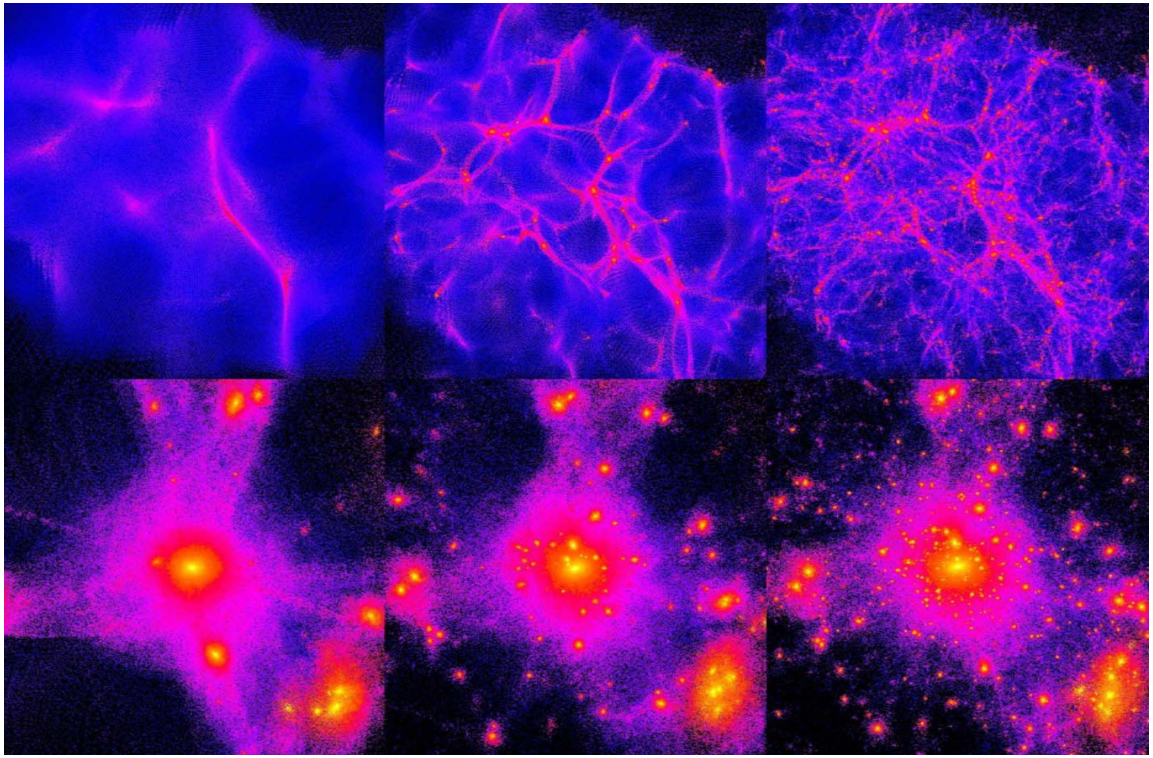
Some like it warm

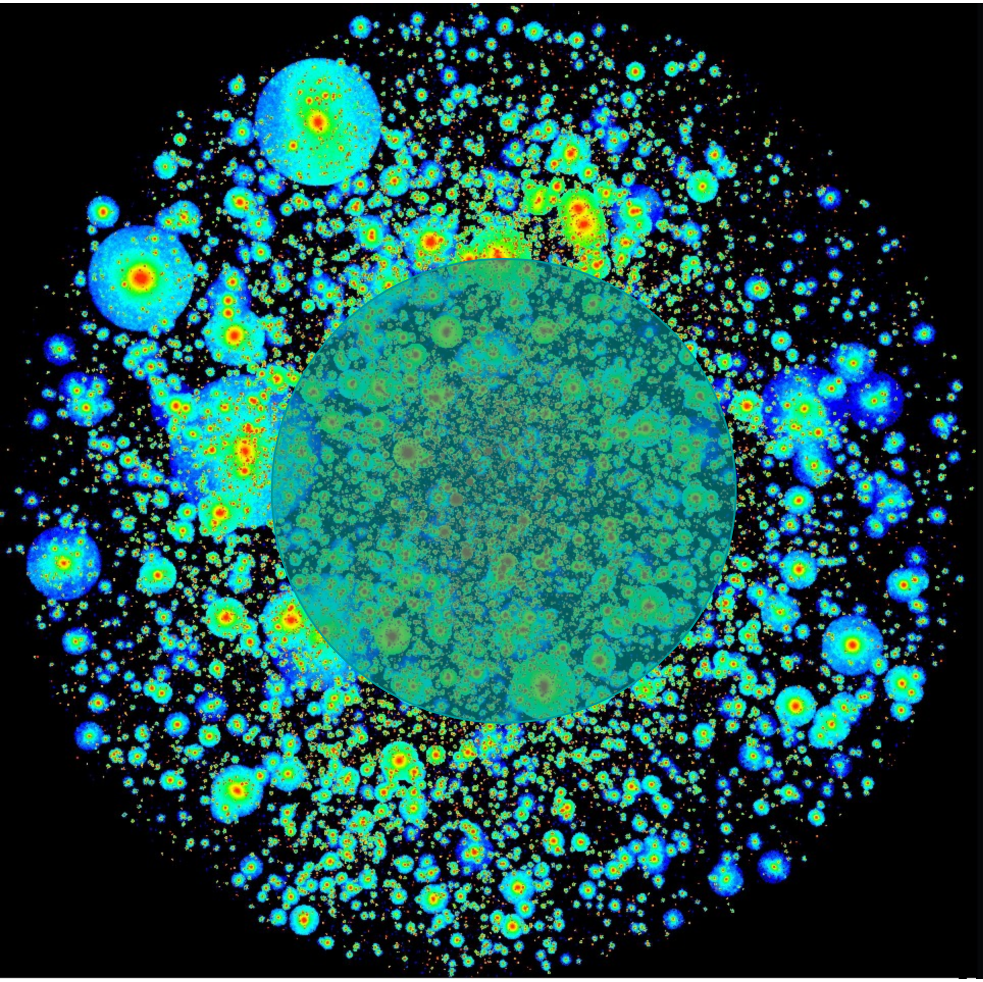


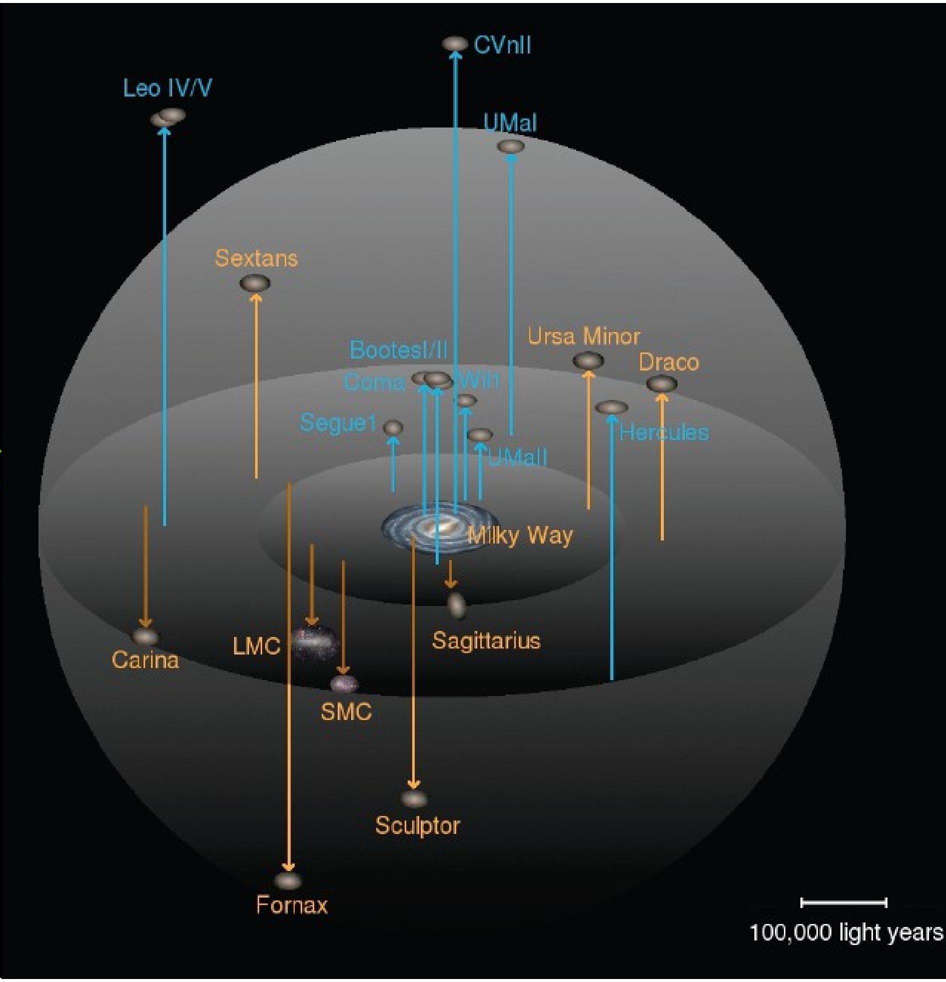
Andrea V. Macciò

MPIA - Heidelberg

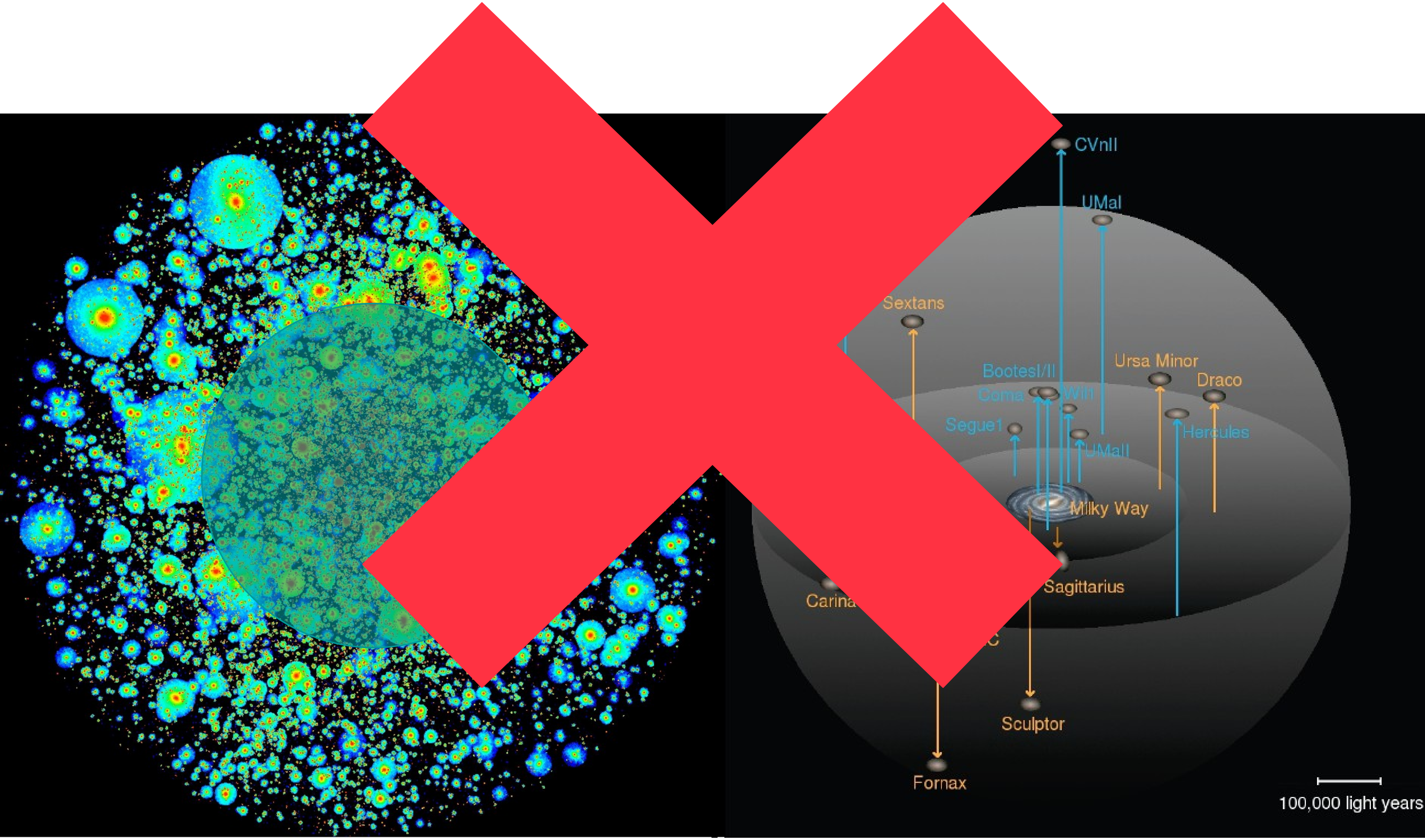
D. Aderhalden, A. Schneider, B. Moore (Zurich),
F. Fontanot (HITS), A. Dutton, J. Herpich, G. Stinson (MPIA), X. Kang (PMO)

CDM problems, hence WDM





CDM problems, hence WDM



Some like it warm

- What if Dark Matter is WARM?

- What happens to structure formation?

- What happens to galaxy formation?

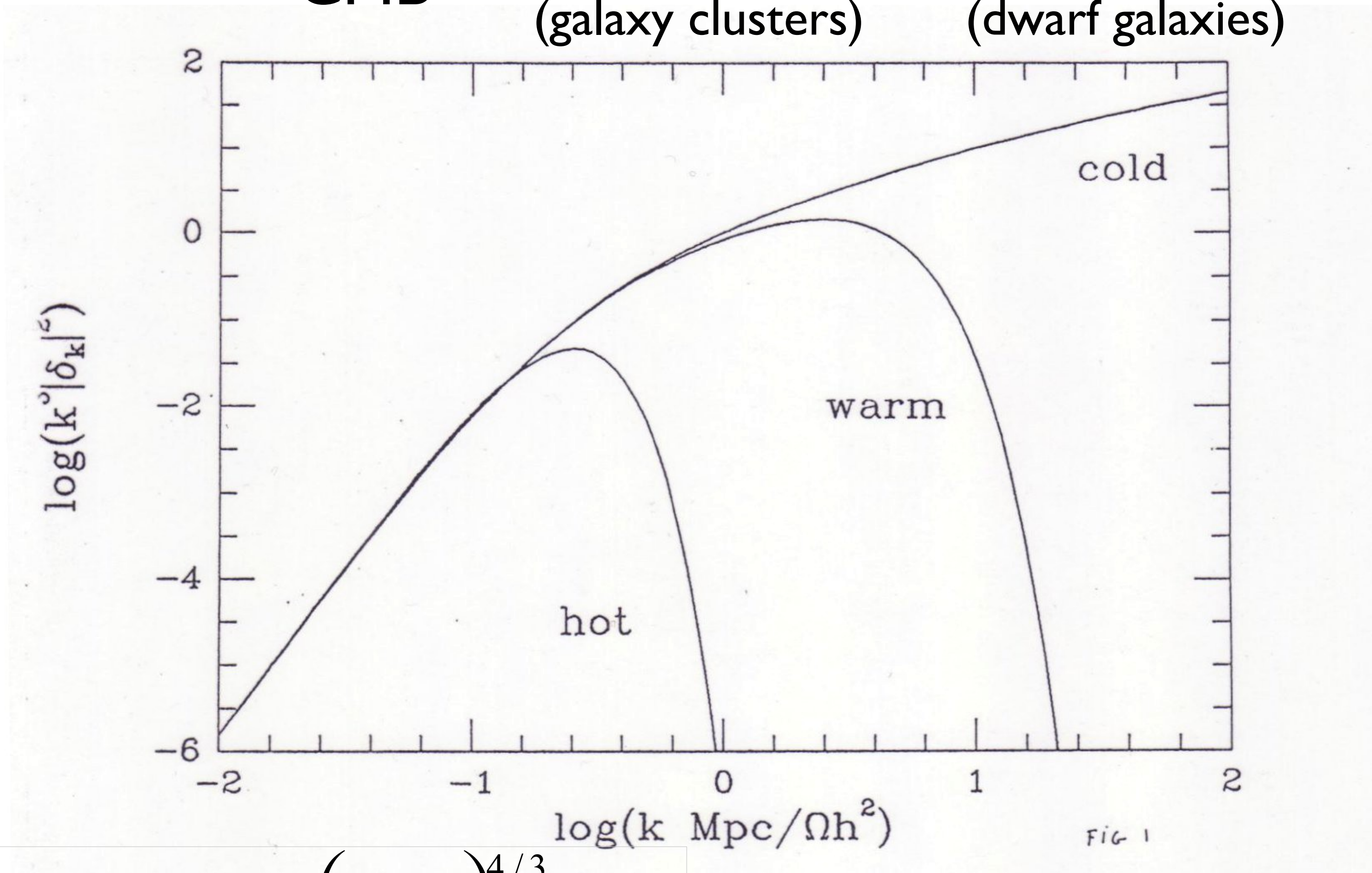
- What limits can we set on WDM from structure/galaxy formation

- Does WDM improve the agreement between predicted and observed galaxy properties?

CMB

Large scales (galaxy clusters)

Small scales (dwarf galaxies)



$$m_{HDM} \sim eV$$

$$m_{WDM} \sim keV$$

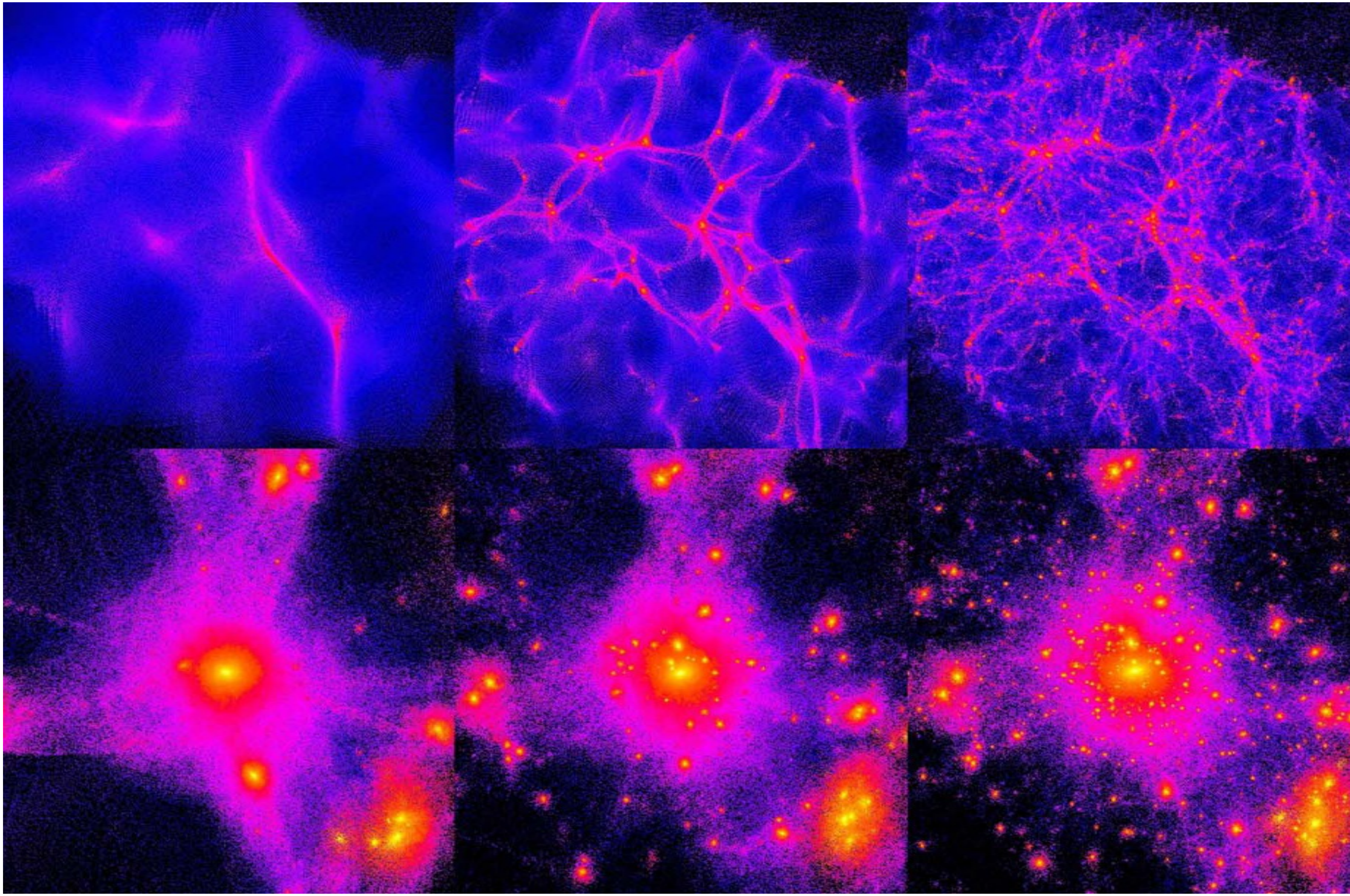
$$m_{CDM} > GeV$$

$$v_0(z) \propto (1+z)\left(\frac{keV}{m_x}\right)^{4/3} km/s$$

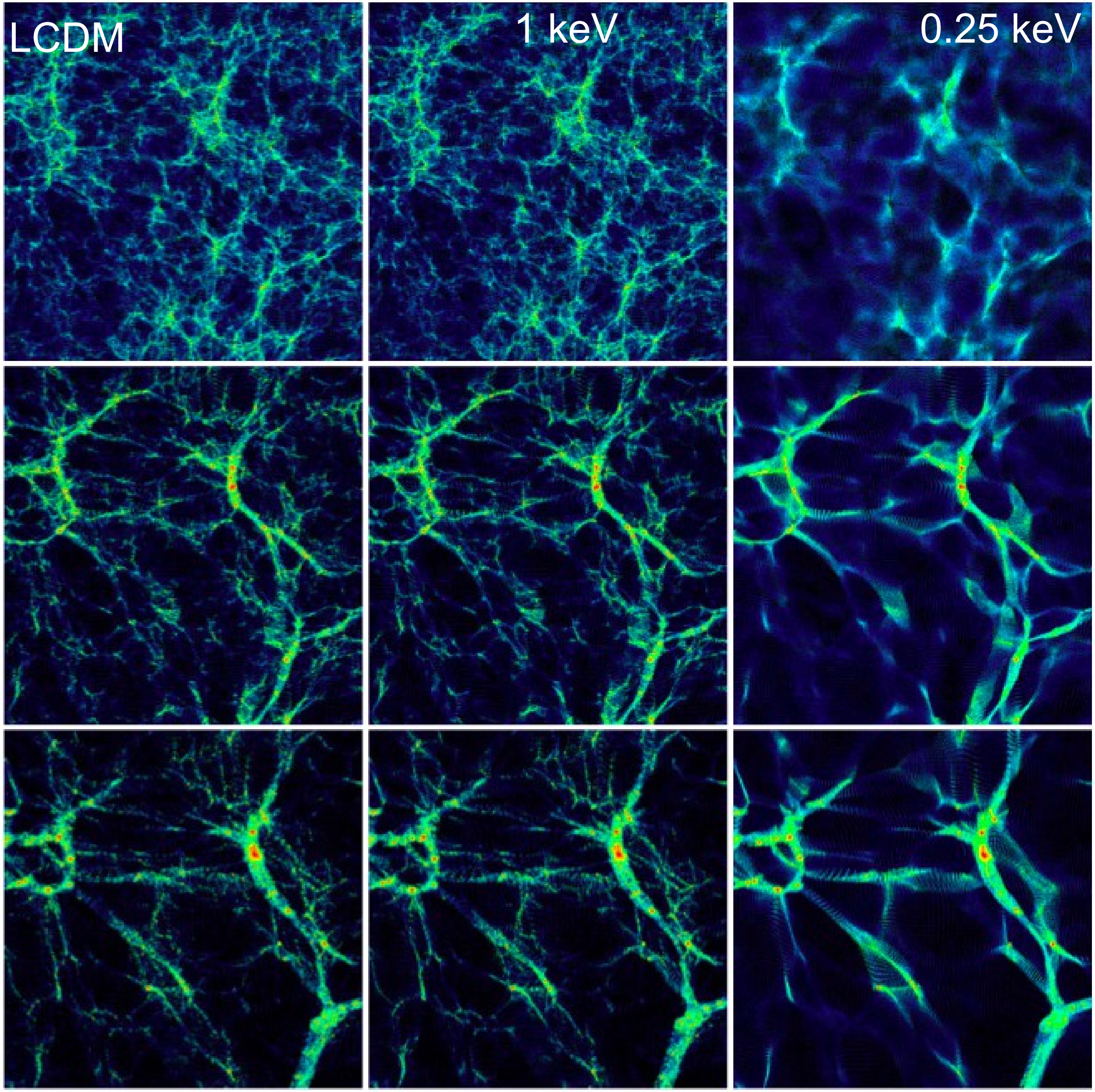
$$k_S \approx \left(\frac{0.3}{\Omega_X}\right)^{0.15}\left(\frac{m_X}{keV}\right)^{1.15} Mpc^{-1}$$

$$M_{\min} = 10^{-9} M_{sun} \quad \text{CDM}$$

$$M_{\min} = 10^{9} M_{sun} \quad m_X = 0.1\ keV$$

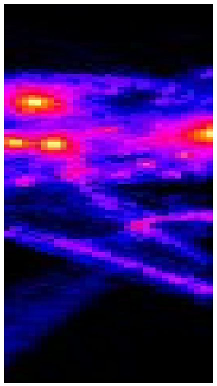


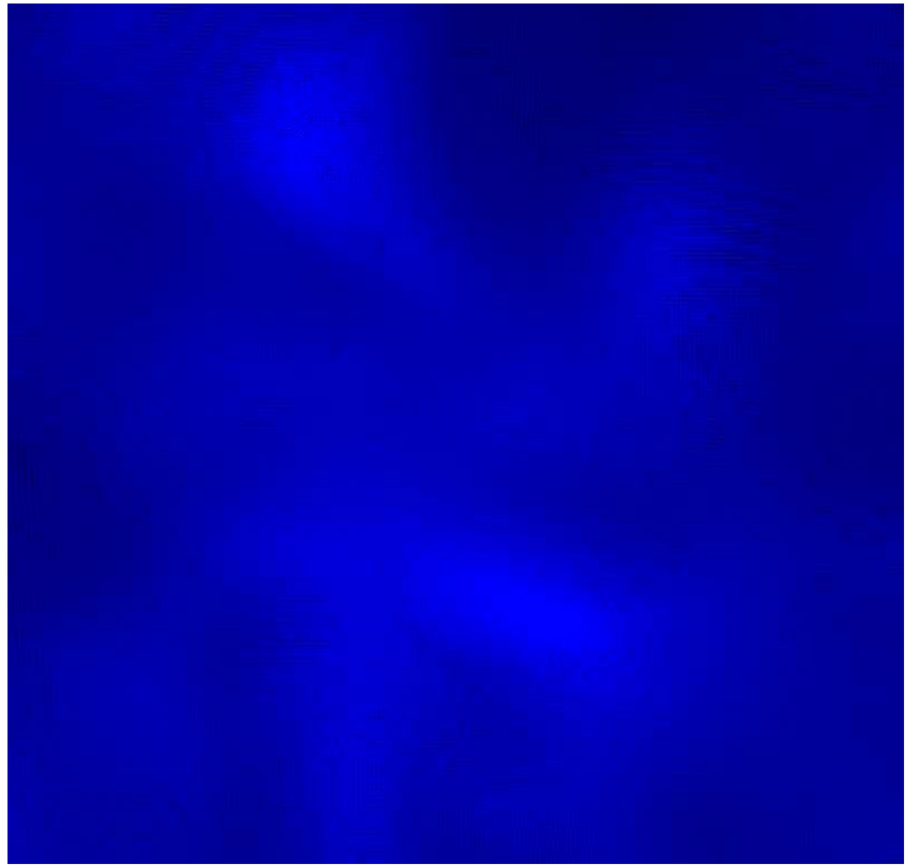
HDM WDM CDM



Schneider, Smith, AM+ 2012

Technical aspects of WDM simulations



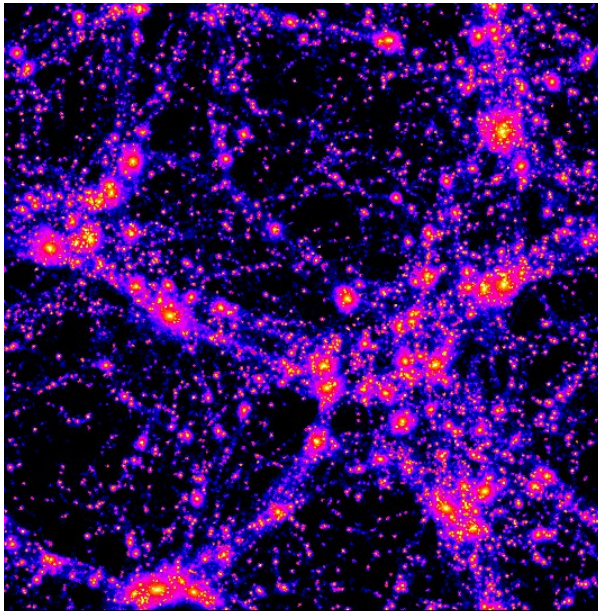


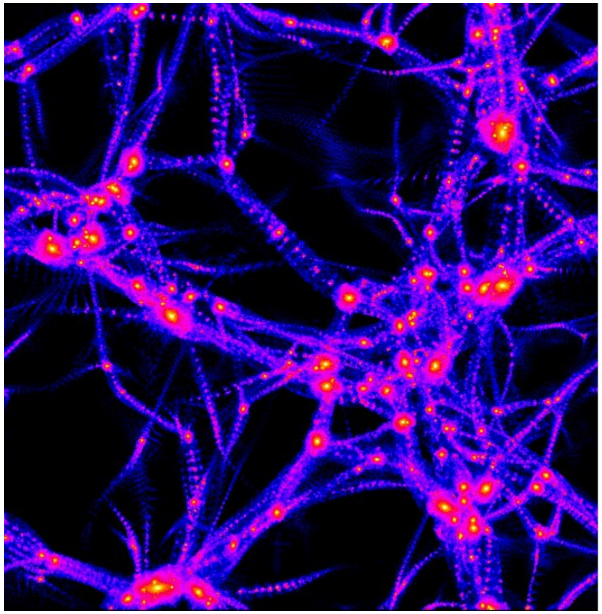
WDM 0.05 keV
movies from S. Paduroio

Melott 83, 90, 07
Wang & White 2007
AM+ 2012

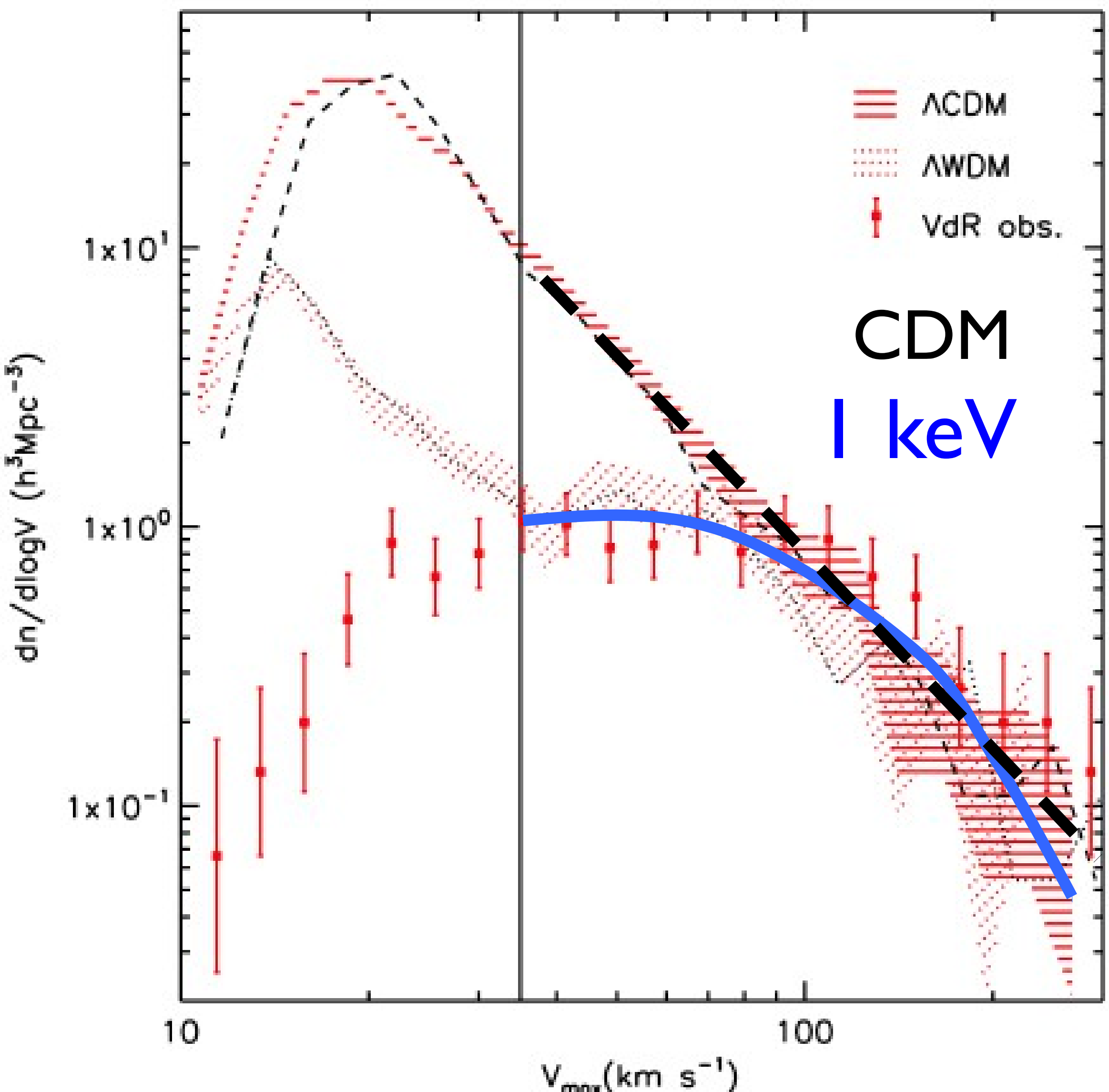
WDM "effects" on structure formation

- Reduction of overall number of low mass haloes





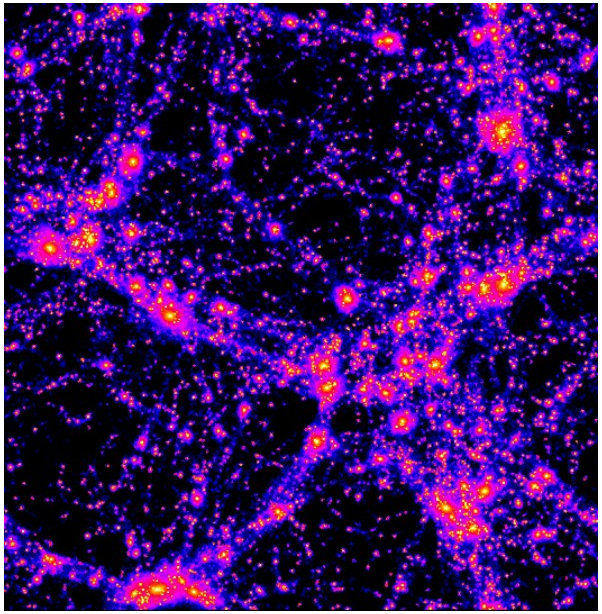
Velocity function in the Local Volume

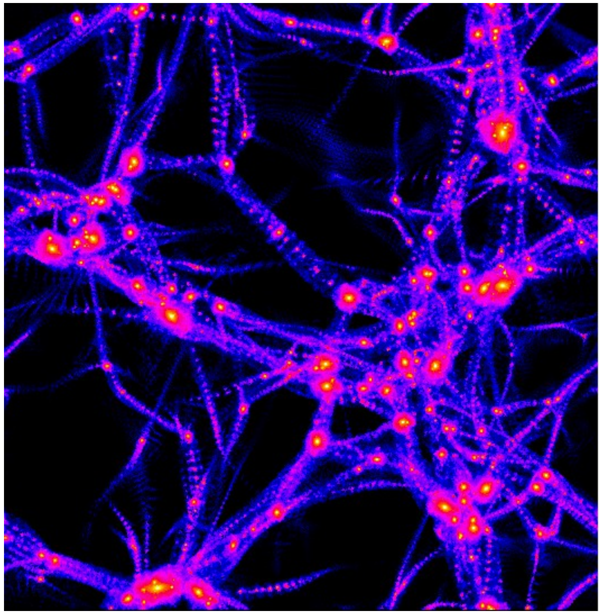


Zavala+09

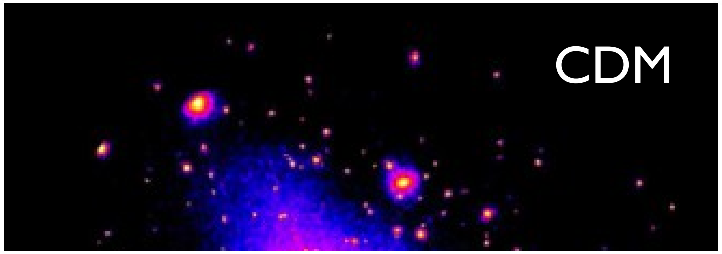
WDM "effects" on structure formation

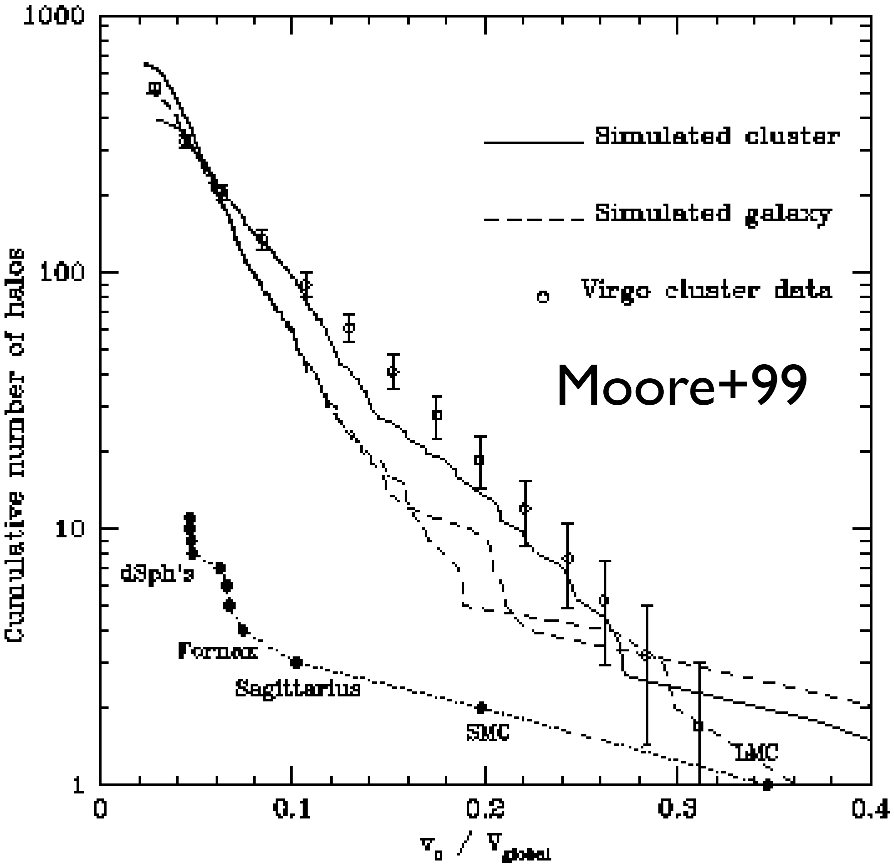
- Reduction of overall number of low mass haloes
- Suppression of the number of low mass satellites in high mass halos

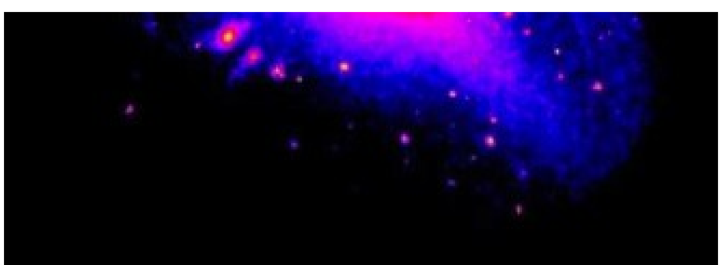


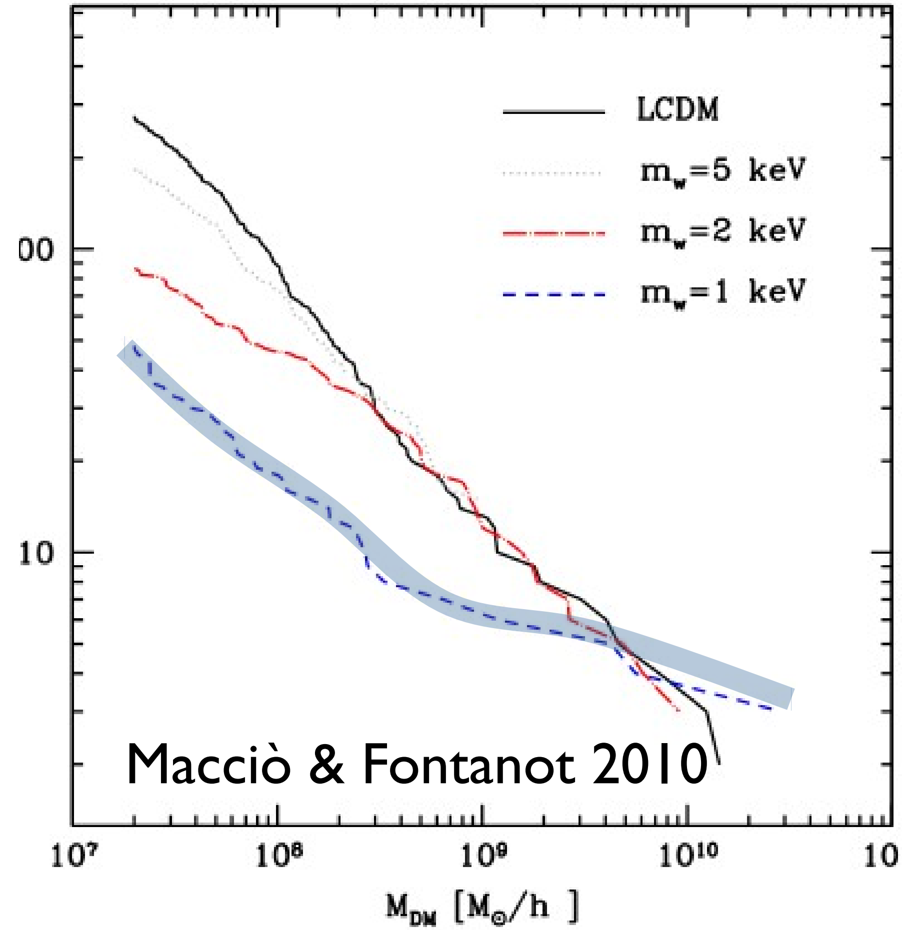


Substructure abundance





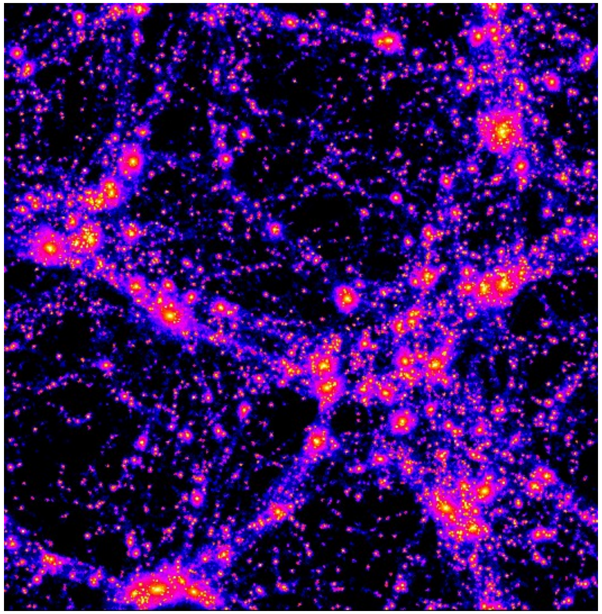


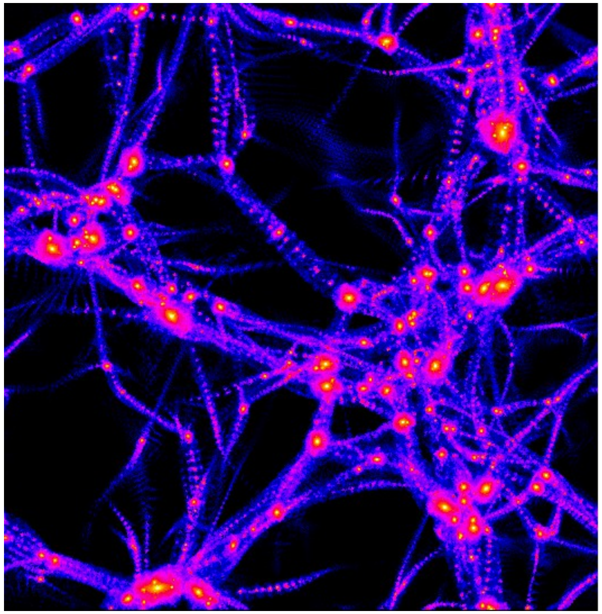


Colin+2000, 2008
Avila-Reese+2001

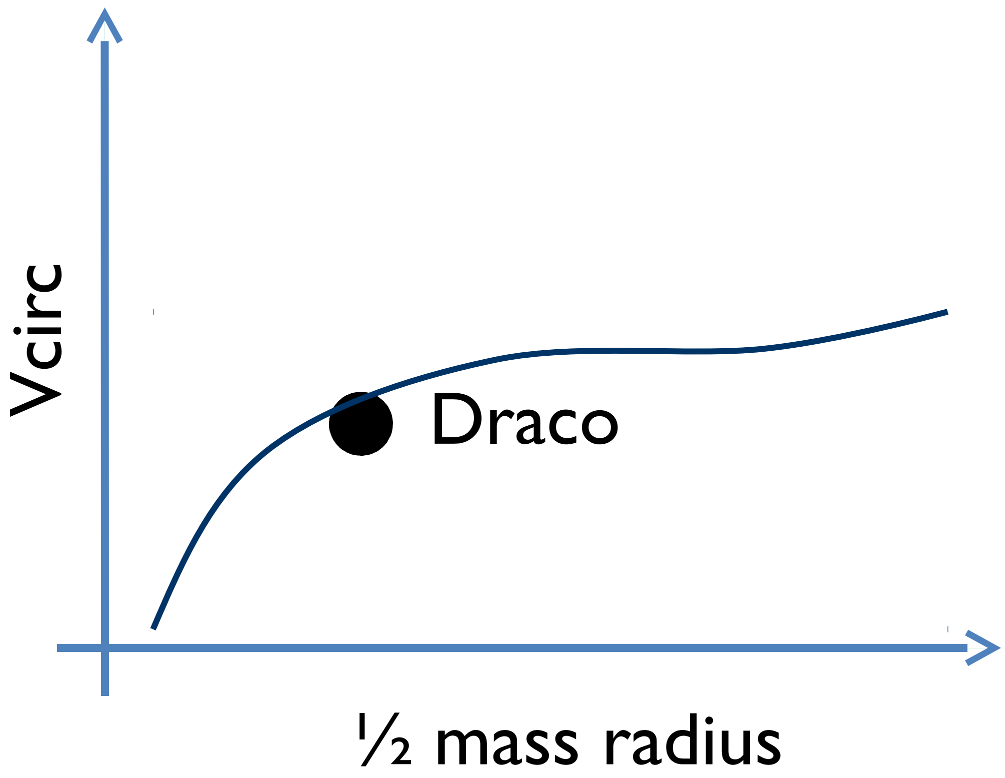
WDM “effects” on structure formation

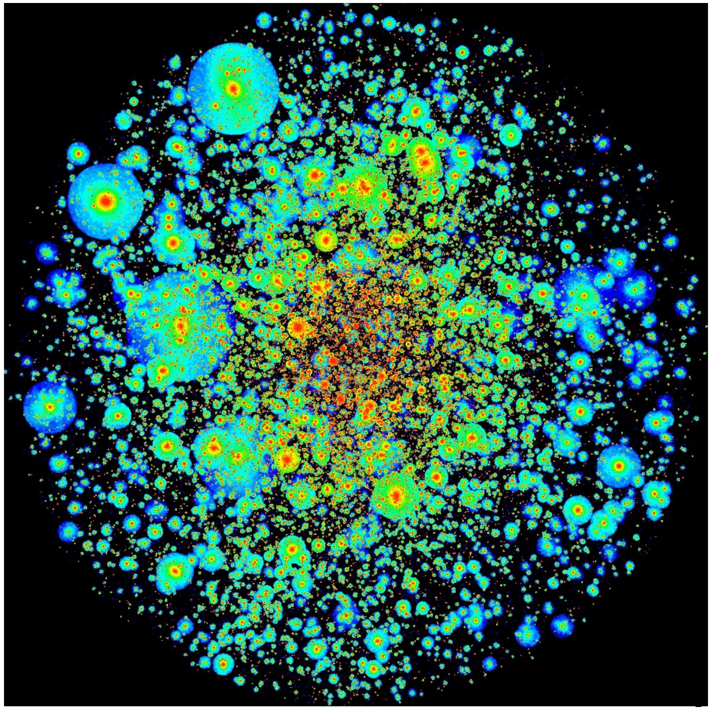
- Reduction of overall number of low mass haloes
- Suppression of the number of low mass satellites in high mass halos
- Delayed structure formation (lower DM halo concentration)



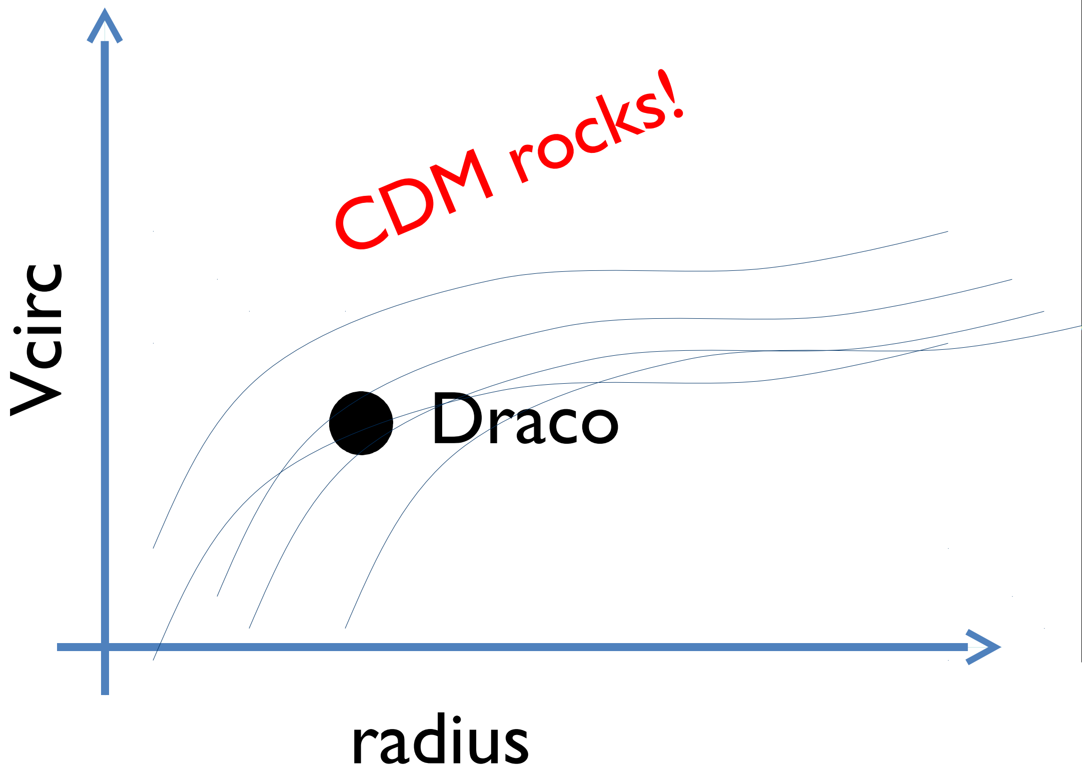


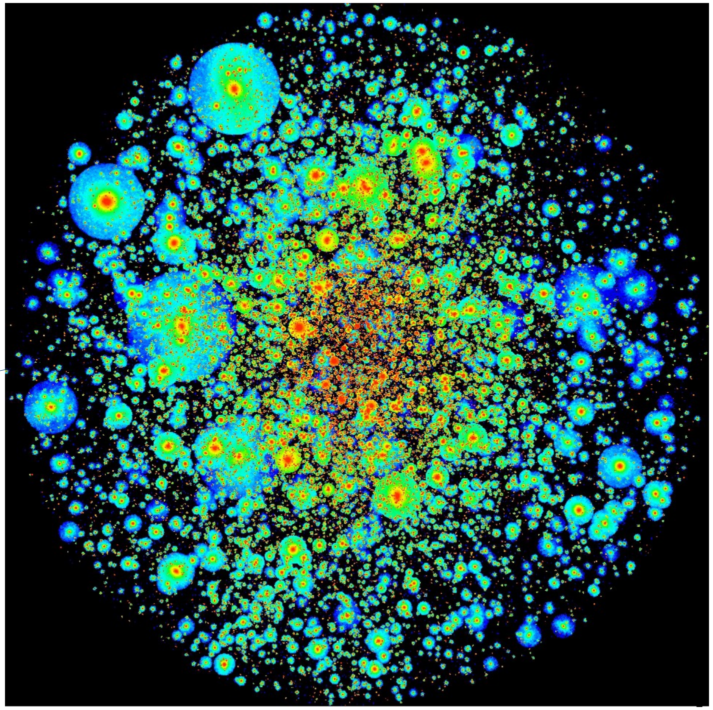
2. MW satellites kinematics





2. MW satellites kinematics





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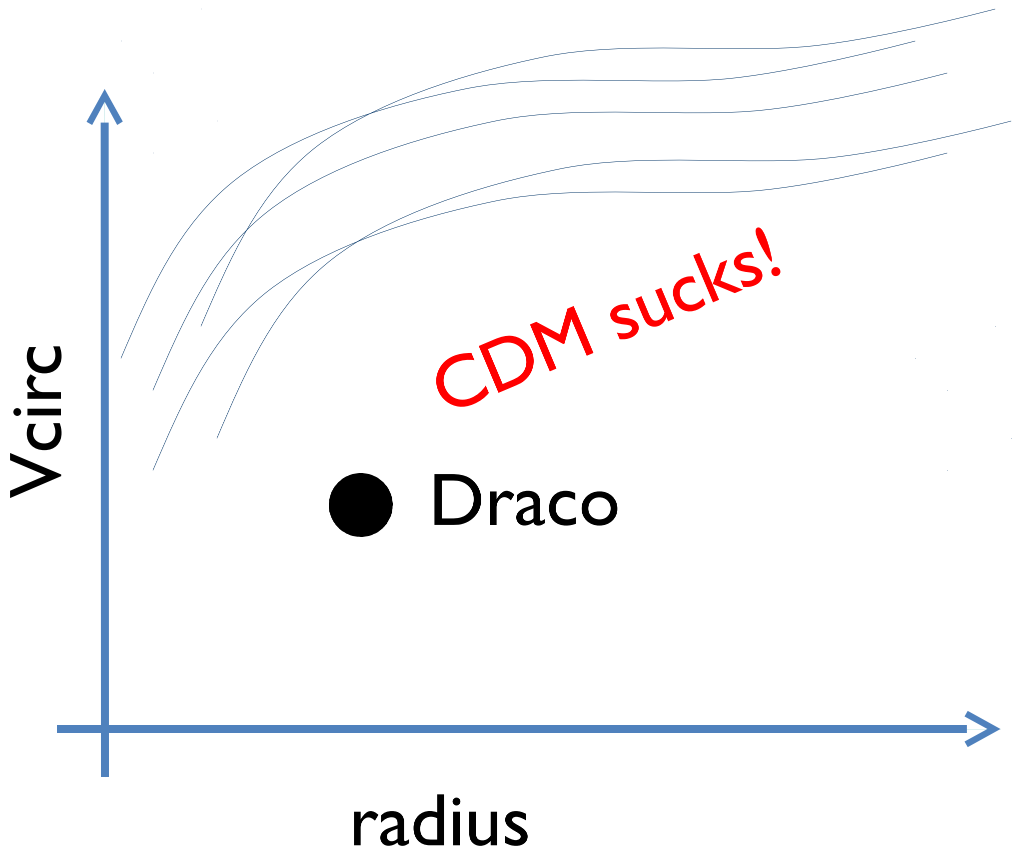
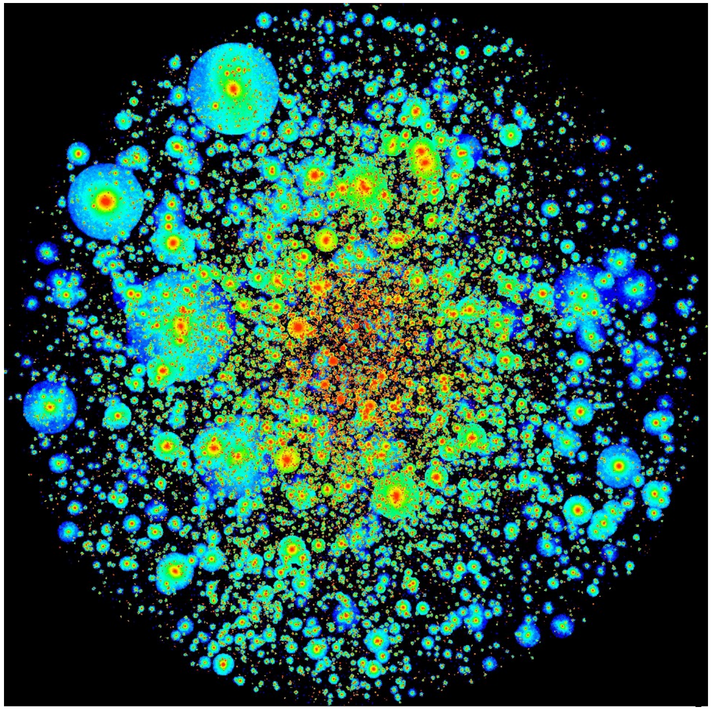
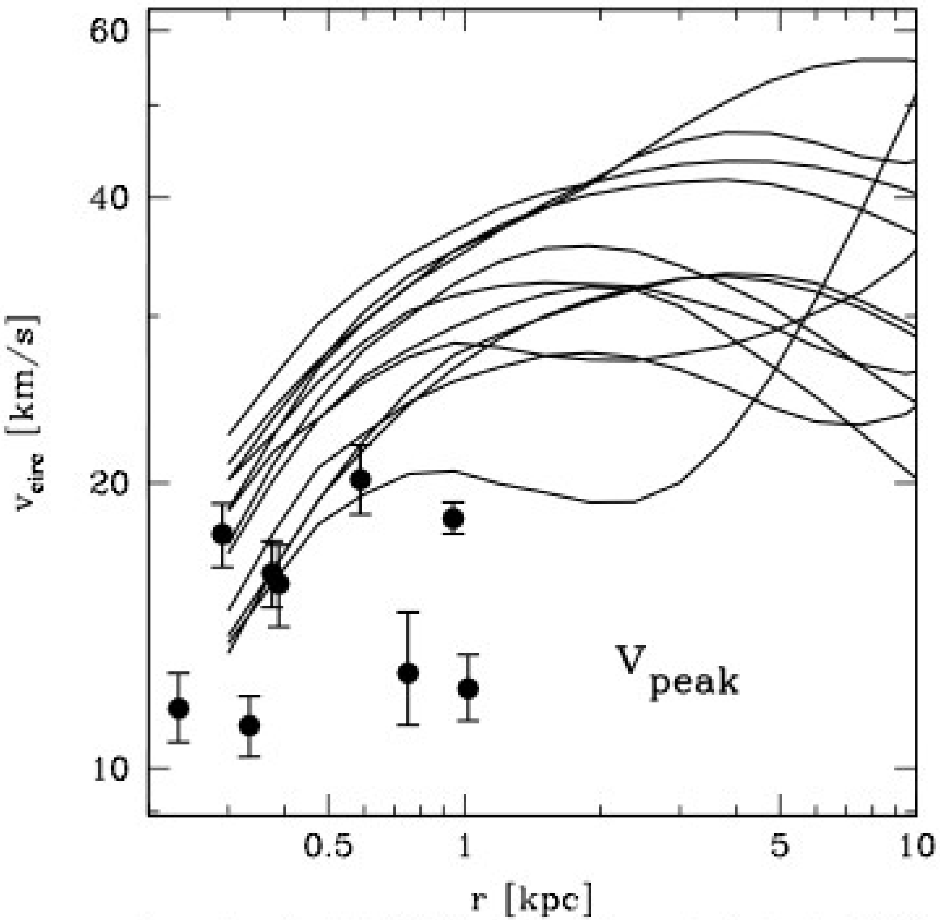


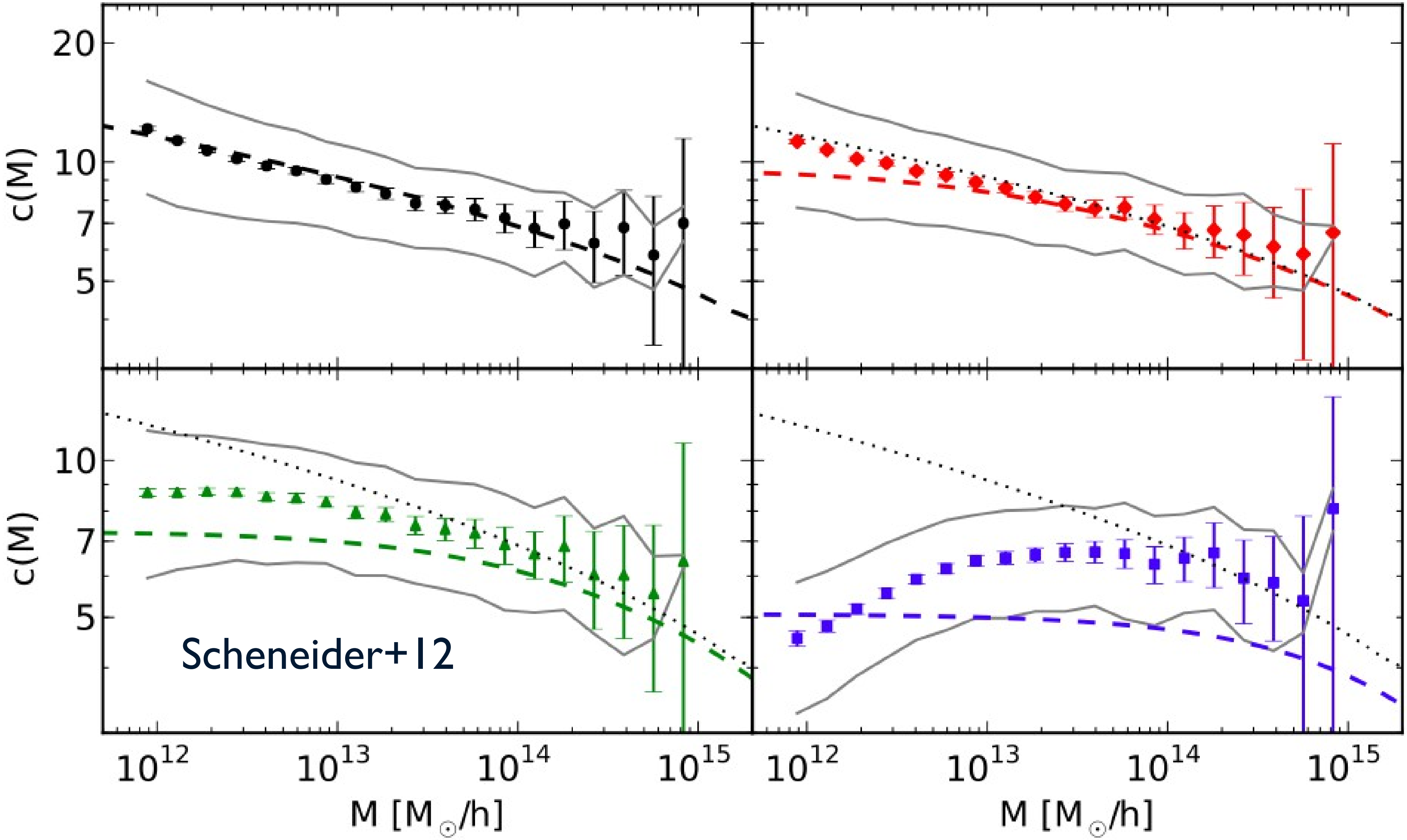


MW satellites Kinematics

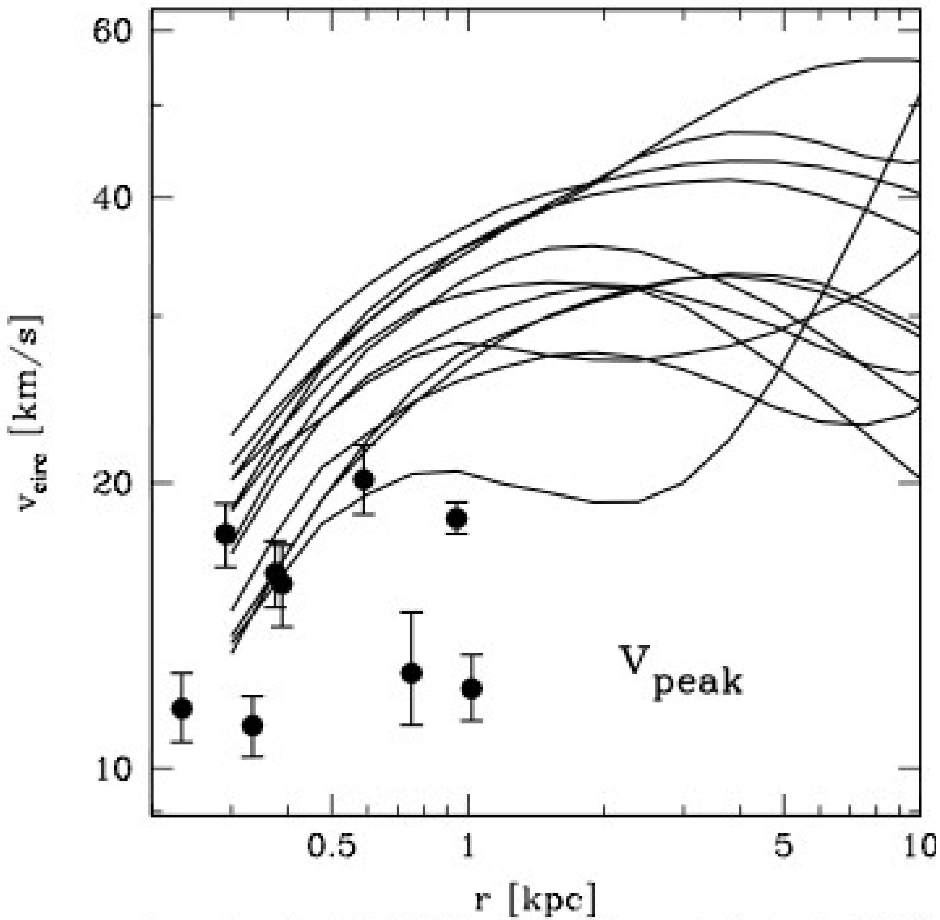


Boylan-Kolchin 2010,2011

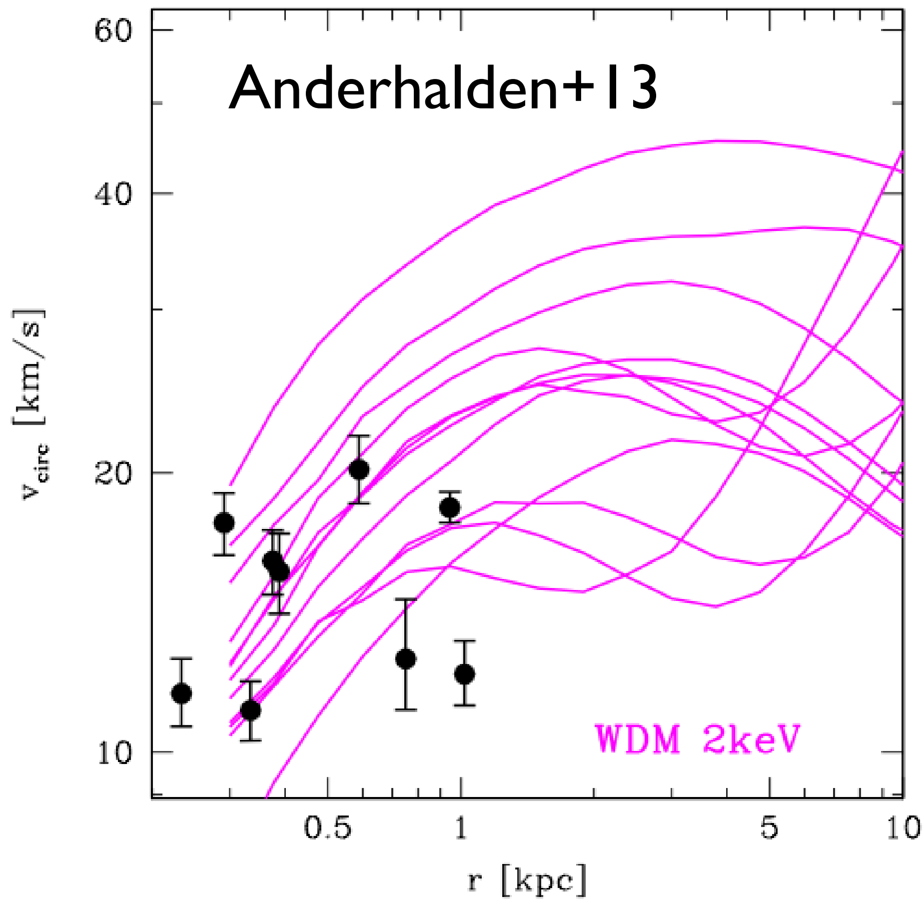
Concentration Mass relation in WDM



MW satellites Kinematics



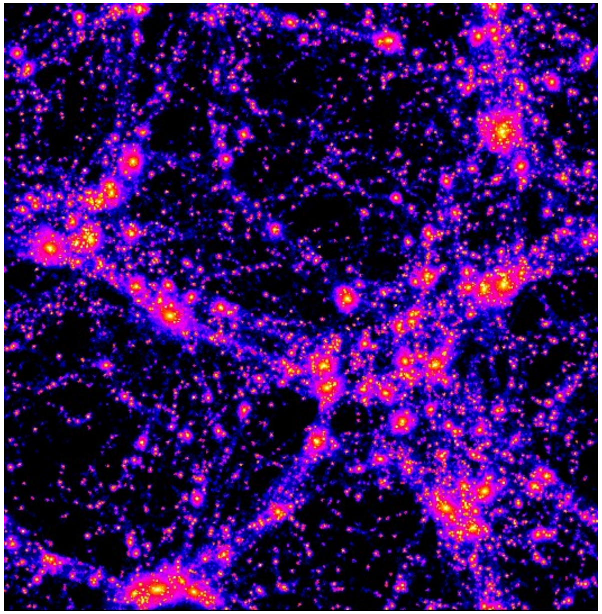
Boylan-Kolchin 2010,2011

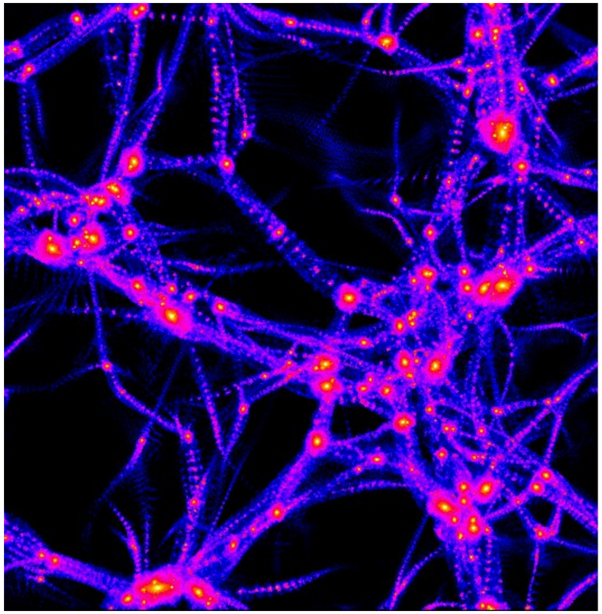


Lovell+12
Kennedy+14
dependence on MW halo mass

WDM "effects" on structure formation

- Reduction of overall number of low mass haloes
- Suppression of the number of low mass satellites in high mass halos
- Delayed structure formation (lower DM halo concentration)
- Upper limit in the density profile of dark matter haloes
v0 + Luiville Theorem (PS~ς/σ3)





Density profiles

- For a collisionless and dissipationless gas the *fine-grained* value of the phase space density (Q) is conserved.
- Deformation of "phase sheet": the *coarse-grained* phase space density can only decrease

$$f(\vec{x},\vec{v}) \approx Q \equiv \frac{\rho}{\sigma^3}$$

$$v_{thermal}(z) \propto (1+z)\left(\frac{keV}{m_x}\right)^{4/3} km/s$$

$$Q(z=100) = \frac{\Omega_m \rho_{cr}}{\sigma^3_{thermal}}$$

$$Q(z=0) = \frac{\rho_{central}}{\sigma^3_{central}}$$

Cold $m_x > 10^7 keV \rightarrow \sigma_{th} \sim 0 \quad Q \rightarrow \infty, \quad \rho_{central} \rightarrow \infty$ **Cuspy profile**

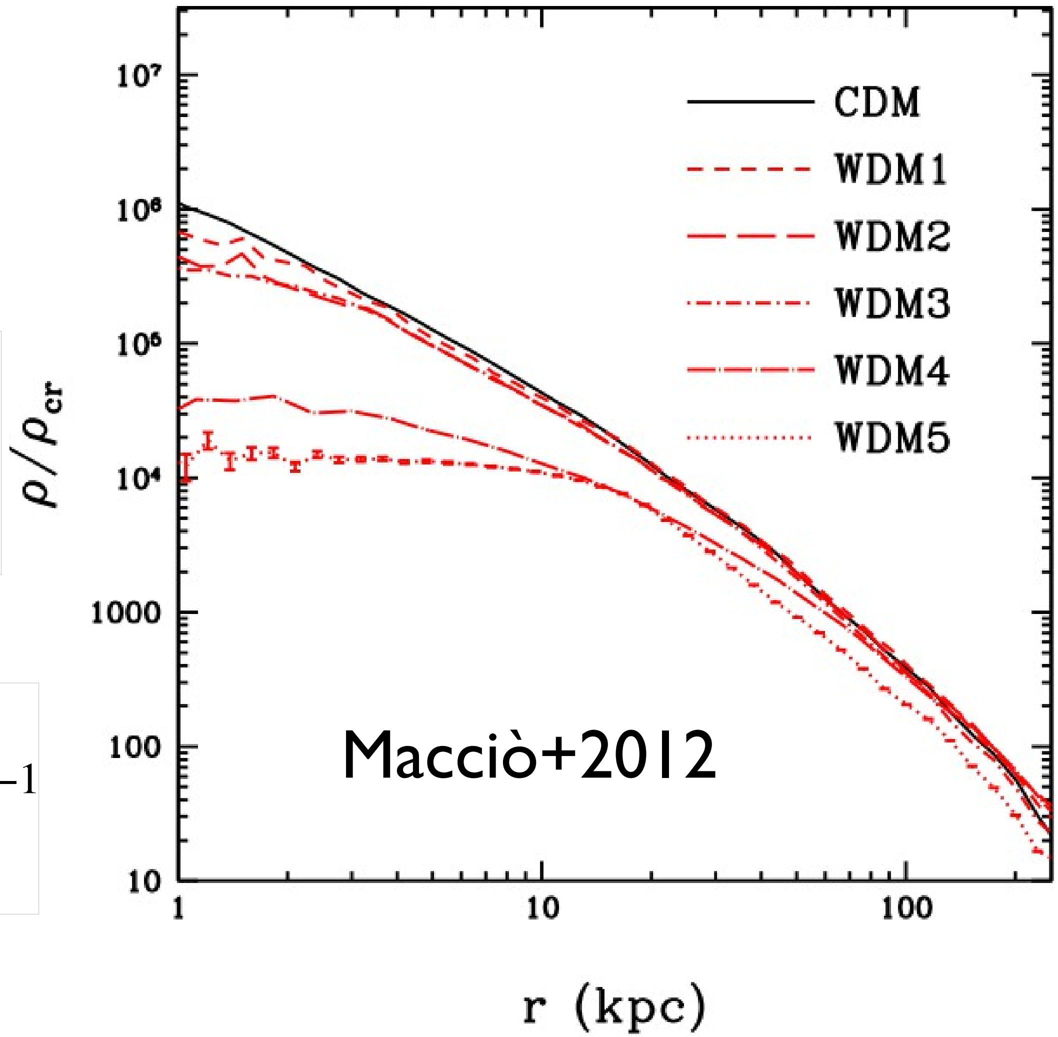
Warm $m_x \sim keV \rightarrow \sigma_{th} \sim 5 km/s \quad Q \rightarrow Q_{\max}, \quad \rho_{central} \rightarrow \rho_0$ **Cored profile**

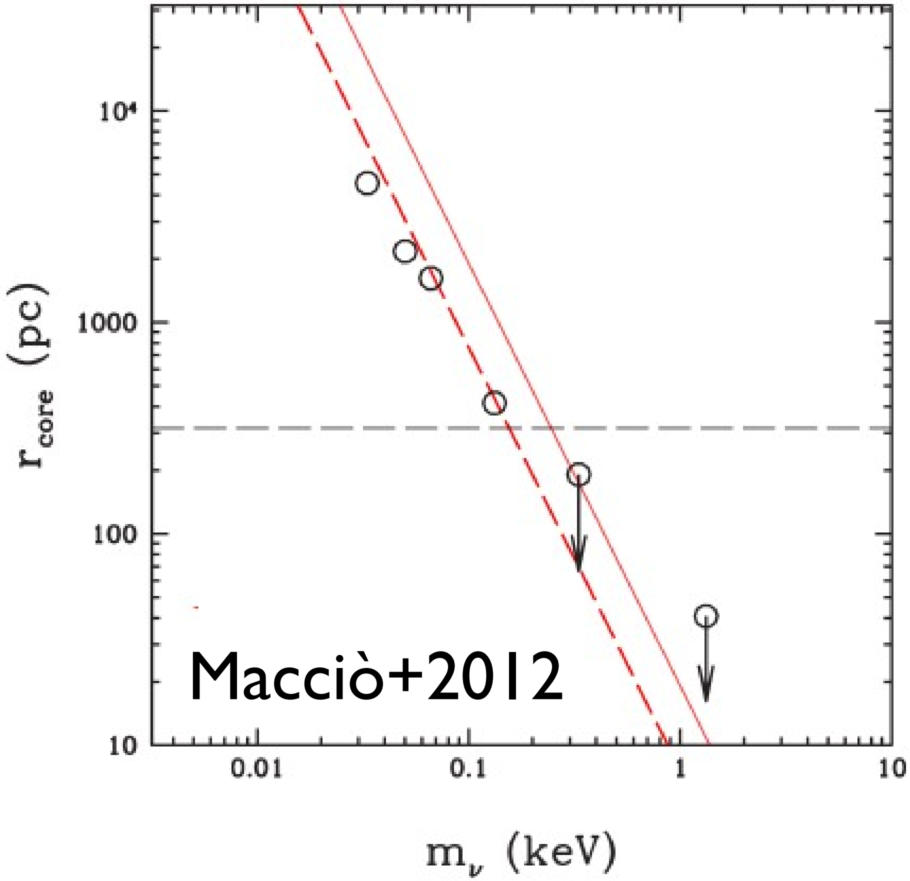
WDM & halo profile

Label	m_ν (keV)	$m_{\nu,\mathrm{vel}}$ (keV)
CDM	∞	
WDM1	2.0	2.0
WDM2	2.0	0.5
WDM3	2.0	0.2
WDM4	2.0	0.1
WDM5	2.0	0.05

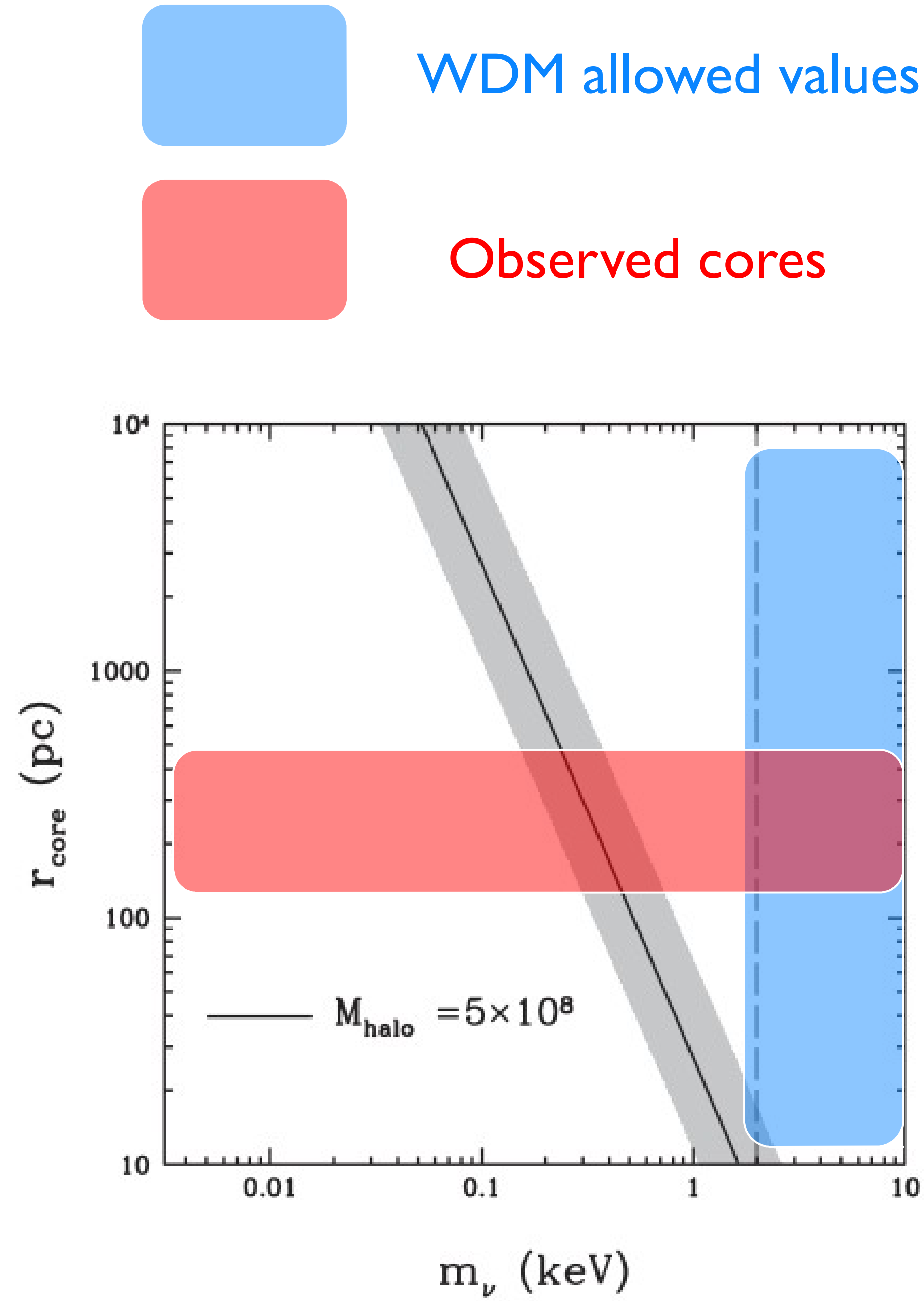
$$v_0(z) \propto (1+z)\left(\frac{keV}{m_{\nu,vel}}\right)^{4/3} \frac{km}{s}$$

$$k_S \approx \left(\frac{0.3}{\Omega_X}\right)^{0.15}\left(\frac{m_\nu}{keV}\right)^{1.15} Mpc^{-1}$$



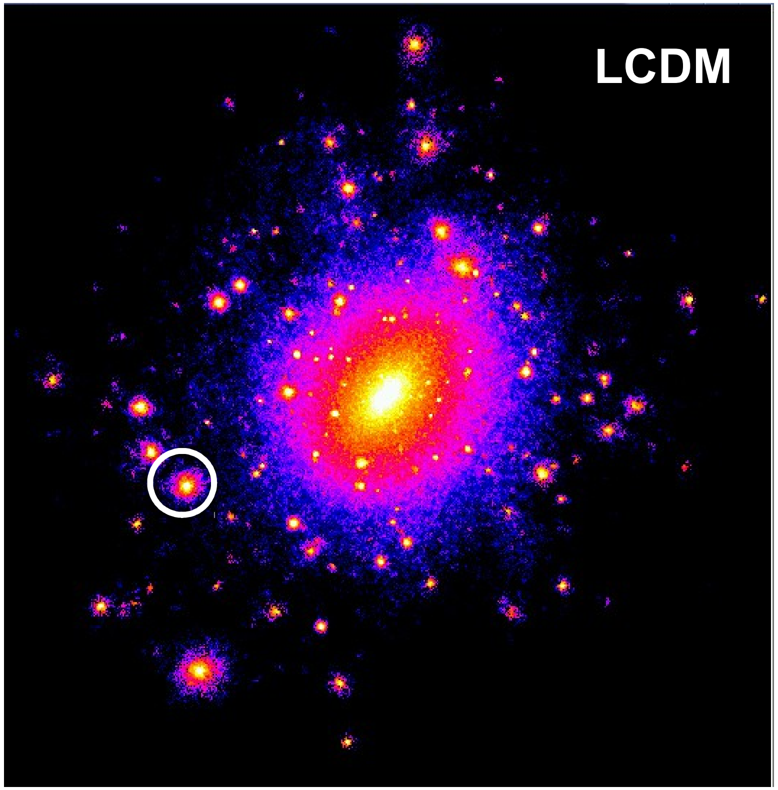


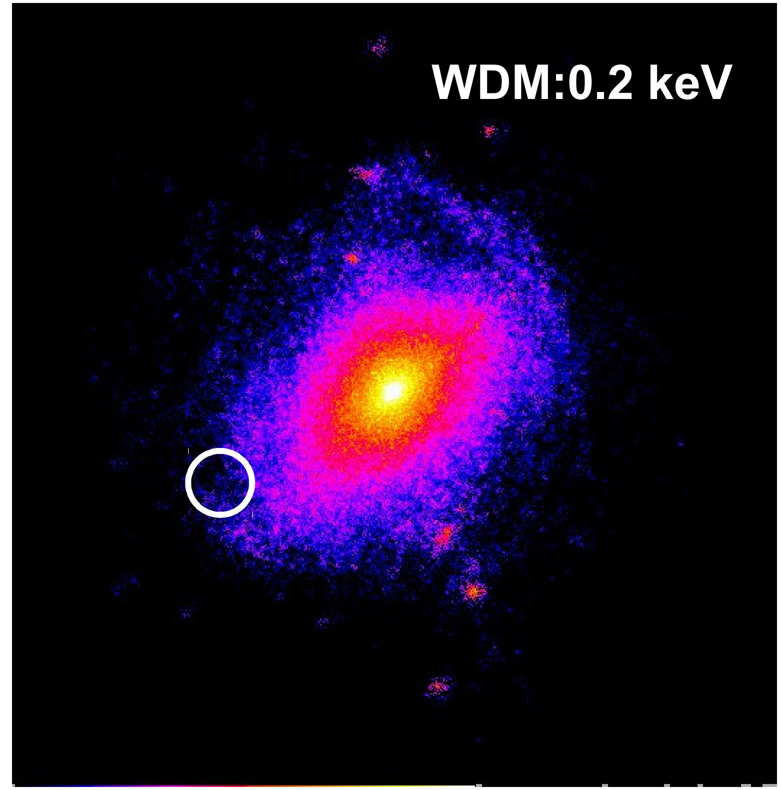
Lyman-α forest
& Lensing:
mν>1-2 keV



Rcore (Fornax) ~ 0.5 kpc → mν=0.2 keV

How does the host galaxy (MW like) of Fornax look like if mν=0.2 keV?





Catch 22 problem:

If you want a large core you won't get the dwarf galaxy

If you get the dwarf galaxy it won't have a large core

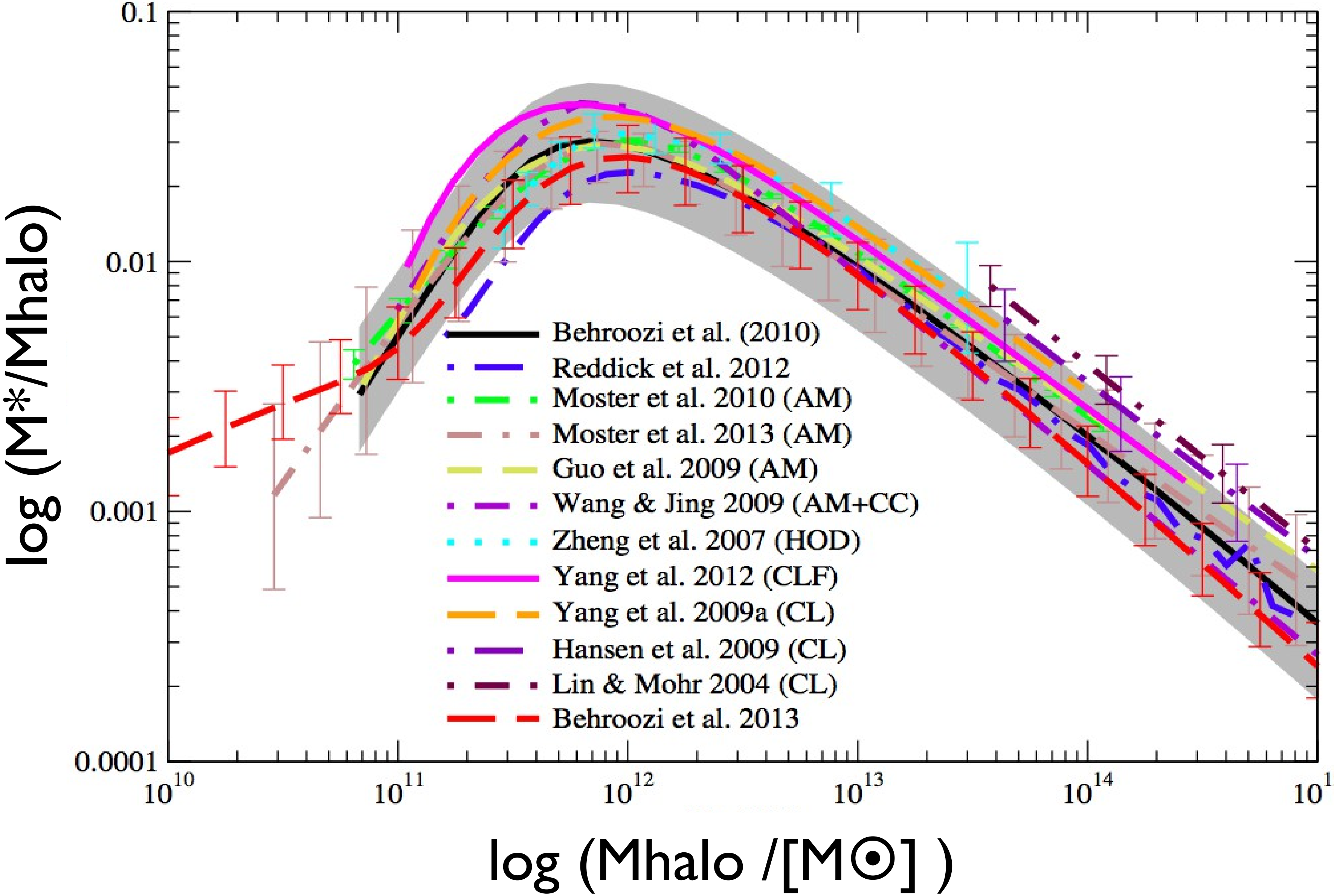
Macciò et al 2012, MNRAS, 458, 34

Structure formation

- WDM reduces the number of Satellites
- WDM reduces Satellites central mass (concentration)
- WDM suppresses low mass galaxies.
- WDM cannot create cores larger than 10-50 pc.

Galaxy formation

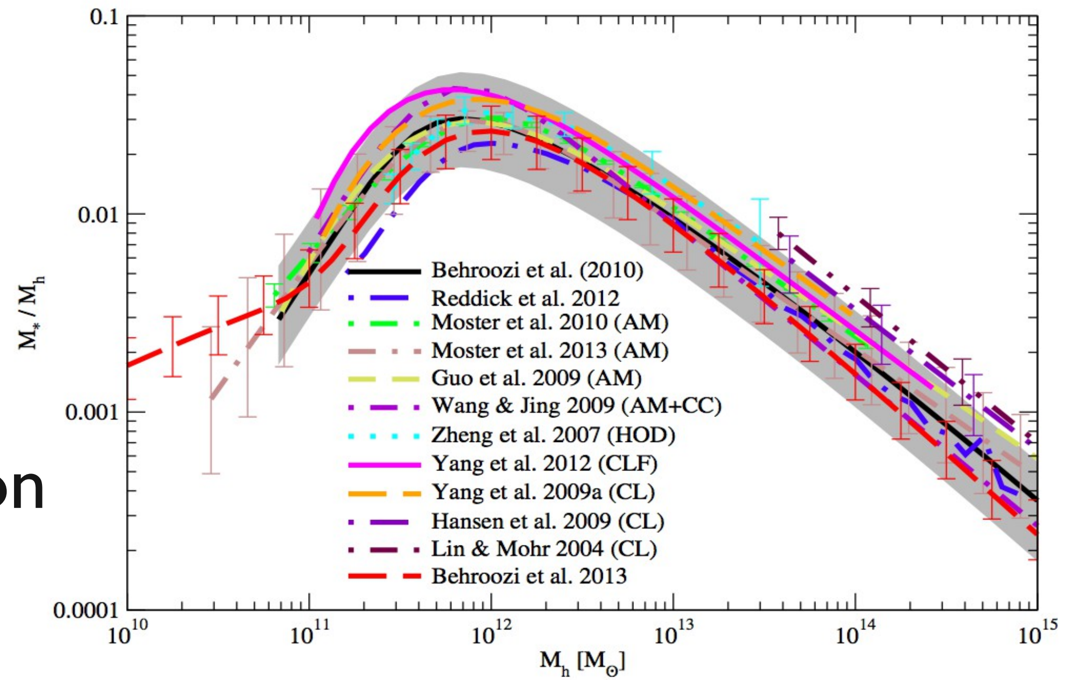
Galaxy formation



Galaxy formation

Galaxy formation inefficient at low masses due to feedback
(SN, UV radiation, etc.)

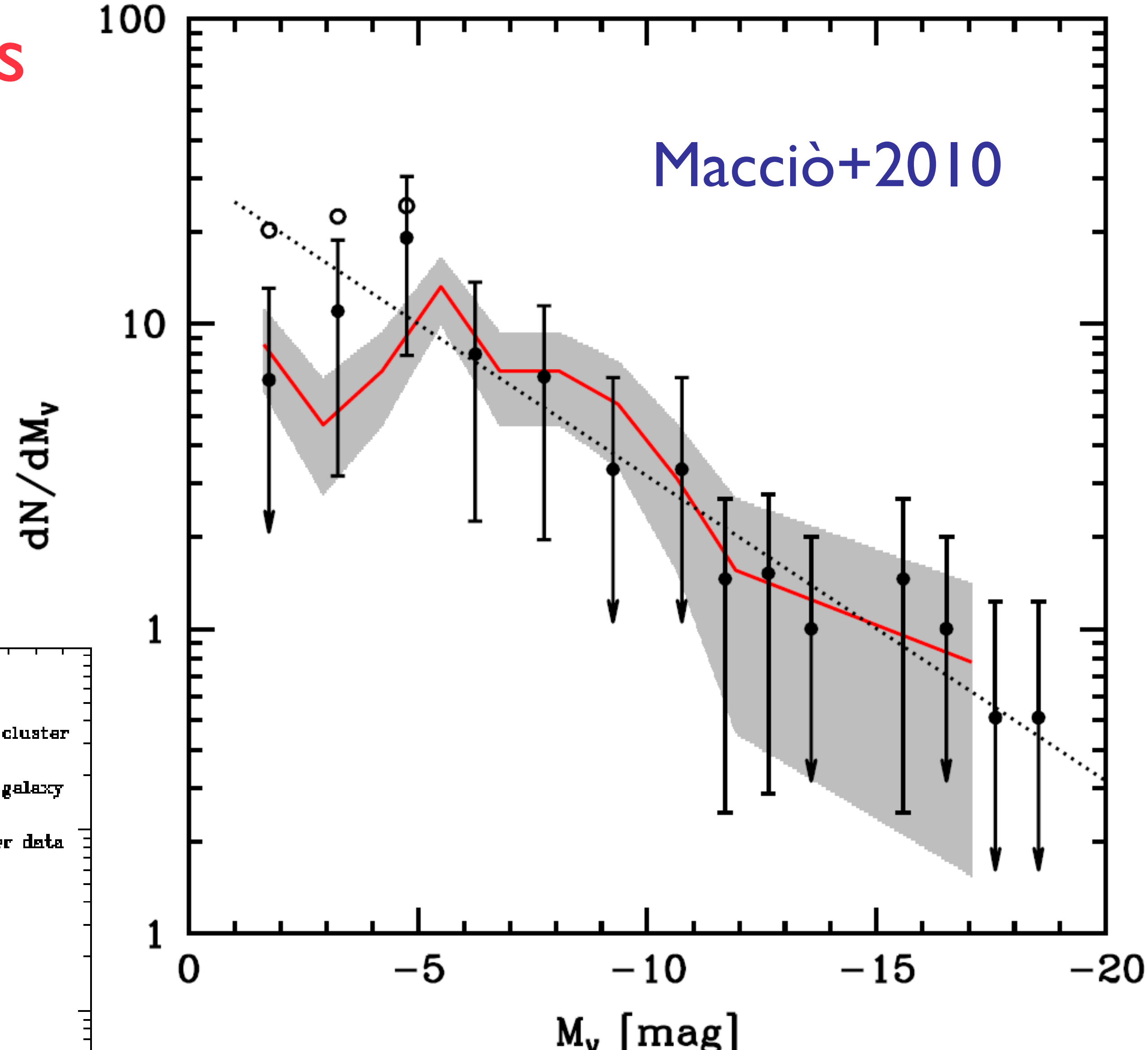
In WDM structure formation inefficient at low masses



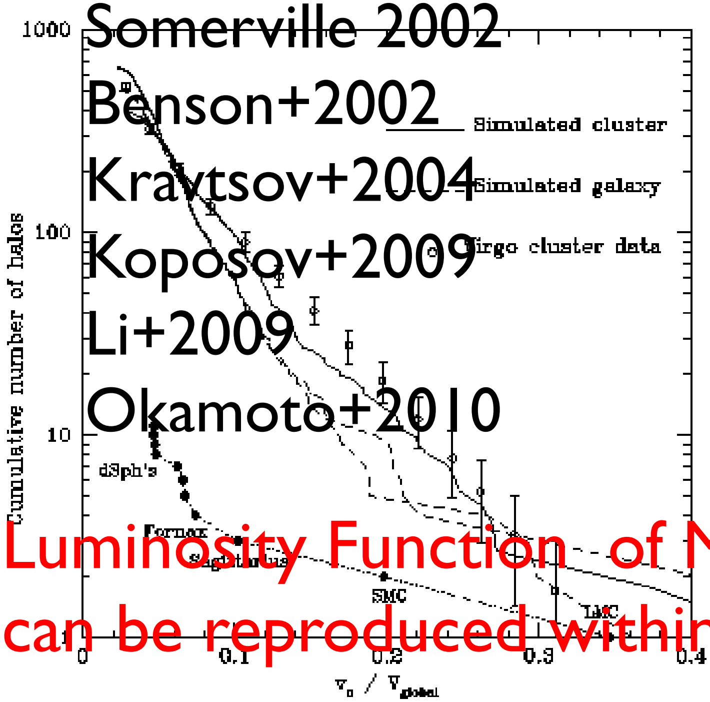
Galaxy formation vs. WDM

CDM + baryons

SN feedback
+
Reionization
+
GAS removal



Bullock+2000
Somerville 2002
Benson+2002
Kravtsov+2004
Koposov+2009
Li+2009
Okamoto+2010

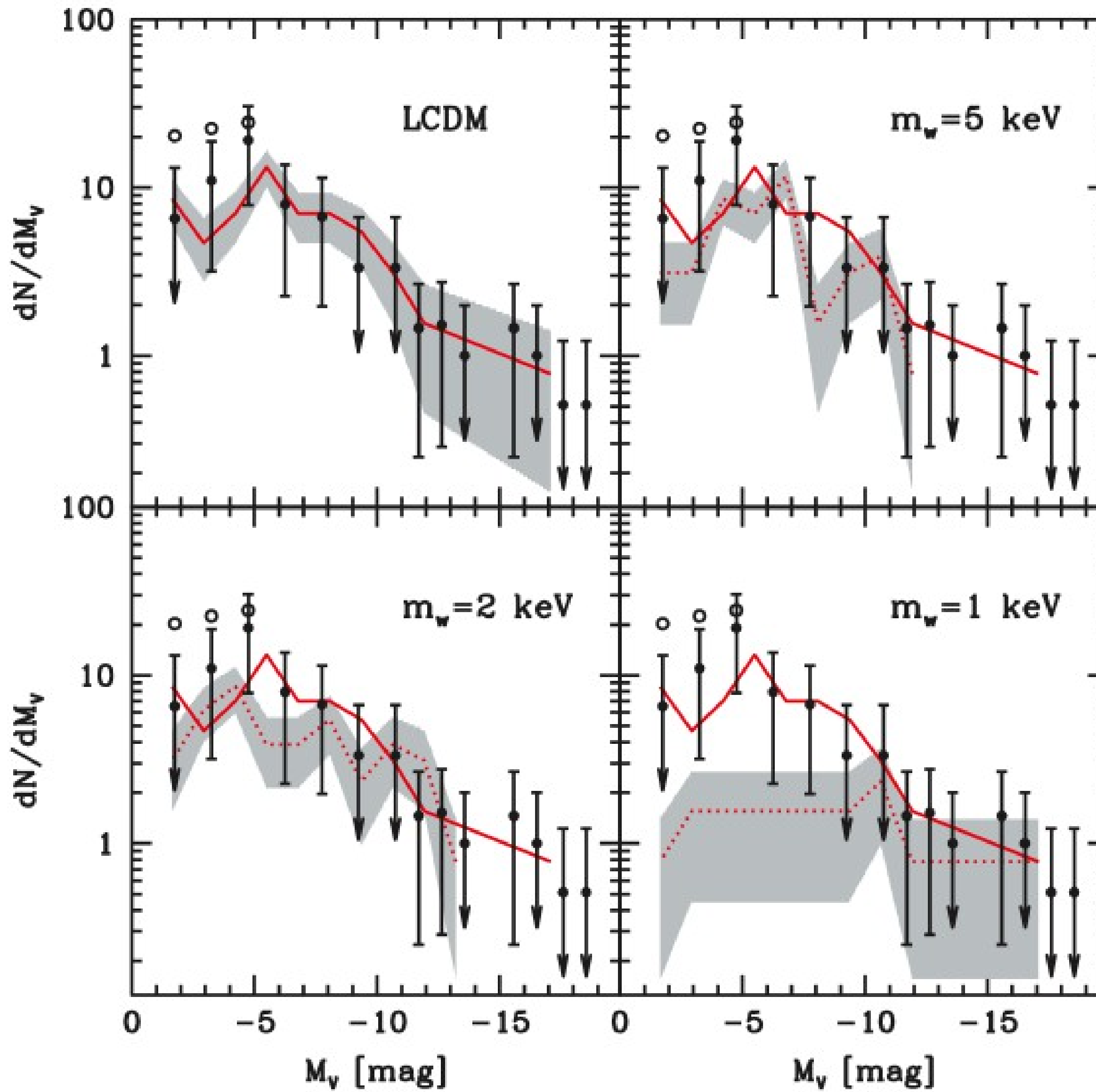


Luminosity Function of Milky Way satellites can be reproduced within the CDM model

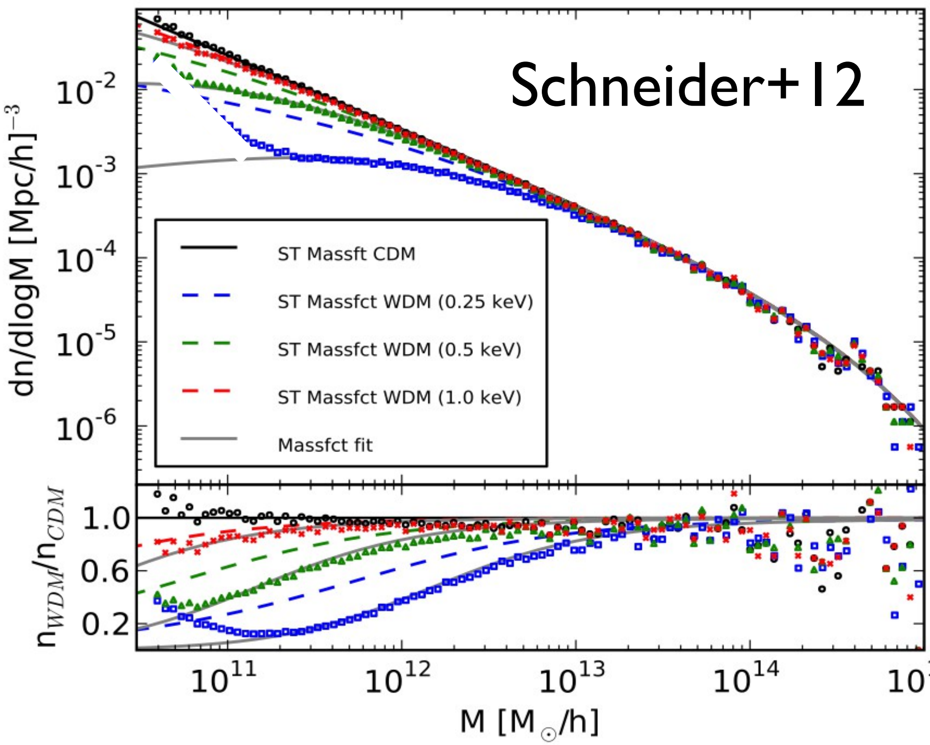
WDM + Baryons

Macciò & Fontanot 2010

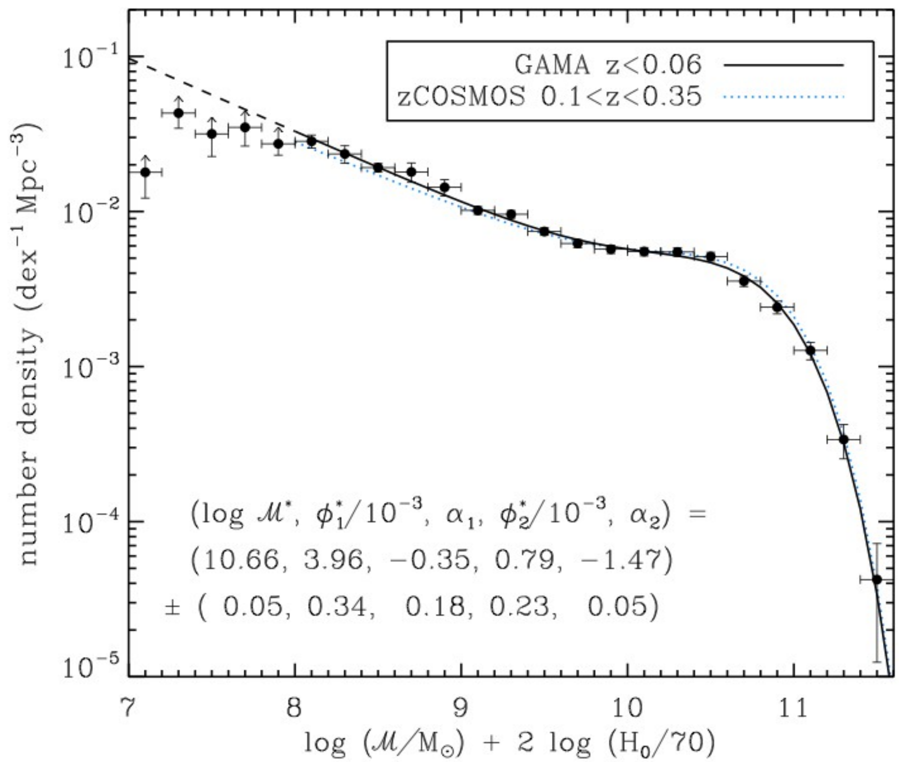
Too few satellites in WDM to match observations if Mwdm< 2 keV



WDM and galaxy formation

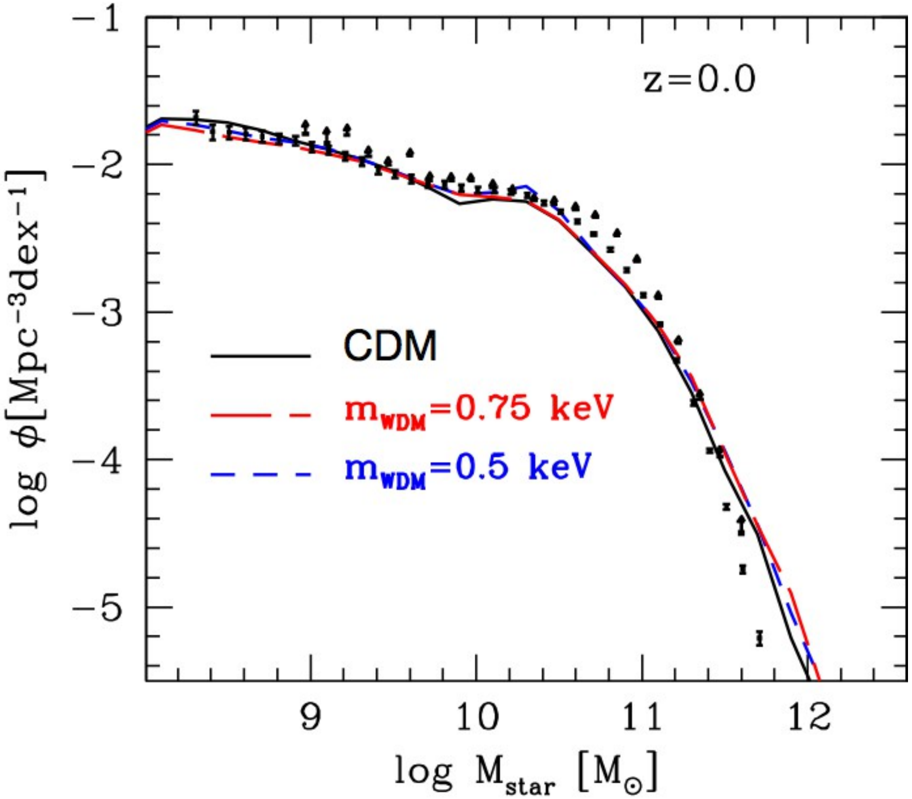


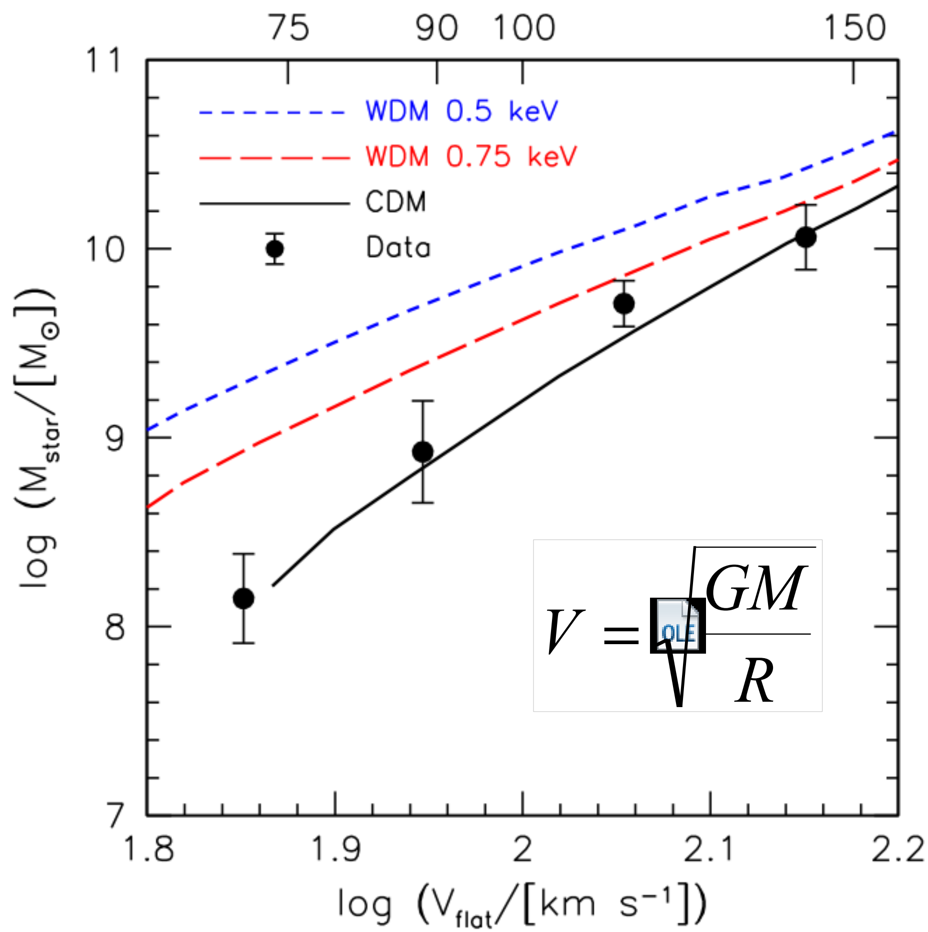
Halo mass function in WDM



Observed Stellar mass function

WDM and galaxy formation





$$V = \sqrt{\frac{GM}{R}}$$

Kang, AM, Dutton 2012

Reduced feedback in WDM

More stars per DM halo in WDM w.r.t. CDM

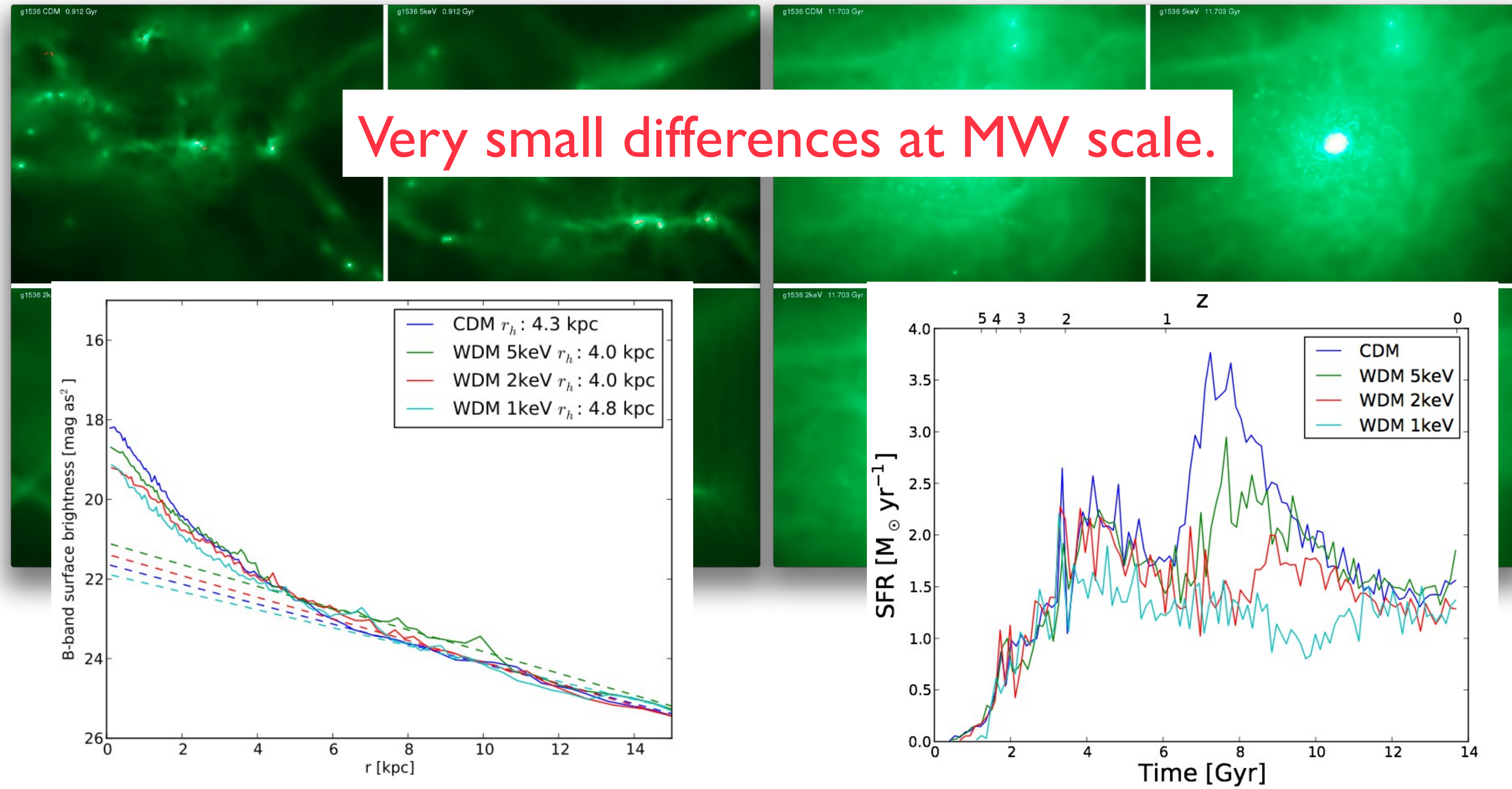
Constraints on WDM from galaxy formation

WDM and galaxy formation

Self-consistent simulations of WDM + baryons
Herpich+14


g1536 CDM 0.000 Gyr
g1536 5keV 0.000 Gyr
g1536 2keV 0.000 Gyr
g1536 1keV 0.000 Gyr

WDM and Galaxy formation



Herpich, Stinson, AM+14

Galaxy formation

- Galaxy formation is inefficient at low masses
- Amplifies the effect of WDM
- WDM + Galaxy formation mwdm > 1 keV
- WDM acts as "feedback" reducing SF
- No large effects on Milky Way scale

Is WDM “better” than CDM?

It depends on the WDM mass

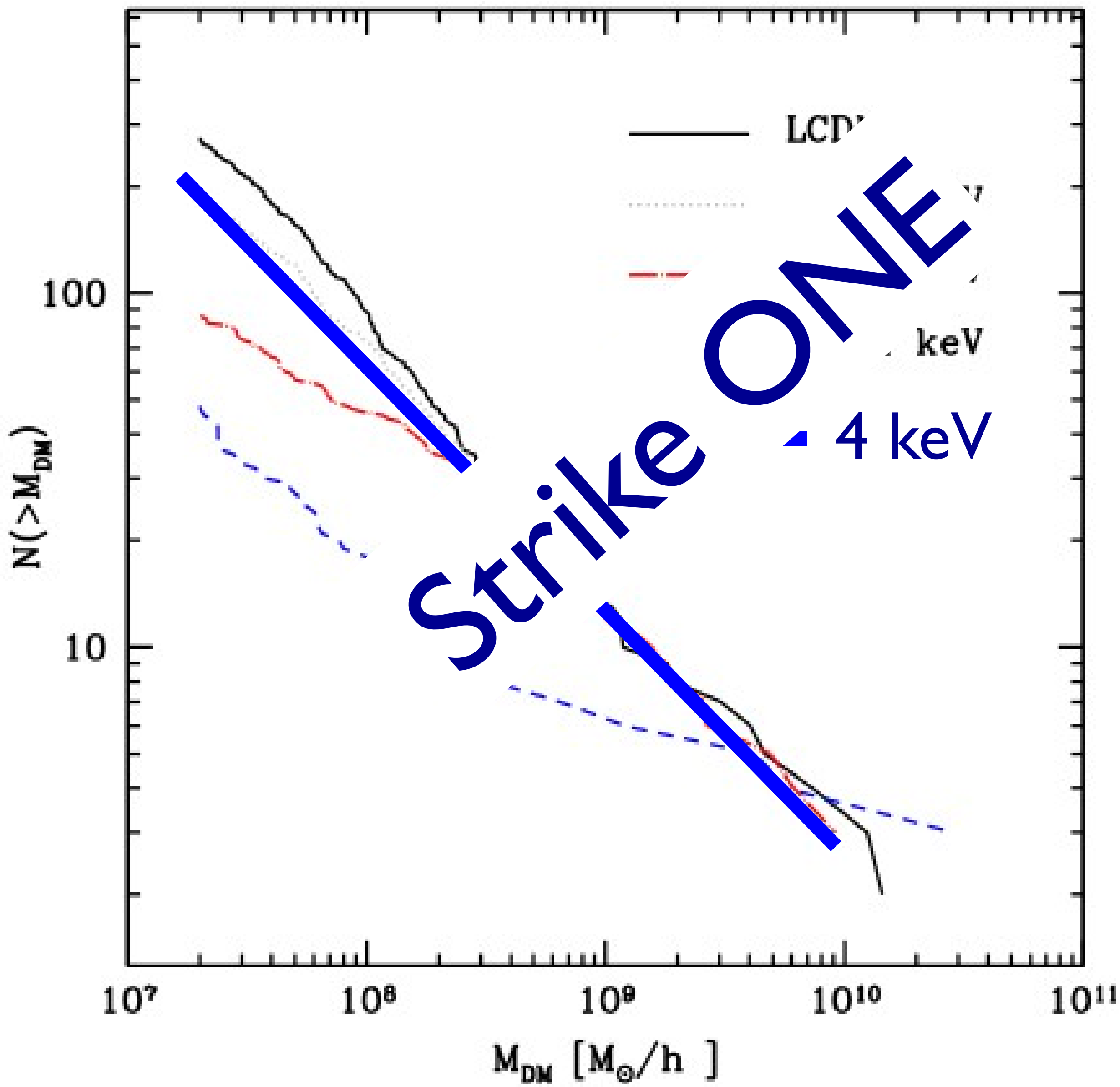
Viel+13 L-alpha forest: mwdm>3.3 keV
(with maximum likelihood 4 keV)

Polentsky & Ricotti 2013: mwdm>3.5 keV

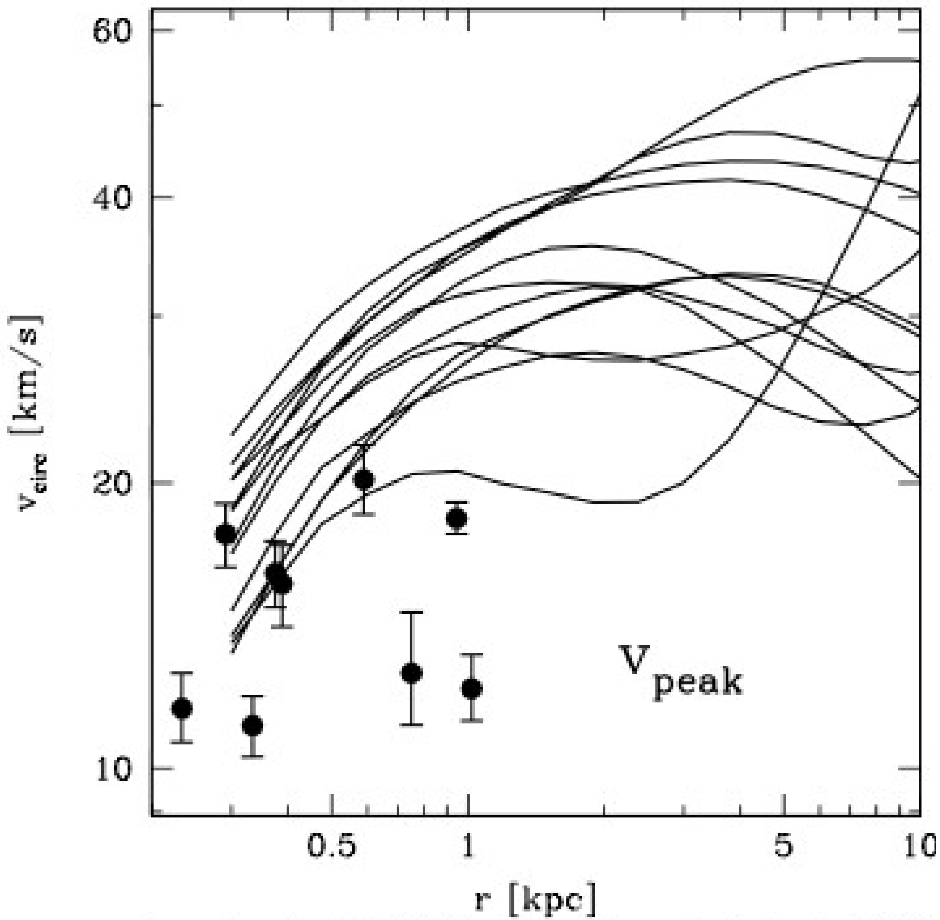
Is a WDM candidate with a mass of 4 keV different from CDM?

Schneider, Anderhalden, Macciò, Diemand 2014, MNRAS

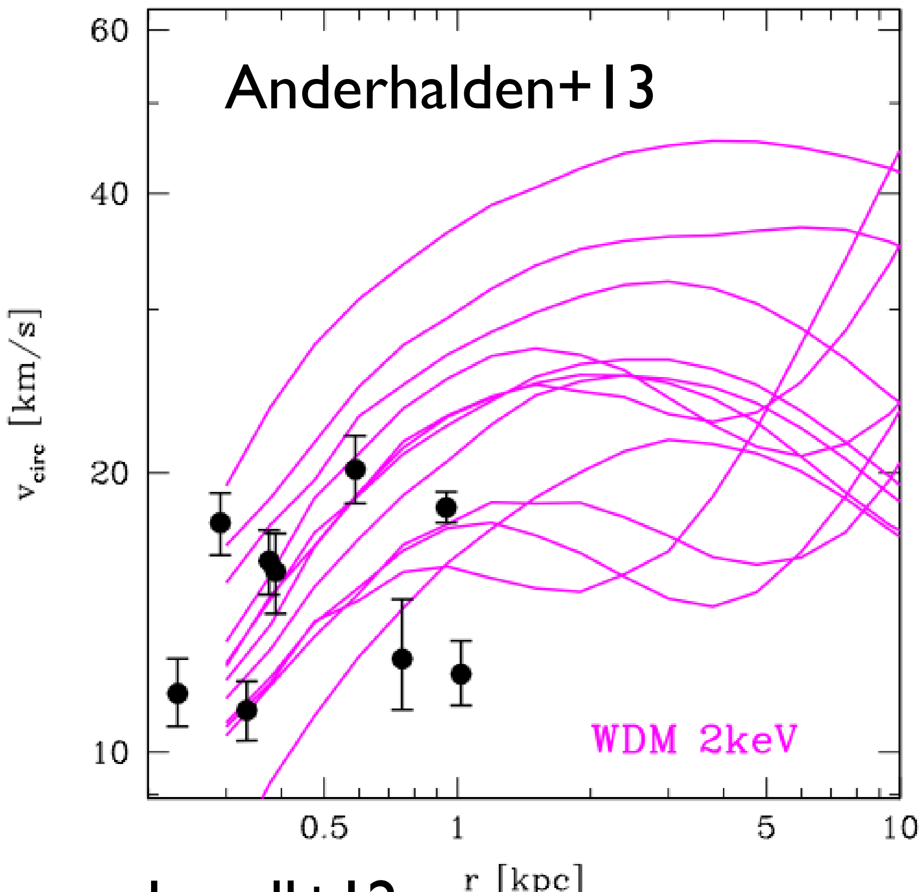
1. Substructure abundance



2. MW satellites Kinematics

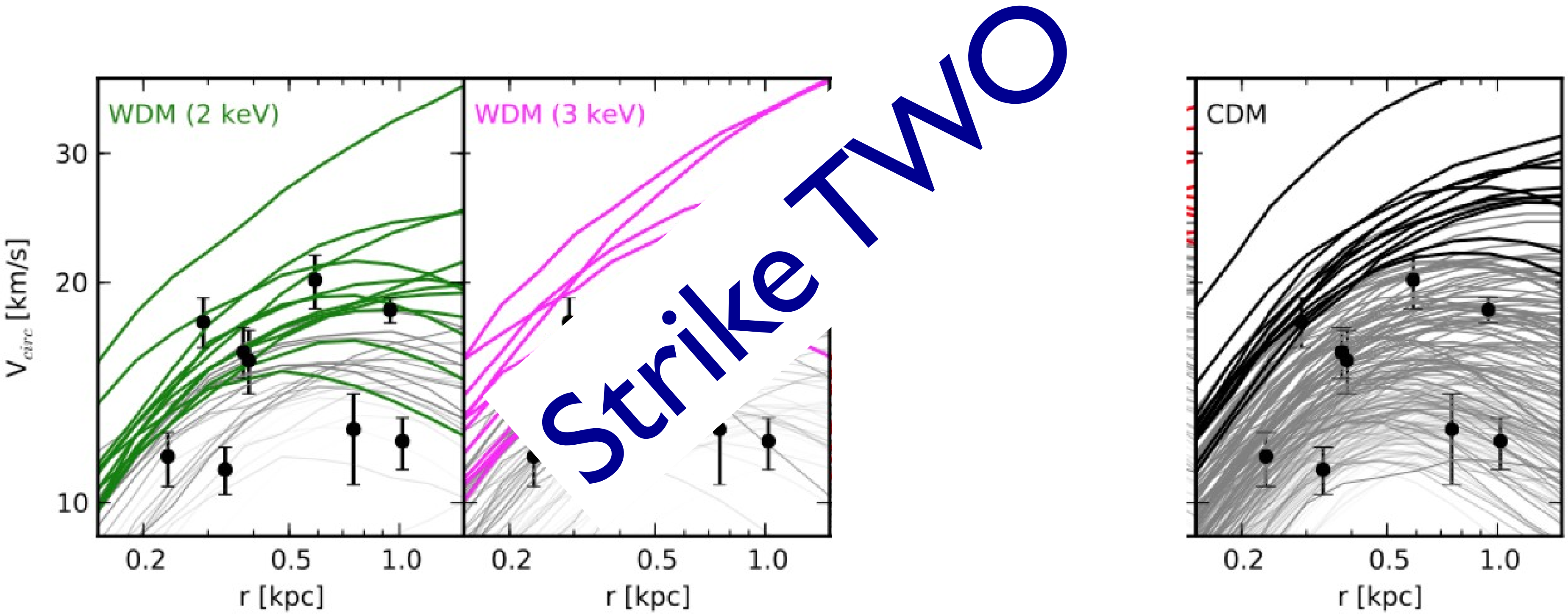


Boylan-Kolchin 2010,2011



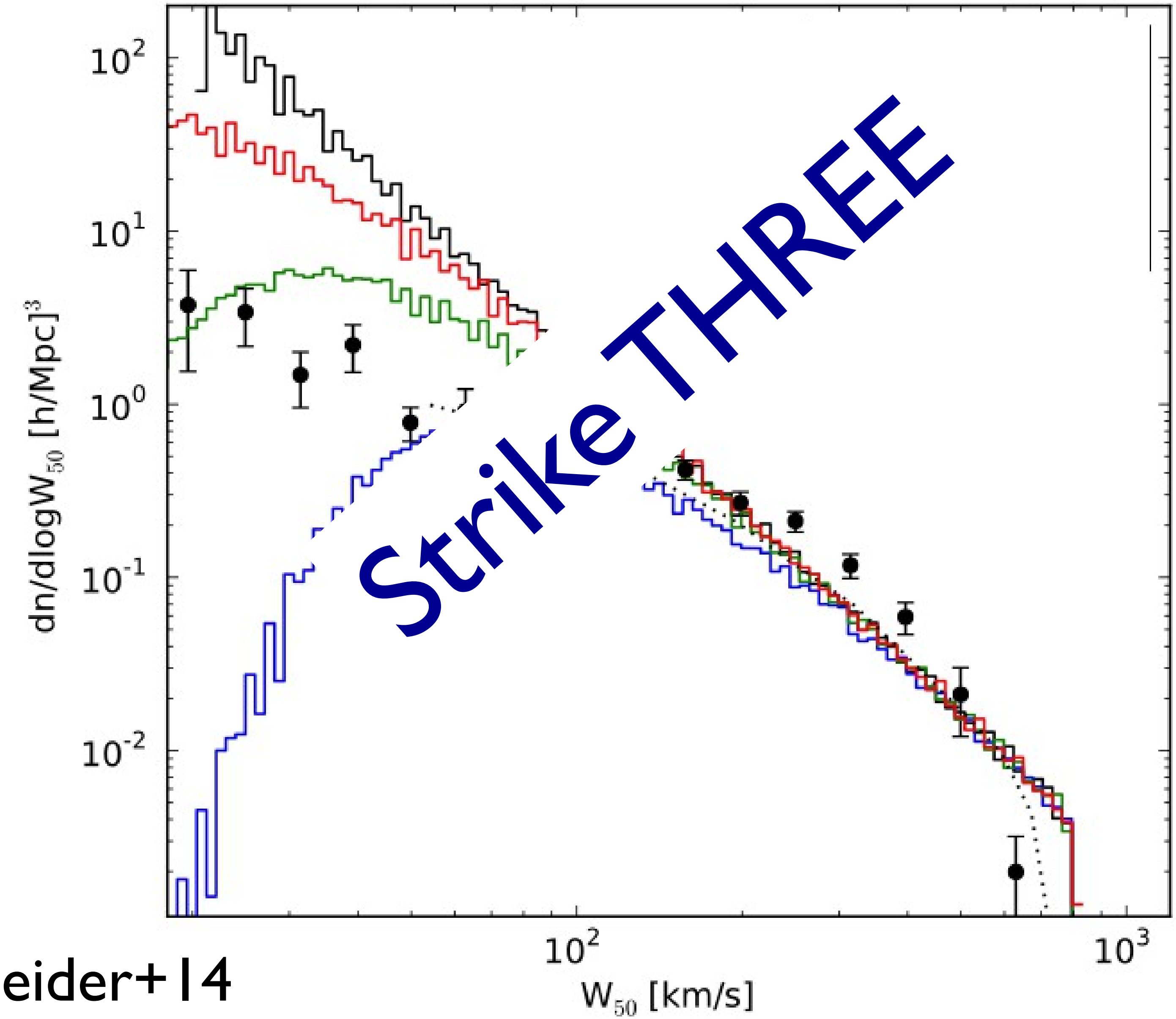
Lovell+12
Kennedy+14
dependence on MW halo mass

2. MW satellites Kinematics



Schneider, Anderhalden, Macciò, Diemand 2014

3. Velocity function in the Local Volume



Schneider+14

Is WDM "better" than CDM?

- Viel+13: mwdm>3.3 keV (m.l. 4 keV)
- Polentsky & Ricotti 2013: mwdm>3.5 keV

A WDM candidate with m=4 keV
is practically not distinguishable from CDM.

Schneider, Anderhalden, Macciò, Diemand 2014, MNRAS

Conclusions

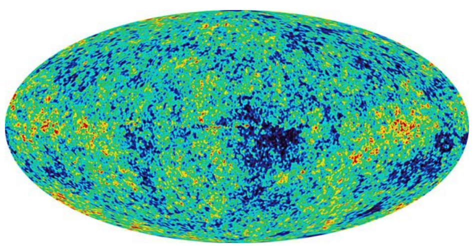
- WDM is a viable candidate independently on possible CDM issues.
- WDM and galaxy formation must be studied together. Feedback can mimic WDM.
- WDM when restricted to current limits (>4 keV) is astrophysically equivalent to CDM.

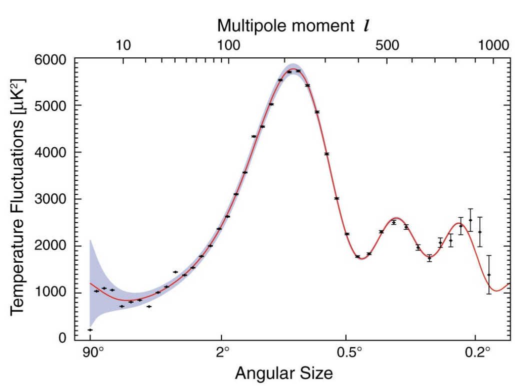
Thank you

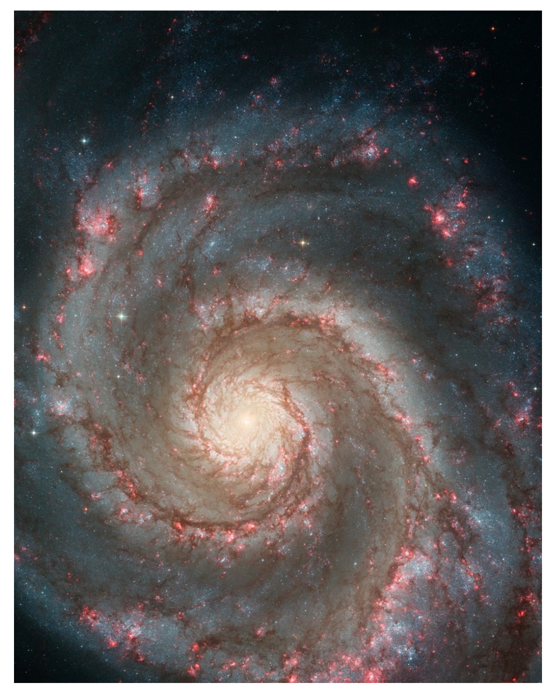
MaGICC

Making Galaxies in a Cosmological Context

AM, G. Stinson, A. Dutton, N. Fanidakis. R. Kannan, C. Penzo, J. Herpich (MPIA)
C. Brook (Univ. Madrid), M. Baldi (Bologna), S. Gottlöber (AIP)



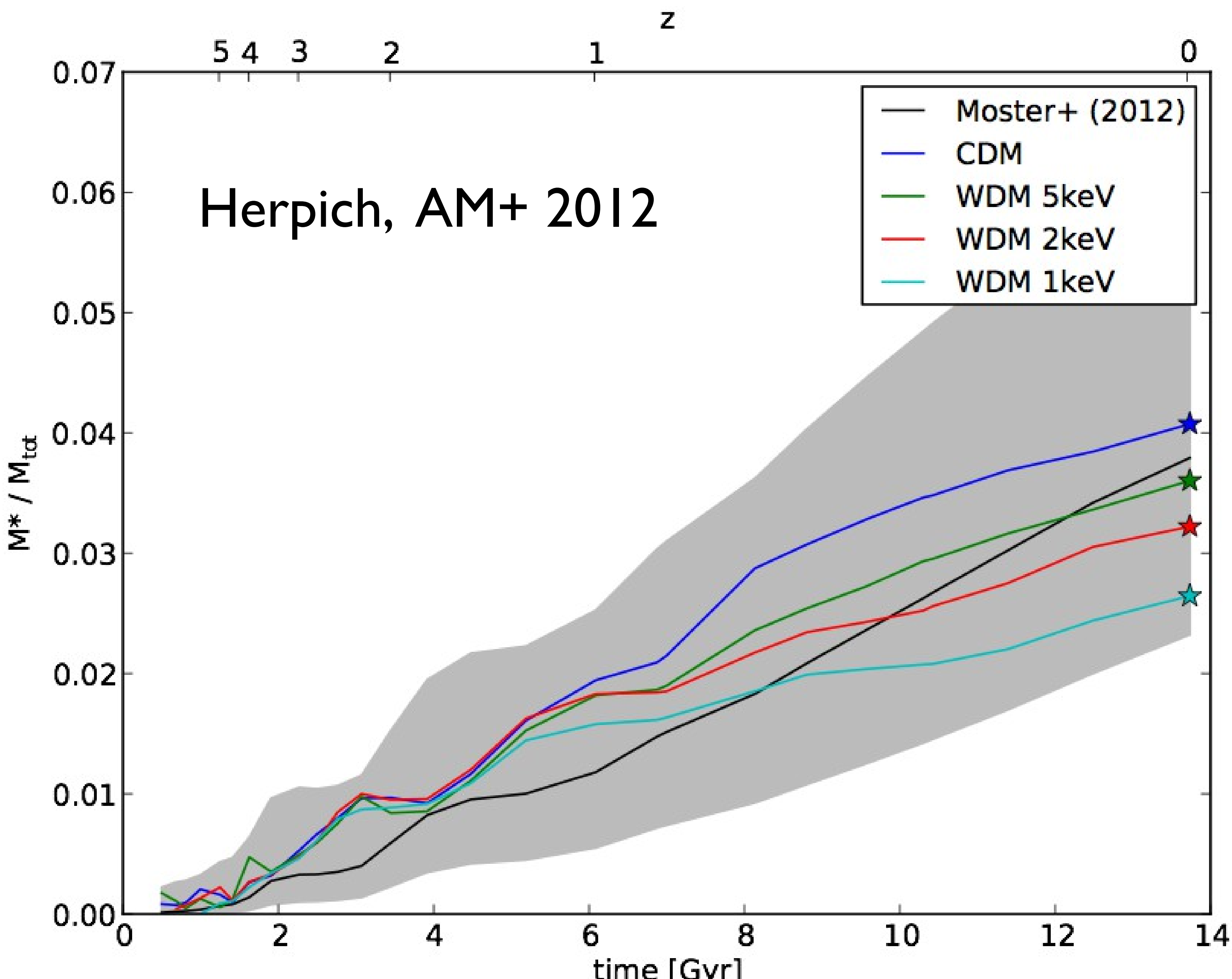




MaGICC galaxy simulation

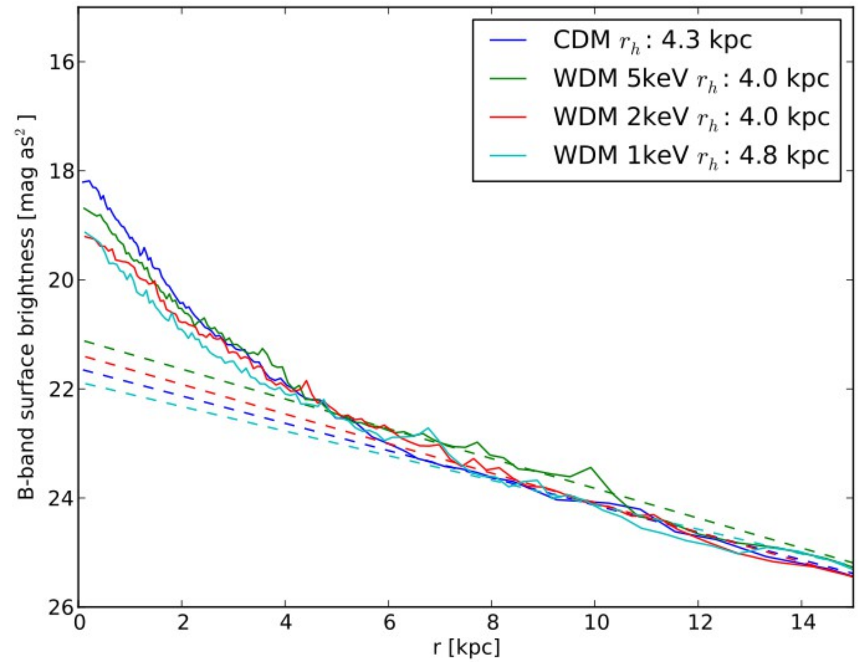
Stinson, Brook, AM+2012

green = GAS red/blue/ = stars (DM not shown)

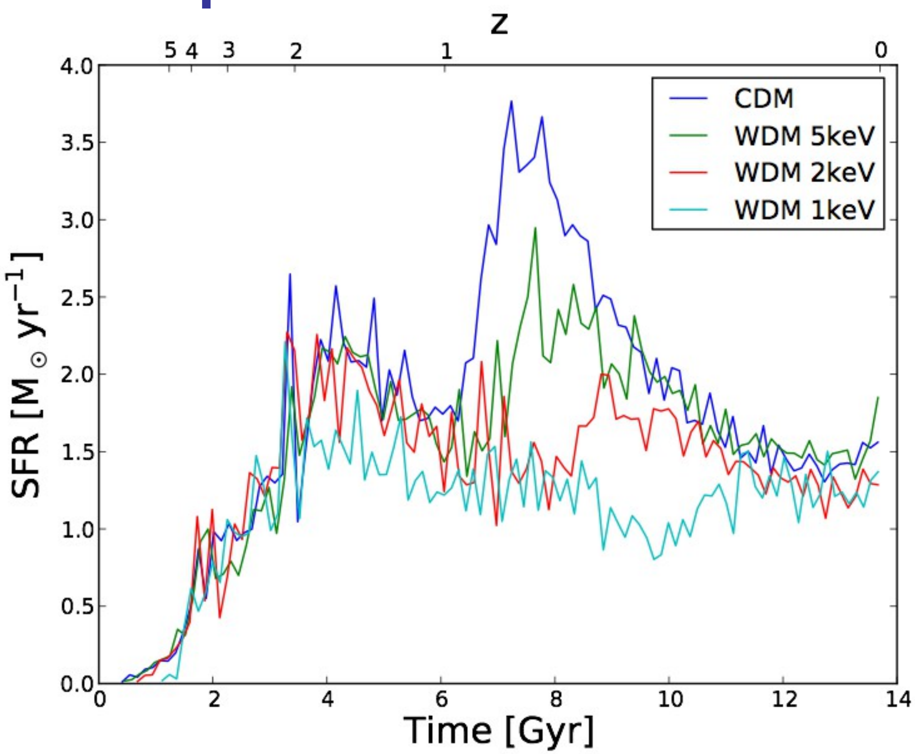


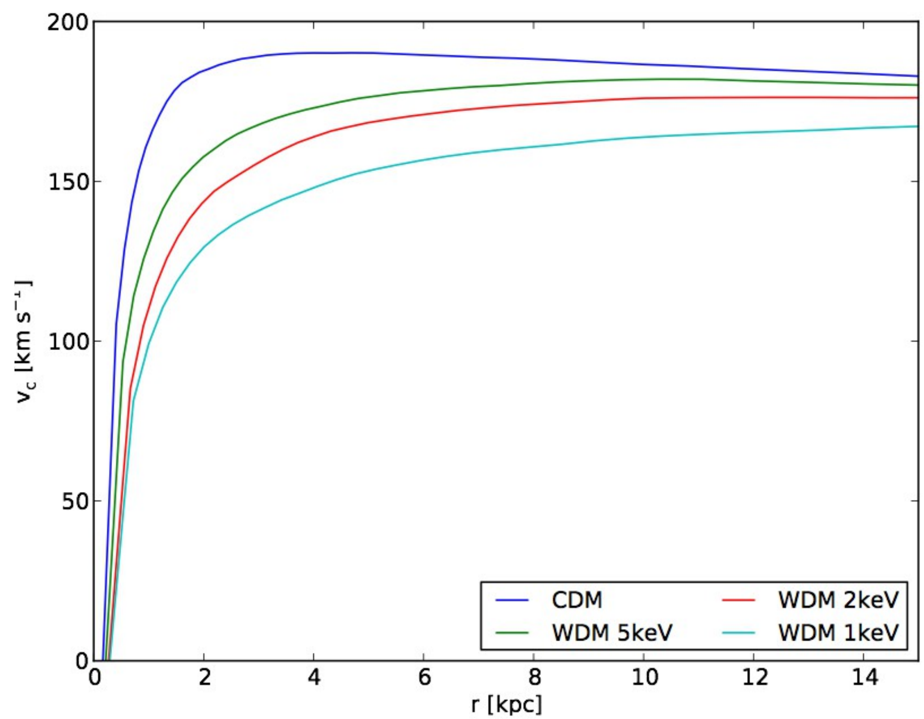
z
5 4 3 2 1 0
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
M* / M_tot
Herpich, AM+ 2012
Moster+ (2012)
CDM
WDM 5keV
WDM 2keV
WDM 1keV
0 2 4 6 8 10 12 14
time [Gyr]

WDM vs. CDM



Herpich, AM+ 2012





Conclusion: If you like it COLD

1 - Abundance of local satellites does NOT require WDM.
Actually it can be used to constrain it.

2 - Flat density profiles can NOT be explained by WDM alone.

Baryons + CDM can explain most of the observations

Wait for good SUSY news from LHC

Conclusion: If you like it WARM

1 – 2 keV WDM in agreement with all current constraints

2 – Better than CDM on small scales *(doesn't solve but helps)*

3 – Possible new tight constraints from M*/Mdm ratio

Why WDM?
Cores in very faint MW satellites could require
WDM & baryons to act together.
Baryons and WDM must be simulated together

Wait for *no* SUSY evidence from LHC

I am covered in both cases

THANK YOU!