The universal dark halo scaling relation for the dwarf satellites

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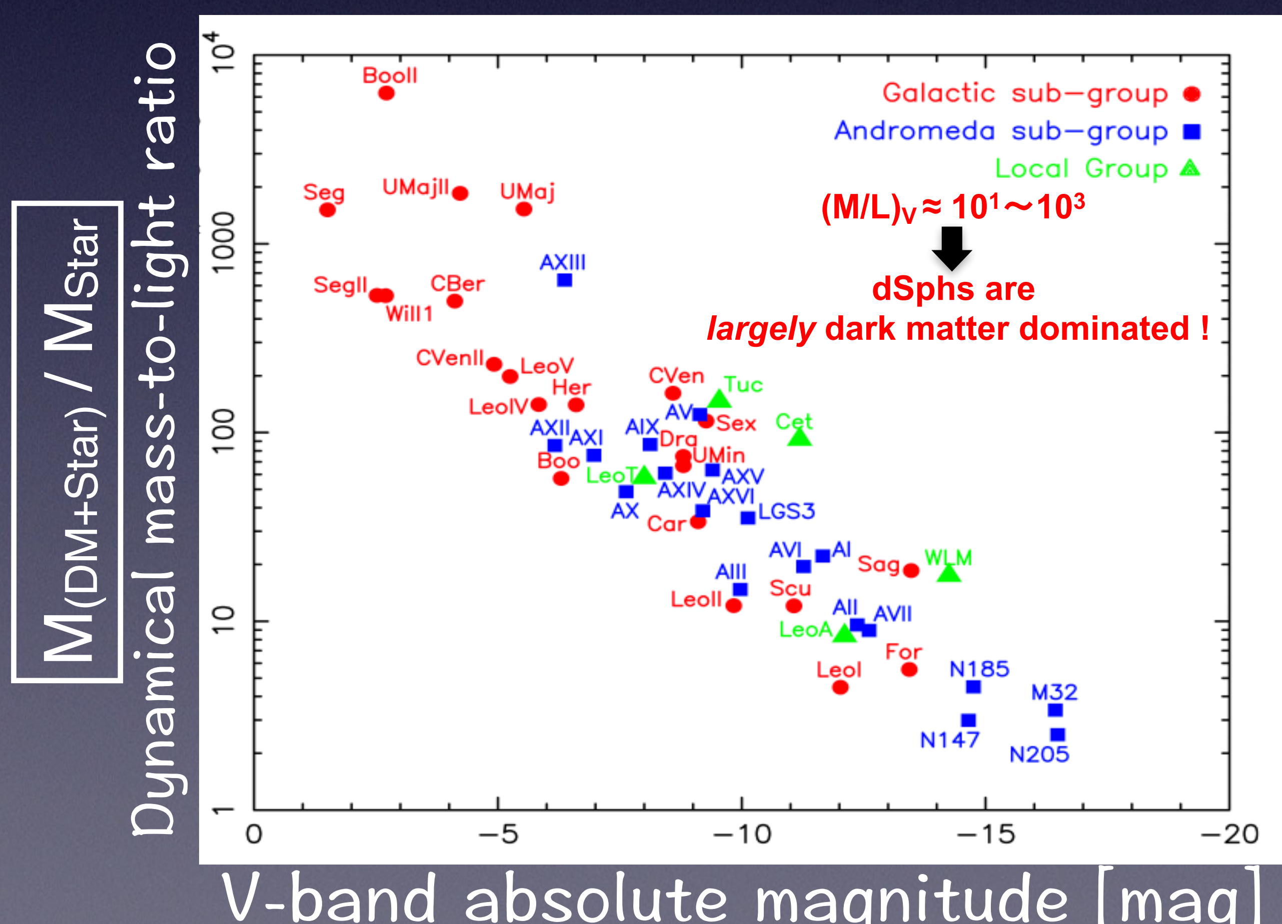
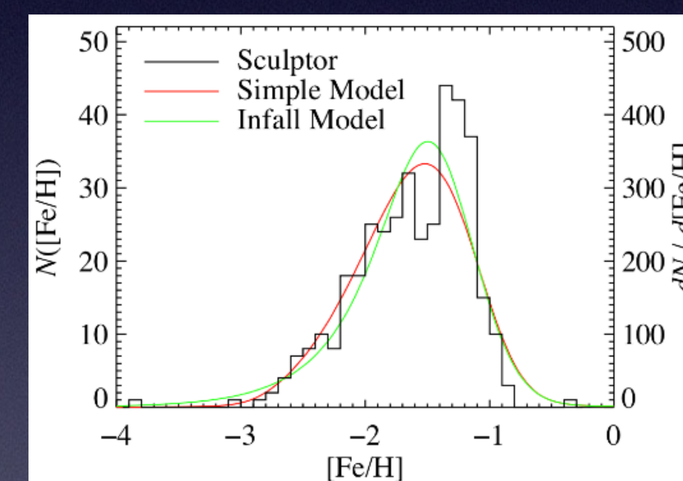
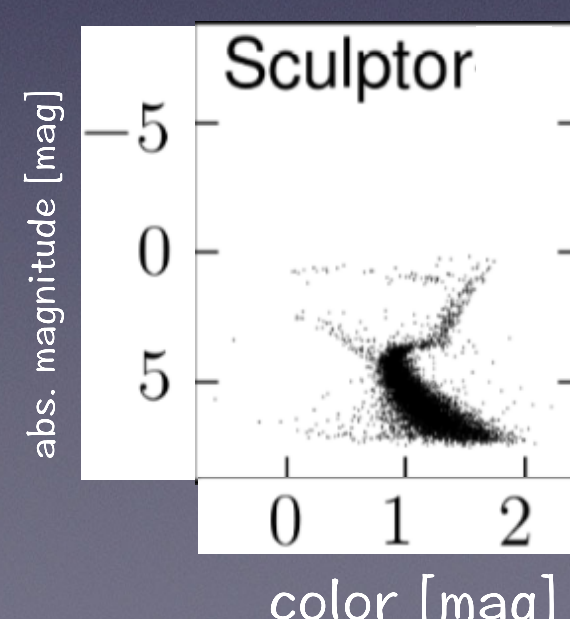
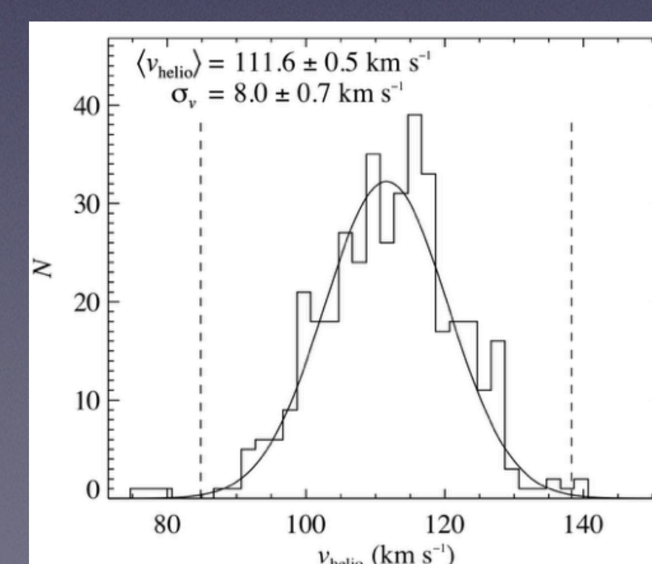
Dwarf spheroidal (dSph) galaxy

- The faintest and smallest galaxy in the Universe
- associate with luminous galaxies as satellite
- no gas, no current star formation
- chemo-dynamical analysis of resolved stars
- dark matter rich









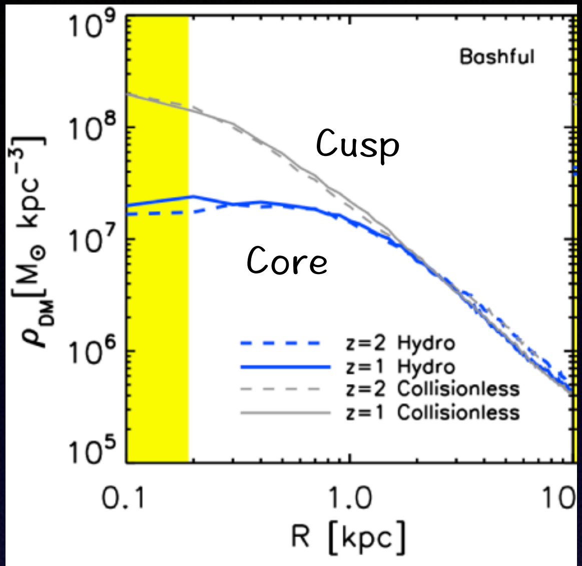
Importance of dSphs in light of astrophysics : Small scale problems in ΛCDM

※Core-cusp problem
- Too steep dark matter density profile of CDM subhalos

※Missing satellite problem
- Overabundance of CDM subhalos

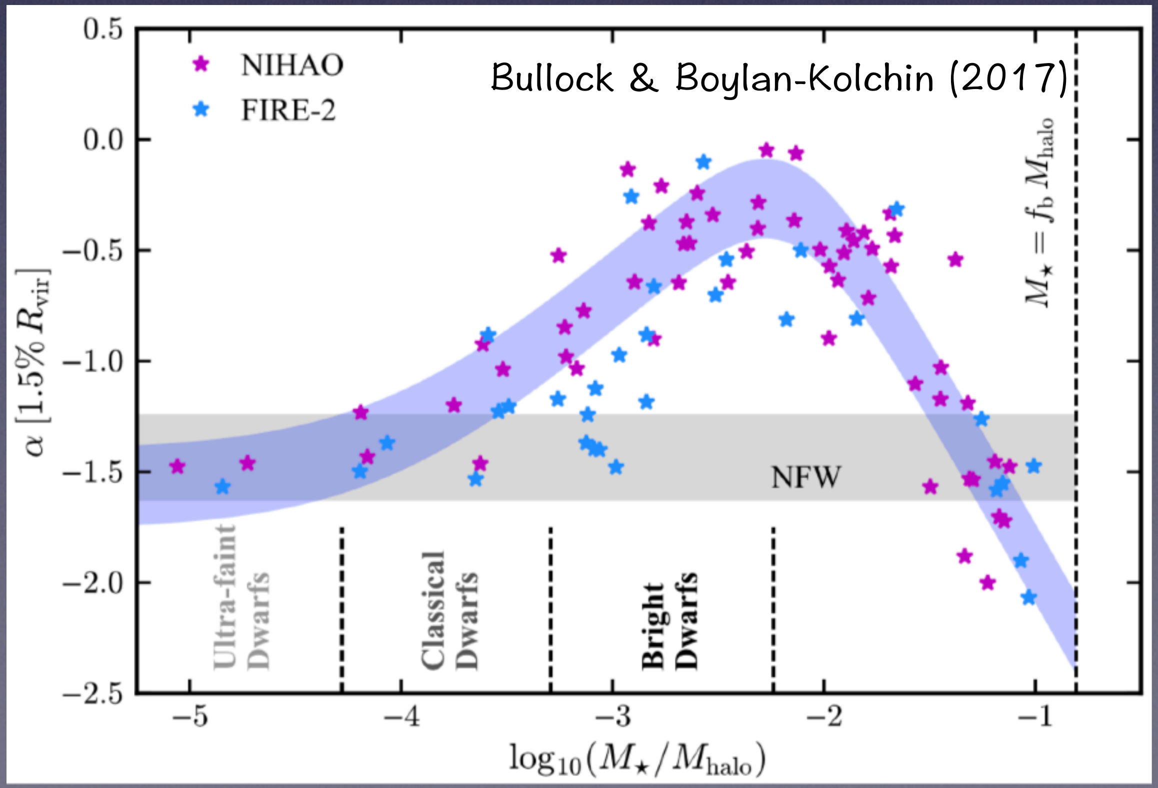
※Too-big-to-fail problem
- Too concentrated most massive CDM subhalos

＋others (satellite plane, shape of DM halo…)



Solution:
- Baryon feedbacks?
- Alternative DM models?
- Incomplete obs. data?
- Incomplete dynamical analysis?

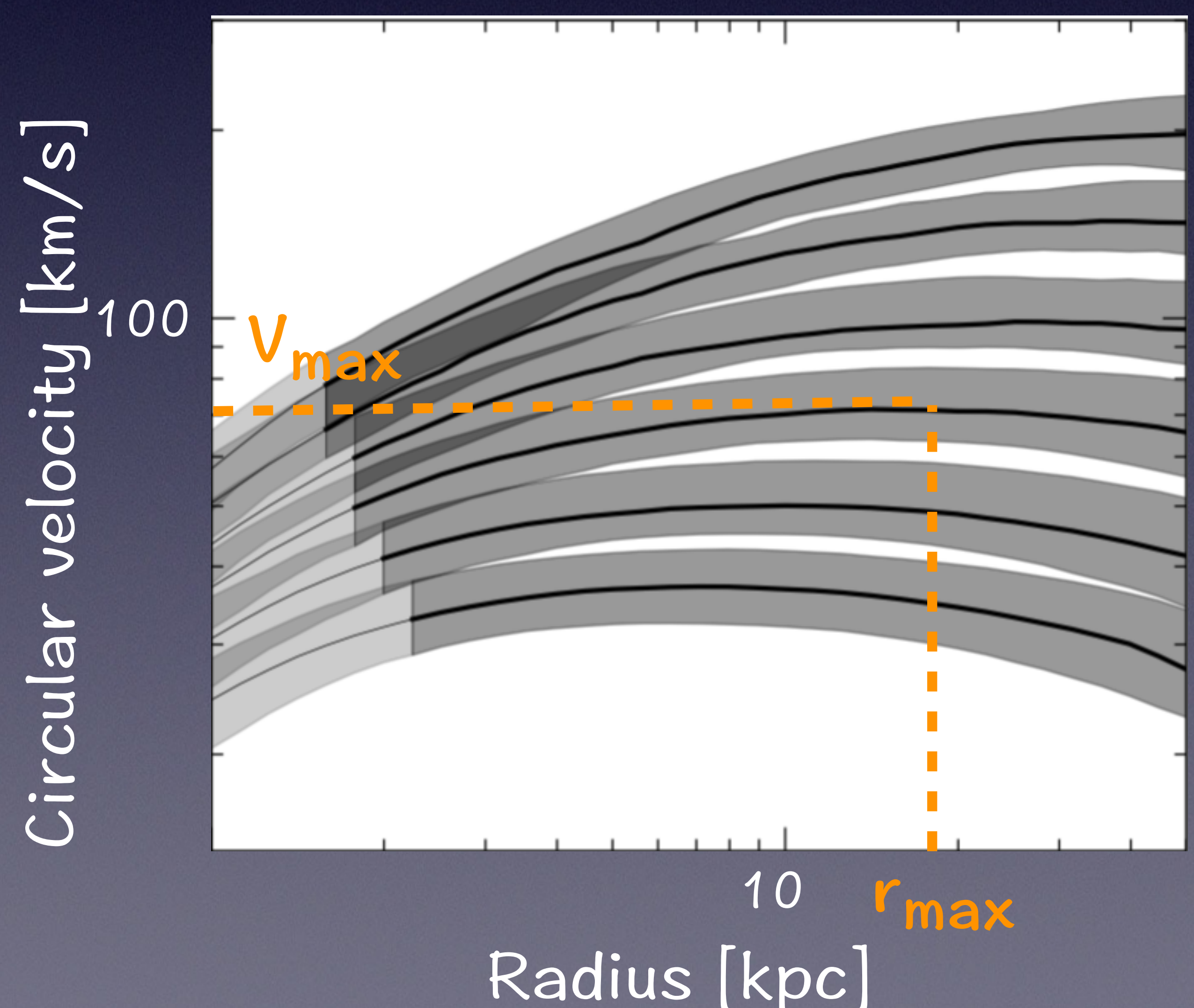
- Baryon effects depend on stellar-dark halo mass ratio.
- There is no relation b/w dark halo and stellar properties from observations so far.
- Actually, we do not know how baryon feedbacks affect dark matter profiles.



➡ Search for dark halo property without baryonic effects

Dark halo surface density within a radius of Vmax

$$\Sigma_{V_{\rm max}} = \frac{M(r_{\rm max})}{\pi r_{\rm max}^2}$$



- Circular velocity in a dark halo potential

$$V_{\rm circ}(r) = \sqrt{\frac{GM(<r)}{r}}$$

Estimate from dynamical analysis based on Jeans equations

- Dark halo mass distribution

$$M(<r) = \int_0^r 4\pi\rho_{\rm dm}(r')r'^2 dr'$$

☆POINTS☆

1. This surface density can compare directly with dark matter simulations.
2. Surface density ($\propto \rho_s r_s$) can avoid the effects of strong degeneracy between ρ_s and r_s.
3. r_{max} is better tracer for studying dark halo because this radius is much larger than star formation region.

Dark halo surface density within a

$$\Sigma_{V_{\rm max}} = \frac{M(r_{\rm m}\ldots}{\pi r^2_{\rm m}\ldots}$$

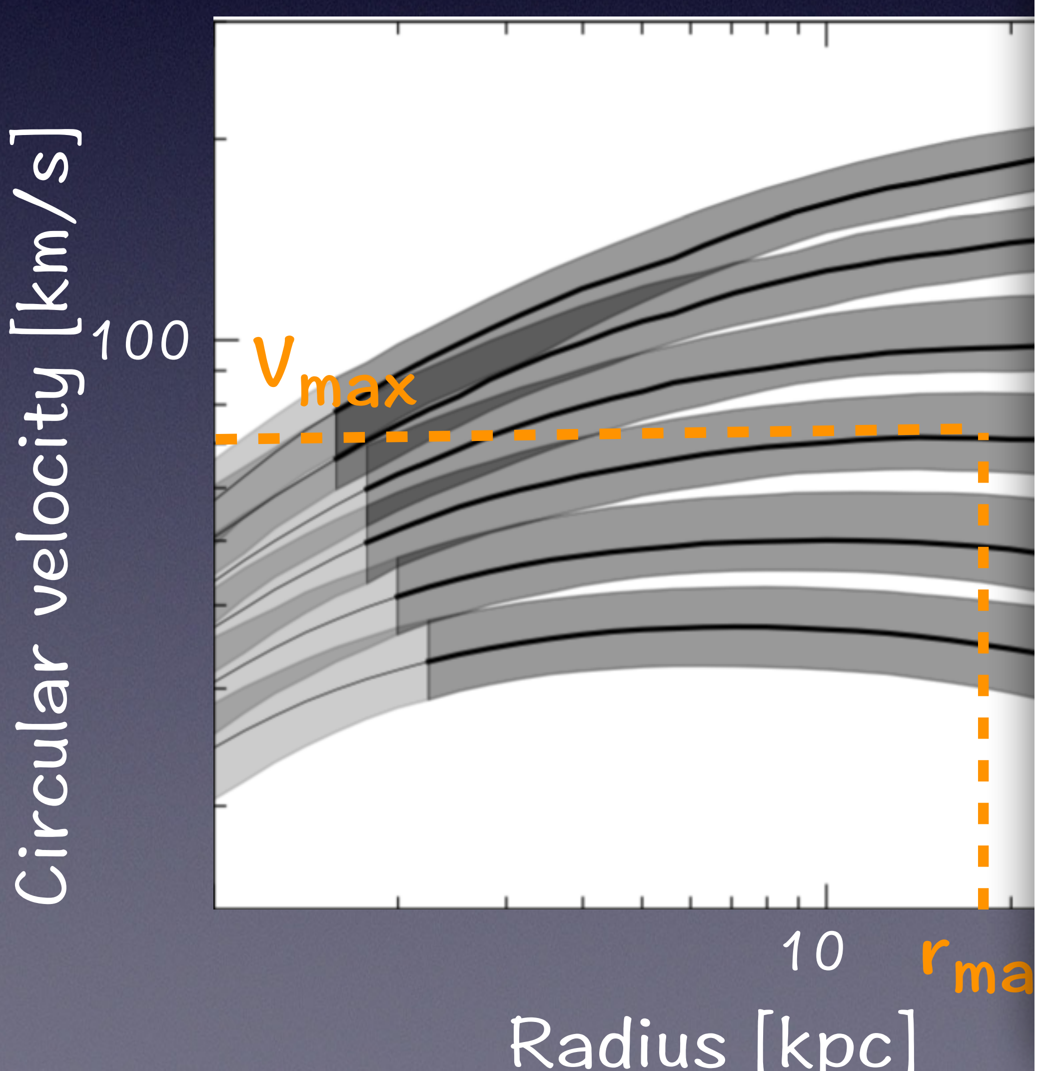


Table 1. The estimates for $V_{\rm max}$ and $\Sigma_{V_{\rm max}}$ of the eight MW and the five M31 dSphs.

Object	$V_{\rm max}$ [km s^{-1}]	$\Sigma_{V_{\rm max}}$ [M$_\odot$ pc^{-2}]
Milky Way		
Carina	$27.9^{+10.3}_{-5.7}$	$10.9^{+5.9}_{-3.7}$
Fornax	$23.3^{+3.8}_{-1.6}$	$21.0^{+4.6}_{-2.4}$
Sculptor	$24.6^{+3.5}_{-2.1}$	$28.1^{+9.0}_{-4.4}$
Sextans	$25.7^{+18.6}_{-6.9}$	$9.8^{+6.3}_{-3.2}$
Draco	$76.4^{+25.5}_{-19.6}$	$38.6^{+25.4}_{-12.1}$
Leo I	$22.7^{+6.6}_{-3.3}$	$13.4^{+19.1}_{-6.8}$
Leo II	$27.9^{+19.9}_{-6.6}$	$16.8^{+13.9}_{-7.9}$
Ursa Minor	$19.7^{+3.9}_{-1.9}$	$18.4^{+22.6}_{-11.1}$
Andromeda		
Andromeda I	$61.3^{+25.8}_{-17.2}$	$27.7^{+21.9}_{-9.2}$
Andromeda II	$44.3^{+9.0}_{-7.5}$	$11.9^{+5.3}_{-2.7}$
Andromeda III	$47.7^{+30.8}_{-15.6}$	$21.3^{+20.9}_{-9.2}$
Andromeda V	$27.3^{+8.8}_{-3.5}$	$31.1^{+32.6}_{-16.8}$
Andromeda VII	$29.4^{+8.2}_{-3.5}$	$54.1^{+122.3}_{-33.3}$

Cosmological Dark Matter Simulations

Simulation	High-resolution (Ishiyama+16)	Cosmogrid (Ishiyama+13)
$(\Omega_m, \Omega_\Lambda, h, \sigma_8)$	(0.31, 0.69, 0.68, 0.83)	(0.3, 0.7, 0.7, 0.8)
(m_{DM}[Msun], ε [pc])	(7.54e3, 176.5)	(1.28e5, 175.7)
# of particles	2048^3	2048^3
Box size [Mpc]	11.8	30

◆ Selection for MW-sized dark halos

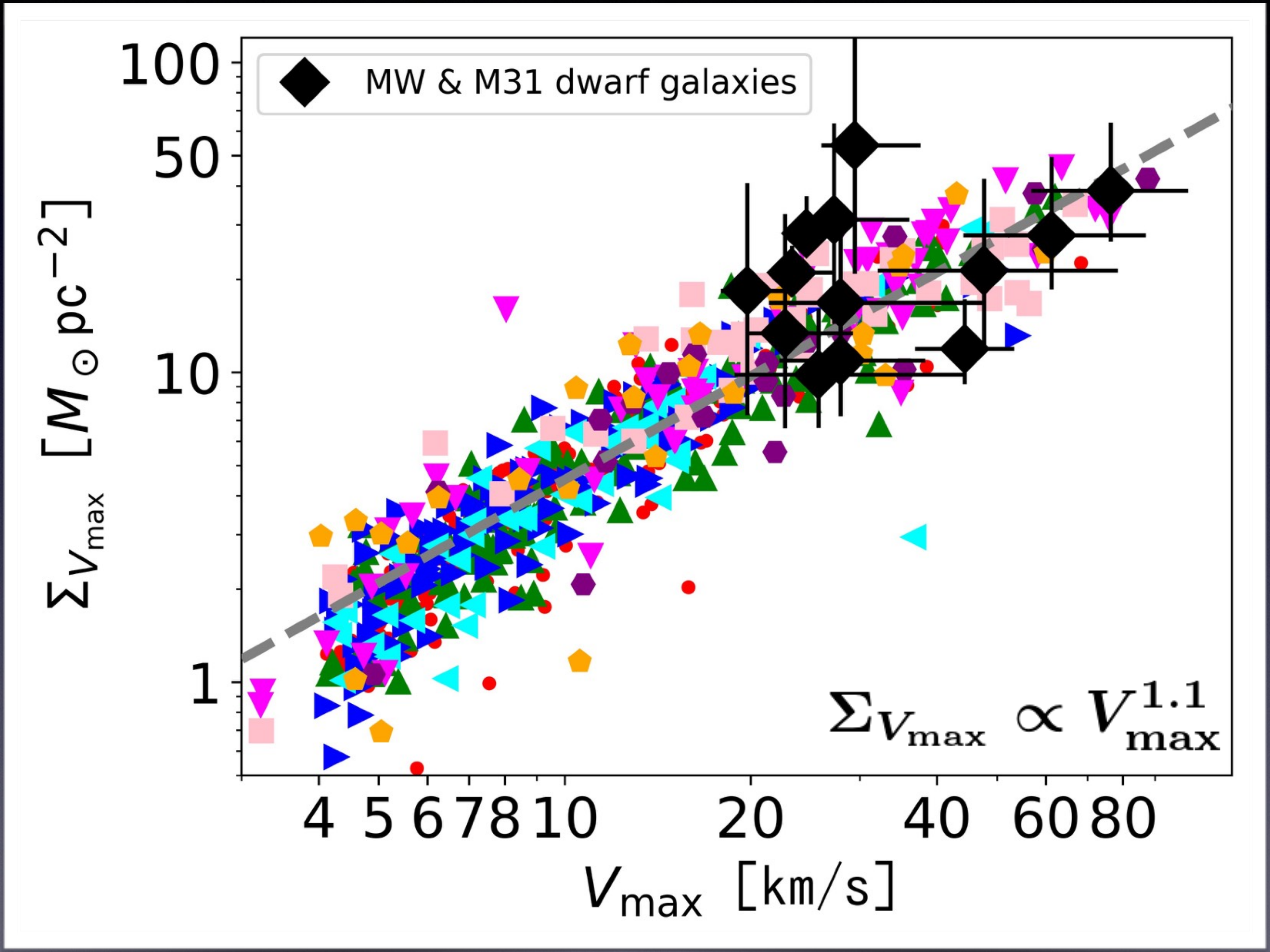
1. 1.0 ~ 3.0×10^{12} Msun (for the high-resolution simulations)
2. 1.0 ~ 6.0×10^{12} Msun (for the Cosmogrid simulations)

◆ Subhalo Criteria

1. A scale radius of subhalo should be larger than twice the softening length.
2. A virial mass of subhalo should be more massive than ~10^7Msun (~10^8Msun) in the high-resolution (the Cosmogrid) simulations.
3. The subhalos should settle within a virial radius of a host halo at z=0.
4. The subhalos should have parent ID of a host halo.

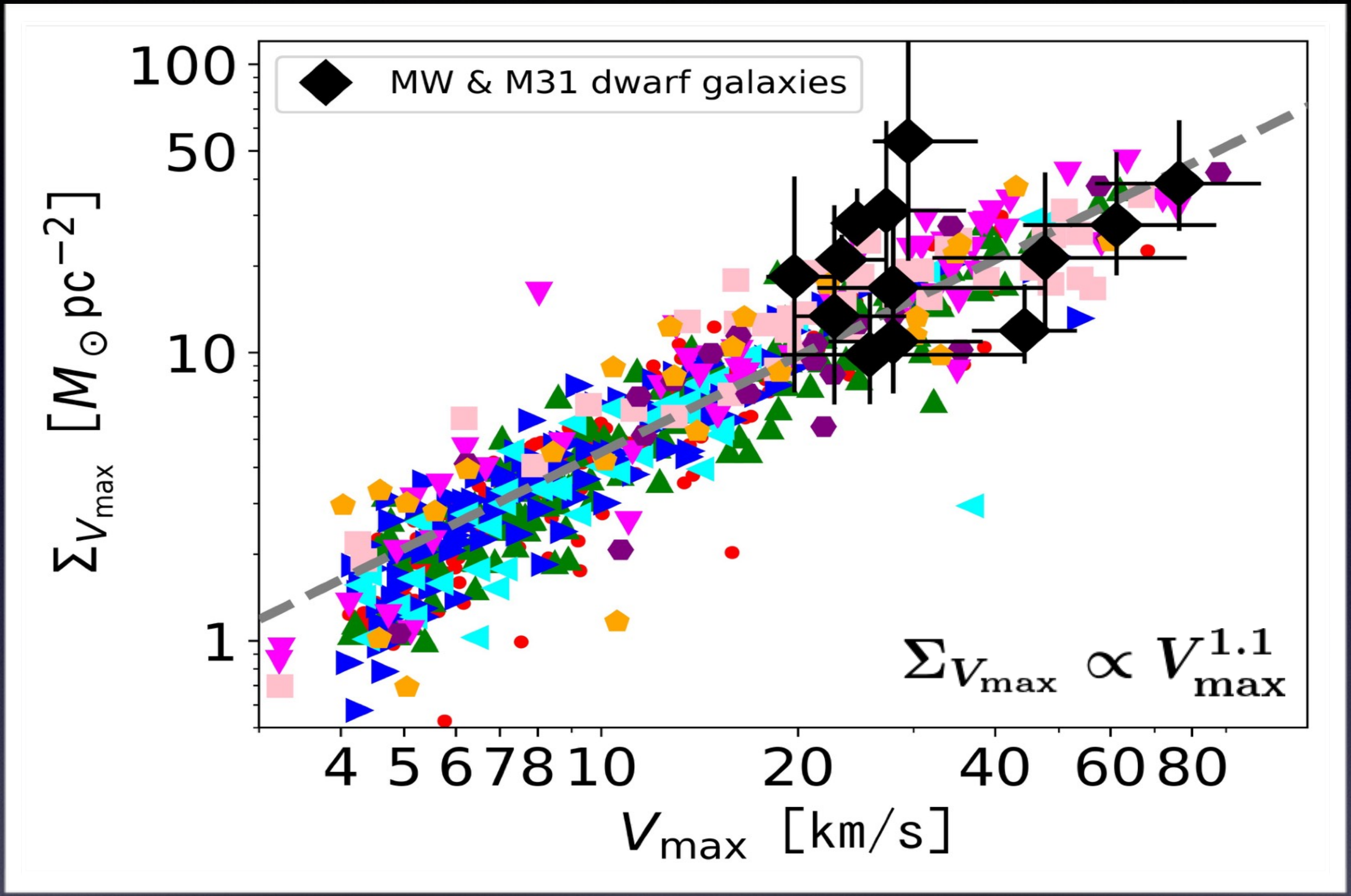
The universal dark halo relation for the dwarf spheroidals

DM surface density



The universal dark halo relation for the dwarf spheroidals

DM surface density

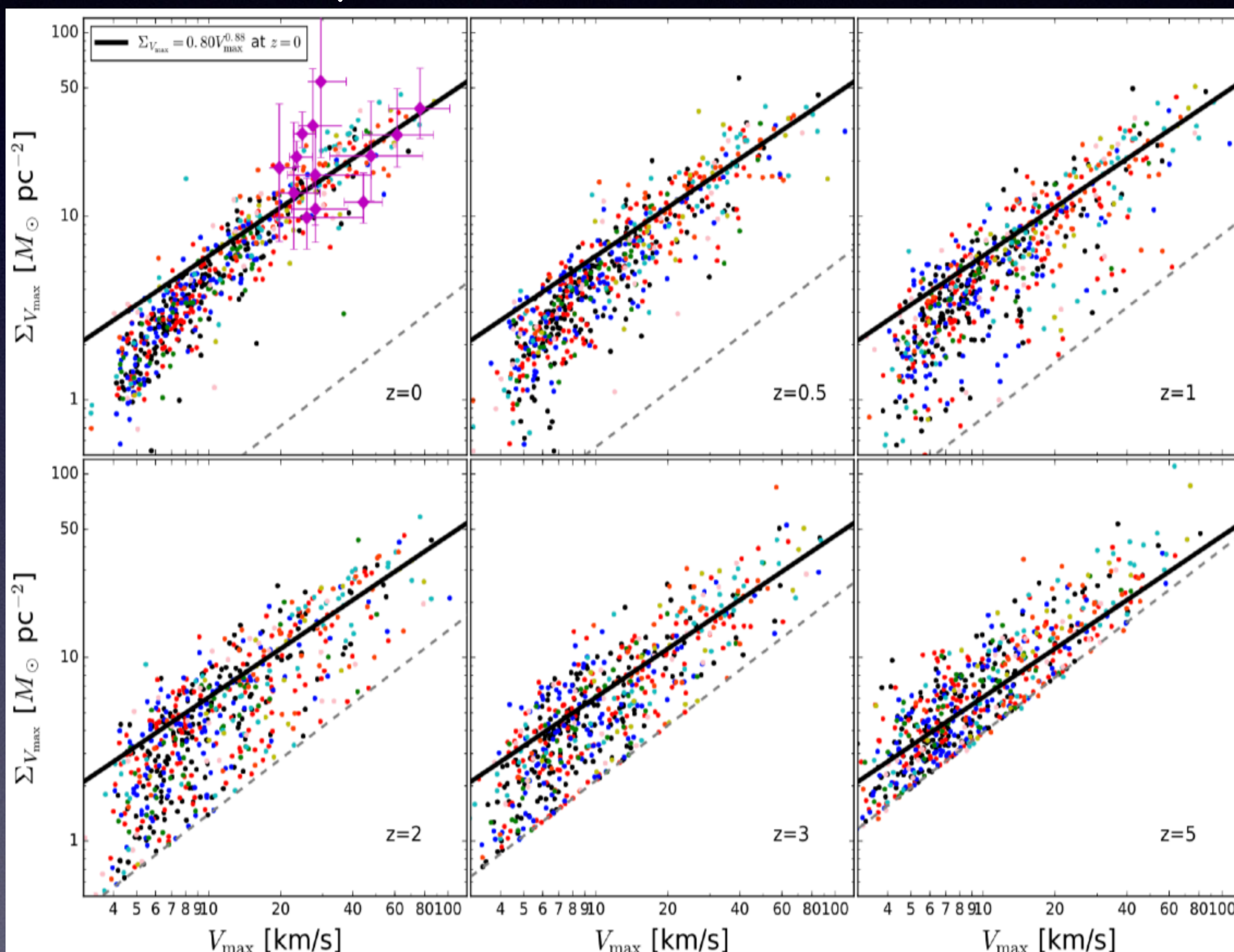


- Dark halo surface densities calculated from ΛCDM simulations agree very well with those from MW & M31 satellites.
- Dark halos associated with a host halo reside along the universal relation, irrespective of the differences in host halo's properties and orbital evolution of subhalos.

The universal dark halo relation for the dwarf spheroidals

Redshift dependence of Σ_{Vmax}-Vmax relation

DM surface density



- The relation has indeed been kept roughly invariant since its emergence.
- The relation may apply to substructure studies at higher redshifts (e.g., substructure lensing).
- To confirm this invariance robustly, we should look into observed Σ_{Vmax}-Vmax relation at higher redshift.

At higher redshift, some subhalos would not be dynamical stable, thereby r_{max} cannot be identified clearly and thus regarded as r_{vir}. This is why a fraction of the subhalos that are along the r_{max}=r_{vir} lines (dashed lines) increase with redshift.

Summary

1. To compare dark halo properties from CDM simulations and real galaxies without baryon effects, we propose dark halo surface density within a radius of Vmax.
2. This surface density can avoid influence of baryon feedbacks on dark matter profiles because rmax is much larger than star forming regions.
3. Focusing on this dark halo surface density on dwarf-galaxy scales, simulated ΛCDM subhalos are in remarkable agreement with dark halos within the observed dSphs.
4. We found the universal dark halo scaling relation, irrespective of the differences in host halo's properties, in orbital evolutions of subhalos, and in redshift evolutions.