Constraints on dark matter-neutrino scattering from Milky-Way satellite observations and semi-analytical subhalo modeling for dark acoustic oscillations

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arXiv: 2305.01913

Accepted in JCAP 20th year special issue

PPC 2023 Daejeon June 13

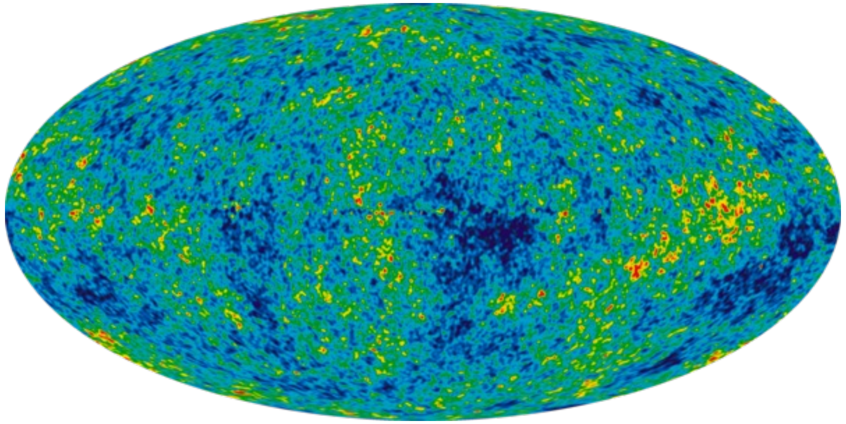
Introduction

Dark Matter (DM)

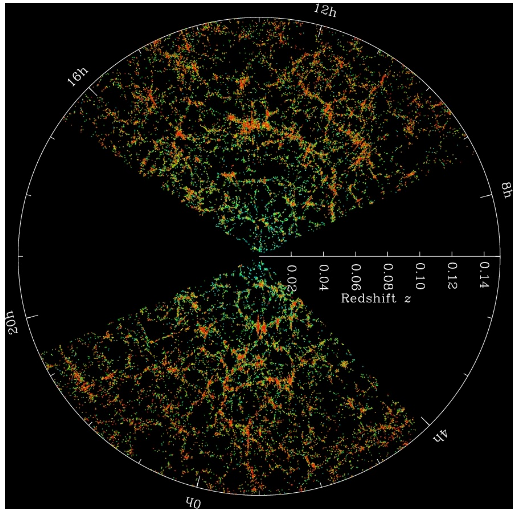
DM is gravitationally confirmed by cosmological observations,
e.g., structure formation.

DM properties:
- 27 % of the total energy of the universe
- Massive
- Stable

However, we don't know
- mass
- interactions beyond gravity.



https://map.gsfc.nasa.gov/media/121238/index.html

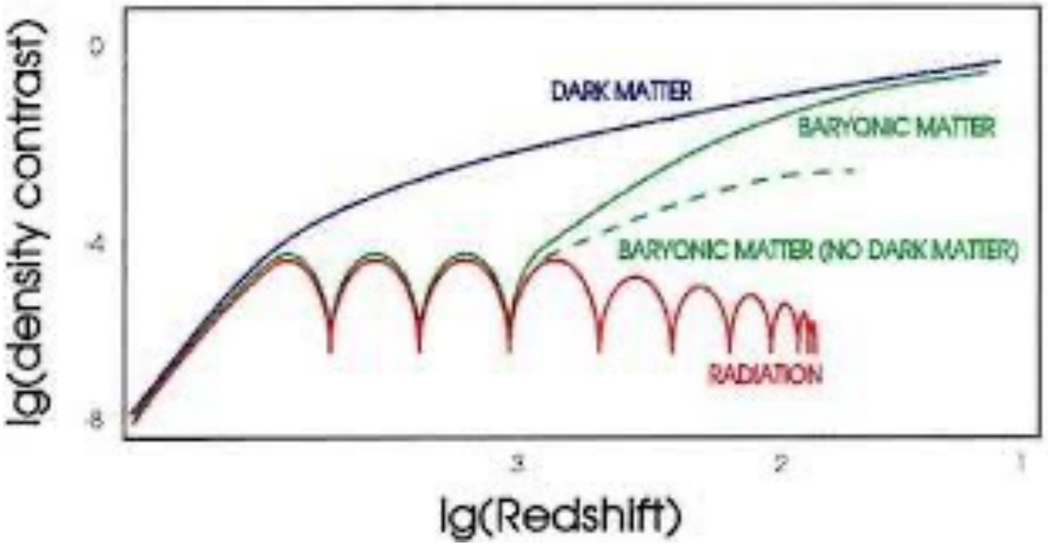


https://www.darkenergysurvey.org/supporting-science/large-scale-structure/

Structure formation

DM plays an important role in the structure formation of the universe and DM properties are more constrained.

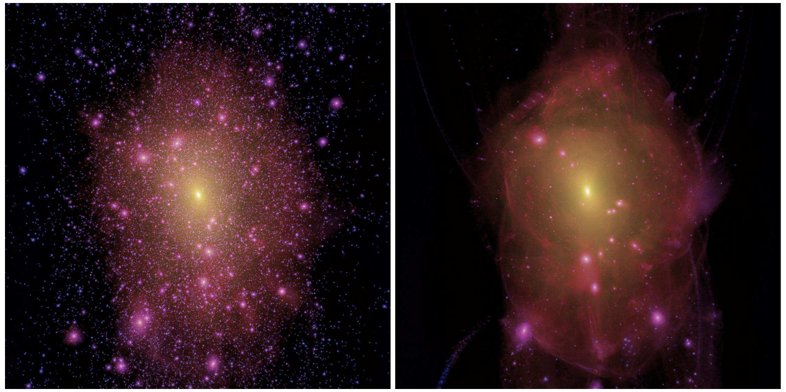
https://www.ir.isas.jaxa.jp/~cpp/teaching/cosmology/documents/cosmology02-03.pdf



- The potential of DM is required for galaxy formation.

DM properties from structure formation
- DM is non-relativistic/semi-relativistic (cold/warm)

Can we learn more from structure formation?



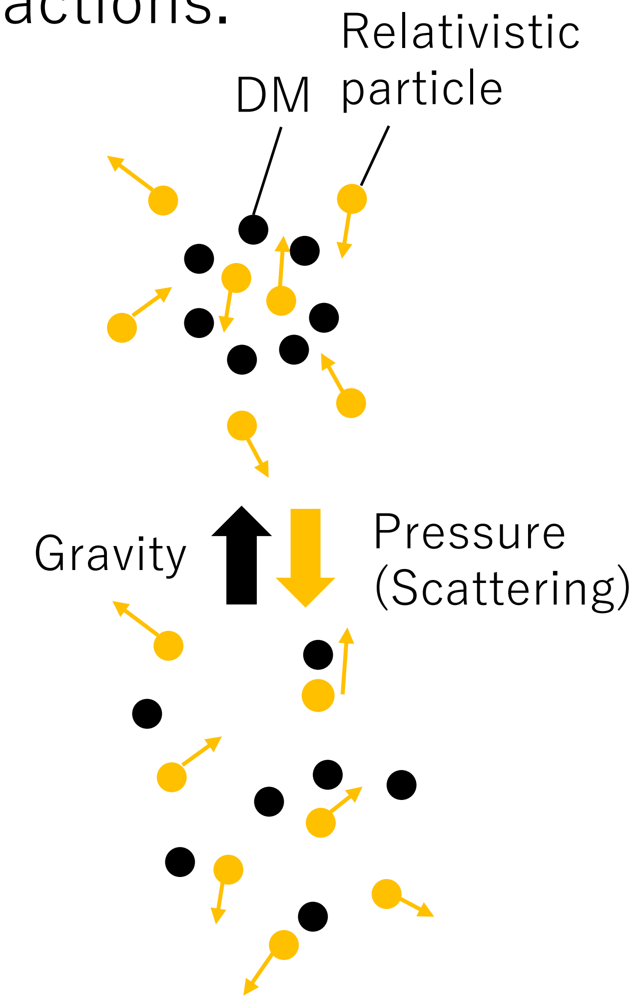
[M. R. Lovel, et al. (2011)] Cold Warm

Dark acoustic oscillations (DAOs)

- Standard DM has (approximately) only gravitational interactions.

- If DM has **interactions with relativistic particles**, DM fluctuations are suppressed due to their pressure.

- DM oscillations between gravity and pressure: Dark acoustic oscillations



We can constrain DM interactions
from the observations of the structure formation.

DM-Neutrino scattering

Neutrinos are mysterious particles. Neutrinos may interact with DM.

- We focus on the DM-cosmic relic neutrino scattering:

$$\sigma_{\mathrm{DM}-\nu,n} \propto E_\nu^n \propto a^{-n}, \quad (n = 0, 2, 4)$$

Neutrino energy

- The modified Euler equations for DM and neutrino fluctuations:

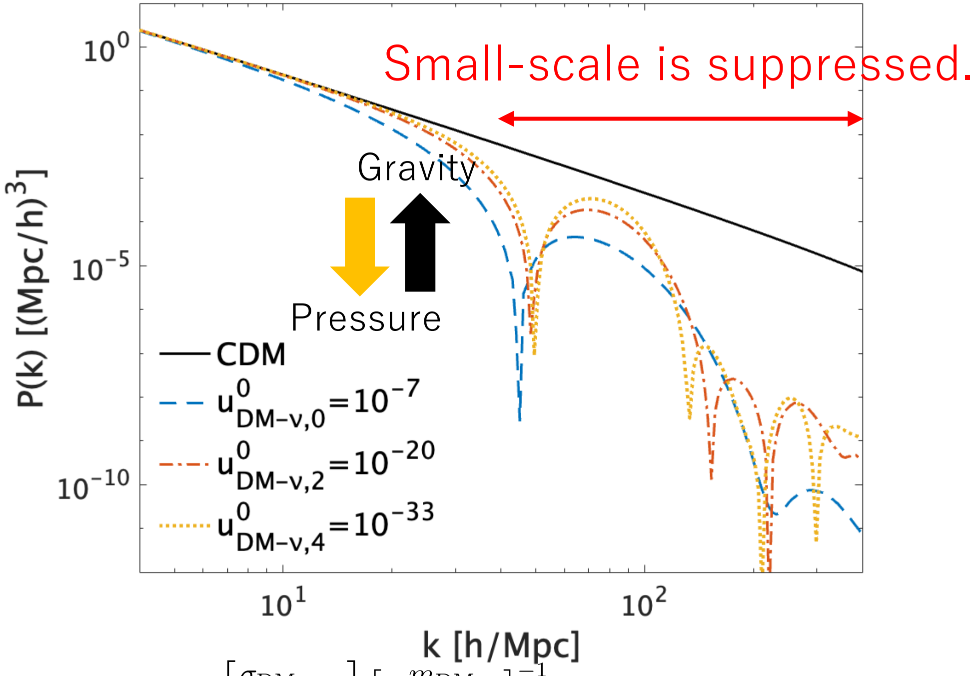
$$\dot{\theta}_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \underline{\Gamma_{\nu-\mathrm{DM}}(\theta_\nu - \theta_{\mathrm{DM}})},$$

$$\dot{\theta}_{\mathrm{DM}} = k^2\psi - \mathcal{H}\theta_{\mathrm{DM}} - \underline{\Gamma_{\mathrm{DM}-\nu}(\theta_{\mathrm{DM}} - \theta_\nu)}, \ \ldots$$

Velocity divergence

$$\Gamma_{\nu-\mathrm{DM}} = a\sigma_{\mathrm{DM}-\nu}n_{\mathrm{DM}}, \qquad \Gamma_{\mathrm{DM}-\nu} = \frac{4\rho_\nu}{3\rho_{\mathrm{DM}}}\Gamma_{\nu-\mathrm{DM}}.$$

The matter power spectrum on small-scale is suppressed!



$$u_{\mathrm{DM}-\nu,n} \equiv \left[\frac{\sigma_{\mathrm{DM}-\nu,n}}{\sigma_{\mathrm{Th}}}\right]\left[\frac{m_{\mathrm{DM}}}{100\ \mathrm{GeV}}\right]^{-1}, \qquad u_{\mathrm{DM}-\nu,n} = u^0_{\mathrm{DM}-\nu,n}a^{-n},$$

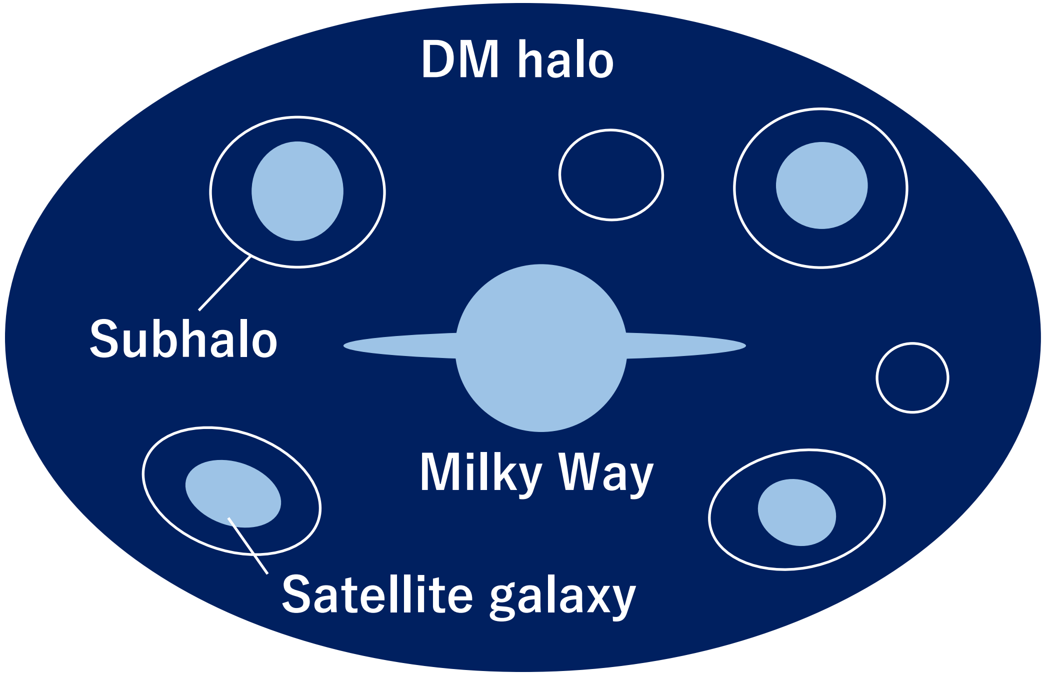
Milky-Way (MW) satellite galaxies

Milky-Way satellite galaxies, objects on small-scale structure, would have very good information to test DM-neutrino interactions.

Suppression of the matter power spectrum
→reducing the number of satellites

In this talk,

- We develop a subhalo model for DAOs.
- We constrain DM-neutrino scattering using the latest data of MW satellites.



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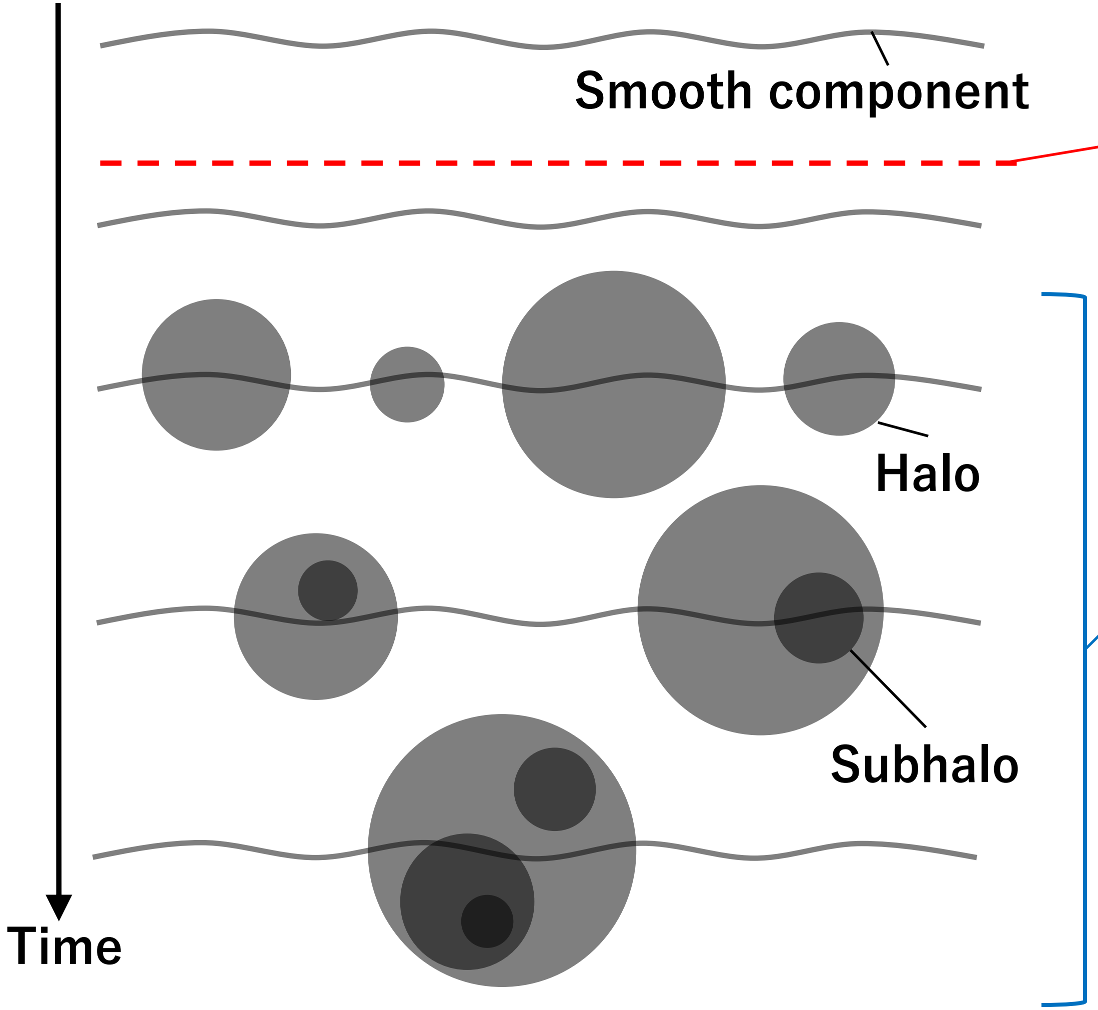
Schematic history of dark matter



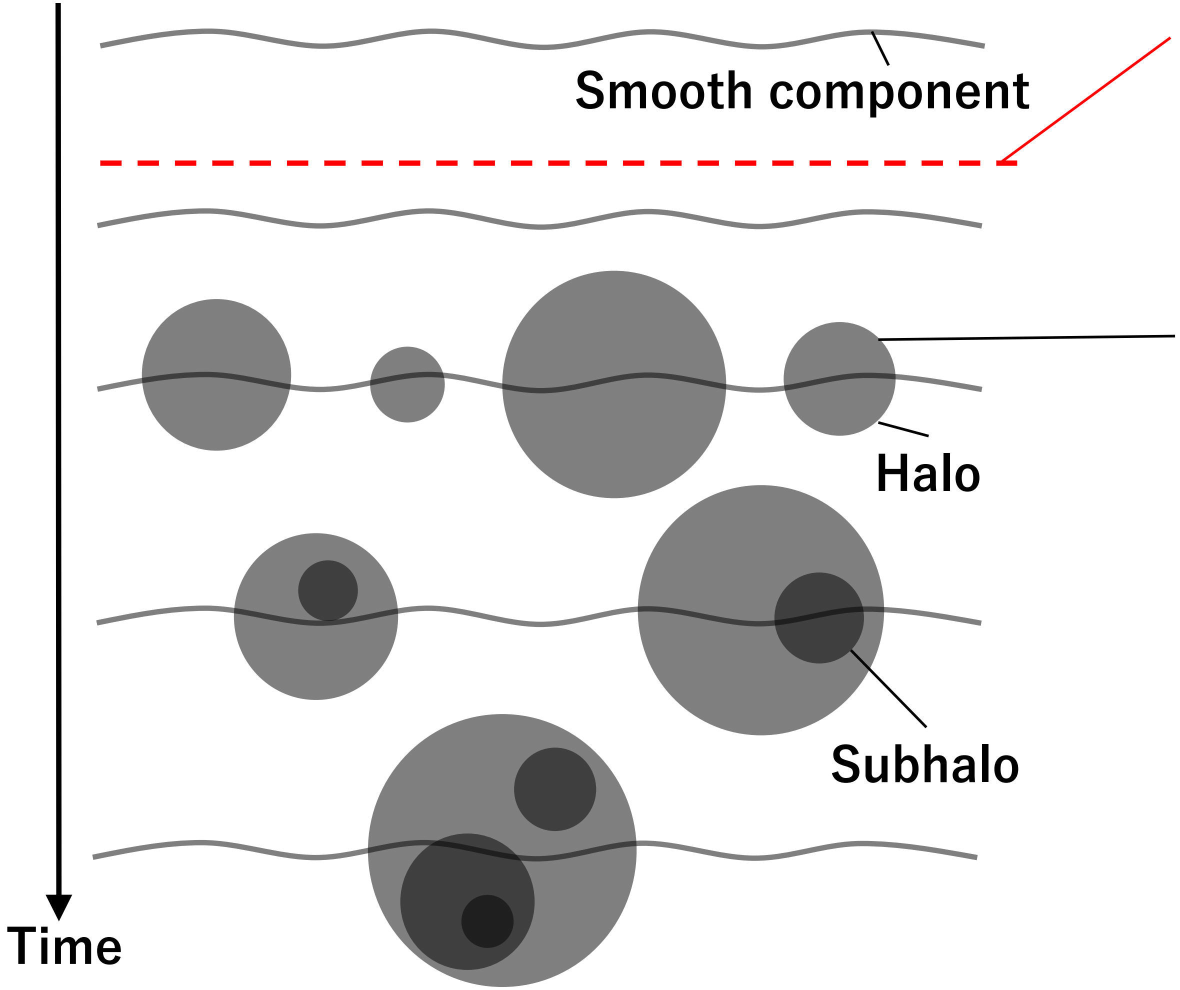
- DM decouples with neutrinos in the linear region if DM-neutrino interactions are weak.

- DM gravitationally collapses, forming halos.
- Halos merge, forming subhalos.

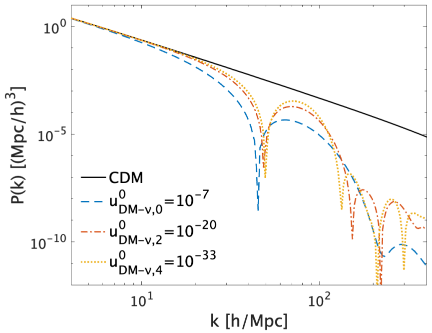
➡ DM evolution is non-linear and computationally expensive.

Semi-analytical subhalo modeling is needed!

Subhalo modeling for dark acoustic oscillations



Initial condition:



Modeling:

- **DM fluctuations are <u>spherically</u> smoothed:**

$$\delta(\boldsymbol{x};R)=\int\delta(\boldsymbol{x}')W(\boldsymbol{x}-\boldsymbol{x}';R)d^3x',$$

$$W(\boldsymbol{x}-\boldsymbol{x}';R)\begin{cases}<1 & |\boldsymbol{x}-\boldsymbol{x}'|\lesssim R\\ =0 & |\boldsymbol{x}-\boldsymbol{x}'|\gtrsim R\end{cases}$$

We adopt <u>the smooth-k filter</u> (in the Fourier space):

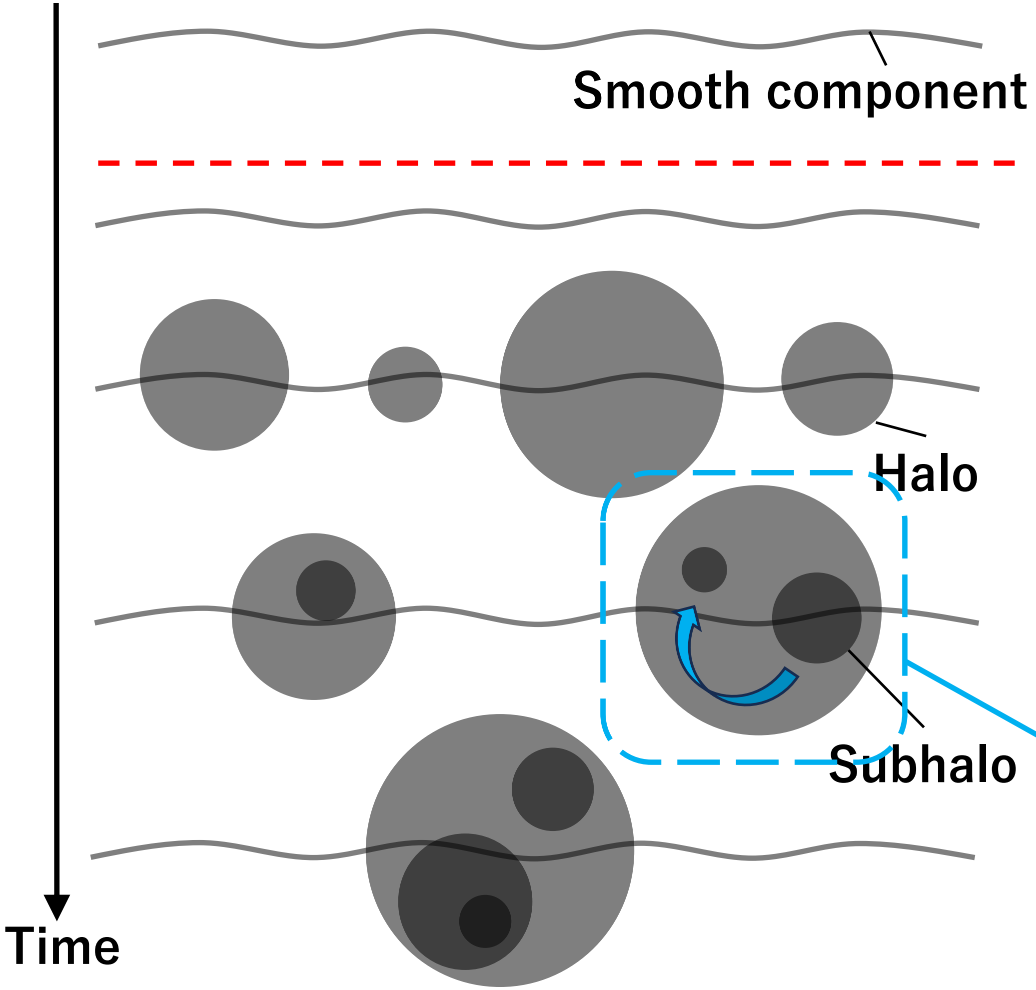
This is different from CDM and WDM cases.

$$\widetilde{W}^{\rm smooth-k}(kR)=\frac{1}{1+(kR)^\beta}\qquad\beta=3.5$$

- **DM spherically collapses into halos with** $M(\leftrightarrow R)$

at $\delta(\boldsymbol{x};R)>\delta_c\simeq\delta_{\rm CDM}=1.686$ at $z=0$

Subhalo modeling for dark acoustic oscillations



Modeling:

- **Distribution of halos and subhalos:**

  Extended Press-Schechter formalism

  -Subhalo distributions at $z = z_a$

$$\frac{d^2 N_{\rm a}}{dm_a dz_a} \propto \frac{1}{\sqrt{2\pi}} \frac{\delta_a - \delta_M}{(s_a - S_M)^{3/2}} \exp\left[-\frac{(\delta_a - \delta_M)^2}{2(s_a - S_M)} \right]$$

Smoothed fluctuation and standard deviation with mass

m_a : subhalo mass M : Host halo mass

- **Tidal stripping:**

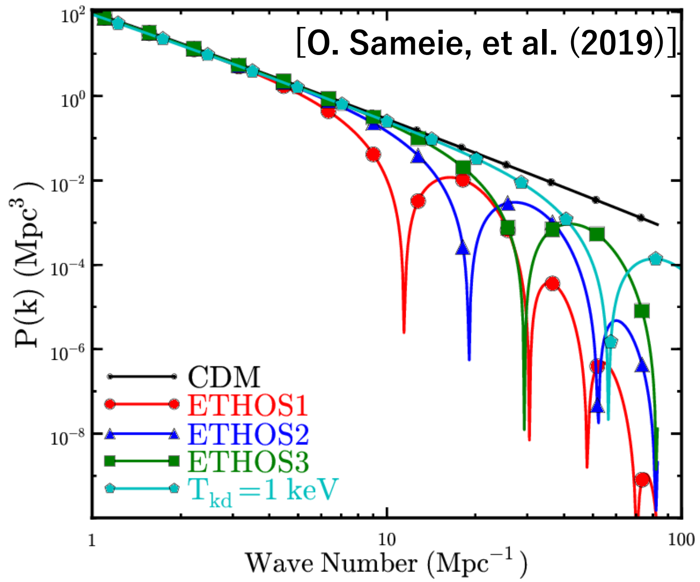
$$\dot{m}(z) = -A \frac{m(z)}{\tau_{\rm dyn}(z)} \left[\frac{m(z)}{M(z)} \right]^{\zeta}$$

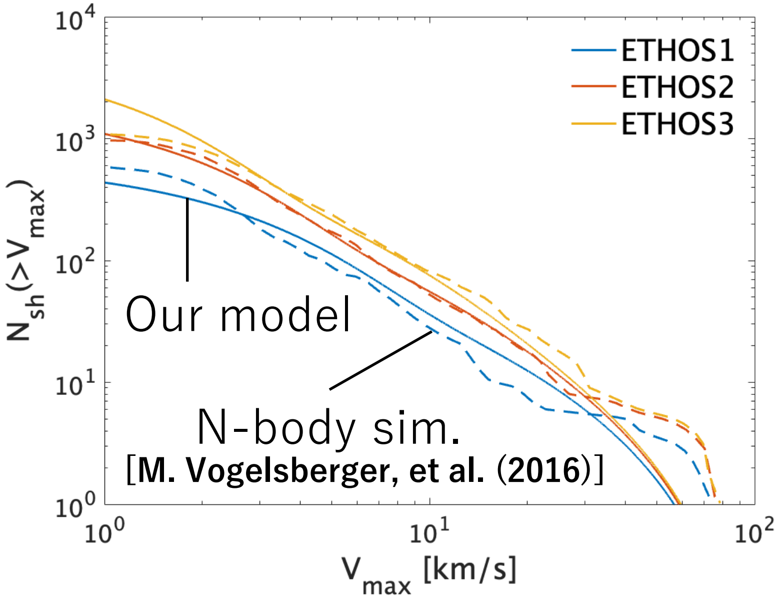
Fitting parameters by N-body simulations

Subhalo mass

Host halo mass

Comparison with N-body simulations





- Unfortunately, there is no such simulation for DM-neutrino interactions.
- There is N-body simulations for DM-Dark Radiation (DR) interactions (called ETHOS models). [M. Vogelsberger, et al. (2016)]
- Our model is in very good agreement with the N-body simulations <u>within a factor of 1.8</u>!

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Constraints on DM-neutrino scattering

We use the latest data of 270 Milky-Way satellite galaxies from Dark Energy Survey (DES) and PanSTARRS1 (PS1). **[DES collaboration (2020)]**

Imposing a satellite forming condition of $m_a > 10^8 M_\odot$,
we obtain the strongest constraints
of $\sigma_{\mathrm{DM}-\nu,n} \propto E_\nu^n \quad (n = 0, 2, 4)$ at 95% CL

Subhalo mass at accretion

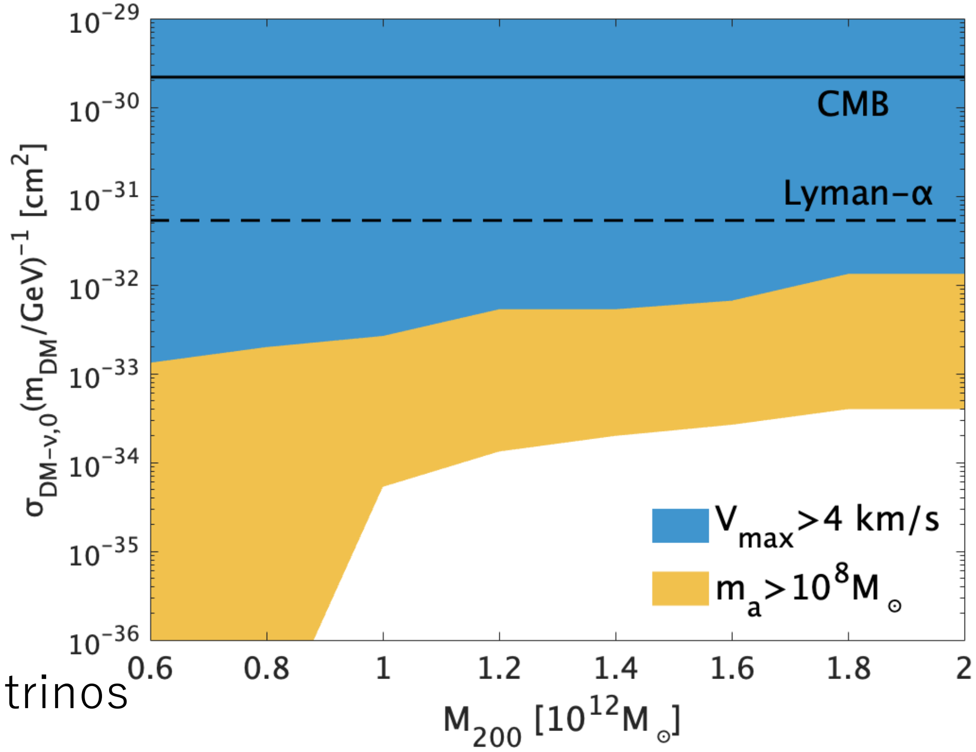
$$\sigma_{\mathrm{DM}-\nu,0} < 4 \times 10^{-34}\ \mathrm{cm}^2\ (m_{\mathrm{DM}}/\mathrm{GeV})$$

$$\sigma_{\mathrm{DM}-\nu,2} < 10^{-46}\ \mathrm{cm}^2\ (m_{\mathrm{DM}}/\mathrm{GeV})(E_\nu/E_\nu^0)^2$$

$$\sigma_{\mathrm{DM}-\nu,4} < 7 \times 10^{-59}\ \mathrm{cm}^2\ (m_{\mathrm{DM}}/\mathrm{GeV})(E_\nu/E_\nu^0)^4$$

$E_\nu^0 \simeq 6.1\ K$: the average momentum of relic cosmic neutrinos

The case of n=0



MW halo mass

Comparison with constraints from high energy neutrinos

Observations of neutrinos with $E_\nu \sim 10\ \mathrm{TeV}$ from an active galaxy NGC 1068:

$$\boxed{\sigma_{\mathrm{DM}-\nu} \lesssim 10^{-30}\ \mathrm{cm}^2\ (m_{\mathrm{DM}}/\mathrm{GeV})}$$

[J. M. Cline, M. Puel (2023)]

There is no simple comparison between cosmological and astrophysical constraints <u>due to the different energy scales of neutrinos</u>.

Ex1) Dirac fermion DM, scalar mediator

- <u>Milky-Way satellites</u>: $m_{\mathrm{mediator}} \gtrsim m_{\mathrm{DM}} \gg E_\nu$

$$\sigma_{\mathrm{DM}-\nu} \simeq \frac{g^2 g'^2 E_\nu^2}{2\pi m_\phi^4},$$

$$g \lesssim \underline{8 \times 10^{-5}} \left(\frac{g'}{1}\right)^{-1} \left(\frac{m_{\mathrm{DM}}}{\mathrm{MeV}}\right)^{1/2} \left(\frac{m_\phi}{\mathrm{MeV}}\right)^{2} \left(\frac{E_\nu}{E_\nu^0}\right)^{-1} \left(\frac{\sigma_{\mathrm{DM}-\nu}/m_{\mathrm{DM}}}{10^{-49}\ \mathrm{cm}^2/\mathrm{MeV}}\right)^{1/2}.$$

- <u>High energy neutrinos</u>: $E_\nu \gg m_{\mathrm{mediator}} \gtrsim m_{\mathrm{DM}}$

$$\sigma_{\mathrm{DM}-\nu} \simeq \frac{g^2 g'^2}{32\pi E_\nu m_{\mathrm{DM}}},$$

$$g \lesssim 5 \times 10^{-2} \left(\frac{g'}{1}\right)^{-1} \left(\frac{m_{\mathrm{DM}}}{\mathrm{MeV}}\right) \left(\frac{E_\nu}{10\ \mathrm{TeV}}\right)^{1/2} \left(\frac{\sigma_{\mathrm{DM}-\nu}/m_{\mathrm{DM}}}{10^{-33}\ \mathrm{cm}^2/\mathrm{MeV}}\right)^{1/2}.$$

Ex2) Dirac fermion DM, vector mediator

- <u>Milky-Way satellites</u>: $m_{\mathrm{mediator}} \gtrsim m_{\mathrm{DM}} \gg E_\nu$

$$\sigma_{\mathrm{DM}-\nu} \simeq \frac{g^2 g'^2 E_\nu^2}{2\pi m_\phi^4},$$

$$g \lesssim 8 \times 10^{-5} \left(\frac{g'}{1}\right)^{-1} \left(\frac{m_{\mathrm{DM}}}{\mathrm{MeV}}\right)^{1/2} \left(\frac{m_\phi}{\mathrm{MeV}}\right)^{2} \left(\frac{E_\nu}{E_\nu^0}\right)^{-1} \left(\frac{\sigma_{\mathrm{DM}-\nu}/m_{\mathrm{DM}}}{10^{-49}\ \mathrm{cm}^2/\mathrm{MeV}}\right)^{1/2}$$

- <u>High energy neutrinos</u>: $E_\nu \gg m_{\mathrm{mediator}} \gtrsim m_{\mathrm{DM}}$

$$\sigma_{\mathrm{DM}-\nu} \simeq \frac{g^2 g'^2}{4\pi m_\phi^2},$$

$$g \lesssim \underline{6 \times 10^{-6}} \left(\frac{g'}{1}\right)^{-1} \left(\frac{m_\phi}{\mathrm{MeV}}\right) \left(\frac{m_{\mathrm{DM}}}{\mathrm{MeV}}\right)^{1/2} \left(\frac{\sigma_{\mathrm{DM}-\nu}/m_{\mathrm{DM}}}{10^{-33}\ \mathrm{cm}^2/\mathrm{MeV}}\right)^{1/2}.$$

Cosmological and astrophysical constraints are highly complementary!

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Conclusions

- We have developed a semi-analytical subhalo model for dark acoustic oscillations.
- Our model is in very good agreement with N-body simulation of ETHOS models with DM-DR interactions within a factor of 1.8.
- Using the latest data of Milky-Way satellite galaxies from DES and PS1 survey, we have obtained the most stringent constraints on DM-neutrino scattering of $\sigma_{\mathrm{DM}-\nu,n} \propto E_\nu^n \quad (n = 0, 2, 4)$:

$$\sigma_{\mathrm{DM}-\nu,0} < 4 \times 10^{-34}\ \mathrm{cm}^2\ (m_{\mathrm{DM}}/\mathrm{GeV})$$

$$\sigma_{\mathrm{DM}-\nu,2} < 10^{-46}\ \mathrm{cm}^2\ (m_{\mathrm{DM}}/\mathrm{GeV})(E_\nu/E_\nu^0)^2$$

$$\sigma_{\mathrm{DM}-\nu,4} < 7 \times 10^{-59}\ \mathrm{cm}^2\ (m_{\mathrm{DM}}/\mathrm{GeV})(E_\nu/E_\nu^0)^4$$

Thank you!