Light neutrinophilic WIMP in the $\mathrm{U(1)_{B-L}}$ model

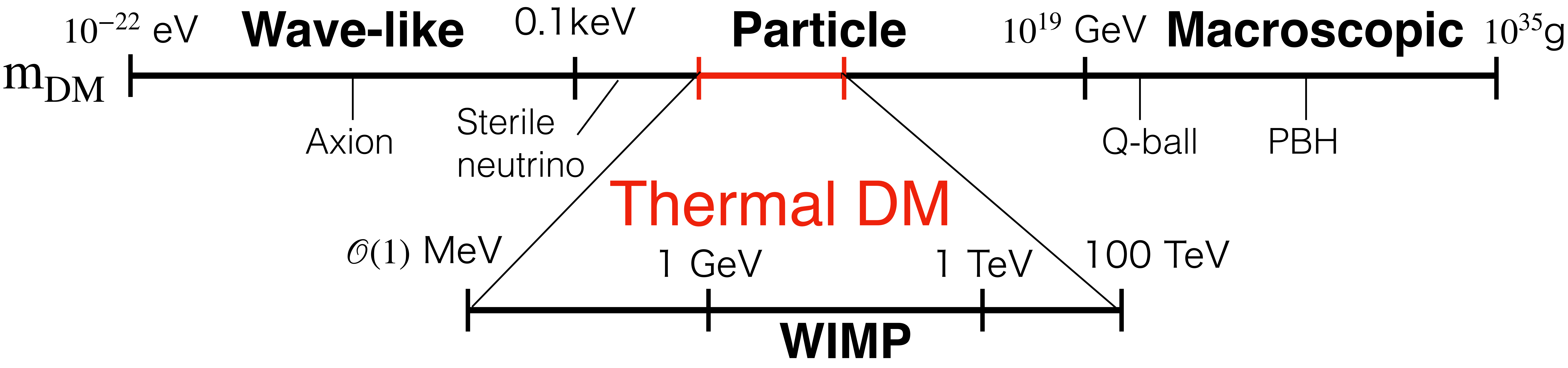
(In progress)

Yu Watanabe
(IPMU)

with Shigeki Matsumoto(IPMU),Yuki Watanabe(IPMU),
Tatsuya Aonashi(IPMU)

DM candidates

Mass range spans almost 90 orders of magnitudes…

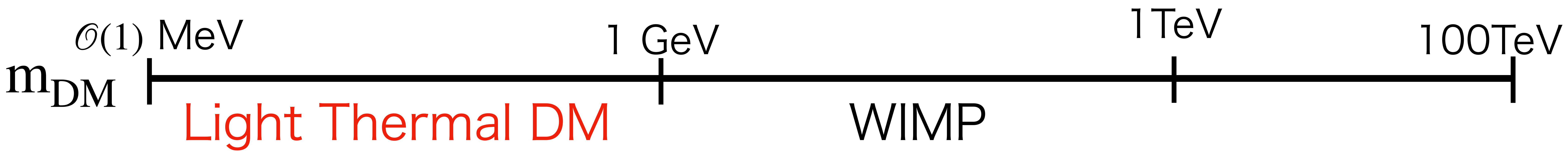


- ∃Various candidates, and one of the most attractive candidate is the thermal DM.

  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.

Light thermal DM

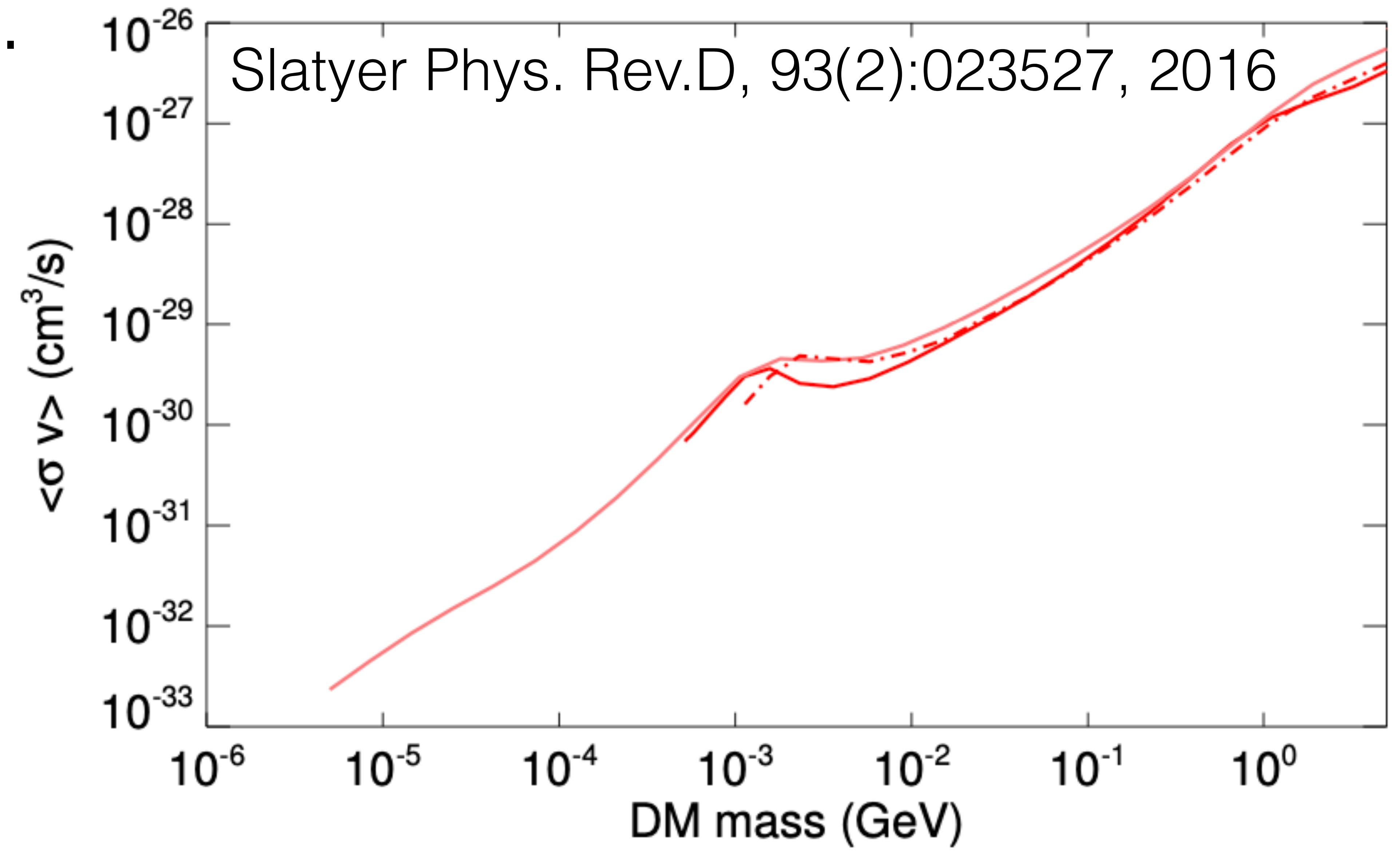


- **Motivation**
  - WIMP has been intensively searched for due to the 'WIMP miracle' and the connection to the EWSB (SUSY, UED, Little Higgs), however not found.
  - Different mass region, light and heavy thermal DMs, are getting more attention.
  - The light thermal DM may solve the core-cusp problem.
- **Model**
  - DM should be singlet under SM gauge group. ($\because$ Relic abundance)
  - Minimal model (SM + scalar DM: Higgs portal) was already excluded.
  - Next minimal model is SM + DM + mediator.
  - MED should be singlet ($\because$ Collider) and $m_{MED} \sim m_{DM}$. ($\because$ Relic abundance)

We consider SM + light singlet DM + light singlet MED models.

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.
- Several mechanisms can be utilized to overcome this.
    - Different proceses (Co-annihilation, SIMP, ADM….)
    - Non-standard cosmology (late-time inflation)
    - Velocity-dependent annihilation
    - Annihilations into harmless particles (neutrino)



- We found neutrinophilic parameter region in models with $\mathrm{U(1)_{B-L}}$ vector mediator.

As an example, we consider SM + singlet scalar DM + $\mathrm{U(1)_{B-L}}$ vector mediator model.

SM + Scalar DM + $\mathrm{U(1)_{B-L}}$ mediator model

- Gausing $\mathrm{U(1)_{B-L}}$ needs the right-handed neutrinos, N to cancel the anomaly.
- We also consider the scalar DM, φ and $\mathrm{U(1)_{B-L}}$ breaking scalar, S.
- After EWSB, $\mathrm{U(1)_{B-L}}$ boson mixes with $\mathrm{U(1)_Y}$ boson.

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$	Z_2
S	1	1	0	2	+
N_i	1	1	0	−1	+
φ	1	1	0	q_φ	−

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm BL} + \mathcal{L}_{\rm DM},$$

$$\mathcal{L}_{\rm BL} = -\frac{1}{4} V^{\mu\nu} V_{\mu\nu} + |D_\mu S|^2 + \sum_{i=1}^{3} \bar{N}_i i\gamma^\mu D_\mu N_i + V(S,H)$$
$$- g_{\rm B-L} V_\mu J^\mu_{\rm B-L} - \frac{\xi}{2} B_{\mu\nu} V^{\mu\nu} - \sum_{i,j=1}^{3} \left[y^{(\nu)}_{ij} \bar{L}_i H N_j + \frac{1}{2} y^{(N)}_{ij} \bar{N}^c_i N_j S + h.c. \right],$$

$$\mathcal{L}_{\rm DM} = |D_\mu \varphi|^2 - M_\varphi^2 |\varphi|^2 - \frac{\lambda_{\varphi H}}{4} |\varphi|^2 |H|^2 - \frac{\lambda_{\varphi S}}{4} |\varphi|^2 |S|^2 - \frac{\lambda_\varphi}{4} |\varphi|^4,$$

EFT @ MeV scale

- After diagonalizing the mass matrix, the following interactions are obtained.
  - SM-MED:
    - Lepton: $g_{\mathrm{B-L}}\, \bar{\nu}_{L,i} \not{Z}' \nu_{L,i} + (g_{\mathrm{B-L}} - \xi g' \cos^2\theta_W)\, \bar{\ell} \not{Z}' \ell$
    - Pion: $(g_{\mathrm{B-L}} - \xi g' \cos^2\theta_W)\, \epsilon^{\mu\nu\rho\sigma} (\partial_\mu \pi^0) \left\{ (\partial_\nu A_\rho) Z'_\sigma + (\partial_\nu Z'_\rho) A_\sigma \right\}$
    - Nucleon: $-(g_{\mathrm{B-L}} - \xi g' \cos^2\theta_W)\, \bar{p} \not{Z}' p - g_{\mathrm{B-L}}\, \bar{n} \not{Z}' n$
  - DM-MED:

$$-i\, q_\varphi\, g_{\mathrm{B-L}}\, Z'^\mu (\varphi^* \overleftrightarrow{\partial}_\mu \varphi) + (q_\varphi\, g_{\mathrm{B-L}})^2 Z'^\mu Z'_\mu |\varphi|^2 - \lambda_\varphi/4\, |\varphi|^4$$

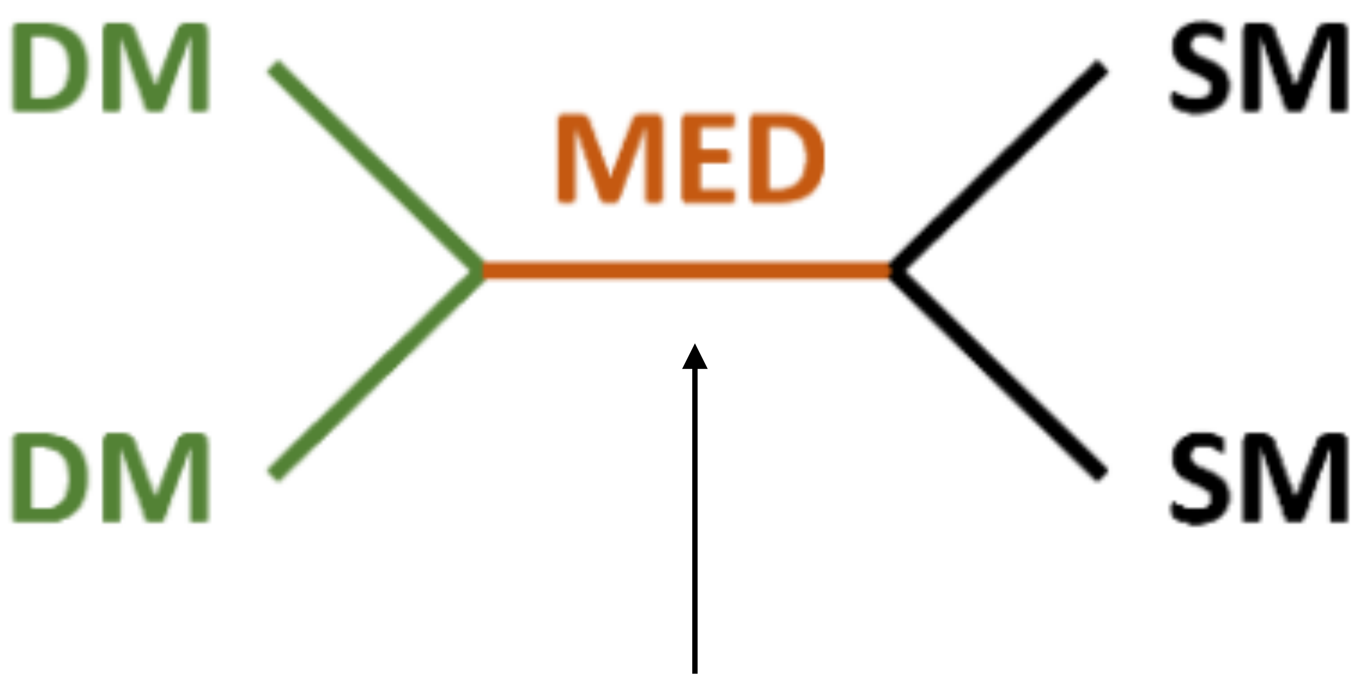
- When $g_{\mathrm{B-L}} \simeq \xi g' \cos^2\theta_W$, DM interacts only with ν and n.
- ∴ Experimental constraints are weak.

We investigate if ∃parameter sets survinving from present constraints.

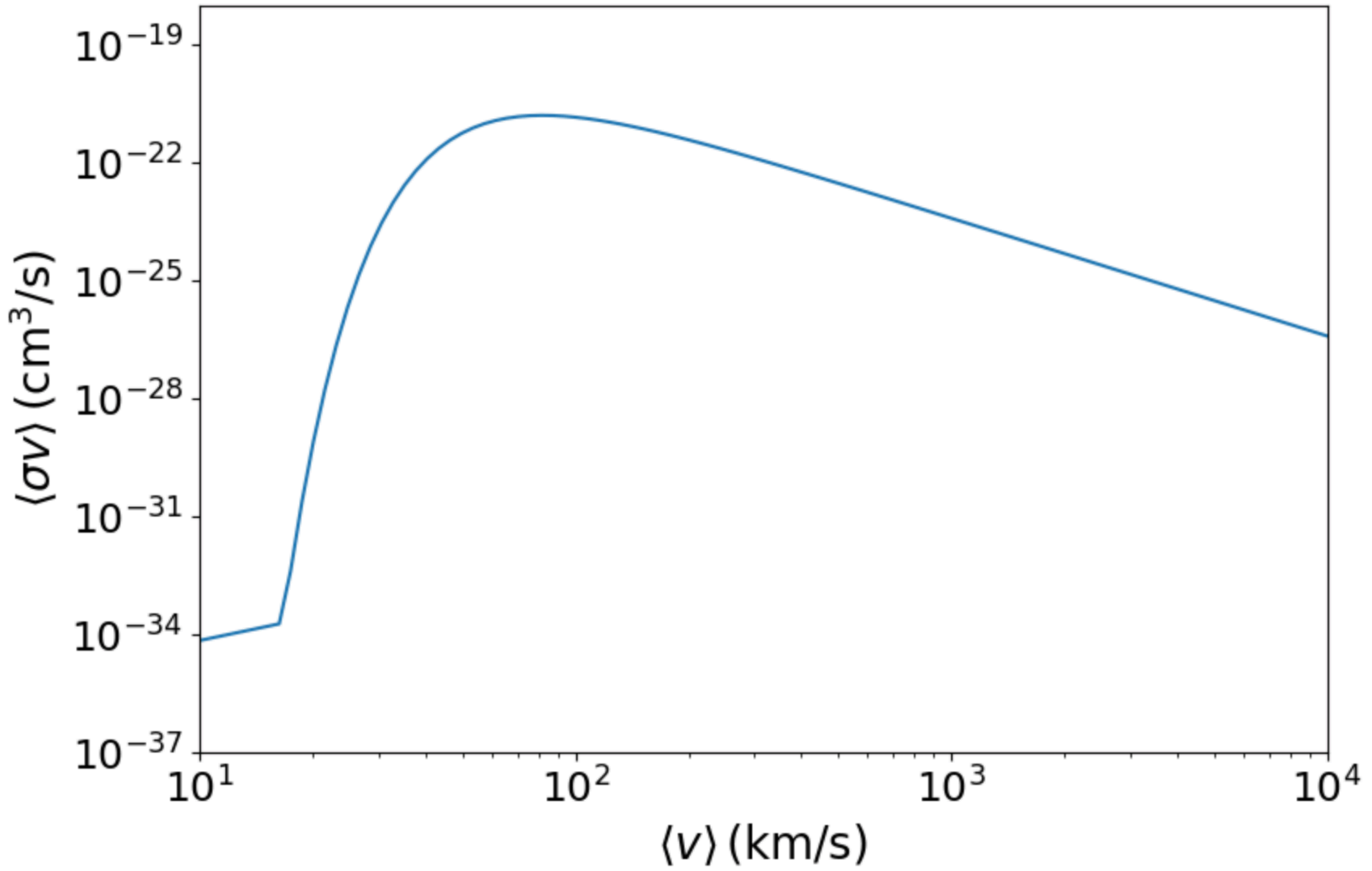
Benchmark point

- We consider the following benchmark point as an example.
- We assume $2m_{\rm DM} \lesssim m_{\rm MED} \equiv 2m_{\rm DM}(1+v_R^2/8)$ to solve the core-cusp problem. DM annihilates into $\nu\nu$ via MED in s-channel, and at $v_{\rm DM} = v_{\rm R}$, the annihilation hitts the resonance.

m_φ (MeV)	$v_{\rm R}$ (km/s)	$g_{\rm B-L}$	q_φ
7.7	100	9.23e-11	2.11e7



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



We investigate if this parameter set survives from present experiments and observations, and solves the core-cusp problem.

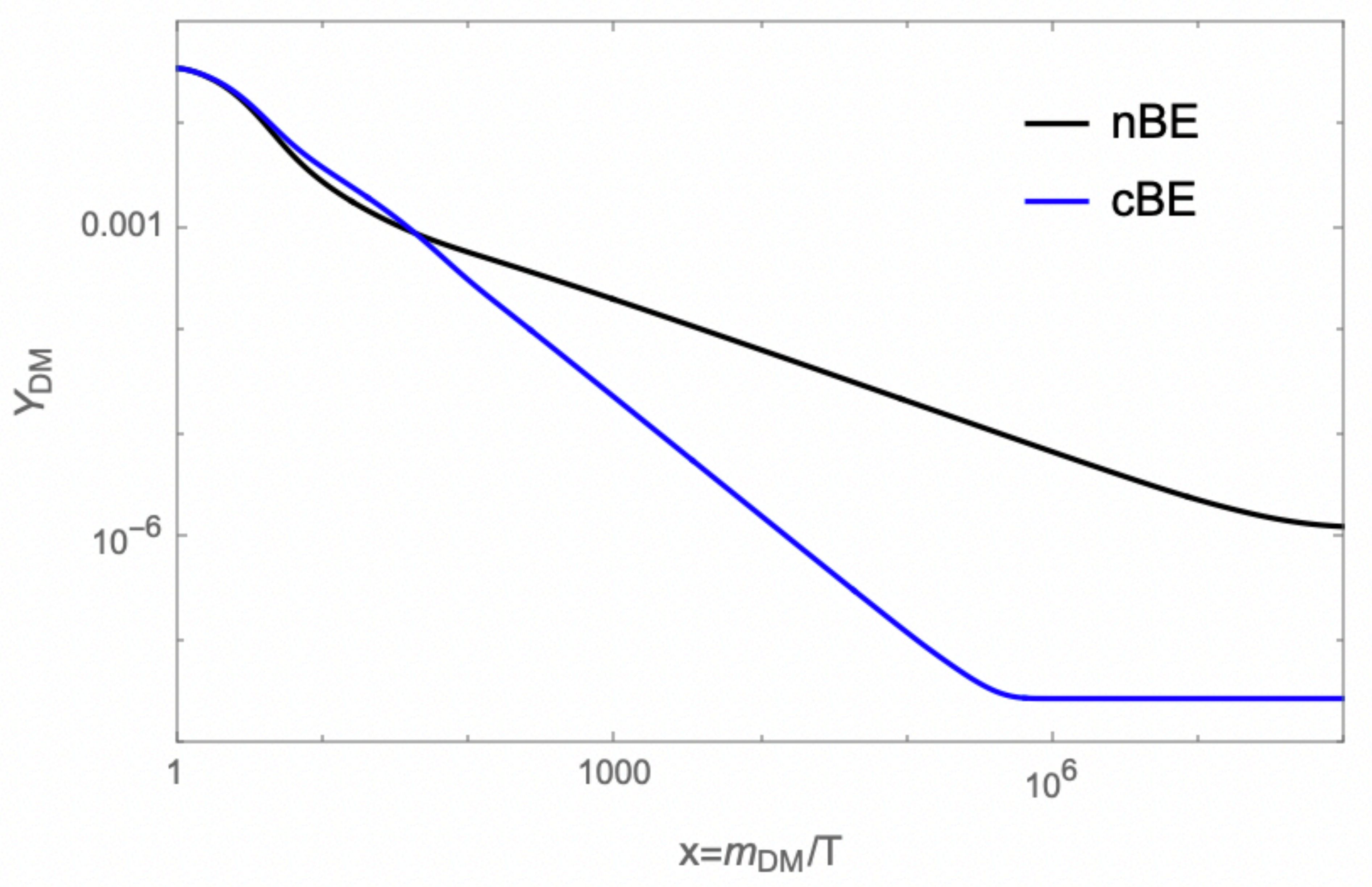
Constraints from cosmology

- CMB
  - Constraint on $\langle \sigma v \rangle$: Alleviated $\because$ Neutrinophilic
  - Constraint on $m_{\rm DM}$: asymmetrical entropy injection into EM-plasma and ν alters expansion rate of universe. $m_{\rm DM} \gtrsim 5\,{\rm MeV}$
- BBN
  - Constraint on $\langle \sigma v \rangle$: Photons emitted by DM annihilations may destroy the light elements. Alleviated $\because$ Neutrinophilic
  - Constraint on $m_{\rm DM}$: Light thermal particle affects $T_{\gamma(\nu)}$ and the expansion rate, then light element abundances. $m_{\rm DM} \gtrsim 2\,{\rm MeV}$
- Leptogenesis
  - Since $m_{\rm MED}$~10 MeV and $g_{\rm B-L}$~1e-10, ${\rm U(1)_{B-L}}$ breaking scale ~ 1e8 GeV. $\therefore$ Sufficient baryon asymmetry can be produced.

Benchmark point survives from cosmological constraints and can explain baryon asymmetry.

Relic abundance

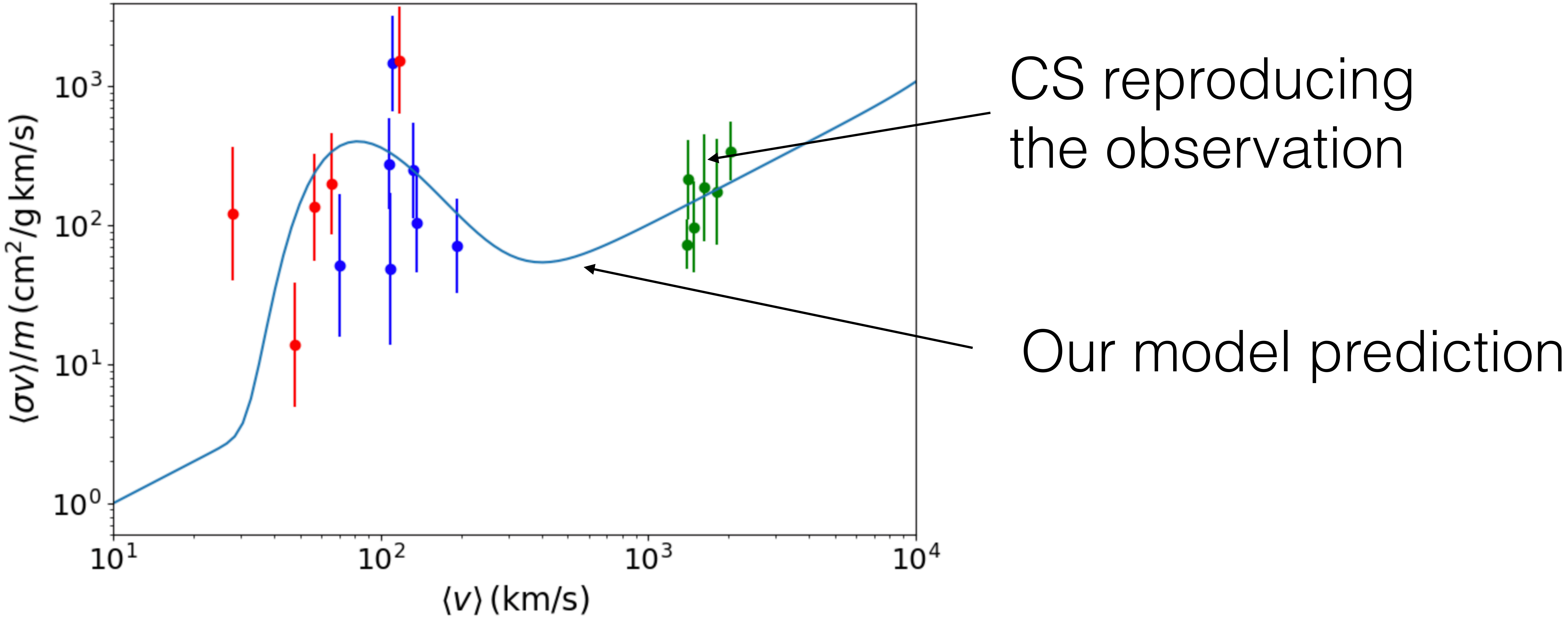
- Boltzmann eq: $\hat{L}[f] = \hat{C}_a[f] + \hat{C}_s[f]$ is numerically hard.
- Standard simplification is assuming kinetic equilibrium and using 0th moment $n_{\rm DM}$.
  $\rightarrow \dot{n} + 3Hn = - <\sigma v> (n^2 - n_{eq}^2)$
- In the resonant case, annihilations are enhanced, however scattering are not.
  $\therefore T_{DM} \neq T_{SM}$ (Early kinetic decoupling)
- We consider 1st moment $T_{\rm DM}$ with DRAKE code (T.Bibder…Eur. Phys. J. C, 81:577, 2021).



Benchmark point predict $\Omega h^2 = 0.119 \simeq \Omega_{\rm Planck} h^2 = 0.12$

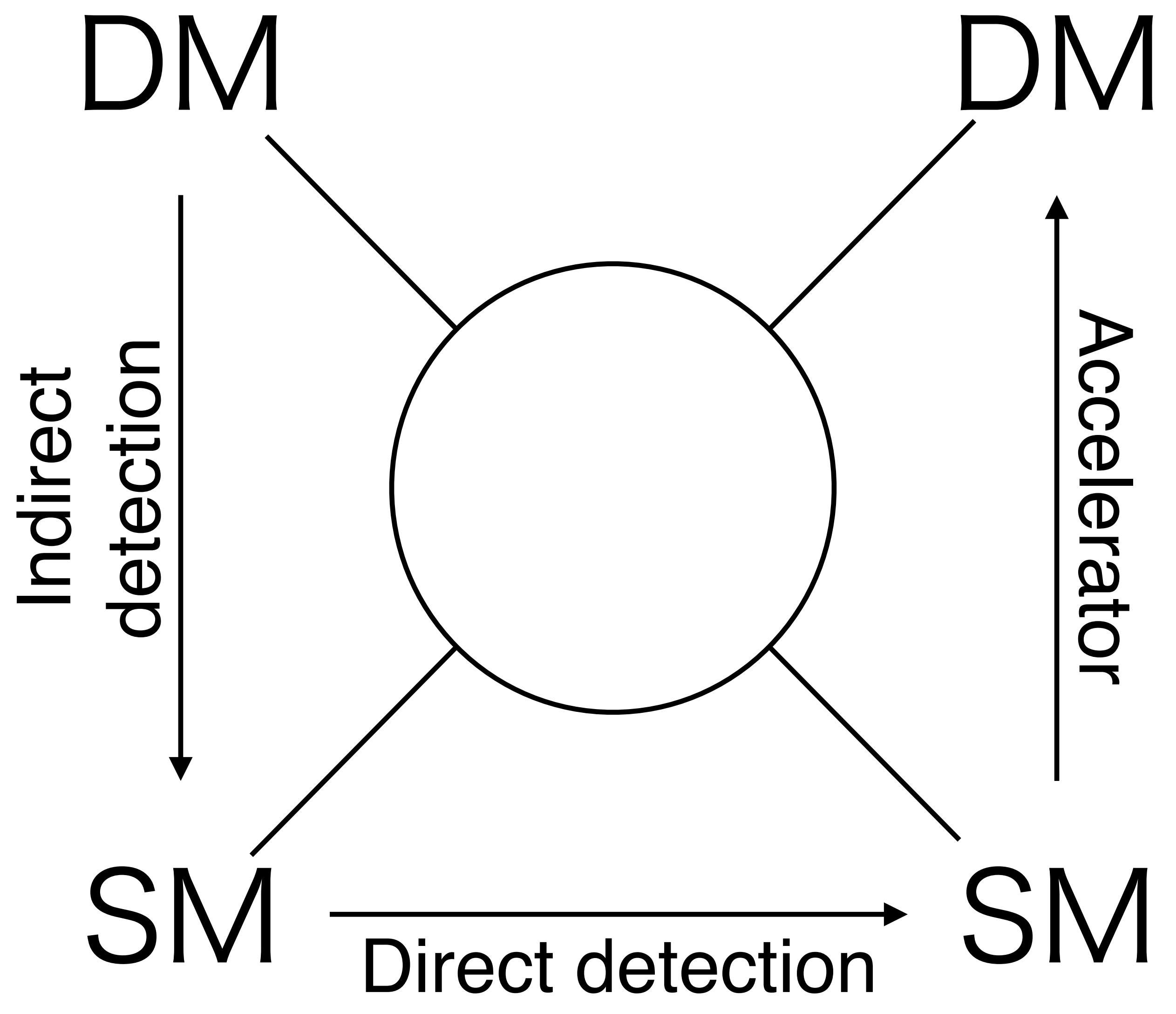
Self-Scattering

- Core-Cusp problem ⋯ mismatch of DM density profiles at the GC prefered by simulation(cusp) and observation(core).
- Self-scattering of DM may solve this by thermalizing DM at the GC.



Benchmark point can solve core-cusp problem.

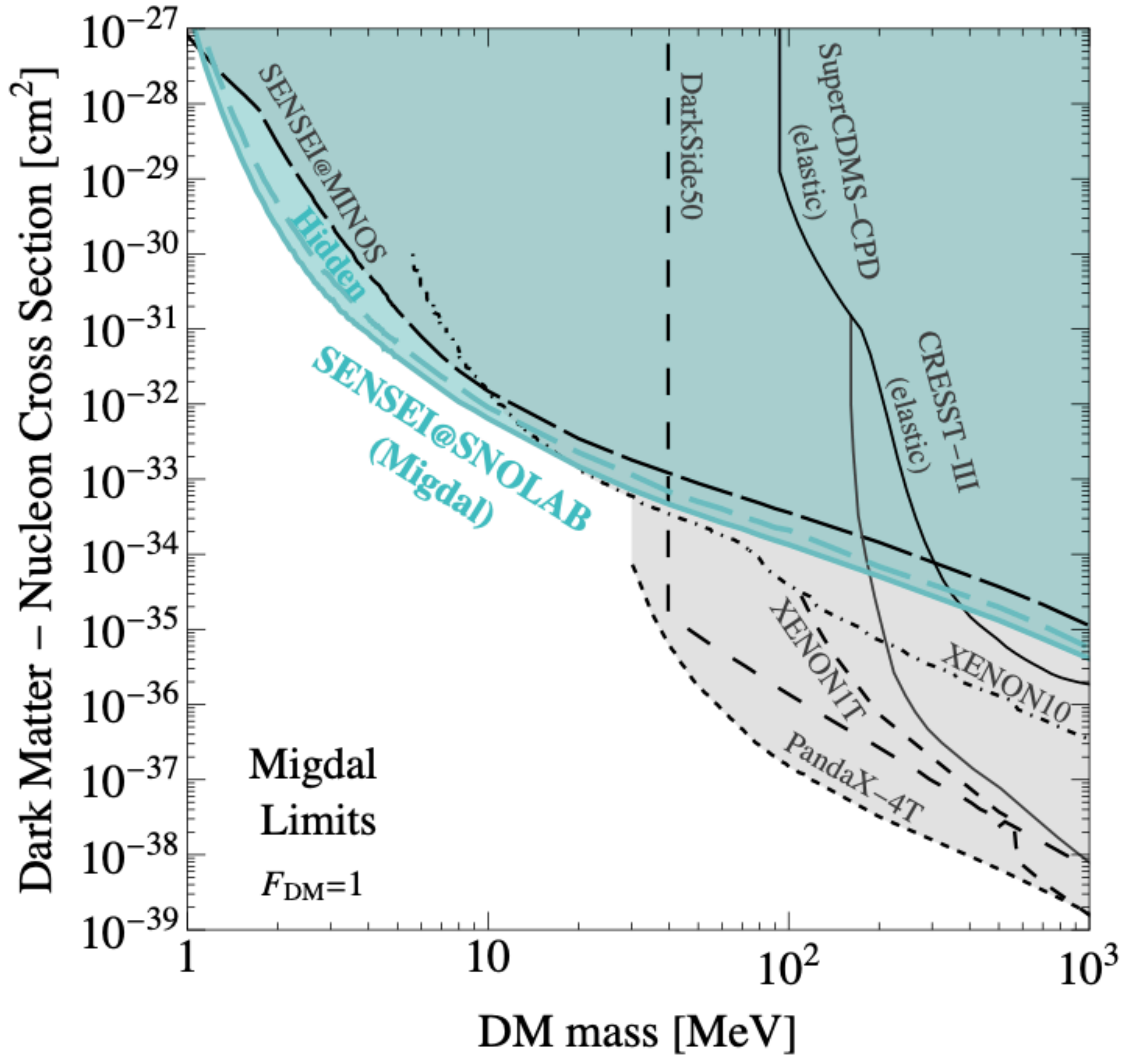
Detection of DM



- ∃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.
- Benchmark point: Only interacts with n. The scattering is suppressed compared to the annihilation. $\to \sigma_n \sim 10^{-51}\,\mathrm{cm}^2$

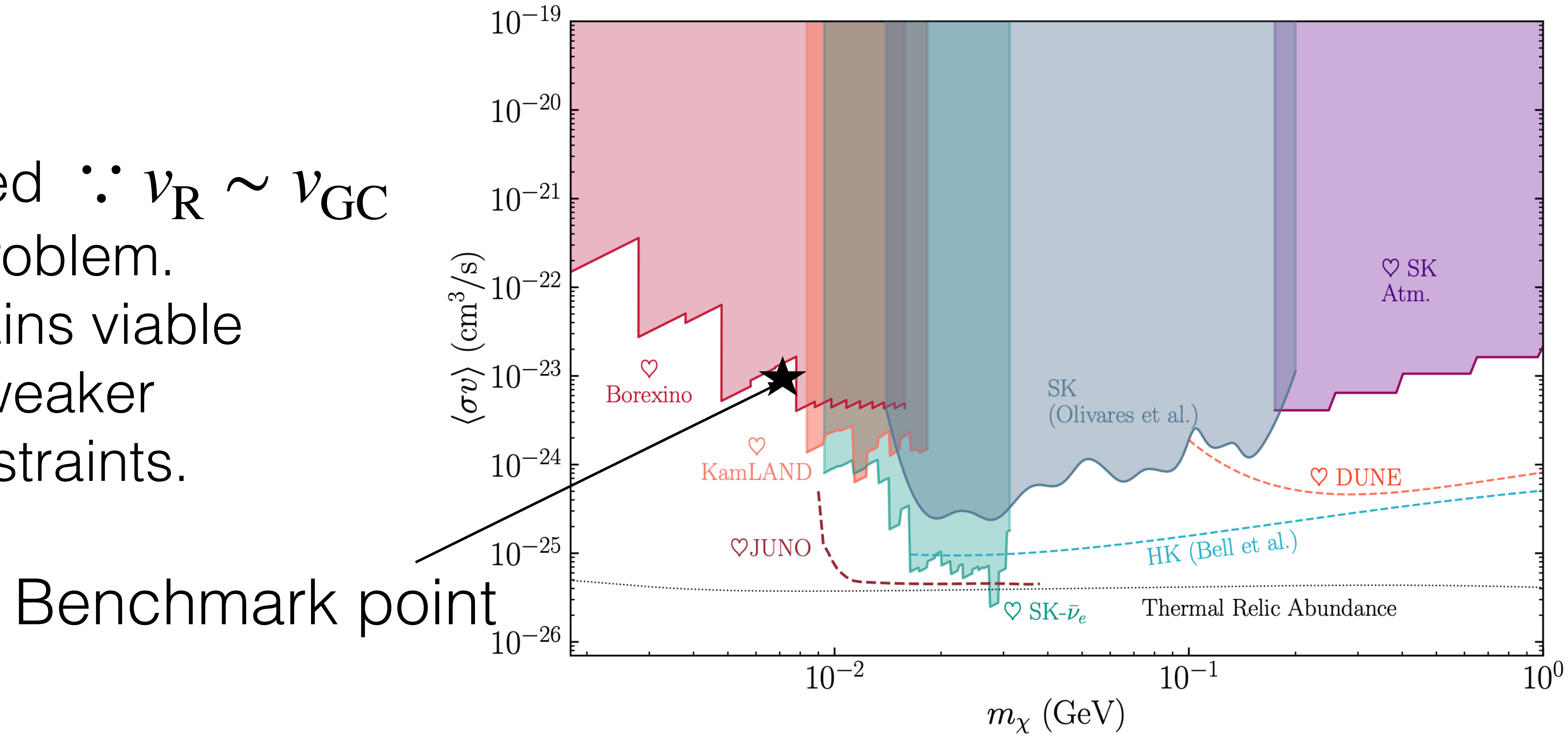


Accelerator (Production of DM by high energy SM particles collisions)

- MED does not interact with e, p and $\pi^0\gamma$.
- $\therefore$ No strong constraints.

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

- DM can produce ν.
- The annihilation is enhanced $\because v_R \sim v_{GC}$ to explain the core-cusp problem.
- The benchmark point remains viable because the constraint is weaker compared to the γ-ray constraints.



The benchmark point survives from all of the present experiments and observations, and solves the core-cusp problem thanks to the neutrinophilic nature.

Summary

- **Light Thermal DM** is getting more and more attention.
- There are stringent constraints different from traditional WIMP, and the **neutrinophilic DM** offers an effective way to overcome them. We identified this region in the gaused $\mathrm{U(1)_{B-L}}$ model, and explored **SM + singlet scalar DM and $\mathrm{U(1)_{B-L}}$ vector mediator model** as an example.
- We confirmed the existence of the parameter set solving the core-cusp problem, explaining the relic density via freeze-out mechanism and surviving from all of the current experiments and observation, taking a benchmark point.

Backup

Is $g_{\mathrm{B-L}} \simeq \xi g' \cos^2\theta_W$ fine-tuning?

- Our model is indistinguishable from the $\mathrm{U(1)_{B-L+xY}}$ extension of SM.
- Our model can be regarded as one example of $\mathrm{U(1)_{B-L+xY}}$

$$D_\mu = \partial_\mu - i\left(g_S G_\mu + g W_\mu + g' Y B_\mu + g_{\mathrm{B-L}} q V_\mu\right),$$

$$B_\mu \to B_\mu + \frac{g_{\mathrm{B-L}}}{g'} x V_\mu,$$

$$D_\mu \to D_\mu = \partial_\mu - i\left[g_S G_\mu + g W_\mu + g' Y B_\mu + g_{\mathrm{B-L}}(q + xY)V_\mu\right].$$

$$\begin{aligned}\mathscr{L}_{\mathrm{B-L}} \supset& -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{\xi}{2}B_{\mu\nu}V^{\mu\nu}\\ &\to -\frac{1}{4}\left(1 + 2\frac{g_{\mathrm{B-L}}}{g'}x\xi + \frac{g_{\mathrm{B-L}}^2}{g'^2}x^2\right)V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}\left(\frac{g_{\mathrm{B-L}}}{g'}x + \xi\right)B_{\mu\nu}V^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}.\end{aligned}$$