Galactic Rotation Curves with Dark Matter Self-Interactions

Ayuki Kamada (UC Riverside)

9/3 2015 @ Kavli IPMU

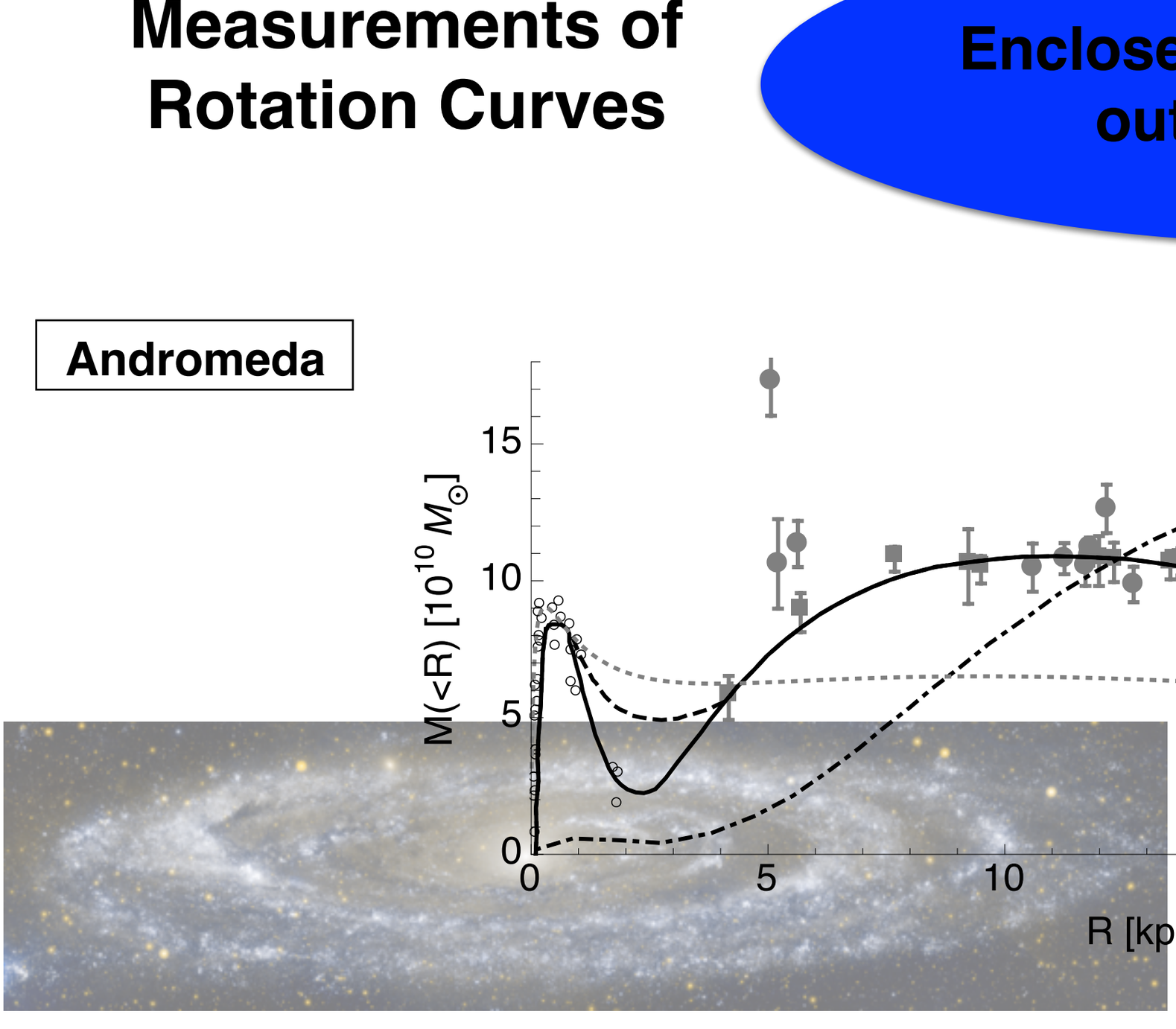
Rotation Curves

1970 Rubin, Ford

Measurements of Rotation Curves

Enclosed mass increases outside the disk

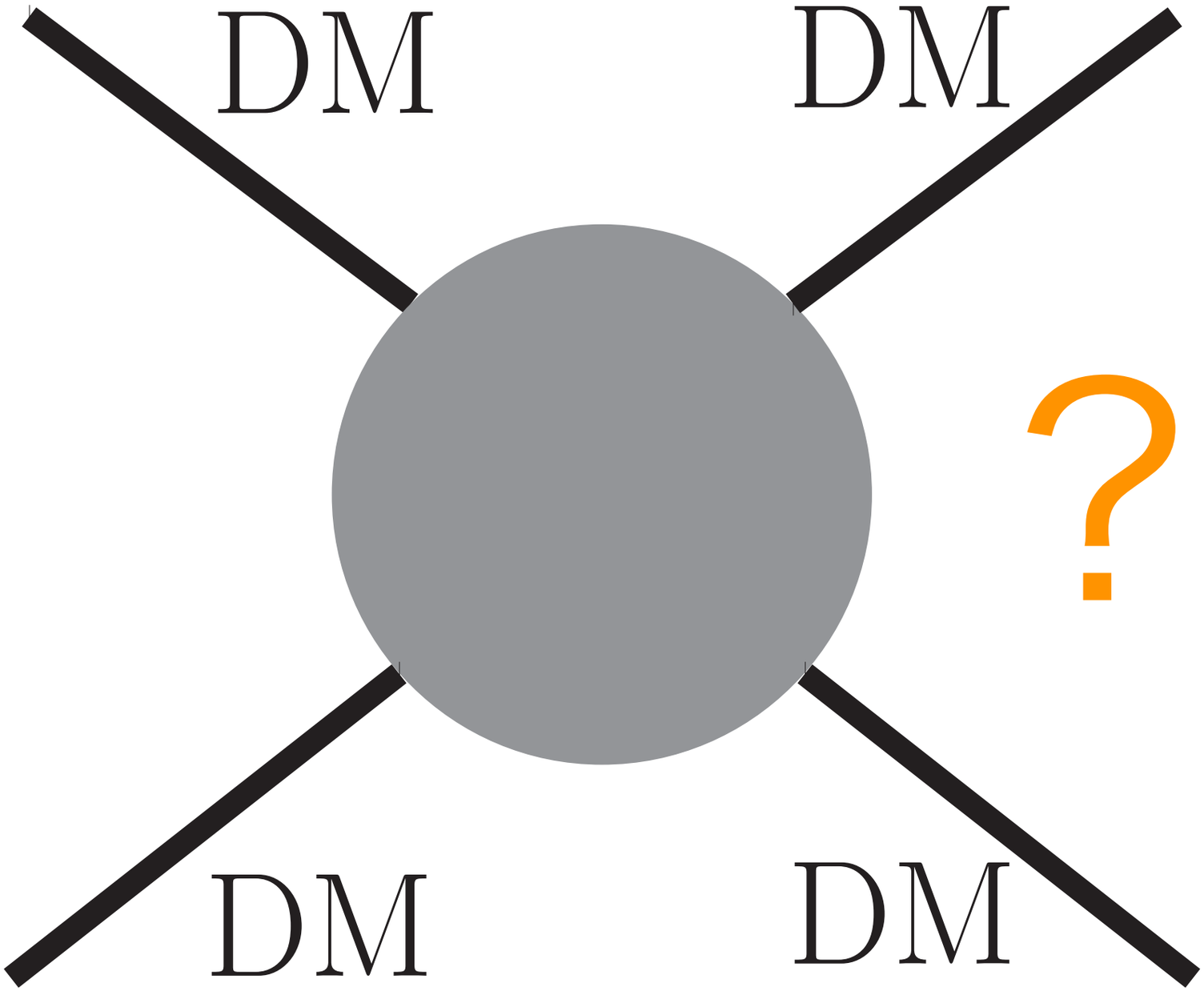
Andromeda



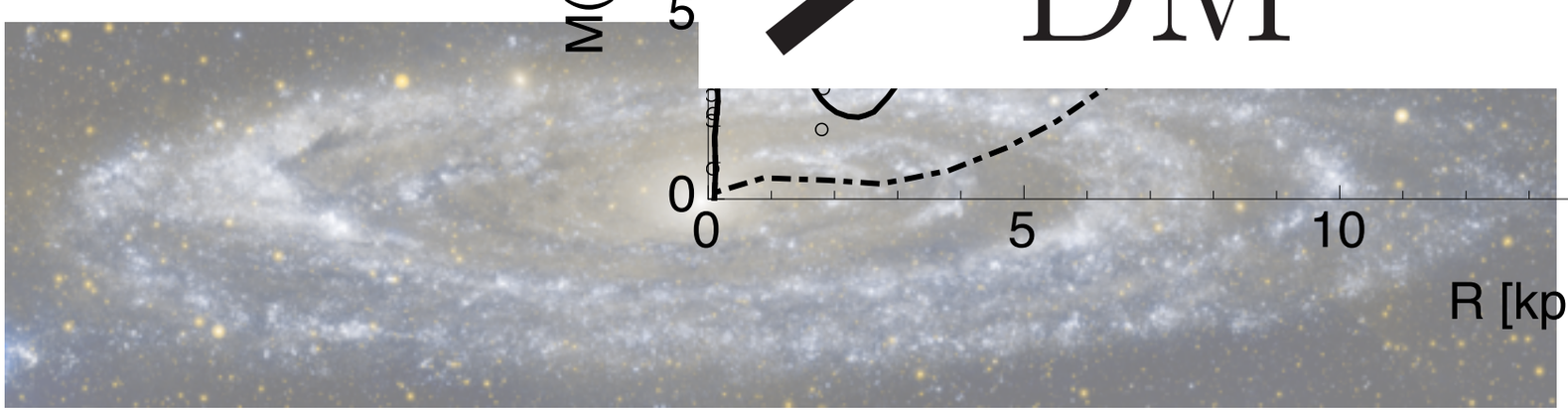
Rotation Curves

1970 Rubin, F

Measuremer
Rotation Cu



Andromeda



Outline

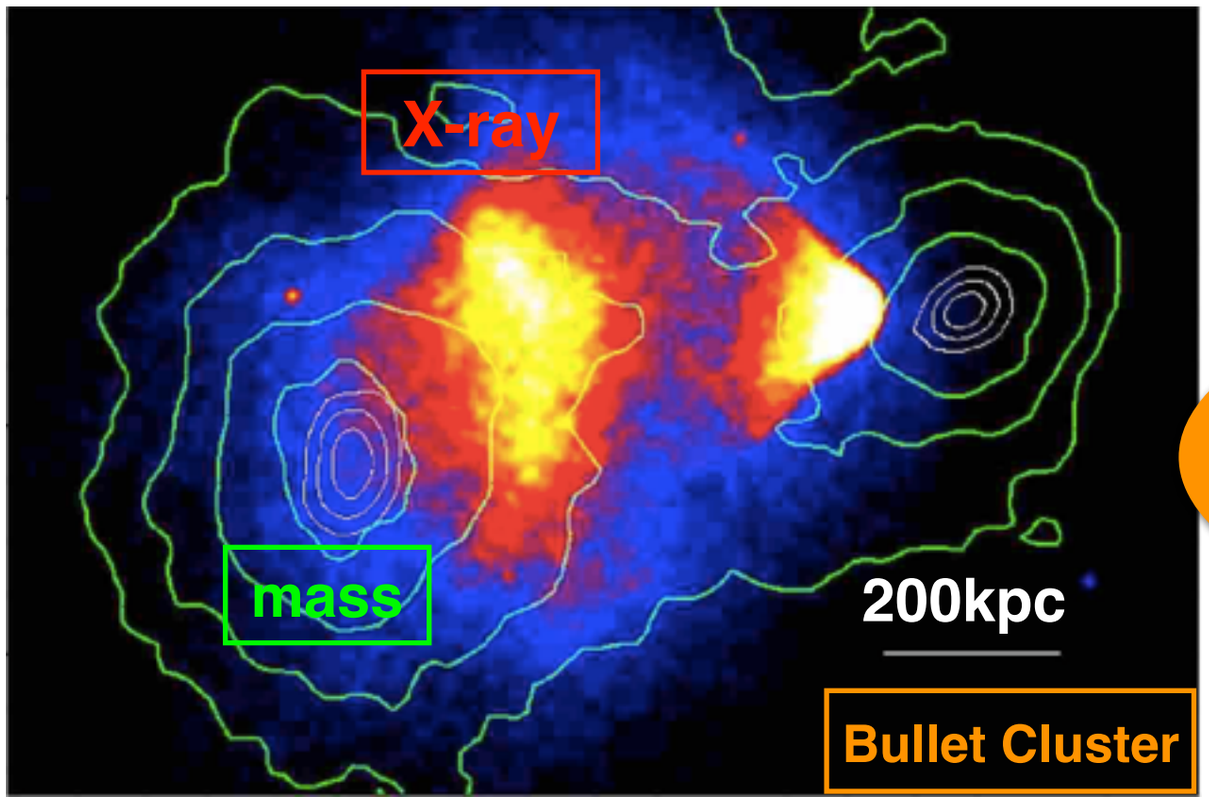
1. Issues in Cold Dark Matter Model

2. Interesting Alternatives

3. Self-Interacting Dark Matter and Rotation Curves

4. Summary

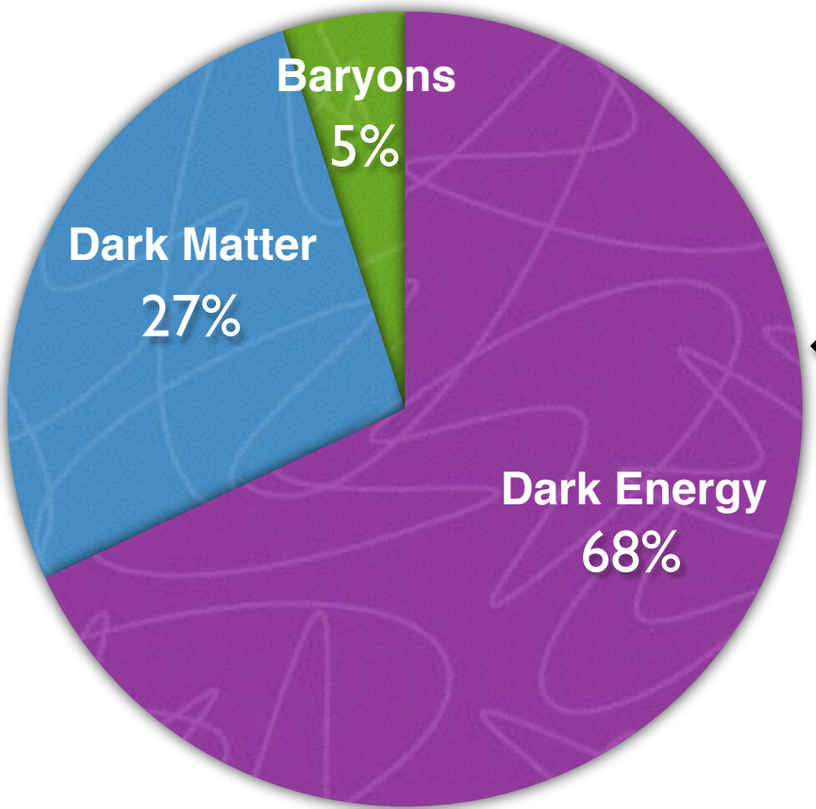
Evidence of Dark Matter

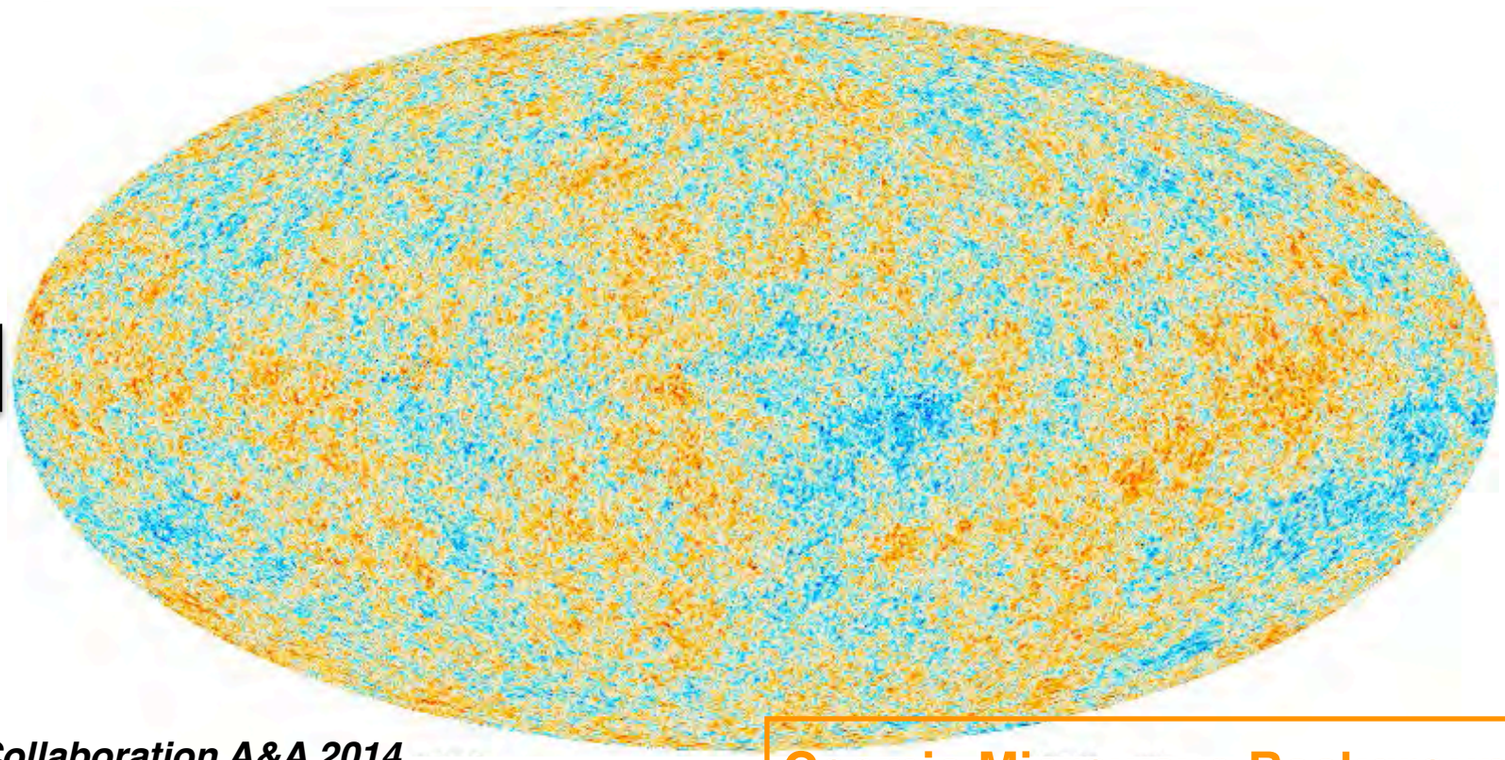


Mass peak and **X-ray peak** **do not** coincide

Invisible masses pass through each other

De-Chang Dai et al. PRD 2008



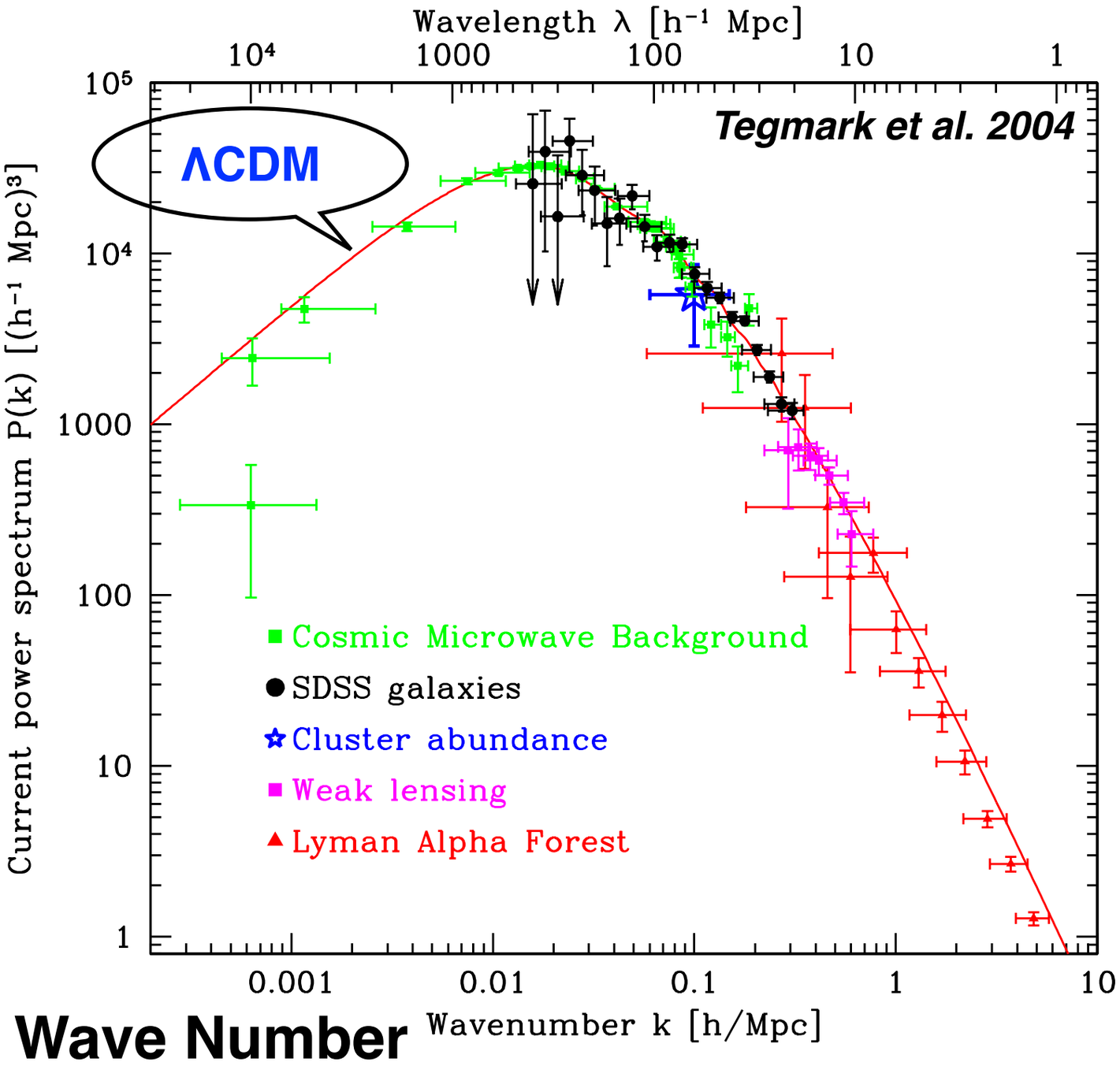


Planck Collaboration A&A 2014

Cosmic Microwave Background

Success of CDM at LSS

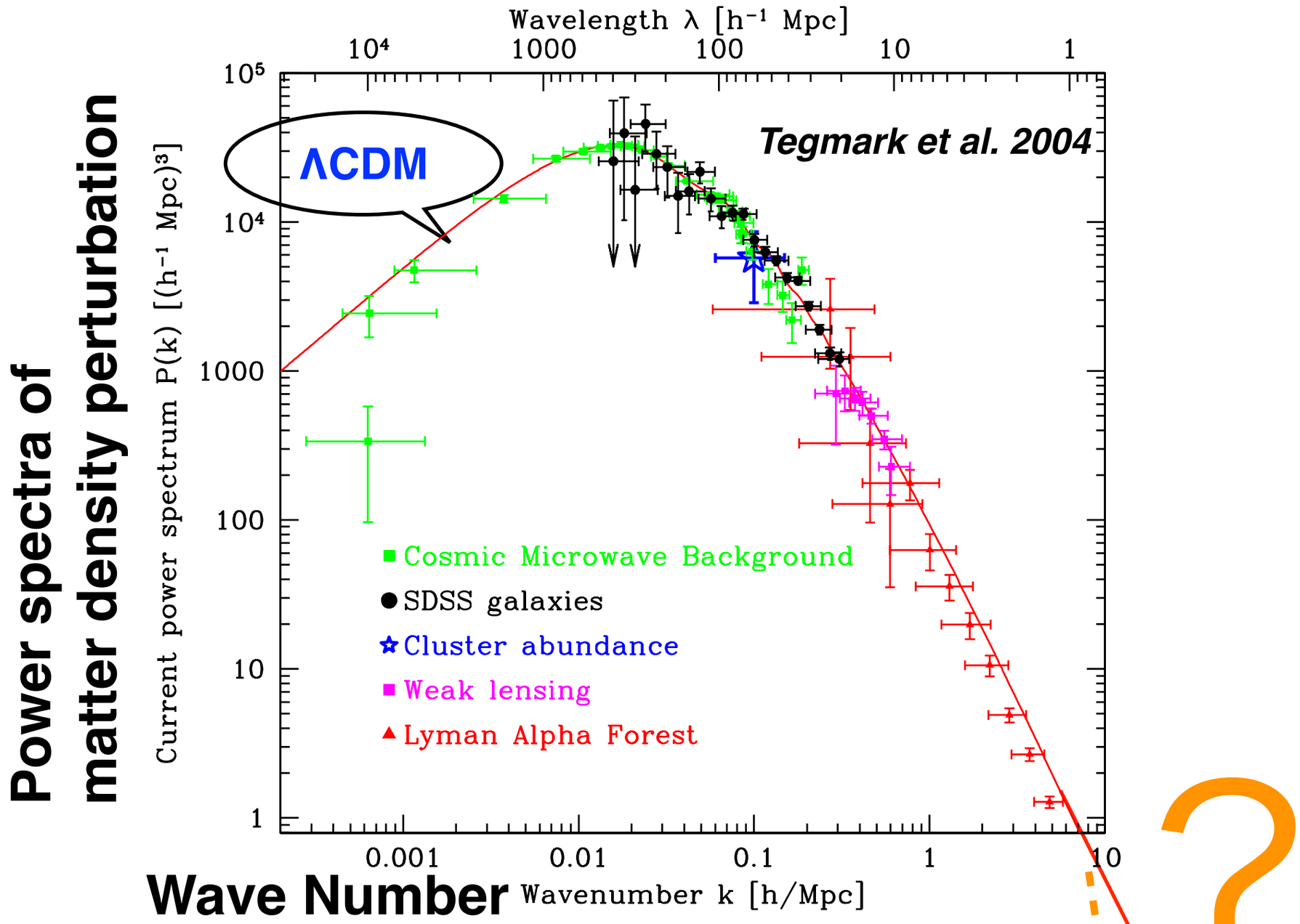
Power spectra of matter density perturbation



Wave Number

ΛCDM cosmology prediction is concordant with observed large scale structures

Small Scale Structure

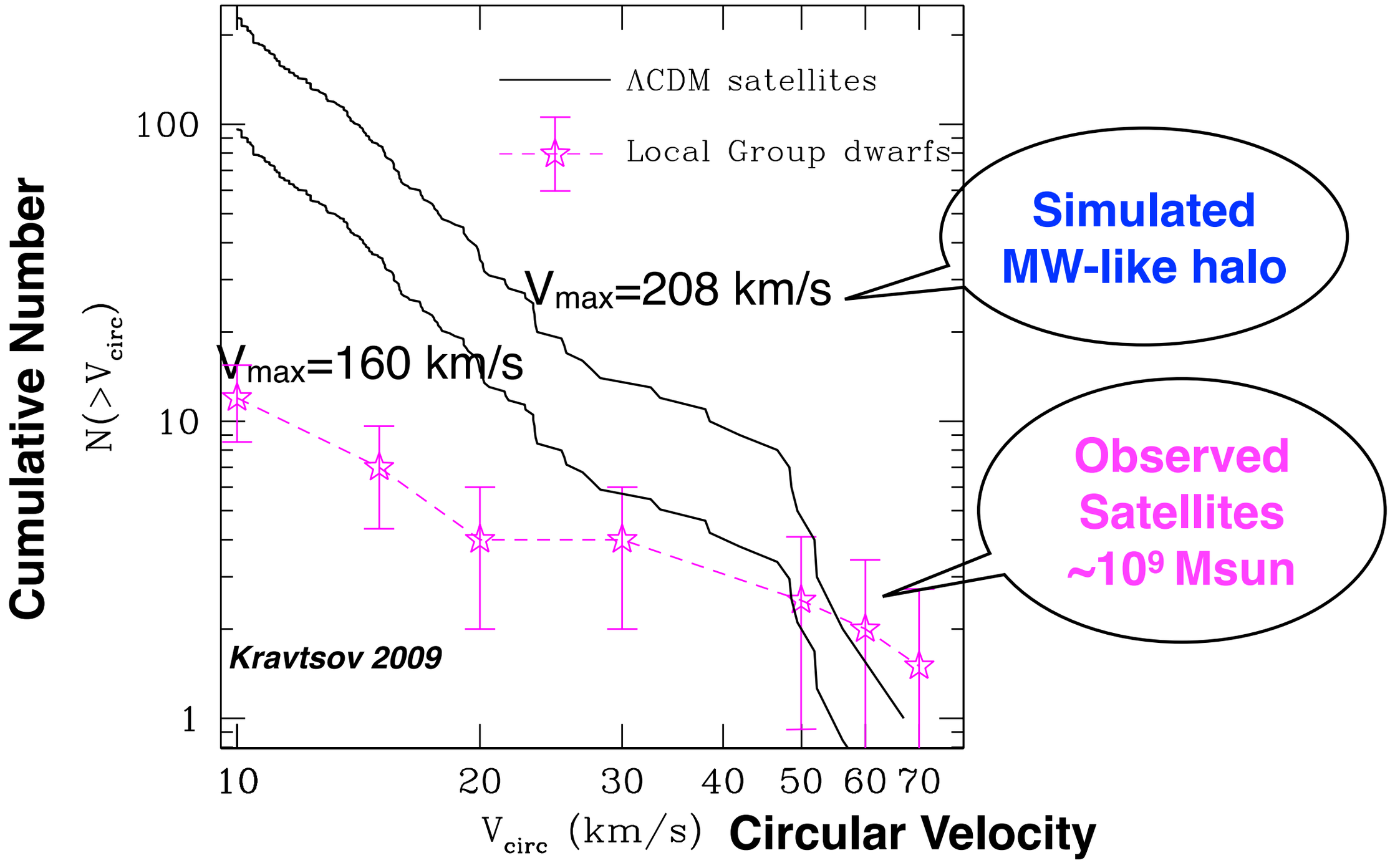


?

Several problems are reported at (sub-)galactic scales

- **Small Scale Crisis**

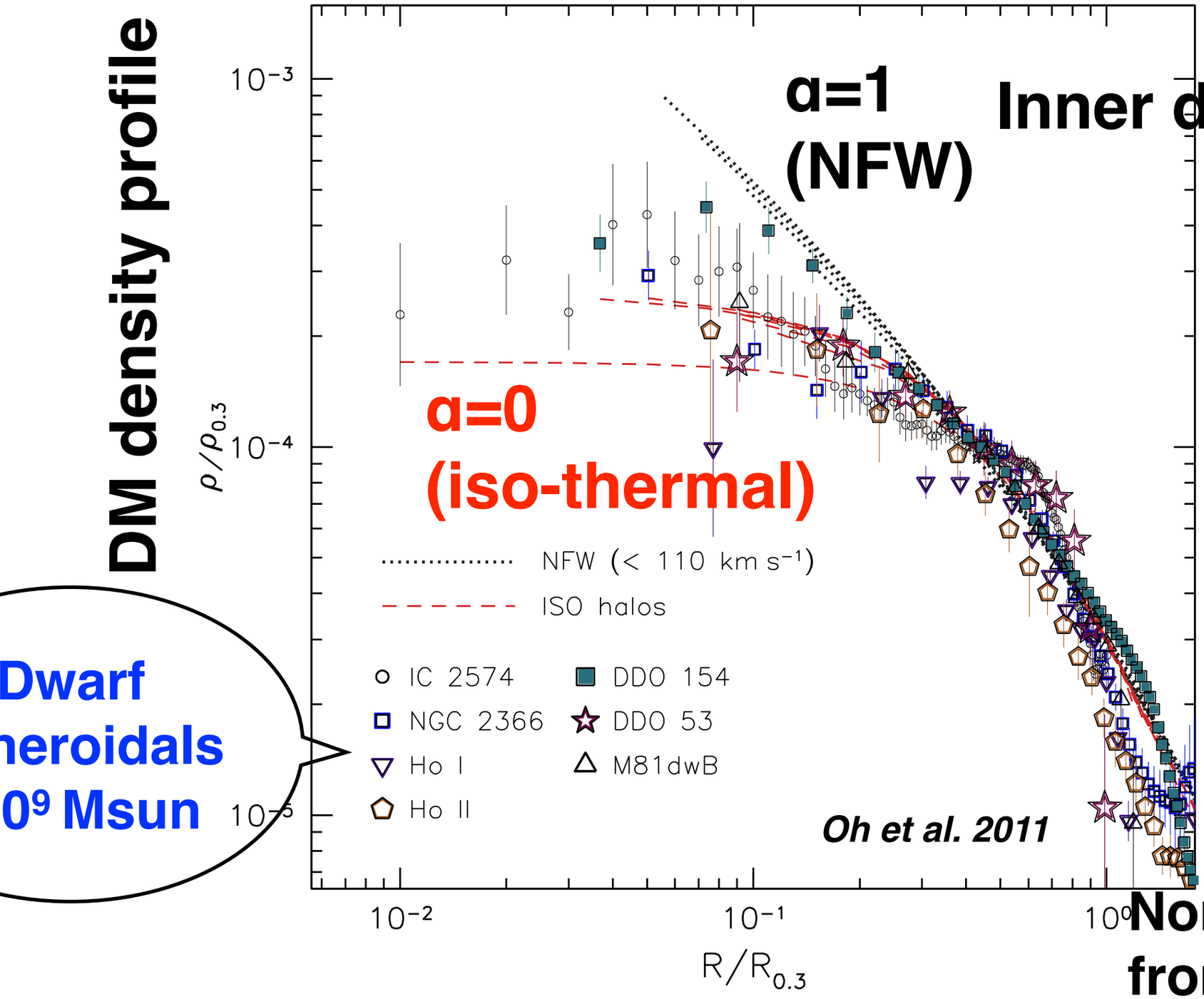
Missing Satellite Problem



Predicted number of subhalos in CDM model

>> number of observed satellites in Local Group

Cuspy Halo Problem



Inner density profile

$\rho \propto r^{-\alpha}$

Dwarf Spheroidals ~10^9 Msun

Normalized distance from the center

Predicted density profile in CDM model is too steep compared with observed dwarf spheroidals

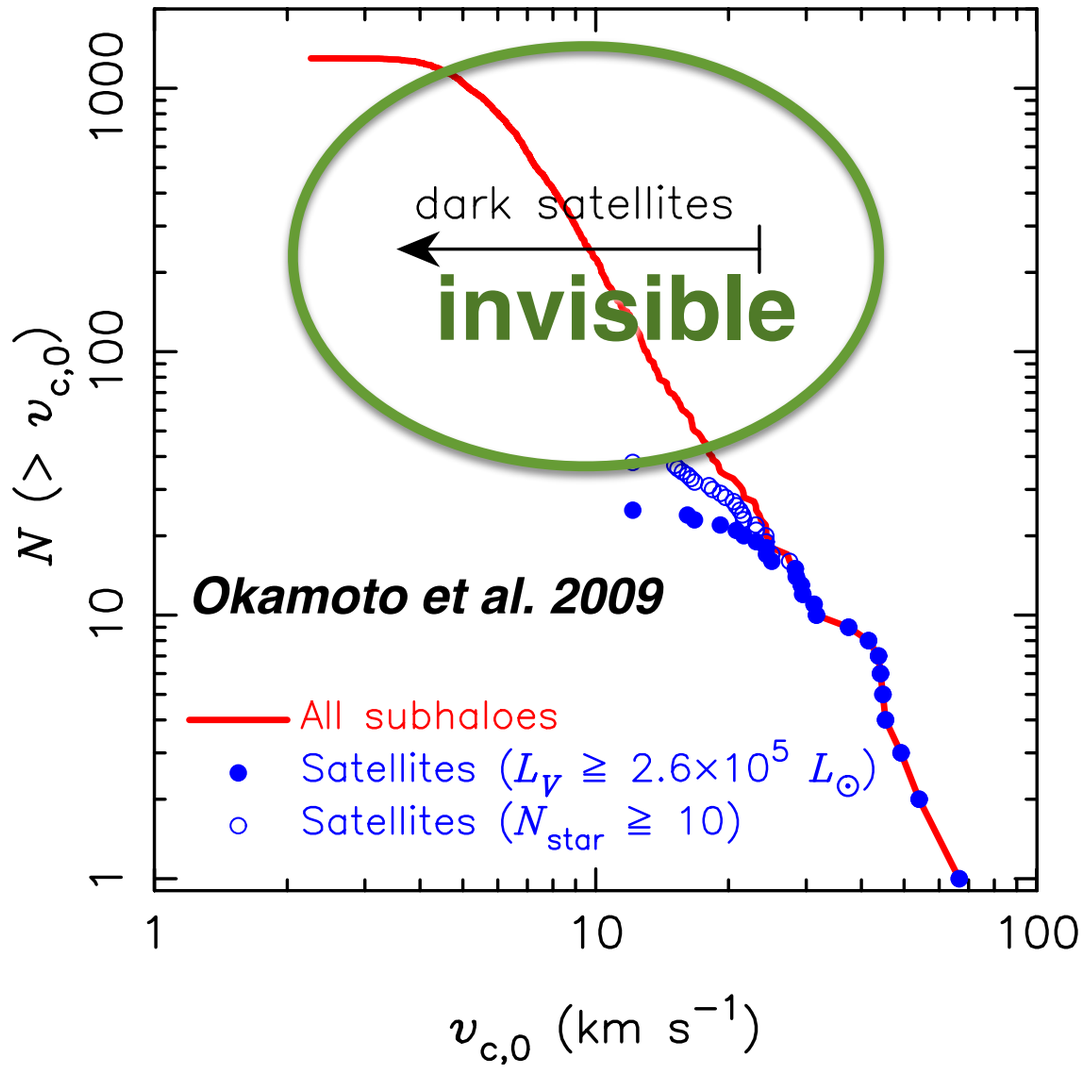
Possible Solutions

Baryon Dynamics

- Supernova Feedback
- UV Flux

Alternatives to CDM

- Thermal Velocity
- Interaction between DM-SM particles
- Interaction between DM-DM particles



Hot/Cold DM

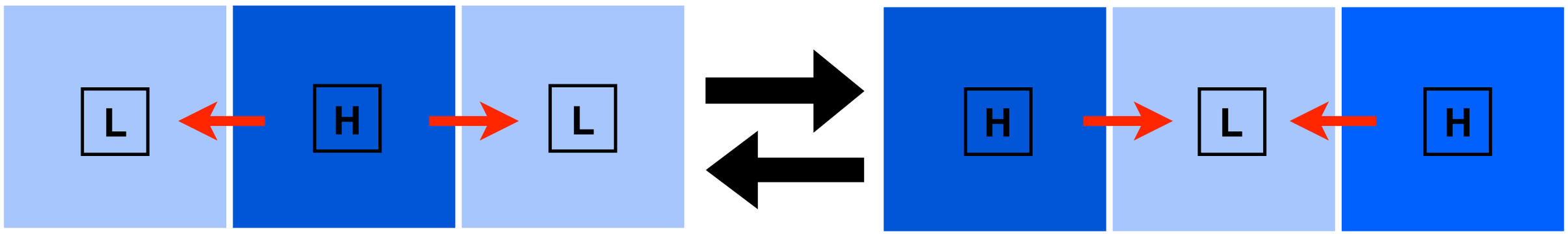
Heavy Neutrino

Cold Dark Matter (CDM) : negligible thermal velocity

Light Neutrino

Hot Dark Matter (HDM) : large thermal velocity

v~0.05×c around matter radiation equality $z_{eq} \sim 3000$



DM density **Flux = velocity × density**

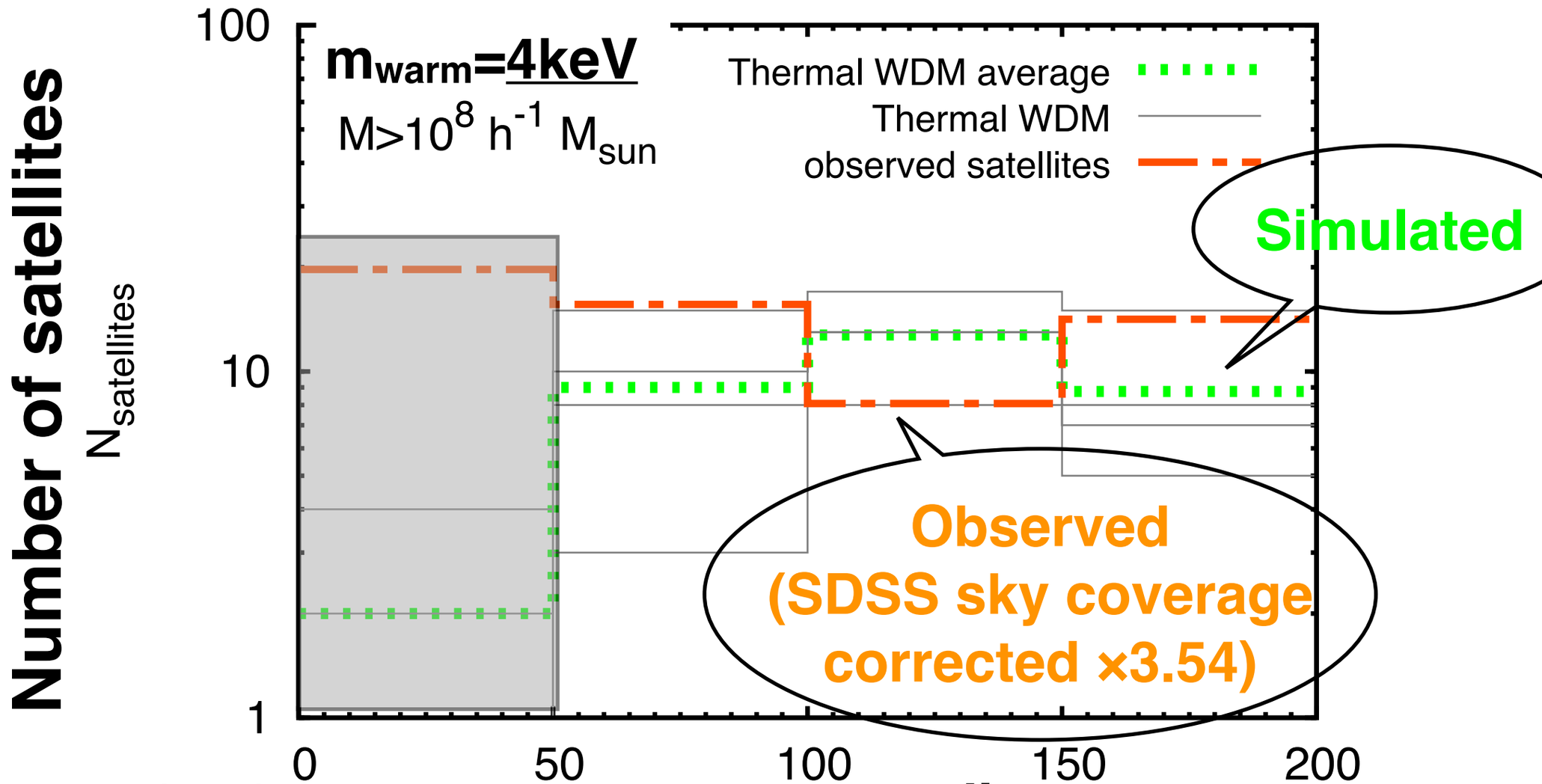
Thermal Velocity → Effective Pressure

Jeans length $\lambda_J \sim 100$ Mpc

Warm Dark Matter

Warm Dark Matter (WDM) : moderate thermal velocity

Not Cold nor Hot **Jeans length $\lambda_J \sim 1$ Mpc**



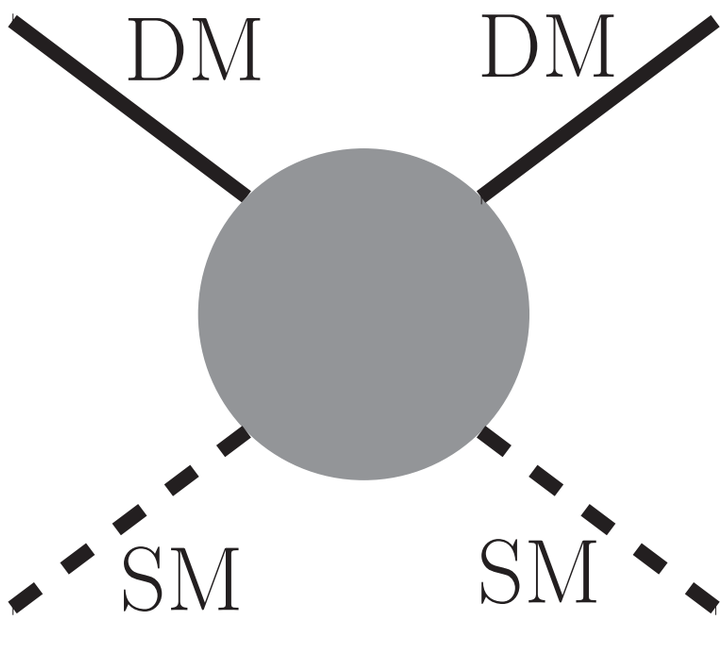
m_{warm}=2-4 keV (SDSS corrected)

m_{warm}=1-2 keV (SDSS uncorrected)

is preferred

AK, Yoshida, Kohri, Takahashi 2013

DM-SM interaction



: chemical interaction
the number of DM is not conserved.
the energy&momentum of DM are redistributed.

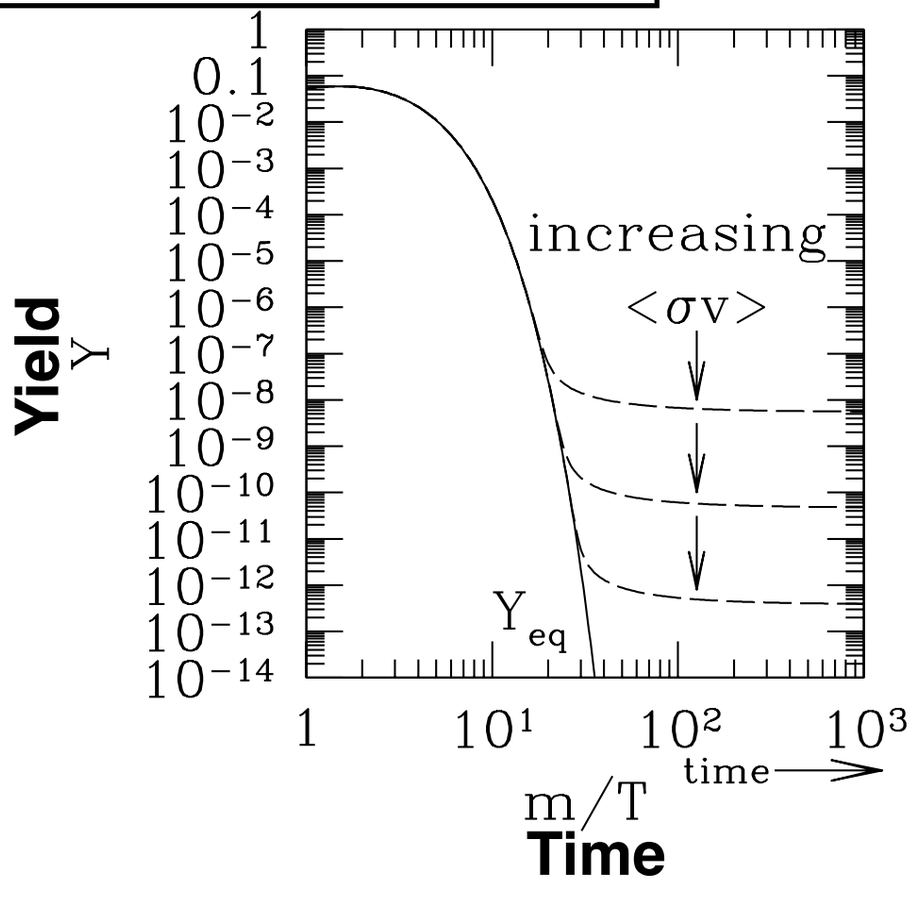
At the chemical decoupling,
the number density of DM freezes out.

Observational consequence:
relic abundance of DM

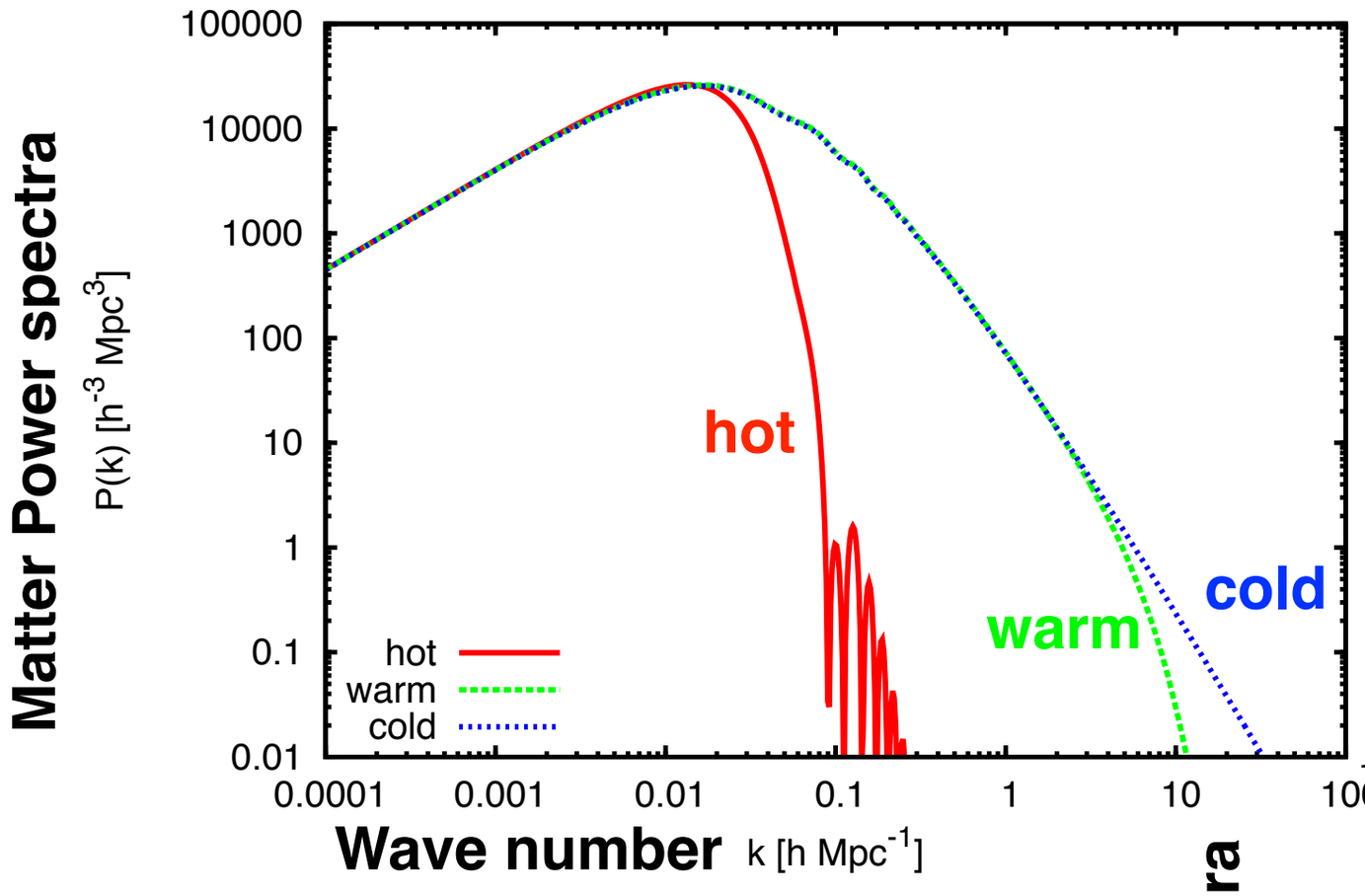
: kinetic interaction
the number of DM is conserved.
the energy&momentum of DM are redistributed.

After the kinetic decoupling,
DM streams freely.

Observational consequence:
Minimum mass of (sub-)halo



DM-SM interaction mimics WDM

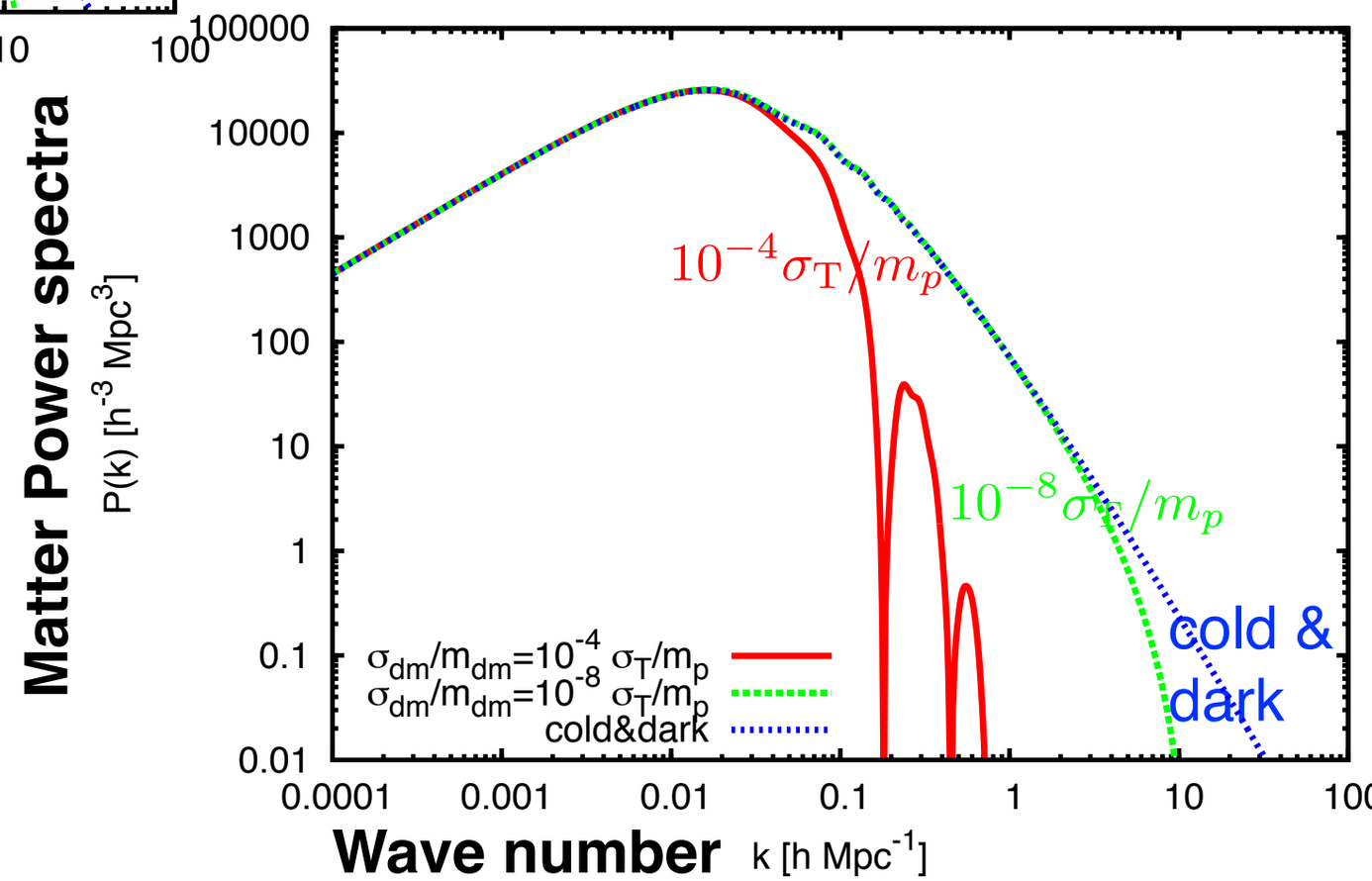


Thermal Velocity

→ **Effective Pressure**

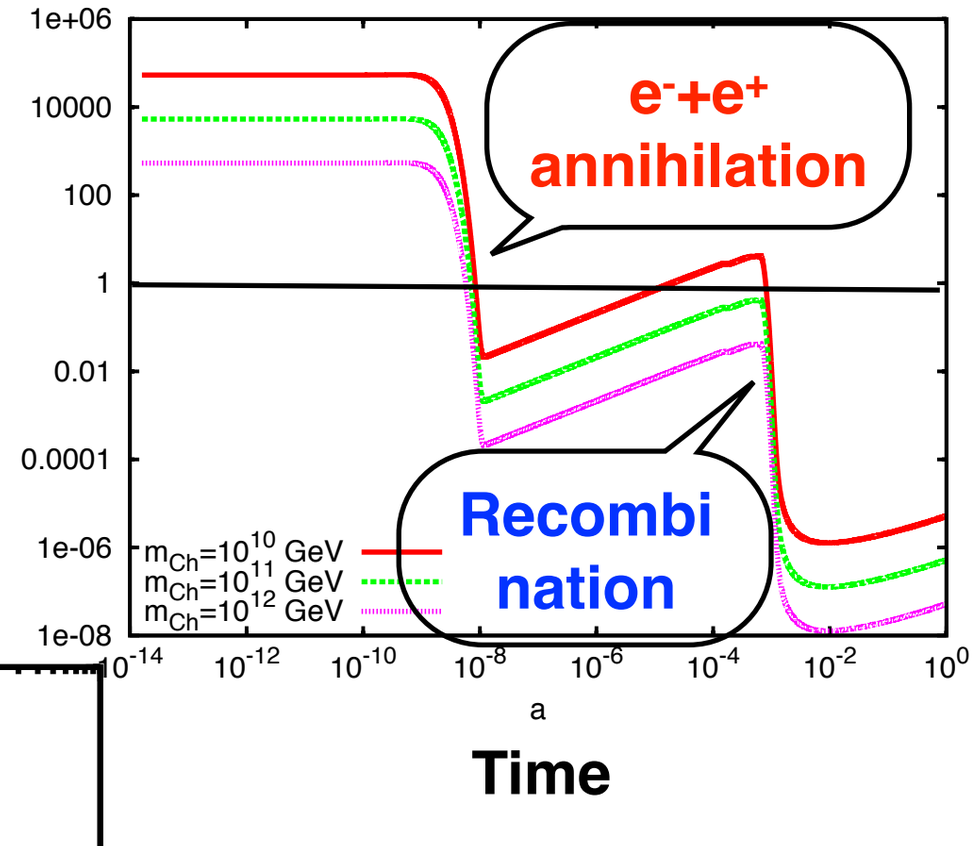
DM-SM interaction

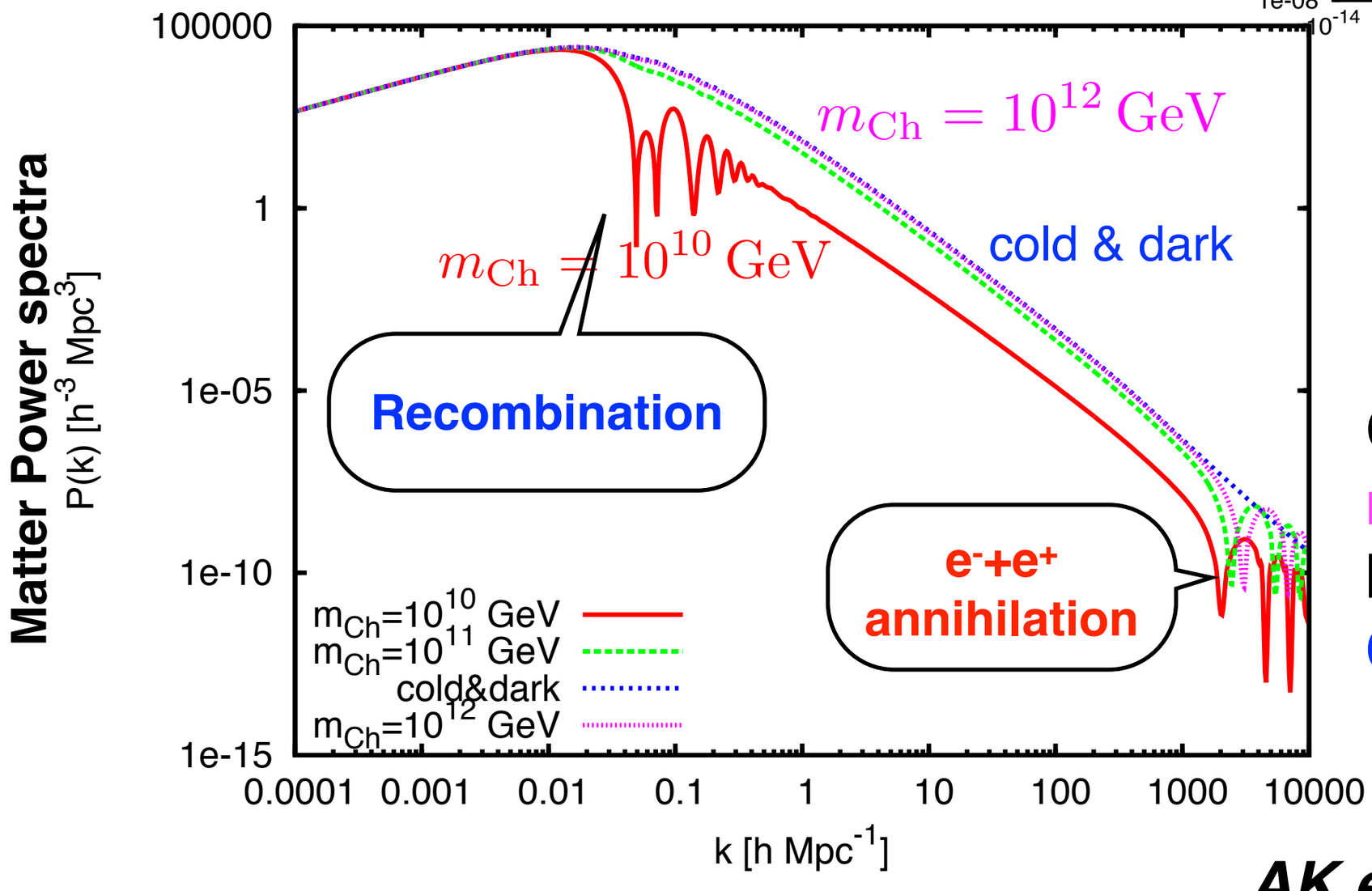
→ **Plasma Pressure**



CHAMP

CHAged Massive Particles (CHAMPs) account for DM

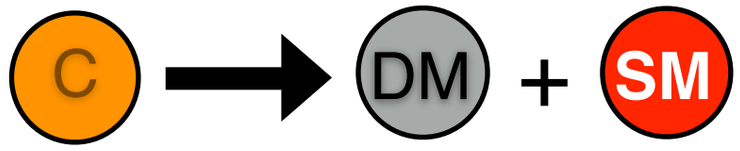


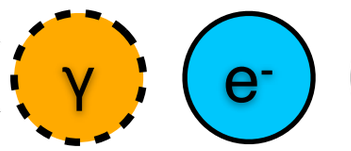


Quite Heavy CHAMP $m_{Ch}>10^{12}$ GeV can not be distinguished from CDM

AK et al. to be published

Long-Lived CHAMP

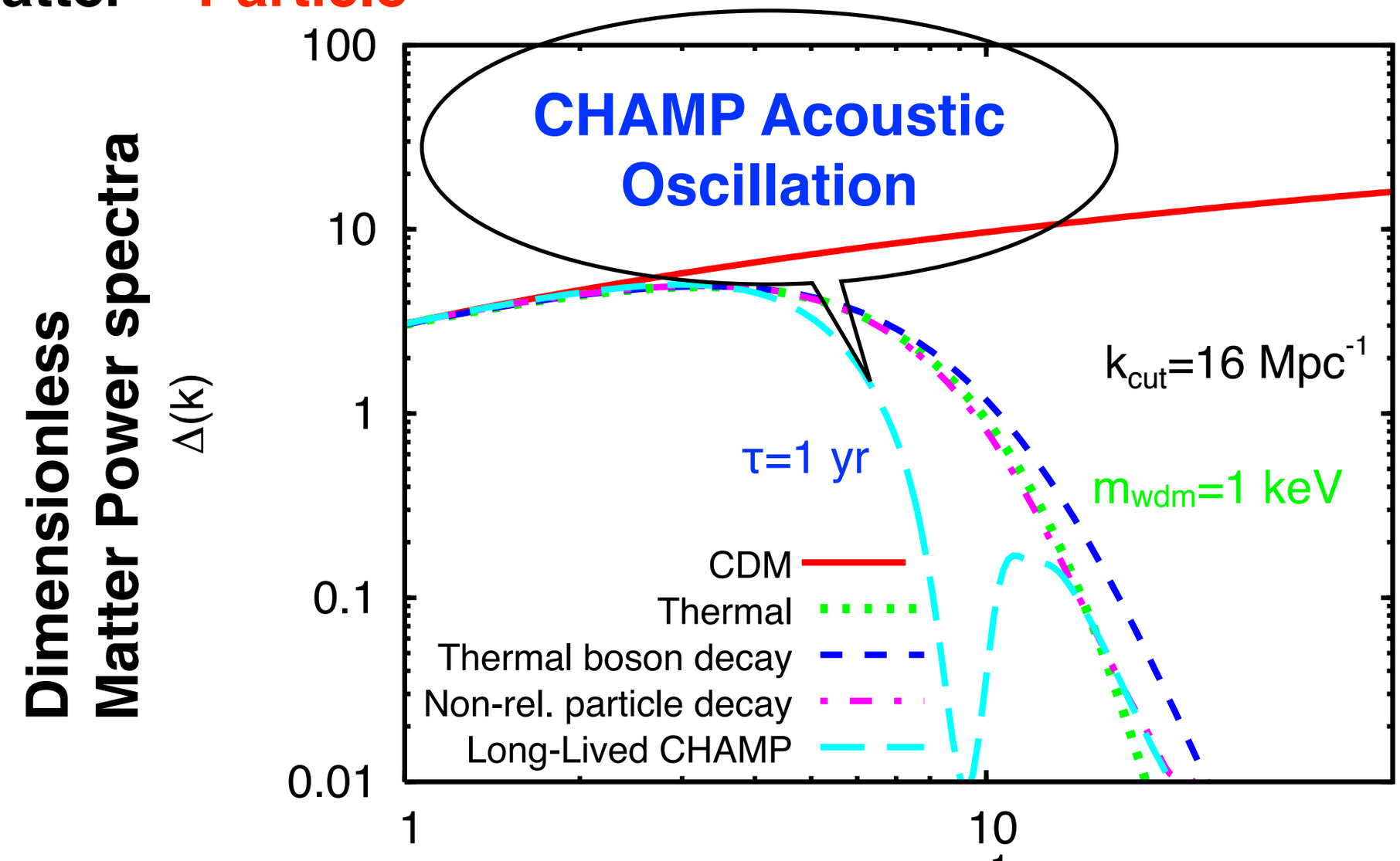


Plasma (

) pressure

CHAMP — **Neutral Dark Matter** — **Charged SM Particle**

prevents CHAMPs from falling into the bottom of gravitational potential



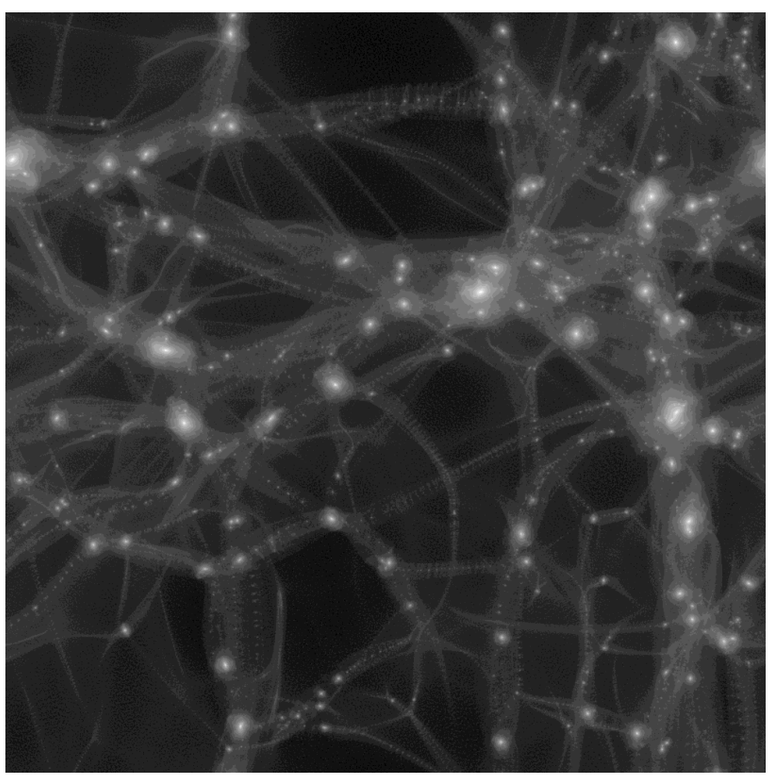
AK, Yoshida, Kohri, Takahashi 2013

Wave Number

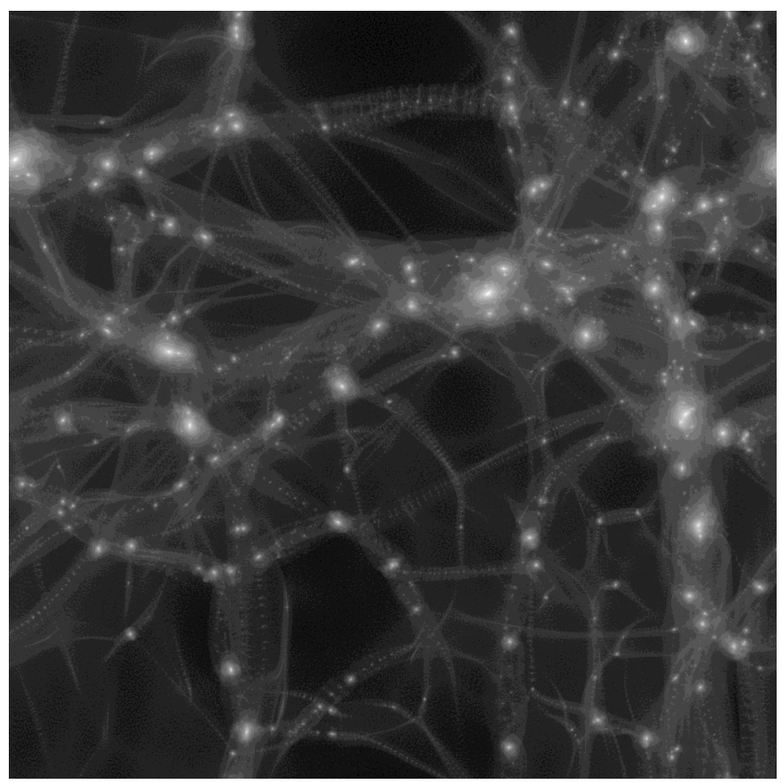
DM Structure in alternative Models

10 Mpc

CDM



Long-Lived CHAMP
or
WDM

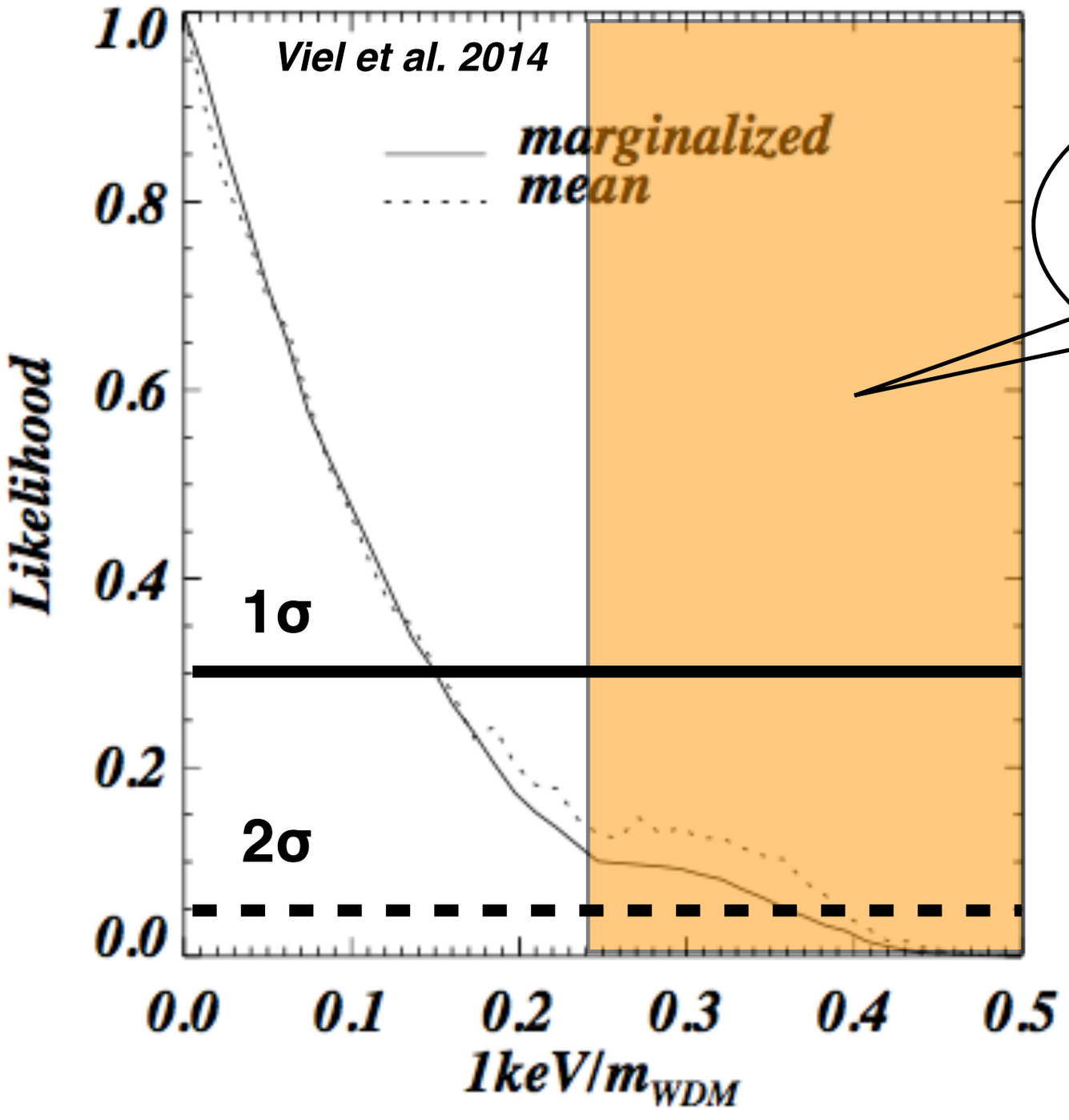


WDM
or
Long-Lived CHAMP

Structures in Long-Lived CHAMP model and WDM model are similar to each other

Lyman-alpha forest constraint

Spectrum data of z>4 Quasers from HIRES+MIKE



Preferred from
Small Scale Crisis
(SDSS correction)

m_{warm}=2-4keV
is excluded at 90% CL

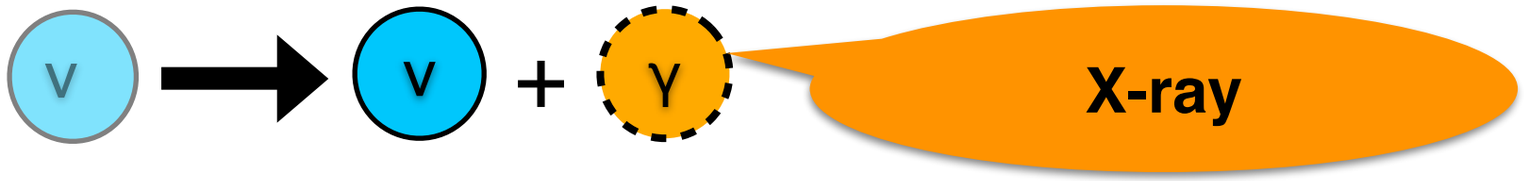
Sterile Neutrino

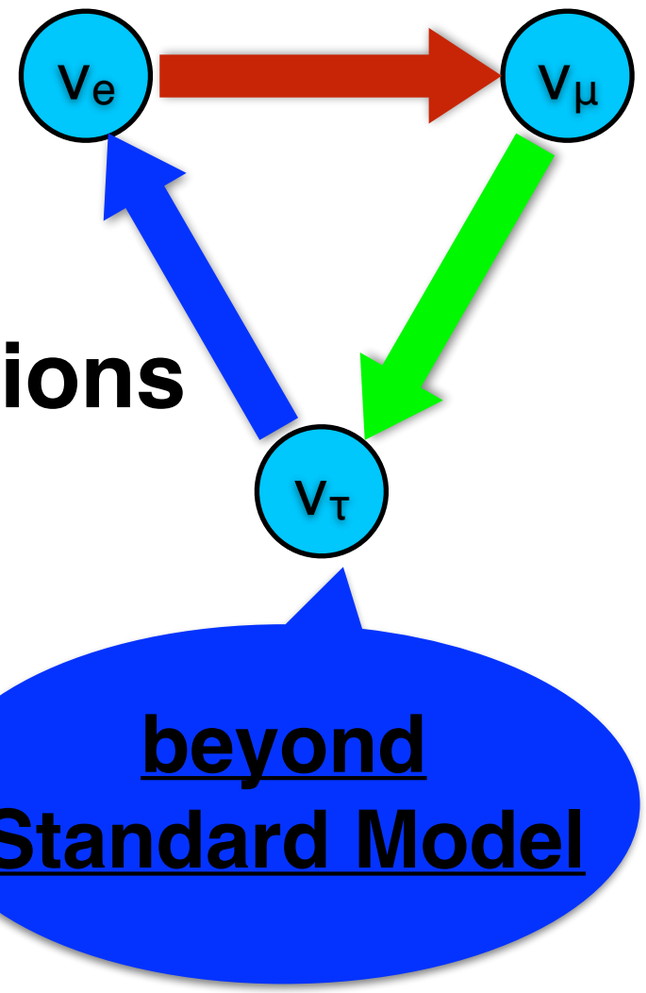
Sterile Neutrino : 

Explain Neutrino Oscillation

Do not have electroweak/strong interactions

Radiative Decay $\tau = 10^{27}$ s





Anomalous X-ray line @ 3.5 keV ?

Bulbul et al. 2014 ***Boyarsky et al. 2014*** **XMM-Newton, Chandra**

↔ null detection ***Tamura et al. 2014*** ***Sekiya et al. 2015*** **Suzaku**

Mixed Dark Matter

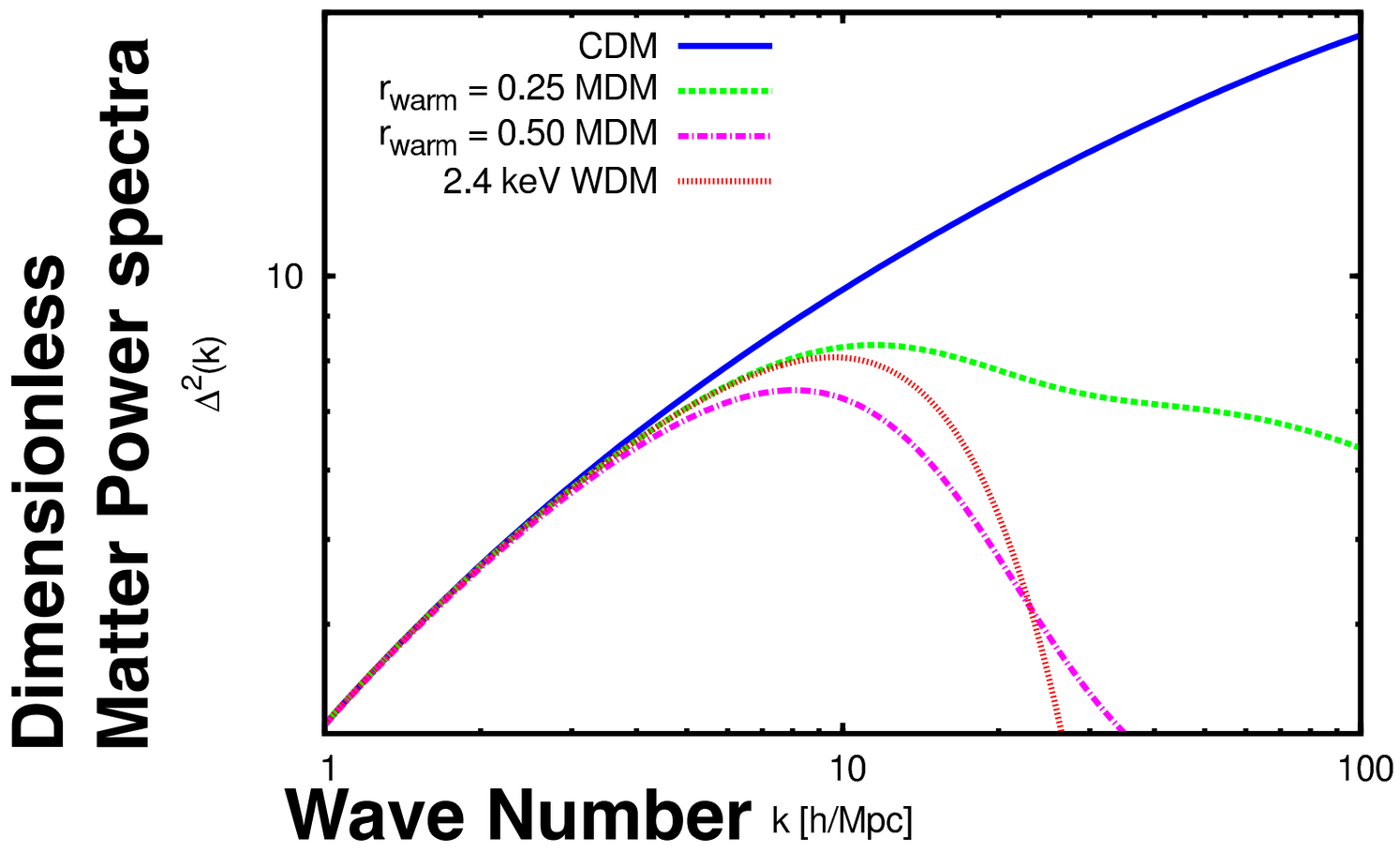
Can radiative decay of sterile neutrino explain it?

Abazajian 2014 Yes, but requires large lepton asymmetry

$n_L/n_\gamma \sim 10^{-4}$ c.f. $n_B/n_\gamma \sim 10^{-10}$

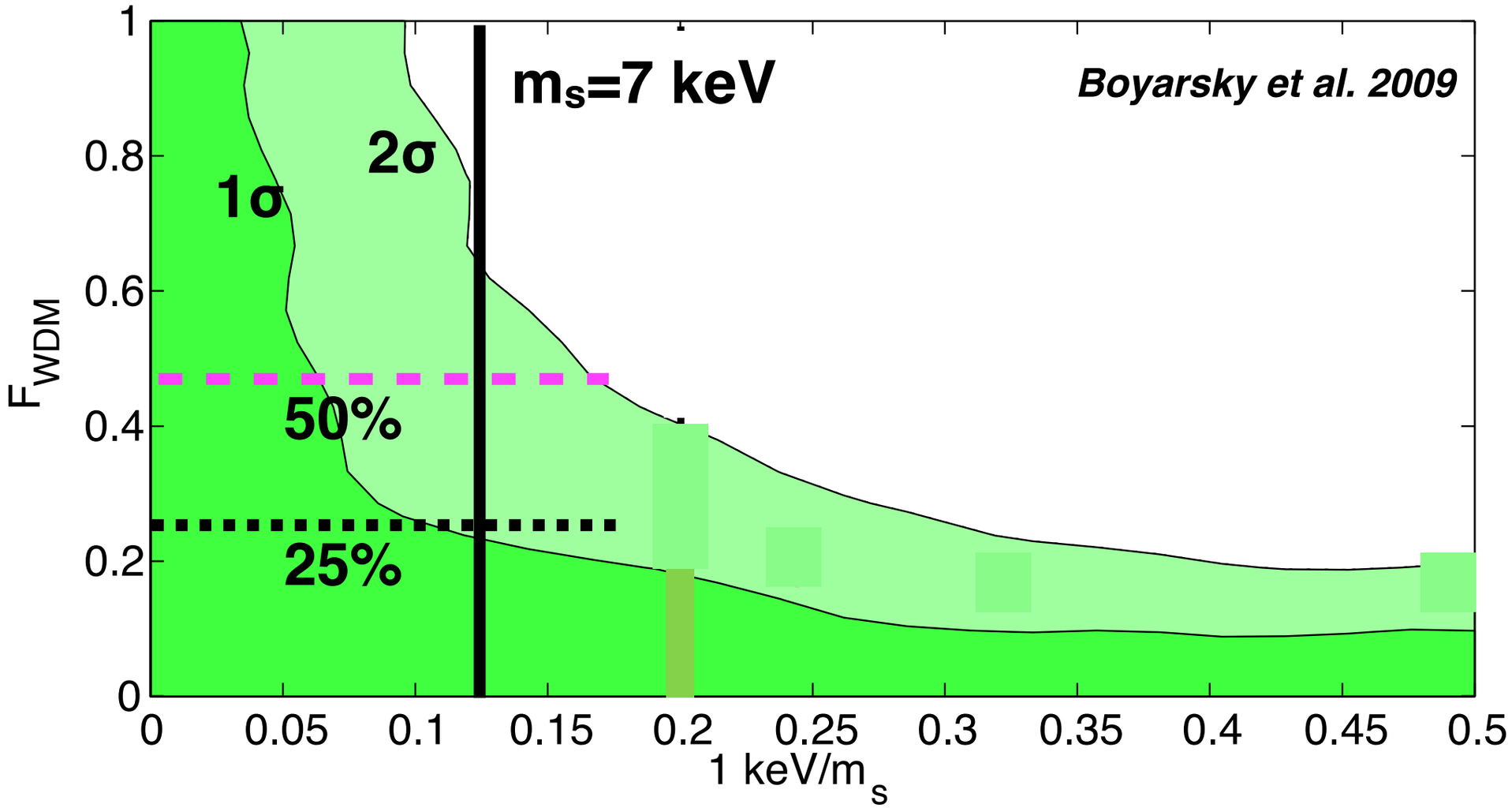
Harada, AK 2014 Yes, but accounts for only 20-60% of DM

Assume the rest consists of cold and stable particle



Matter power spectra are suppressed, but slightly compared with pure WDM model

Lyman-alpha forest constraint



Pure warm dark matter model of 7 keV sterile neutrino is excluded at 95% CL

50% and 25% are within 2σ and 1σ, respectively

CVF in MDM models

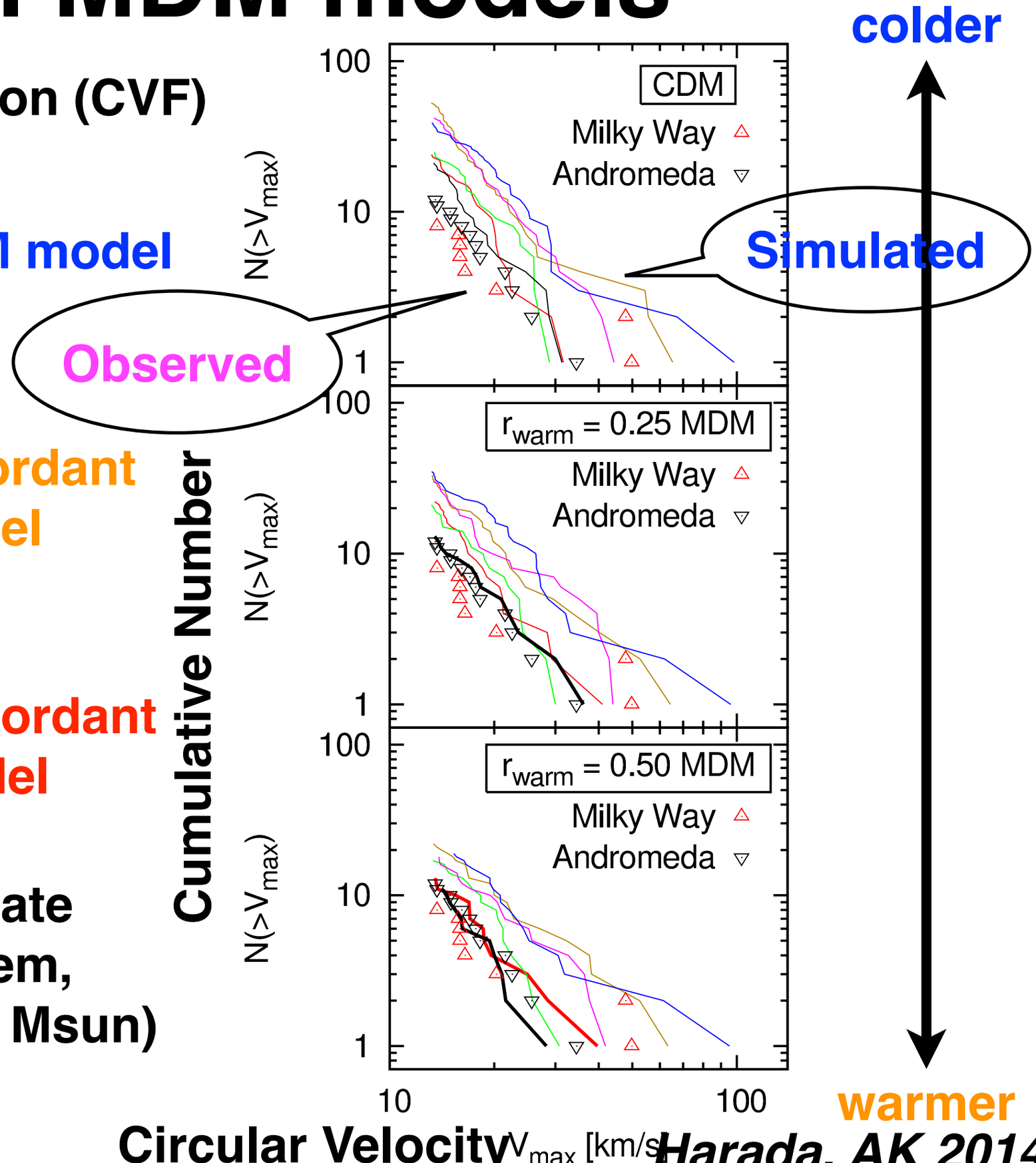
Cumulative Velocity Function (CVF)

Too many subhalos in CDM model

1 out of 6 halos has concordant CVF in 25% MDM model

2 out of 6 halos have concordant CVF in 50% MDM model

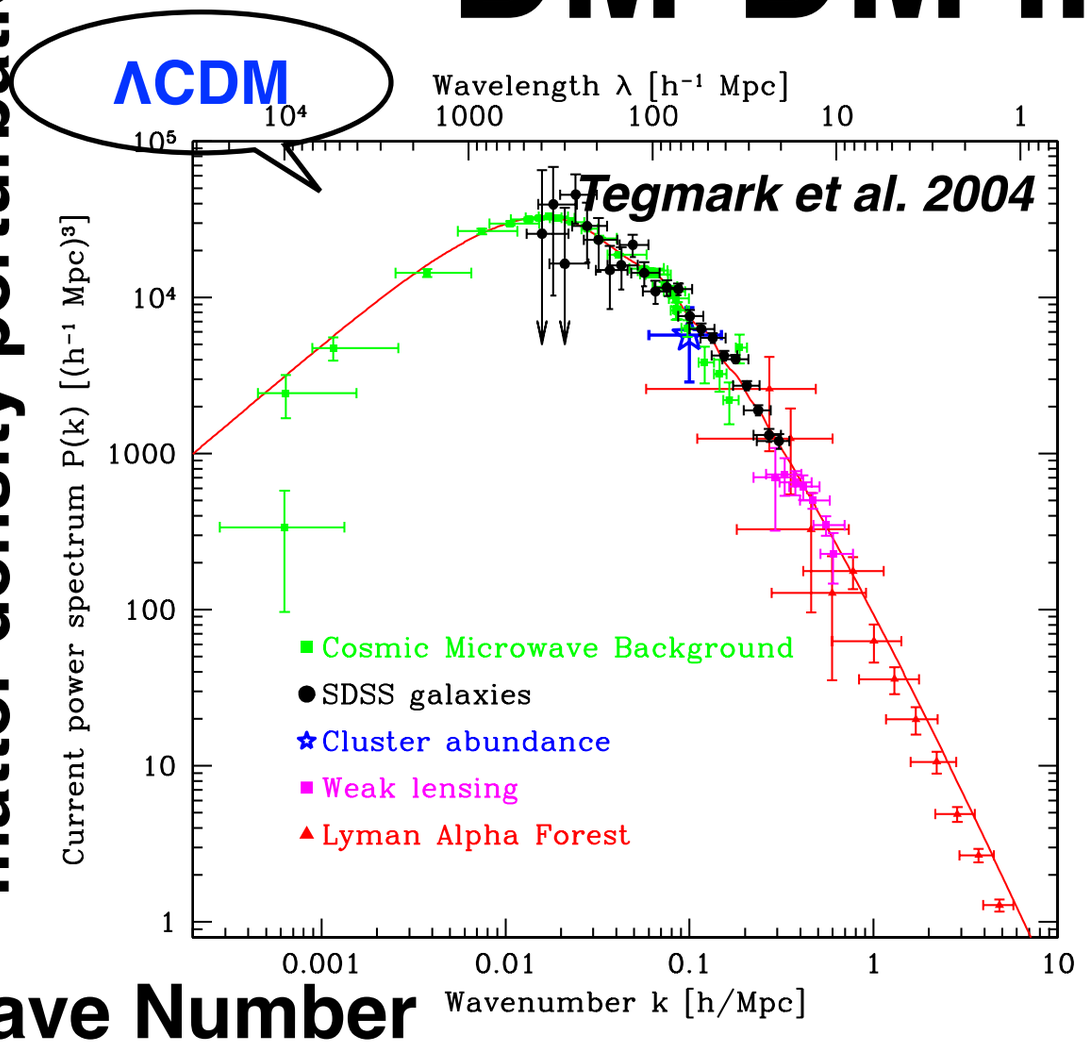
MDM models can mitigate missing satellite problem, preferring lighter (< 2×10¹² Msun) MW halos



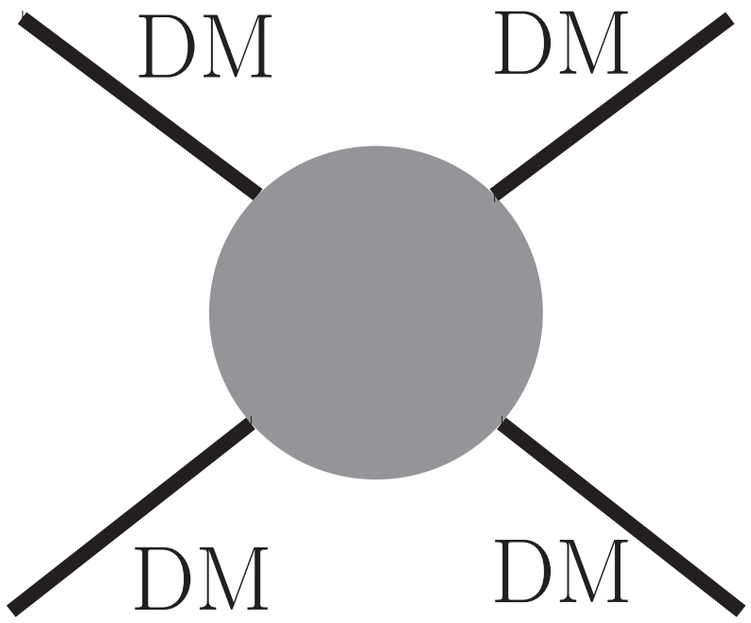
Harada, AK 2014

DM-DM interaction

Power spectra of matter density perturbation



Wave Number



Interaction rate Γ=σvρ/m

σ: cross section

v: relative velocity

ρ: DM mass density

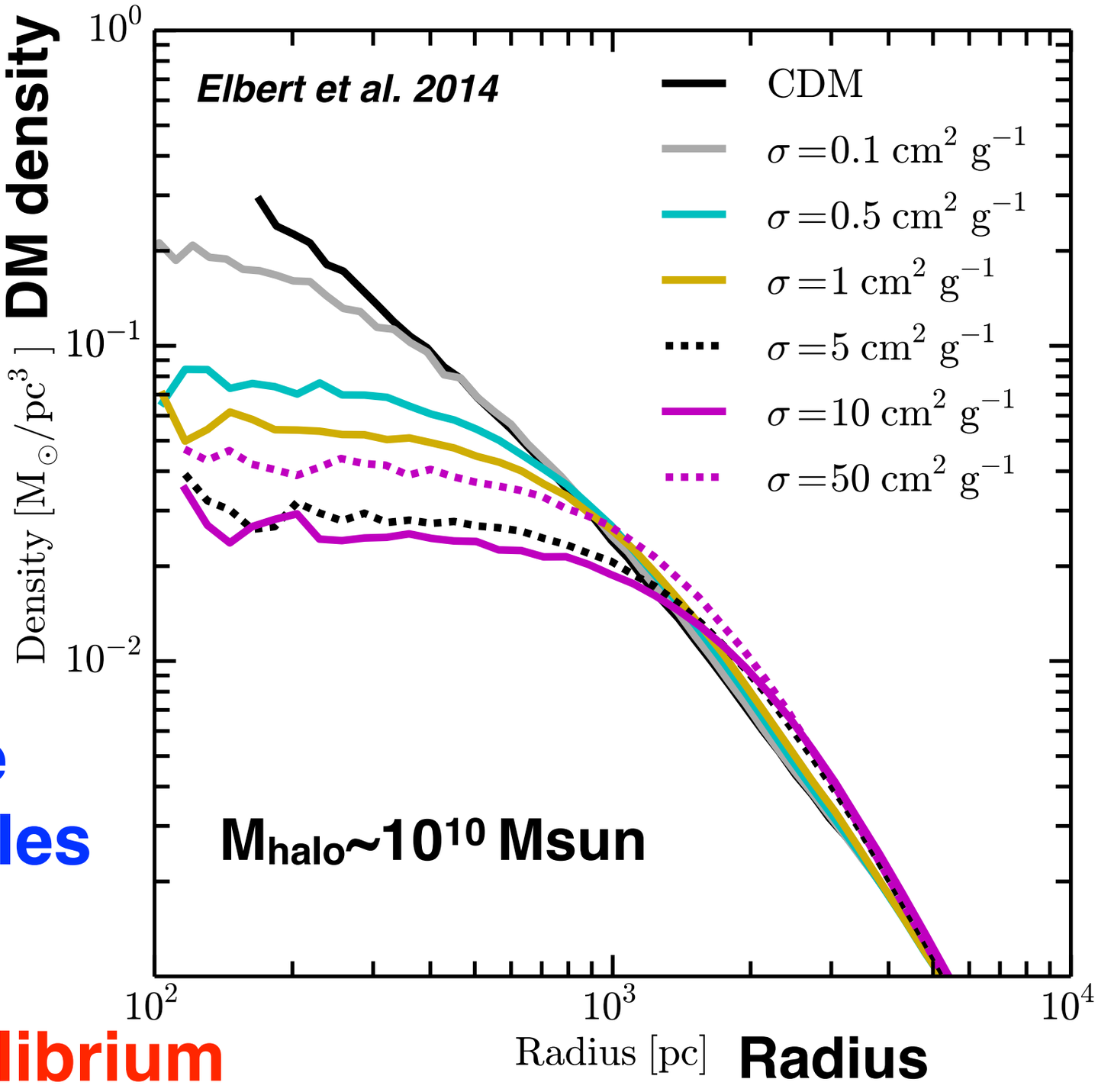
m: DM mass

The same linear matter power spectra as ΛCDM, but DM-DM interactions become important as structure formation proceeds ↔ ρ increases

Cored Halos in SIDM model

As σ/m increases, central density decreases

Inverted at some point



DM particles outside scatter off the particles inside

In local thermal equilibrium

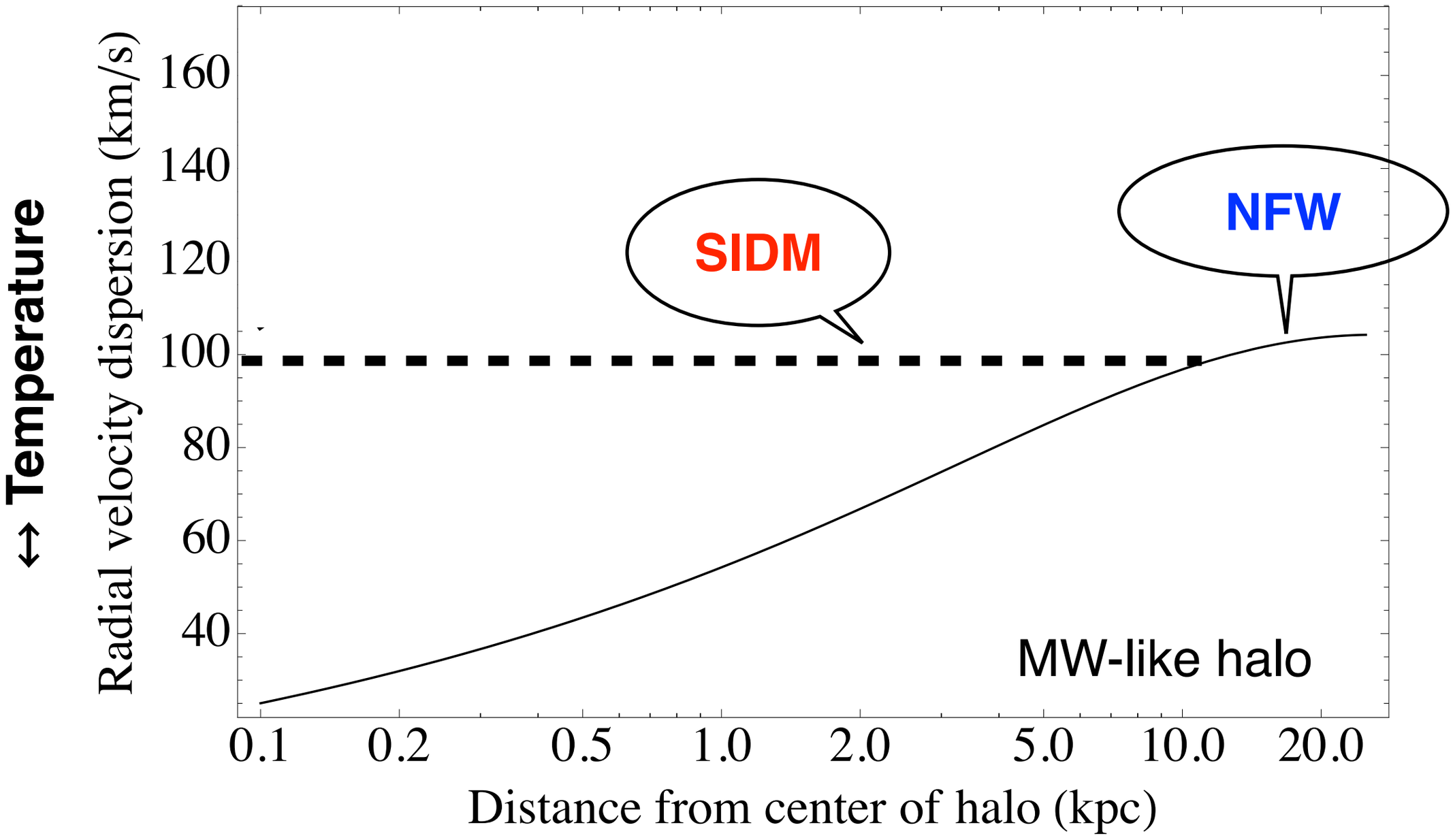
→ gravo-thermo instability

σ/m~0.1-10 cm²/g preferred

Isothermal profile in SIDM model

SIDM w/ σ/m~0.1-10 cm²/g follow isothermal distribution

Inner density profile $\rho \propto r^{-\alpha}$ α=0: cored



Constraints and Models

Halo shape - ellipticity

galaxy cluster MS 2137–23

$\sigma/m<0.02$ cm^2/g ***MIRALDA-ESCUDE 2002*** **simple estimate**

↔ $\sigma/m<1$ cm^2/g ***Peter et al. 2013*** **SIDM simulation**

velocity-independent cross section ***Hochberg et al. 2015…***

SIMP miracle **3→2 reaction: relic density of SIMP**

2→2 reaction: self-interaction

velocity-dependent cross section ***Tulin et al. 2012…***

Introduce MeV scale mediator (m_{med}~m_{DM} v_{gal}/c)

v~1000 km/s @ cluster scale σ~$1/v^4$: suppressed

v~10-100 km/s @ (sub-)galactic scale σ~$1/m_{med}^2$: const.

Our Analysis

Aim: Take a closer look at Rotation Curves of High Surface Brightness Galaxies in SIDM models

Take circular velocity data of high surface brightness spiral galaxies from McGaugh 2004

Density profile of DM and (Exponential) Disk: Each have two parameters (scale length, scale density)

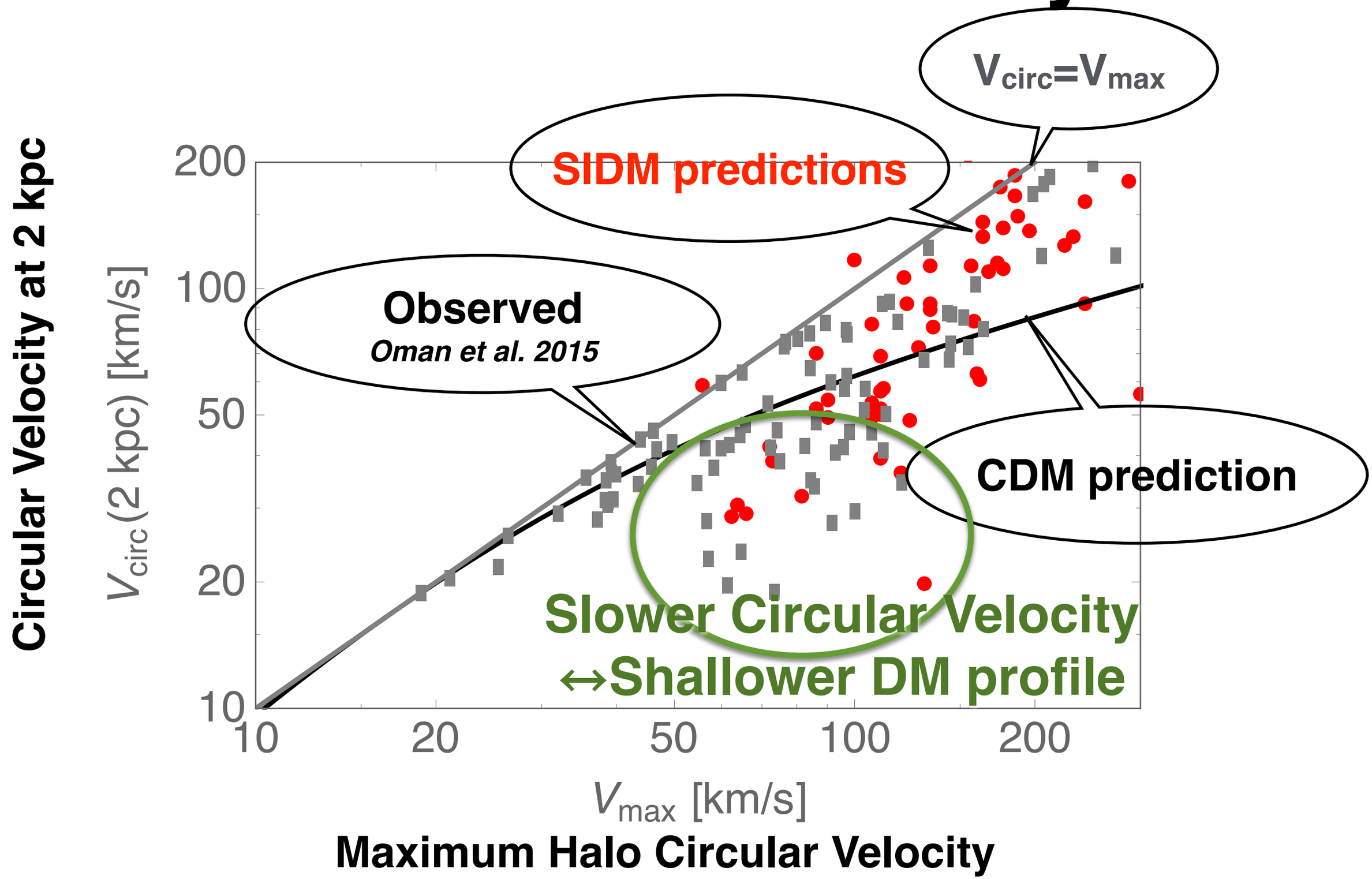
Disk radius: observed (fitted)

Disk surface mass density: fixed to minimize the Tully-Fisher relation

SIDM length and density parameters: fixed to reproduce observed circular velocity at 2.2×Disk radius (Disk has maximum contributions to circular velocity) and infinity

For CDM, c-V_{max} relation and V_{max} as a free parameter

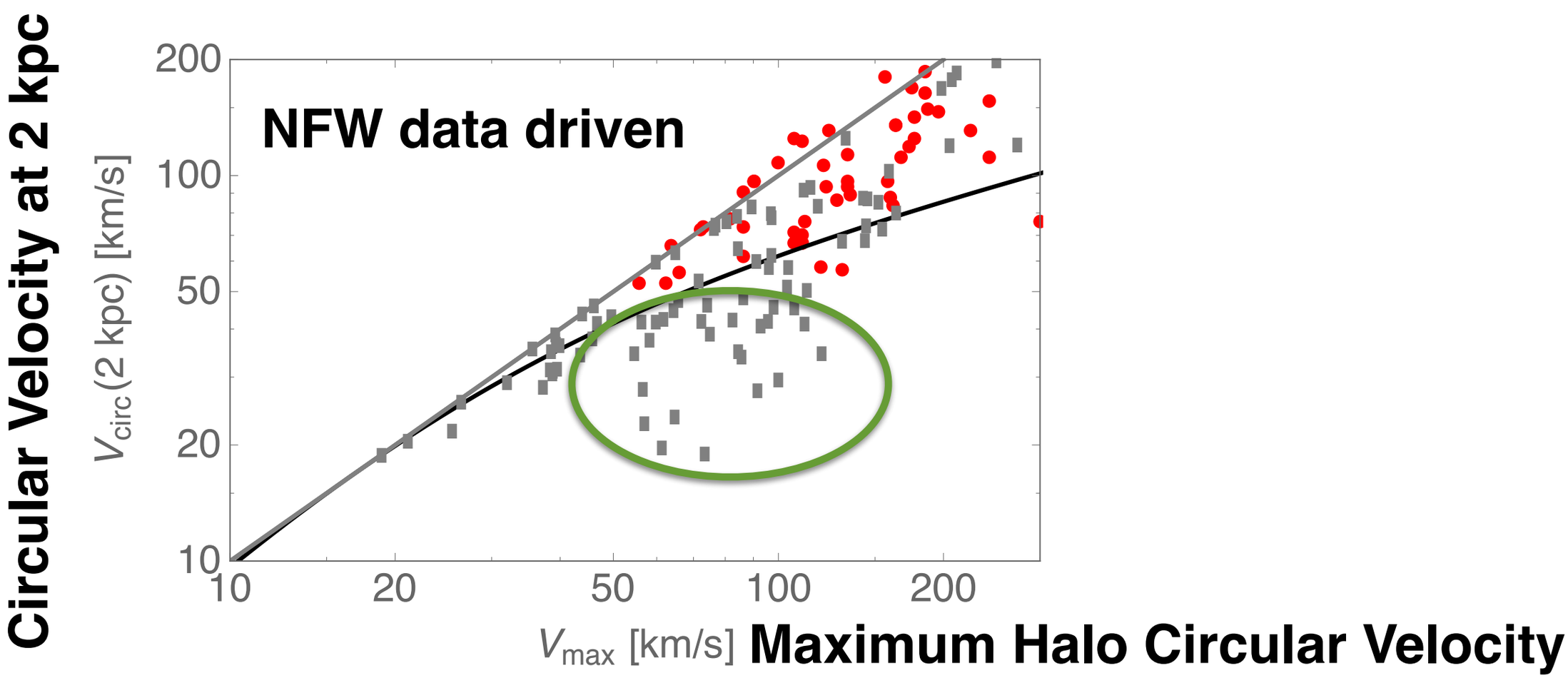
Inner Circular Velocity



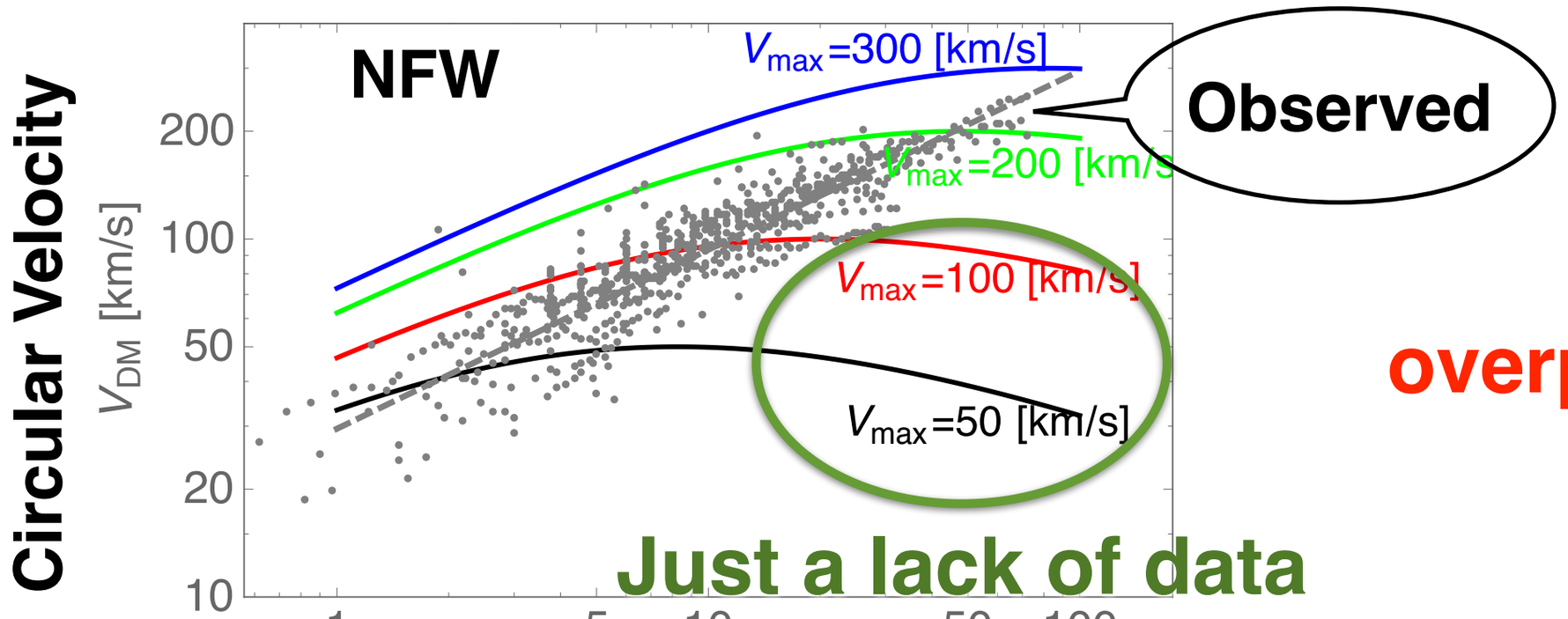
Inner Circular Velocity in ΛCDM

For CDM, c-V_{max} relation and V_{max} as a free parameter

CDM length and density parameters: fixed to reproduce observed circular velocity at 2.2×Disk radius (Disk has maximum contributions to circular velocity) and infinity

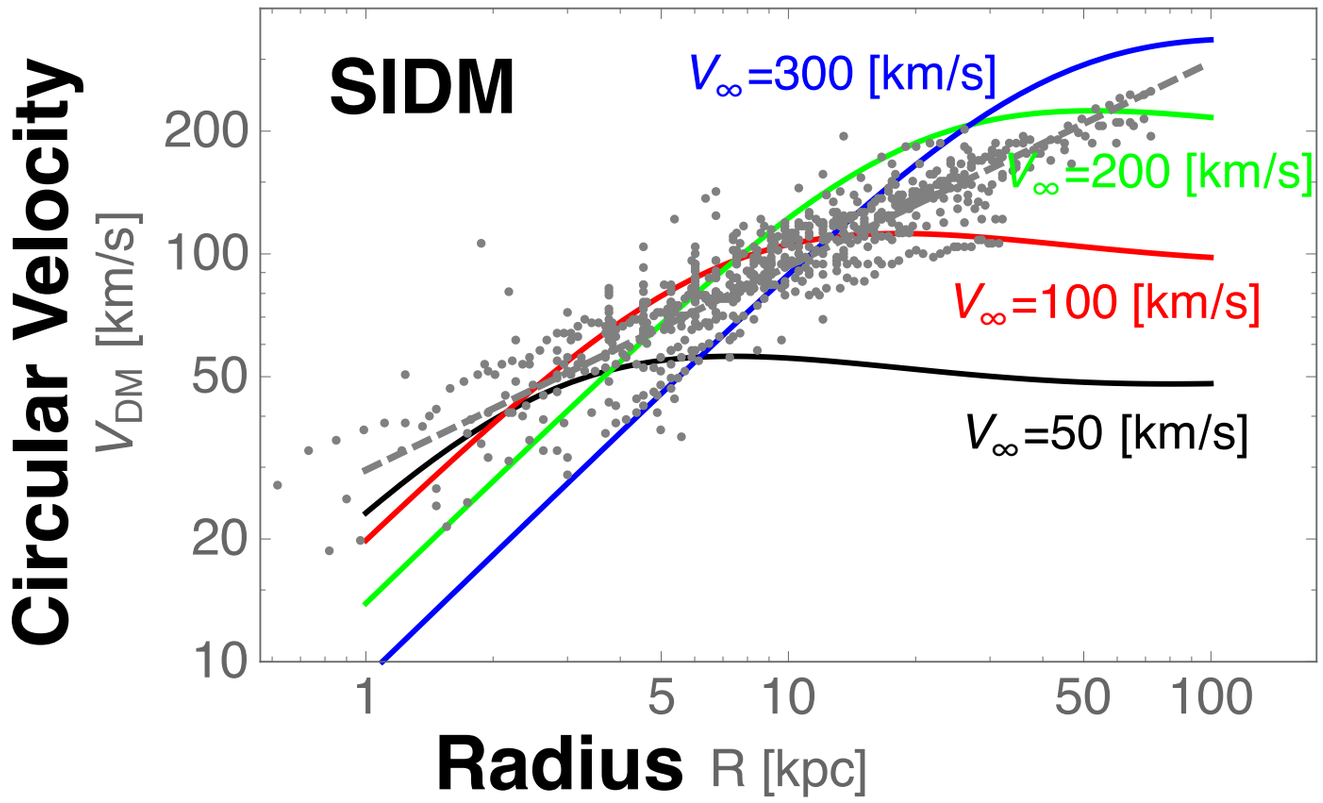


Intermediate Rotation Curve

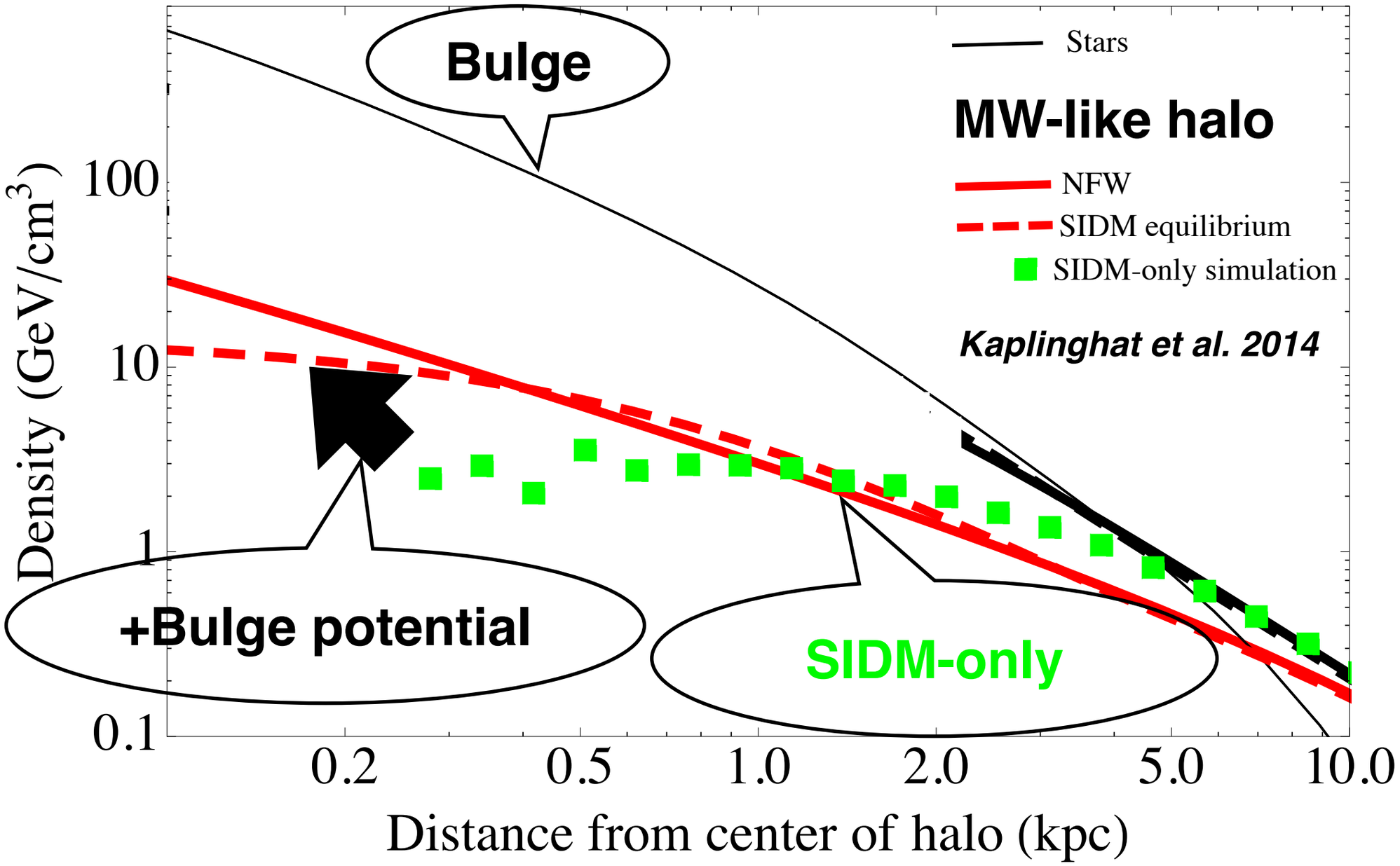


?

underpredict

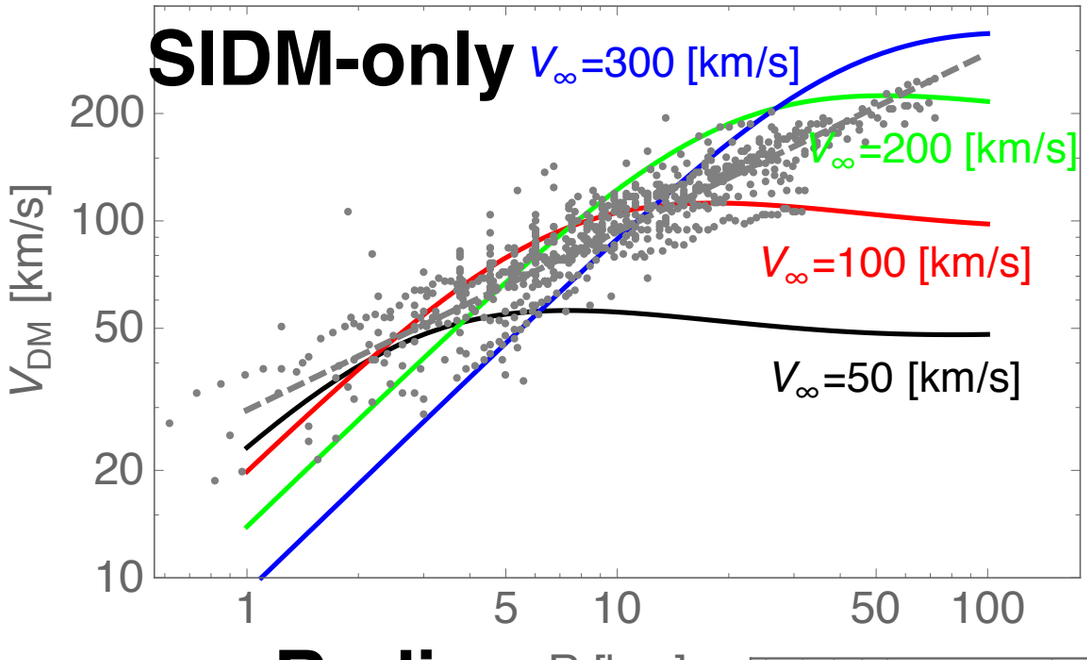


Effect of Baryon Potentials



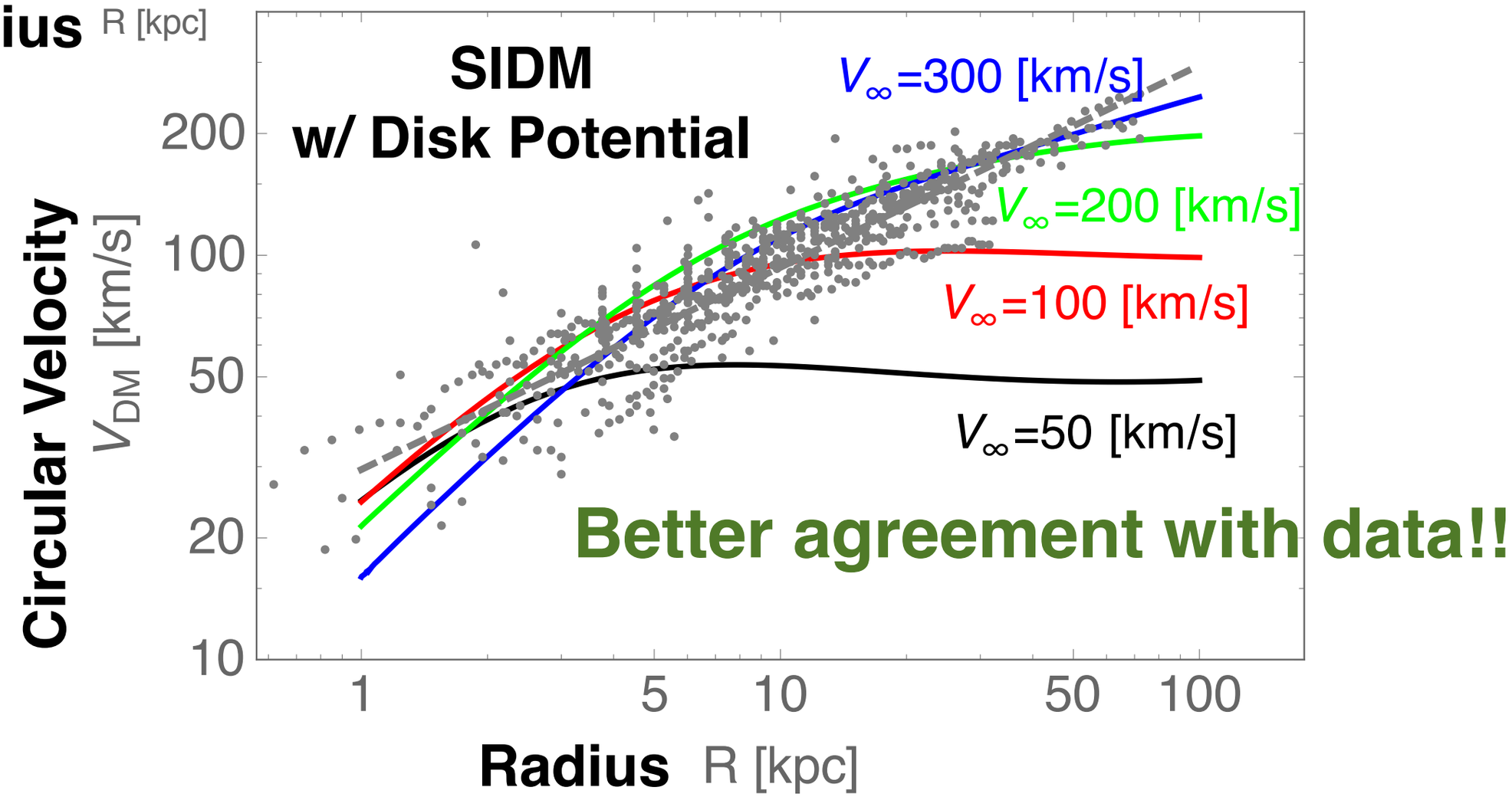
Once Bulge potential is taken into account,
DM core size shrinks and central density increases

Incorporate Disk Potential



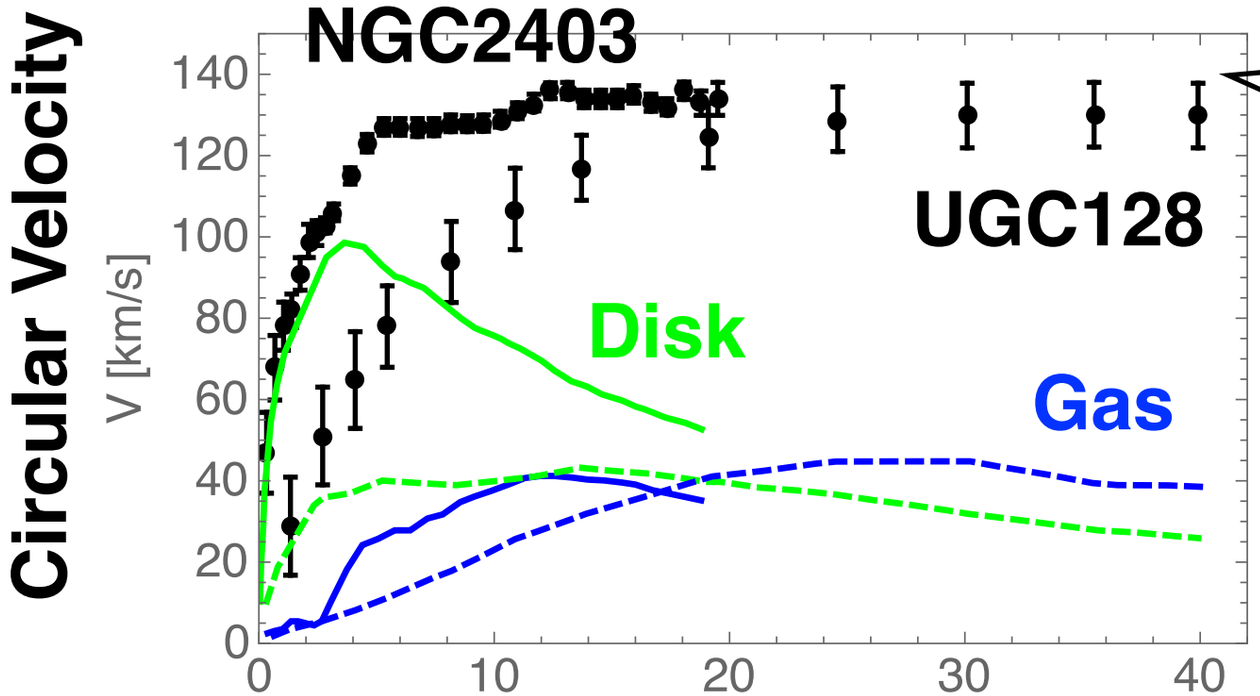
Circular Velocity

Radius R [kpc]



Better agreement with data!!

Universal Halo Profile

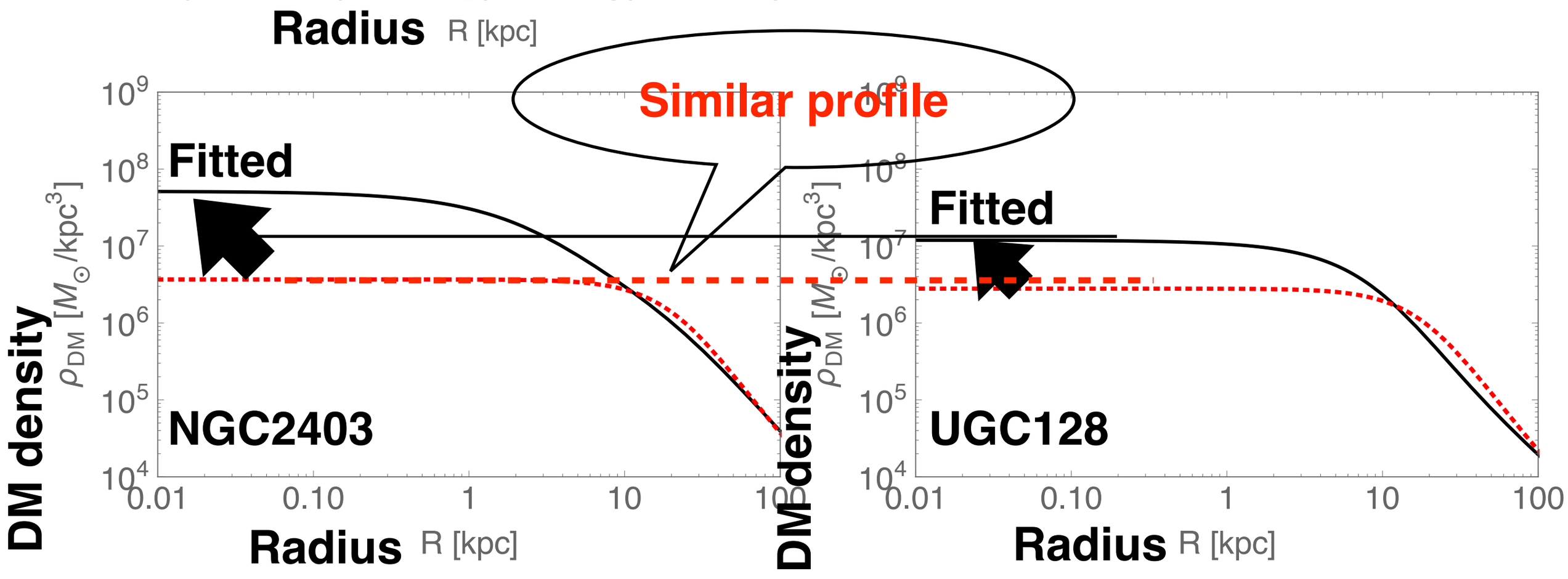


Similar V_{inf}
↔ Similar profile

like NFW in CDM model

Completely Different Rotation Curves

Similar profile



Summary

ΛCDM model has success in reproducing large scale structure of the Universe, but not small scales - small scale crisis

Alternatives to CDM model may solve or mitigate the small scale crisis

- **Thermal Velocity (Warm Dark Matter)**
- **DM-SM interaction**
- **DM-DM interaction**

in tension w/ observations of high-redshift matter distribution

Self-Interacting Dark Matter can be in good agreement with observed rotation curves when baryon potentials are incorporated