Astrophysical Connections between Dark Matter and Sterile Neutrinos

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Outline

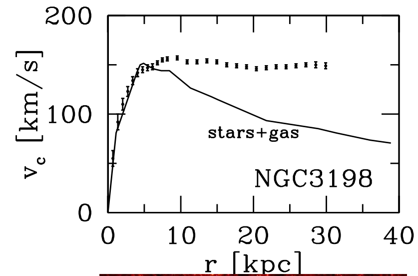
- Introduction

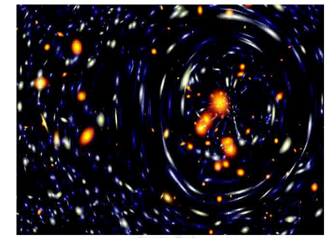
  cold dark matter controversies

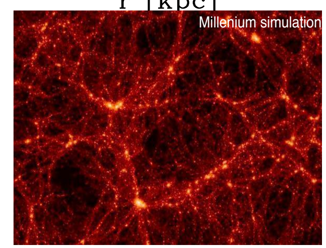
- Self-Interacting DM
- eV Sterile Neutrinos
- A Toy Model
- Summary

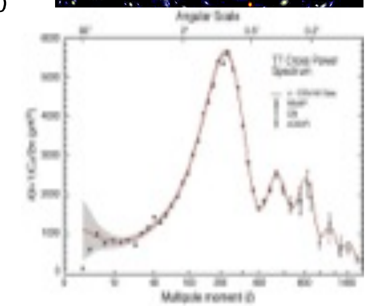
Dark Matter Evidence

- Rotation Curves of Galaxies
- Gravitational Lensing
- Large Scale Structure
- CMB anisotropies, …



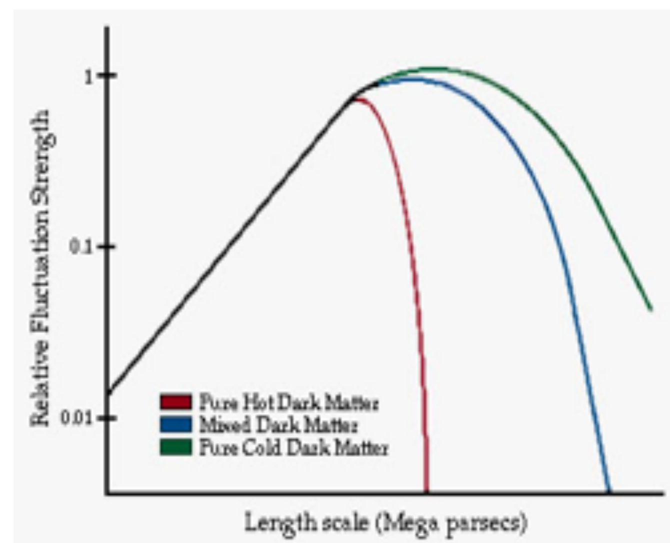






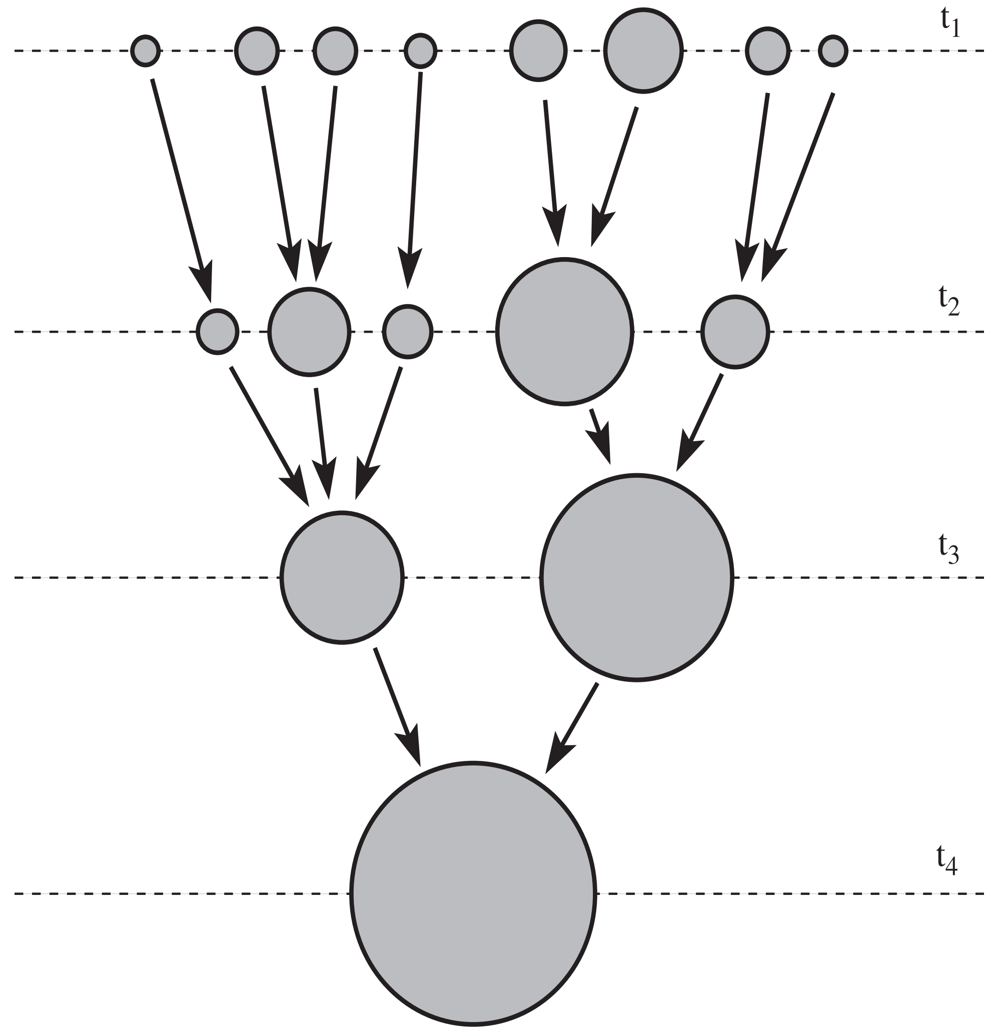
All confirmed evidence comes from gravitational interaction

CDM: negligible velocity, WIMP
WDM: keV sterile neutrino
HDM: active neutrino

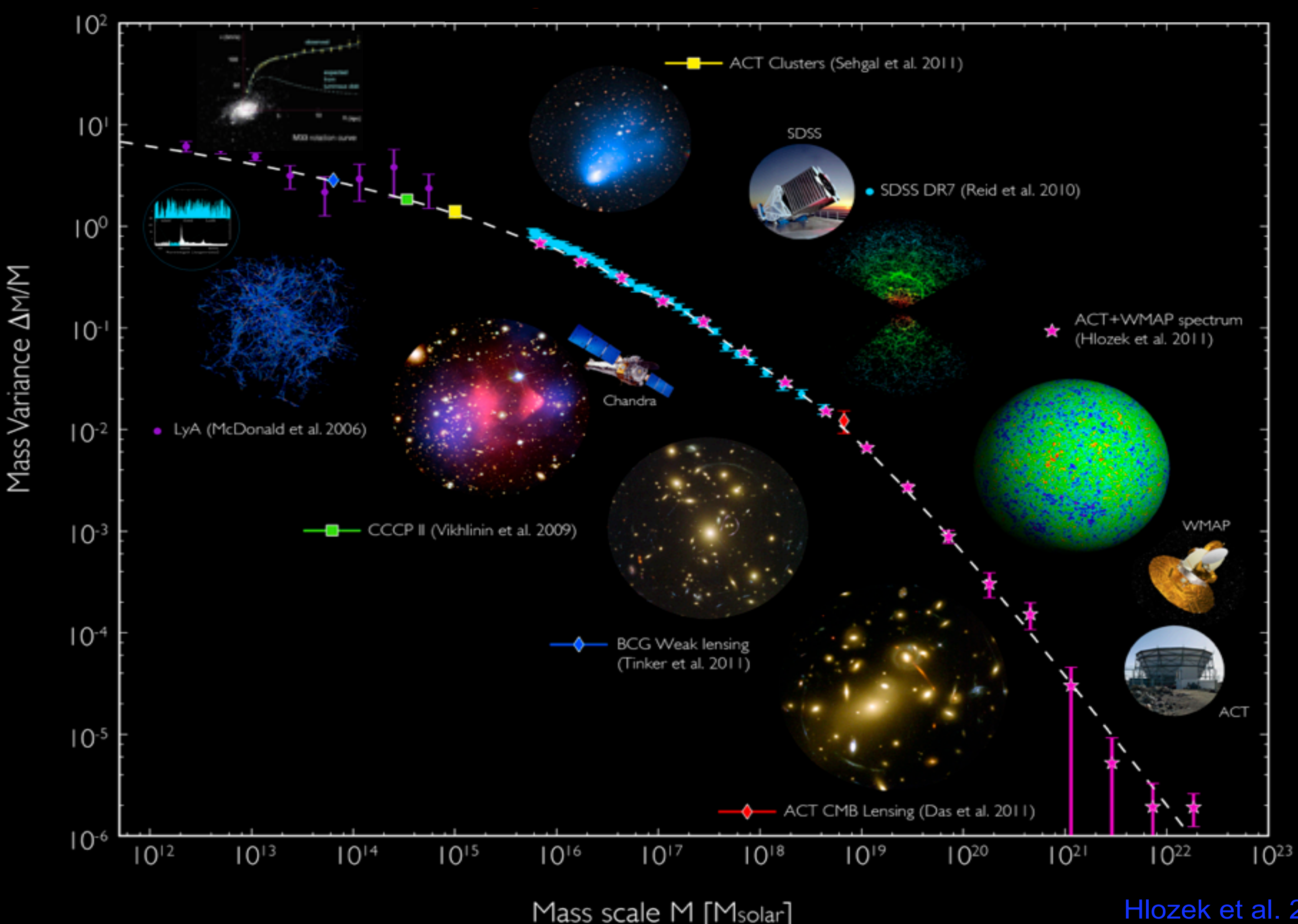


Merger History of Dark Halo

- standard picture
- DM halo grow hierarchically
- first small scale structures form
- then merge into larger halo



ΛCDM: successful on large scales



Hlozek et al. 2012

CDM Controversies on small scales?

Weinberg, Bullock, Governato, de Naray, Peter, 1306.0913

- Cusp-vs-Core problem
- Missing satellites problem
- To-big-to-fail problem

Be cautious!

No consensus, simulations are very complicated when including baryon effects.

Cusp vs. Core

DM density profiles

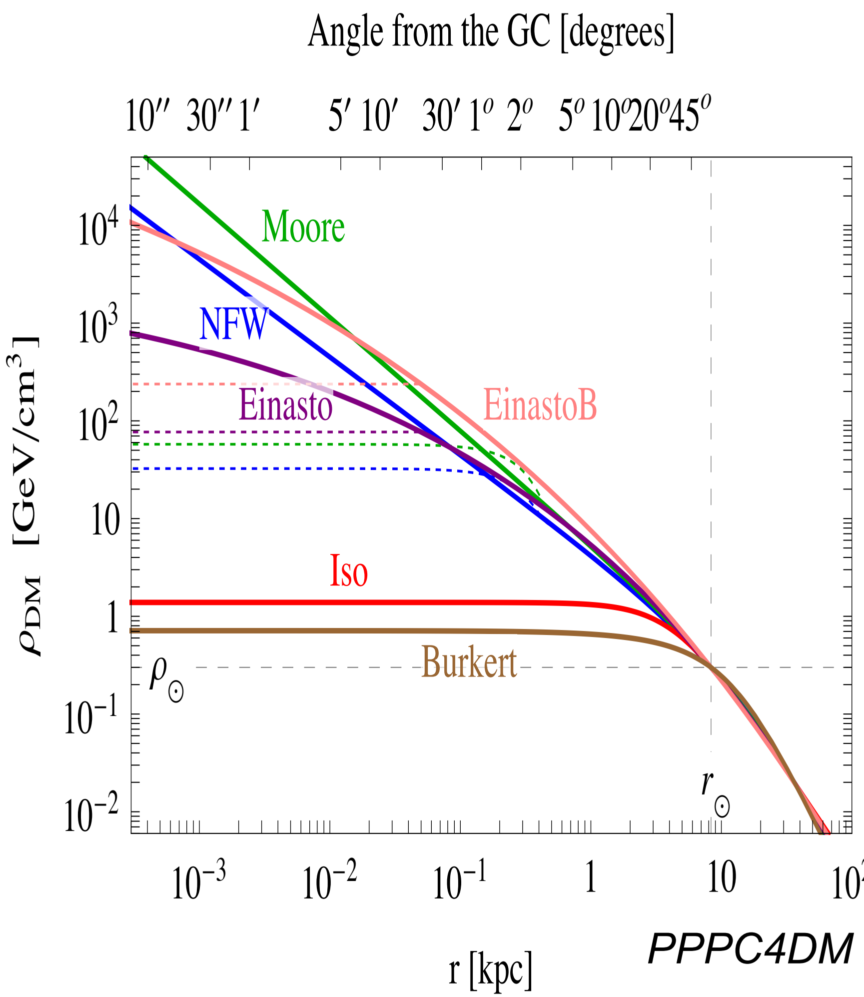
$$\text{NFW}: \quad \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\text{Ein}}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\text{Isothermal}: \quad \rho_{\text{Iso}}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

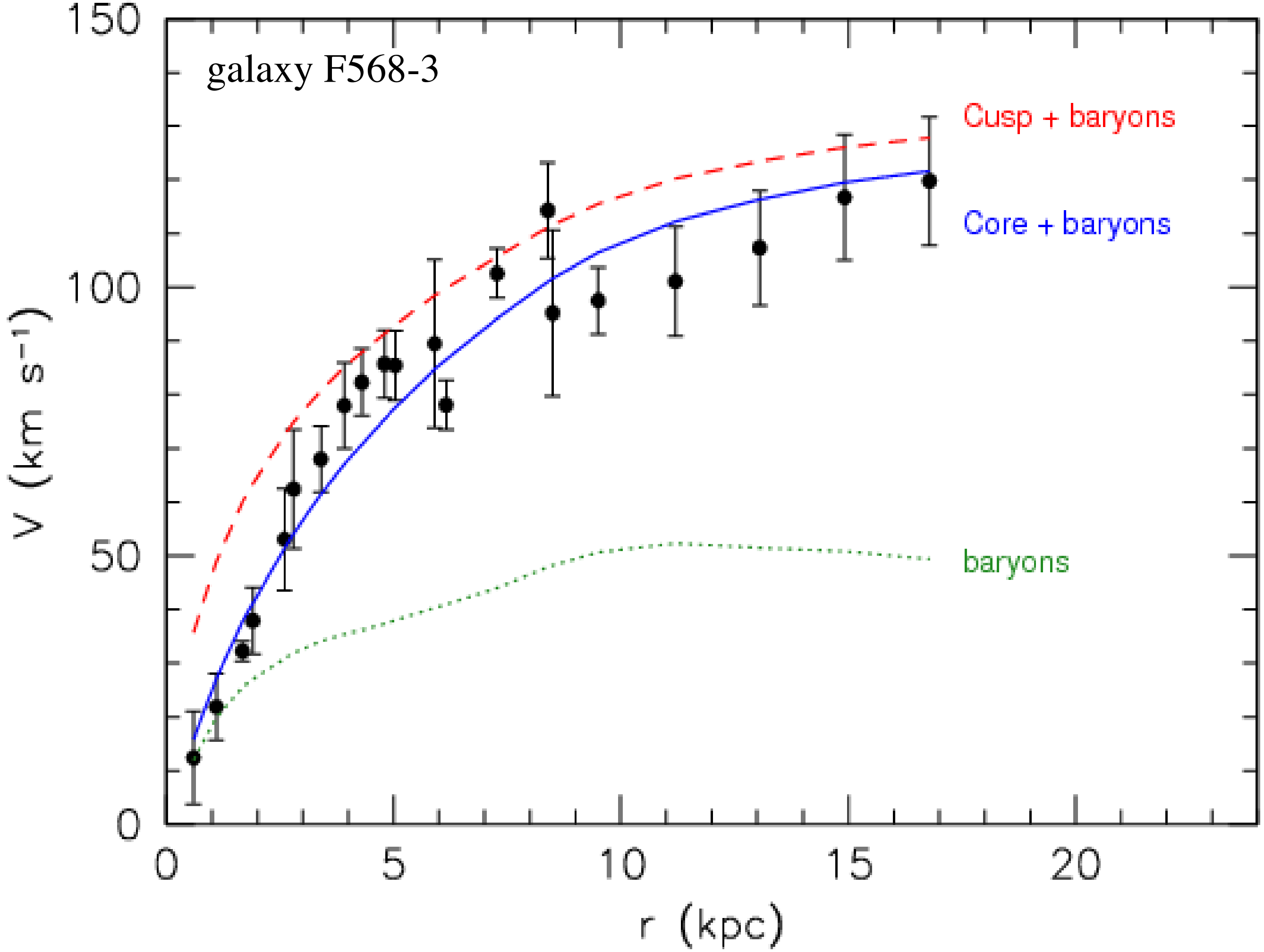
$$\text{Moore}: \quad \rho_{\text{Moo}}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$



PPPC4DM

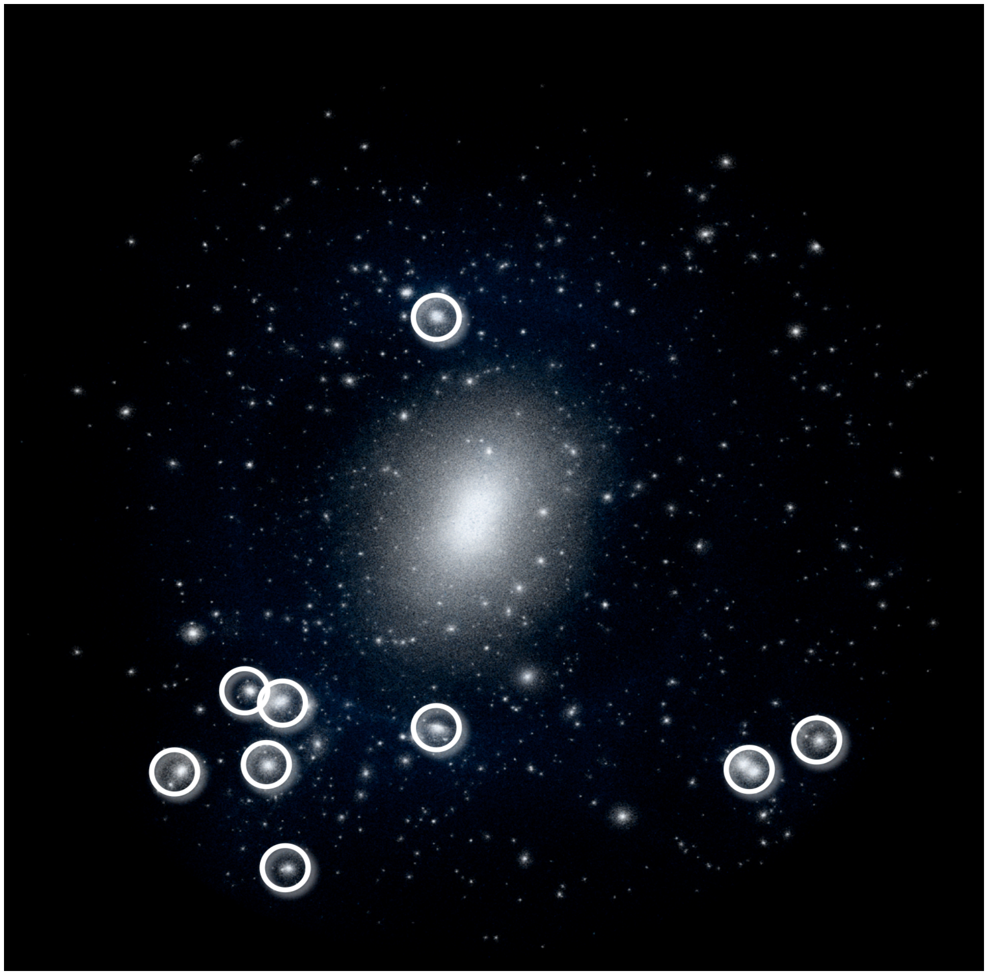
Cusp profiles, such as NFW, are predicted by N-body simulation of CDM

Cusp vs. Core



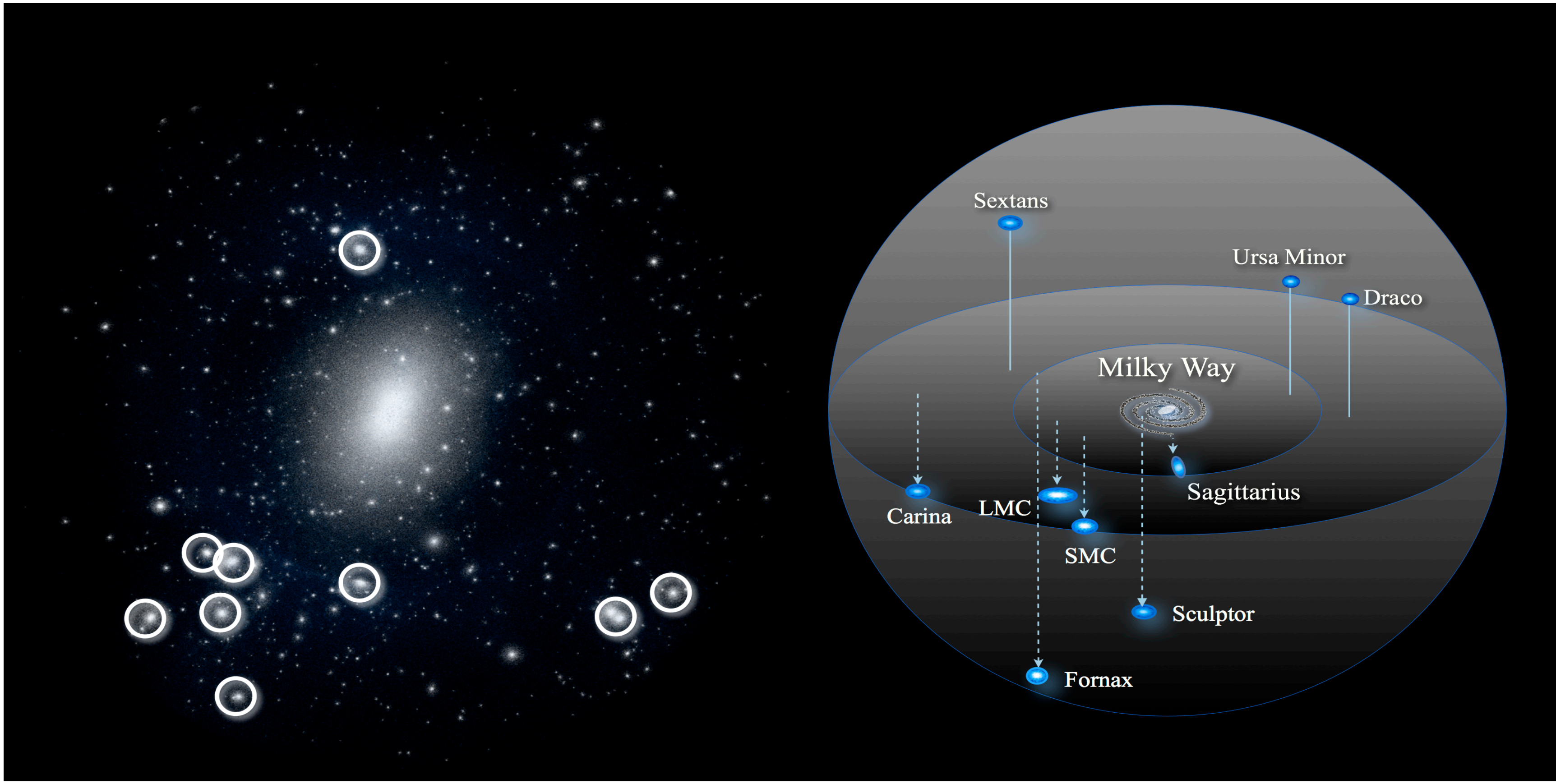
galaxy F568-3
Cusp + baryons
Core + baryons
baryons
V (km s⁻¹)
r (kpc)
150
100
50
0
0
5
10
15
20

“missing satellites” problem



- Projected dark matter distribution of a simulated CDM halo.
- The numerous small subhalos far exceed the number of known Milky Way satellites.
- Circles mark the nine most massive subhalos.

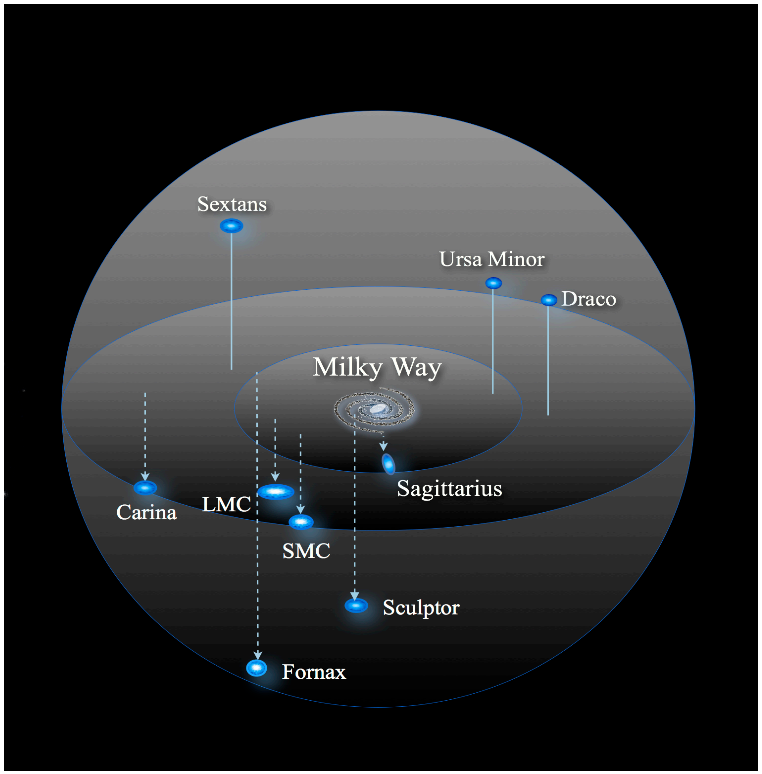
"too-big-to-fail" problem

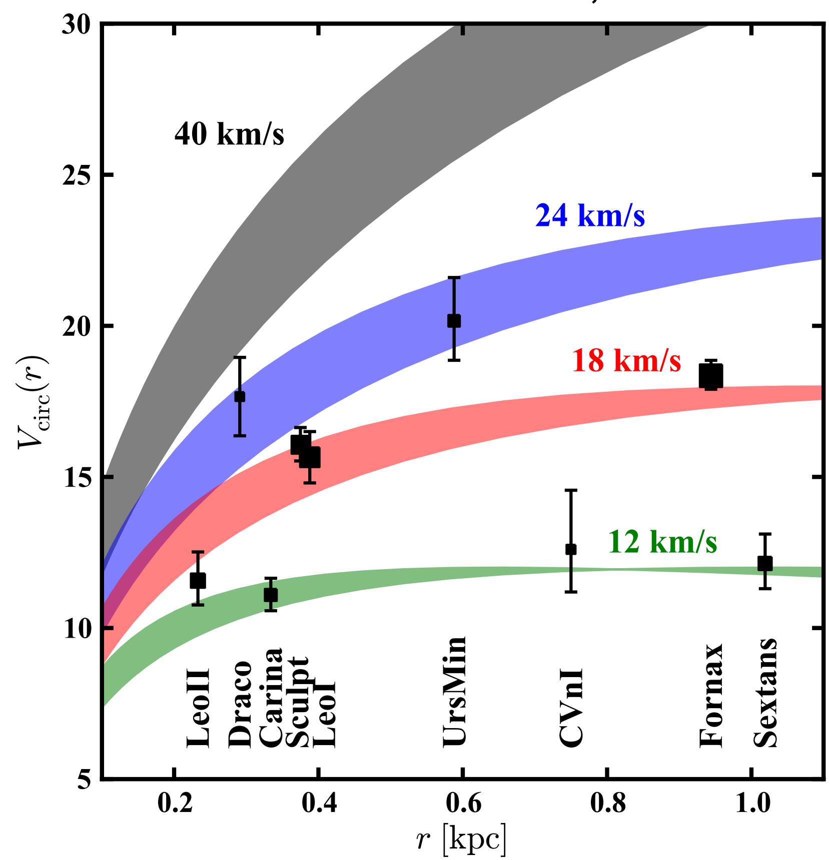


The central densities of the subhalos in the left panel are too high to host the dwarf satellites in the right panel, predicting stellar velocity dispersions higher than observed.

"too-big-to-fail" problem

Bullock et al,1111.2048





- Right Panel: Observed circular velocity of the nine bright dSphs, along with rotation curves corresponding to NFW subhalo.

Possible solutions

- Baryonic physics:
  gas cooling, star formation,
  supernova feedback,…

- Dark Matter:
  warm dark matter
  Decaying DM
  Self-Interacting DM

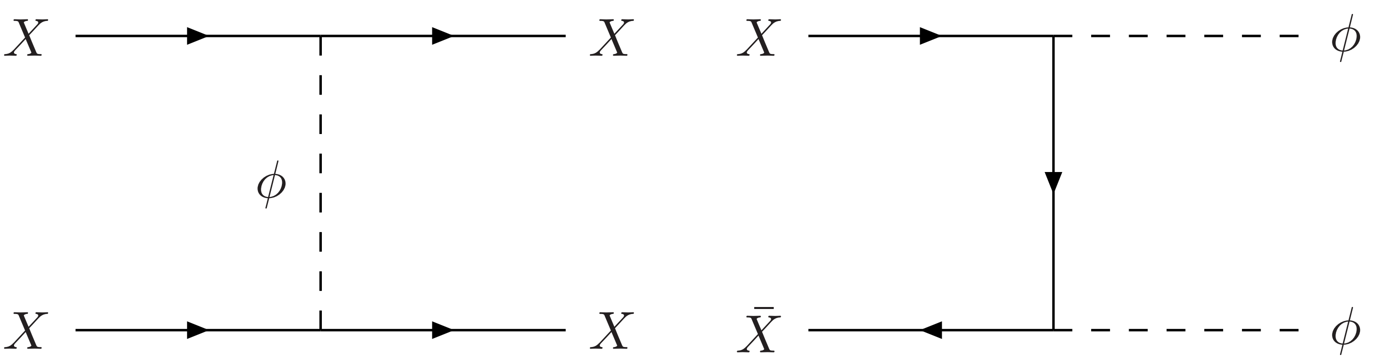
Spergel et al, Sigurdson et al,
Boehm et al, Kaplinghat et al,
Loeb et al, Tulin et al,
van de Aarseen et al,
….

What is SIDM?

- DM-DM scattering cross section is around

$$\frac{\sigma}{M_X} \sim \mathrm{cm}^2/\mathrm{g} \sim \mathrm{barn}/\mathrm{GeV}$$

- It can still be the usual WIMP



DM self-interactions

$$\sigma_{\rm SI} \sim \frac{\alpha^2}{m_\phi^2}$$

DM annihilation

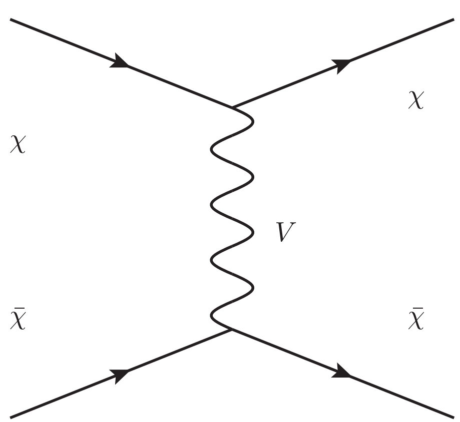
$$\sigma_{\rm ann} \sim \frac{\alpha^2}{M_X^2}$$

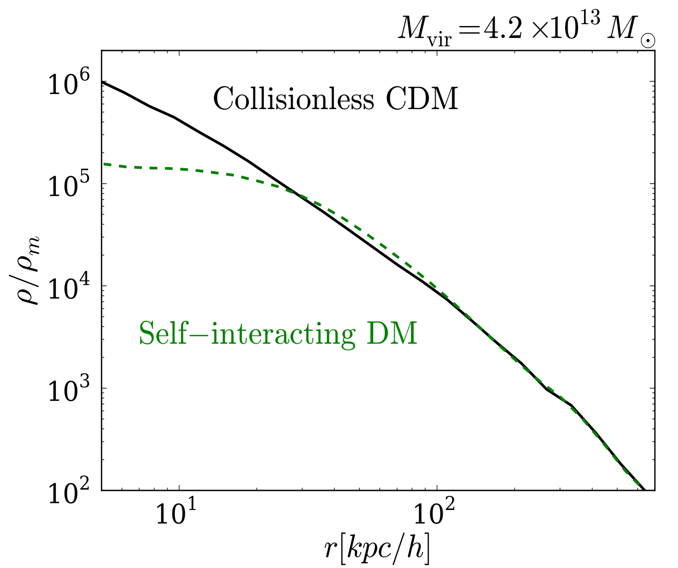
Effects

- In-falling dark matter is scattered before reaching the center of the galaxy. These collisions increase the entropy of the dark matter phase space distribution and lead to a dark matter halo profile with a shallower density profile.
- It can flatten the halo centre, solving the "***cusp-vs-core***" and "***too-big-to-fail***" problems.

But not "***Missing Satellites***"!

- MeV mediator can provide the right elastic scattering cross section for TeV dark matter

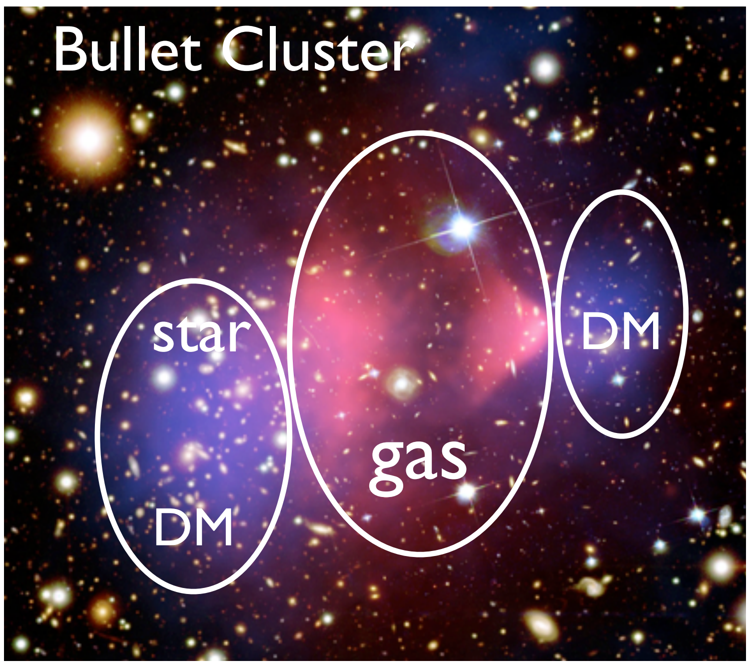




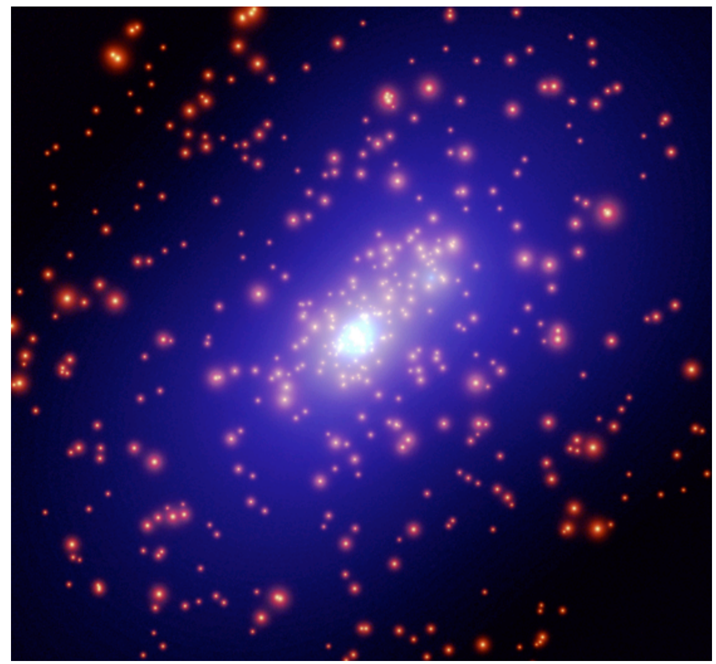
Astrophysical Constraints

- Bullet Cluster, elliptical halo shapes

$$\frac{\sigma_{\rm SI}}{M_X} \lesssim 0.1 - 1\ {\rm cm^2/g}$$



$V \sim 1000$ km/s for cluster



$V \sim 200$ km/s for galaxies

Velocity dependence

Feng et al, Buckley & Fox, Leob & Weiner, Tulin & Yu et al,…

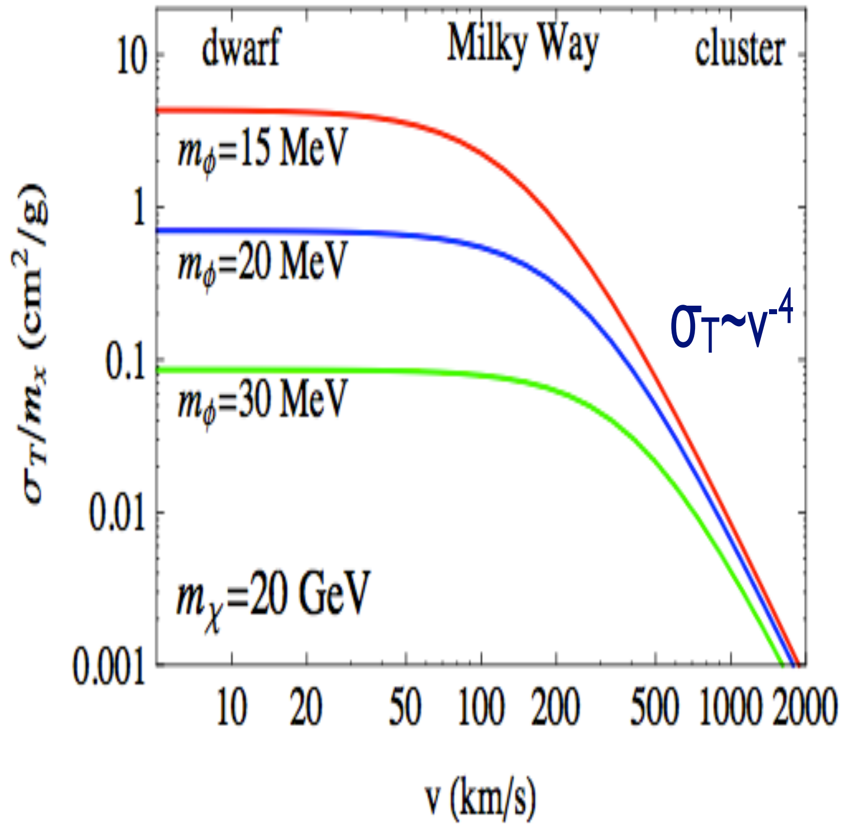
In the Born limit ($\alpha_X m_X/m_\phi \ll 1$),

$$\sigma_T^{\rm Born} = \frac{8\pi\alpha_X^2}{m_X^2 v^4}\left(\log\left(1+m_X^2v^2/m_\phi^2\right) - \frac{m_X^2v^2}{m_\phi^2+m_X^2v^2}\right),$$

in the classical limit ($m_X v/m_\phi \gg 1$),

$$\sigma_T^{\rm clas} = \begin{cases} \frac{4\pi}{m_\phi^2}\beta^2\ln\left(1+\beta^{-1}\right) & \beta \lesssim 10^{-1} \\ \frac{8\pi}{m_\phi^2}\beta^2/\left(1+1.5\beta^{1.65}\right) & 10^{-1}\lesssim\beta\lesssim 10^3 \\ \frac{\pi}{m_\phi^2}\left(\ln\beta+1-\frac{1}{2}\ln^{-1}\beta\right)^2 & \beta\gtrsim 10^3 \end{cases}$$

where $\beta \equiv 2\alpha_X m_\phi/(m_X v^2)$.



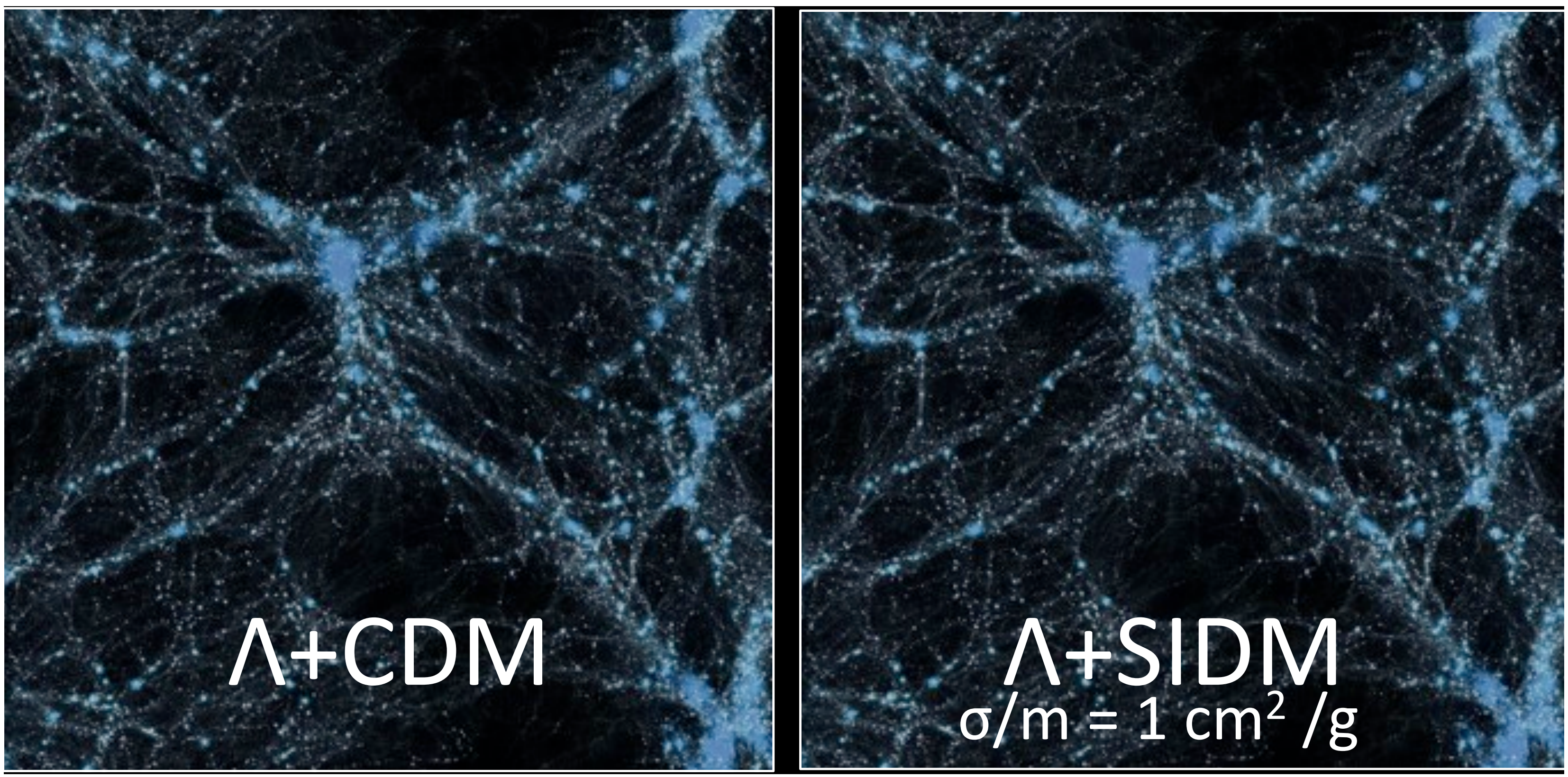
- For scalar dark matter and scalar mediator

Ko&Tang,1402.6449(JCAP)

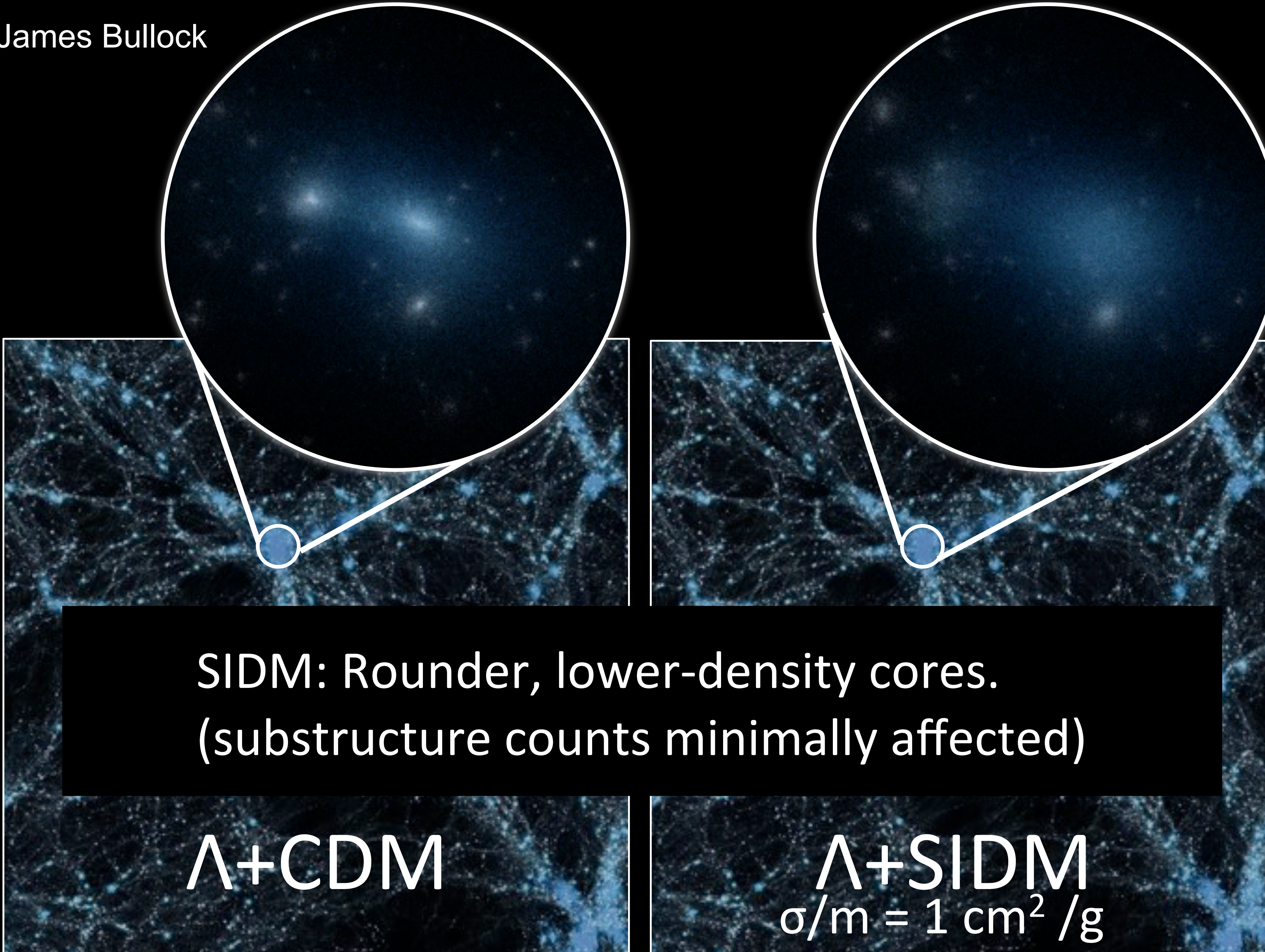
$$\alpha_\phi \equiv \frac{\lambda_{\phi X}^2}{4\pi}\left(\frac{v_\phi}{2M_X}\right)^2 \quad \text{and} \quad \beta \equiv \frac{2\alpha_\phi M_{H_2}}{M_X v_{\rm rel}^2}.$$

Identical LSS

James Bullock



James Bullock



SIDM: Rounder, lower-density cores.
(substructure counts minimally affected)

eV Sterile Neutrinos?

- Motivated by neutrino experiments to solve anomalies,
- accelerator, ($\bar{\nu}_\mu \to \bar{\nu}_e$) LSND and MiniBooNE
- reactor, (deficit of $\bar{\nu}_e$ flux)
- gallium anomalies ($^{71}Ga + \nu_e \to {}^{71}Ge + e^-$)

GALLEX and SAGE

$$\Delta m_{14}^2 \sim \mathrm{eV}^2,\ \sin^2 2\theta_{14} \sim 0.05$$

Cosmological Bounds

- Extra radiation, N_{eff} ,
- eV sterile neutrinos as hot dark matter, BBN, CMB, LSS

Joint CMB+BBN, 95% CL preferred ranges *Planck 2015, arXiv:1502.01589*

$$N_{\mathrm{eff}} = \begin{cases} 3.11^{+0.59}_{-0.57} & \text{He+}\textit{Planck}\text{ TT+lowP,} \\ 3.14^{+0.44}_{-0.43} & \text{He+}\textit{Planck}\text{ TT+lowP+BAO,} \\ 2.99^{+0.39}_{-0.39} & \text{He+}\textit{Planck}\text{ TT,TE,EE+lowP,} \end{cases}$$

Constraints on sterile neutrino mass

$$\left.\begin{aligned} N_{\mathrm{eff}} &< 3.7 \\ m_{\nu,\,\mathrm{sterile}}^{\mathrm{eff}} &< 0.52\ \mathrm{eV} \end{aligned}\right\} \quad 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+BAO.}$$

Difficulty

- With such mixing parameters,

$$\Delta m_{14}^2 \sim \mathrm{eV}^2,\ \sin^2 2\theta_{14} \sim 0.05$$

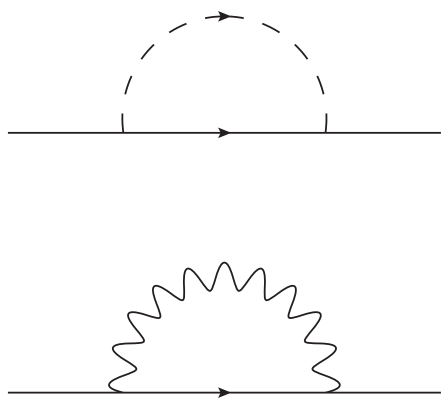
- neutrino oscillation would bring sterile neutrino into equilibrium in the early universe, then contribute $\Delta N_{\rm eff} \simeq 1$, in tension with *CMB* and *LSS*
- This is not true in case there is a large lepton asymmetry, or a self-interaction for sterile neutrinos, which induces a matter potential $V_{\rm eff}$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos 2\theta_0 - \frac{2E}{\Delta m^2} V_{\rm eff}\right)^2 + \sin^2 2\theta_0},\quad V_{\rm eff} \sim \frac{G_X}{M_X^2} T^5$$

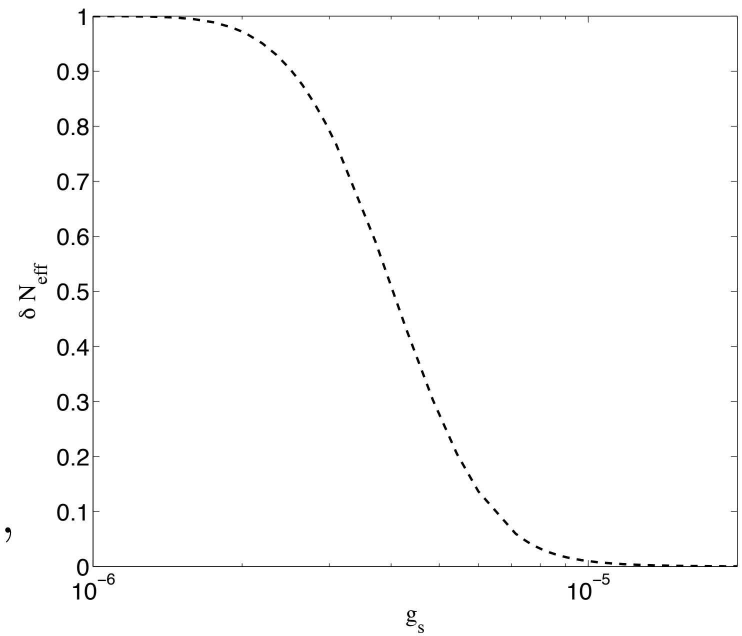
Hannestad,Hansen,Tram, ***1310.5926****(PRL);* Dasgupta,Kopp, ***1310.6337****(PRL)*

Interacting Sterile Neutrinos

- Partial thermalization at BBN



Archidiacono et al, 1404.5915v1



$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos 2\theta_0 - \frac{2E}{\Delta m^2} V_{\rm eff}\right)^2 + \sin^2 2\theta_0},$$

- *The new interaction might lead to fla*vor equilibrium after BBN, A. Mirizzi *et al*, ***1410.1385**, disfavored by cosmological neutrino mass bounds*

YT, 1501.00059; Chu, Dasgupta and Kopp, 1505.02795

Kinetic Equations

two-flavor mixing for ν_a-ν_s

$$\rho = \begin{pmatrix} \rho_{aa} & \rho_{as} \\ \rho_{sa} & \rho_{ss} \end{pmatrix}$$

density matrix is evolving as

$$i\frac{d\rho}{dt} = [H, \rho] + C(\rho)$$

where $H = \begin{pmatrix} -\frac{\delta m^2}{2E}\cos 2\theta_0 + V_{\rm eff} & \frac{\delta m^2}{2E}\sin 2\theta_0 \\ \frac{\delta m^2}{2E}\sin 2\theta_0 & \frac{\delta m^2}{2E}\cos 2\theta_0 - V_{\rm eff} \end{pmatrix}$

and C(ρ) is the collision term.

Kinetic Equations

Reparametrize

$$\rho = \begin{pmatrix} \rho_{aa} & \rho_{as} \\ \rho_{sa} & \rho_{ss} \end{pmatrix} = \frac{1}{2} f_0 \left(P_0 + \vec{P} \cdot \vec{\sigma} \right), \quad f_0 = 1/(e^{E/T} + 1)$$

$$P_a \equiv P_0 + P_z = 2\frac{\rho_{aa}}{f_0}, \qquad P_s \equiv P_0 - P_z = 2\frac{\rho_{ss}}{f_0},$$

$$\dot{P}_a = V_x P_y + \Gamma_a \left[2\frac{f_{eq,a}}{f_0} - P_a \right],$$

$$\dot{P}_s = -V_x P_y + \Gamma_s \left[2\frac{f_{eq,s}}{f_0} - P_s \right],$$

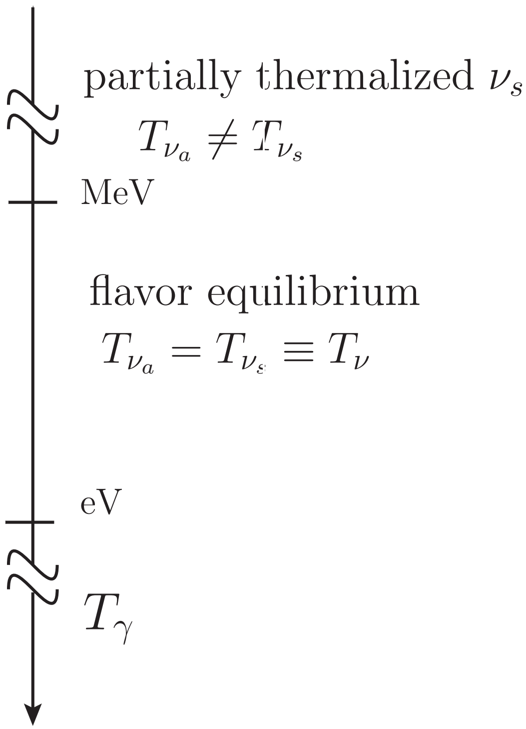
$$\dot{P}_x = -V_z P_y - D P_x,$$

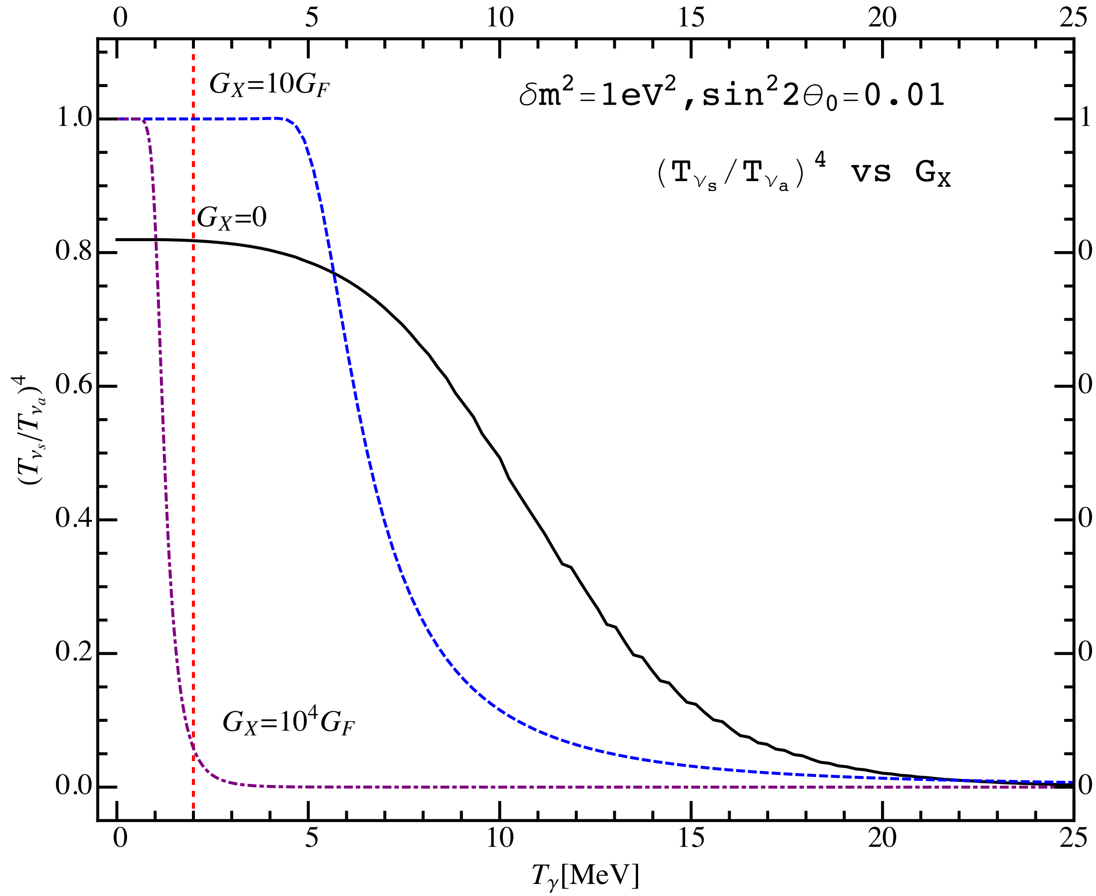
$$\dot{P}_y = V_z P_x - \frac{1}{2} V_x (P_a - P_s) - D P_y. \qquad D \simeq \frac{1}{2} (\Gamma_a + \Gamma_s)$$

Hannestad, Hansen, Tram, ***LASAGNA***

Flavor Equilibrium after BBN

YT, arXiv:1501.00059





$$\nu_e : \nu_\mu : \nu_\tau : \nu_s = 1:1:1:0 \Rightarrow \frac{3}{4} : \frac{3}{4} : \frac{3}{4} : \frac{3}{4}$$ disfavored for eV scale

δNeff < 0 ?

- Neff at BBN and CMB

$$\delta N_{\rm eff}^{\rm bbn} = n \times \left(\frac{T_{\nu_s}}{T^0_{\nu_a}}\right)^4 .$$

- Flavor equilibrium:

number density is conserved

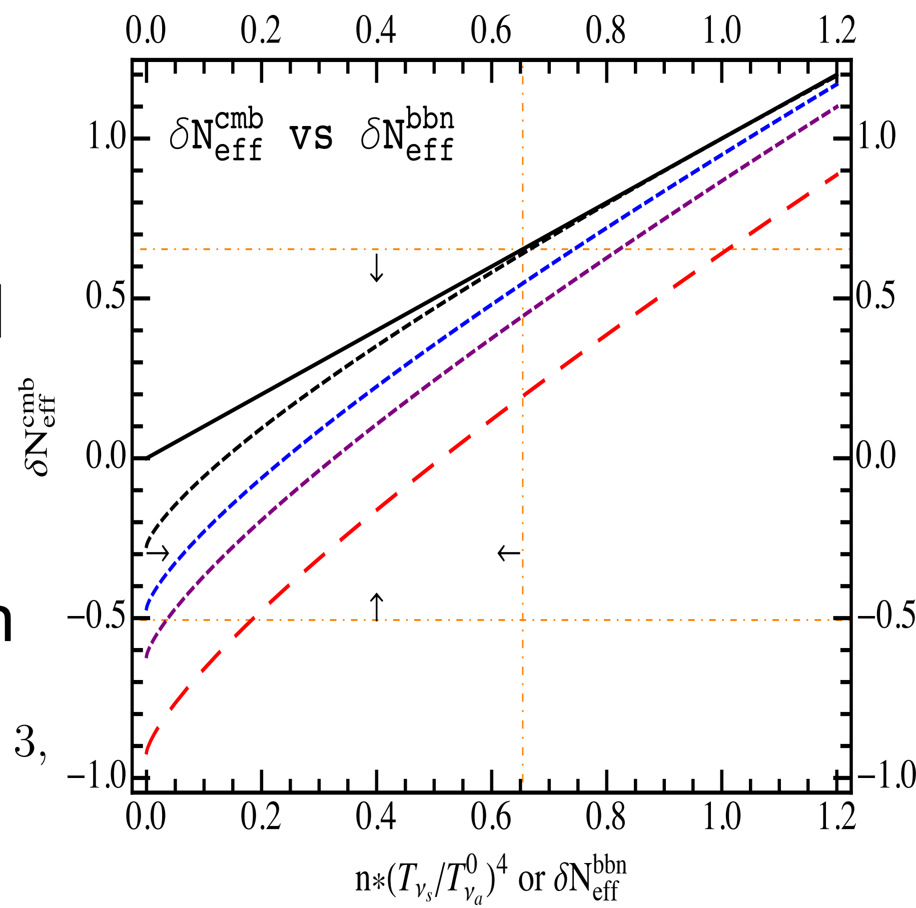
$$3 \times \left(T^0_{\nu_a}\right)^3 + n \times T^3_{\nu_s} = (3+n) \times T^3_{\nu},$$

Assume Fermi-Dirac Distribution

$$\delta N_{\rm eff}^{\rm cmb} = (3+n)^{-1/3} \times \left[3 + n \times \left(\frac{T_{\nu_s}}{T^0_{\nu_a}}\right)^3\right]^{4/3} - 3,$$

Neff can be even reduced.

YT, arXiv:1501.00059



Similar observations in Bringmann, Hasenkamp, Kersten, JCAP 1407 (2014) 042 and Mirizzi, Mangano, Pisanti, Saviano, PRD 91 (2015) 025019.

Cosmological Mass bound

Planck2015

$$\left.\begin{array}{r} N_{\rm eff} < 3.7 \\ m^{\rm eff}_{\nu,\,\rm sterile} < 0.52\ \rm eV \end{array}\right\} \quad 95\%,\ \textit{Planck}\ \rm TT{+}lowP{+}lensing{+}BAO.$$

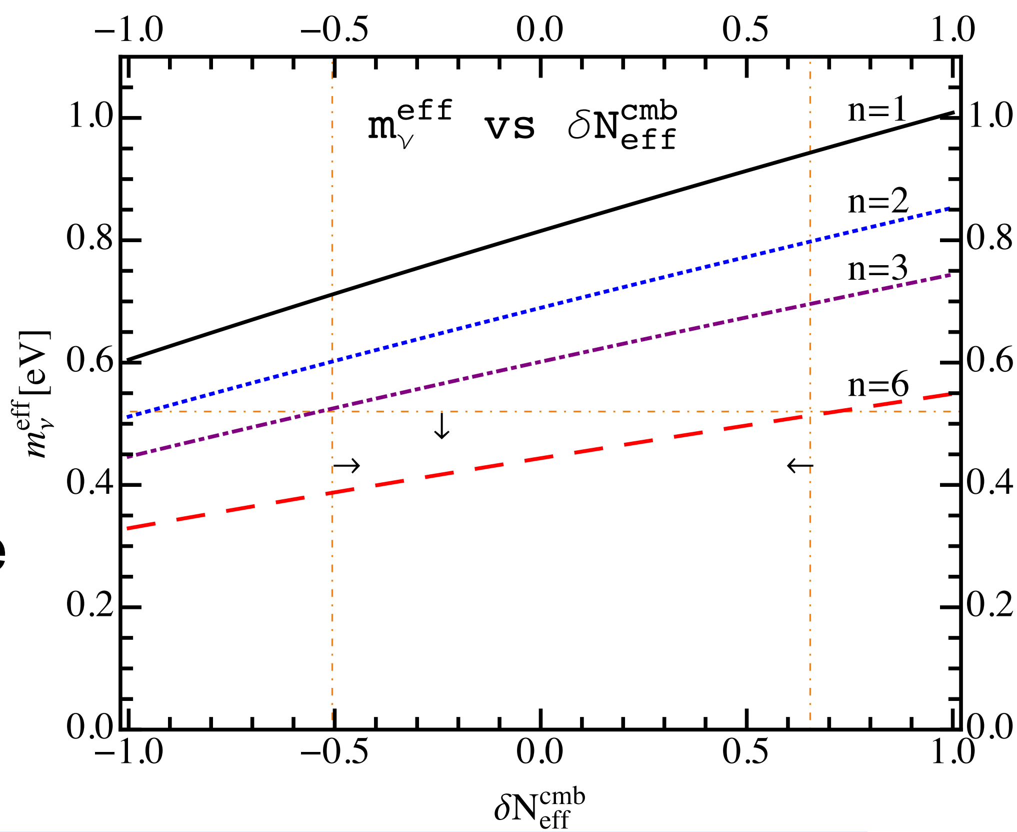
$$m_\nu^{\rm eff} \equiv \frac{\sum_i n_{\nu_i} m_{\nu_i}}{n^0_{\nu_a}} = \sum_i \left(\frac{T_{\nu_i}}{T^0_{\nu_a}}\right)^3 m_{\nu_i} \simeq 94.1\text{eV} \times \Omega_\nu h^2,$$

YT, arXiv:1501.00059

Assuming one ~ eV, and all others are light

$$m_\nu^{\rm eff} \simeq \left(\frac{T_\nu}{T^0_{\nu_a}}\right)^3 m_{\nu_4}.$$

Increasing n would make the number density of each species decrease.

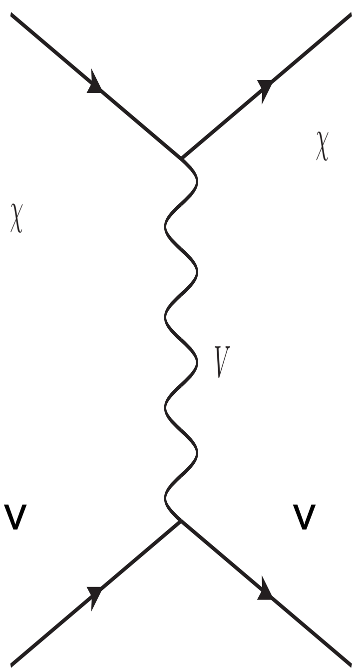


related works

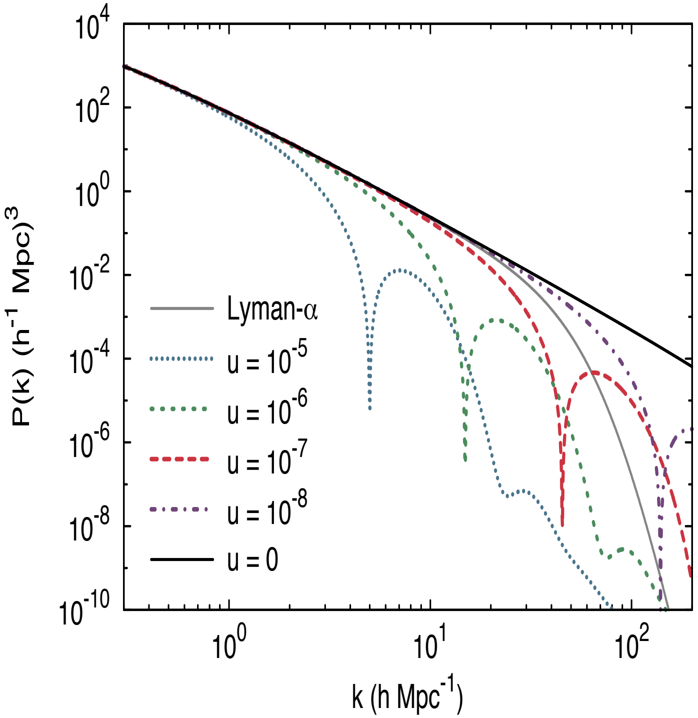
- Large lepton asymmetry [Foot and Volkas, 1995; Hannestad, Hansen, Tram, 2013]
- Secret interactions in the sterile sector [Hannestad, Hansen, Tram, PRL 112 (2014) 031802; Dasgupta, Kopp, PRL 112 (2014) 031803; Bringmann, Hasenkamp, Kersten, JCAP 1407 (2014) 042; Ko, Tang, PLB 739 (2014) 62; Archidiacono, Hannestad, Hansen,Tram, arXiv:1404.5915; Mirizzi, Mangano, Pisanti, Saviano, PRD 90 (2014) 113009, PRD 91 (2015) 025019;Cherry, Friedland,Shoemaker, arXiv:1411.1071;Bertoni, Ipek, McKeen and Nelson, arXiv:1412.3113; Tang, arXiv:1501.00059, Chu, Dasgupta and Kopp, arXiv:1505.02795]
- A larger cosmic expansion rate at the time of sterile neutrino production [Rehagen, Gelmini JCAP 1406 (2014) 044]
- MeV dark matter annihilation [Ho, Scherrer, PRD 87 (2013) 065016]
- Invisible decay [Gariazzo, Giunti, Laveder, arXiv:1404.6160]
- Modified primordial power spectrum [Gariazzo, Giunti, Laveder, arXiv:1412.7405]

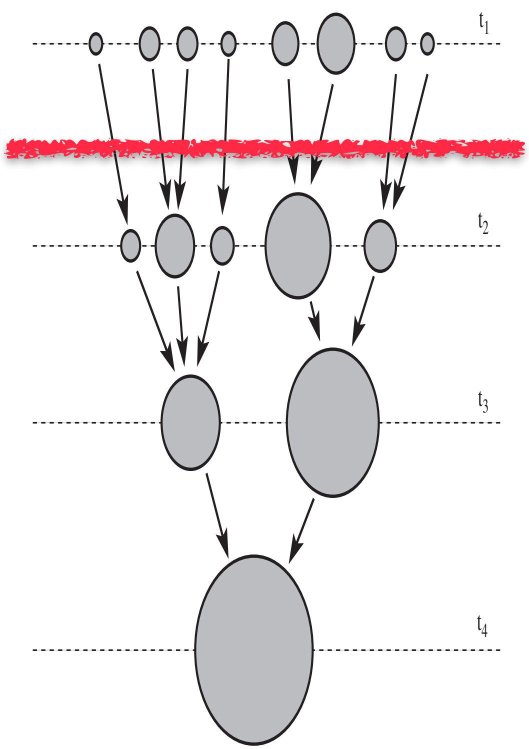
Connection with DM

Interaction with relativistic particles can induce a cut-off in the matter power spectrum by collisional damping, solving the "***missing satellites***" problem.



Wilkinson et al, 1401.7597





An Example Model

P. Ko, YT, 1404.0236(PLB)

We introduce two right-handed gauge singlets, a dark sector with an extra U(1)x gauge symmetry

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_i i\partial\!\!\!/ N_i - \left(\frac{1}{2} m^R_{ij} \bar{N}^c_i N_j + y_{\alpha i} \bar{L}_\alpha H N_i + h.c\right) - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon \hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$$
$$+ \bar{\chi}\left(iD\!\!\!\!/ - m_\chi\right)\chi + \bar{\psi}\left(iD\!\!\!\!/ - m_\psi\right)\psi + D^\dagger_\mu \phi^\dagger_X D^\mu \phi_X - \left(f_i \phi^\dagger_X \bar{N}^c_i \psi + g_i \phi_X \bar{\psi} N_i + h.c\right)$$
$$- \lambda_\phi \left[\phi^\dagger_X \phi_X - \frac{v^2_\phi}{2}\right]^2 - \lambda_{\phi H}\left[\phi^\dagger_X \phi_X - \frac{v^2_\phi}{2}\right]\left[H^\dagger H - \frac{v^2_h}{2}\right],$$

$v_\phi \sim \mathcal{O}\,(\mathrm{MeV})$ for our interest

Various Mixings

- Kinetic mixing term $\frac{1}{2}\sin\epsilon \hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$ leads to three physical neutral gauge boson mixing,
- Scalar interaction term $\lambda_{\phi H}\left[\phi_X^\dagger \phi_X - \frac{v_\phi^2}{2}\right]\left[H^\dagger H - \frac{v_h^2}{2}\right]$ leads to Higgs mixing,

$$h = H_1\cos\alpha - H_2\sin\alpha,$$
$$\phi = H_1\sin\alpha + H_2\cos\alpha,$$

- $y_{\alpha i}\bar{L}_\alpha H N_i,\ f_i\phi_X^\dagger \bar{N}_i^c\psi,\ g_i\phi_X\bar{\psi}N_i$ give rise to neutrino mixing.

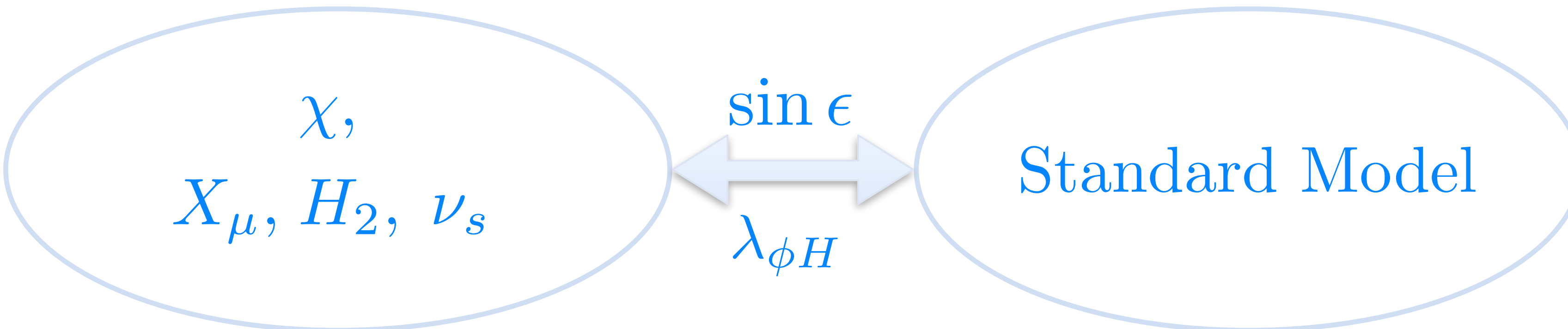
Physical Spectrum

- Neutrino Mixing

$$\begin{pmatrix} \nu_\alpha \\ N_i^c \\ \psi_L \\ \psi_L^c \end{pmatrix} = U \begin{pmatrix} \nu_a \\ \nu_{s4} \\ \vdots \\ \nu_{s7} \end{pmatrix}_L , \ \mathbb{M} = \begin{pmatrix} 0_{3\times 3} & \frac{v}{\sqrt{2}}[y_{\alpha i}]_{3\times 2} & 0_{3\times 2} \\ \frac{v}{\sqrt{2}}[y_{\alpha i}]^T_{2\times 3} & \left[m^R_{ij}\right]_{2\times 2} & \frac{v_\phi}{\sqrt{2}}(f_i \ g_i)_{2\times 2} \\ 0_{2\times 3} & \frac{v_\phi}{\sqrt{2}}(f_i \ g_i)^T_{2\times 2} & \begin{pmatrix} 0 & m_\phi \\ m_\phi & 0 \end{pmatrix} \end{pmatrix} .$$

- Dark Matter, dark gauge boson X_μ, dark Higgs H_2, and 4 sterile neutrinos ν_s,

Thermal History



- DM chemically decoupled, determining its relic density,
- Then the whole dark sector decoupled from SM thermal bath, and entropy is conserved separately. Effective number of neutrinos can be calculated.
- Relativistic particles at CMB time contribute as hot dark matter. Sterile neutrinos are not thermalized before BBN due to the new interaction.

velocity dependent σ

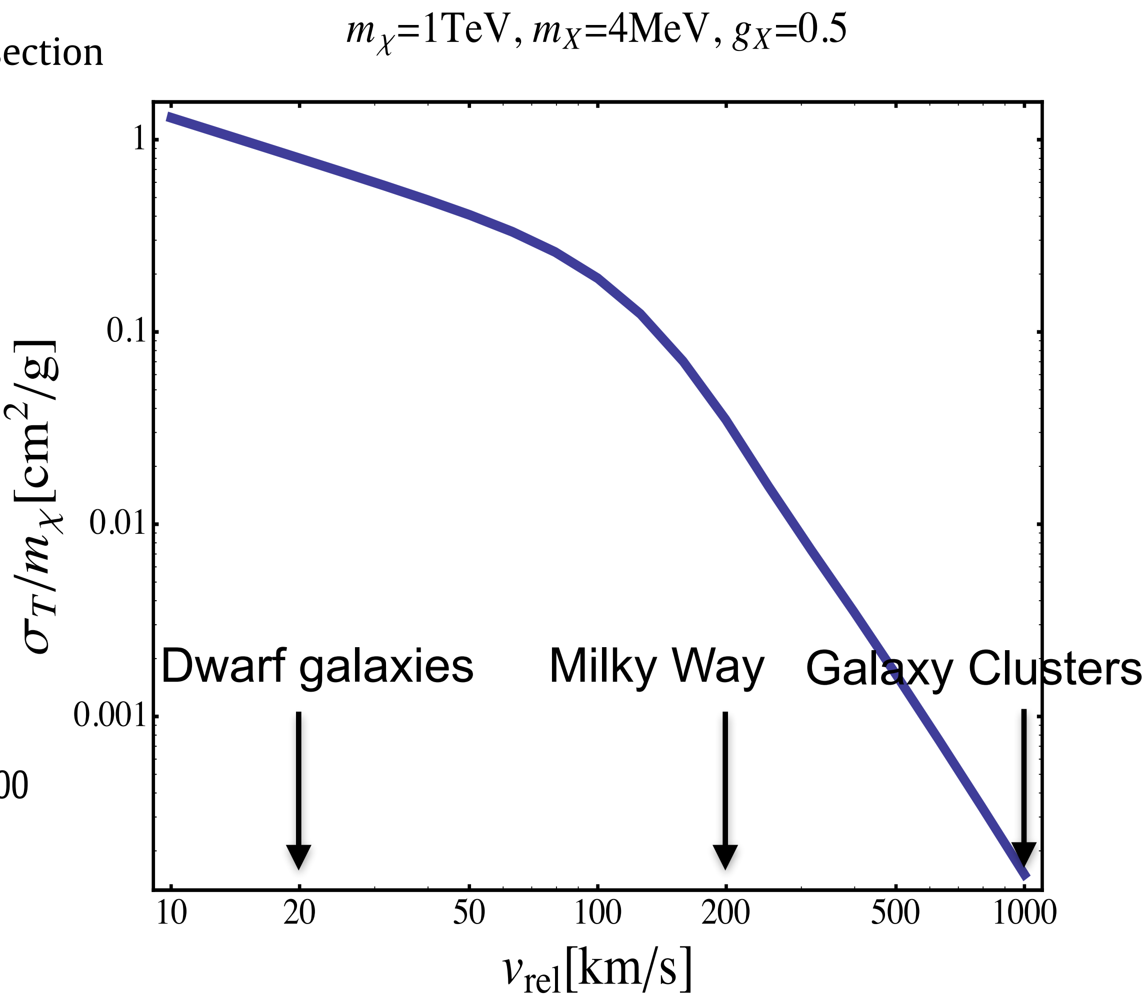
DM self-scattering is the transfer cross section

$$\sigma_T \equiv \int d\Omega (1 - \cos\theta) \frac{d\sigma}{d\Omega}.$$

$$\sigma_T = \frac{8\pi}{m_X^2}\beta^2\left[\ln\left(1+R^2\right) - \frac{R^2}{1+R^2}\right],$$

$$\alpha_X = \frac{g_X^2}{4\pi}, \qquad \beta = \frac{2\alpha_X m_X}{m_\chi v_{\rm rel}^2}, \qquad R = \frac{m_\chi v_{\rm rel}}{m_X},$$

$$\sigma_T = \begin{cases} \frac{4\pi}{m_X^2}\beta^2 \ln(1+\beta^{-1}) & \beta \lesssim 0.2 \\ \frac{8\pi}{m_X^2}\beta^2/(1+1.5\beta^{1.65}) & 0.2 \lesssim \beta \lesssim 1300 \\ \frac{\pi}{m_X^2}(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta)^2 & \beta \gtrsim 1300 \end{cases}$$



Kinetic decoupling

Kinetic decoupling of χ from ν_s happens when the elastic scattering rate for $\chi\nu_s \leftrightarrow \chi\nu_s$ drops below Hubble parameter H. The decoupling temperature is given by

$$T_\chi^{\rm kd} \simeq 1{\rm keV}\left(\frac{0.1}{g_X}\right)\left(\frac{T_\gamma}{T_{\nu_s}}\right)^{\frac{3}{2}}_{\rm kd}\left(\frac{m_\chi}{\rm TeV}\right)^{\frac{1}{4}}\left(\frac{m_X}{\rm MeV}\right),$$

The kinetic decoupling of DM from the relativistic particles imprints on the matter power spectrum, for which there are two relevant scales: the comoving horizon $\tau_{\rm kd} \propto 1/T_\chi^{\rm kd}$ and free-streaming length $\left(T_\chi^{\rm kd}/m_\chi\right)^{1/2}\tau_{\rm kd}$. For our interested regime, $\tau_{\rm kd}$ is much larger and relevant. Thus $T_\chi^{\rm kd}$ can be translated into a cutoff in the power spectrum of matter density perturbation with

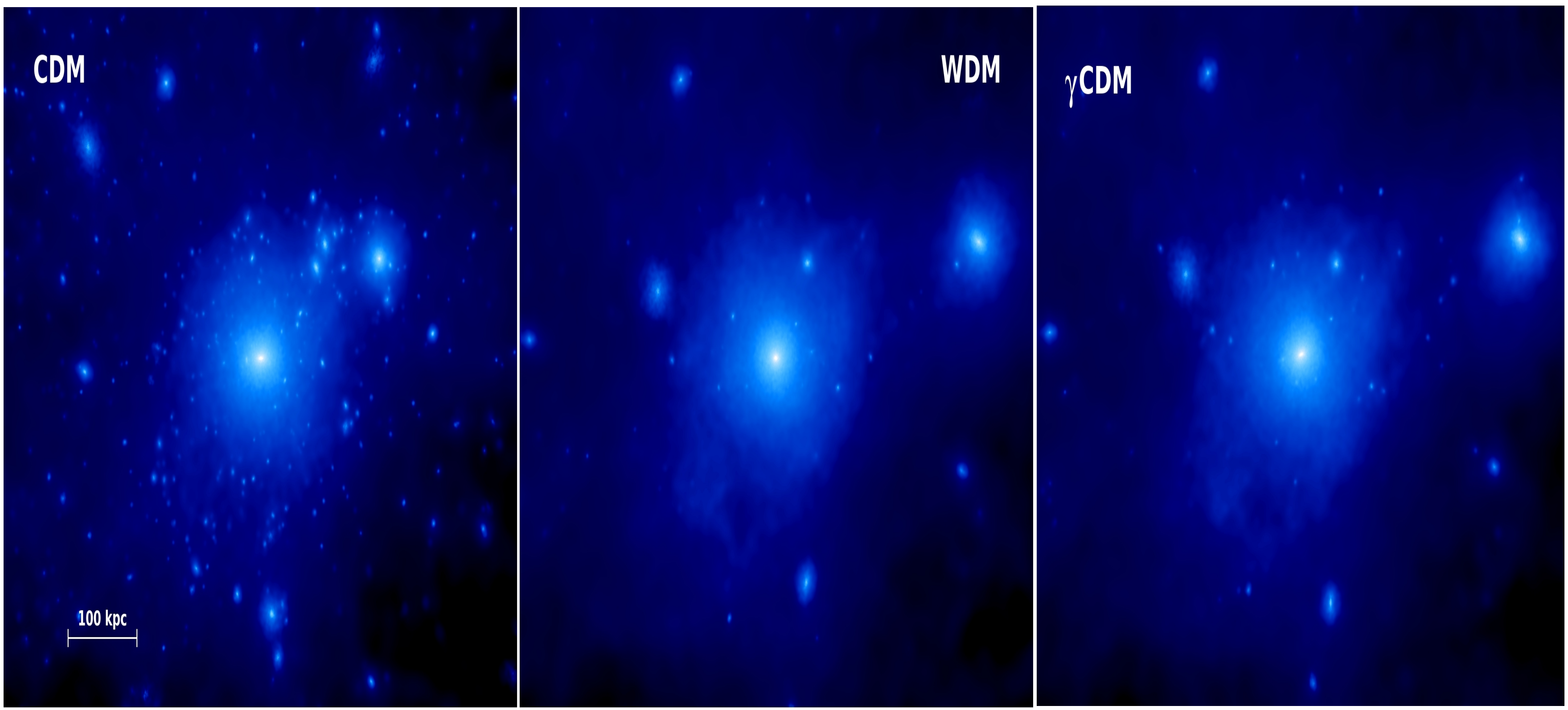
$$M_{\rm cut} = \frac{4\pi}{3}\rho_{\rm M}\left(c\tau_{\rm kd}\right)^3 \sim 2\times 10^8\left(\frac{T_\chi^{\rm kd}}{\rm keV}\right)^{-3} M_\odot,$$

Then $M_{\rm cut} \sim \mathcal{O}(10^9)M_\odot$ can be easily obtained for explanation of *missing satellites problem* for $\mathcal{O}$(TeV) χ and $\mathcal{O}$(MeV) X_μ.

Simulation

- DM-γ/ν interaction ~ $2 \times 10^{-9}\ \sigma_{\rm Th}\,(m_{\rm DM}/{\rm GeV})$

Boehm, Schewtschenko, Wilkinson, Baugh and Pascoli, *1404.7012*



Summary

- Introduction of three controversies in CDM paradigm, *cusp-vs-core, too-big-to-fail, and missing satellites* problems.
- Self-interacting DM is an attractive solution.
- eV sterile neutrino is motivated from anomalies, but cosmologically disfavored, relaxed if large lepton asymmetry, new interactions or more light species are introduced.
- We study a simple model *νΛMDM* based on an extra U(1) gauge symmetry that connects sterile neutrinos and DM.

Thanks for your attention.