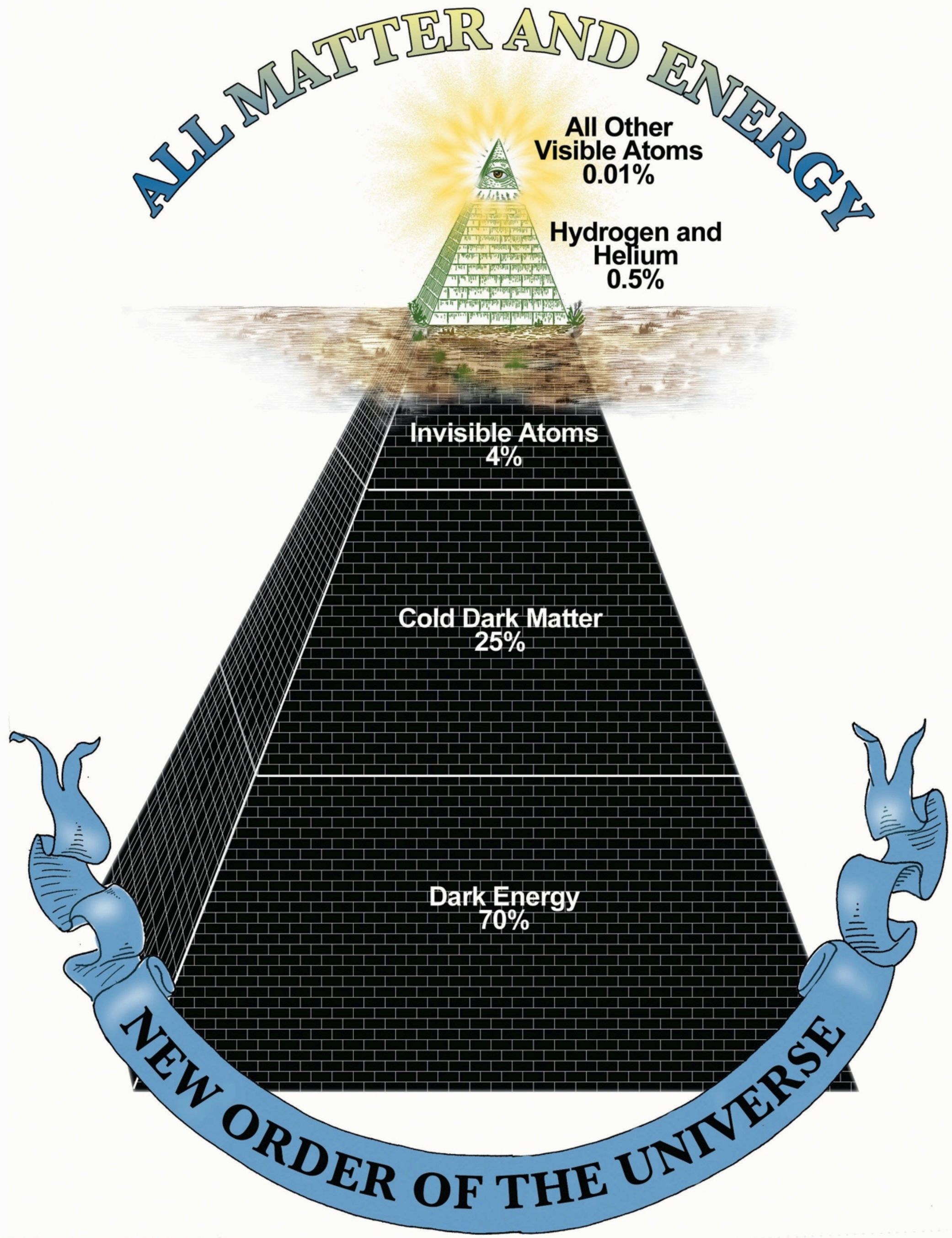
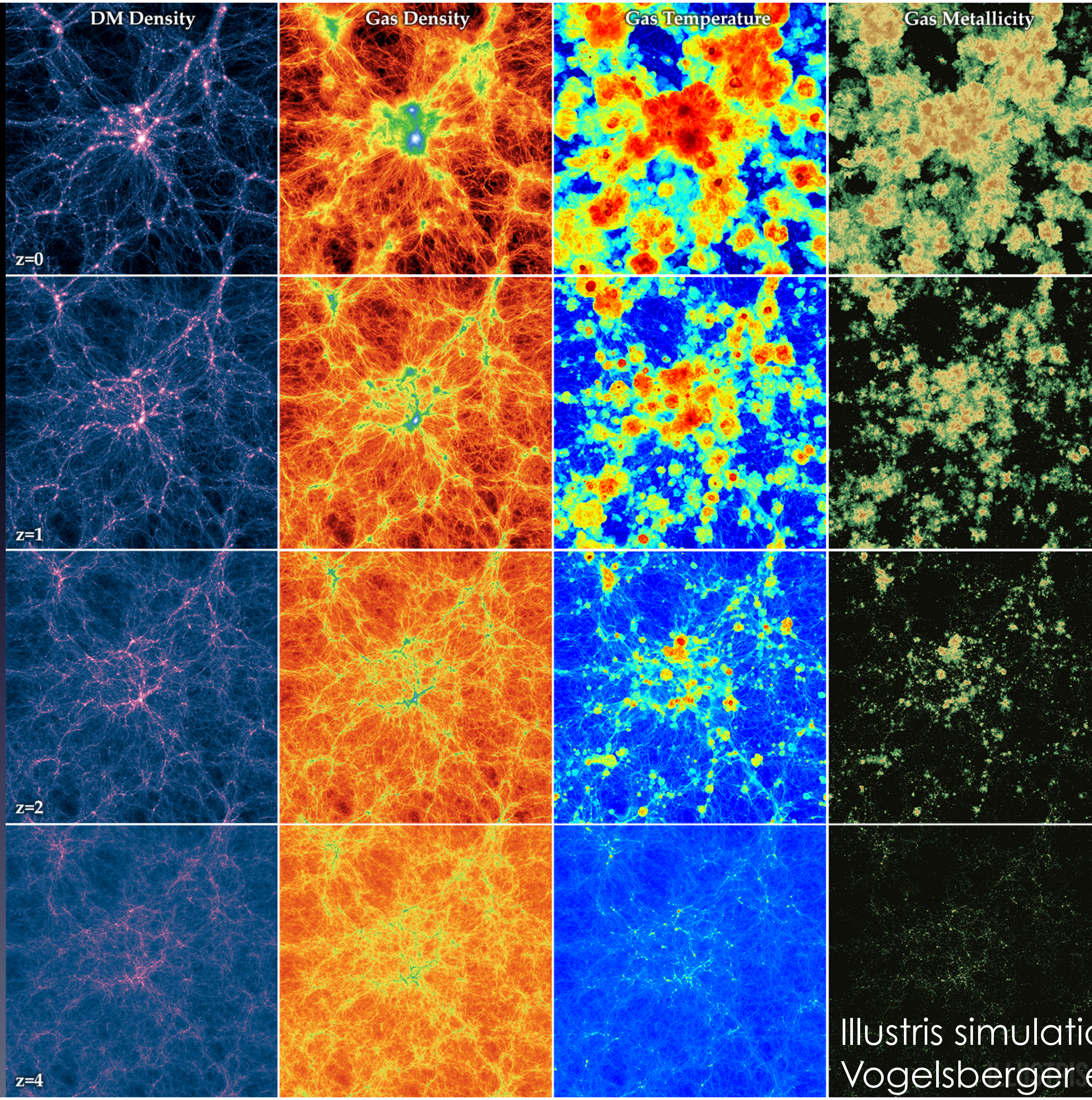
Probing Galaxy Evolution with the Next Generation of UVOIR Telescopes

rachel somerville
Rutgers University


ALL MATTER AND ENERGY
All Other Visible Atoms 0.01%
Hydrogen and Helium 0.5%
Invisible Atoms 4%
Cold Dark Matter 25%
Dark Energy 70%
NEW ORDER OF THE UNIVERSE

today

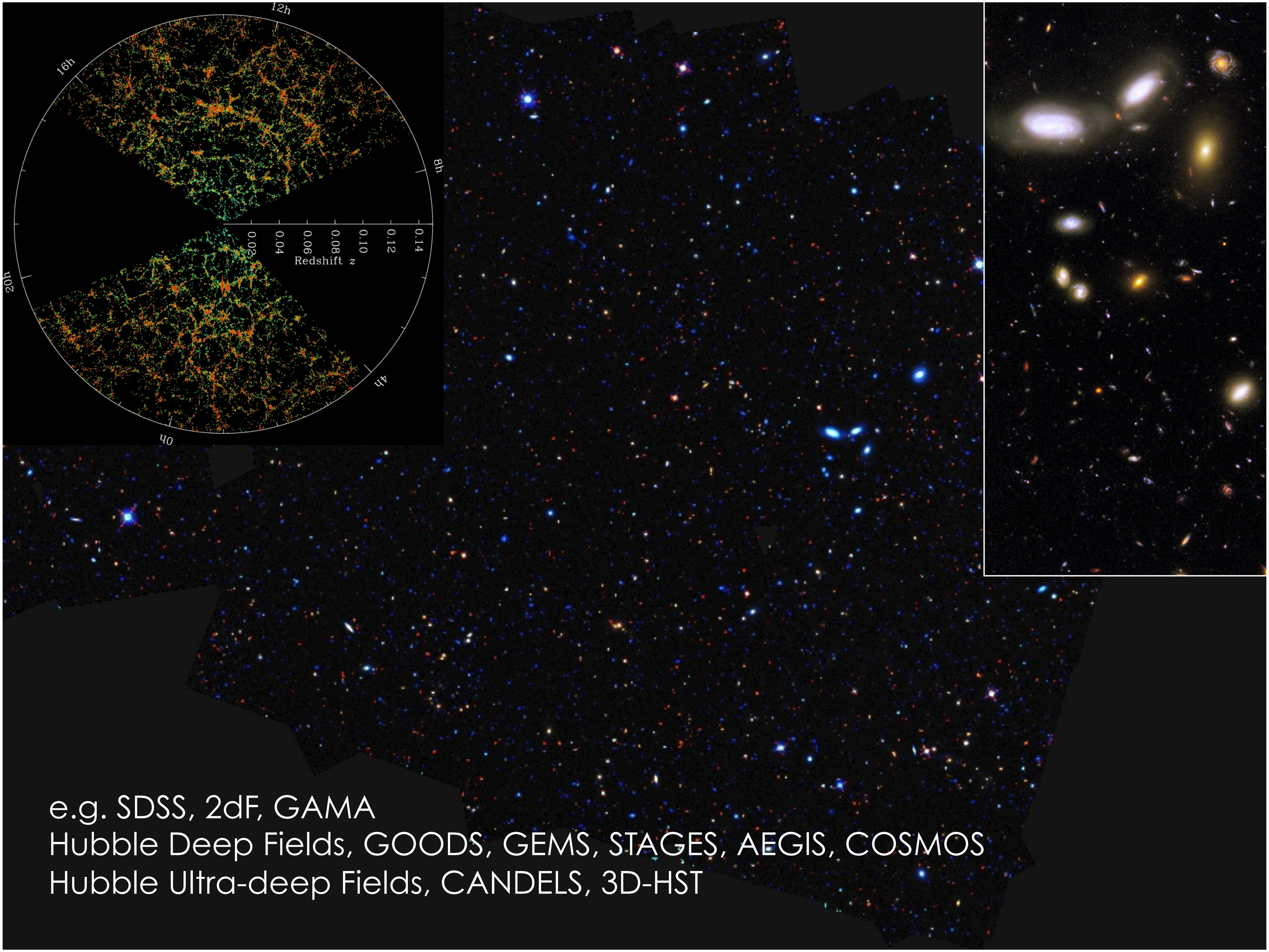


~12 Gyr ago

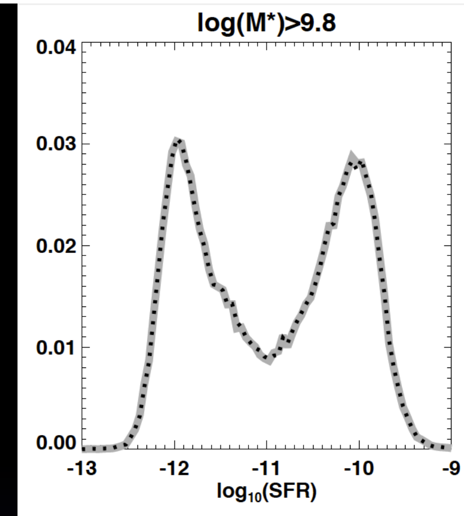
Illustris simulation
Vogelsberger et al. 2014

A Theorist's wish list

- high-resolution maps of dark matter, all phases of gas (inside and outside of galaxies), stars, metals, and dust over a representative part of cosmic volume, from 'cosmic dawn' to the present day.
- spatially resolved kinematics of gas and stars

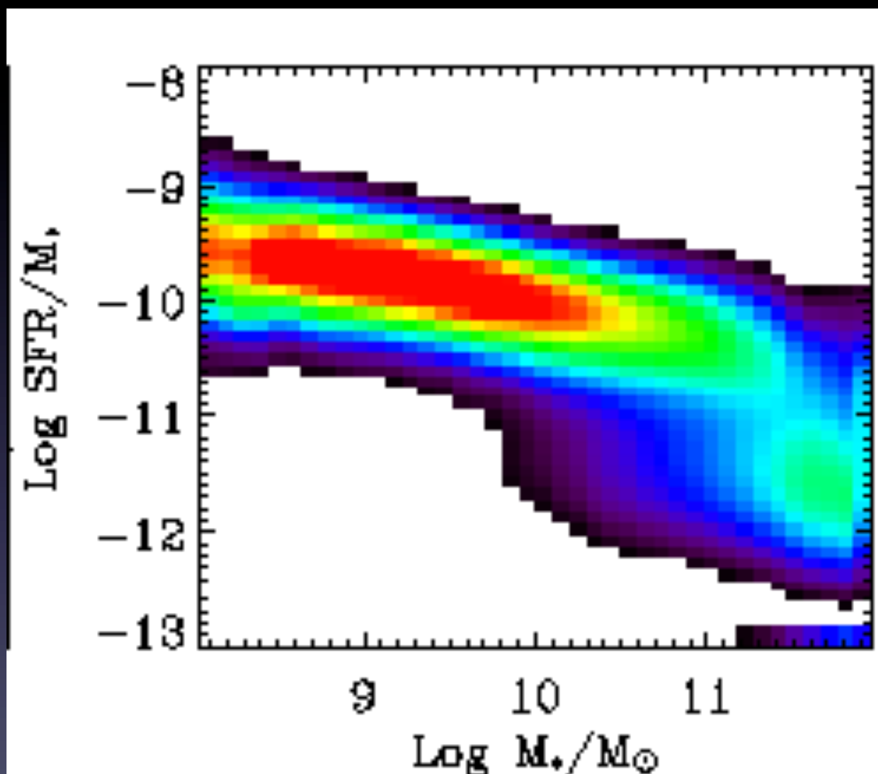

12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z
e.g. SDSS, 2dF, GAMA
Hubble Deep Fields, GOODS, GEMS, STAGES, AEGIS, COSMOS
Hubble Ultra-deep Fields, CANDELS, 3D-HST

why do we see two populations of galaxies?



z~0 (today)

specific star formation rate

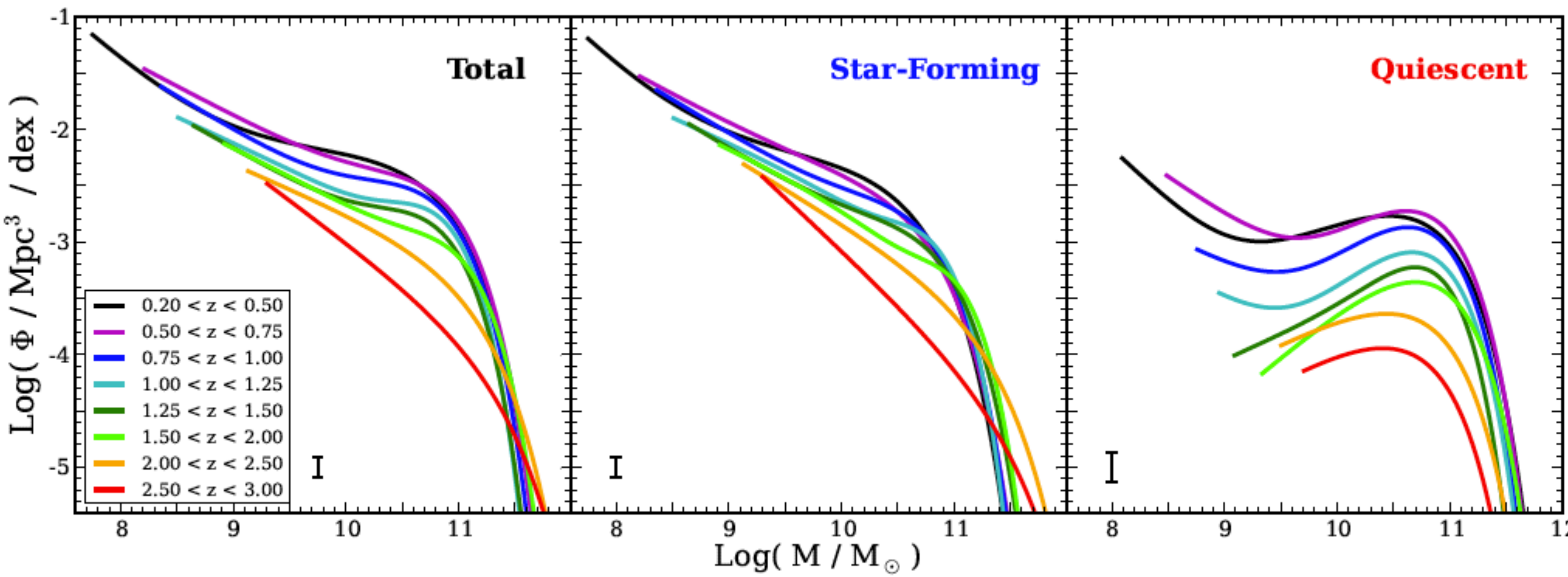


stellar mass

- two distinct populations: star forming and quiescent galaxies (seen up to z~3-4)
- SF galaxies live on a surprisingly tight 'star forming main sequence' (seen up to z~6)

Brinchmann et al. 2003
Kauffmann et al. 2003
Baldry et al. 2004

what physical process is responsible for quenching star formation in galaxies?



number/mass in SF galaxies increases little or not at all

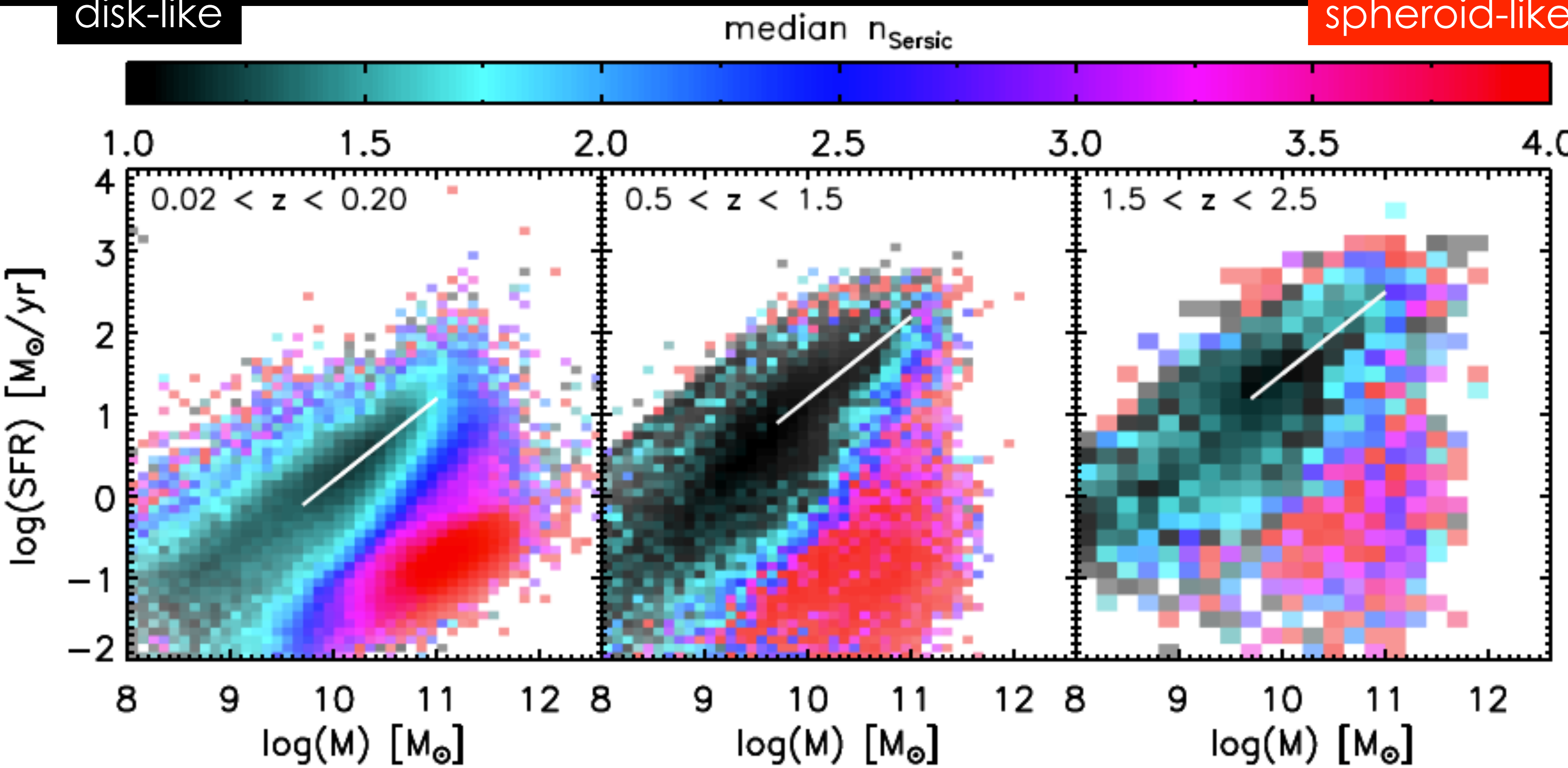
number/mass of quiescent galaxies increases rapidly

→*implies SF galaxies must be transformed into quiescent galaxies (quenching)*

- *internal structure and quenching are linked* -- strong observed correlation between quiescence and bulge fraction or central density

disk-like

spheroid-like

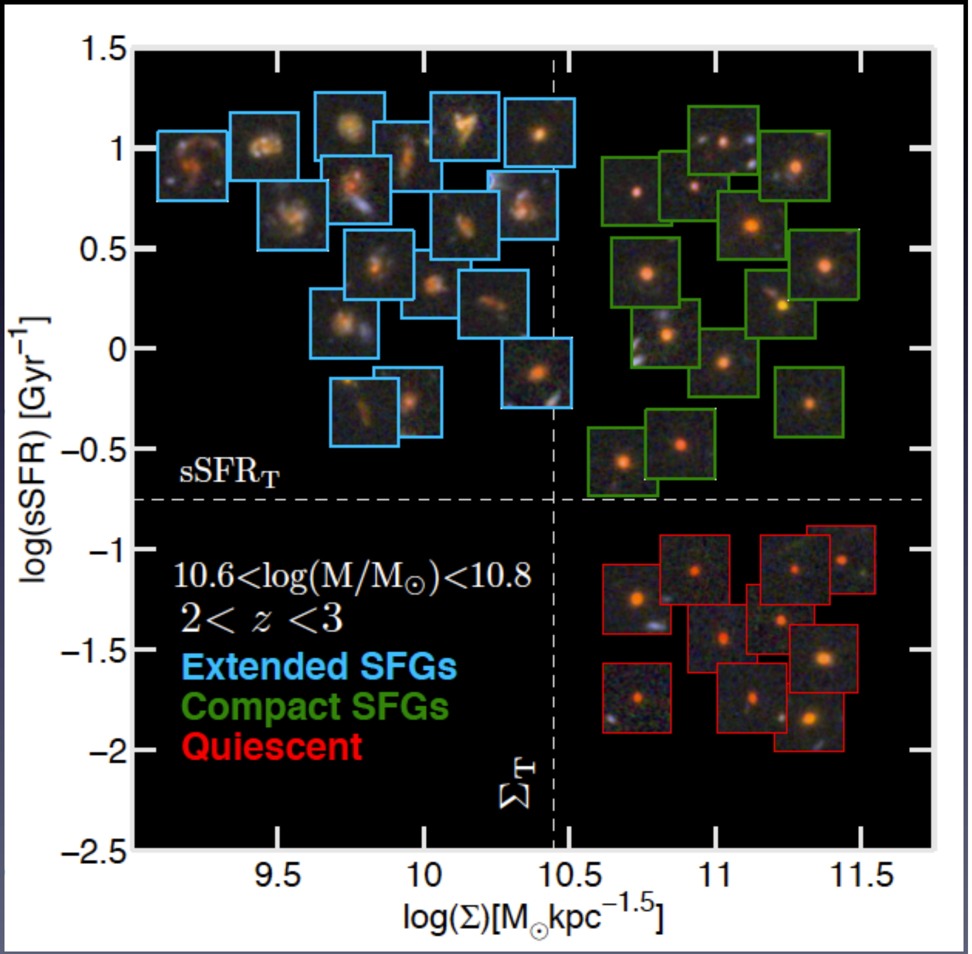


see also Bell et al. 2008, 2012; Cheung+'12; Fang+'13

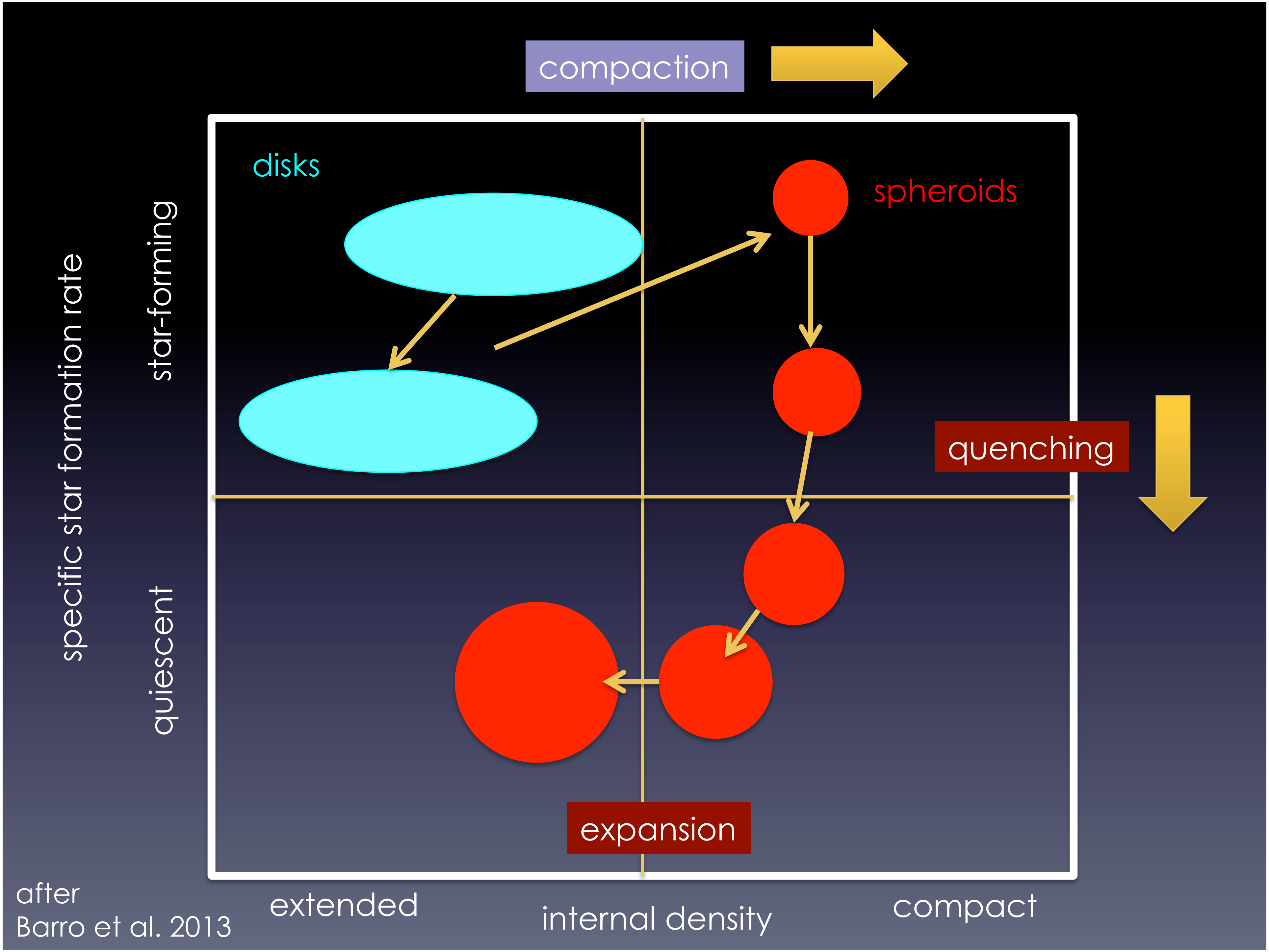
Wuyts et al. 2011

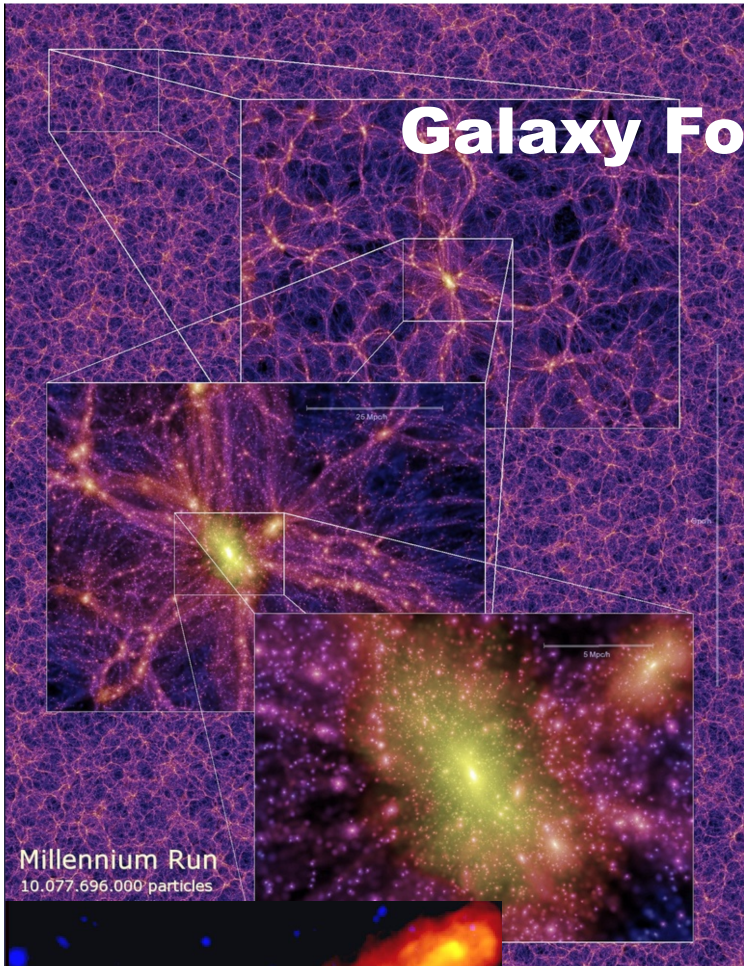
galaxy assembly and transformation since cosmic high noon

- galaxies assembled their mass over cosmic time in a `staged' fashion
- build-up of 'spheroid'-dominated galaxies
- star formation quenching
- [some] galaxies compactify and then grow in radius
- clear link between quenching and internal structure



Barro et al. 2013 'compactness'

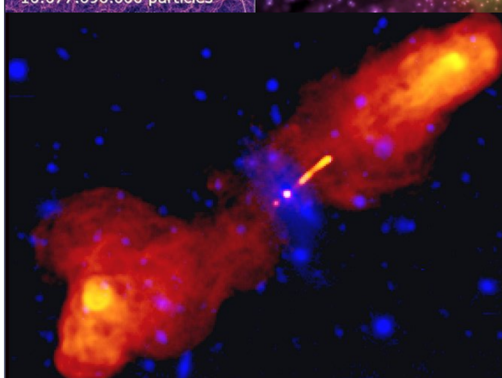

compaction
disks
spheroids
quenching
expansion
specific star formation rate
star-forming
quiescent
extended
internal density
compact
after
Barro et al. 2013

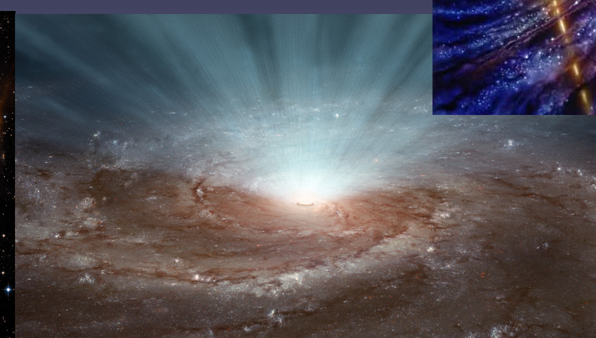


Galaxy Formation: The Grand Challenge

large-scale structure: 100's of Mpc
galaxy environment: ~1-8 Mpc
galaxy internal structure ~0.1-1 kpc
Giant Molecular clouds: ~10's of pc
star clusters/SNae: pc/sub-pc
structures associated with supermassive BH: pc/sub-pc

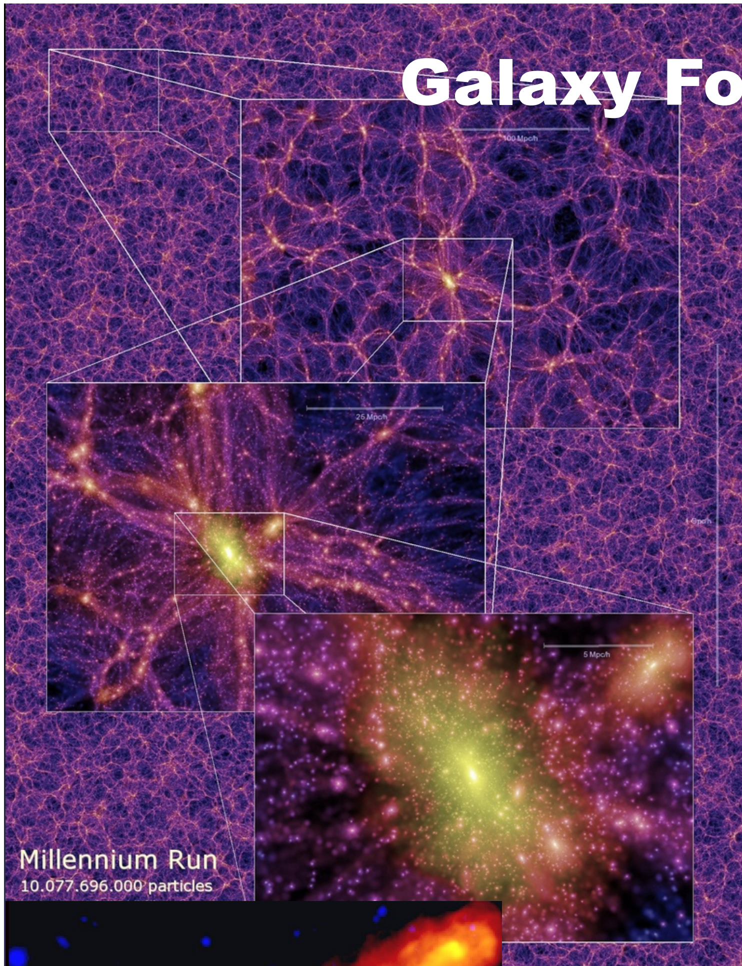
+ diverse array of physical processes

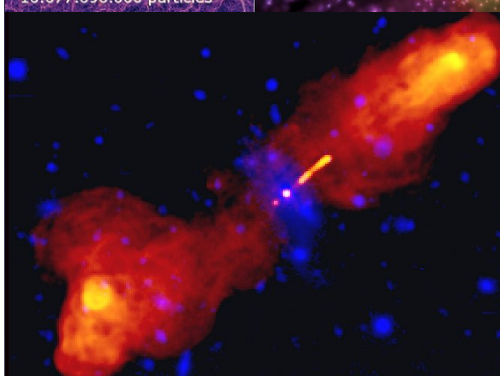


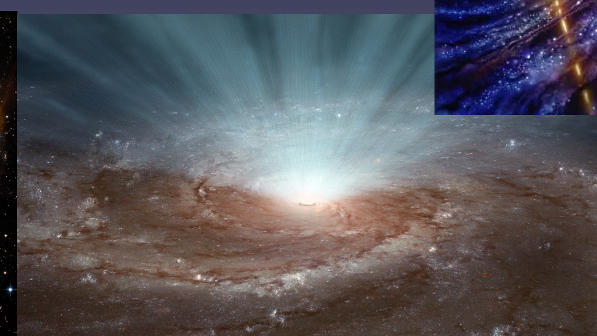




Galaxy Formation: The Grand Challenge

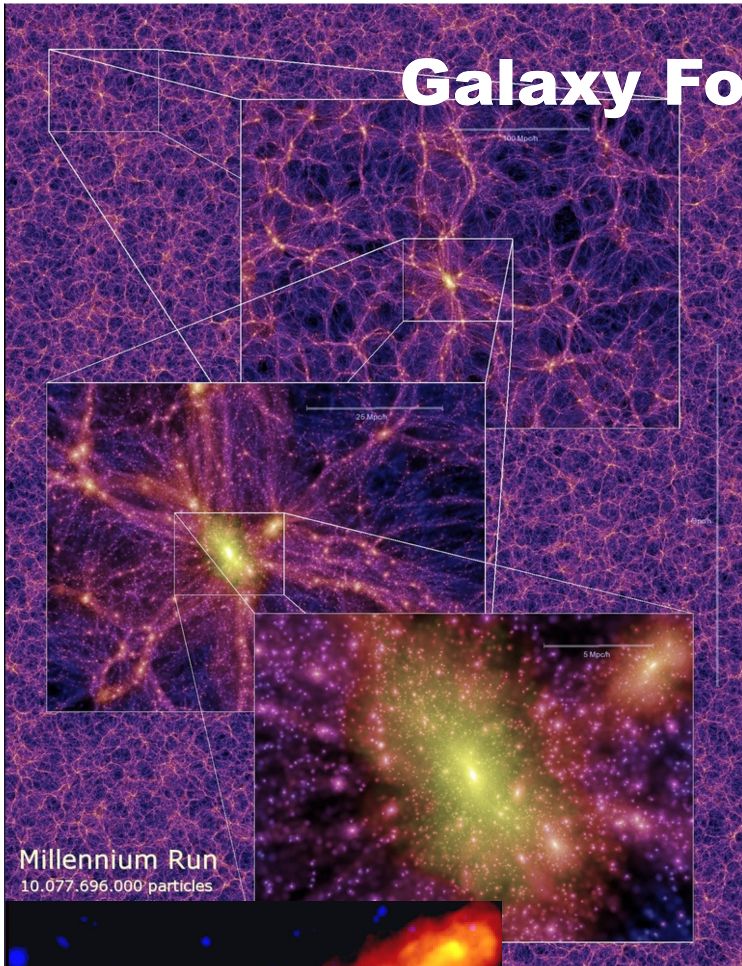
as a result, all numerical simulations of galaxy and SMBH formation in a cosmological context must implement `sub-grid' recipes to treat processes that occur on scales smaller than the explicit resolution of the simulation.





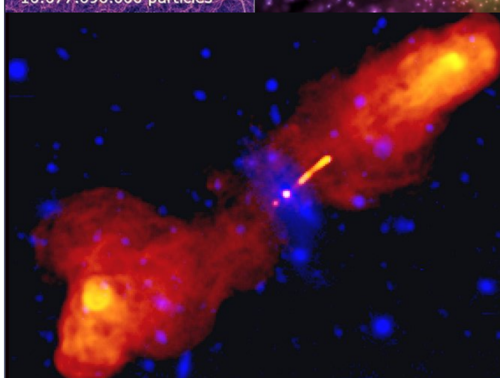


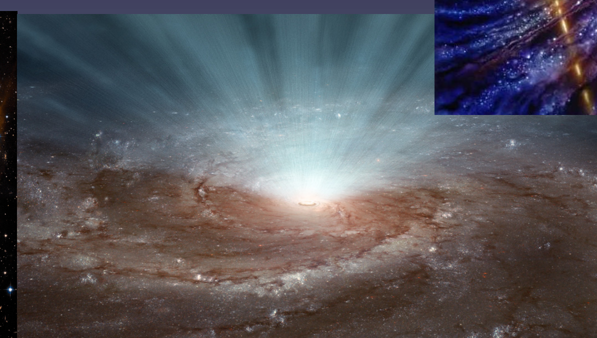
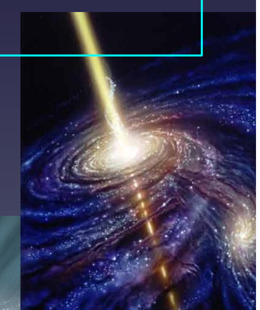
Galaxy Formation: The Grand Challenge

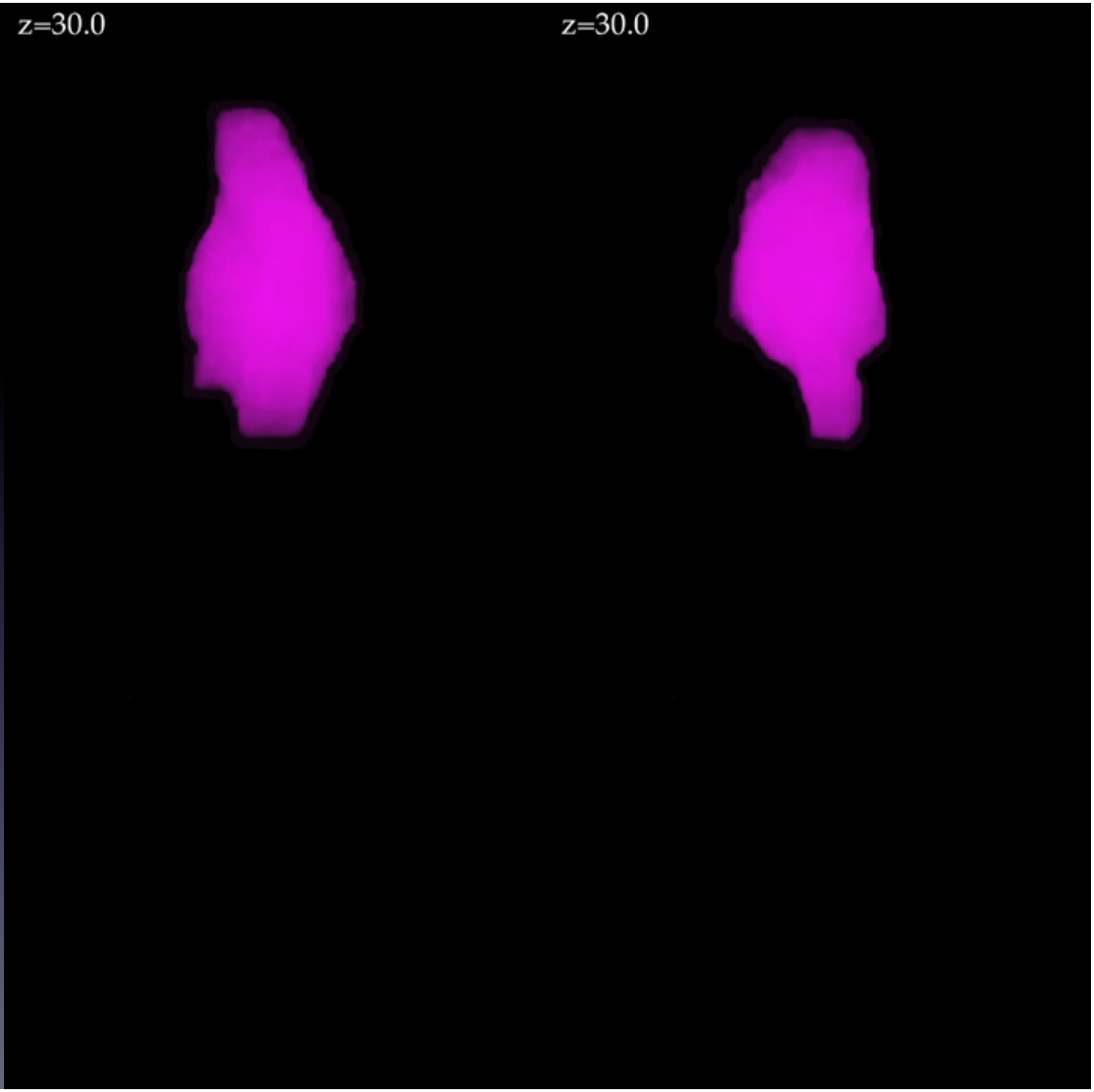


as a result, all numerical simulations of galaxy and SMBH formation in a cosmological context must implement `sub-grid’ recipes to treat processes that occur on scales smaller than the explicit resolution of the simulation.

- can *any* sub-grid approximation accurately capture the essential physics for the purposes of predicting global galaxy properties?
- what is the minimal set of physical processes that we need to include?
- what is the minimum scale that we need to resolve?

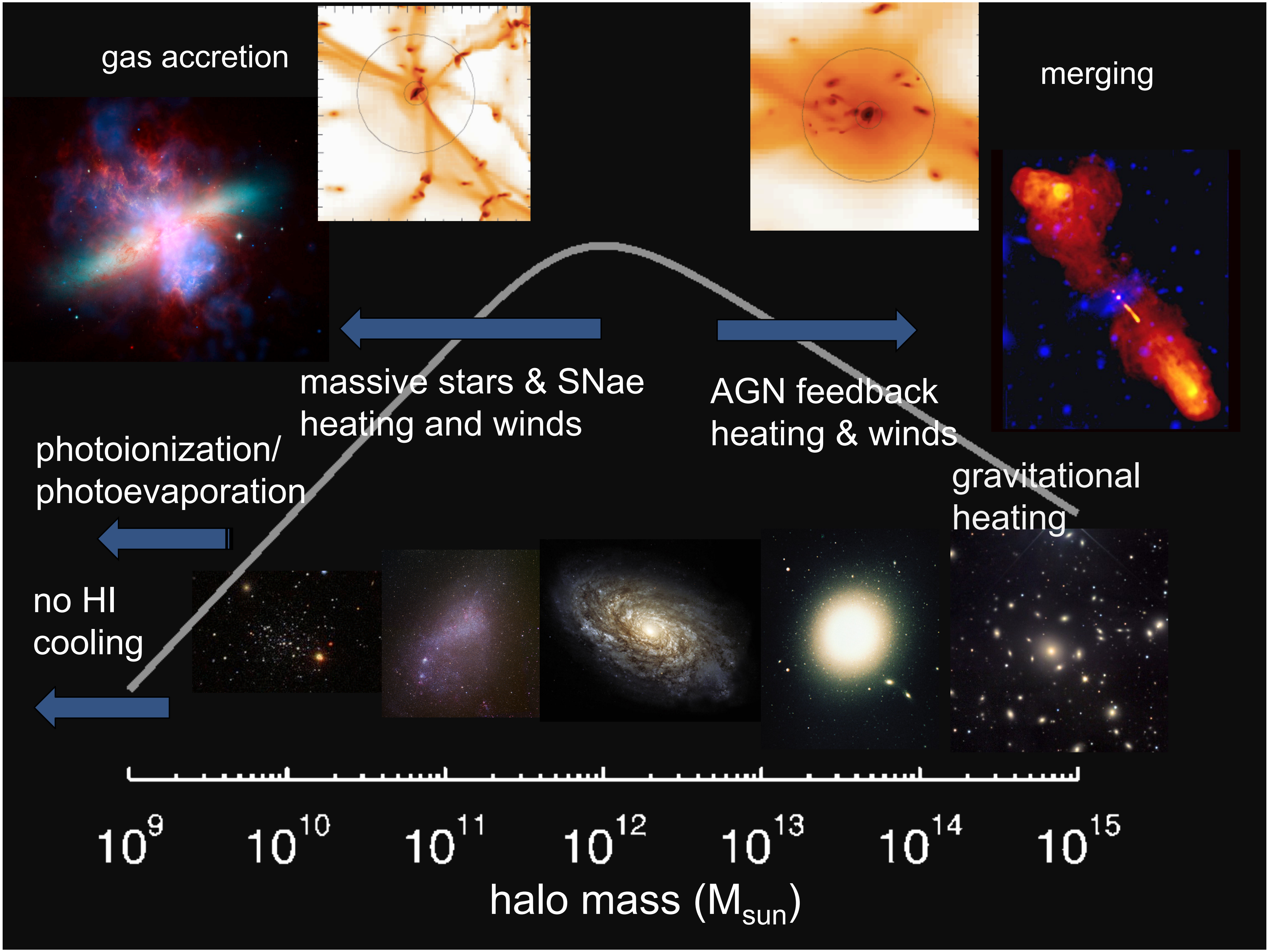




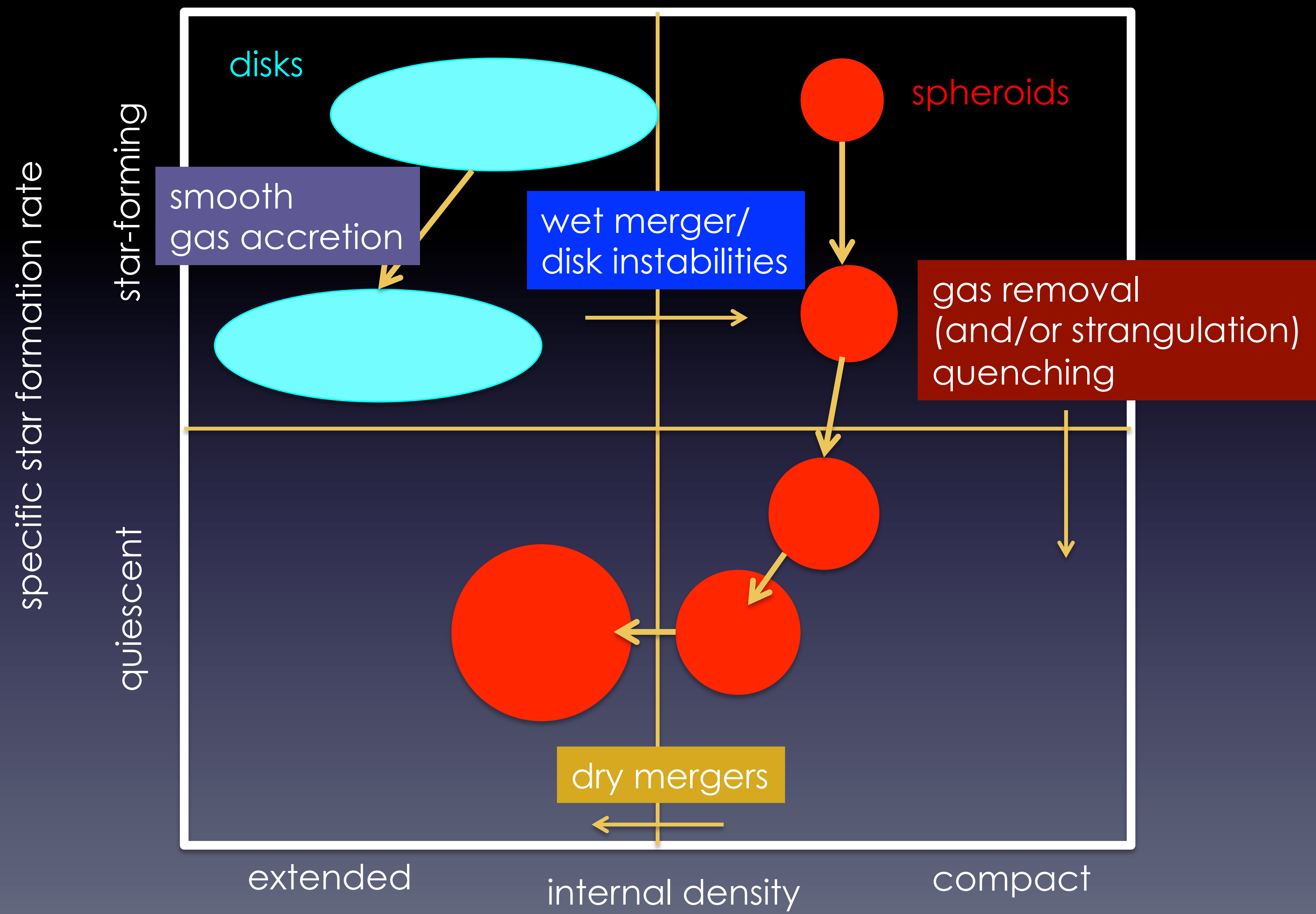
http://fire.northwestern.edu/

FIRE
Feedback In Realistic Environments



gas accretion
merging
massive stars & SNae
heating and winds
AGN feedback
heating & winds
photoionization/
photoevaporation
gravitational
heating
no HI
cooling
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
halo mass (M_{sun})

theoretical picture: see discussion in Barro et al. 2013, 2014; also Naab et al. 2009; Hilz et al. 2013; Porter, rss et al. 2014 and references therein



example: stellar feedback

‘sub-grid’ treatment → explicit physical treatment

galaxy-scale phenomenological wind scalings	input of thermal energy and/or momentum, using `tricks’ to mimic sub-grid processes	resolve individual stars & SNae & multiphase ISM; explicitly simulate all physical processes

semi-analytic models
Oppenheimer & Davé
Illustris

EAGLE
Naab+

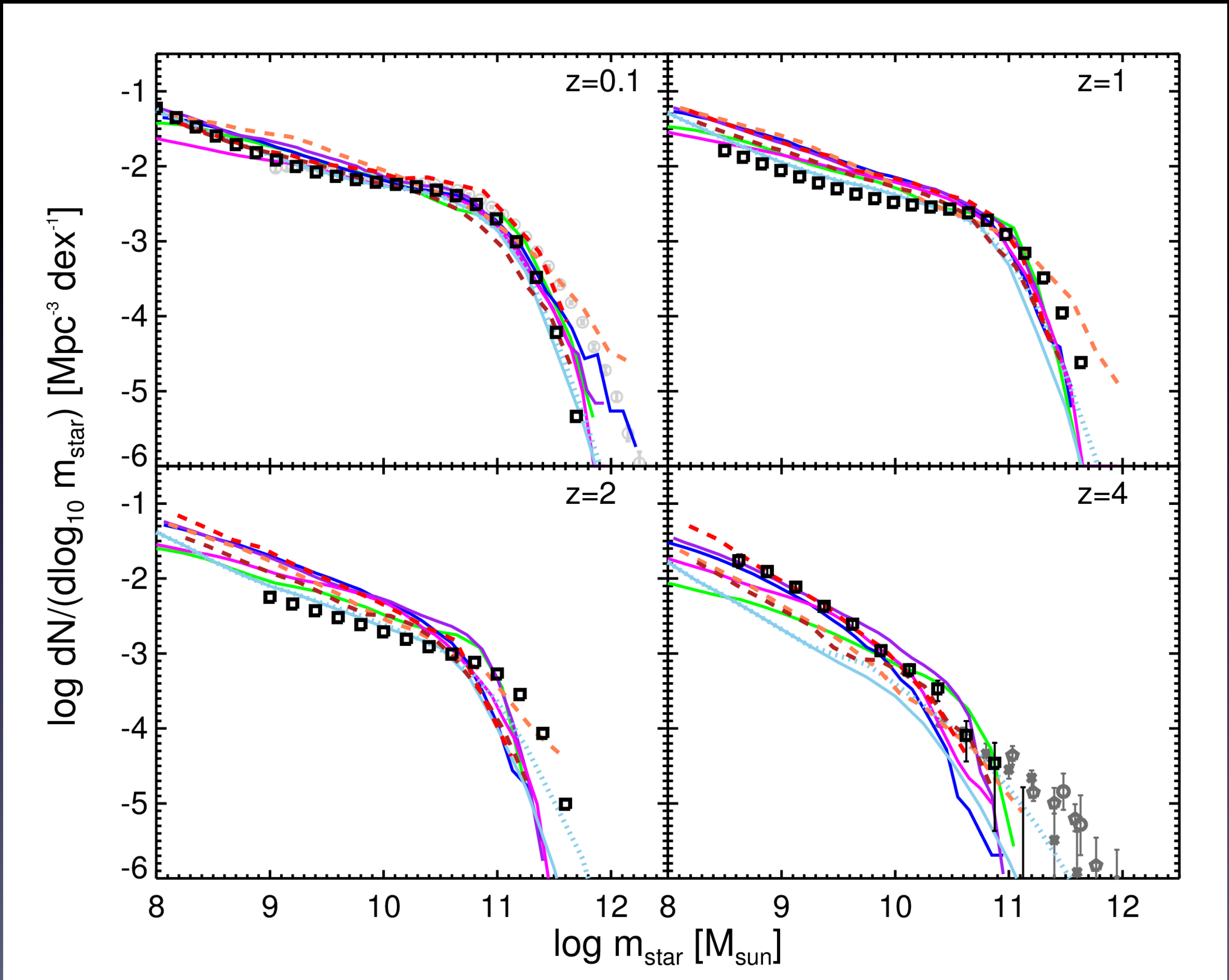
GASOLINE
RAMSES
hydro-ART

FIRE
Agertz
& Kravtsov

cosmological volumes (100-500 Mpc)^3

zoom-ins (individual halos)
idealized individual galaxies

consensus on the main physical processes that shape galaxy evolution?



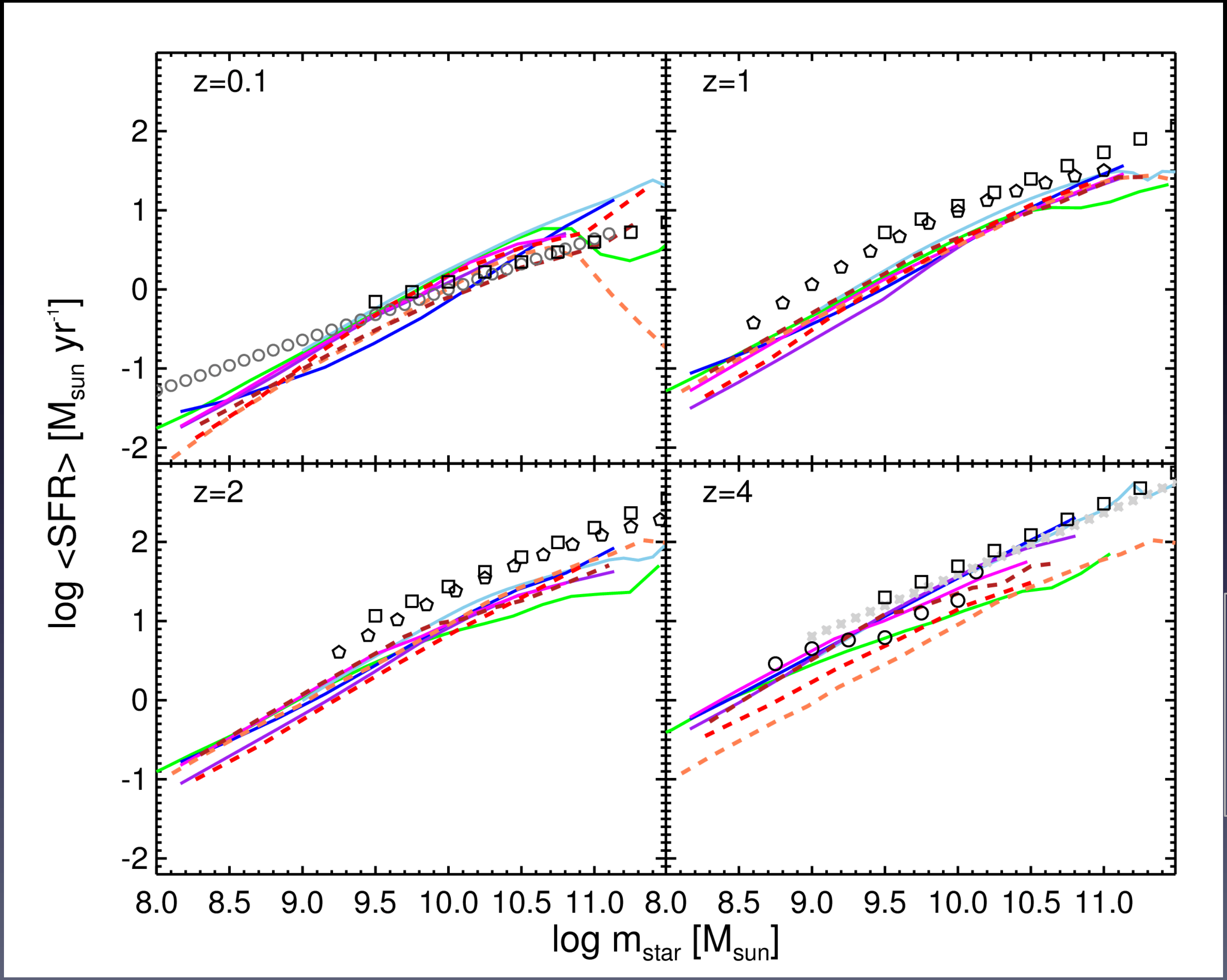
observational estimates are shown by symbols

lines show predictions from 5 semi-analytic models (solid) and 3 numerical hydrodynamic simulations (dashed)

Santa Cruz SAM; GALFORM; MPA Millennium SAM; SAGE SAM; Lu SAM Illustris simulation; EAGLE simulation; Oppenheimer & Davé ezw simulation

Somerville & Davé ARAA, 2015

what is the origin of the star forming main sequence?

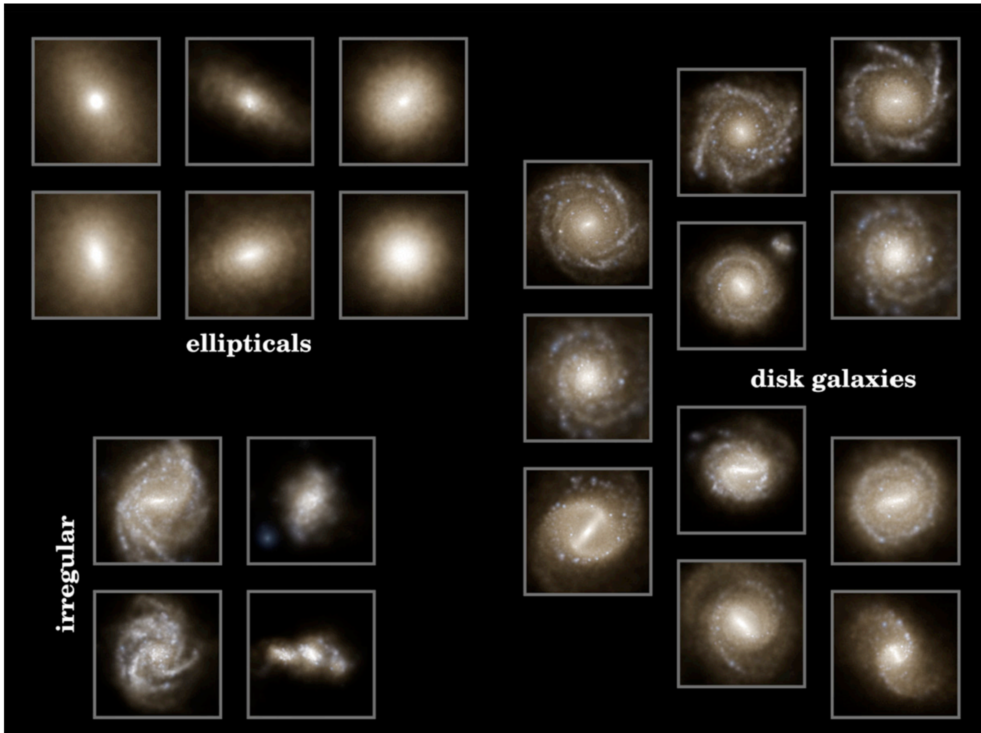


observational estimates are shown by symbols

lines show predictions from 5 semi-analytic models (solid) and 3 numerical hydrodynamic simulations (dashed)

behavior can be explained by a simple 'equilibrium' model)

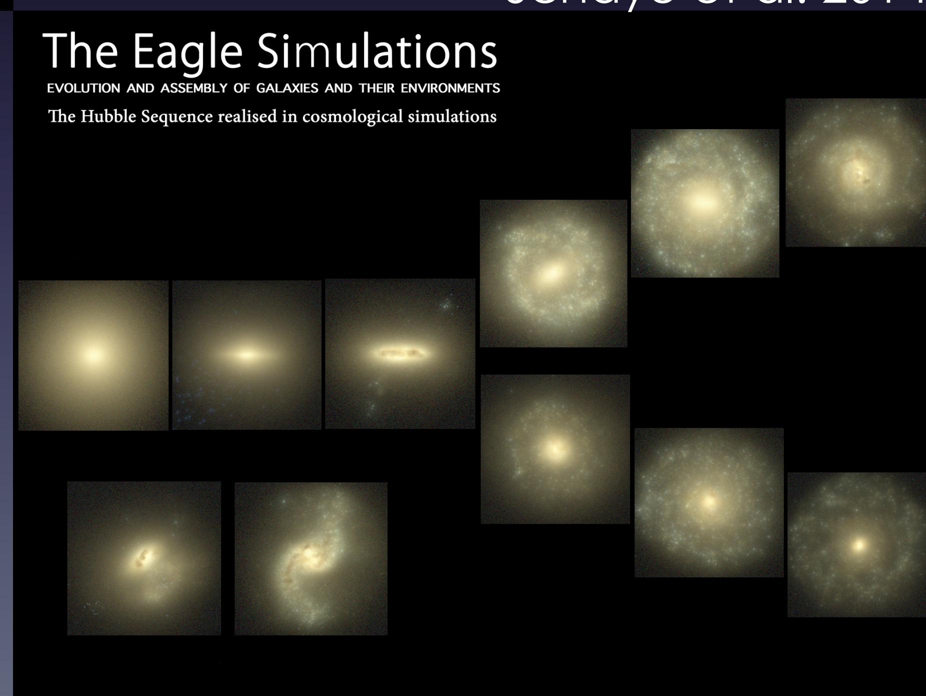
Somerville & Davé ARAA, 2015

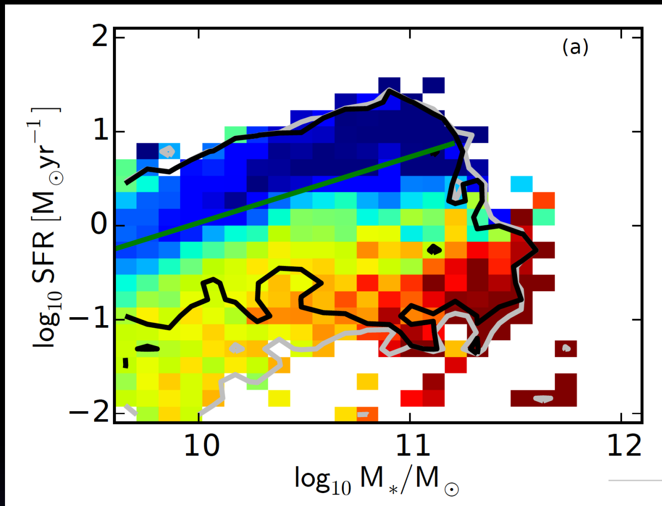


modern simulations produce a diverse range of galaxy morphologies

Schaye et al. 2014

Illustris (Vogelsberger et al. 2014)

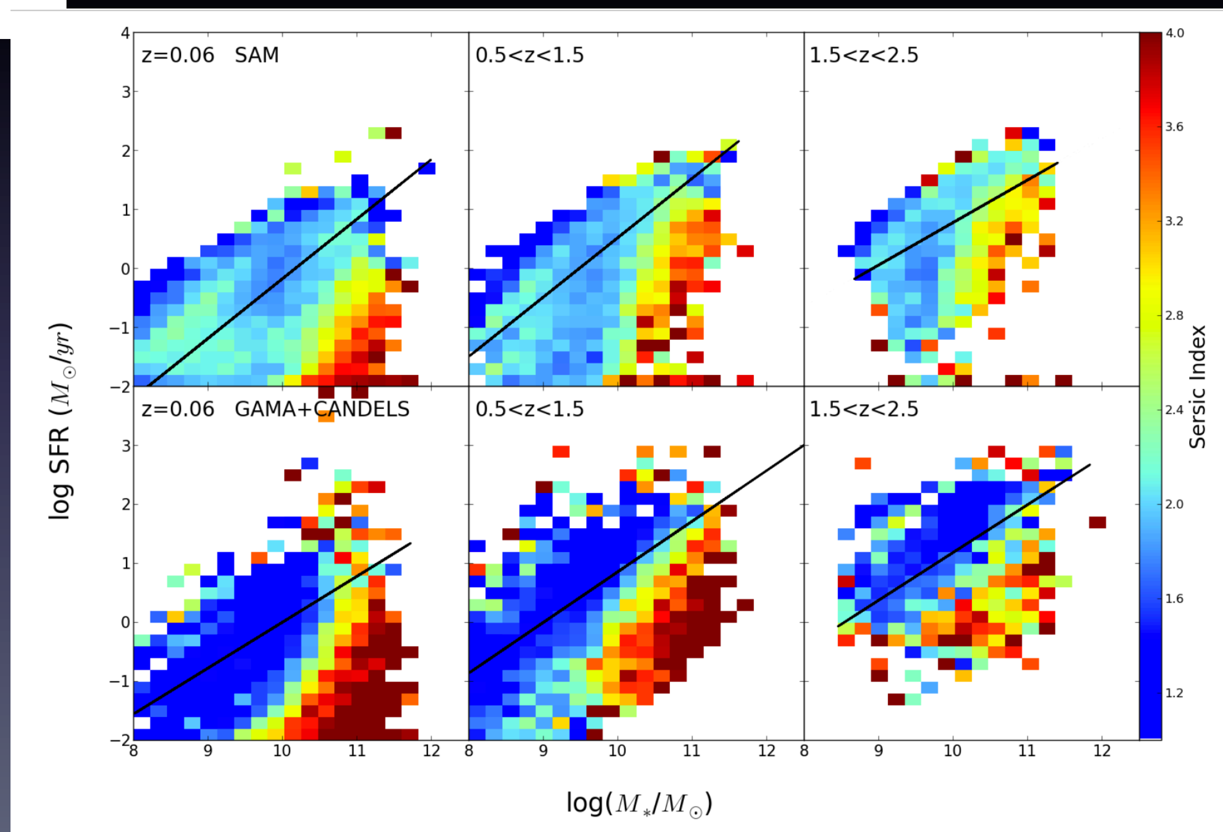


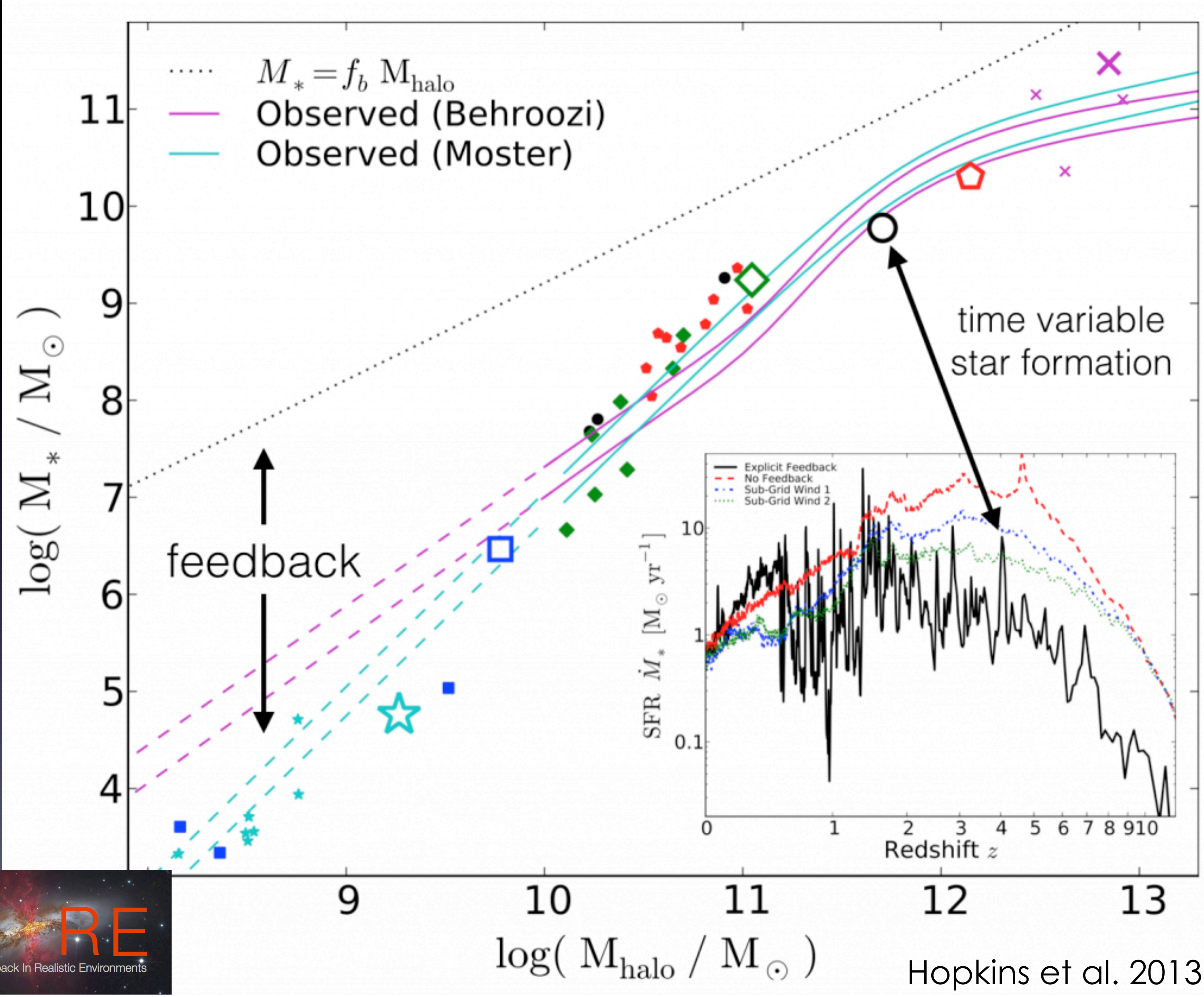


despite the crudeness of current ‘sub-grid’ recipes, simulations qualitatively capture the observed correlation between quenching and internal structure

Snyder et al. 2015
Illustris simulation

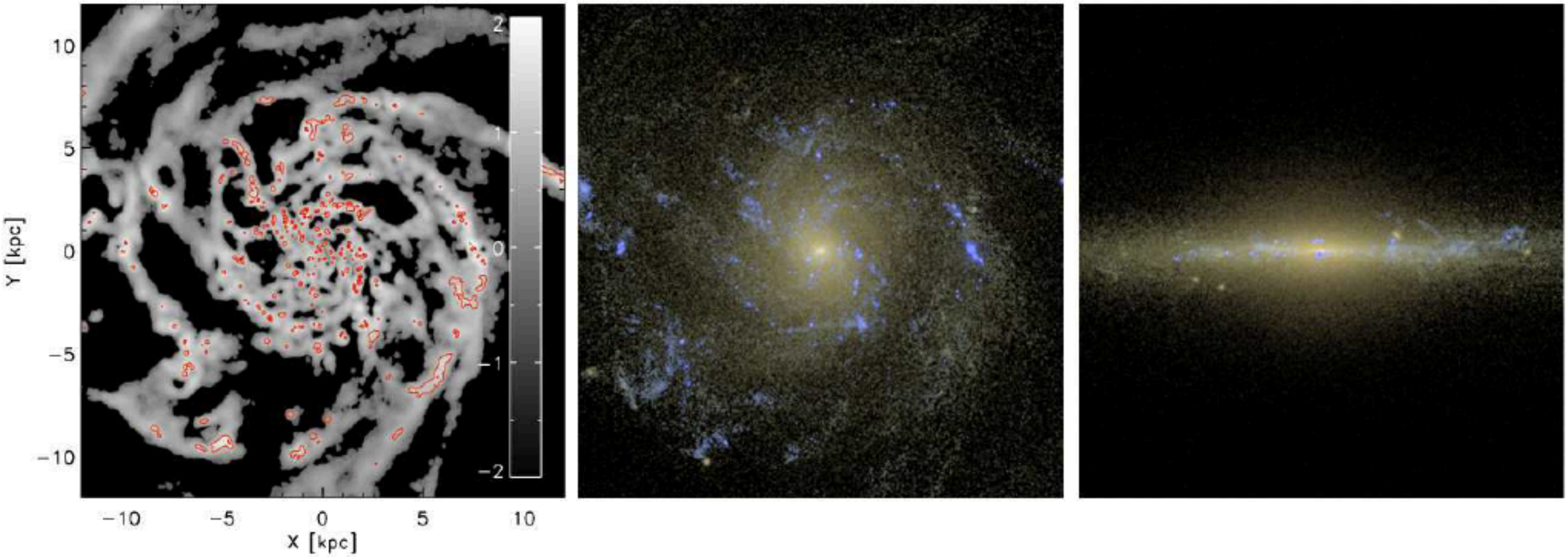
Brennan et al. 2015 semi-analytic model





Hopkins et al. 2013

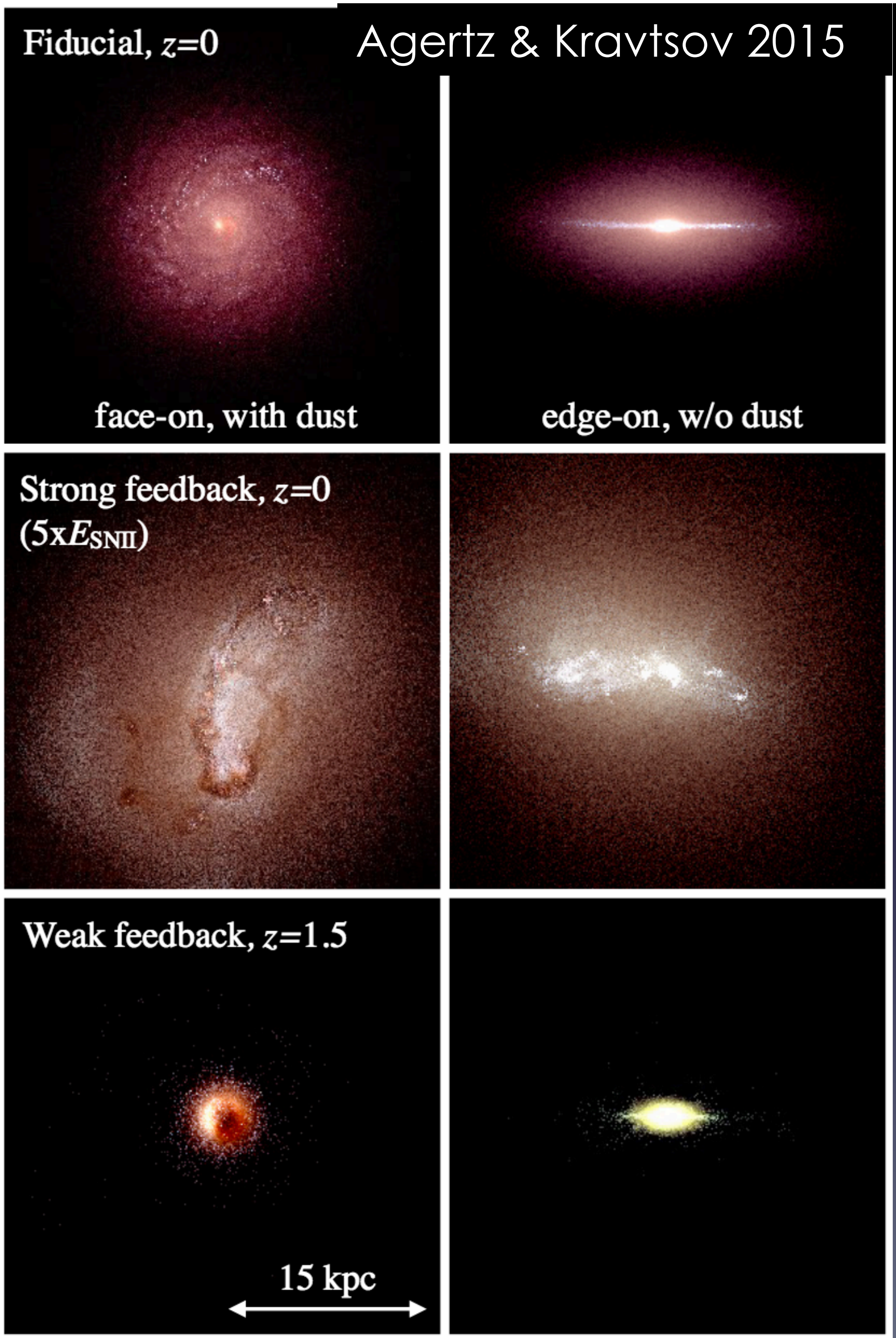
angular momentum catastrophe solved (?) – combination of resolution, more physical treatment of ISM, star formation, stellar feedback

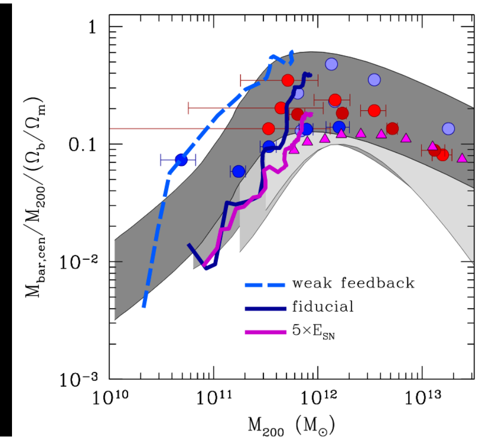


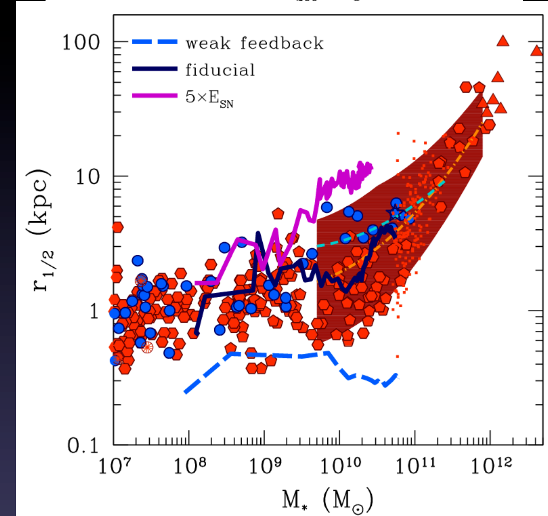
GASOLINE simulation including metal cooling, H_2 chemistry & simplified radiative transfer

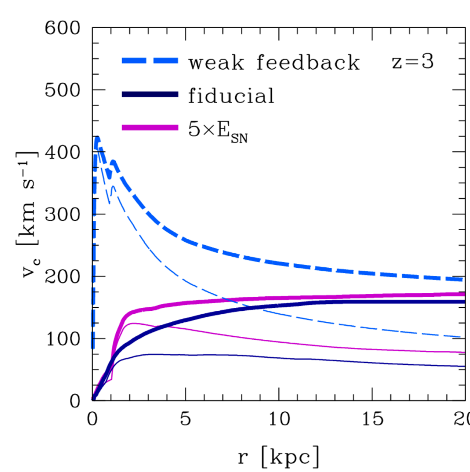
Christensen et al. 2012
see also Guedes et al. 2011; Brooks et al. 2011; Governato et al. 2010

Agertz & Kravtsov 2015

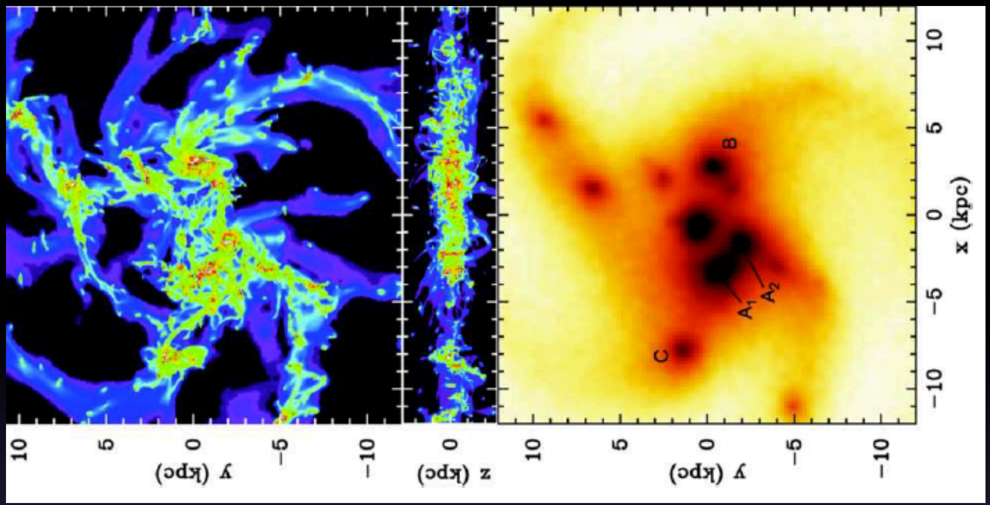








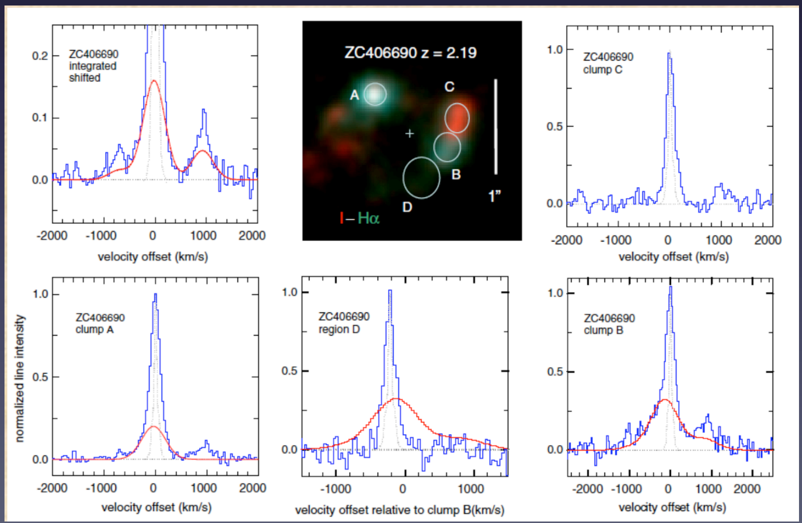
Clumps and Disk Instabilities



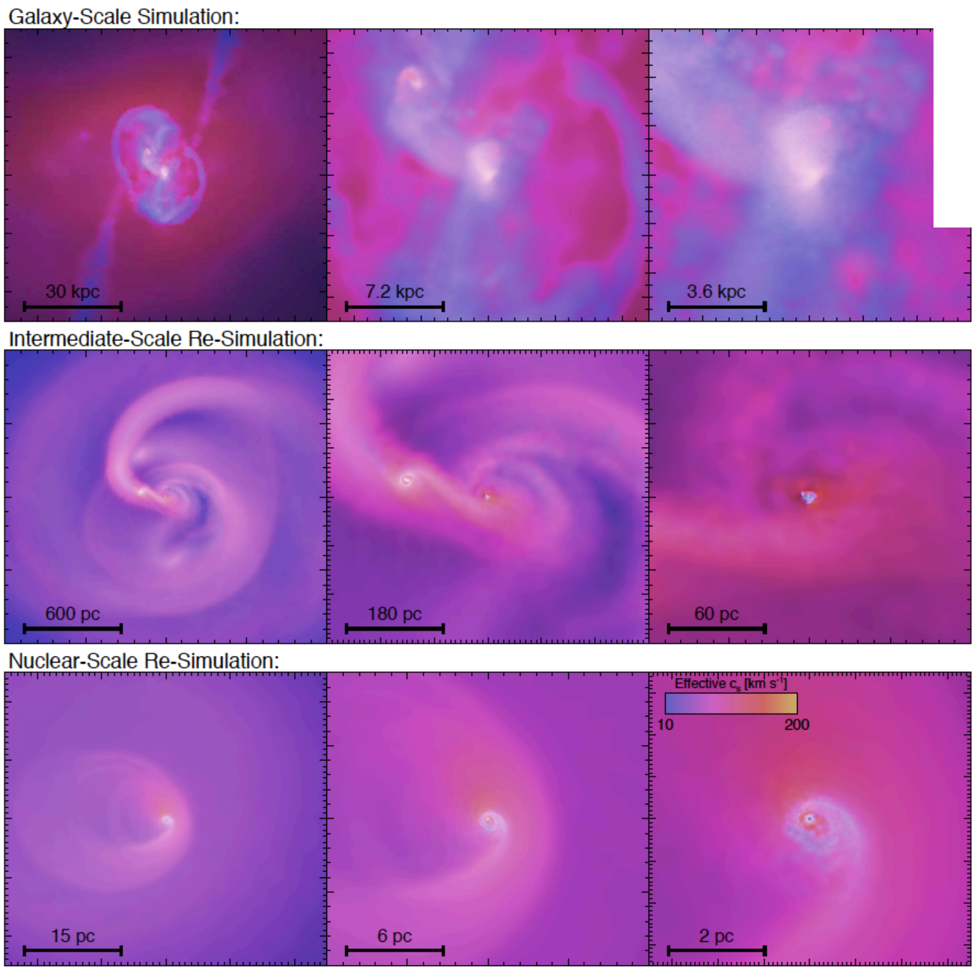
Dekel et al. 2009; Bournaud, Dekel et al. 2011

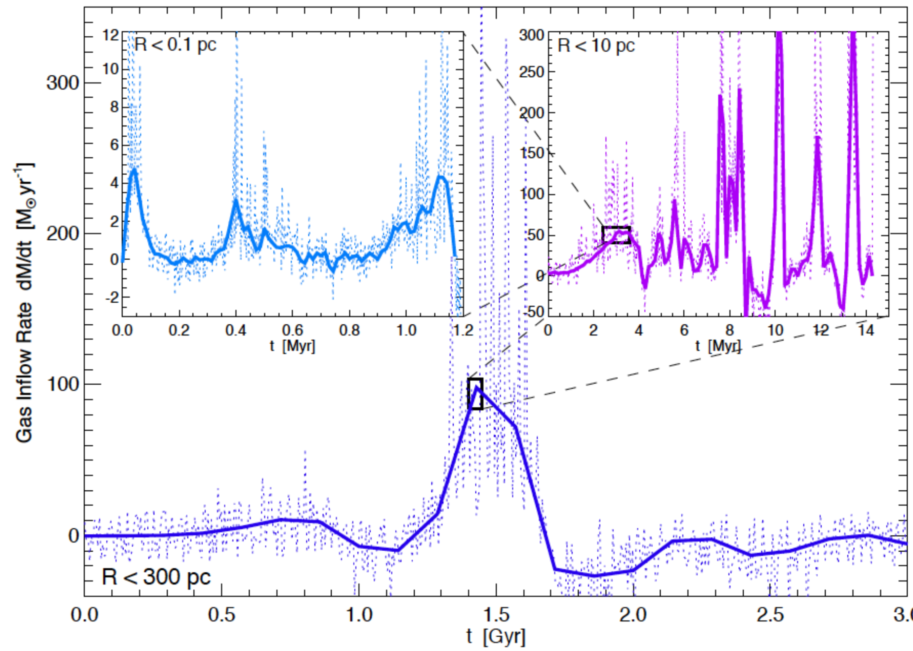
Y. Guo (CANDELS)

- internal gravitational instabilities may lead to formation of clumps
- these may drive nuclear inflows & migrate to the center, forming a spheroid & feeding the BH
- outflows from individual clumps detected (Genzel et al. 2011)



How do black holes accrete? Why are some BH feasting while others are starving?





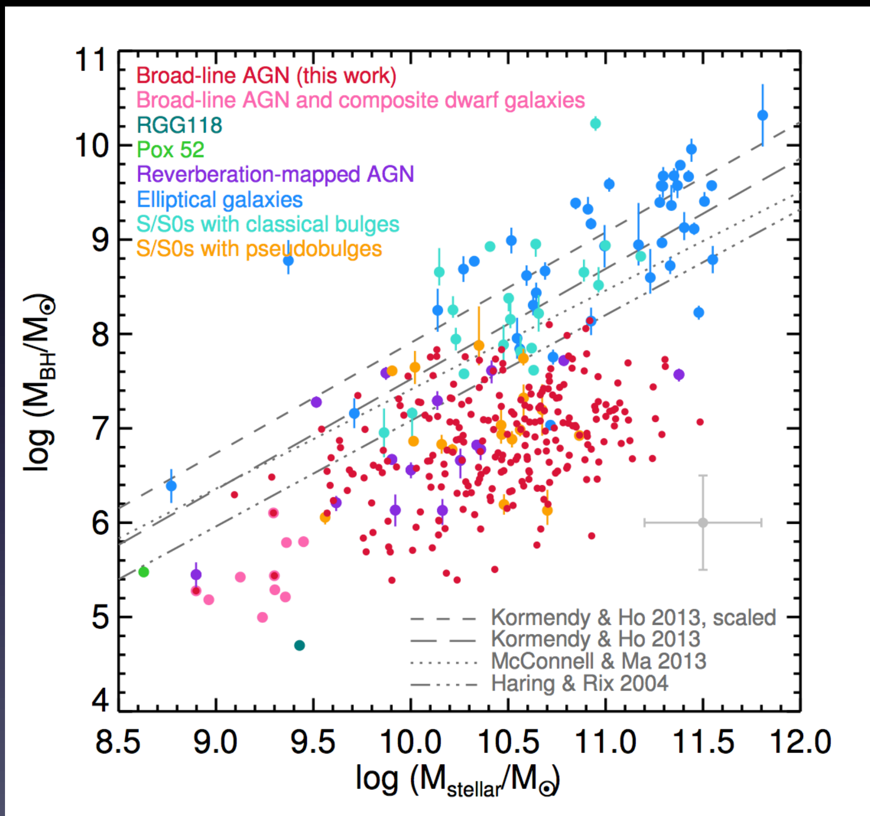
$$\dot{M}_{\rm Torque} \approx \alpha_{\rm T}\, f_{\rm disk}^{5/2} \times \left(\frac{M_{\rm BH}}{10^8\,{\rm M_\odot}}\right)^{1/6} \left(\frac{M_{\rm disk}(R_0)}{10^9\,{\rm M_\odot}}\right) \times \left(\frac{R_0}{100\,{\rm pc}}\right)^{-3/2} \left(1+\frac{f_0}{f_{\rm gas}}\right)^{-1} {\rm M_\odot\,yr^{-1}},$$

$$f_0 \approx 0.31\, f_{\rm disk}^2\, (M_{\rm disk}(R_0)/10^9{\rm M_\odot})^{-1/3},$$

$$f_{\rm gas}(R_0) \equiv M_{\rm gas}(R_0)/M_{\rm disk}(R_0),$$

Hopkins & Quataert 2011

black hole scaling relations

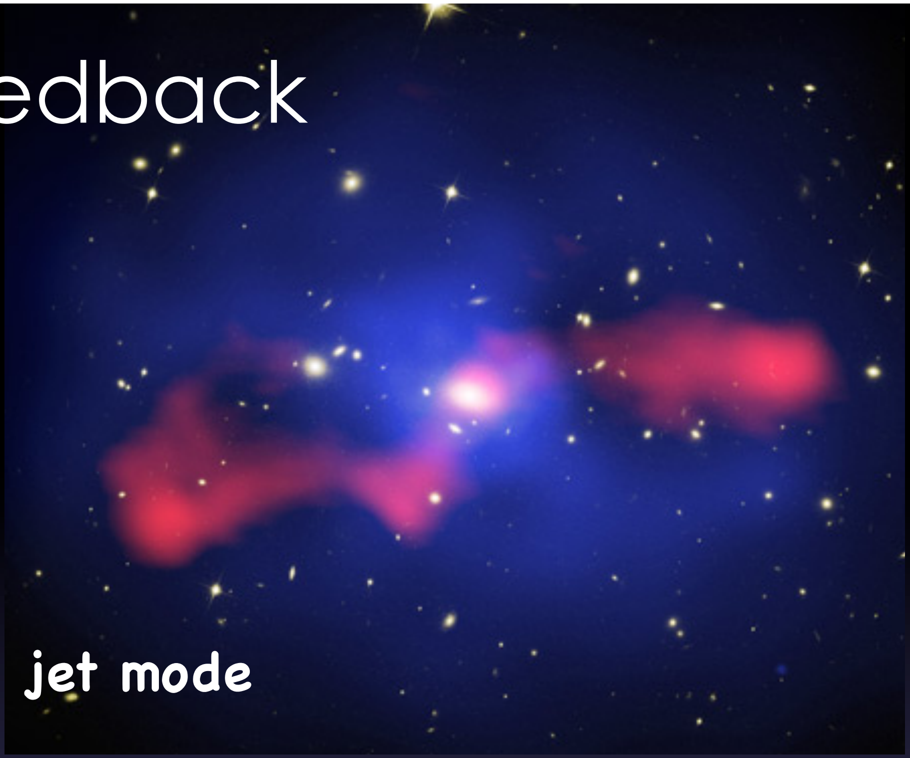


Reines & Volonteri 2015

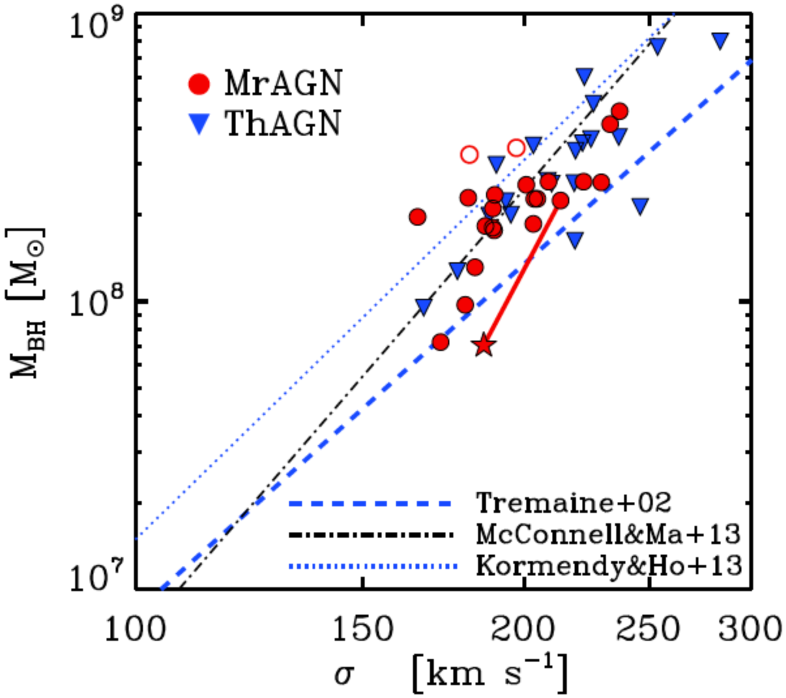
- [how often] do low mass galaxies contain black holes?
- how do BH scaling relations evolve over cosmic time?
- which parameter has the most fundamental correlation with BH mass?

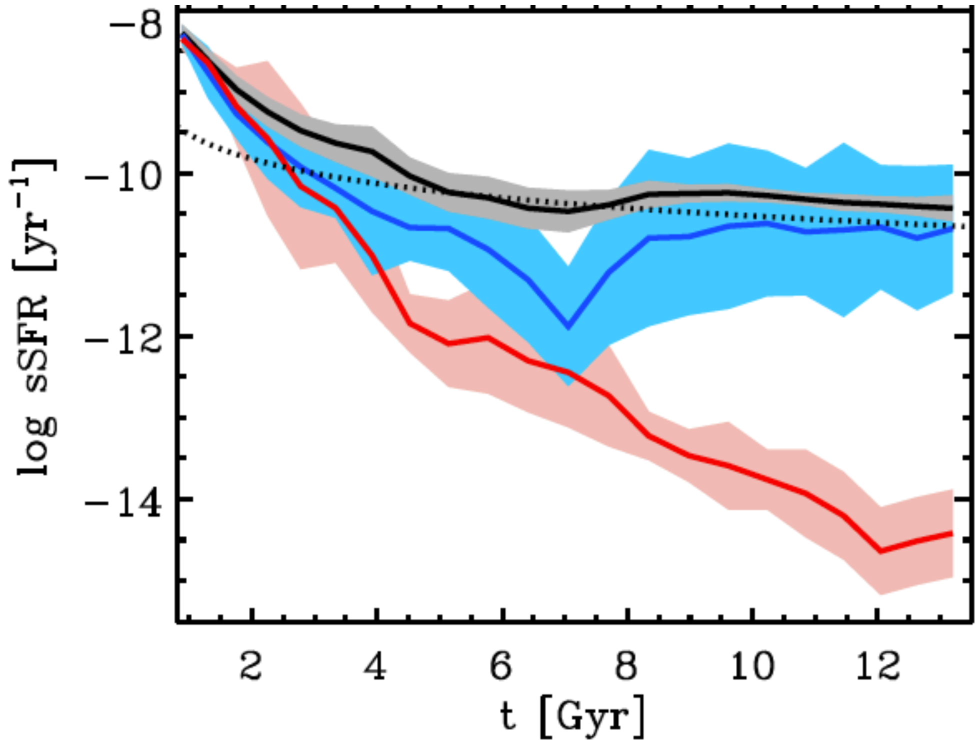
AGN feedback

- heating (Compton, photo-ionization, photo-electric)
- winds driven via radiation pressure on spectral lines, free electrons, or dust
- ionization and photo-dissociation of gas

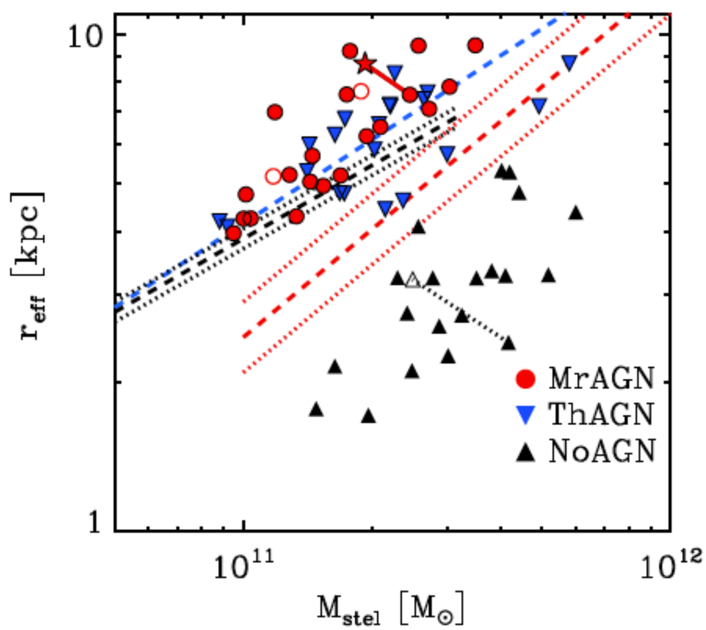


- relativistic jets of charged particles heat diffuse hot gas via sound waves, weak shocks, and viscosity
- may also drive outflows of dense, cold material



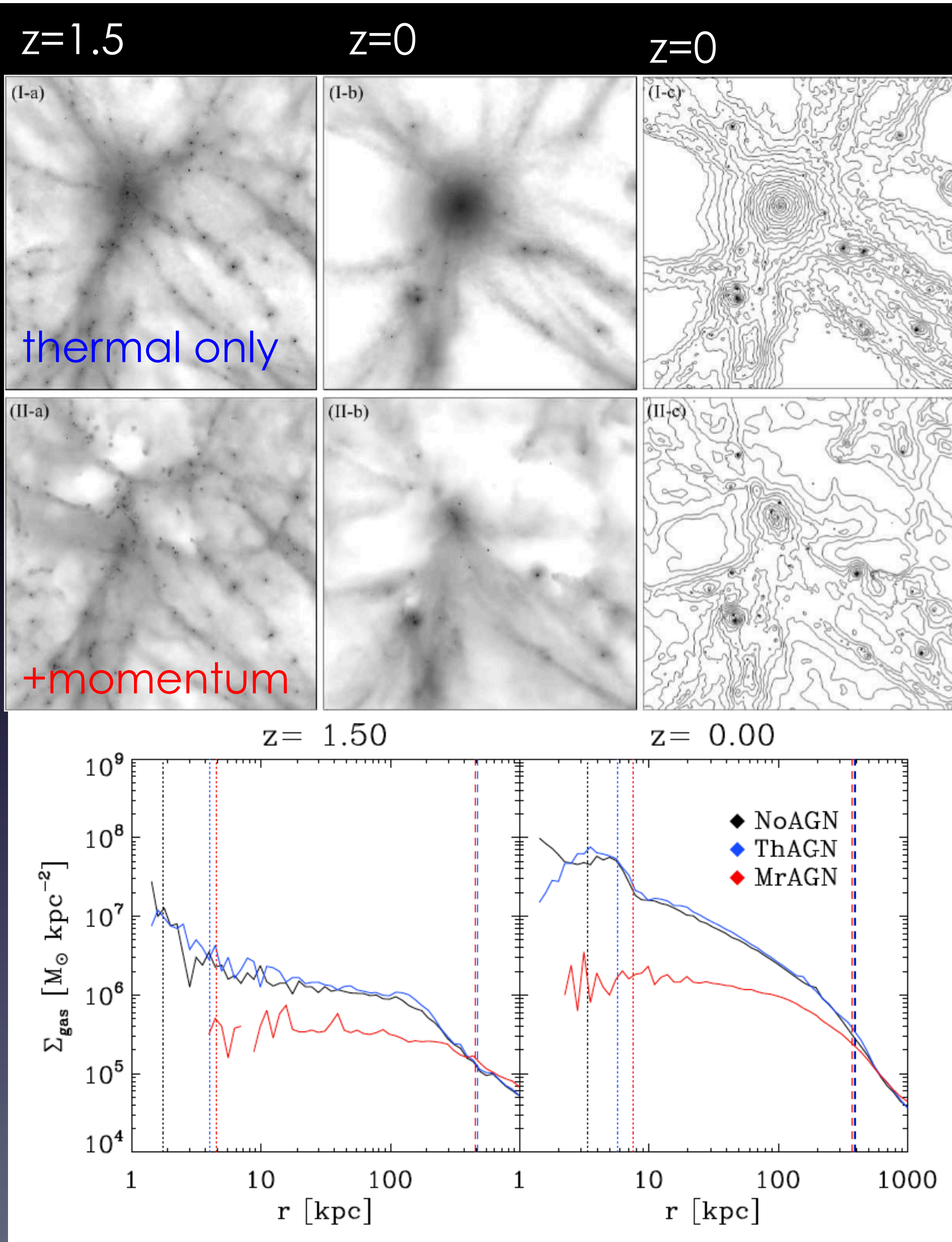


(lines are observational estimates; points are simulation predictions)



both AGN FB models produce similar results for global and structural properties of galaxies, but model with no AGN FB produces galaxies that are too compact

Choi et al. 2015; see also di Matteo+05, Springel+05; Robertson+05; Sijacki+07,11,14



Simulations with Momentum feedback from AGN

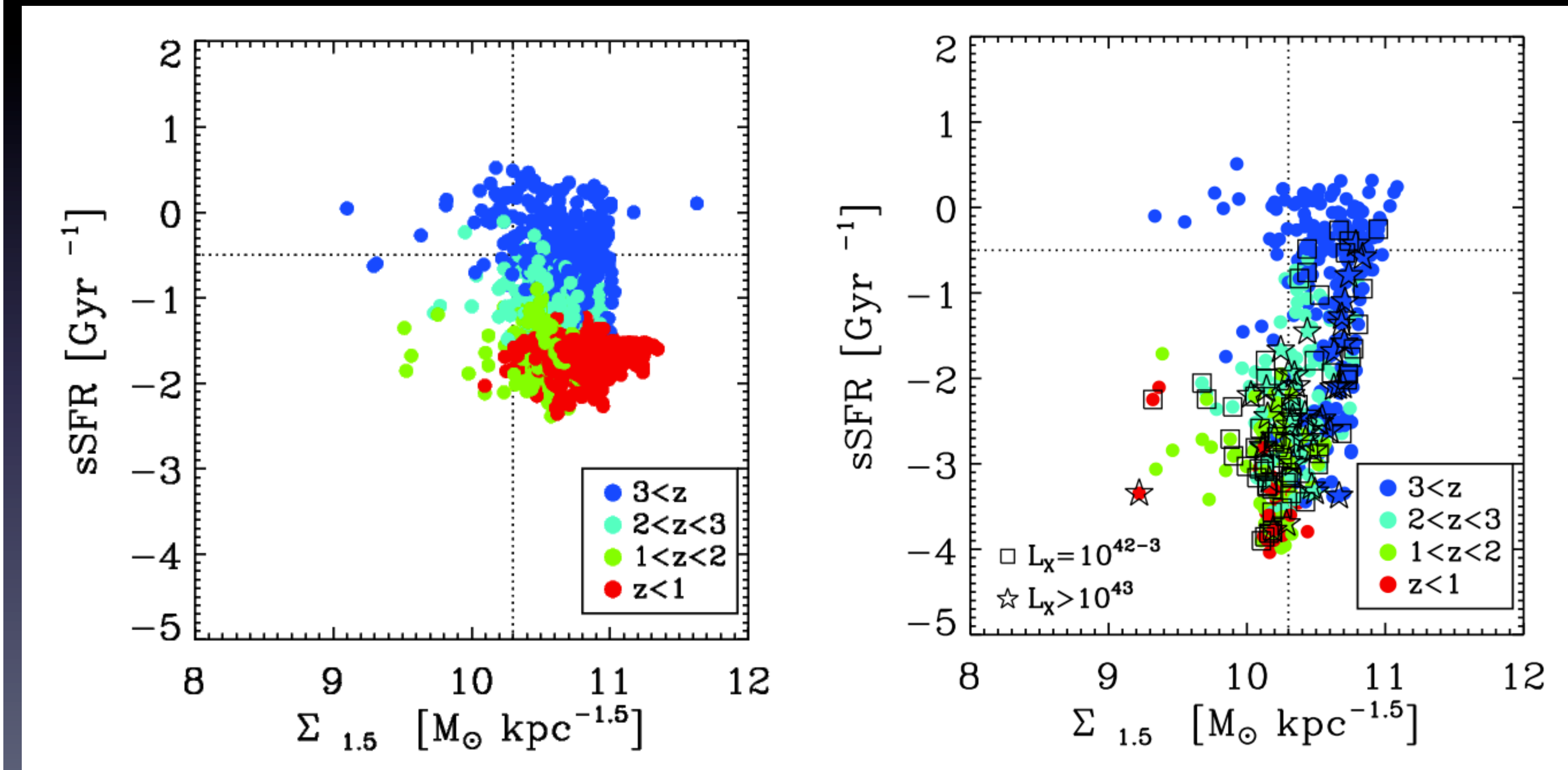
cosmological zoom-in sims
star and gas particles 6E06 M_{sun}
DM particles 3.6E07 M_{sun}
comoving softening 571 pc
2.3E12<M_h/M_{sun}<1.3E13
~10^6 particles per halo

fixed wind velocity 10,000 km/s
+ radiative feedback

Choi et al. 2014; Choi et al. 2015
w/ J. Ostriker, T. Naab, L. Oser
see also Debuhr et al. 2010, 2011

no AGN feedback—
incomplete quenching
indefinite compaction

with AGN-driven winds—
compaction→quenching→
expansion



Choi, rss et al. in prep; rss et al. in prep

Mapping the bulk of the baryons and metals since z~1

- theoretical models rely on efficient stellar and AGN-driven winds to get gas out of galaxies
- galaxy properties are a blunt tool – CGM should provide much stronger constraints on ‘sub-grid’ physics
- many unanswered questions!

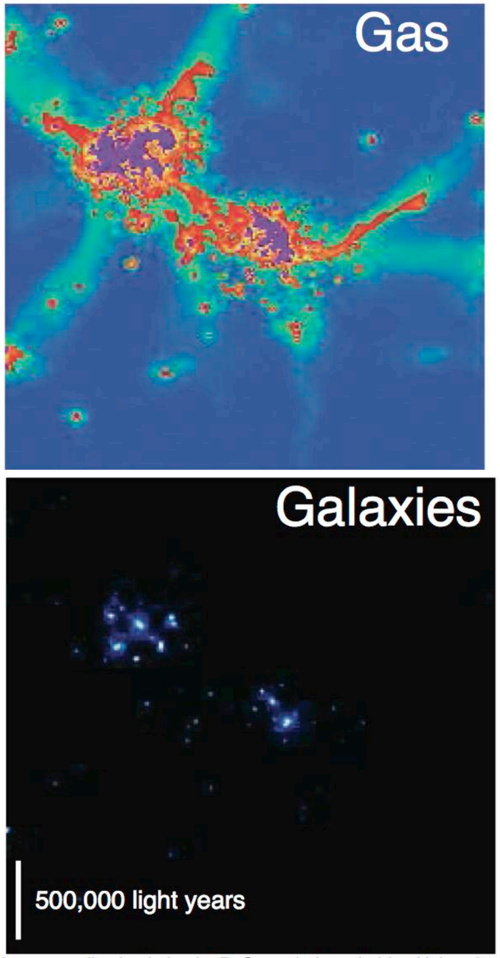
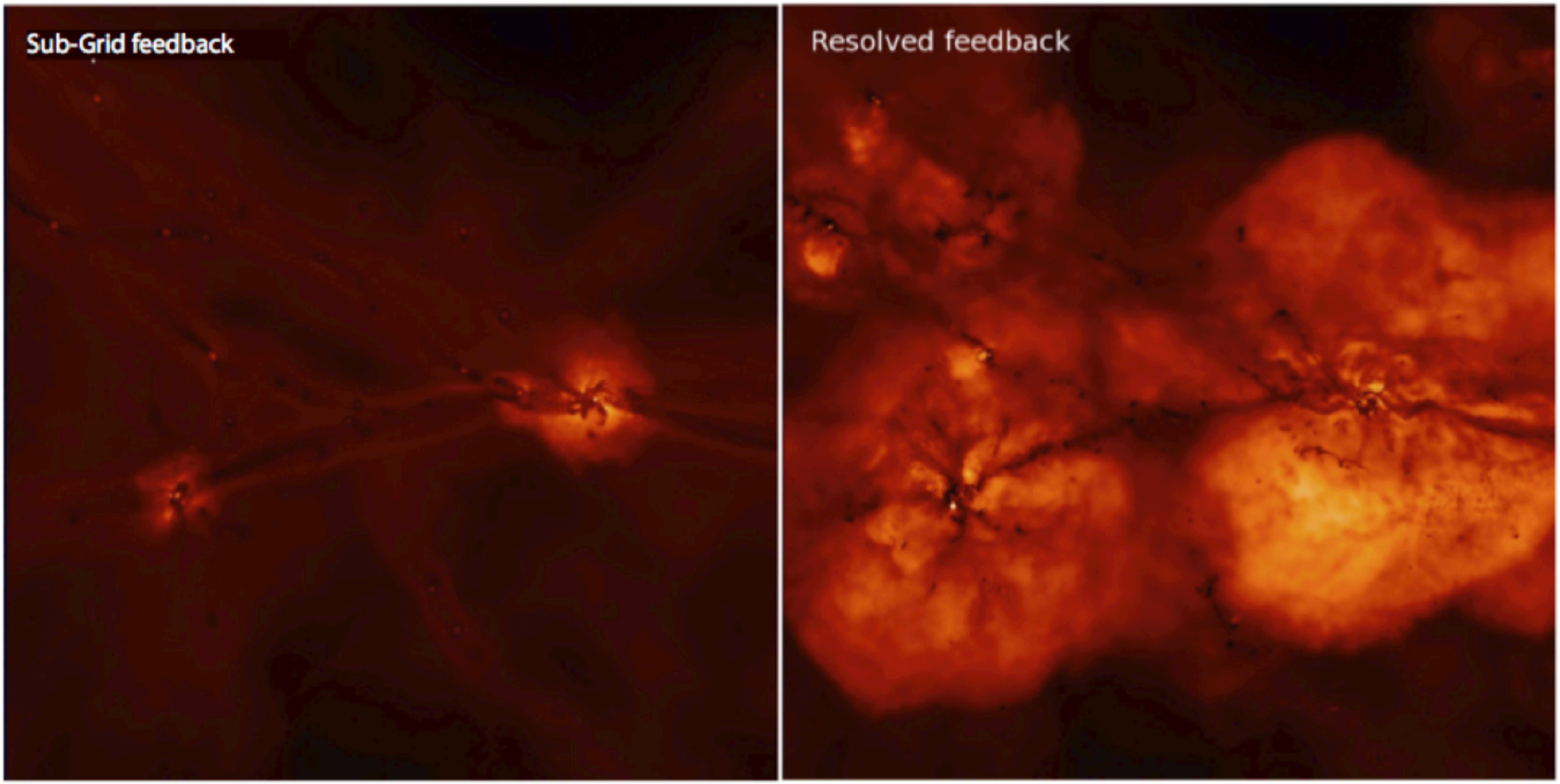
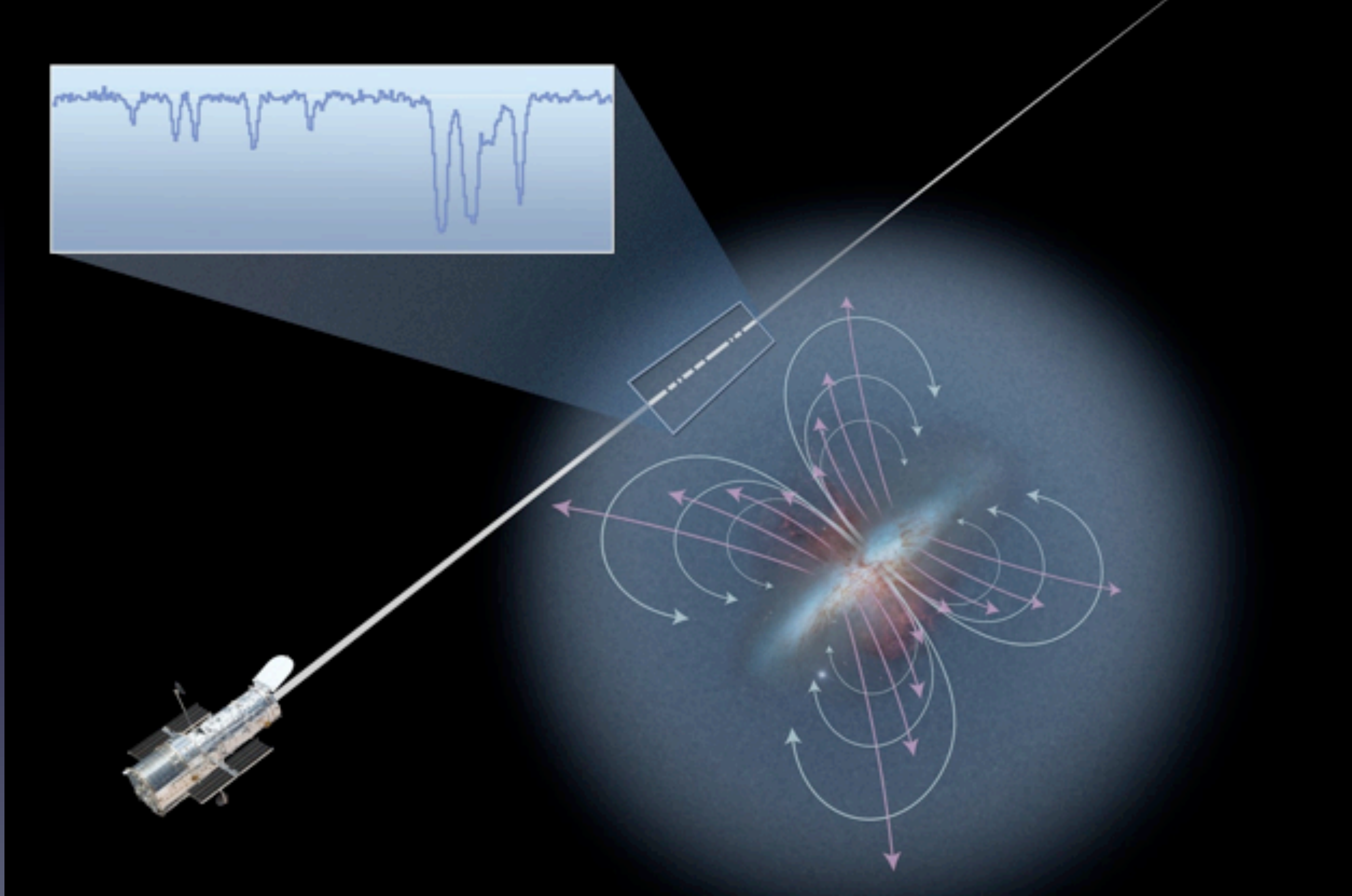


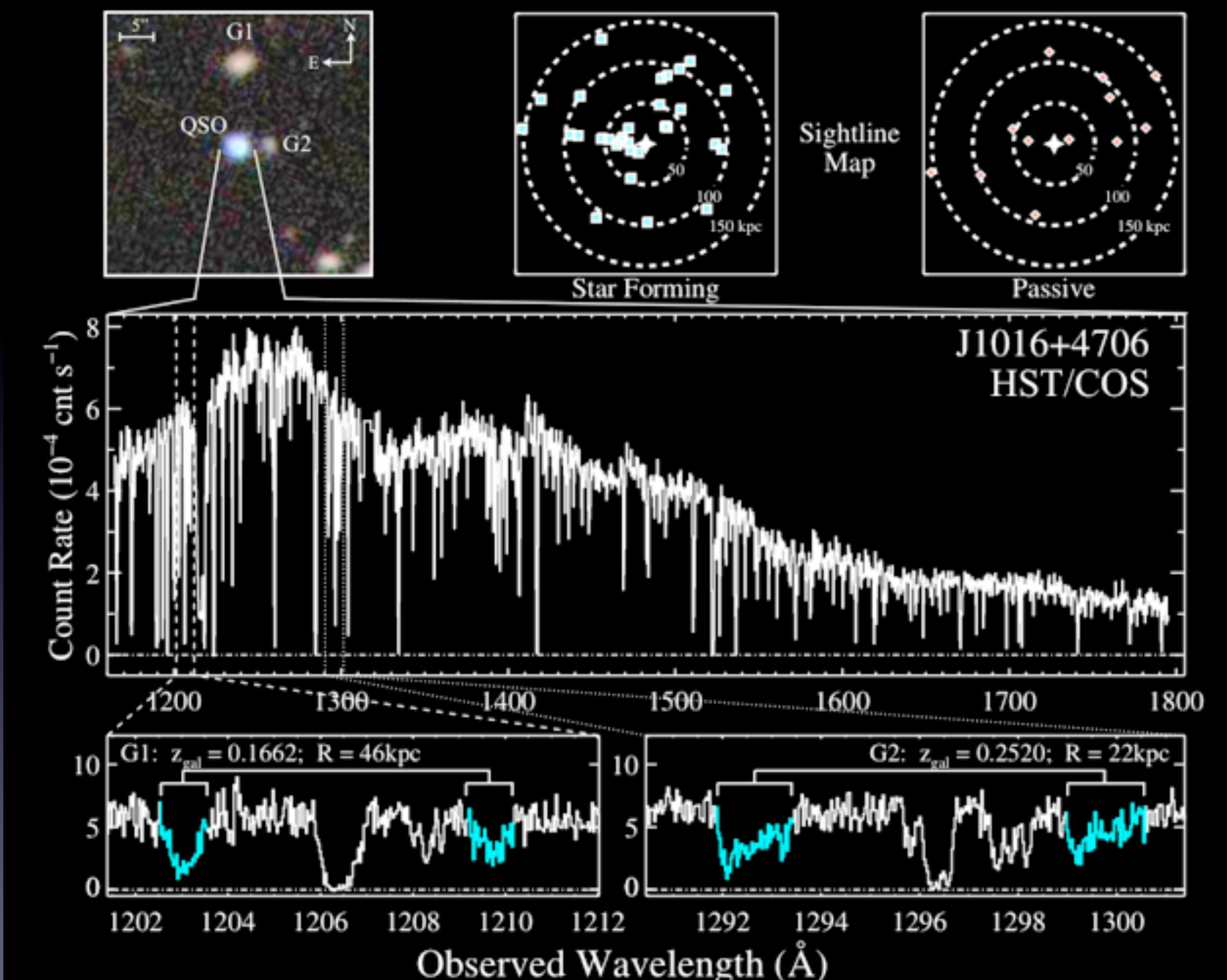
Image credit: simulation by B. Oppenheimer, Leiden University



P. Hopkins

COS-halos & COS-dwarfs





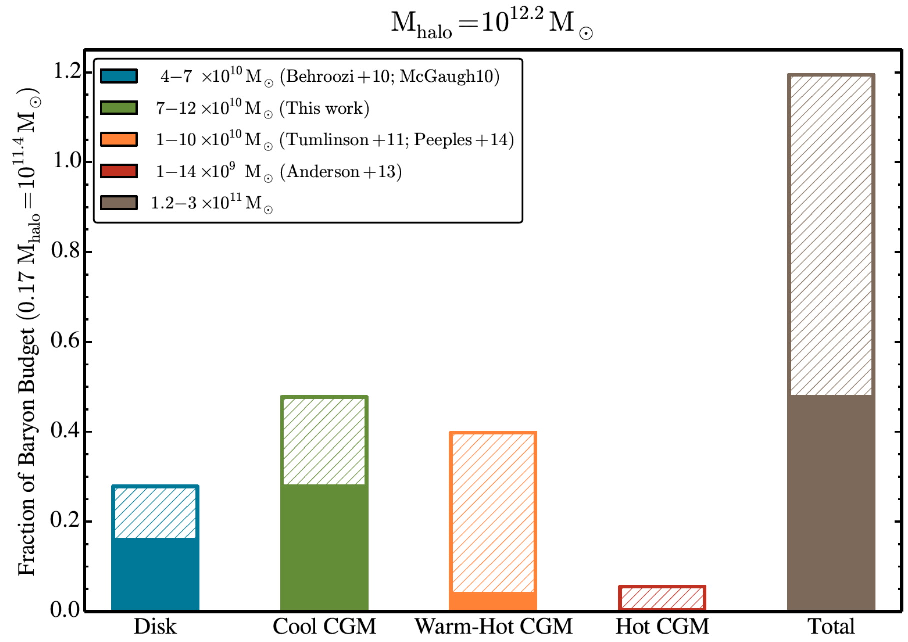
5"
G1
N
E
QSO
G2
Sightline
Map
50
100
150 kpc
Star Forming
Passive
J1016+4706
HST/COS
Count Rate (10^{-4} cnt s^{-1})
0
2
4
6
8
1200
1300
1400
1500
1600
1700
1800
G1: z_{gal} = 0.1662; R = 46kpc
G2: z_{gal} = 0.2520; R = 22kpc
10
5
0
1202
1204
1206
1208
1210
1212
1292
1294
1296
1298
1300
Observed Wavelength (Å)

CGM lessons and questions

- CGM contains a lot of baryons & metals
- it also contains a large amount of primordial gas, which may be a signature of accretion
- some halos possess gas at $\sim 10^6$ K, which may be the long-sought ‘missing baryons’
- quenched galaxies have a lot of gas in their CGM too, begging the question of how they stay quenched over long timescales!

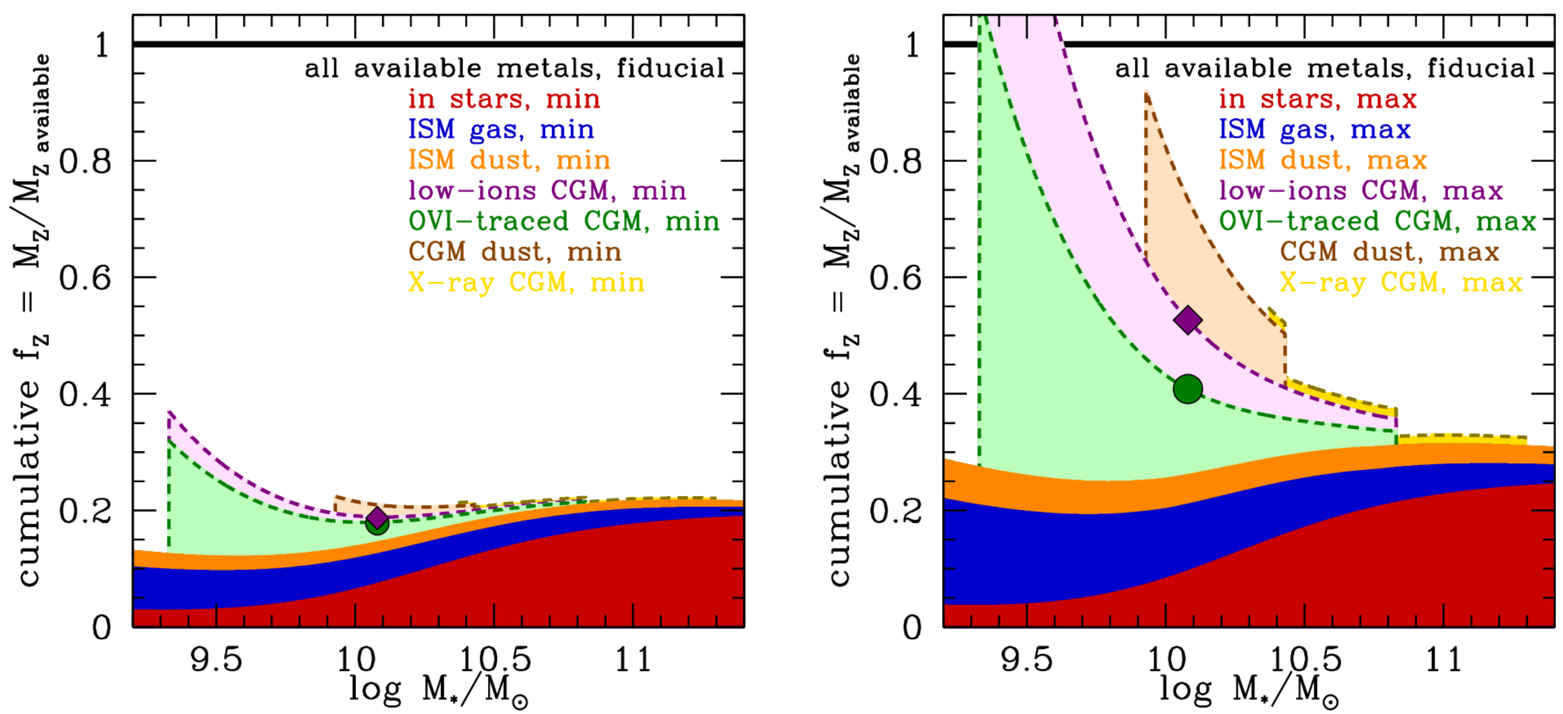
J. Tumlinson, HST whitepaper

Werk et al. 2014



COS-halos: the baryons and metals in the circumgalactic medium likely exceed those in stars and the ISM

Peeples et al. 2014



CGM lessons and questions

- what is the dynamical state of the CGM (fraction of primordial accretion, outflowing material, recycled accretion, etc)?
- how (in detail) do gas and metals cycle through the CGM?
- how do quenched galaxies stay that way while surrounded by lots of gas?
- do we finally have a complete census of baryons and metals?

J. Tumlinson, HST whitepaper

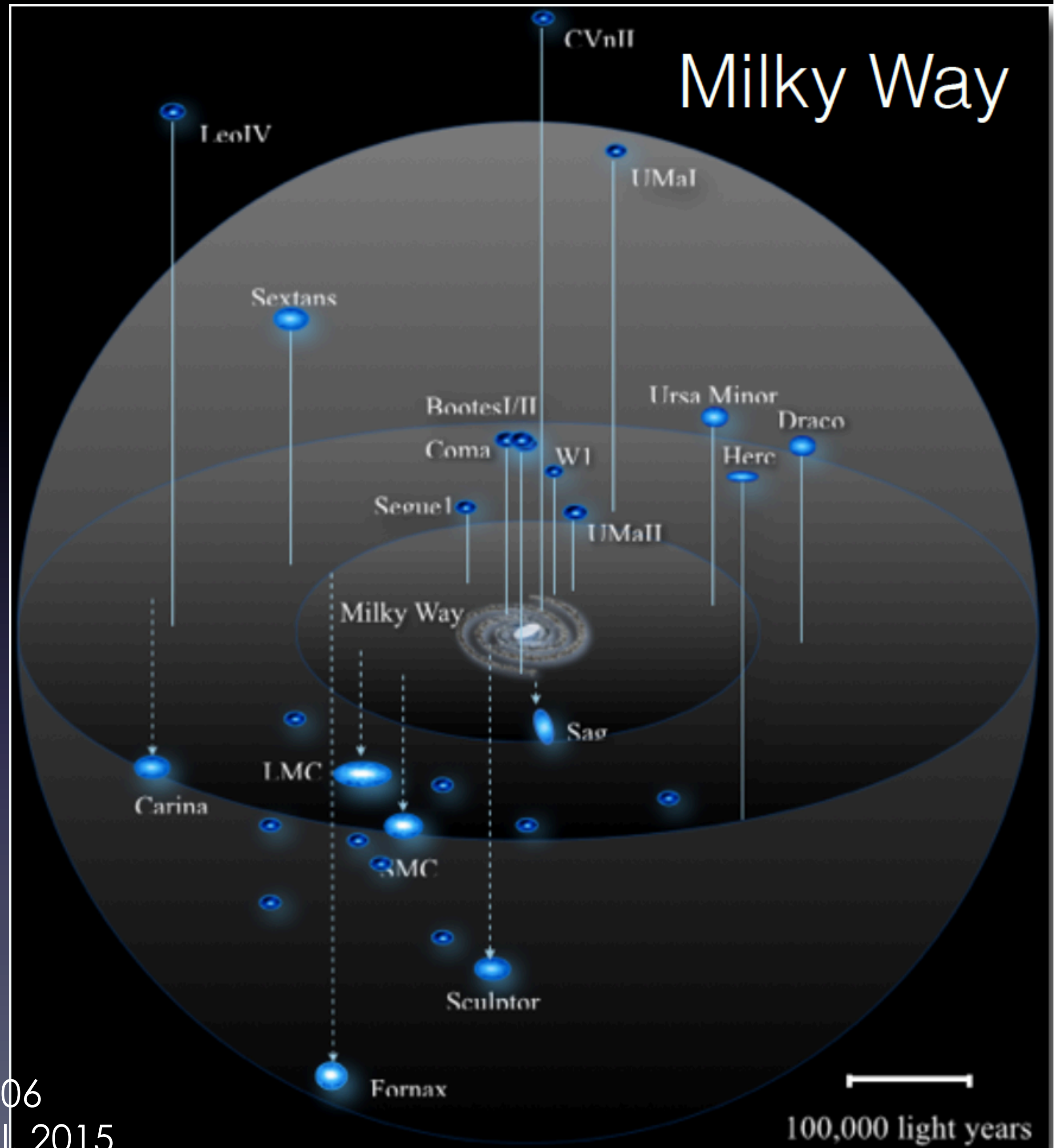
Dwarf galaxies as laboratories for fundamental physics: missing satellites, cusps & cores, & "too big to fail"

discovery of new "ultrafaint" dwarf galaxies in the Local Group (satellite count has tripled in past decade; SDSS/Segue/DES/DECam/ LSST)

-very high M/L

-pure ancient stellar pop

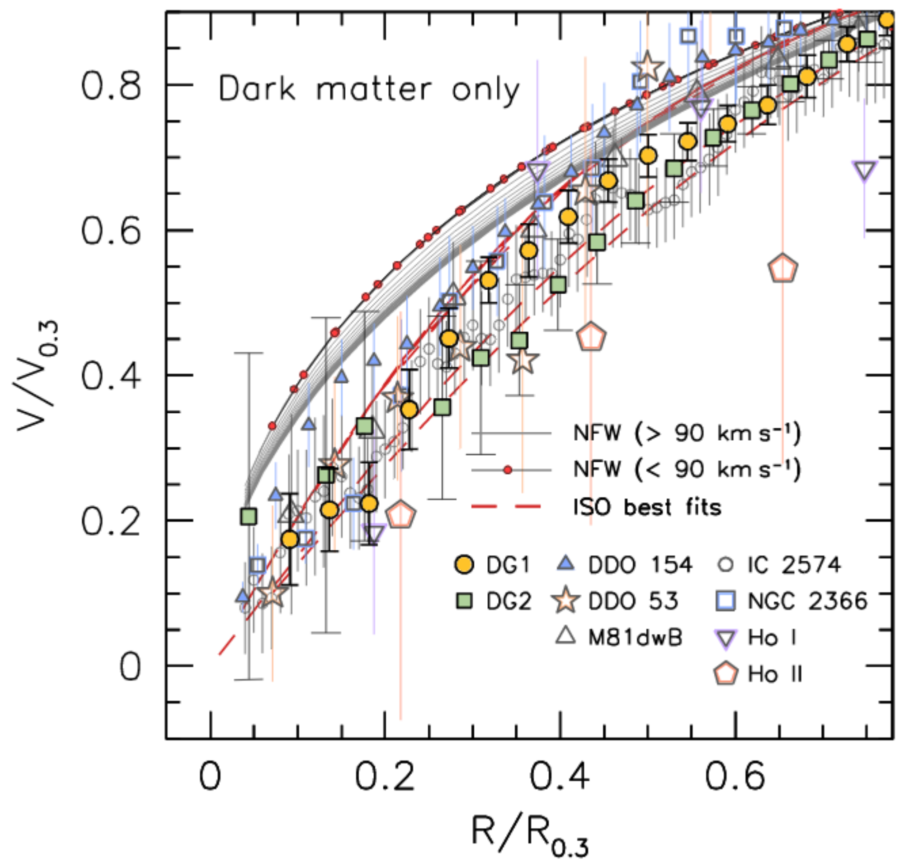
-fossils of reionization?

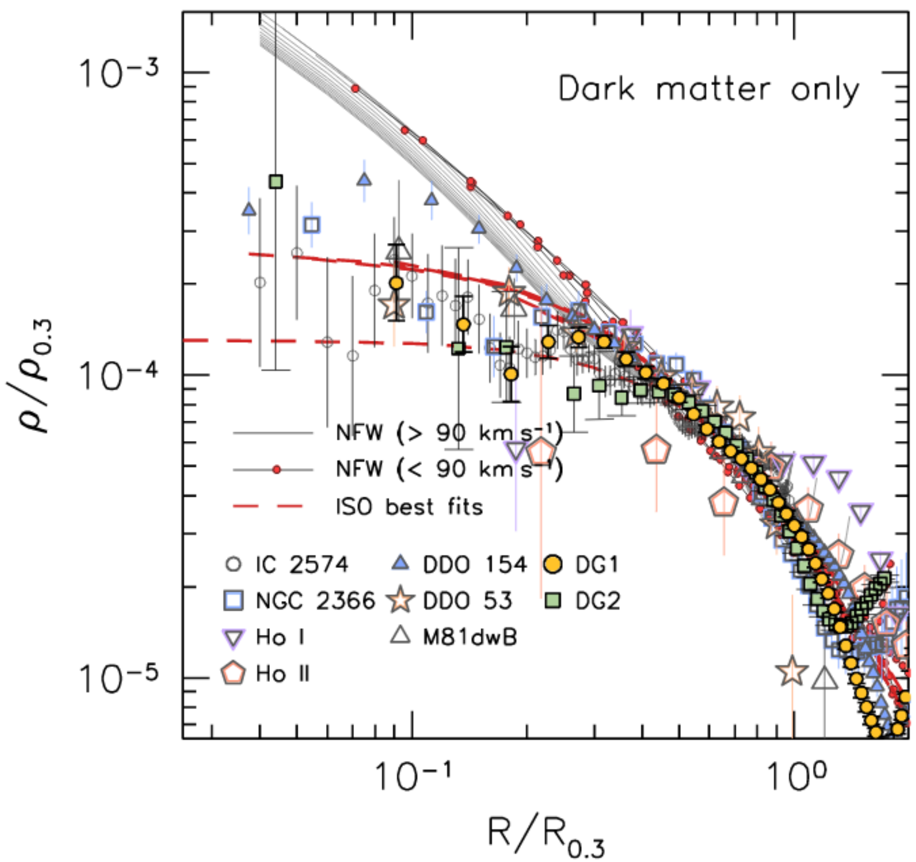


Willman et al. 2005; Zucker et al. 2006
Belokurov et al. 2007; Koposov et al. 2015
Bechtol et al. 2015; Kim et al. 2015

slide credit: J. Bullock

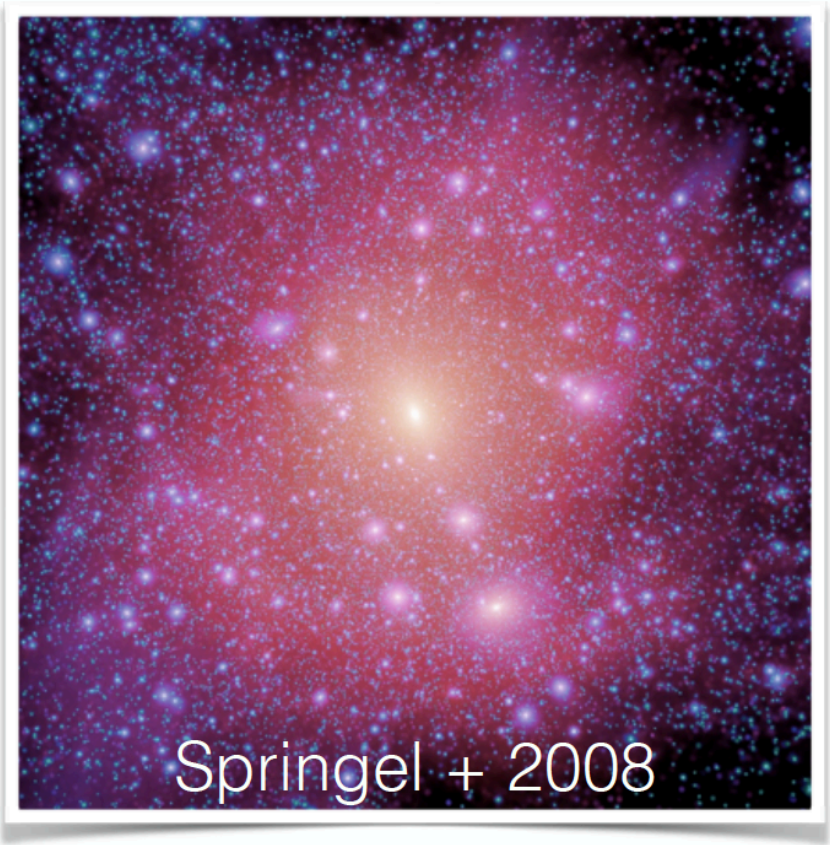
highly stochastic star formation and strong stellar winds *can* convert cuspy halos into cored halos



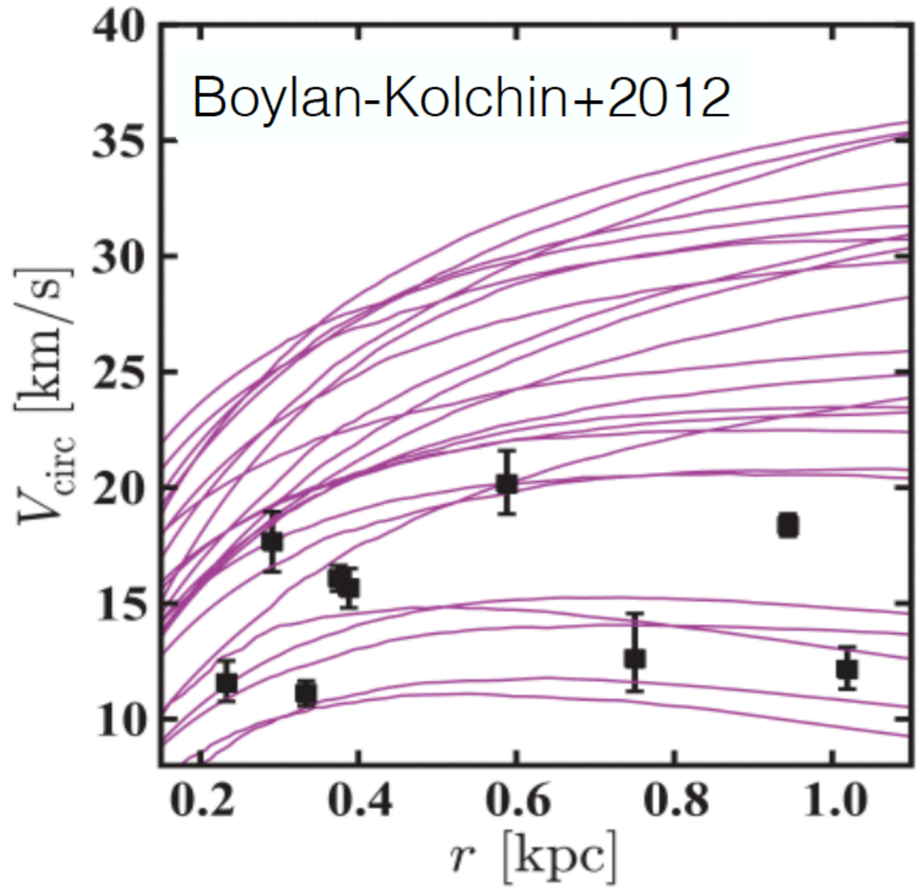


Oh et al. 2011; Pontzen & Governato 2012

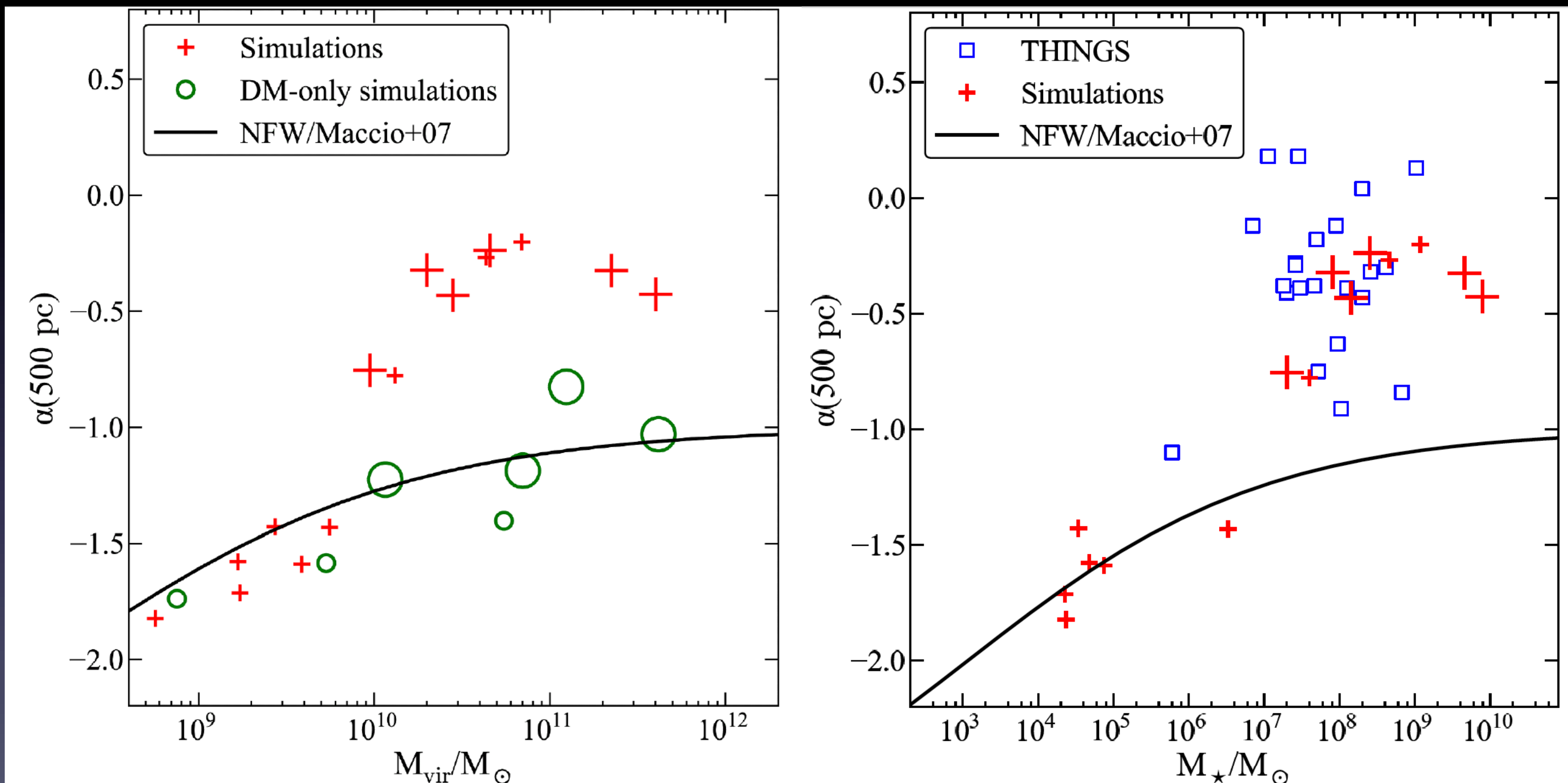
TOO BIG TO FAIL



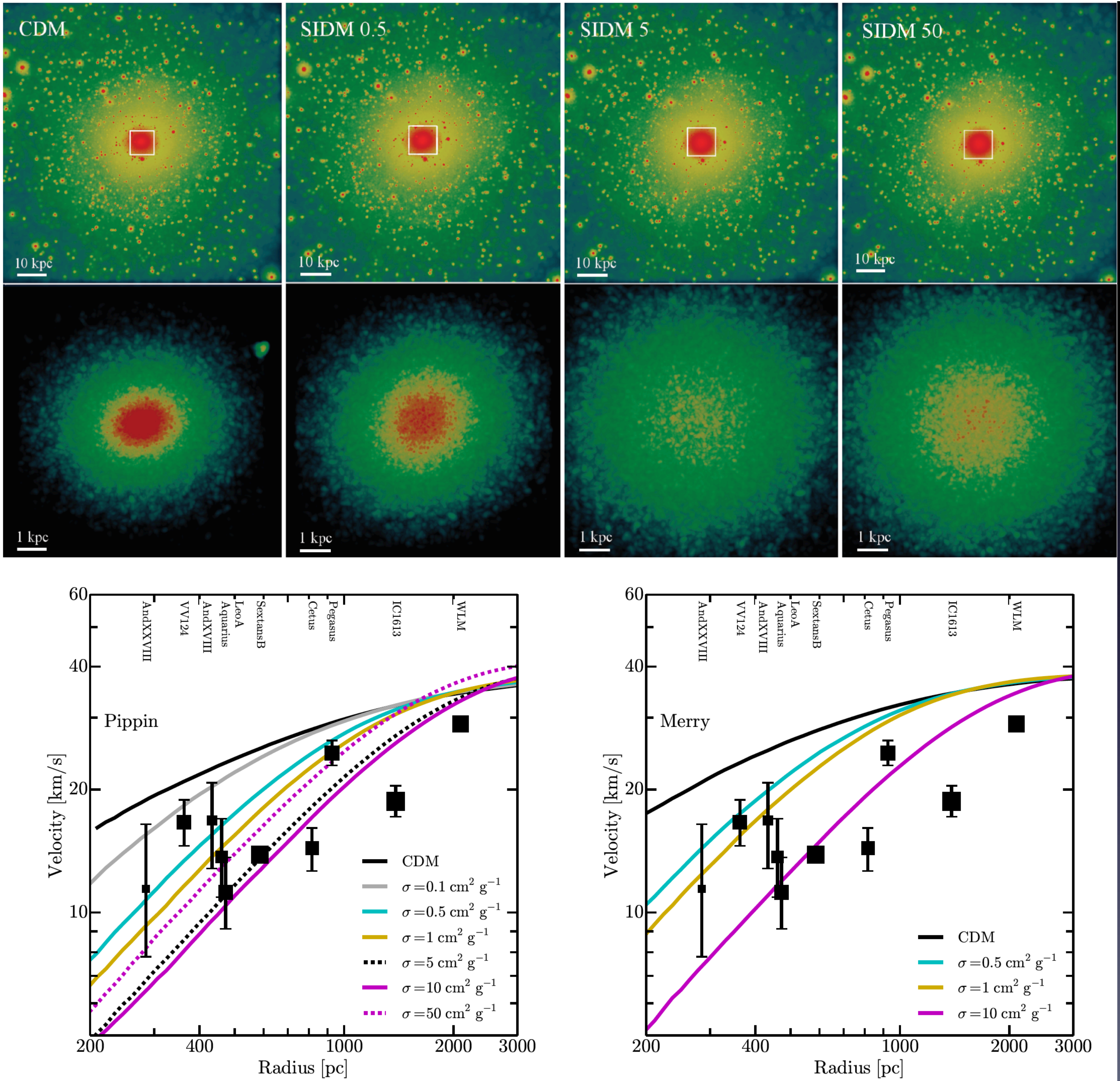
Can feedback lower densities?



below a critical mass, halos do not produce enough stars to create cores (Peñarrubia et al. 2012)



Governato et al. 2012

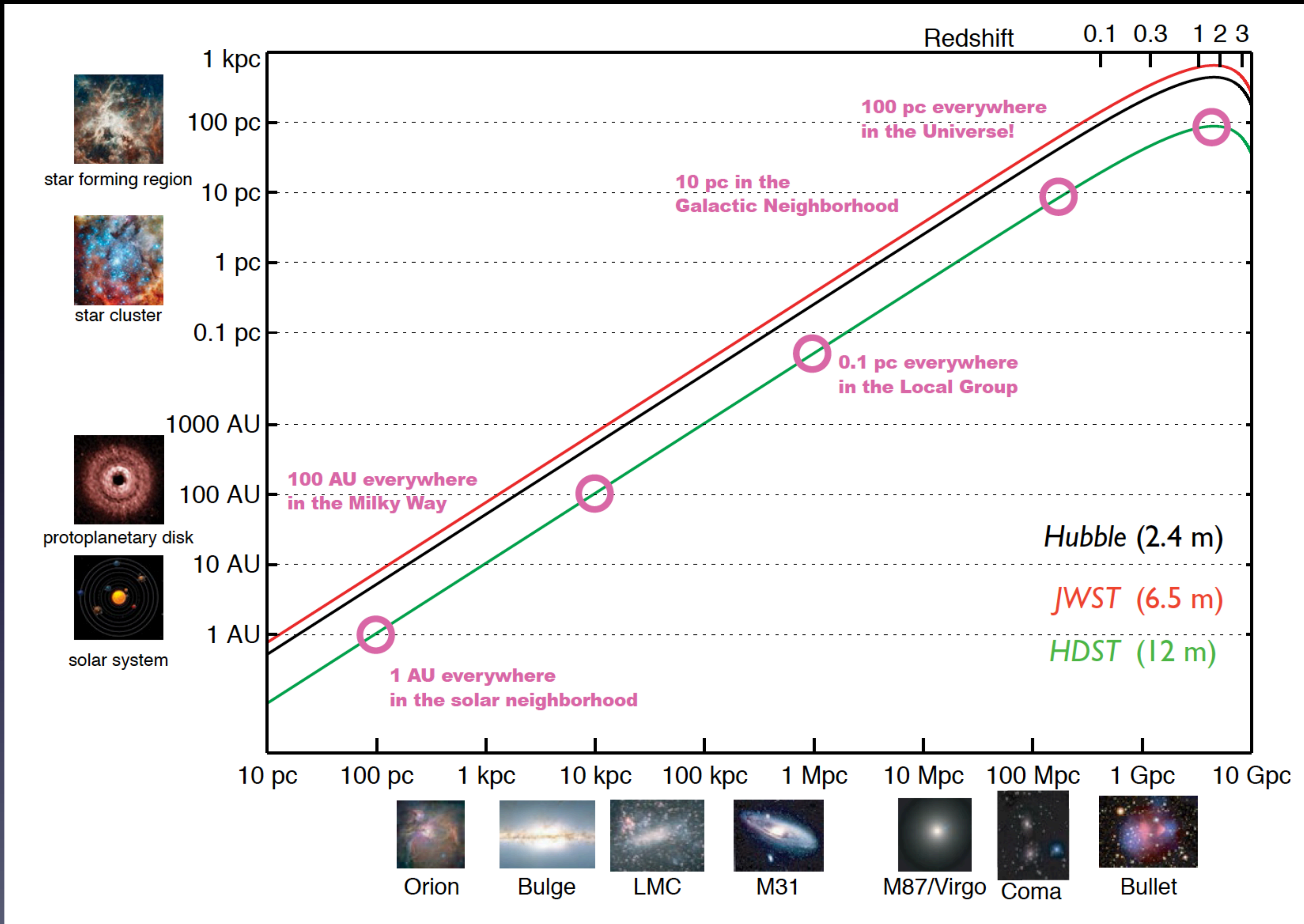


embarrassingly, there is a large parameter space for 'non-boring' variants of dark matter that is not ruled out by current observations

e.g. self-interacting DM (Spergel & Steinhardt 2000)

range of interaction cross sections produce cored halos

Elbert et al. 2014



spatial resolution

distance to object

FCB2LE

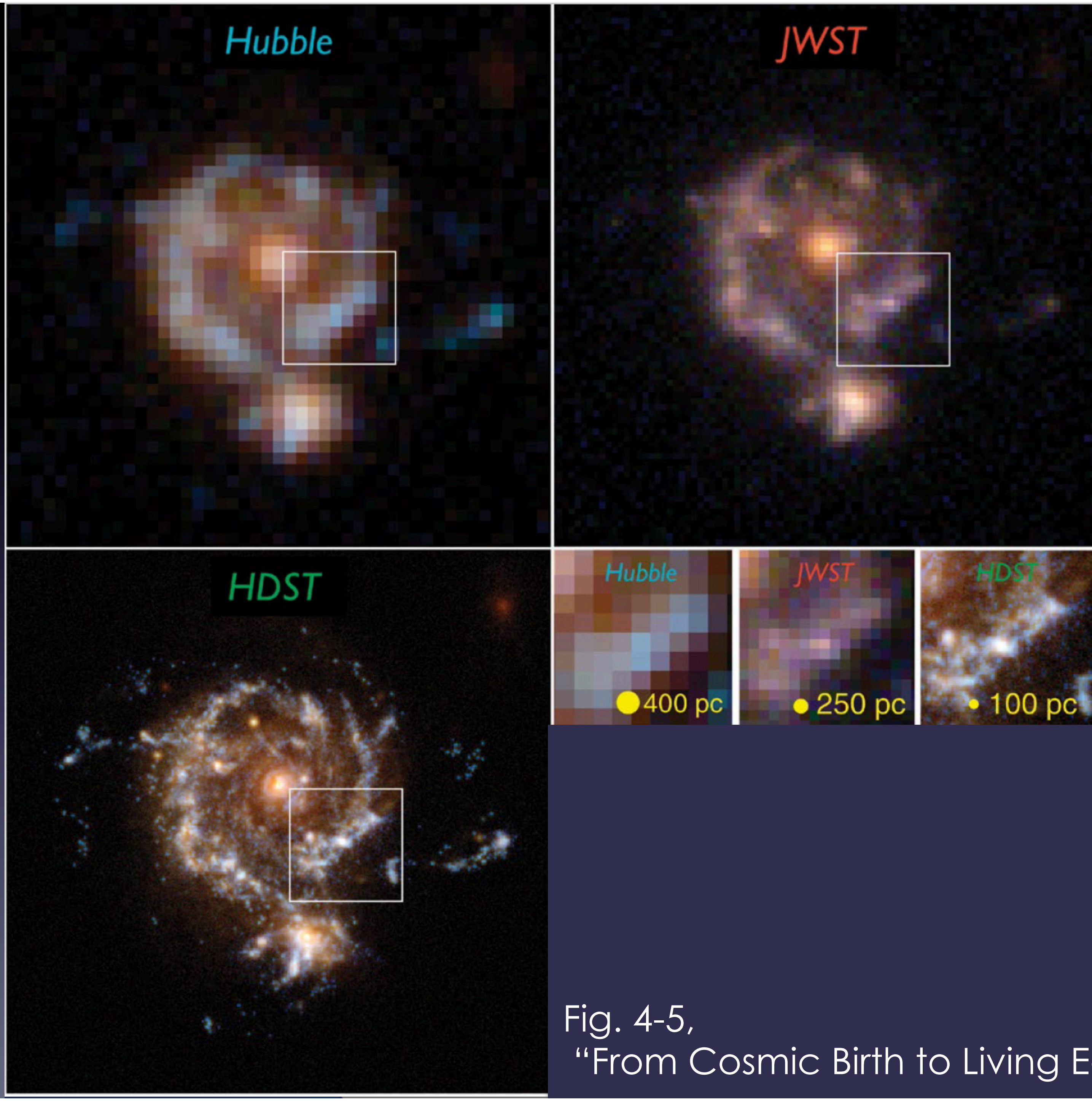
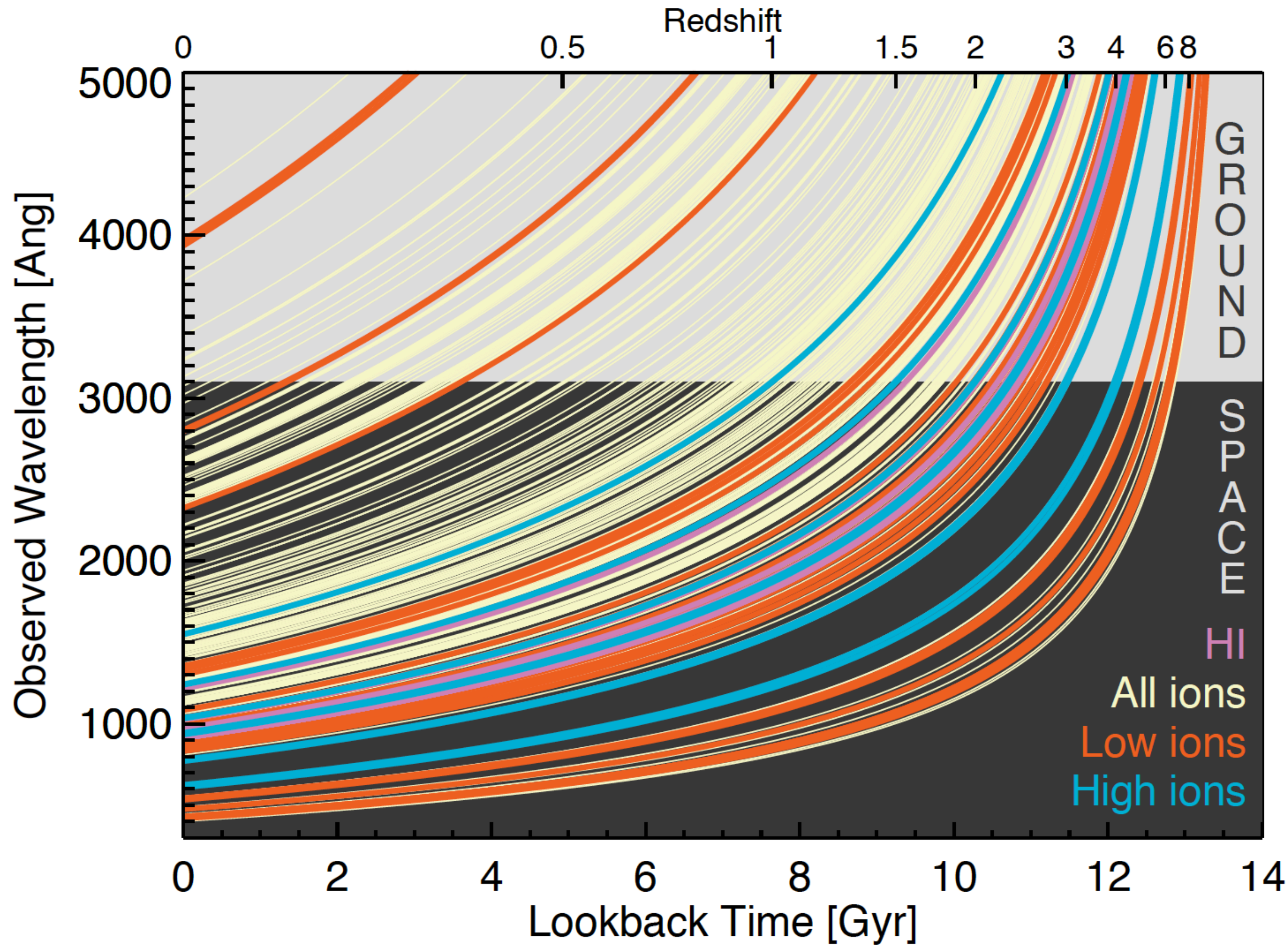


Fig. 4-5,
"From Cosmic Birth to Living Earths"


Redshift
0
0.5
1
1.5
2
3
4
6
8
5000
4000
3000
2000
1000
Observed Wavelength [Ang]
GROUND
SPACE
HI
All ions
Low ions
High ions
0
2
4
6
8
10
12
14
Lookback Time [Gyr]

FCB2LE

summary: Big Questions that a large-aperture UVOIR telescope could help answer!

- how are "small scale" physics and global galaxy properties connected?
- how does gas cycle in and out of galaxies?
- is the dark sector simple or complex?