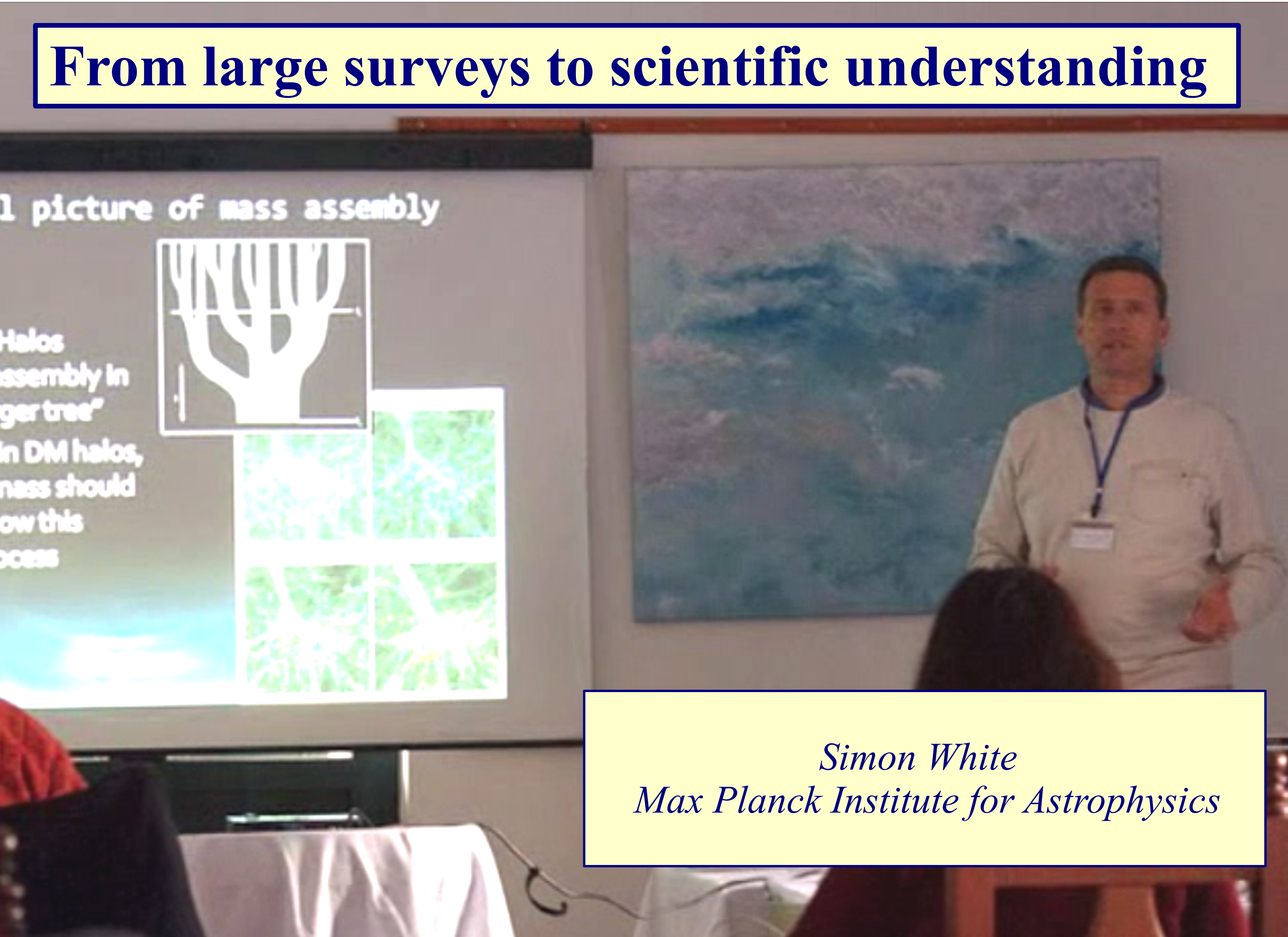
From large surveys to scientific understanding



Simon White
Max Planck Institute for Astrophysics

Cafayate, 2011

Cafayate,   2011

Cafayate, Argentina, 2011


Where is the light?
Tracing the evolution of
the distribution of light in
Bulges and Disks since z~0.8
LAM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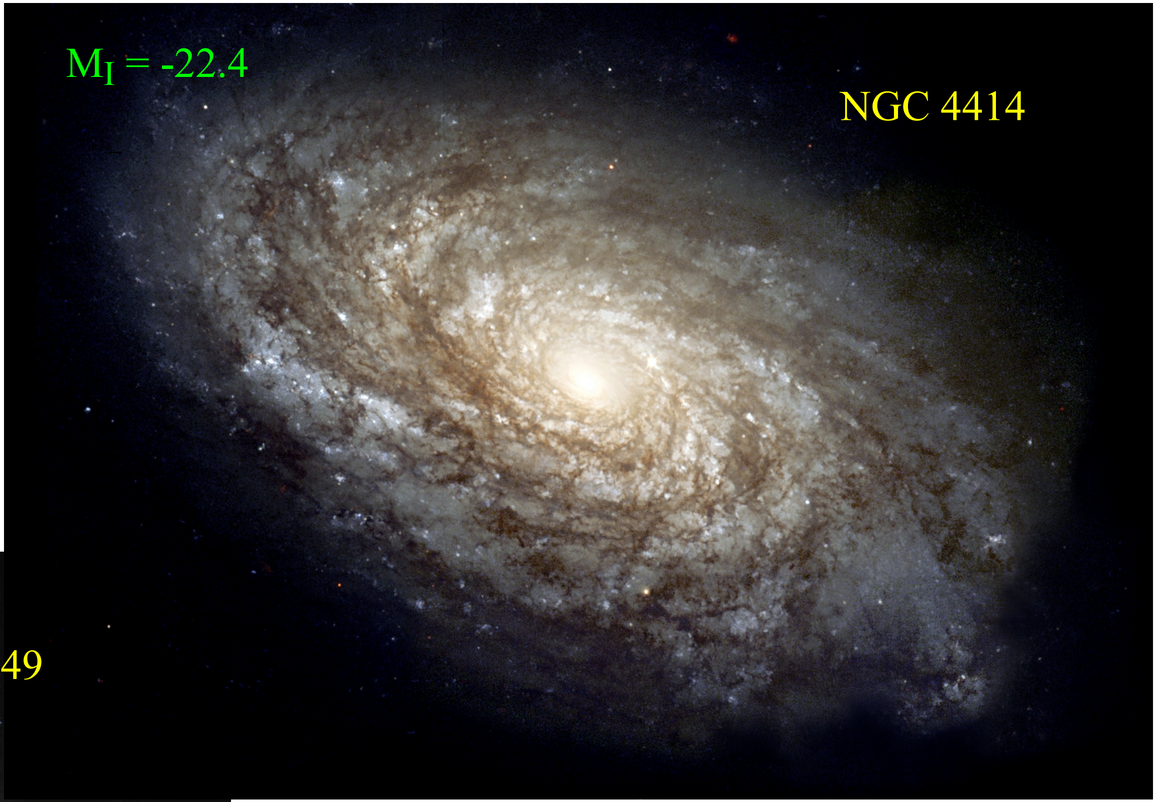
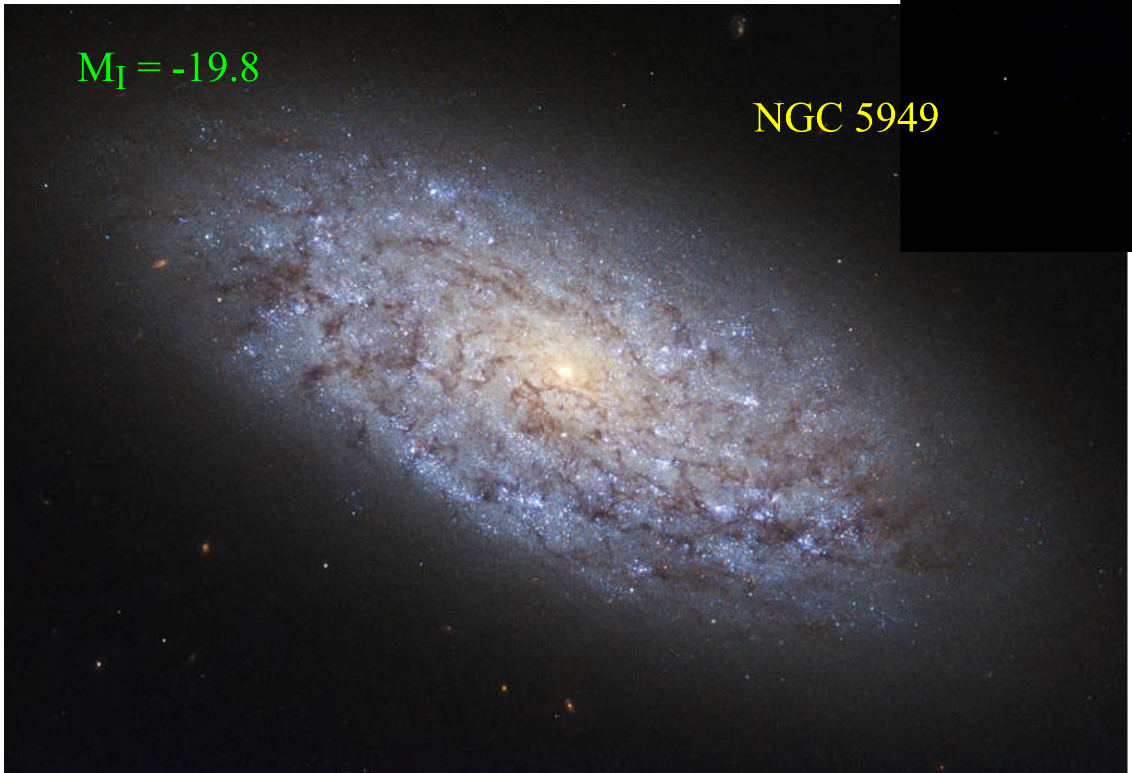
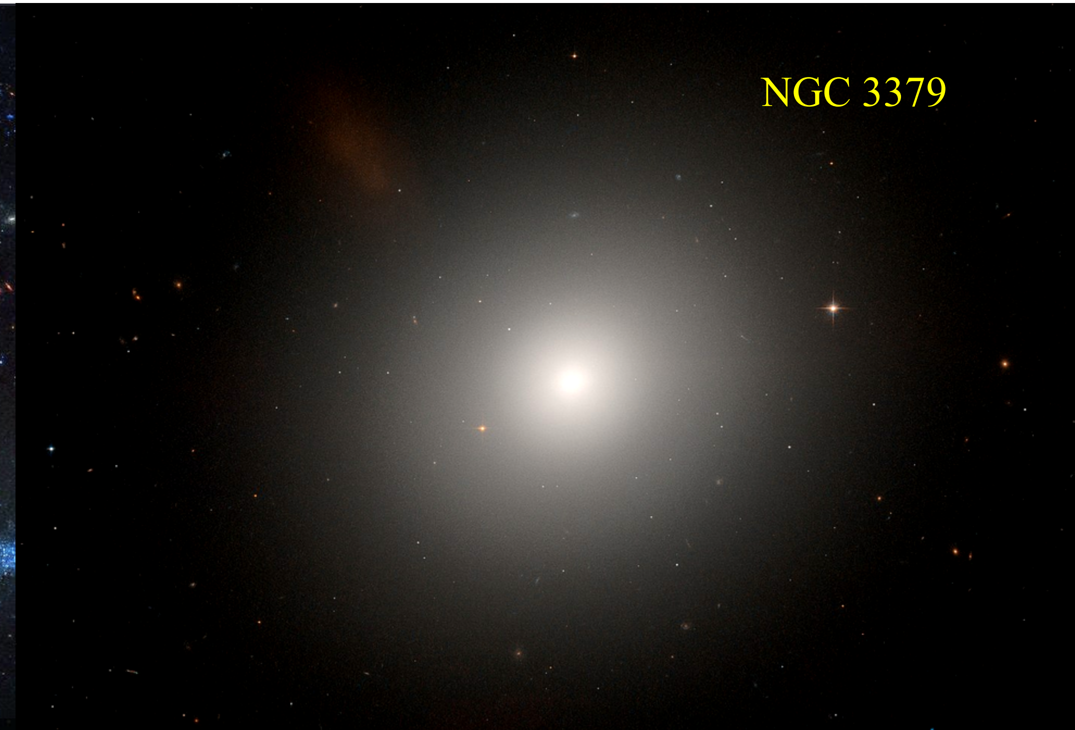
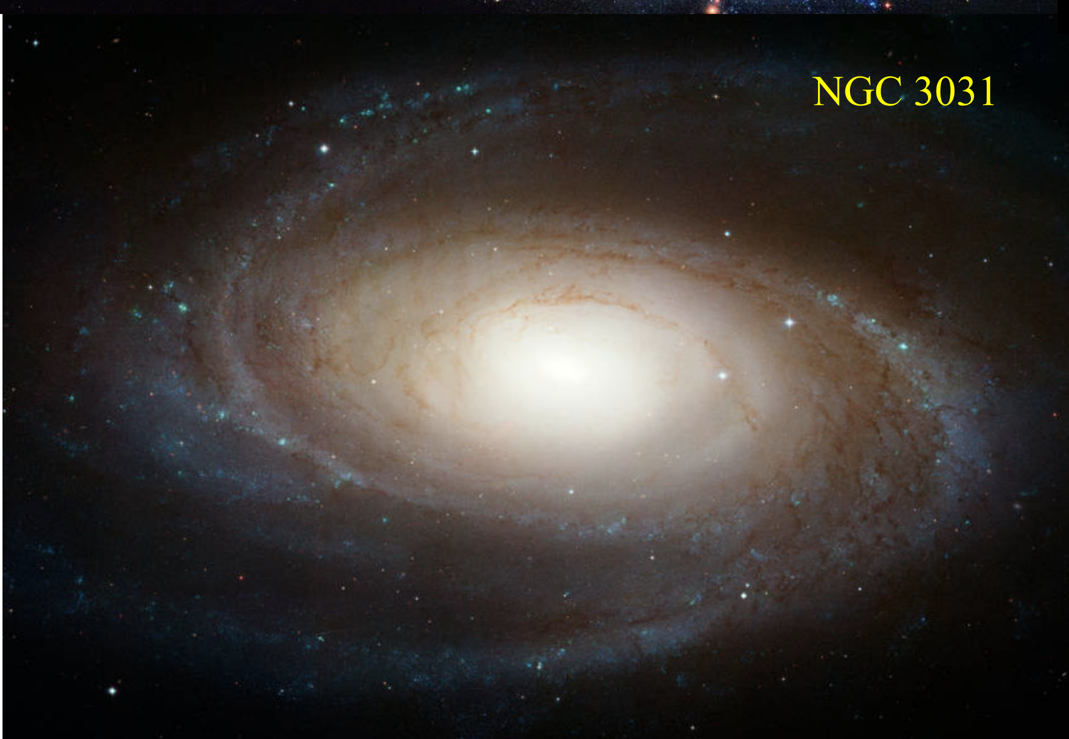
Galaxies of very different mass/size can look similar

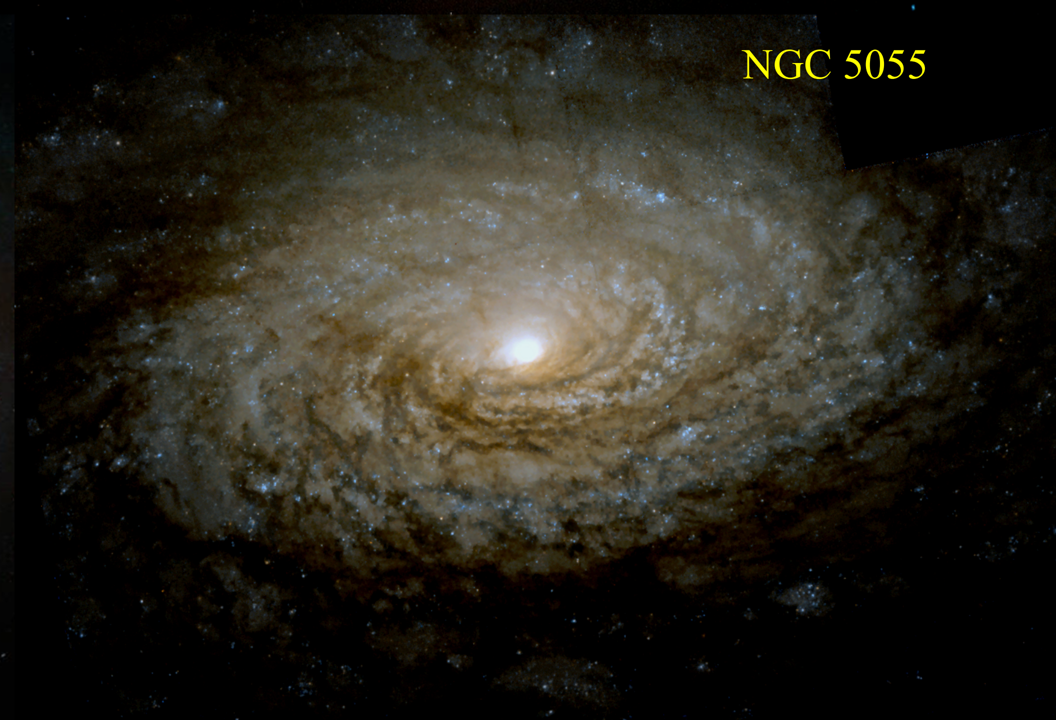




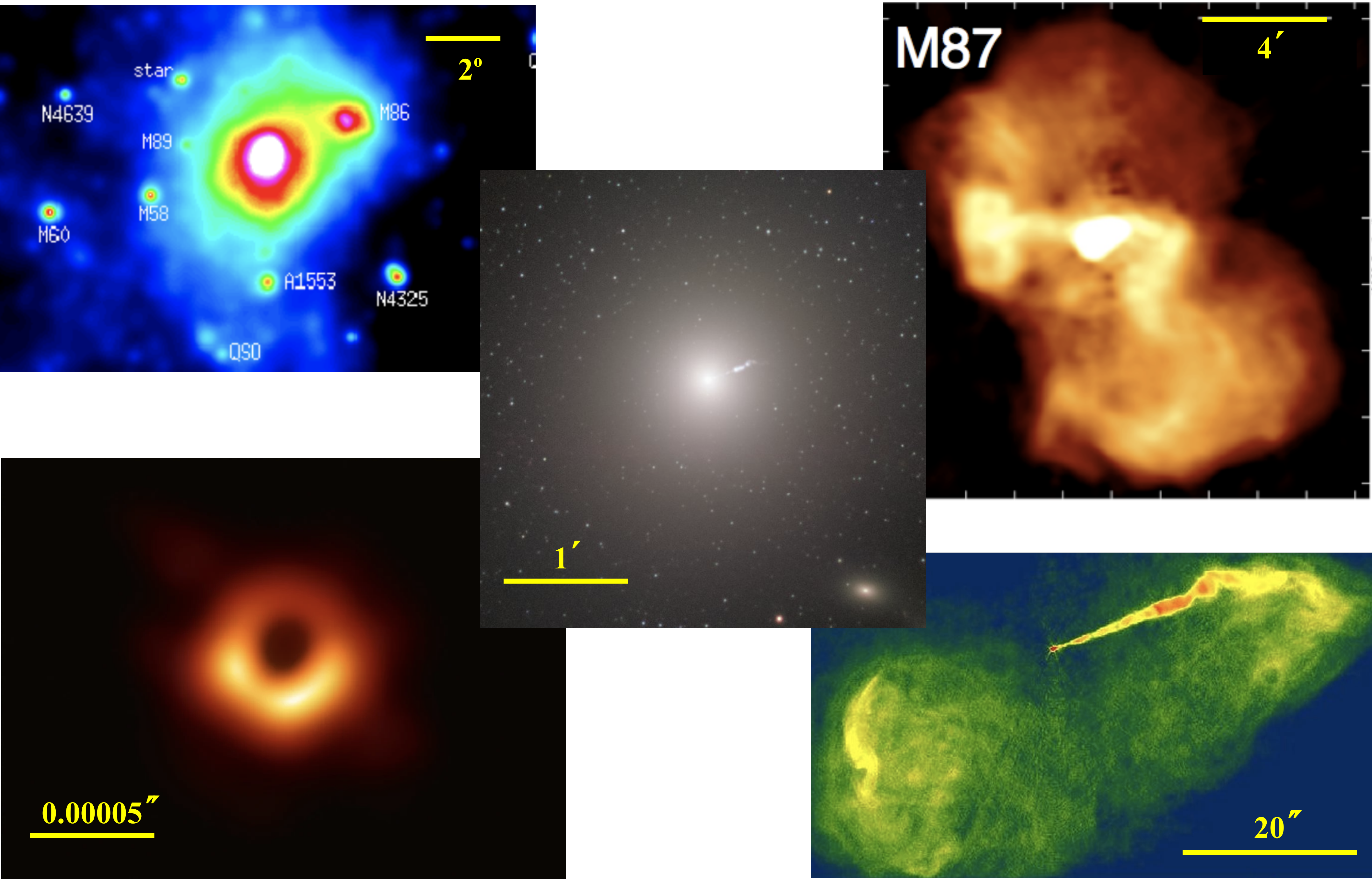
Galaxies of similar luminosity can look very different







One galaxy can look very different on different scales/wavelengths



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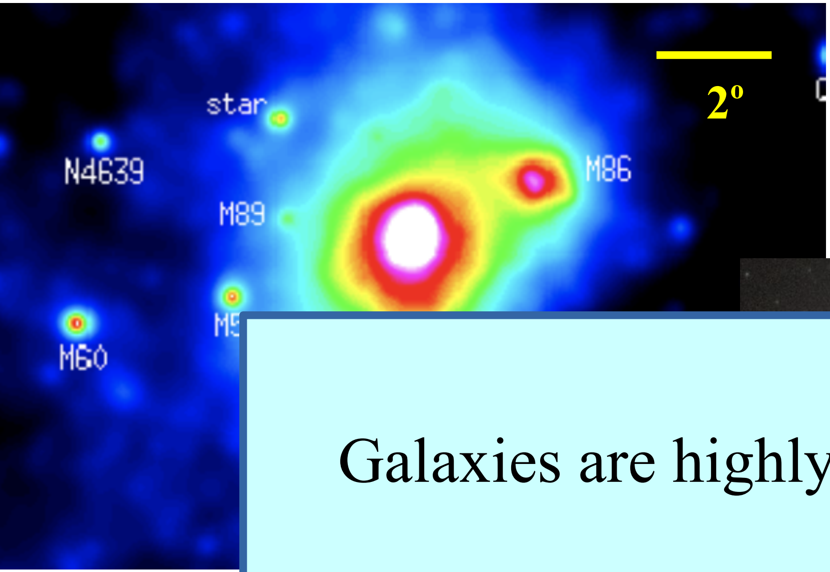
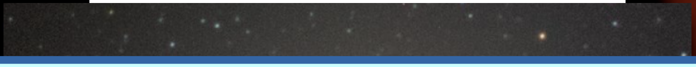
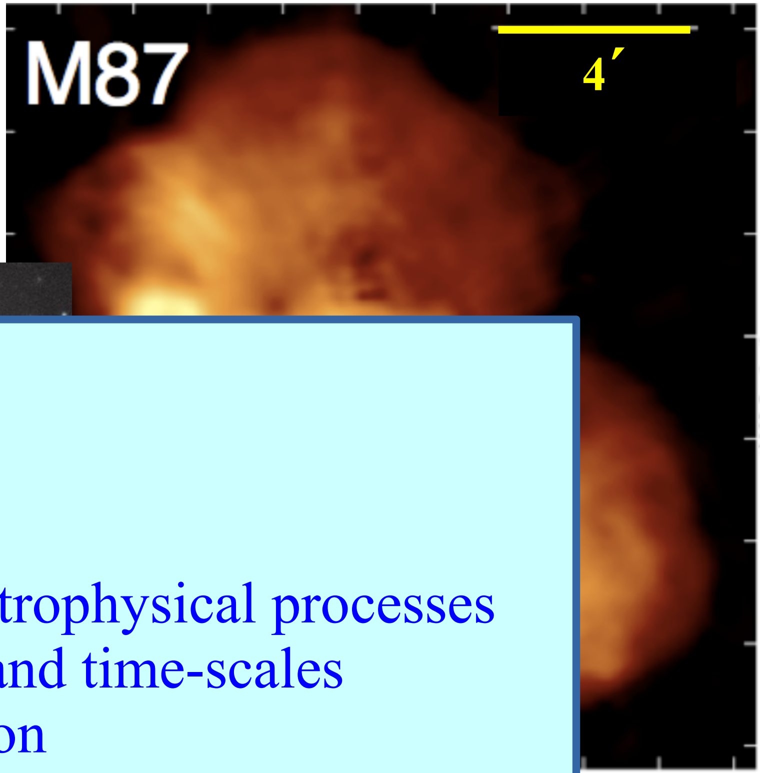


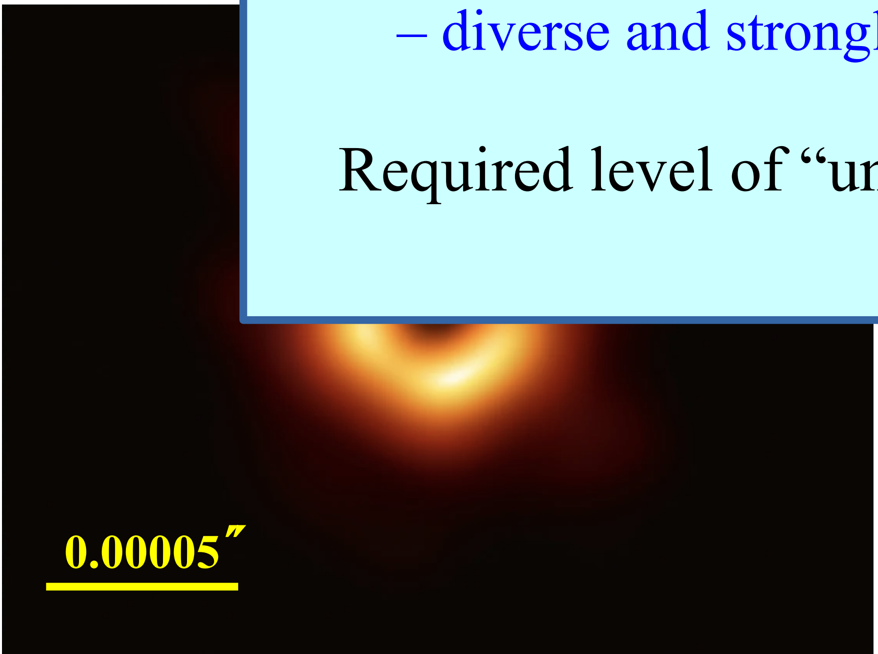


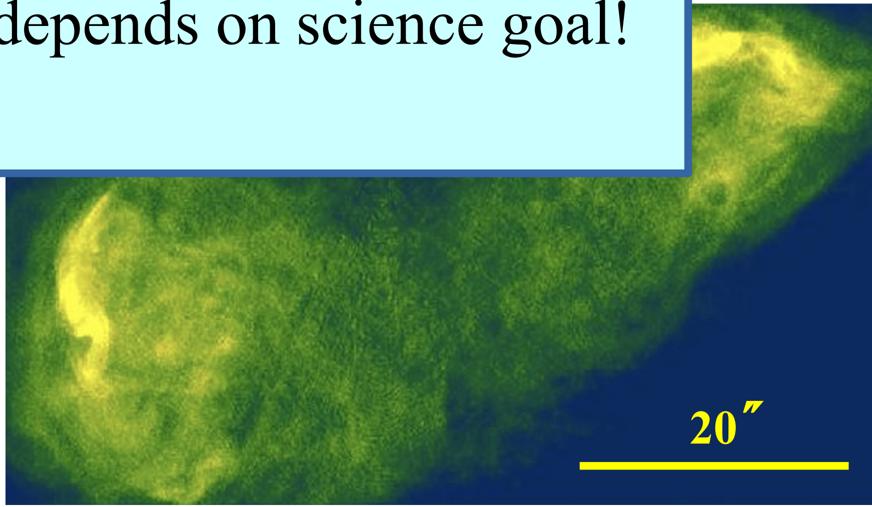


Galaxies are highly complex systems!

- many, strongly coupled components/astrophysical processes
- huge dynamic range in mass-, length- and time-scales
- diverse and strongly evolving population

Required level of “understanding” depends on science goal!





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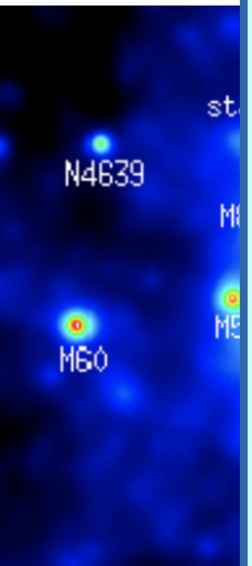

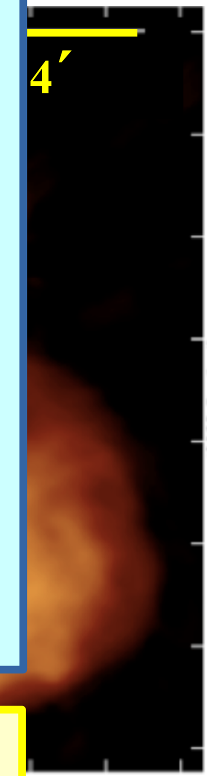

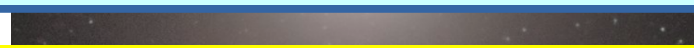

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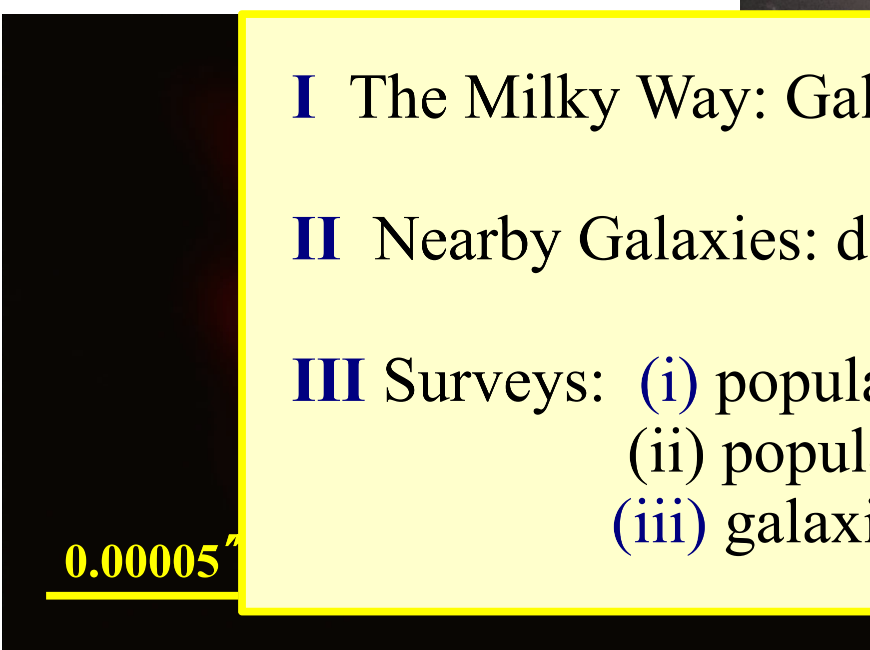

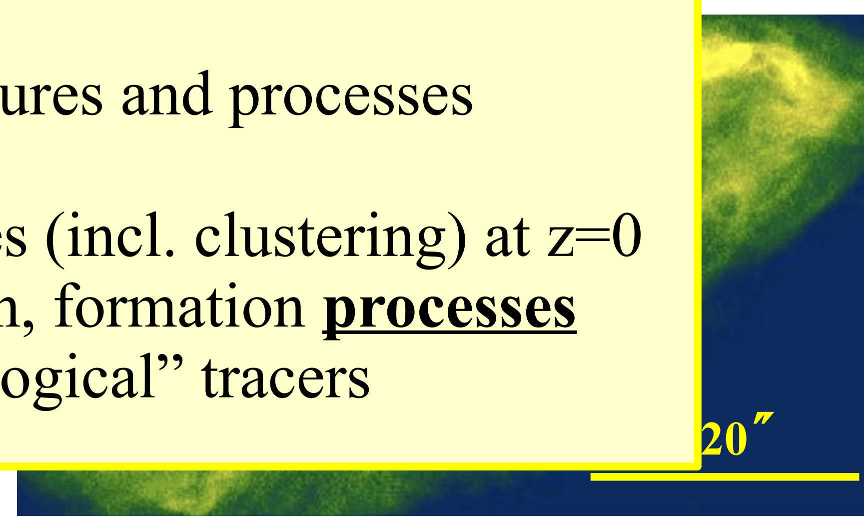

I The Milky Way: Galactic Archeology, "Astrogeophysics"

II Nearby Galaxies: details of structures and processes

III Surveys: (i) population properties (incl. clustering) at z=0
(ii) population evolution, formation **processes**
(iii) galaxies as "cosmological" tracers

Epistemology for complex systems

(galaxy formation, climate change, ecology, macro-economics, brain function)

- Agreement of the galaxy population in a modern cosmological hydrodynamical simulation with (aspects of) real populations may contribute rather little to our knowledge/understanding of galaxy formation, since
  - part of the agreement is due to calibration/tuning
  - simulations with *different* subgrid models often agree equally well
  - unexamined (but linked) aspects often disagree with observation
  - better resolution or subgrid modelling may ruin the agreement

- It is important to understand *why* simulation and observation agree. Intuition is often helped by models which isolate individual processes

- Stronger conclusions can often be drawn from showing that some aspects of the observations *cannot* be fit, implying e.g. that
  - the integration scheme is insufficiently accurate, or
  - the subgrid models incorrectly represent the astrophysics, or
  - critical processes are not yet included, or
  - ΛCDM is wrong

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Complex simulations of limited realism/fidelity ⟷ knowledge? ⟷ Limited observations of a more complex reality

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Galaxy formation is an insoluble problem

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Galaxy formation is a solved problem

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- Galaxies form as gas cools and condenses at the centres of a population of massive halos growing by gravitational amplification of fluctuations in an initially near-uniform distribution of pre-existing dark matter

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Semi-analytic and Subhalo Abundance Matching models <u>assume</u> this in ΛCDM and tune a physically based (SAM) or purely statistical (SHAM) relation between galaxy properties and subhalo history to fit observation.

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Consistent evolution over redshift, is required for interpretation of deep surveys (even for cosmology). This is enforced by SAMs and the most recent SHAM models (Emerge, Universe Machine…) but NOT by HOD's.

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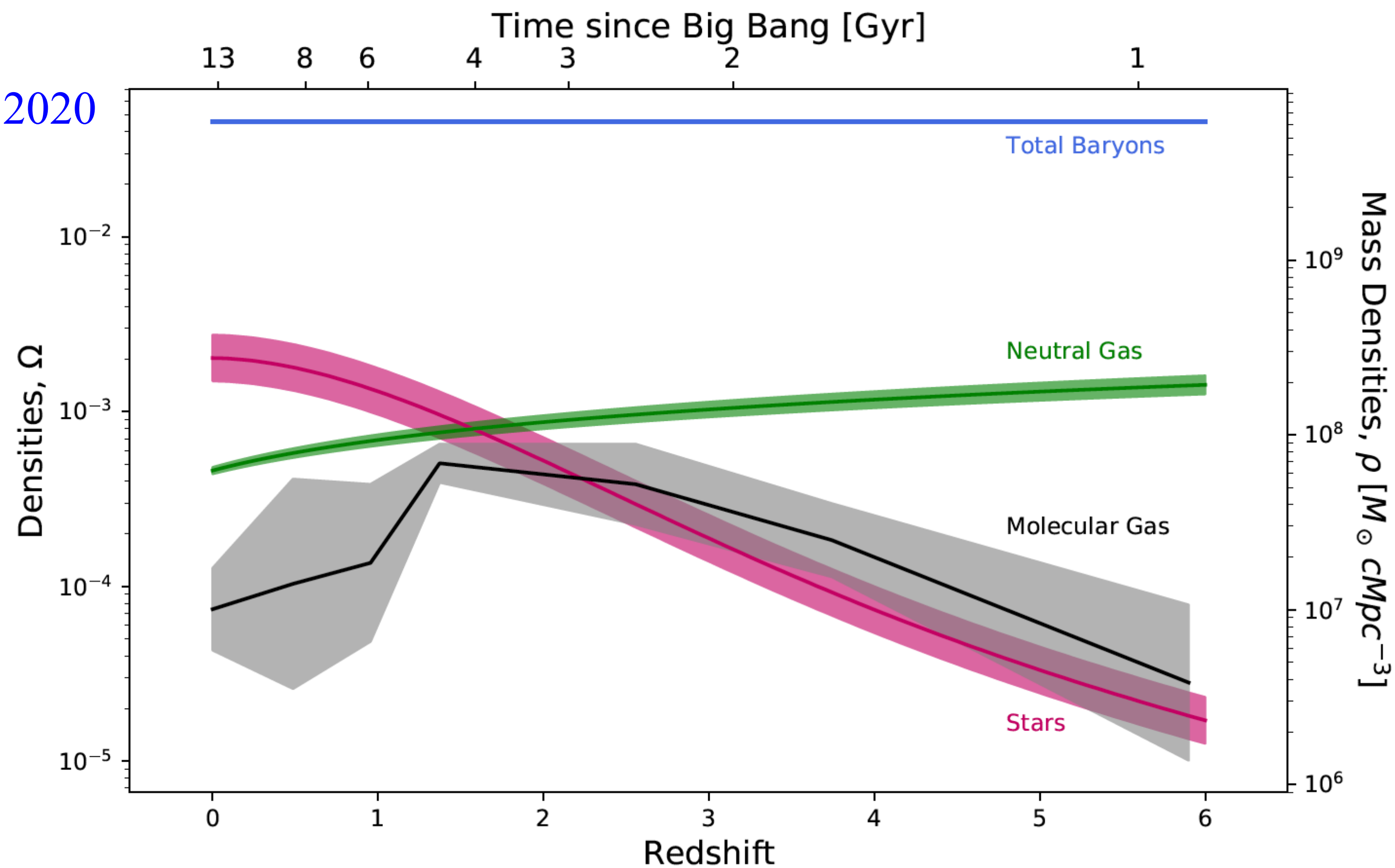
Main outstanding issues are:

I. The dependence of the survival of satellite subhalos on resolution, integration accuracy, and baryon effects – the "orphan" problem

II. The number of properties of subhalo histories needed to predict their galaxy content to the required precision – the "assembly bias" problem

Baryon fraction in galaxies since z = 6

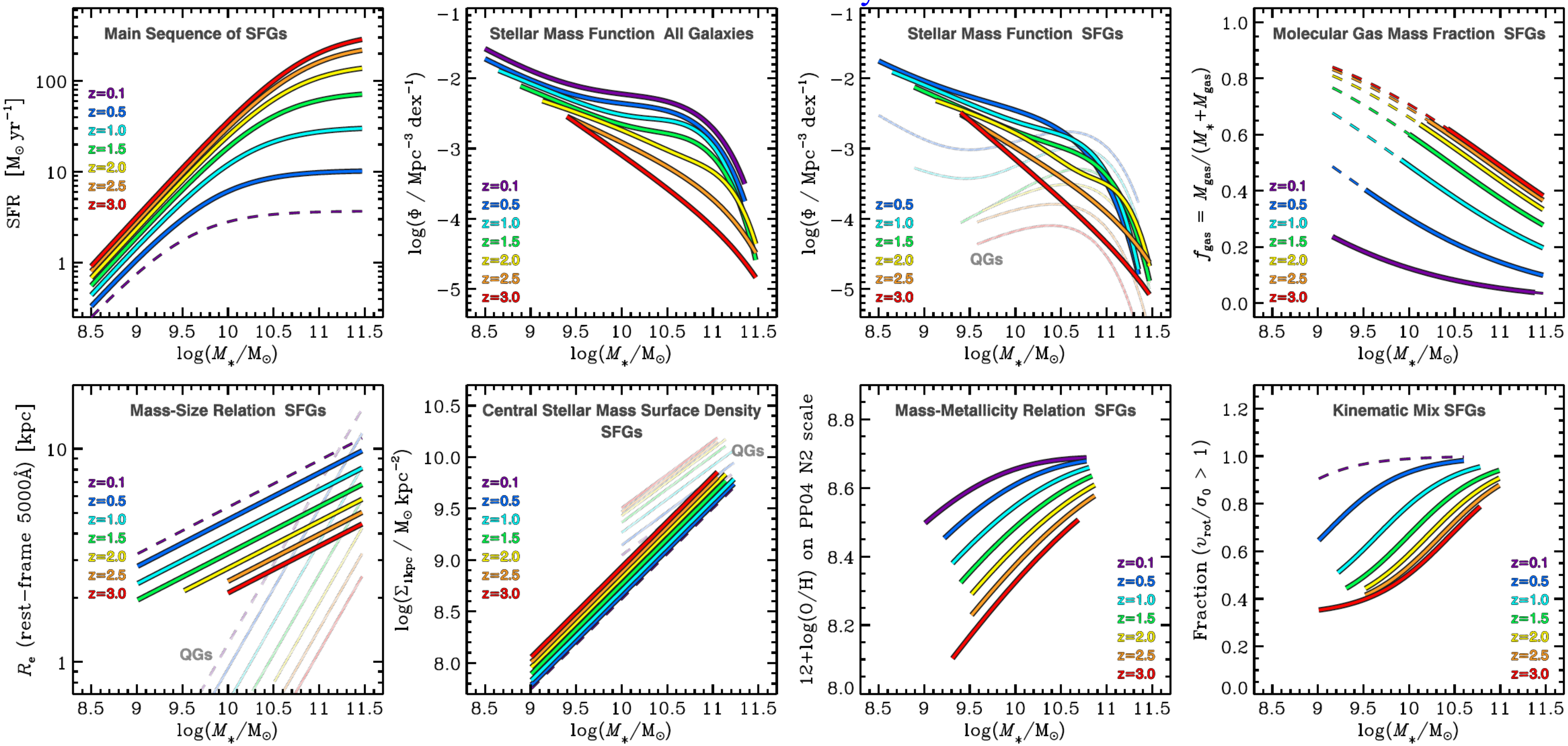
Péroux & Howk 2020



- Fraction of baryons in galaxies has grown from ~2% (z = 6) to ~5% (z = 0)
- Galaxies are cold gas-dominated at z > 1, star-dominated at z < 1
- The cold gas is HI-dominated, strongly so at z < 1 and z > 3
- Molecular gas tracks stars at z > 3

Evolution of galaxy scaling relations since z = 3

Förster-Schreiber & Wuyts 2020



- Both a census and scaling relations are now available out to at least z = 3

- How do these reflect evolutionary processes?
  - (a) inferences without assuming a <u>detailed</u> underlying model
  - (b) inferences assuming a ΛCDM context

A toy model for the star-forming main sequence

- For an "isothermal" halo: $M_h(V, t) = V^3 t / 2\pi G$
- Baryon accretion rate: $\dot{M}_b(V, t) = f_b V^3 / 2\pi G$ with $f_b = \Omega_b / \Omega_m$
- Take cold gas reheating rate: $\dot{M}_{reh} V^2 = \varepsilon_{fb} \dot{M}_* = \varepsilon_{fb}\, \varepsilon_* M_{cg} / t$
- Under self-regulation: $\dot{M}_b - \dot{M}_{reh} \ll \dot{M}_b$ → $M_{cg} \sim f_b V^3 t / 2\pi G \varepsilon_{fb}\, \varepsilon_*$

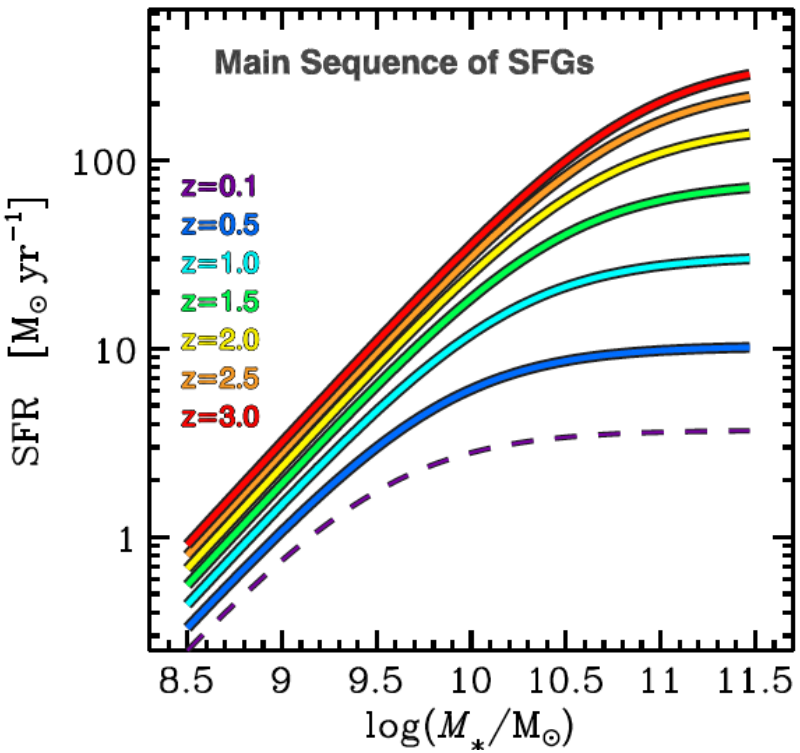
  $\dot{M}_* \sim f_b V^5 / 2\pi G \varepsilon_{fb}$

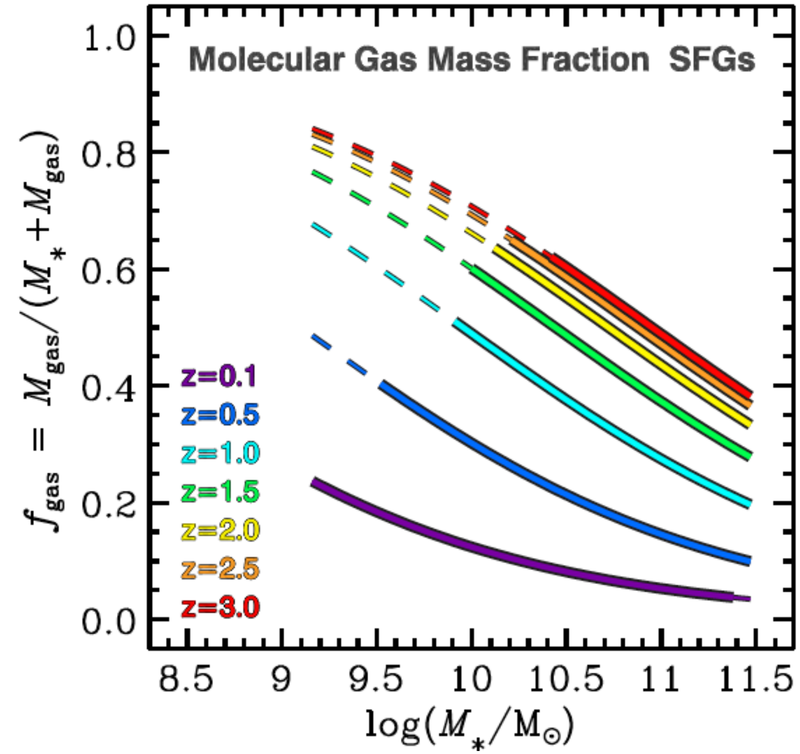
- Thus if $M_* \sim \dot{M}_* t$: Main Sequence slope and amplitude are unity and t^{-1}

  $M_{cg} / M_* \sim \varepsilon_*^{-1}$ independent of t and M_*

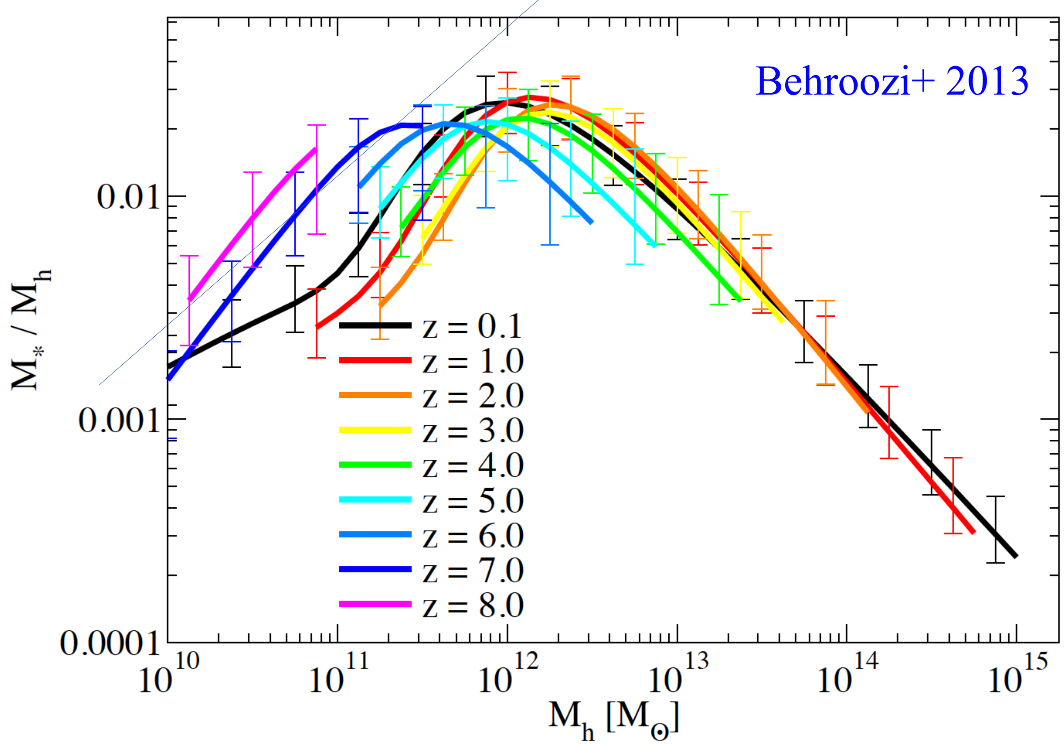
  $M_* / M_h = f_b V^2 / \varepsilon_{fb} = f_b / \varepsilon_{fb} (2\pi G M_h / t)^{2/3}$

Most (but not all) these relations fit observation at least qualitatively


Main Sequence of SFGs
z=0.1
z=0.5
z=1.0
z=1.5
z=2.0
z=2.5
z=3.0
SFR [M⊙ yr⁻¹]
100
10
1
8.5
9
9.5
10
10.5
11
11.5
log(M*/M⊙)


Molecular Gas Mass Fraction SFGs
z=0.1
z=0.5
z=1.0
z=1.5
z=2.0
z=2.5
z=3.0
f_gas = M_gas/(M* + M_gas)
1.0
0.8
0.6
0.4
0.2
0.0
8.5
9
9.5
10
10.5
11
11.5
log(M*/M⊙)

2/3


Behroozi+ 2013
z = 0.1
z = 1.0
z = 2.0
z = 3.0
z = 4.0
z = 5.0
z = 6.0
z = 7.0
z = 8.0
M* / Mh
0.01
0.001
0.0001
10^10
10^11
10^12
10^13
10^14
10^15
Mh [M⊙]

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- The efficiency of galaxy formation is limited by feedback that is most effective at low and at high halo mass. Different astrophysical processes are required in the two cases.

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At low mass: Reionization heating; Star-formation-driven winds
At high mass: Inefficient cooling; AGN feedback

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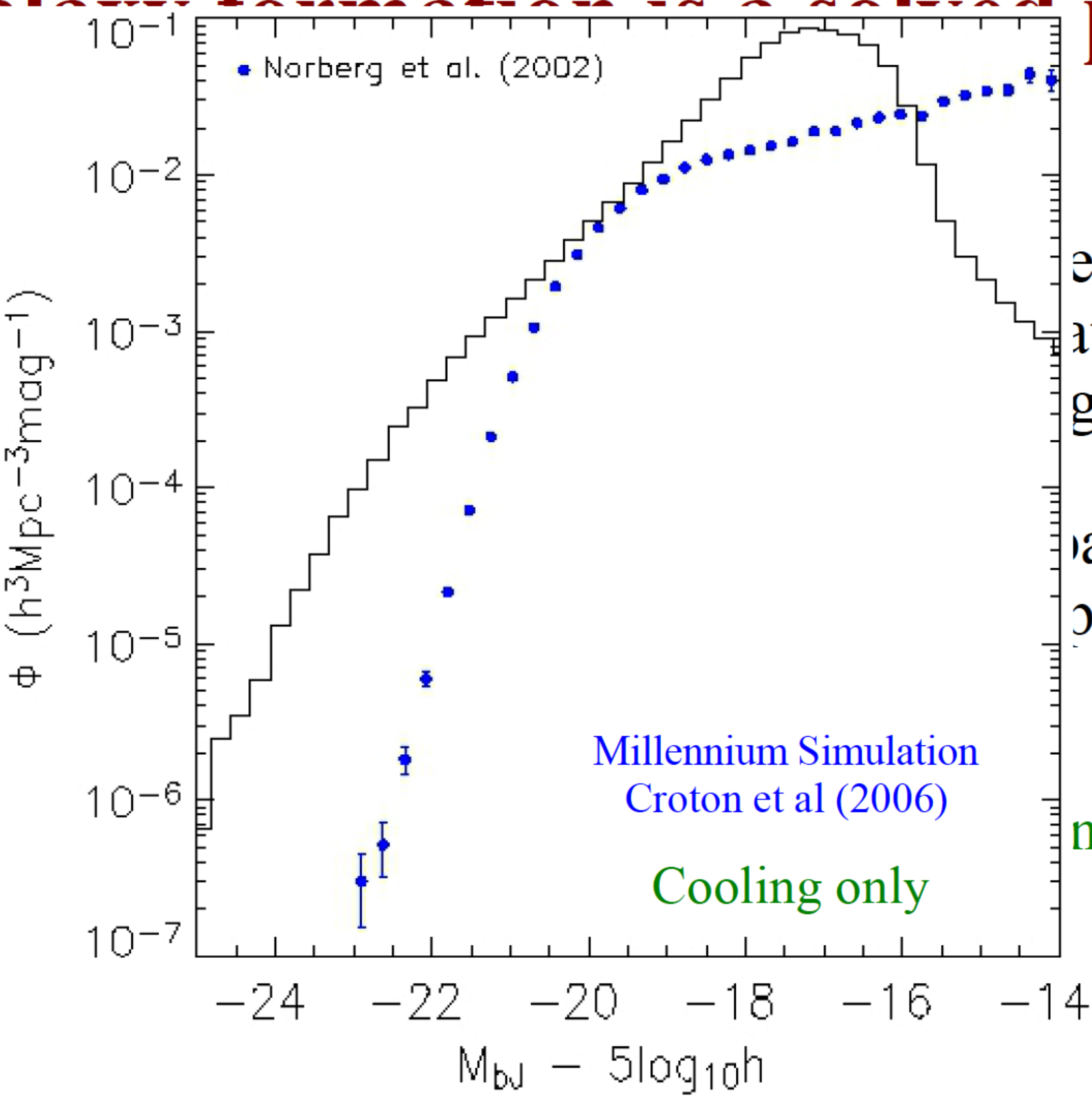

- Galaxies f… es of a population of massive ha… ation of fluctuations in an initia… g dark matter
- The efficie… back that is most effective a… physical processes are require…

At low ma… n winds
At high ma…

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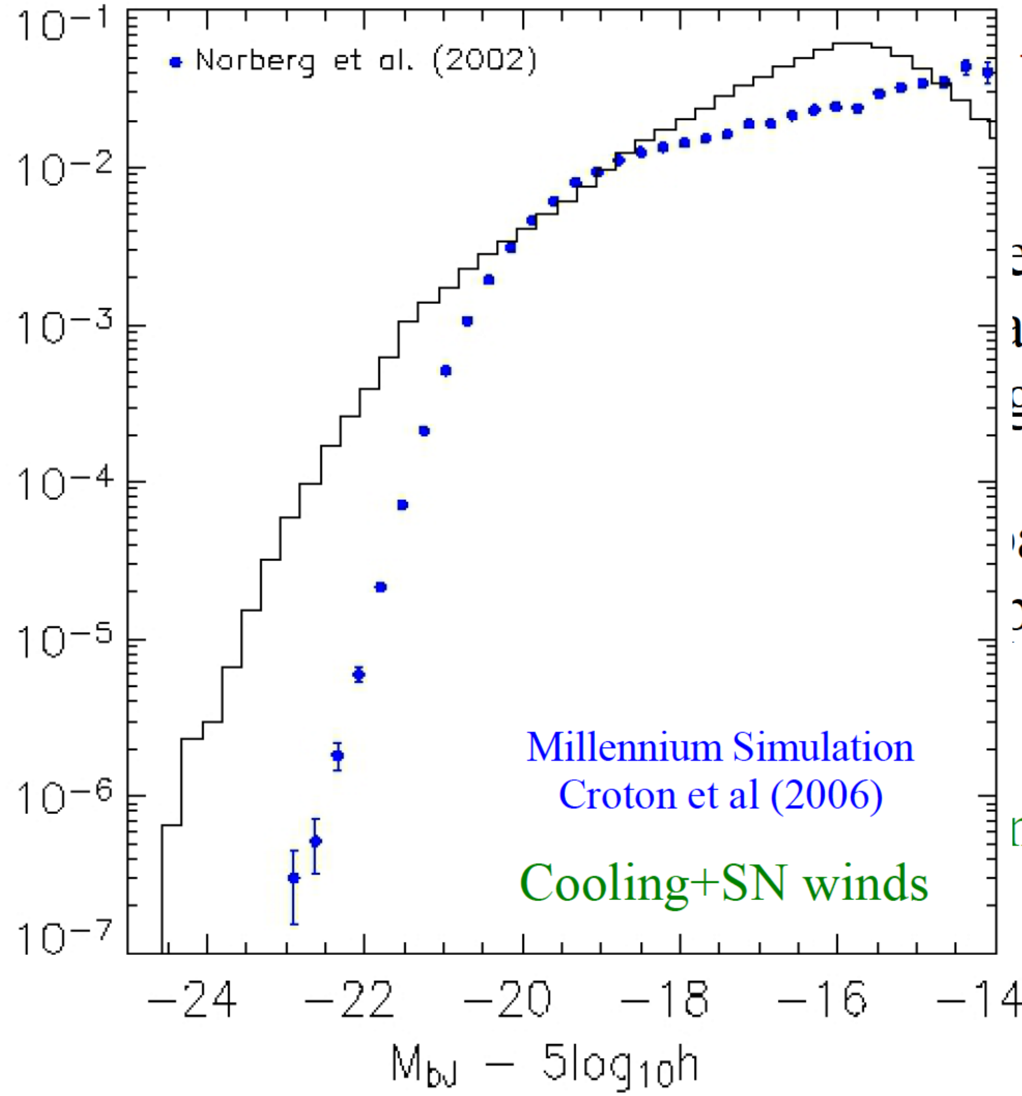

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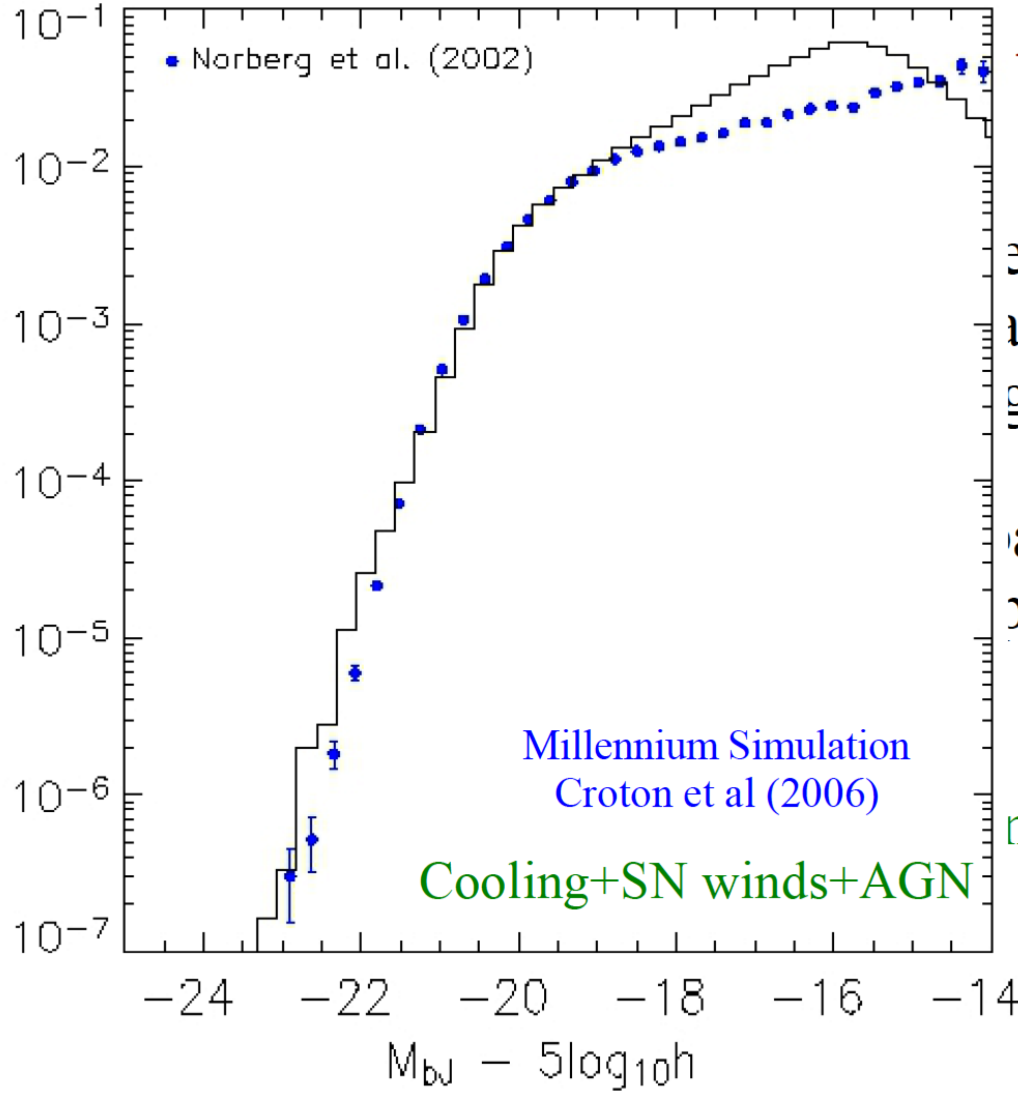

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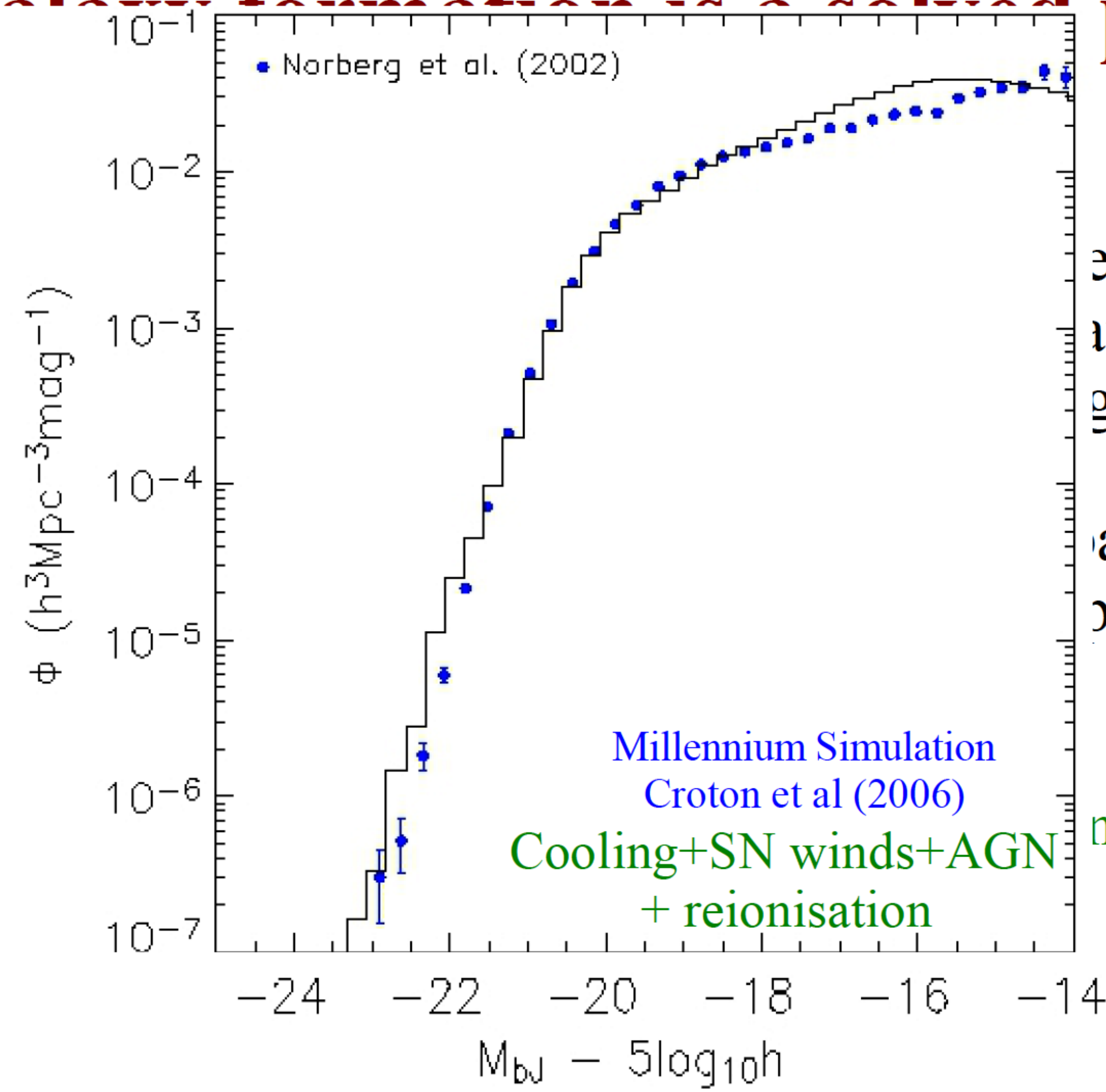
G… problem



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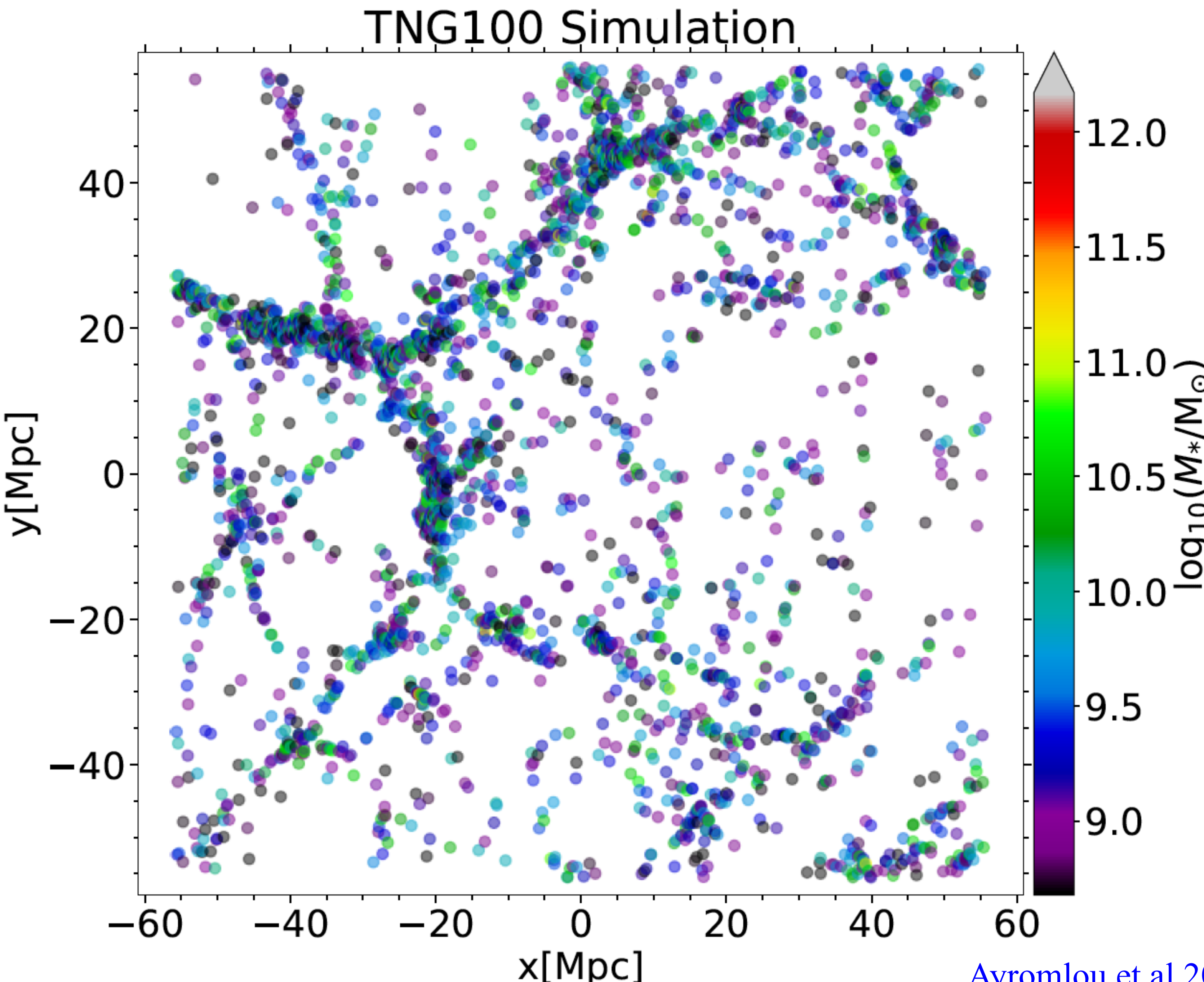
At high mass: Inefficient cooling; AGN feedback

Main outstanding issues:
I. Mechanical/radiative feedback, B-fields/cosmic rays, ejection/recycling
II. Can “subgrid” processes be sufficiently well/uniquely characterised?

Semianalytic versus full MHD simulations



Ayromlou et al 2021

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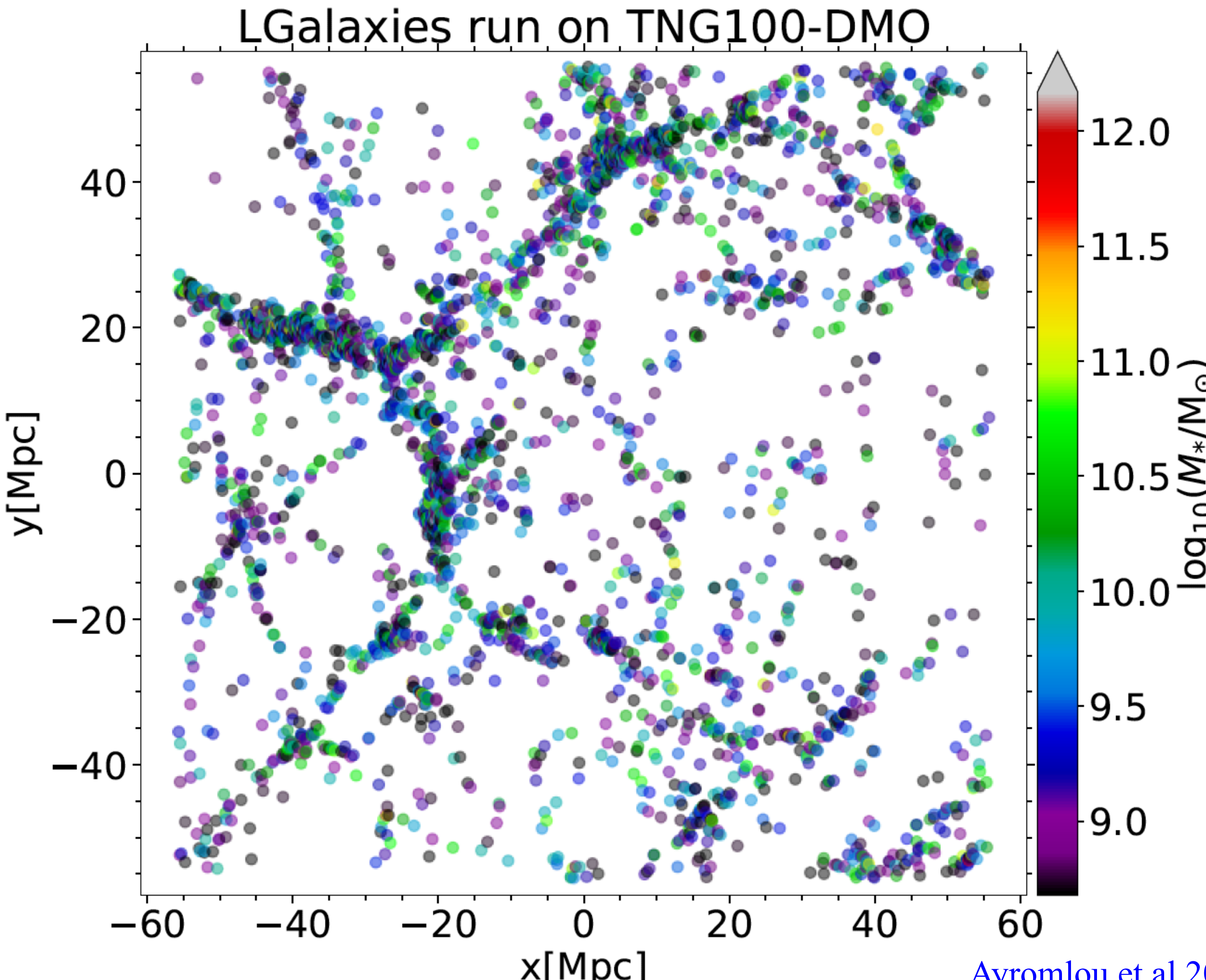

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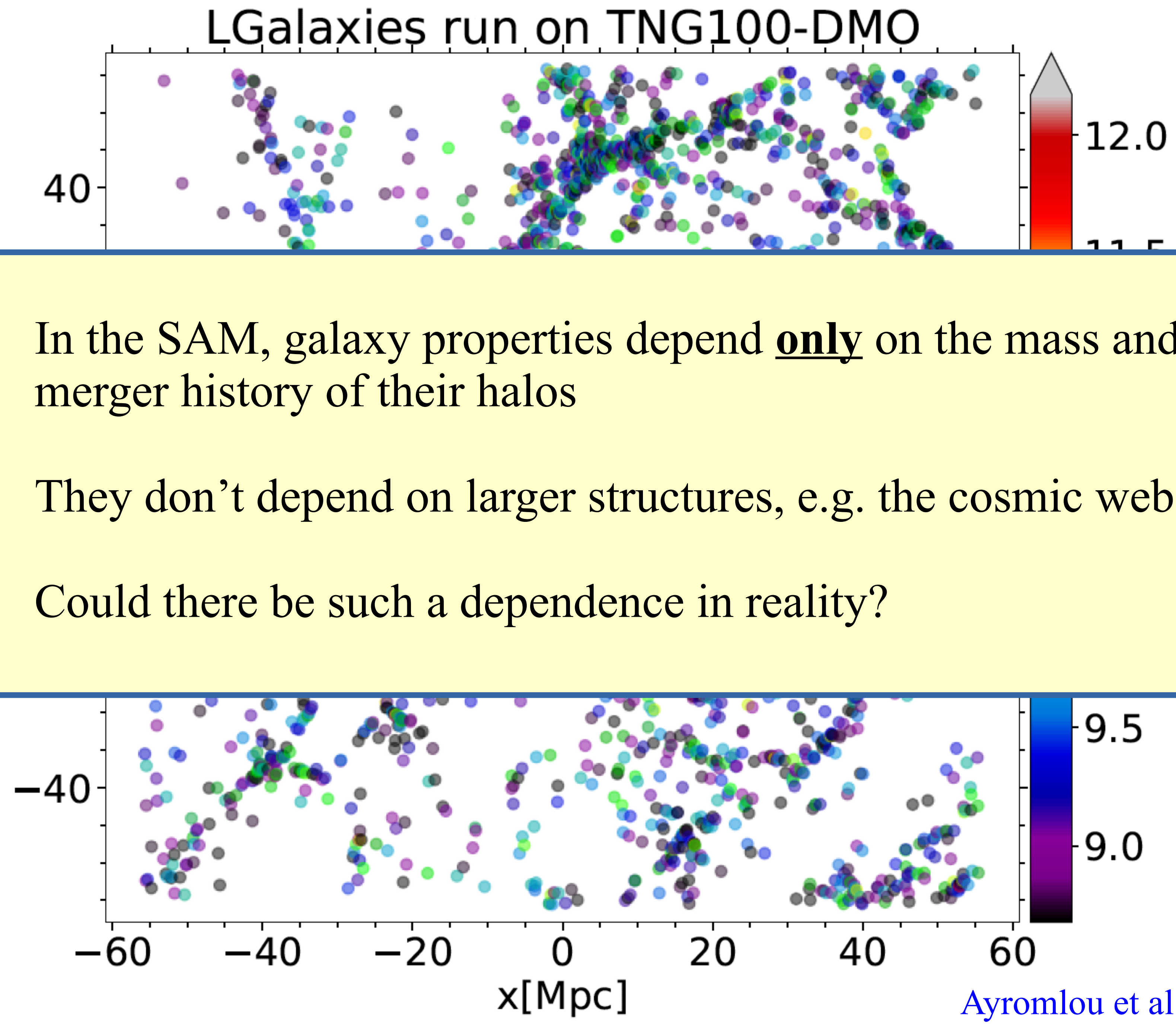


In the SAM, galaxy properties depend **<u>only</u>** on the mass and merger history of their halos

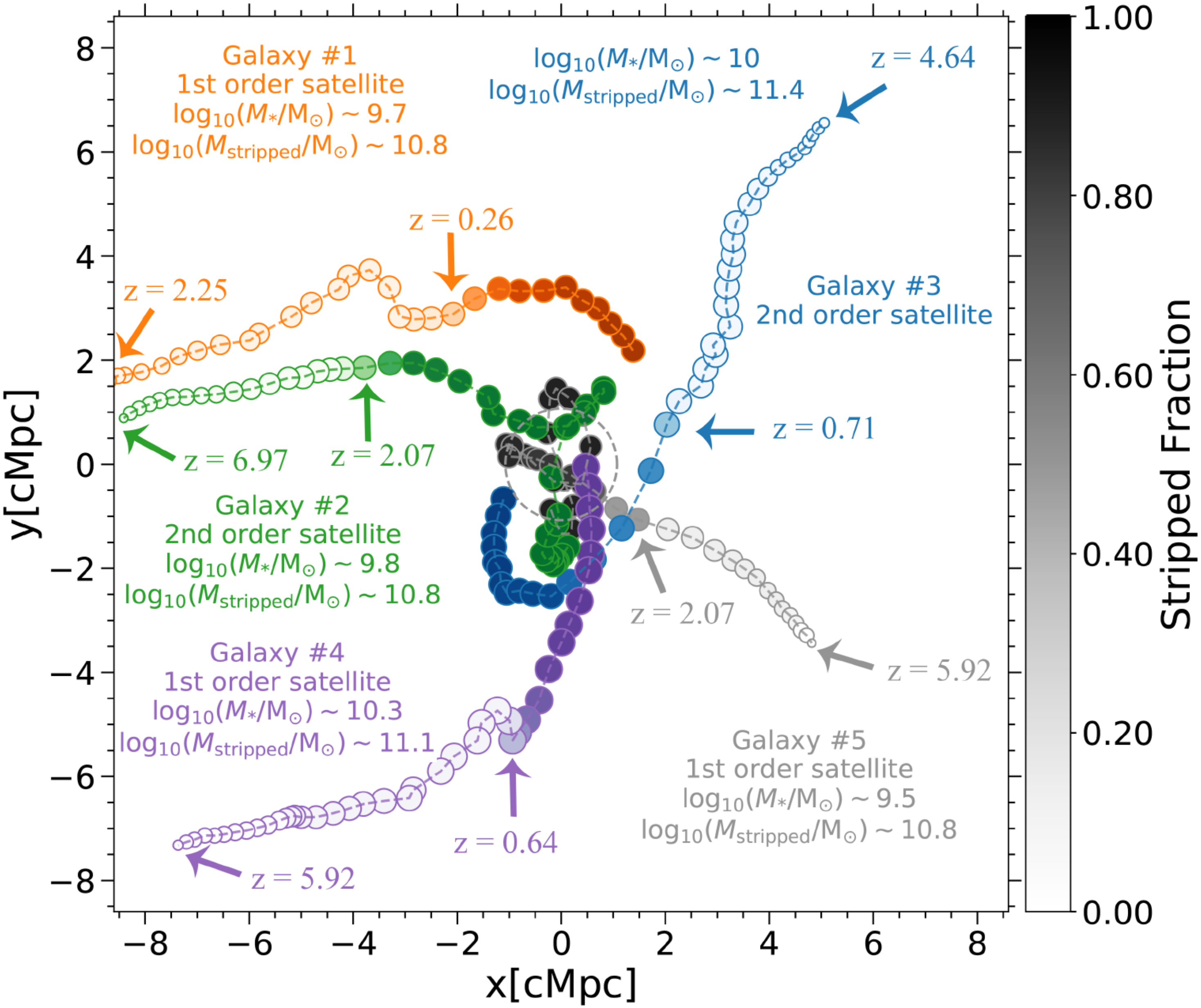
They don't depend on larger structures, e.g. the cosmic web

Could there be such a dependence in reality?

Ayromlou et al 2021

Quenching of galaxies through "starvation"

Ayromlou+ 2021

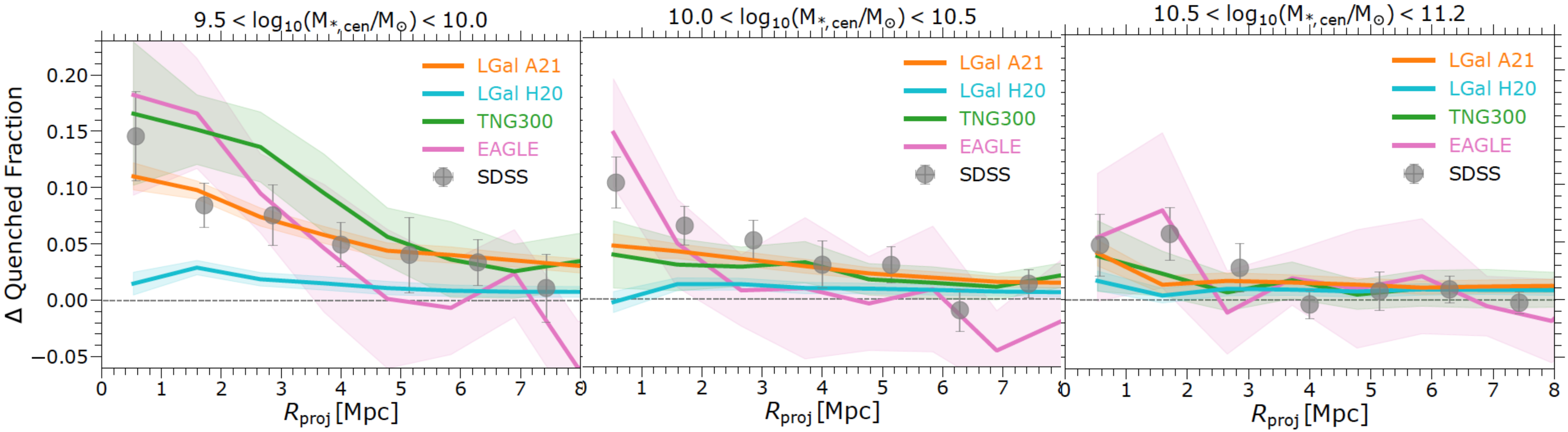


Galaxies will quench if their gas reservoir is removed by ram-pressure.

Here the properties of DM surrounding each halo are used to infer ρ and V for the gas environment.

Reservoirs can be stripped for galaxies which are not within massive halos

Stripping as a source of galactic conformity



Ayromlou+ 2022

Galactic Conformity: The probability that a neighbour of a central galaxy is quenched is larger if the central galaxy itself is quenched.

For lower mass centrals, this effect is observed in SDSS out to ~5 Mpc

This is fit by a SAM provided reservoirs are stripped also outside clusters

Take-home points?

- The inability of a model to fit observation is often more instructive than an apparent success.
- Different science goals require different levels/kinds of understanding
- Cosmological interpretation of upcoming surveys will likely require models with consistent <u>evolution</u> of halo/galaxy populations
- Stars are a small fraction of the condensed baryonic content of hi-z galaxies. They are mostly made of HI.
- Galaxy properties depend strongly on the mass/assembly history of their haloes but only weakly on the larger cosmic web (alignments).