Analytical model for MW satellites: constraints on WDM mass (submitted)

Xi Kang
Purple Mountain Observatory, China

Sep 30@SAO, Russian

Key challenges for the MW formation in CDM

- **Survival of the MW disk**: the CDM theory predicts 95% of MW-type halos have experienced mergers of $5*10^{10}\ M_\odot$ in the last 10Gyr, 70% have merger of object $>10^{11} M_\odot$
- **Missing satellite problem**: CDM predicts hundreds sats, but less than 50 sats are observed
- **Great plane of the Satellites**: satellites are not randomly distributed, but in a thin plane
- **Too-big-to-Fail**: CDM predicts sats which are too compact than observed

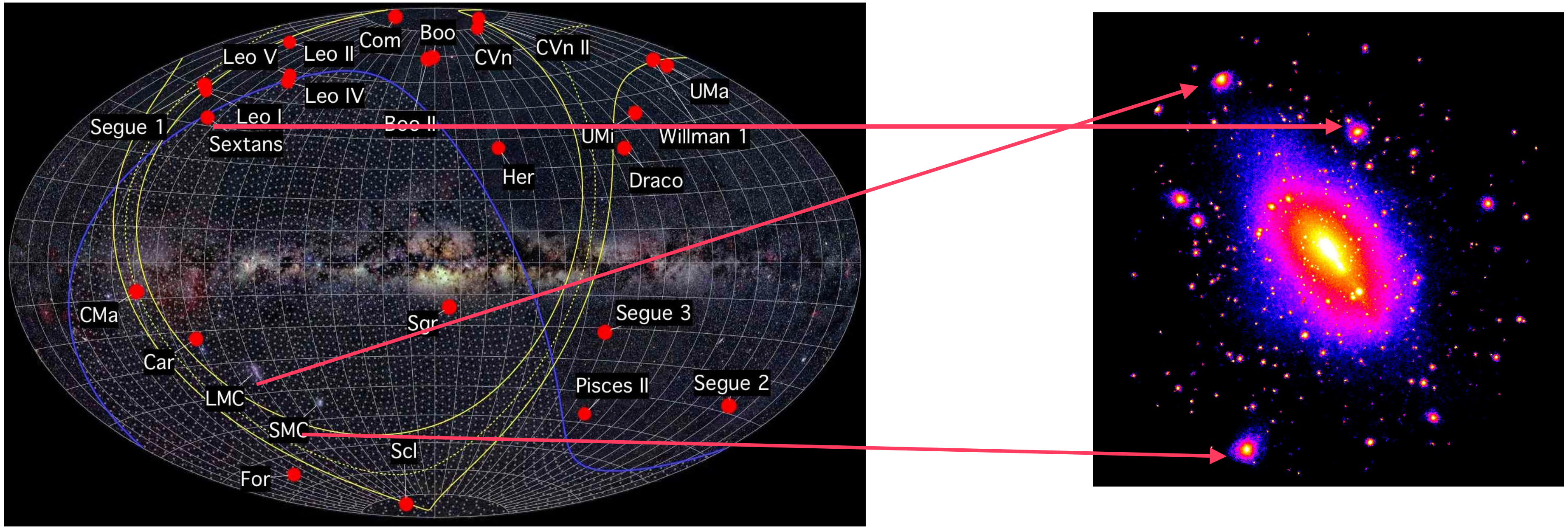
For review of MW satellite problem

Small-Scale Challenges to the ΛCDM Paradigm

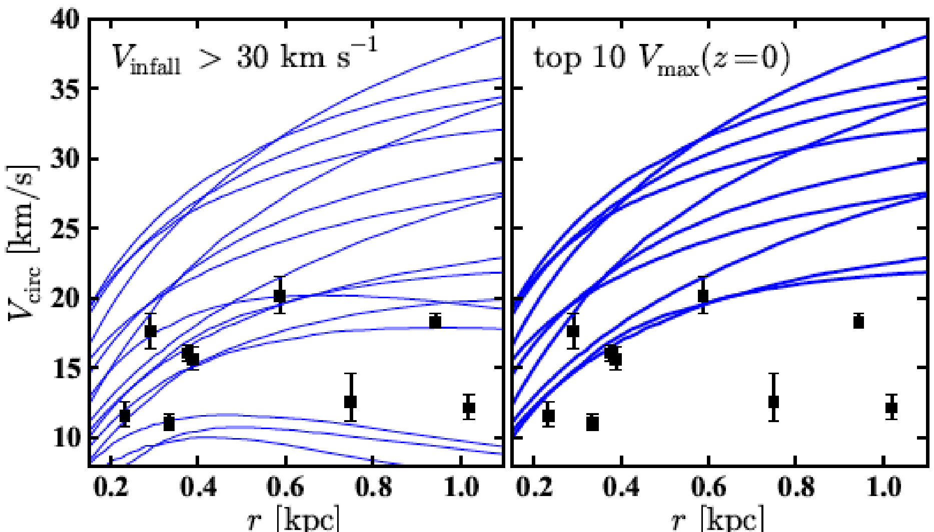
Annual Review of Astronomy and Astrophysics
Vol. 55:343-387 (Volume publication date August 2017)
First published as a Review in Advance on June 28, 2017
https://doi.org/10.1146/annurev-astro-091916-055313

Bullock & Boylan-Kolchin 2017, ARA&A

How to connect the observed sats with subhalos from Simulation?



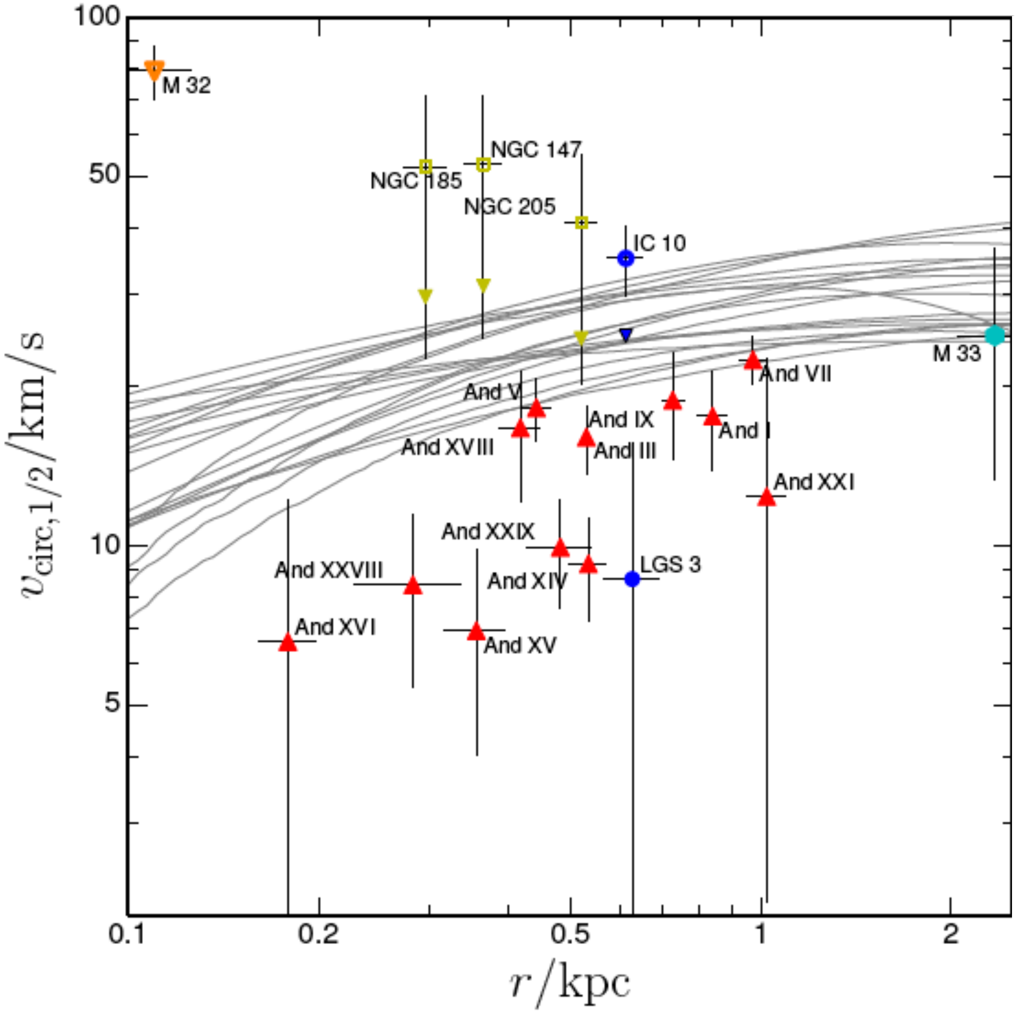
Boylan-Kolchin et al 2012



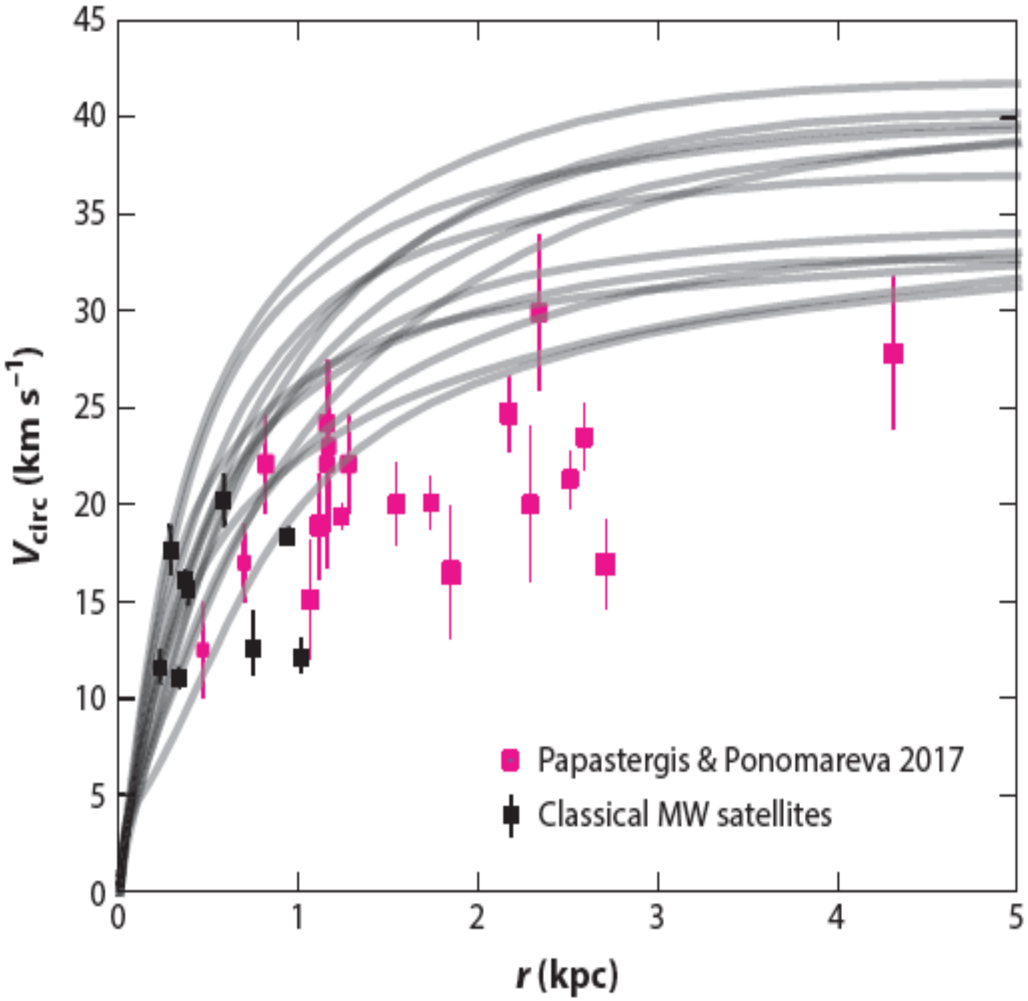
Observed sats have circular velocity lower than the (massive) subhalos from simulation (massive subhalos fail to form stars ? this violates TBTF)

TBTF also exists for M31 and field dwarf galaxies

M31 satellites



Field dwarfs



Tollerud + 2014

solutions for the TBTF problem

- nature or nurture?
- baryonic process (feedback), environmental (tides)
- alternative dark matter (WDM, Self-interacting DM…)

Another view of the Velocity distribution of MW satellites

Object	V_{max} ($km\,s^{-1}$)	Reference
MW	170.0 ± 15.0	[1]
LMC	91.7 ± 18.8	[2]
SMC	60.0 ± 5.0	[3]
Sagittarius	(25.1 ± 1.5)	
Bootes II	(23.1 ± 16.3)	
Draco	$20.5^{+4.8}_{-3.9}$	[5]
Ursa Minor	$20.0^{+2.4}_{-2.2}$	[5]
Fornax	17.8 ± 0.7	[5]
Sculptor	$17.3^{+2.2}_{-2.0}$	[5]
Leo I	$16.4^{+2.3}_{-2.0}$	[5]
Ursa Major I	14^{+3}_{-1}	[4]
Ursa Major II	13^{+4}_{-2}	[4]
Leo II	$12.8^{+2.2}_{-1.9}$	[5]
Sextans	$11.8^{+1.0}_{-0.9}$	[5]
Canes Venatici I	$11.8^{+1.3}_{-1.2}$	[5]
Carina	$11.4^{+1.1}_{-1.0}$	[5]
Canes Venatici II	$11^{+2}_{-2.1}$	[4]
Hercules	$11^{+3}_{-1.6}$	[4]
Segue I	$10^{+7}_{-1.6}$	[4]
Coma Berenices	$9.1^{+2.9}_{-0.9}$	[4]
Willman 1	$8.3^{+2.7}_{-0.8}$	[4]
Leo V	$(8.1^{+5.1}_{-3.1})$	

Jiang & vd Bosch 2015

A big gap in Vmax between SMC and Sagittarius

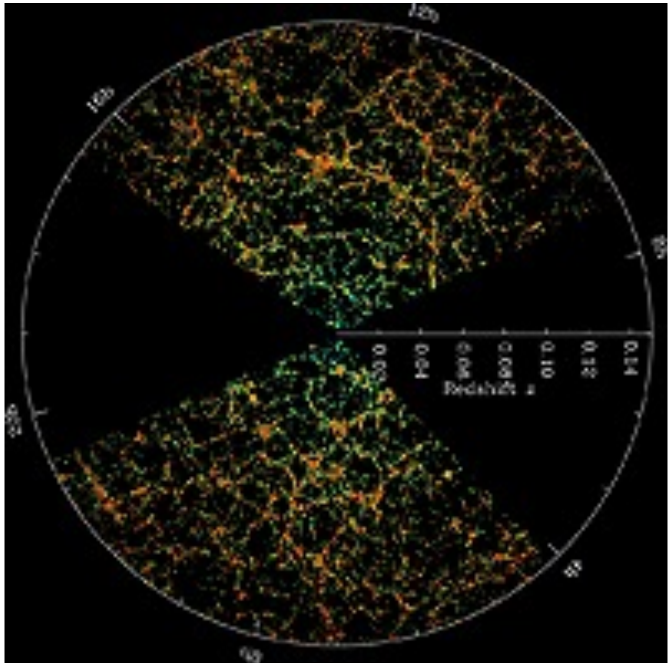
IF TBTF is nature, What's the chance of such a velocity gap in MW size galaxy in CDM?

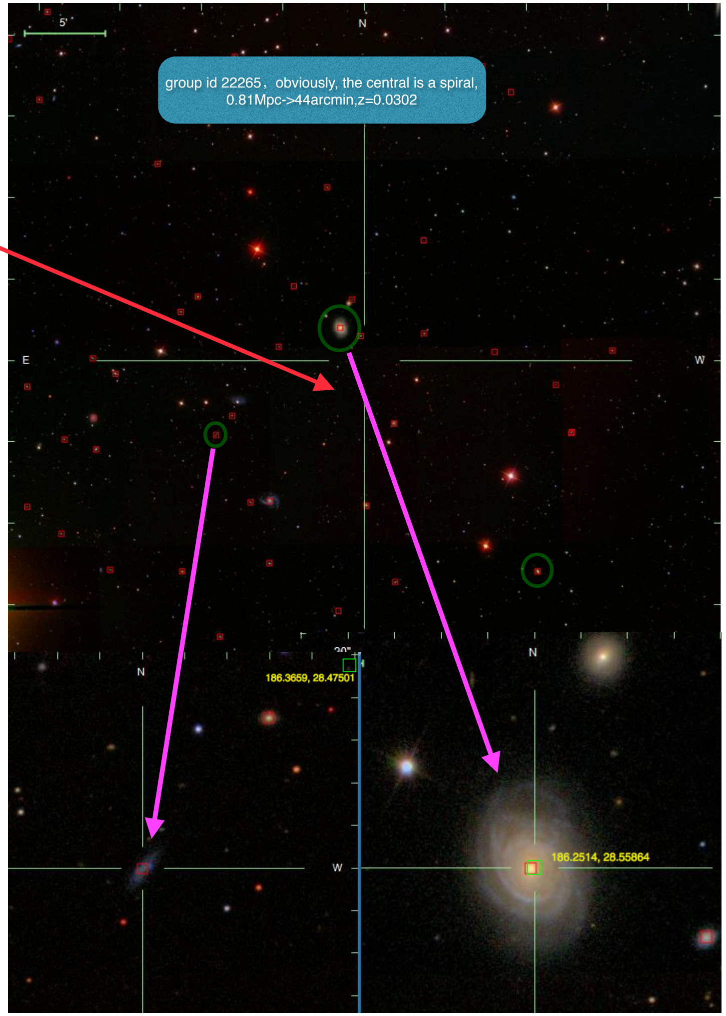
— Jiang & vd Bosch 2015 for theoretical study of MW-type halo

—Observational Sample size of MW scale is limited

Alternatively, we use galaxy group catalog from SDSS to see the gap in stellar mass (trying to find MW analogs…)

MW analog:
Δ12 >1, central galaxy is a spiral

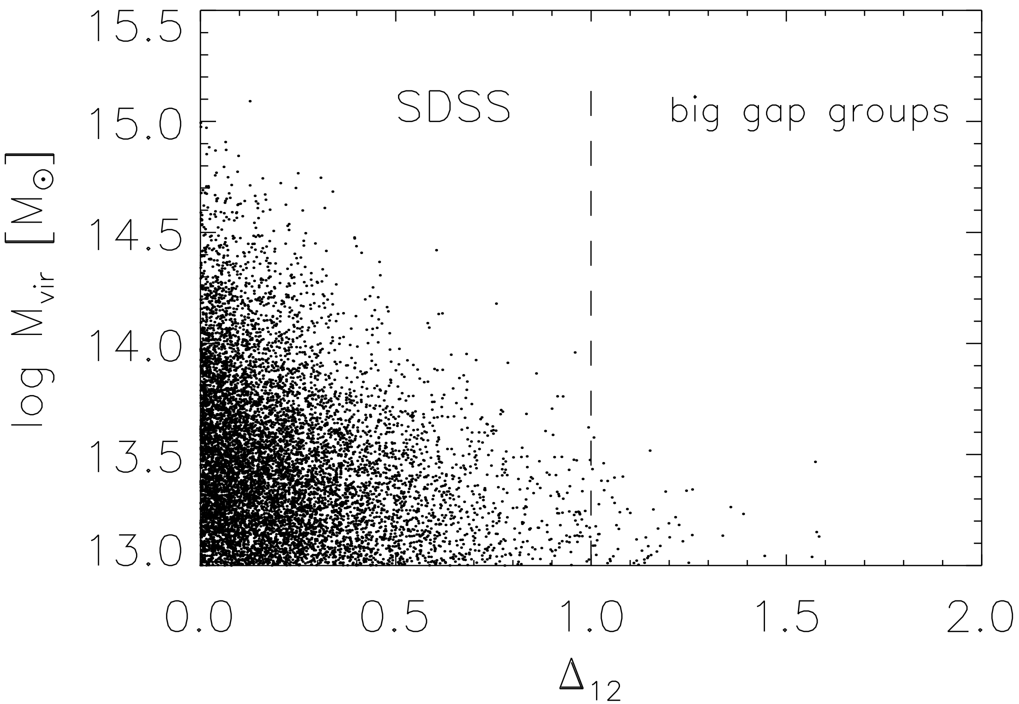




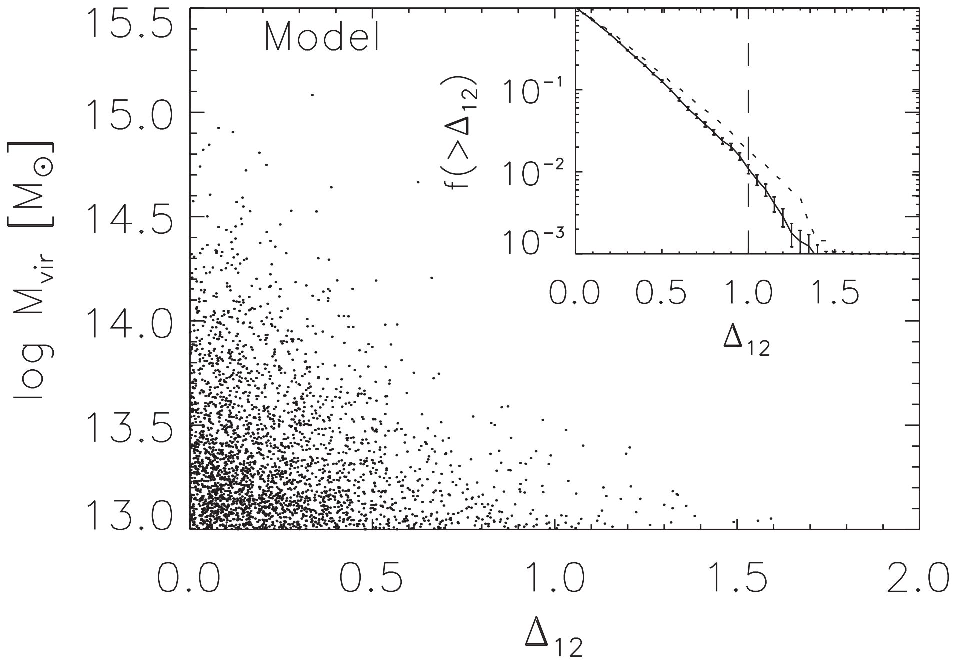
two satellites

Milky Way Satellite-III: Too-big-to-Fail problem

SDSS group

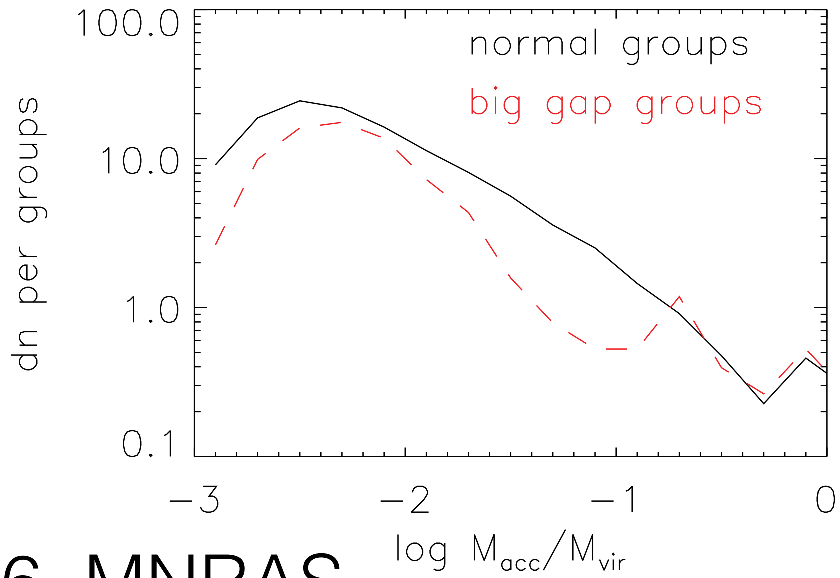


SAM prediction



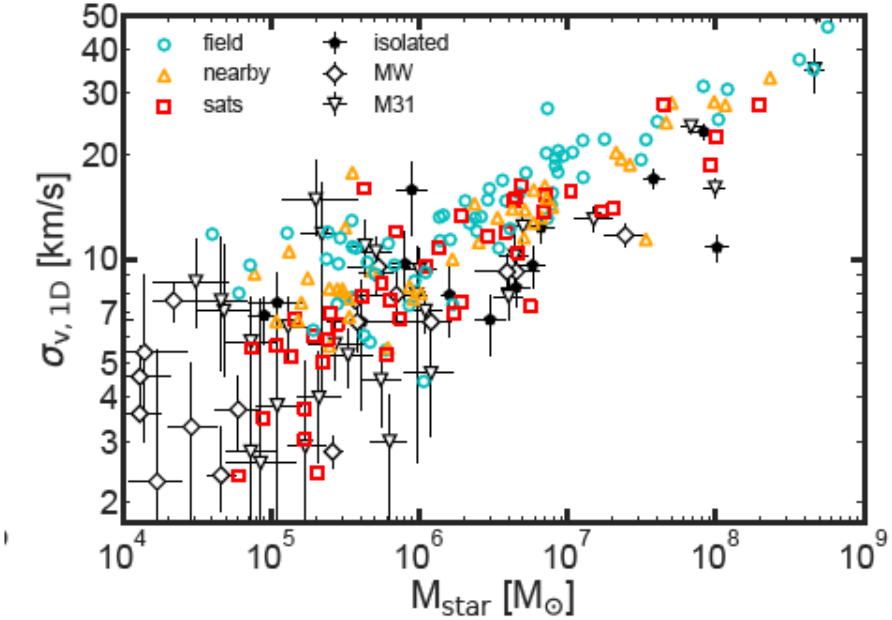
The groups with big gap are from their formation history

—->MW may have not accreted enough massive subhalos (with Vcir between SMC and Sagts), so the TBTF problem can be avoided, although with only 1% chance.

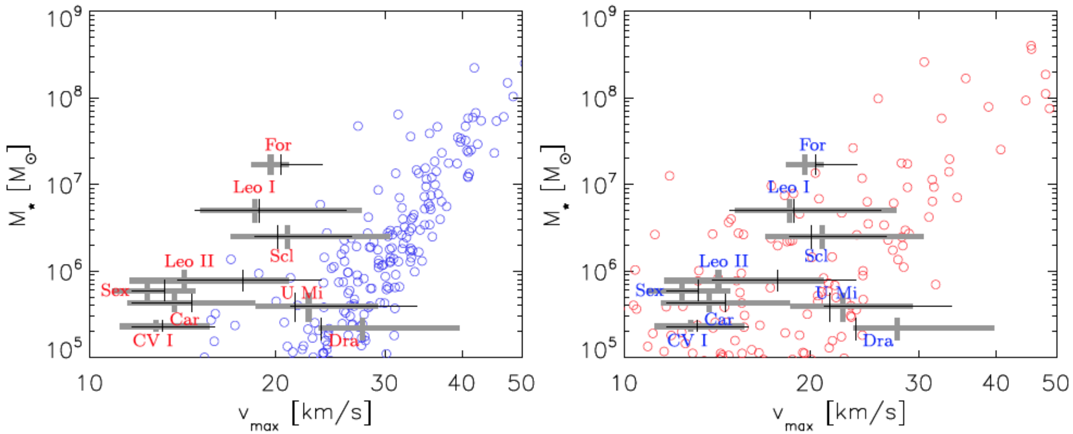


Kang et al. 2016, MNRAS

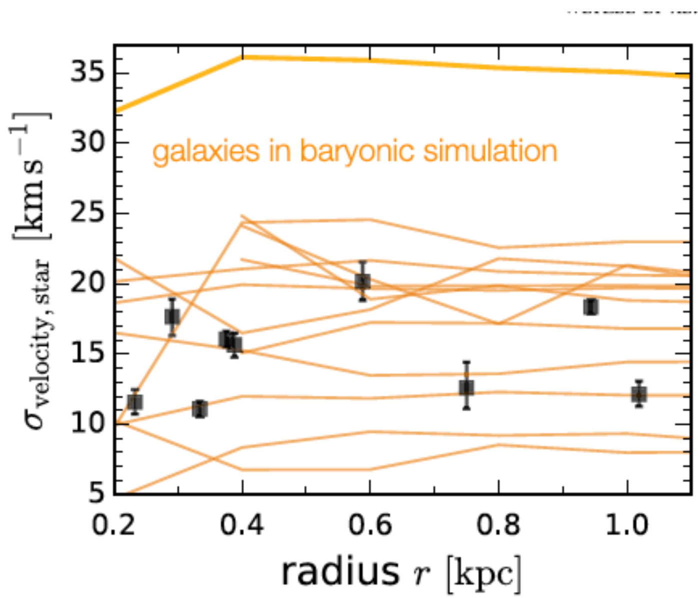
State-of-the-art hydro-sims: baryonic feedback
+tidal process can solve the TBTF



NIHAO-XV: Buck+ 2019

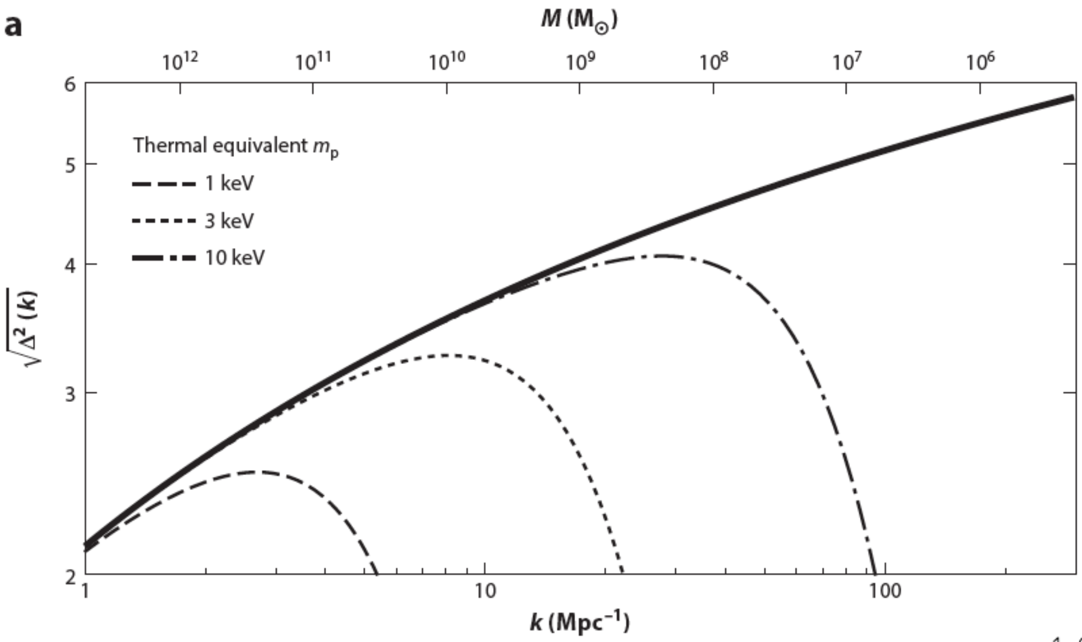


APOSTLE: Sawala+ 2016

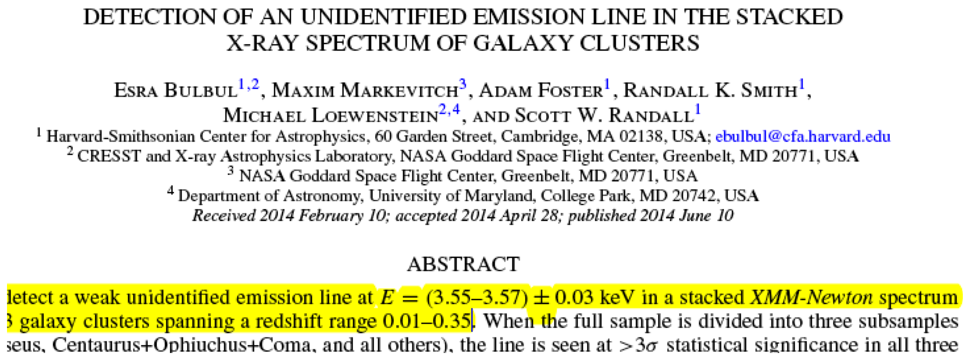


FIRE: Wetzel+ 2016

Warm dark matter ?



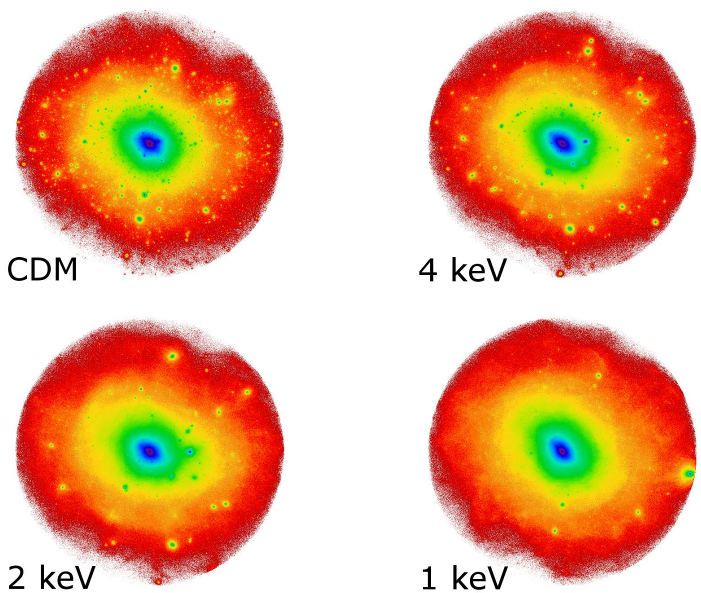
3.5Kev line in X-ray cluster


DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[3], Adam Foster[1], Randall K. Smith[1], Michael Loewenstein[2,4], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; ebulbul@cfa.harvard.edu
[2] CRESST and X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[3] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[4] Department of Astronomy, University of Maryland, College Park, MD 20742, USA
Received 2014 February 10; accepted 2014 April 28; published 2014 June 10

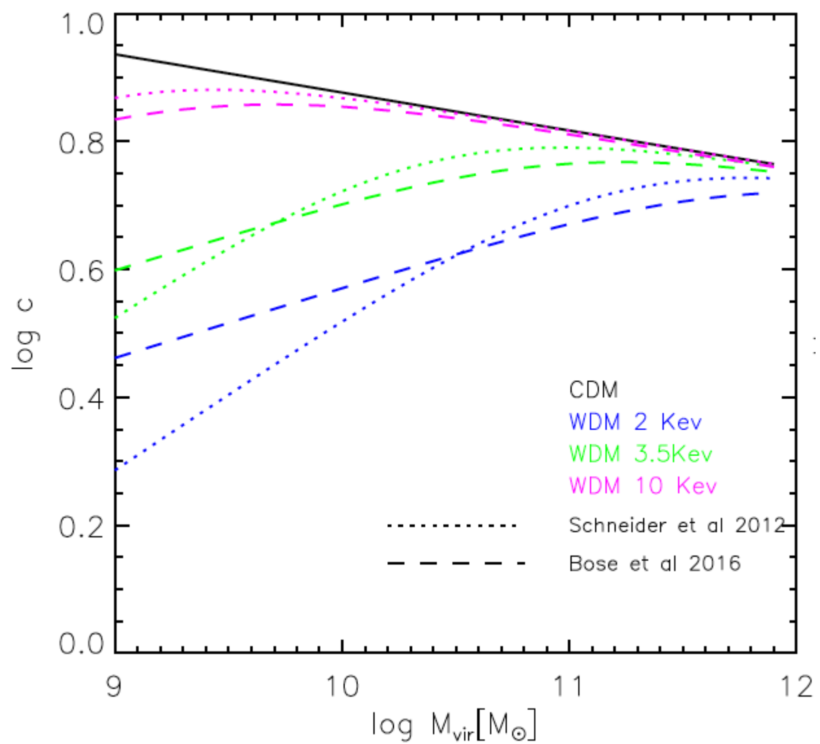
ABSTRACT

letect a weak unidentified emission line at $E = (3.55\text{–}3.57) \pm 0.03$ keV in a stacked *XMM-Newton* spectrum
3 galaxy clusters spanning a redshift range 0.01–0.35. When the full sample is divided into three subsamples
seus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $>3\sigma$ statistical significance in all three



Maccio+12

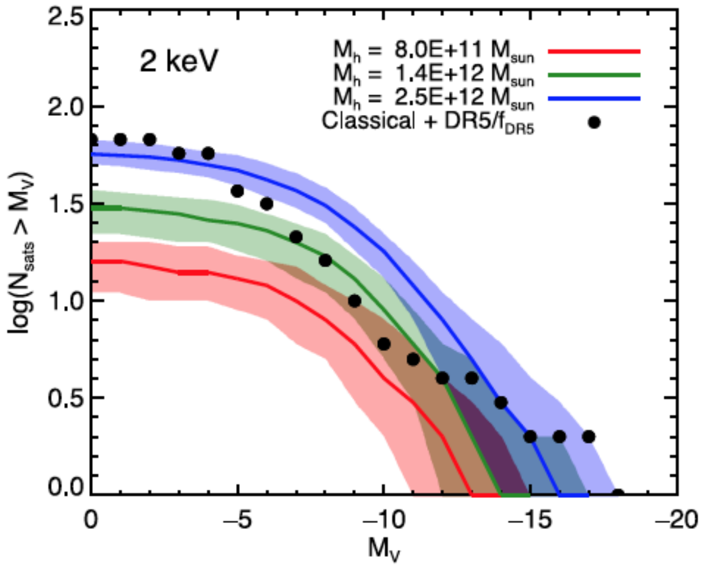
halo concentration is lower in WDM

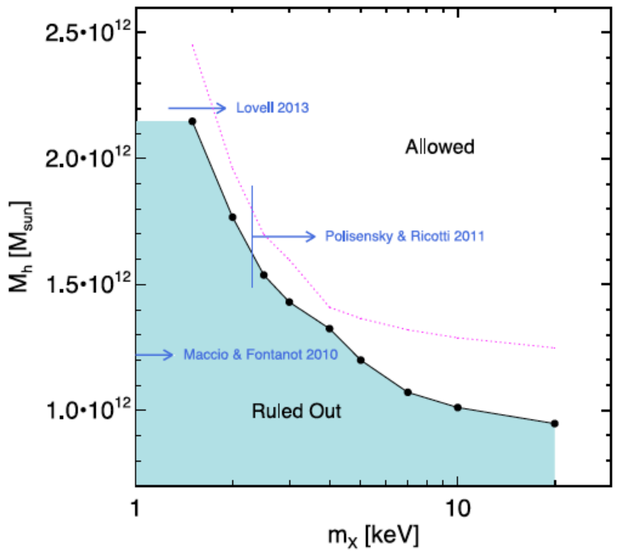


Milky Way Satellite-II: Too-big-to-Fail problem

Effefcts of WDM on satellite count and TBTF

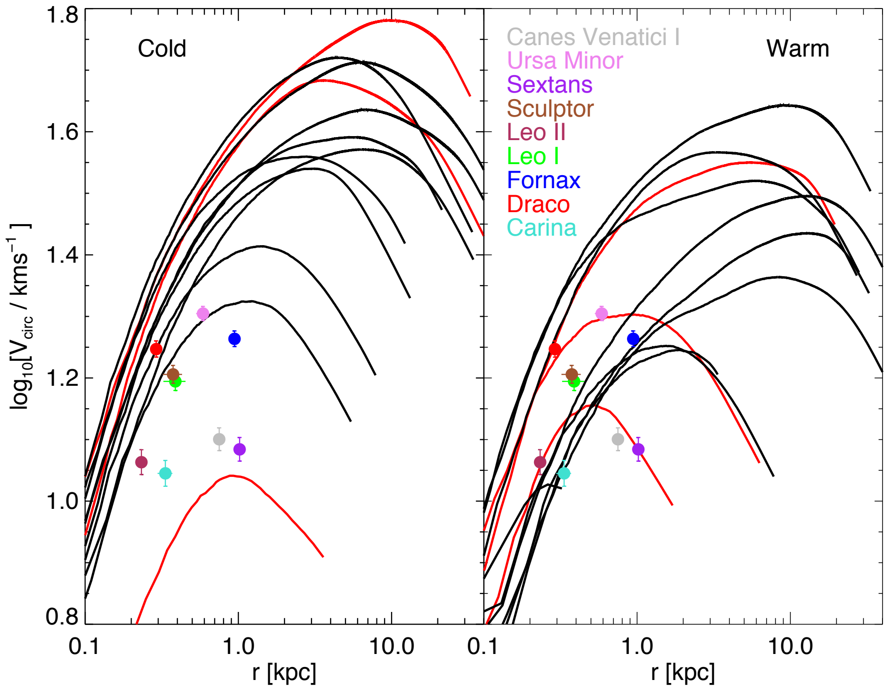
satellite luminosity function





Kennedy+14

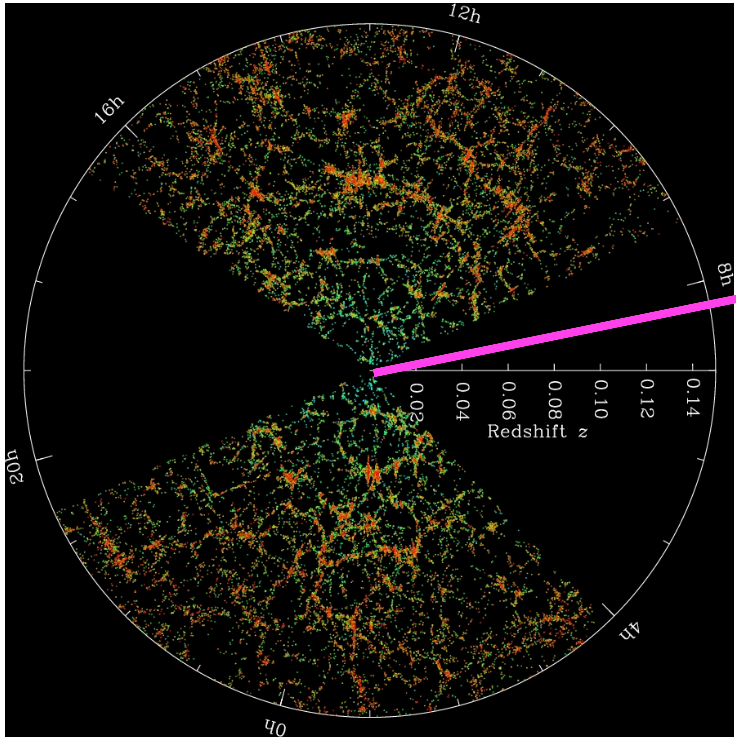
m_{wdm}=2kev



Lovell etal. 2012

They ignored baryonic effect

Why do we need analytical model?



MW is just one normal galaxy

Limits of current hydro-simulation

- Just a few galaxies, may not capture formation history of MW
- Most simulation have too-low resolutions (can not resolve to r~0.2 Kpc)
- High computational cost

Analytical model for satellite galaxy evolution

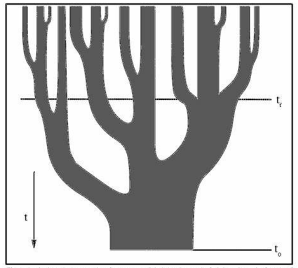
Kang 2019, submitted

The model includes:

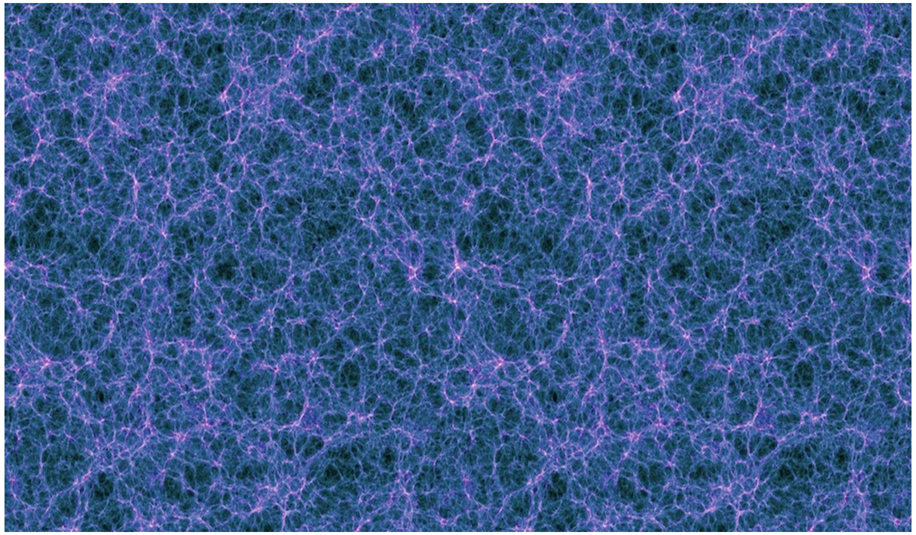
- Monte-Carlo merger tree
- star formation in dark matter halo (Semi-analytical model)
- NFW for CDM and WDM, but different c-M relation
- Supernova feedback induced core
- After infall, tidal stripping and tidal heating modify satellite DM density profile
- The model can be applied to merger tree from any cosmology and any dark matter model

with above procedure, we can predict the circular velocity for each satellites, and compared with data

How to plant Merger trees?



From simulations (accurate)



From EPS based Monte-Carlo method
(fast, high resolution)

$$f(M_1|M_2)\,\mathrm{d}\ln M_1 = \sqrt{\frac{2}{\pi}}\,\frac{\sigma_1^2(\delta_1-\delta_2)}{\left[\sigma_1^2-\sigma_2^2\right]^{3/2}} \times \exp\left[-\frac{1}{2}\frac{(\delta_1-\delta_2)^2}{\left(\sigma_1^2-\sigma_2^2\right)}\right]\left|\frac{\mathrm{d}\ln\sigma}{\mathrm{d}\ln M_1}\right|\mathrm{d}\ln M_1, \quad (1)$$

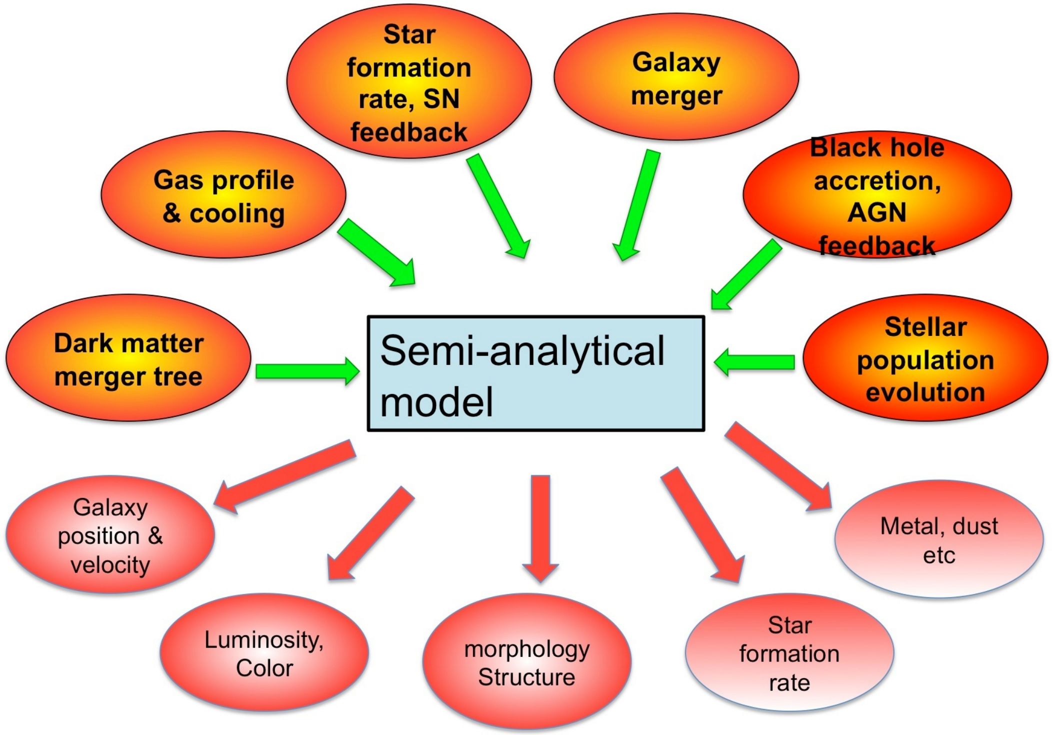
conditional mass function

We use the Parkinson etal (2008) EPS code to produce 5000 MW-type halos (with mass around 10^12 solar mass) for CDM and WDM with m_v=1.0, 2.0, 3.5, 10 keV

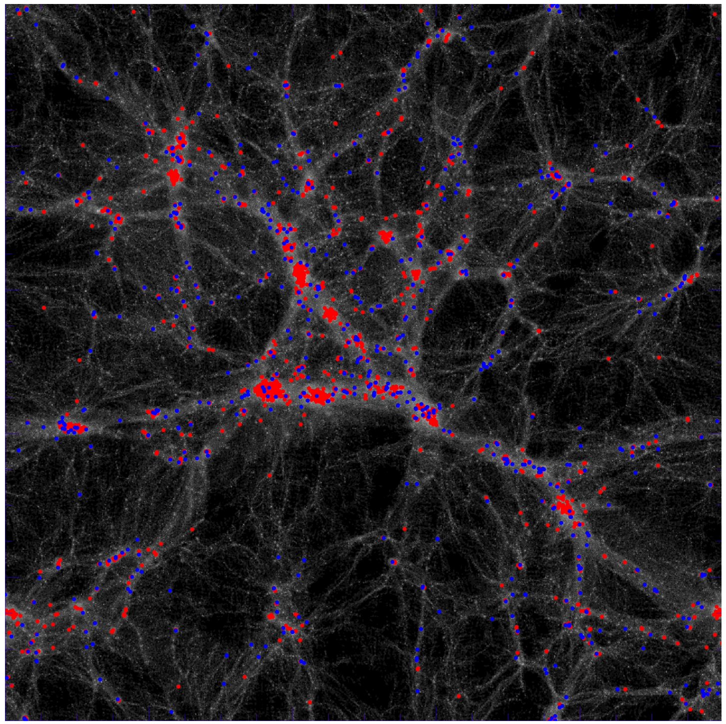
Model component: populate DM subhalo with satellite galaxy

Two methods we use:

- Using SAM to populate DM halo with galaxy
- Similar to Abundance matching, we selecting the most massive subhalo (at accretion) to host satellites, assign observed stellar mass (of satellites) to those subhaloes



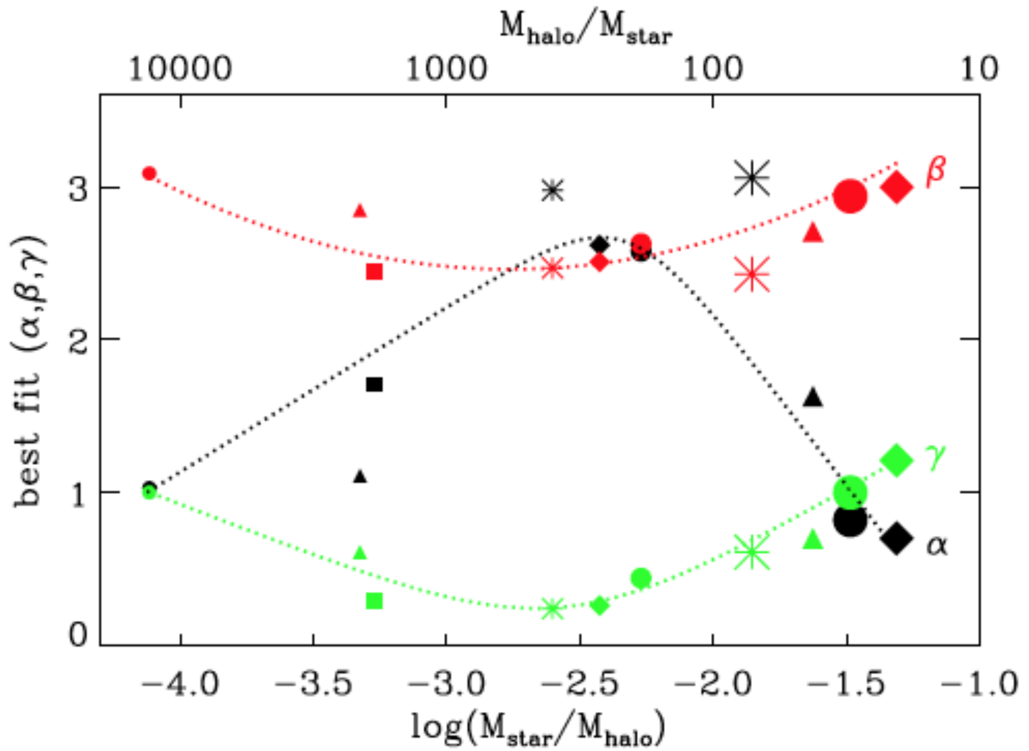
SAM ingredients and outputs



Kang+05,12,14

Milky Way Satellite-III: Too-big-to-Fail problem

halo expansion or contraction?



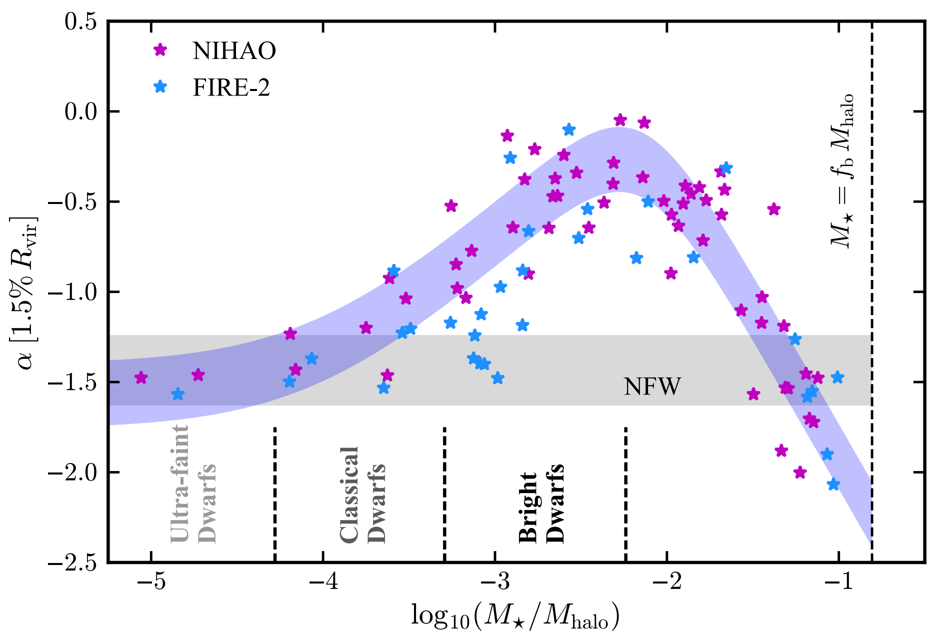
$$\alpha = 2.94 - \log_{10}[(10^{X+2.33})^{-1.08} + (10^{X+2.33})^{2.29}]$$

$$\beta = 4.23 + 1.34X + 0.26X^2$$

$$\gamma = -0.06 + \log_{10}[(10^{X+2.56})^{-0.68} + (10^{X+2.56})], \quad (3)$$

where $X = \log_{10}(M_\star/M_{\rm halo})$.

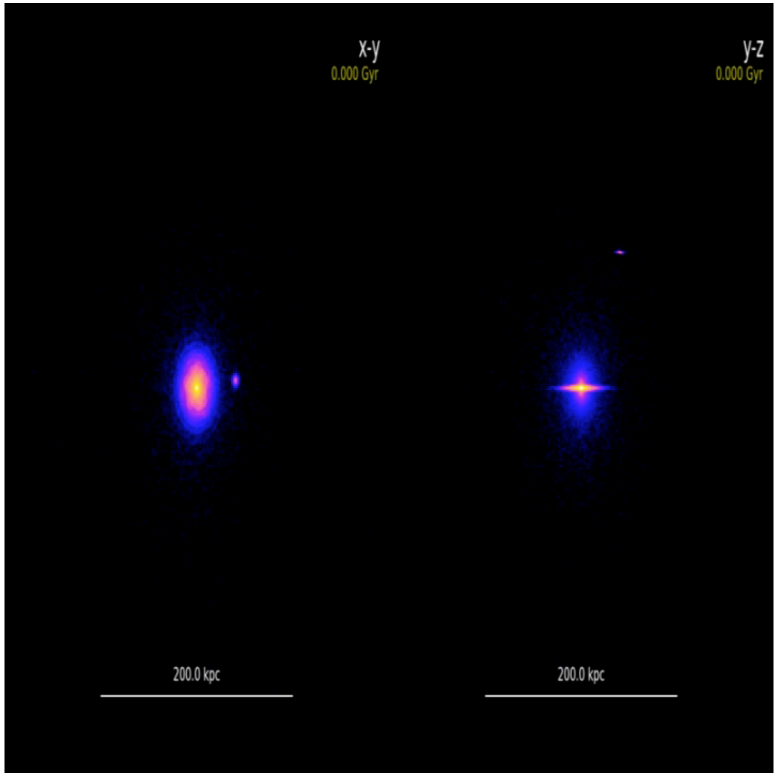
Di Cintio+ 2014



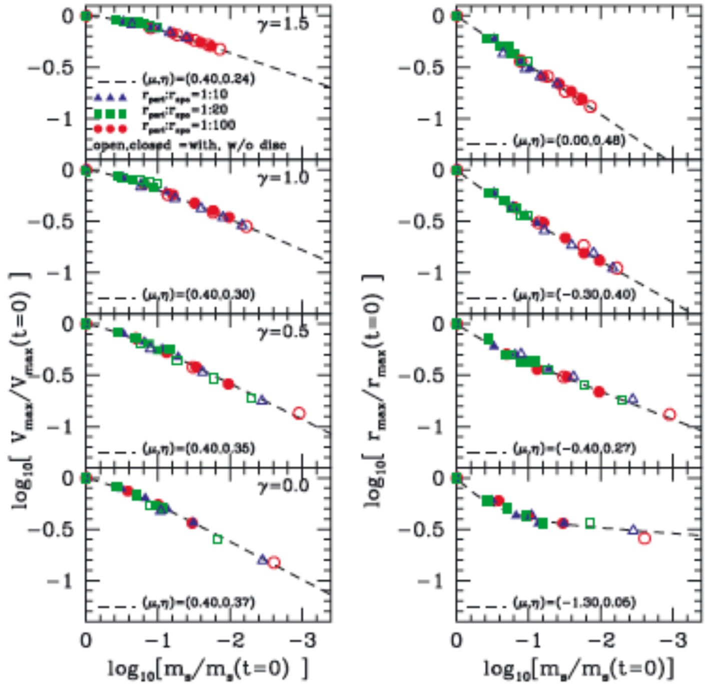
Better agreement between different simulations (but see Bose+19)
Bullock, Boylan-kolchin, 2017 ARA&A

- There is no universal DM density profile
- The inner slope depends on Mstar/Mhalo
- Core can be created and destructed, depending on star formation history

Tidal stripping and heating: reduce the DM mass of satellite and re-distribute its inner mass



Penarrubia et al. 2010



They found: the effects on V_max an r_max depend solely on total stripped DM mass and initial density profile **Y**

$$g(x) = \frac{2^{\mu} x^{\eta}}{(1+x)^{\mu}},$$

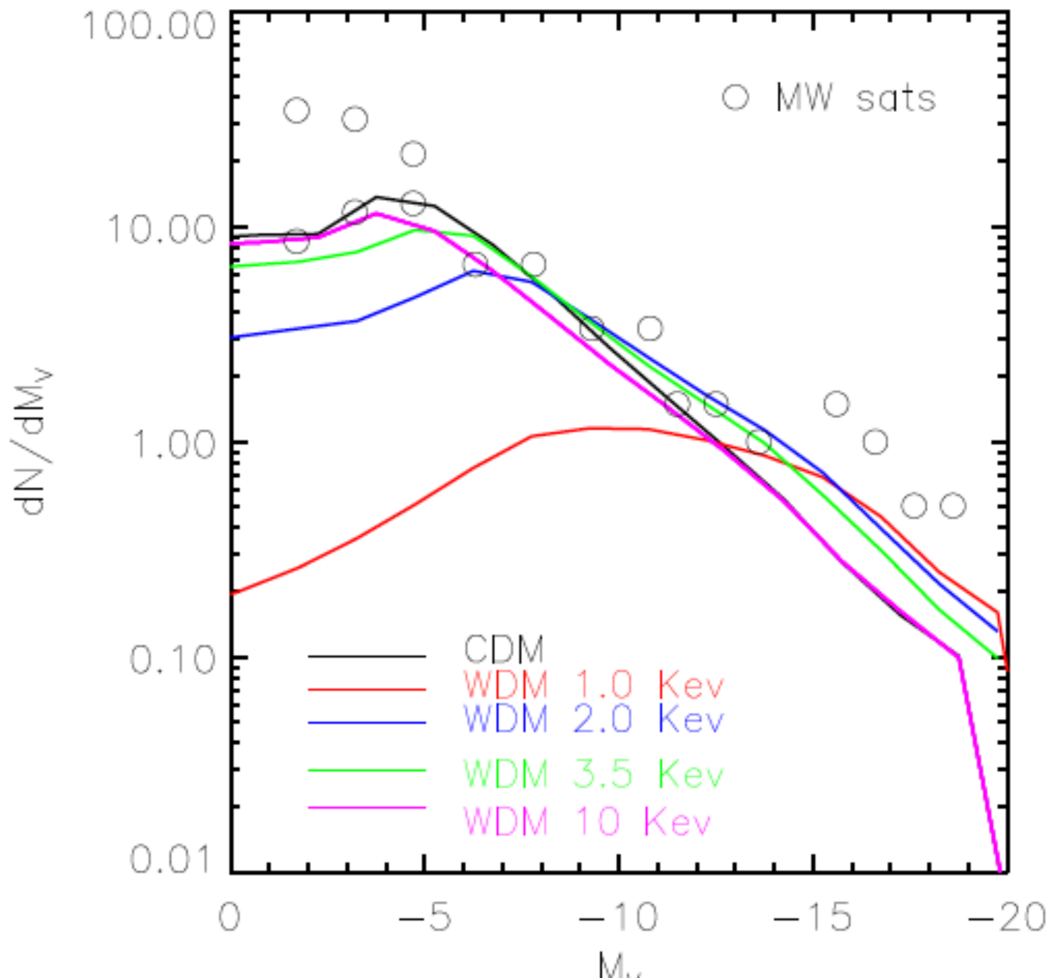
where $x \equiv m_s/m_s(t=0)$ and $g(x)$ represents either $v_{\max}$ or

$$\frac{dm}{dt} = -\frac{m}{\tau}(m/M_{host})^{\zeta}$$

We also use the Giocoli+ 2008 model for subhalo mass loss

We now apply our model to both CDM and WDM and compare model predictions to the data:

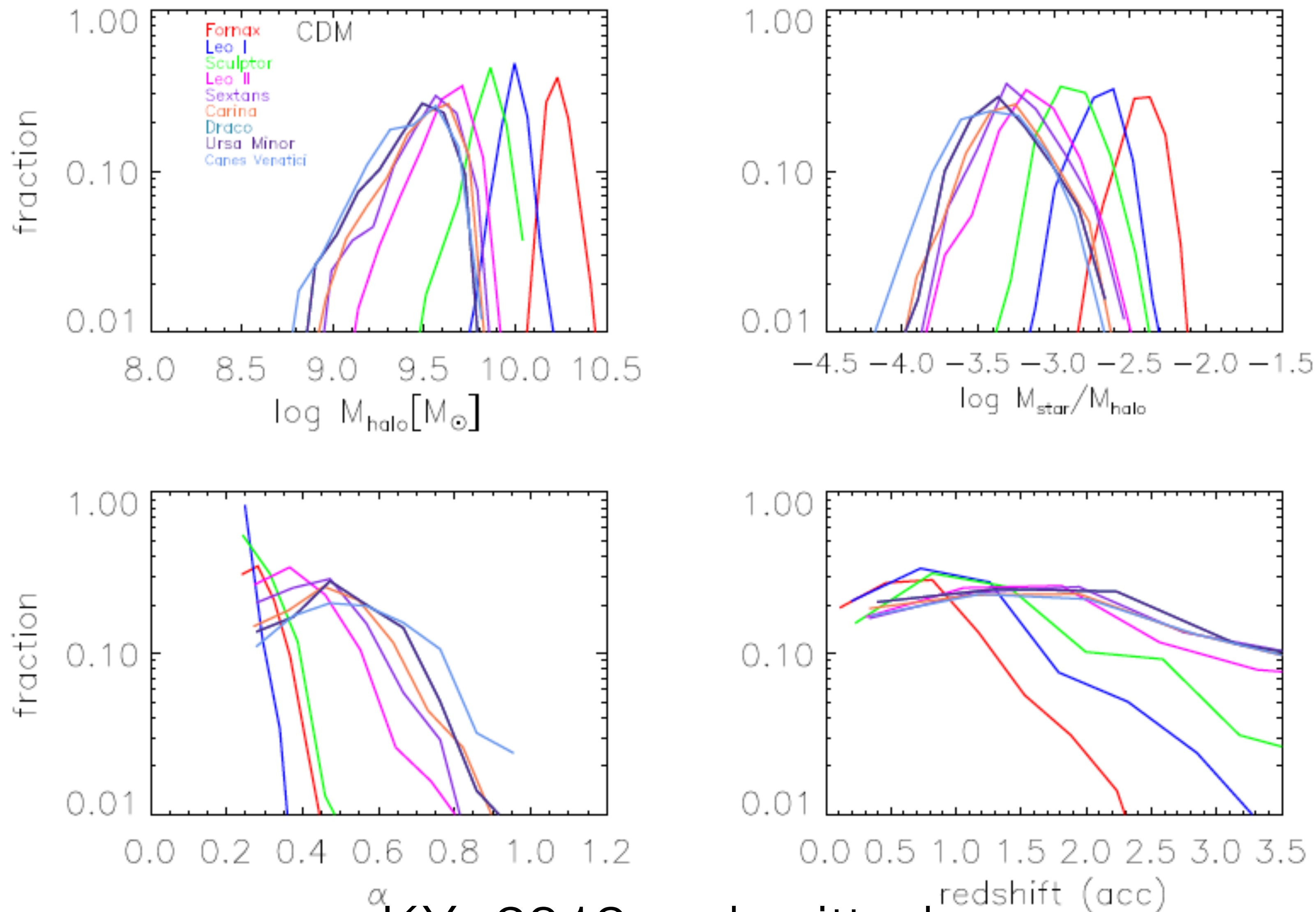
- Investigate which effect (feedback or tidal) is important
- Constraints on WDM mass



by tuning free parameters, WDM>2 keV gives better LF of MW satellites

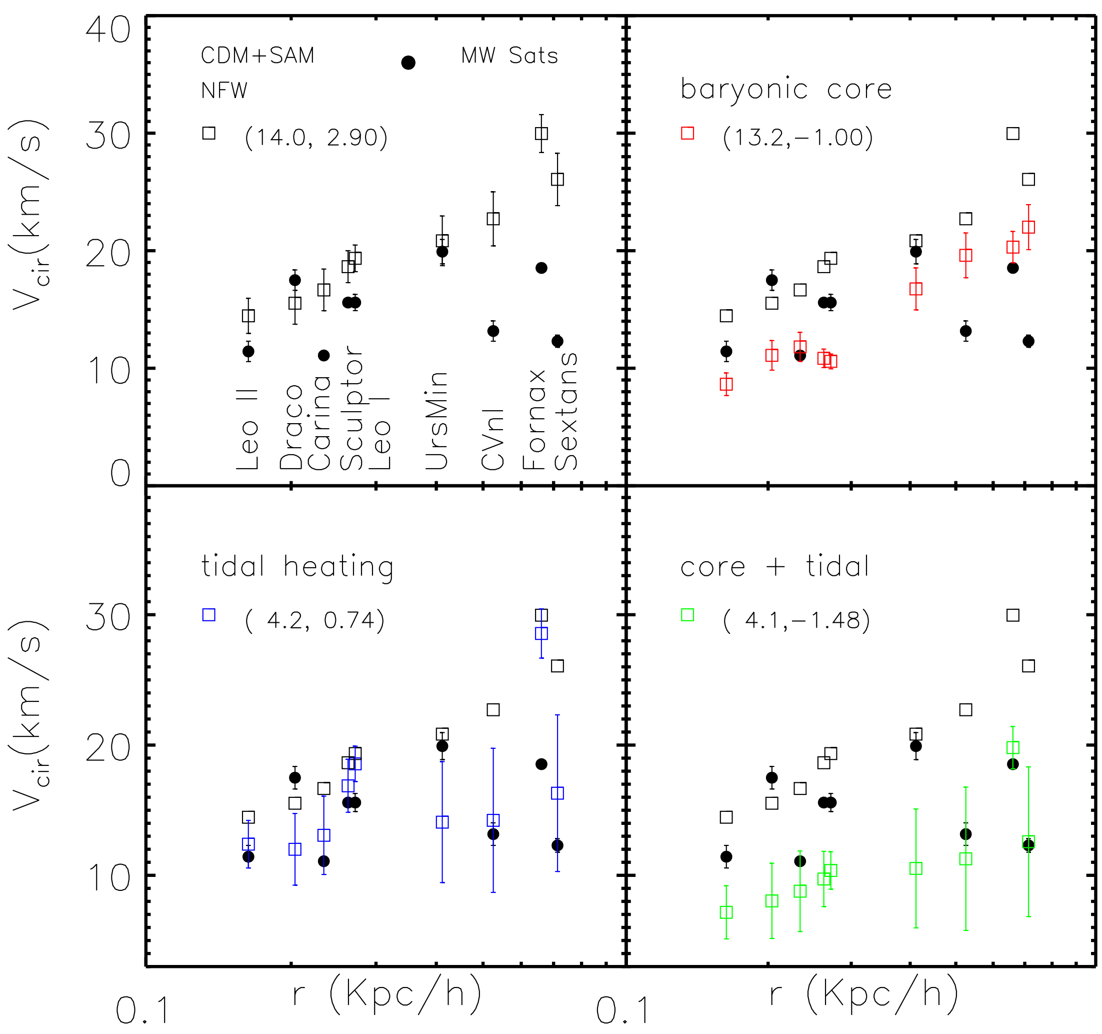
WDM ~ 1 keV can be excluded using LF

Model predictions on satellite DM mass (at accretion), density profile and accretion redshift



KX, 2019, submitted

circular velocities of satellites at half-light radii



for CDM+SAM

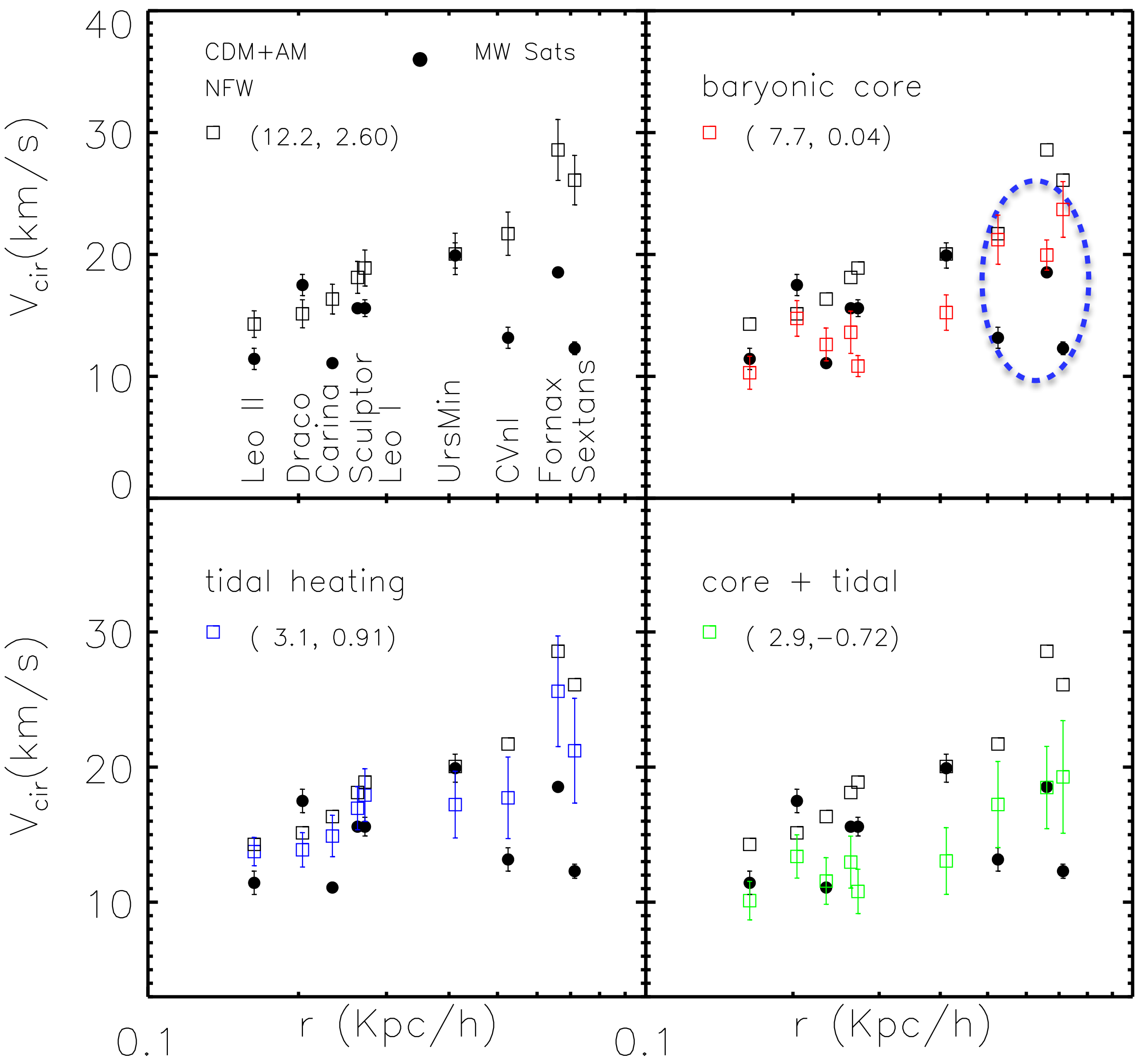
No fd, no tides, model Vcir too high

Only fd, agreement is not improved much

tidal heating seems to work better

with both (fd, tidal), model predictions are lower than the data systematically

circular velocities of satellites at half-light radii



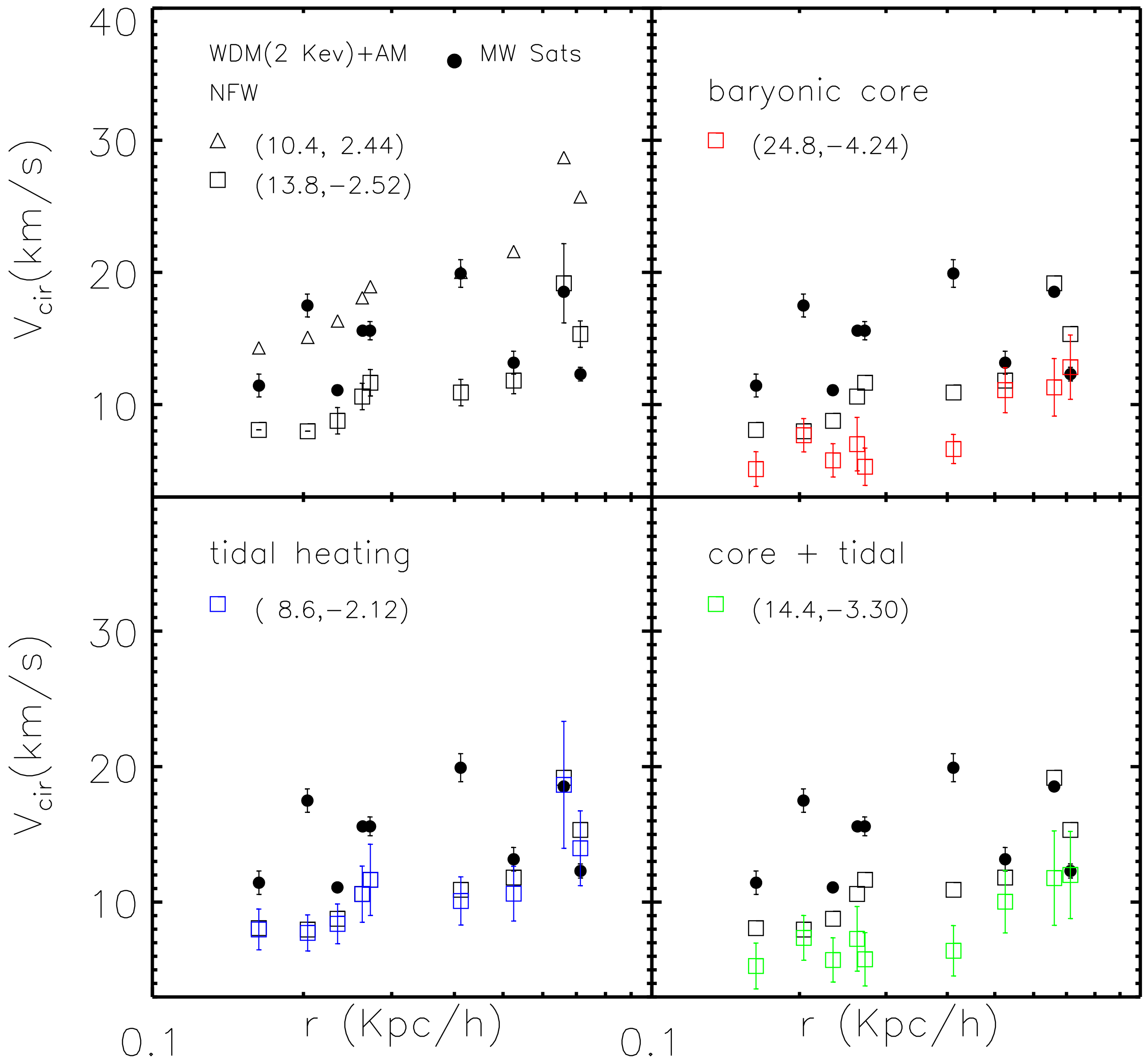
for CDM+AM (satellites form in most massive subhalo at accretion)

Both fd and tidal effects are weaker

fd alone can not solve the problem

with fd and tidal, agreement is OK

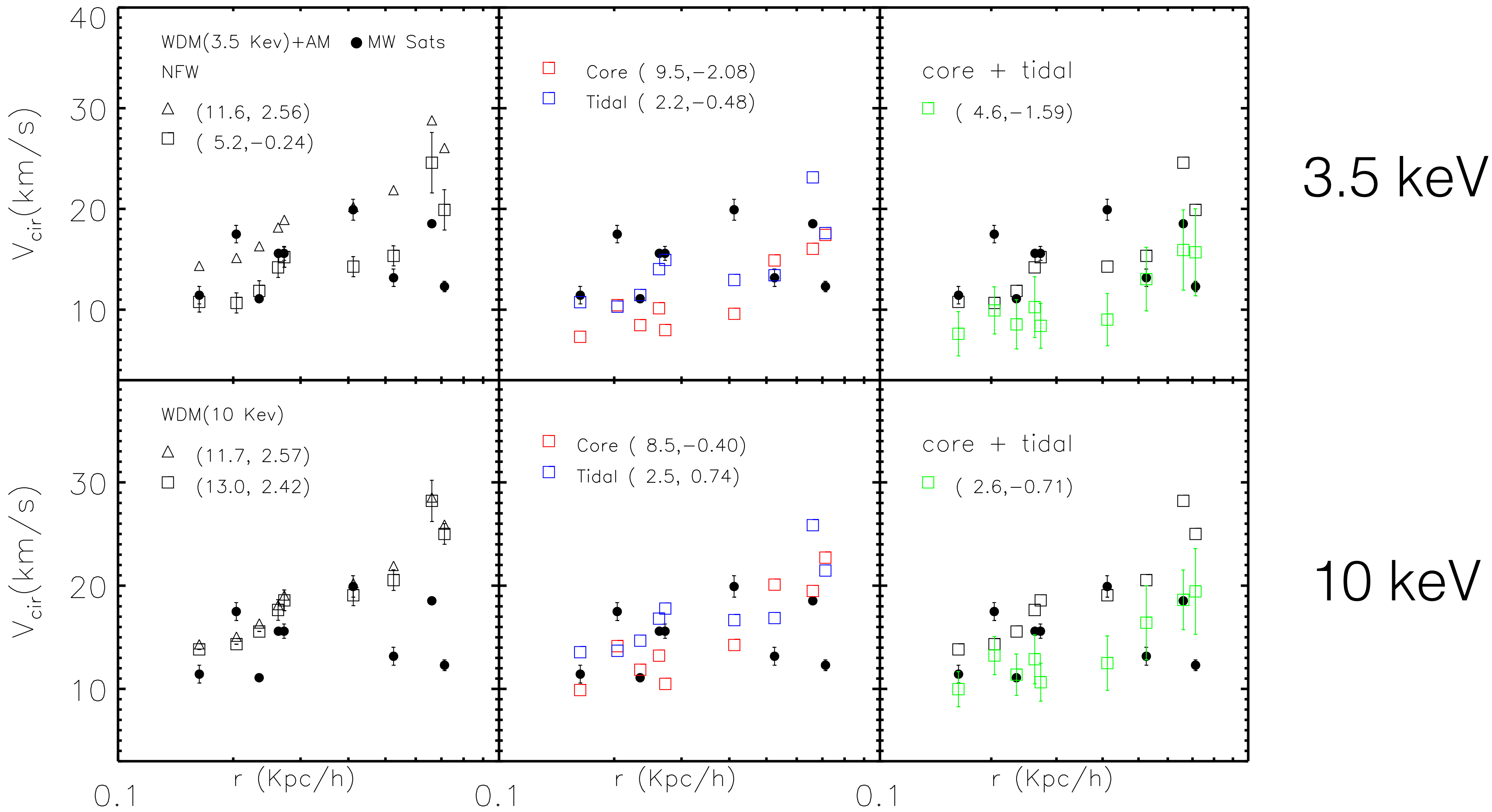
WDM = 2.0 Kev



Velocity is too low

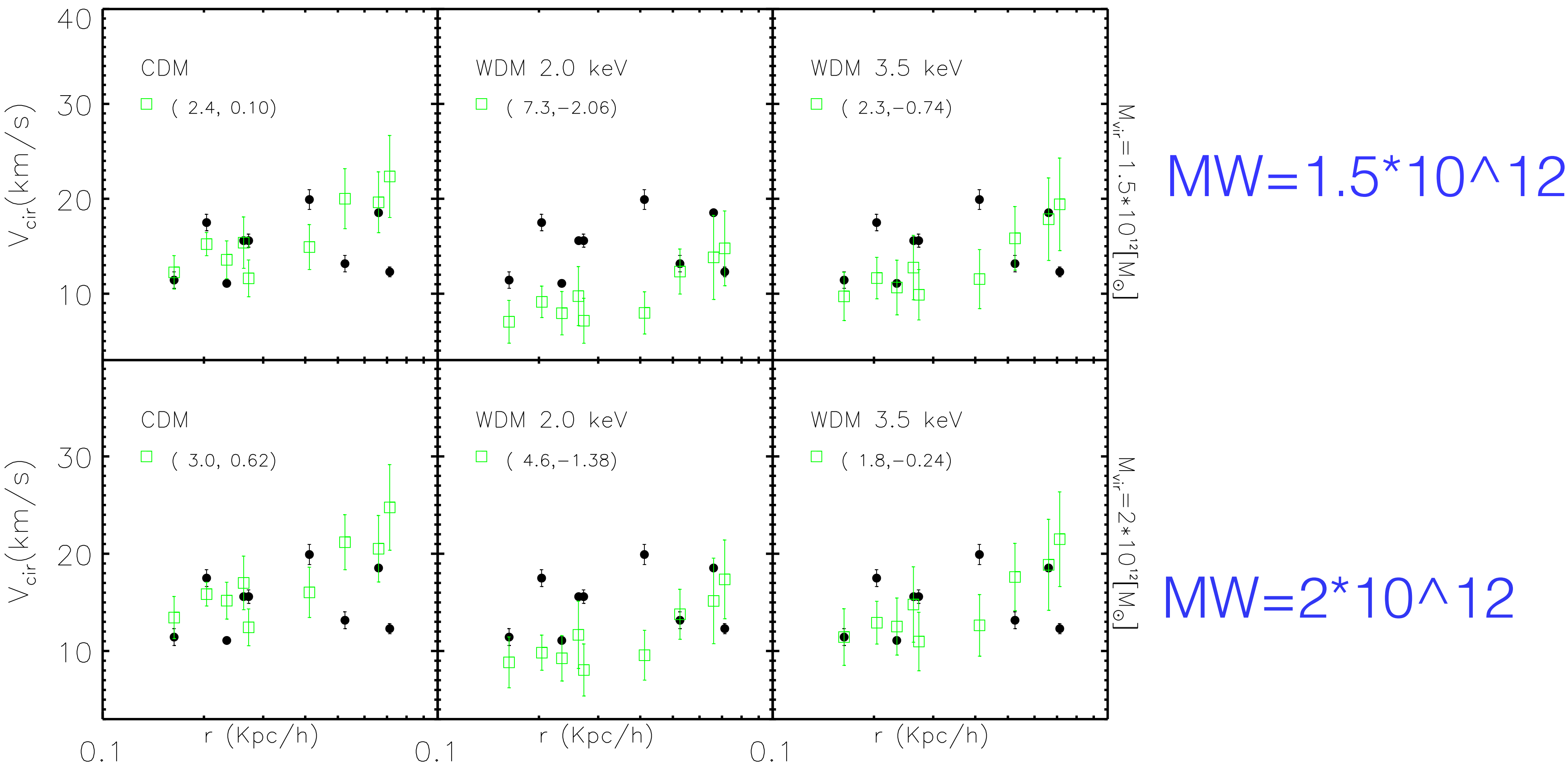
2.0 Kev ✕

Two other WDM mass



3.5 keV model predictions still lower than data with (fd, tides)
10 keV model is acceptable, close to CDM predictions

If MW has higher halo mass than 10^12 solar mass



CDM: halo mass around 1.5*10^12 Msun is favored !

WDM=2.0 kev can be safely excluded

if WDM=3.5 keV, requires MW >= 1.5*10^12 solar mass

Summary

- Our model can apply to any cosmological and dark matter model (given a power spectrum)

- Too-big-to-fail: can be solved by stellar feedback and tidal process, seems tidal process is more important to get a flat distribution, in agreement with most hydro-dynamical simulations
- New constraints on Warm dark matter mass using MW sats
  —-> 2 keV can be safely excluded, even MW=2*10^12
  —-> 3.5 keV WDM requires MW>1.5*10^12
  —> 10 keV: OK with current data and model

Thanks !