Light particle dark matter and MeV gamma-ray observation

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Papers: JHEP01 (2023) 106, JHEP07 (2019) 050.

- ✓ MeV gamma-ray observations, e.g., COSI, are now being developed.
- ✓ These enable us to probe light particle dark matter candidates.
- ✓ CMB observation severely constrains such candidates, and it requests some discussions to be a target of the observations.
- ✓ We propose a framework to discuss the candidates at future MeV gamma-ray observations, using some concrete examples.

Dark matter problem & what we know

○ The dark matter problem:

We know that dark matter (DM) exists in our universe.
We know how the DM is distributed in our universe.
We know little about the microscopic nature of the DM.

○ What we know about the DM:

The DM must be (almost) electrically neutral.
The DM must be (enough) stable. (Its lifetime >> Age of U.)
The DM must be (enough) cold (non-relativistic) at present.
The DM must be (enough) weak-interacting.
The mass of the DM must be between 10^{-22}eV and 10^{35}g.

$m_{DM} > 10^{-22}$eV: λ_D(De Broglie W. L.) = $2\pi/(mv)$ < Galaxy size.
$m_{DM} < 10^{+35}$ g : DM must be lighter enough than a host galaxy.

DM candidates & MeV-γ observation

Wave-like | **Particle-like** | **Macroscopic** → **DM Mass**

10^{-22} eV — 0.1 eV — 10^{19} GeV — 10^{35} g

(ALPs) (Light DMs) (PBHs)

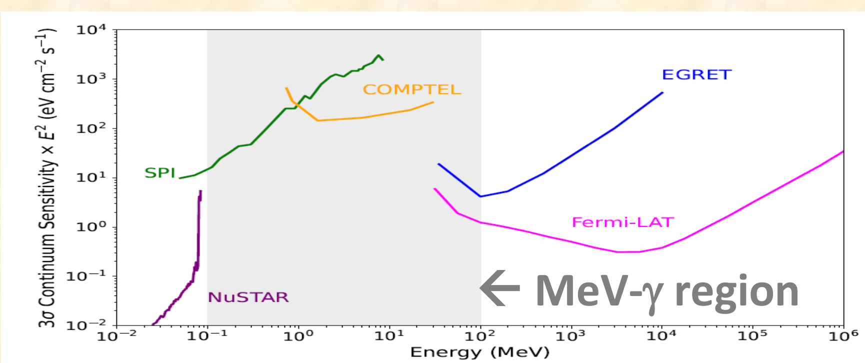
○ Three DM mass regions:

$m_{DM} <$ 10^{-1} eV: The occupation number of DM in a galaxy > O(1).

$m_{DM} >$ 10^{19}GeV: DM cannot be a particle, $\lambda_C = 2\pi/m > r_S = 2m/m_{pl}^2$.

DM can be a particle if its mass is 10^{-1} eV < m_{DM} < 10^{19}GeV.

○ DM targets @ MeV-γ region:



Observing MeV gamma will be developed shortly @ COSI, etc.

- ✓ ALP (Wave-like cand.)
  →Fabrizio's talk tomorrow
- ✓ pBH (Macroscopic 〃.)
  [T. Siegert, et al, MNRAS 511, (2002)]
- ✓ Light DM (Particle 〃.)

We will focus on the particle dark matter candidates in this talk.

Dark matter processes producing MeV-γ

O Dark matter decay:

∃Meny well-motivated candidates producing MeV gamma-rays.

✓ **Sterile neutrino DM (N):**

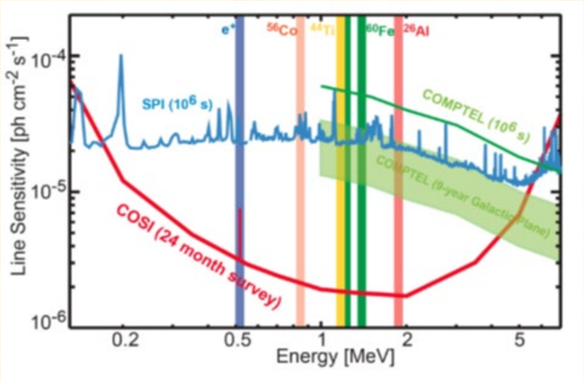
Motivated by the generation of the neutrino masses/mixings based on B-L gauge sym. (Split seesaw, etc.)

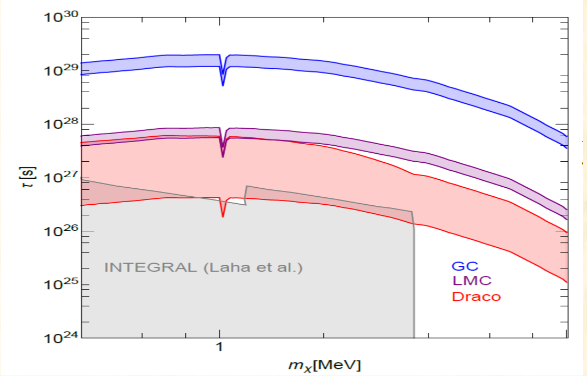
✓ **Gravitino DM (ψ_μ):**

Motivated by the supersymmetric SM, including a (leptonic) R-parity violation due to some motivations.

✓ **Heavy ALP DM (a):**

Motivated by the cosmology predicted by the string theory. (Axiverse).





[A. Caputo, M. Negro, M. Regis, M. Taoso, JCAP02, 006, 2023.]

Their masses are predicted to be around the MeV scale and are not absolutely stable, giving a monochromatic gamma-ray signal.

Dark matter processes producing MeV-γ

○ Dark matter annihilation:

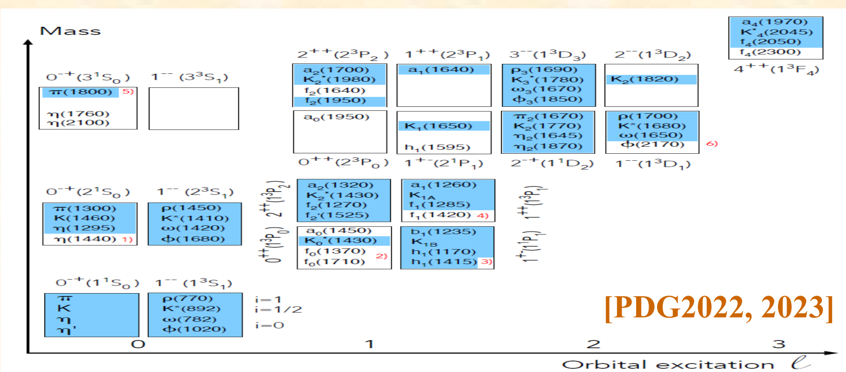
Well-motivated candidate = Thermal DM, a natural extension of the WIMP, i.e., the one that was in thermal equilibrium with SMs.

- Free from the initial condition problem of DM abundance.
- Detectable based on interactions maintaining the equilibrium.
- Its mass is predicted to be between ~1MeV and ~1PeV.

Light thermal DM (<< EW scale) is similar to WIMP but different!

✓ About hadronic final states

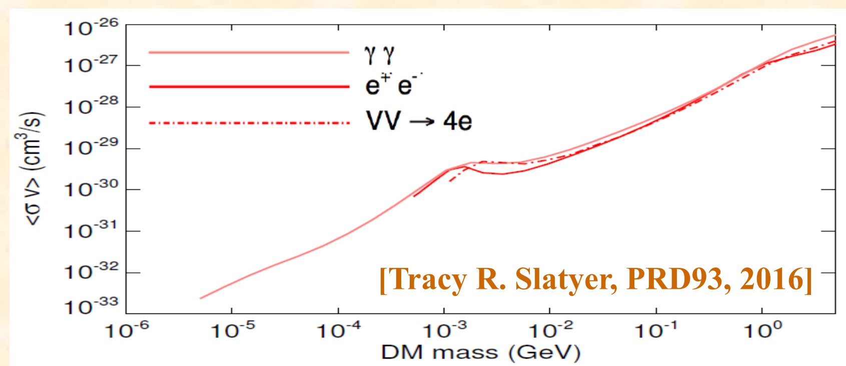
When the light DM couples to quarks, we must treat final states with various hadrons.



[PDG2022, 2023]

✓ About the cross-section

Annihilation cross-section of the light DM at recombination epoch is severely constrained.



[Tracy R. Slatyer, PRD93, 2016]

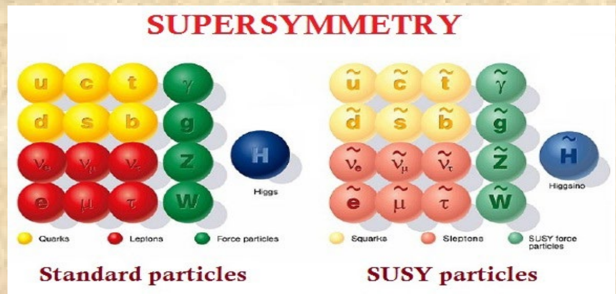
Models for MeV-γ from DM annihilation?

Which strategy is being adopted for the case of WIMP (GeV-γ)?

O Based on concrete models:

WIMP (GeV-g) signals are computed in concrete UV models (SUSY, etc.)

→ No vanilla models for the light DM.



O Based on annihilation processes:

The signal is computed at each process: e^-e^+, qq, $\gamma\gamma$, W^-W^+, ….

→ Not good for the light DM, as stated in the previous slide.
(It may work for the DM whose mass is below O(10) MeV.)

O Based on simplified (minimal renormalizable) models:

This is the strategy between the above two.

✓ Simplified models can be embedded in UV models.

✓ The models describe some parameter regions of UV models.

→ This strategy works for light DMs: Hadronic decays are well-defined, and various observables are well-computed.

Simplified models for the light DM

✓ Renormalizability: The spin of the DM should be 0, ½, or 1.
✓ Quantum numbers: The DM should be singlet under SM sym.
✓ Stability: We assume that the DM is stable due to a Z_2 sym.

• Spin = 0 case:

The simplest (SM+DM) one has been ruled out for the light DM.

↓

The next one is (SM+DM+MED), with MED being a bosonic med.

• Spin = ½ case:

No renormalizable int. in the (SM+DM) model.

↓

The simplest model is the SM+DM+MED one, with MED being again a bosonic mediator.

• Spin = 1 case:

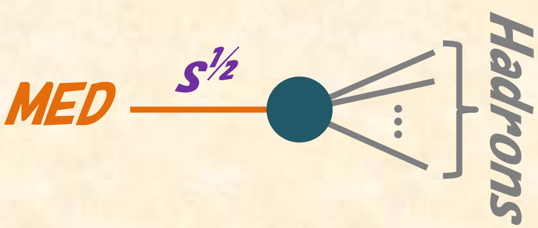
The minimal model is the so-called U(1) extension of the SM.

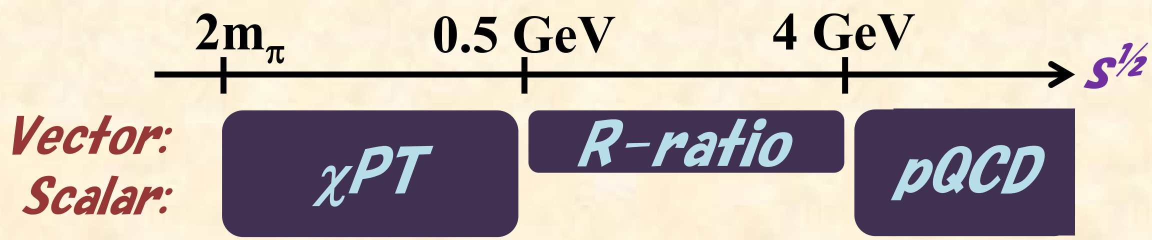
↓

An Abelian Higgs field which breaks the U(1) plays the role of med.

The light DM couples to SM via a bosonic (scalar, vector) med!

○ Hadronic final states in light DM annihilation:





Simplified models for the light DM

O Avoiding CMB constraint

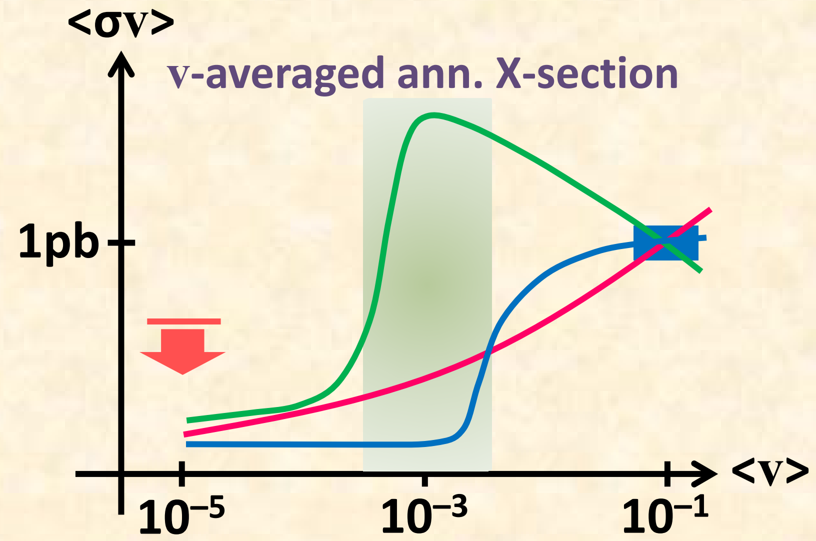
Light DM with a velocity-dependent annihilation!

With the averaged DM velocity $\langle v \rangle$,

$\langle v \rangle \ll 10^{-3}$: Avoiding CMB constraint.

$\langle v \rangle \sim 10^{-3}$: MeV-$\gamma$ observation window.

$\langle v \rangle \sim 10^{-1}$: For relic abundance cond.



✓ p-wave annihilation: $\sigma v \propto v^2$ @ $v \to 0$.

s-wave one is suppressed by angular and CP conservations.

✓ Resonant annihilation: $\sigma v \propto [(v^2 - v_R{}^2)^2 + 16\,\Gamma_{Res}{}^2/M_{Res}{}^2]^{-1}$.

Annihilation is dominated by an s-channel resonant diagram.

✓ Forbidden annihilation: $\sigma v \propto (v^2 - v_{Cut}{}^2)^{l+1/2}\,\theta(v^2 - v_{Cut}{}^2)$.

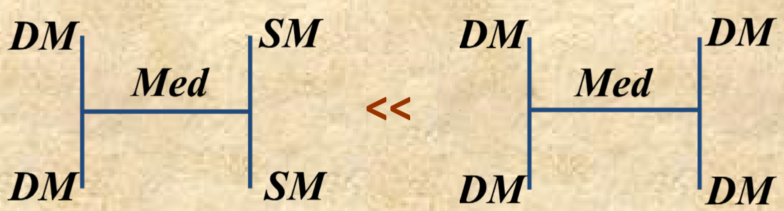
DM annihilation is slightly forbidden Kinematically at v = 0.

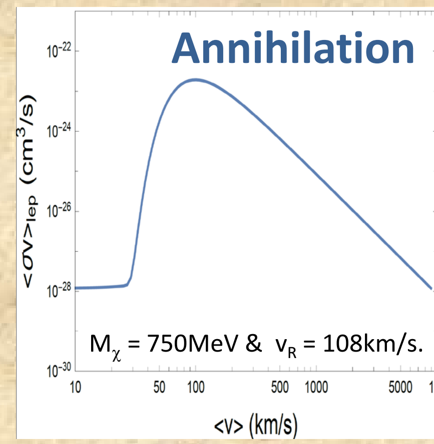
Light DM having a v-dependent annihilation often becomes SIDM, giving a solution to the small-scale (core-cusp) crisis of our U!

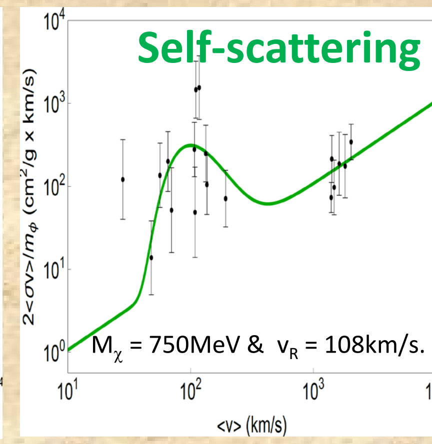
Example: Scalar DM + Scalar MED

[T. Binder, S. Chakraborti, S. M., Y. Watanabe, JHEP01, 2022.]

At $m_{DM} \sim m_{MED}/2$ with appropriate choosing parameters, annihilation and self-scattering processes are







[Data: M. Kaplinghat, S. Tulin, H. Yu, PRL116, 2016] ⮥

O Global analysis

Conditions/Constraints

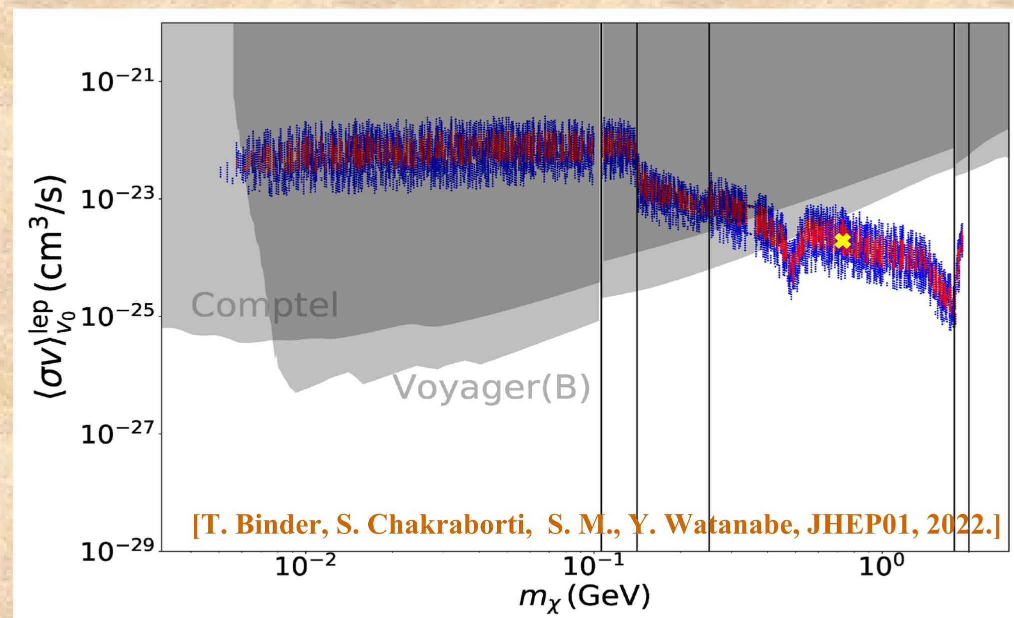
- ✓ Relic abundance condition,
- ✓ CMB constraints on $\langle \sigma v \rangle$,
- ✓ Self-scattering condition.

Indirect DM detection?

- ✓ COMPTEL(γ) & Voyager(e).

Future MeV-γ observation?

- ✓ COSI, AMEGO, GECCO, etc.

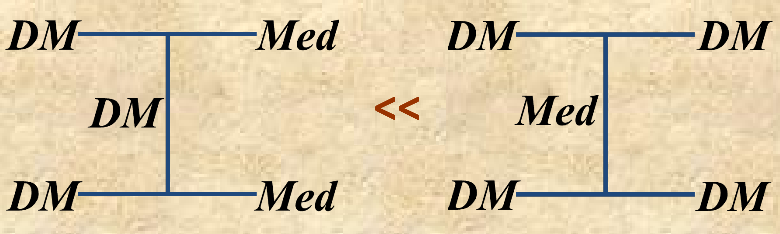


Example: Majorana DM + Scalar MED

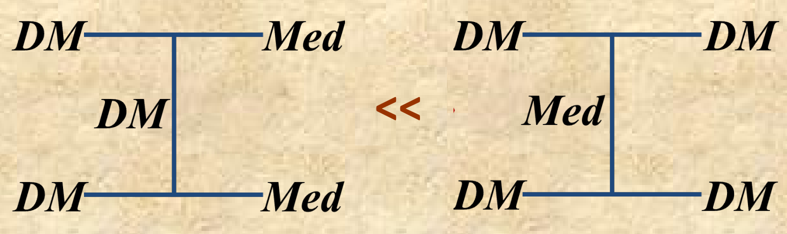
[S.M., Y. Tsai, P. Tseng, JHEP07, 2019.]

When CP is conserved by interactions that DM participates in, the DM annihilation proceeds in the p-wave, i.e., in the s-wave is suppressed.

Attractive regions predicting a large self-scattering are as follows:



Light MED region ($m_{MED} << m_{DM}$)



Forbidden region ($m_{MED} << m_{DM}$)

O Global analysis

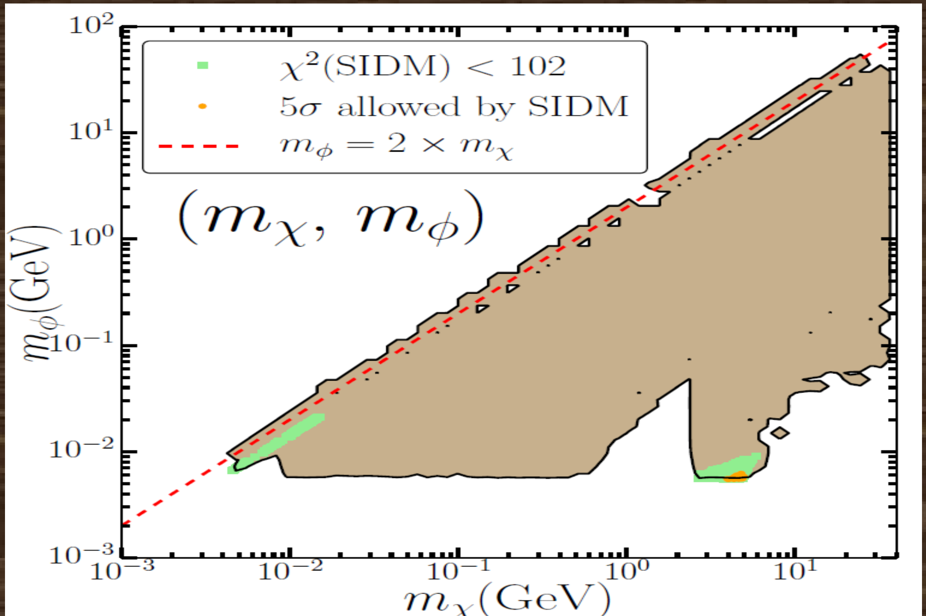
Conditions/Constraints

- ✓ Relic abundance condition,
- ✓ CMB constraints on $\langle \sigma v \rangle$,
- ✓ Direct detection constraint,
- ✓ Various collider constraints,

+ Self-scattering condition,

Light MED ··· m_{DM} = O(1) GeV,

Forbidden ··· m_{DM} = O(10) MeV.



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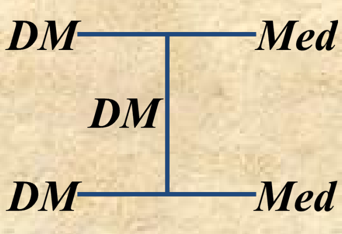

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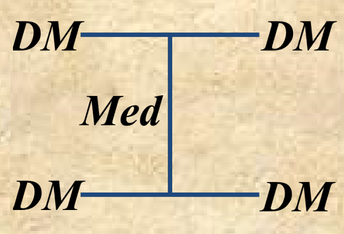
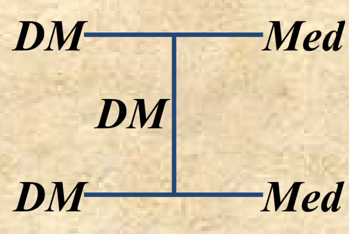


Light MED region ($m_{MED} << m_{DM}$)



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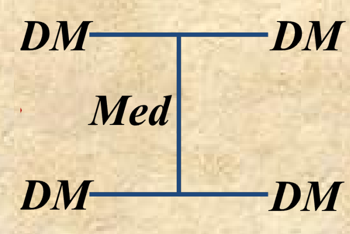

Forbidden region ($m_{MED} << m_{DM}$)

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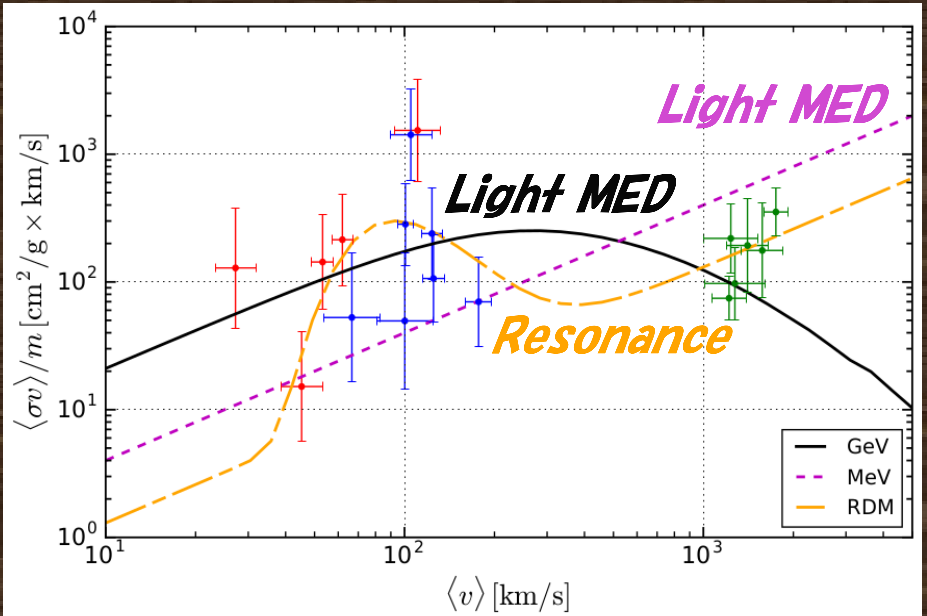

Summary

We discussed a framework of the light thermal dark matter aimed at quantitatively discussing the capability of future MeV-γ observations.

- ✓ It seems best to use the so-called simplified models (as in the case of LHC experiments for WIMP) involving the light dark matter and the bosonic mediator. Both are singlet under SM gauge interactions.

- ✓ Annihilation into hadrons is systematically described (using chiral perturbation theory, R-ratio observation, and perturbative QCD), except for a scalar mediator case with its mass, m_{MED} = 0.5—4 MeV. Candidates with a velocity-dependent (e.g., p-wave, resonant, and forbidden) annihilation cross-section at the NR region should be considered to avoid the CMB constraint. Such candidates often predict a large self-scattering cross-section and become SIDM.

- ✓ Because the energy of photons probed by COSI is 100KeV to 5MeV and line gamma-rays are searched for with excellent sensitivity, we should focus on the light DM, whose mass is O(MeV), annihilating into two photons (via 1-loop, etc.) and/or (low-energy) $e^-e^+(\gamma)$.