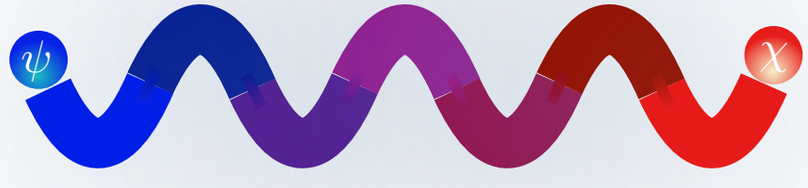

# Phases of Particle Dark Matter



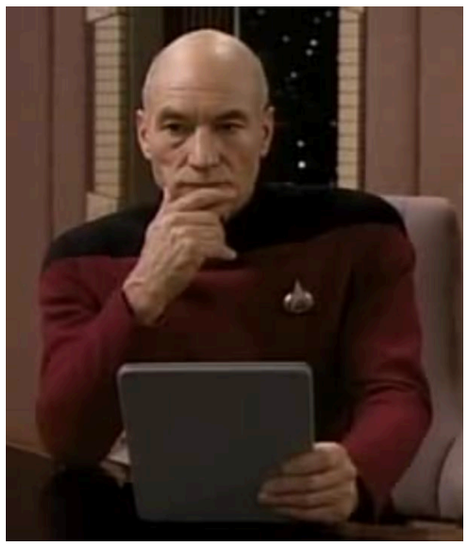

Josh Ruderman (NYU)

@Blois, 10/22/2024

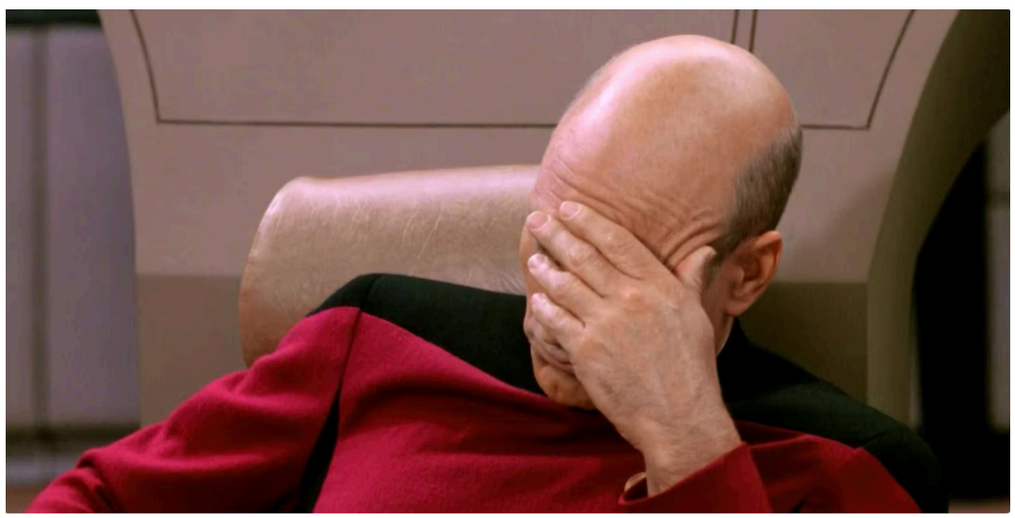


How was dark matter produced?

When was dark matter produced?



How can we test it?



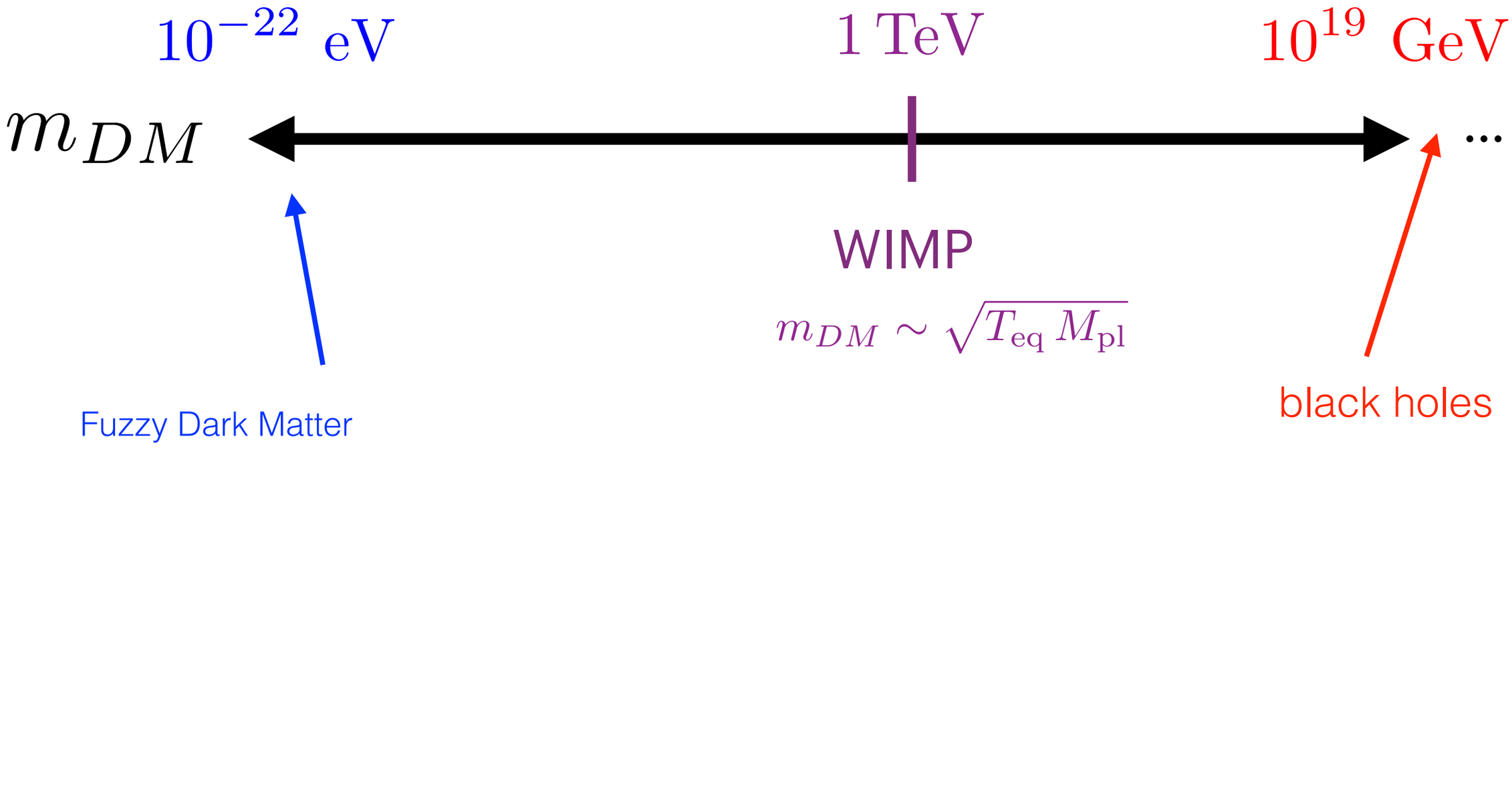
# Plan

I. WIMP Warmup

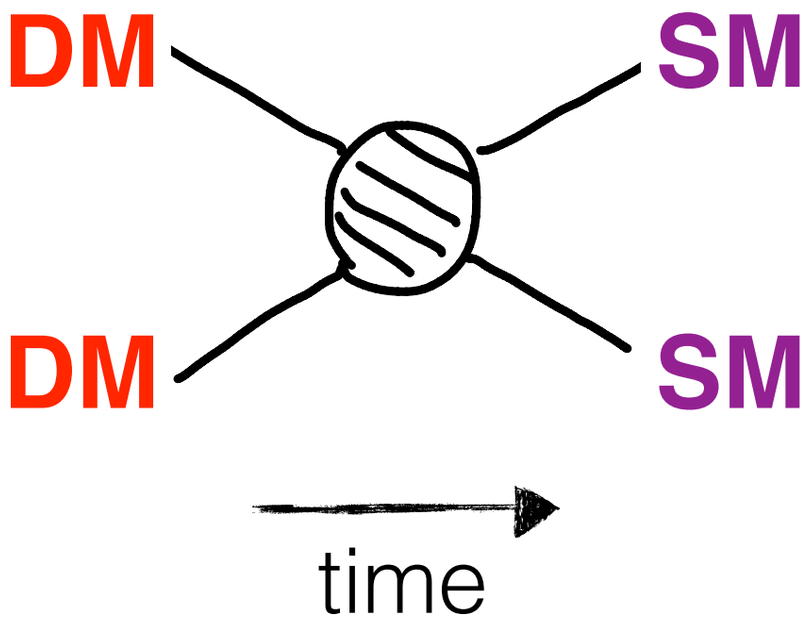
II. Thermal Relic DM

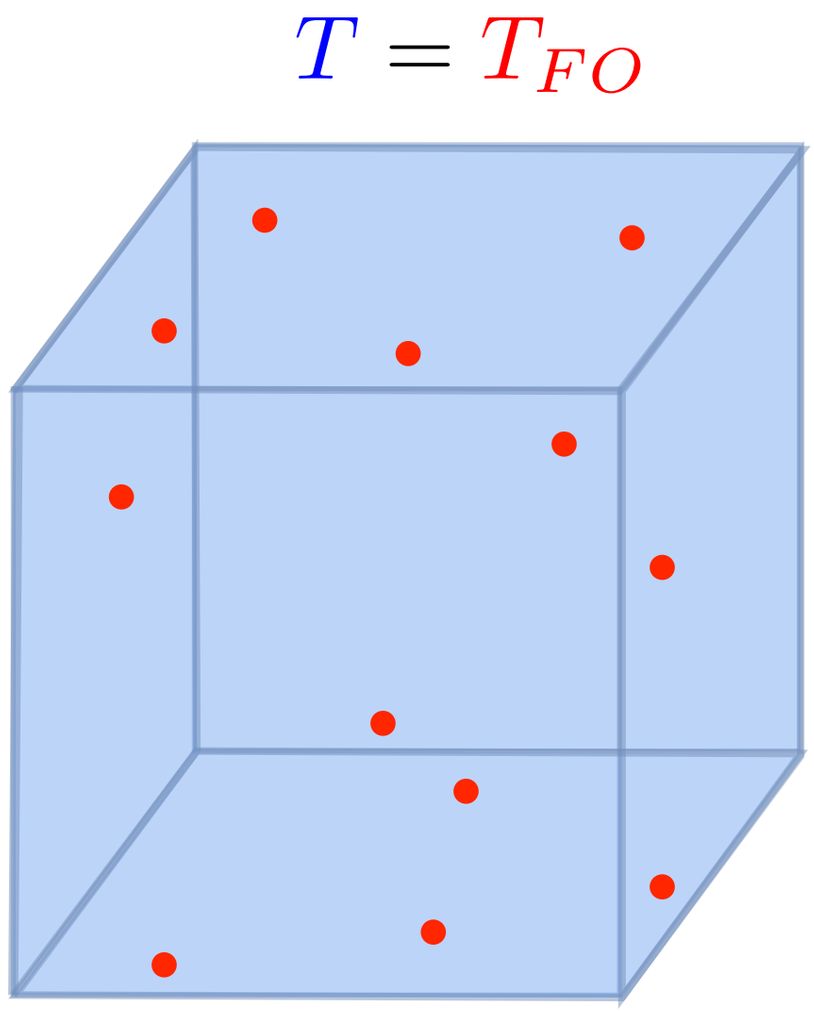
III. Feebly Interacting DM

# I. WIMP Warmup



# WIMP Freezeout

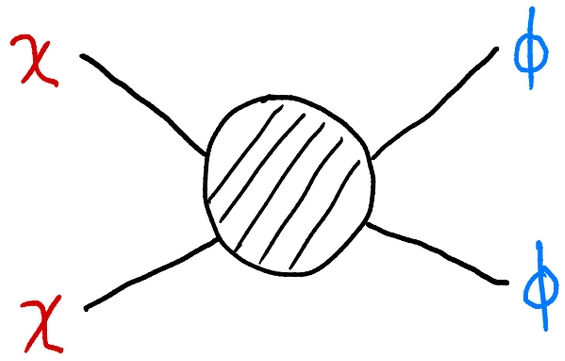


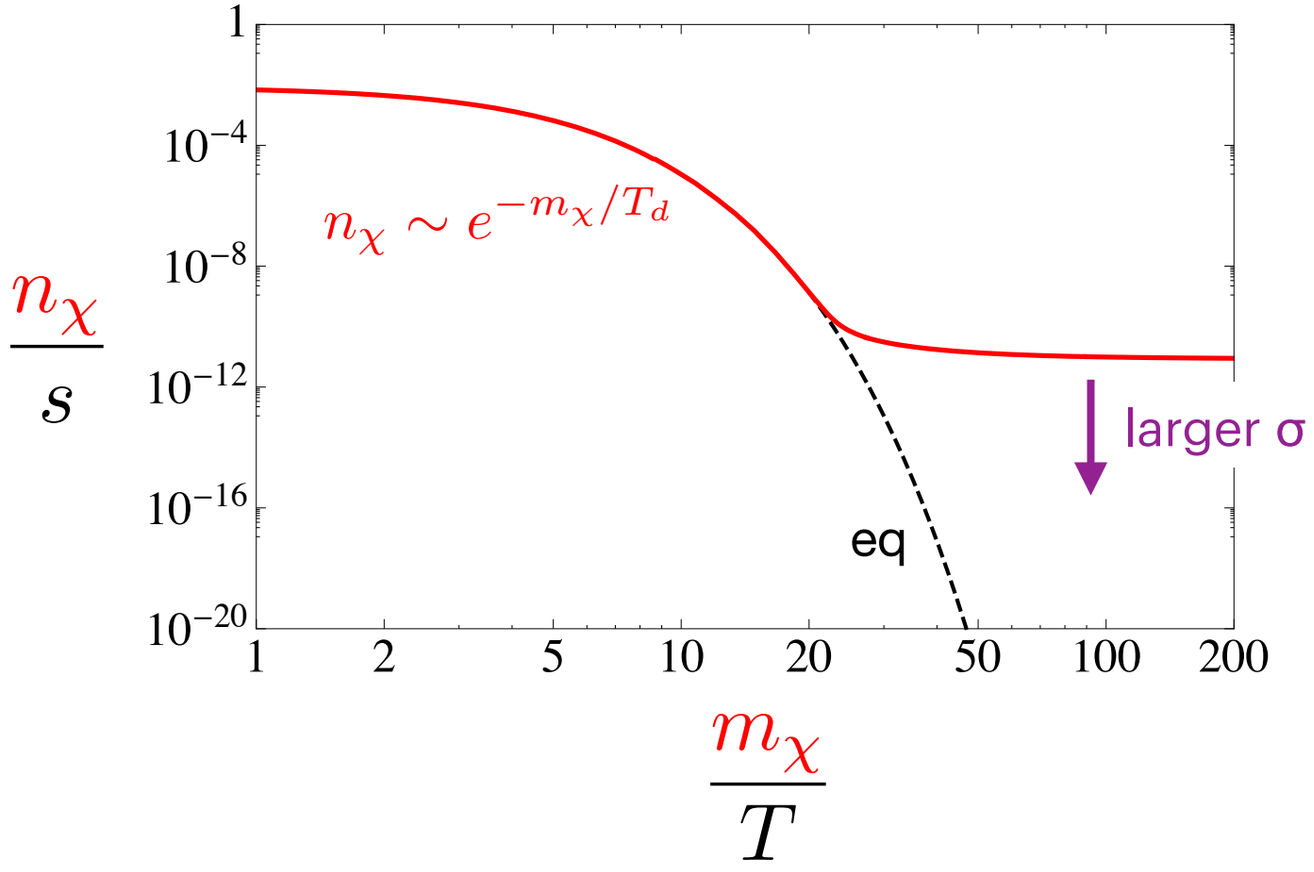

comoving volume: $V \propto s^{-1} \propto T^{-3}$

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

# WIMP Freezeout




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




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

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

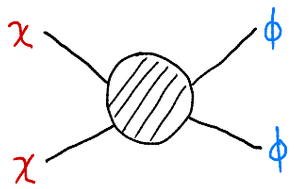
# When was Dark Matter Produced?


WIMP

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

# Experiment vs WIMPs

## Indirect

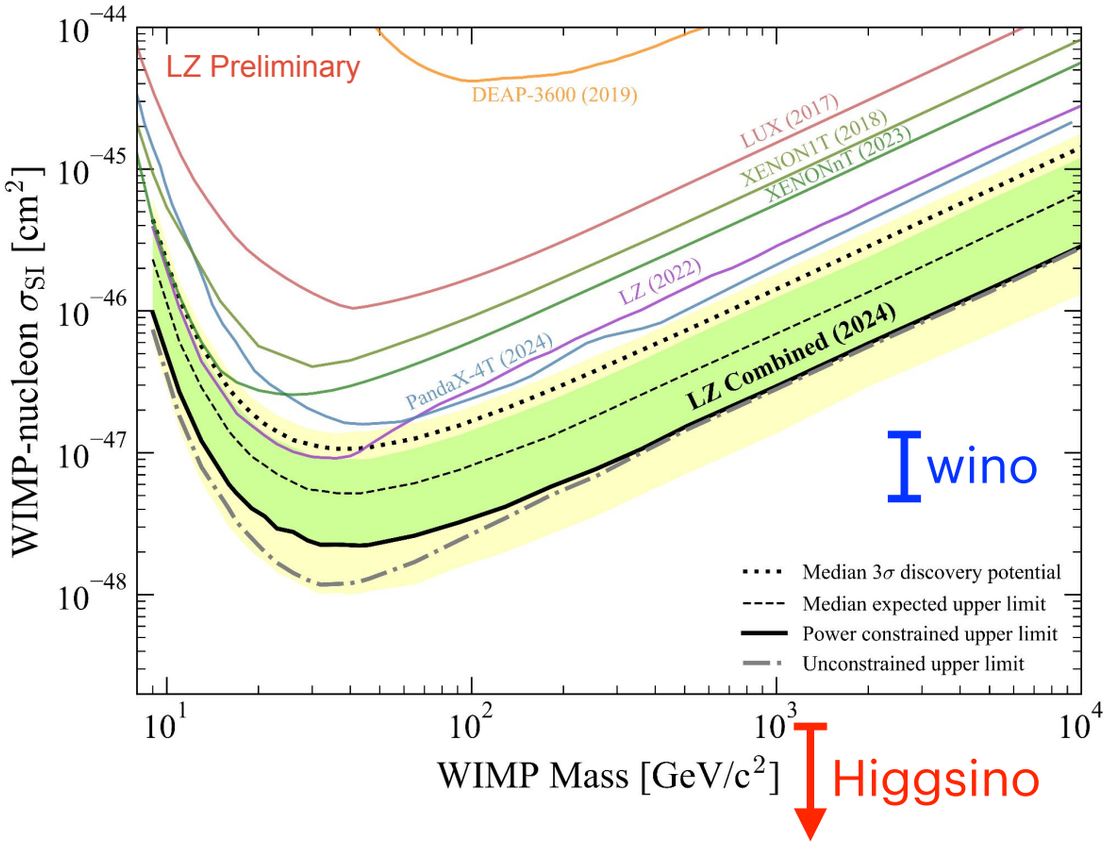



(if ϕ is SM or decays to SM)




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

## Direct

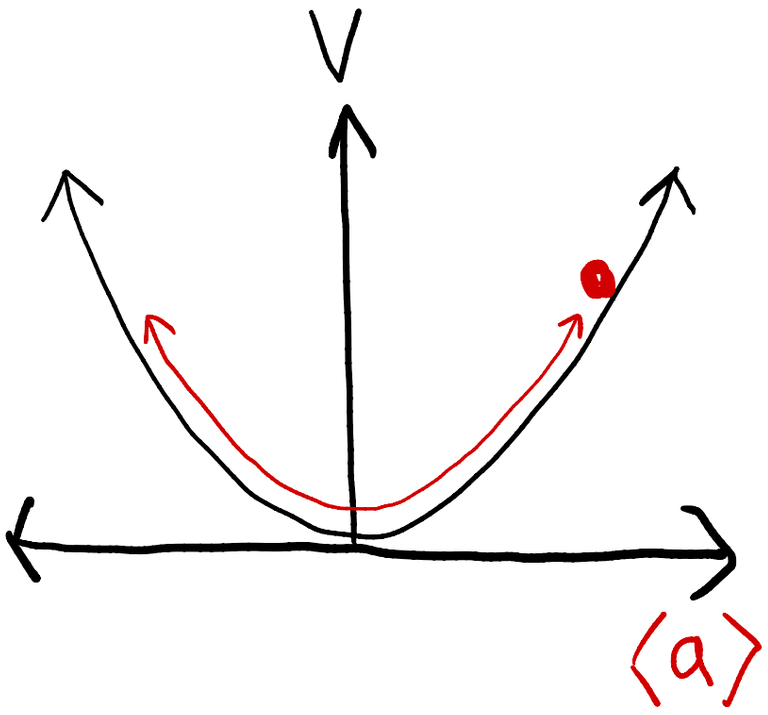



Scott Haselschwardt's talk at TeVPA2024

# Axion Dark Matter

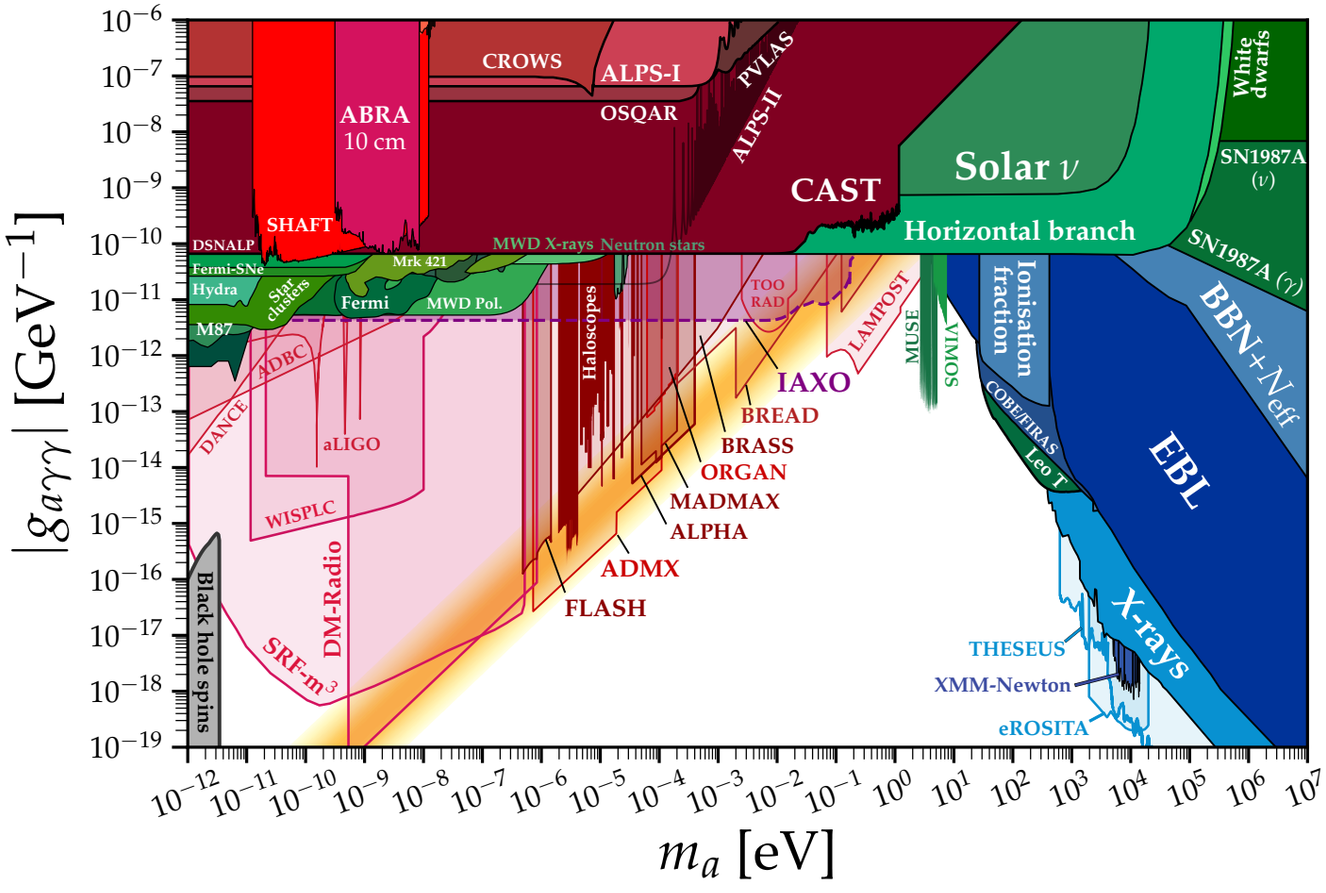
misalignment mechanism:

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




**QCD axion:**

at the minimum: $\theta G\tilde{G}$ $\theta \to 0$




Snowmass, **2203.14923**

- 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

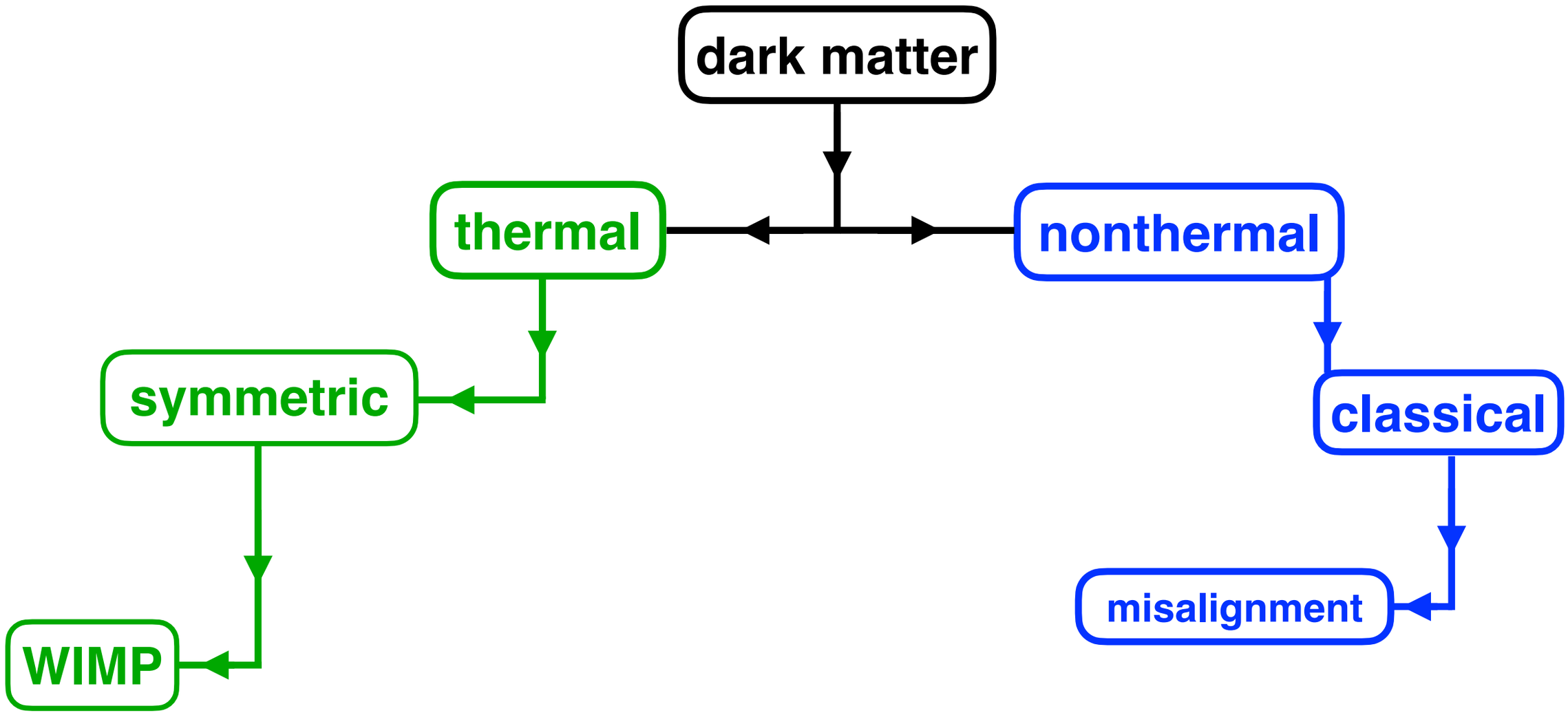
# When was Dark Matter Produced?


WIMP

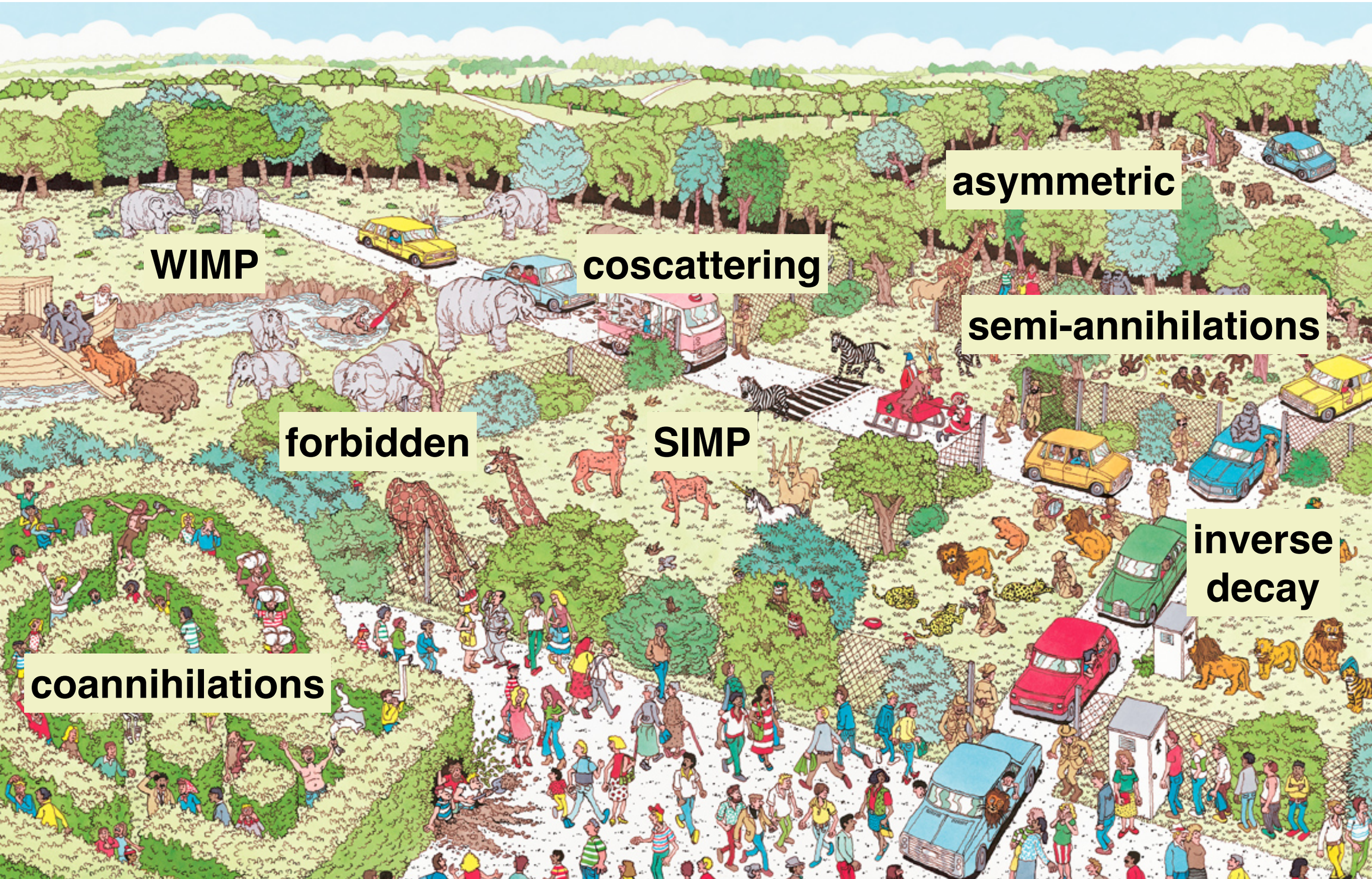
axion

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

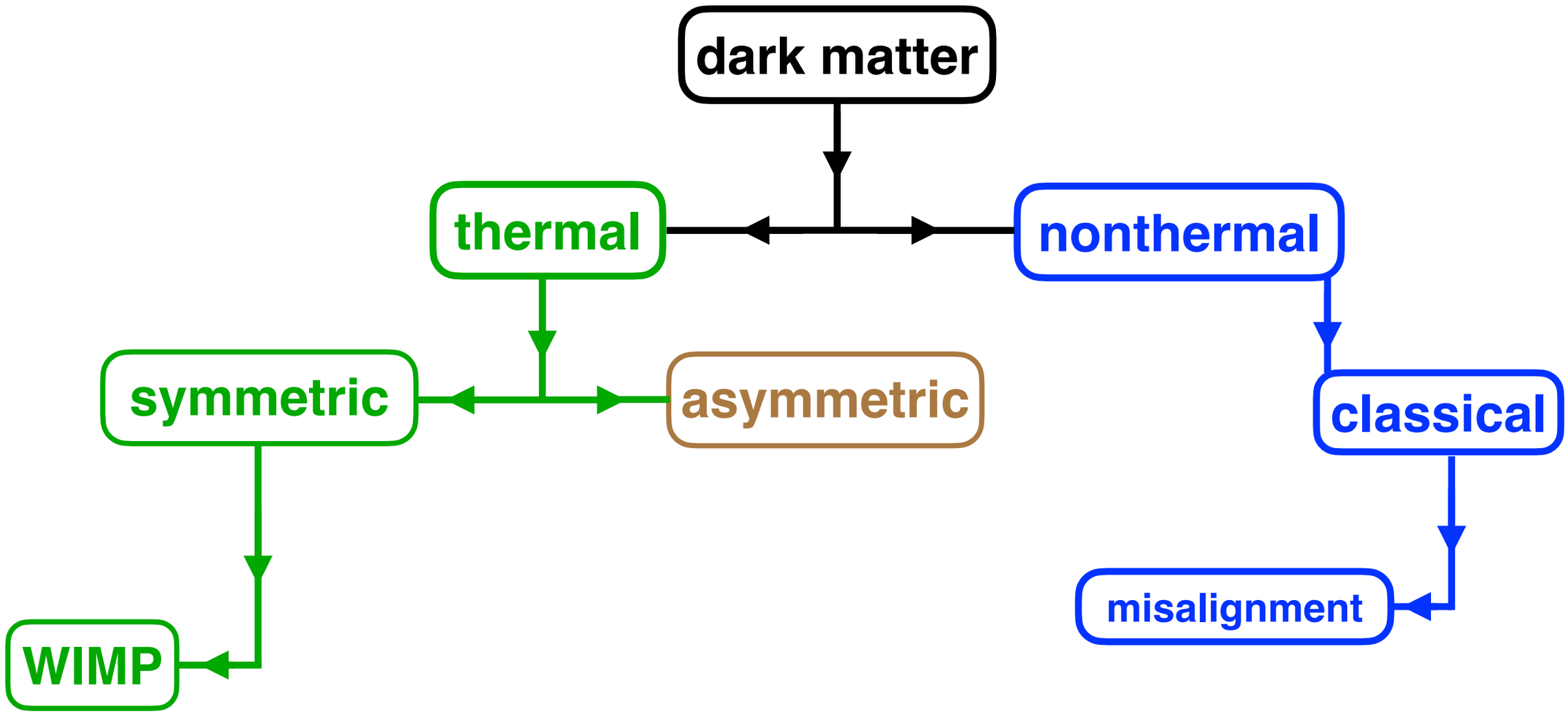
# Cosmic Production Mechanisms



# II. Thermal Relic Dark Matter



# Cosmic Production Mechanisms

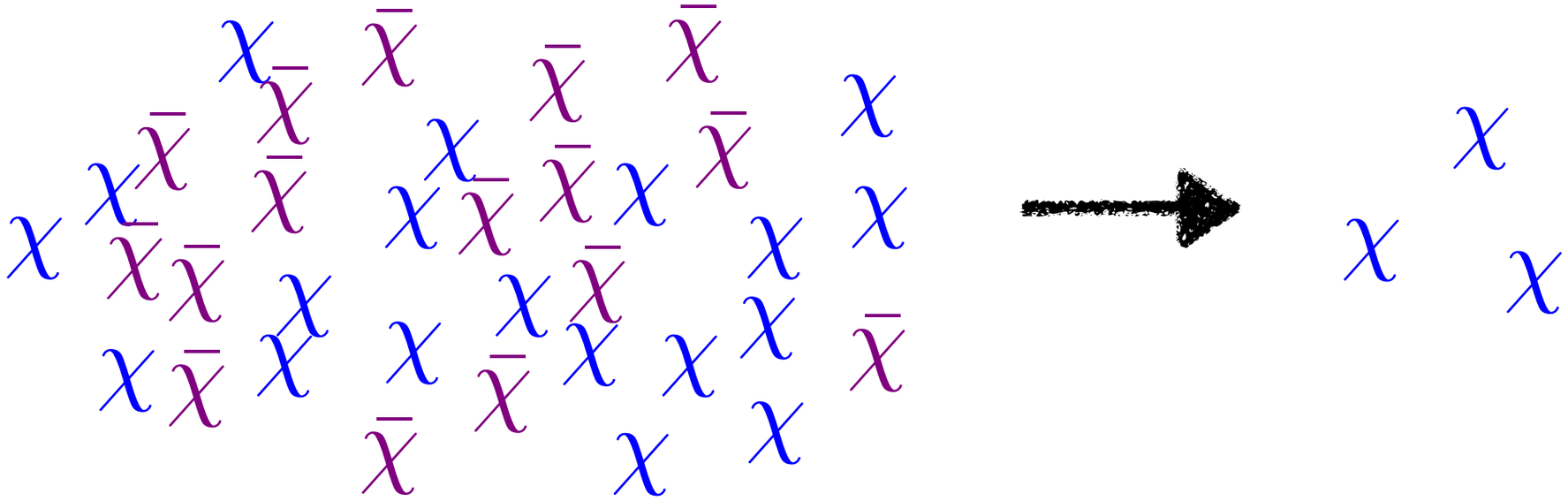


# Asymmetric Dark Matter

DM: $\chi$

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

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

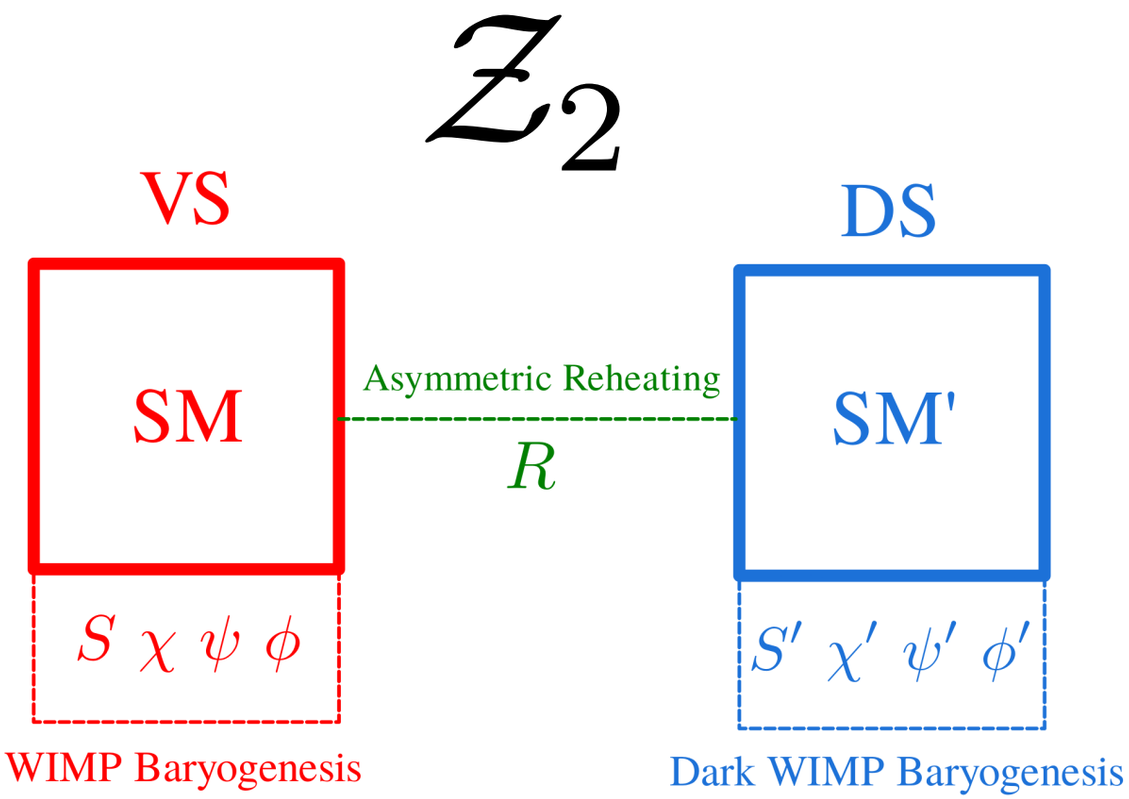


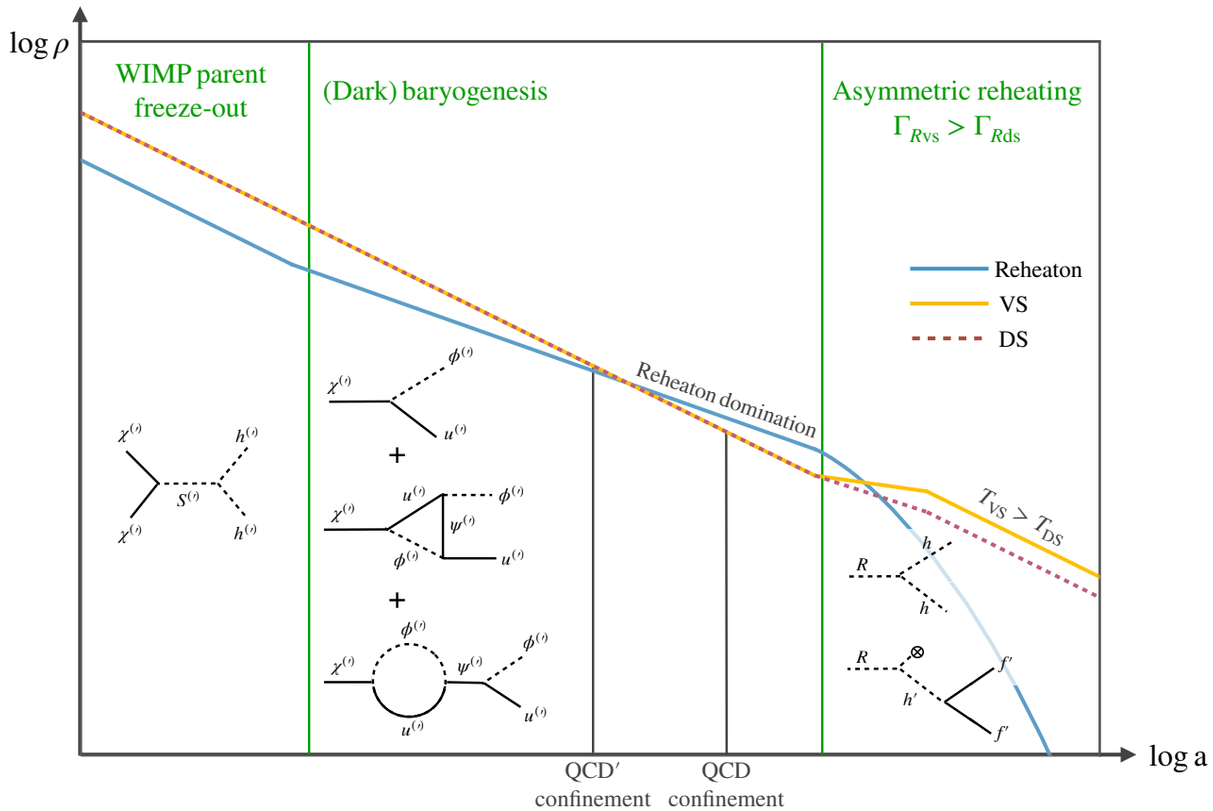
Kaplan, Luty, Zurek, **0901.4117**

dark matter vs. baryon abundance:

$$\frac{\Omega_\chi}{\Omega_B} = \left(\frac{n_\chi - n_{\bar{\chi}}}{n_B - n_{\bar{B}}}\right) \frac{m_\chi}{m_p} \approx 5$$

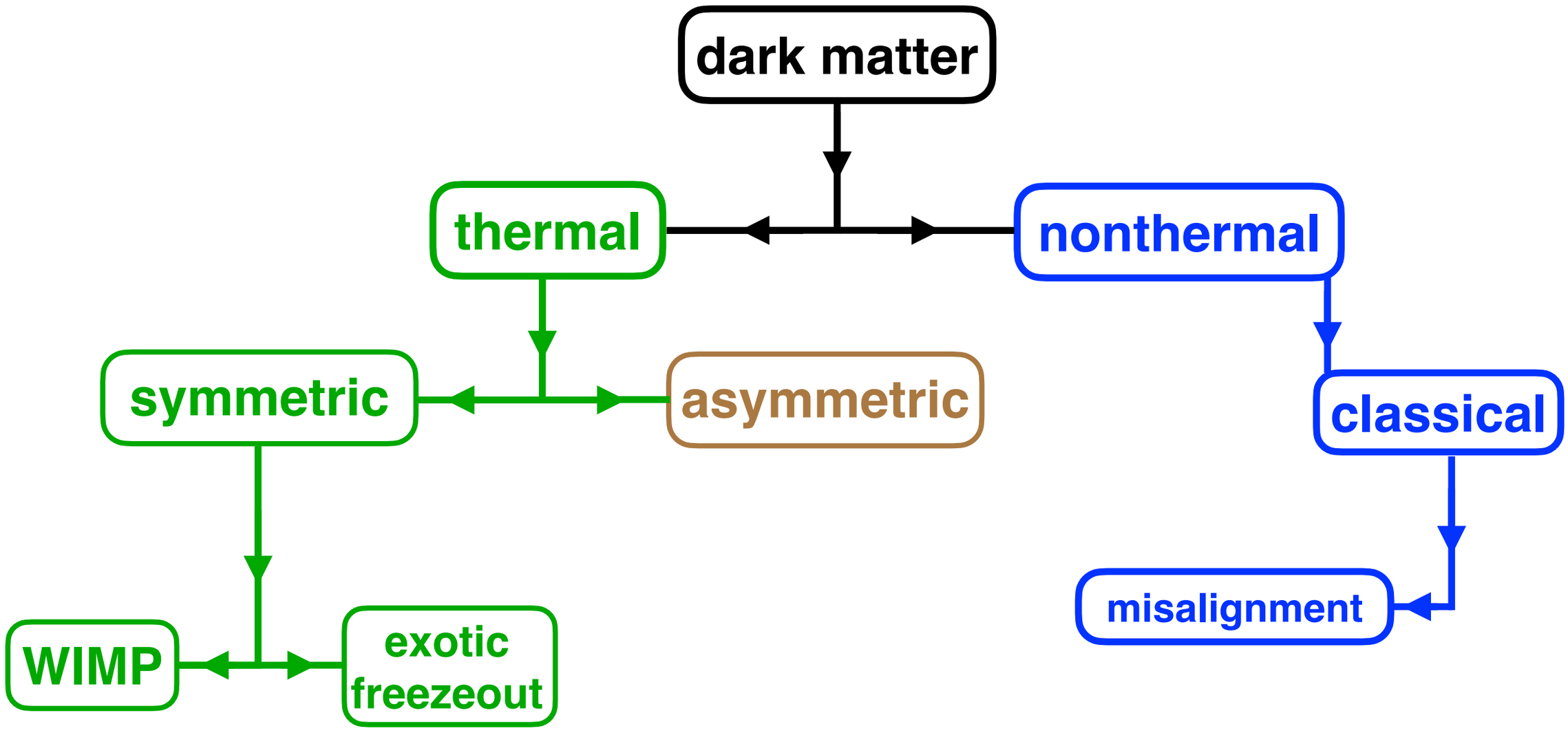
# Asymmetric Dark Matter



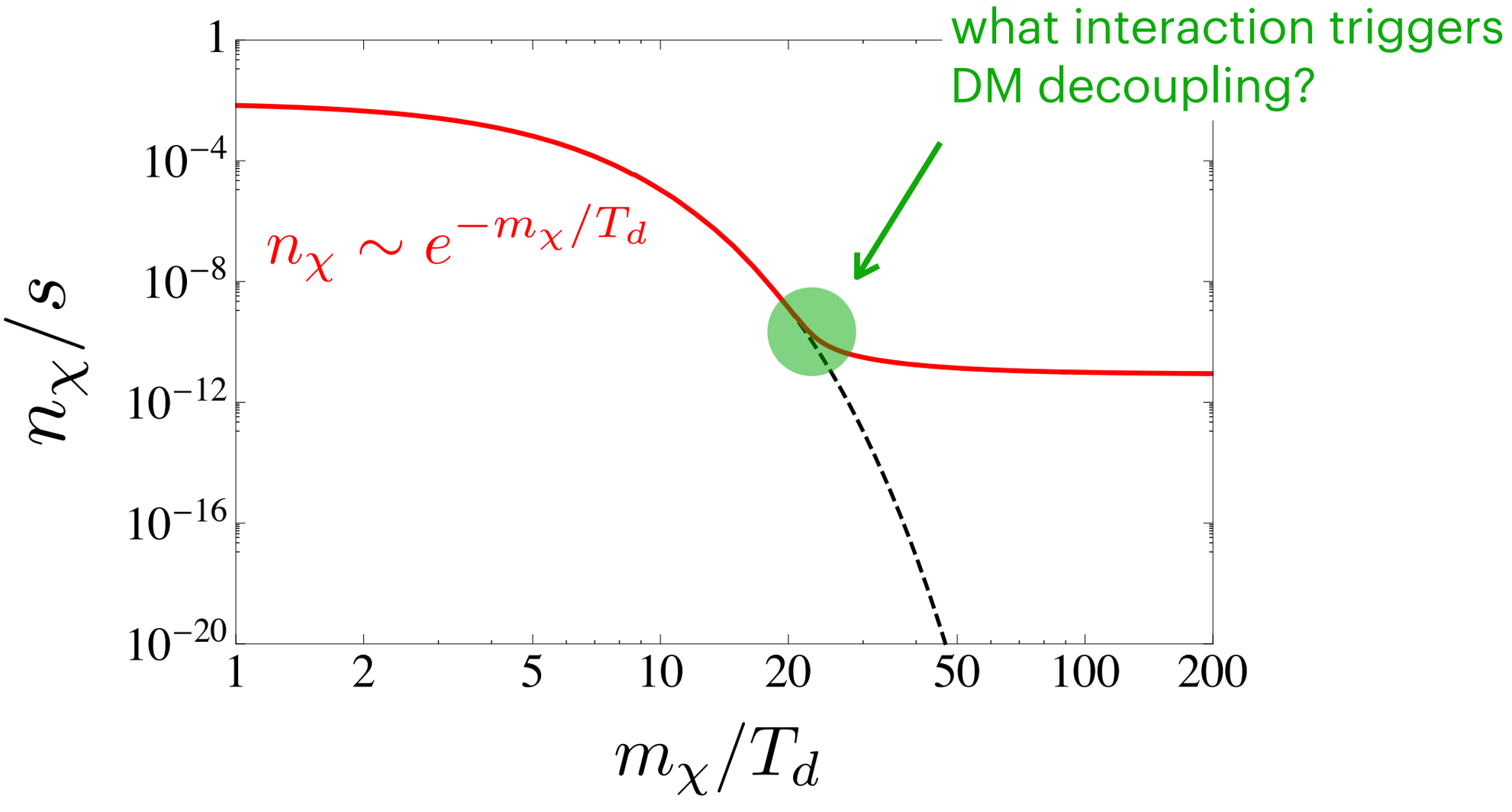




Bodas, Buen-Abad, Hook, Sundrum, **2401.12286**

# Cosmic Production Mechanisms



# Exotic Freezeout Processes

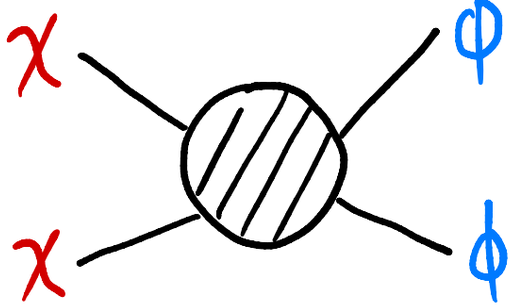


# Exotic Freezeout Processes

*forbidden*

indirect

$m_\chi < m_\phi$

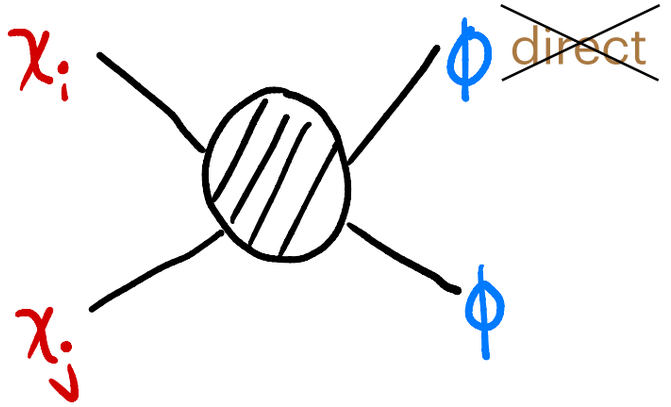



- Griest, Seckel 1991
- D'Agnolo, JTR **1505.07107**

*coannihilations*

indirect

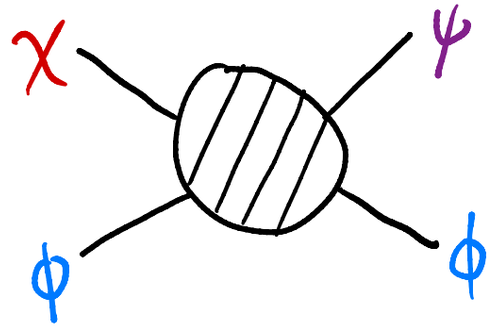
direct




- Griest, Seckel **1991**

*coscattering*

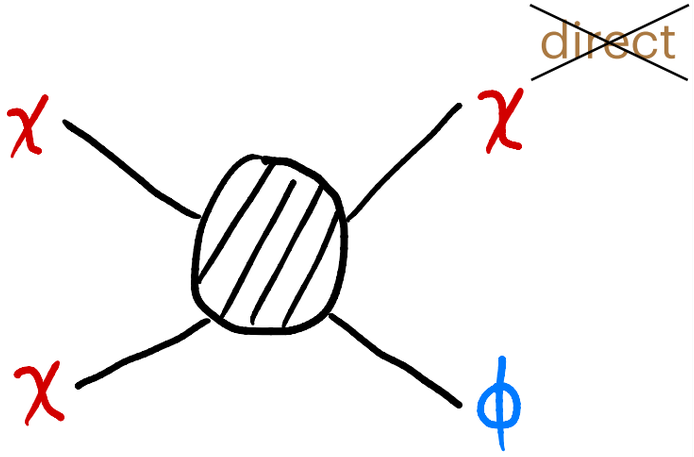
indirect




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

*semi-annihilations*

direct

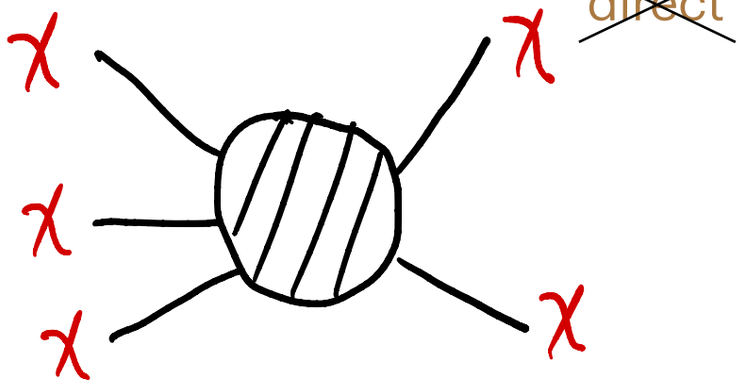



- D'Eramo, J. Thaler **1003.5912**

*SIMP*

indirect

direct

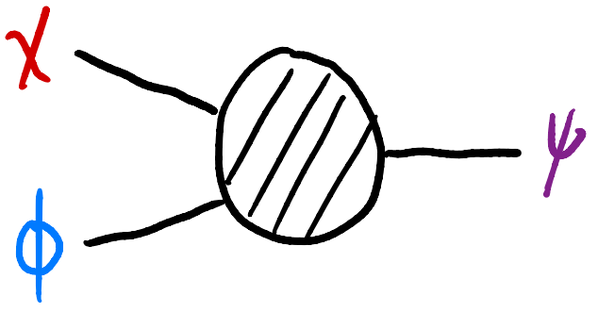



- Hochberg, Kuflik, Volansky, Wacker **1402.5143**

*inverse decay*

indirect

direct




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

# When was Dark Matter Produced?

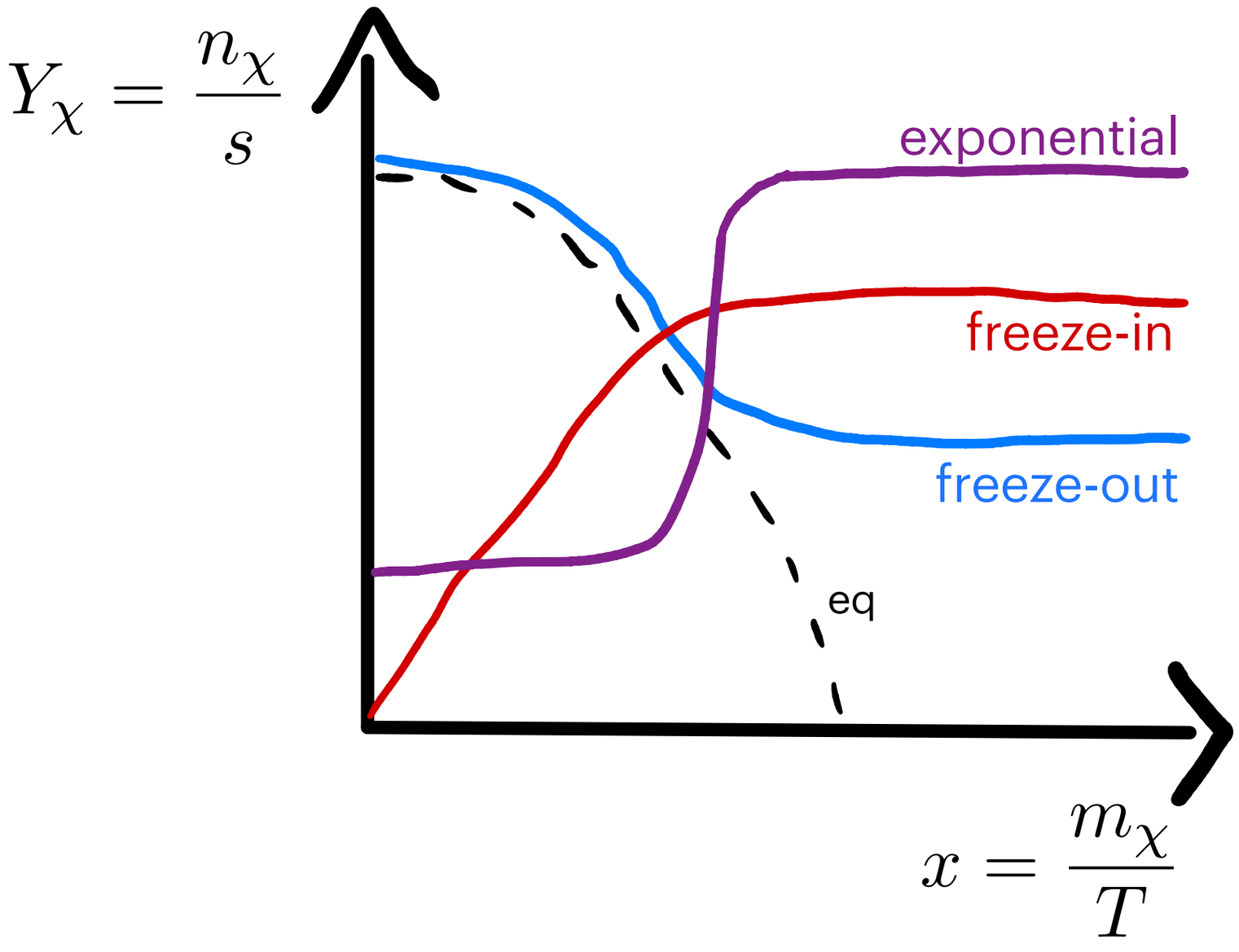

thermal relic

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

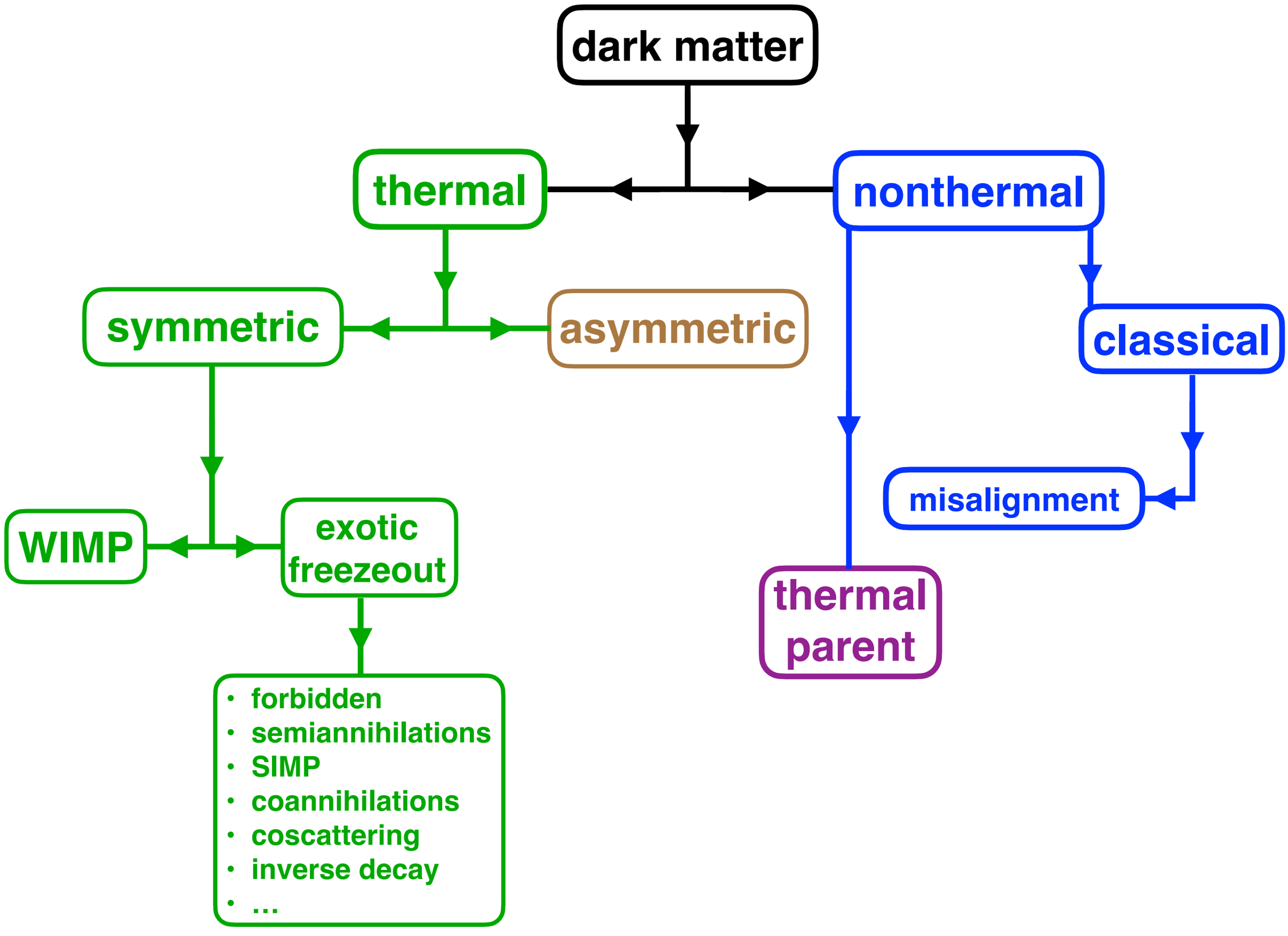
axion

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

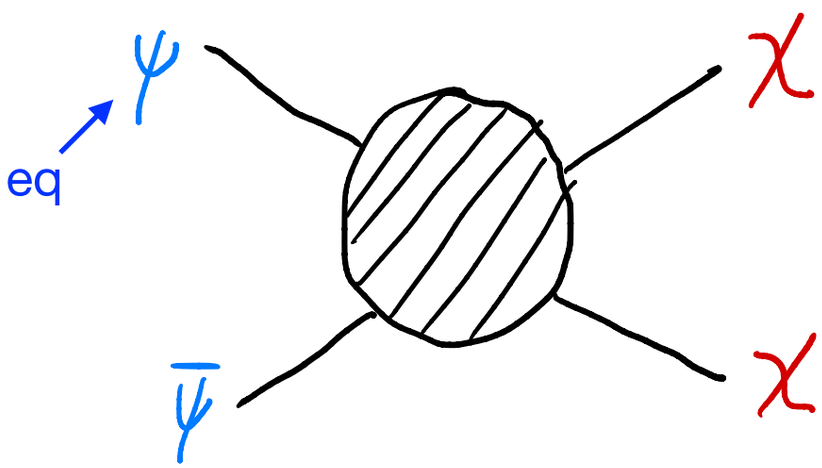
# III. Feebly Interacting Dark Matter



# Cosmic Production Mechanisms

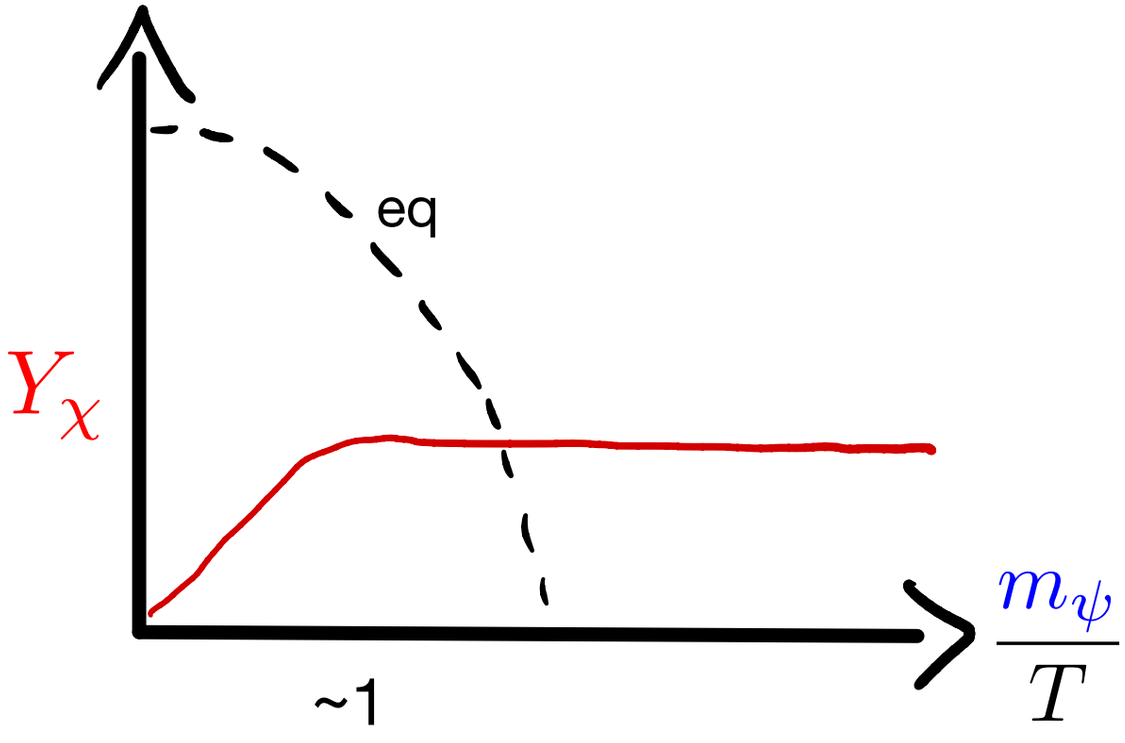


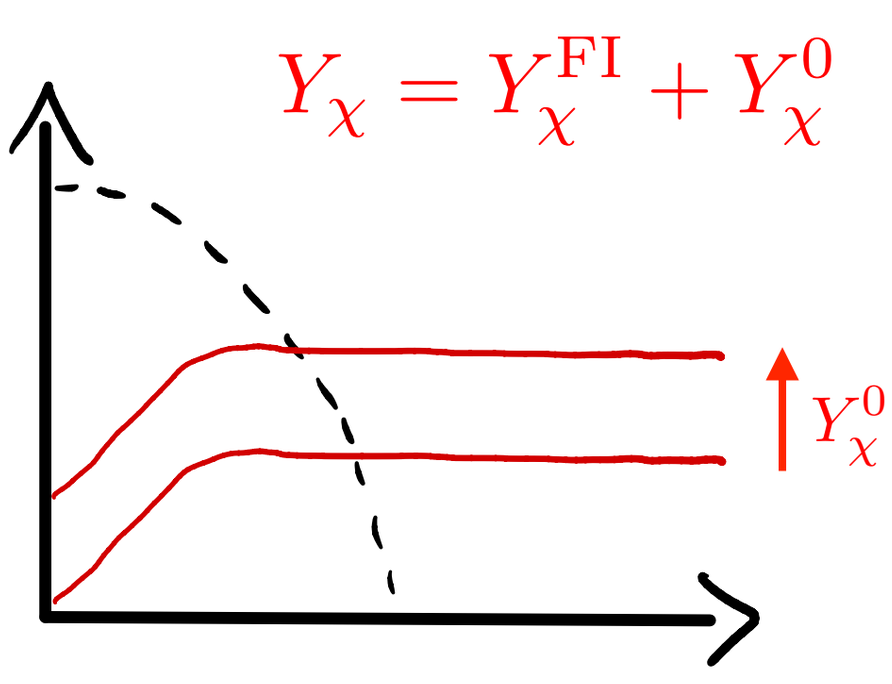
# Freeze-In




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

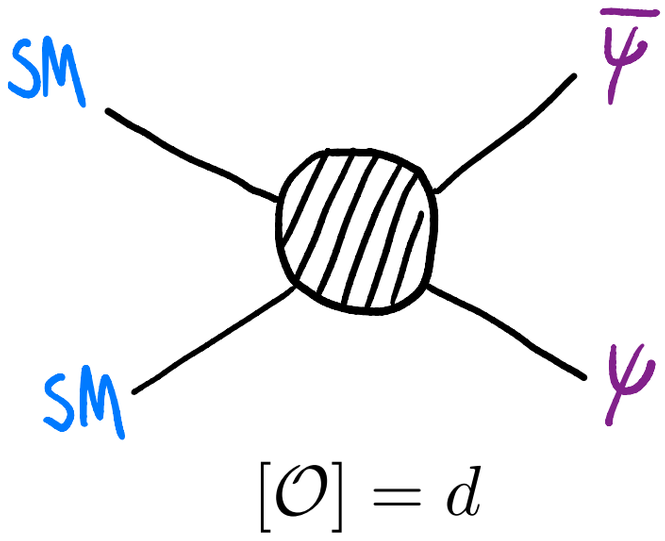
sensitive to initial condition:




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

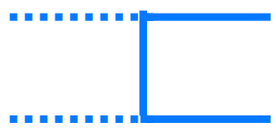
# IR vs. UV Freeze-In



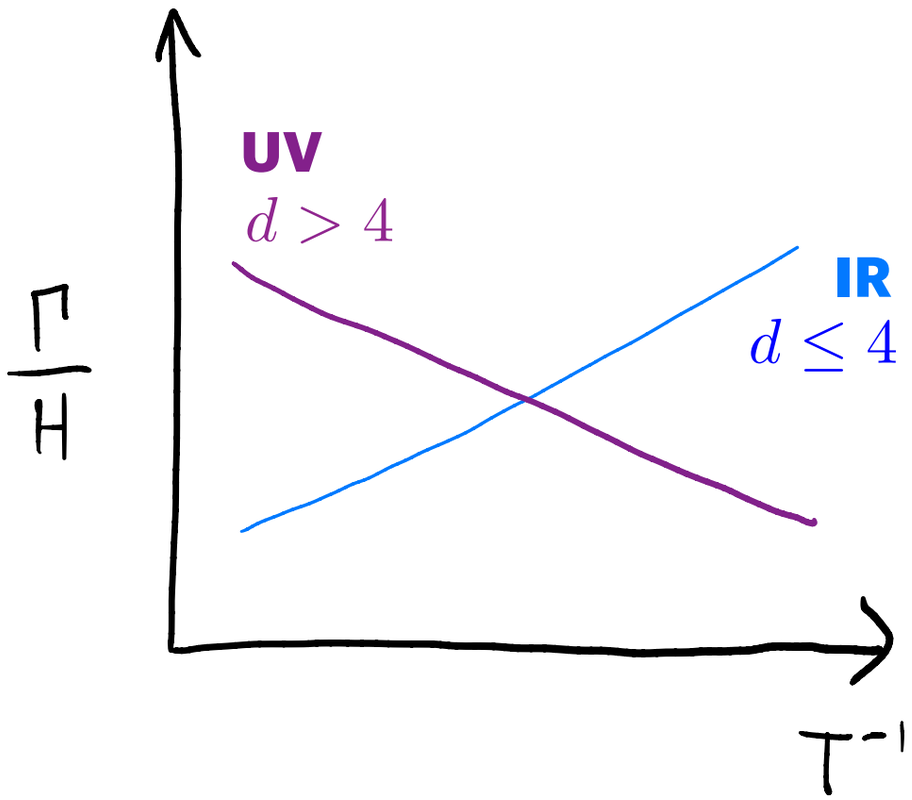

$$[\mathcal{O}] = d$$

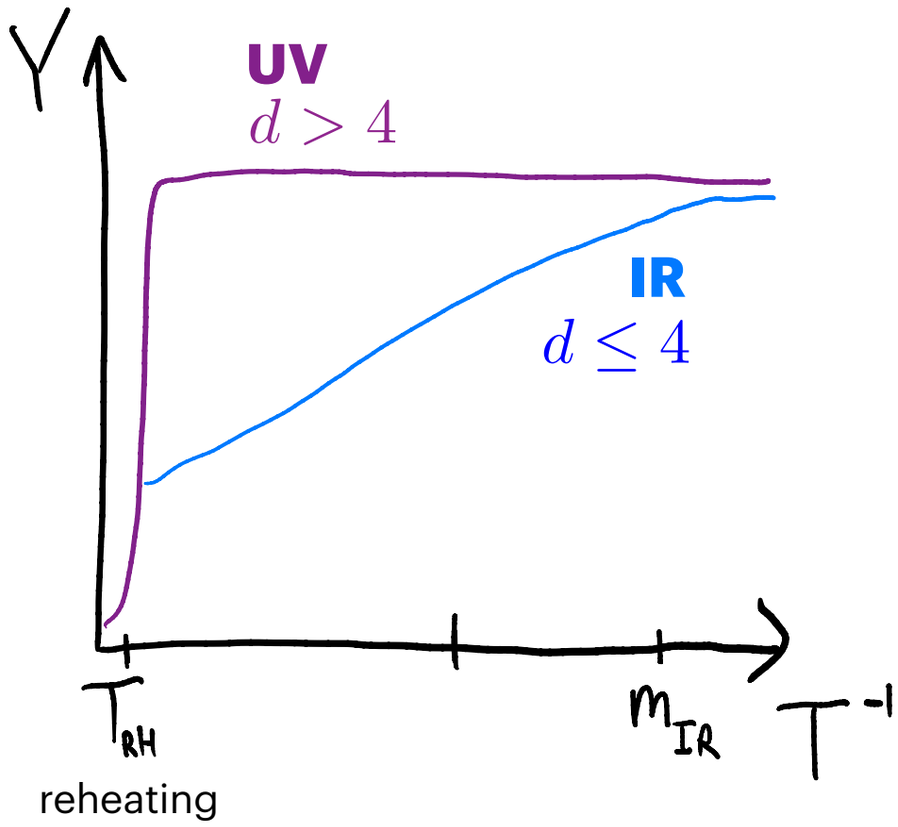
$$\frac{\Gamma}{H} \sim \frac{M_{pl}}{\Lambda^{2(d-4)}} T^{2(d-4)-1}$$

**IR-dominated:** $d \leq 4$ ex) Yukawa



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




reheating

# When was Dark Matter Produced?


thermal relic

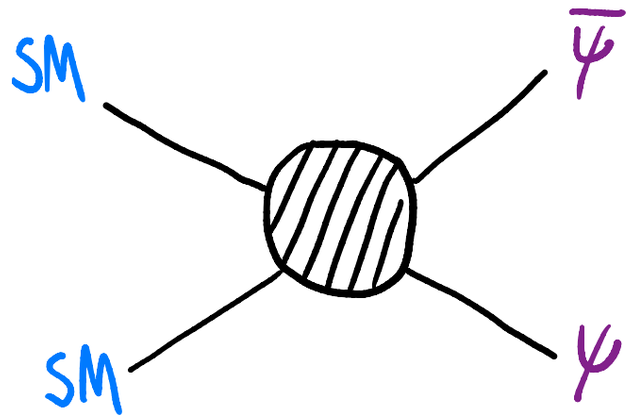
freeze-in
$d \leq 4$

axion

UV freeze-in
$d > 4$

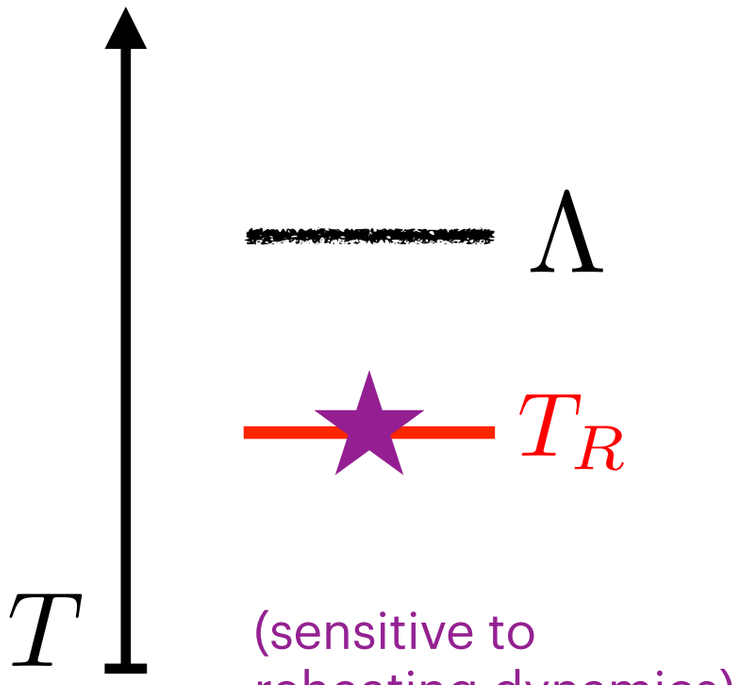
# Nonthermal DM from EFT

suppose that DM decouples from the SM as: $\Lambda \to 0$



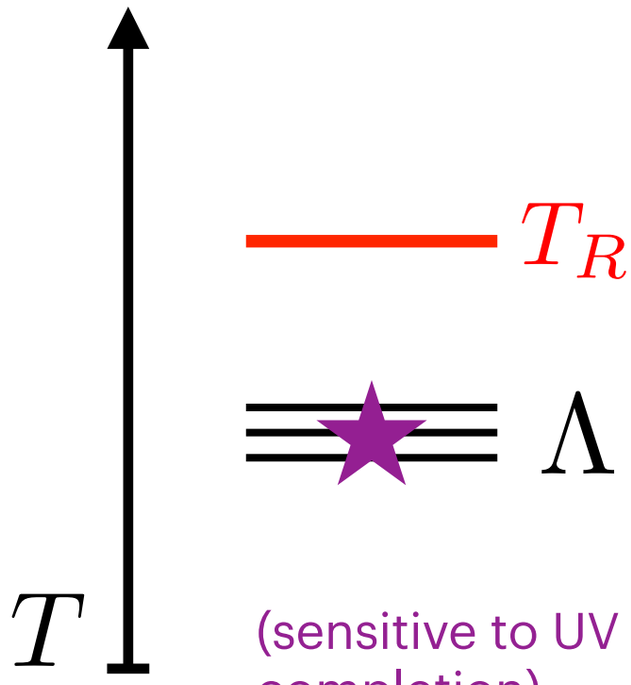

$$\frac{\mathcal{O}}{\Lambda^{d-4}} \quad d > 4$$

$\Lambda > T_R$




(sensitive to reheating dynamics)

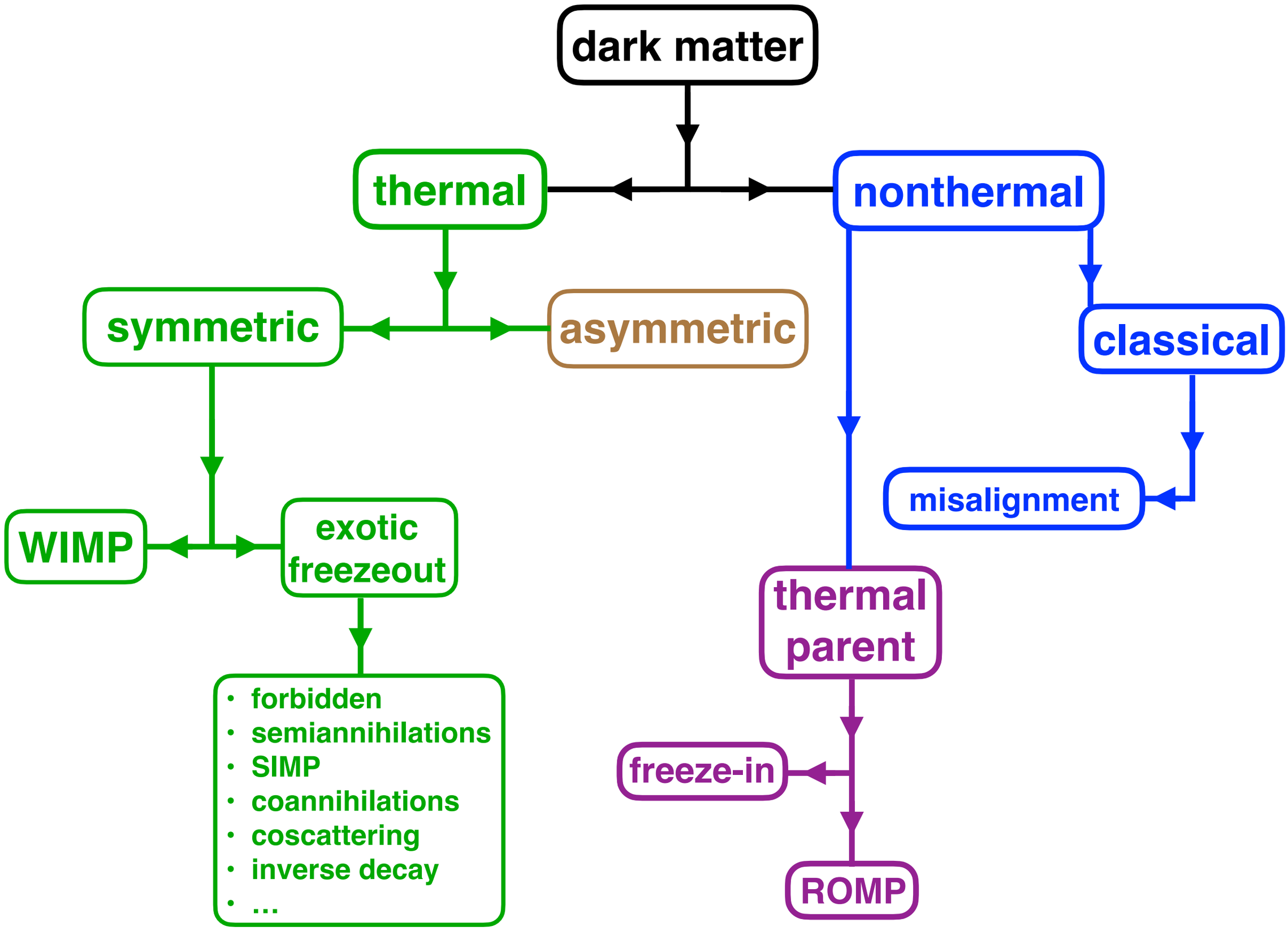
$\Lambda < T_R$



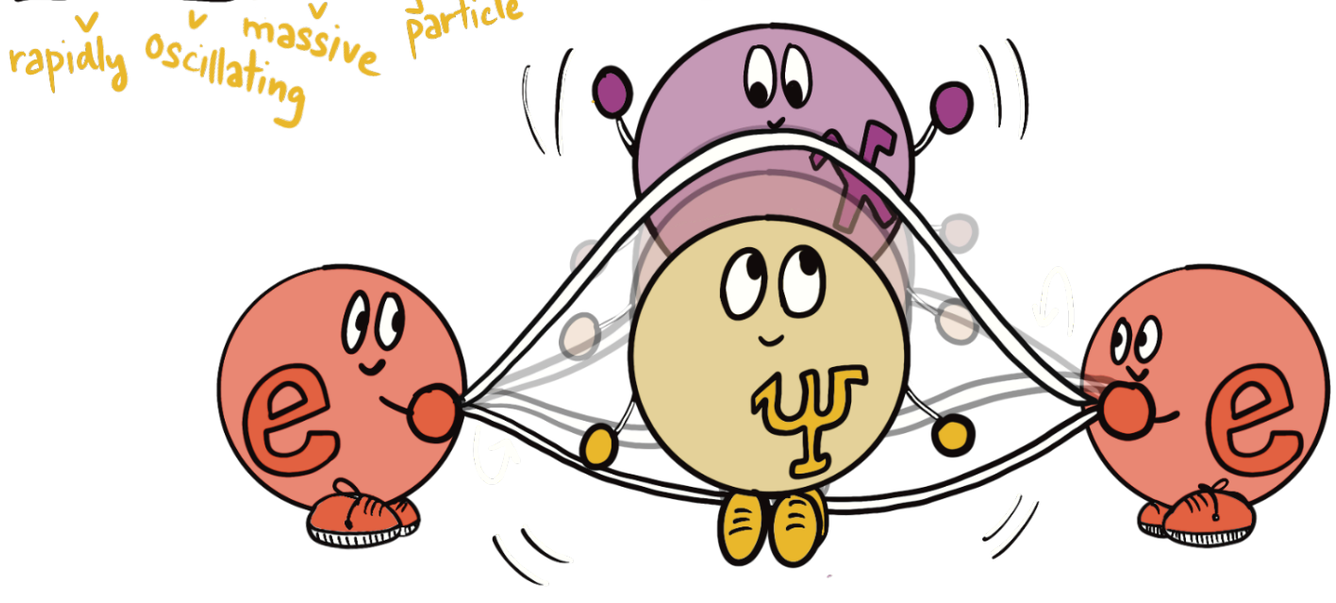

(sensitive to UV completion)

DM production

# Cosmic Production Mechanisms



# ROMP DARK MATTER

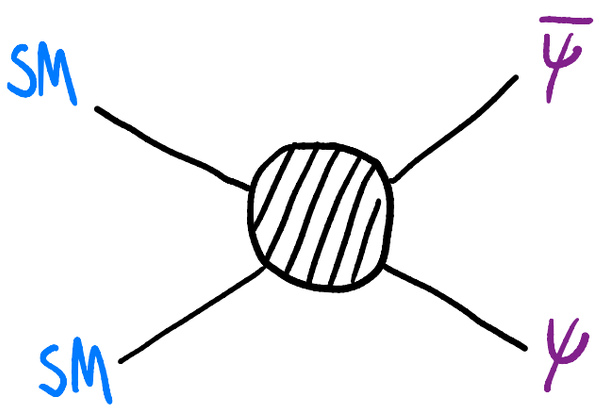


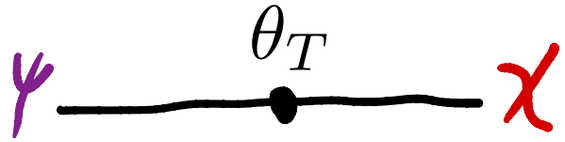

cartoon credit: Saniya

work in progress w/ David Dunsky and Saniya Heeba

## ROMP

**R**apidly **O**scillating **M**assive **P**article



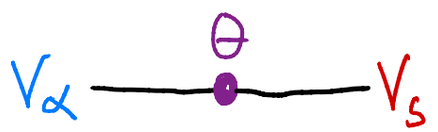




ex) sterile neutrinos

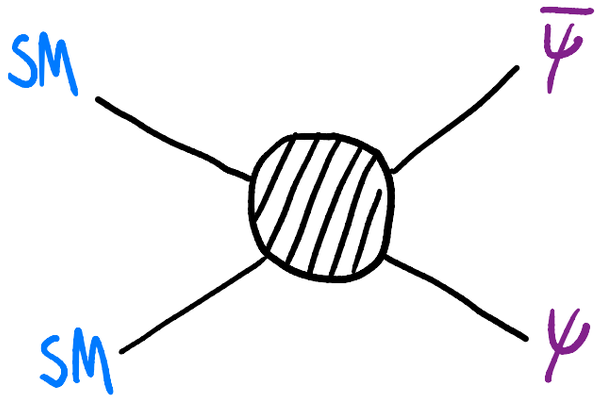
(Dodelson & Widrow, **hep-ph/9303287**)

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

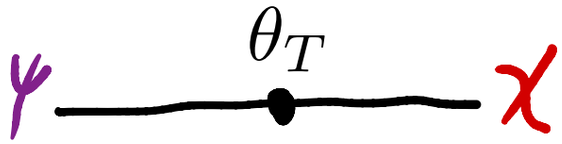
$$G_F\, \bar{\nu}_\alpha \gamma^\mu \nu_\alpha\, \bar{e}_L \gamma_\mu e_L$$



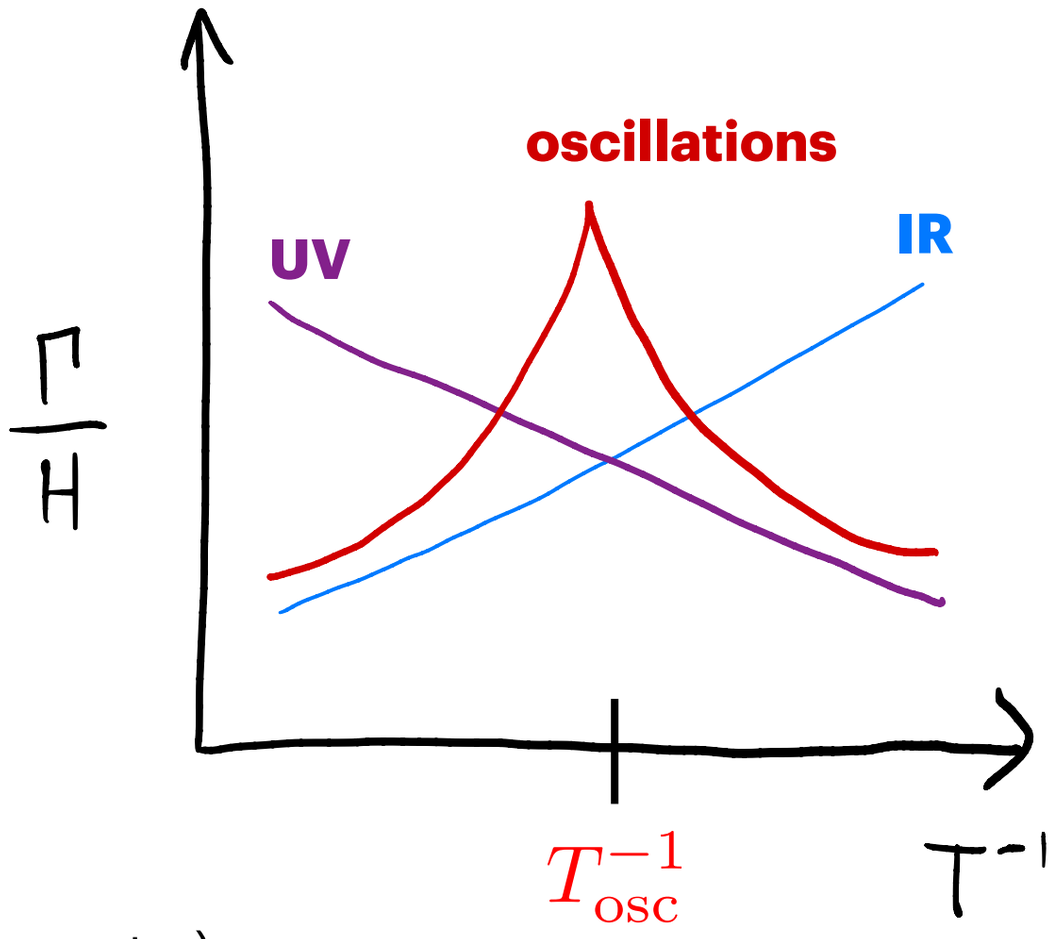
# ROMP Production




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




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



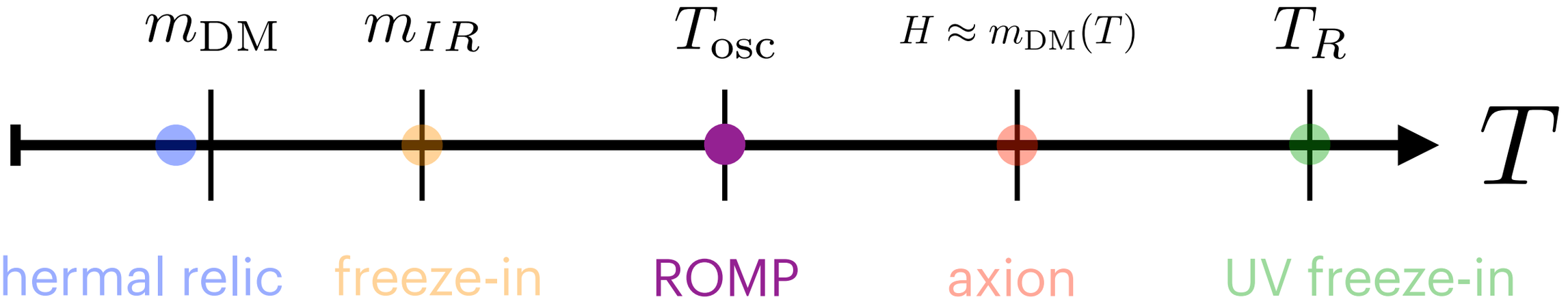

- at high temperatures: $\theta_T \propto T^{-n}$

(power depends on operator)

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

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

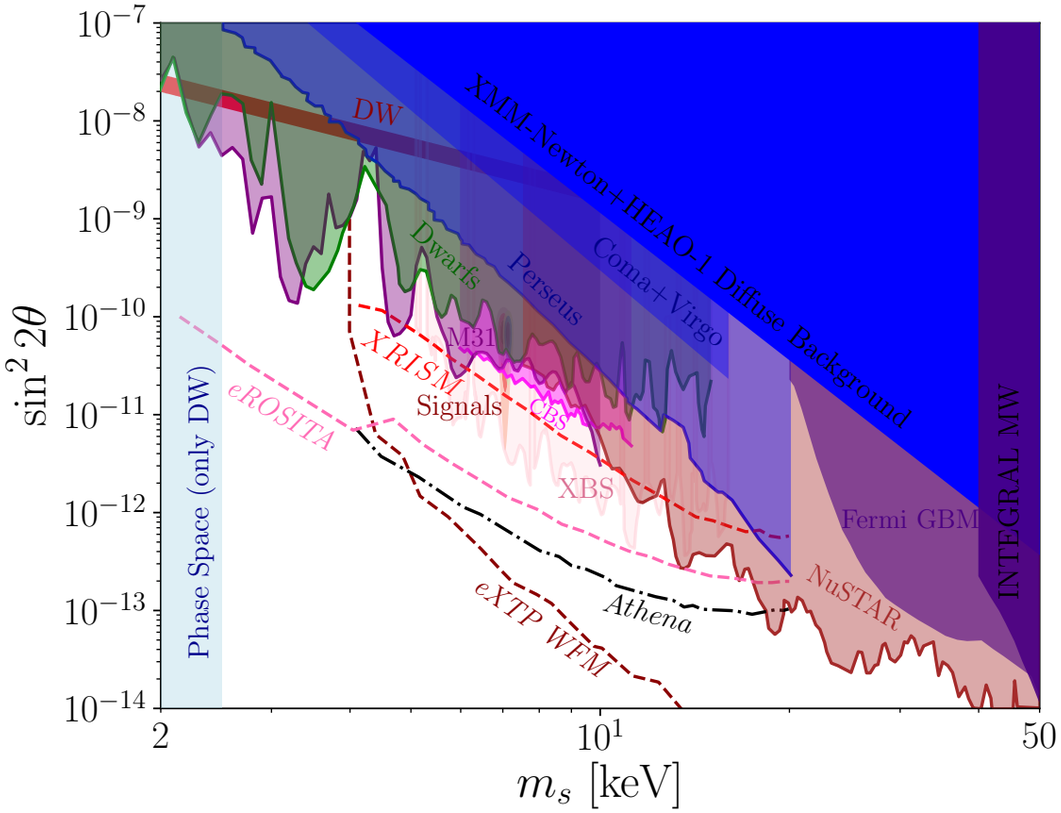
# When was Dark Matter Produced?




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

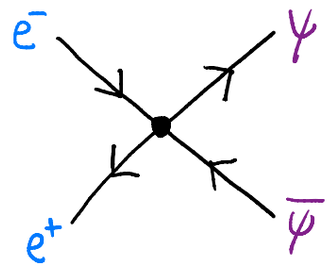
# Sterile Neutrino and Beyond

## sterile neutrino

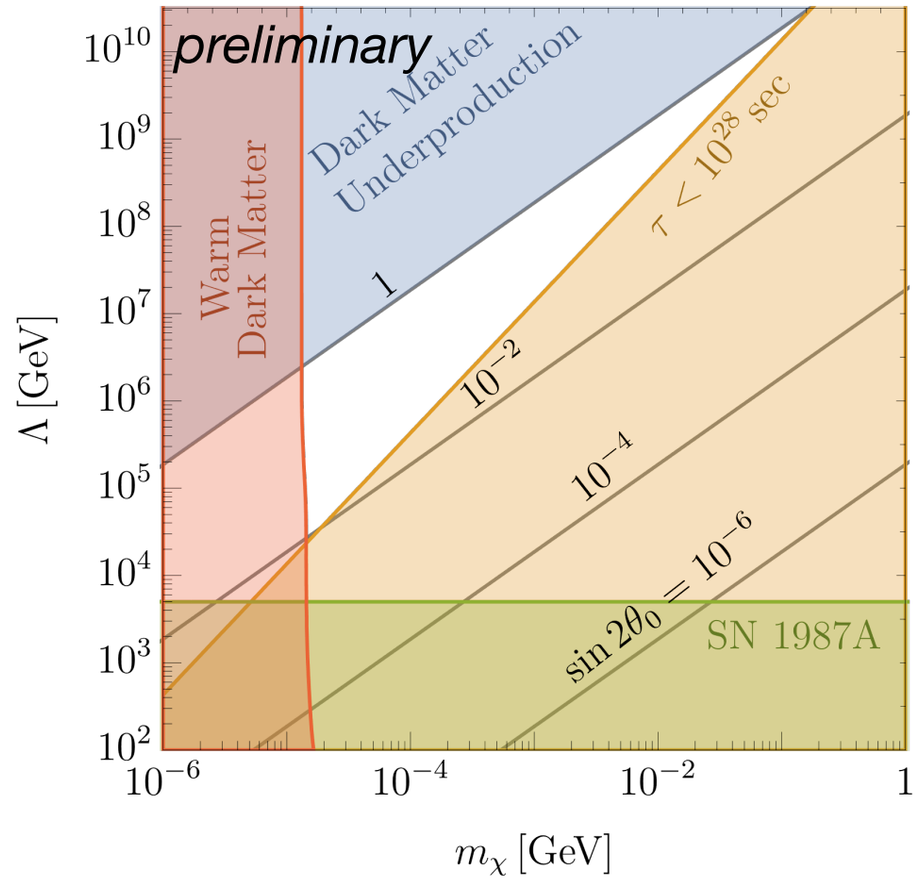



Snowmass, **2203.07377**

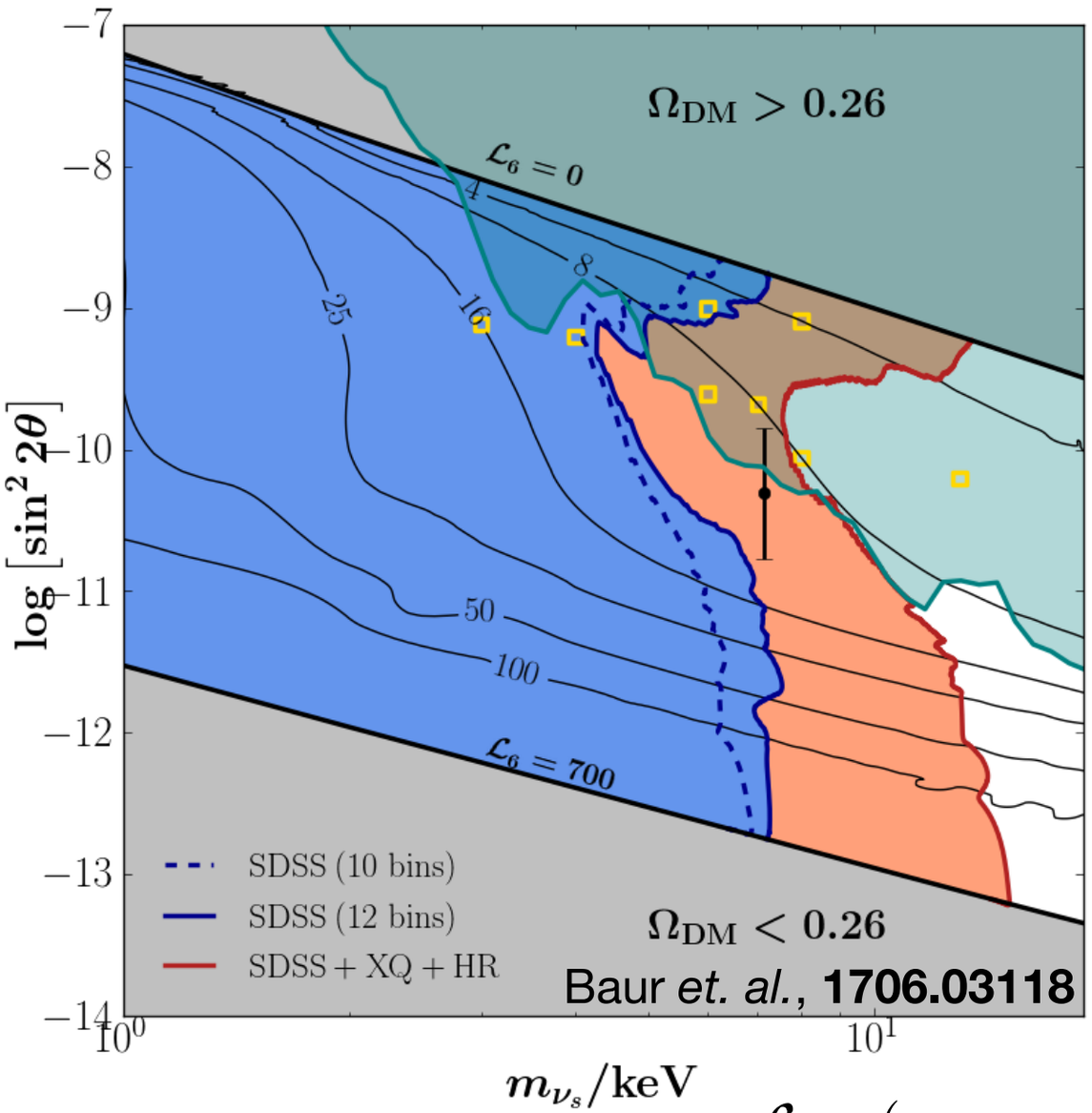
## new state w/ new operator




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



# Sterile Neutrinos from Shi-Fuller Mechanism




- necessary lepton asymmetry:

$$Y_\nu - Y_{\bar{\nu}} \sim 10^{-6} - 10^{-3}$$

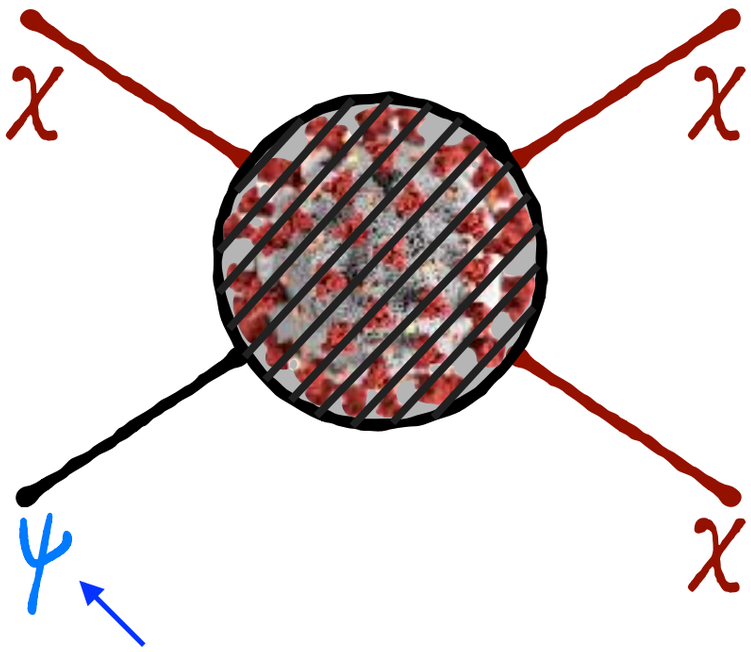
- observed baryon asymmetry:

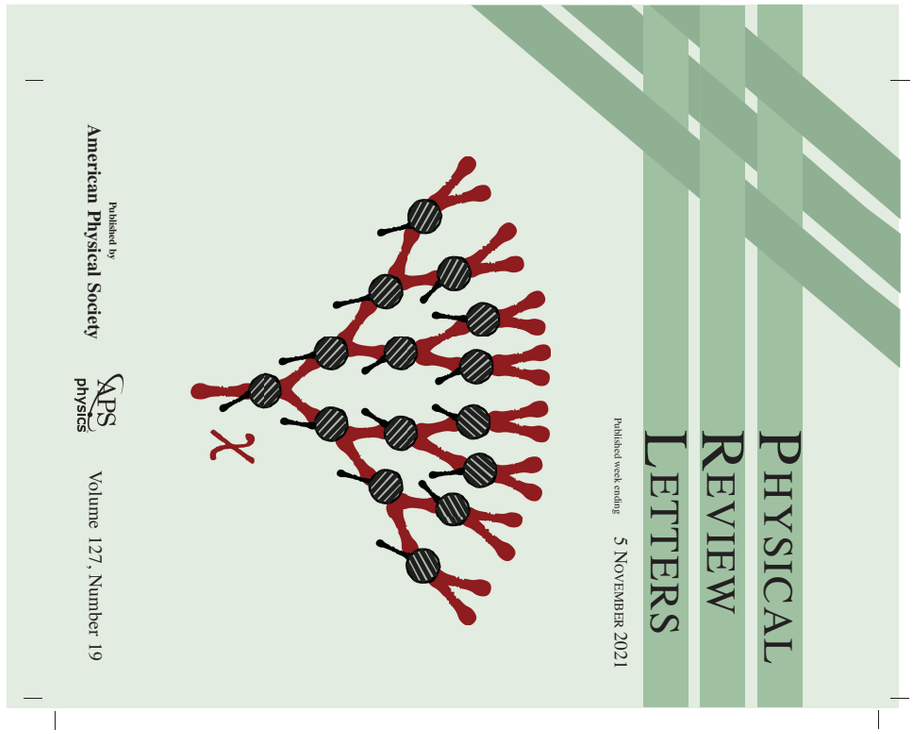
$$Y_B - Y_{\bar{B}} = 8.7 \times 10^{-11}$$

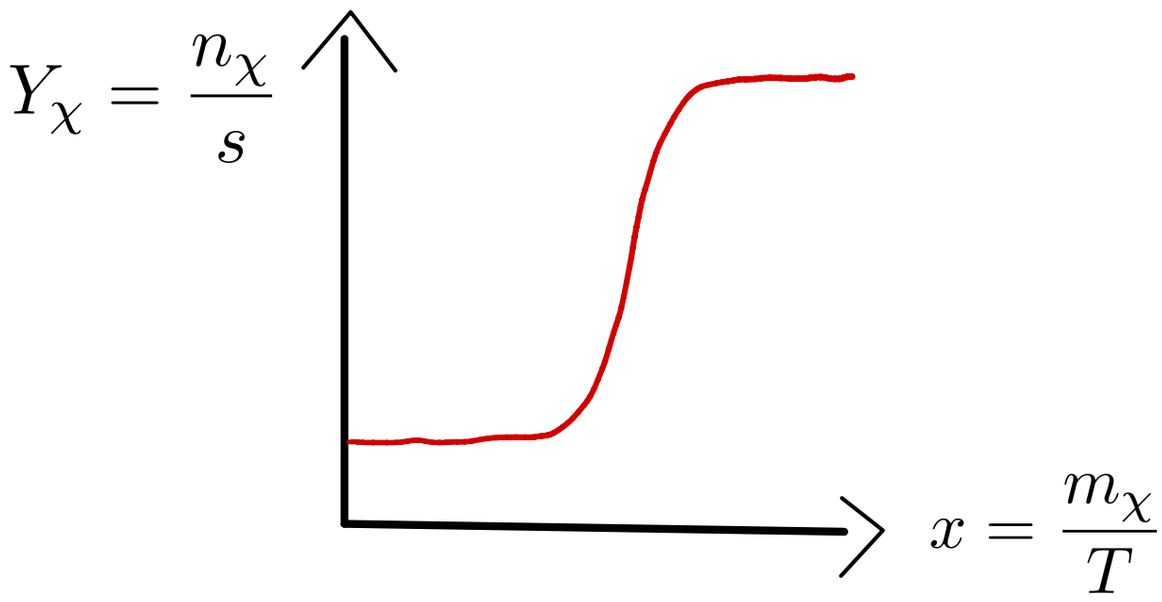
$$\mathcal{L} = (n_{\nu_e} - n_{\bar{\nu}_e})/s$$

Shi, Fuller, **astro-ph/9810076**

# Exponentially Growing Dark Matter

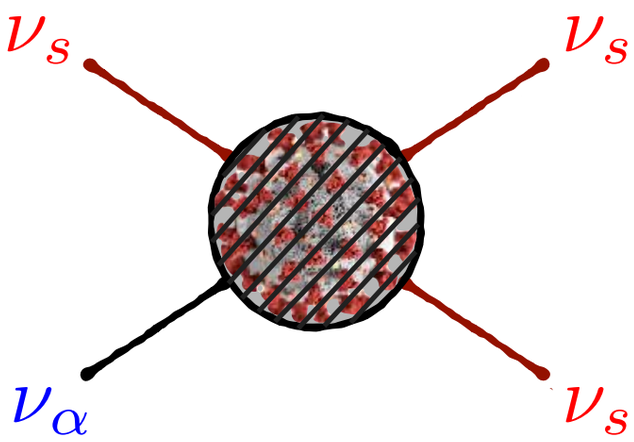


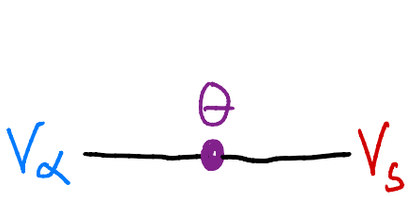



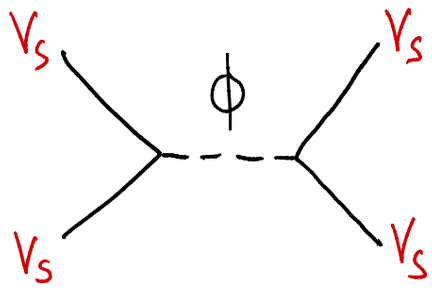

Bringmann, Depta, Hufnagel, JTR, Schmidt-Hoberg **2103.16572**

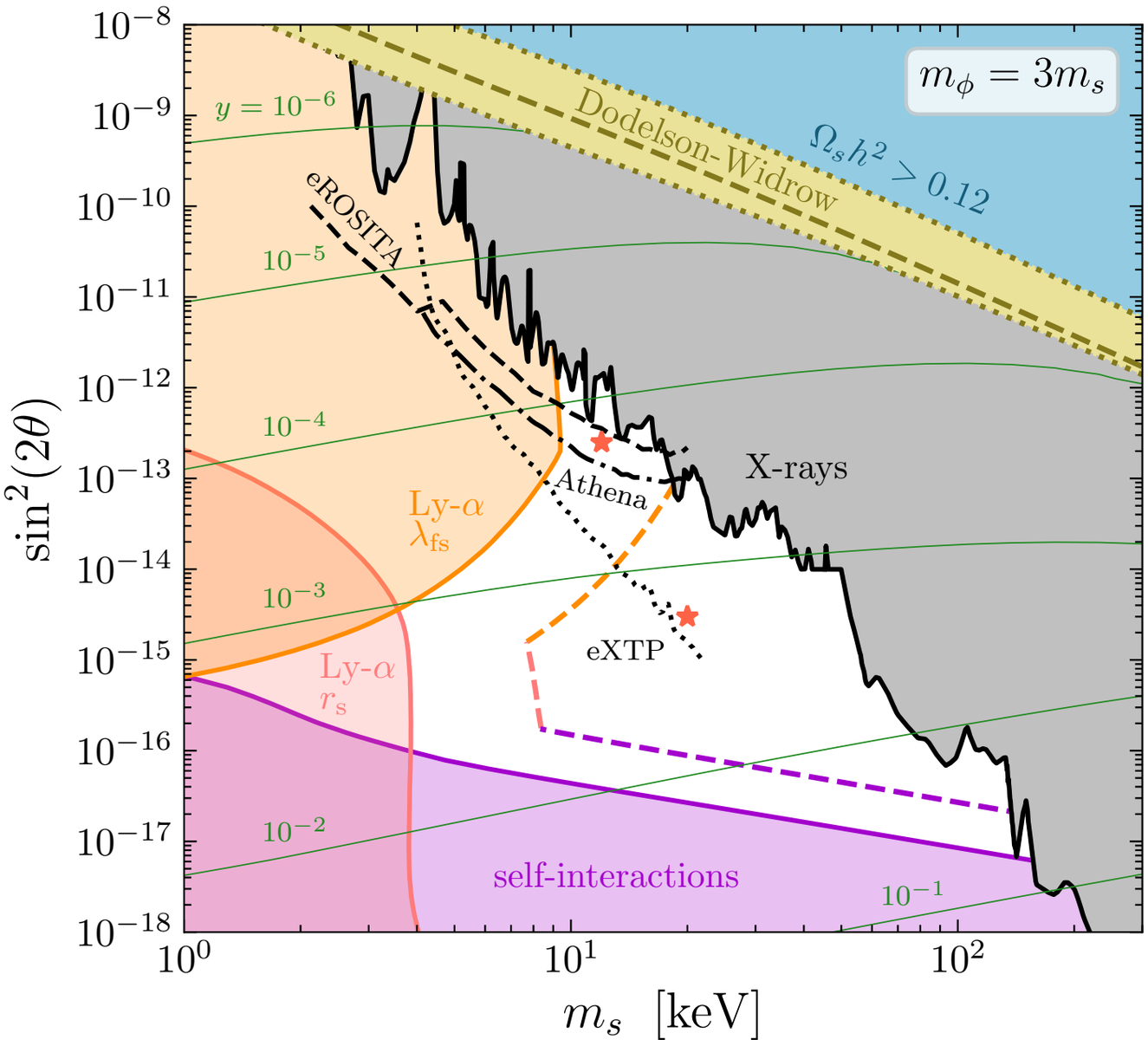
# Sterile Neutrinos from Exponential Growth




growth reaction generated if sterile ν have self-interactions:

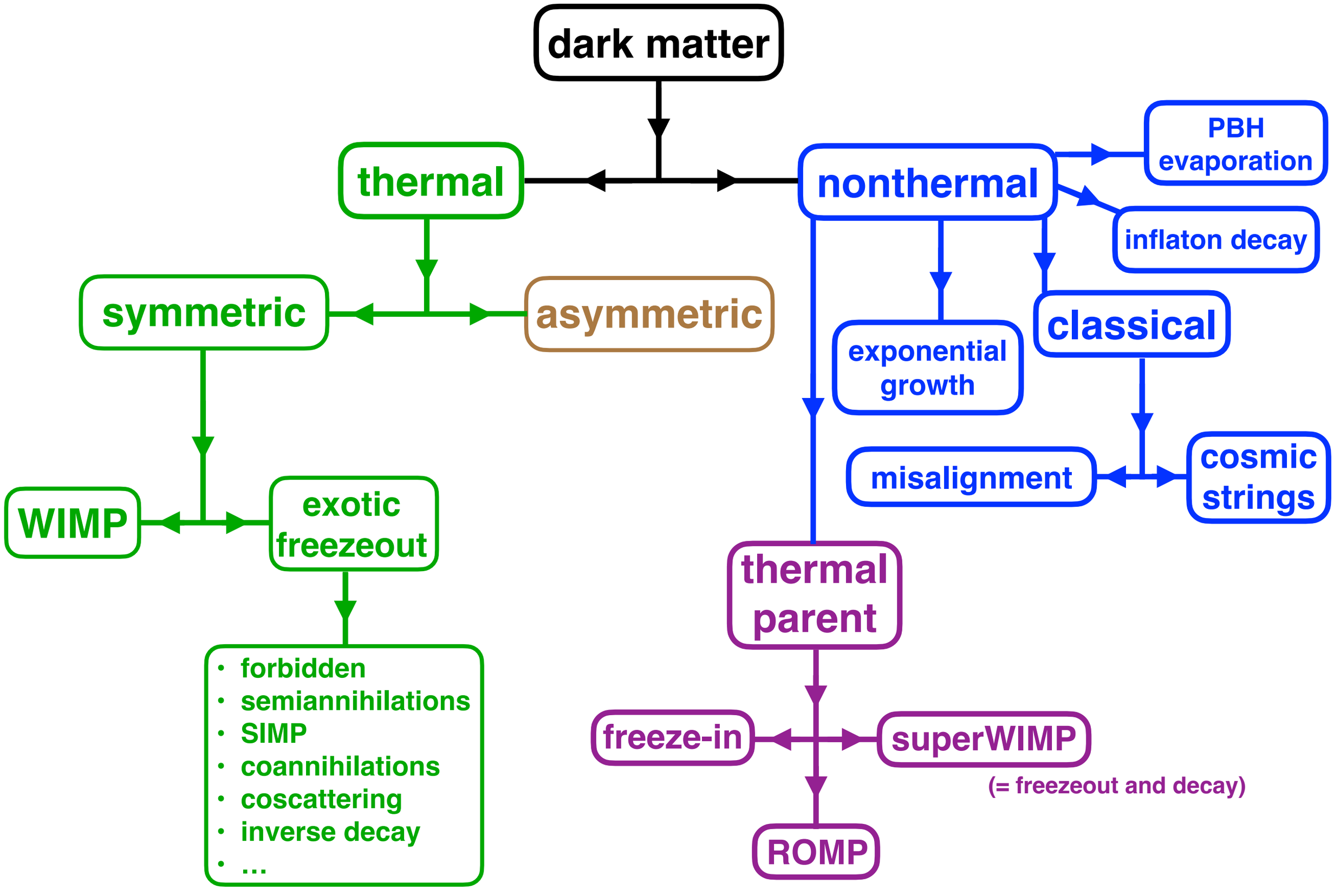


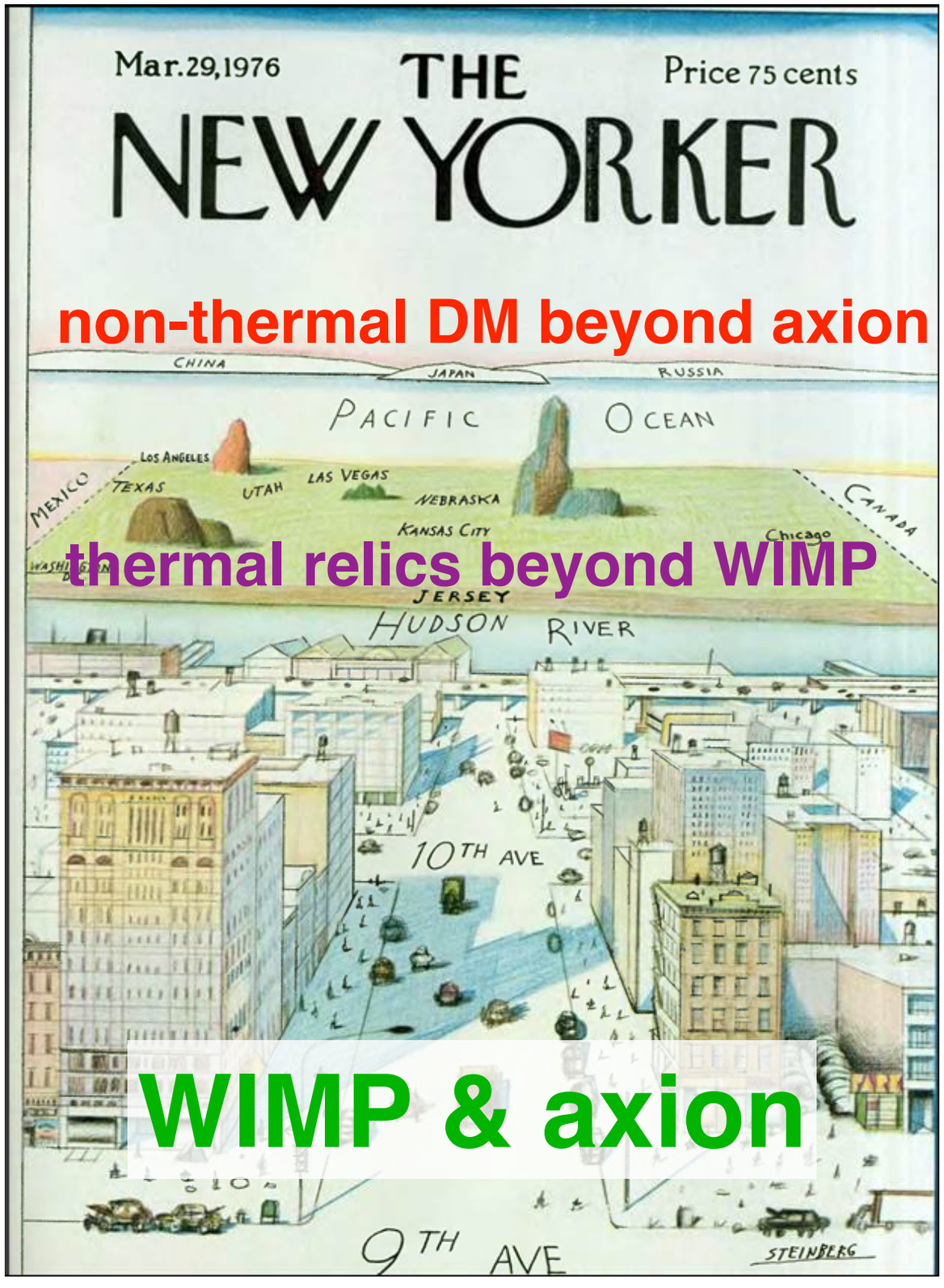




Bringmann, Depta, Kersten, Hufnagel, JTR, Schmidt-Hoberg **2206.10630**

# Cosmic Production Mechanisms



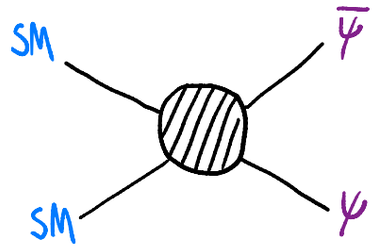


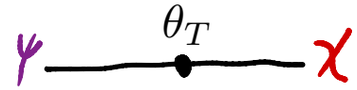

**non-thermal DM beyond axion**

**thermal relics beyond WIMP**

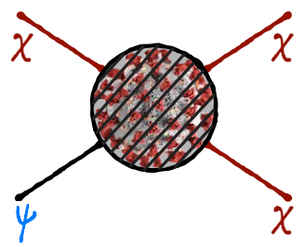
**WIMP & axion**

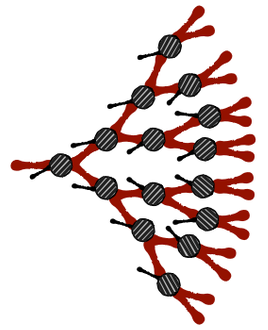
ROMPs:



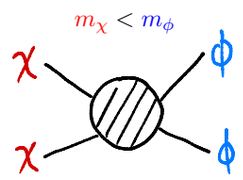




ExpDM:



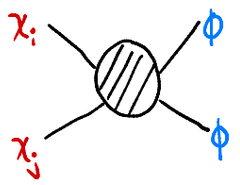


*forbidden*



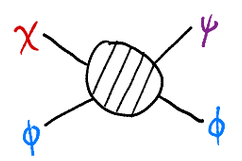

- Griest, Seckel 1991
- D'Agnolo, JTR **1505.07107**

*coannihilations*



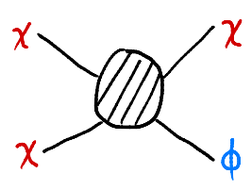
- Griest, Seckel **1991**

*coscattering*



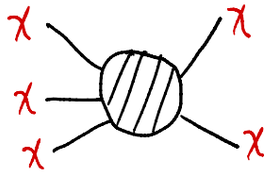
- D'Agnolo, Pappadopulo, JTR **1705.08450**

*semi-annihilations*



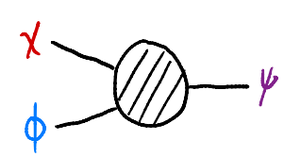
- D'Eramo, J. Thaler **1003.5912**

*SIMP*



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

*inverse decay*



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