2023 Cosmology Workshop on the Crossroad of Astrophysics and Particle physics: dark matter

Toward Dark World beyond WIMP

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What is Dark Matter?

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What particle is dark matter?

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- Mass?
- (Non-gravitational) Interactions?

  DM - SM

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DM - SM → i) Observation, ii) Amount of DM

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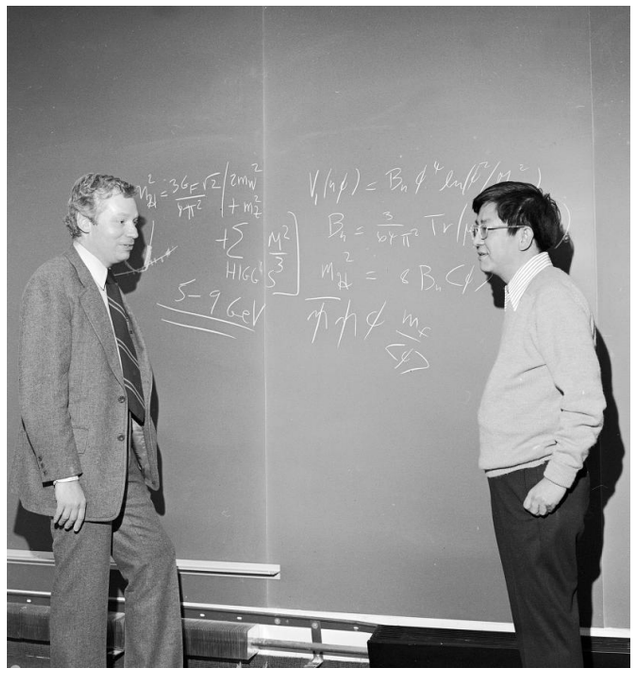
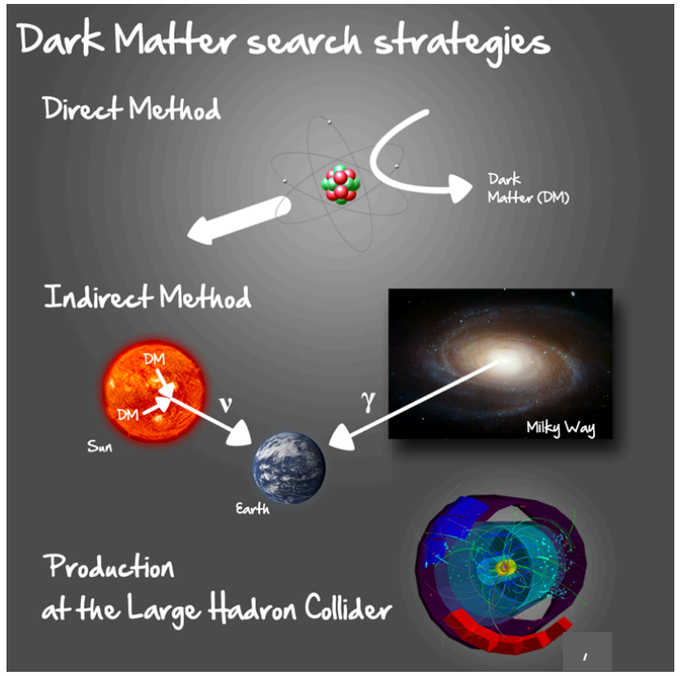
Preferred candidate so far

Weakly Interacting Massive Particle (WIMP)





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WIMP strongly constrained!

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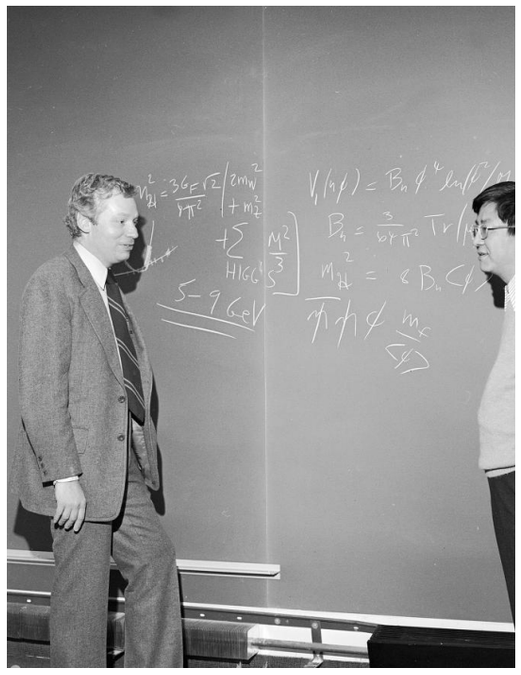
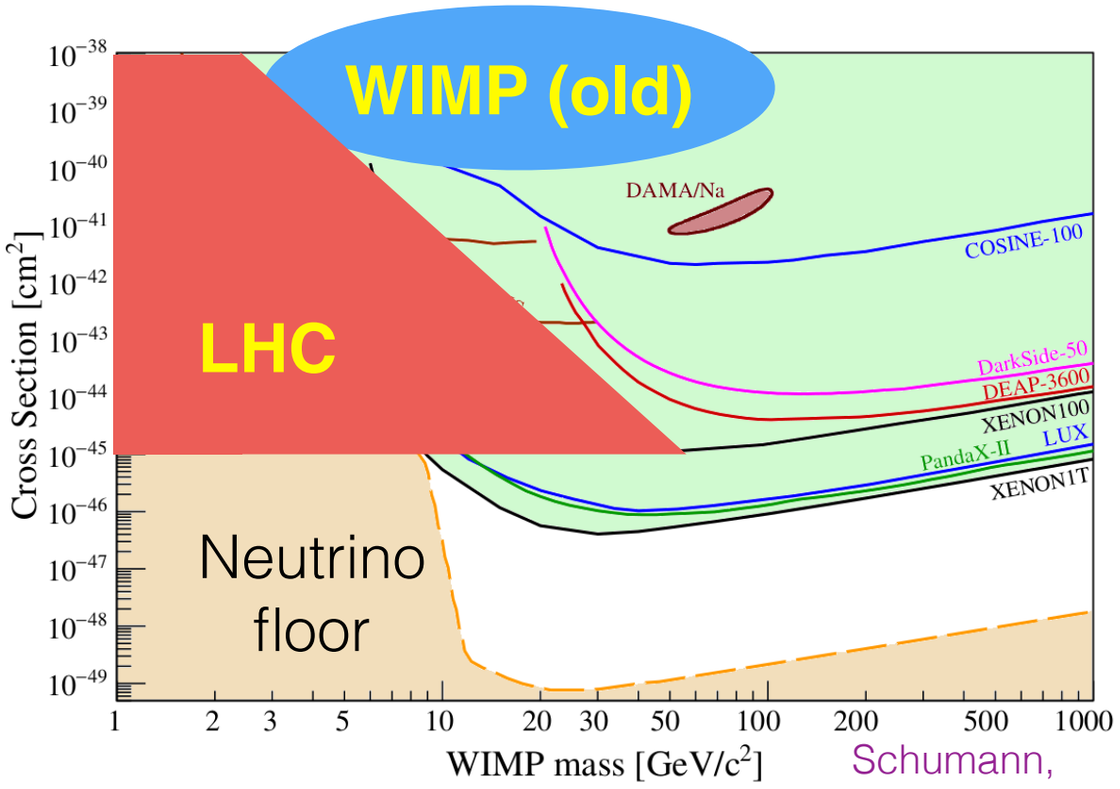
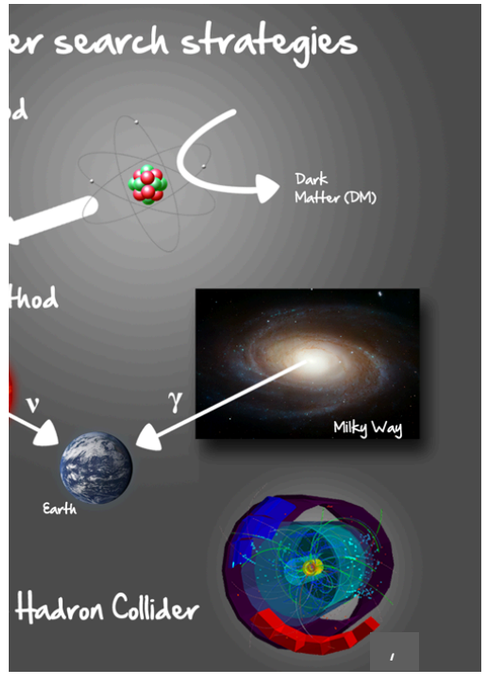
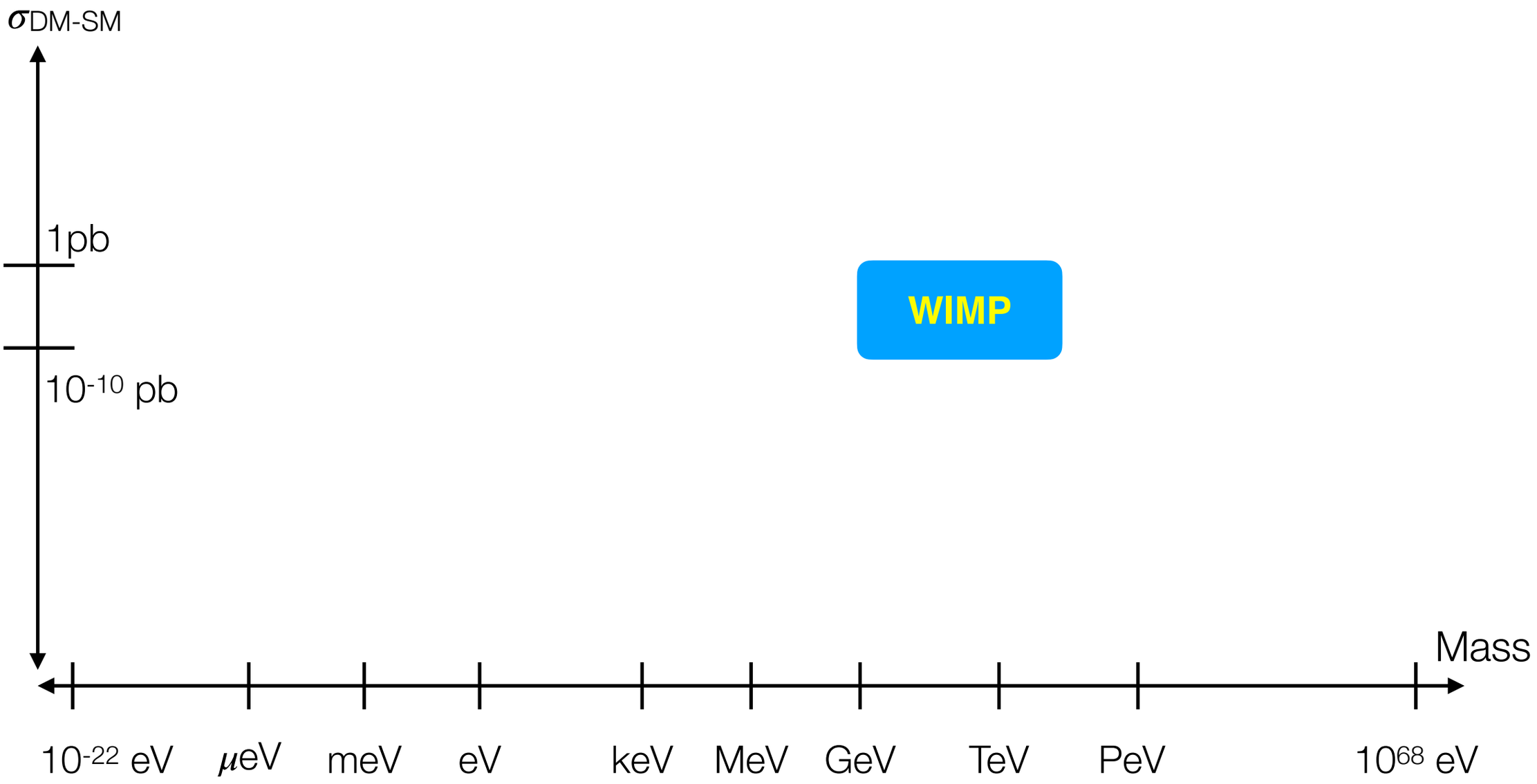




Schumann, 1903.03026



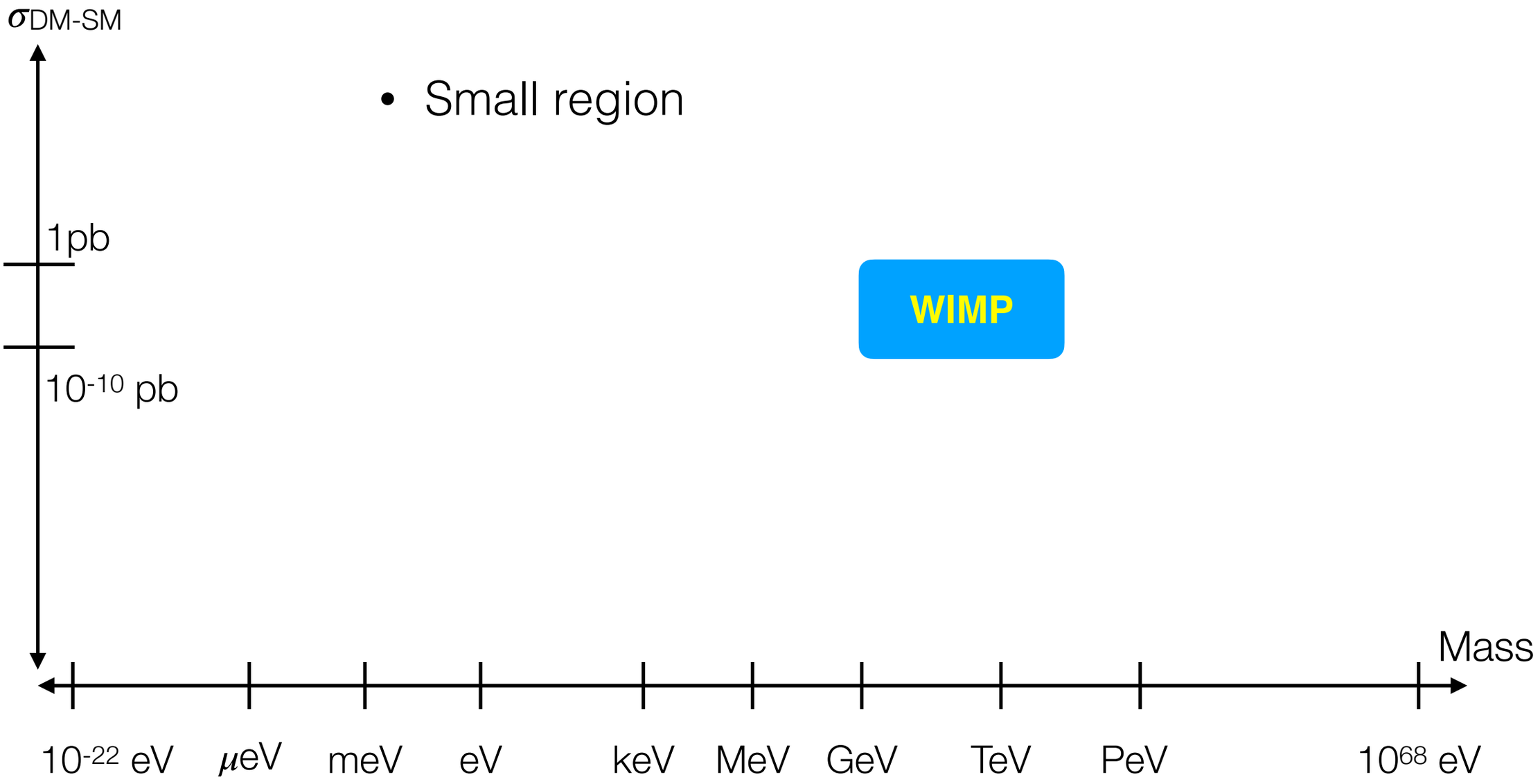
Dark world beyond WIMP



- WIMP: a single species of particles with thermal relic via freeze-out

- Mass in between 1 GeV $\lesssim m_\chi \lesssim$ 100 TeV roughly

Dark world beyond WIMP



- Small region

WIMP

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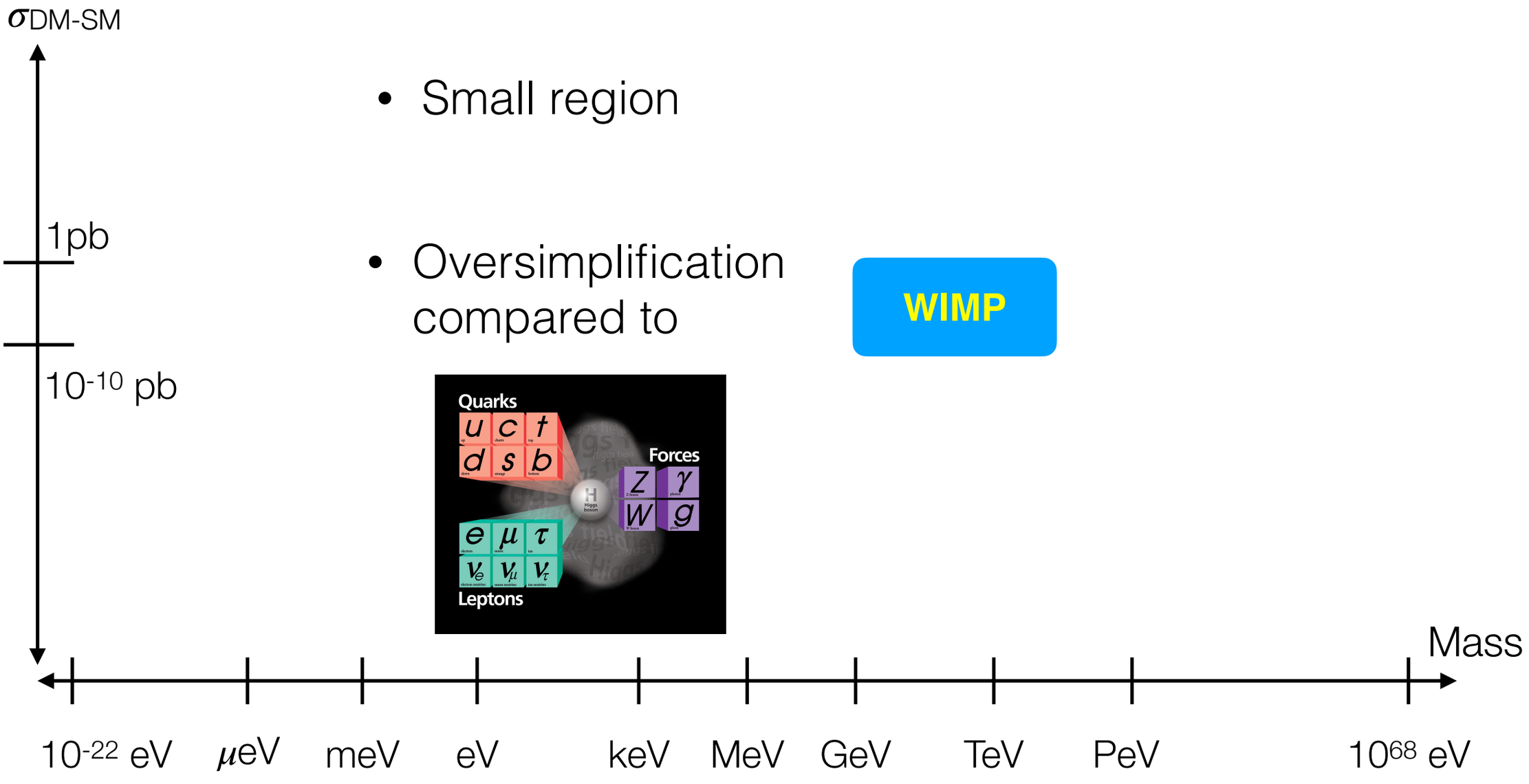
Dark world beyond WIMP



- Small region

- Oversimplification compared to

WIMP

- WIMP: a single species of particles with thermal relic via freeze-out

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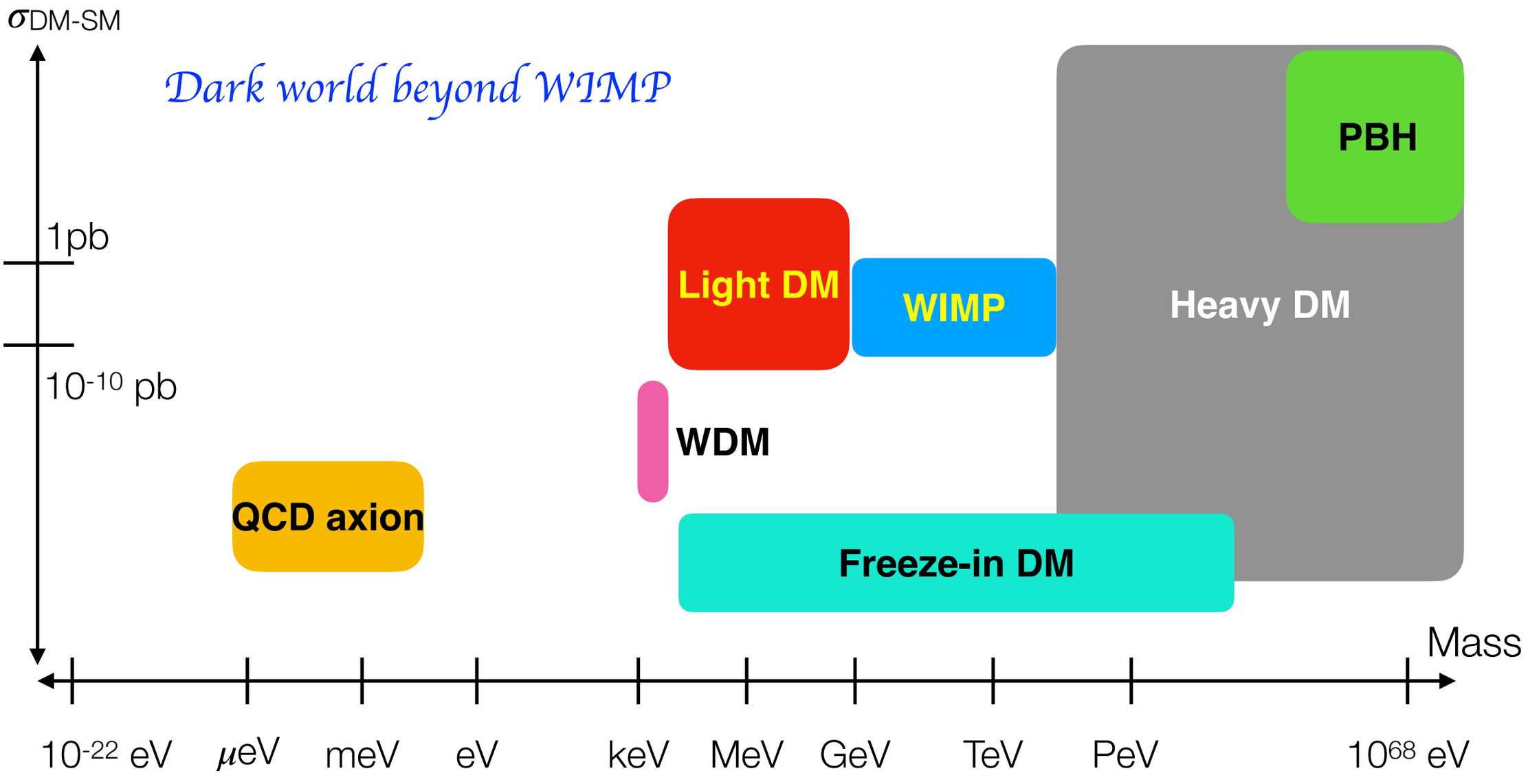
Dark world beyond WIMP



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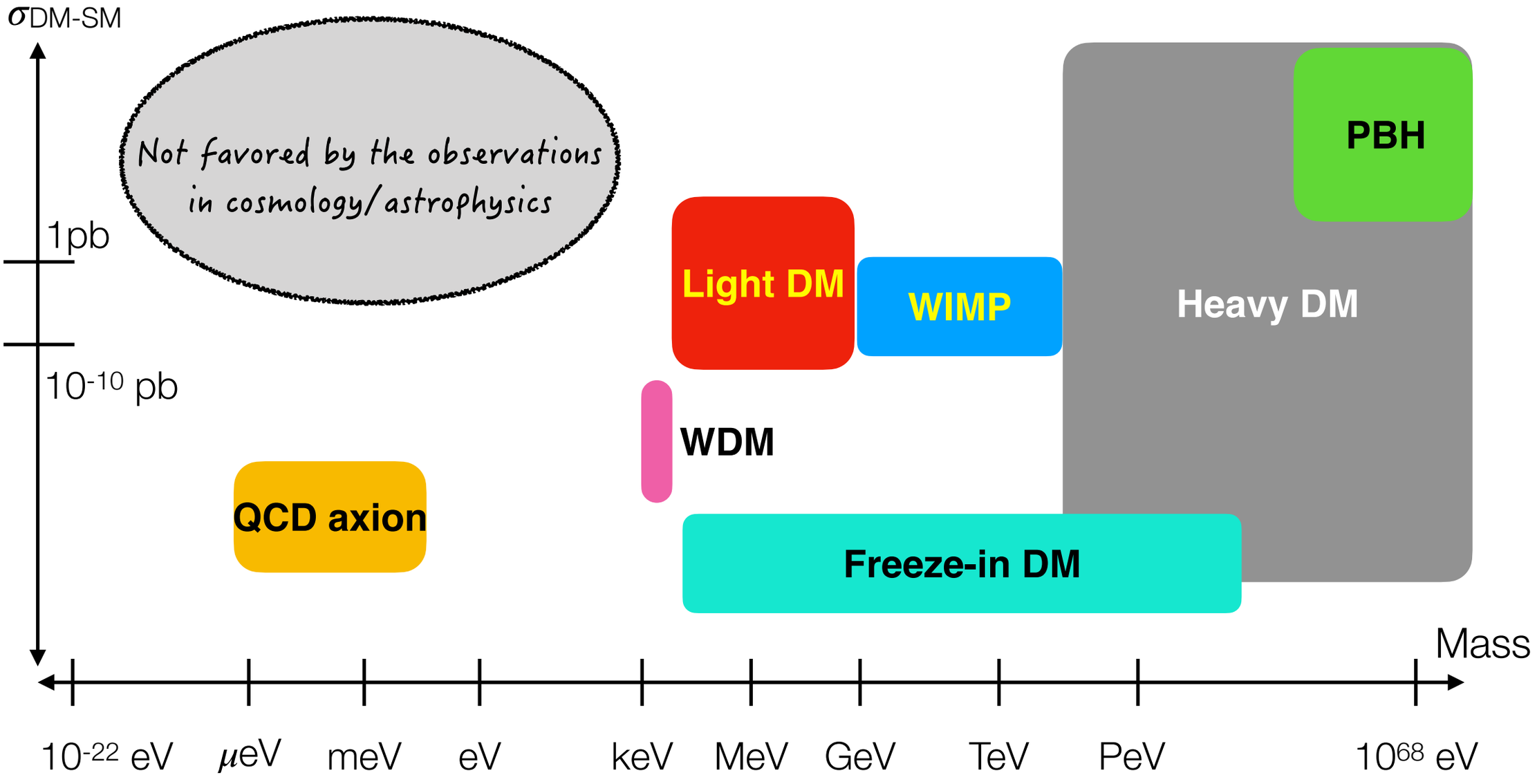
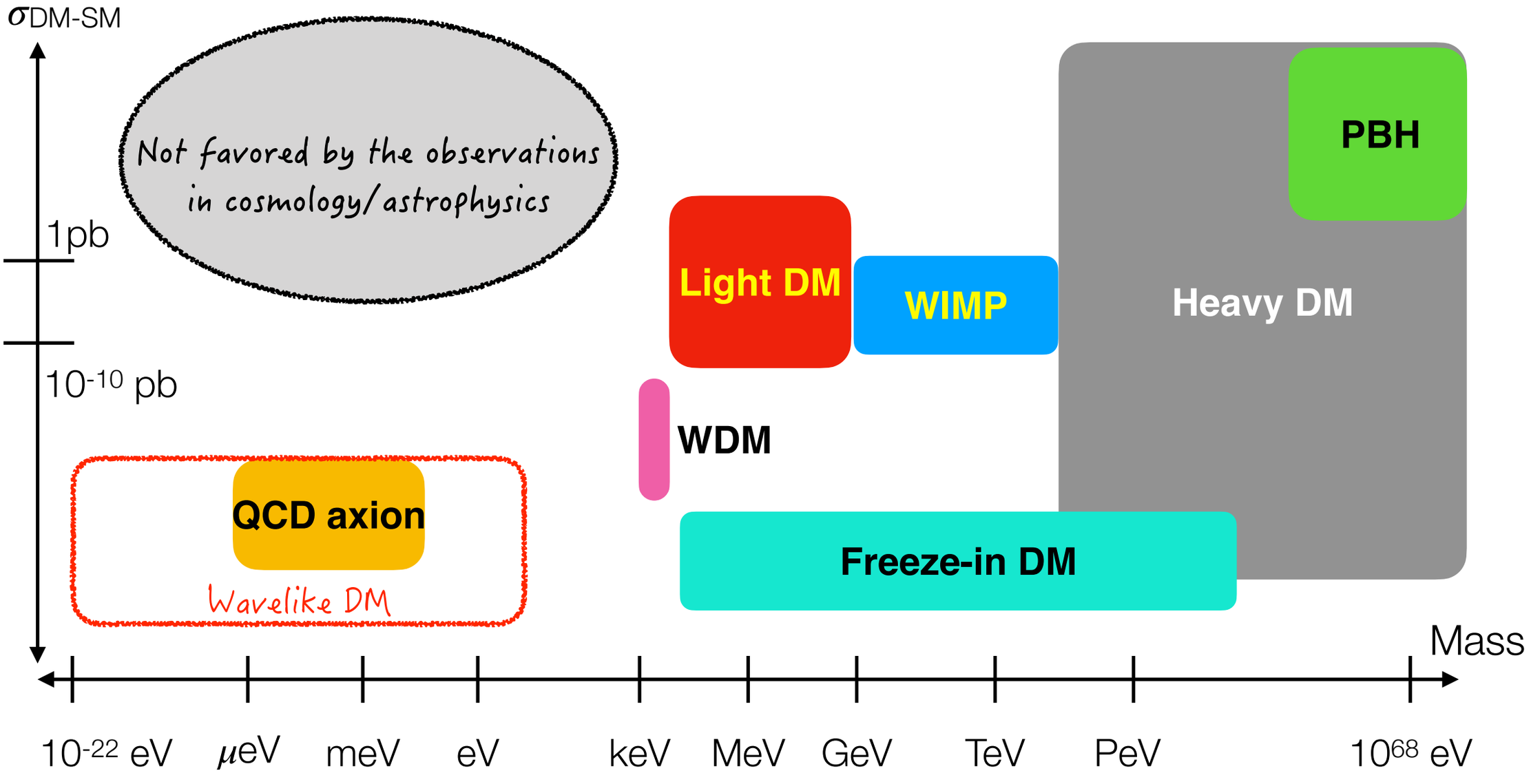


Dark world beyond WIMP

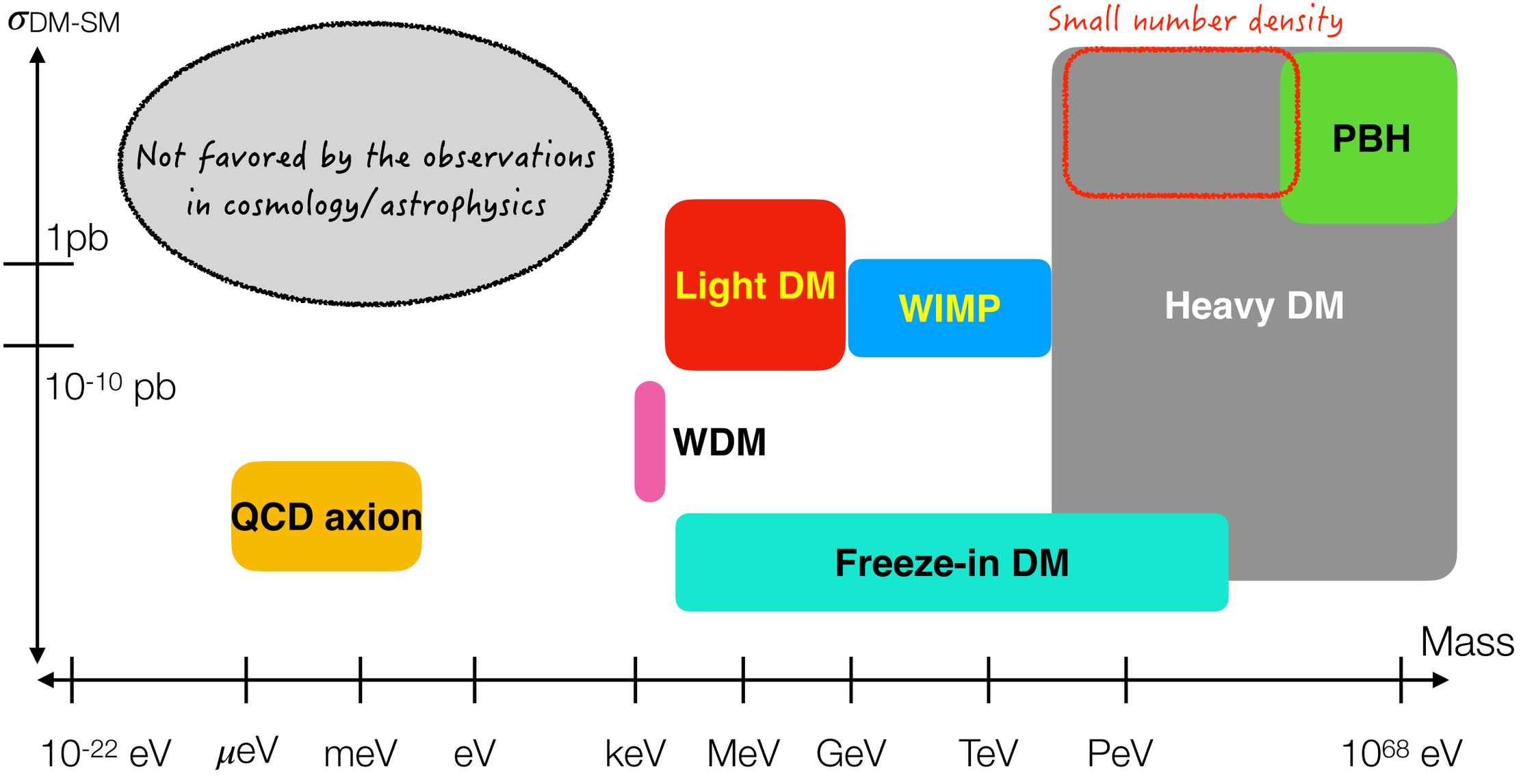


- Wavelike DM: occupation number is large so that the particles are described by classical waves, e.g., axion or ALP

- Experimental probes: axion or ALP search experiments

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

Dark world beyond WIMP

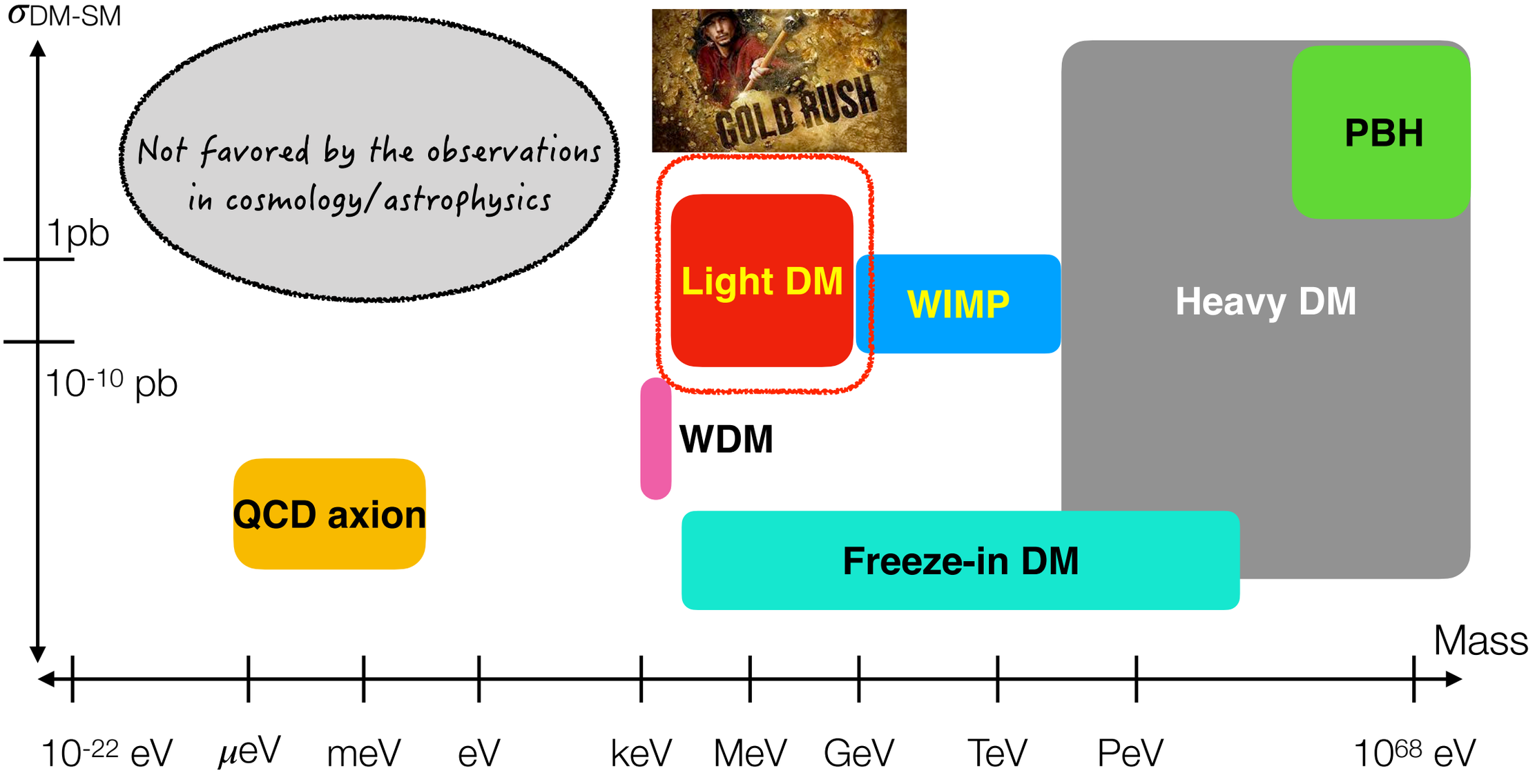


- Heavy DM (small n) with large $\sigma_{\text{DM-SM}}$: multiple scattering signals

  Bramante et al., PRD 2019, PRD 2018

- Primordial Black Hole: cosmo/astro observations

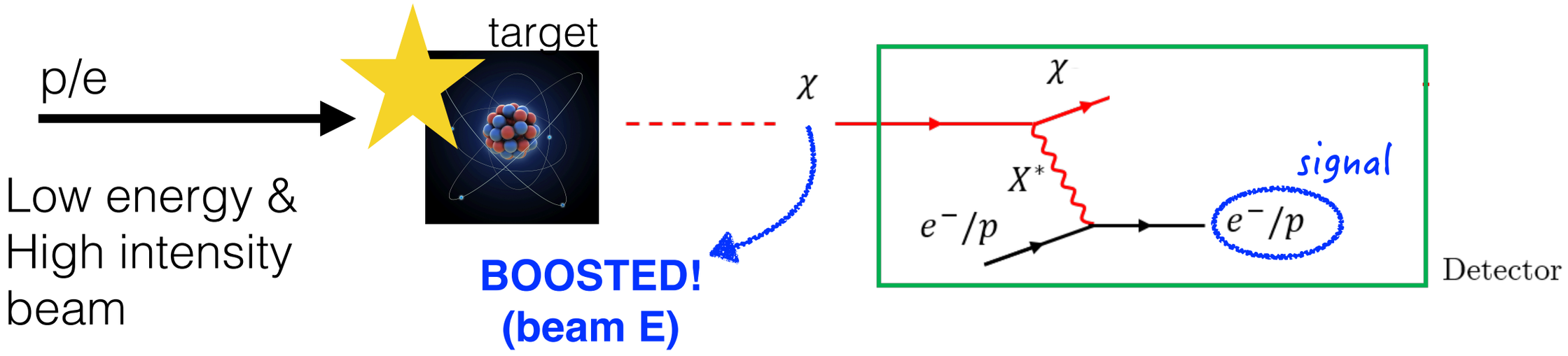
Dark world beyond WIMP



- 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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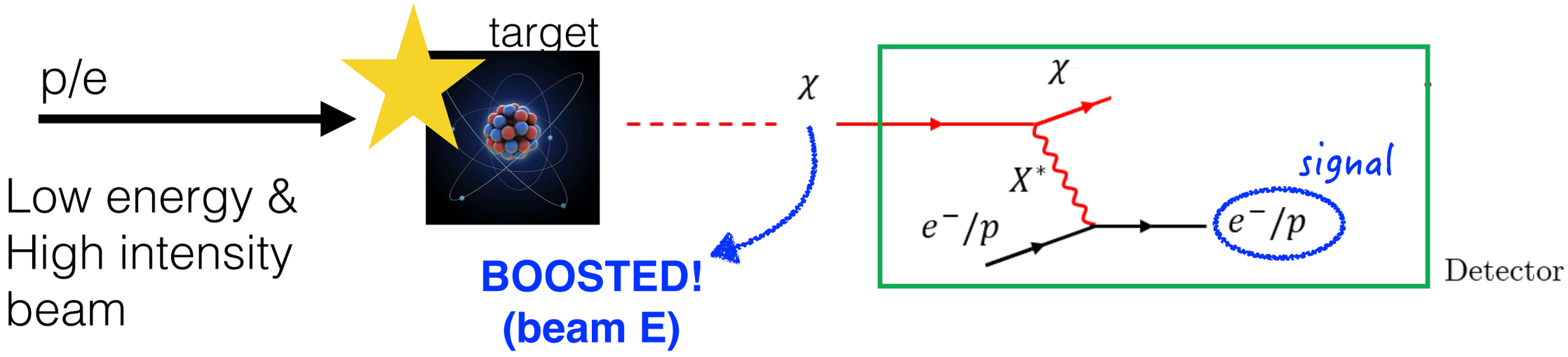
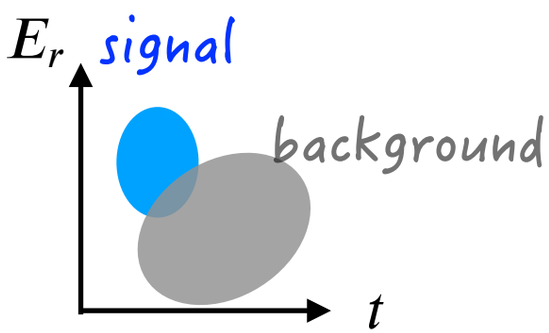


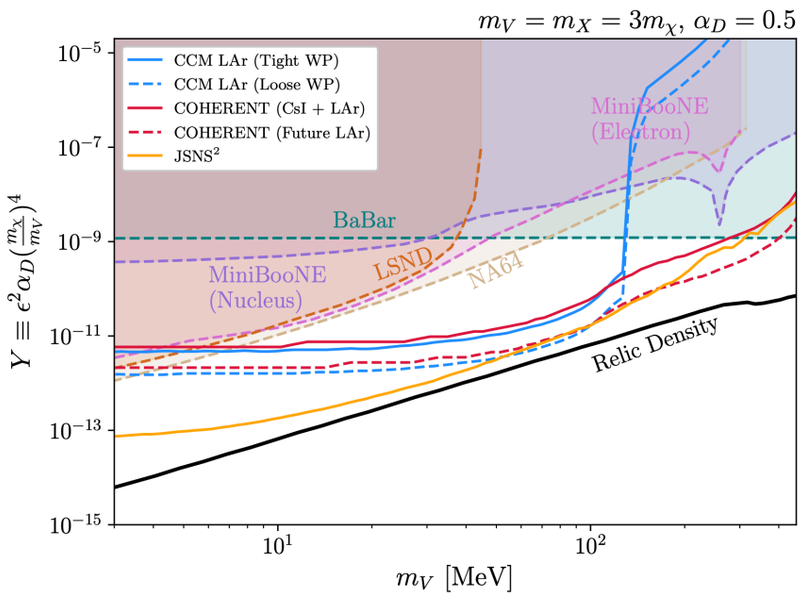
Pulsed beam with high intensity

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

- Applied to COHERENT, CCM, JSNS², …

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





Example: intensity frontier

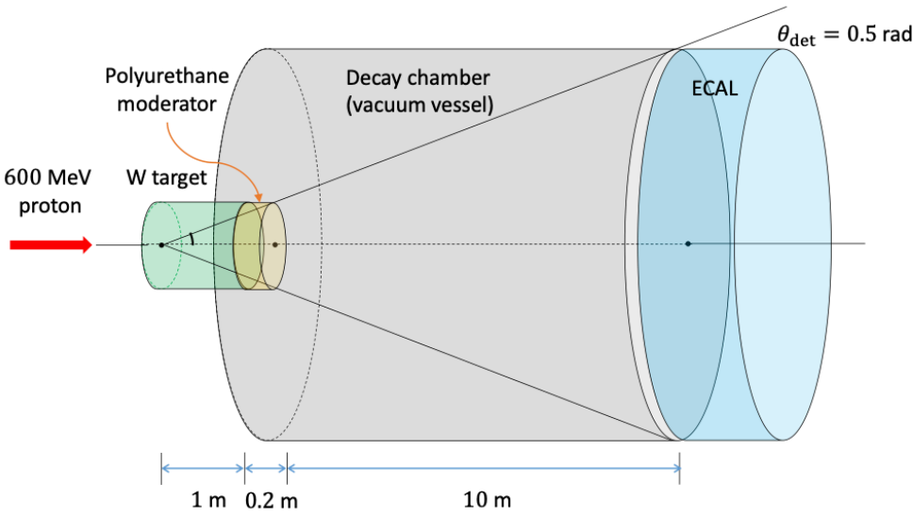
Dump produced Aboriginal Matter Searches at an Accelerator

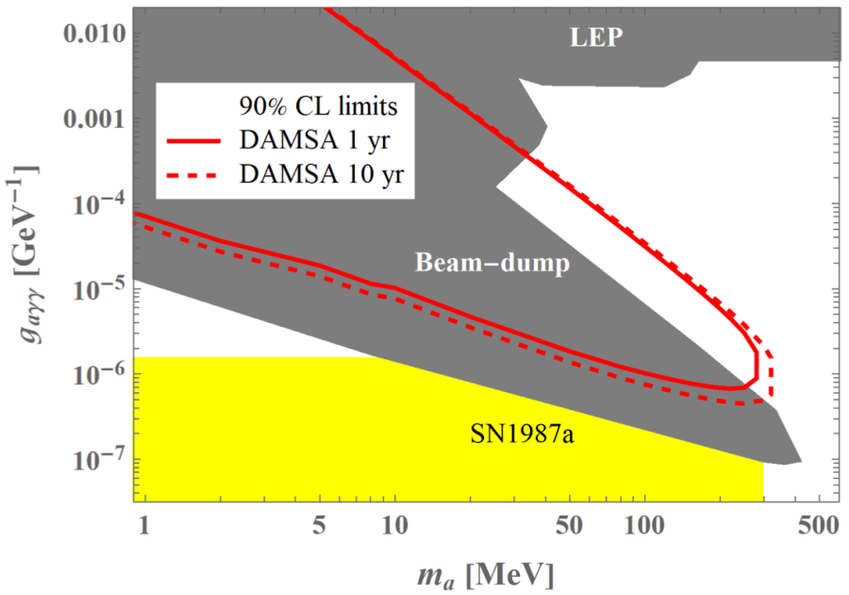
담사: 깊은 생각 潭思

Search Prospects for Axion-like Particles at Rare Nuclear Isotope Accelerator Facilities

PRD 2023

Wooyoung Jang,[1] Doojin Kim,[2] Kyoungchul Kong,[3] Youngjoon Kwon,[4] Jong-Chul Park,[5] Min Sang Ryu,[6,7] Seodong Shin,[8] Richard G. Van de Water,[9] Un-Ki Yang,[10] and Jaehoon Yu[1]

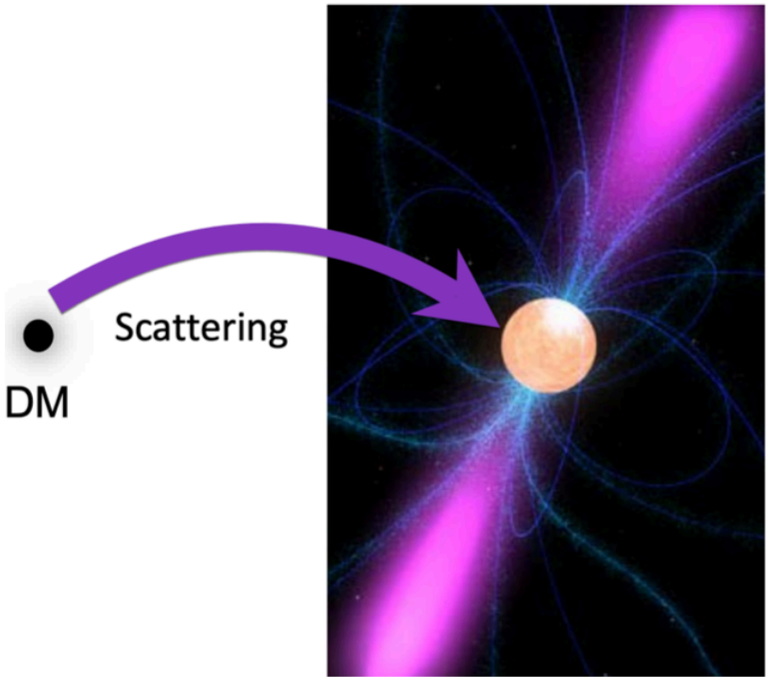


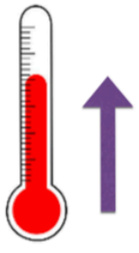


Interplay with Astrophysics

Astrophysics: DM heating celestial body

- Dark matter collides with stars and increases its temperature
  - Heating the neutron star M. Baryakhtar et al. 1704.01577 (PRL)
    - Light dark matter/DD suppressed with velocity/q
  - Detection with infrared telescopes, James Webb Space Telescope etc



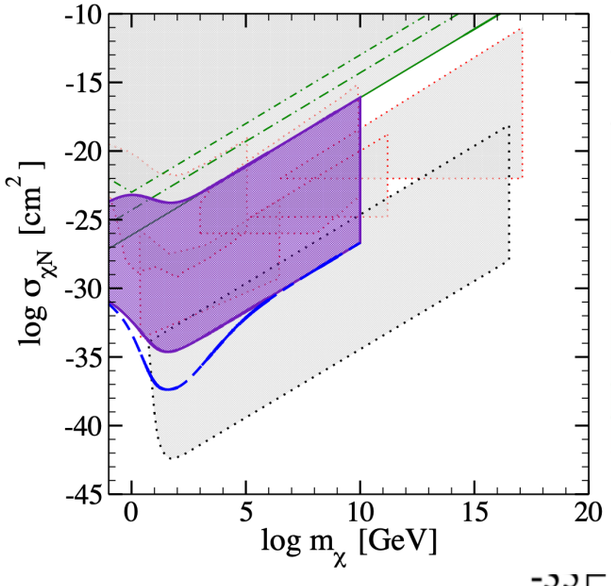


T_{NS} ~1700 K

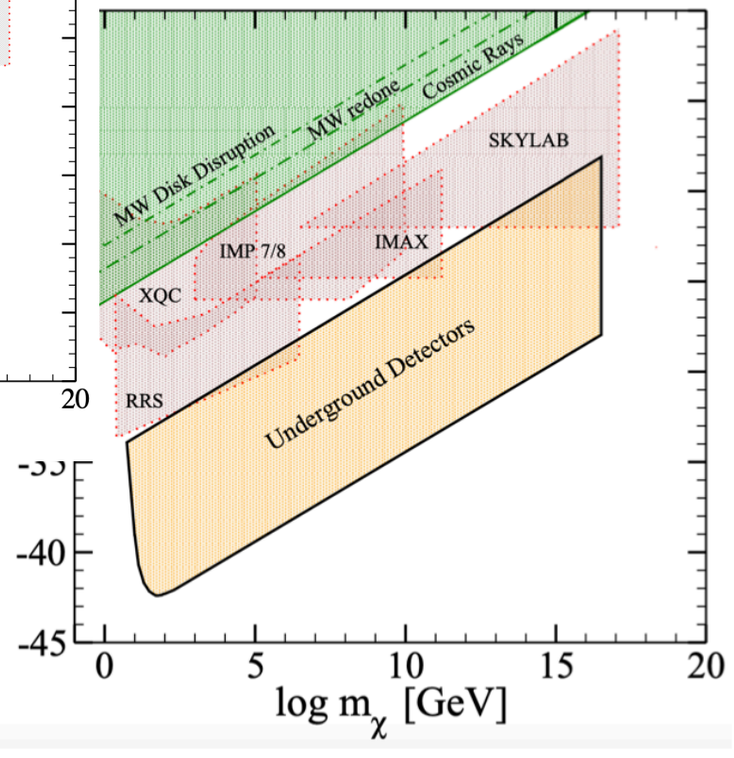
1 - 2 μm

near IR

- Captured DM annihilation in the celestial body
  - Heating the Earth
  - Detect with high-altitude balloons, rockets, or satellites



J. Beacom et al. 0705.4298 (PRD)



Jia Liu, PPC 2023

Interplay with Astrophysics



장재혁

Johns Hopkins University and University of Maryland

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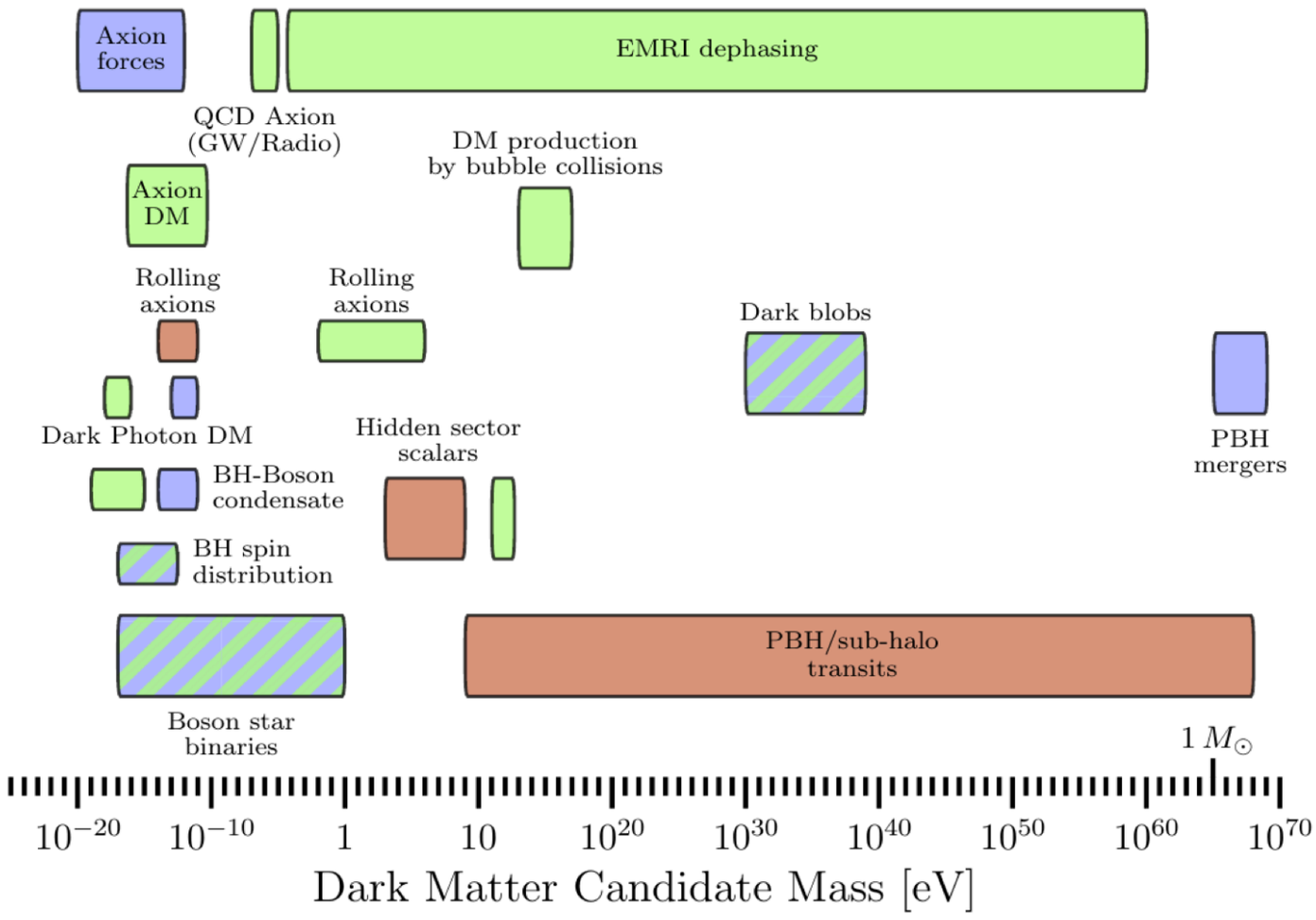
진행중인 암흑물질 관련 연구 주제:

Light dark sector searches from astrophysical objects

Effects of particle interactions on astrophysics and cosmology

Interplay with Astrophysics

4 Dark Matter imprints on Gravitational Waves



Tjonnie Li, PPC 2023

Potential constraints from gravitational waves

- Current interferometers (blue)
- Future interferometers (green)
- Pulsar Timing Arrays (red).

G. Bertone et al. *arXiv e-prints*, arXiv:1907.10610 (2019)

Interplay with Cosmology

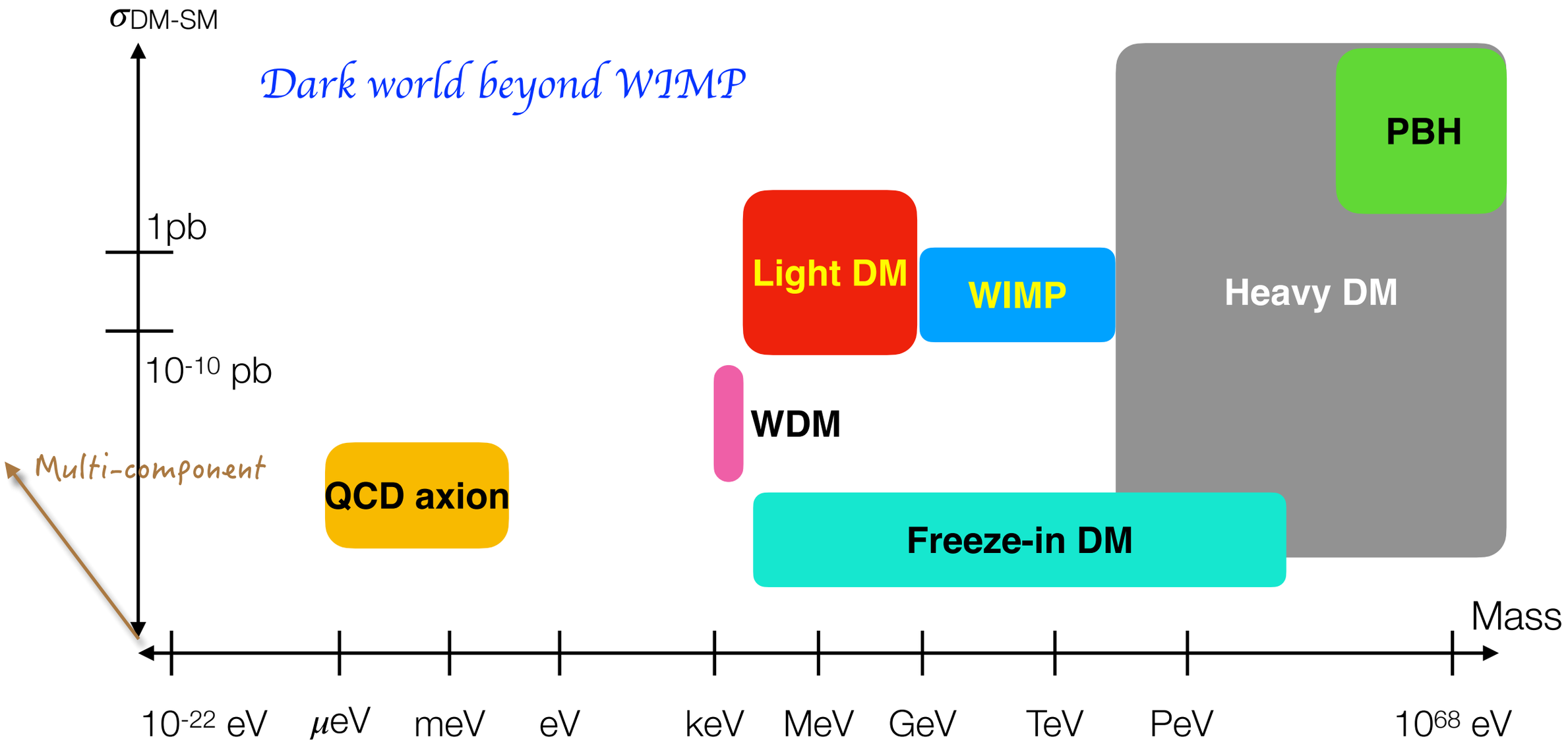
- Big Bang Nucleosynthesis: photo-dissociation of light elements

  e.g., $e\gamma_b \to e'\gamma'$ changes the ratio of D, ^{3}He, ^{4}He, ..

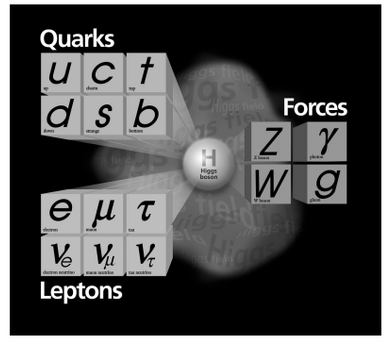
- Cosmic microwave background: $N_{\rm eff}$ if χ_1 freeze-out at $T \lesssim T_{\nu,\rm dec}$,

  Energy injection by $\chi_1\chi_1 \to$ SM at the recombination epoch

Dark world beyond WIMP



- Dark sector: multiple species of particles? Symmetries?



- Non-trivial structures give unique signals: e.g., iDM

Smith, Weiner, PRD 2001

Reference: Multi-component BDM

heavy DM

light DM

χ_0

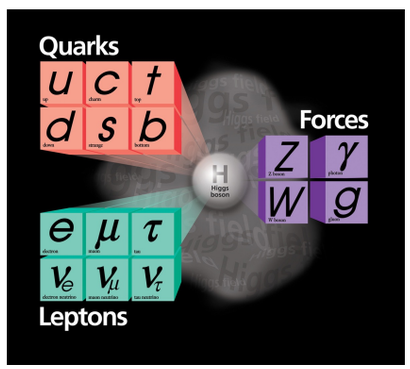
χ_1

Negligible amount

Gravitational interaction

Non-gravitational interaction

Safe from experimental results on WIMP



New perspectives

Kim, Park, Shin, PRL 2017

Giudice, Kim, Park, **Shin**, PLB 2018

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

Reference: Multi-component BDM



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

(indirect detection of χ_0)

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Assume: NFW

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

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

Agashe et al., JCAP 2014

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

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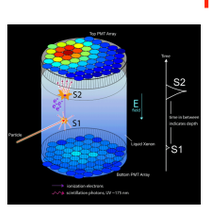


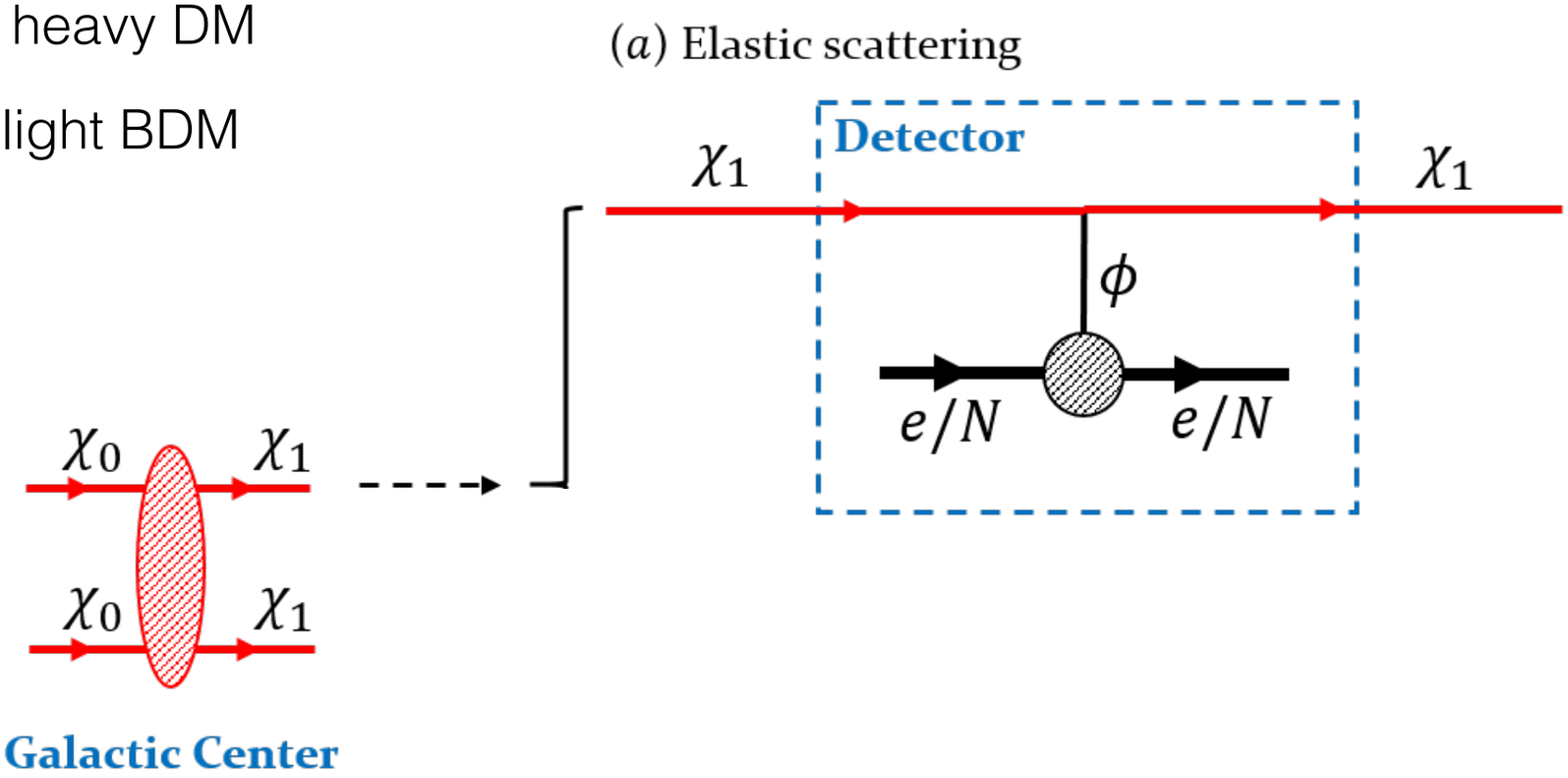
comparable **if $m_0 \lesssim$ 1 GeV**

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

Reference: Multi-component BDM

χ_0: heavy DM

χ_1: light BDM



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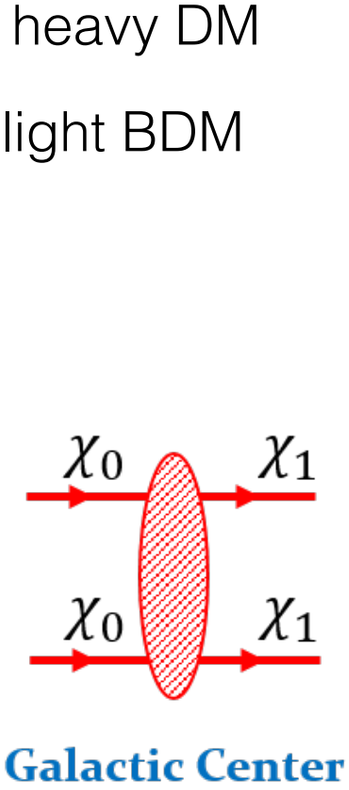
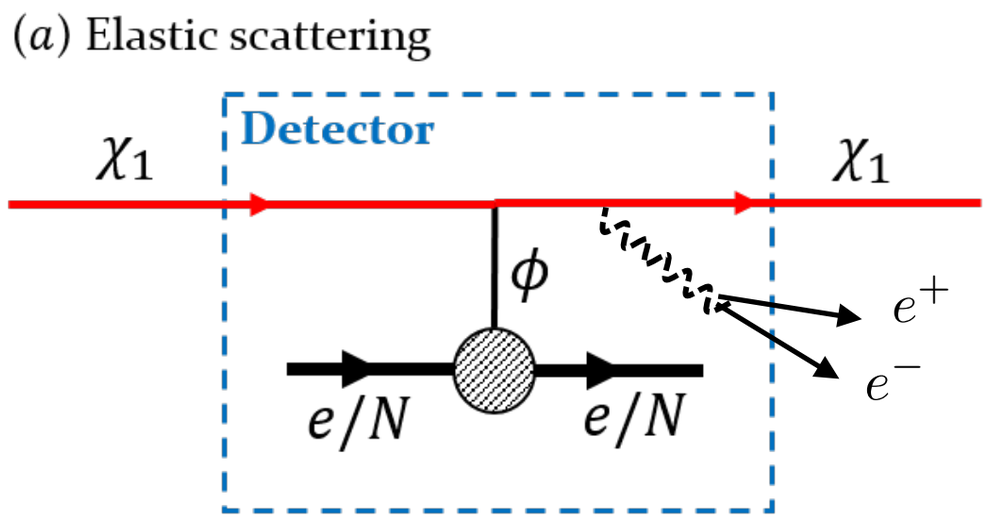


Galactic Center



Darkstrahlung

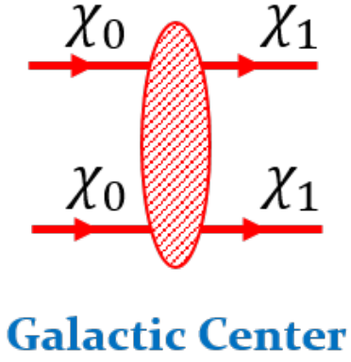
Kim, Park, **SS**, PRD 100, no. 3, 035033 (2019)

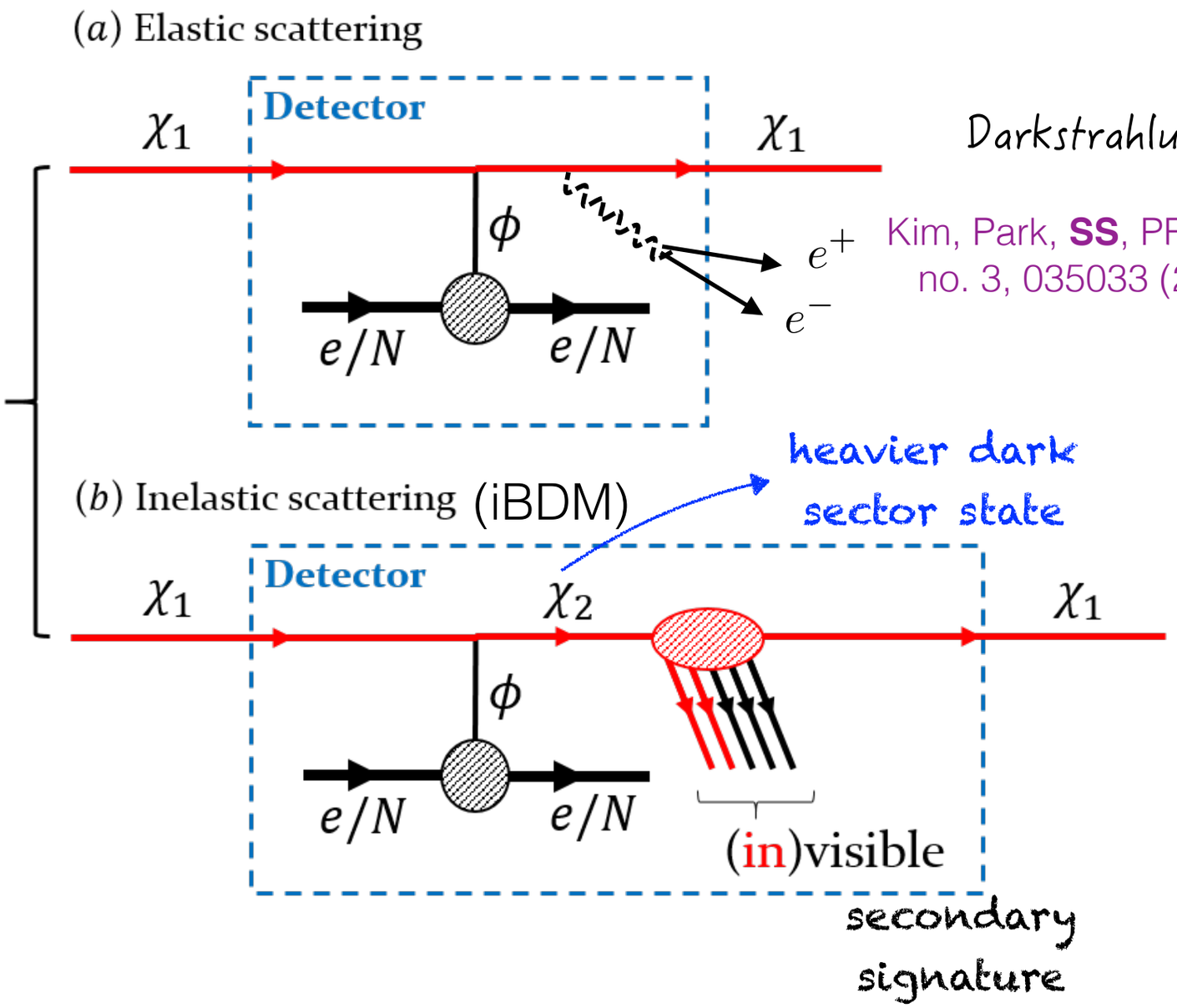
Reference: Multi-component BDM

χ_0: heavy DM

χ_1: light BDM

χ_2: excited state





Kim, Park, **SS**, PRD 100, no. 3, 035033 (2019)

Kim, Park, **SS**, PRL 119, 161801 (2017)

Giudice, Kim, Park, **SS**, PLB 780, 543 (2018)

Reference: Multi-component BDM



iBDM

Fiducial volume

p_e

χ_1: light BDM, χ_2: excited state

Reference: Multi-component BDM



iBDM

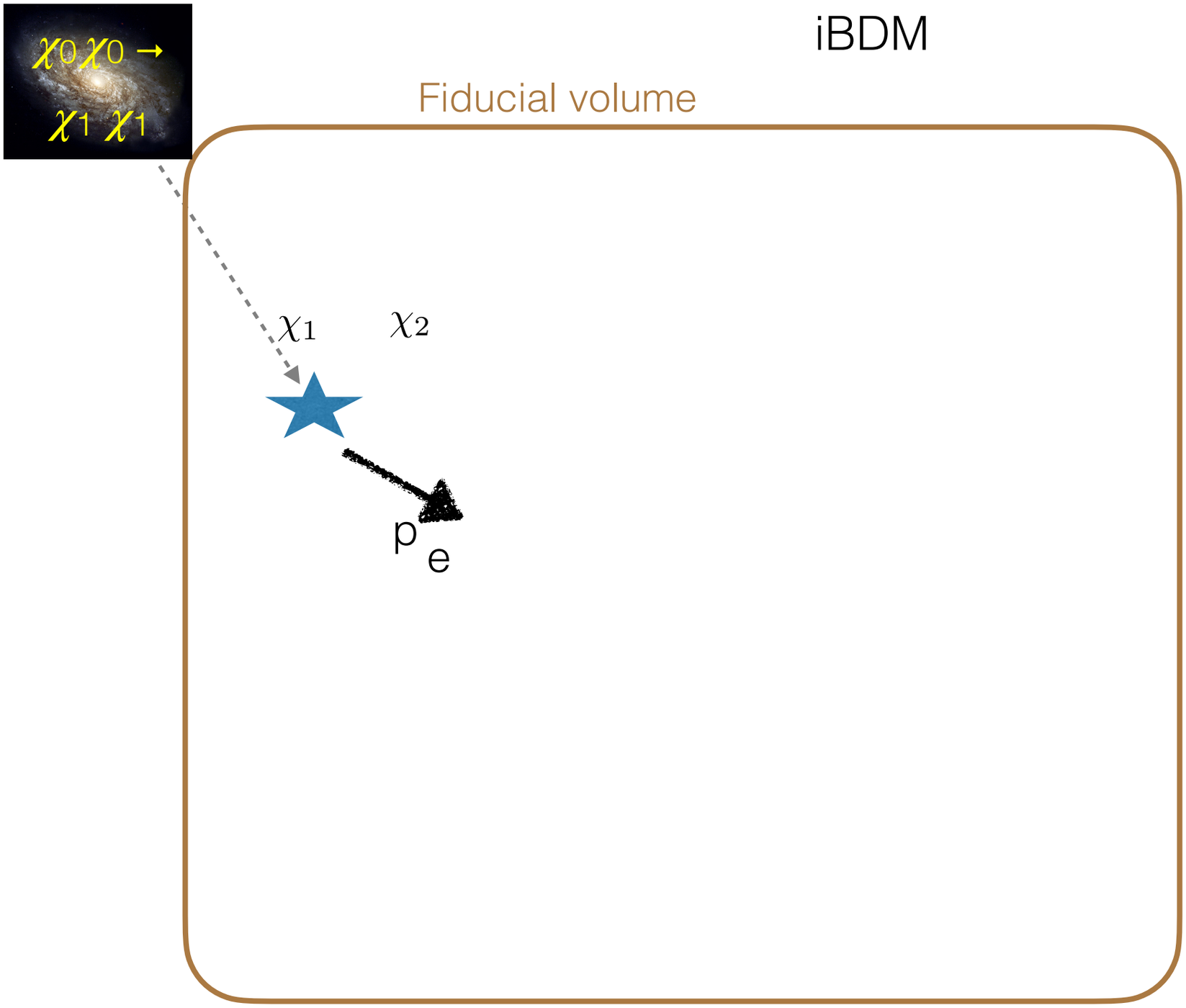
Fiducial volume

χ_1

p_e

χ_1: light BDM, χ_2: excited state

Reference: Multi-component BDM



χ_1: light BDM, χ_2: excited state

Reference: Multi-component BDM



iBDM

Fiducial volume

χ_1 χ_2

p e

Primary signature

- e-scattering
- p-scattering
- DIS

χ_1: light BDM, χ_2: excited state

Reference: Multi-component BDM



iBDM χ_1

Fiducial volume

χ_2

χ_1

p

e

Primary signature

- e-scattering
- p-scattering
- DIS

χ_1: light BDM, χ_2: excited state

Reference: Multi-component BDM



iBDM χ_1

Fiducial volume

χ_2

χ_1

prompt or
displaced

e- μ^- γ
e+ μ^+ $\pi, \cdots$

Secondary signature

p
e

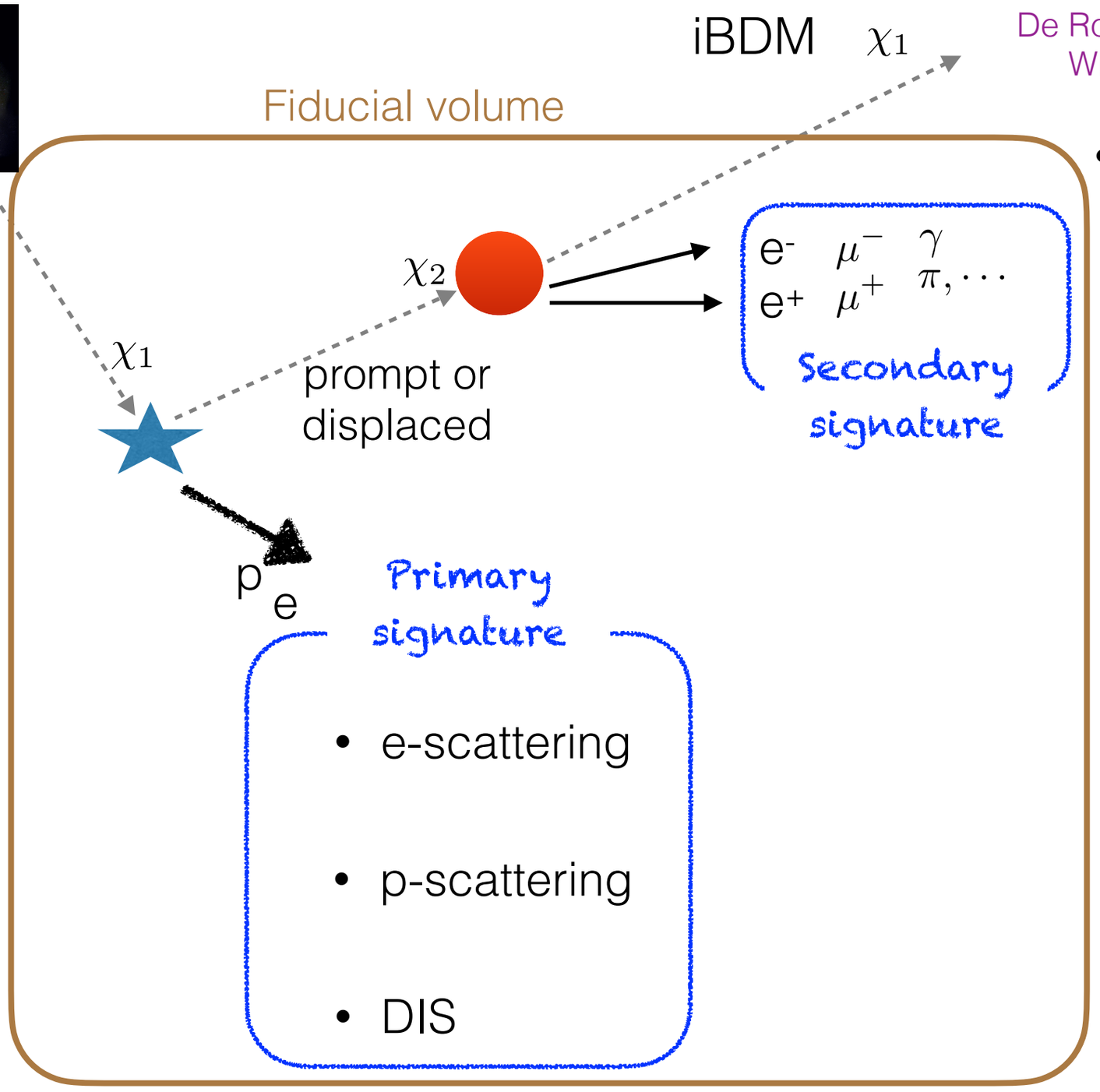
Primary signature

- e-scattering
- p-scattering
- DIS

χ_1: light BDM, χ_2: excited state

Reference: Multi-component BDM





χ_1: light BDM, χ_2: excited state

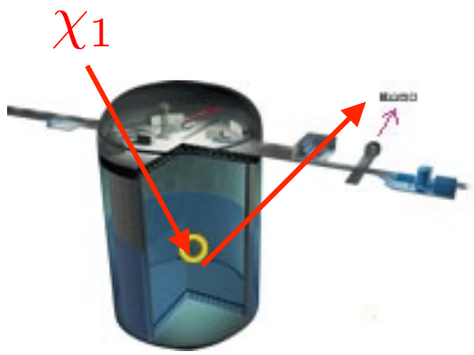
De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead, JHEP 11, 043 (2020)

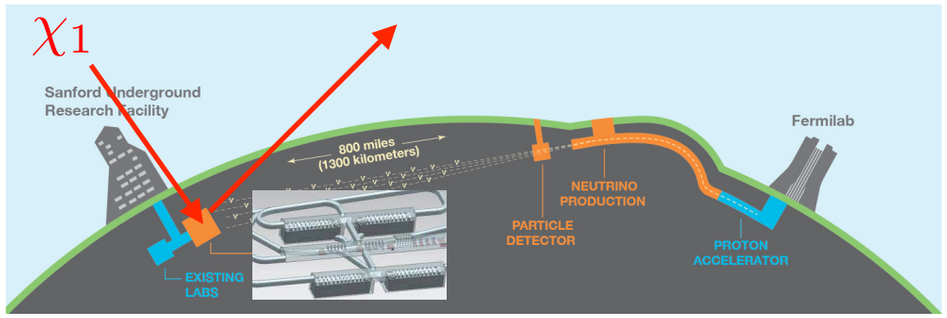
- Tracks pop-up inside fiducial volume (reject the tracks extending outside the fiducial volume)
- Two signatures can be separated beyond the position and angular resolutions.
  (1cm for all and
  1° for e, 5° for p)
- dE/dx for the merged e-recoil signal events

Zero - O(10) bkg. (conservative)

Reference: Multi-component BDM

- Neutrino Experiments





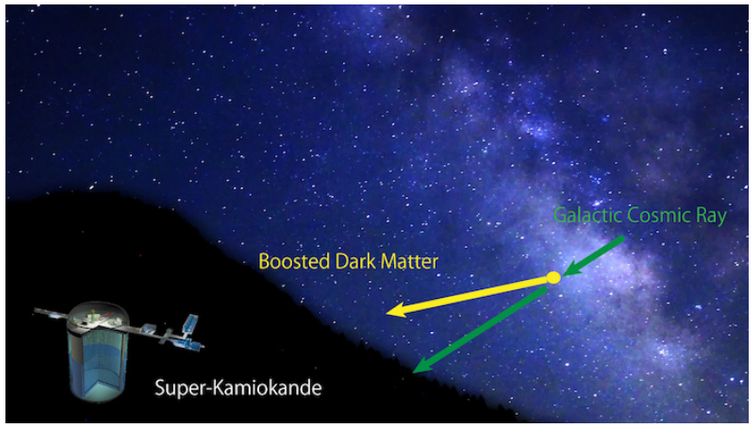
PHYSICAL REVIEW LETTERS **120,** 221301 (2018)

Editors' Suggestion

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

8.8 Dark Matter Probes . . . . . DEEP UNDERGROUND NEUTRINO EXPERIMENT
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



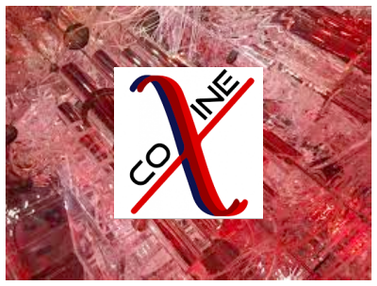
PHYSICAL REVIEW LETTERS **130,** 031802 (2023)

Editors' Suggestion Featured in Physics

Search for Cosmic-Ray Boosted Sub-GeV Dark Matter Using Recoil Protons at Super-Kamiokande

Reference: Multi-component BDM

- Dark Matter direct detection experiments

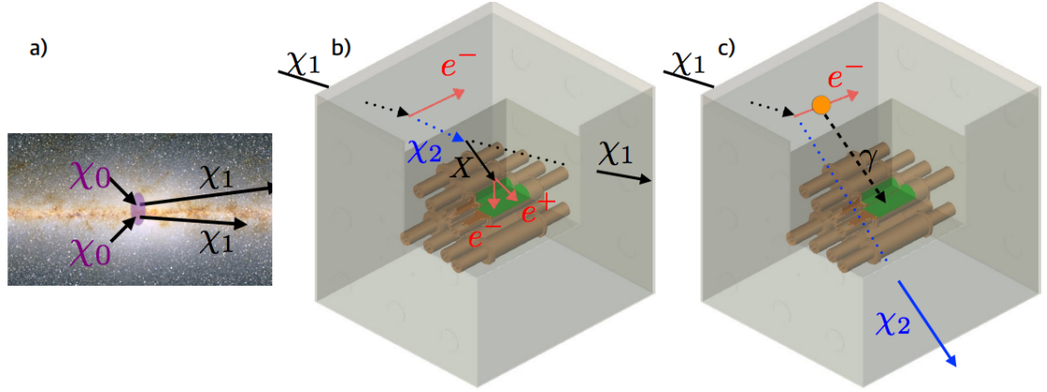


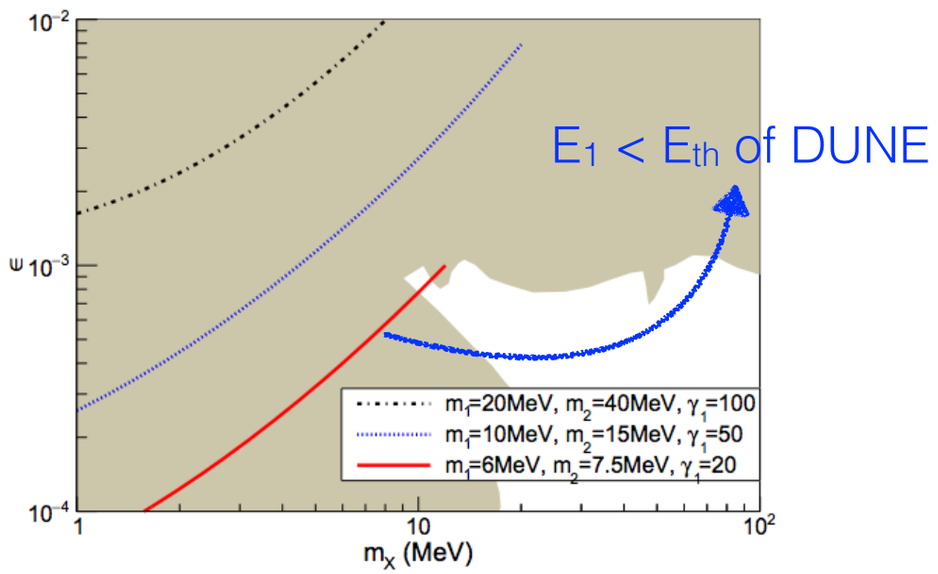
PHYSICAL REVIEW LETTERS **122,** 131802 (2019)

Editors' Suggestion

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

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





Search for Boosted Dark Matter in COSINE-100

G. Adhikari,[1] N. Carlin,[2] J. J. Choi,[3,4] S. Choi,[3] A. C. Ezeribe,[5] L. E. França,[2] C. Ha,[6] I. S. Hahn,[7,8,9] S. J. Hollick,[1] E. J. Jeon,[4] J. H. Jo,[1] H. W. Joo,[3] W. G. Kang,[4] M. Kauer,[10] B. H. Kim,[4] H. J. Kim,[11] J. Kim,[6] K. W. Kim,[4] S. H. Kim,[4] S. K. Kim,[3] W. K. Kim,[9,4] Y. D. Kim,[4,12,9] Y. H. Kim,[4,13,9] Y. J. Ko,[4] D. H. Lee,[11] E. K. Lee,[4] H. Lee,[9,4] H. S. Lee,[4,9] H. Y. Lee,[4] I. S. Lee,[4] J. Lee,[4] J. Y. Lee,[11] M. H. Lee,[4,9] S. H. Lee,[9,4] S. M. Lee,[3] Y. J. Lee,[6] D. S. Leonard,[4] N. T. Luan,[11] B. B. Manzato,[2] R. H. Maruyama,[1] R. J. Neal,[5] J. A. Nikkel,[1] S. L. Olsen,[4] B. J. Park,[9,4] H. K. Park,[14] H. S. Park,[13] K. S. Park,[4] S. D. Park,[11] R. L. C. Pitta,[2] H. Prihtiadi,[4] S. J. Ra,[4] C. Rott,[15,16] K. A. Shin,[4] D. F. F. S. Cavalcante,[2] A. Scarff,[5] N. J. C. Spooner,[5] W. G. Thompson,[1] L. Yang,[17] and G. H. Yu[15,4]
(COSINE-100 Collaboration)

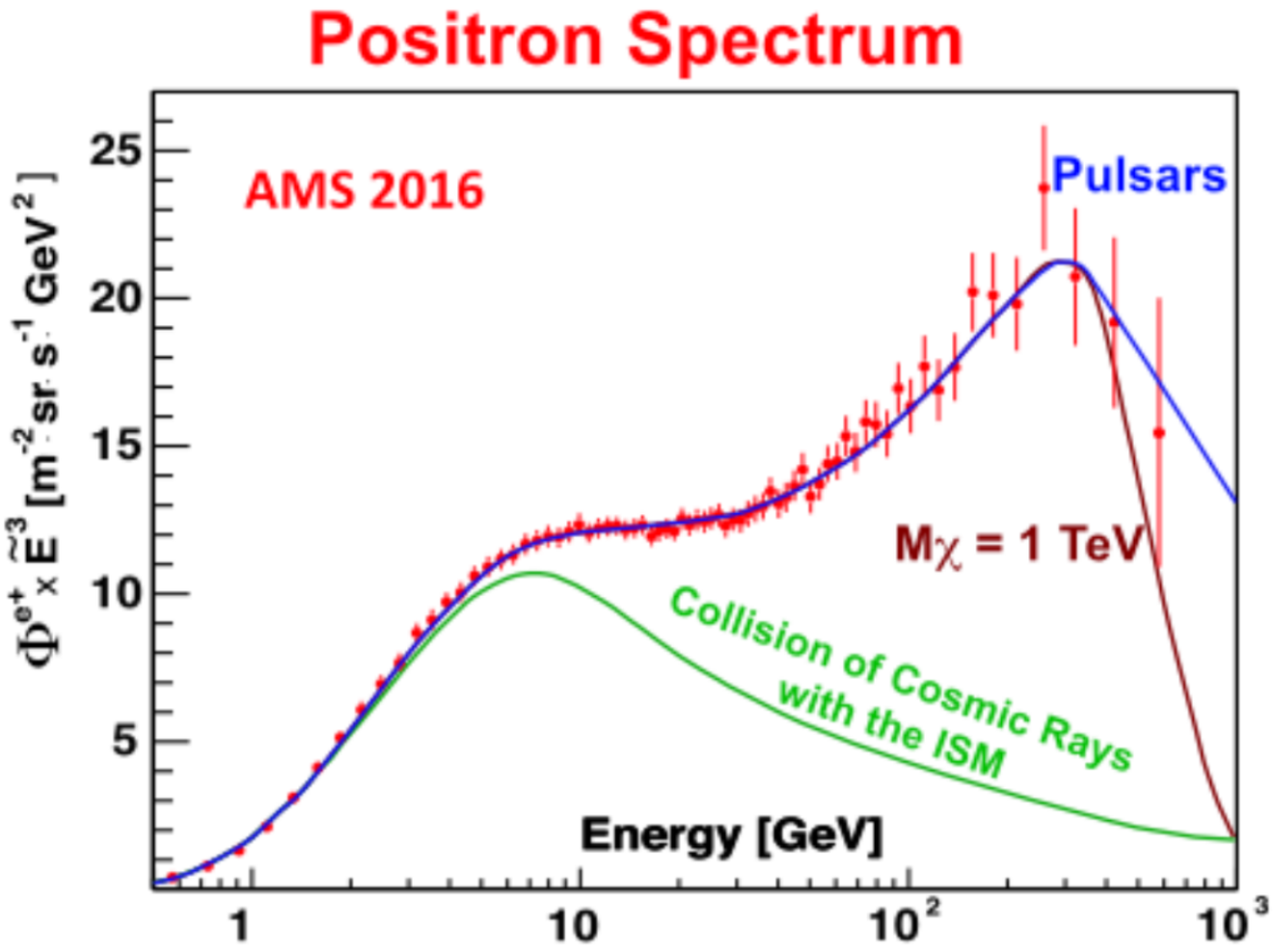
arXiv:2306.00322

BDM 2023



Indirect detection: positron excess?

AMS-02 press release (Dec, 2016)



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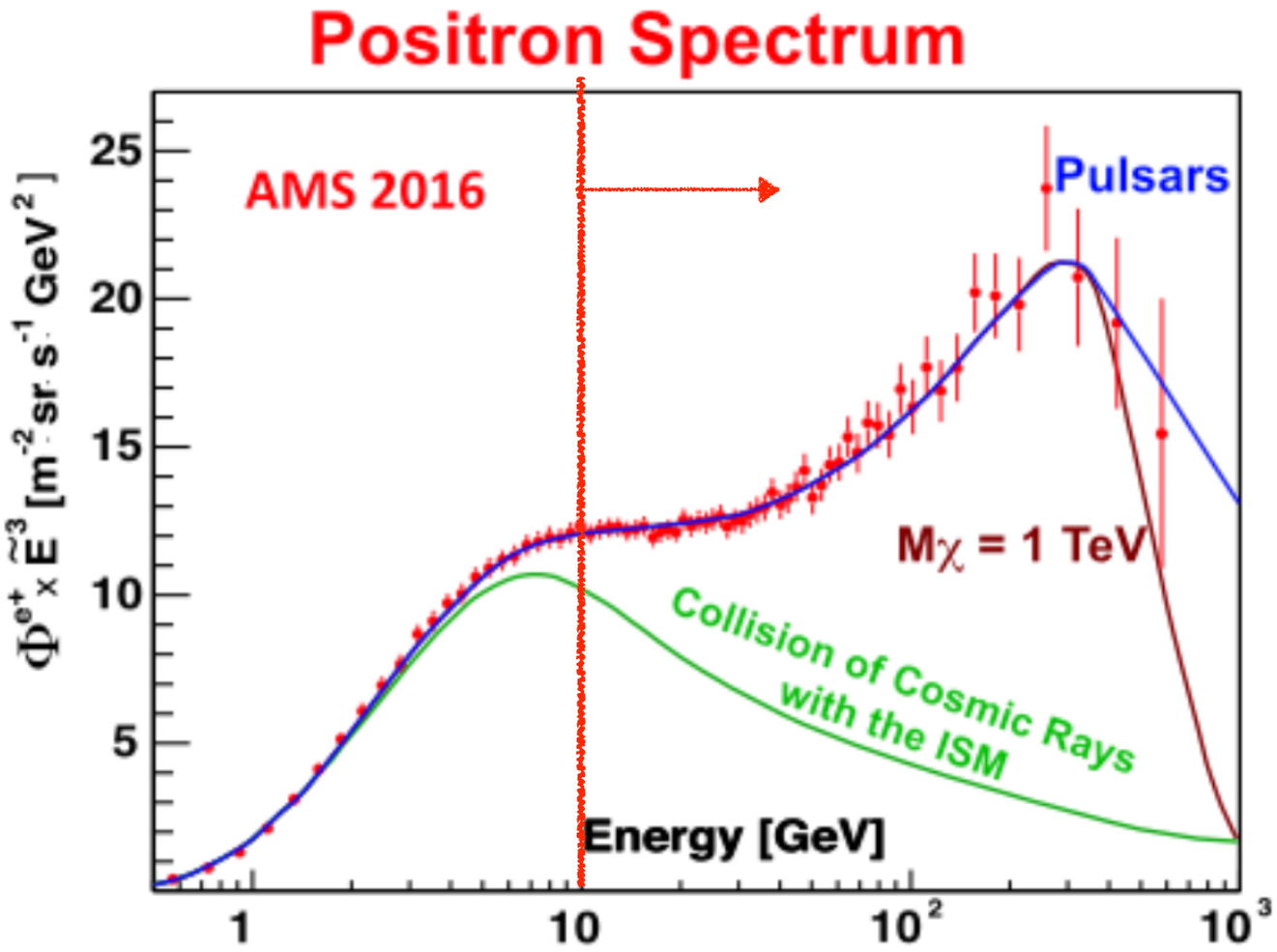
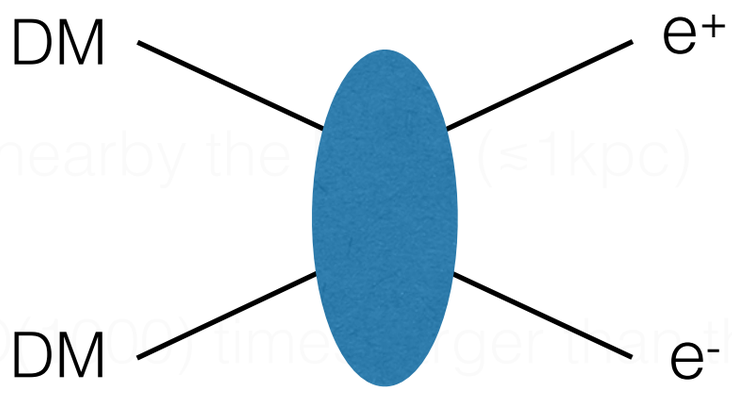


E > 10 GeV

- DM or Pulsars?
  Need more data
- Similar in old data of AMS-02 & PAMELA

Indirect detection: positron excess?



Energy of e^+: mass range of thermal DM

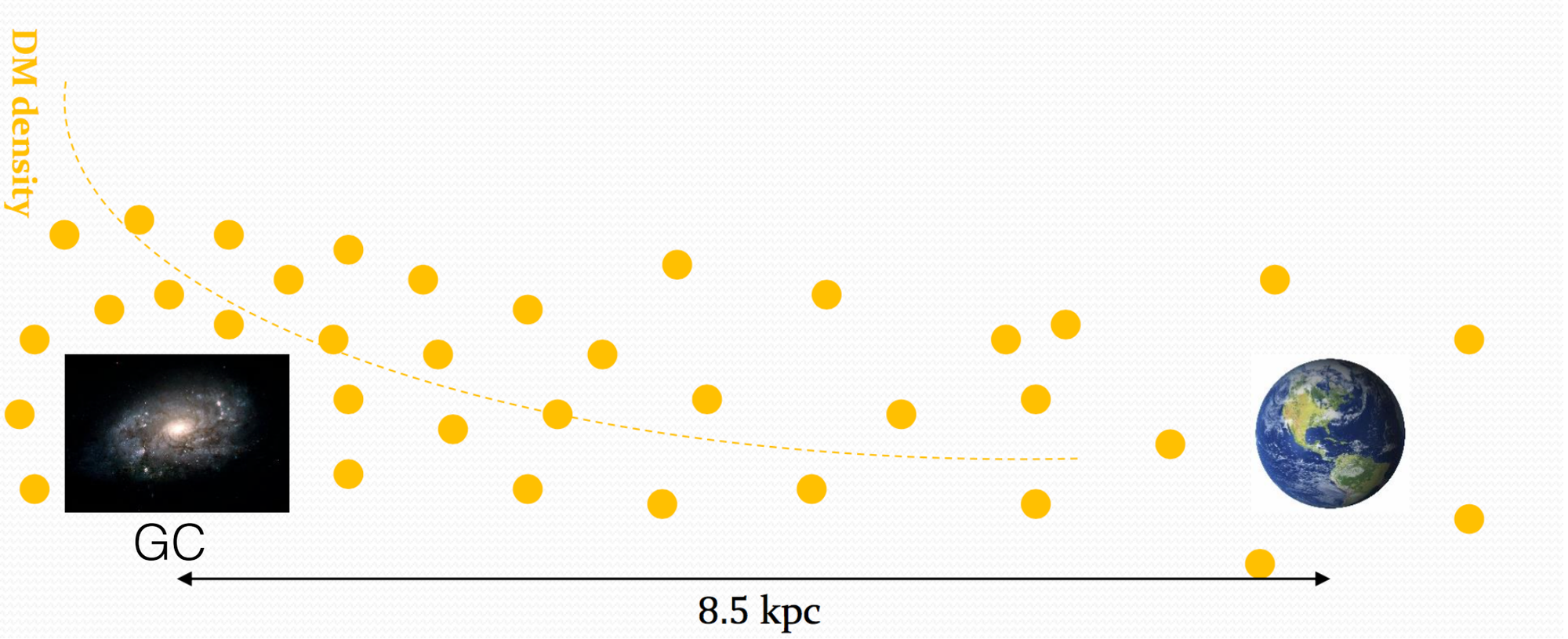


Figure by Doojin Kim

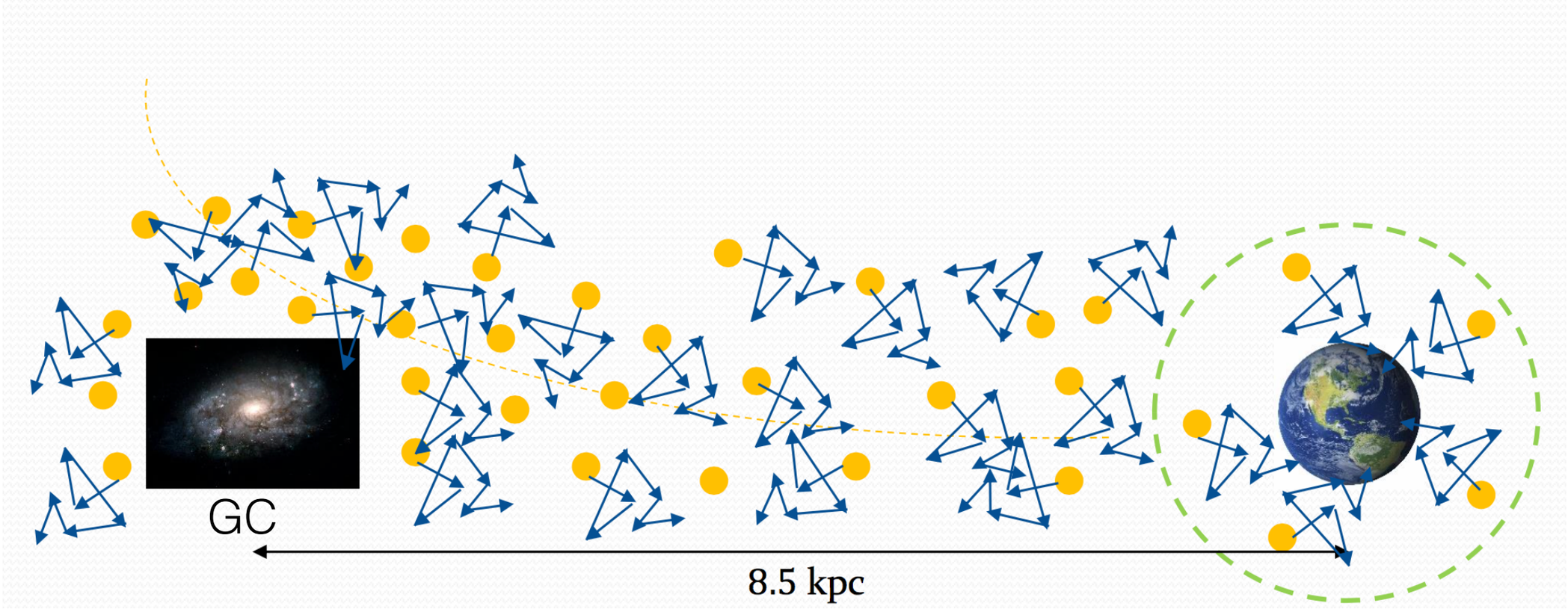
Indirect detection: positron excess?

- Mostly from DM nearby the Earth (≲1kpc): diffusion & E loss

- Observed flux: O(1000) times larger than that in thermal DM

(s-wave dominant)

$\Phi \propto \rho^2 < \sigma v >$ need enhancement



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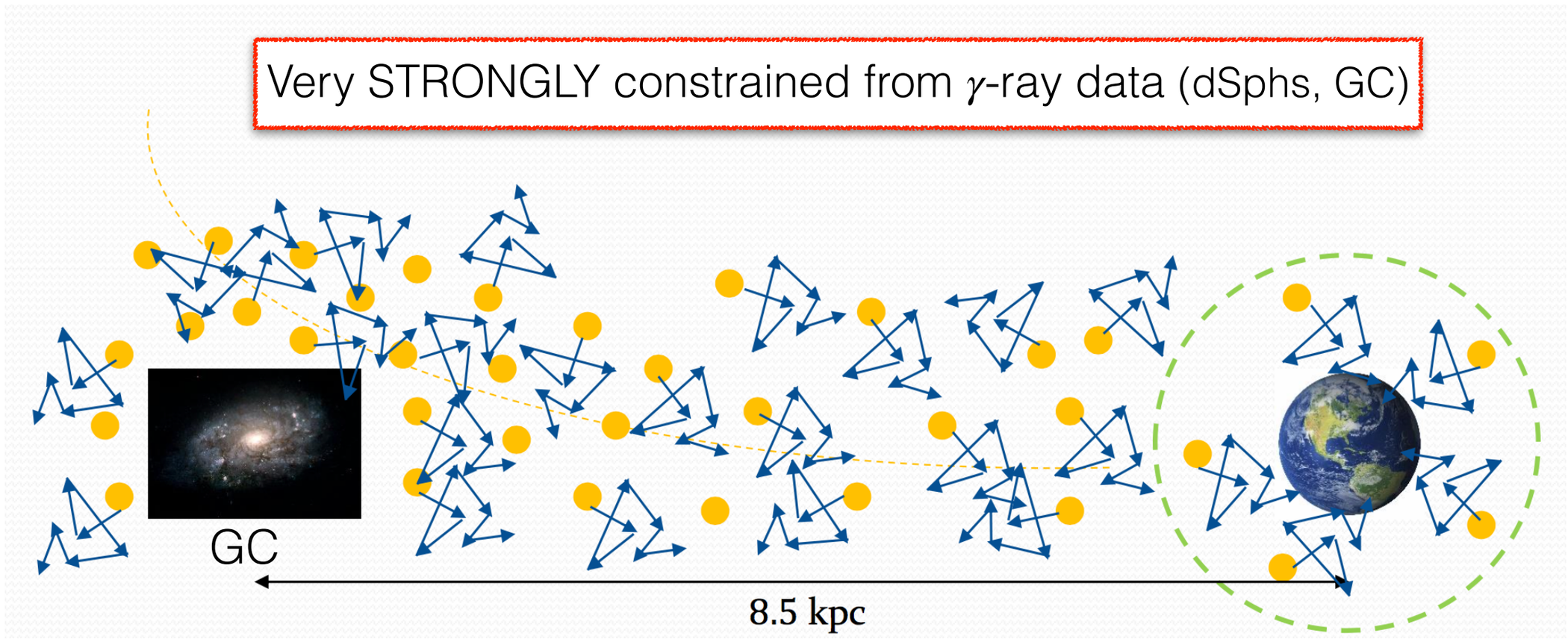
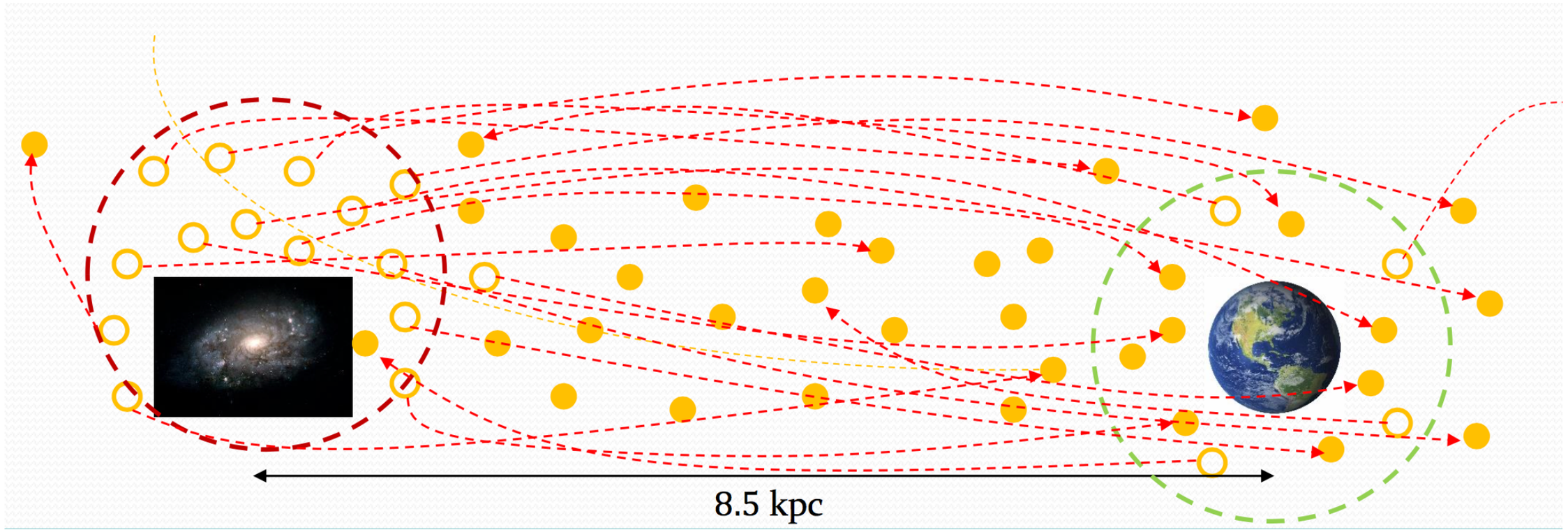


Indirect detection: positron excess?

Think about using the DM around Galactic Center



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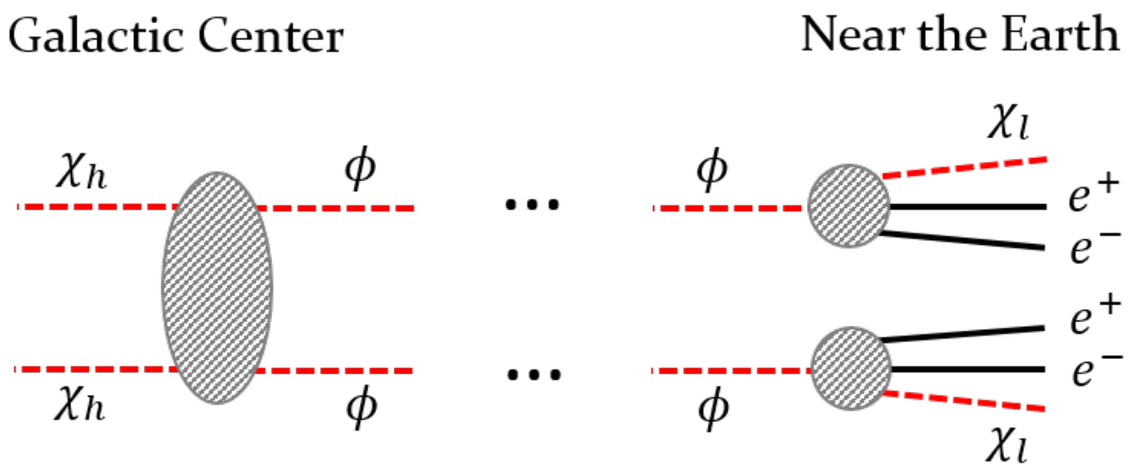
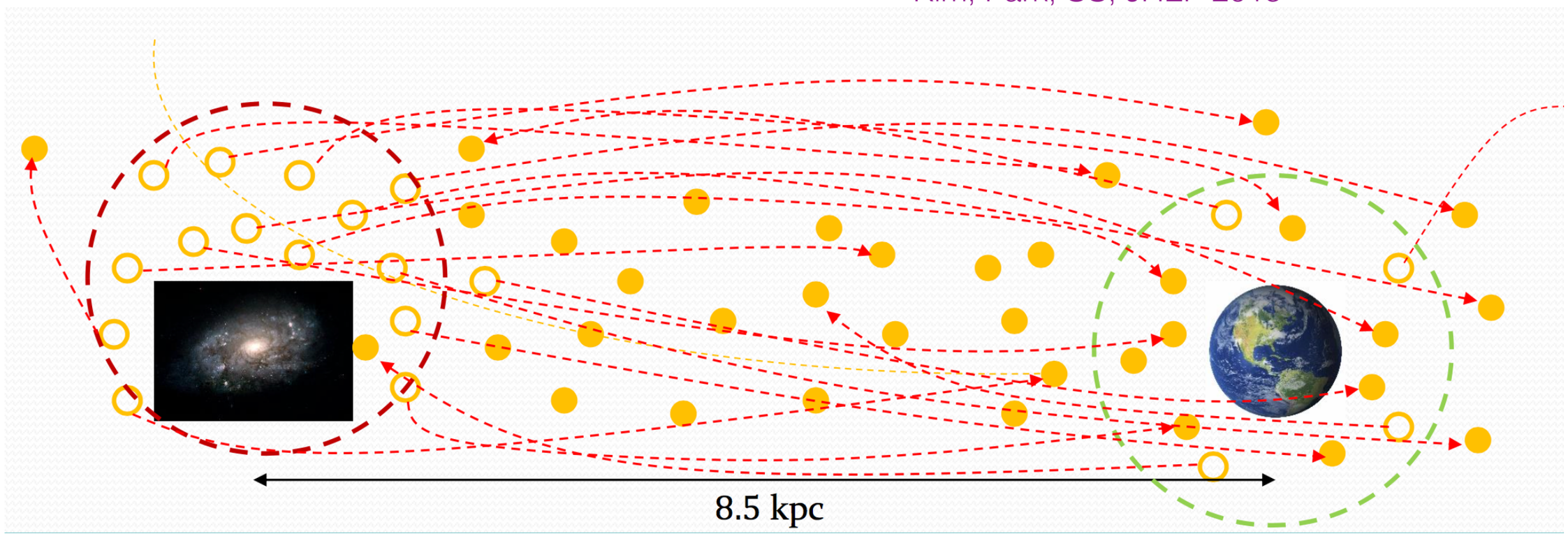
Effectively TRANSPORT
DM: GC → Earth



Kim, Park, **SS**, JHEP 2018



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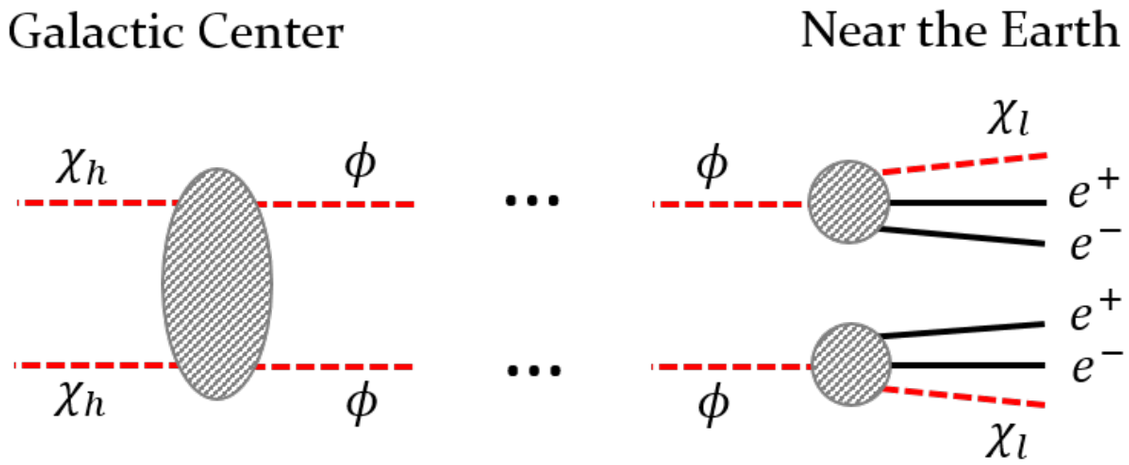
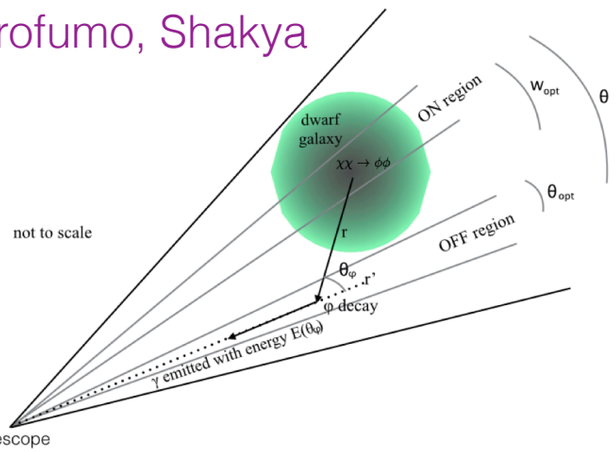


Kim, Park, **SS**, JHEP 2018

Gori, Profumo, Shakya



Reference: Multi-component BDM

heavy DM

light DM

χ_0

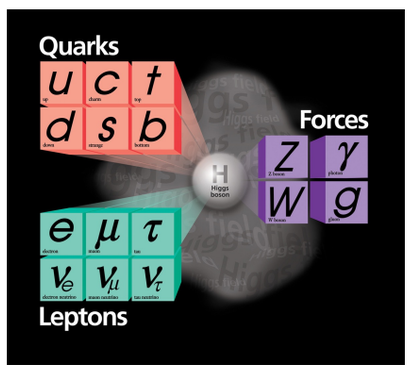
χ_1

Negligible amount

Gravitational interaction

Non-gravitational interaction

Safe from experimental results on WIMP



New perspectives

Kim, Park, Shin, PRL 2017

Giudice, Kim, Park, **Shin**, PLB 2018

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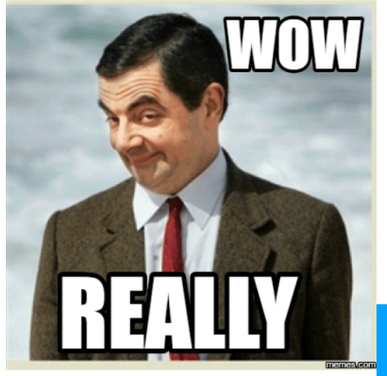

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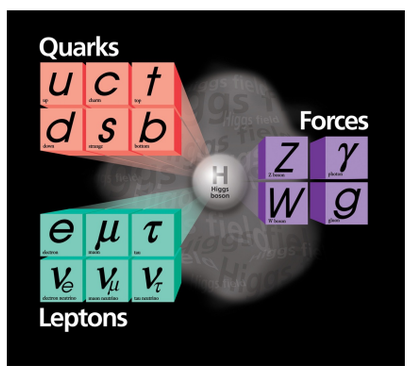


New perspectives

Kim, Park, Shin, PRL 2017

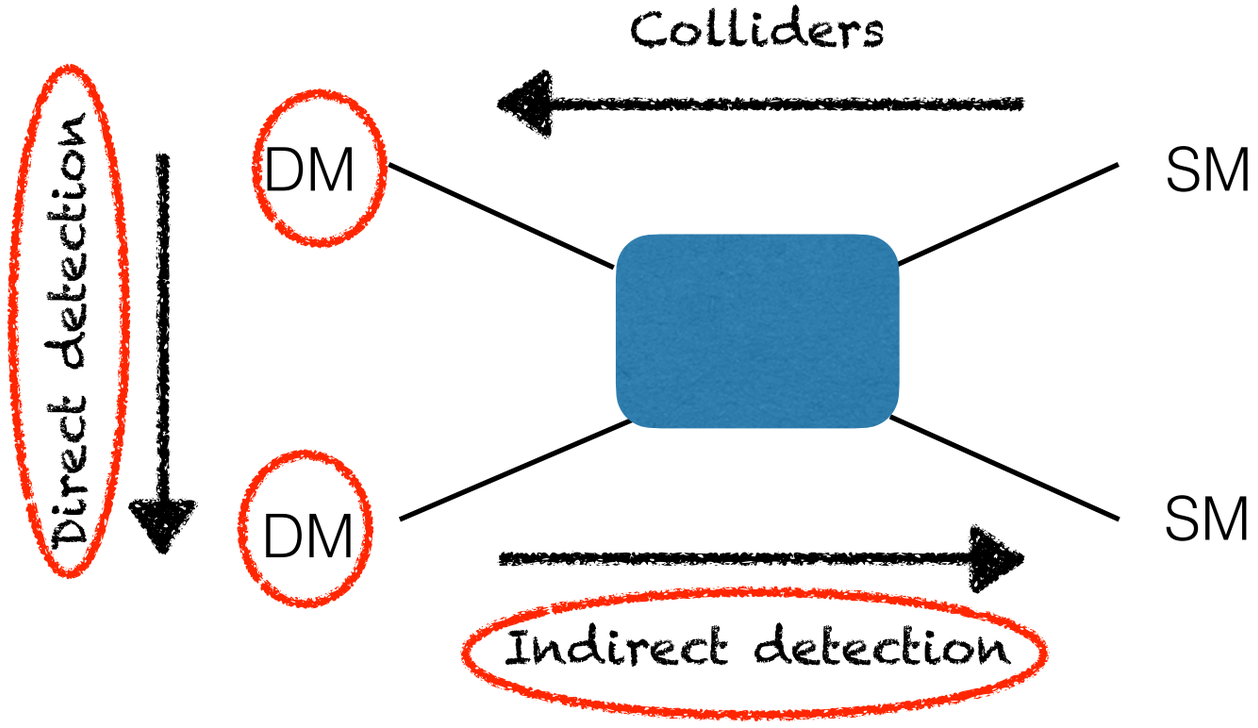
Giudice, Kim, Park, **Shin**, PLB 2018

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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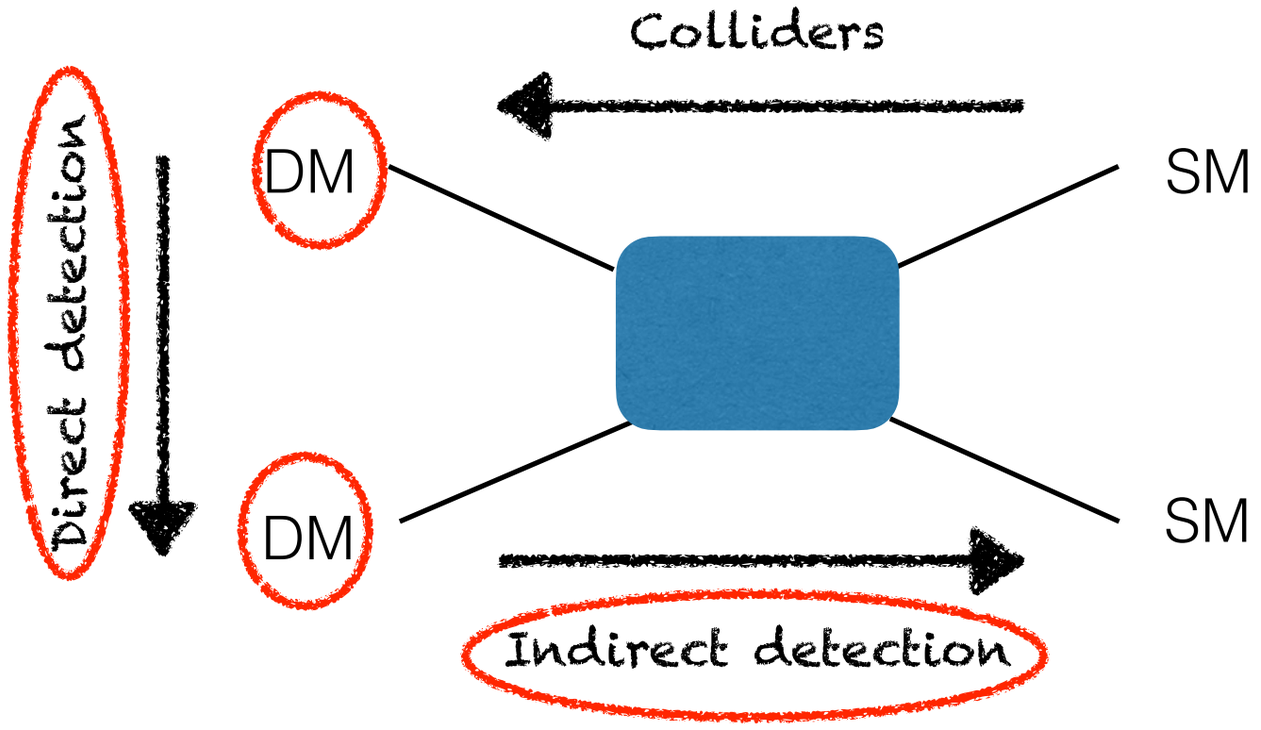

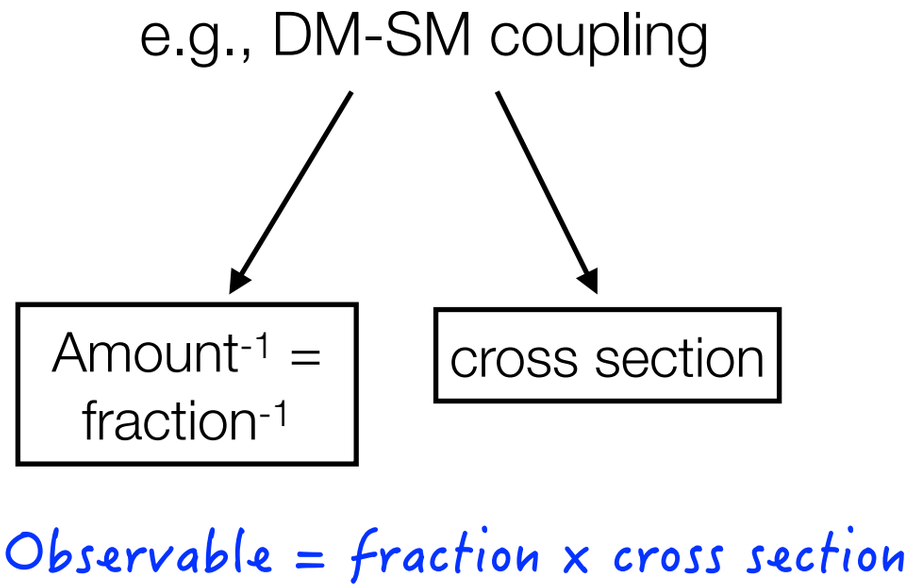

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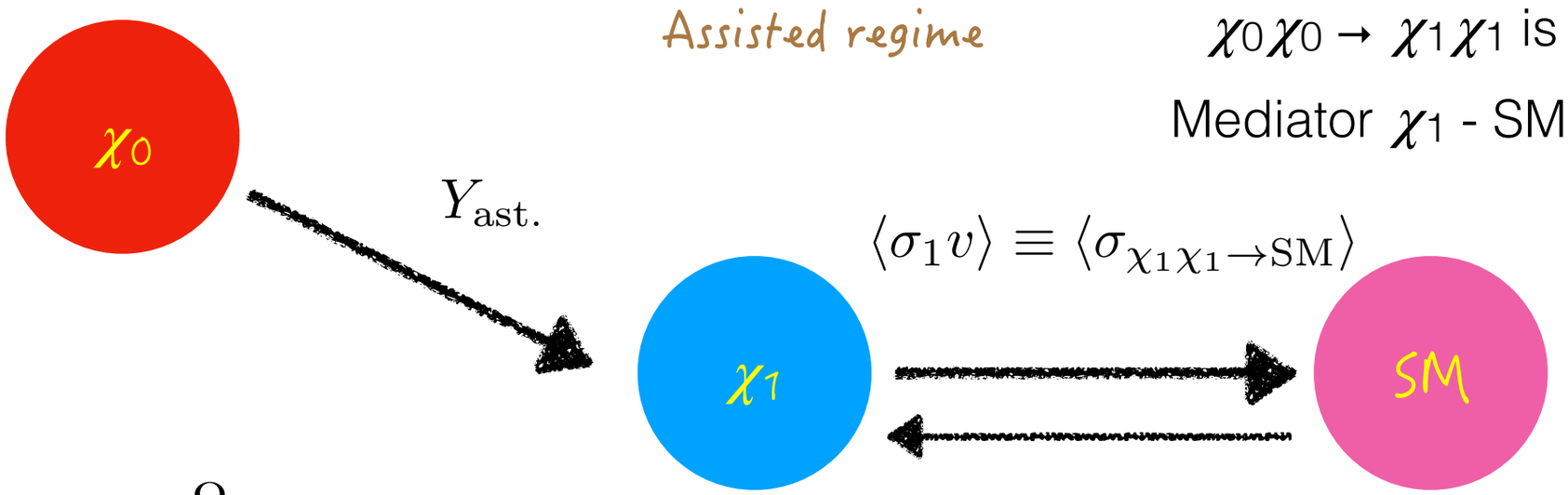

- For a fixed $r_1 \ll 1$, $\chi_1\chi_1 \to$ SM should be even larger to deplete the contribution by the residual annihilation $\chi_0\chi_0 \to \chi_1\chi_1$ ($Y_{\rm ast.}$).

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

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

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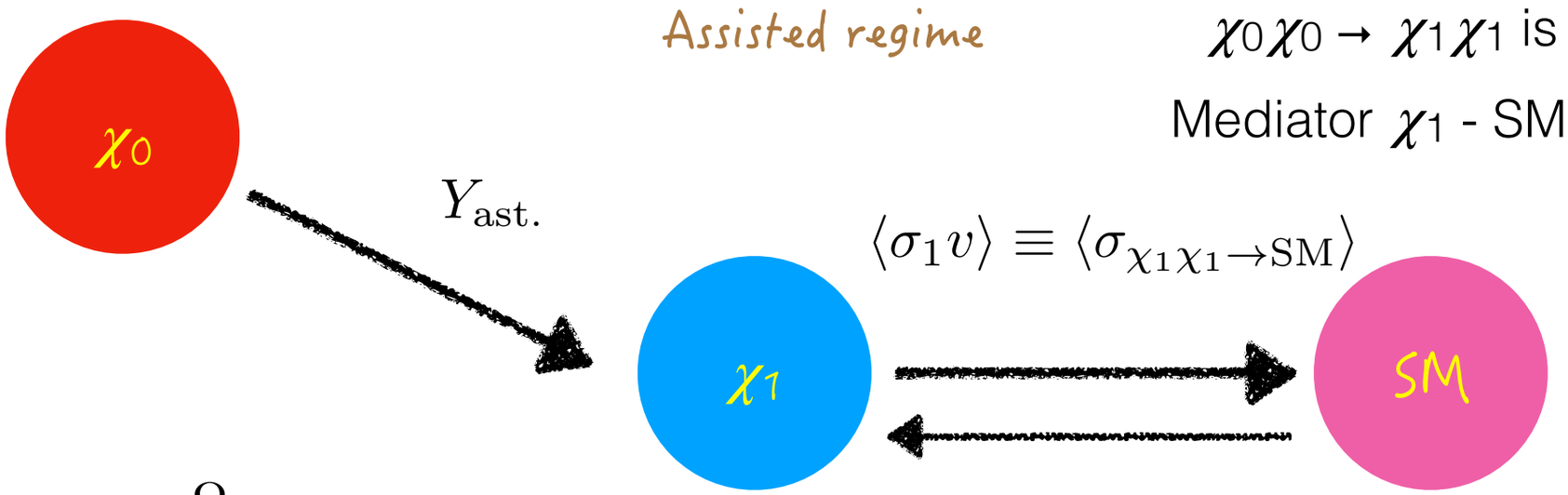

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observables $\propto\ n_{\chi_1}^2 \langle\sigma_1 v\rangle \ \to$ No r_1 suppression! (even enhanced)

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

Sub-dominant component is hidden?

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_{eff} if χ_1 freeze-out at $T \lesssim T_{\nu,dec}$,

  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.

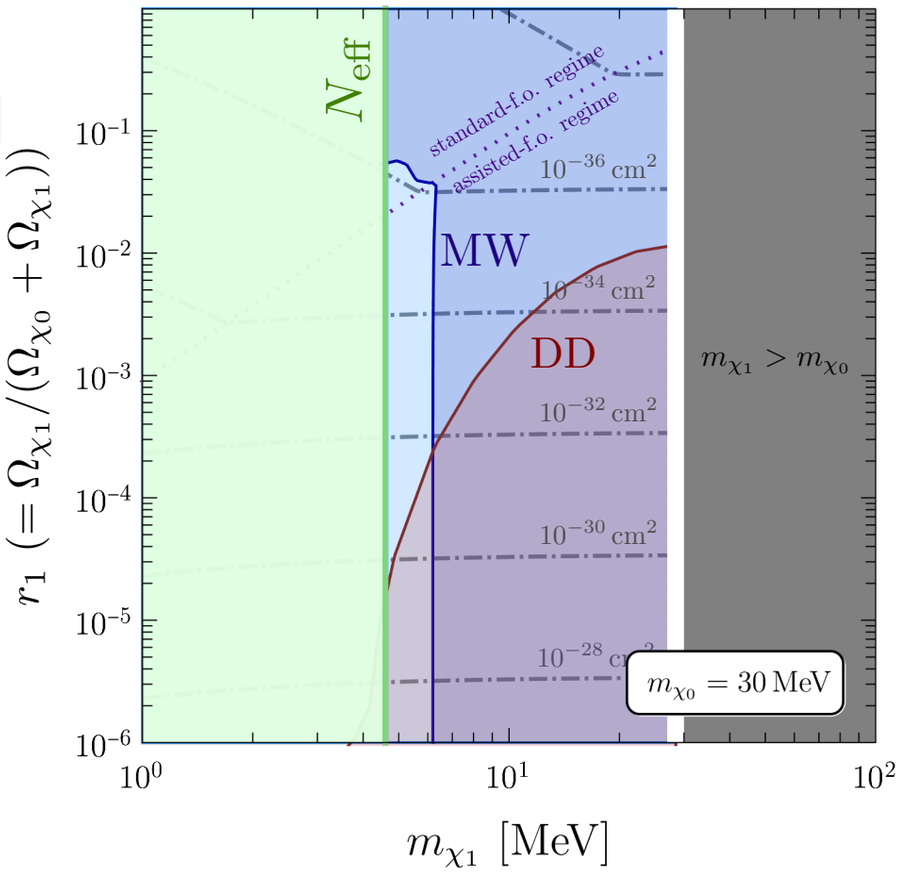
  (depending on the model)

Sub-dominant component is hidden?

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

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



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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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 $O(1)$ dark sector coupling.

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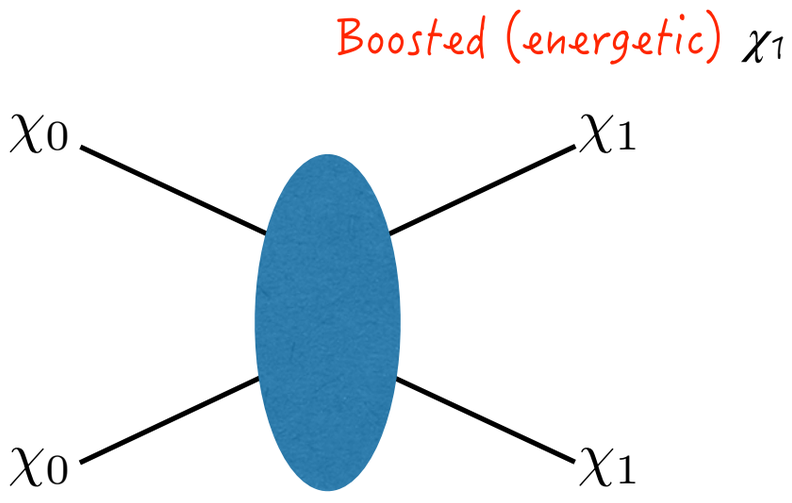

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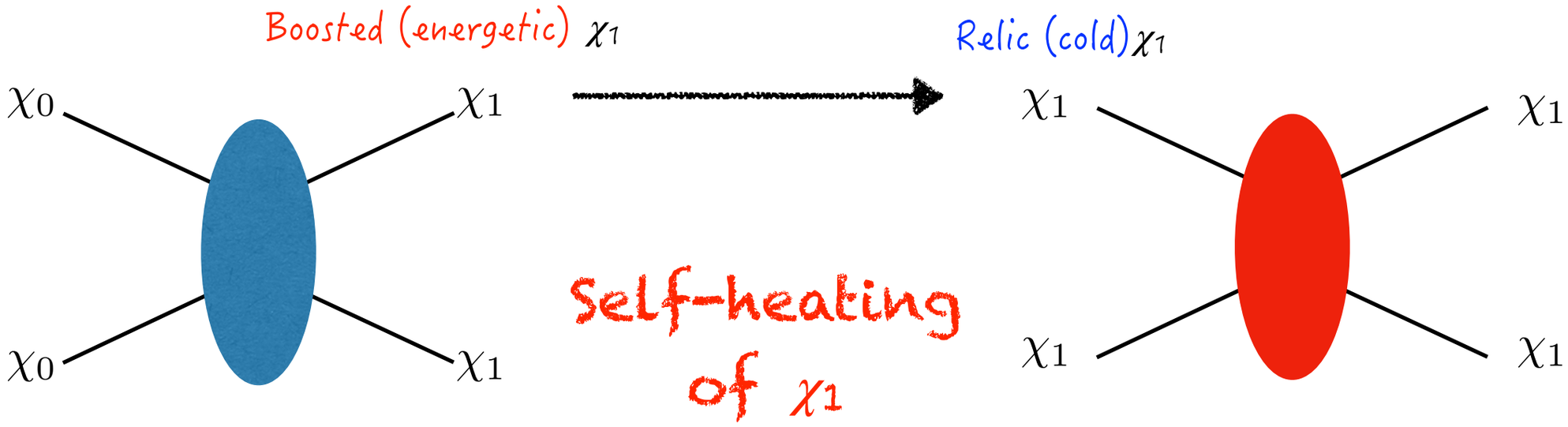
Kamada, Kim, Park, **SS**, JCAP 10, 052 (2022)



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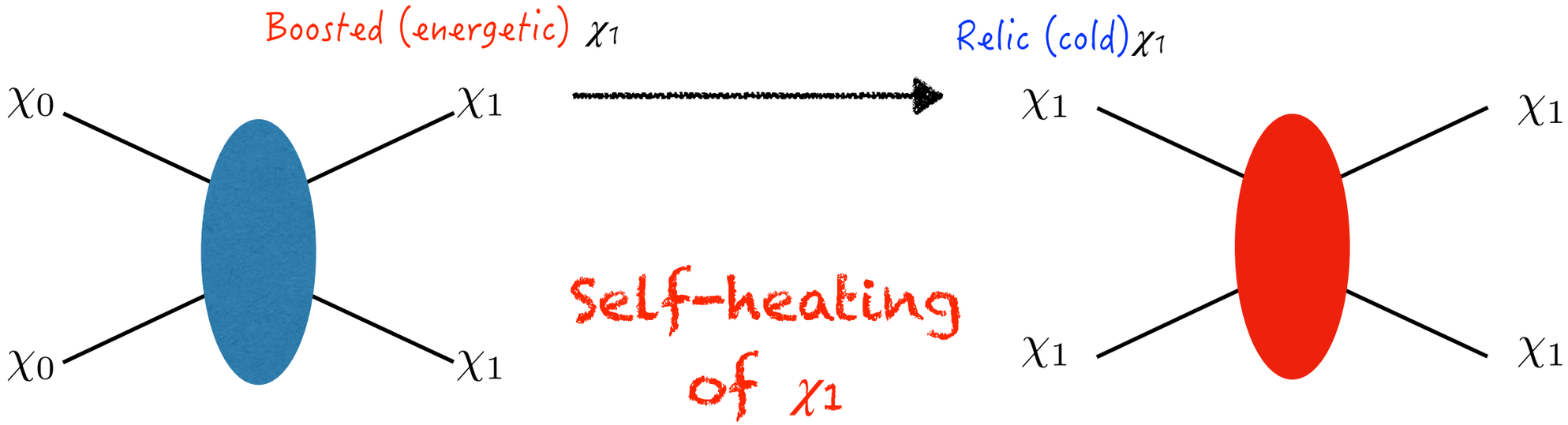


Kamada, Kim, Kim, Sekiguchi, PRL 2018

Chu, Garcia-Cely, JCAP 2018

Vogelsberger, Zavala, Schutz, Slatyer, MNRAS 2018

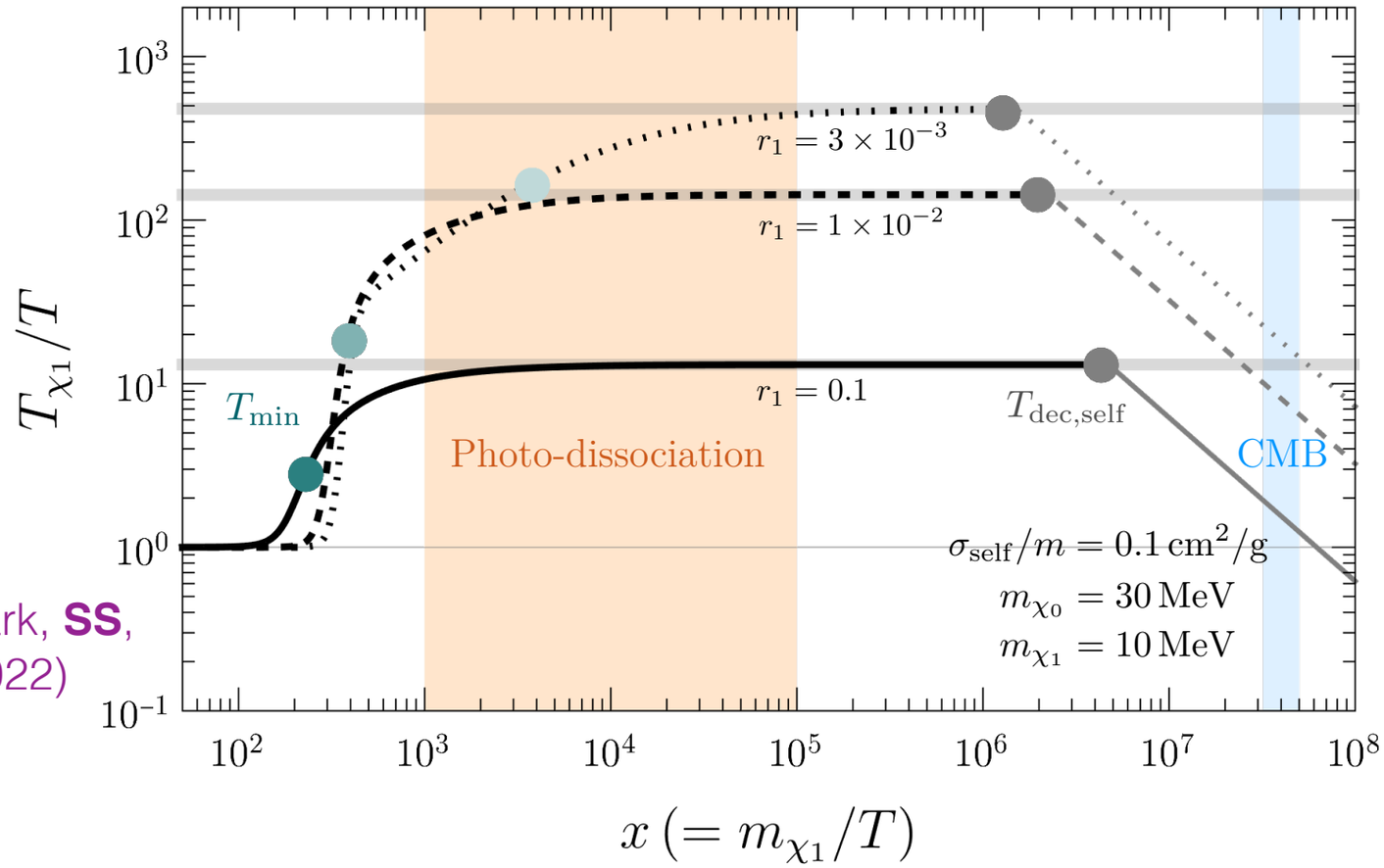
Self-heating of χ_1



Self-heating of χ_1



Temperature evolution of χ_1



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

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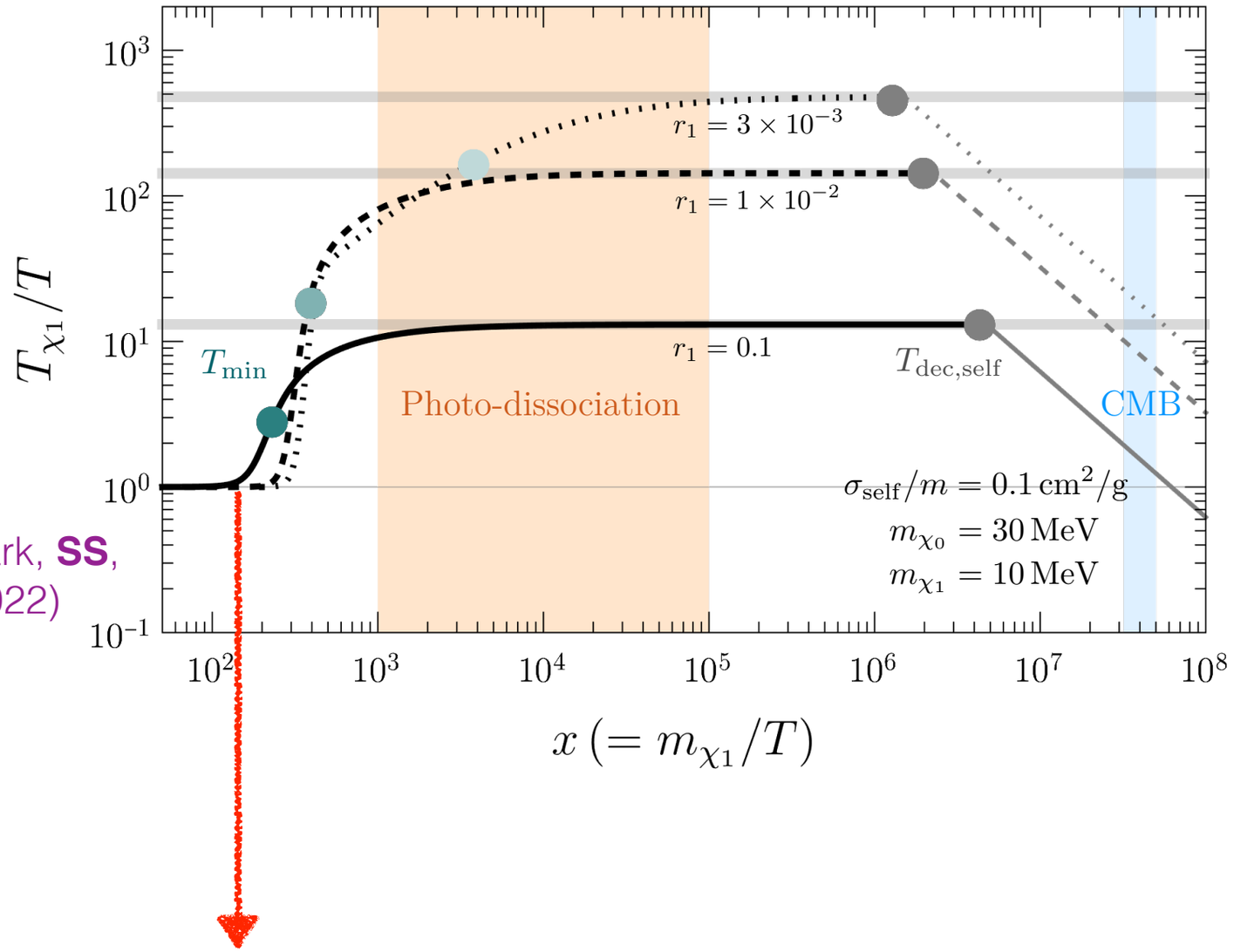

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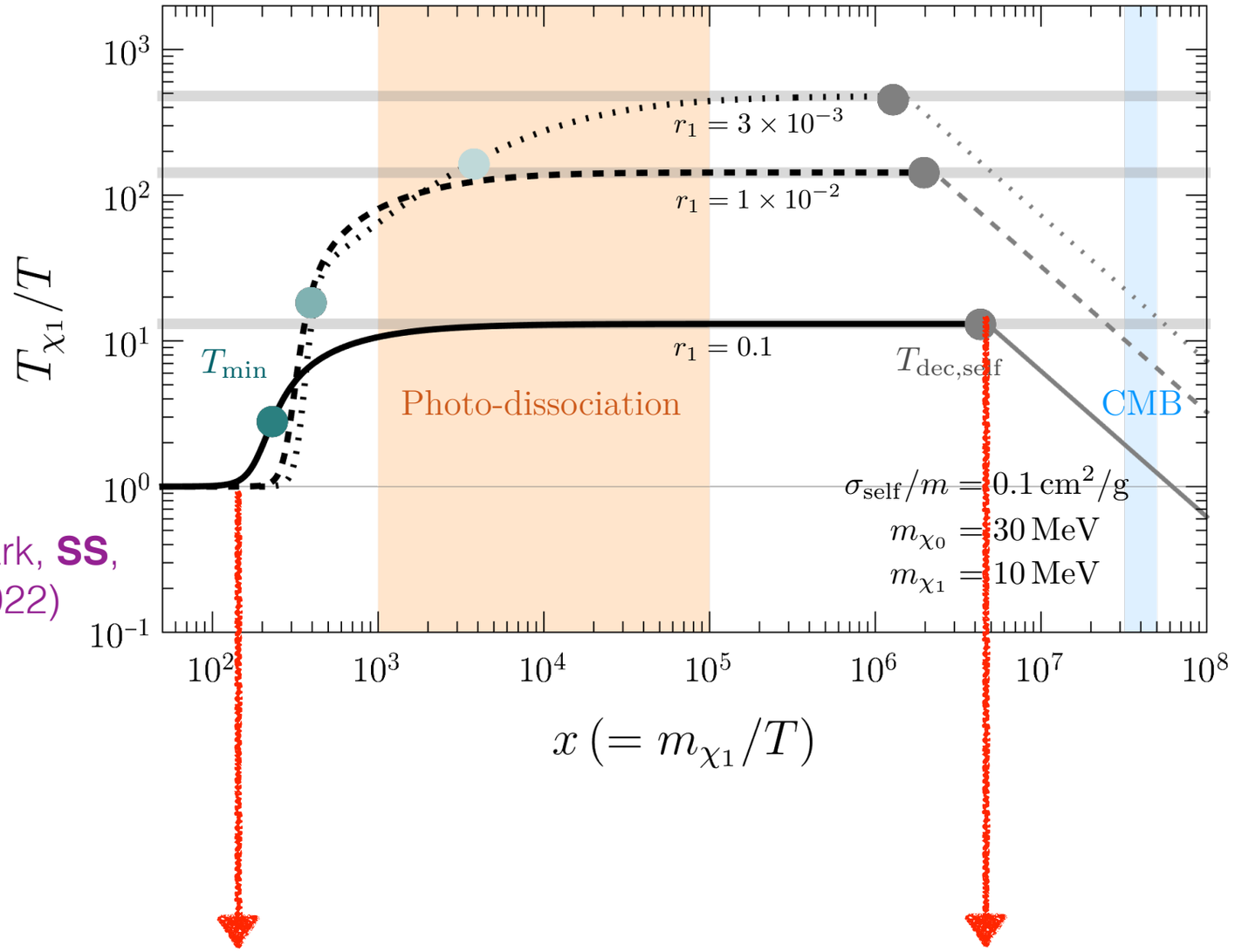
Kinetic decoupling of χ_1 (from the SM)

Temperature evolution of χ_1



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

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$\Gamma_{\chi_1-\chi_1} \sim H$

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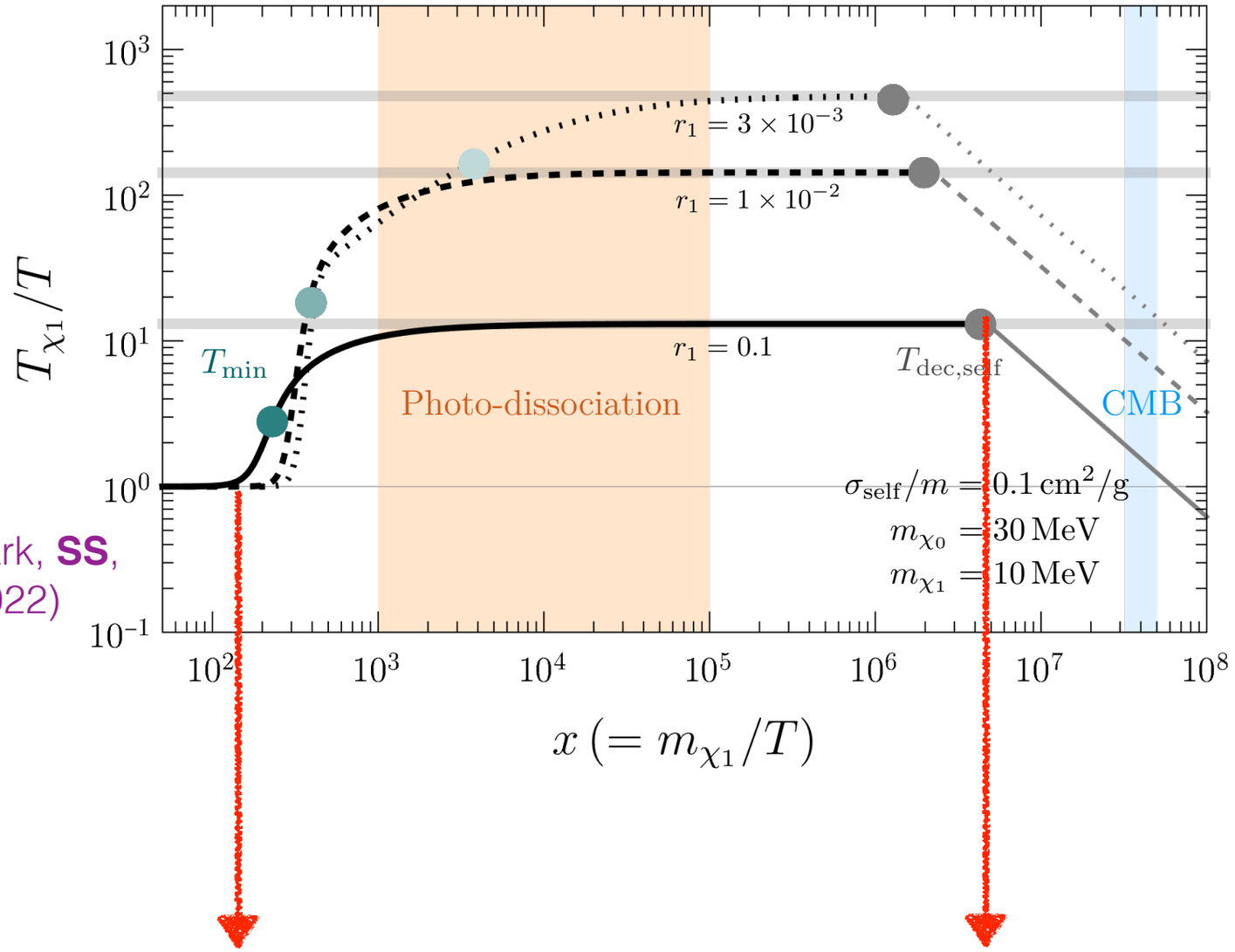

Kamada, Kim, Park, **SS**, JCAP 10, 052 (2022)

Kinetic decoupling of χ_1 (from the SM)

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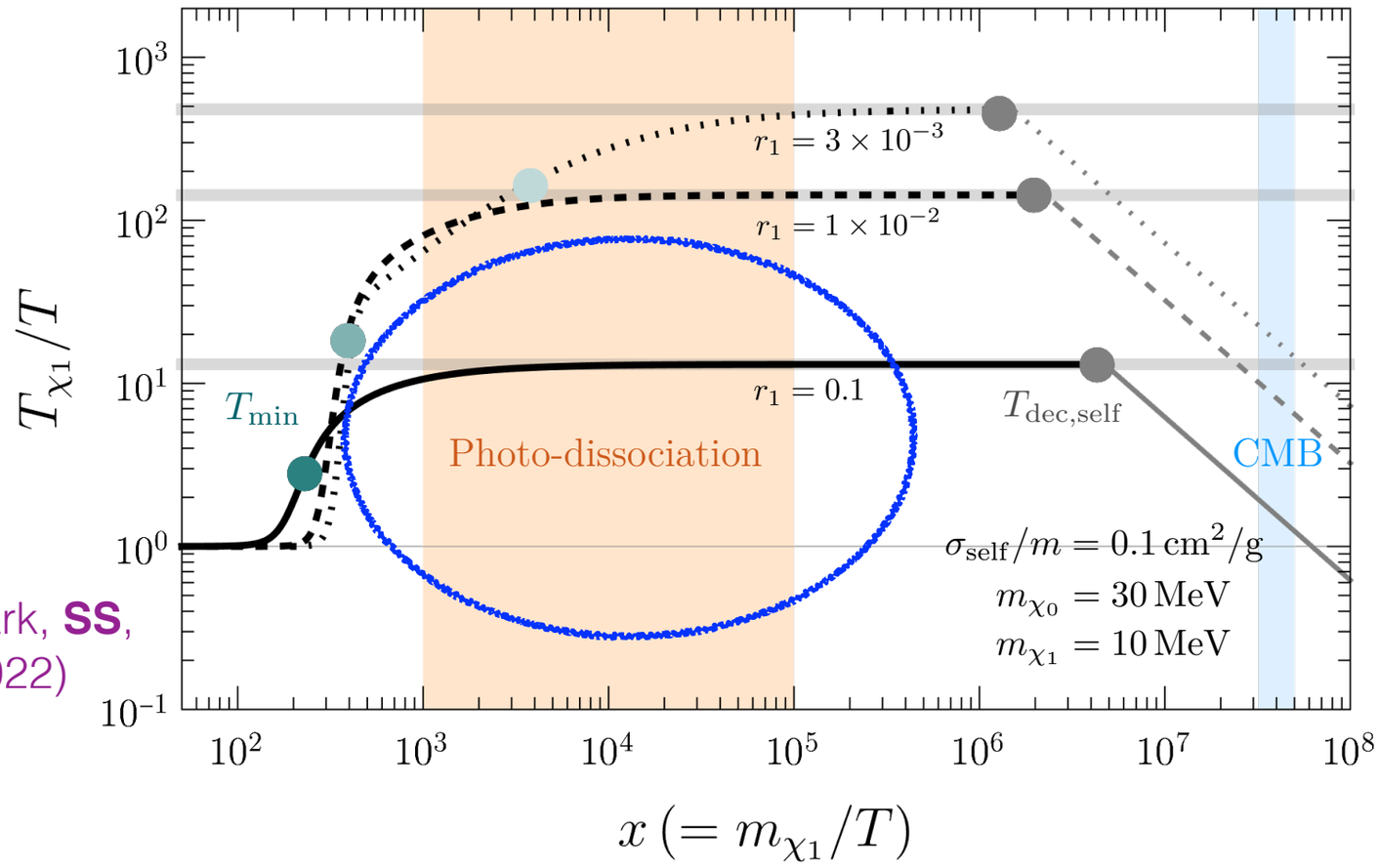
- If self-heating is efficient even after the kinetic decoupling, the temperature evolution of χ_1 makes it behave like a radiation.

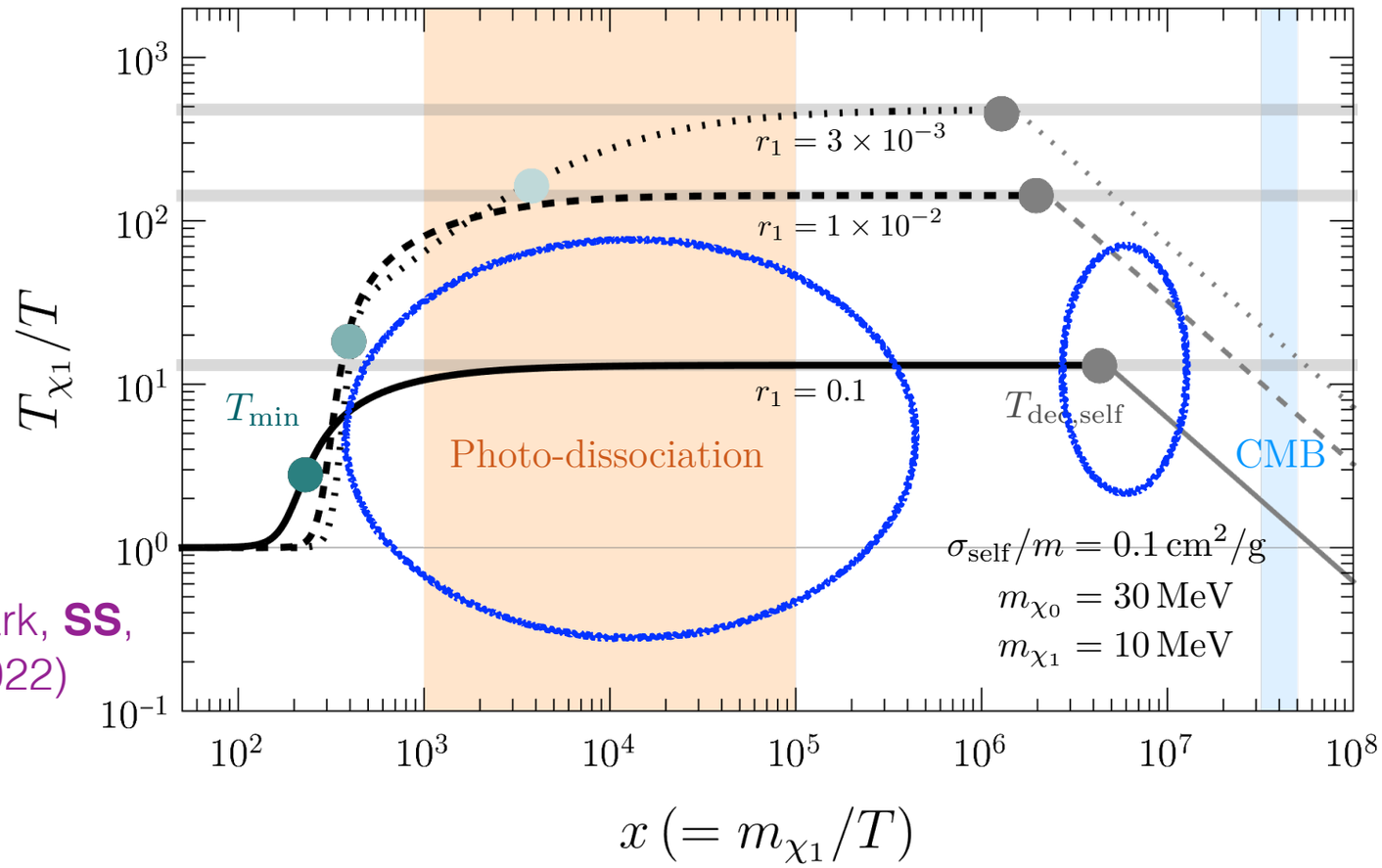
Temperature evolution of χ_1



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

- Strong photo-dissociation bounds for 100 eV ≲ T ≲ 10 keV after BBN

Temperature evolution of χ_1

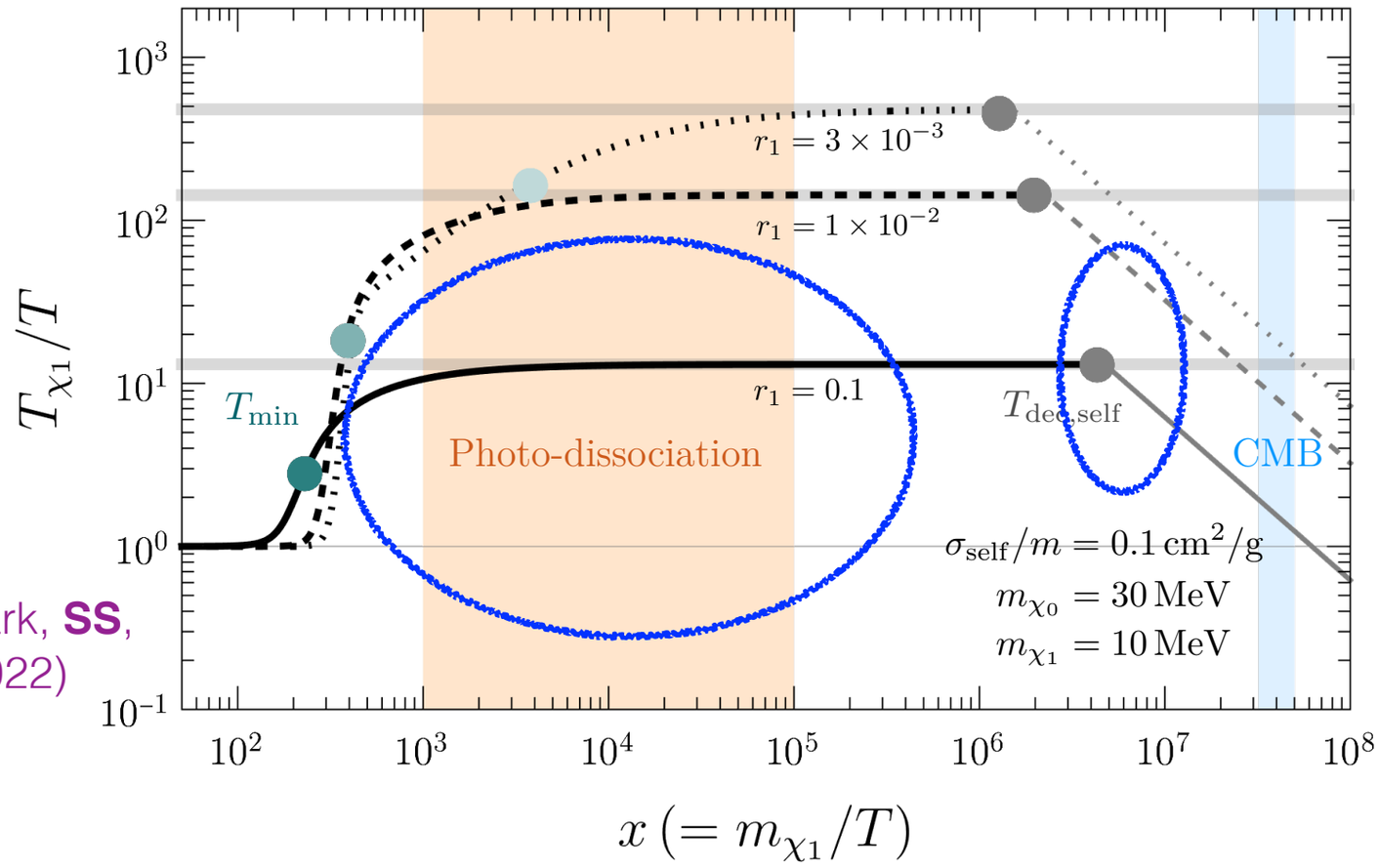


Kamada, Kim, Park, **SS**, JCAP 10, 052 (2022)

- Strong photo-dissociation bounds for 100 eV ≲ T ≲ 10 keV after BBN

- For $r_1 \gtrsim 0.07$, the self-heating epoch can persist even until the matter-radiation equality.

Temperature evolution of χ_1



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

- Strong photo-dissociation bounds for 100 eV ≲ T ≲ 10 keV after BBN

- For $r_1 \gtrsim 0.07$, the self-heating epoch can persist even until the matter-radiation equality.

χ_1 can be sub-GeV Warm Dark Matter!!

Lyman-α

# of satellites

New bounds due to self-heating

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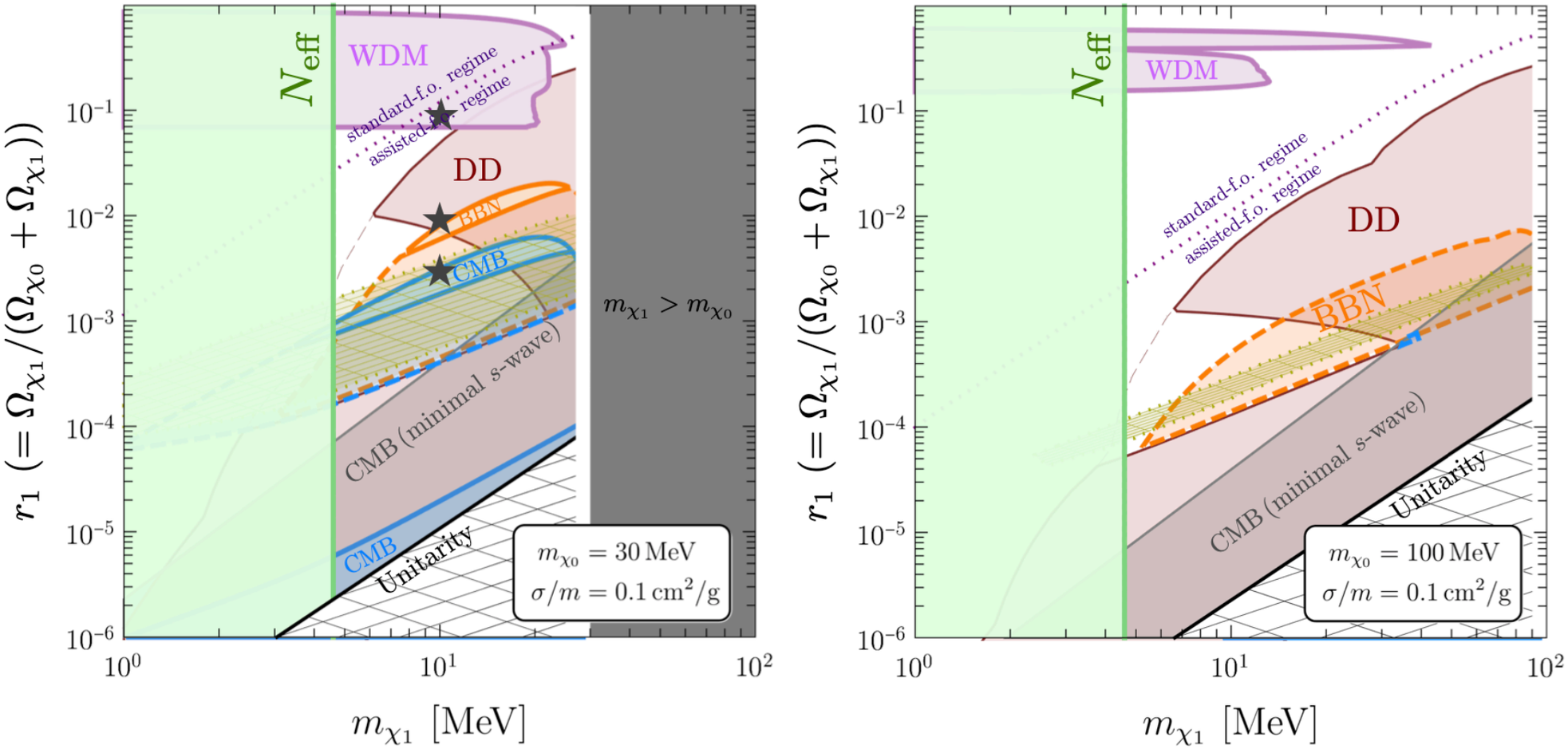


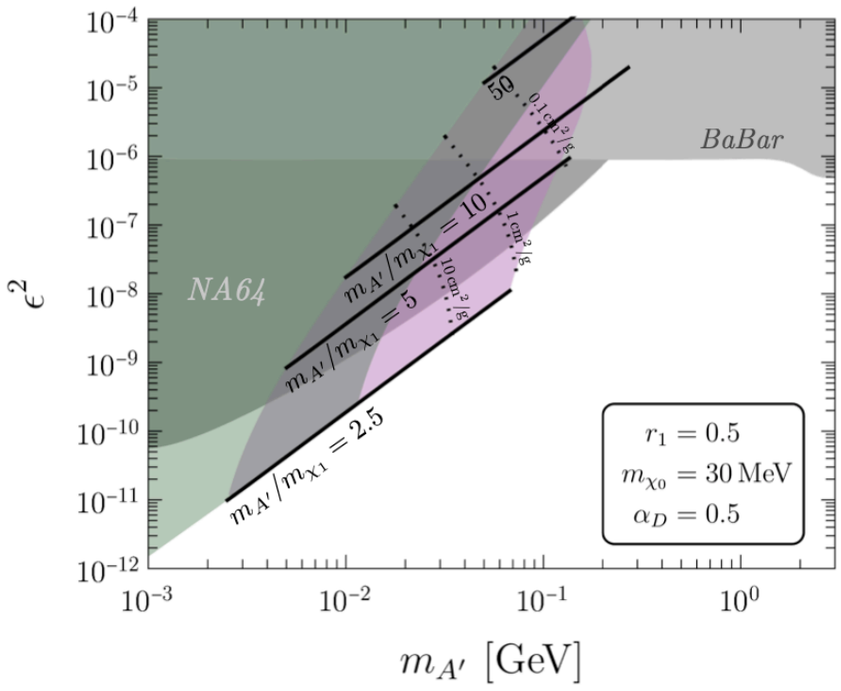
- WDM constraint enters when $r_1 \gtrsim 0.07$ even for $m_{\chi 1} \sim 40$ MeV.

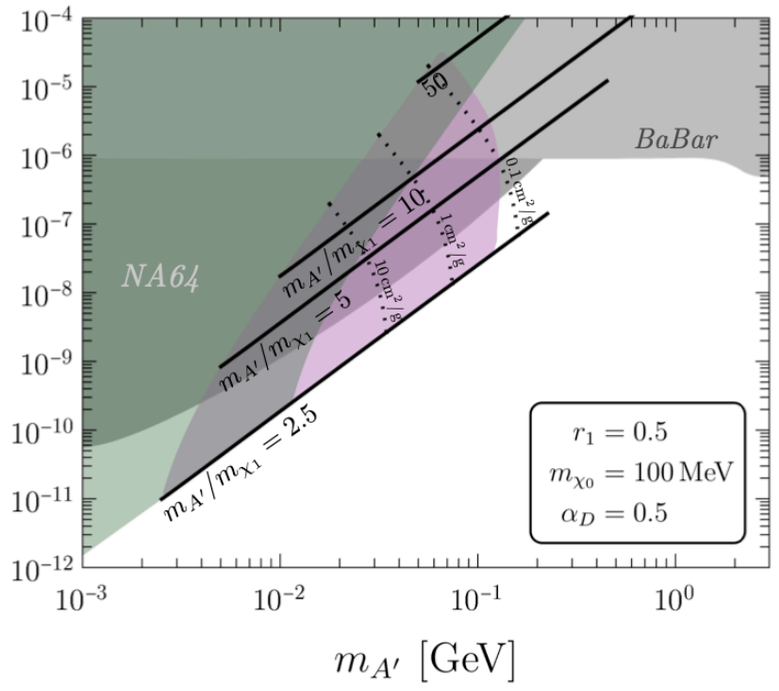
- Direct detection bounds get weaken since $n_{\chi 1}$ inside our MW decreases due to the kinetic energy of χ_1

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

Complementary searches

Light DM can be produced in accelerators with high intensities!





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

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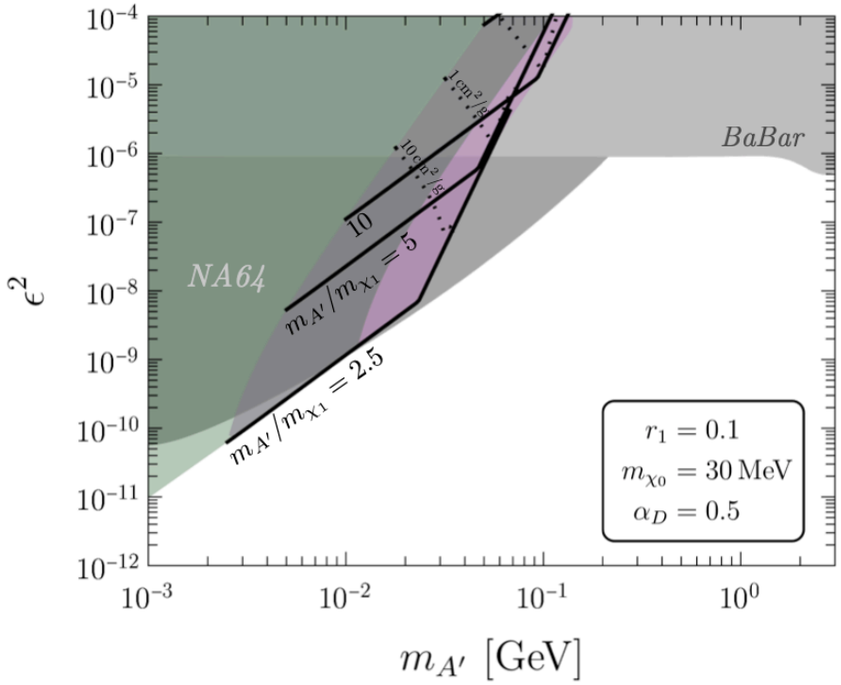

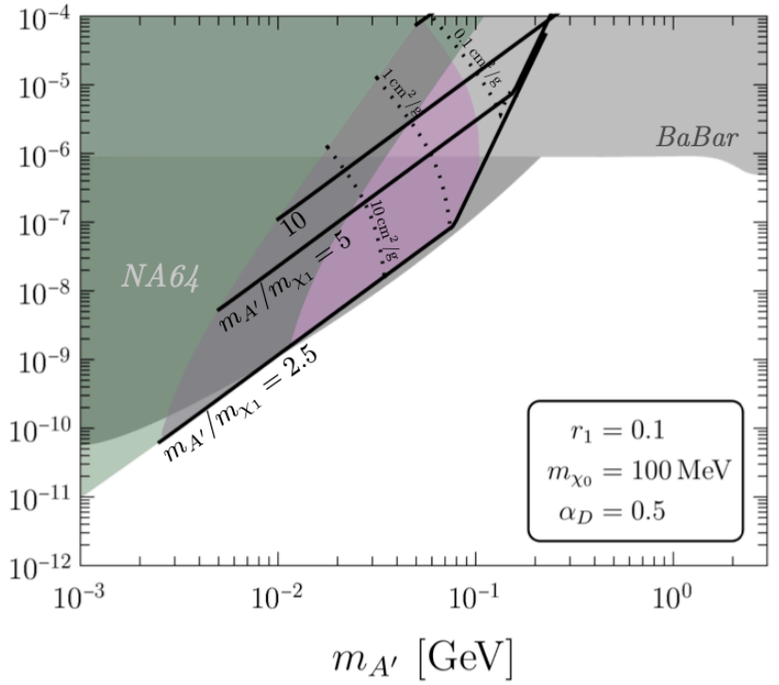

Complementary searches

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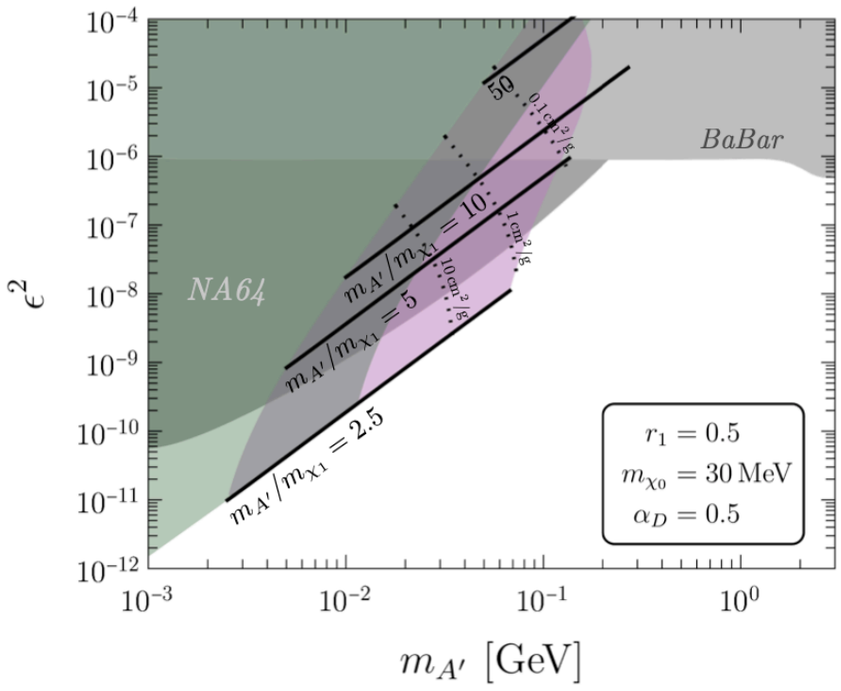

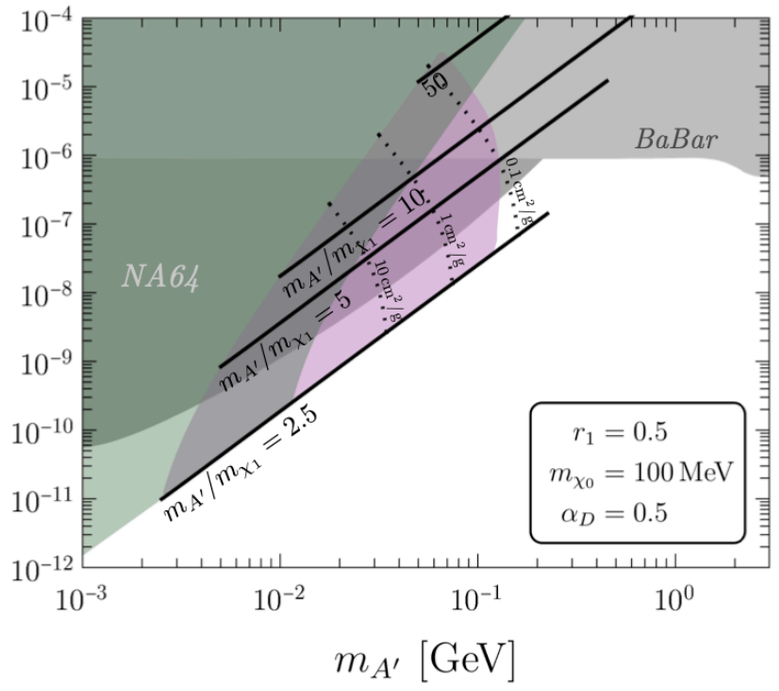

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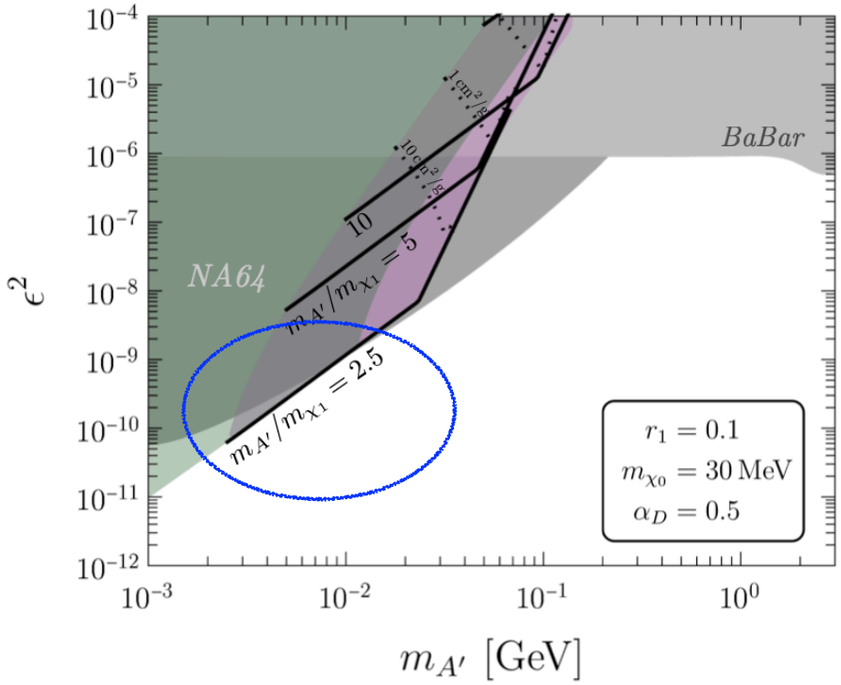
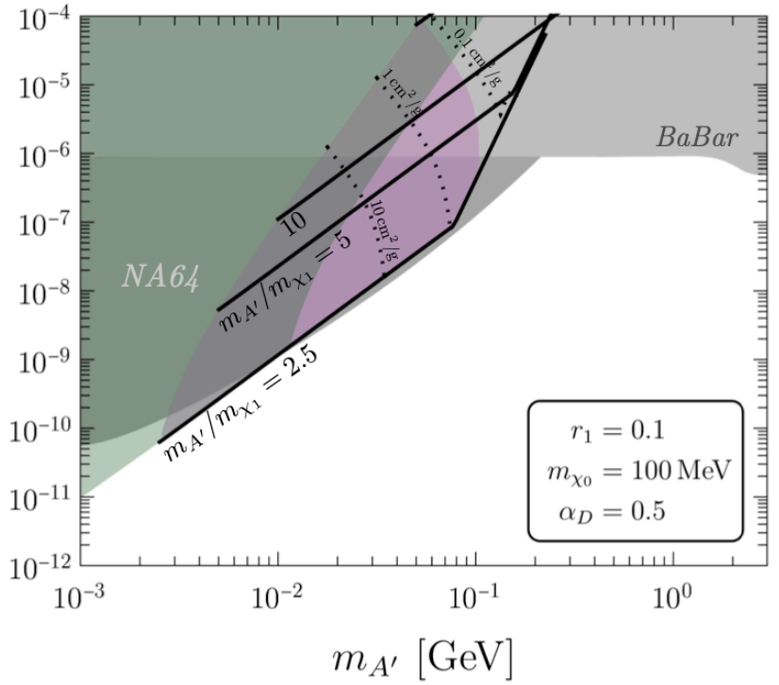
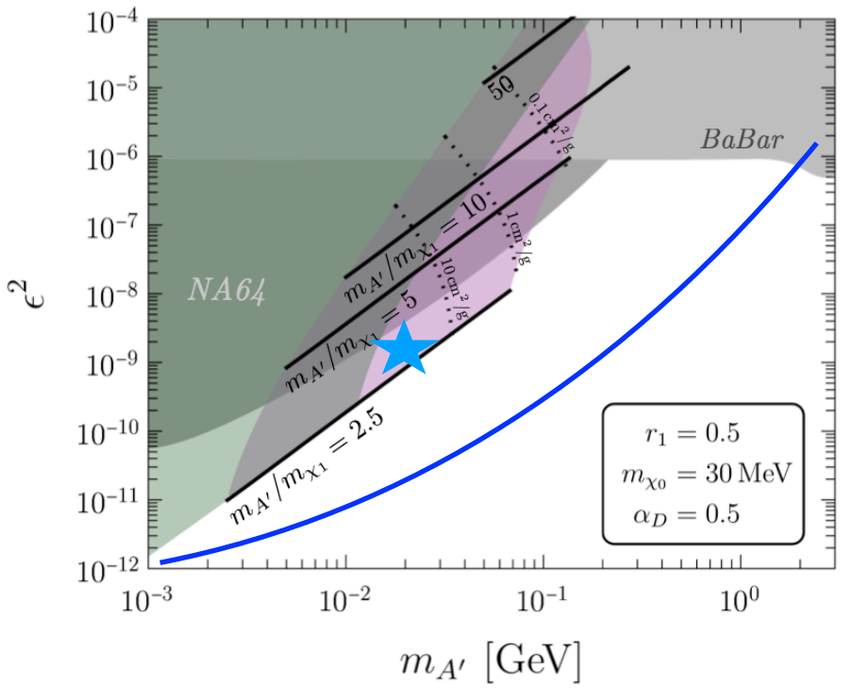


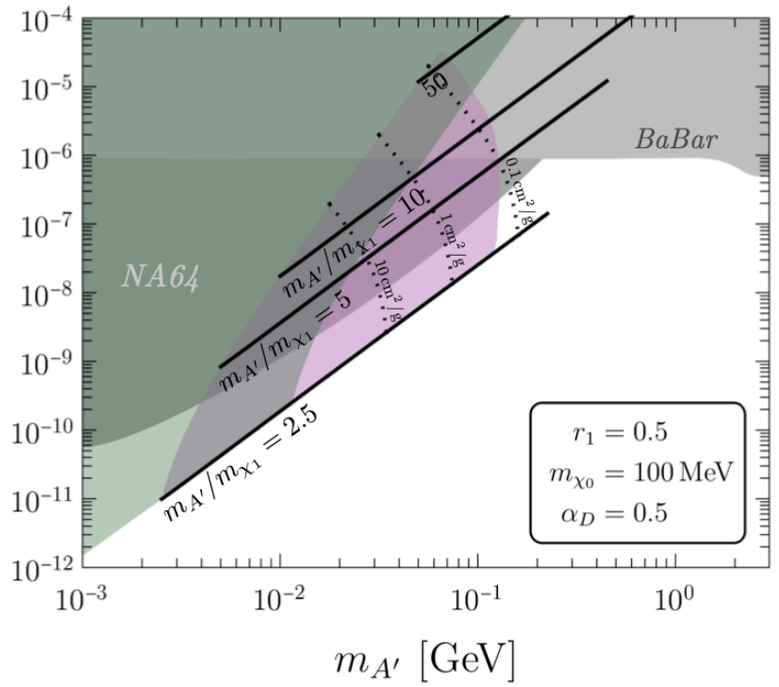


- For $r_1 \lesssim 0.07$, not preferred by the accelerator results.

Complementary searches

Light DM can be produced in accelerators with high intensities!





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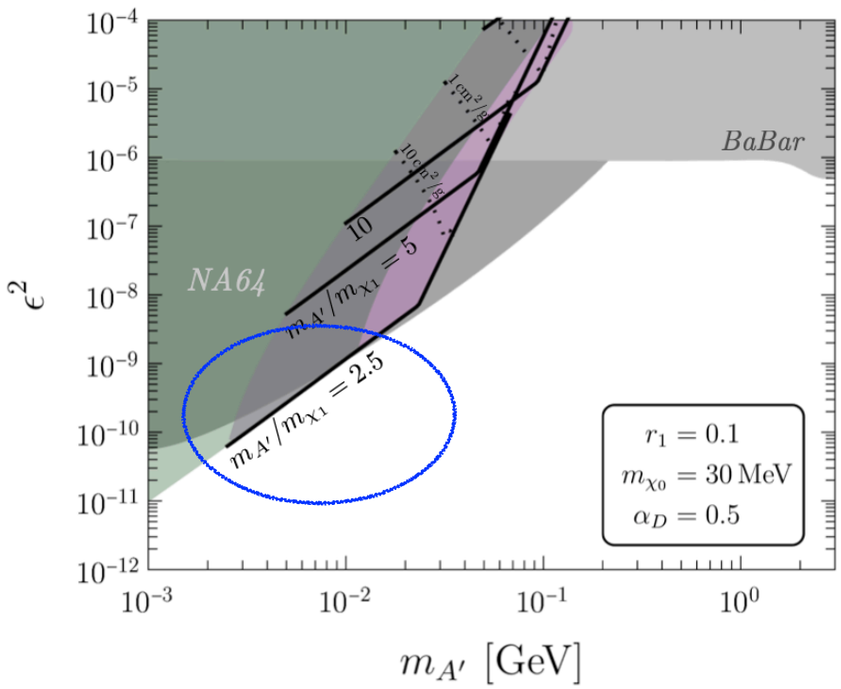

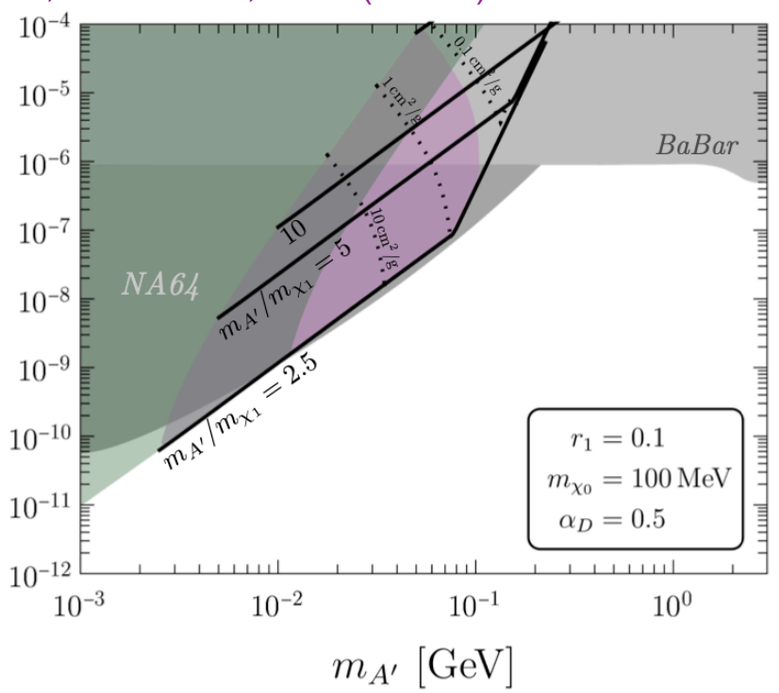

- Reference model: singlet scalar DM + dark photon (p-wave)
- Green: N_{eff}, Pink: WDM for $r_1 \gtrsim 0.07$.
- For $r_1 \lesssim 0.07$, not preferred by the accelerator results.
- Future discovery can tell the dark sector details.

Conclusions

- Dark sector with multi-component DM can provide a new avenue.

- Cosmological & astrophysical aspects: different from the WIMP case.

- 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.)

- 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.