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Hidden dynamics of a sub-component dark matter

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Ayuki Kamada, Hee Jung Kim, Jong-Chul Park, **SS**, arXiv: 2111.06808

What is Dark Matter?

What particle is dark matter?

- Mass?
- (Non-gravitational) Interactions?

  DM - SM

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  ii) Amount of DM

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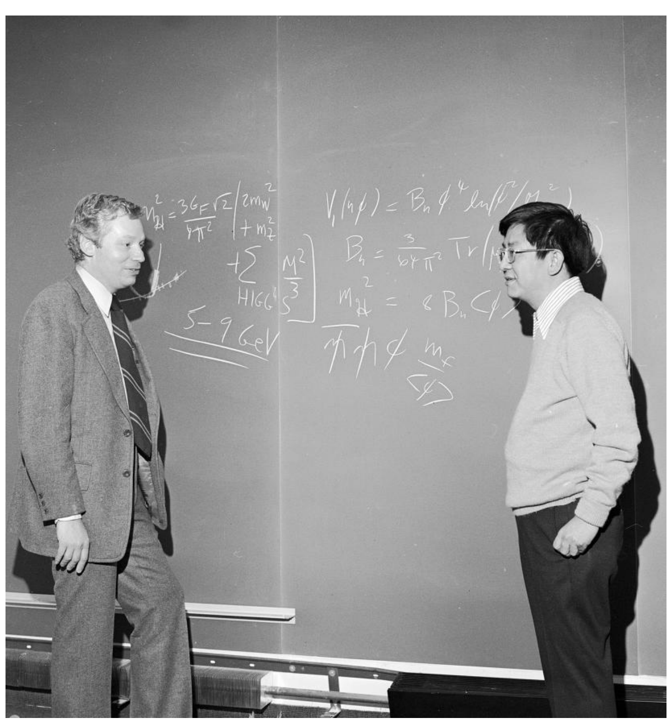
Preferred candidate so far was

Weakly Interacting Massive Particle (WIMP)



- Weak scale mass: $O(1 \sim 10^5) \times$ proton mass
- Weak interaction with the SM particles:
  about $< 10^{-12}$ (in cross section) smaller than EM

Byproduct of many BSM theories for resolving the hierarchy problem

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WIMP strongly constrained!

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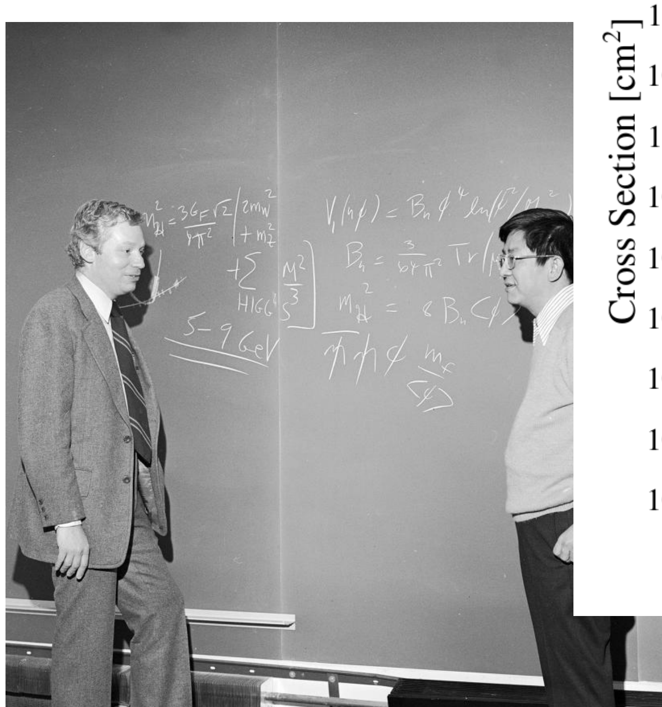

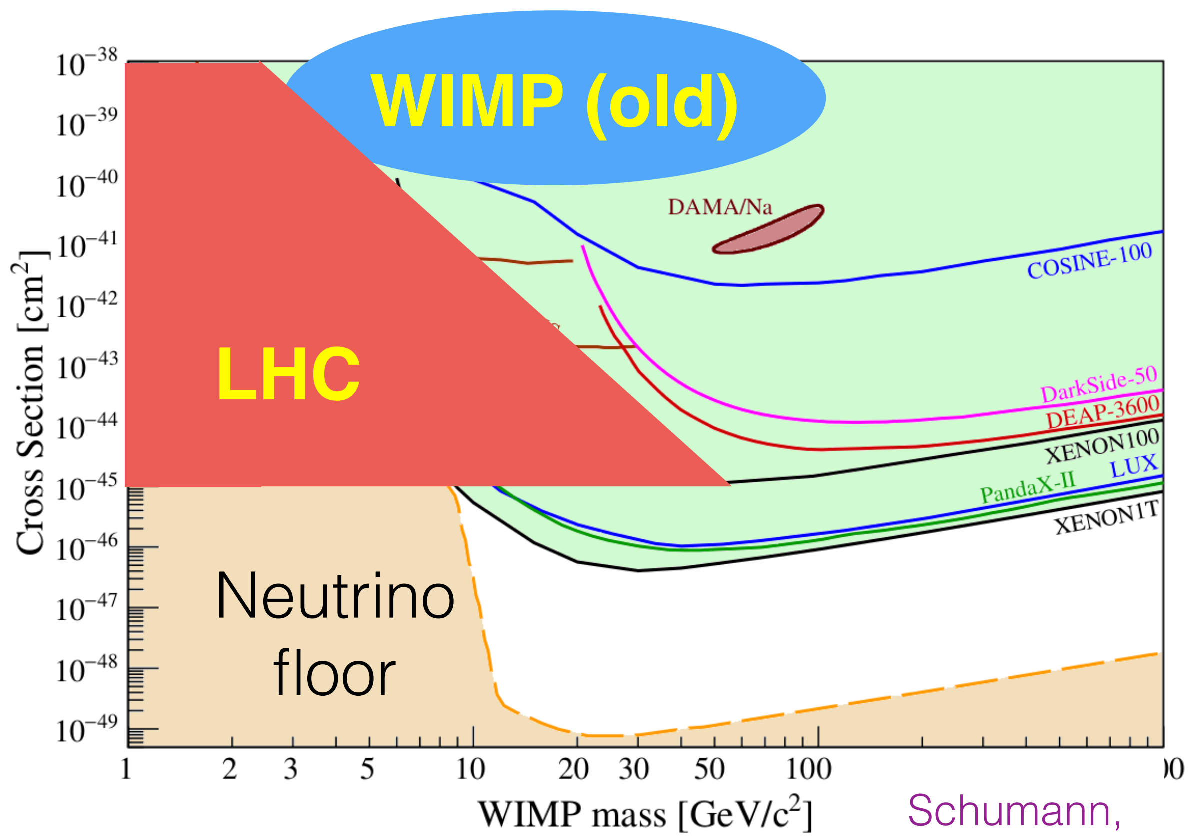

Schumann, 1903.03026

theories

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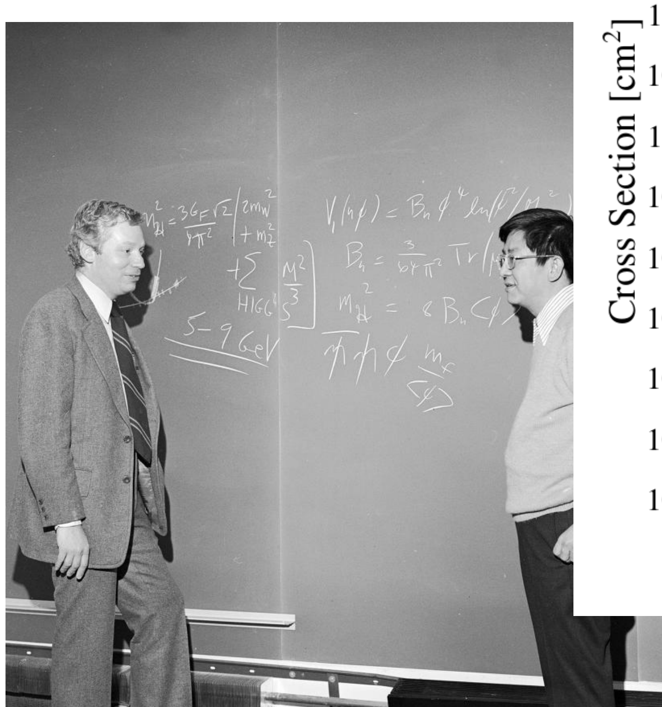

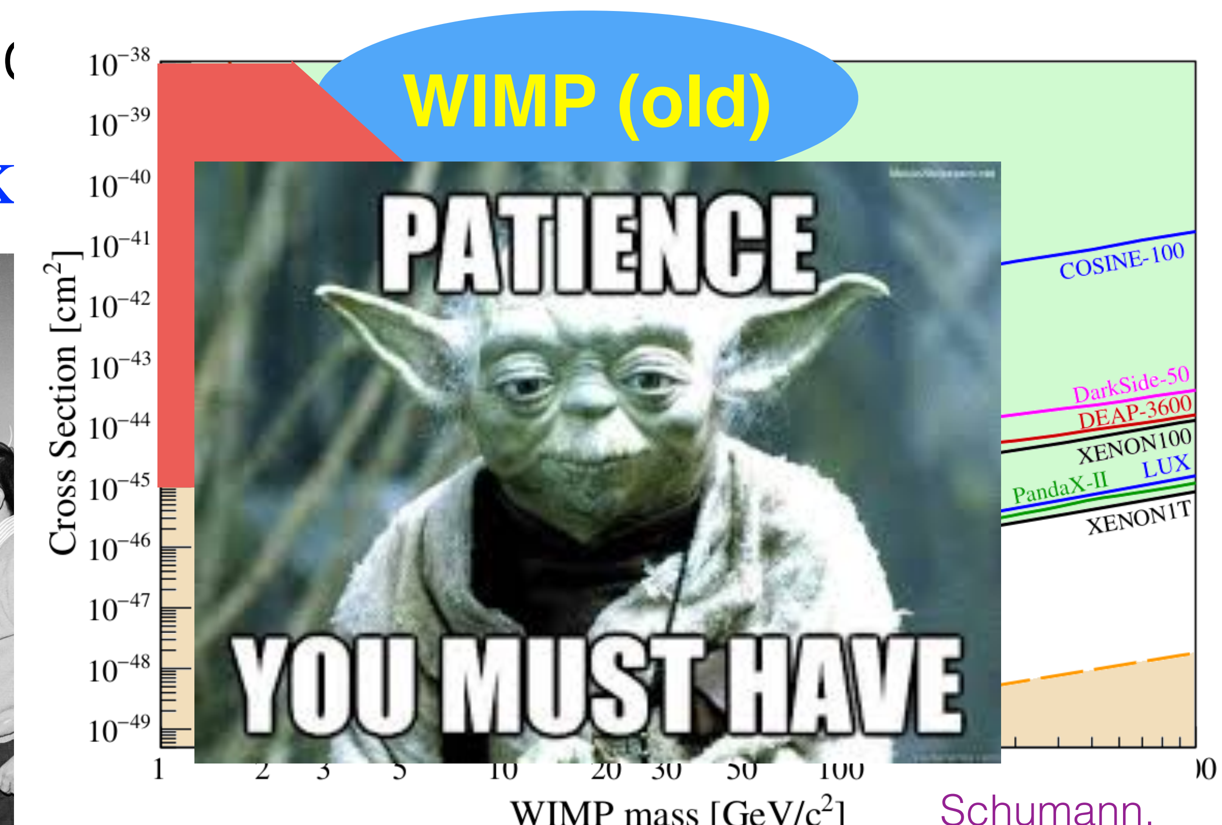

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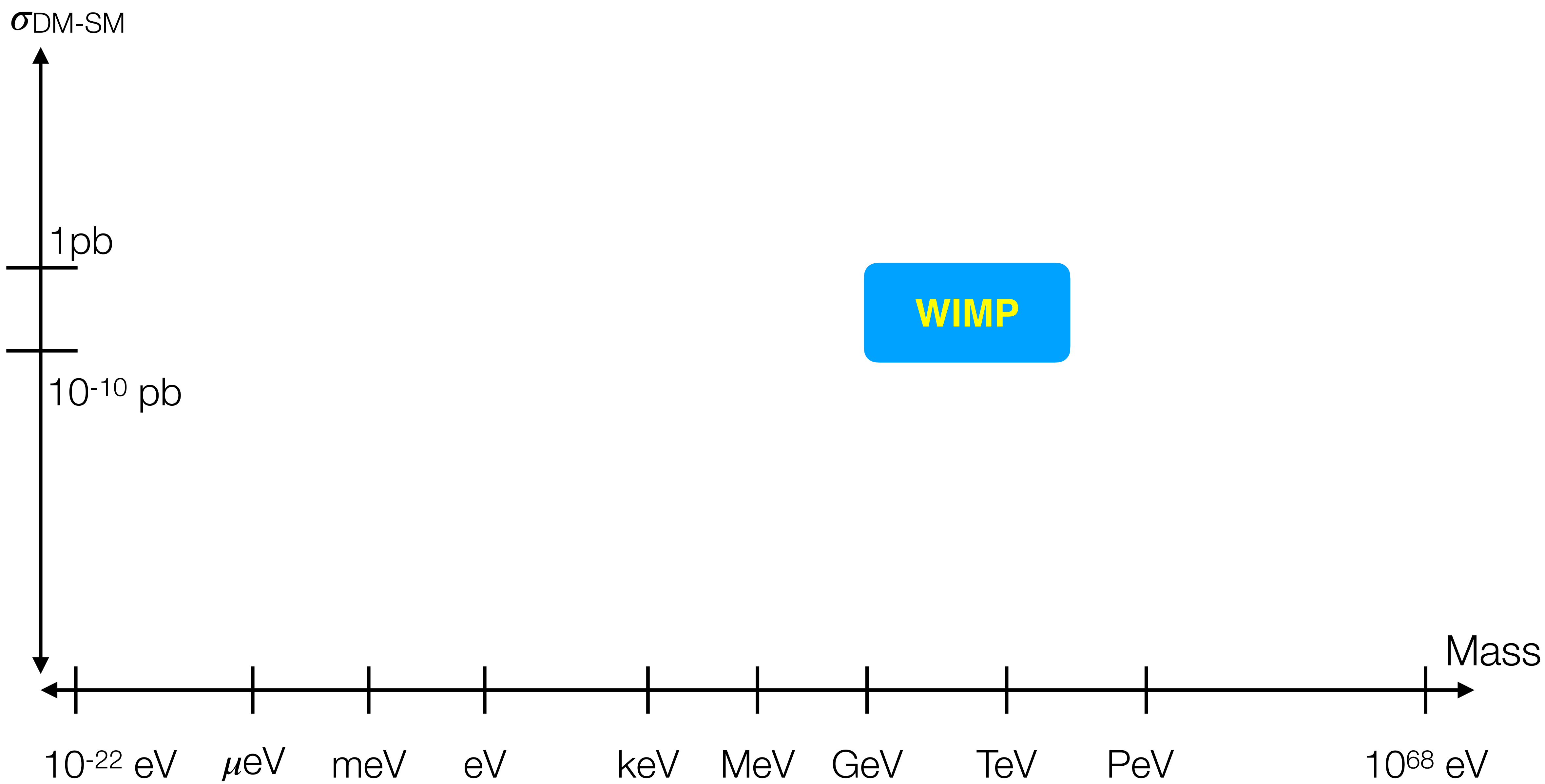
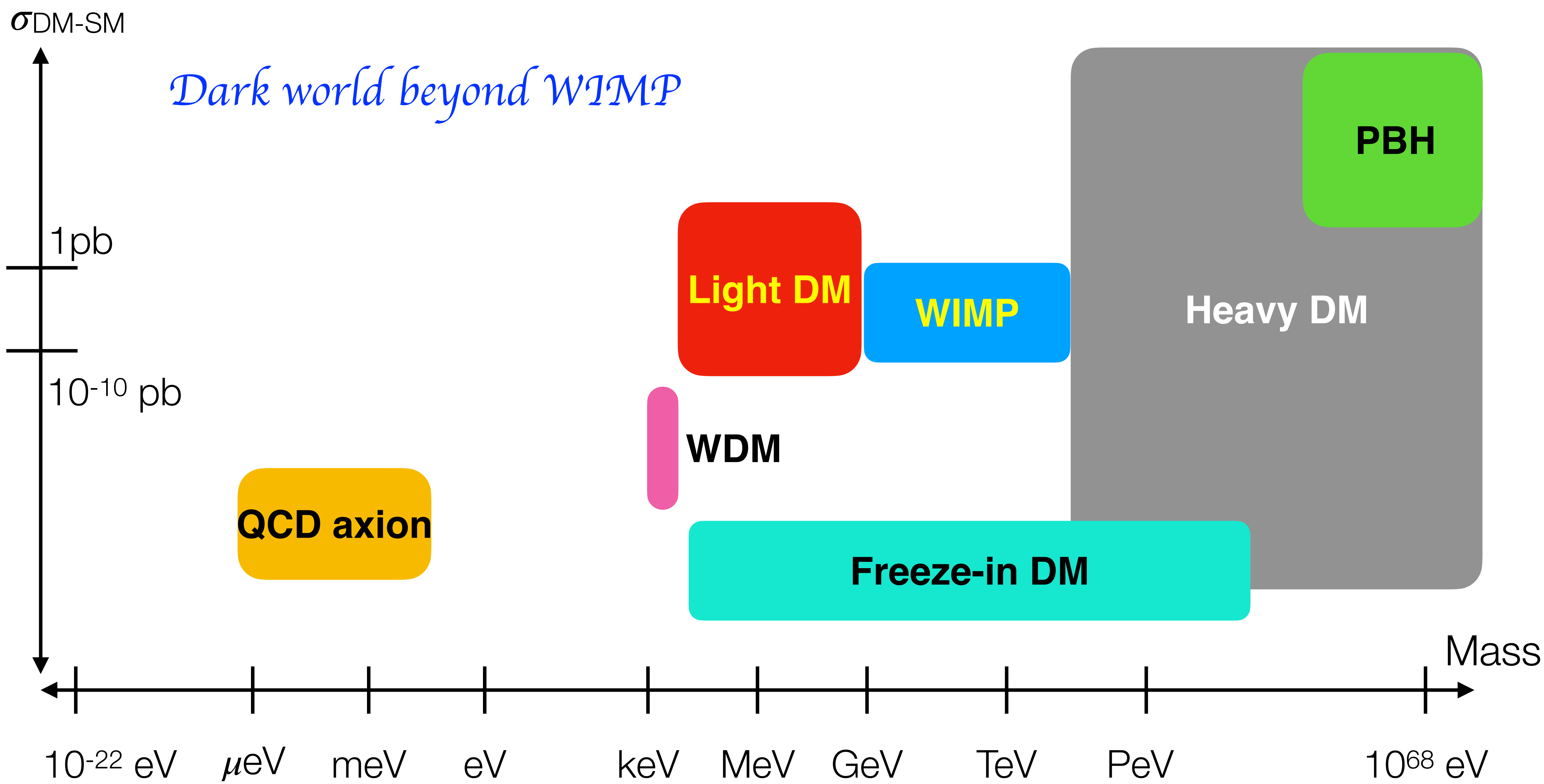
for resolving the ...y problem

Dark world beyond WIMP



- WIMP: a single species of particles with thermal relic via freeze-out
- Mass in between 1 GeV $\lesssim m_\chi \lesssim$ 100 TeV roughly

Dark world beyond WIMP



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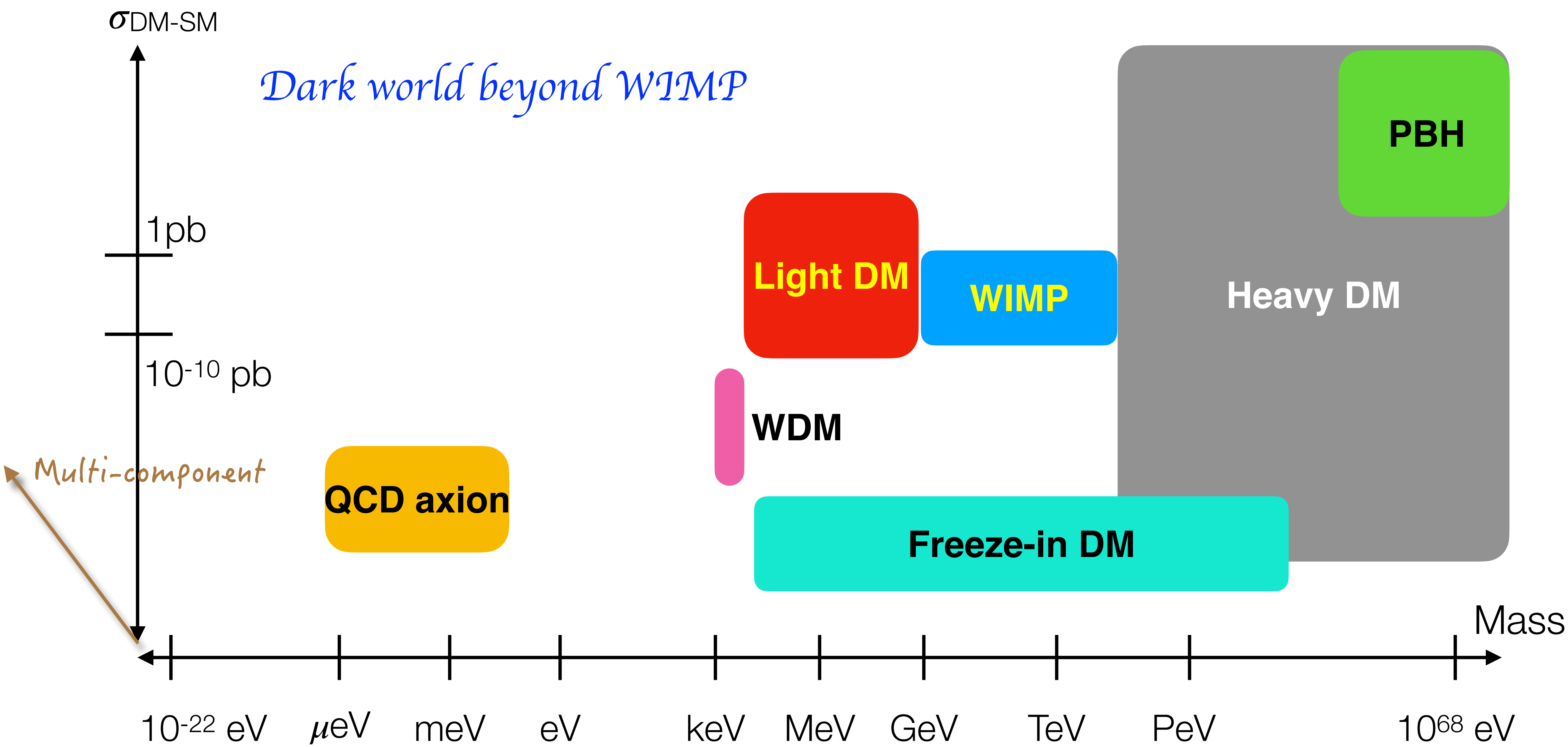
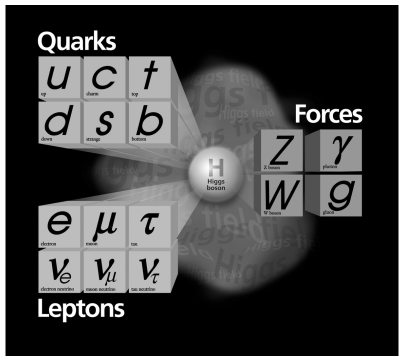


- Dark sector: multiple species of particles? Symmetries?
- Non-trivial structures give unique signals: e.g., iDM



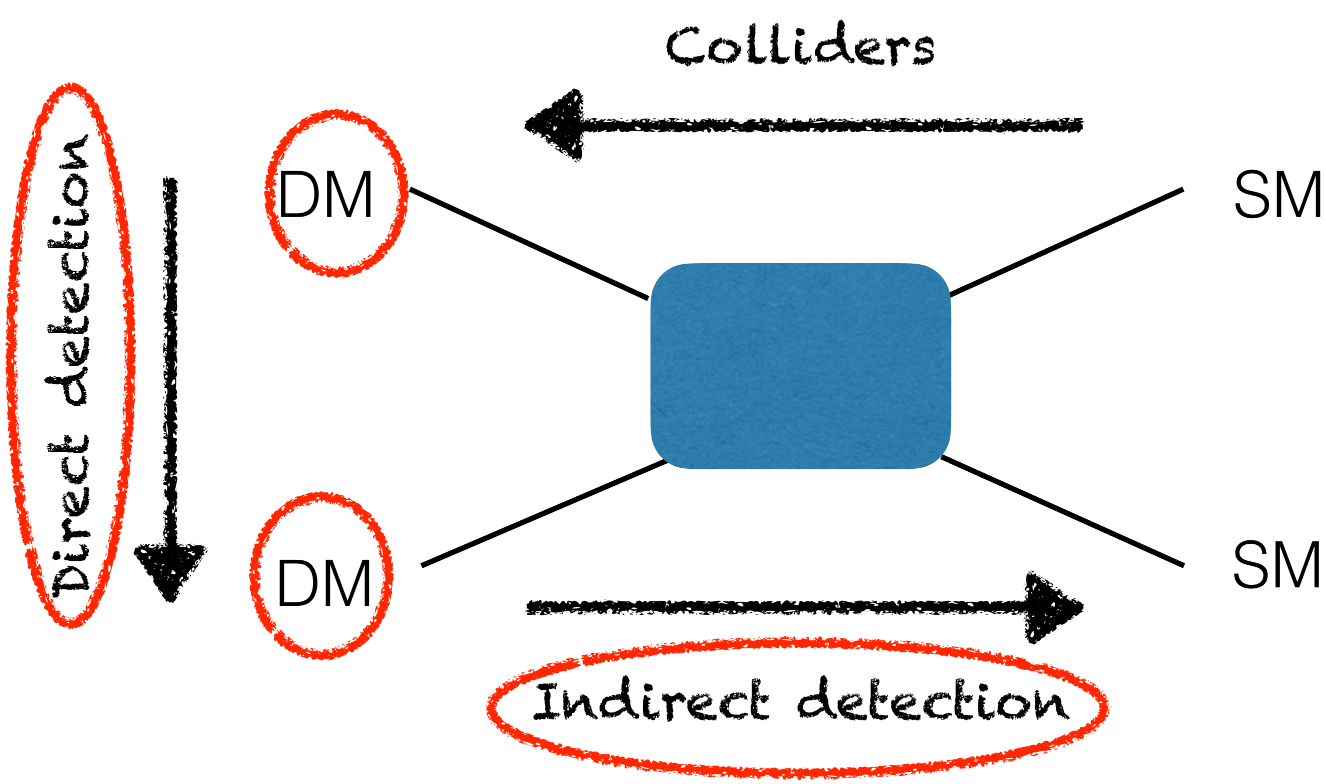
Smith, Weiner, PRD 2001

Sub-dominant component is hidden?

- Conventionally, sub-dominant DM components are thought to be hidden in direct/indirect detection experiments: observables $\propto$ fraction

- Particularly useful in the scenarios where the dominant relic communicates with the SM sector through the sub-dominant relic.

- Question is how the amount of the sub-dominant relic is determined.



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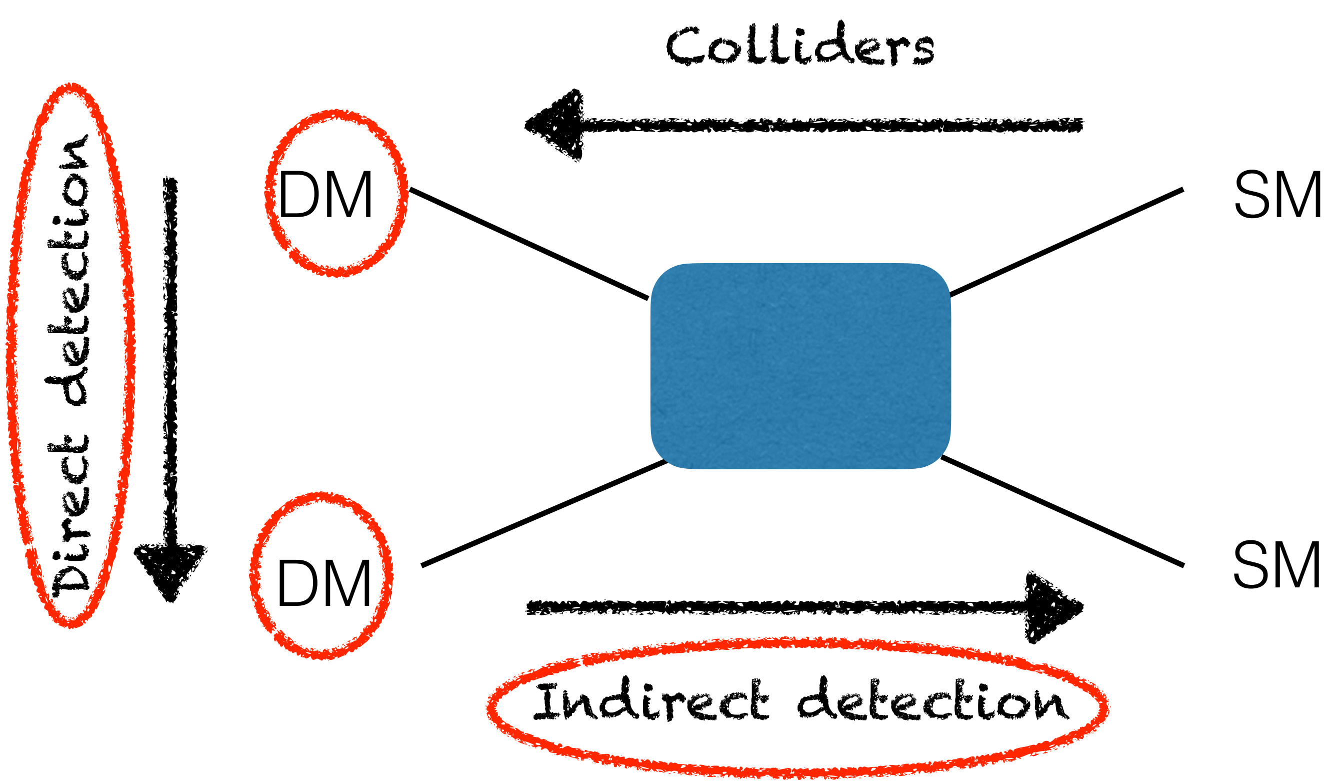

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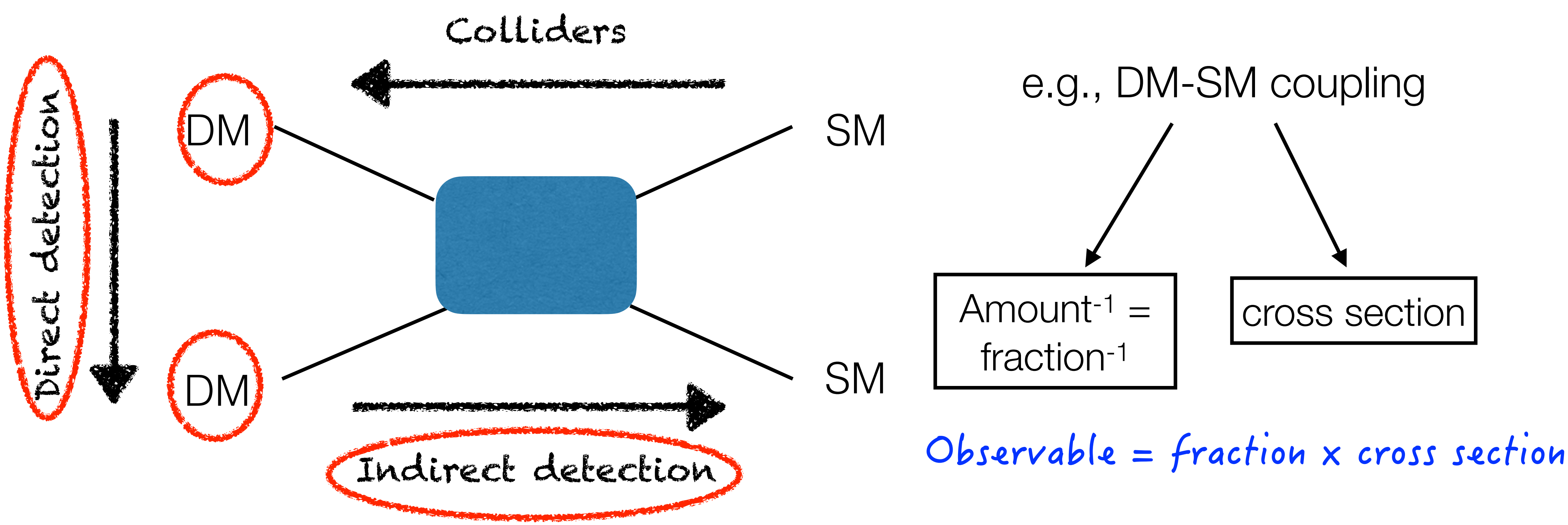
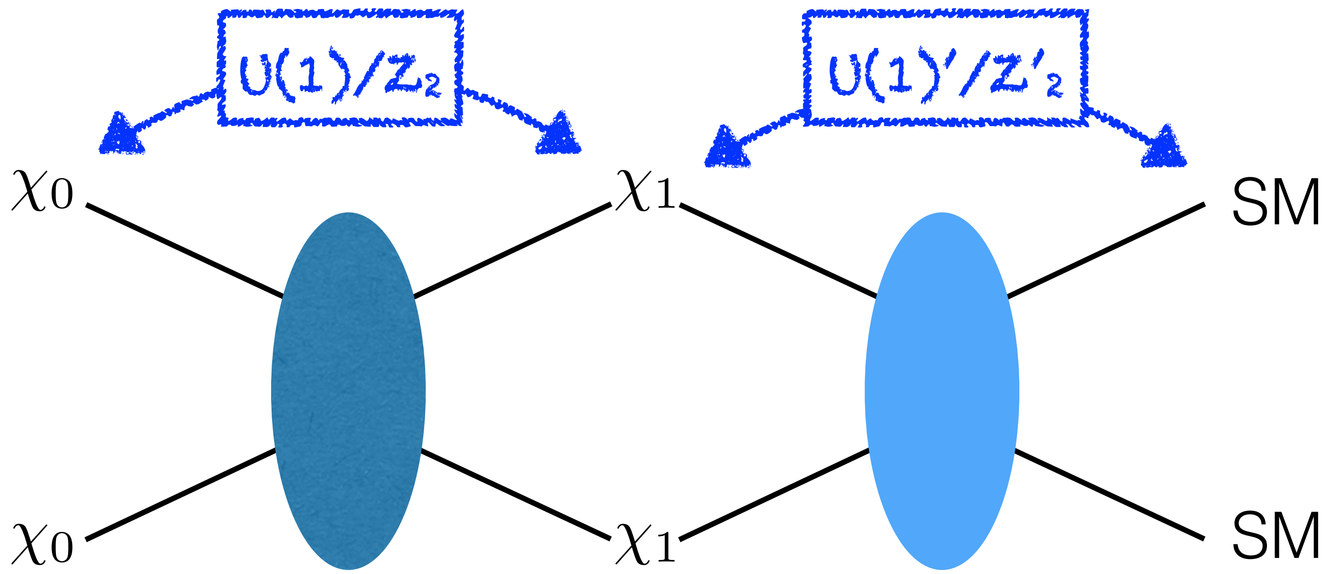


Reference: Multi-component BDM

χ_0: heavy, χ_1: light



Agashe, Cui, Necib, Thaler, JCAP 2014

Kim, Park , **SS**, PRL 2017

Giudice, Kim, Park , **SS**, PLB 2018

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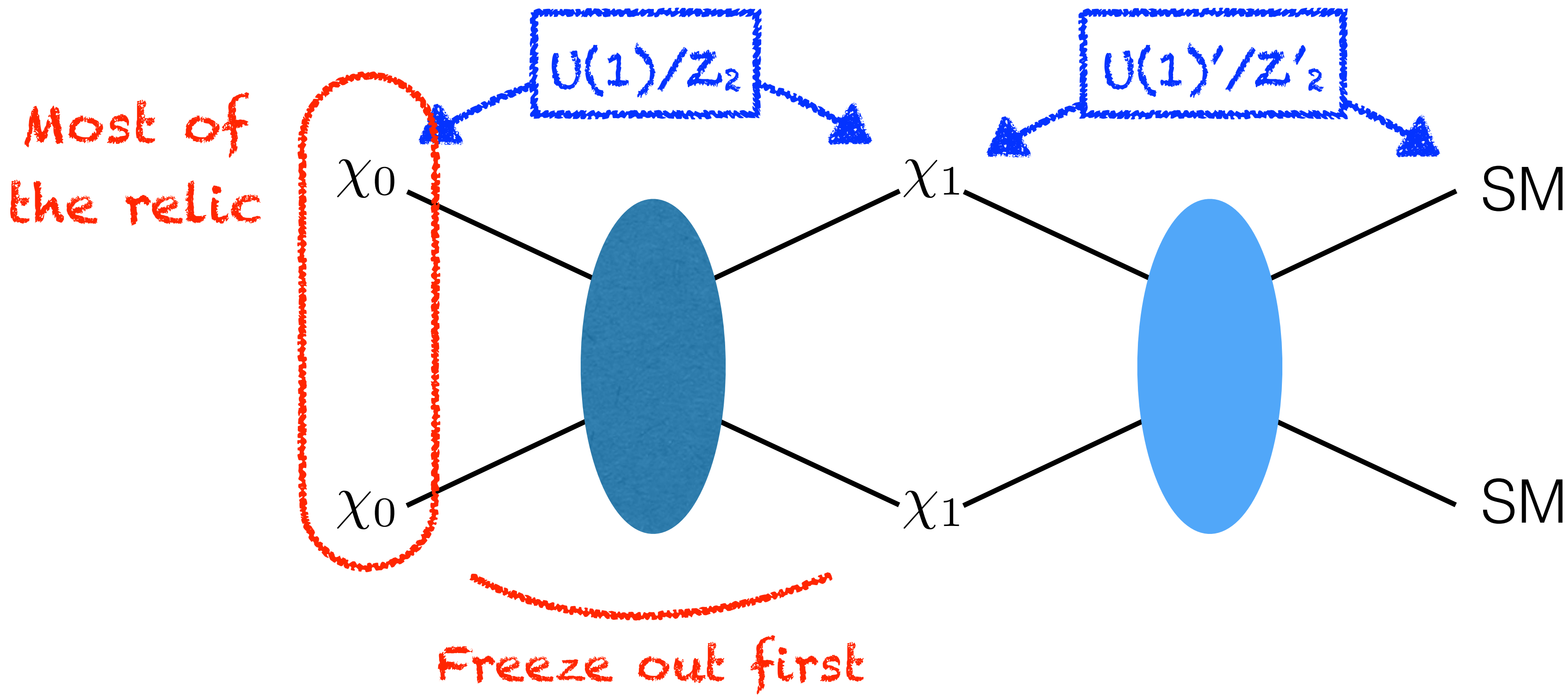

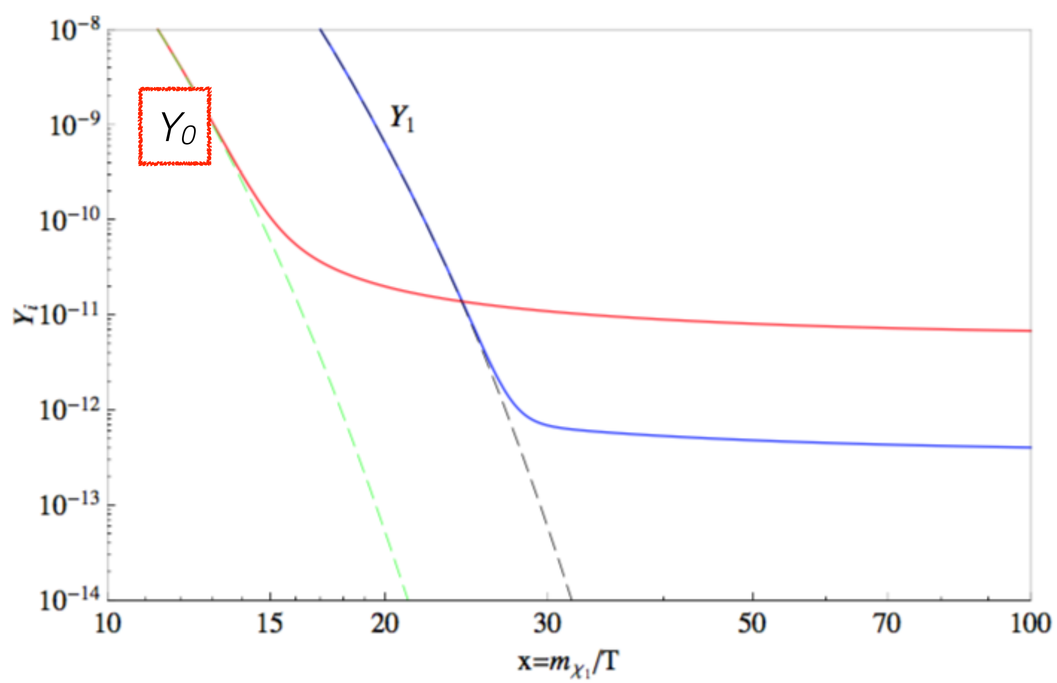

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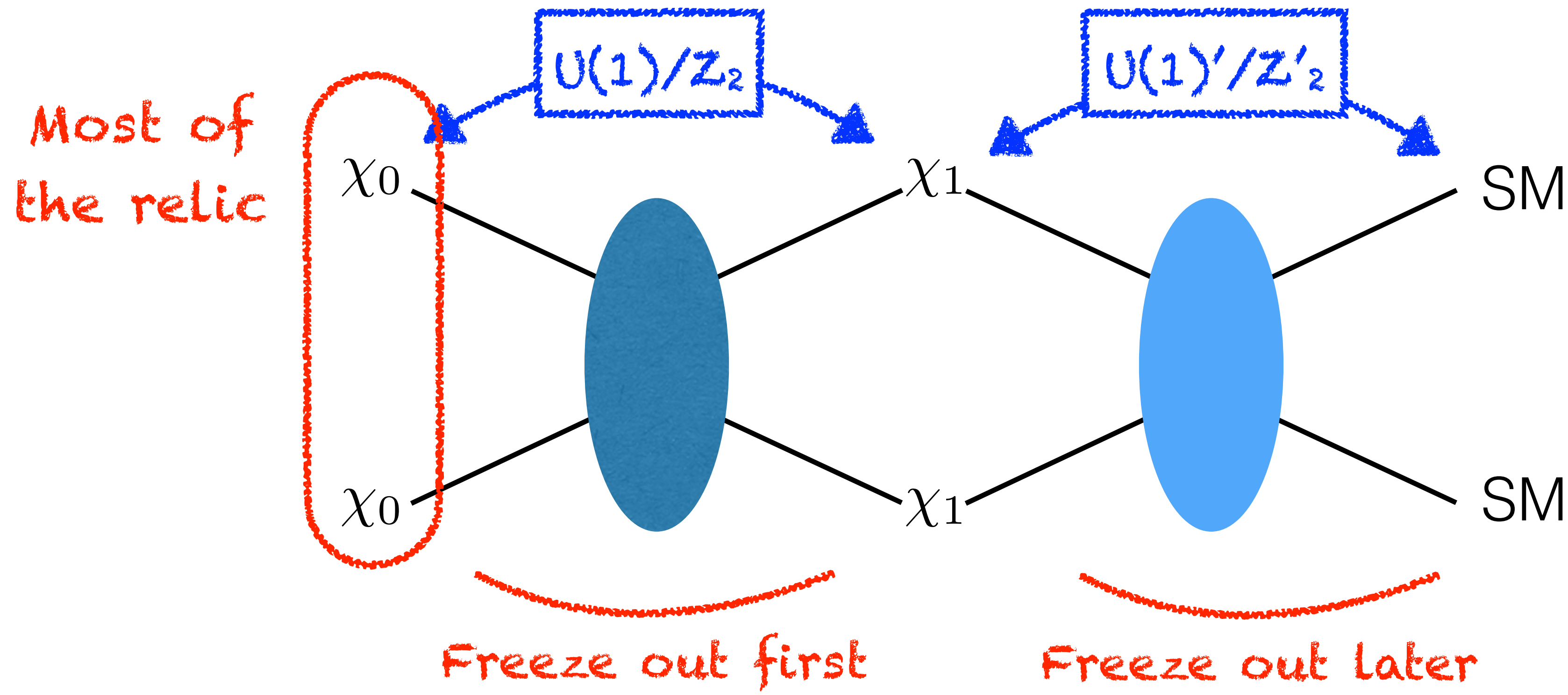

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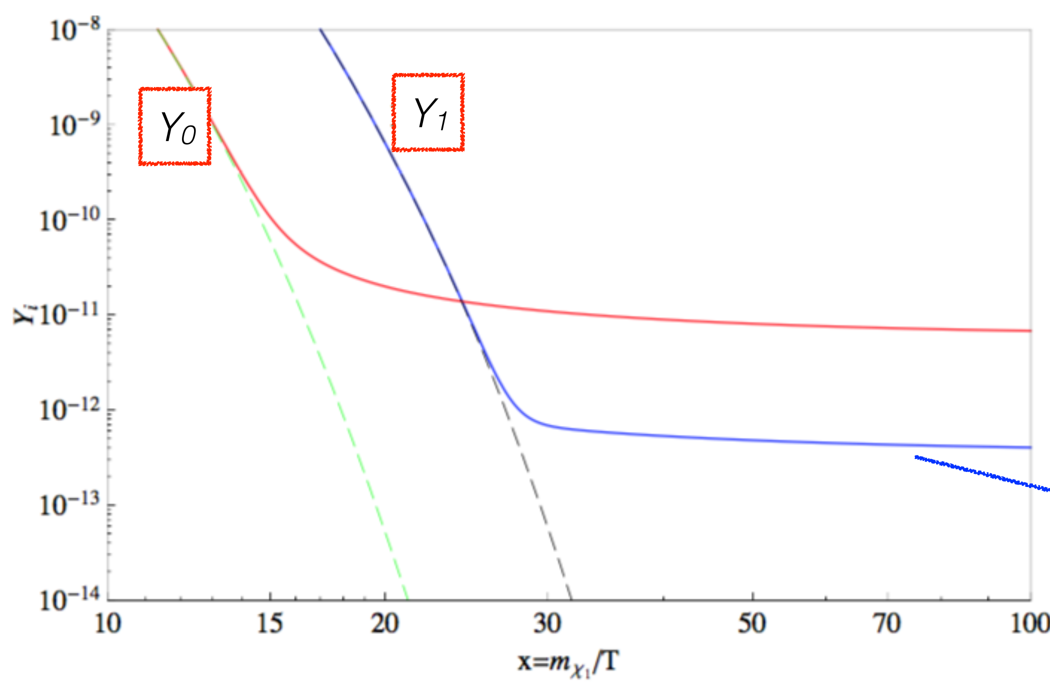


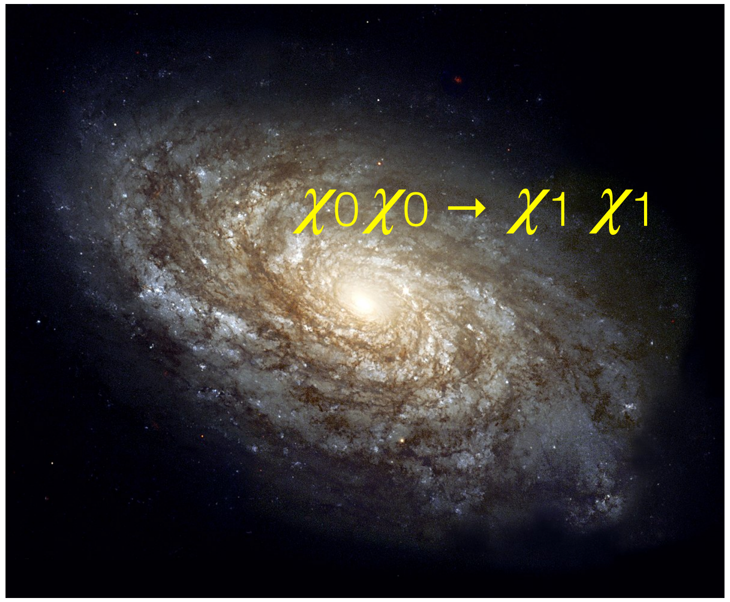
Belanger, Park, JCAP 2012

Assisted freeze-out mechanism

non-relativistic relic χ_1 (negligible)

$Y_0 \gg Y_1$

Reference: Multi-component BDM



- χ_0 : accumulated
  (GC,　Sun,　dSphs)

- $\chi_0 \chi_0 \rightarrow \chi_1 \chi_1$ (current universe) relativistic

  ※ relic χ_1 is non-relativistic

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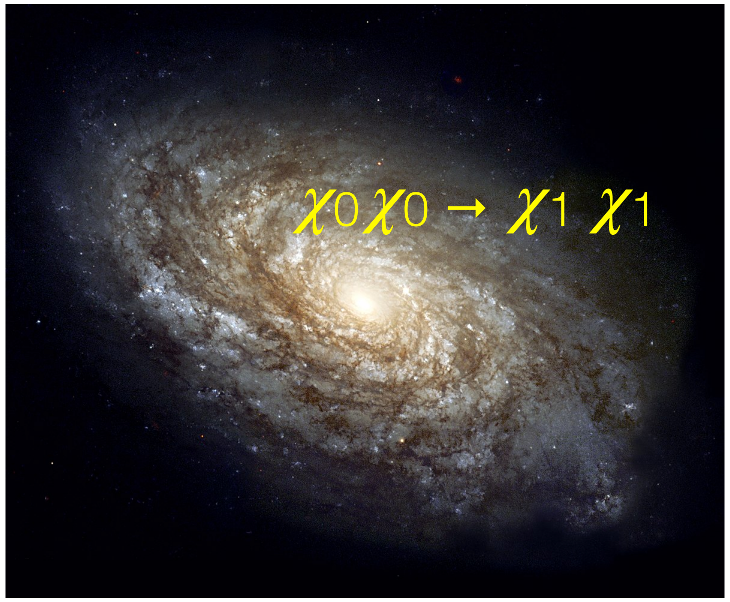

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(indirect detection of χ_0)

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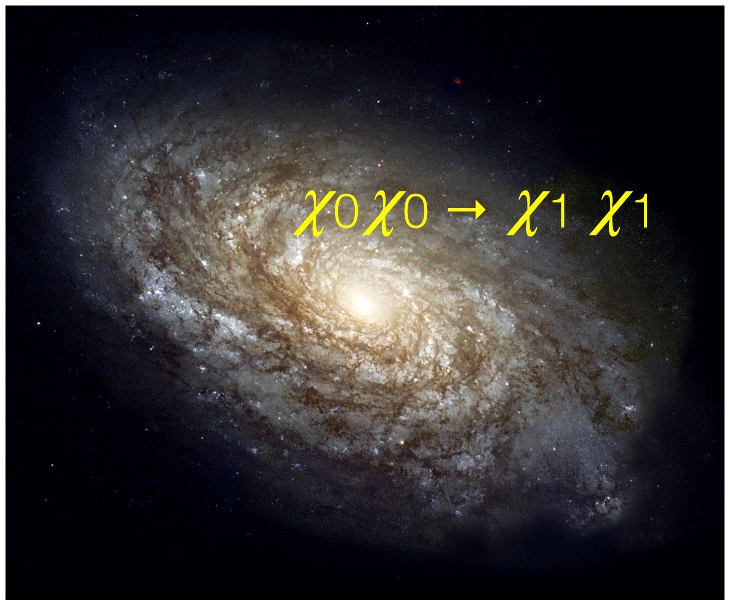

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Assume: NFW

Fixed ~ 1 if **s-wave** annihilation dominates (throughout this work for simplicity)

10,000 times smaller than the flux of atmospheric ν if m_0 ~ 100 GeV

Agashe et al., JCAP 2014

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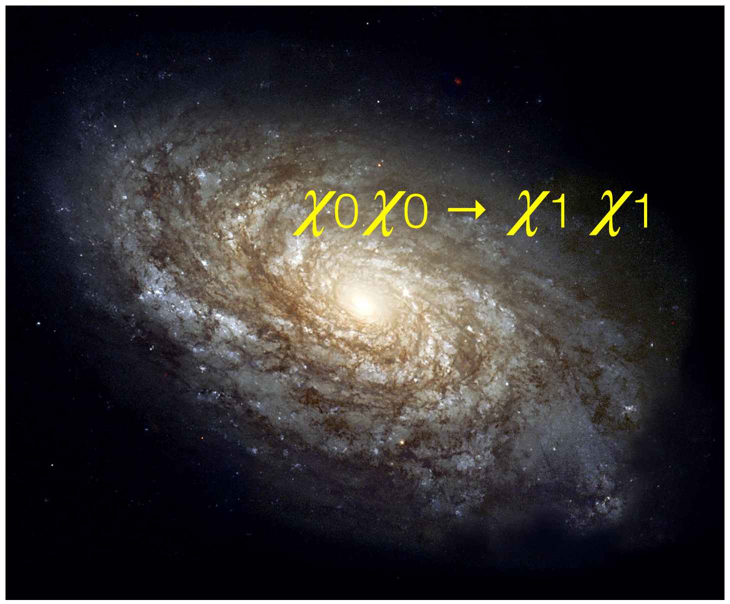

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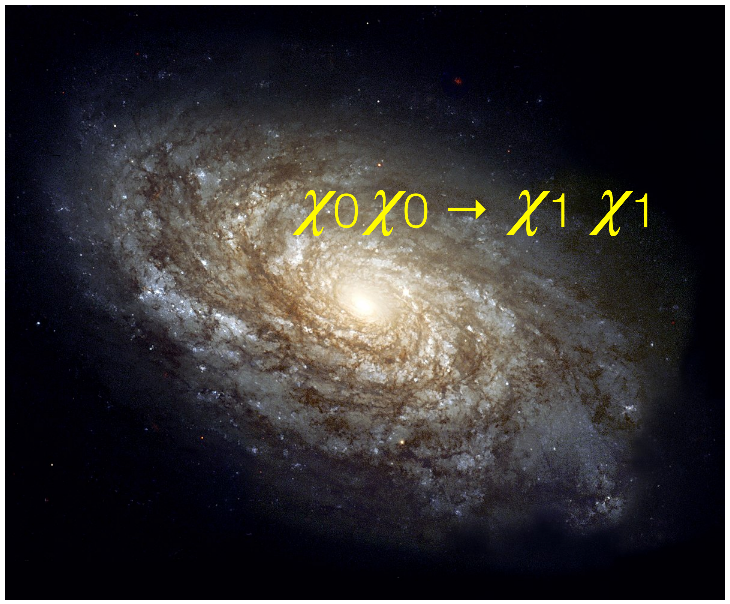

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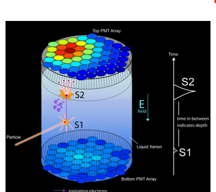

comparable **if $m_0 \lesssim 1$ GeV**

Giudice, Kim, Park , **SS**, PLB 2018

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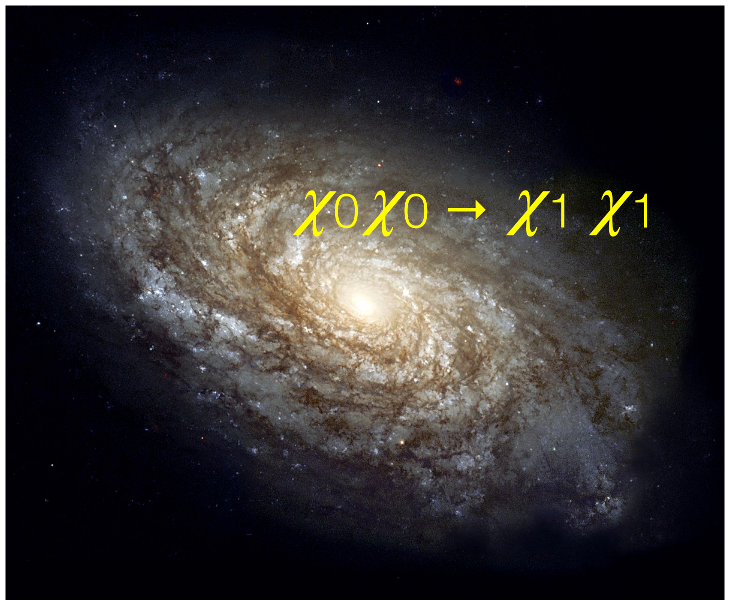

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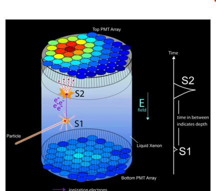


Talk by Mohlabeng

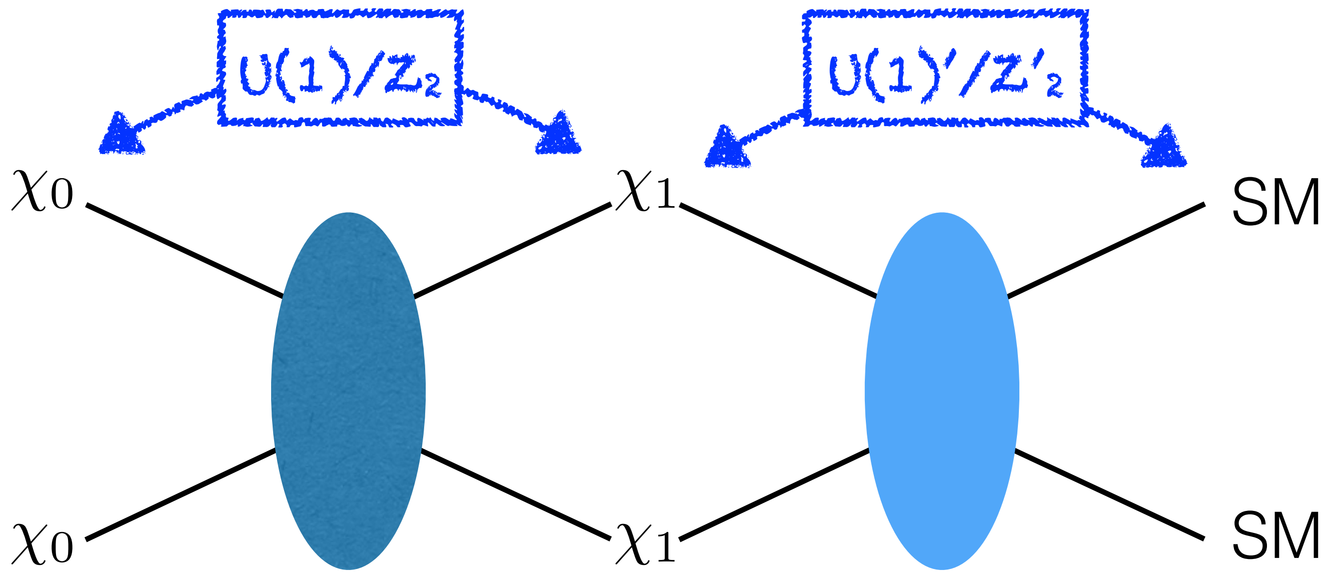
comparable **if $m_0 \lesssim$ 1 GeV**

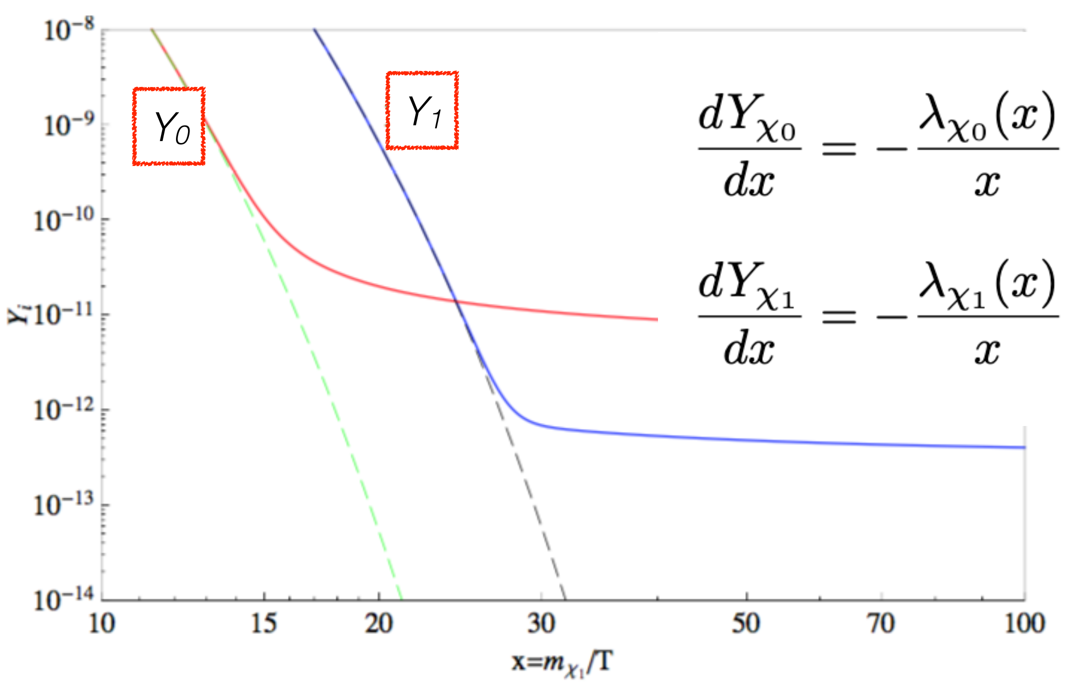
Kim, Park , **SS**, PRL 2017

Giudice, Kim, Park , **SS**, PLB 2018

Structure of $\chi_1 \chi_1 \rightarrow$ SM

χ_0: heavy (dominant), χ_1: light (subdominant)





$$\frac{dY_{\chi_0}}{dx} = -\frac{\lambda_{\chi_0}(x)}{x}\left[Y_{\chi_0}^2 - \left(\frac{Y_{\chi_0}^{\rm eq}(x)}{Y_{\chi_1}^{\rm eq}(x)}\right)^2 Y_{\chi_1}^2\right],$$

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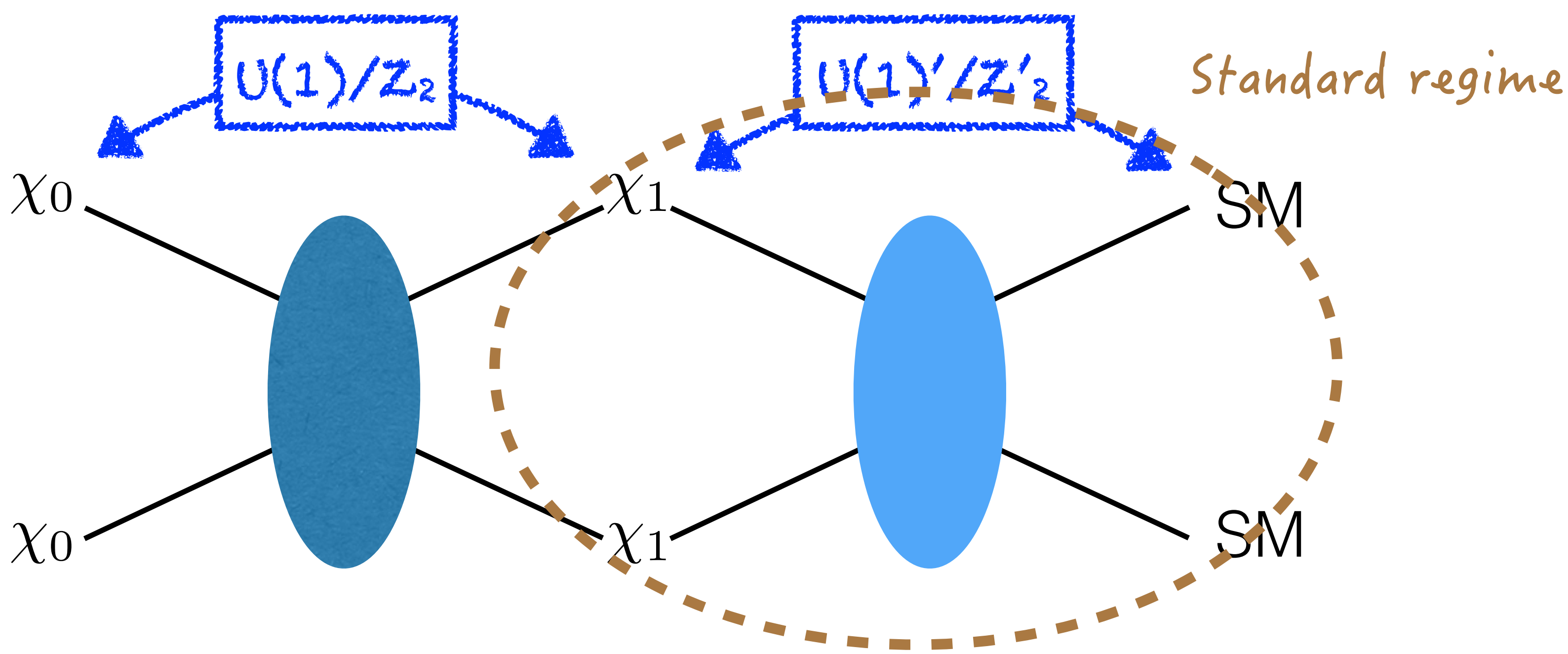

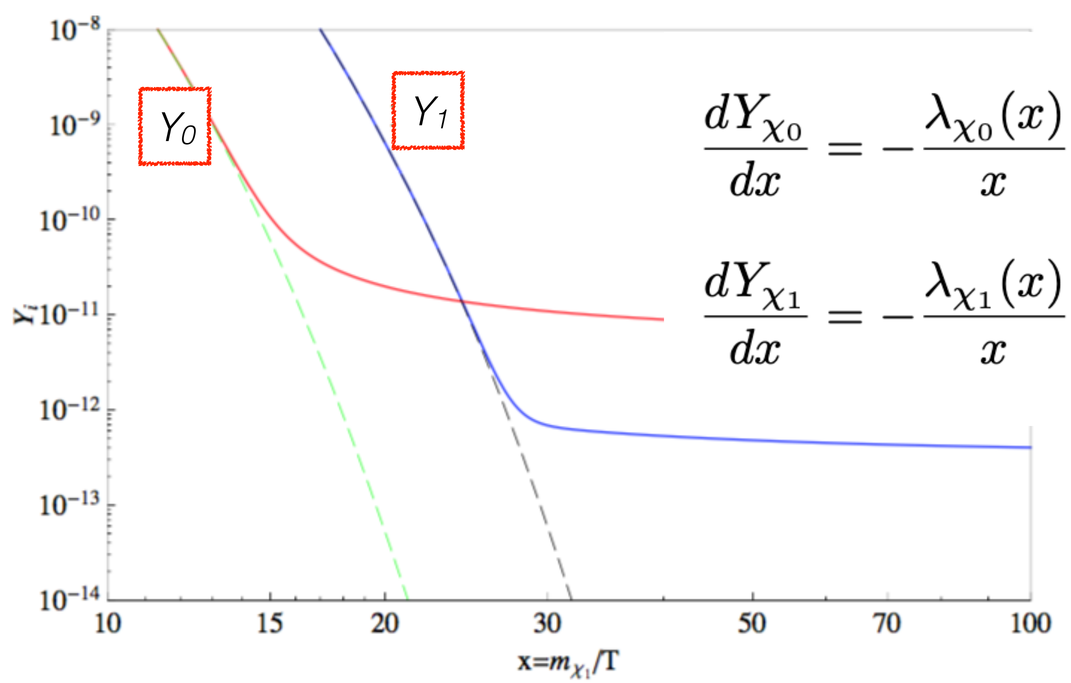

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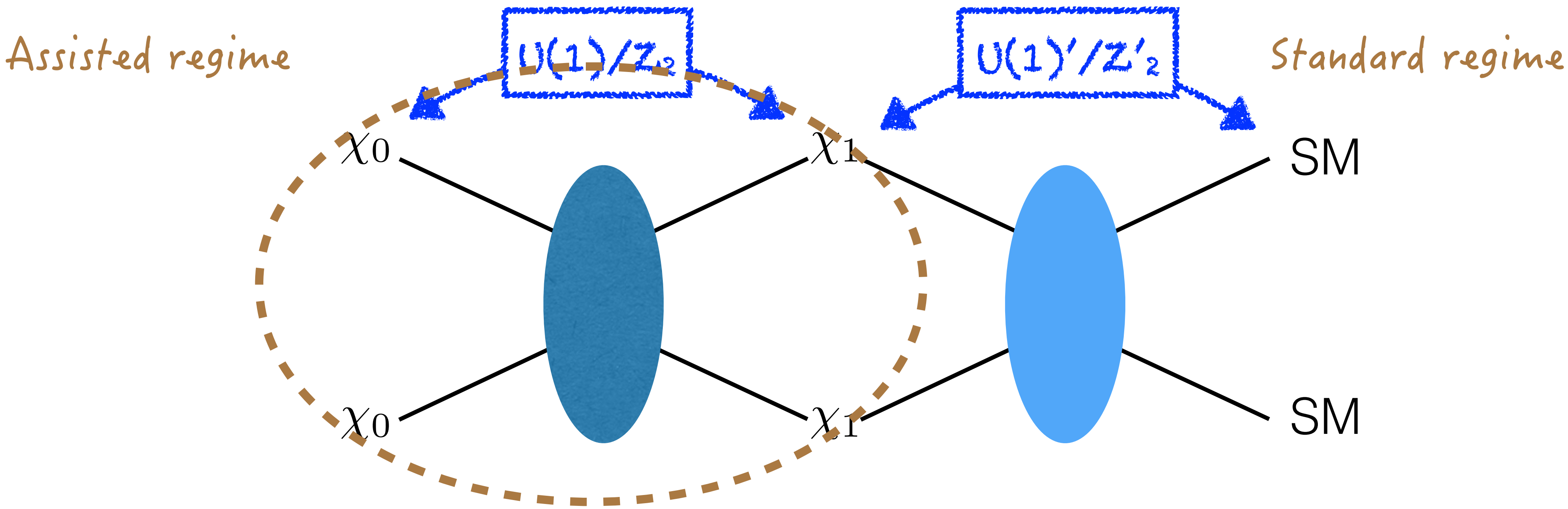

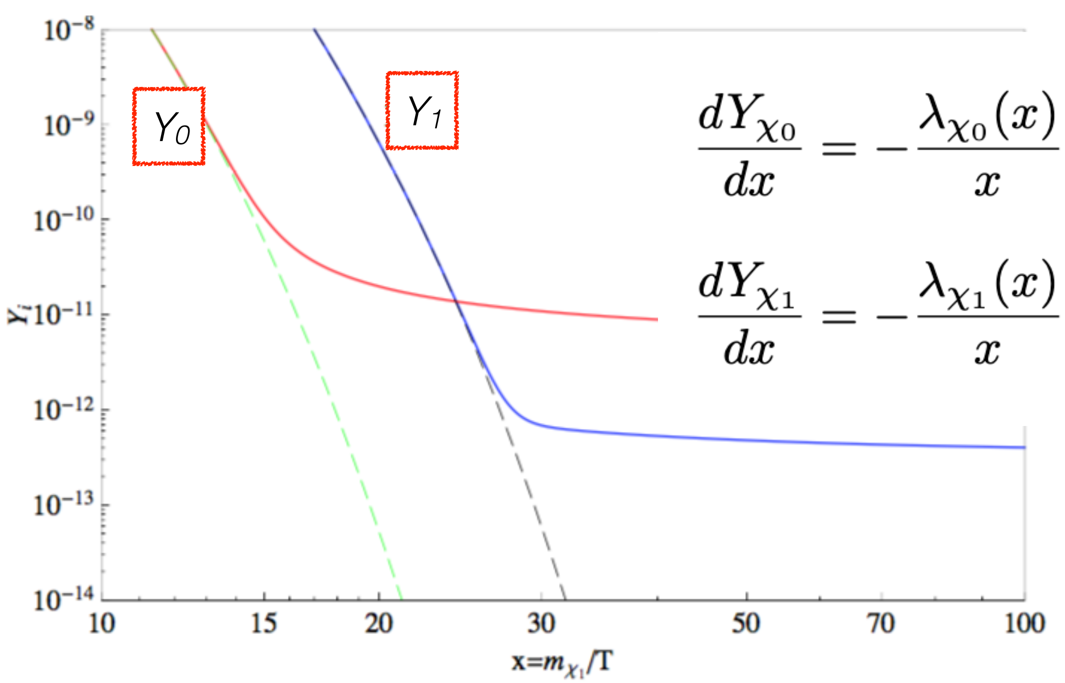

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with SM — with heavy DM χ_0

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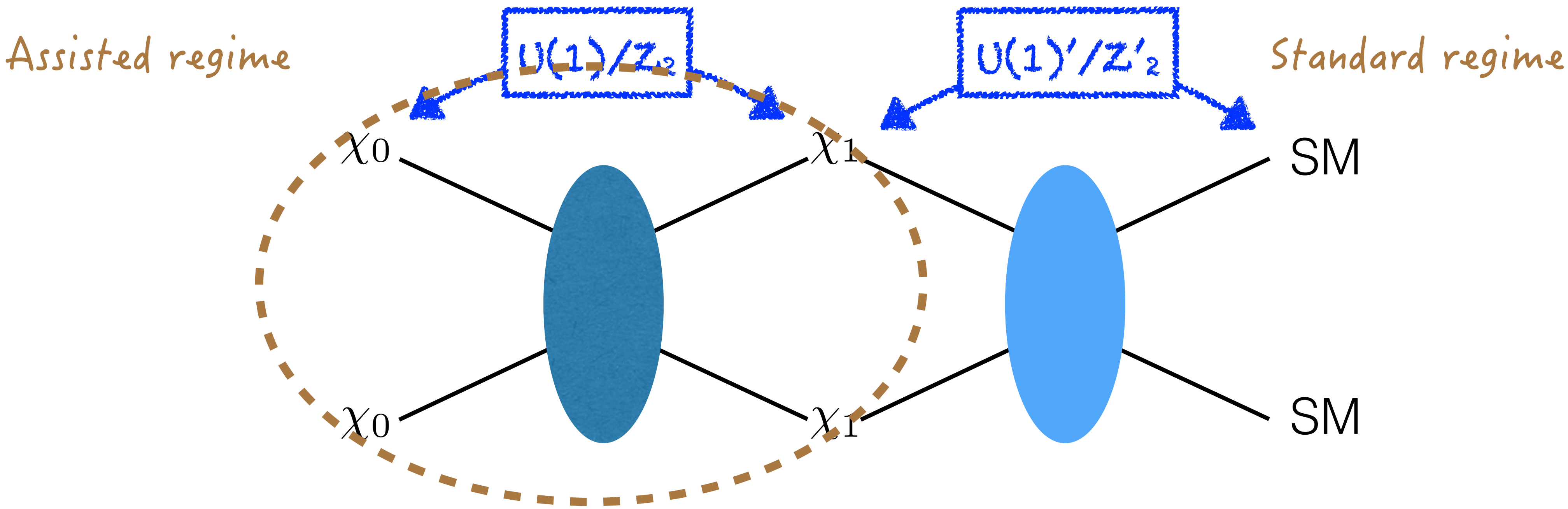
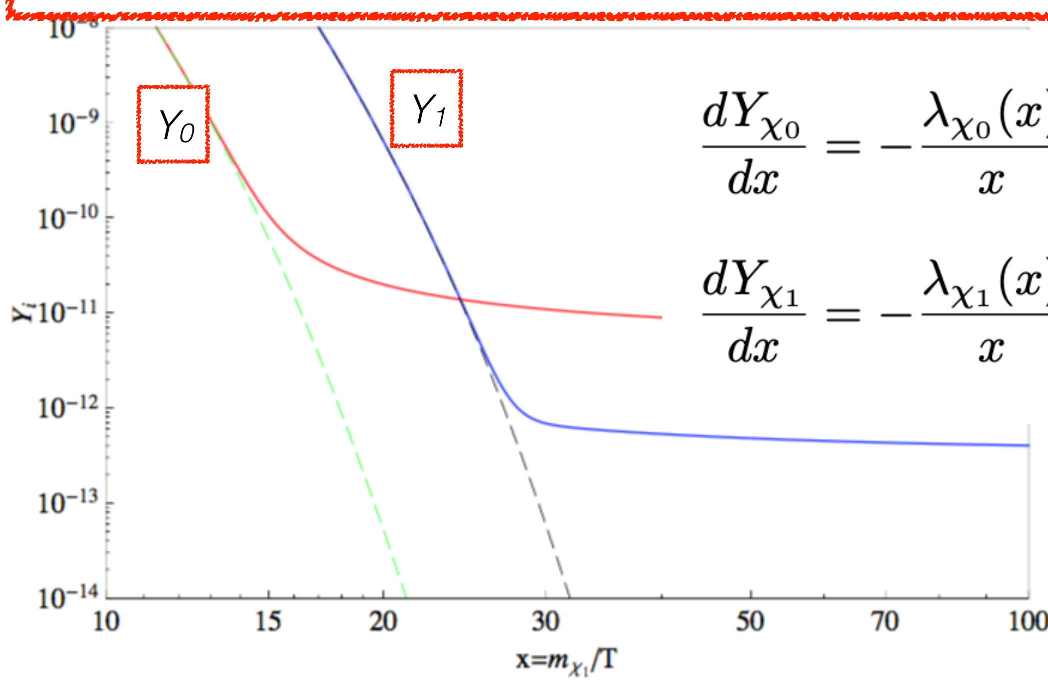


Assumption: $\chi_0 \chi_0 \to \chi_1 \chi_1$ is s-wave & the mediator χ_1 - SM is heavier than χ_1.



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with SM   with heavy DM χ_0

$$\lambda_{\chi_i} = s\langle \sigma_i v_{\rm rel}\rangle / H$$

Structure of $\chi_1\chi_1 \to$ SM

After the heavy component χ_0 freezes-out

$$\frac{dY_{\chi_1}}{dx} \simeq -\frac{\lambda_{\chi_1}(x)}{x}\left[Y_{\chi_1}^2 - \left(Y_{\chi_1}^{\rm eq}(x)\right)^2 - Y_{\rm ast.}^2(x)\right]$$

$\chi_0\chi_0 \to \chi_1\chi_1$ for a while

where $Y_{\rm ast.}(x) = \sqrt{\frac{\langle\sigma_0 v_{\rm rel}\rangle}{\langle\sigma_1 v_{\rm rel}\rangle}} Y_{\chi_0}(x)$ $\quad r_1 = \frac{\Omega_{\chi_1}}{\Omega_{\rm DM,tot}}$

During the decoupling, assume χ_1 is in kinetic equilibrium with the SM ($\sigma_{\chi 0\text{-}\chi 1} < \sigma_{\chi 1\text{-SM}}$)

- If $Y_{\rm ast.}$ is negligible, χ_1 freezes out at T ~ $m_1/20$ as usual.

- If the fraction of χ_1 is very small, i.e., $r_1 \ll 1$, however, departure from thermal equilibrium is delayed and $Y_{\rm ast.}$ is non-negligible compared to $Y_{\chi_1}^{\rm eq}$

Kamada, Kim, Park, **SS**, arXiv: 2111.06808

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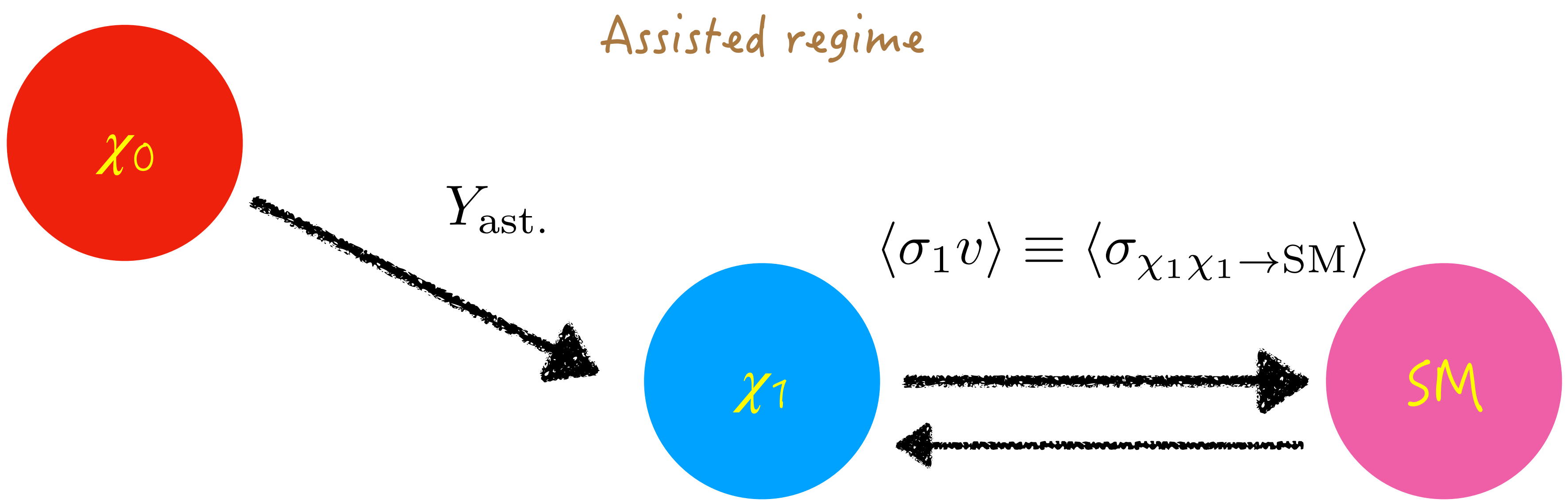

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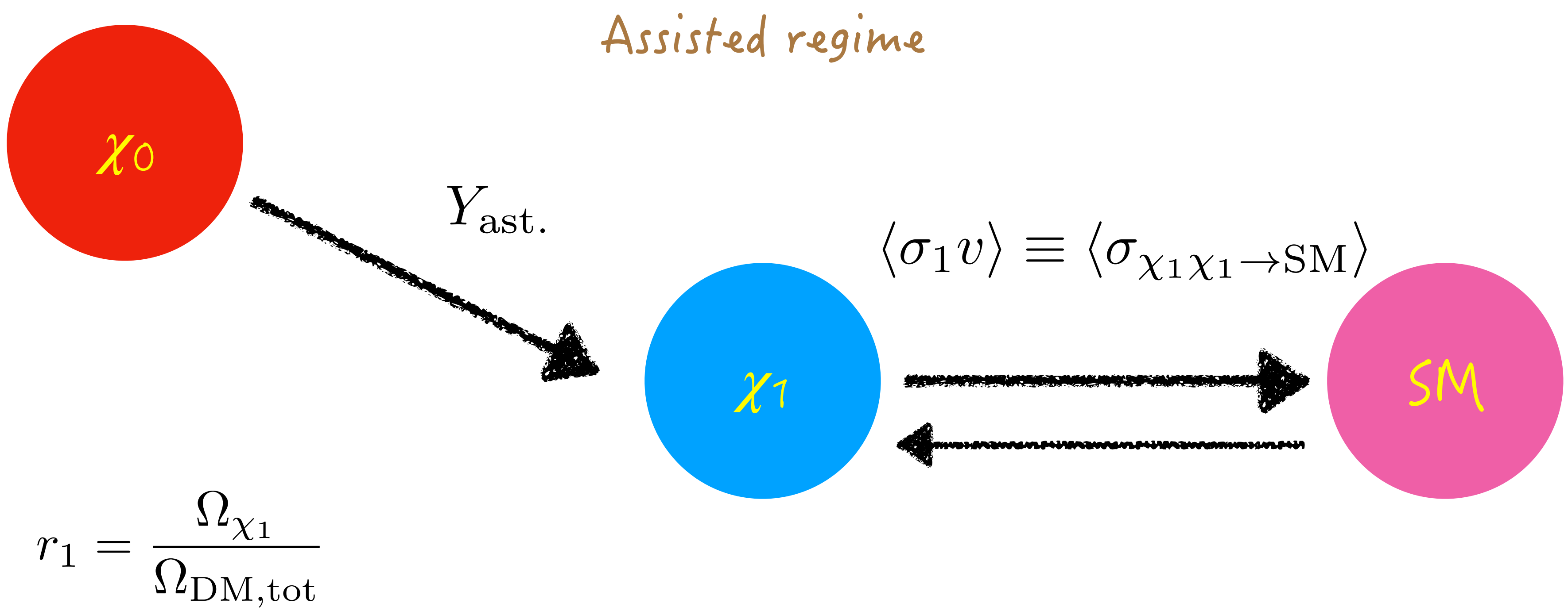

- For a fixed $r_1 \ll 1$, $\chi_1\chi_1 \to$ SM should be even larger to deplete the contribution by the residual annihilation $\chi_0\chi_0 \to \chi_1\chi_1$ ($Y_{\rm ast.}$).

- We find $\langle\sigma_1 v\rangle \propto 1/r_1^2\ , 1/r_1^3$ for s-wave and p-wave, respectively.

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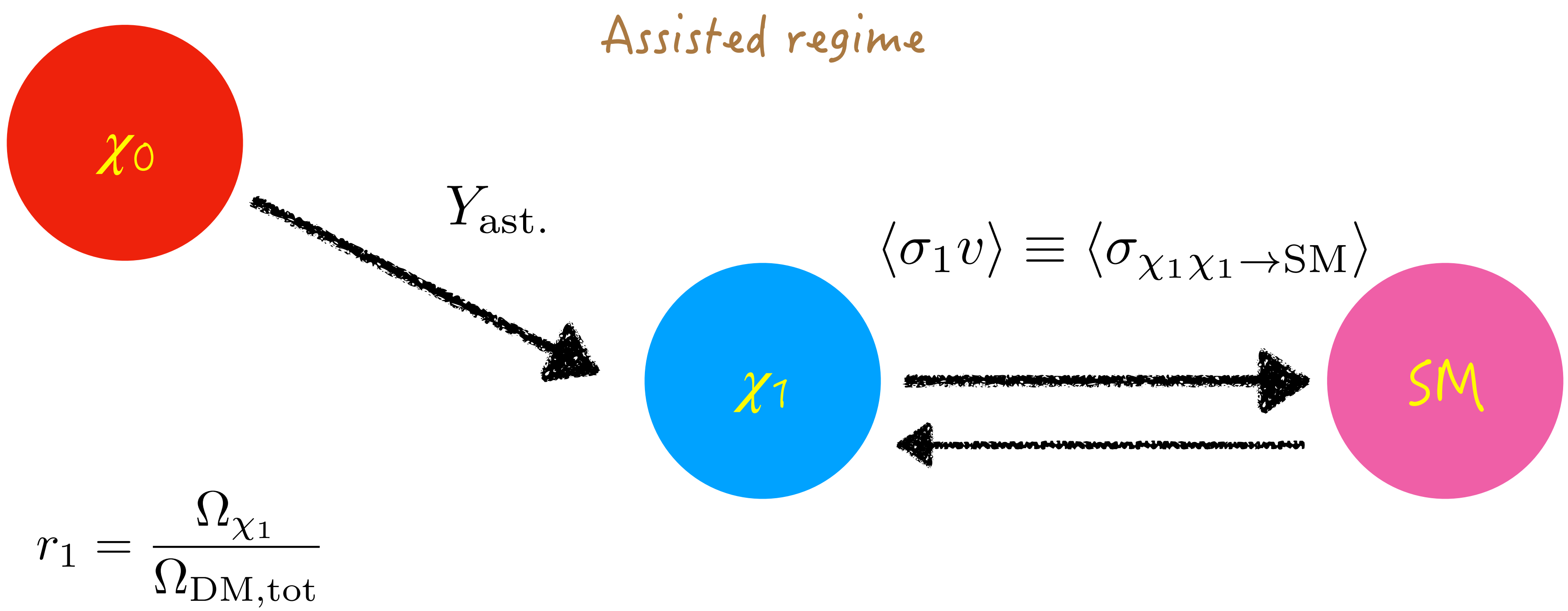
Structure of $\chi_1\chi_1 \rightarrow$ SM



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  observables $\propto$ $n_{\chi_1}^2 \langle \sigma_1 v \rangle$ $\rightarrow$ No r_1 suppression!

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Effects of χ_1 to various observables

Sub-component DM can be not hidden and affect

- Big Bang Nucleosynthesis: photo-dissociation of light elements

  primordial elements if freeze-out T $\lesssim$ $T_{\nu,\mathrm{dec}}$

- Cosmic microwave background: $\chi_1\chi_1 \to$ SM after the last scattering,

  N_{eff} constraints if freeze-out T $\lesssim$ $T_{\nu,\mathrm{dec}}$

- Diffuse X-rays and γ-rays in the Milky Way

- Direct detection if the crossing symmetry is effective (severer)

  observable $\propto n_{\chi_1}\sigma$

Effects of χ_1 to various observables

Unprecedented role of a sub-dominant DM component

- For s-wave dominant $\chi_1\chi_1 \to$ SM SM, the nominal constraints directly apply because $n_{\chi_1}^2 (\sigma_1 v_{\rm rel})_{\rm s} \sim r_1^2 \cdot \frac{1}{r_1^2} = {\rm no}\ r_1$: **s-wave not preferred!**

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χ_1 - χ_1
self-interaction

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Self-heating of χ_1

- Self-interacting DM models have been proposed actively recently.

- Self-interactions always exist. The question is how efficient they can transfer energy long after the freeze-out (not effective for WIMP).

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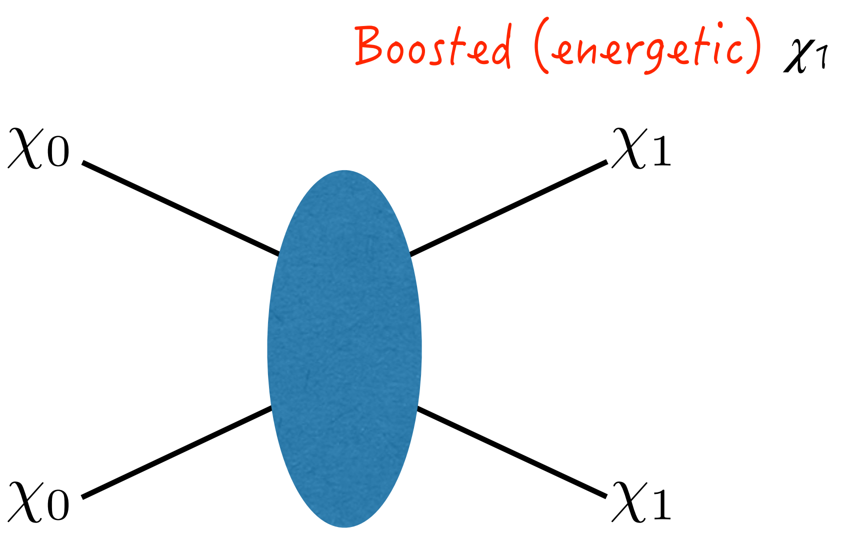

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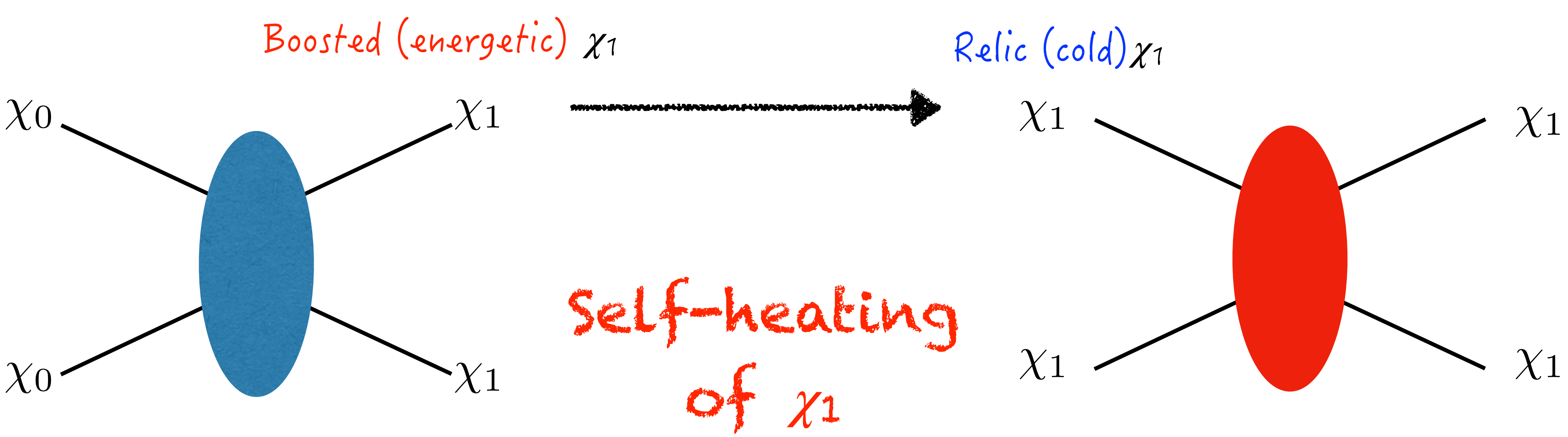

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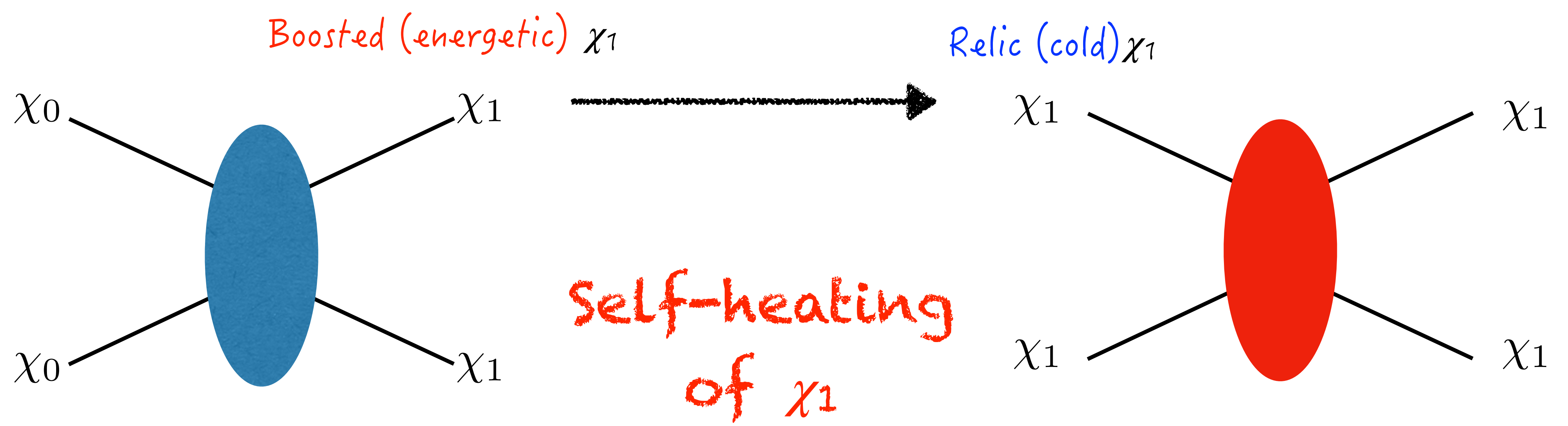
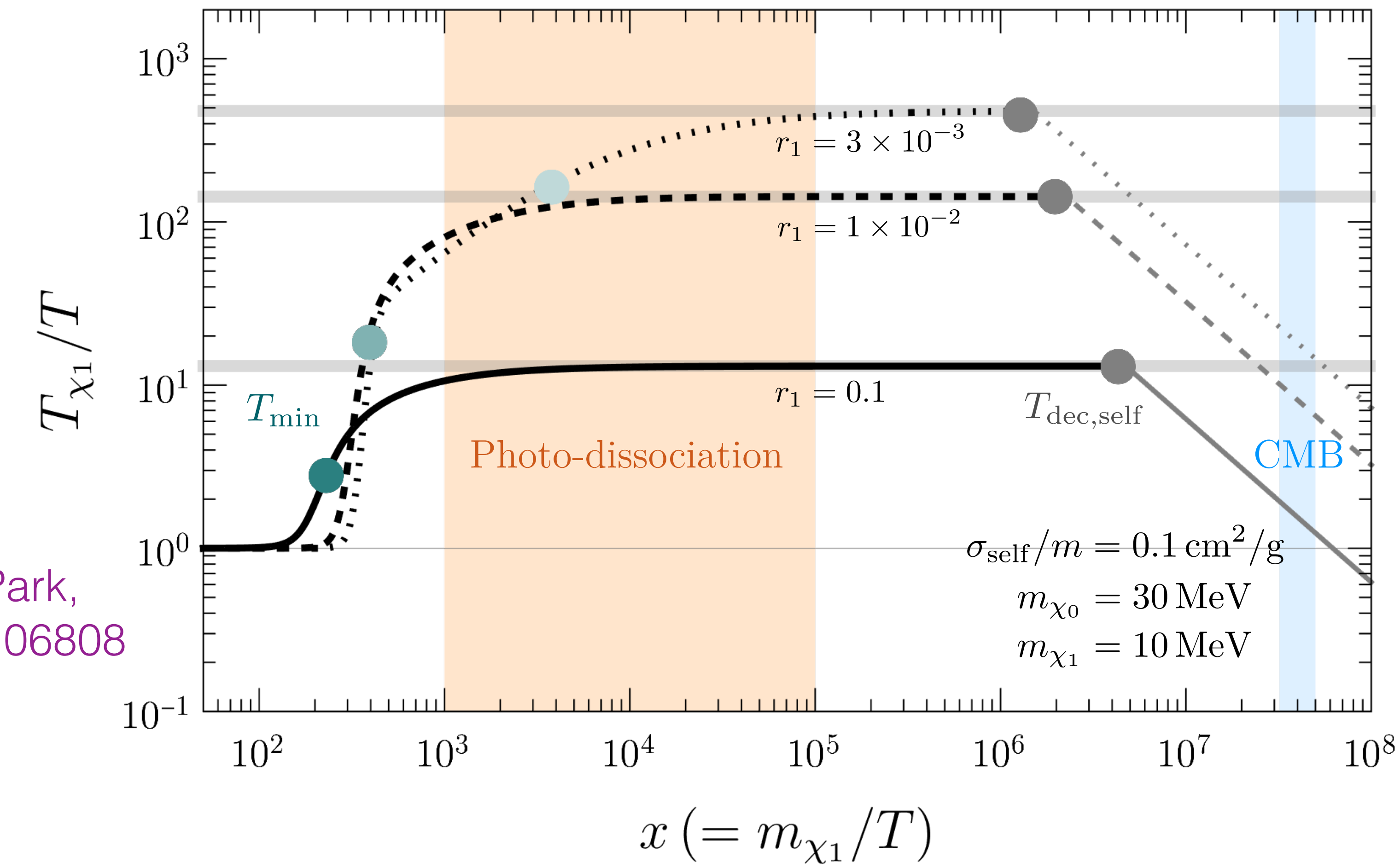


Kamada, Kim, Kim, Sekiguchi, PRL 2018

Chu, Garcia-Cely, JCAP 2018

Vogelsberger, Zavala, Schutz, Slatyer, MNRAS 2018

Temperature evolution of χ_1



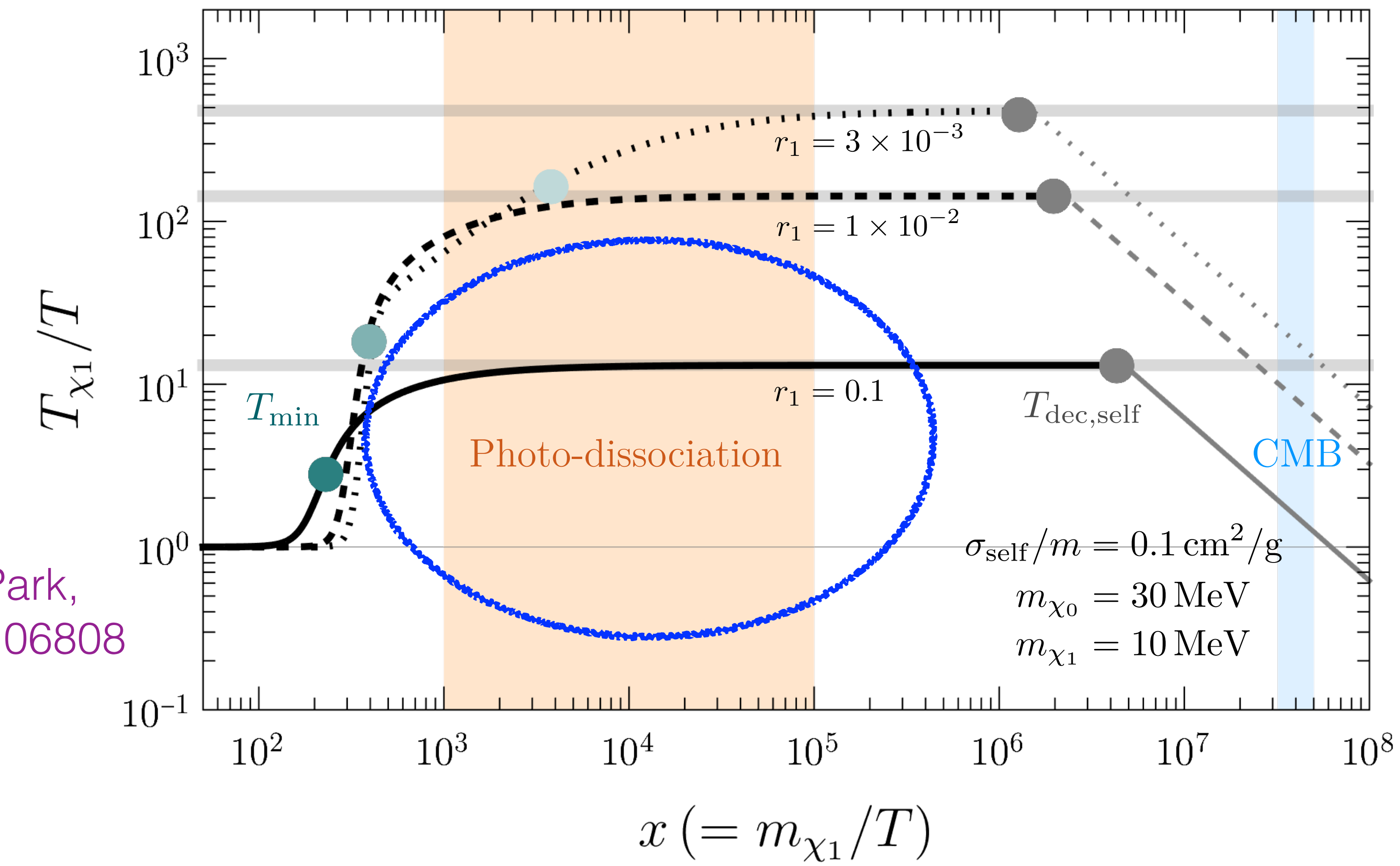
Kamada, Kim, Park, **SS**, arXiv: 2111.06808

- If self-heating is efficient even after the kinetic decoupling, the temperature evolution of χ_1 makes it behave like a radiation.

- The self-heating lasts as r_1 (hence n_1) & the self-interaction are sizable.

- The temperature increases rapidly as $1/r_1$ (large χ_1 - SM cross section).

Temperature evolution of χ_1



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- The photo-dissociation bounds become severer.

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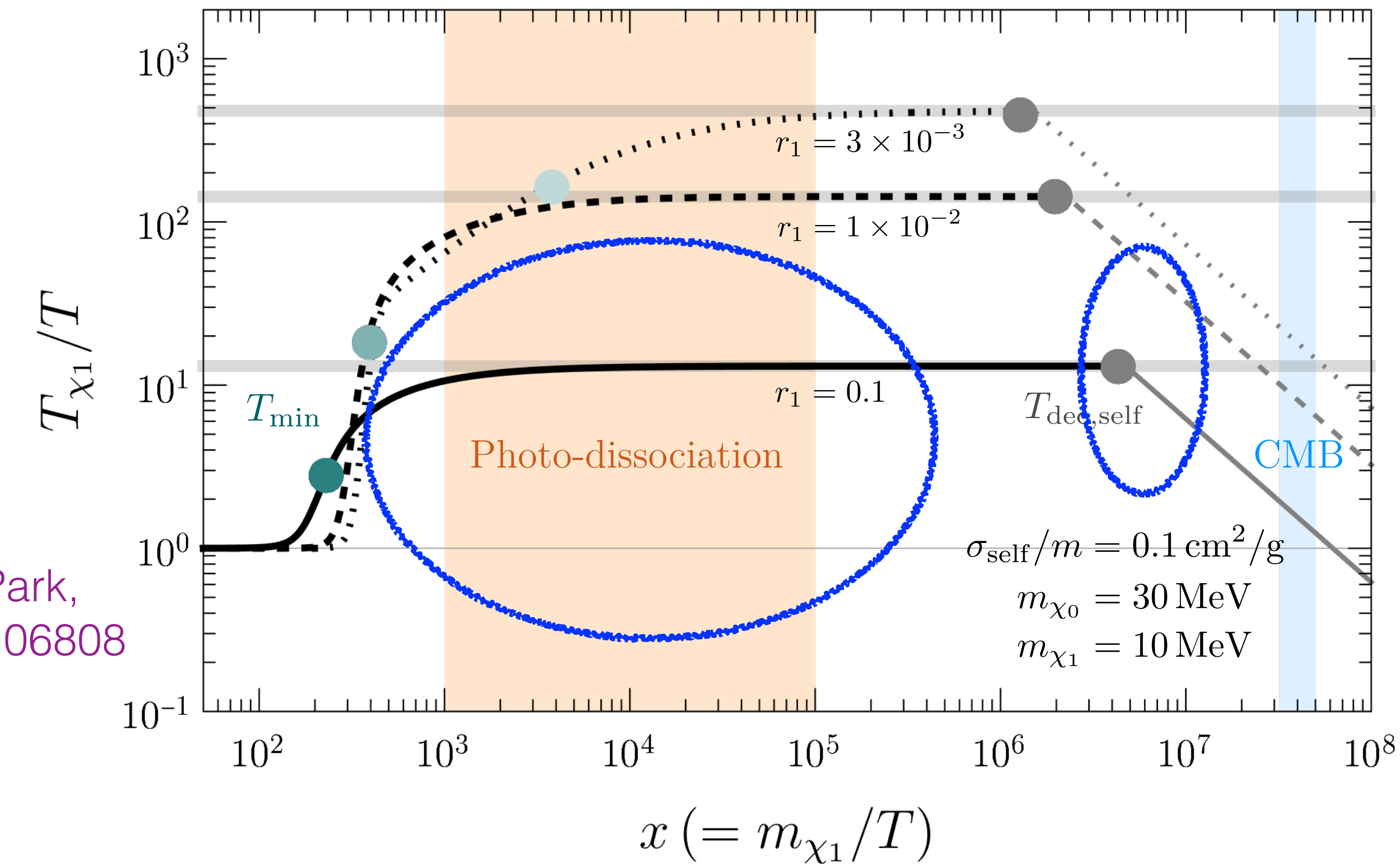

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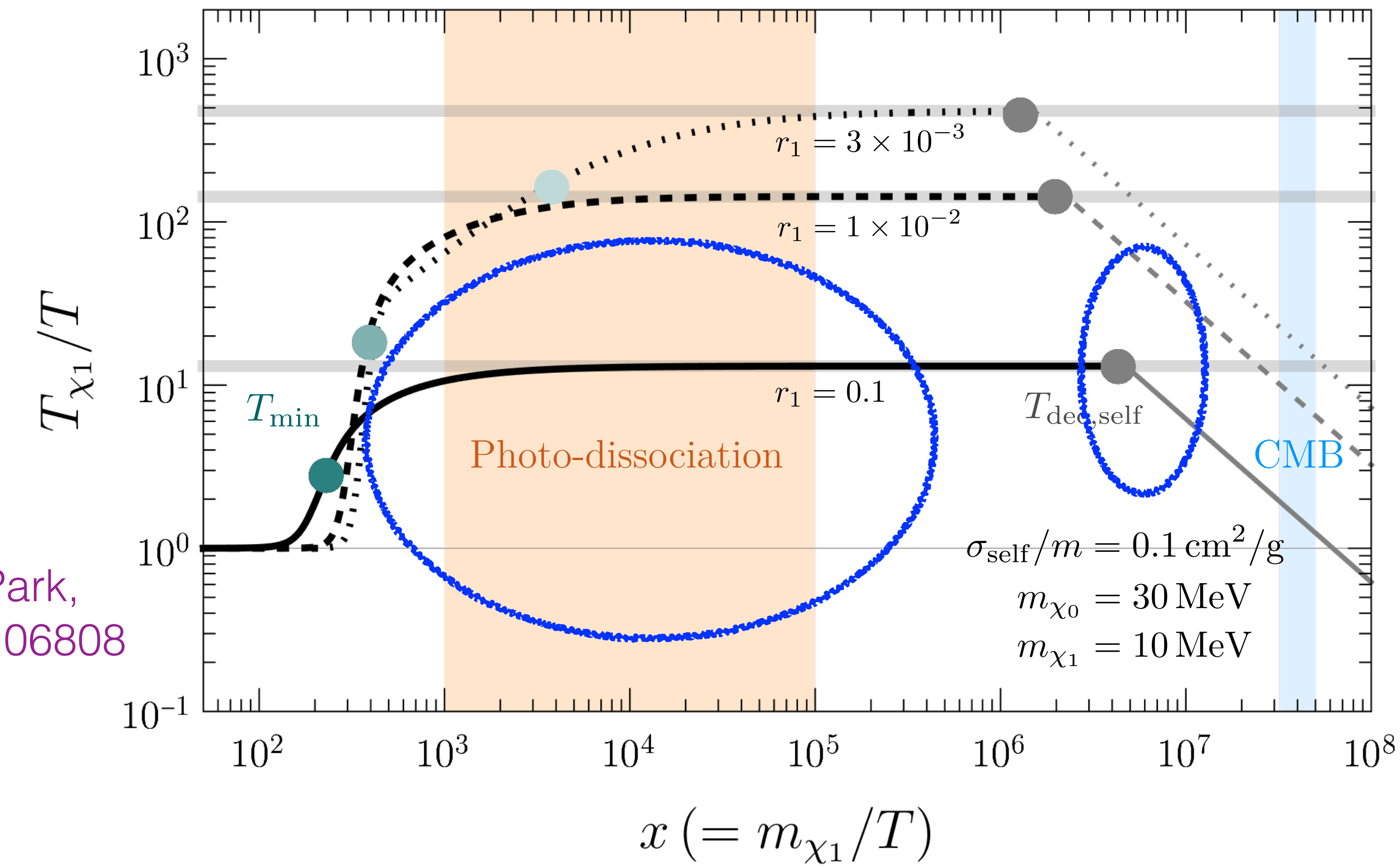

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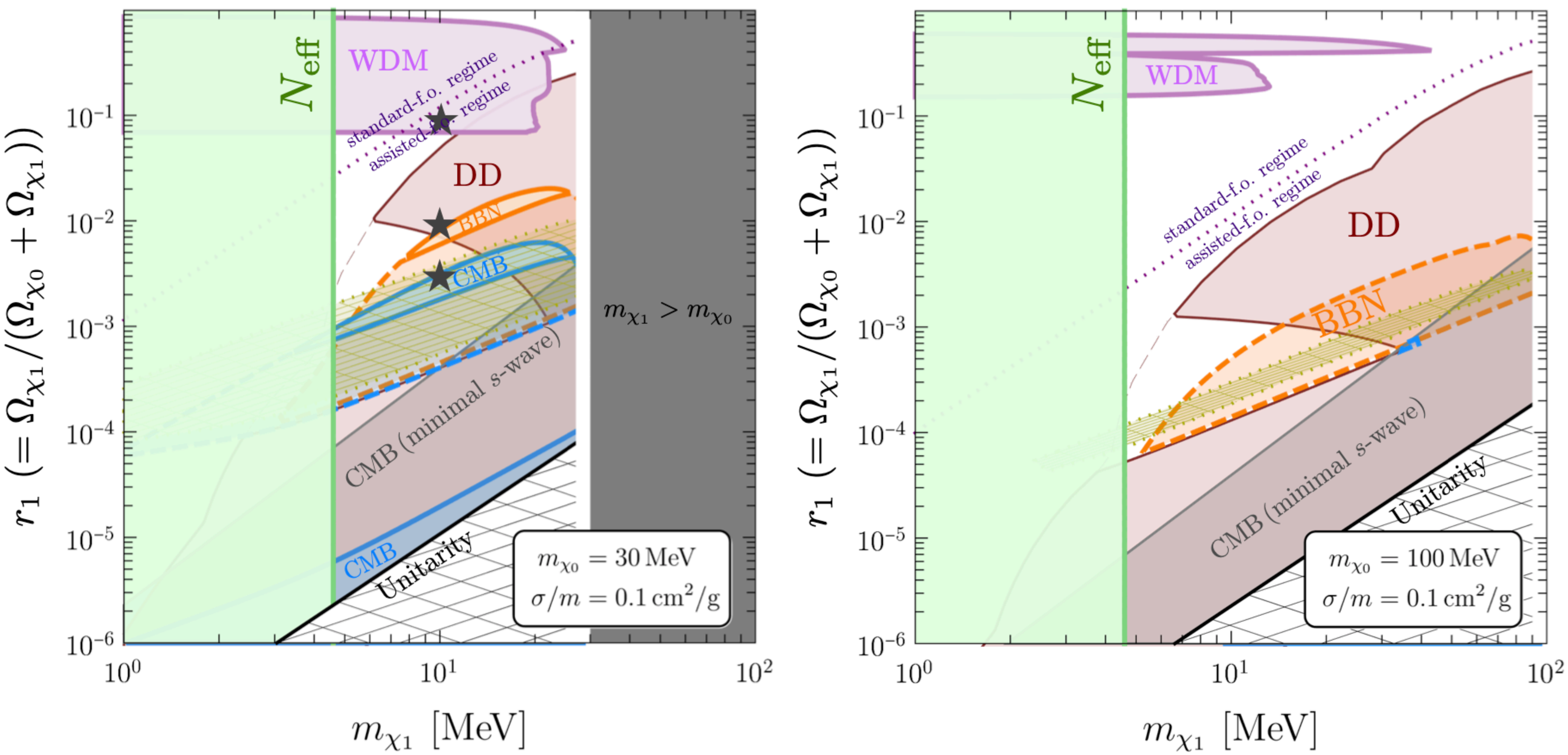
χ_1 can be sub-GeV Warm Dark Matter!!

Lyman-α

# of satellites

New bounds due to self-heating

Kamada, Kim, Park, **SS**, arXiv: 2111.06808



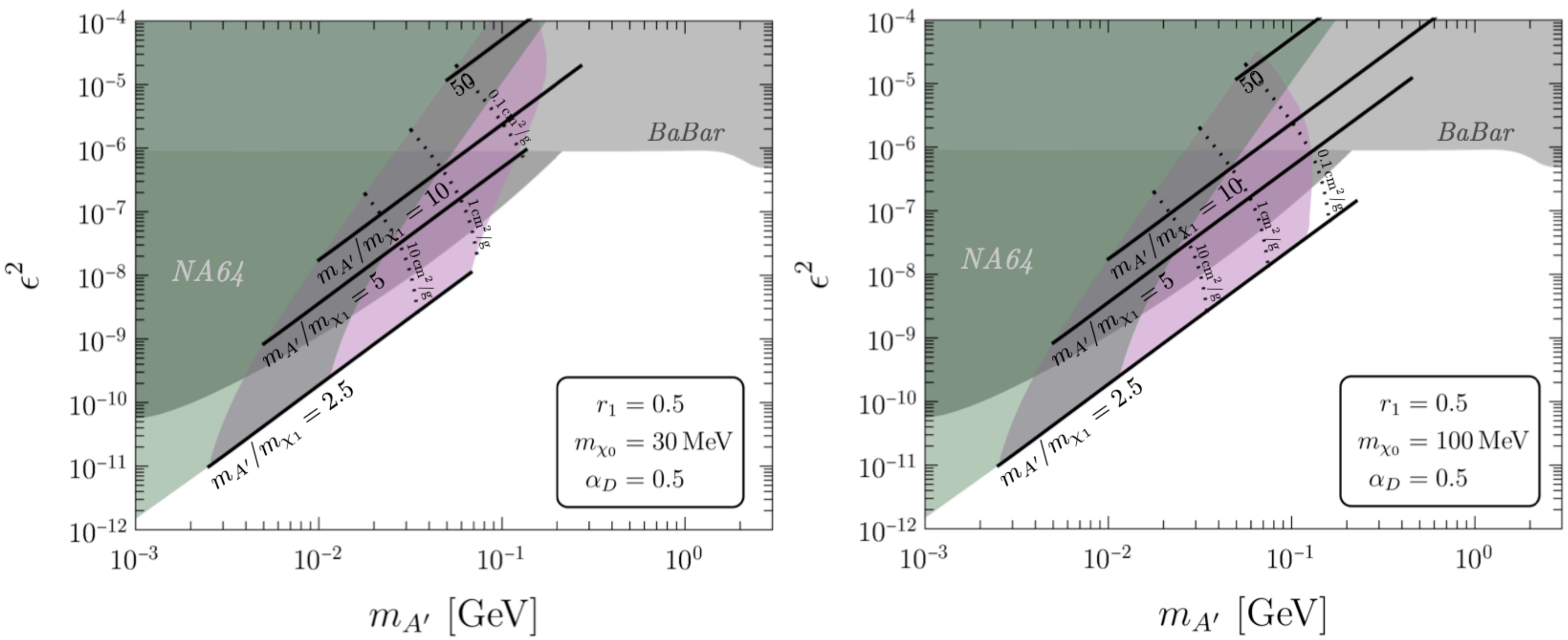
- WDM constraint enters when $r_1 \gtrsim 0.07$ even for $m_{\chi 1} \sim 40$ MeV.

- Direct detection bounds get weaken since $n_{\chi 1}$ inside our MW decreases due to the kinetic energy of χ_1

- ★: reference values of r_1 in the temperature evolution (previous slide)

Complementary searches

Light DM can be produced in accelerators with high intensities!



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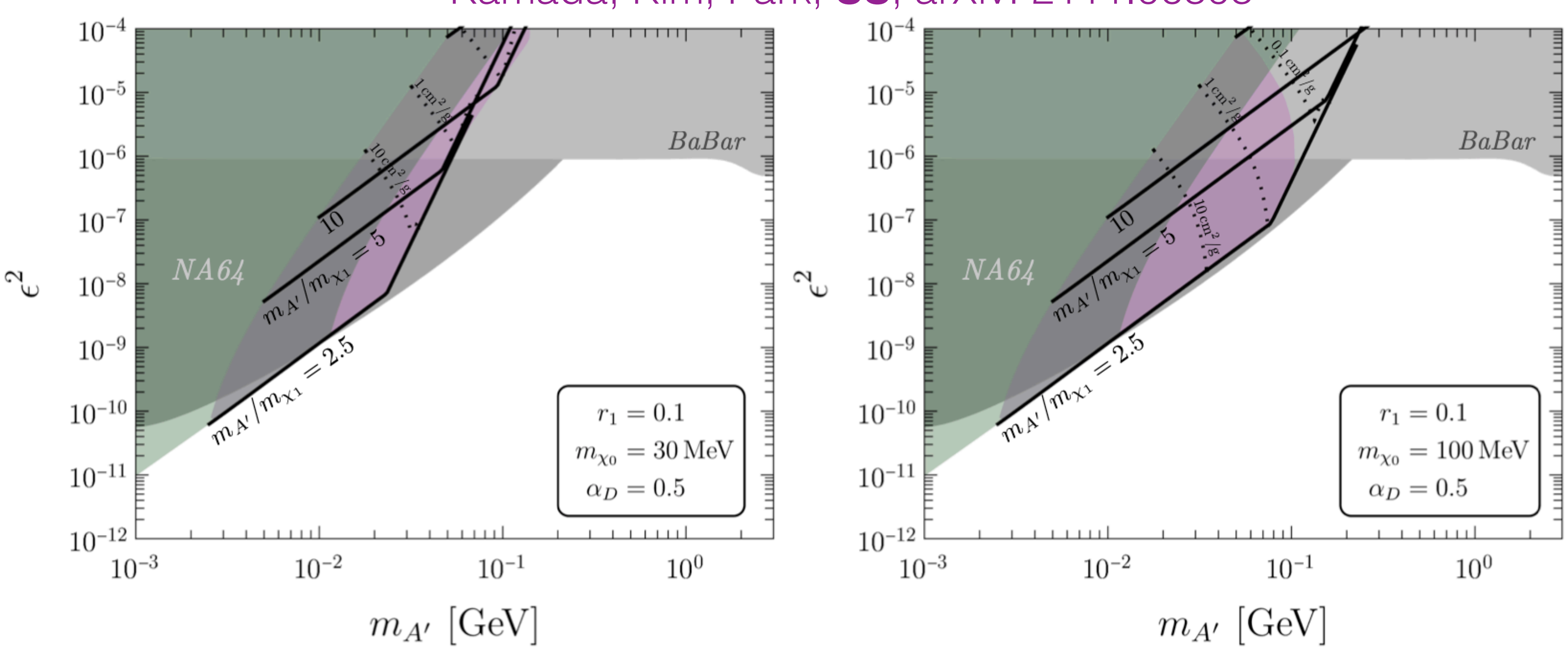

- Reference model: singlet scalar DM + dark photon (p-wave)
- Green: N_{eff}, Pink: WDM for $r_1 \gtrsim 0.07$.

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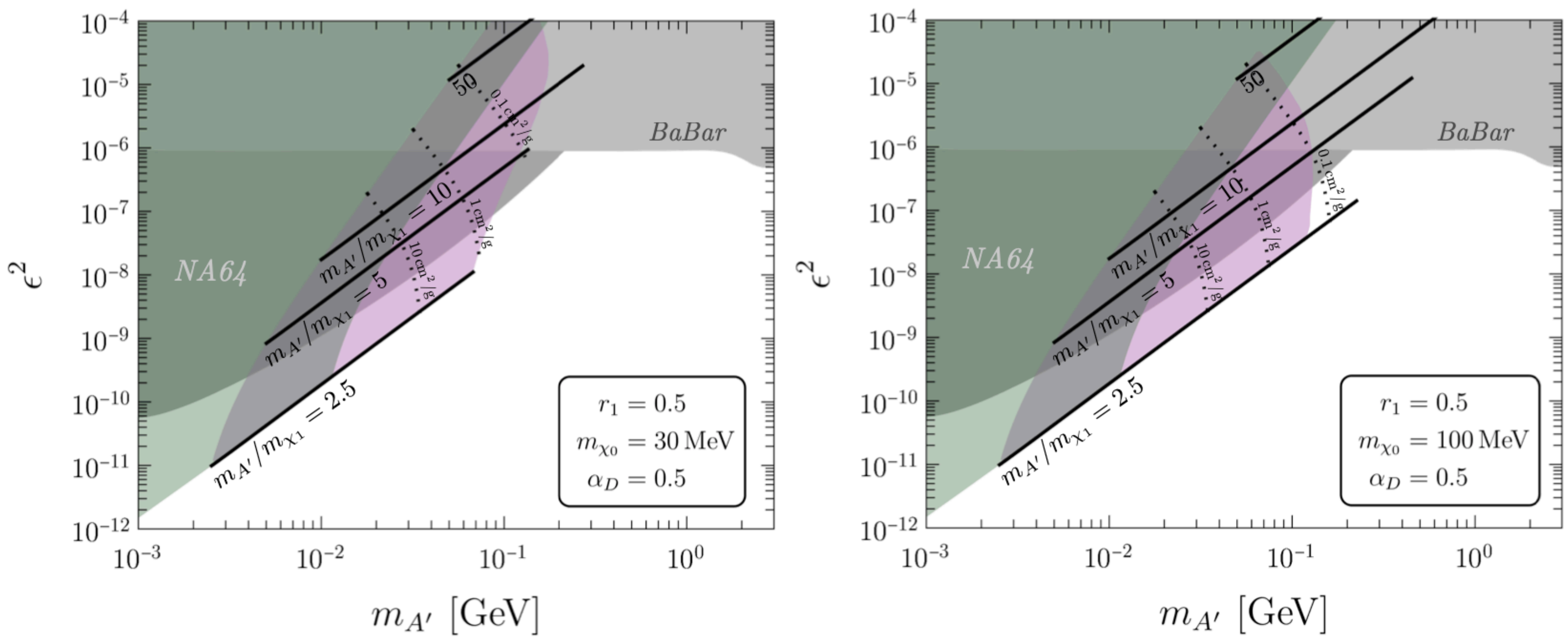

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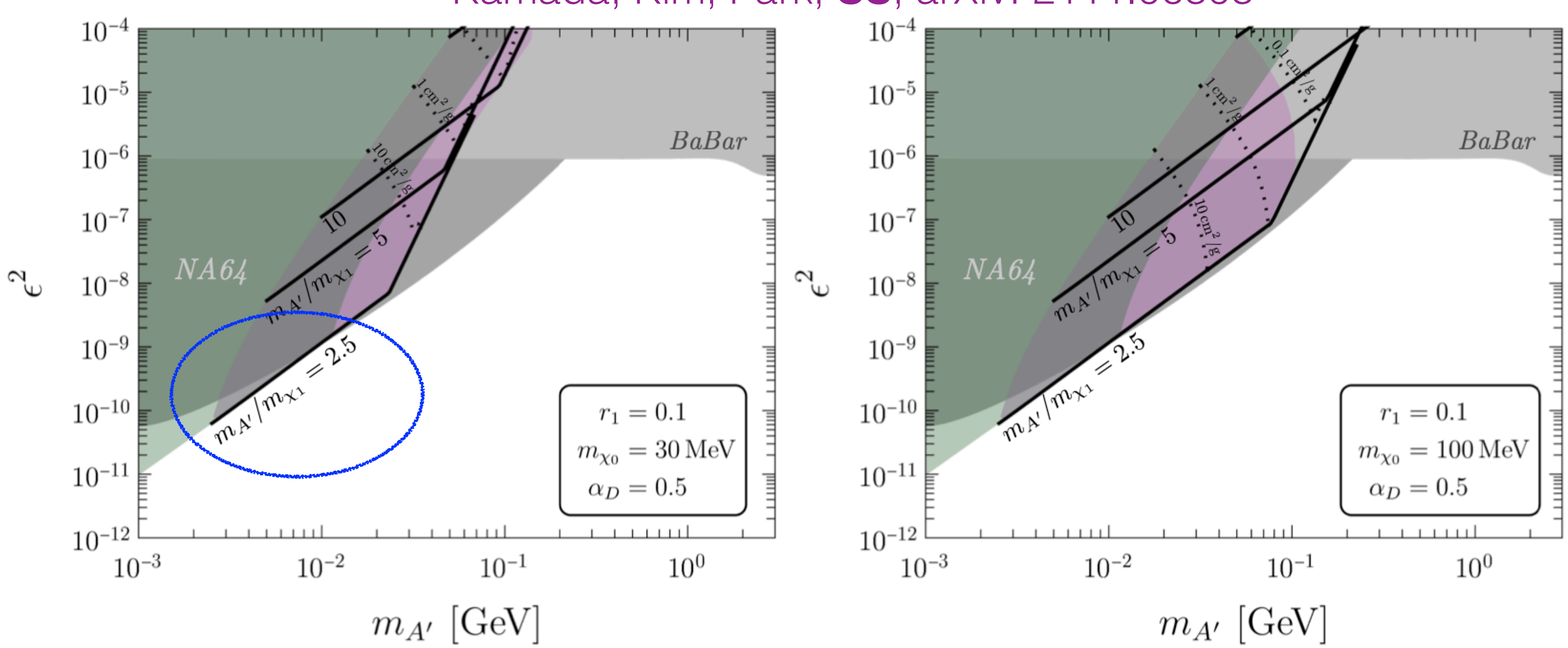

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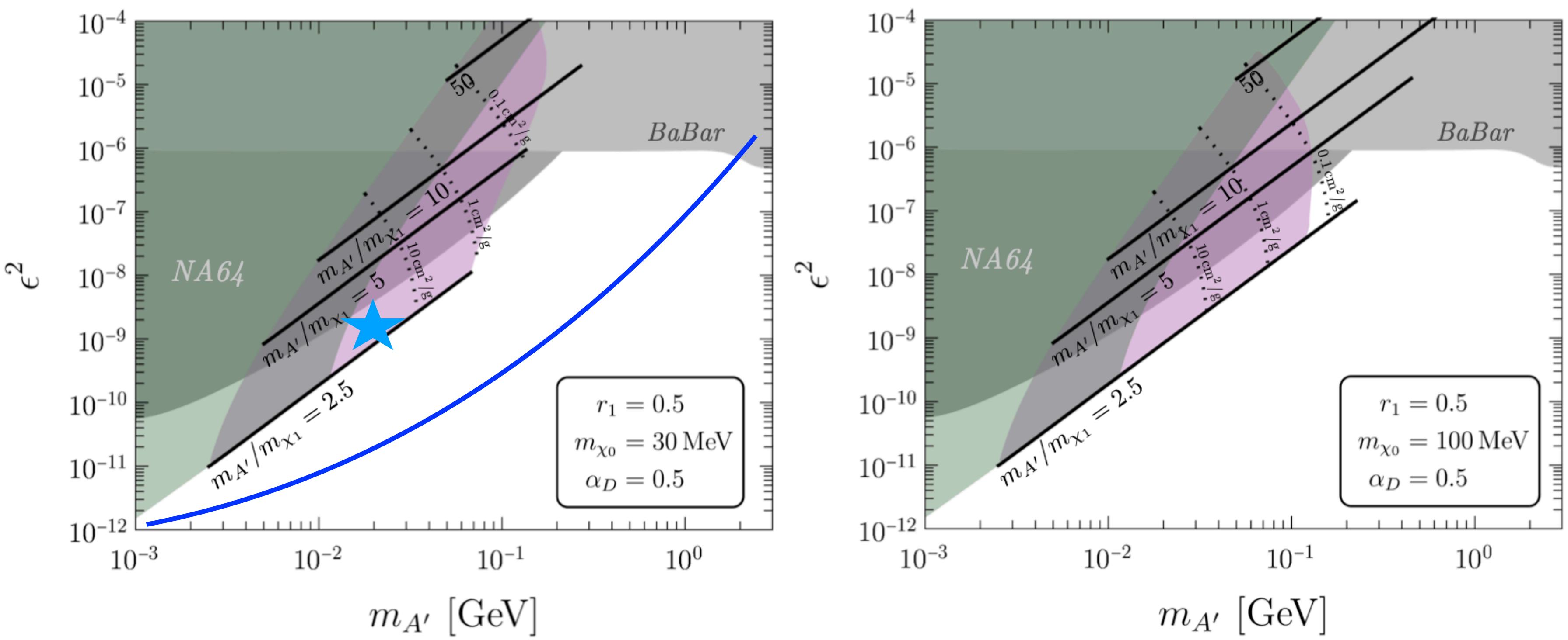

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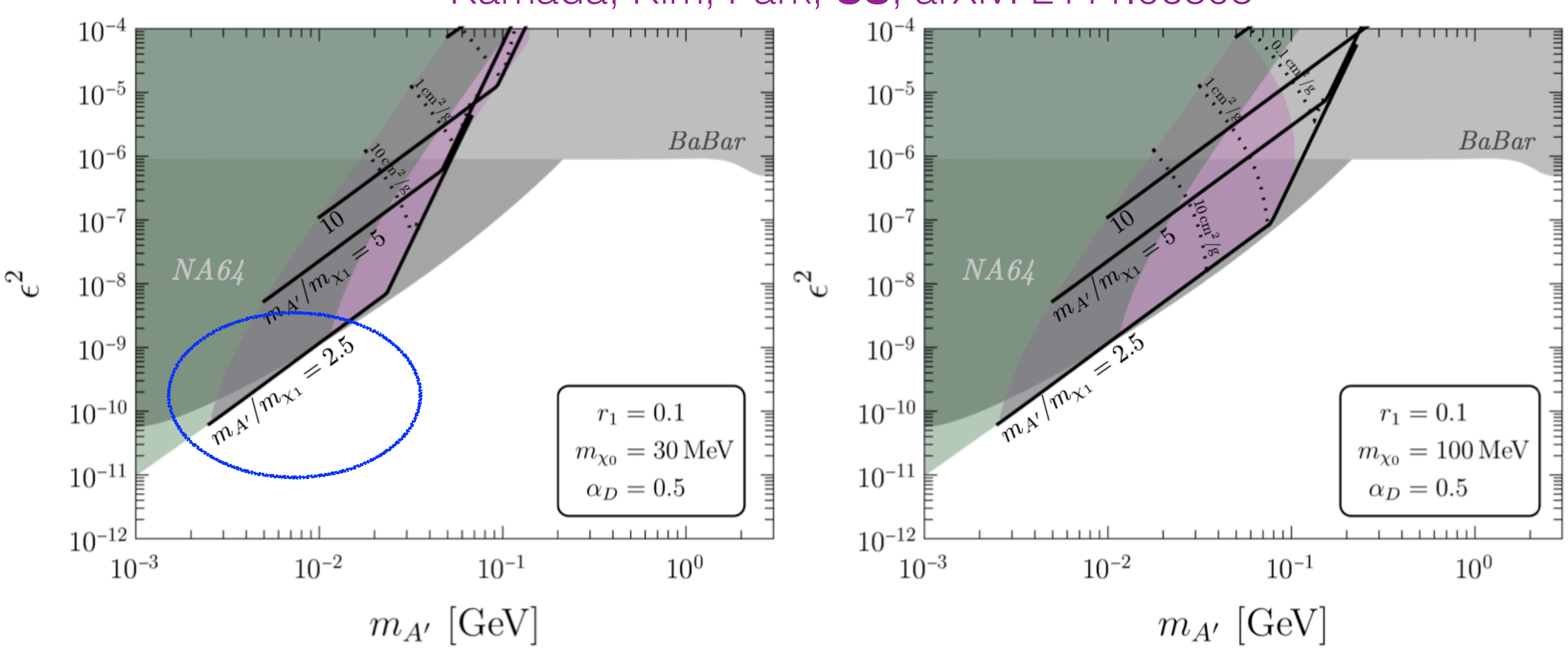

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- For $r_1 \lesssim 0.07$, not preferred by the accelerator results.
- Future discovery can tell the dark sector details.

Conclusions

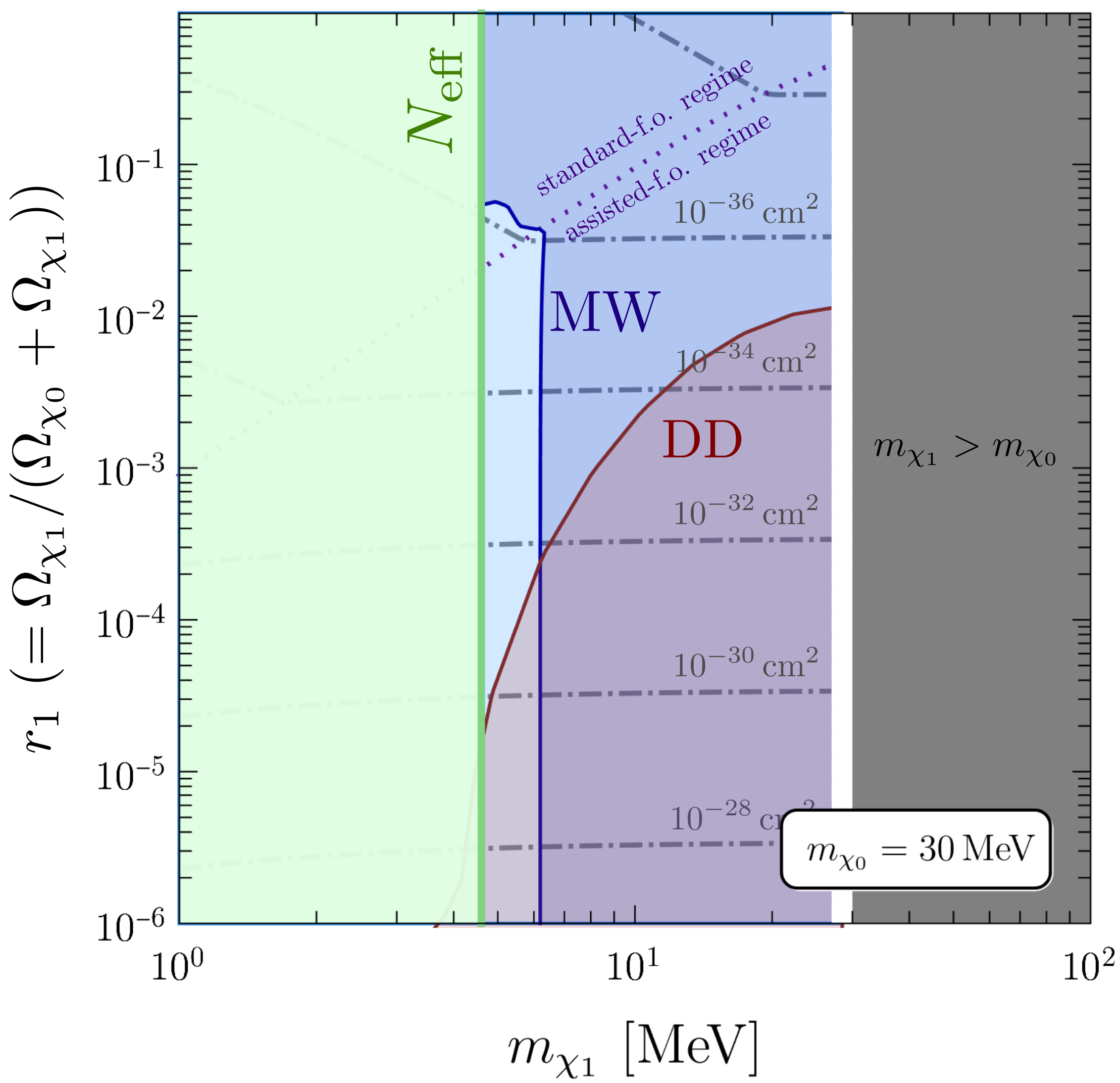
- A sub-component DM (χ_1) can severely affect the cosmo/astro observables (χ_1 - SM: p-wave preferred!).
- Self-heating naturally arises in a wide range of parameter space and changes the evolution of the temperature of χ_1 after the freeze-out.
- The temperature evolution affects the structure formation of χ_1:

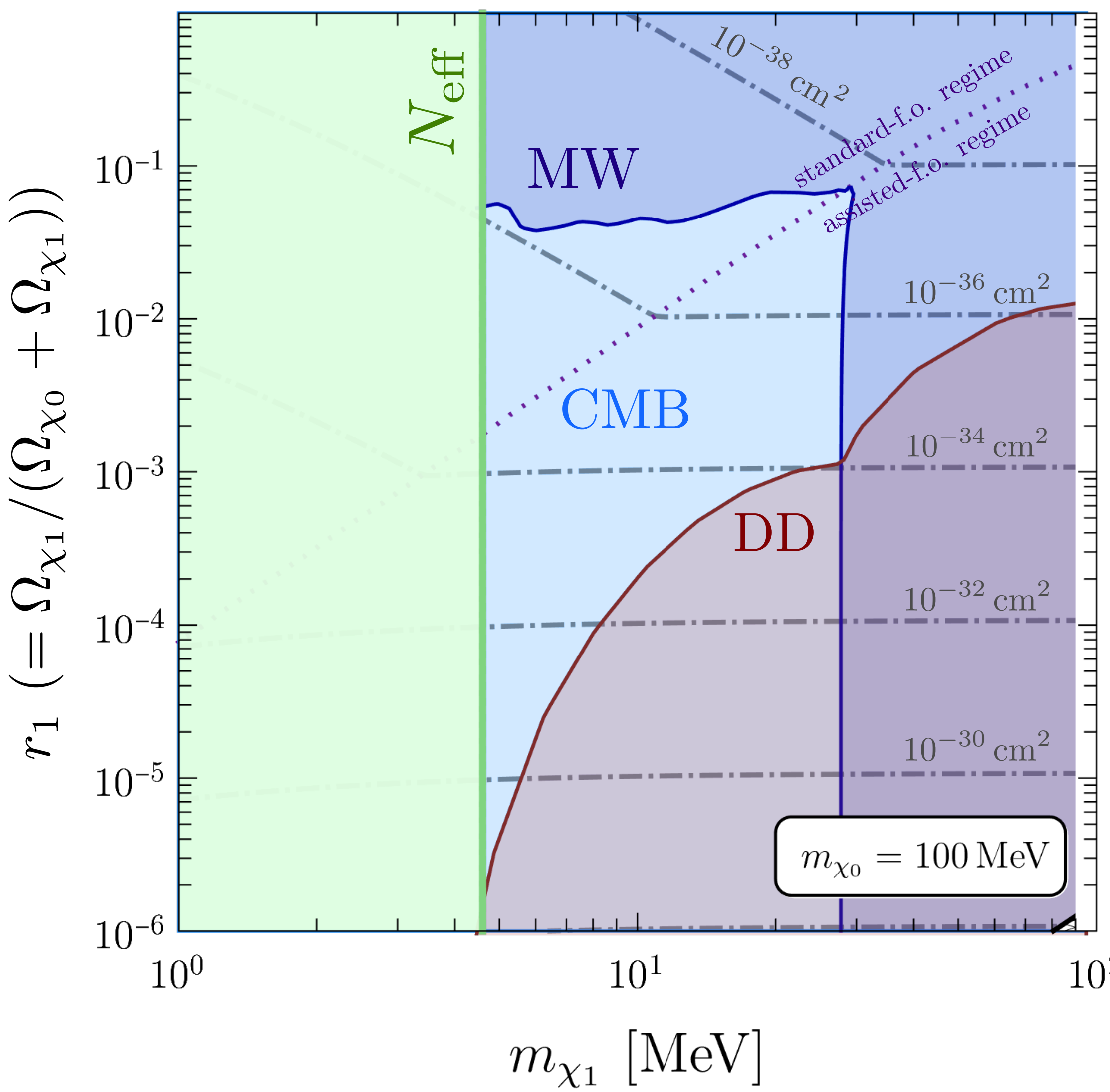
  a sub-GeV mass Warm Dark Matter (heavy WDM) for $r_1 \gtrsim 0.07$!

  → This is true even when χ_1 is a dominant component DM.
- Complementary searches in accelerators can give hints on the dark sector details (disfavor $r_1 \lesssim 0.07$ for a reference model).

Bakup

When $\chi_1\chi_1\rightarrow$ SM is dominated by s-wave





- CMB kills almost everywhere.

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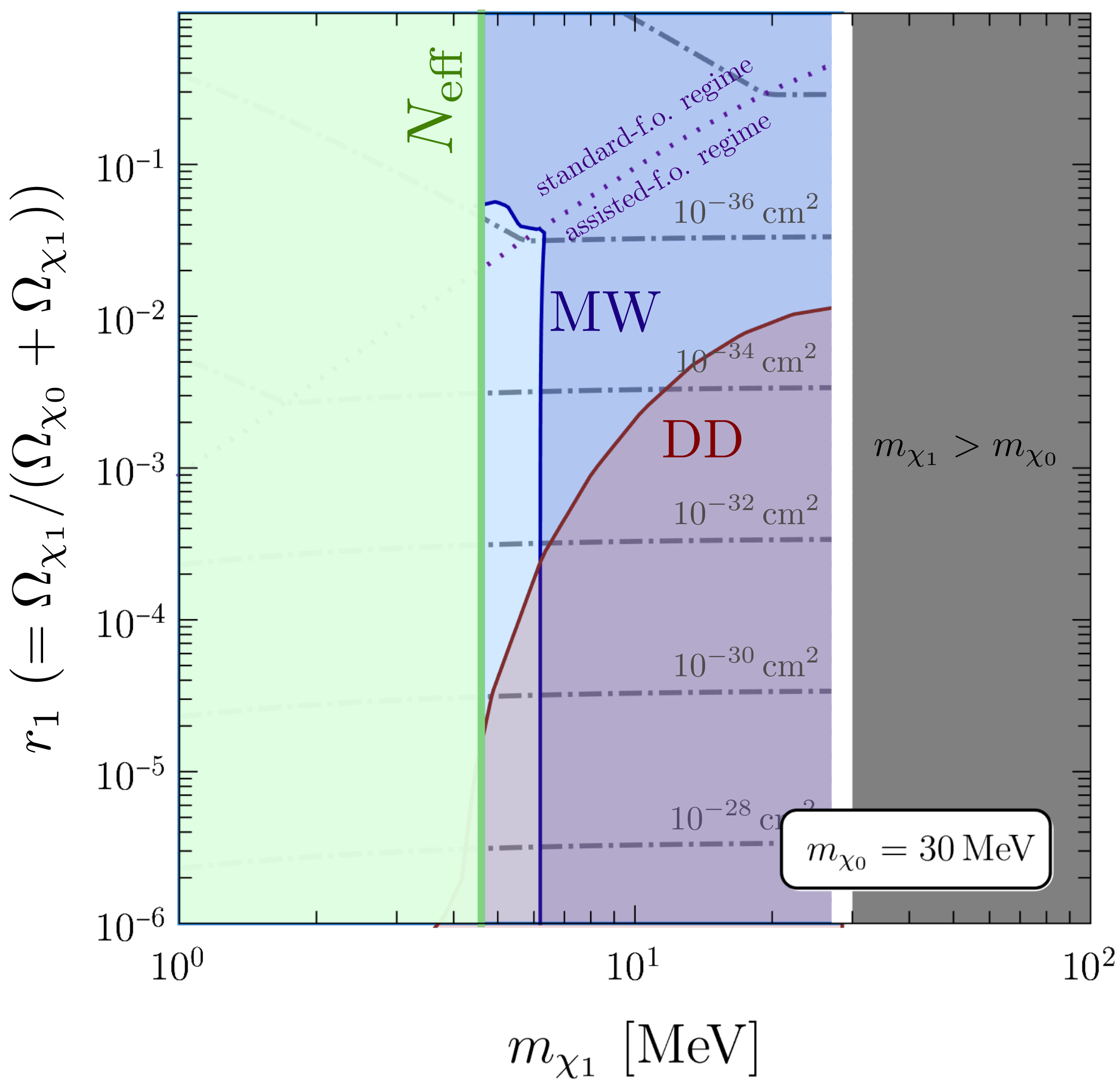

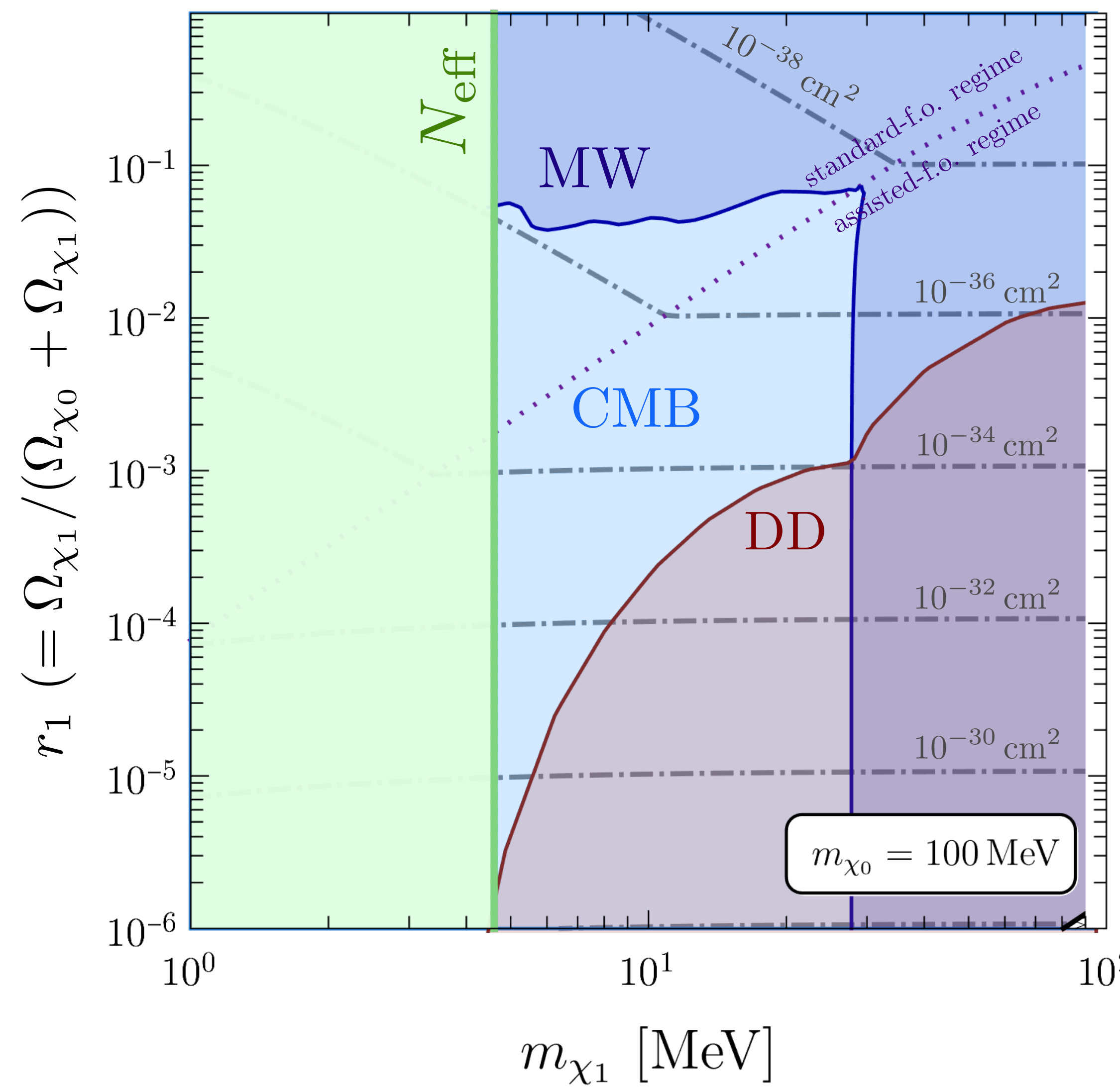

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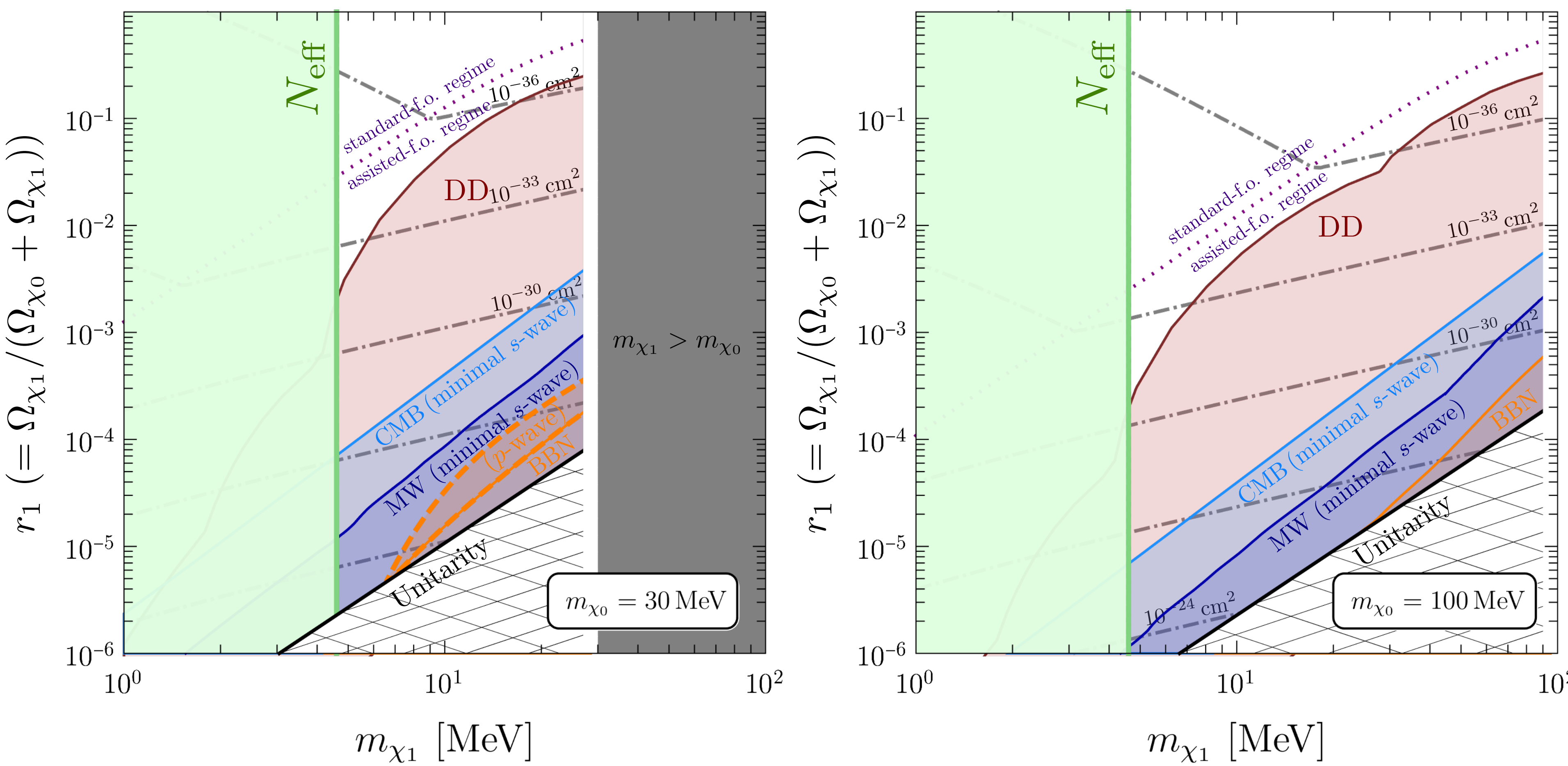

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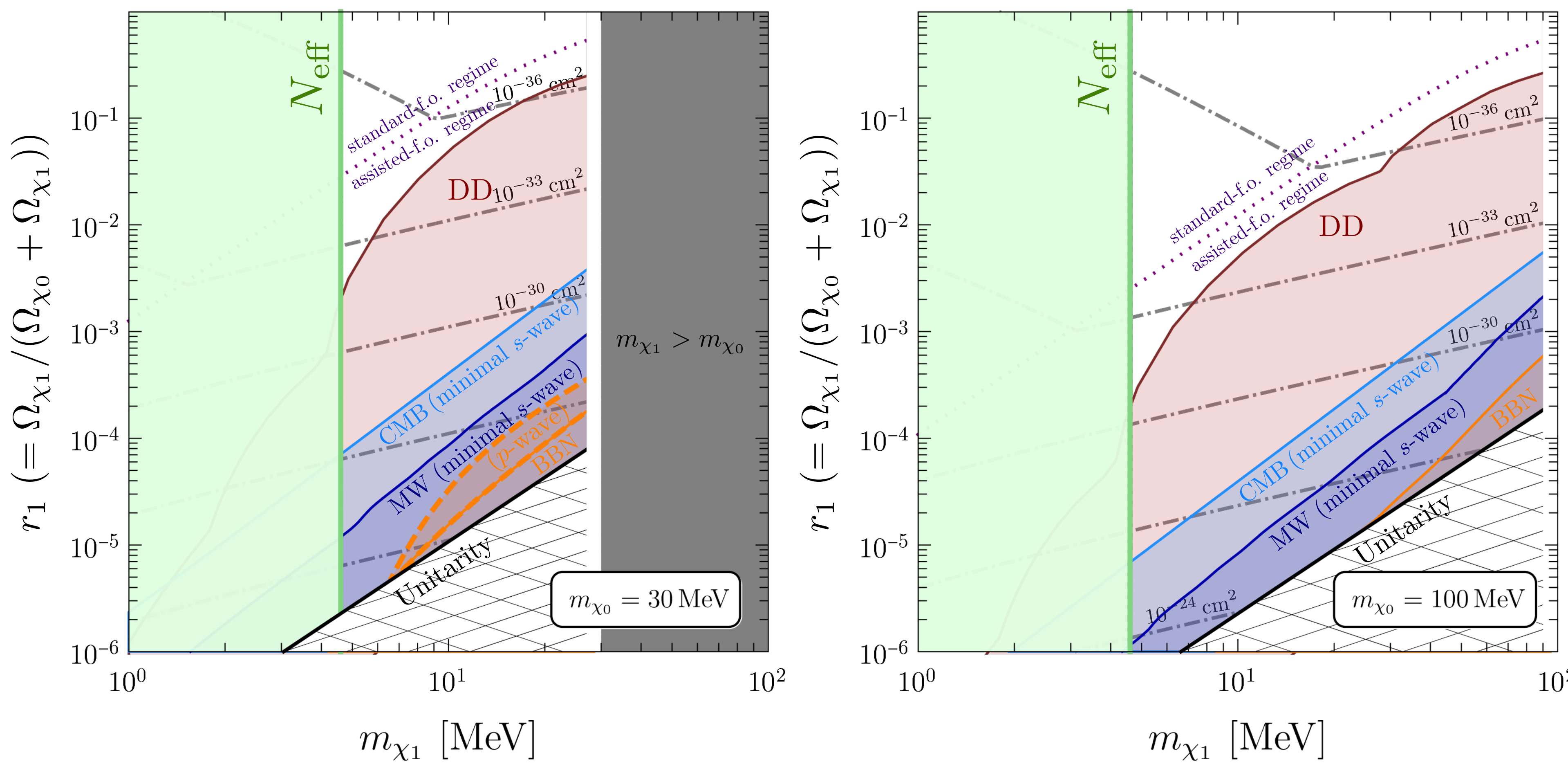

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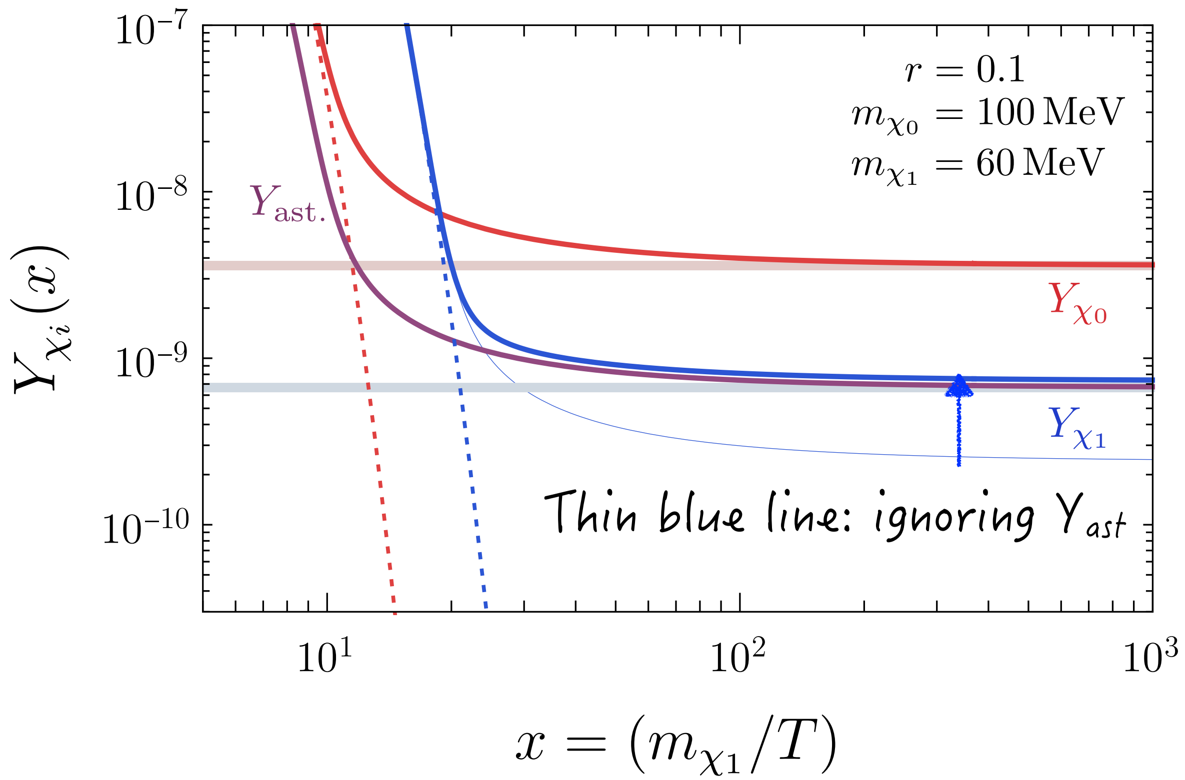

Assisted regime

Kamada, Kim, Park, **SS**, arXiv: 2111.06808

- For $r_1 \ll 1$, Y_{χ_1} is lifted-up by $Y_{\rm ast.}$ (follows it when $T \lesssim m_1/30$).

- The annihilation cross section $\chi_1\chi_1 \to$ SM is enhanced by $1/r_1{}^2$.

$$(\sigma_1 v_{\rm rel})_s \simeq 4.7 \times 10^{-24} {\rm cm}^3/{\rm s} \left(\frac{0.1}{r_1}\right)^2 \left(\frac{m_{\chi_1}/m_{\chi_0}}{0.6}\right)^2 \left(\frac{\sqrt{g_*}}{g_{*S}}\right)_{x_{\rm fo,0}}$$

$$\langle \sigma_1 v_{\rm rel}\rangle \simeq (\sigma_1 v_{\rm rel})_2 + (\sigma_1 v_{\rm rel})_p v_{\rm rel}^2$$

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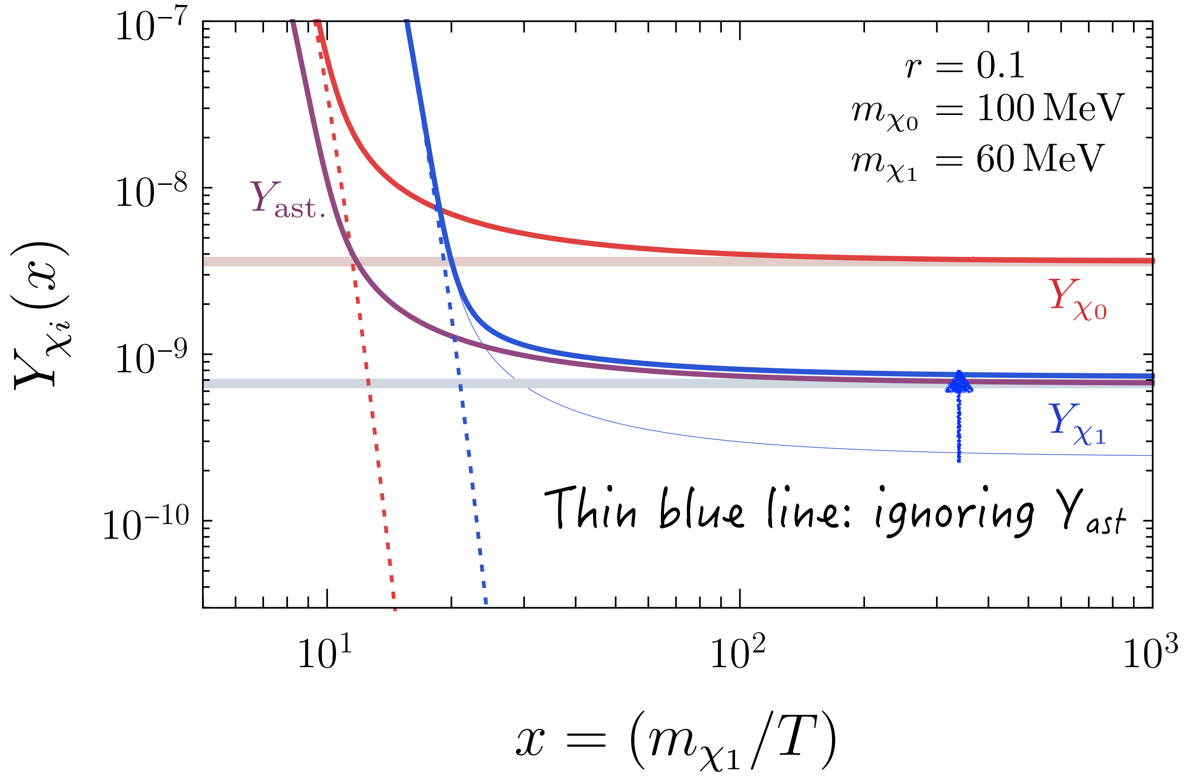

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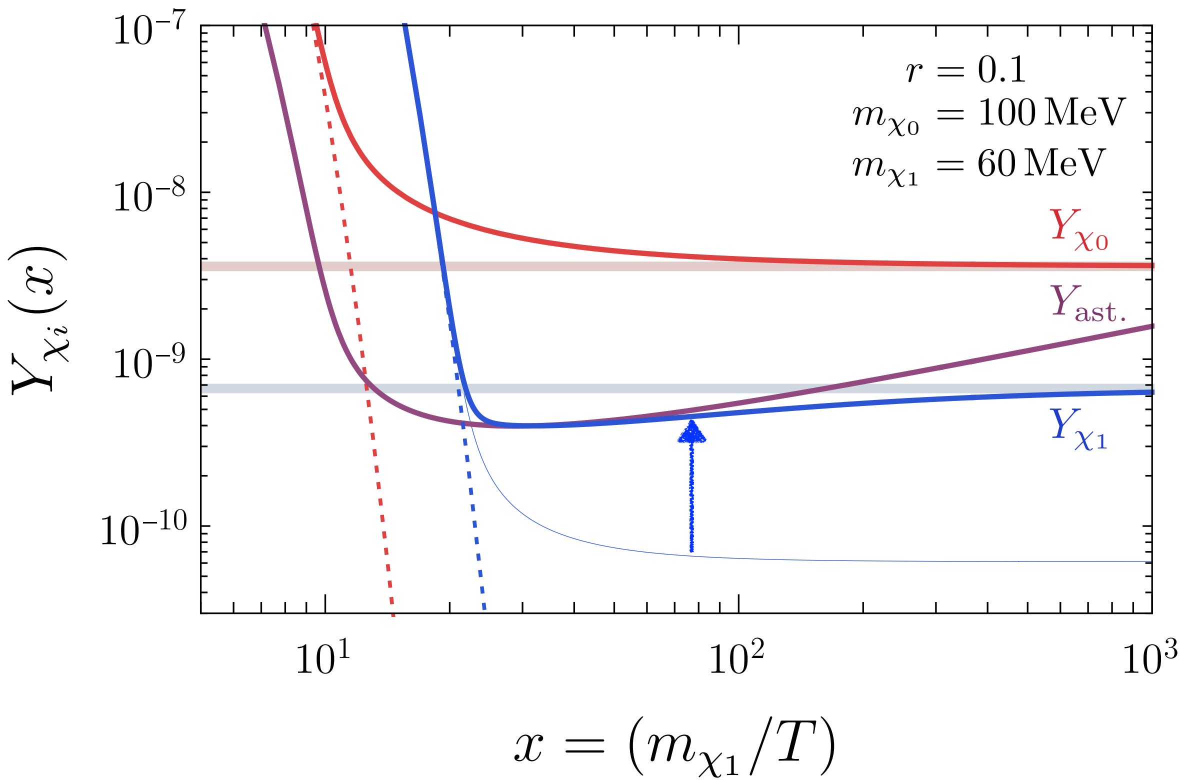
Safe from constraints?



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$$r_1 = \frac{\Omega_{\chi_1}}{\Omega_{\mathrm{DM,tot}}}$$

- For $r_1 \ll 1$, Y_{χ_1} is lifted-up even more by $Y_{\mathrm{ast.}}$ (until T ~ $m_1/80$).

- The annihilation cross section $\chi_1\chi_1 \to$ SM increases as $1/r_1{}^3$ so the process can be also sensitive to various observables.

$$(\sigma_1 v_{\mathrm{rel}})_p \simeq 4.2 \times 10^{-24}\,\mathrm{cm}^3/\mathrm{s} \left(\frac{c'}{0.35}\right)^4 \left(\frac{m_{\chi_1}/m_{\chi_0}}{0.6}\right)^4 \left(\frac{0.1}{r_1}\right)^3 \left(\frac{g_{*S}}{\sqrt{g_*}}\right)^4_{x'_{\mathrm{fo}}} \left(\frac{\sqrt{g_*}}{g_{*S}}\right)^2_{x_{\mathrm{fo},0}}$$

$$(Y_{\mathrm{ast.}} - Y_{\chi_1})/Y_{\mathrm{ast.}} = c'$$