Indirect search for sub-GeV dark matter with neutrino telescopes

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arXiv: 2011.03165 [hep-ph]

Collaborators: Kento Asai (Yokohama Natl. U), Koji Tsumura (Kyushu U)

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EXCELENCIA
MARÍA
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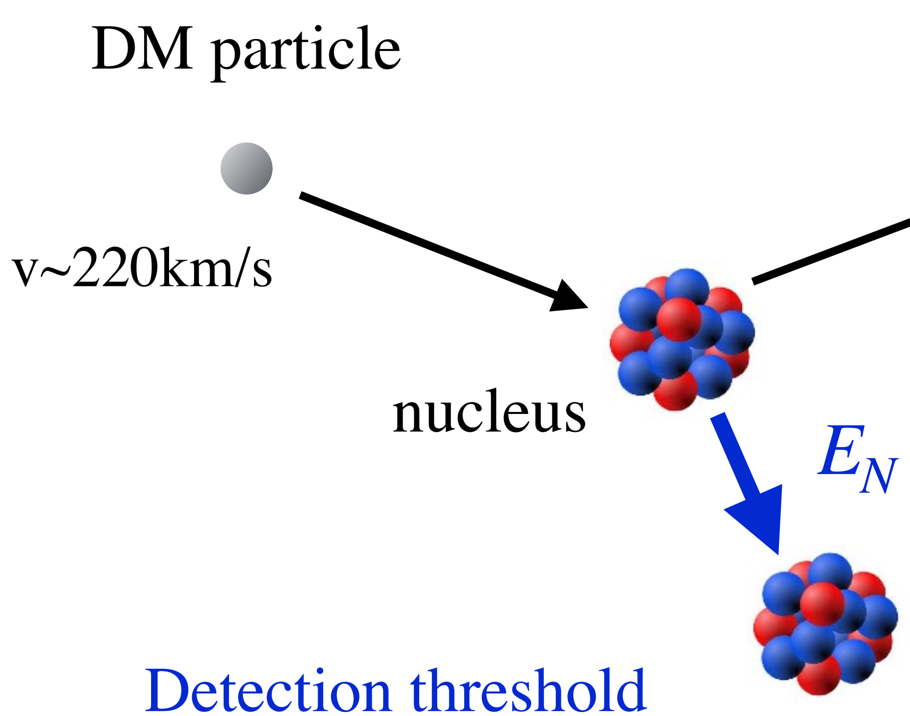
2020-2023

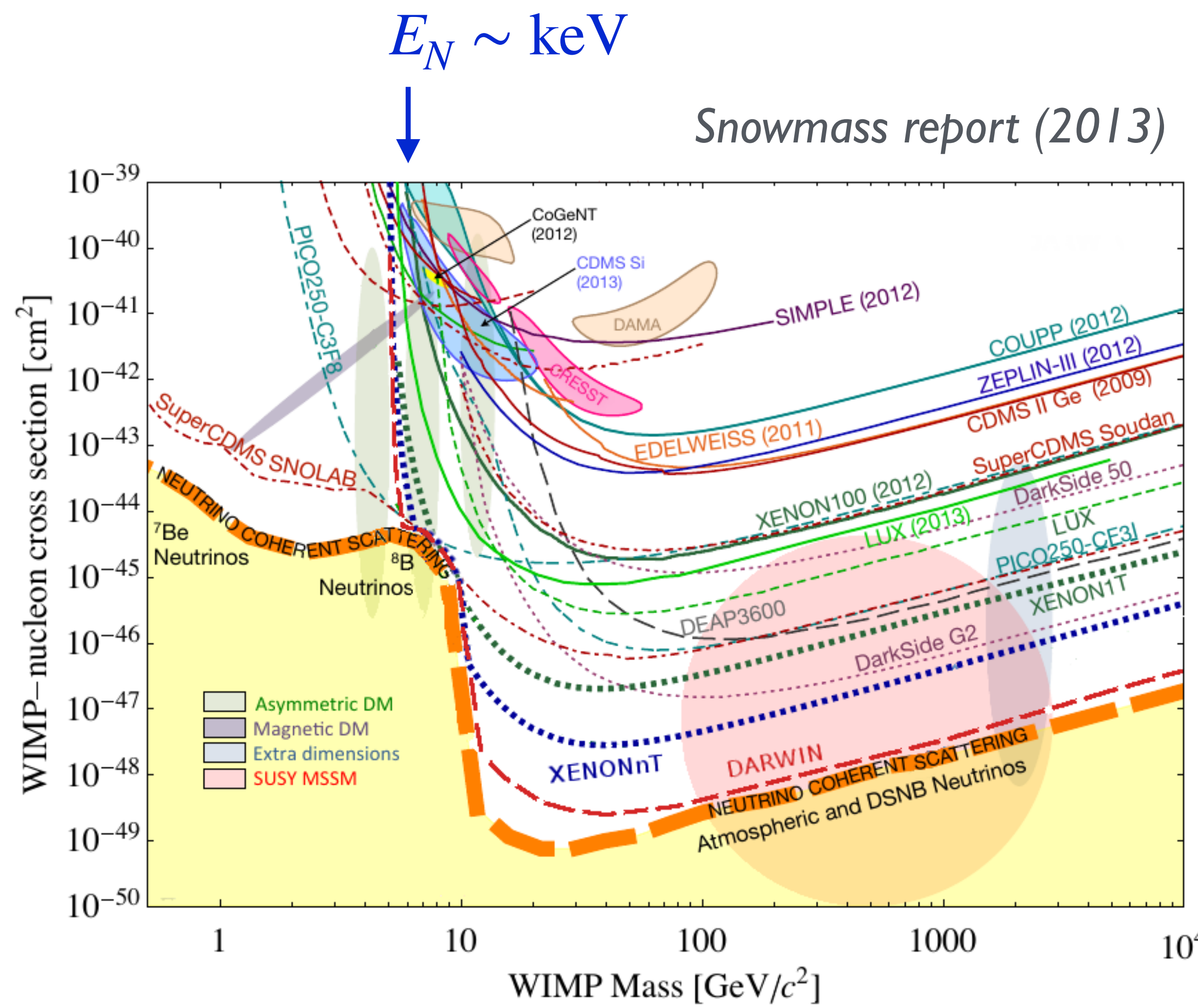
Motivation for sub-GeV dark matter

■ Direct detection of dark matter



Detection threshold

$E_N^{\mathrm{thr}} \sim 1 - 10\,\mathrm{keV}$



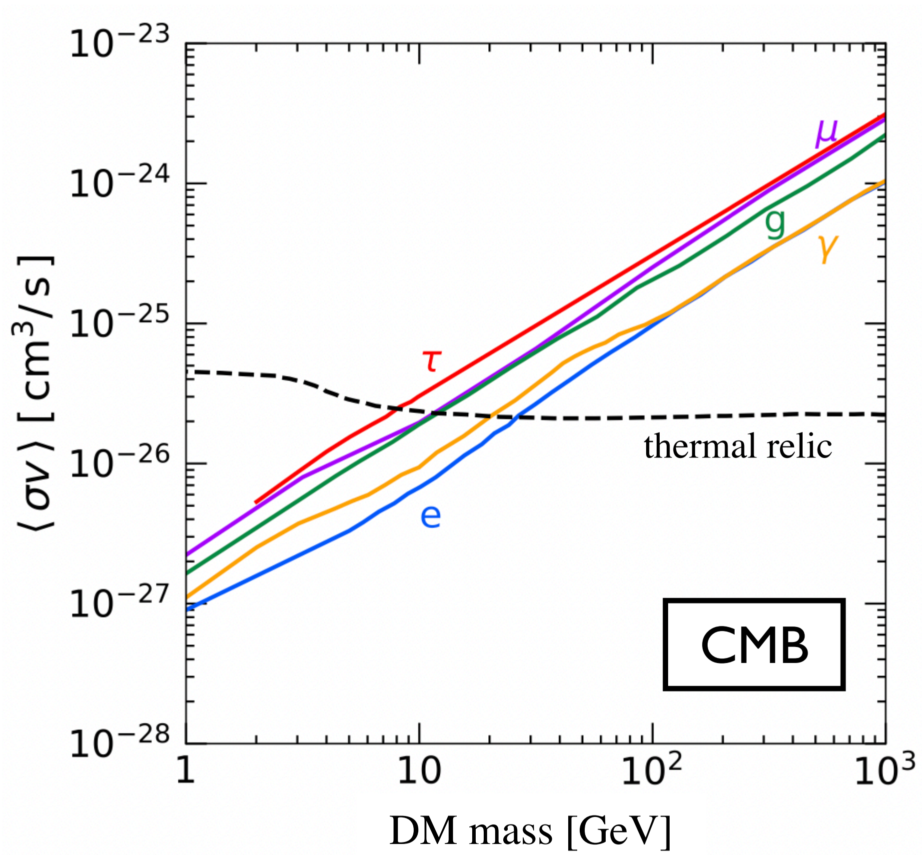
Snowmass report (2013)

$$E_N \le \frac{2\mu_{\mathrm{DM-N}}^2 v^2}{m_N} \simeq 0.1\,\mathrm{keV}\left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right)^2\left(\frac{20\,\mathrm{GeV}}{m_N}\right)$$

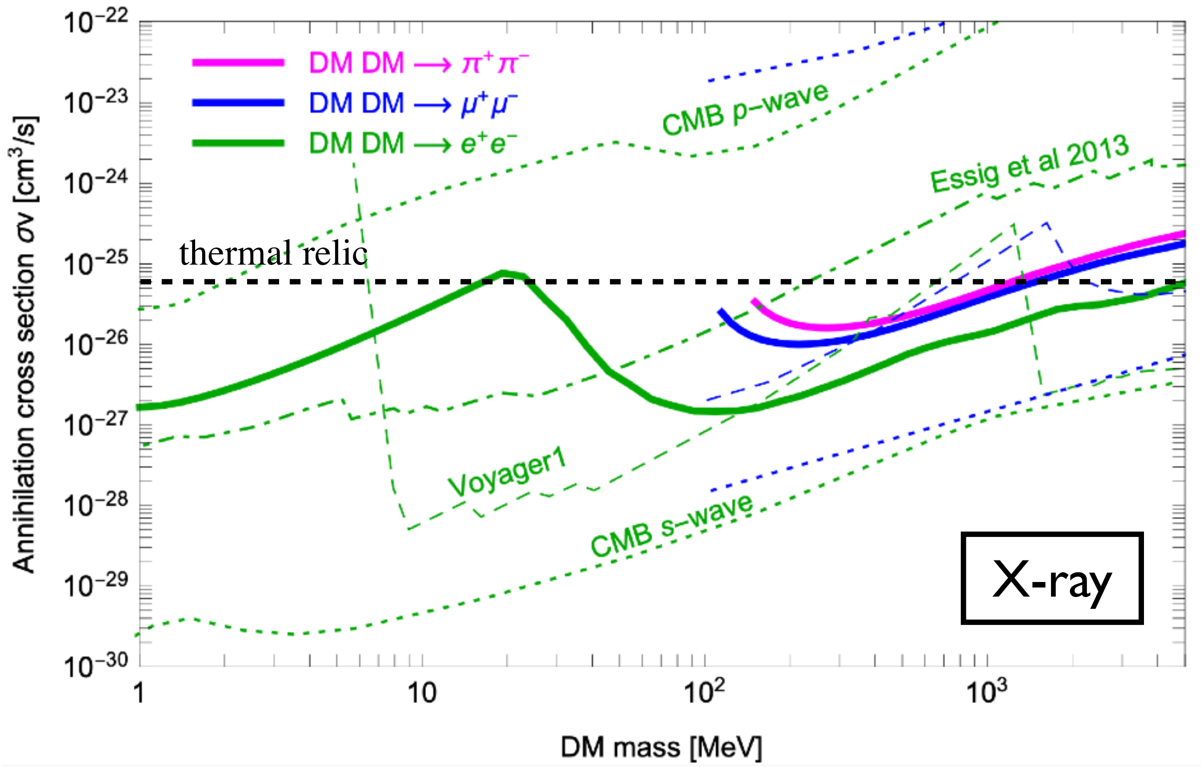
Direct detection hardly operates for light DM below a few GeV

Indirect detection constraints on sub-GeV DM

CMB observation and X-ray/gamma-ray searches strongly constrain DM annihilation to charged particles and photon



Leane, Slatyer, Beacom, Ng (2018)



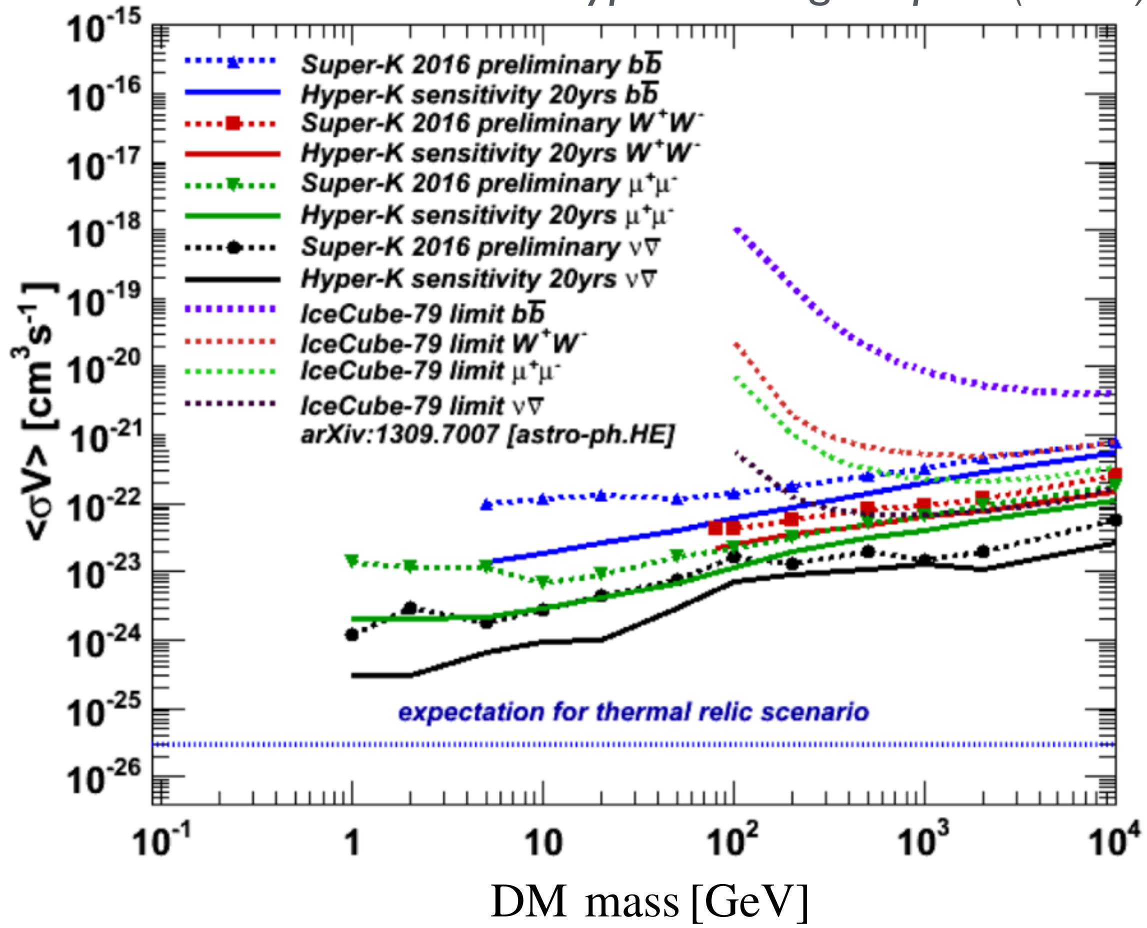
Cirelli, Fornengo, Kavanagh, Pinneti (2020)

- How about DM annihilation into neutrinos?

Indirect search with neutrino telescopes

- Traditional WIMP mass region
  - standard search programs in most neutrino telescopes experiments

Hyper-K design report (2018)



Indirect search with neutrino telescopes

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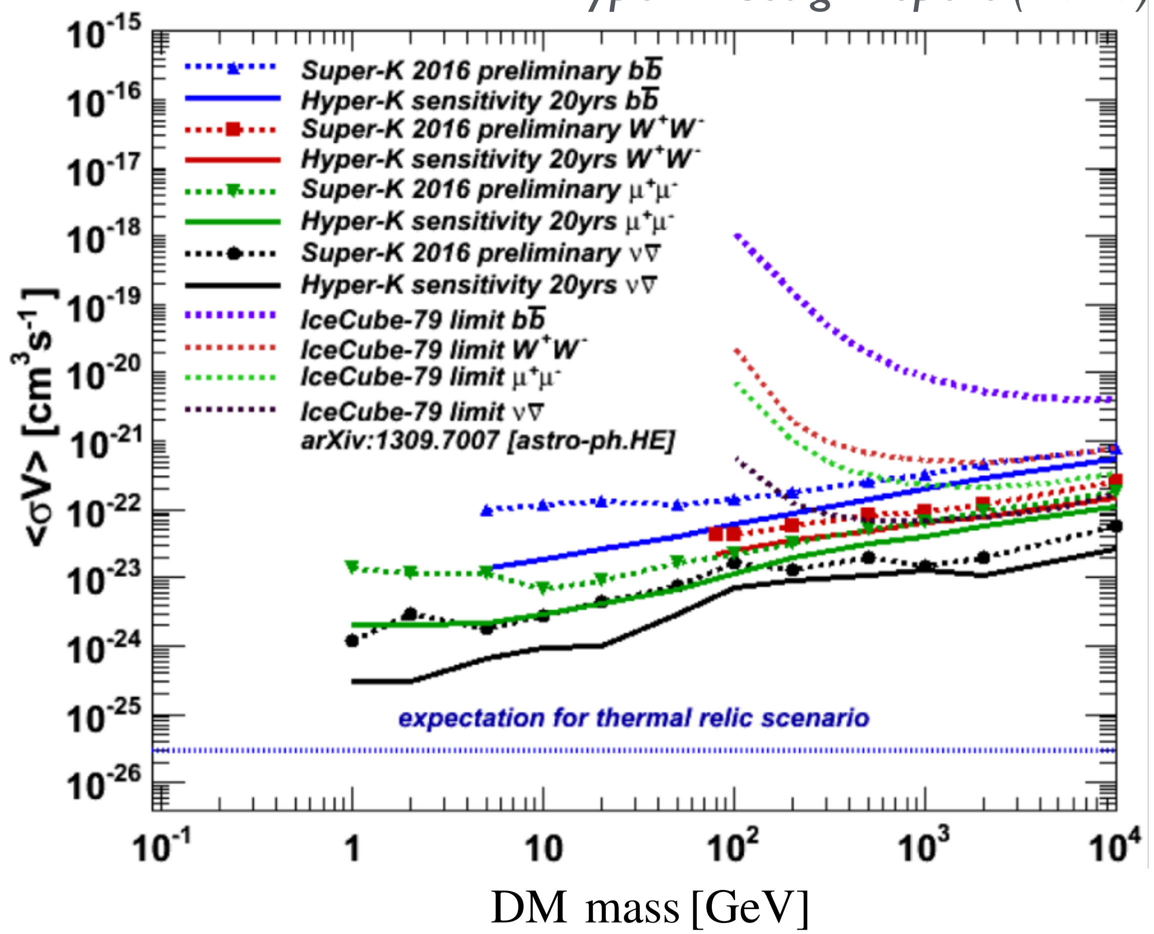

- Sub-GeV mass region
  - $\text{DM DM} \to \nu\bar{\nu}$
    - first analysis in 2007

Yüksel+ (2007), Palomares-Ruiz, Pascoli (2007)

Indirect search with neutrino telescopes

- Traditional WIMP mass region
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- Sub-GeV mass region
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      Yüksel+ (2007), Palomares-Ruiz, Pascoli (2007)
    - more quantitative analysis performed in the last 5 years

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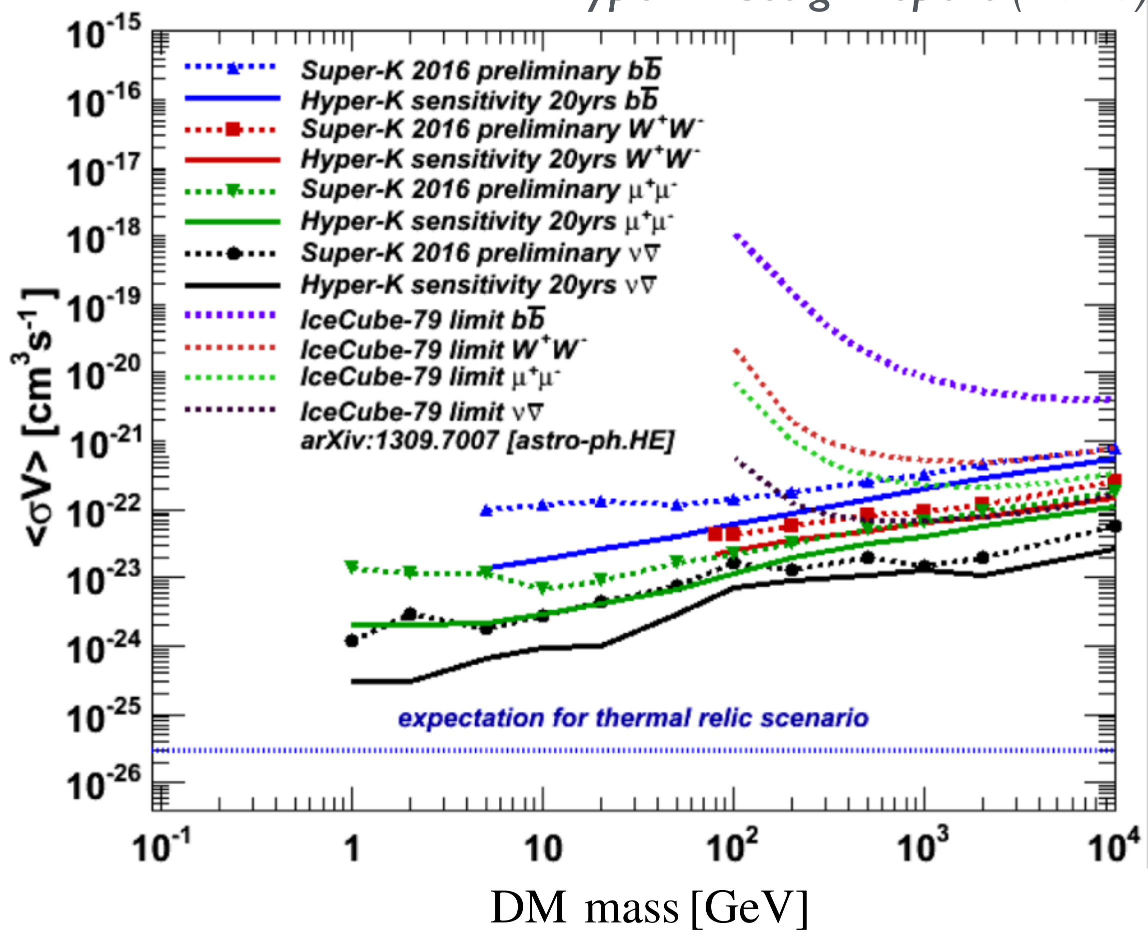
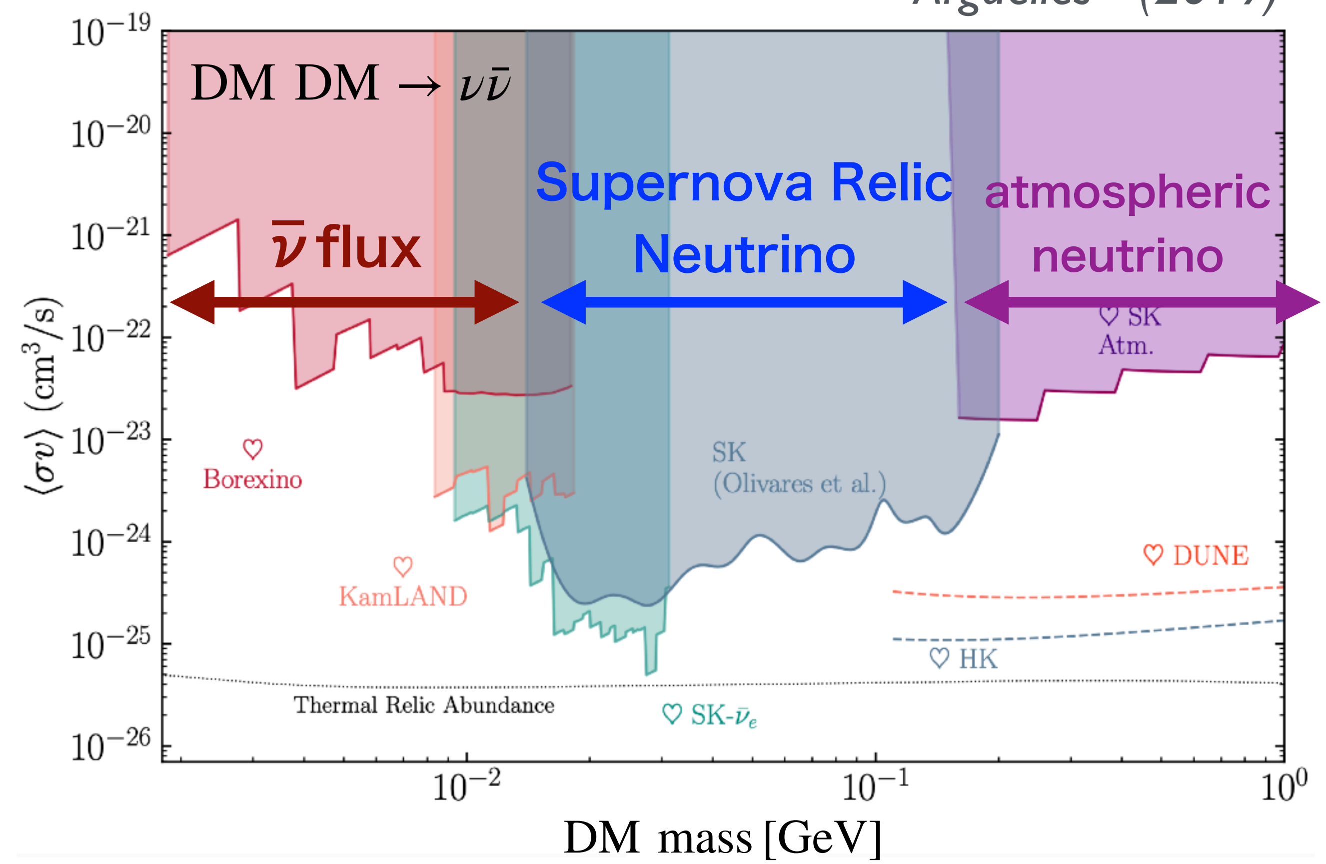


Argüelles+ (2019)



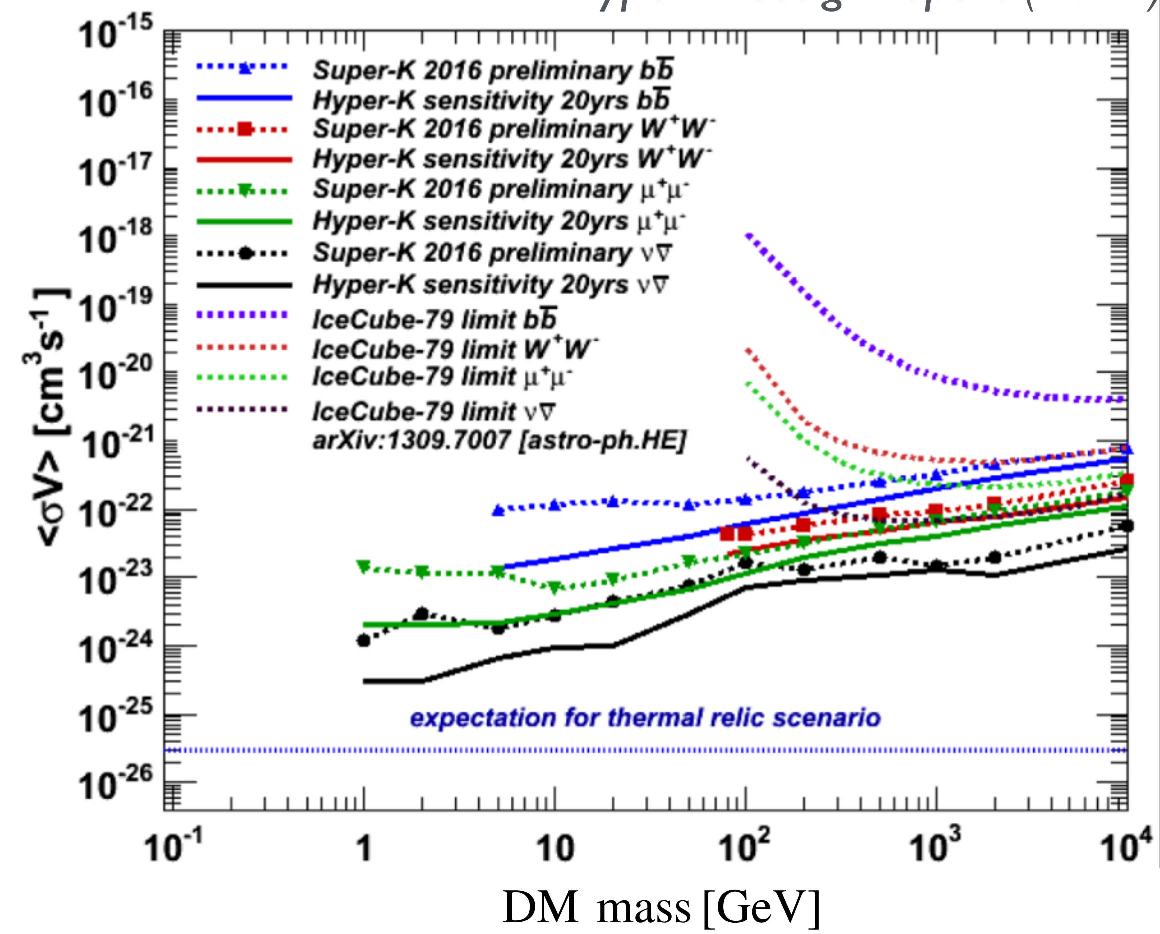
Indirect search with neutrino telescopes

- Traditional WIMP mass region
  - standard search programs in most neutrino telescopes experiments
- Sub-GeV mass region
  - DM DM $\rightarrow \nu\bar{\nu}$
    - first analysis in 2007

      Yüksel+ (2007), Palomares-Ruiz, Pascoli (2007)
    - more quantitative analysis performed in the last 5 years
  - DM DM $\rightarrow VV \rightarrow 2\nu 2\bar{\nu}$ <u>*This Talk*</u>
    - major process for sub-GeV DM, but not studied until we did

Asai, SO, Tsumura (2020)

Hyper-K design report (2018)



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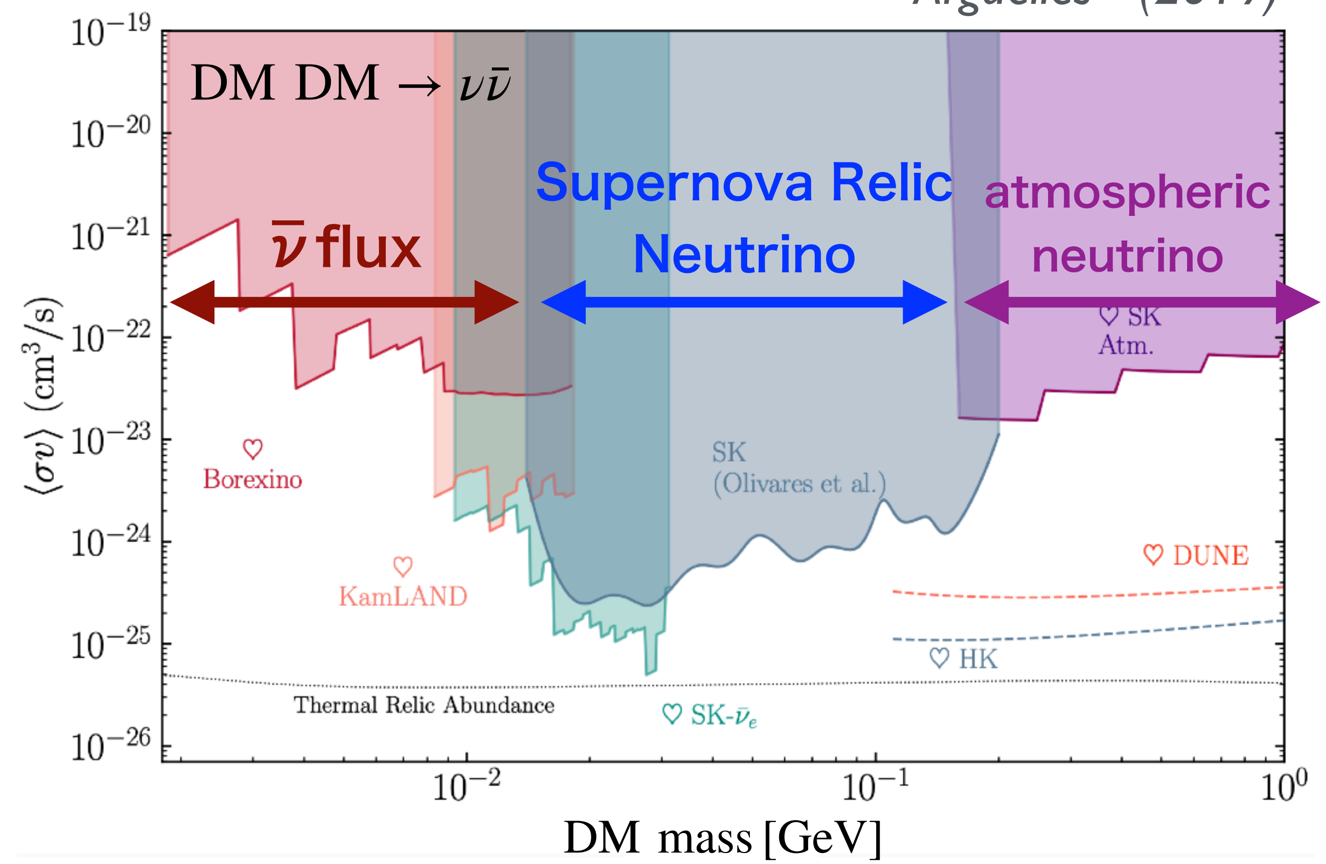


Neutrino flux from galactic DM annihilation

$$\frac{d\Phi_{\nu_e}}{dE_\nu} = \frac{1}{4\pi} \underbrace{\sum_i \frac{\langle \sigma v \rangle_i}{2m_{\rm DM}^2} \kappa \frac{dN_i}{dE_\nu}} \times \underbrace{\int_{\rm l.o.s} dl d\Omega \left[\rho_{\rm DM}(l,\Omega)\right]^2}$$

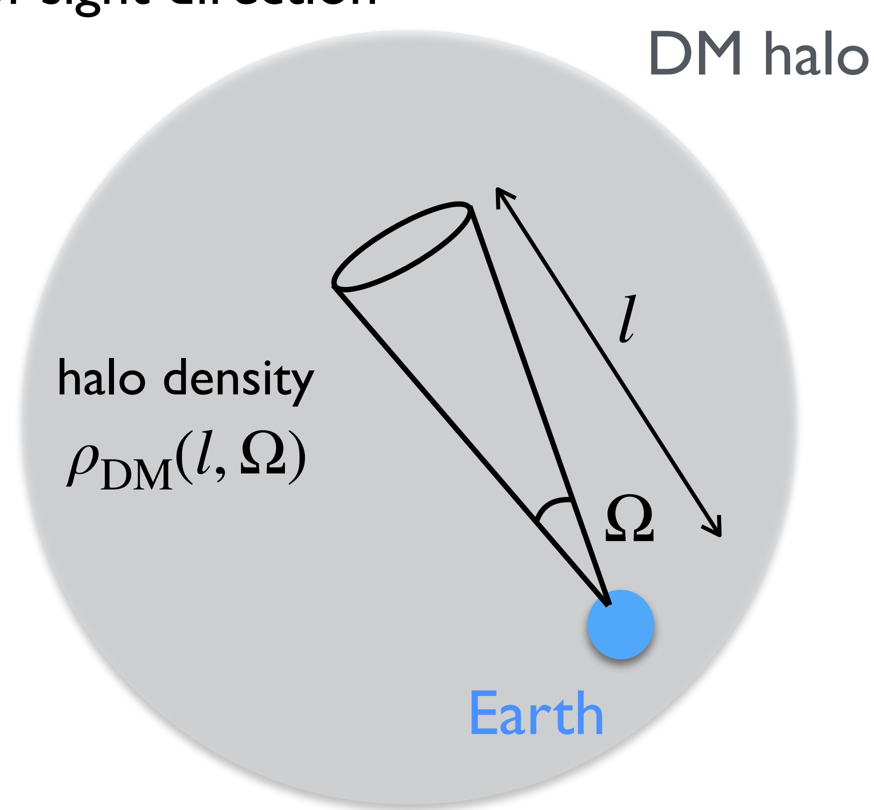
Particle physics

$\langle \sigma v \rangle_i$	DM annihilation cross section into a final state i
$\frac{dN_i}{dE_\nu}$	neutrino spectrum for a final state i
κ	electron-neutrino flavor fraction e.g.) $\nu_e : \nu_\mu : \nu_\tau = 1:1:1 \Rightarrow \kappa = 1/3$

*Here we fix $\kappa = 1/3$

Astrophysics

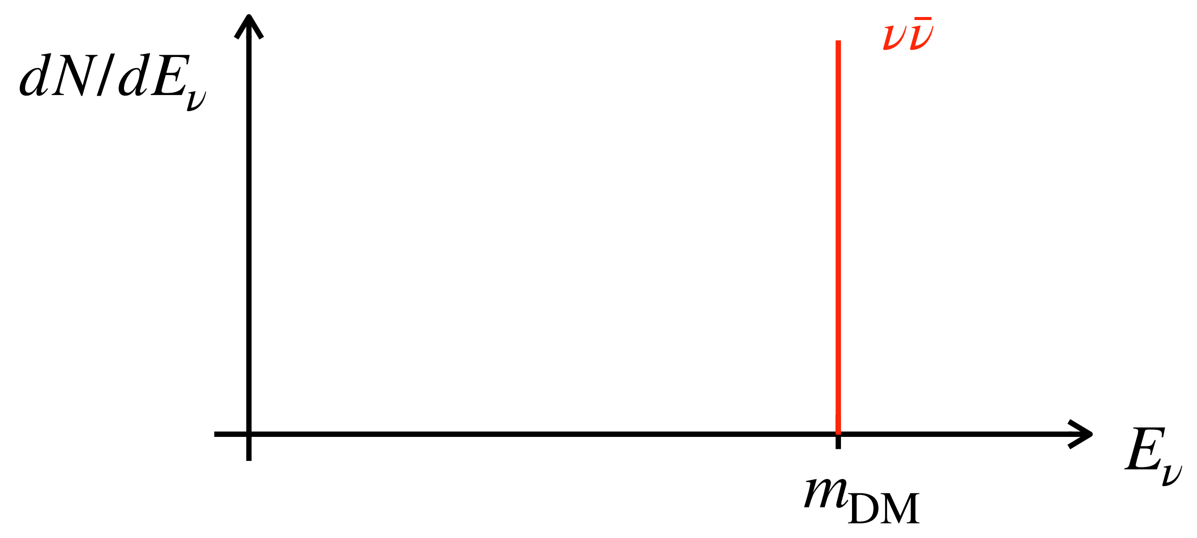
sum up all contribution along the line-of-sight direction



Neutrino spectrum for two annihilation modes

- <u>DM DM $\to \nu\bar{\nu}$</u>

$$\frac{dN}{dE_\nu} = \delta(E_\nu - m_{\rm DM})$$



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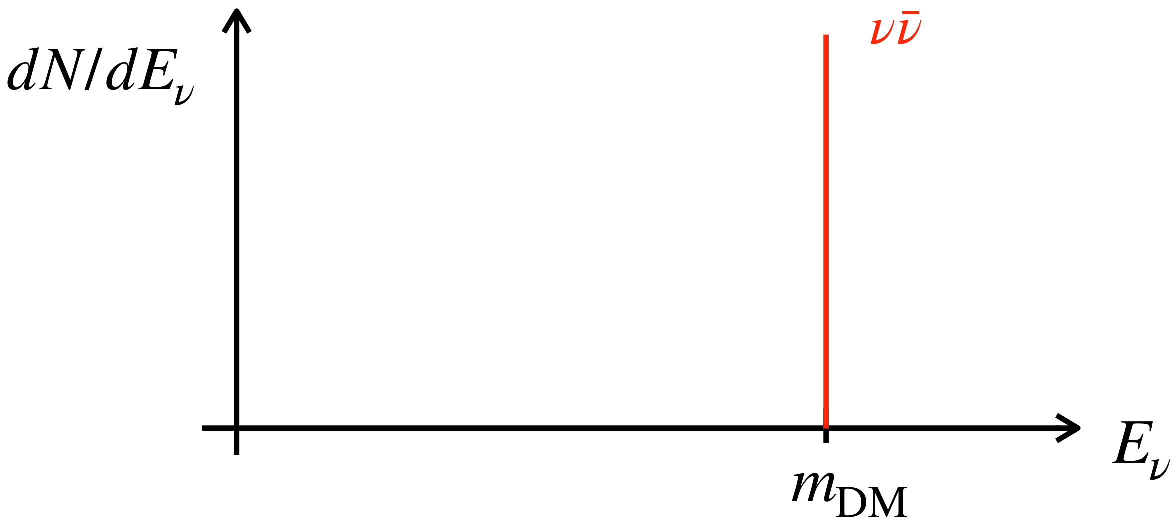


- DM DM $\rightarrow VV \rightarrow 2\nu 2\bar{\nu}$

Neutrino spectrum for two annihilation modes

■ <u>DM DM $\rightarrow \nu\bar{\nu}$</u>

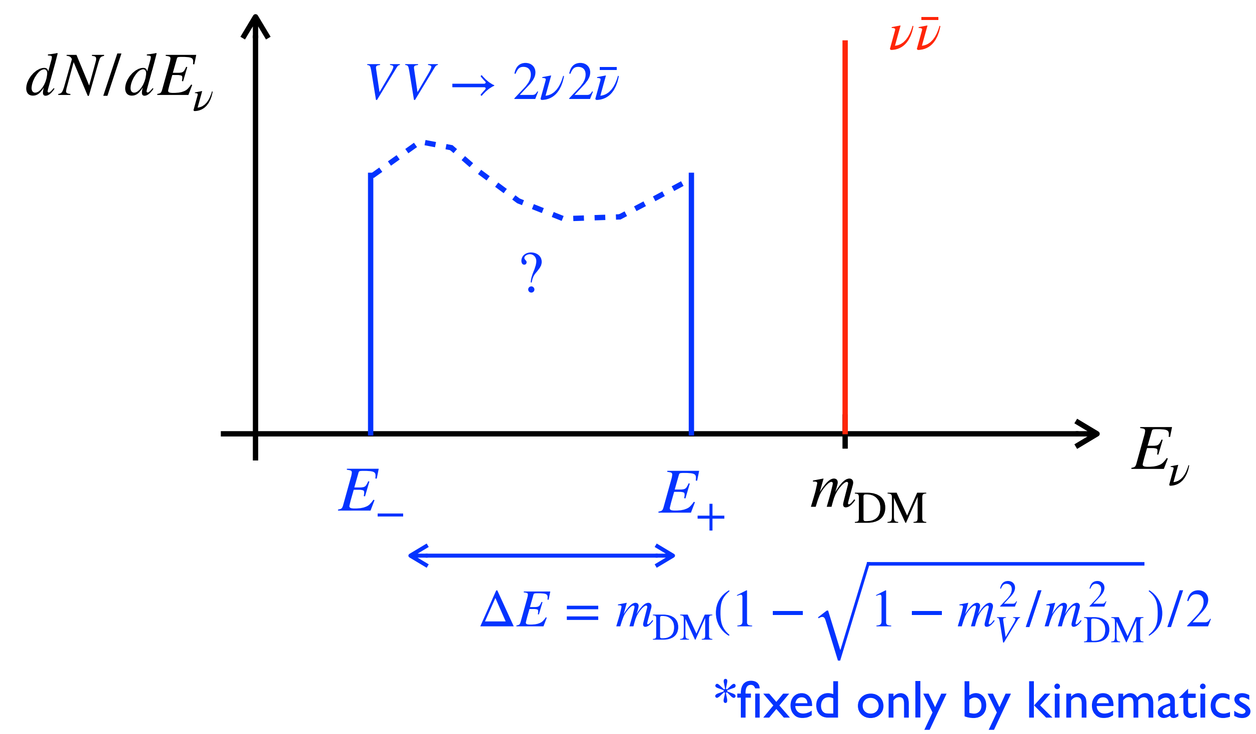
$$\frac{dN}{dE_\nu} = \delta(E_\nu - m_{\rm DM})$$

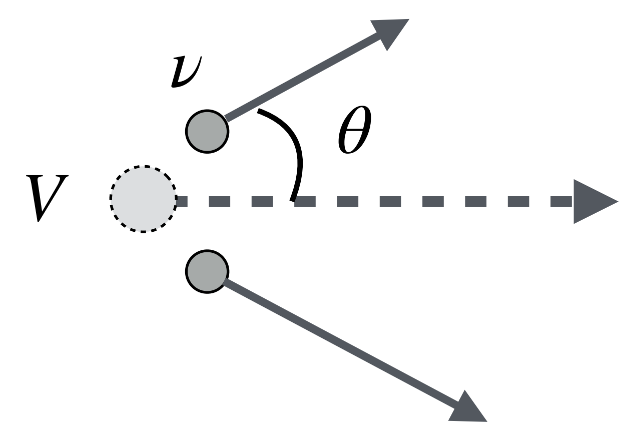
■ <u>DM DM $\rightarrow VV \rightarrow 2\nu 2\bar{\nu}$</u>

<Neutrino energy in the lab frame>

$$E_\nu = \frac{m_V^2/(2m_{\rm DM})}{1 - \sqrt{1 - m_V^2/m_{\rm DM}^2}\cos\theta}$$

$$E_- = E_\nu(\theta = 180^\circ) < E_\nu < E_\nu(\theta = 0^\circ) = E_+$$





Neutrino spectrum for two annihilation modes

- DM DM → $\nu\bar{\nu}$

$$\frac{dN}{dE_\nu} = \delta(E_\nu - m_{\rm DM})$$

- DM DM → $VV \to 2\nu 2\bar{\nu}$

<Neutrino energy in the lab frame>

$$E_\nu = \frac{m_V^2/(2m_{\rm DM})}{1 - \sqrt{1 - m_V^2/m_{\rm DM}^2}\cos\theta}$$

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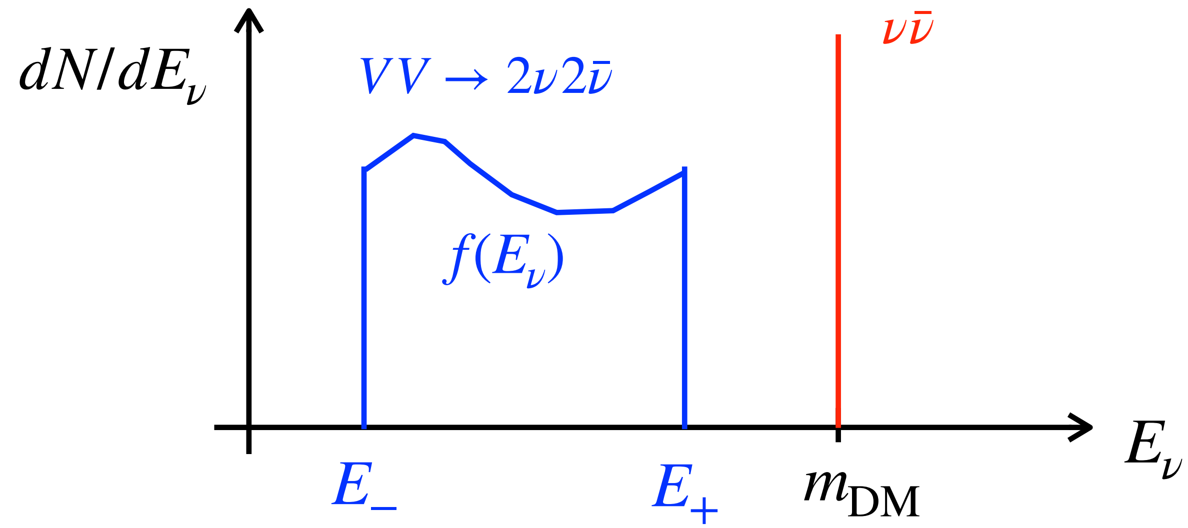
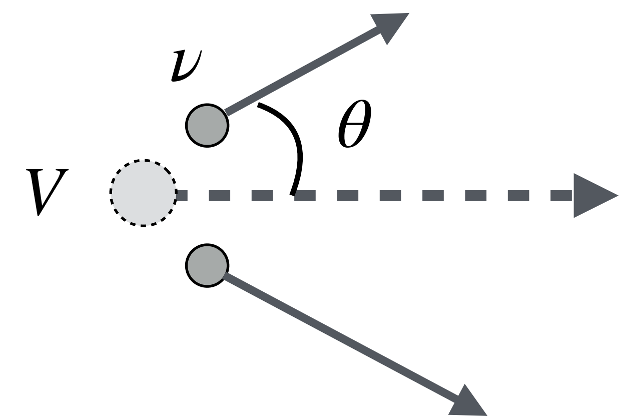


$$\Delta E = m_{\rm DM}(1 - \sqrt{1 - m_V^2/m_{\rm DM}^2})/2$$

*fixed only by kinematics



$$\frac{dN}{dE_\nu} = f(E_\nu)\,\Theta(E_\nu - E_-)\,\Theta(E_+ - E_\nu)$$

Garcia-Cely, Heeck (2016)

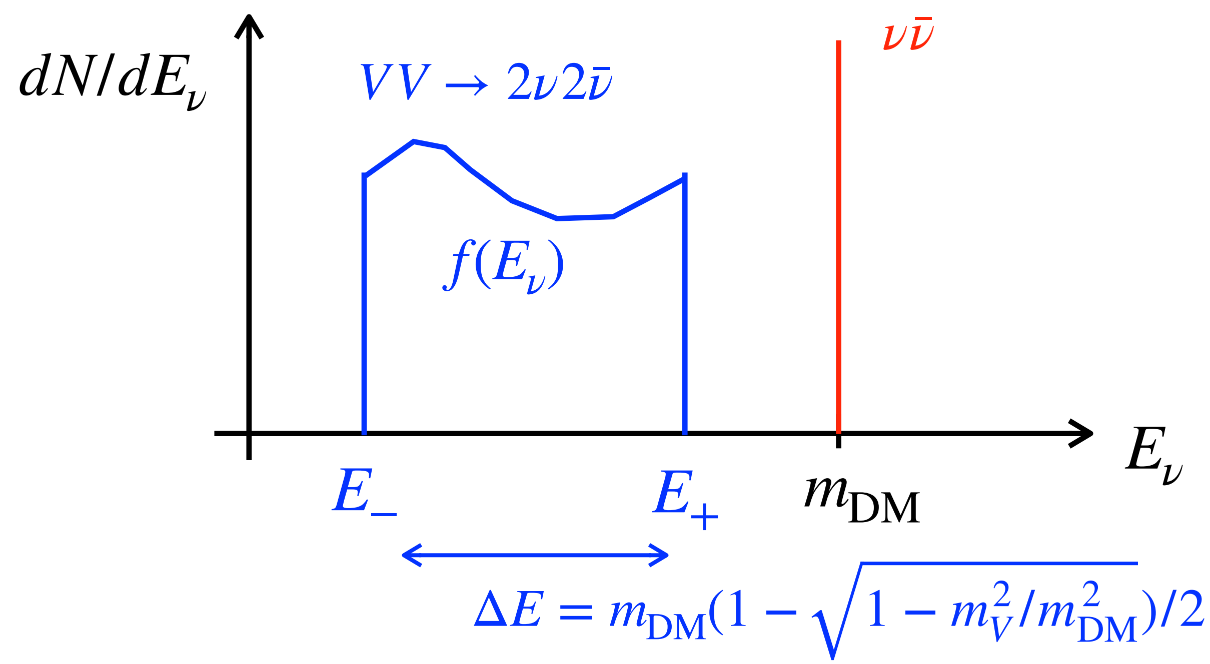
depends on polarizations of V boson

Neutrino spectrum for two annihilation modes

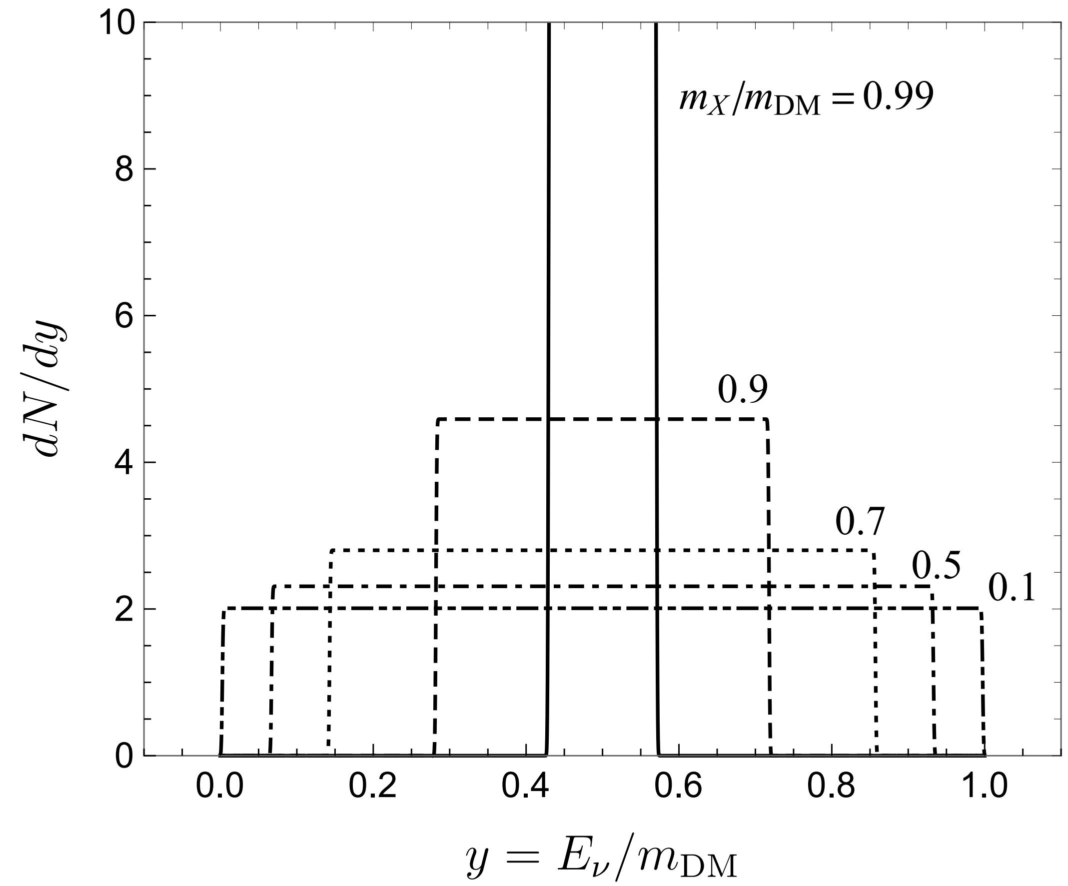
■ DM DM $\rightarrow \nu\bar{\nu}$

$$\frac{dN}{dE_\nu} = \delta(E_\nu - m_{\rm DM})$$

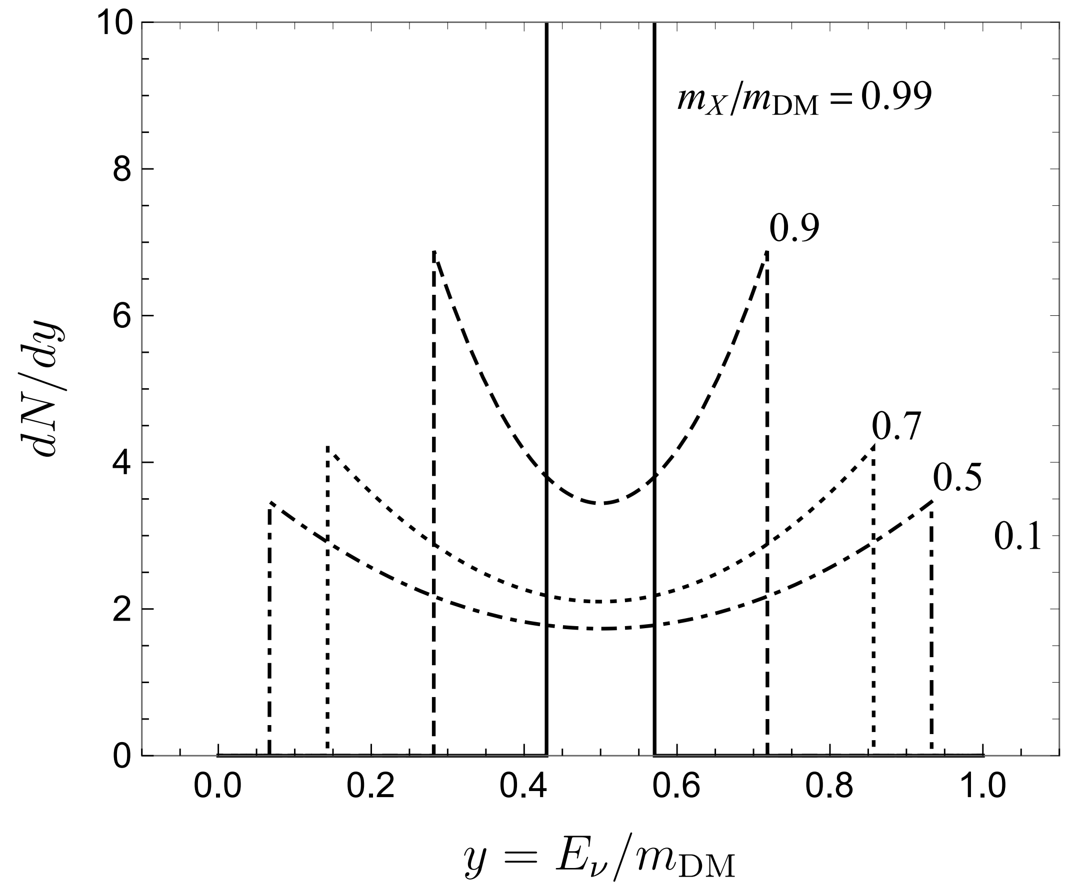
■ DM DM $\rightarrow VV \rightarrow 2\nu 2\bar{\nu}$



V = scalar or unpolarized vector

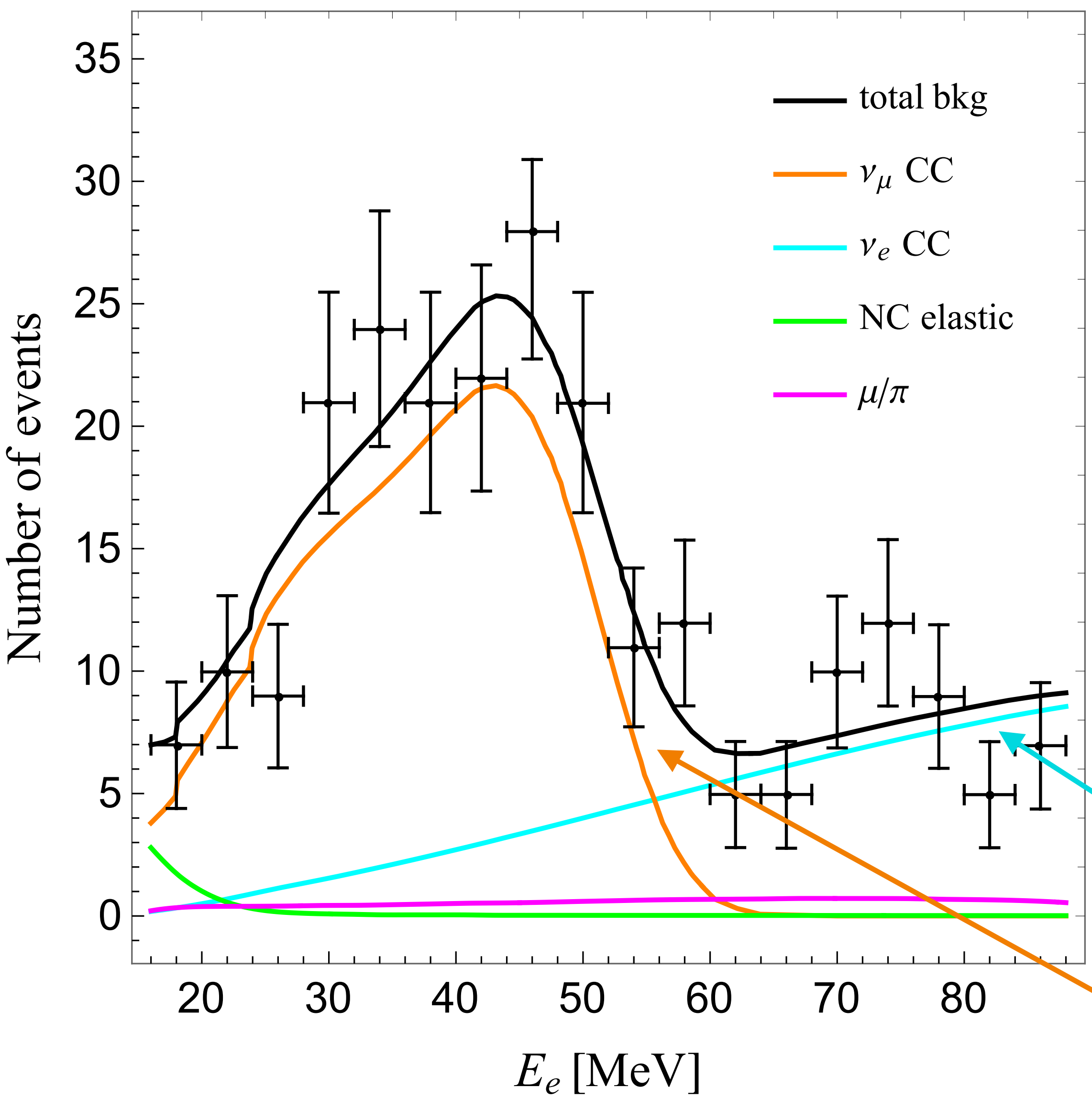


V = transversely polarized vector



Details of our analysis

- Supernova relic neutrino search at Super-Kamiokande (2011)



- We reinterpret existing 2,853days data taken during SK phase 1~3
- Signal is electrons/positrons produced by

$$\bar{\nu}_e + p \to n + e^+ \quad (E_e \simeq E_\nu - 1.3\,\mathrm{MeV})$$

$$\nu_e/\bar{\nu}_e + {}^{16}\mathrm{O} \to e^-/e^+ + (\text{atomic state})$$

$$(E_e \simeq E_\nu - 10\,\mathrm{MeV})$$

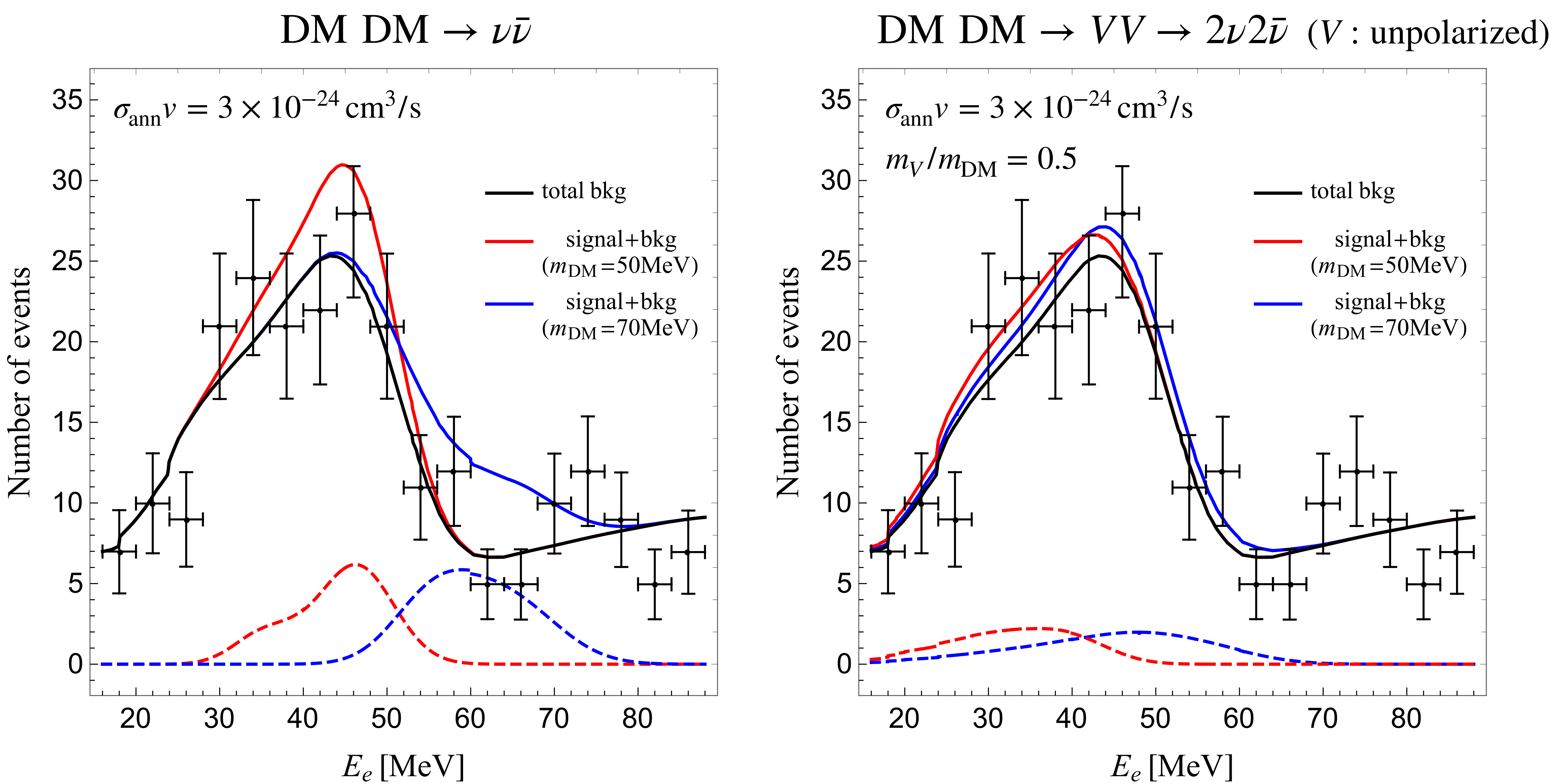
- Backgrounds from atmospheric neutrinos

$$\bar{\nu}_e + p \to n + e^+$$

$$\bar{\nu}_\mu + p \to n + \mu^+ (\to e^+ \nu_e \bar{\nu}_\mu)$$

$$(T_\mu \lesssim 50\,\mathrm{MeV})$$

Expected and observed events at the SK

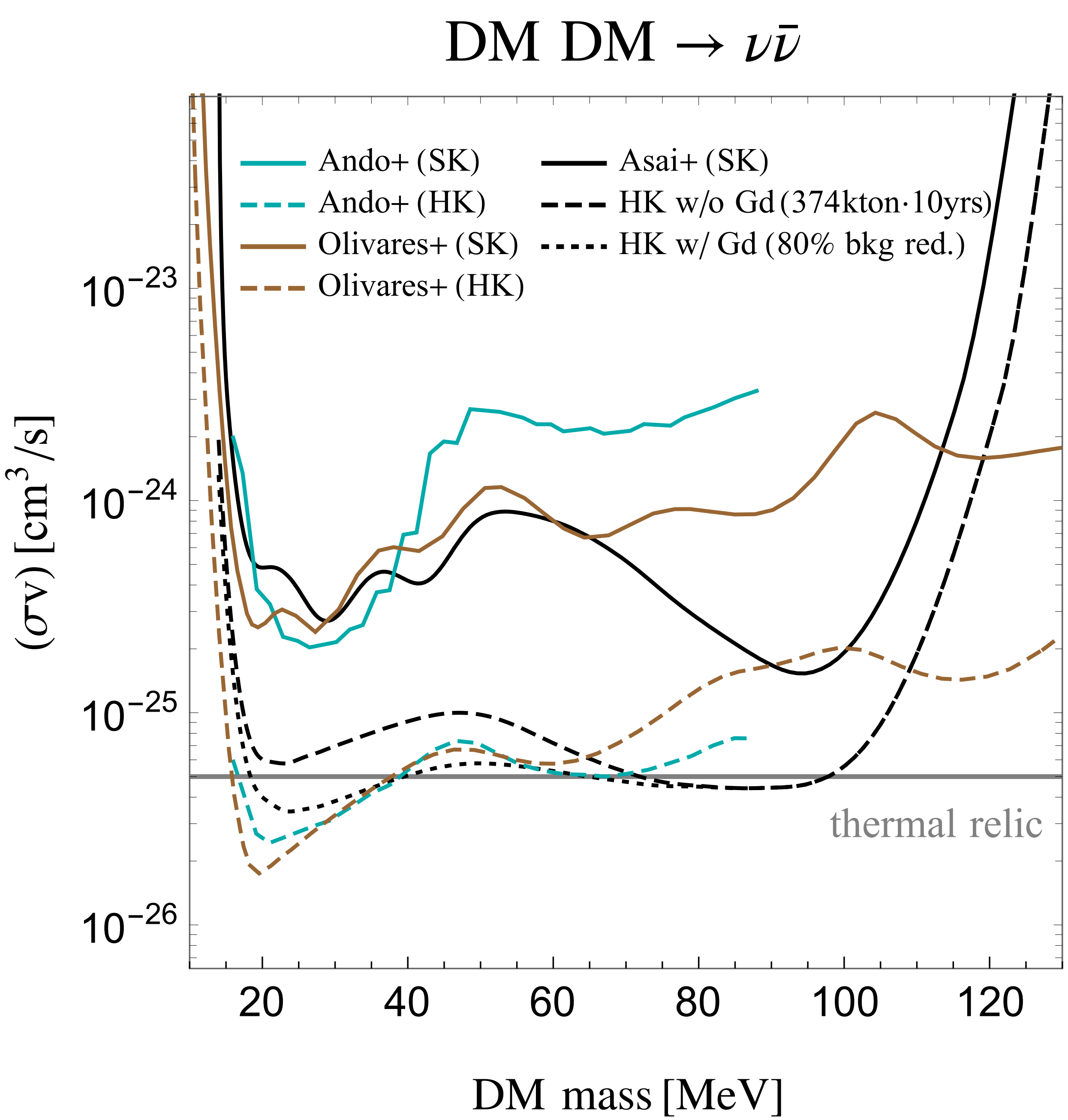


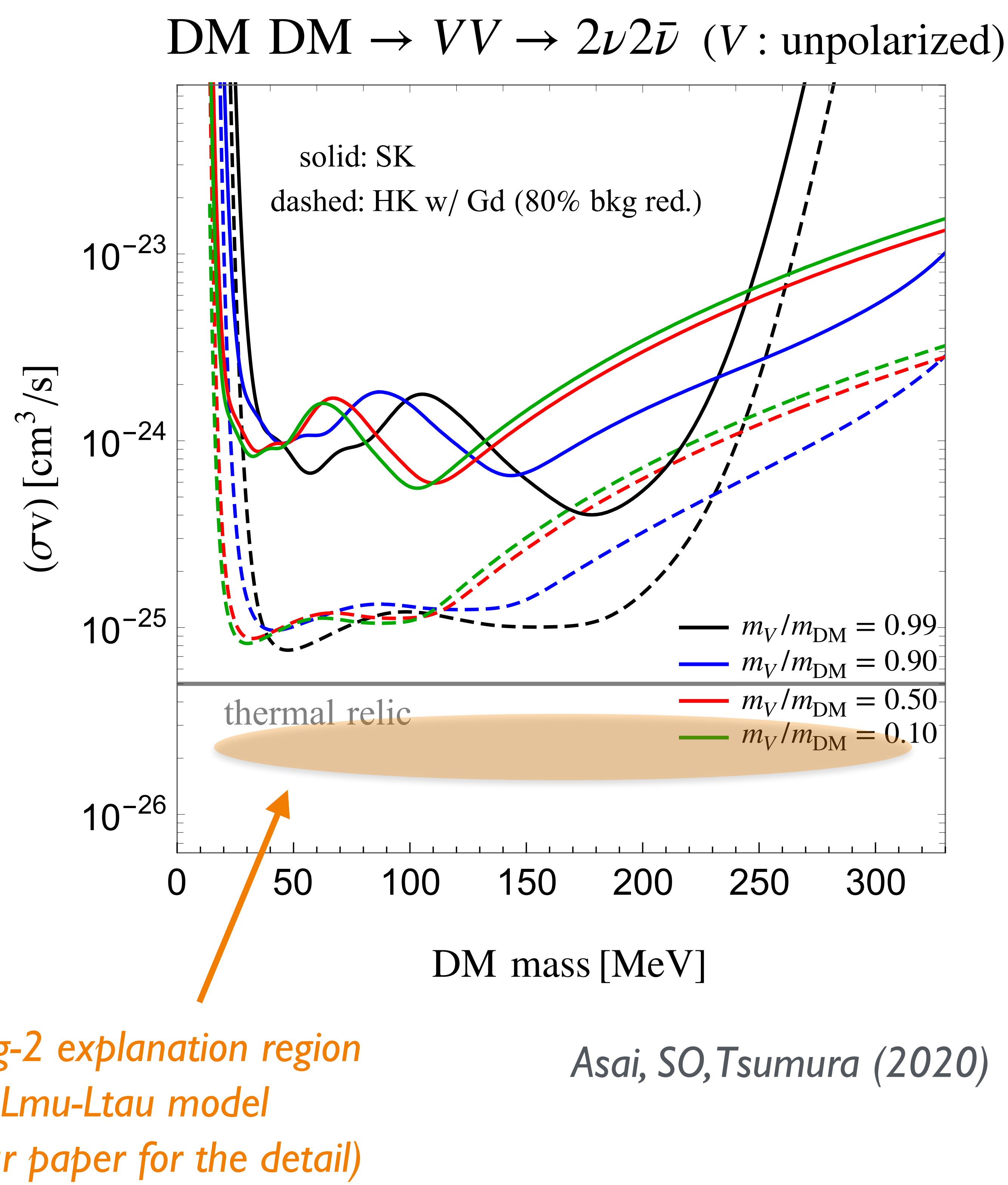
- $\nu\bar{\nu}$: sharp peak in signals

- $2\nu 2\bar{\nu}$: broad but comparable events in multiple bins

Asai, SO, Tsumura (2020)

Sensitivity to DM annihilation cross section

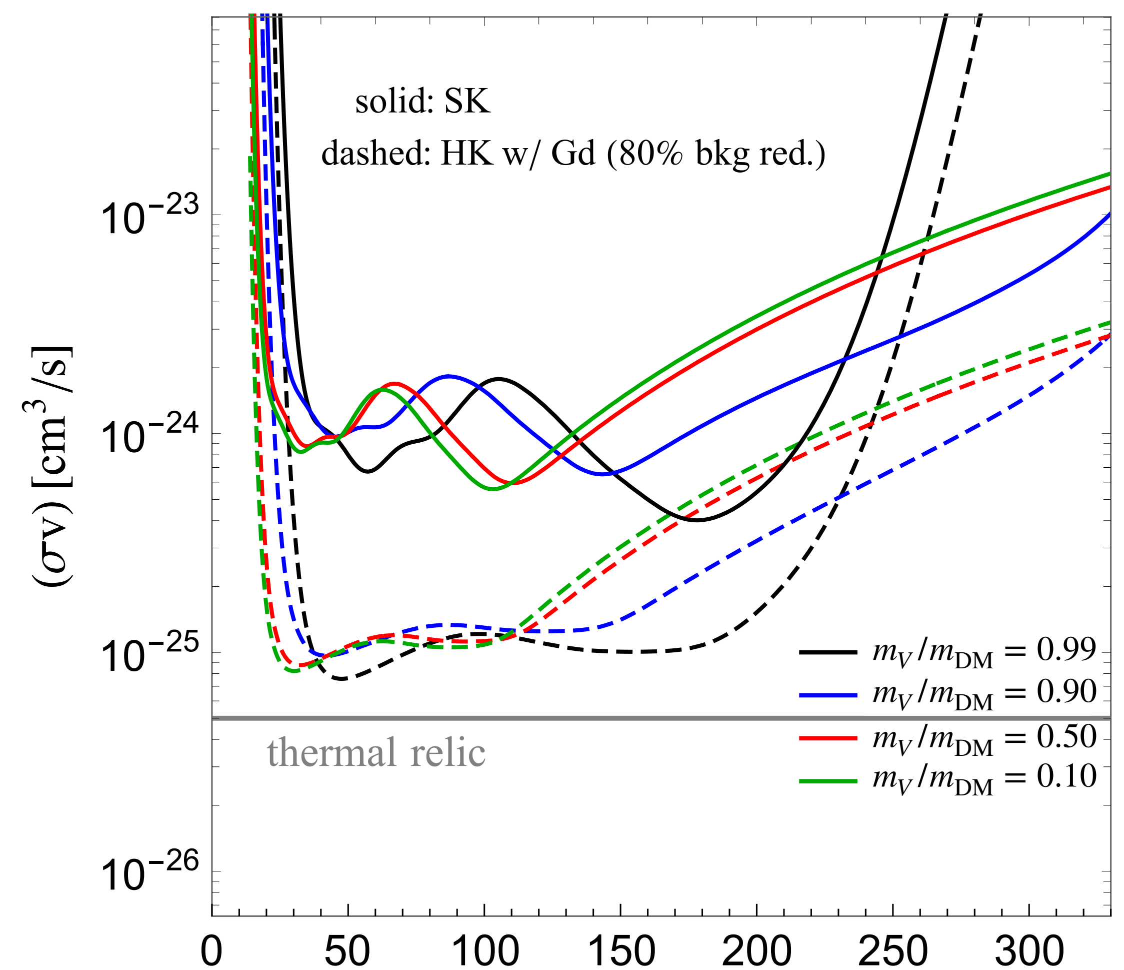




Asai, SO, Tsumura (2020)

Summary

- Sub-GeV DM has drawn significant attention in recent years
- Future neutrino telescopes are capable of probing sub-GeV DM
  - We analyze two major annihilation modes
    - $\text{DM DM} \to \nu\bar{\nu}$
    - $\text{DM DM} \to VV \to 2\nu 2\bar{\nu}$
  - Further improvements needed to probe thermal relic parameter space
    - background reduction technique?
    - directional information?
    - any other ideas?



Thank you for your attention!

Back up

Expected number of events at the SK detector

$$N_{i,\mathrm{sig}} = N_{\mathrm{SK}}\, T_{\mathrm{SK}} \int dE_\nu \frac{d\Phi_{\nu_e}}{dE_\nu} \int_{E_i}^{E_{i+1}} dE_{\mathrm{vis}} \int dE_e\, R(E_e, E_{\mathrm{vis}})\, \epsilon(E_{\mathrm{vis}})$$
$$\times \left\{ \frac{d\sigma_{\bar{\nu}_e p}}{dE_e}(E_\nu, E_e) + \frac{1}{2}\left(\frac{d\sigma_{\nu_e \mathrm{O}}}{dE_e}(E_\nu, E_e) + \frac{d\sigma_{\bar{\nu}_e \mathrm{O}}}{dE_e}(E_\nu, E_e) \right) \right\}$$

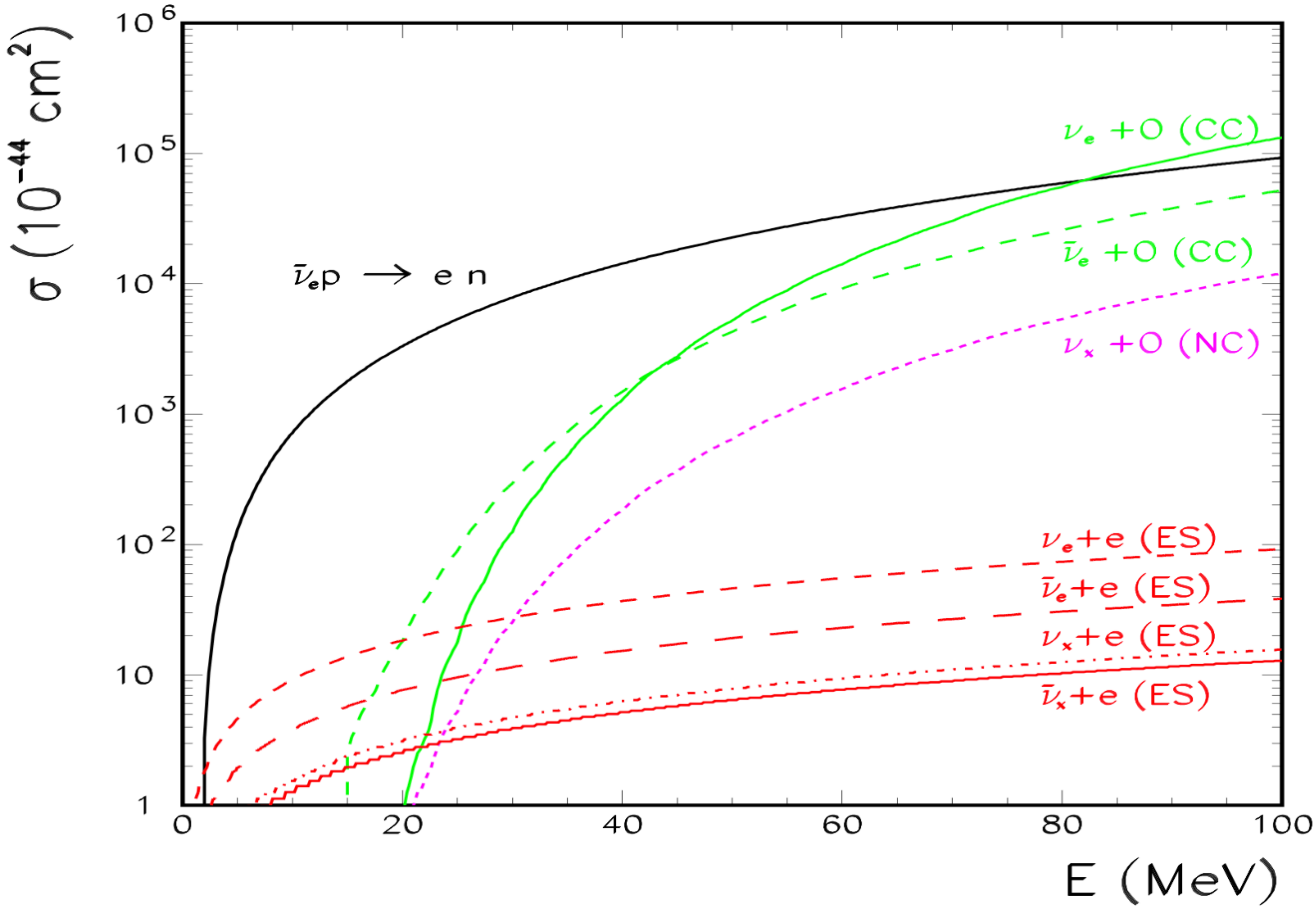
N_{SK} : number of free proton

T_{SK} : SK run time

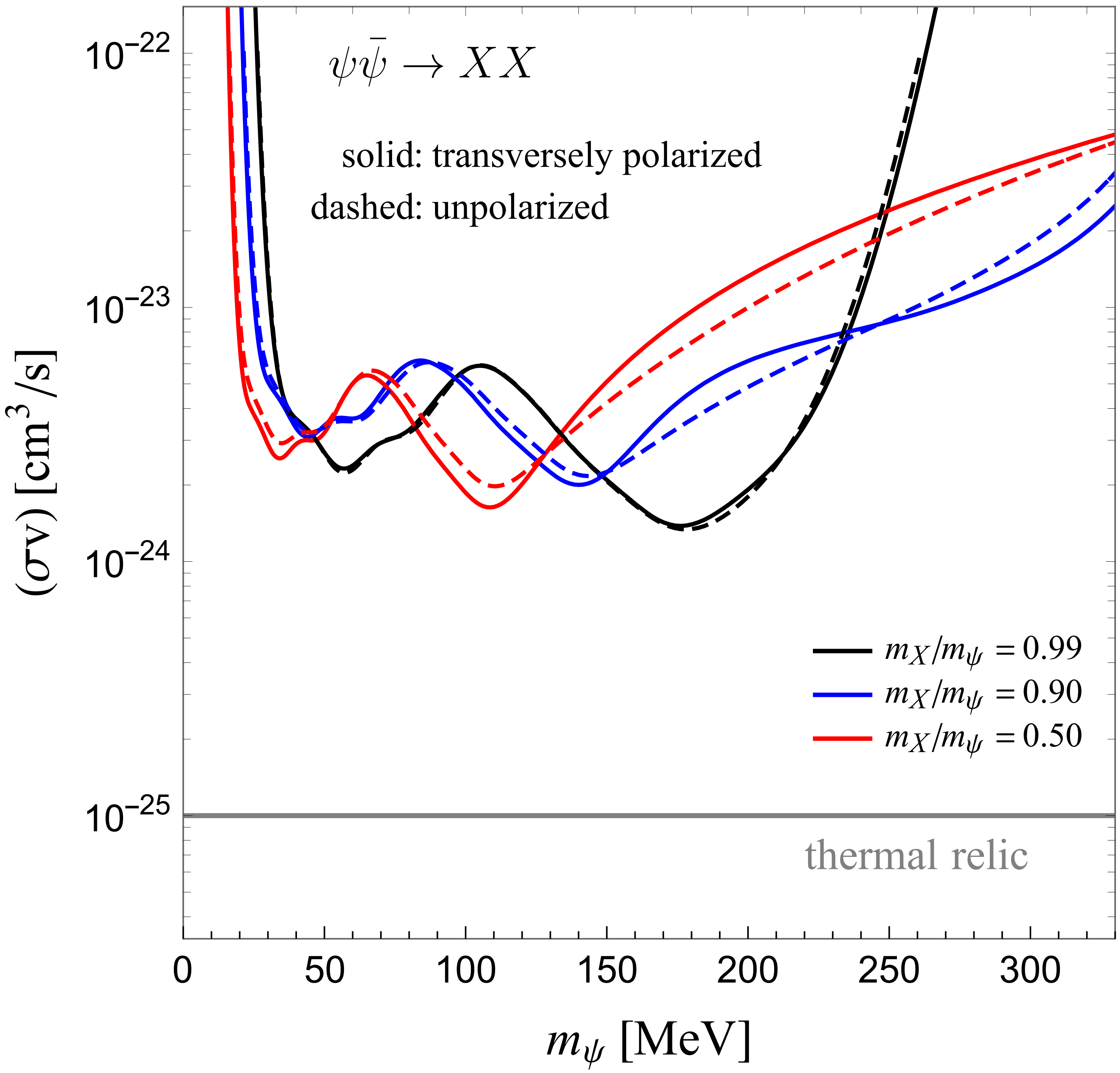
$R(E_e, E_{\mathrm{vis}})$: Gaussian resolution function

$\epsilon(E_{\mathrm{vis}})$: detector efficiency

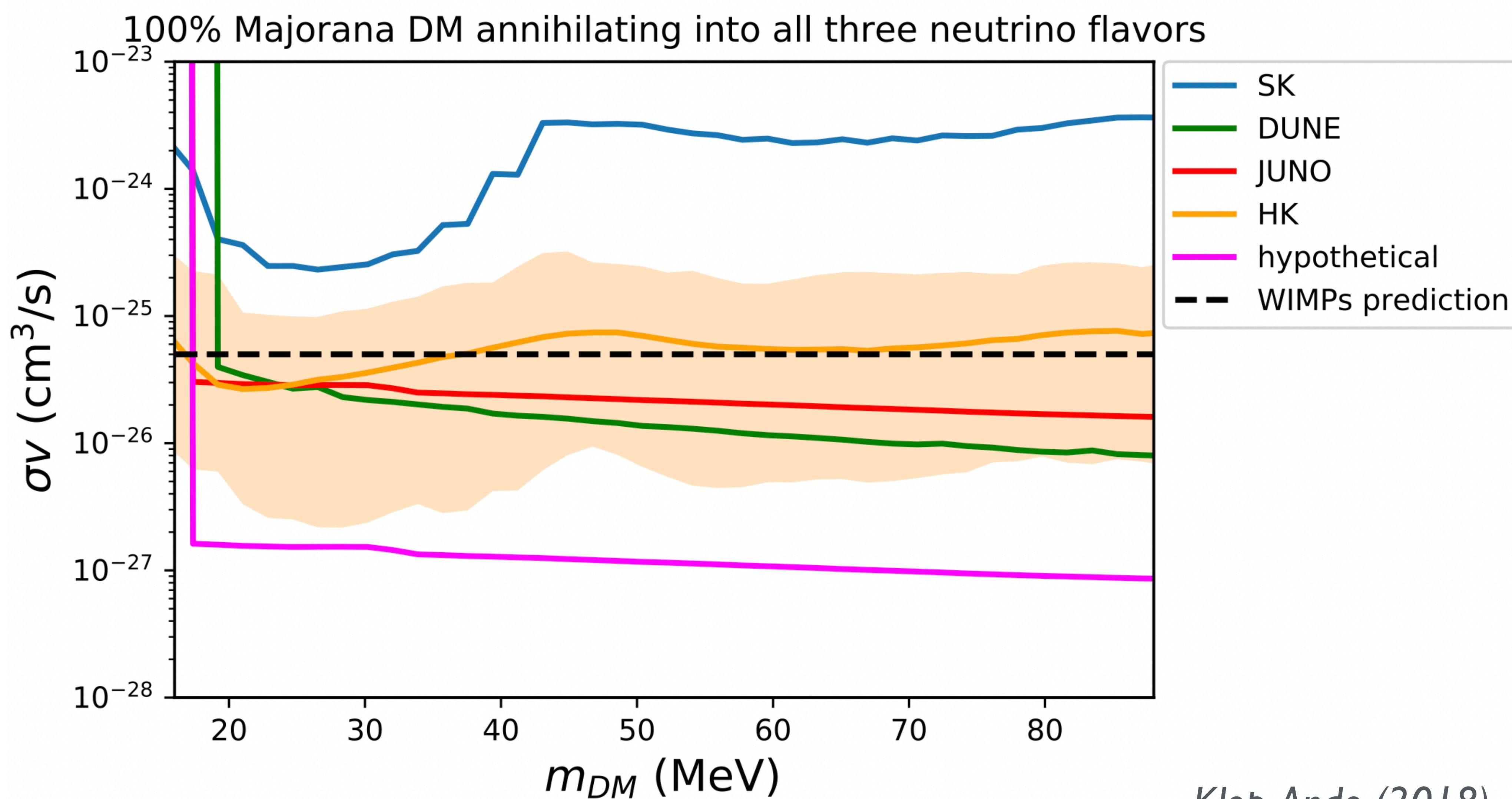
Reaction cross sections



Impact of vector boson polarizations



Sensitivity of DUNE and JUNO



Klop, Ando (2018)

- DUNE and JUNO have better sensitivity than HK?
- We may be able to extend our study by following their analysis