Self-Interacting Dark Matter with Local U(1) Symmetry

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P.Ko, YT, arXiv:1404.0236,1402.6449

Outline

- Introduction

  Cold dark matter controversies,

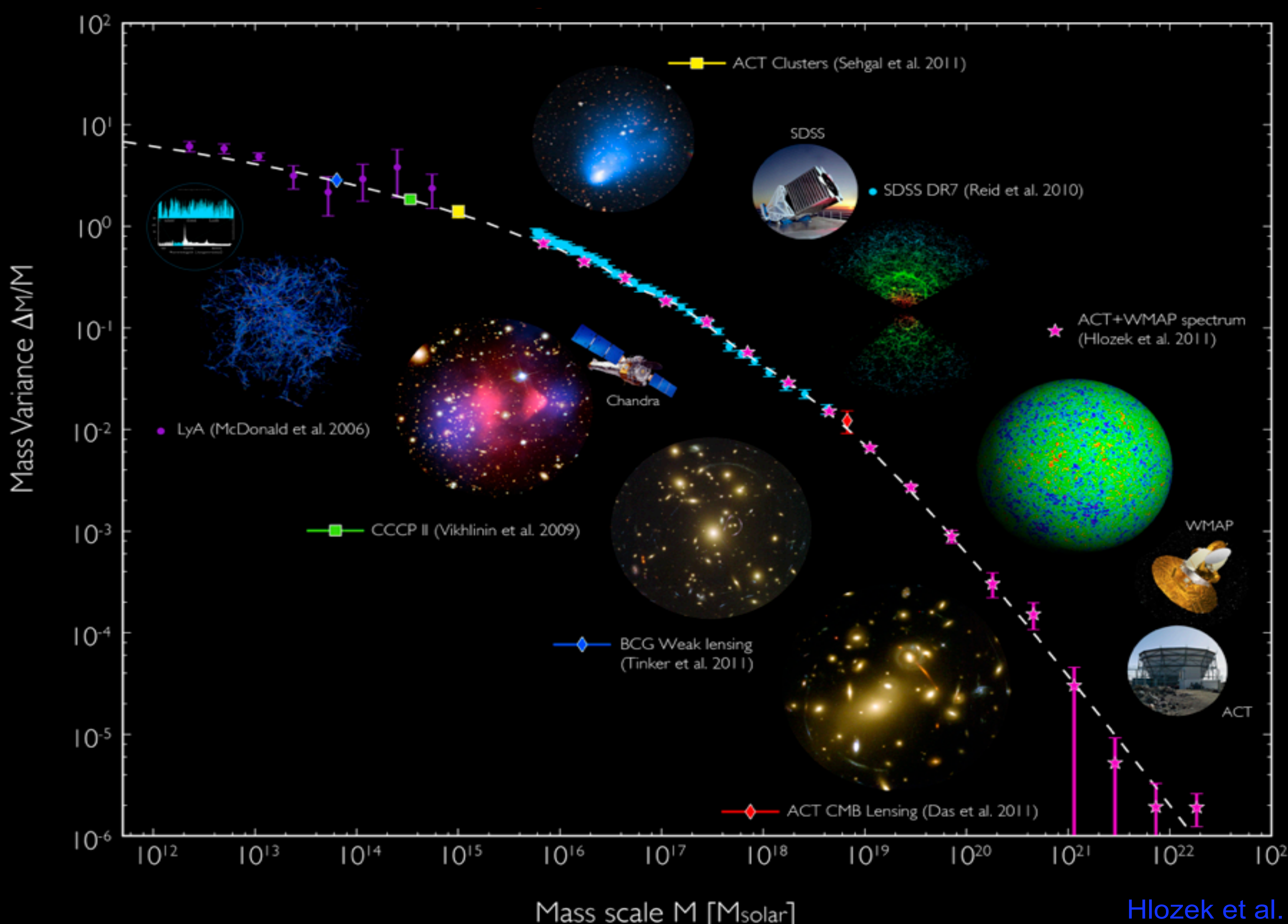
  Self-Interacting dark matter,

- Model 1—$\nu\Lambda$MDM

- Model 2—Z3 symmetry

- Summary

ΛCDM: successful in large scales



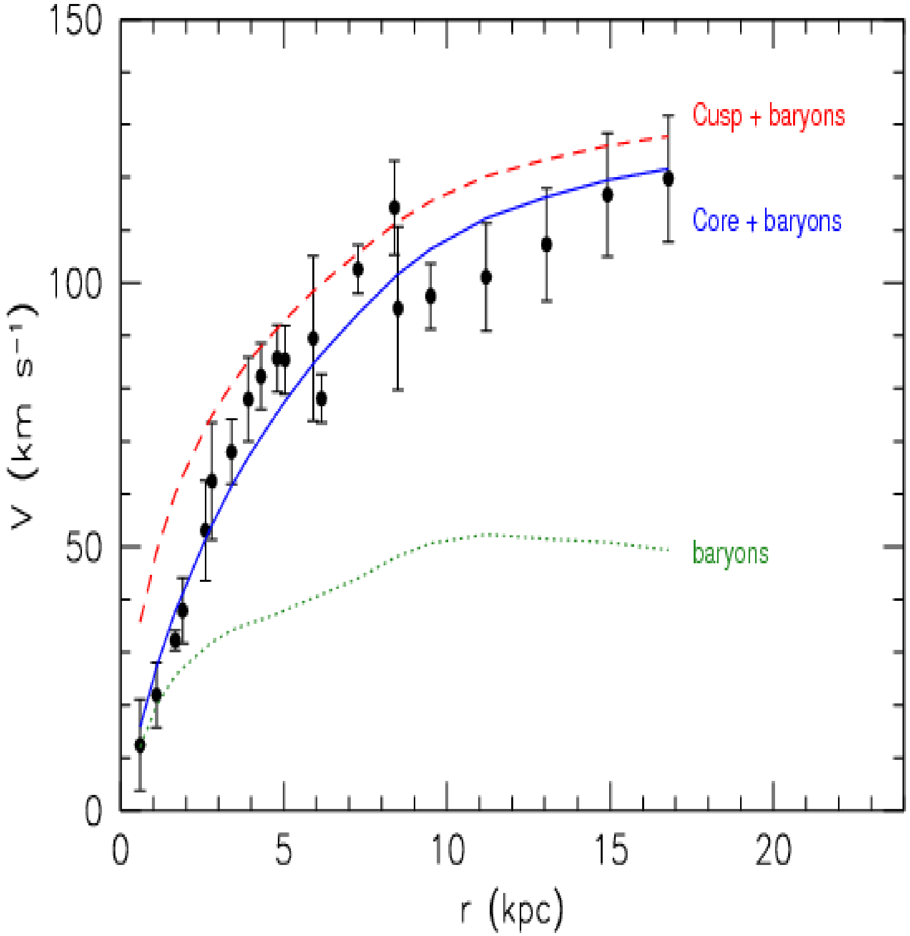
Hlozek et al. 2012

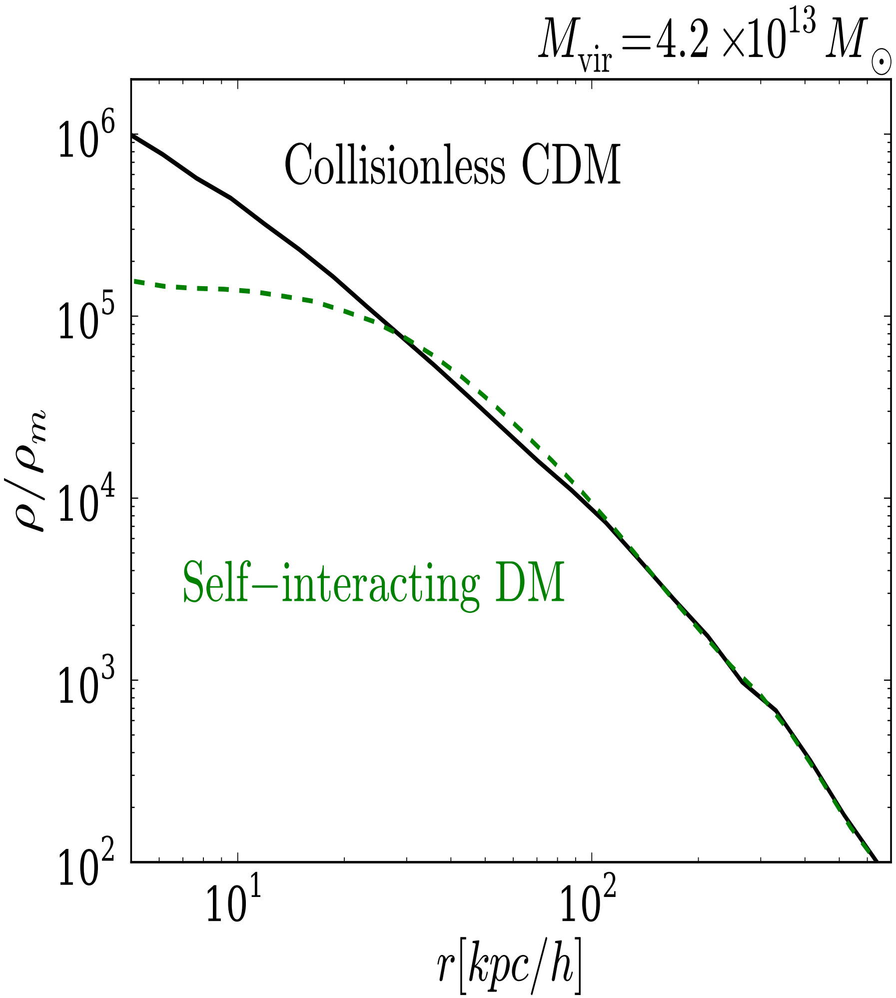
CDM Controversies?

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

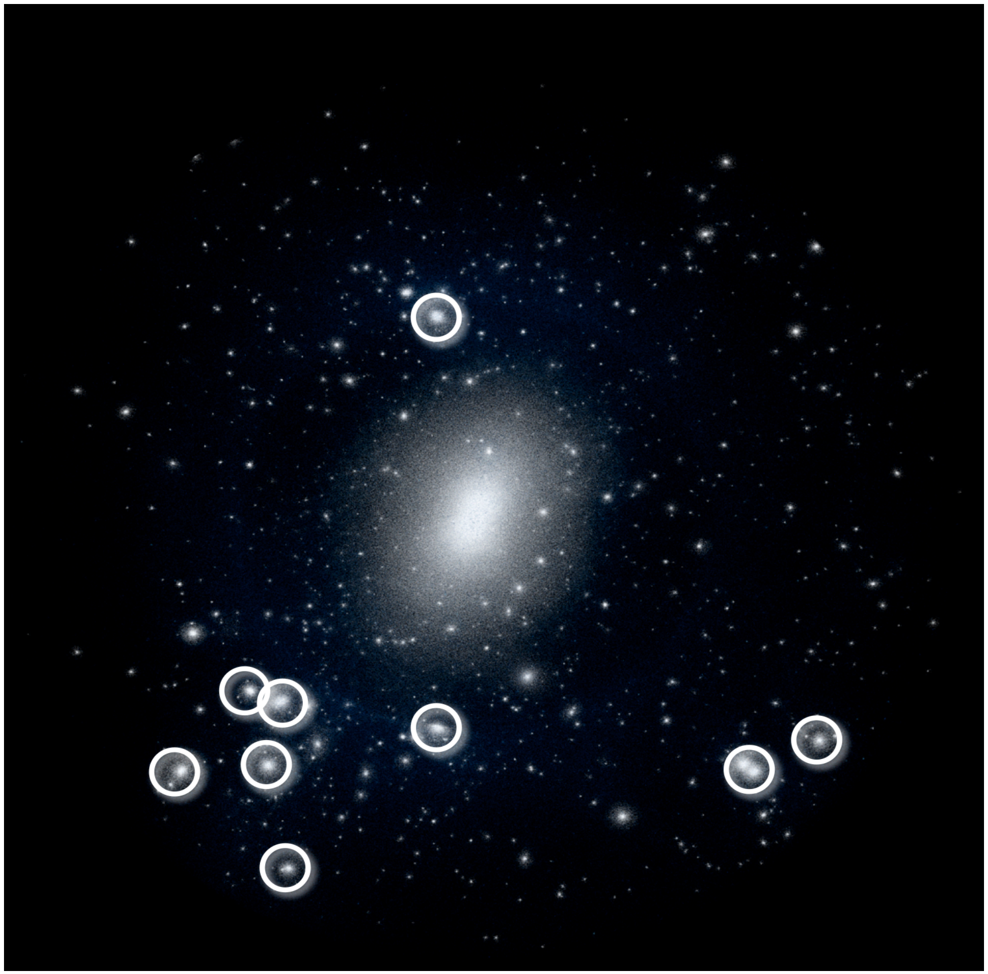
Ref. 1306.0913

Cusp vs. Core


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

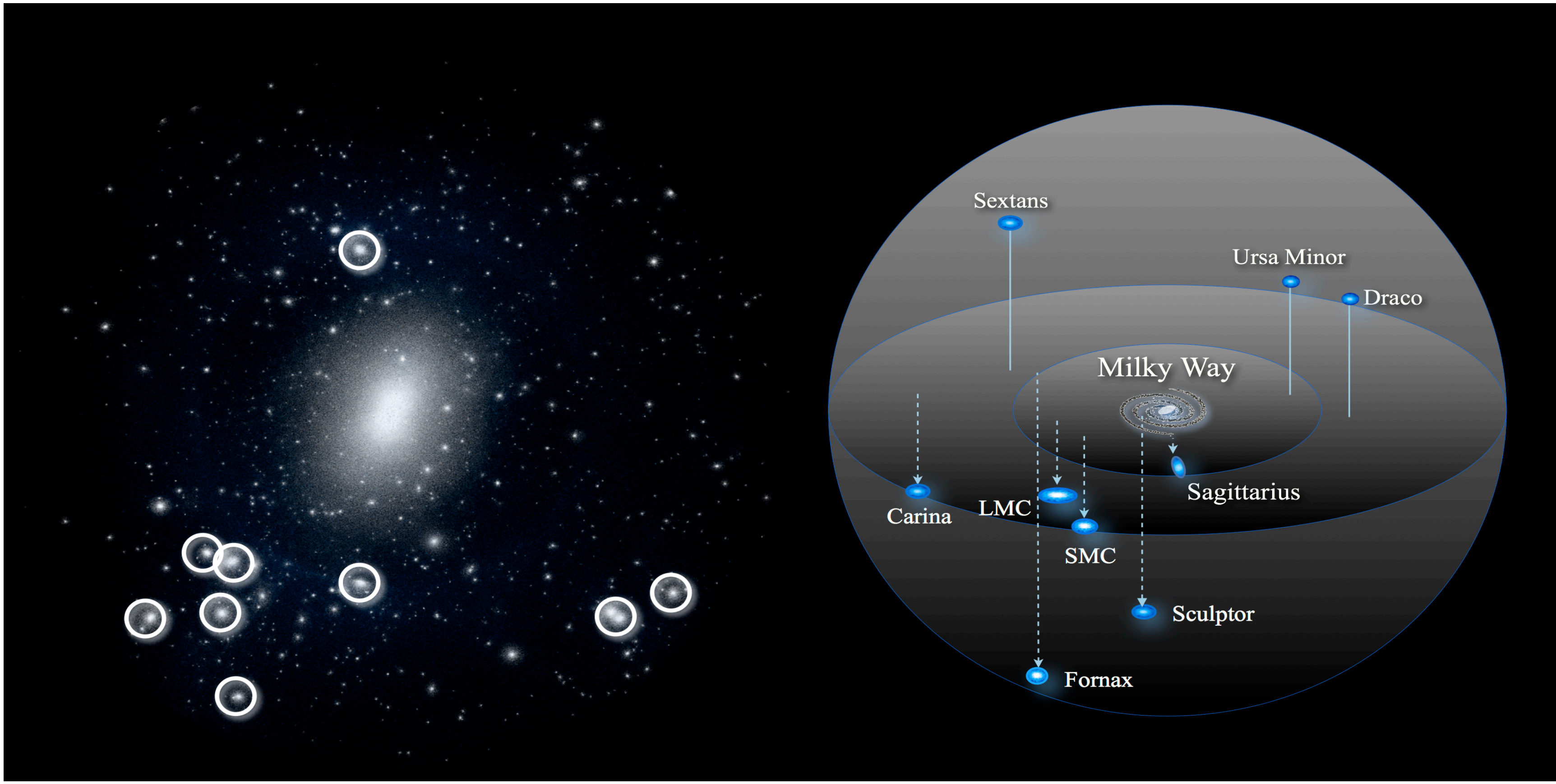

$M_{\rm vir} = 4.2 \times 10^{13} M_\odot$
10^6
10^5
10^4
10^3
10^2
ρ/ρ_m
Collisionless CDM
Self−interacting DM
10^1
10^2
$r[kpc/h]$

“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.

Possible solutions

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

- Dark Matter:
  warm dark matter,
  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?

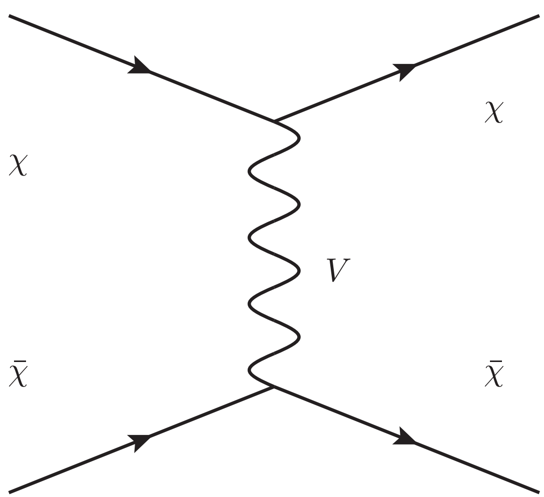
- DM-DM scattering cross section is around

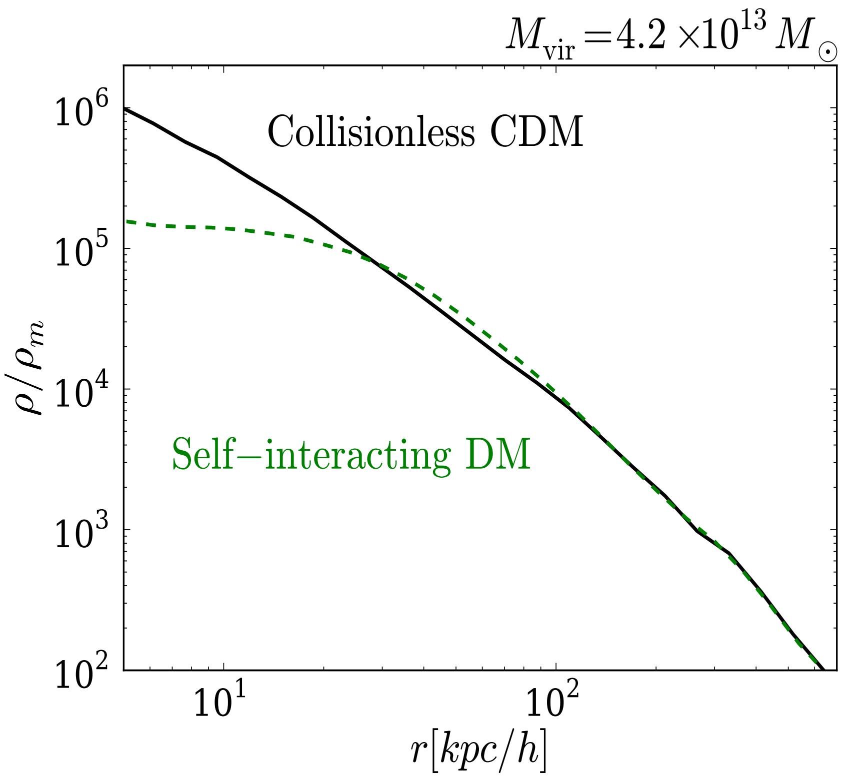
$$\frac{\sigma}{M_X} \sim \mathrm{cm}^2/\mathrm{g} \sim \mathrm{barn}/\mathrm{GeV}$$

- It can flatten the halo centre, solving the "cusp-core" and "too-big-to-fail" problems.
- Interaction with relativistic particles can induce a cut-off in the matter power spectrum by collisional damping, solving the "missing satellites" problem.

How?

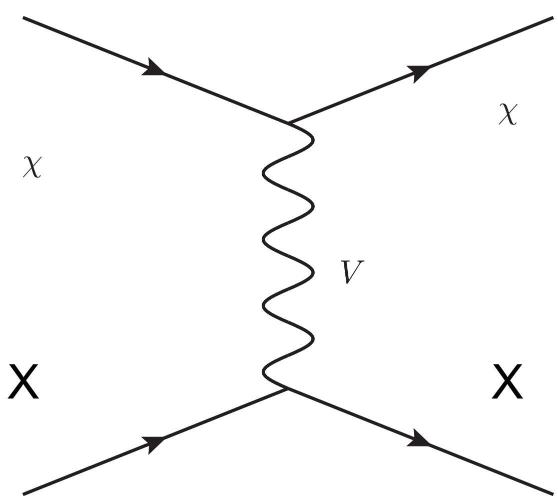
- MeV mediator can provide the right elastic scattering cross section for TeV dark matter,



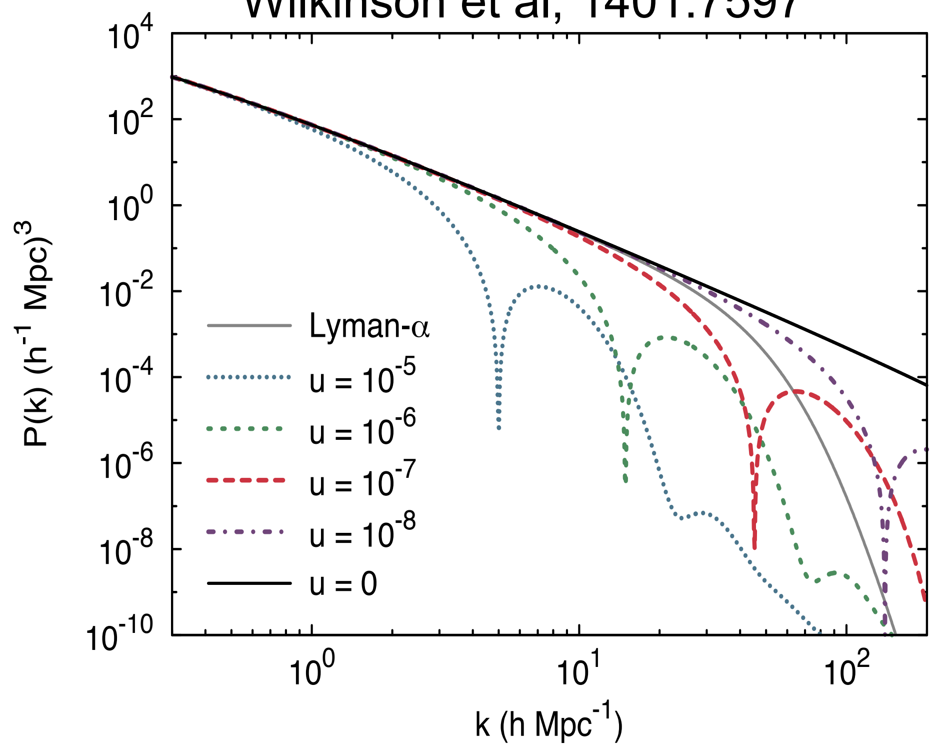


How?

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

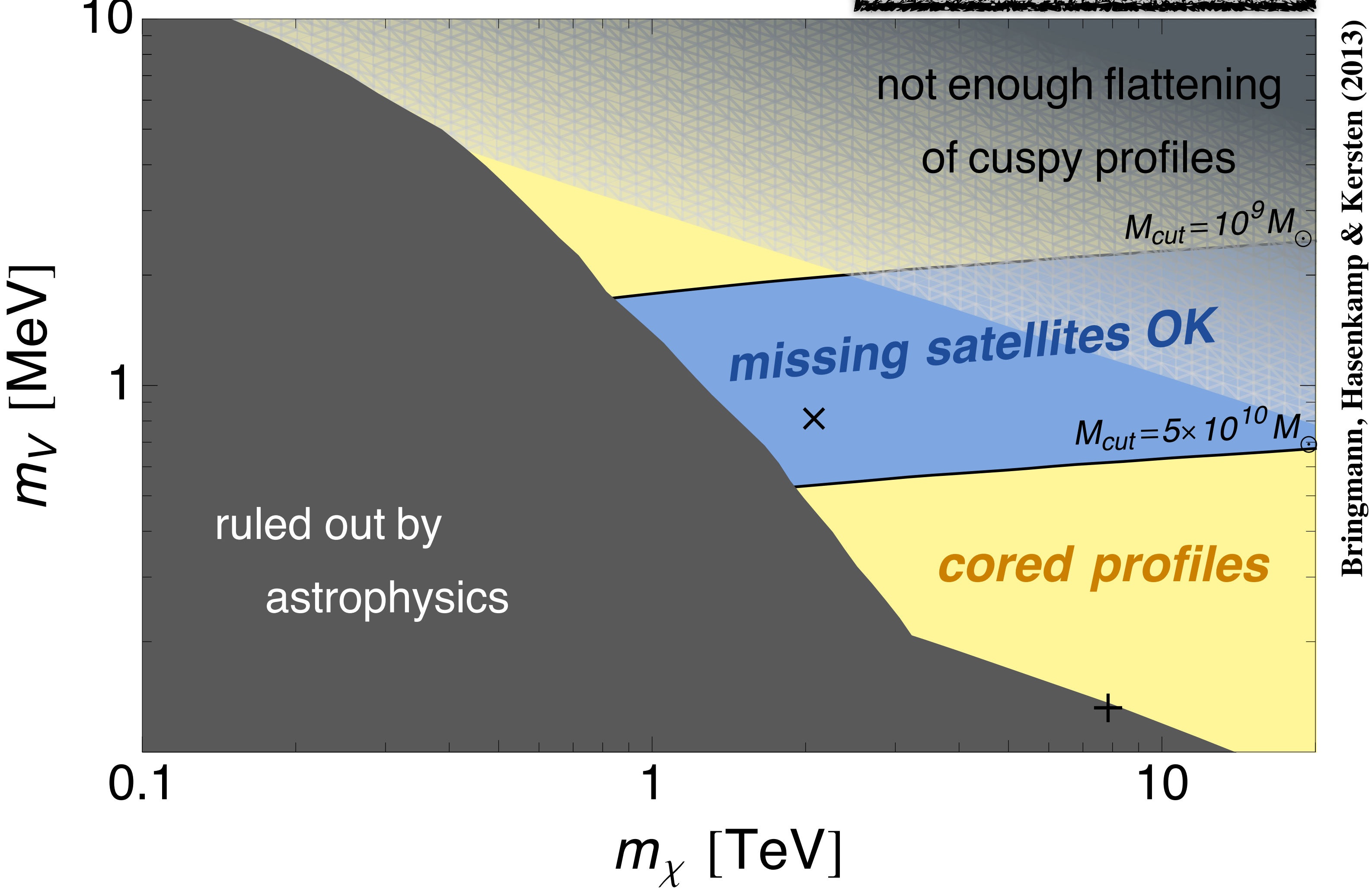


Wilkinson et al, 1401.7597



How?

Bringmann et al,1312.4947



Model 1—vΛMDM

P. Ko, YT, 1404.0236

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

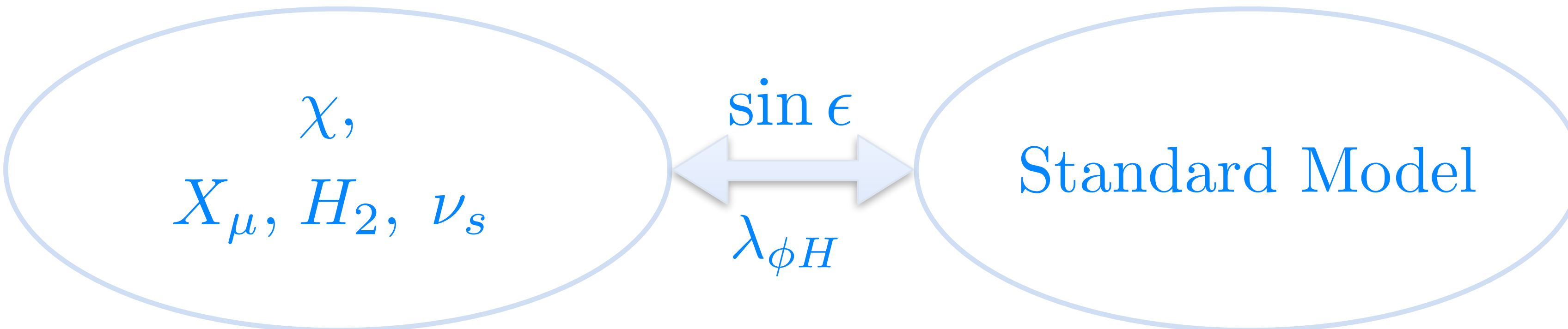
Various Mixings

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

Physical Spectrum

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

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.

$\Delta N_{eff}(BBN)$

When only sterile neutrinos are relativistic at the time just before BBN epoch, we have

$$\Delta N_{\rm eff}(T) = 4 \times \frac{T_{\nu_s}^4}{T_{\nu_a}^4} = 4 \times \left[\frac{g_{*s}(T)}{g_{*s}^x(T)} \times \frac{g_{*s}^x(T)\,T_{\nu_s}^3}{g_{*s}(T)\,T_{\nu_a}^3}\right]^{\frac{4}{3}}$$

$$= 4 \times \left[\frac{g_{*s}(T)}{g_{*s}^x(T)} \times \frac{g_{*s}^x(T_x^{\rm dec})}{g_{*s}(T_x^{\rm dec})}\right]^{\frac{4}{3}},$$

and

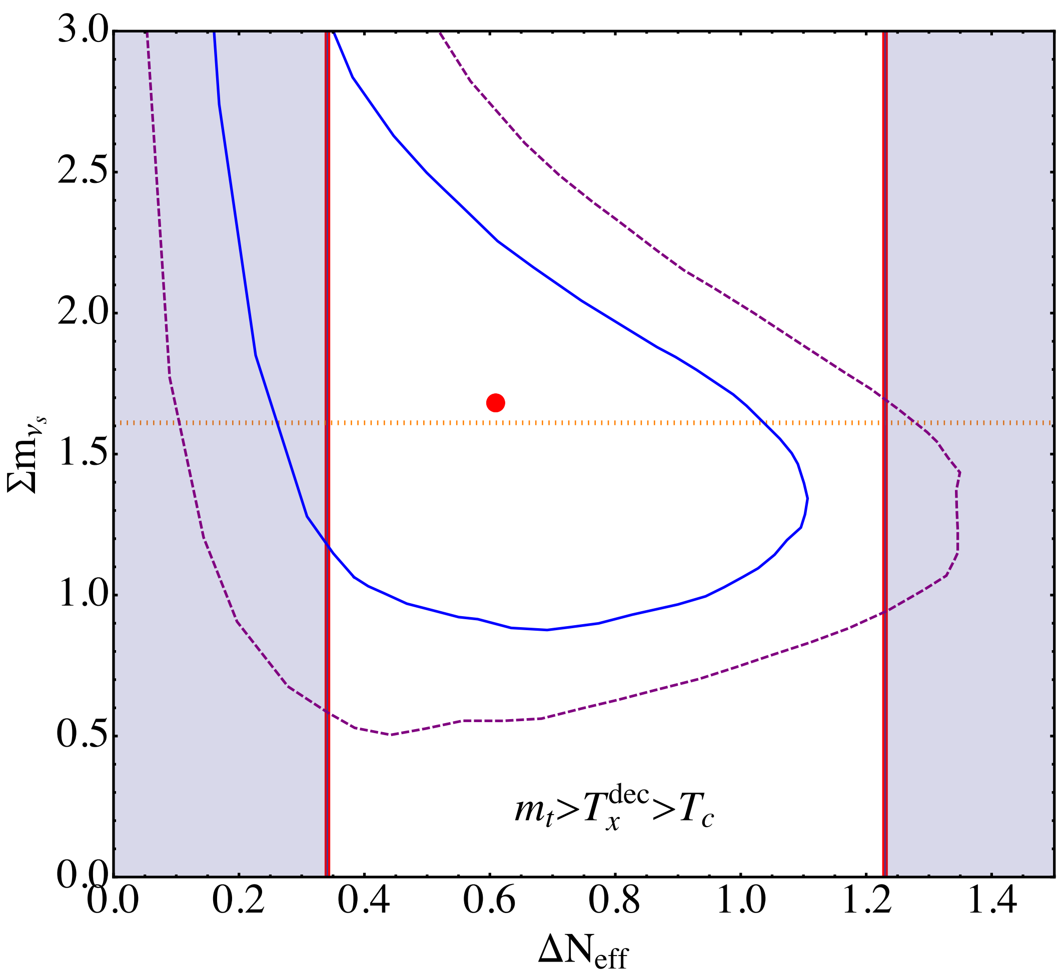
$$g_{*s}^x(T_x^{\rm dec}) = 3 + 1 + \frac{7}{8} \times (4 \times 2) = 11,$$

$$g_{*s}^x(T_{\rm bbn}) = \frac{7}{8} \times (4 \times 2) = 7.$$

$g_{*s}(T_x^{\rm dec}) \simeq 72$ for $m_c < T_x^{\rm dec} < m_\tau$. It gives

$$\Delta N_{\rm eff} = 4 \times \left[\frac{\frac{43}{4} \times 11}{7 \times 72}\right]^{\frac{4}{3}} \simeq 0.579.$$

ΔN_{eff}(CMB) and m_{ν_s}



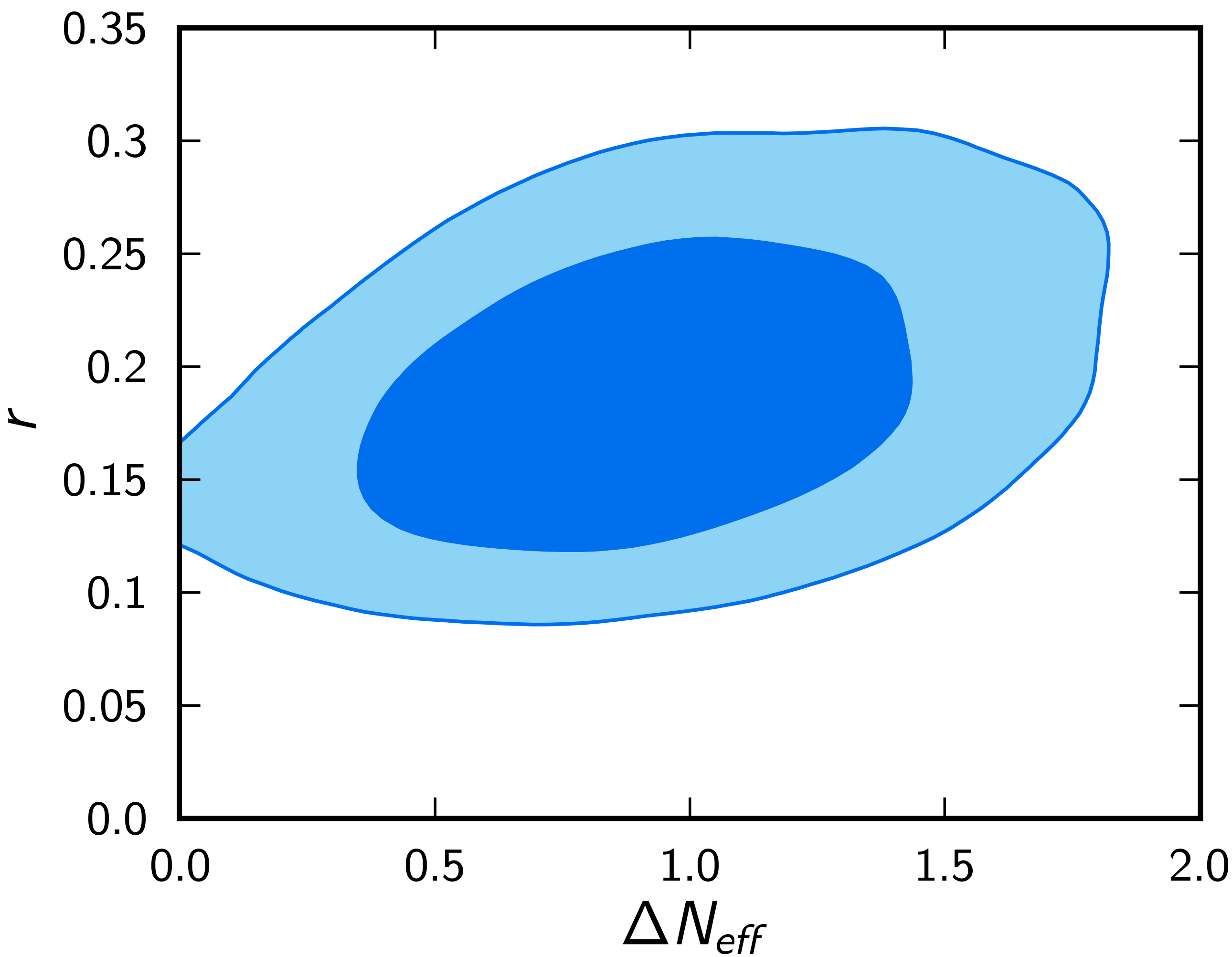
Contours for CMB data, *1308.3255*

Dot line marks the centre value for 3+2 scenario for neutrino oscillation, *1303.3011*

Region between two vertical lines are allowed in our model, *1404.0236*

ΔN_{eff} helps reconcile Planck and BICEP2

C.Dvorkin, M.Wyman, D.Rudd, W.Hu, arXiv:1403.8049



Features

- *ultraviolet* complete theory for cold dark matter and sterile neutrinos that can accommodate both cosmological data and neutrino oscillation experiments within 1σ level,
- DM's self-scattering and scattering-off sterile neutrinos can resolve three controversies for cold DM on small cosmological scales, *cusp vs. core, too-big-to-fail* and *missing satellites problem*,
- eV *sterile neutrinos* can fit some neutrino oscillation anomalies, contribute to dark radiation and also reconcile the tension between the data by Planck and BICEP2 on the *tensor-to-scalar* ratio.

Model 2—Z3 symmetry

P, Ko, YT, arXiv:1402.6449

Again an extra $U(1)_X$ gauge symmetry is introduced, with scalar DM X and dark higgs with charges 1 and 3, respectively.

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

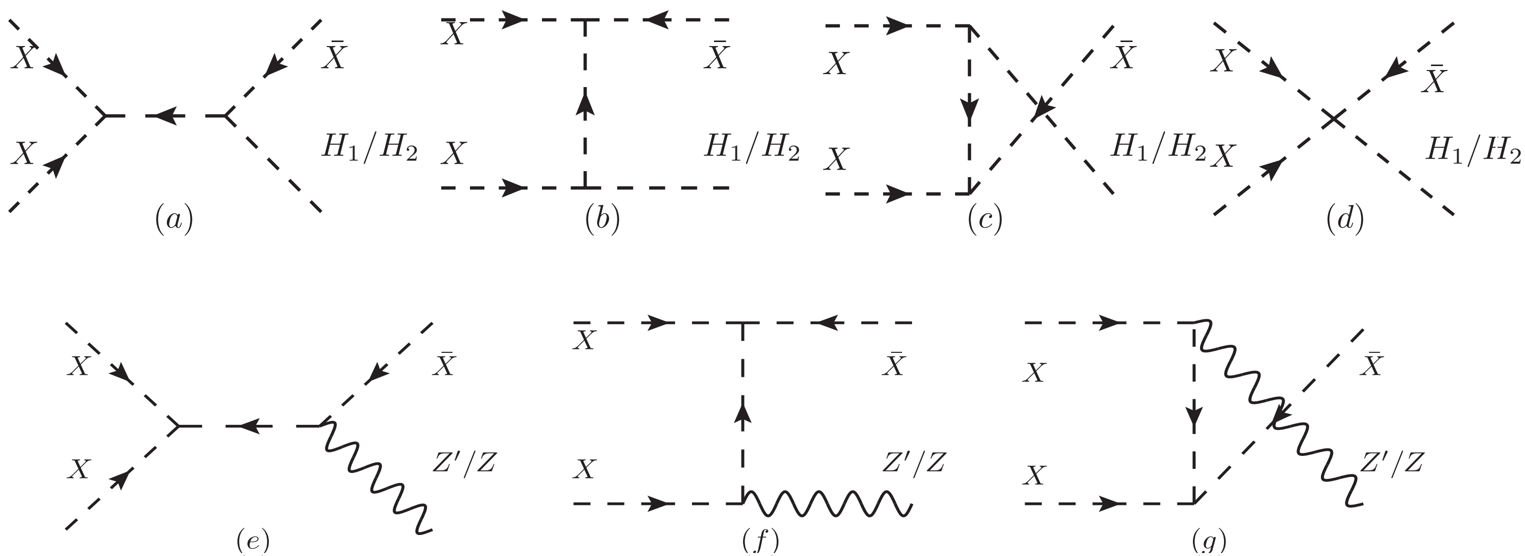
$$V = -\mu_H^2 H^\dagger H + \lambda_H\left(H^\dagger H\right)^2 - \mu_\phi^2\phi_X^\dagger\phi_X + \lambda_\phi\left(\phi_X^\dagger\phi_X\right)^2 + \mu_X^2 X^\dagger X + \lambda_X\left(X^\dagger X\right)^2$$

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

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

Z3 symmetry $\quad X^\dagger \to e^{-\mathrm{i}\frac{2\pi}{3}}X^\dagger \qquad X^3 + X^{\dagger 3}$

Semi-annihilation

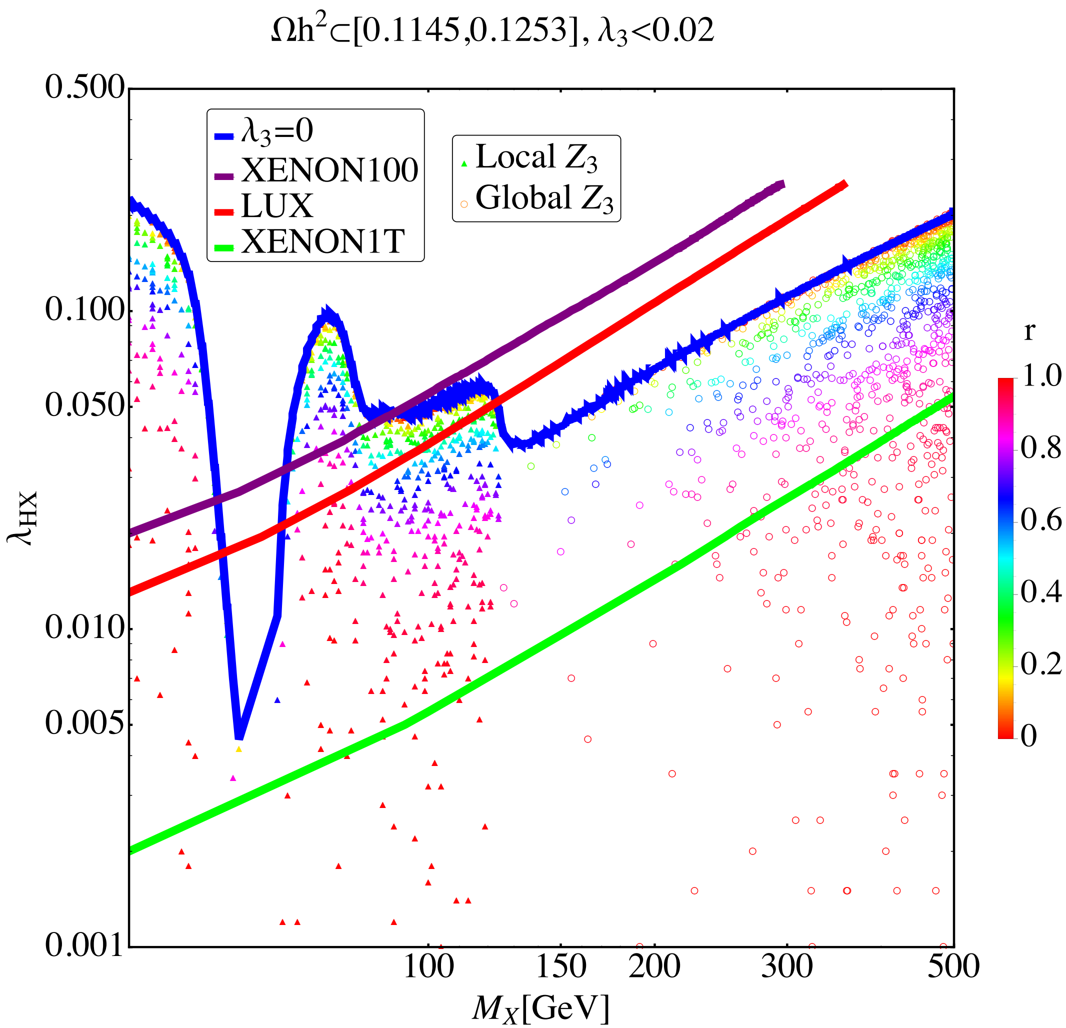


$$\frac{dn_X}{dt} = -v\sigma^{XX^*\to YY}\left(n_X^2 - n_{X\,\mathrm{eq}}^2\right) - \frac{1}{2}v\sigma^{XX\to X^*Y}\left(n_X^2 - n_X n_{X\,\mathrm{eq}}\right) - 3Hn_X,$$

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

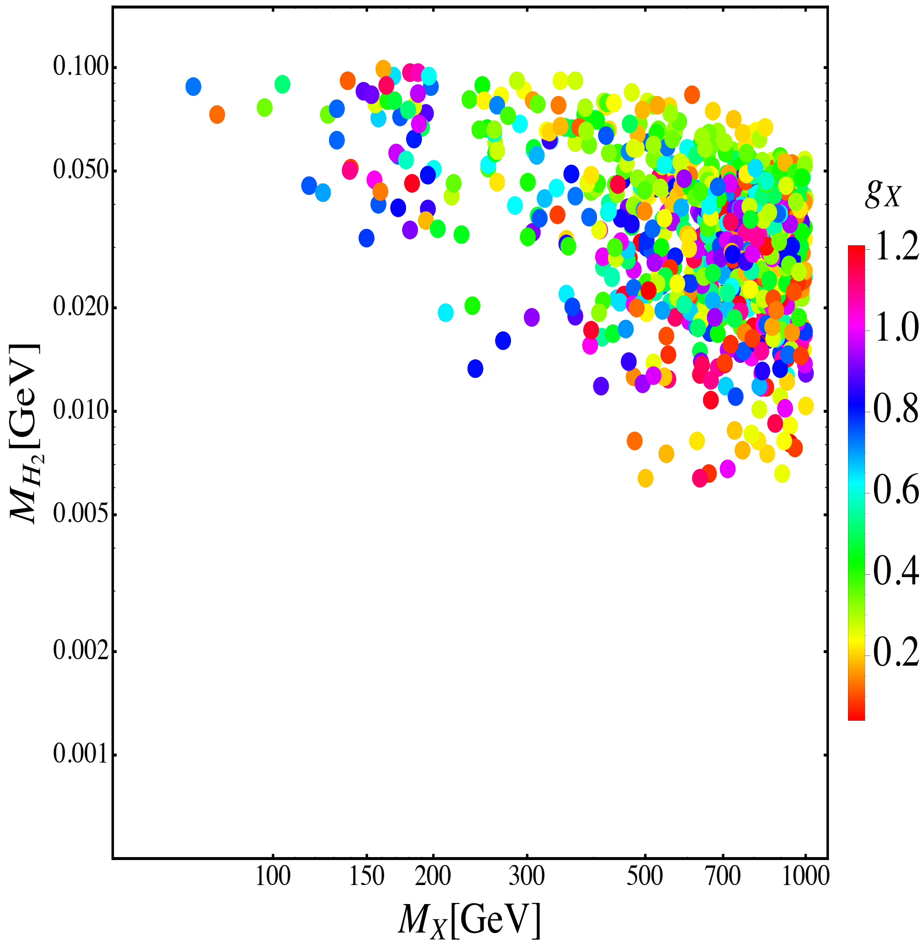
micrOMEGAs

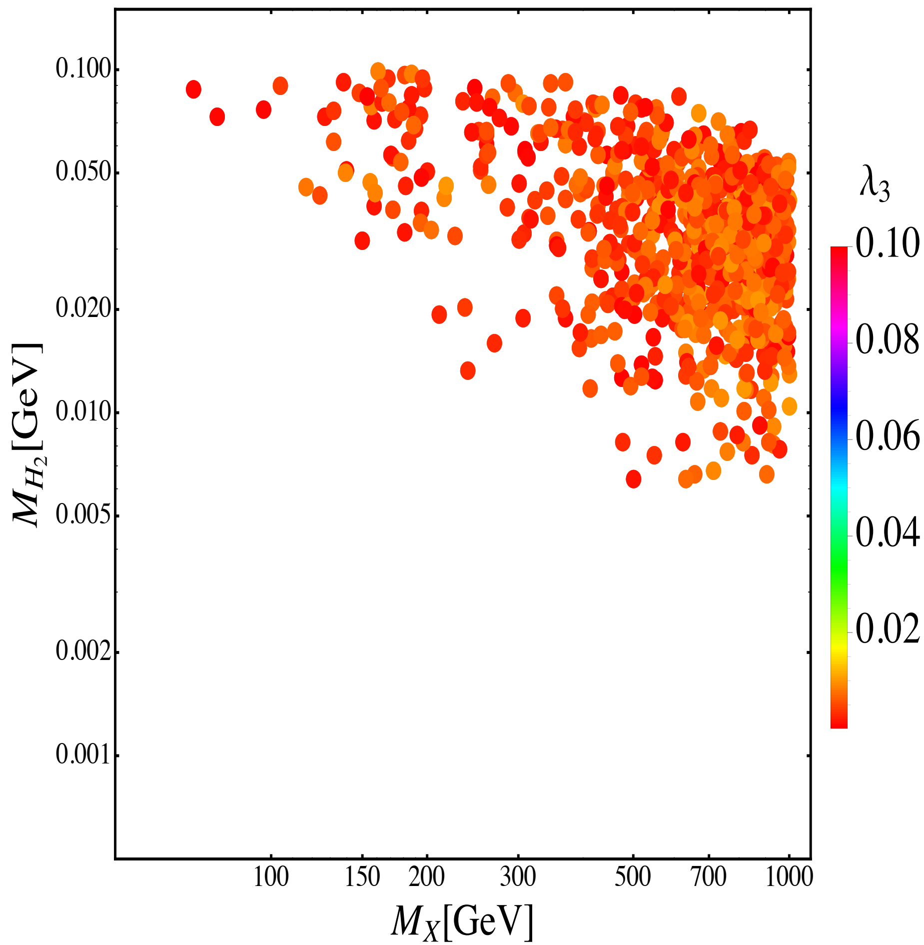
Relic density and Direct Search



- Blue band marks the upper bound,
- All points are allowed in our local Z3 model,1402.6449
- only circles are allowed in global Z3 model,1211.1014

illustrations





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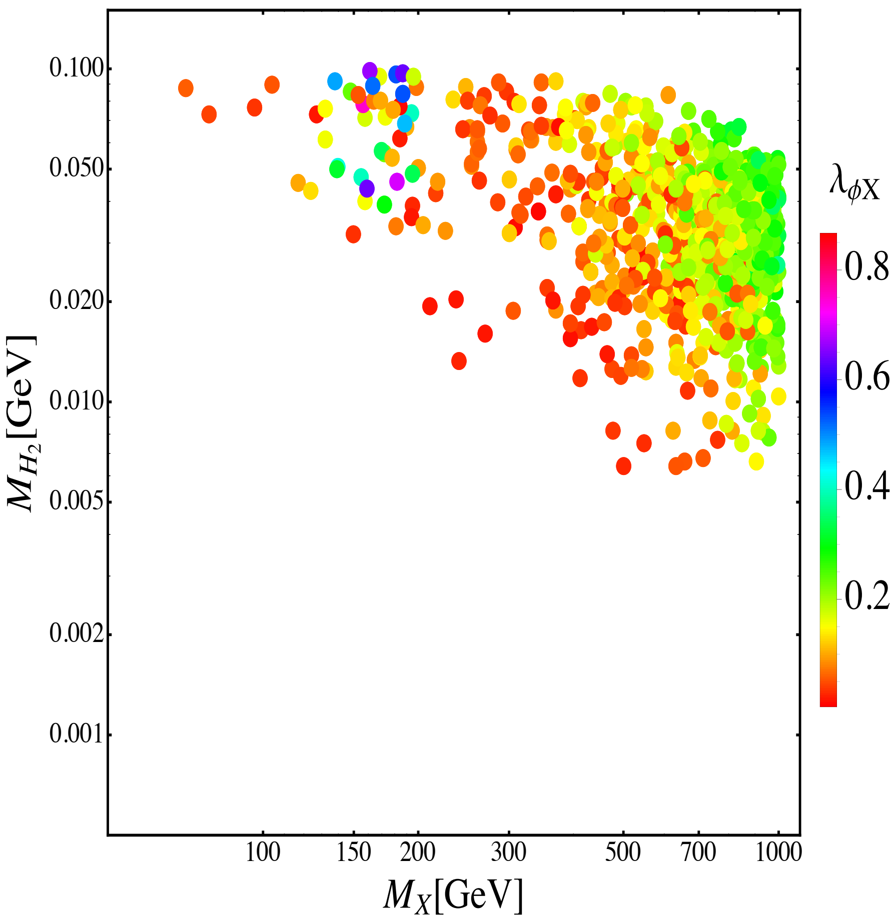

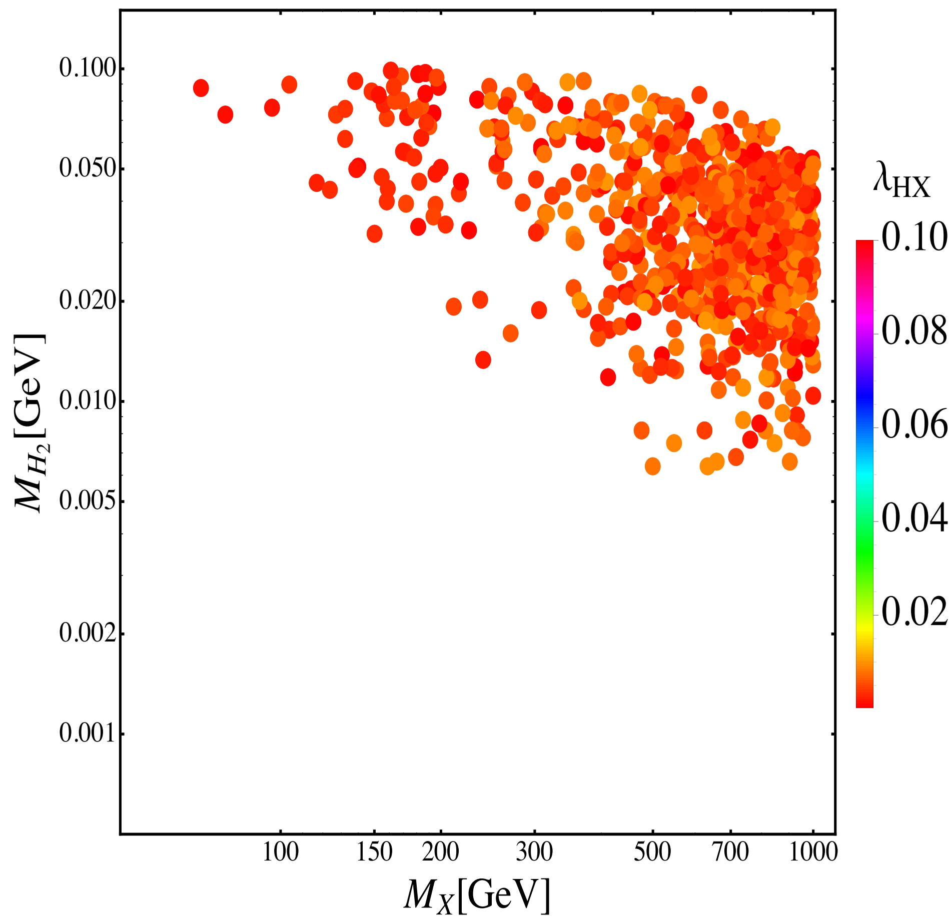

Summary

- Introduction of the controversies in CDM paradigm
- Self-interacting DM is an attractive solution
- We propose a model νΛMDM based on an extra U(1) gauge symmetry for sterile neutrinos and DM for various purposes
- We also introduce a model with discrete Z_3 symmetry for SIDM.

THANK YOU!