Interacting Dark Matter and Radiation in Cosmology

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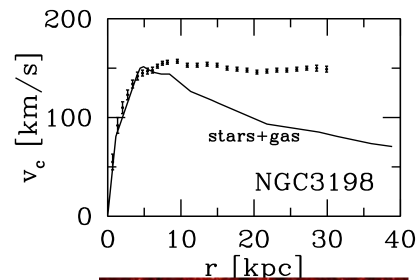
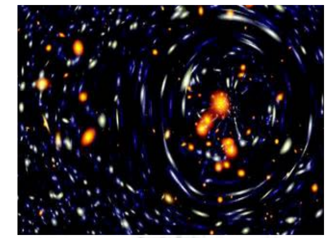
IBS-CTPU, Daejeon

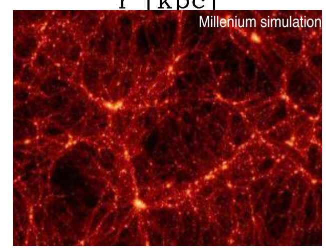
July 11-15, 2016

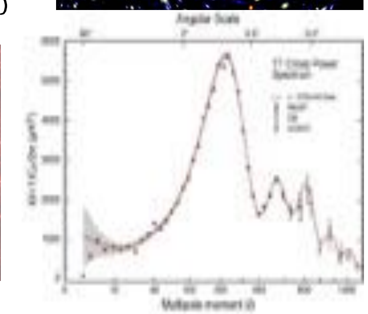
Dark Matter Evidence

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



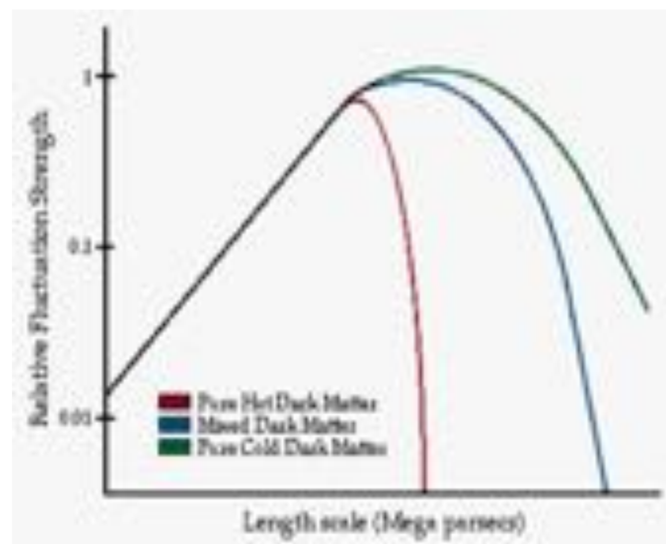






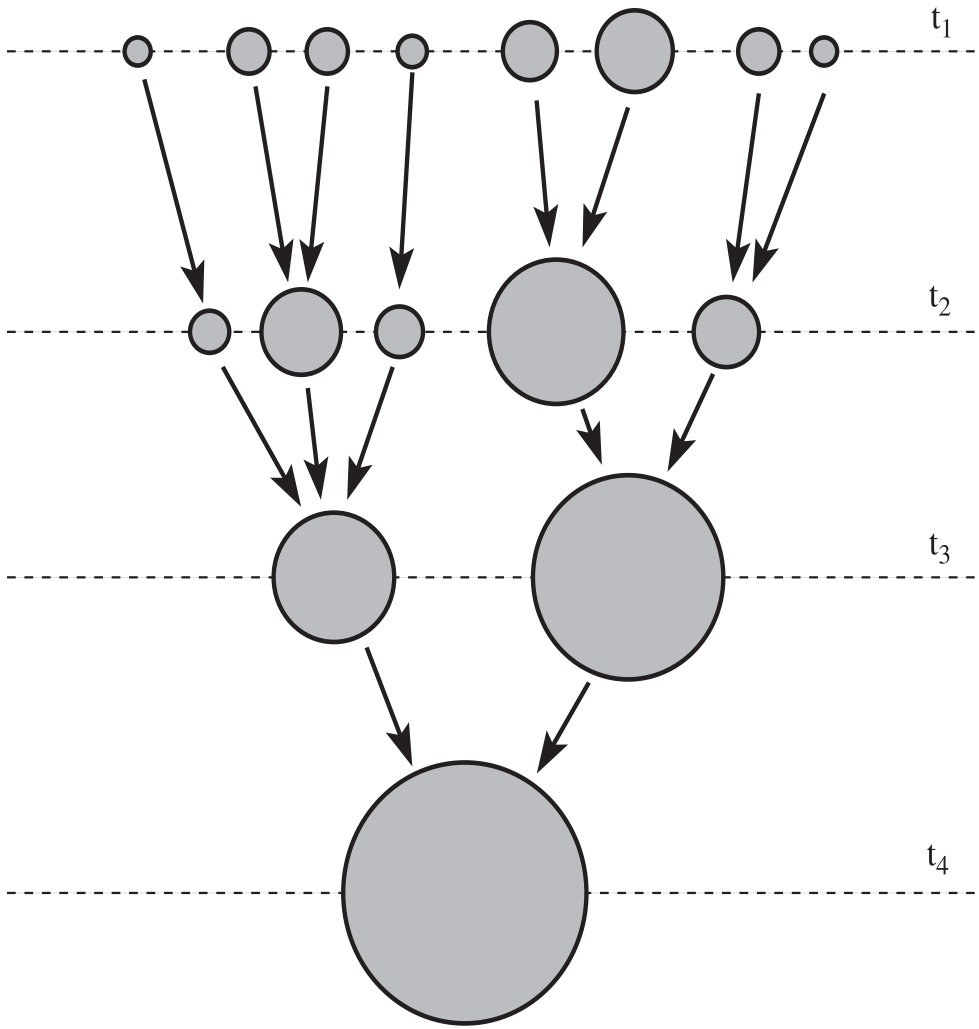
All confirmed evidence comes from gravitational interaction, consistent with DM as particle

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



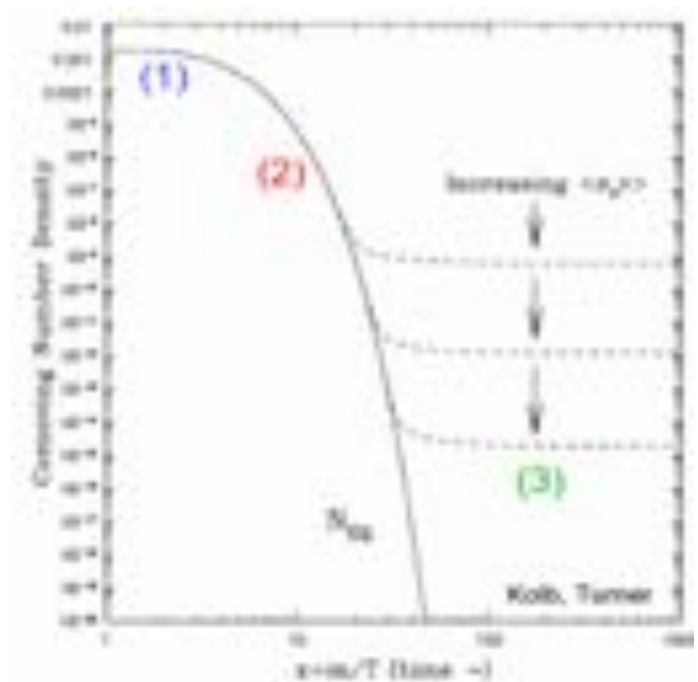
Merger History of Dark Halo

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

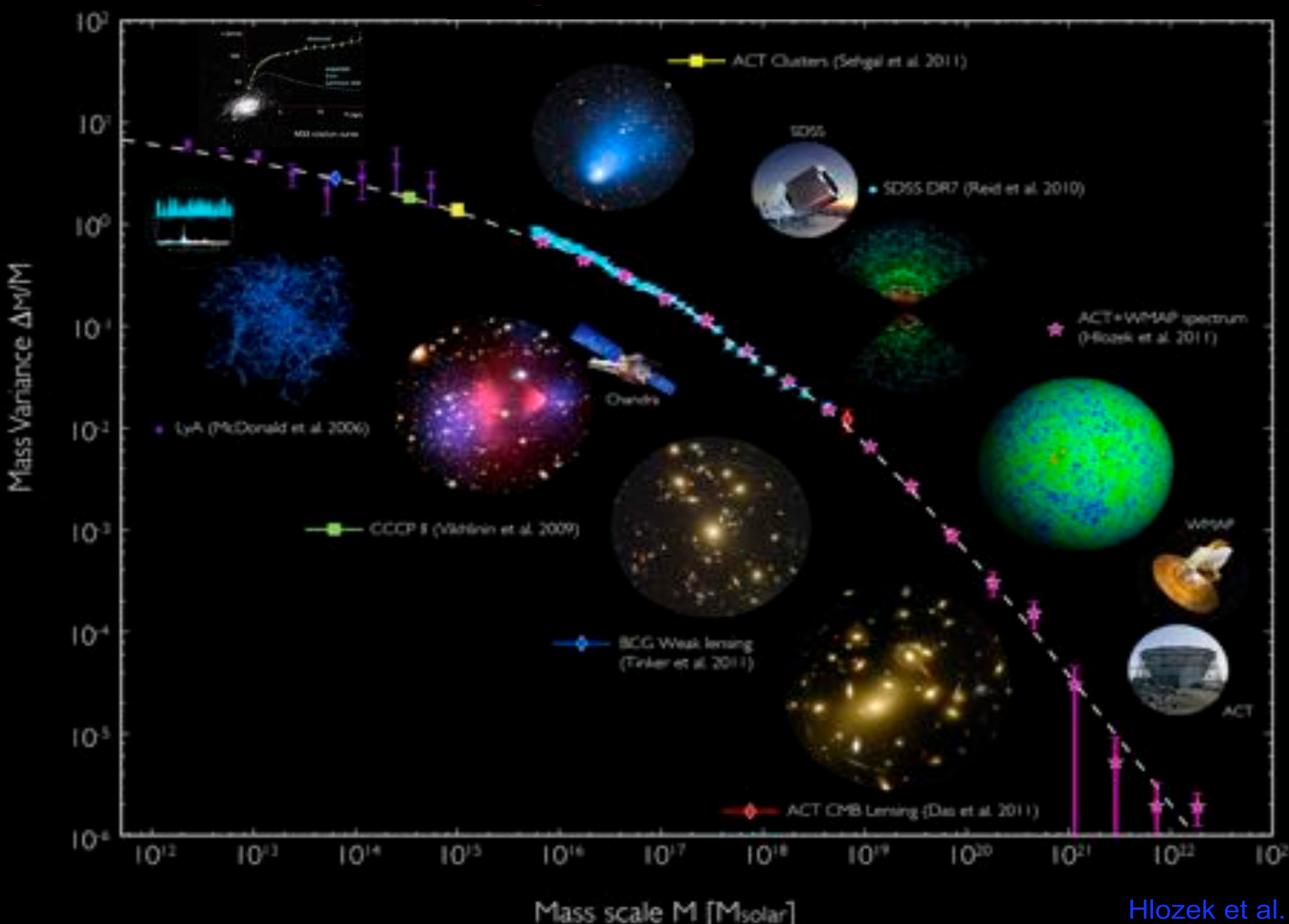


Weakly Interacting Massive Particle (WIMP)

- Mass around ~100GeV
- Coupling ~ 0.5
- Correct relic abundance Ω~0.3
- Thermal History
  - Equilibrium XX<>ff
  - Equilibrium XX >ff
  - Freeze-out
- Cold Dark Matter (CDM)



ΛCDM: successful on large scales



Hlozek et al. 2012

(Self-)Interacting dark matter

Why?

- Theoretically interesting
  - Atomic DM, Mirror DM, Composite DM
  - Eventually, all DM is *interacting* in some way, the question is how strongly?
  - Self-Interacting DM $\frac{\sigma}{M_X} \sim \mathrm{cm}^2/\mathrm{g} \sim \mathrm{barn}/\mathrm{GeV}$
- Possible new testable signatures
  - LSS, CMB, BBN,
  - other astrophysical effects,…
- Solution of CDM controversies

CDM Controversies on small scales?

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

HM***Lee's***, ***Tulin***'s talks

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

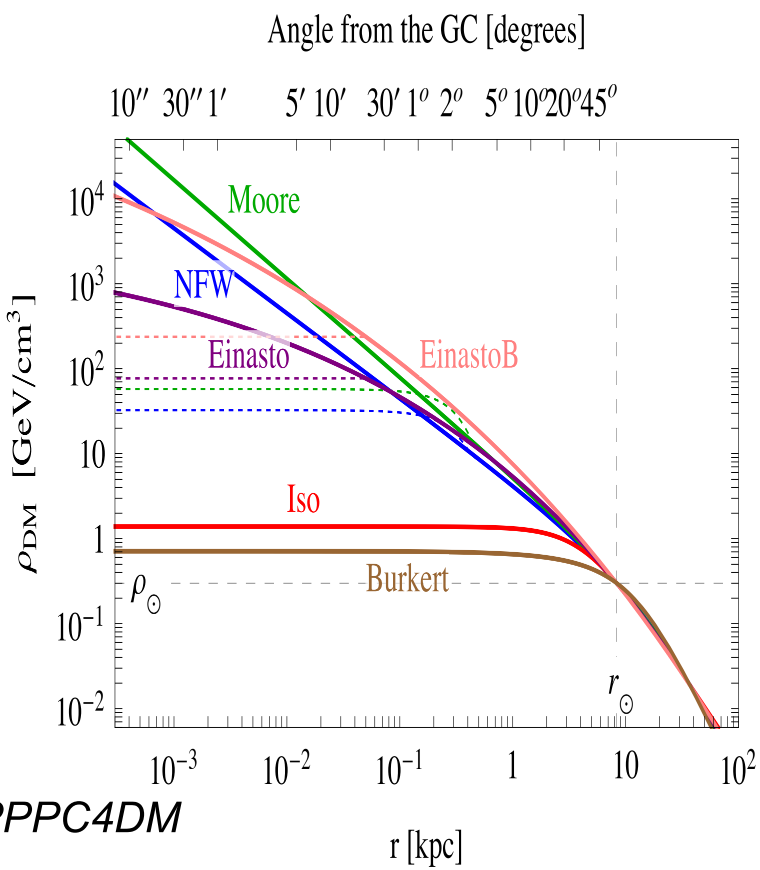
tensions between ***simulations*** and ***observations***

Be cautious!

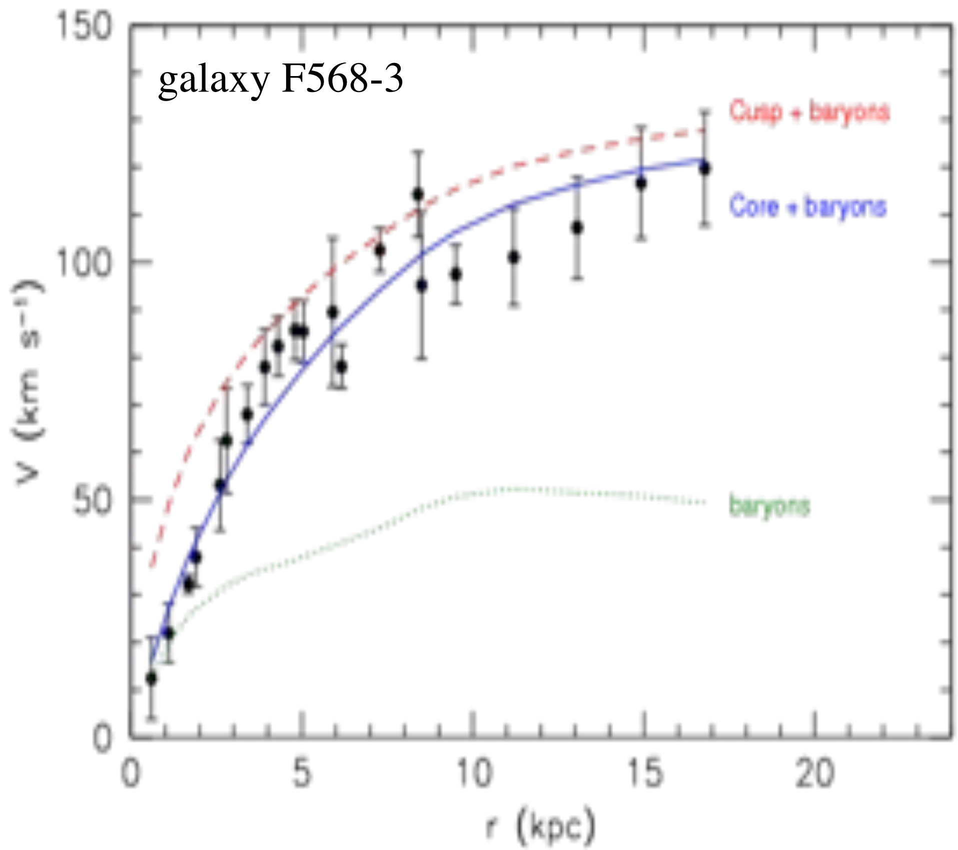
No consensus, simulations are very complicated when including baryon effects.

Cusp vs. Core

DM density profiles



PPPC4DM



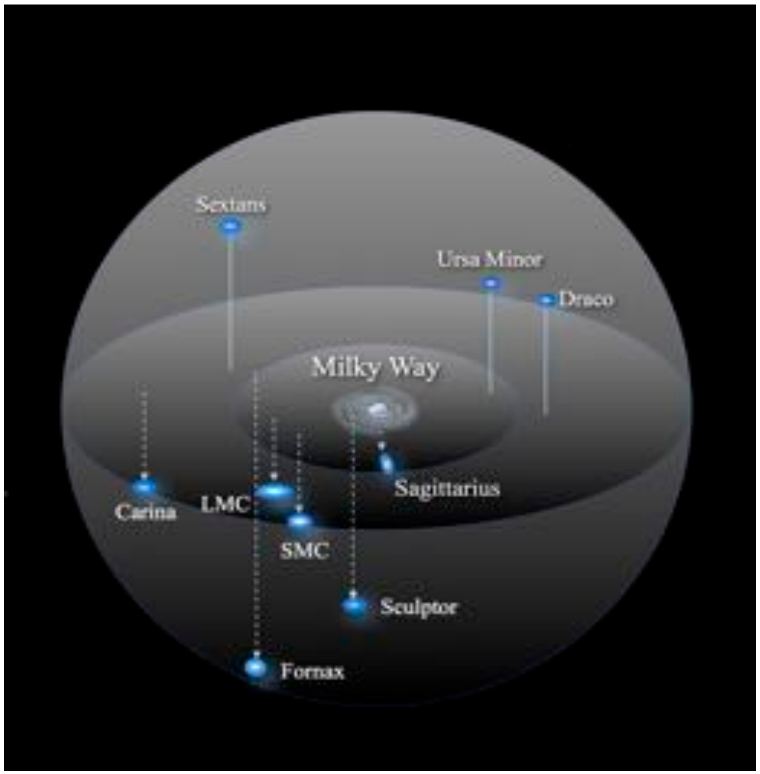
Cusp profiles, such as NFW, are predicted by N-body simulation of CDM

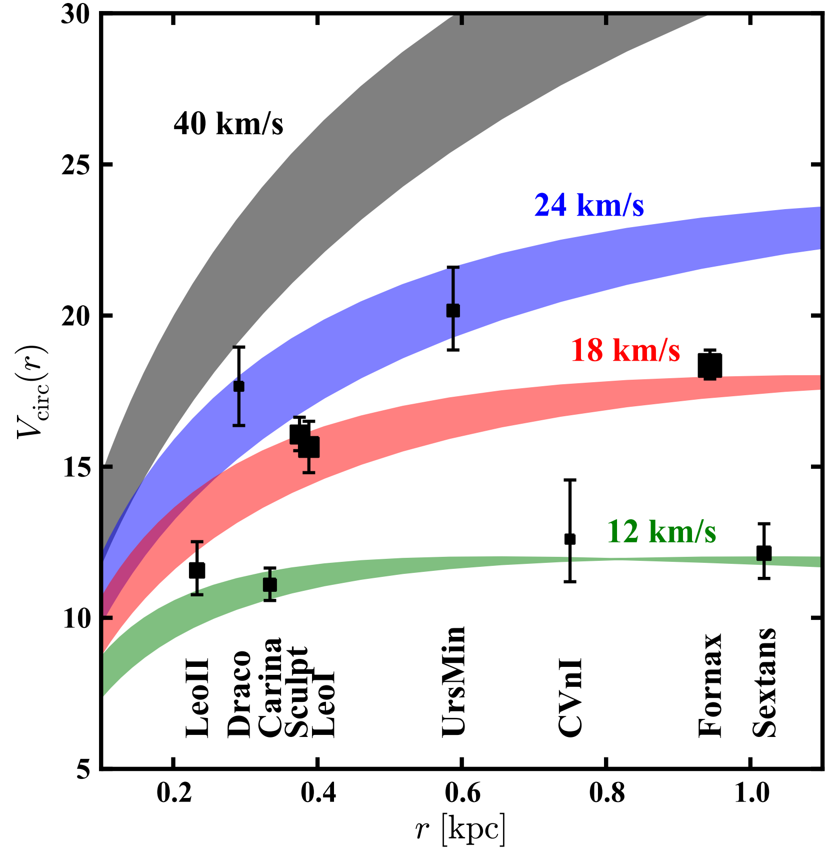
“missing satellites” problem

- 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

Bullock et al,1111.2048





- Right Panel: Observed circular velocity of the nine bright dSphs, along with rotation curves corresponding to NFW subhalo. The central densities of the sub halos are too high to host the dwarf satellites, predicting stellar velocity dispersions higher than observed.

Possible solutions

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

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

Carlson et al, 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?

- Strongly-Interacting Dark Matter? or
- Self-Interacting Dark Matter?

More concretely, it refers the scenarios that

- DM-DM scattering cross section is around

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

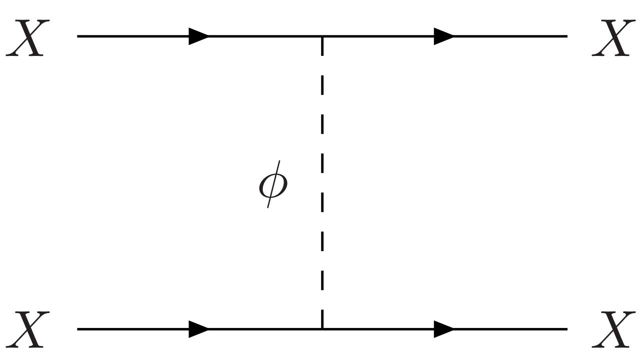
- It can still be simple φ^3, φ^4,even φ^5 with M~O(100MeV)
- composite DM, atomic DM…

WIMP as SIDM?

- DM-DM scattering cross section is around

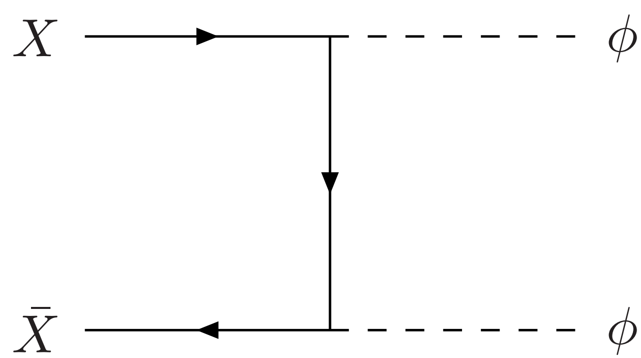
$$\frac{\sigma}{M_X} \sim \mathrm{cm}^2/\mathrm{g} \sim \mathrm{barn}/\mathrm{GeV}$$

- It can still be the usual WIMP



DM self-interactions

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



DM annihilation

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

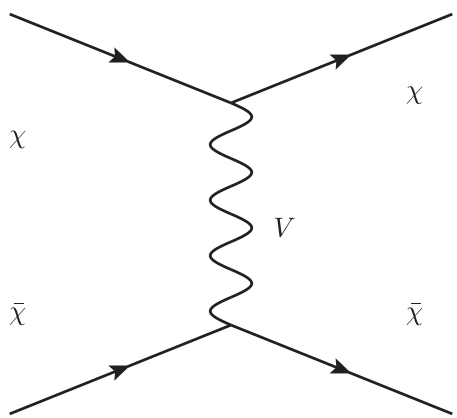
Effects

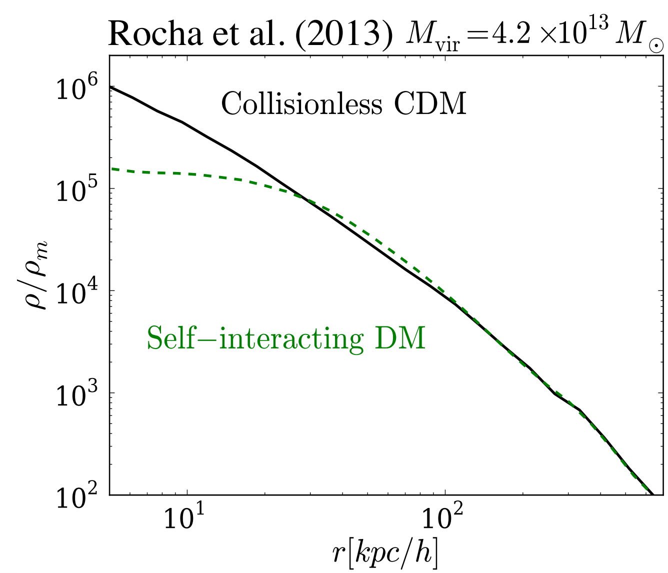
Spergel, Steinhardt (2000)

- 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***" problem!

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





Radiation

- ultra relativistic particle E>>m
- photon (CMB)
- neutrino when T>m
- light sterile neutrino
- ….

Extra radiation, $N_{\rm eff}$,

$N_{\rm eff}$=3.046 for neutrinos in standard cosmology

Cosmological Bounds

- Extra radiation contributes as hot dark matter, constrained by 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

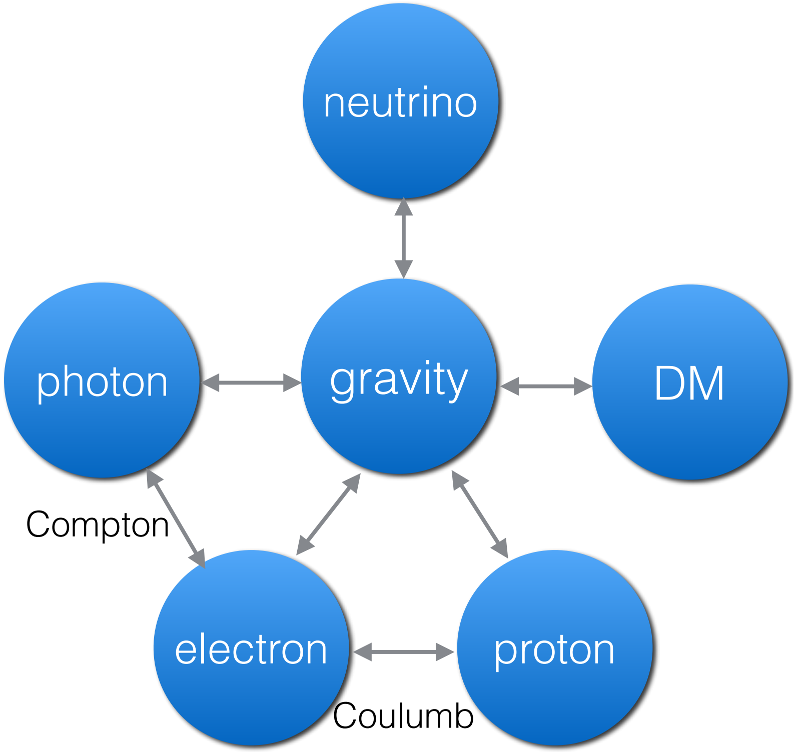
$$\left.\begin{aligned} N_{\rm eff} &< 3.7 \\ m^{\rm eff}_{\nu,\,\rm sterile} &< 0.52\ \text{eV} \end{aligned}\right\} \quad 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+BAO.}$$

Cosmological Evolution

- all components are connected by Einstein's equation

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

- first-order perturbation of Boltzmann equation
  - anisotropy in CMB
  - power spectrum for LSS



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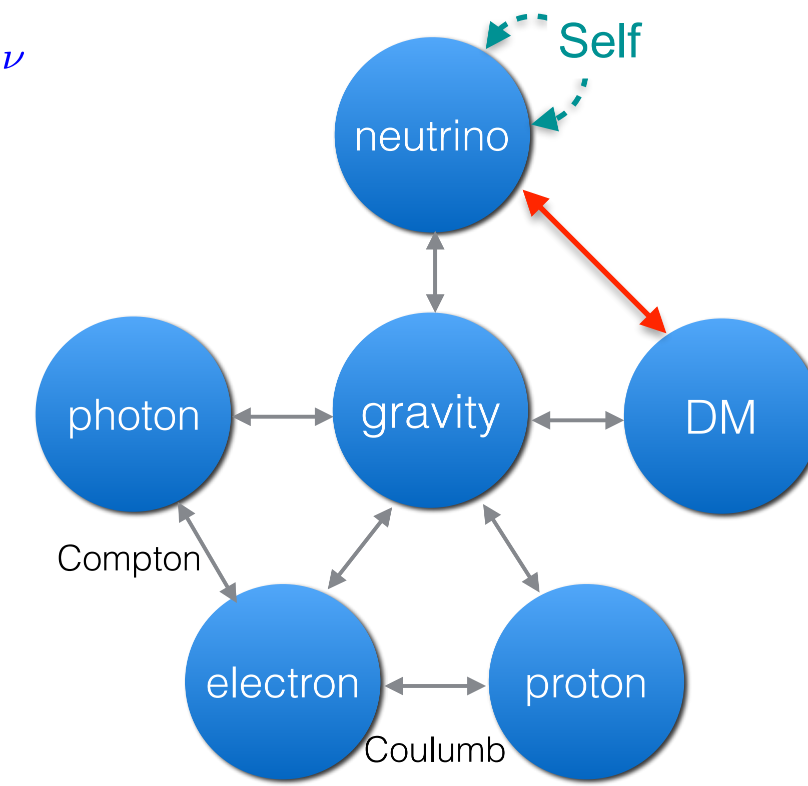
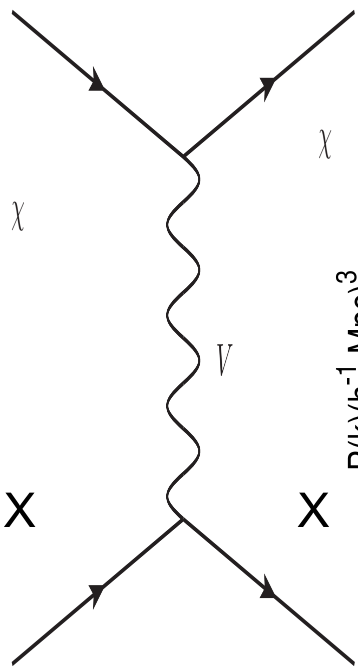
- first-order perturbation of Boltzmann equation
  - anisotropy in CMB
  - power spectrum for LSS
- (Self-)Interaction sometimes also matters

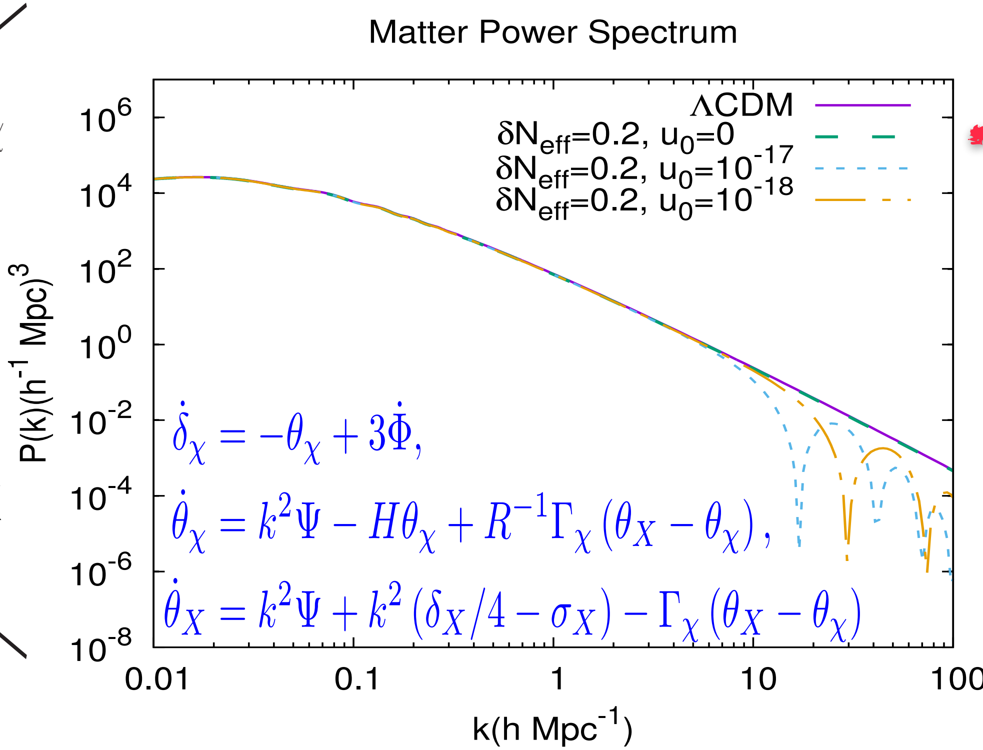


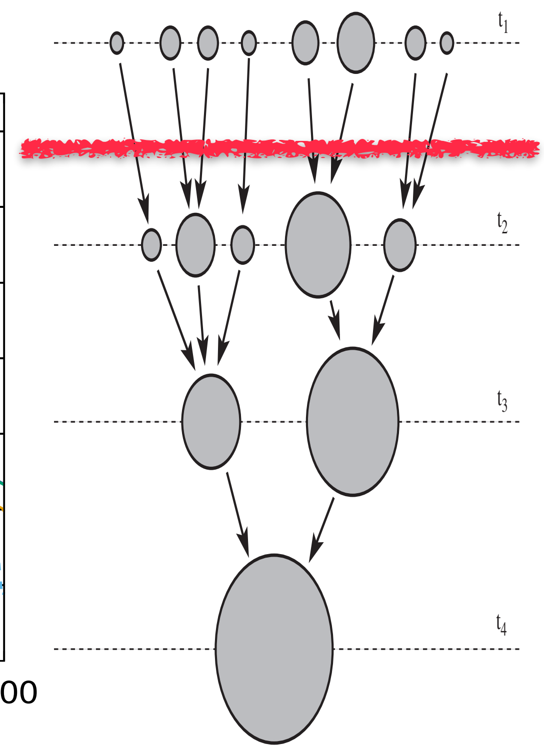
Late Kinetic Decoupling

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

Y.Tang, arXiv.1603.00165



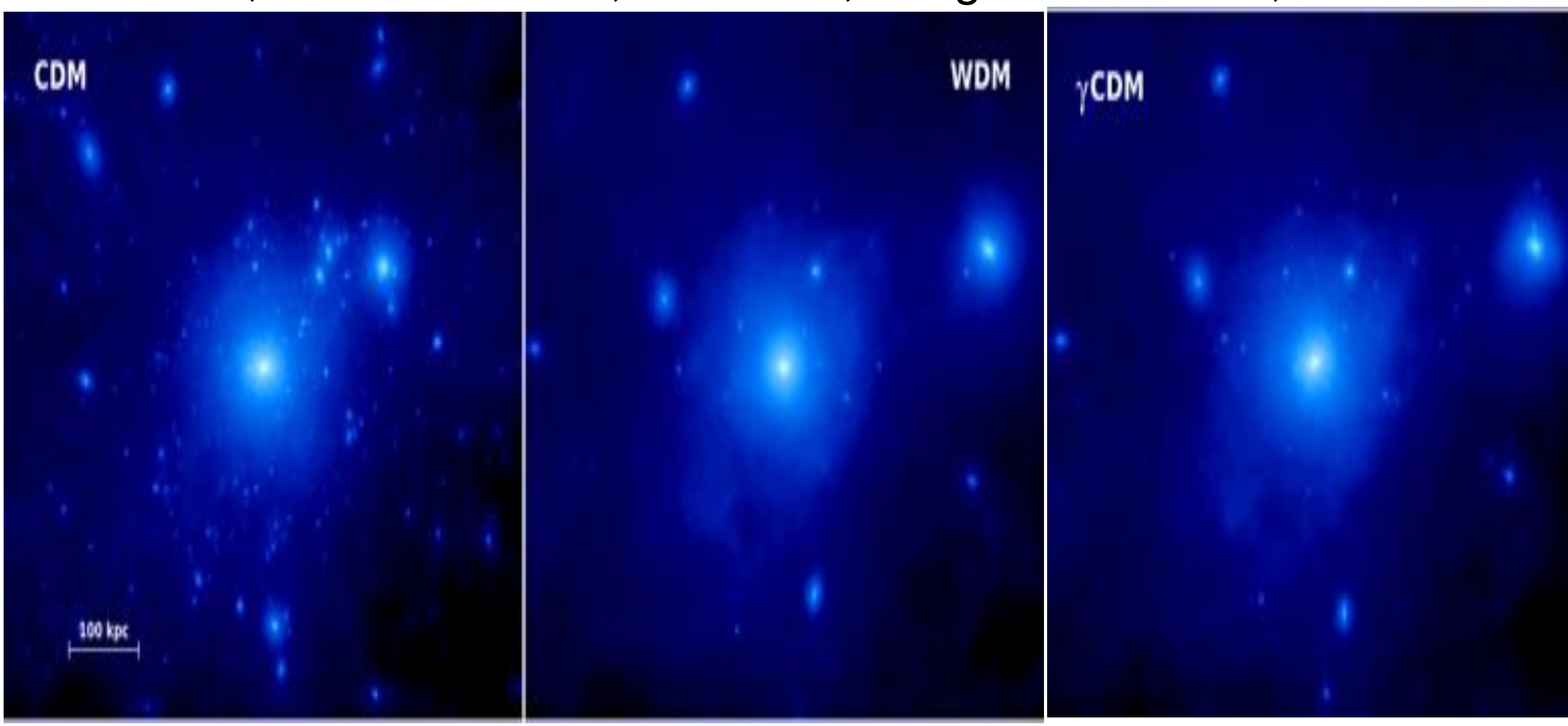




Simulation

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

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



Interacting Radiation

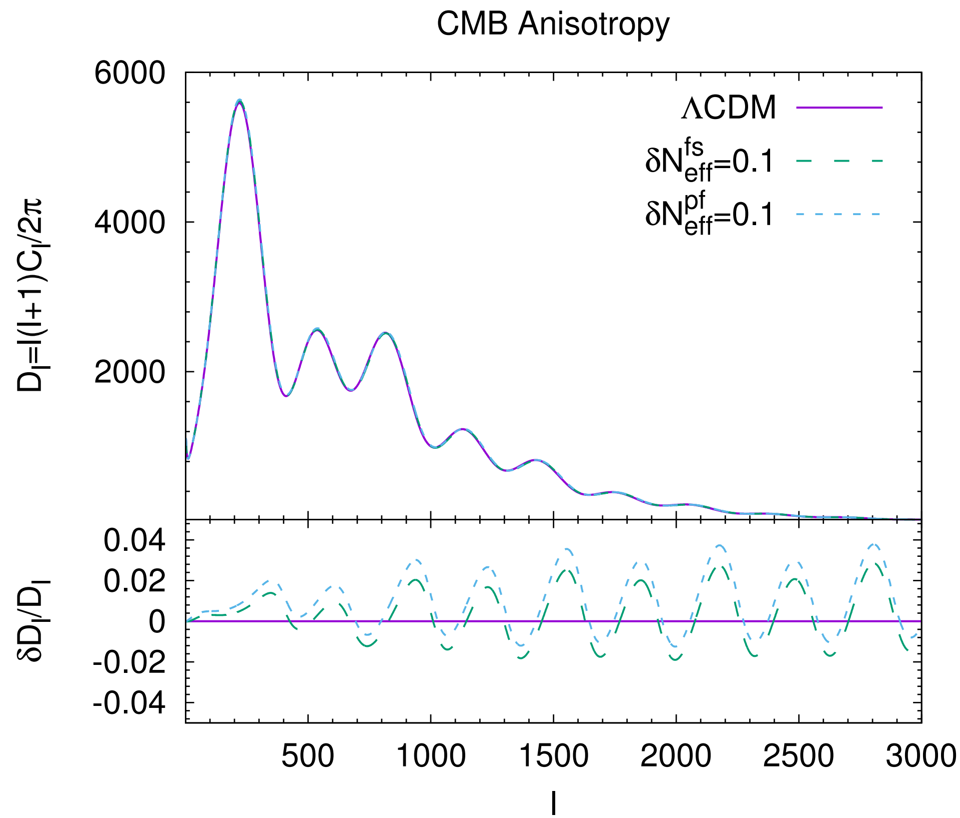
- free-streaming

Y.Tang, arXiv:1603.00165(PLB)

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu + 4\dot{\phi} ,$$

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

$$\dot{F}_{\nu l} = \frac{k}{2l+1}\left[lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}\right] ,$$



- perfect fluid $\Gamma \gg \mathcal{H}$

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu + 4\dot{\phi} ,$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) + k^2\psi , \quad \sigma_\nu=0$$

Neutrinos as perfect fluid excluded, *Audren* **et al 1412.5948**

Dark U(1)

P.Ko, YT, 1404.0236(PLB)

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

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

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

A Toy Model

Y.Tang, arXiv:1603.00165(PLB)

- fermionic DM ψ and scalar radiation ϕ

$$\delta\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m_\psi)\psi - \bar{\psi}(g_i^s + i g_i^p \gamma_5)\psi\phi_i + \frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i - \mathcal{V},$$

$$\mathcal{V} \supset \frac{1}{2}m_i^2\phi_i^2 + \frac{\mu_{ijk}}{3!}\phi_i\phi_j\phi_k + \frac{\lambda_{ijkl}}{4!}\phi_i\phi_j\phi_k\phi_l,$$

- No UV origin is assigned for the scalars, there could be some theoretical issues for a very light scalar, *naturalness*

A Toy Model

Y.Tang, arXiv:1603.00165(PLB)

- fermionic DM ψ and scalar radiation ϕ

$$\delta\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m_\psi)\psi - \bar{\psi}(g_i^s + i g_i^p \gamma_5)\psi\phi_i + \frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i - \mathcal{V},$$

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- If DM is a scalar field X,

$$X^\dagger X\left(\mu_i\phi_i + g_{ij}\phi_i\phi_j\right)$$

- connection with standard model

$$\lambda\phi^2 H^\dagger H, \; \frac{1}{\Lambda}\bar{\psi}\psi H^\dagger H$$

Cosmological observables

- Scalar radiation contributes to N_{eff}

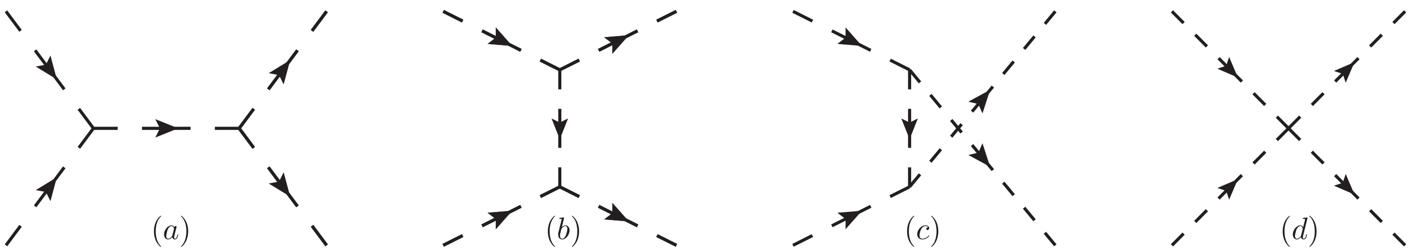
$$\delta N_{\rm eff}^{\phi_1} \equiv \frac{\rho_{\phi_1}}{\rho_\nu} = \frac{4}{7}\frac{T_{\phi_1}^4}{T_\nu^4} = \frac{4}{7}\left[\frac{g_{*s}\left(T_\nu\right)}{g_{*s}^{\phi}\left(T_{\phi_1}\right)} \times \frac{g_{*s}^{\phi}\left(T_{\phi_1}\right)T_{\phi_1}^3}{g_{*s}\left(T_\nu\right)T_\nu^3}\right]^{\frac{4}{3}}$$

$$= \frac{4}{7}\left[\frac{g_{*s}\left(T_\nu\right)}{g_{*s}^{\phi}\left(T_{\phi_1}\right)}\frac{g_{*s}^{\phi}\left(T^{\rm dec}\right)\left(T^{\rm dec}\right)^3}{g_{*s}\left(T^{\rm dec}\right)\left(T^{\rm dec}\right)^3}\right]^{\frac{4}{3}} = \frac{4}{7}\left[\frac{g_{*s}\left(T_\nu\right)}{g_{*s}^{\phi}\left(T_{\phi_1}\right)}\frac{g_{*s}^{\phi}\left(T^{\rm dec}\right)}{g_{*s}\left(T^{\rm dec}\right)}\right]^{\frac{4}{3}},$$

g_{*s}: effective dof in SM, or particles in KE with neutrinos
g_{*s}^{ϕ}: effective dof that are in KE with ϕ_1
$T^{\rm dec}$: kinetic decoupling temperature
typical value for $\delta N_{\rm eff}$ would be around $\mathcal{O}(0.1)$.

if $T^{\rm dec} \sim 1{\rm GeV}$, we have $\delta N_{\rm eff} \simeq 0.045$

Interacting scalar radiation



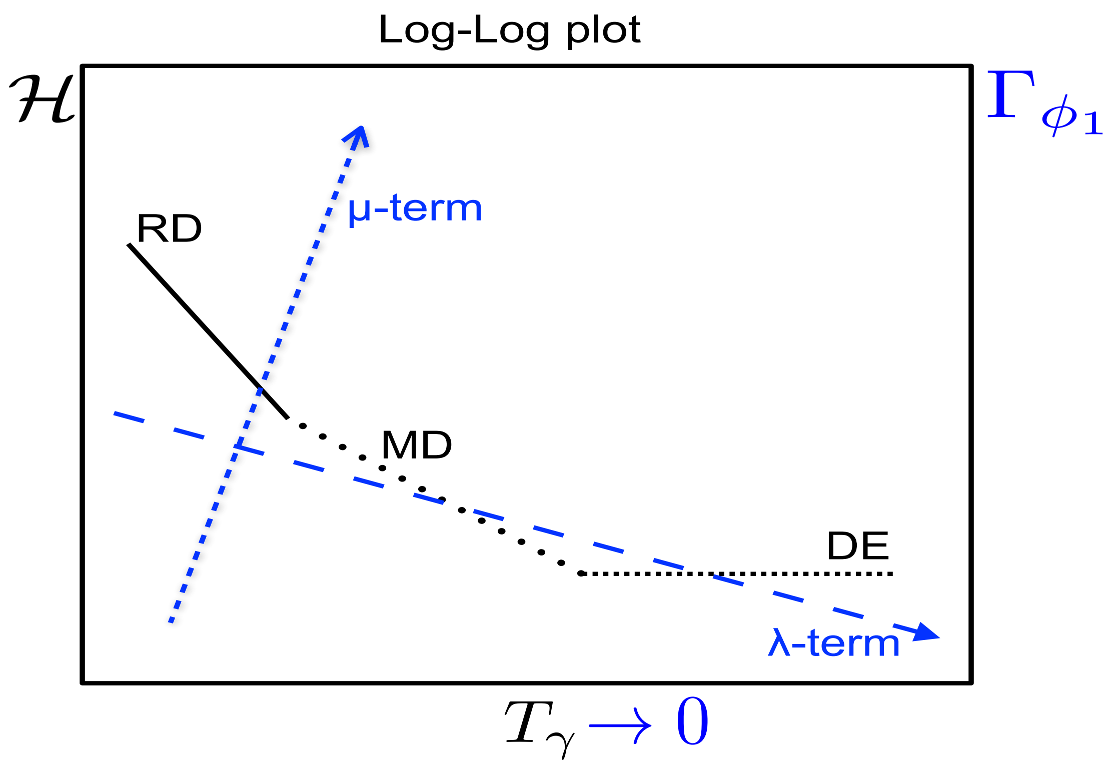
- Interacting rate is given by

$$\Gamma_{\phi_1} = n_{\phi_1} \times \langle \sigma v \rangle \sim T_{\phi_1}^3 \times \left[\frac{3\mu_1^4}{T_{\phi_1}^6} + \frac{\lambda_1^2}{T_{\phi_1}^2} \right] = \frac{3\mu_1^4}{T_{\phi_1}^3} + \lambda_1^2 T_{\phi_1},$$

- compare with Hubble parameter

$$\mathcal{H}^2 \equiv \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \sum_i \rho_i \Rightarrow \mathcal{H} = \sqrt{\frac{8\pi G}{3}} \left[\rho_{r0} \left(\frac{T_\gamma}{T_{\gamma 0}} \right)^4 + \rho_{m0} \left(\frac{T_\gamma}{T_{\gamma 0}} \right)^3 + \rho_{de} \right]^{1/2},$$

Self-Interacting Rate



1. $\mu_1 \neq 0$: There must be a time at which $\Gamma_{\phi_1} \gtrsim \mathcal{H}$.

2. $\mu_1 = 0$ but $\lambda_1 \neq 0$: $\Gamma_{\phi_1} \gtrsim \mathcal{H}$ happens at RD or MD.

3. $\mu_1 = 0$ and $\lambda_1 = 0$: free-streaming after KD,like neutrinos.

Interacting Radiation

- free-streaming

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu + 4\dot{\phi} ,$$

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

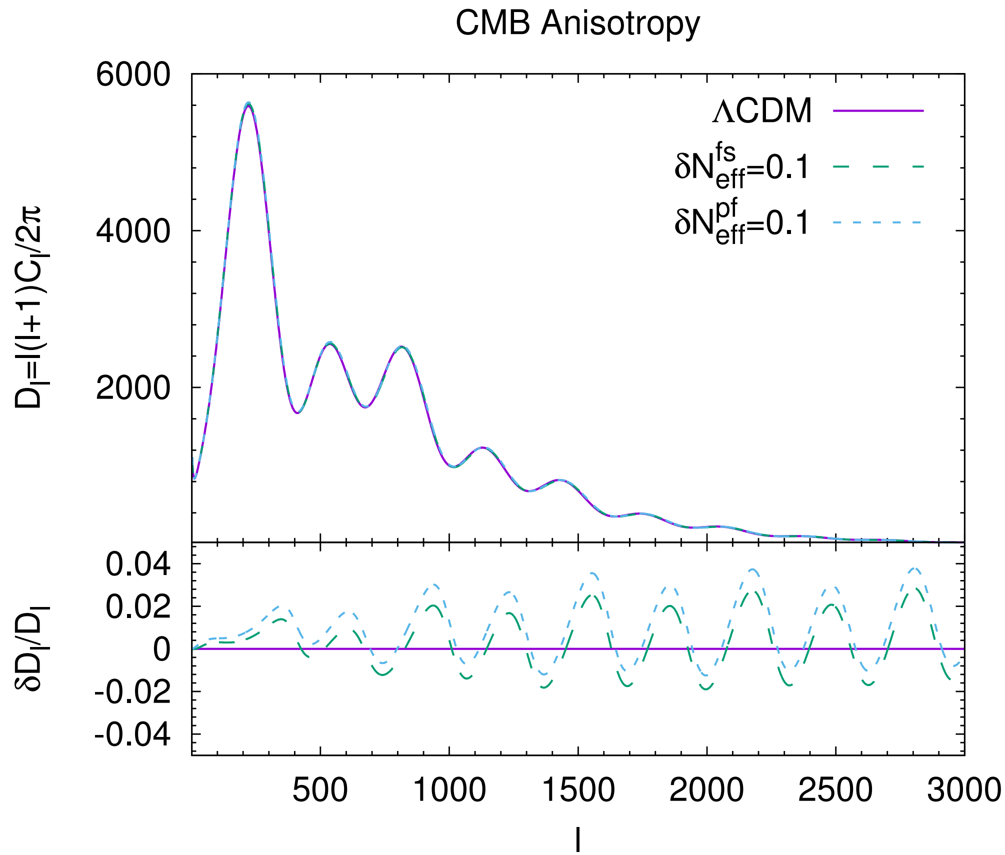
$$\dot{F}_{\nu l} = \frac{k}{2l+1}\left[lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}\right] ,$$

- perfect fluid

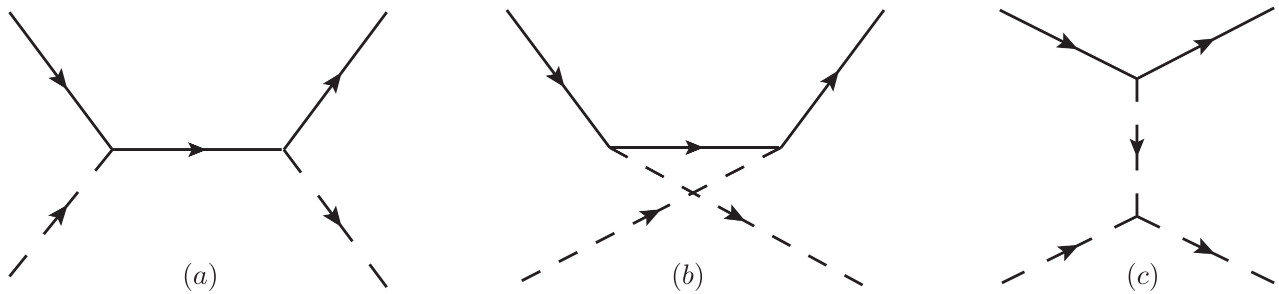
$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu + 4\dot{\phi} ,$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) + k^2\psi , \quad \sigma_\nu=0$$

Y.Tang, arXiv:1603.00165(PLB)



DM-DR scattering rate

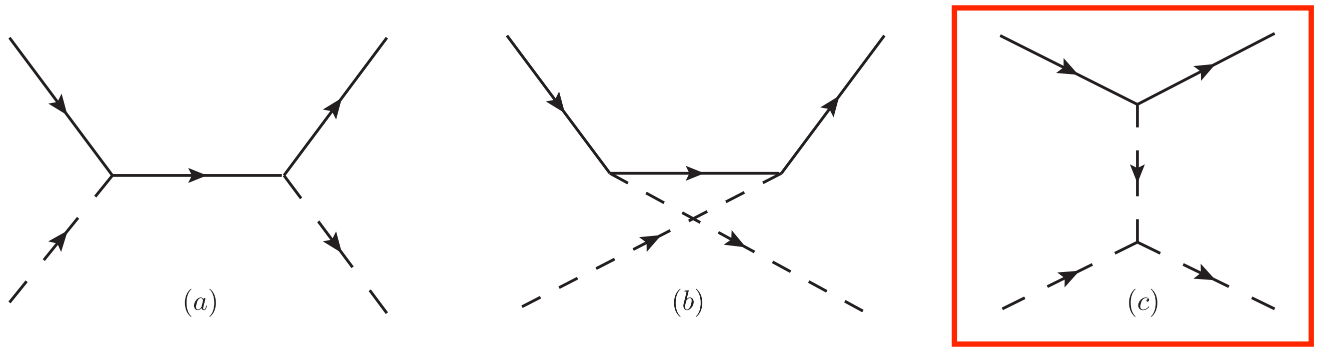


$$\Gamma_{\psi\phi_1}^{a+b} = n_{\phi_1}\langle\sigma v\rangle_{a+b} \sim T_{\phi_1}^3 \times \left[\frac{(g_1^s)^4}{m_\psi^2} + \frac{(g_1^p)^4}{m_\psi^4} T_{\phi_1}^2\right],$$

$$\Gamma_{\psi\phi_1}^{c} = n_{\phi_1}\langle\sigma v\rangle_{c} \sim T_{\phi_1}^3 \times \left[\frac{(g_1^s)^2 \mu_1^2}{T_{\phi_1}^4} + \frac{(g_1^p)^2 \mu_1^2}{m_\psi^2}\frac{1}{T_{\phi_1}^2}\right],$$

- $\Gamma > \mathcal{H}$ can happen at later times, unlike the baryon-photon case (BAO).

DM-DR scattering rate



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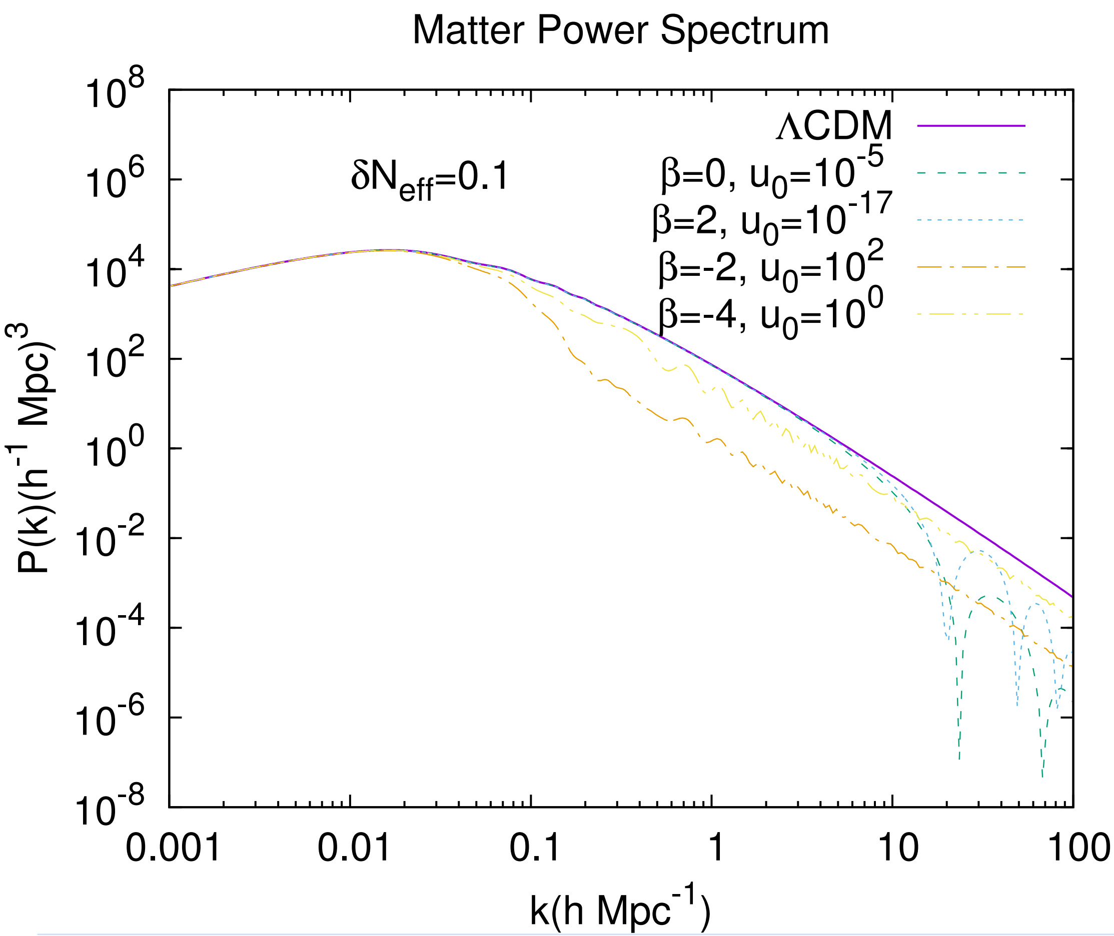
- $\Gamma > \mathcal{H}$ can happen at later time, unlike the baryon-photon case (BAO).

Effects on LSS

$$u_0 \equiv \left[\frac{\sigma_{\psi\phi_1}}{\sigma_{\rm Th}}\right]\left[\frac{100{\rm GeV}}{m_\psi}\right], u_\beta(T) = u_0\left(\frac{T}{T_0}\right)^\beta,$$



- Dark acoustic oscillation arise
- Patterns depend on the interacting type, or underlying particle model
- Both at small and large scale
- Constraint, *T*~keV decoupling for β>0

Summary

- Interacting DM is an interesting possibility.
- controversies in CDM paradigm, *cusp-vs-core, too-big-to-fail, and missing satellites* problems.
- Interaction with radiation could have observable effects. Effects also depend on the nature of DR.
- We also show with $U_X(1)$ with sterile neutrino, and a toy model about DM-DR system where scalar DR can have quite different late time behavior on LSS.

Thanks for your attention.