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

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with

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# Dark Matter (DM)

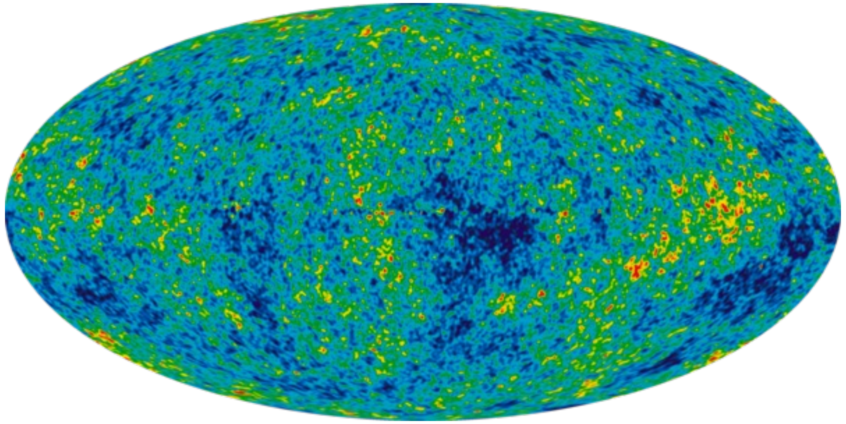
DM is gravitationally confirmed by cosmological observations.

**DM properties:**

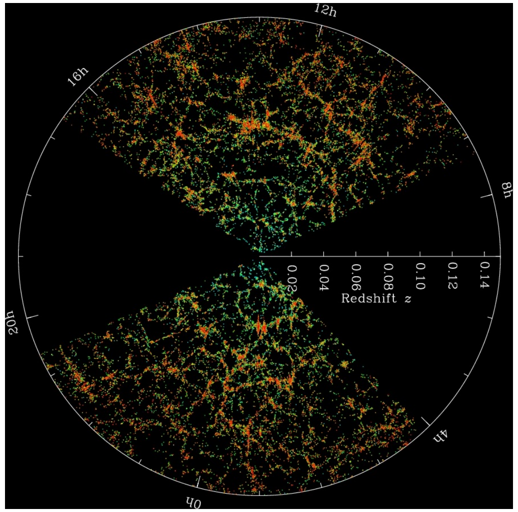
- Dominant matter in the universe
- Massive
- Stable

However, we don't know

- mass
- interactions beyond gravity.

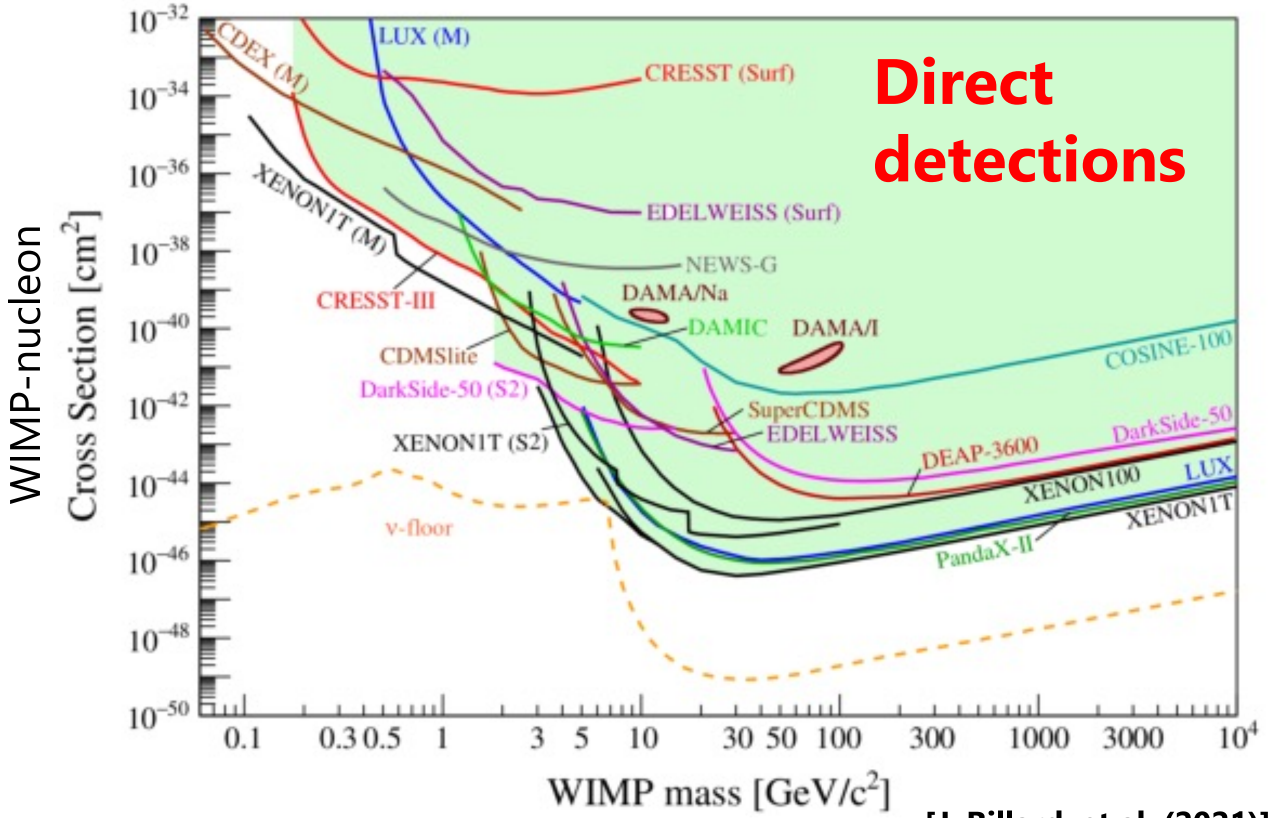


https://map.gsfc.nasa.gov/media/121238/index.html

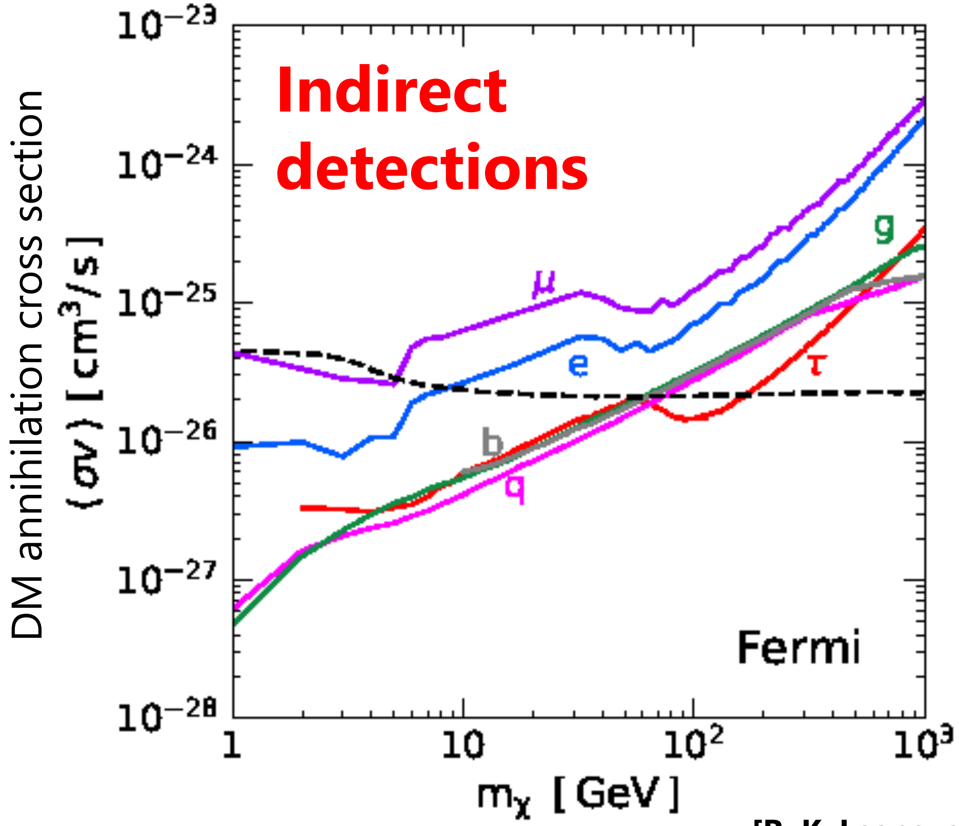



https://www.darkenergysurvey.org/supporting-science/large-scale-structure/

# DM detections




[J. Billard, et al. (2021)]




[R. K. Leane, et al. (2018)]

Thermally produced DM with the weak interactions is severely constrained.

→We would like to test more broadly DM mass, interactions, … .

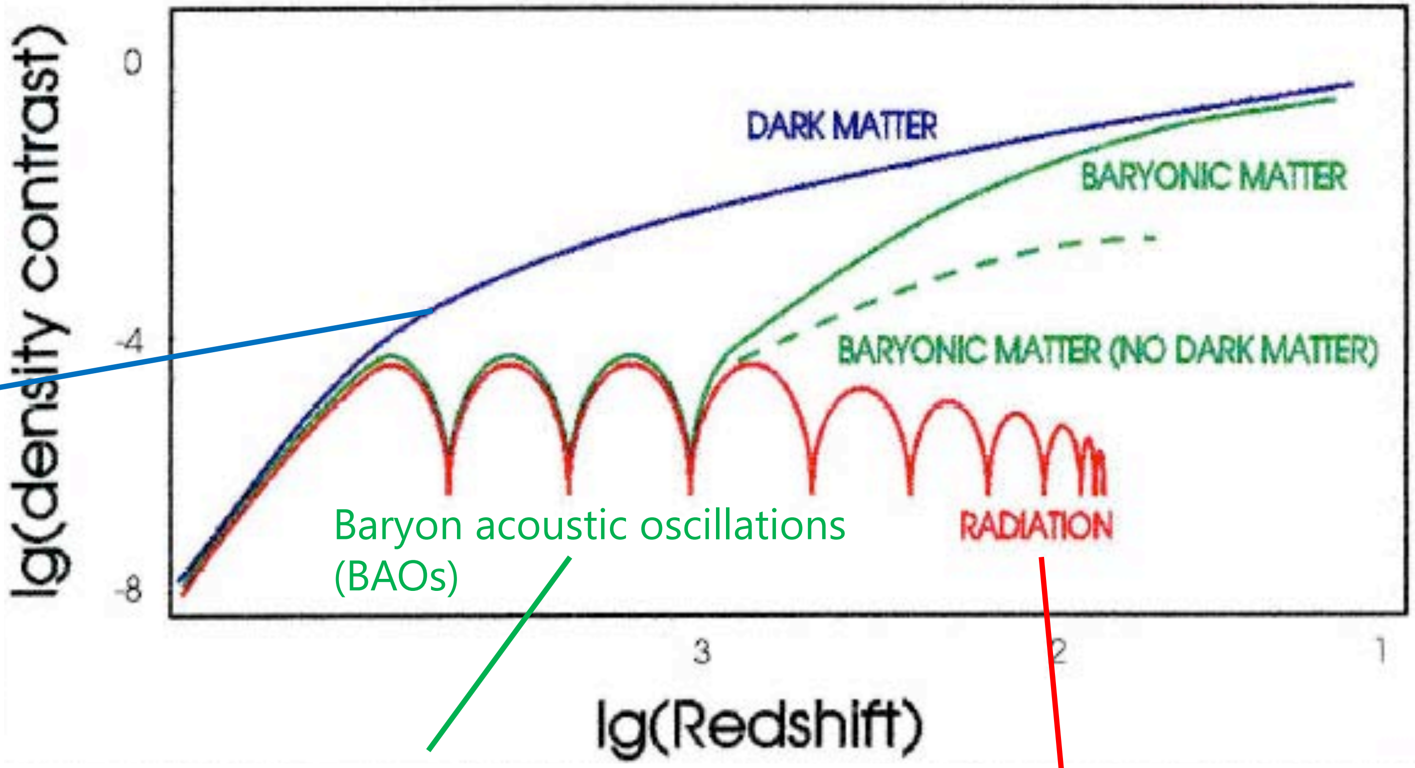
# Structure formation of the universe

The potential of DM is required for galaxy formation.

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

Can we learn more from structure formation?

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




Baryon coupled with radiation is suppressed by radiation pressure.

Relativistic particle grows less by its large velocity dispersion.

# Dark acoustic oscillations (DAOs)

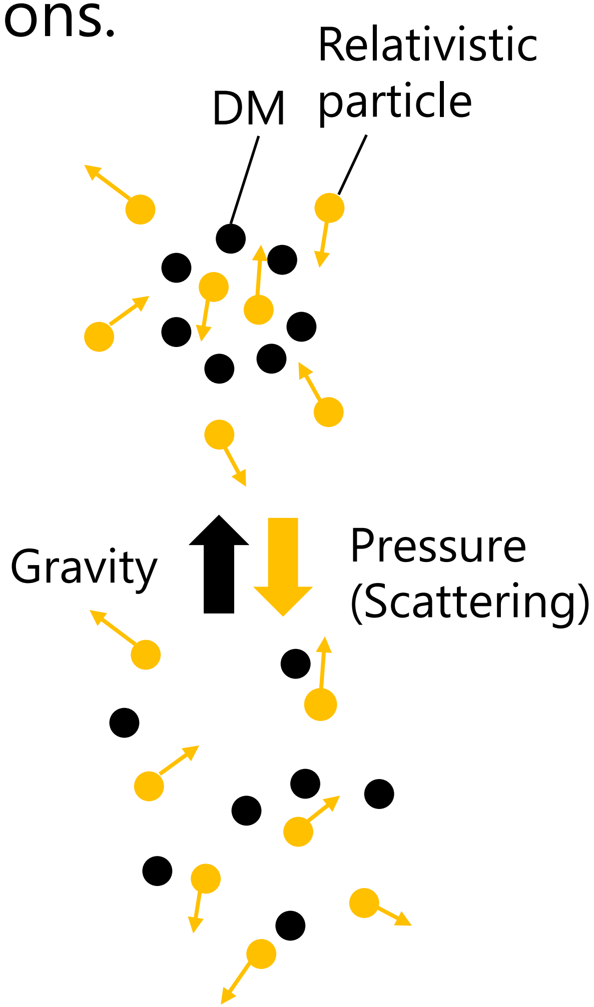
- Standard DM has (approximately) only gravitational interactions.

  WIMP, axion, …

  Neutrinos, photons, baryons (coupled to photons) and dark radiation

- If DM has interactions with **relativistic particles**, DM fluctuations are **suppressed** by 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:

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

Neutrino energy — The scale factor of the universe

- The modified Euler equations for DM and neutrino fluctuations:

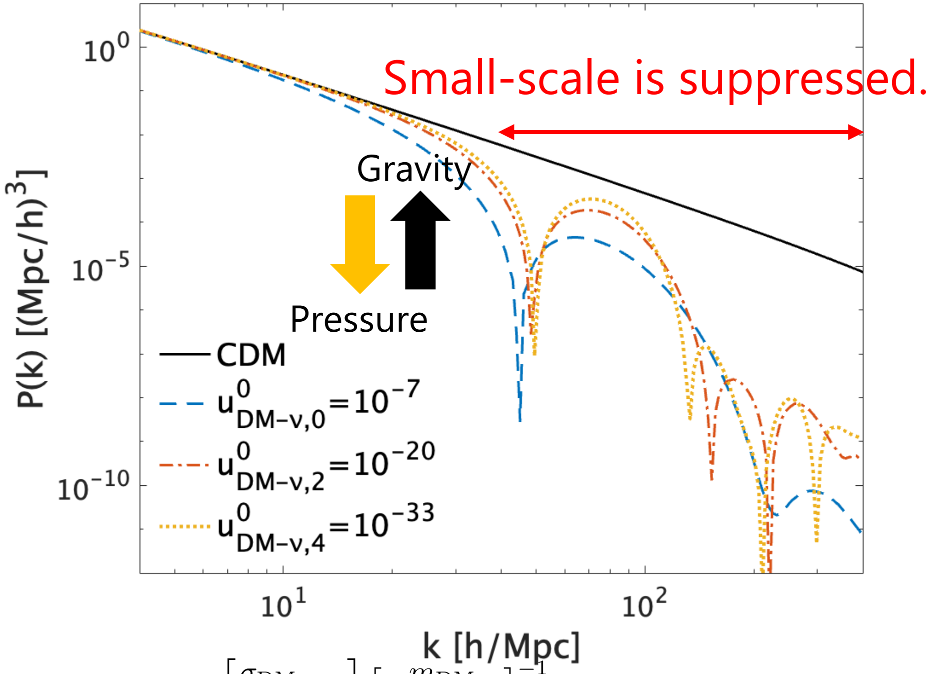
[C. Boehm, et al. (2002)]

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

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

Velocity perturbation — Additional terms

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




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

The matter power spectrum on small-scale is suppressed.

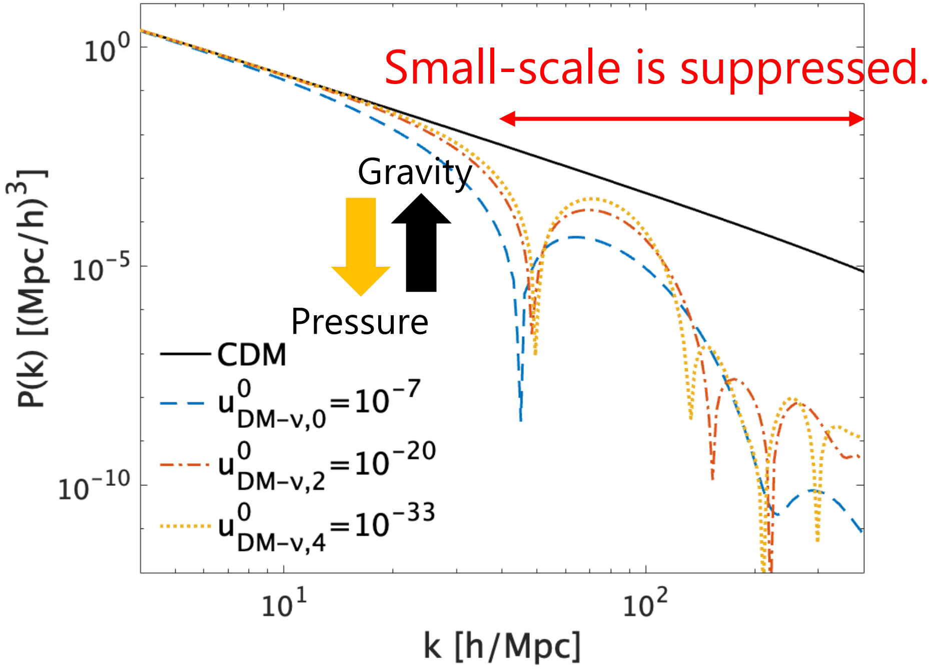
# DM-Neutrino scattering

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

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

Velocity divergence　　Additional terms

$$\Gamma_{\nu\text{–DM}} = a\sigma_{\rm DM\text{–}\nu}n_{\rm DM},\qquad \Gamma_{\rm DM\text{–}\nu} = \frac{4\rho_\nu}{3\rho_{\rm DM}}\Gamma_{\nu\text{–DM}}.$$




$$\Gamma_{\nu-{\rm DM}} \propto \Gamma_{{\rm DM}-\nu} \propto \sigma_{{\rm DM}-\nu}\frac{\rho_{\rm DM}}{m_{\rm DM}}$$

・The power spectrum is more suppressed for light DM.

Light DM can easily have velocity via scattering.

*We use a publicly available modified version of CLASS code for DM-neutrino interactions.

**[J. Stadler, et al. (2019)]**
**[N. Becker, et al. (2021)]**

# 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 scattering?

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

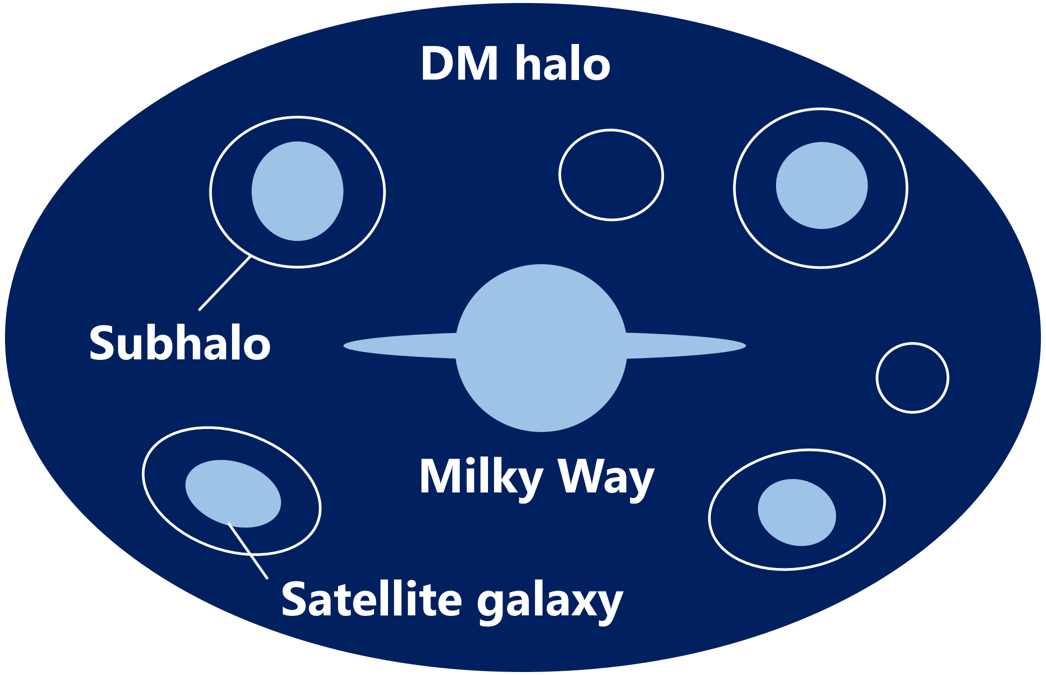
  Muon, tau rapidly decay→DM would not scatter with mu, tau.
  $U(1)_{L_\mu - L_\tau}$ symmetry→DM-electron interactions would be suppressed.

# 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

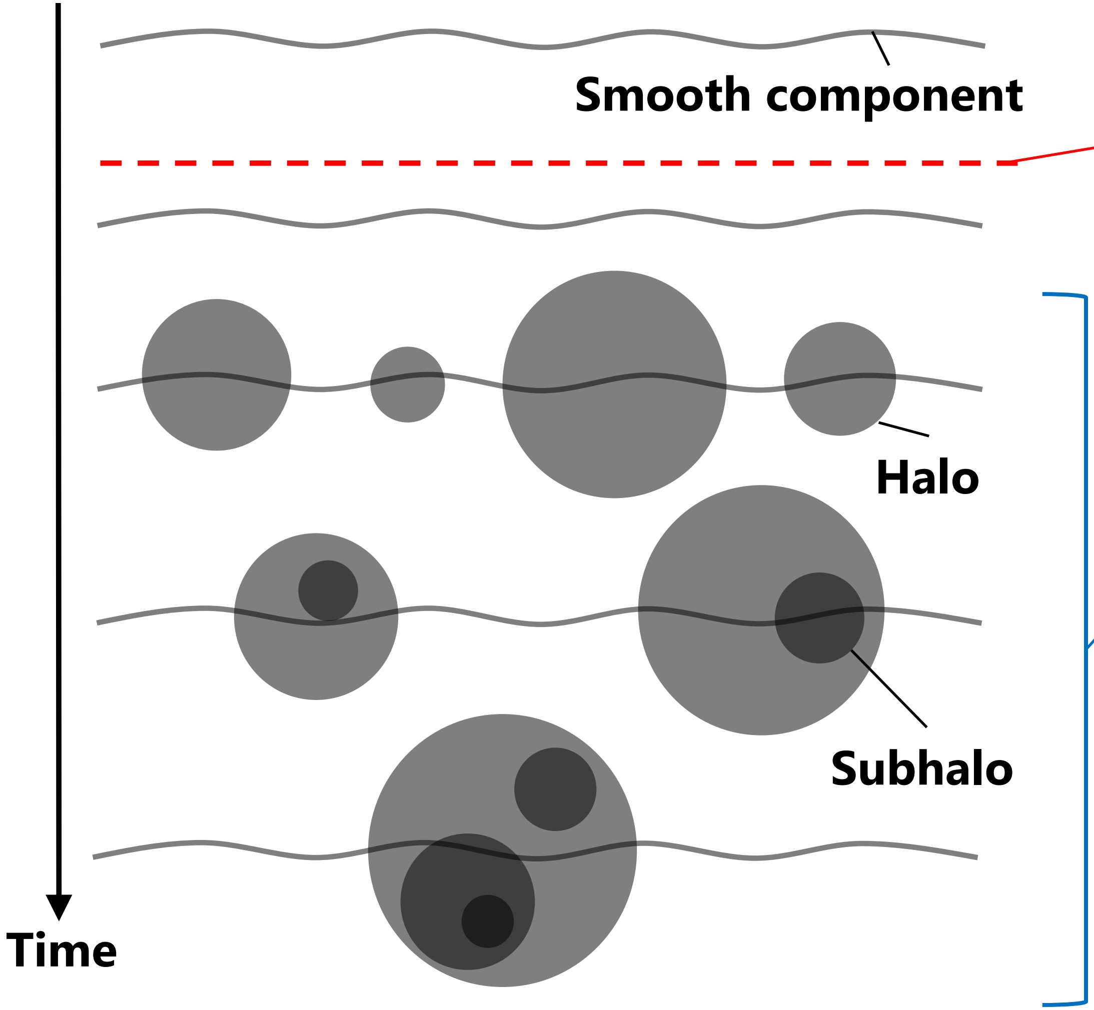
[N. Hiroshima, et al. (2018)]
[A. Dekker, et al. (2022)]

- Introduction

We use a modified version of sashimi code developed by Shin'ichiro+.
https://github.com/shinichiroando/sashimi-c
https://github.com/shinichiroando/sashimi-w

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

# Schematic history of dark matter



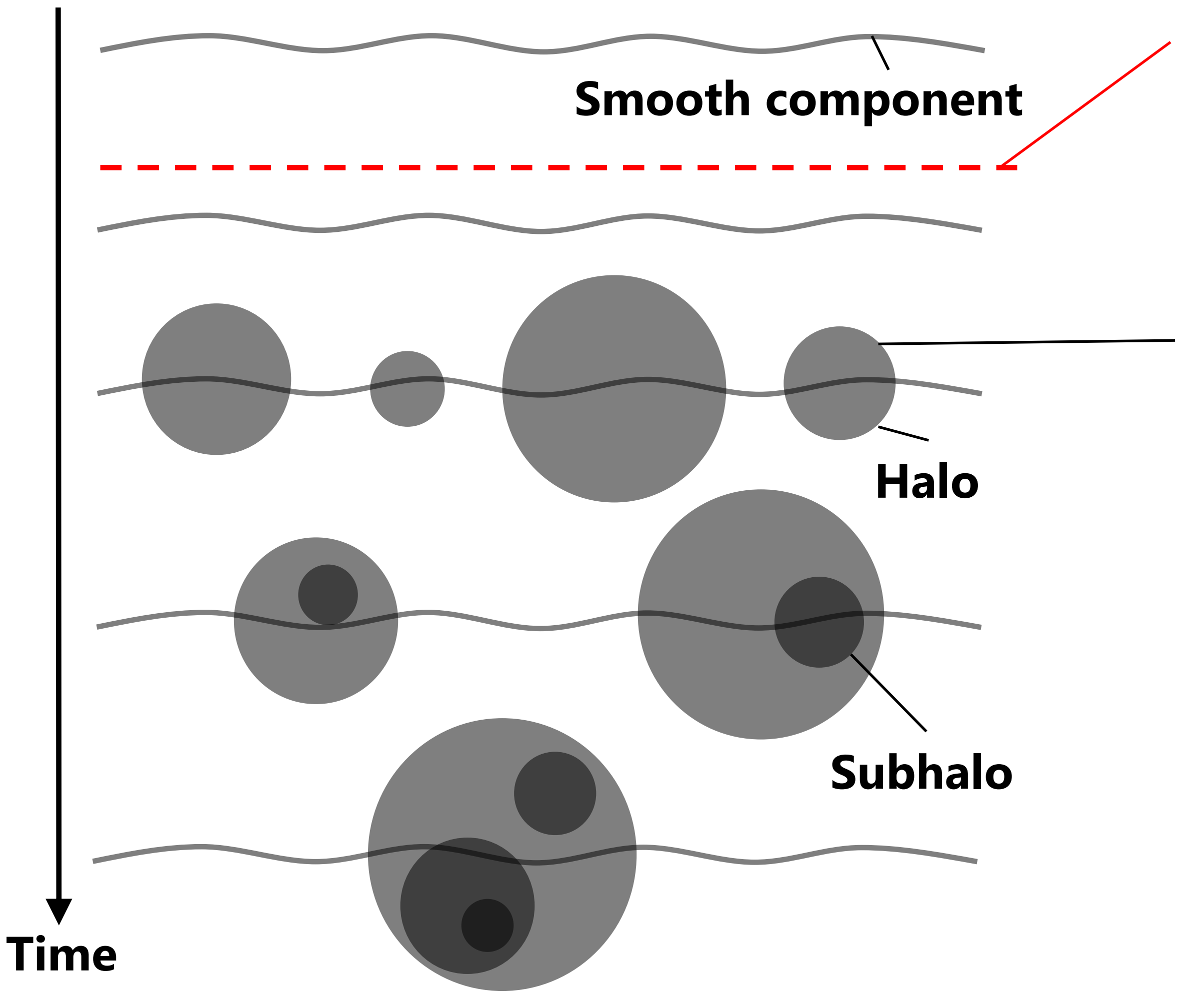

- DM decouples with neutrinos in the linear region for weak DM-neutrino interactions.

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

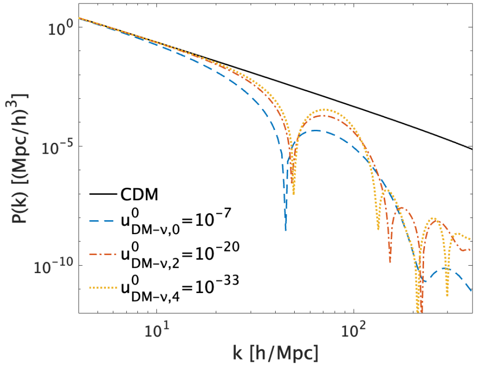
DM evolution is non-linear and computationally expensive.

**Semi-analytical subhalo model is needed!**

# Subhalo modeling for dark acoustic oscillations




**Initial condition:**




**Modeling:**

- **DM fluctuations are spherical:**

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

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

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

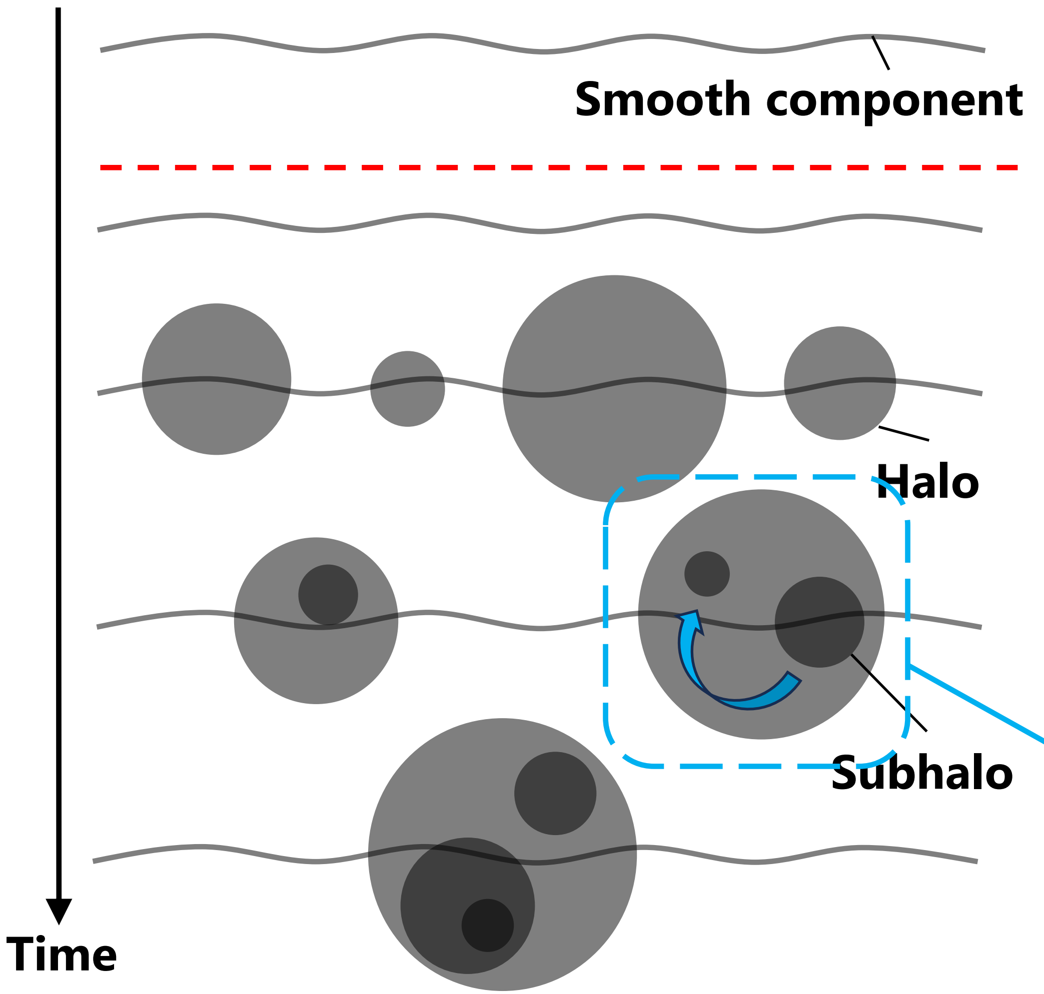
This is different from CDM and WDM cases.

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

**[M. Leo, et al. (2018)]**

- **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 $z = z_a$

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

Smoothed fluctuation and standard deviation with mass

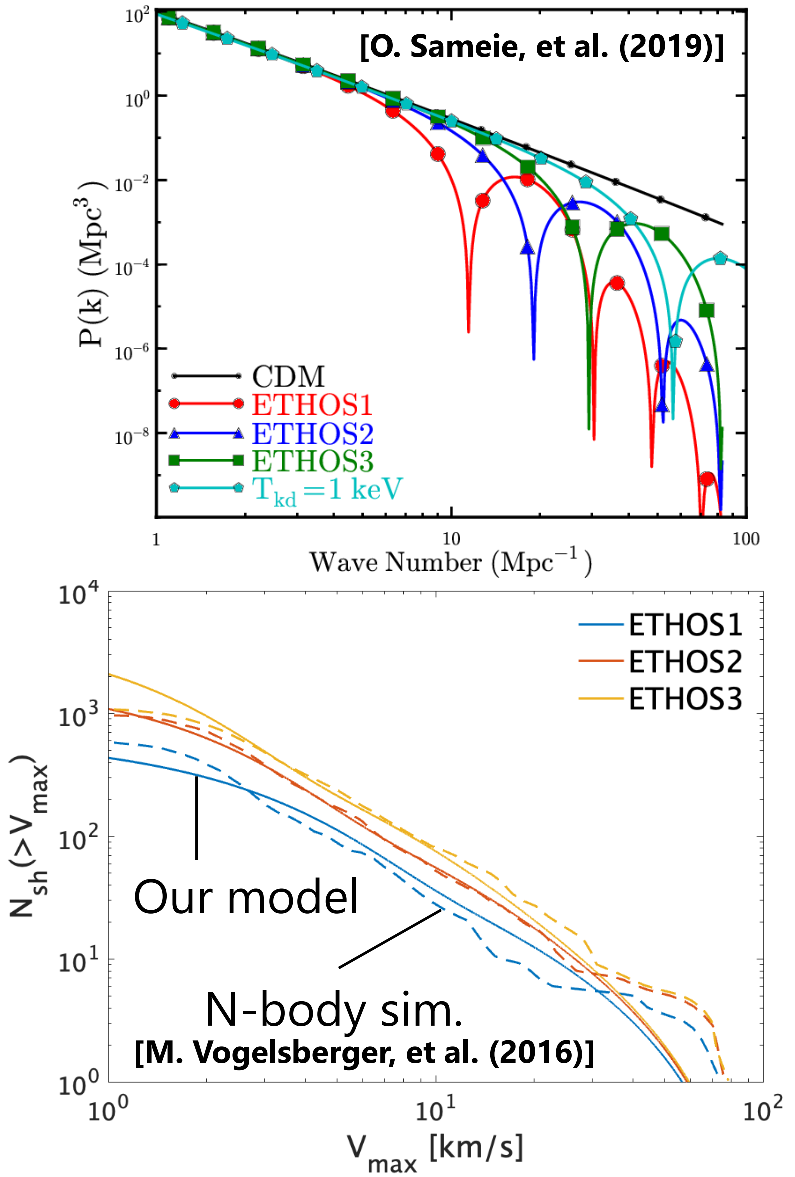
$m$ : subhalo mass $M$ : Host halo mass

- **Tidal stripping:**

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

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!

# Outline

- Introduction
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- Constraints on DM-neutrino scattering from the MW satellites
- Conclusions

# 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:

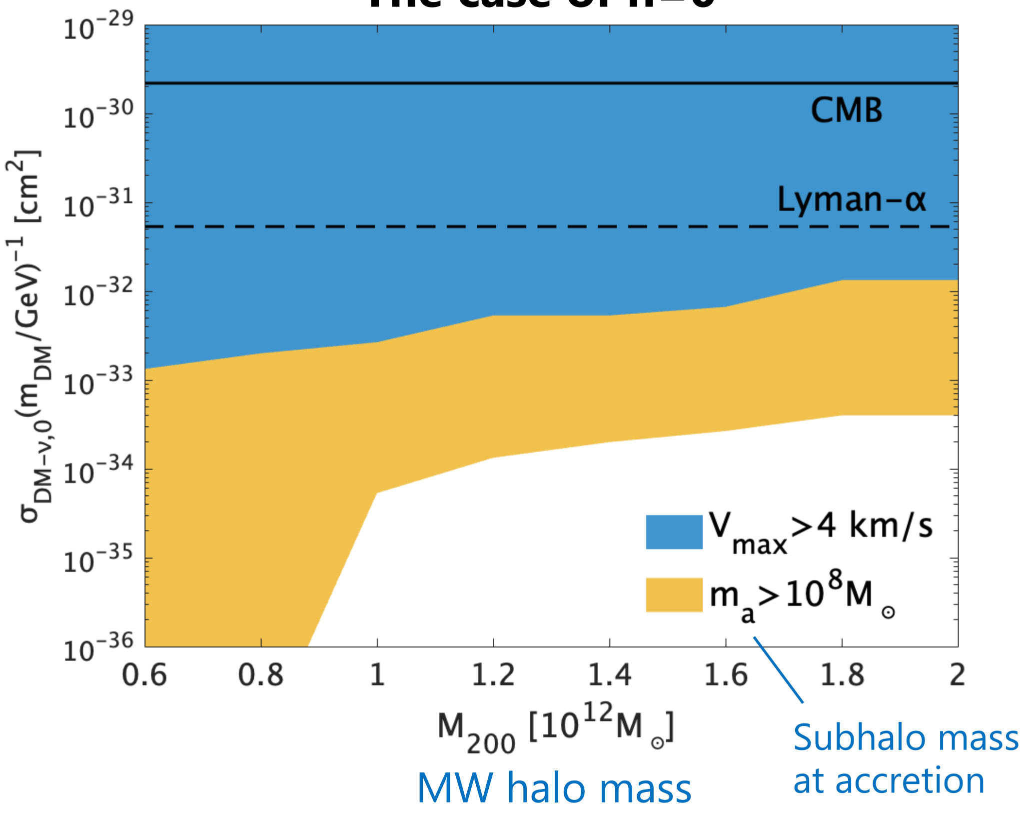
$$\sigma_{\mathrm{DM}-\nu,0} < 4 \times 10^{-34}\ \mathrm{cm}^2\ (m_{\mathrm{DM}}/\mathrm{GeV})$$

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

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

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

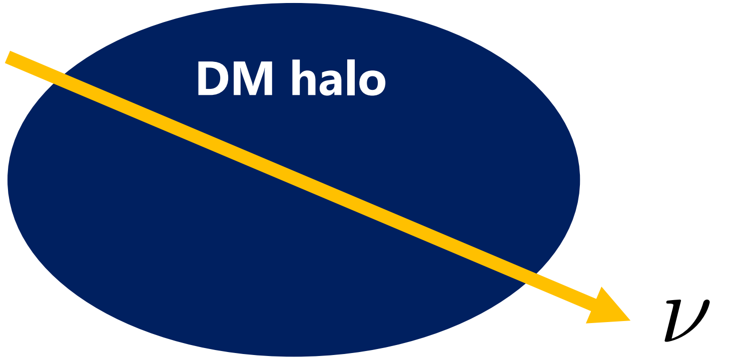
**The case of n=0**



# Constraints from high energy neutrinos

High energy neutrinos propagate in DM.

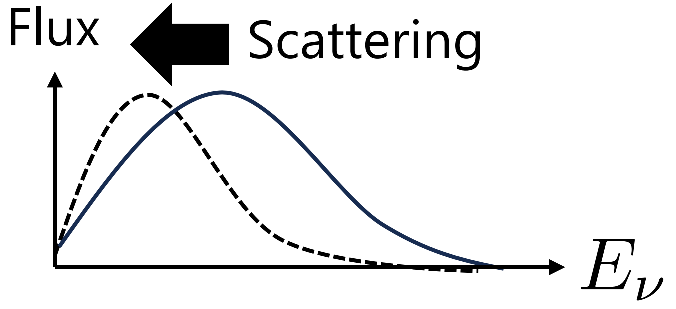
→Neutrino scattering with DM reduces neutrino energy.




Observations of neutrinos from an active galaxy NGC 1068:

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

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




There is no simple comparison between cosmological and astrophysical constraints .

E.g.) Propagator: $\dfrac{1}{p^2 - m_{\mathrm{med}}^2}$ →
- $1/m_{\mathrm{med}}^2$ for relic cosmic neutrinos
- $1/p^2$ for high energy neutrinos

We should NOT compare the cross sections <u>with the same energy dependence</u>.

# Comparison with constraints from high energy neutrinos

Ex1) Dirac fermion DM, scalar mediator **[C. A. Argu¨ells, et al (2017)]**

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

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

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

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

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

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

# Comparison with constraints from high energy neutrinos

Ex2) Dirac fermion DM, vector mediator [C. A. Argu¨ells, et al (2017)]

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

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

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

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

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

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

Cosmological and astrophysical constraints are highly complementary!

# Outline

- Introduction
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# 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 one of 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

# Uncertainties of constraints

- A companion paper of [DES collaboration (2020)] find $220 \pm 50$ Milky-Way satellites at 1σ level.

  If we adopt 170 satellites instead of 270 satellites,
  our strongest constraints become weaker by

| | | |
|---|---|---|
| 3 | for | $\sigma_{\mathrm{DM}-\nu} = \mathrm{const.}$ |
| 40 | for | $\sigma_{\mathrm{DM}-\nu} \propto E_\nu^2$ |
| 600 | for | $\sigma_{\mathrm{DM}-\nu} \propto E_\nu^4$ |

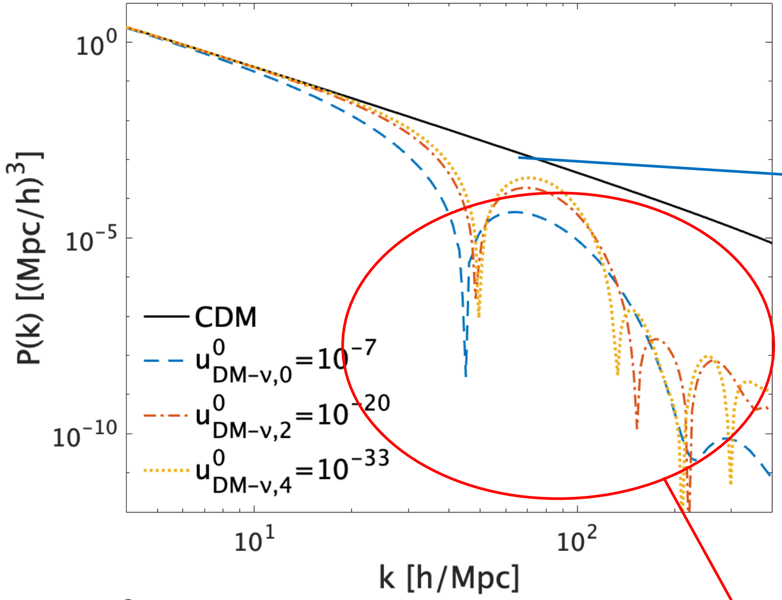
- The predicted satellites by our model deviates from N-body simulations by 1.8 at most.
  →This might also induce similar uncertainties as above.
  (But N-body simulations themselves also include uncertainties.)

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

# Window function $W(\boldsymbol{x}-\boldsymbol{x}', R)$

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

Window function is <u>artificially</u> determined to match N-body simulations.




- Top-hat filter:

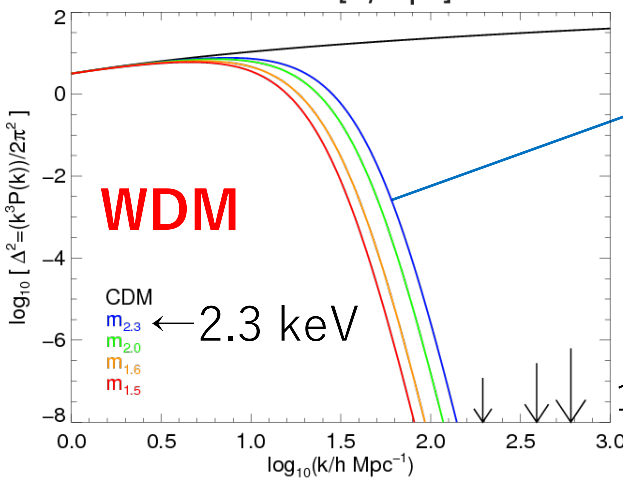
$$W(r,R) = \begin{cases} \frac{3}{4\pi R^3} & r \le R \\ 0 & r > R \end{cases}$$

$$\widetilde{W}(kR) = \frac{3}{(kR)^3}[\sin(kR) - (kR)\cos(kR)]$$

- Sharp-k filter:

$$\widetilde{W}(r,R) = \frac{1}{2\pi^3 r^3}[\sin(r/R) - (r/R)\cos(r/R)]$$

$$\widetilde{W}(kR) = \begin{cases} 1 & k \le 1/R \\ 0 & k > 1/R \end{cases}$$




1308.1399

To match N-body simulations for DAO scenarios,
An intermediate window function would be needed.

# Window function $W(\boldsymbol{x}-\boldsymbol{x}', R)$

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

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

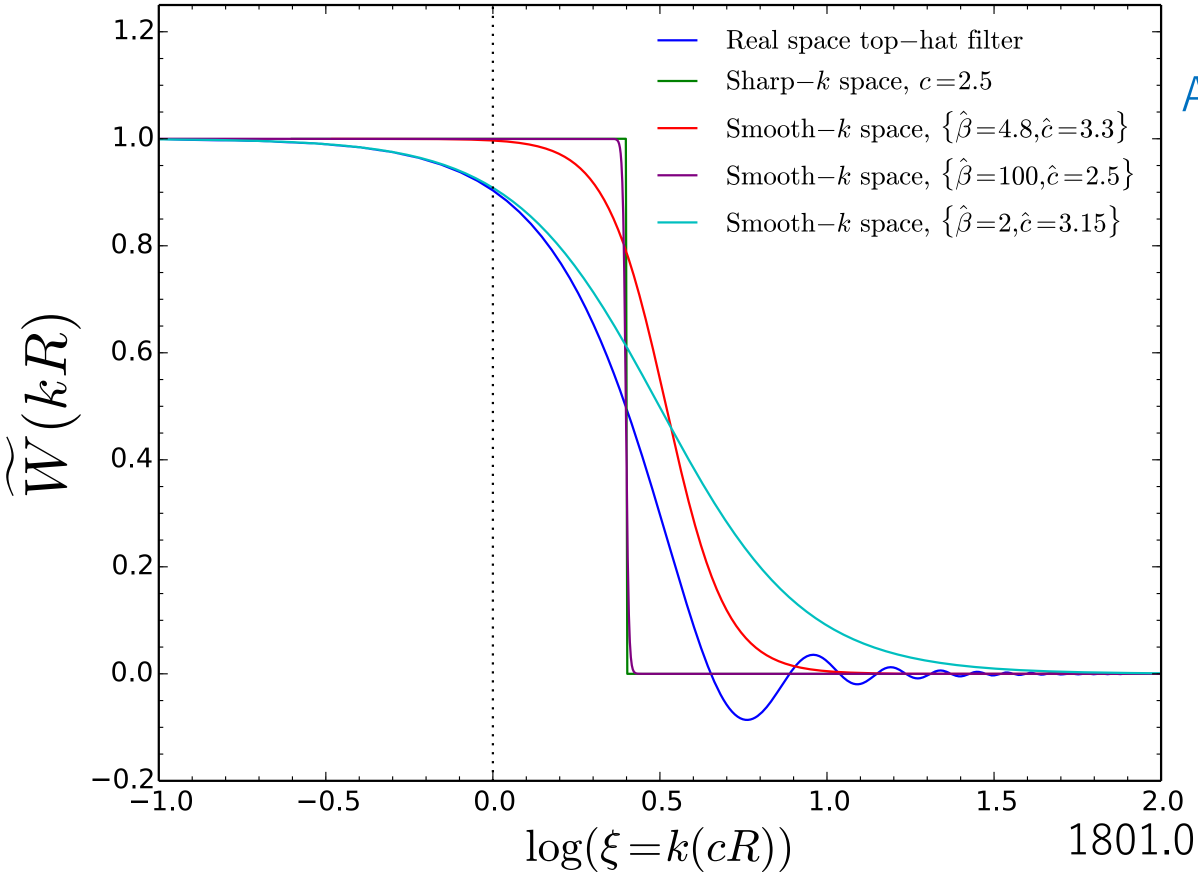
We adopt the smooth-k filter 1801.02547

$$\widetilde{W}^{\mathrm{smooth-k}}(kR) = \frac{1}{1+(kR)^{\beta}} \qquad M = \frac{4\pi}{3}\bar{\rho}(cR)^3 \quad (\beta, c) = (3.5, 3.7)$$

1810.11040

Average matter density

controlls small-scale shape.




1801.02547

- the smooth-k (and sharp-k) filter cannot define the mass $M$ well.
  We assign the mass as $M = \frac{4\pi}{3}\bar{\rho}(cR)^3$ .
  Free parameter
  This is a problem but still matches simulations...

- Our model matches well simulations.
  (We will discuss later.)

https://campuspress.yale.edu/astro610/

# Distributions of DM halos

The variance of the smoothed fluctuations at $z=0$:

$$S(M) = \sigma^2(M) = \langle |\delta(\boldsymbol{x};M)|^2 \rangle$$

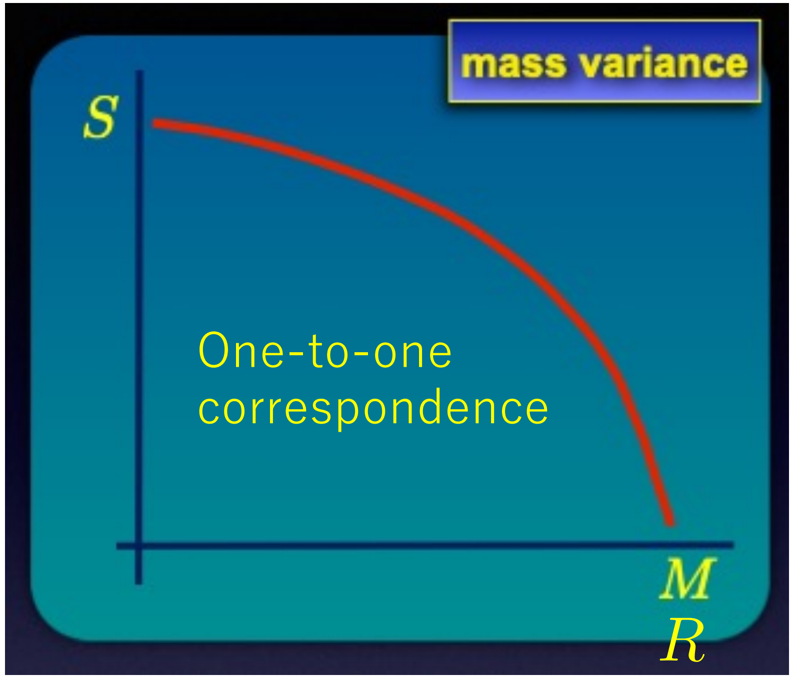
$\leftrightarrow R$

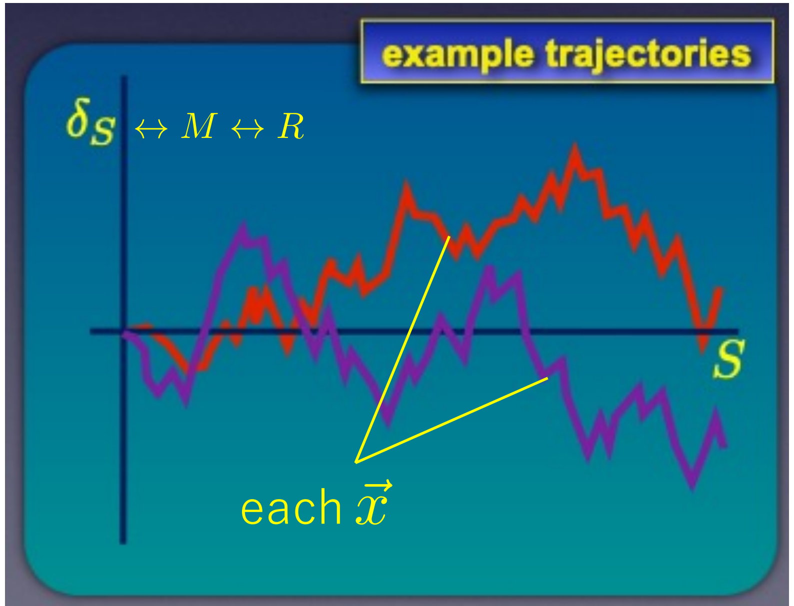
$$= \frac{1}{2\pi^2}\int P(k)\widetilde{W}^2(kR)k^2dk$$

- S is a monotonically decreasing function of M.
- For $S \to 0$ , $M \to \infty$ and $\delta_S \to 0$.
  Each trajectory starts at $(S, \delta_S) = (0,0)$ .
- Trajectories might be random walk with the variance $S(M)$.

$$\delta_S(\boldsymbol{x}) = \int d^3k\widetilde{W}(kR)\delta_{\boldsymbol{k}}e^{i\boldsymbol{kx}} \sim \int_{k<k_c} d^3k\delta_{\boldsymbol{k}}e^{i\boldsymbol{kx}} \qquad k_c = 1/R$$

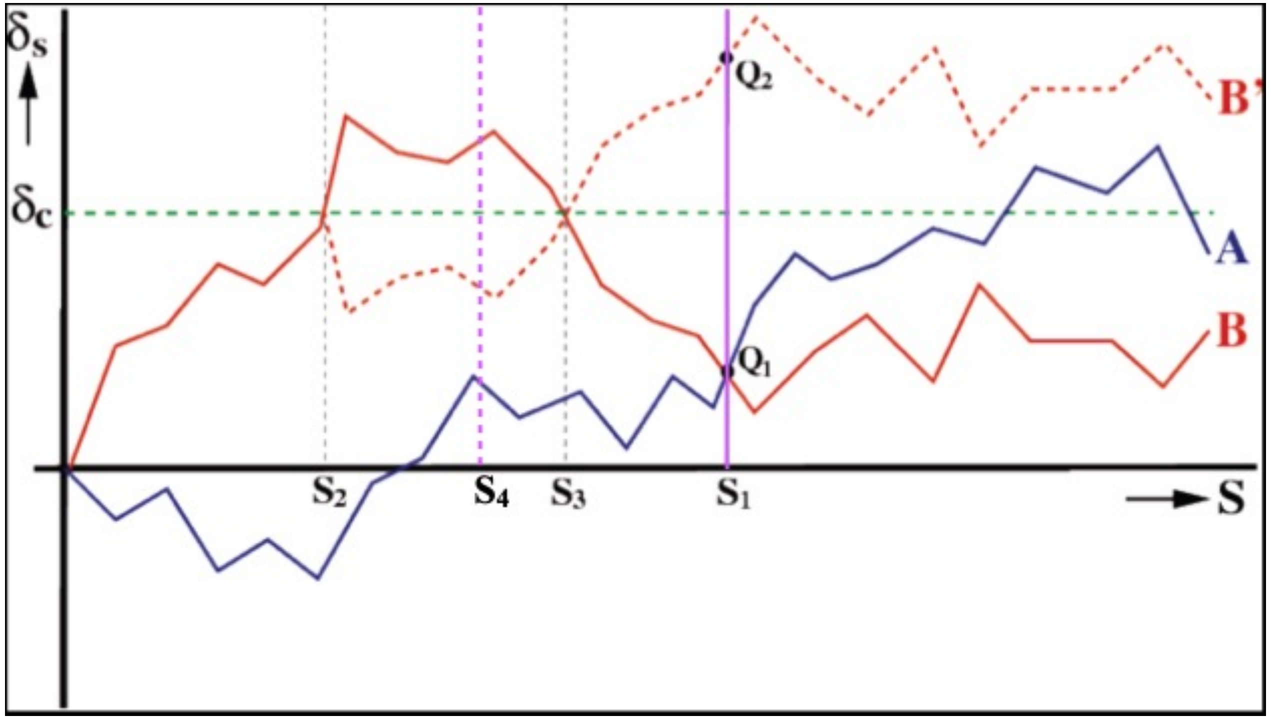
using the sharp-k filter



# Distributions of DM halos

https://campuspress.yale.edu/astro610/




The first upcrossing of $\delta_c$ at $S > S_1$

⇔ The mass fraction with $M < M_1$

(We assume $\delta$ follows the Gaussian distribution.)

$$F_{\mathrm{FU}}(>S_1) = \int_{-\infty}^{\delta_c} Q d\delta_S$$

$$Q(\delta_S, S, \delta_c) = \frac{1}{\sqrt{2\pi S}}\left\{\exp(-\delta_S^2/2S) - \exp[-(2\delta_c - \delta_S)^2/2S]\right\}$$

The probability of forming halos with $S$

$$f_{\mathrm{FU}}(S, \delta_c) = -\frac{\partial}{\partial S} F_{\mathrm{FU}}(>S_1),$$
$$= \frac{\delta_c}{(2\pi)^{1/2} S^{3/2}} \exp\left[-\frac{\delta_c^2}{2S}\right]$$

The halo mass function

$$\frac{\partial n(M,t)}{\partial M} = \frac{\bar{\rho}}{M} f_{\mathrm{FU}}(S, \delta_c) \left|\frac{dS}{dM}\right|$$

# Constraints on DM-neutrino scattering

For conservative constraints, all subhalos host satellites galaxies.

[A. Dekker, et al. (2021)]

We use the kinematics data of 94 Milky-Way satellites with $V_{\rm circ} > 4 \ {\rm km \ s^{-1}}$.

We obtain the strong constraints

of $\sigma_{{\rm DM}-\nu,n} \propto E_\nu^n \quad (n = 0, 2, 4)$ at 95% CL

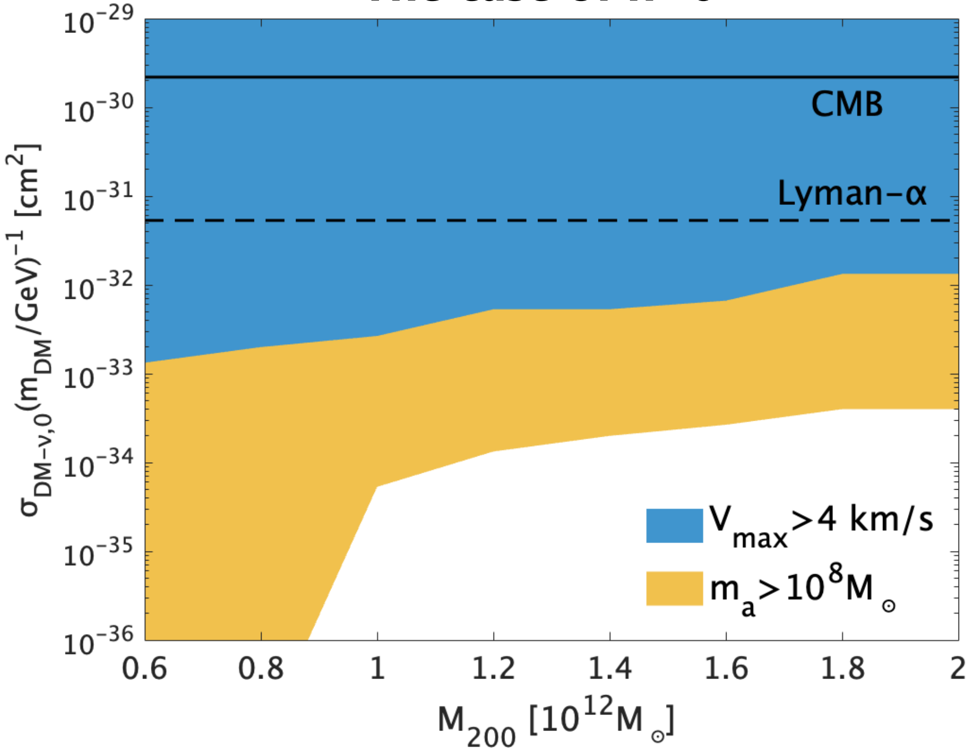
$$\sigma_{{\rm DM}-\nu,0} < 10^{-32} \ {\rm cm}^2 \ (m_{\rm DM}/{\rm GeV})$$

$$\sigma_{{\rm DM}-\nu,2} < 10^{-43} \ {\rm cm}^2 \ (m_{\rm DM}/{\rm GeV})(E_\nu/E_\nu^0)^2$$

$$\sigma_{{\rm DM}-\nu,4} < 10^{-54} \ {\rm cm}^2 \ (m_{\rm DM}/{\rm GeV})(E_\nu/E_\nu^0)^4$$

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

The case of n=0



MW halo mass