Dark Matter-Neutrino Interactions in JUNO experiment

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with

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based on
arXiv: 2206.06755

7th IBS-ICTP-MultiDark Workshop

Dec. 01 2022

Outline

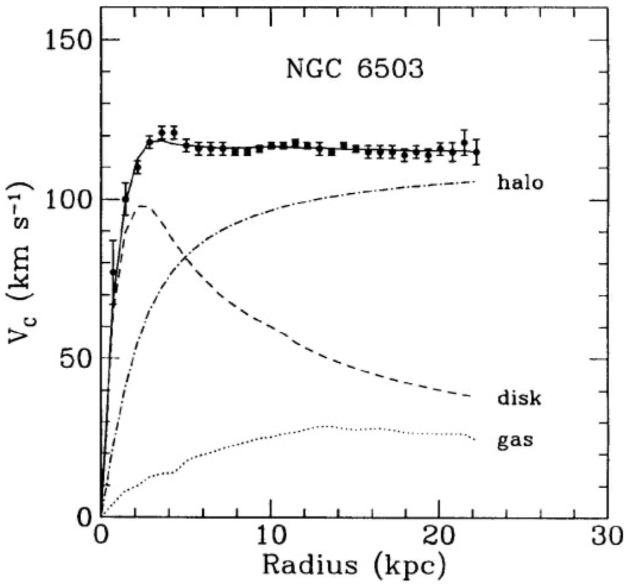
- Introduction -Dark Matter (DM)-
- Dark Matter-Neutrino Interactions
- Neutrino lines from DM annihilations and decays in JUNO
- Conclusions

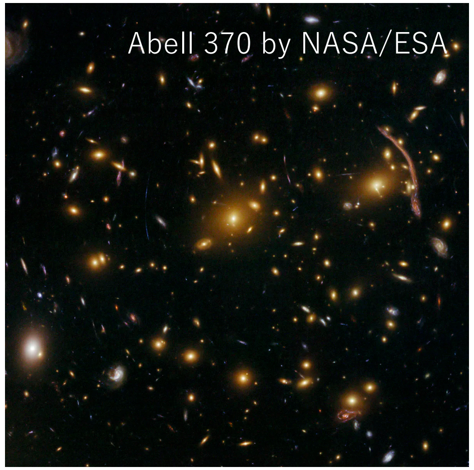
Dark Matter (DM)

- **Evidence**
  - Rotation curves of galaxies
  - Bullet cluster
  - Gravitational lensing

- **General Feature**
  - Electrically neutral/ almost neutral
  - Stable/ Long-lived
  - Non-relativistic/ Massive

K.Freeze (2009)

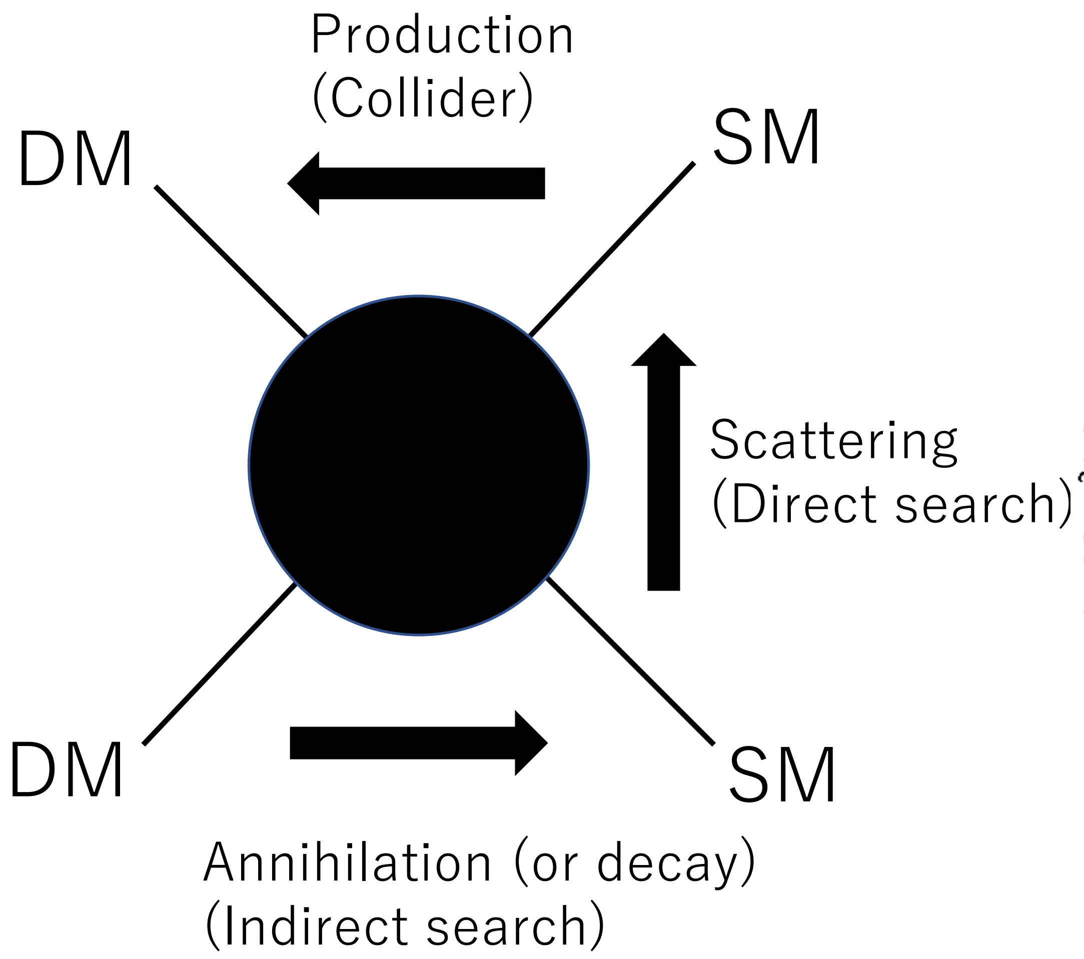


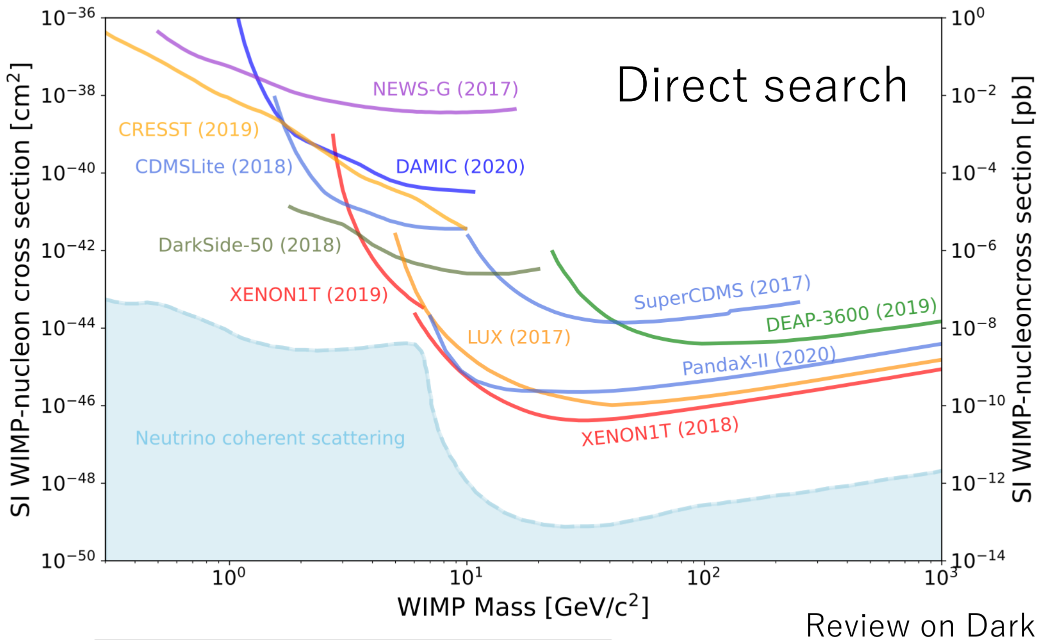


➡ No candidate in the Standard Model (SM)

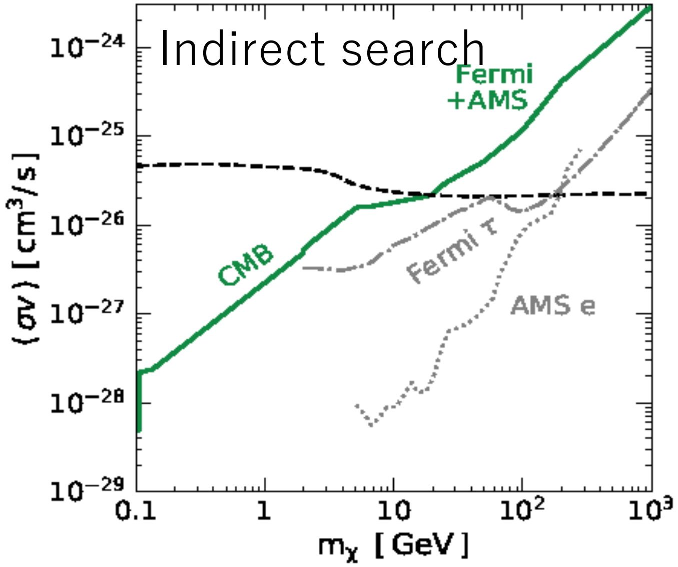
Still many possibility for the nature of DM such as mass and interactions.

DM search





Review on Dark Matter,
L. Baudis and S. Profumo



R. K. Leane et al. 1805.10305

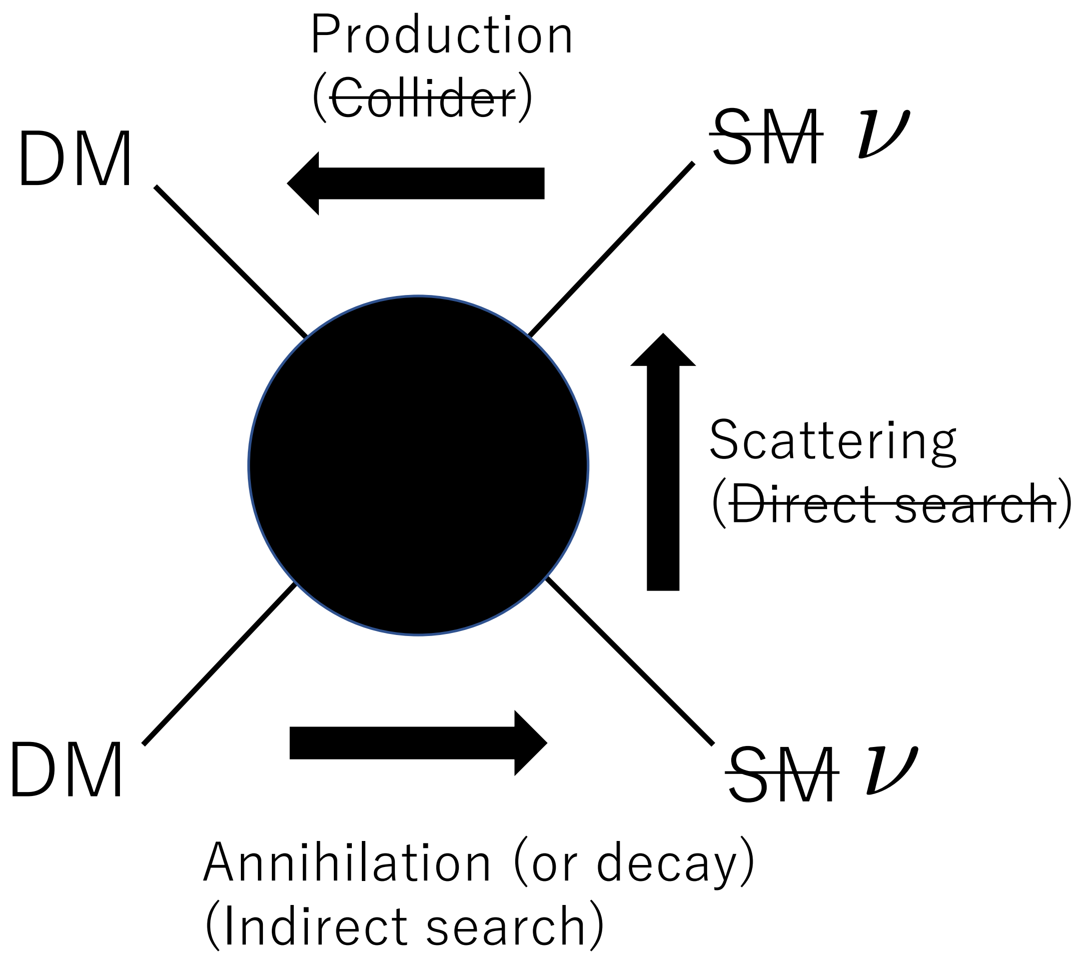
← Constraints on
DM annihilation into SM
except for neutrinos

We impose <u>only</u> severe constraints…

How about the neutrino state?

Dark Matter-Neutrino Interactions

Dark Matter-Neutrino interactions



DM-Neutrino interactions are <u>less</u> constrained.

- <u>DM annihilation</u> (and decay) into neutrinos:
  - Neutrino telescopes can detect this signal.
  - $\Delta N_{\rm eff}$ constrains the annihilation with $m_{\rm DM} \lesssim 1$ MeV.

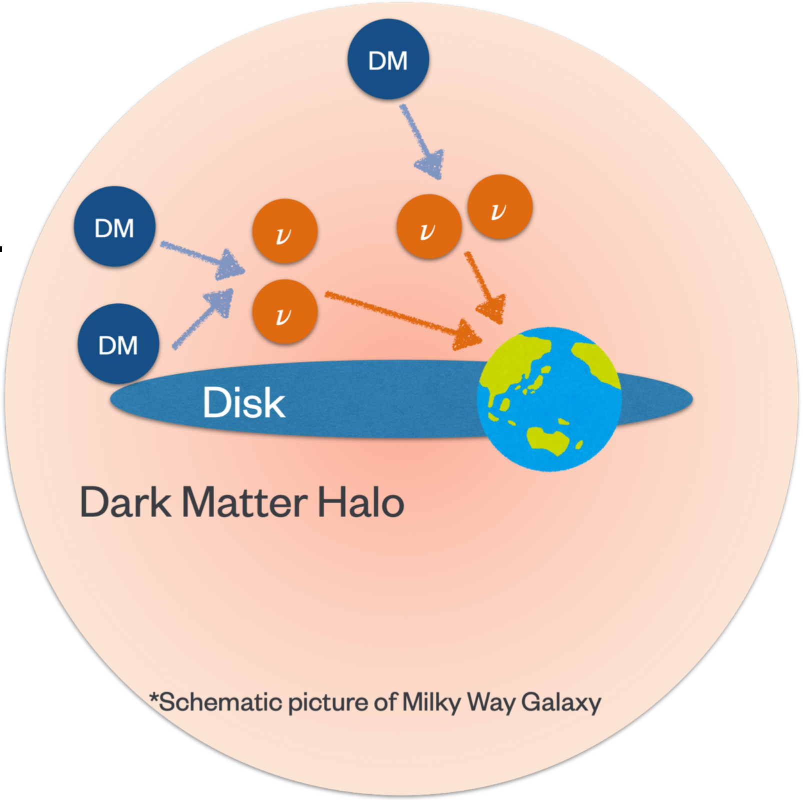
- <u>DM scattering</u>
  1. with astrophysical ν :
     Astrophysical ν <u>flux</u> can be modified.
  2. with cosmic ν :
     The structure of the universe can be modified.

DM annihilation into neutrinos

- Neutrino telescope can constrain the annihilation due to
  - large volume detector
  - less background than γ -ray signal

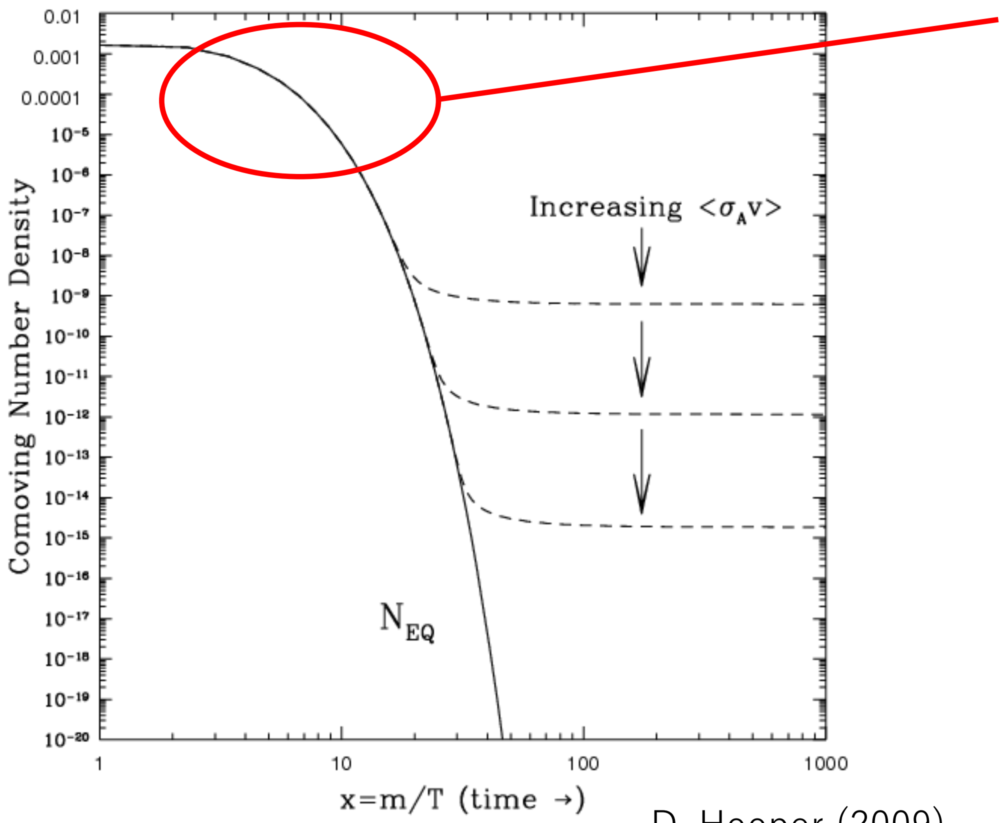
- Next-generation neutrino detector will improve the sensitivity.
  - Super-Kamiokande with Gadolinium (2020-)
  - JUNO (2023 ?-)
  - Hyper-Kamiokande (2027 ?-)

  etc...



DM annihilation into neutrinos

- Light thermal DM can increase $\Delta N_{\rm eff}$.



D. Hooper (2009)

DM annihilation into neutrino increases $\Delta N_{\rm eff}$
if the annihilation occur after neutrino decoupling.

CMB and BBN observation can constrain

$$\frac{m_{\rm DM}}{T_{\nu,{\rm dec}}} \sim 1 \qquad (T_{\nu,{\rm dec}} \sim 2\ {\rm MeV})$$

- The current BBN+Planck constraint

$$m_{\rm DM} \gtrsim 3.7\ {\rm MeV}$$

N. Sabti et al. 1910.01649

- The future CMB-S4 sensitivity

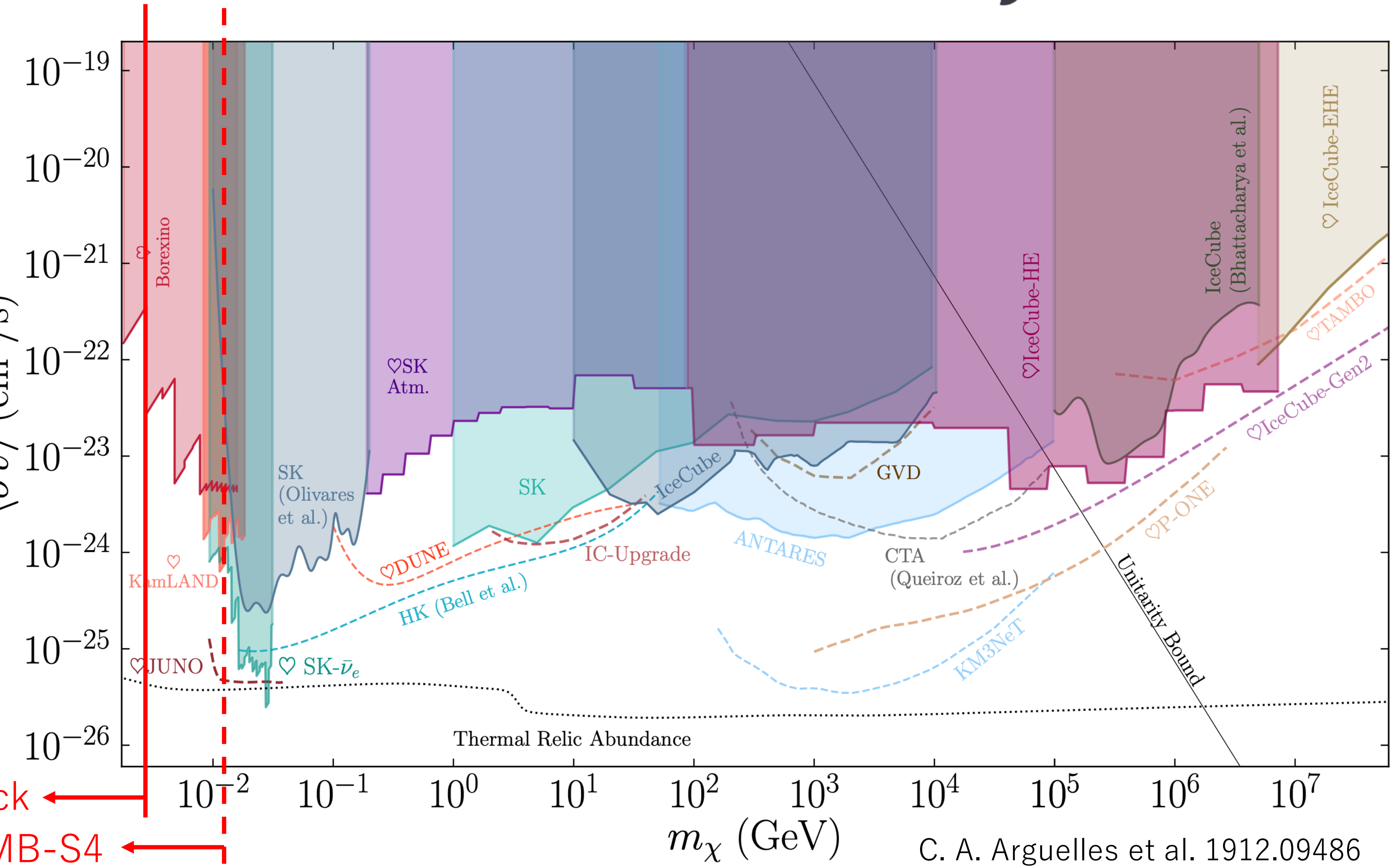
$$m_{\rm DM} \gtrsim 10.5\ {\rm MeV}$$

DM annihilation into neutrinos

Shaded region: Existing limits
Dashed lines:
Expected sensitivity (5-year data)

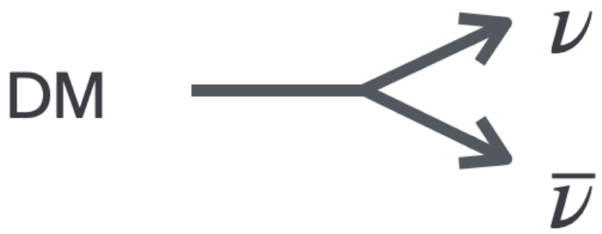
Currently
thermal relic abundance
has not been tested...

In the future
This abundance may be tested
in a wide mass region!



C. A. Arguelles et al. 1912.09486

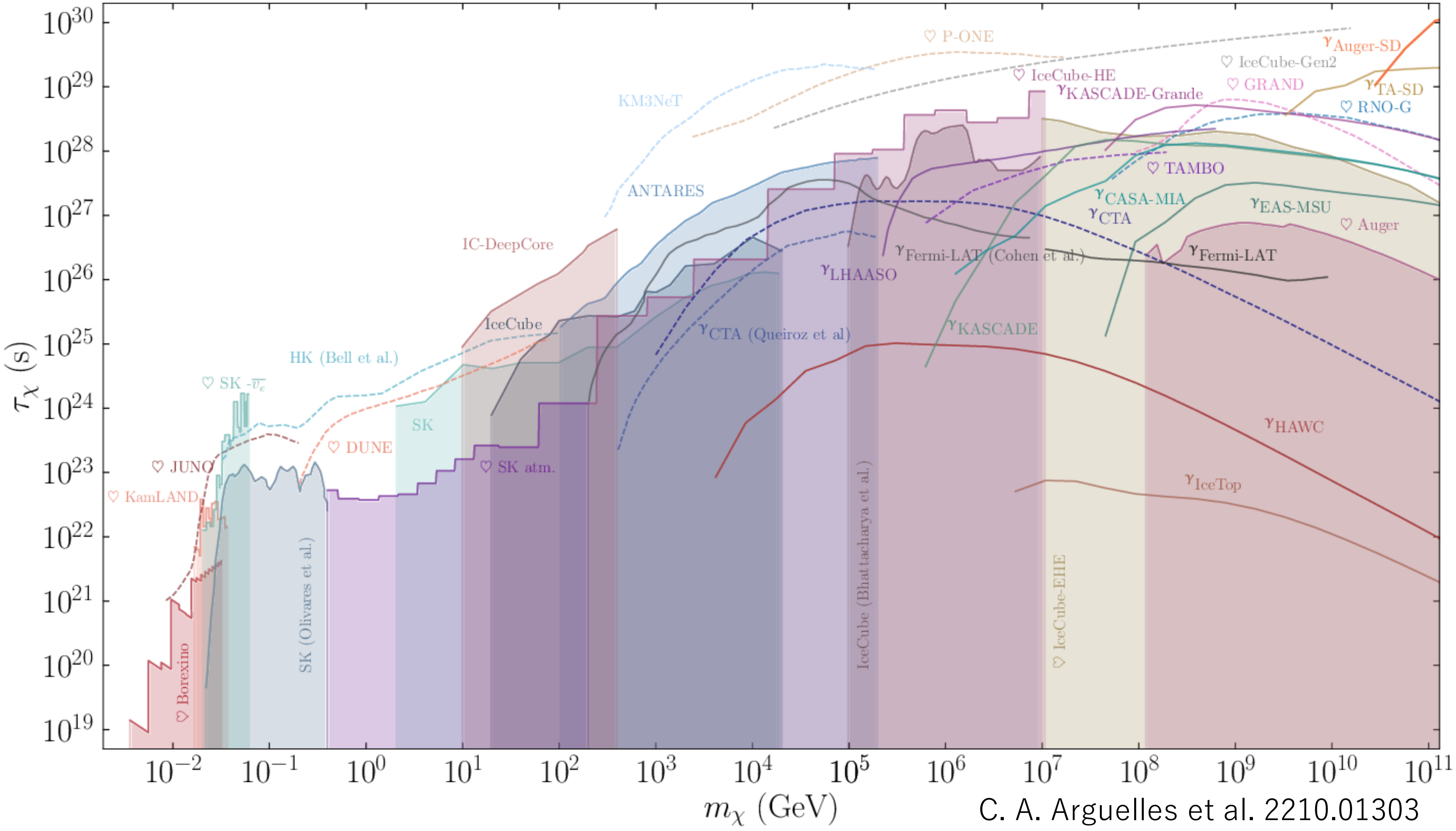
DM decay into neutrinos



Neutrino telescope can constrain DM decay.

The age of universe:

$$t_0 \simeq 4.35 \times 10^{17} \text{ s}$$



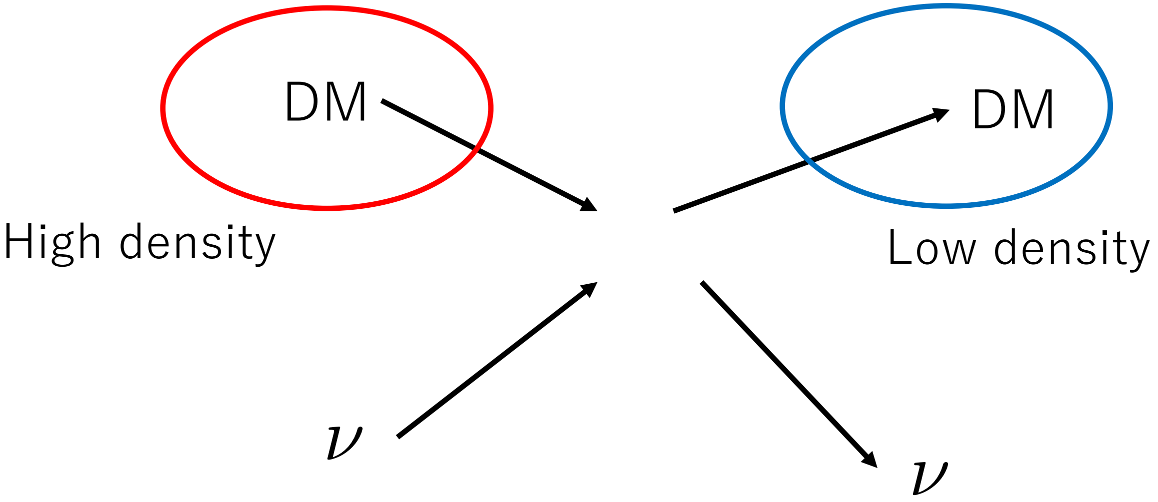
C. A. Arguelles et al. 2210.01303

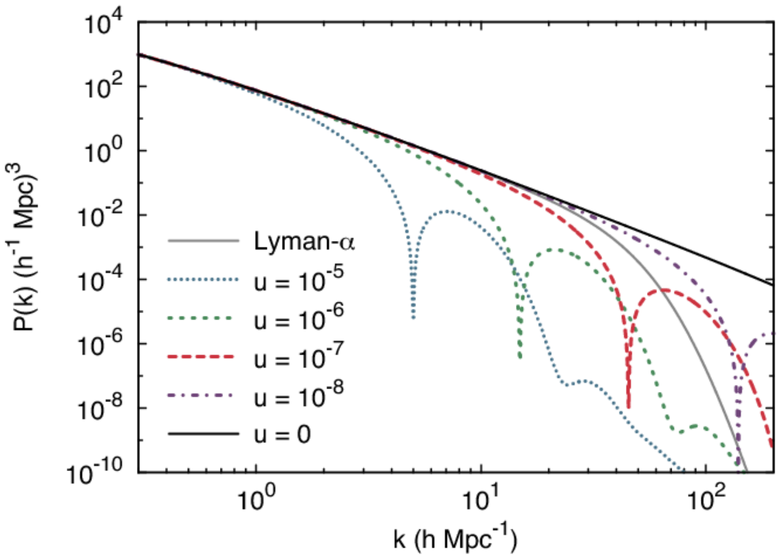
DM scattering with cosmic neutrinos

- DM-Cosmic Neutrino Background (CnuB) scattering induces the so-called <u>DM acoustic oscillations</u> analogous to Baryon acoustic oscillations (BAO).

⇨ Suppress the primordial matter density fluctuations.

⇨ Affect the observation of the CMB and the structure of the universe.





Matter power spectrum

$$u = \left[\frac{\sigma_{\mathrm{DM}-\nu}}{\sigma_{\mathrm{Th}}}\right]\left[\frac{m_{\mathrm{DM}}}{100\ \mathrm{GeV}}\right]^{-1}$$

$$\sigma_{\mathrm{Th}} = 6.7 \times 10^{-28}\ \mathrm{cm}^2$$

Thomson scattering rate

R.J.Wilkinson et al. 1401.7597

DM scattering with cosmic neutrinos

- The CMB constraints: R.J.Wilkinson et al. 1401.7597

$$\sigma_{\mathrm{DM}-\nu} \lesssim 10^{-28} \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right) \ \mathrm{cm}^2$$ if the cross section is constant.

$$\sigma_{\mathrm{DM}-\nu} \lesssim 10^{-40} \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right) \left(\frac{E_\nu}{T_0}\right)^2 \ \mathrm{cm}^2$$ if it depends on the energy-squared.

$T_0 \simeq 2.7\ \mathrm{K}$: the current CMB temperature

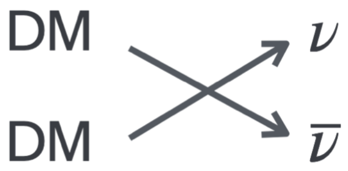
- The Lyman- α constraints: R.J.Wilkinson et al. 1401.7597

$$\sigma_{\mathrm{DM}-\nu} \lesssim 10^{-33} \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right) \ \mathrm{cm}^2 \qquad \sigma_{\mathrm{DM}-\nu} \lesssim 10^{-45} \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right) \left(\frac{E_\nu}{T_0}\right)^2 \ \mathrm{cm}^2$$

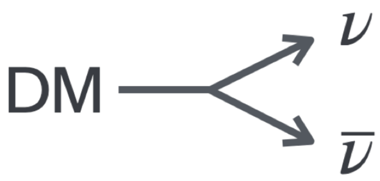
Neutrino lines
from DM annihilations and decays
in JUNO experiment

Neutrino lines from DM

- Neutrino production in the Milky Way (MW)



$$\frac{d\Phi_{\rm anni}}{dE_\nu} = \Phi_{\rm anni}\delta\left(E_\nu - m_{\rm DM}\right)$$



$$\frac{d\Phi_{\rm dec}}{dE_\nu} = \Phi_{\rm dec}\delta\left(E_\nu - \frac{m_{\rm DM}}{2}\right)$$

One-to-one correspondence between E_ν and $m_{\rm DM}$

- Neutrino production in the whole MW

$$\Phi_{\rm anni} = \frac{1}{6}\int\frac{ds\,d\Omega}{4\pi}\langle\sigma_{\rm anni}v\rangle\, n_{\rm DM}^2 \propto m_{\rm DM}^{-2}$$

$$\Phi_{\rm dec} = \frac{1}{6}\int\frac{ds\,d\Omega}{4\pi}2\tau^{-1}n_{\rm DM}^1 \propto m_{\rm DM}^{-1}$$

$n_{\rm DM} = \frac{\rho_{\rm DM}}{m_{\rm DM}}$: DM number density $\rho_{\rm DM}$: DM profile

Φ gets smaller as $m_{\rm DM}$ larger.

The largest uncertainty: DM profile $\rho_{\mathrm{DM}}(r)$

- Neutrino flux and DM profile in the Milky Way

$$\Phi_{\mathrm{anni}} = \frac{1}{6}\int_{\text{line of sight}} \frac{ds\, d\Omega}{4\pi} \langle \sigma_{\mathrm{anni}} v \rangle \left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)^2$$

$$\Phi_{\mathrm{dec}} = \frac{1}{6}\int_{\text{line of sight}} \frac{ds\, d\Omega}{4\pi} 2\tau^{-1} \left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)$$

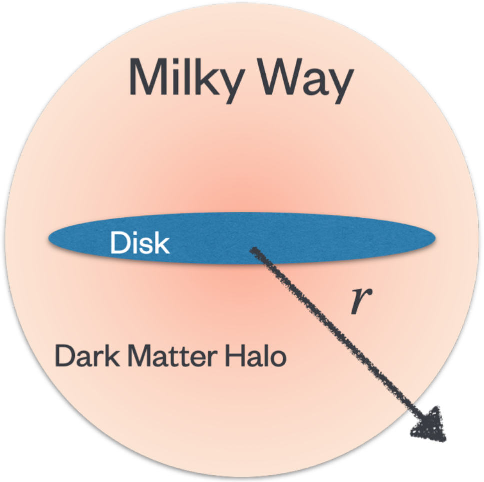
⇨

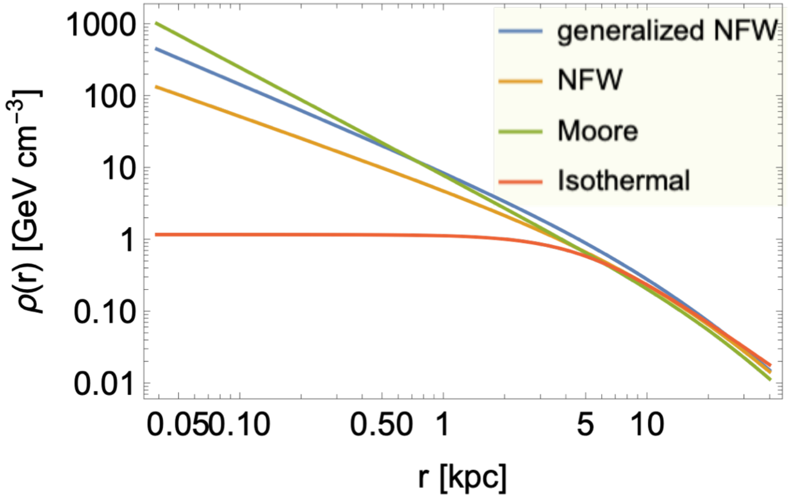
Annihilation

$$\mathscr{J} = \int_{\text{line of sight}} ds\, d\Omega\, \rho_{\mathrm{DM}}^2 ,$$

Decay

$$\mathscr{D} = \int_{\text{line of sight}} ds\, d\Omega\, \rho_{\mathrm{DM}} .$$





$\mathscr{J}$ [10^{23} GeV^{2}cm^{-5}], $\mathscr{D}$ [10^{23} GeVcm^{-2}]

	$\mathscr{J}$	$\mathscr{D}$
Generalized NFW	2.3	2.5
NFW	0.88	1.9
Moore	2.7	2.5
Isothermal	0.53	1.9

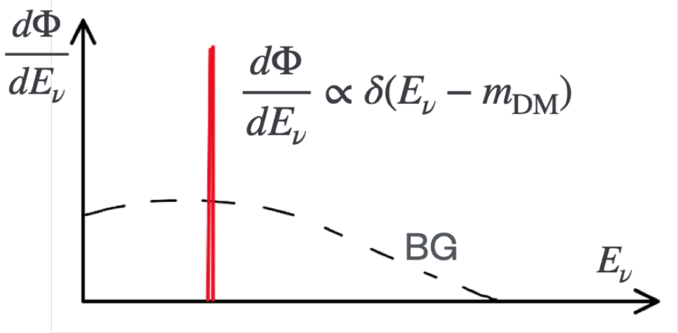
JUNO experiment

	Super Kamiokande	JUNO
Detection	Water	liquid scintillator
Volume	$\simeq 22.5\,\mathrm{kton}$	$17\,\mathrm{kton}$
Resolution	$\simeq 40\,\%$ at $1\,\mathrm{MeV}$ [Palomares-Ruiz et al. [0710.5420]]	$3\,\%$ at $1\,\mathrm{MeV}$

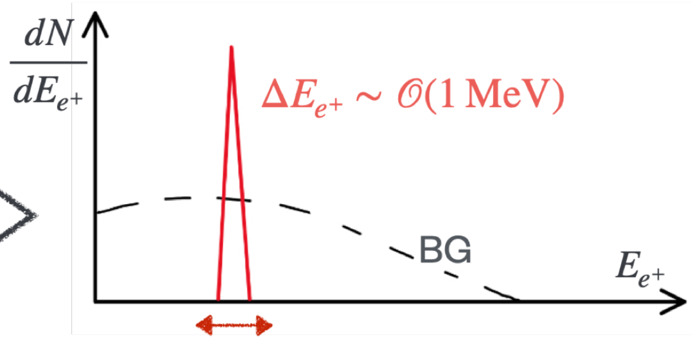
Wikipedia

- Detection channel: inverse beta decay (IBD) $\bar{\nu}_e + p \to e^+ + n$
  - Main channel at $10\mathrm{MeV} \lesssim E_\nu \lesssim 100\mathrm{MeV}$
  - Little smearing effect $\Delta E_{e^+} \equiv E_{\max} - E_{\min} = \frac{2}{m_p} E_\nu^2 \sim 5\ \mathrm{MeV} \left(\frac{E_\nu}{50\ \mathrm{MeV}} \right)$

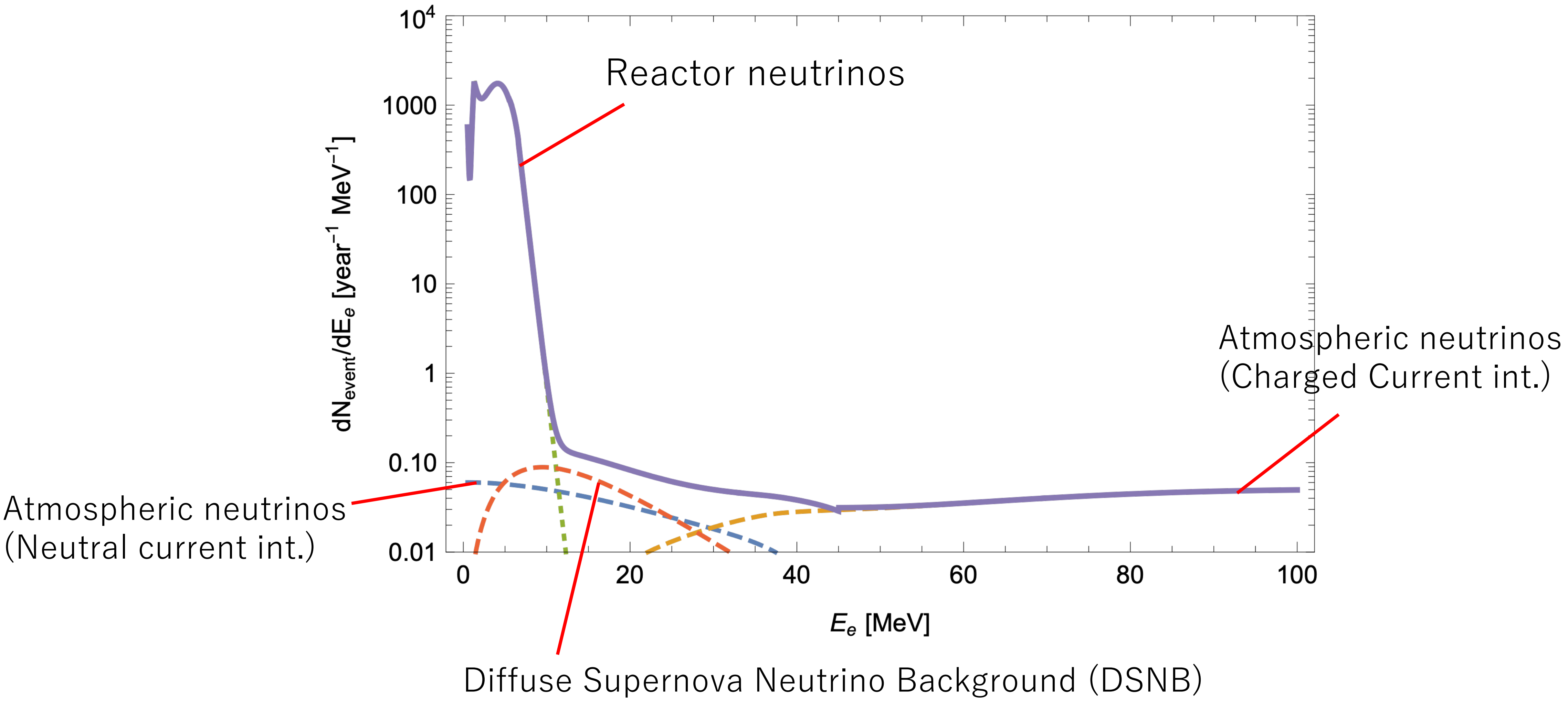
⇨ Easy to distinguish the signal from background



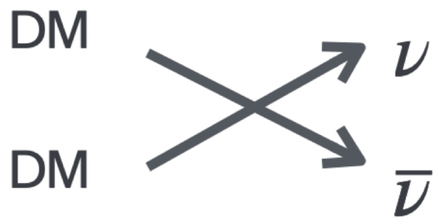
IBD



Background (1-year data-taking)



Result -DM annihilation to neutrinos-



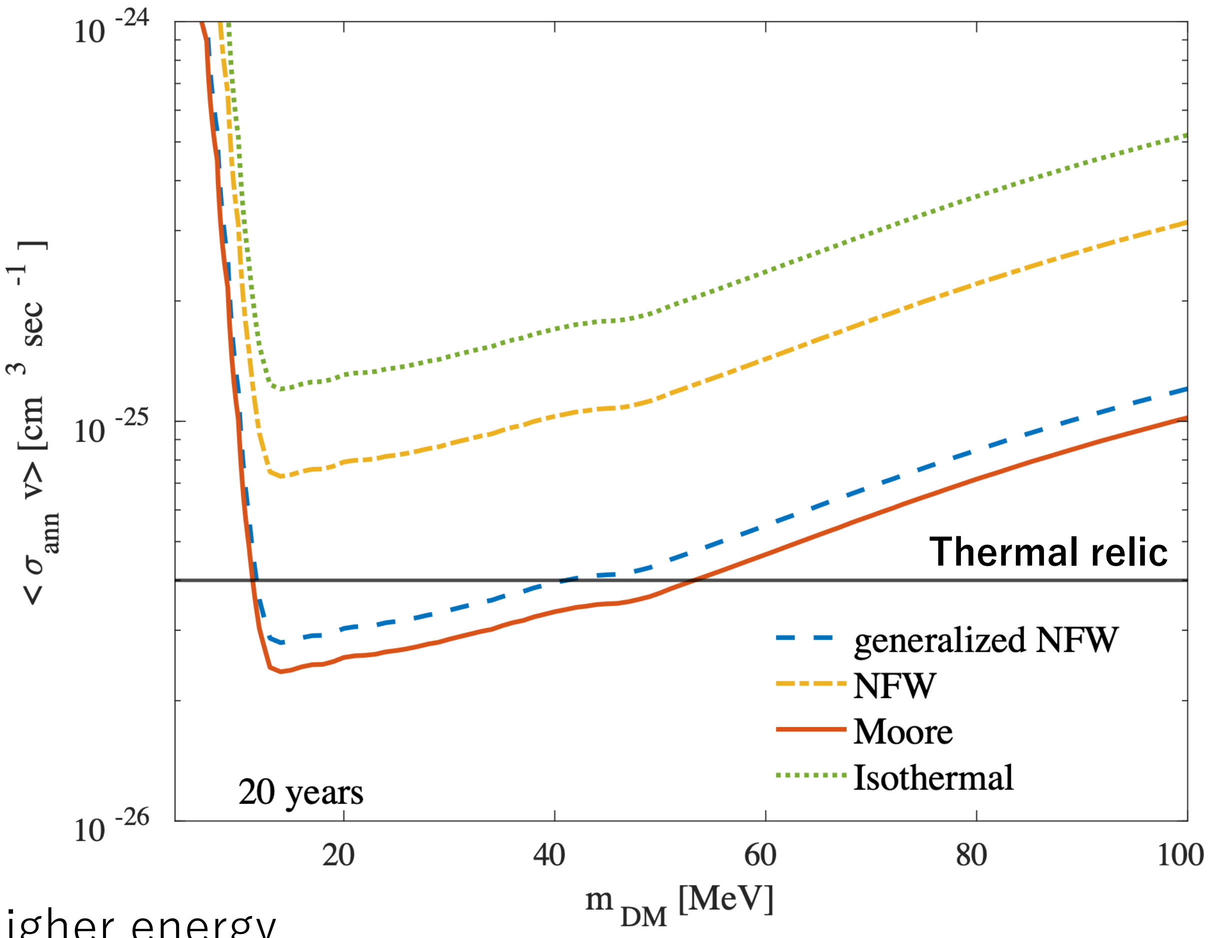
$$\frac{dN}{dE_{e^+}} = \epsilon N_t T \int \frac{d\sigma}{dE_{e^+}}(E_{e^+}, E_\nu)\frac{d\Phi}{dE_\nu}dE_\nu$$

$\epsilon = 0.6$: detector efficiency

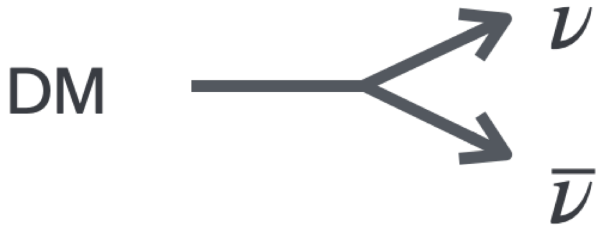
$N_t = 1.21 \times 10^{33}$: number of free protons

$T = 20$ years : data-taking

- JUNO may test the thermal relic abundance in $10\ \mathrm{MeV} \lesssim m_{\mathrm{DM}} \lesssim 50\ \mathrm{MeV}$.
- Factor 5 uncertainty due to DM profile
- Neutrino Flux $\propto m_{\mathrm{DM}}^{-2}$: weaker constraint in the higher energy



Result -DM decay to neutrinos-



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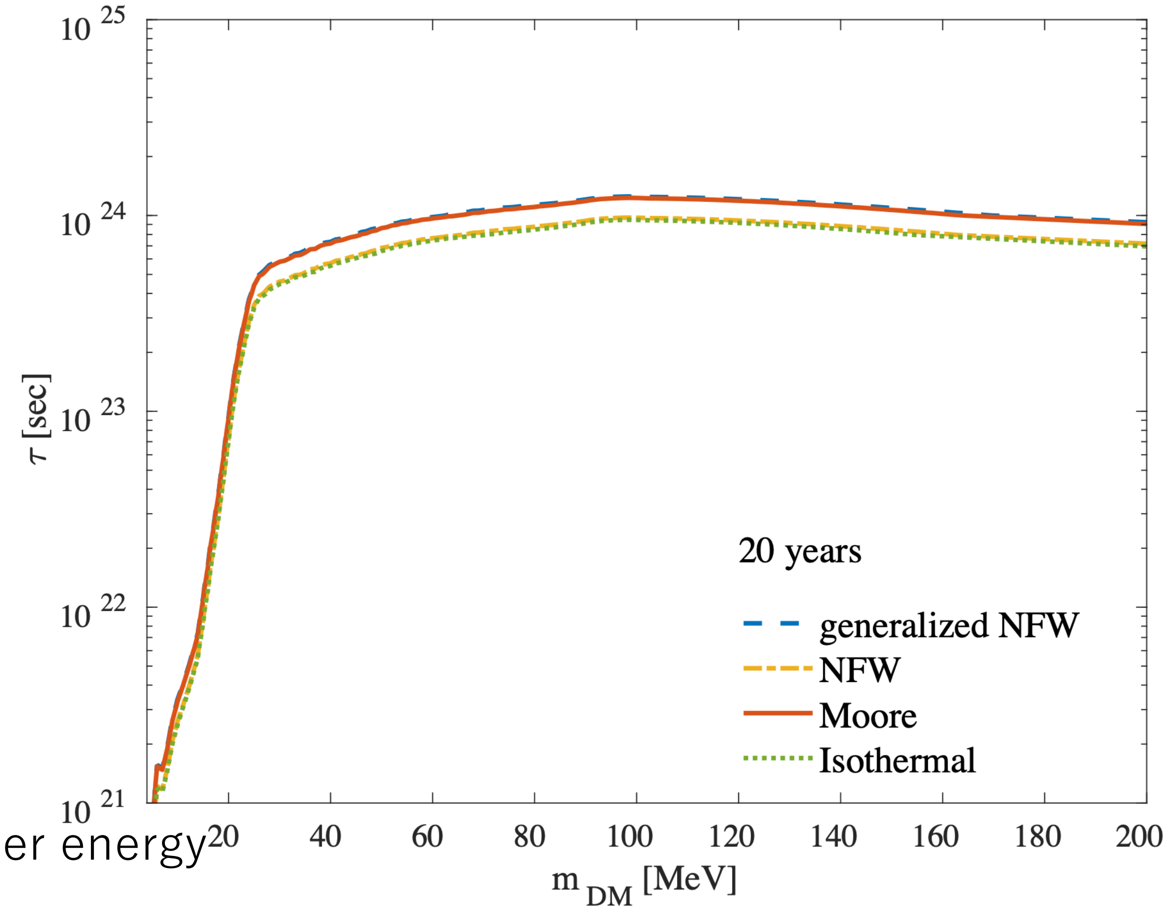


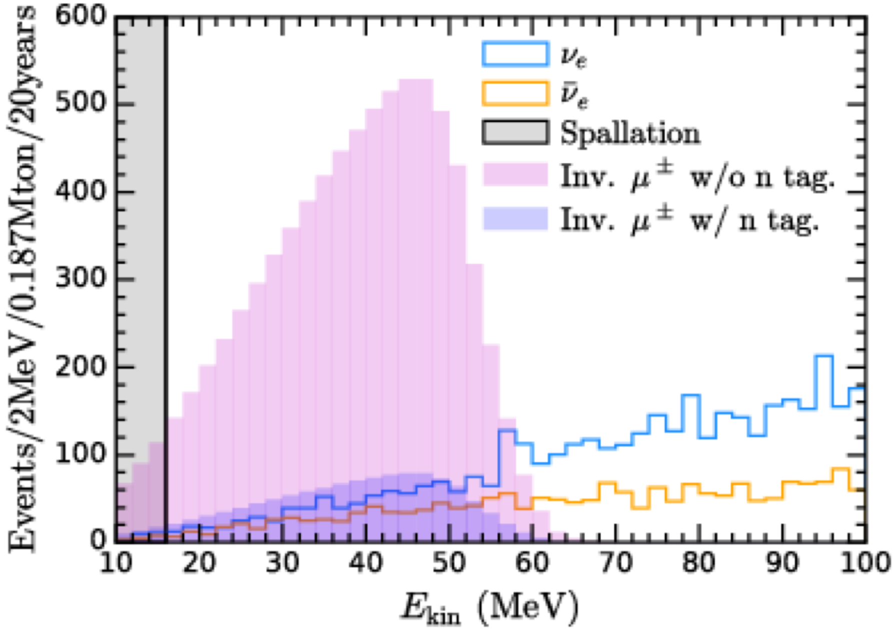
- $\tau \simeq 1 \times 10^{24}$ s in $30\ \mathrm{MeV} \lesssim m_{\mathrm{DM}} \lesssim 200\ \mathrm{MeV}$
- Factor 2 uncertainty due to DM profile
- Neutrino Flux $\propto m_{\mathrm{DM}}^{-1}$: weaker constraint in the higher energy

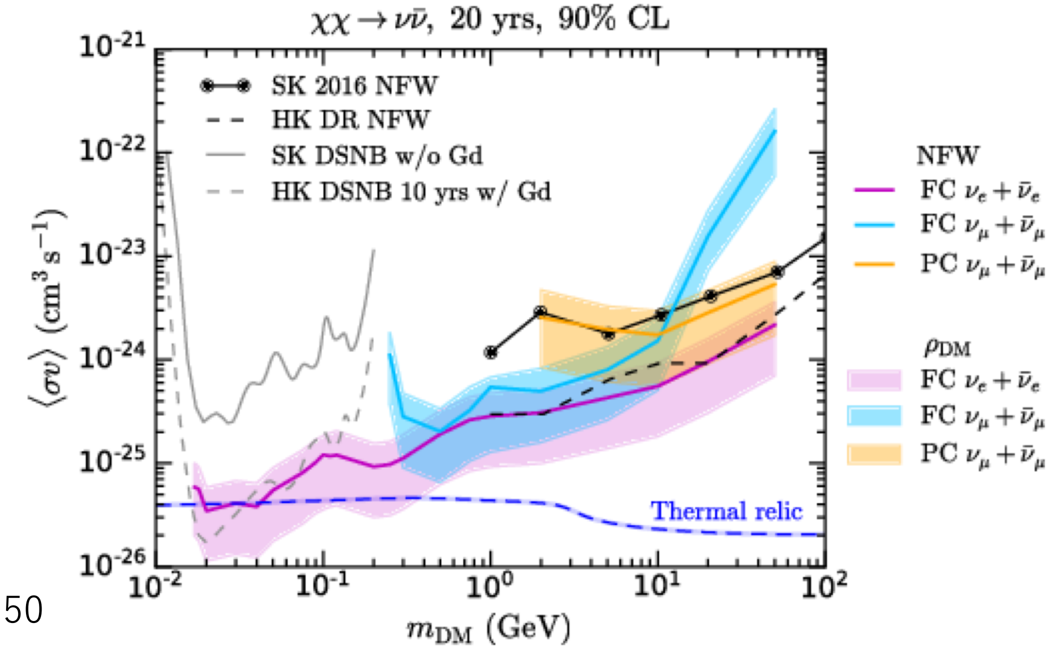
Discussions

- Prospect for DM annihilation in HK
  - HK can test test the thermal relic abundance around $m_{\mathrm{DM}} \sim 20\ \mathrm{MeV}$.
- CMB-S4 observations have the sensitivity with $m_{\mathrm{DM}} \lesssim 10\ \mathrm{MeV}$. N. Sabti et al. 1910.01649

JUNO, HK, CMB-S4 will complementary improve the MeV-DM annihilation cross section into neutrinos!

Background and sensitivity in HK





N. F. Bell et al. 2005.01950

Conclusions

- DM annihilation, decay and scattering into neutrinos are constrained by Neutrino Telescopes and Cosmological observations.

- Future neutrino telescopes can significantly improve the sensitivity for the DM annihilations and decays.

- JUNO experiments may test the thermal average DM annihilation cross sections in $10\ \mathrm{MeV} \lesssim m_{\mathrm{DM}} \lesssim 50\ \mathrm{MeV}$, assuming the Moore or generalized NFW profile.

- JUNO also have the sensitivity for DM decay into neutrinos with $\tau \simeq 1 \times 10^{24}\ \mathrm{s}$ in $30\ \mathrm{MeV} \lesssim m_{\mathrm{DM}} \lesssim 200\ \mathrm{MeV}$.

Thank you!