Dark Matter and Sterile Neutrinos with Astrophysical Connections

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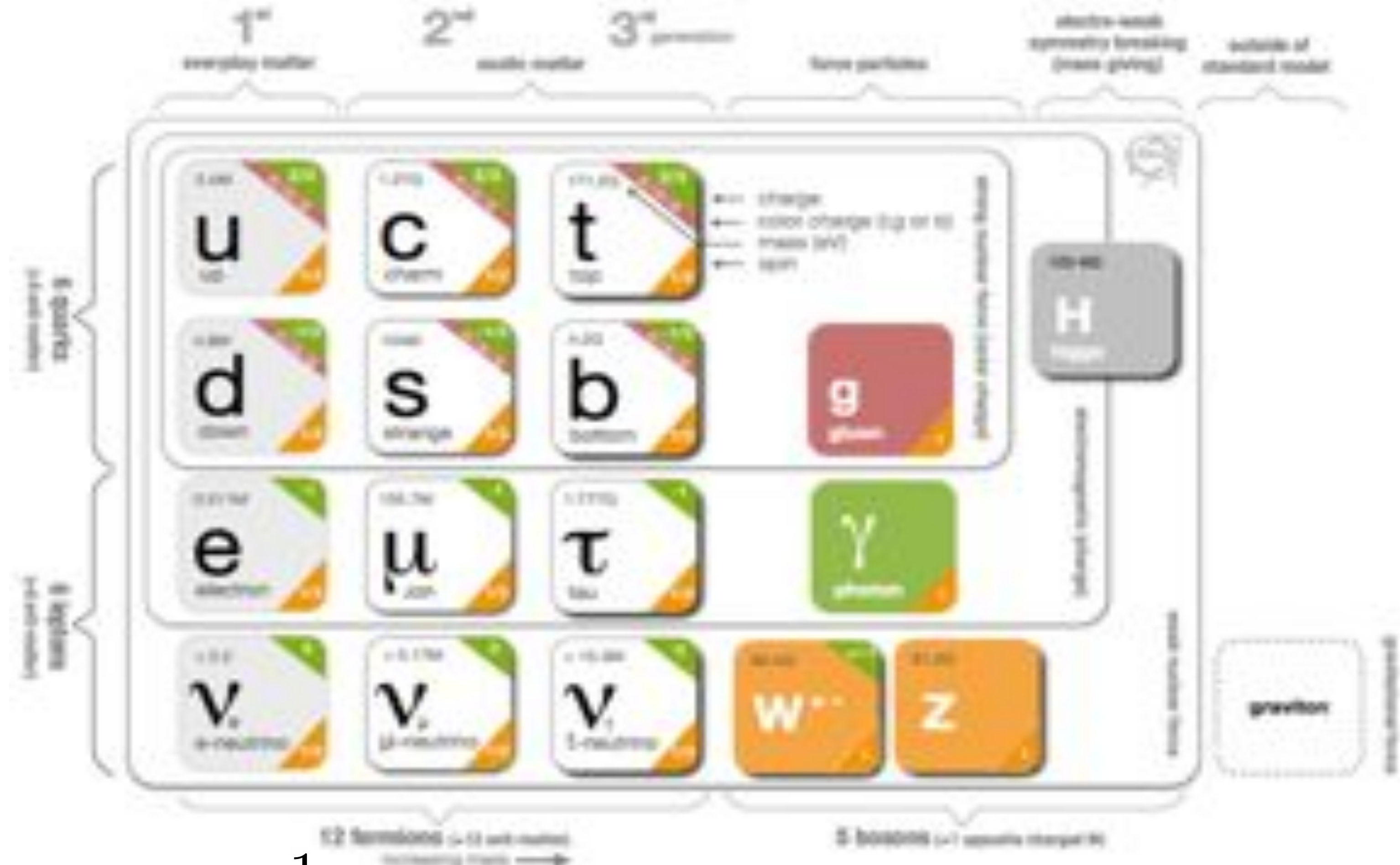
Outline

- Introduction
  - DM evidence
  - cold dark matter controversies
- Self-Interacting DM
- Sterile Neutrinos
- Summary

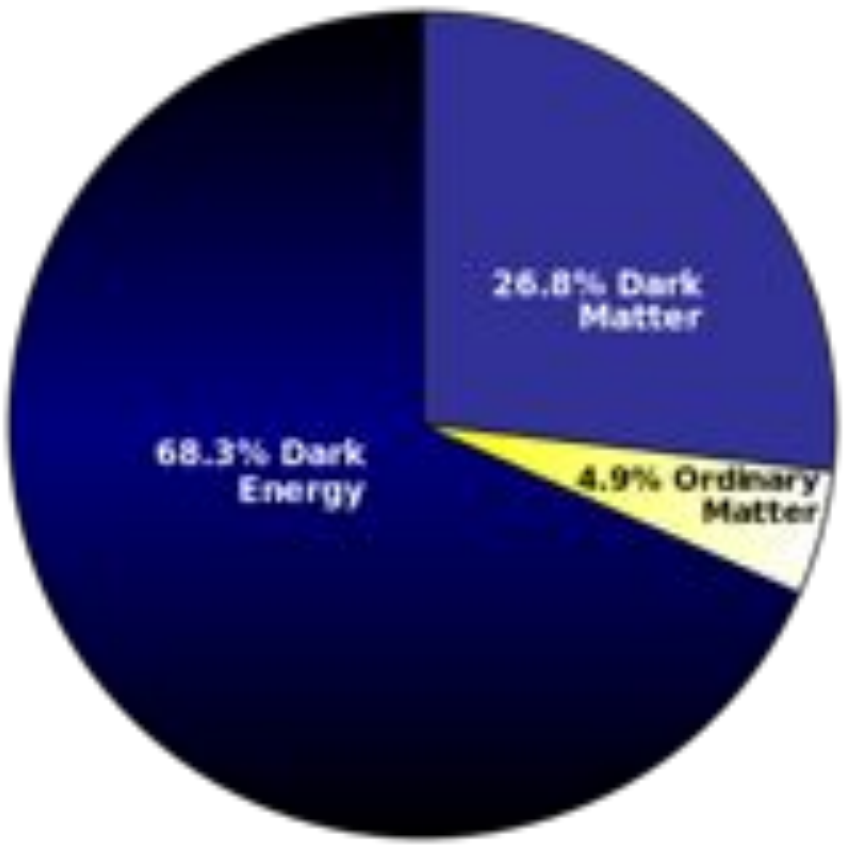
Standard Model



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{\psi_i} i\gamma \cdot D\psi_i + |D_\mu H|^2$$

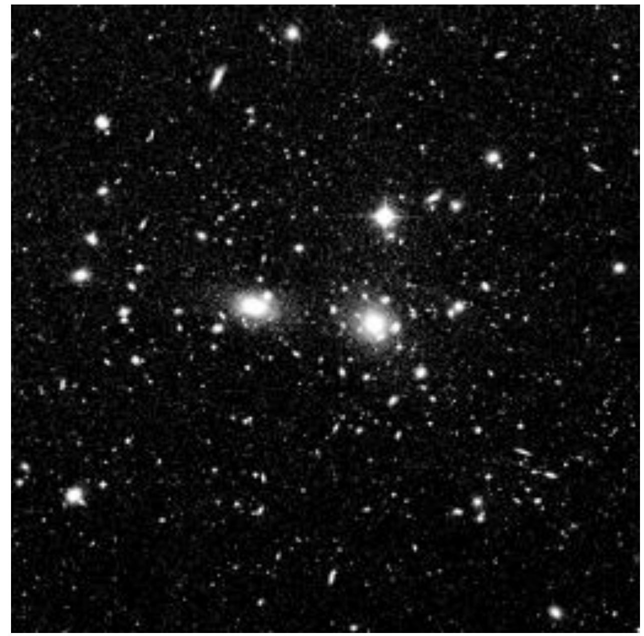
$$+ (y_{ij}\ \overline{\psi_{iL}}\psi_{jR}H + h.c.) - \mathcal{V}(H).$$

Cosmic Pie



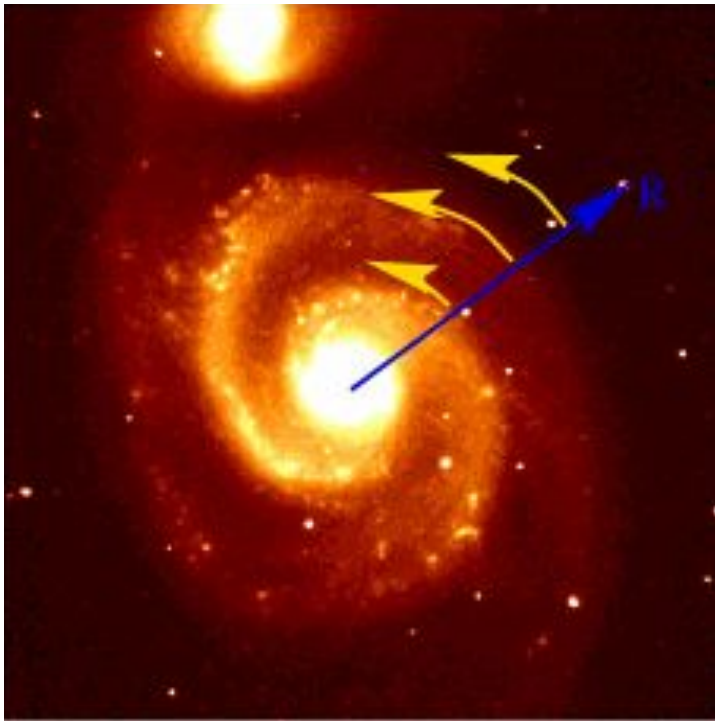
- "Ordinary Matter": baryon, photon, neutrino, mostly described by particle physics standard model
- Dark Energy: cosmological constant?
- Dark Matter: WIMP, (sterile) neutrino, axion, …

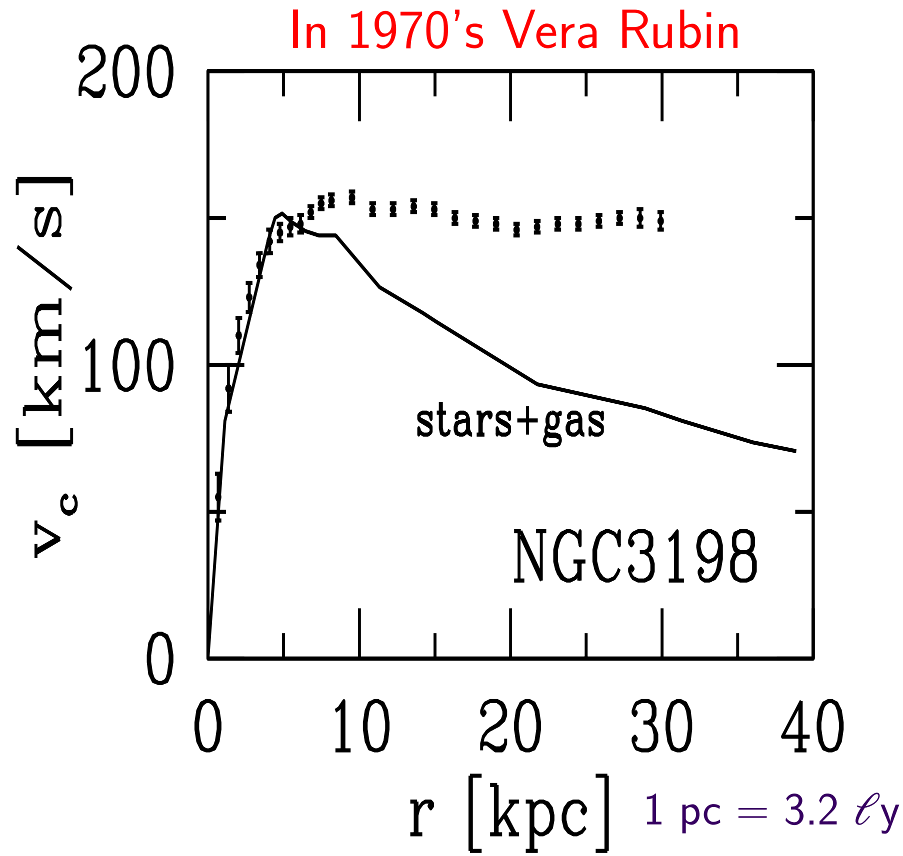
Pre-history



- Fritz Zwicky, 1933, coma cluster
- galaxies were moving too fast,
- extra invisible mass is needed, Dark Matter

Rotational Curve



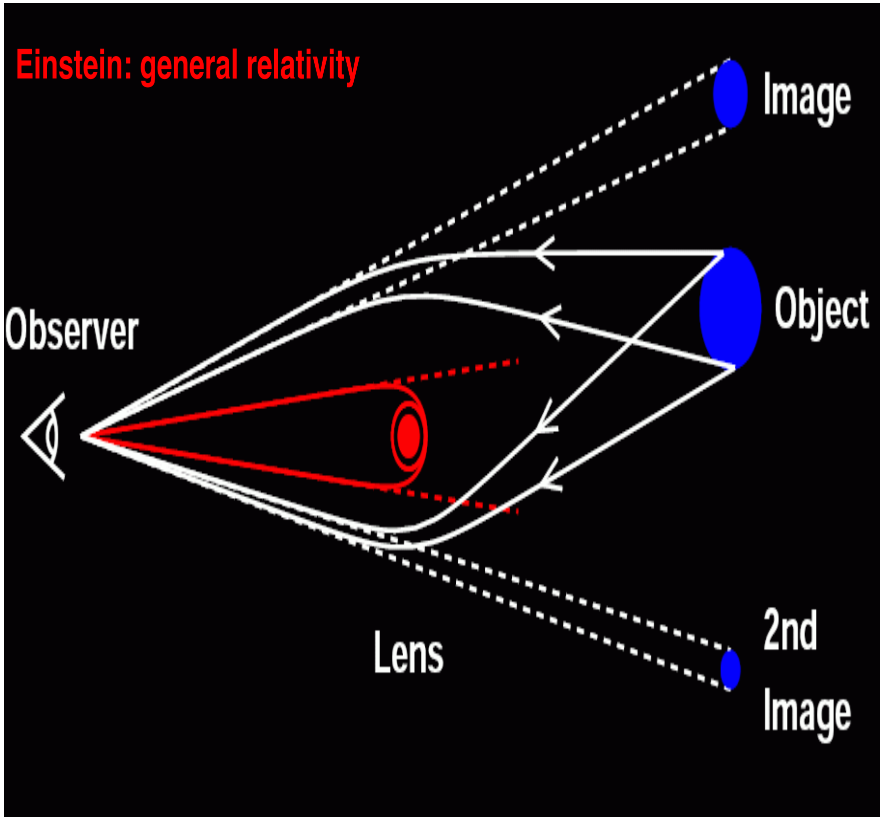


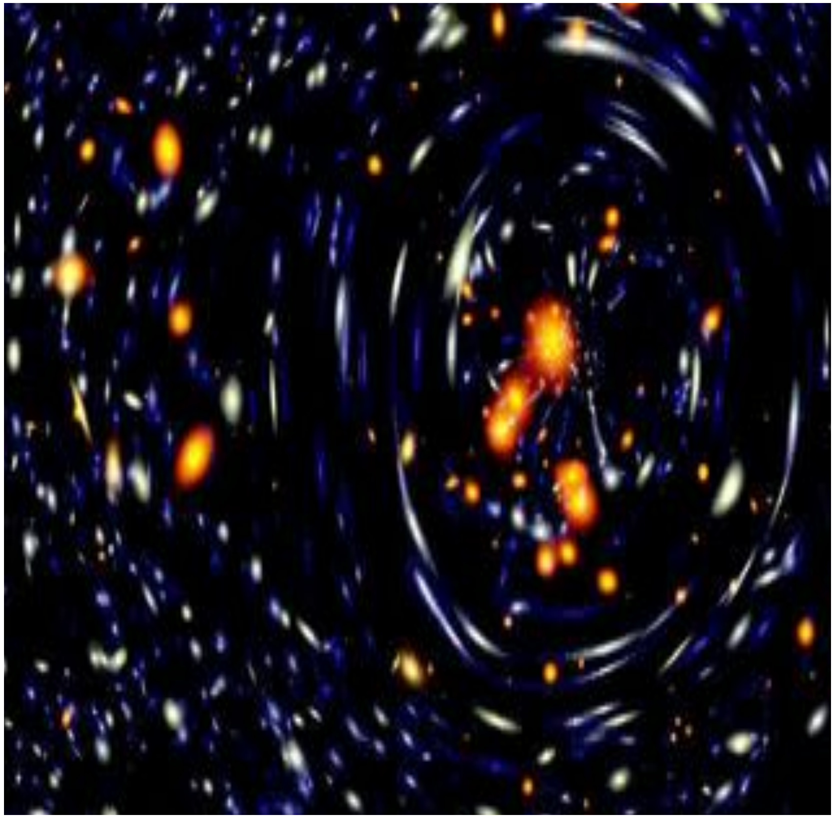
$$\frac{GMm}{r^2} = m\frac{v^2}{r} \Rightarrow v = \sqrt{\frac{GM(r)}{r}}$$

$$v = const. \Rightarrow M(r) \sim r$$

- $M/M_{vis} > 4$

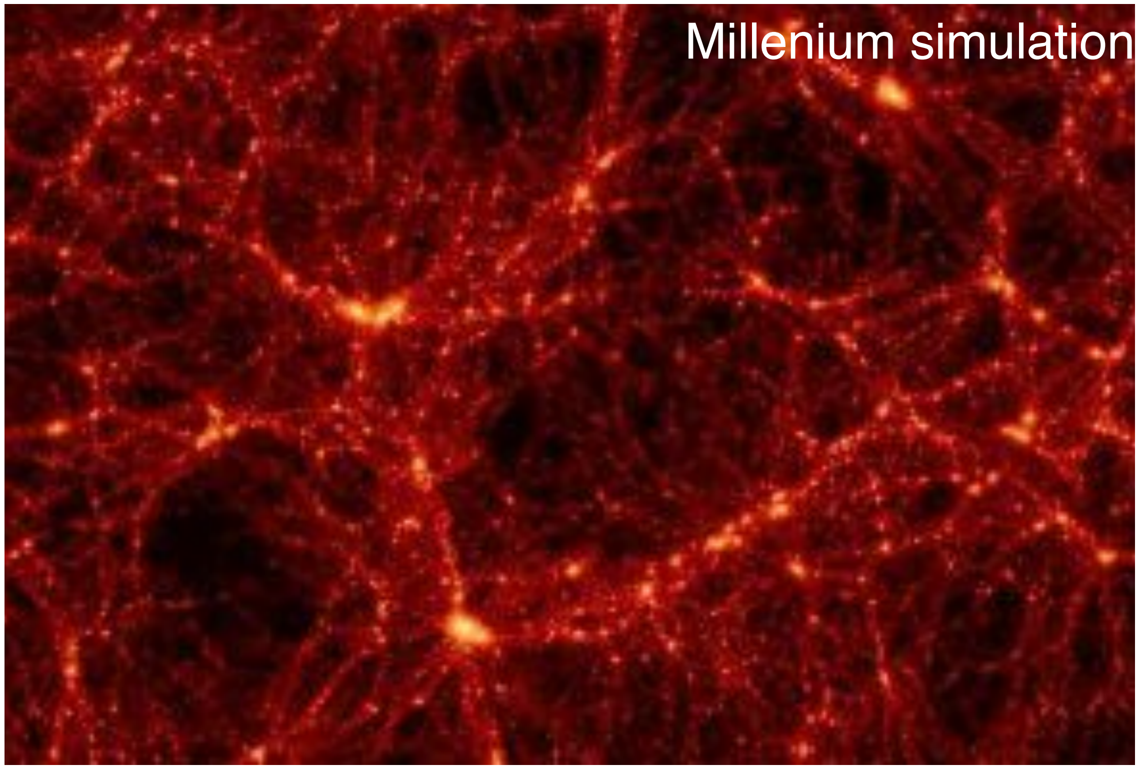
Gravitational Lensing





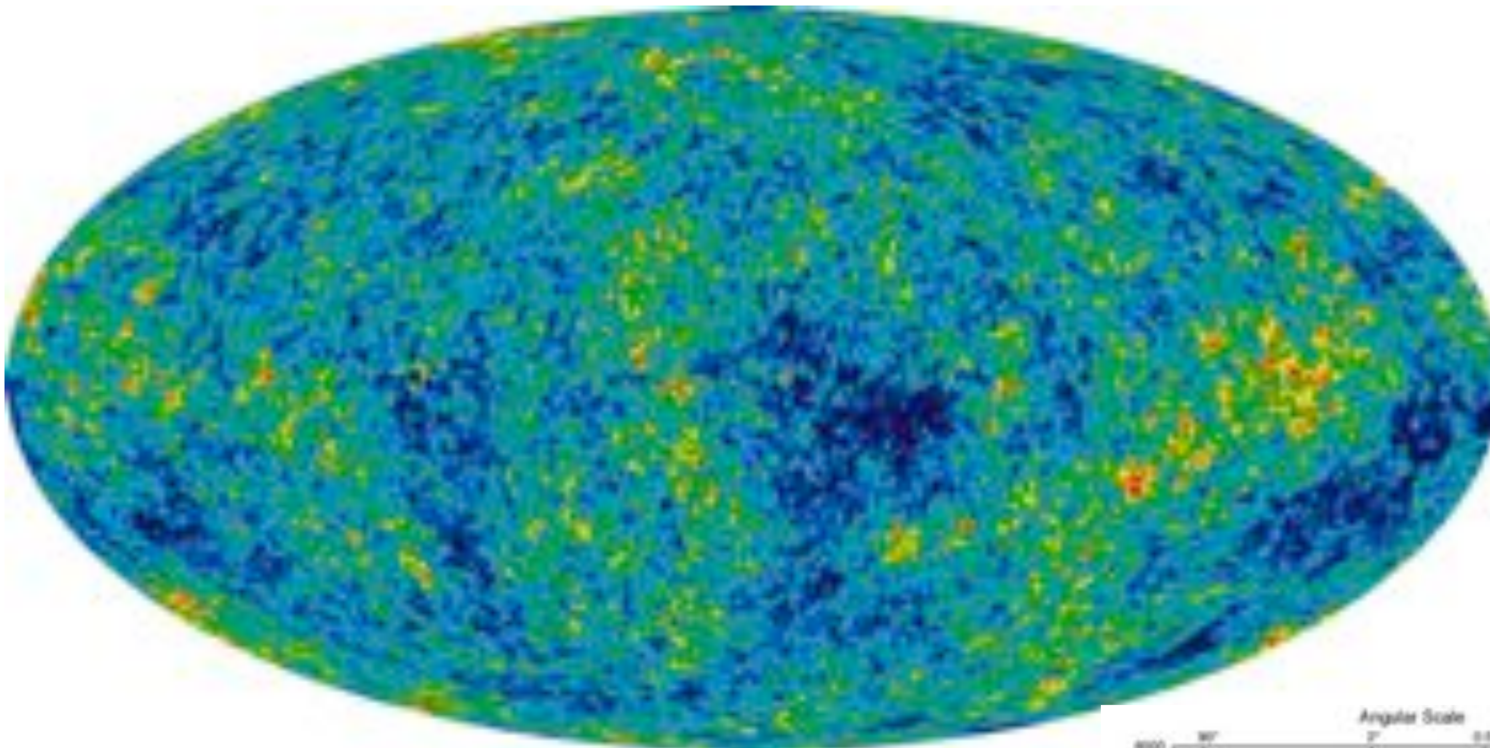
- determine the total mass, missing mass

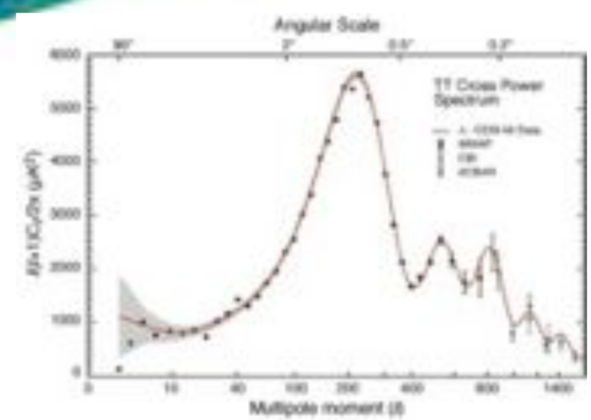
Large Scale Structure



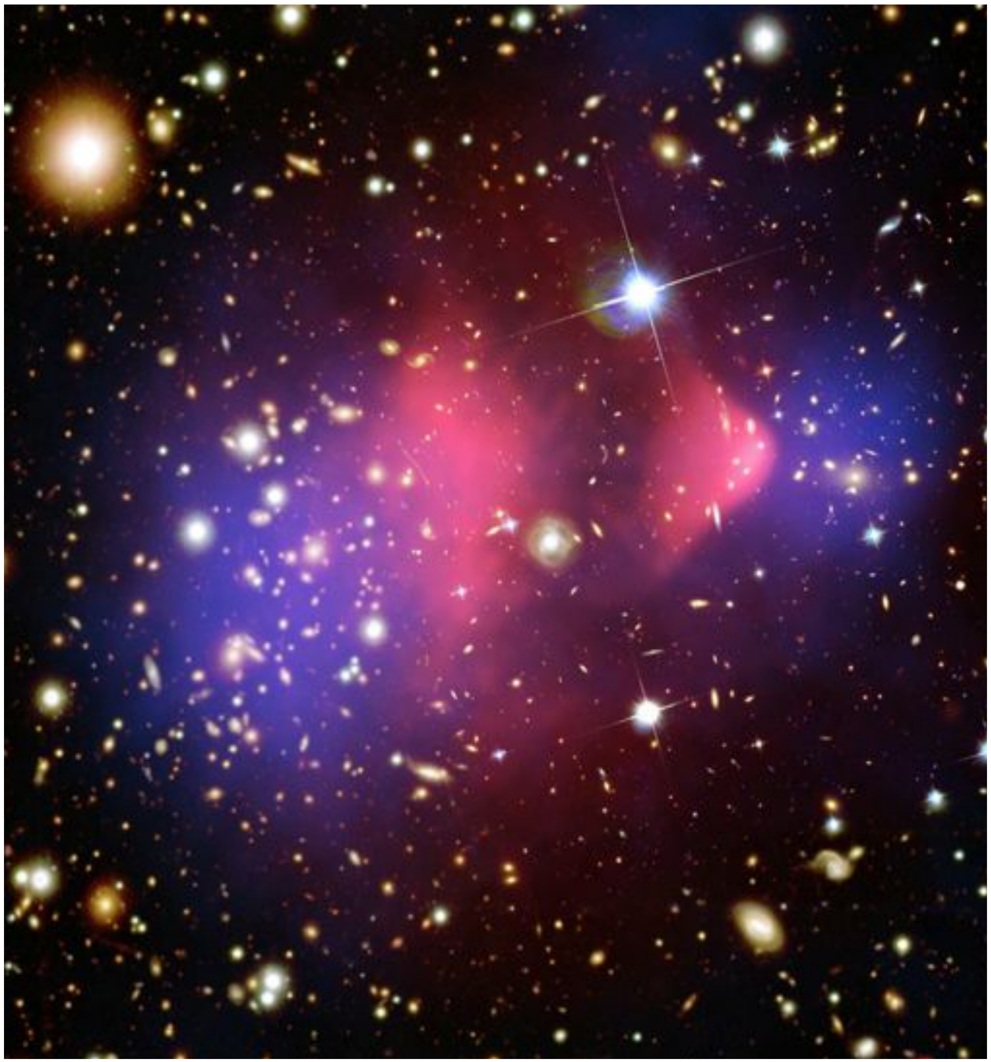
- if only visible matter, matter power spectrum does not match; matched if dark matter included

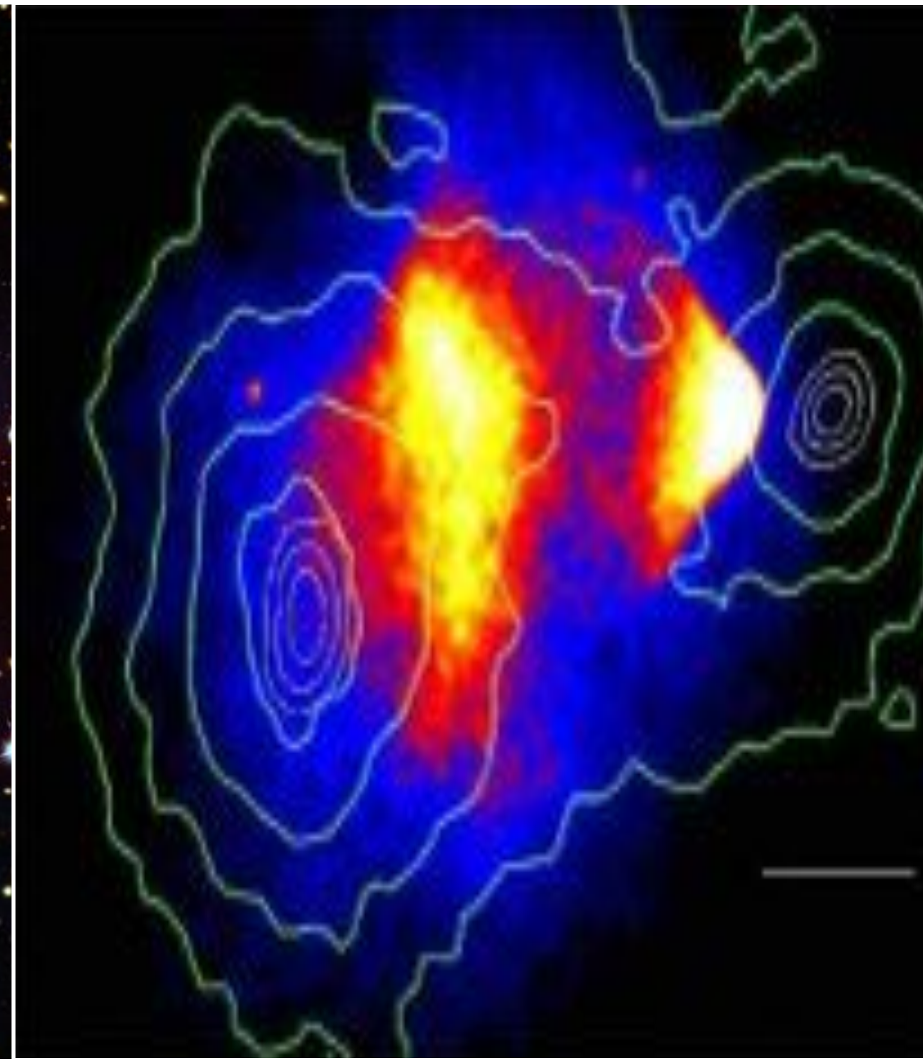
CMB anisotropy





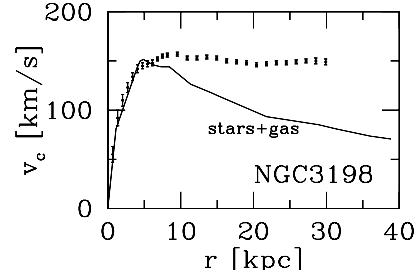
Bullet Cluster

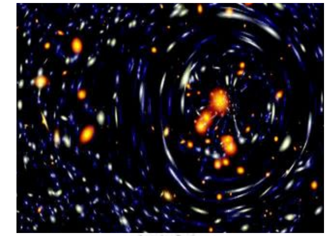


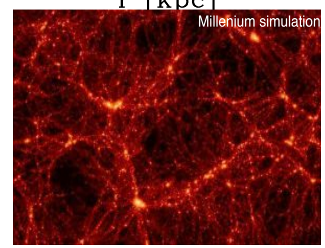


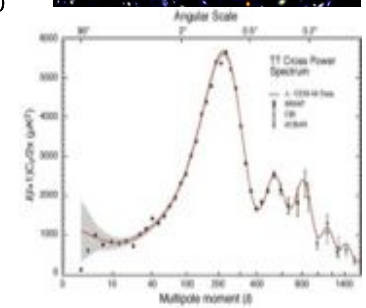
Dark Matter Scenario

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







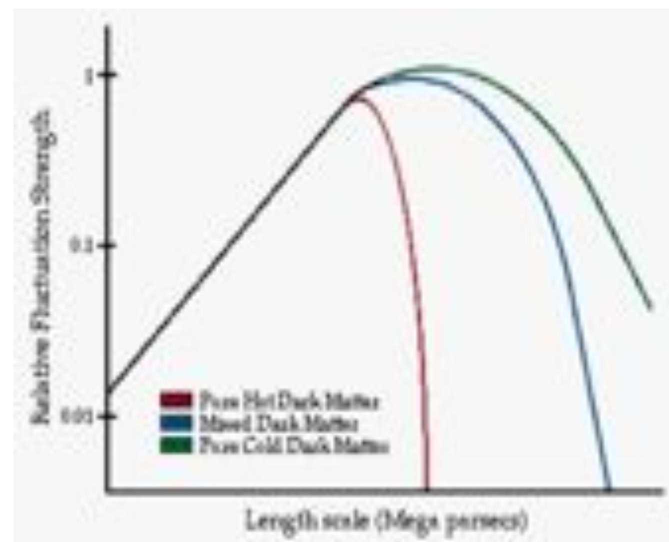


All *confirmed* *evidence comes from gravitational interaction*

***CDM**: velocity dispersion is negligible for structure formation, a popular candidate, WIMP*

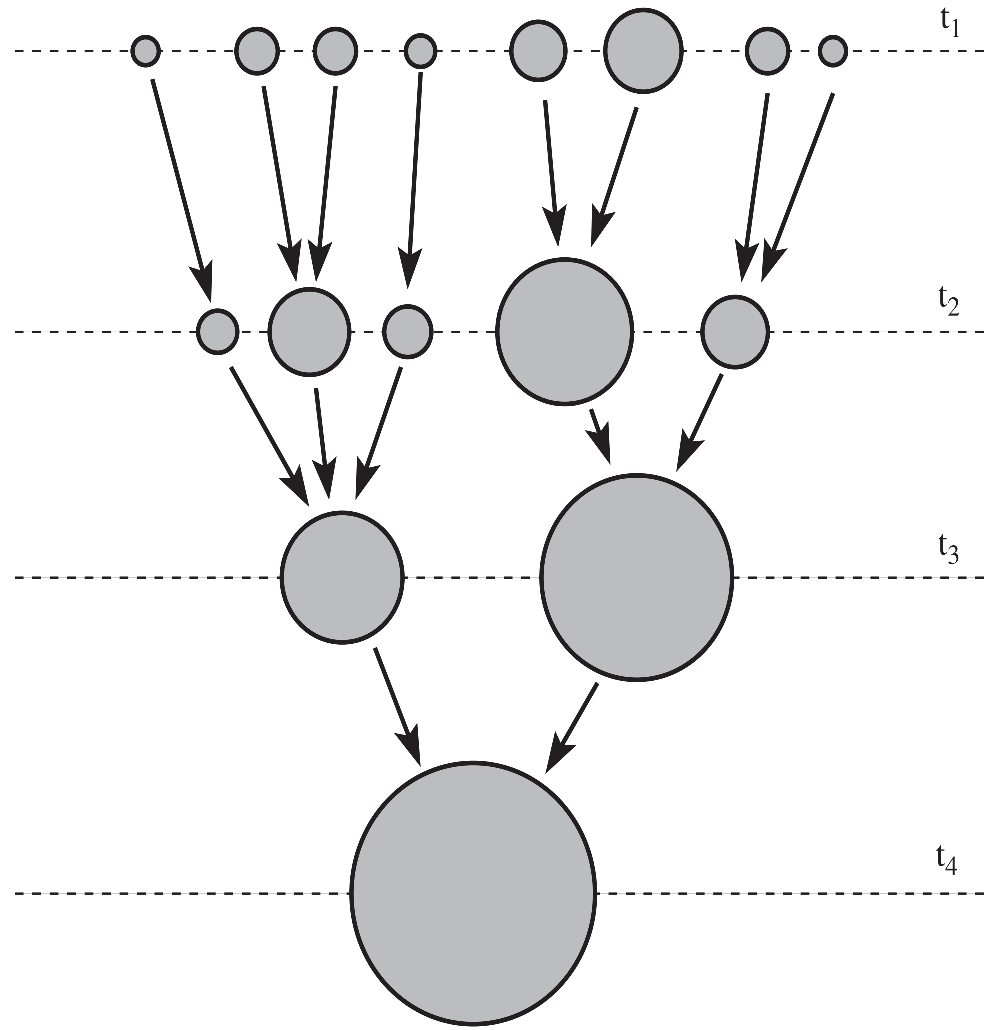
***WDM**: keV sterile neutrino*

***HDM**: active neutrino*



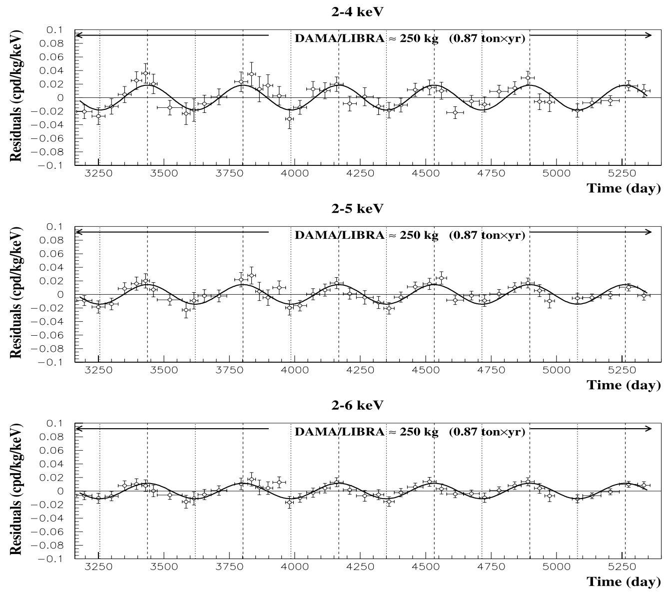
Merger History of Dark Halo

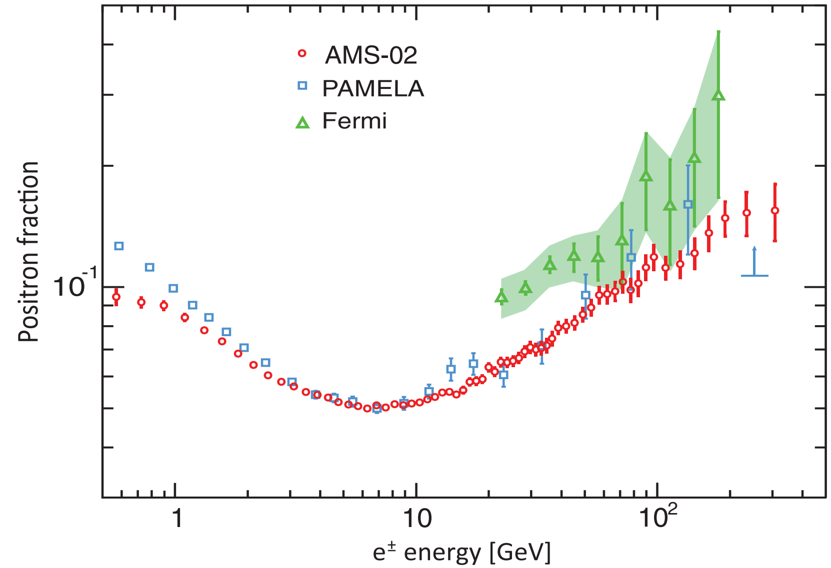
- standard picture
- DM halo grow hierarchically
- first small scale structures form
- then merge into larger halo



Tentative Evidence

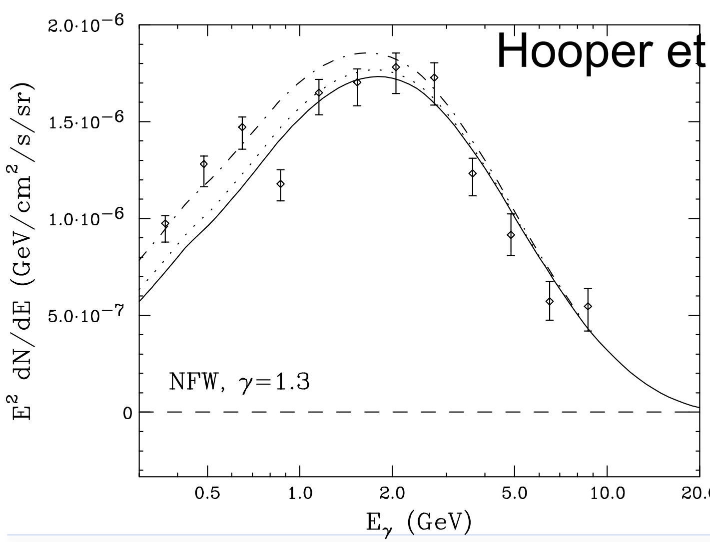
DAMA

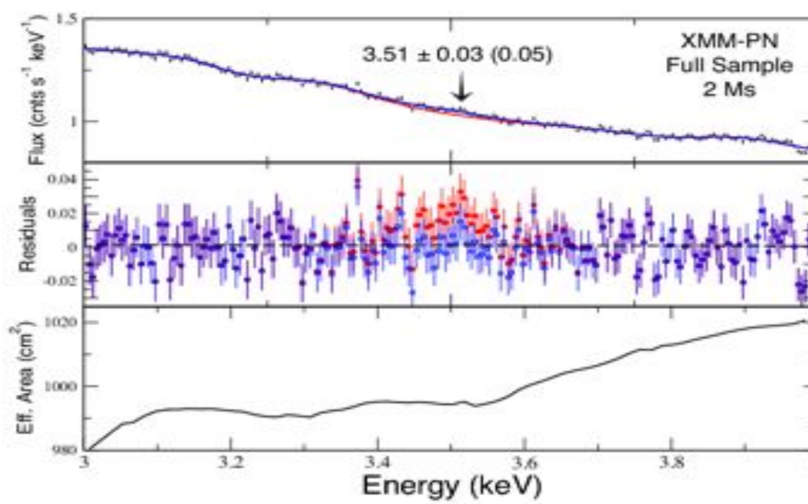




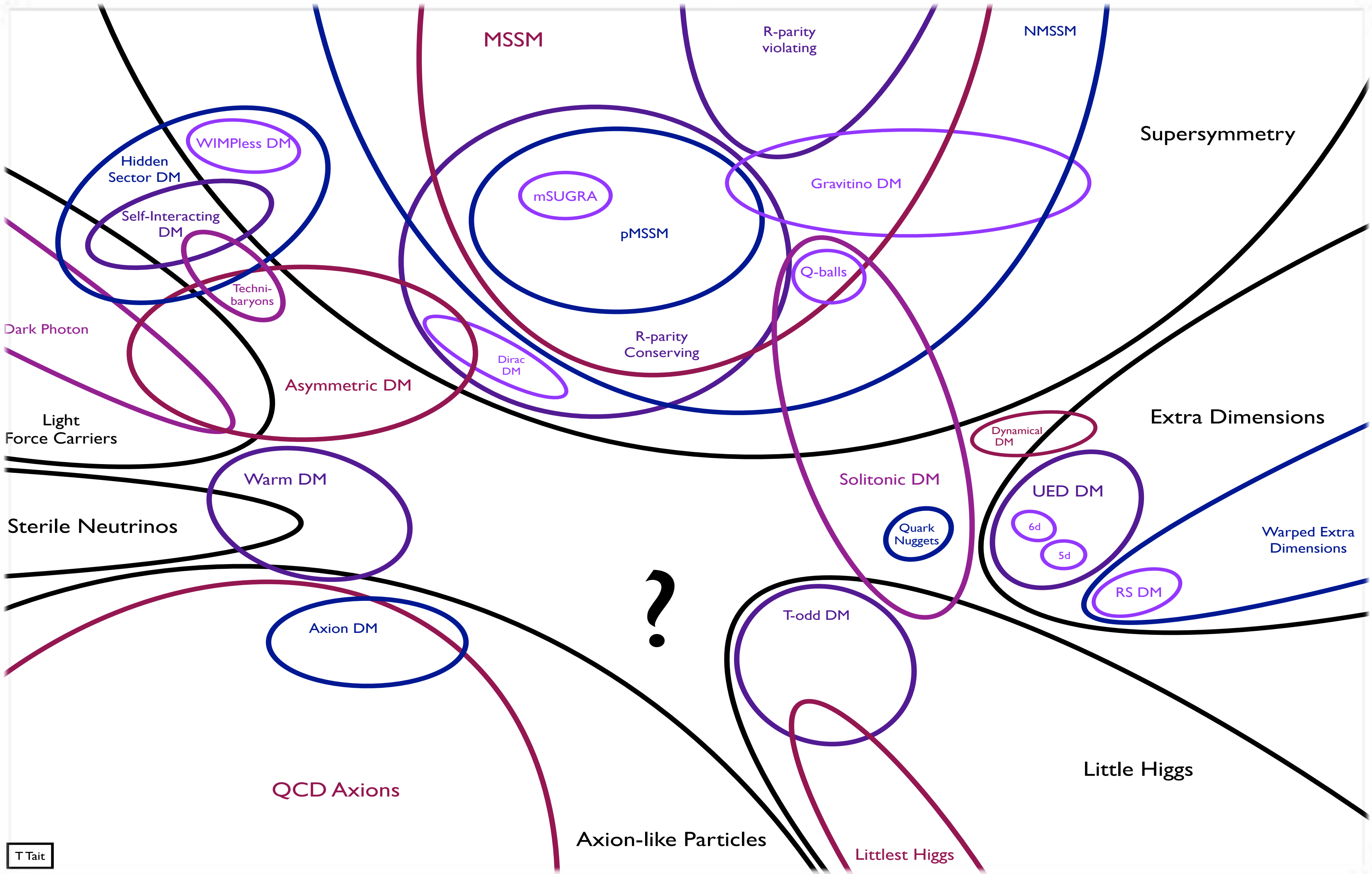
Unidentified line from Bulbul et al.; Boyarsky et al.

Hooper et al





Dark Matter Theories



The WIMP Miracle

- WIMPs have masses O(100 GeV)
- miracle: ~ correct abundance:

1) Assume a new (heavy) particle χ is initially in thermal equilibrium:

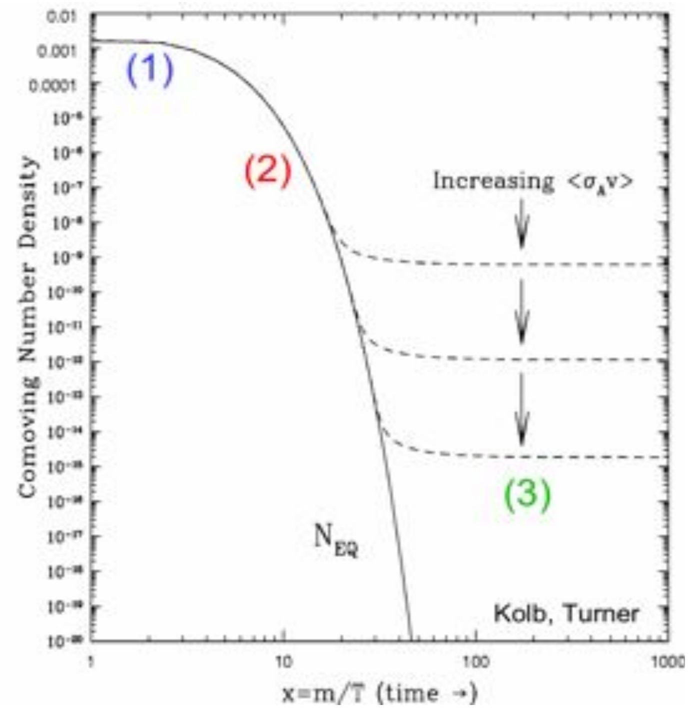
$$\chi\chi \leftrightarrow ff$$

2) Universe cools:

$$\chi\chi \;\substack{\rightarrow \\ \not\leftarrow}\; ff$$

3) "freeze out"

$$\chi\chi \;\substack{\not\rightarrow \\ \not\leftarrow}\; ff$$



- Amount of DM ~ (x-section)$^{-1}$
- Natural x-section ~ 1/m^2
  → abundance fixed by EW scale

→ **remarkable coincidence: Ω_{DM} ~ 0.2 for m_{WIMP} ~ 100-1000 GeV**

→ **BSM AND correct abundance point towards WIMPs**

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_A v\rangle_T \left[(n_\chi)^2 - (n_\chi^{eq})^2\right]$$

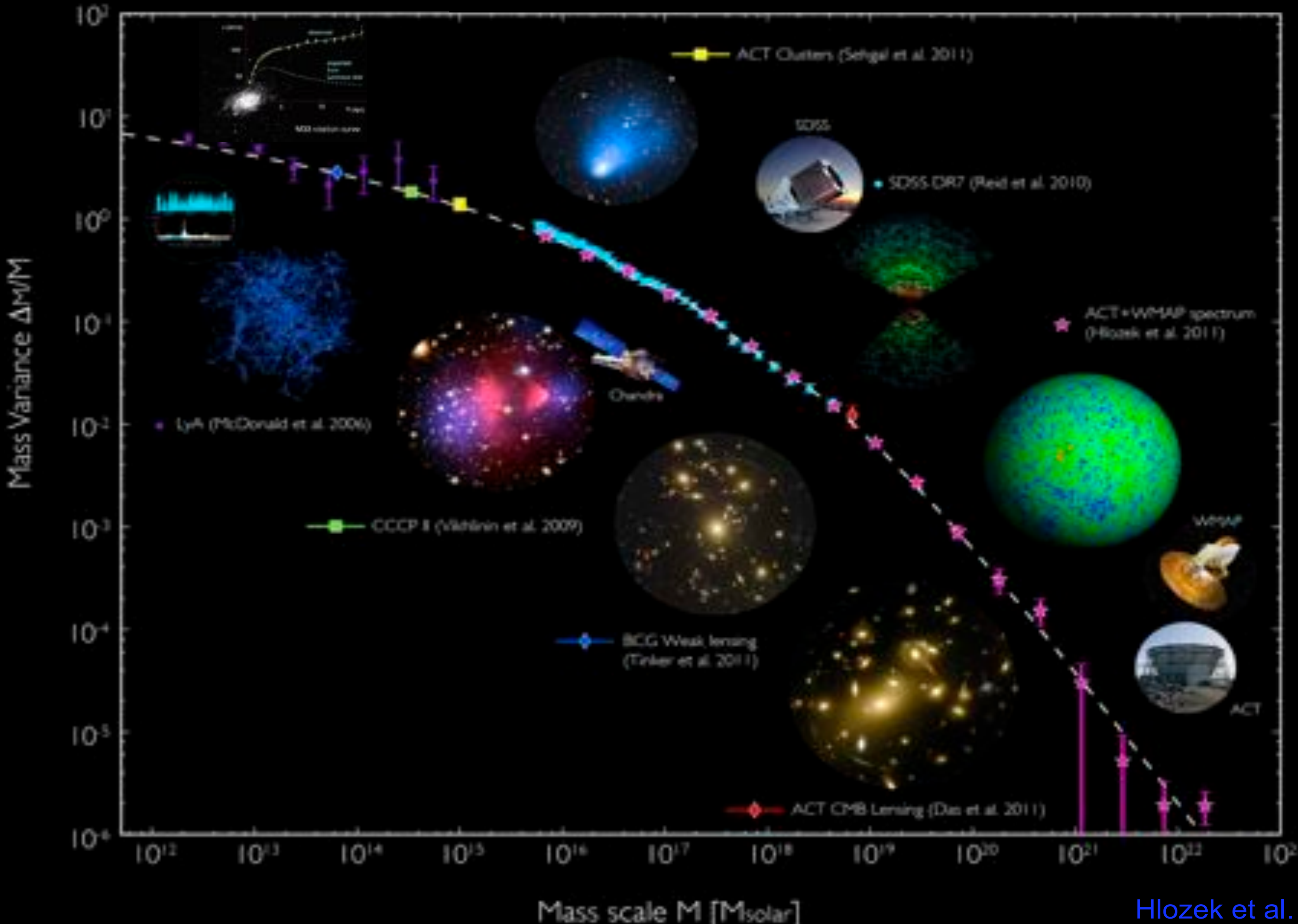
dilution by Universe expansion

thermally averaged annihilation cross section

$P\bar{P} \to \chi\bar{\chi}$

$\chi\bar{\chi} \to P\bar{P}$

ΛCDM: successful at 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

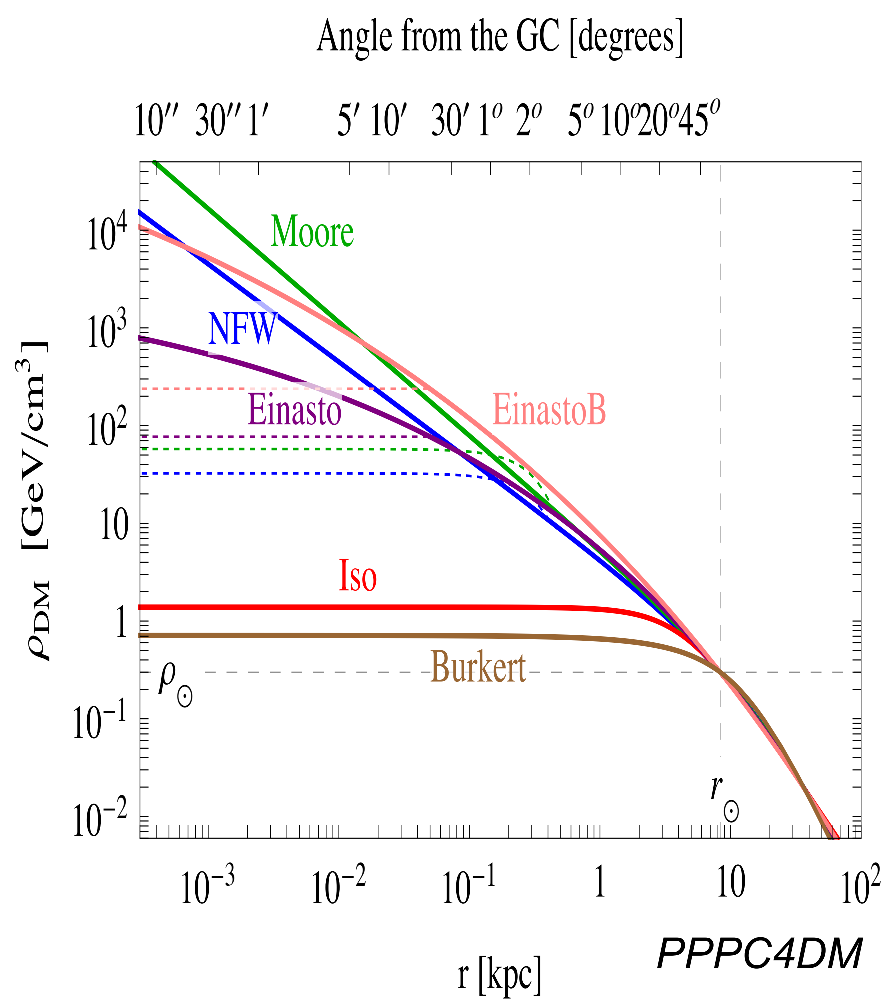
$$\text{NFW}: \quad \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

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

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

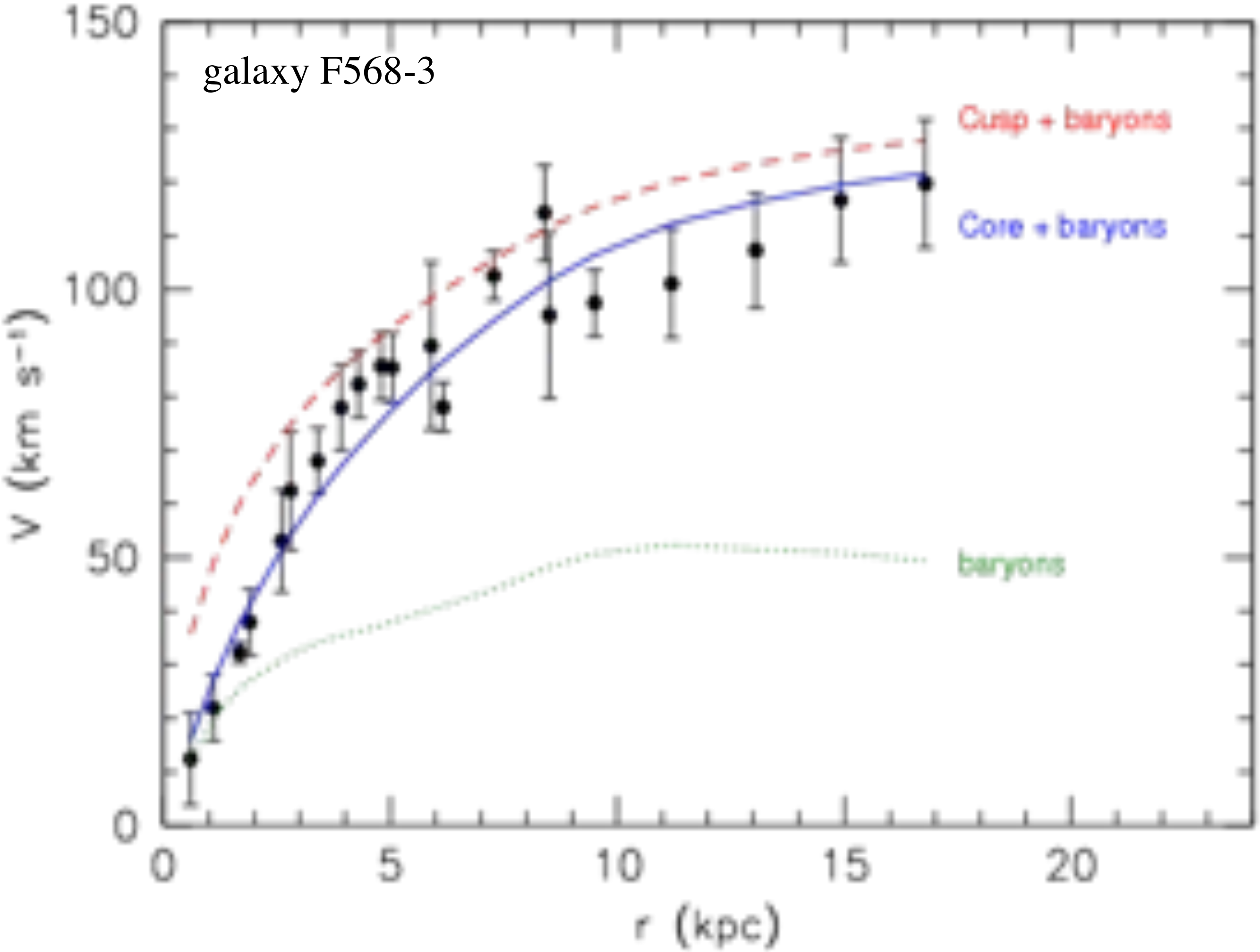
$$\text{Burkert}: \quad \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

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



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

Cusp vs. Core

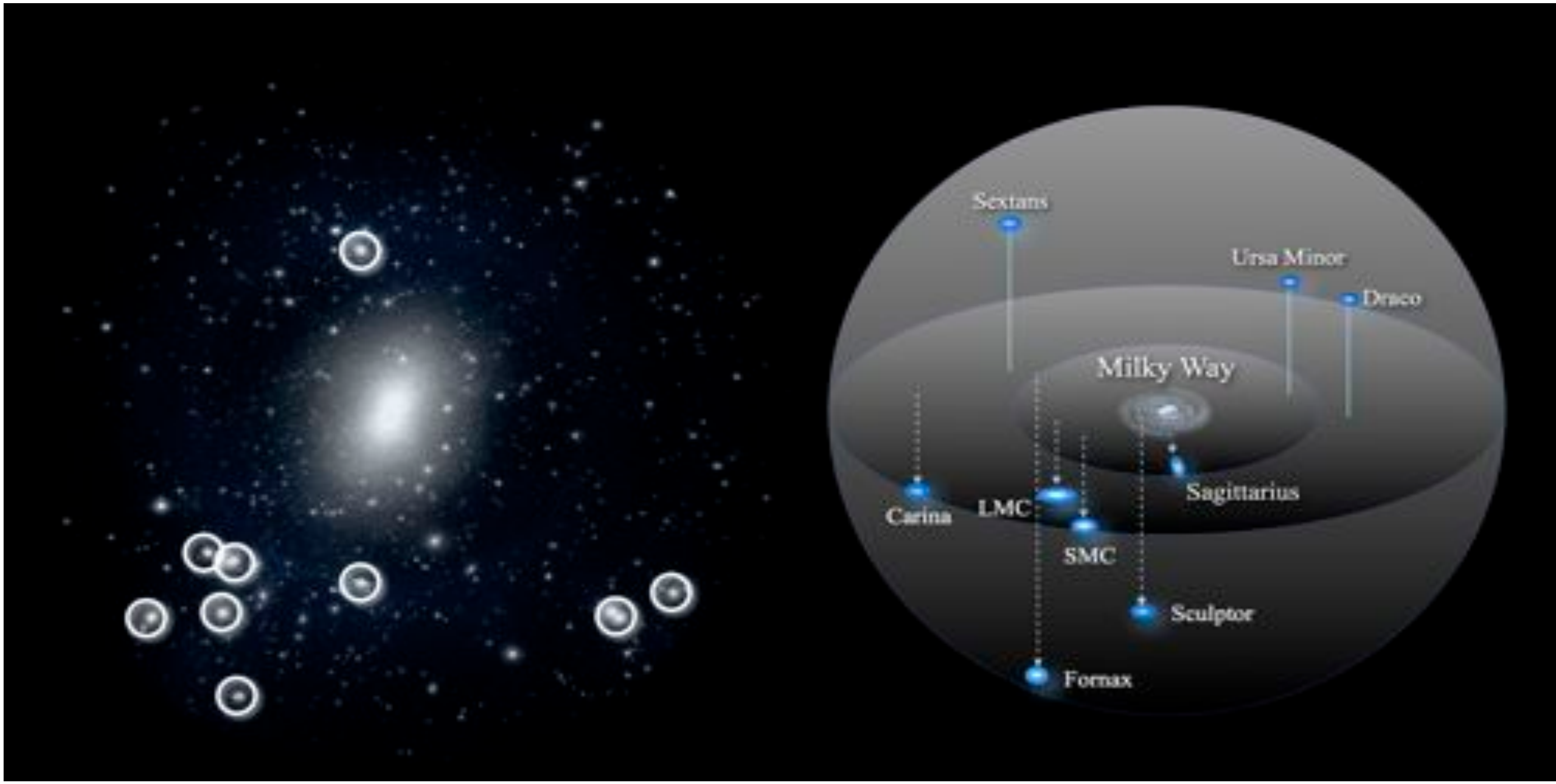


galaxy F568-3
Cusp + baryons
Core + baryons
baryons
V (km s⁻¹)
r (kpc)
150
100
50
0
0
5
10
15
20

“missing satellites” problem

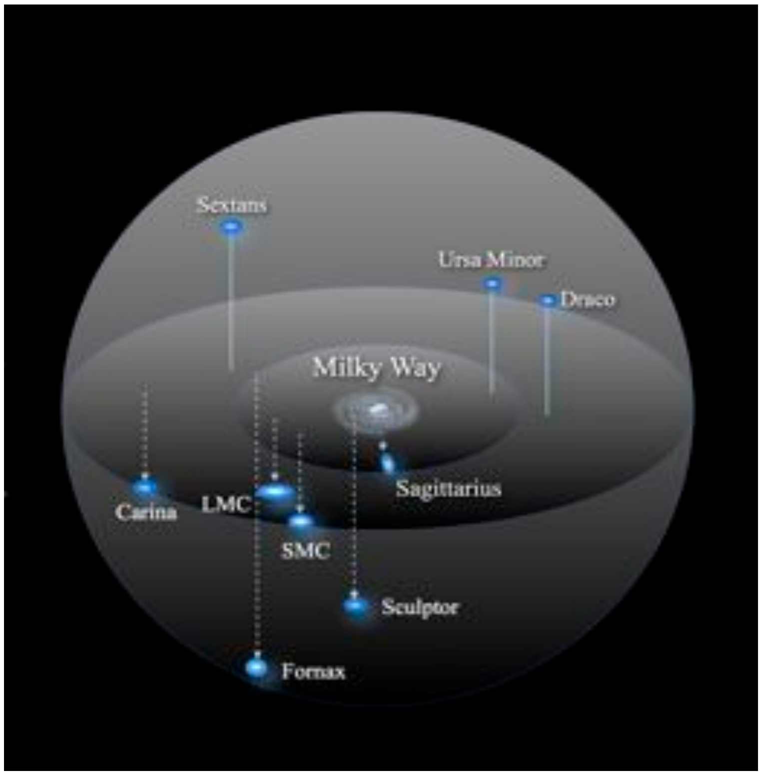
- Projected dark matter distribution of a simulated CDM halo.
- The numerous small subhalos far exceed the number of known Milky Way satellites.
- Circles mark the nine most massive subhalos.

“too-big-to-fail” problem

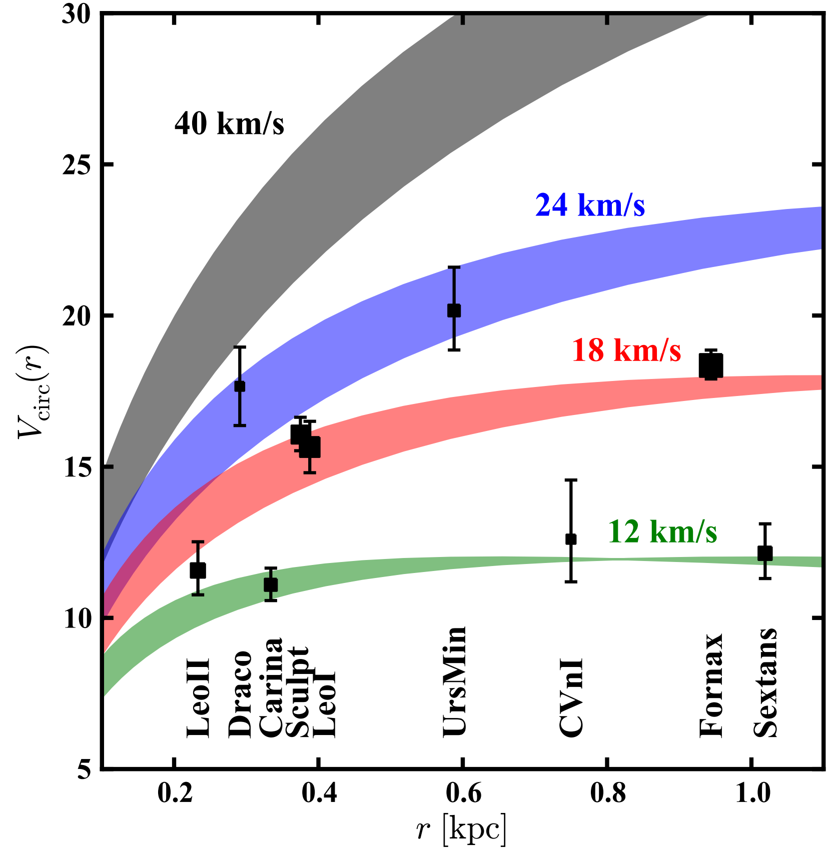


The central densities of the subhalos in the left panel are too high to host the dwarf satellites in the right panel, predicting stellar velocity dispersions higher than observed.

“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

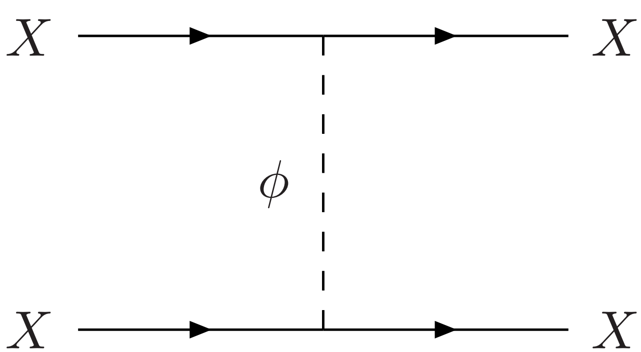
Spergel et al, Sigurdson et al,
Boehm et al, Kaplinghat et al,
Loeb et al, Tulin et al,
van de Aarseen et al,
….

What is SIDM?

- DM-DM scattering cross section is around

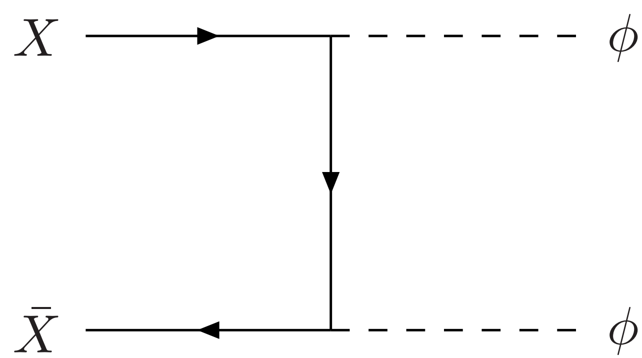
$$\frac{\sigma}{M_X} \sim \mathrm{cm}^2/\mathrm{g} \sim \mathrm{barn}/\mathrm{GeV}$$

- It can still be the usual WIMP



DM self-interactions

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



DM annihilation

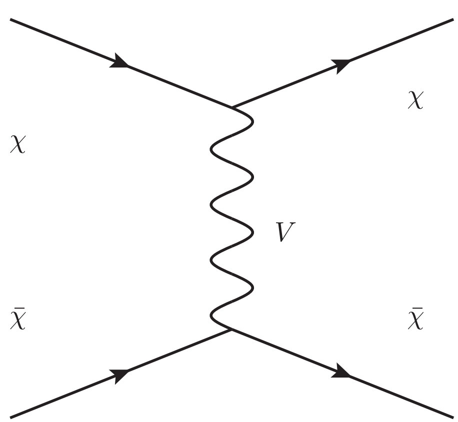
$$\sigma_{\mathrm{ann}} \sim \frac{\alpha^2}{M_X^2}$$

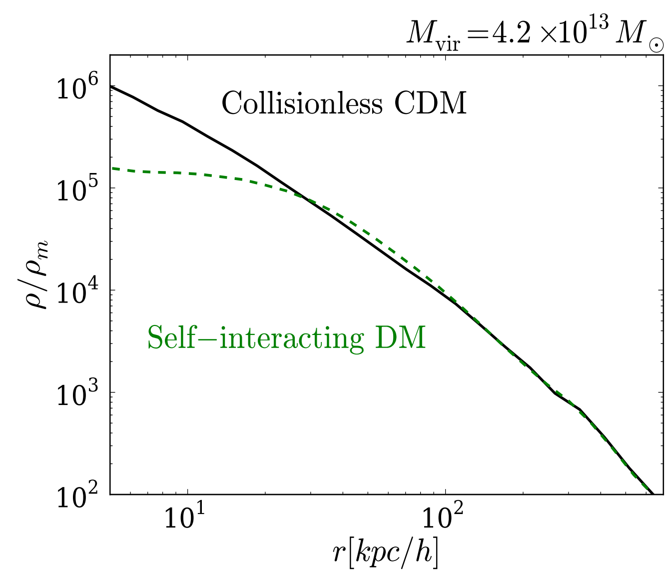
Effects

- 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

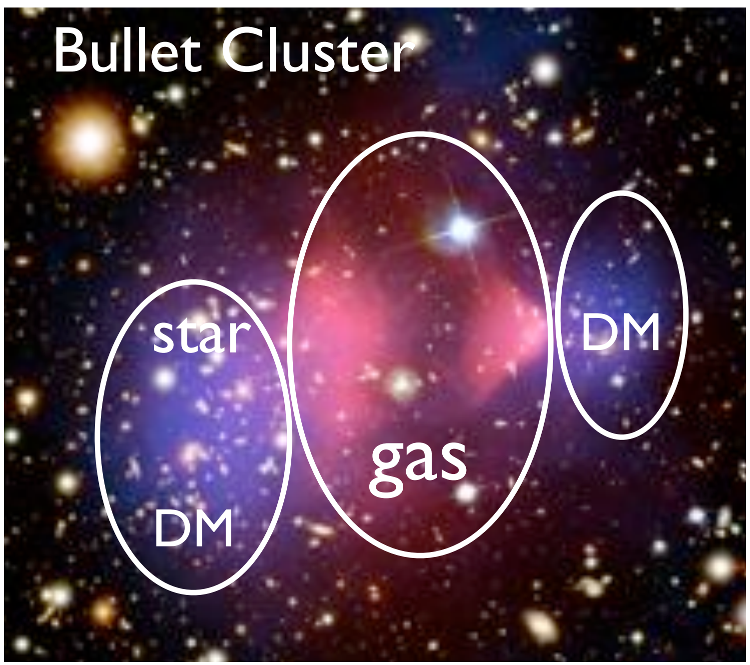


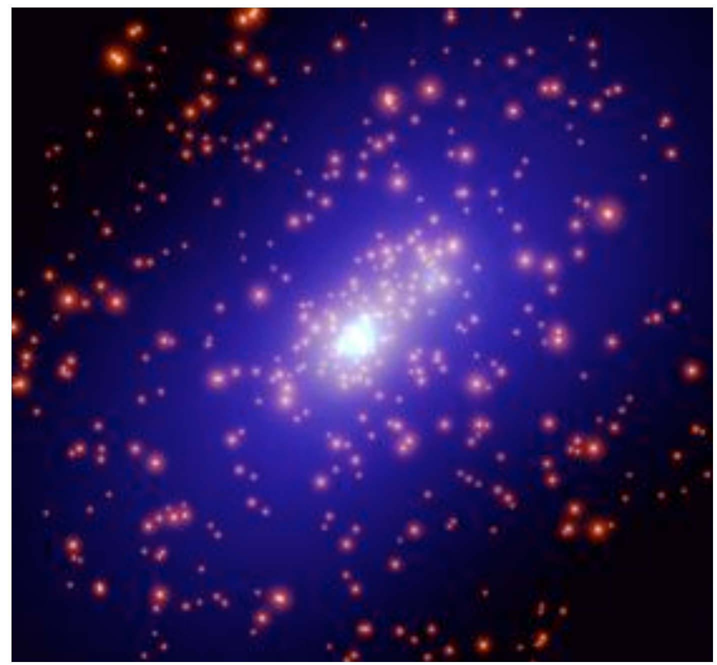


Astrophysical Constraints

- Bullet Cluster, elliptical halo shapes

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





$V \sim 1000 \ {\rm km/s}$ for cluster

$V \sim 200 \ {\rm km/s}$ for galaxies

Velocity dependence

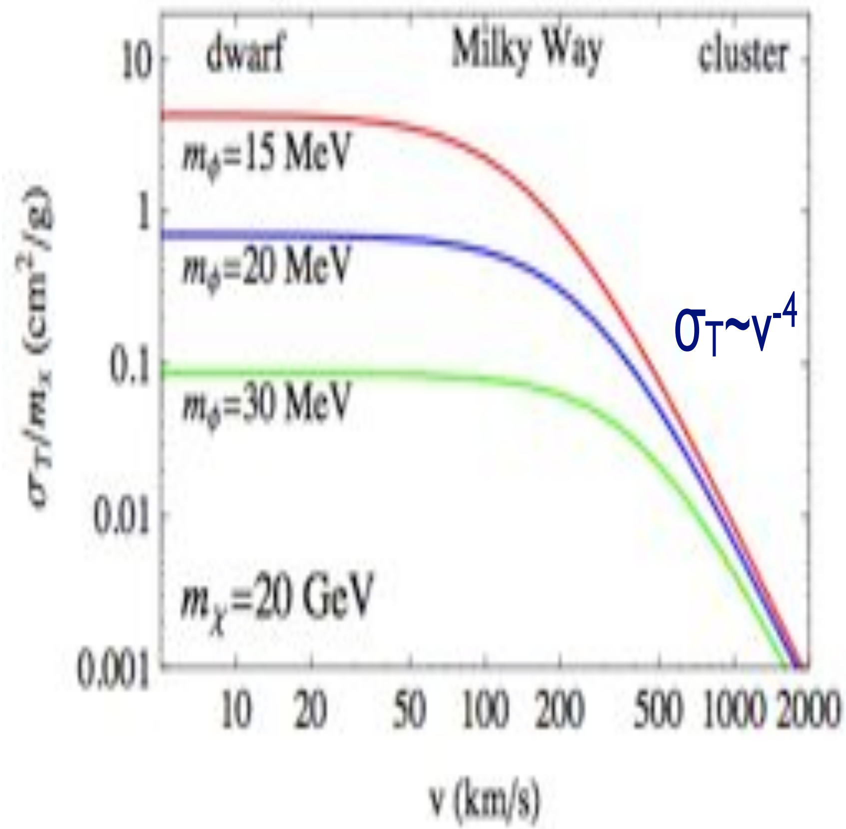
In the Born limit ($\alpha_X m_X/m_\phi \ll 1$),

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

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



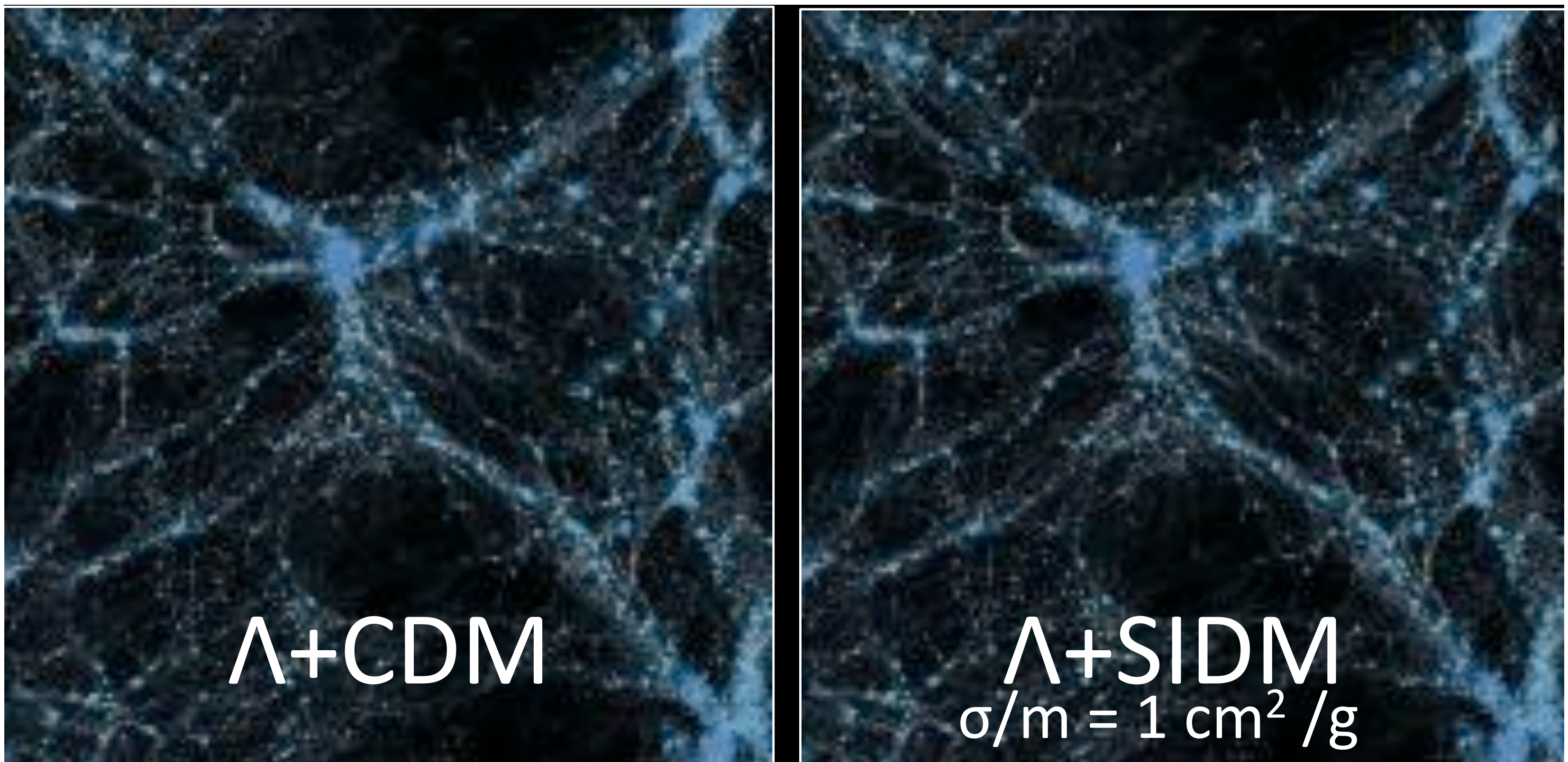
Feng et al, Buckley & Fox, Leob & Weiner, Tulin & Yu et al,…, Ko&Tang

- For scalar dark matter and scalar mediator

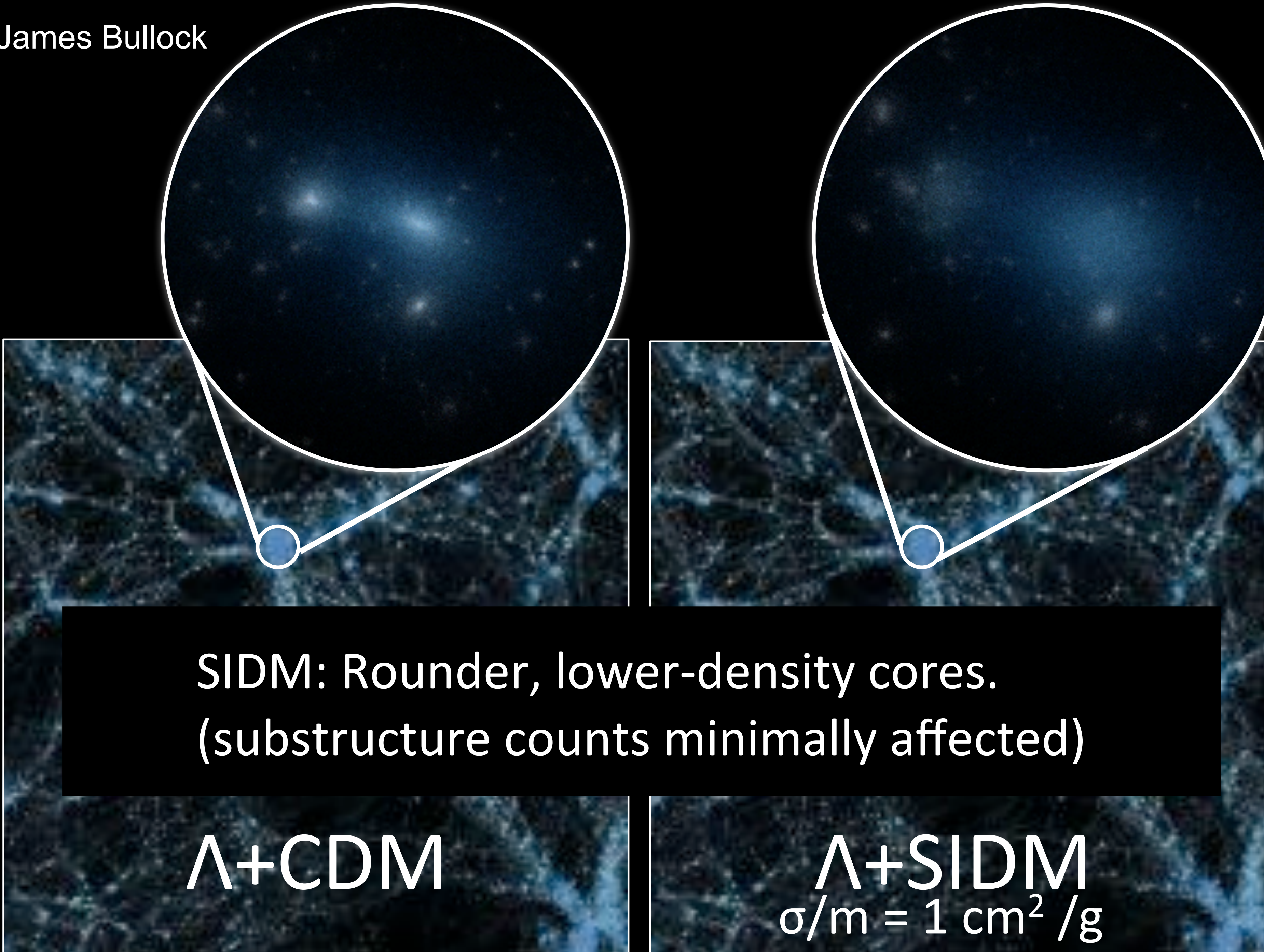
$$\alpha_\phi \equiv \frac{\lambda_{\phi X}^2}{4\pi}\left(\frac{v_\phi}{2M_X}\right)^2 \text{ and } \beta \equiv \frac{2\alpha_\phi M_{H_2}}{M_X v_{\rm rel}^2}.$$

Identical LSS

James Bullock



James Bullock



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

Global Symmetry

Longevity protected by symmetry, $Z_2, \phi \to -\phi$

$$\mathcal{L} = \frac{1}{2}\partial^\mu \phi \partial_\mu \phi - \frac{1}{2} m^2 \phi^2 - \lambda \phi^4 - \lambda_{\phi H} \phi^2 H^\dagger H + \mathcal{L}_{\rm SM}$$

There are some reasons to expect that global symmetries are not respected by non-perturbative quantum gravity.

Global charges can be absorbed by black holes which then evaporate, *R.Kallosh, A.Linde, D.Linde and L.Susskind, hep-th/9502069*

There is no global symmetry in string theory, symmetry must be gauged, *Banks & Seiberg, arXiv:1011.5120*

$$\delta \mathcal{L}_{\rm eff} = \frac{g}{M_{\rm pl}} \phi \mathcal{O}_{\rm SM}, \ \mathcal{O}_{\rm SM} = F_{\mu\nu} F^{\mu\nu}, \ \bar{f} \gamma \cdot D f, \ \bar{f}_L f_R H, ...$$

$$\tau \sim \frac{1}{g^2} \left(\frac{1 \mathrm{TeV}}{M_\phi} \right)^3 \times 10^4 \mathrm{s}$$

Discrete symmetry from gauge symmetry

An extra U(1)x *gauge symmetry* is introduced, with scalar DM X and dark higgs with charges 1 and 3, respectively.

P, Ko, YT, arXiv:1402.6449(JCAP)

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon \tilde{X}_{\mu\nu}\tilde{B}^{\mu\nu} + D_\mu \phi_X^\dagger D^\mu \phi_X + D_\mu X^\dagger D^\mu X - V$$

$$V = -\mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 - \mu_\phi^2 \phi_X^\dagger \phi_X + \lambda_\phi \left(\phi_X^\dagger \phi_X\right)^2 + \mu_X^2 X^\dagger X + \lambda_X \left(X^\dagger X\right)^2$$

$$+ \lambda_{\phi H} \phi_X^\dagger \phi_X H^\dagger H + \lambda_{\phi X} X^\dagger X \phi_X^\dagger \phi_X + \lambda_{HX} X^\dagger X H^\dagger H + \boxed{\left(\lambda_3 X^3 \phi_X^\dagger + H.c.\right)}$$

$$X \to e^{i\frac{2\pi}{3}} X$$

$\boxed{\text{Z}_3 \text{ symmetry}}$

$$X^\dagger \to e^{-i\frac{2\pi}{3}} X^\dagger$$

$$X^3 + X^{\dagger 3}$$

Limits

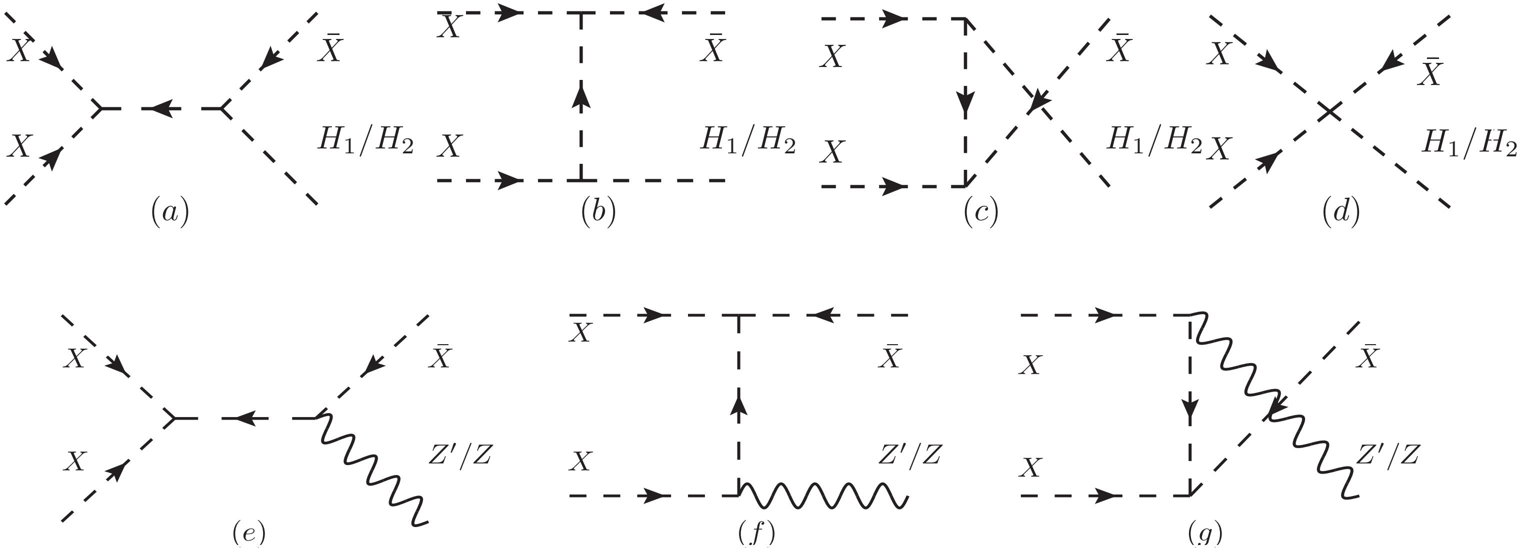
- If the masses of dark gauge boson and dark higgs are much heavier, we have effective theory, global Z3,

$$
\begin{aligned}
\mathcal{L} =& \mathcal{L}_{\mathrm{SM}} + \partial_\mu X^\dagger \partial^\mu X - V \\
V =& \mu_X^2 X^\dagger X + \lambda_X \left(X^\dagger X\right)^2 + \lambda_{HX} X^\dagger X H^\dagger H + (\mu_3 X^3 + h.c)
\end{aligned}
$$

- If the cubic term vanishes, further simplified

$$
\begin{aligned}
\mathcal{L} =& \mathcal{L}_{\mathrm{SM}} + \partial_\mu X^\dagger \partial^\mu X - V \\
V =& \mu_X^2 X^\dagger X + \lambda_X \left(X^\dagger X\right)^2 + \lambda_{HX} X^\dagger X H^\dagger H
\end{aligned}
$$

Semi-annihilation

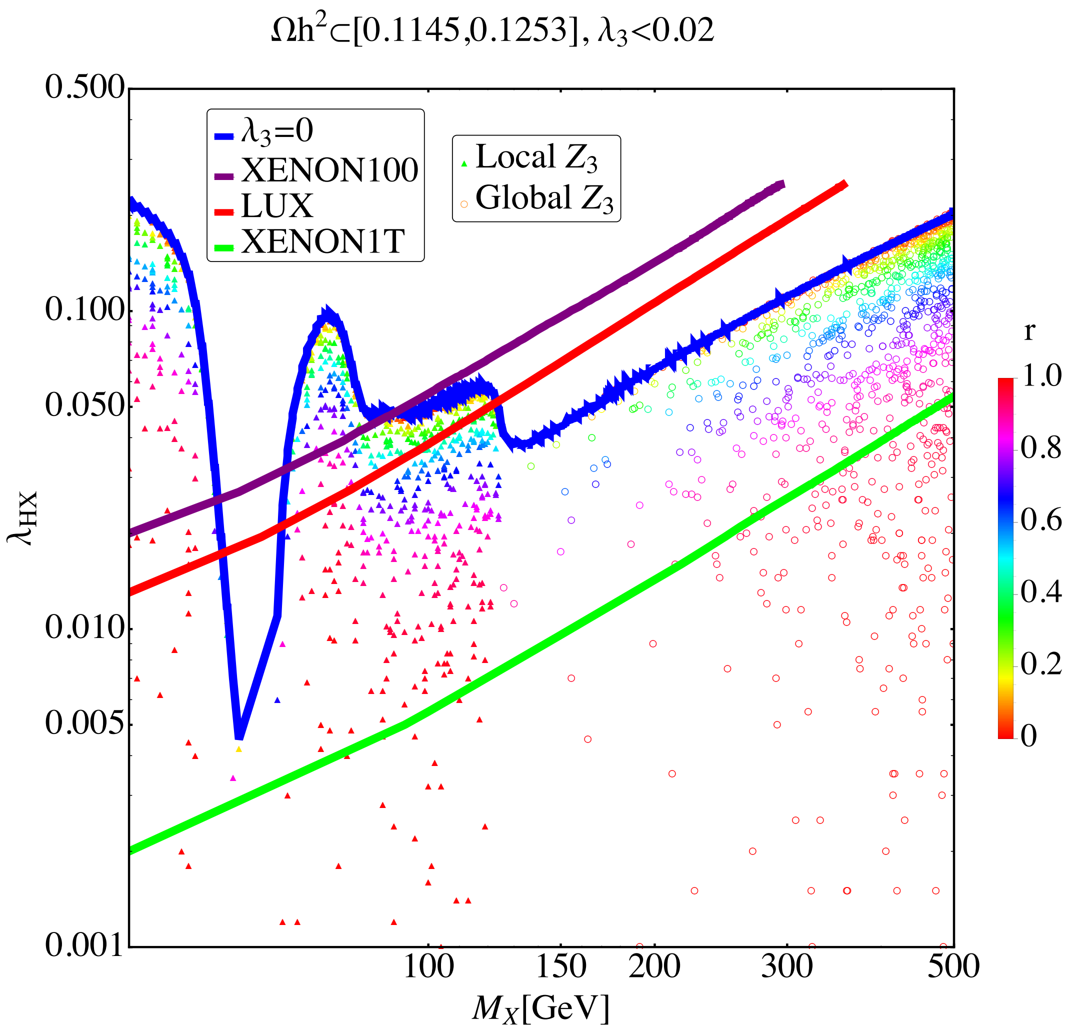


$$\frac{dn_X}{dt} = -v\sigma^{XX^*\to YY}\left(n_X^2 - n_{X\,\mathrm{eq}}^2\right) - \frac{1}{2}v\sigma^{XX\to X^*Y}\left(n_X^2 - n_X n_{X\,\mathrm{eq}}\right) - 3Hn_X,$$

$$r \equiv \frac{1}{2}\frac{v\sigma^{XX\to X^*Y}}{v\sigma^{XX^*\to YY} + \frac{1}{2}v\sigma^{XX\to X^*Y}}.$$

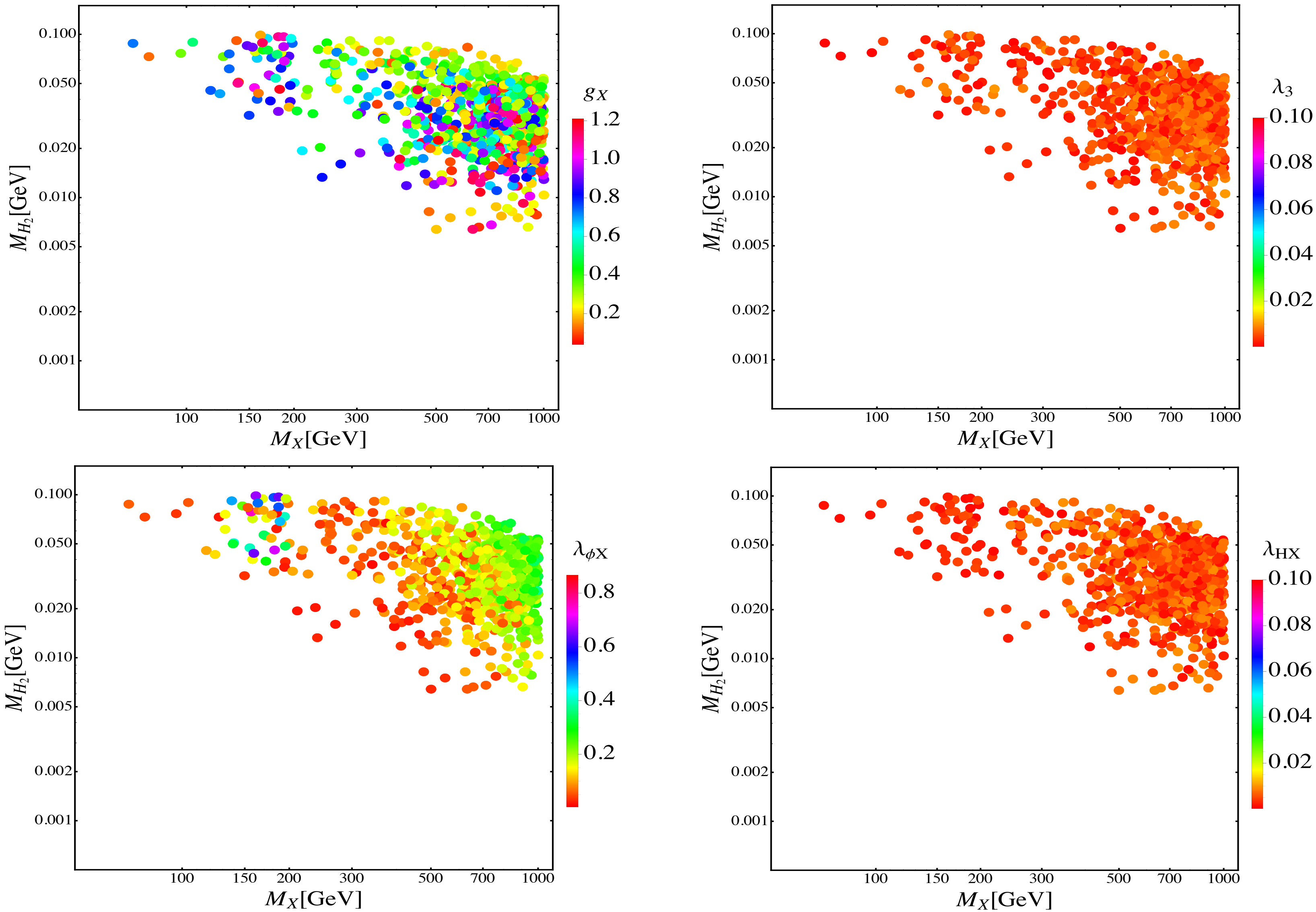
$\boxed{\text{micrOMEGAs}}$

Relic density and Direct Search



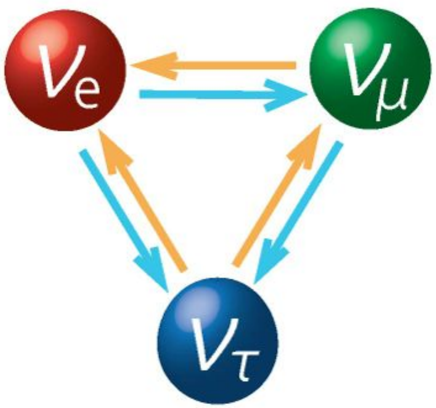
- Blue band marks the upper bound, $\lambda_{HX} X^\dagger X H^\dagger H$
- All points are allowed in our local Z3 model, 1402.6449
- only circles are allowed in global Z3 model,1211.1014

Parameters for SIDM



Sterile Neutrinos

Neutrinos in SM



For 2-flavor mixing,

$$|\nu_\alpha\rangle = \cos\theta \; |\nu_1\rangle + \sin\theta \; |\nu_2\rangle,$$

$$|\nu_\beta\rangle = -\sin\theta \; |\nu_1\rangle + \cos\theta \; |\nu_2\rangle,$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2}{4E} L \right).$$

- Neutrinos in SM are massless, no mixing and oscillation
- One can extend SM with sterile right-handed neutrinos to give mass. But their masses are not known.
- Sterile neutrinos do not have SM interactions, but can mix with active neutrinos.

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, $N_{\rm eff}$,
- eV sterile neutrinos as hot dark matter, BBN, CMB, LSS

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

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

Constraints on sterile neutrino mass

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

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 $V_{\rm eff}$

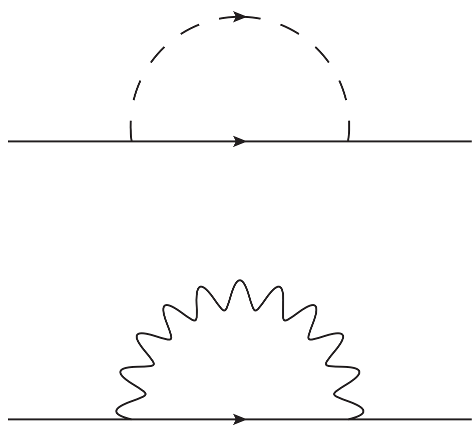
MSW effect, Akhmedov, hep-ph/0001264

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

Hannestad et al, *1310.5926*, Dasgupta&Kopp *1310.6337*,

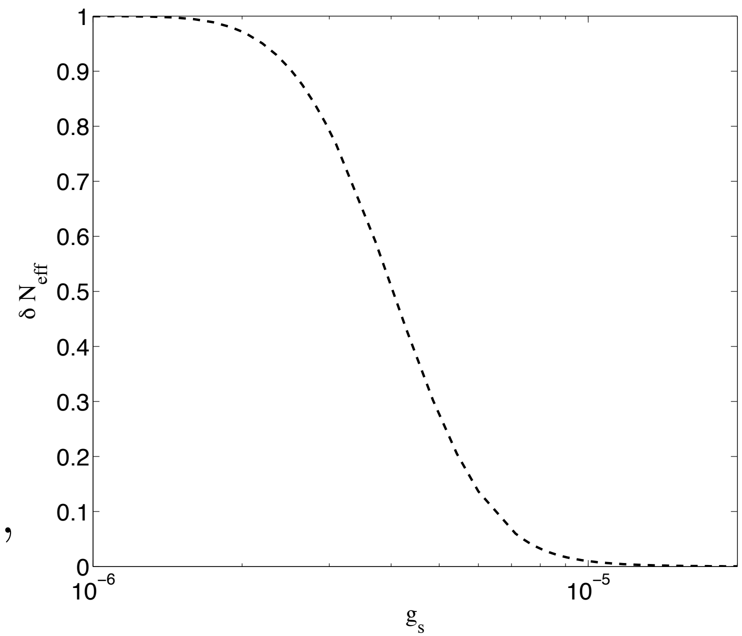
Interacting Sterile Neutrinos

- Partial thermalization at BBN



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

Archidiacono et al, 1404.5915



- T*he new interaction could lead to fla*vor equilibrium after BBN, A. Mirizzi *et al*, *1410.1385, inconsistent with cosmological neutrino mass bounds*

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

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

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

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

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

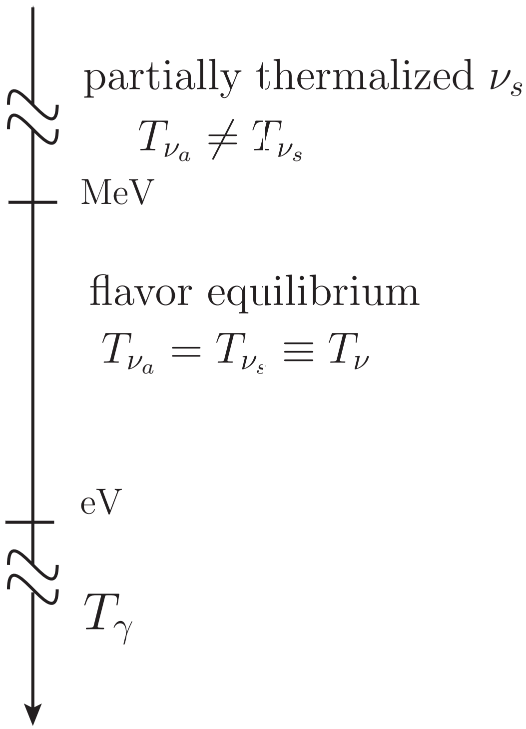
$$\dot{P}_x = -V_z P_y - D P_x,$$

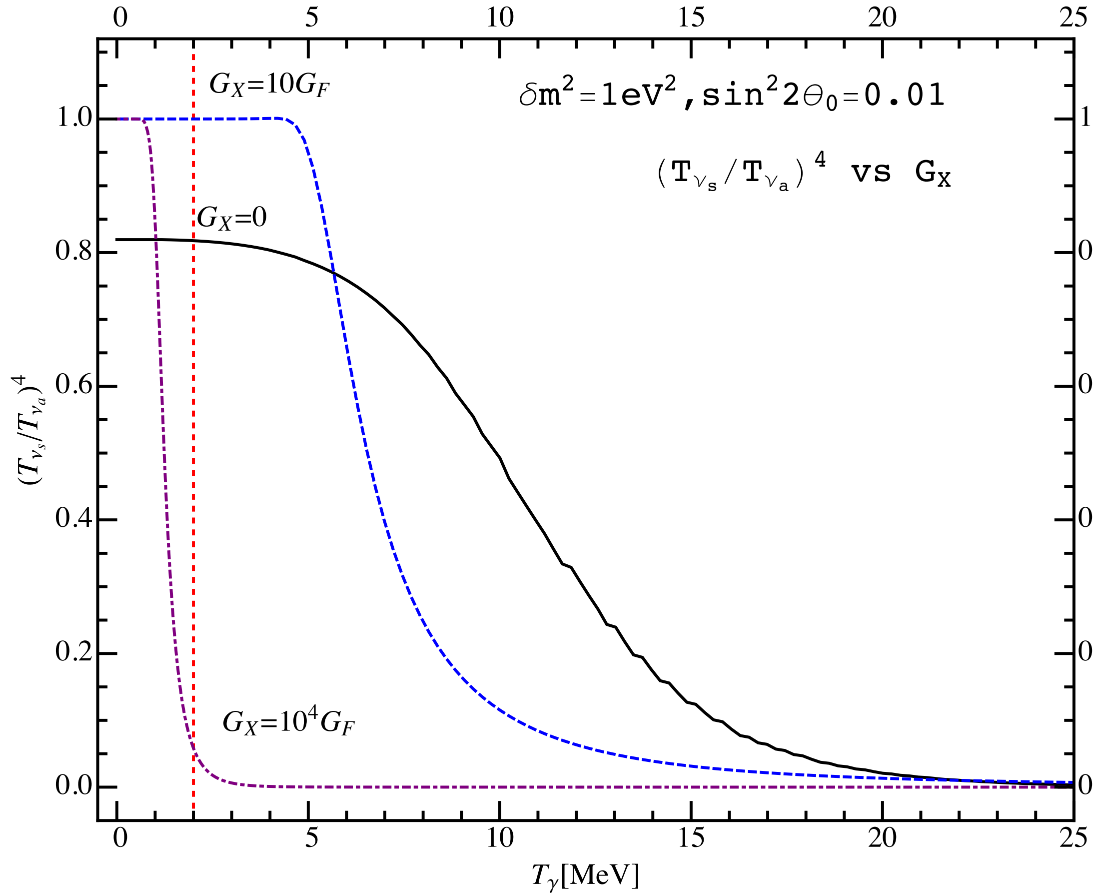
$$\dot{P}_y = V_z P_x - \frac{1}{2} V_x (P_a - P_s) - D P_y. \qquad D \simeq \frac{1}{2} (\Gamma_a + \Gamma_s)$$

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

Flavor Equilibrium after BBN

YT, arXiv:1501.00059





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

Excluded 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:

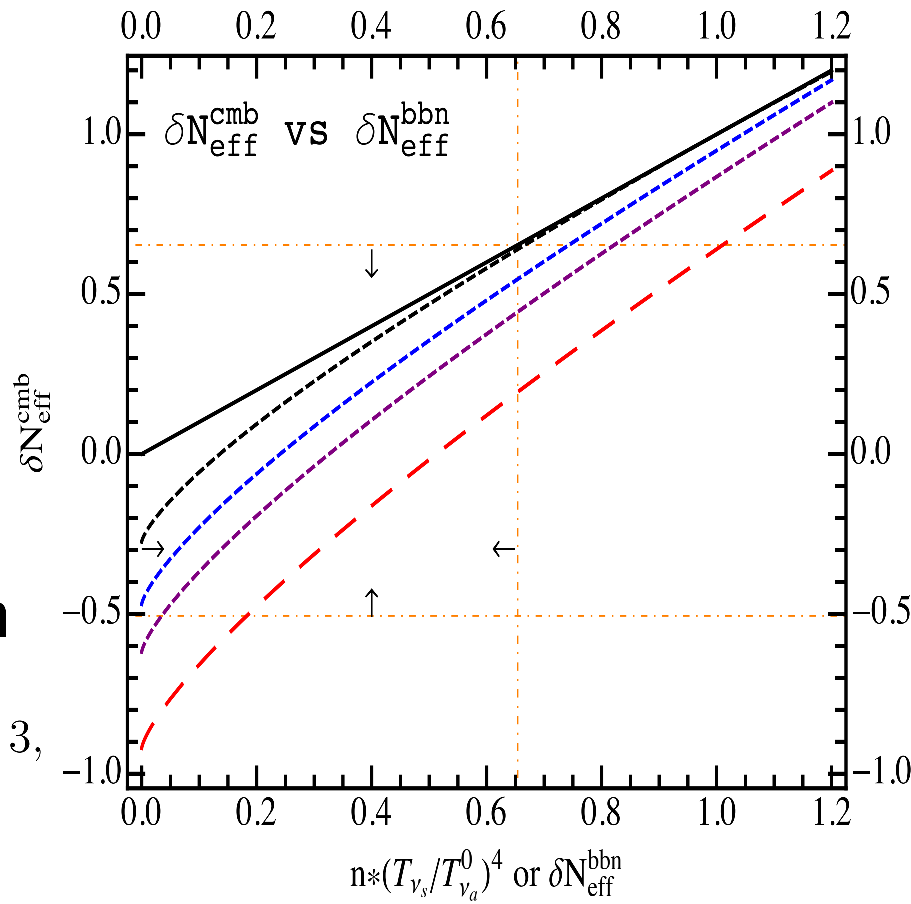
number density is conserved

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

Assume Fermi-Dirac Distribution

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

YT, arXiv:1501.00059



Neff can be even reduced.

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

Cosmological Mass bound

Planck2015

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

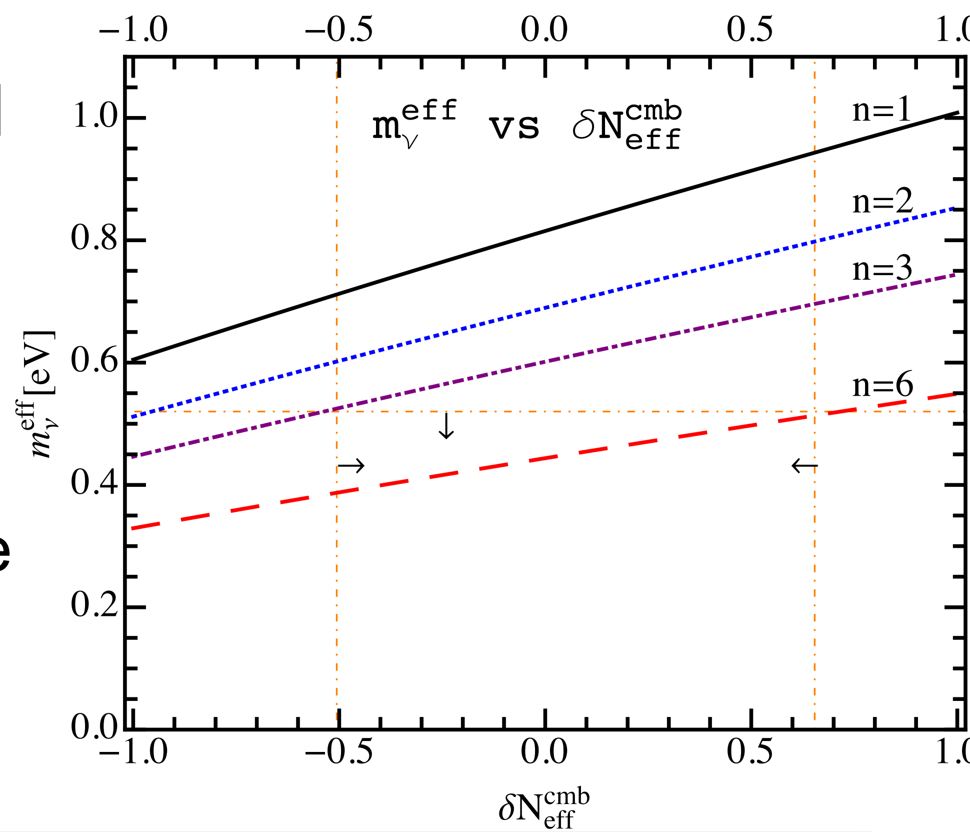
$$m_\nu^{\text{eff}} \equiv \frac{\sum_i n_{\nu_i} m_{\nu_i}}{n^0_{\nu_a}} = \sum_i \left(\frac{T_{\nu_i}}{T^0_{\nu_a}}\right)^3 m_{\nu_i} \simeq 94.1\text{eV} \times \Omega_\nu h^2,$$

YT, arXiv:1501.00059

Assuming one ~ eV, and all others are light

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

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



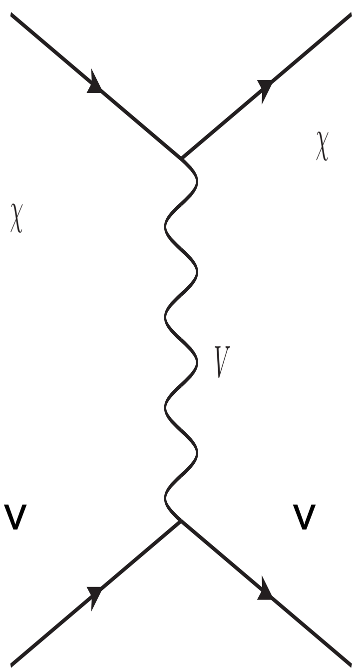
related works

- 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]

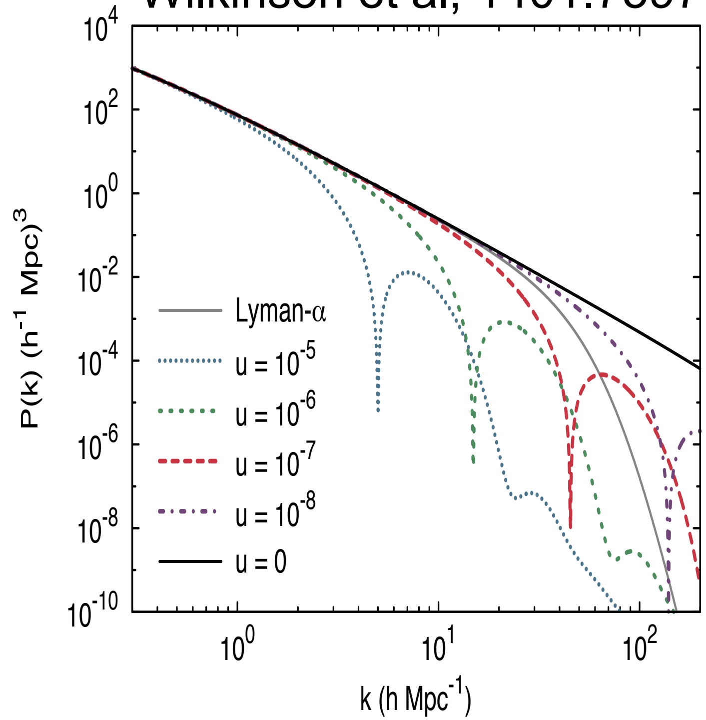
Connection with DM

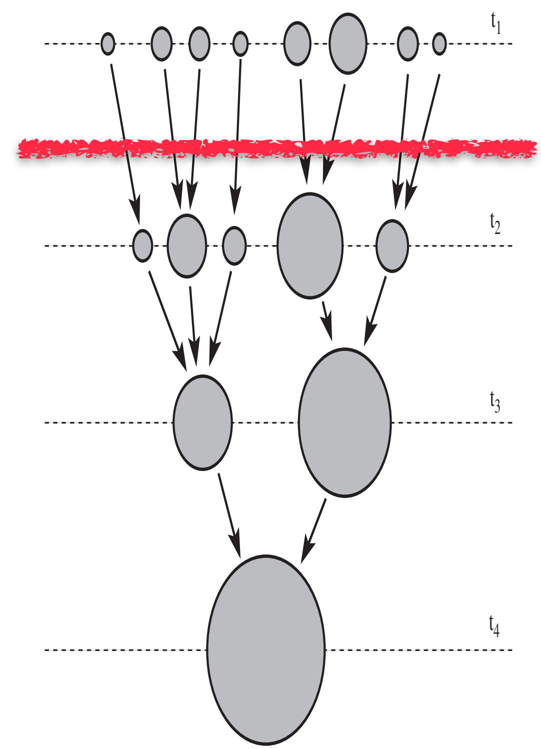
Aarssen, Bringmann and Pfrommer, 1205.5809(PRL)

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

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

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

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

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

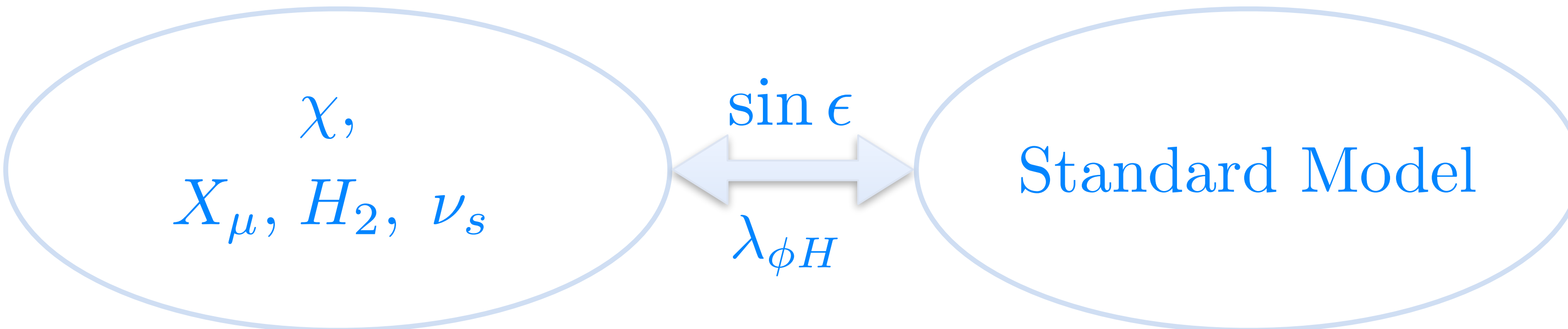
Physical Spectrum

- Neutrino Mixing

$$\begin{pmatrix} \nu_\alpha \\ N_i^c \\ \psi_L \\ \psi_L^c \end{pmatrix} = U \begin{pmatrix} \nu_a \\ \nu_{s4} \\ \vdots \\ \nu_{s7} \end{pmatrix}_L, \ \mathbb{M} = \begin{pmatrix} 0_{3\times3} & \frac{v}{\sqrt{2}}[y_{\alpha i}]_{3\times2} & 0_{3\times2} \\ \frac{v}{\sqrt{2}}[y_{\alpha i}]^T_{2\times3} & \left[m^R_{ij}\right]_{2\times2} & \frac{v_\phi}{\sqrt{2}}(f_i\ g_i)_{2\times2} \\ 0_{2\times3} & \frac{v_\phi}{\sqrt{2}}(f_i\ g_i)^T_{2\times2} & \begin{pmatrix} 0 & m_\phi \\ m_\phi & 0 \end{pmatrix} \end{pmatrix}.$$

- 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 due to the new interaction.

velocity dependent σ

DM self-scattering is the transfer cross section

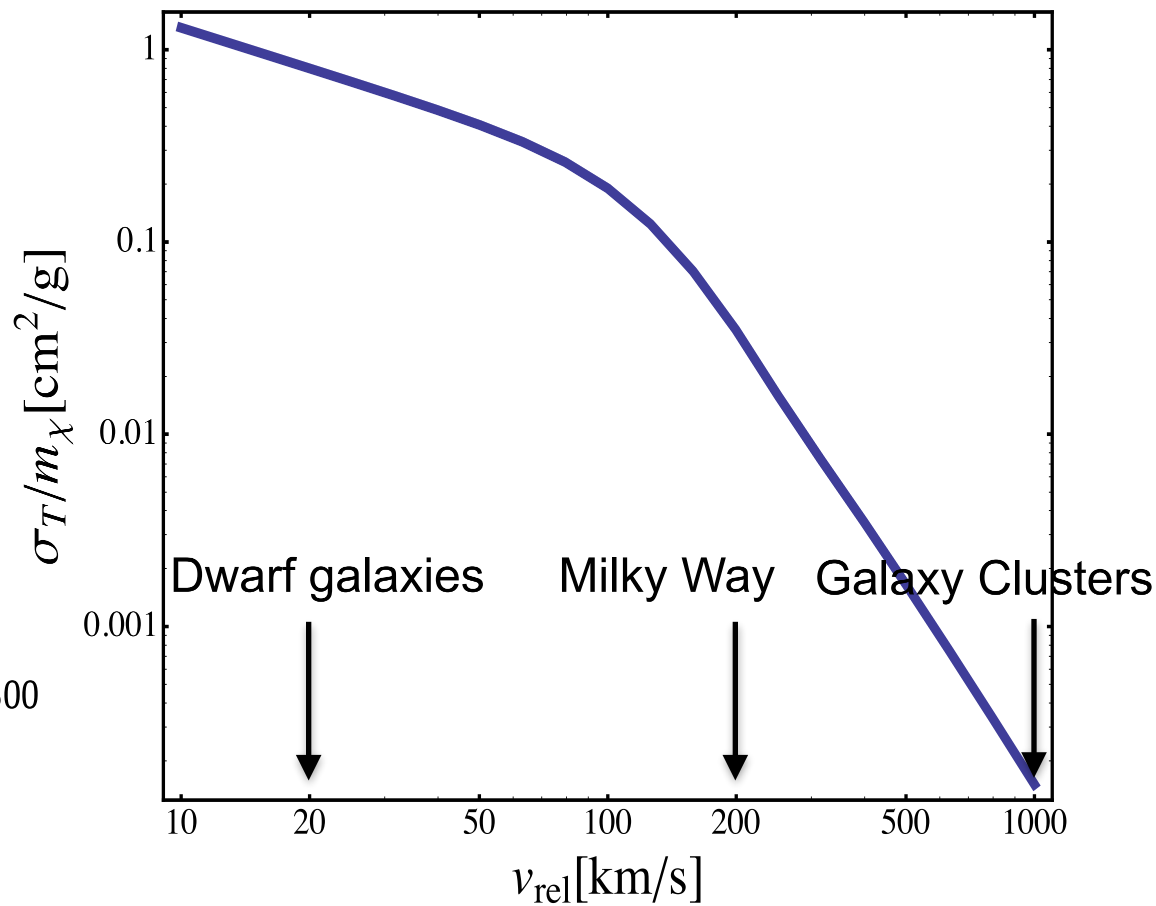
$$\sigma_T \equiv \int d\Omega (1-\cos\theta)\frac{d\sigma}{d\Omega}.$$

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

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

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

m_χ=1TeV, m_X=4MeV, g_X=0.5



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

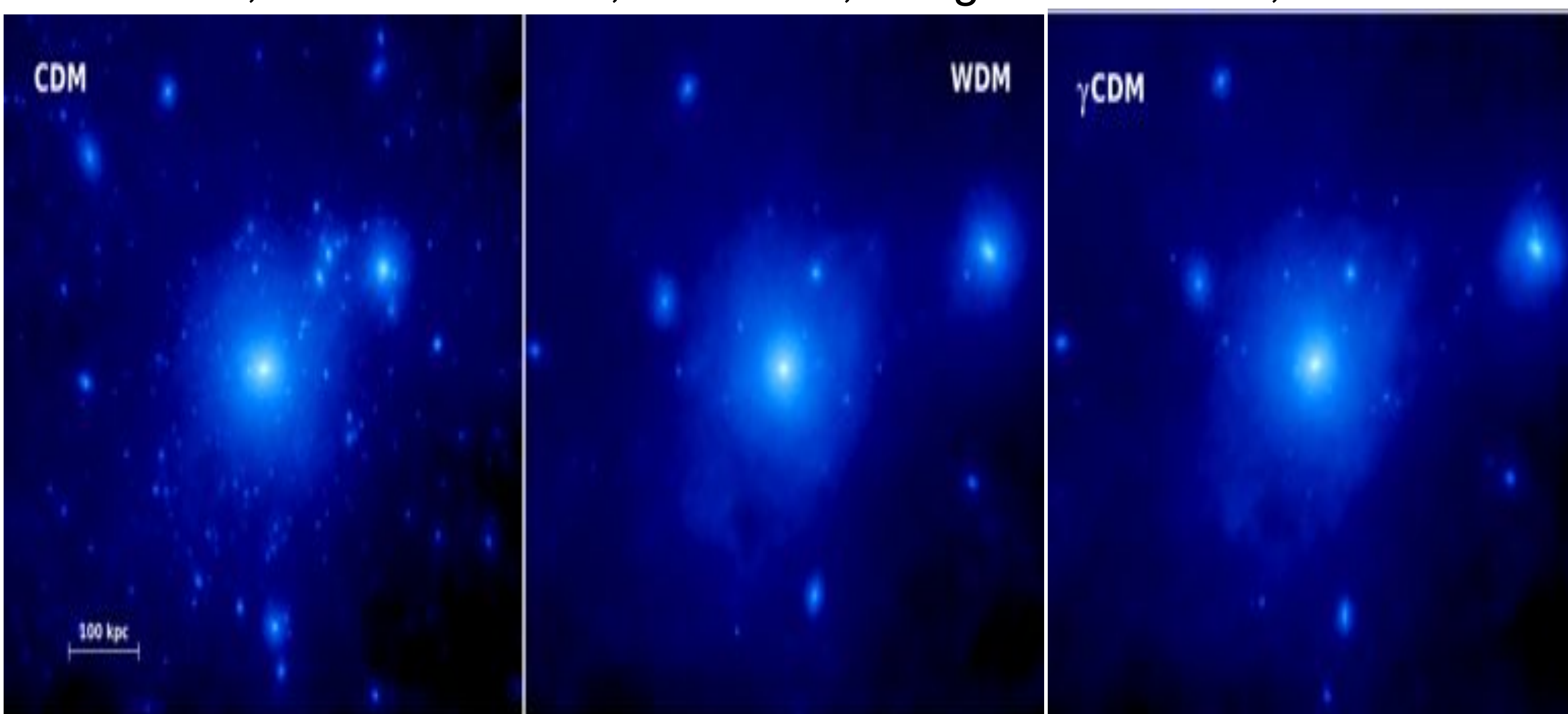
$$M_{\rm cut} = \frac{4\pi}{3}\rho_{\rm M}\left(c\tau_{\rm kd}\right)^3 \sim 2\times 10^8\left(\frac{T_\chi^{\rm kd}}{\rm keV}\right)^{-3} M_\odot,$$

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 *$\nu\Lambda$MDM* based on an extra U(1) gauge symmetry that connects sterile neutrinos and DM.

Thanks for your attention.