“The next frontier of first quasars and massive galaxies”

Predictions from BlueTides Simulation

Tiziana DiMatteo (CMU)
Yu Feng (Berkeley)
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Simeon Bird (CMU)
Ananth Tenneti (CMU)
Nick Battaglia (Princeton)
Mark Straka (NCSA)

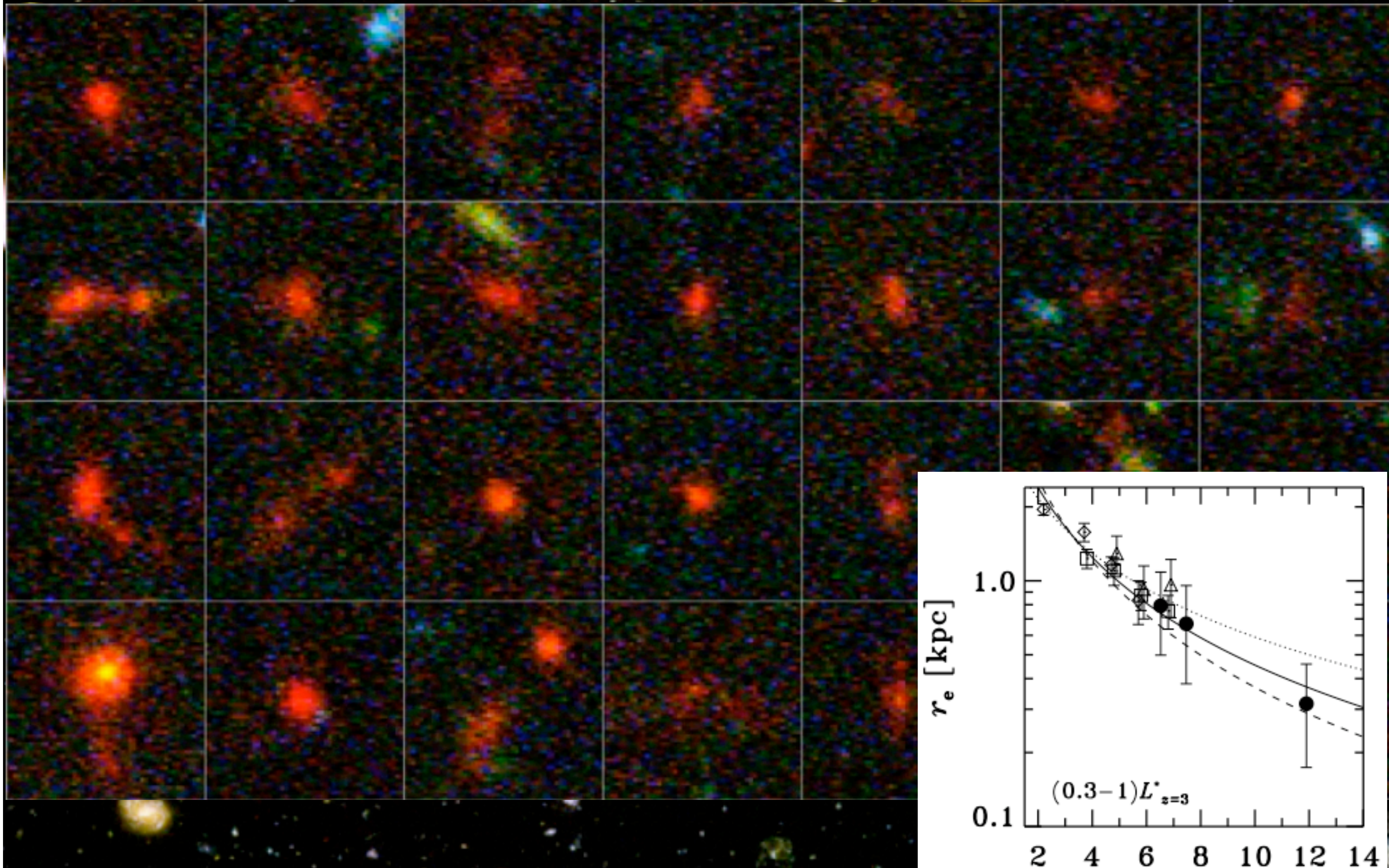
http://bluetides- project.org

The first 600 million years (z=7+):

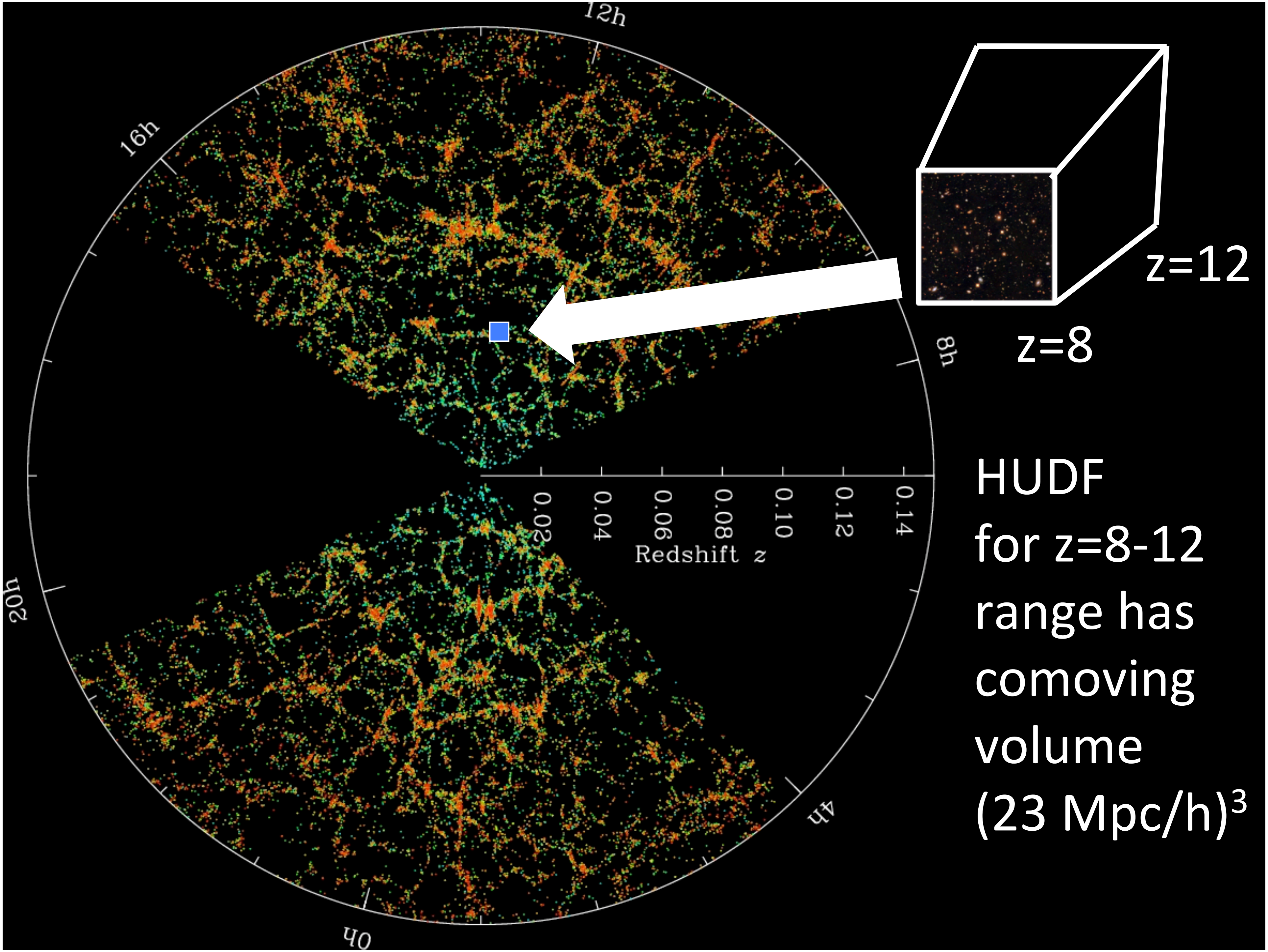
What are galaxies like?

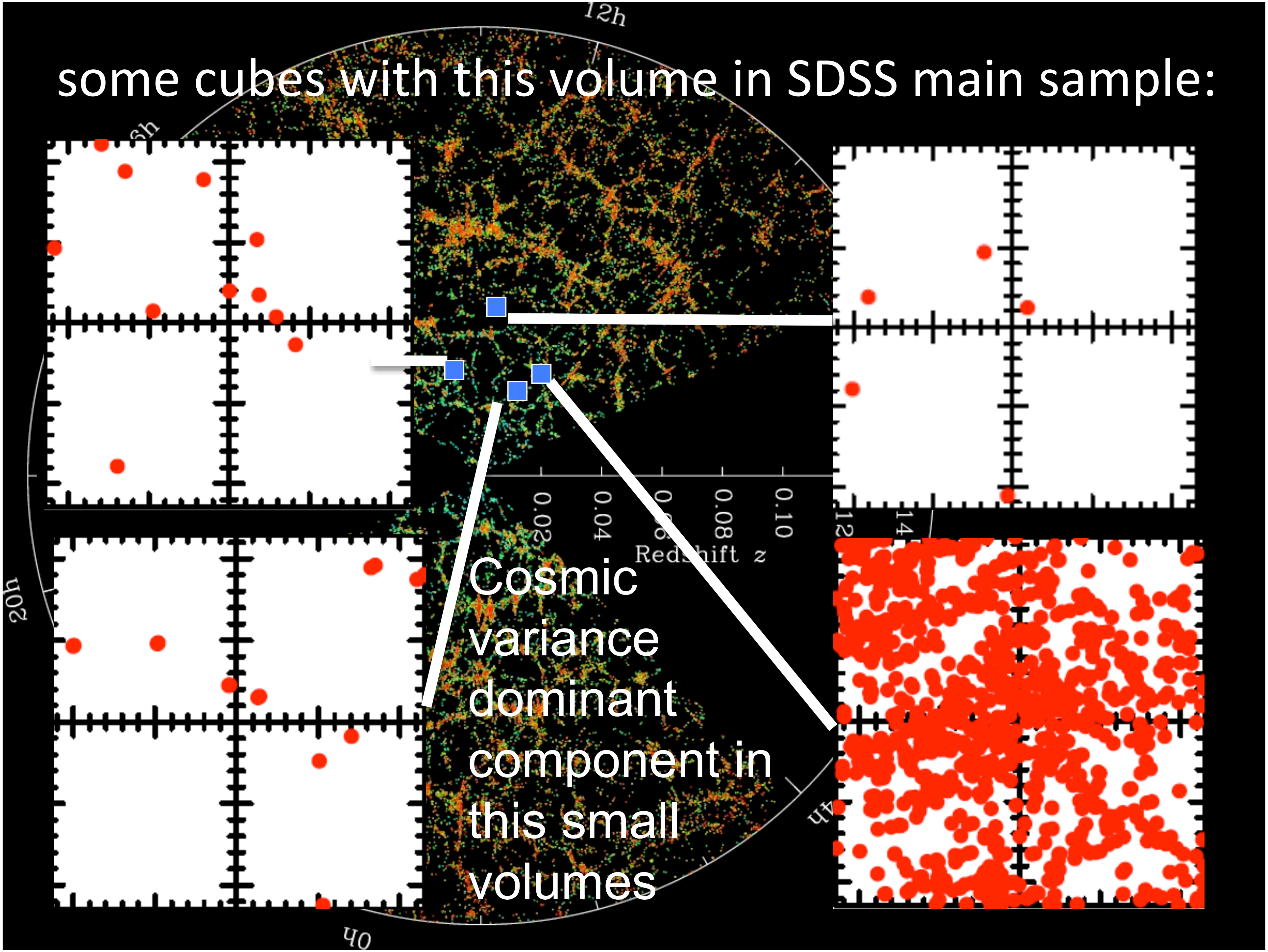
Observations:

Tiny (few arcmin^2) Hubble Legacy Ultra Deep Fields show compact, clumpy and irregular morphologies..



Onu+, 12


12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z
z=8
z=12
HUDF
for z=8-12
range has
comoving
volume
(23 Mpc/h)^3


some cubes with this volume in SDSS main sample:
Cosmic variance dominant component in this small volumes
12h
6h
20h
0h
4h
0.02
0.04
0.06
0.08
0.10
Redshift z

The first and last 'first quasar'?

At z=7, 1 in a Gpc^3

LETTER TO NATURE

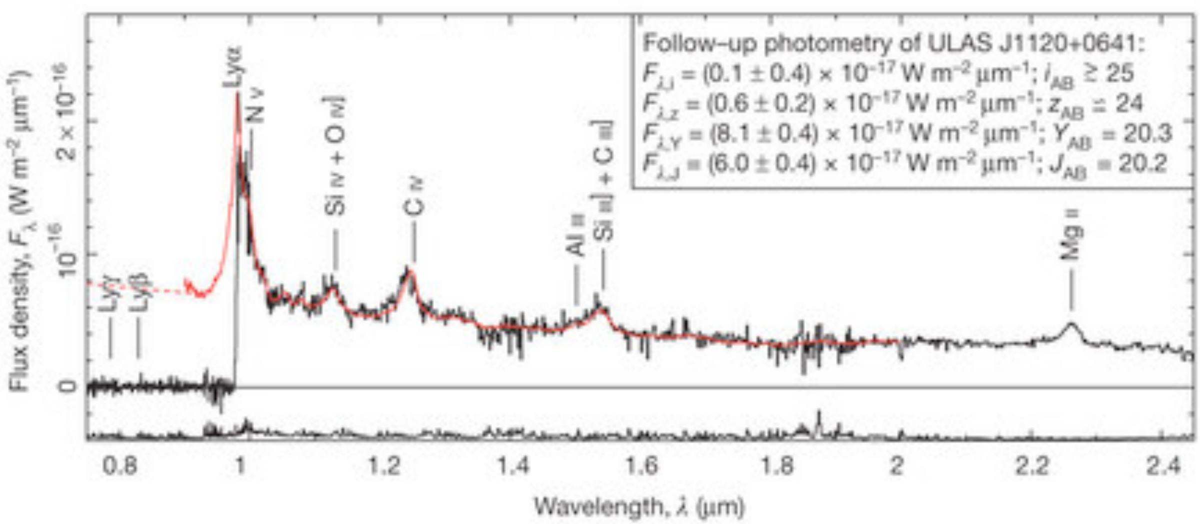
A luminous quasar at a redshift of $z = 7.085$

Daniel J. Mortlock[1], Stephen J. Warren[1], Bram P. Venemans[2], Mitesh Patel[1], Paul C. Hewett[3], Richard G. McMahon[3], Chris Simpson[4], Tom Theuns[5,6], Eduardo A. Gonzáles-Solares[3], Andy Adamson[7], Simon Dye[8], Nigel C. Hambly[9], Paul Hirst[10], Mike J. Irwin[3], Ernst Kuiper[11], Andy Lawrence[9] & Huub J. A. Röttgering[11]

30 Jun 2011

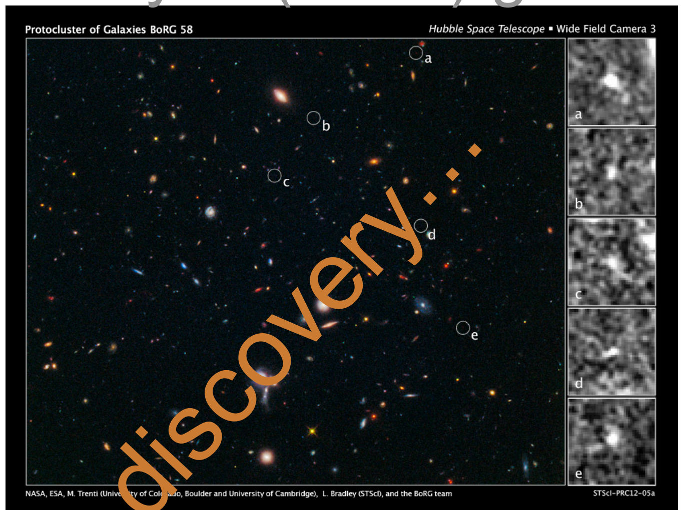
The intergalactic medium was not completely reionized until approximately a billion years after the Big Bang, as revealed[1] by observations of quasars with redshifts of less than 6.5. It has been difficult to probe to higher redshifts, however, because quasars have historically been identified[2–4] in optical surveys, which are insensitive to sources at redshifts exceeding 6.5. Here we report observations of a quasar (ULAS J112001.48+064124.3) at a red-

troscopically confirmed to have even higher redshifts, two are faint $J_{AB} \gtrsim 26$ galaxies[10,11] and the other is a γ-ray burst which has since faded[12]. Indeed, it has not been possible to obtain high signal-to-noise ratio spectroscopy of any sources beyond the most distant quasars previously known: CFHQS J0210−0456[13] ($z = 6.44$), SDSS 1148+5251[3] ($z = 6.42$) and CFHQS J2329+0301[14] ($z = 6.42$). Follow-up measurements of ULAS J1120+0641 will provide the first opportunity to explore the 0.1 Gyr between $z = 7.08$ and $z = 6.44$,



At z> 7:

Plenty of ('faint') galaxies in tiny volumes



Hubble Legacy Fields

Room for discovery...

1 quasar

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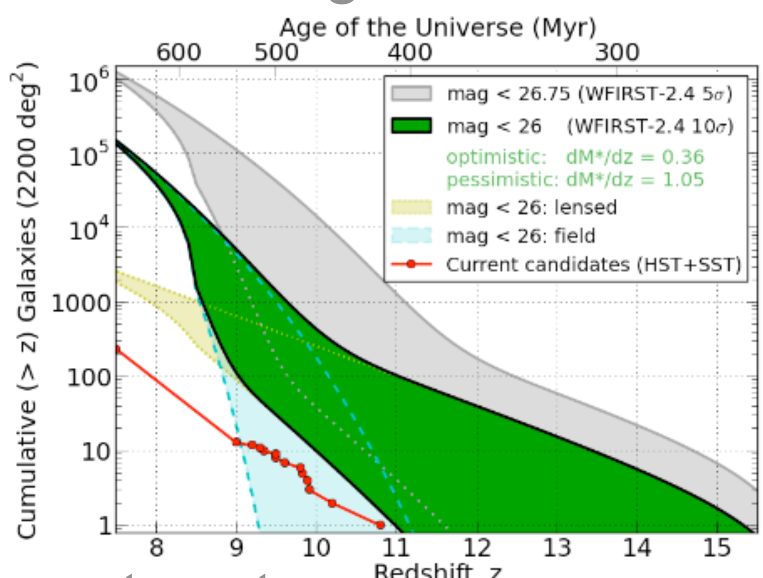
WFIRST > 50,000 galaxies

+quasars

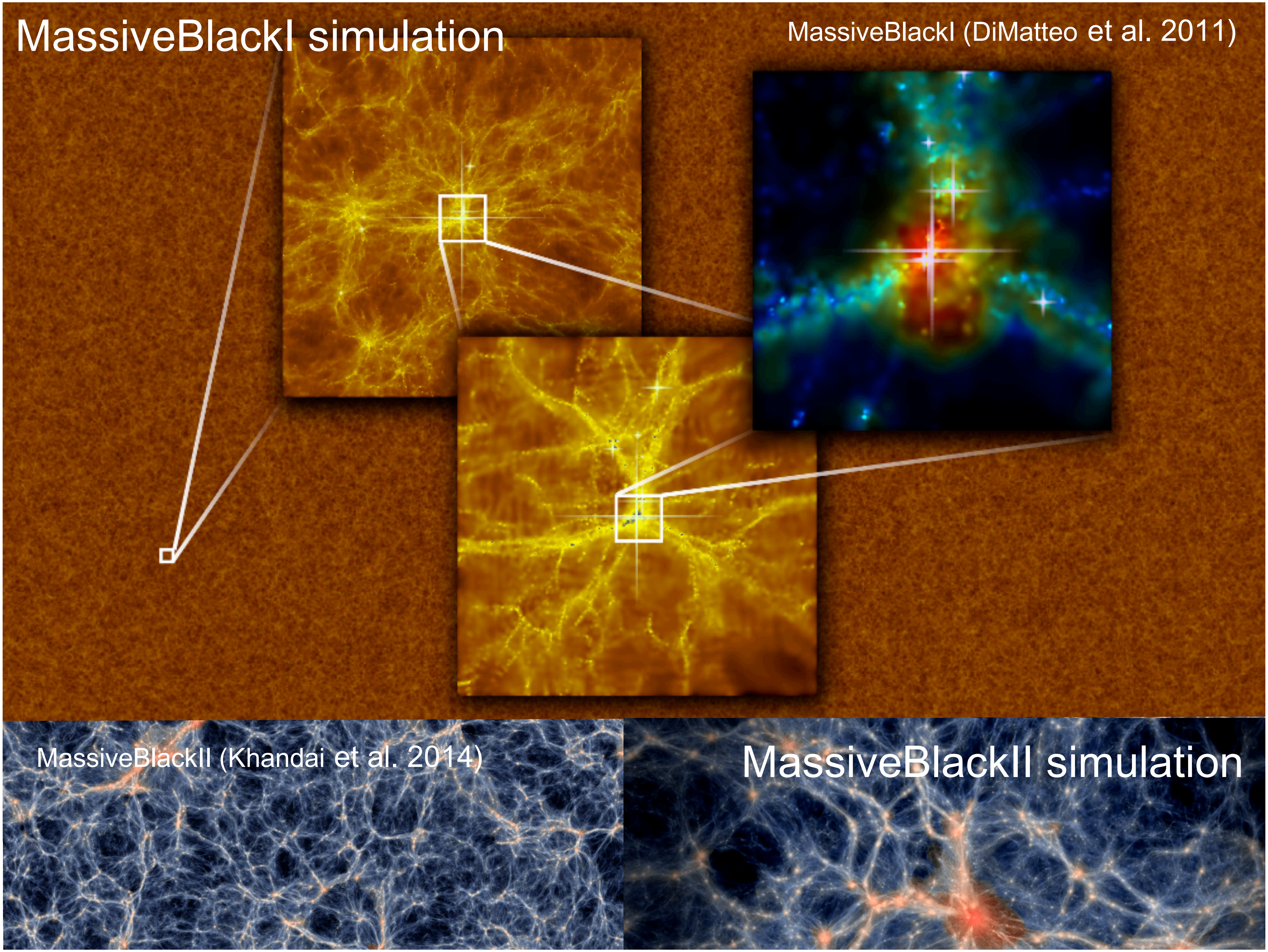


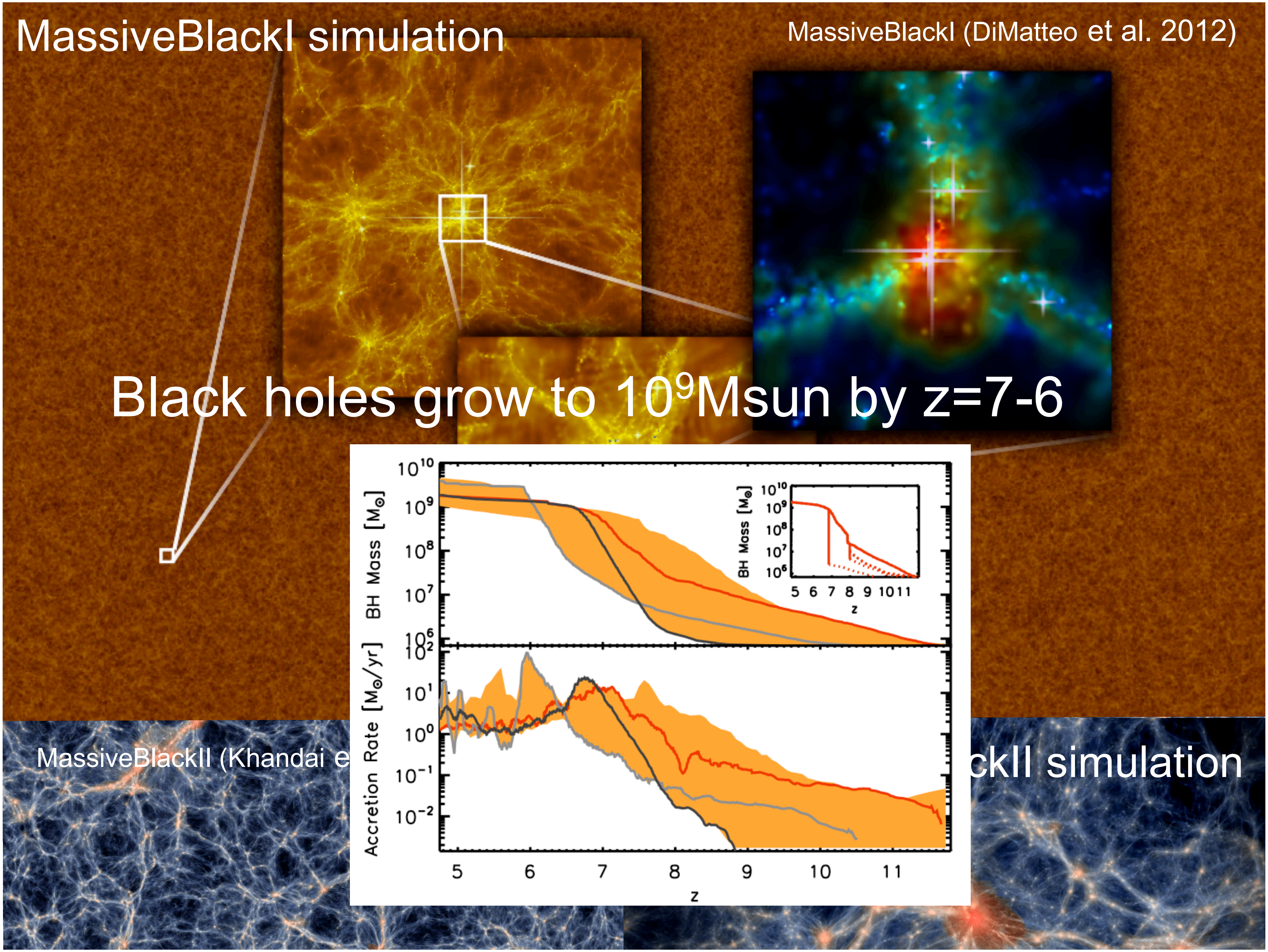
JWST spectra etc..

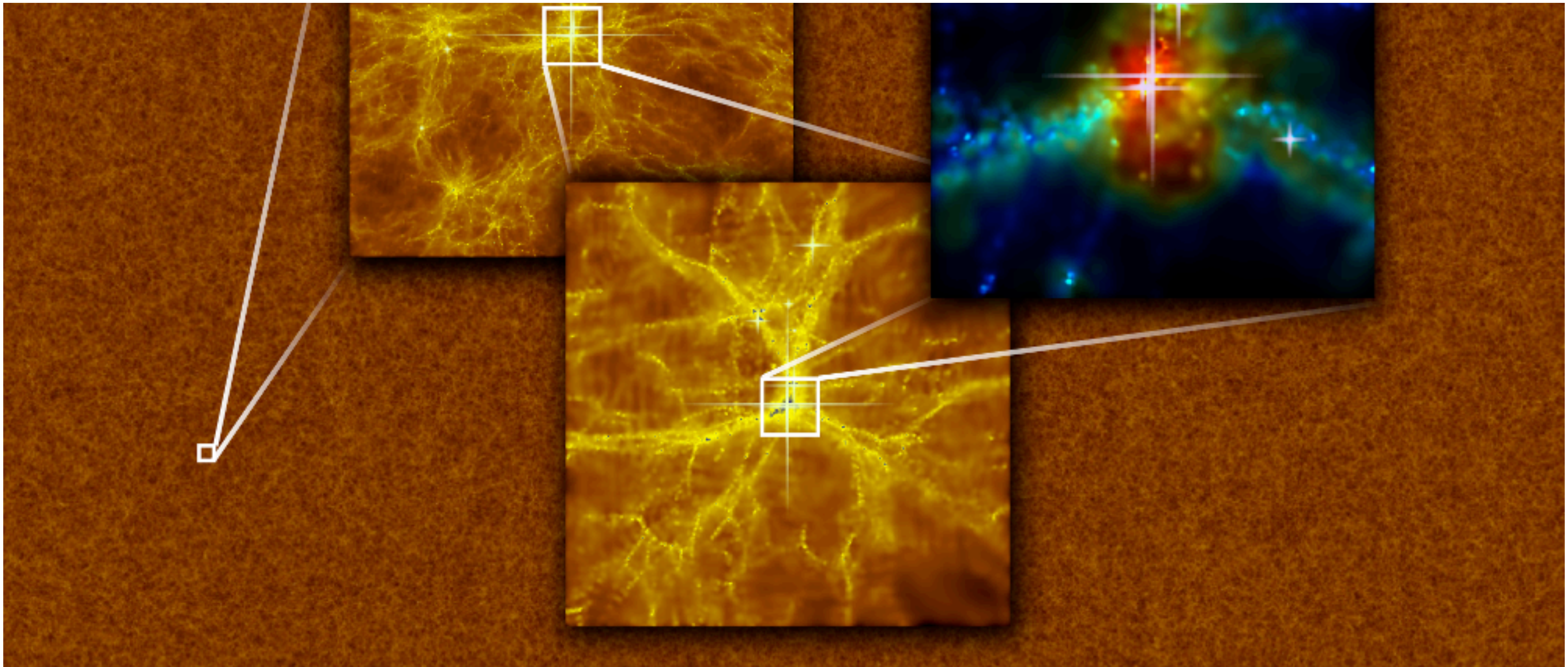
The first 500 million years ($z=7+$):

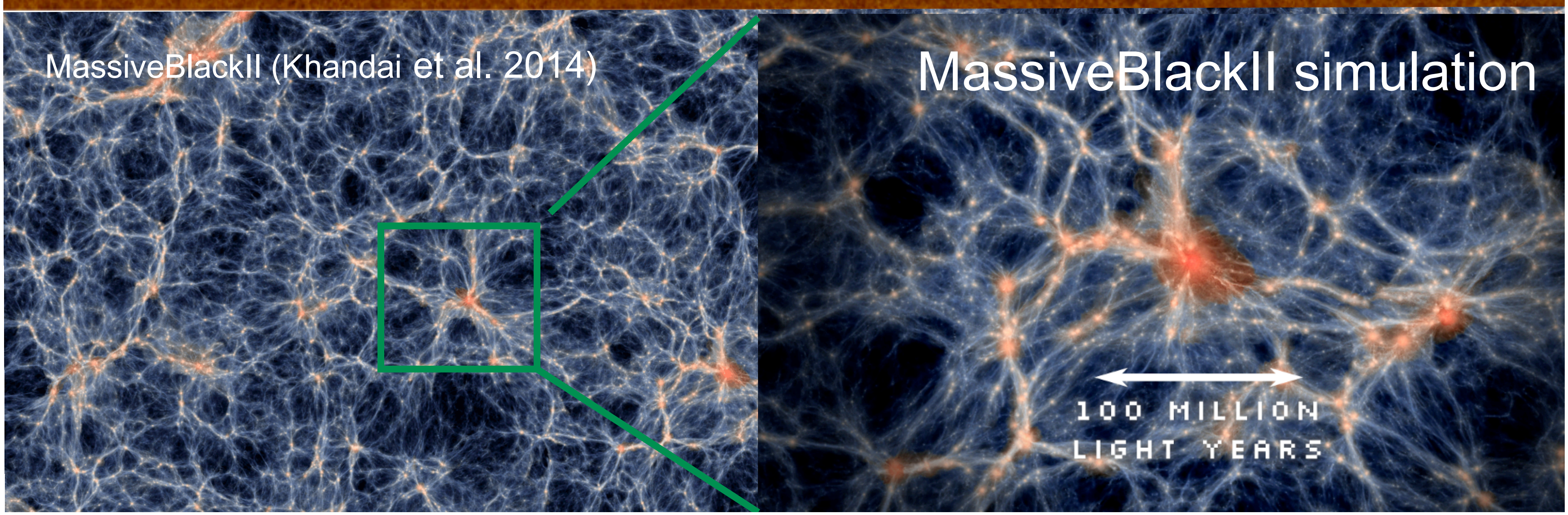
What are galaxies like?

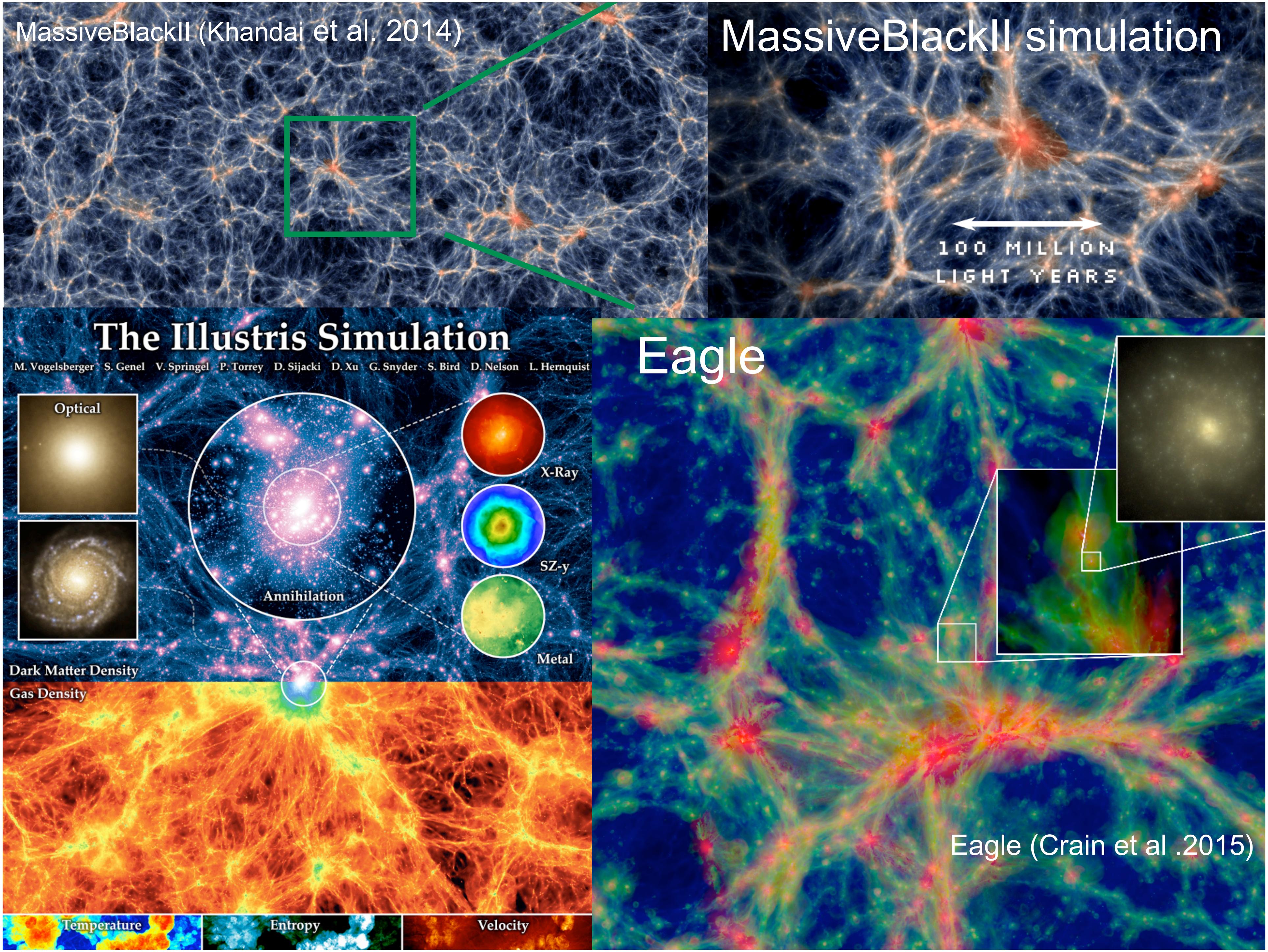
Predictions:

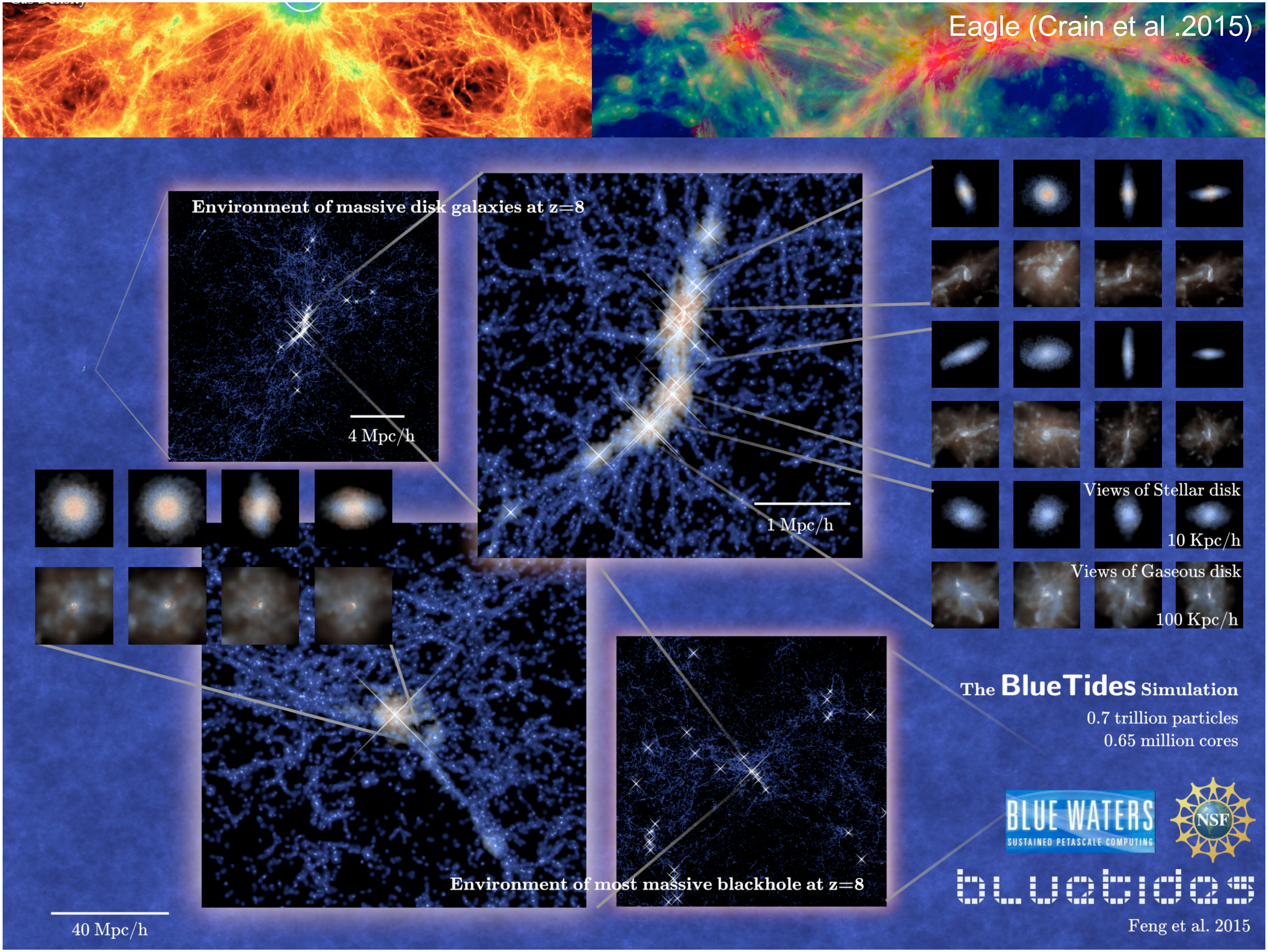

MassiveBlackI simulation
MassiveBlackI (DiMatteo et al. 2011)
MassiveBlackII (Khandai et al. 2014)
MassiveBlackII simulation


MassiveBlackI simulation
MassiveBlackI (DiMatteo et al. 2012)
Black holes grow to 10^9Msun by z=7-6
MassiveBlackII (Khandai e
ckII simulation
BH Mass [M⊙]
Accretion Rate [M⊙/yr]
z
5 6 7 8 9 10 11

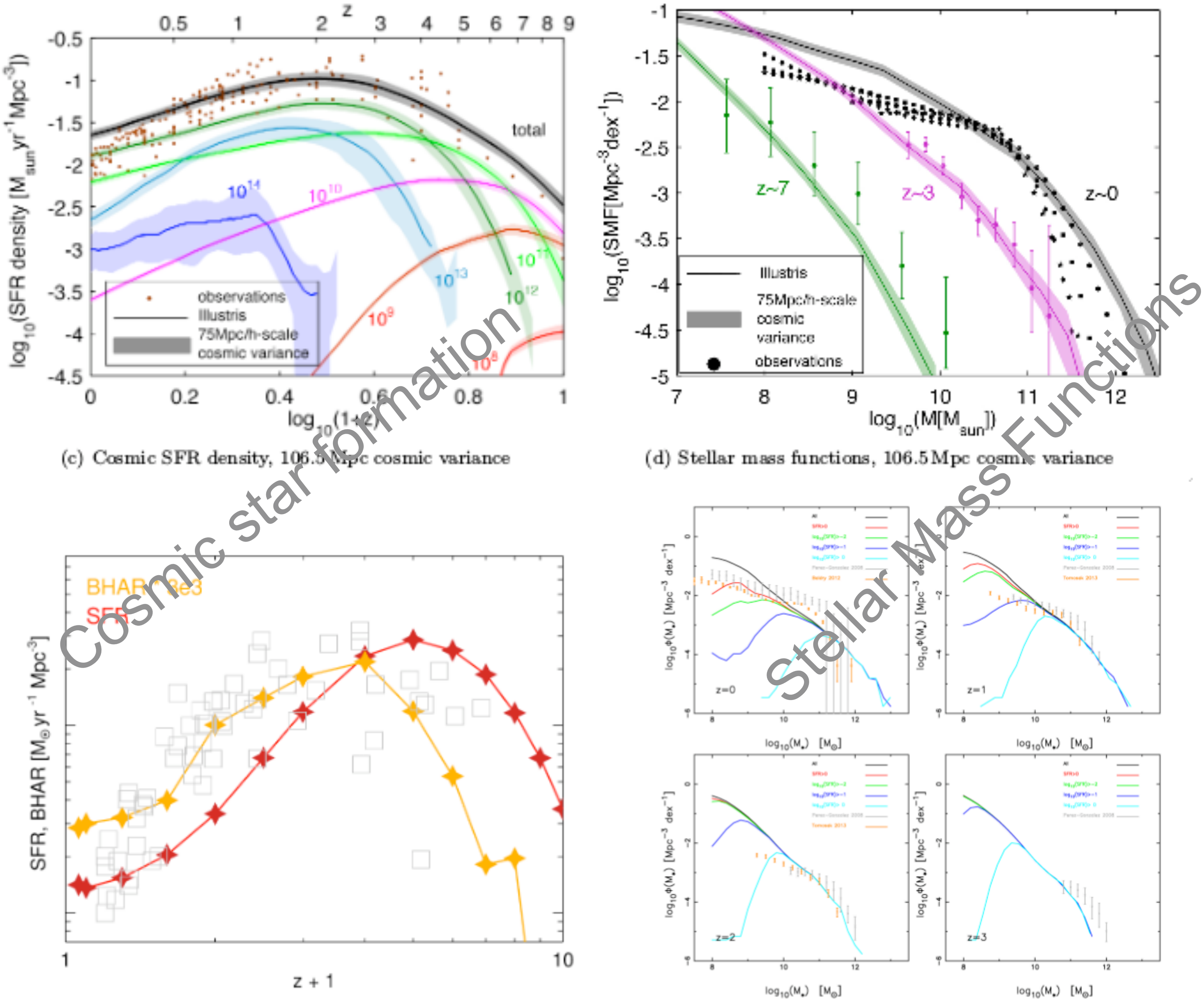



MassiveBlackII (Khandai et al. 2014)
MassiveBlackII simulation
100 MILLION
LIGHT YEARS


MassiveBlackII (Khandai et al. 2014)
MassiveBlackII simulation
100 MILLION LIGHT YEARS
The Illustris Simulation
M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist
Optical
X-Ray
SZ-y
Annihilation
Metal
Dark Matter Density
Gas Density
Temperature
Entropy
Velocity
Eagle
Eagle (Crain et al .2015)

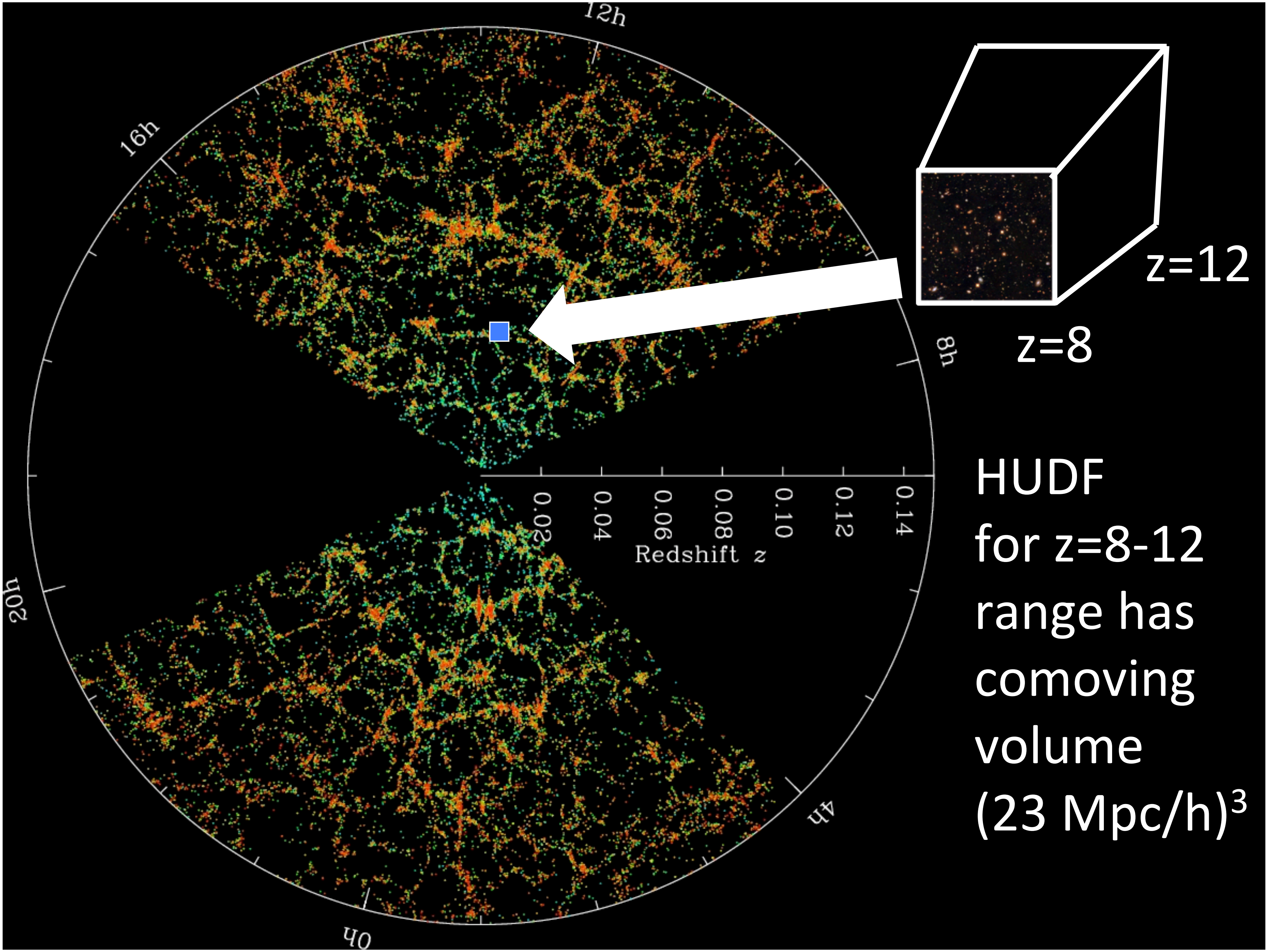

Eagle (Crain et al .2015)
Environment of massive disk galaxies at z=8
4 Mpc/h
1 Mpc/h
Views of Stellar disk
10 Kpc/h
Views of Gaseous disk
100 Kpc/h
The BlueTides Simulation
0.7 trillion particles
0.65 million cores
BLUE WATERS
SUSTAINED PETASCALE COMPUTING
NSF
bluetides
Environment of most massive blackhole at z=8
40 Mpc/h
Feng et al. 2015

Simulations reproduce statistics of galaxy formation

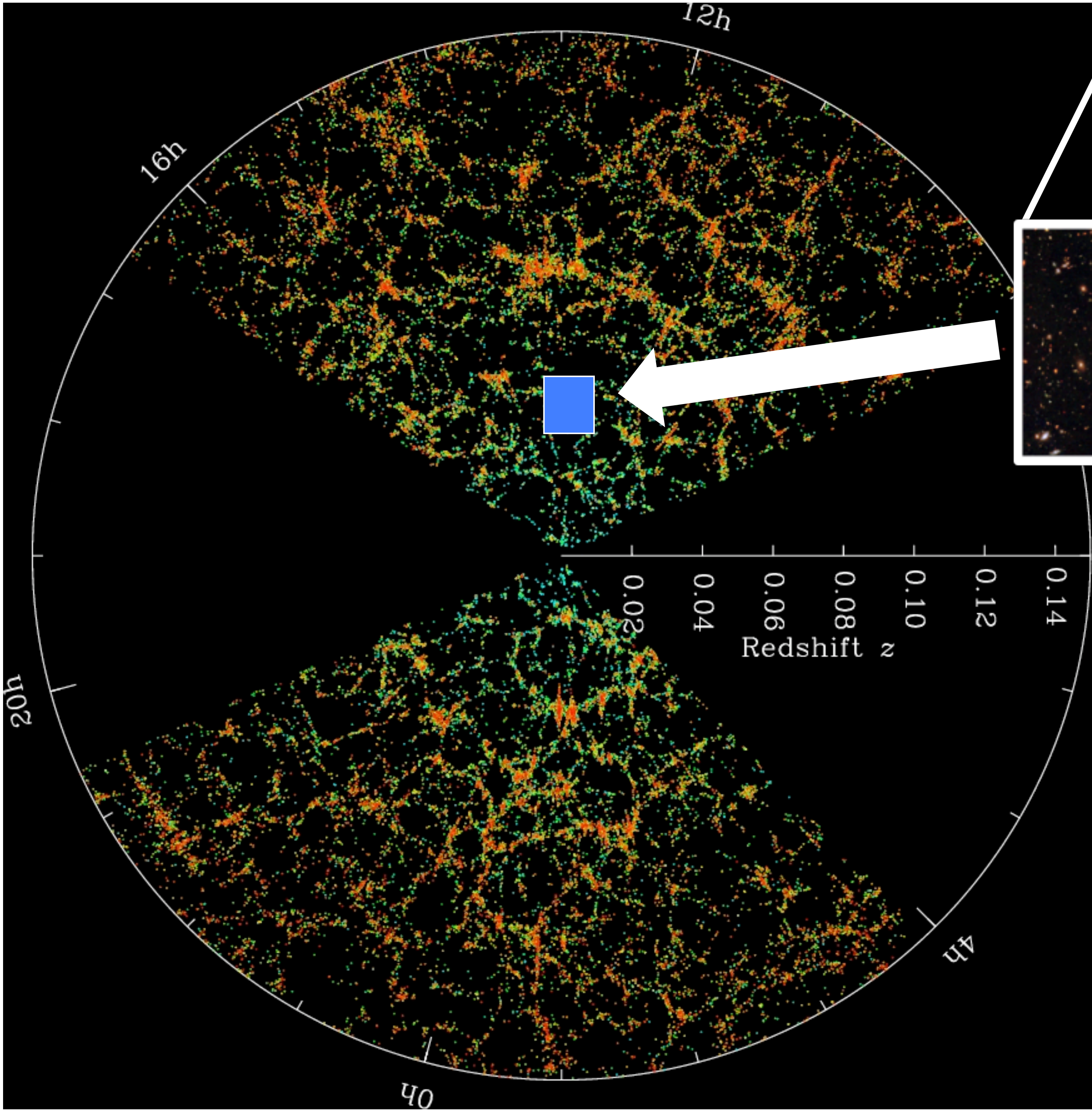


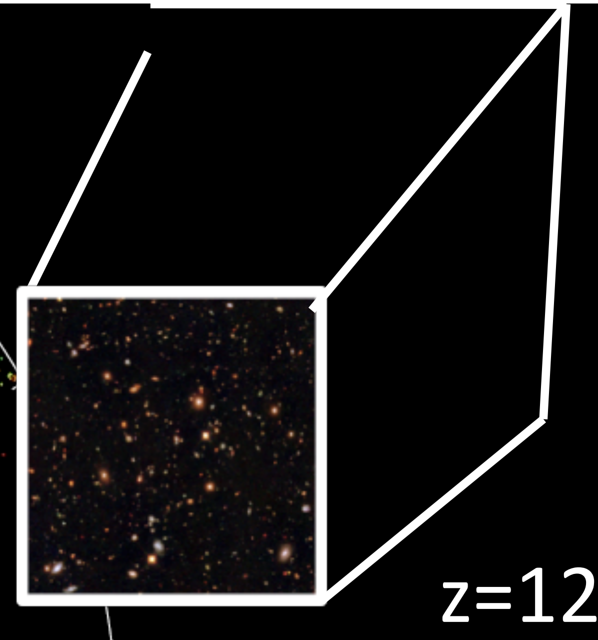
(c) Cosmic SFR density, 106.5 Mpc cosmic variance

(d) Stellar mass functions, 106.5 Mpc cosmic variance



12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z
z=12
z=8
HUDF
for z=8-12
range has
comoving
volume
(23 Mpc/h)³





Illustris, MBII for z=8-12 range has comoving volume $(3\text{-}4)^3$xHUDF

However, theoretical predictions lacking at z=7+

simulations have either: insufficient resolution or too small volumes for massive objects

MassiveBlack I (DiMatteo et al 2011) 533 Mpc/h & 5.5 Kpc/h

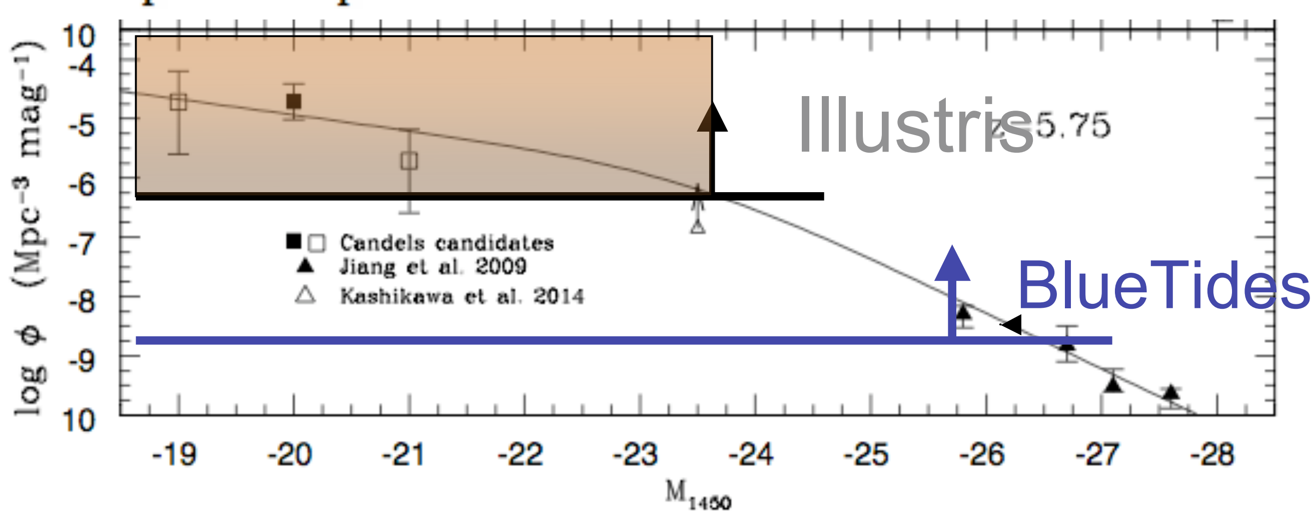
MassiveBlack II (Khandai et al 2014) 100 Mpc/h & 1.8 Kpc/h

Illustris (Vogelsberger et al 2014) : 72.5 Mpc/h & 1 Kpc/h

Eagles (Crain et al 2015) : 100 Mpc/h 2.6 Kpc/h

100Mpc/h ~0.2 sq degrees at z=8-9

e.g: High-z QSO lum. Function (Giallongo 15)



BlueTides Simulation:

0.7 million cores on NCSA BlueWaters

Goals:

- Technology Path Finder for future hydro simulation
- Predictions for high-redshift surveys

714 Mpc on the side
200 pc resolution at z=9
2×7040^3 (0.7 trillion) particles
Star formation/ AGN model compatible with Illustris

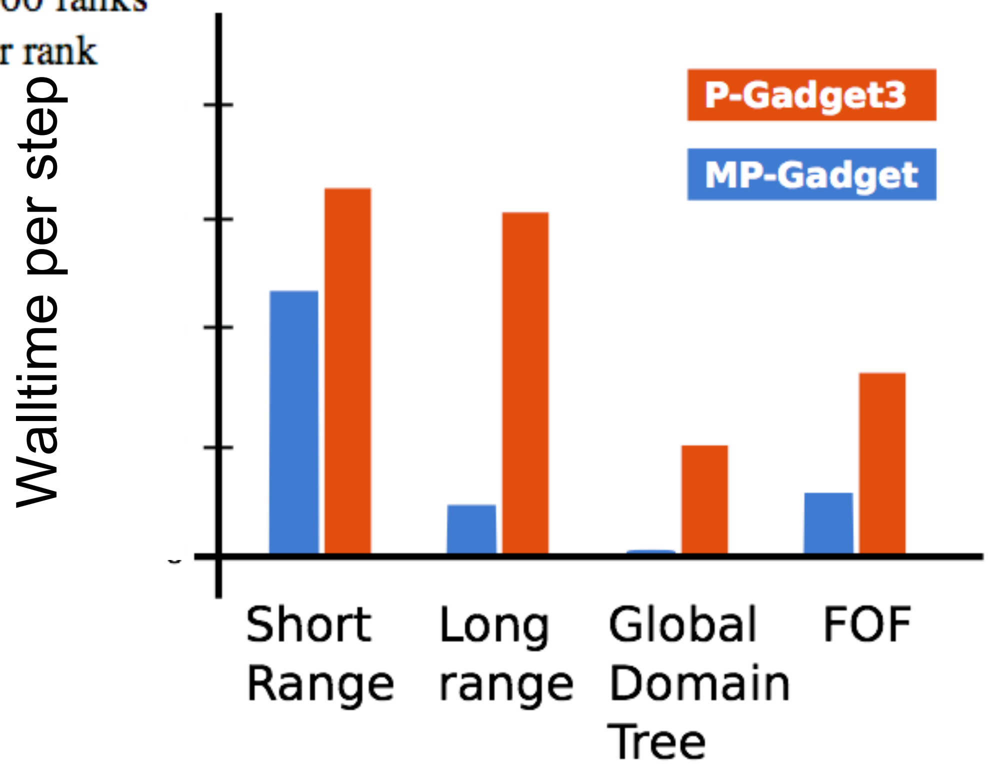
50 times bigger volume with highest resolution

BlueTides Simulation: Technology

Technology Path-Finder:
- From P-Gadget to MP-Gadget
- 81000 MPI ranks, 8 OpenMP threads per rank
- Large, distributed FFT: 10,000 mesh on 81000 ranks
- Efficient thread parallism up to 32 threads per rank

Spinoffs and Open source contributions:
- bigfile : hierachical snapshot format
- MP-sort : practical parallel sorting
- sharedmem : parallel data analysis

- PFFT : large-scale distributed FFT



Long range force calculation (PM): New solver:

E.g. 8 processes:

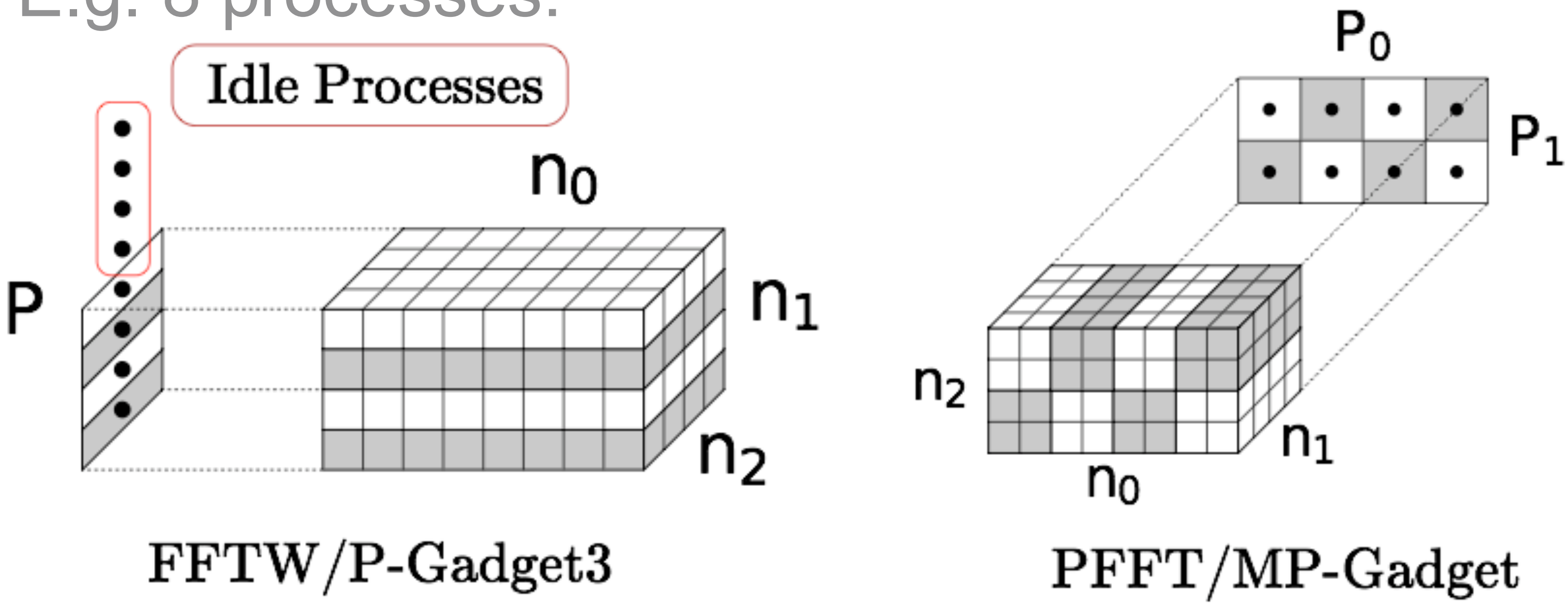


Figure from M.Pippig 2013

Blue Tides:
N= 10000 slabs
on 81000 MPI ranks

Pencil beam domain decomposition

8 x speed-up

Open Source: Added new Array-execution interface and python binding to PFFT (http://github.com/mpip/pfft)

BlueTides Simulation: Science

Physics modelling in BlueTides

- Hydrodynamics (pSPH)
- Primodial cooling
- Multi-phase medium star-formation
- SN wind feedback
- H2 molecule fraction
- AGN feedback
- Metal enrichment and cooling
- Non-uniform UV background calibrated from rad. Hydro sims (Battaglia+13)

Science of high redshift galaxy

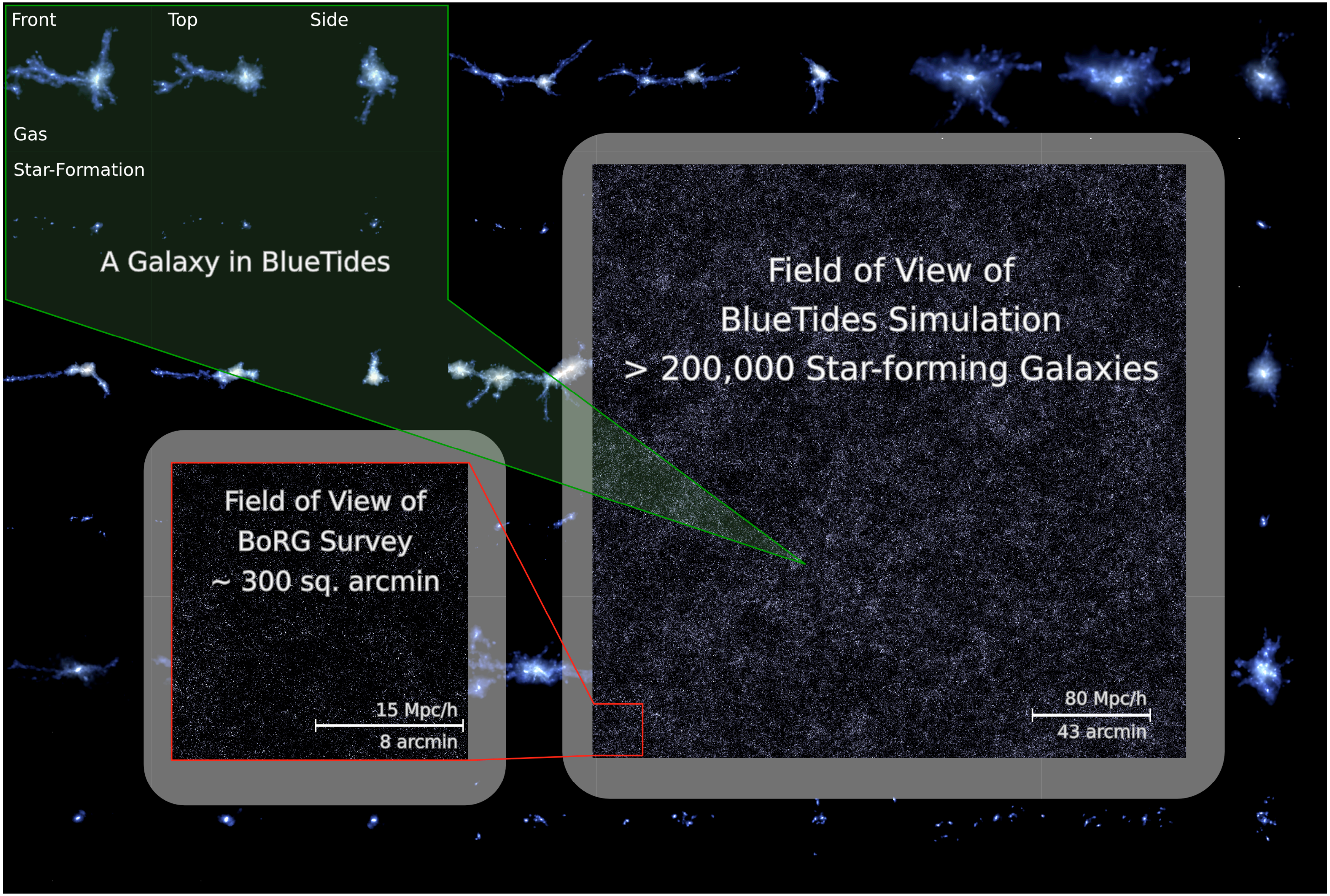
- a statistical sample of high redshift galaxies, accessible only via uniform simulations
- reionization
- morphology
- mock surveys
- high redshift AGNs
- ....

The first 500 million years (z=7+):

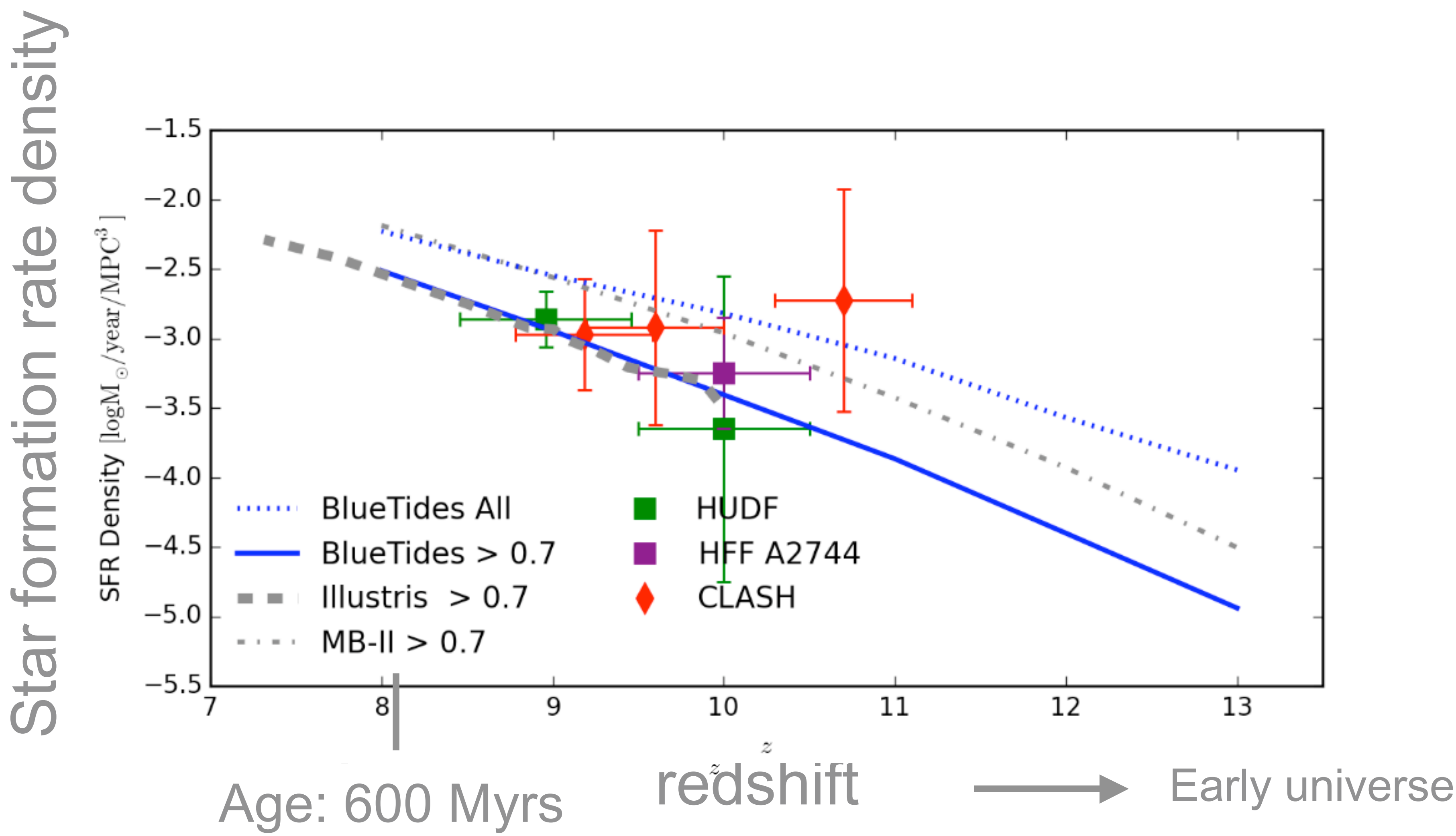
What are galaxies like?

Predictions from BlueTides:

BlueTides 400 x volume of HUDF



BlueTides Simulation: Global SFRD is consistent with current observational limits.



Feng et al., 2015a

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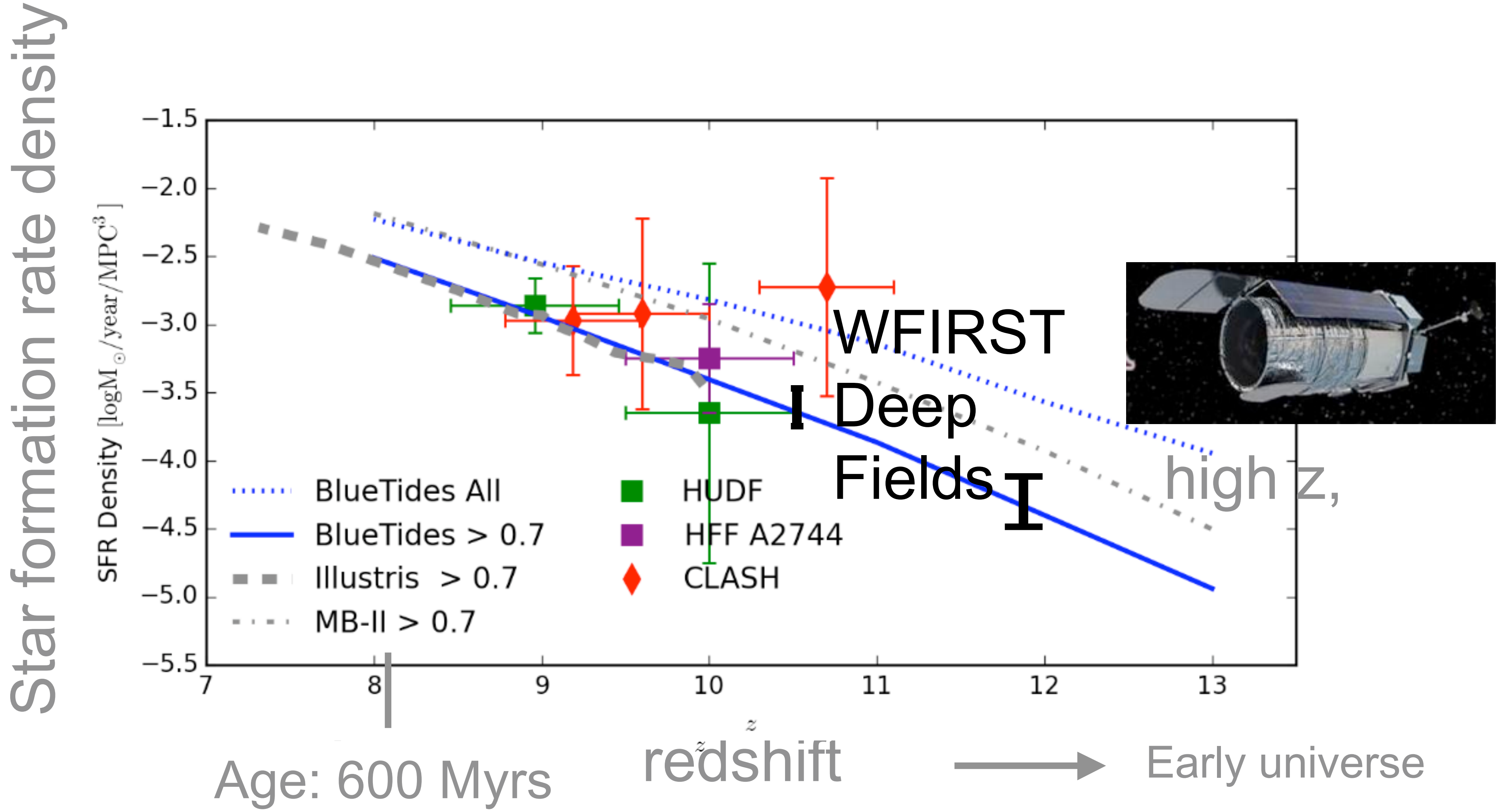
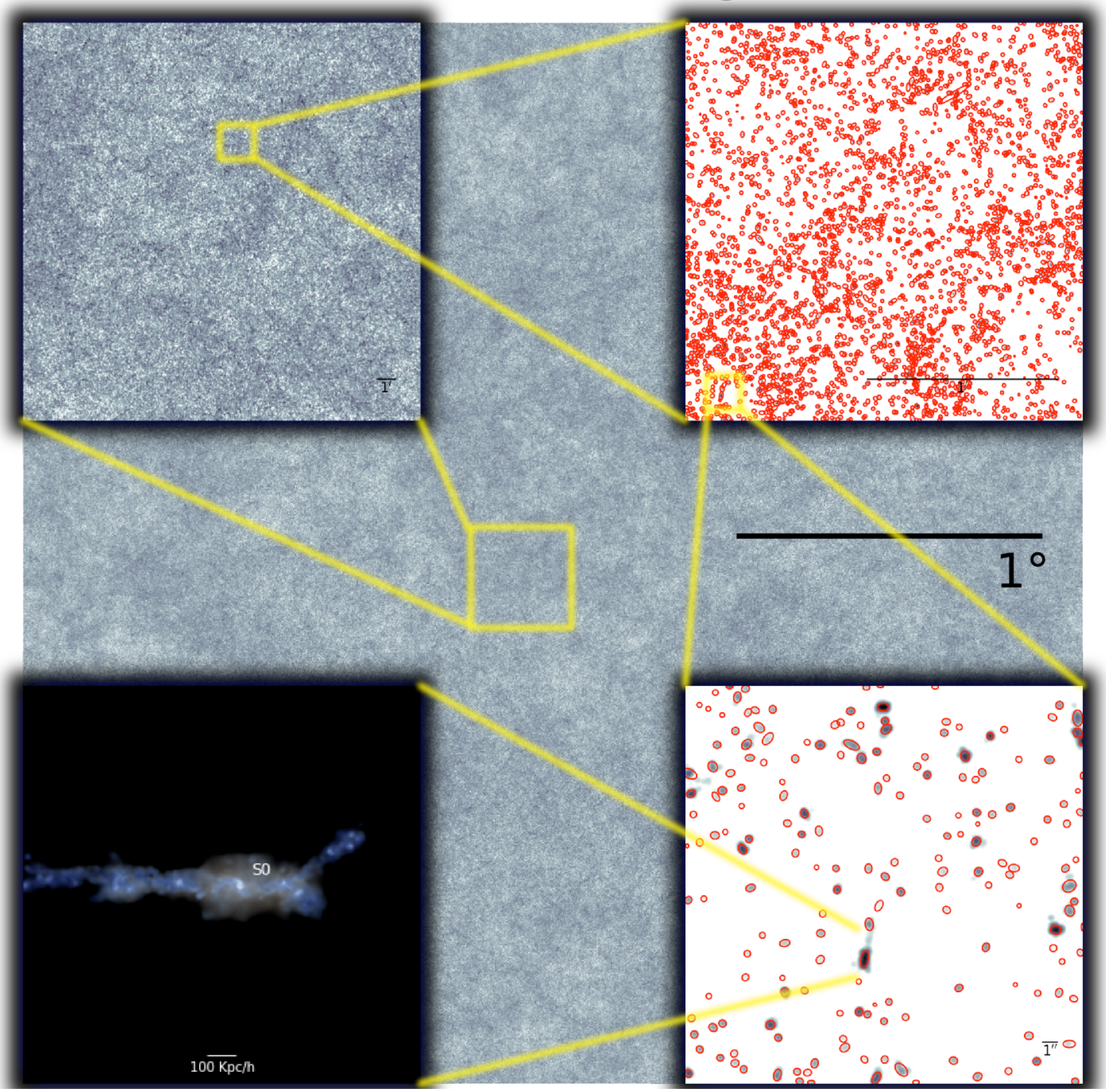
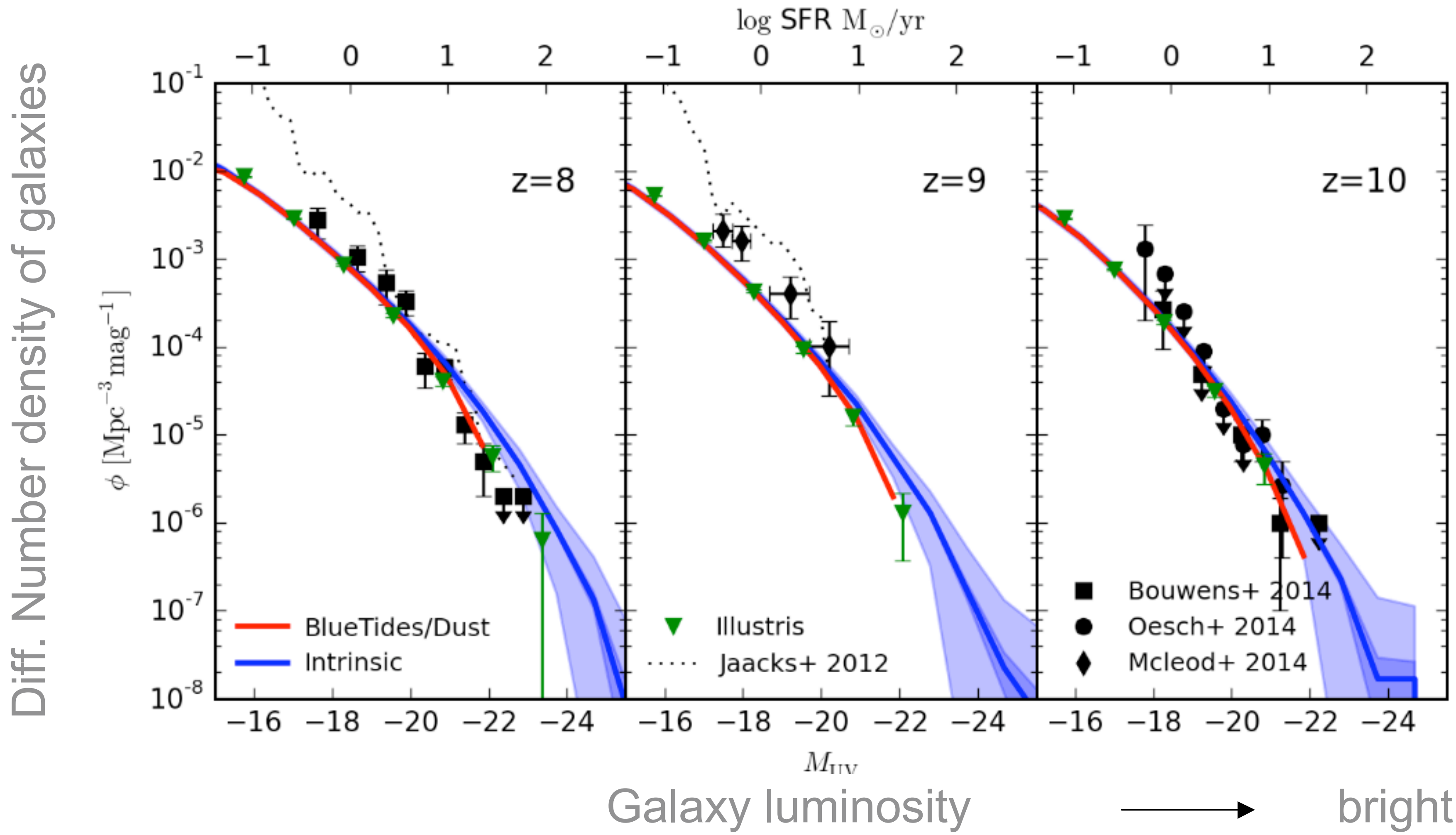


Feng et al., 2015a

Simulations like Observations: Create Mock Fields. Source extract detection to find galaxies

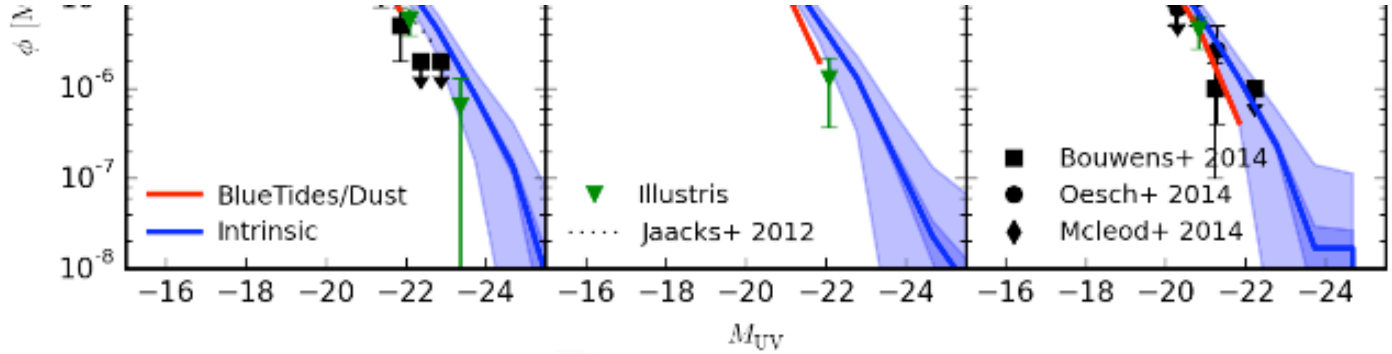


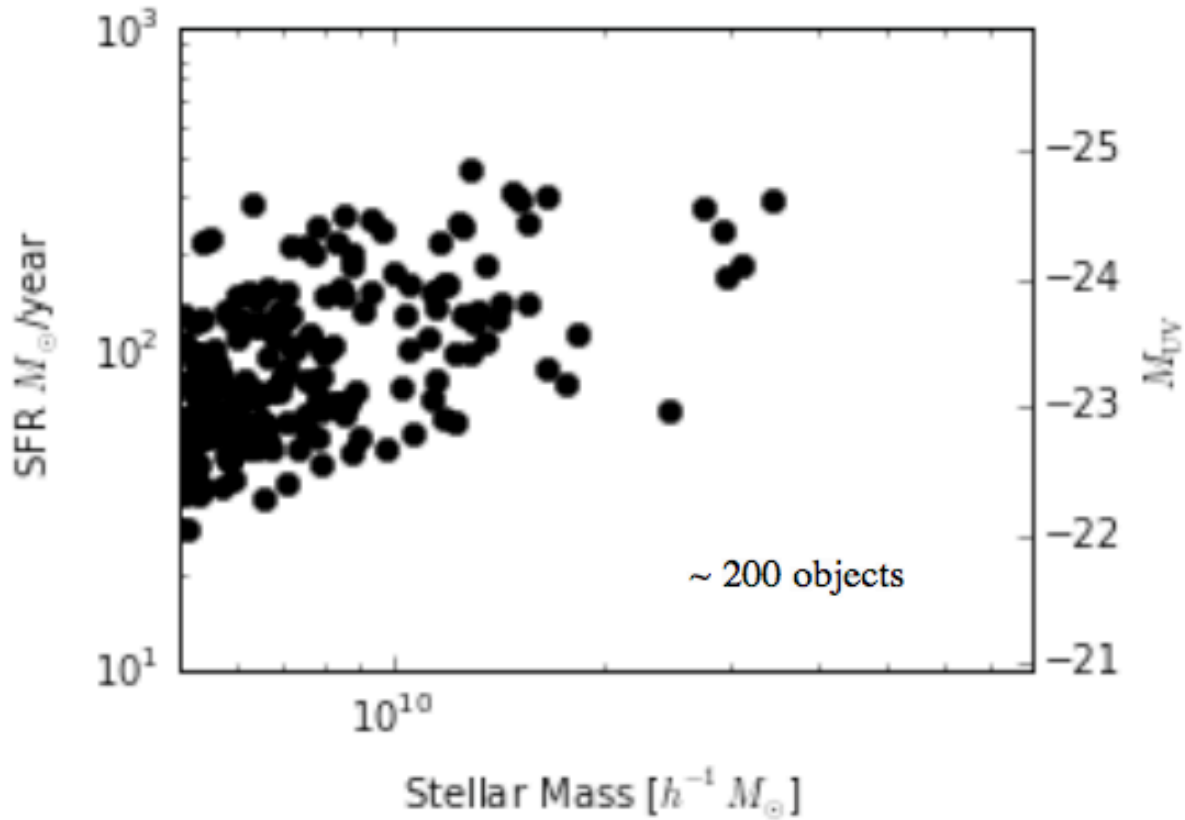
Galaxy Luminosity Function in BlueTides consistent with Hubble Legacy Fields



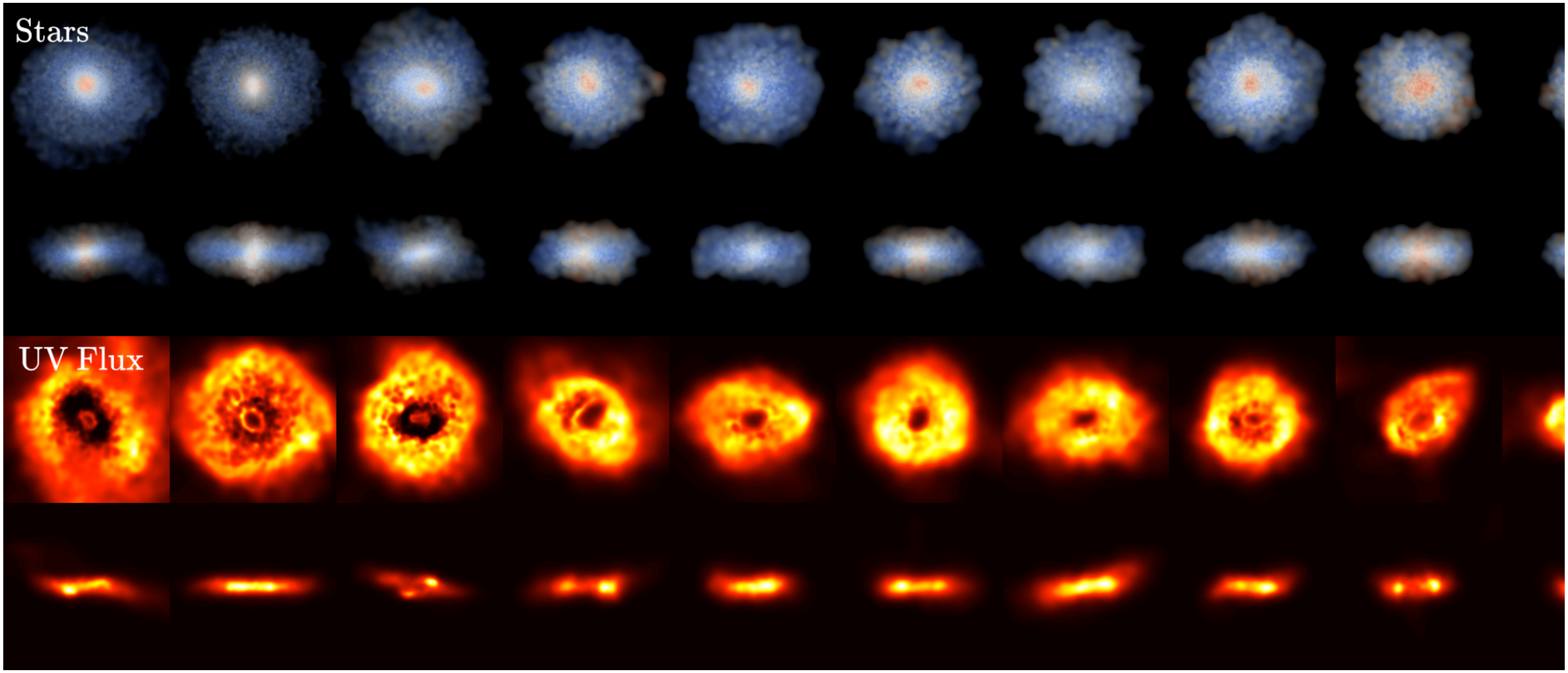
Feng et al., 2015a

Predictions for the brightest Galaxies at z=8:

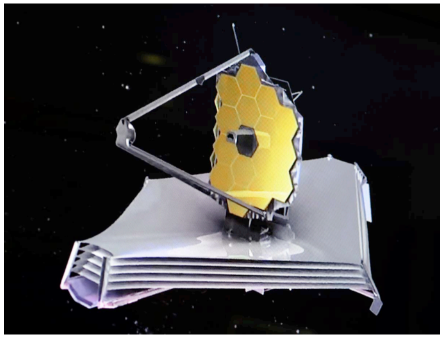




z=8 Milky Way (/Massive) galaxies are disks!

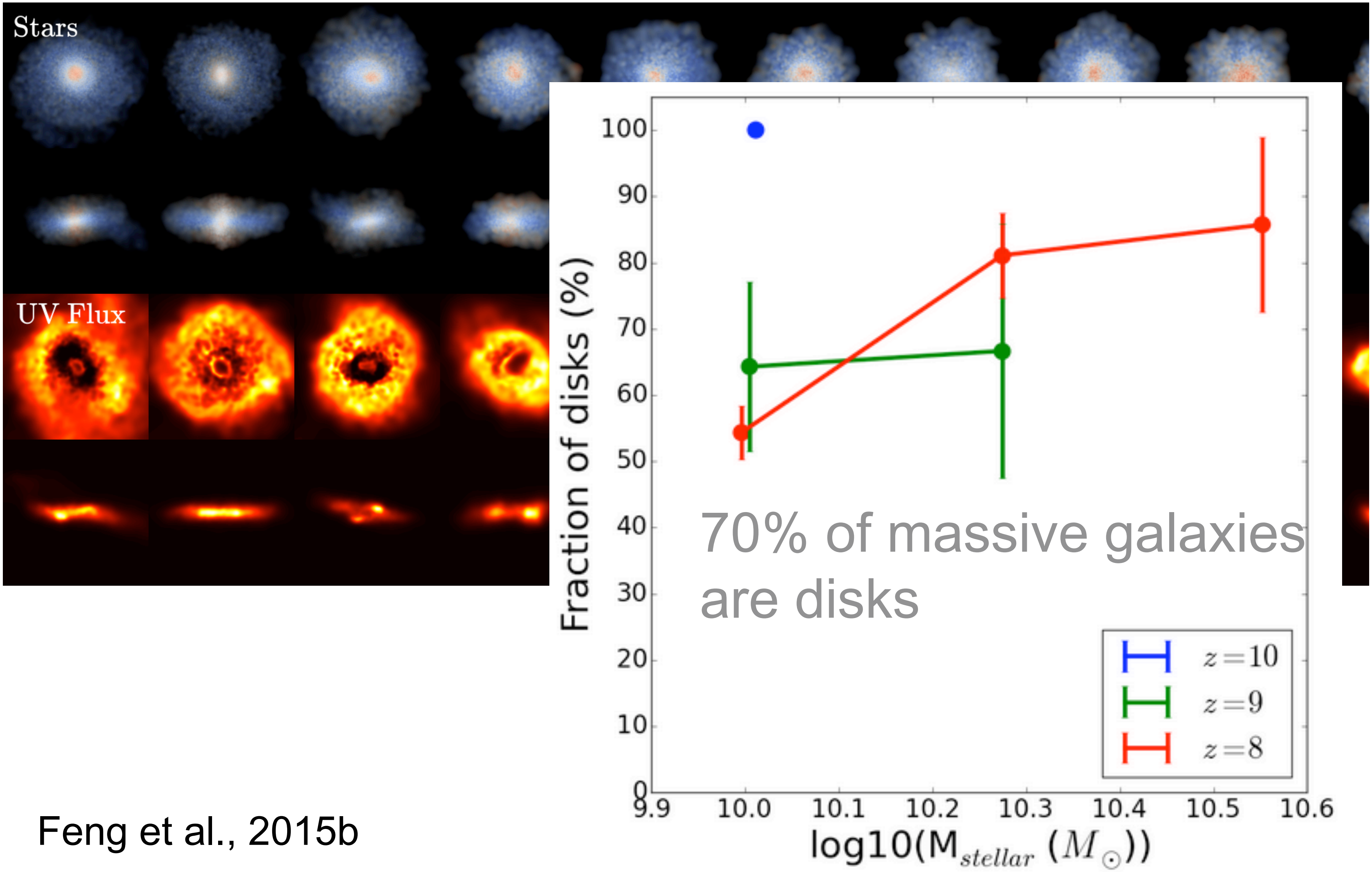


JWST

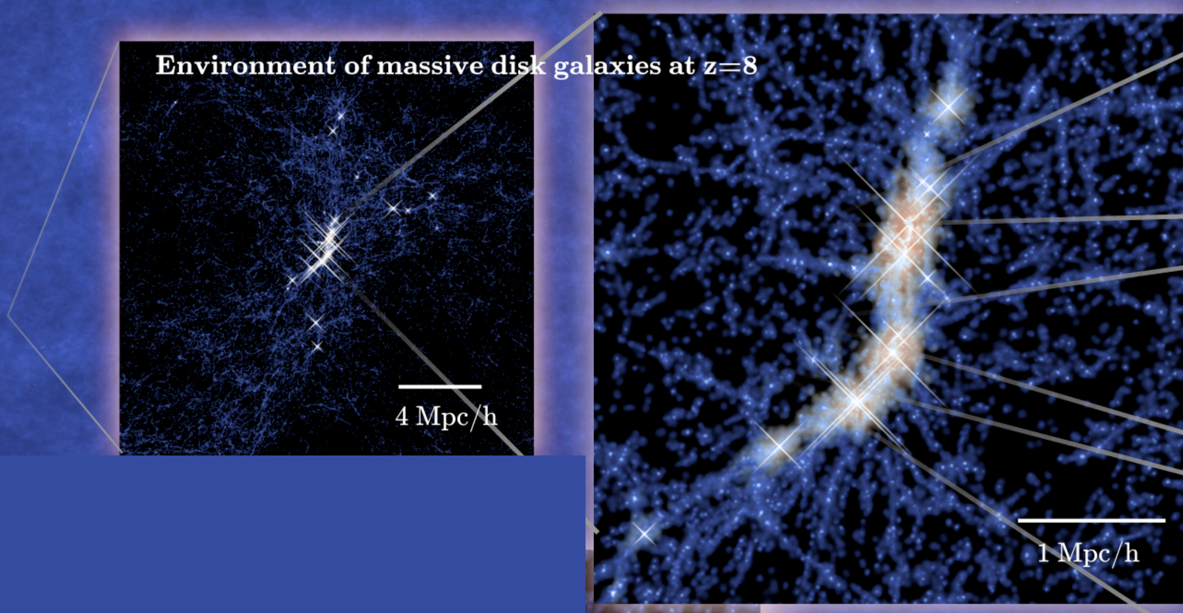


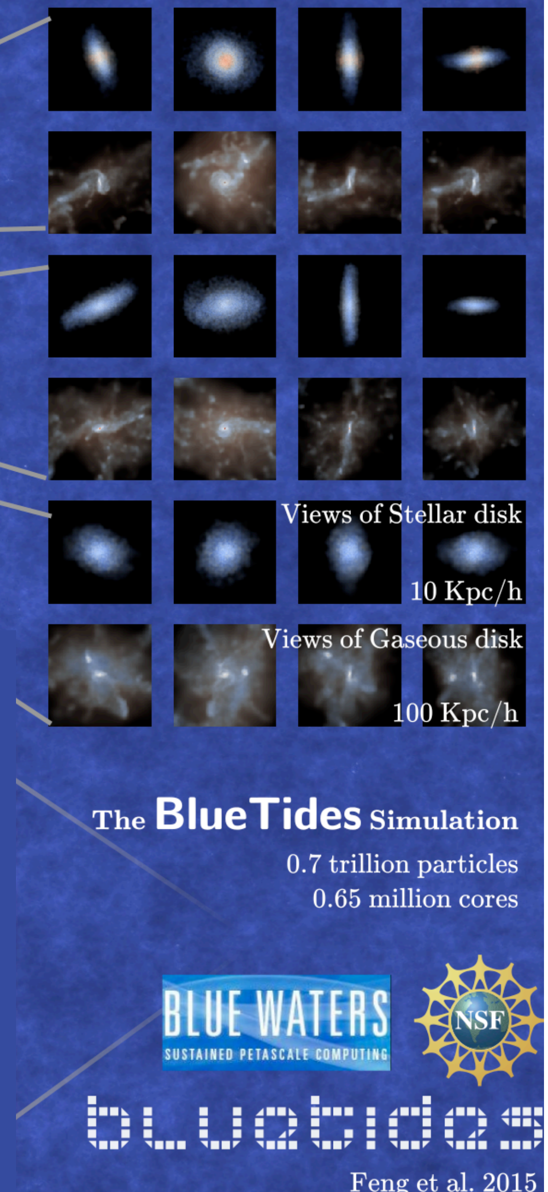
Feng et al., 2015b

z=8 Milky Way (/Massive) Halos look like disks!



Feng et al., 2015b

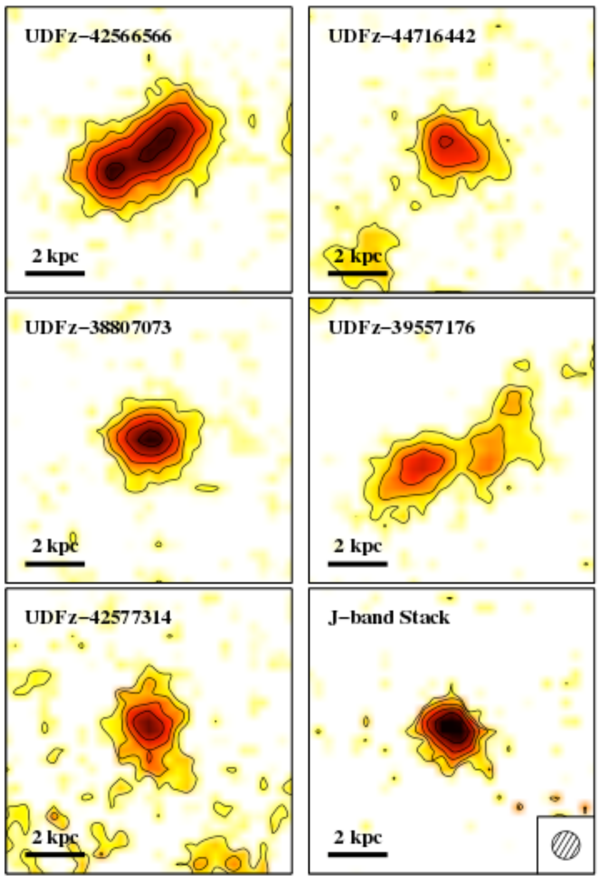




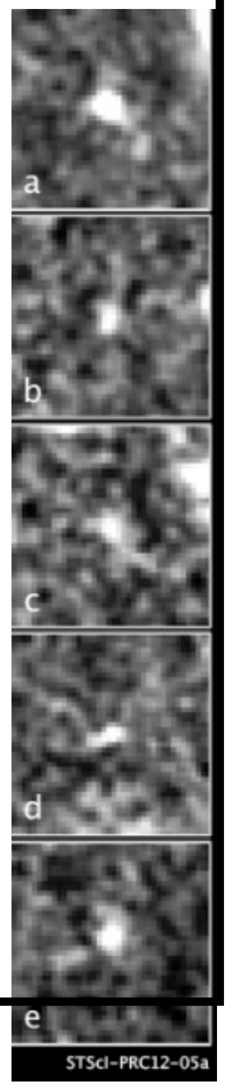
WFIRST
should detect
~ 8000 Milky Way
mass disks
at z=7-8

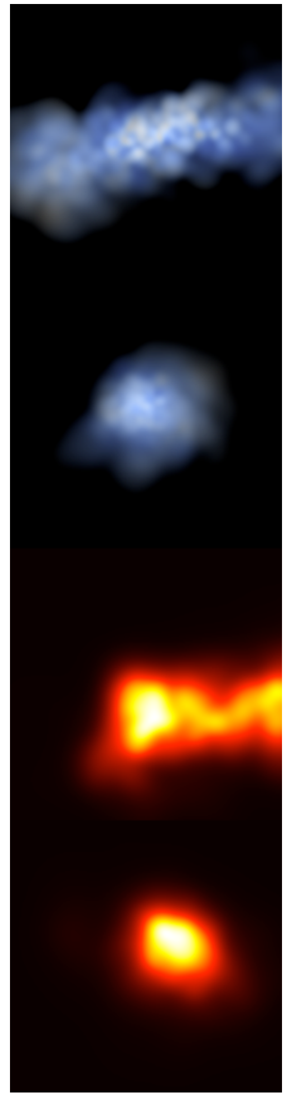
z=8 Milky Way (Massive) galaxies are disks!

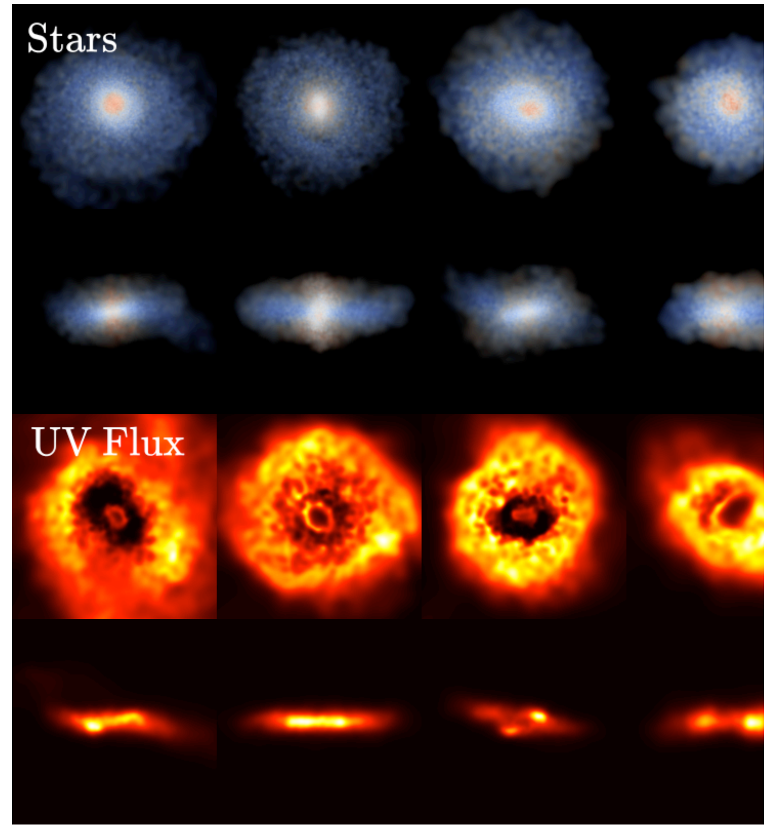
But small faint galaxies are irregular ….



HST Ultra-Deep field



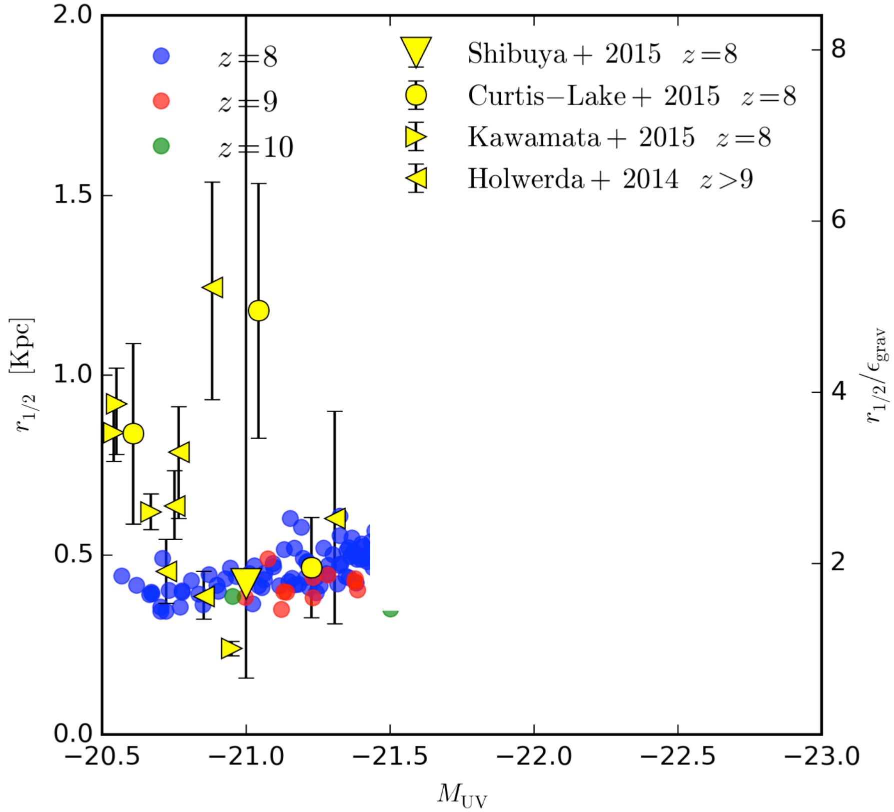




Feng et al., 2015b

The sizes of galaxies in BlueTides are consistent with HST observations

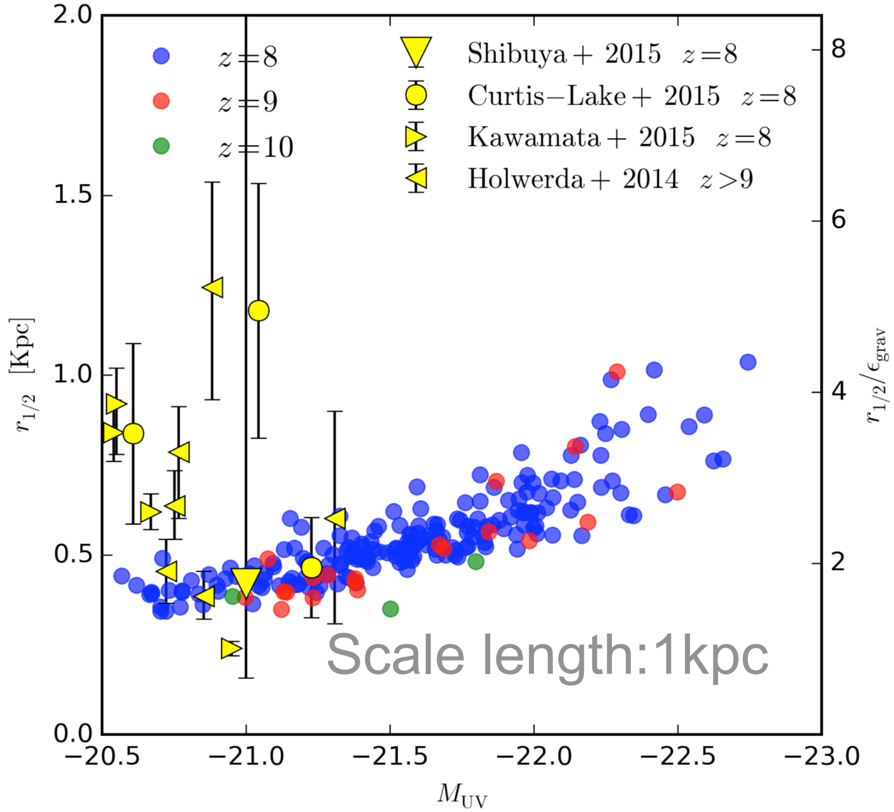
z=8



Feng et al., 2015a

The sizes of galaxies in BlueTides are consistent with HST observations --> 'massive' disks in bright bright galaxies are compact

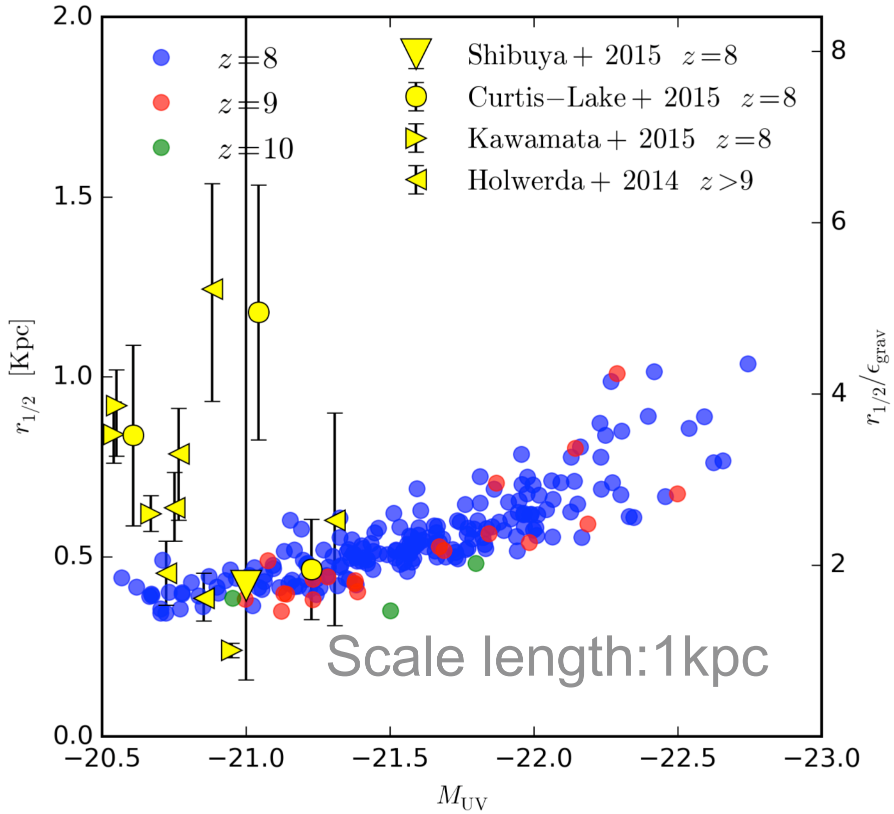
z=8

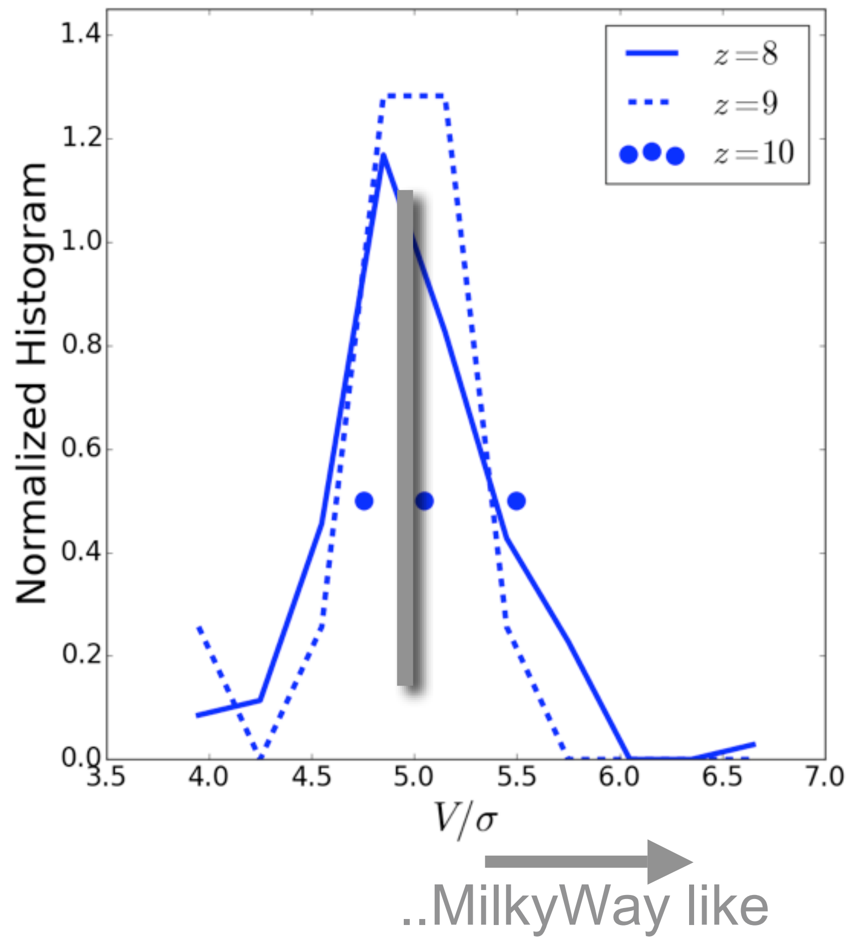


Feng et al., 2015a

The sizes of galaxies in BlueTides are consistent with HST observations --> 'massive' disks in bright galaxies are compact rotationally supported

z=8

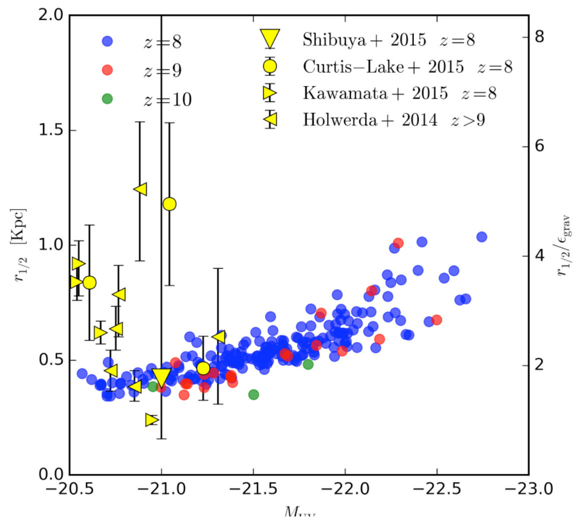


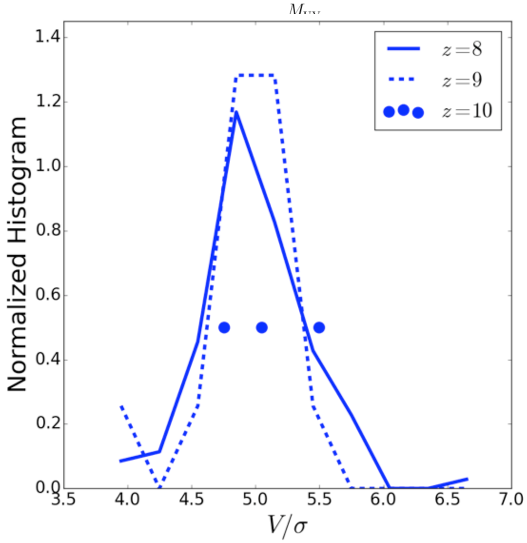


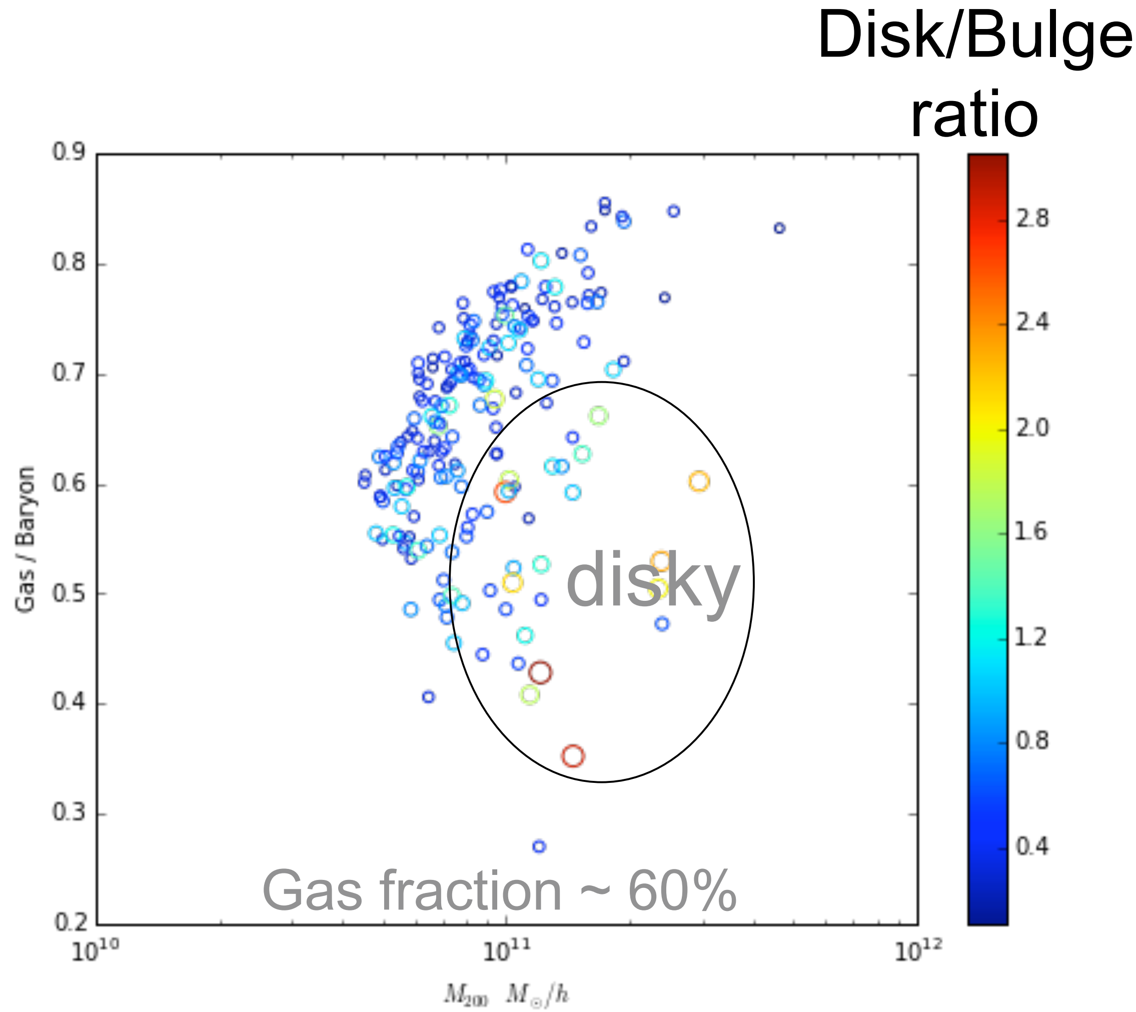
Feng et al., 2015a

Massive Disks at z=8, more compact gas rich

z=8



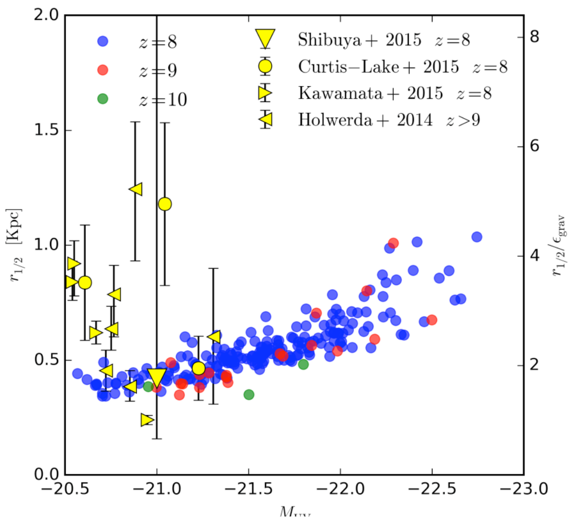


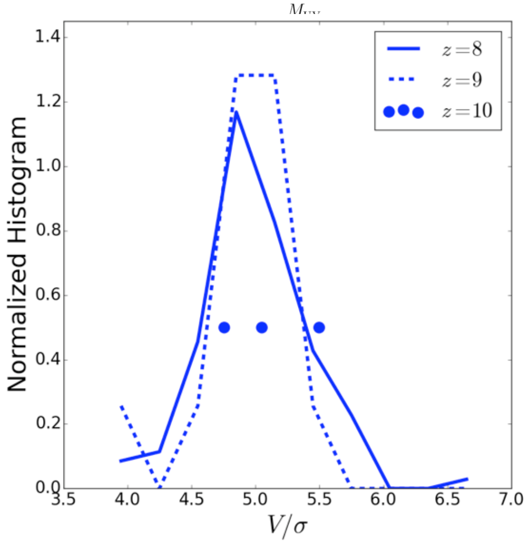


Feng et al., 2015a

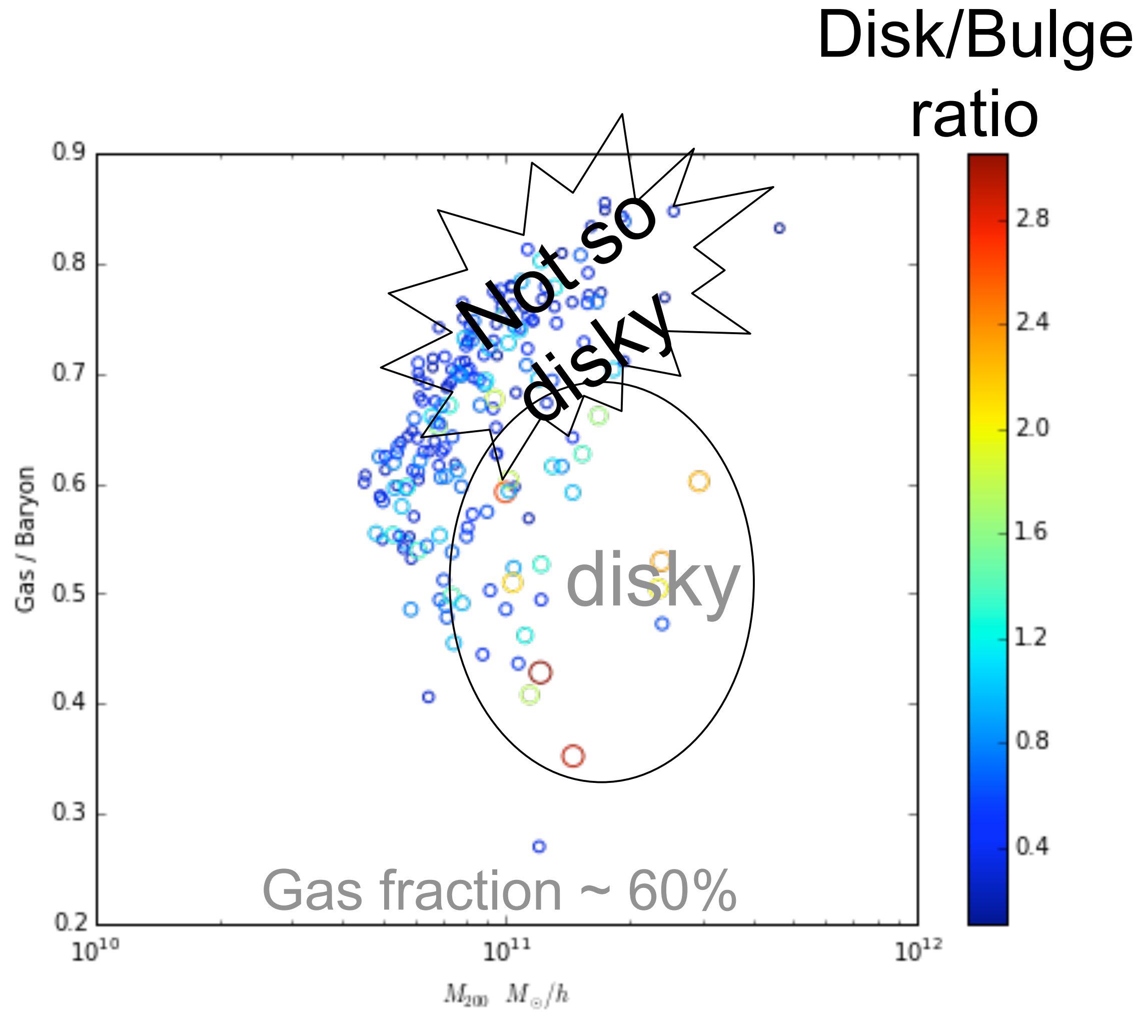
Gas richest systems have less dominant disk….

z=8





Feng et al., 2015a

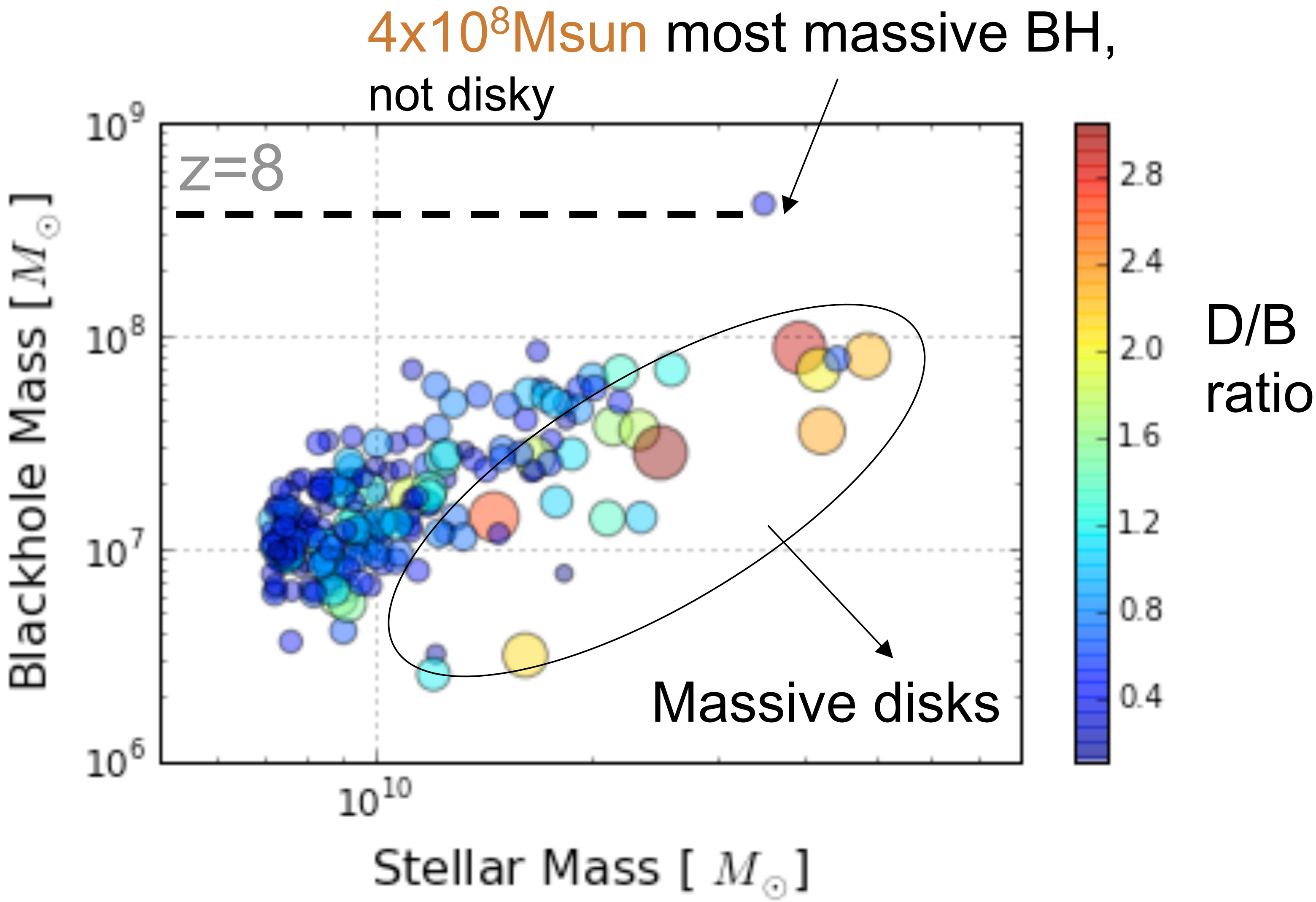


The first 600 million years (z=7+):

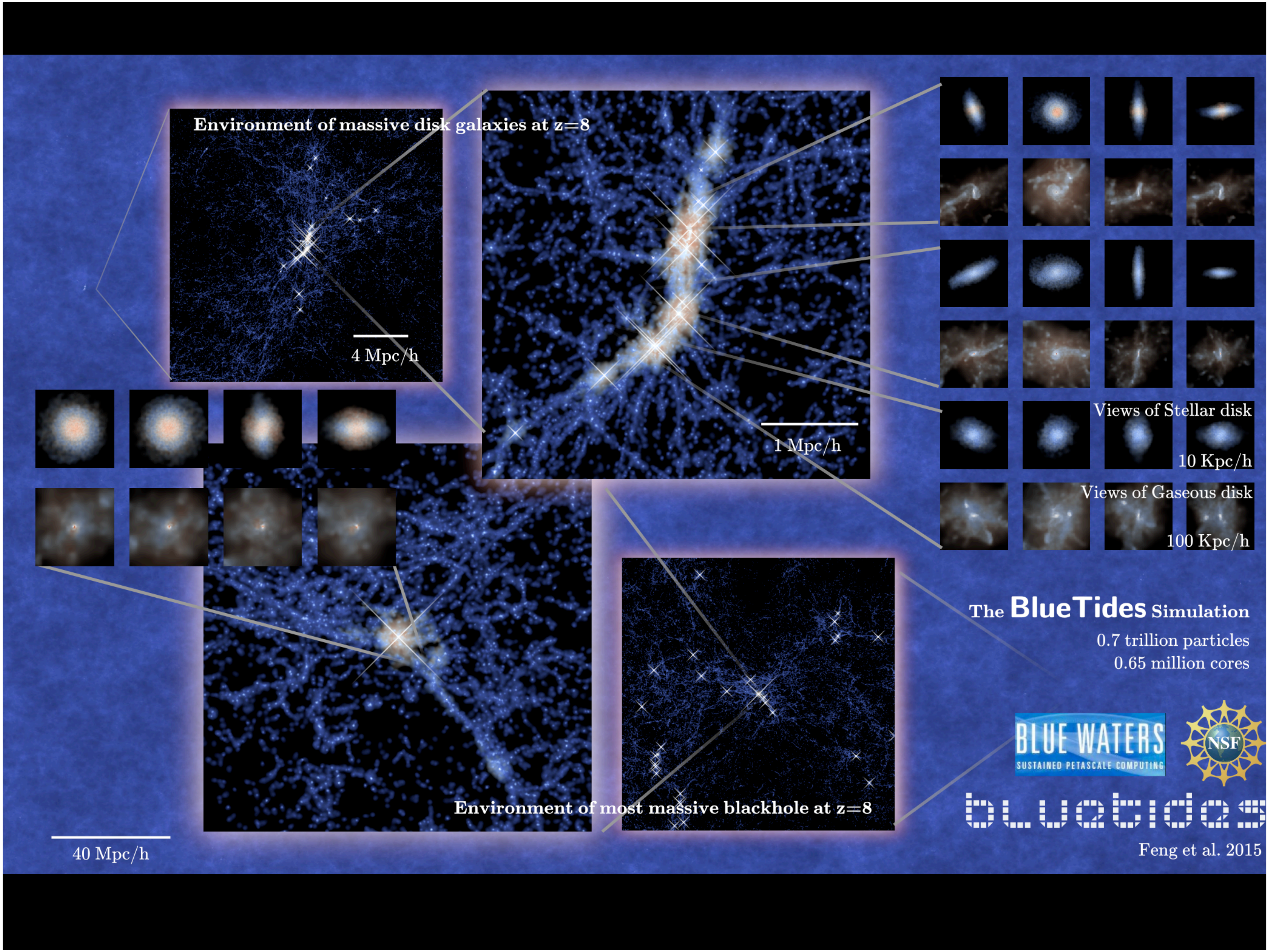
What are quasars like?

Predictions from
BlueTides:

Most massive black holes at z=8, about 10^8Msun



Fastest growing, massive black holes are not found in the massive disk galaxies!



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1 Mpc/h
Views of Stellar disk
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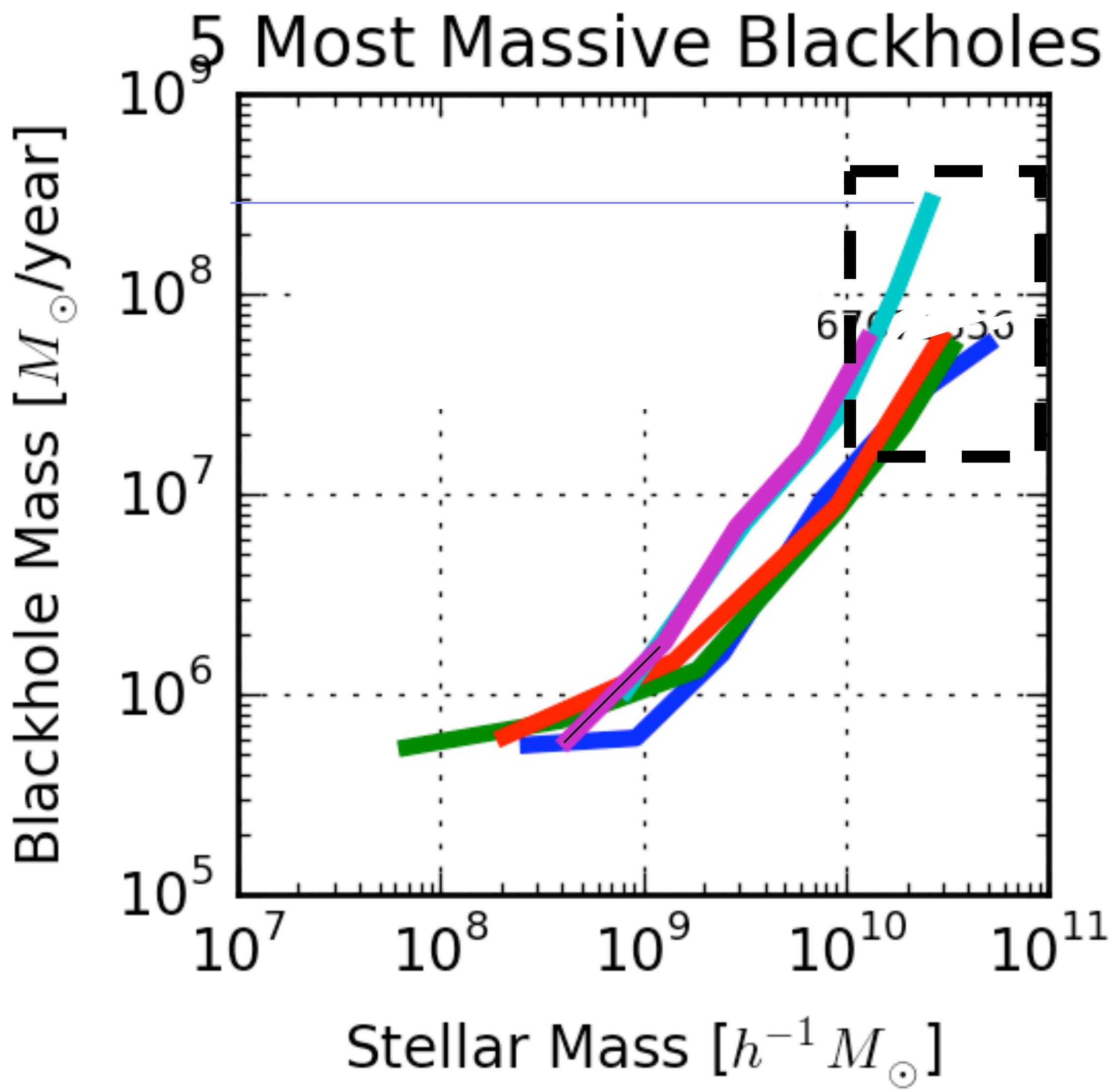
bluetides
Feng et al. 2015

How do massive BH and galaxies grow?

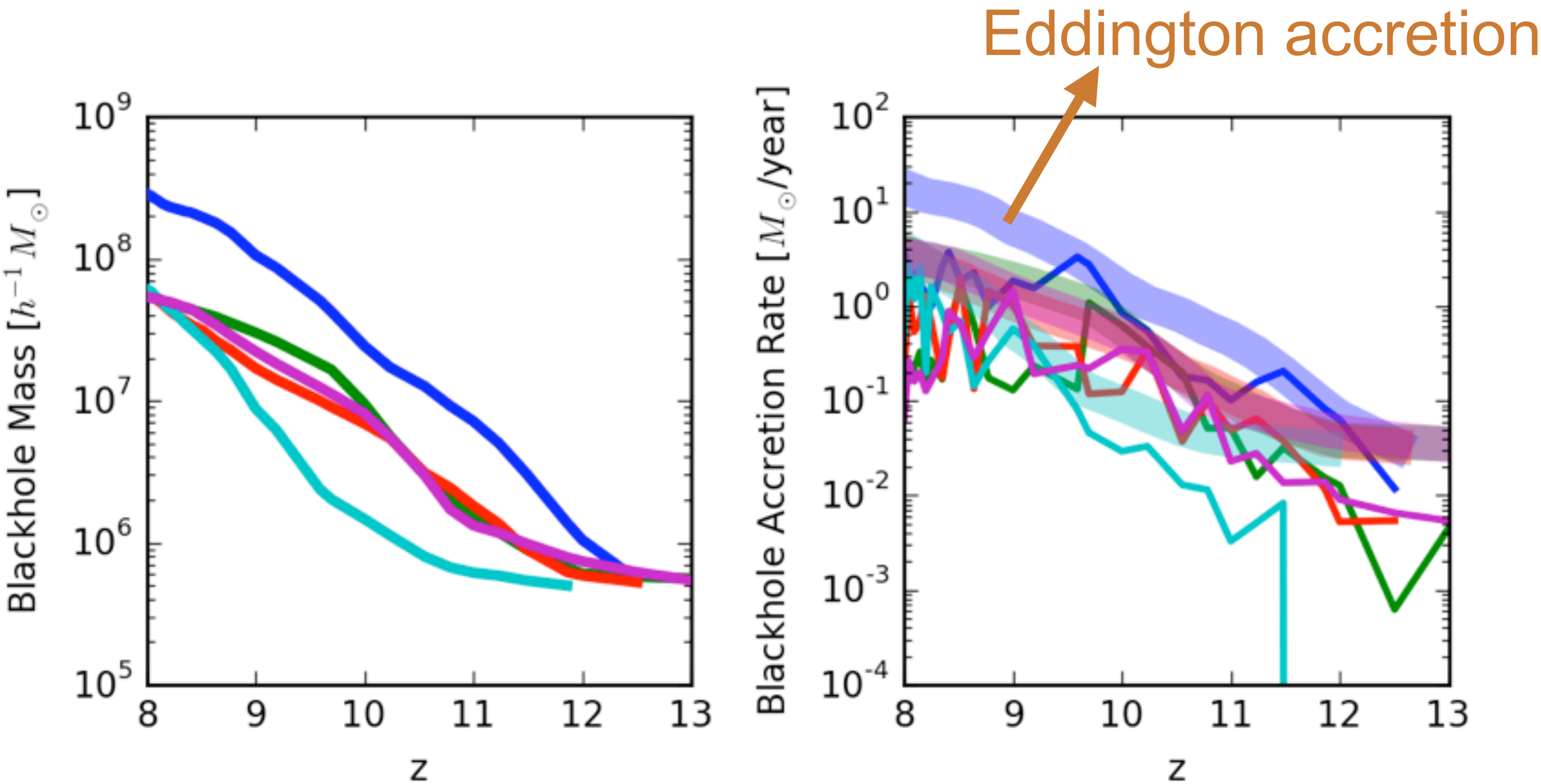


Steepest BH Growth →

No disk

No major mergers

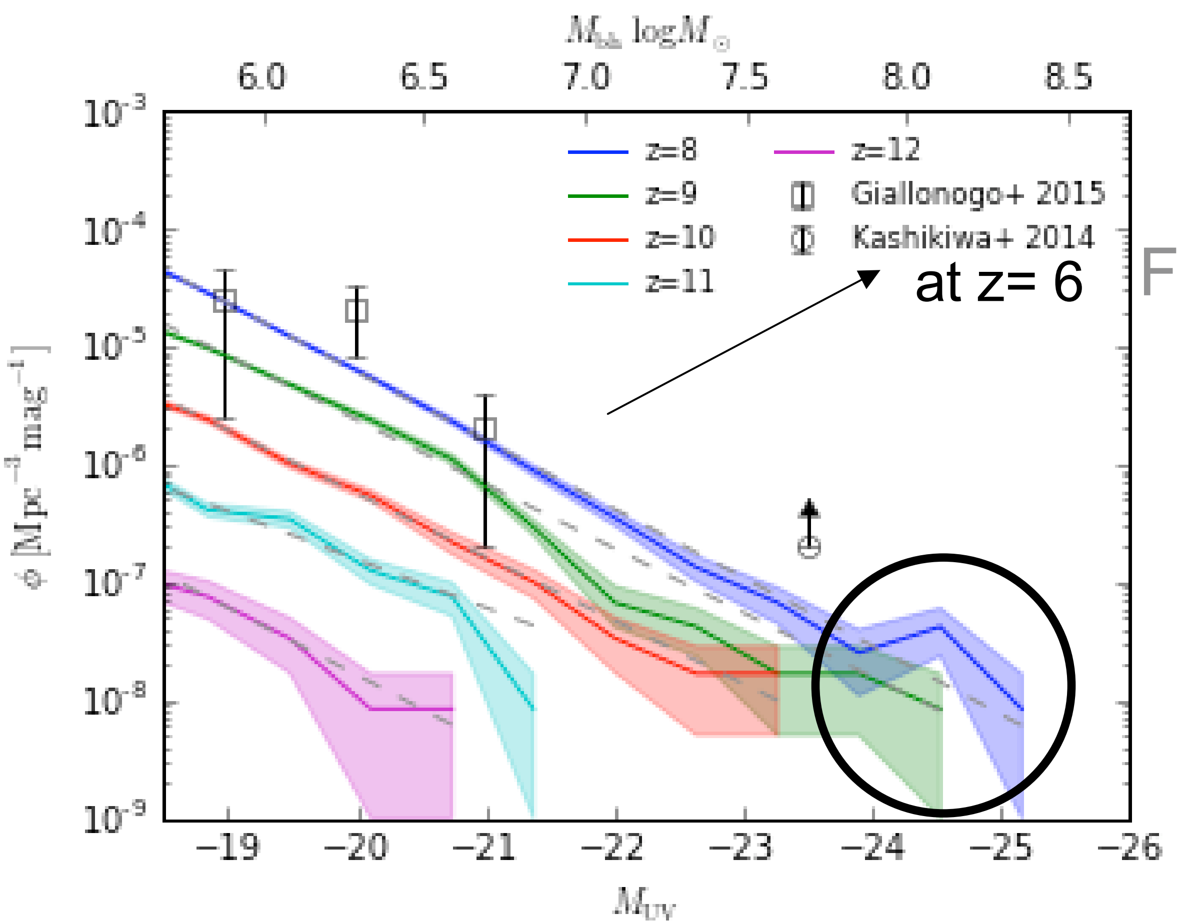
Assembly of largest BHs at z=8,



Black Hole/AGN Luminosity Function in BlueTides

Consistent → Predictions for first quasars

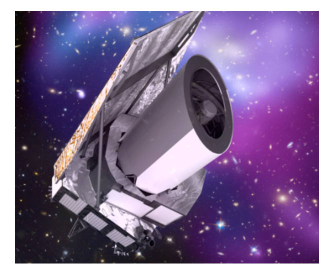
Diff. Number density of black Holes



BH luminosity → bright

First Quasars at z=8+

WFIRST

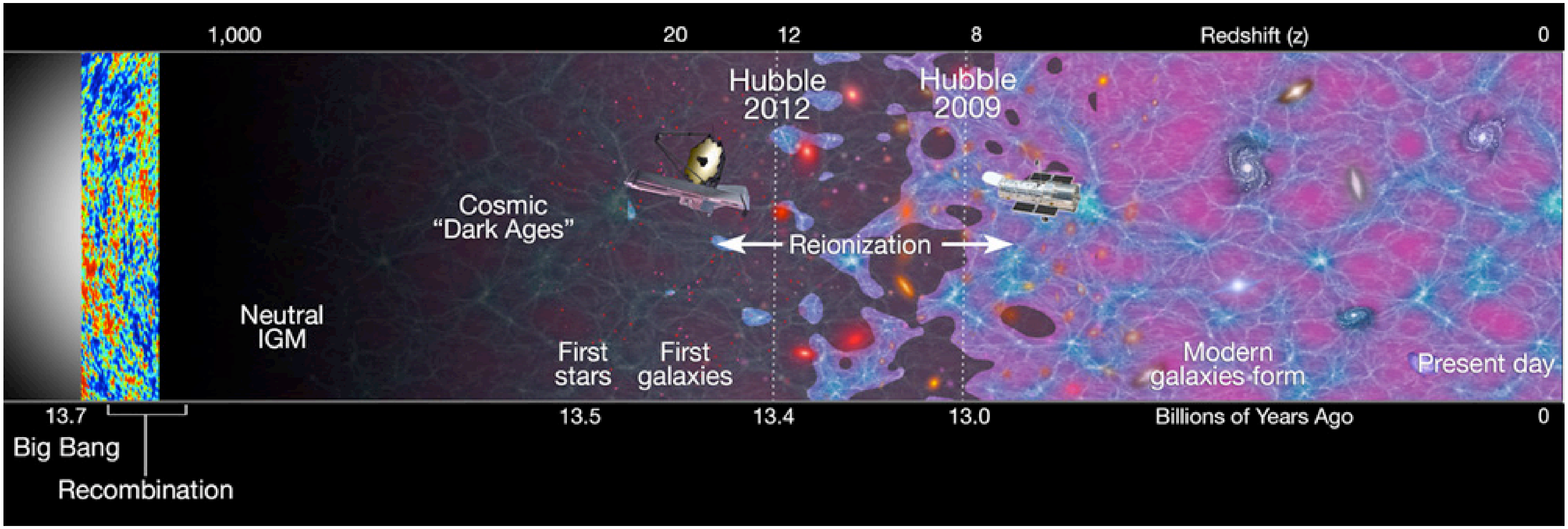


Euclid
Deep
Fields

Feng et al., 2015a

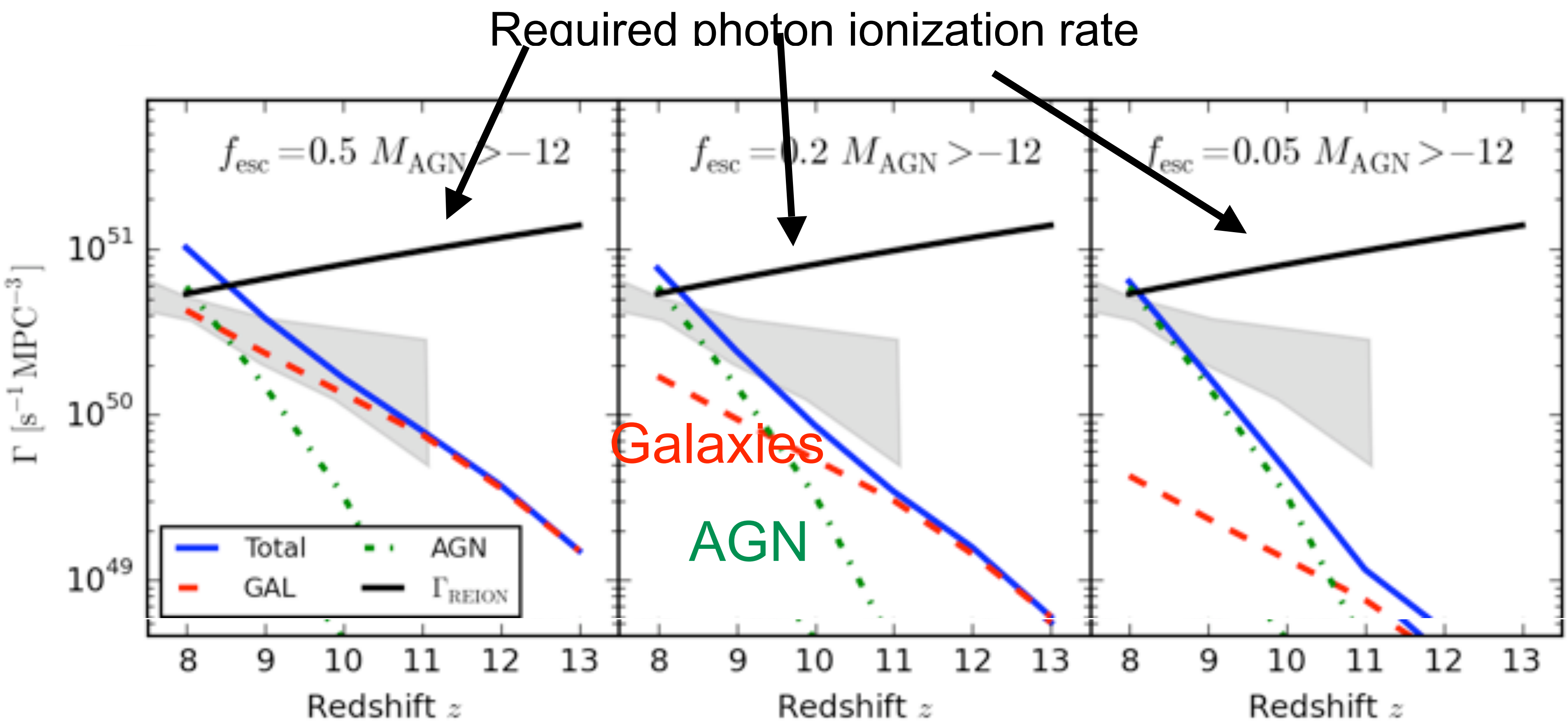
What sources reionize the Universe?

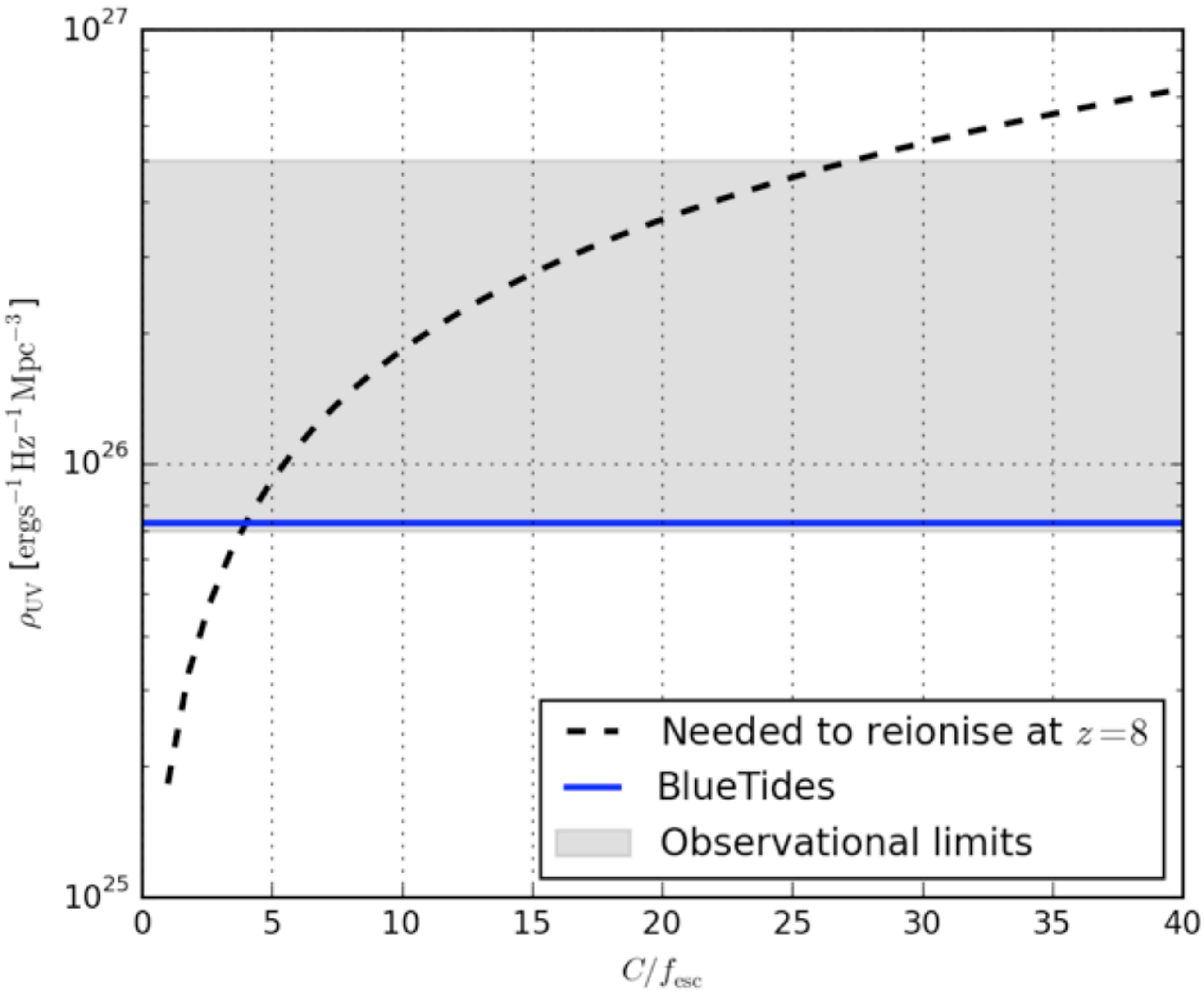
Galaxies and AGNs in BlueTides



BlueTides and Re-ionization history of the Universe

Galaxies can reionize the universe for high escape photon fractions. But AGNs can contribute (very?) significantly





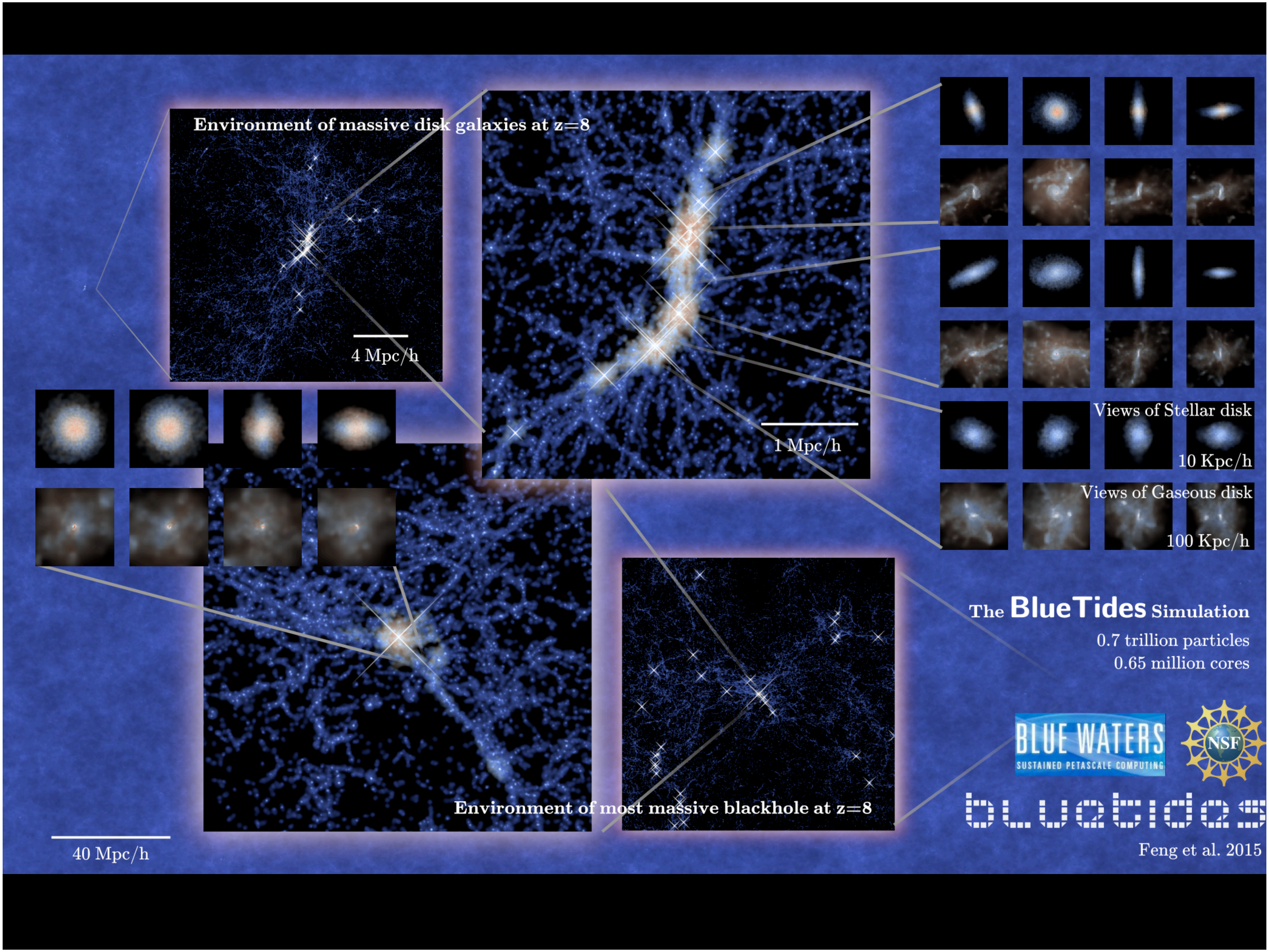
10^{27}
10^{26}
10^{25}
$\rho_{\rm UV}$ [ergs^{-1} Hz^{-1} Mpc^{-3}]
0
5
10
15
20
25
30
35
40
$C/f_{\rm esc}$
Needed to reionise at $z=8$
BlueTides
Observational limits

Conclusions:

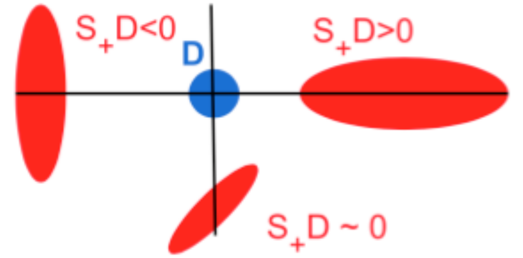
New large volume high res BlueTides Simulation predicts (at z>7):

- Population of massive, compact disks --> WFIRST should detect thousands

- Most massive black holes, 10^8 Msun --> WFIRST tens of objects


Environment of massive disk galaxies at z=8
4 Mpc/h
1 Mpc/h
Views of Stellar disk
10 Kpc/h
Views of Gaseous disk
100 Kpc/h
The BlueTides Simulation
0.7 trillion particles
0.65 million cores
BLUE WATERS
SUSTAINED PETASCALE COMPUTING
NSF
bluetides
Feng et al. 2015
Environment of most massive blackhole at z=8
40 Mpc/h

Intrinsic Alignements of Galaxies from full hydro (MBII) simulation - Effects of Baryon Physics.



Projected-shape density ($w_{\delta+}$) correlation

- $M > 10^{12} h^{-1} M_{\odot}$
- For stellar matter, larger ellipticities increase $w_{\delta+}$ (Tenneti et al. 2015, arXiv:1505.03124)