Manifesting hidden dynamics of a sub-component dark matter

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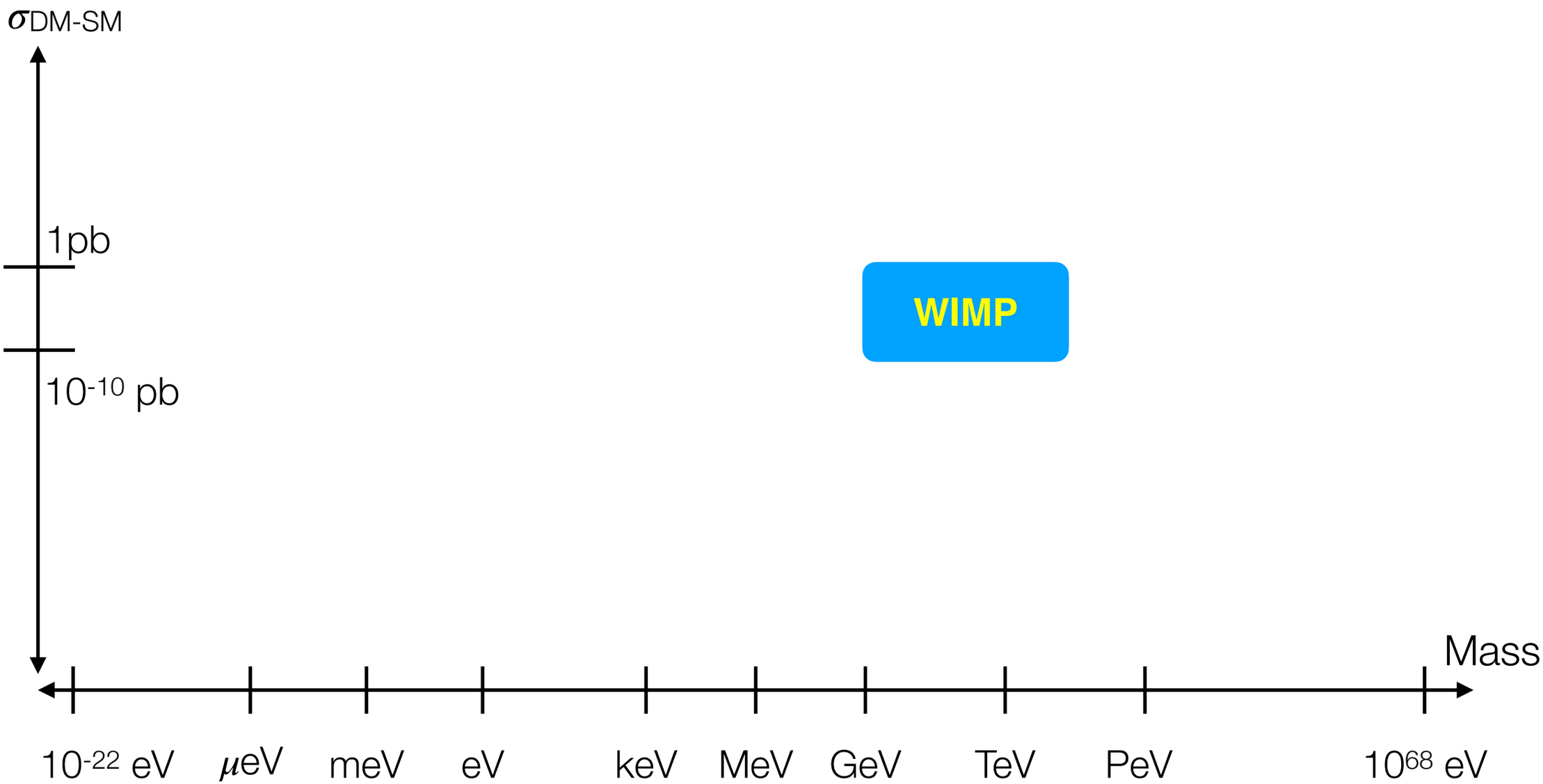
Ayuki Kamada, Hee Jung Kim, Jong-Chul Park, **SS**, JCAP 10, 052 (2022), arXiv: 2111.06808

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

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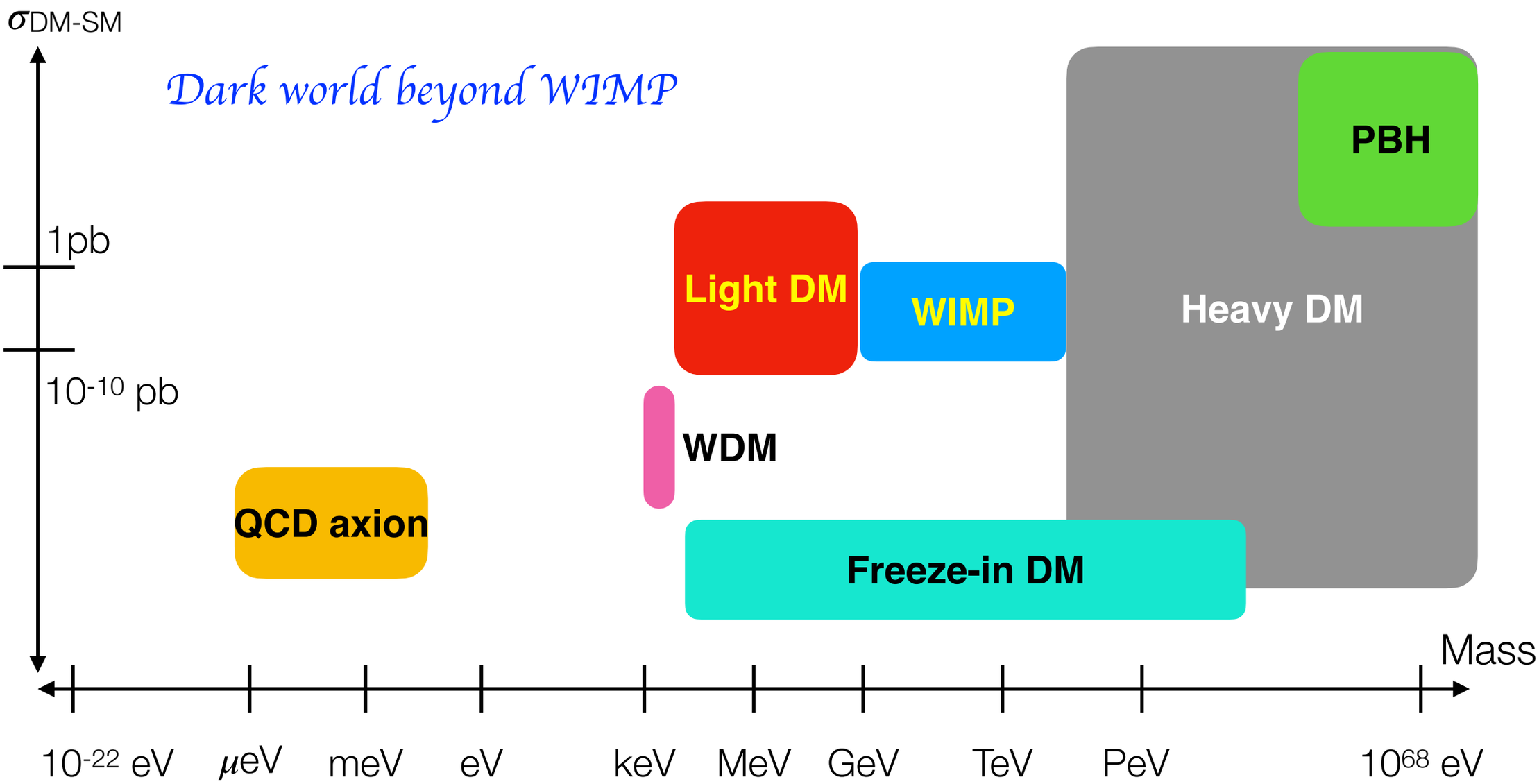

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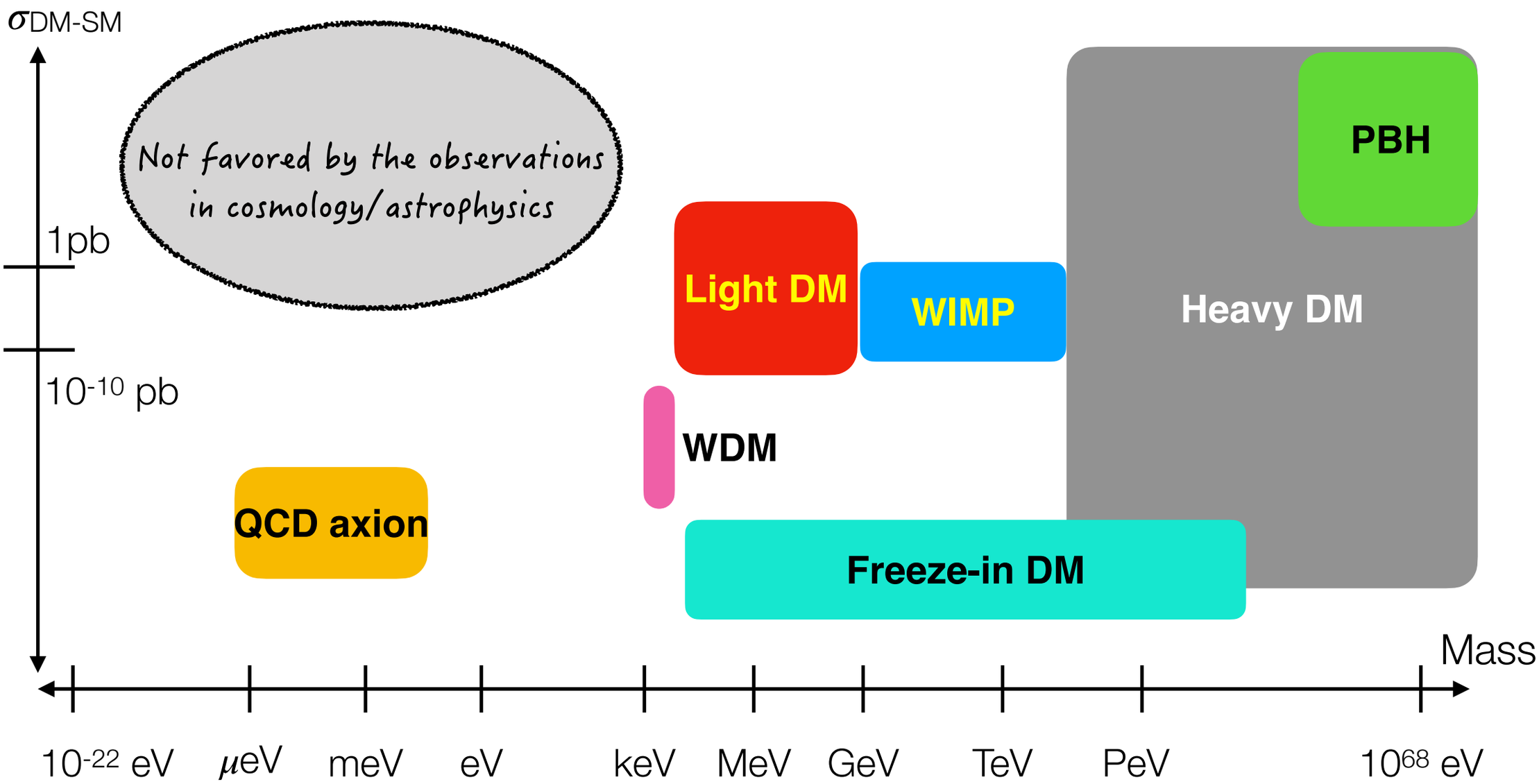

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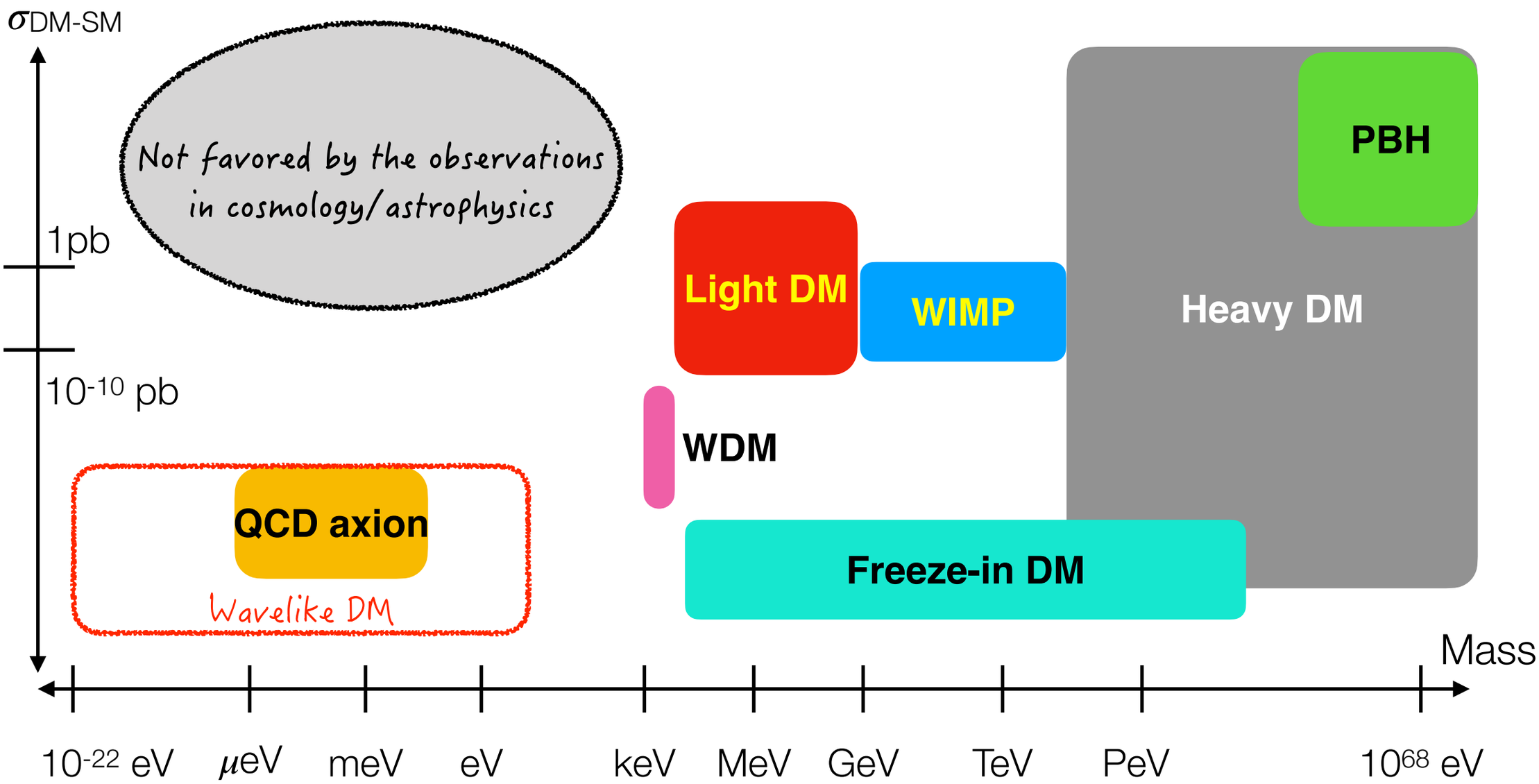
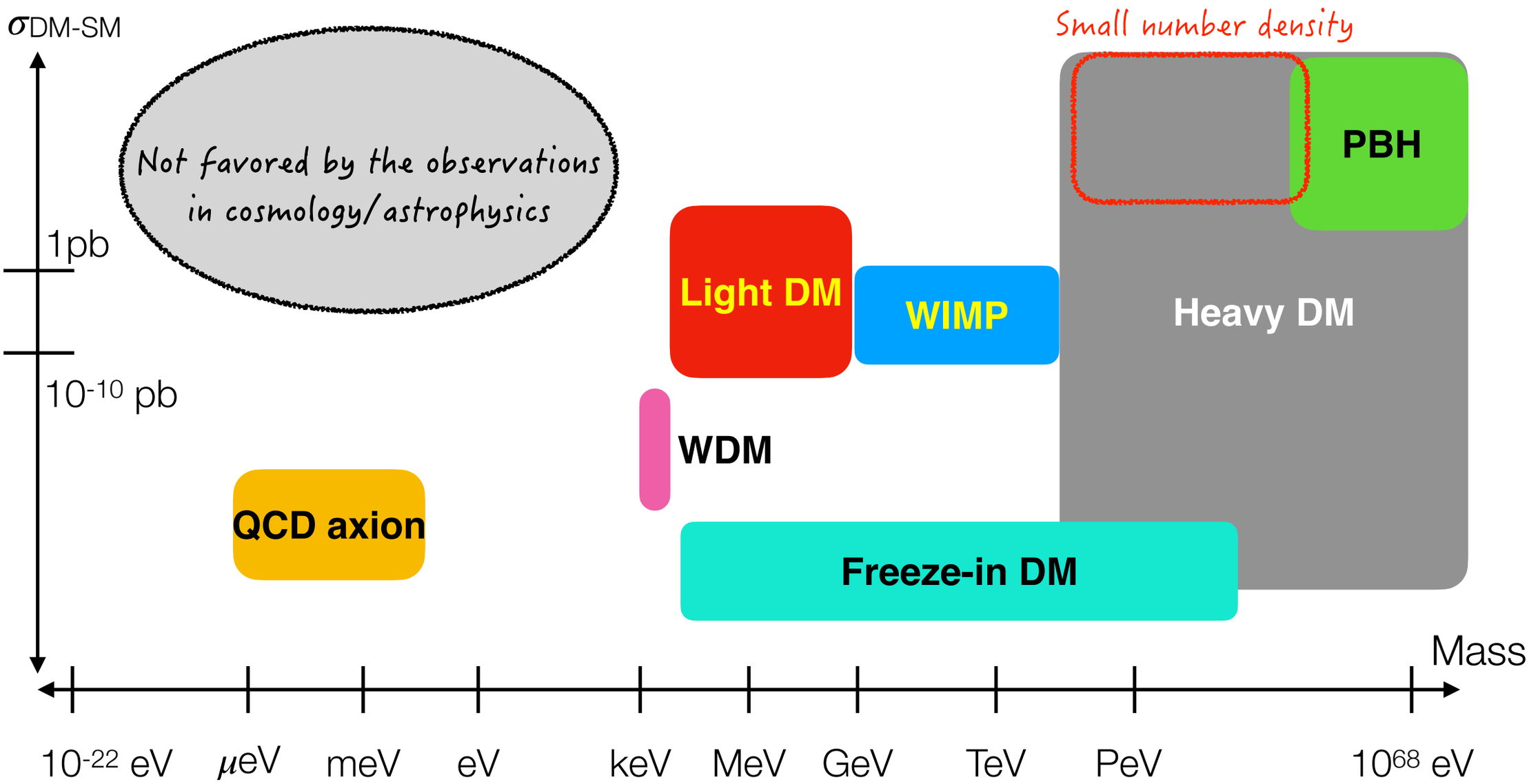


- Wavelike DM: occupation number is large so that the particles are described by classical waves, e.g., axion or ALP

- Experimental probes: axion or ALP search experiments

See also Ann. Rev. Nucl. Part. Sci. (2021) by Choi, Im, Shin

Dark world beyond WIMP

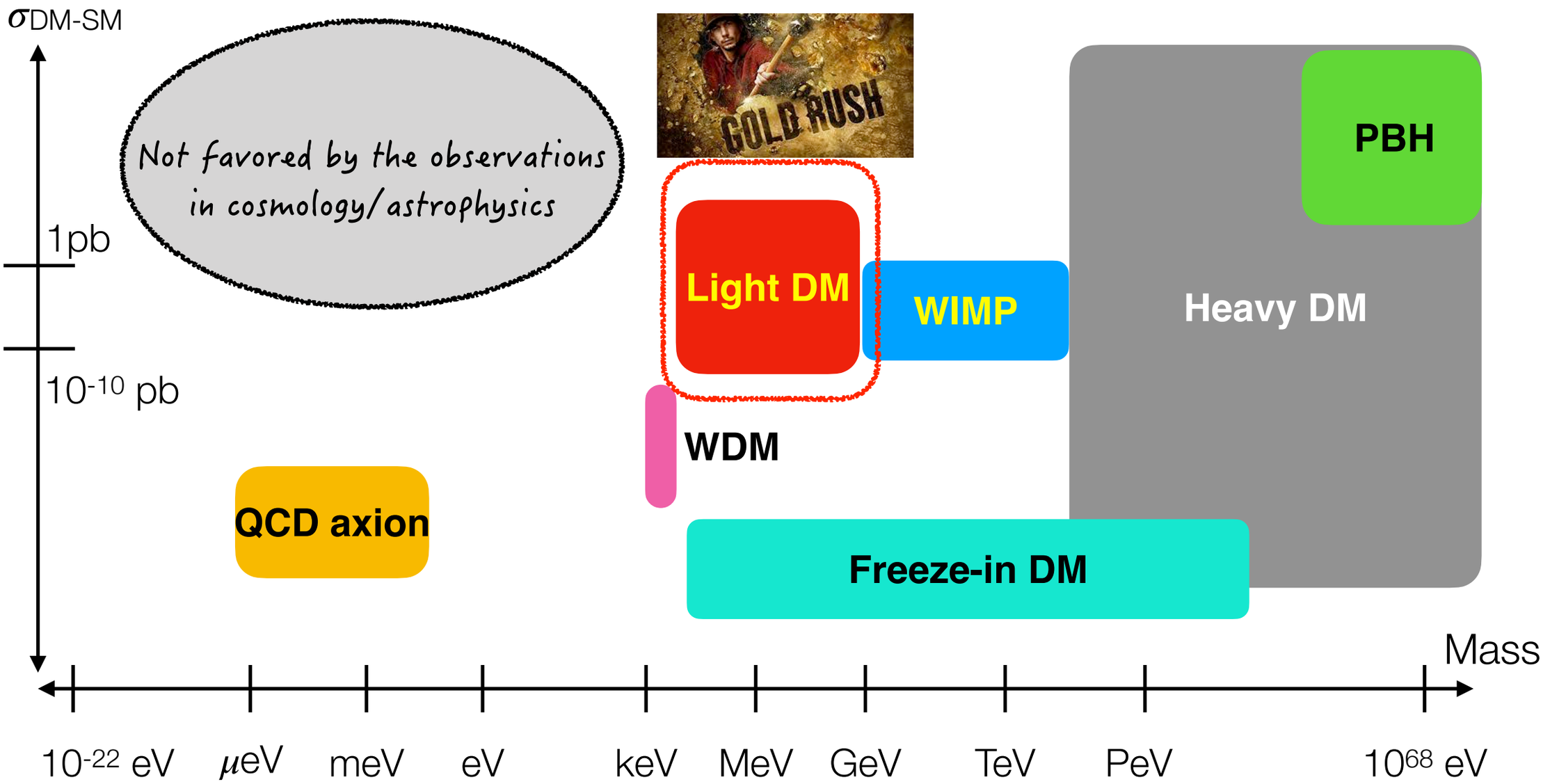


- Heavy DM (small n) with large $\sigma_{\text{DM-SM}}$: multiple scattering signals

  Bramante et al., PRD 2019, PRD 2018

- Primordial Black Hole: cosmo/astro observations

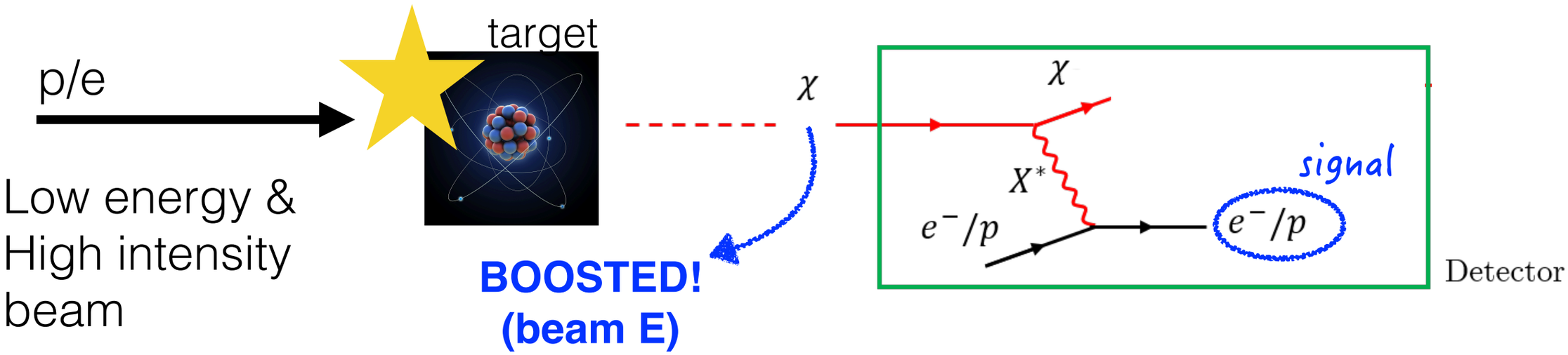
Dark world beyond WIMP



- Light CDM (keV ~ sub GeV): high intensity low energy accelerators, DM - e recoil, ν-experiments, B-factories long-lived particle searches, etc.

New ideas!

Example: intensity frontier



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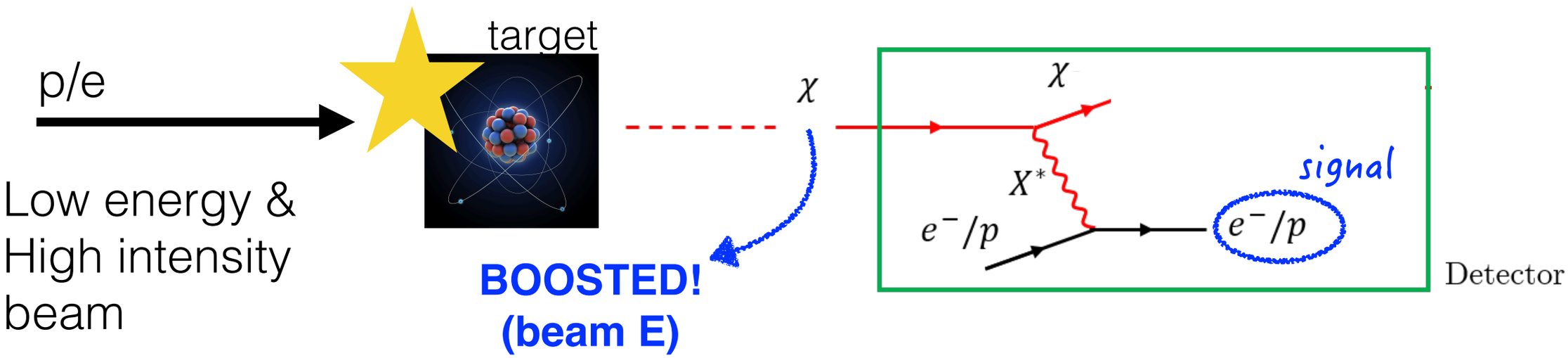
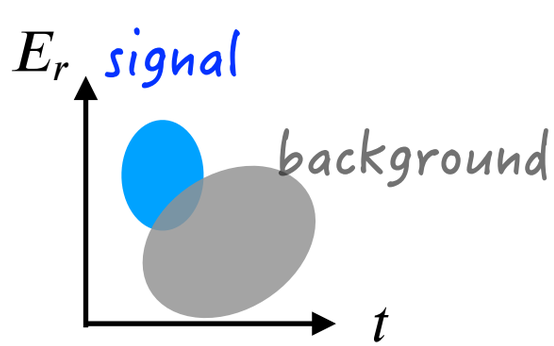


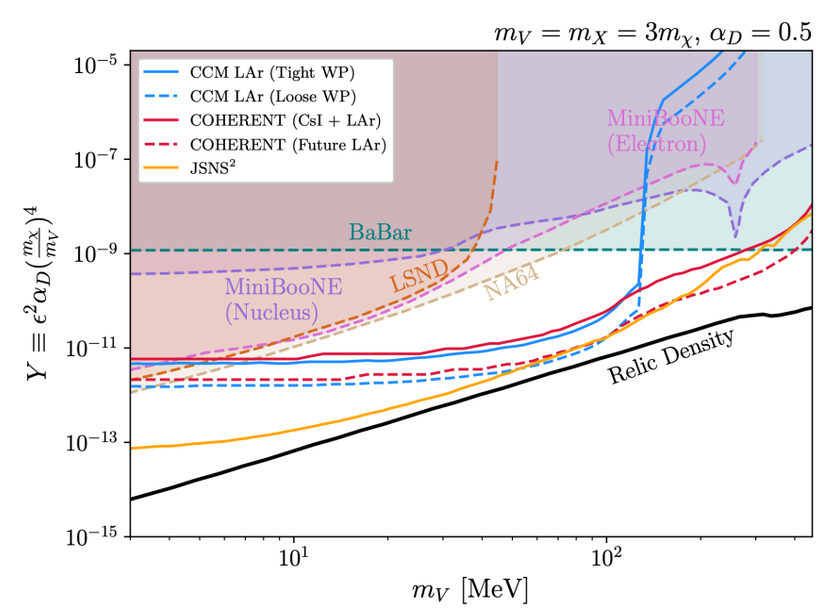
Pulsed beam with high intensity

- Increase the signal sensitivity enormously by using timing & energy information together. Dutta, Kim, Liao, Park, **SS**, Strigari, PRL 2020

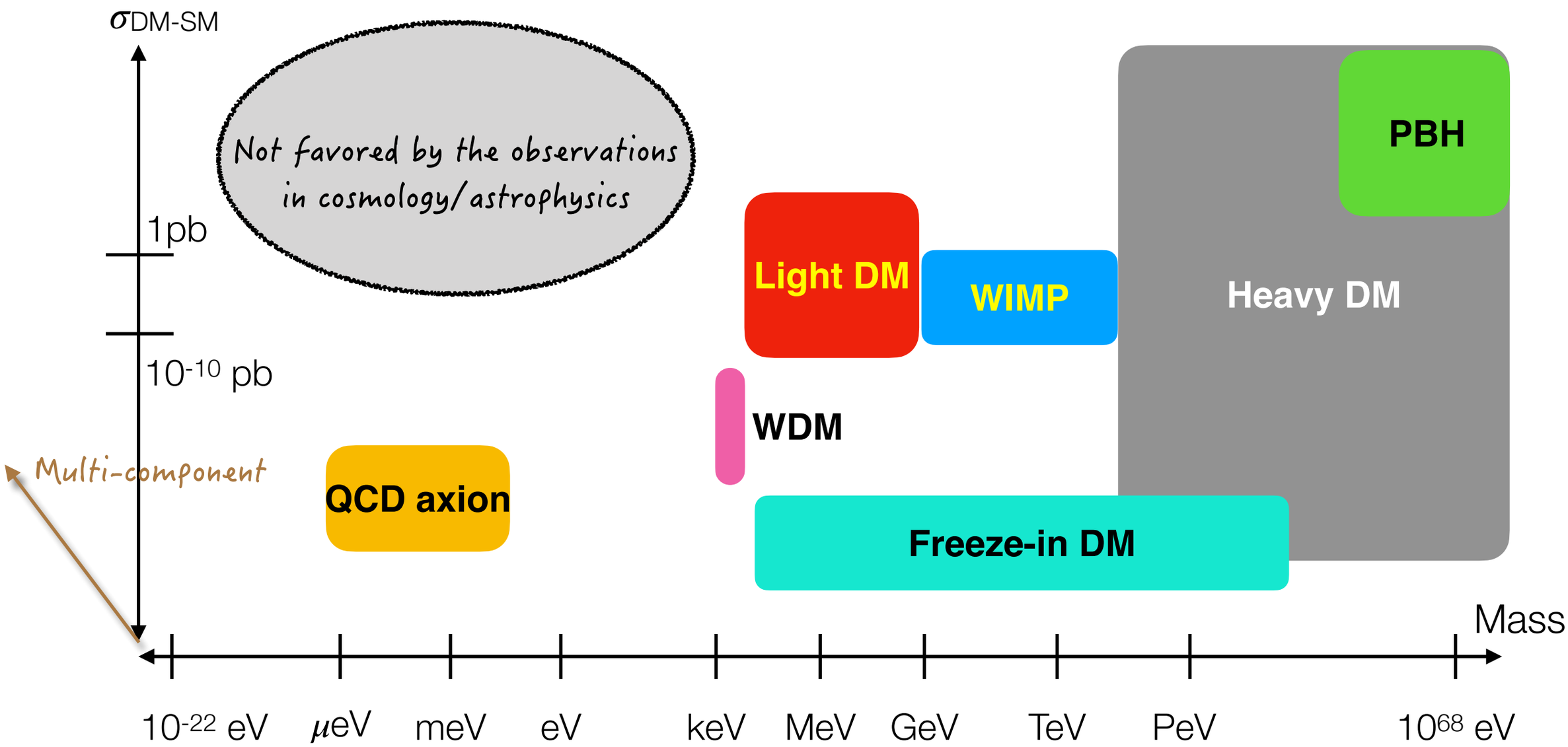
- Applied to COHERENT, CCM, JSNS^2, …

  Dutta, Kim, Liao, Park, **SS**, Strigari, Thompson, JHEP 2022



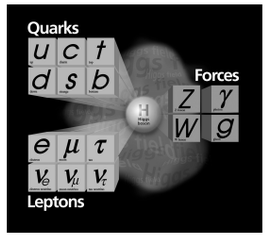


Multi-component dark sector



- Non-trivial dark sector structure: e.g., iDM

Smith, Weiner, PRD 2001



- Hybrid models with fruitful experimental signatures: e.g., BDM

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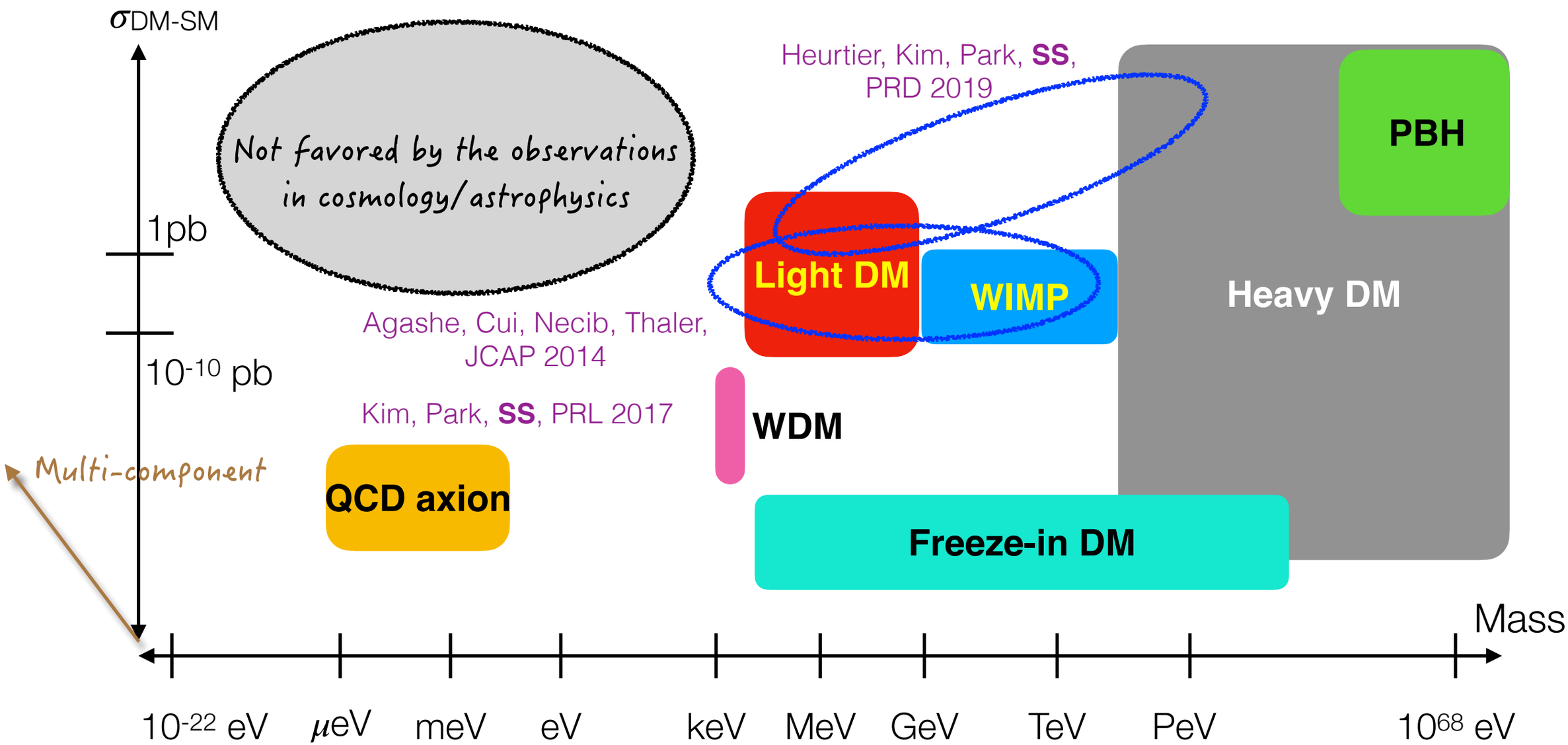

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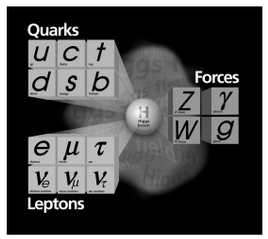

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Sub-dominant component is hidden?

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

- The dominant relics might be safe from the experiments so far if it communicates with the SM sector through the sub-dominant relic?

- Question is <u>how the amount of the sub-dominant relic is determined</u>.

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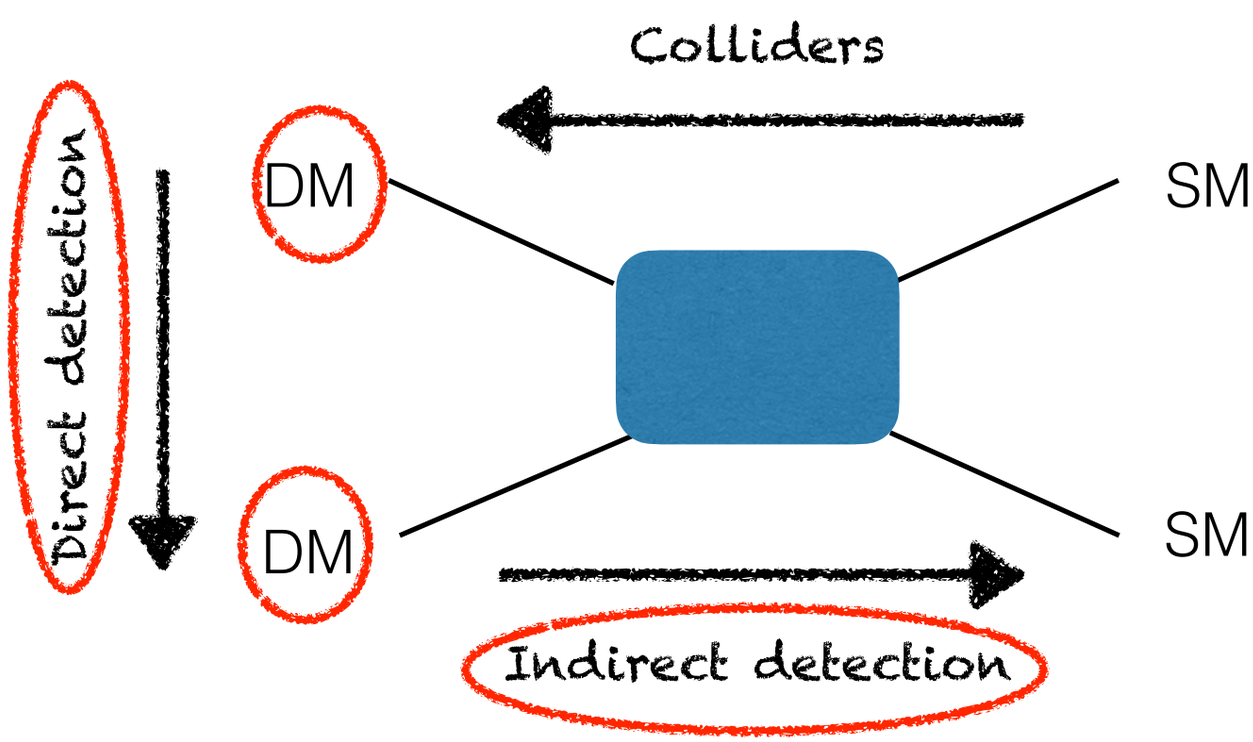

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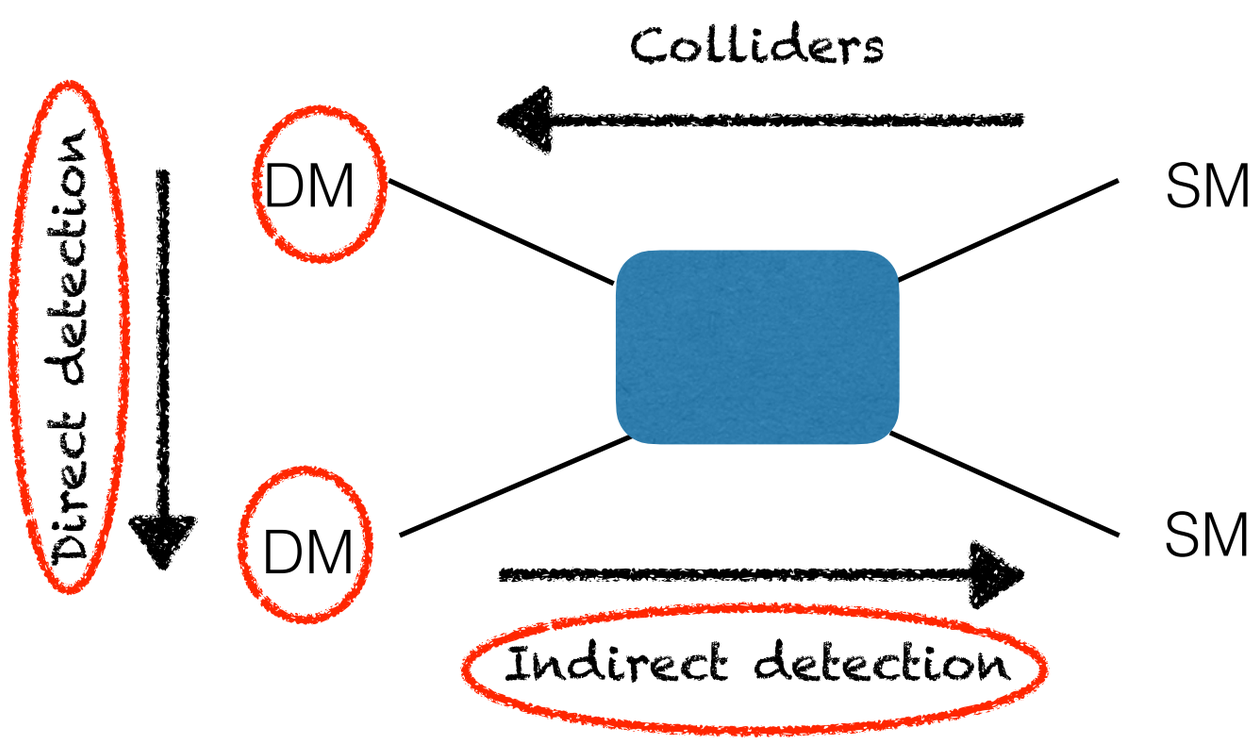

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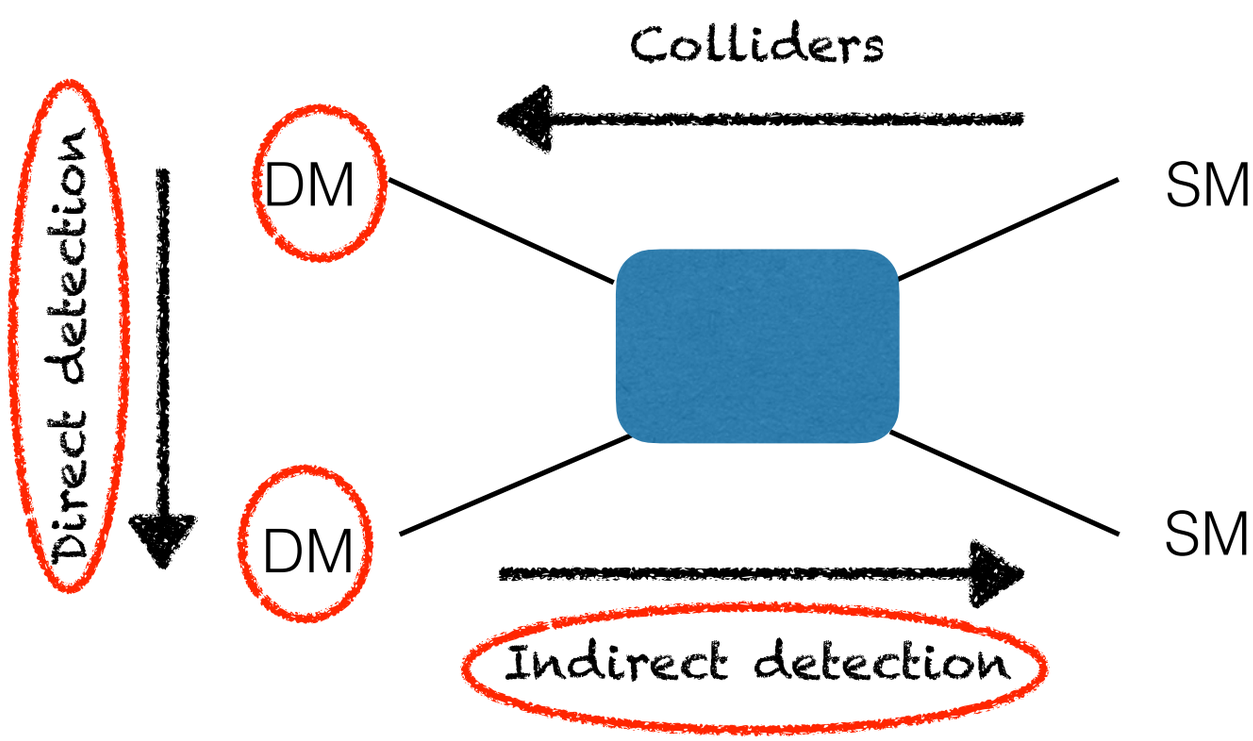

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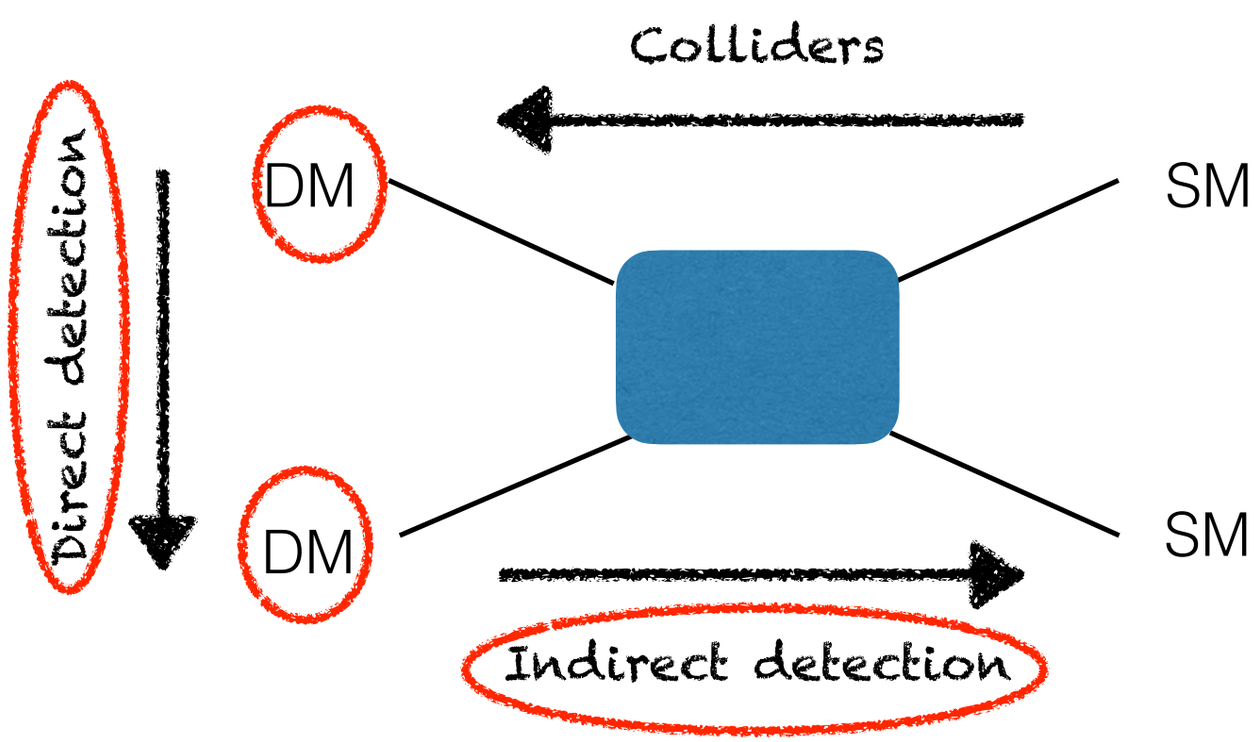


e.g., DM-SM coupling

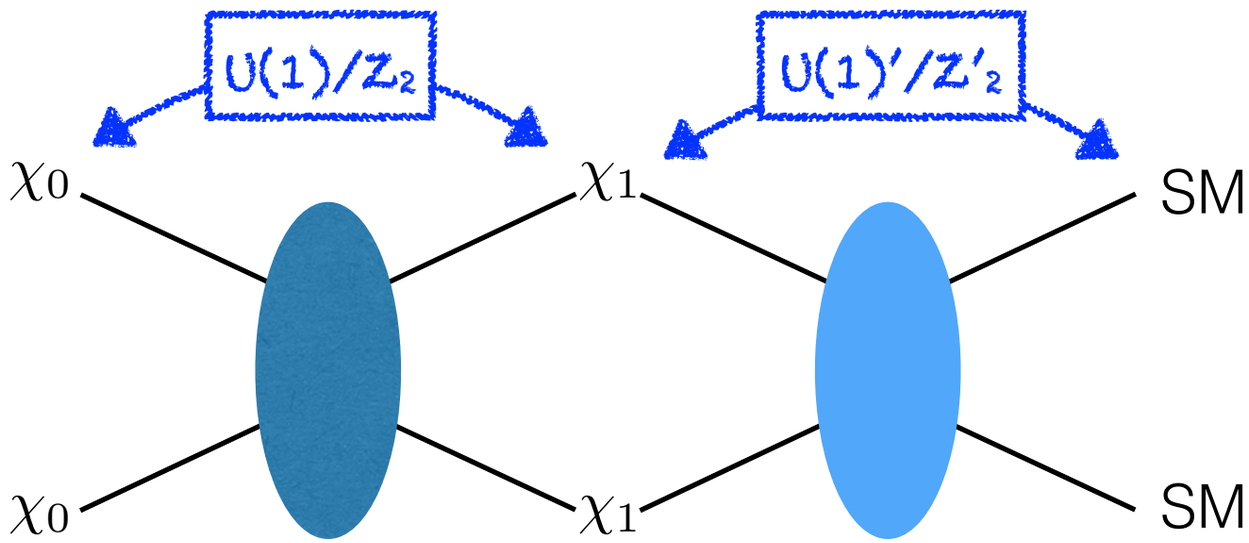
Amount^{-1} = fraction^{-1}

cross section

Observable = fraction x cross section

Reference: Multi-component BDM

χ_0: heavy, χ_1: light



Agashe, Cui, Necib, Thaler, JCAP 2014

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

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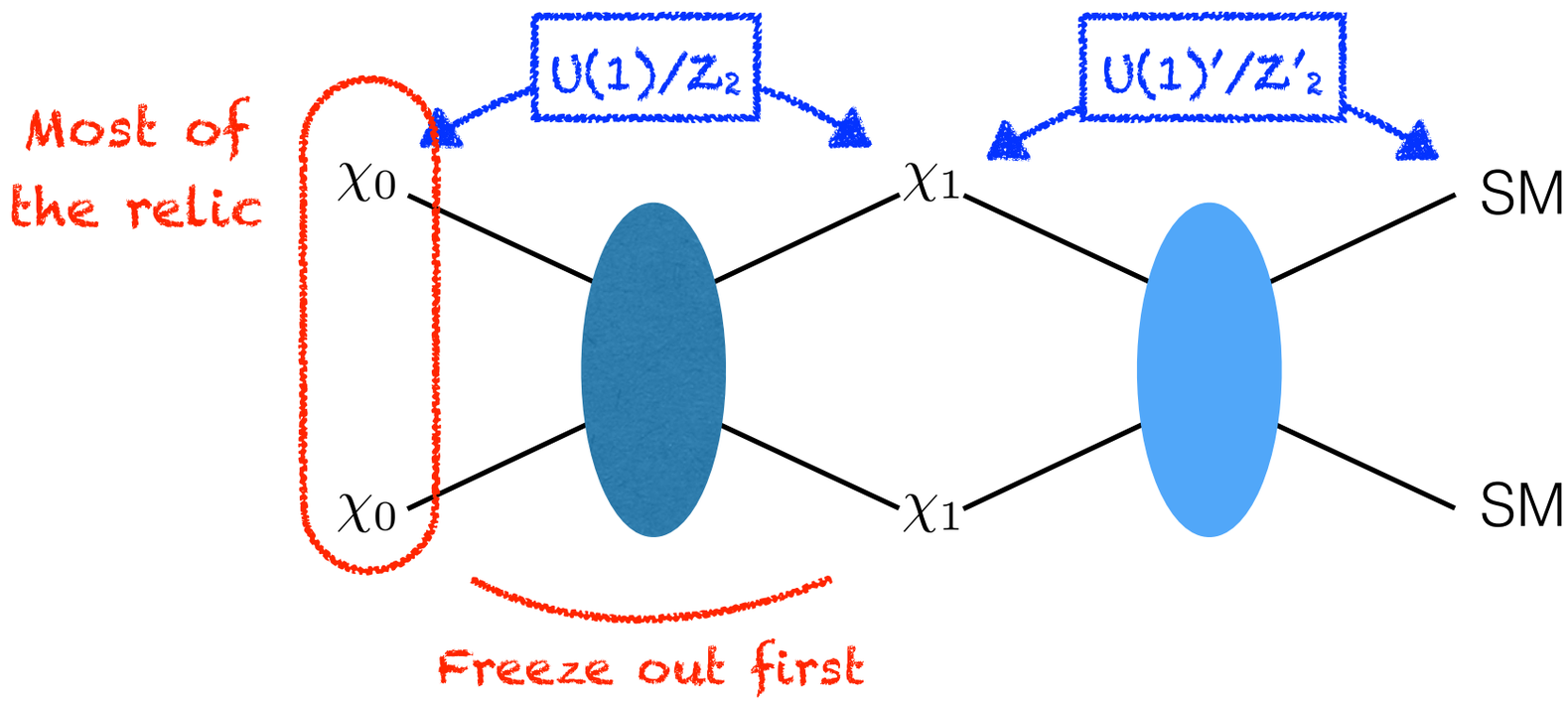

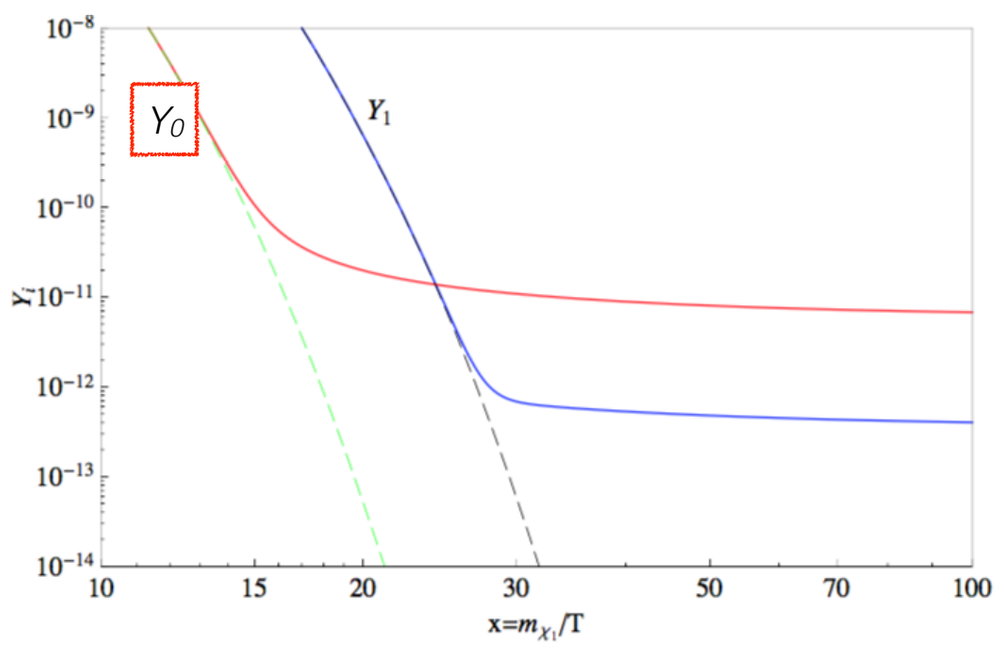

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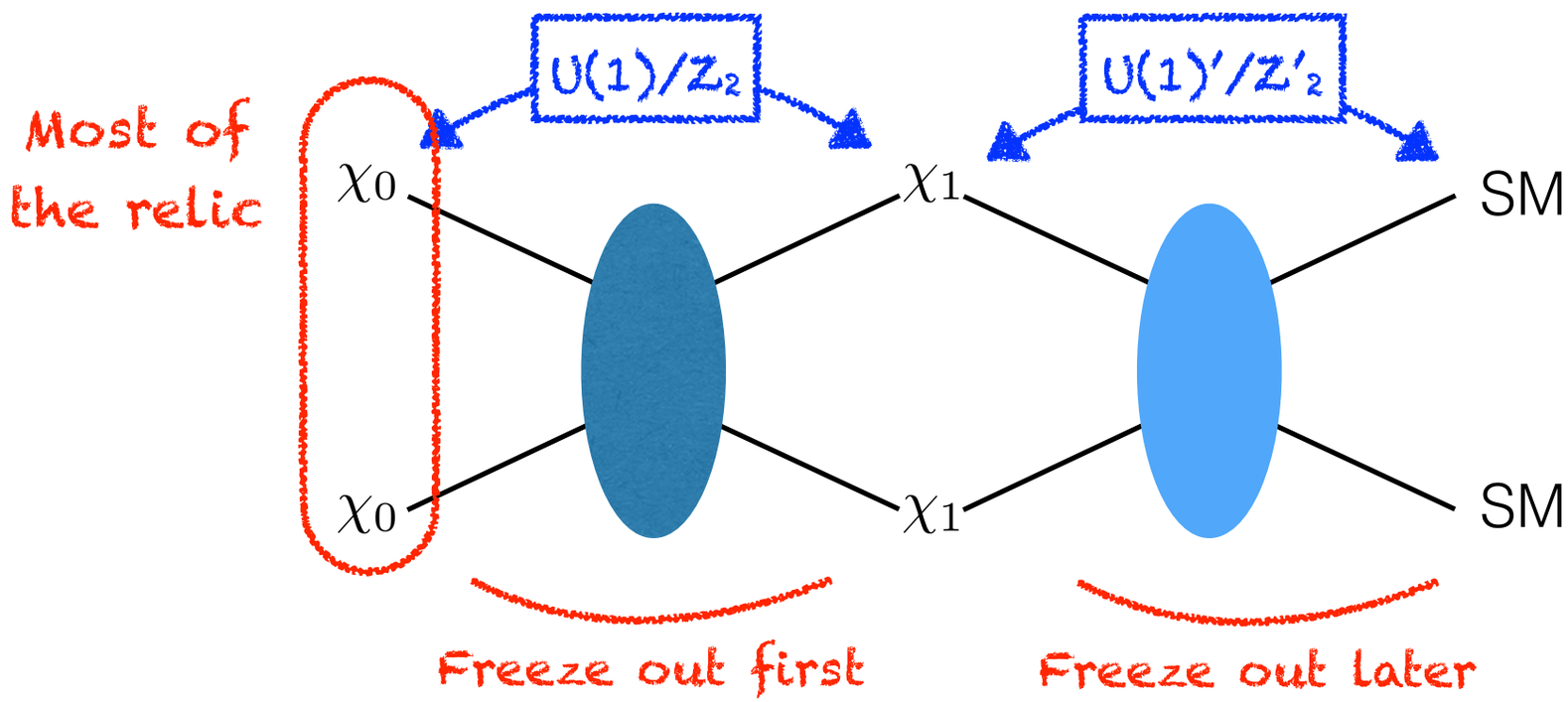

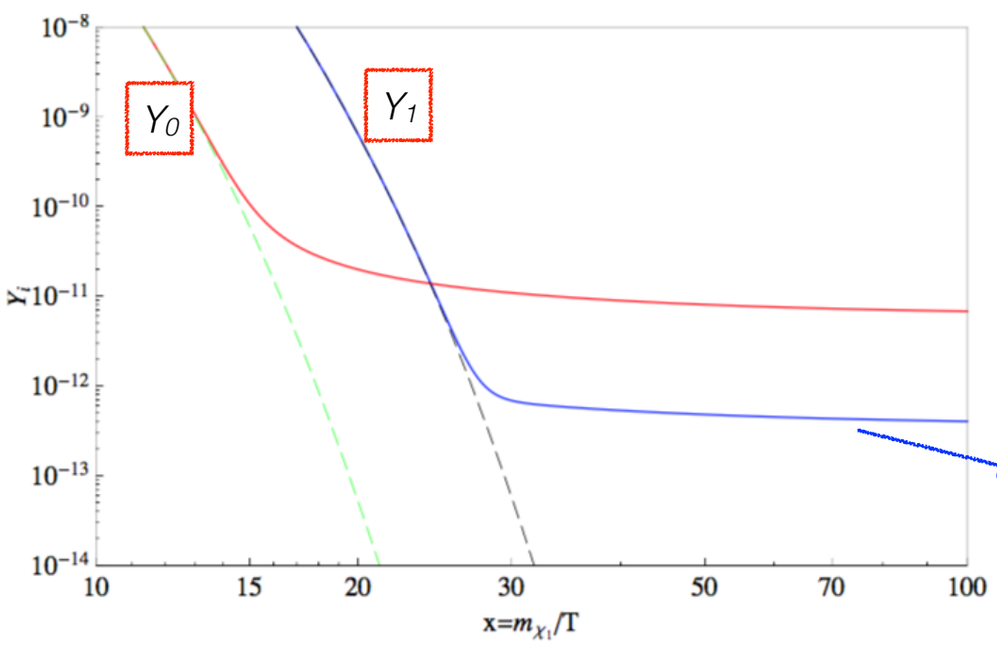

Agashe, Cui, Necib, Thaler, JCAP 2014

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

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

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)

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

  ※ relic χ_1 is non-relativistic

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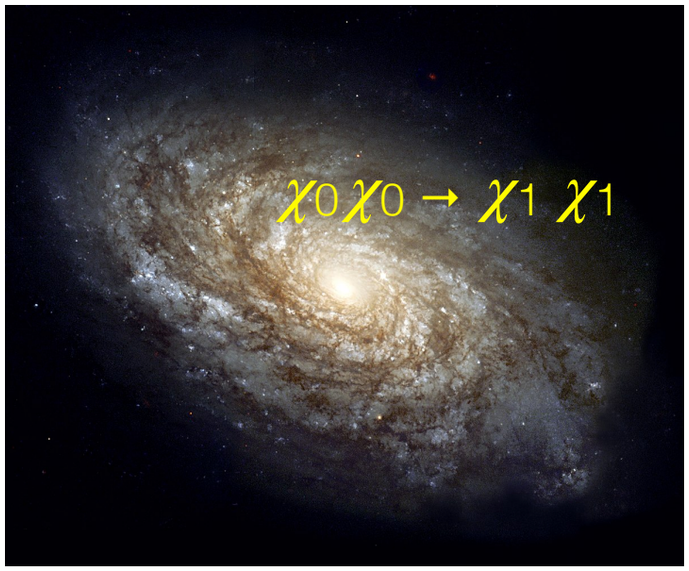

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(indirect detection of χ_0)

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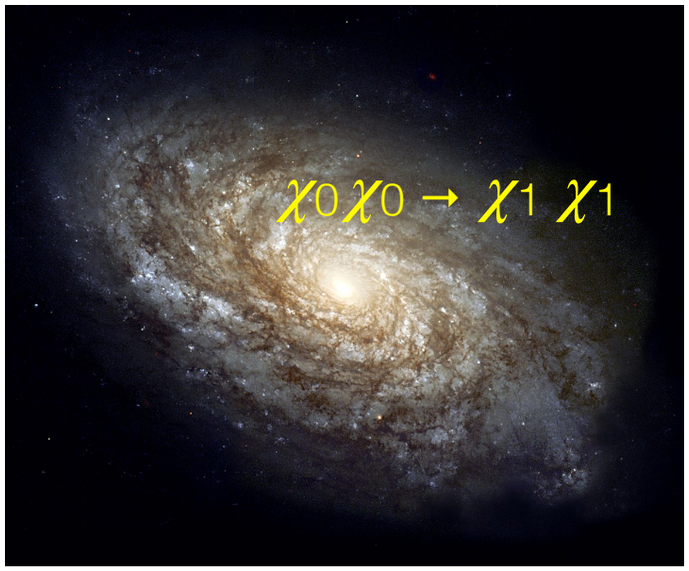

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Assume: NFW

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

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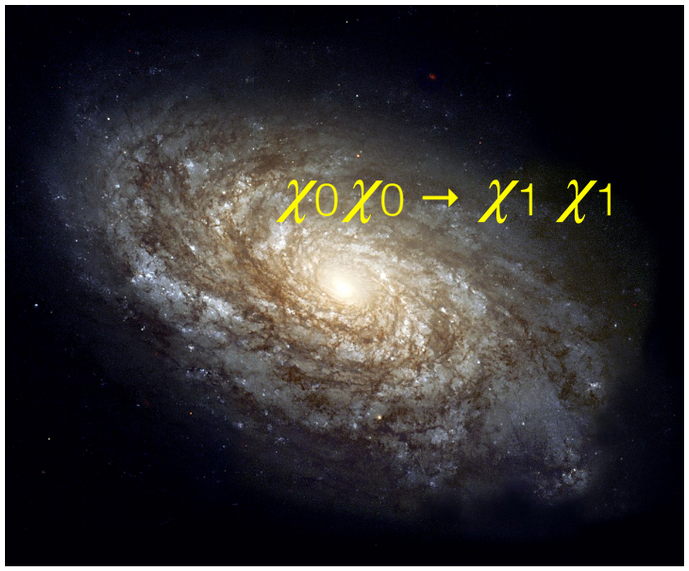

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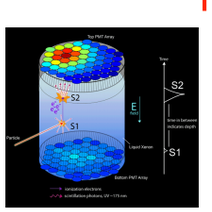
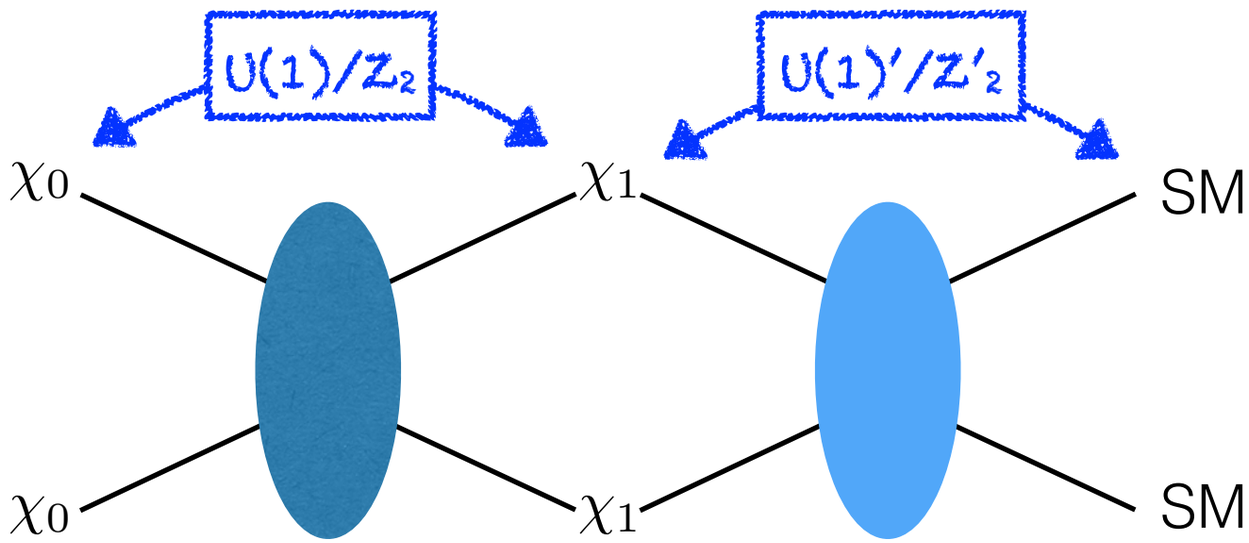


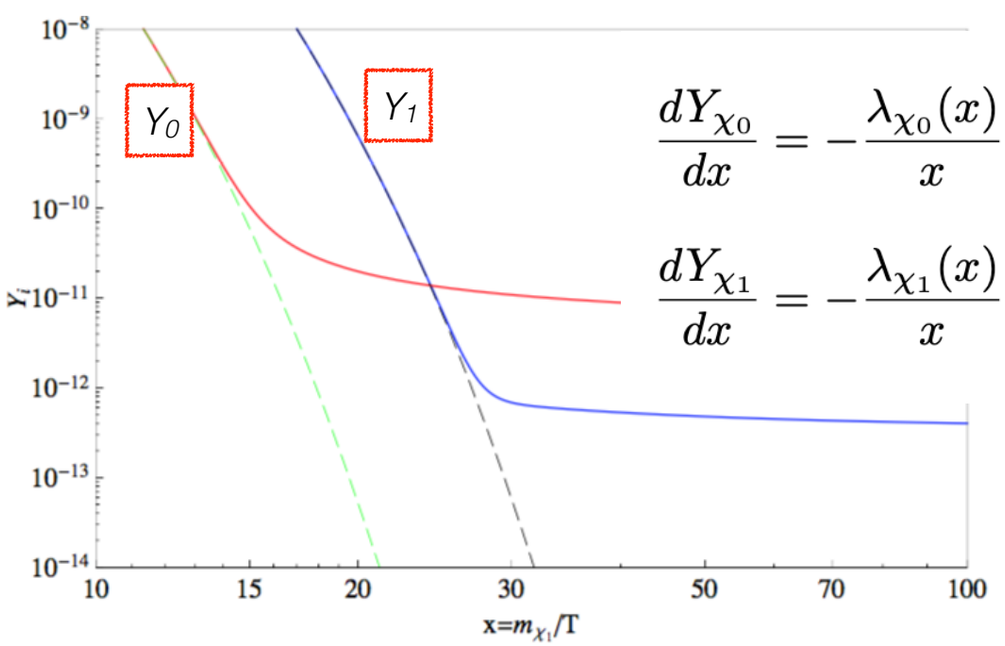
comparable **if $m_0 \lesssim 1$ GeV**

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

Structure of $\chi_1\chi_1 \to$ SM

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





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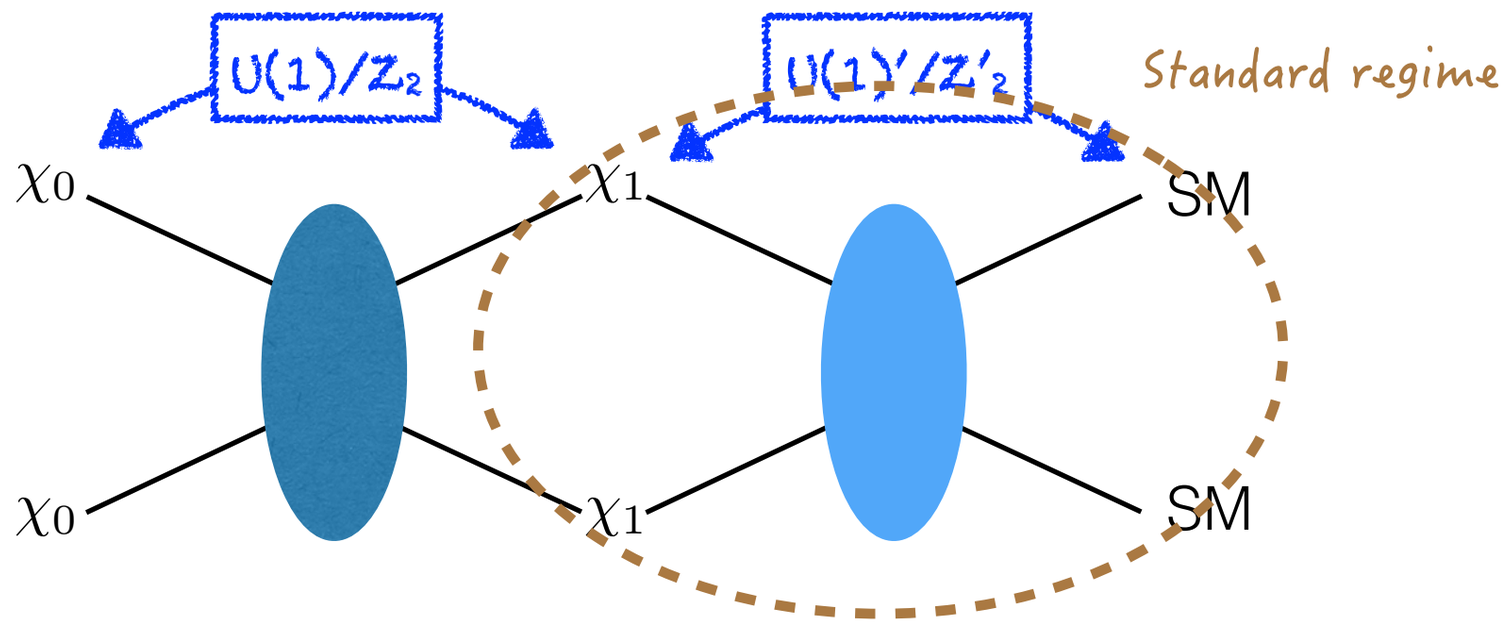

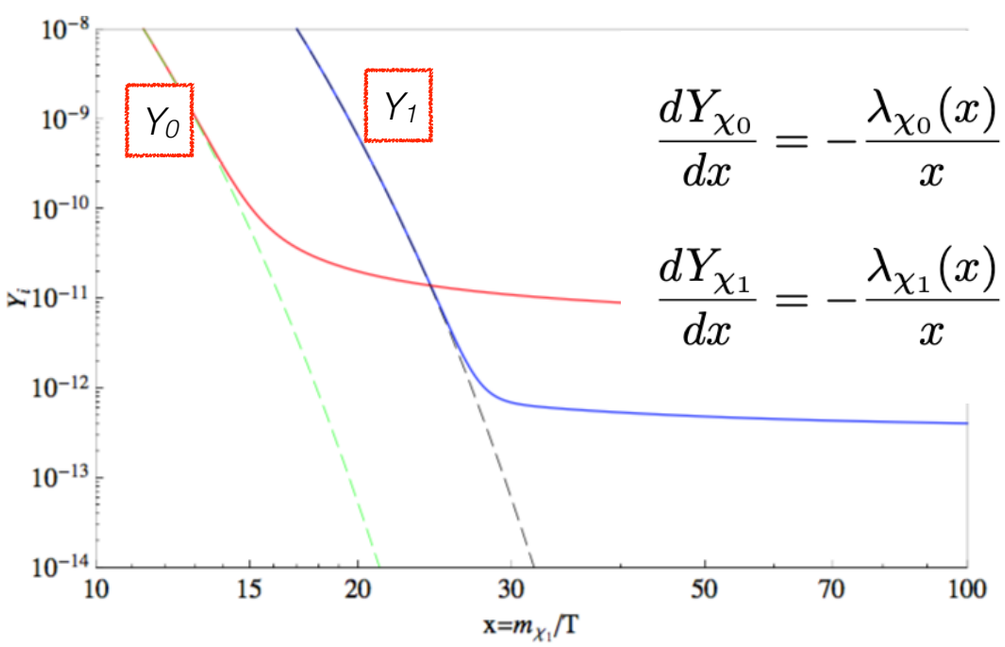

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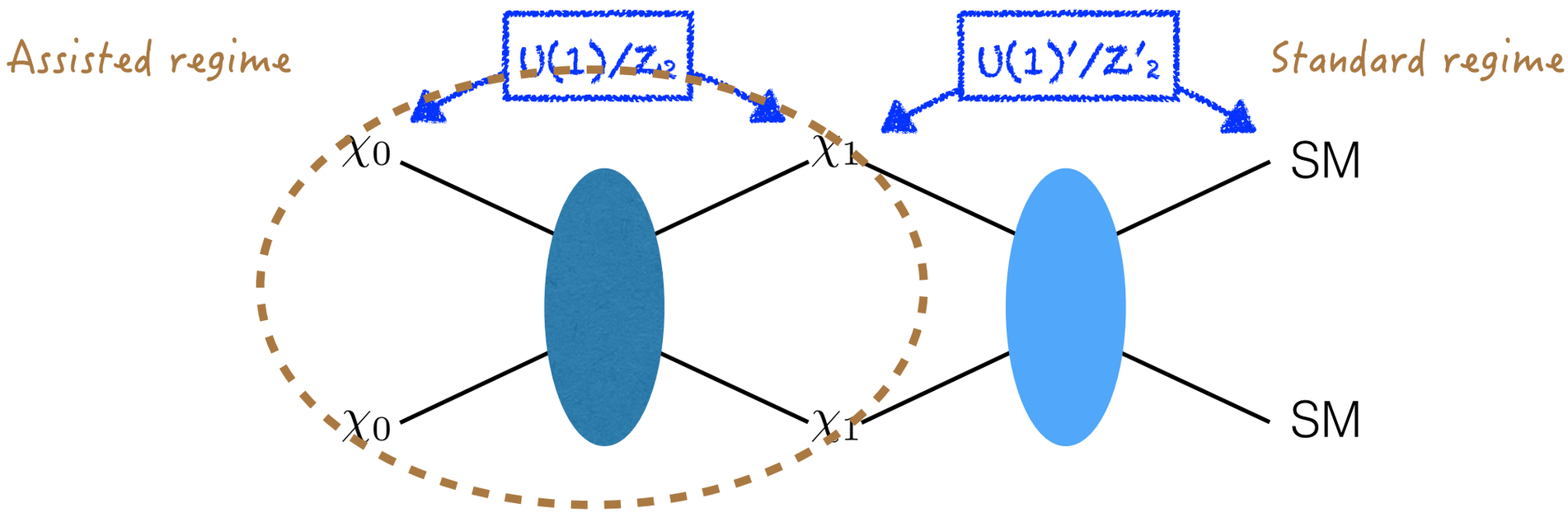

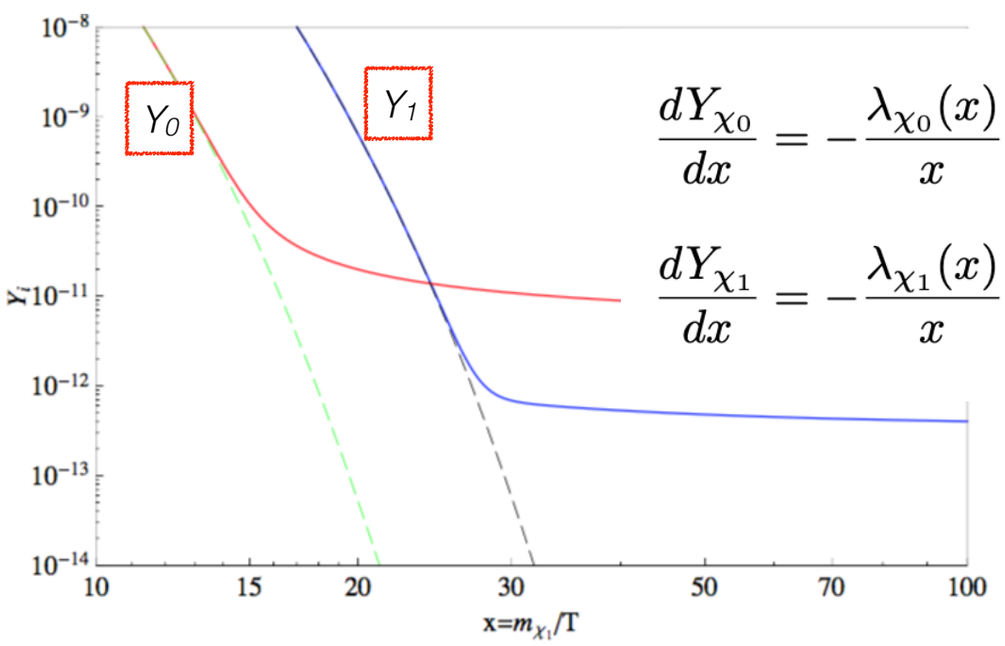

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with SM

with heavy DM χ_0

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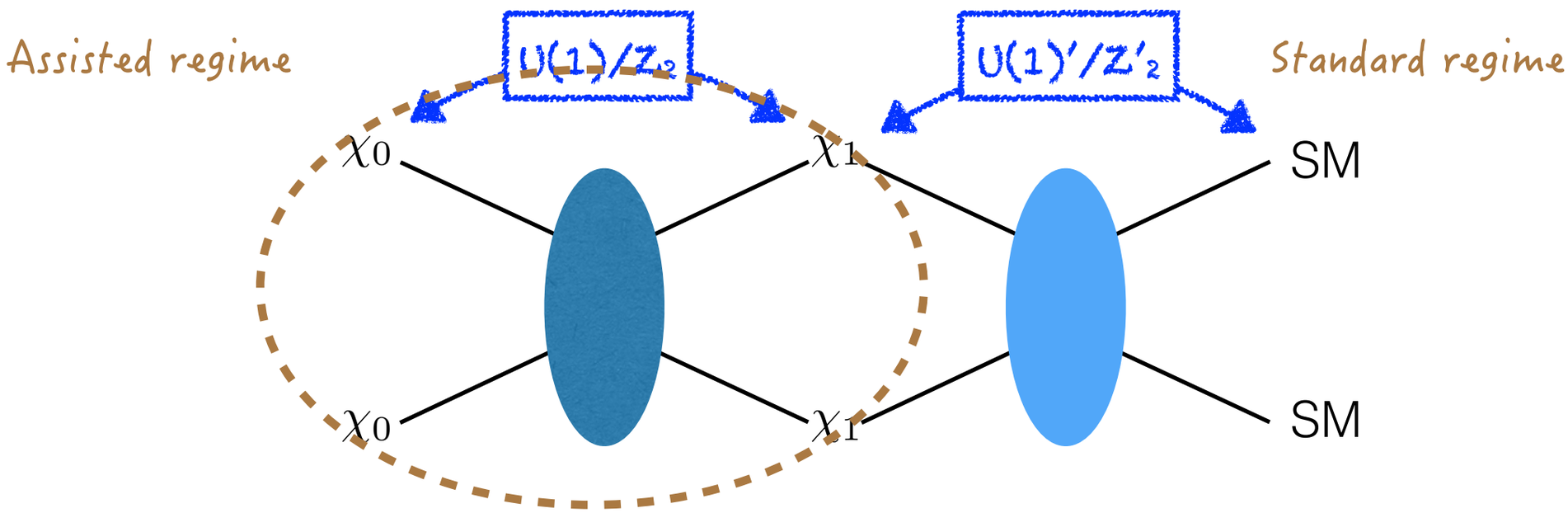
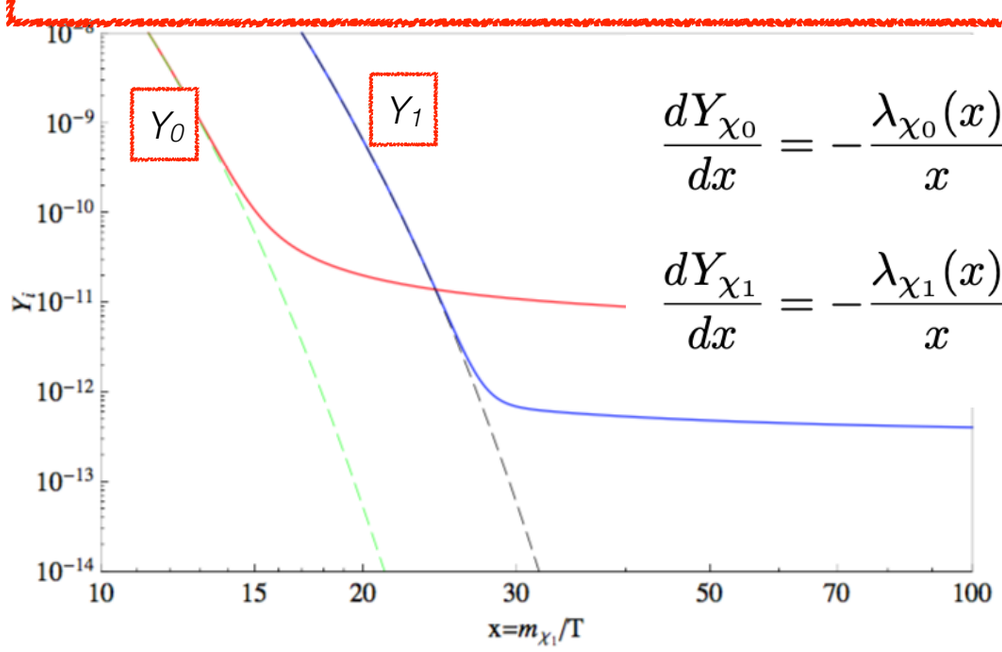
Structure of $\chi_1\chi_1 \to$ SM

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



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

$$\frac{dY_{\chi_1}}{dx} \simeq -\frac{\lambda_{\chi_1}(x)}{x}\left[Y_{\chi_1}^2 - \left(Y_{\chi_1}^{\rm eq}(x)\right)^2 - \underbrace{Y_{\rm ast.}^2(x)}_{\chi_0\chi_0 \to \chi_1\chi_1}\right]$$

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

($\sigma_{\chi_0\text{-}\chi_1} < \sigma_{\chi_1\text{-SM}}$)

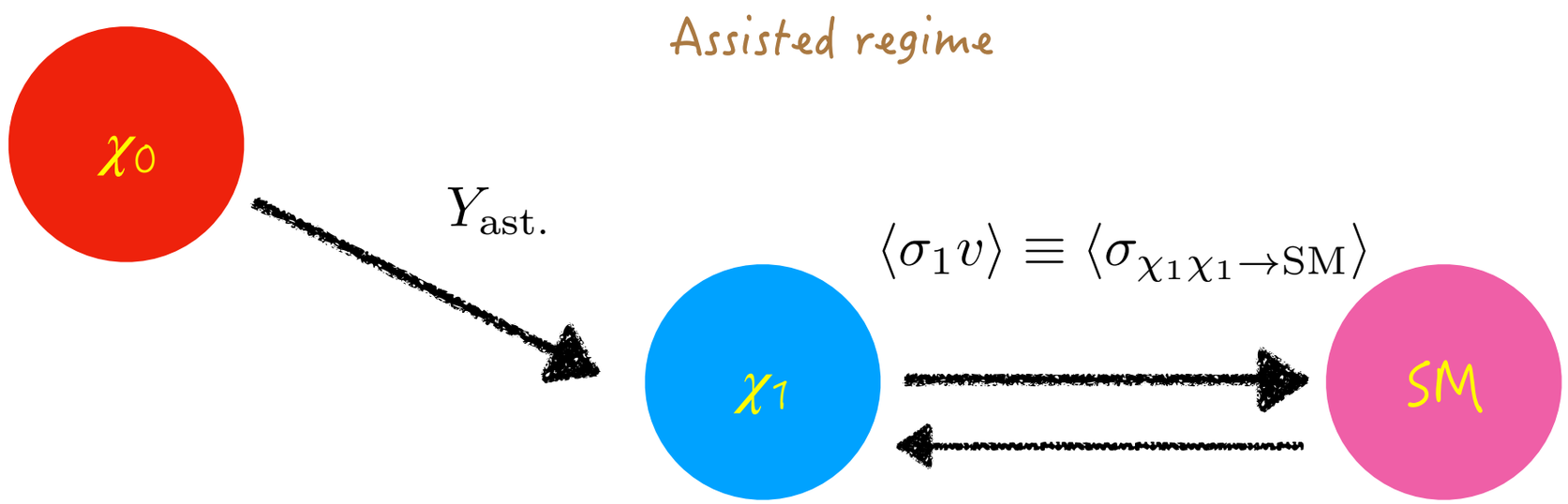
- If $Y_{\rm ast.}$ is negligible, χ_1 freezes out at T ~ $m_1/20$ as usual. Standard regime

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

Assisted regime

Kamada, Kim, Park, **SS**, JCAP 10, 052 (2022)

Structure of $\chi_1\chi_1 \to$ SM



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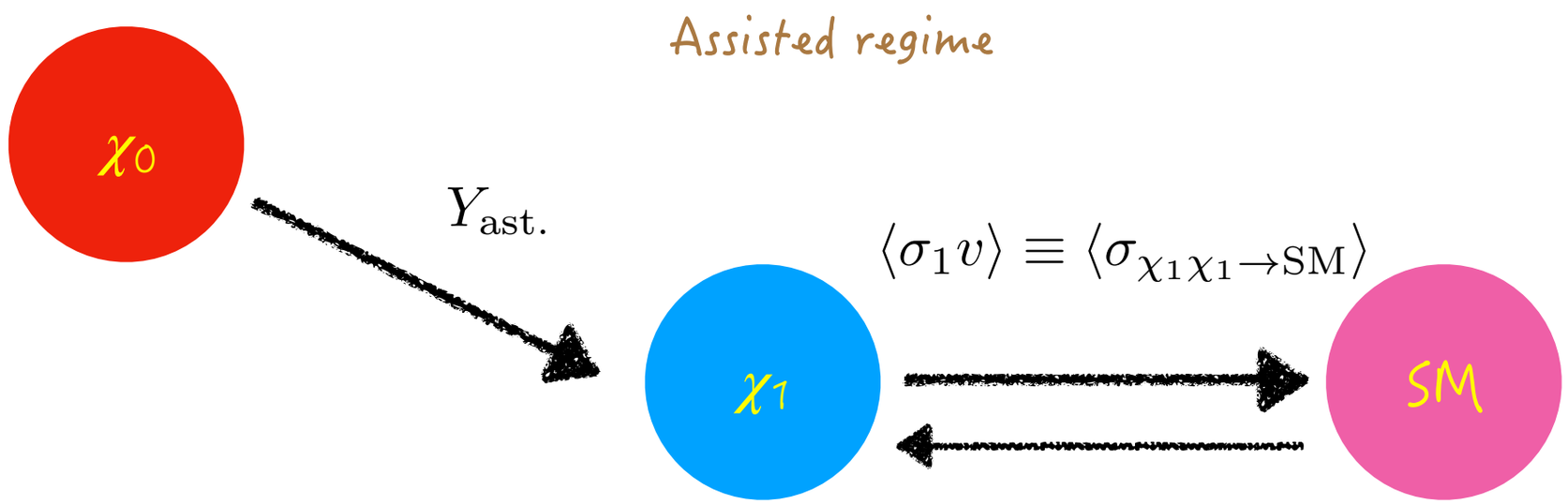

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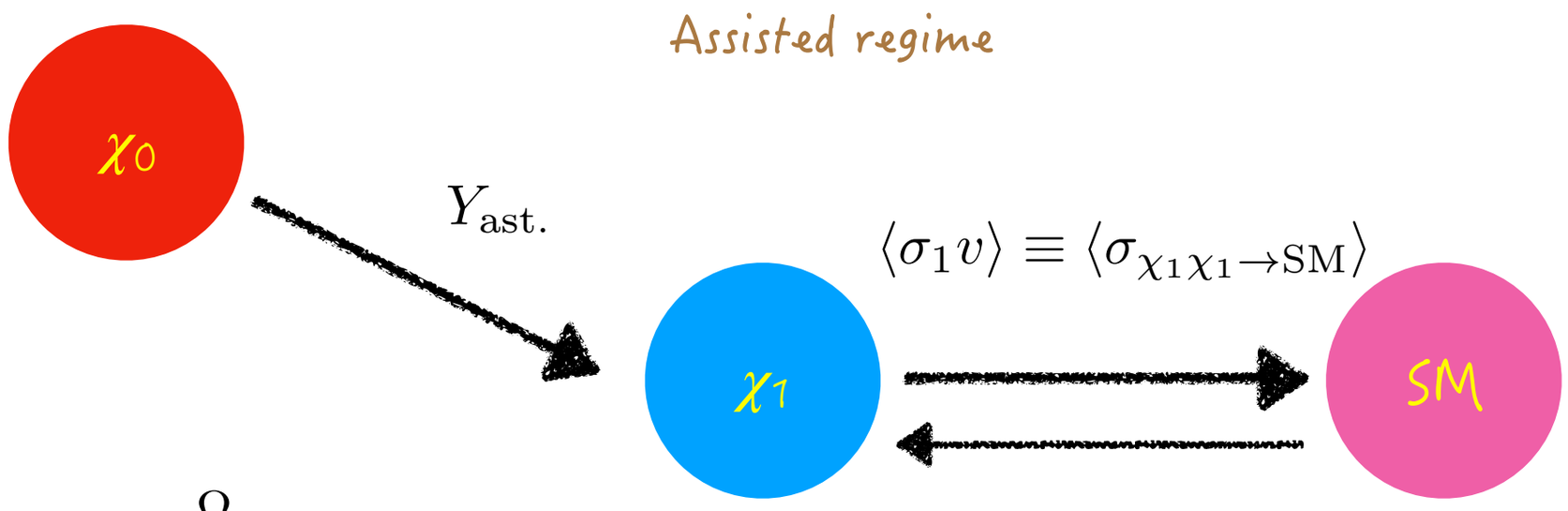

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- We find for s-wave and p-wave, respectively.

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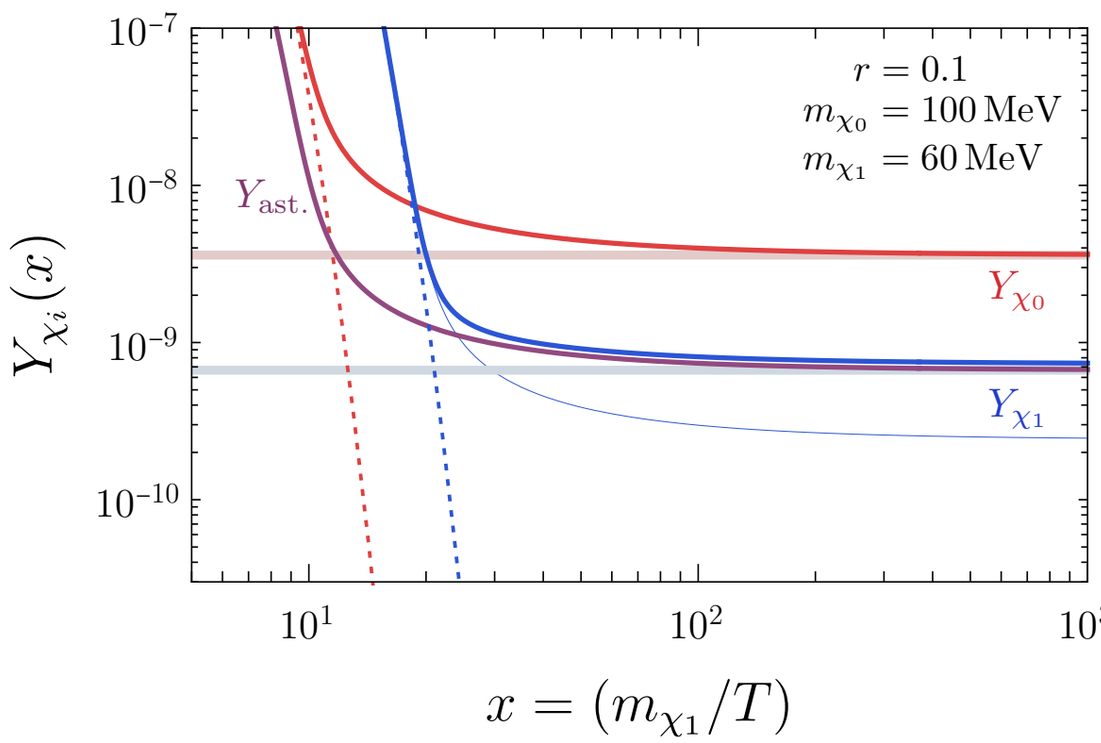
Structure of $\chi_1\chi_1 \to$ SM

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



Assisted regime

Kamada, Kim, Park, **SS**, JCAP 10, 052 (2022)

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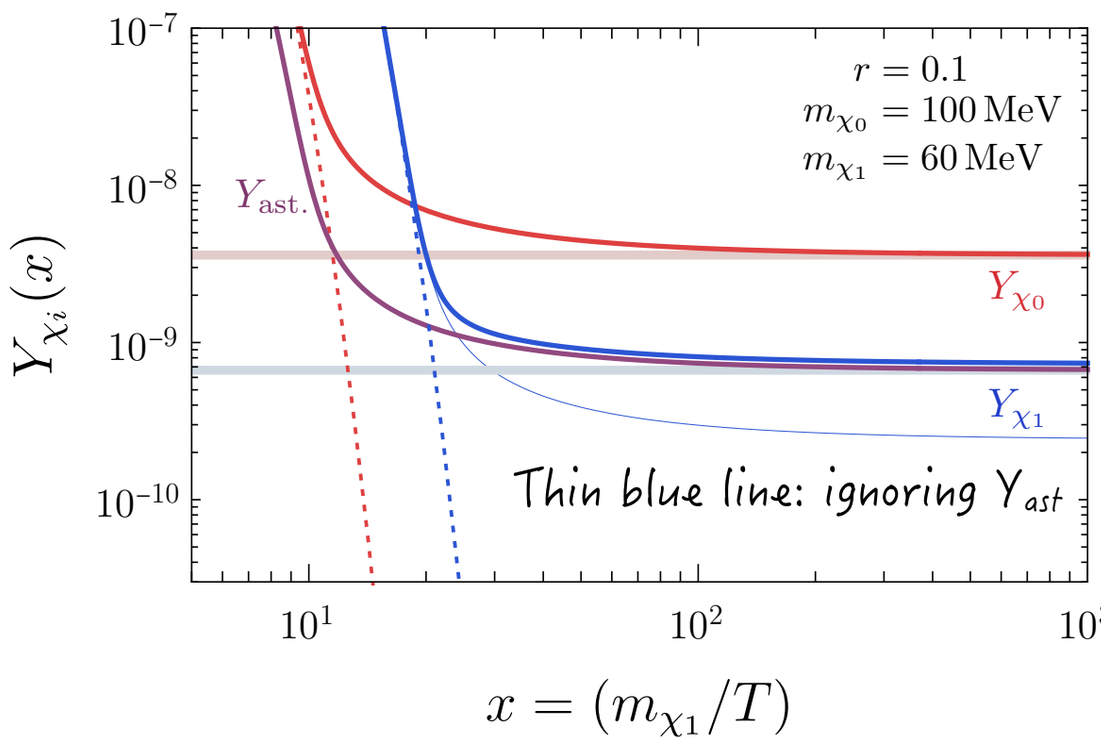

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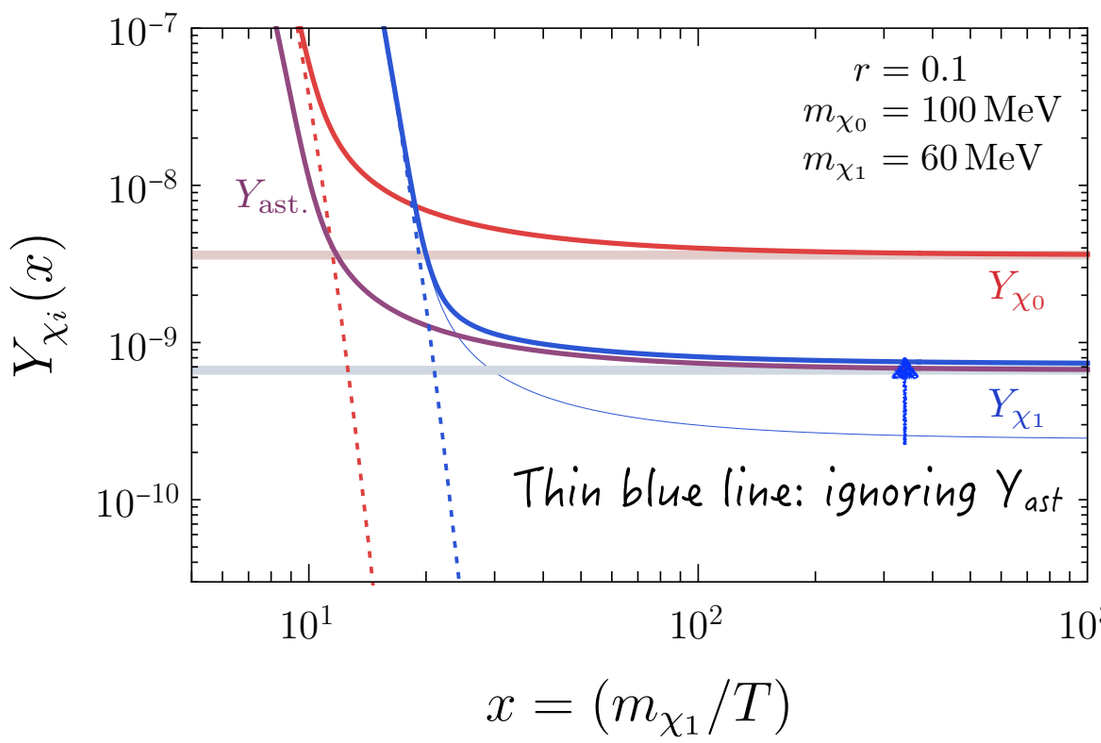

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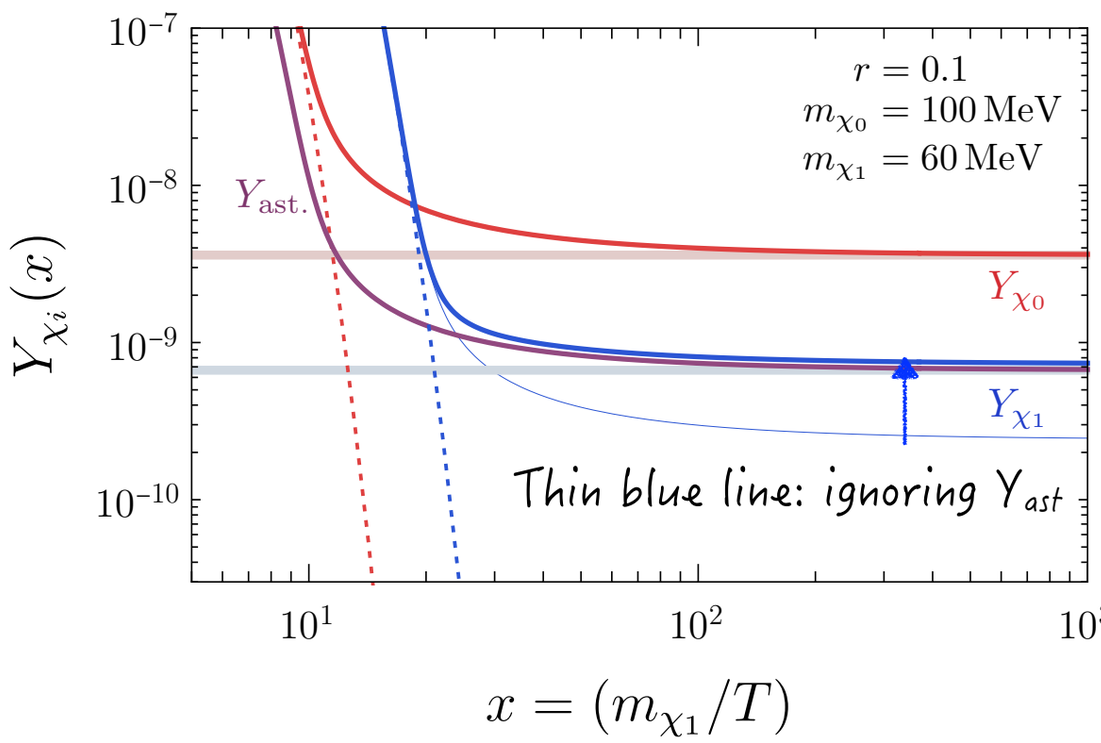

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- The annihilation cross section $\chi_1\chi_1 \to$ SM is enhanced by $1/r_1{}^2$.

Structure of $\chi_1\chi_1 \to$ SM

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Safe from constraints?

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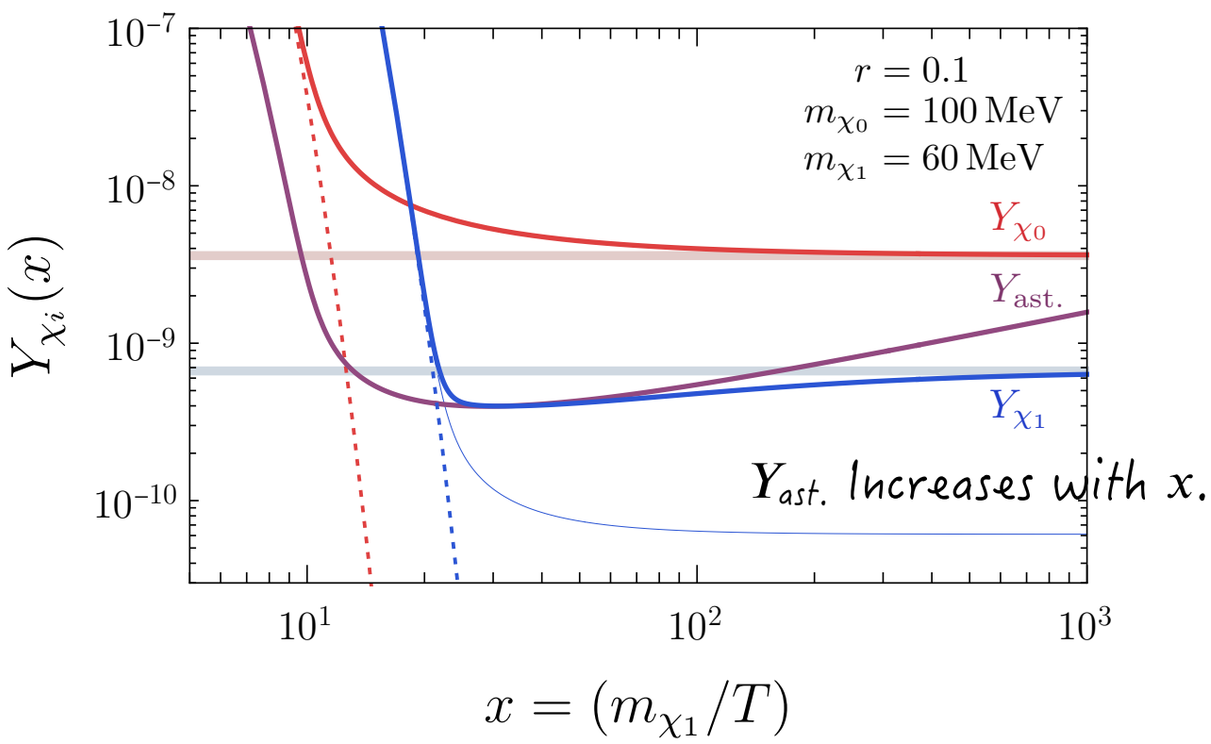

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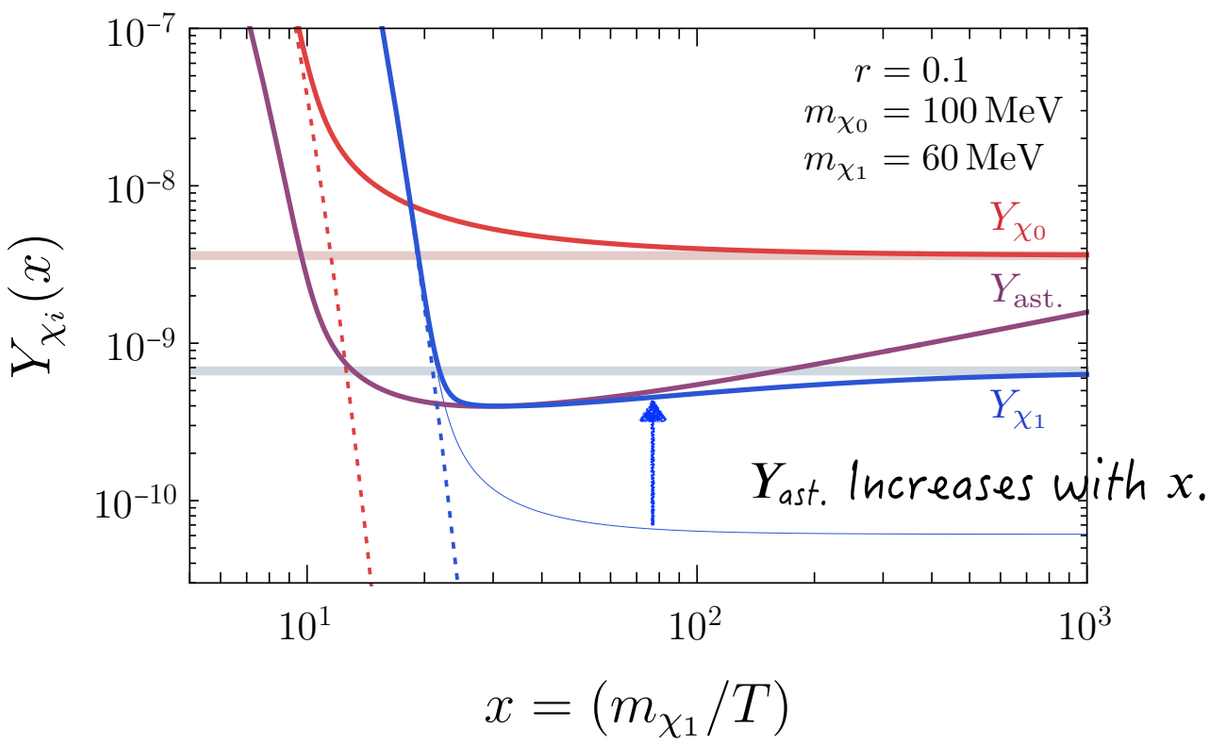

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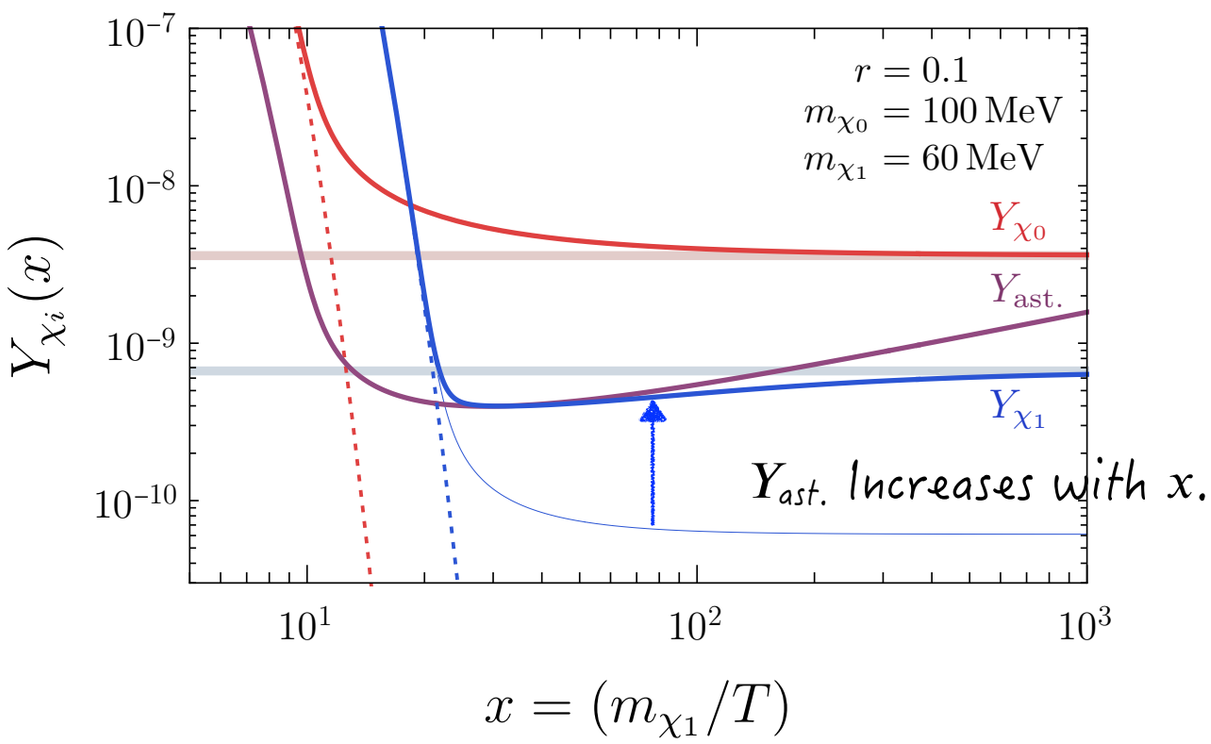

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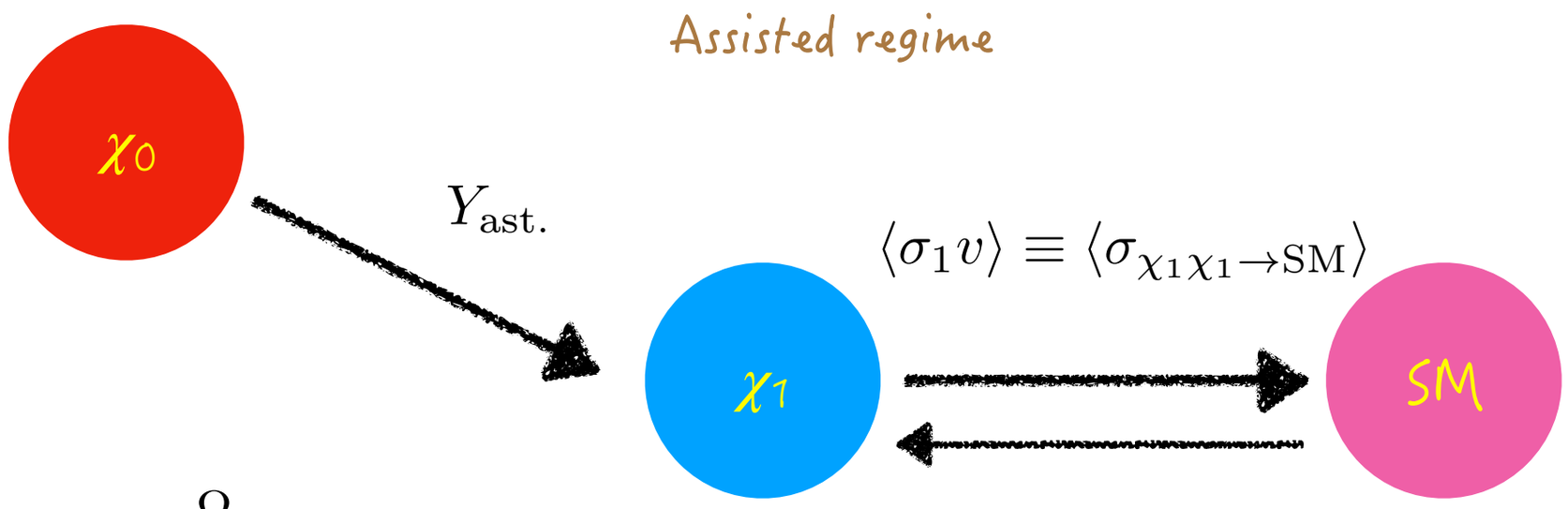
- The annihilation cross section $\chi_1\chi_1 \to$ SM increases as $1/r_1^{\,3}$ so the process can be also sensitive to various observables.

Structure of $\chi_1\chi_1 \to$ SM



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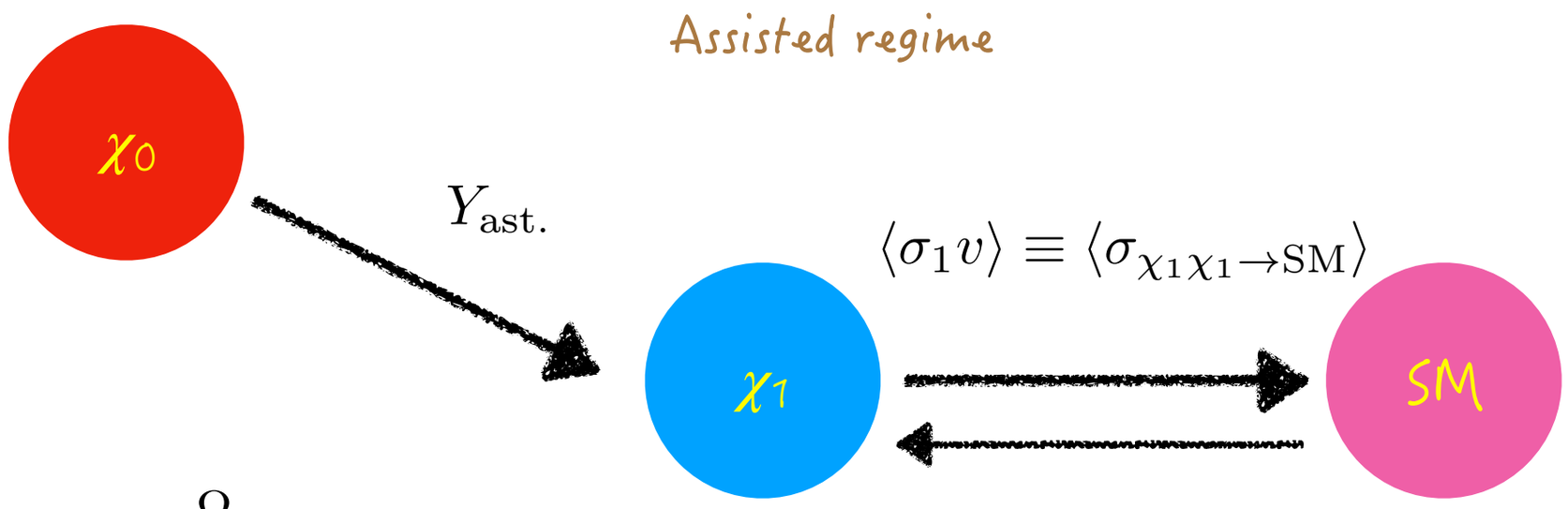

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  observables $\propto$ $n_{\chi_1}^2 \langle \sigma_1 v \rangle$ $\to$ No r_1 suppression! (even enhanced)

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Effects of χ_1 to various observables

Sub-component DM can be not hidden and $\chi_1\chi_1 \to$ SM affect

- Big Bang Nucleosynthesis: photo-dissociation of light elements
  e.g., $e\gamma_b \to e'\gamma'$ changes the ratio of D, ^{3}He, ^{4}He, ..

- Cosmic microwave background: $N_{\rm eff}$ if χ_1 freeze-out at $T \lesssim T_{\nu,\rm dec}$,
  Energy injection by $\chi_1\chi_1 \to$ SM at the recombination epoch

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

- Direct detection if the crossing symmetry is effective.
  (depending on the model)

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 $n_{\chi_1}^2 (\sigma_1 v_{\rm rel})_{\rm s} \sim r_1^2 \cdot \frac{1}{r_1^2} = \text{no } r_1$: **s-wave not preferred!**

  (preconception: $n_{\chi_1}^2 \langle \sigma_1 v_{\rm rel} \rangle_{\rm standard} \sim r_1$ is not true!)

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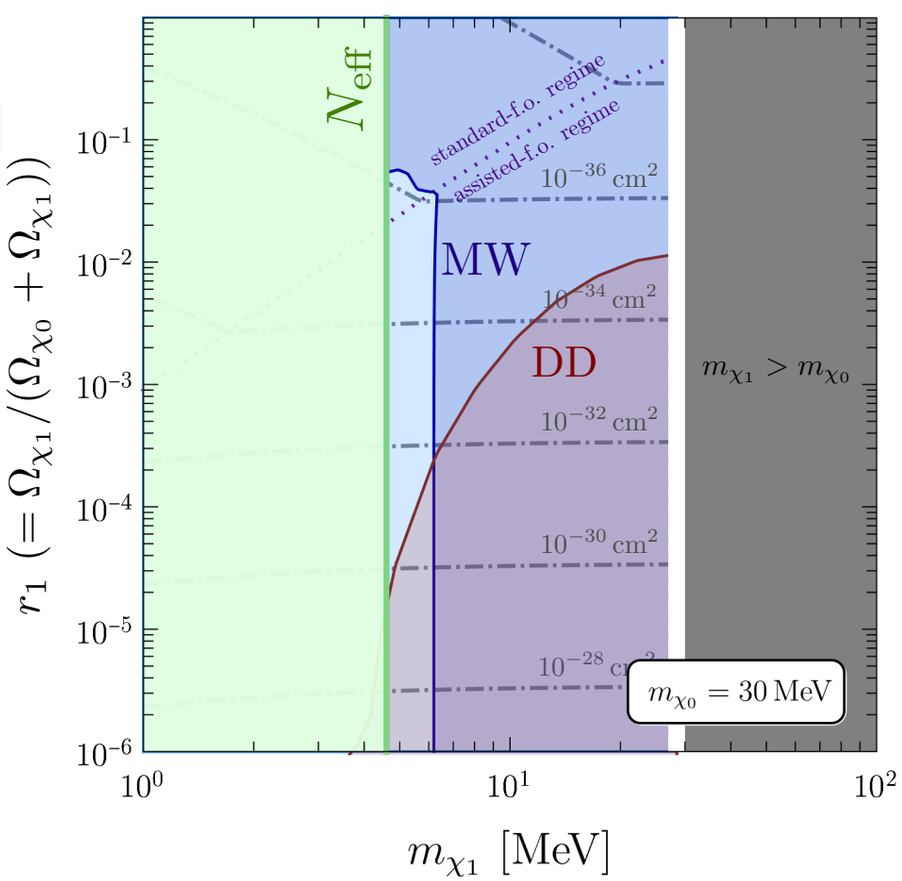

CMB bound (sky blue): disfavor the whole parameter space

Galactic diffuse X/γ-ray (deep blue)

$N_{\rm eff}$ (green): almost independent of r_1

Direct detection bound (brown): XENON10, 100, DarkSide-50

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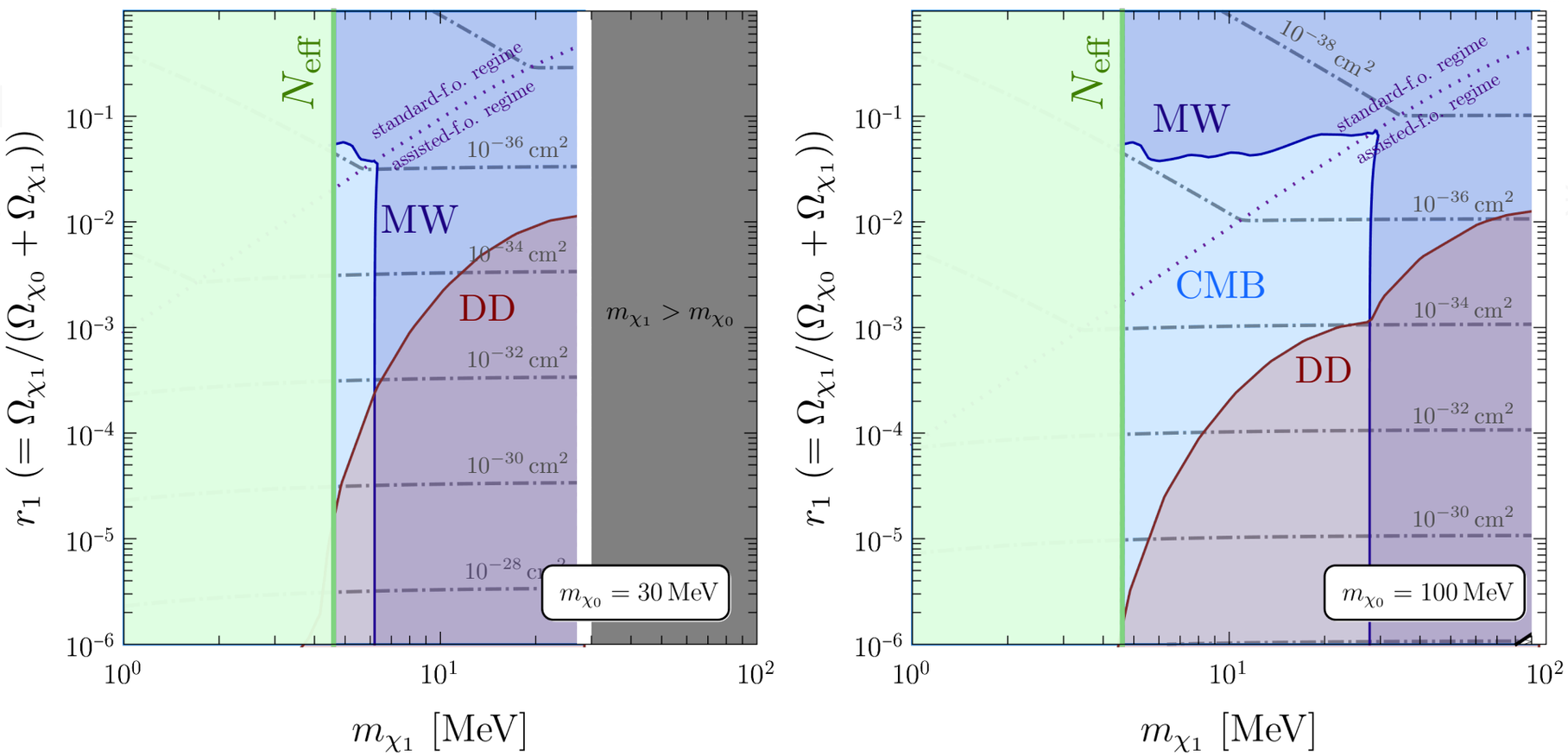

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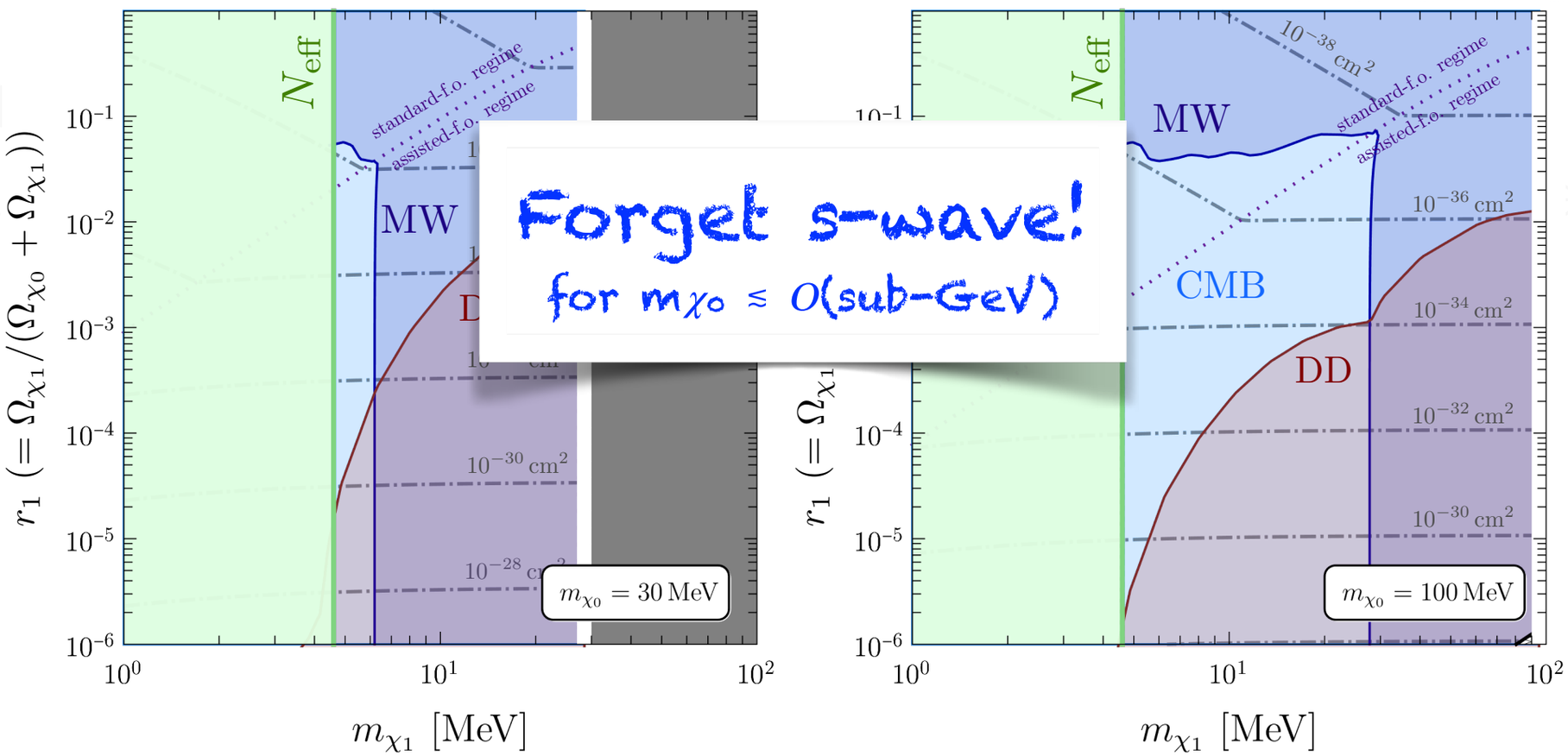

Forget s-wave!
for $m_{\chi_0} \lesssim O$(sub-GeV)

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χ_1 - χ_1 self-interaction

Sensitive to the evolution of the temperature of χ_1 in the early Universe

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 $\mathcal{O}(1)$ dark sector coupling.

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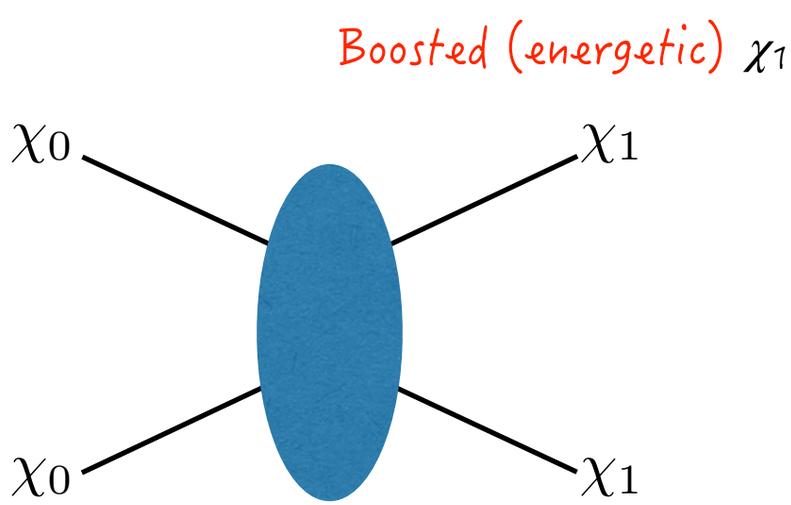

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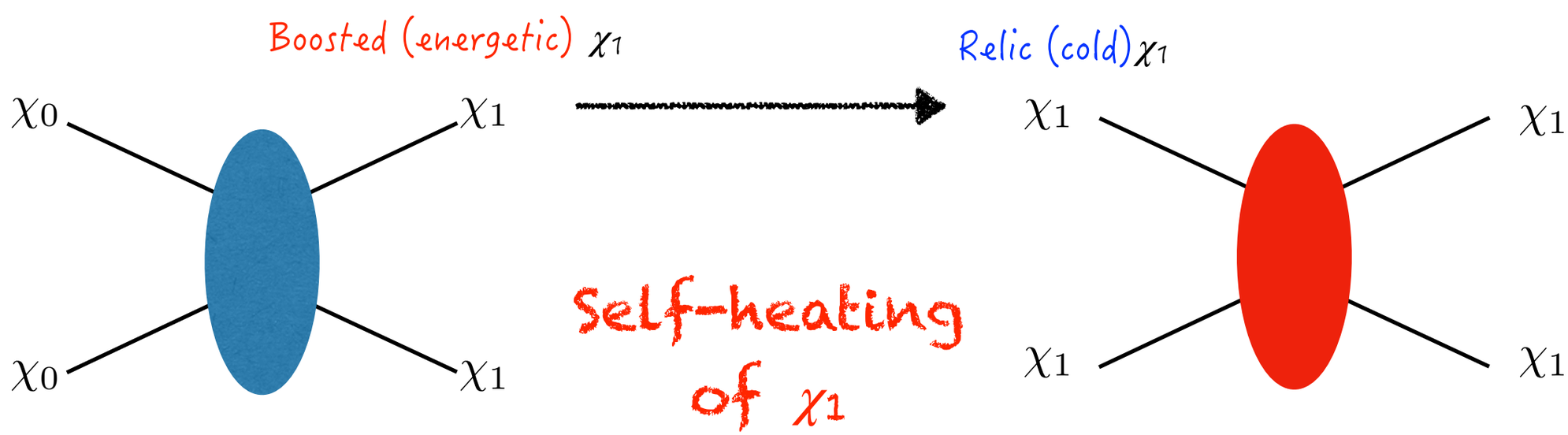

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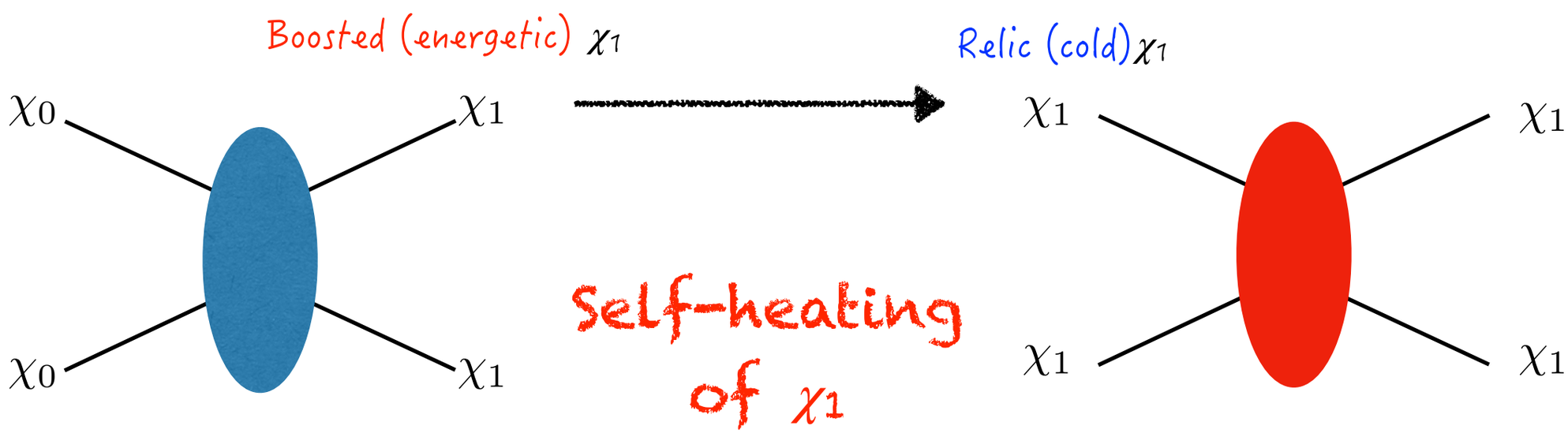
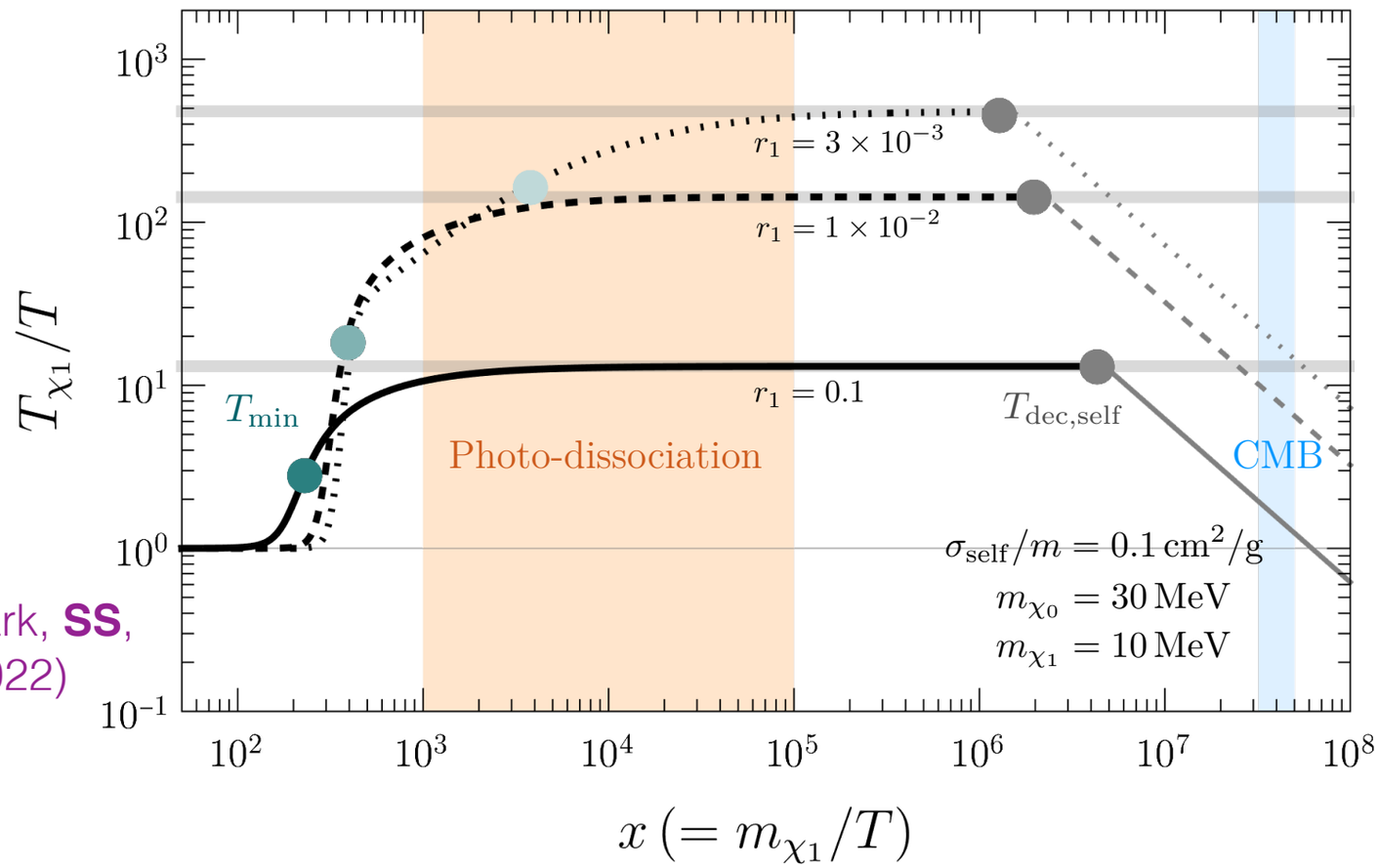


Kamada, Kim, Kim, Sekiguchi, PRL 2018

Chu, Garcia-Cely, JCAP 2018

Vogelsberger, Zavala, Schutz, Slatyer, MNRAS 2018

Temperature evolution of χ_1



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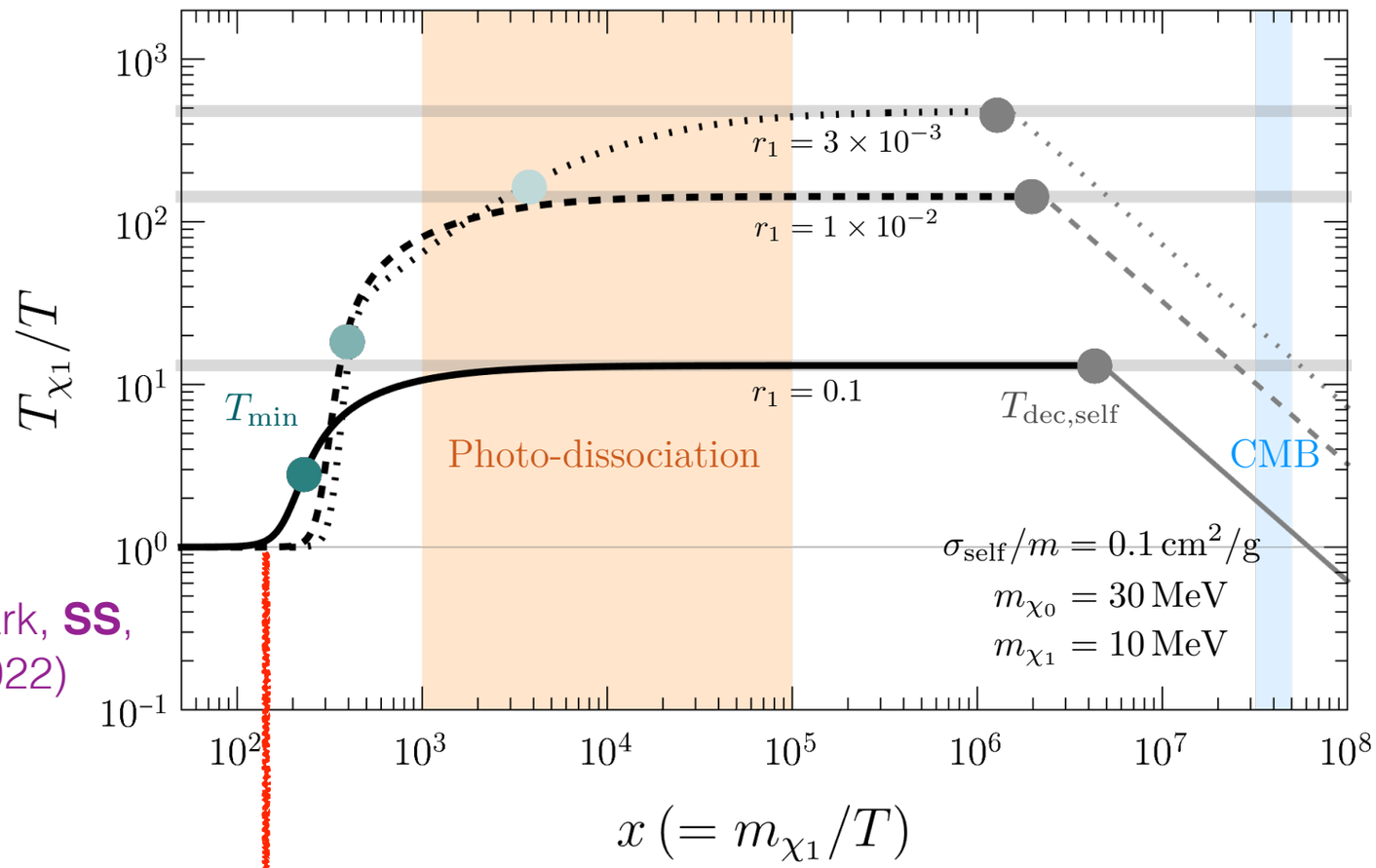

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Kinetic decoupling of χ_1 (from the SM)

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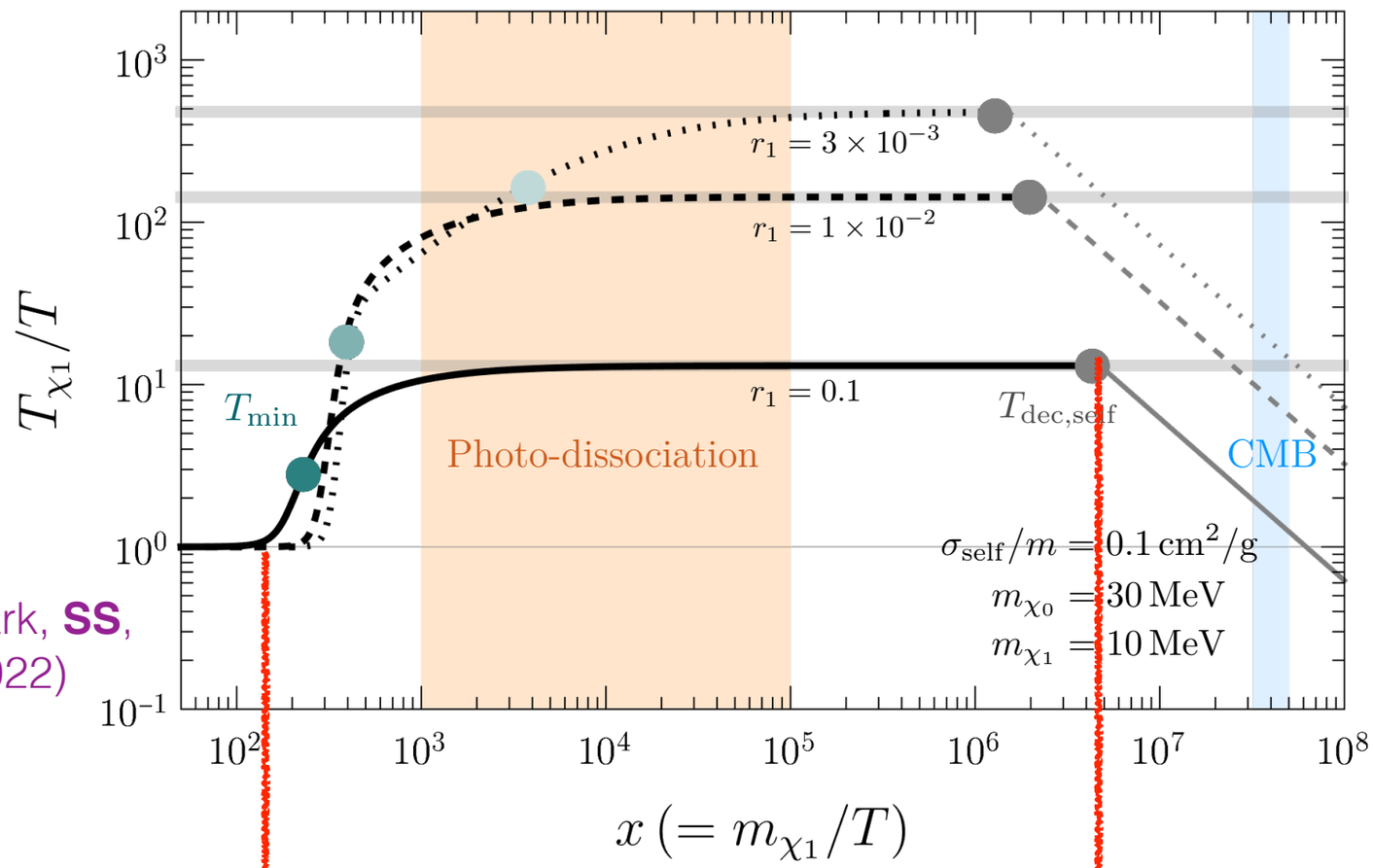

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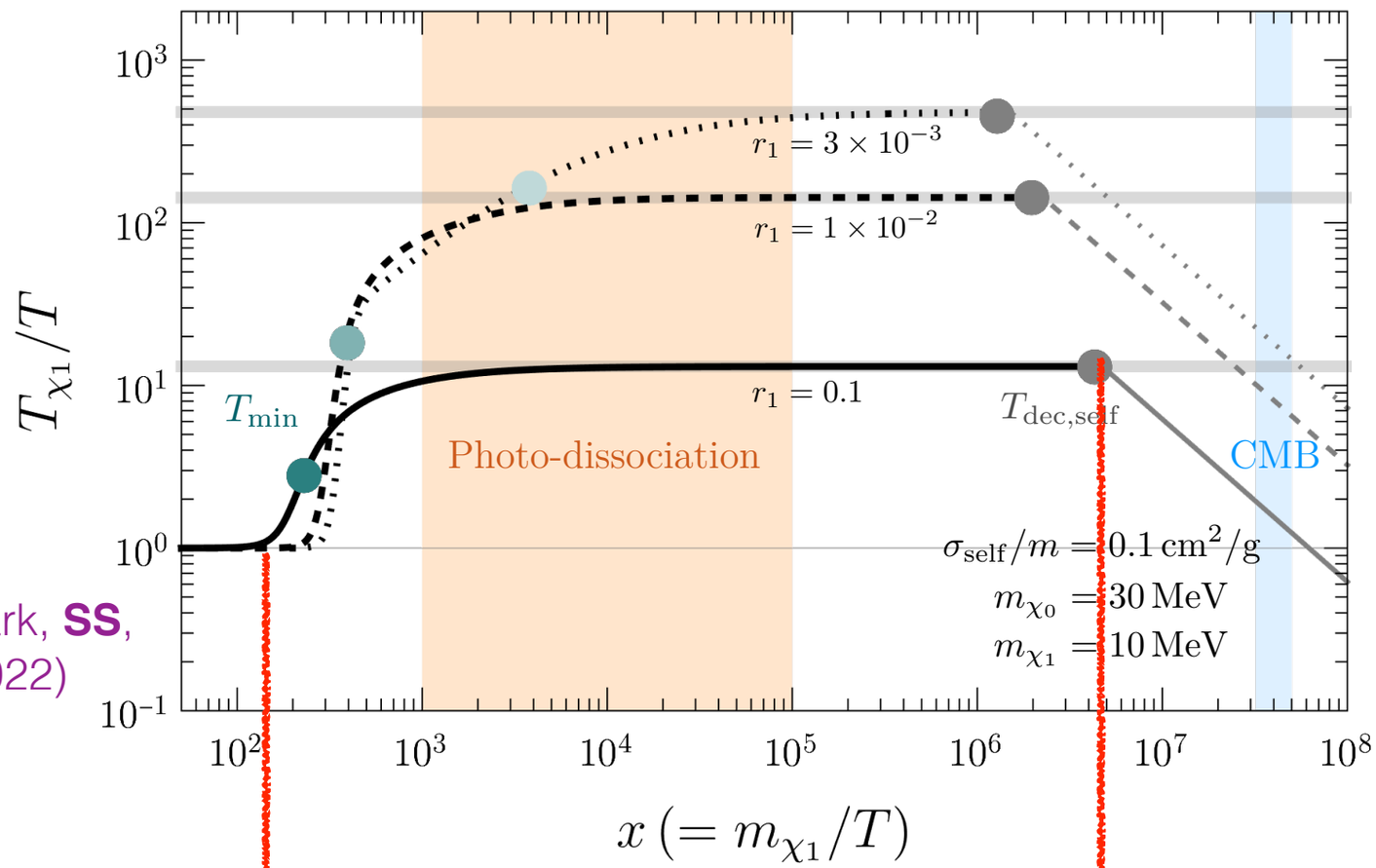

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Kinetic decoupling of χ_1 (from the SM)

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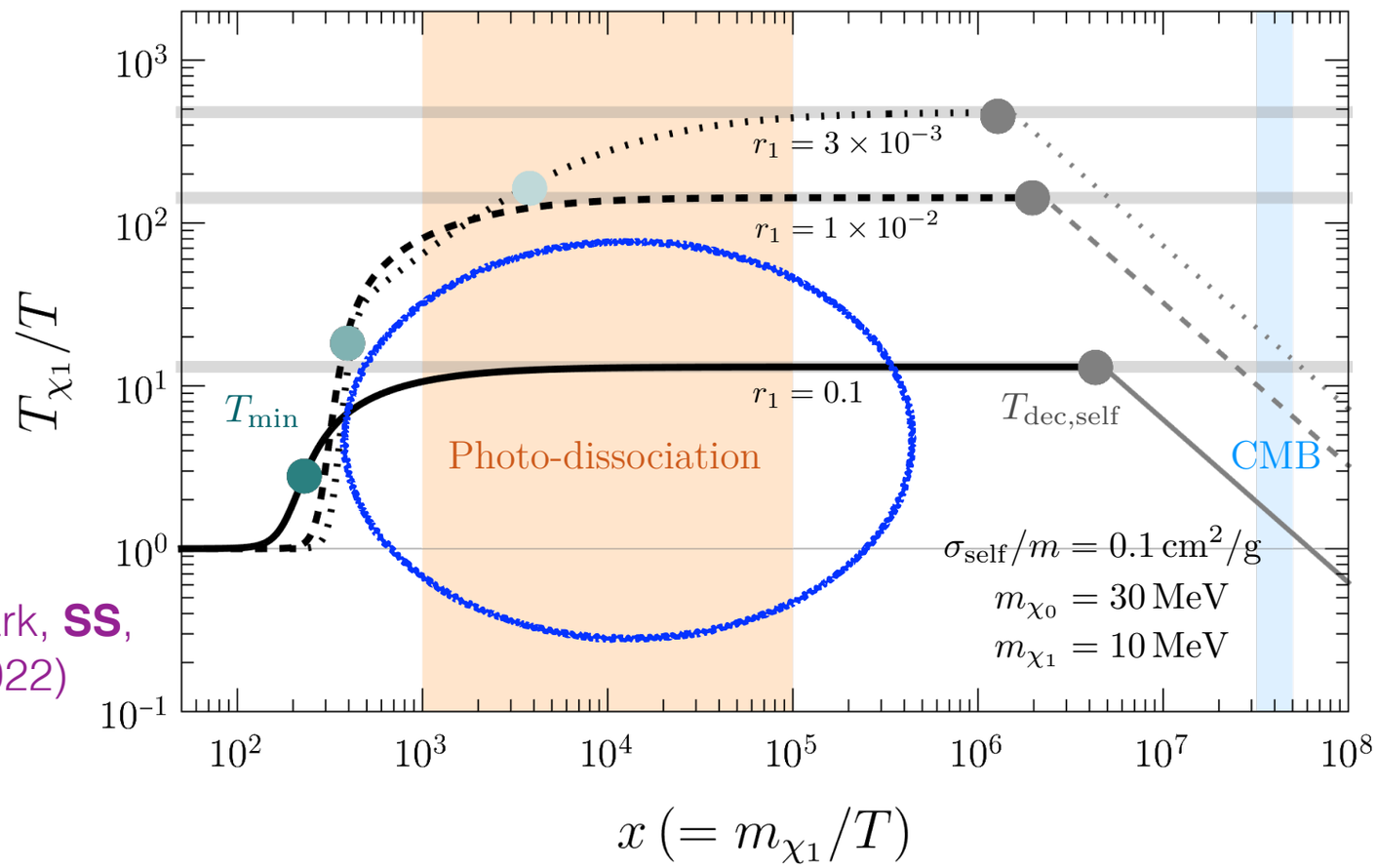
- If self-heating is efficient even after the kinetic decoupling, the temperature evolution of χ_1 makes it behave like a radiation.

Temperature evolution of χ_1



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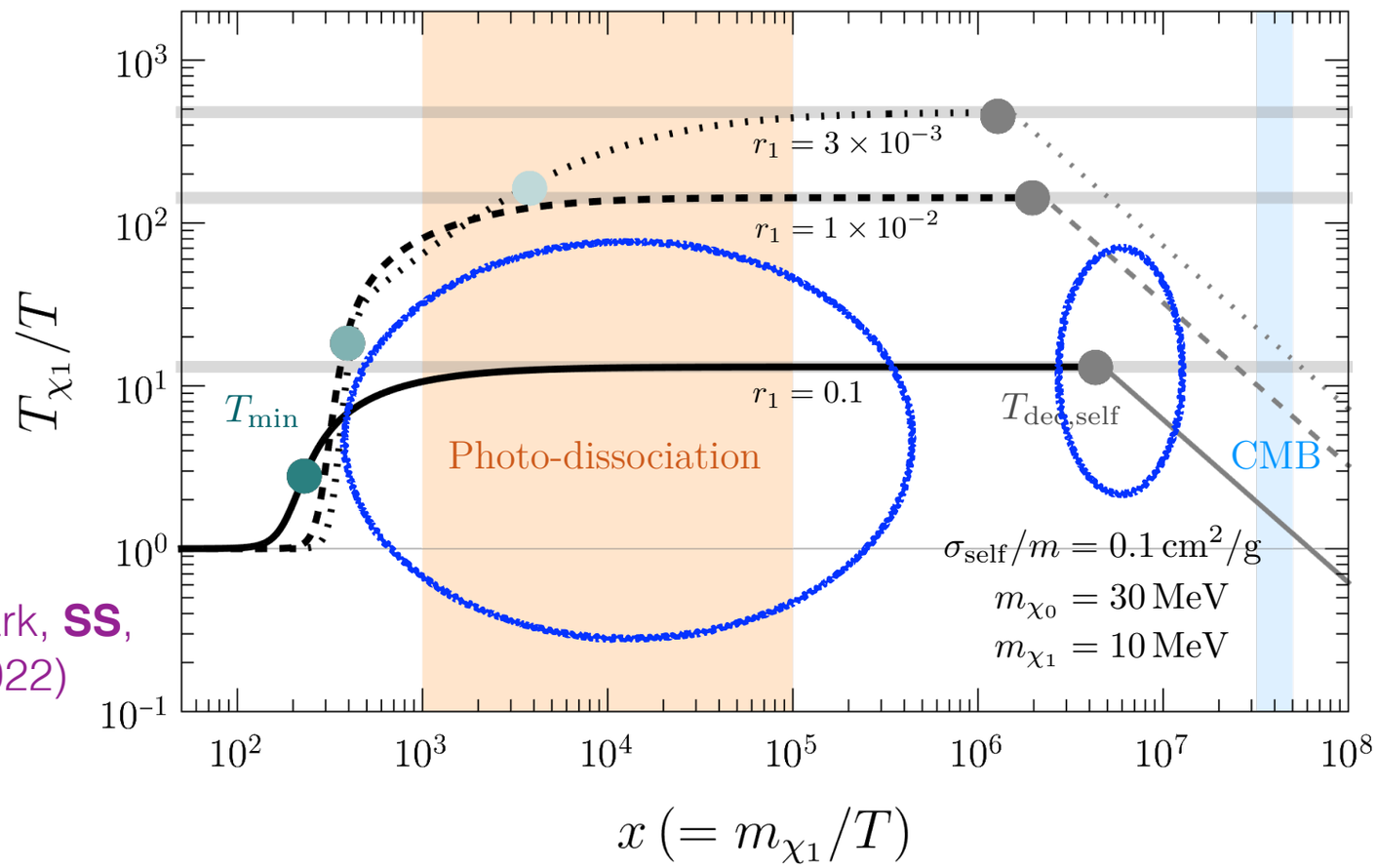

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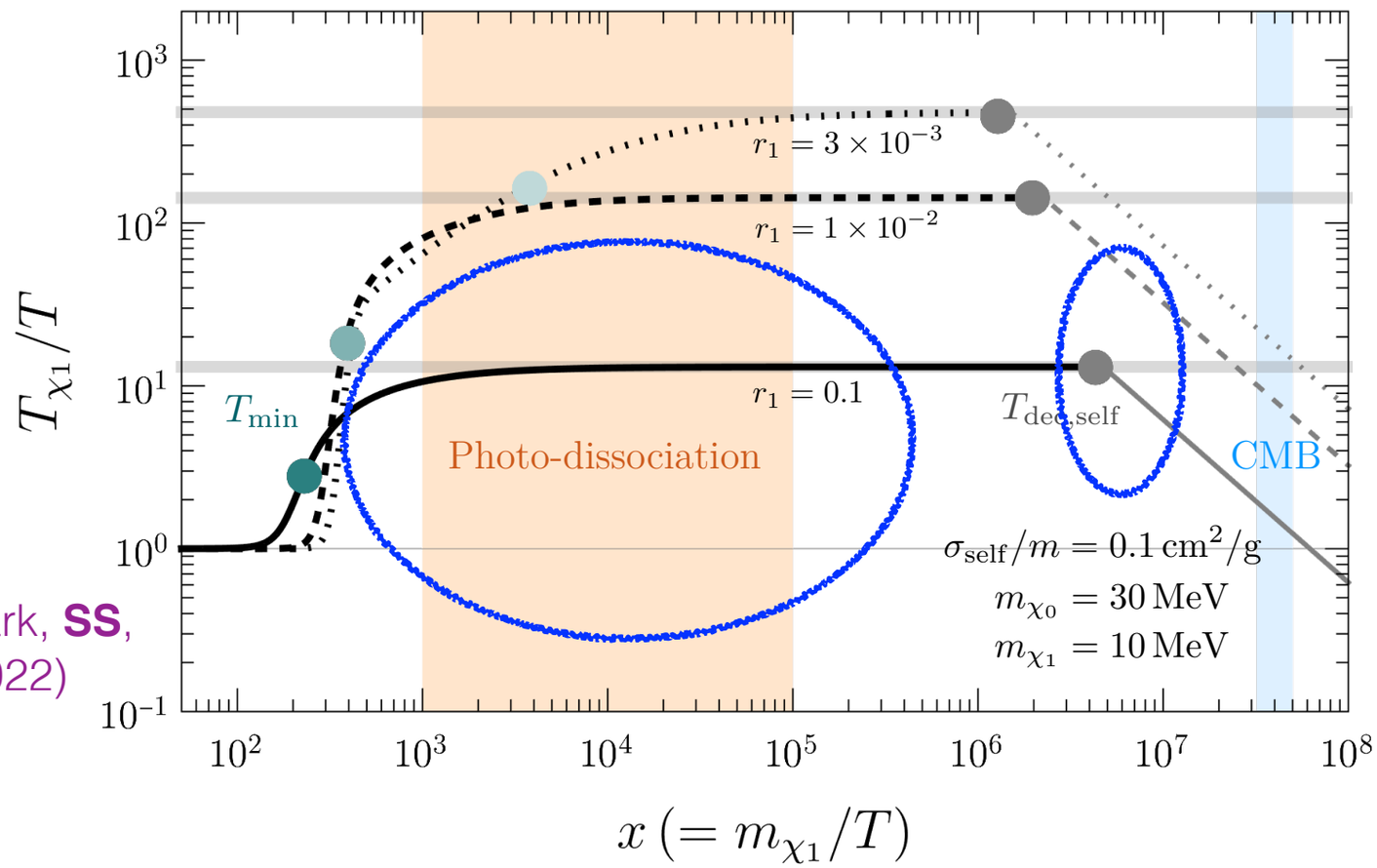

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χ_1 can be sub-GeV Warm Dark Matter!!

Lyman-α

# of satellites

New bounds due to self-heating

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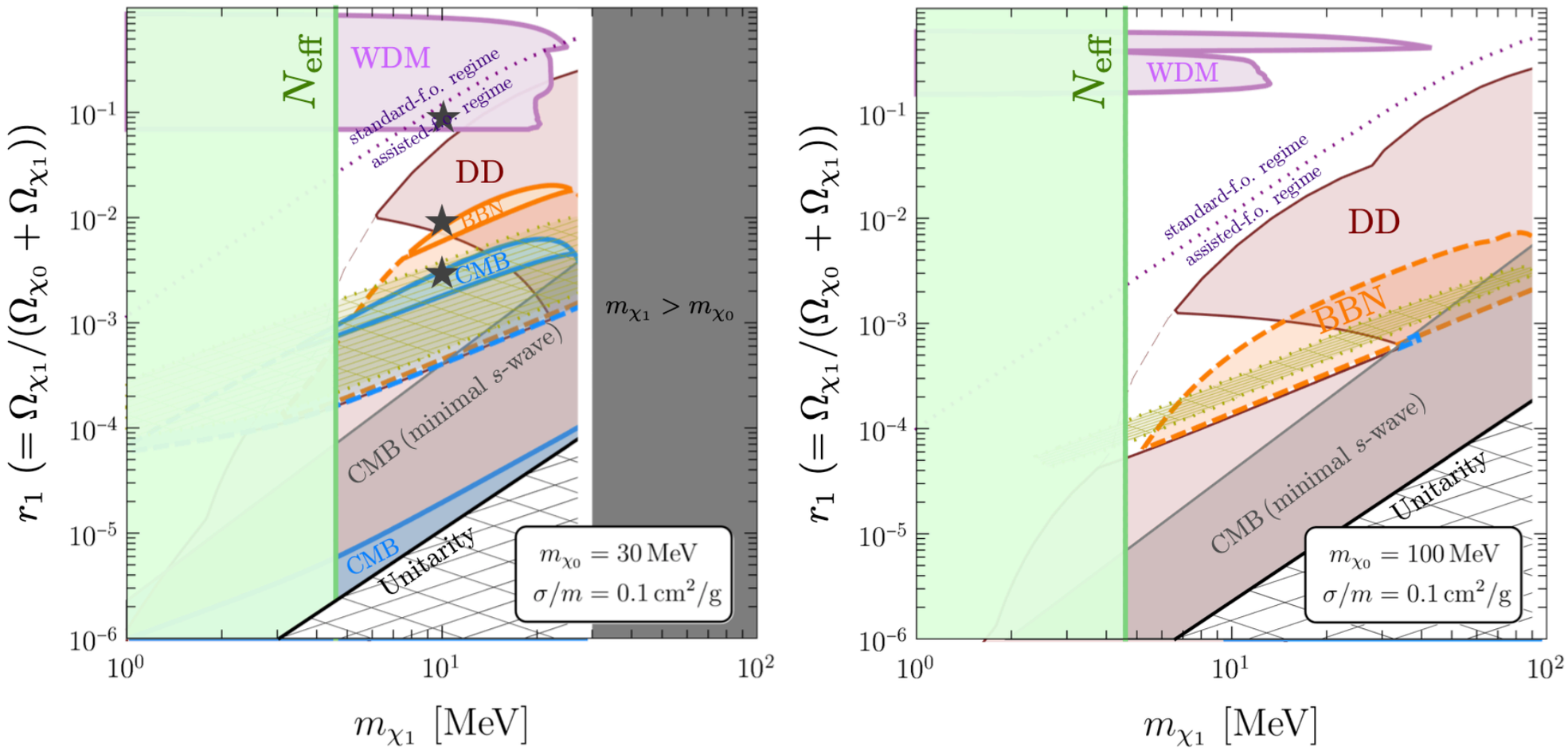


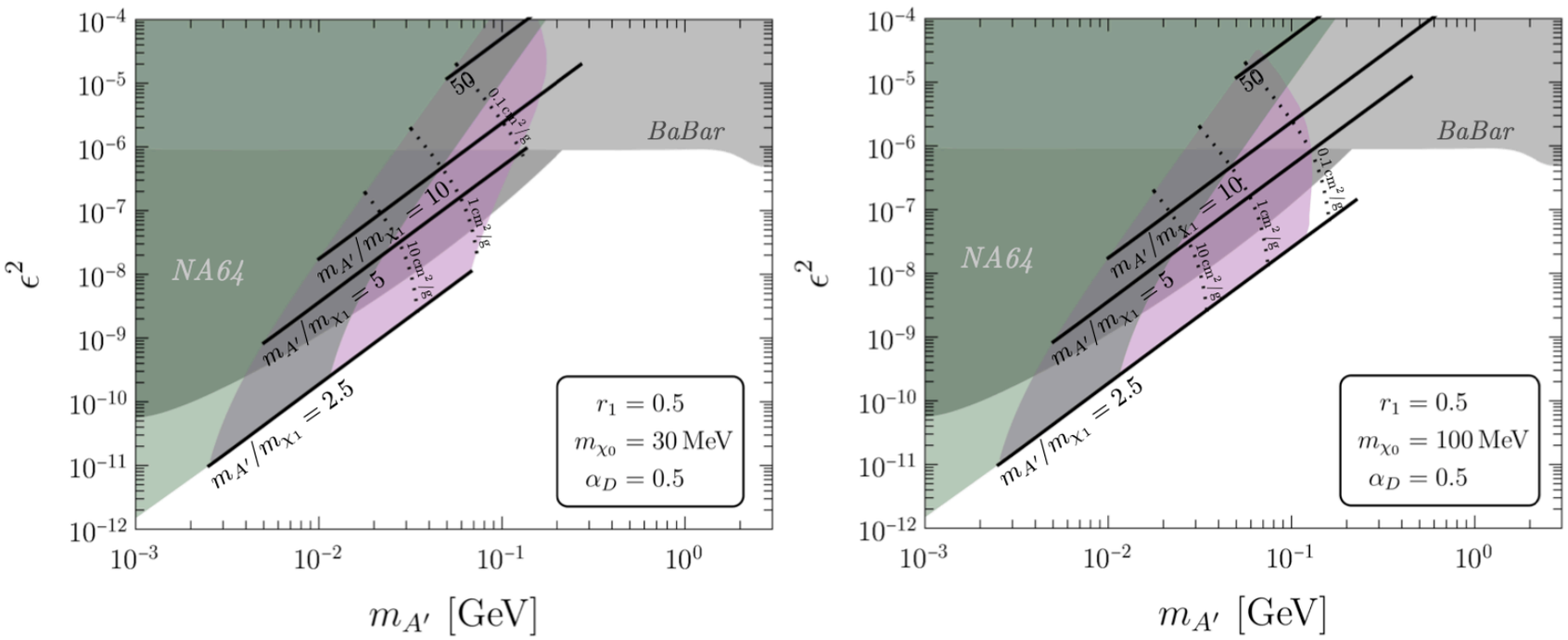
- WDM constraint enters when $r_1 \gtrsim 0.07$ even for $m_{\chi_1} \sim 40$ MeV.

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

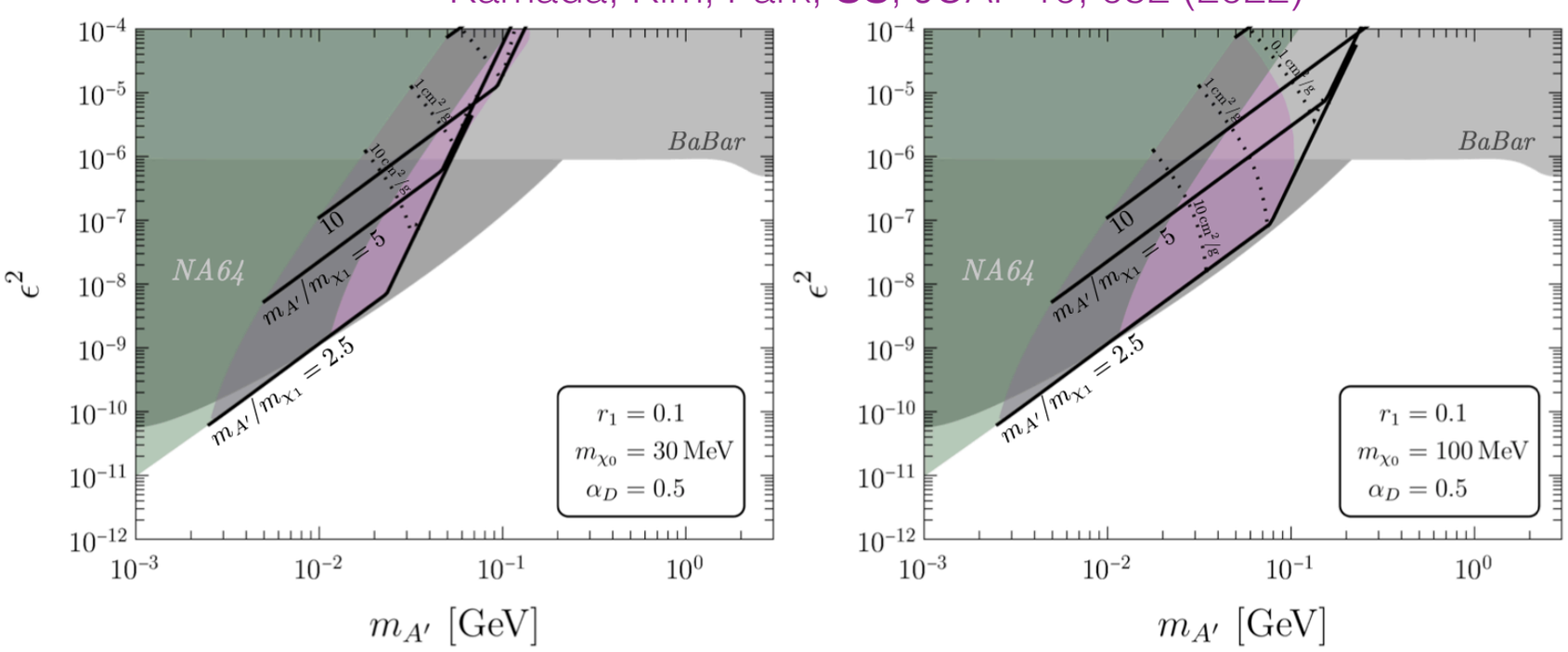
- ★: reference values of r_1 in the temperature evolution (previous slide)

Complementary searches

Light DM can be produced in accelerators with high intensities!



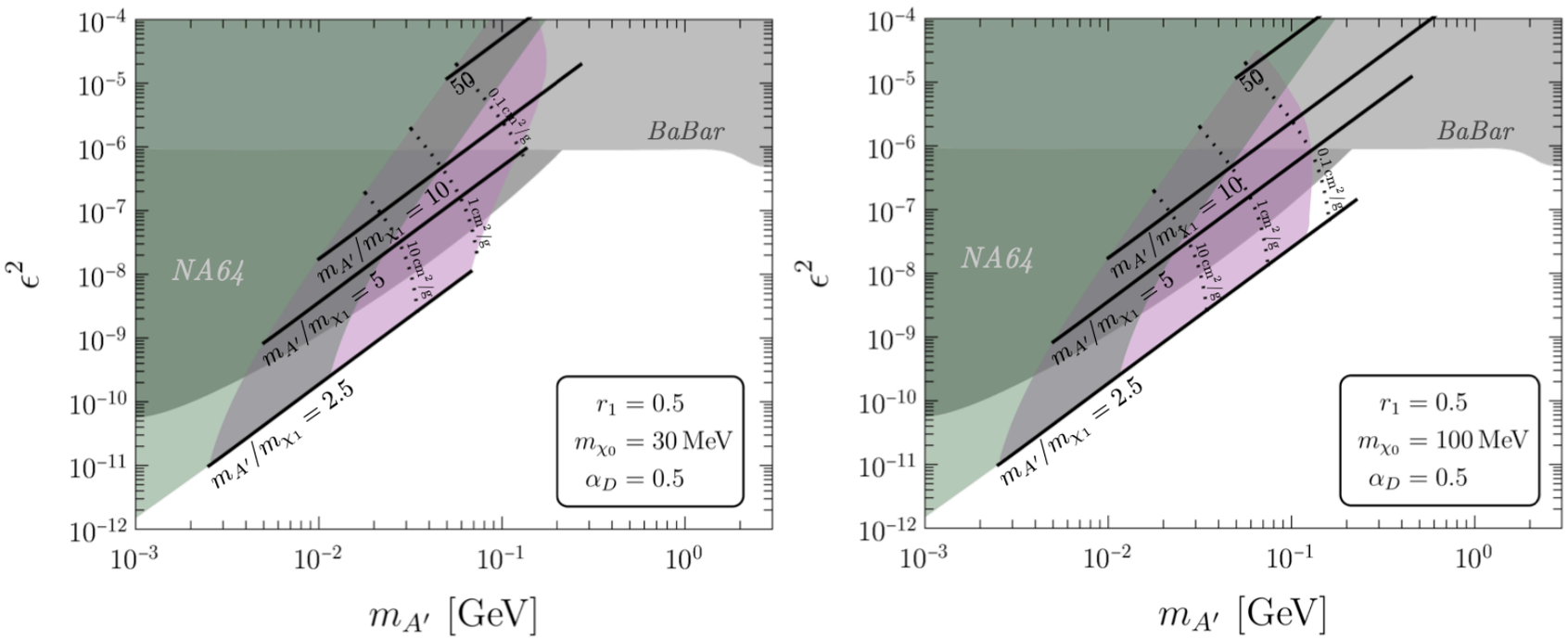
Kamada, Kim, Park, **SS**, JCAP 10, 052 (2022)



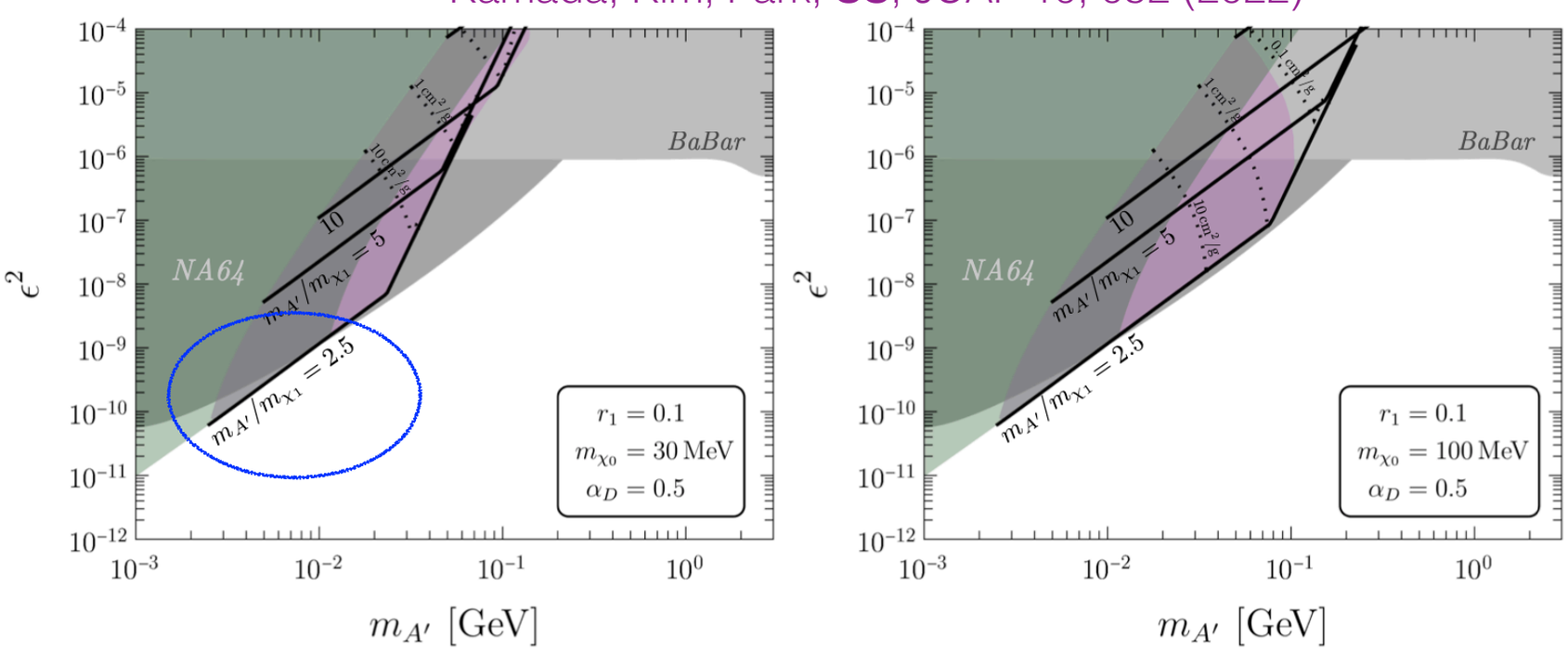
- Reference model: singlet scalar DM + dark photon (p-wave)
- Green: N_{eff}, Pink: WDM for $r_1 \gtrsim 0.07$.

Complementary searches

Light DM can be produced in accelerators with high intensities!



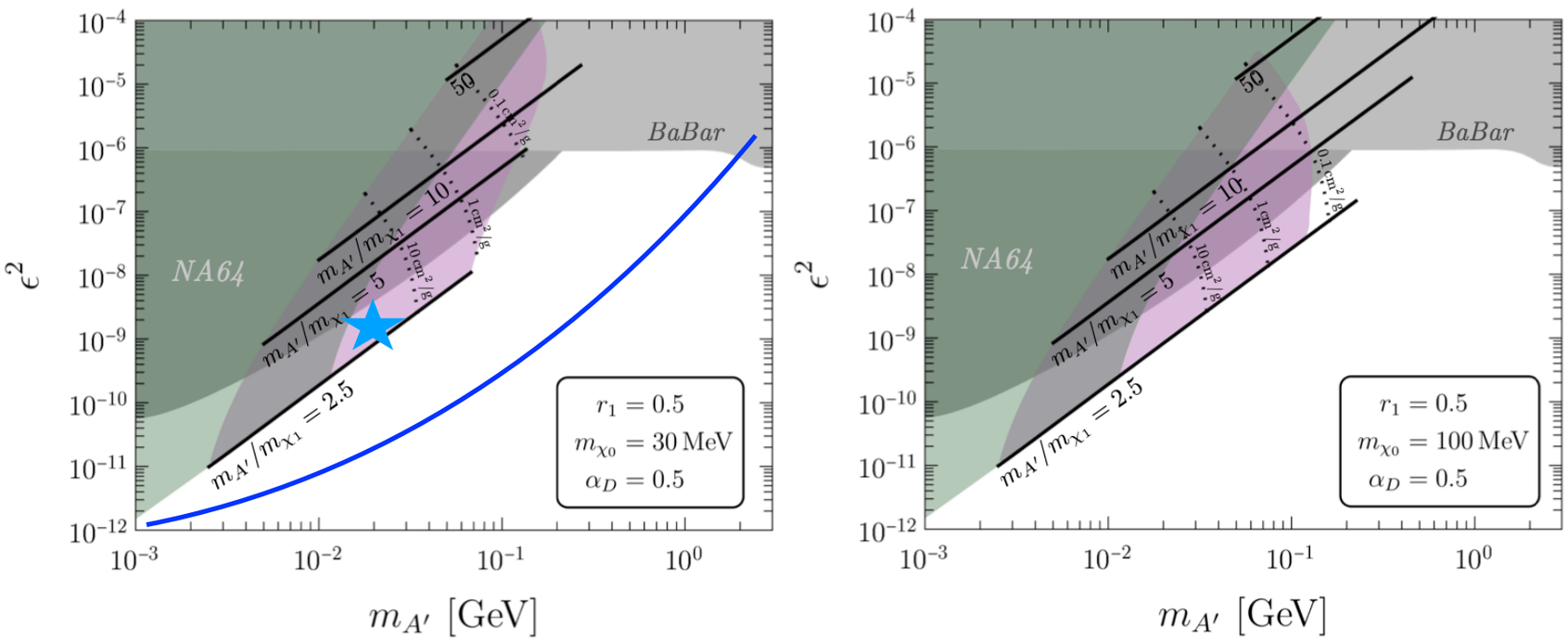
Kamada, Kim, Park, **SS**, JCAP 10, 052 (2022)



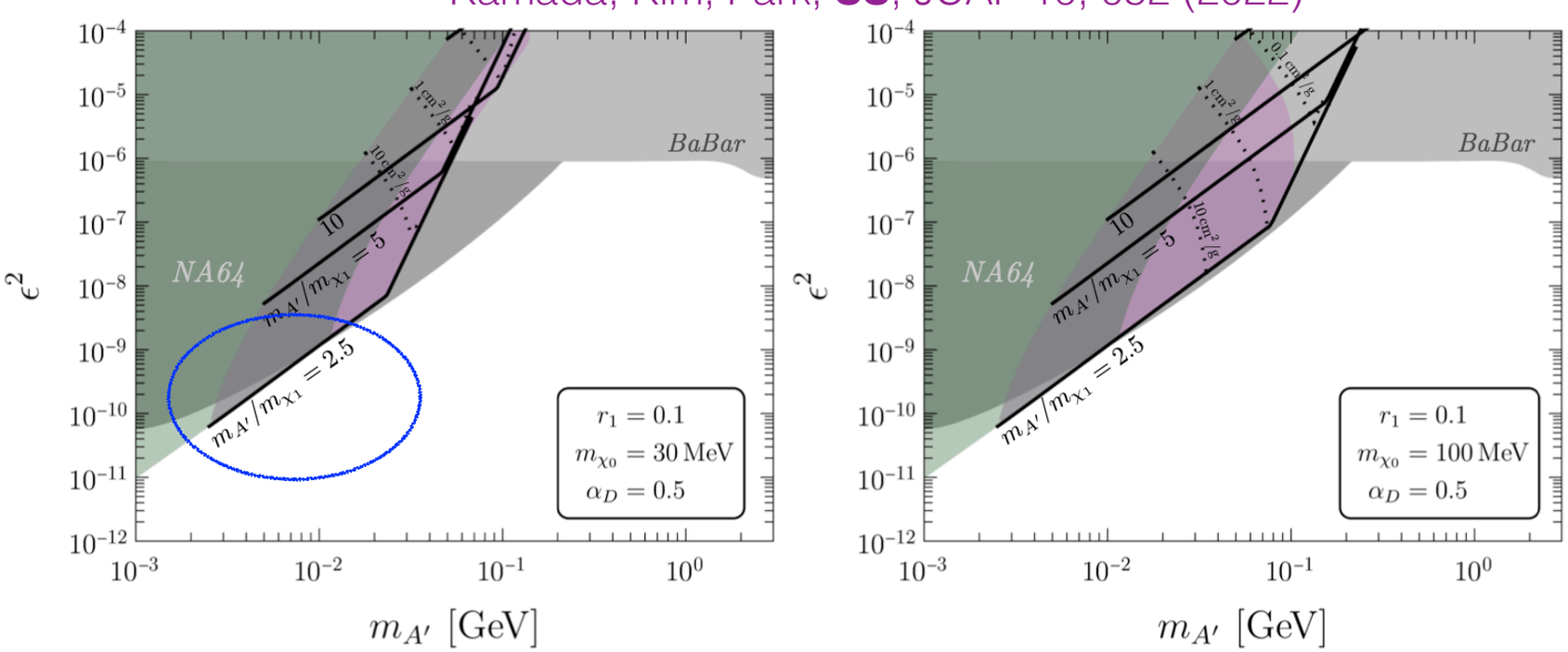
- Reference model: singlet scalar DM + dark photon (p-wave)
- Green: N_{eff}, Pink: WDM for $r_1 \gtrsim 0.07$.
- For $r_1 \lesssim 0.07$, not preferred by the accelerator results.

Complementary searches

Light DM can be produced in accelerators with high intensities!



Kamada, Kim, Park, **SS**, JCAP 10, 052 (2022)



- Reference model: singlet scalar DM + dark photon (p-wave)
- Green: N_{eff}, Pink: WDM for $r_1 \gtrsim 0.07$.
- 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: p-wave χ_1 - SM is preferred but still constrained!. (Multi-component p-wave scenarios are not always safe.)

- 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:

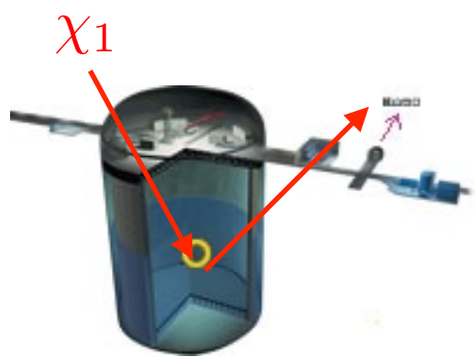
  a sub-GeV mass Warm Dark Matter (heavy WDM) for $r_1 \gtrsim 0.07$!

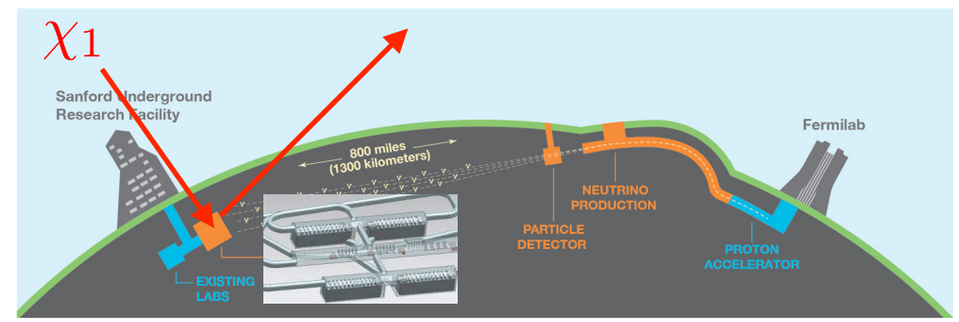
  → This is true even when χ_1 is a dominant component DM.

- Complementary searches in accelerators can give hints on the dark sector details (disfavor $r_1 \lesssim 0.07$ for a reference model).

Backup

- Neutrino Experiments





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

Editors' Suggestion

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

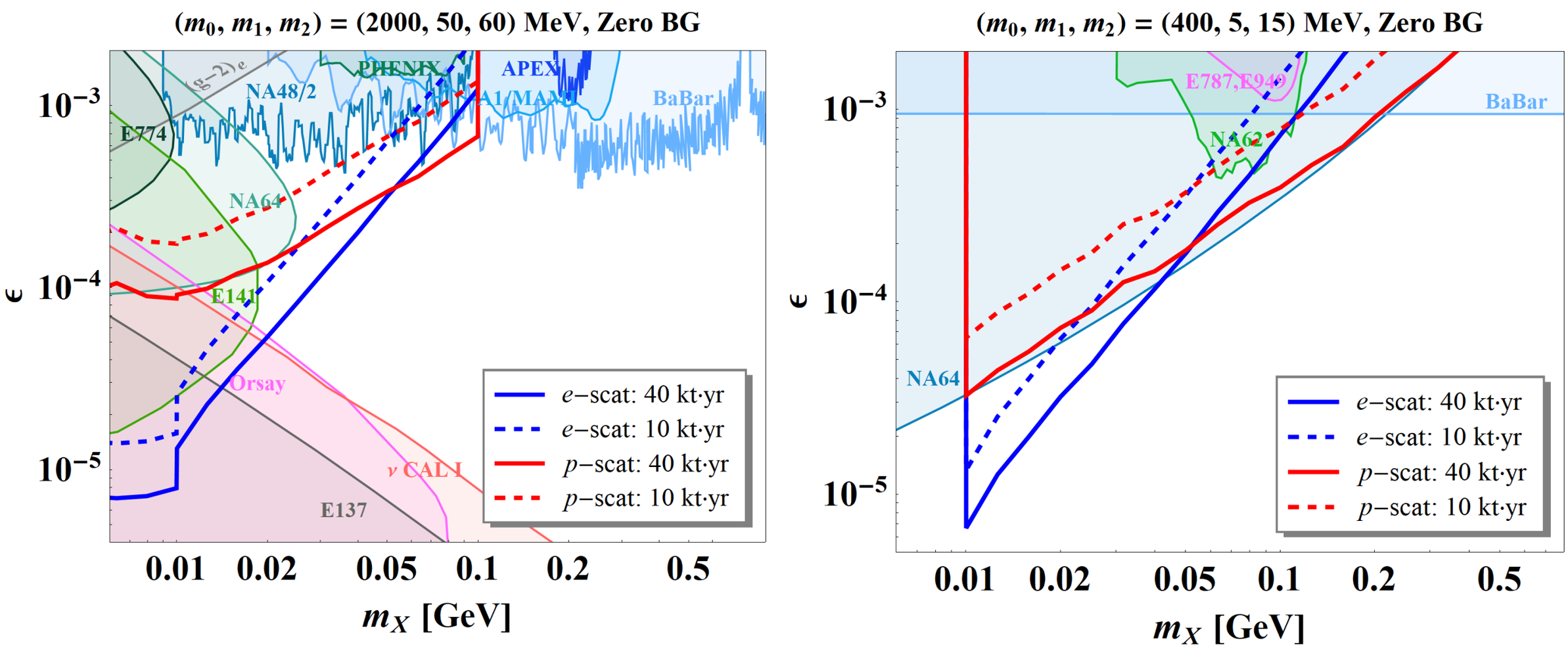
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

8.8 Dark Matter Probes . . . . . .
8.8.1 Benchmark Dark Matter Models . . . . . .
8.8.2 Search for Low-Mass Dark Mater at the Near Detector . .
8.8.3 Inelastic Boosted Dark Matter Search at the DUNE FD .
8.8.4 Elastic Boosted Dark Matter from the Sun . . . . . .

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

Backup

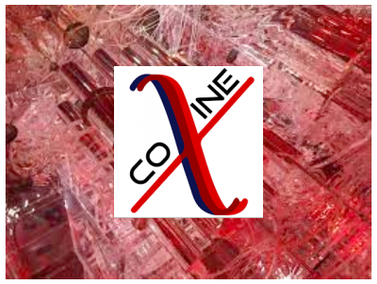
DUNE



De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead,2005.08979

Backup

- Dark Matter direct detection experiments

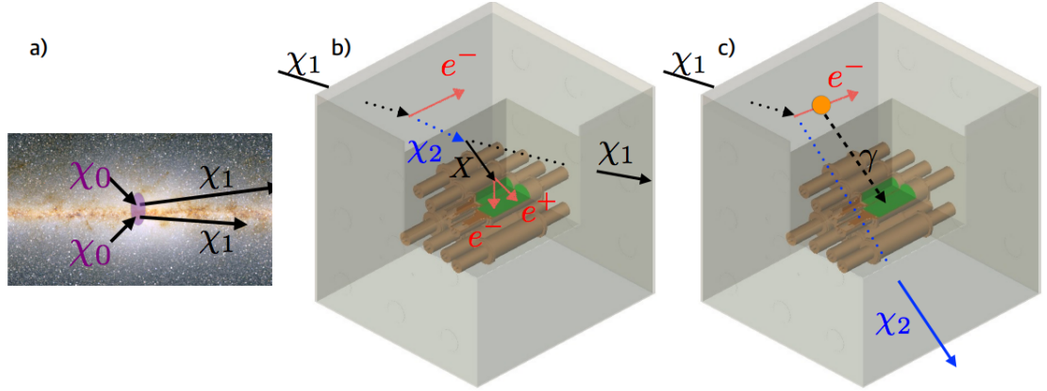


PHYSICAL REVIEW LETTERS **122,** 131802 (2019)

Editors' Suggestion

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

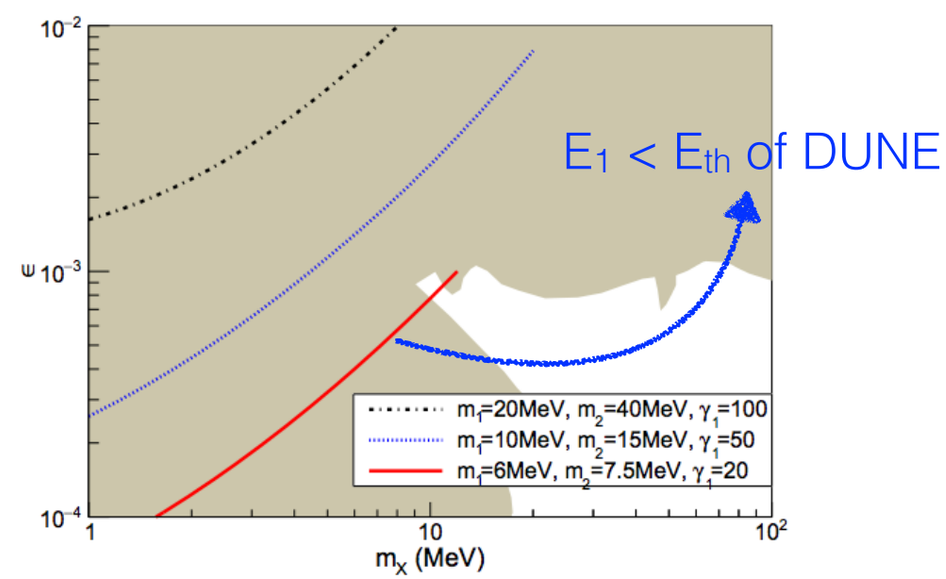
Based on the suggestion in Giudice, Kim, Park, **SS**, PLB 2018



2200L of liquid scintillator
(~ 2 ton)

106kg array of 8 ultra-pure NaI(Tl) crystals
immersed in an active veto detector

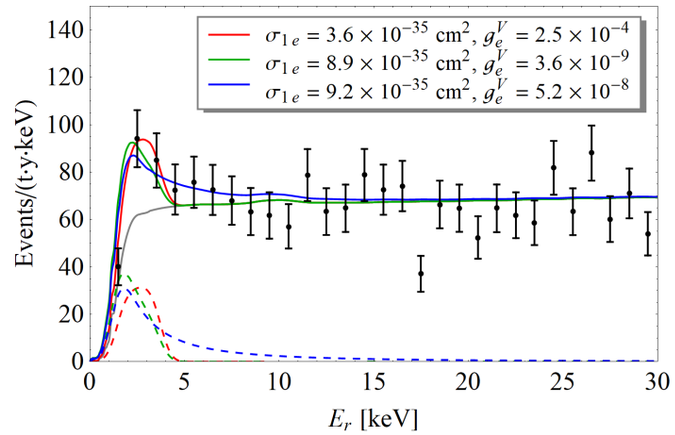
Observed: 21 events
Background expected: 16.4 ± 2.1



Backup

- Dark Matter direct detection experiments

June 2020



Smoking gun??

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

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

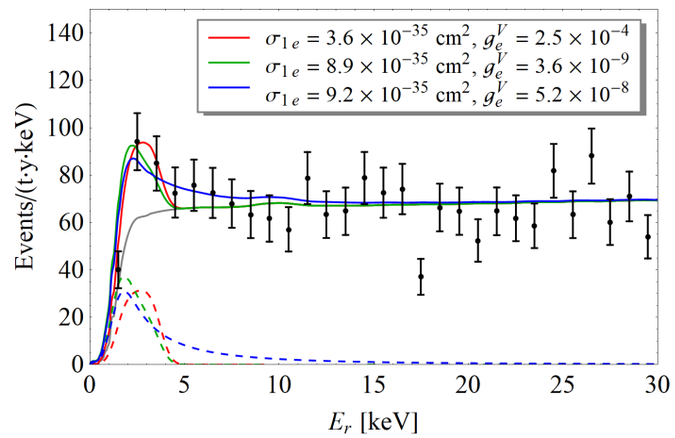
Backup

- Dark Matter direct detection experiments

Smoking gun??

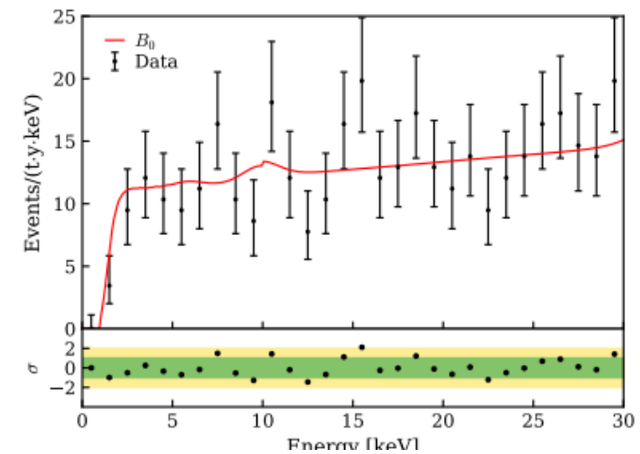
Giudice, Kim, Park, **SS**, PLB 2018

June 2020



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

July 2022



Tritium contamination in Xe1T

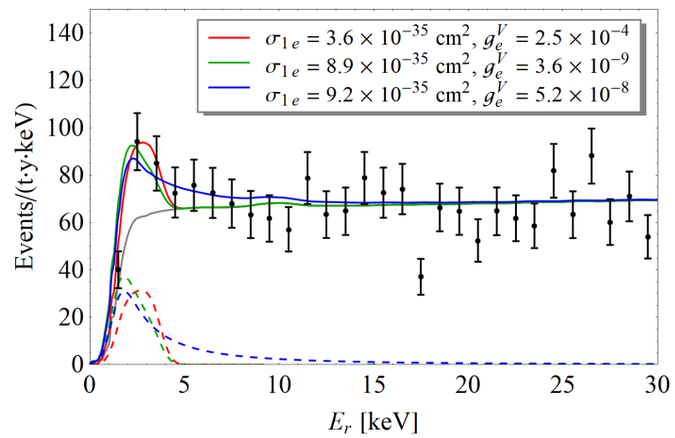
Backup

- Dark Matter direct detection experiments

Smoking gun??

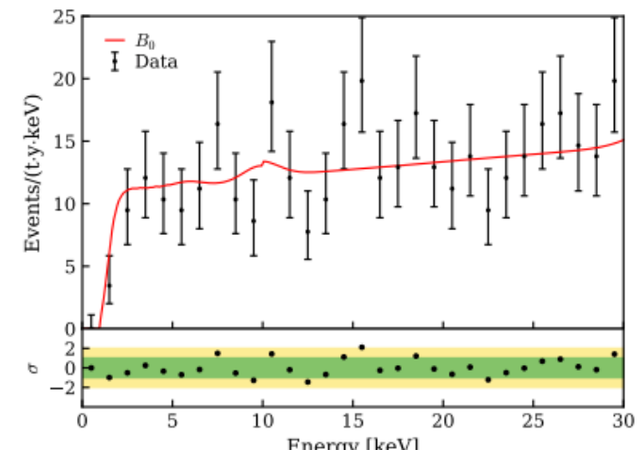
Giudice, Kim, Park, **SS**, PLB 2018

June 2020



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

July 2022



Tritium contamination in Xe1T

Nevertheless, many powerful DM direct detection experiments are underway and let's see what they can discover!