Light Thermal Dark Matter and MeV Gamma-ray Detection

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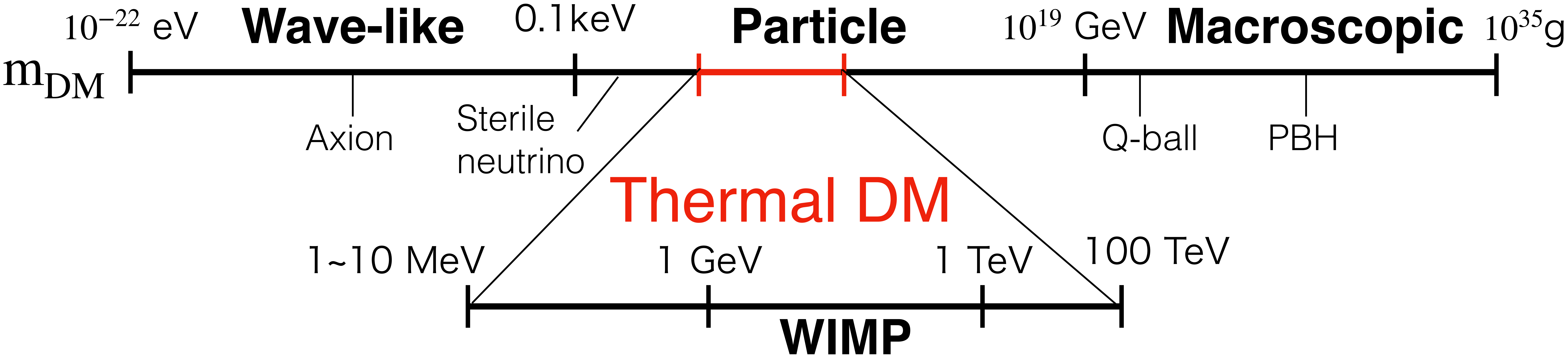
DM candidates

Mass range spans almost
90 orders of magnitudes…

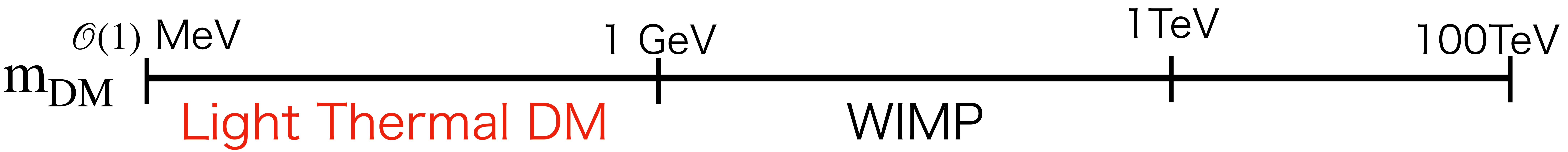


- ∃Various candidates, and one of the most attractive candidate is the thermal DM.

  Def: Experienced equilibrium with SM particles in the early universe.

  Motivation:
  - Free from the initial condition problem of the DM density today.
  - Detectable based on the interaction dependable on maintaining equilibrium.
  - DM density today can be from the freeze-out mechanism.

Motivation of light thermal DM



- WIMP has been intensively searched for due to the ‘WIMP miracle’ and the connection to the EWSB (SUSY, UED, Little Higgs), however not found.
- Different mass region, light and heavy thermal DMs, are getting more attention.
- Many experiments are being planned to search for the light thermal DM.
- The light thermal DM is expected to produces MeV γ-ray signal, and the COSI has a chance to detect the signal.
- From the COSI view point, it is important to study light thermal DM complehensively and figure out whether the COSI can prove them.

Light thermal DM models

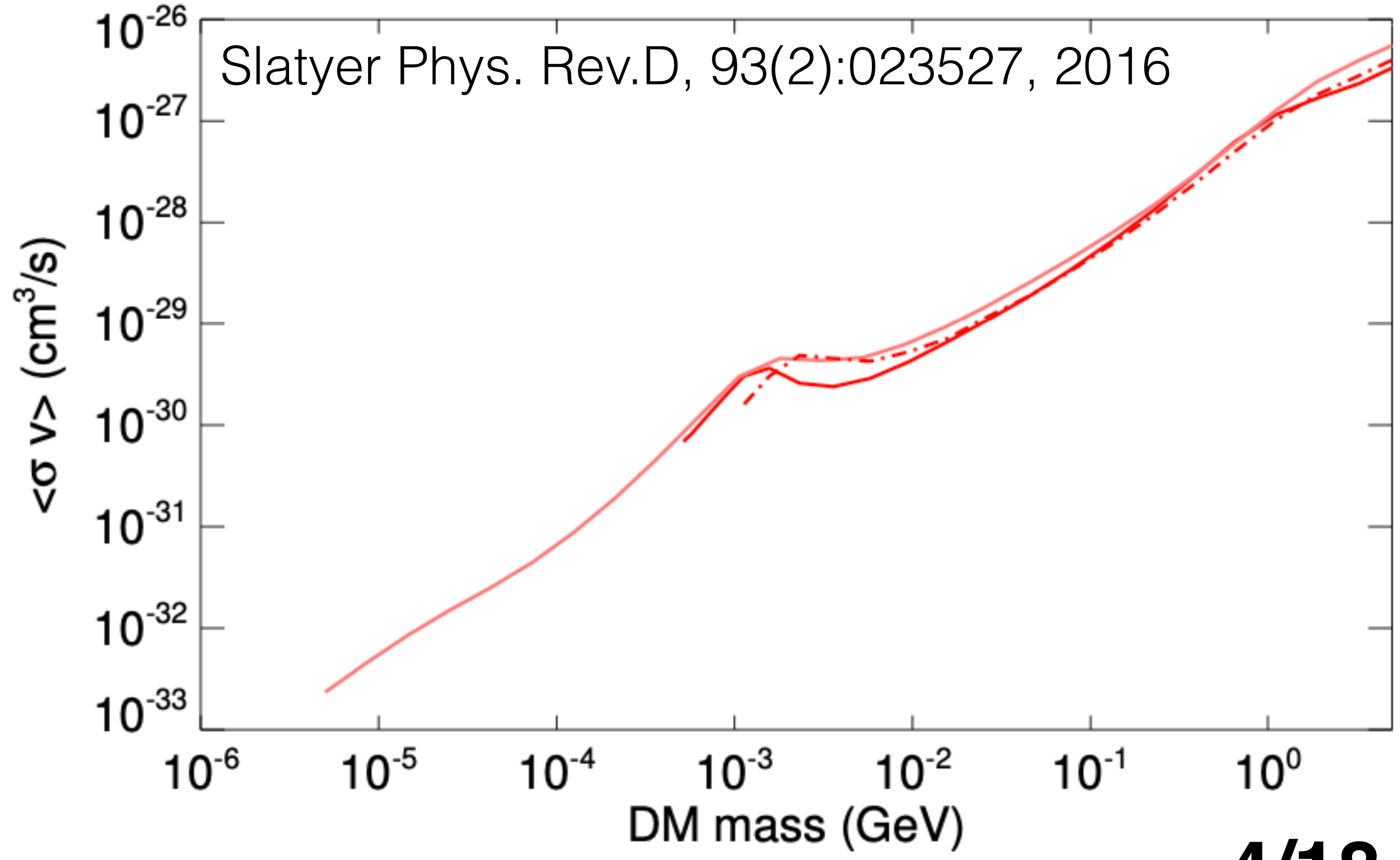
- What model is favored with the minimlaity, renormalizability and Z_2 symmetry?
- DM should be singlet under SM gauge group. (Relic abundance)
- Minimal model (SM + scalar DM: Higgs portal) was already excluded.
- Next minimal model is SM + DM + mediator.
- We consider the extention of SM with singlet DM and singlet mediator, where DM ($m_{\rm DM} \lesssim$ 100 MeV) is a scalar or fermion and the mediator is a scalar or vector. We consider the dark photon and $\mathrm{U(1)_B}$ boson scenarios for the vector mediator.
- We name these models as:

DM \ MED	Scalar	Vector (DP)	Vector (U(1)B)
Scalar	SS	SV(DP)	SV(B)
Fermion	FS	FV(DP)	FV(B)

- We investigated all the models to figure out viable model parameter regions.

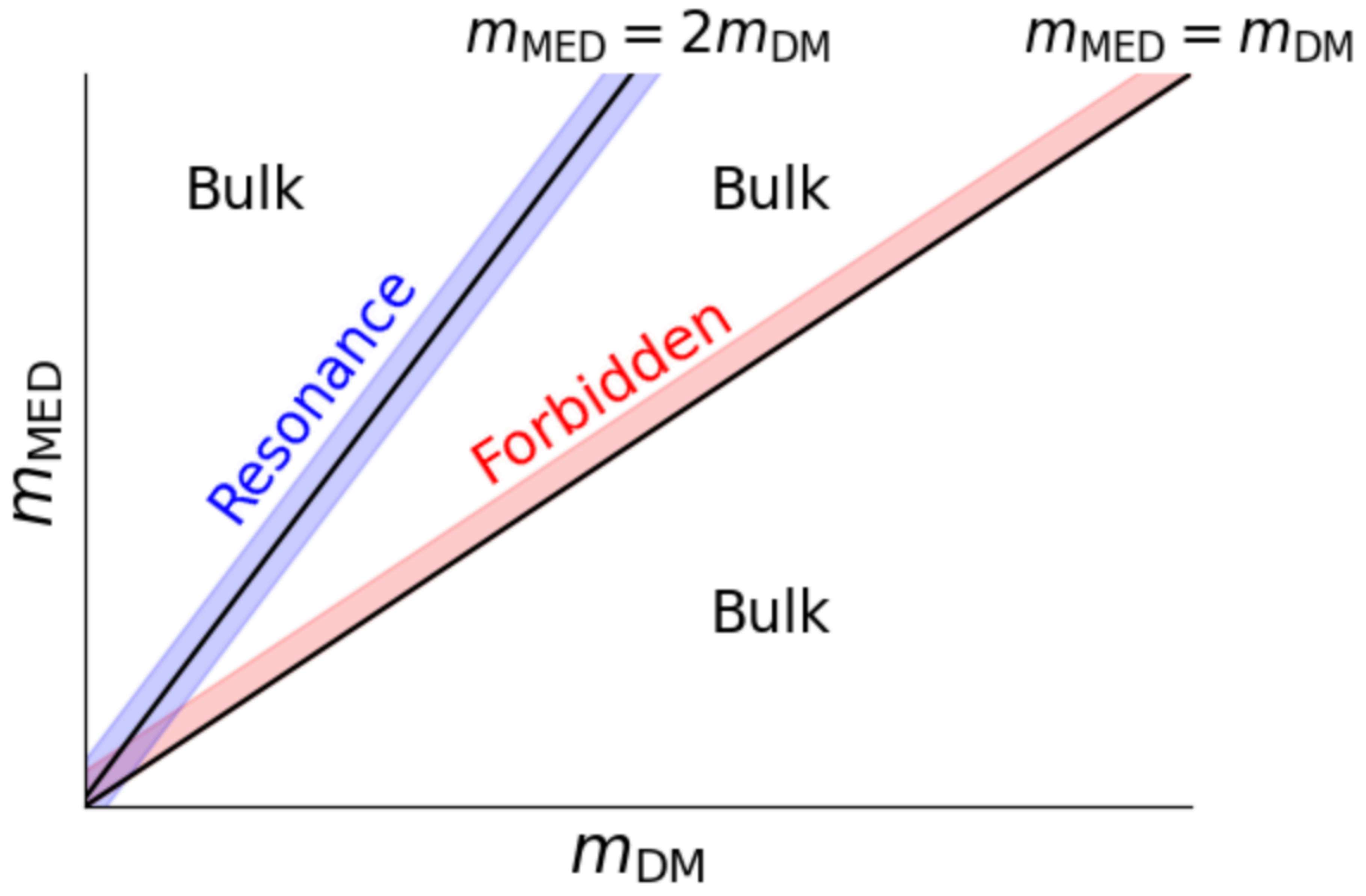
Constraint on $\langle \sigma v \rangle$ from CMB

- DM annihilations into primordial plasma may modify the anisotropy of the CMB, which is not observed, resulting in $\langle \sigma v \rangle \lesssim 10^{-27}\mathrm{cm}^3/\mathrm{s}\,(\mathrm{m_{DM}}/\mathrm{GeV})$ @ recommbination
- $\leftrightarrow$ relic abundance: $\langle \sigma v \rangle \approx 10^{-26}\mathrm{cm}^3/\mathrm{s}$ @ freeze-out.
- Simple s-wave annihilaltion is not good.
- Several mechanisms can be utilized to overcome this.
  - Annihilations into harmless particles (neutrino)
  - Different proceses (Co-annihilation, SIMP, ADM….)
  - Non-standard cosmology (late-time inflation)
  - Velocity-dependent annihilation
- We focus on the last one.



∃velocity-dependent annihilation?

- Thanks to the ∃MED, ∃4 regions with velocity-dependent $\langle \sigma v \rangle$
- P-wave (Bulk): Speciphic combinations of DM & MED spins
- Forbidden: DM annihilates into a pair of slightly heavior MEDs.
- Resonance: DM annihilates via the resonance of MED.
  - Visible: not hitting the pole, but suppressed by p-wave.
  - Invisible: hitting the pole.

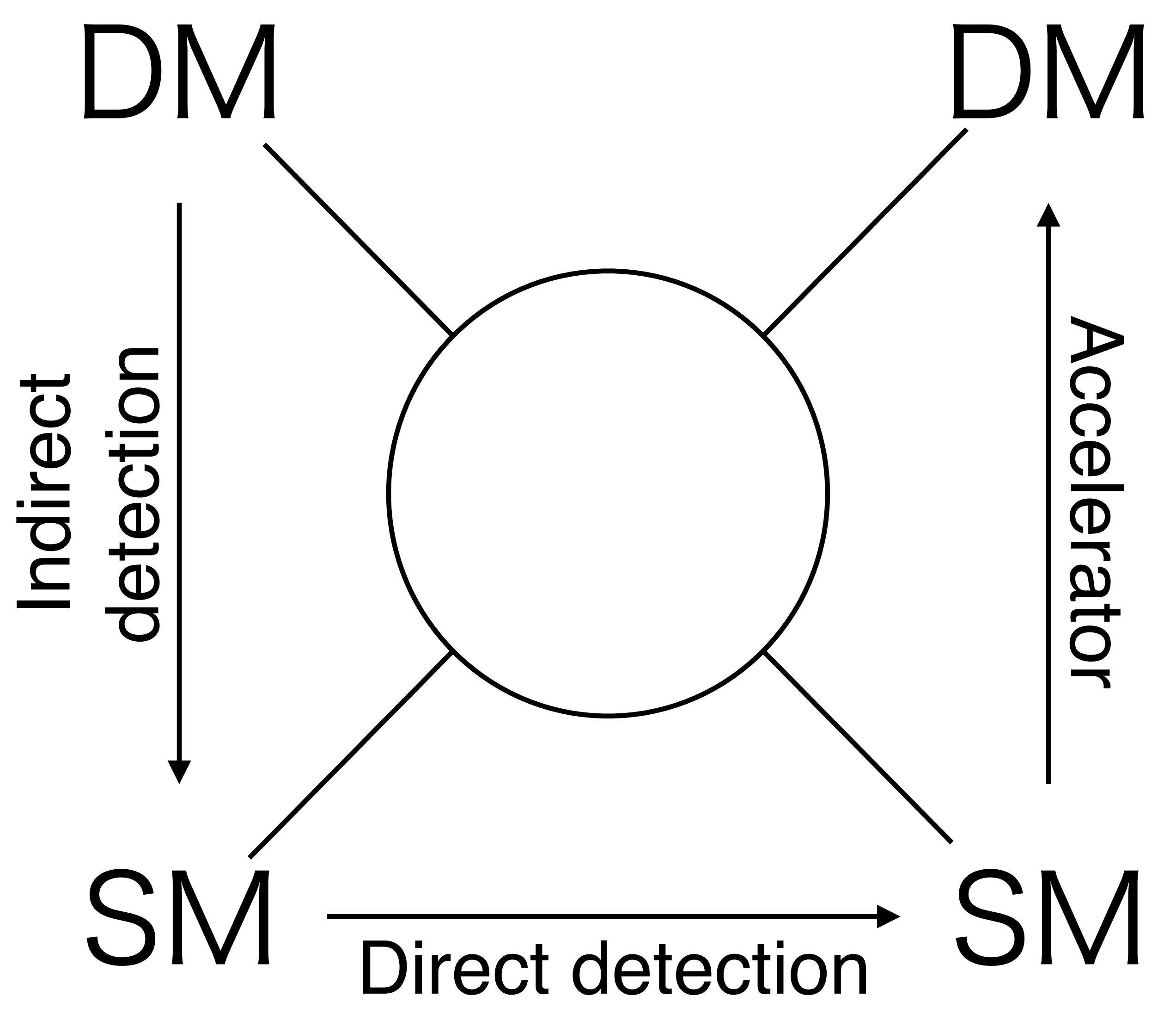


We investigated all the regions for each model to figure out if ∃parameter regions survinving from present experiments and observations.

Constraints from cosmology

- $\exists$ many constraints… We implemented all the constraints.
- CMB
  - Constraint on $\langle \sigma v \rangle$
  - Relic abundance
  - Constraint on m_{DM}: asymmetrical entropy injection into EM-plasma and ν alters expansion rate of universe. $m_{\mathrm{DM}} \gtrsim \mathcal{O}(1)\,\mathrm{MeV}$
- BBN
  - Constraint on $\langle \sigma v \rangle$: Photons emitted by DM annihilations may destroy the light elements. Deutrium abundance results in $\langle \sigma v \rangle \lesssim 10^{-24}\mathrm{cm}^3/\mathrm{s}\ (m_{\mathrm{DM}} \gtrsim 2\,\mathrm{MeV})$ @ $T_\gamma \sim \mathcal{O}(1)$ keV.
  - Constraint on m_{DM}: Light thermal particle affects $T_{\gamma(\nu)}$ and the expansion rate, then light element abundances. $m_{\mathrm{DM}} \gtrsim \mathcal{O}(0.1)\,\mathrm{MeV}$
- Lyman - α
  - Late kinetic decoupling of DM suppresses the structure formation,resulting in $T_{\mathrm{kd}} \gtrsim 200$ eV.

Detection of DM



- ∃3 types of DM-SM interaction, and ∃appropriate searching strategy for each.

Direct detection (Observation of DM-SM scatterings at underground laboratories)

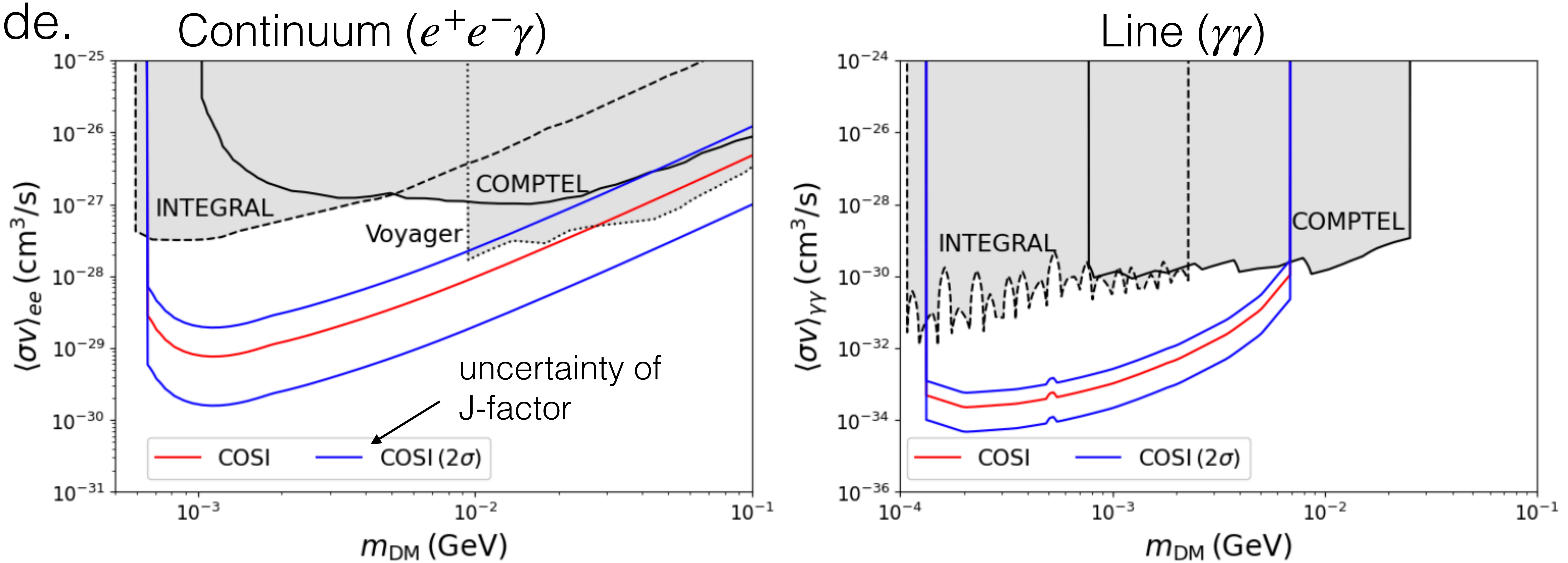
- Traditional experiments (Xenon, etc.) lose the sensitivity for the light DM, as the recoil energy is small then falls below the detector threshold.
- Several strategy are being considered to overcome this: detector with low threshold, Migdal effect, electron scattering.

Accelerator (Production of DM by high energy SM particles collisions)

- ∃many constraints from accelerator experiments.
- ∃many types (collider, fixed target, beam dump) and accelarating SM particles (e and p).
- ∃many signals (Higgs invisible decay, MED production (invisible decay, visivle decay)).

Indirect detection (Observation of SM particles produced by DM annihilations in the universe)

- DM can produce cosmic-ray and γ-ray.
- Cosmic-ray is the low energy $e^{\pm}$, which cannot enter the heliosphere by the solar magnetic field. Only Voyager I can detect this.
- γ-ray has energy of MeV. This is known to be difficult to detect ('MeV gap'), resulting in usage of only old experiments (COMPTEL, INTEGRAL).
- We assume NFW profile considering these uncertainties at 2σ.
- COSI(2 years observations of the GC ($|\theta| < 20°$)) improves sensitivity by several orders of magnitude.

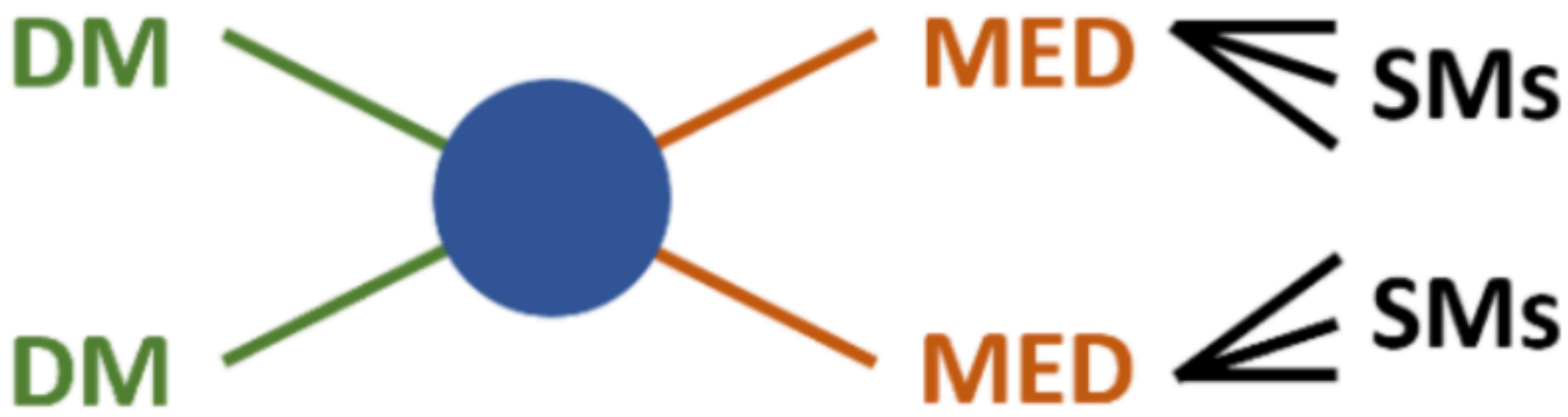


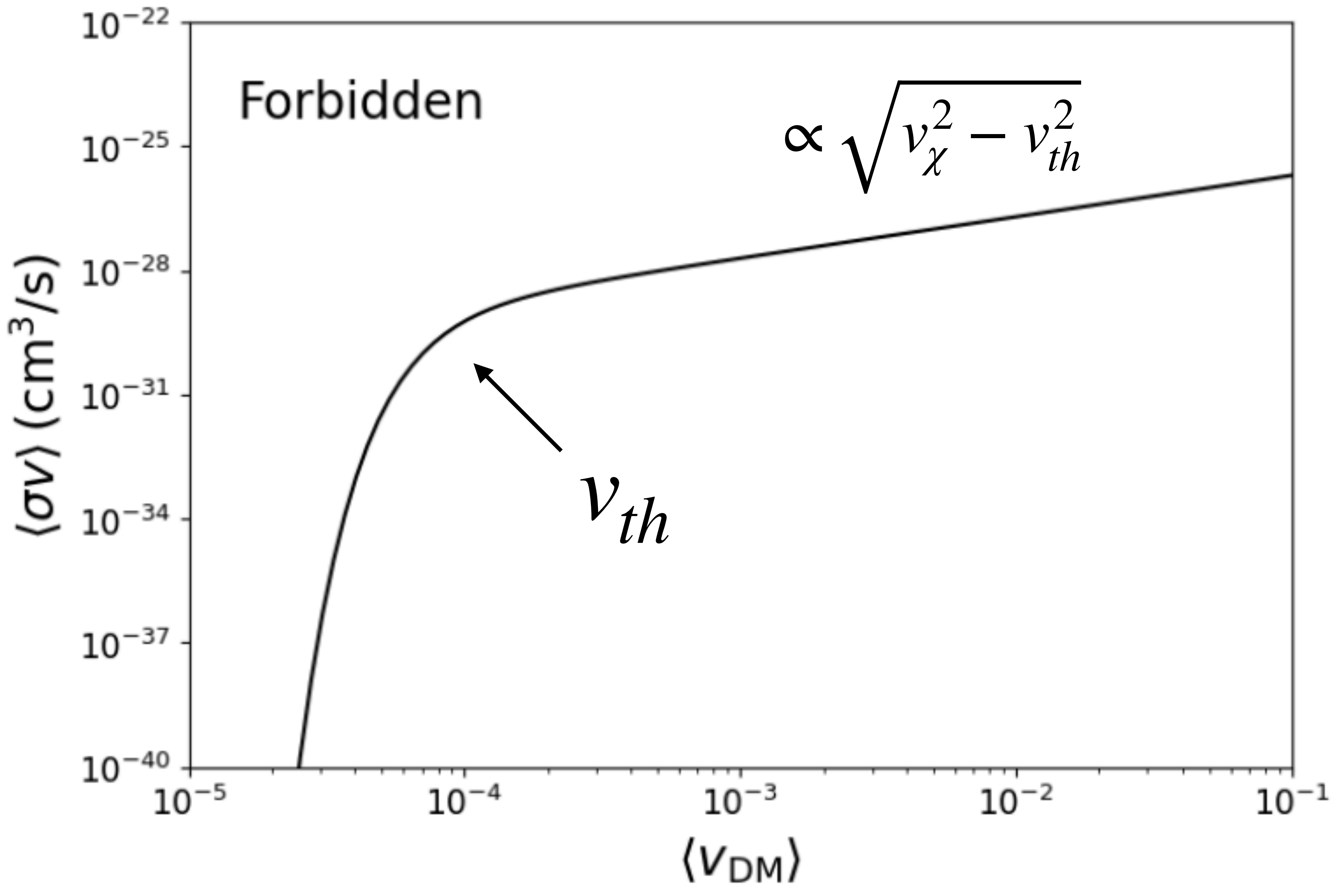
We write the code scanning the parameter space for each model and find regions surviving from all mentioned constraints and conditions.

Ex. Forbidden DM

- As an example, we consider SS model, whose Lagrangian is following.
- MED mixes with Higgs and behaves as a light Higgs boson. ∃interactions among DM, MED, Higgs.
- We parametrize $m_{\rm DM} \lesssim m_{\rm MED} \equiv m_{\rm DM}(1 + v_{th}^2/8)$. DM with $v_{\rm DM}$>(<) v_{th} can(cannot) annihilates into a pair of MED. MED subsequently decays into SM particles.

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \mu_{SH} S|H|^2 - \frac{\lambda_{SH}}{2} S^2 |H|^2 - \mu_1^3 S + \frac{\mu_S^2}{2} S^2 - \frac{\mu_3}{3!} S^3 - \frac{\lambda_S}{4!} S^4$$
$$+ \frac{1}{2}(\partial_\mu \phi)^2 - \frac{\mu_\phi^2}{2}\phi^2 - \frac{\mu_{S\chi}}{2} S\phi^2 - \frac{\lambda_{\Phi S}}{4} S^2\phi^2 - \frac{\lambda_{H\phi}}{2}|H|^2\phi^2 - \frac{\lambda_\phi}{4!}\phi^4$$

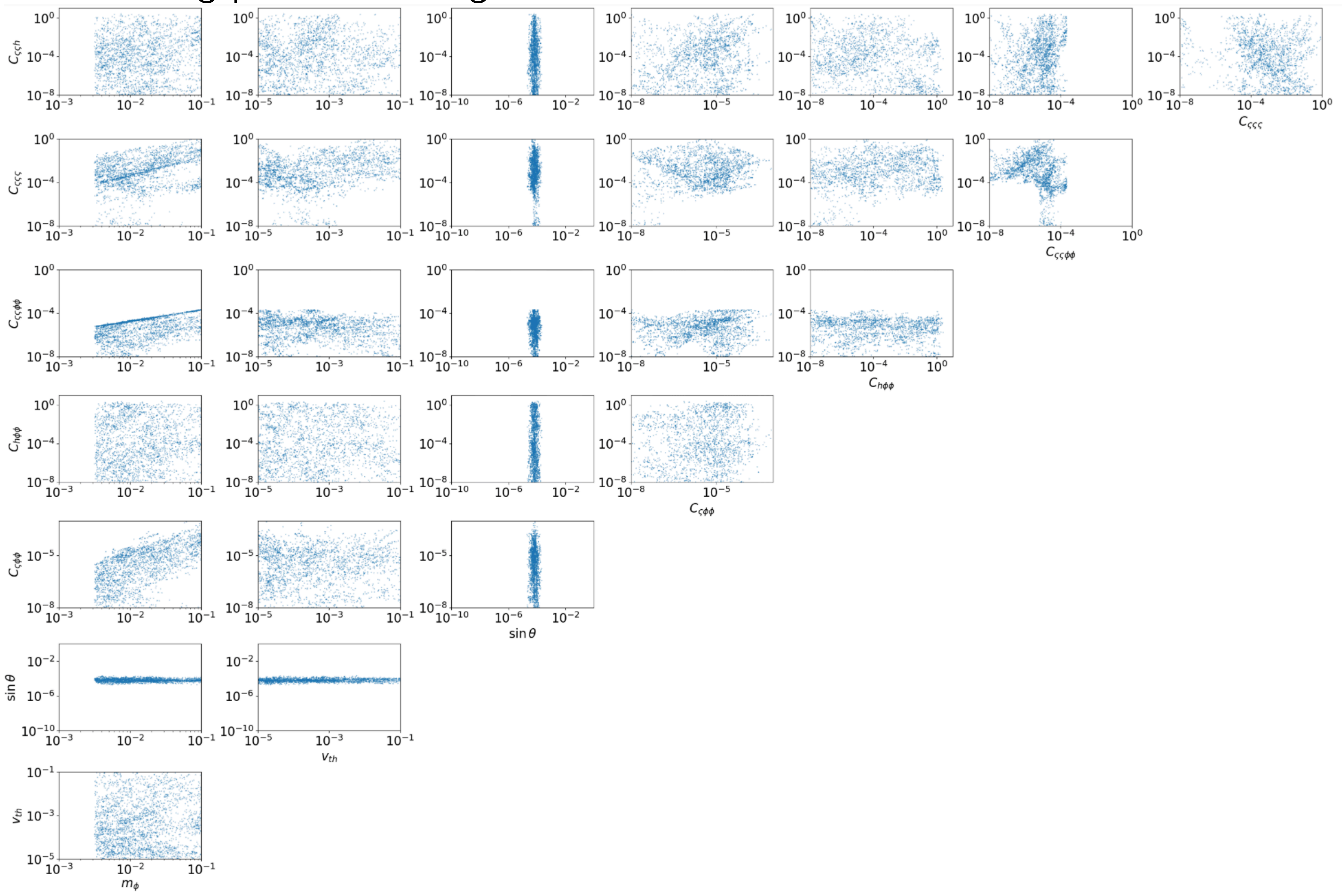




We find out viable parameter region and compare its prediction of the MeV γ-ray signal to the COSI sensitivities.

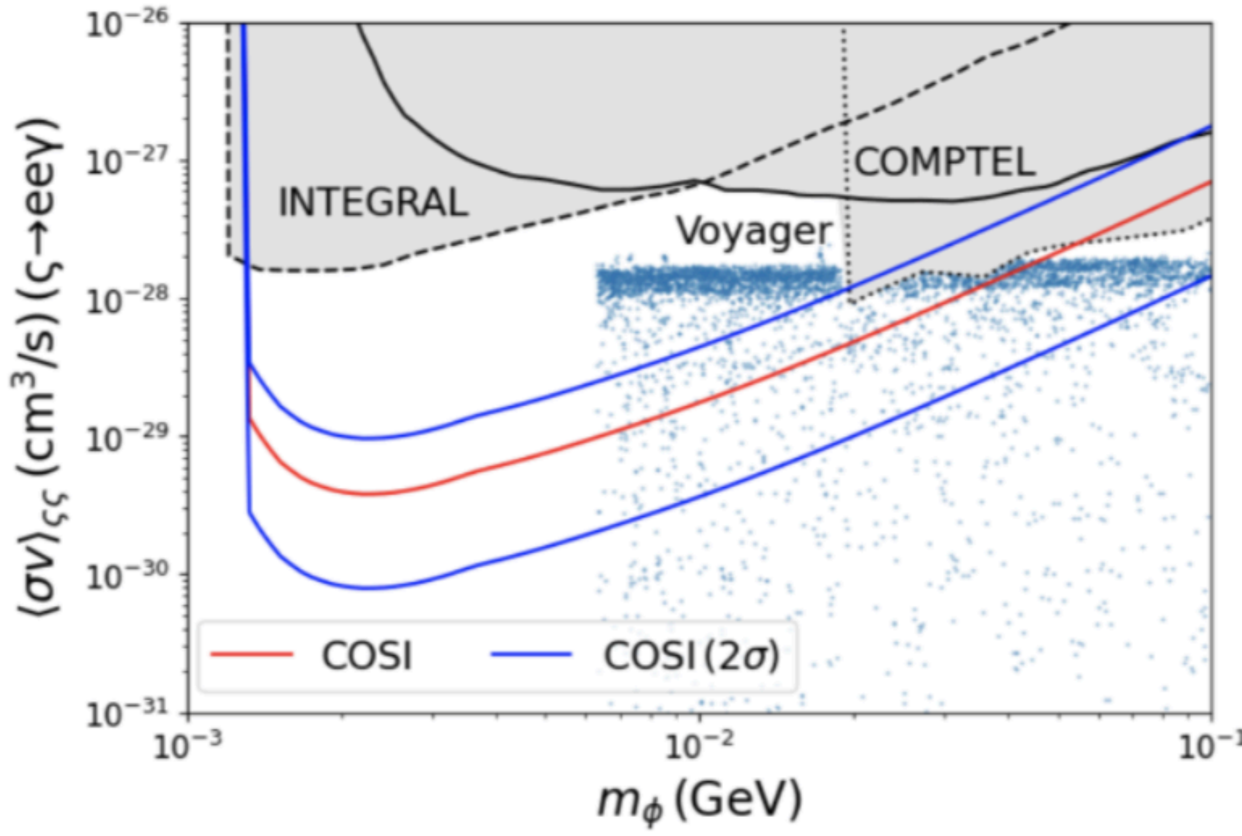
Scan of favored parameter sets

Surviving parameter region in SS-Forbidden model

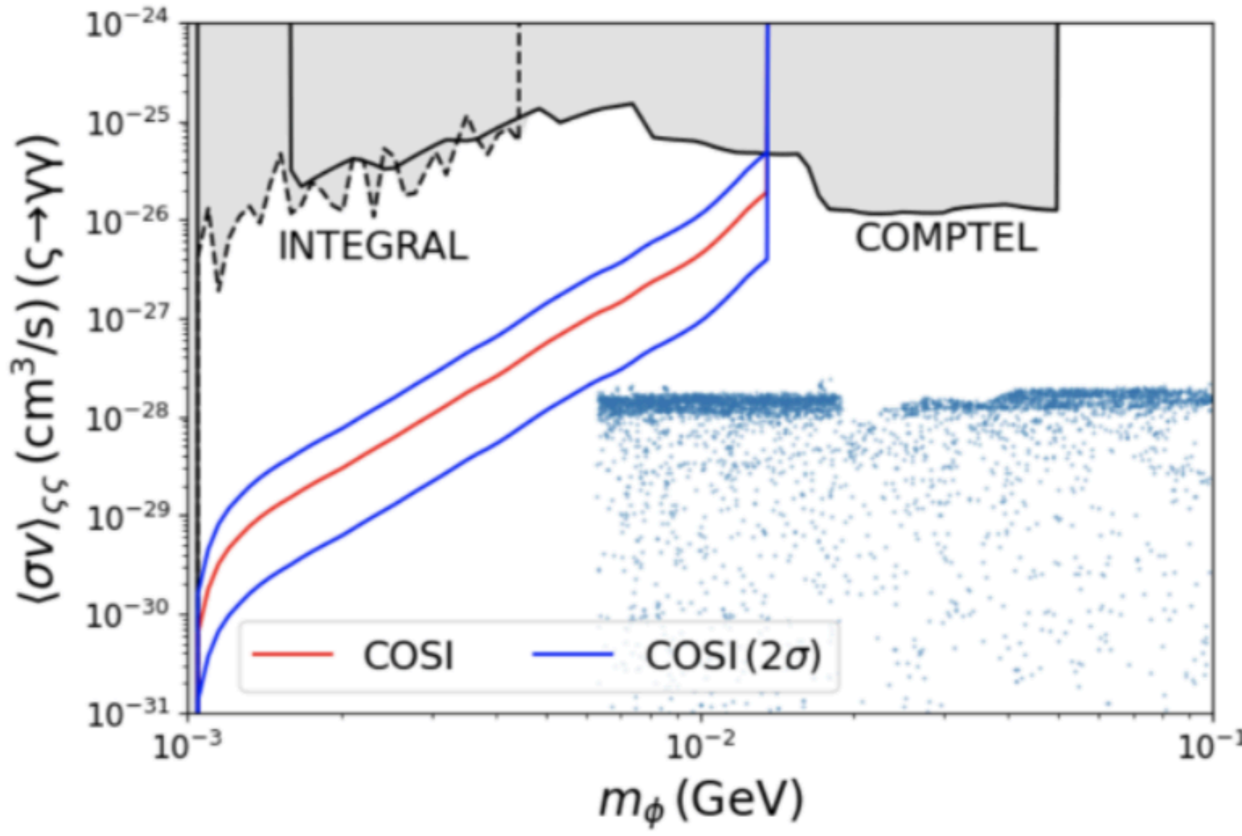


Prediction of SS-F model

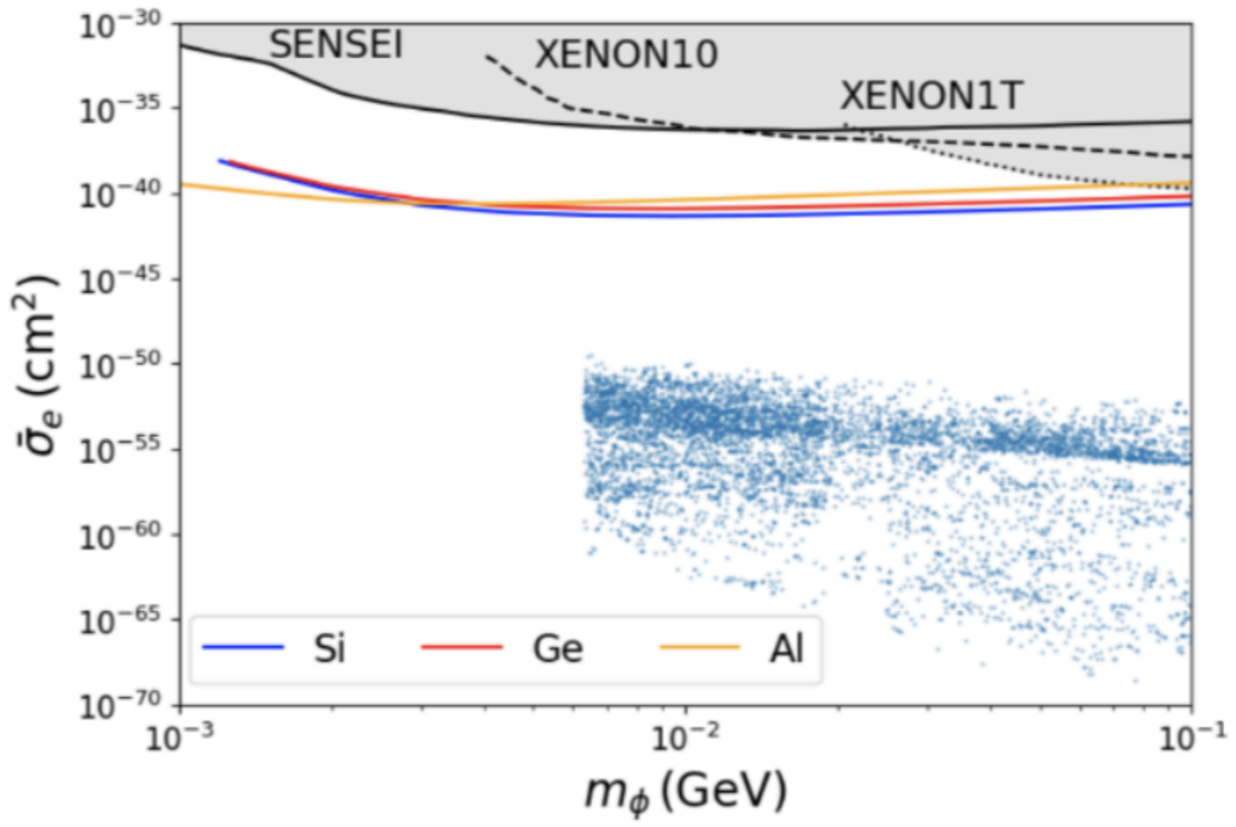
- Indirect detection (continuum)



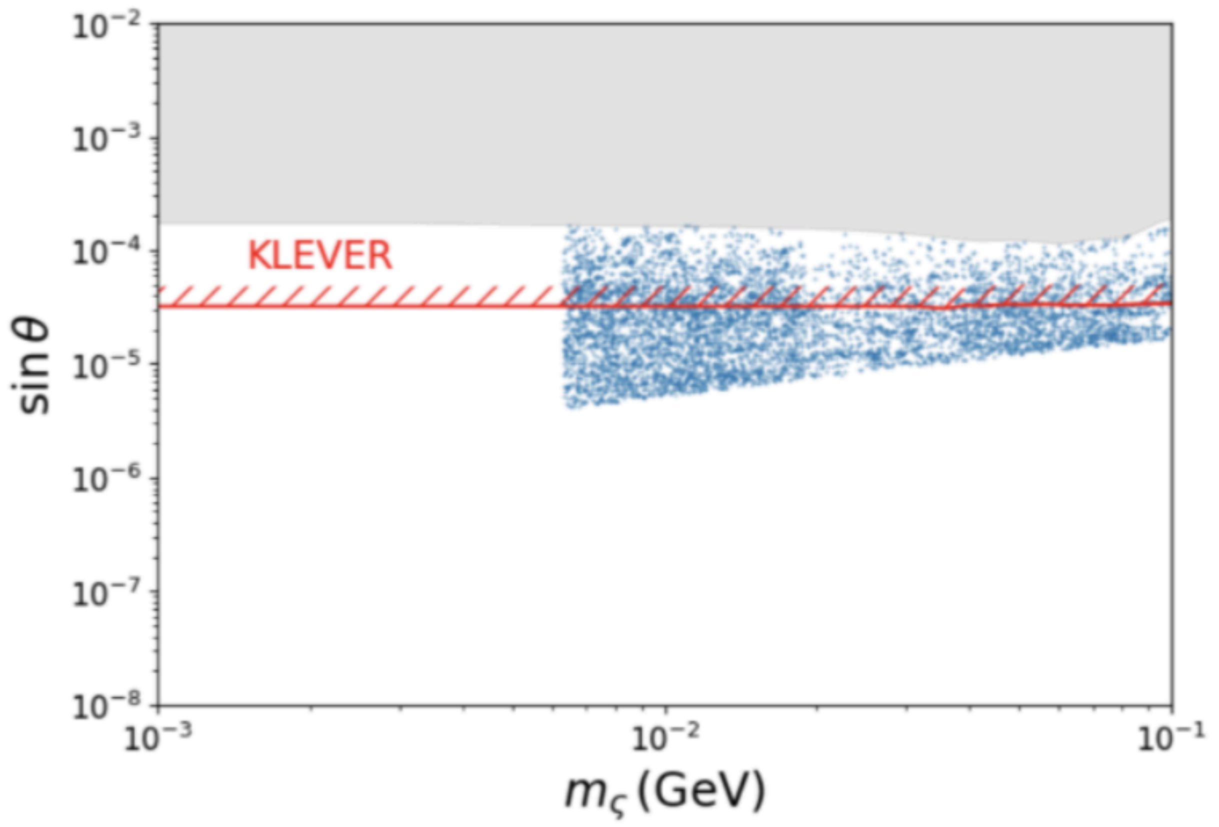
- Indirect detection (line)



- Direct detection



- Accelerator



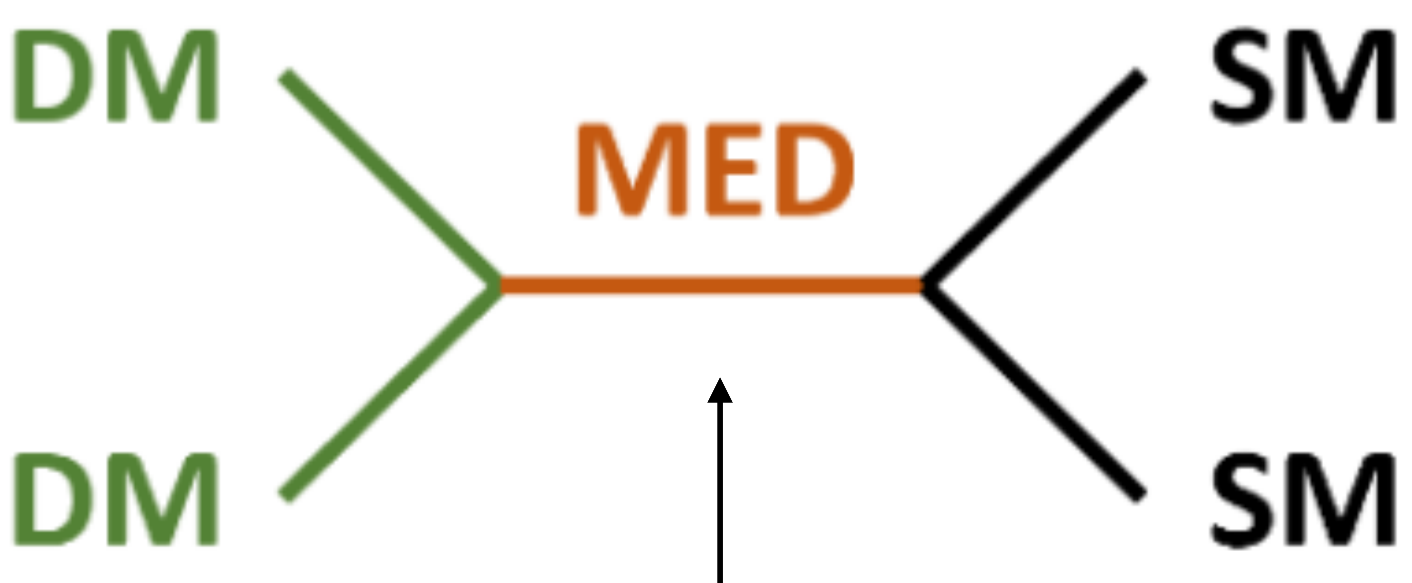
- COSI is expected to detect continuum γ-ray.
- COSI may probe line γ-ray with a more cuspy DM density profile.
- Direct detection is not effective due to the tiny y_e.
- Future accelerator KLEVER can detect some parameters.

S-channel (visible)~ p-wave+resonance

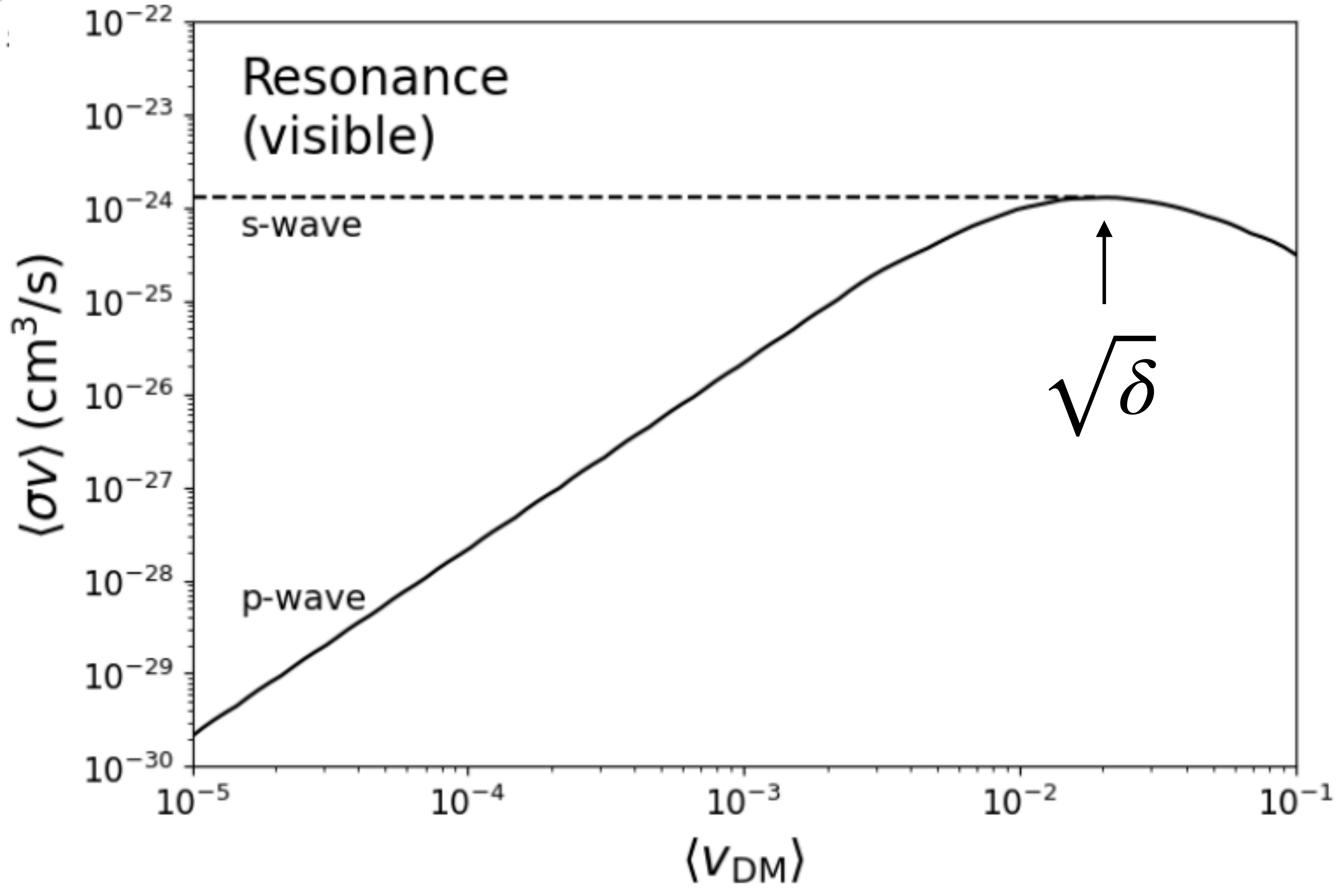
- As an example, we consider SV(DP) model, whose Lagrangian are following.
- MED mixes with Z boson. DM annihilates into ee via MED in s-channel.
- We parametrize $2m_{\rm DM} \gtrsim m_{\rm MED} \equiv 2m_{\rm DM}(1-\delta/8)$. As $v_{\rm DM}$ decrease, $\langle\sigma v\rangle$ enhances approaching the resonance, with cutoff, $\sqrt{\delta}$.

$$\mathscr{L} \ni \mathscr{L}_{\rm SM} + |(\partial_\mu + i g_V q_\varphi V_\mu)\varphi|^2 - m_\varphi^2|\varphi|^2 - g_V \sum_f q_f \bar{f} V_\mu \gamma^\mu f$$

$$-\frac{1}{4}(V_{\mu\nu})^2 + \frac{1}{2}M_V^2(V_\mu)^2 - \frac{\xi}{2}V_{\mu\nu}B^{\mu\nu}$$



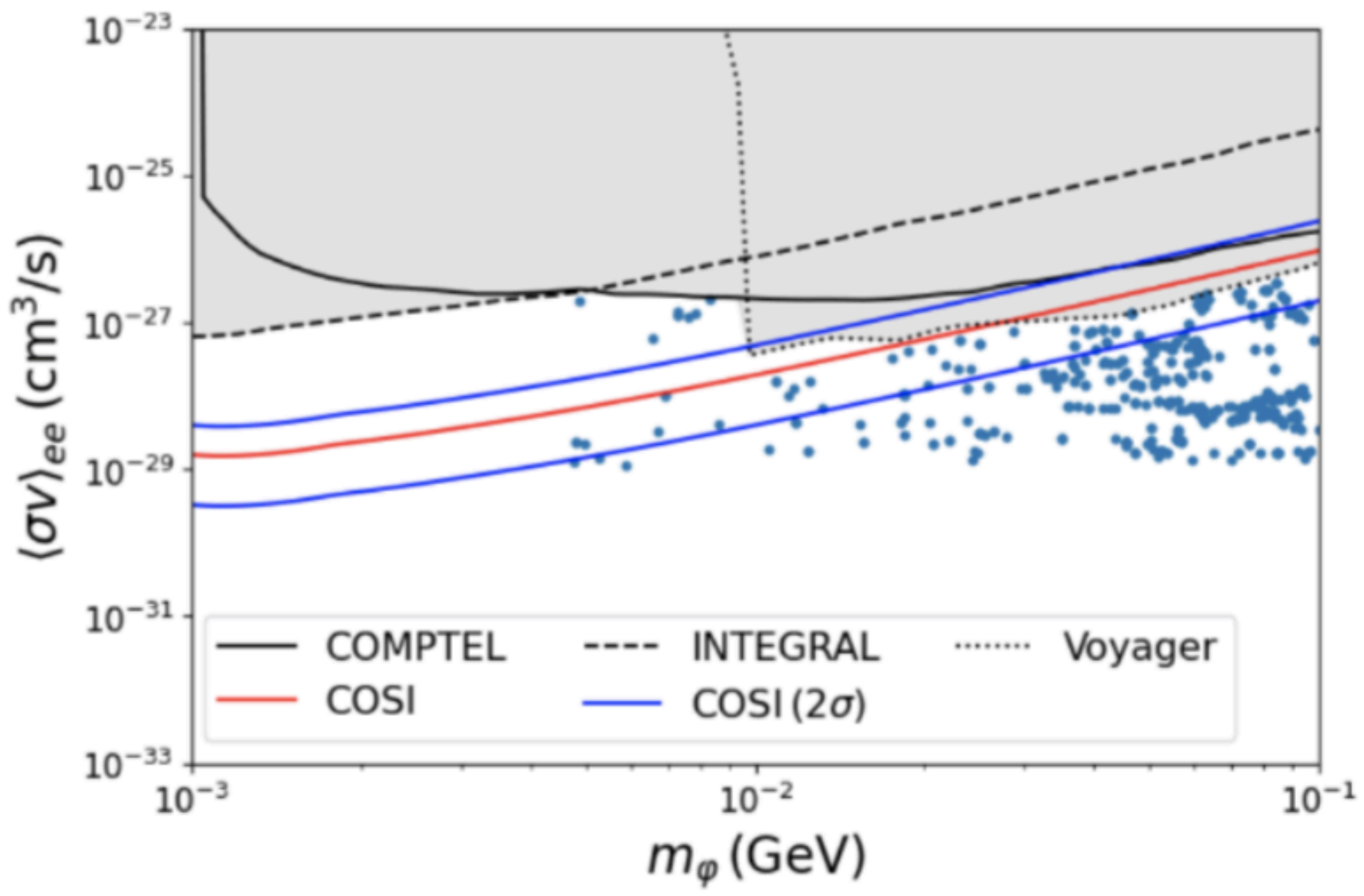
$$\frac{1}{(s-m_{\rm MED}^2)^2 + s\Gamma_{\rm MED}^2(s)} \simeq \frac{1}{m_{\rm DM}^4}\frac{1}{(v^2+\delta)^2 + 16(\Gamma_{\rm MED}(s)/m_{\rm MED})^2}$$



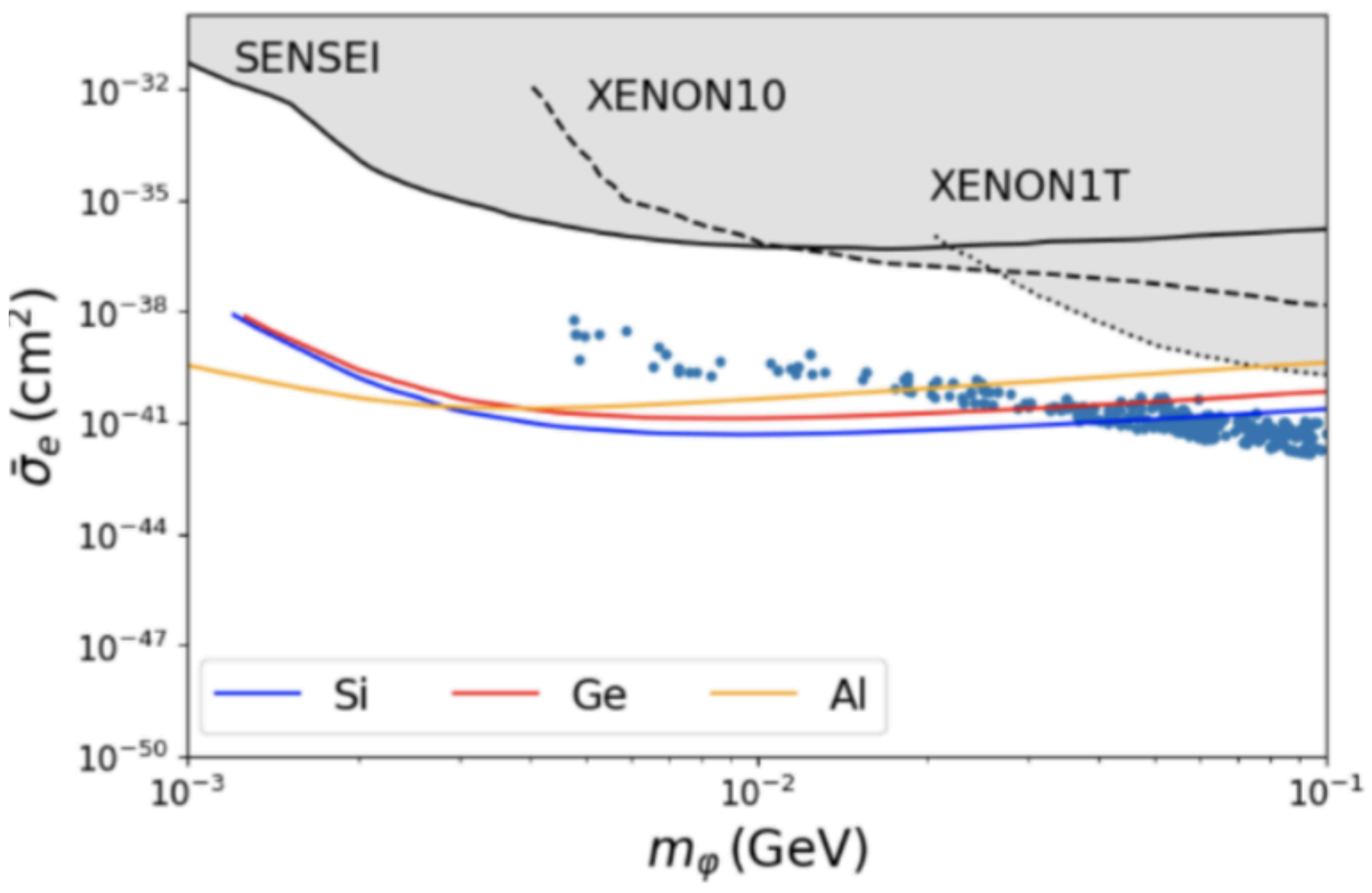
We find out viable parameter region and compare its prediction of the MeV γ-ray signal to the COSI sensitivities.

Prediction of SV(DP)-R(vis) model

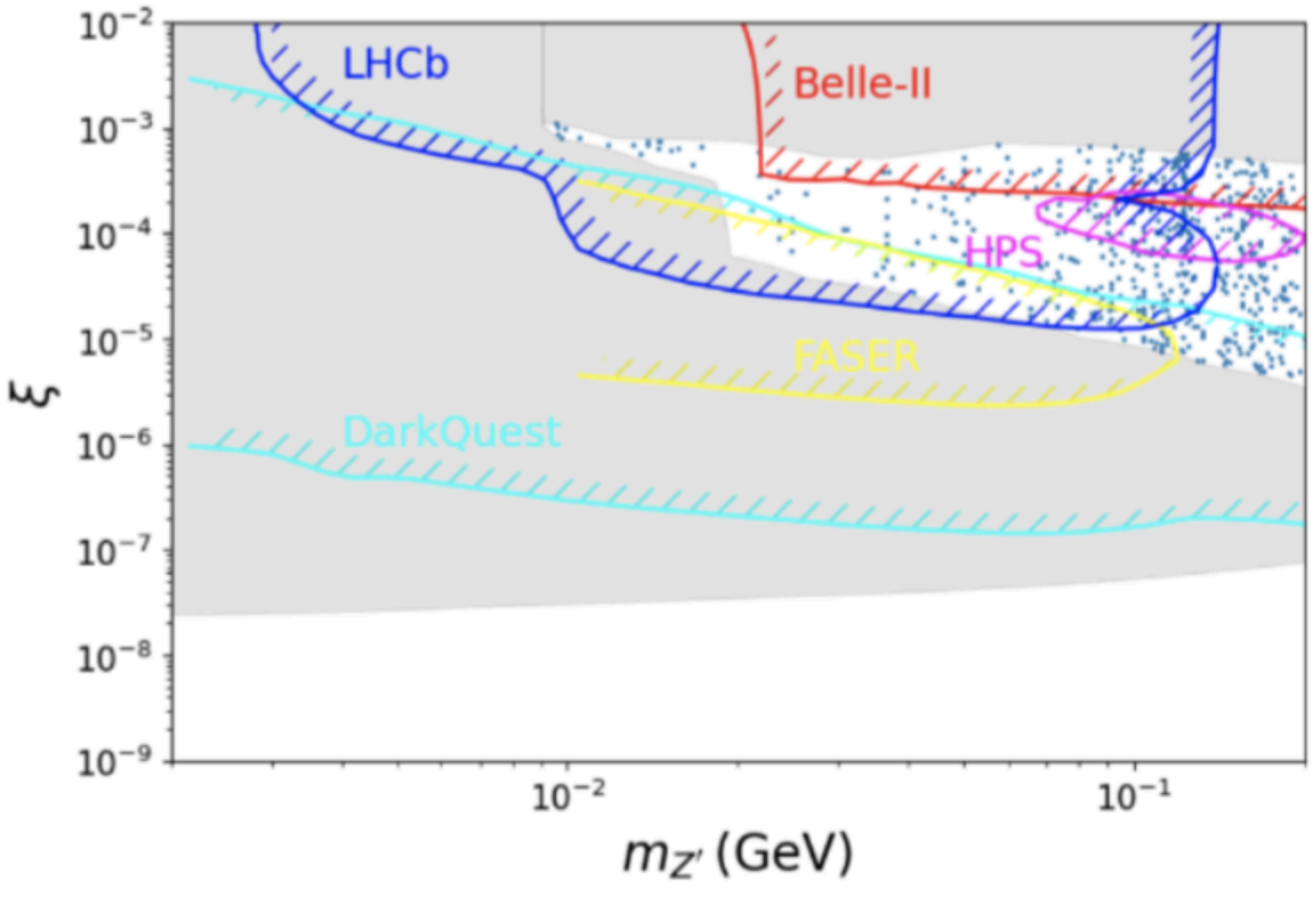
- Indirect detection (continuum)



- Direct detection



- Accelerator



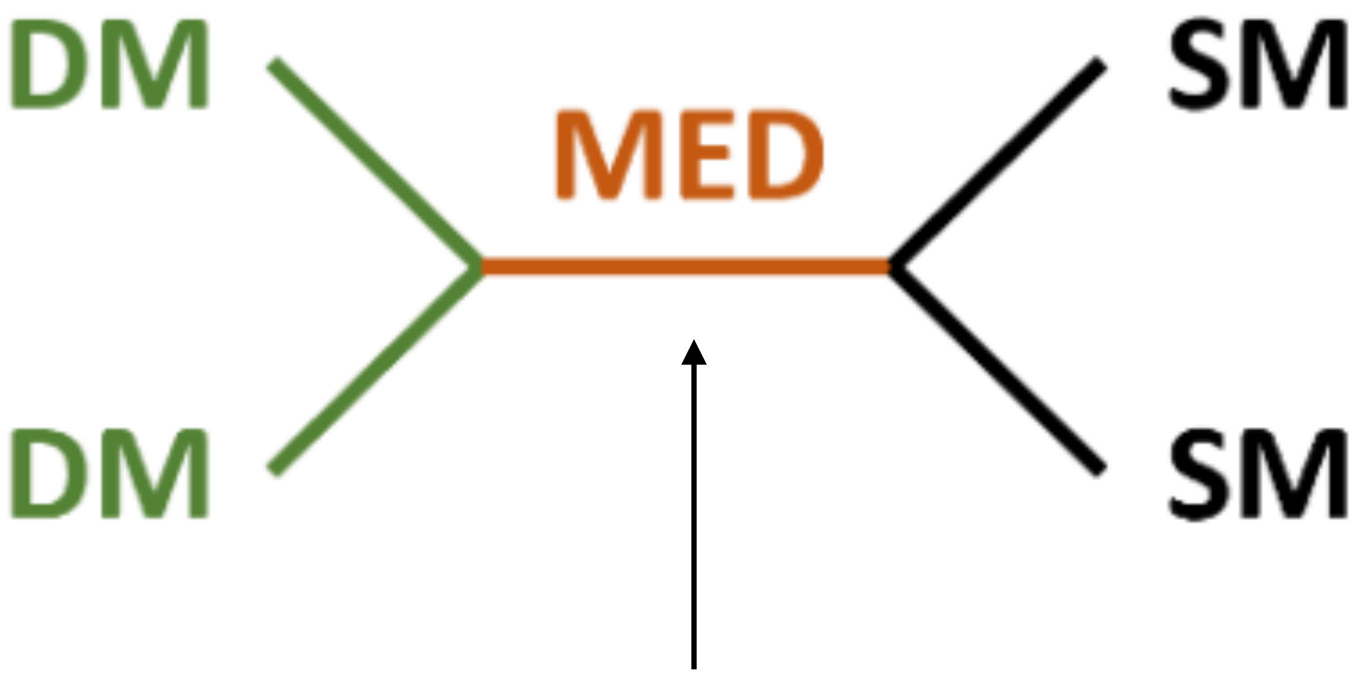
- COSI is expected to detect continuum γ-ray.
- No $\gamma\gamma$ $\because$ vector mediator
- Future direct detections have the potential to detect some points.
- Future accelerator can detect almost all of the parameters.

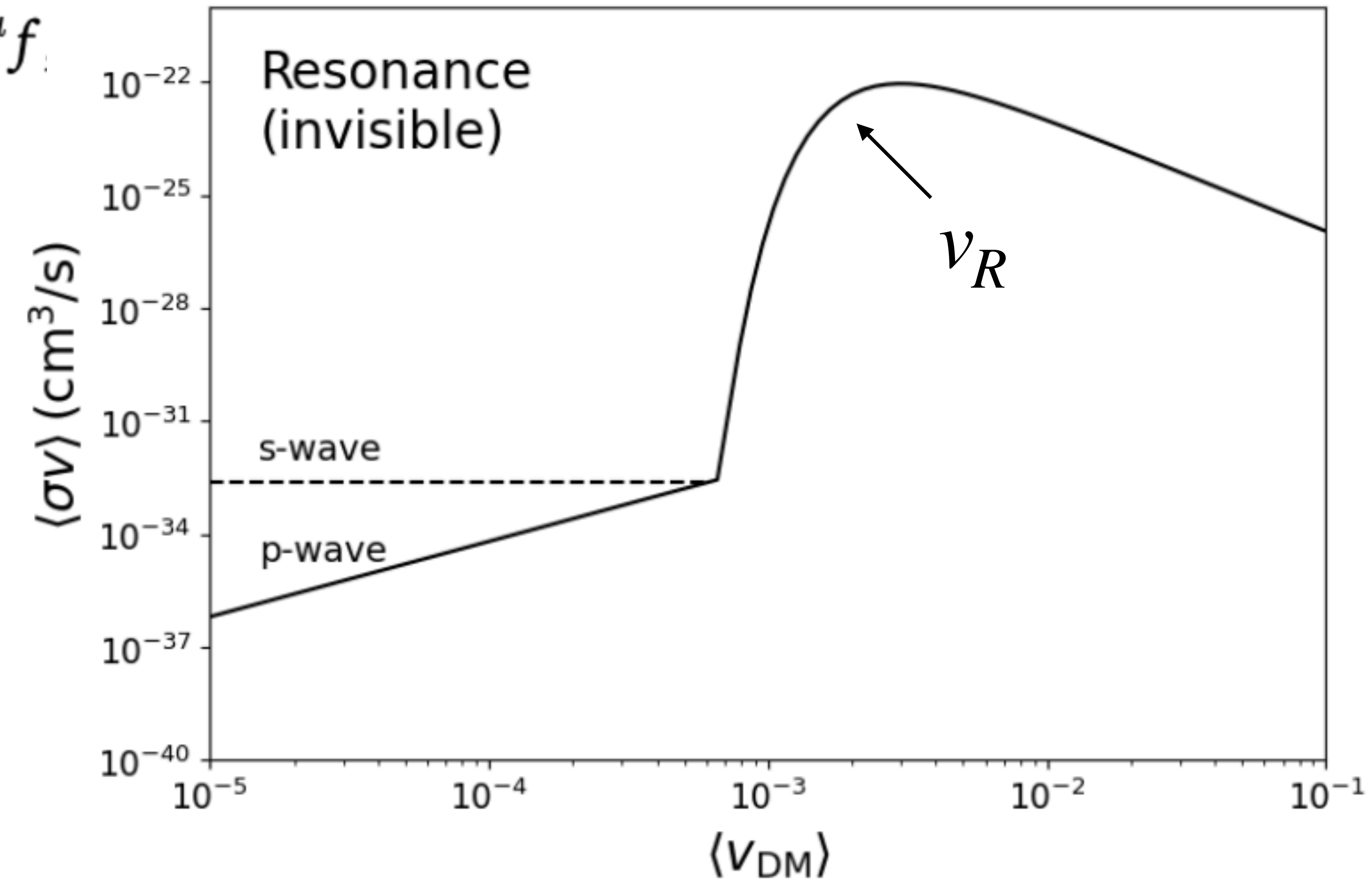
S-channel (invisible)

- As an example, we consider SV(DP) model, whose Lagrangian are following.
- MED mixes with Z boson. DM annihilates into ee via MED in s-channel.
- We parametrize $2m_{\rm DM} \lesssim m_{\rm MED} \equiv 2m_{\rm DM}(1+v_R^2/8)$. At $v_{\rm DM} = v_{th}$, the annihilation the resonance.

$$\mathscr{L} \ni \mathscr{L}_{\rm SM} + |(\partial_\mu + i g_V q_\varphi V_\mu)\varphi|^2 - m_\varphi^2 |\varphi|^2 - g_V \sum_f q_f \bar{f} V_\mu \gamma^\mu f$$

$$-\frac{1}{4}(V_{\mu\nu})^2 + \frac{1}{2}M_V^2 (V_\mu)^2 - \frac{\xi}{2} V_{\mu\nu} B^{\mu\nu}$$



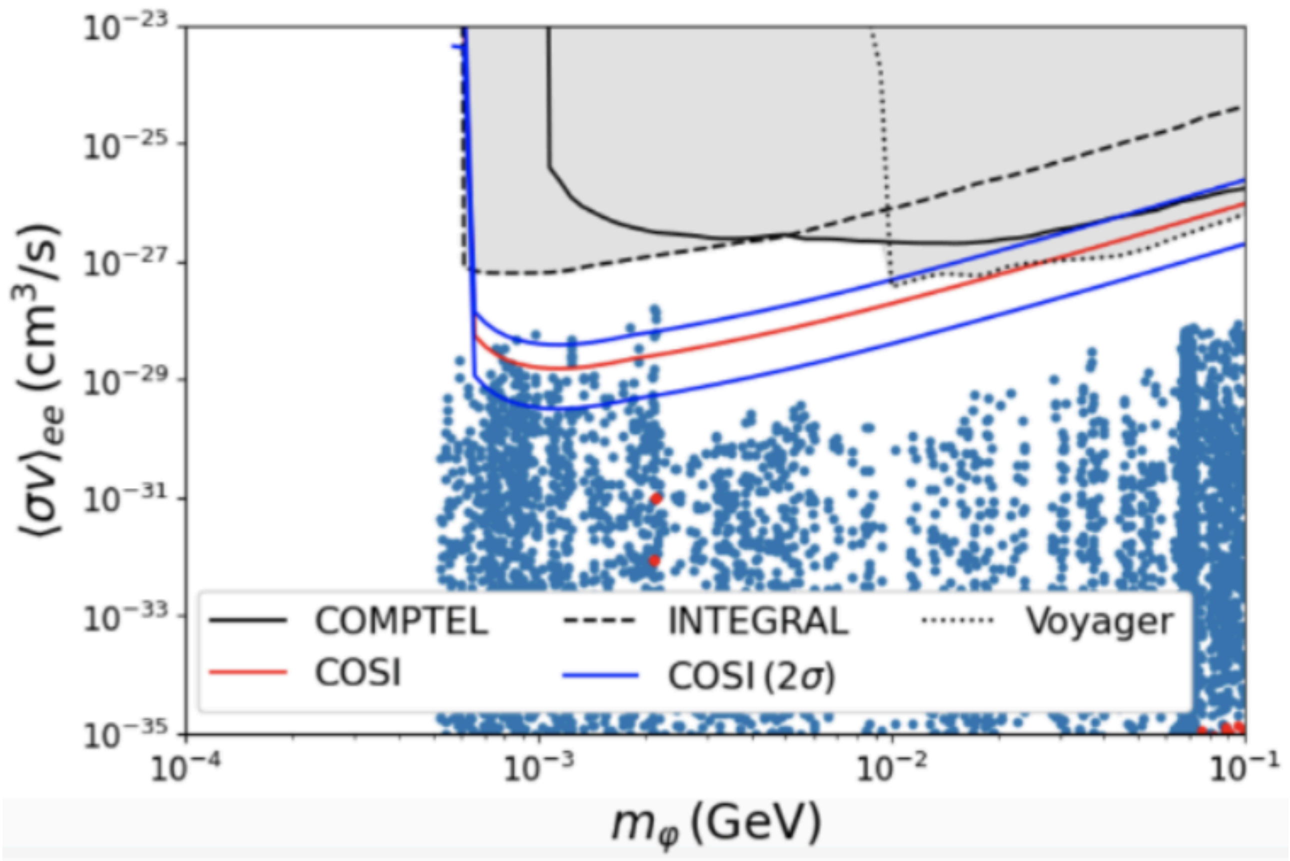


$$\frac{1}{(s - m_{\rm MED}^2)^2 + s\Gamma_{\rm MED}^2(s)} \simeq \frac{1}{m_{\rm DM}^4} \frac{1}{(v^2 - v_R^2)^2 + 16(\Gamma_{\rm MED}(s)/m_{\rm MED})^2}$$

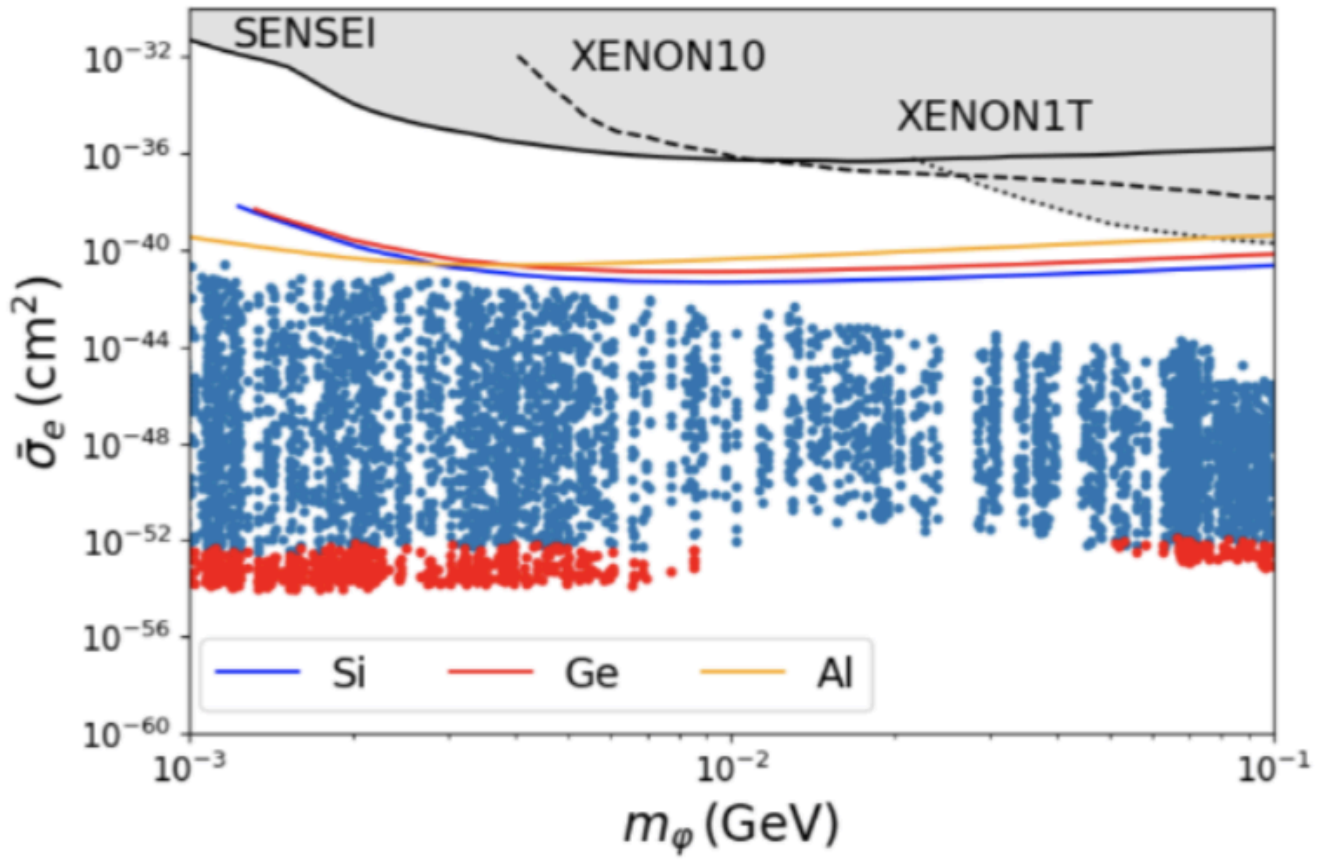
We find out viable parameter region and compare its prediction of the MeV γ-ray signal to the COSI sensitivities.

Prediction of SV(DP)-R(inv) model

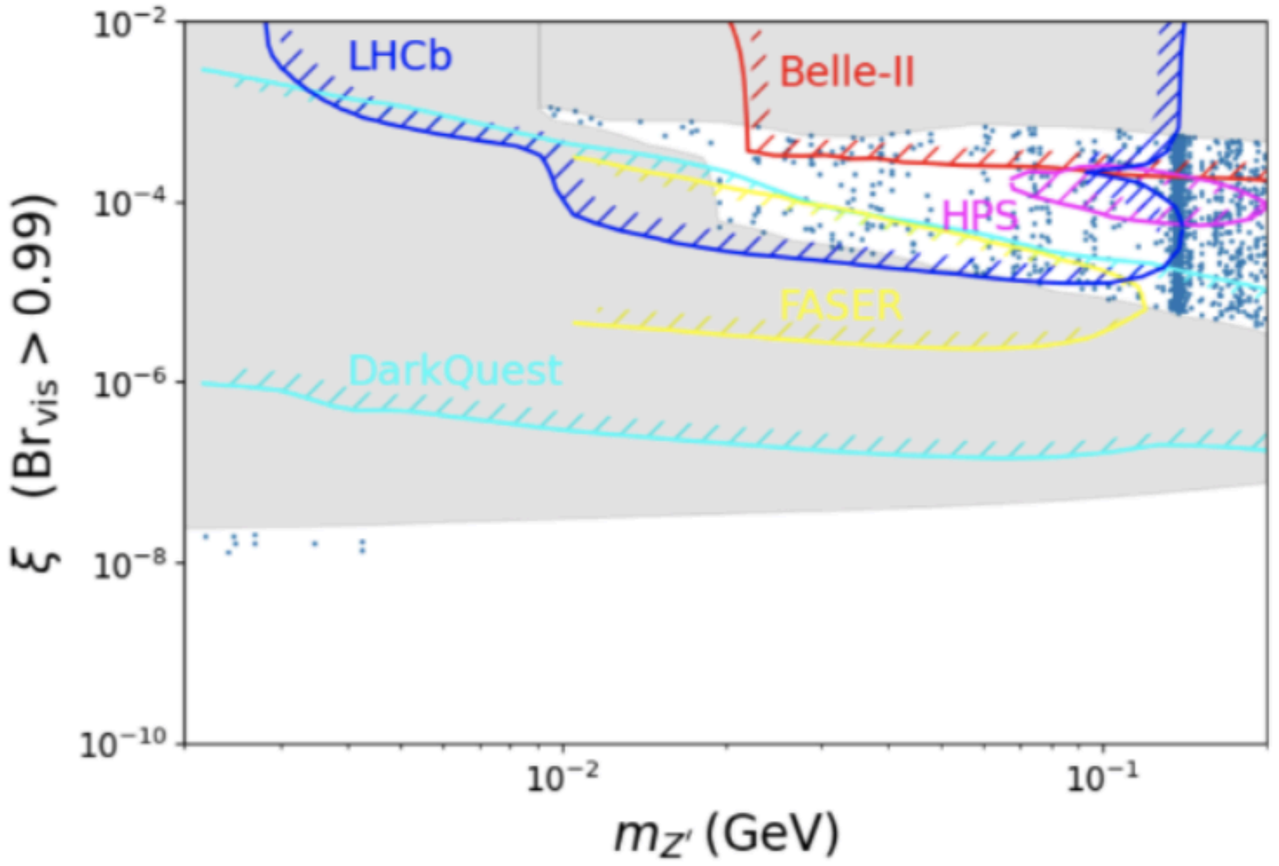
- Indirect detection (continuum)



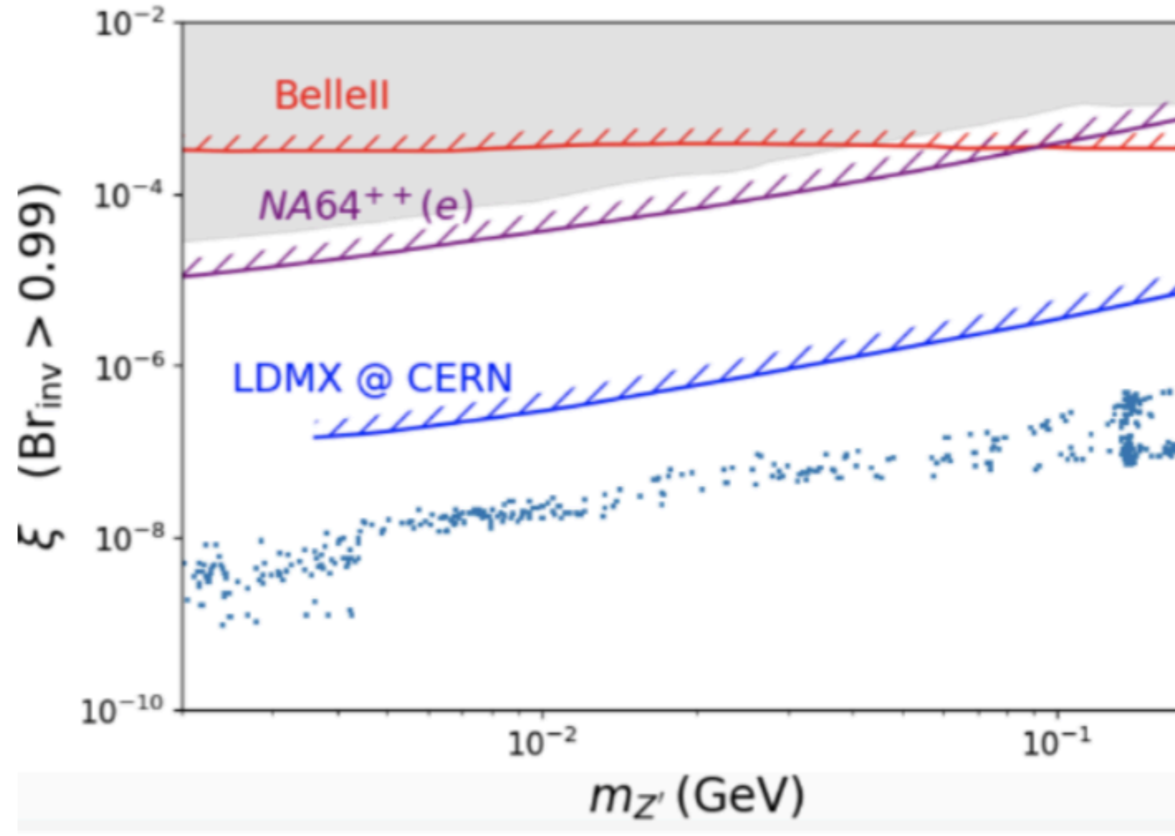
- Direct detection



- Accelerator(visible)



- Accelerator(invisible)

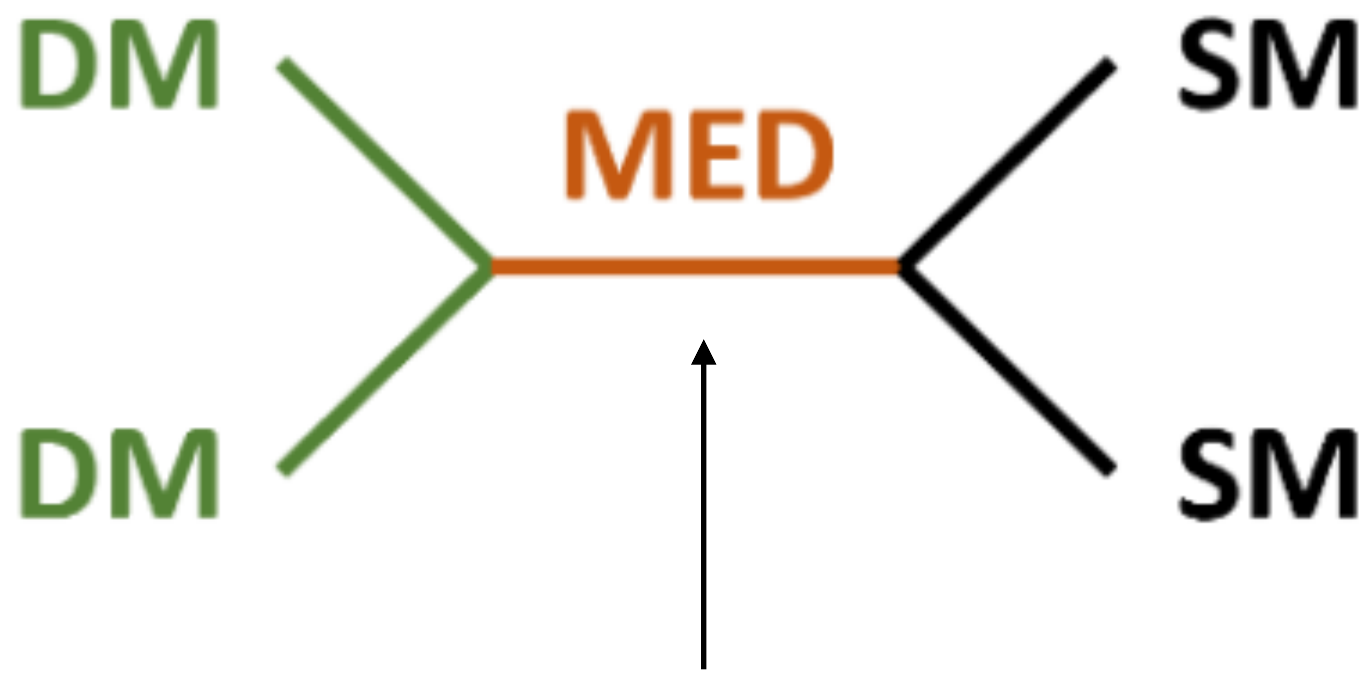


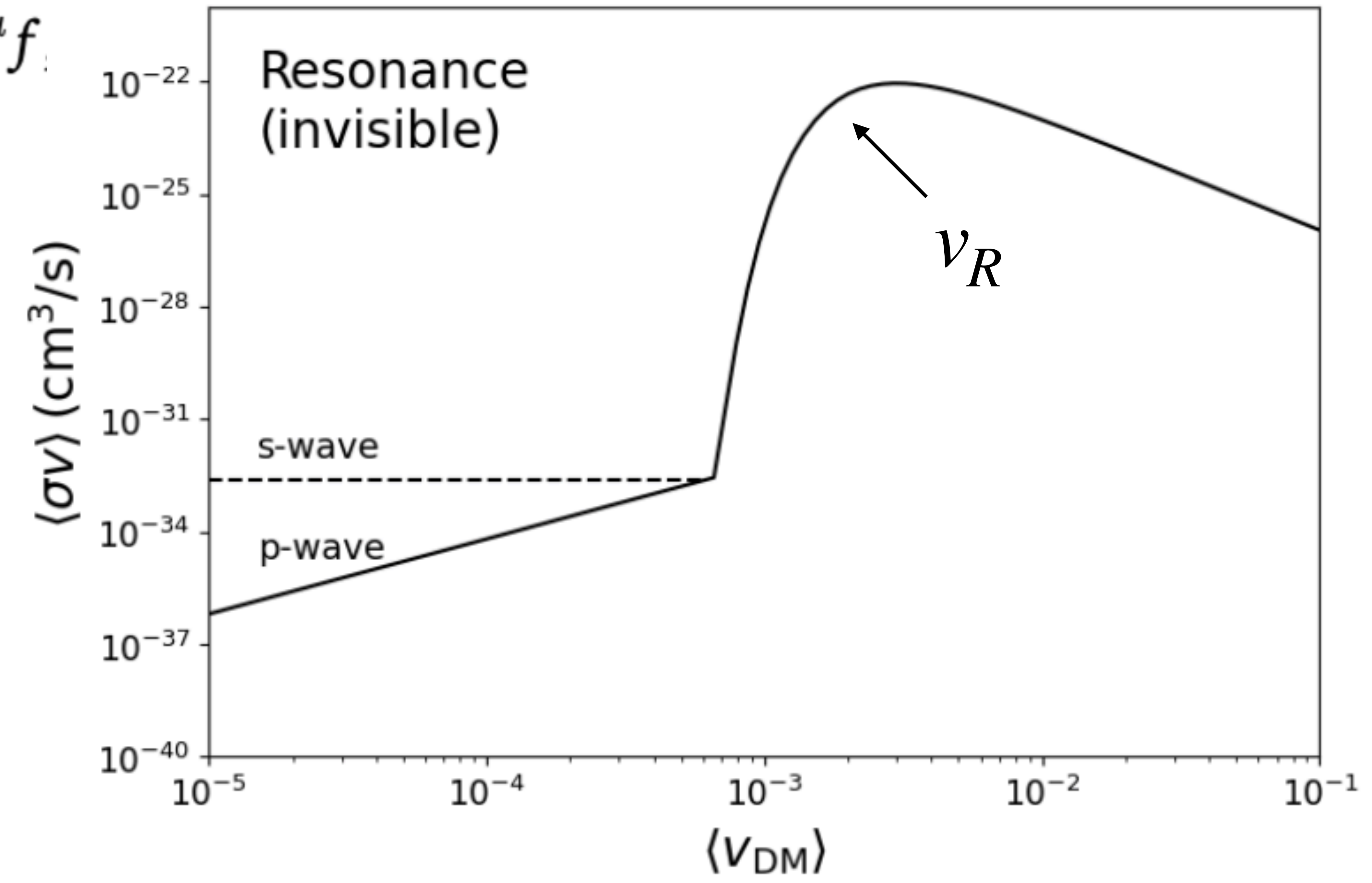
- COSI is expected to detect continuum γ-ray.
- Direct detection is not effective due to the suppression of t,u-channel diagrams.
- Future accelerator can detect visible mediator.
- Future accelerator cannot detect invisible mediator.

S-channel(invisible)

- We consider $\mathrm{SV(U(1)_B)}$ model, which is similar to the SV(DP) model.
- Charge asignments are $q_l = 0$, $q_q = 1/3$.
- Strong line signal is expected by the $\pi^0\gamma$ annihilation mode.

$$\mathscr{L} \ni \mathscr{L}_{\mathrm{SM}} + |(\partial_\mu + i g_V q_\varphi V_\mu)\varphi|^2 - m_\varphi^2|\varphi|^2 - g_V \sum_f q_f \bar{f} V_\mu \gamma^\mu f$$
$$- \frac{1}{4}(V_{\mu\nu})^2 + \frac{1}{2}M_V^2 (V_\mu)^2 - \frac{\xi}{2} V_{\mu\nu} B^{\mu\nu}$$



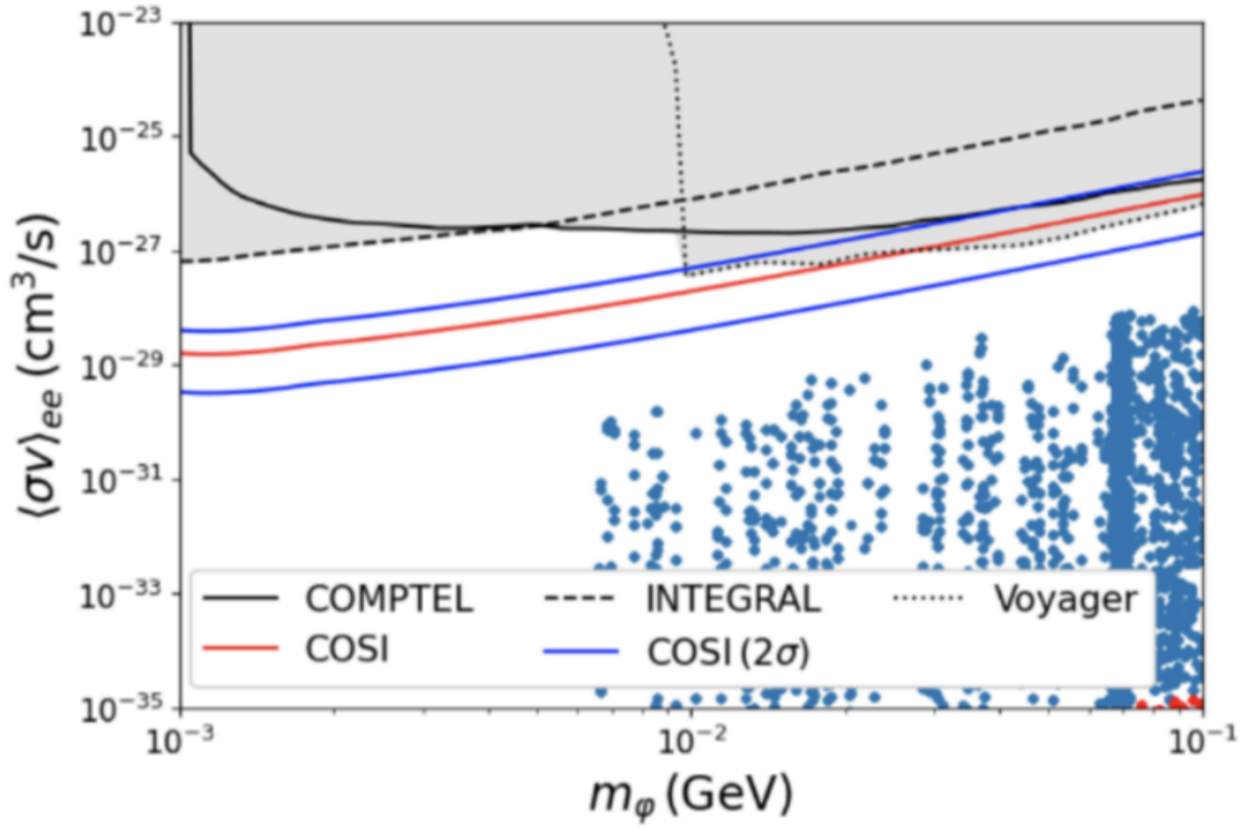


$$\frac{1}{(s - m_{\mathrm{MED}}^2)^2 + s\Gamma_{\mathrm{MED}}^2(s)} \simeq \frac{1}{m_{\mathrm{DM}}^4}\frac{1}{(v^2 - v_R^2)^2 + 16(\Gamma_{\mathrm{MED}}(s)/m_{\mathrm{MED}})^2}$$

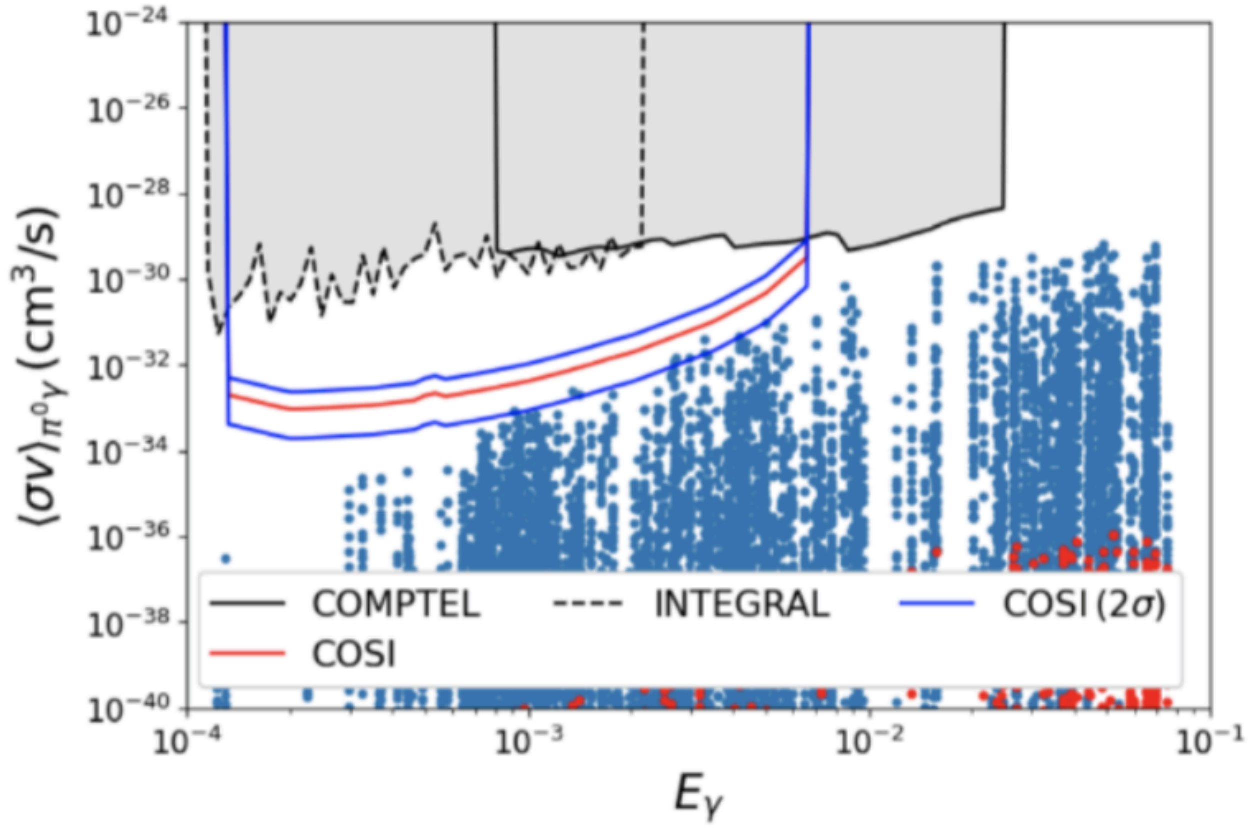
We find out viable parameter region and compare its prediction of the MeV γ-ray signal to the COSI sensitivities.

Prediction of SV($\mathrm{U}(1)_\mathrm{B}$)-R(inv) model

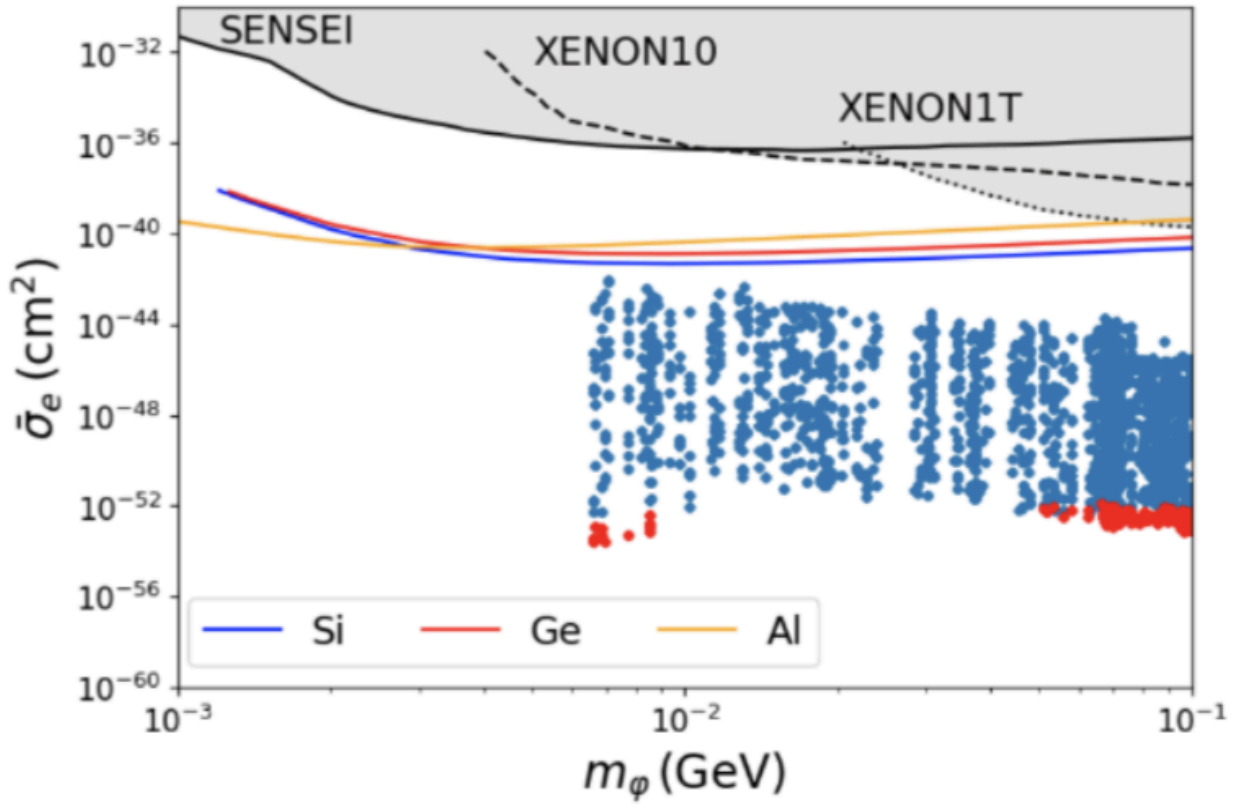
- Indirect detection (continuum)



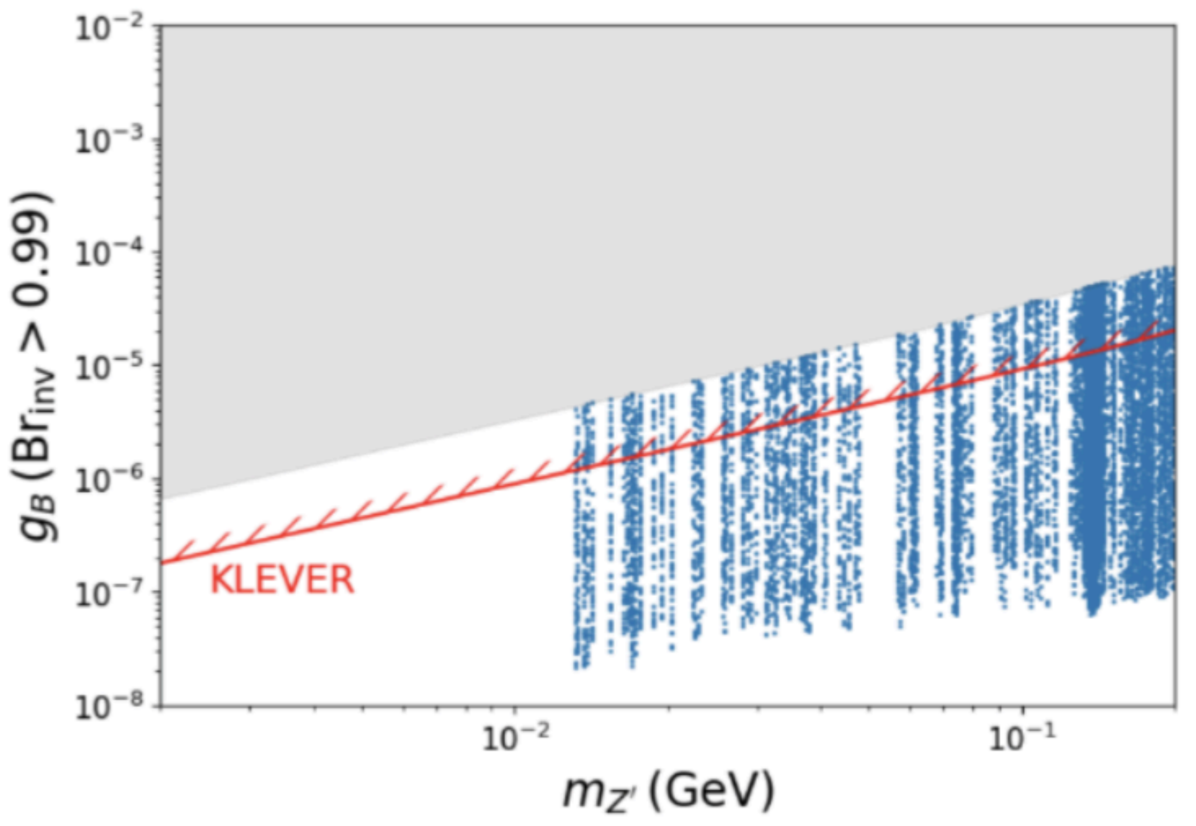
- Indirect detection (line)



- Direct detection



- Accelerator



- COSI cannot efficiently detect continuum γ-ray.
- COSI is expected to detect also line γ-ray in $\pi^0\gamma$ modes.
- Direct detection is not effective due to the suppression of t,u-channel diagrams.
- Future accelerator KLEVER can detect some points.

Summary

- **Light Thermal DM** is getting more and more attention. Many experiments are being planed to search for them, and **COSI** is the only approved indirect detection experiments.
- We for the first time consider all possible light thermal DM models. ∃Many constraints different from WIMP case, and only regions with velocity dependent $\langle\sigma v\rangle$ (Bulk, forbidden and resonance) are viable.
- We for the first time calculated the sensitivities and detectability of these regions.

	SS	FS	SV(DP)	FV(DP)	SV(B)	FV(B)
Bulk	—	○	○	—	—	—
Forbidden	○ (red)	○ (red)	○ (blue)	○	—	—
Resonance(vis)	—	—	○ (blue)	—	—	—
Resonance(inv)	—	—	○ (blue)	○ (blue)	○ (red)	○ (red)

○ ∃ surviving parameters

○ (blue) COSI can detect continuum γ-ray

○ (red) COSI can detect continuum and line γ-ray