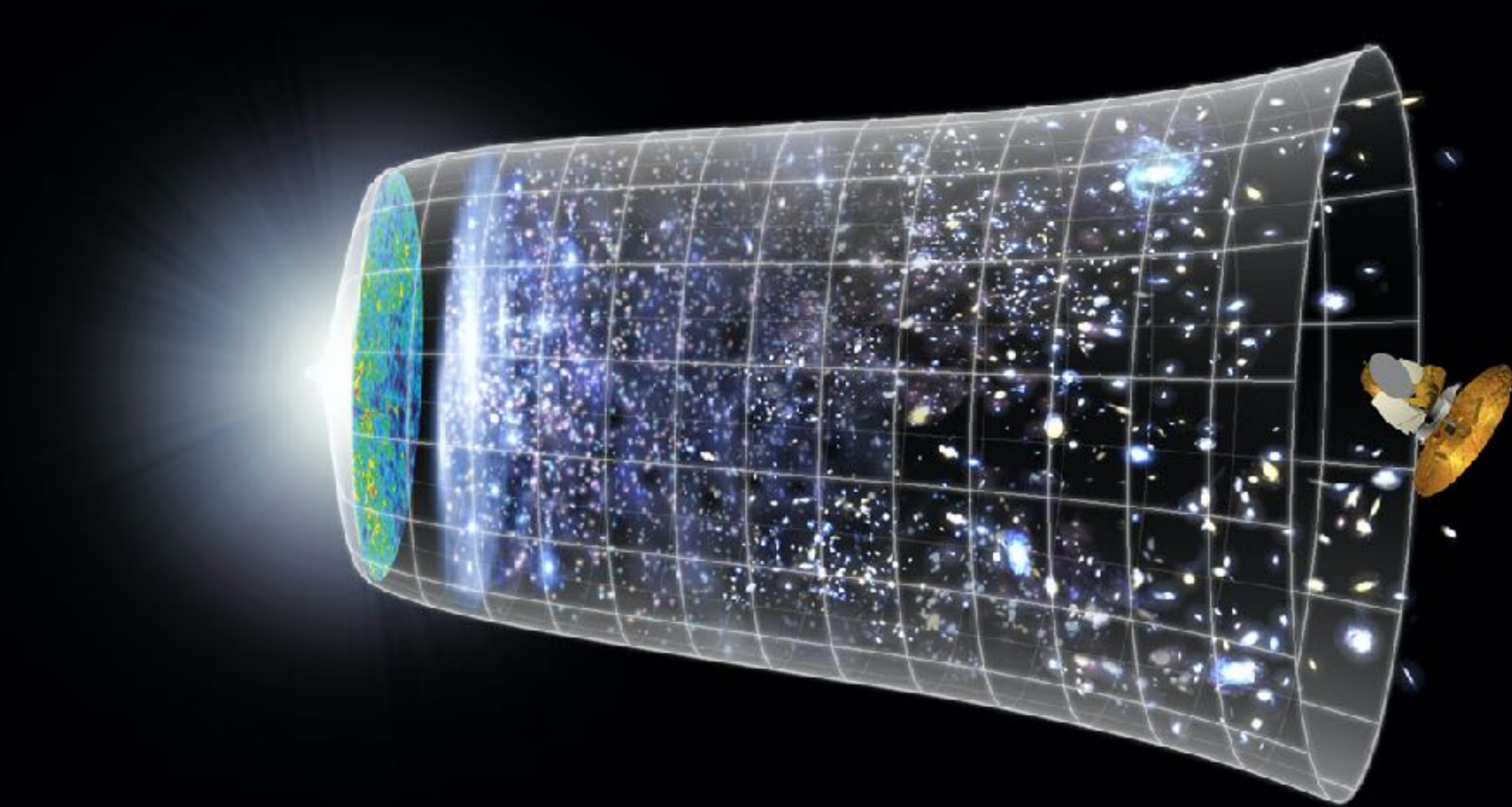
Prospects for Simulations of Galaxy Formation

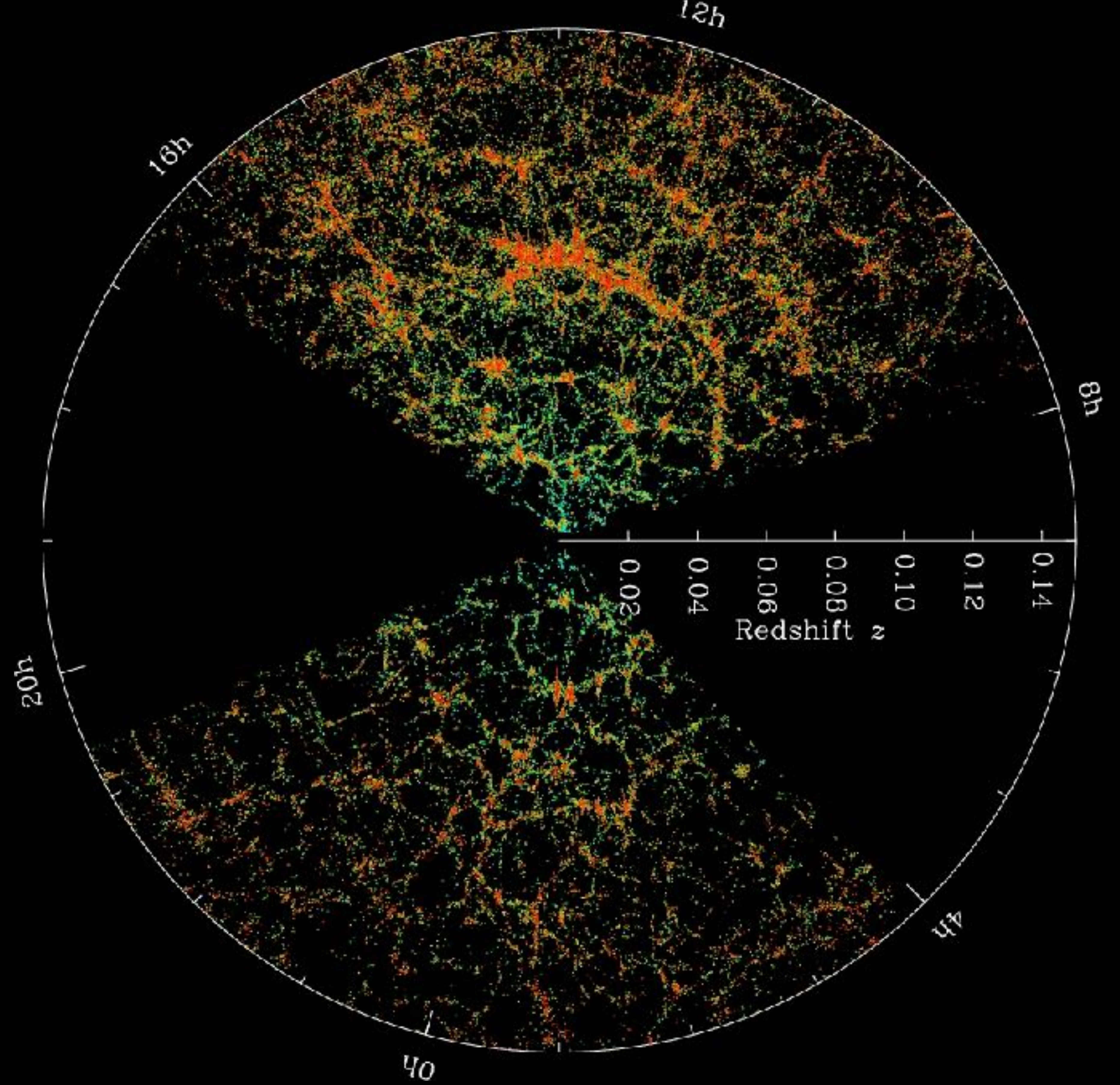
Yutaka Hirai
Special Postdoctoral Researcher (SPDR),
Particle Simulator Research Team,
RIKEN Center for Computational Science

How is the universe with various kinds of astronomical objects formed?

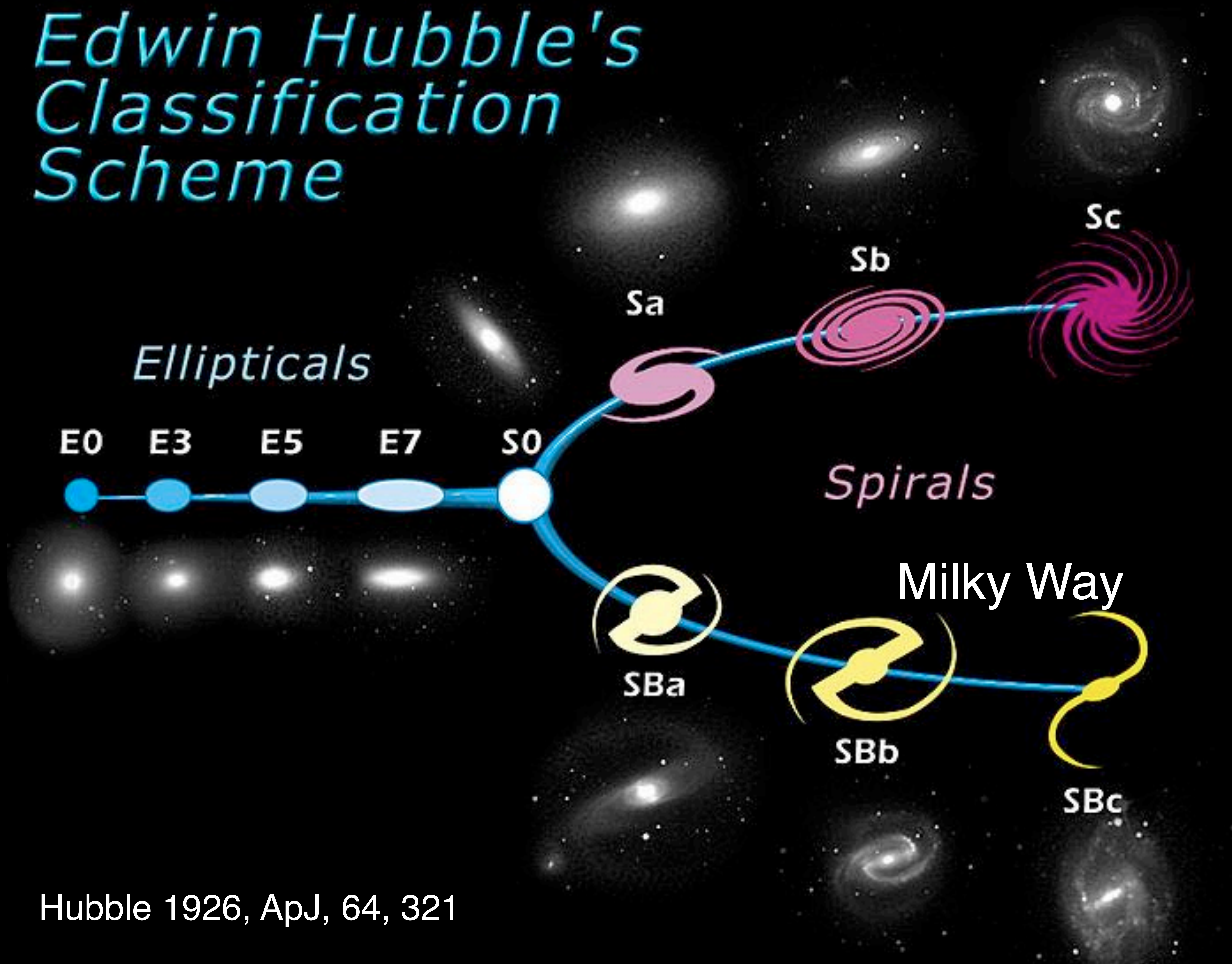


NASA/WMAP Science Team

Galaxies are 'atoms' of the universe.



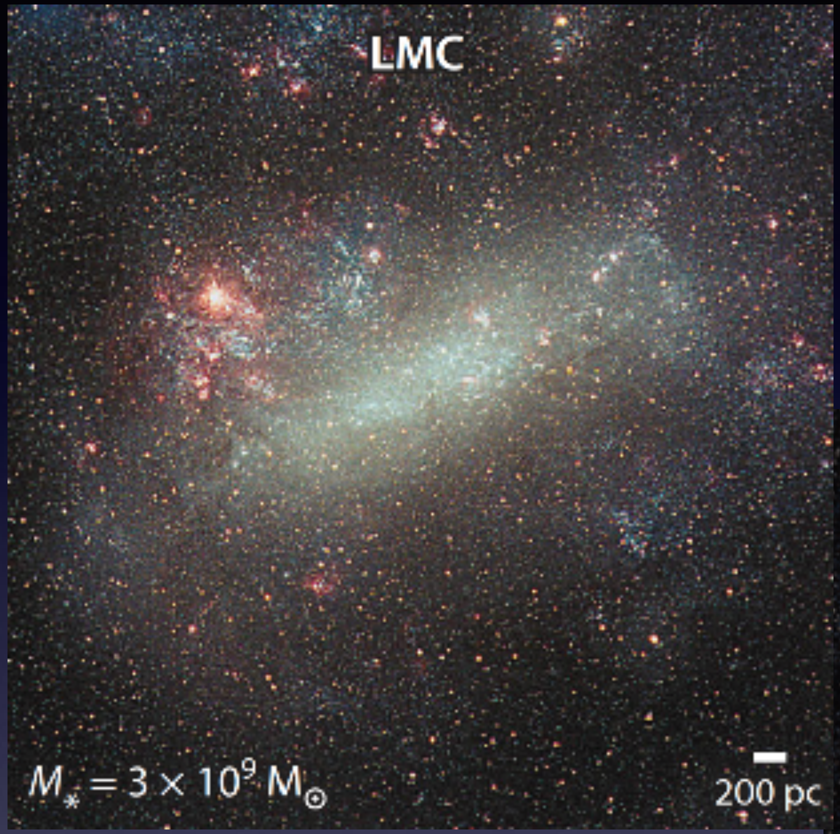
www.sdss.org



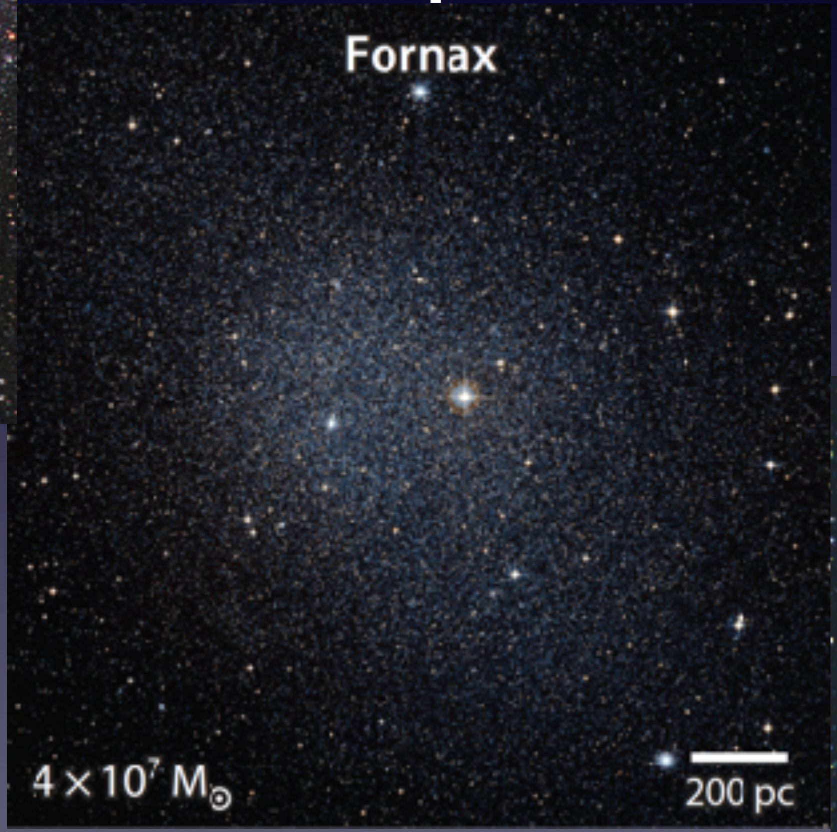
Hubble 1926, ApJ, 64, 321

Dwarf galaxies

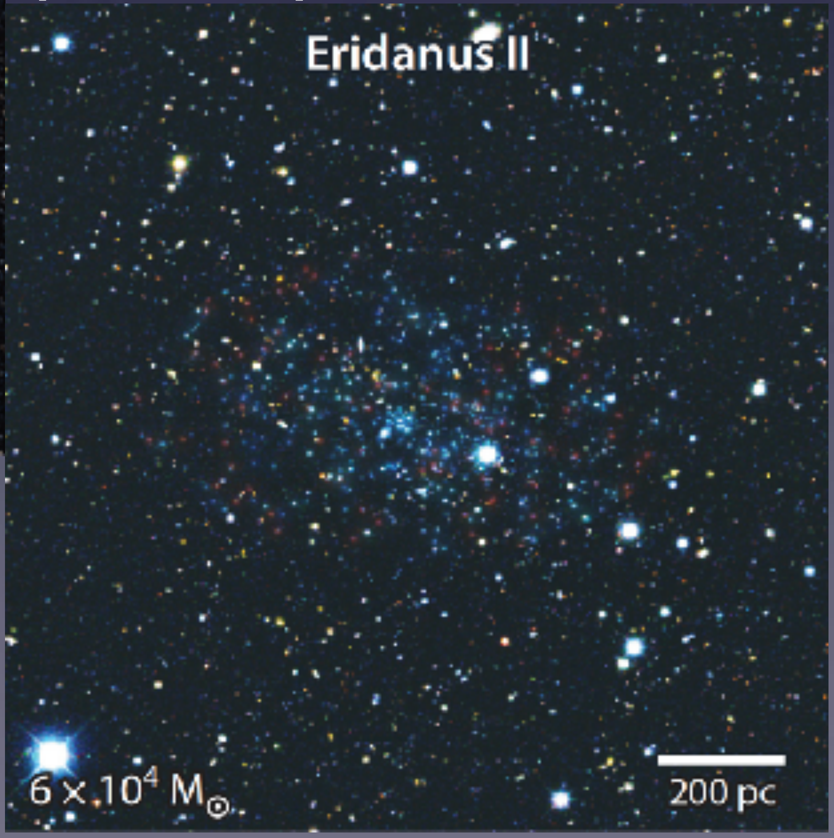
Dwarf irregulars (dIrr)



Dwarf spheroidals (dSph)

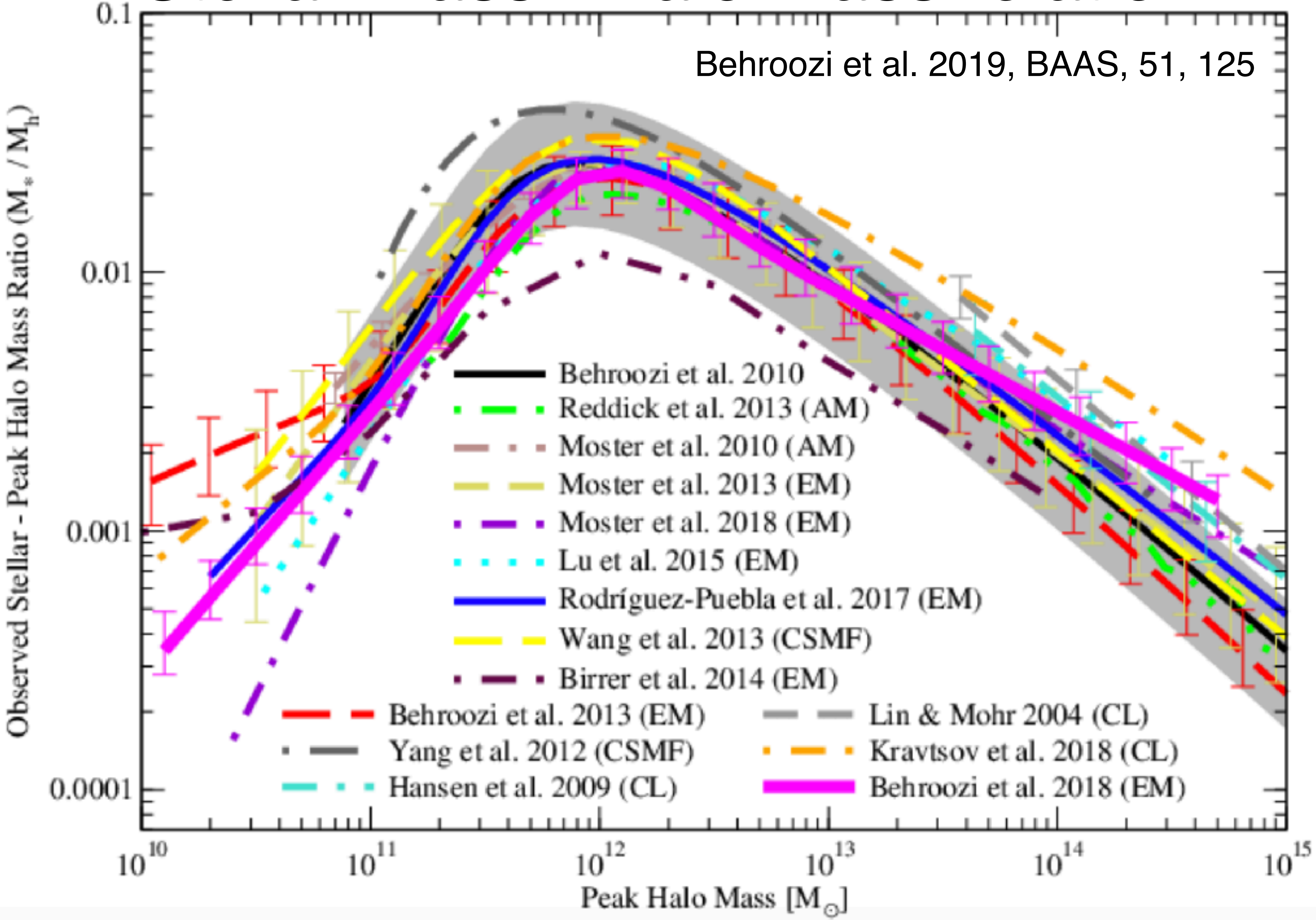


Ultrafaint dwarfs (UFD)



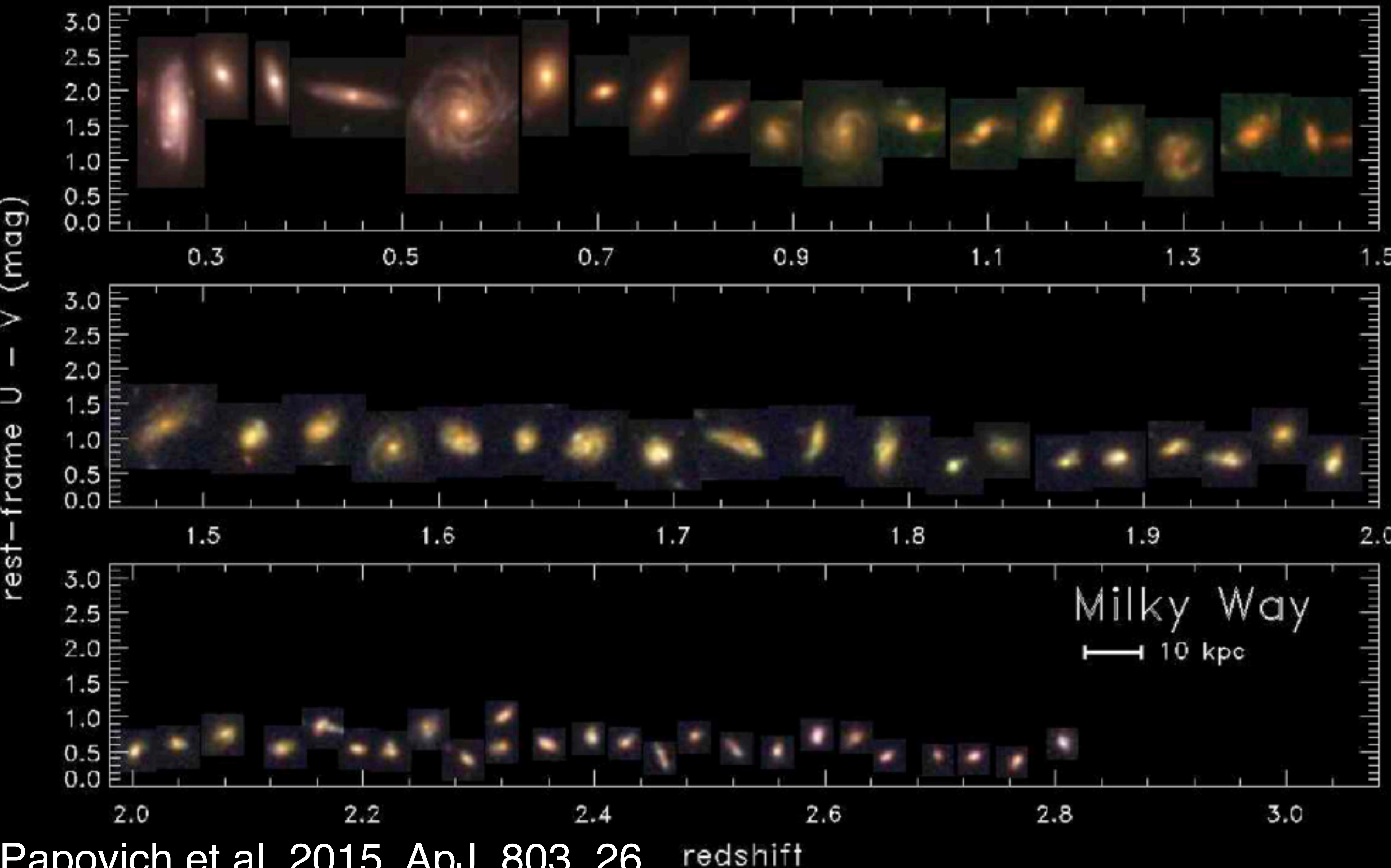
Bullock & Boylan-Kolchin 2017, ARA&A, 55, 343

Stellar mass—halo mass relation



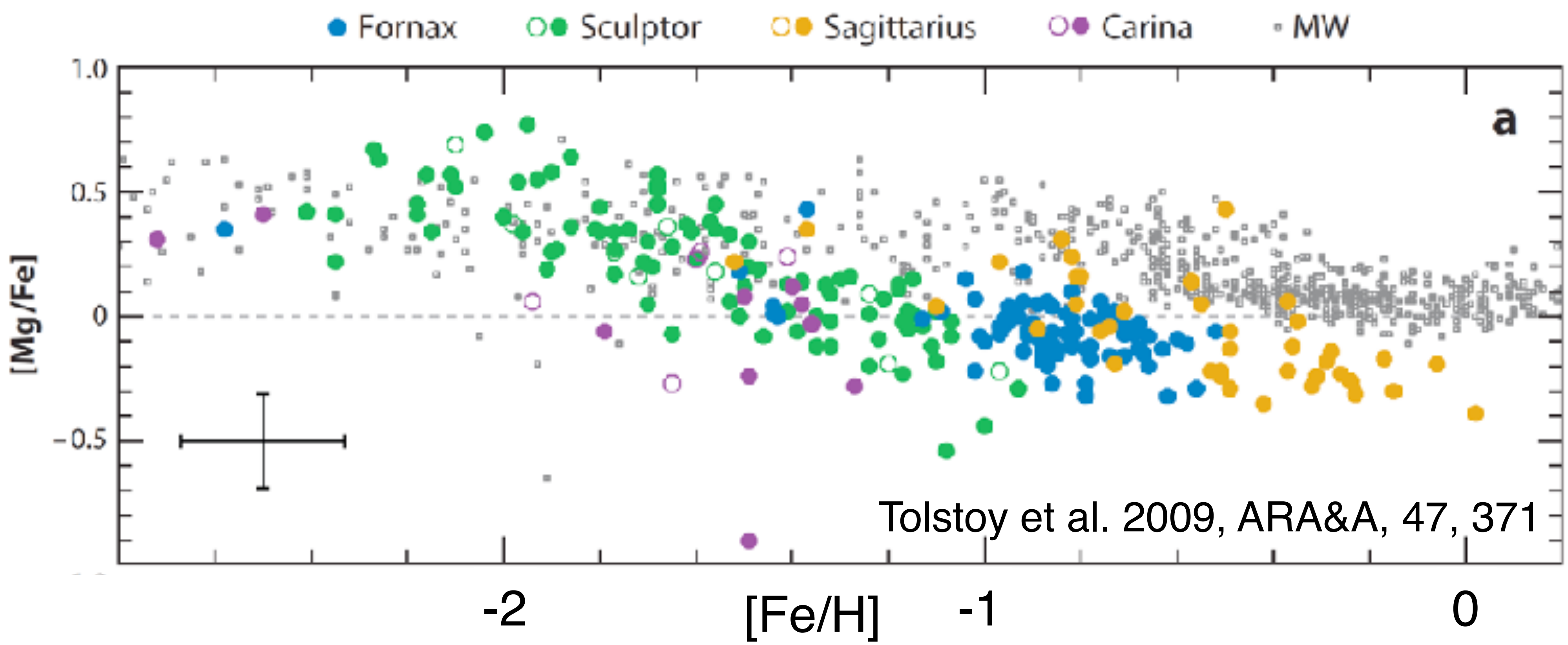
Approaches to studying galaxy formation

Observing the "past"

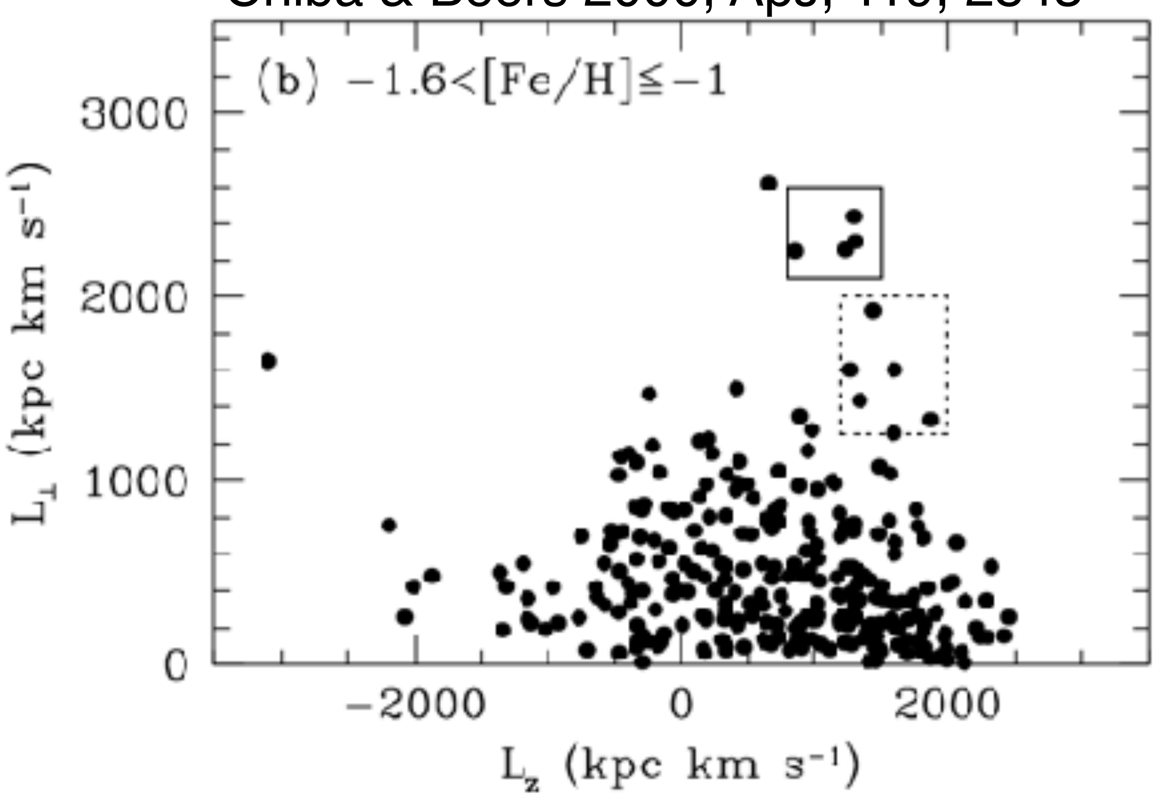


Papovich et al. 2015, ApJ, 803, 26

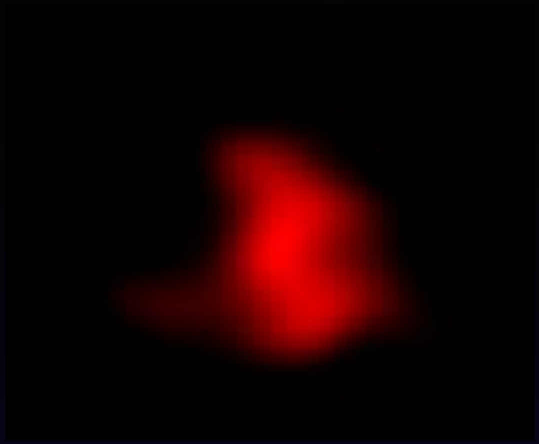
Observing the "present"



Chiba & Beers 2000, ApJ, 119, 2843



Credit: Harvard Gazette



How is the universe with various kinds of astronomical objects formed?

Simulation is a powerful tool to study galaxy formation.

How is the universe with various kinds of astronomical objects formed?

What physics derives the galaxy formation?

How does the chemo-dynamical structure of galaxies relate to their history?

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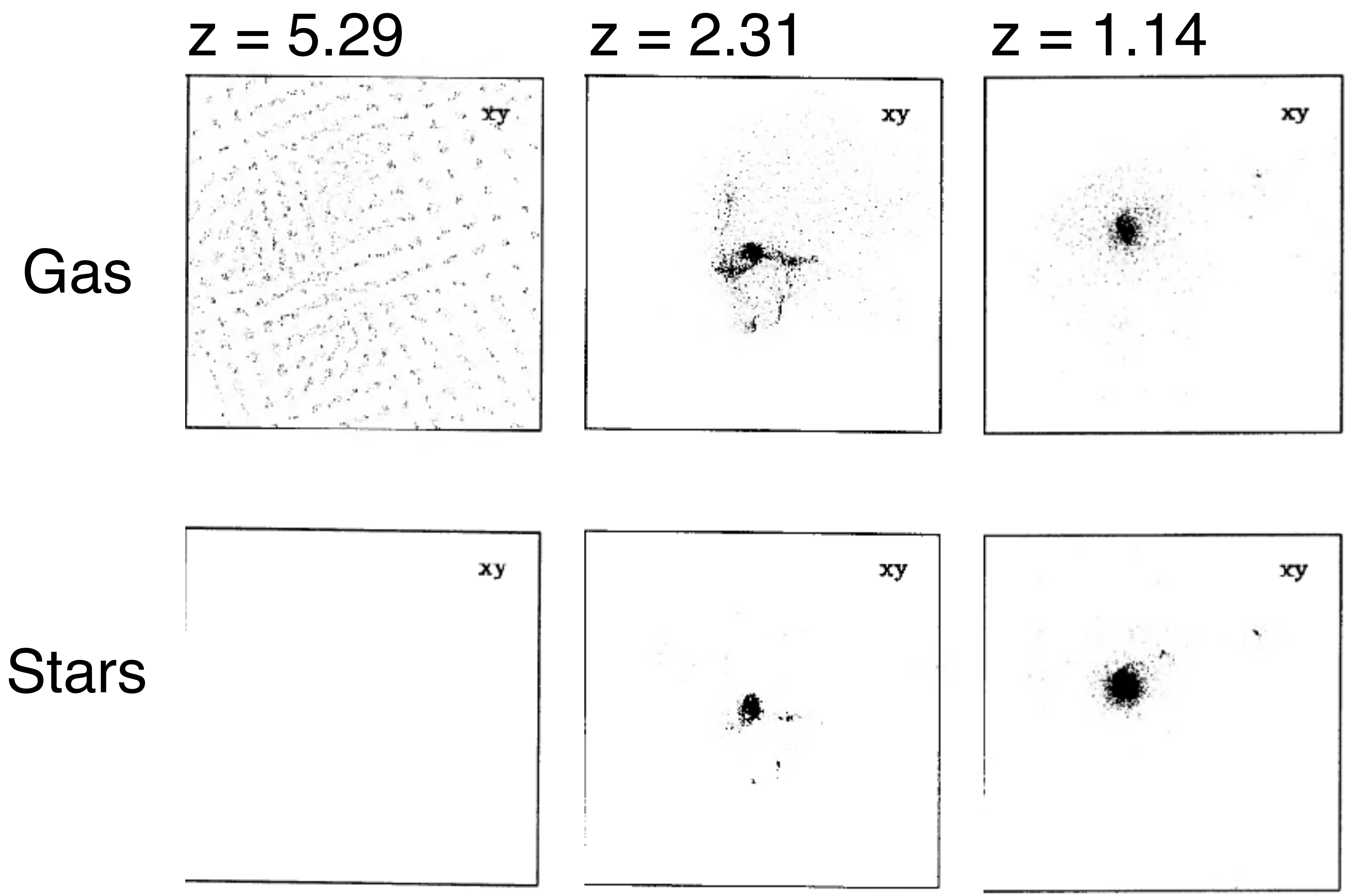
What physics derives the galaxy formation?

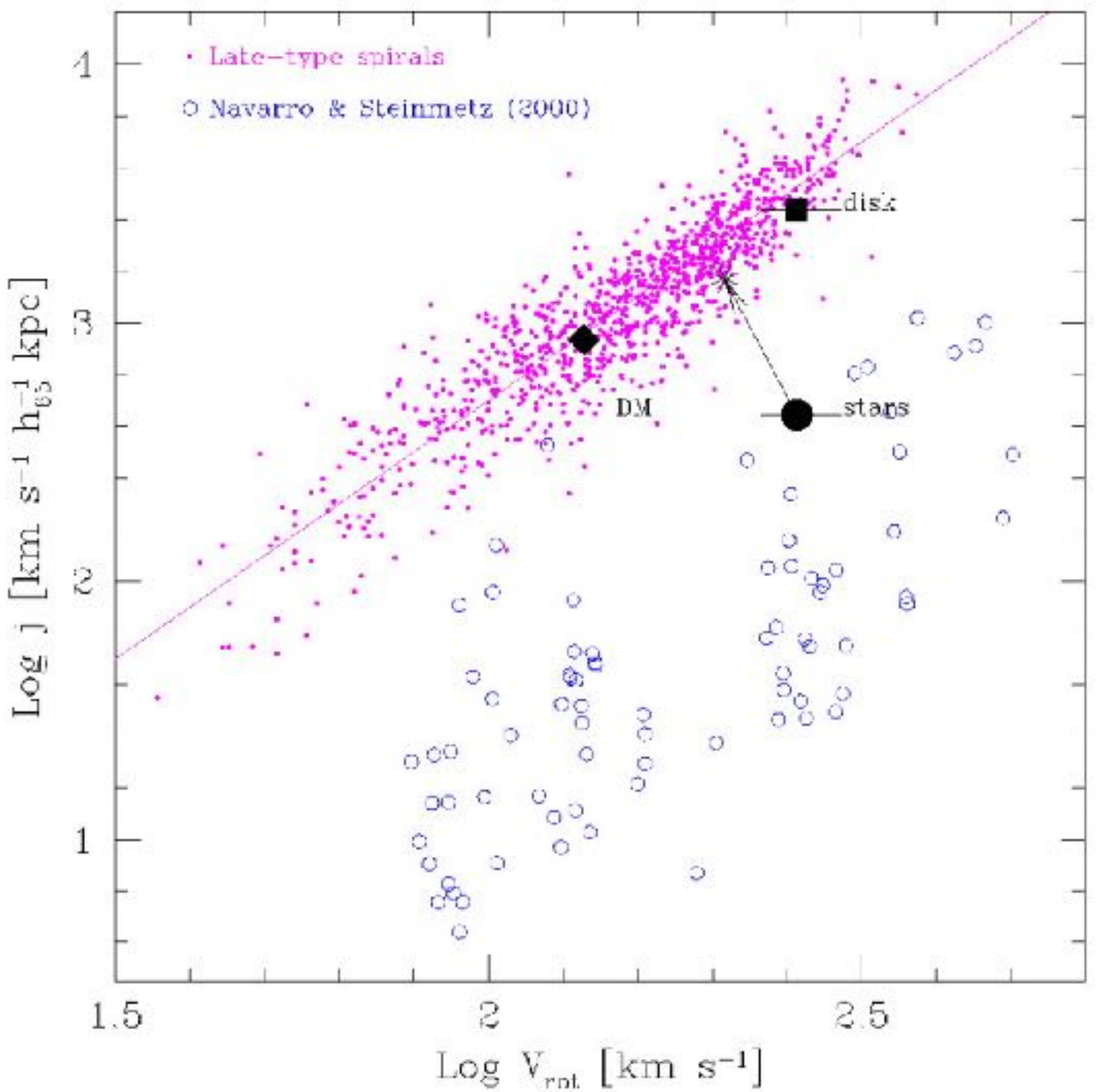
How does the chemo-dynamical structure of galaxies relate to their history?

Simulations galaxy formation on the 1990s



Katz 1992, ApJ, 391, 502 (see also, Steinmetz & Müller, 1994, A&A, 281, L97)

Angular momentum problem



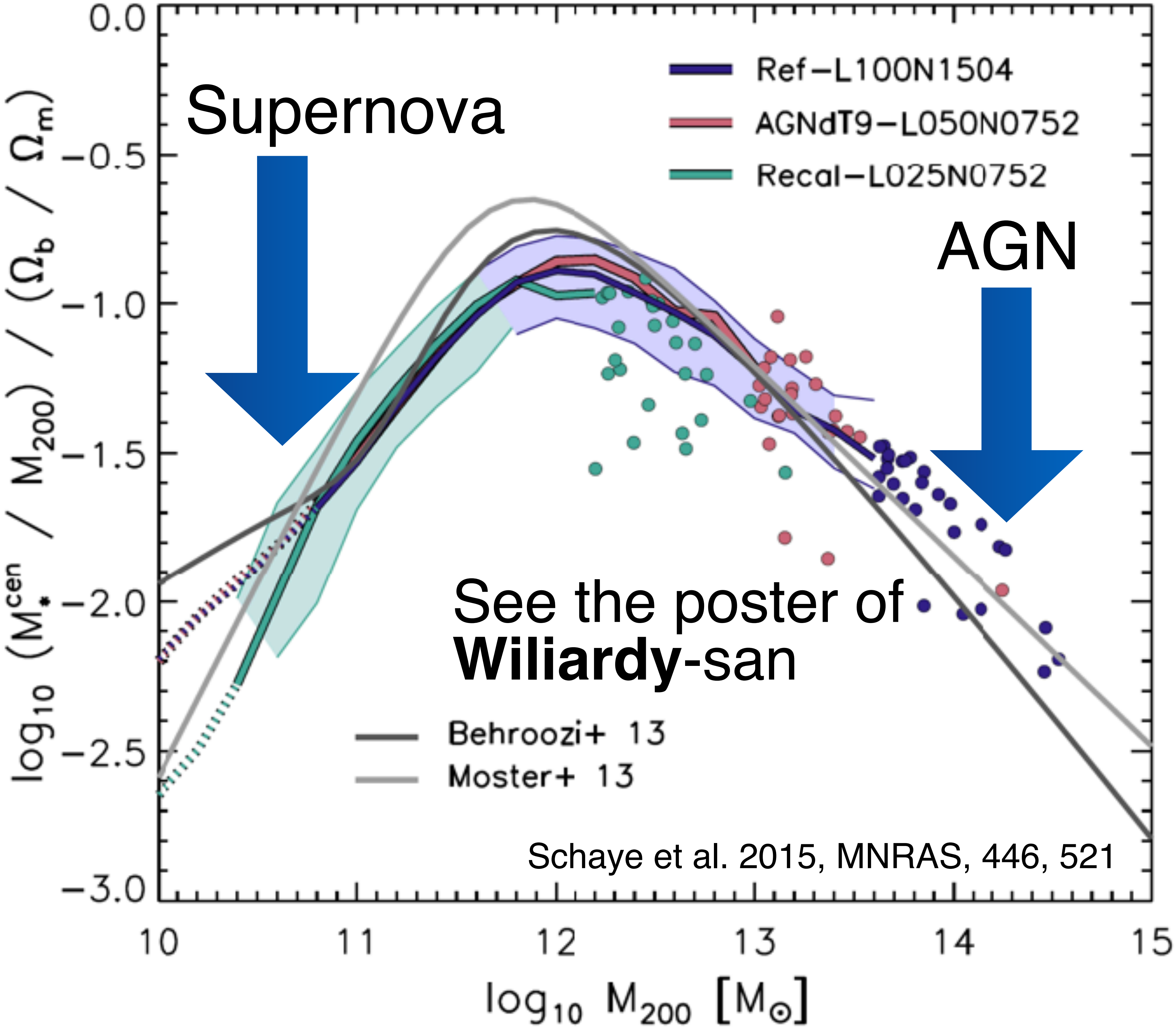
Abadi & Navarro 2003, ApJ, 591, 499

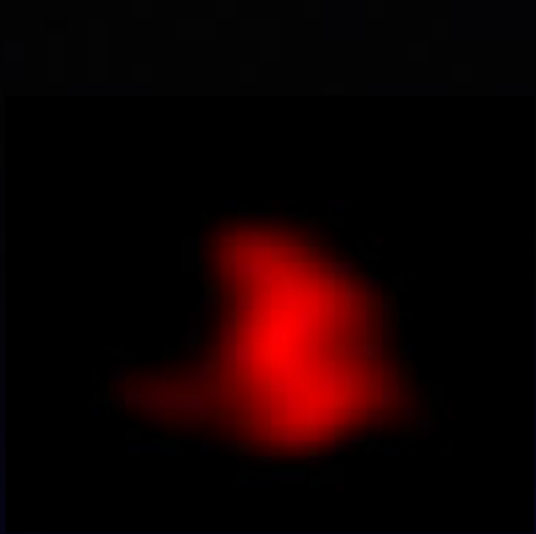
Inefficient supernova feedback

Transfer of angular momentum from baryons to dark matter

Galaxies with too massive bulges

Feedback regulates the stellar mass—halo mass ratio.



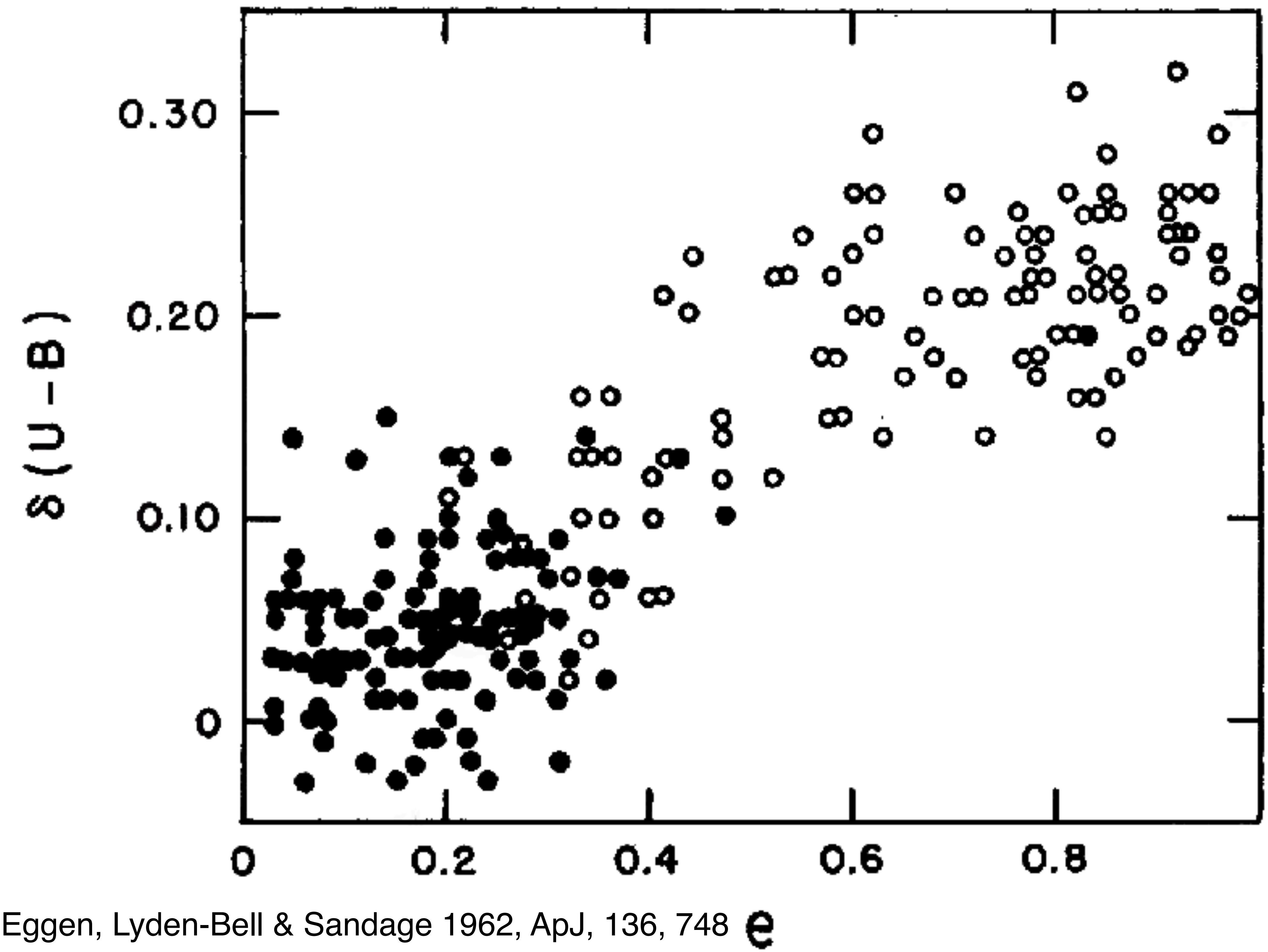


How is the universe with various kinds of astronomical objects formed?

What physics derives the galaxy formation?

How does the chemo-dynamical structure of galaxies relate to their history?

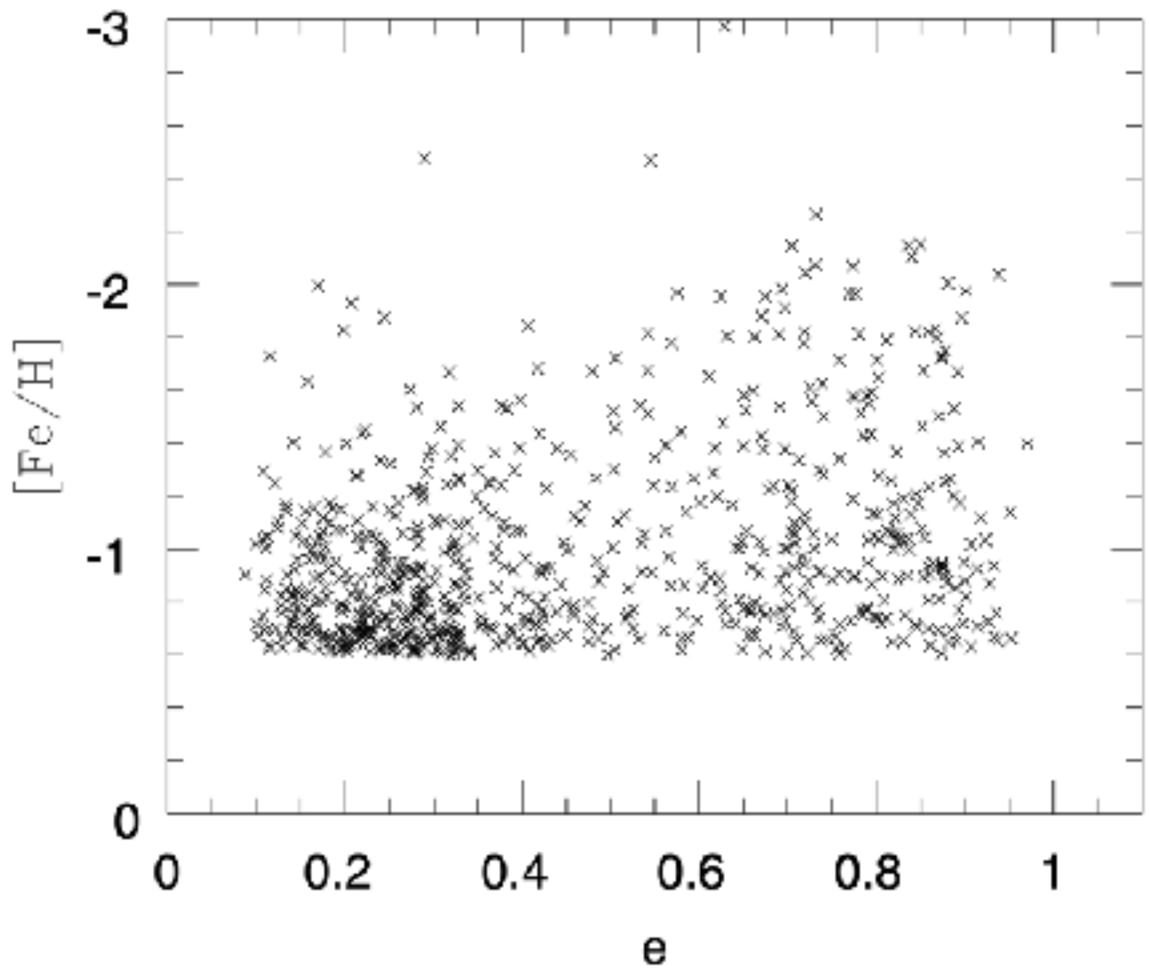
Correlation with color (metallicity) and eccentricity?



Eggen, Lyden-Bell & Sandage 1962, ApJ, 136, 748

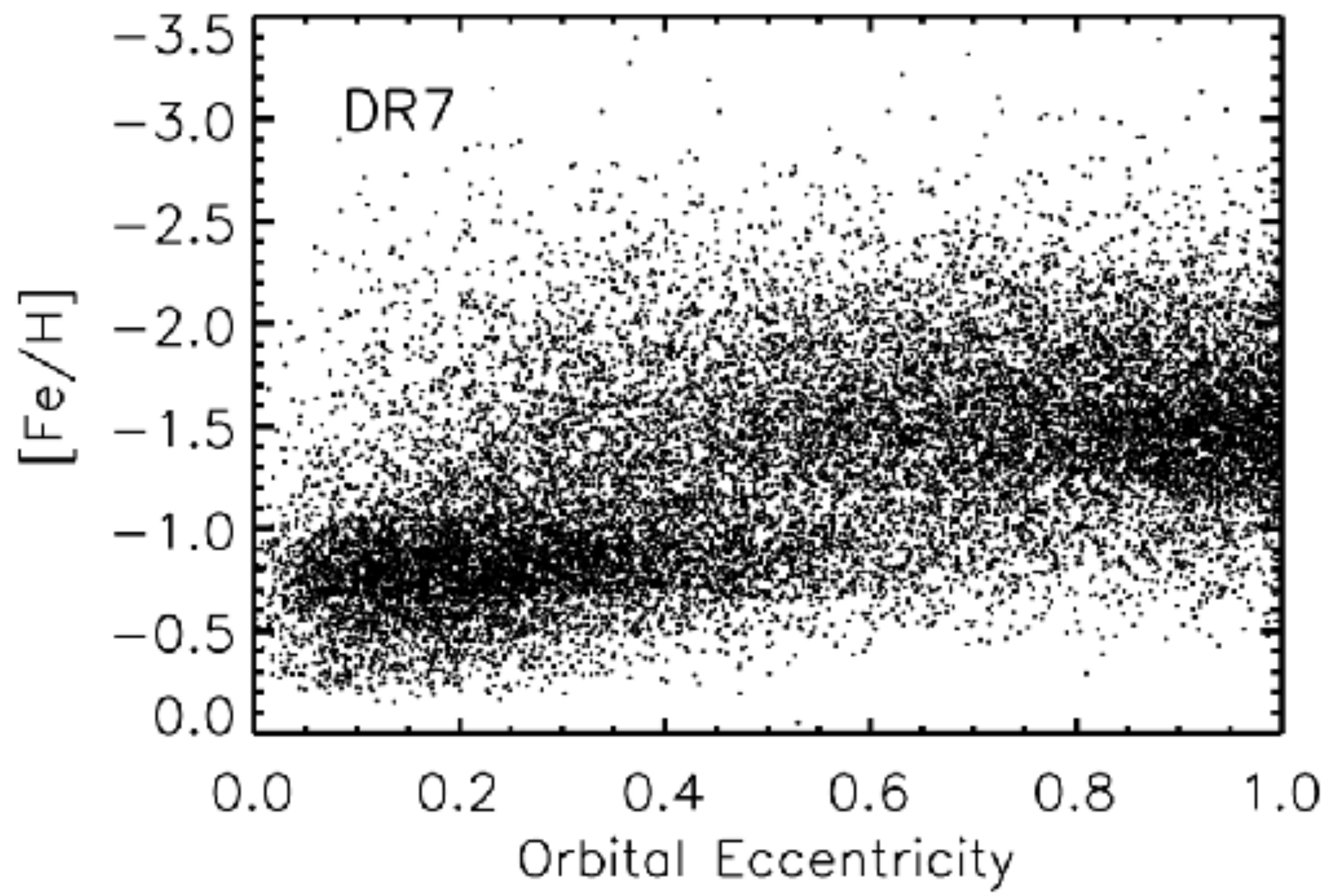
No correlation

Simulation



Bekki & Chiba 2001, ApJ, 391, 502

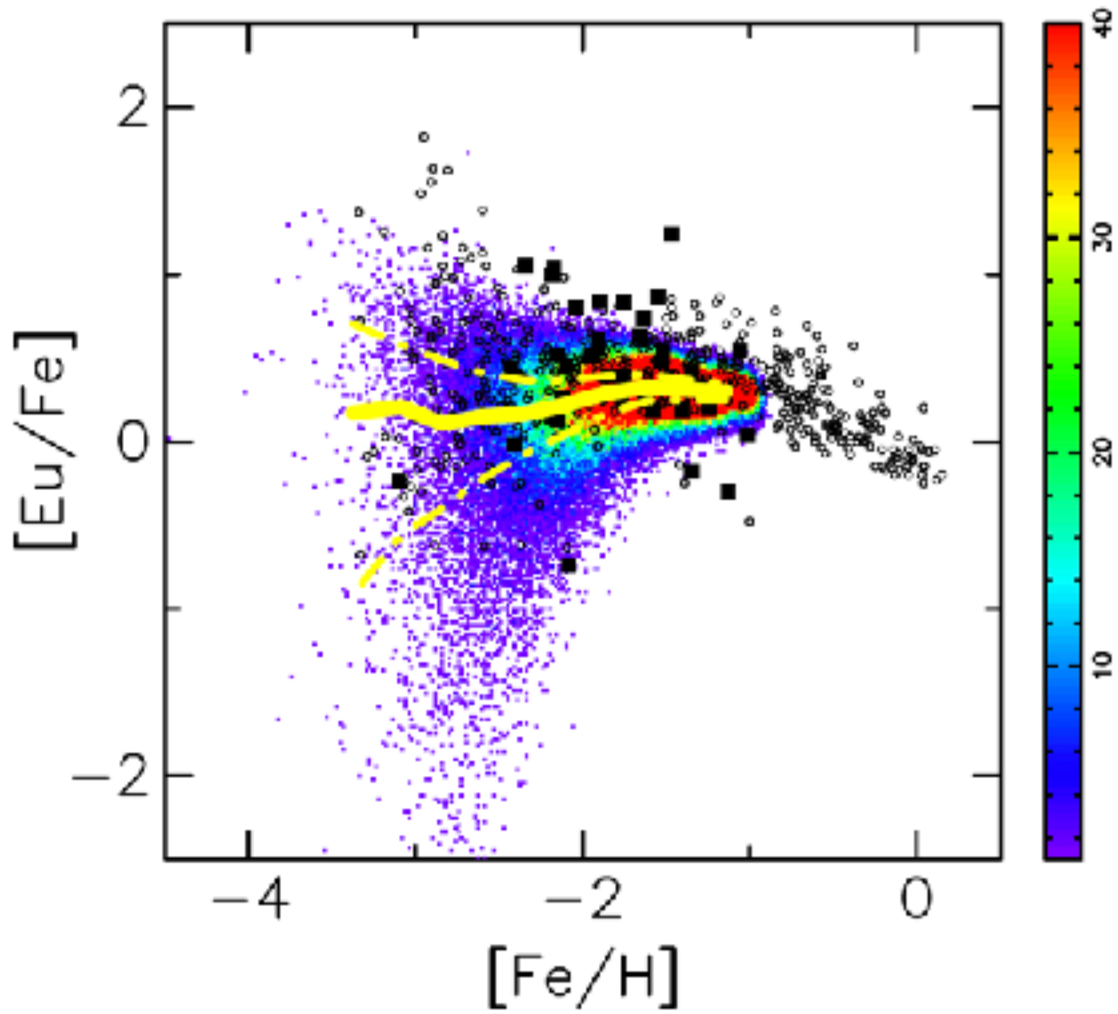
Observation



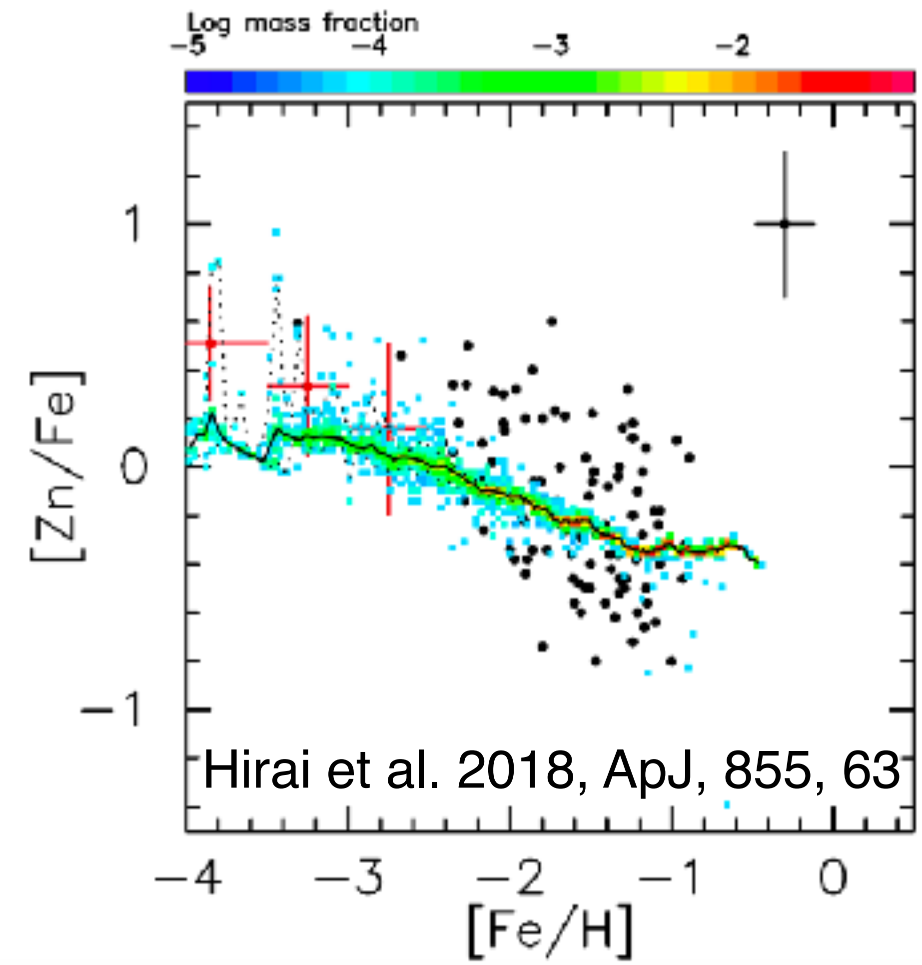
Carollo et al. 2010, ApJ, 712, 692

Consistent with hierarchical structure formation scenario

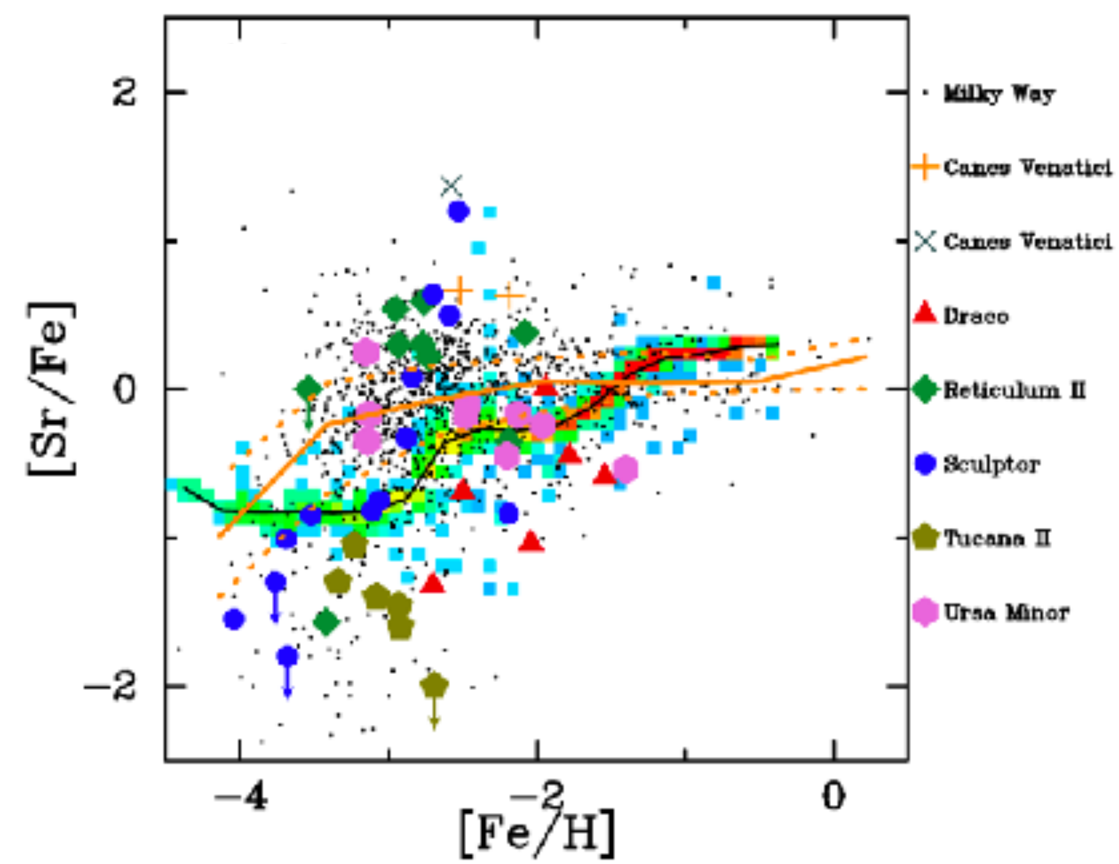
Identifying the origin of elements



Hirai et al. 2015, ApJ, 814, 41



Hirai et al. 2018, ApJ, 855, 63

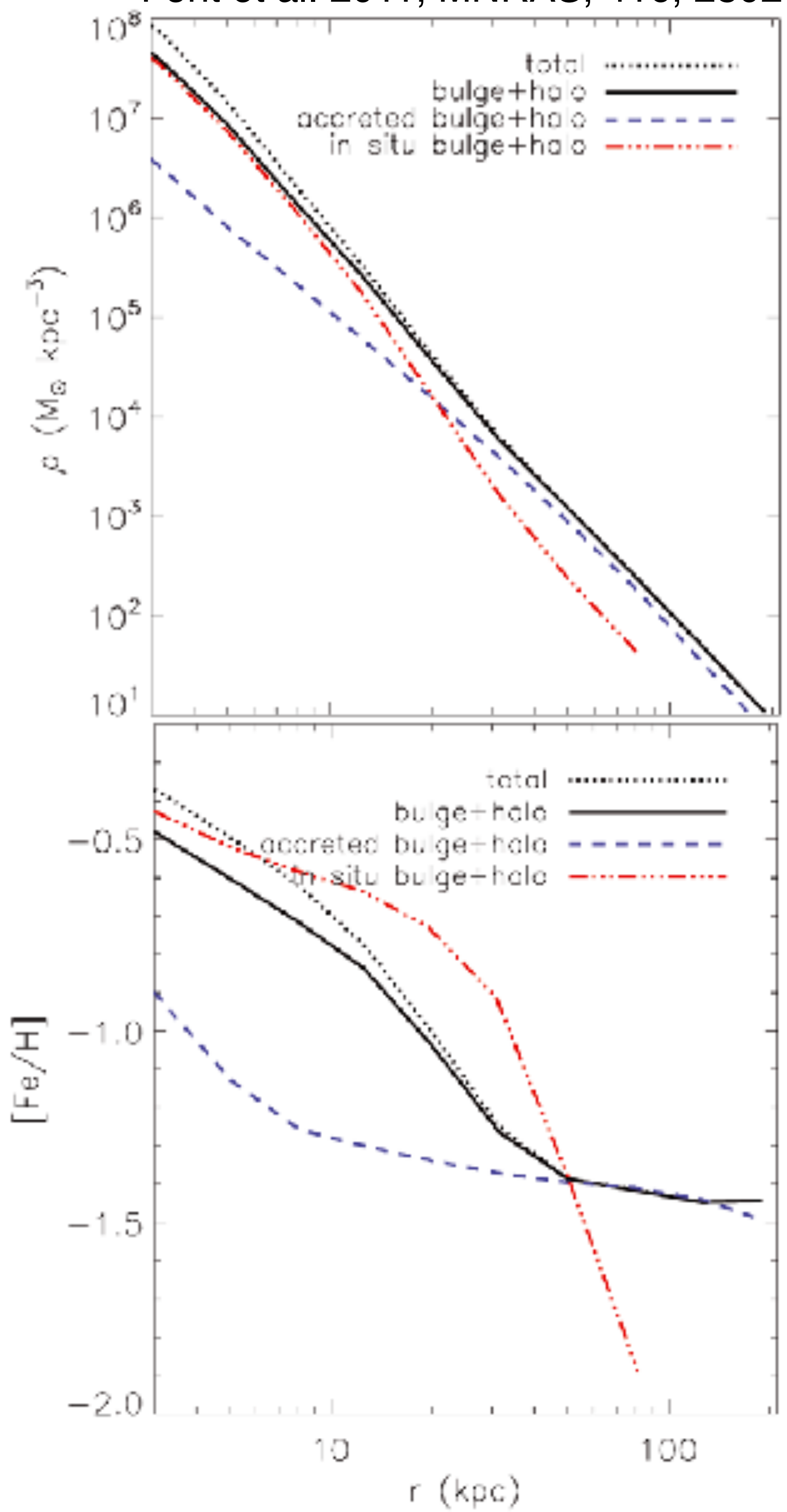


Hirai et al. 2019, ApJ, 885, 33

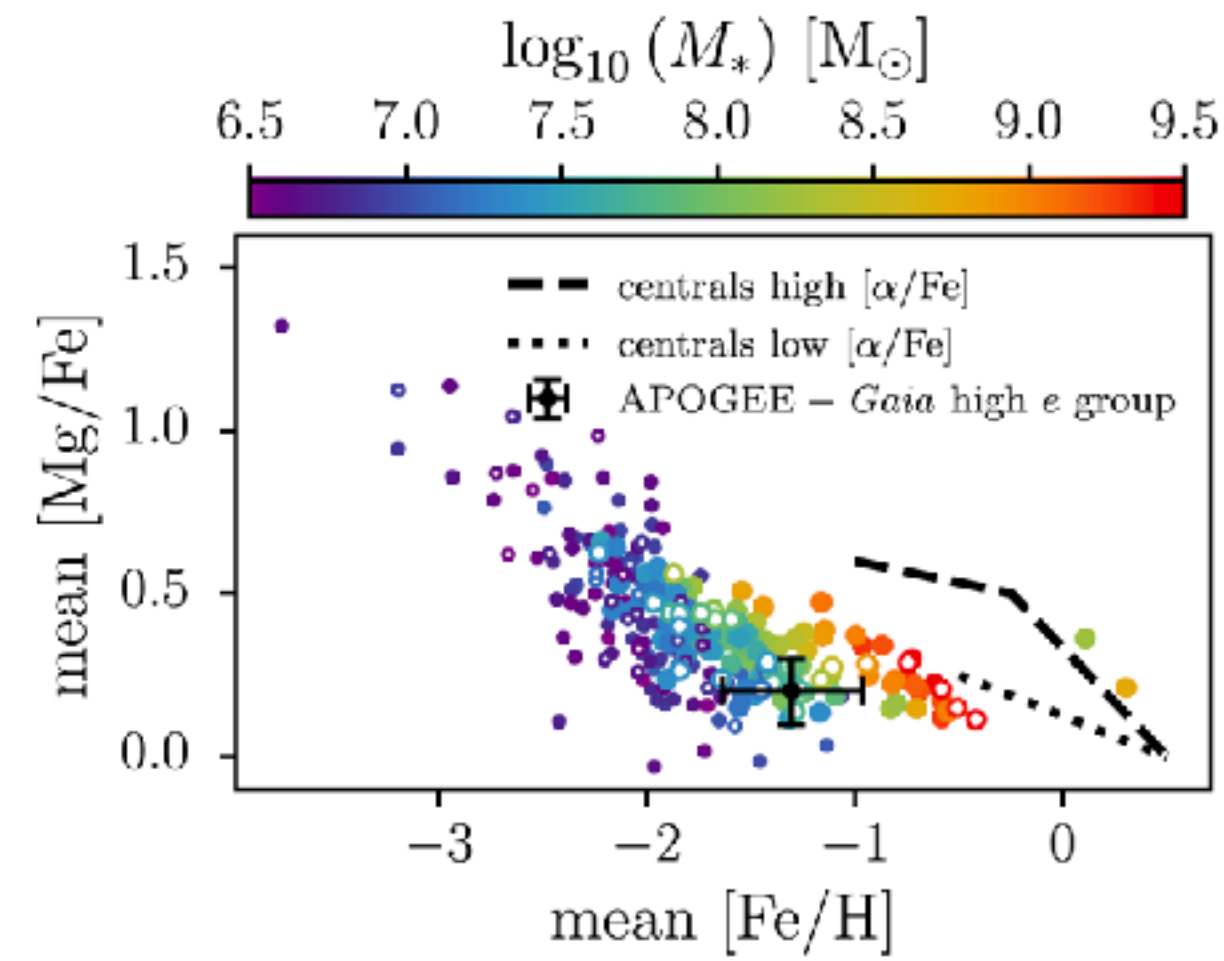
See posters of
Kirihara-san and **Fukushima**-san

Chemo-dynamical features of the accreted satellites

Font et al. 2011, MNRAS, 416, 2802



Accreted components have an extended profile with low metallicity.



The mass of the accreted satellite found in Gaia is $10^{8.5} \lesssim M_* \lesssim 10^9\ M_{\rm sun}$.

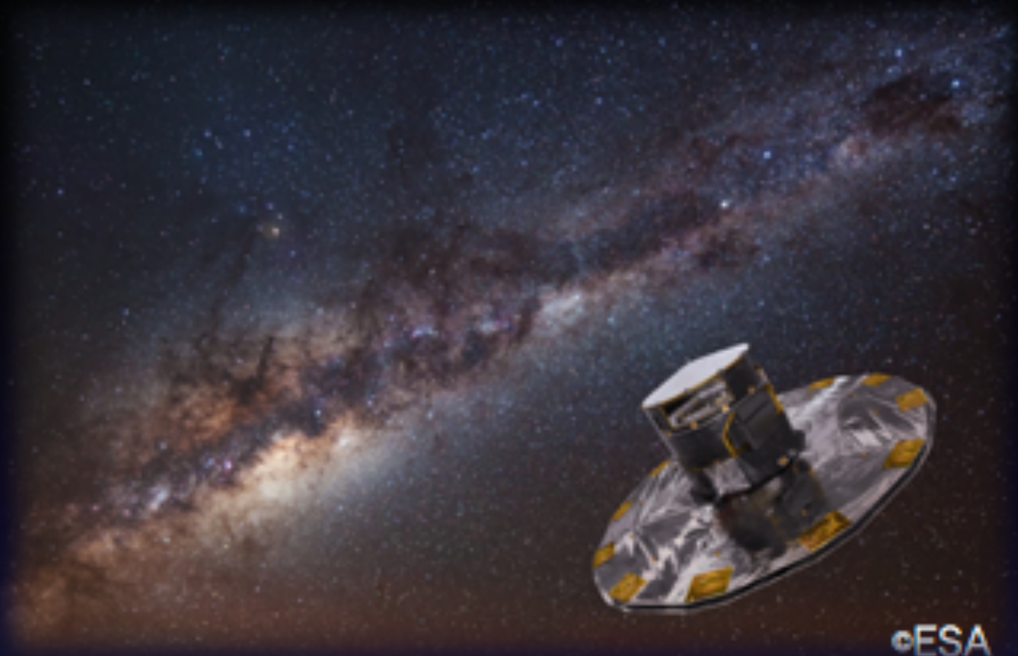
Mackererth et al. 2019, MNRAS, 482, 2802

See the poster of **Hozumi**-san

Prospects

Simulations

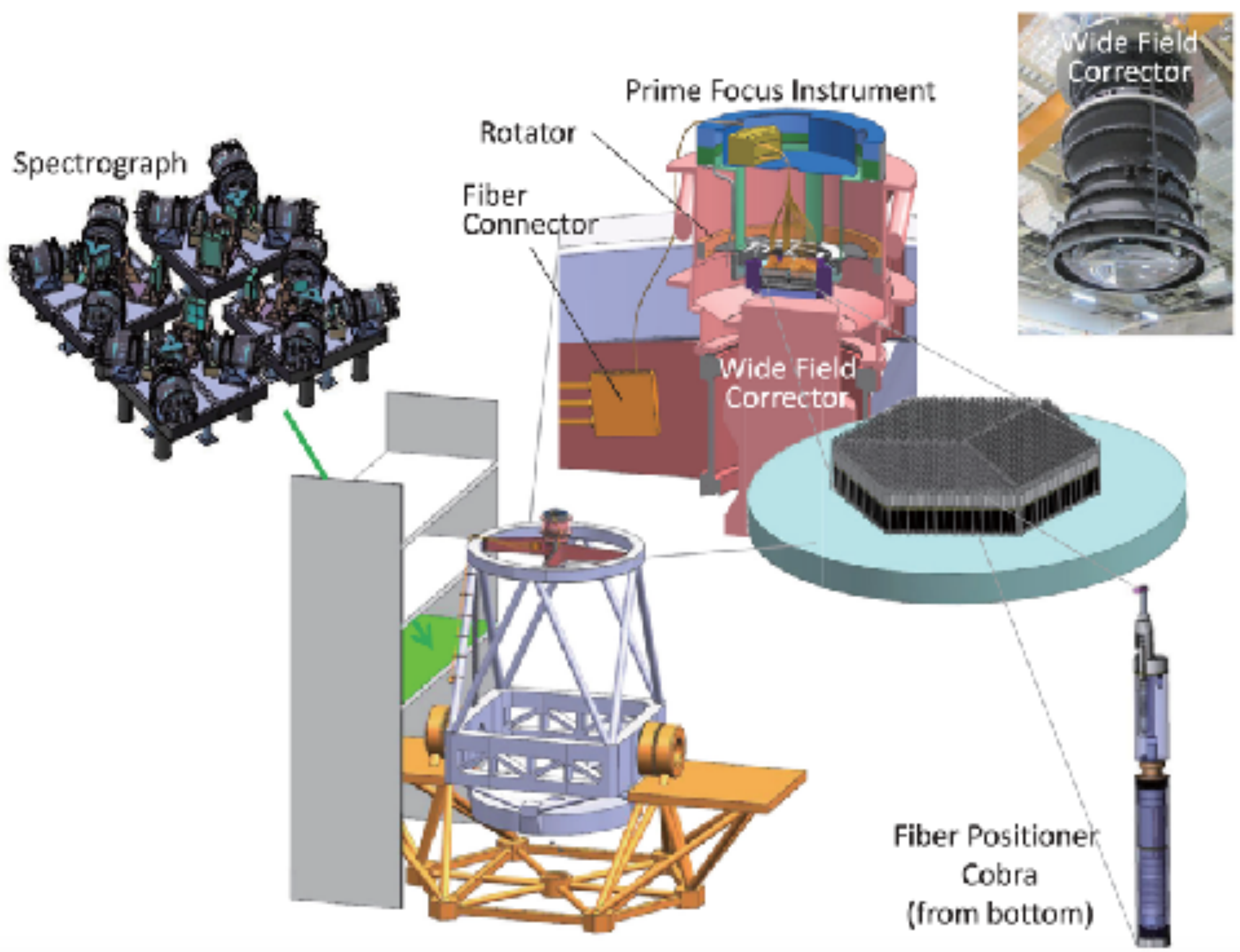
Kinematics of stars



Chemical abundances

Subaru Prime Focus Spectrograph (PFS)

Takada et al. 2015, PASJ, 454, 83



Field of View: 1.38 deg
Number of fibers: 2394

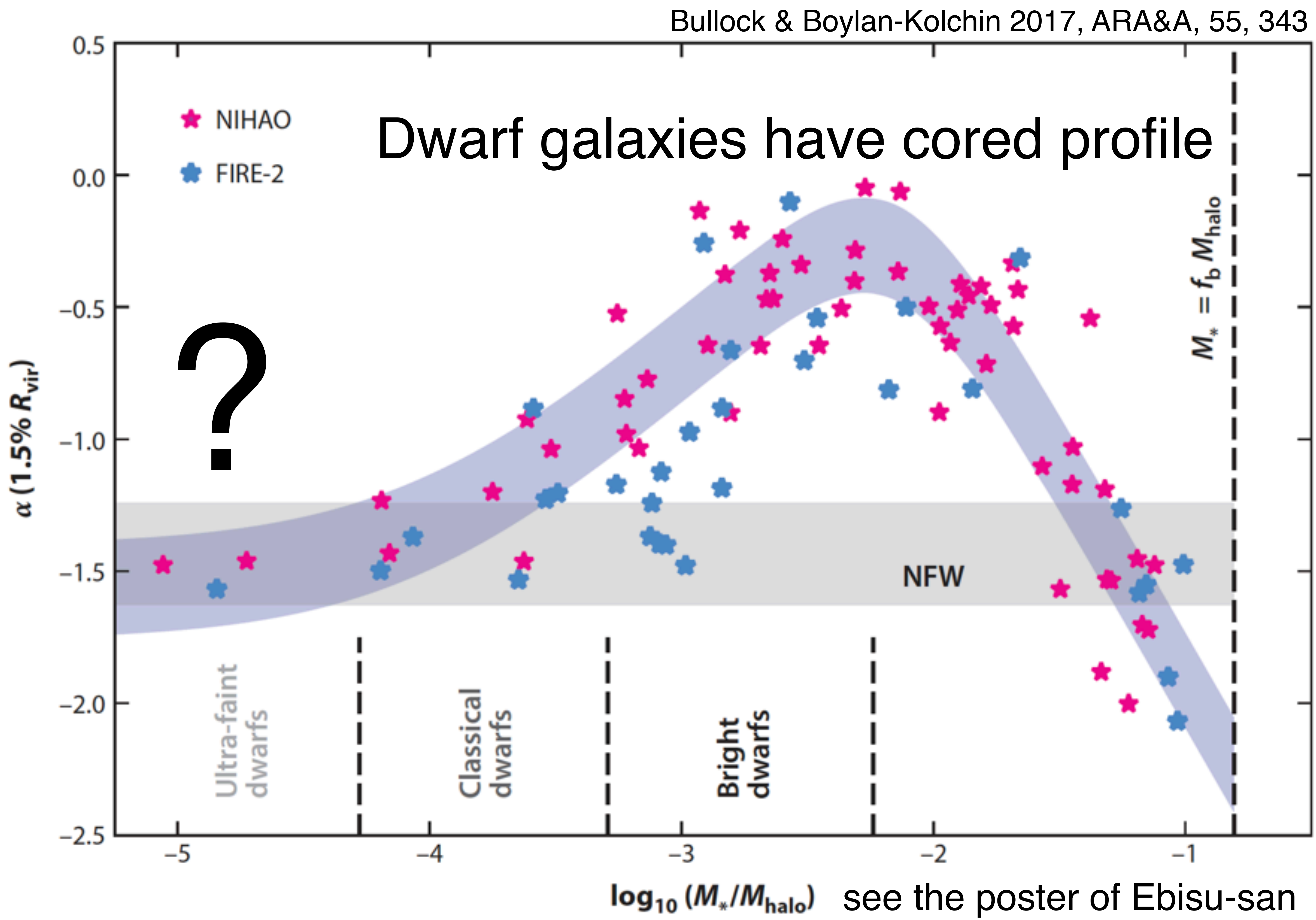
Spectral resolution:
380— 650 nm: ~2300
630 — 970 nm
(Low Res.): ~3000
710 — 885 nm
(Mid Res.): ~5000
940 — 1260 nm: ~4300

Science of Subaru Prime Focus Spectrograph (PFS)

Testing ΛCDM	Assembly history of galaxies	Importance of IGM
Nature of DM	**Stellar kinematics**	**Cosmic reionization**
Search for DM subhalos	$M_*/M_{\rm halo}$ **Outflows & inflows of gas**	**Tomography of gas & DM**
Small-scale tests of structure growth	**Environment-dependent evolution**	**dSph as relic probe of reionization feedback**

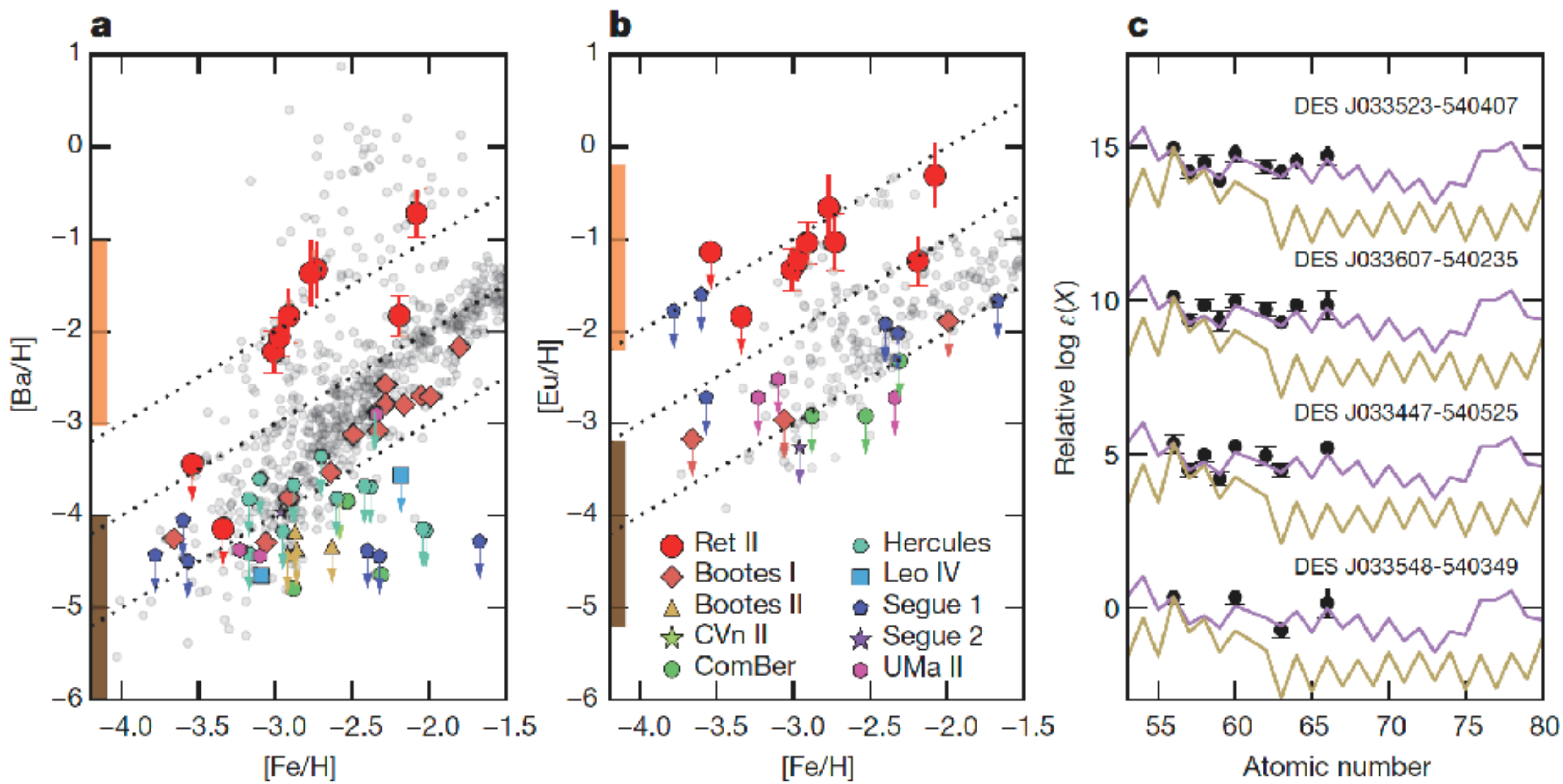
blue: Galactic Archaeology **yellow: Galaxy Evolution**

Inner profiles of dark matter halos



see the poster of Ebisu-san

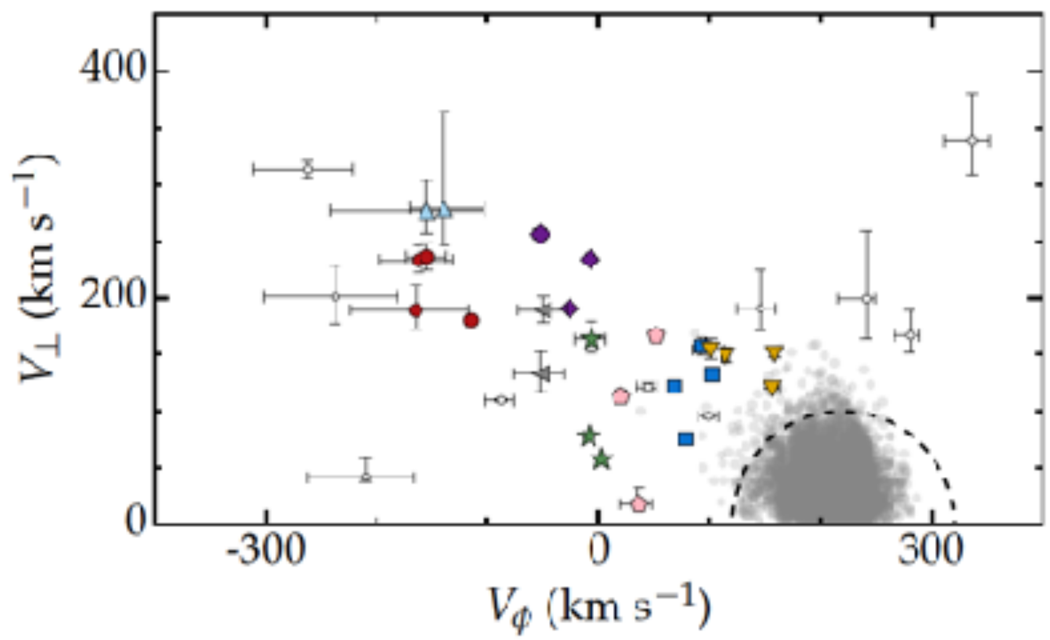
r-process enhanced stars in the Reticulum II ultrafaint dwarf galaxy



Ji et al. 2016, Nature, 531, 610

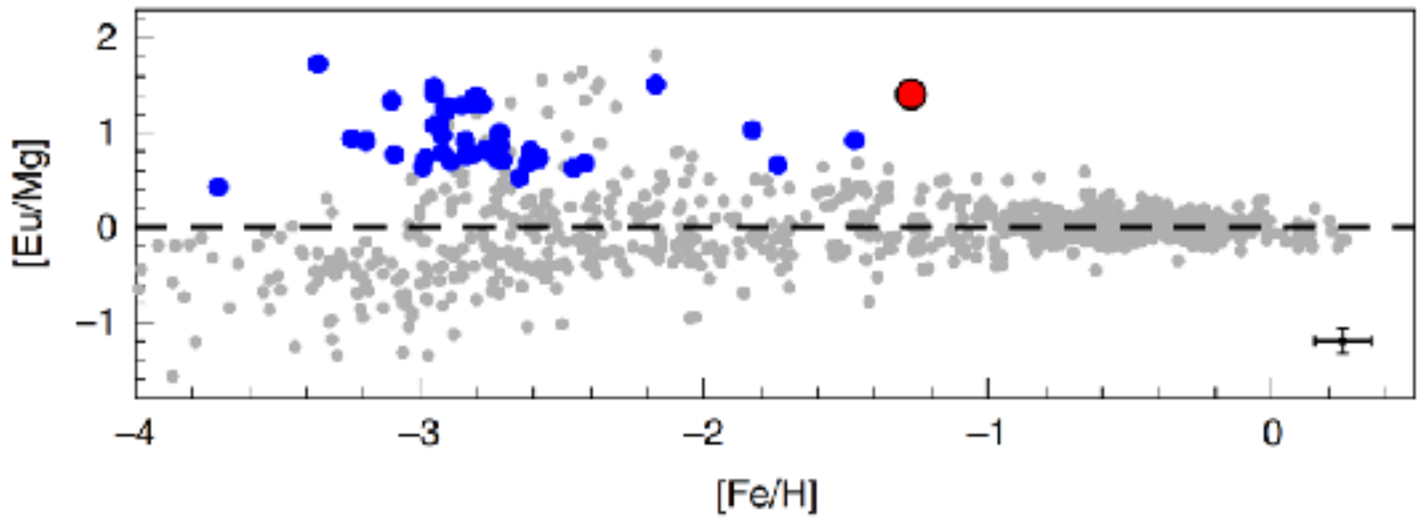
Origin of r-process enhanced stars

No disk like orbit



Roederer et al. 2018, AJ, 156, 179

Elemental composition similar to dwarf galaxies

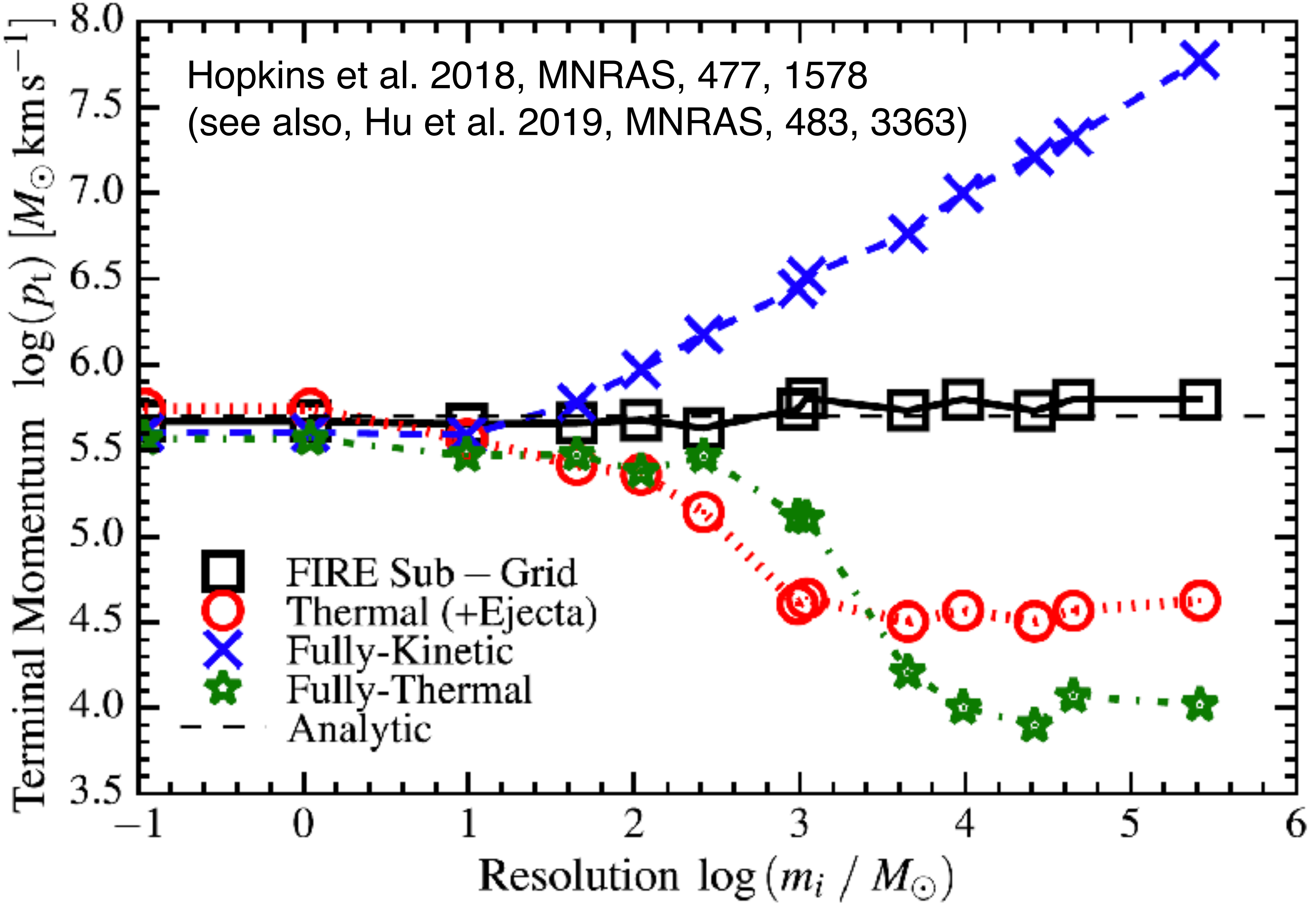


Xing et al. 2019, Nature Astronomy

r-process enhanced stars come from accreted dwarf galaxies?

Simulations resolving **a scale of UFDs ($m_* \sim 10^3\ M_{sun}$)** are critical to making a connection between chemical abundance and assembly histories of galaxies.

Independence on the models of supernova feedback at sufficiently high resolution (< 100 M_{sun})



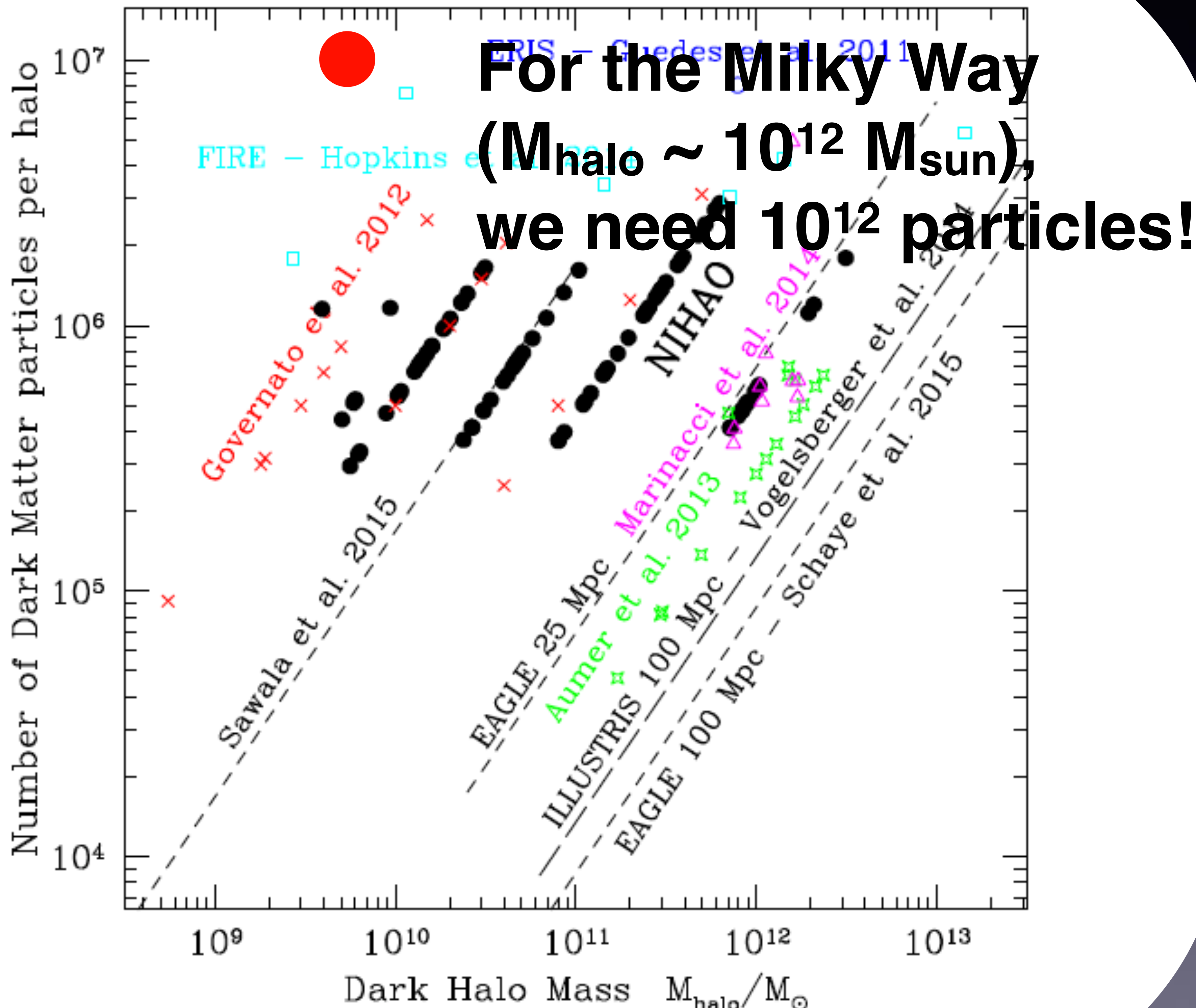
See the poster of **Oku**-san

Simulations resolving **a scale of UFDs ($m_* \sim 10^3$ M_{sun})** are critical to making a connection between chemical abundance and assembly histories of galaxies.

↓

Star-by-star simulations will achieve a breakthrough in understanding the early evolution of galaxies.

The difficulty for resolving individual stars in simulations of galaxy formation

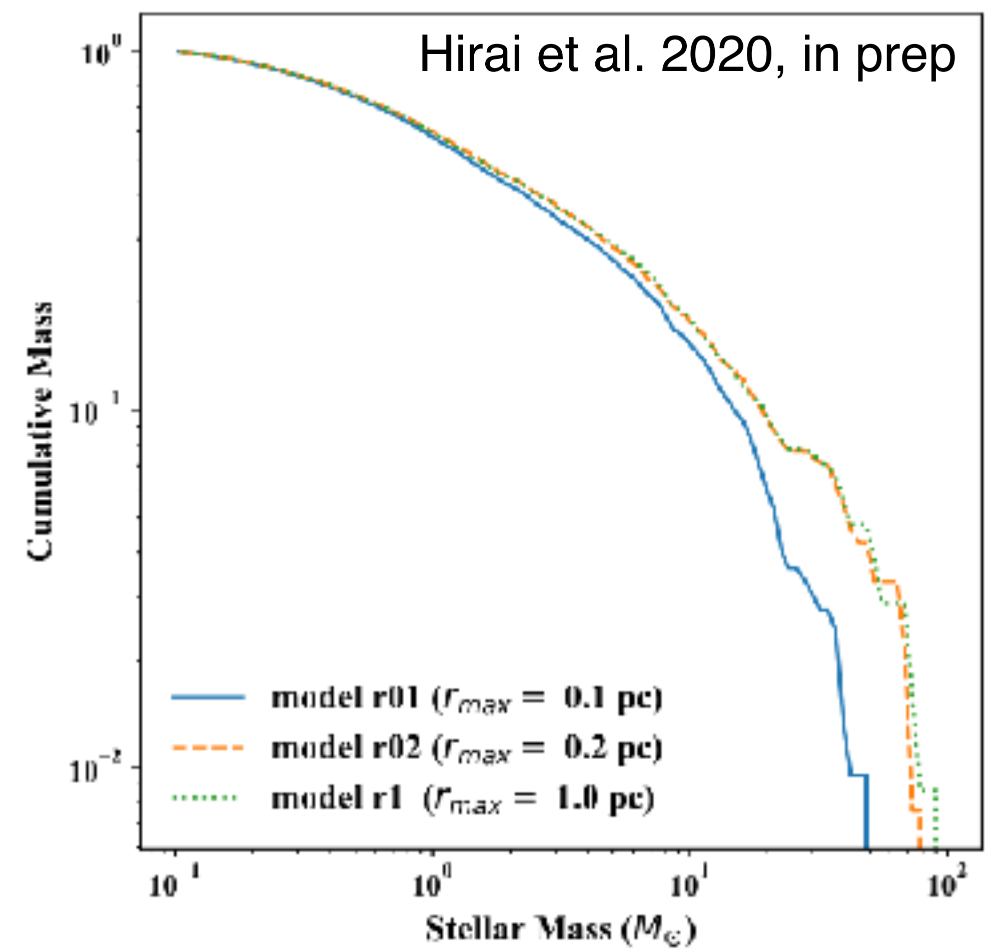


Wang et al. 2015, MNRAS, 454, 83

Star-by-star simulations

CELib

Saitoh 2017, AJ, 153, 85
Hirai et al. 2020, in prep



star formation ↑ ↓ mass, lifetime, yield, energy

ASURA/BRIDGE

Hydrodynamics+*N*-body (Tree)

Saitoh et al. 2008, PASJ, 60, 667;
Saitoh et al. 2009, PASJ, 61, 481;
Fujii et al. 2007, PASJ, 59, 1095

Information of particles →

←

Domain decomposition
Particle exchange
Computation of interaction

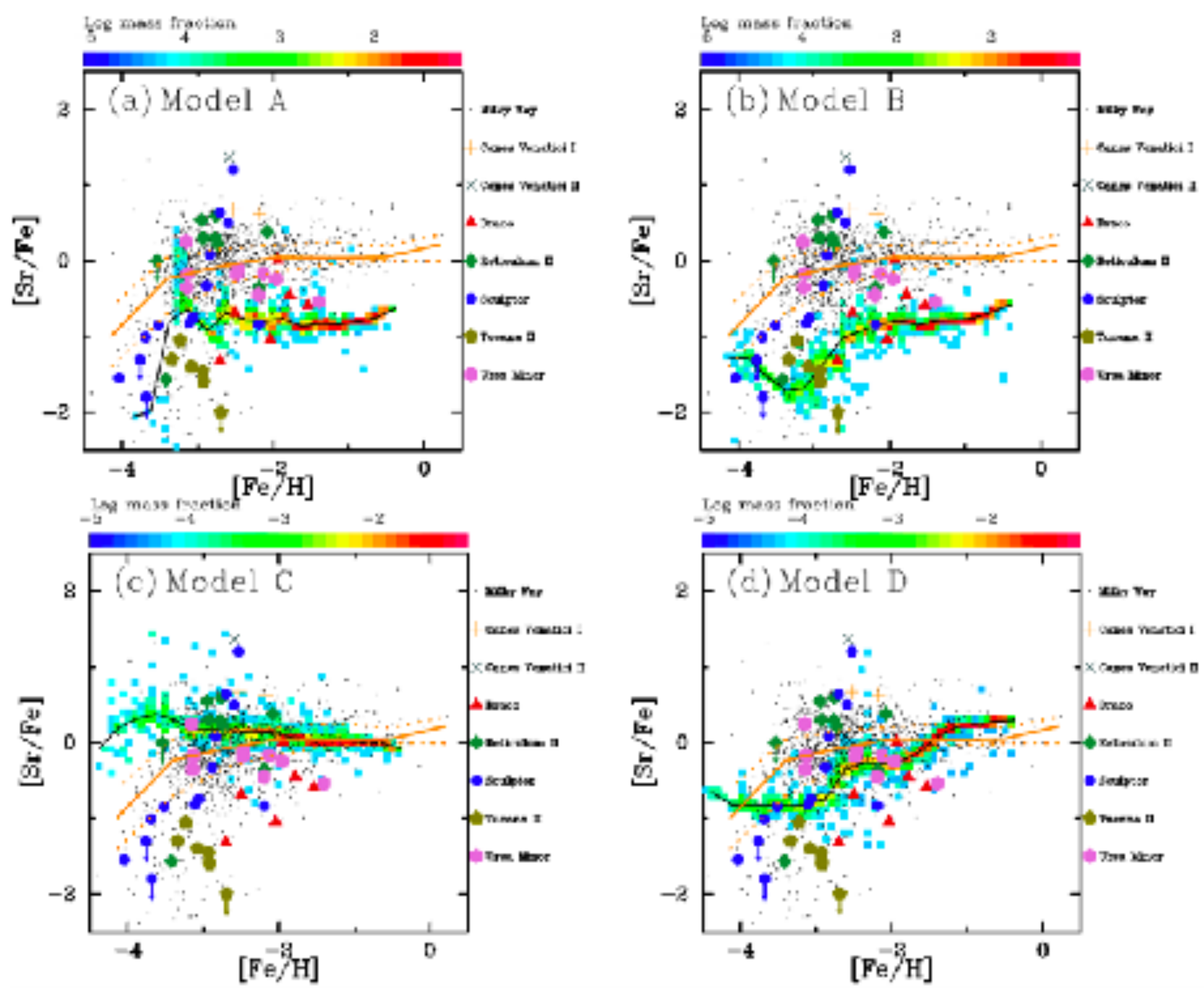
FDPS

Iwasawa et al. 2016, PASJ, 68, 54

See the poster of **Nomura**-san

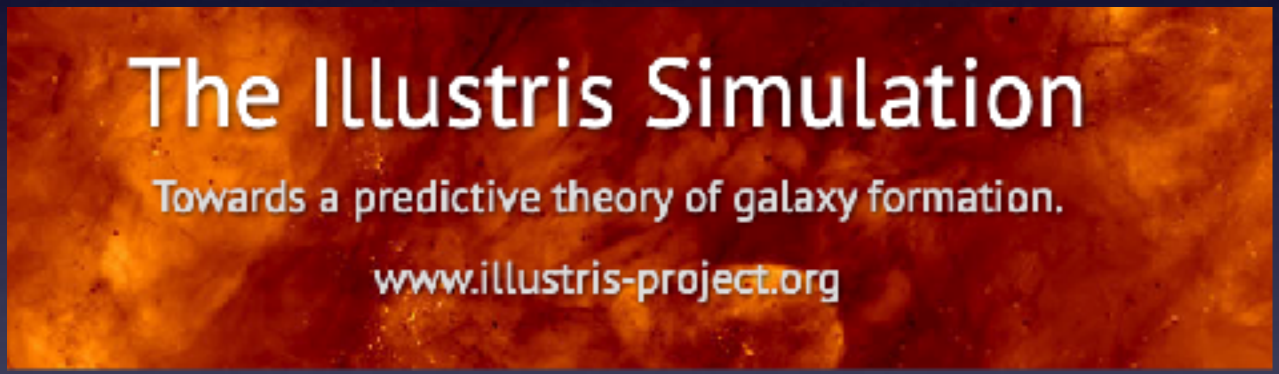
Requests to CfCA

Increasing the priority of the bulk queue



Hirai et al. 2019, ApJ, 885, 33

Clarifying the uncertainties of parameters are also important!



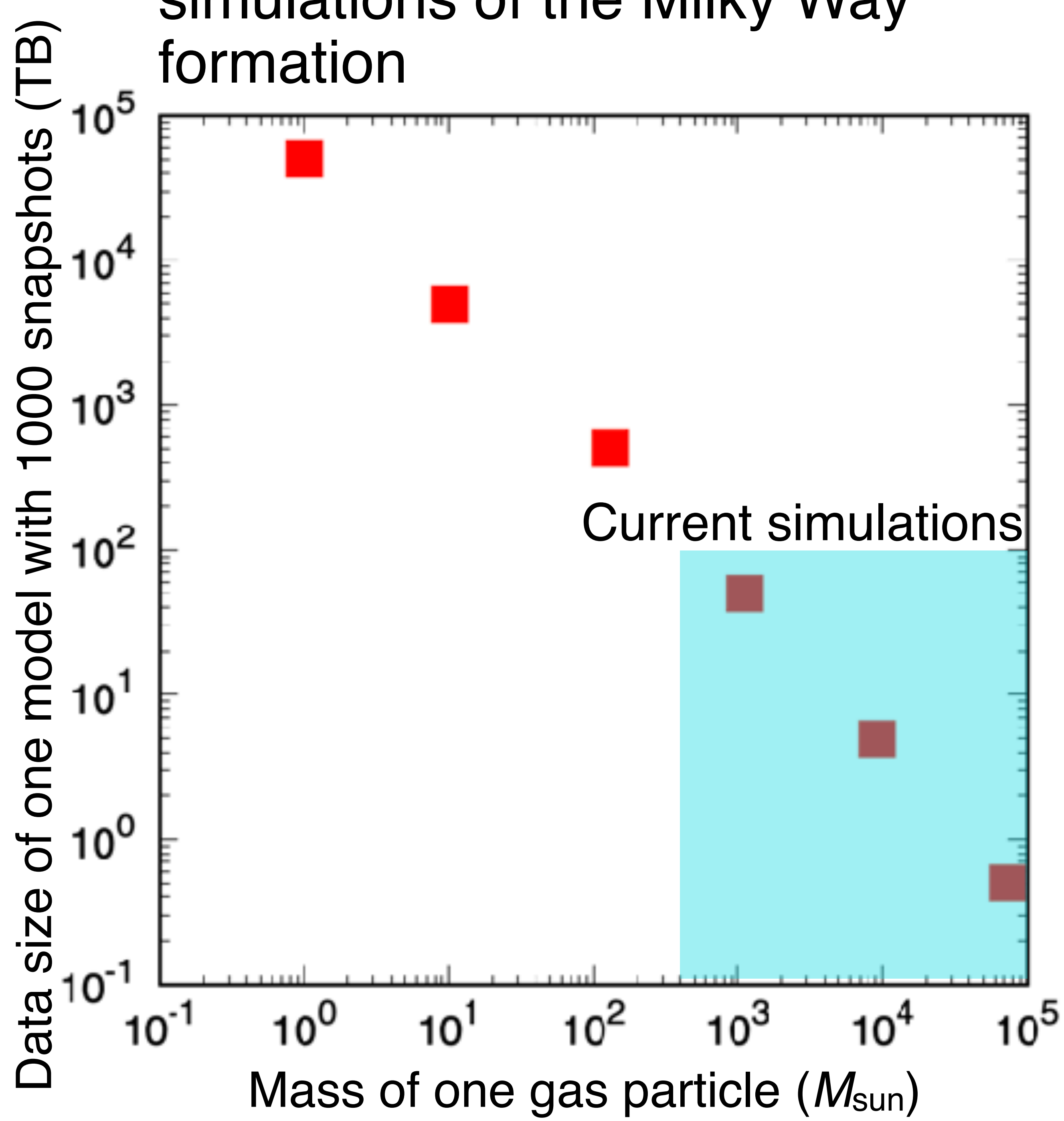
Several galaxy formation projects had a great success using a small number of cores (~1000 cores).

How about a group category?

Requests to CfCA

Increasing the amount of storage in the file server

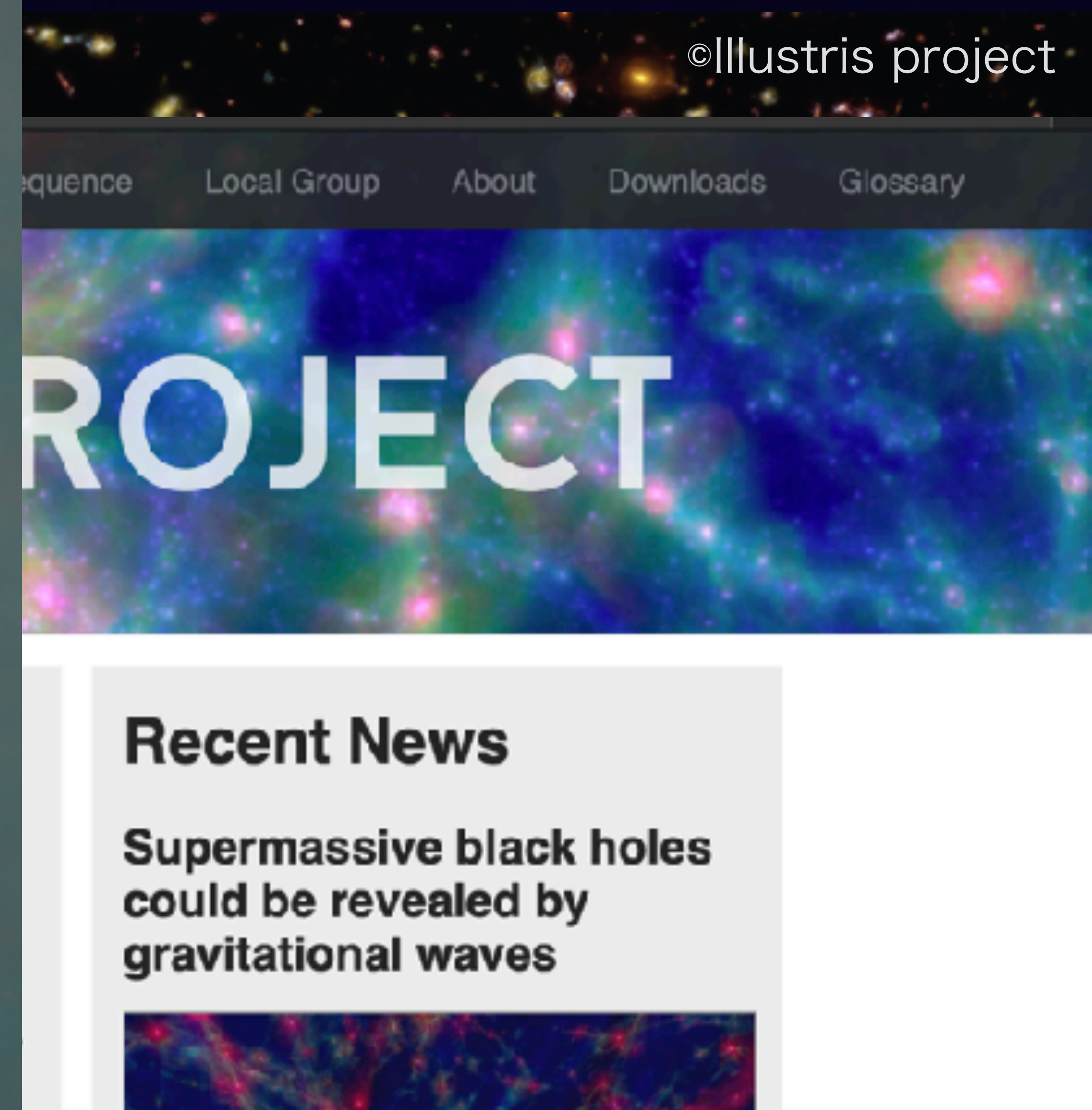
Example of the data size of simulations of the Milky Way formation



Petabyte scale storage will be necessary for the next generation simulations.

Outreach

Enhancing support for creating materials for outreach



Summary

- Numerical simulations are powerful tools to study galaxy formation.
- **Feedback** regulates star formation in galaxies.
- Studies of **chemo-dynamical evolution** become increasingly important.
- Future **cosmological star-by-star simulations** will make a breakthrough in the understanding of galaxy formation.
- **I am grateful for the support of CfCA.**