WCCP 2021, Jeju

Astrophysical territory of multi-component (boosted) dark matter: Hidden dynamics of a sub-component

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JEONBUK NATIONAL UNIVERSITY

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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  DM - SM → i) Observation
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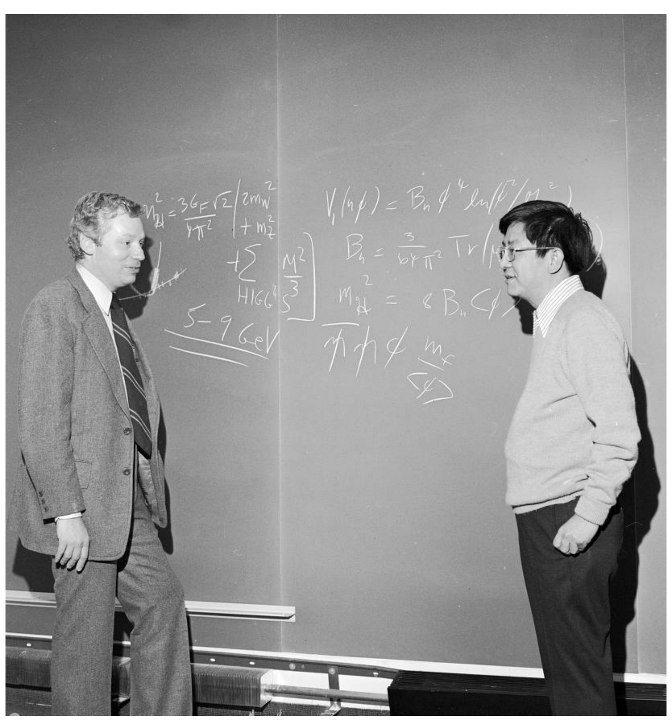
Preferred candidate so far was

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

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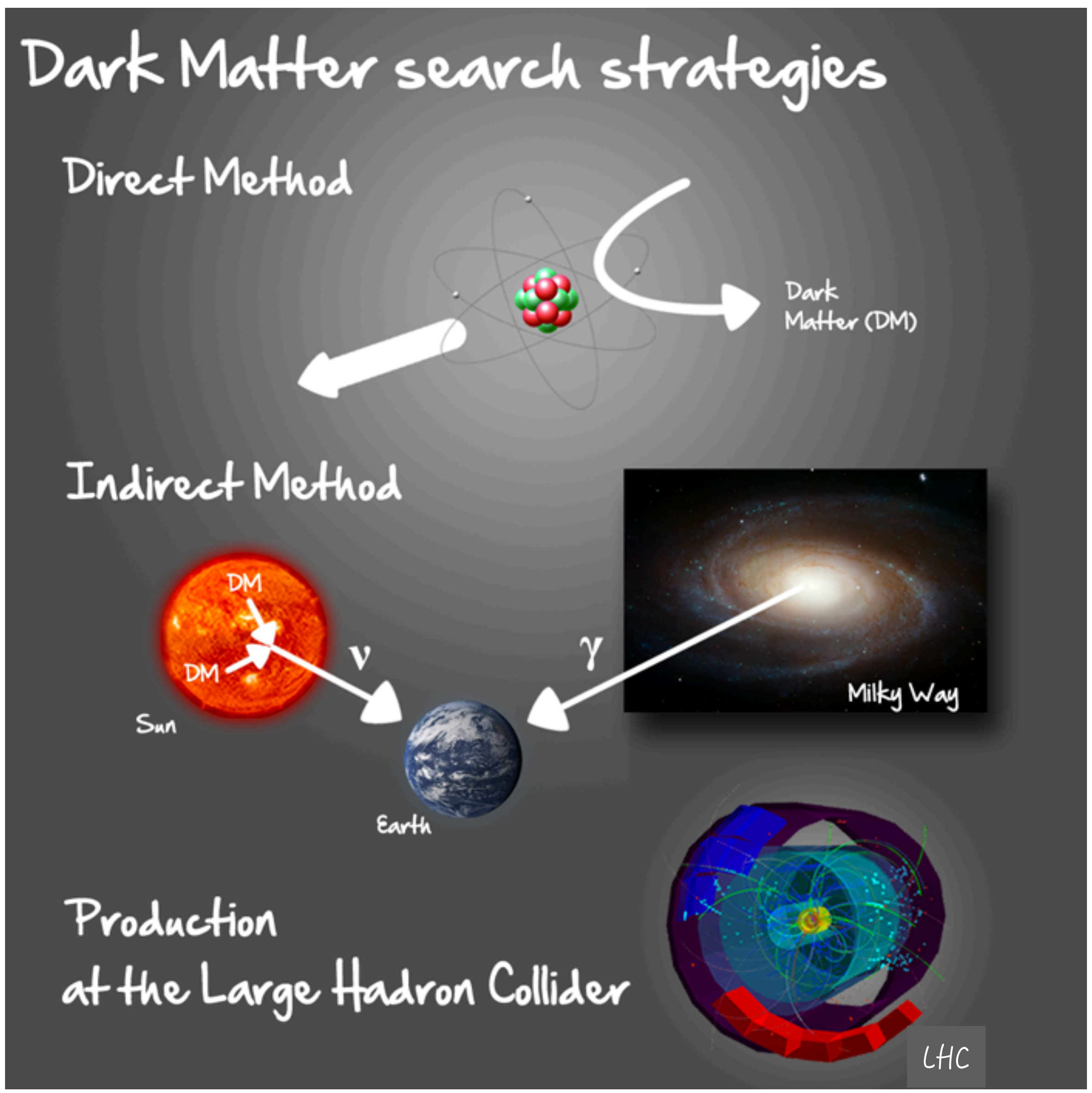
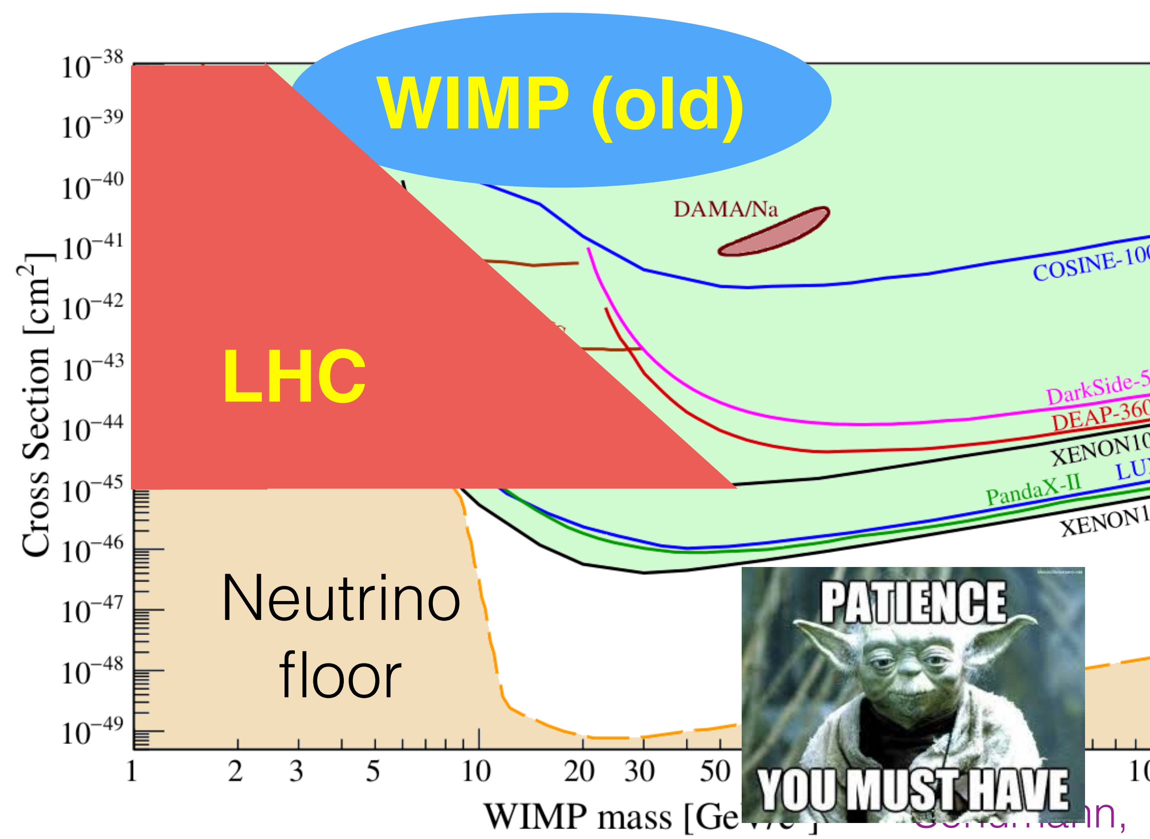


WIMP strongly constrained!



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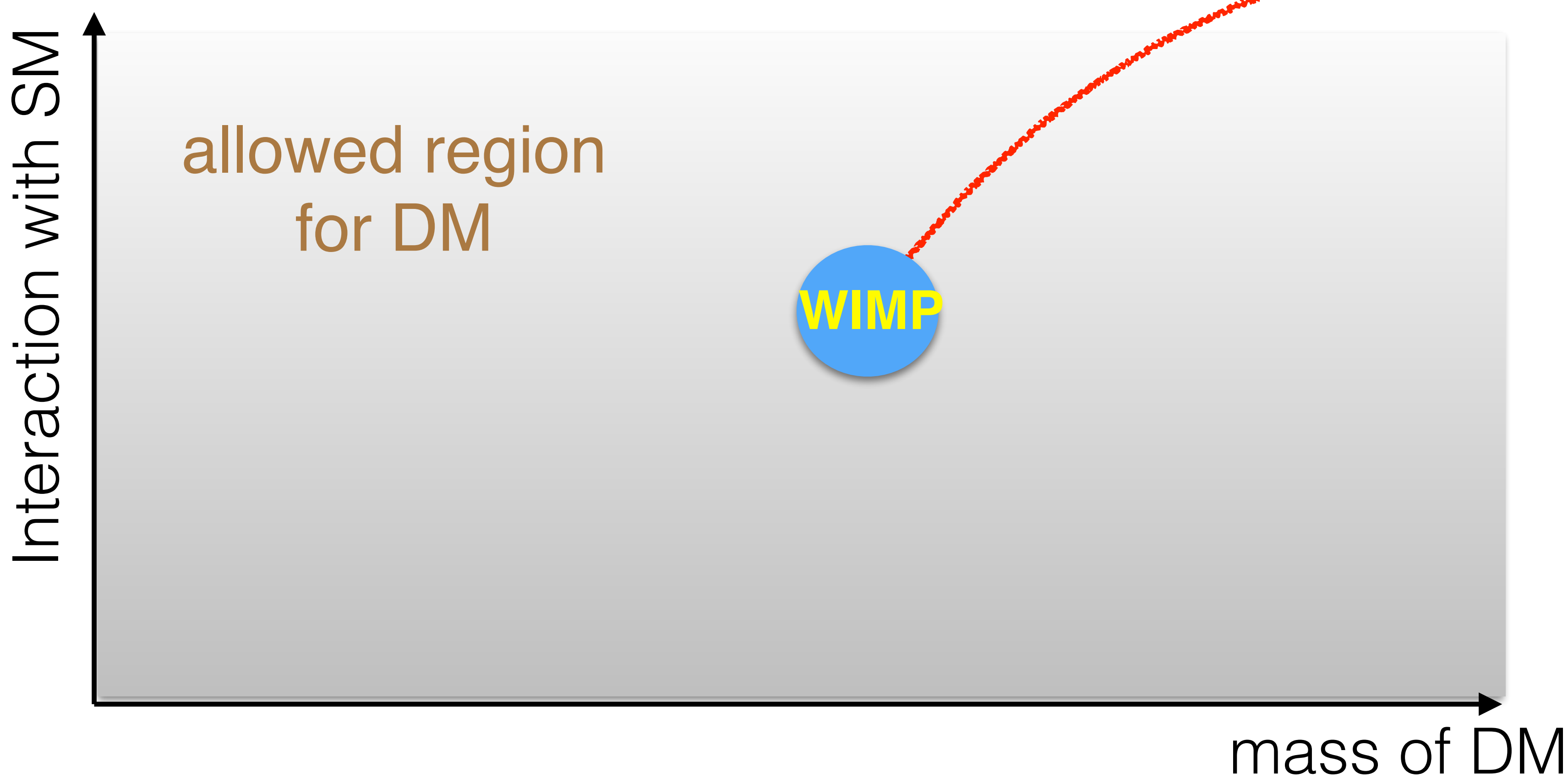
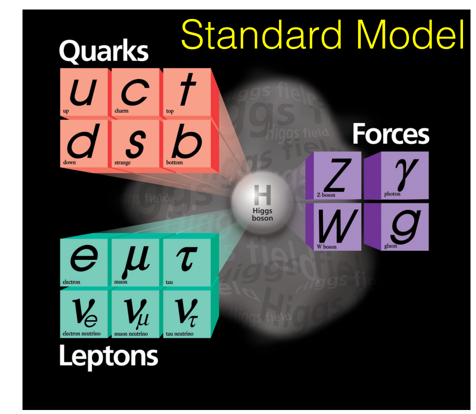
Dark World beyond WIMP

WIMP may be a theoretical bias.



- Small region
- Oversimplification compared to



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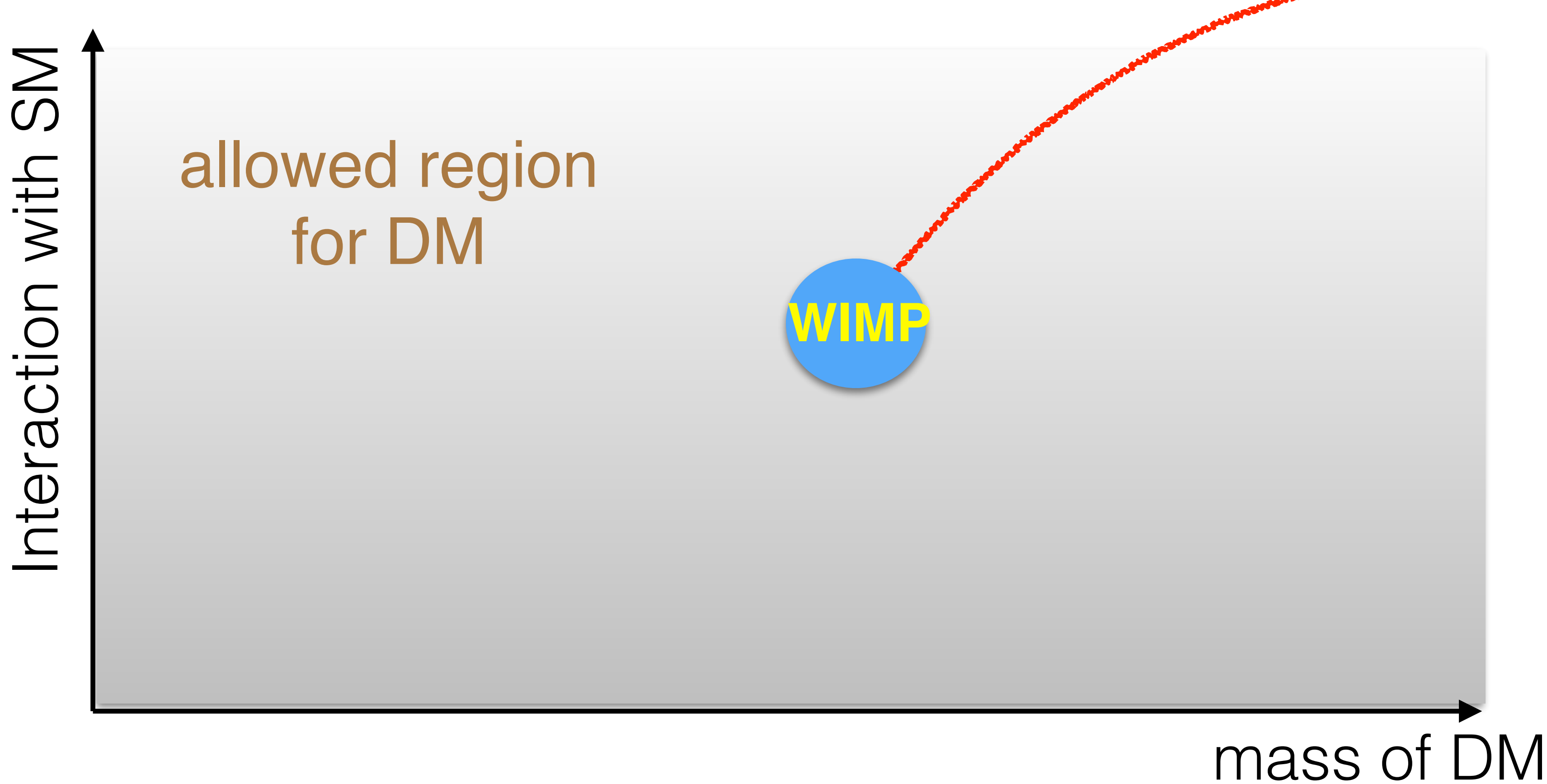

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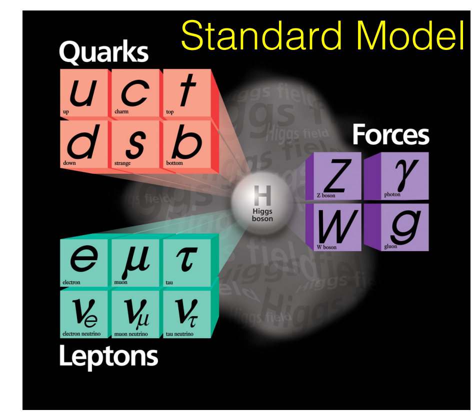

- Dark matter theories with novel dark sector structures beyond WIMP have been actively proposed nowadays.

- Boosted Dark Matter (BDM) where a (or multiple) light boosted DM is produced by the unique dark sector structure or energy transfer processes at the present universe is being focused recently.

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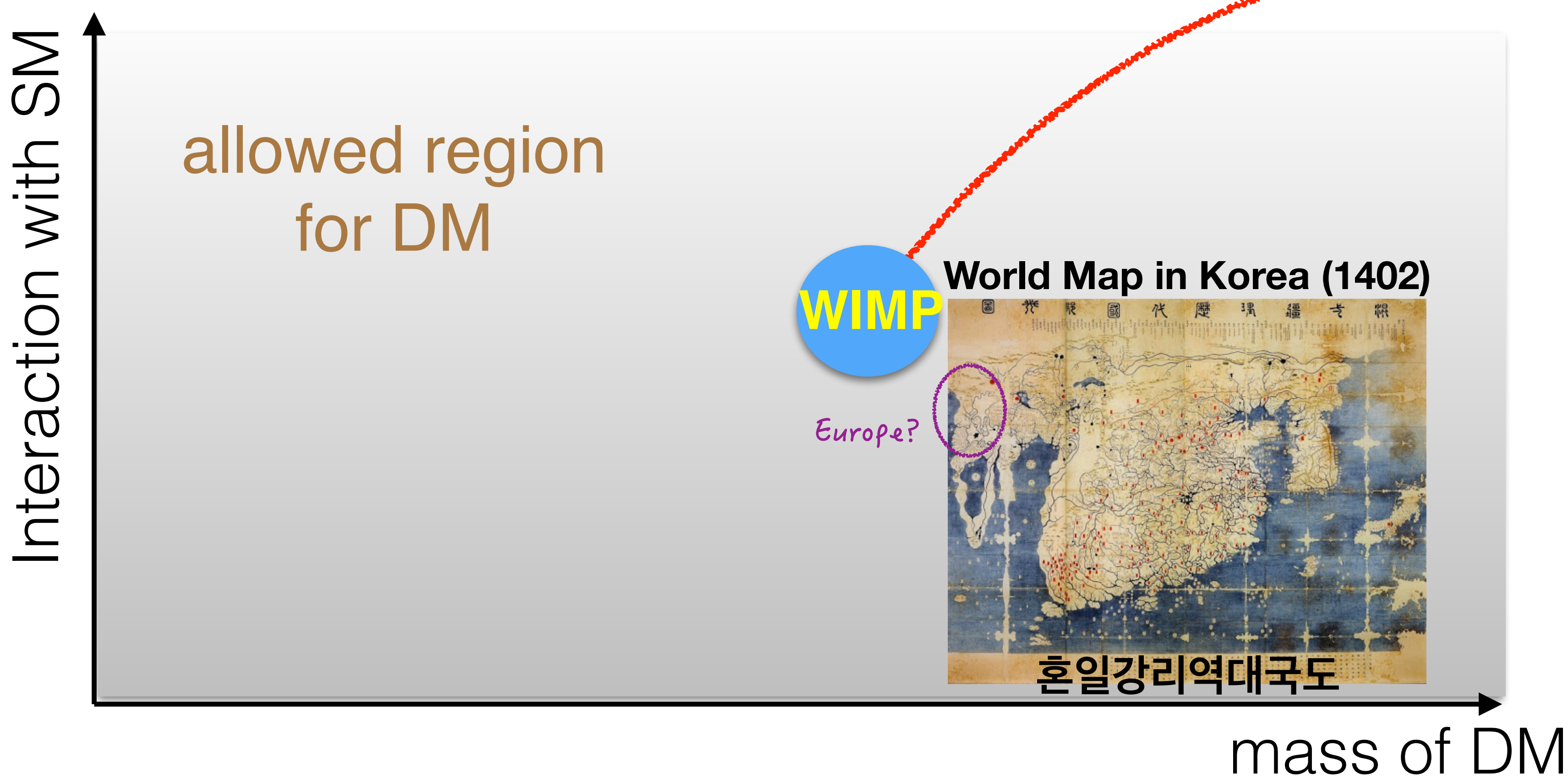

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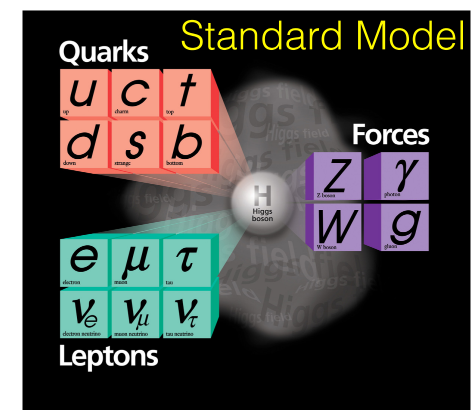

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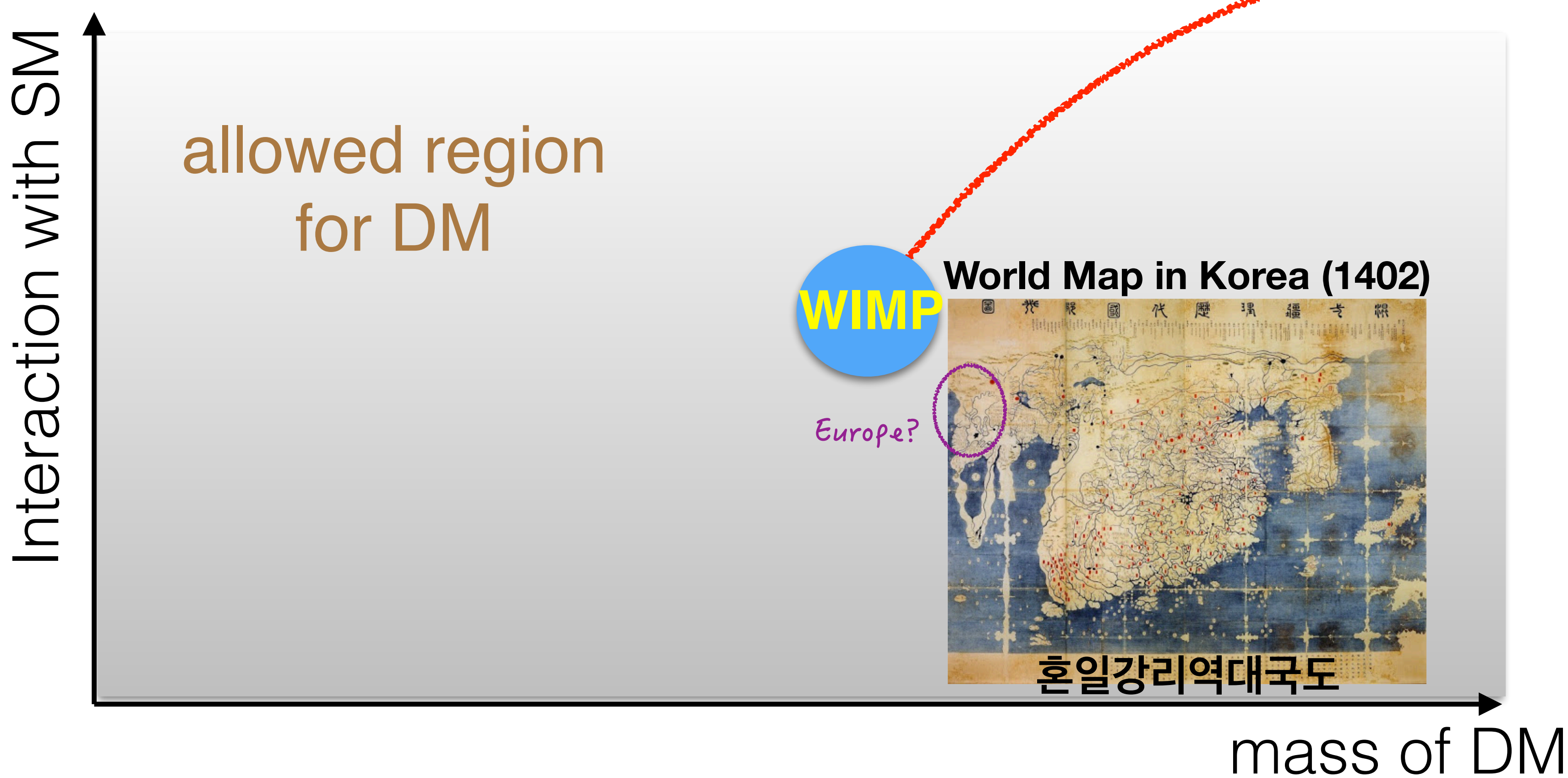

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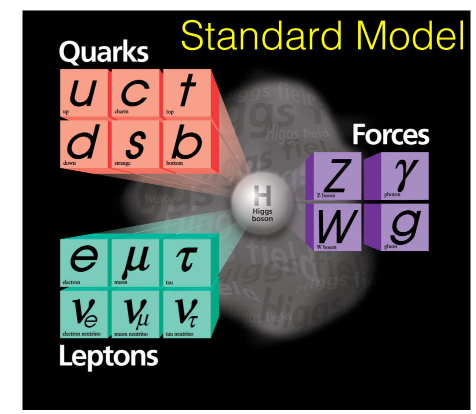

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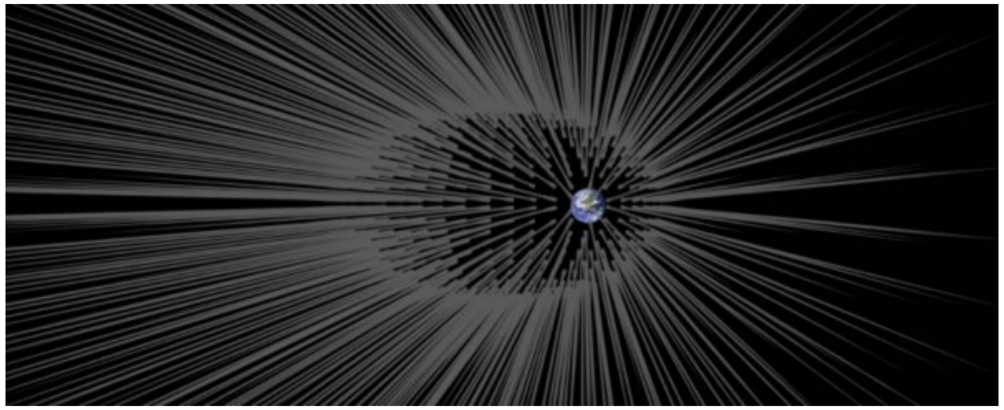
Mechanisms of Boosted Dark Matter

WIMP wind ~ $\mathcal{O}$(100 km/s)



Mechanisms of Boosted Dark Matter

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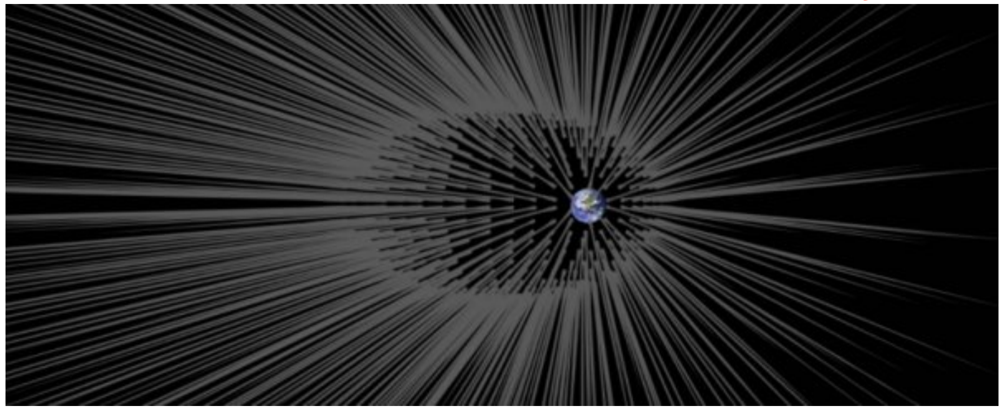

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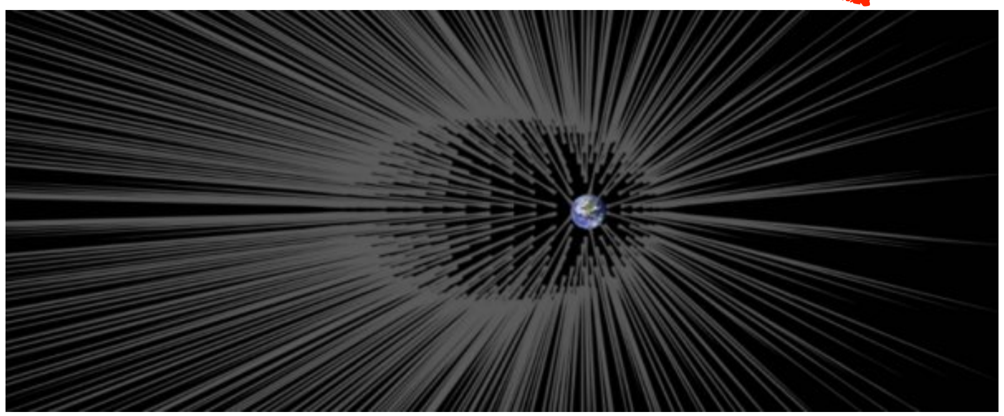


- Dark sector structure

  Agashe, Cui, Necib, Thaler, JCAP 2014 Kim, Park, **SS**, PRL 2017

  Bhattacharya, Gandhi, Gupta, JCAP 2015 Heurtier, Kim, Park, **SS**, PRD 2019

- Scattering with energetic background

  Yin, 1809.08610 Bringmann, Pospelov, PRL 2019 Ema, Sala, Sato, PRL 2019

  Cappiello, Ng, Beacom, PRD 2019 Jho, Park, Park, Tseng, 2021 Cho, Choi, Yoo, 2020

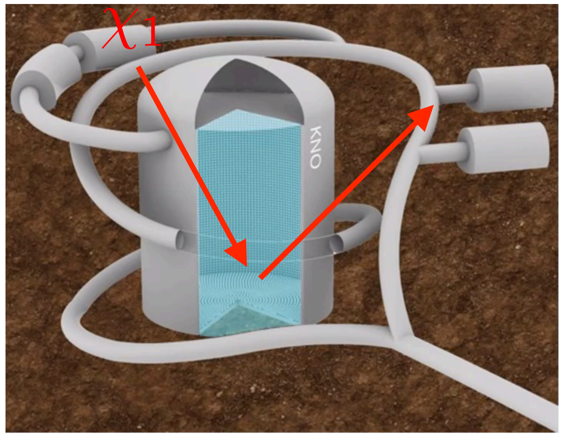
- Production in an astrophysical object providing large kinetic energy, e.g., SN, PBH

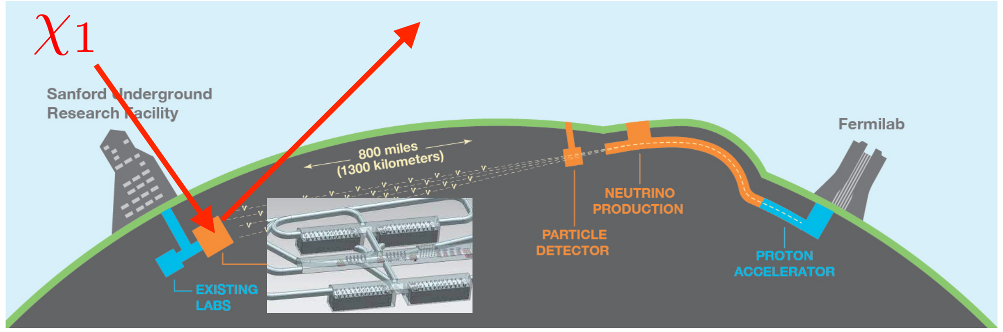
  DeRocco, Graham, Kasen, Marques-Tavares, Rajendran, PRD 2019

  Calabrese, Chianese, Fiorillo, Saviano, 2107.13001

Detection prospects of BDM

- Neutrino Experiments





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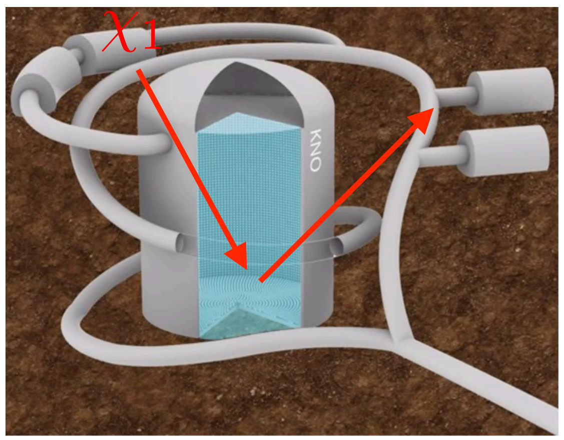
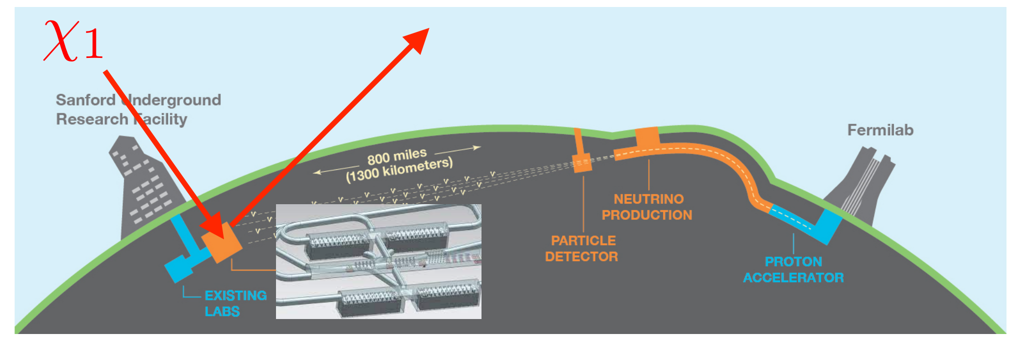


PHYSICAL REVIEW LETTERS **120,** 221301 (2018)

Editors' Suggestion

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



DEEP UNDERGROUND NEUTRINO EXPERIMENT

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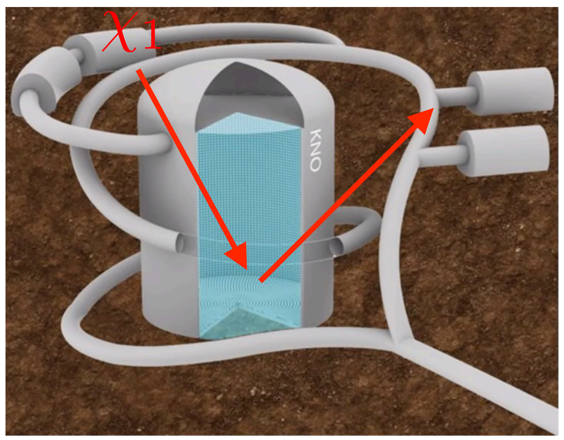

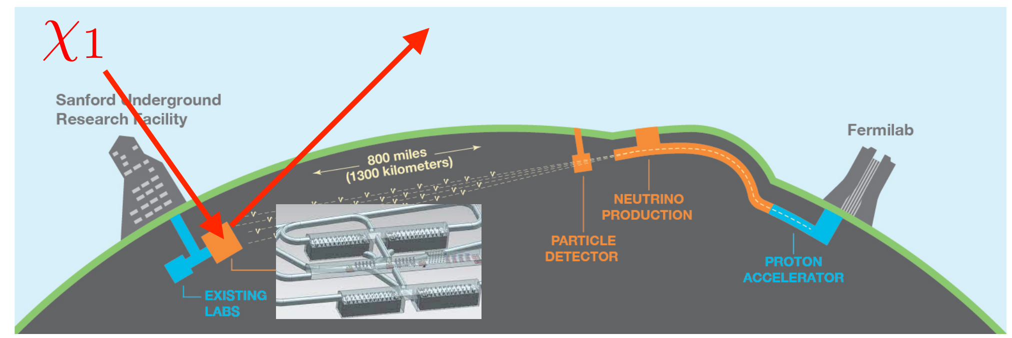

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DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Dark Matter direct detection experiments

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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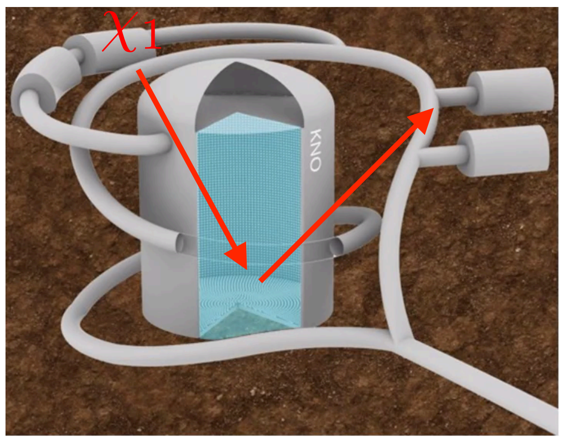

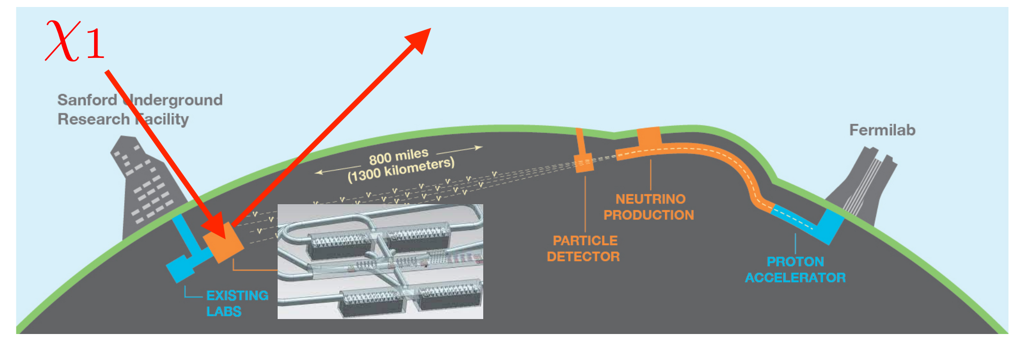

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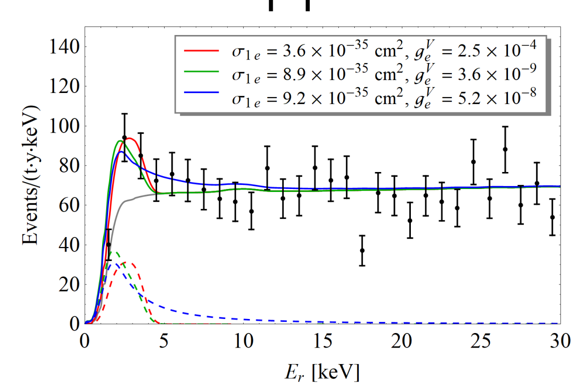
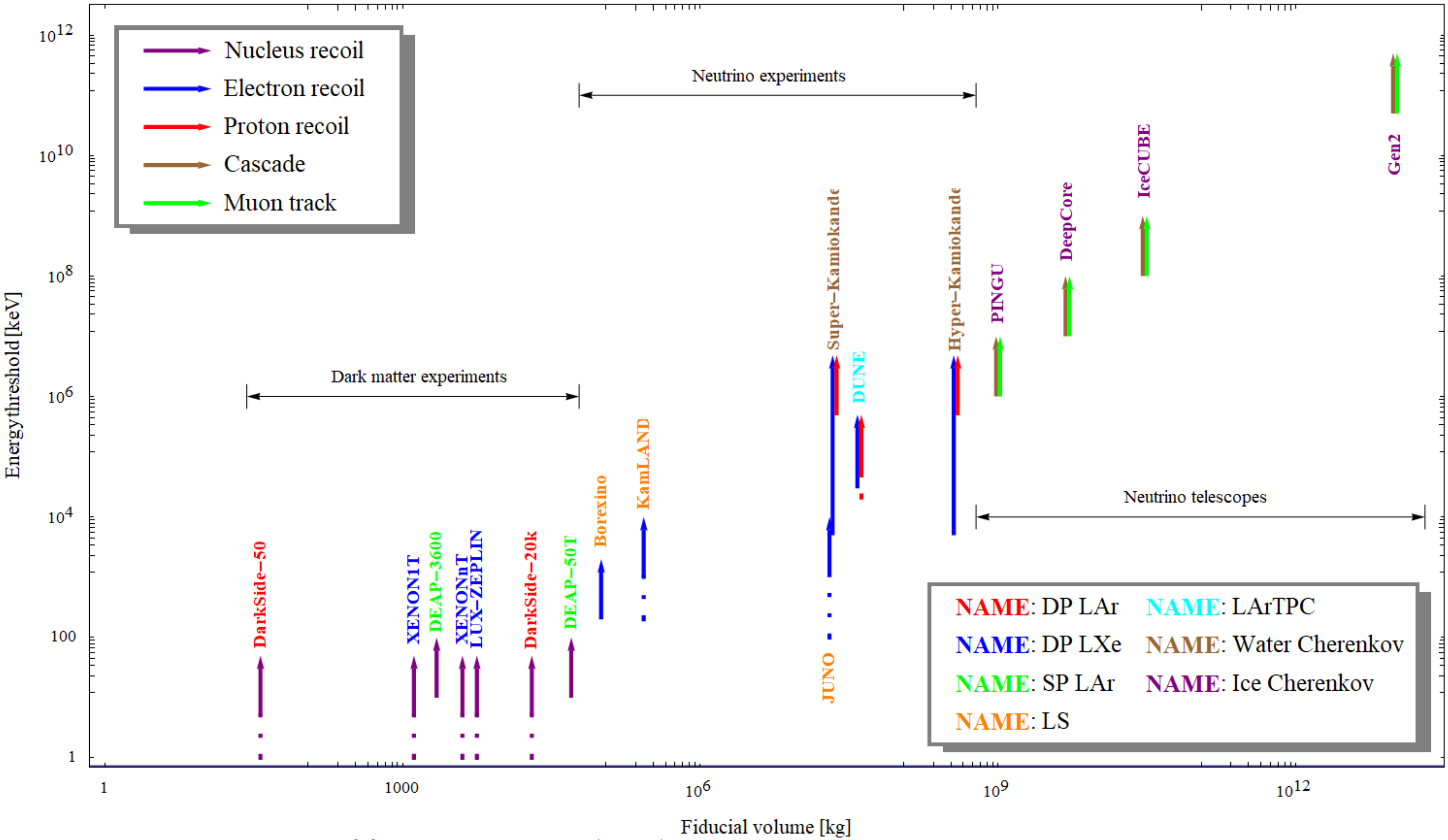
More systematic approach in possible BDM signals



Alhazmi, Kim, Kong, Mohlabeng, Park, **SS**, JHEP 05, 055 (2021)

Detection prospects of BDM



Kim, Machado, Park, **SS**, JHEP 2007, 057 (2020)

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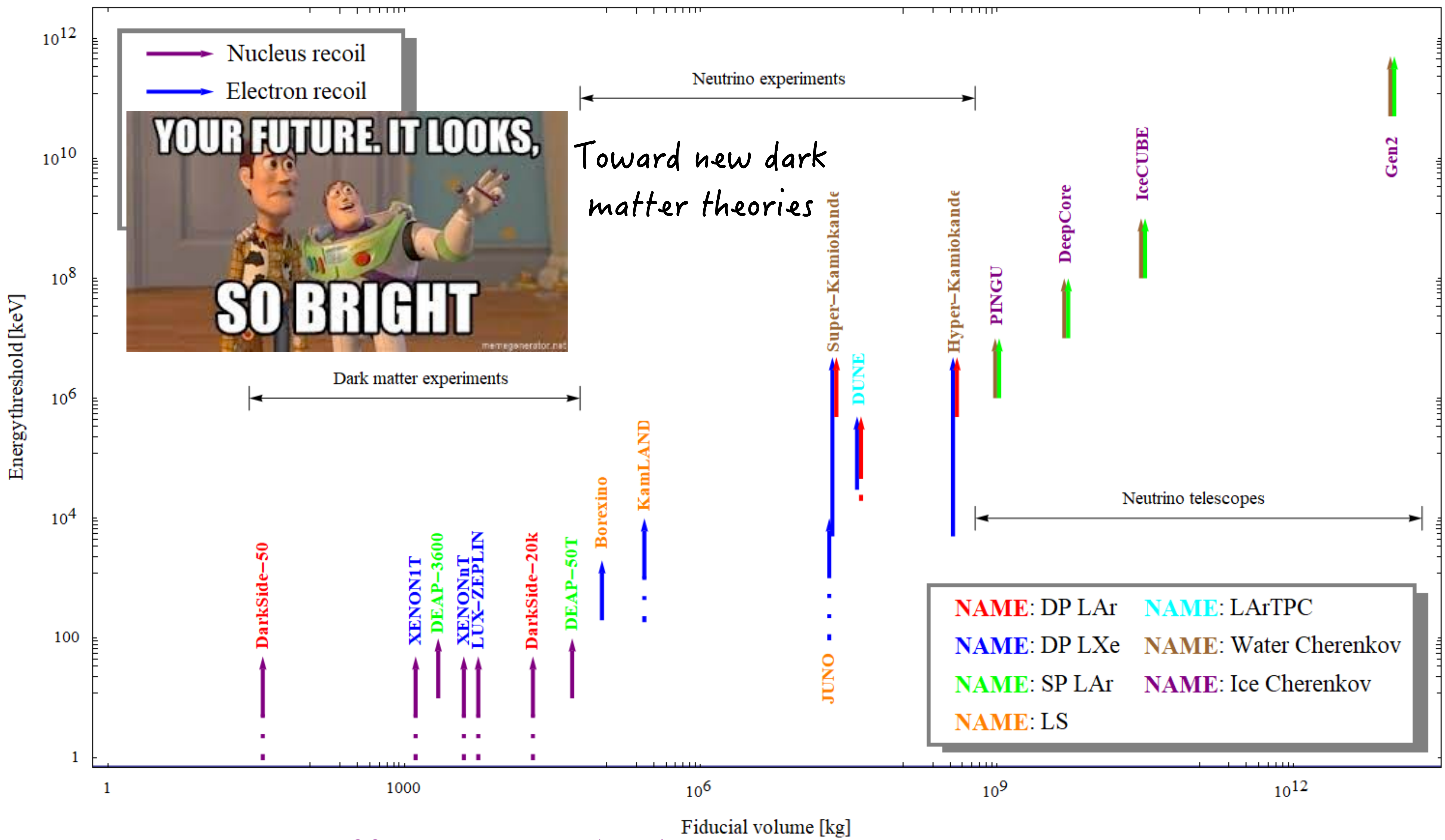
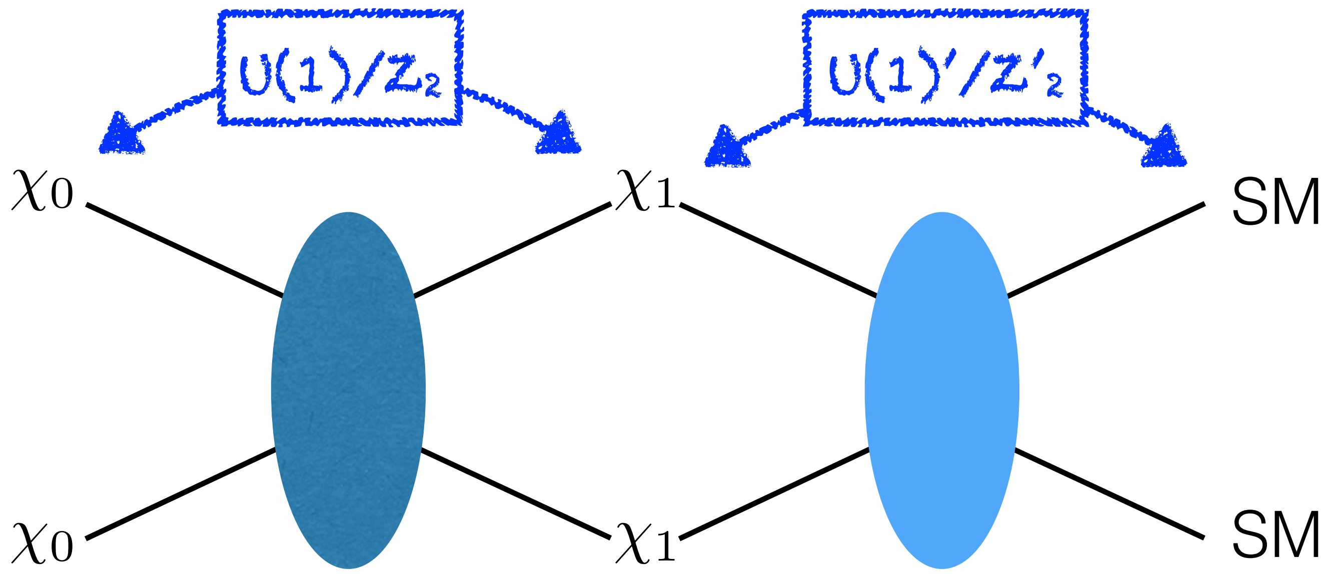


Kim, Machado, Park, **SS**, JHEP 2007, 057 (2020)

Multi-component BDM

χ_0: heavy, χ_1: light



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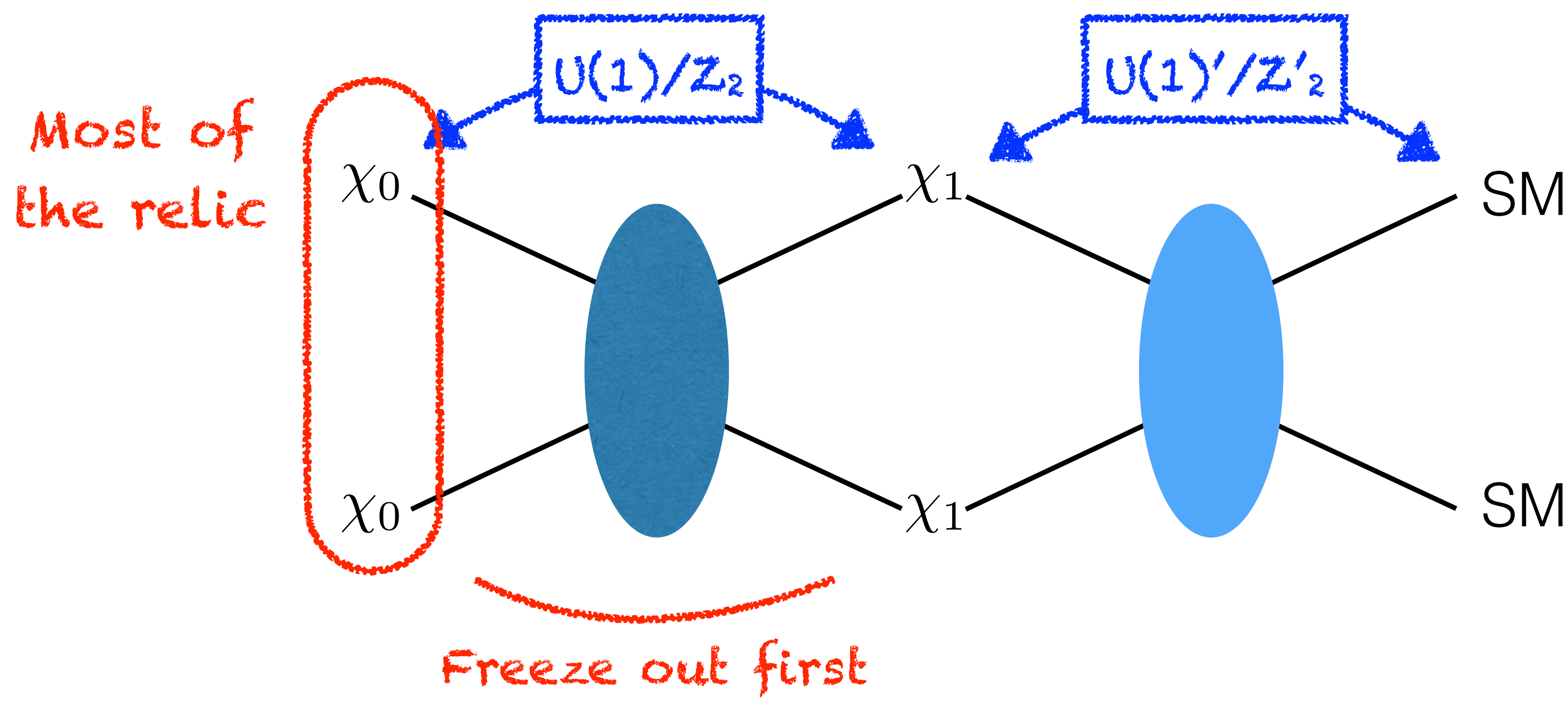

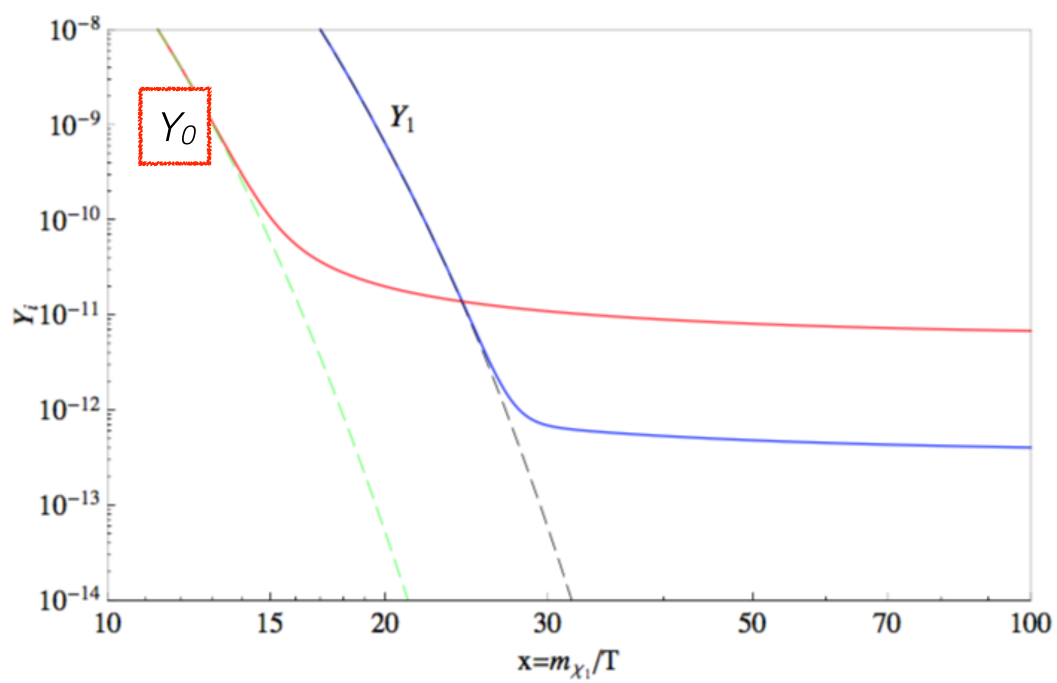

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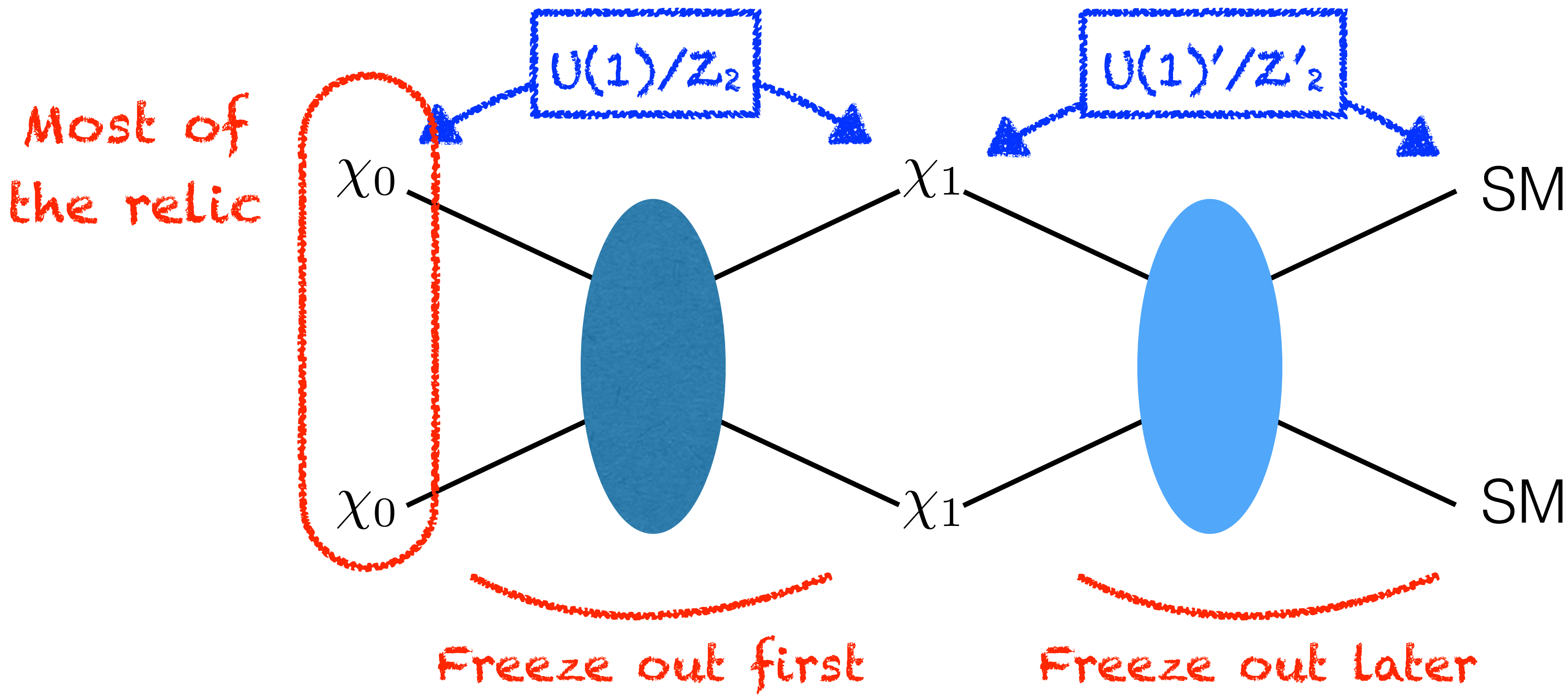
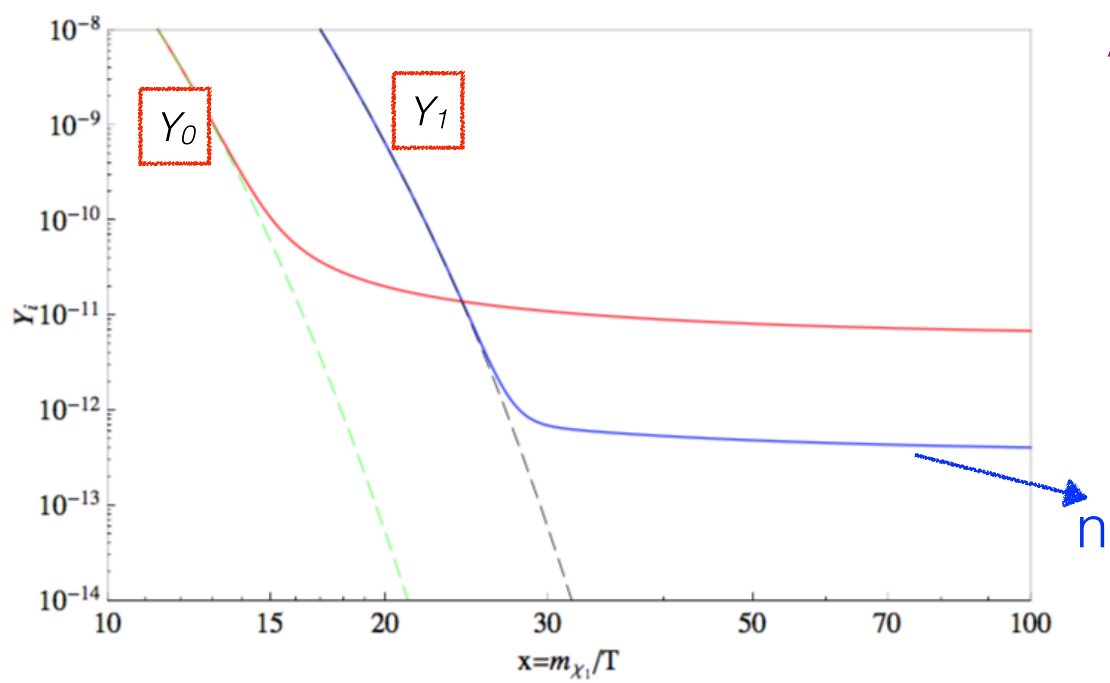




Agashe, Cui, Necib, Thaler,1405.7370

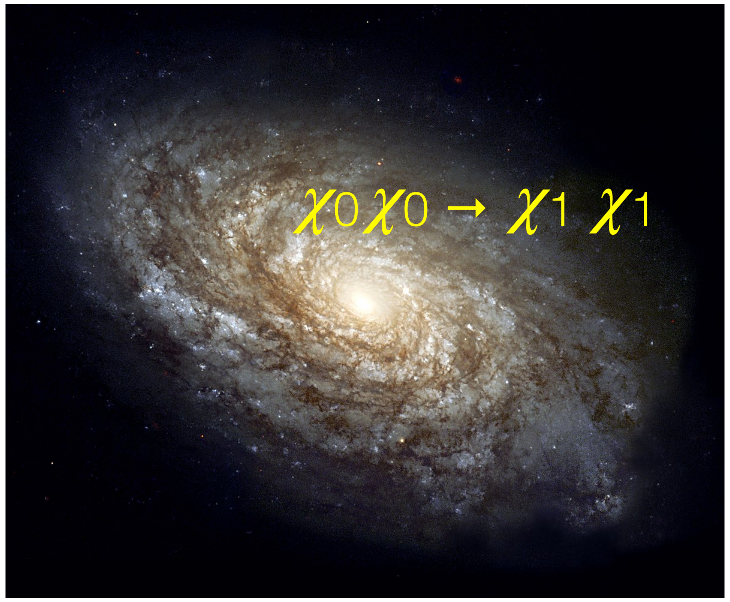
Belanger, Park, 1112.4491

Assisted freeze-out mechanism

non-relativistic relic χ_1 (negligible)

$Y_0 \gg Y_1$

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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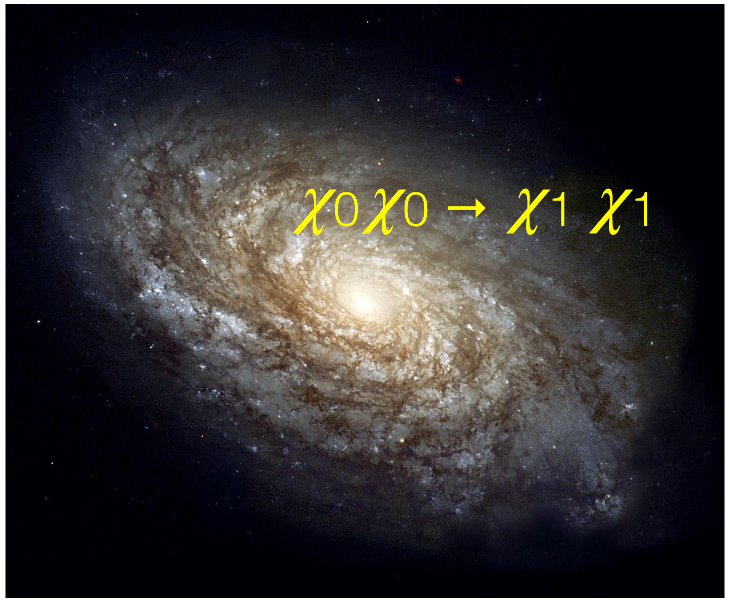

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Observe χ_1 scattering off target with $E_1 > E_{th}$

(indirect detection of χ_0)

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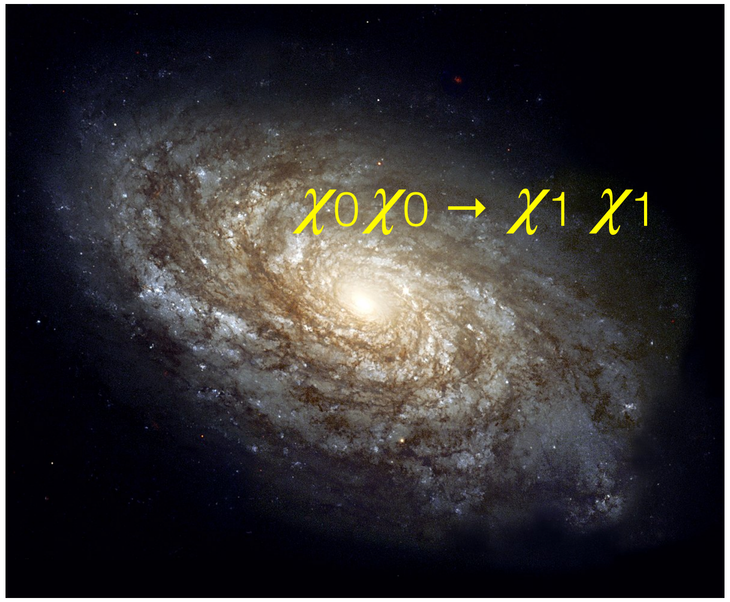

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Flux of χ_1 $\simeq 1.6 \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \times \left(\frac{\langle\sigma v\rangle_{0\to 1}}{5\times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}}\right) \times \left(\frac{100\,\mathrm{GeV}}{m_0}\right)^2$

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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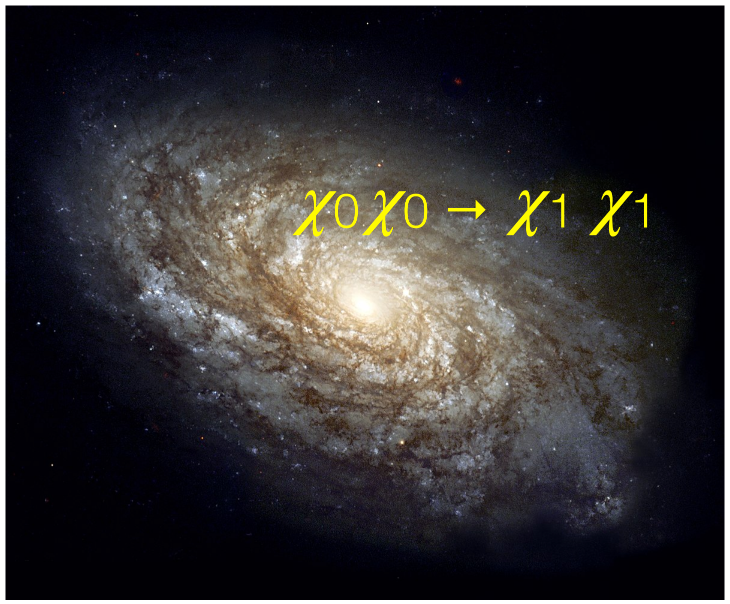

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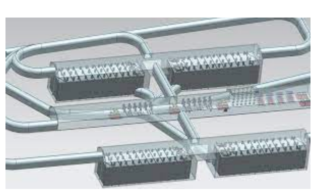

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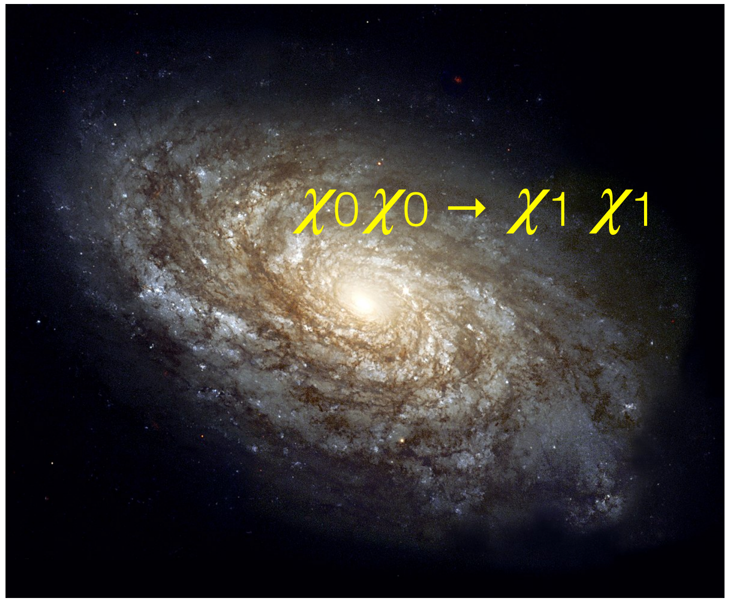

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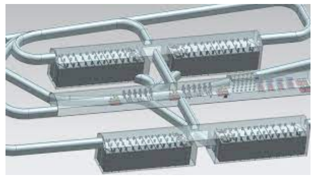

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comparable **if $m_0 \lesssim 1$ GeV**

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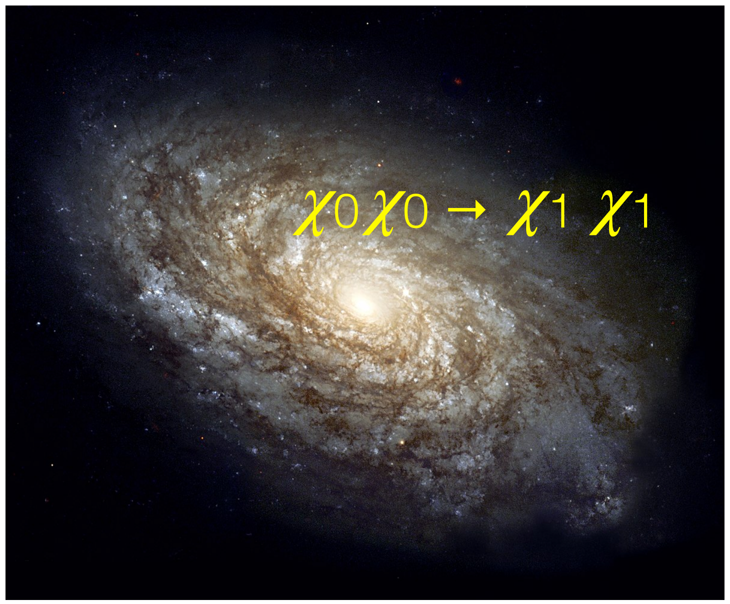

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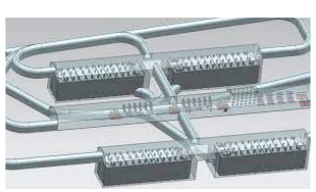

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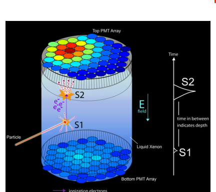

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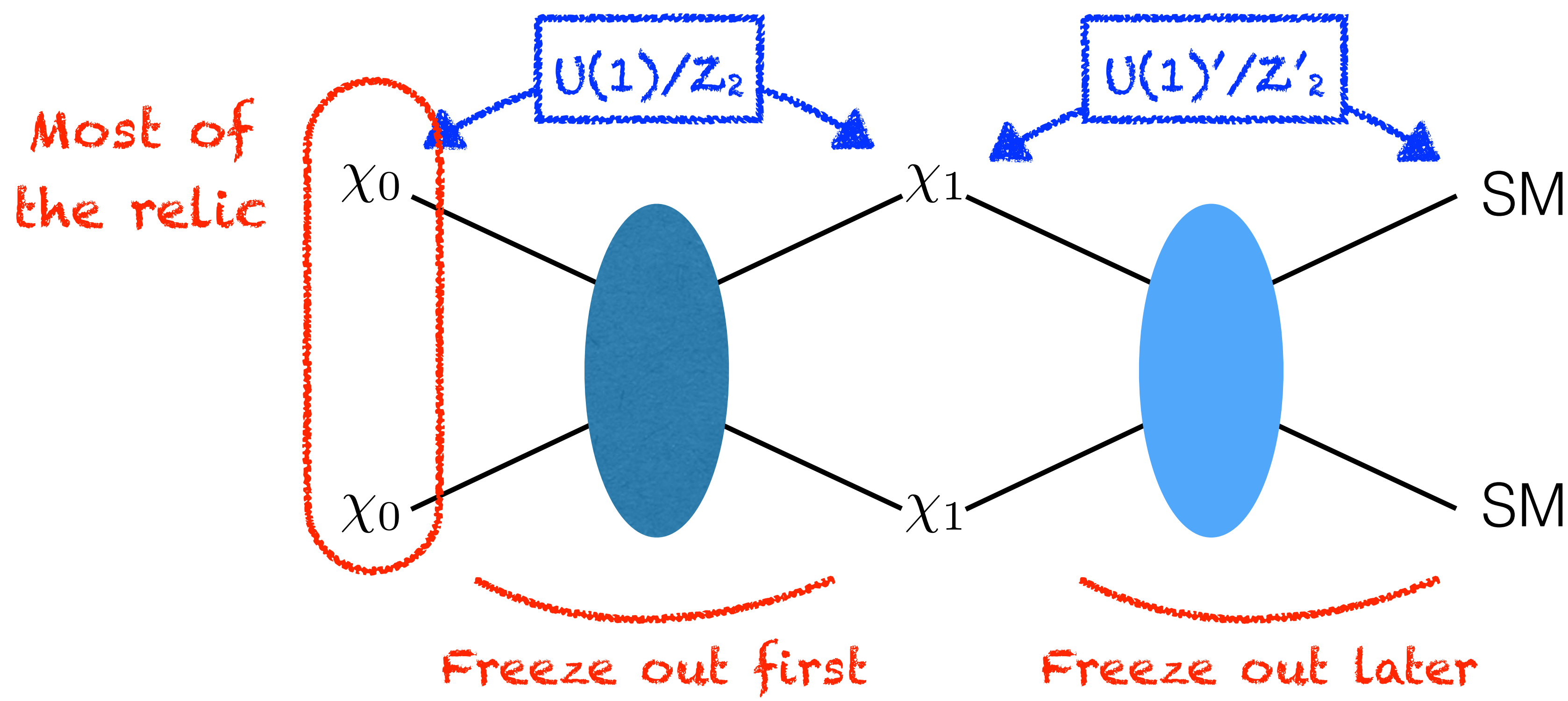

Agashe, Cui, Necib, Thaler,1405.7370

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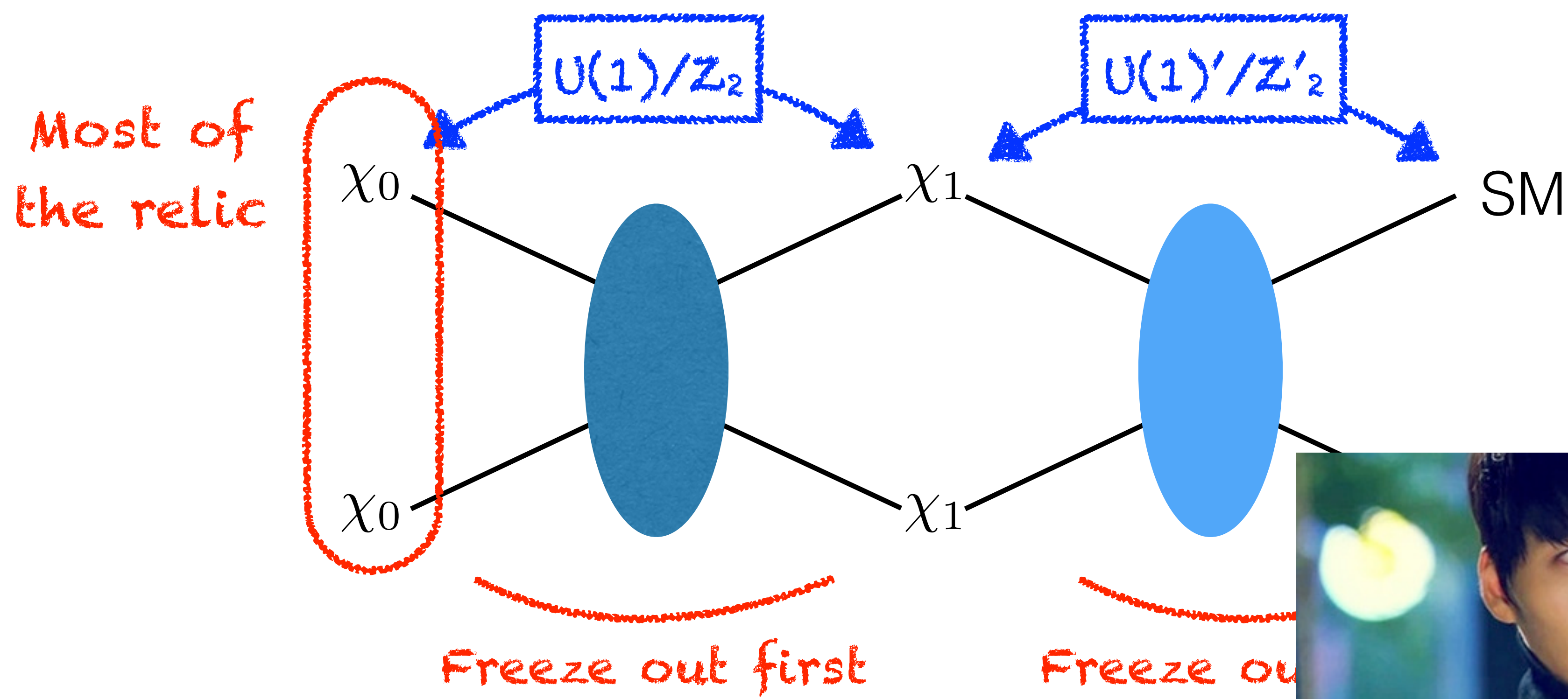

Agashe, Cui, N

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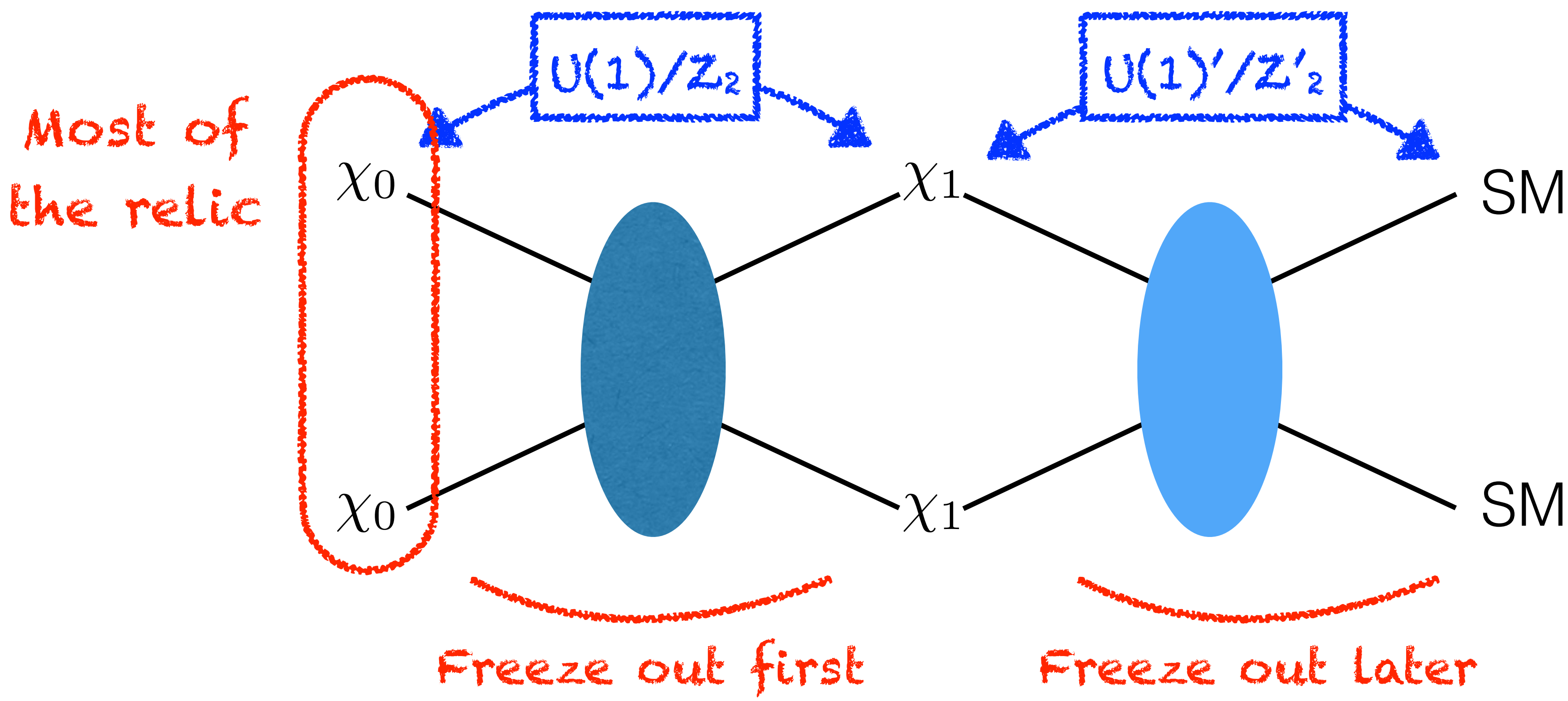

Agashe, Cui, Necib, Thaler,14

- Hidden role of a subdominant component relic χ_1 in cosmological/ astrophysical observables & DM direct detection?

- Possible restrictions on the annihilation channel between χ_1 and SM?

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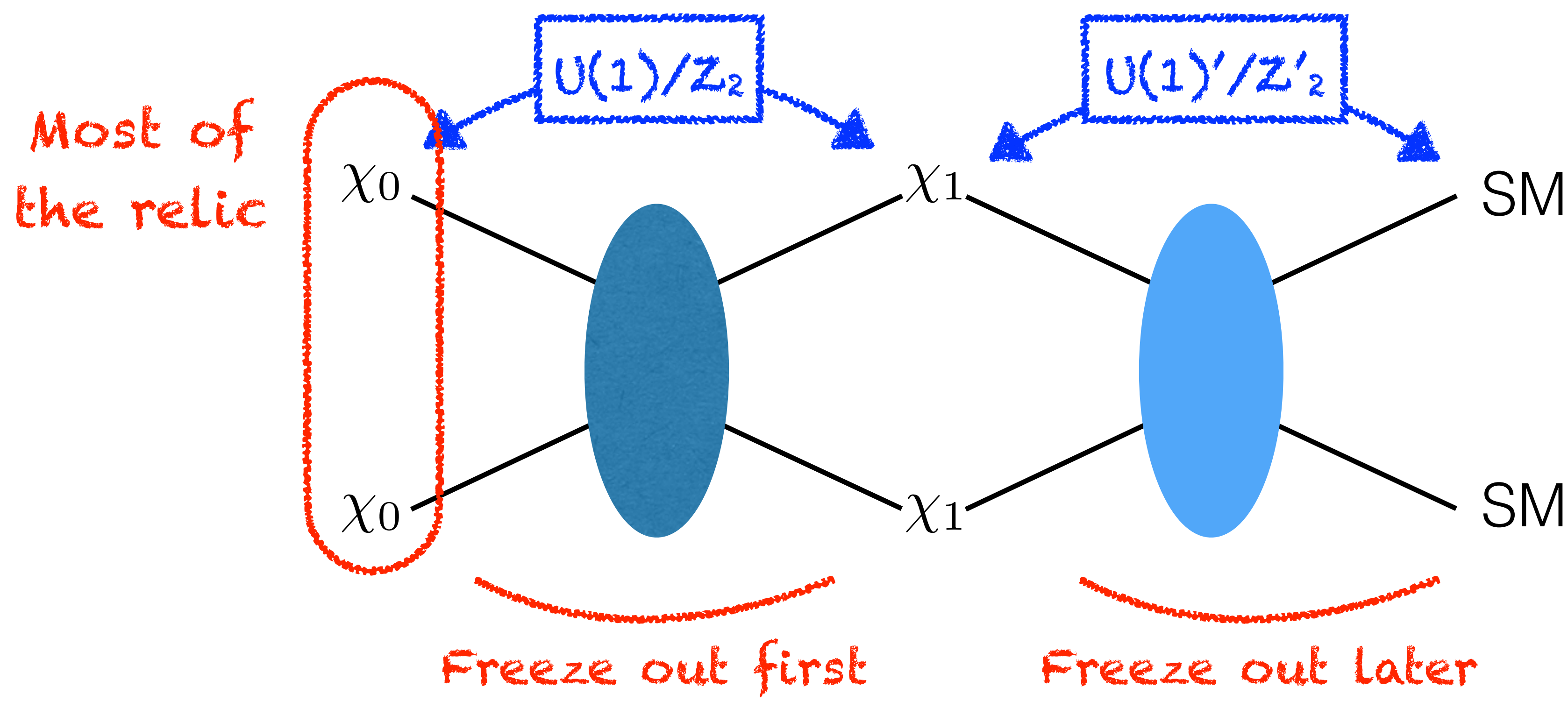
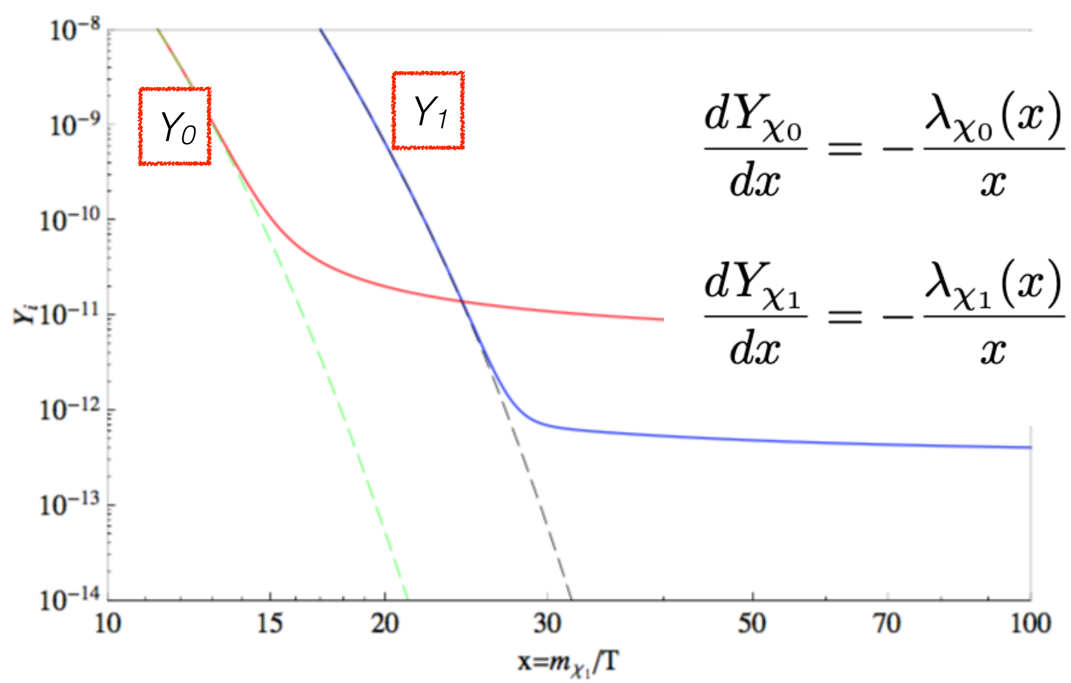


$\lambda_{\chi_i} = s \langle \sigma_i v_{\rm rel} \rangle / H$

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



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

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

with SM

with heavy DM χ_0

Multi-component BDM

After the heavy component χ_0 freezes-out

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

Annihilation of heavy DM χ_0 for a while

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

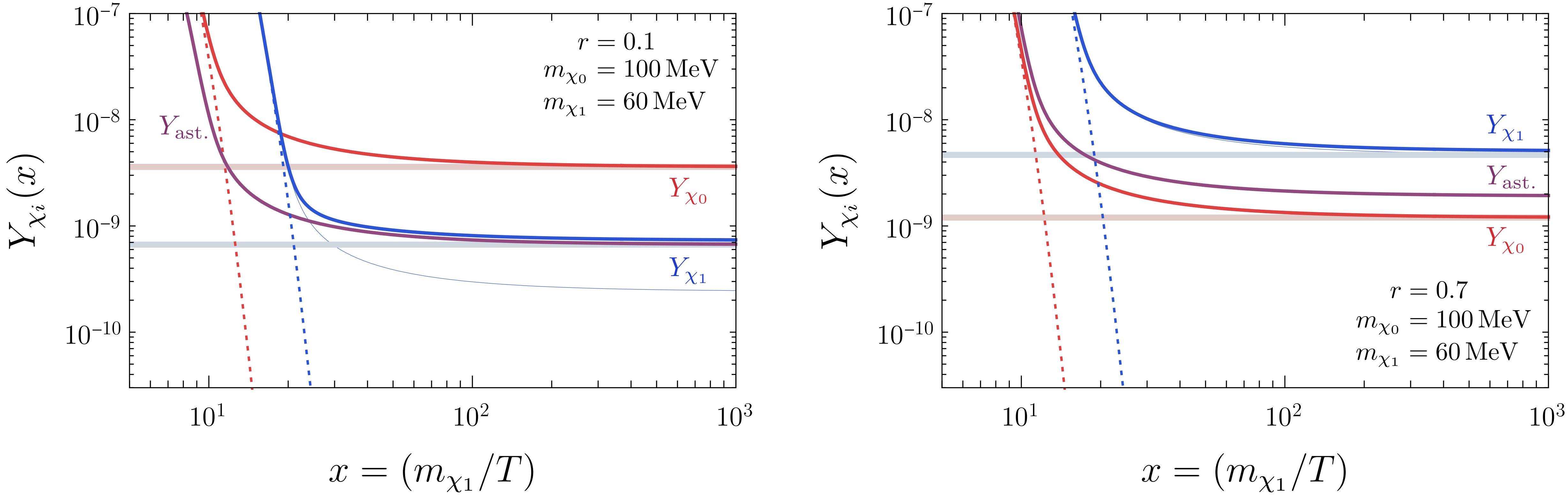
During the decoupling, assume χ_1 is in kinetic equilibrium with the SM

- 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.

Multi-component BDM

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



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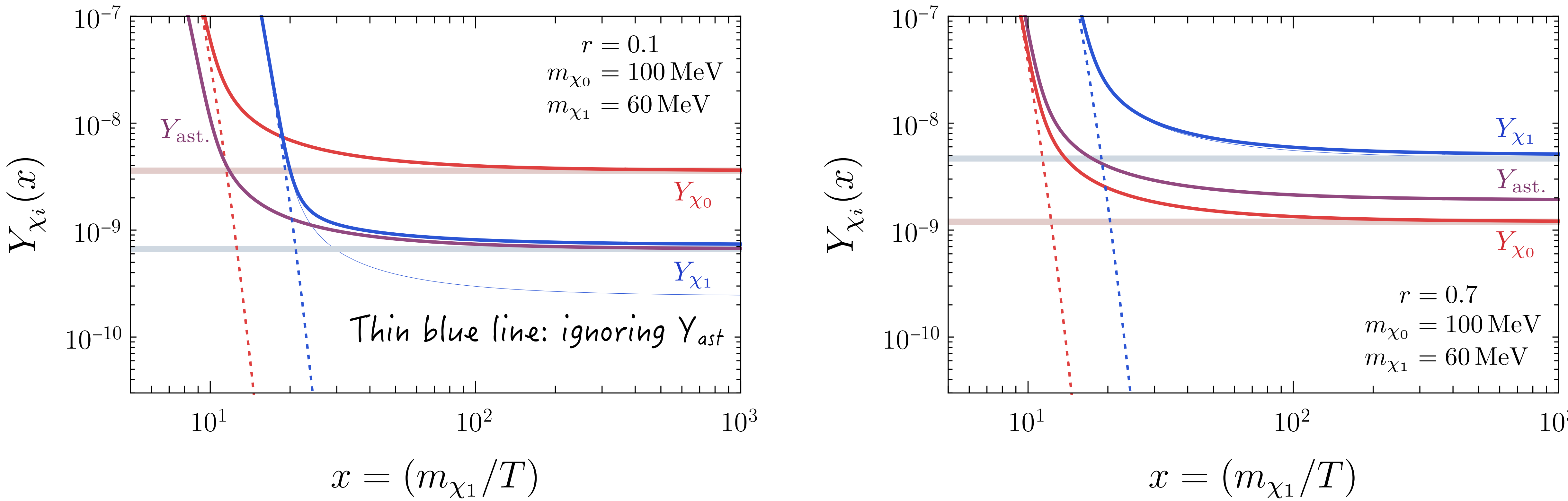

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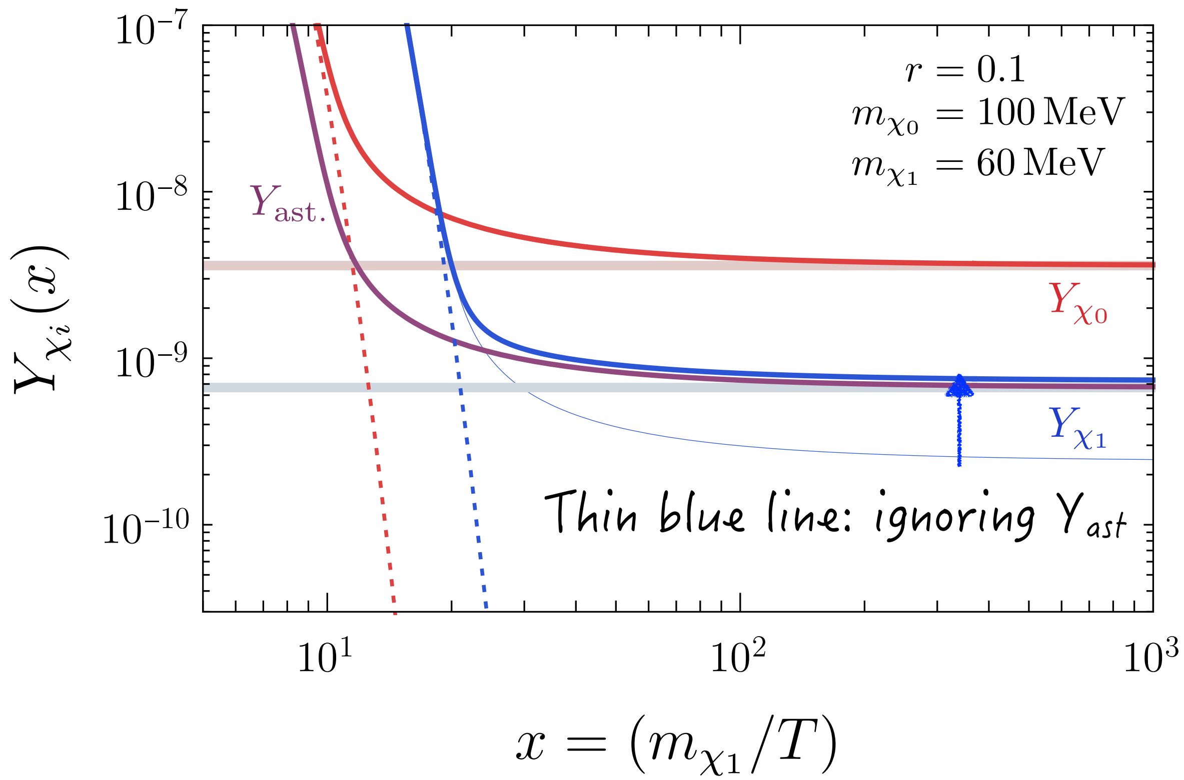

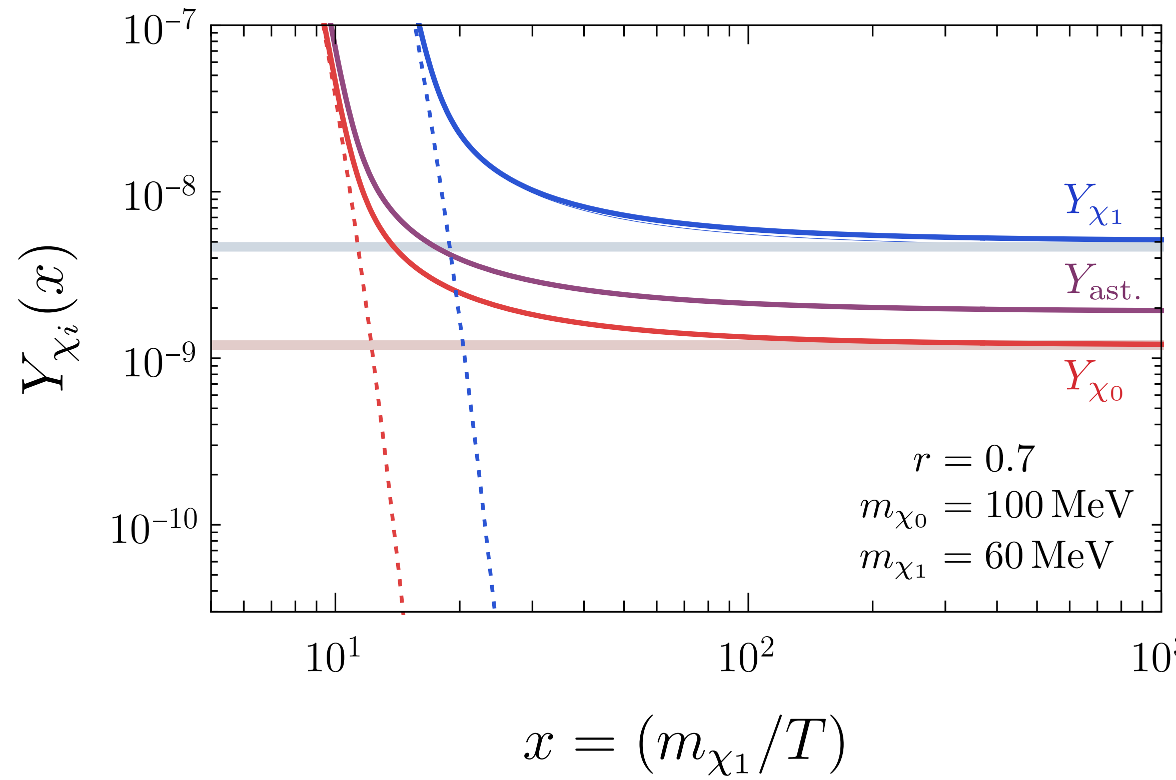

- For $r_1 \ll 1$, Y_{χ_1} is lifted-up by $Y_{ast.}$ (follows it when $T \lesssim m_1/30$).

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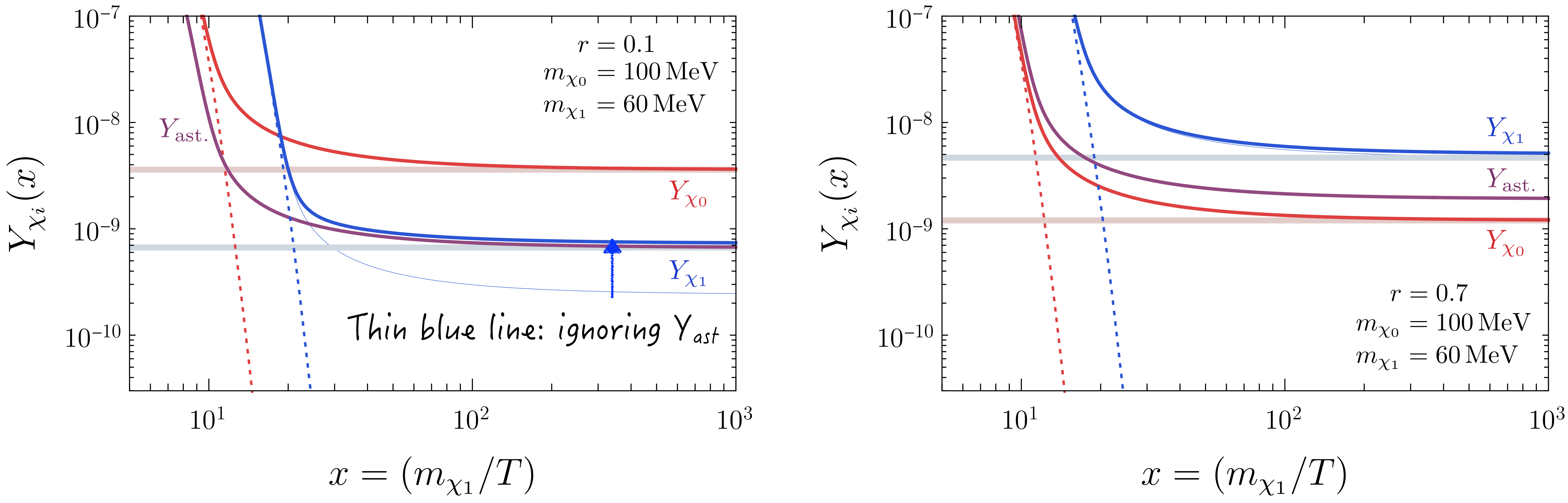


- For $r_1 \ll 1$, Y_{χ_1} is lifted-up by $Y_{\mathrm{ast.}}$ (follows it when $T \lesssim m_1/30$).

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

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

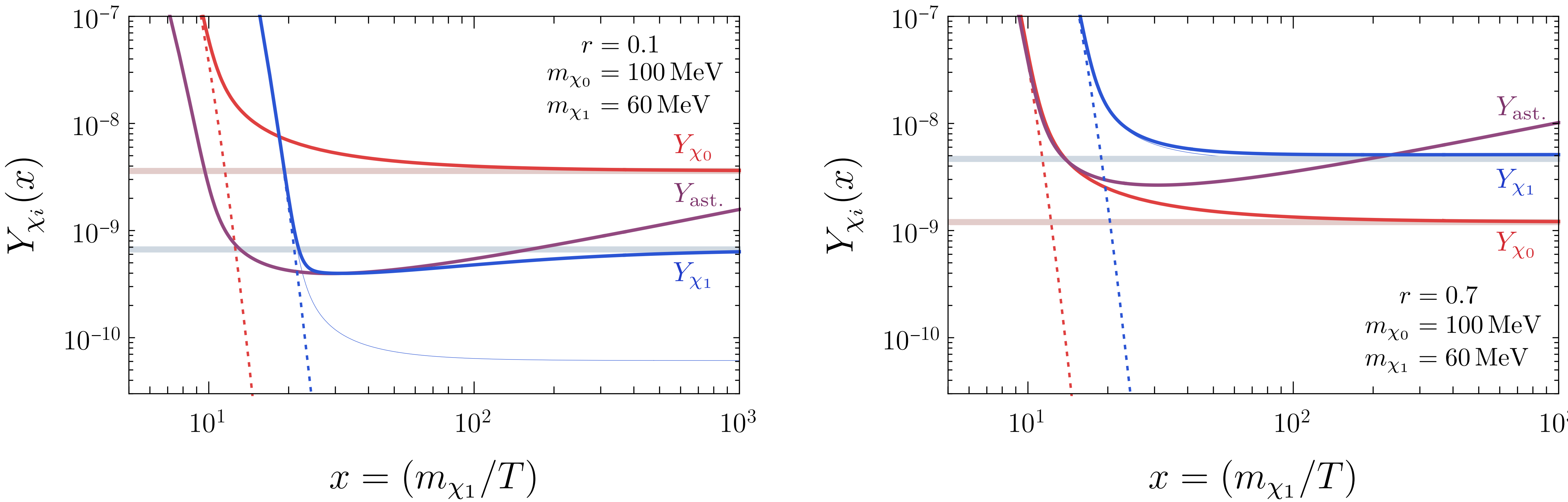
$$\langle\sigma_0 v_{\rm rel}\rangle \simeq (\sigma_0 v_{\rm rel})_s + (\sigma_0 v_{\rm rel})v_{\rm rel}^2$$

Multi-component BDM

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

Multi-component BDM

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



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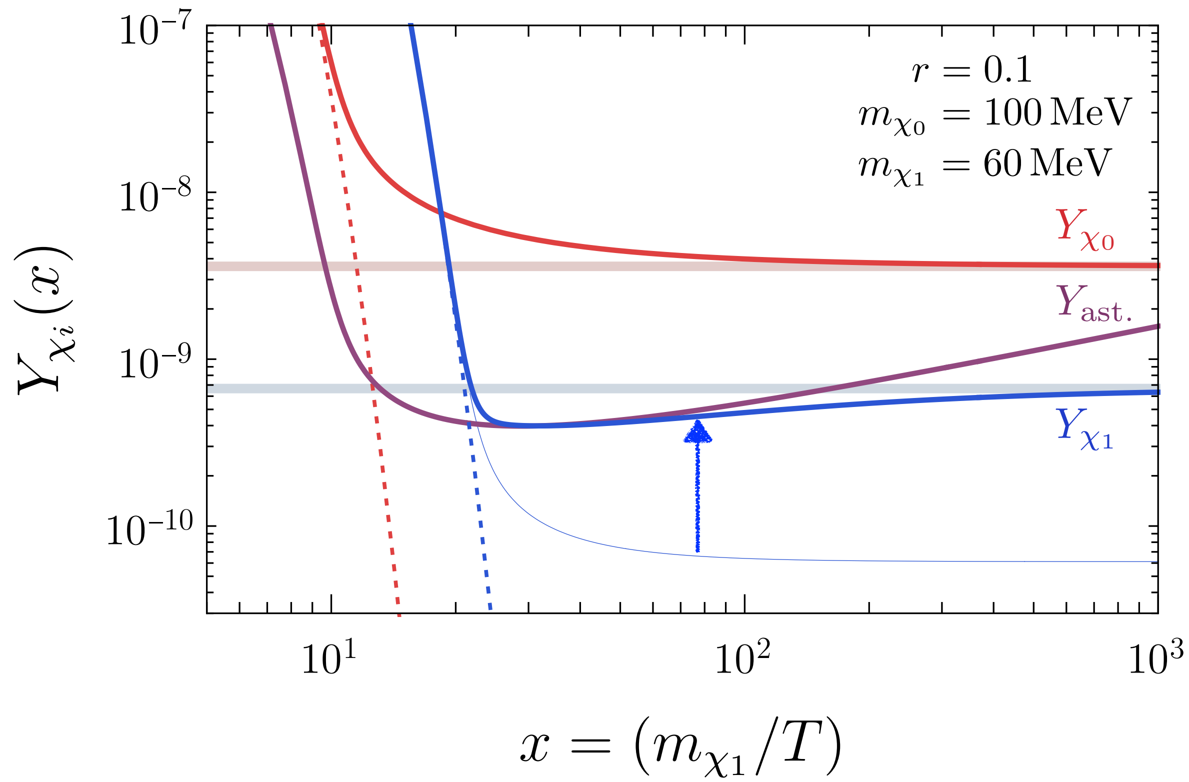
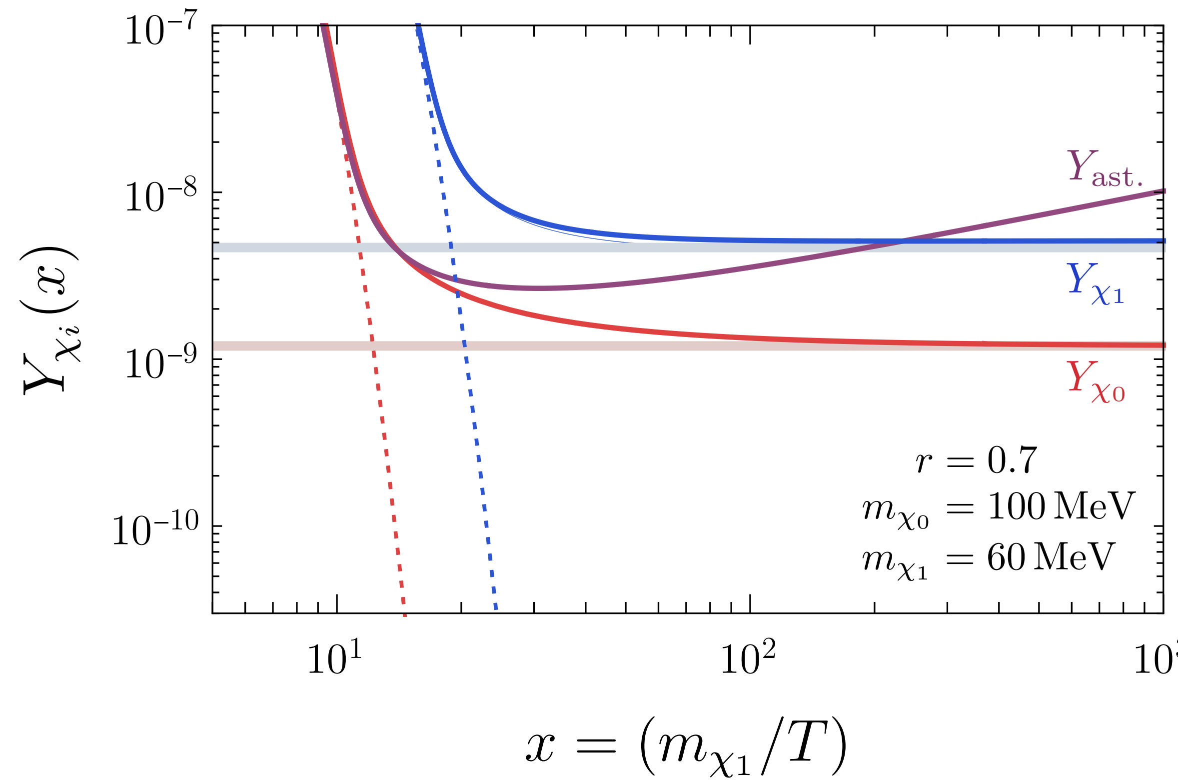
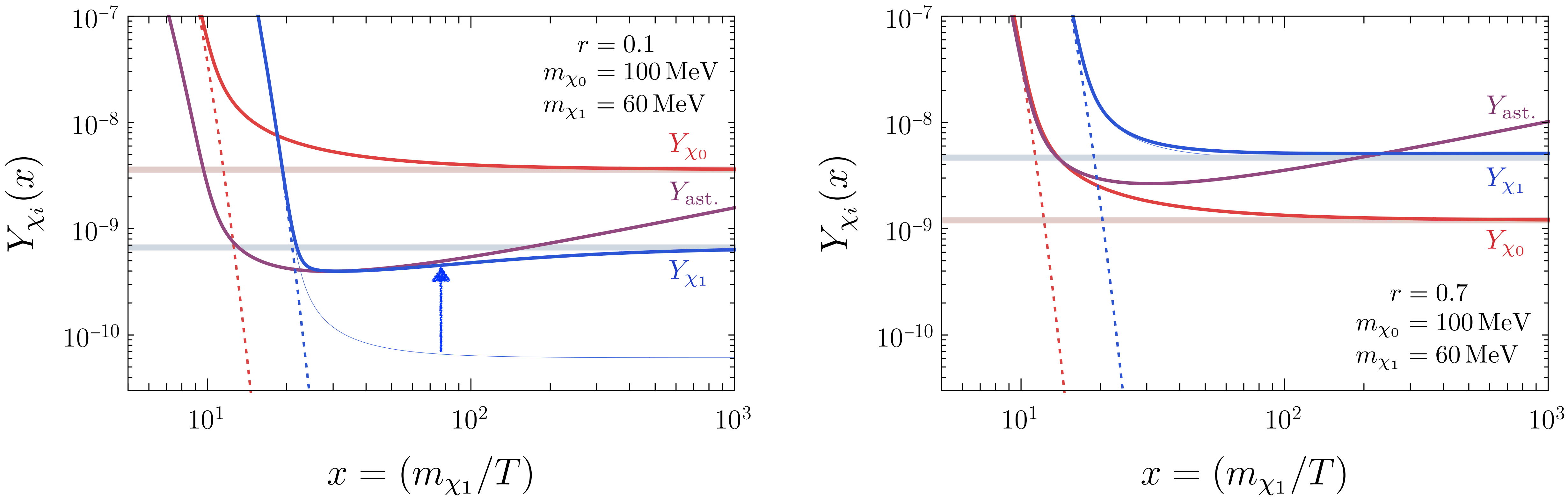




- For $r_1 \ll 1$, Y_{χ_1} is lifted-up even more by $Y_{\mathrm{ast.}}$ (unitl T ~ $m_1/80$).

Multi-component BDM

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



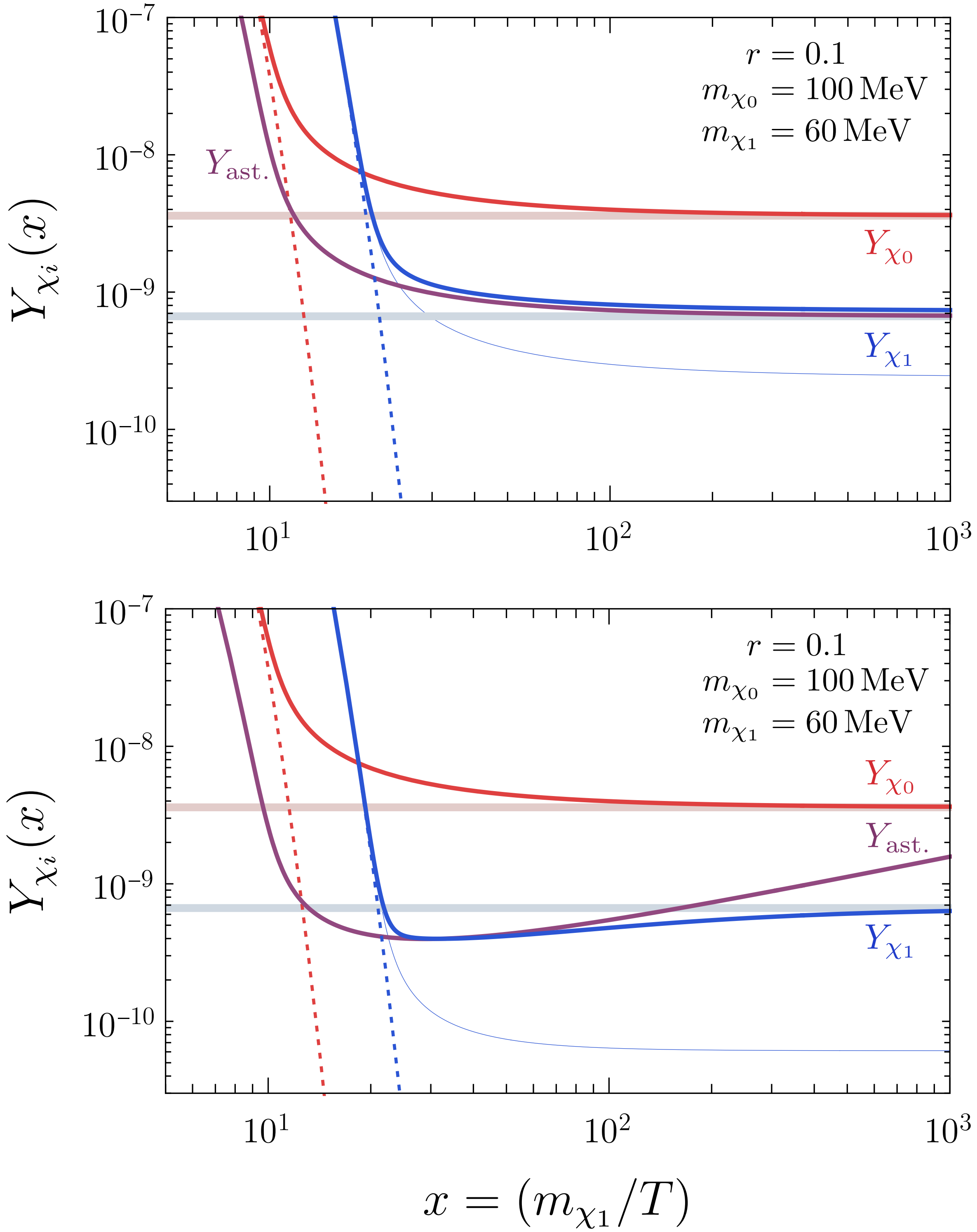
- For $r_1 \ll 1$, Y_{χ_1} is lifted-up even more by $Y_{\mathrm{ast.}}$ (unitl T ~ $m_1/80$).

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

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

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

Multi-component BDM



- 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 cases where the crossing symmetry is effective, it affects the direct detection experiments. (conventionally ignored so far!)

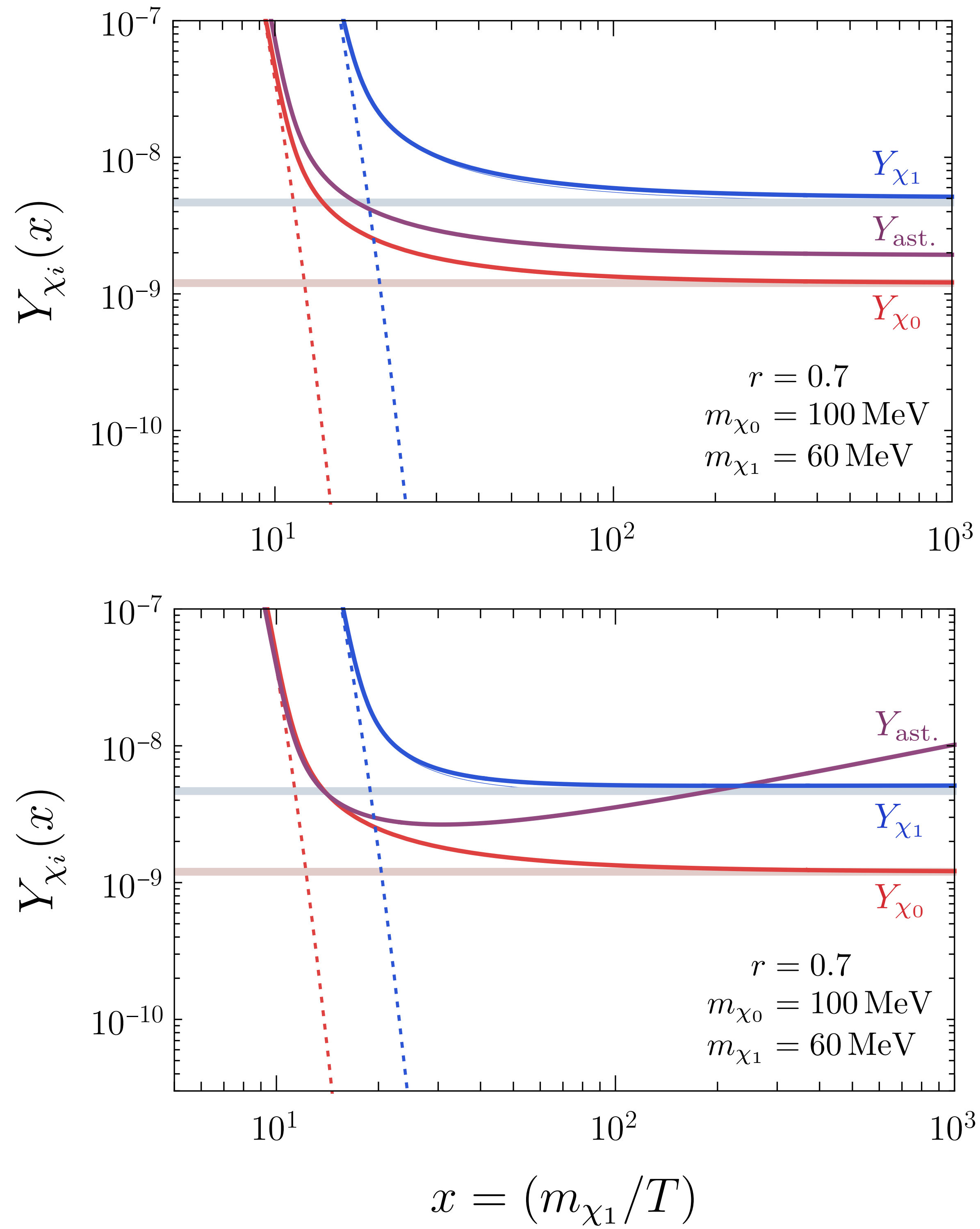
Assisted regime

Multi-component BDM

- Here, Y_{χ_1} is not affected by $Y_{ast.}$

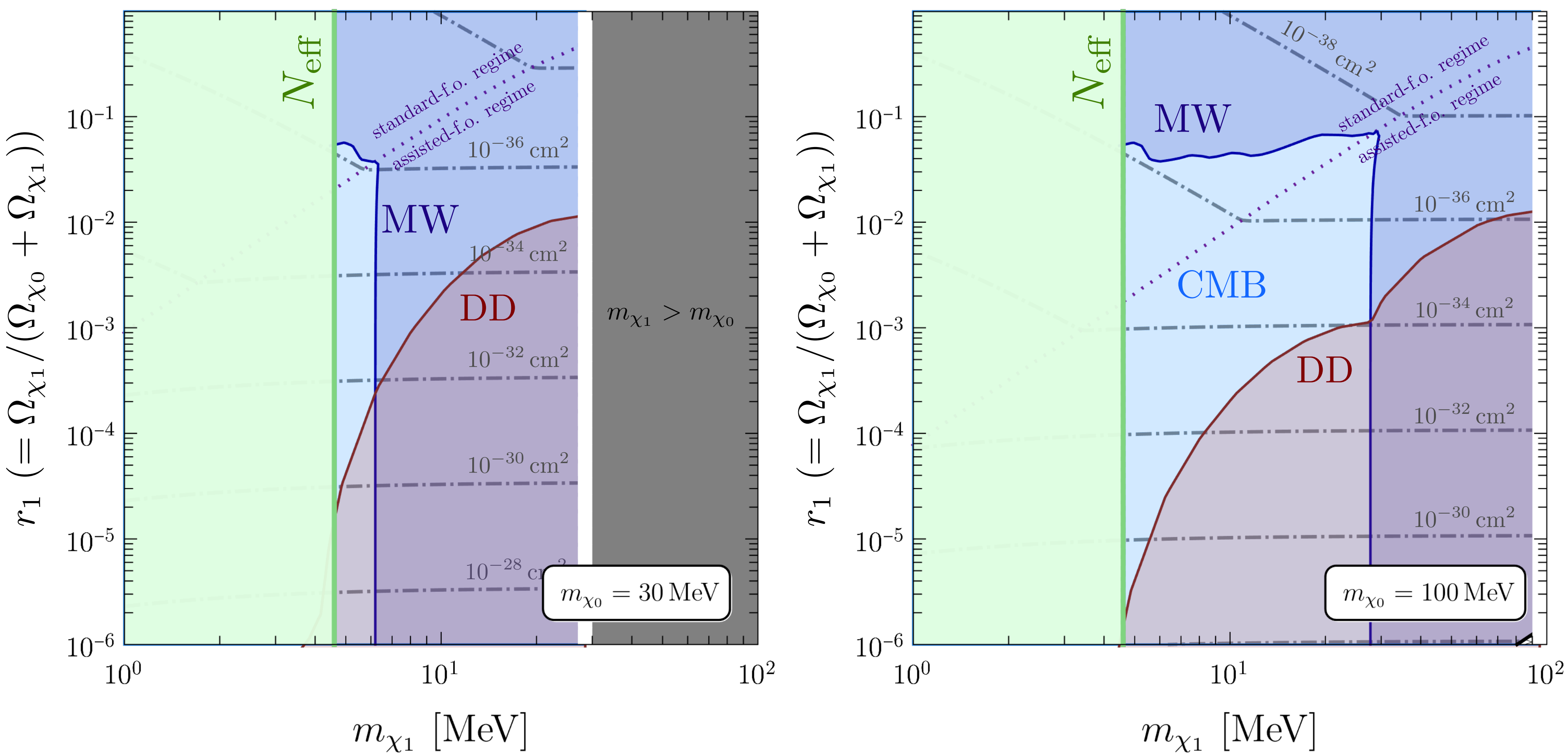
- In this example, the fraction of χ_1 is already large enough to affect various observables.

Standard regime



Affects of χ_1 to various observables

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



- The cosmological/astrophysical 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 though as remedy because $n_{\chi_1}^2 \langle \sigma_1 v_{\rm rel} \rangle_{\rm standard} \sim r_1$

Affects of χ_1 to various observables

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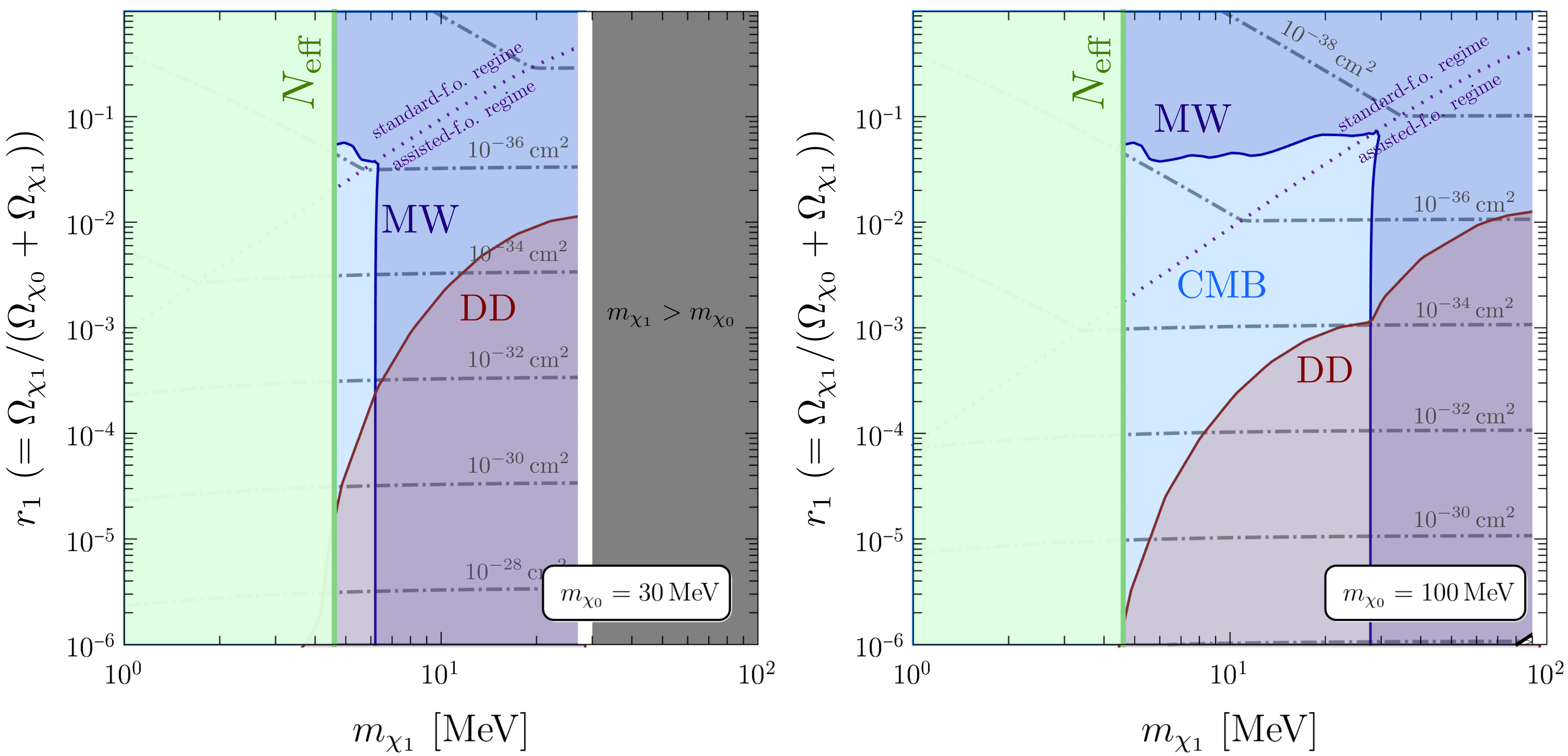

- In the assisted regime viable in a wide range of parameter space, however, this is not true since $n_{\chi_1}^2 (\sigma_1 v_{\rm rel})_{\rm s} \sim r_1^2 \cdot \frac{1}{r_1^2} = \text{no } r_1$

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

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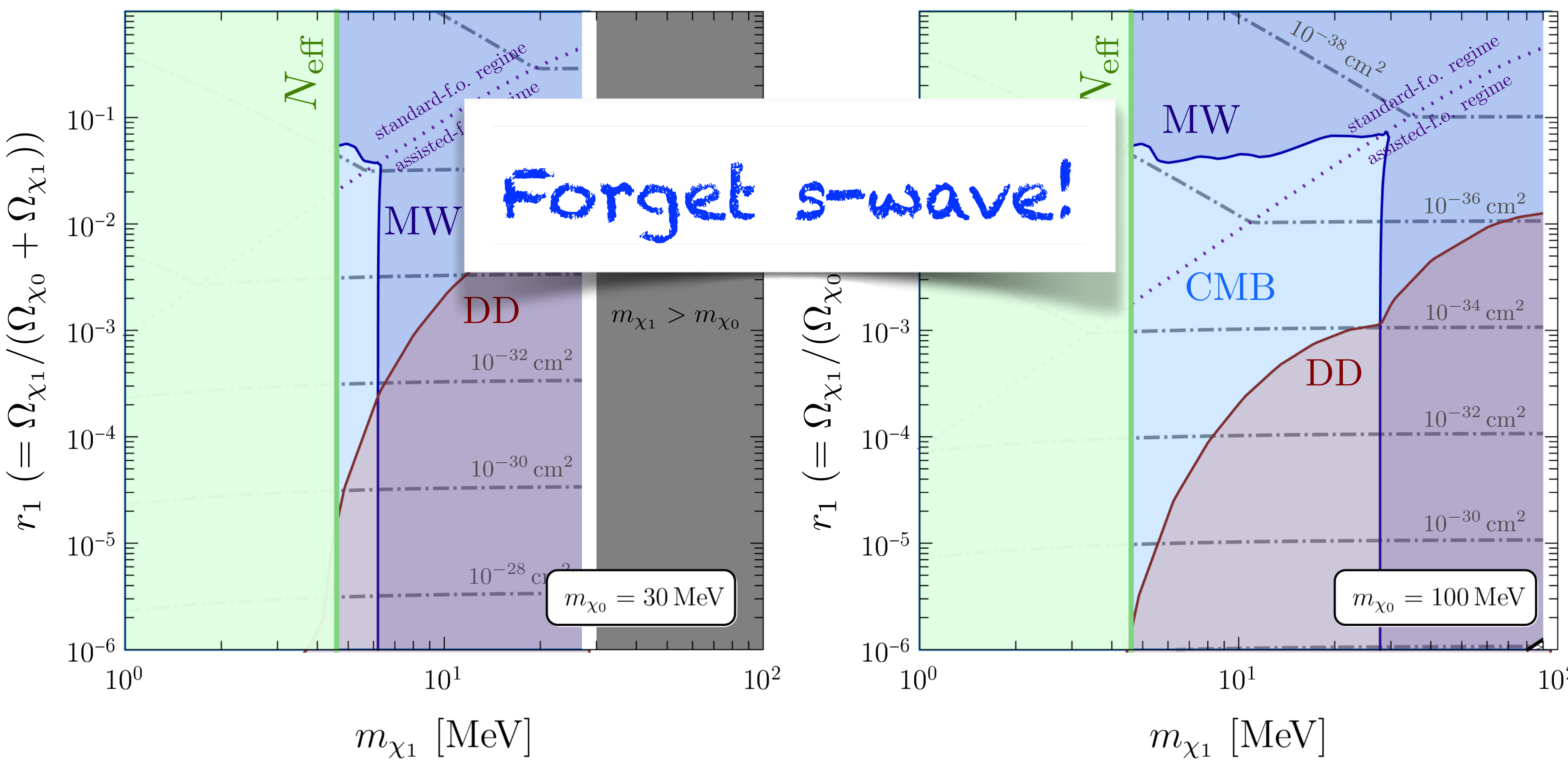

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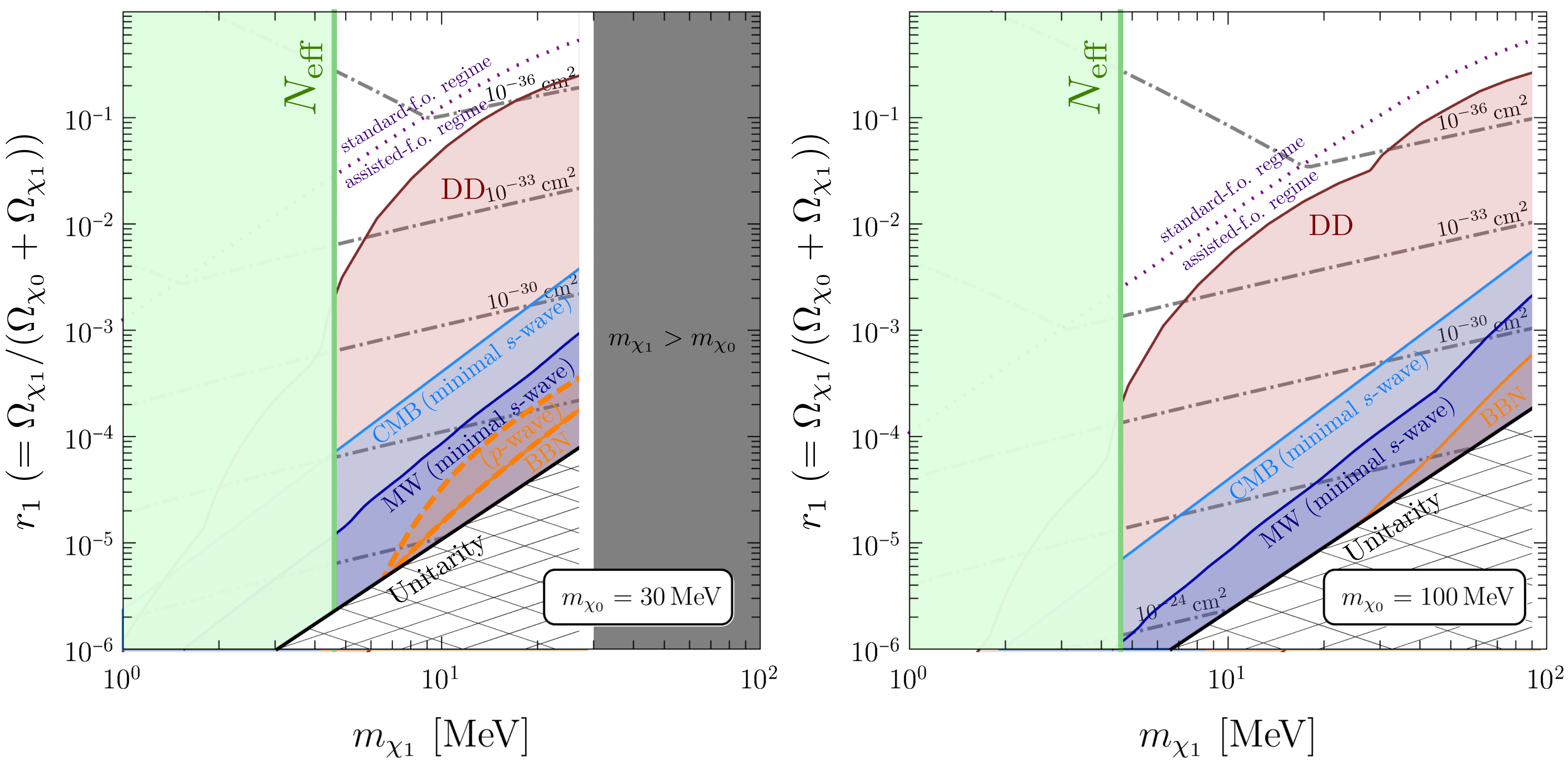
When $\chi_1\chi_1 \rightarrow$ SM is dominated by p-wave

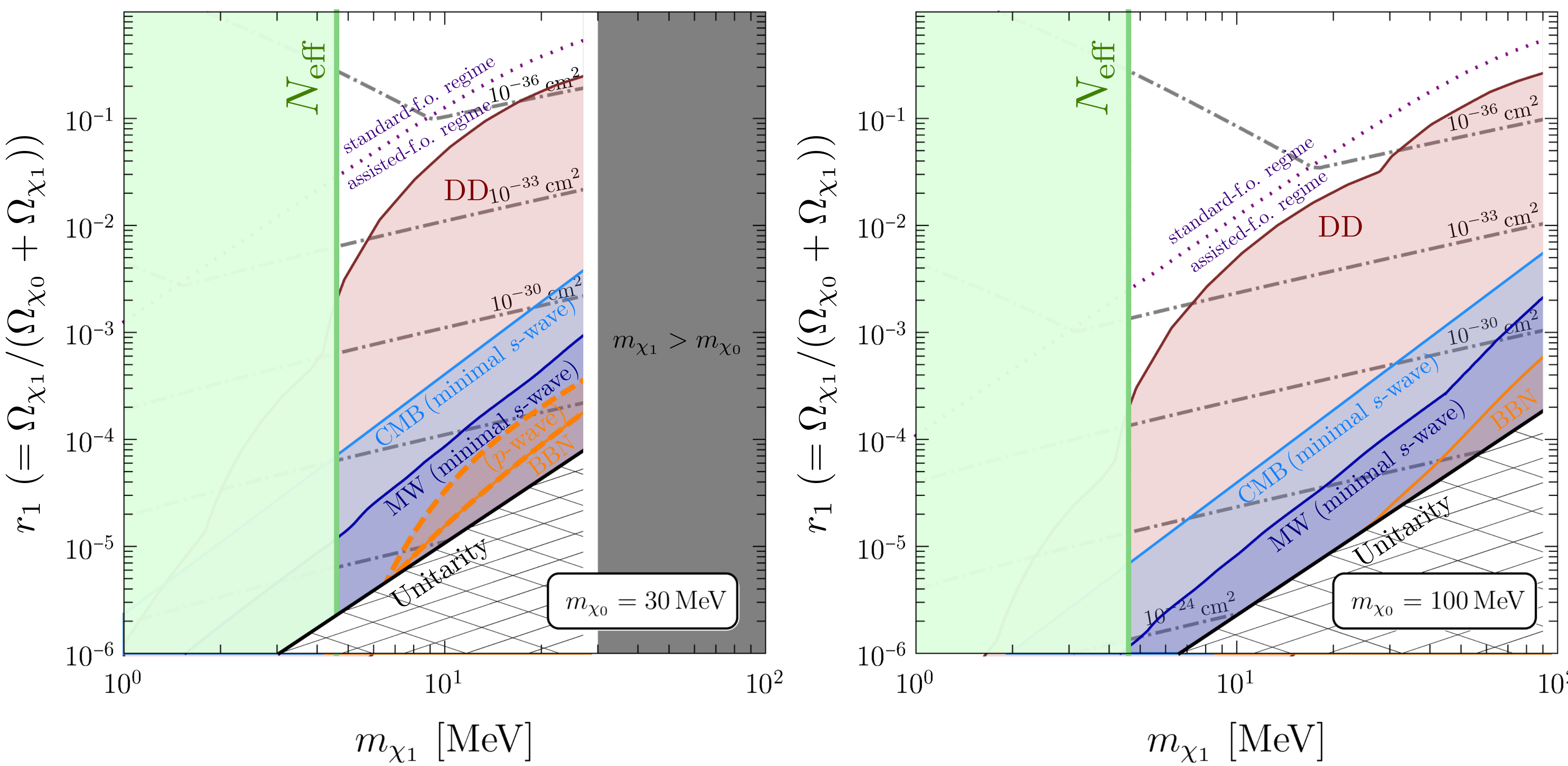


- In the assisted regime, the kinetic decoupling can occur after the freeze-out of $\chi_1\chi_1 \rightarrow e^+e^-$: photo-dissociation if 100 eV $\lesssim T_{kd} \lesssim$ 10 keV after BBN.

- The CMB and the DM direct detection (assuming crossing symmetry) bounds enter for small r_1.

Affects of χ_1 to various observables

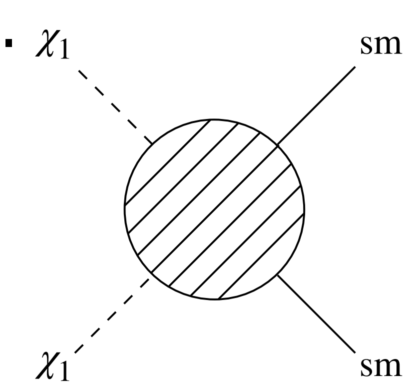
When $\chi_1\chi_1 \to$ SM is dominated by p-wave

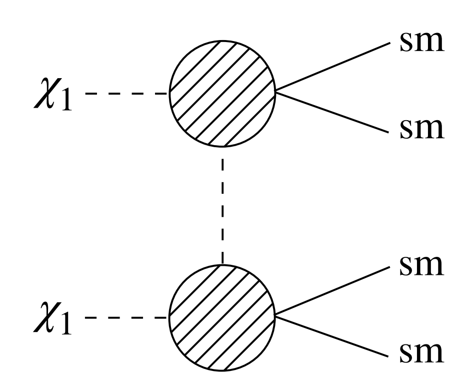


- Even when the annihilation is dominated by p-wave, it can be comparable to the 4-body s-wave in later time.

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

Minimal s-wave





Self-heating of χ_1

Hyun Min's talk

- 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 component relic χ_1 can be large for the dark gauge coupling $O(1)$ depending on the mass parameters.

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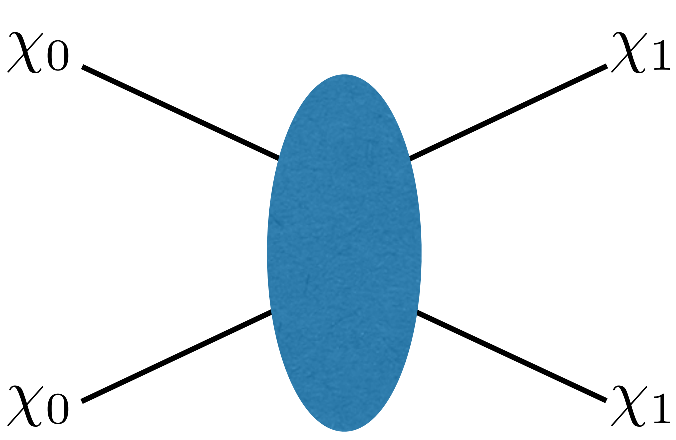
Boosted (energetic) χ_1



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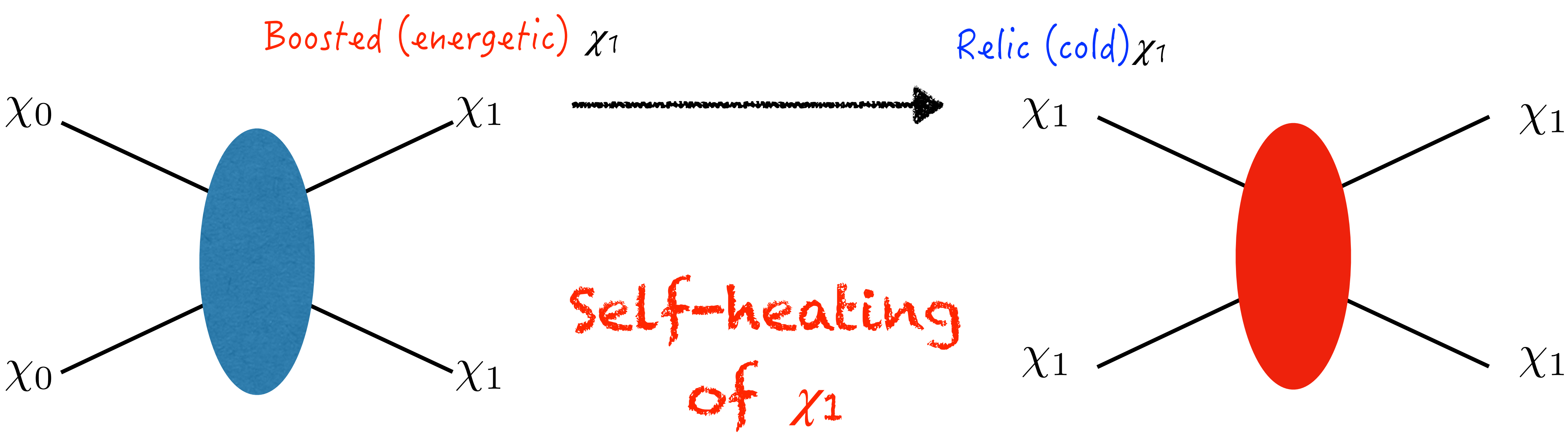

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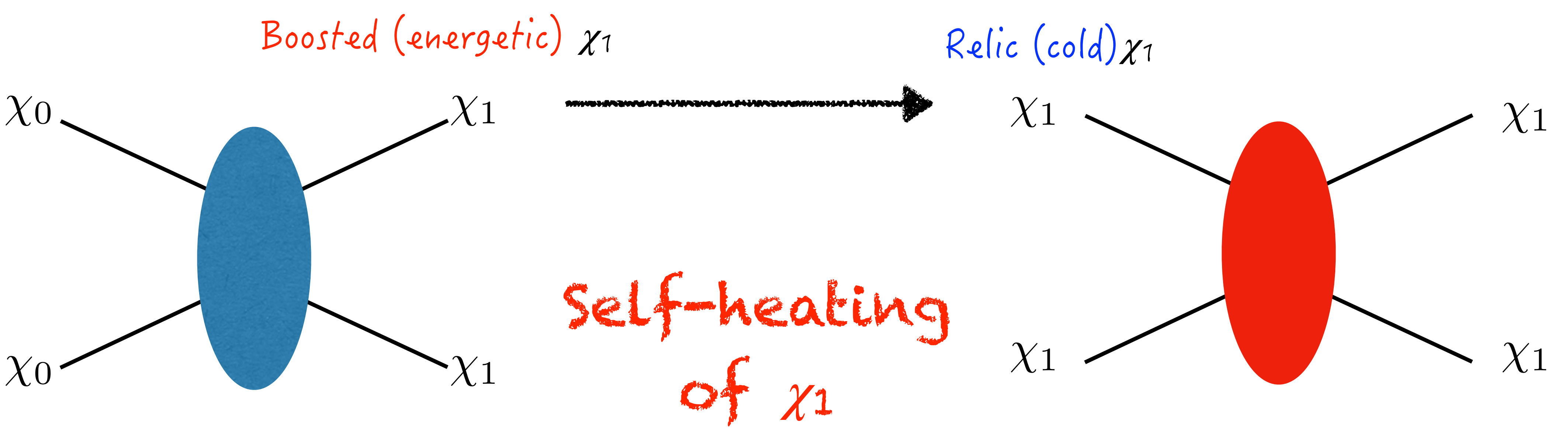
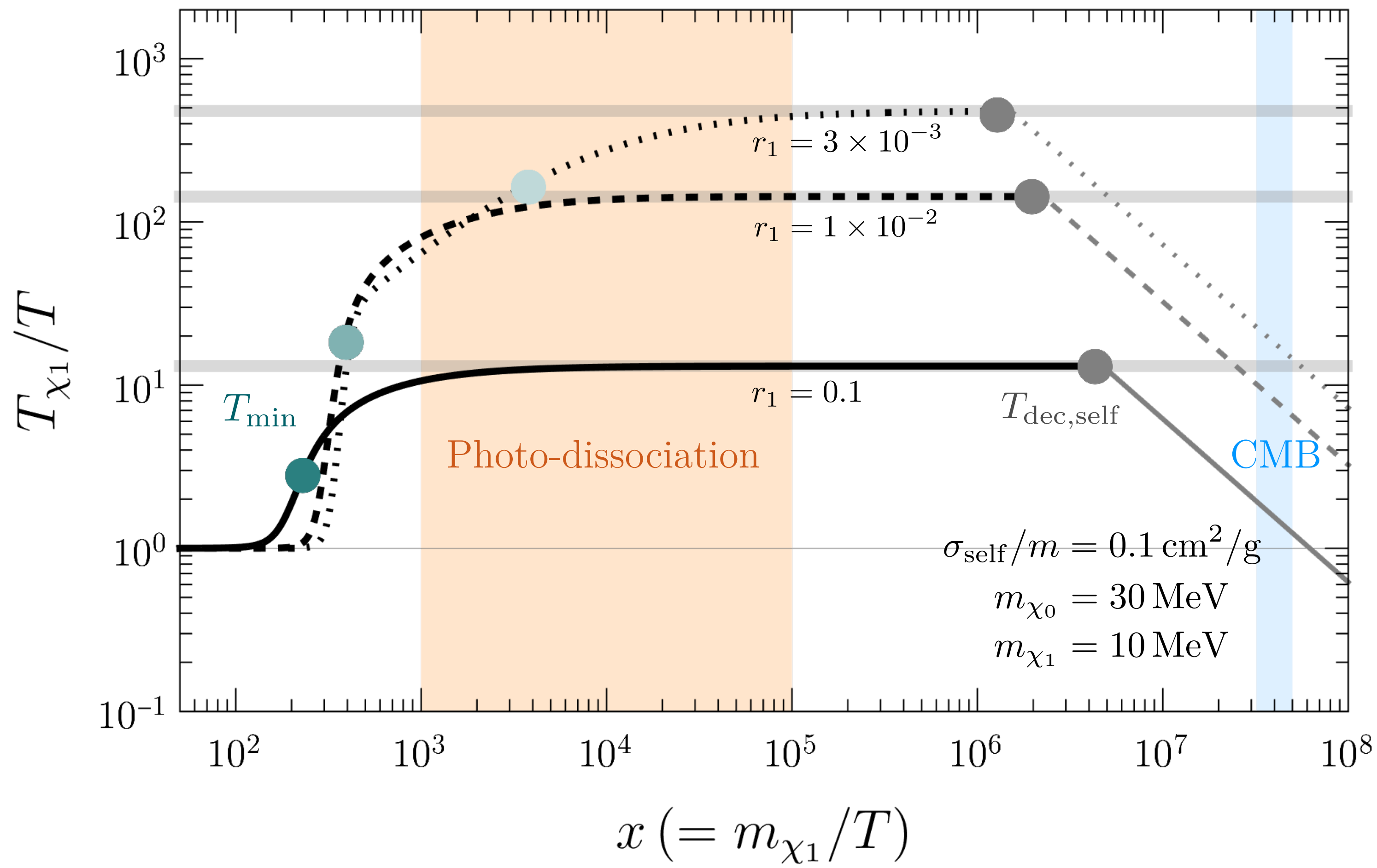


Kamada, Kim, Kim, Sekiguchi, PRL 2018

Chu, Garcia-Cely, JCAP 2018

Vogelsberger, Zavala, Schutz, Slatyer, MNRAS 2018

Temperature evolution of χ_1

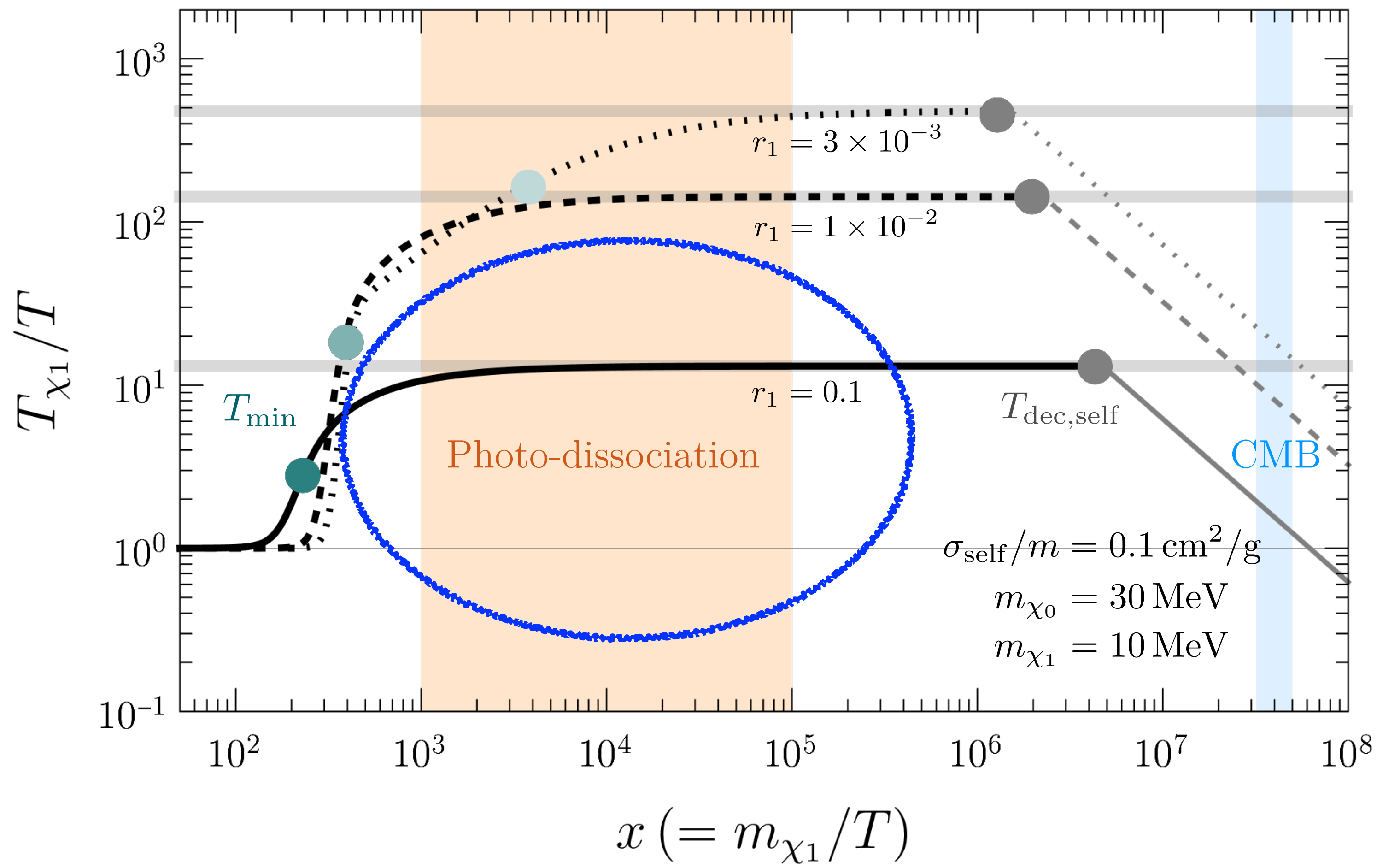


- If self-heating is efficient even after the kinetic decoupling, the temperature evolution of χ_1 shows an interesting dynamics.

- Such an effect increases as r_1 and the strength of the self-interaction.

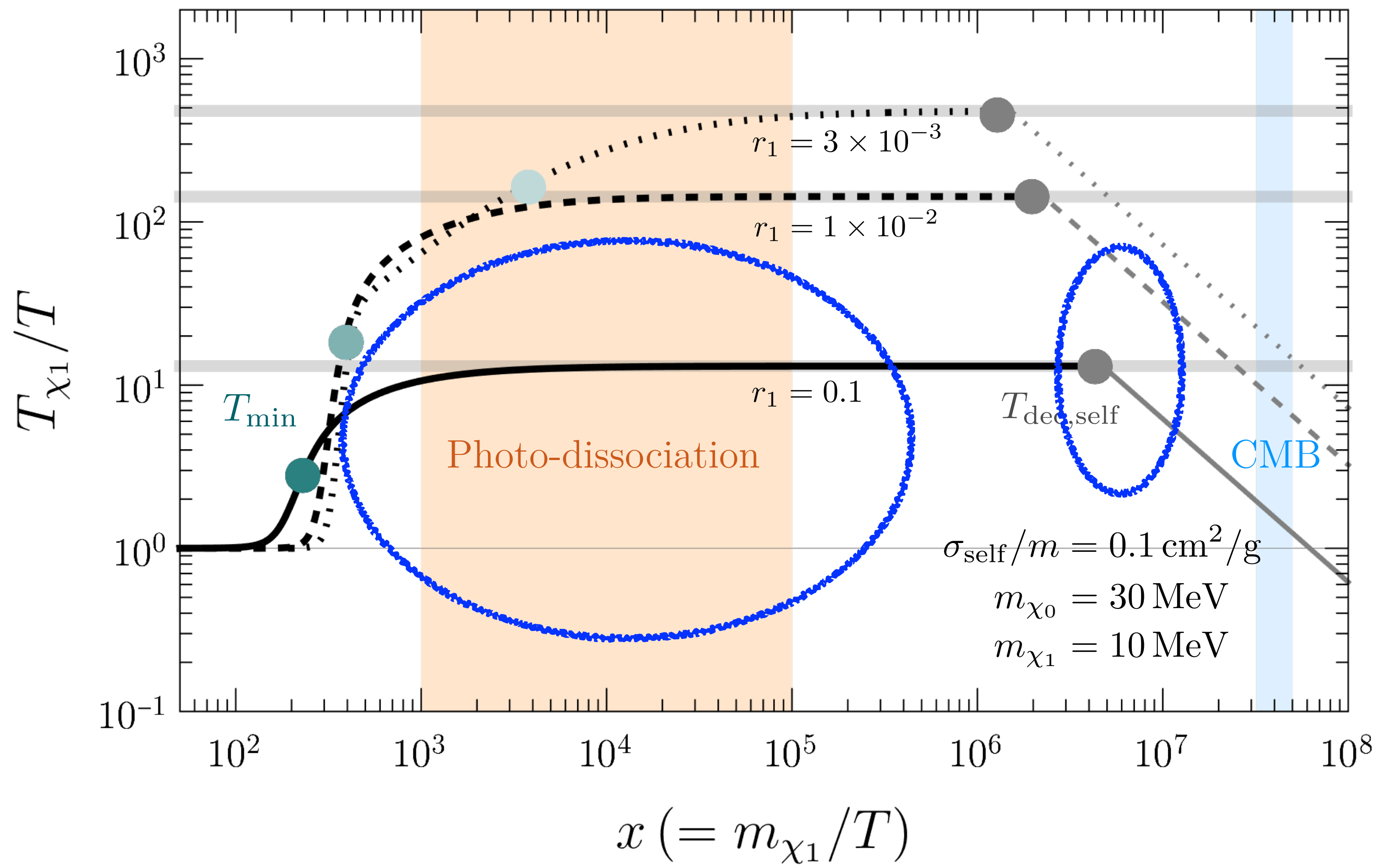
$$T_{\rm dec,self} \simeq \frac{m_e}{20}\left(\frac{m_{\chi_1}}{100\,{\rm MeV}}\right)^{1/3}\left(\frac{0.1}{r_1}\right)^{2/3}\left(\frac{10^{-6}\,{\rm cm^2/g}}{\sigma_{\rm self}/m}\right)^{2/3}$$

Temperature evolution of χ_1



- The photo-dissociation bounds become severer.

Temperature evolution of χ_1



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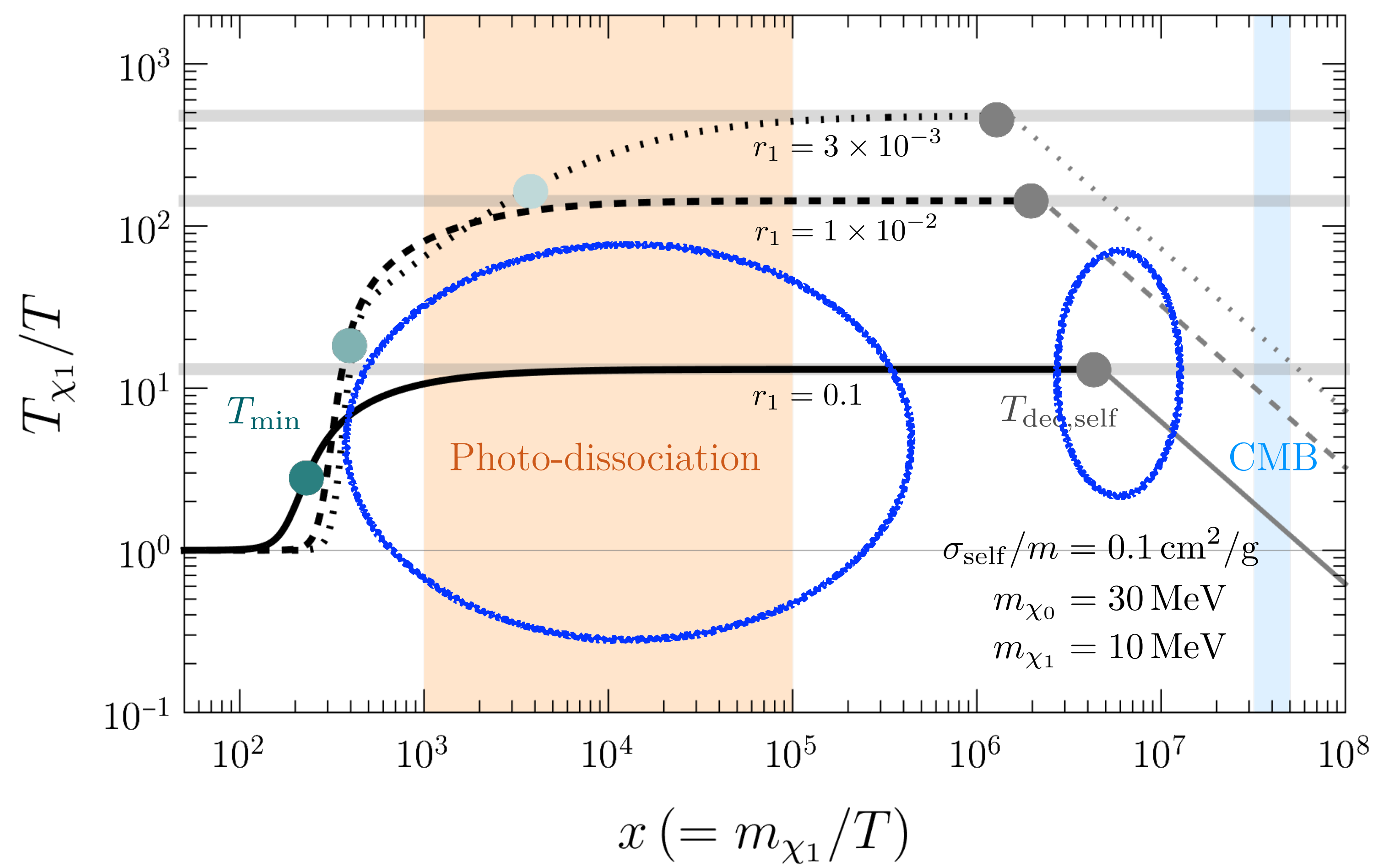

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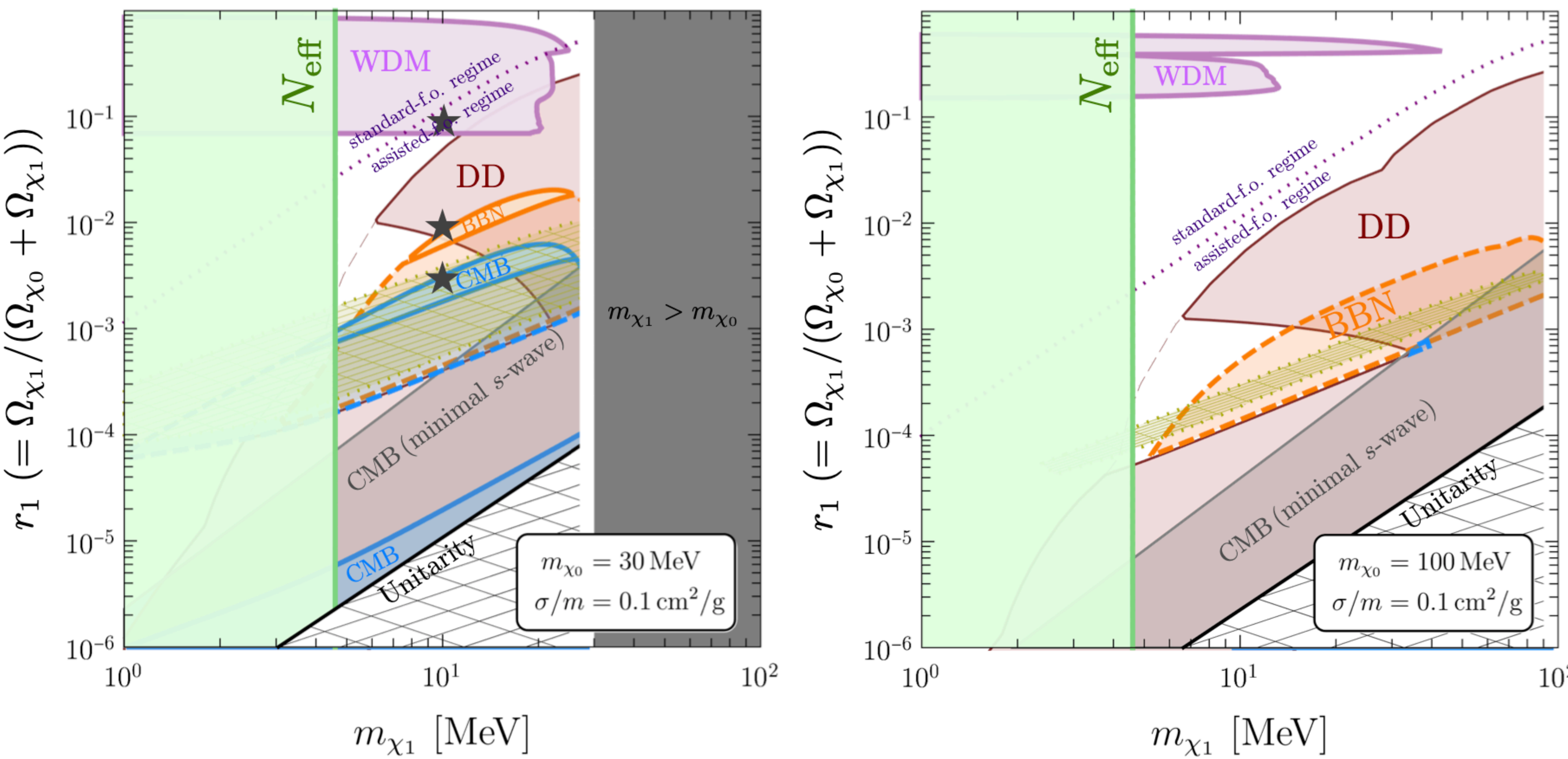
χ_1 can be sub-GeV Warm Dark Matter!!

Lyman-α

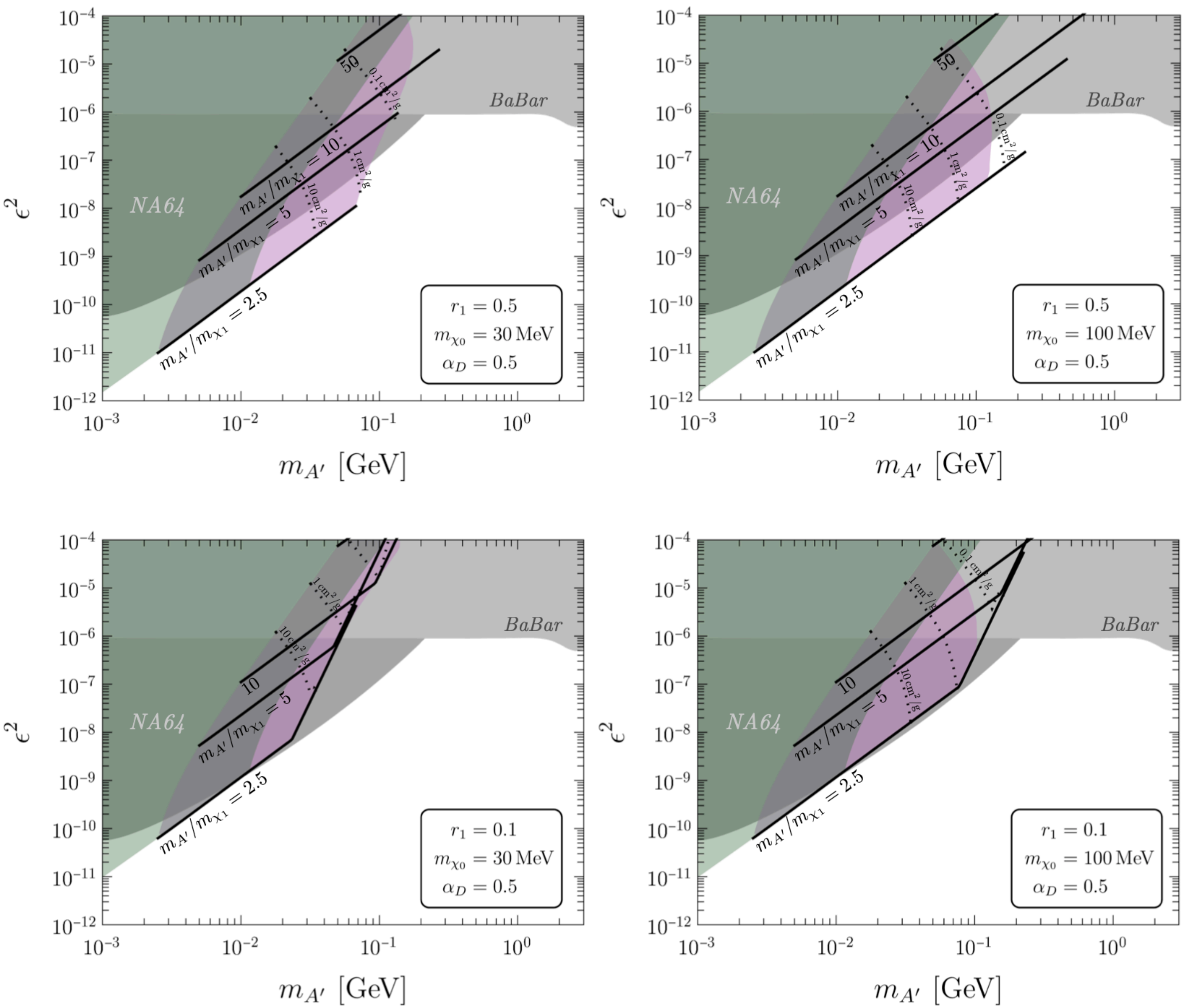
# of satellites

New bounds due to self-heating



Complementary searches

Light DM can be produced in accelerators!



- Reference model: singlet scalar DM + dark photon
- Green: N_{eff}, Pink: WDM for $r_1 \gtrsim 0.1$.
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- Future discovery can tell the dark sector details.

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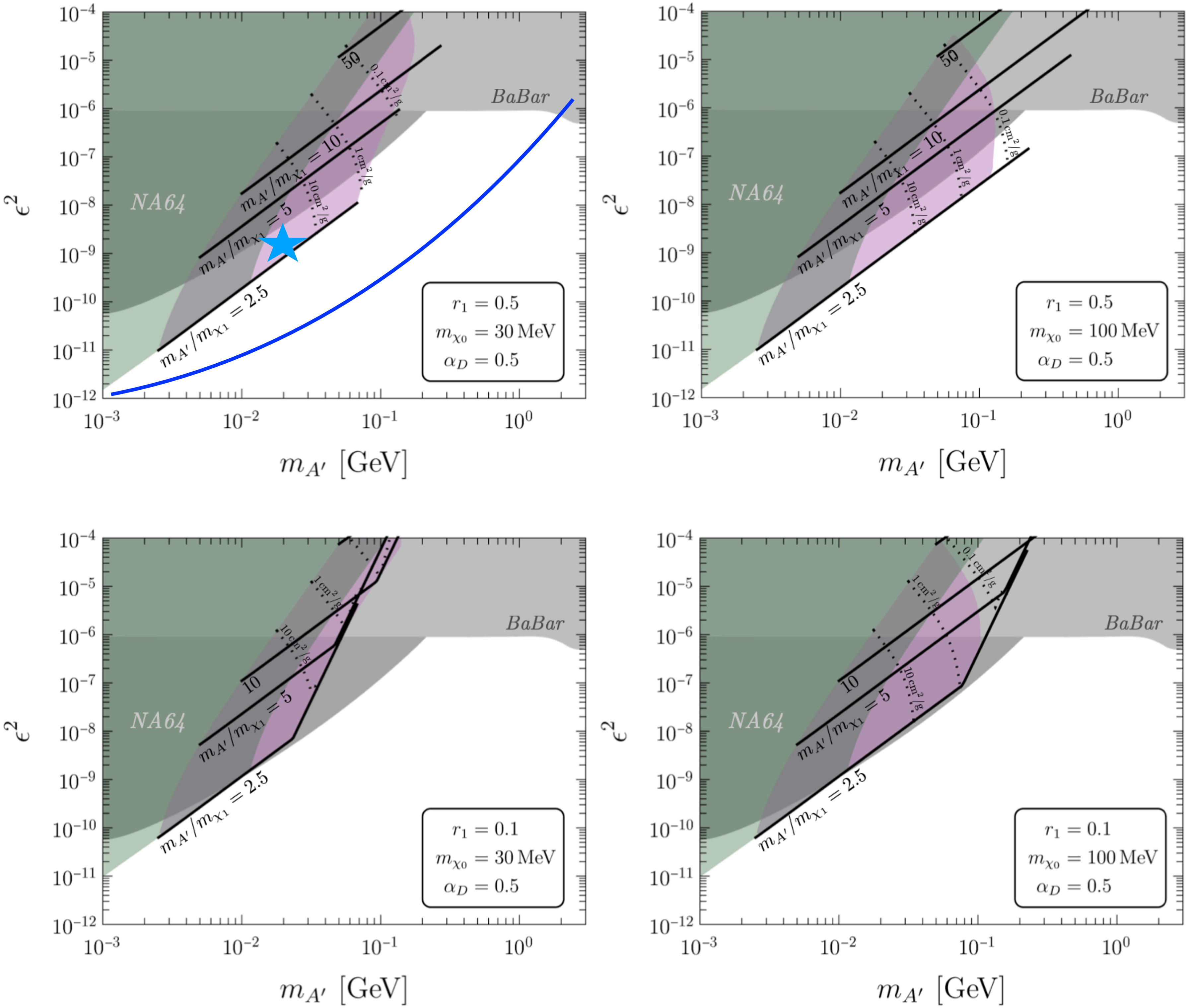

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Conclusions

- A sub-component DM in general multi-component dark sector theories can severely affect the cosmological/astrophysical observables. (Sub-component and SM interaction should be p-wave!)

- Suppression of the fraction of the sub-component does not avoid the detections unlike the conventional expectations so far.

- 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: Light Dark Matter recoiling electron

Where do we probe the LDM recoiling electron target?

- Light WIMP (non-relativistic) at DM direct detection experiments: sometimes new devices are proposed.

Kopp, Niro, Schwetz, Zupan, PRD 2009 Essig, Mardon, Volansky, PRD2012, w/ Manalaysay, Sorensen, PRL 2012

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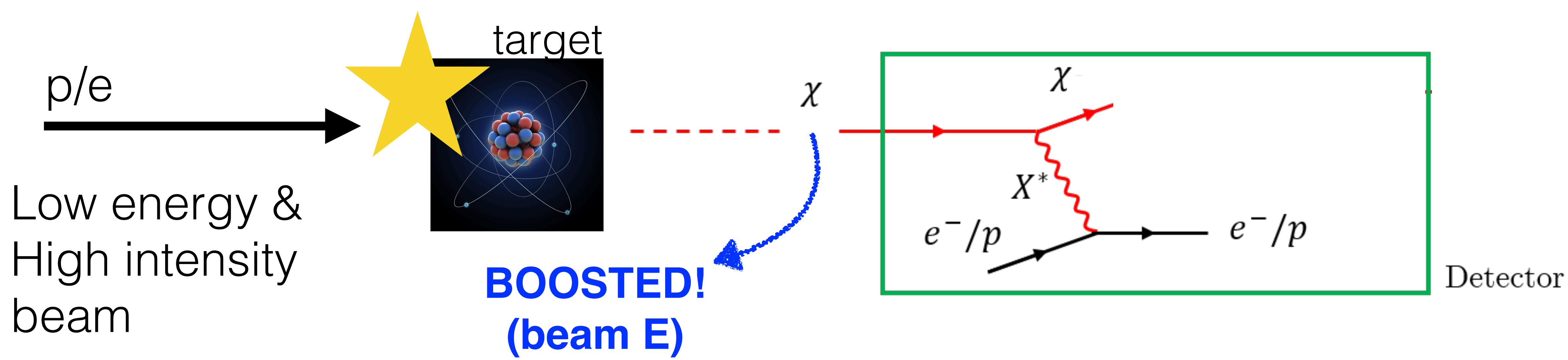

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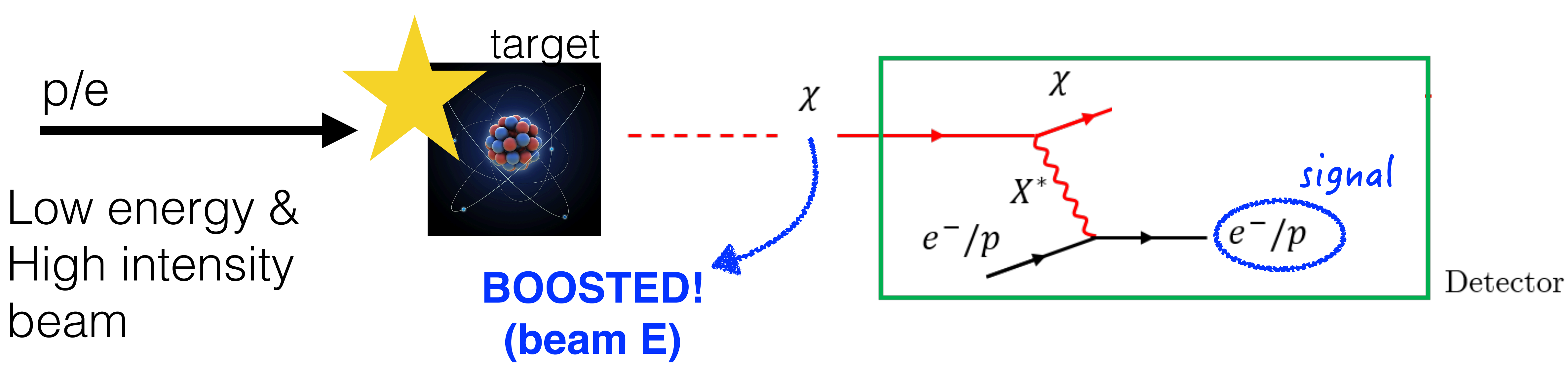

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Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

- COHERENT (Oak Ridge)
- Coherent Captain Mills (Los Alamos)
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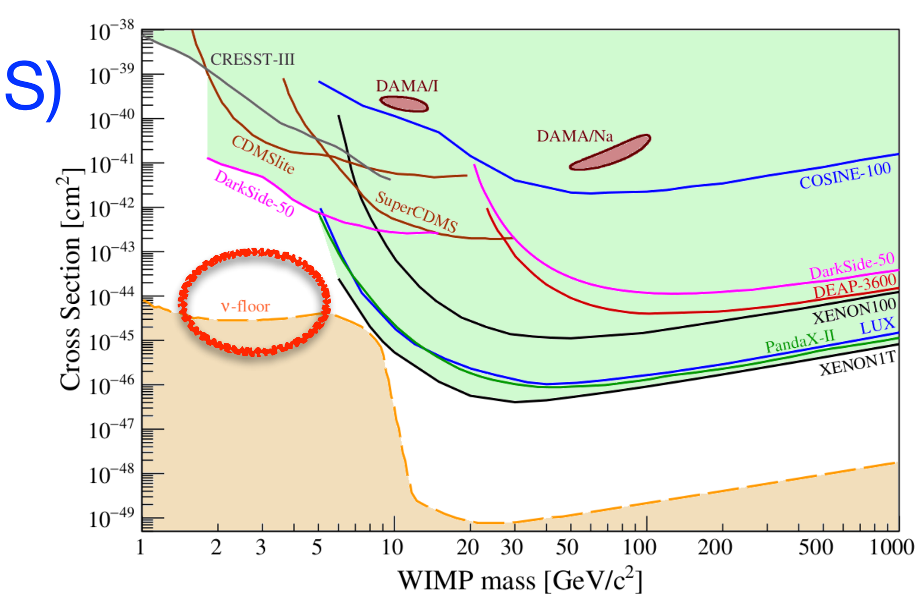

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Timing & Energy cut

Dutta, Kim, Liao, Park, **SS**, Strigari, PRL 2020

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3σ level mild **excess** in 2018 CsI data (4446 kg·day)

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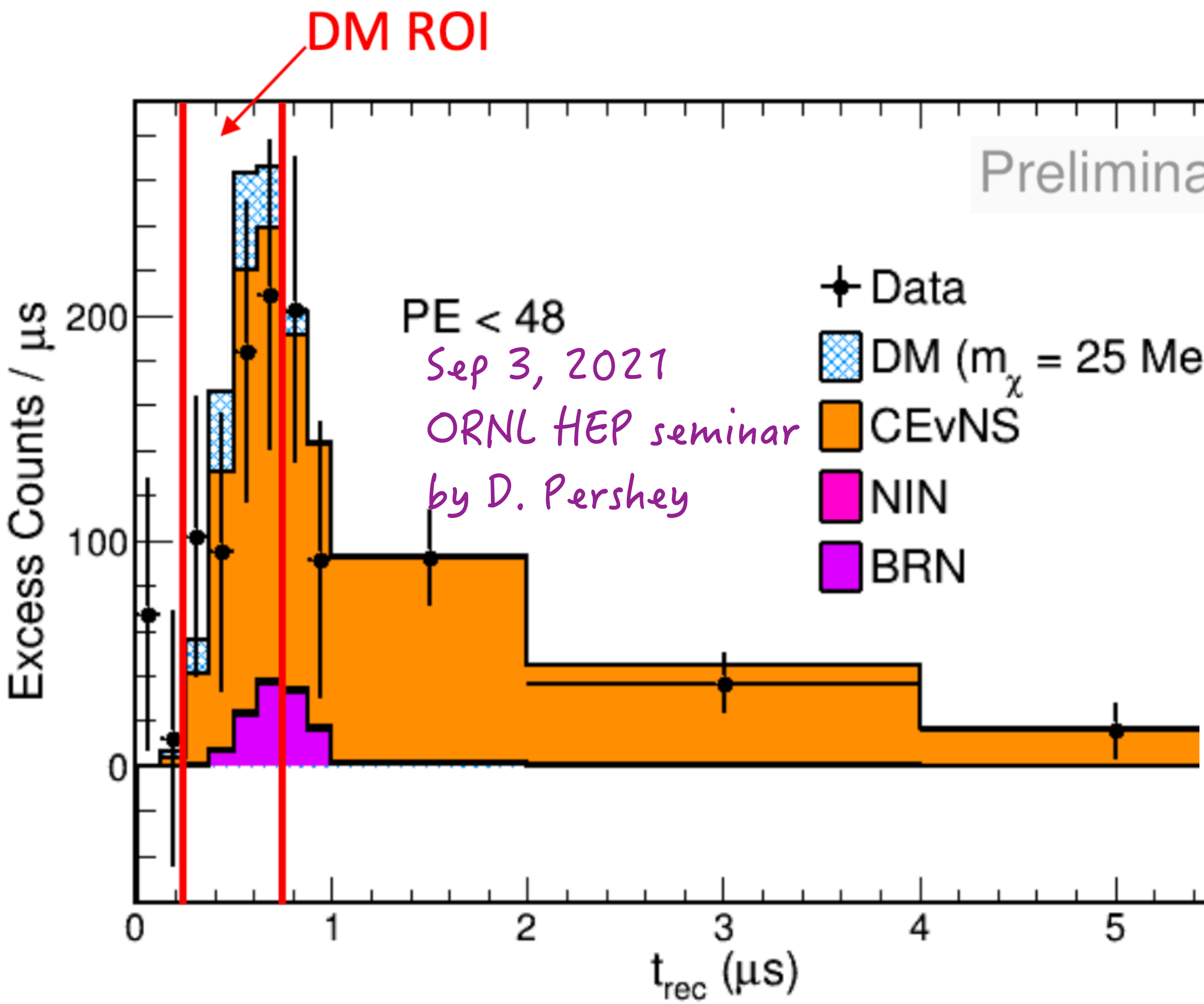
Backup: Light Dark Matter recoiling electron

tron target?



experiments:

Man... PRL 2012

- Afterglow background: mysterious glow
- xxxxxx backgrounds…

Timing & Energy cut

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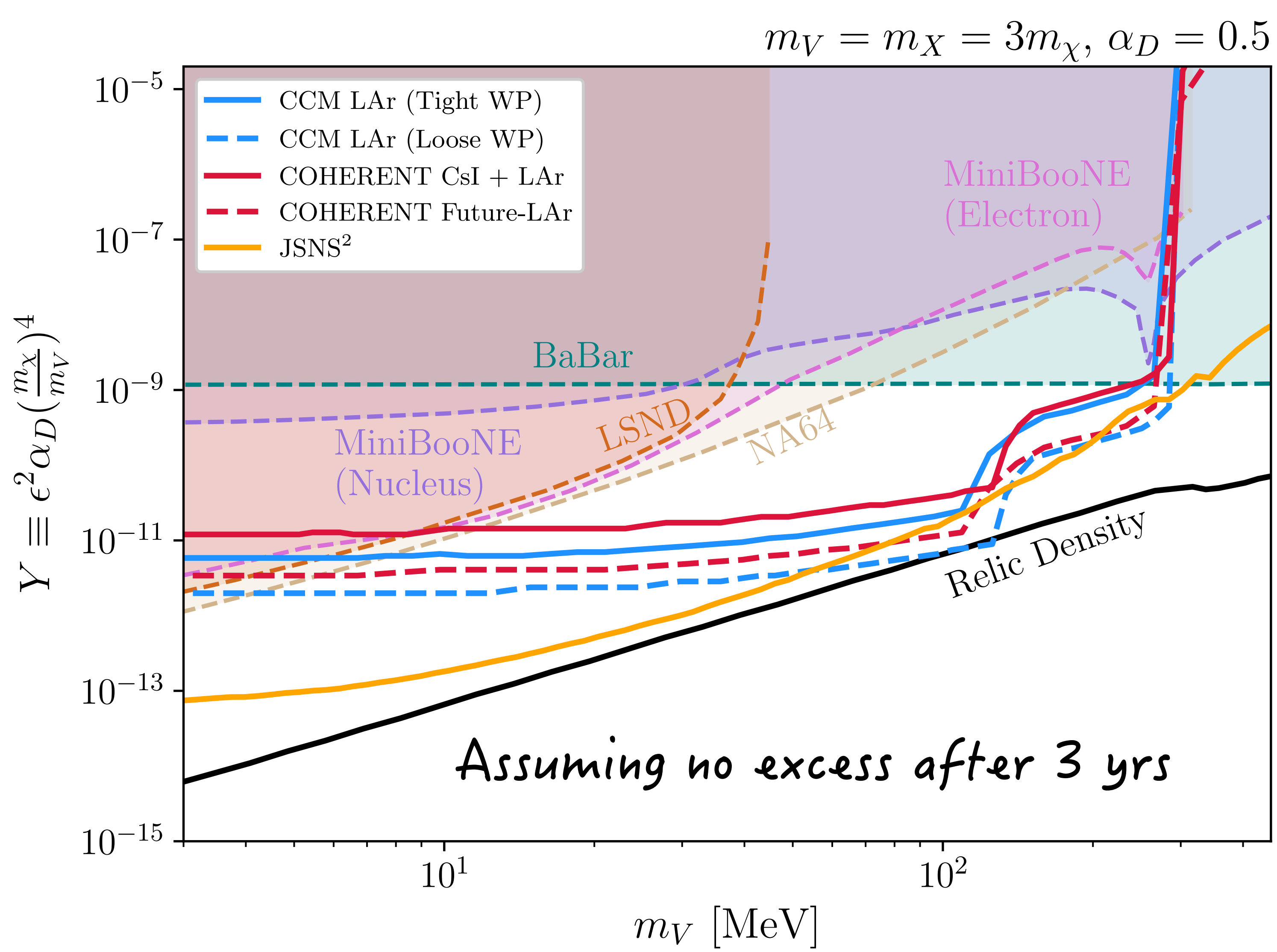
Backup: Light Dark Matter recoiling electron

Whe **arget?**



- Light
  some iments:

  Kopp, Niro, ... say, Sorensen, PRL 2012

  Roberts, Dz ... afdi, PRD 2015 + many…

- Light

- Light

  Bjorken, ... Cosmic Vision, 1707.04591

Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

- COHERENT (Oak Ridge

3σ level mild **excess** in 2018 CsI data (4446 kg·day)

Timing & Energy cut

- Coherent Captain Mills (

Dutta, Kim, Liao, Park, **SS**, Strigari, PRL 2020

Dutta, Kim, Liao, Park, **SS**, Strigari, Thompson, 2006.08386

- JSNS² (J-PARC)

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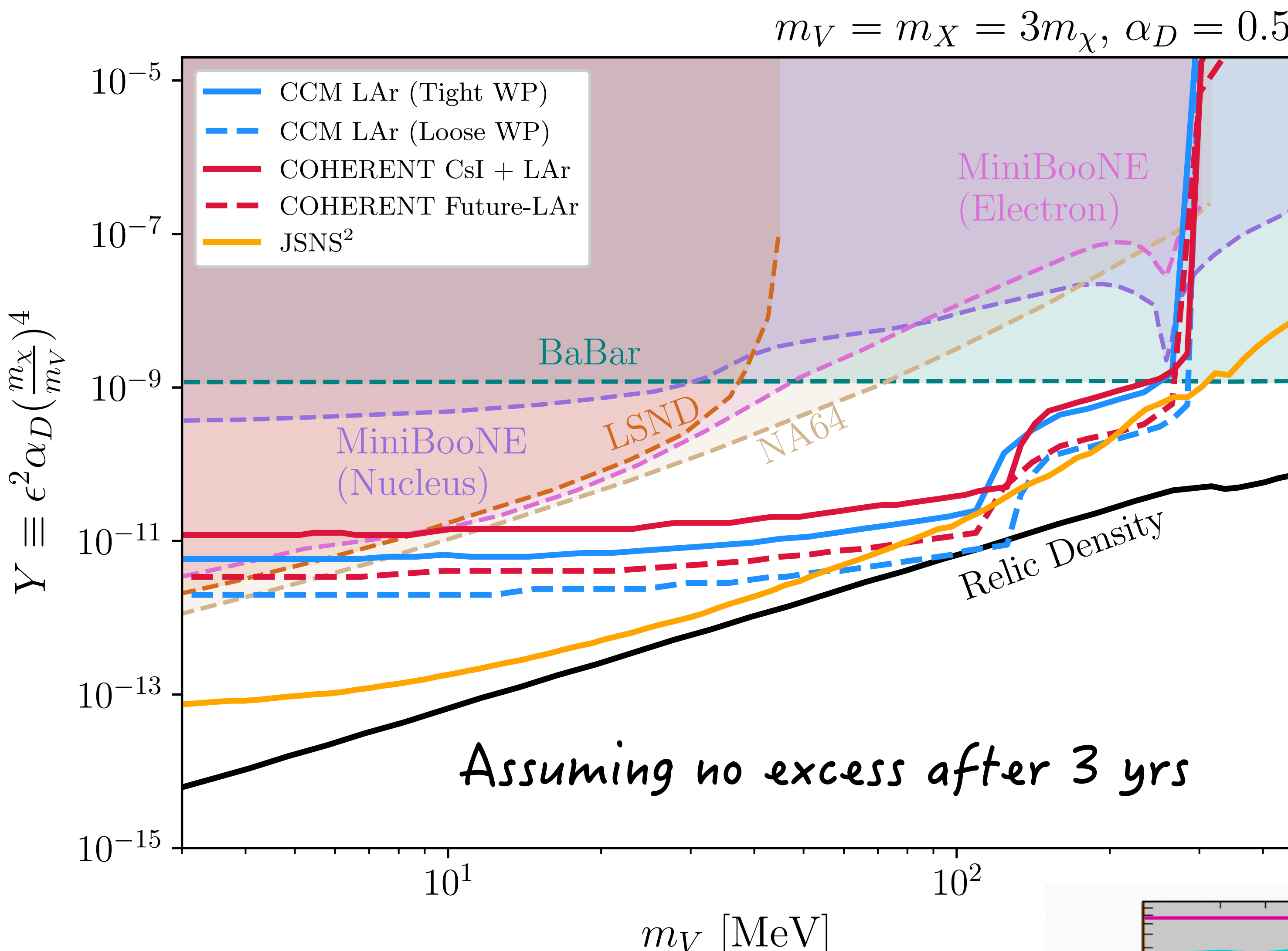
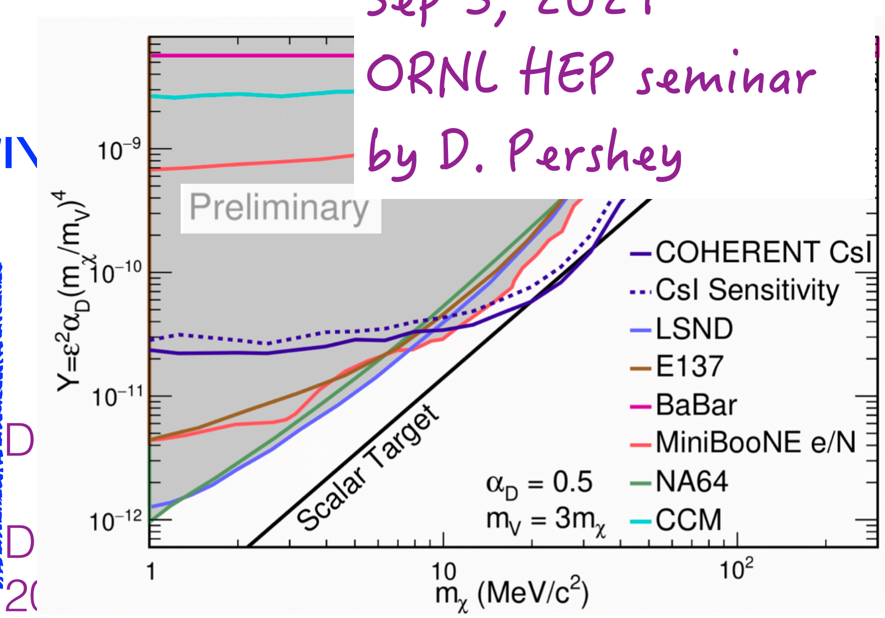


- Light

- Light

Bjorken,

Sep 3, 2021
ORNL HEP seminar
by D. Pershey



Coherent Elastic Neutrino Nucleus Scattering (CEvN

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(4446 kg·day)

D 0

D on,

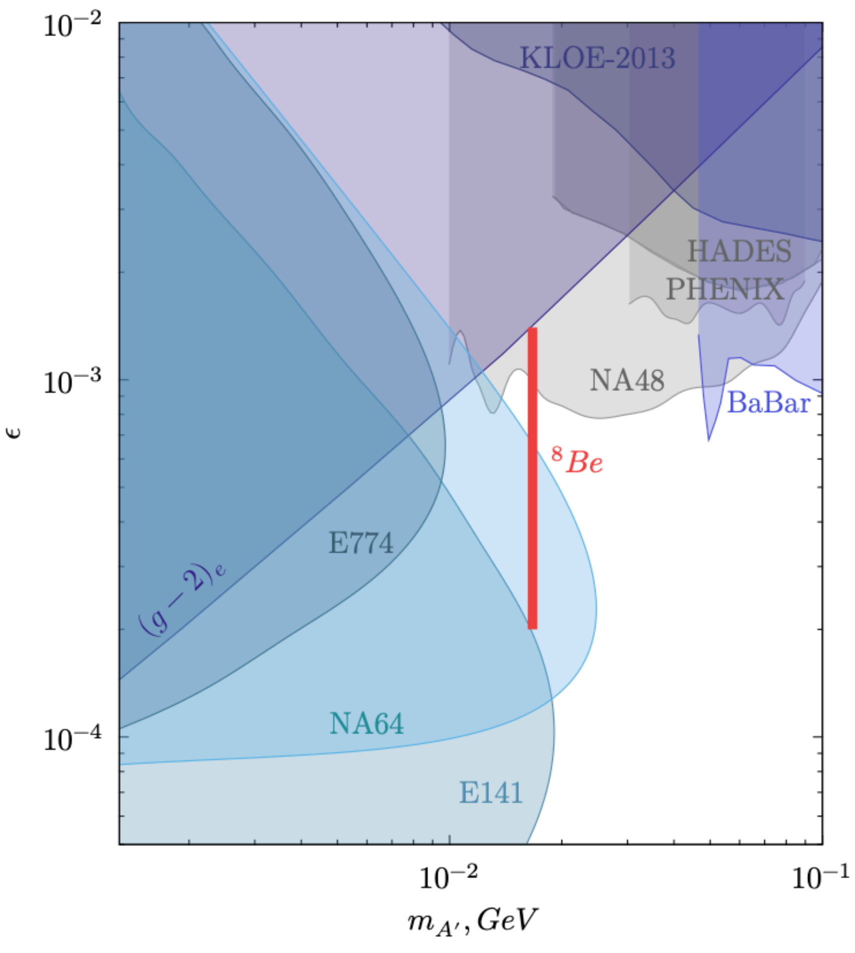
20

Backup: DM experiments

Kim, Machado, Park, **SS**, JHEP 2007, 057 (2020)

Dark Matter Experiments	Target Material	Volume [t] Active	Volume [t] Fiducial	Depth [m]	E_{th} [keV]	Resolution Position [cm]	Resolution Angular [°]	Resolution Energy [%]	PID	Run Time	Refs.
DarkSide −50	LAr DP-TPC	46.4 kg	36.9 kg	3,800 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	$\lesssim 10$	–	2013-	[112]
DarkSide −20k	LAr DP-TPC	23	20	3,800 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	$\lesssim 10$	–	goal: 2021–	[79]
XENON1T	LXe DP-TPC	2.0	1.3	3,600 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	–	–	2016 –2018	[113, 114]
XENONnT	LXe DP-TPC	5.9	~ 4	3,600 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	–	–	goal: 2020–	[113]
DEAP -3600	SP LAr S1 only	3.26	2.2	2,000	$\mathcal{O}(10)$	< 10	–	$\sim 10-20$	–	2016-	[99–101]
DEAP −50T	SP LAr S1 only	150	50	2,000	$\mathcal{O}(10)$	15	–	–	–	–	[99]
LUX-ZEPLIN	LXe DP-TPC	7	5.6	1,500	$\mathcal{O}(1)$	$\sim 0.1-1$	–	2.5 MeV: 2	–	goal: 2020–	[115, 116]

Backup: constraints & comparisons



NA64, arXiv:1912.11389