Massive galaxies and their gaseous halos - Insights from numerical simulations

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Outline

- The challenge of galaxy formation / evolution
- Massive galaxies at z~2-3 (cosmic noon)
- The circum-galactic medium around massive galaxies

Galaxies

Galaxies form at the centers of DM halos

Galaxies are “eco”systems

Inflow of gas:

- from cosmic web
- cooling out of hot gas halo
- feeds SF in central galaxy

Outflow of gas:

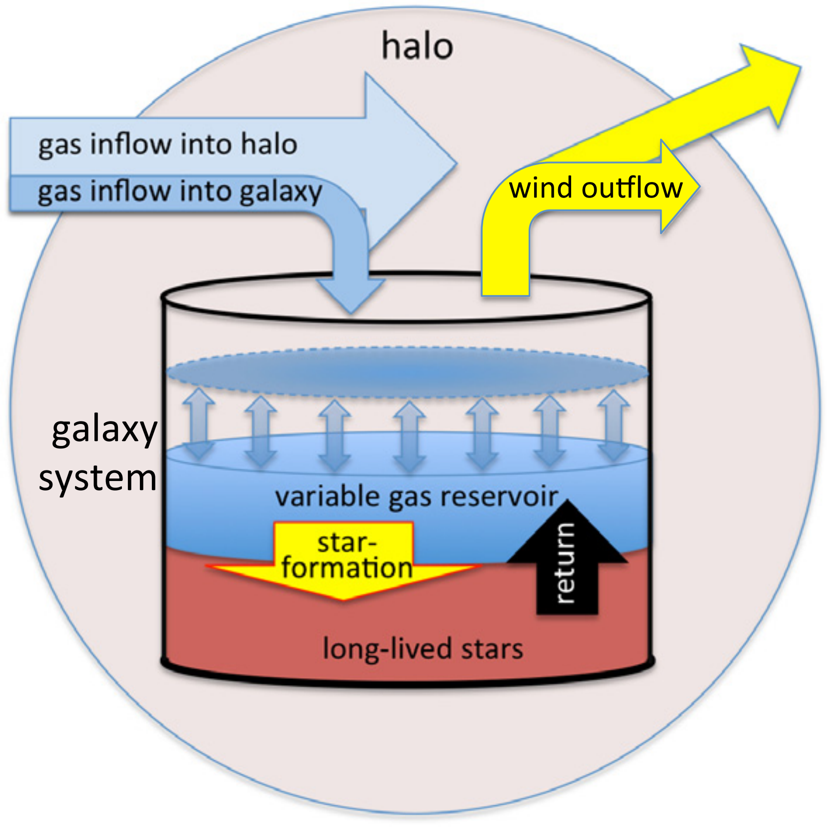
- powered by star formation or AGN

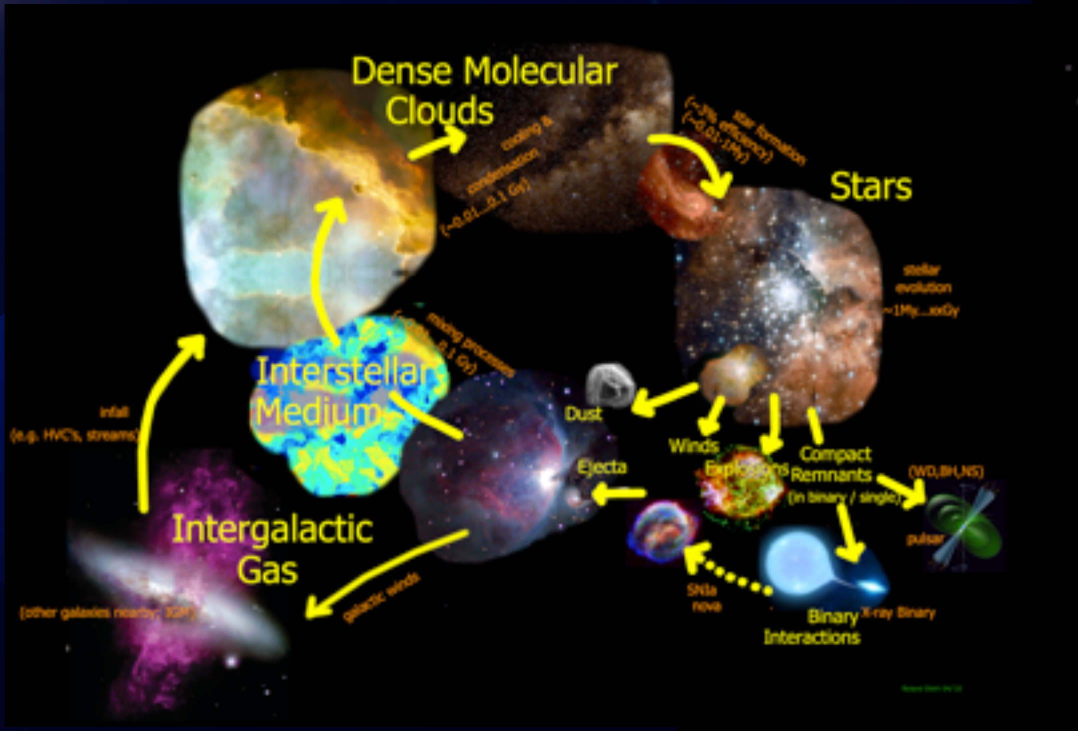
Transformation of gas:

- Star formation
- Chemical conversion

Feedback from stars (and AGN):

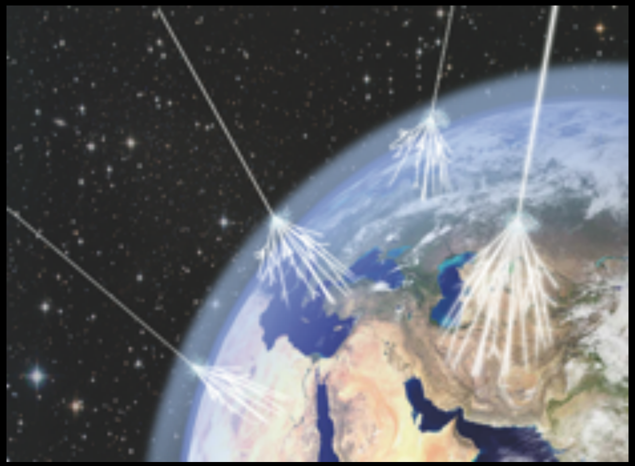
- energetic, momentum, mass
- enrichment



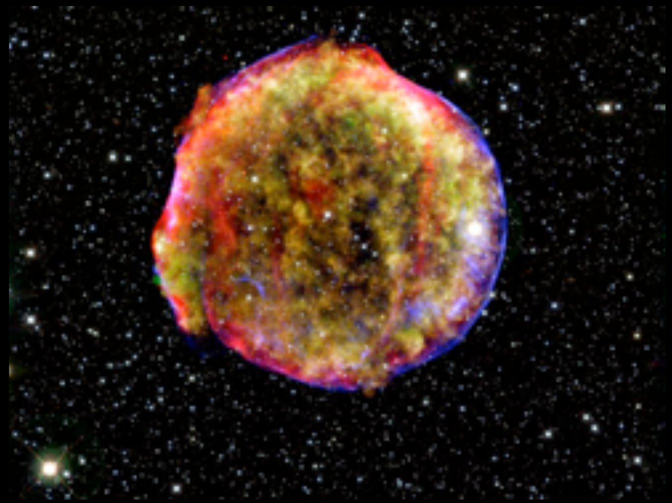


Physical processes

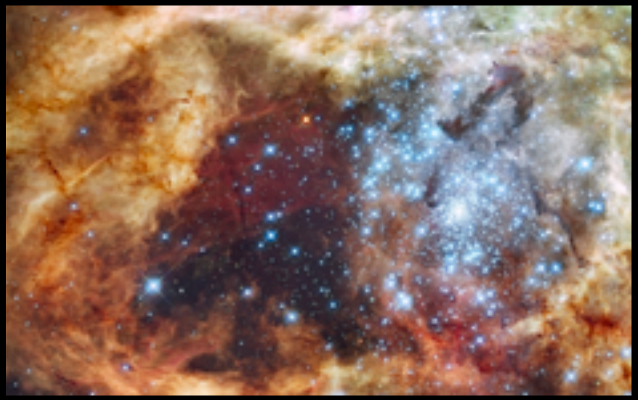
Cosmic Rays



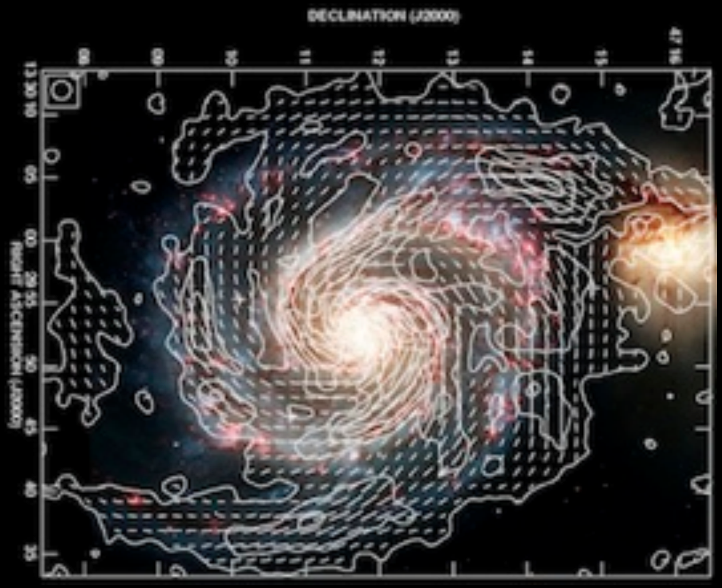
Fluid dynamics



Stellar Feedback



Magnetic fields

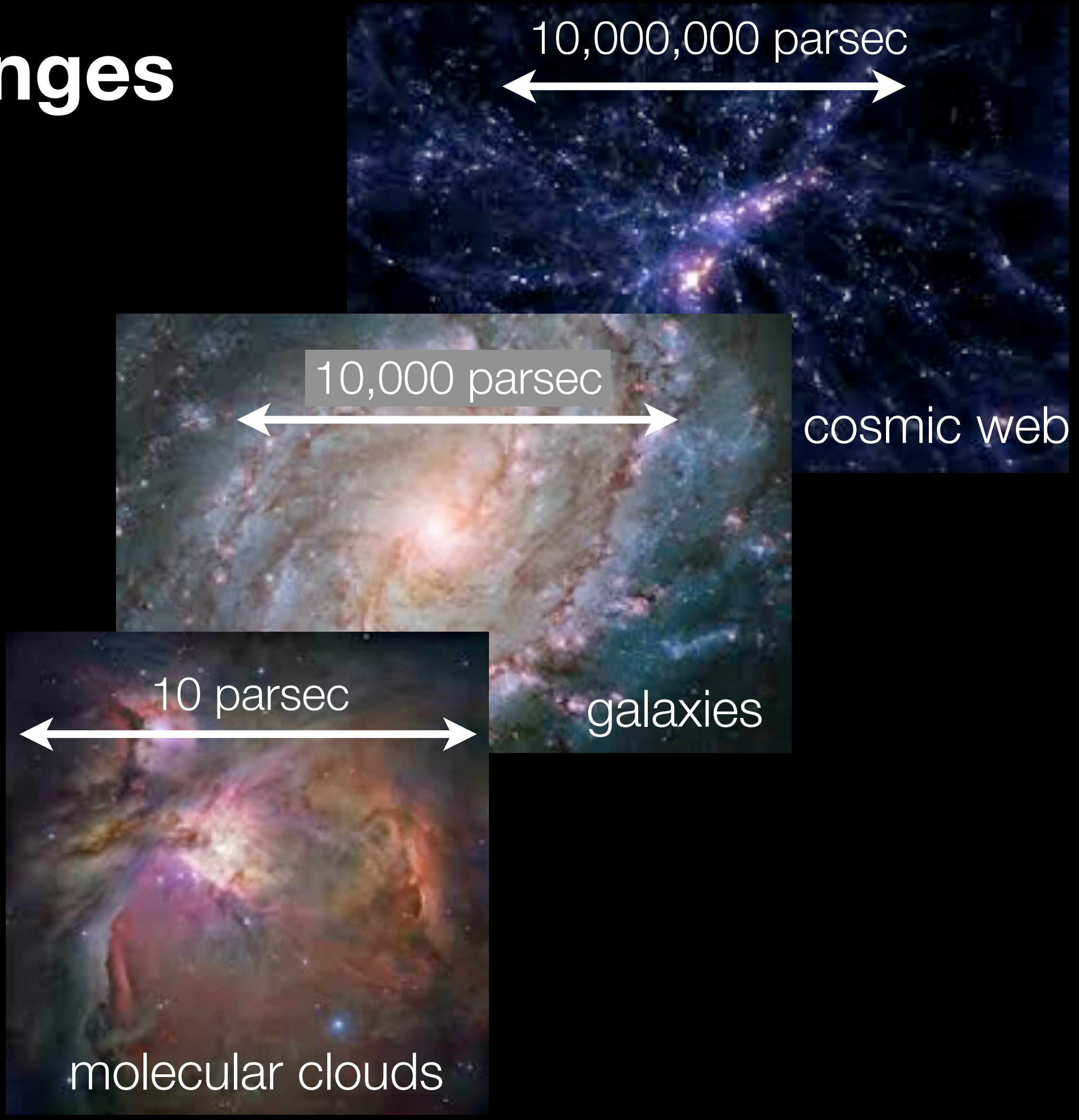


Gravity

Black hole feedback

gas cooling, star formation, radiative transfer, chemical reactions, ...

Modeling Challenges



Dynamical Range problem

Spatial Scales:

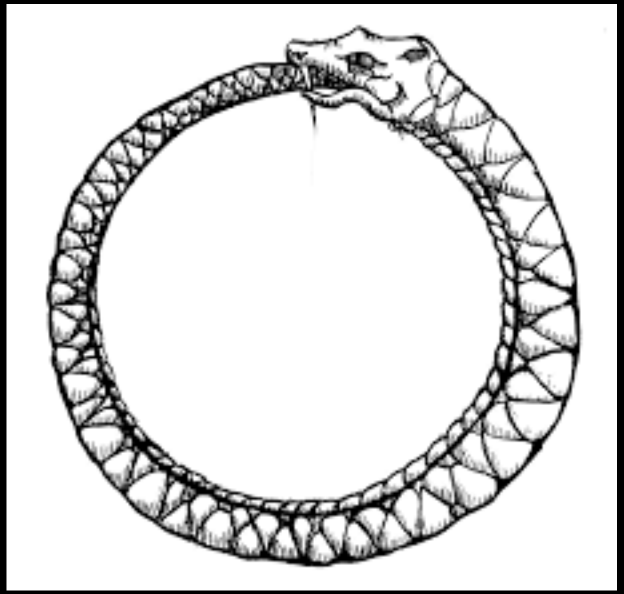
- tides from large scale cosmology: $\geq 10^7$ pc
- star formation: $\leq$ pc scale

Time Scales:

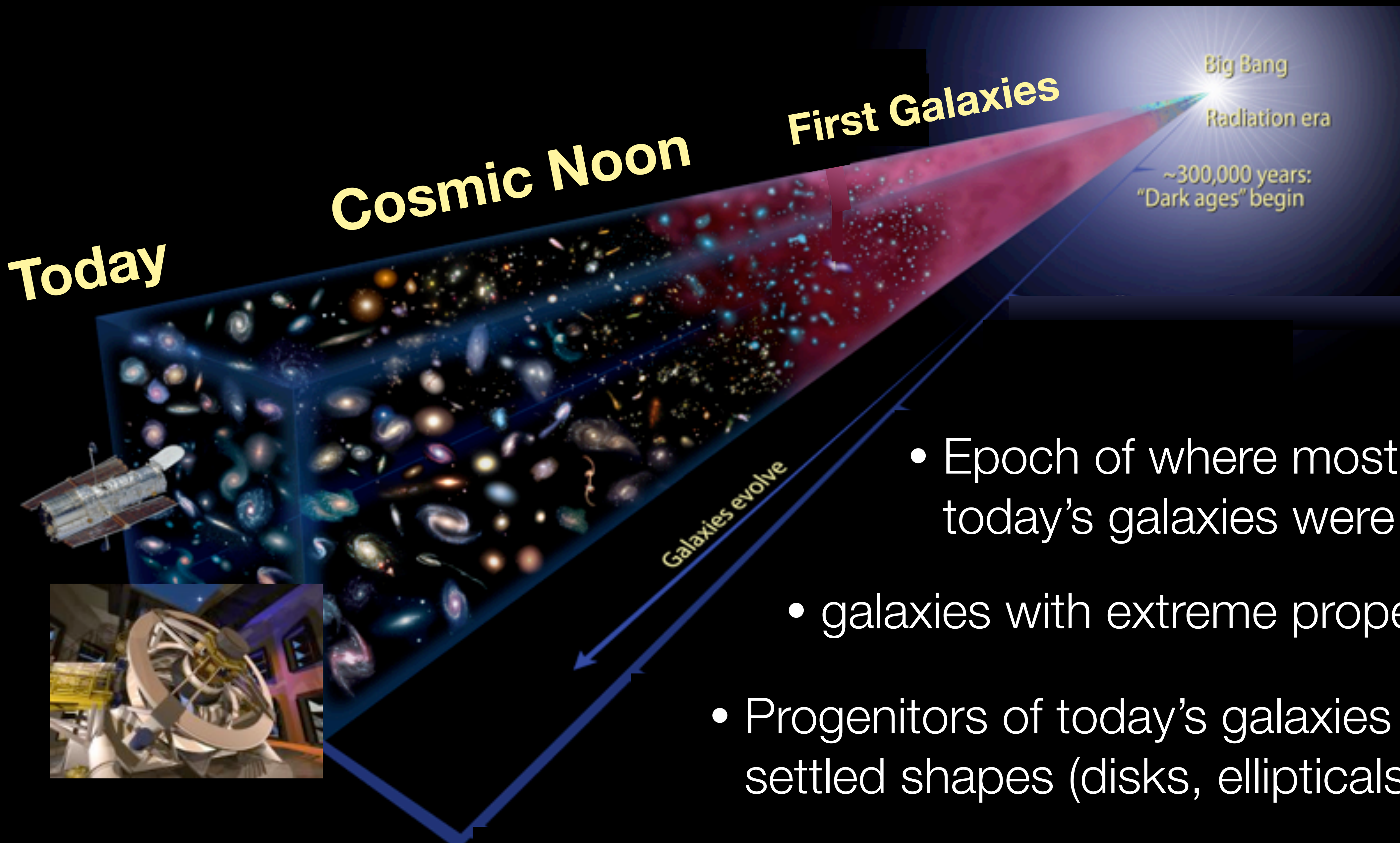
- age of the Universe: ~ 10^{10} years
- dynamical time of galaxies, physics of star formation: ~ $10^{5\text{-}6}$ years

Coupling of Scales problem

- large scales provide boundary conditions for small scales
- feedback from small scales affects large scales



Cosmic noon: z~2-3



- Epoch of where most stars in today's galaxies were formed
- galaxies with extreme properties
- Progenitors of today's galaxies appear, settled shapes (disks, ellipticals etc)
- first massive groups and clusters form

A **main target** of current and future **observational missions** and **theoretical model efforts**

Massive Galaxies at z~2-3

Highest

Lowest

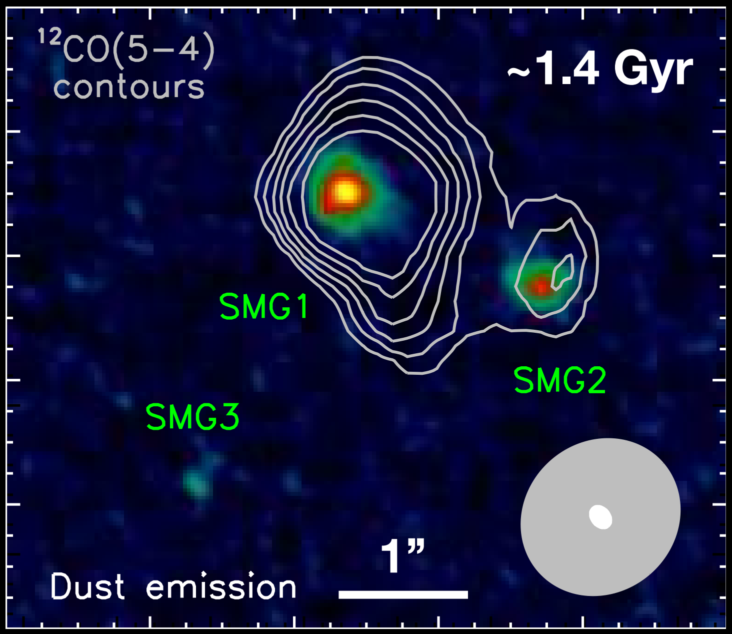
Starbursting galaxies

- form stars at rates ~1000 times that of our Galaxy, very dusty
- luminous in sub-mm
  up to 10,000,000,000,000 x the Sun
- massive (≳ our own Galaxy)
- few examples in today's Universe: all major galaxy mergers

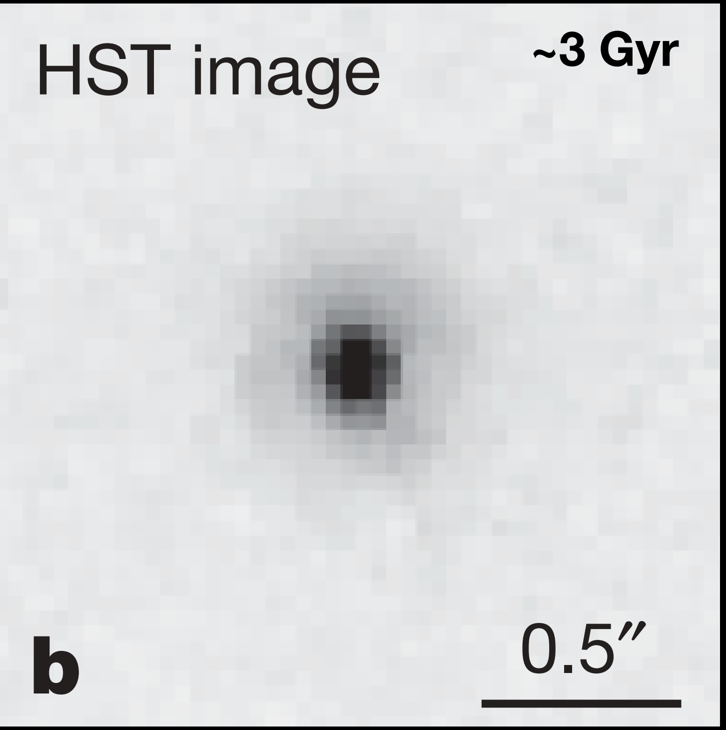
Quiescent galaxies

- low star formation, little dust
- often very compact (≲ kpc)
- massive (≳ our own Galaxy)
- almost all massive galaxies in today's Universe are quiescent

ALMA: 870μm + CO

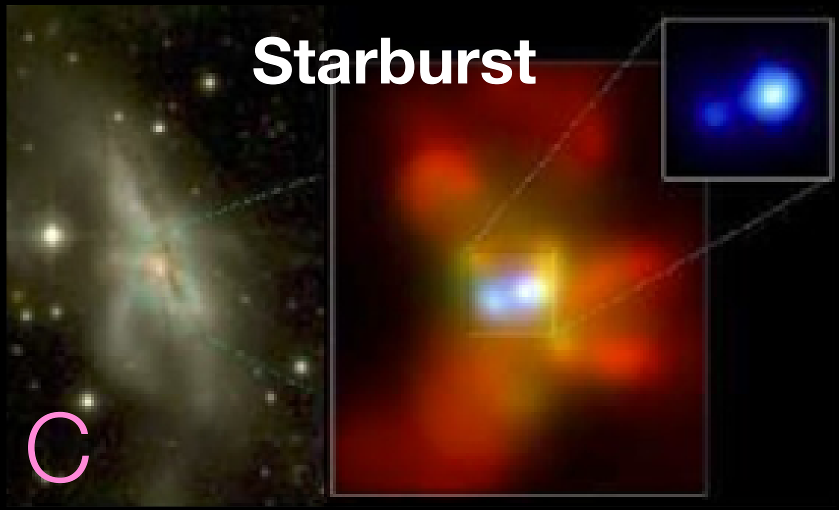


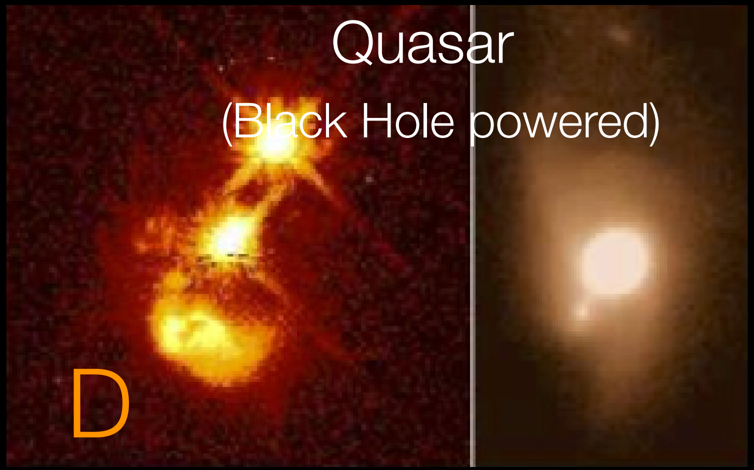
Oteo et al. 2016

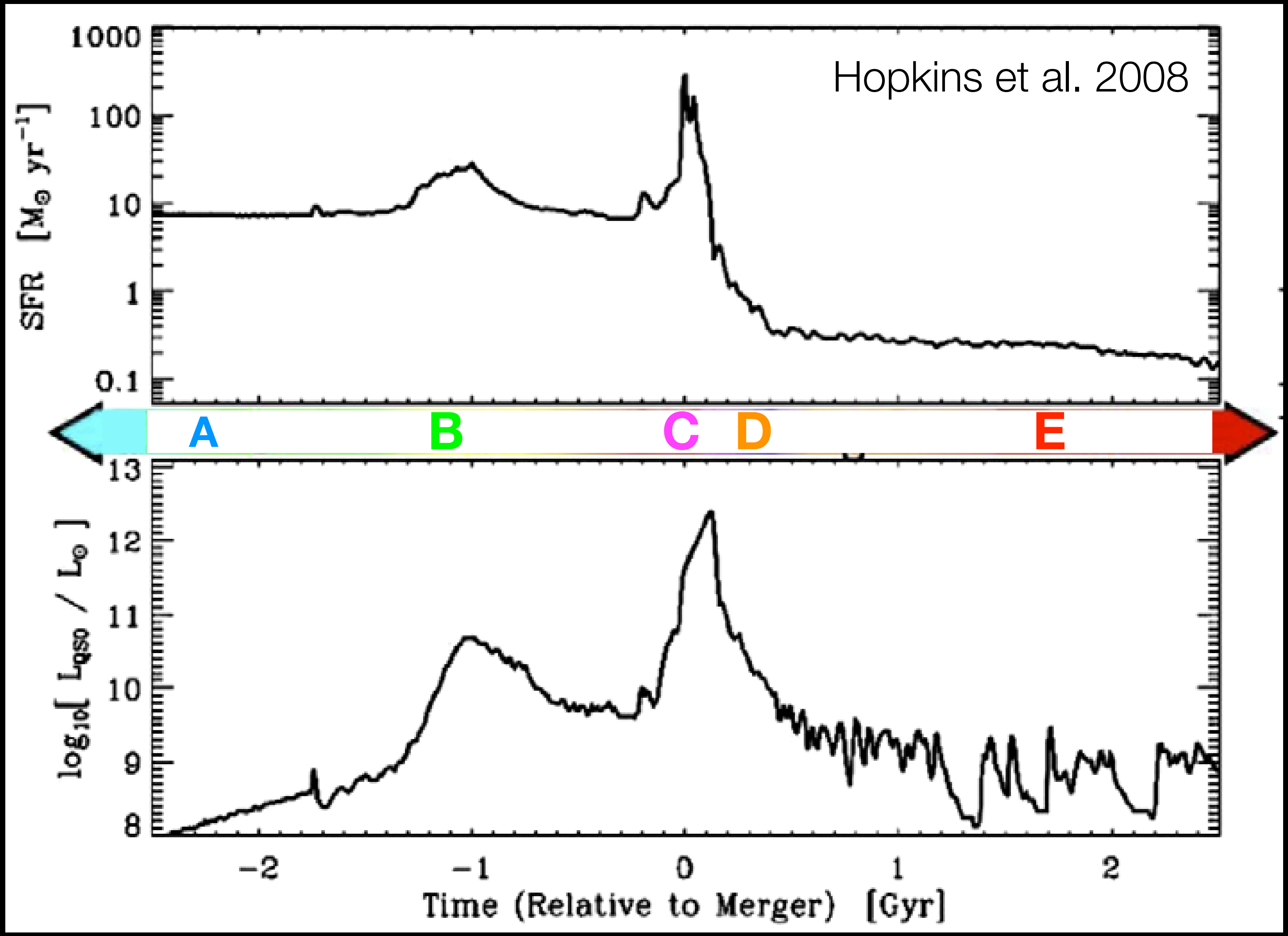


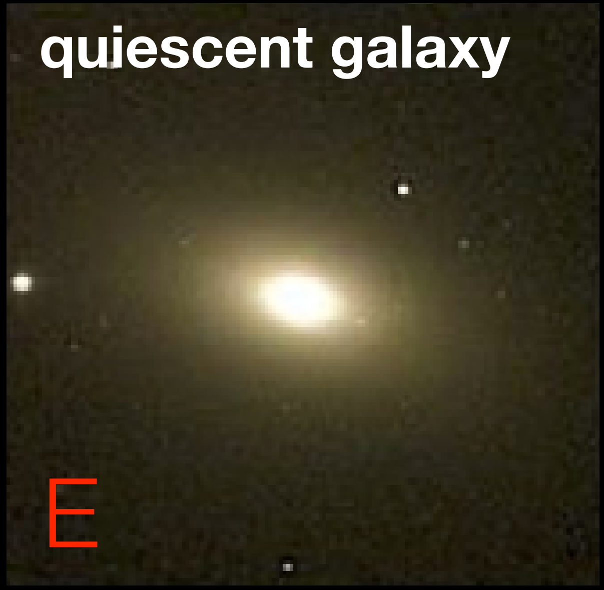
van Dokkum et al. 2009

Major merger based paradigm









Major merger based paradigm

Success of this picture

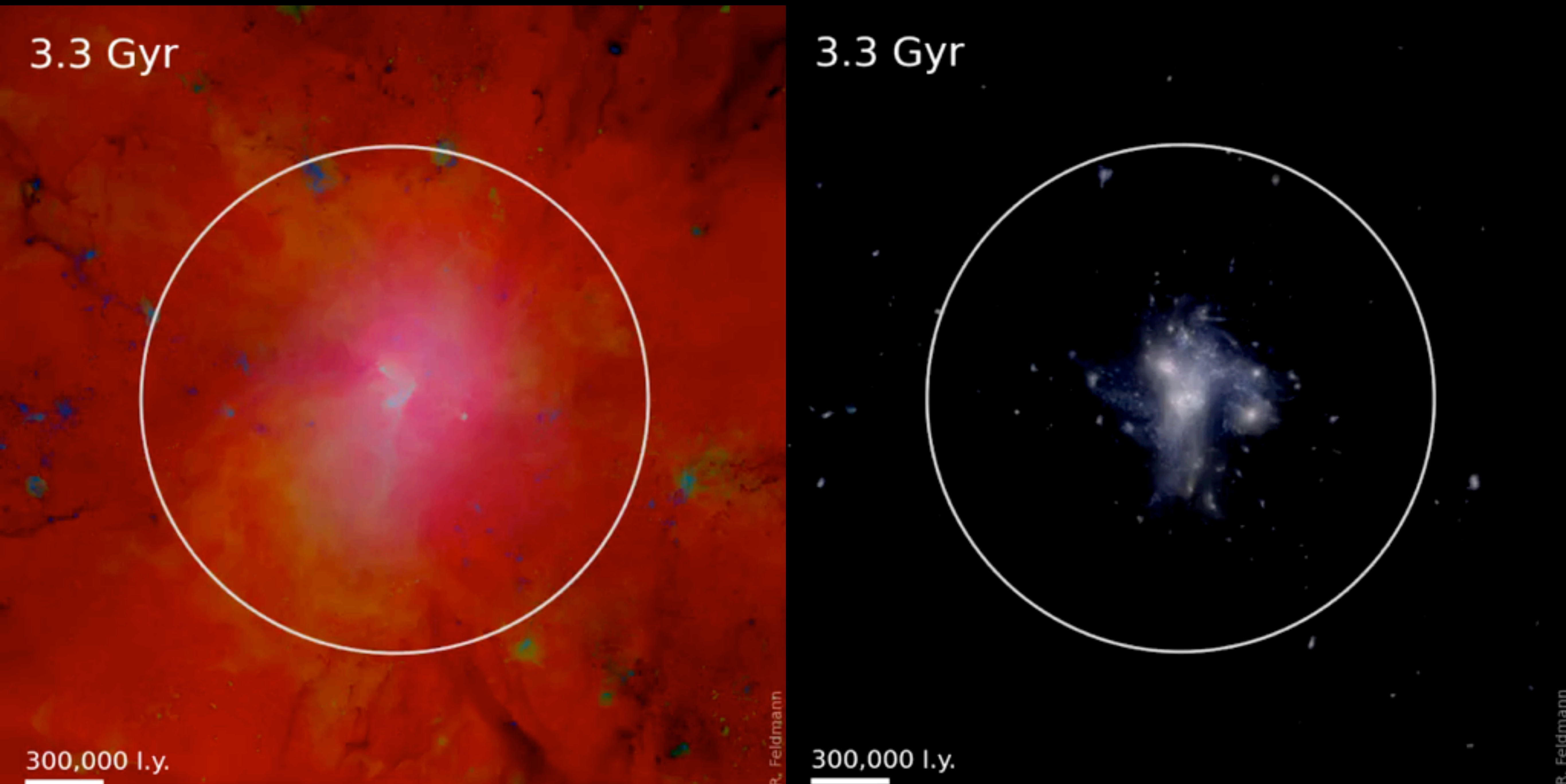
- explains/links origin of starbursting and quiescent galaxies
- evidence for AGN driven outflows (e.g., Nesvadba+08, Genzel+14, Carniani+16)
- many galaxies at high z show disturbed morphologies, mergers
- may explain correlation between central density and quiescence

Challenges

- fails to reproduce observed number density of starbursting galaxies
    - short duty cycle of star bursts
    - rate of major mergers between galaxies is too low
    - mergers do not produce enough sub-mm flux efficiently
- Unclear whether super-massive black hole regulate/stop star formation

- Sample of ~40 simulated massive galaxies at z~2 with resolved internal structure
- cosmological, zoom-in simulations
- halo masses: $3{\times}10^{12}$ - $3{\times}10^{13}$ $M_\odot$

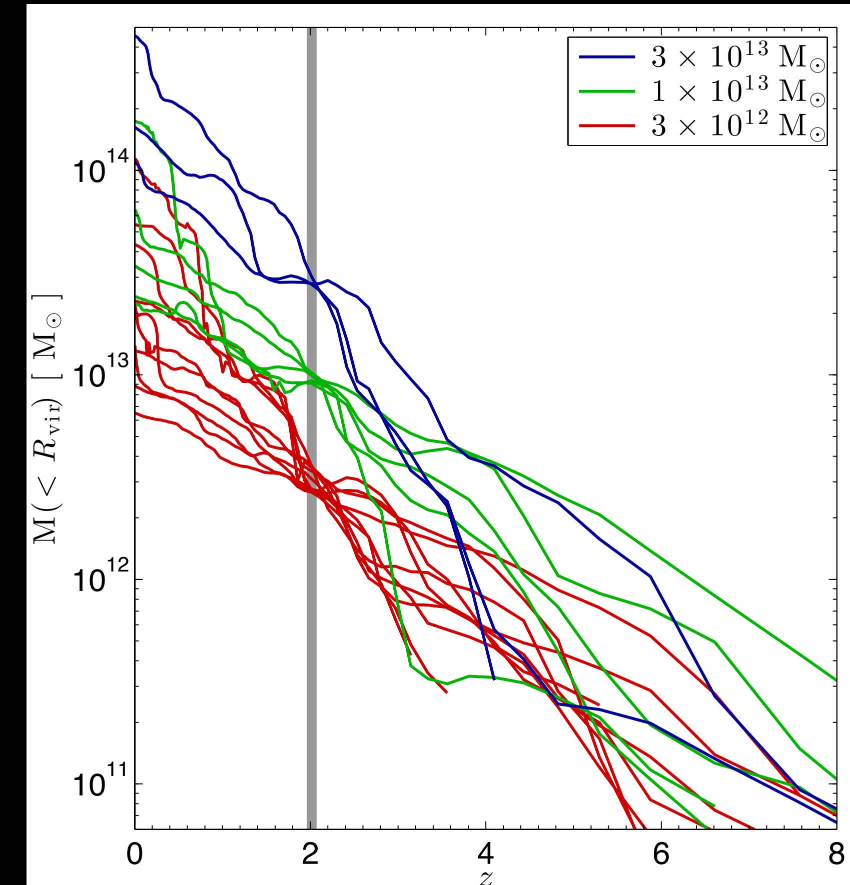
RF et al. 2016 MNRAS



Massive FIRE

Feedback In Realistic Environments

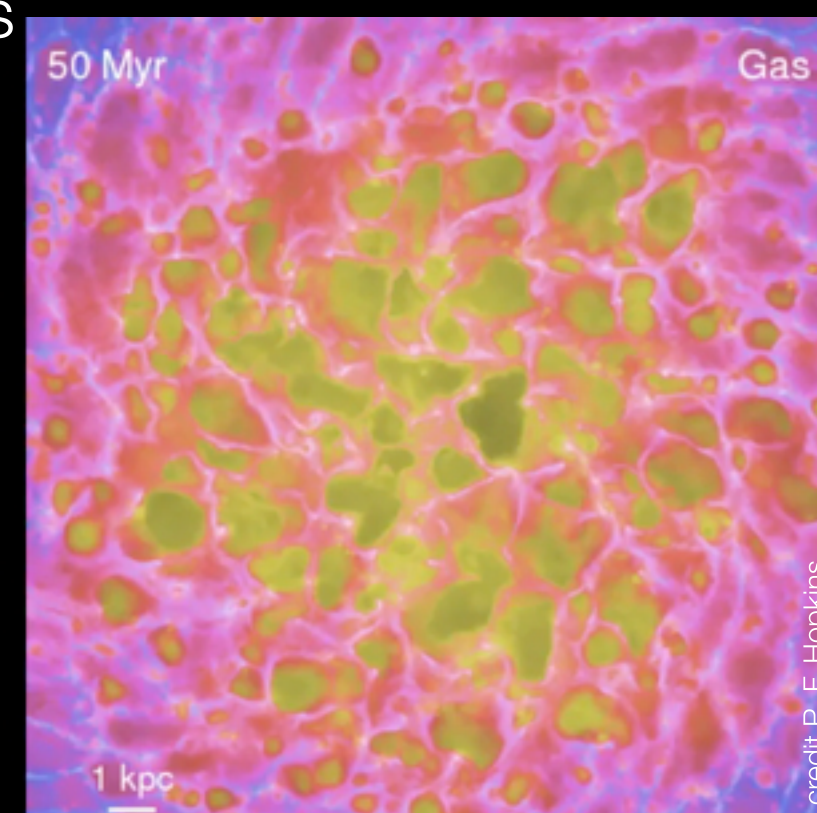
- Variety of halo growth histories



- Outstanding numerical resolution (~10 parsecs, 10^4 solar masses)

- State-of-the-art hydrodynamical solver (next generation SPH, GIZMO)

- Sophisticated modeling of **star formation** and **stellar feedback** (FIRE)
  - star formation not tuned to empirical scaling relations
  - stellar feedback physically modeled (no “recipes”): radiation pressure, stellar winds, supernovae



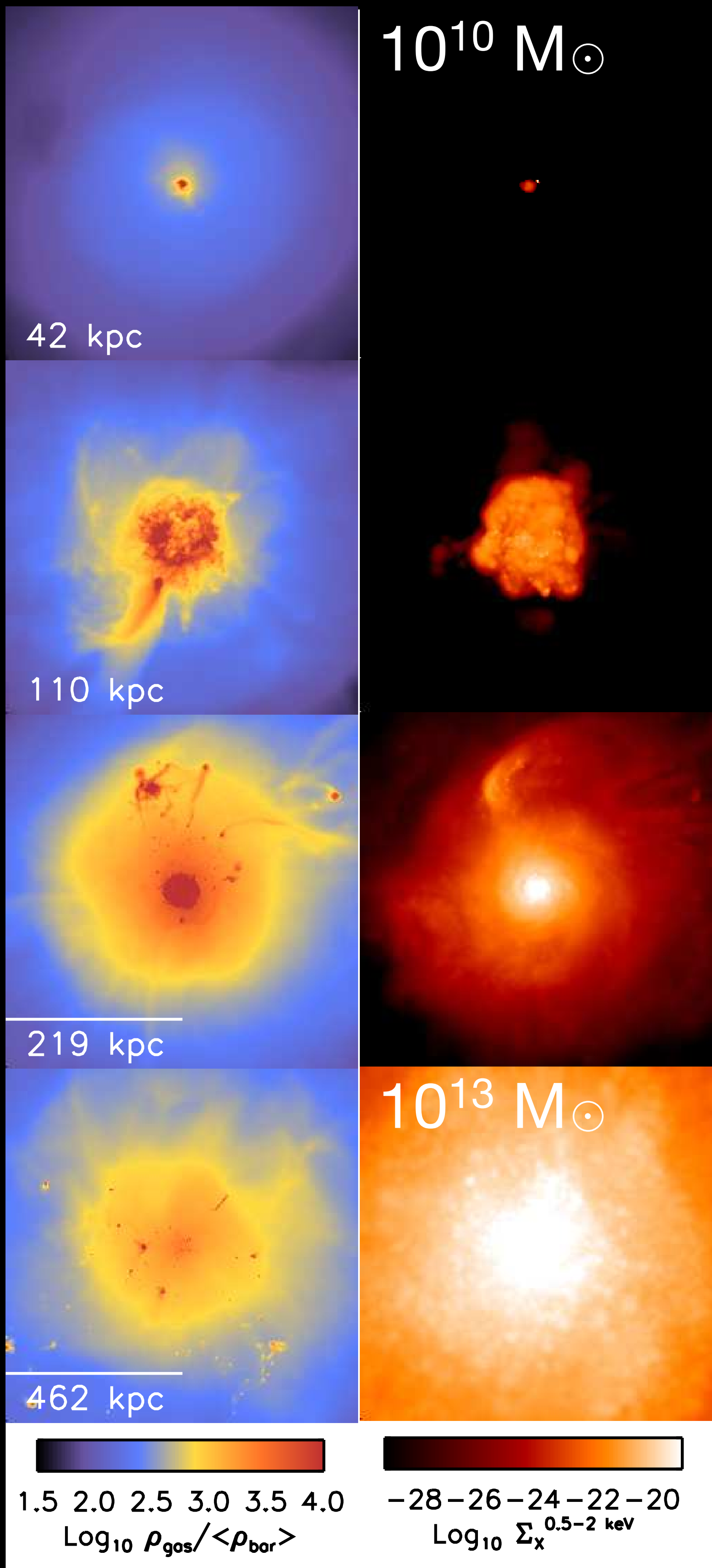
- **no** *energy / momentum injection from* **supermassive black holes**

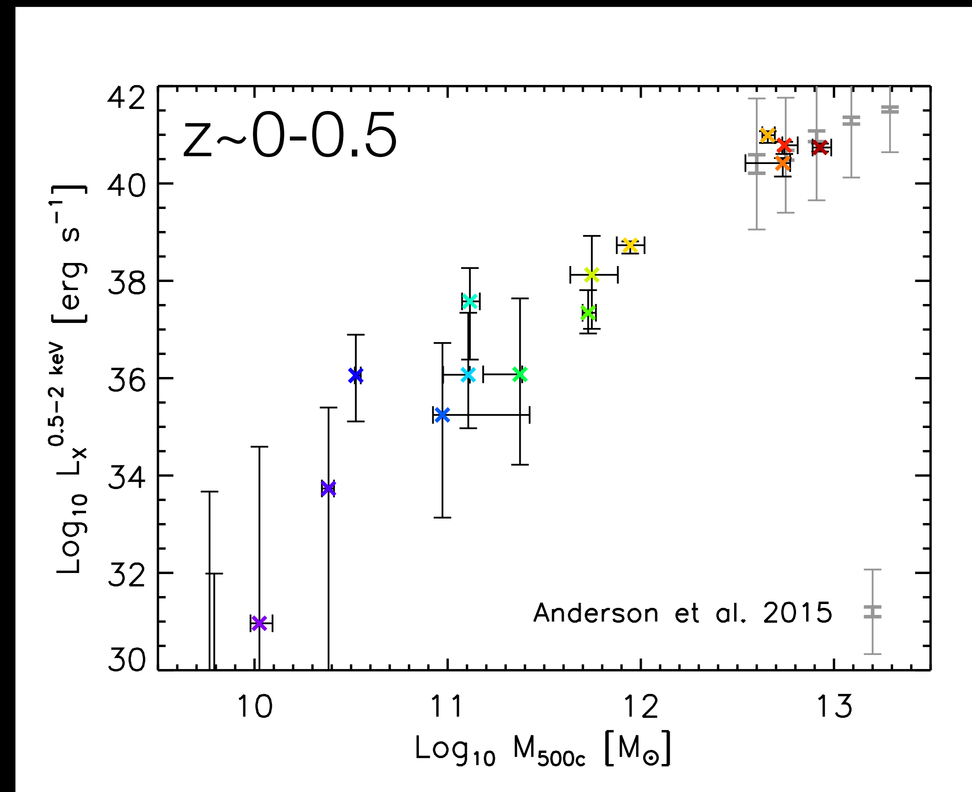
Physical model contains no ad hoc parameters

Validation of the physical model

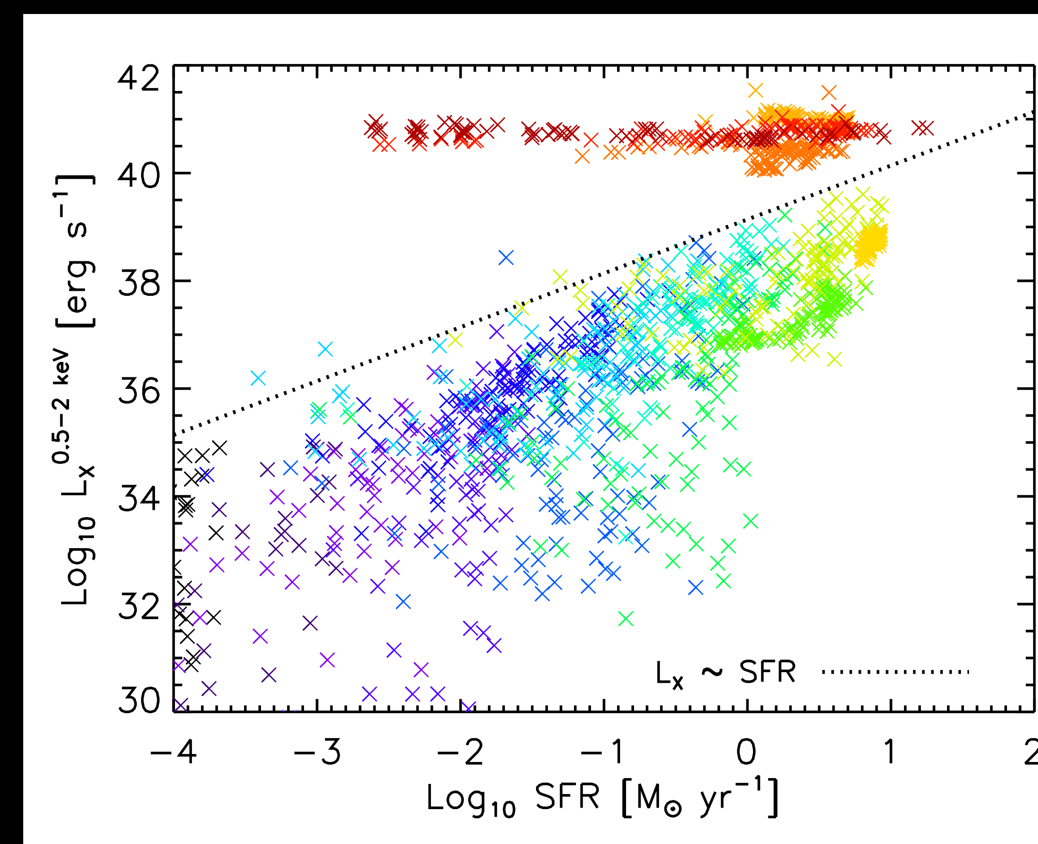
- properties of galaxies in today's Universe, e.g., relations between star formation rate, gas content, heavy element content (e.g. Hopkins et al. 2014, Ma et al. 2016)
- properties of outflows driven by stellar energy/momentum injection (Muratov et al. 2015)
- Variability of the star formation rate in galaxies (Sparre, Hayward, RF et al. 2016)
- Emission lines from gas in halos at t~1.5-3 Gyr (Sravan, ..., RF et al. 2016)
- covering fractions of neutral hydrogen in massive halos (Faucher-Giguère, RF, et al. 2016)
- Soft X-ray emission, Sunyaev-Zel'dovich signal (van de Voort, Quataert, RF et al. subm.)
- presence/origin of large star forming clumps in massive, young galaxies (Oklopčić, Hopkins, RF, et al. subm.)
- ...

Soft X-ray emission





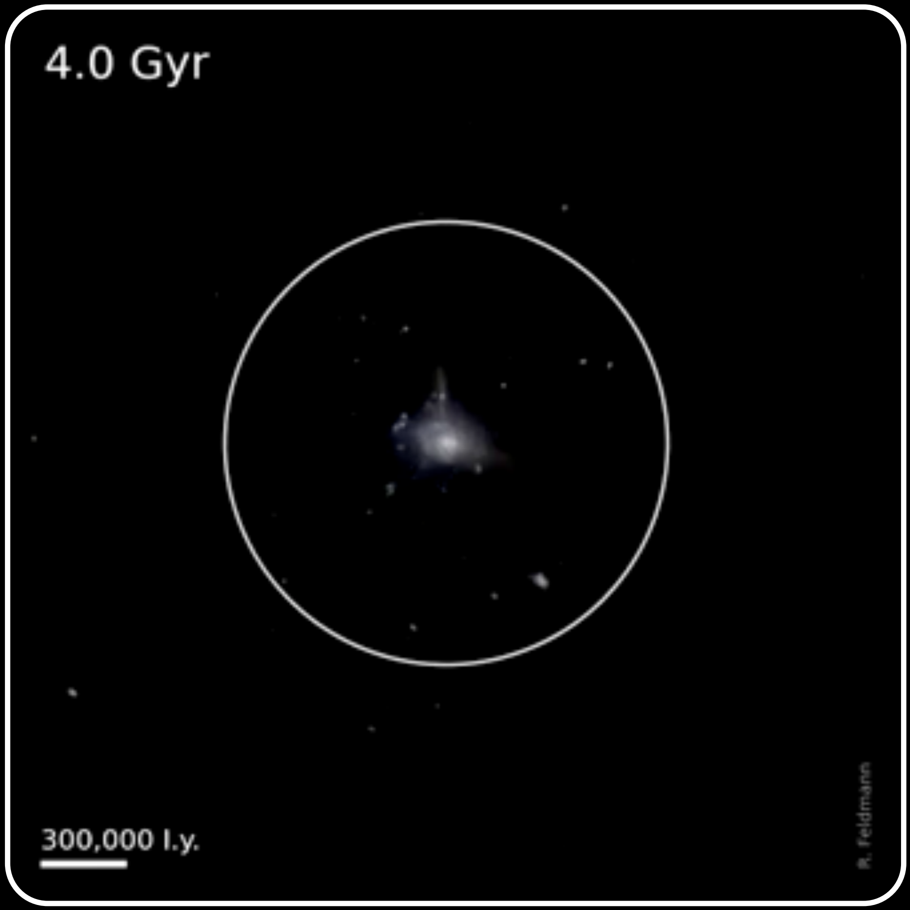
van de Voort et al. subm.

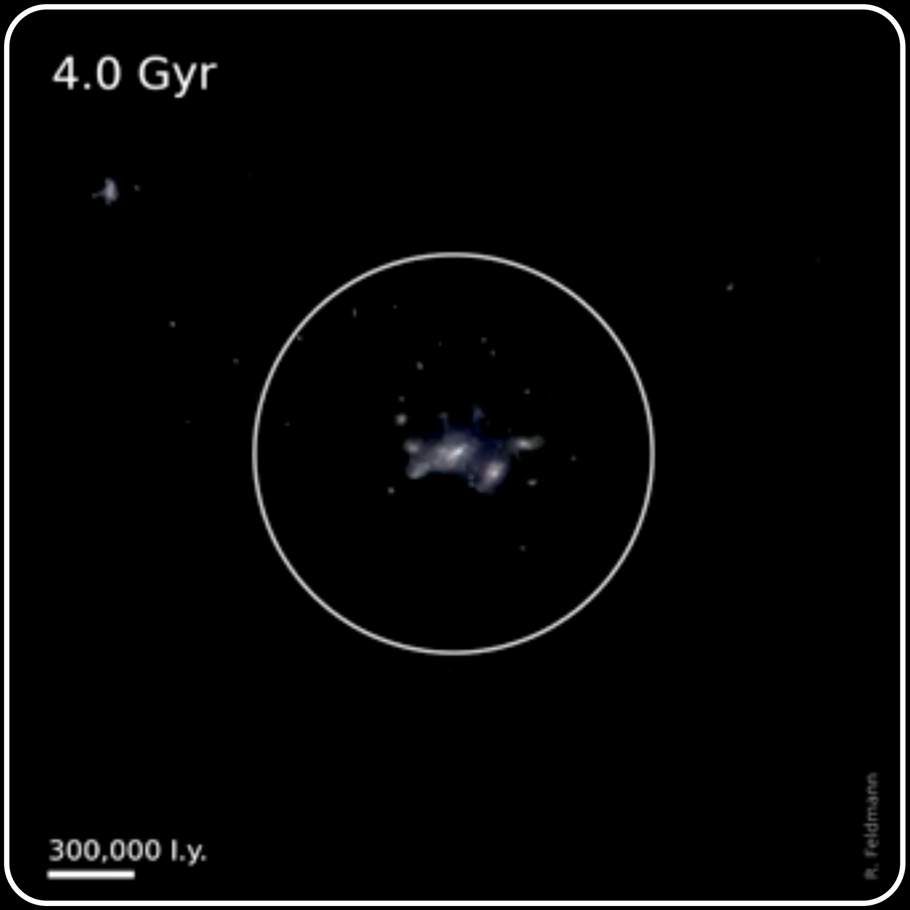


SF driven outflows drive X-ray lum. in low mass halos

Star forming galaxies

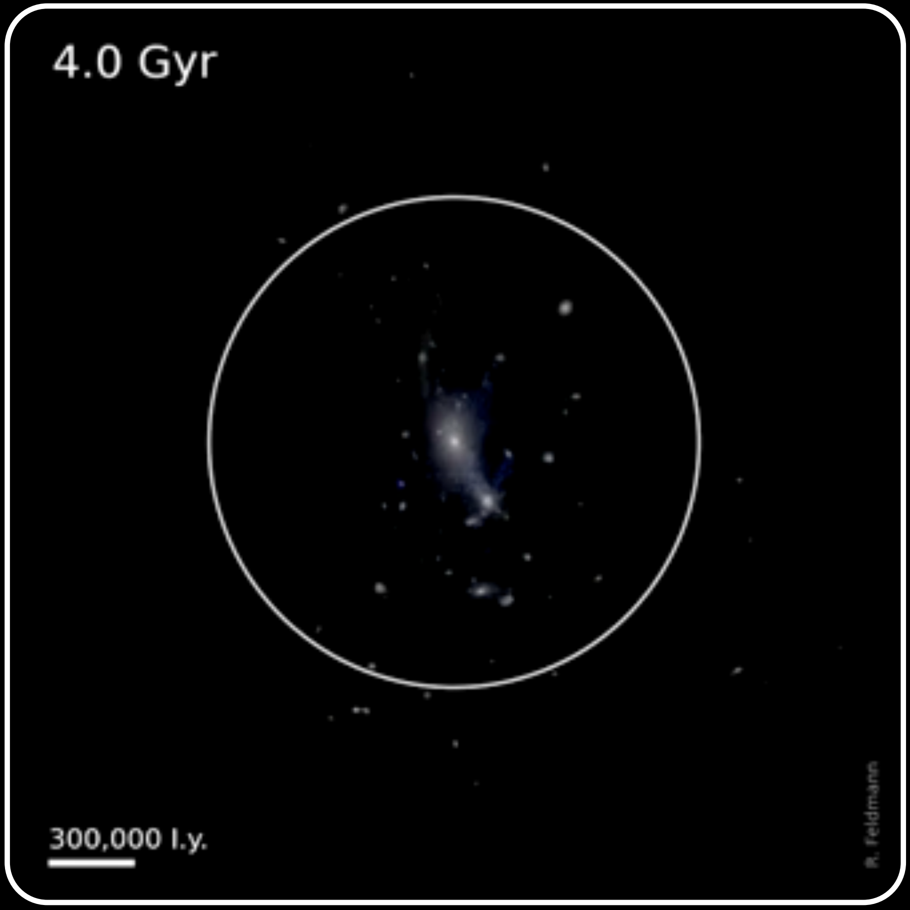
- dusty
- disturbed morphologies
- blueish colors

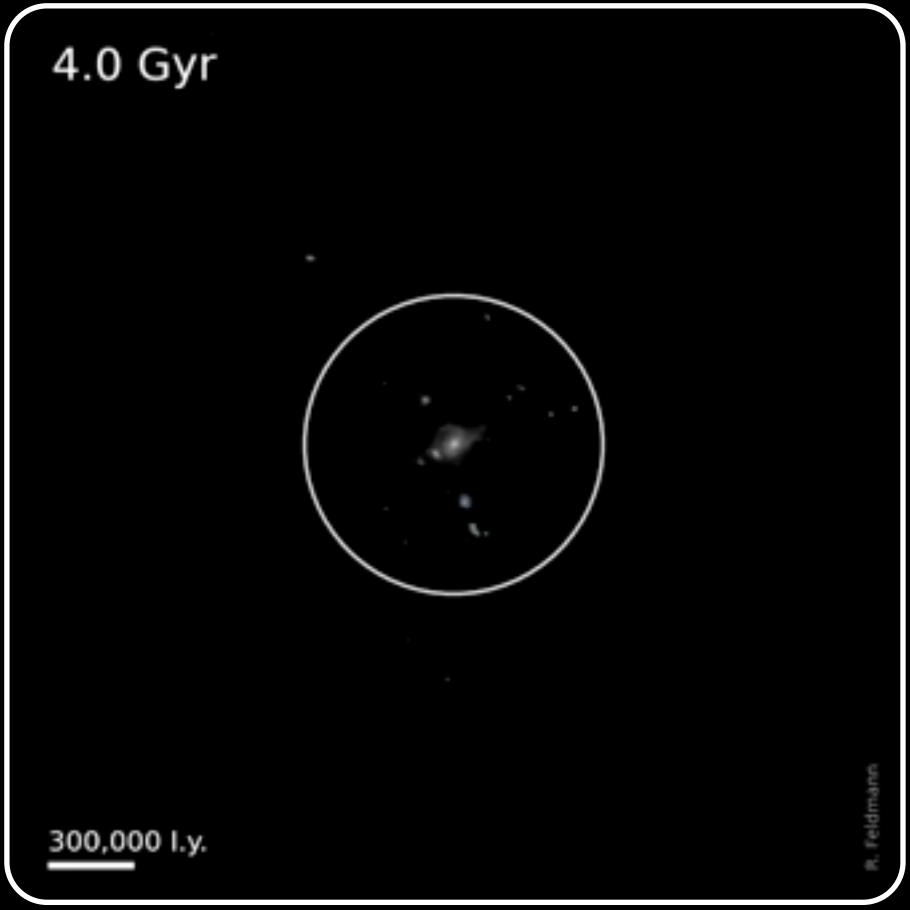




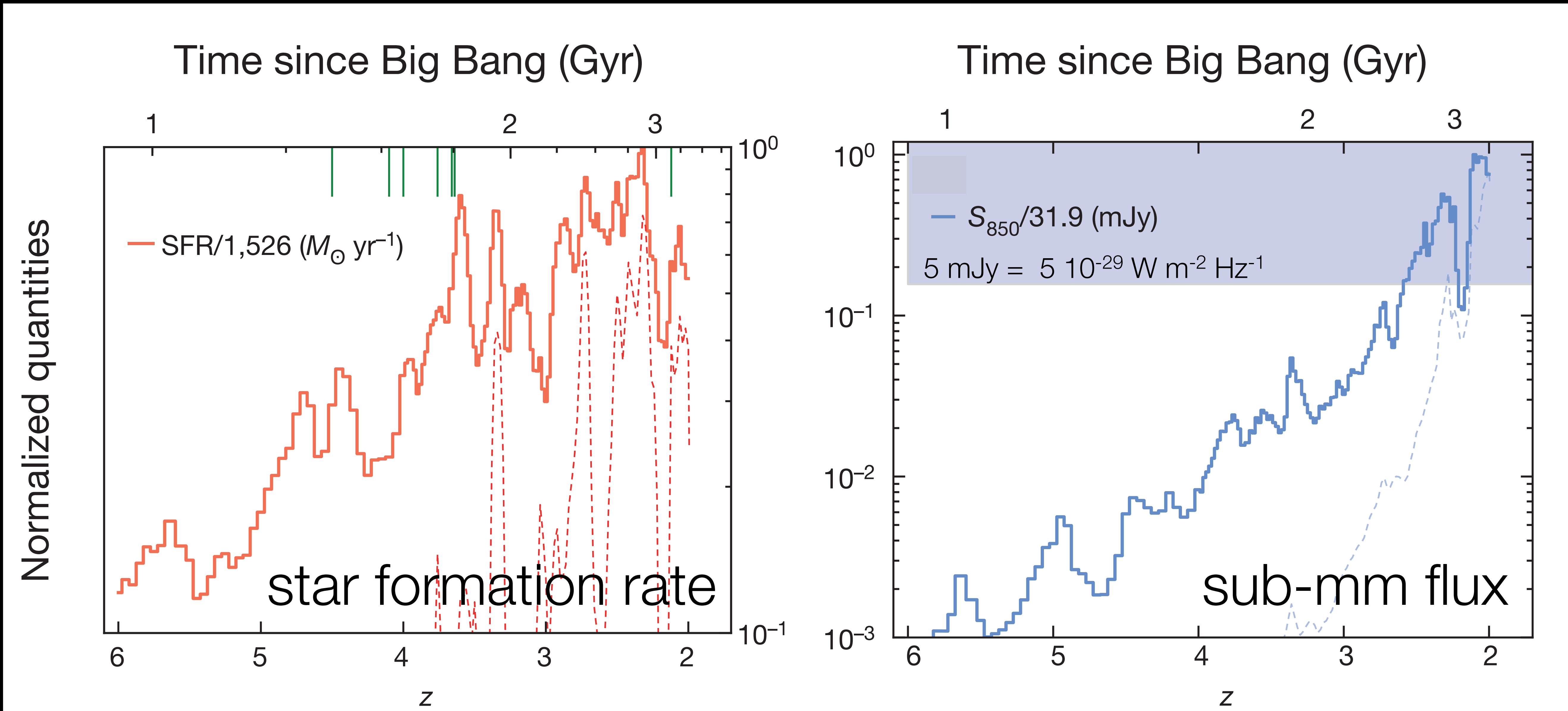
Quiescent galaxies

- dust-poor
- spherical/elliptical
- yellow-ish colors





Extreme starbursts (DSFGs/SMGs)

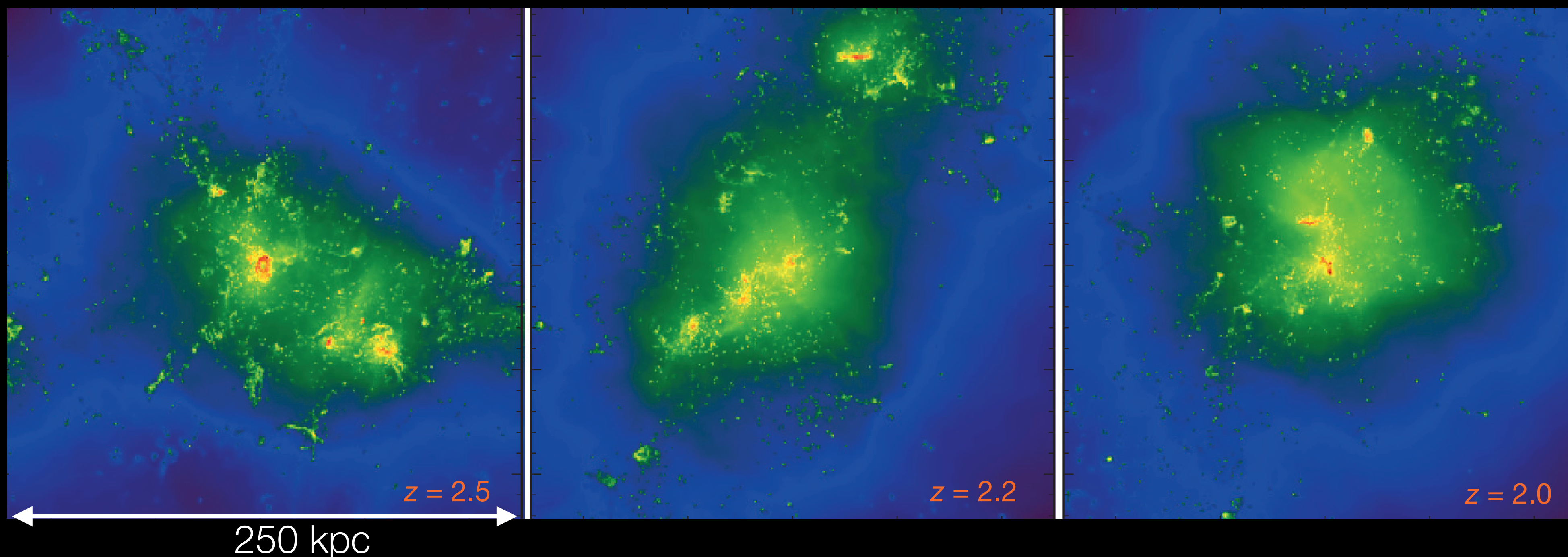


Narayanan, Turk, RF, et al. 2015 Nature

- extreme star formation rate, high sub-mm emission
- would be classified as "sub-mm galaxy"
- spectrum agrees well with observations of real sub-mm galaxies

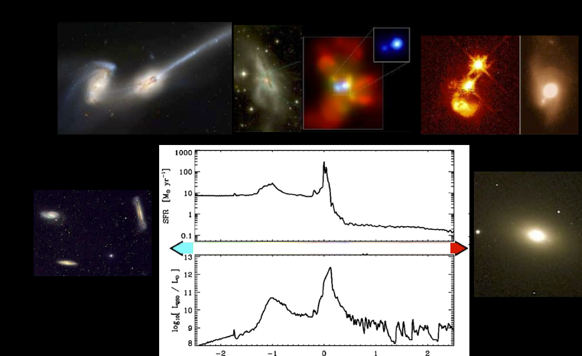
Extreme starbursts (DSFGs/SMGs)

- galaxy is often surrounded by smaller (but still luminous) companions
- many earlier sub-mm observations confused multiple sources into one



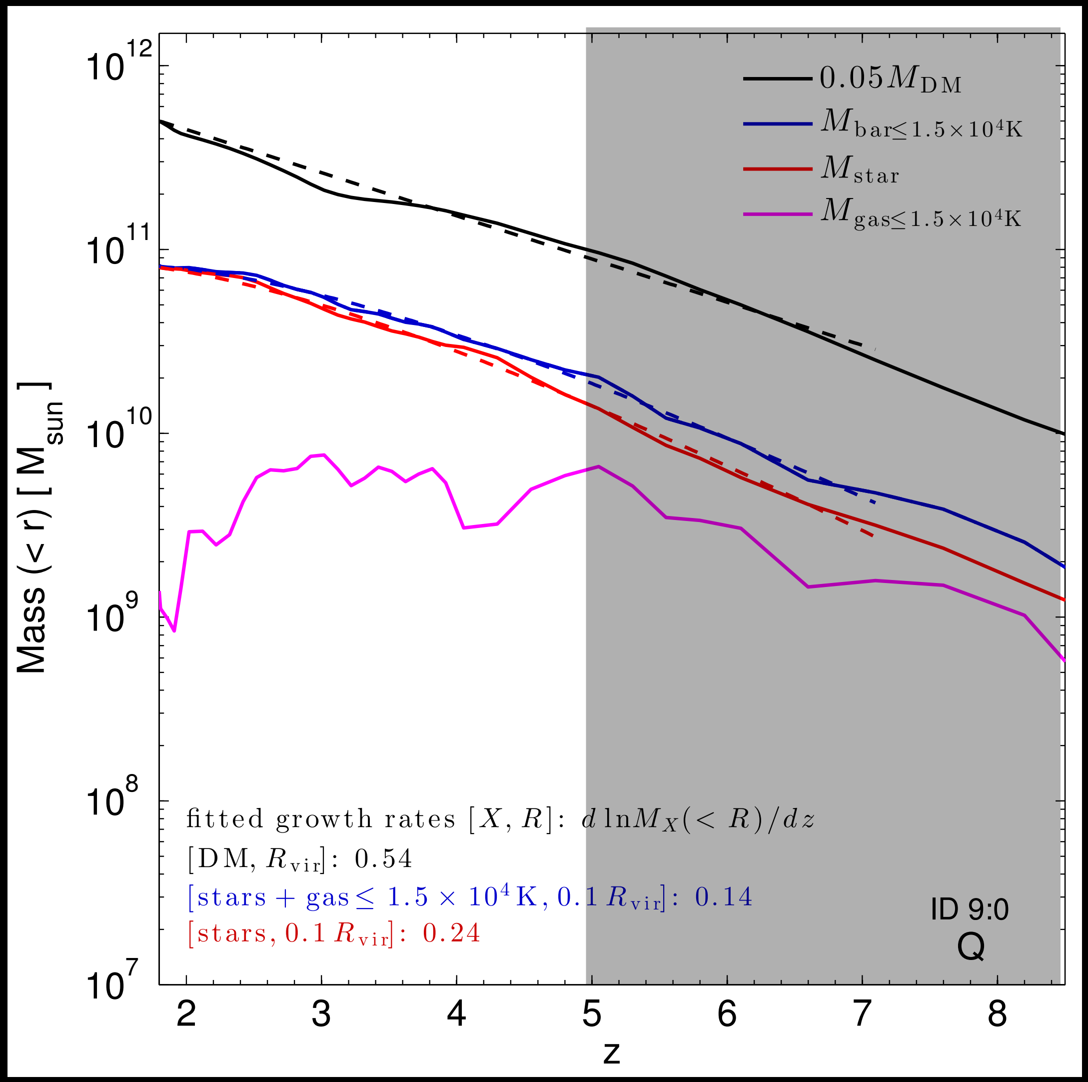
- sub-mm phase **not** initiated by major merger (last finished ~1 Gyr earlier)
- star formation is powered by large gas reservoir:
    - inflow of gas from cosmic web
    - re-accretion of gas expelled via outflows
- star formation remains high for long time (~1 Gyr)

solves problem with number counts



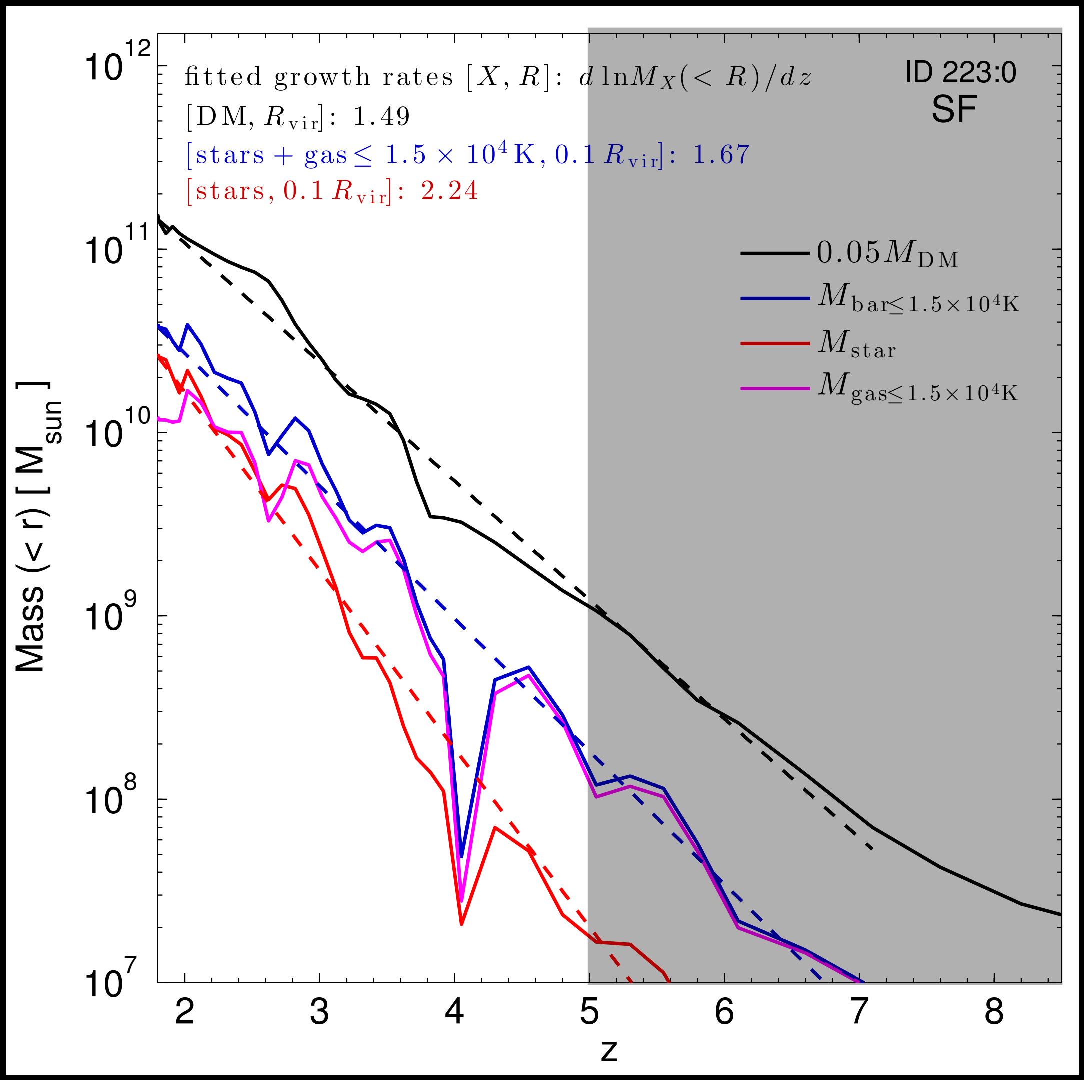
Origin of Quiescent Galaxies

Quiescent galaxy



Gyr 4 3 2 1.5 1 cosmic time ←

Star forming galaxy

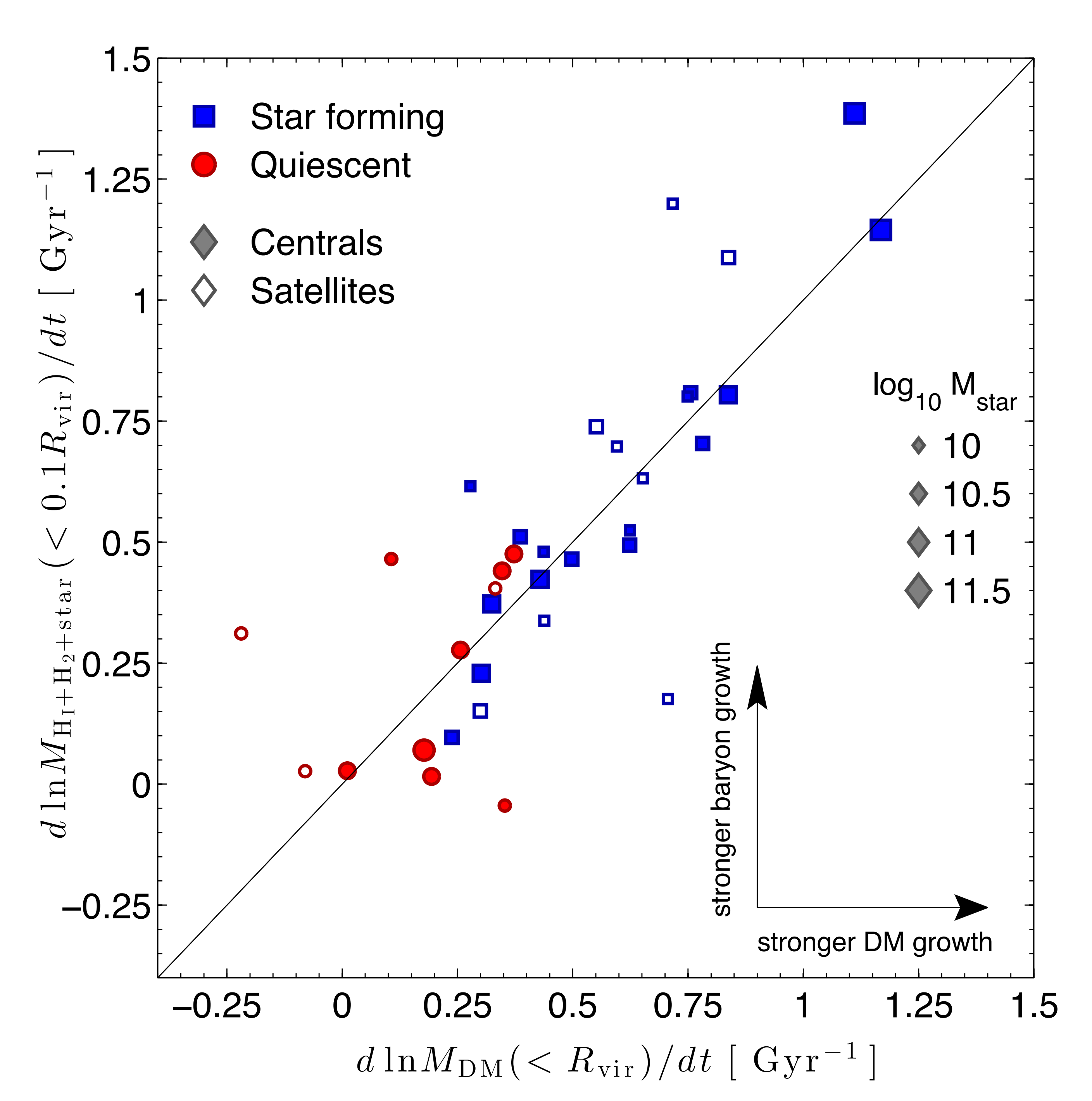


Gyr 4 3 2 1.5 1 cosmic time ←

$$M(t) \propto e^{-\gamma z(t)} [1 + z(t)]^{\beta}$$

- used for mass of dark matter, stars, ...
- average mass growth over past few Gyr
- “smoothes out” bumps and wiggles

galaxy growth (stellar + gas mass)

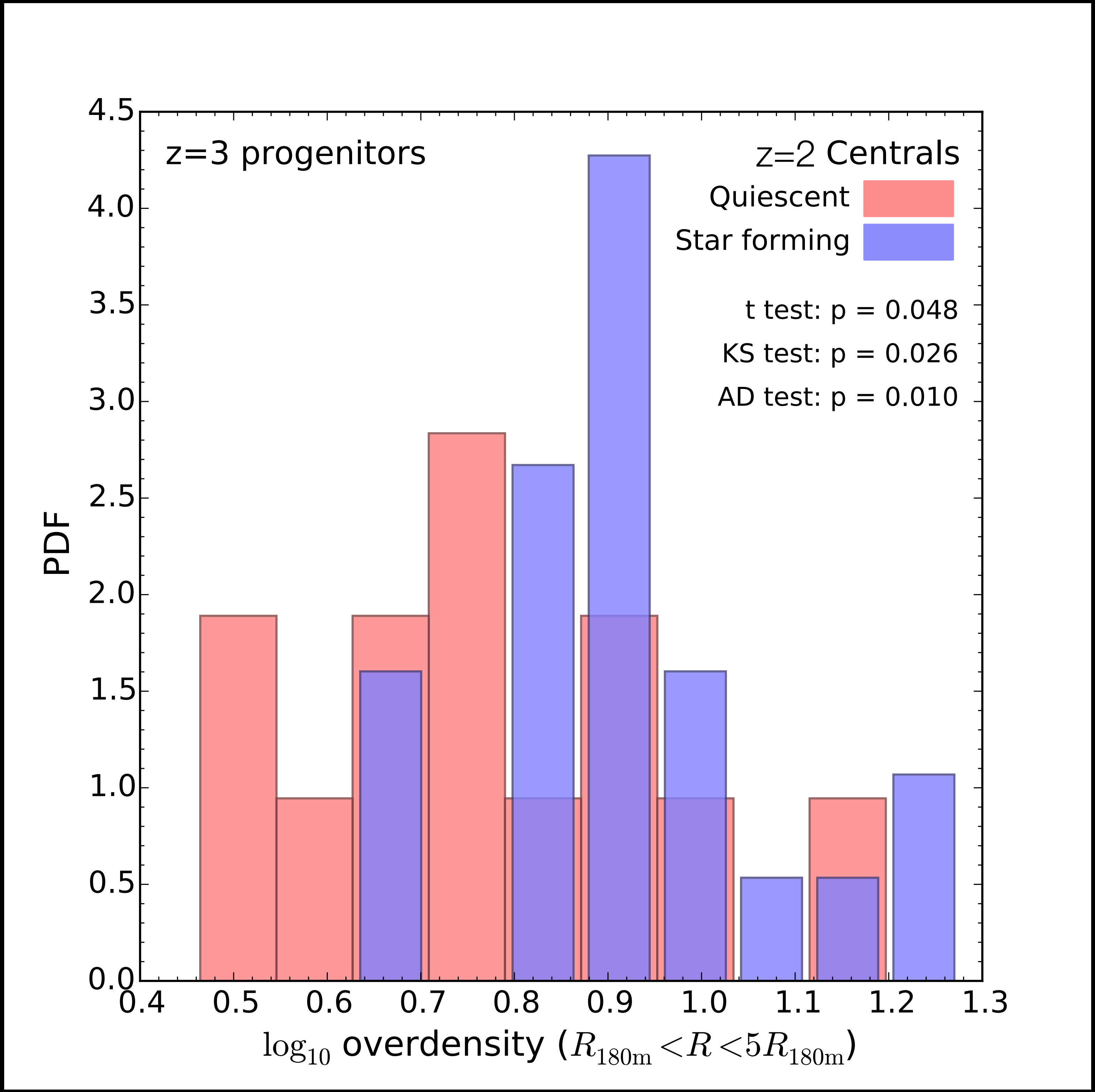


RF et al. 2016 MNRAS, see also RF & Mayer 2015

dark matter halo growth

- galaxy & halo growth are strongly correlated
- grow on similar timescales
- quiescent galaxies have low (specific) growth rates

‘Cosmological starvation’



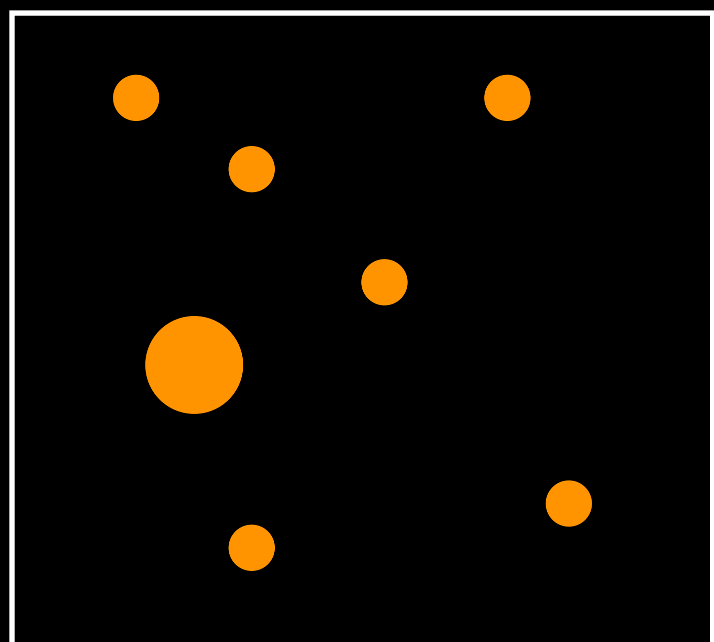
RF, et al. in prep

- progenitors of quiescent centrals tend to reside in less dense regions than progenitors of star forming centrals

Abundance matching

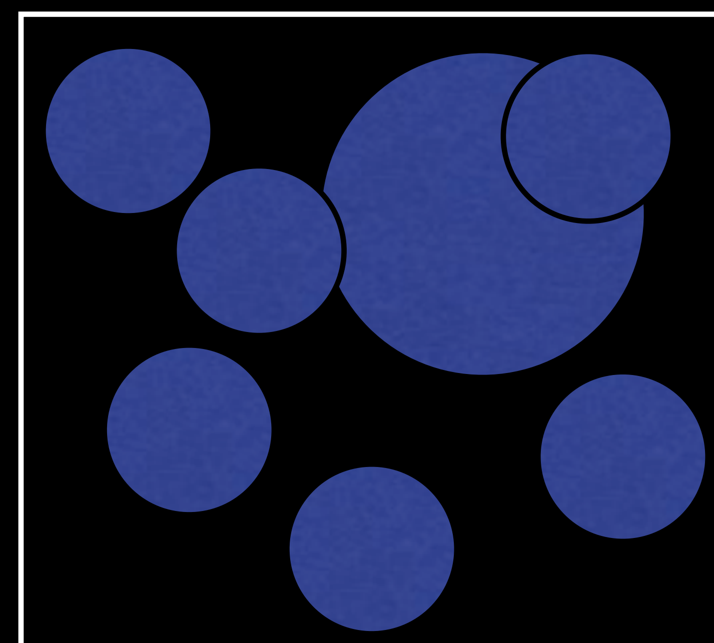
establishes link between halo mass and galaxy mass

galaxies (observation)



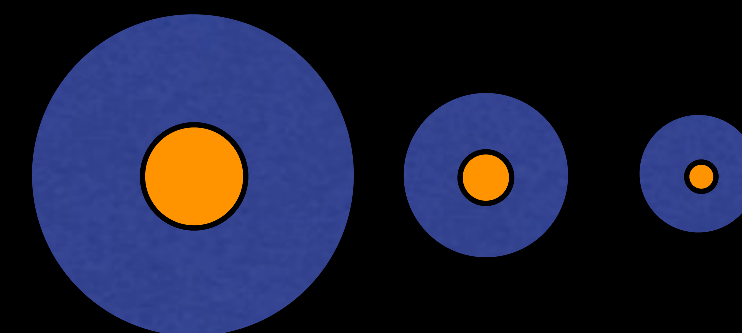
cosmological volume

dark matter halos (sim)



same cosmological volume

match number densities



correctly predicts
galaxy clustering!

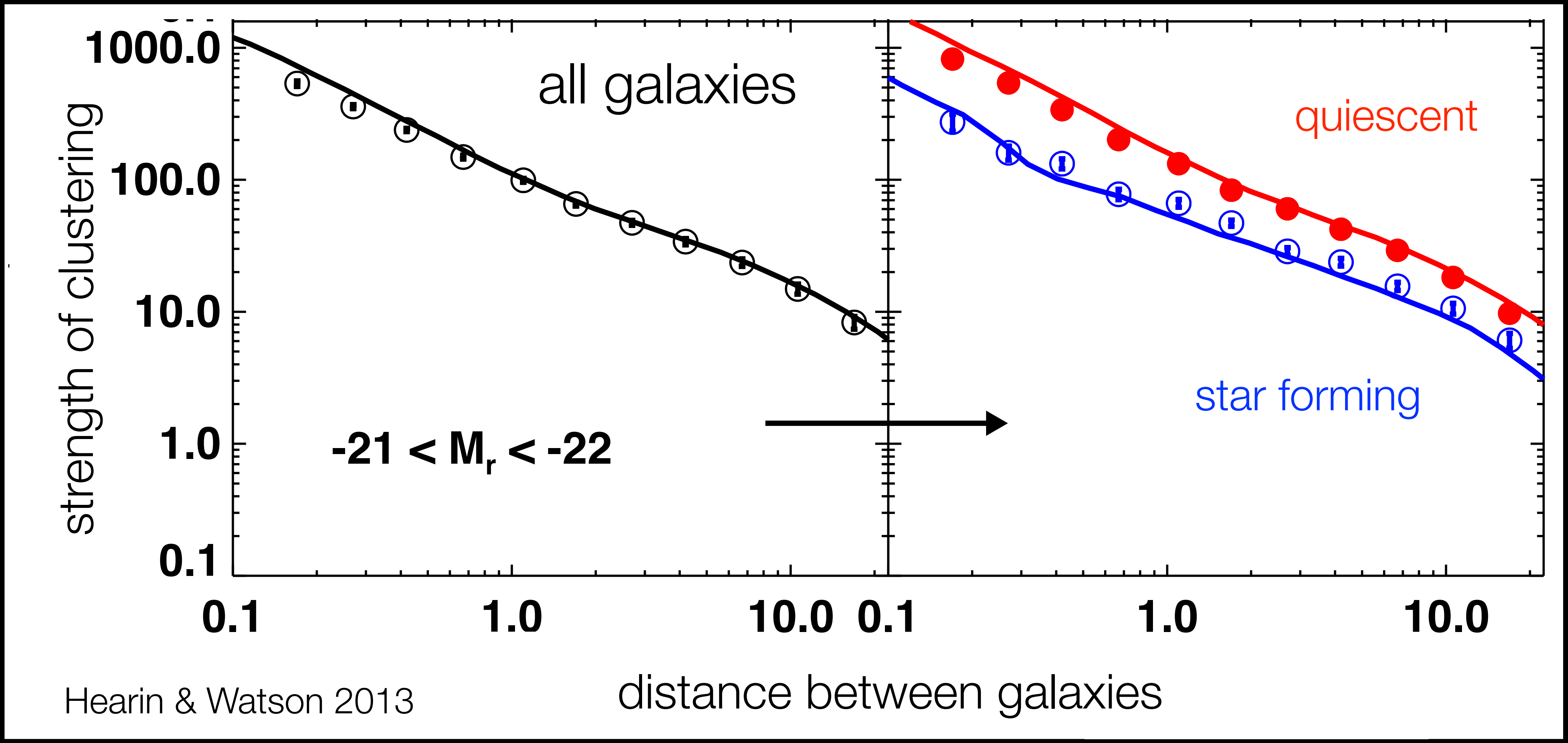
does not distinguish between level of SF of galaxy => Age matching

Assumption:
- Halo formation time = second parameter
- quiescent galaxy = halo forms early, star forming galaxy = halo forms late

Age matching

establishes link between halo accretion rate and SFR the central galaxy

Success:
- correctly predicts clustering of star forming (blue) and quiescent (red) galaxies in today's Universe.
- has not yet been repeated for galaxies at earlier times



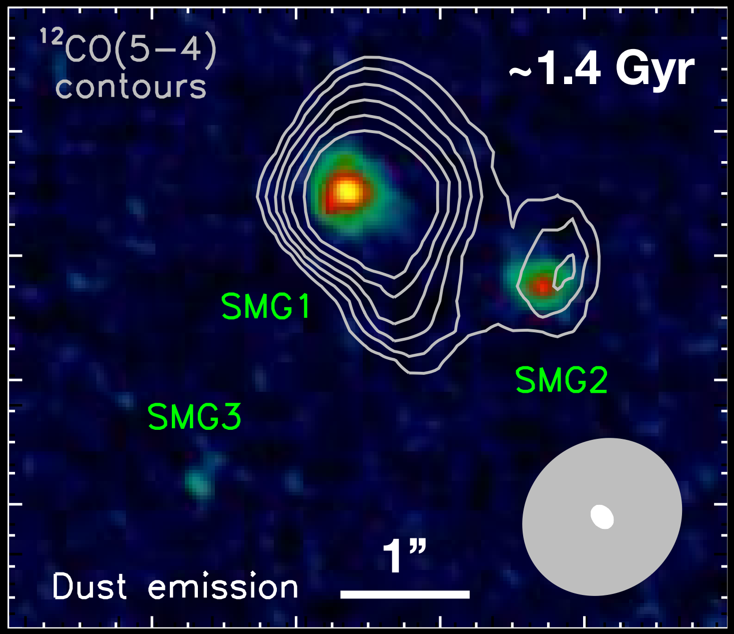
see also: Zentner et al. 2014, Hearin et al. 2015, Watson et al. 2015, Rodríguez-Puebla et al. 2015, Becker et al. 2015, Lim et al. 2016, Ying et al. 2016, ...

Upshot

- Galaxies that reside at the centers of fast growing halos grow quickly

Relevant for:

- typical star forming galaxies in the young Universe
- (at least some of the) most extreme starbursts



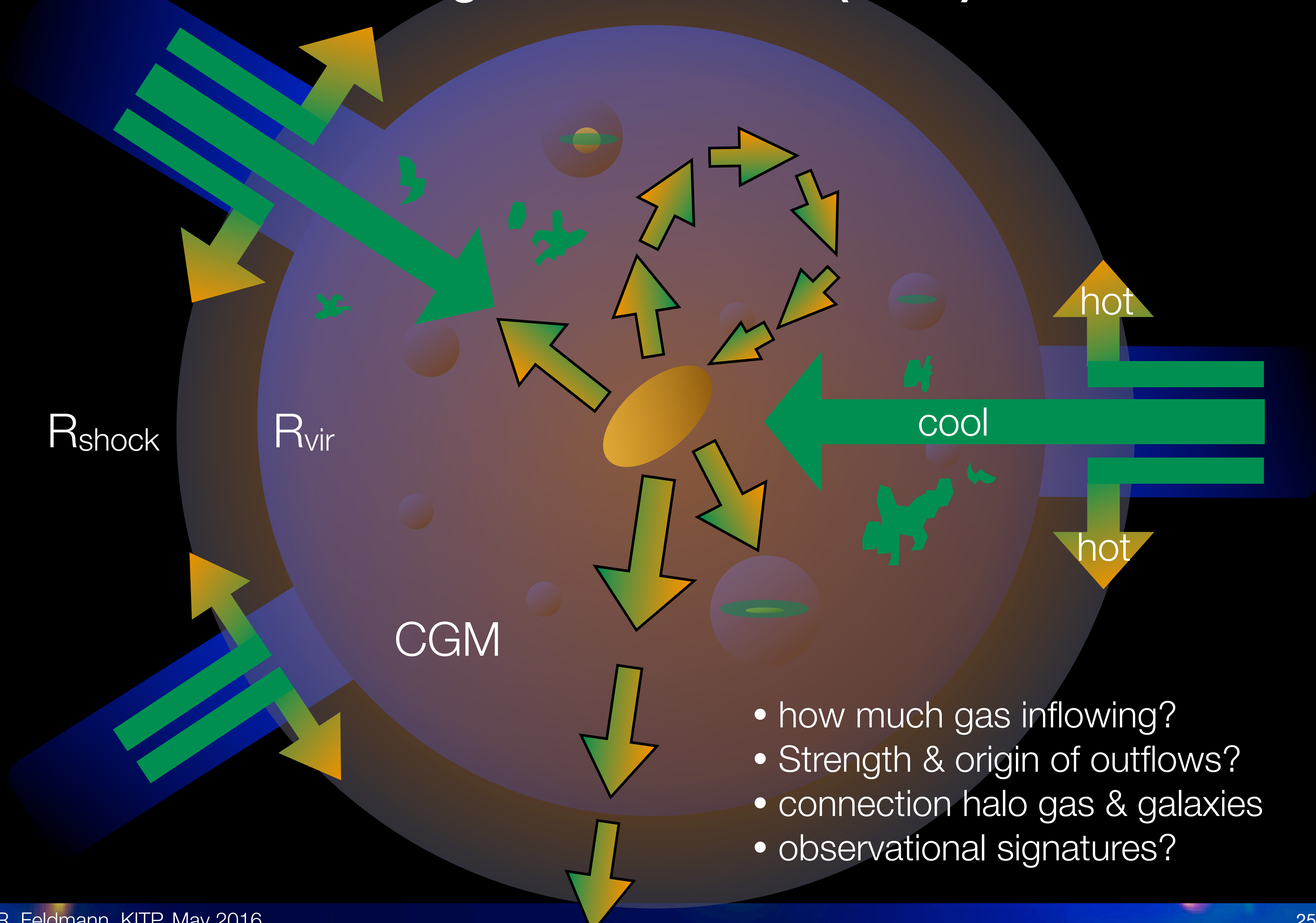
Oteo et al. 2016

- Galaxies that reside at the centers of slowly growing halos grow slowly (cosmological starvation)

Relevant for:

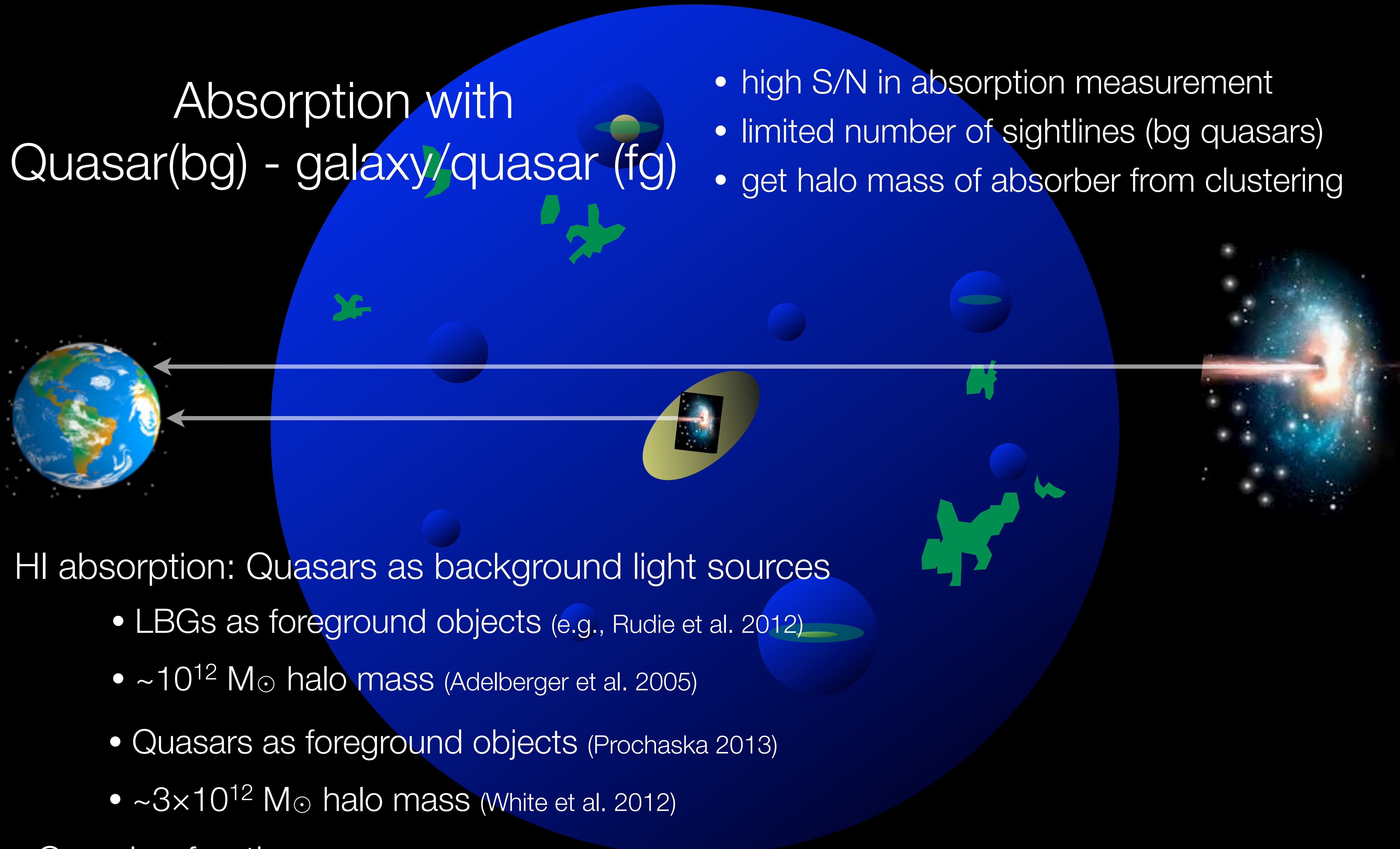
- massive quiescent galaxies in the young Universe
- satellite galaxies

The circum-galactic medium (CGM) at z~2



- how much gas inflowing?
- Strength & origin of outflows?
- connection halo gas & galaxies
- observational signatures?

Cold gas in massive halos at z~2



Absorption with
Quasar(bg) - galaxy/quasar (fg)

- high S/N in absorption measurement
- limited number of sightlines (bg quasars)
- get halo mass of absorber from clustering

HI absorption: Quasars as background light sources

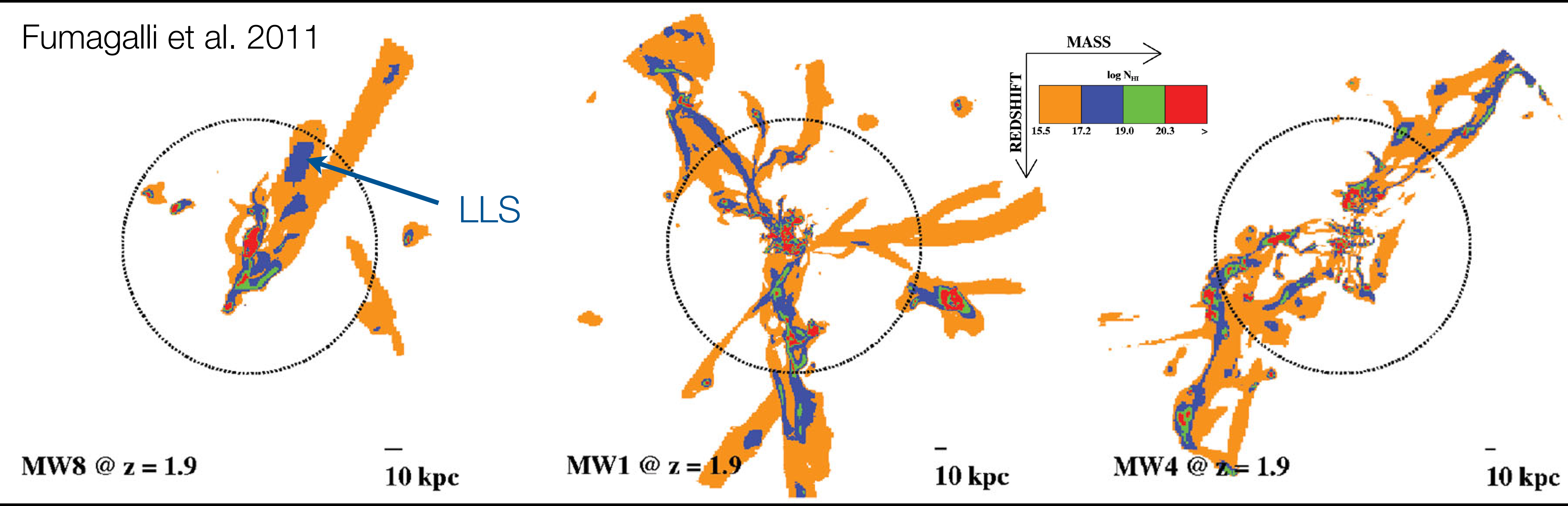
- LBGs as foreground objects (e.g., Rudie et al. 2012)
- ~10^{12} $M_\odot$ halo mass (Adelberger et al. 2005)
- Quasars as foreground objects (Prochaska 2013)
- ~3×10^{12} $M_\odot$ halo mass (White et al. 2012)

Covering fraction:

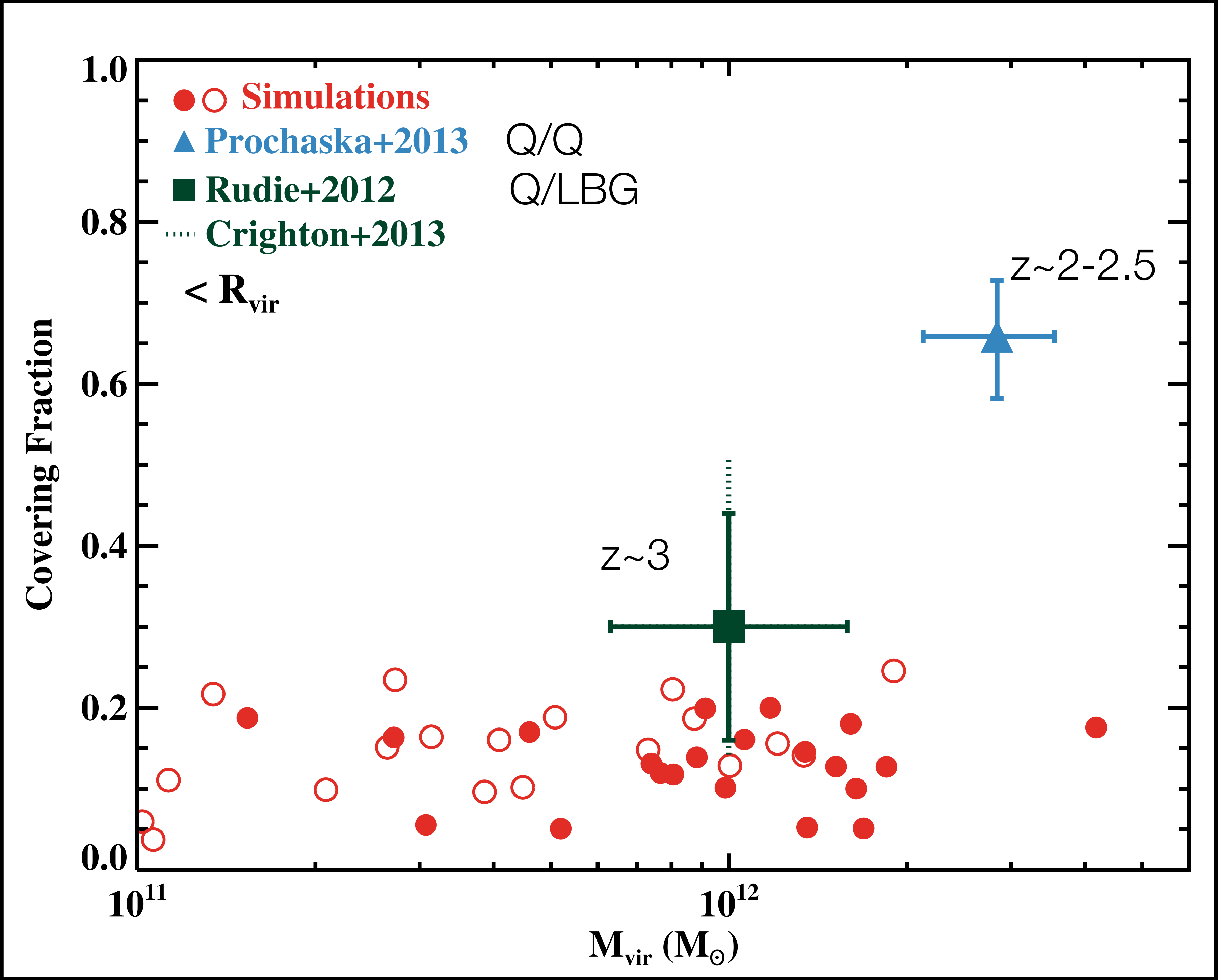
- fraction of projected area within R_{vir} covered with $N_{HI} > 10^{17.3}$ cm^{-2} gas

Theoretical predictions

- typically low HI covering fraction (~10-20%) at z~2
- majority produced by cold gas filaments (van de Voort et al. 2012, Shen et al. 2013)
- **high uncertainty regarding feedback**



Observations



- Fair agreement for $M_{halo} \lesssim 10^{12}\ M_\odot$
- stark disagreement for more massive halos

Fumagalli et al. 2014, see also Steward et al. 2011, Faucher-Giguere et al. 2011, 2015, Shen et al. 2013, Rahmati et al. 2015

What does that mean?

- high covering fraction in 3×10^{12} $M_\odot$ not just from “cold streams”
- cold gas mass $\sim10^{11}$ $M_\odot$ (Prochaska et al. 2013) => large reservoir of baryons

Explanation?

- produced by strong outflows powered by the host AGN

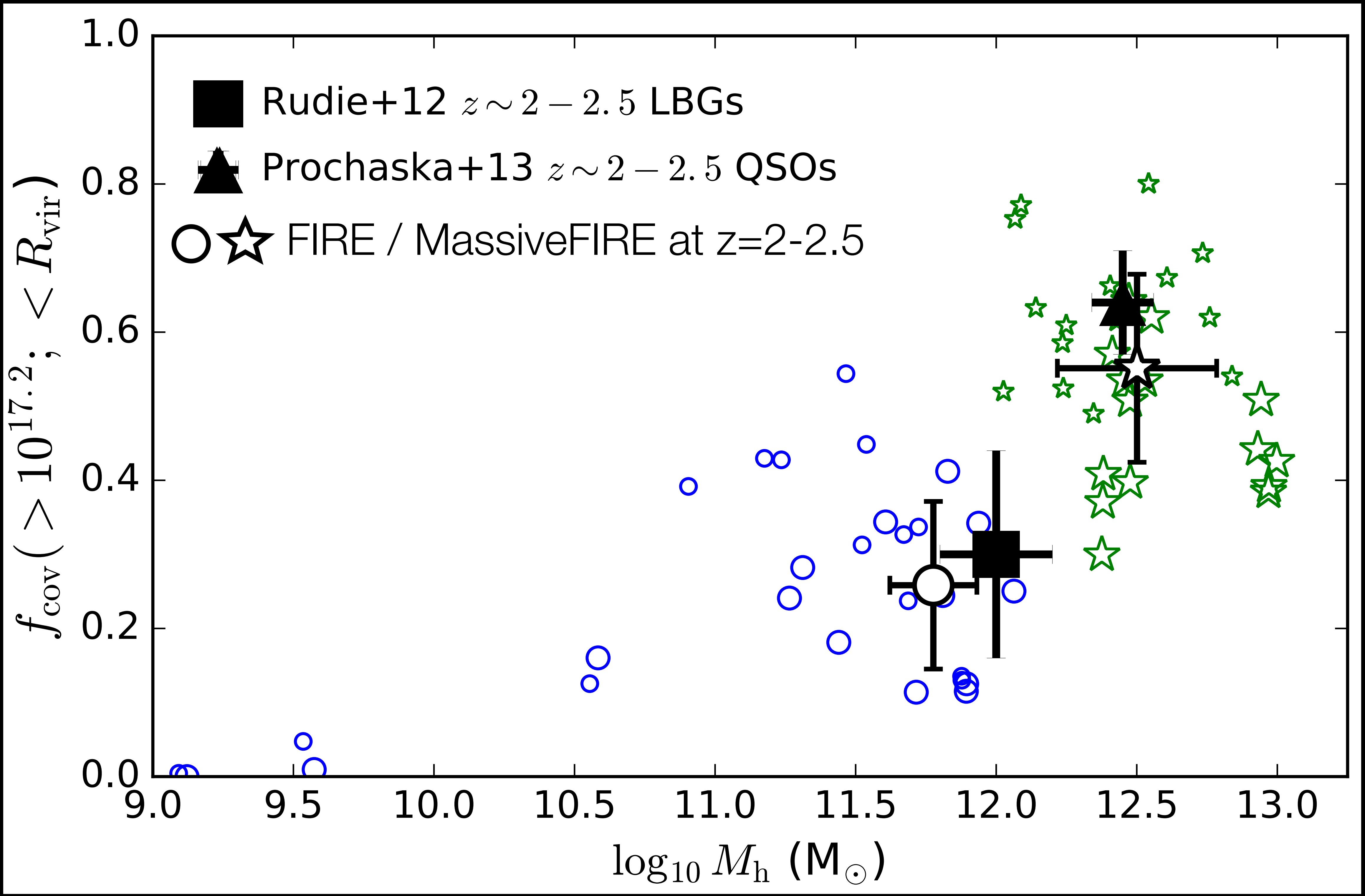
Smoking gun of “quasar” feedback?

- AGN does not fully photo-ionize gas in their halos (at least $\perp$ to l.o.s.)
- likely anisotropic emission from AGN (Hennawi & Prochaska 2007)

Alternatives:

- strong outflows powered by stellar feedback
- outflows/stripping from infalling satellites

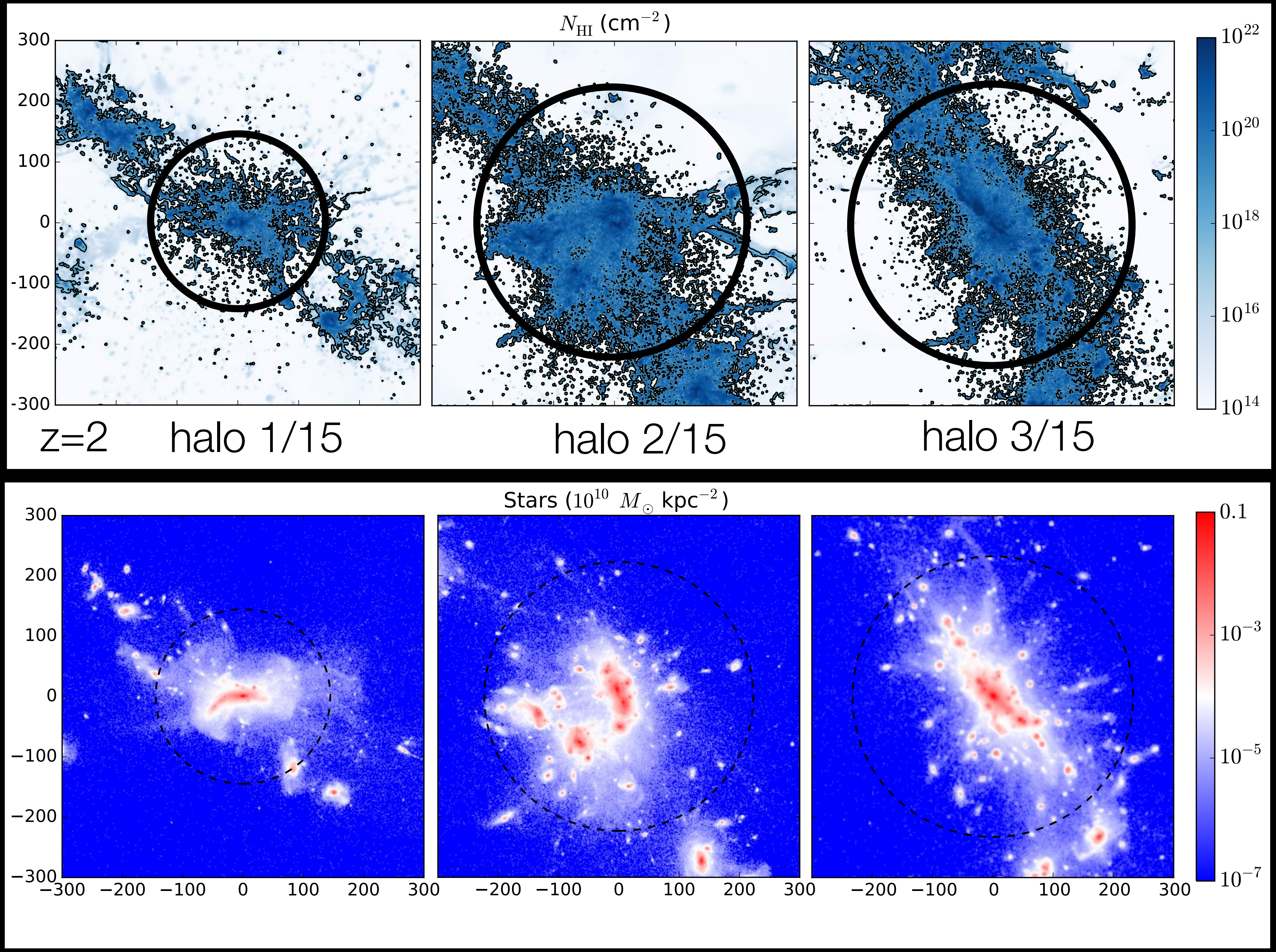
HI covering fraction in MassiveFIRE



Faucher-Giguère, RF, et al. 2016, MNRAS

Good agreement for both $M_{halo} \lesssim 10^{12}\, M_\odot$ and for more massive halos!

Origin of the cold gas?



- gas associated with infalling satellites (outflows, stripping, cold streams)
- outflows from / galactic fountain of central galaxy

Summary

- *Starbursting galaxies:*
  - traditionally associated with major mergers between galaxies
  - may in fact be driven by gas accretion from cosmological distances
- *Quiescent galaxies:*
  - Often assumed to be the result of energy injection from supermassive black holes
  - may in fact turn quiescent as a result of a slow down of their cosmic accretion of gas
- *Cool (HI) CGM:*
  - observations: high HI covering fractions in massive halos
  - gas inflow (cold streams) cannot explain high HI covering fractions
  - stellar feedback essential (AGN feedback not required)

Evolution of galaxies, their CGM, and their halos are tightly linked