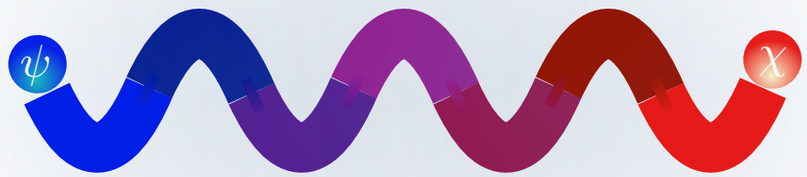


Phases of Dark Matter Production

Josh Ruderman (NYU)

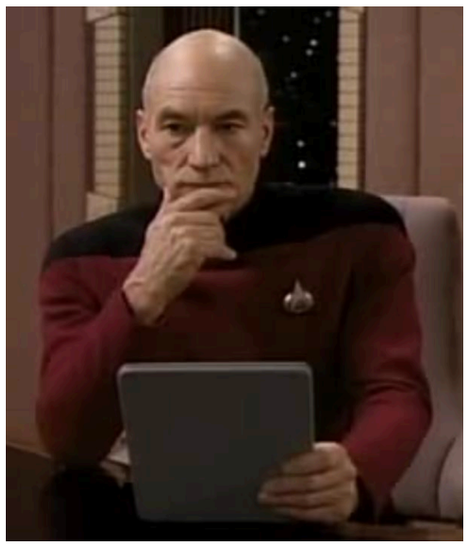
@ICFP2026, 10/24



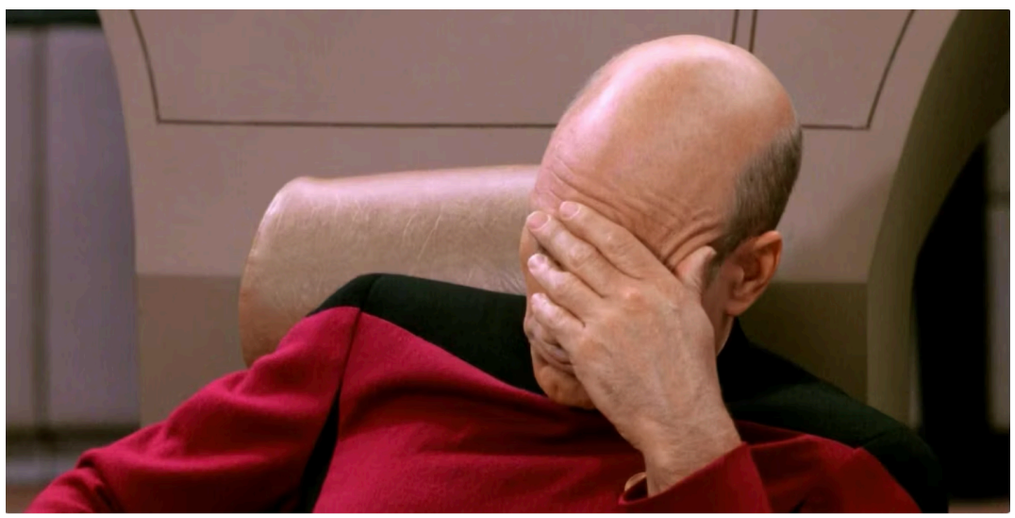
How was dark matter produced?



When was dark matter produced?



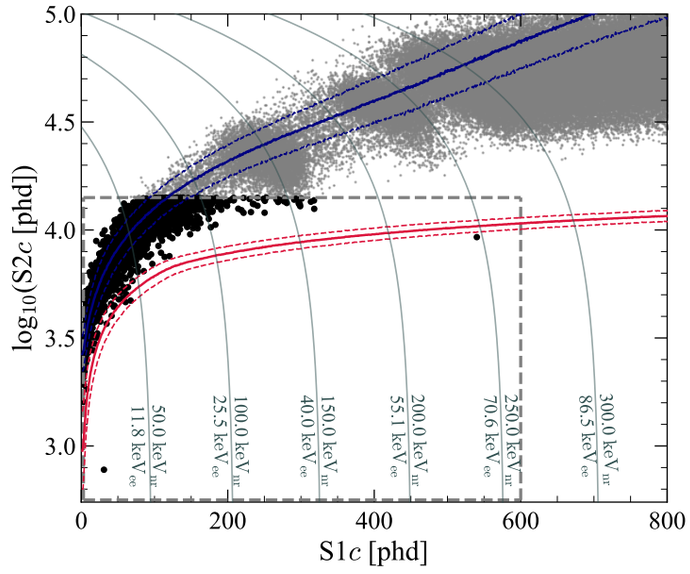
How can we test it?



DM Model Building Strategies

1) connect to another problem ex)
- hierarchy
- strong CP
- $\frac{\Omega_{DM}}{\Omega_b} \approx 5.3$

2) explain an anomaly



LZ, **2609.02823**

3) classify production mechanisms

this talk

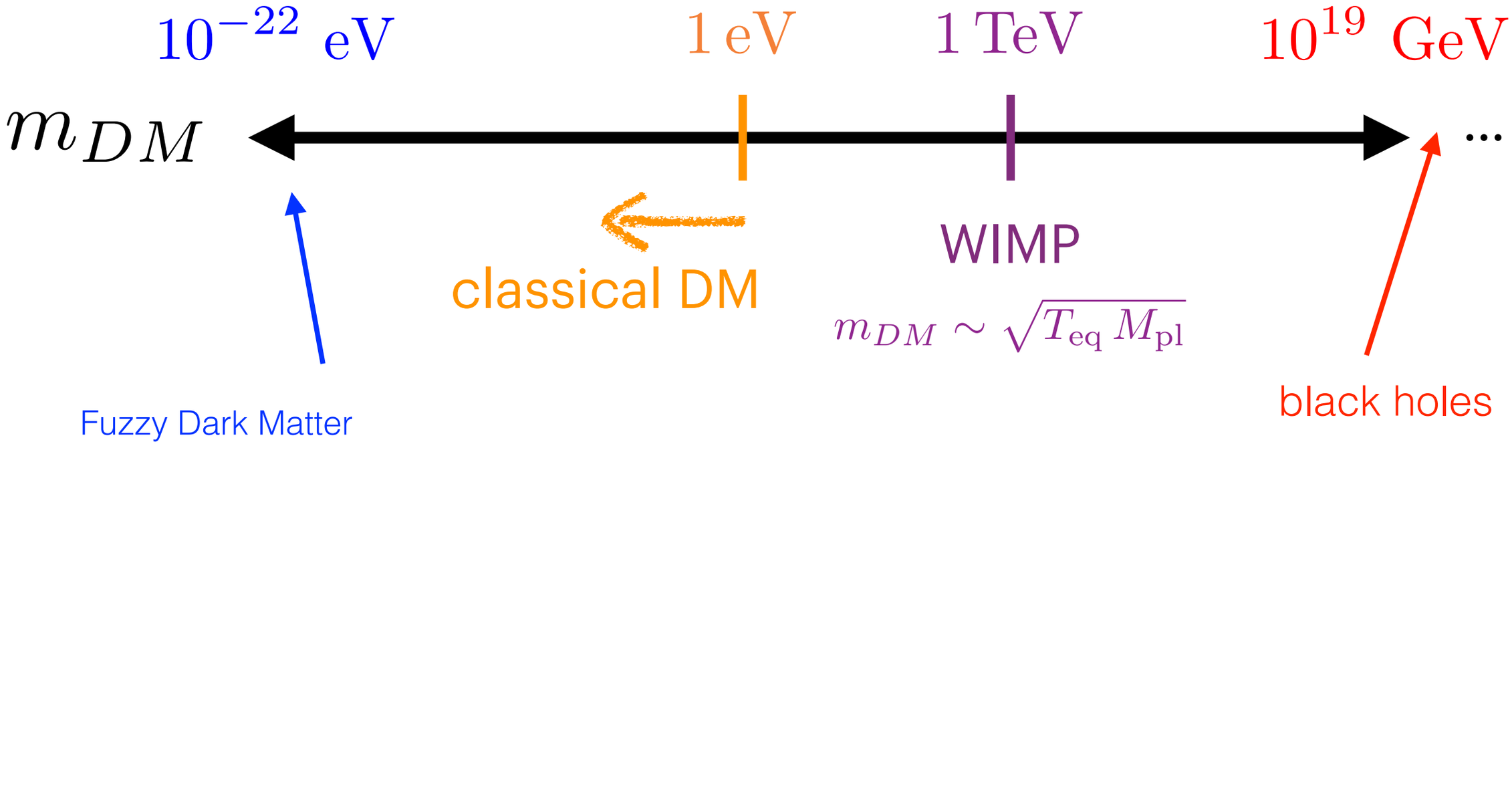
Plan

I. WIMP Warmup

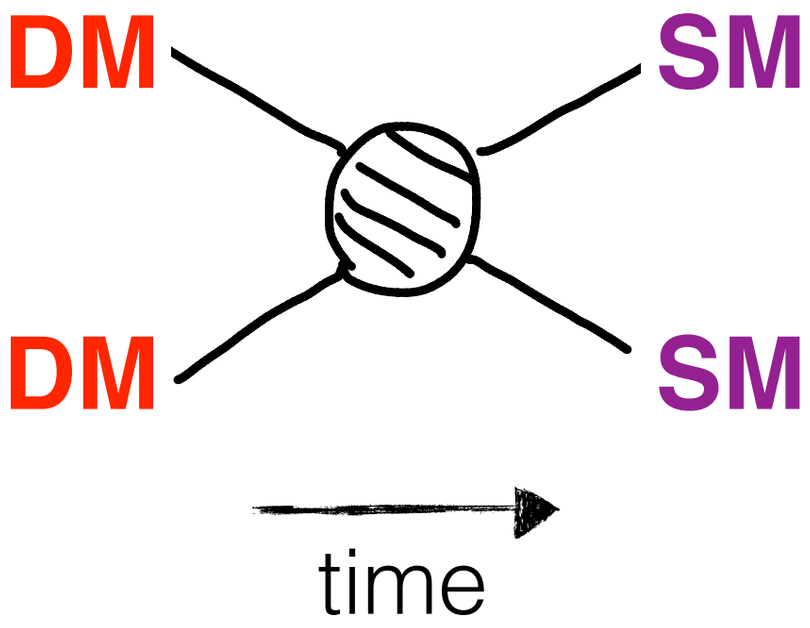
II. Thermal Relic DM

III. Feebly Interacting DM

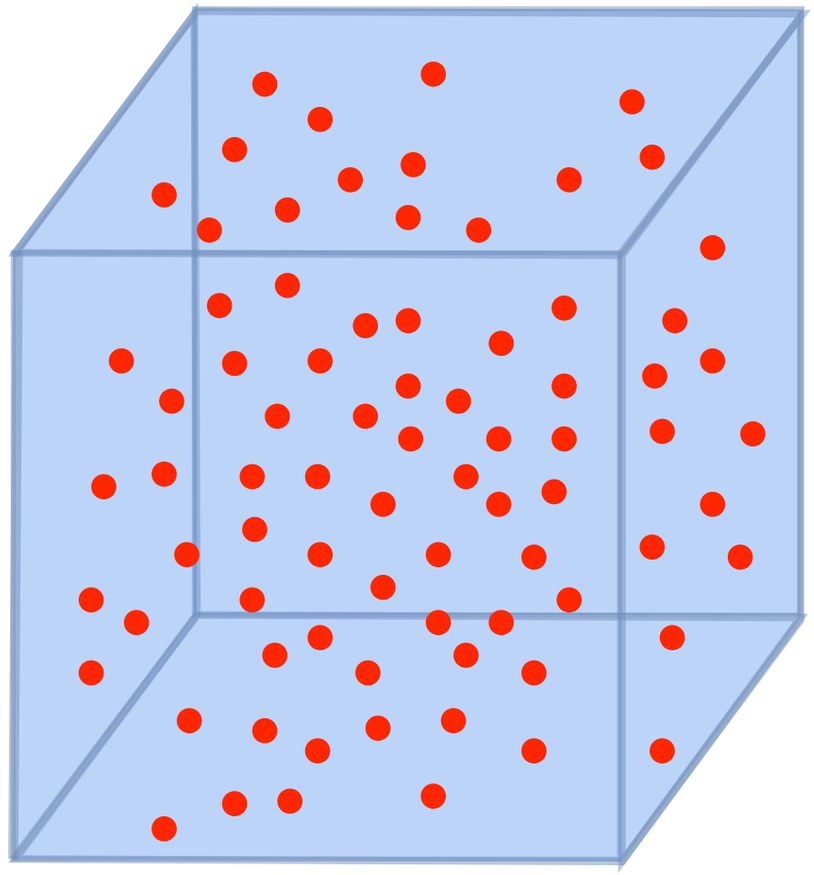
I. WIMP Warmup



WIMP Freezeout



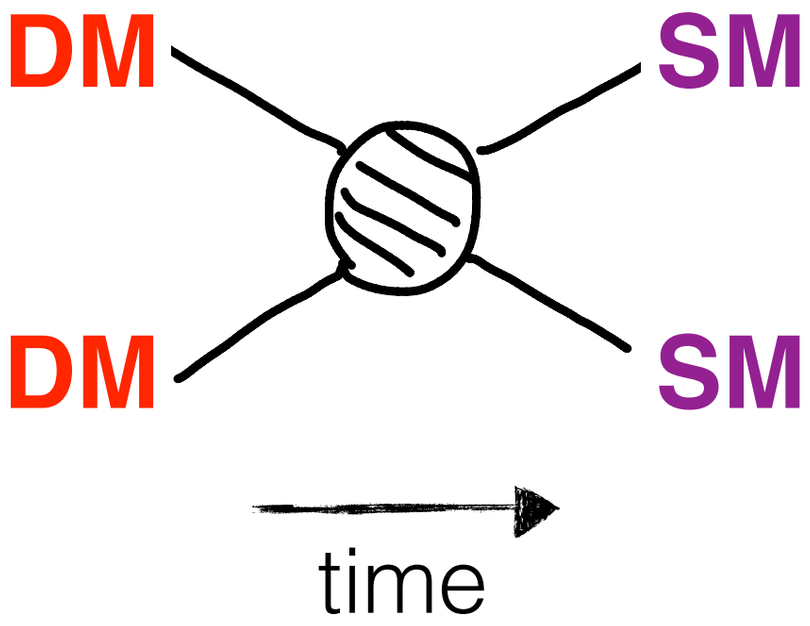
$T = m_{DM}$

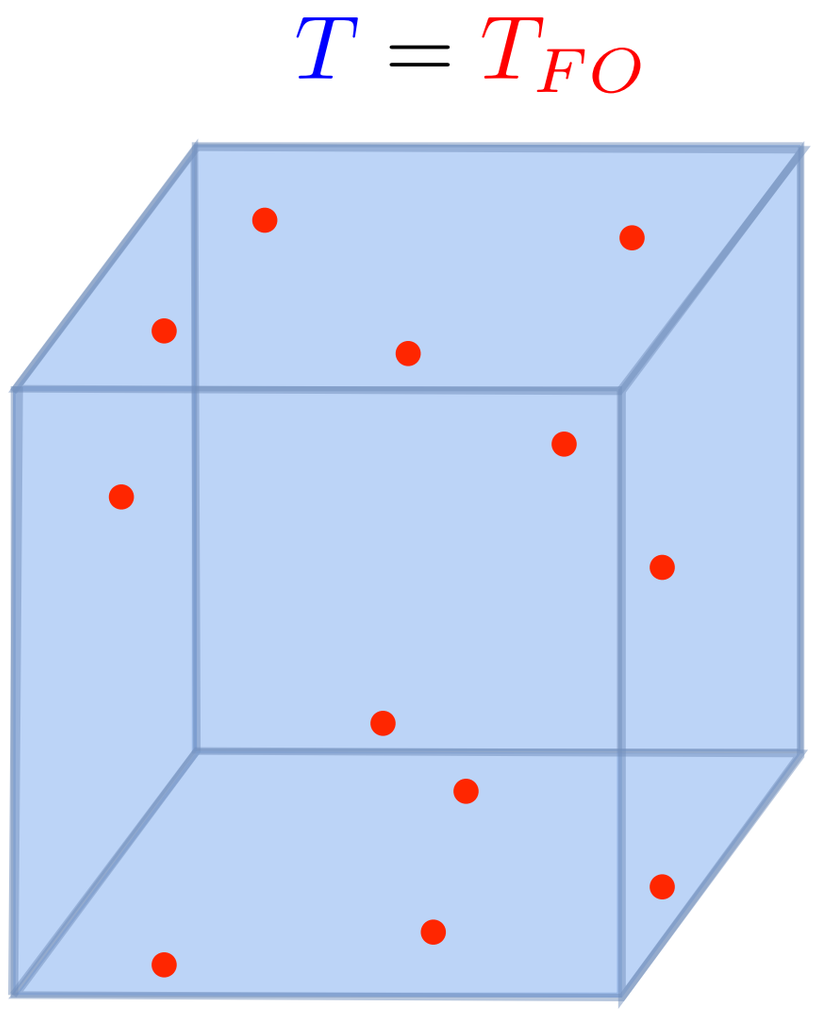


comoving volume: $V \propto s^{-1} \propto T^{-3}$

Lee, Weinberg, Phys. Rev. Lett. **39**, 165 (1977)

WIMP Freezeout

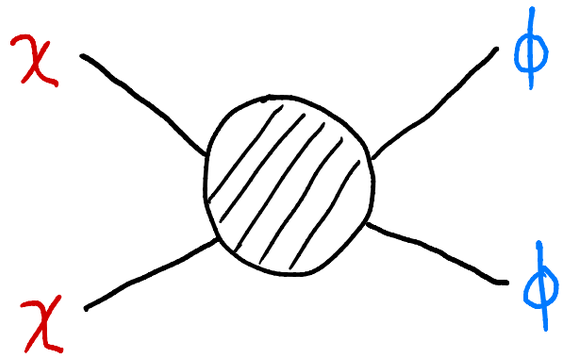




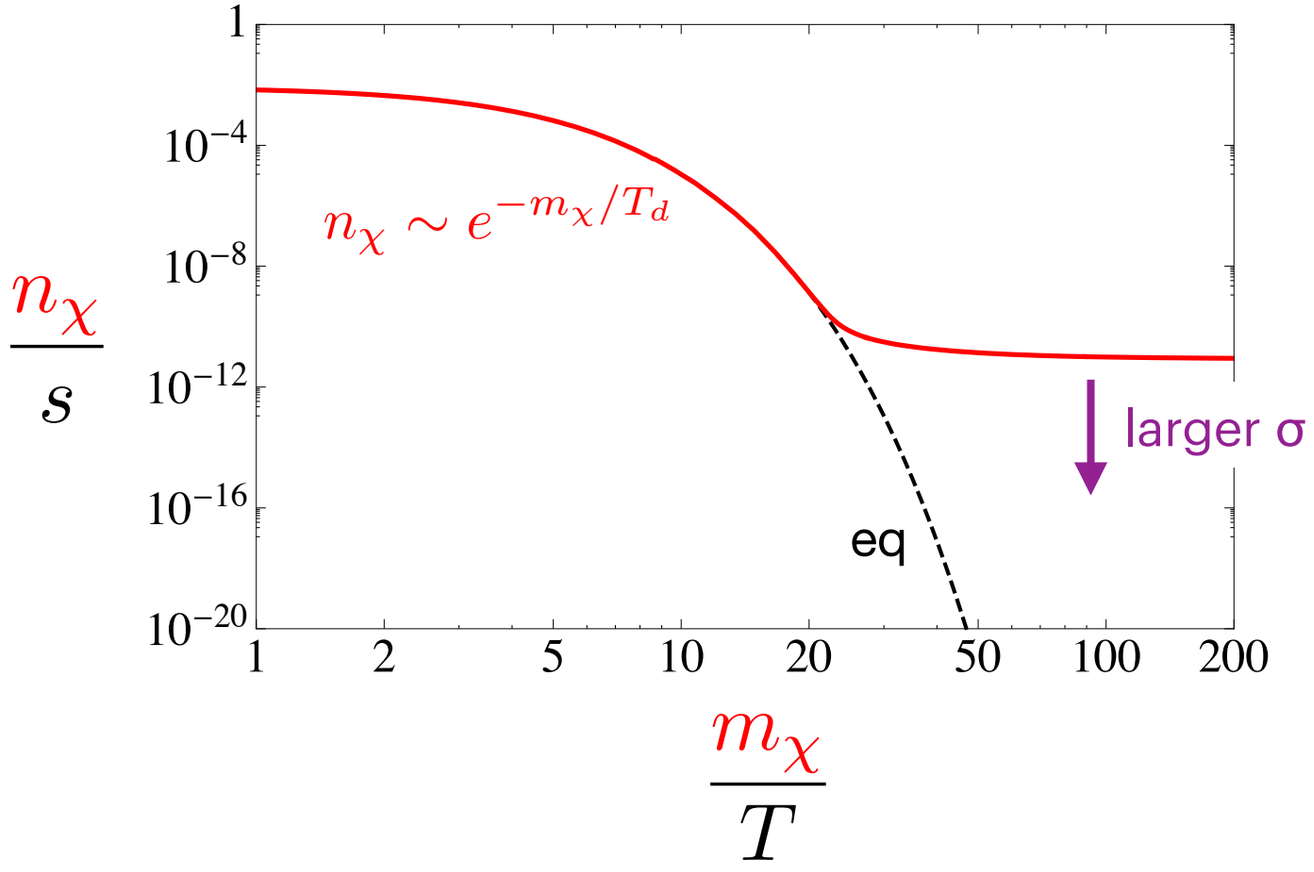
comoving volume: $V \propto s^{-1} \propto T^{-3}$

Lee, Weinberg, Phys. Rev. Lett. **39**, 165 (1977)

WIMP Freezeout



$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - (n_\chi^{\rm eq})^2\right)$$



$$\langle\sigma v\rangle \sim \frac{1}{T_{\rm eq} M_{\rm pl}} \approx \frac{1}{(20\,{\rm TeV})^2}$$

$$\sim (2-3)\times 10^{-26}{\rm cm}^3/{\rm s}$$

When was Dark Matter Produced?

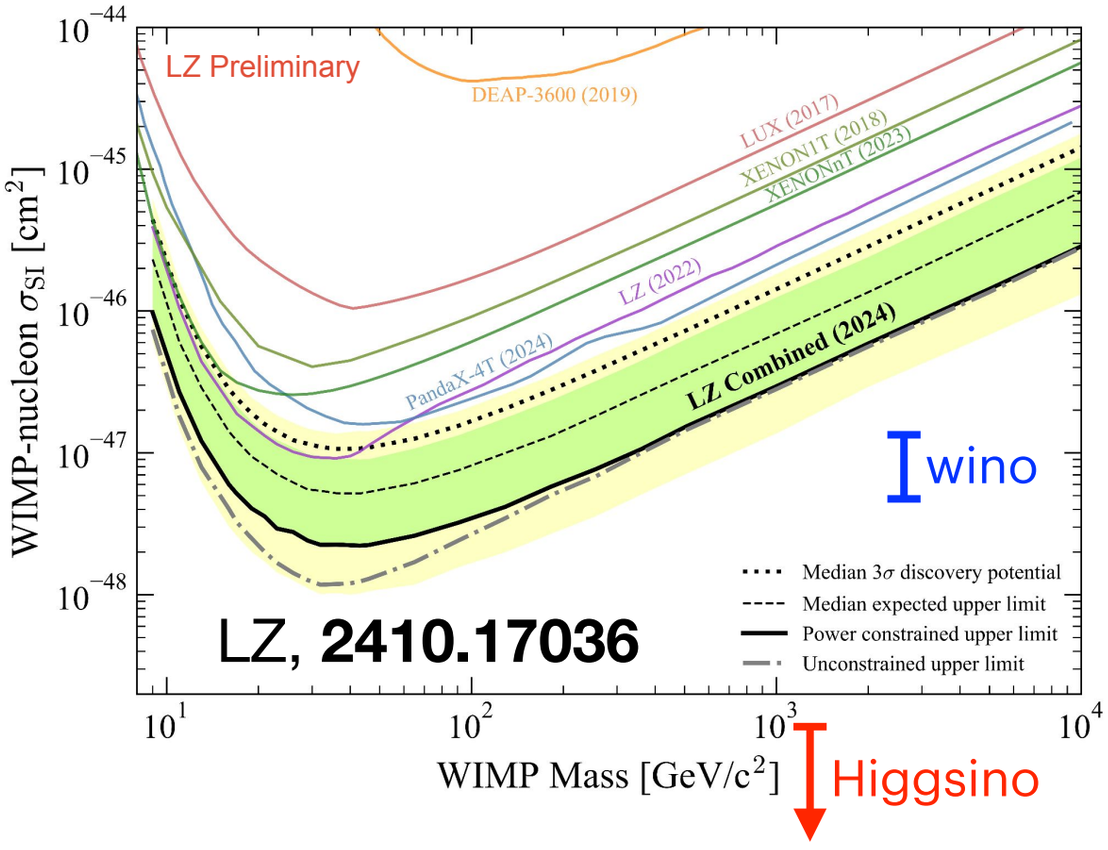


WIMP

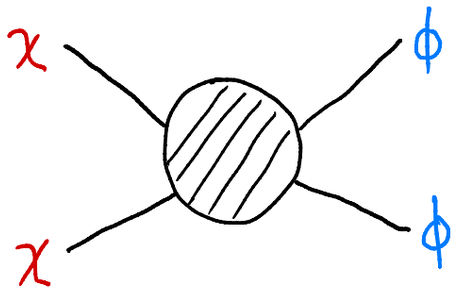
$$T \sim \frac{m_{\rm DM}}{20}$$

Experiment vs WIMPs

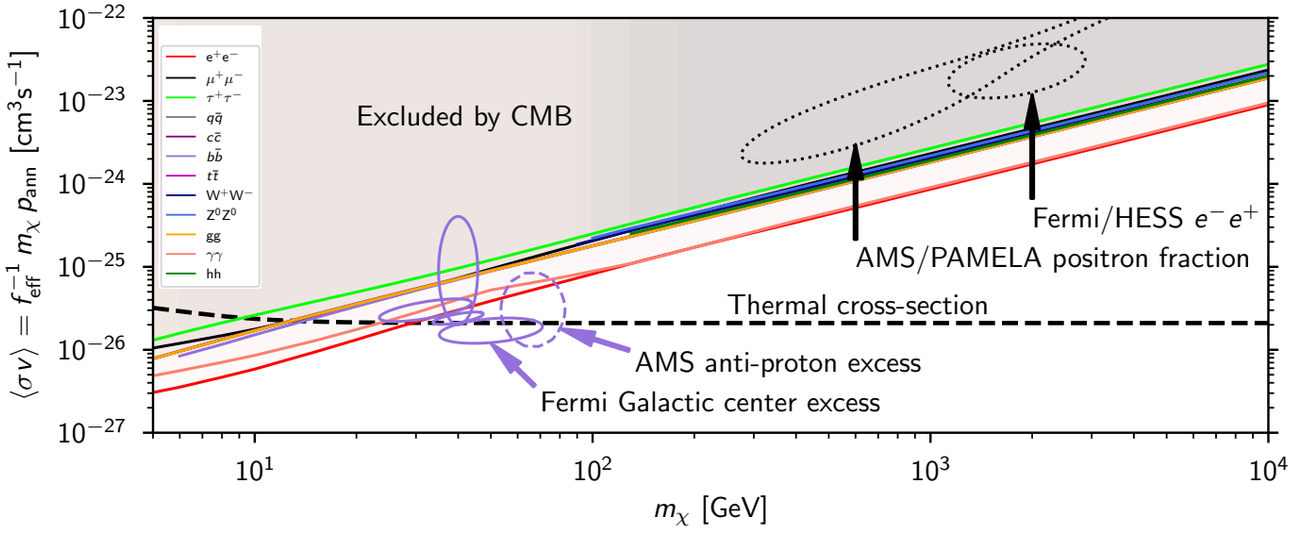
Direct



Indirect



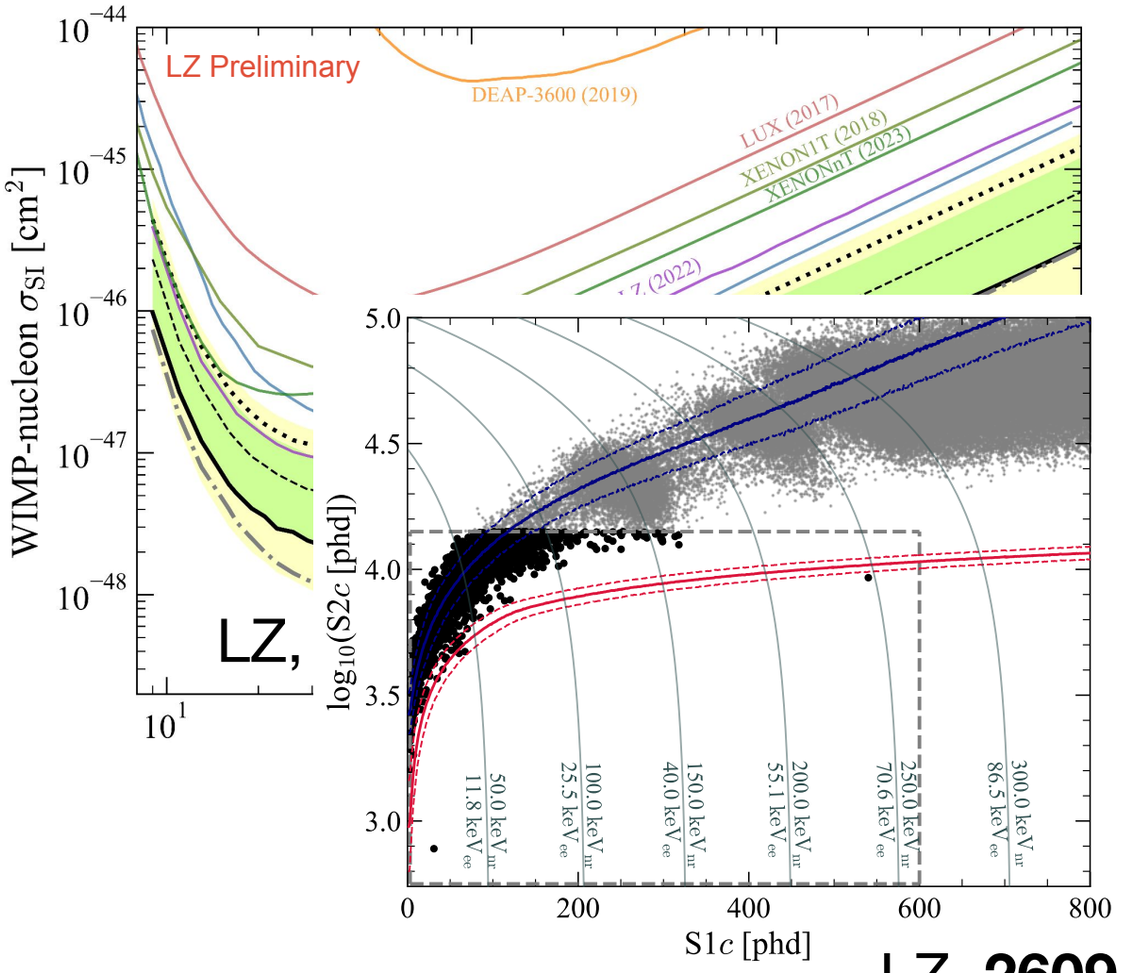
(if ϕ is SM or decays to SM)



- Planck, **1807.06209**
- Slatyer, **1506.03811**

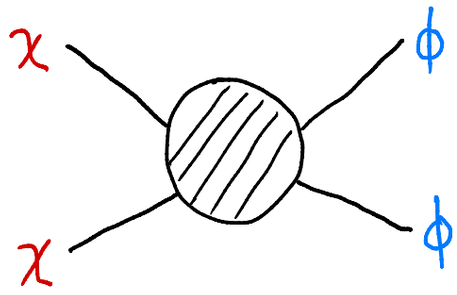
Experiment vs WIMPs

Direct

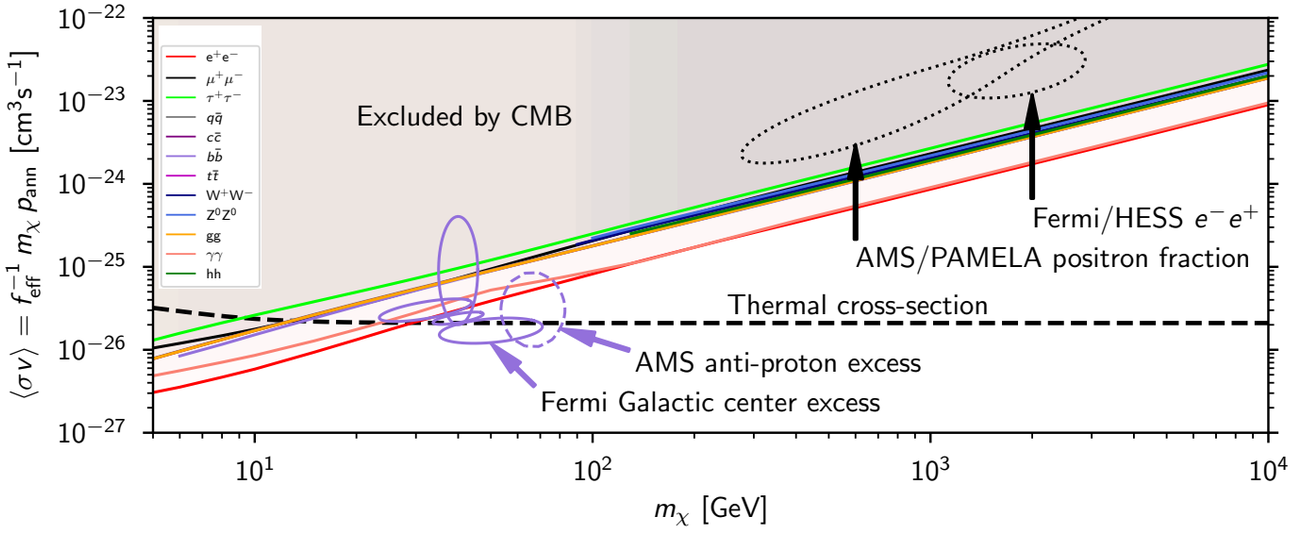


LZ, **2609.02823**

Indirect



(if ϕ is SM or decays to SM)

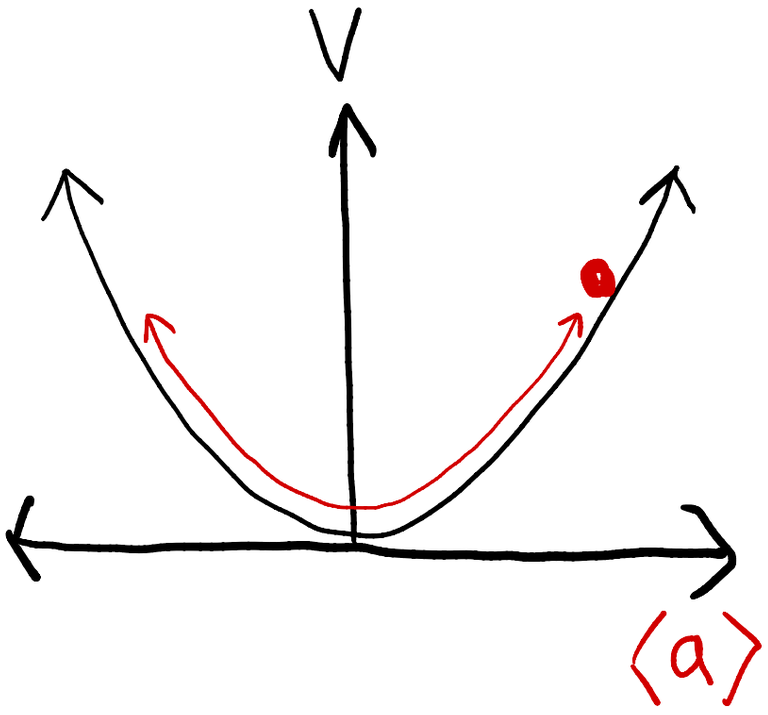


- Planck, **1807.06209**
- Slatyer, **1506.03811**

Axion Dark Matter

misalignment mechanism:

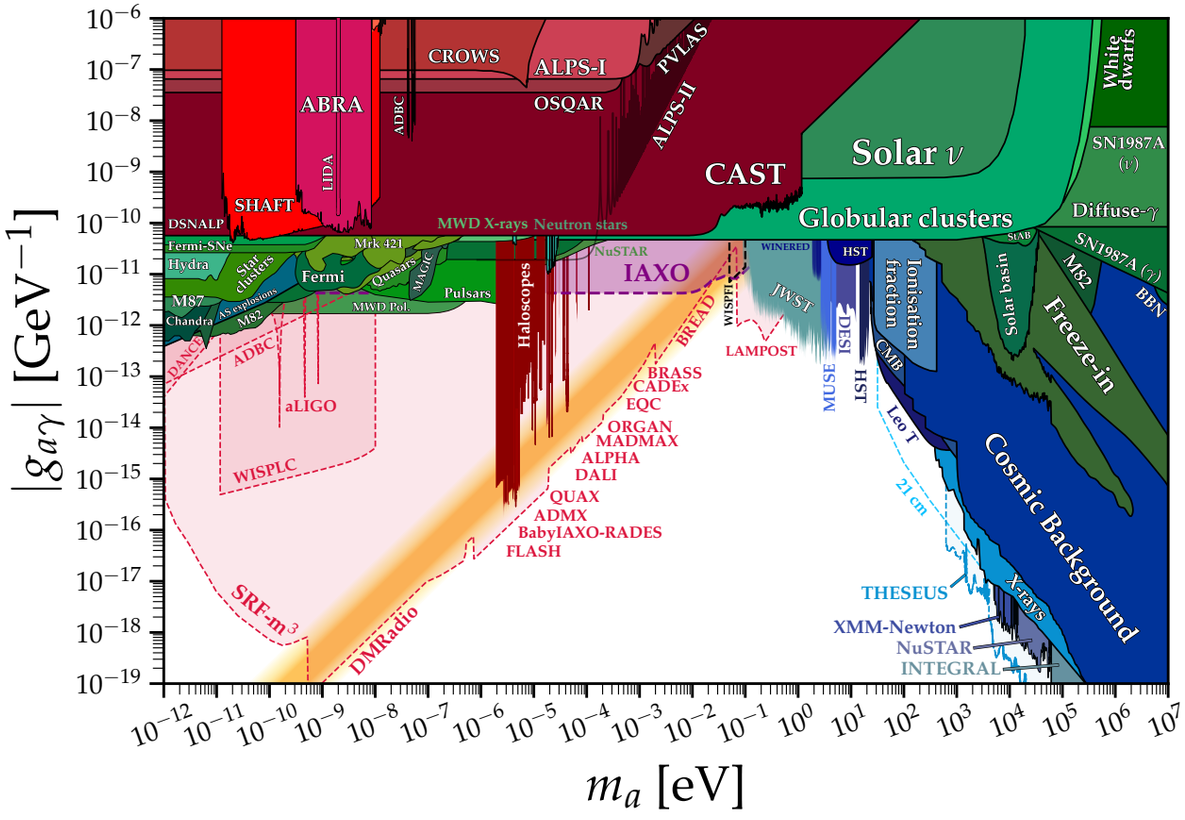
$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$



QCD axion:

at the minimum: $\theta G\tilde{G}$

$\theta \to 0$



O'Hare, **AxionLimits**

- Preskill, Wise, Wilczek, Phys. Lett. B **120** (1983) 127
- Abbott, Sikivie, Phys. Lett. B **120** (1983) 133
- Dine, Fischler, Phys. Lett. B 1**20** (1983) 137

When was Dark Matter Produced?

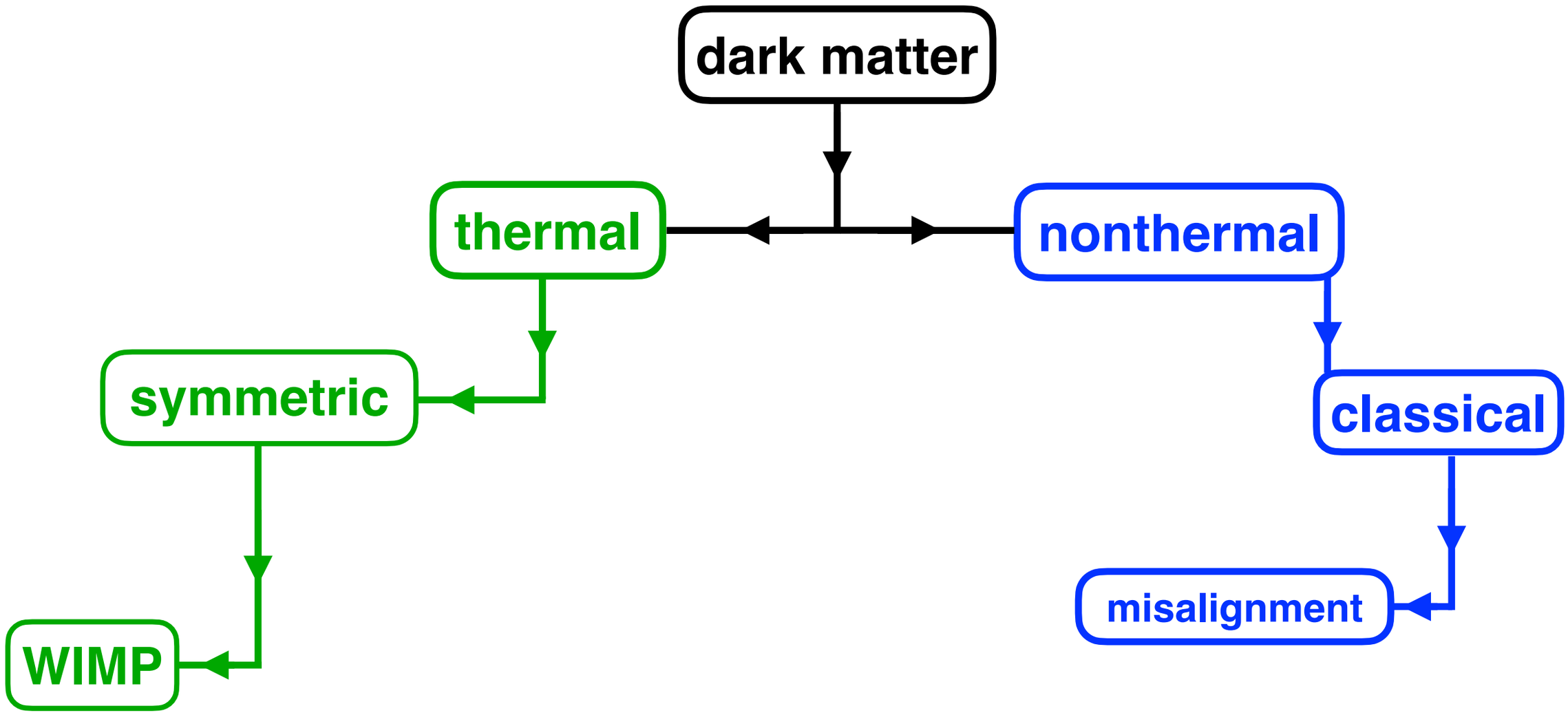


WIMP

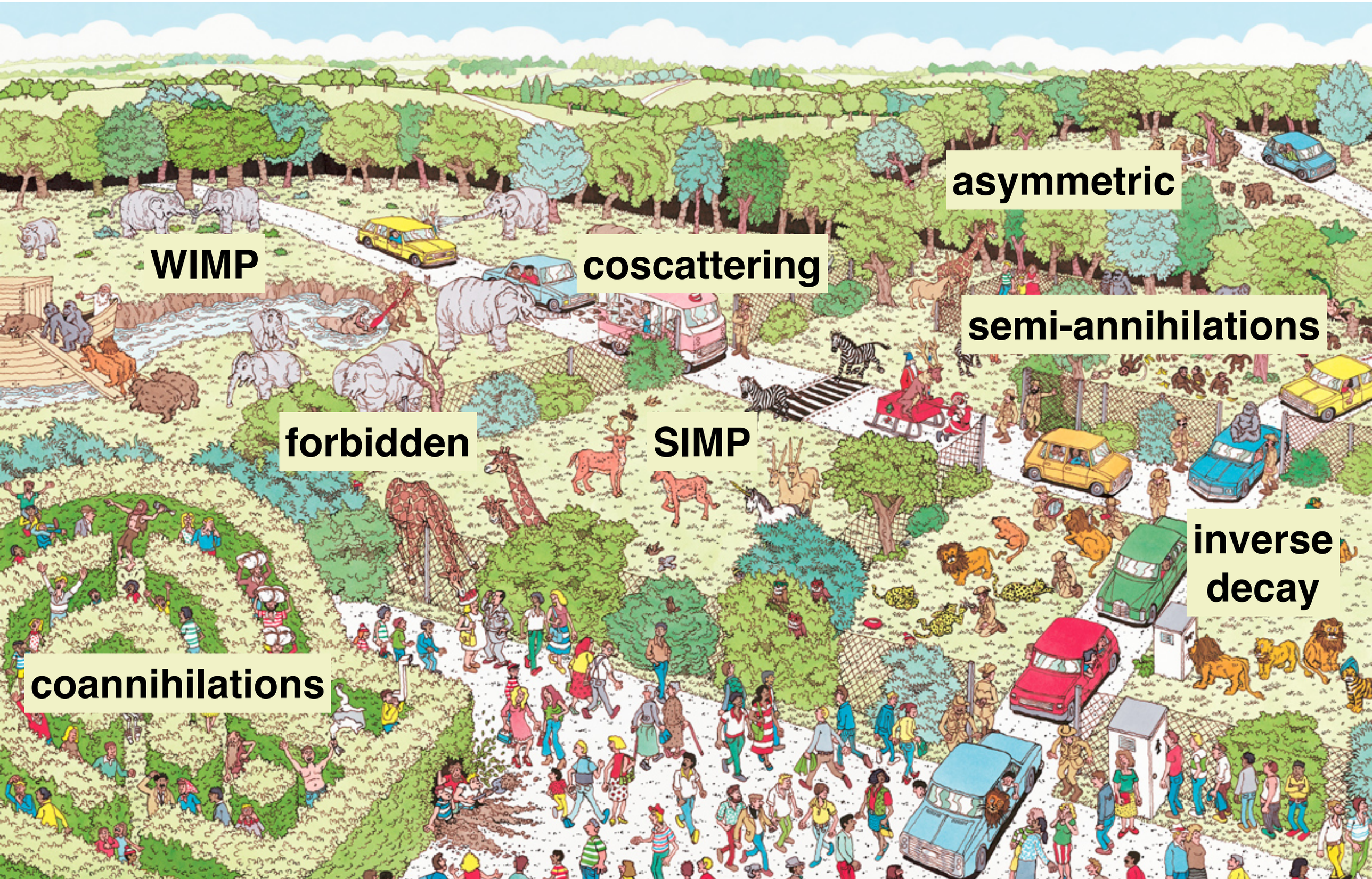
axion

$$T \sim \sqrt{M_{\rm pl}\, m_{\rm DM}(T)}$$

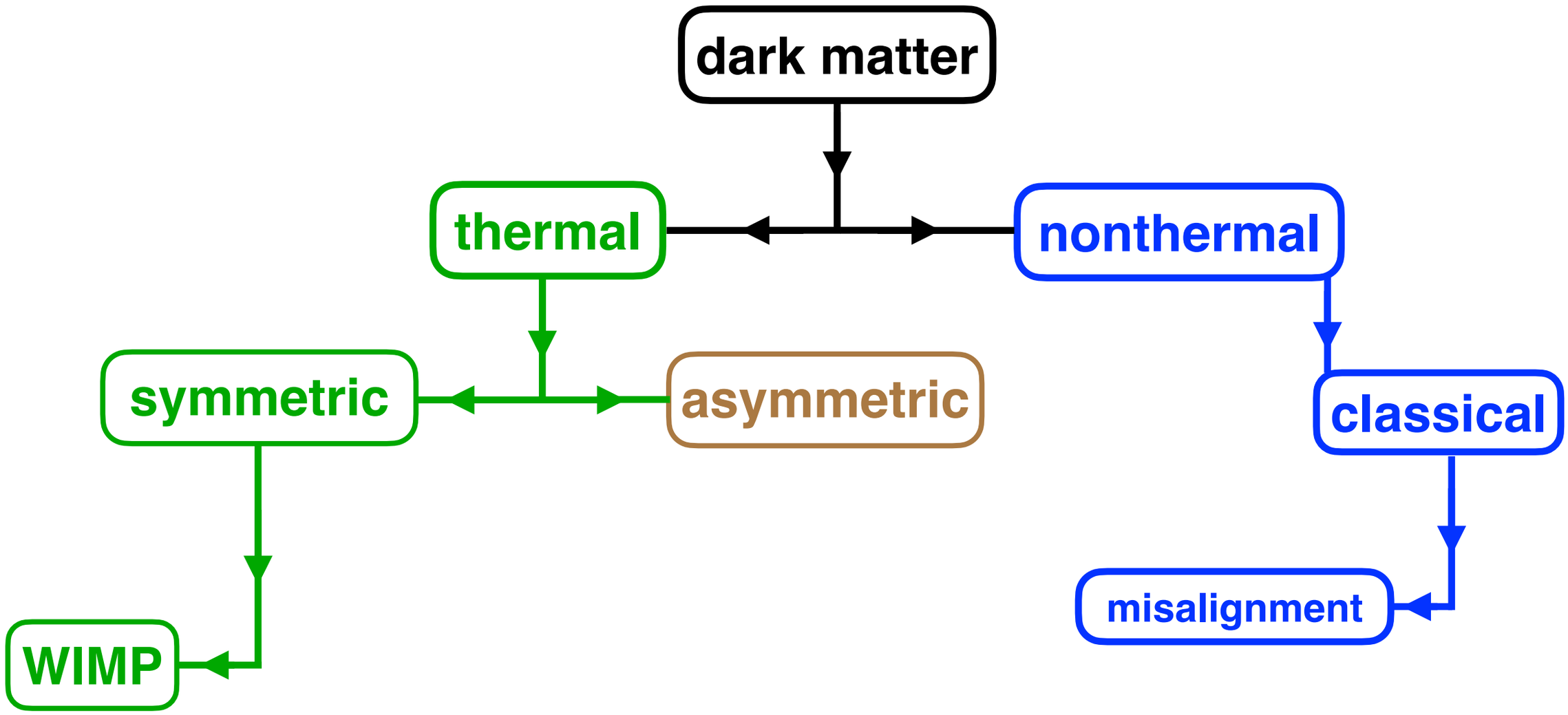
Cosmic Production Mechanisms



II. Thermal Relic Dark Matter



Cosmic Production Mechanisms

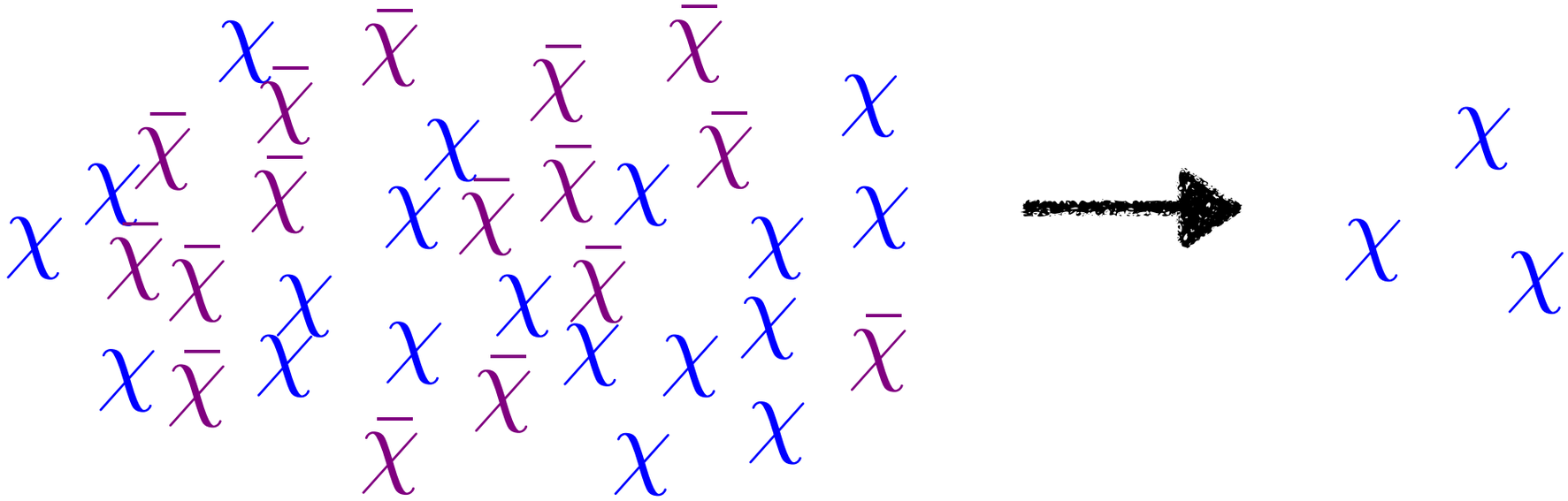


Asymmetric Dark Matter

DM: χ

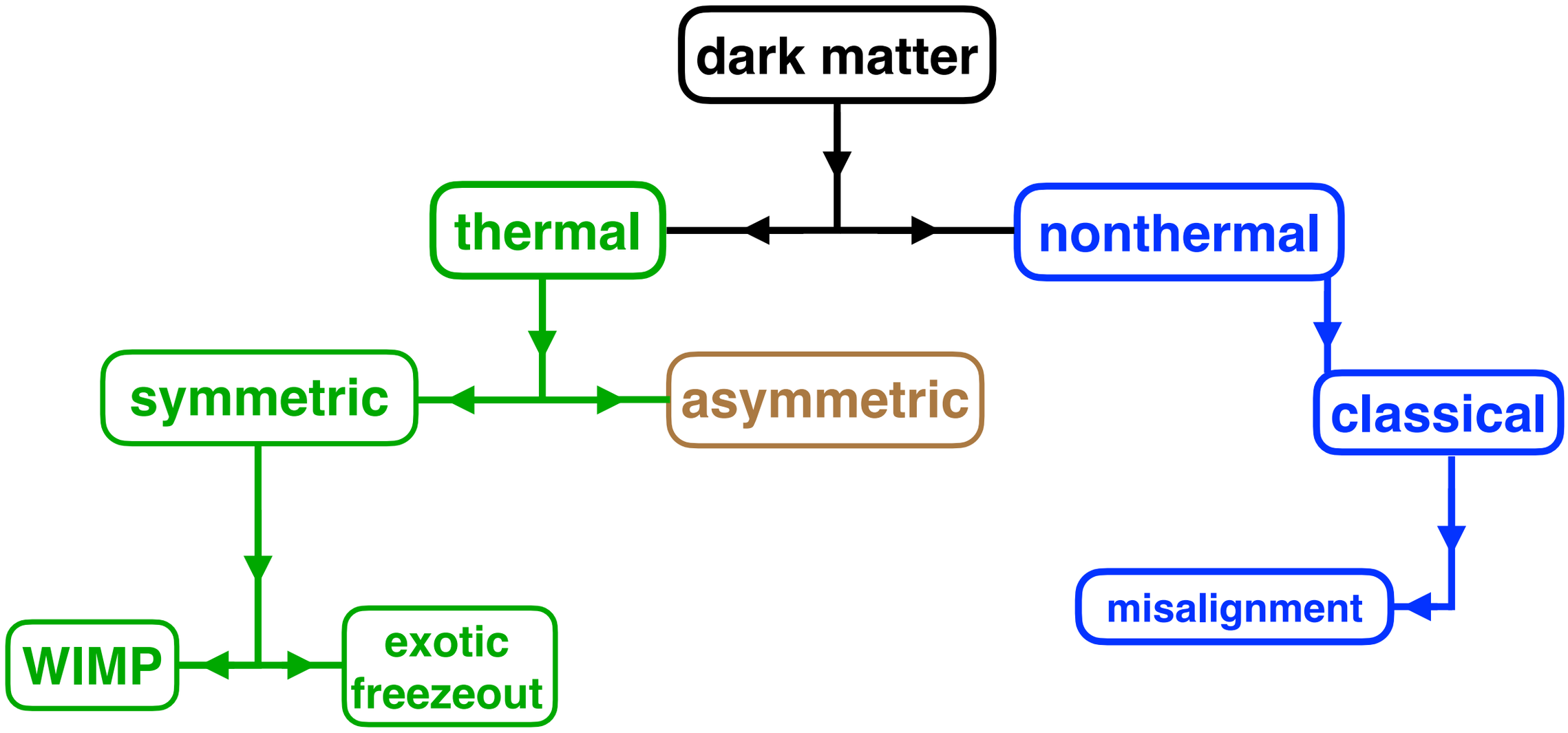
anti-DM: $\bar{\chi}$

$$n_\chi > n_{\bar{\chi}}$$

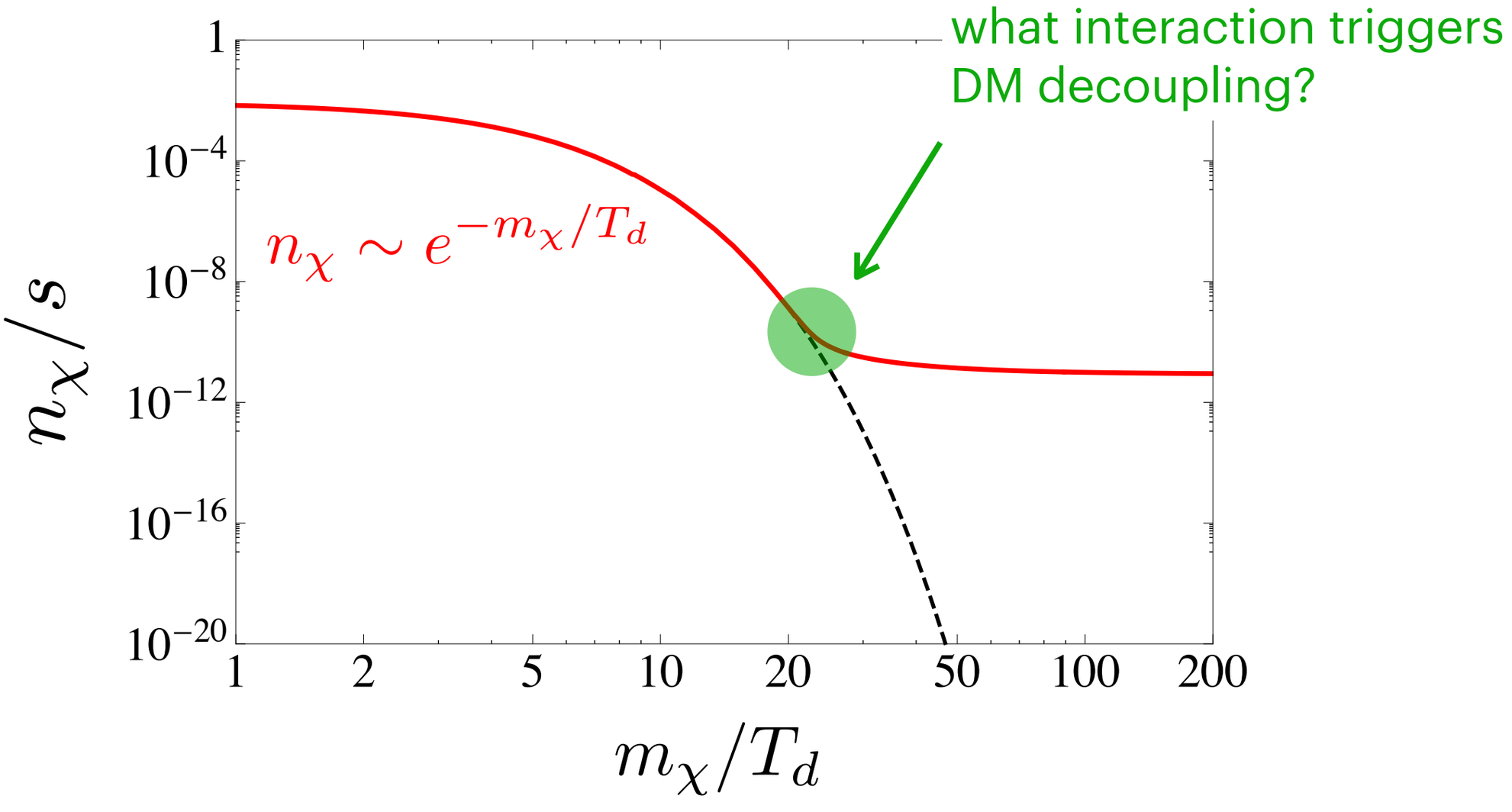


Kaplan, Luty, Zurek, **0901.4117**

Cosmic Production Mechanisms



Exotic Freezeout Processes

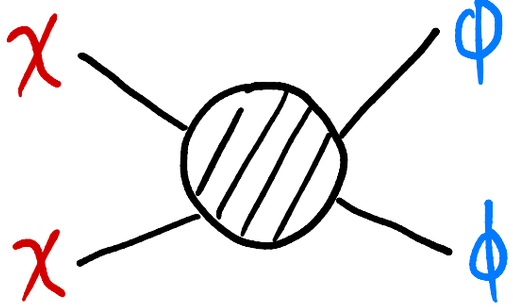


Exotic Freezeout Processes

forbidden

indirect

$m_\chi < m_\phi$

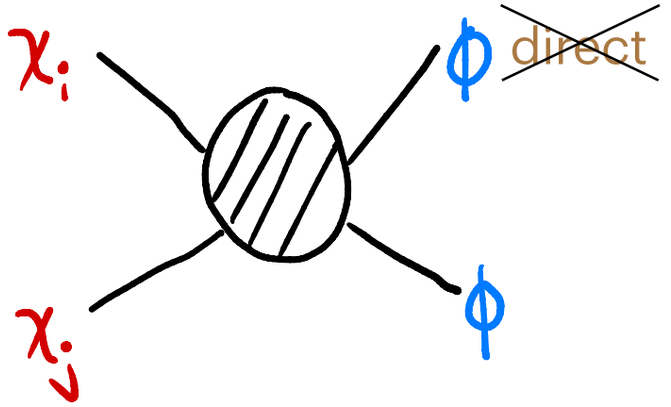


- Griest, Seckel 1991
- D'Agnolo, JTR **1505.07107**

coannihilations

indirect

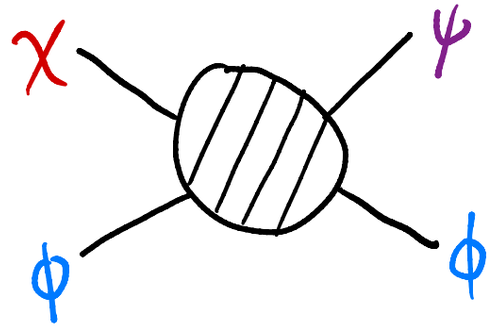
direct



- Griest, Seckel **1991**

coscattering

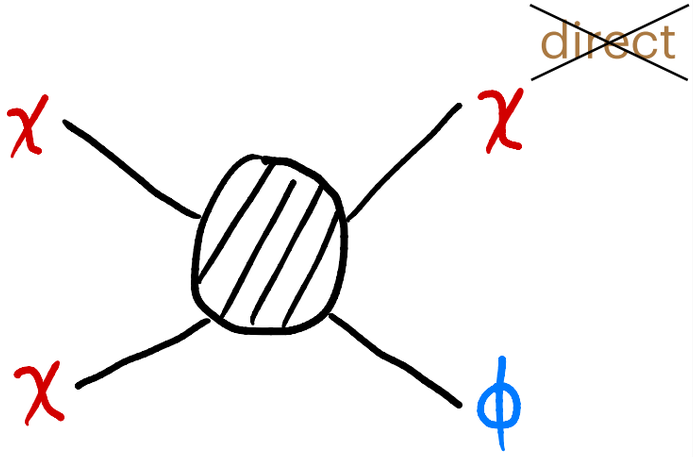
indirect



- D'Agnolo, Pappadopulo, JTR **1705.08450**

semi-annihilations

direct

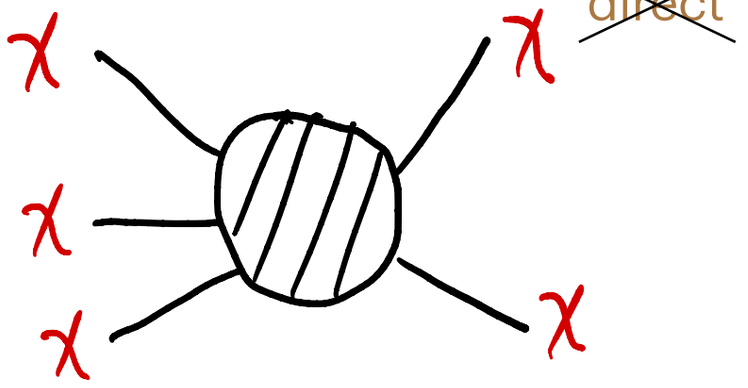


- D'Eramo, J. Thaler **1003.5912**

SIMP

indirect

direct

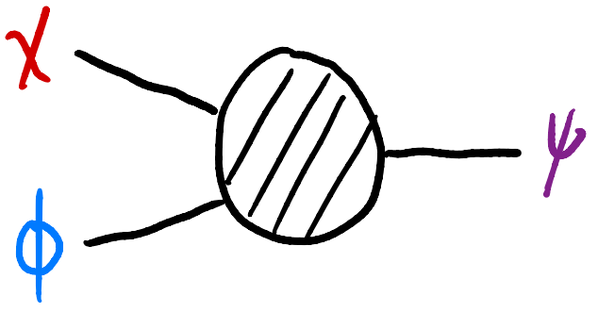


- Hochberg, Kuflik, Volansky, Wacker **1402.5143**

inverse decay

indirect

direct



- Frumkin, Hochberg, Kuflik, Murayama **2111.14857**

When was Dark Matter Produced?



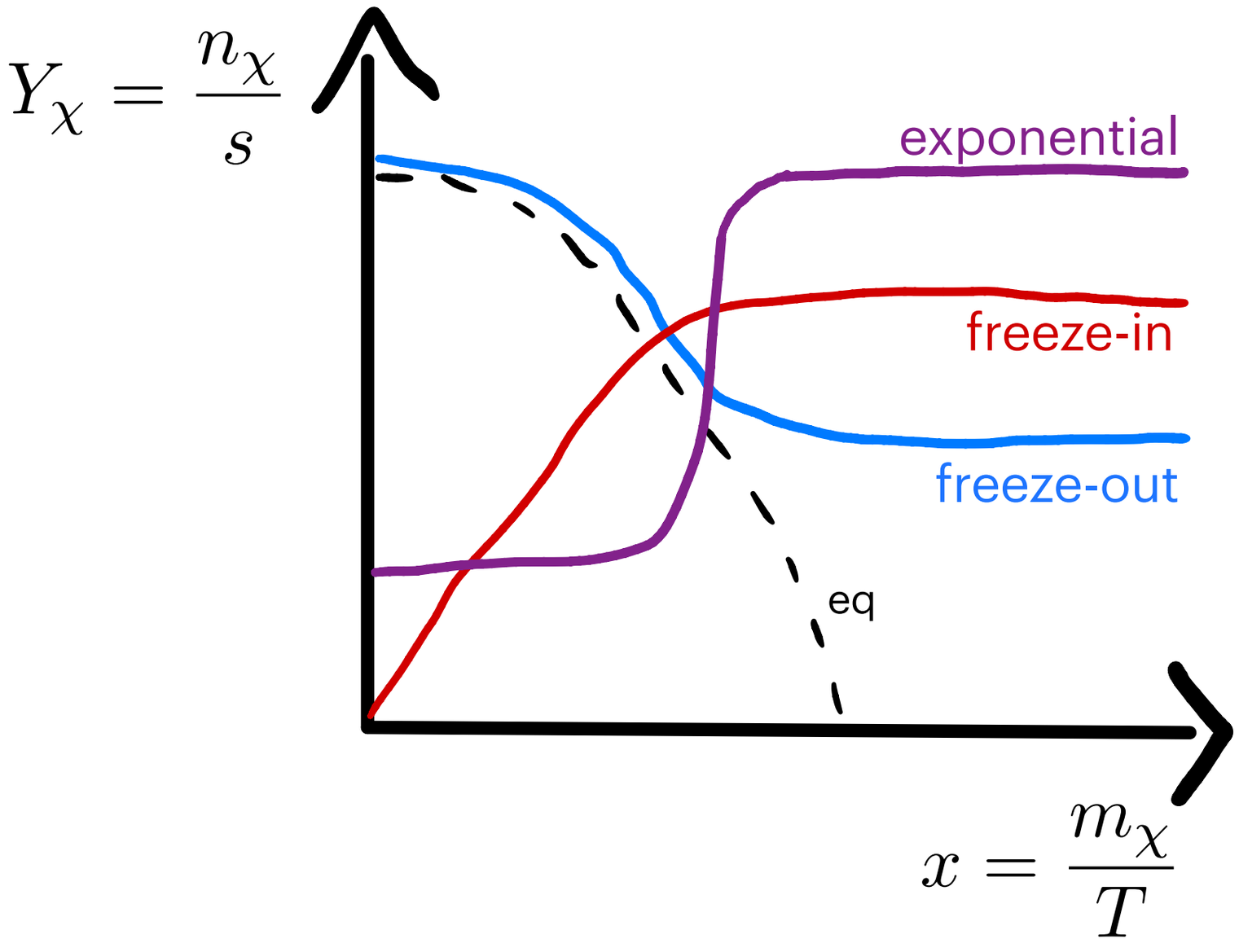
thermal relic

$$T \sim \frac{m_{\rm DM}}{20}$$

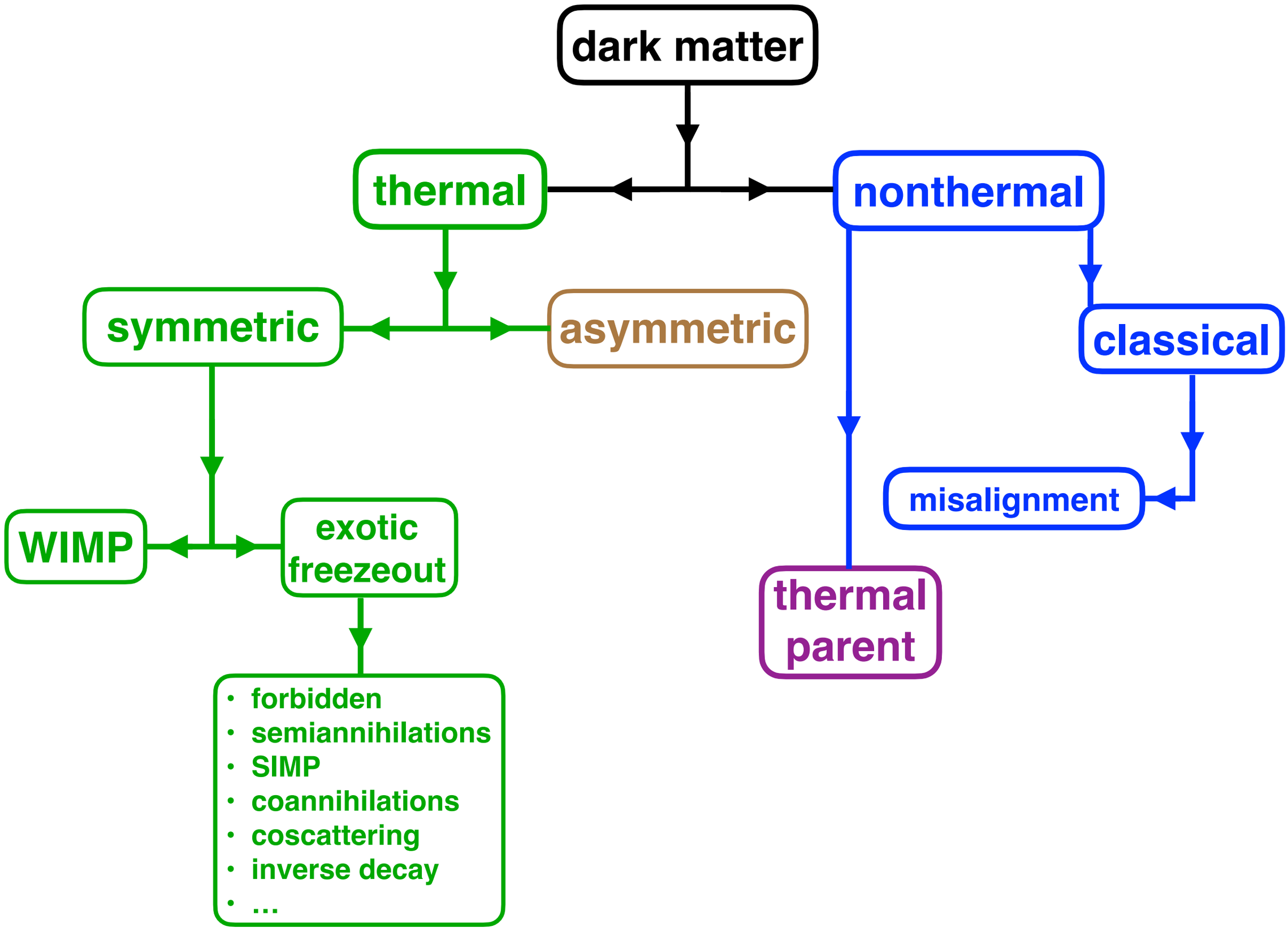
axion

$$T \sim \sqrt{M_{\rm pl}\, m_{\rm DM}(T)}$$

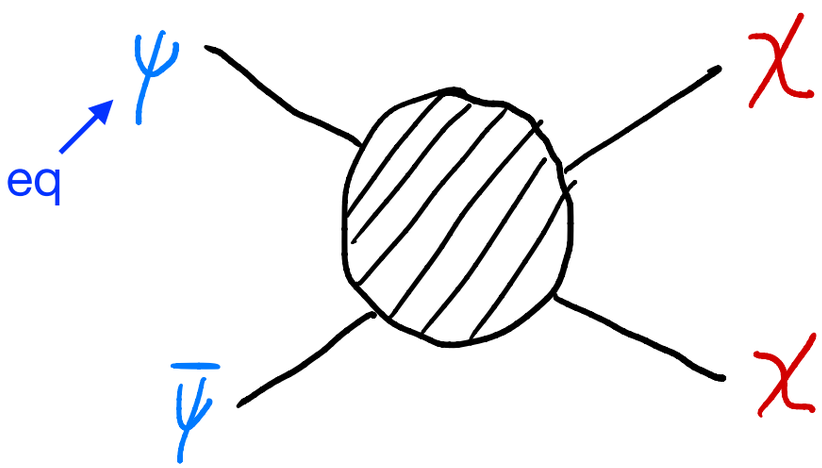
III. Feebly Interacting Dark Matter



Cosmic Production Mechanisms

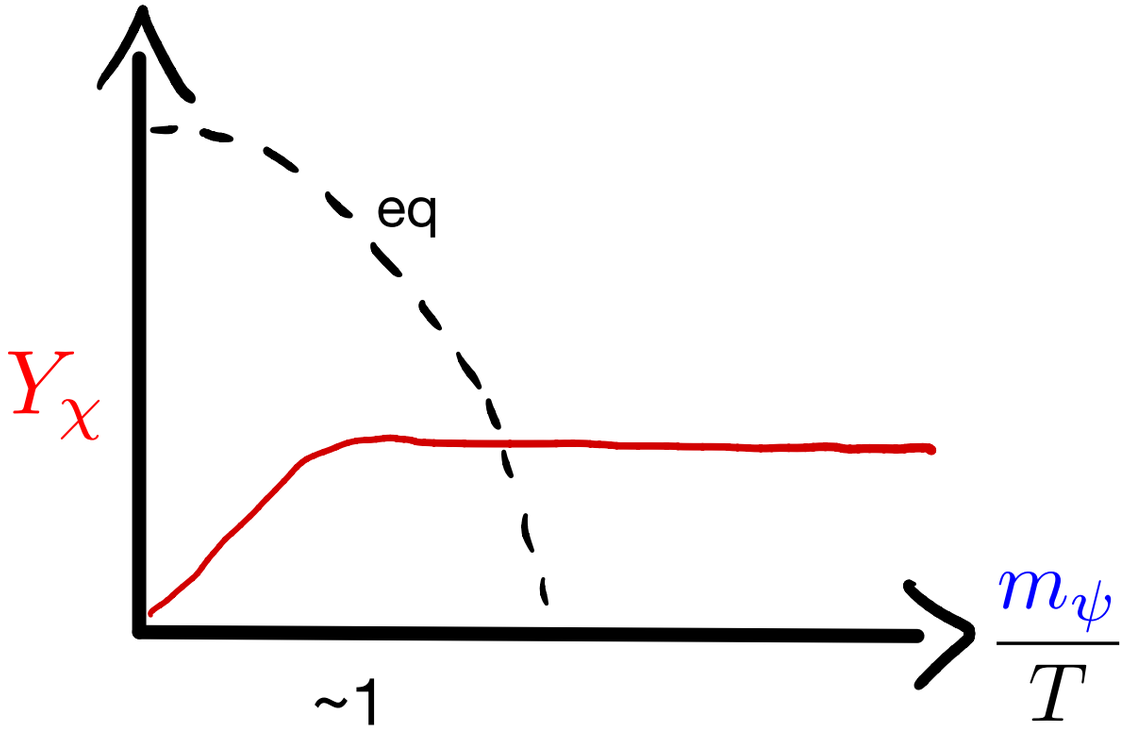


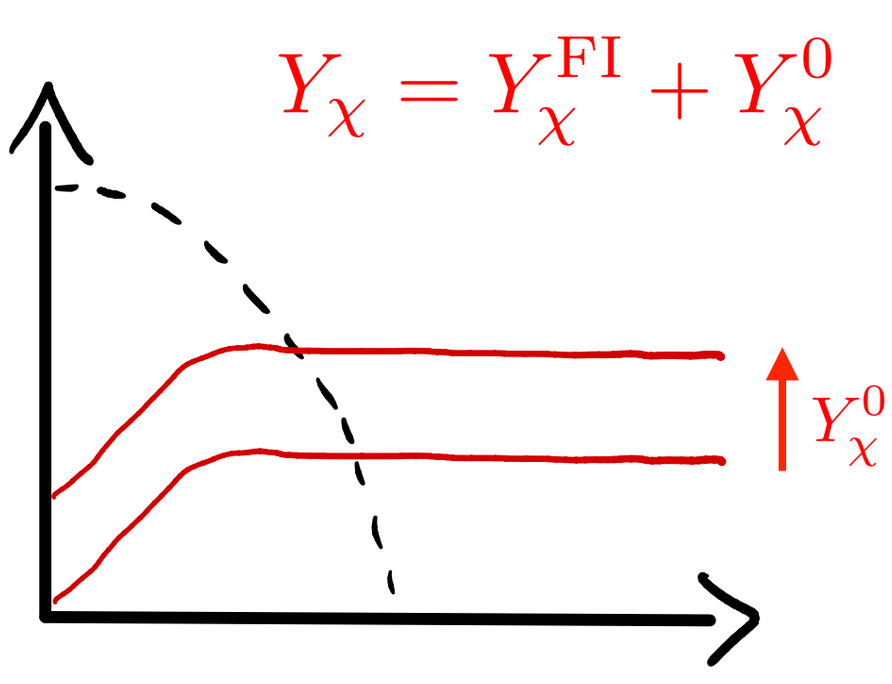
Freeze-In



$$\dot{n}_\chi + 3Hn_\chi = (n_\psi^{eq})^2 \langle \sigma v \rangle$$

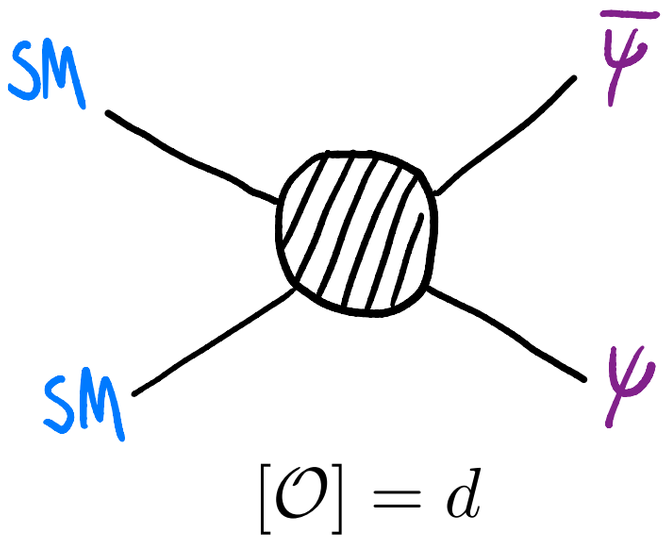
sensitive to initial condition:





Hall, Jedamzik, March-Russell, West, **0911.1120**

IR vs. UV Freeze-In



$$[\mathcal{O}] = d$$

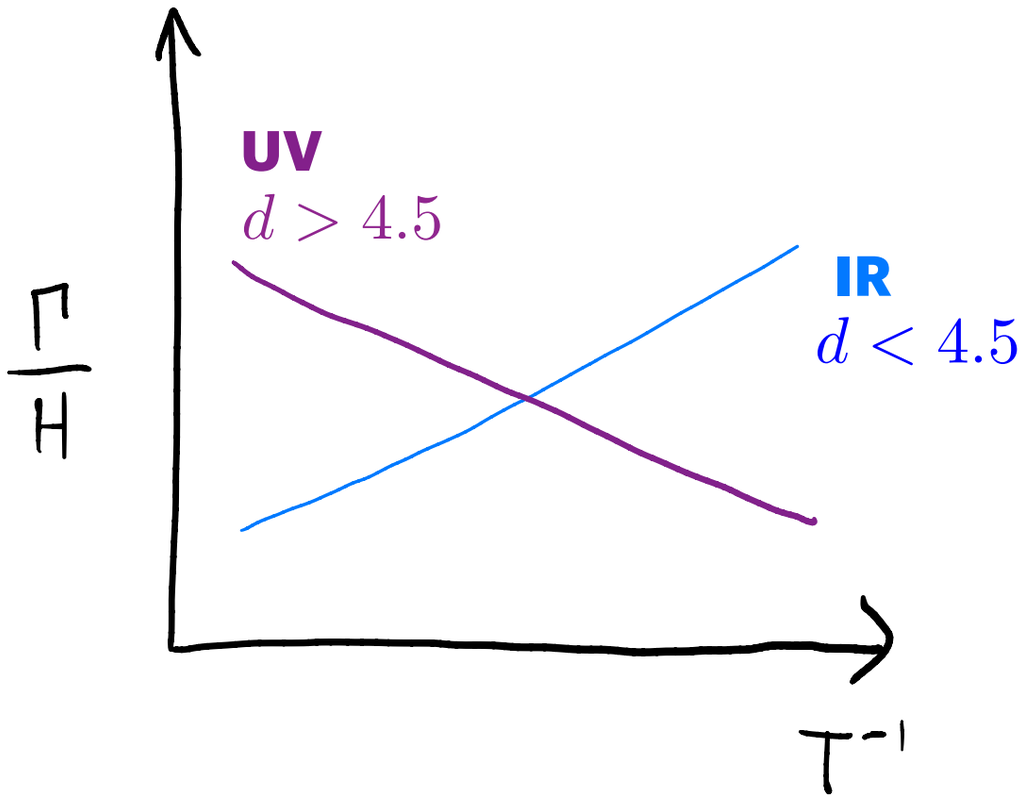
$$\frac{\Gamma}{H} \sim \frac{M_{pl}}{\Lambda^{2(d-4)}} T^{2(d-4)-1}$$

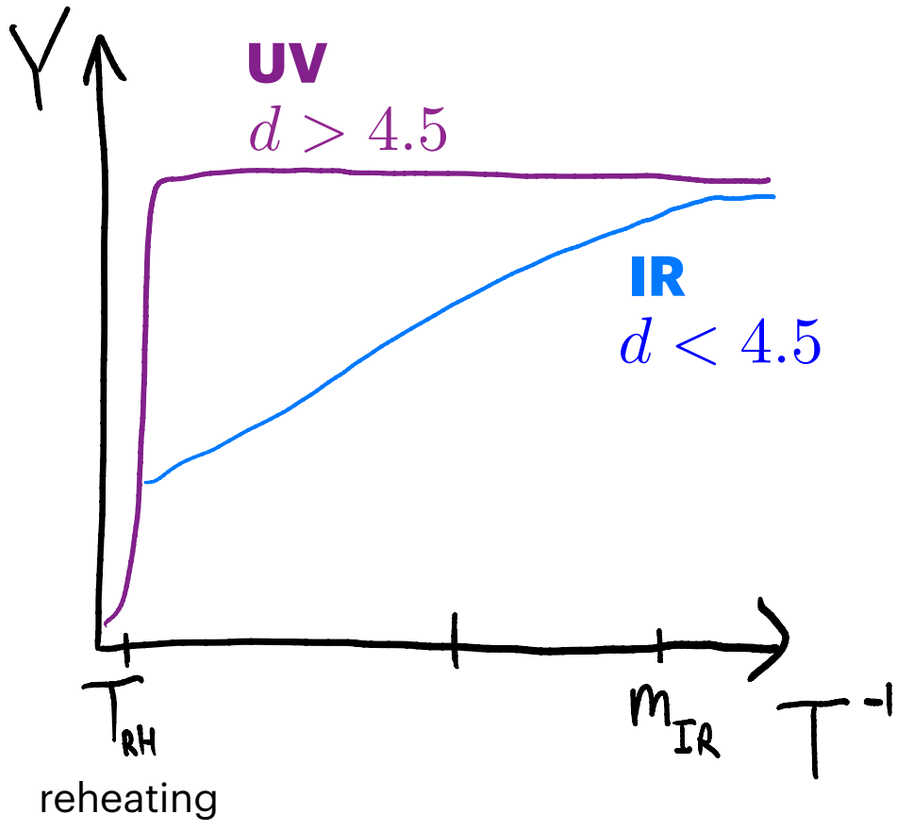
IR-dominated: $d < 4.5$ ex) Yukawa



UV-dominated: $d > 4.5$ ex) 4-Fermi







reheating

When was Dark Matter Produced?



thermal relic

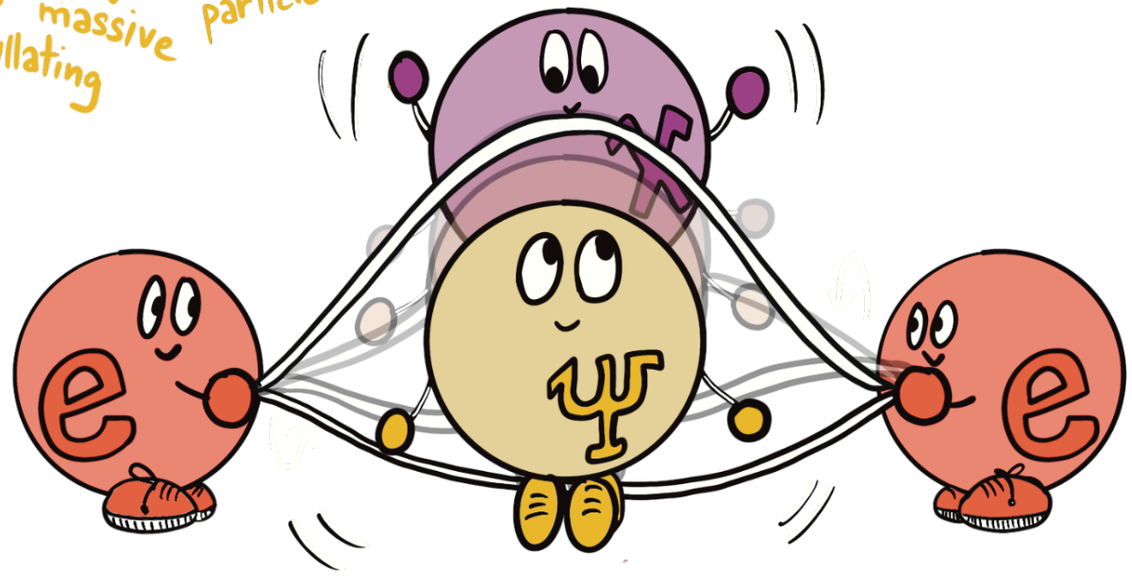
freeze-in
$d \leq 4$

axion

UV freeze-in
$d > 4$

ROMP DARK MATTER

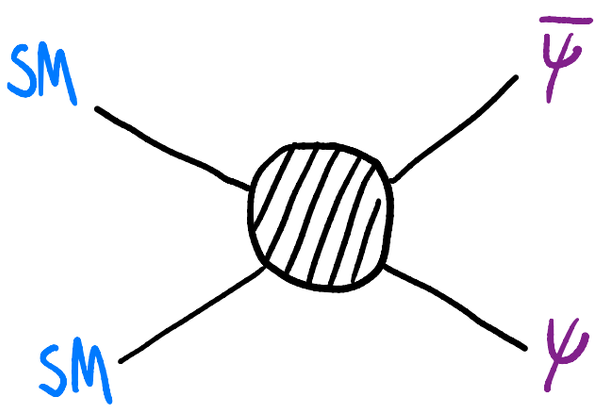
rapidly oscillating massive particle

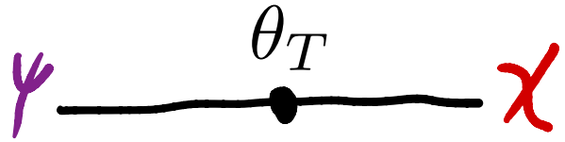


David Dunsky, Saniya Heeba, JTR

ROMP

Rapidly **O**scillating **M**assive **P**article



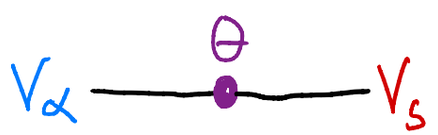


ex) sterile neutrinos

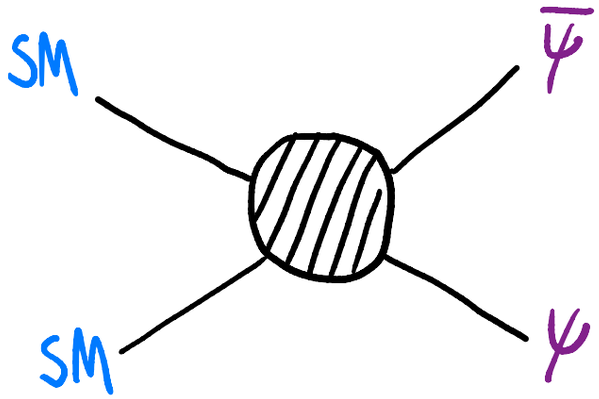
(Dodelson & Widrow, **hep-ph/9303287**)

$$\psi \to \nu_\alpha$$

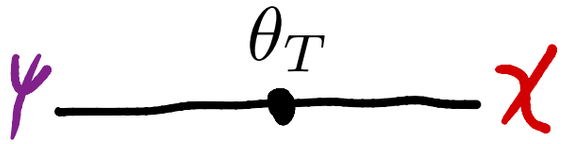
$$G_F\, \bar{\nu}_\alpha \gamma^\mu \nu_\alpha\, \bar{e}_L \gamma_\mu e_L$$



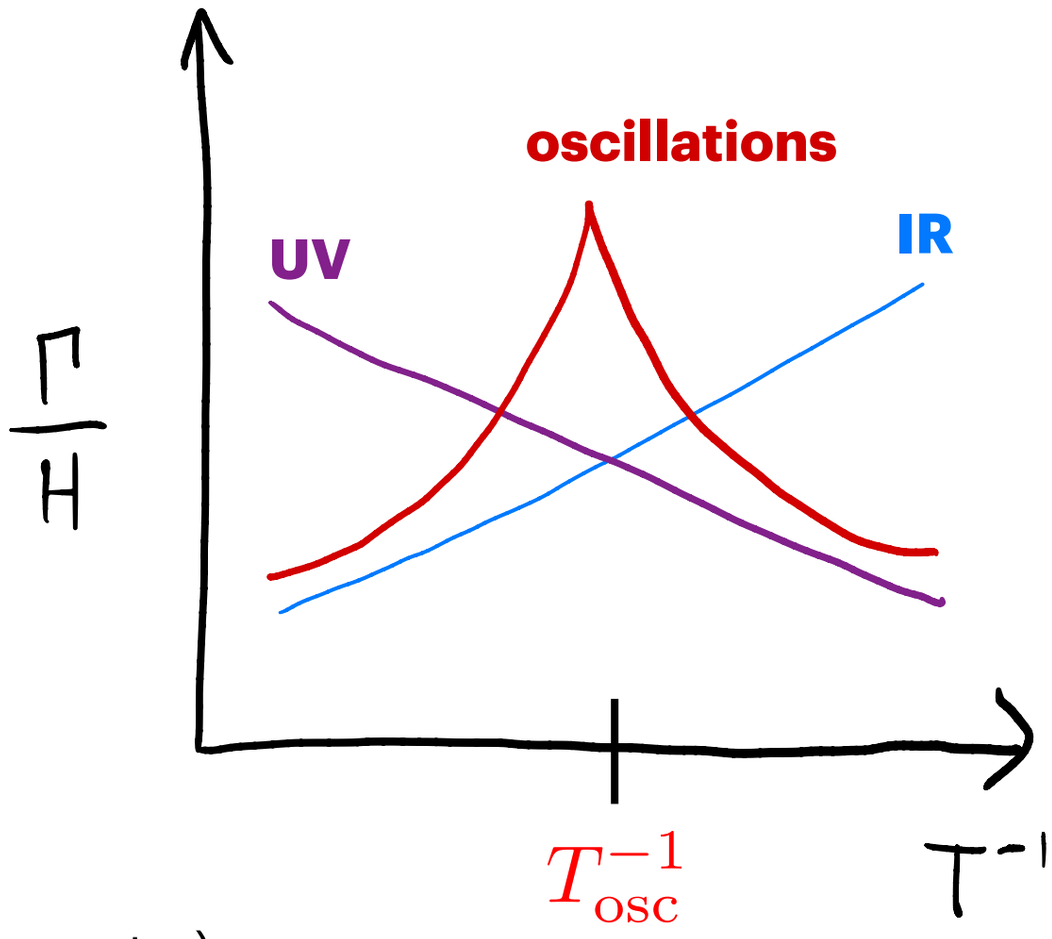
ROMP Production



$$[\mathcal{O}] = d$$



$$\frac{\Gamma}{H} \sim \frac{M_{pl}}{\Lambda^{2(d-4)}} \theta_T^2 \, T^{2(d-4)-1}$$



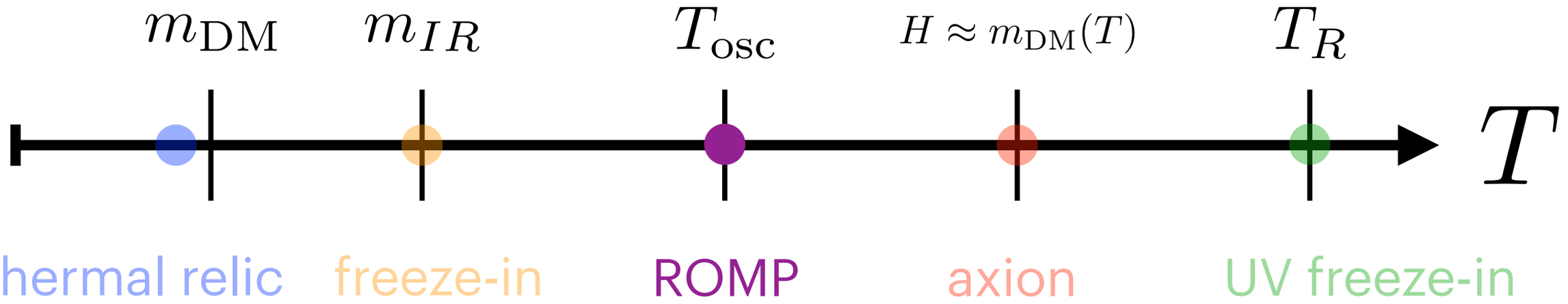
- at high temperatures: $\theta_T \propto T^{-n}$

(power depends on operator)

- UV production shuts off when: $n \geq d - 4$

- for sterile neutrinos: $G_F \, \bar{\nu}_\alpha \gamma^\mu \nu_\alpha \, \bar{e}_L \gamma_\mu e_L$ $\quad d = 6, \; n = 6 \quad \rightarrow \quad \frac{\Gamma}{H} \propto T^{-9}$

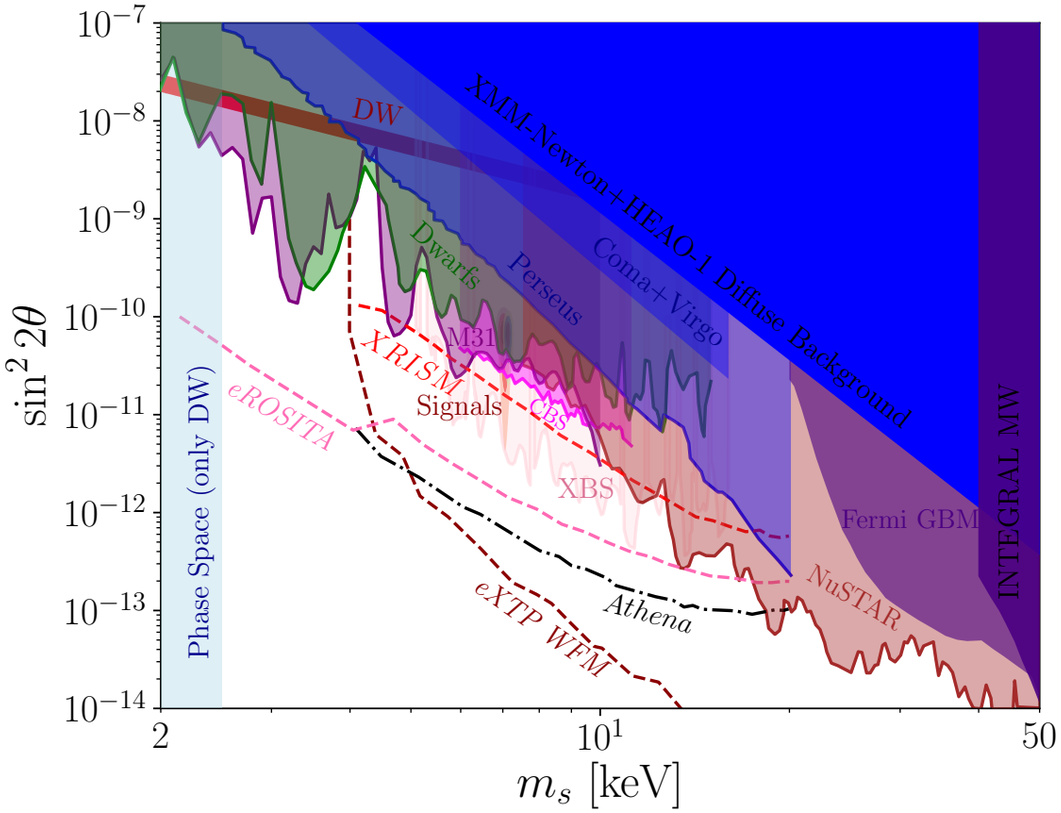
When was Dark Matter Produced?



$$T_{\rm osc} \sim m_{\rm IR}^{2/n} \Lambda^{1-2/n}$$

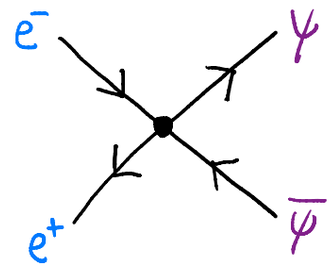
Sterile Neutrino and Beyond

sterile neutrino

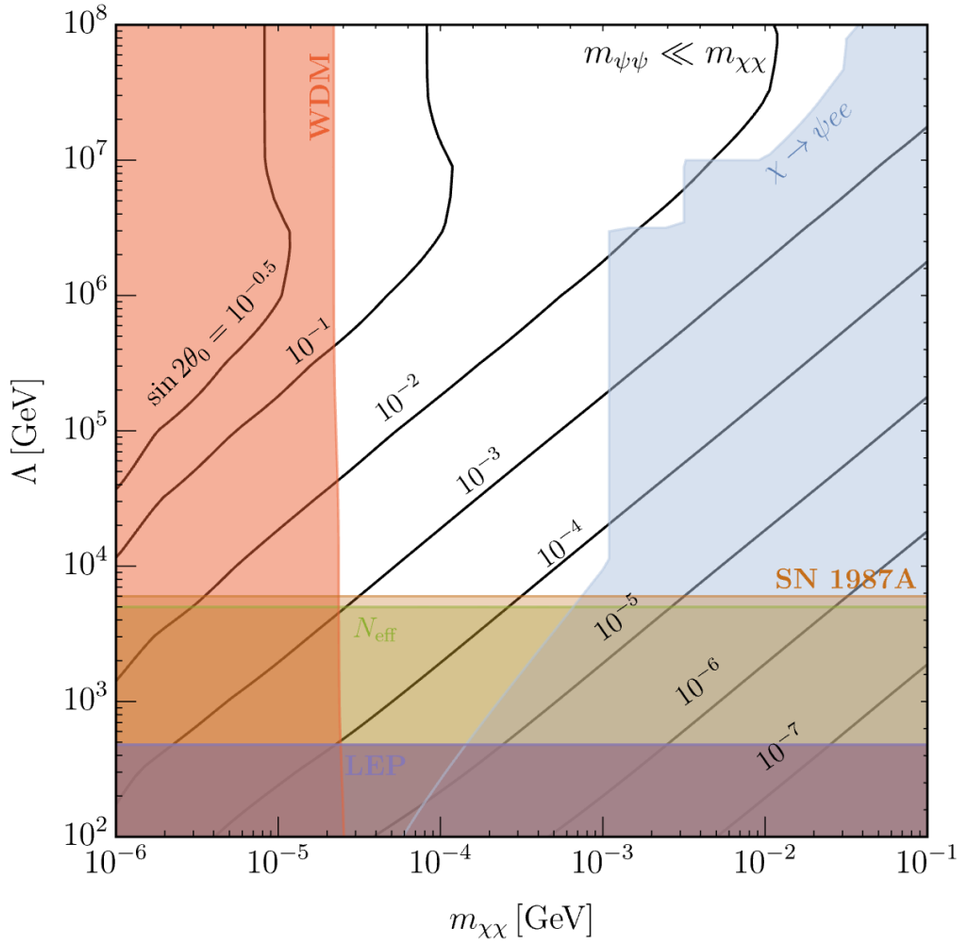


Snowmass, **2203.07377**

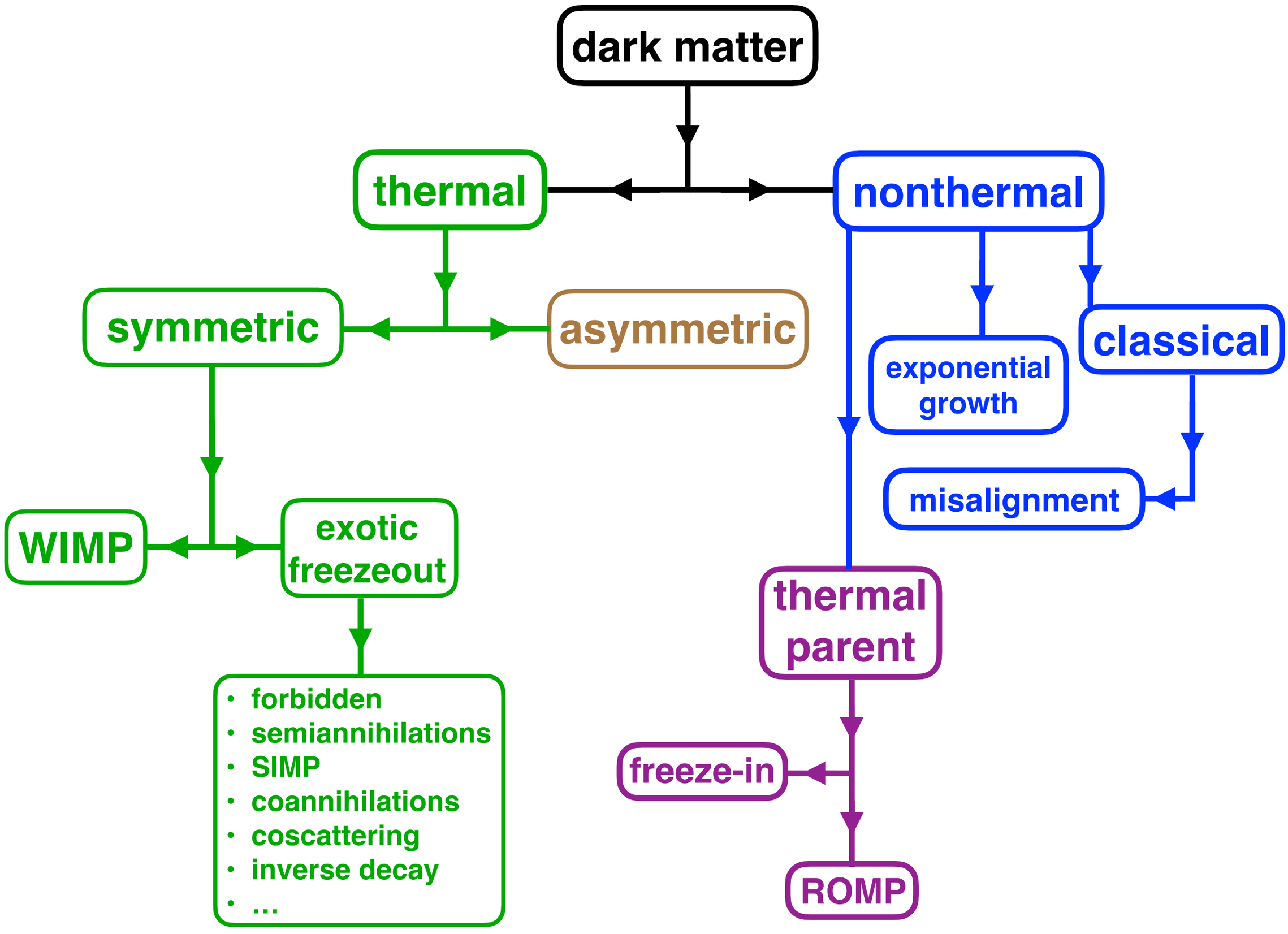
new state w/ new operator



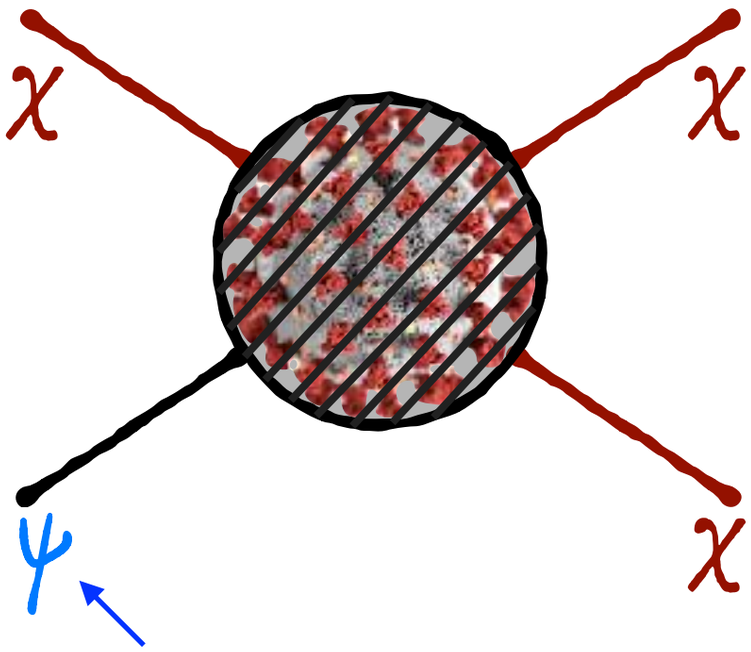
$$\mathcal{L} \supset \frac{\bar{e}_L \gamma^\mu e_L \, \bar{\psi}_L \gamma_\mu \psi_L}{\Lambda^2}$$

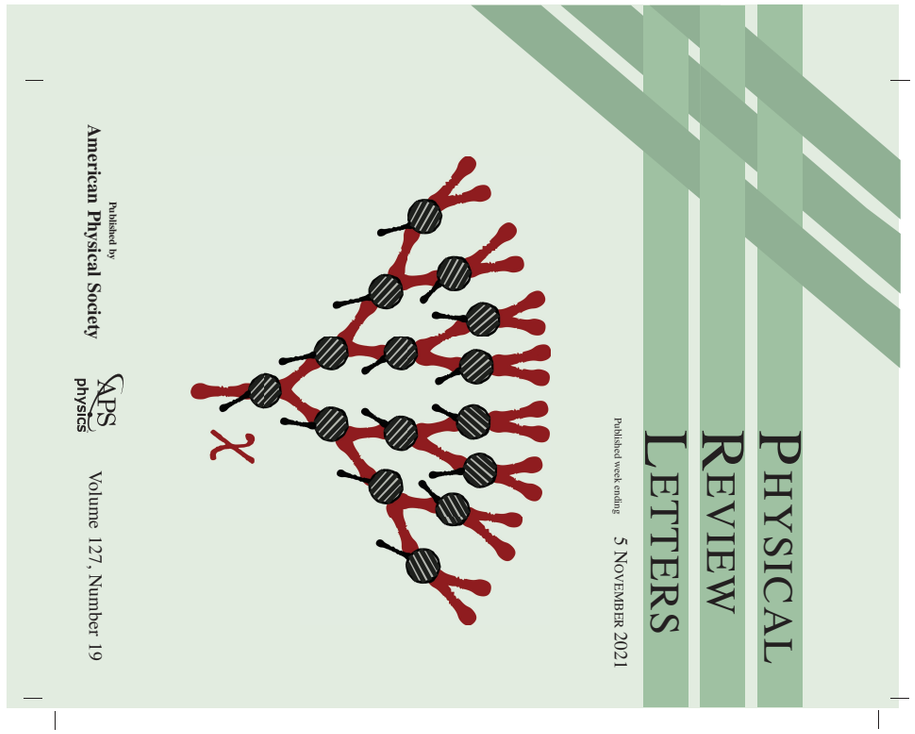


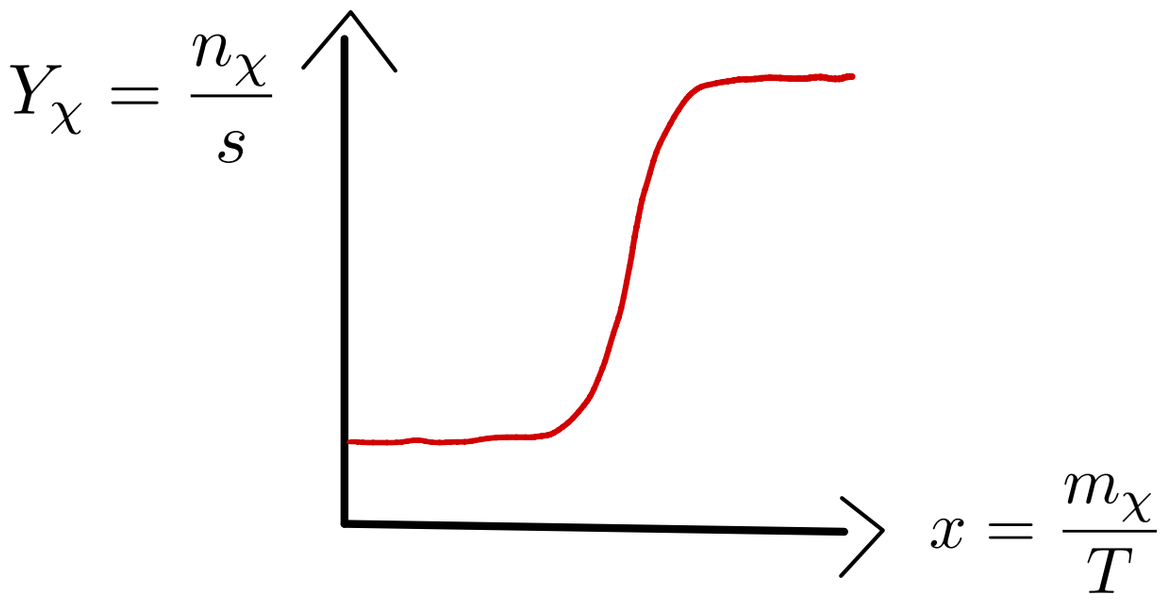
Cosmic Production Mechanisms



Exponentially Growing Dark Matter

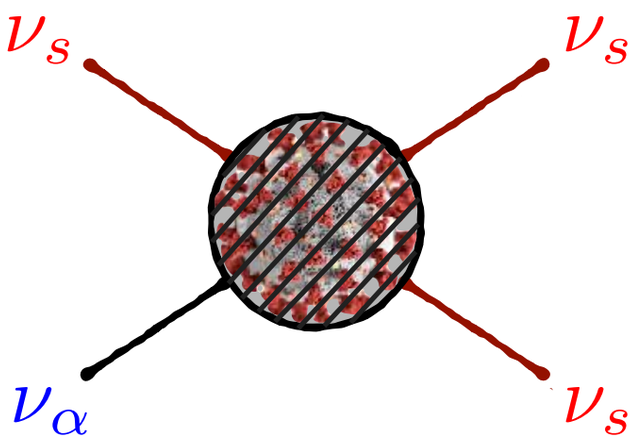




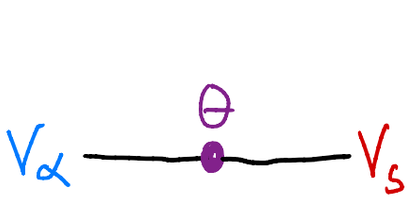


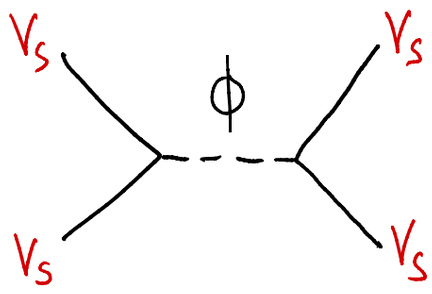
Bringmann, Depta, Hufnagel, JTR, Schmidt-Hoberg **2103.16572**

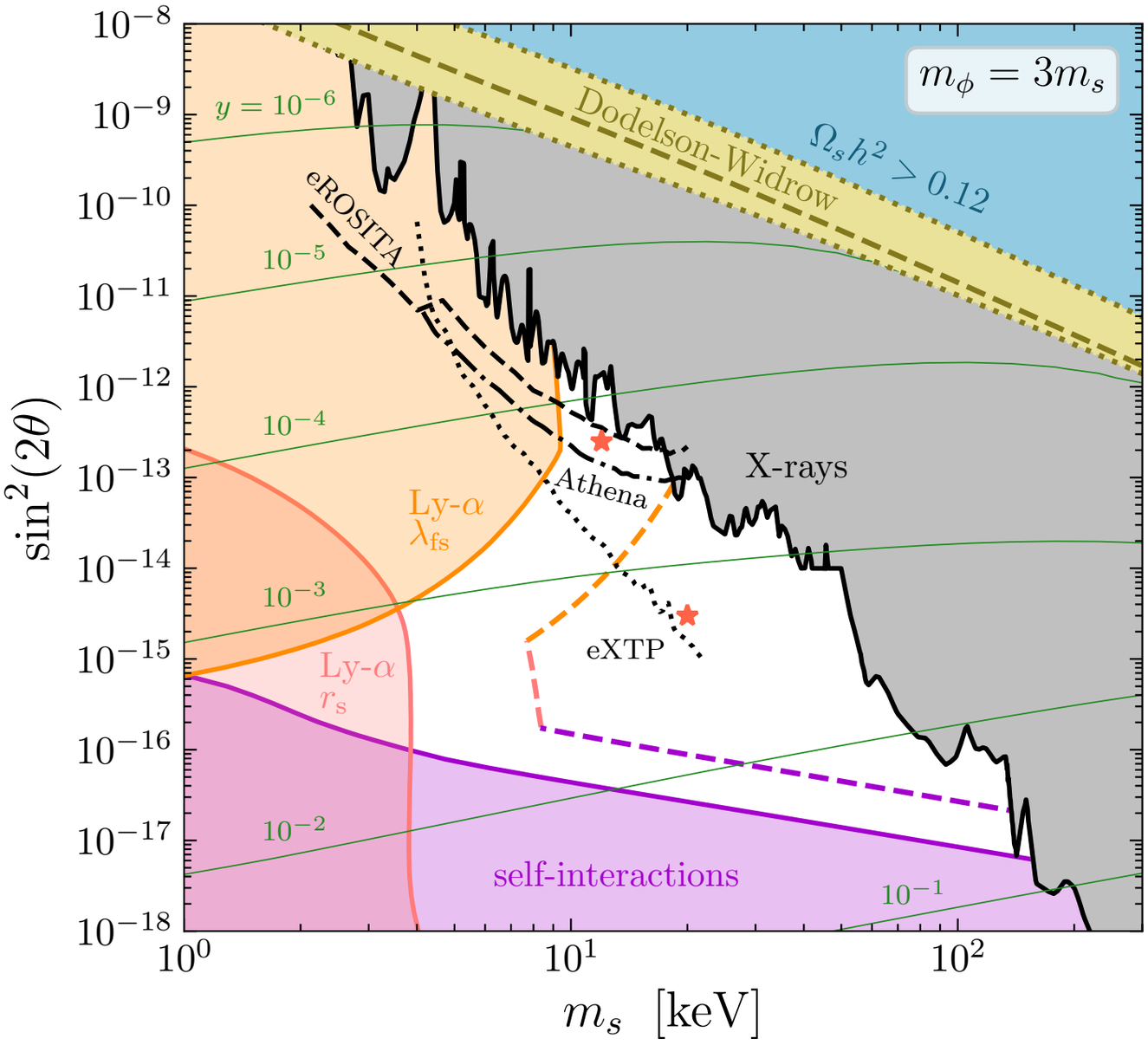
Sterile Neutrinos from Exponential Growth



growth reaction generated if sterile ν have self-interactions:

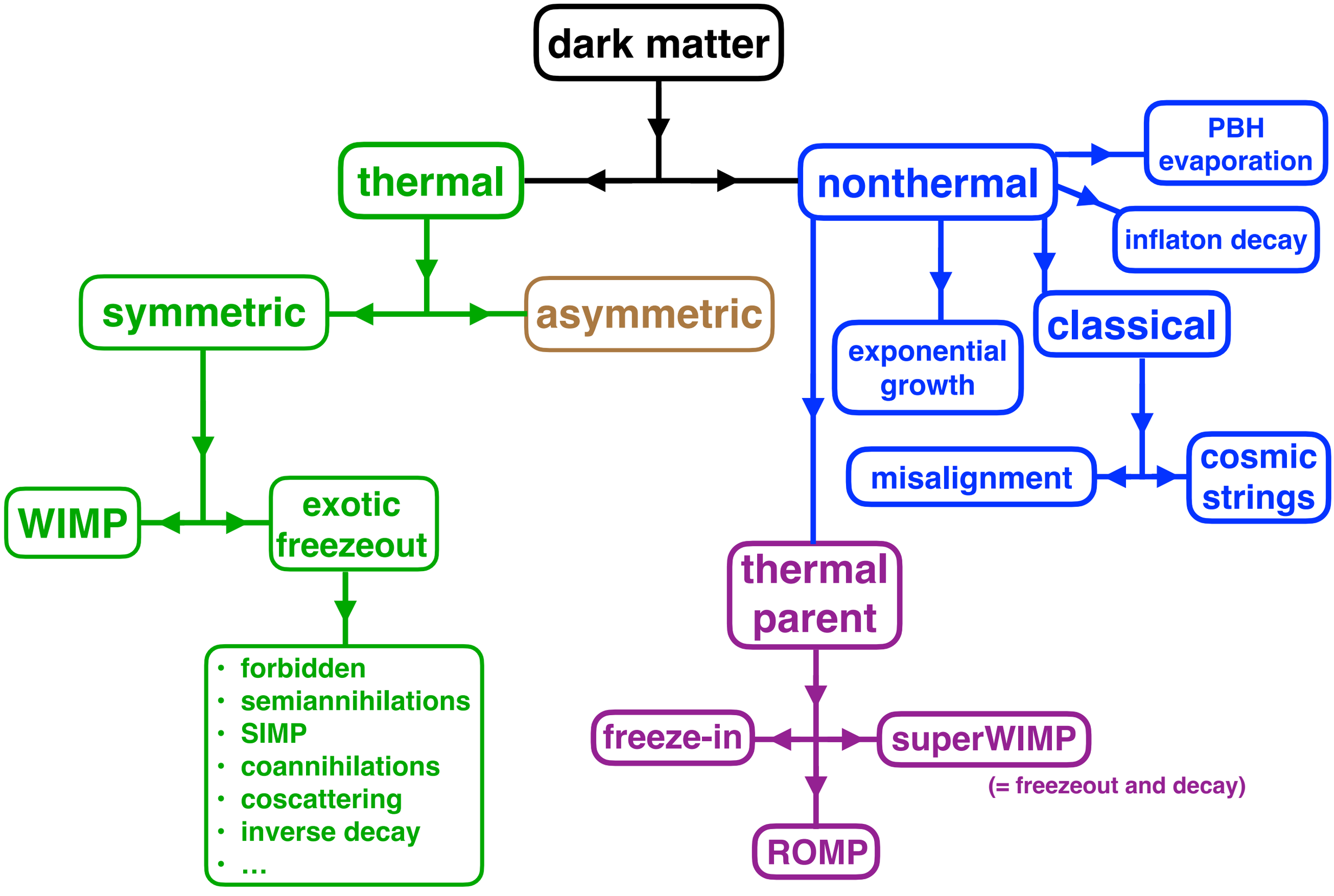


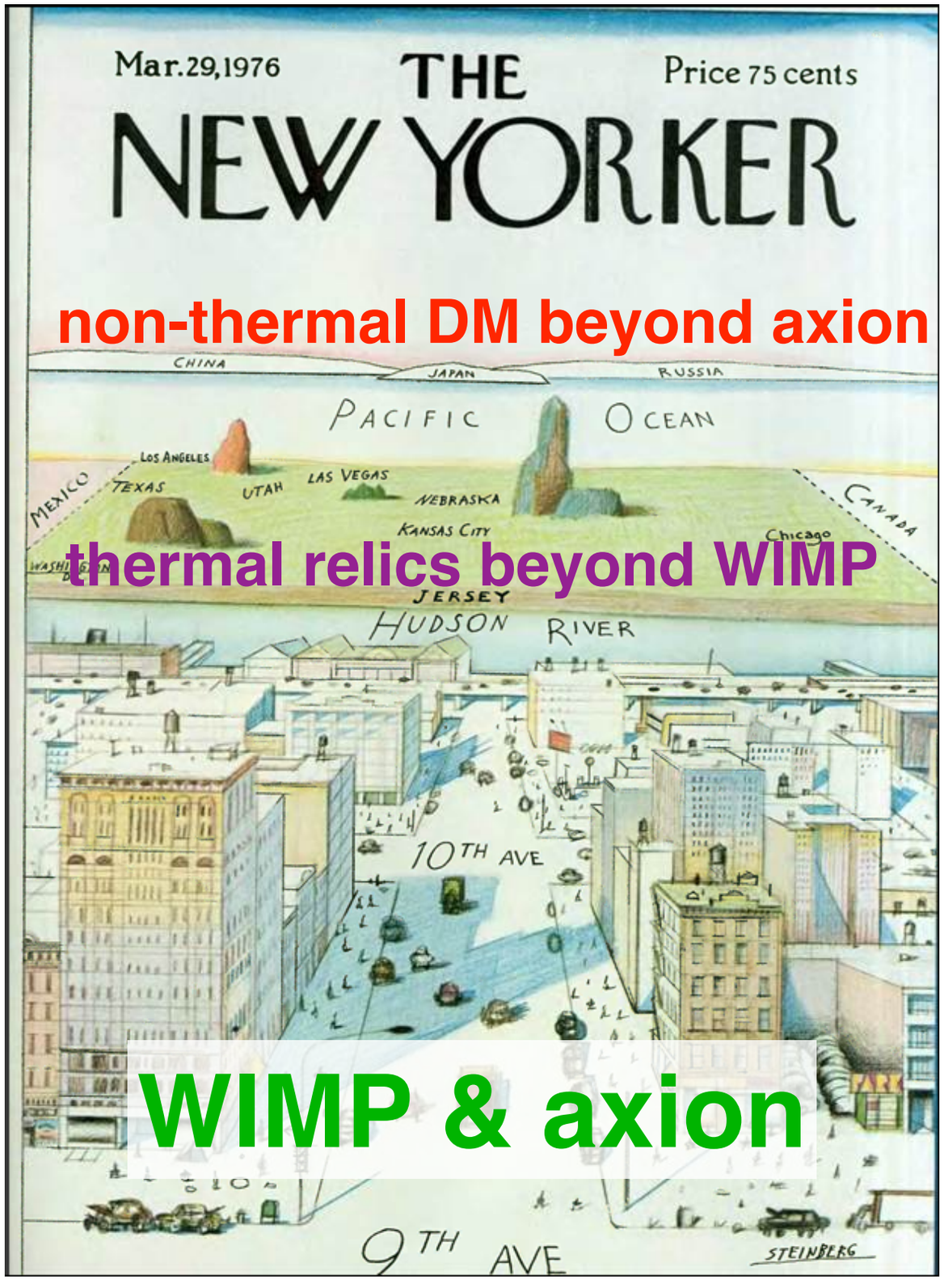




Bringmann, Depta, Hufnagel, Kersten, JTR, Schmidt-Hoberg **2206.10630**

Cosmic Production Mechanisms



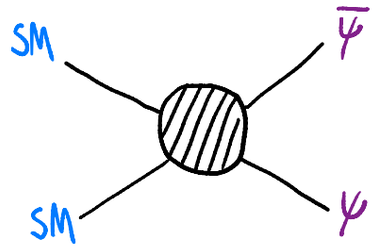


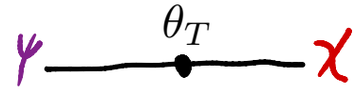
non-thermal DM beyond axion

thermal relics beyond WIMP

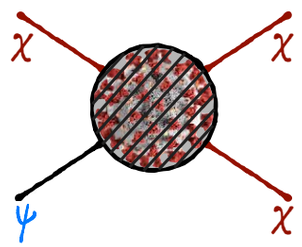
WIMP & axion

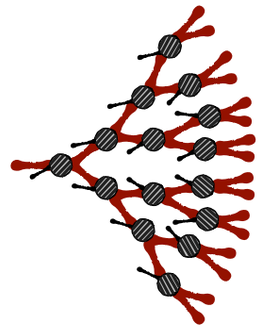
ROMPs:



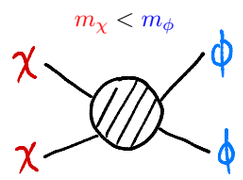


ExpDM:



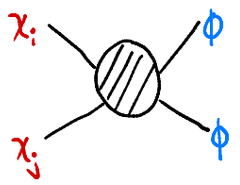


forbidden



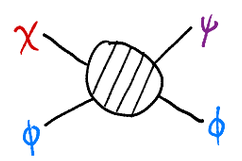
- Griest, Seckel 1991
- D'Agnolo, JTR **1505.07107**

coannihilations



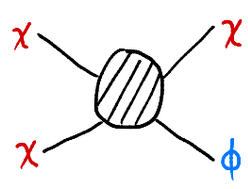
- Griest, Seckel **1991**

coscattering



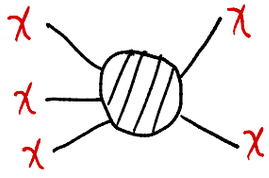
- D'Agnolo, Pappadopulo, JTR **1705.08450**

semi-annihilations



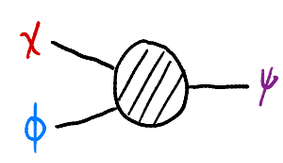
- D'Eramo, J. Thaler **1003.5912**

SIMP

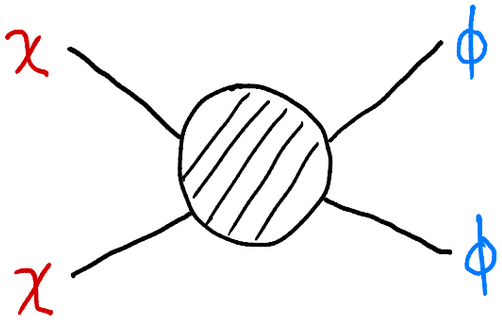


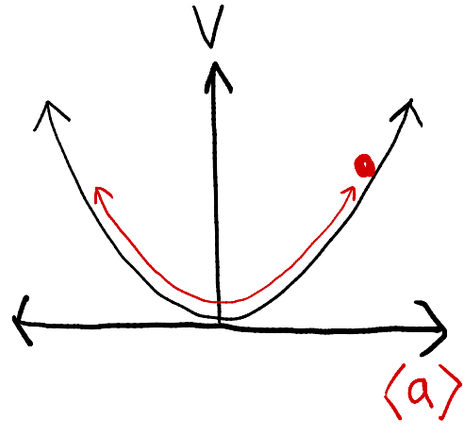
- Hochberg, Kuflik, Volansky, Wacker **1402.5143**

inverse decay



- Frumkin, Hochberg, Kuflik, Murayama **2111.14857**







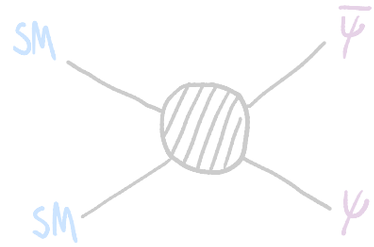
non-thermal DM beyond axion

thermal relics bey

thanks!!!

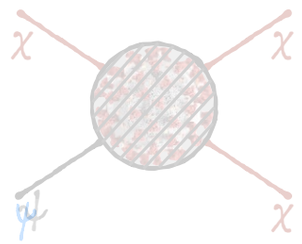
WIMP & axion

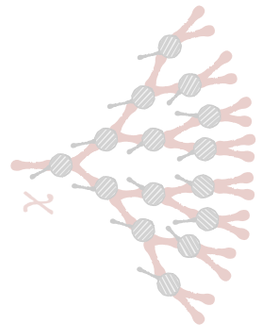
ROMPs:





ExpDM:





forbidden



coannihilations

- Griest, Seckel **1991**

coscattering



- D'Agnolo, Pappadopulo, JTR **1705.08450**

semi-annihilations



- D'Eramo, J. Thaler **1003.5912**

SIMP



- Hochberg, Kuflik, Volansky, Wacker **1402.5143**

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