Today Schedule

- Lecture
- Forth tutorial session / coffee break
- Lecture
- Fifth tutorial session / student presentations
- Bye-bye… and hope to see you soon

4. Dwarf Galaxies as challenges to cosmology

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Annual Review of Astronomy and Astrophysics

Small-Scale Challenges to the ΛCDM Paradigm

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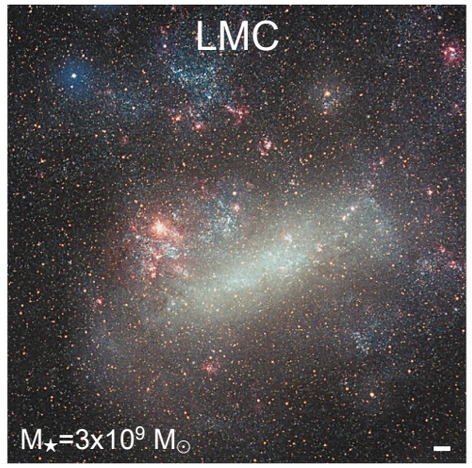
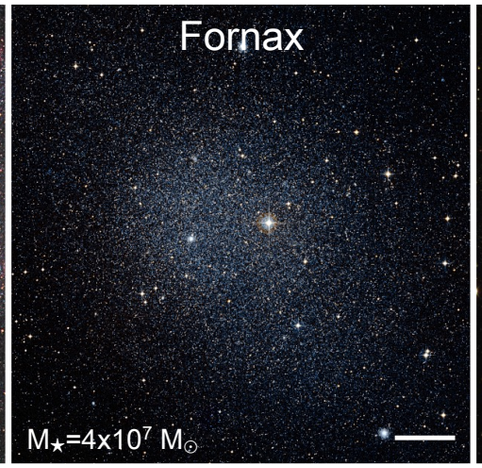
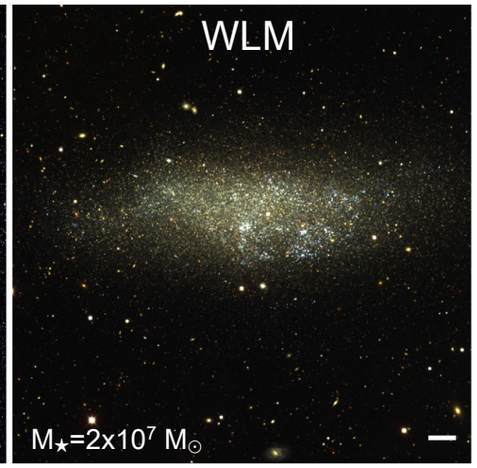
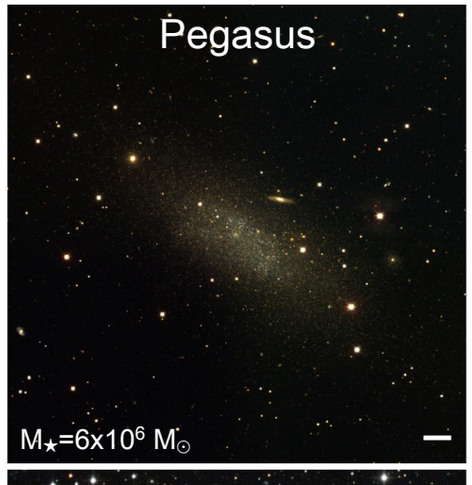
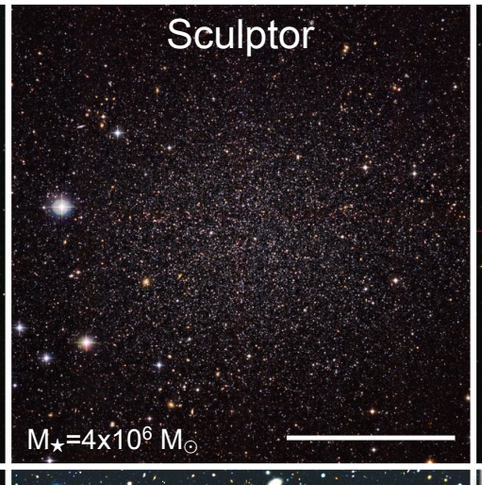
The zoo of dwarf galaxies

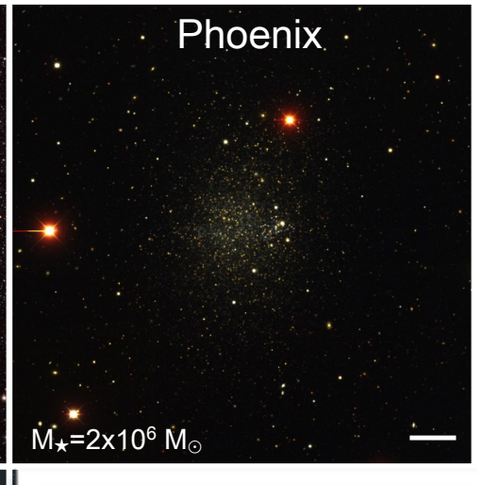


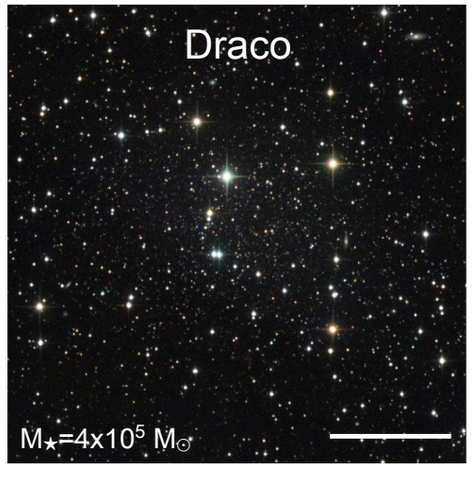


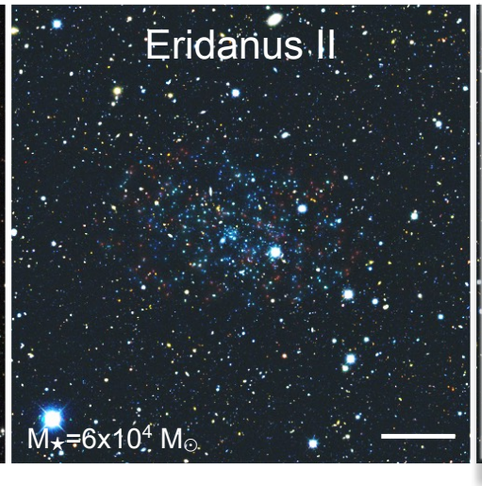












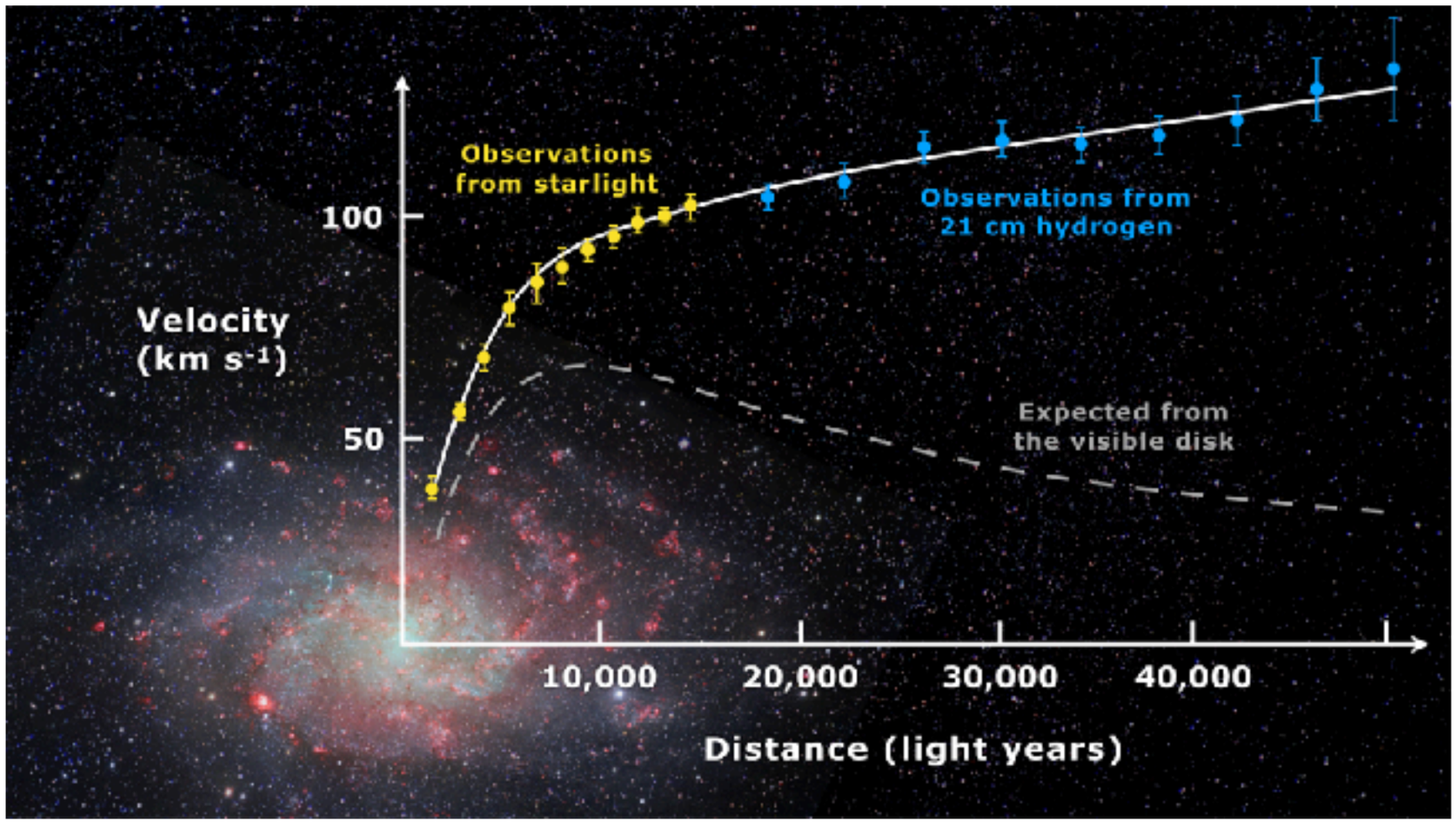
ADOPTED DWARF GALAXY NAMING CONVENTION

Bright Dwarfs: $M_\star \approx 10^{7-9} M_\odot$
– the faint galaxy completeness limit for field galaxy surveys

Classical Dwarfs: $M_\star \approx 10^{5-7} M_\odot$
– the faintest galaxies known prior to SDSS

Ultra-faint Dwarfs: $M_\star \approx 10^{2-5} M_\odot$
– detected within limited volumes around M31 and the Milky Way

Dwarf dynamics

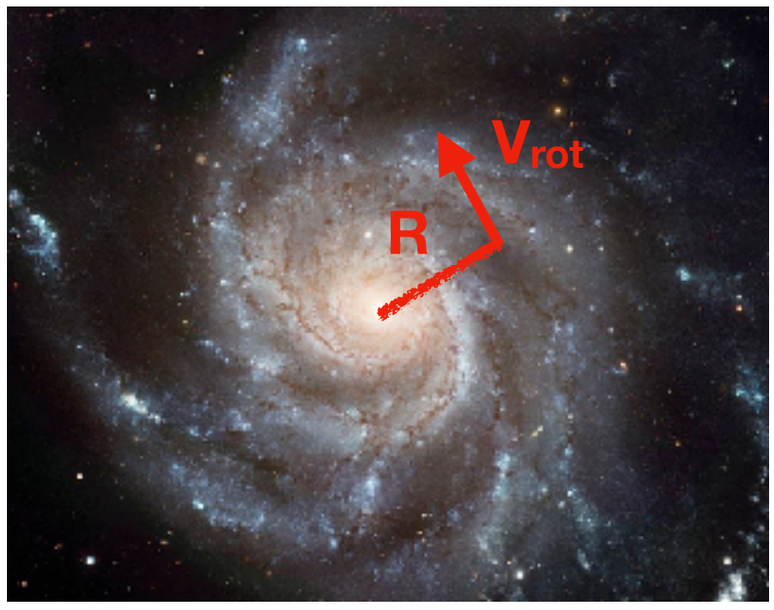


rotation curves

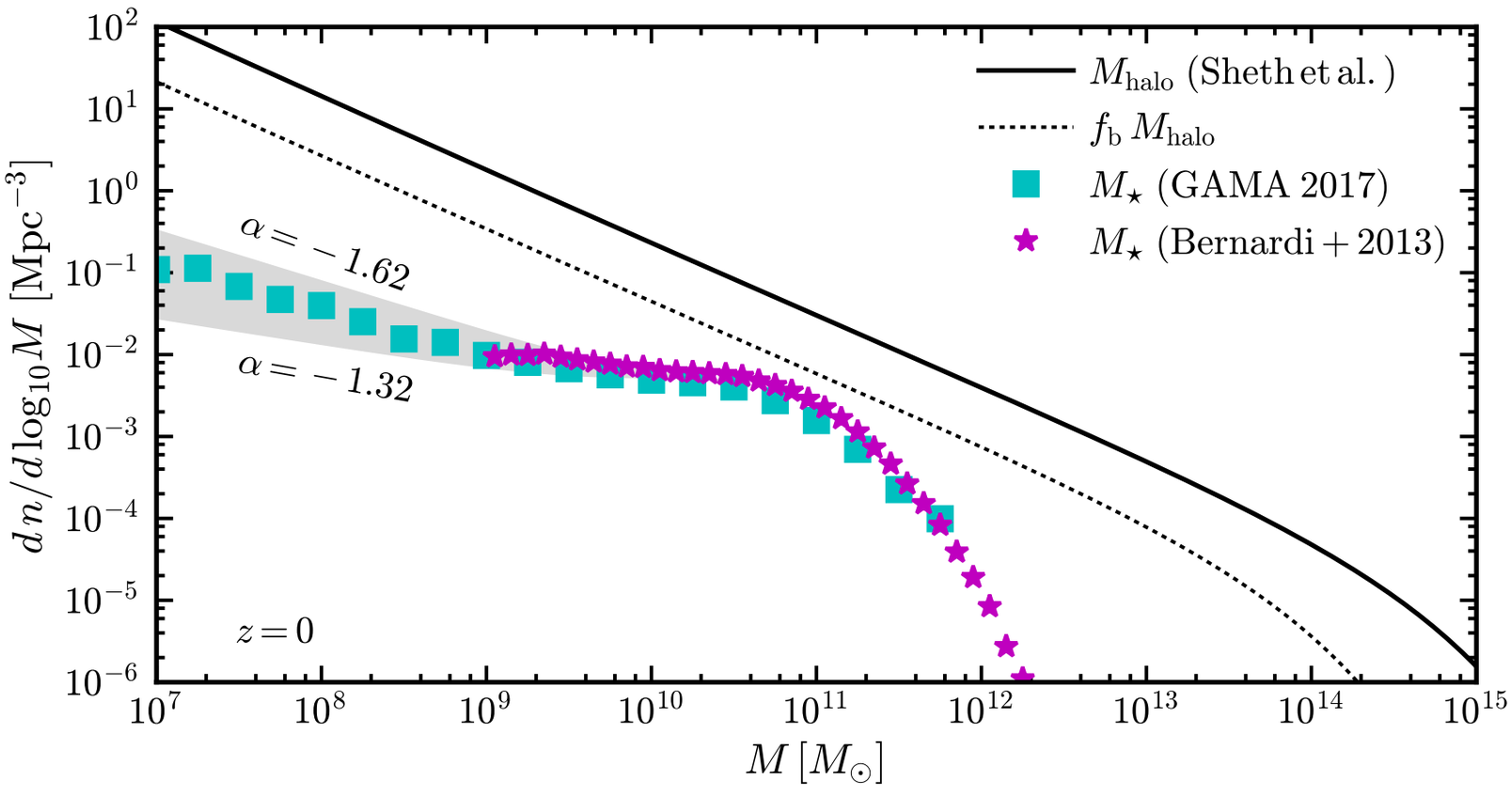
$$V_c^2 = V_{\rm rot}^2 - \sigma_r^2 \left(\frac{\partial \ln \Sigma(r)}{\partial \ln R} + \frac{\partial \ln \sigma^2}{\partial \ln R} - \beta \right) + \frac{kT}{\mu m_{\rm H}} \left(\frac{\partial \ln \Sigma(r)}{\partial \ln R} + \frac{\partial \ln T}{\partial \ln R} \right)$$

$$V_c \equiv [GM(<r)/r]^{1/2}$$

$$\beta \equiv 1 - \sigma_\phi^2/\sigma_r^2$$

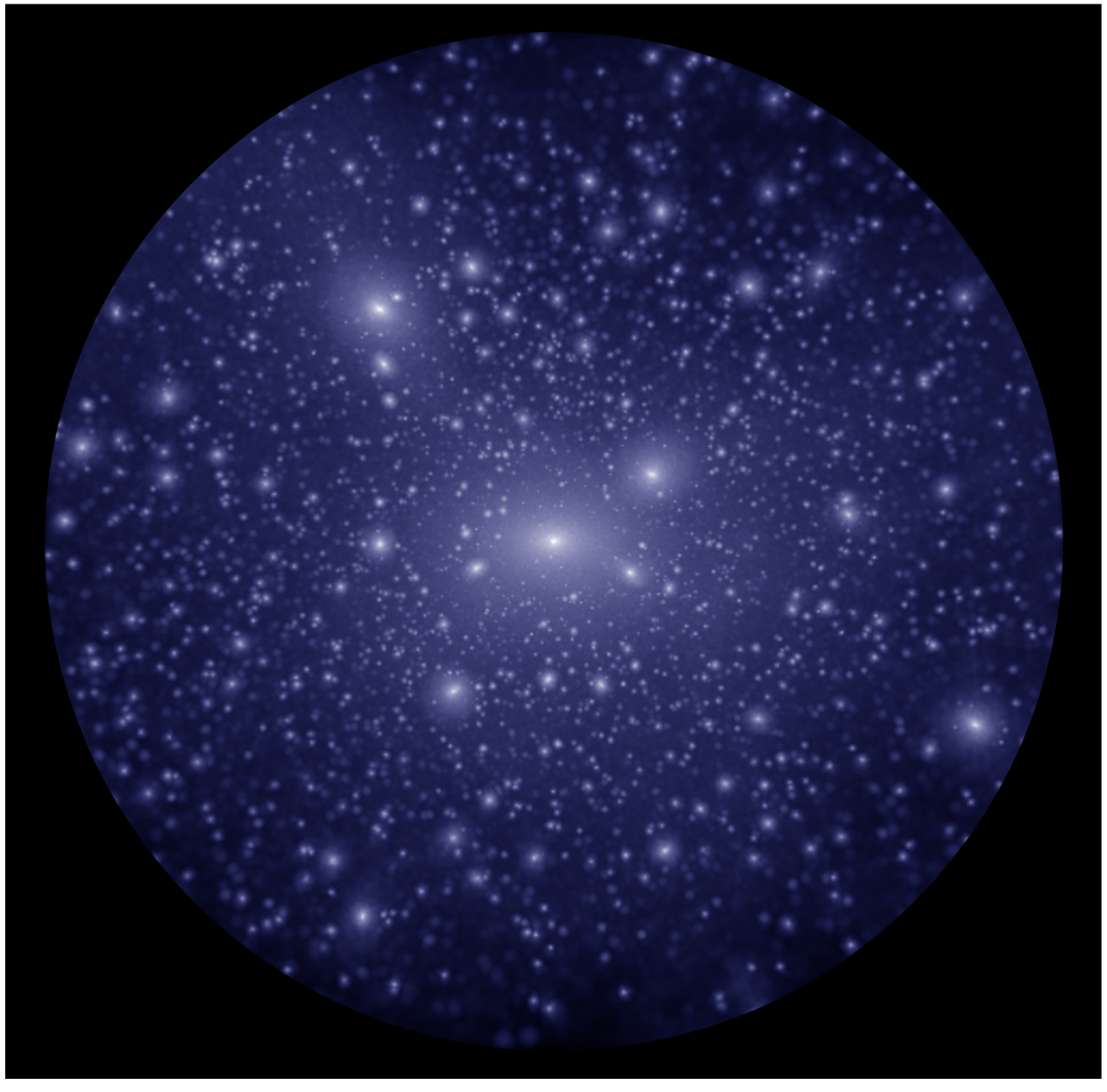


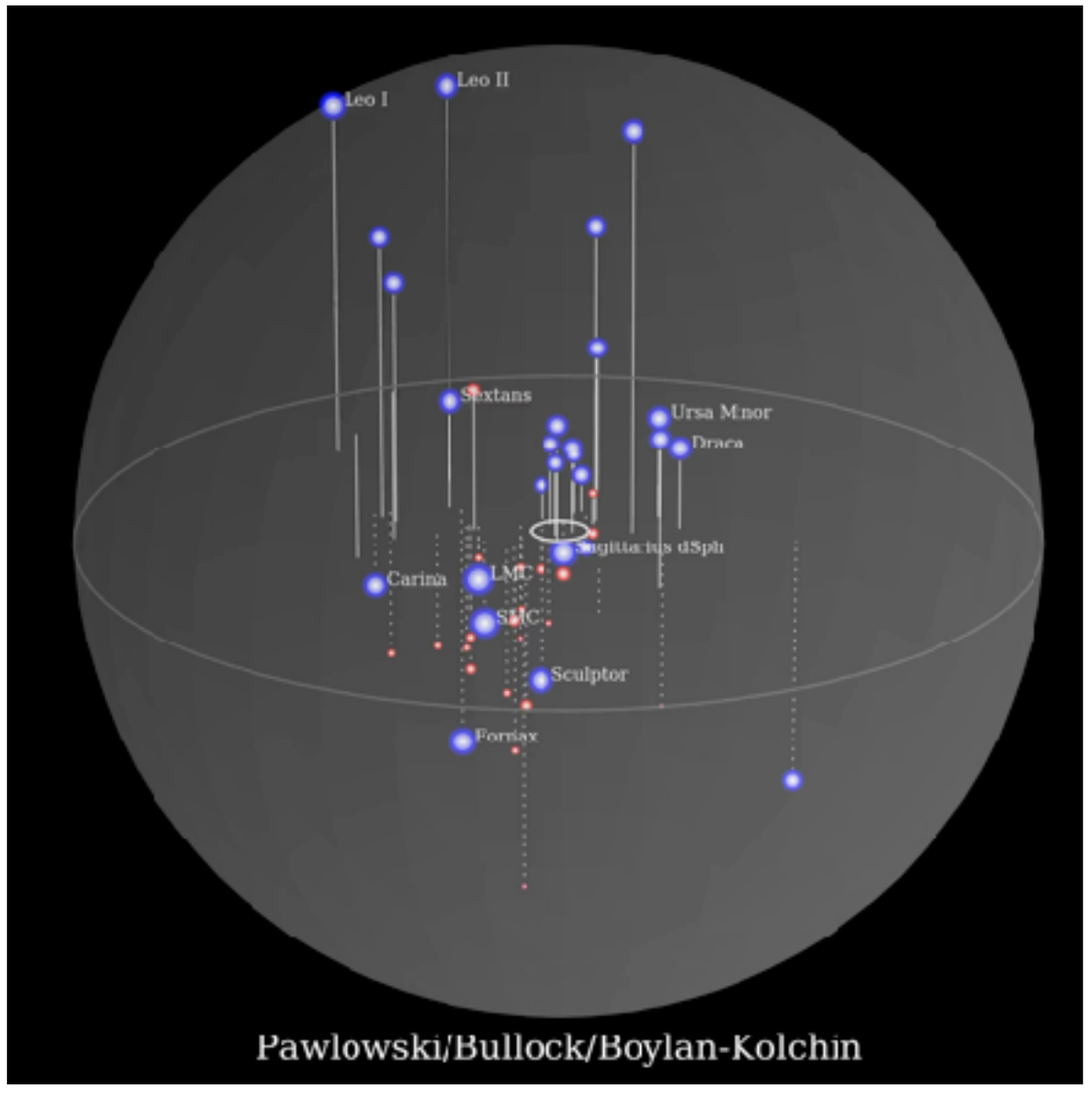
galaxies-haloes mistmach



The Missing Satellites Problem

low number of satellites





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WHERE ARE THE MISSING GALACTIC SATELLITES?

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DARK MATTER SUBSTRUCTURE WITHIN GALACTIC HALOS

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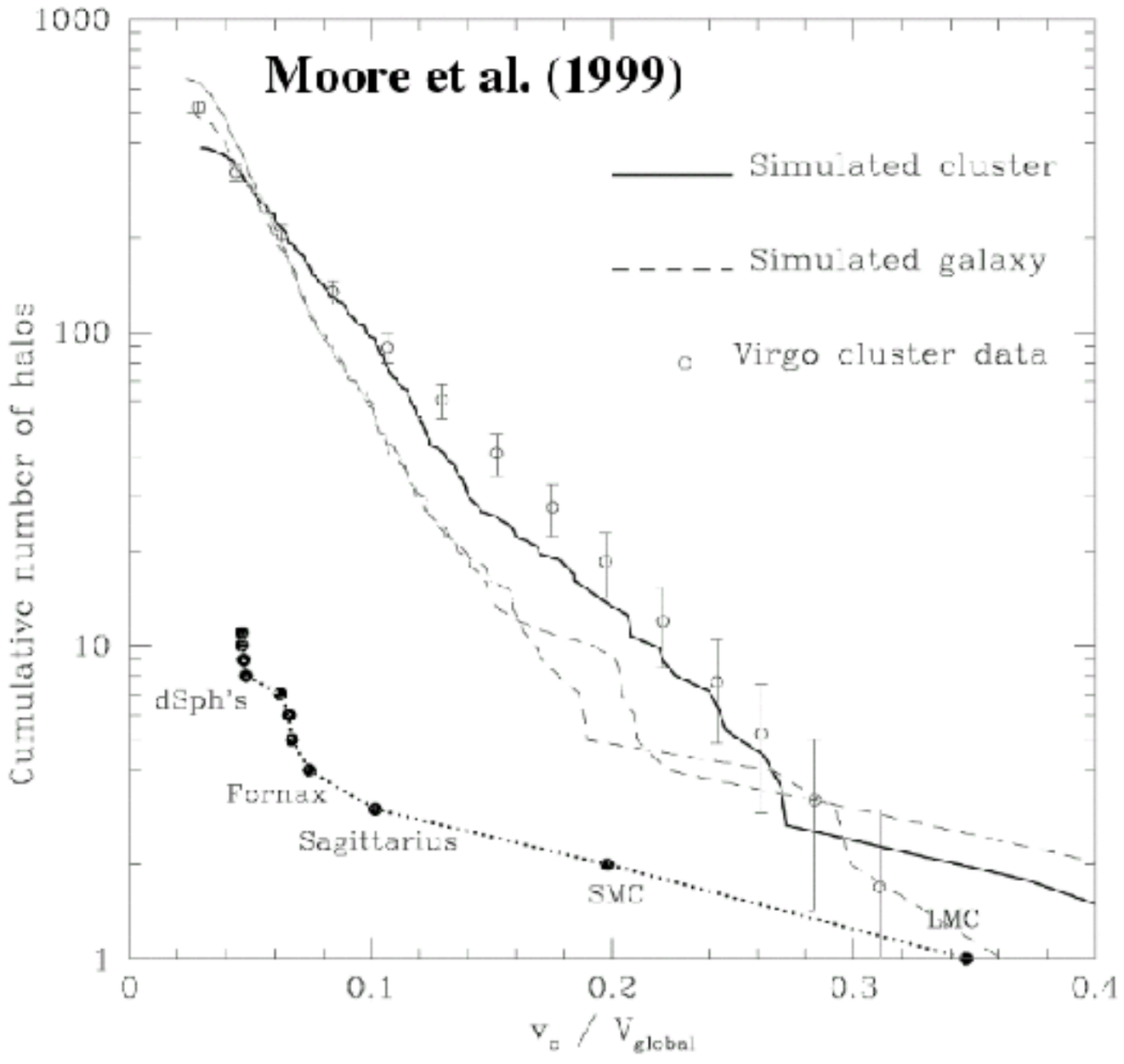
Quantifying the Missing Satellites Problem

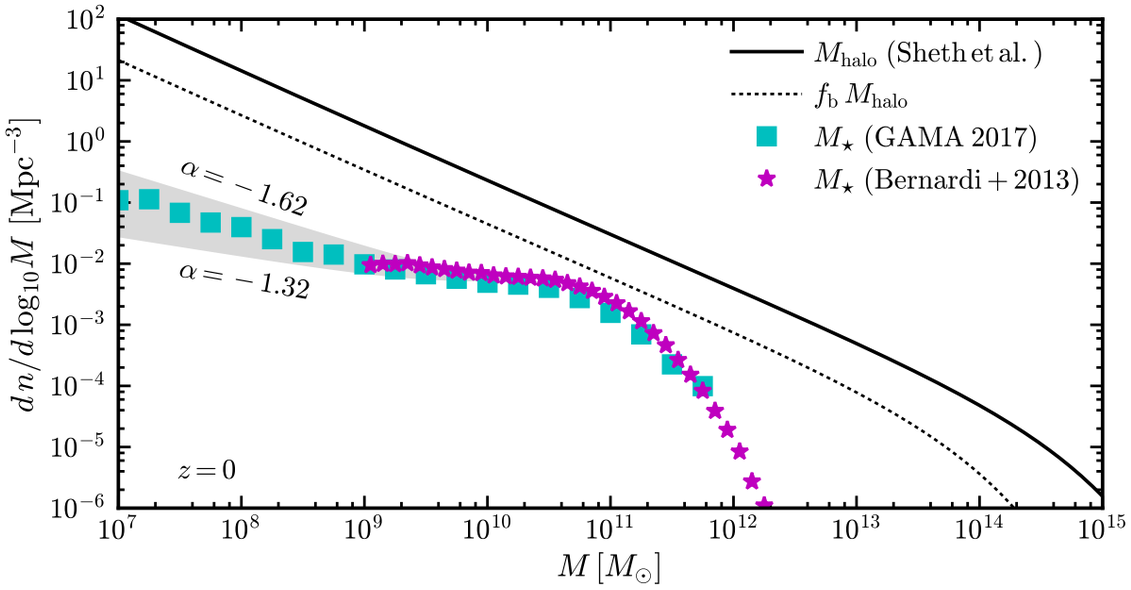
Cumulative peak circular velocity function (CVF)

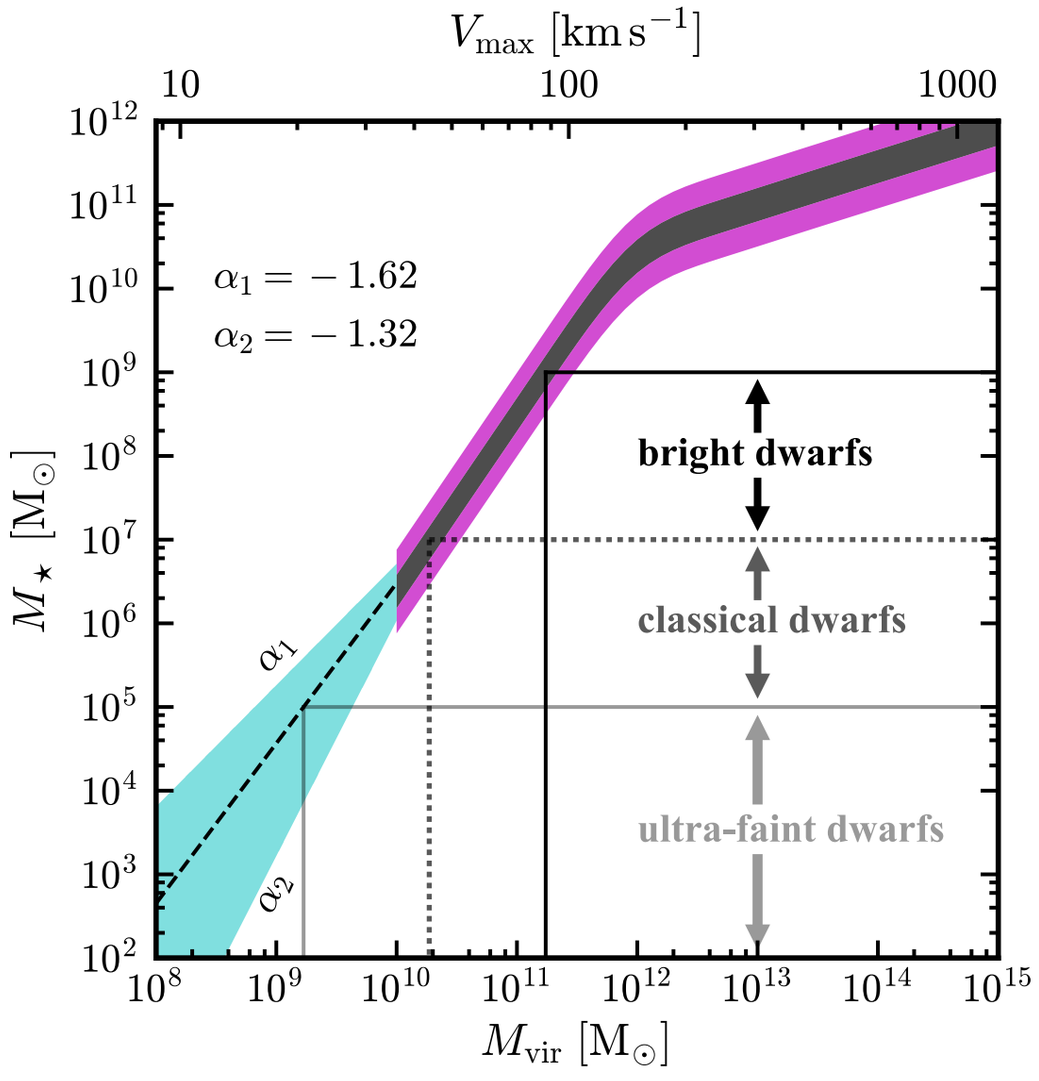


Vmax of satellites normalized to the Vvir of the parent halo

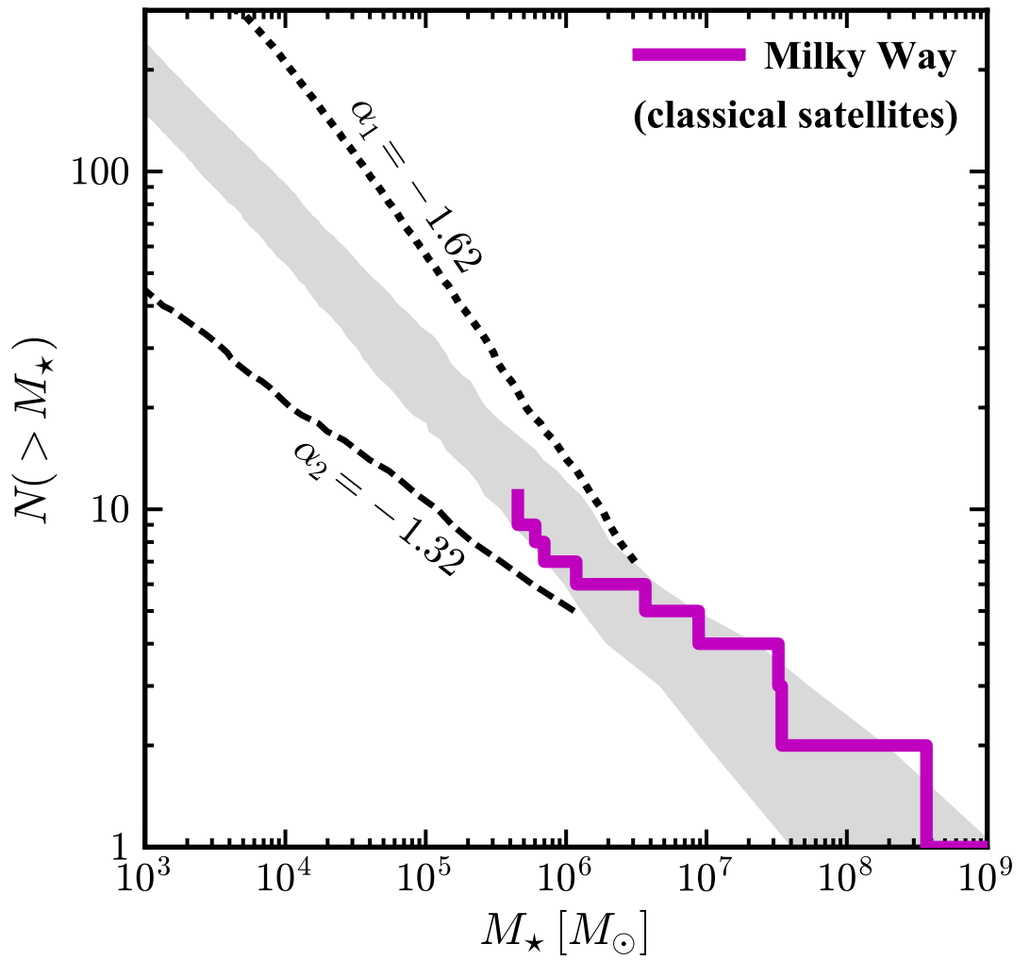
Discrepancy of ~ 2 orders of magnitude between the number of satellites predicted by numerical simulations of galactic systems and the Local Group.

Possible Solutions





possible solutions (I)



Which physical process drive this?

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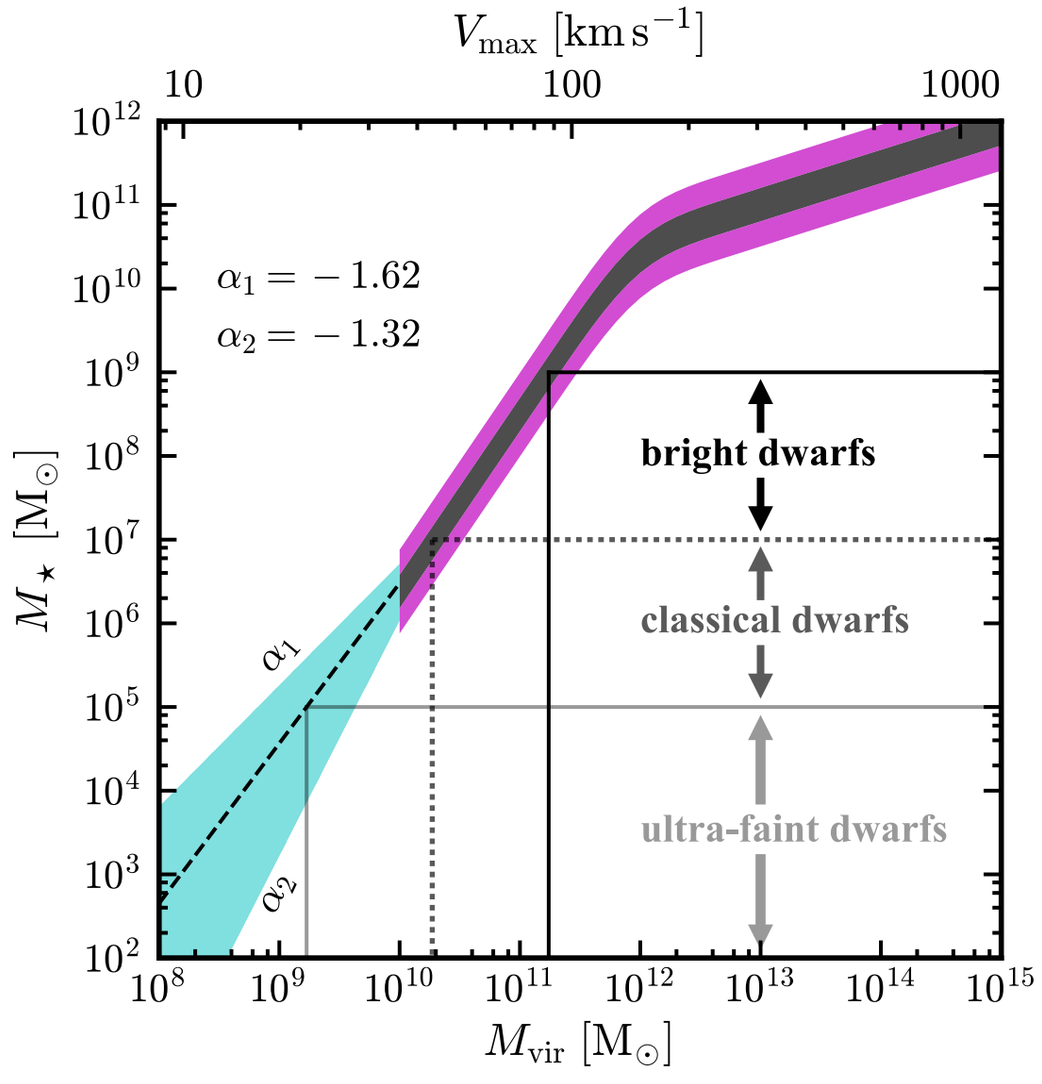
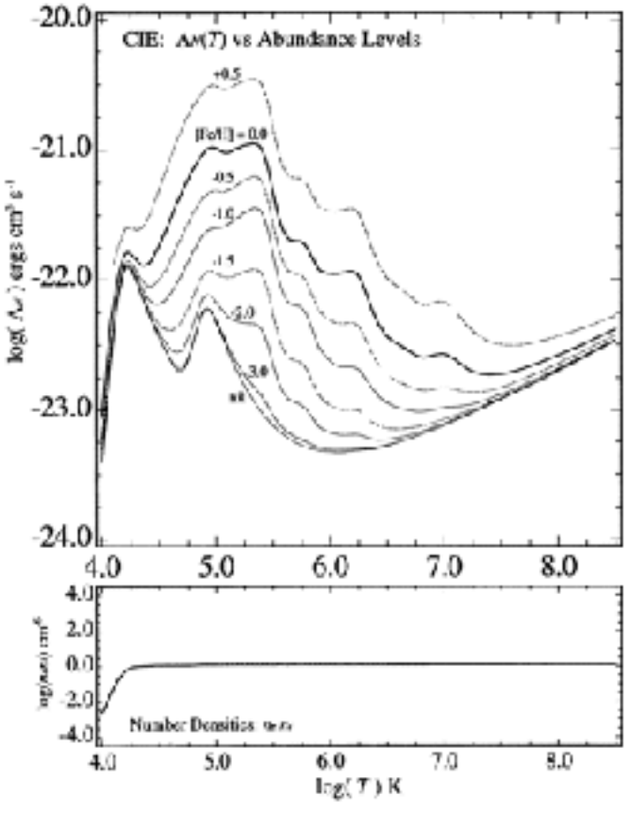


inefficient atomic cooling

The temperature of the shocked gas in a halo with virial velocity $V_{\rm vir}$ is

$$T_{\rm sh} \simeq \frac{\zeta}{3} \frac{\mu m_{\rm p}}{k_{\rm B}} V_{\rm vir}^2$$

- minimum mass for atomic hydrogen cooling
- it corresponds to T=10^4 K (Mvir ~10^8 Msun)
- only V_{vir} < 15 km/s



(Rees & Ostriker 1977)

UV feedback

- photoevaporation of dwarf galaxies during the epoch of reionization
- heating of the intergalactic medium to ~1-2 10^4 K
- suppress galaxy formation in halos with T_{vir}<1-2 10^4 K
- This means V_{vir}<20 km/s at z=6 (M_{vir} < 10^9 Msun)
- This may work for Ultra Faint Dwarfs

(Efstathiou 1992, Bullock et al. 2000, Benson et al. 2002, Bovill & Ricotti 2009, Sawala et al. 2016)

stellar feedback

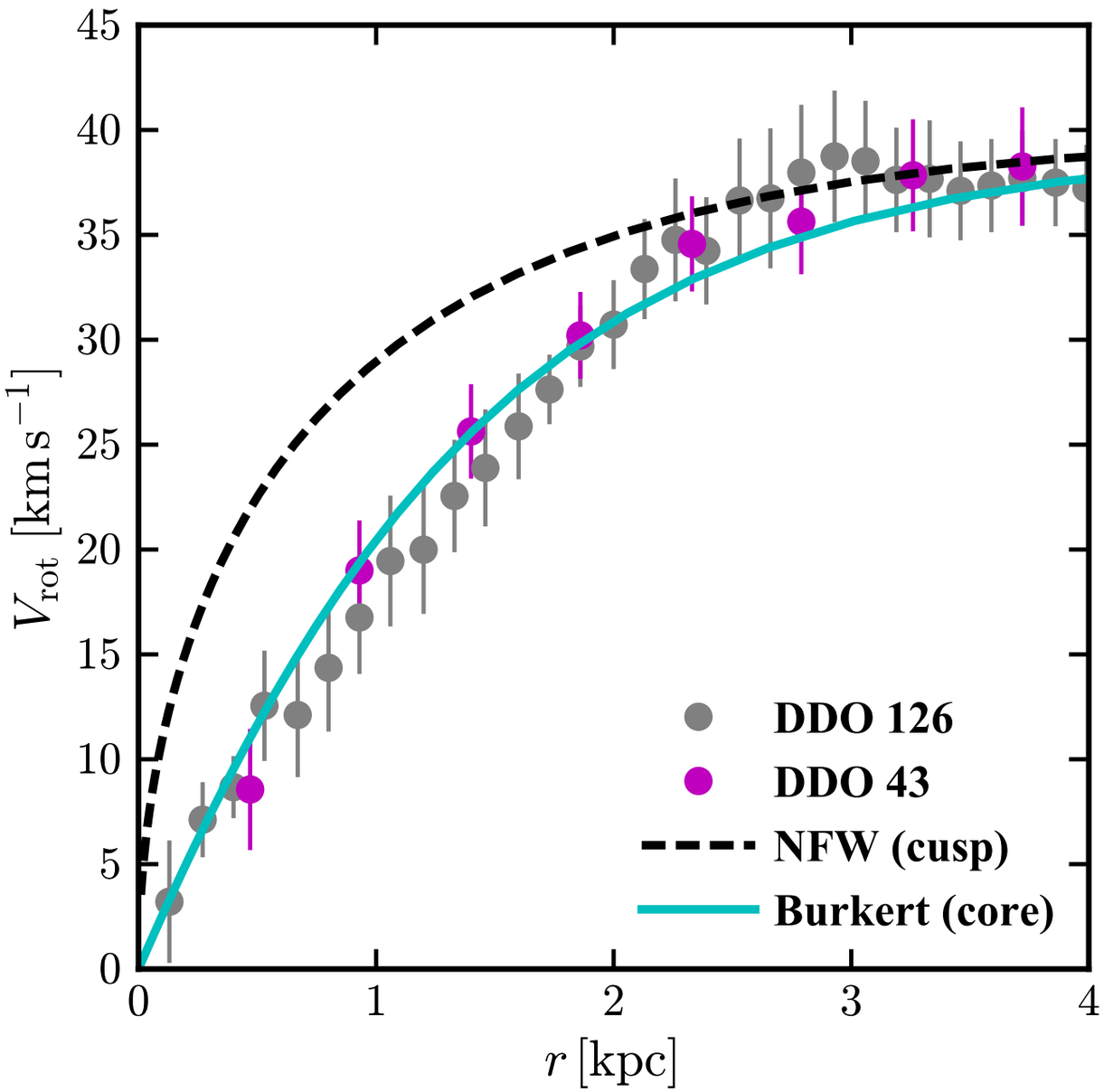
- efficient in ejecting star-forming gas
- in heating cold and dense gas
- in preventing star formation on galaxy-scales
- in halos upto $M_{vir}<10^{11}\ M_{sun}$ or $V_{vir} < 100$ km/s

(Dekel & Silk 1986)

z=30.0

The Cusp-Core problem

A problem in the inner slope of DM profile (α)



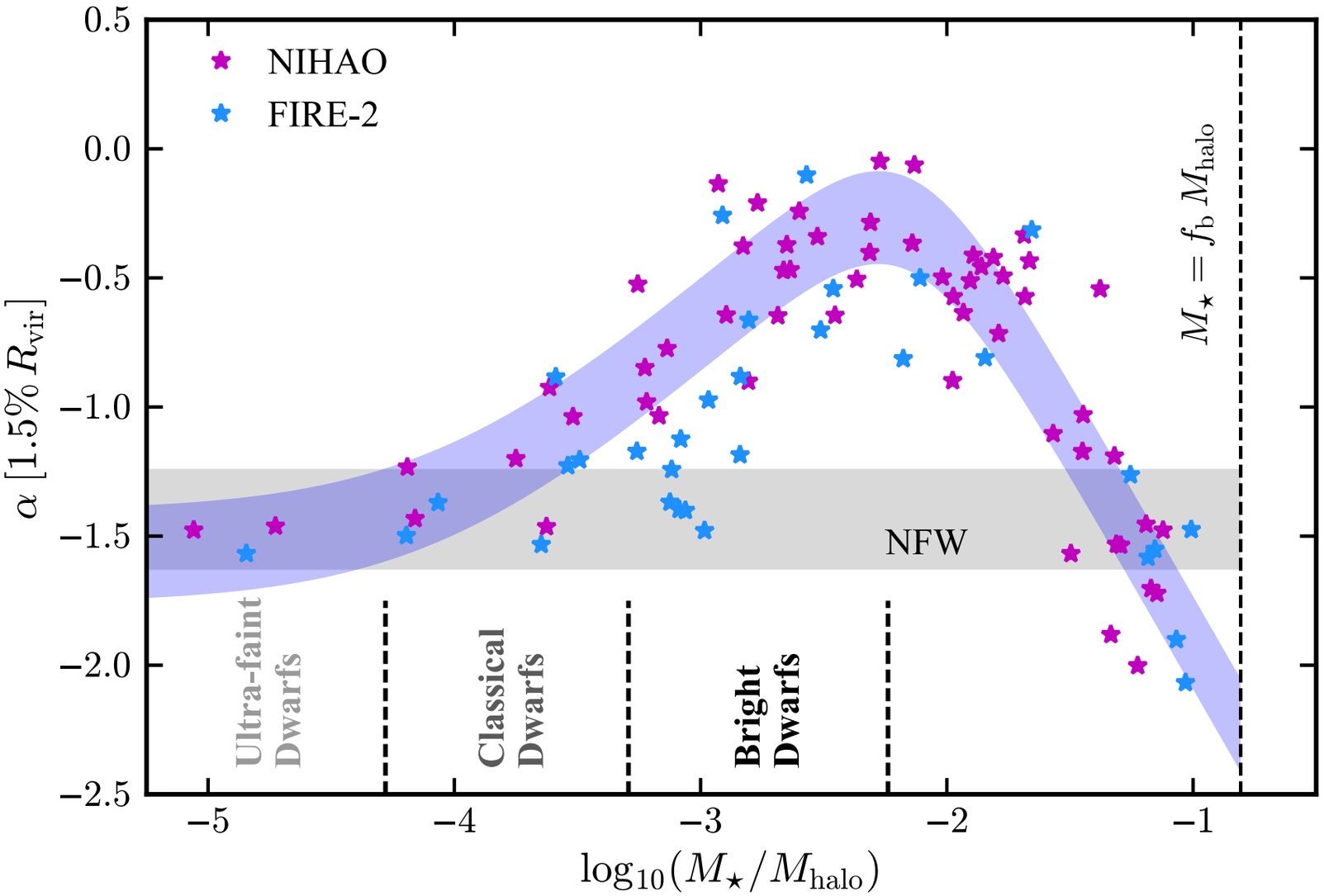
but $V_{rot} \neq V_c$

$$V_c \equiv [GM(<r)/r]^{1/2}$$

"ΛCDM halos are too cuspy in their centres compared with many observed galaxies"

(McGaugh et al. 2001, Marchesini et al. 2002, Simon et al. 2005, de Blok et al. 2008, Kuzio deNaray et al. 2008)

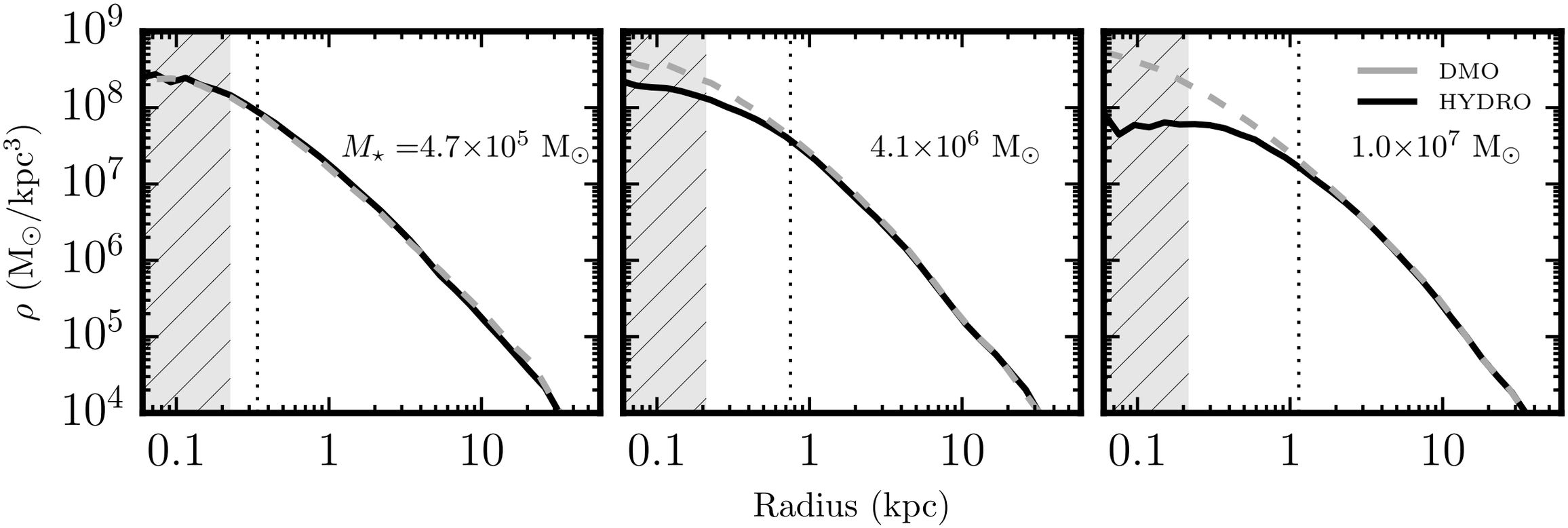
possible solution (II)



Feedback is the main suspect again…

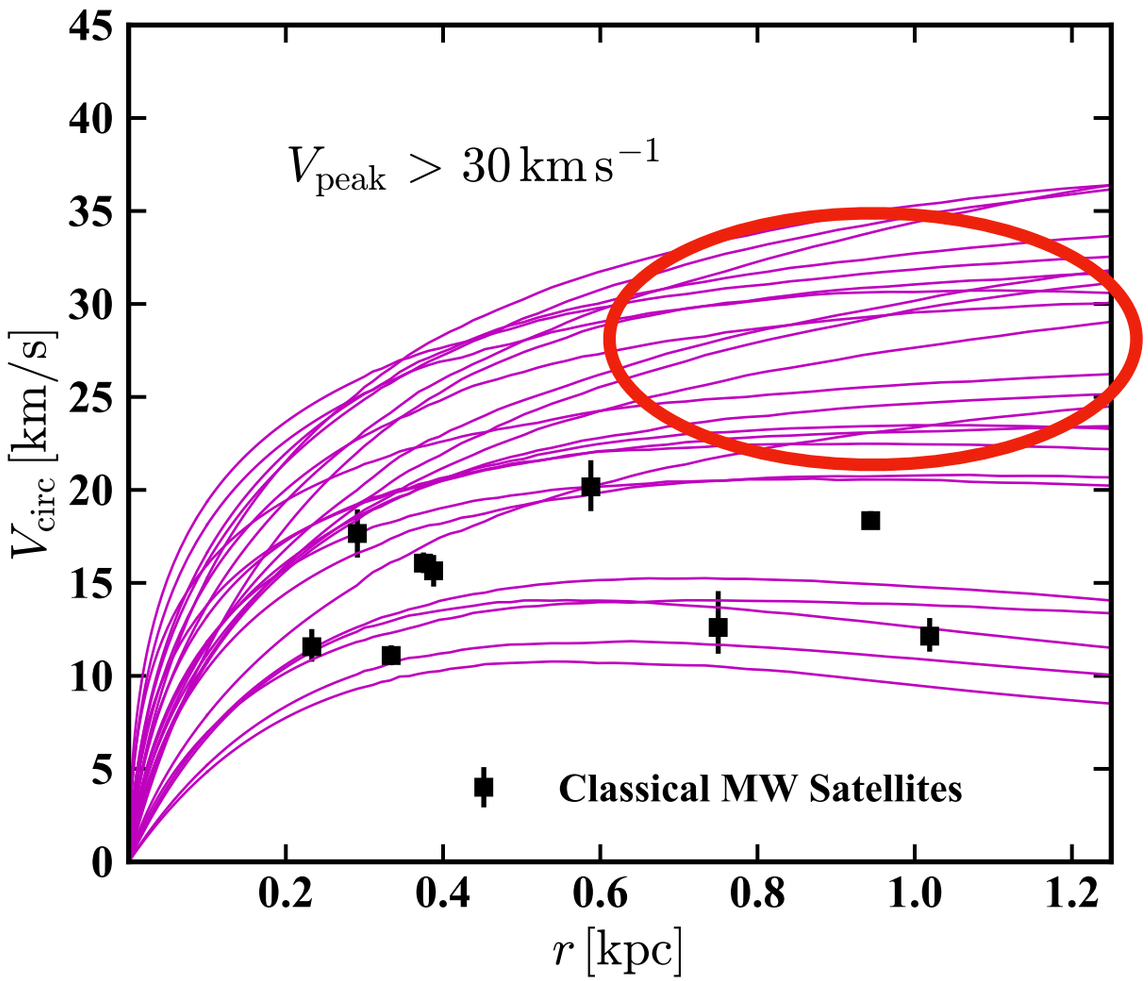
- Feedback drives repetitive gas blowups
- It shakes the gravitational potential
- it induces gravitational heating in the central halo
- only if star formation is intense (Ultra-faint dwarfs remain cuspy)
- and if gravitational potential is not too deep

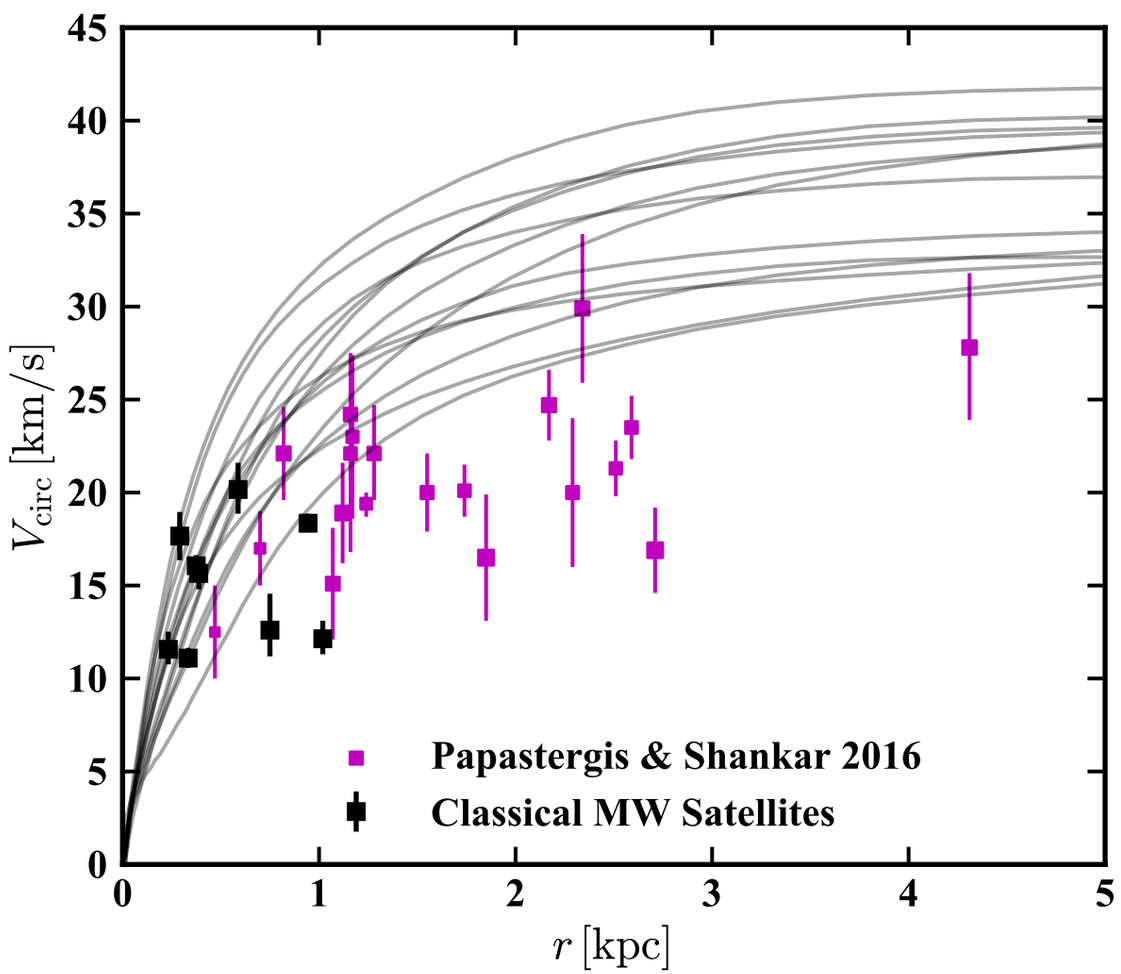
feedback creates cores above ultra-faint dwarfs



The Too-Big-to-Fail Problem

Classical Dwarfs are too dense

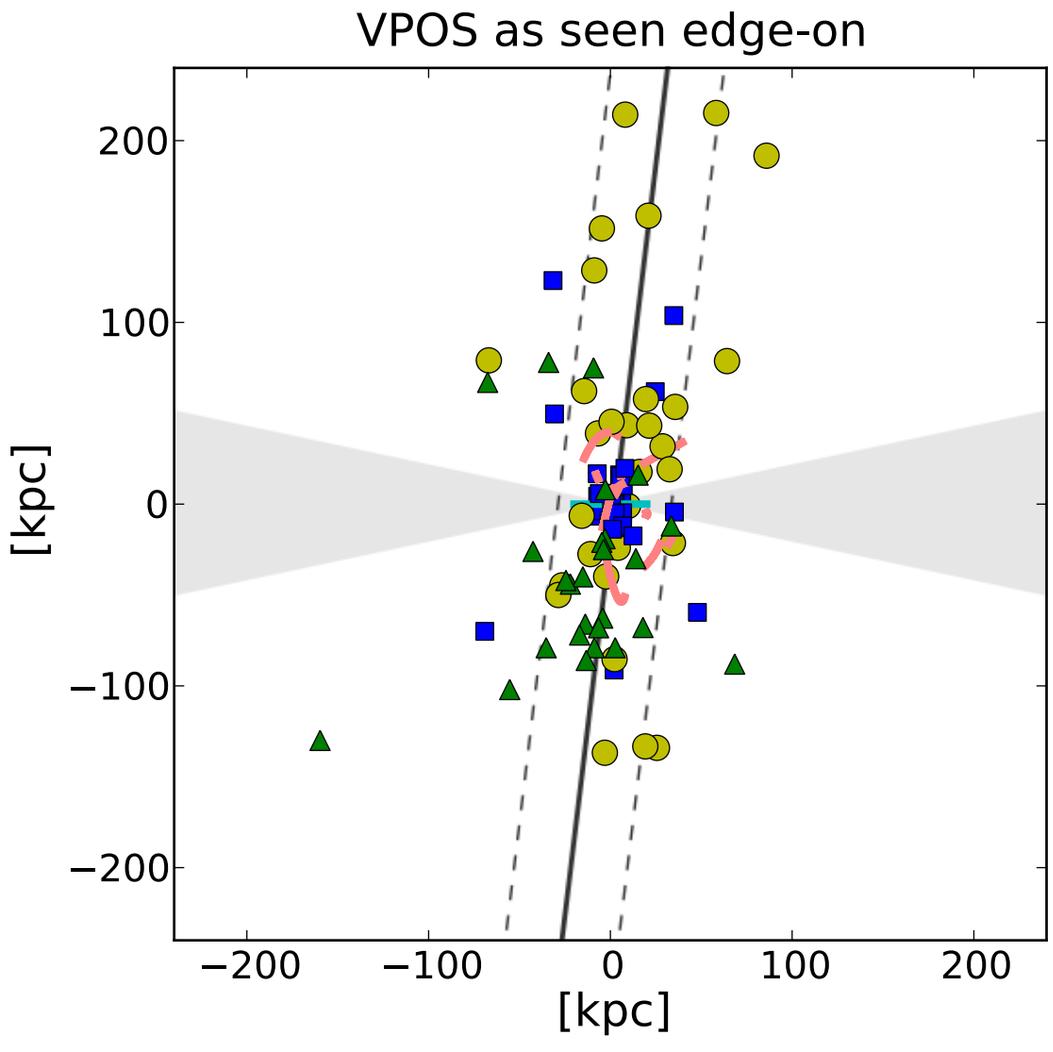


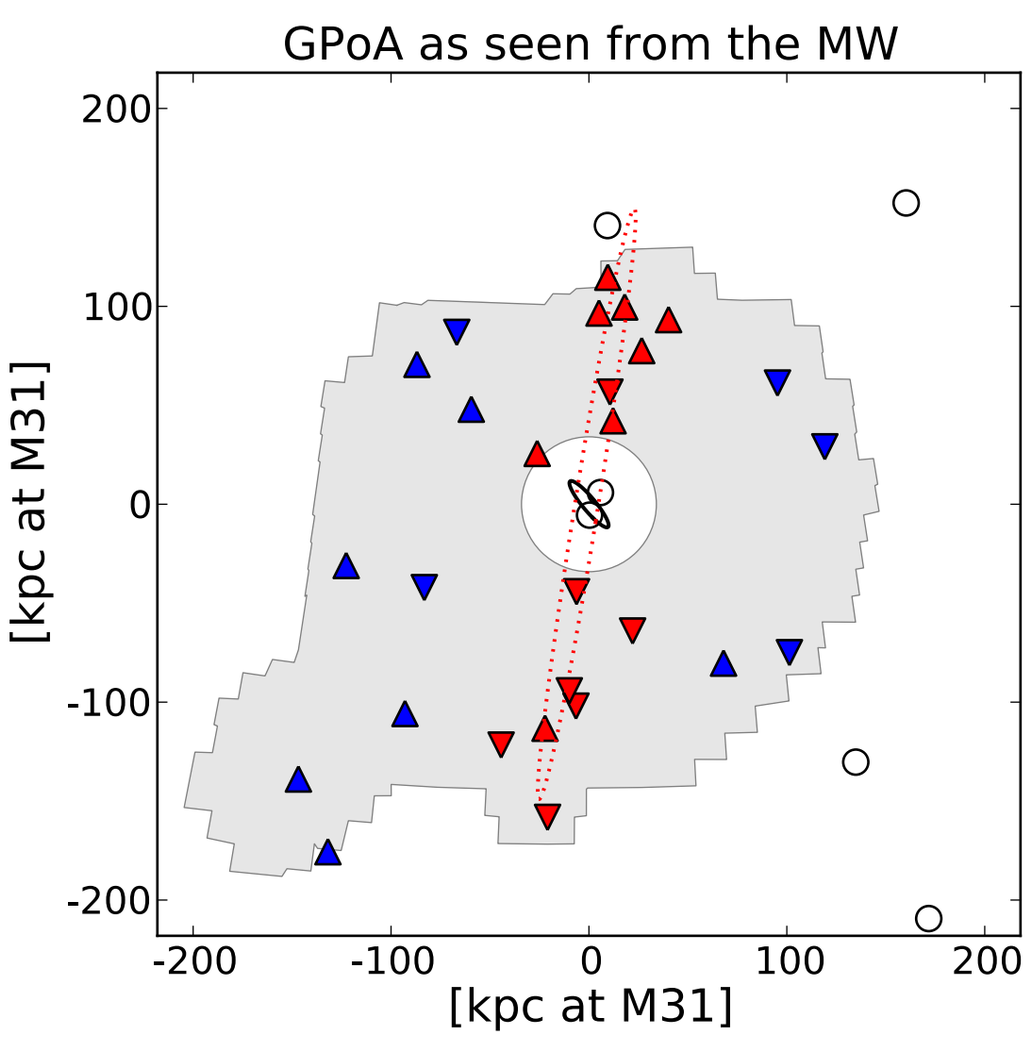


possible solutions (III)

- feedback
- interactions between satellites and the MW: tidal stripping, disk shocking, ram pressure stripping
- isolated field dwarfs

Planes of Satellites


VPOS as seen edge-on
200
100
0
−100
−200
[kpc]
−200
−100
0
100
200
[kpc]


GPoA as seen from the MW
200
100
0
-100
-200
[kpc at M31]
-200
-100
0
100
200
[kpc at M31]

possible solutions (IV)

- filamentary accretion within ΛCDM
- limited coverage in observations
- rotational supported motions?

Three take-home messages

- Missing Satellite Problem
- ΛCDM halos are too cuspy and dense in their centres compared with many observed galaxies
- Planes of Satellites

THANKS

Forth Tutorial Section