Constraining feedback by satellite galaxies

岡本 崇 (Durham・筑波)

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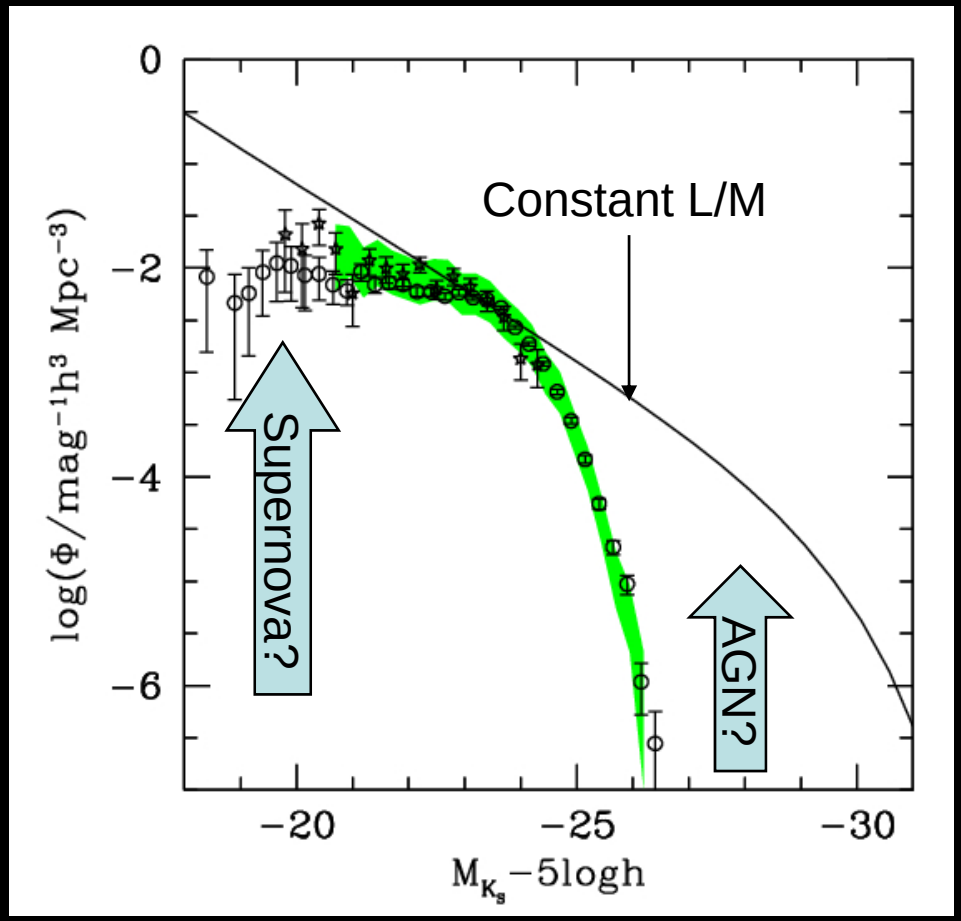
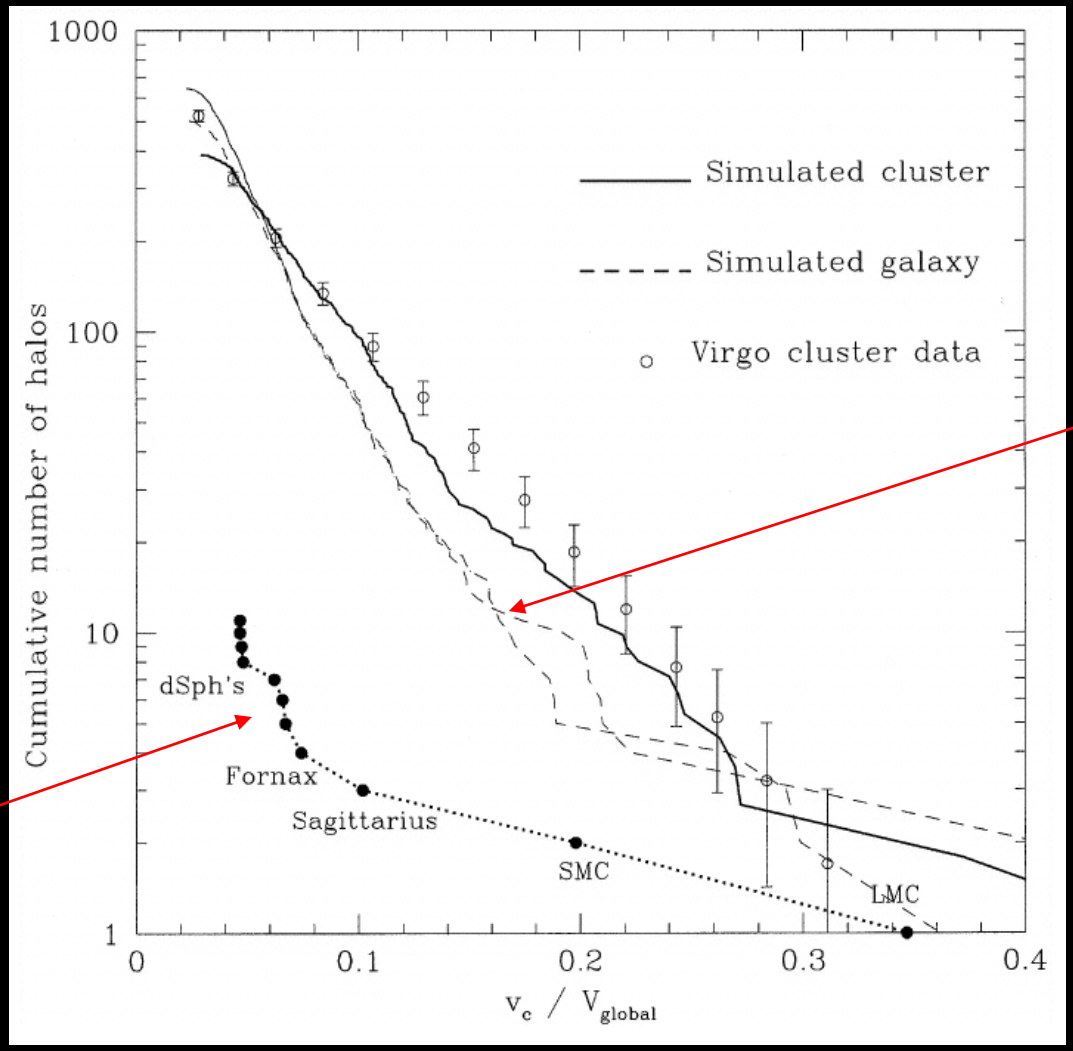
ΛCDM & galaxy formation



Benson+'03

Baryonic physics is a key!

Satellite problem



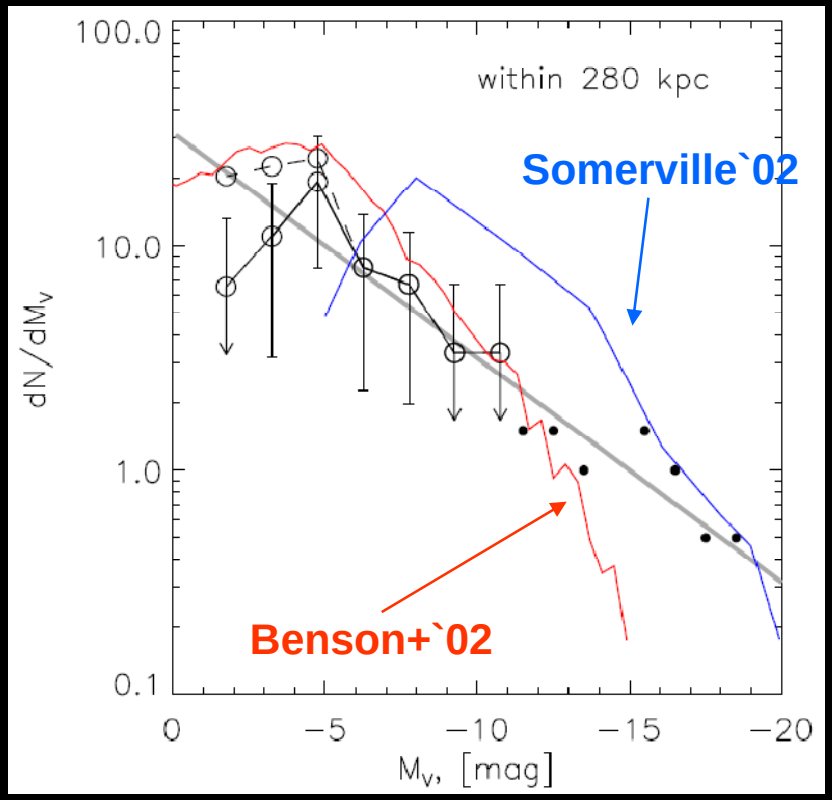
Simulated sub-halos

Observed satellites

Moor+'99, Klypin+'99

Previous studies

LF of MW satellites

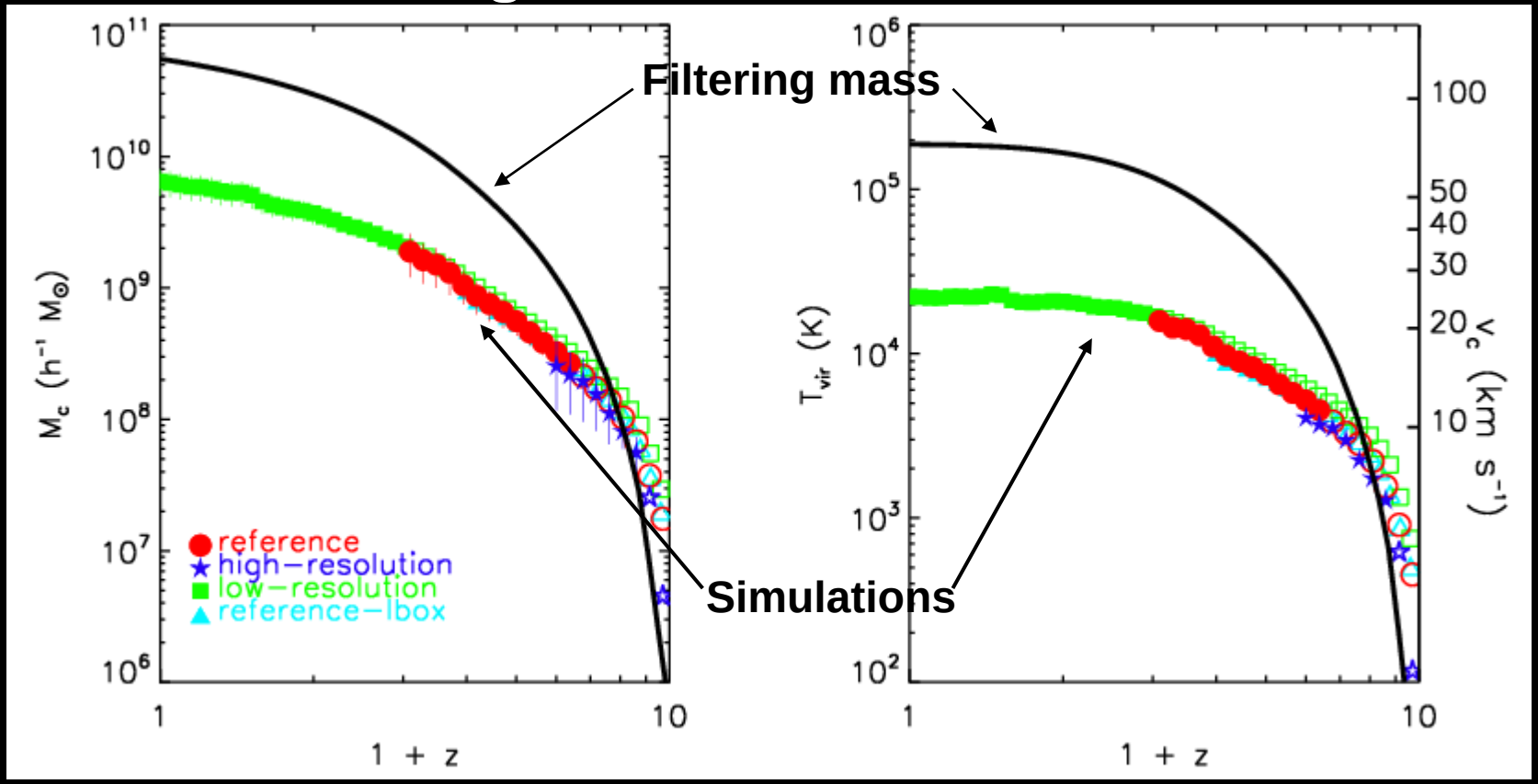


Koposov+`08

- Semi-analytic models suggested that the inclusion of the effects of reionization-heating, photo-heating, and SN feedback can solve the satellite problem.

However

- These SA models overestimated the effects of a UV-background.



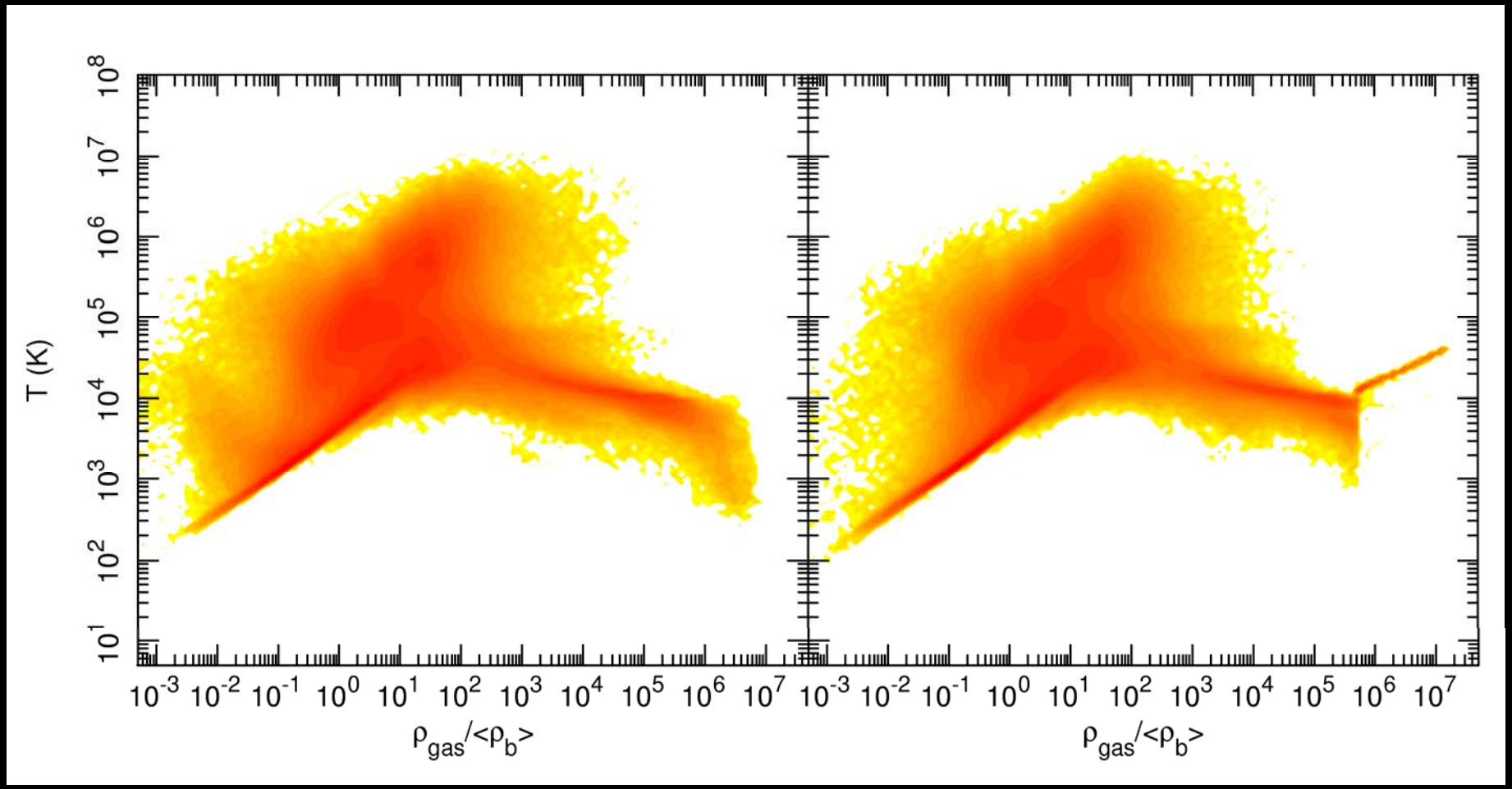
Okamoto, Gao, Theuns '08

Cosmological simulations

- 3 MW-candidate halos from the Aquarius project (Springel+' 08)
  - Aq-A, Aq-C, and Aq-D
- Resolution
  - Reference: $M_{\rm SPH} \sim 4 \times 10^5\ {\rm M}_\odot$
  - High-resolution: $M_{\rm SPH} \sim 3.5 \times 10^4\ {\rm M}_\odot$
- ISM
  - Standard
  - Multiphase-model (Okamoto+' 08)
    - Harder EOS for star-forming gas: $P_{\rm min} \propto \rho^{1.4}$
  - Star formation is normalized to reproduce the Kennicutt relation

Phase diagrams

Standard **Multiphase**



Phenomenological models for feedback

- Assuming 100% of the SN energy is converted to the kinetic energy of winds
- Two types of energy conserving winds
  - Wind models are characterised by the wind speed, v_w, and the mass loading factor, η, where $\dot{M}_w = \eta \dot{M}_*$.

$$\begin{cases} v_w \propto \sigma \text{ and } \dot{M}_{\rm w} = \left(\dfrac{\sigma}{\sigma_0}\right)^{-\frac{1}{2}} \dot{M}_* & \text{(Similar to SA models)} \\ v_w = const. \text{ and } \eta = const. & \text{(a la Springel \& Hernquist)} \end{cases}$$

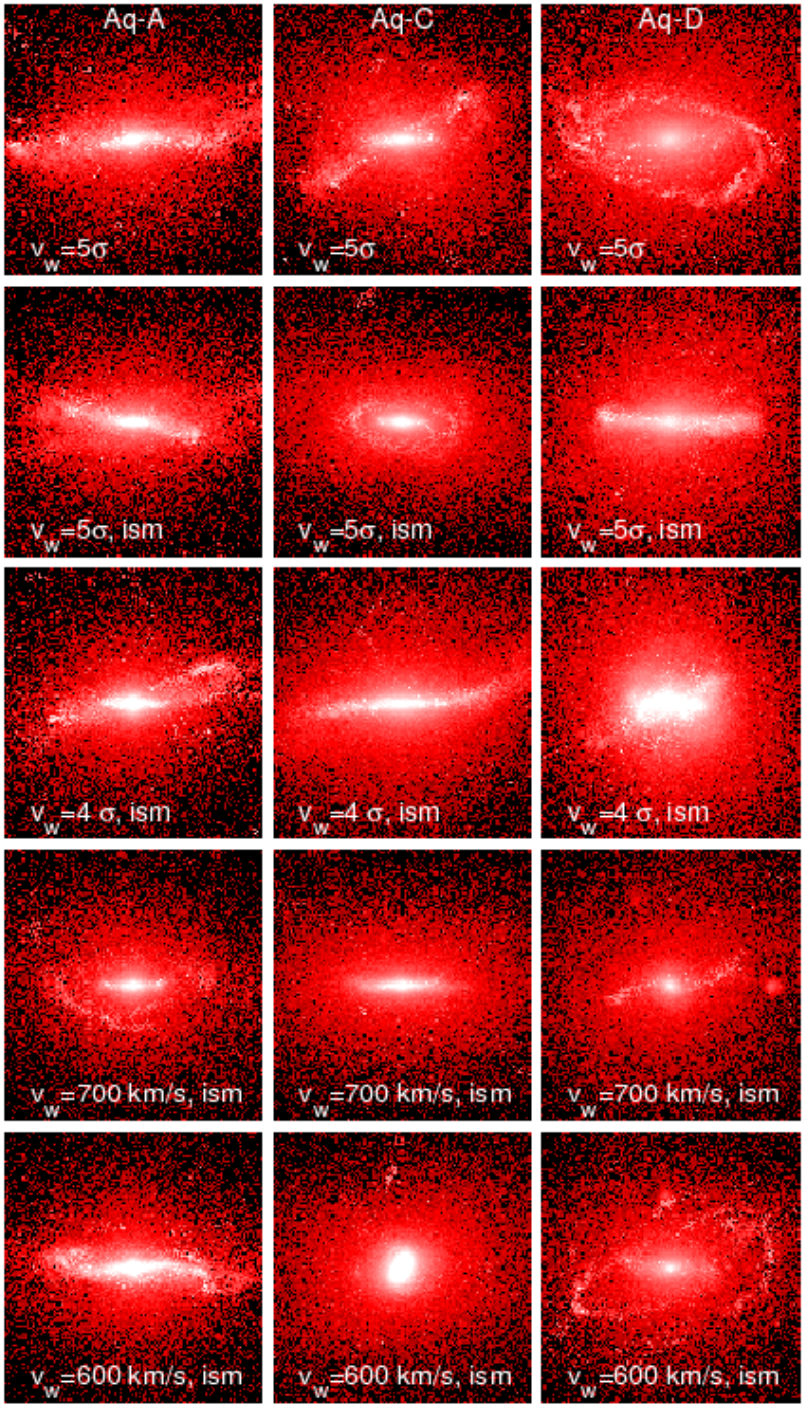
Simulations

- 3 MW candidate halos
- WMAP1 cosmology
- Time dependent, spatially uniform UV-background (Haardt & Madau '01; $z_{reion} = 9$)
- Chemical evolution by Type II and Ia SNe and AGB stars
- Metallicity dependent cooling
- SF is normalized to reproduce the Kennicutt relation
- FB is modeled as winds

Models

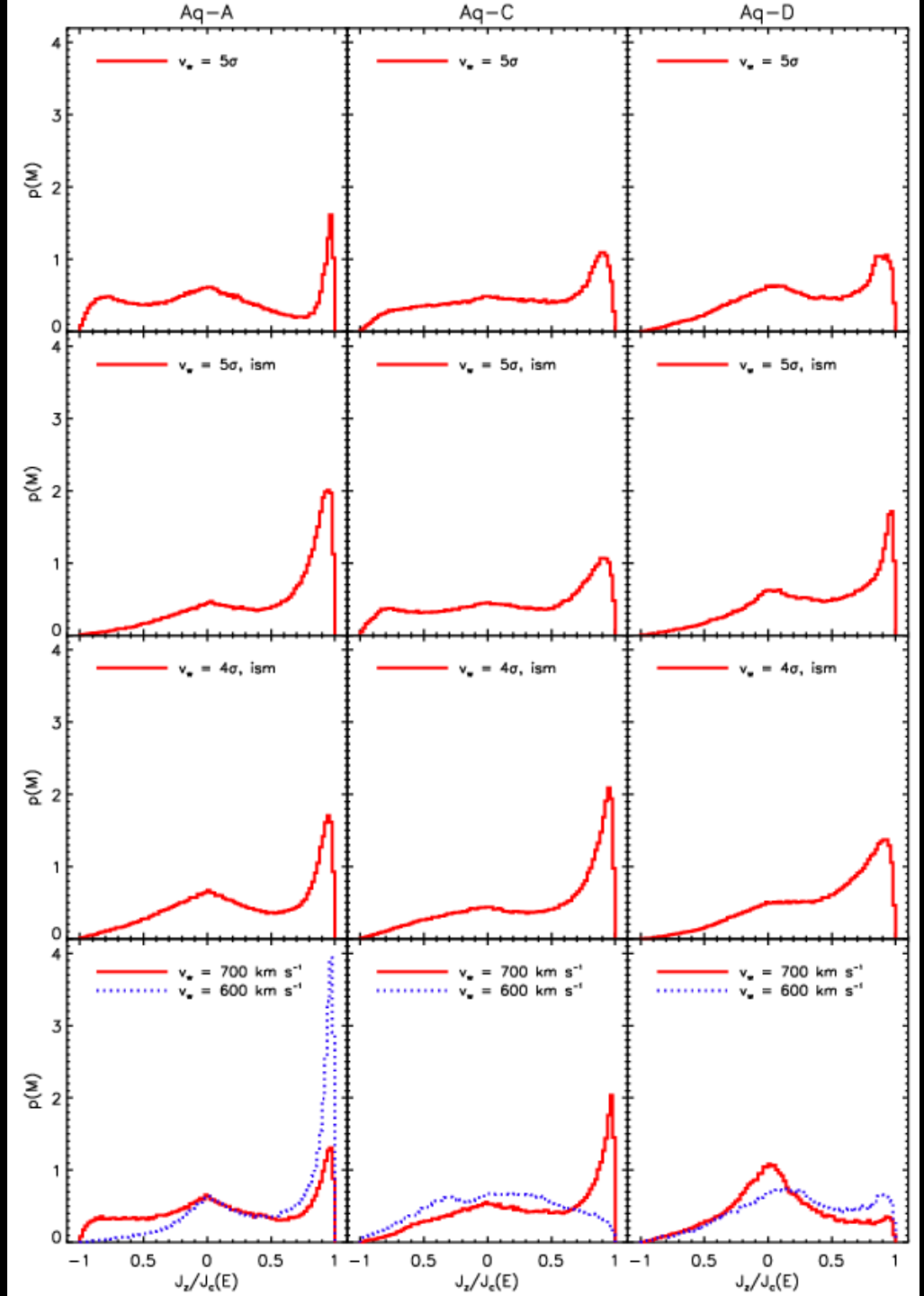
Model	multiphase	v_w	σ_0 or η
5σ	No	5σ	σ_0~217 km/s
5σ, ism	Yes	5σ	σ_0~217 km/s
4σ, ism	Yes	4σ	σ_0~271 km/s
700 km s^{-1}	Yes	700 km s^{-1}	η ~ 2.4
600 km s^{-1}	Yes	600 km s^{-1}	η ~ 3.3

η and σ_0 are computed by considering only contribution from SNeII. There is also contribution from SNeIa in the simulations.



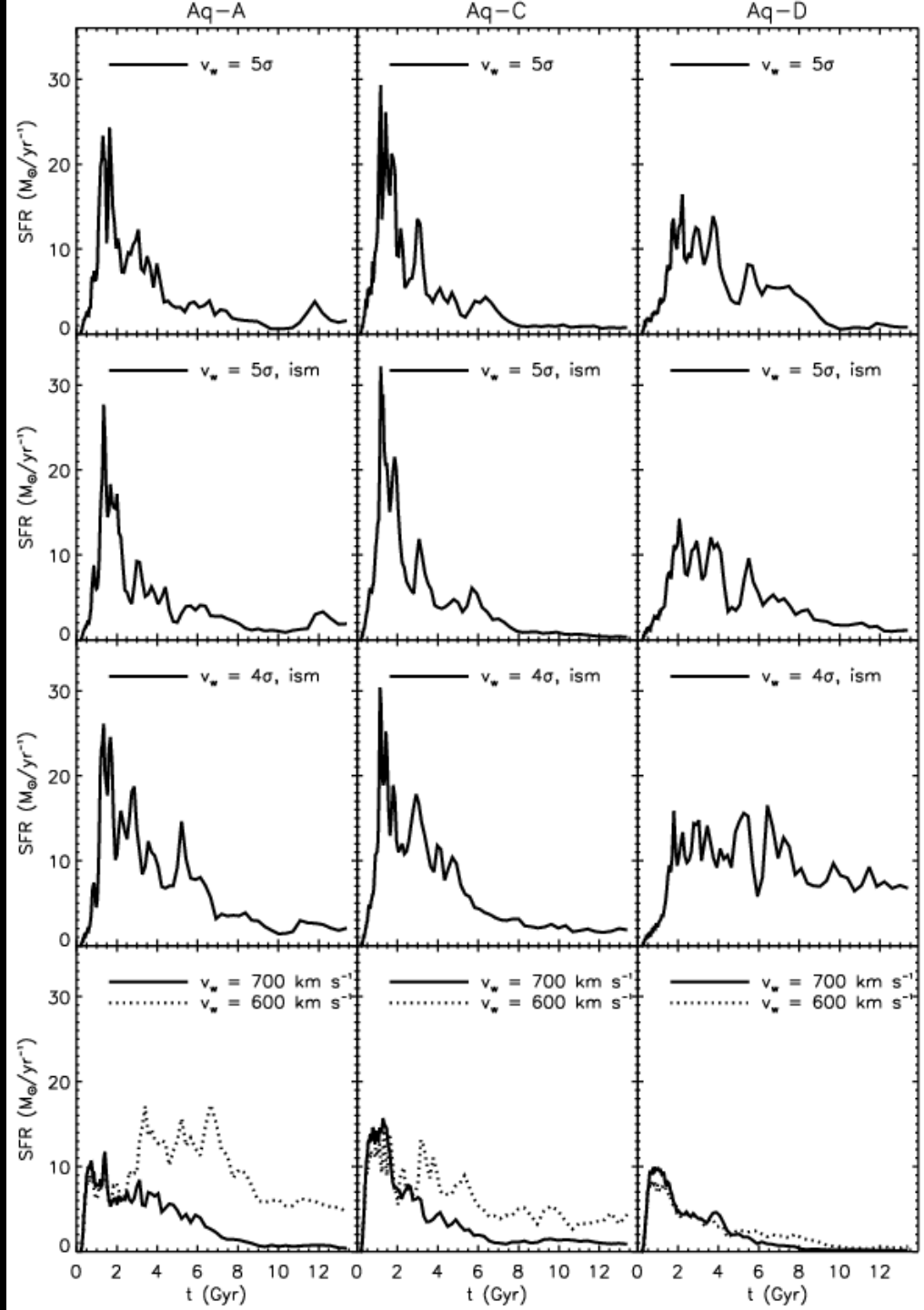
Central galaxies

- Edge-on views of B-band surface brightness
- Z-axis is defined by angular momentum of stars within 0.05 Rvir.



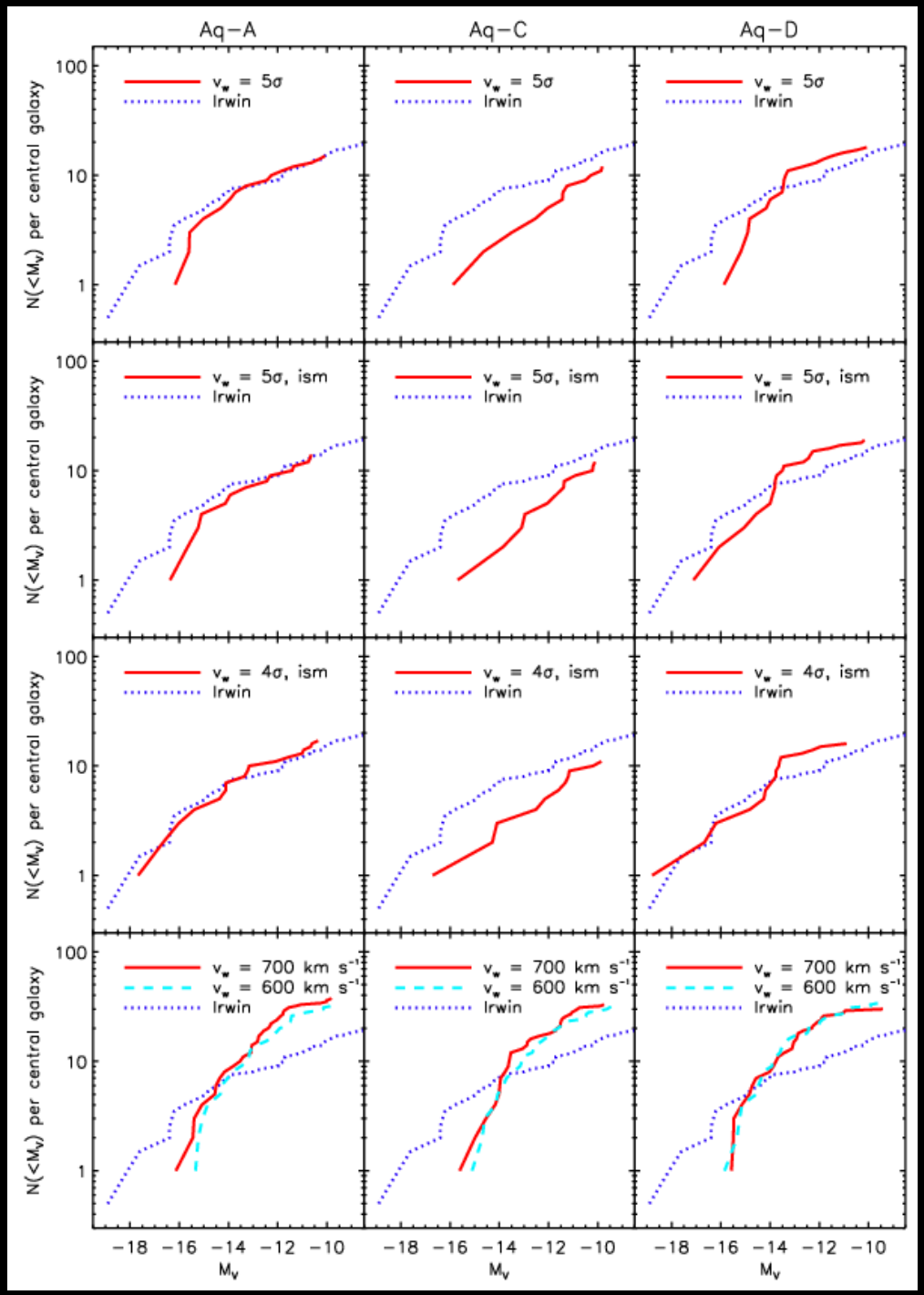
Morphology of the central galaxies

- Orbital circularity ($J_z/J_c(E)$) of stars within R_{vir} on the disk plane (stars belonging to satellites are excluded).
- z-axes are defined by the angular momentum of stars within 0.05 R_{vir}.



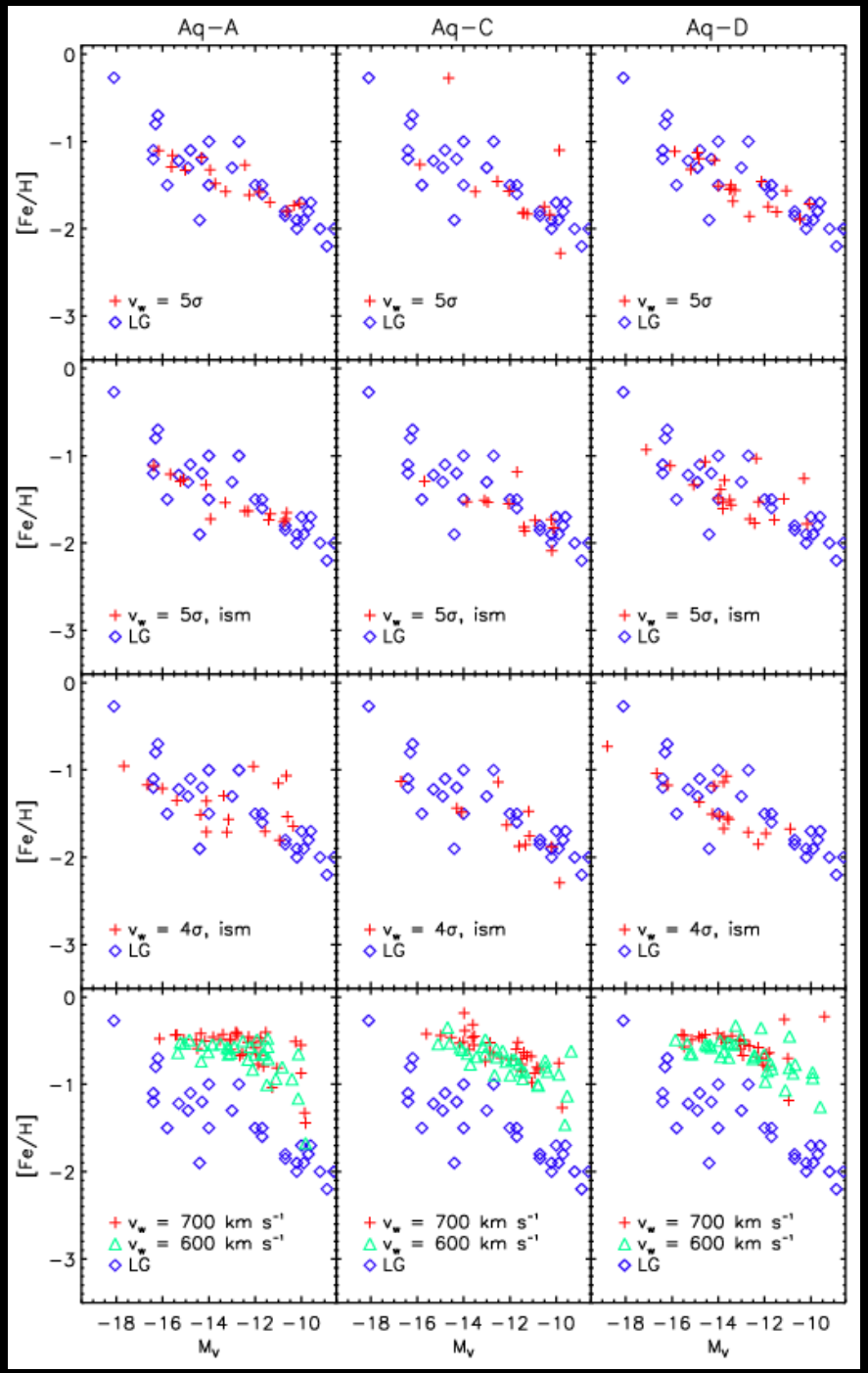
Star formation histories of the central galaxies

- Formation histories of stars within 0.1 R_{vir}. Stars belonging to the satellites are excluded.
- Simulations with and without the multiphase model are very similar.



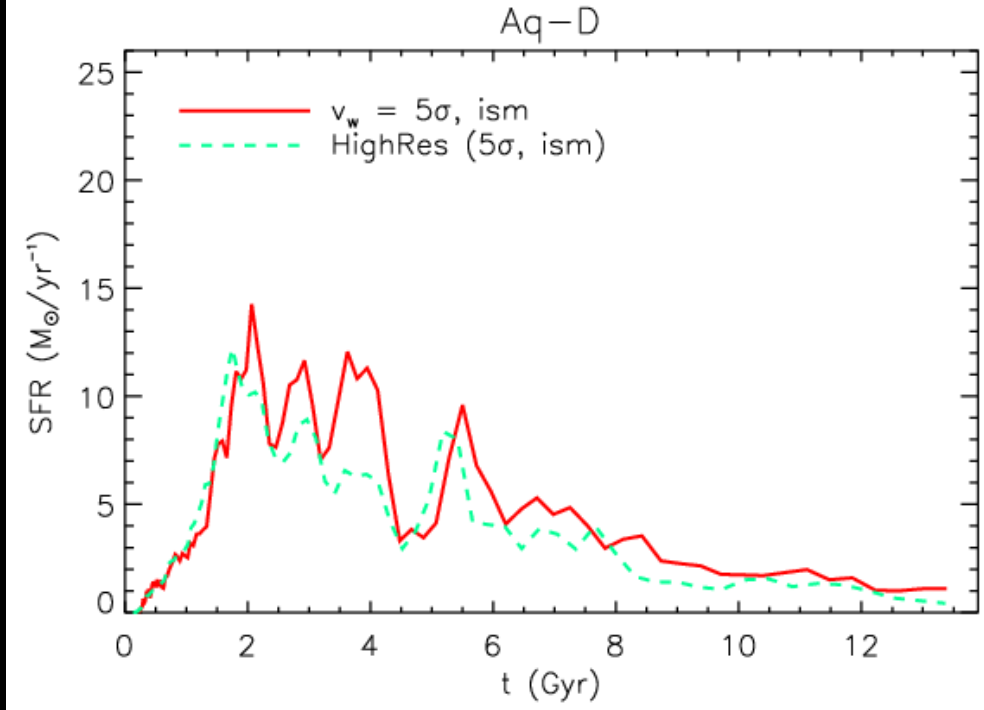
Satellite luminosity functions

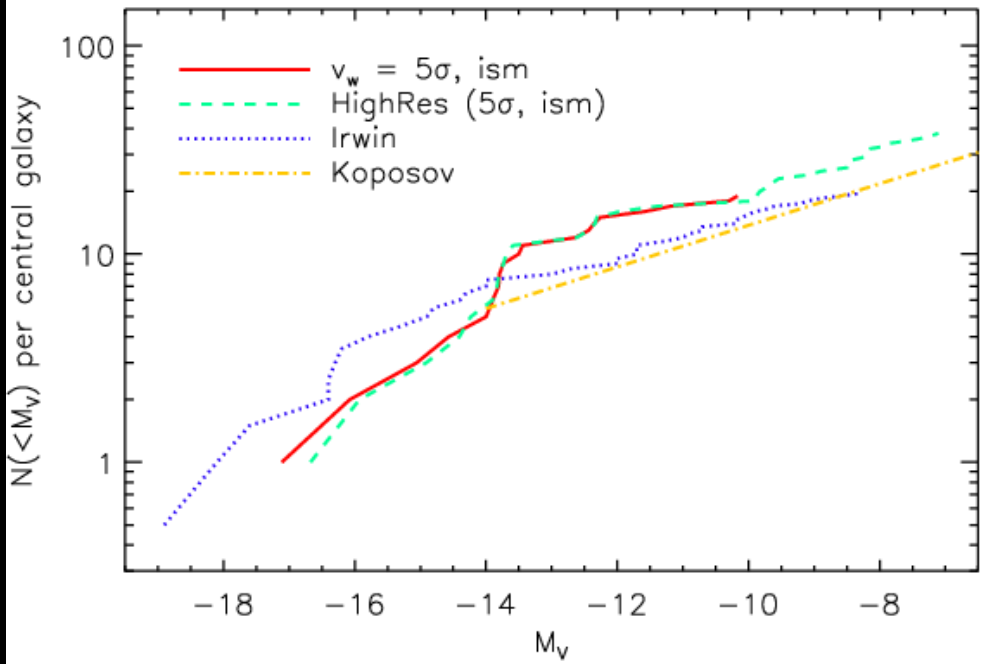
- V-band luminosity functions
- Blue: local group satellites
- Red (and light blue): simulated satellites
- $v_w \propto \sigma$ $(\eta \propto \sigma^{-2})$ is favored
- Larger mass loading is needed for smaller galaxies.



Metallicity-luminosity relations

- [Fe/H] vs. Mv
- Blue: local group satellites
- Red (and green): simulated satellites
- $\sigma_w \propto \sigma(r_{vir})$
- is again favored.





Convergence tests

- Reference:
  $M_{\rm SPH} \sim 4 \times 10^5\ {\rm M}_\odot$
- High-resolution:
  $M_{\rm SPH} \sim 3.5 \times 10^4\ {\rm M}_\odot$
- Upper: SFHs of the central galaxies
- Lower: V-band satellite luminosity functions
  - dotted: Observational data for the bright satellites
  - dot-dashed: Fit to the faint MW satellites by Koposov et al.
- Excellently converged!!

Conclusion

- CDM model can reproduce the observed properties of the MW satellites.
- $v_w \propto \sigma$ $(\eta \propto \sigma^{-2})$ is preferred to the constant wind speed models v_w and η (constant)
  - Physics?
- Most of SN energy should be converted to the kinetic energy of winds.
  - Other energy sources?