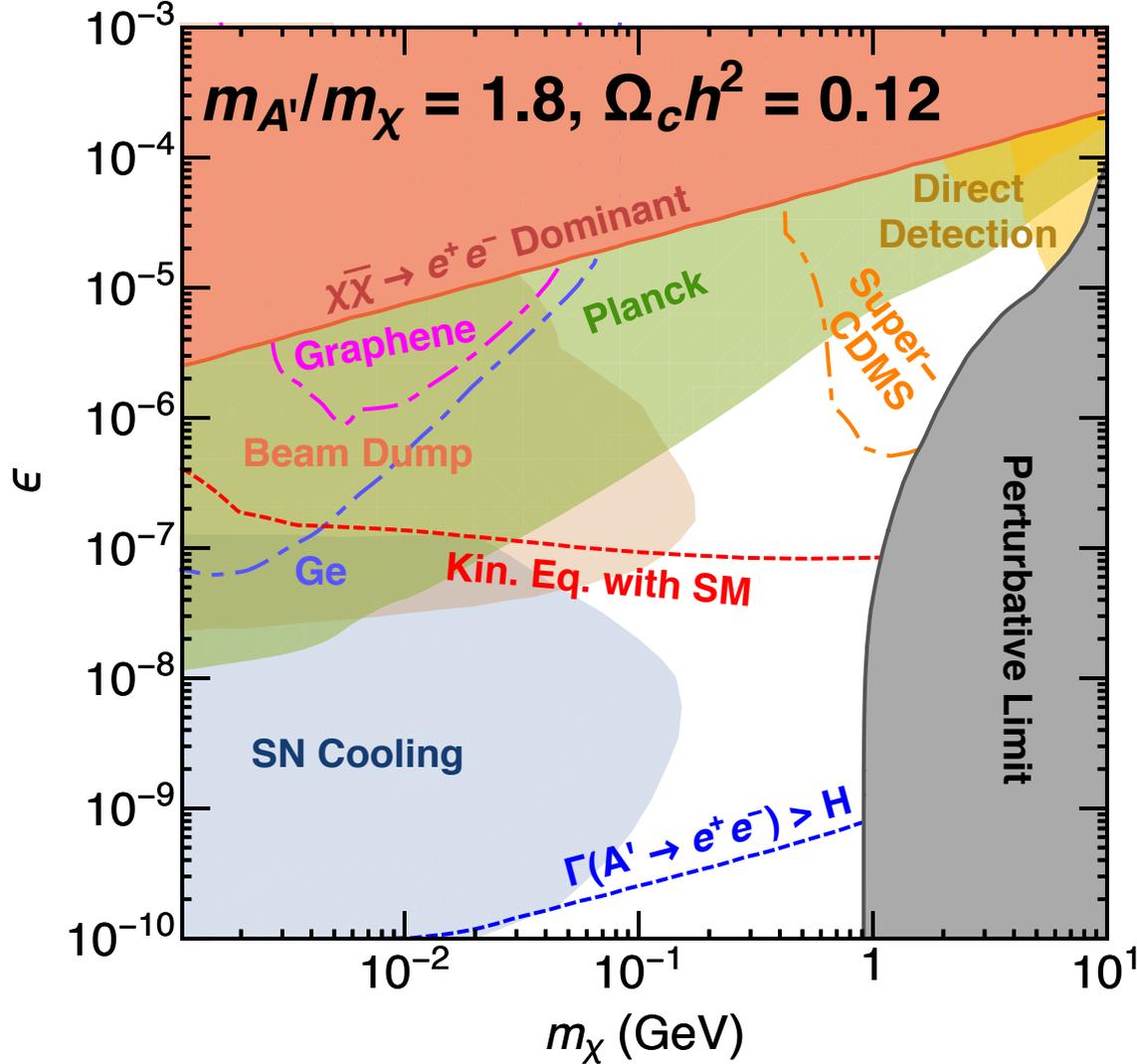


● ● ●
Solve Boltzmann equation for
3 processes, 2 species, varying:
 $\epsilon, \alpha', m_\chi, m_{A'}$

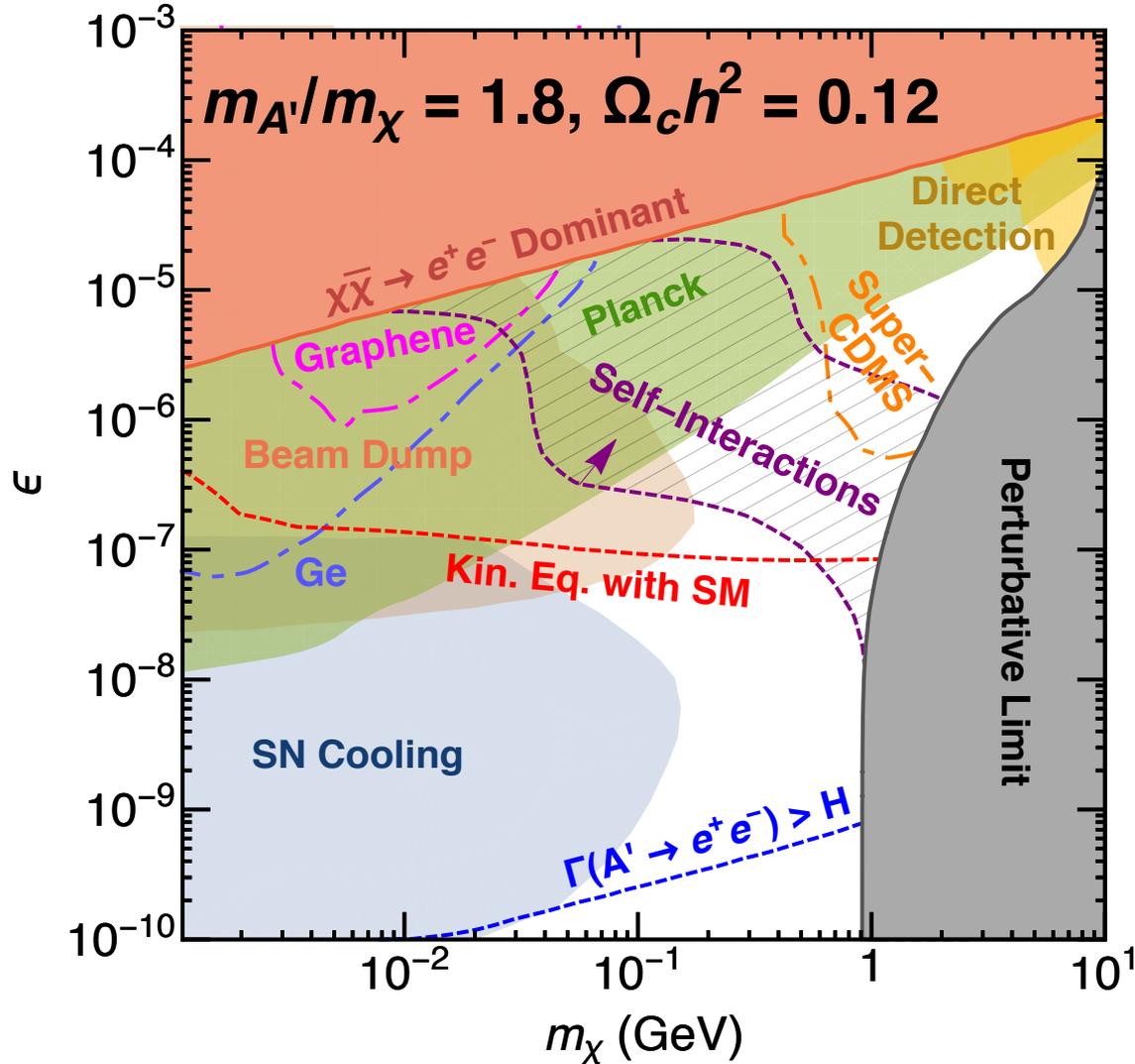
● ● ● ● **DM Abundance**



● ● ● ● **Constraints**



● ● ● ● **Self-Interactions**



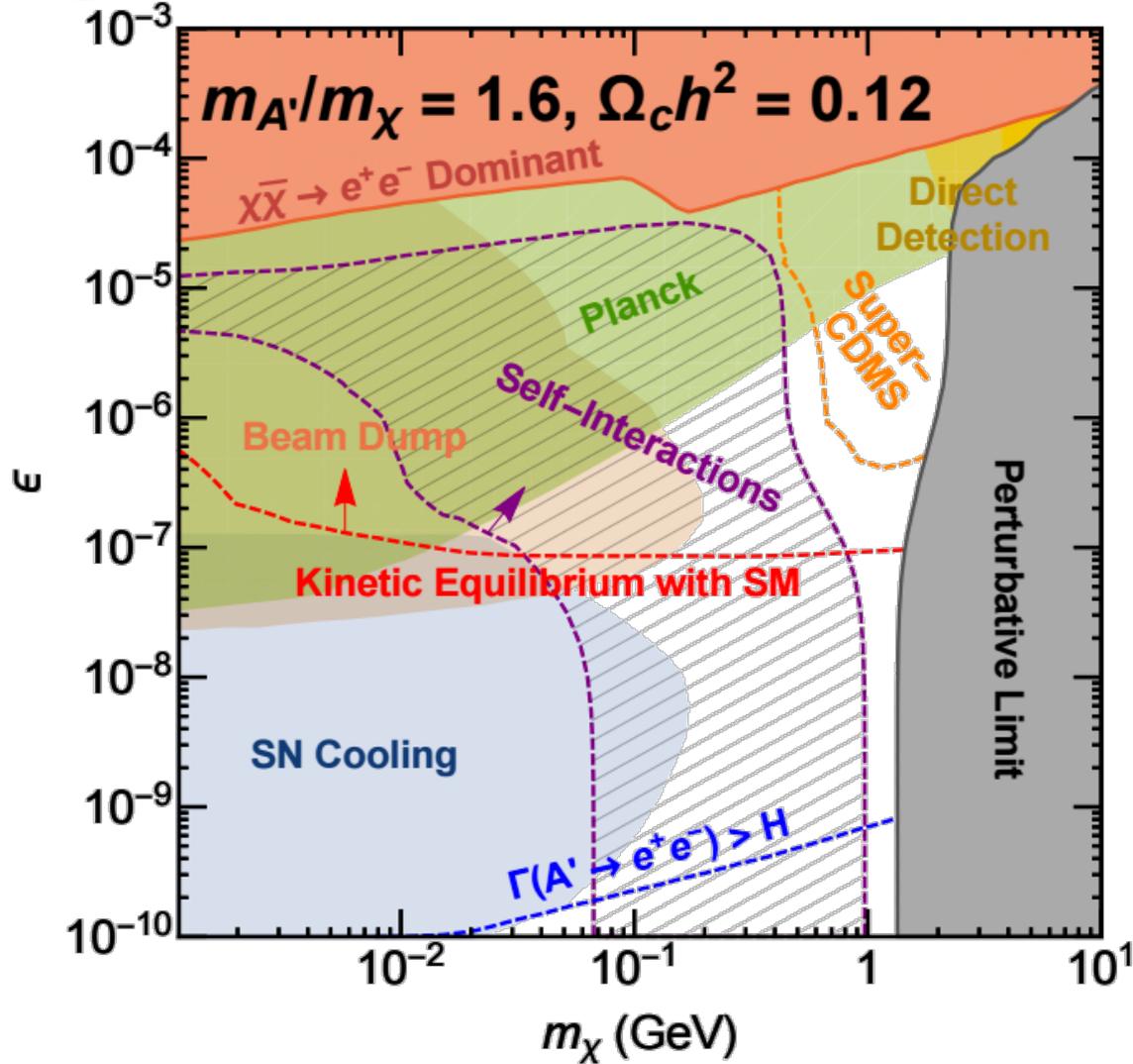
●●●● Conclusion — arXiv: 1702.07716

- **3 to 2 annihilations are important** when 2 to 2 annihilations are kinematically forbidden.
- **Not-Forbidden Dark Matter** leads to **light dark matter** (MeV – GeV) consistent with experimental constraints and relic abundance.
- **NFDM** can have self-interaction cross sections that **potentially solve small-scale structure problems**.
- Having multiple species and processes lead to **interesting freeze-out scenarios**.

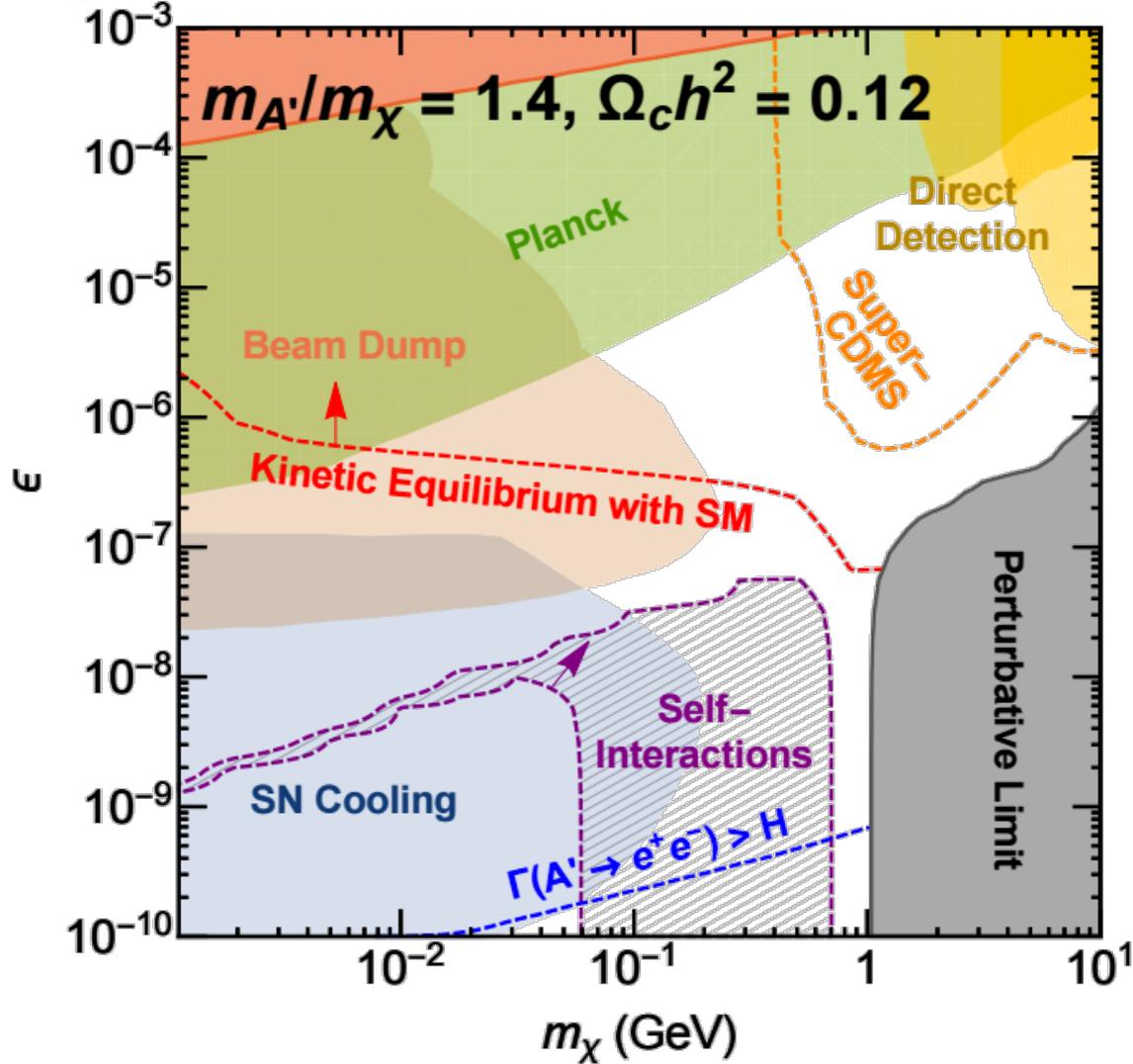


Backup Slides

● ● ● ● **Constraints**

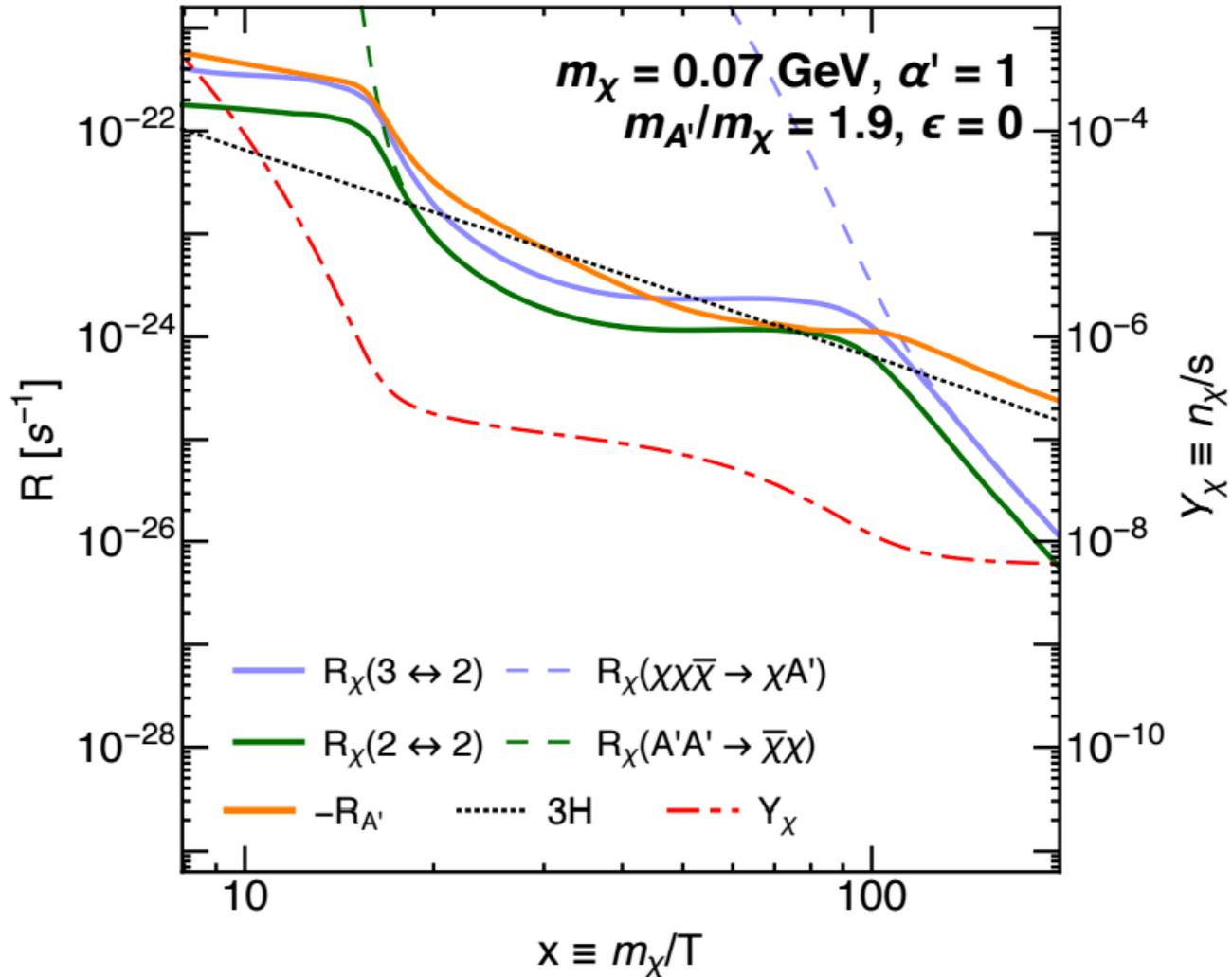


● ● ● ● **Constraints**



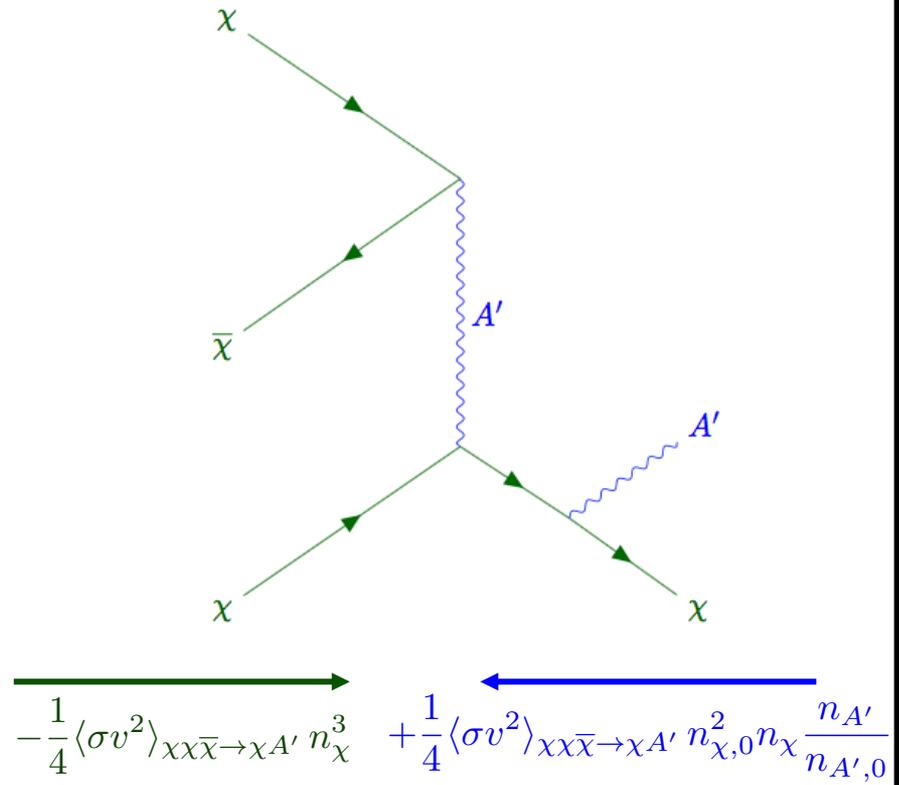
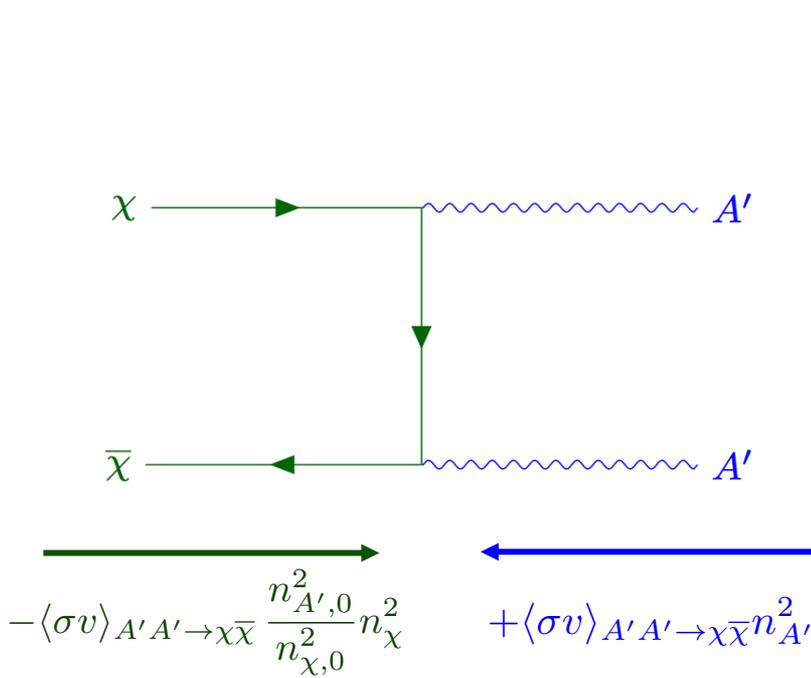


Secluded Sector - Rates



●●●● **2 Processes, 2 Species**

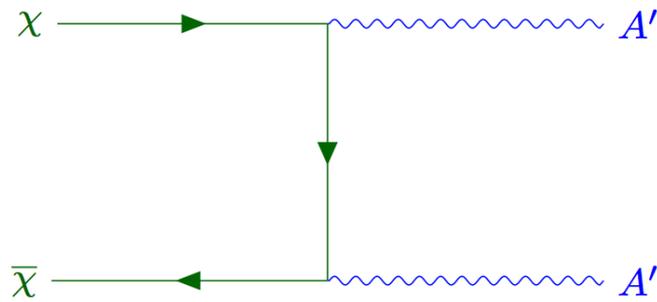
$$\epsilon \rightarrow 0$$



●●● At high temperatures, forward and backward rates are fast and almost equal.

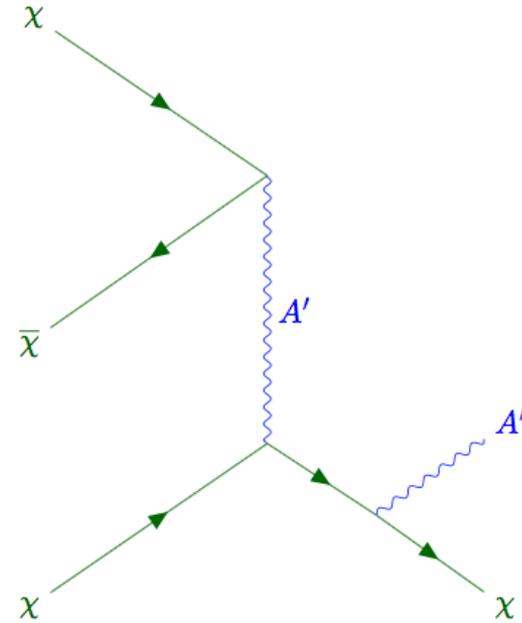
● ● ● ● **2 Processes, 2 Species**

$$\epsilon \rightarrow 0$$



$$-\langle \sigma v \rangle_{A'A' \rightarrow \chi \bar{\chi}} \frac{n_{A',0}^2}{n_{\chi,0}^2} n_{\chi}^2 \quad + \langle \sigma v \rangle_{A'A' \rightarrow \chi \bar{\chi}} n_{A'}^2$$

~ equal



$$-\frac{1}{4} \langle \sigma v^2 \rangle_{\chi \chi \bar{\chi} \rightarrow \chi A'} n_{\chi}^3 \quad + \frac{1}{4} \langle \sigma v^2 \rangle_{\chi \chi \bar{\chi} \rightarrow \chi A'} n_{\chi,0}^2 n_{\chi} \frac{n_{A'}}{n_{A',0}}$$

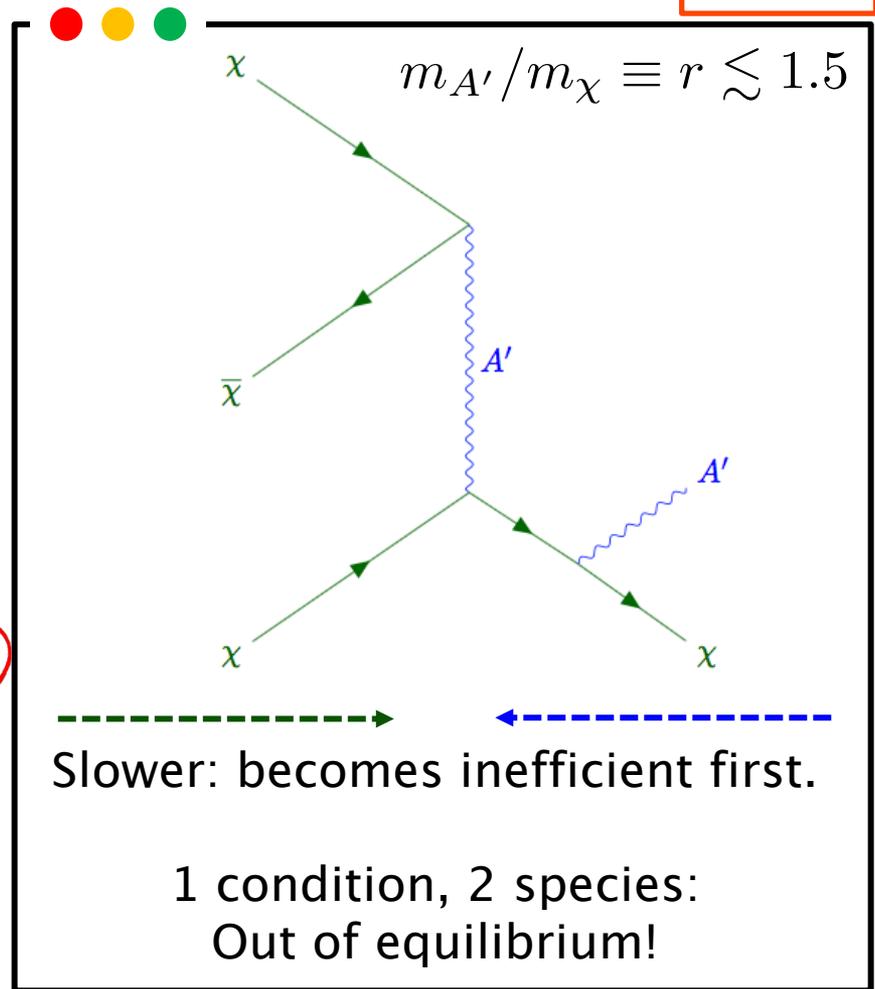
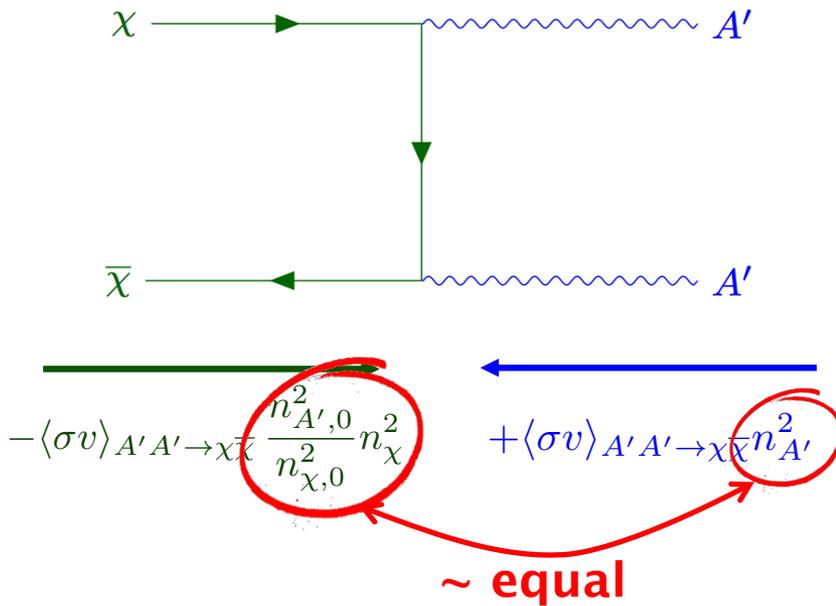
~ equal

● ● ●

2 conditions, 2 species:
enforces equilibrium distribution

2 Processes, 2 Species

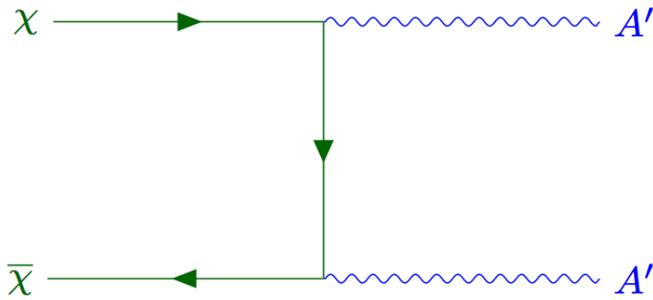
$$\epsilon \rightarrow 0$$



2 Processes, 2 Species

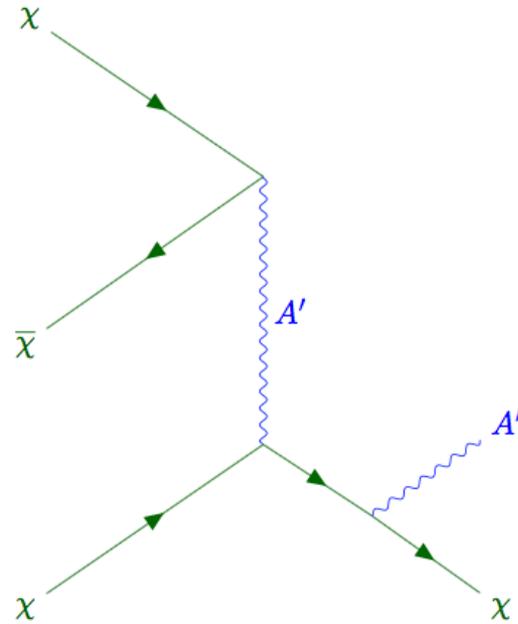
$$\epsilon \rightarrow 0$$

$$m_{A'}/m_\chi \equiv r \gtrsim 1.5$$



Slower: becomes inefficient first.

1 condition, 2 species:
Out of equilibrium!

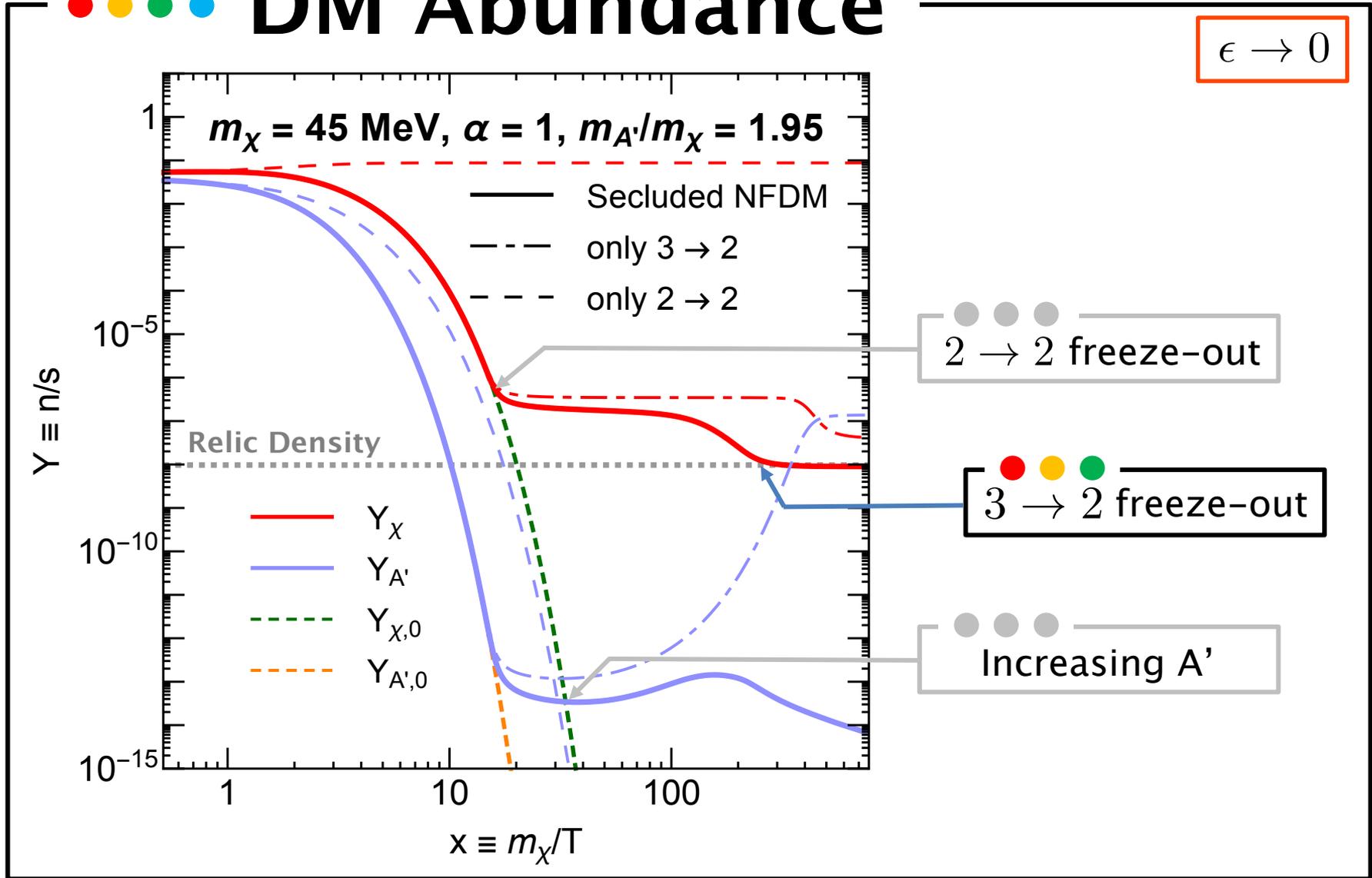


$$-\frac{1}{4} \langle \sigma v^2 \rangle_{\chi\chi\bar{\chi} \rightarrow \chi A'} n_\chi^3 + \frac{1}{4} \langle \sigma v^2 \rangle_{\chi\chi\bar{\chi} \rightarrow \chi A'} n_\chi^2 \frac{n_{A'}}{n_{A',0}}$$

~ equal

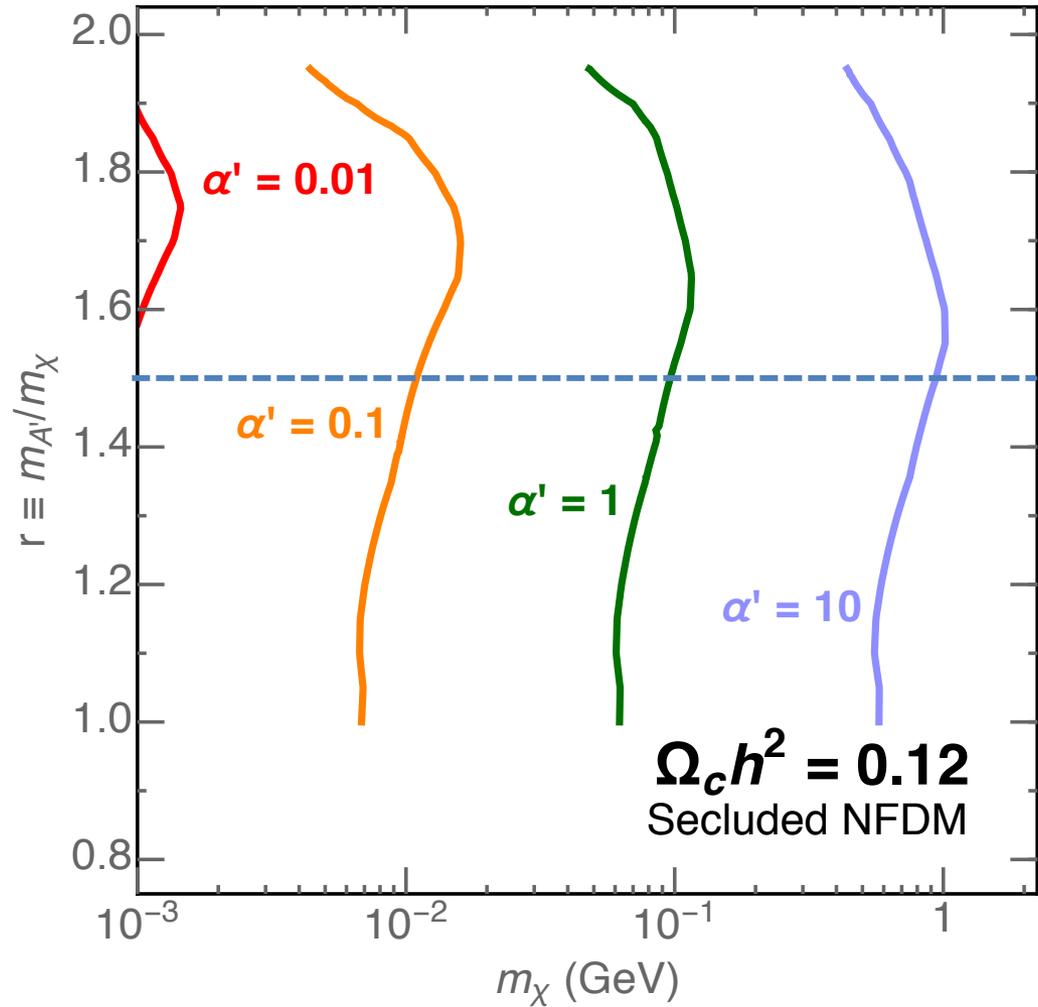
● ● ● ● **DM Abundance**

$\epsilon \rightarrow 0$



● ● ● ● **Correct Relic Density**

$\epsilon \rightarrow 0$



Determined by:

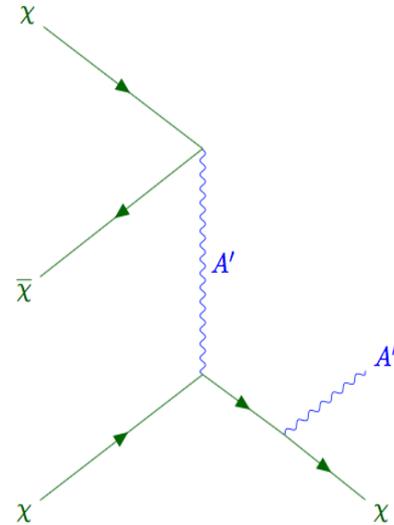
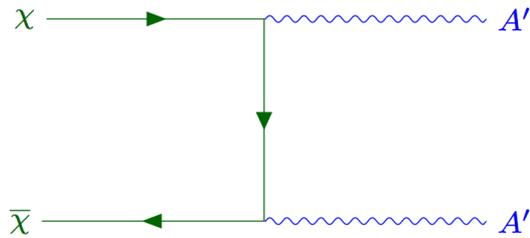
● ● $\chi\chi \rightarrow A'A'$
1st freeze-out

● ● $\chi\chi\bar{\chi} \rightarrow \chi A'$
2nd freeze-out

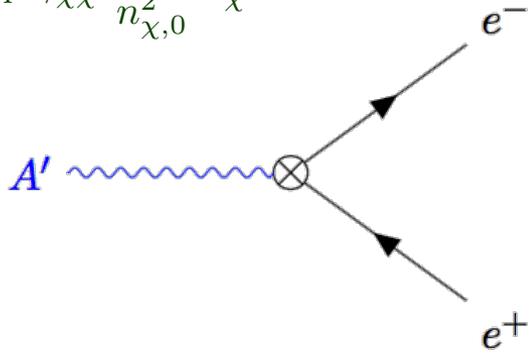
● ● $\chi\chi\bar{\chi} \rightarrow \chi A'$

● ● ● ● **3 Processes, 2 Species**

$\epsilon \gtrsim 10^{-7}$



$$-\langle \sigma v \rangle_{A'A' \rightarrow x\bar{x}} \frac{n_{A',0}^2}{n_{\chi,0}^2} n_\chi^2 \quad + \langle \sigma v \rangle_{A'A' \rightarrow x\bar{x}} n_{A'}^2$$

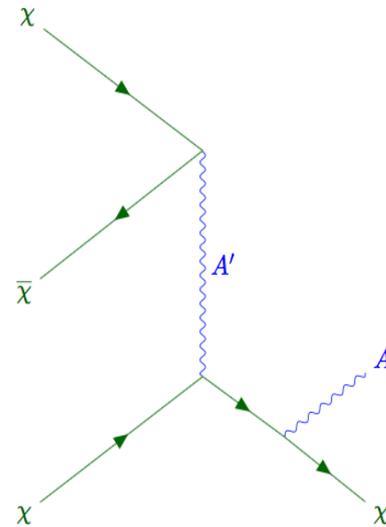
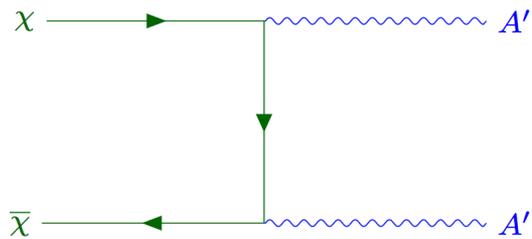


$$-\frac{1}{4} \langle \sigma v^2 \rangle_{x\bar{x}\bar{x} \rightarrow xA'} n_\chi^3 \quad + \frac{1}{4} \langle \sigma v^2 \rangle_{x\bar{x}\bar{x} \rightarrow xA'} n_{\chi,0}^2 n_\chi \frac{n_{A'}}{n_{A',0}}$$

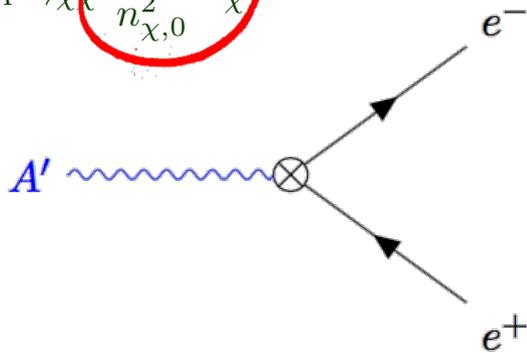
$$-\Gamma_{A' \rightarrow e^+e^-} n_{A'} \quad \Gamma_{A' \rightarrow e^+e^-} n_{A',0}$$

● ● ● ● **3 Processes, 2 Species**

$$\epsilon \gtrsim 10^{-7}$$



$$-\langle \sigma v \rangle_{A'A' \rightarrow x\bar{x}} \frac{n_{A',0}^2}{n_{x,0}^2} n_x^2 \quad + \langle \sigma v \rangle_{A'A' \rightarrow x\bar{x}} n_{A'}^2$$



$$-\frac{1}{4} \langle \sigma v^2 \rangle_{x\bar{x}\bar{x} \rightarrow xA'} n_x^3 + \frac{1}{4} \langle \sigma v^2 \rangle_{x\bar{x}\bar{x} \rightarrow xA'} n_{x,0}^2 n_x \frac{n_{A'}}{n_{A',0}}$$

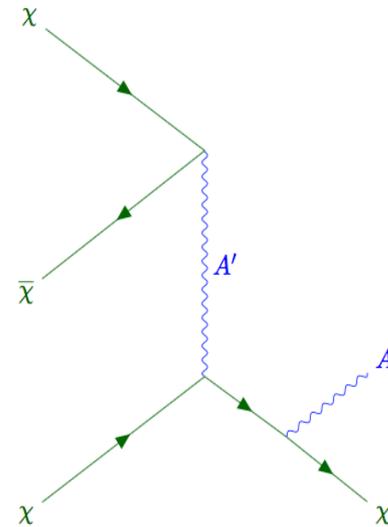
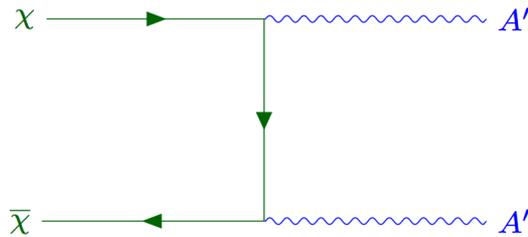
$$-\Gamma_{A' \rightarrow e^+e^-} n_{A'} \quad \Gamma_{A' \rightarrow e^+e^-} n_{A',0}$$

● ● ●
3 equations, 2 species:
Equilibrium!



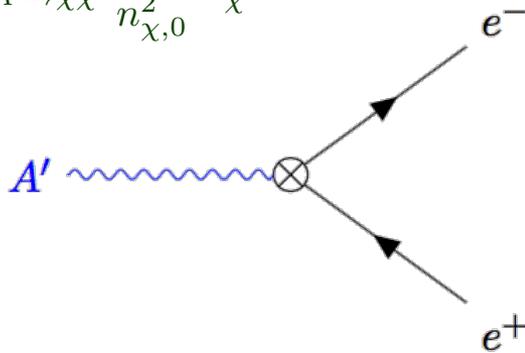
3 Processes, 2 Species

$$\epsilon \gtrsim 10^{-7}$$



For $r \gtrsim 1.5$, SLOOOOW...

$$-\langle \sigma v \rangle_{A'A' \rightarrow x\bar{x}} \frac{n_{A',0}^2}{n_{\chi,0}^2} n_{\chi}^2 \quad + \langle \sigma v \rangle_{A'A' \rightarrow x\bar{x}} n_{A'}^2$$



$$-\frac{1}{4} \langle \sigma v^2 \rangle_{x\bar{x}\bar{x} \rightarrow xA'} n_{\chi}^3 + \frac{1}{4} \langle \sigma v^2 \rangle_{x\bar{x}\bar{x} \rightarrow xA'} n_{\chi,0}^2 n_{\chi} \frac{n_{A'}}{n_{A',0}}$$

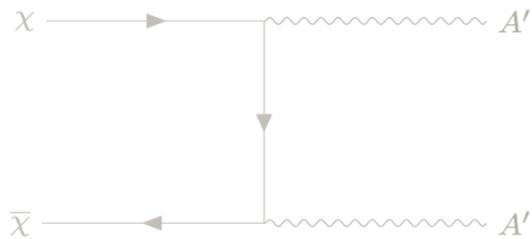
$$-\Gamma_{A' \rightarrow e^+e^-} n_{A'} \quad \Gamma_{A' \rightarrow e^+e^-} n_{A',0}$$

2 equations, 2 species:
Still equilibrium!



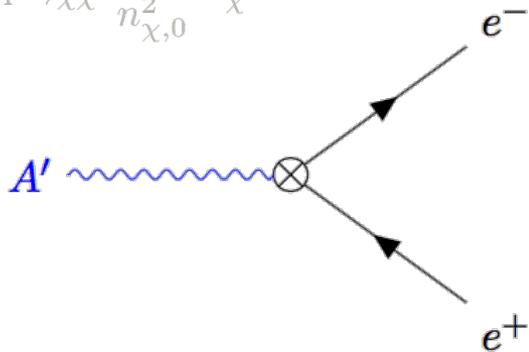
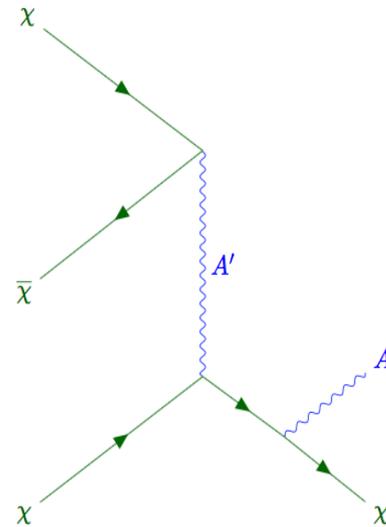
3 Processes, 2 Species

$$\epsilon \gtrsim 10^{-7}$$



For $r \gtrsim 1.5$, SLOOOOW...

$$-\langle \sigma v \rangle_{A'A' \rightarrow x\bar{x}} \frac{n_{A',0}^2}{n_{x,0}^2} n_x^2 \quad + \langle \sigma v \rangle_{A'A' \rightarrow x\bar{x}} n_{A'}^2$$



$$-\frac{1}{4} \langle \sigma v^2 \rangle_{x\bar{x}\bar{x} \rightarrow xA'} n_x^3 + \frac{1}{4} \langle \sigma v^2 \rangle_{x\bar{x}\bar{x} \rightarrow xA'} n_{x,0}^2 n_x \frac{n_{A'}}{n_{A',0}}$$

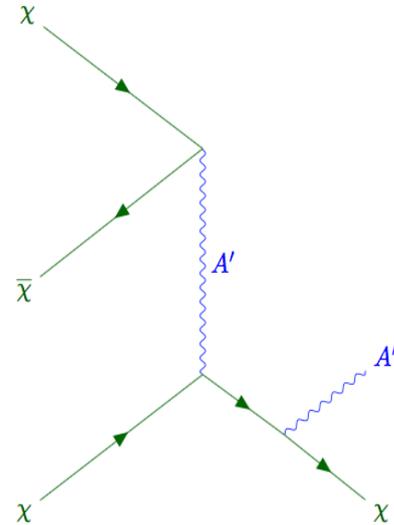
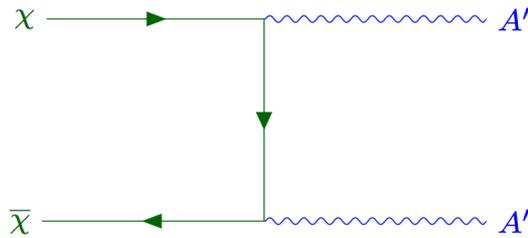
$$-\Gamma_{A' \rightarrow e^+e^-} n_{A'} \quad \Gamma_{A' \rightarrow e^+e^-} n_{A',0}$$

The *slowest* process does not affect freeze-out.



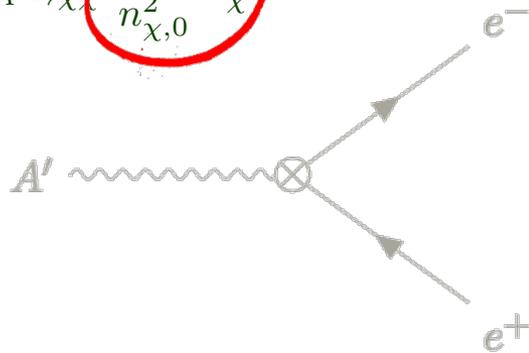
3 Processes, 2 Species

$$\epsilon \rightarrow 0$$



$$-\langle \sigma v \rangle_{A'A' \rightarrow x\bar{x}} \frac{n_{A',0}^2}{n_{x,0}^2} n_x^2$$

$$+\langle \sigma v \rangle_{A'A' \rightarrow x\bar{x}} n_{A'}^2$$



SLOOOW...

$$-\Gamma_{A' \rightarrow e^+e^-} n_{A'}$$

$$\Gamma_{A' \rightarrow e^+e^-} n_{A',0}$$

$$-\frac{1}{4} \langle \sigma v^2 \rangle_{x\bar{x}\bar{x} \rightarrow xA'} n_x^3$$

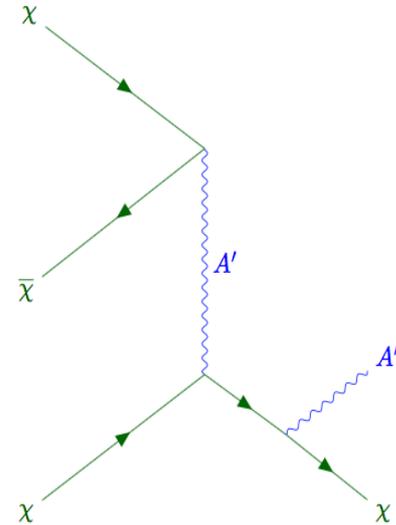
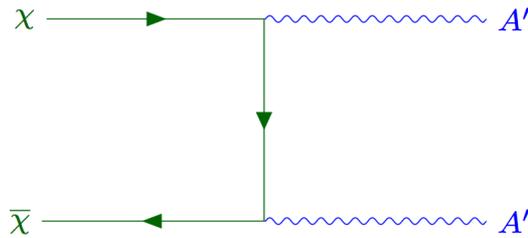
$$+\frac{1}{4} \langle \sigma v^2 \rangle_{x\bar{x}\bar{x} \rightarrow xA'} n_{x,0}^2 n_x \frac{n_{A'}}{n_{A',0}}$$

Secluded case if decays are the slowest process.

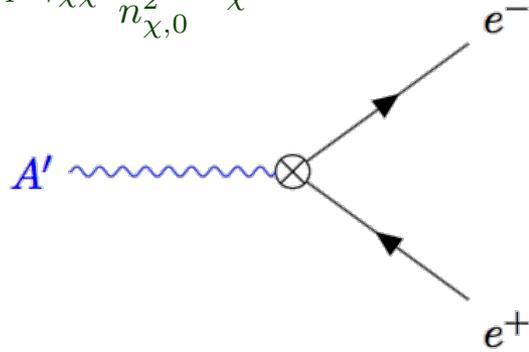


3 Processes, 2 Species

$$\epsilon \gtrsim 10^{-7}$$



$$-\langle \sigma v \rangle_{A'A' \rightarrow \chi\bar{\chi}} \frac{n_{A',0}^2}{n_{\chi,0}^2} n_{\chi}^2 \quad + \langle \sigma v \rangle_{A'A' \rightarrow \chi\bar{\chi}} n_{A'}^2$$



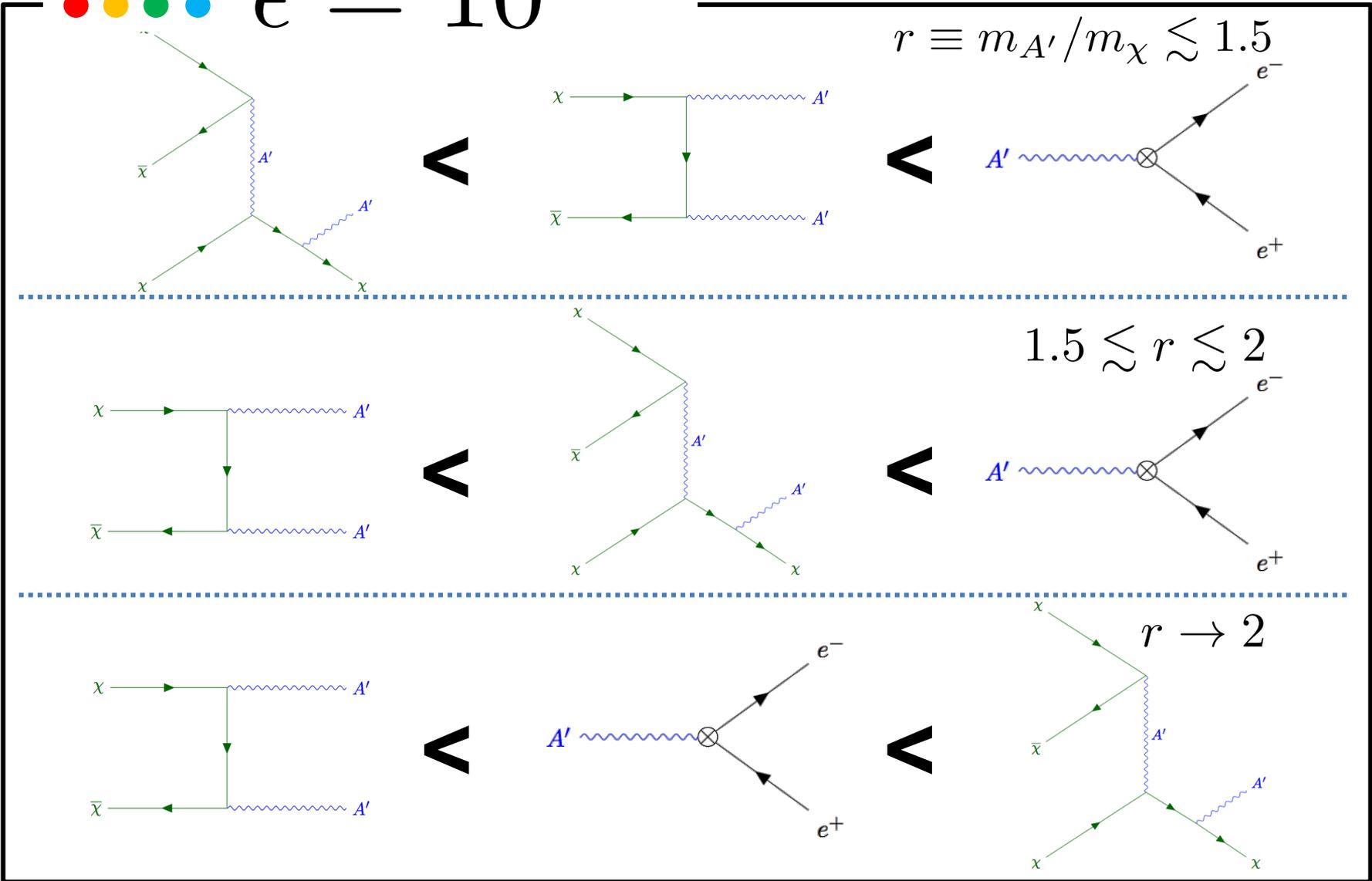
$$-\frac{1}{4} \langle \sigma v^2 \rangle_{\chi\chi\bar{\chi} \rightarrow \chi A'} n_{\chi}^3 \quad + \frac{1}{4} \langle \sigma v^2 \rangle_{\chi\chi\bar{\chi} \rightarrow \chi A'} n_{\chi,0}^2 n_{\chi} \frac{n_{A'}}{n_{A',0}}$$

$$-\Gamma_{A' \rightarrow e^+e^-} n_{A'} \quad \Gamma_{A' \rightarrow e^+e^-} n_{A',0}$$

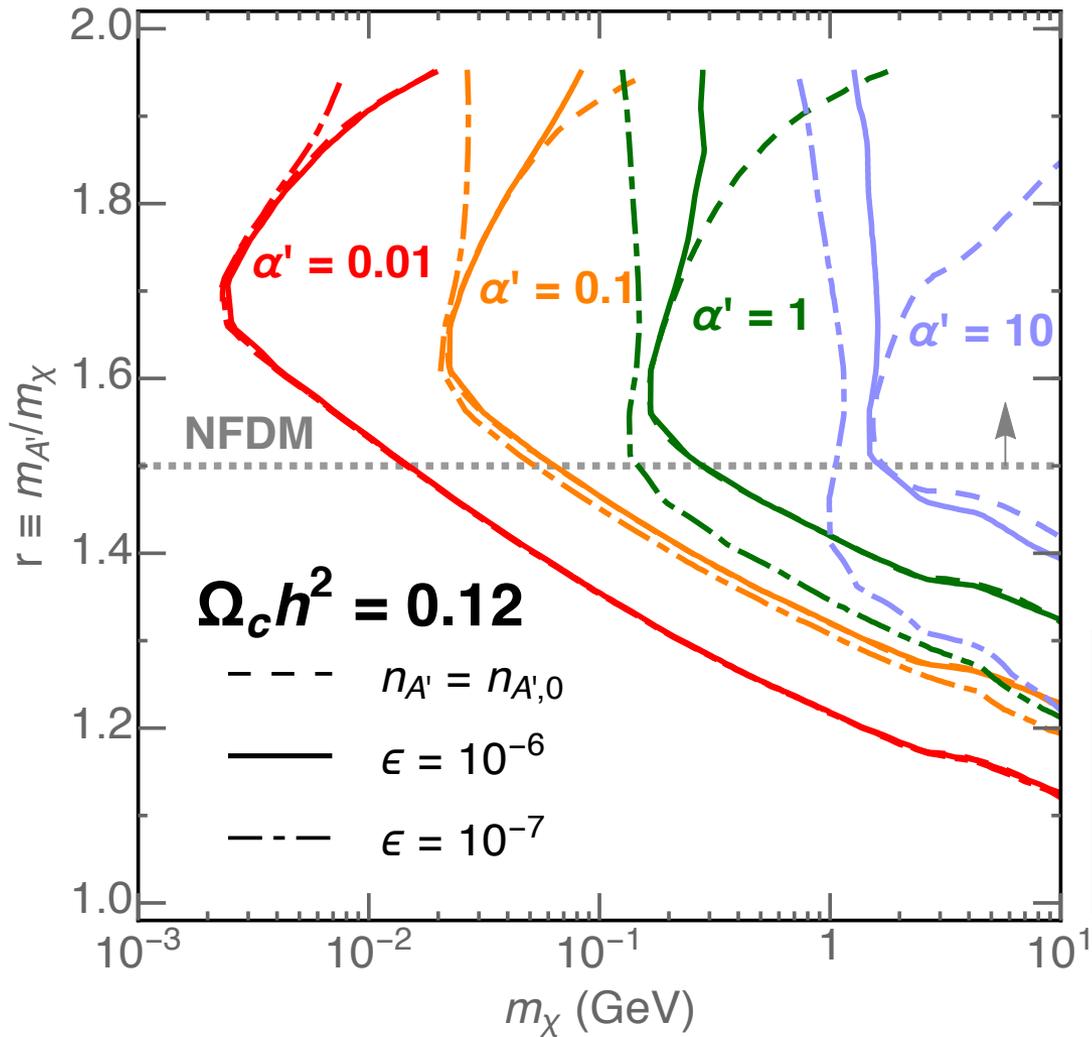
Result depends on the exact value of ϵ .

$\epsilon \gtrsim 10^{-7}$

$\epsilon = 10^{-6}$



Correct Relic Density

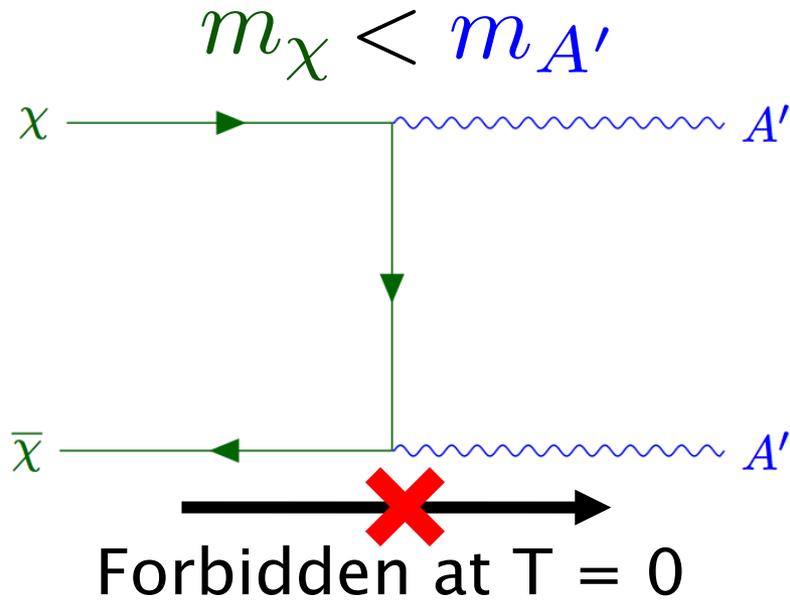


Main Takeaways:

3 to 2 not considered previously: different behavior for $r > 1.5$

Result depend strongly on ϵ even for $r < 1.5$, where 3 to 2 is not important.

Forbidden DM



Relic Density

$$\Omega_c h^2 \sim 0.1 \times \frac{m_\chi^2 / \alpha_D^2}{(20 \text{ TeV})^2} e^{2(r-1)x_f}$$

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

$$x_f \equiv m_\chi / T_f \sim 20$$

Naturally accommodates
Light DM!