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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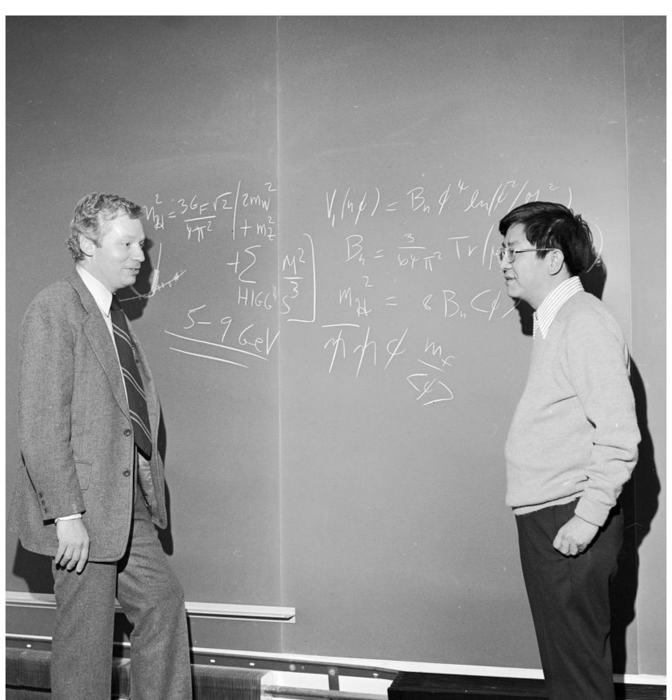
Preferred candidate so far was

Weakly Interacting Massive Particle (WIMP)



- Weak scale mass: O(1 ~ 100) × 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

What is Dark Matter?

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DM - SM → i) Observation
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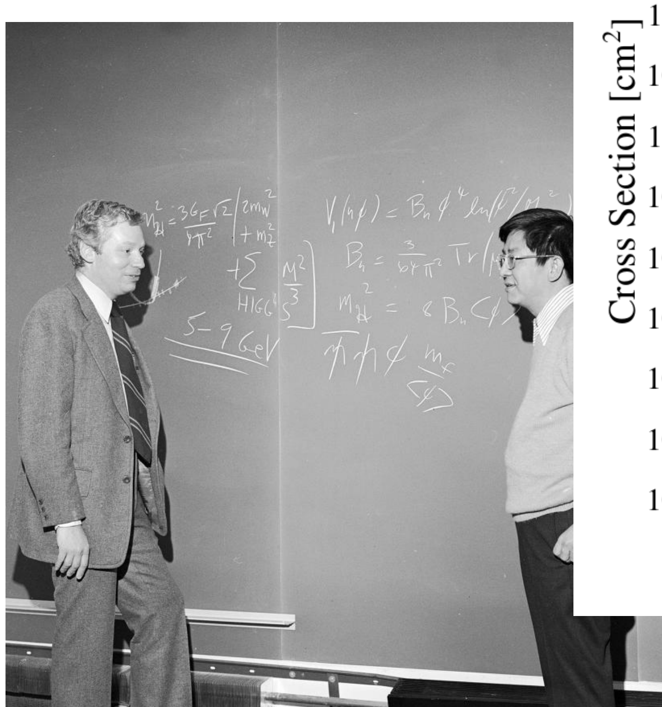
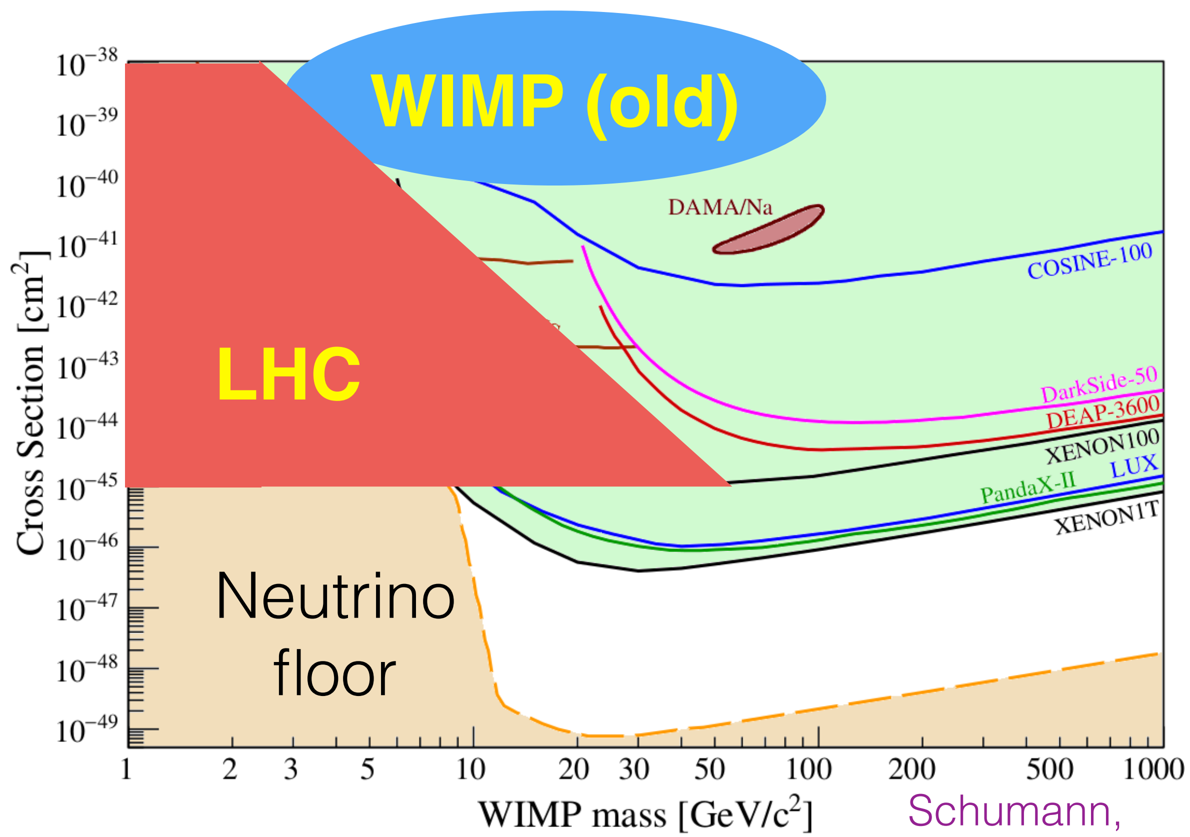
WIMP strongly constrained!

Preferred candi

Weak

MP)





Schumann, 1903.03026

proton mass

rticles:

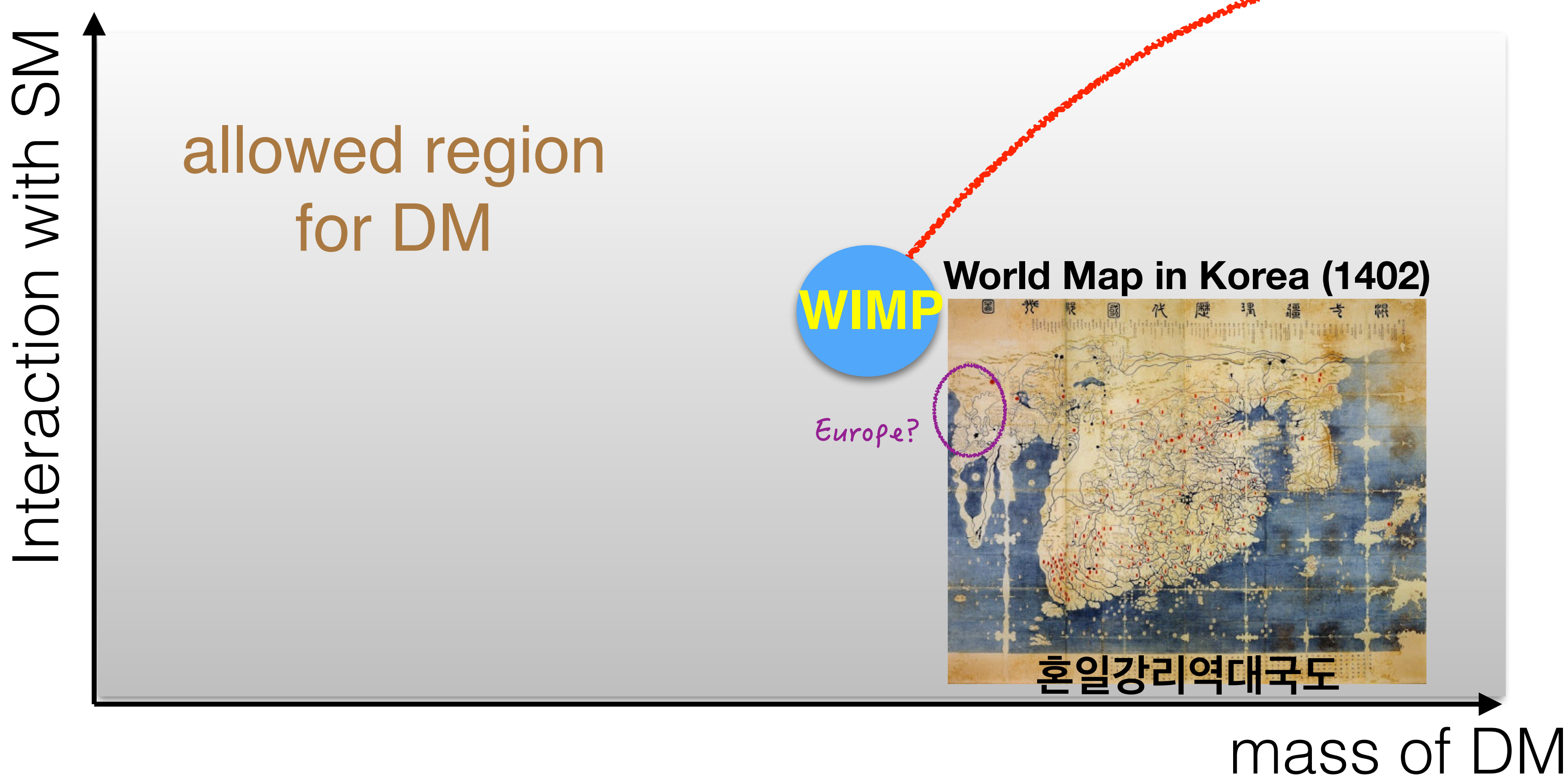
smaller than EM

theories

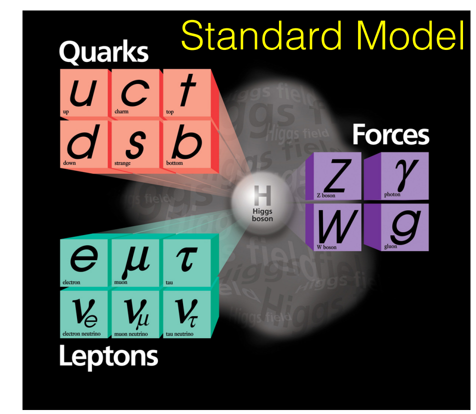
for resolving the hierarchy problem

Dark World beyond WIMP

WIMP may be a theoretical bias.



- Small region
- Oversimplification compared to



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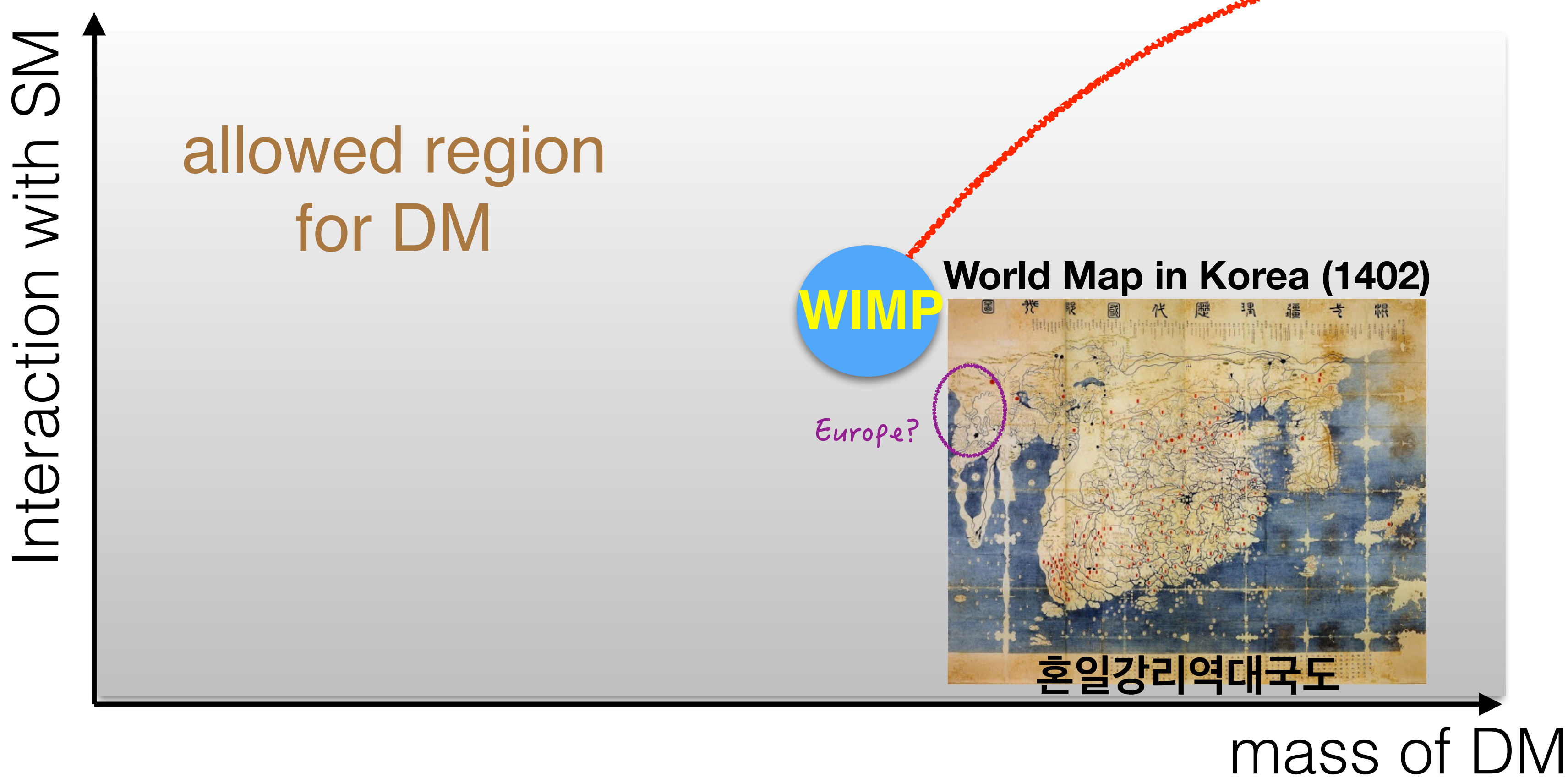

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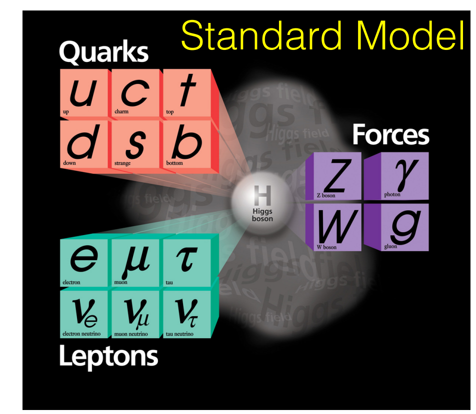


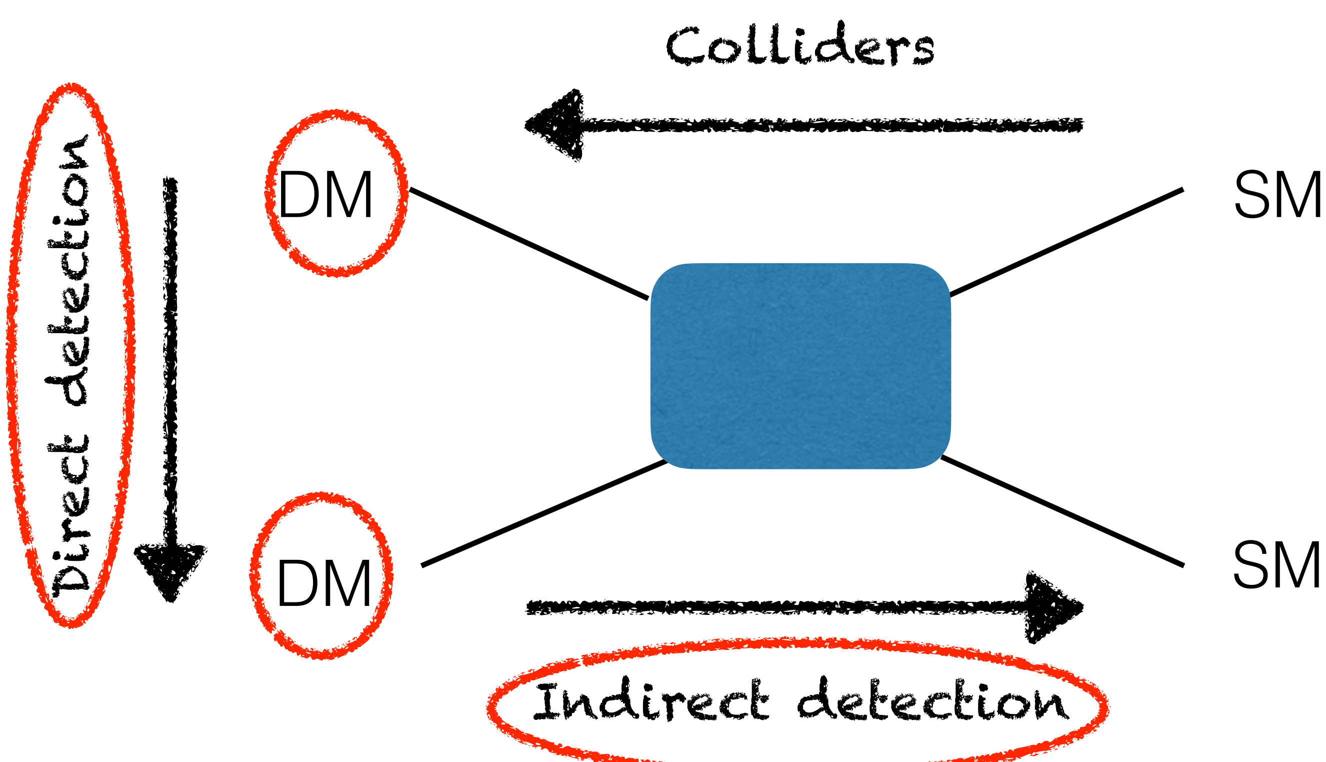
- Dark matter theories with novel dark sector structures beyond WIMP have been actively proposed nowadays.
- Multiple dark matter components are considered in a variety of dark sector theories beyond WIMP, e.g., multi-component boosted dark matter, composite dark matter, etc.

Sub-dominant DM 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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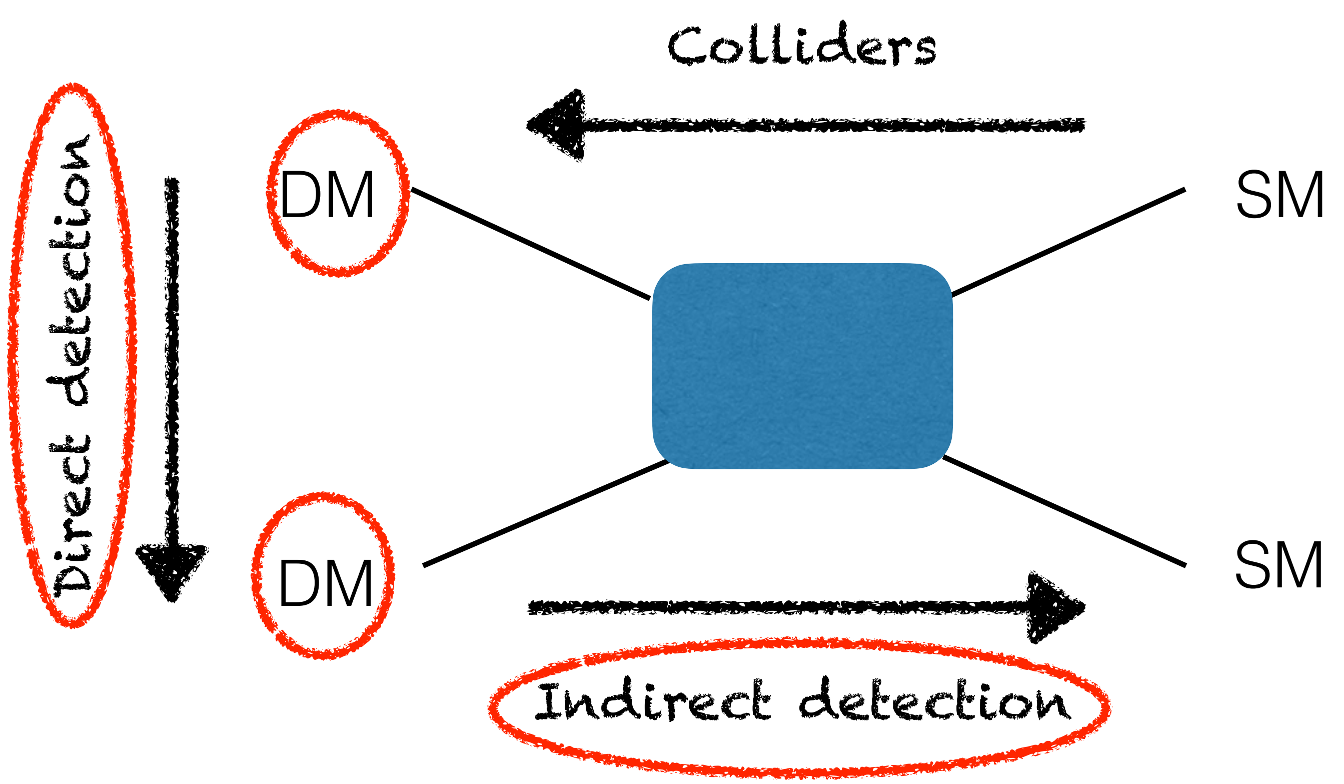

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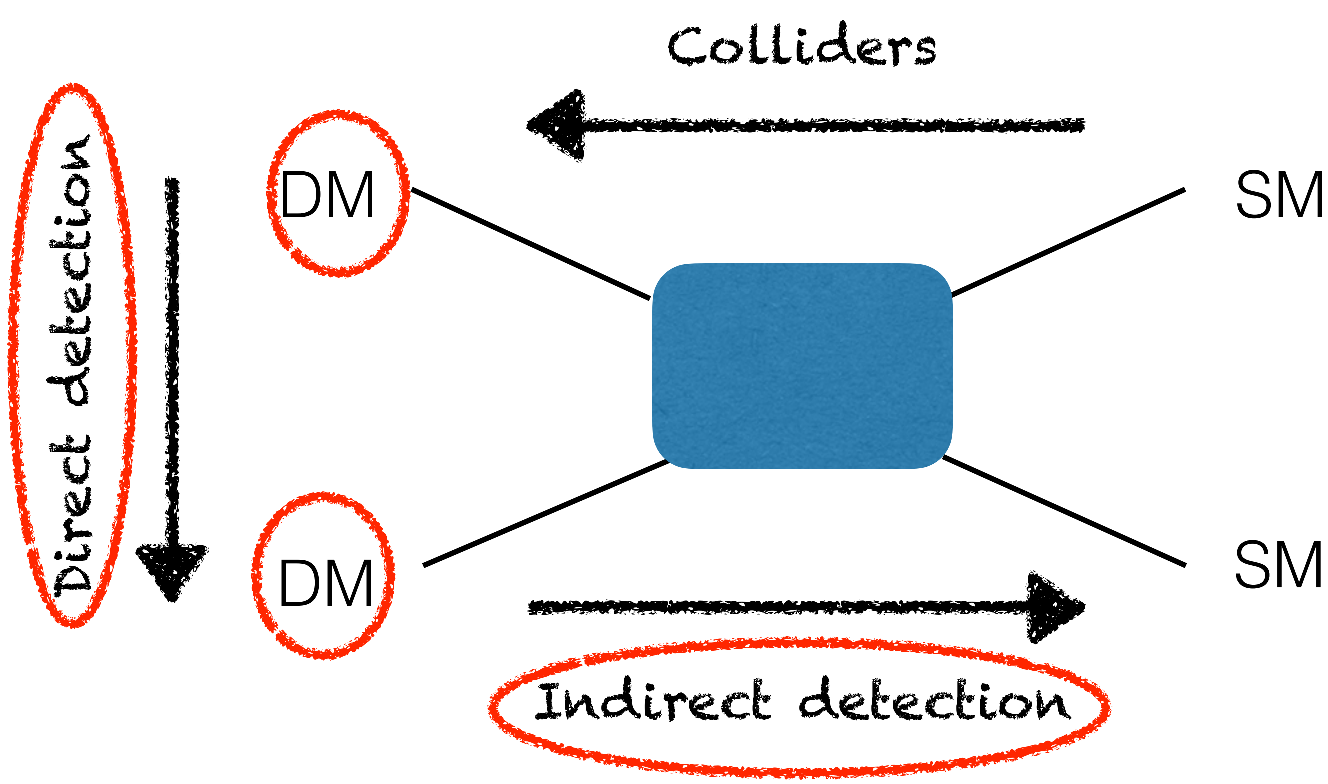
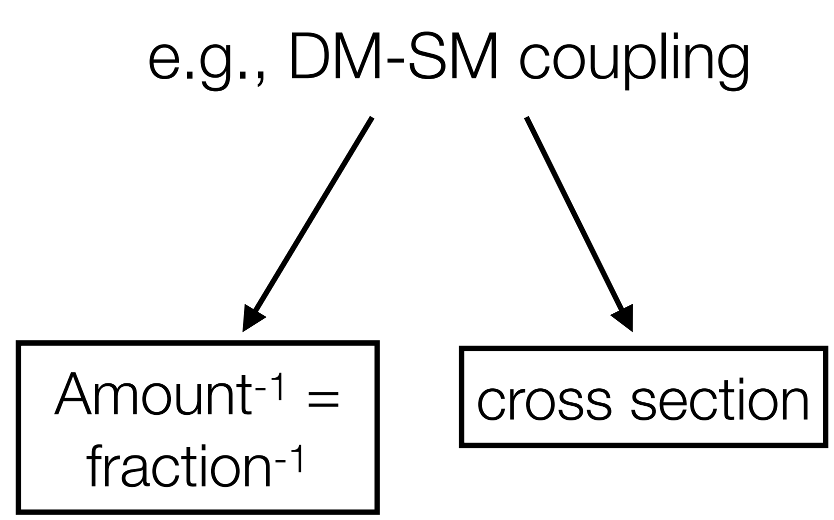
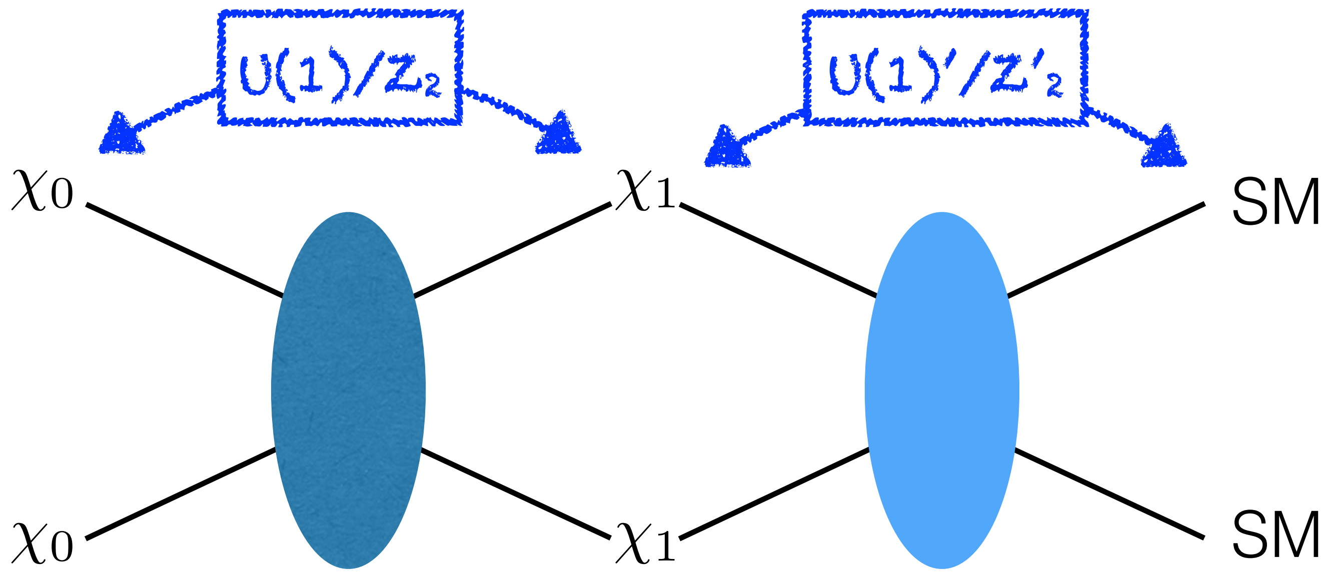




Observable = fraction x cross section

Example: 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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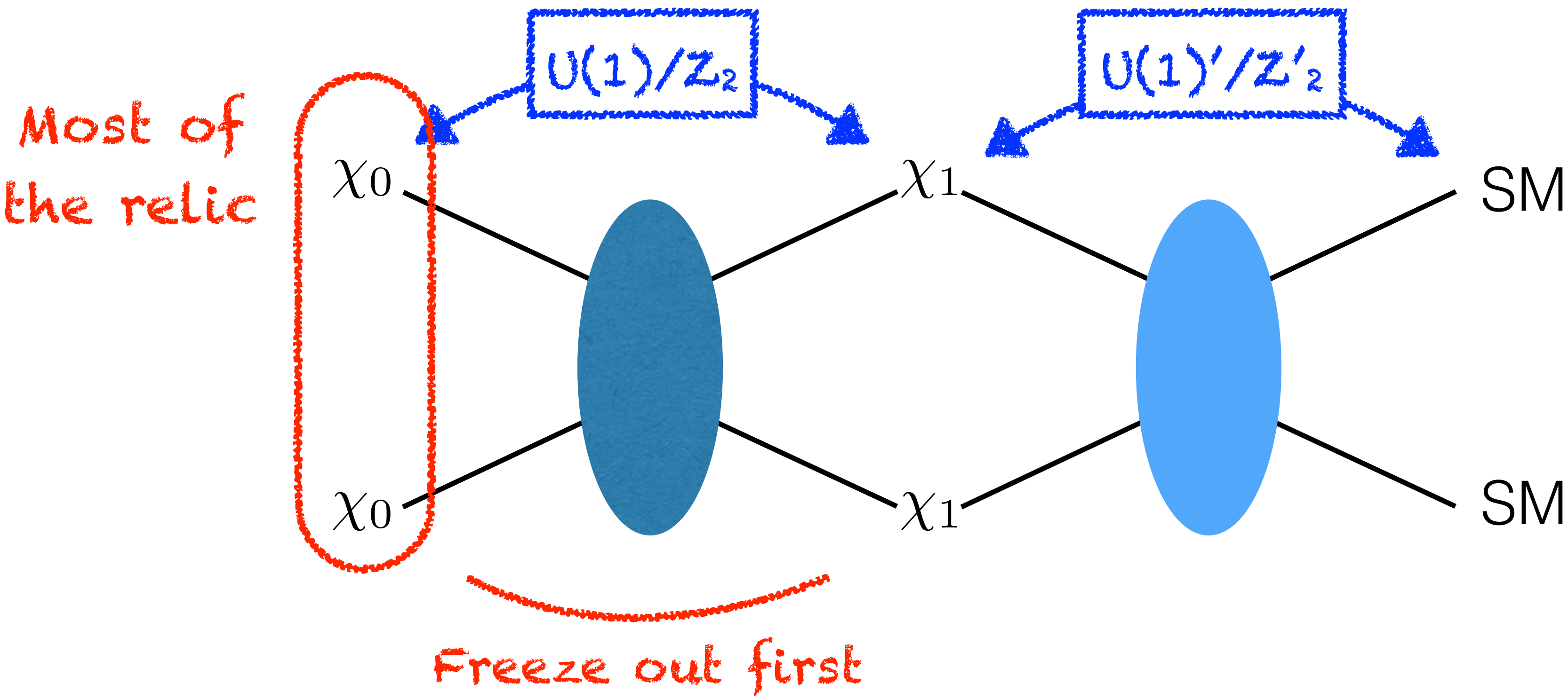

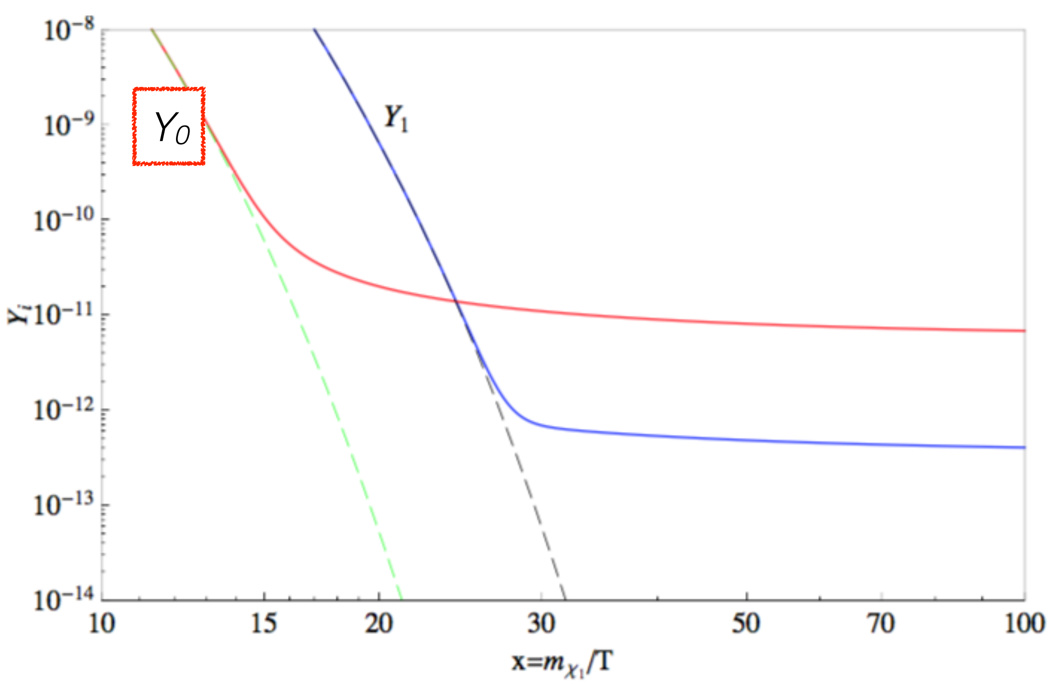

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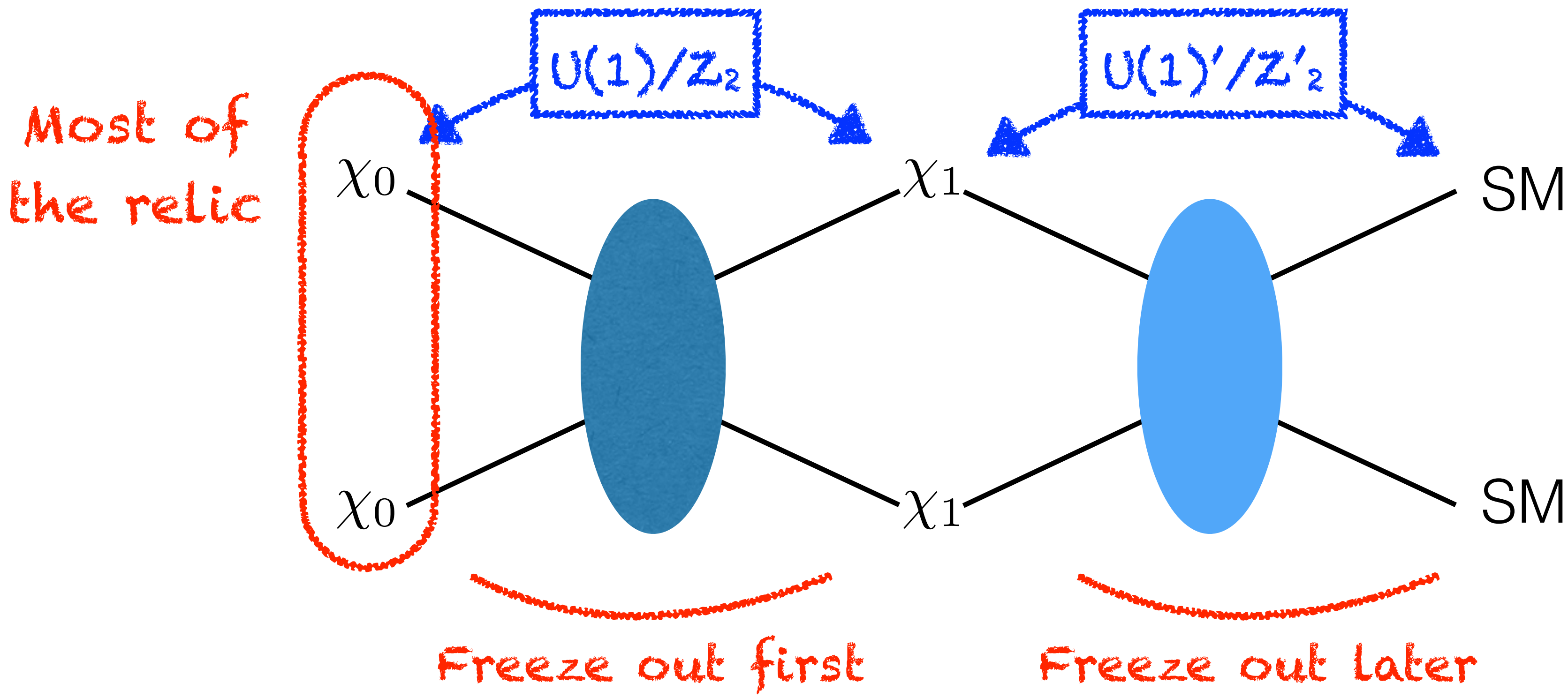

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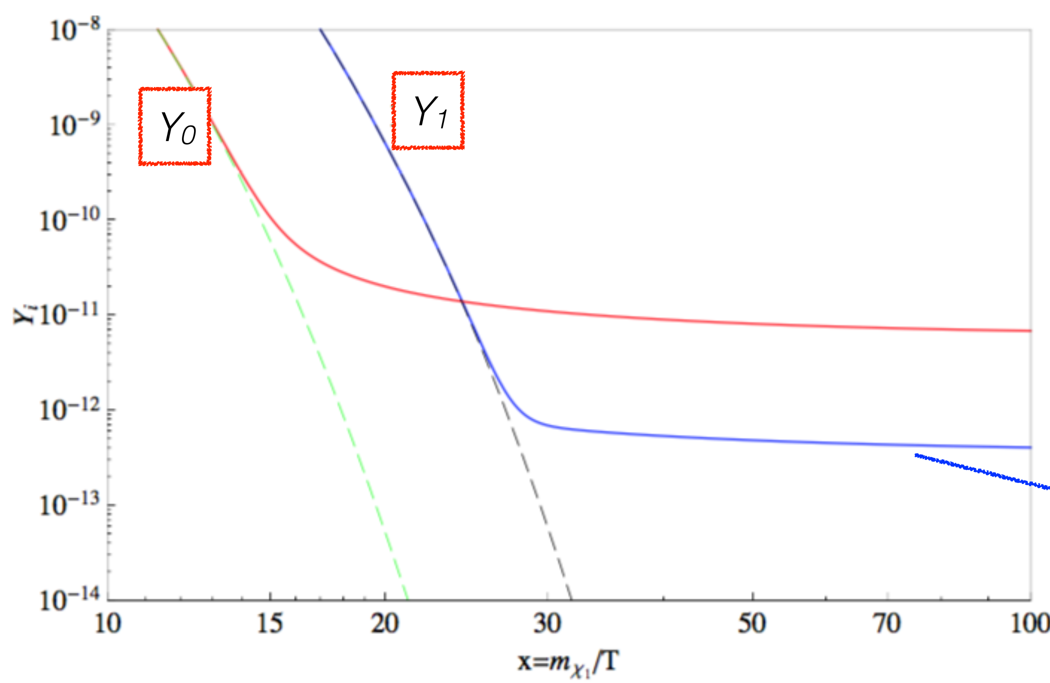

Belanger, Park, JCAP 2012

Assisted freeze-out mechanism

non-relativistic relic χ_1 (negligible)

$$Y_0 \gg Y_1$$

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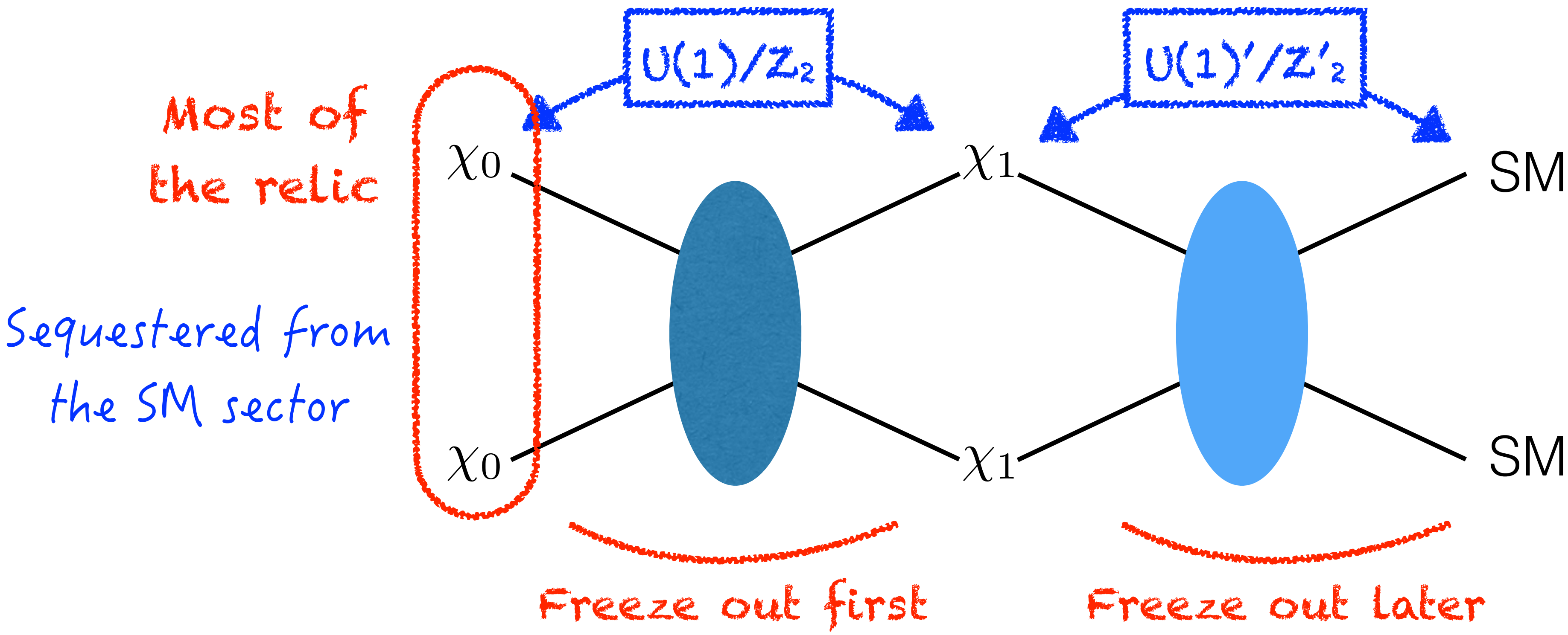

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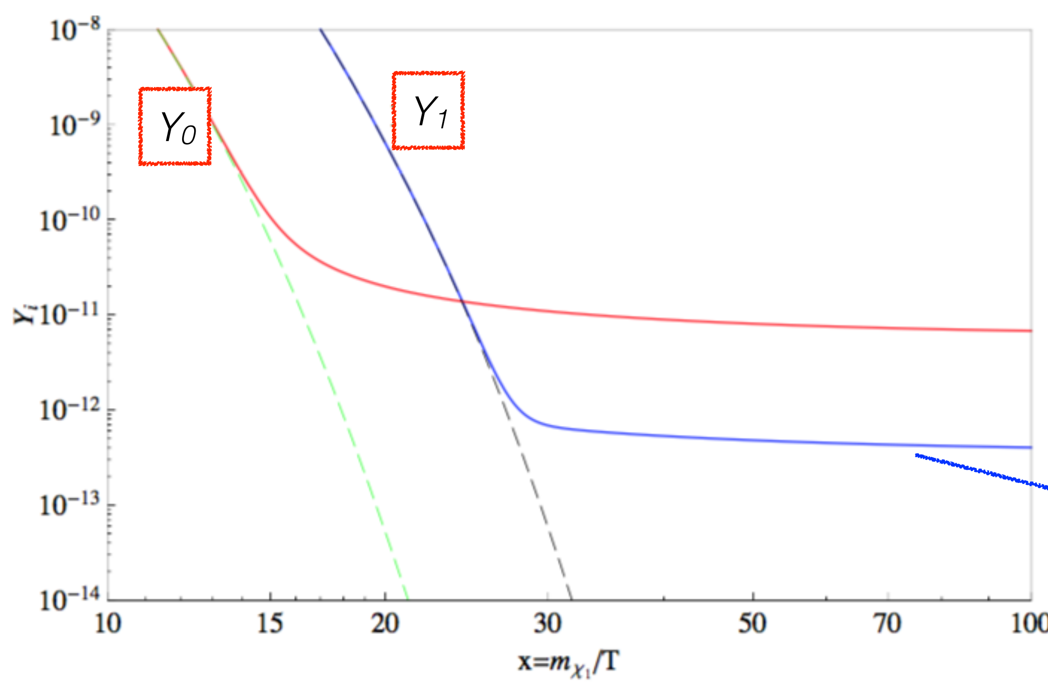

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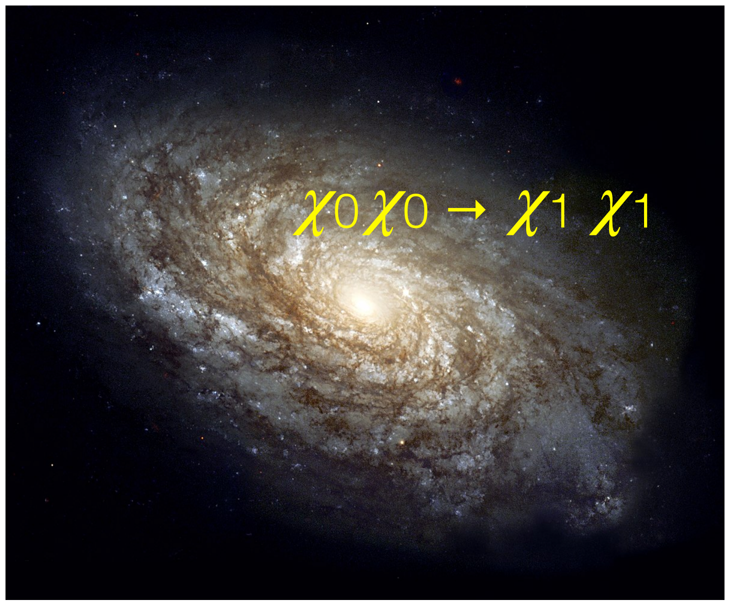

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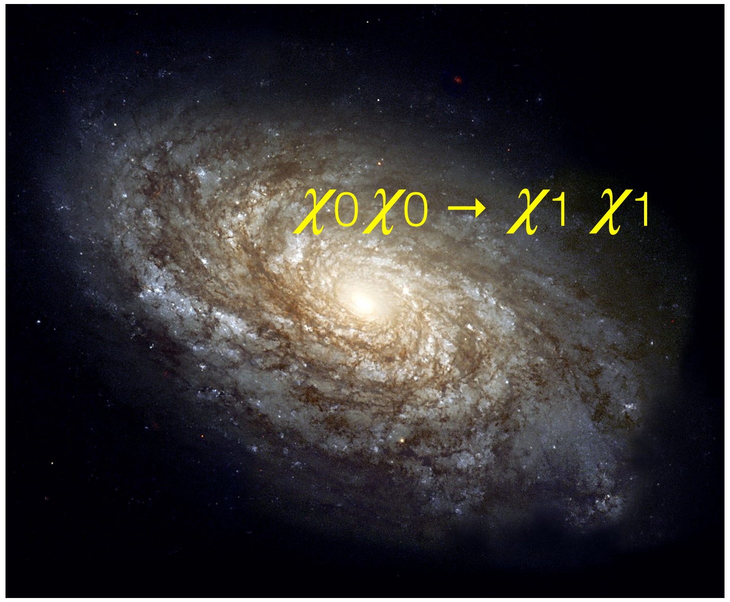

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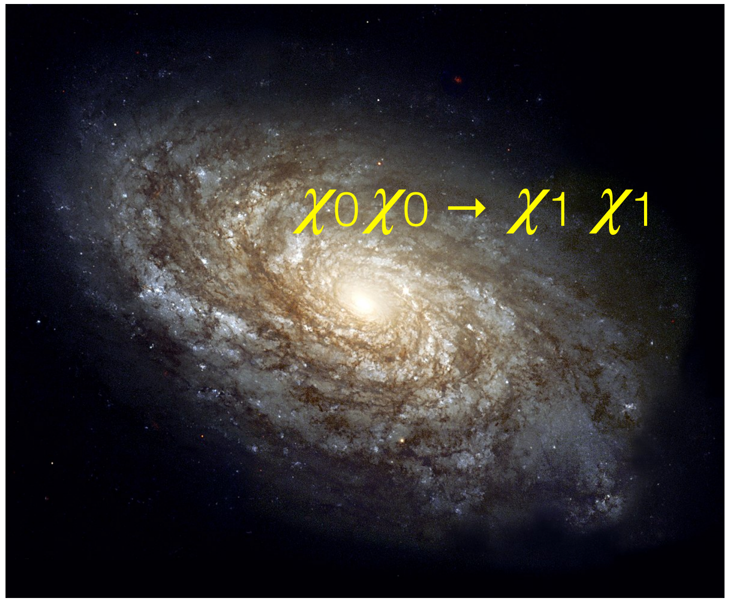

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Assume: NFW

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

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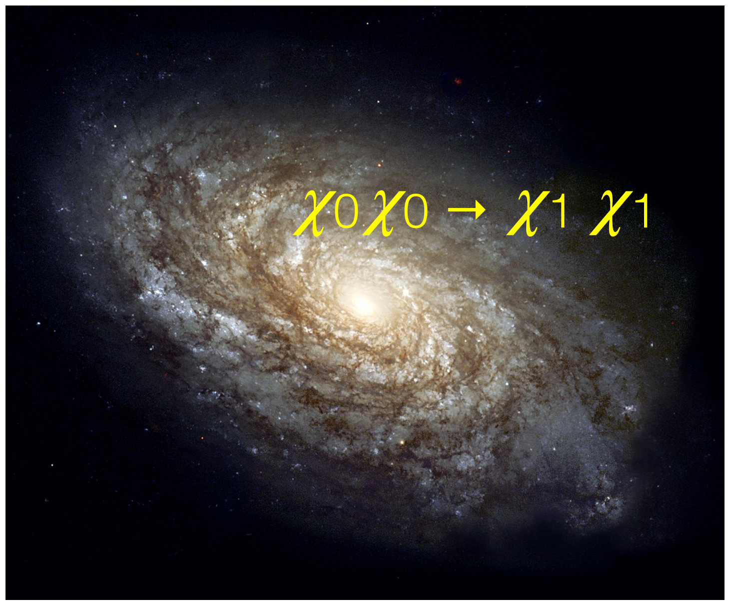

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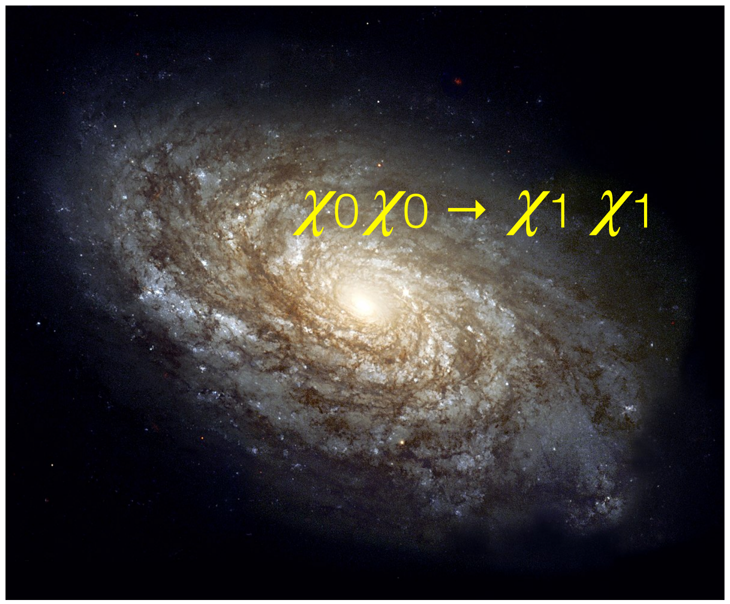

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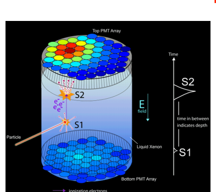
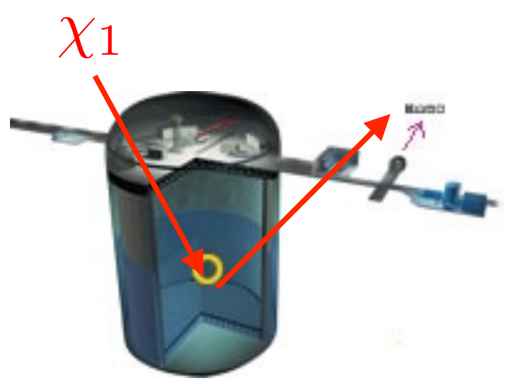


comparable **if $m_0 \lesssim 1$ GeV**

Detection prospects of BDM

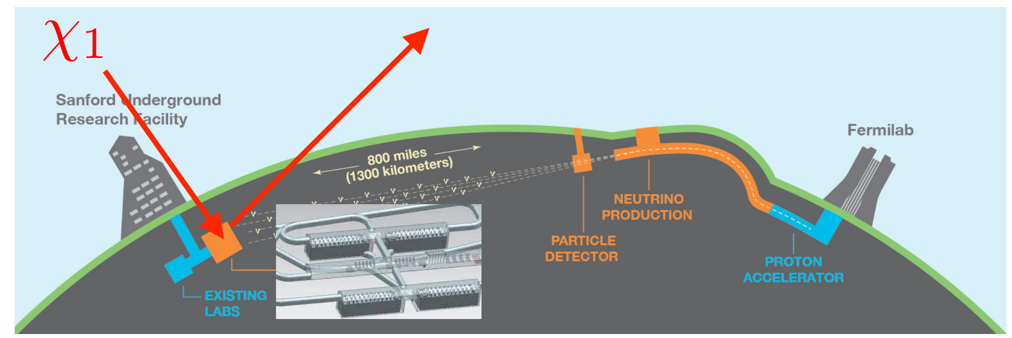
- Neutrino Experiments



PHYSICAL REVIEW LETTERS **120,** 221301 (2018)

Editors' Suggestion

Search for Boosted Dark Matter Interacting with Electrons in Super-Kamiokande



DEEP UNDERGROUND NEUTRINO EXPERIMENT

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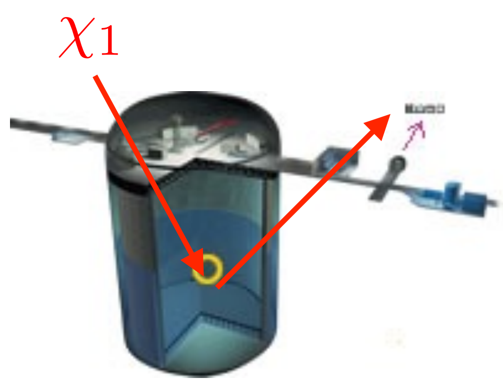

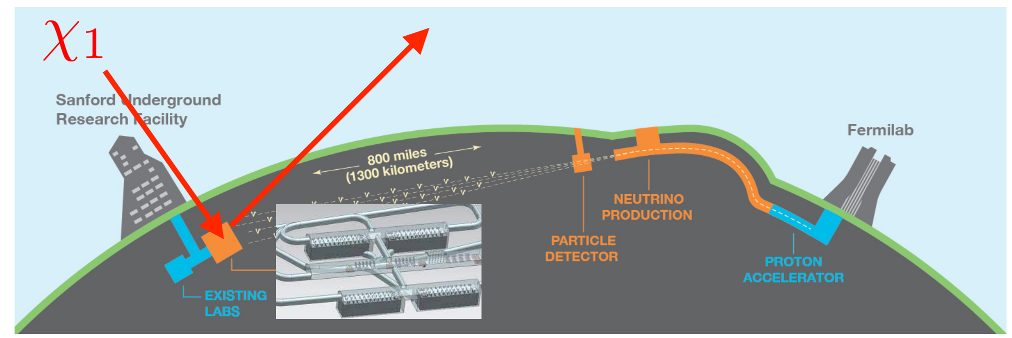

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

PHYSICAL REVIEW LETTERS **120,** 221301 (2018)

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Search for Boosted Dark Matter Interacting with Electrons in Super-Kamiokande

- Dark Matter direct detection experiments

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

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

PHYSICAL REVIEW LETTERS **122,** 131802 (2019)

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First Direct Search for Inelastic Boosted Dark Matter with COSINE-100

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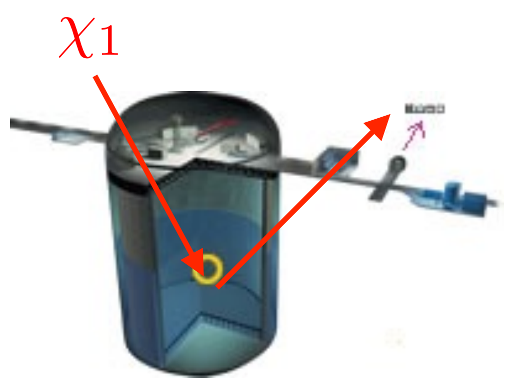

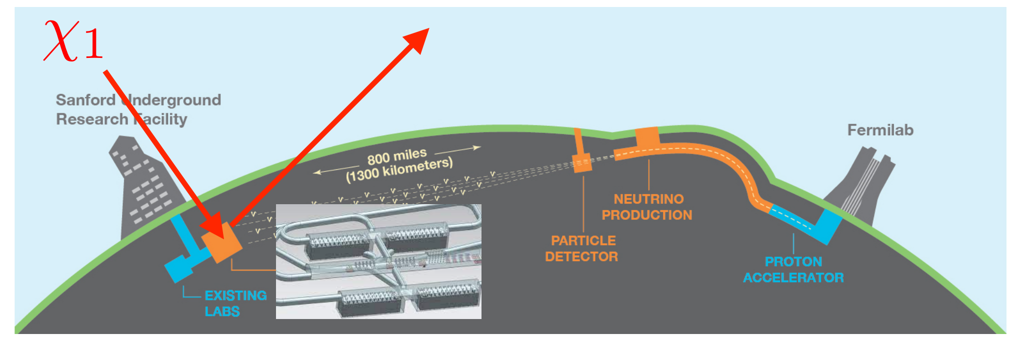

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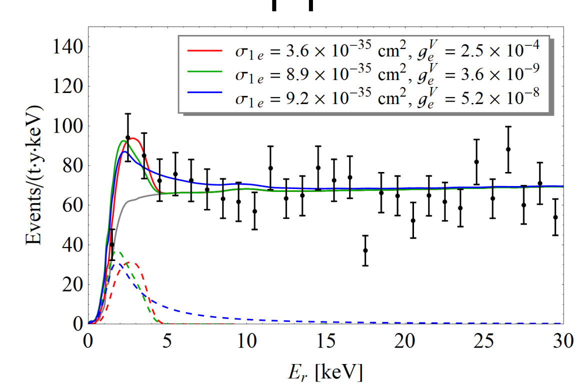
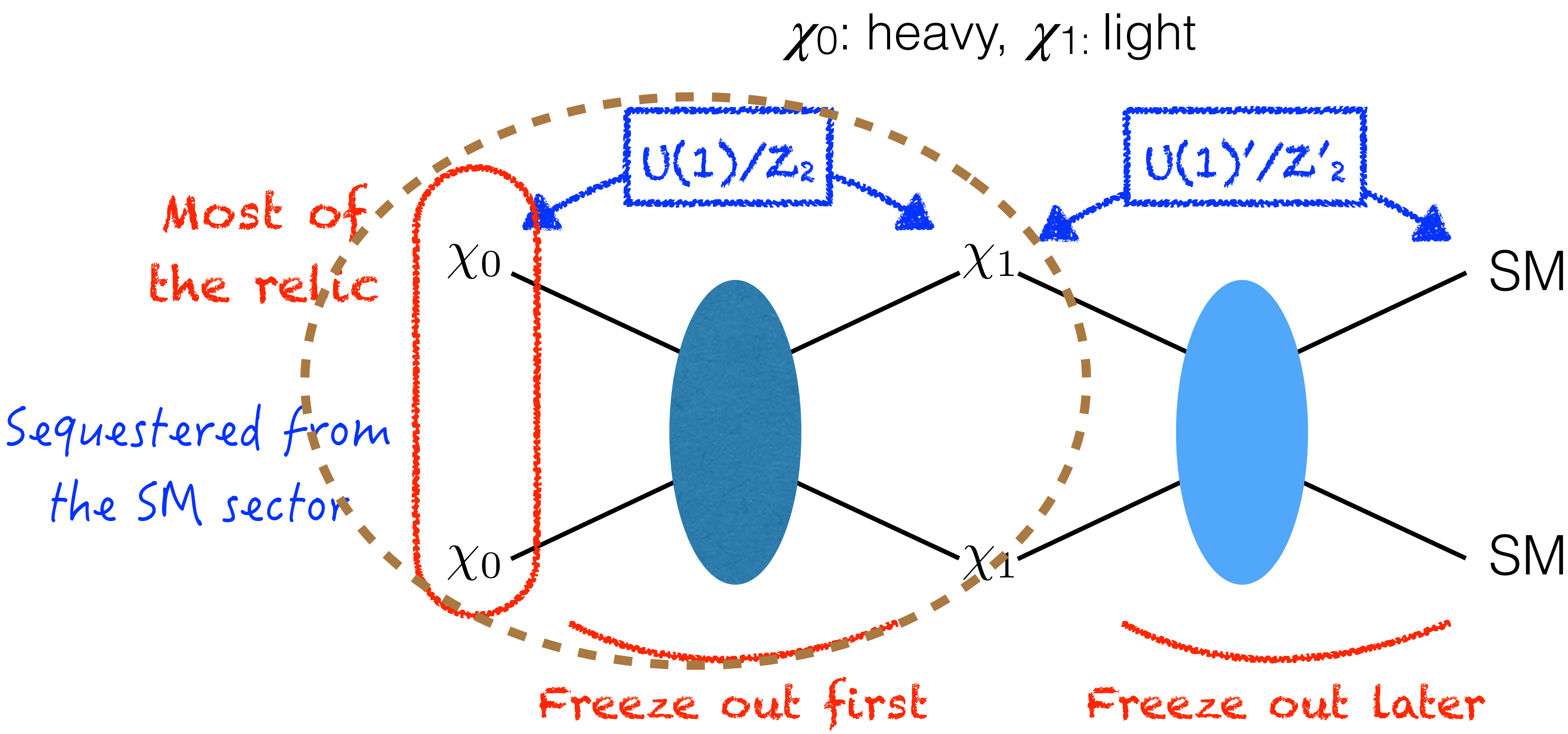
First Direct Search for Inelastic Boosted Dark Matter with COSINE-100

More systematic approach in possible BDM signals



Alhazmi, Kim, Kong, Mohlabeng, Park, **SS**, JHEP 2021

Structure of $\chi_1\chi_1 \rightarrow$ SM



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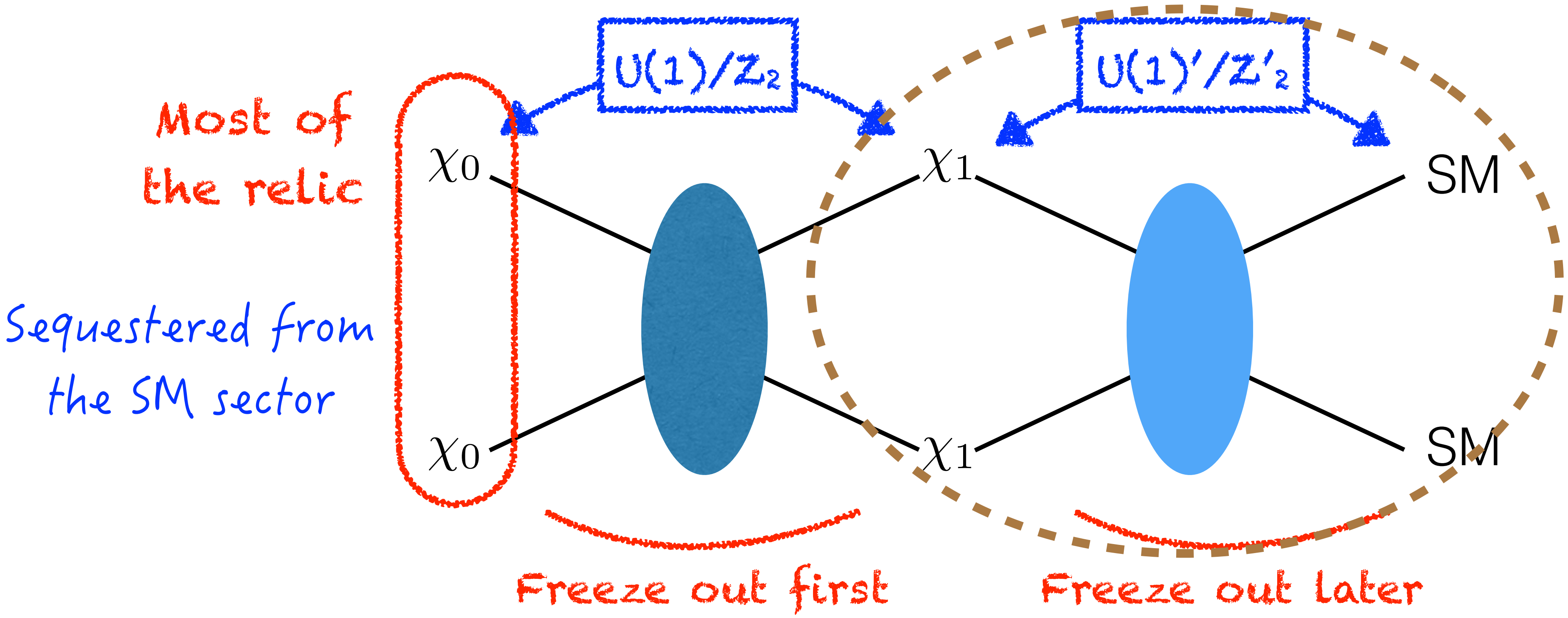
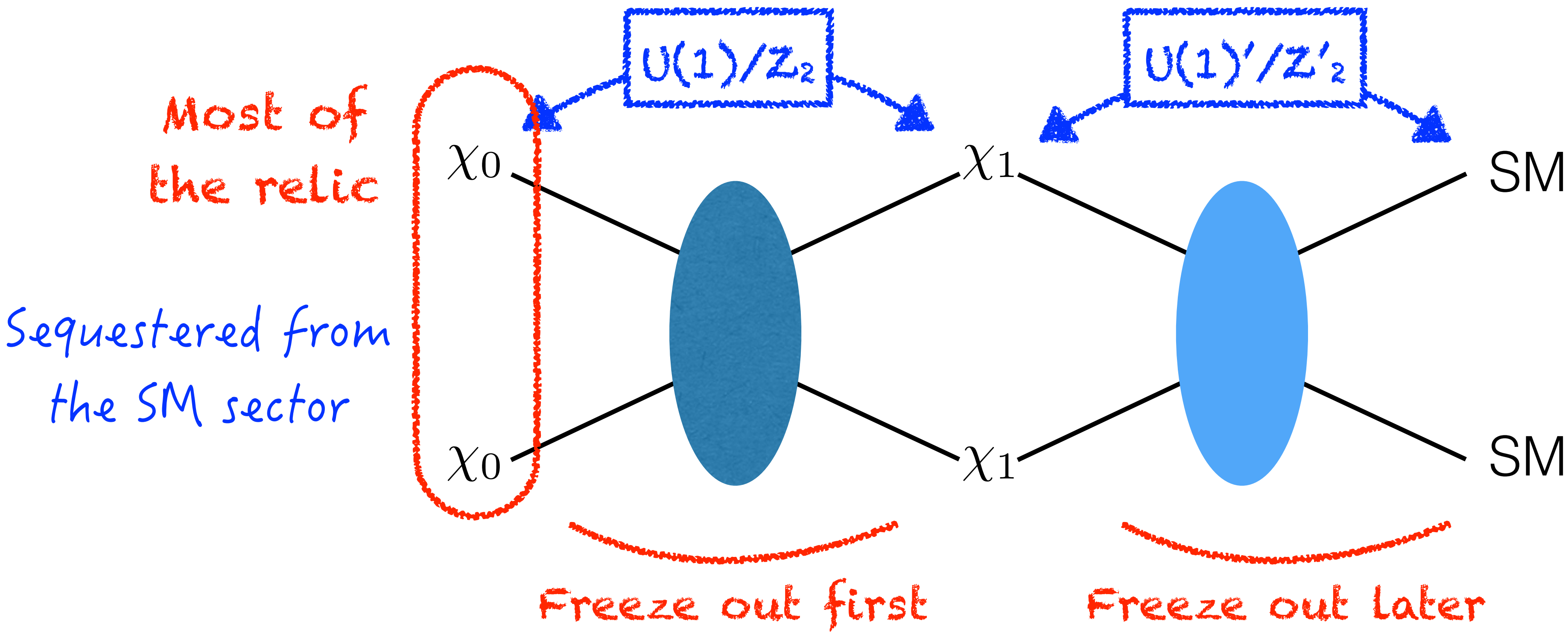


- Focus on the signals of χ_0 and the probes on the negligible relic χ_1 has been ignored. (Conventionally accepted in multi-component DM)

- Now move focus to the structure of sub-dominant and light χ_1 and SM sector interactions and their effects to cosmo/astro observables.

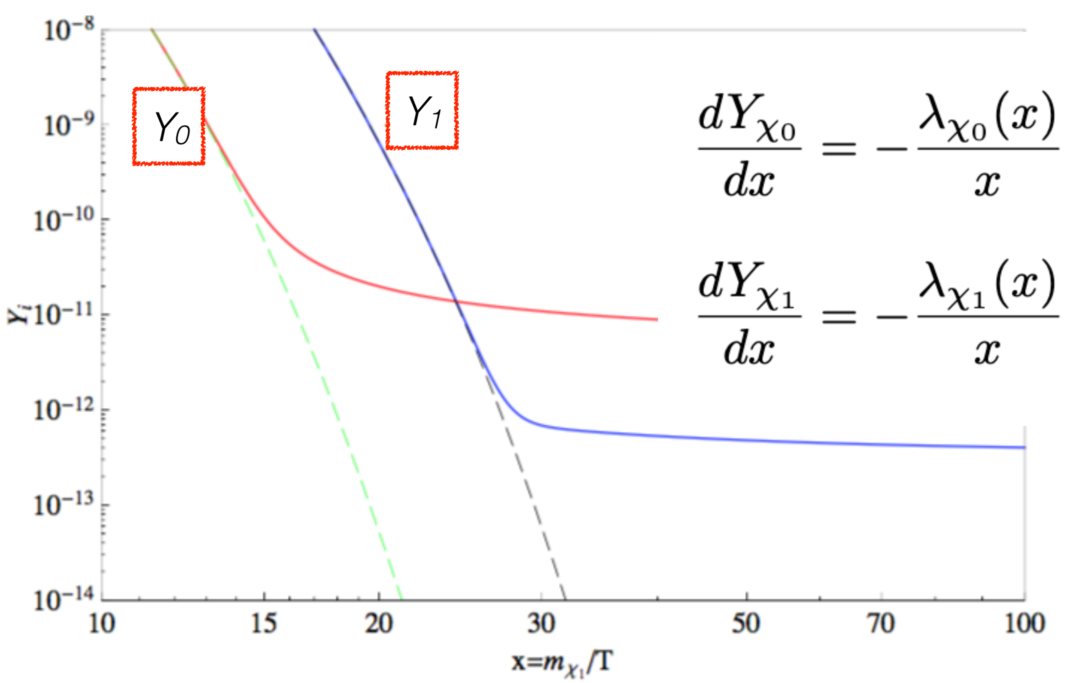
Structure of $\chi_1\chi_1 \to$ SM

χ_0: heavy, χ_1: light



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

$$s = (2\pi^2/45) g_{*S} T^3$$



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

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda_{\chi_1}(x)}{x}\underbrace{\left[Y_{\chi_1}^2 - \left(Y_{\chi_1}^{\rm eq}(x)\right)^2\right]}_{\text{with SM}} + \frac{\lambda_{\chi_0}(x)}{x}\underbrace{\left[Y_{\chi_0}^2 - \left(\frac{Y_{\chi_0}^{\rm eq}(x)}{Y_{\chi_1}^{\rm eq}(x)}\right)^2 Y_{\chi_1}^2\right]}_{\text{with heavy DM } \chi_0},$$

with SM

with heavy DM χ_0

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

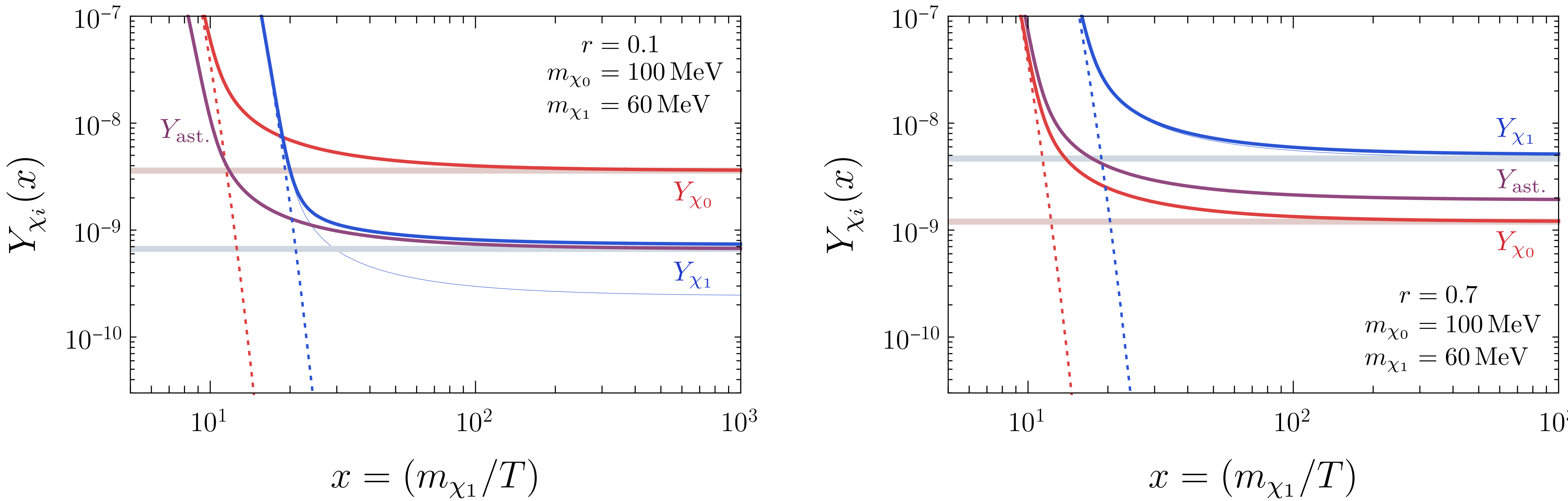
During the decoupling, assume χ_1 is in kinetic equilibrium with the SM

- 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, $Y_{\rm ast.}$ is non-negligible since $\langle\sigma_1 v_{\rm rel}\rangle$ should increase.

Structure of $\chi_1 \chi_1 \to$ SM

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



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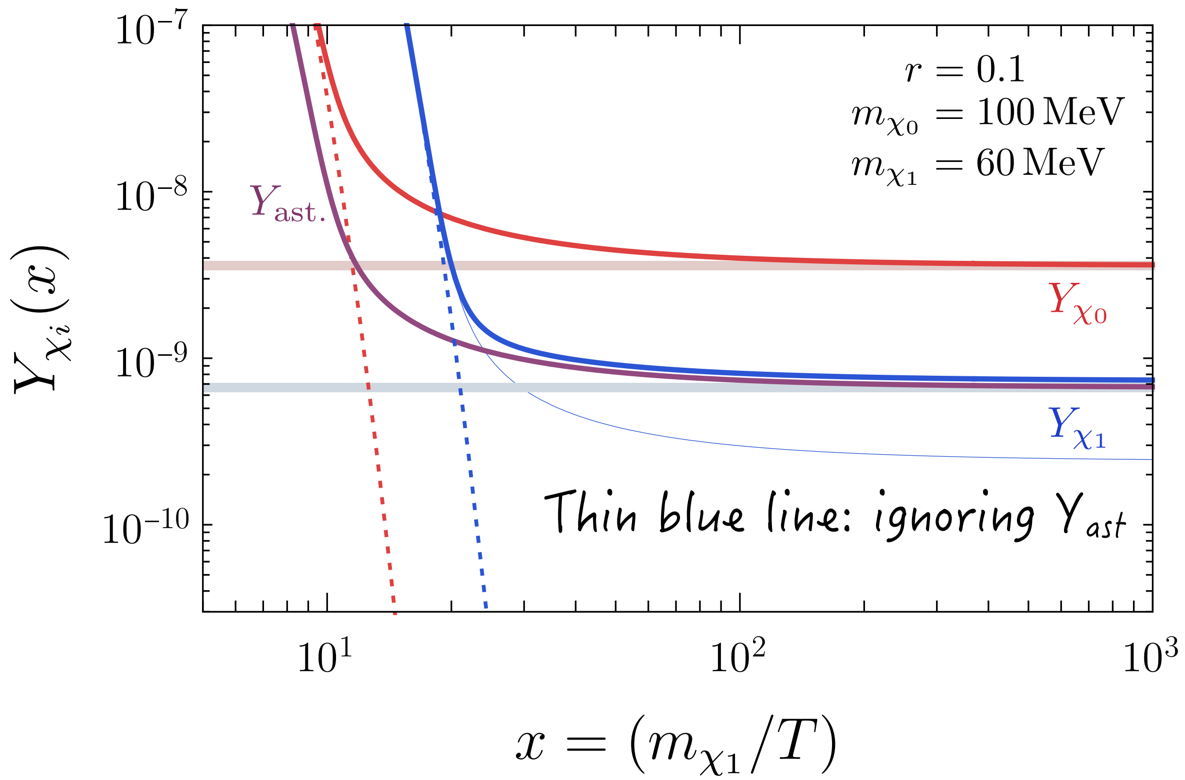

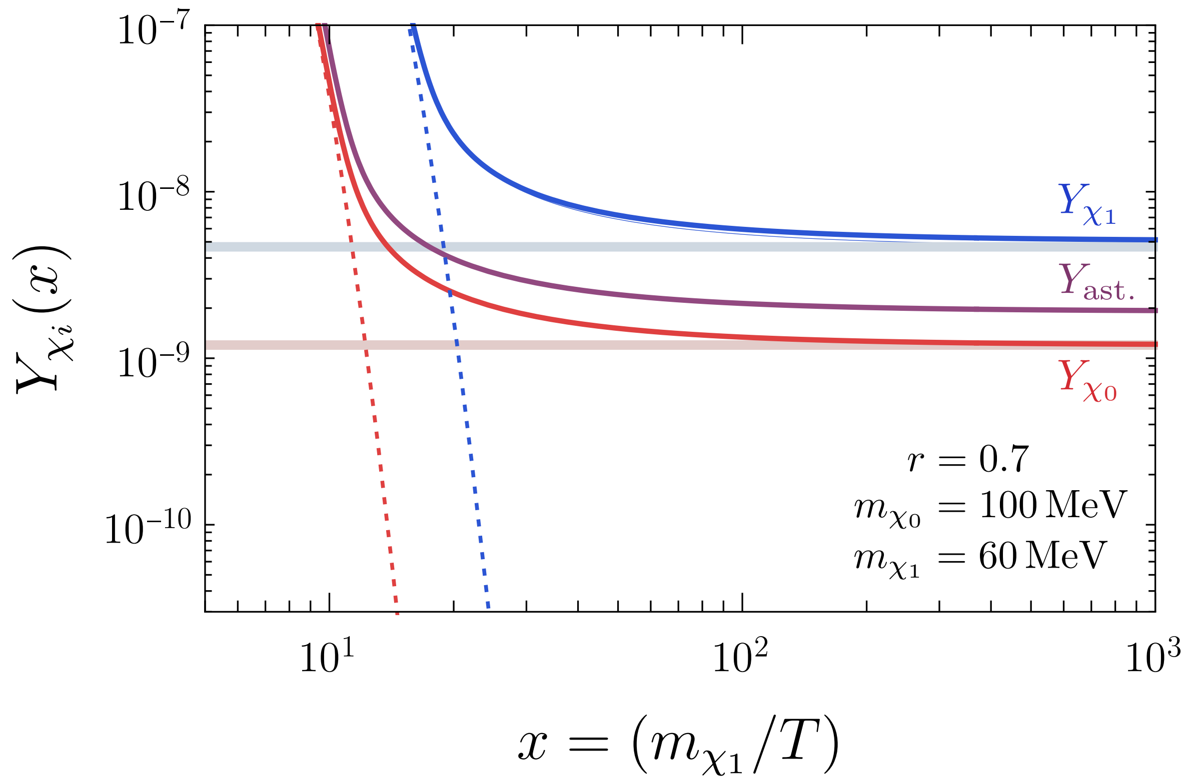

Structure of $\chi_1\chi_1 \rightarrow$ SM

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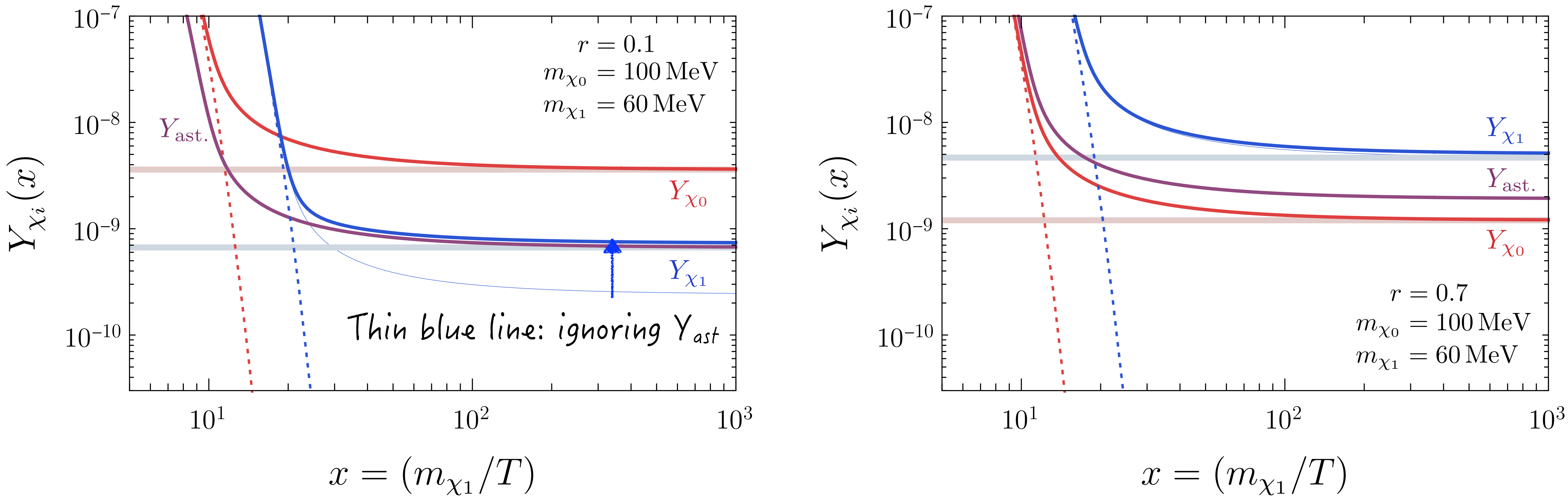

- For $r_1 \ll 1$, Y_{χ_1} is lifted-up by $Y_{\mathrm{ast.}}$ (follows it when $T \lesssim m_1/30$).

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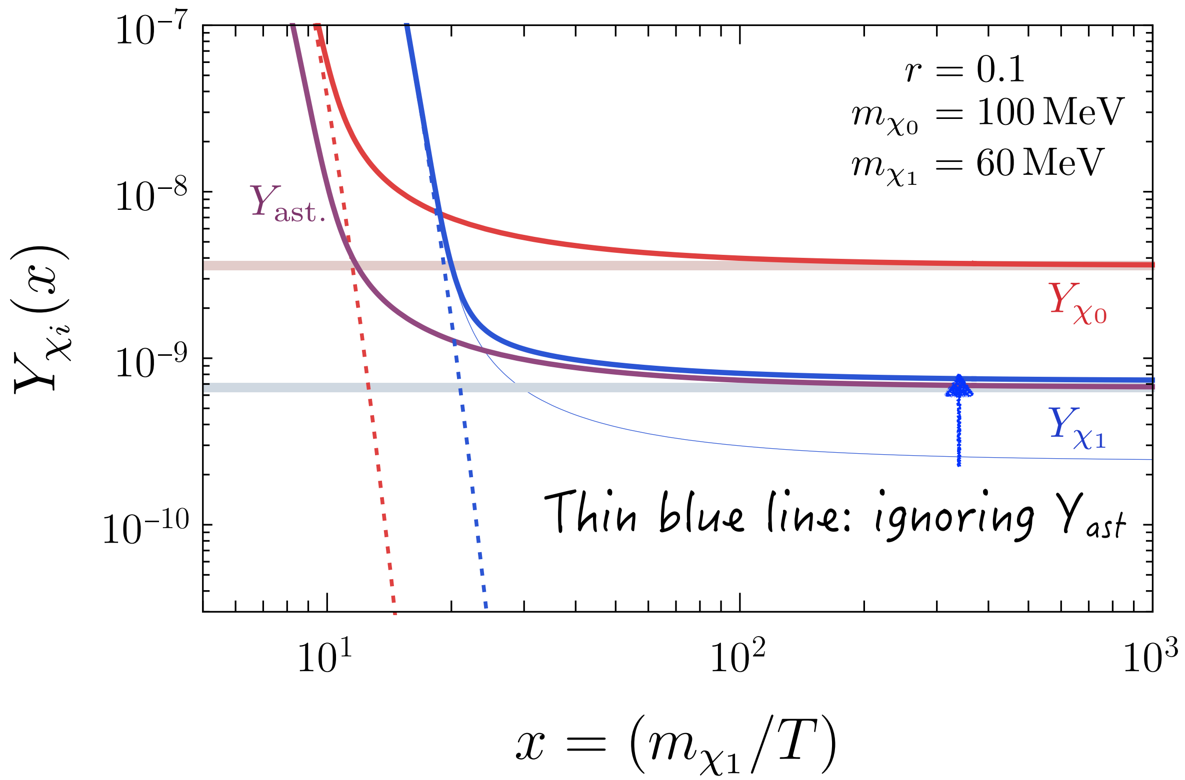
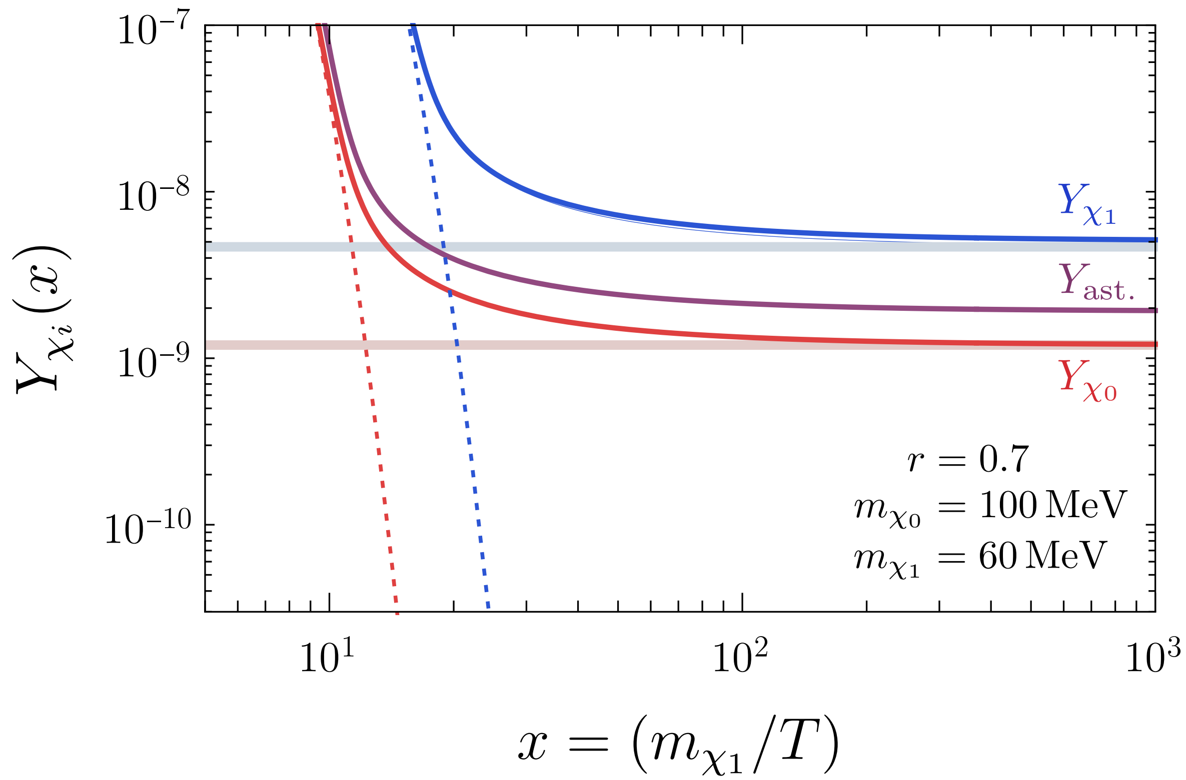




- For $r_1 \ll 1$, Y_{χ_1} is lifted-up by $Y_{\mathrm{ast.}}$ (follows it when $T \lesssim m_1/30$).

- The annihilation cross section $\chi_1\chi_1 \to$ SM increases as $1/r_1^{\,2}$ so the process is sensitive to various observables (strong constraints).

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

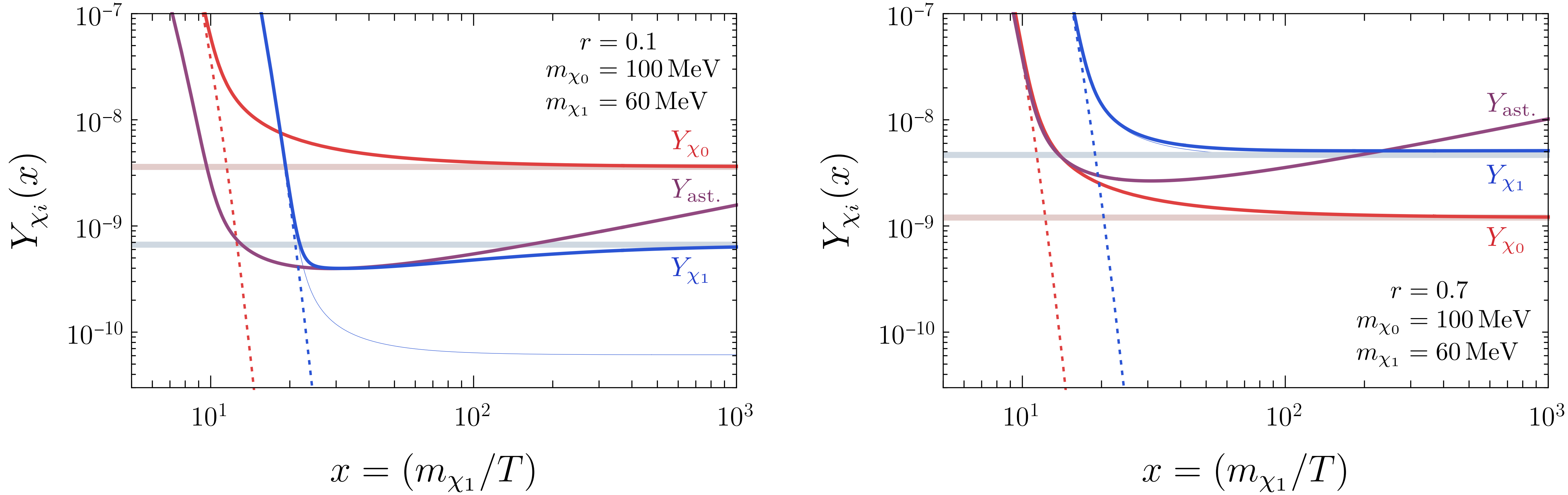
$$\langle \sigma_0 v_{\mathrm{rel}} \rangle \simeq (\sigma_0 v_{\mathrm{rel}})_s + (\sigma_0 v_{\mathrm{rel}})_p v_{\mathrm{rel}}^2$$

Structure of $\chi_1 \chi_1 \to$ SM

When $\chi_1 \chi_1 \to$ SM is dominated by p-wave   Safe from constraints?

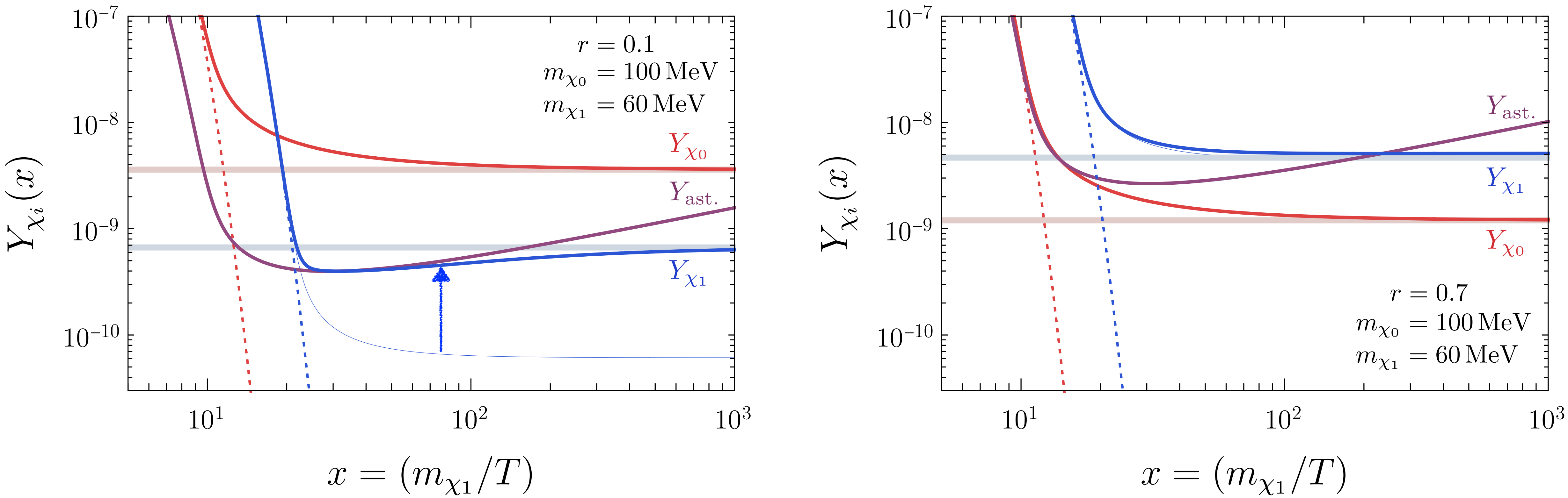
Structure of $\chi_1\chi_1 \to$ SM

When $\chi_1\chi_1 \to$ SM is dominated by p-wave *Safe from constraints?*



Structure of $\chi_1\chi_1 \to$ SM

When $\chi_1\chi_1 \to$ SM is dominated by p-wave   *Safe from constraints?*



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

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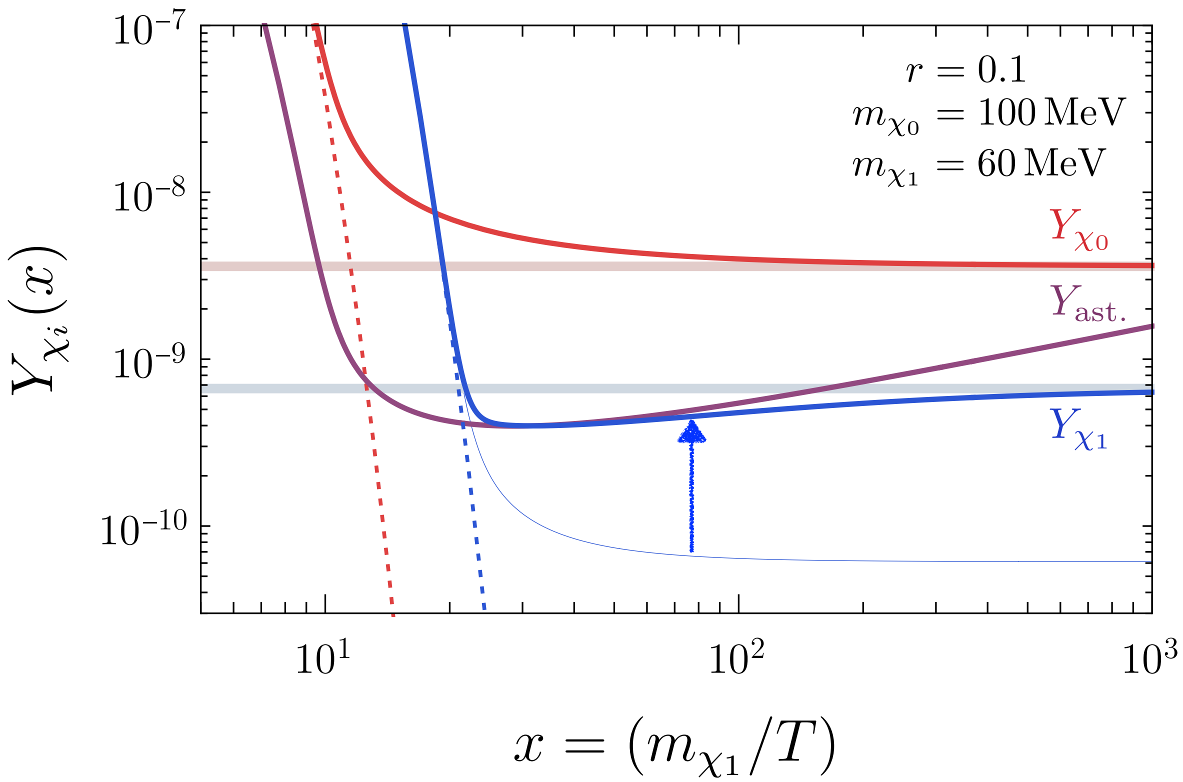
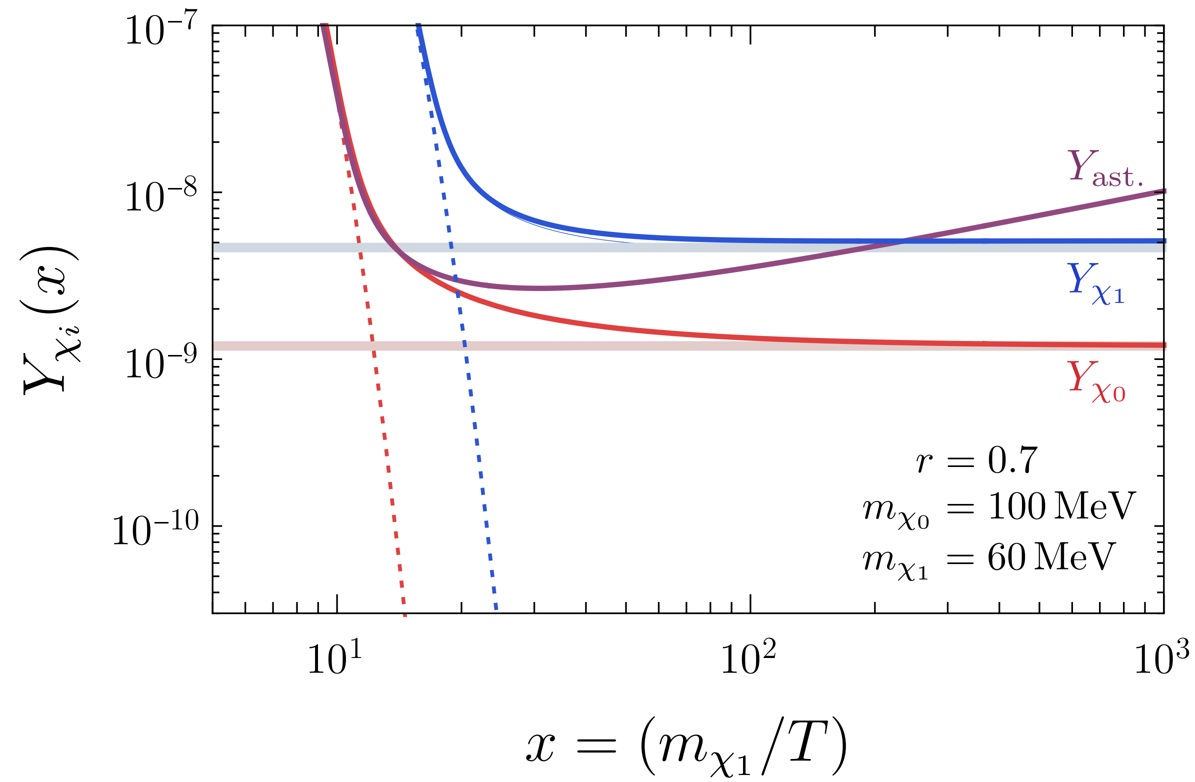




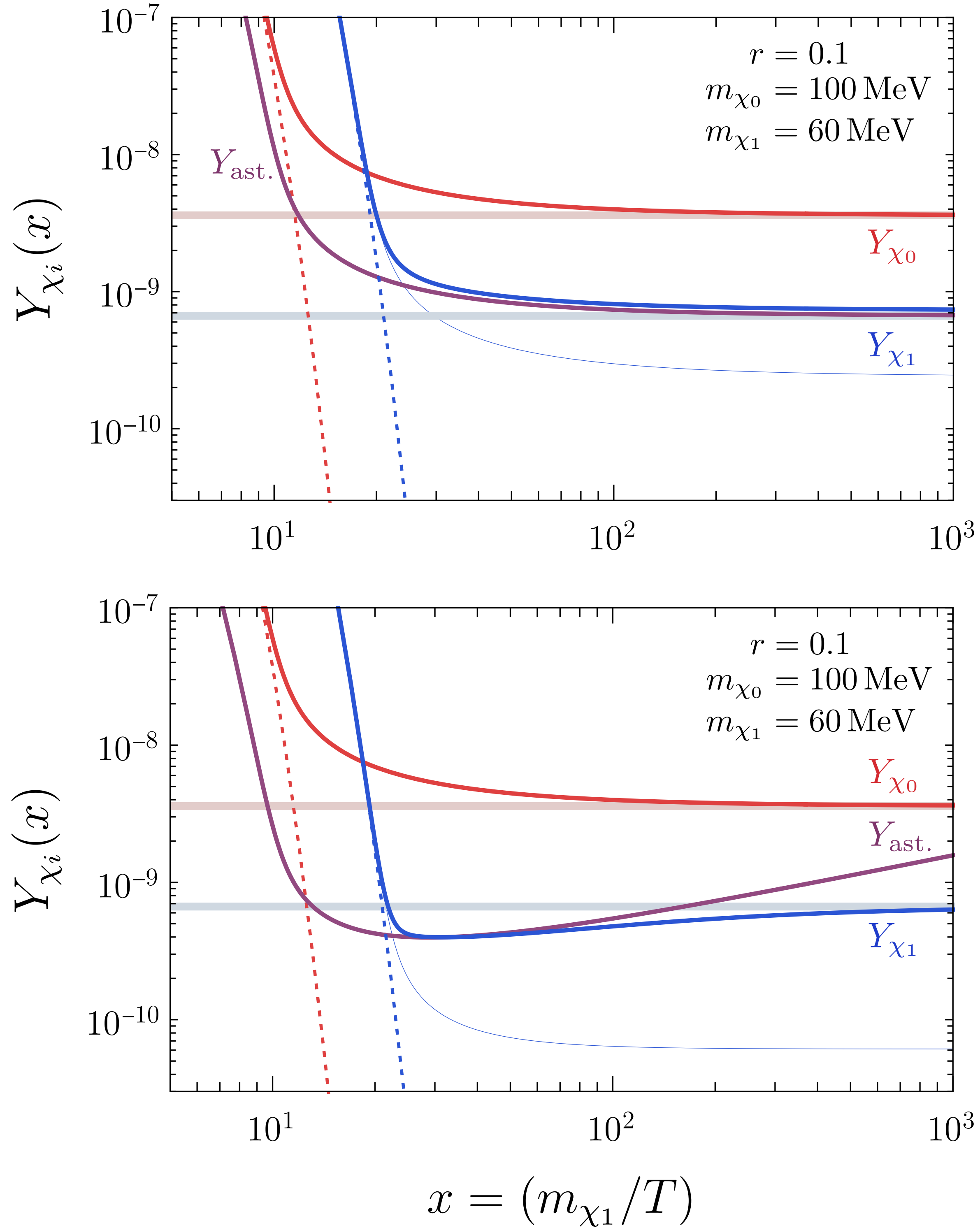
- For $r_1 \ll 1$, Y_{χ_1} is lifted-up even more by $Y_{\mathrm{ast.}}$ (until $T \sim m_1/80$).

- 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.

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

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

Structure of $\chi_1\chi_1 \to$ SM



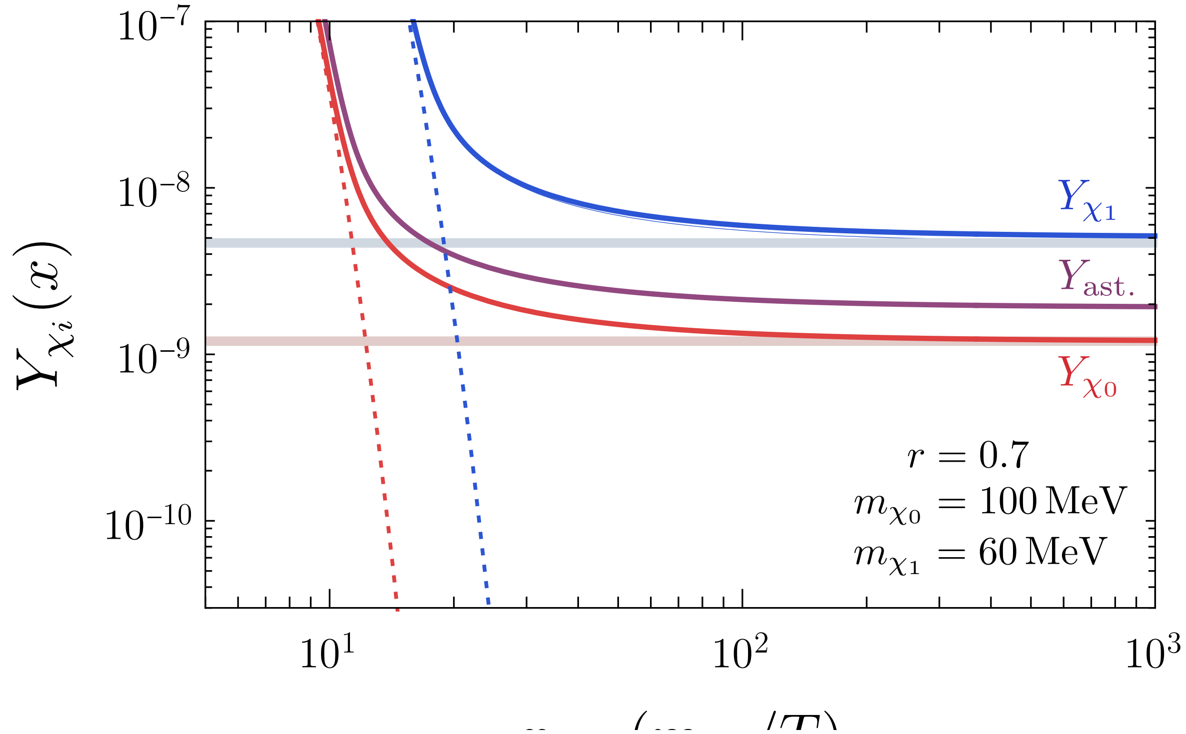
- For $r_1 \ll 1$, Y_{χ_1} is lifted-up by $Y_{\mathrm{ast.}}$

- $\chi_1\chi_1 \to$ SM affects the cosmo/astroph observables.

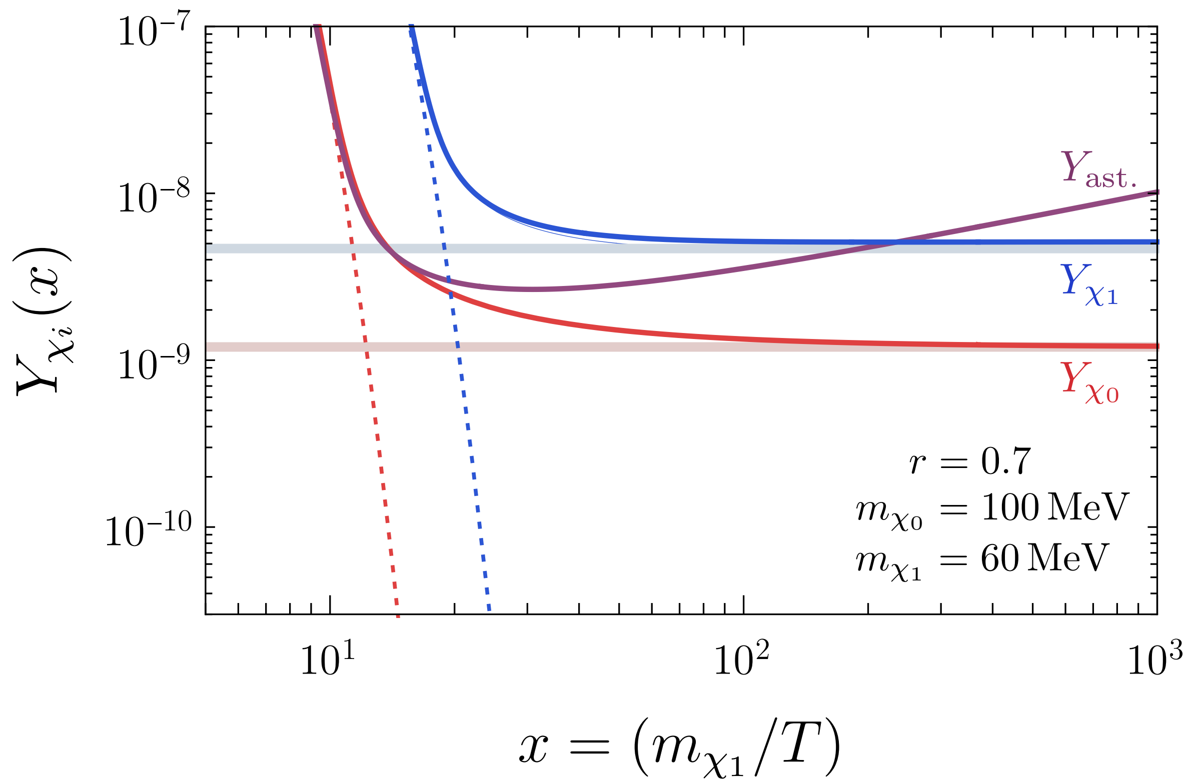
- For the p-wave dominant case, the $\chi_1\chi_1 \to$ SM takes a less role in determining Y_1 than in the s-wave.

Assisted regime

Structure of $\chi_1\chi_1 \to$ SM



- For $r_1 > 0.5$, Y_{χ_1} is not affected by $Y_{\rm ast.}$
- In this example, the fraction of χ_1 is already large enough to affect various observables.



Standard regime

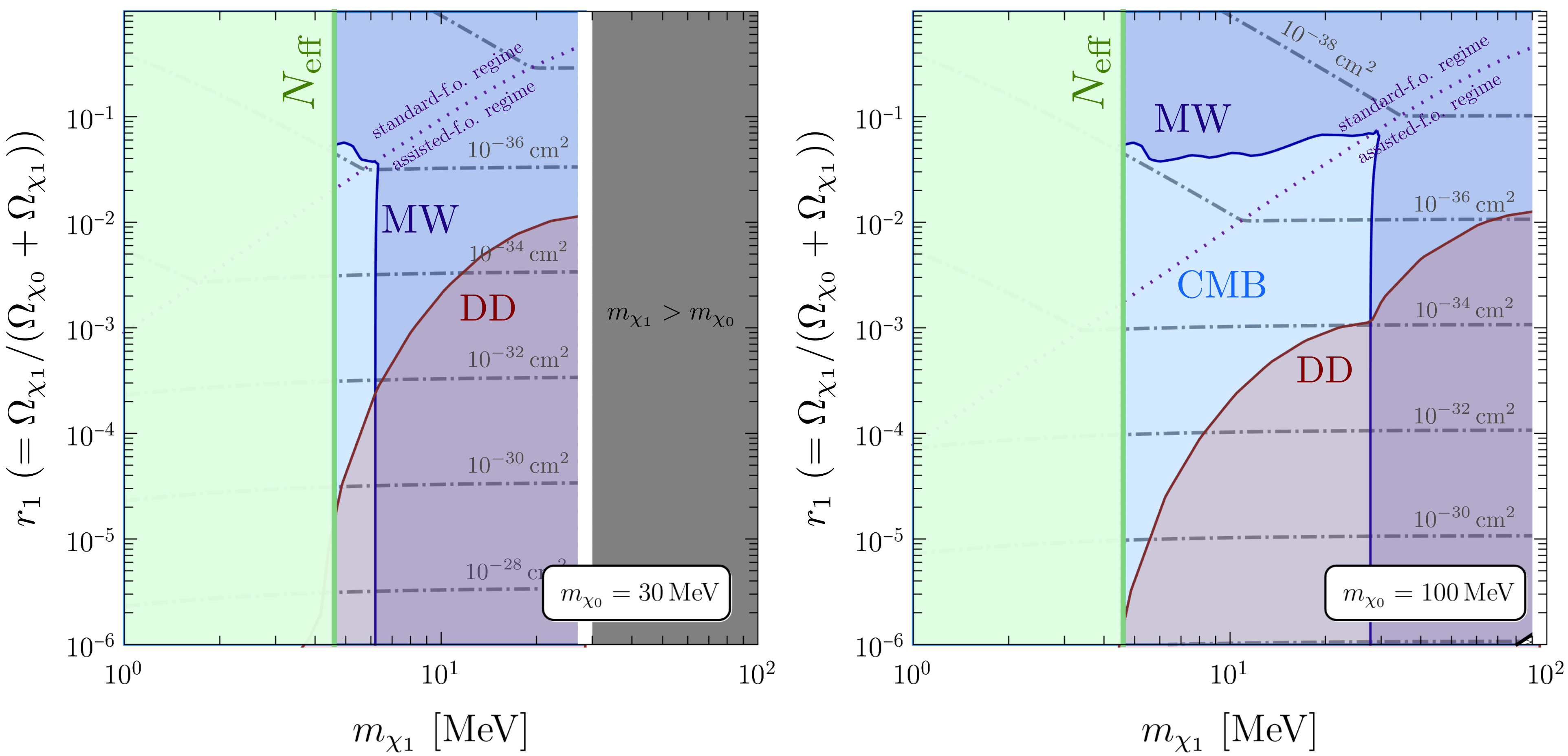
Effects of χ_1 to various observables

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.

Effects of χ_1 to various observables

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

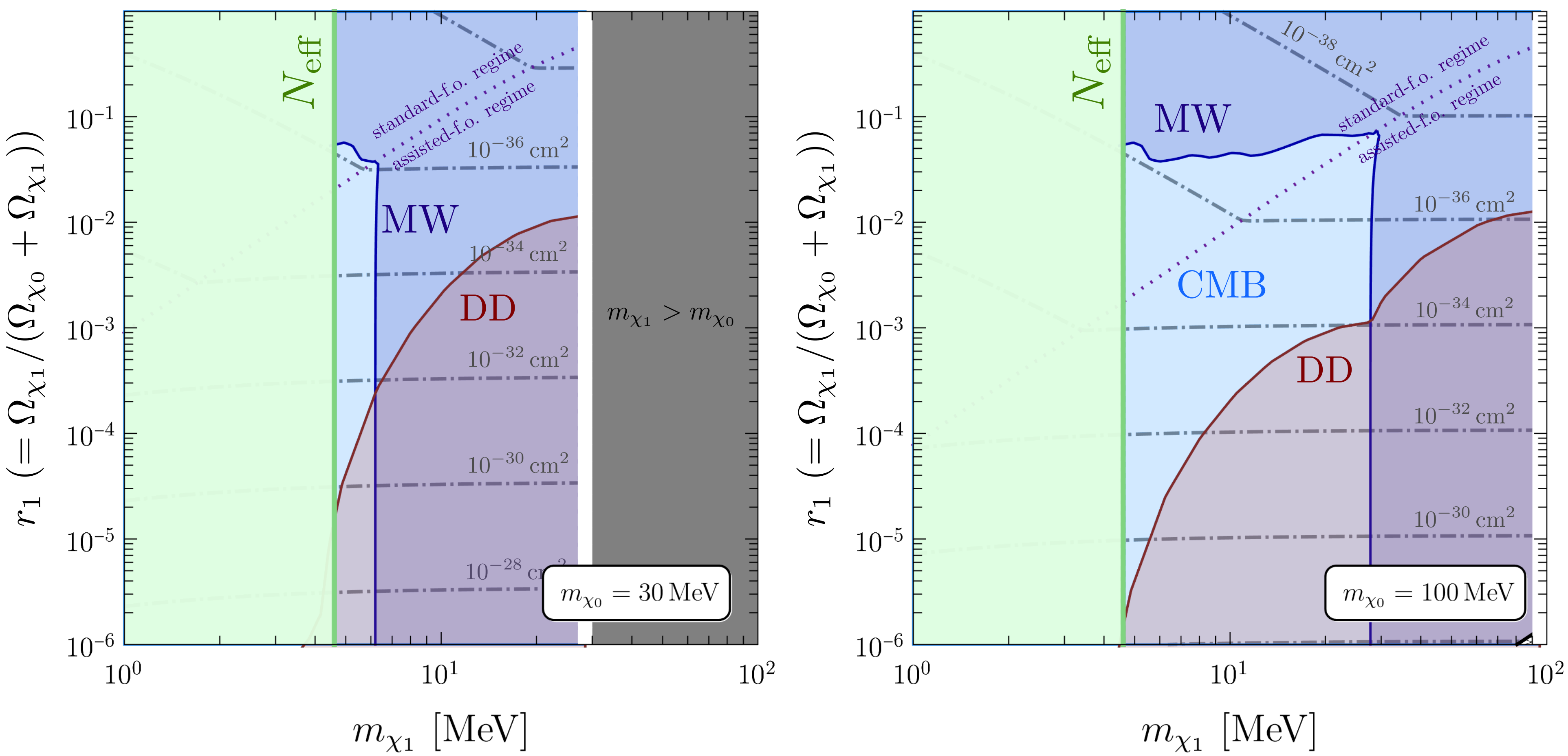


- The cosmo/astro bounds on light DM annihilations are very stringent because of the enhanced number density.

- Conventionally, the existence of sub-component $\chi_1\chi_1 \to$ SM like our structure has been naively thought as remedy because $n_{\chi_1}^2 \langle \sigma_1 v_{\rm rel} \rangle_{\rm standard} \sim r_1$

Effects of χ_1 to various observables

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



- In the assisted regime viable in a wide range of parameter space, however, this is not true since $n_{\chi_1}^2 (\sigma_1 v_{\rm rel})_{\rm s} \sim r_1^2 \cdot \frac{1}{r_1^2} = \text{no } r_1$

- If the crossing symmetry is effective (χ_1 - e), various DM direct detection experiments can have sensitivities to χ_1.

Effects of χ_1 to various observables

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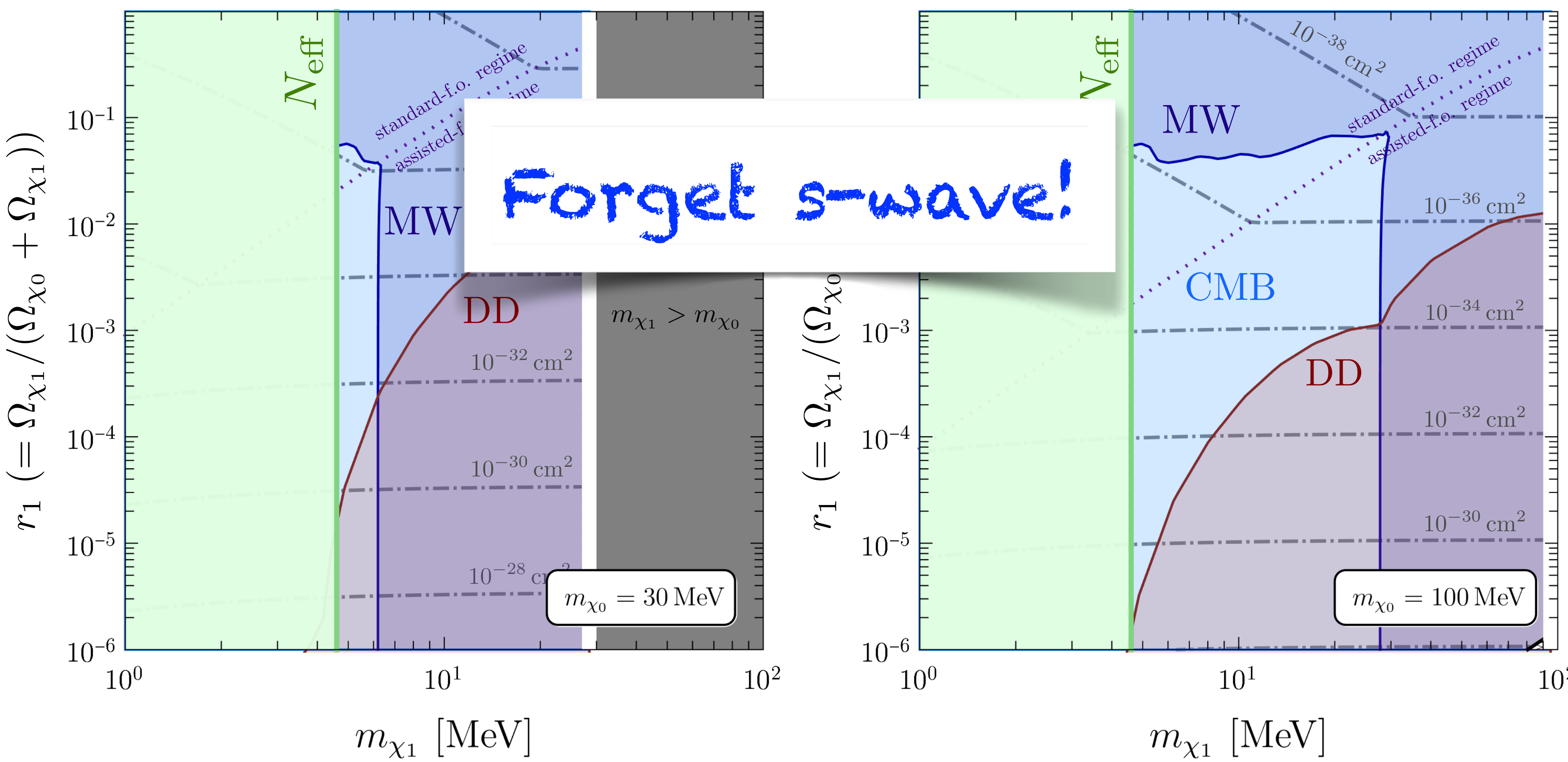

- In the assisted regime viable in a wide range of parameter space, however, this is not true since $n^2_{\chi_1}(\sigma_1 v_{\rm rel})_{\rm s} \sim r_1^2 \cdot \frac{1}{r_1^2} = \text{no } r_1$

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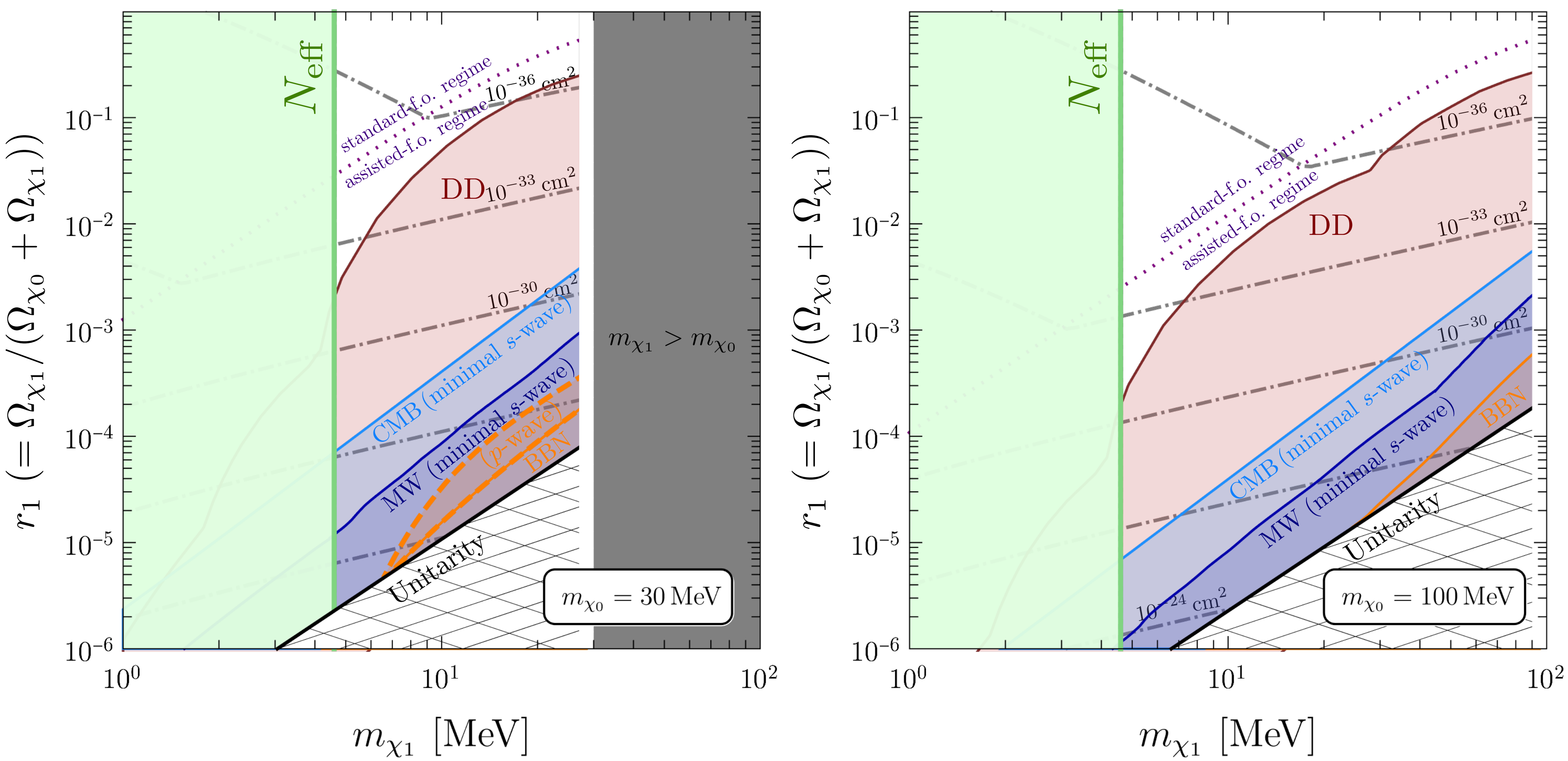
Effects of χ_1 to various observables

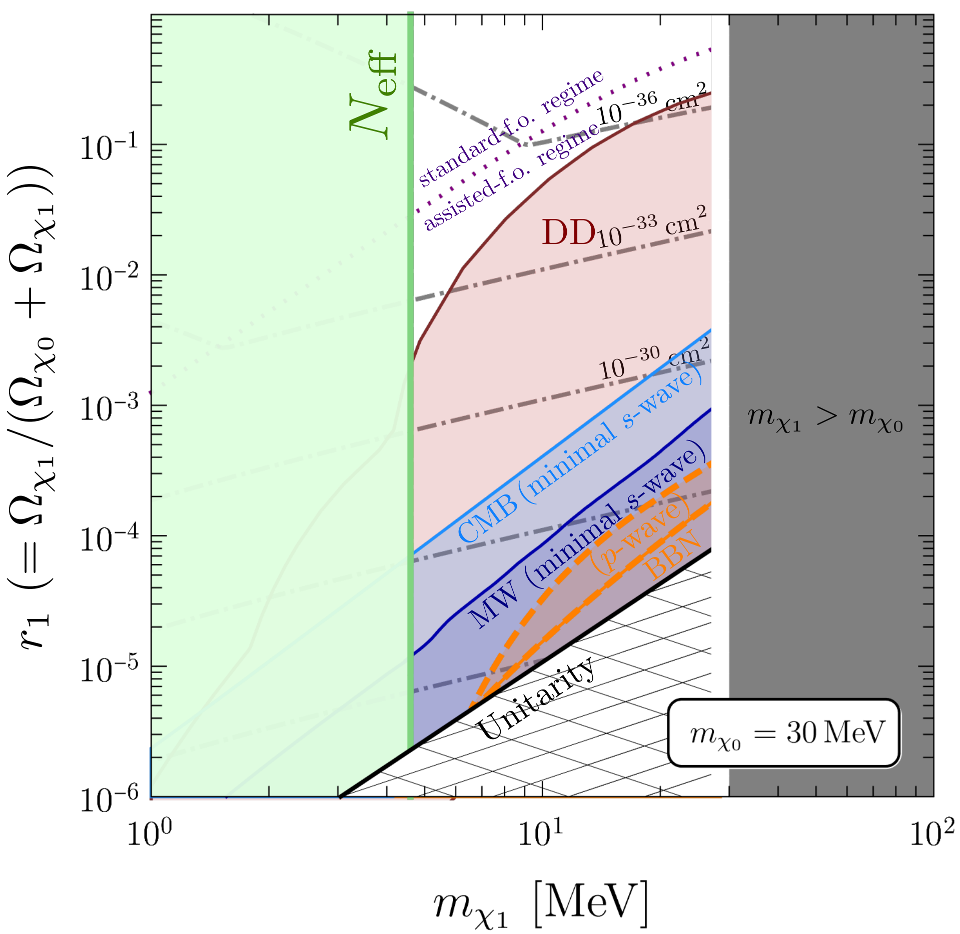
When $\chi_1\chi_1 \rightarrow$ SM is dominated by p-wave

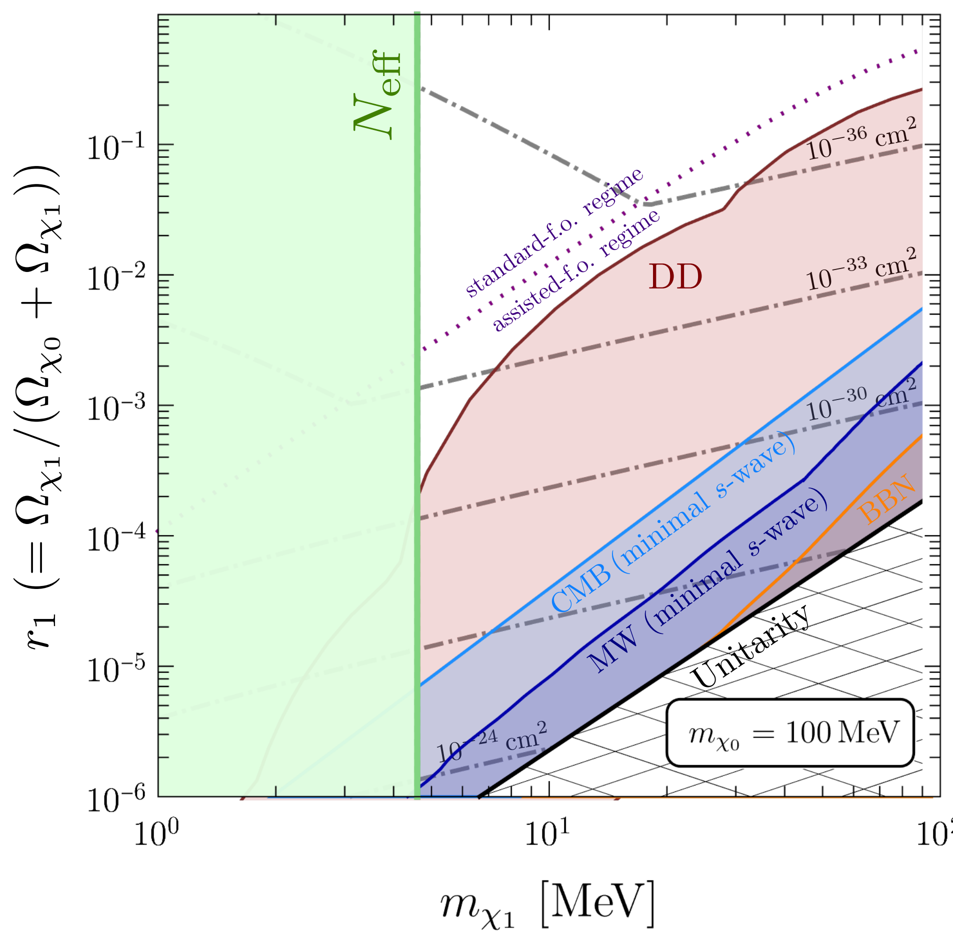


- Robustly constrained by $N_{\rm eff}$ & the DM direct detection (assuming crossing symmetry) bounds enter for small r_1.

Effects of χ_1 to various observables

When $\chi_1\chi_1 \to$ SM is dominated by p-wave

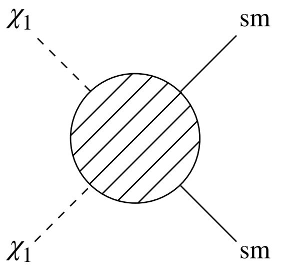


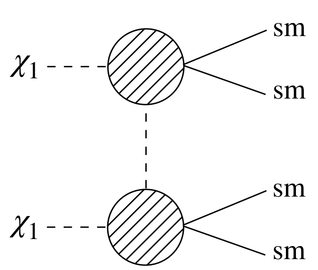


- Robustly constrained by N_{eff} & the DM direct detection (assuming crossing symmetry) bounds enter for small r_1.

- The 4-body s-wave can be dominant over the p-wave in later time (minimal s-wave).

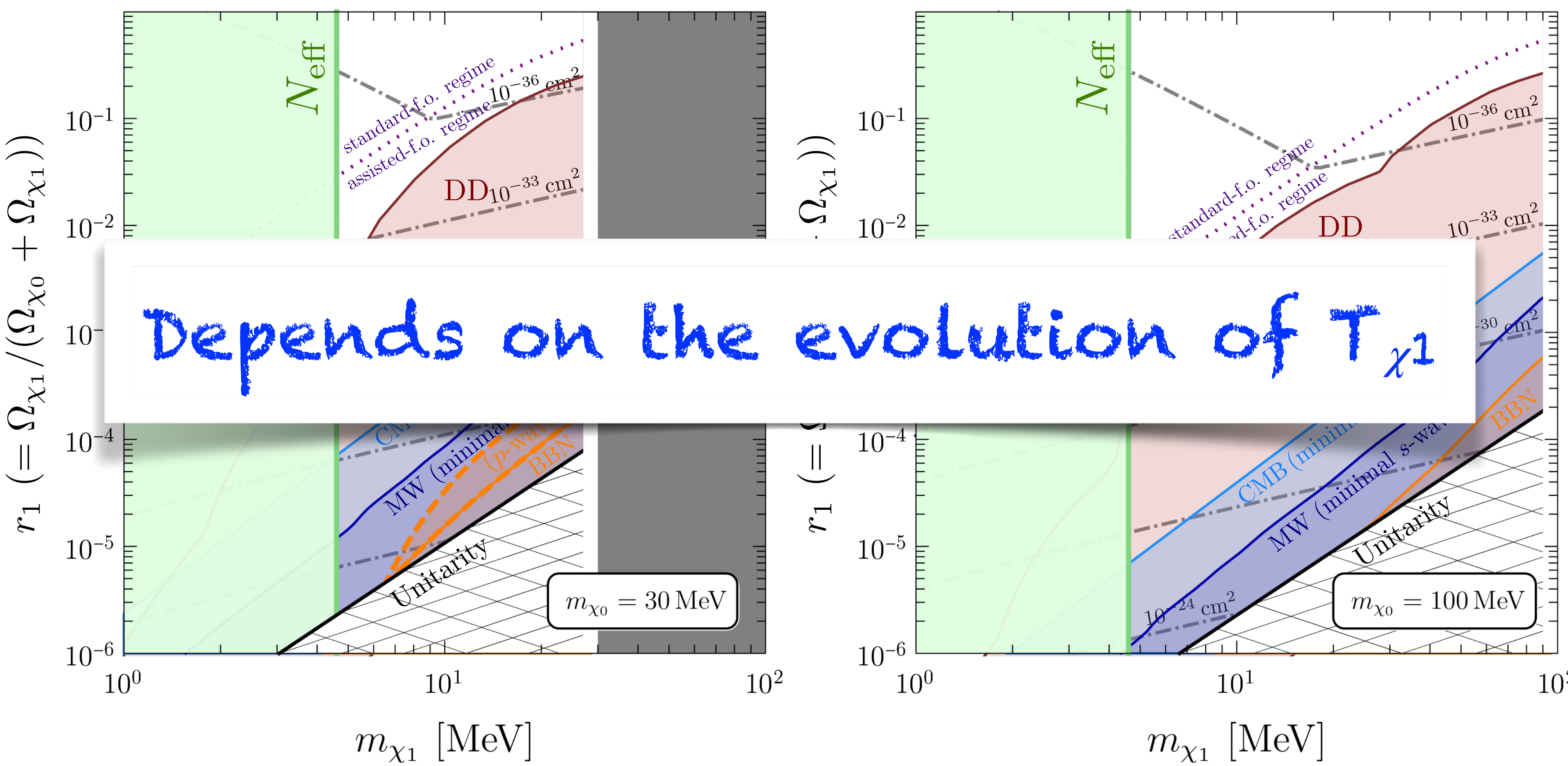
$$(\sigma v_s) \propto \frac{1}{r_1^2} \text{ for } r_1 \ll 1$$





Effects of χ_1 to various observables

When $\chi_1\chi_1 \to$ SM is dominated by p-wave



Depends on the evolution of $T_{\chi 1}$

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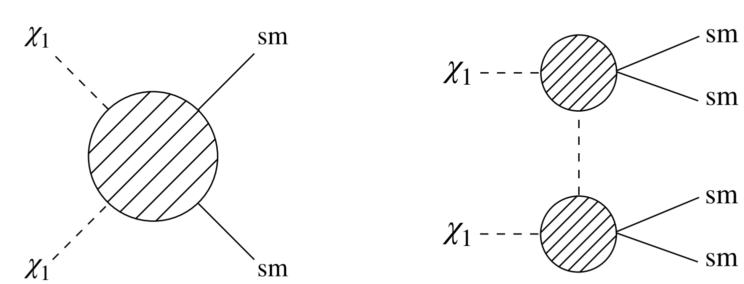

Self-heating of χ_1

- 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).

- Self-interaction of a subdominant DM χ_1 can be large for the $O(1)$ dark sector coupling.

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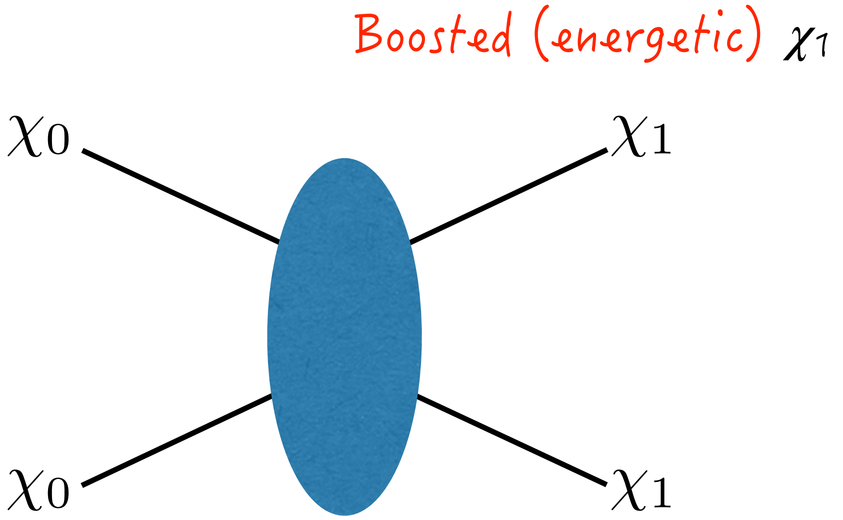

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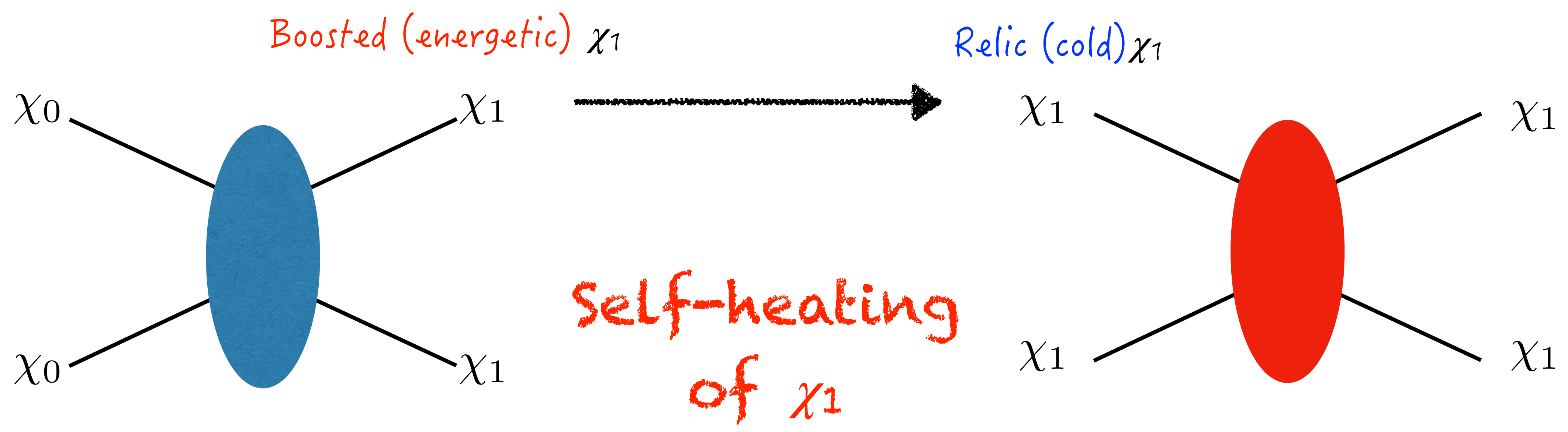

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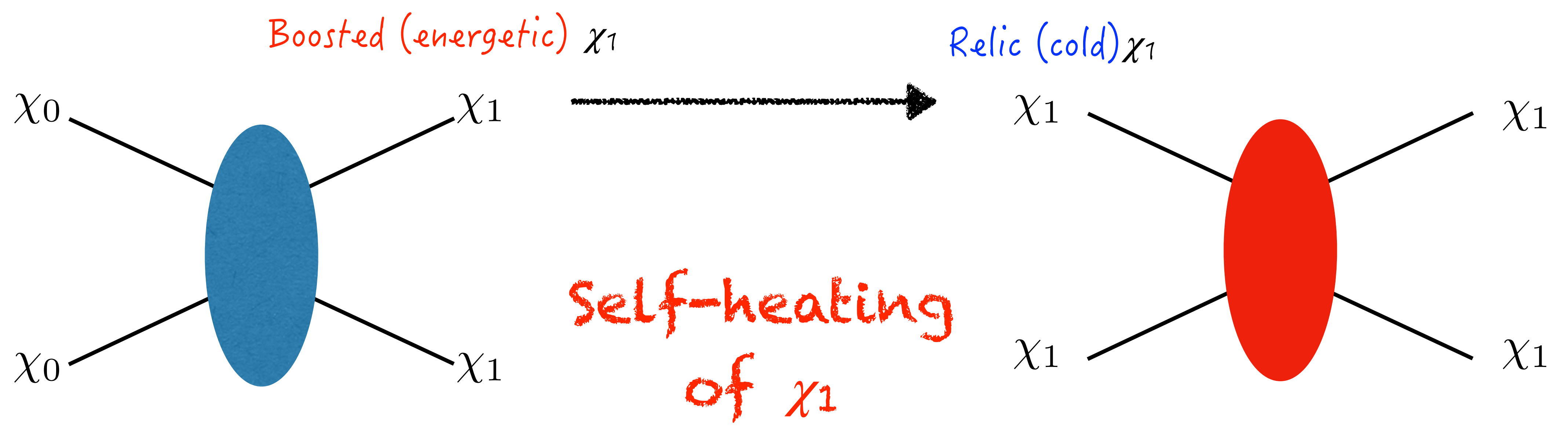
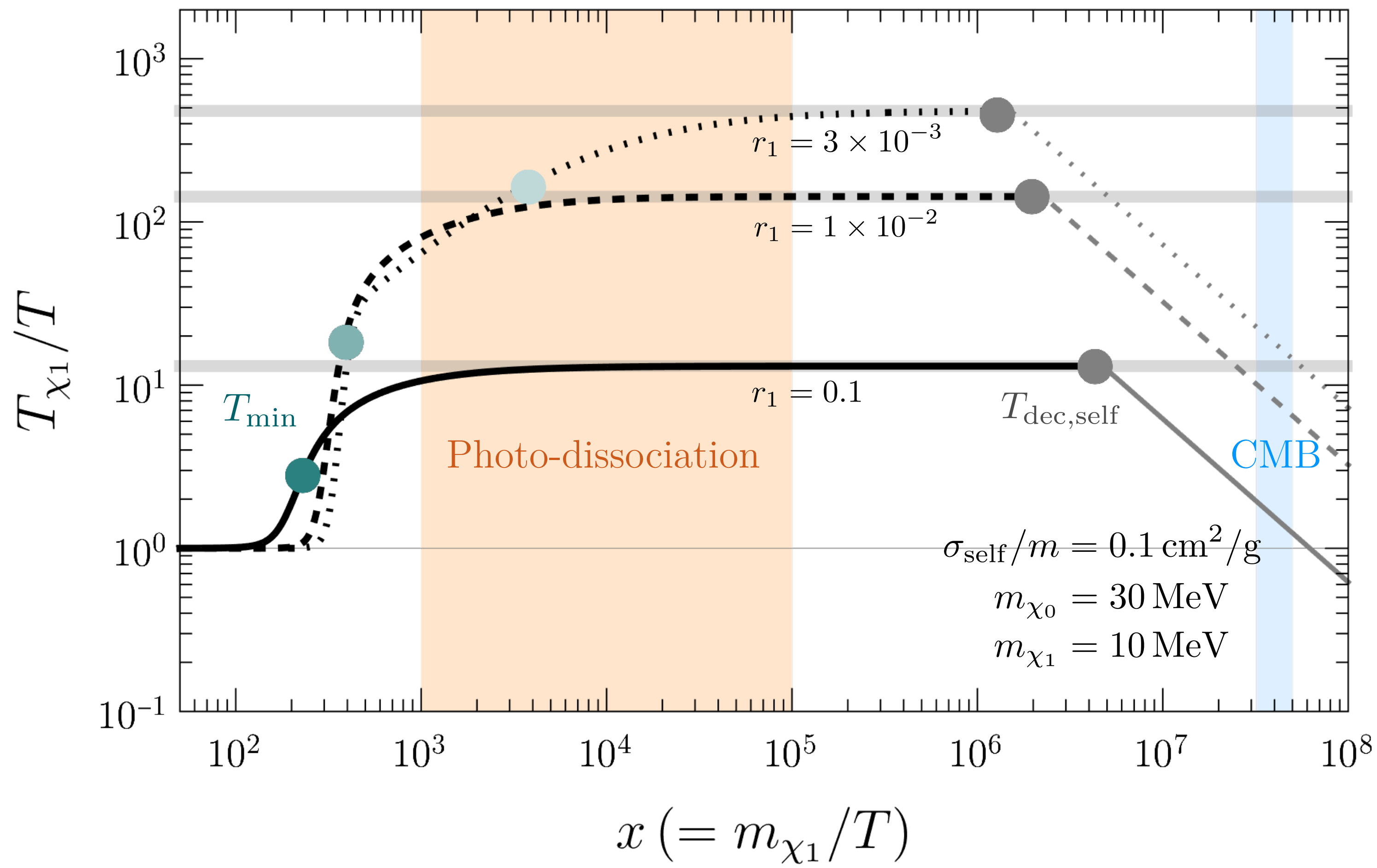


Kamada, Kim, Kim, Sekiguchi, PRL 2018

Chu, Garcia-Cely, JCAP 2018

Vogelsberger, Zavala, Schutz, Slatyer, MNRAS 2018

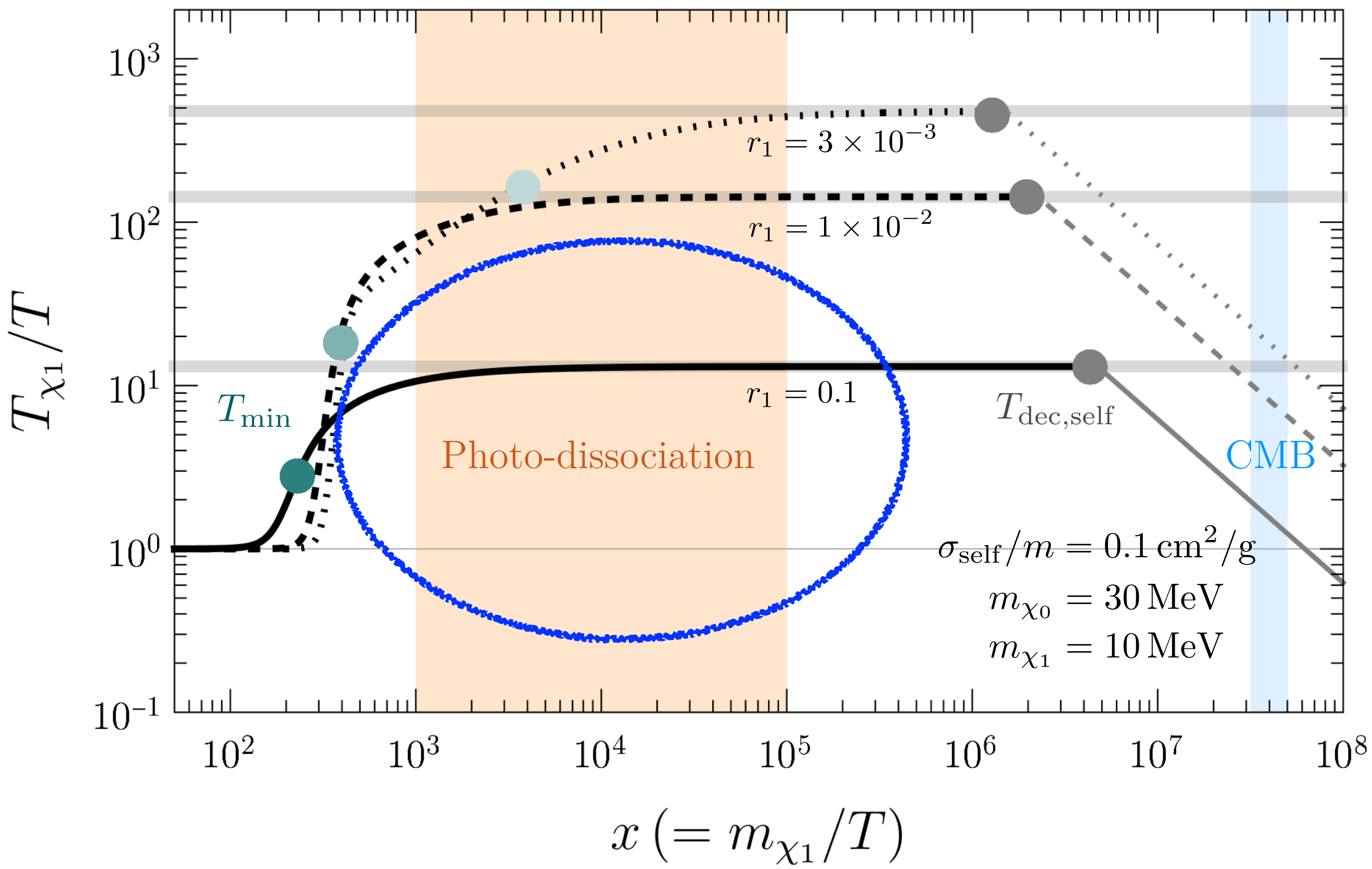
Temperature evolution of χ_1



- If self-heating is efficient even after the kinetic decoupling, the temperature evolution of χ_1 shows an interesting dynamics.
- The effect increases as $1/r_1$ & the strength of the self-interaction.

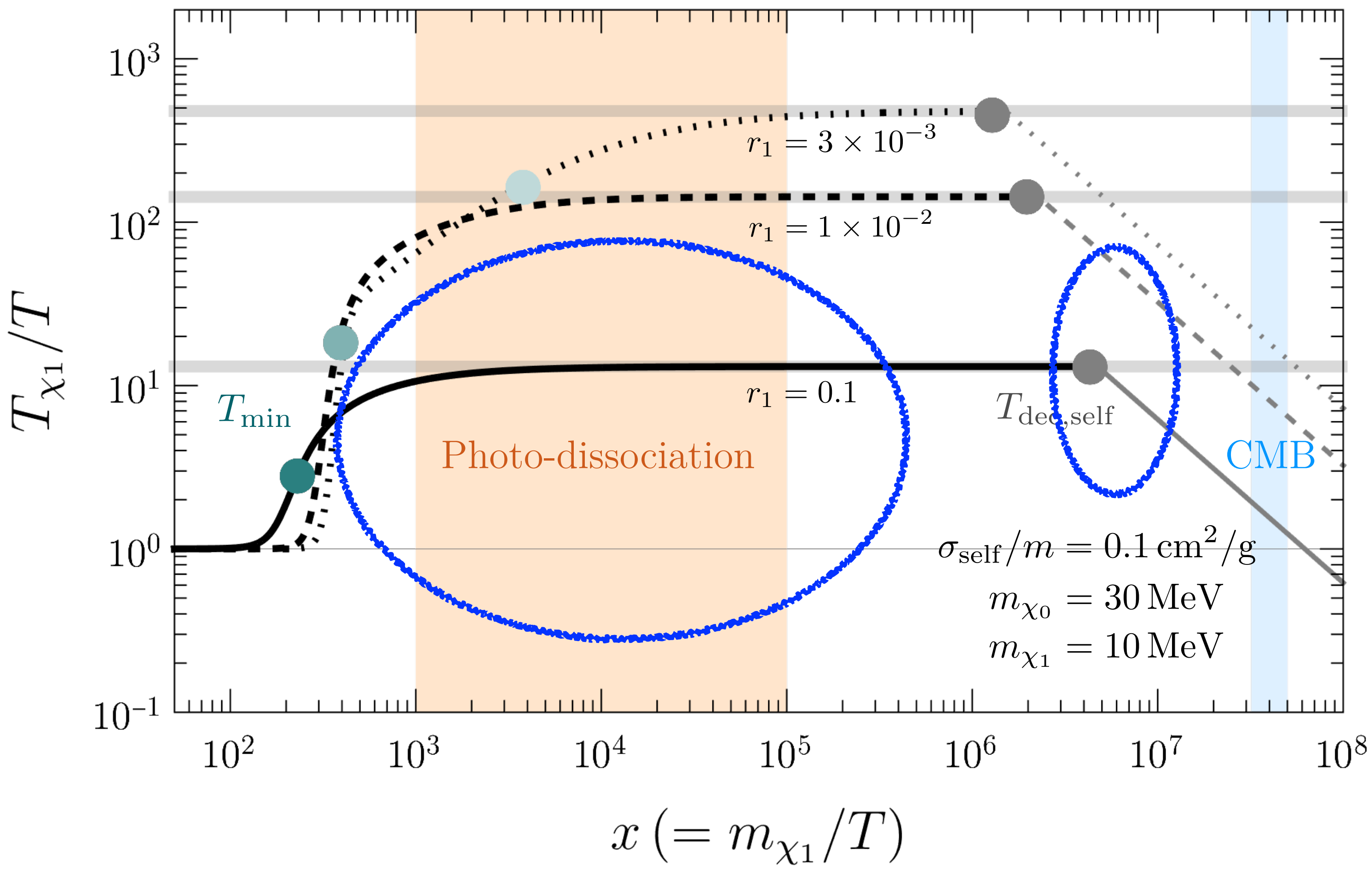
$$T_{\rm dec,self} \simeq \frac{m_e}{20} \left(\frac{m_{\chi_1}}{100\,{\rm MeV}}\right)^{1/3} \left(\frac{0.1}{r_1}\right)^{2/3} \left(\frac{10^{-6}\,{\rm cm^2/g}}{\sigma_{\rm self}/m}\right)^{2/3}$$

Temperature evolution of χ_1



- The photo-dissociation bounds become severer.

Temperature evolution of χ_1



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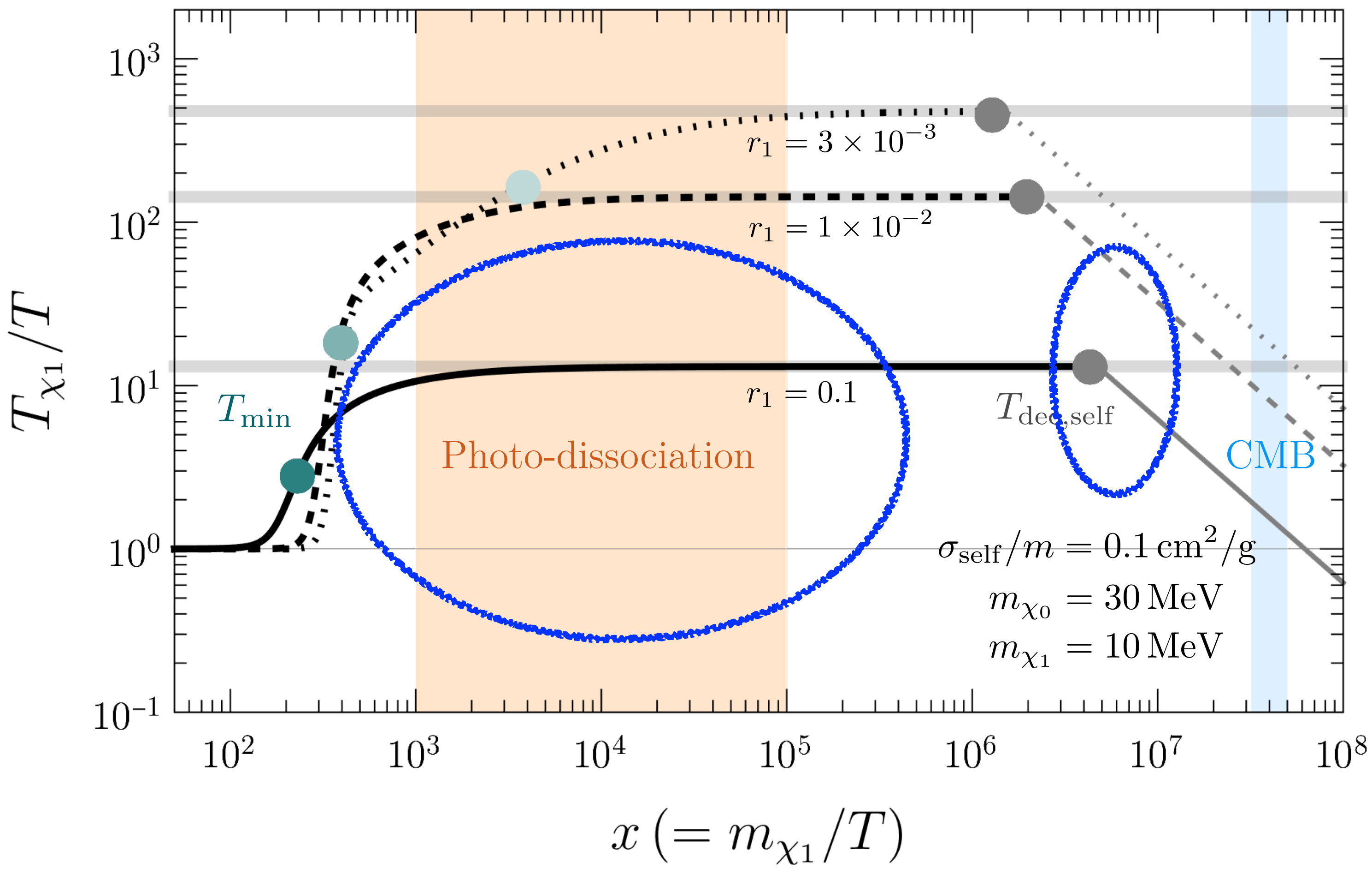

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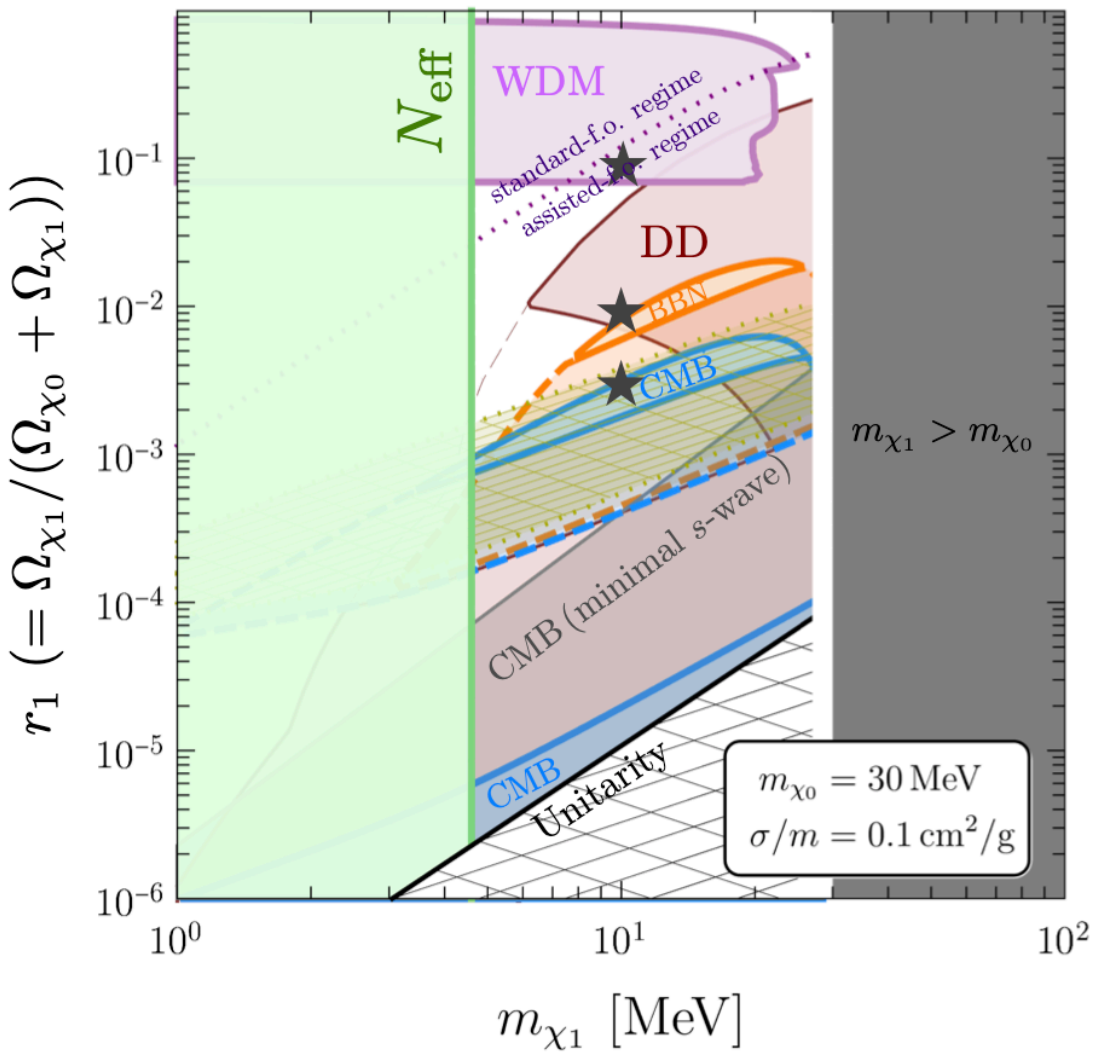
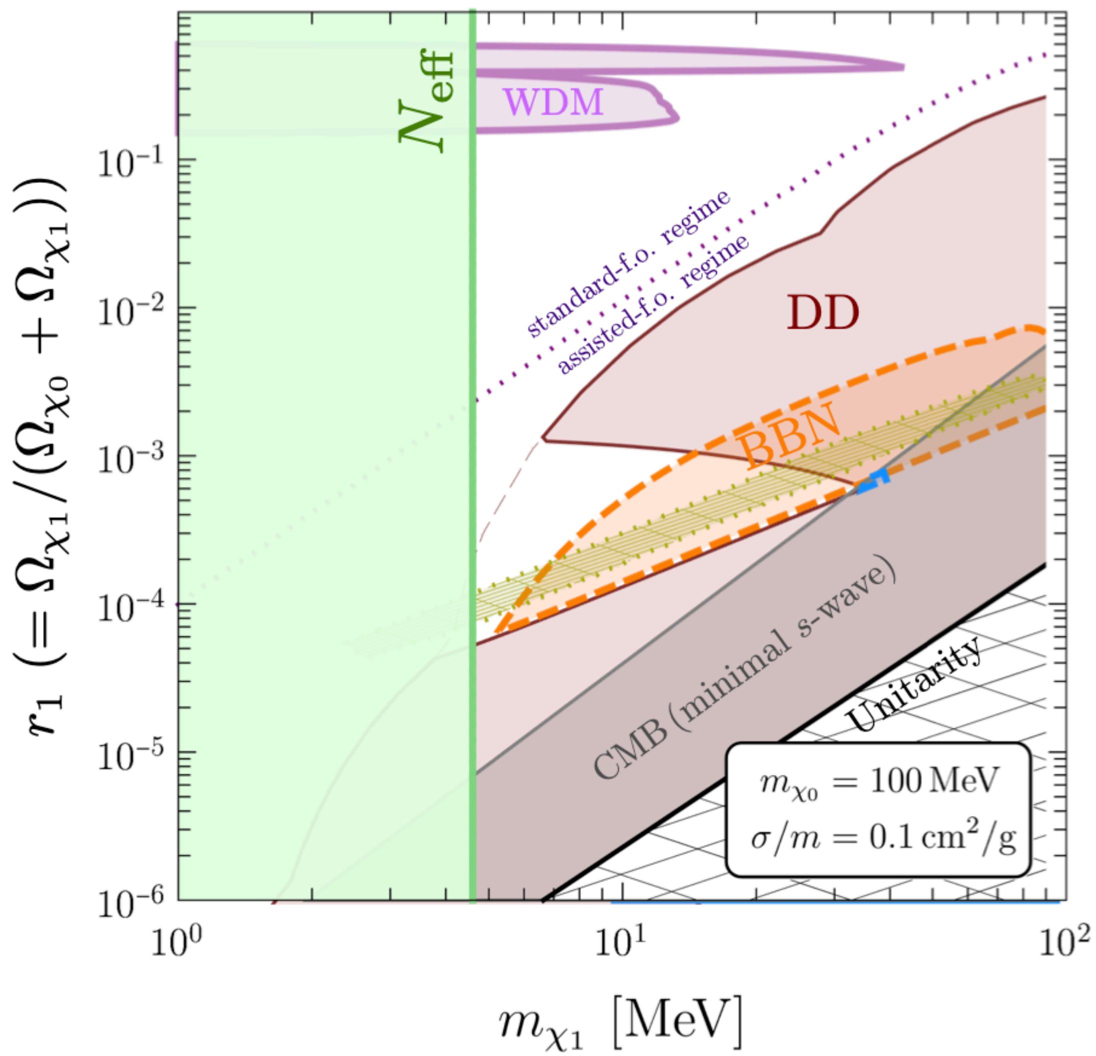
χ_1 can be sub-GeV Warm Dark Matter!!

Lyman-α

# of satellites

New bounds due to self-heating

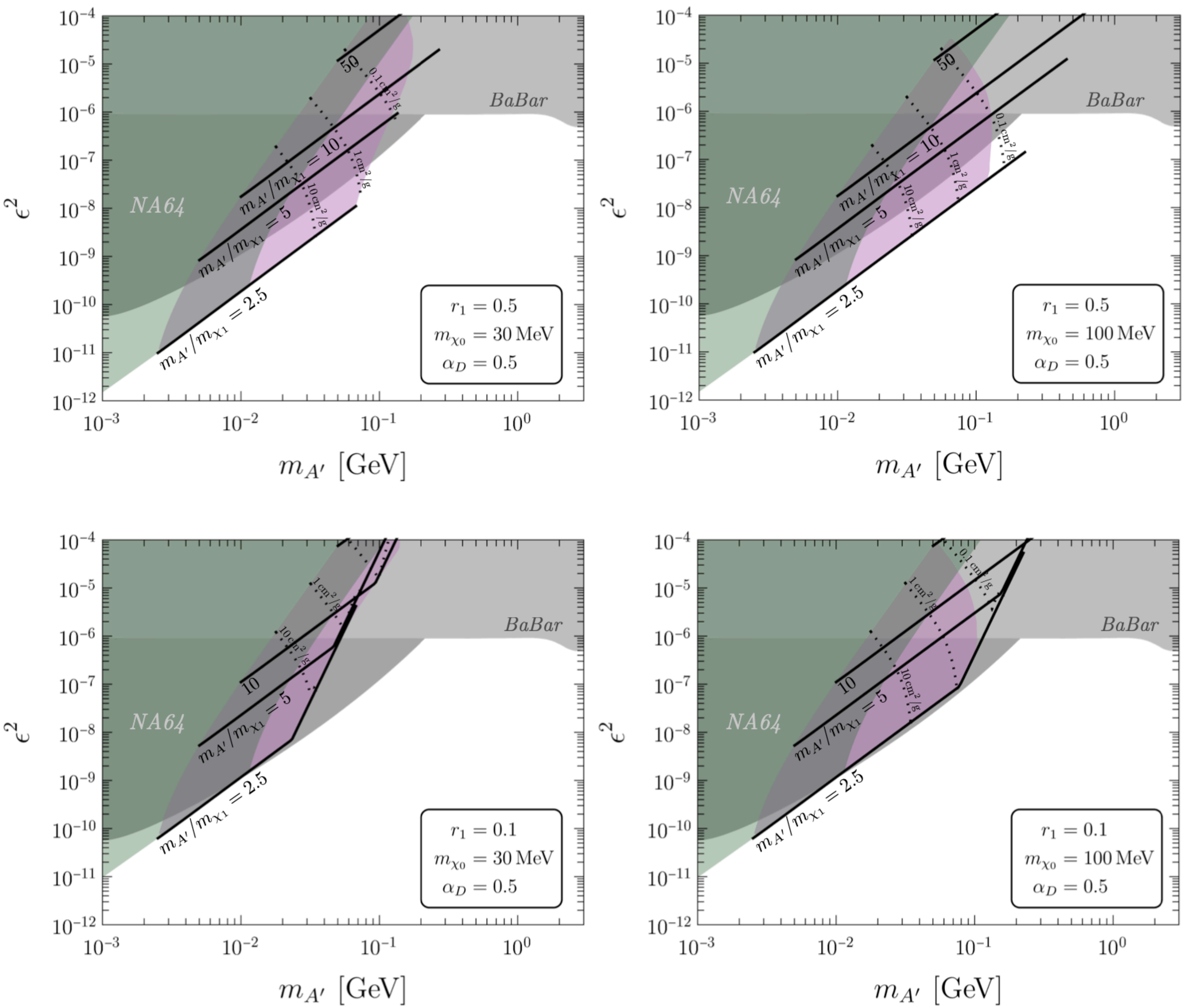




- WDM constraint enters when $r_1 \gtrsim 0.07$ even for $m_{\chi 1} \sim 40$ MeV.
- ★: reference values of r_1 in the temperature evolution (previous slide)
- Direct detection bounds get weaken because of its warmness.

Complementary searches

Light DM can be produced in accelerators!



- Reference model: singlet scalar DM + dark photon
- Green: N_{eff}, Pink: WDM for $r_1 \gtrsim 0.1$.
- For $r_1 \lesssim 0.1$, not preferred by the accelerator results.
- Future discovery can tell the dark sector details.

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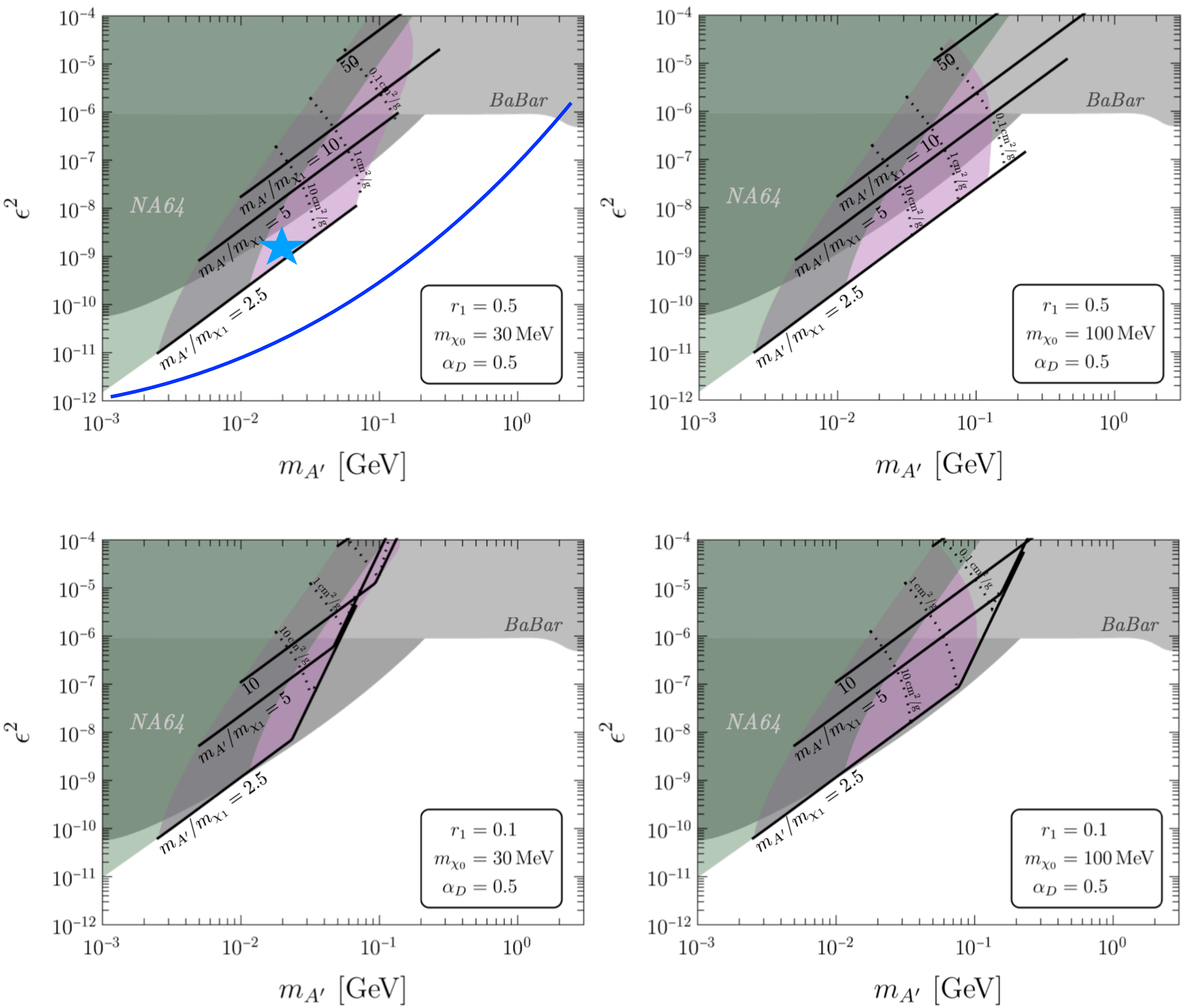

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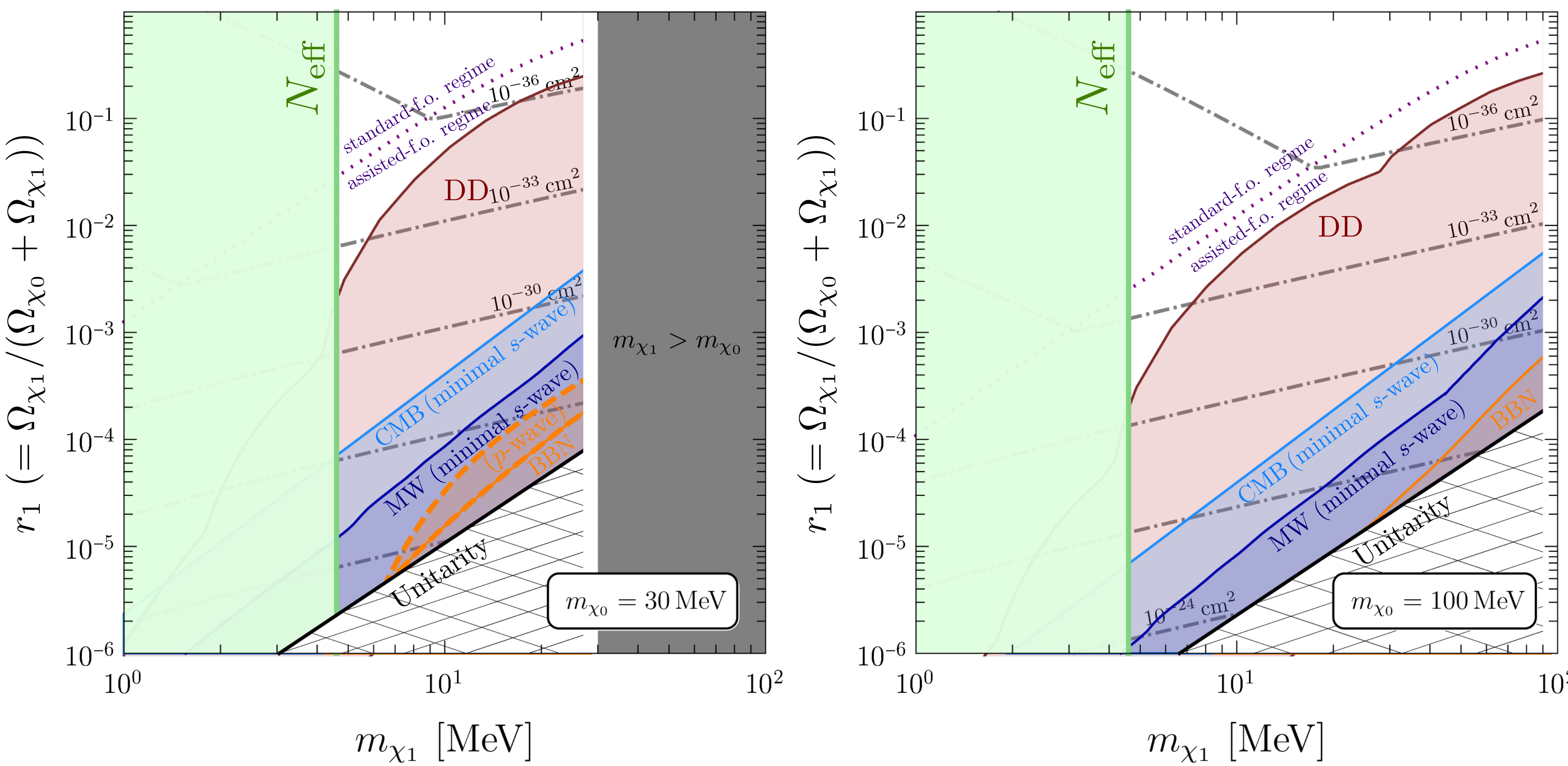
Conclusions

- 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 sub-component can affect the structure formation and be a sub-GeV mass Warm Dark Matter (heavy WDM) for $r_1 \gtrsim 0.1$!
- Complementary searches in accelerators are possible (disfavor $r_1 \lesssim 0.1$)

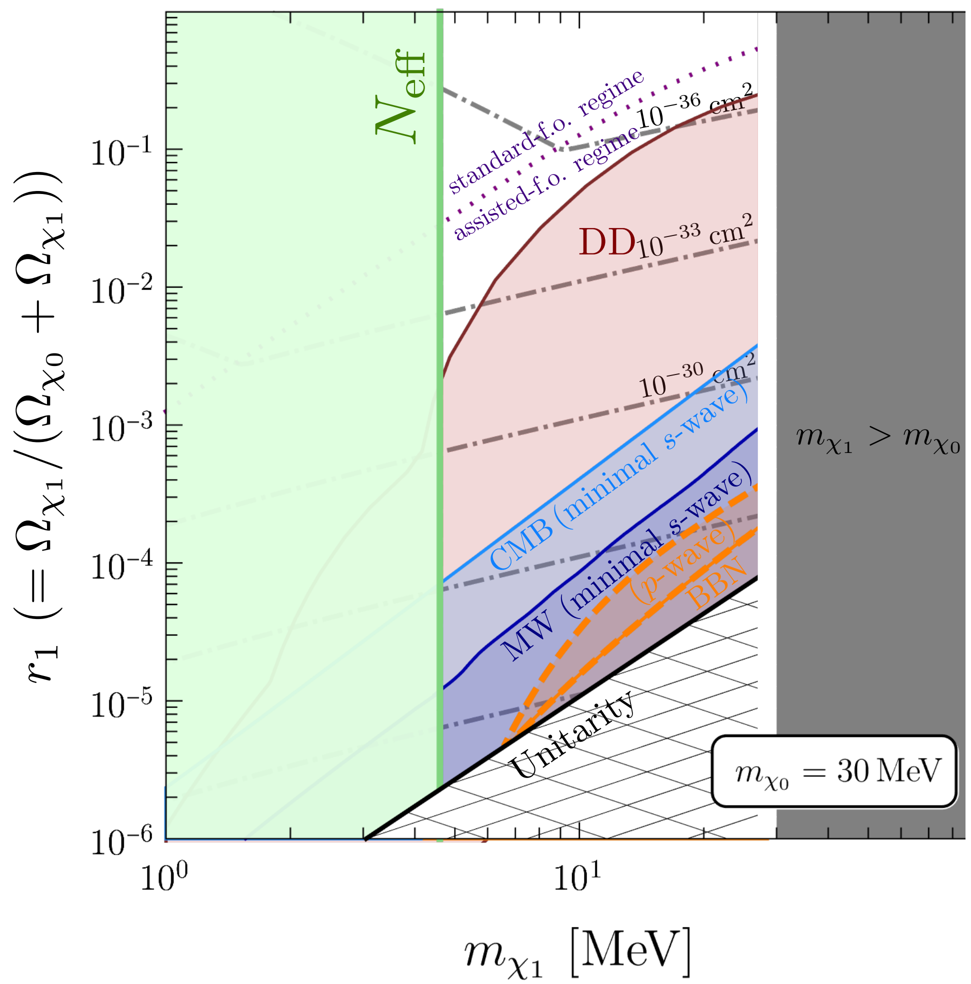
Backup

When $\chi_1\chi_1 \to$ SM is dominated by p-wave

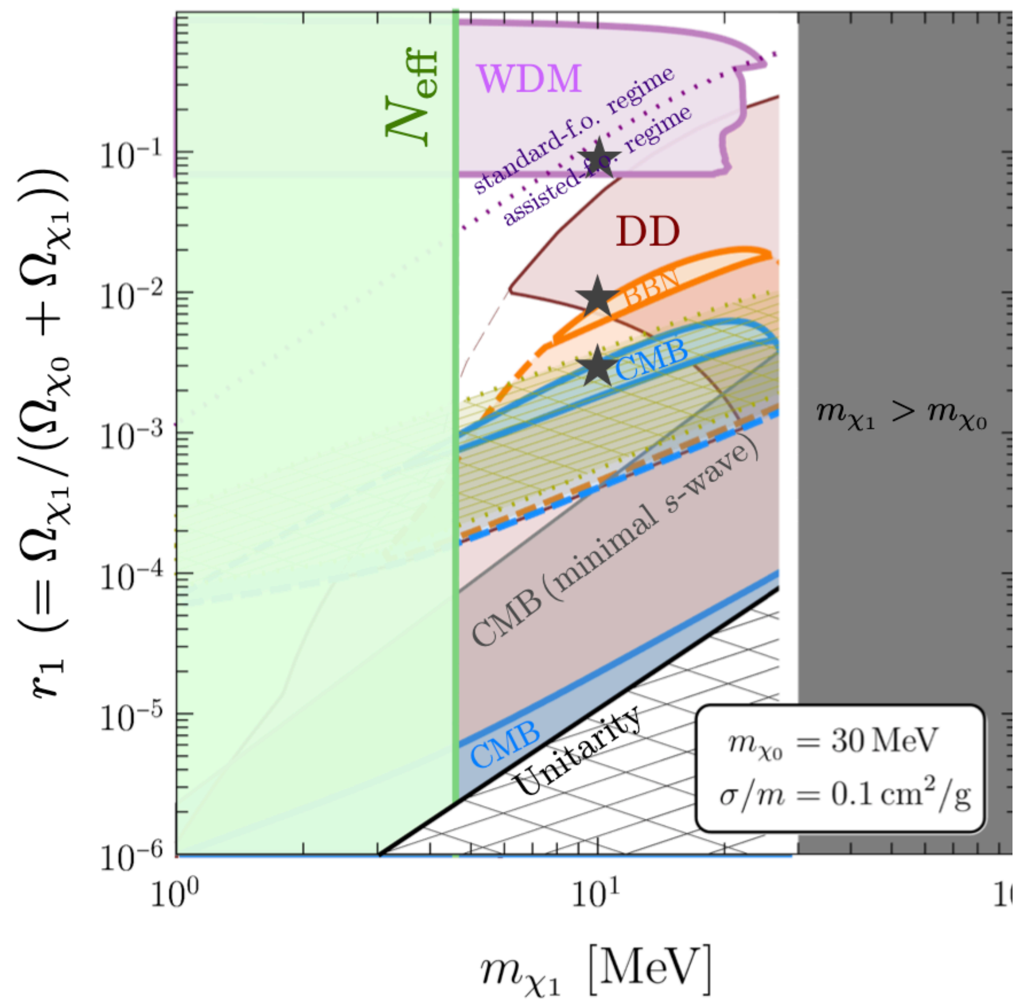


- In the assisted regime, the kinetic decoupling can occur after the freeze-out of $\chi_1\chi_1 \to e^+e^-$: photo-dissociation if 100 eV ≲ T_{kd} ≲ 10 keV after BBN.

Backup



$N_{\rm eff}$
standard-f.o. regime
assisted-f.o. regime
10^{-36} cm^2
DD
10^{-33} cm^2
10^{-30} cm^2
CMB (minimal s-wave)
MW (minimal s-wave)
(p-wave)
BBN
Unitarity
$m_{\chi_0} = 30\,\rm MeV$
$m_{\chi_1} > m_{\chi_0}$
$r_1\ (= \Omega_{\chi_1}/(\Omega_{\chi_0} + \Omega_{\chi_1}))$
m_{χ_1} [MeV]



$N_{\rm eff}$
WDM
standard-f.o. regime
assisted-f.o. regime
DD
BBN
CMB
CMB (minimal s-wave)
CMB
Unitarity
$m_{\chi_0} = 30\,\rm MeV$
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m_{χ_1} [MeV]