Light Thermal Dark Matter and MeV Gamma-ray Detection

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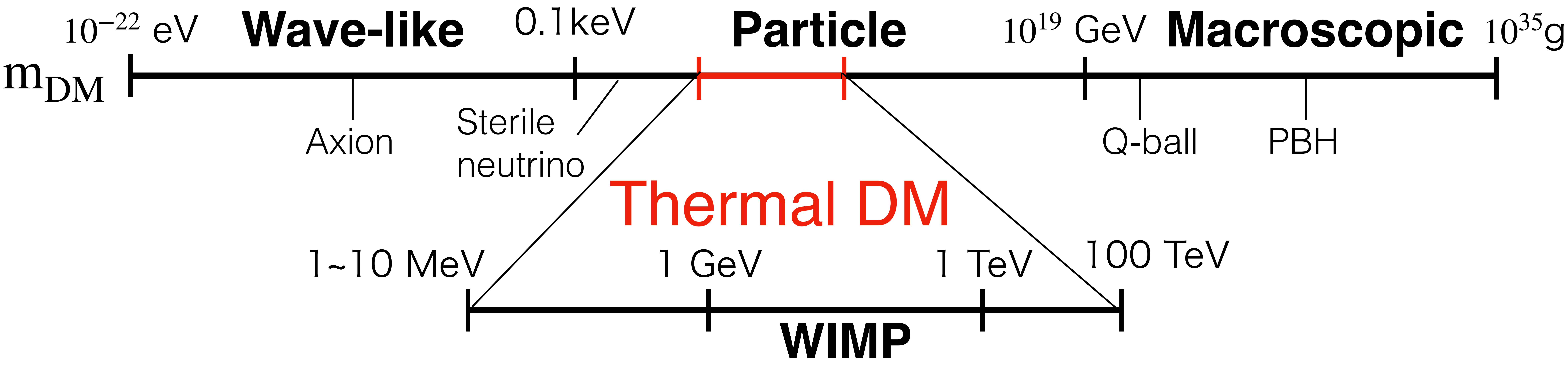
DM candidates

Mass range spans almost
90 orders of magnitudes…



- ∃Various candidates, and we focus on the thermal DM.

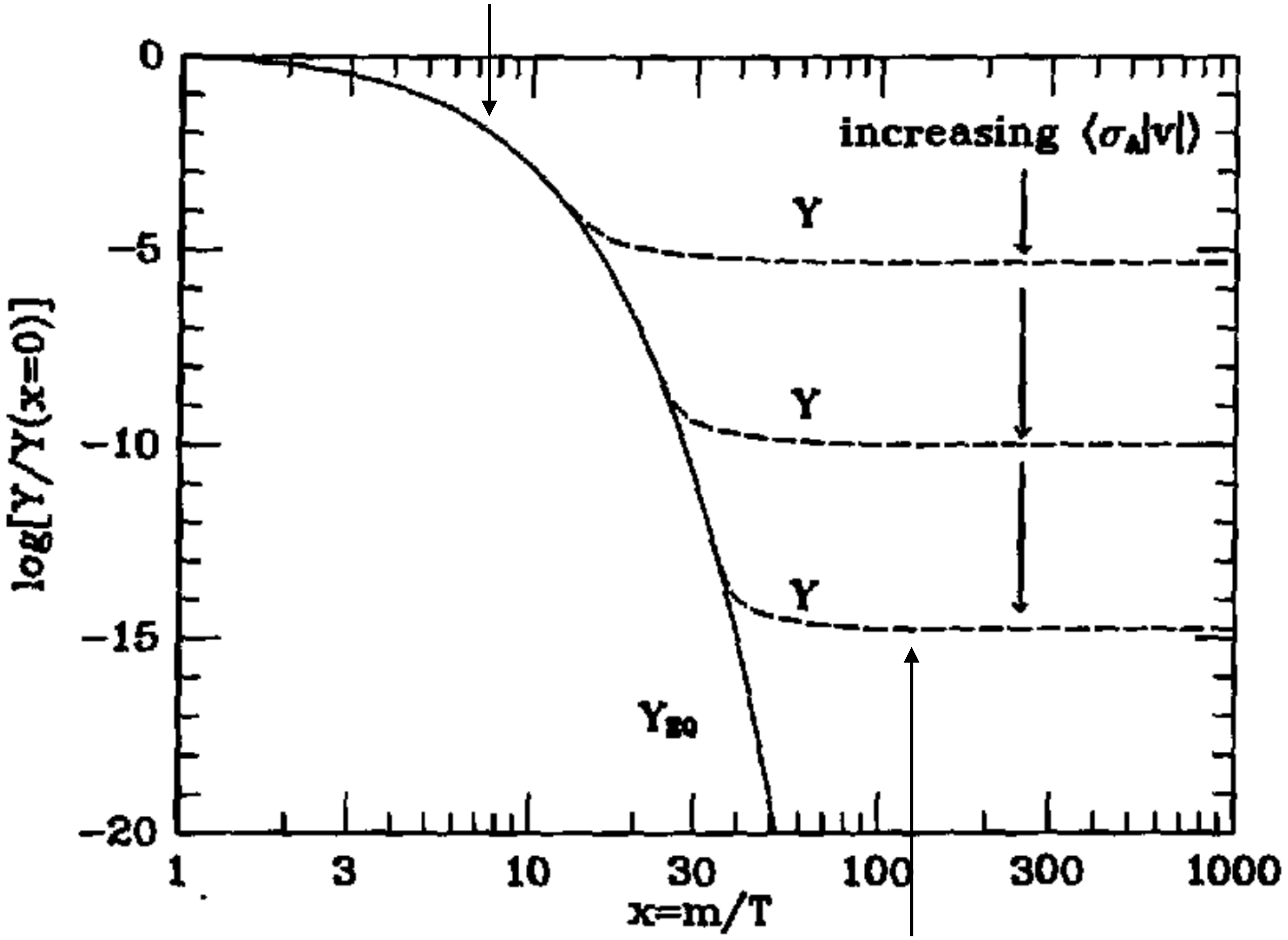
Def: The candidate that experienced equilibrium with SM particles in the early universe.

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.

Freeze-out mechanism

- DM abundance is determined by competition between $\langle \sigma v \rangle$ and H.
- Solution of Boltzmann eq. $\dot{n} + 3Hn = - <\sigma v> (n^2 - n_{eq}^2)$

DM was in equilibrium



Expansion rate of universe > interaction rate

→ abundance is fixed.

$x_f \approx 20$

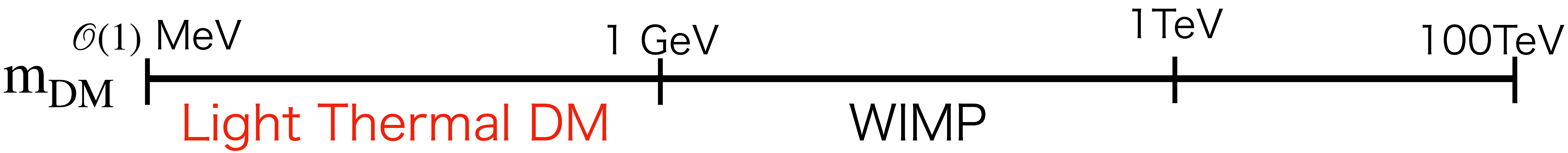
$\Omega h^2 \approx 10^{-27} \mathrm{cm}^3/\mathrm{s}/ <\sigma \mathrm{v}>$

- WIMP Miracle

  Assuming $m_{DM} = \mathcal{O}(1)$ TeV,

  $10^{-26} \mathrm{cm}^3/\mathrm{s} \approx \alpha_2^2/\mathrm{m}_{\mathrm{DM}}^2$

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 project, an approved next generation MeV γ-ray telescope, 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.

IPMU officialy comits to the project and I am involved as a member of the COSI DM science team.

Light thermal DM models

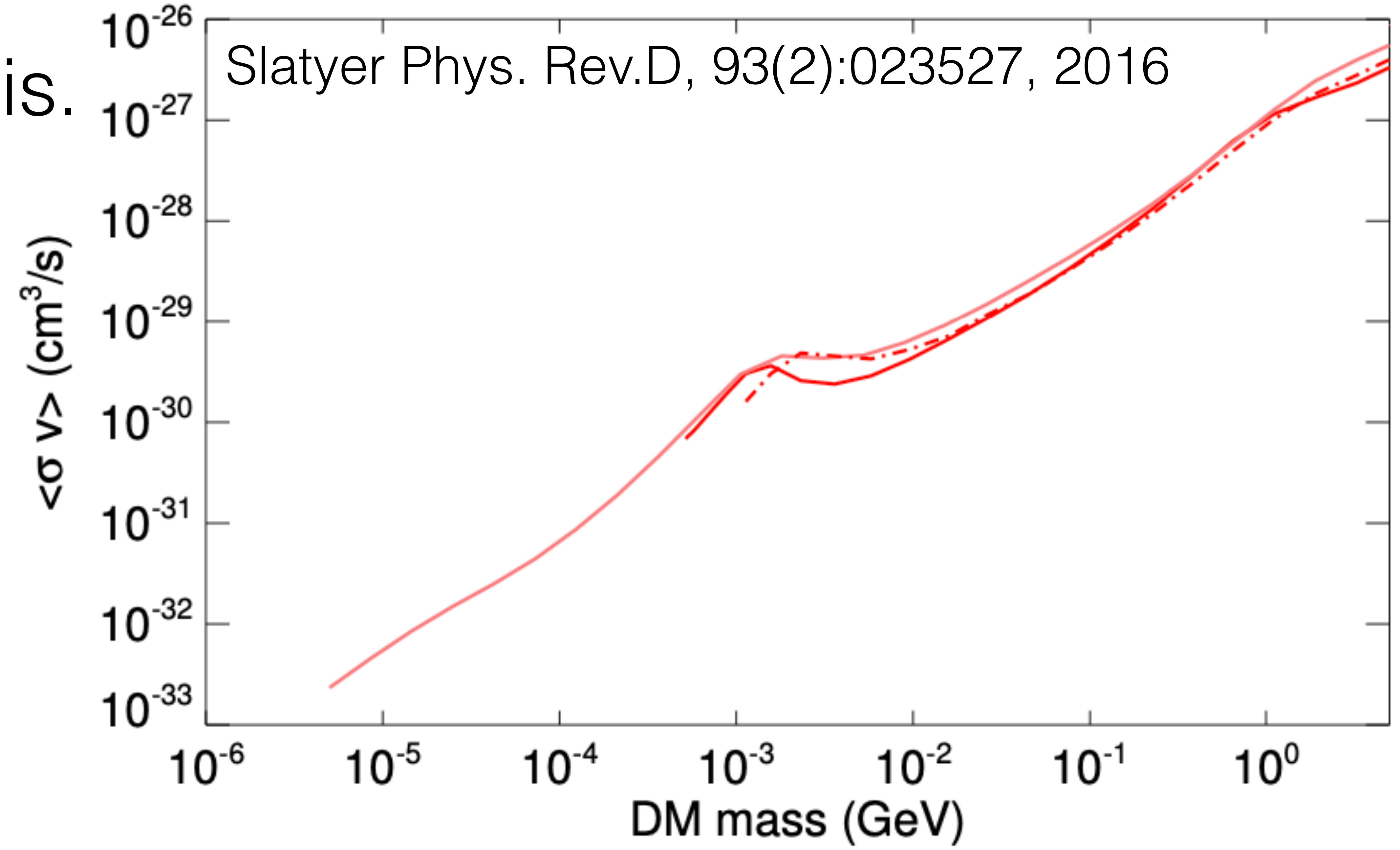
- What model is favored with the minimlaity, renormalizability and Z_2 symmetry?
- DM should be singlet under SM gauge group. (Relic abundance)
- Minimal (i.e. Higgs portal) senario (SM + scalar DM) was already excluded.
- Next minimal model is SM + DM + mediator.
- We consider the extention of SM with 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 $\rm U(1)_B$ 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.

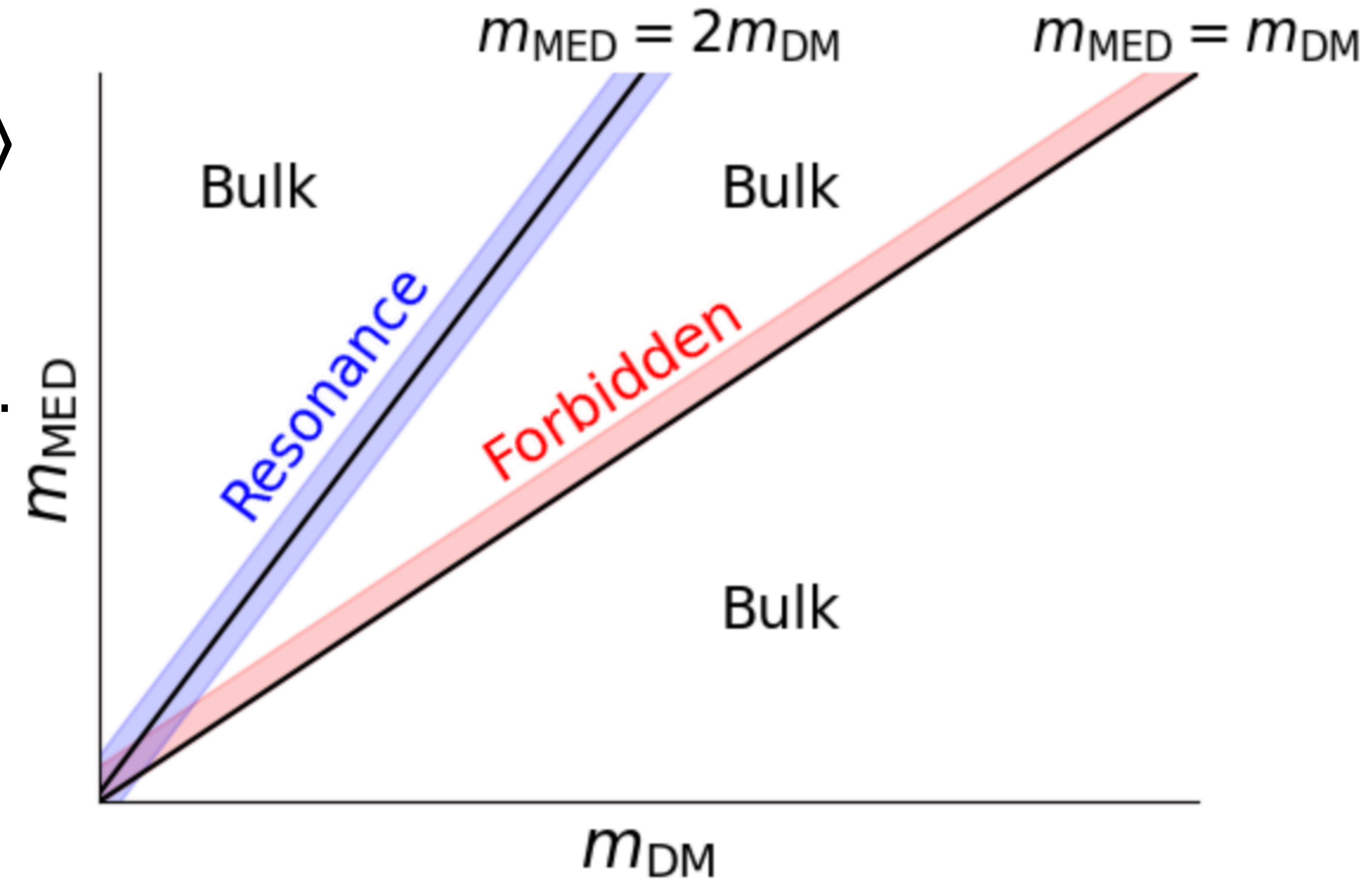
Constraint on $\langle \sigma v \rangle$ from cosmology I

- DM annihilations into primordial plasma may modify the anisotropy of the CMB, which is not observed, resulting in $\langle \sigma v \rangle \lesssim 10^{-27} \mathrm{cm}^3/\mathrm{s}\,(\mathrm{m_{DM}/GeV})$ @ recommbination (Planck 2018)
- ↔ relic abundance: $\langle \sigma v \rangle \approx 10^{-26} \mathrm{cm}^3/\mathrm{s}$ @ freeze-out.
- Simple s-wave annihilaltion scenario 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 in this thesis.



∃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 consider all such parameter regions in all the models: calculating the annihilation cross section in each region at each model and compare with the constraint above.

Constraint on $\langle \sigma v \rangle$ from cosmology II

- $\exists$constraints on $\langle \sigma v \rangle$ from cosmology other than CMB.
- Constraints from BBN
  - 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.
  - This is weaker than that of CMB and relic abundance condition.
  - Only resonant models are constrained.
- Constraints from Lyman - α
  - Late kinetic decoupling of DM suppresses the structure formation,resulting in $T_{\mathrm{kd}} \lesssim 200$ eV.
  - Only resonant mofels are constrained.

Observations of BBN and Lyman - α put constraints to the resonant models.

Constraint on $m_{\rm DM}$ from cosmology

- ∃constraints on $m_{\rm DM}$ from cosmology, as the light thermal DM freeze-out at the late time.
- Constraints from CMB
  - After the ν decoupling, asymmetrical entropy injection into EM-plasma and ν alters expansion rate of universe.
  - For each models, we calculated $N_{\rm eff} = 3[11/4\,(T_\nu/T_\gamma)^3]^{4/3}$ and compared to the observation, $N_{\rm eff} = 2.99 \pm 0.17$ (Planck 2018).
  - In DP scenarios, this constraint can be alleviated by making the ν decoupling later with tiny $\rm U(1)_{B-L}$ charge (interaction with both ν and e) (X.Chu…,2310.06611).
- Constraints from BBN
  - Light thermal particle affects $T_{\gamma(\nu)}$ and the expansion rate, then light element abundances.
  - We calculated $T_{\gamma(\nu)}$ and Y_p with Boltzmann eq. (M.Escudero, JCAP, 02:007, 2019.)
  - This constrains DP scenarios.

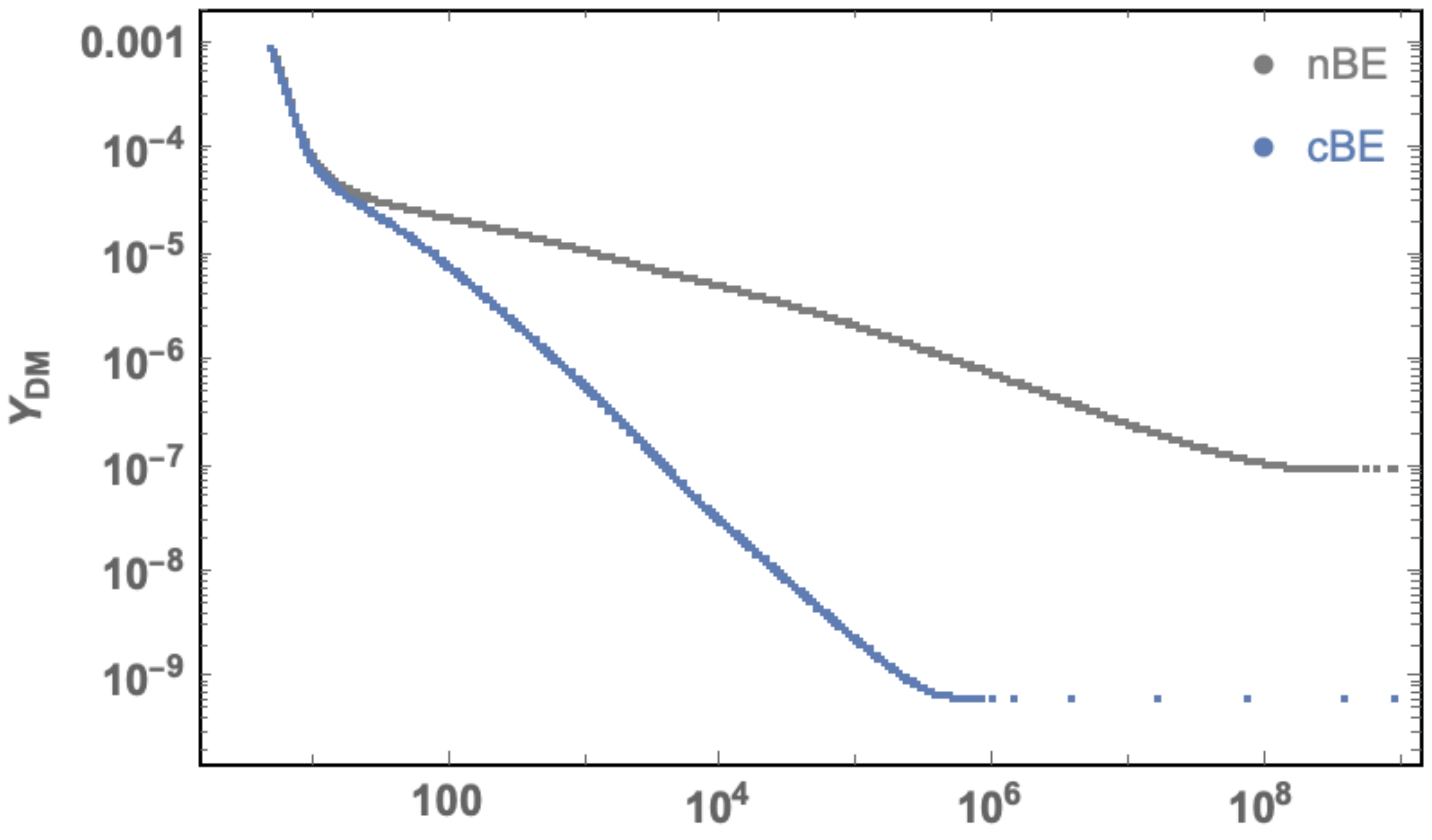
Results are summarized as:

(Constraints in bulk regions depends on $m_{\rm MED}$)

(MeV)	SS	FS	SV(DP)	FV(DP)	SV(B)	FV(B)
Bulk						
Forbidden	6.3	7.5	0.7	0.9	8.8	9.7
Resonance(vis)	4.7	6.4	0.5	0.7	6.6	8.3
Resonance(inv)	4.7	6.4	0.5	0.7	6.6	8.3

Relic abundance calculation

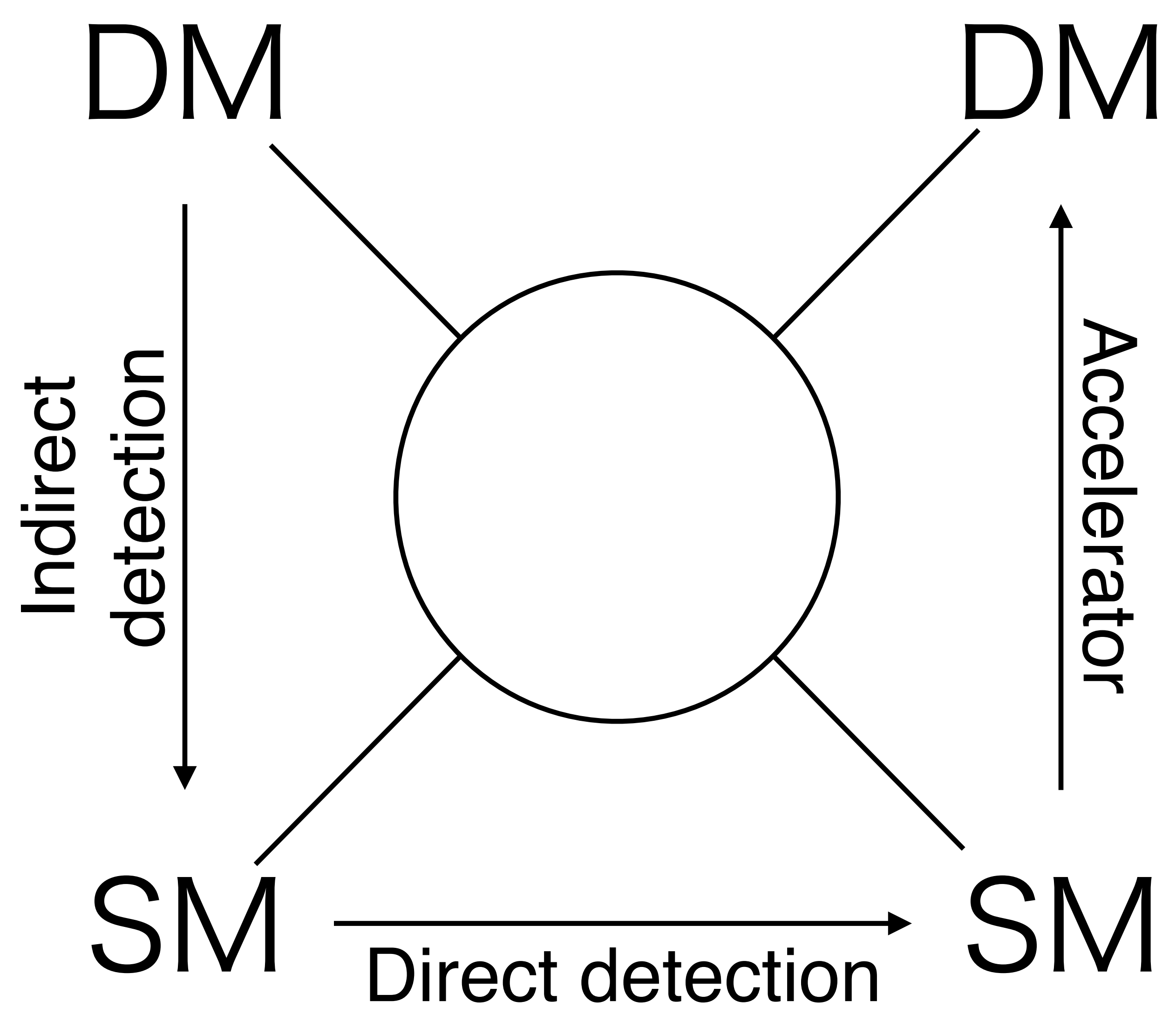
- The DM density is governed by Boltzmann eq : $\hat{L}[f] = \hat{C}_a[f] + \hat{C}_s[f]$.
- It is hard to solve this numerically. Standard simplification is using only the 0th moment $n_{\rm DM}$ with kinetic equilibrium assumption: $\dot{n} + 3Hn = - <\sigma v> (n^2 - n_{eq}^2)$.
- In the bulk and forbidden regions, we use this imposing the kinetic equilibriums between DM-MED (or DM-SM) and MED-SM (i.e. MED $\leftrightarrow$ SM SM).
- In resonant regions, maintaining kinetic equilibrium is difficult, as scattering is always suppressed. (Early kinetic decoupling)
- We have to move one level up using the 1st moment $T_{\rm DM}$. We used the DRAKE code (T.Binder,etc, EPJC, 81:577, 2021).



In each parameter region at each model, we calculate relic abundance based on the above strategy and compare the result to the observation, $\Omega h^2 = 0.12$

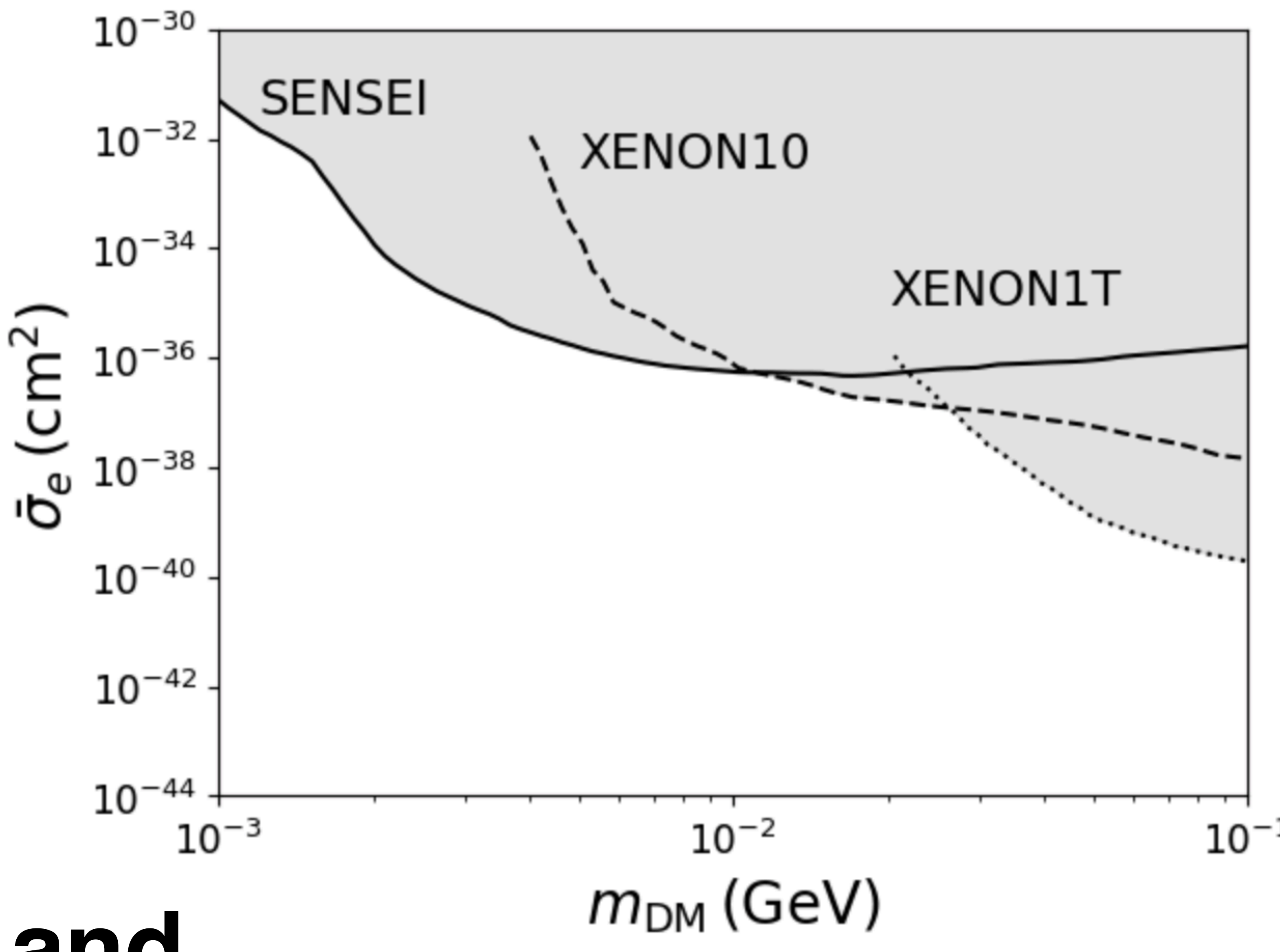
Detection of DM

- ∃3 types of DM-SM interaction, and ∃appropriate searching strategy for each.
- Details differ from those of the WIMP, as the energy scale differs.



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

- Traditional experiments (Xenon) search for DM scatterings off heavy nuclei.
- This loses 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.
- We consider the last one.

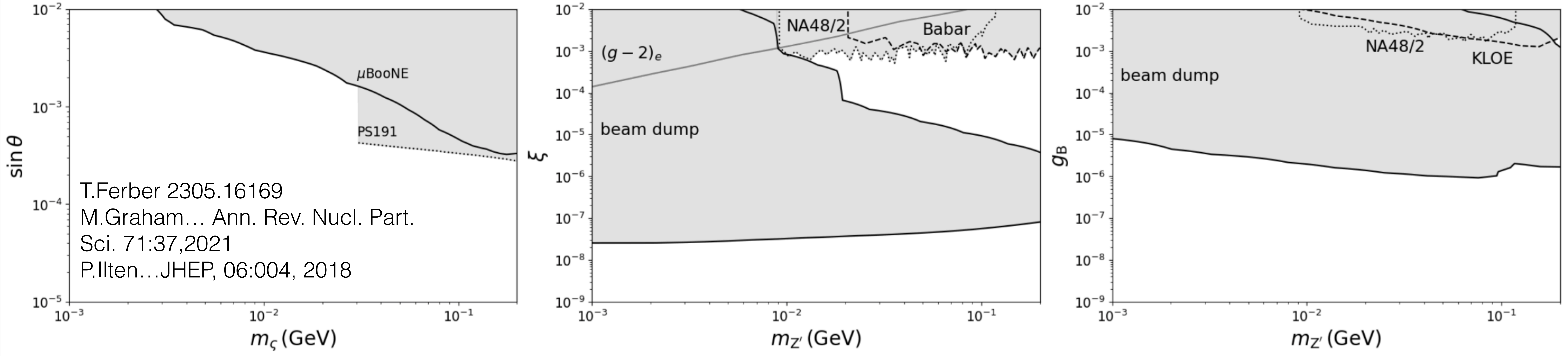


In each model, we calculated σ_e for each parameter region and compare to the experiments.

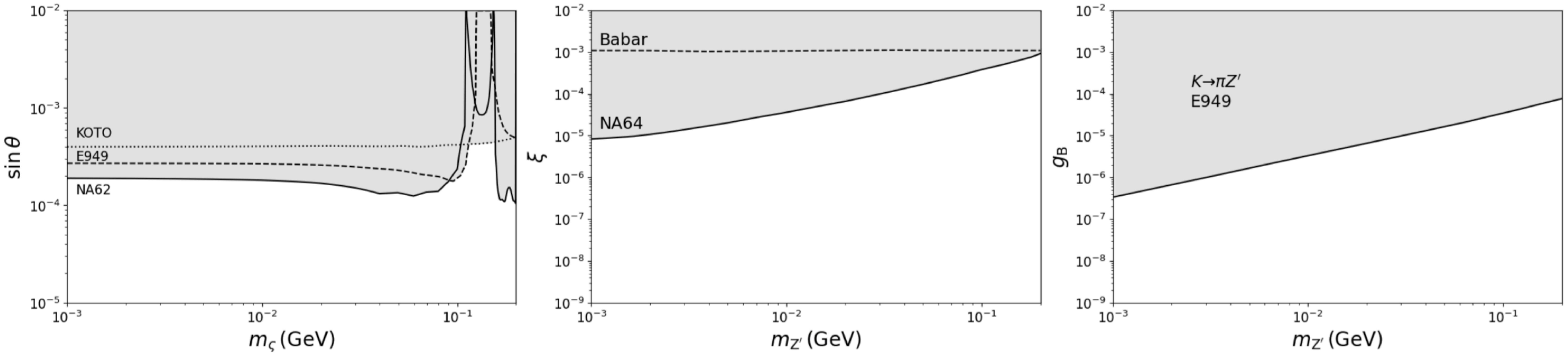
Accelerator (Production of DM by high energy SM particles collisions)

- ∃many constraints from accelerator experiments.
- ∃many types (collider and fixed target(beam dump)) and accelarating SM particles (e and p).
- DM interacts with SM bosons (e.g. Higgs) (→invisible decay search) and MED (→ MED production).
- Mediators can decay visibly (into e^+e^-) or invisibly (into DMs).

- Visible Mediator search

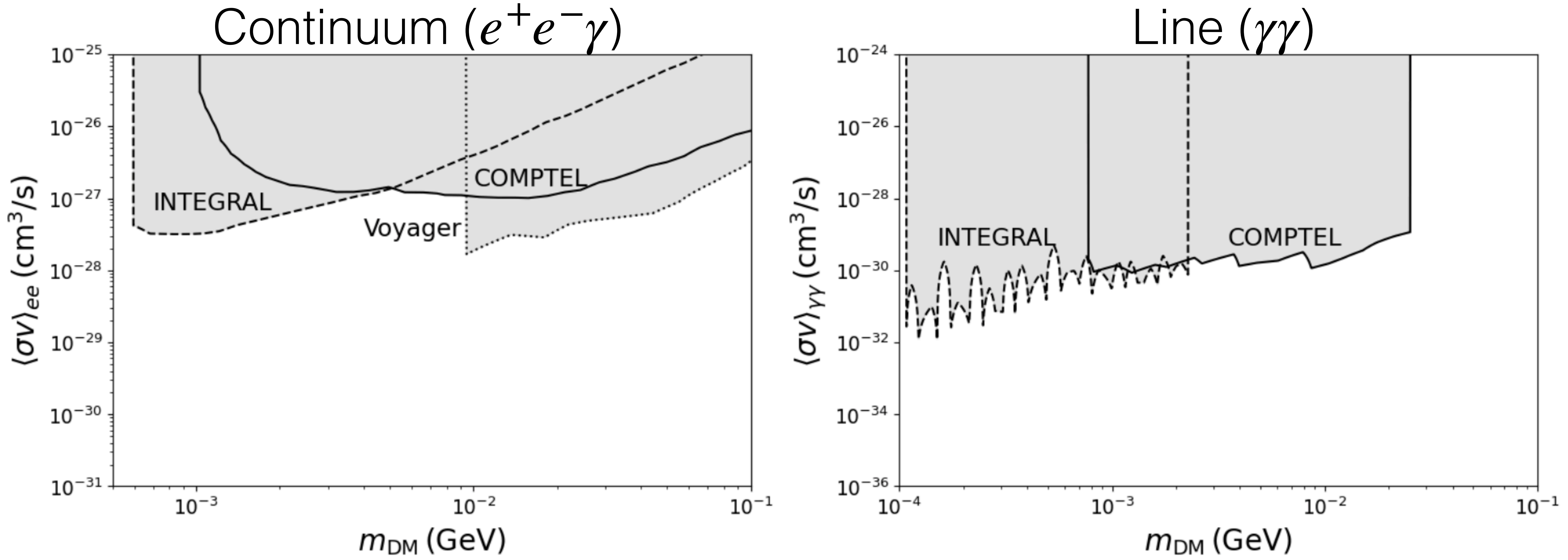


- Invisible Mediator search



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

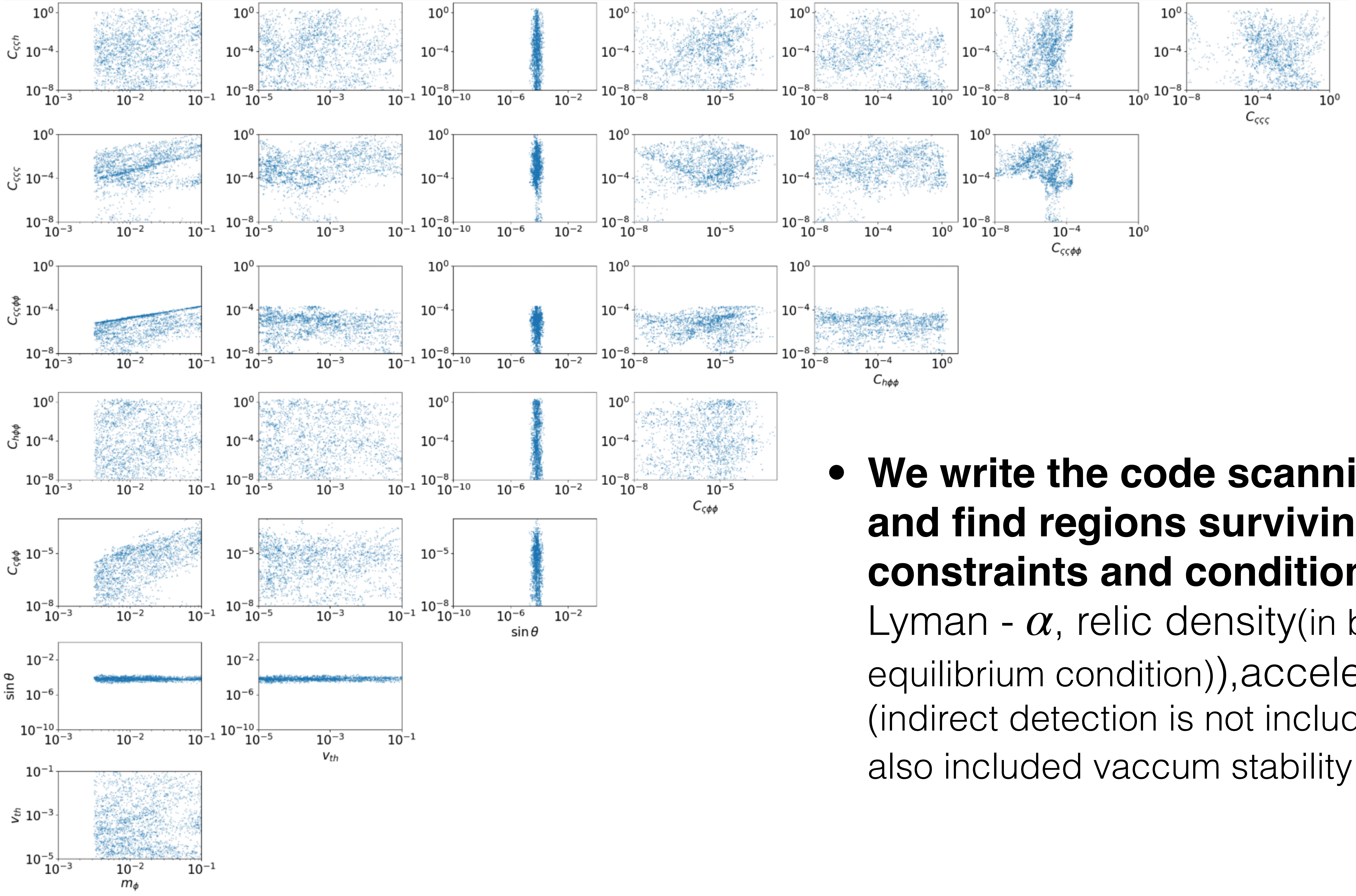
- DM can produce cosmic-ray and γ-ray.
- Cosmic-ray is the low energy $e^{\pm}$, which cannot enter the heliosphere by the solar magnetic field. Only Voyager I can detect this.
- γ-ray has energy of MeV. This is known to be difficult to detect ('MeV gap'), resulting in usage of only old experiments (COMPTEL, INTEGRAL).
- These constraints are suffered from uncertainties of DM density. We assume NFW profile considering these uncertainties at 2σ.



In each model, we calculated $\langle\sigma v\rangle$ for each parameter region and compare to the above constraints.

Scan of favored parameter sets

Ex. Favored parameter region at 95% C.L in SS-Forbidden model



- **We write the code scanning the parameter space and find regions surviving from all mentioned constraints and conditions.** (Cosmology(CMB, BBN, Lyman - α, relic density(in bulk and forbidden region, kinetic equilibrium condition)),accelerator and direct detection) (indirect detection is not included due to the uncertainties) We also included vaccum stability and unitarity.

∃viable parameter region?

- **Results are sumarized in the table below.**

○ ∃viable parameter region
— ¬∃viable parameter region

($m_{\rm DM} \lesssim$ 100 MeV)	SS	FS	SV(DP)	FV(DP)	SV(B)	FV(B)
Bulk	—	○	○	—	—	—
Forbidden	○	○	○	○	—	—
Resonance(vis)	—	—	○	—	—	—
Resonance(inv)	—	—	○	○	○	○

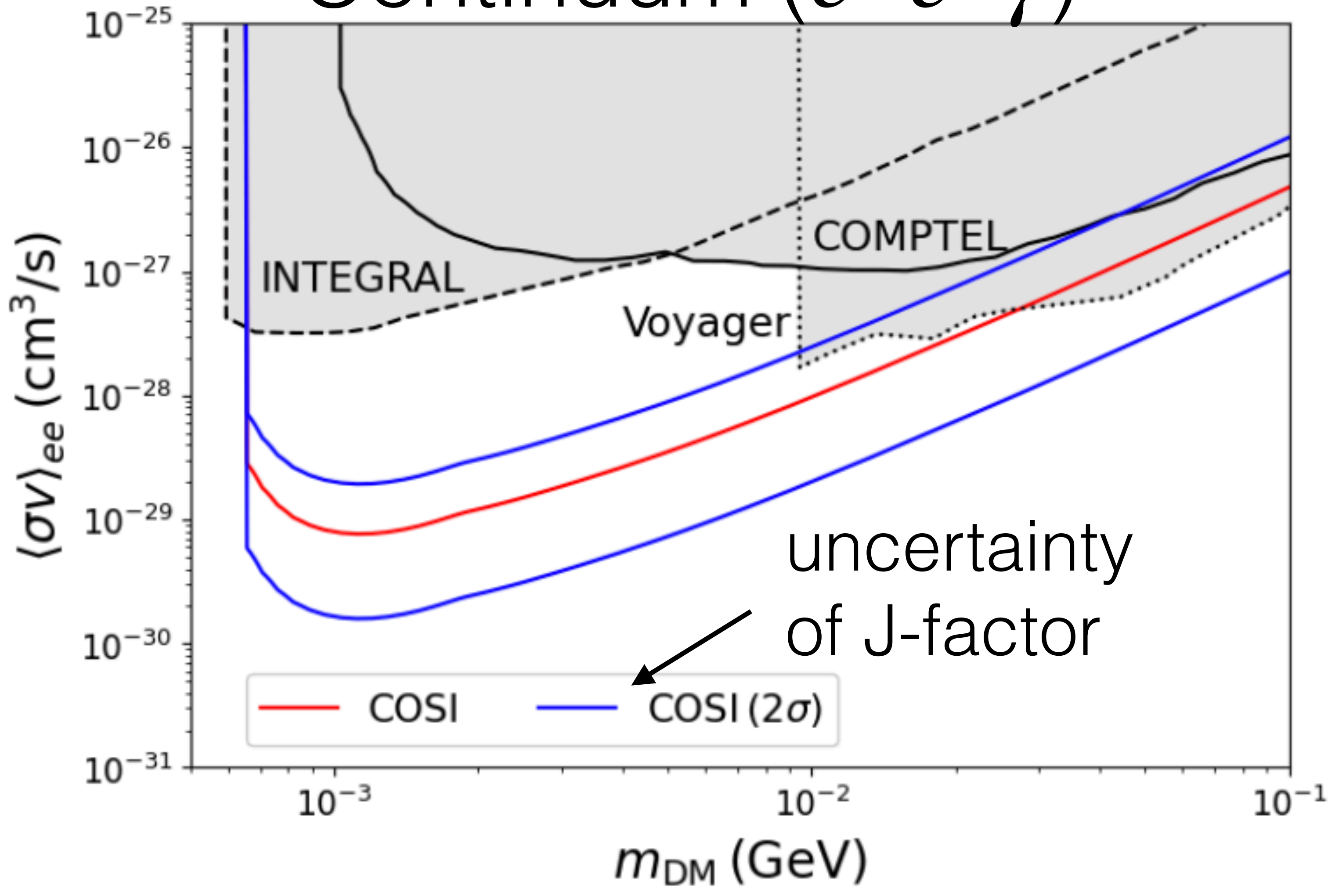
- Several regions are excluded by following reasons:
  - Some bulk scenarios are excluded by CMB dependent on DM and mediator spins.
  - Most of $\rm U(1)_B$ scenarios are difficult to satisfy the relic abundance condition.
  - FV-R(vis) scenario is prohibited by CMB constraint due to the s-wave annihilation.
  - Resonant models with a scalar mediator are excluded by tiny y_e. This requires large $\sin\theta$ or resonance, which are disfavored by accelerators and Indirect detection experiments.

We found several viable parameter regions in each model as shown above.

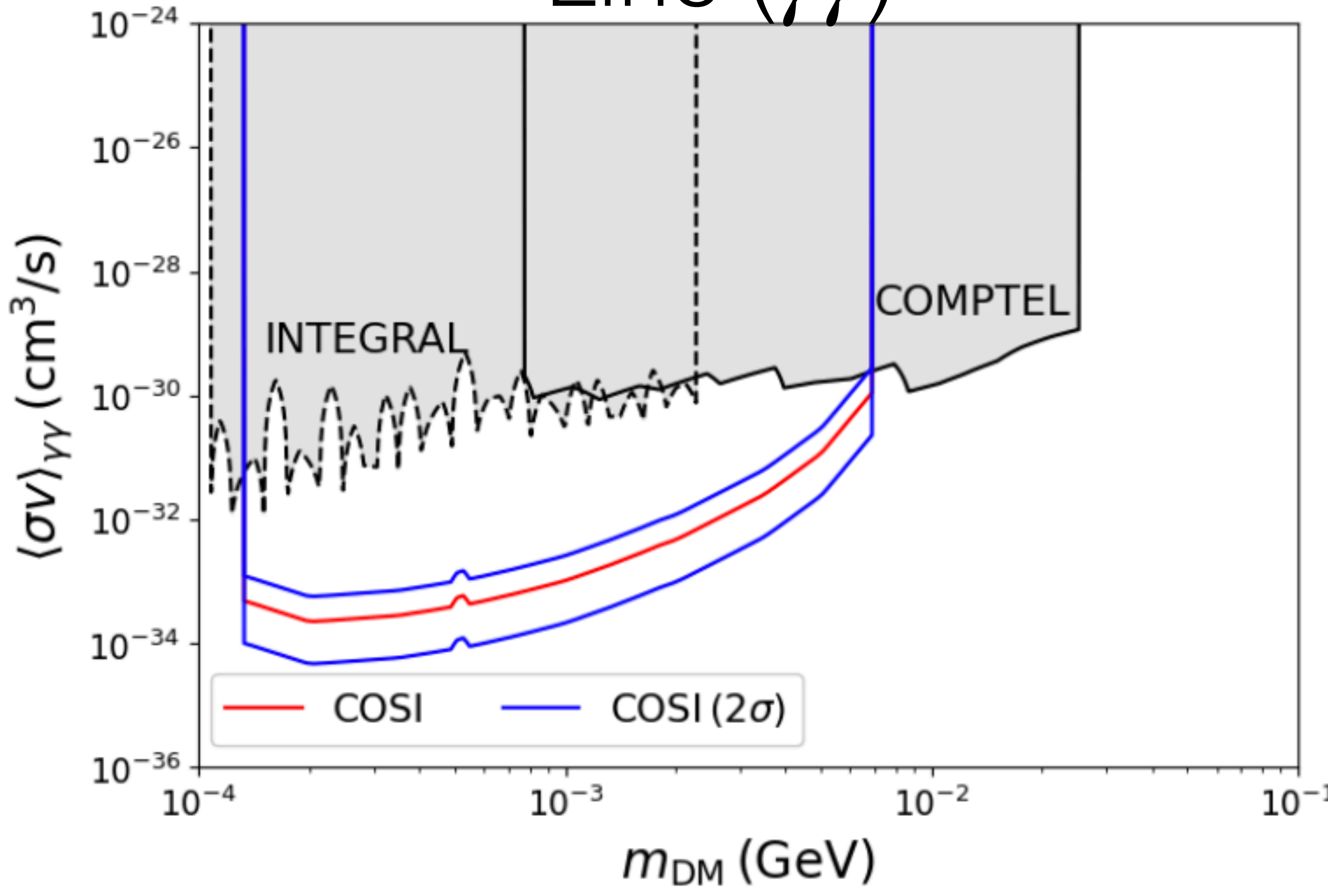
Can COSI detect light thermal DM?

- Advancements in technology and theoretical studies opened up possibilities to detect MeV gamma rays, leading to the approval of COSI.
- COSI is a compton telescope with large FOV at 0.5~5 MeV and will be lauched in 2027.
- IPMU officialy comits to the project and I am involved as a member of the COSI DM science team.
- Point source sensitivities for arbitraly signals are calculated based on the dedicated simulations (J.A.Tomsick..YW, ICRC2023:745,2023)
- Above sensitivities can be recasted to the extended DM source (T.Aramaki…YW, Snowmass 2021, A.Capto…JCAP 02 (2023) 006). Based on this, we calcurated the DM detectability of COSI by 2 years observations of the GC ($|\theta| < 20°$) , taking part in the uncertainties from the DM profiles.

Continuum ($e^+e^-\gamma$)



Line ($\gamma\gamma$)



We found that COSI improves sensitivity by several orders of magnitude.

Can COSI detect light thermal DM?

- In the following slides we show whether COSI can detect the light thermal DM, taking 🔴 models as examples

○ ∃viable parameter region
— ¬∃viable parameter region

($m_{\rm DM} \lesssim$ 100 MeV)	SS	FS	SV(DP)	FV(DP)	SV(B)	FV(B)
Bulk	—	🔴	🔴	—	—	—
Forbidden	🔴	○	○	○	—	—
Resonance(vis)	—	—	🔴	—	—	—
Resonance(inv)	—	—	🔴	○	🔴	○

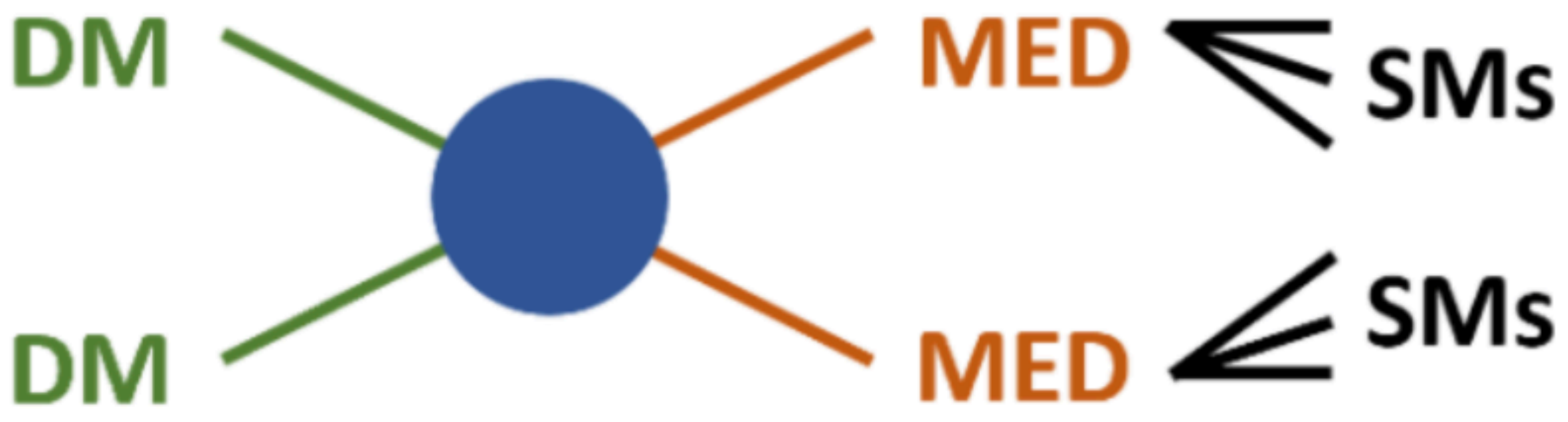
Bulk(p-wave)

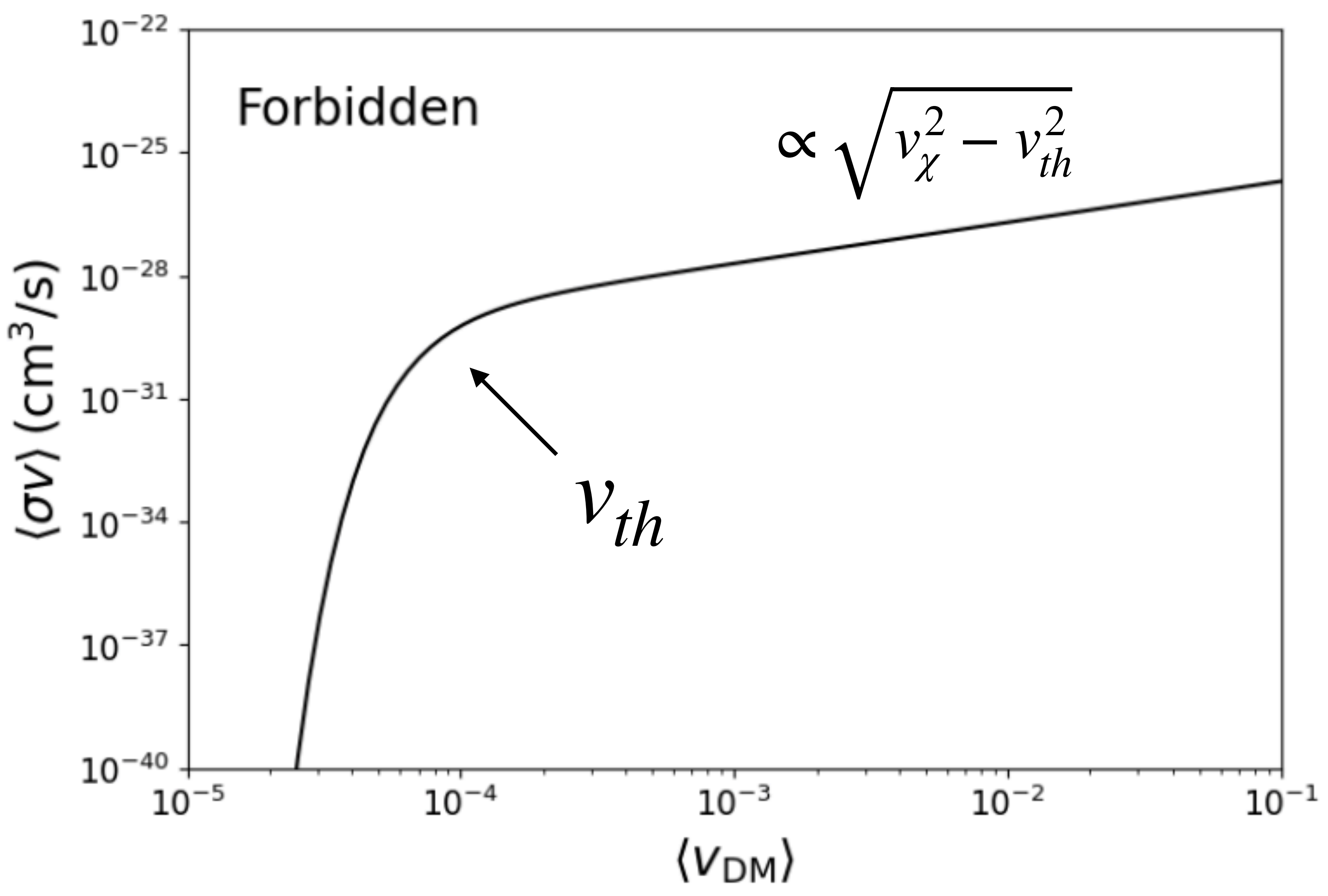
- The relic abundance condition requires $\langle \sigma v \rangle \sim 10^{-26}$ @ freeze-out ($v_{\rm DM}^2 \sim 10^{-1}$).
- Since $v_{\rm DM} \sim 10^{-3}$ @ GC, the annihilation cross section is $\langle \sigma v \rangle \sim 10^{-31}$ @ GC.
- As shown in the previous figures, the COSI sensitivities are $\langle \sigma v \rangle \gtrsim 10^{-30}$.
- COSI cannot detect these regions, as signals are weak.

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.

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

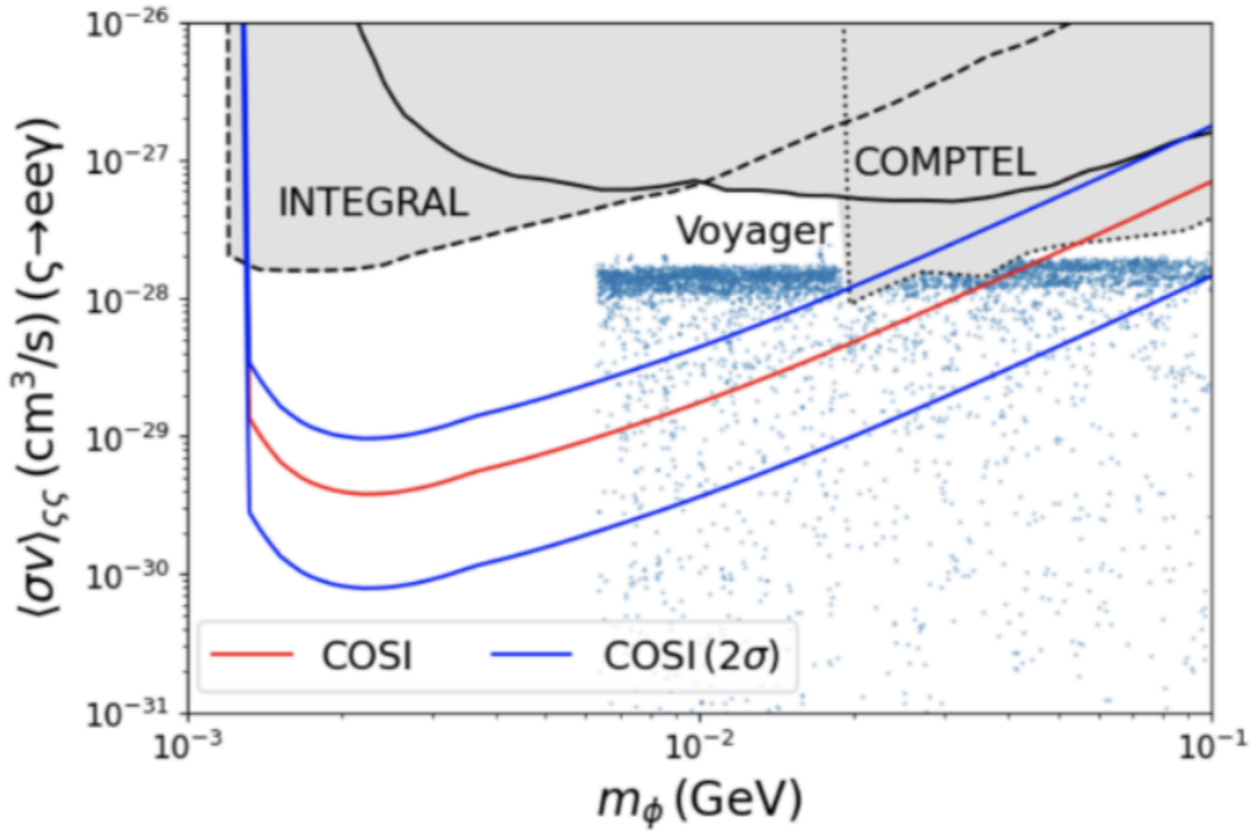




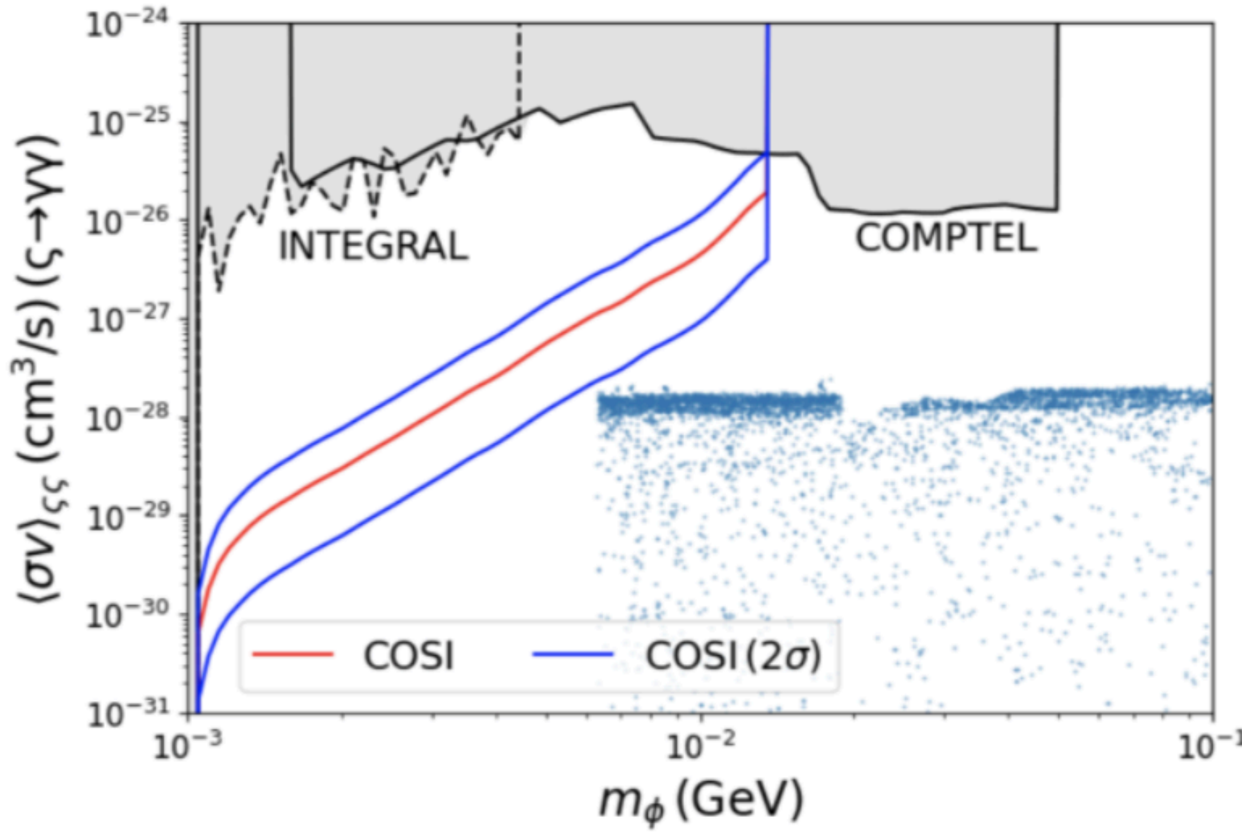
We find out viable parameter region and compare its prediction of the MeV γ-ray signal to the COSI sensitivities.

Prediction of SS-F model

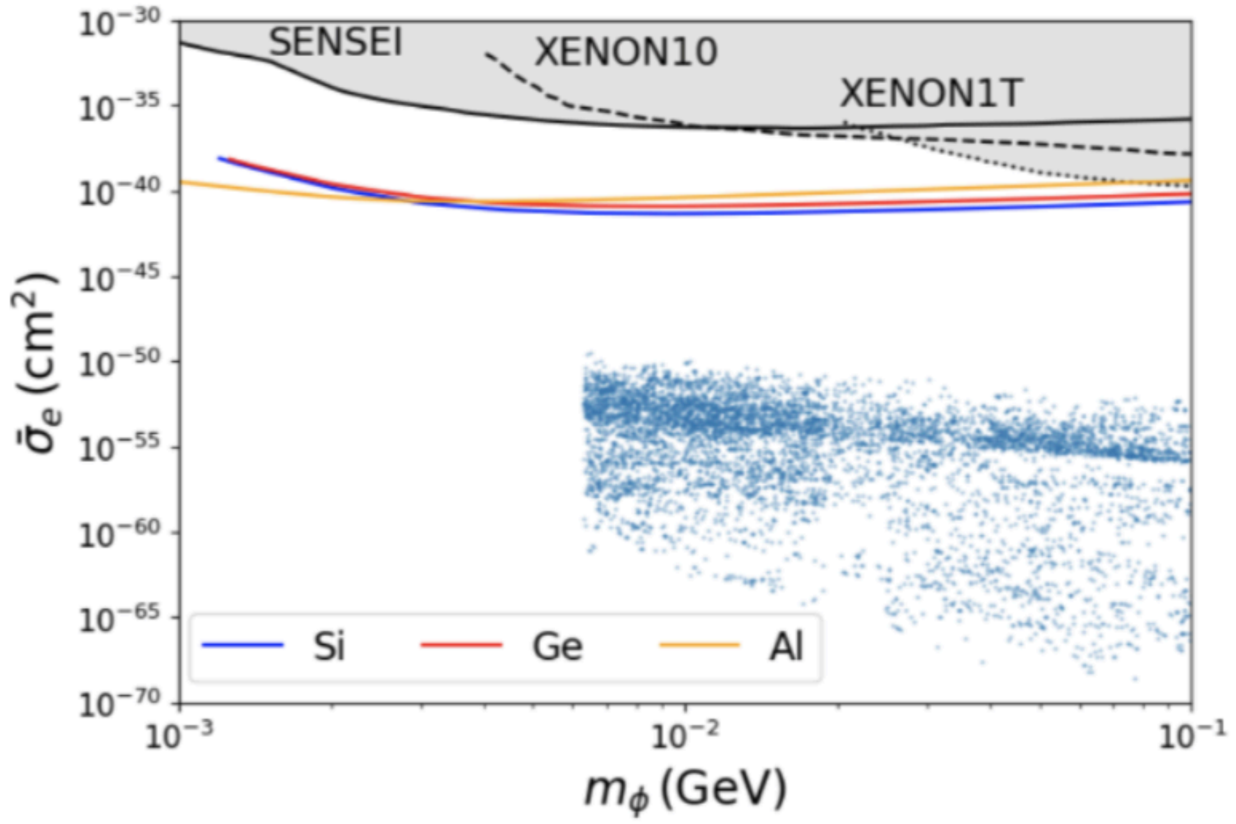
- Indirect detection (continuum)



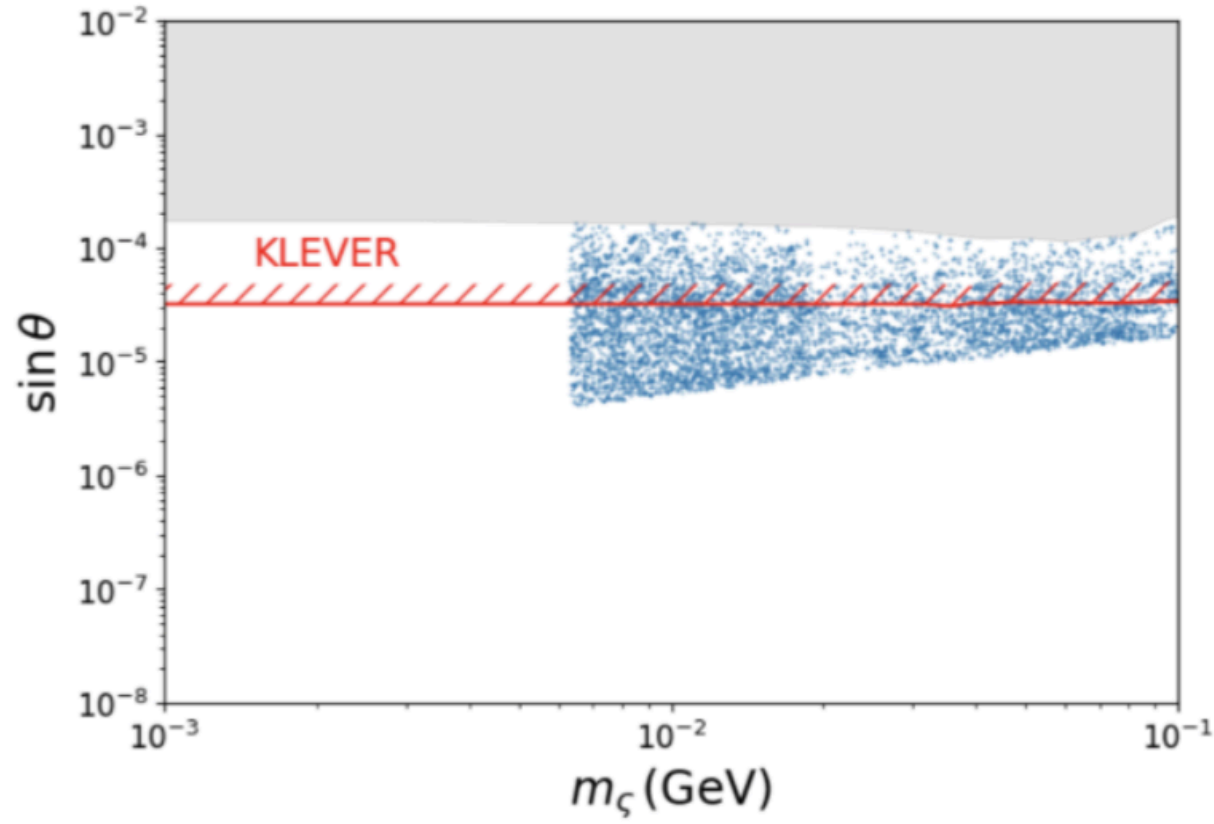
- Indirect detection (line)



- Direct detection



- Accelerator

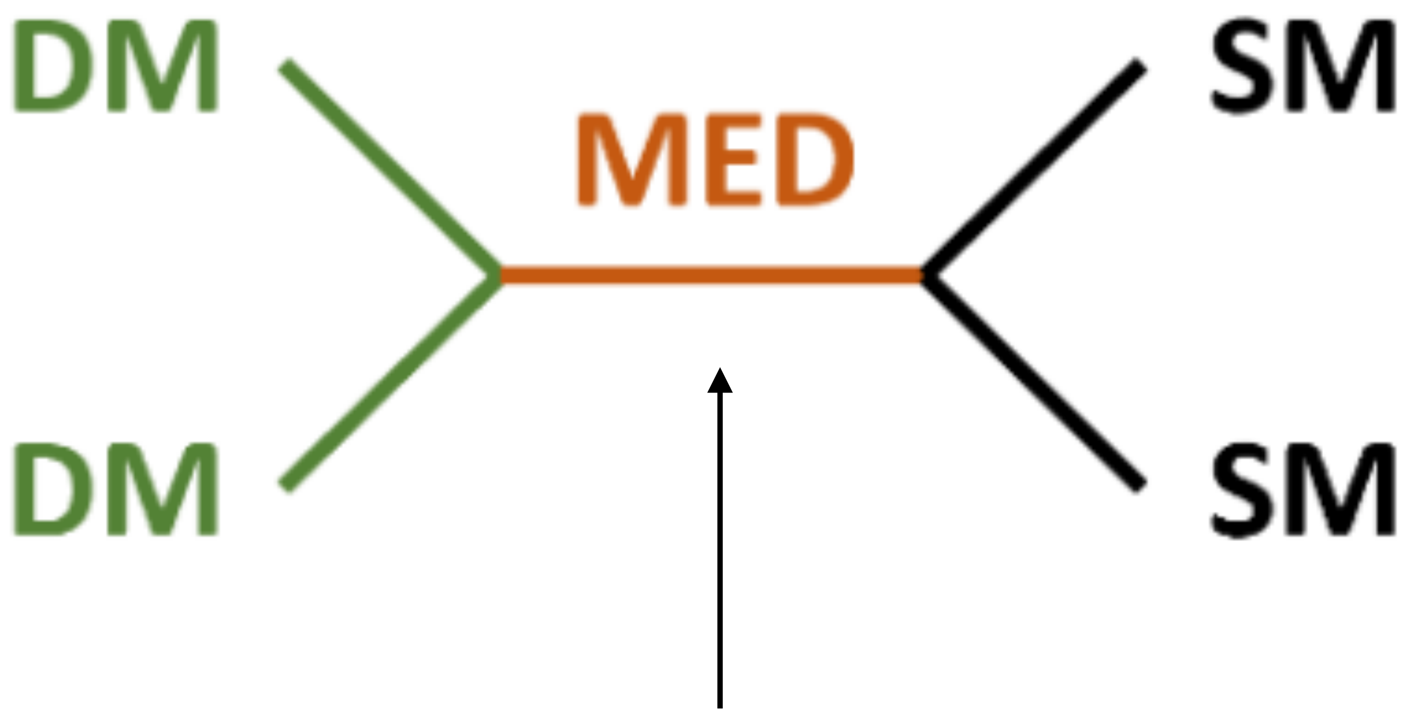


- COSI is expected to detect continuum γ-ray.
- COSI may not probe line γ-ray.
- Direct detection is not effective due to the tiny y_e.
- Future accelerator KLEVER can detect some parameters.

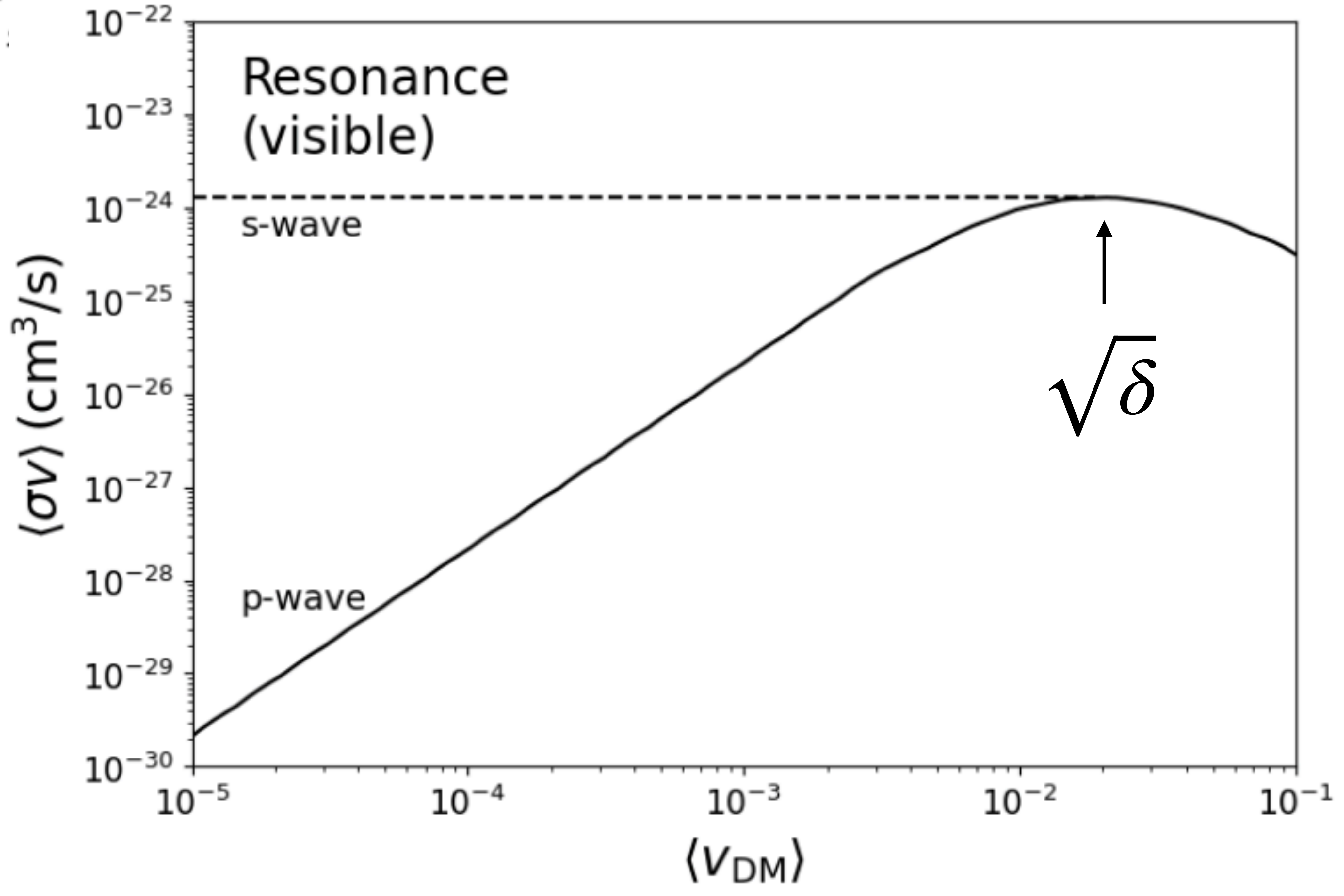
S-channel (visible)~ p-wave+resonance

- 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 $2m_{\mathrm{DM}} \gtrsim m_{\mathrm{MED}} \equiv 2m_{\mathrm{DM}}(1-\delta/8)$. As v_{DM} decrease, $\langle\sigma v\rangle$ enhances approaching the resonance, with cutoff, $\sqrt{\delta}$.

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



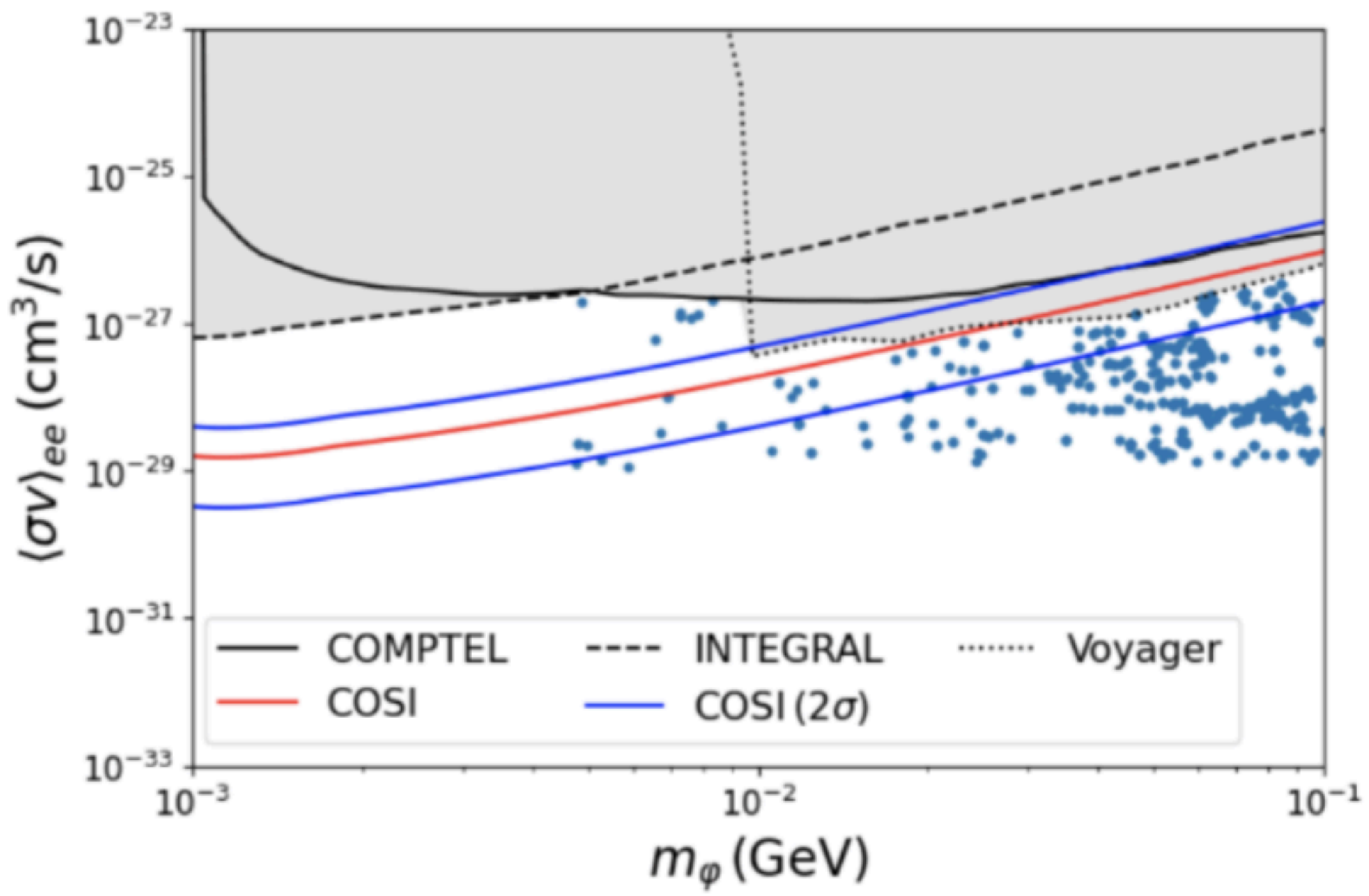
$$\frac{1}{(s-m_{\mathrm{MED}}^2)^2 + s\Gamma_{\mathrm{MED}}^2(s)} \simeq \frac{1}{m_{\mathrm{DM}}^4}\frac{1}{(v^2+\delta)^2 + 16(\Gamma_{\mathrm{MED}}(s)/m_{\mathrm{MED}})^2}$$



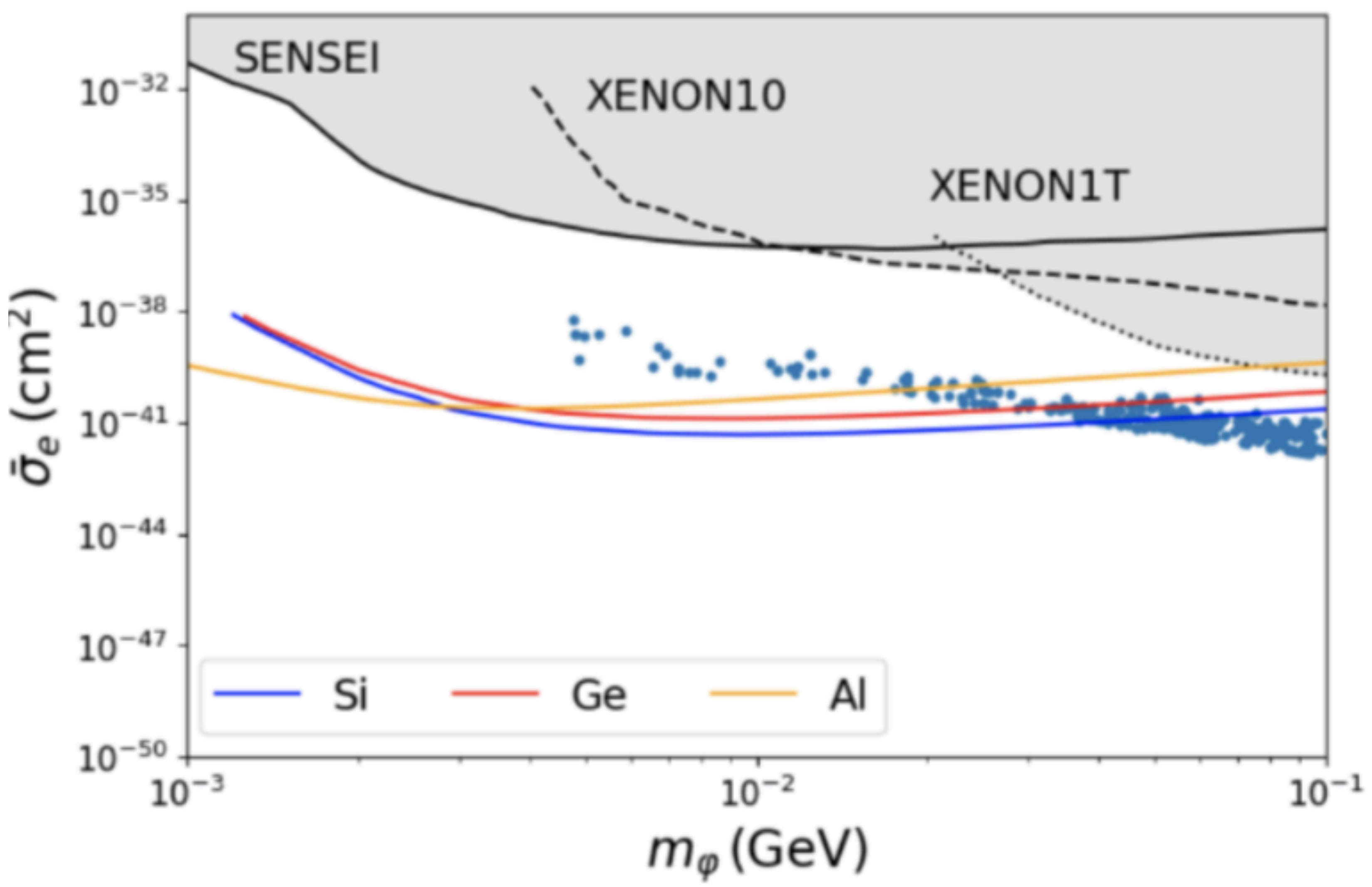
We find out viable parameter region and compare its prediction of the MeV γ-ray signal to the COSI sensitivities.

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

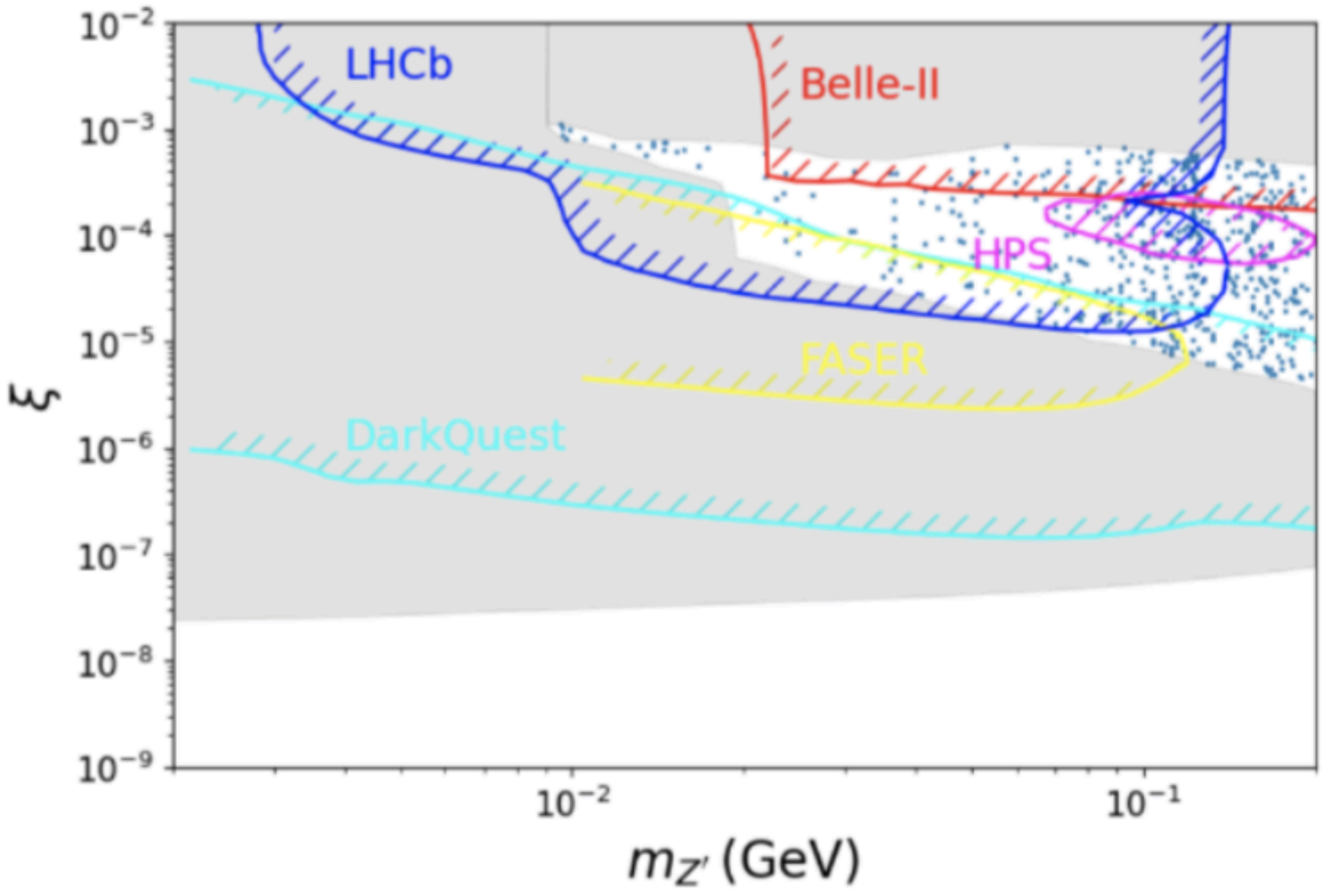
- Indirect detection (continuum)



- Direct detection



- Accelerator

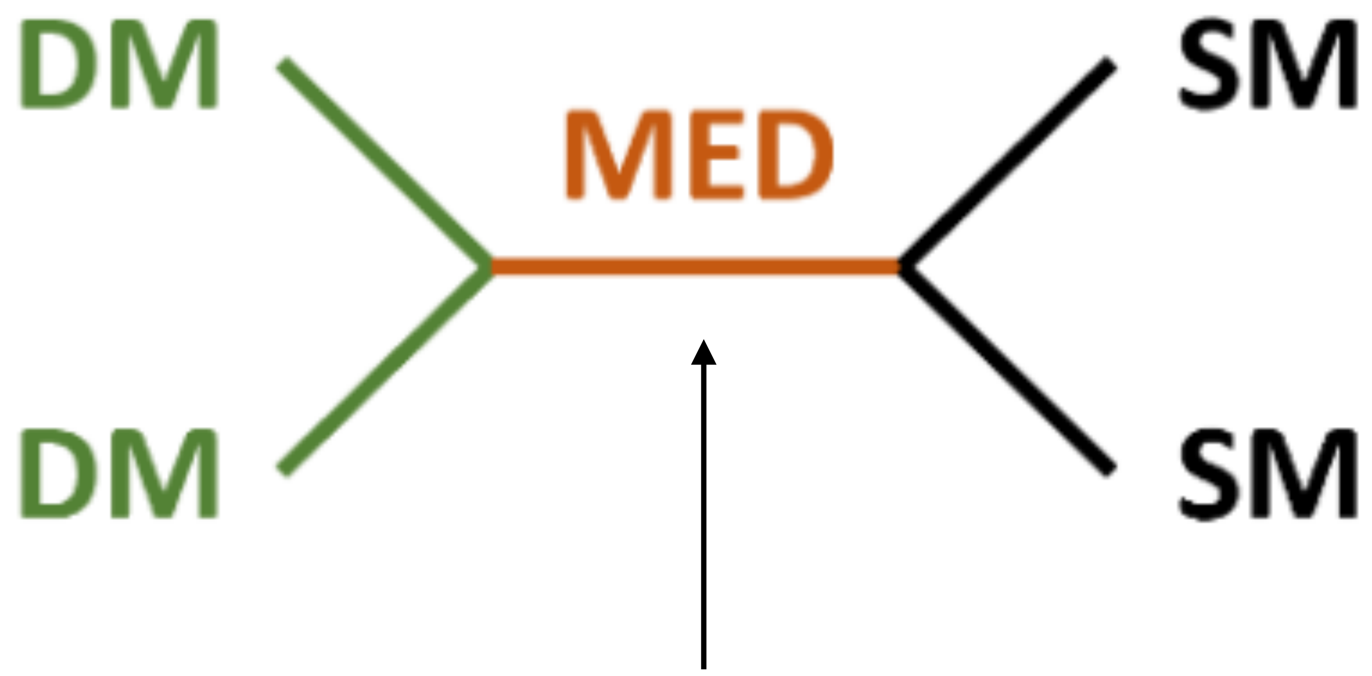


- COSI is expected to detect continuum γ-ray.
- No $\gamma\gamma$ $\because$ vector mediator
- Future direct detections have the potential to detect some points.
- Future accelerator can detect almost all of the parameters.

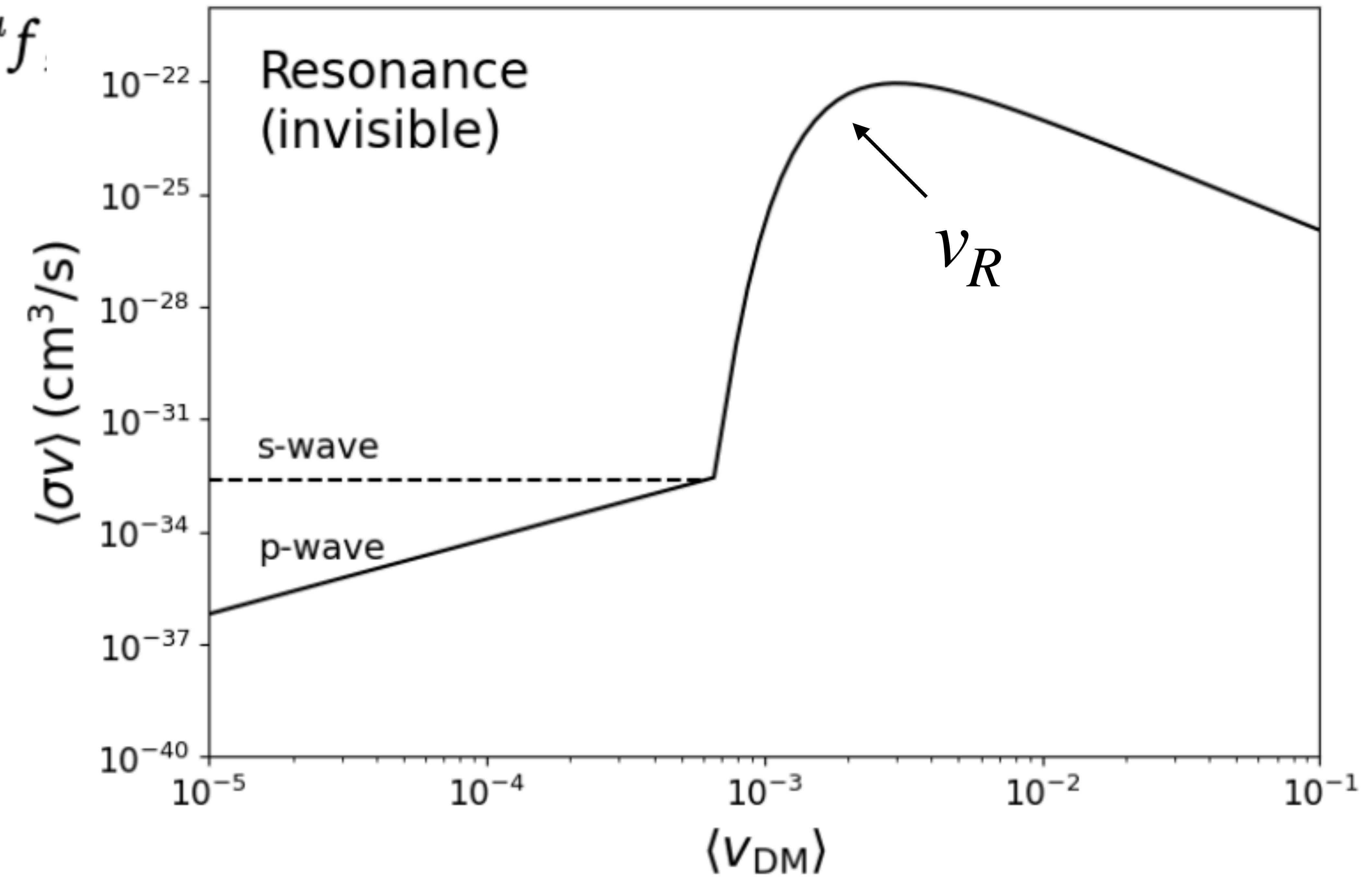
S-channel (invisible)

- 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.

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



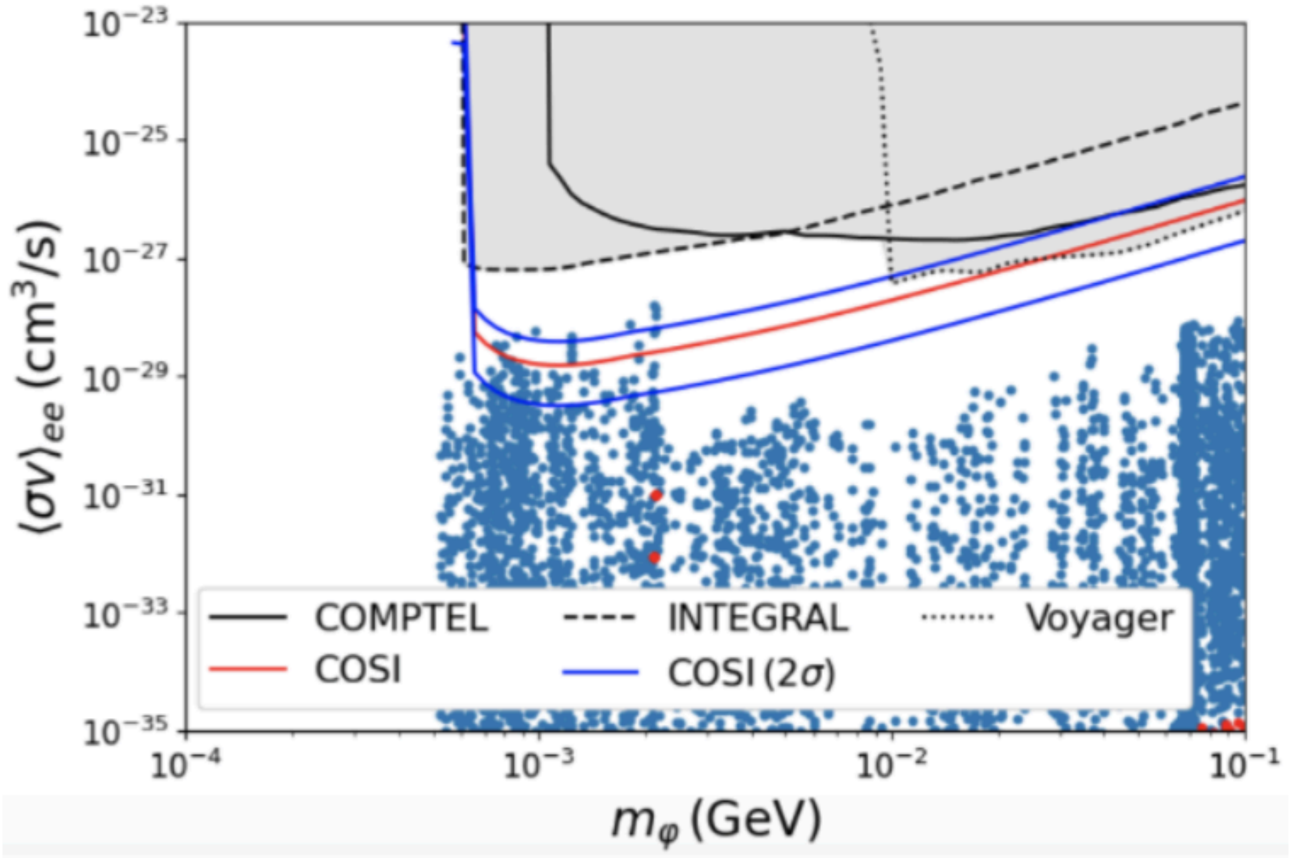
$$\frac{1}{(s - m_{\rm MED}^2)^2 + s\Gamma_{\rm MED}^2(s)} \simeq \frac{1}{m_{\rm DM}^4}\frac{1}{(v^2 - v_R^2)^2 + 16(\Gamma_{\rm MED}(s)/m_{\rm MED})^2}$$



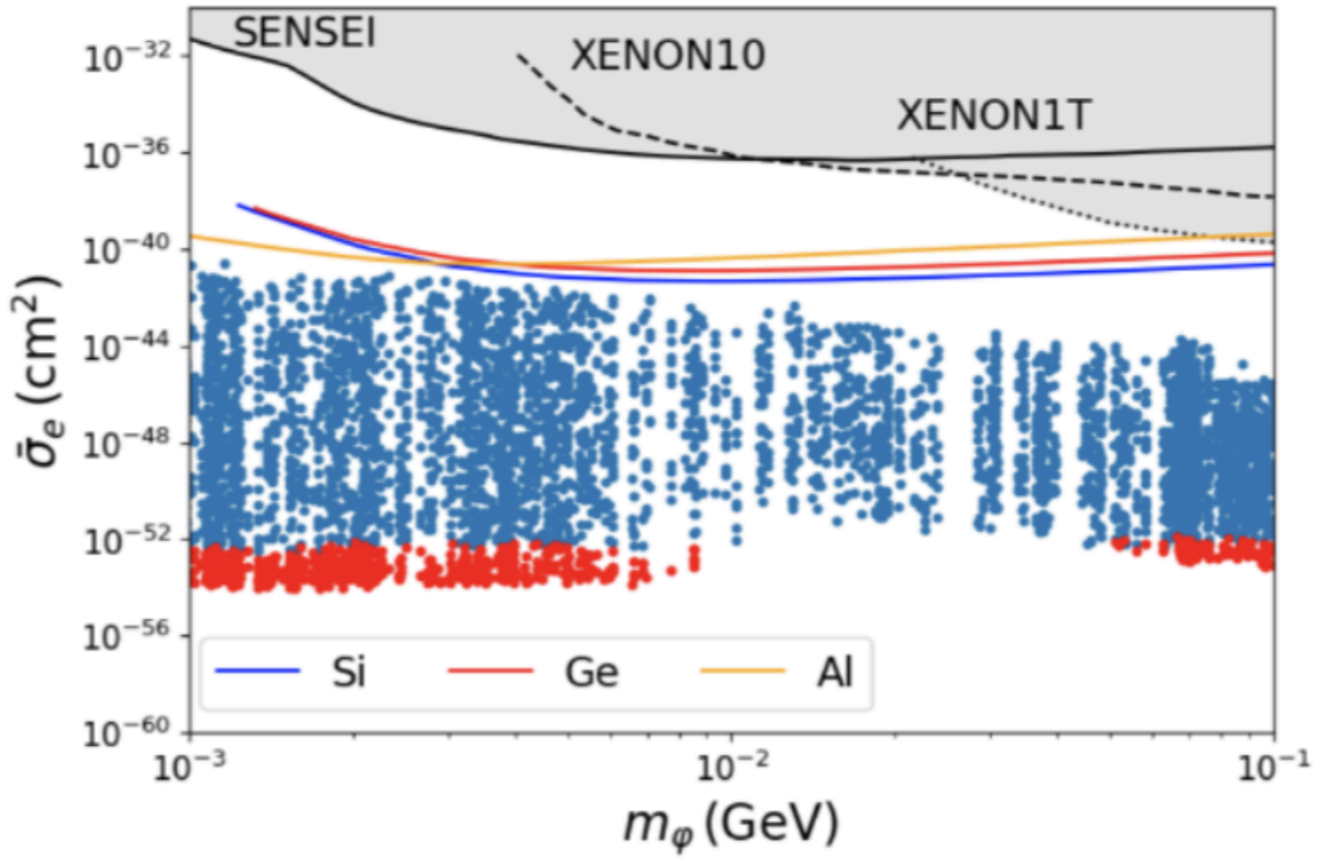
We find out viable parameter region and compare its prediction of the MeV γ-ray signal to the COSI sensitivities.

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

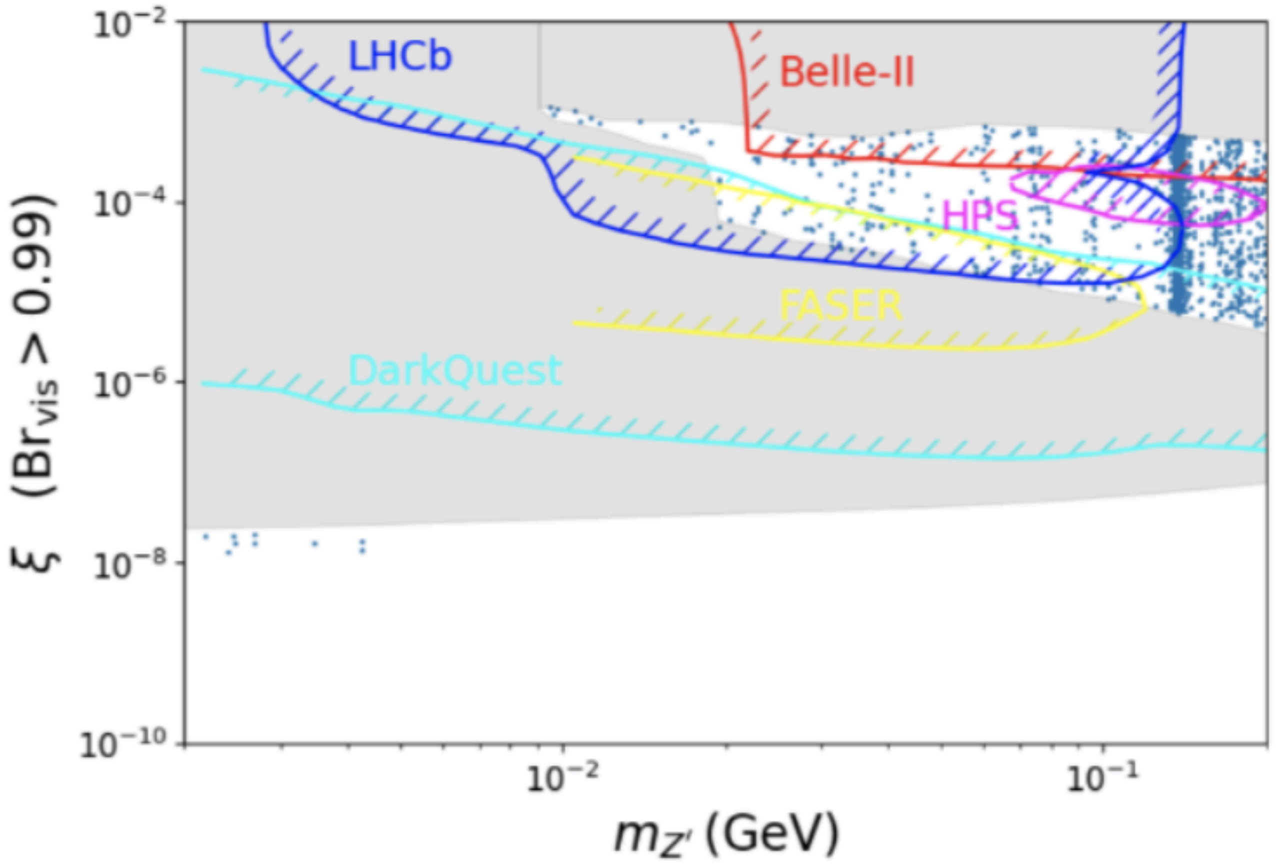
- Indirect detection (continuum)



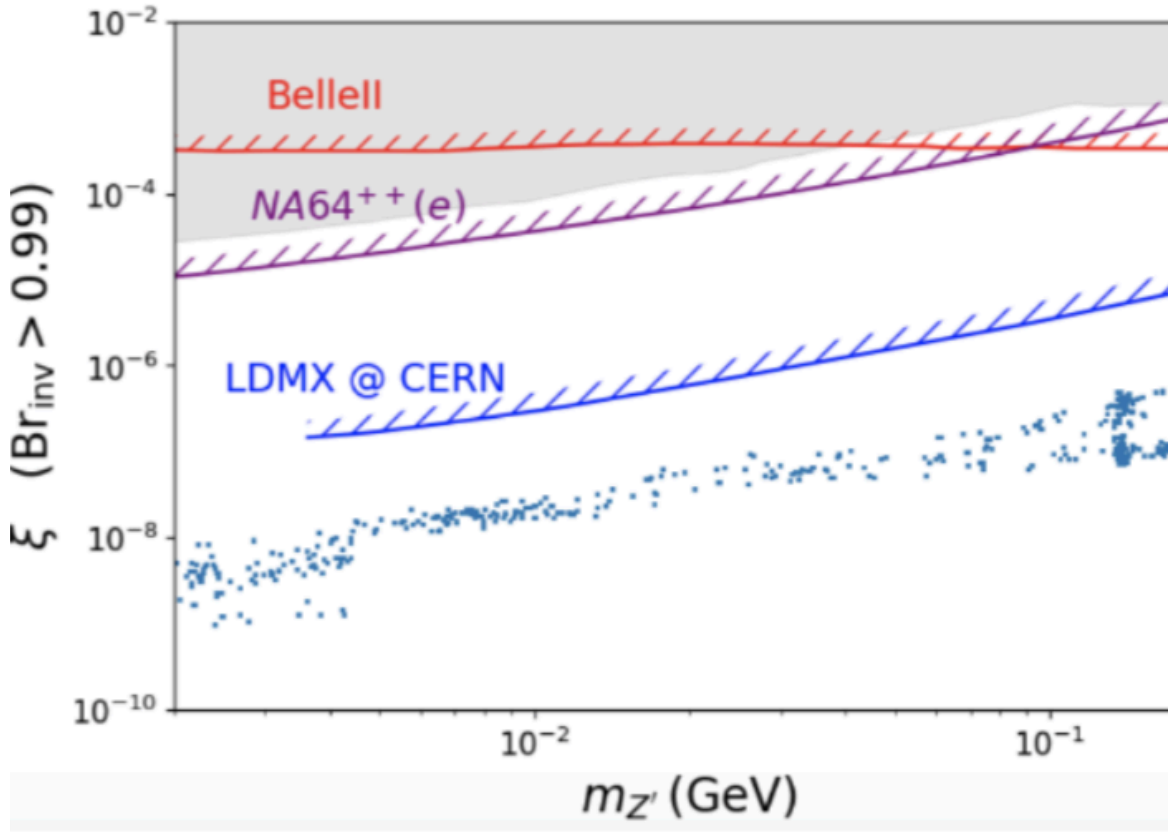
- Direct detection



- Accelerator(visible)



- Accelerator(invisible)

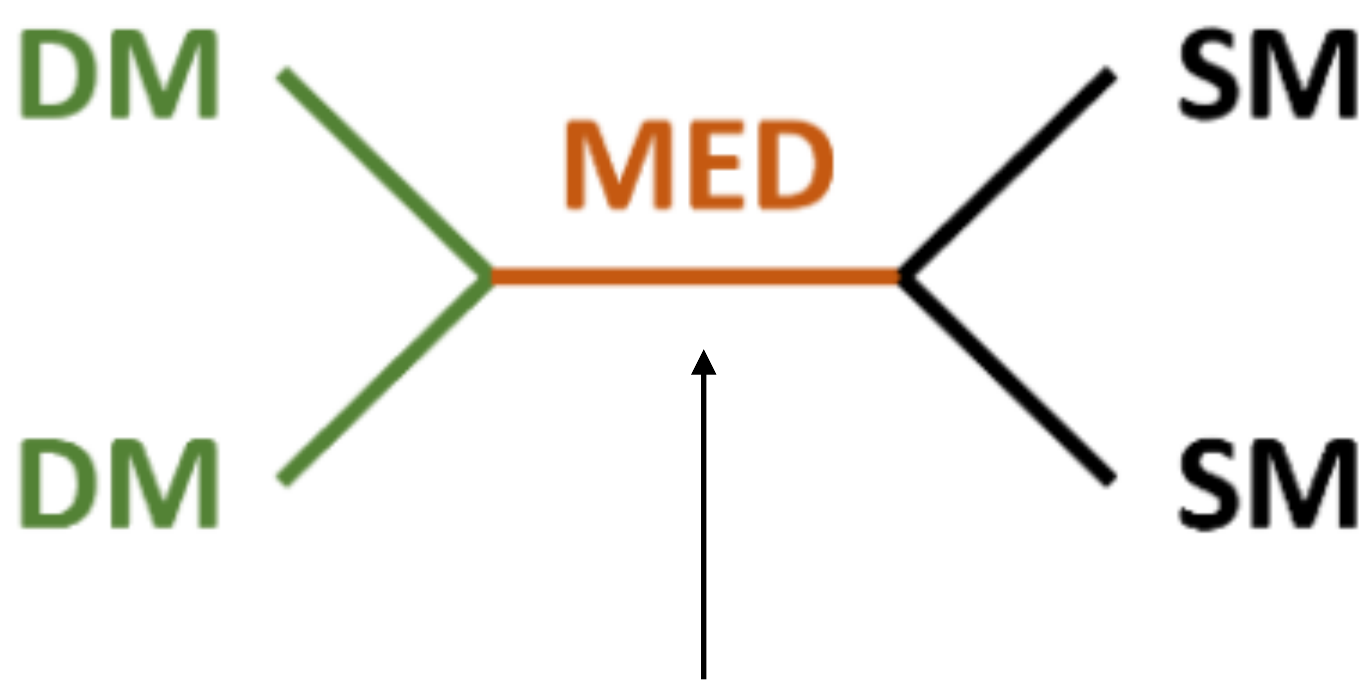


- COSI is expected to detect continuum γ-ray.
- Direct detection is not effective due to the suppression of t,u-channel diagrams.
- Future accelerator can detect visible mediator.
- Future accelerator cannot detect invisible mediator.

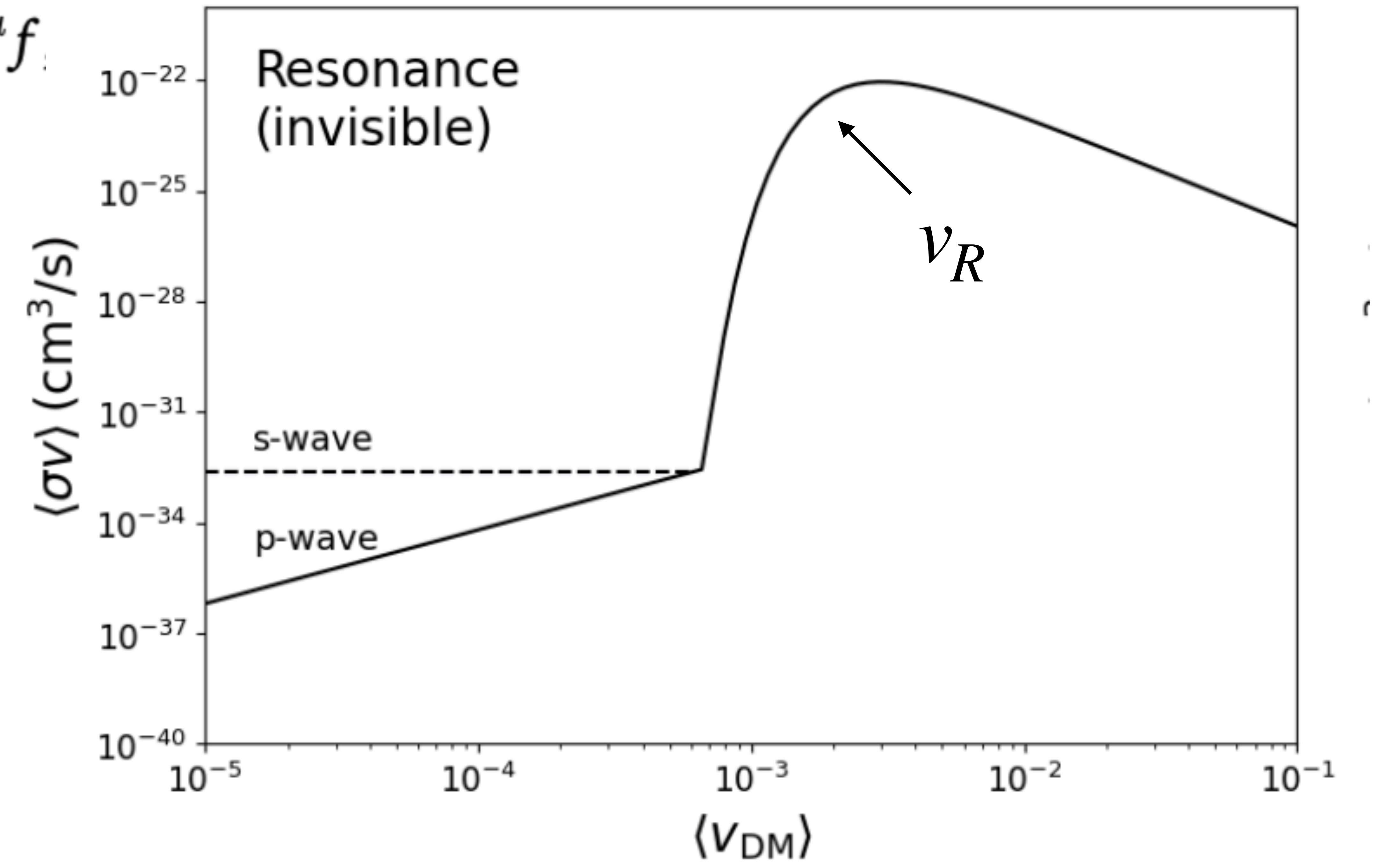
S-channel(invisible)

- We consider SV($\mathrm{U(1)_B}$) 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.

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



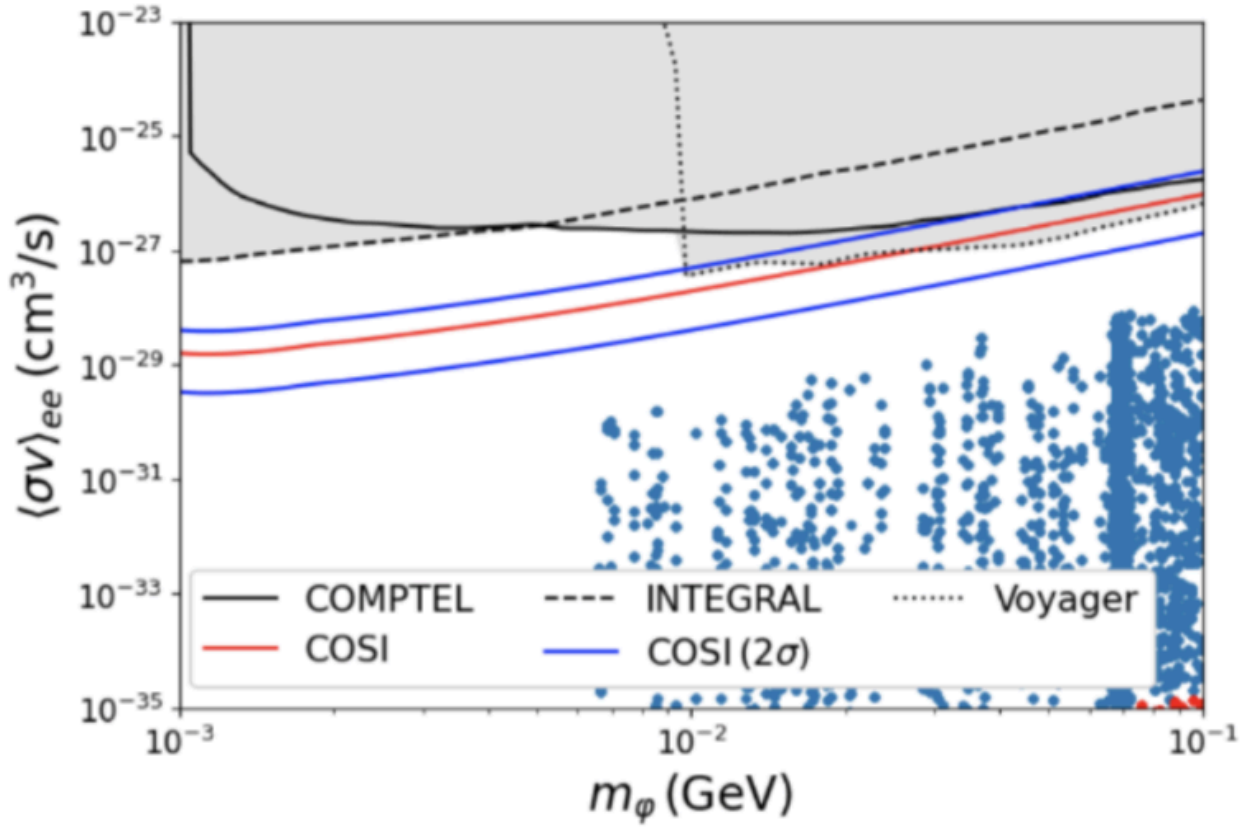
$$\frac{1}{(s - m_{\rm MED}^2)^2 + s\Gamma_{\rm MED}^2(s)} \simeq \frac{1}{m_{\rm DM}^4}\frac{1}{(v^2 - v_R^2)^2 + 16(\Gamma_{\rm MED}(s)/m_{\rm MED})^2}$$



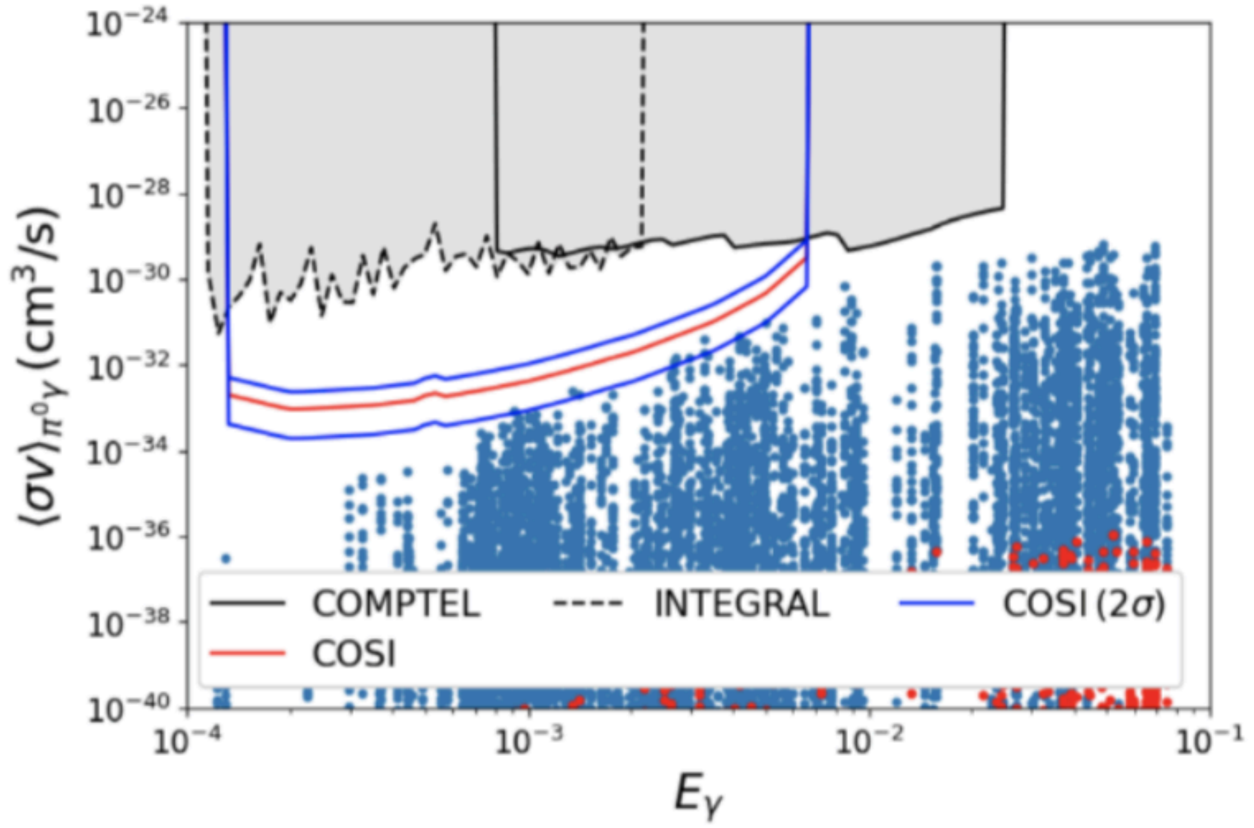
We find out viable parameter region and compare its prediction of the MeV γ-ray signal to the COSI sensitivities.

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

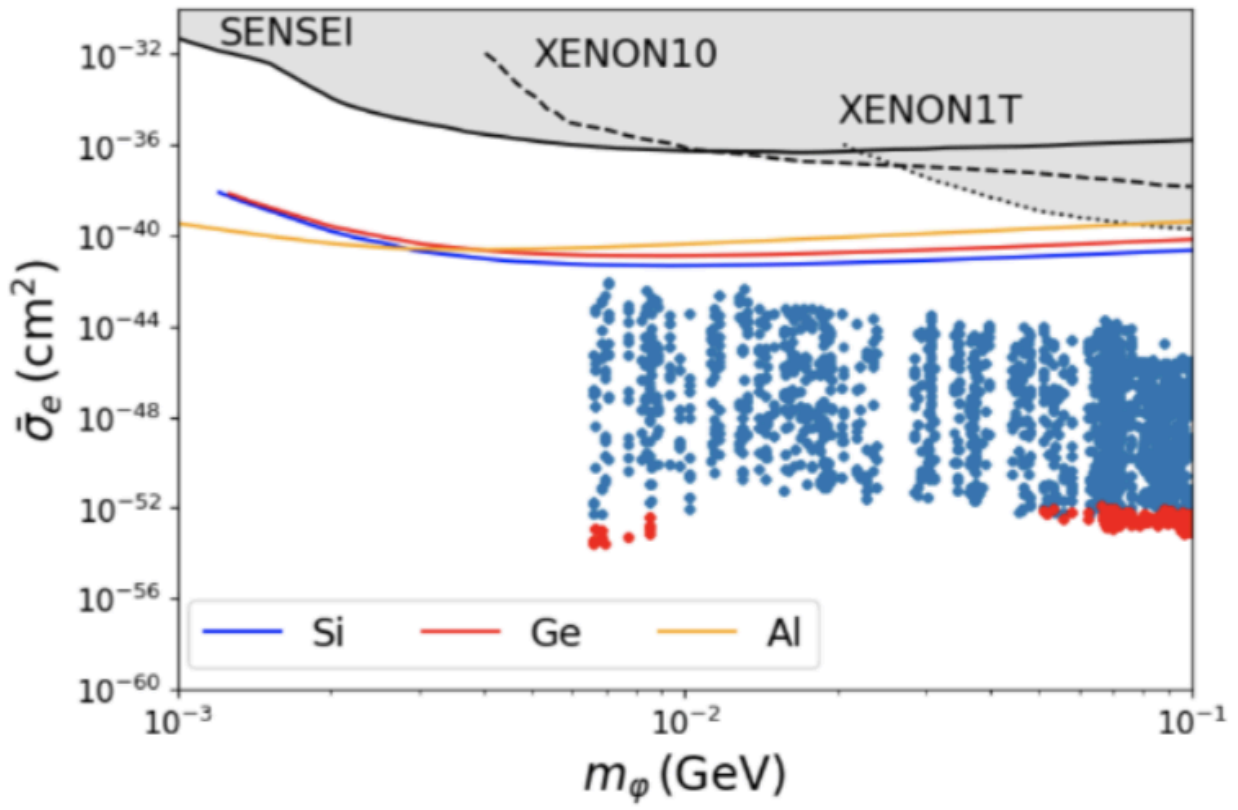
- Indirect detection (continuum)



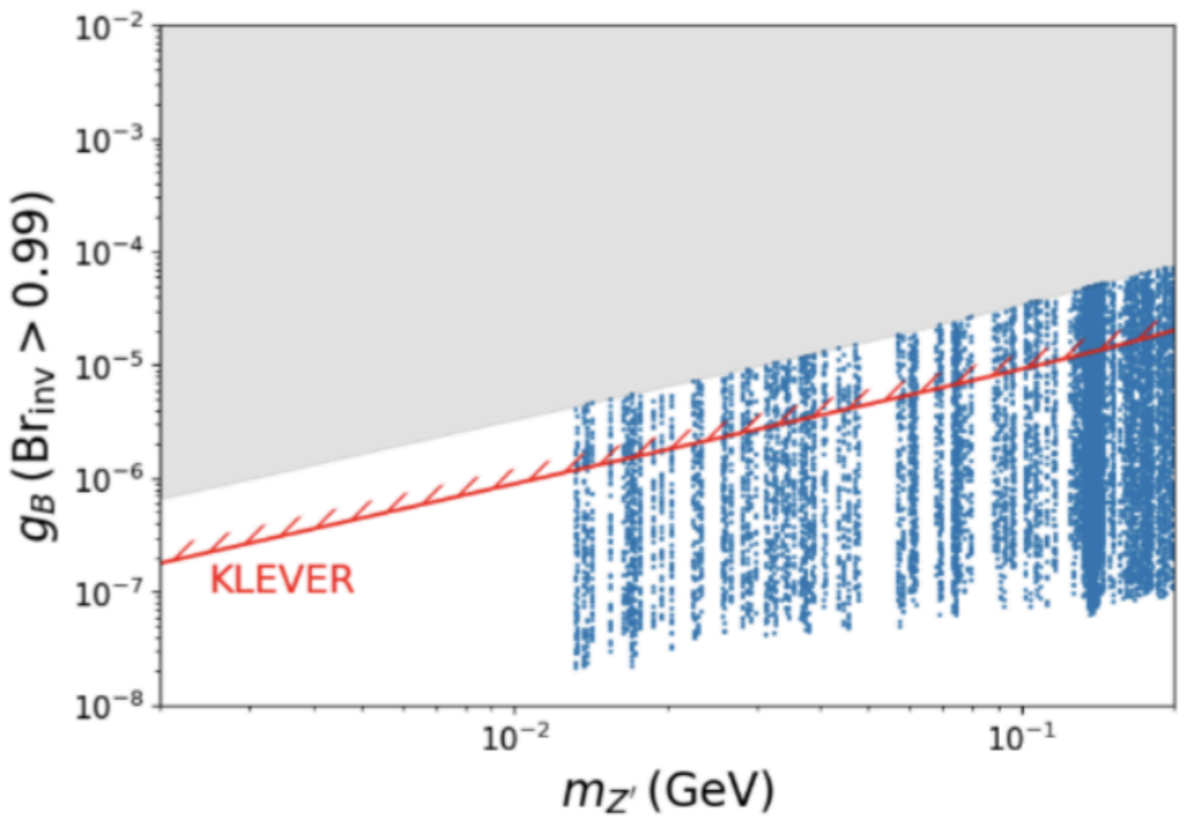
- Indirect detection (line)



- 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.
- IPMU officialy comits to the project and I am involved as a member of the COSI DM science team. From the COSI view point, it is important to study light thermal DM complehensively and figure out whether the COSI can prove them.
- 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. **The results are summarized in the following table**:

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

○ (black) ∃ surviving parameters

○ (blue) COSI can detect continuum γ-ray

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