Constraints on dark matter-neutrino scattering from the Milky-Way satellites and subhalo modeling for dark acoustic oscillations

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arXiv: 2305.01913
accepted in JCAP 20th year anniversary edition

TAUP 2023 Vienna August 28

Dark Matter (DM)

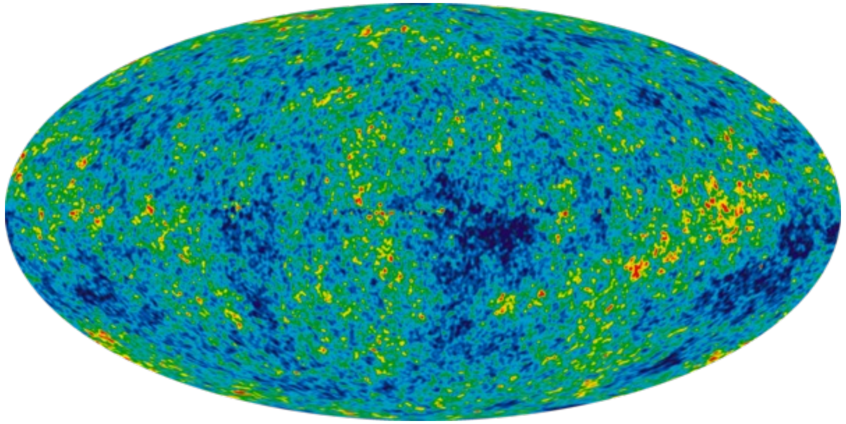
DM is gravitationally confirmed by cosmological observations,
e.g., <u>structure formation</u>.

DM properties:

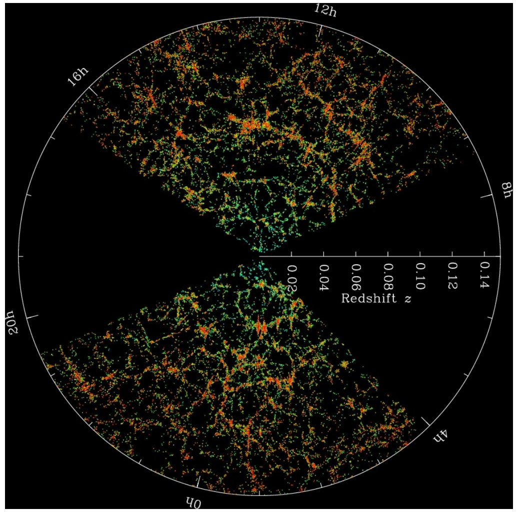
- 27 % of the total energy of the universe
- Massive
- Stable

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/

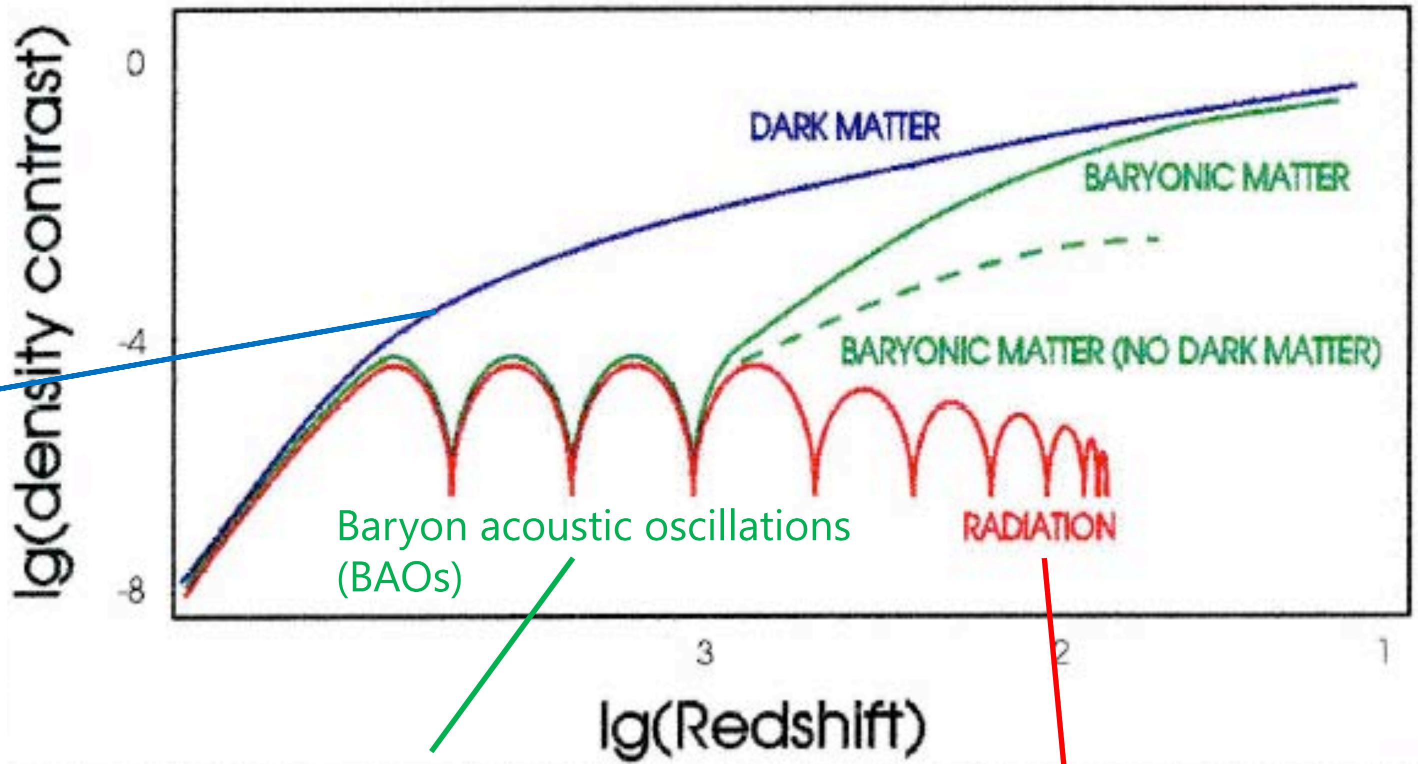
Structure formation of the universe

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

The potential of DM is required for galaxy formation.

DM property :
・<u>Non-relativistic</u>

Can we learn more from structure formation?



Baryon coupled with radiation is suppressed by radiation pressure.

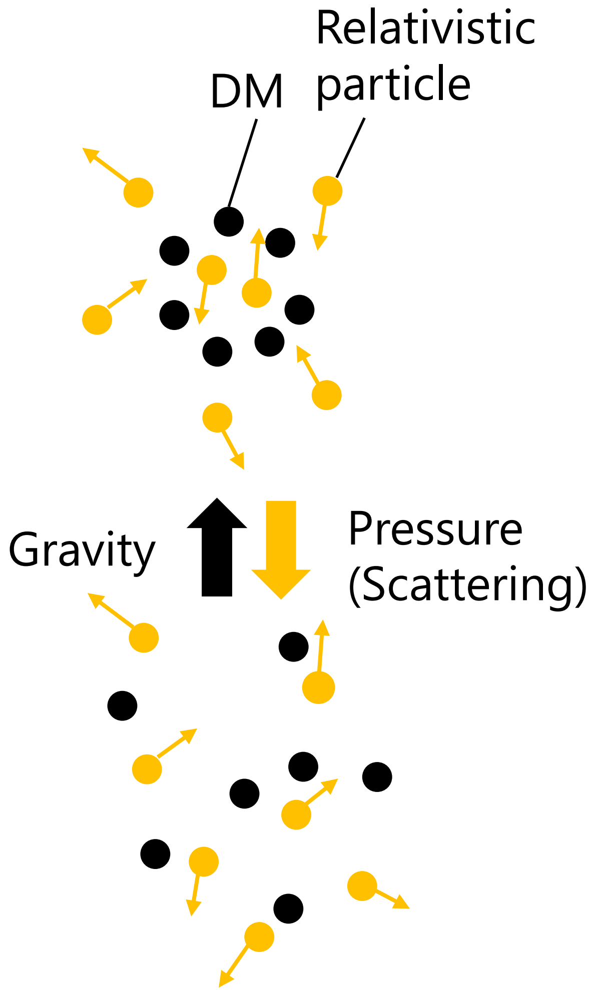
Relativistic particle grows less by its large velocity dispersion.

Dark acoustic oscillations (DAOs)

- 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 test DM interactions from the structure formation.



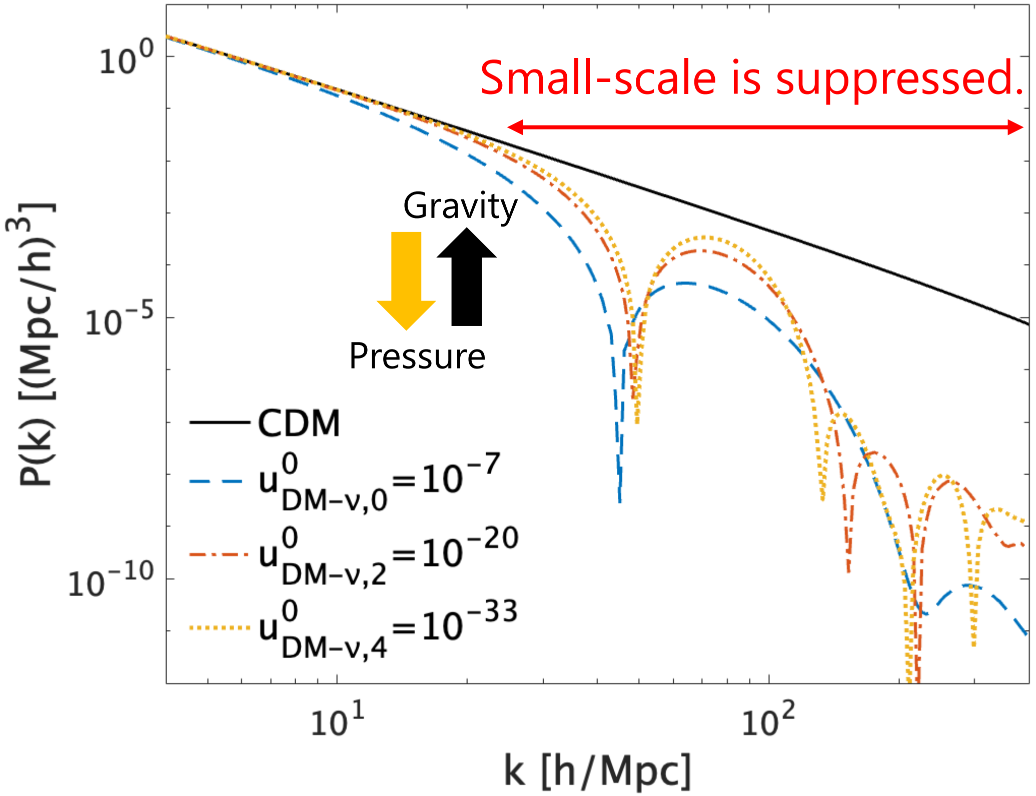
DM-Neutrino scattering

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

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

Neutrino energy

- The matter power spectrum $P(k)$
  on small-scale is suppressed.



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

Thomson scattering cross section

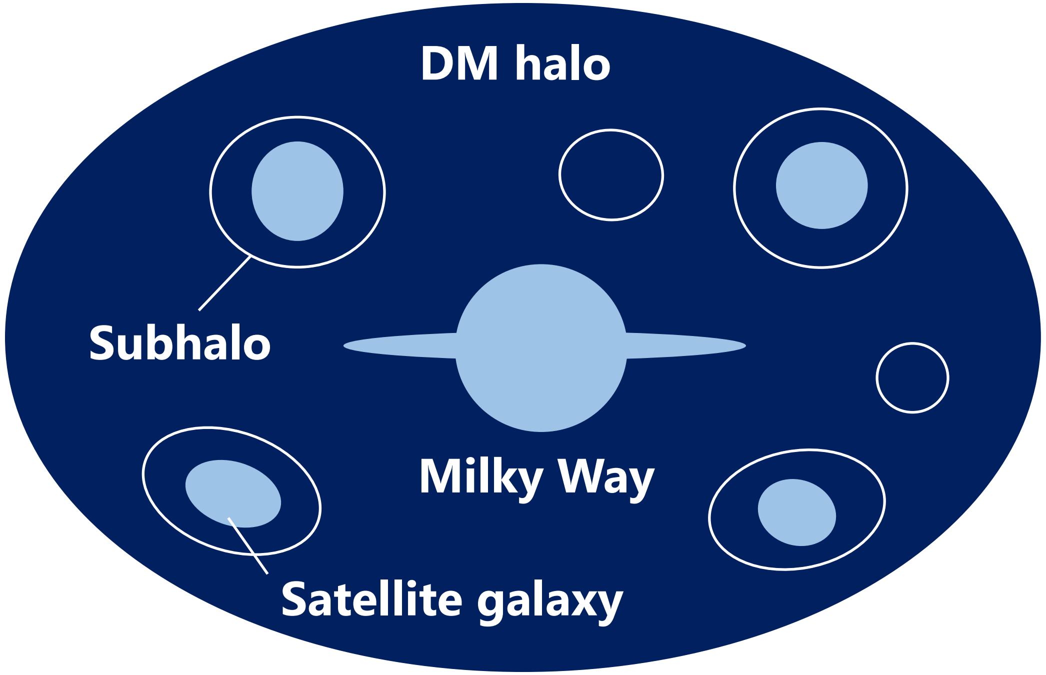
The scale factor of the universe

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

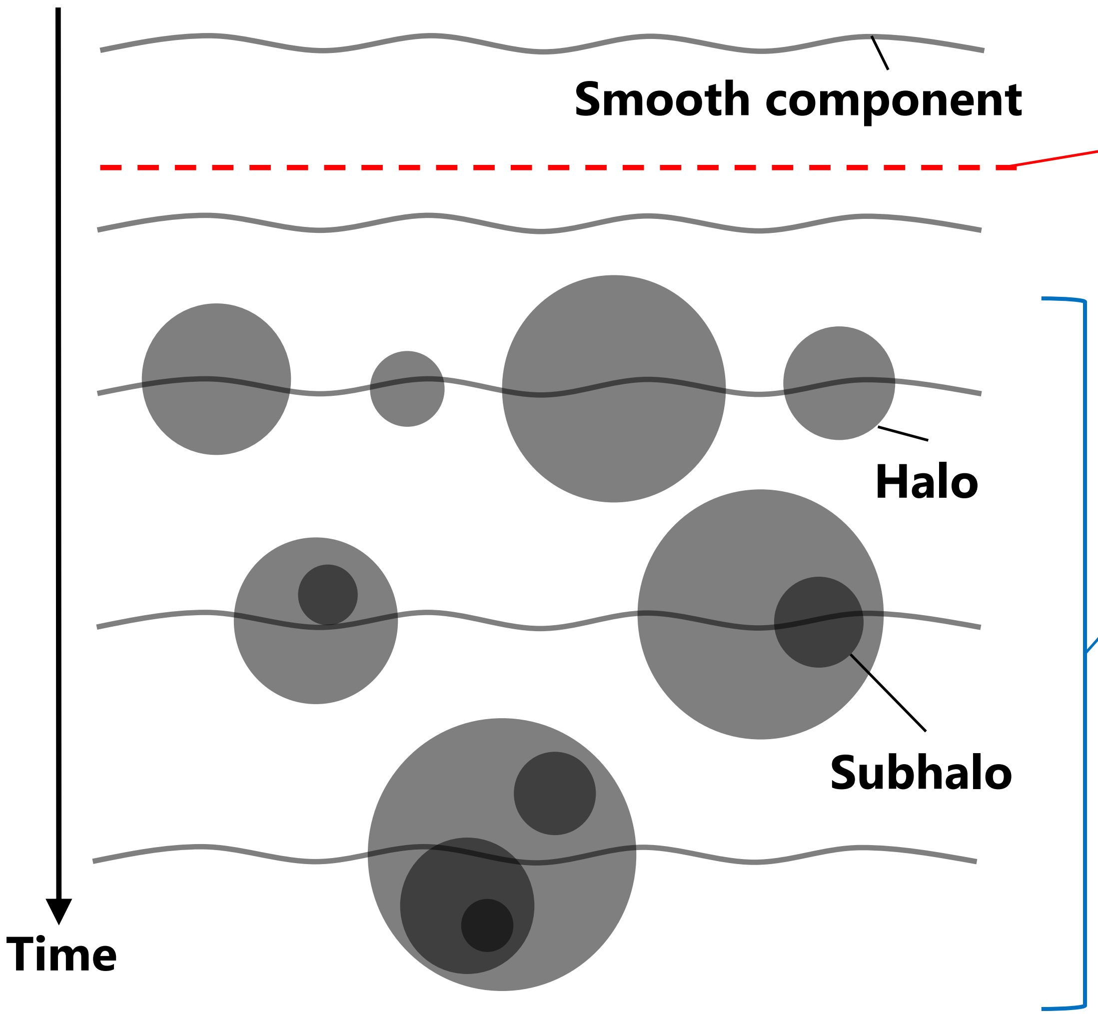
In this talk,
- We develop a subhalo model for DAOs.
- We constrain DM-neutrino scattering using the latest data of MW satellites.



Outline

- Introduction
- Subhalo modeling for dark acoustic oscillations
- Constraints on DM-neutrino scattering from the MW satellites
- Conclusions

Schematic history of dark matter



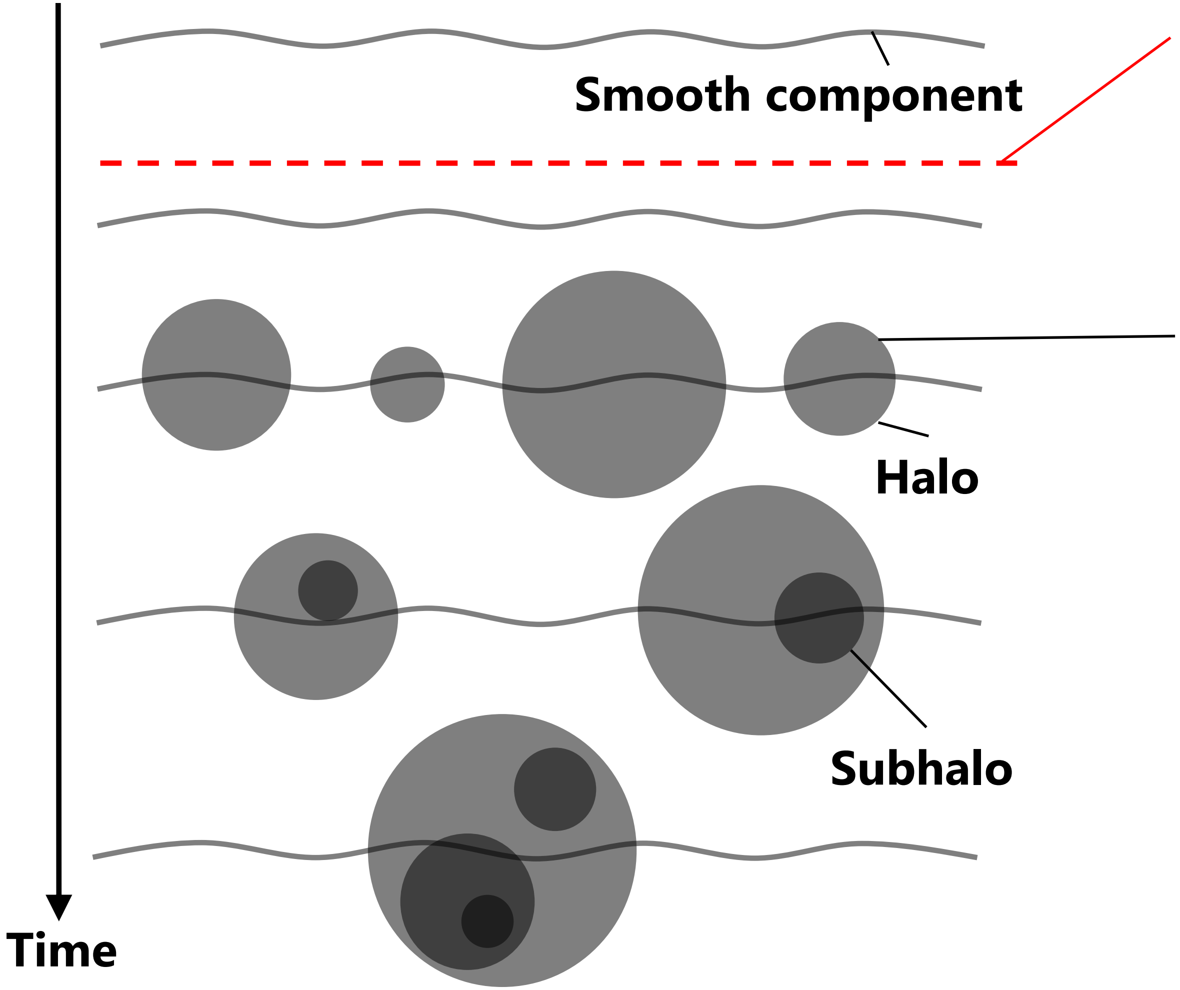
- DM decouples with neutrinos in the linear region for weak DM-neutrino interactions.

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

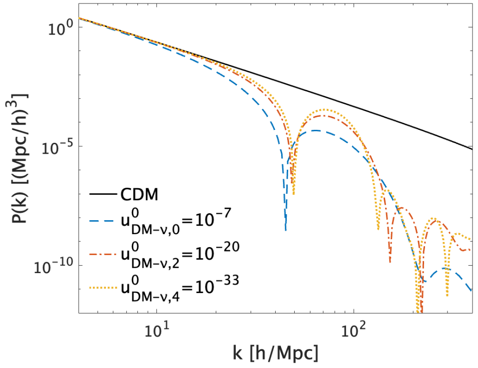
➡ DM evolution is non-linear and computationally expensive.

Semi-analytical subhalo model is needed!

Subhalo modeling for dark acoustic oscillations



Initial condition:



Modeling:

- **DM fluctuations are spherically smoothed:**

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

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

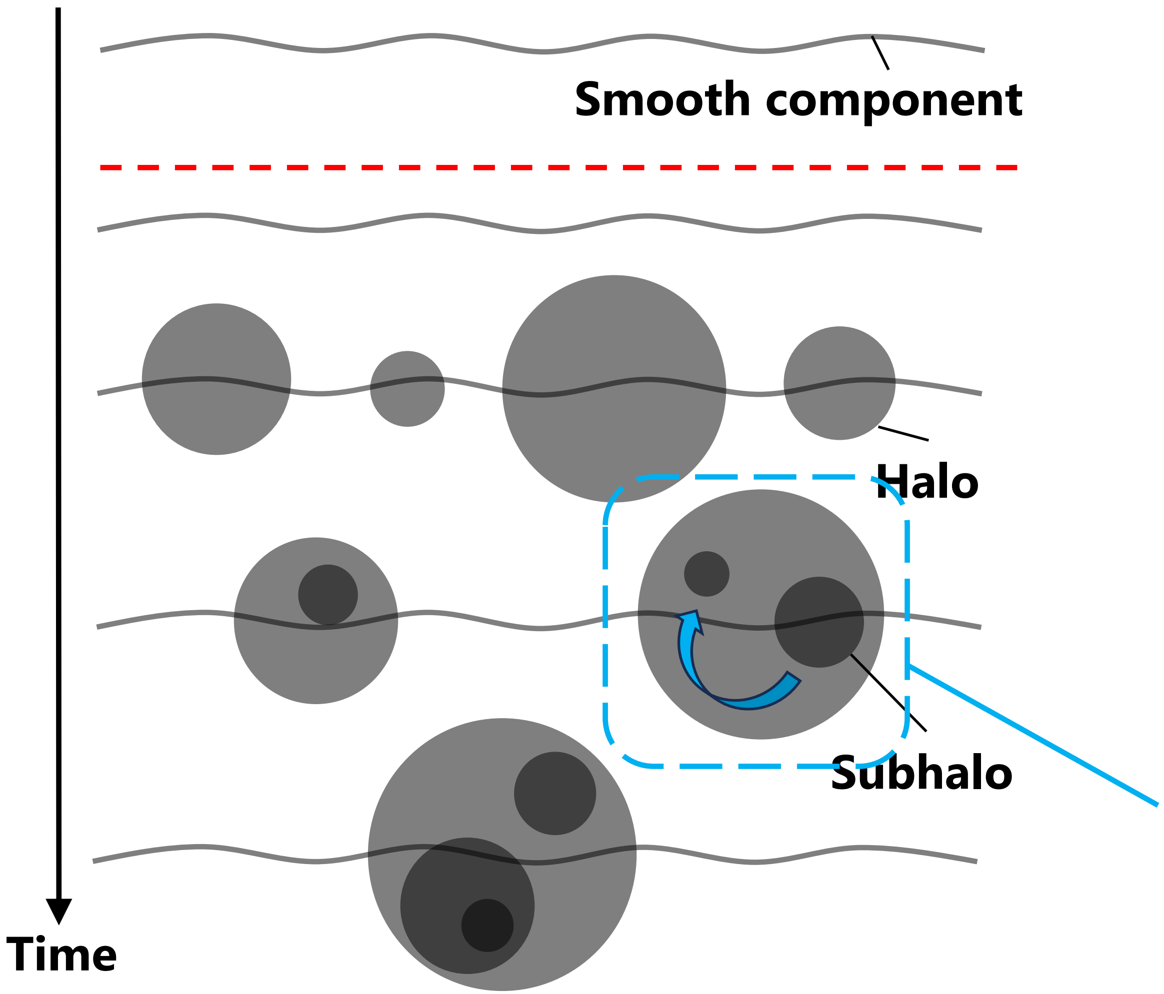
We adopt the smooth-k filter (in the Fourier space):

This is different from CDM and WDM cases.

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

- **DM spherically collapses into halos with** $M(\leftrightarrow R)$ **at a threshold value of** $\delta_c = 1.686$ **at** $z = 0$.

Subhalo modeling for dark acoustic oscillations



Modeling:

- **Distribution of halos and subhalos:**

  Extended Press-Schechter formalism

  -Subhalo distributions at $z = z_a$

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

Smoothed fluctuation and standard deviation with mass

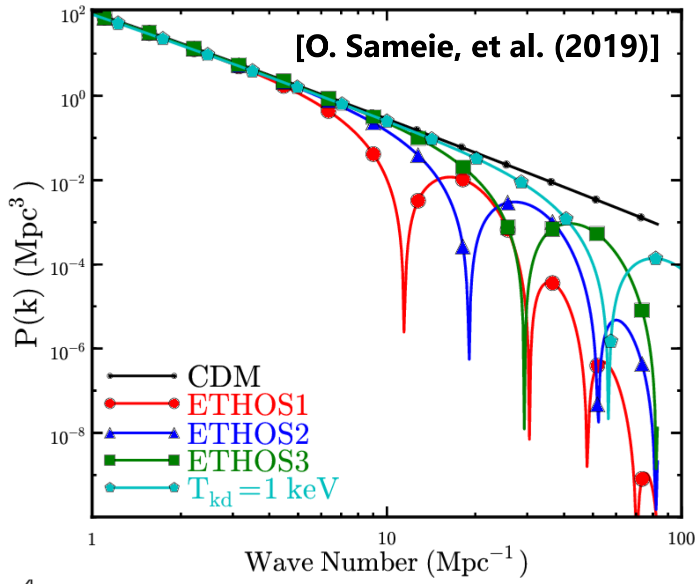
m : subhalo mass M : Host halo mass

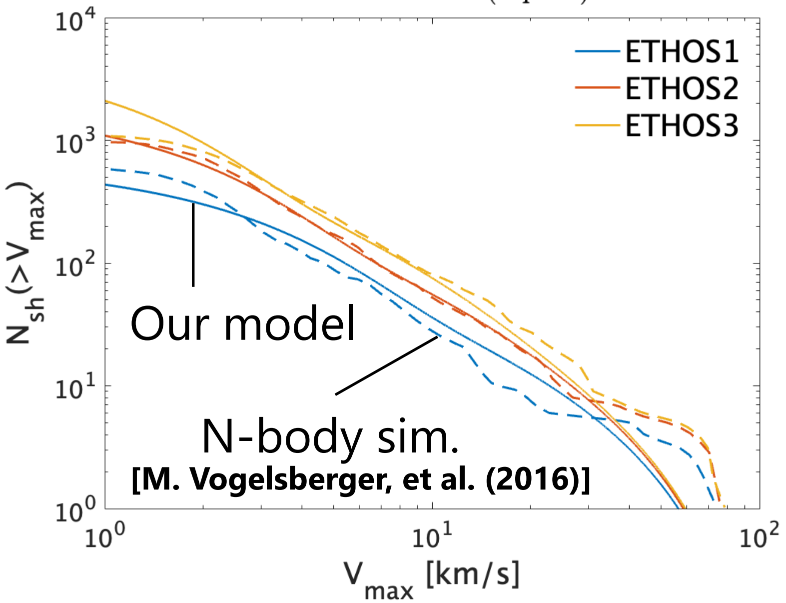
- **Tidal stripping:**

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

Fitting parameters

Comparison with N-body simulations





To confirm that our model is correct,
it is necessary to be compared to N-body simulations.

- Unfortunately, there is no such simulation for DM-neutrino interactions.
- There is simulations for DM-Dark Radiation (DR) interactions (called ETHOS models).

[M. Vogelsberger, et al. (2016)]

- Our model is in very good agreement with the simulations within a factor of 1.8!

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, we obtain the strongest constraints of $\sigma_{\mathrm{DM}-\nu,n} \propto E_\nu^n \quad (n=0,2,4)$ at 95% CL:

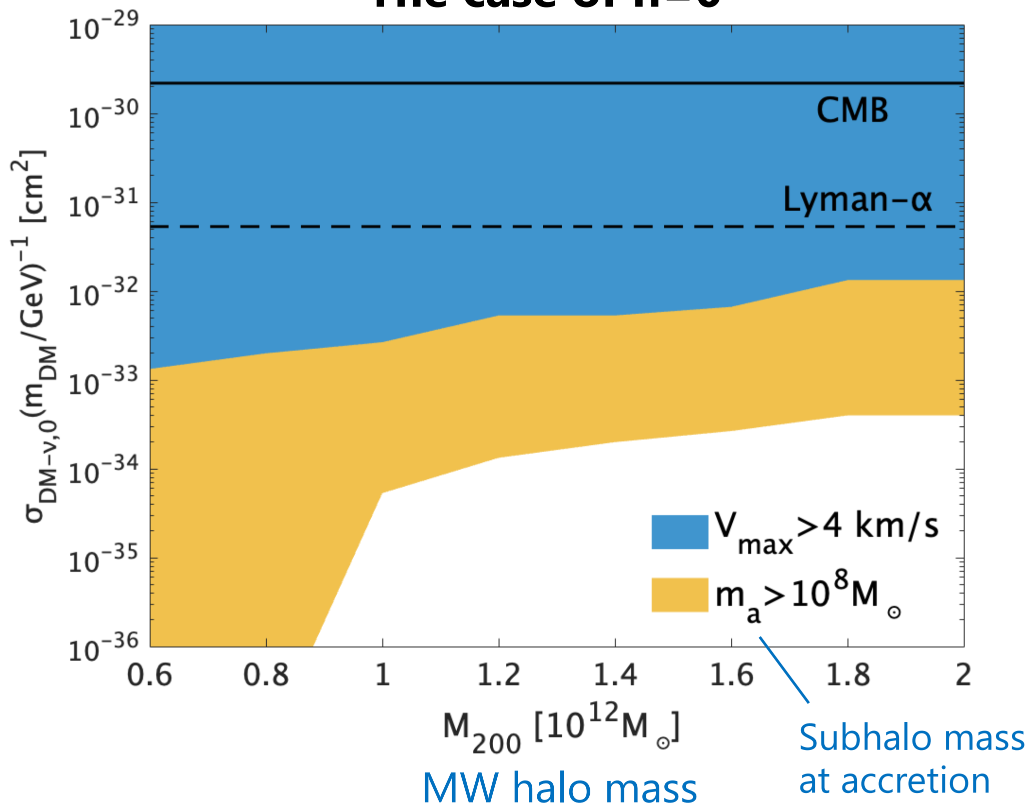
$$\sigma_{\mathrm{DM}-\nu,0} < 4\times 10^{-34}\ \mathrm{cm}^2\ (m_{\mathrm{DM}}/\mathrm{GeV})$$

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

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

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

The case of n=0



Conclusions

- DM-radiation interactions induces dark acoustic oscillations (DAOs), suppressing the structure formation due to radiation pressure.
- We have developed a semi-analytical subhalo model for DAOs.
- Our model is in very good agreement with N-body simulations within a factor of 1.8.
- Using the latest data of Milky-Way satellite galaxies from DES and PS1, 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!

Backup

Why structure formation? DM-neutrino scattering?

Why structure formation?

- We can test light DM scattering with neutrinos, baryons, photons and dark radiations.

- Even if DM is heavy (GeV-scale), asymmetric DM scenarios is not well constrained.

  DM does not annihilate today.
  →Indirect searches are ineffective.

- Large DM scattering cross sections may also be achieved in asymmetric DM scenarios.

Why DM-neutrino (relic cosmic neutrino) scattering?

- We may impose relatively strong constraints on DM scattering with the lepton sector.

  Muon,tau rapidly decay→DM would not scatter with mu, tau.
  $U(1)_{L_\mu - L_\tau}$ symmetry etc→DM-electron interactions would be suppressed.

Comparison with constraints from high energy neutrinos

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

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

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

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

Ex1) Dirac fermion DM, scalar mediator

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

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

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

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

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

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

Ex2) Dirac fermion DM, vector mediator

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

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

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

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

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

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

Cosmological and astrophysical constraints are highly complementary!