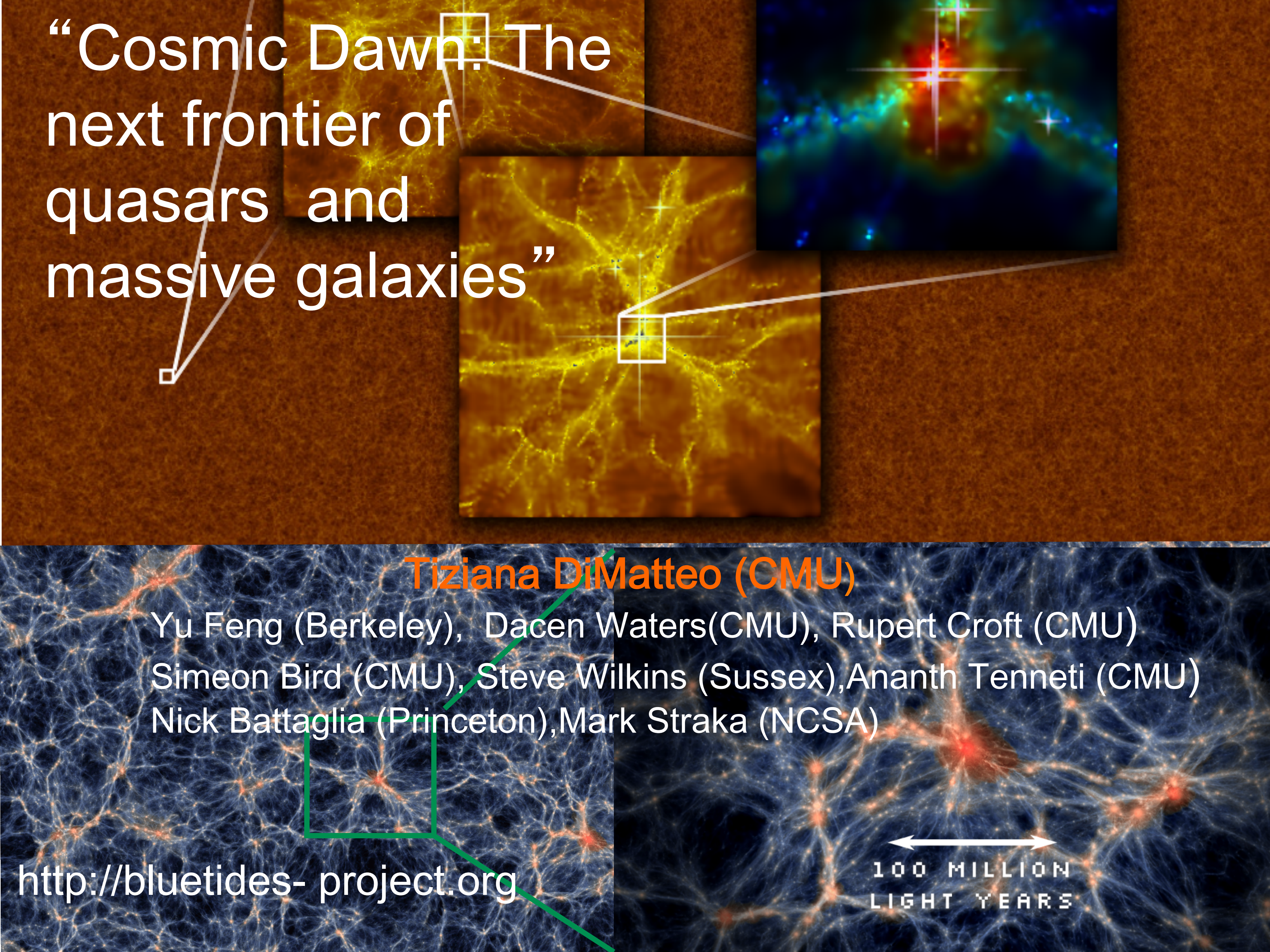
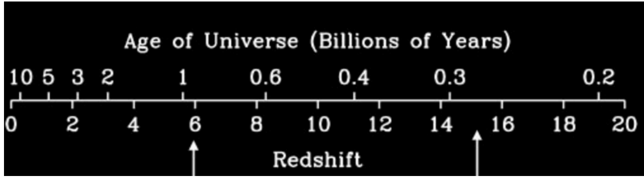
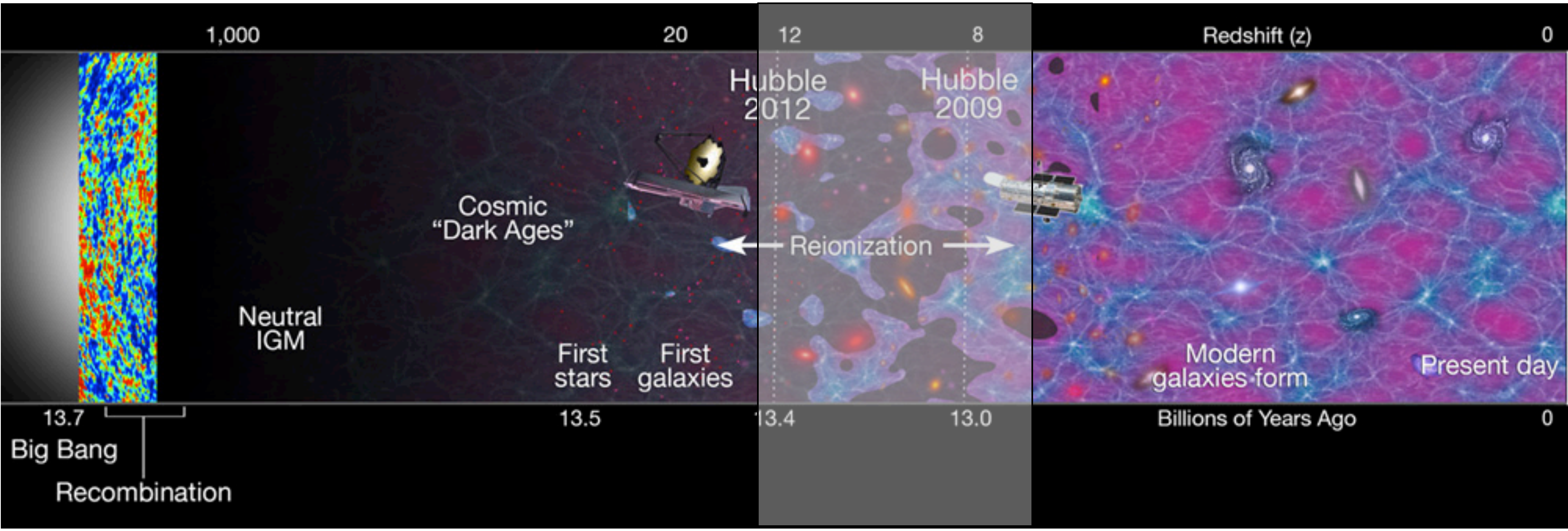

"Cosmic Dawn: The next frontier of quasars and massive galaxies"
Tiziana DiMatteo (CMU)
Yu Feng (Berkeley), Dacen Waters(CMU), Rupert Croft (CMU)
Simeon Bird (CMU), Steve Wilkins (Sussex),Ananth Tenneti (CMU)
Nick Battaglia (Princeton),Mark Straka (NCSA)
http://bluetides- project.org
100 MILLION
LIGHT YEARS



A sketch of Cosmic History

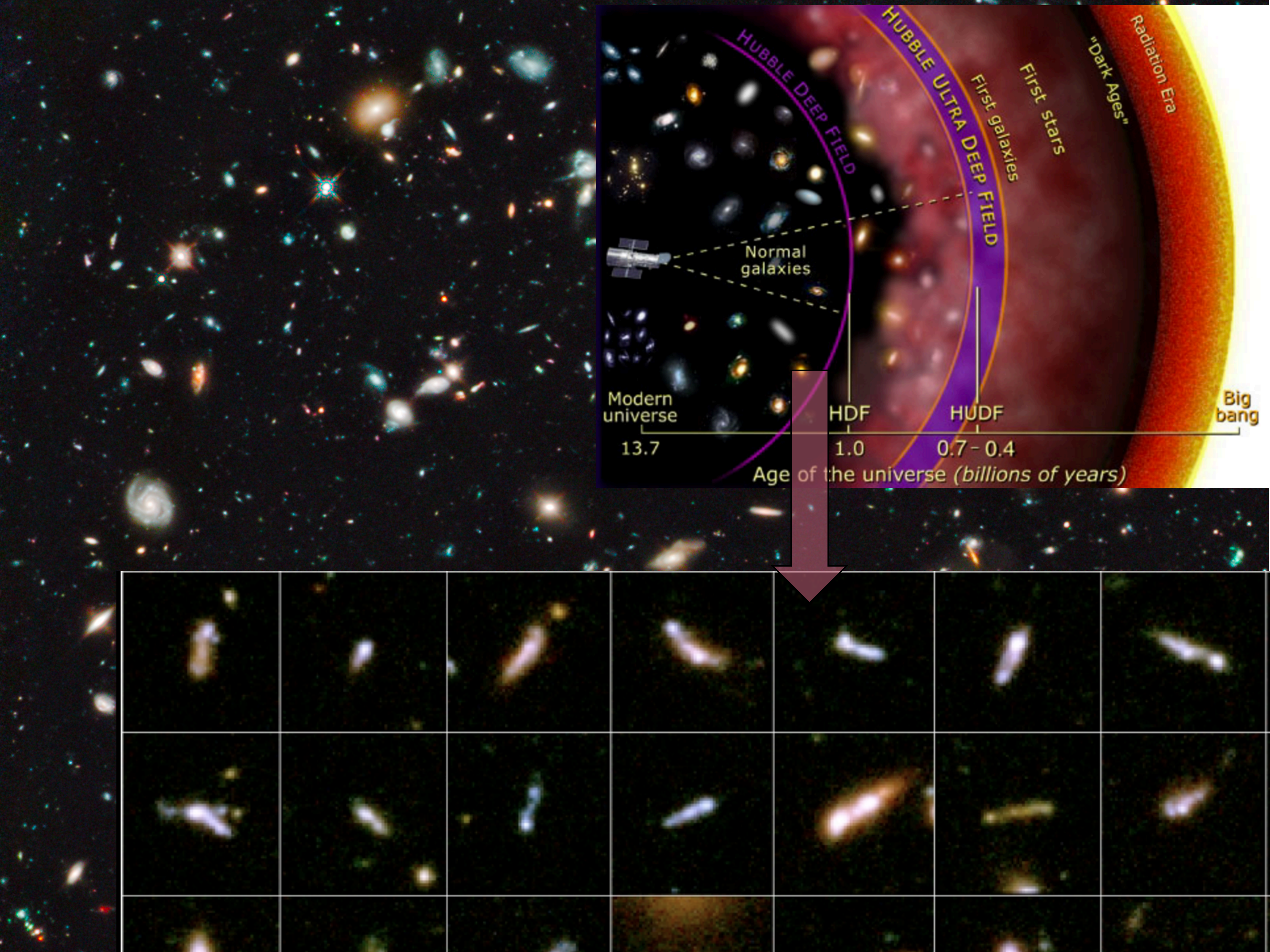


300Myrs 800Myrs

The first 800 million years ($z=7+$):

Observations:

Hubble Deep Field
Hubble Ultra Deep Field
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)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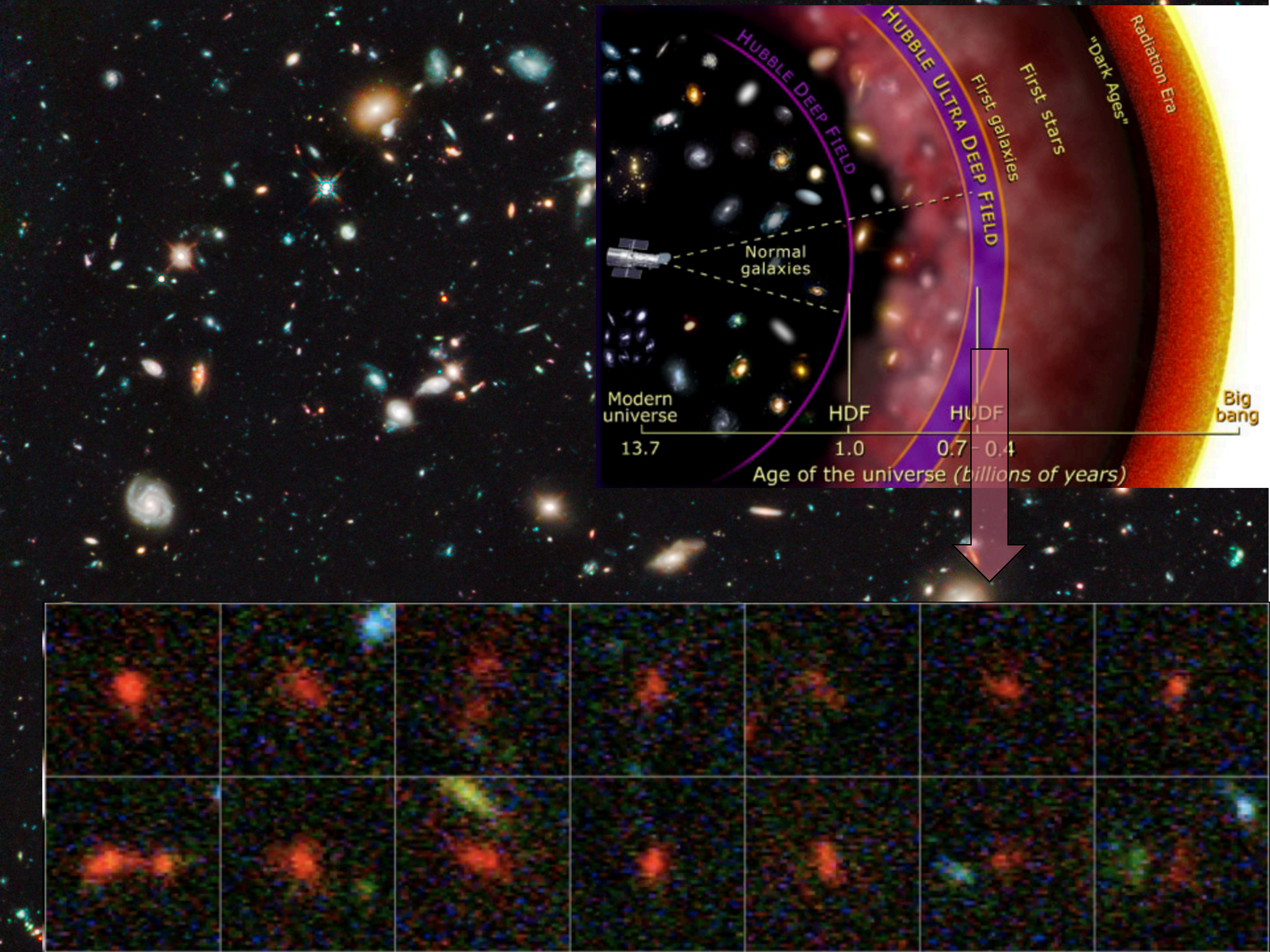
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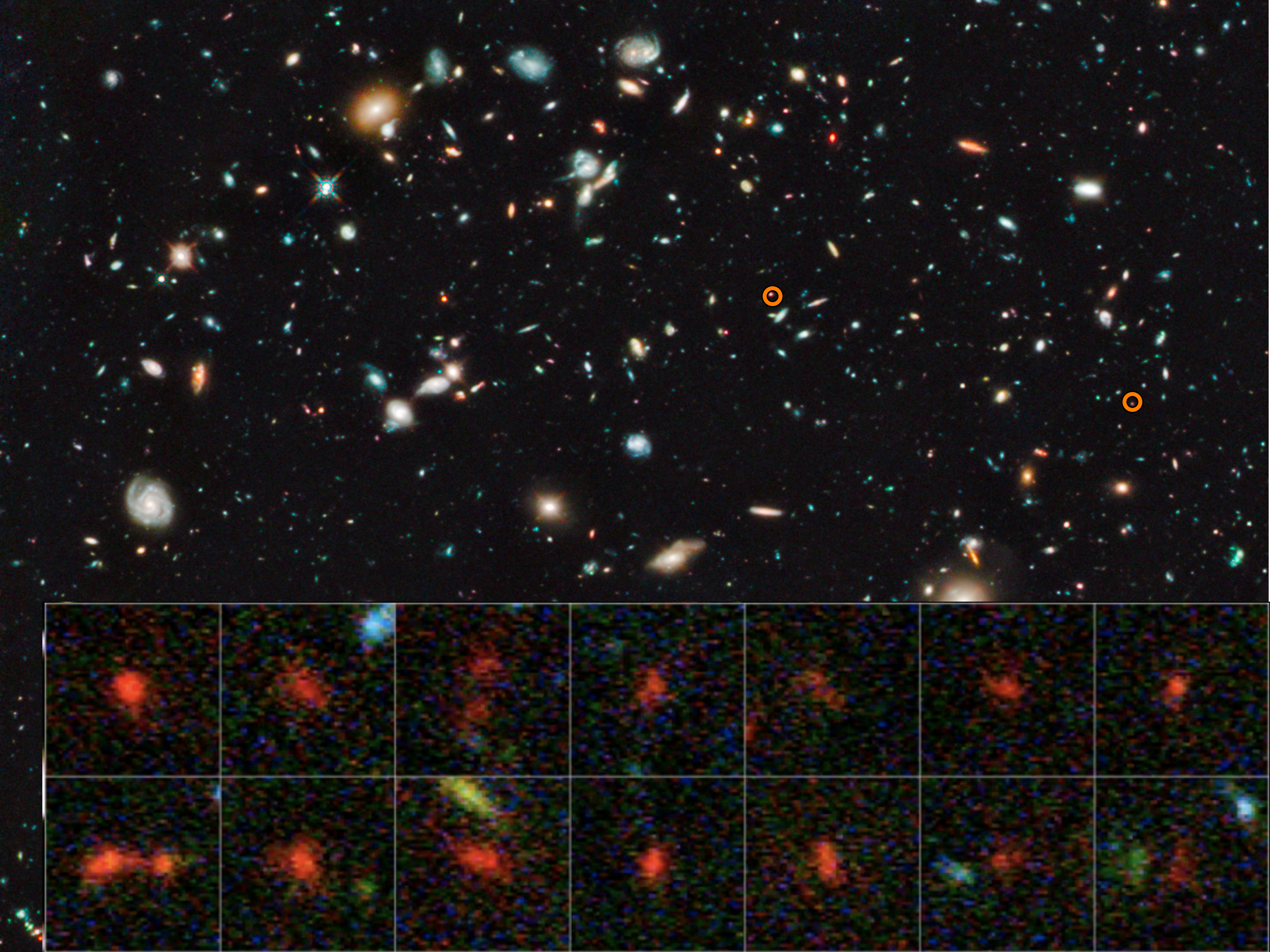
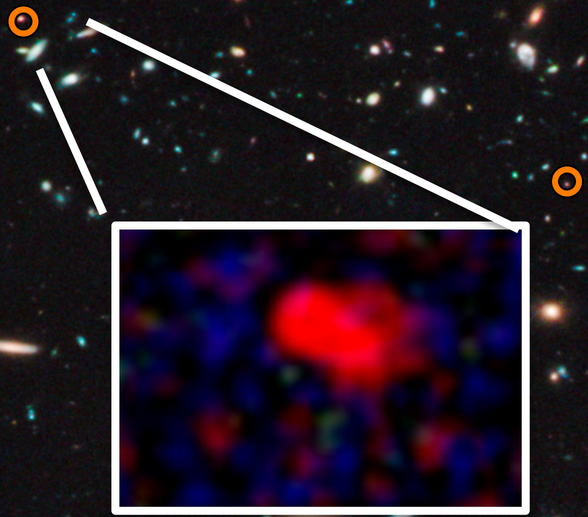


500-700 Million years: Faint, compact smudges

2 million light years away



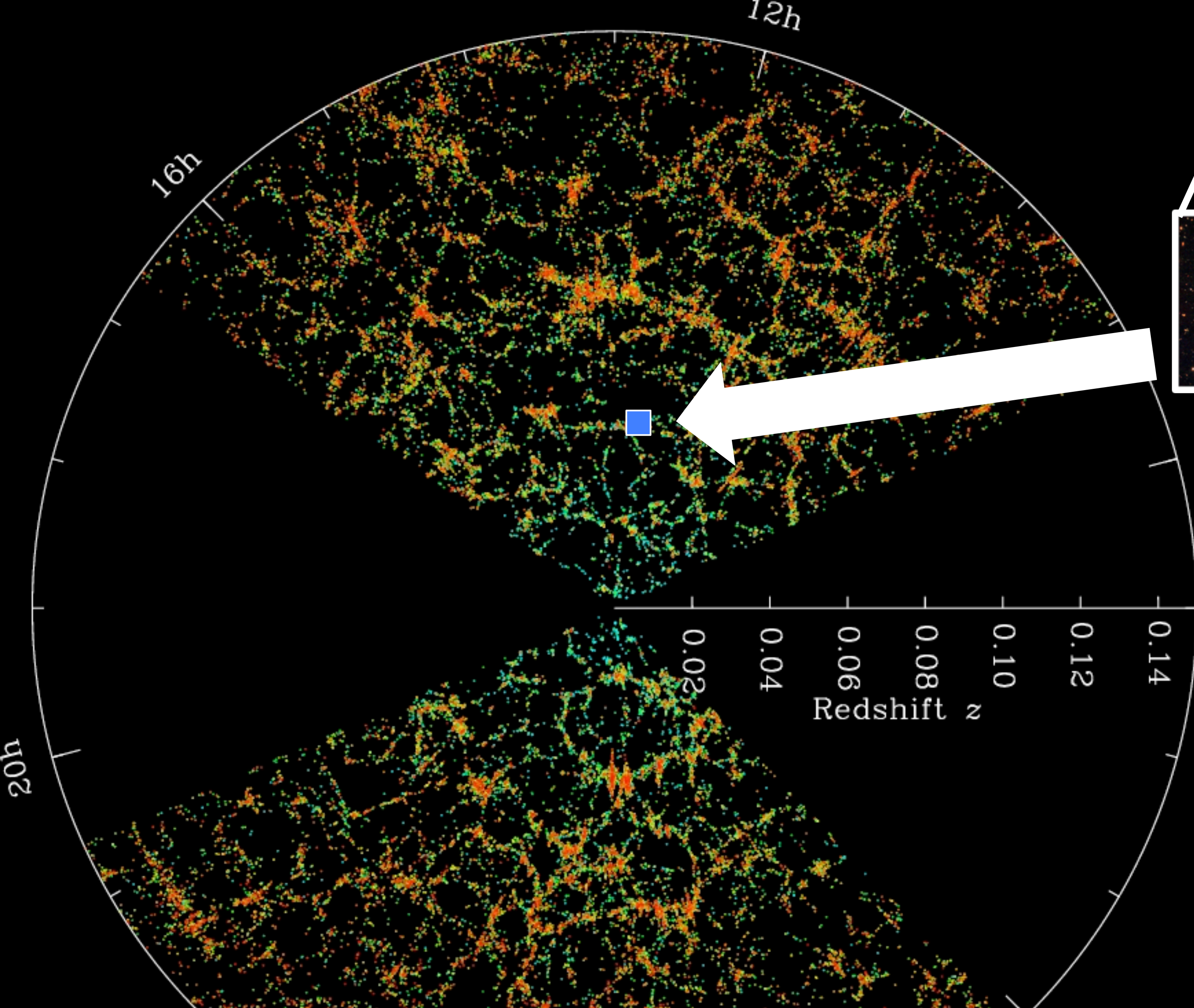
13 billion light years away

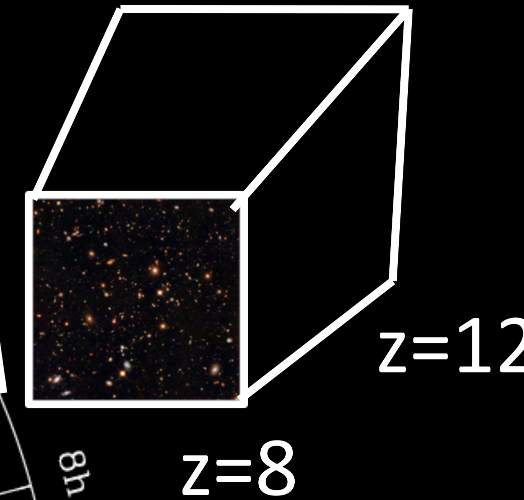
Tiny (few $arcmin^2$) Hubble Legacy Ultra Deep Fields show compact, clumpy and irregular morphologies

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

Is this what the first galaxies are like?

Problem 1:



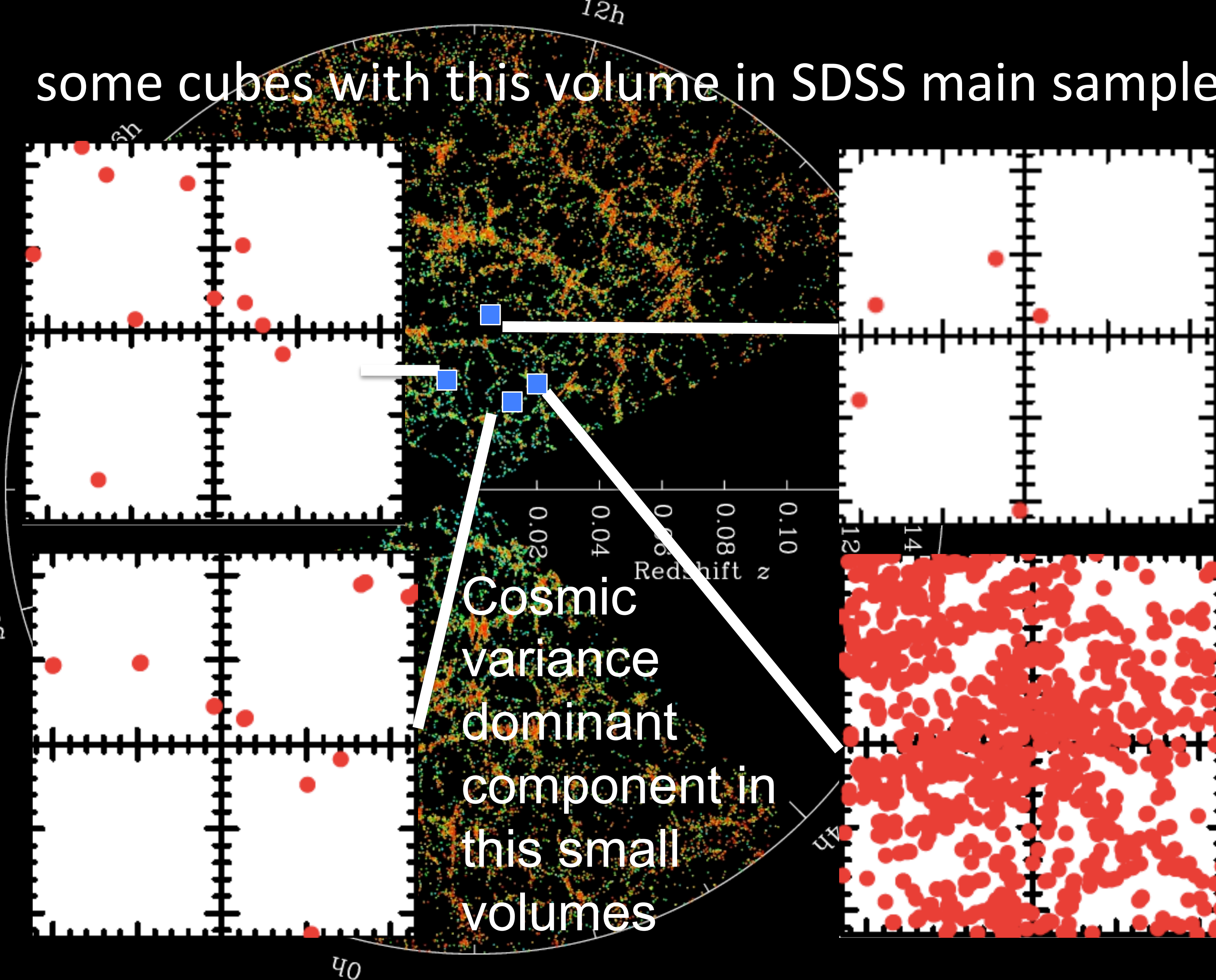


HUDF
for z=8-12
range has
comoving
volume
(23 Mpc/h)^3

1 parsec = ***3.26 light years***

– 1 light year = distance a photon of light can travel in a year – about 5.68 ***trillion*** miles!!

some cubes with this volume in SDSS main sample:



Cosmic variance dominant component in this small volumes

First 600 million years: The first and only 1 quasar …

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]

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-

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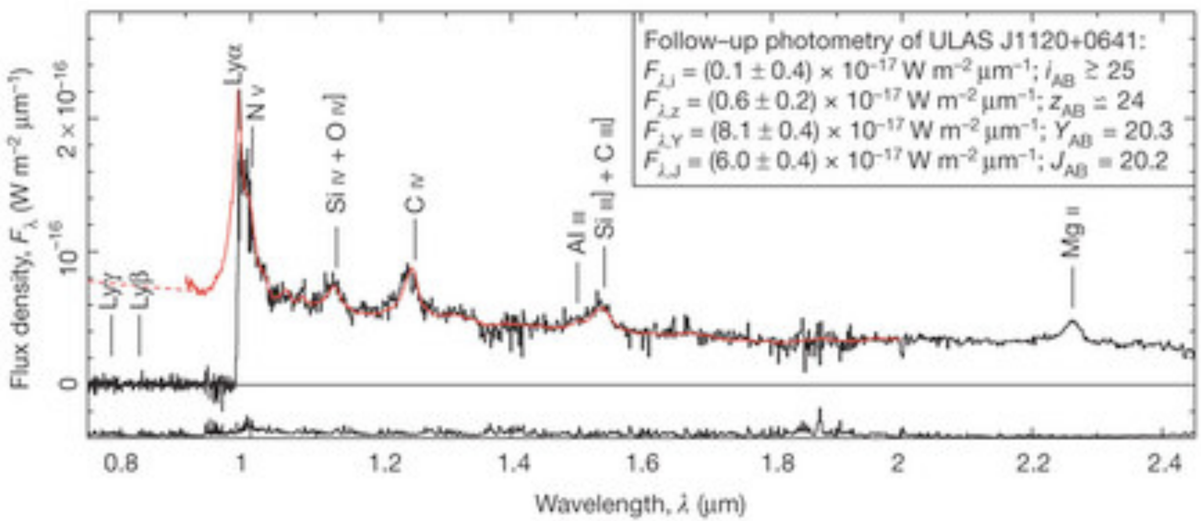
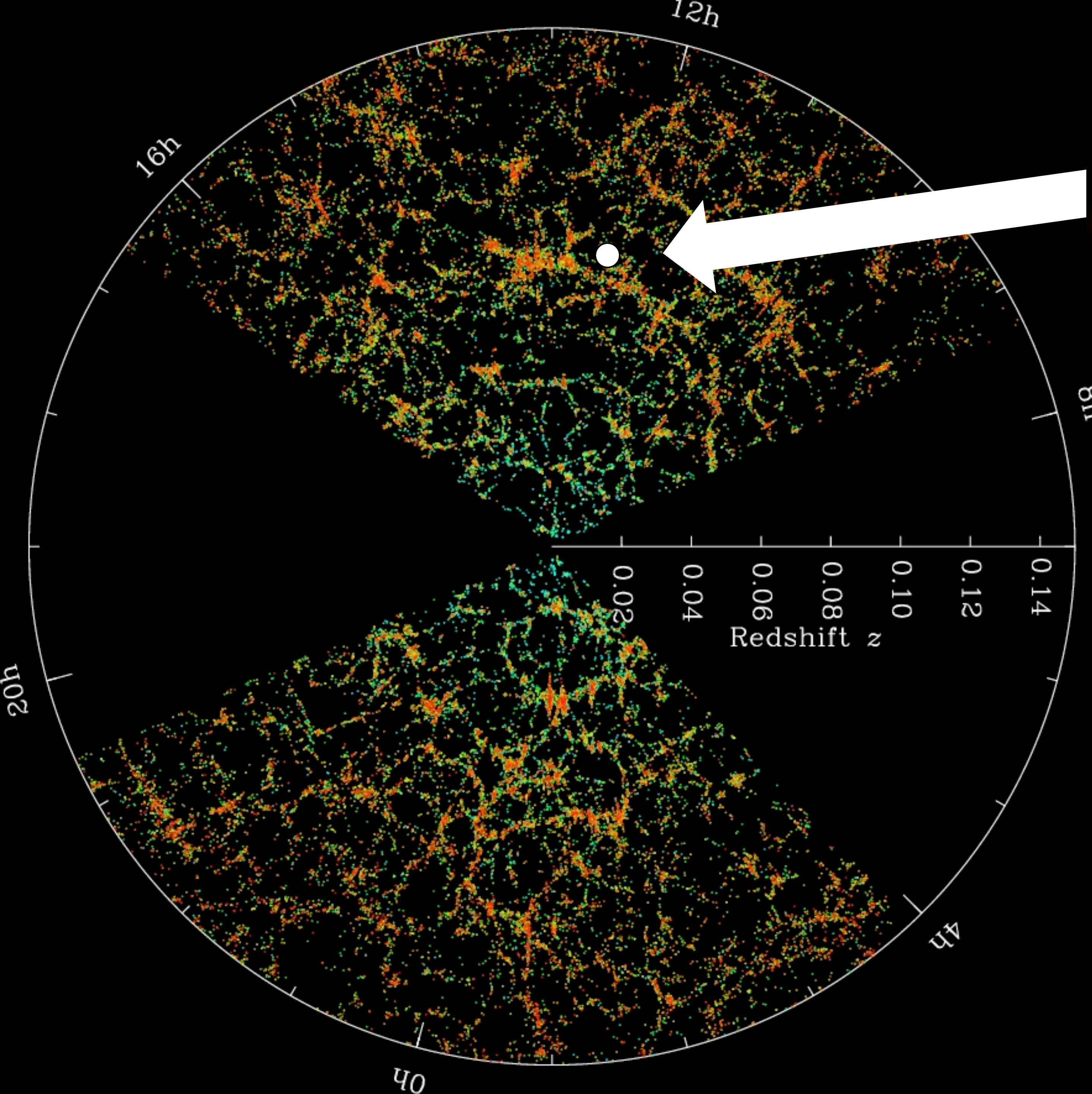
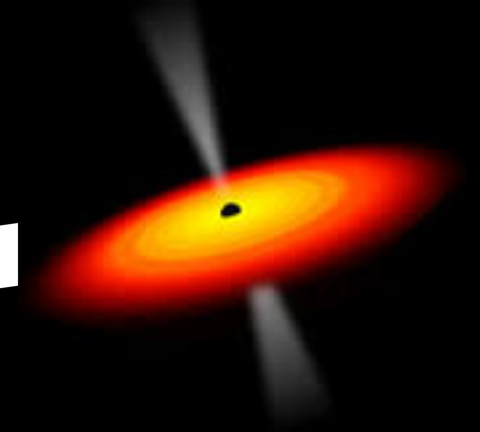
At z=7, 1 in a Gpc^3

$M_{BH}=10^9 M_{sun}$







1 quasar in this volume

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

Do we expect such extreme mass BH?

Problem 2:

How do the first massive black holes grow

1. BH Seed:

- Pop III stellar Remnant
- Gas/stellar Dynamical collapse

THEORY

$M_{BH,seed}$=100-$10^5$$M_{sun}$

High gas density

How do MBH seeds grow at early time?

z=6-7 quasars imply
$M_{BH}=10^9\ M_{sun}$ =
= mass of most massive black holes today

First billion years requires extremely large accretion rates

$$L_{Edd} = \frac{4\pi G c m_p}{\sigma_T} M_{BH} = \varepsilon \dot{M} c^2$$

$$M_{BH} = M_{seed}\ e^{\frac{t}{t_{Edd}}}$$

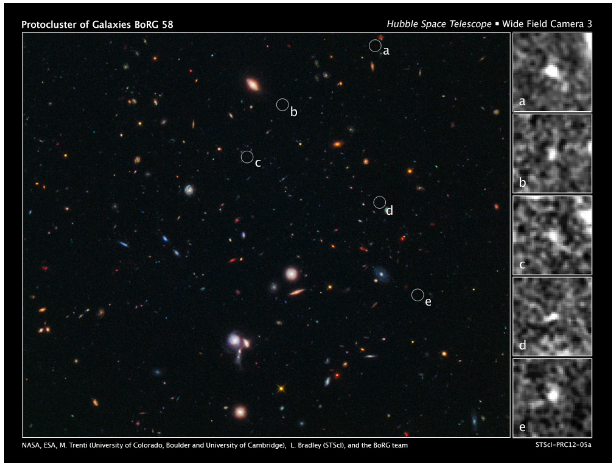
$$t_{Edd} = 450\ Myr \frac{\varepsilon}{1-\varepsilon}; \varepsilon = 0.1$$

$$\ln(M_{BH}/M_{seed}) = \ln[10^9/(100-1e5)]$$
$$= 10-17\ \mathrm{e-foldings}$$

Is it feasible?

At z> 7:

Plenty of (‘smudgy’) galaxies in tiny volumes

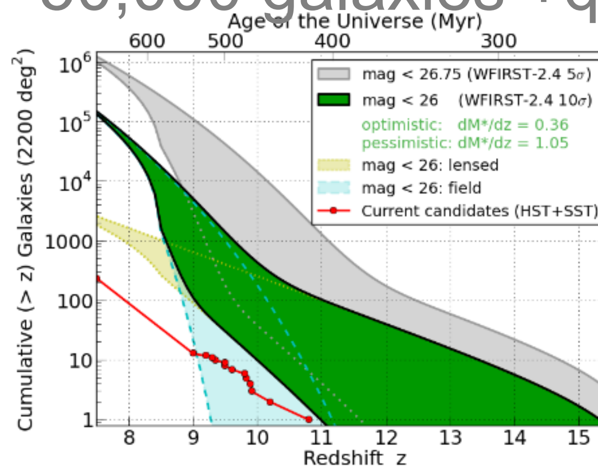


Hubble Legacy Fields

Room for discovery…

WFIRST

> 50,000 galaxies +quasars



1 supermassive quasar

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JWST spectra etc..

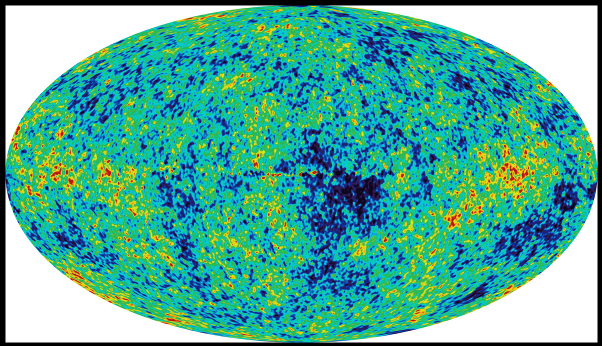
The first 600 million years (z=7+):

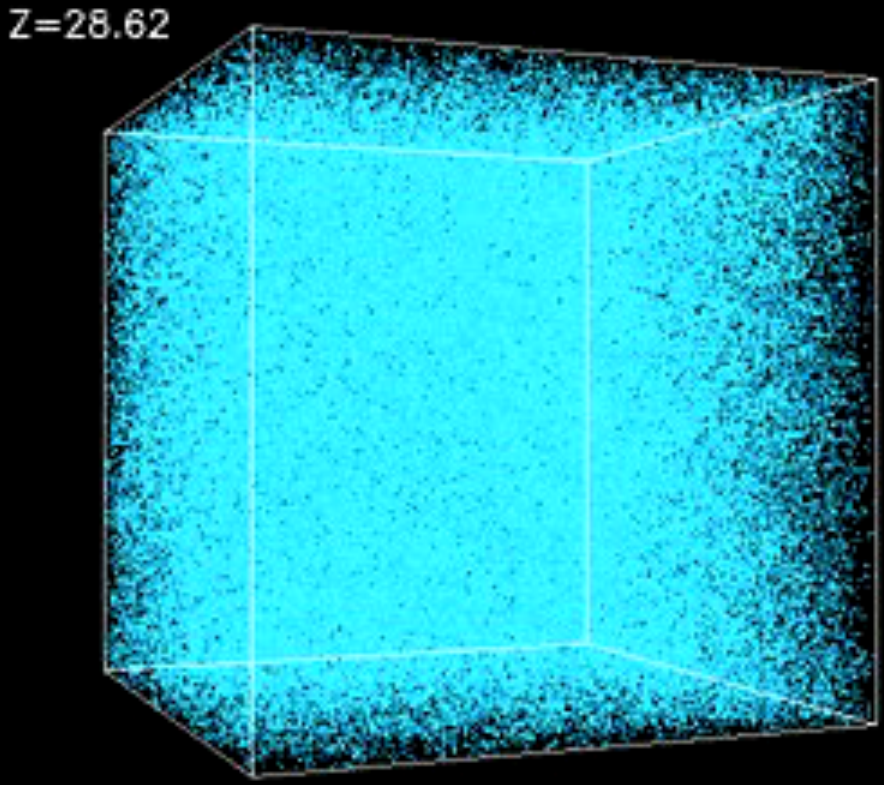
- What are galaxies like?
- How do the first massive black hole grow?

Predictions:

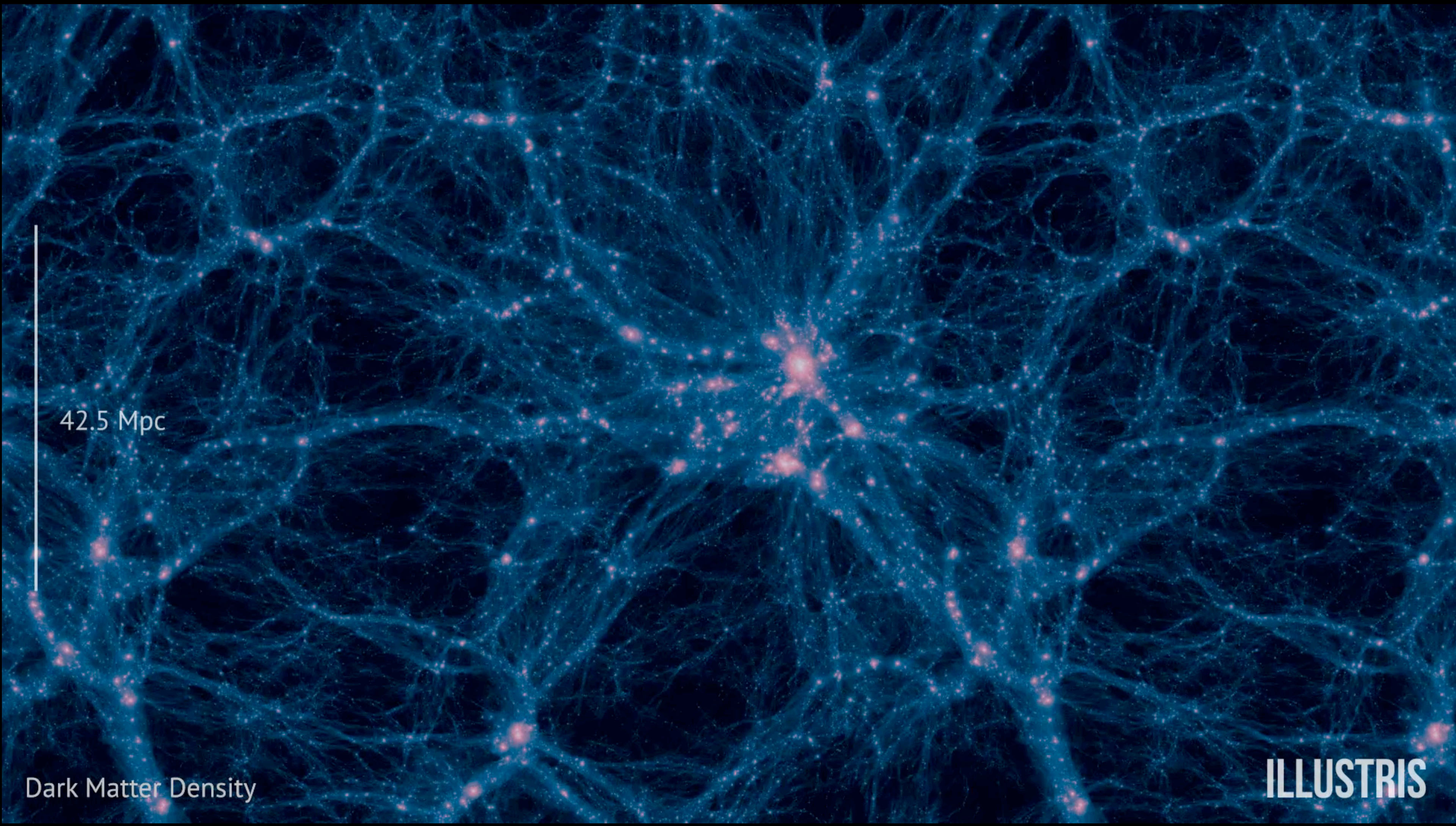
Simulations of structure formation in the Universe

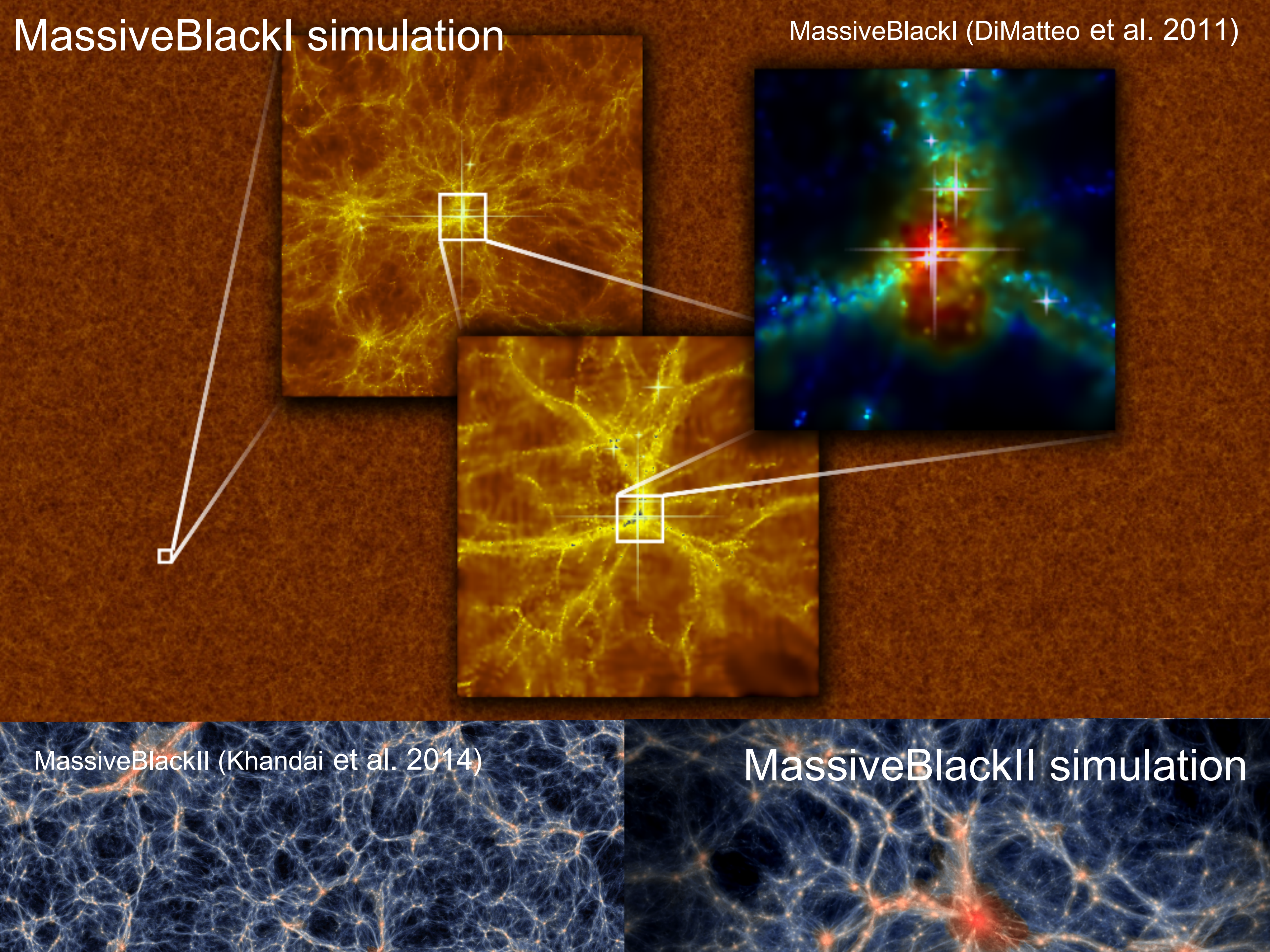
The ICs

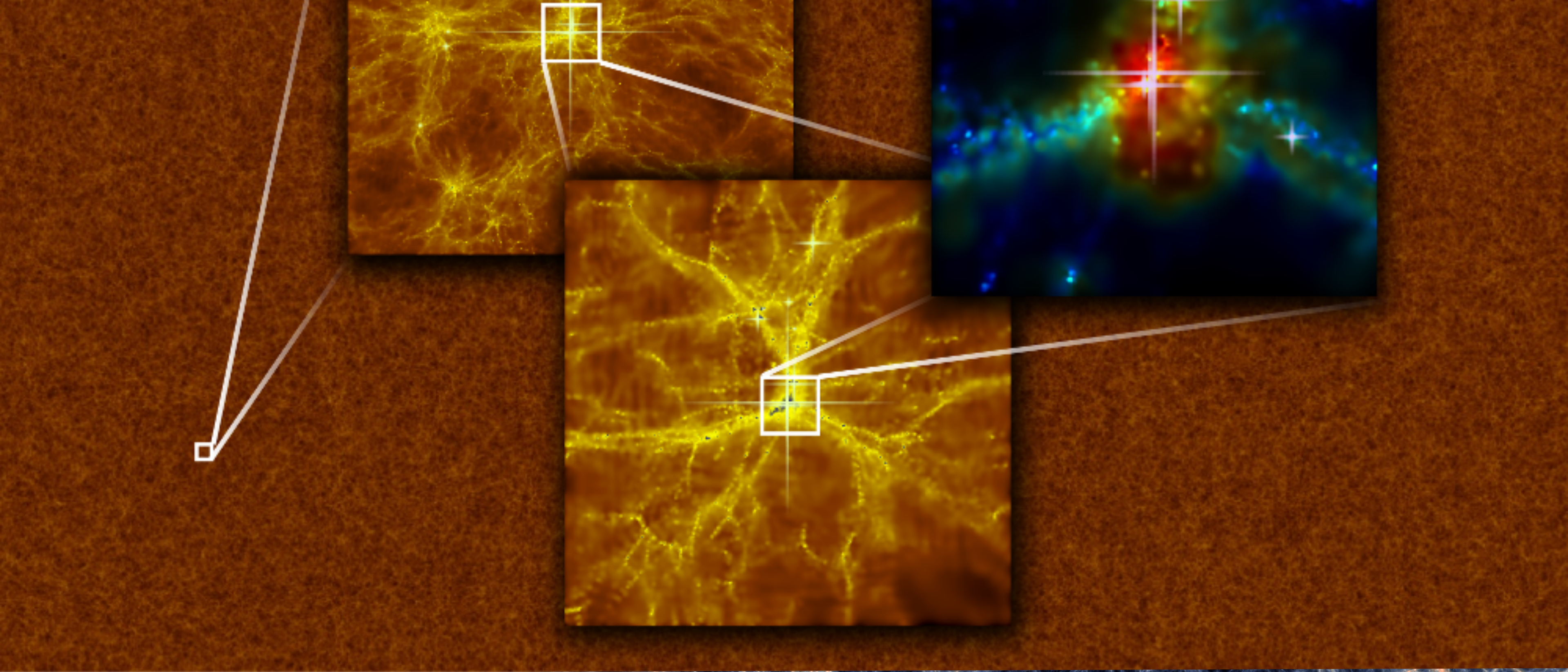


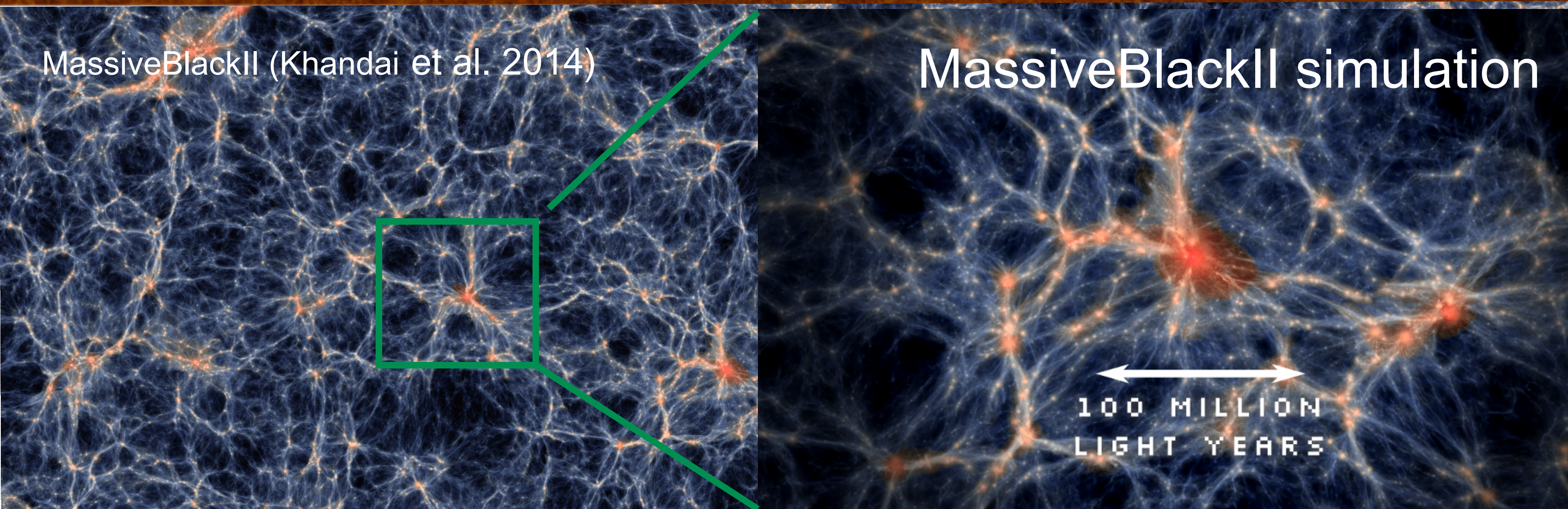


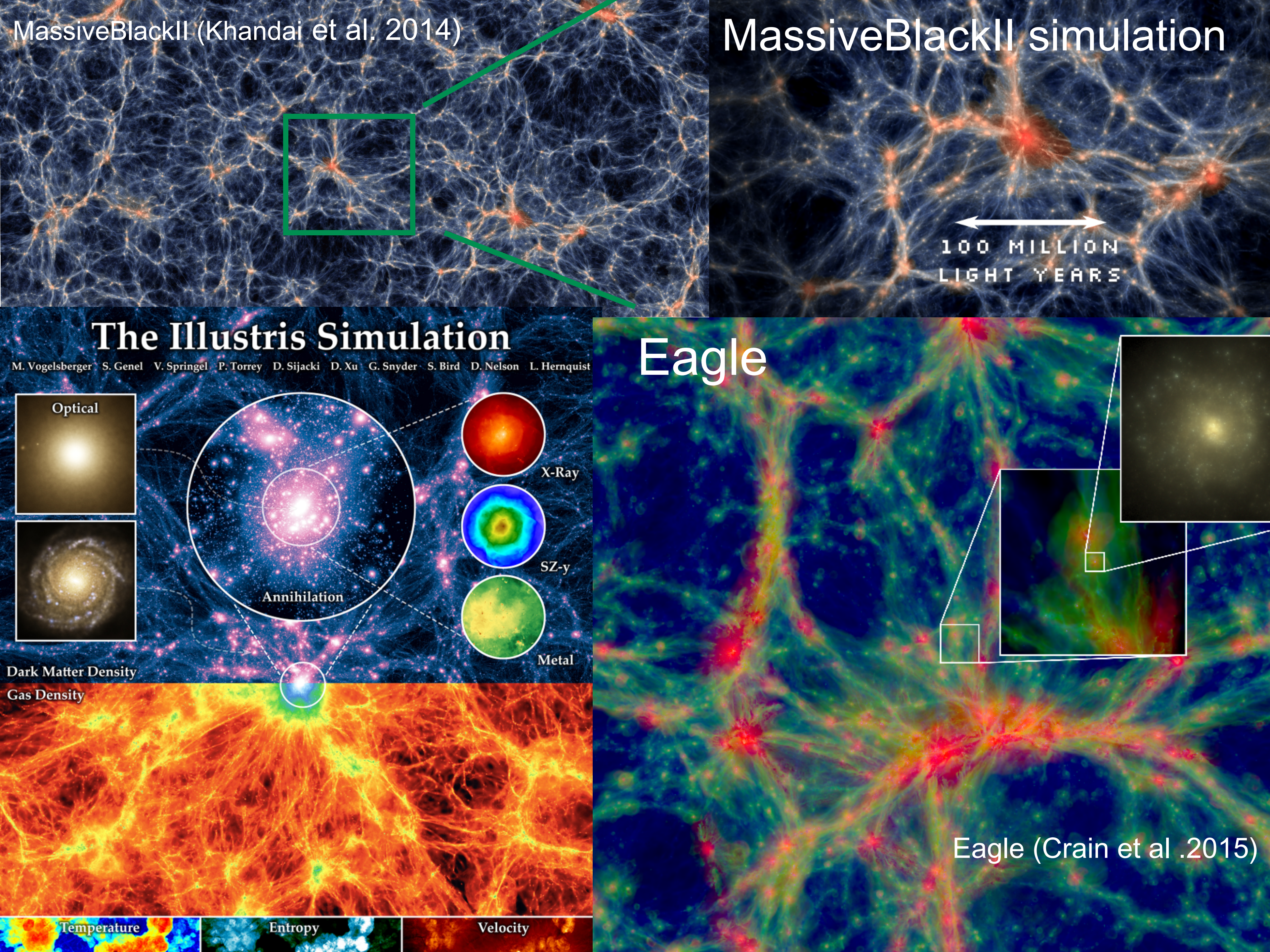
Gravitational instability


42.5 Mpc
Dark Matter Density
ILLUSTRIS

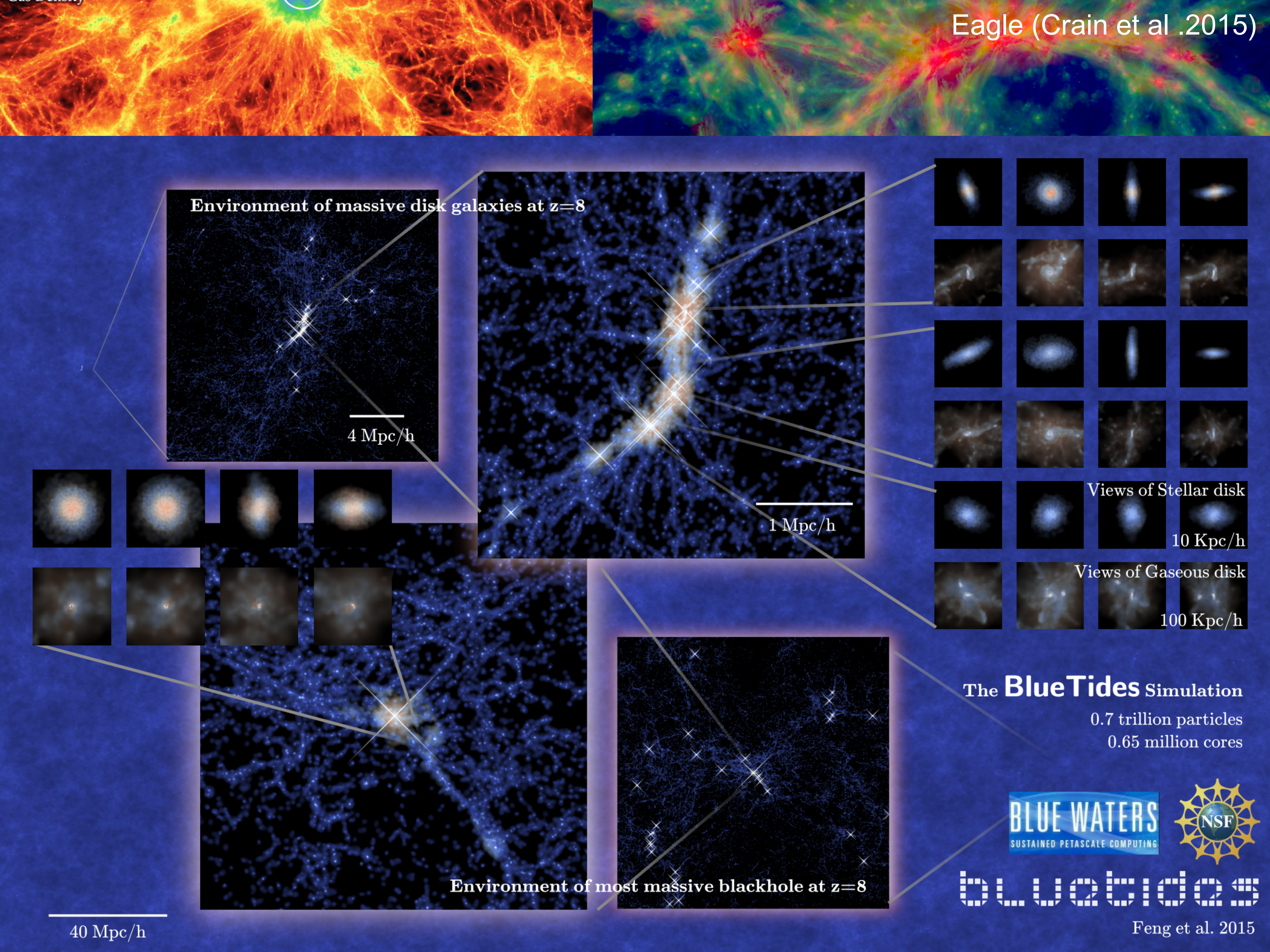

MassiveBlackI simulation
MassiveBlackI (DiMatteo et al. 2011)
MassiveBlackII (Khandai et al. 2014)
MassiveBlackII simulation




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
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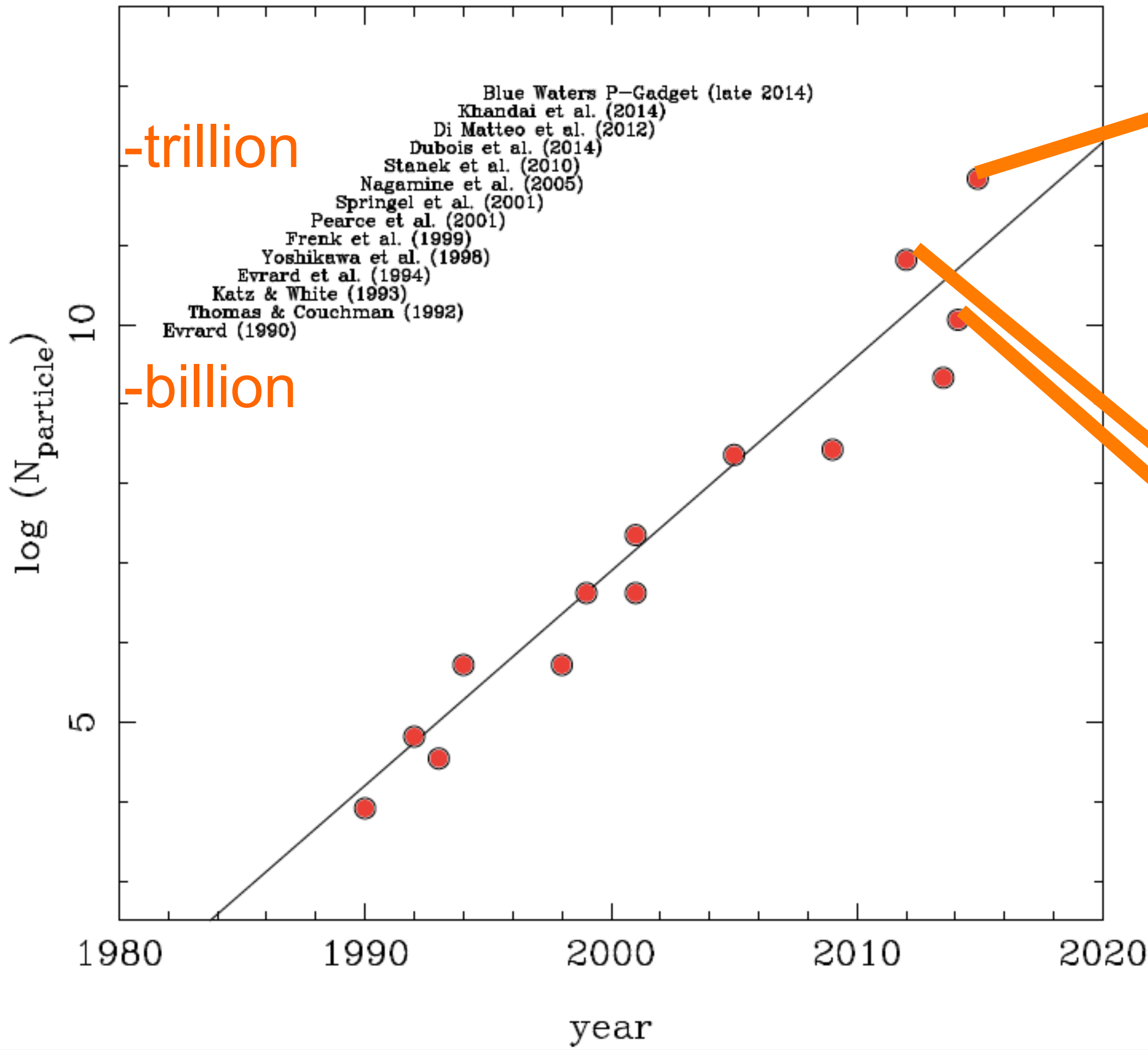
The BlueTides Simulation
0.7 trillion particles
0.65 million cores
BLUE WATERS
SUSTAINED PETASCALE COMPUTING
NSF
bluetides
Environment of most massive blackhole at z=8
40 Mpc/h
Feng et al. 2015

Algorithms keep up with computational power
Hydro simulations:

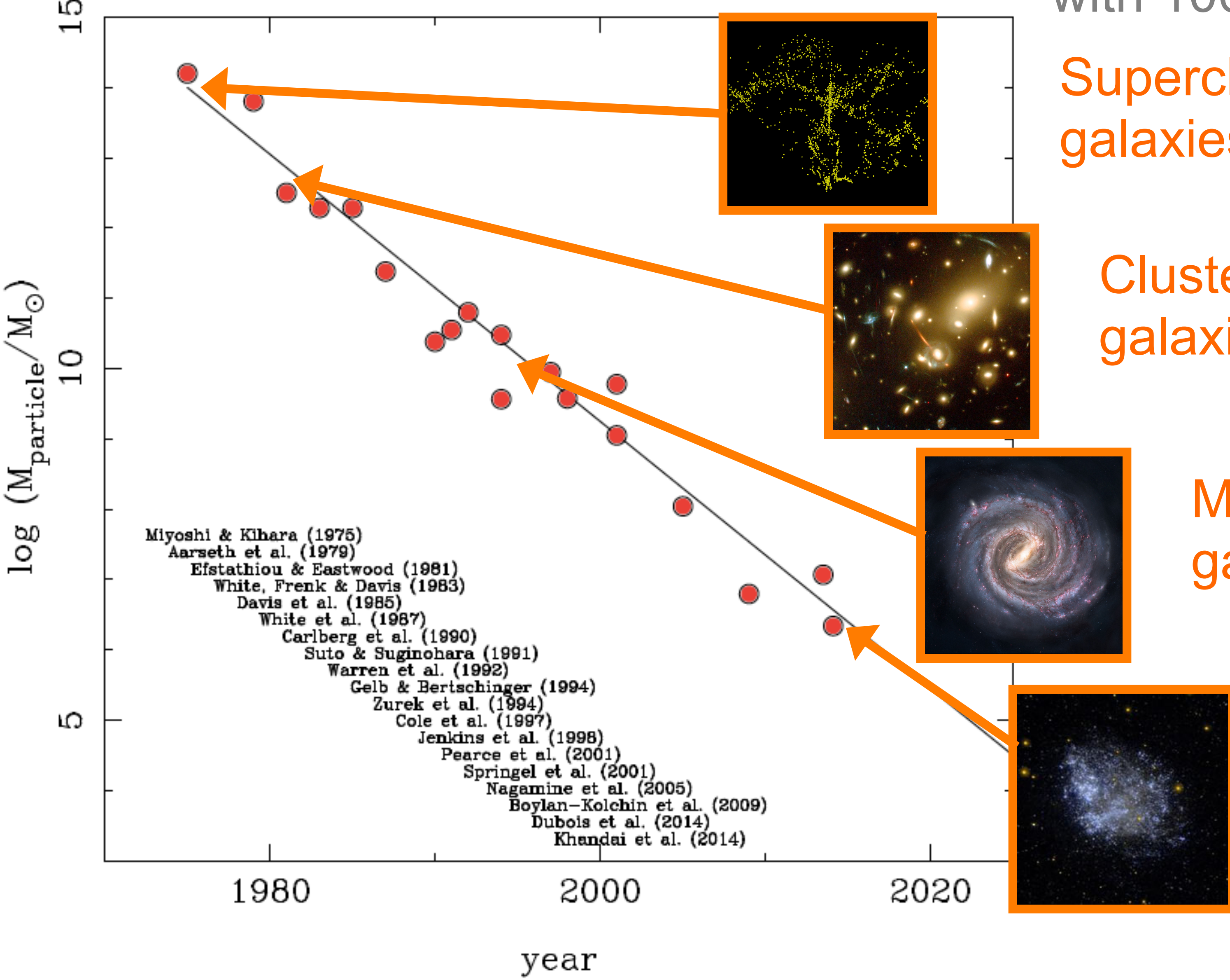


On 0.72m cores
NCSA Cray XE6
Blue Waters

On 112k cores
NICS Cray XT5
Kraken

We resolve galaxies across the full mass function

What we can resolve with 100 particles:



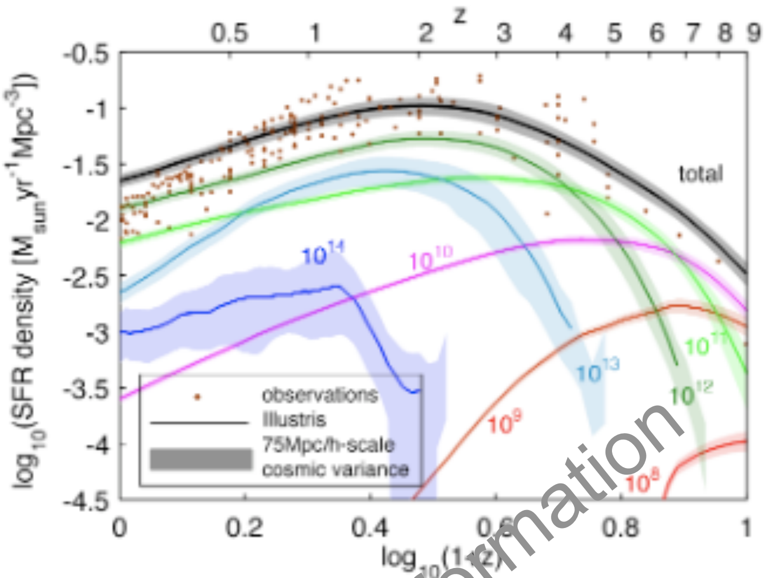
Superclusters of galaxies

Clusters of galaxies

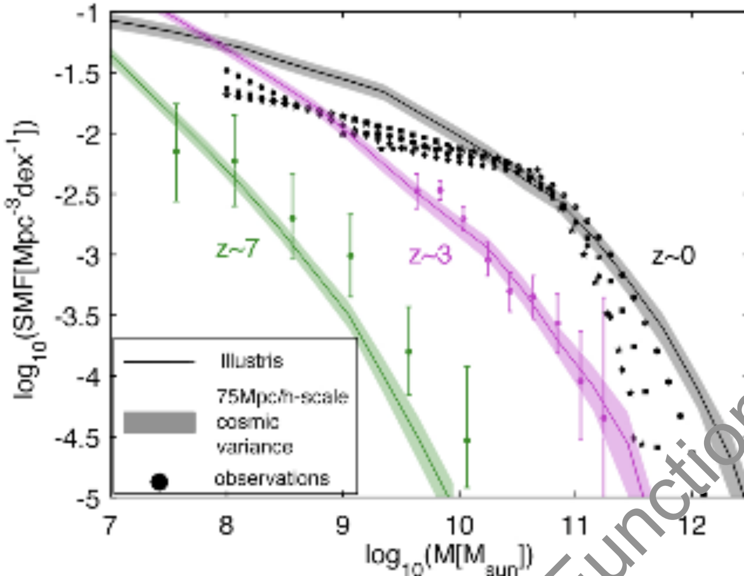
Milky way-sized galaxies

Dwarf galaxies

Simulations reproduce statistics of galaxy formation



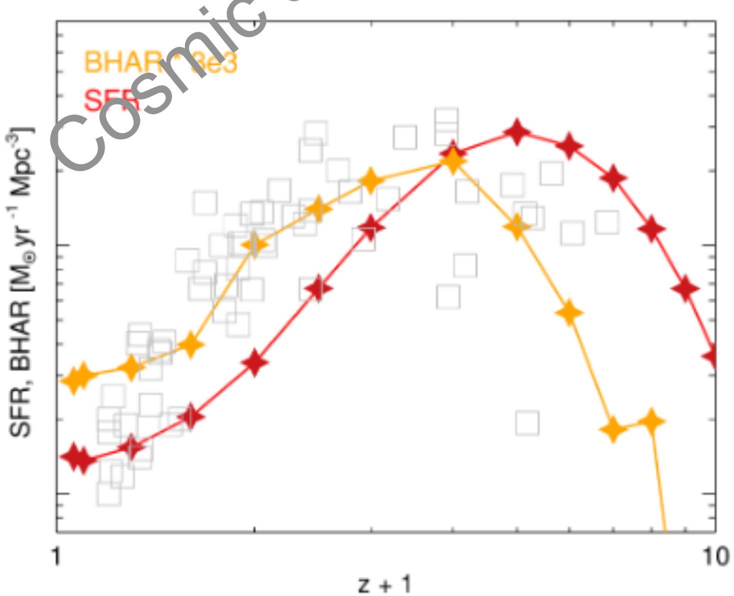
(c) Cosmic SFR density, 106.5 Mpc cosmic variance

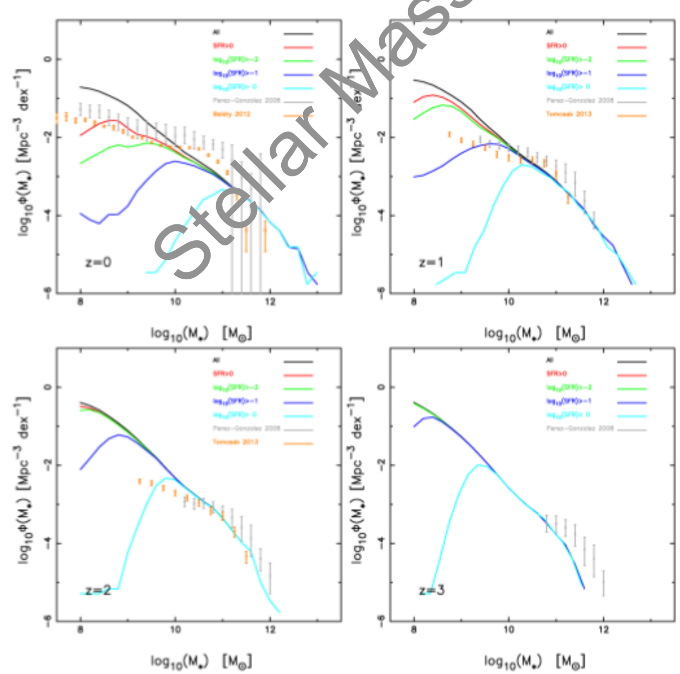


(d) Stellar mass functions, 106.5 Mpc cosmic variance

Cosmic star formation

Stellar Mass Functions





The first 600 million years (z=6+):

Can massive BH grow to billion solar mass?

Problem 2:

Example:

How do the first massive black holes grow

1. BH Seed:

Pop III stellar Remnant

Gas/stellar Dynamical collapse

t < 1 billion yrs

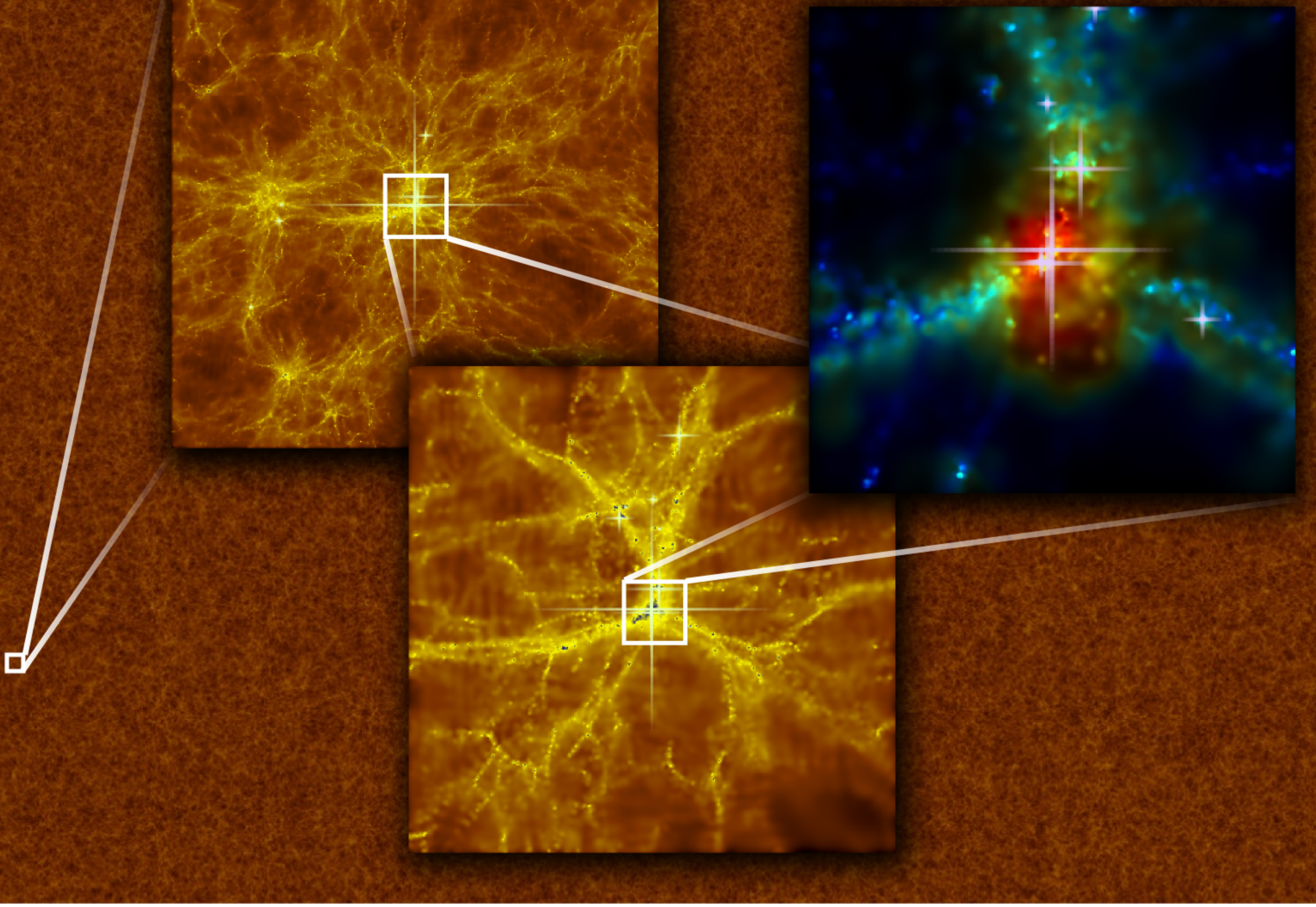
High gas density

2. Gas accretion: Eddington (sustained)

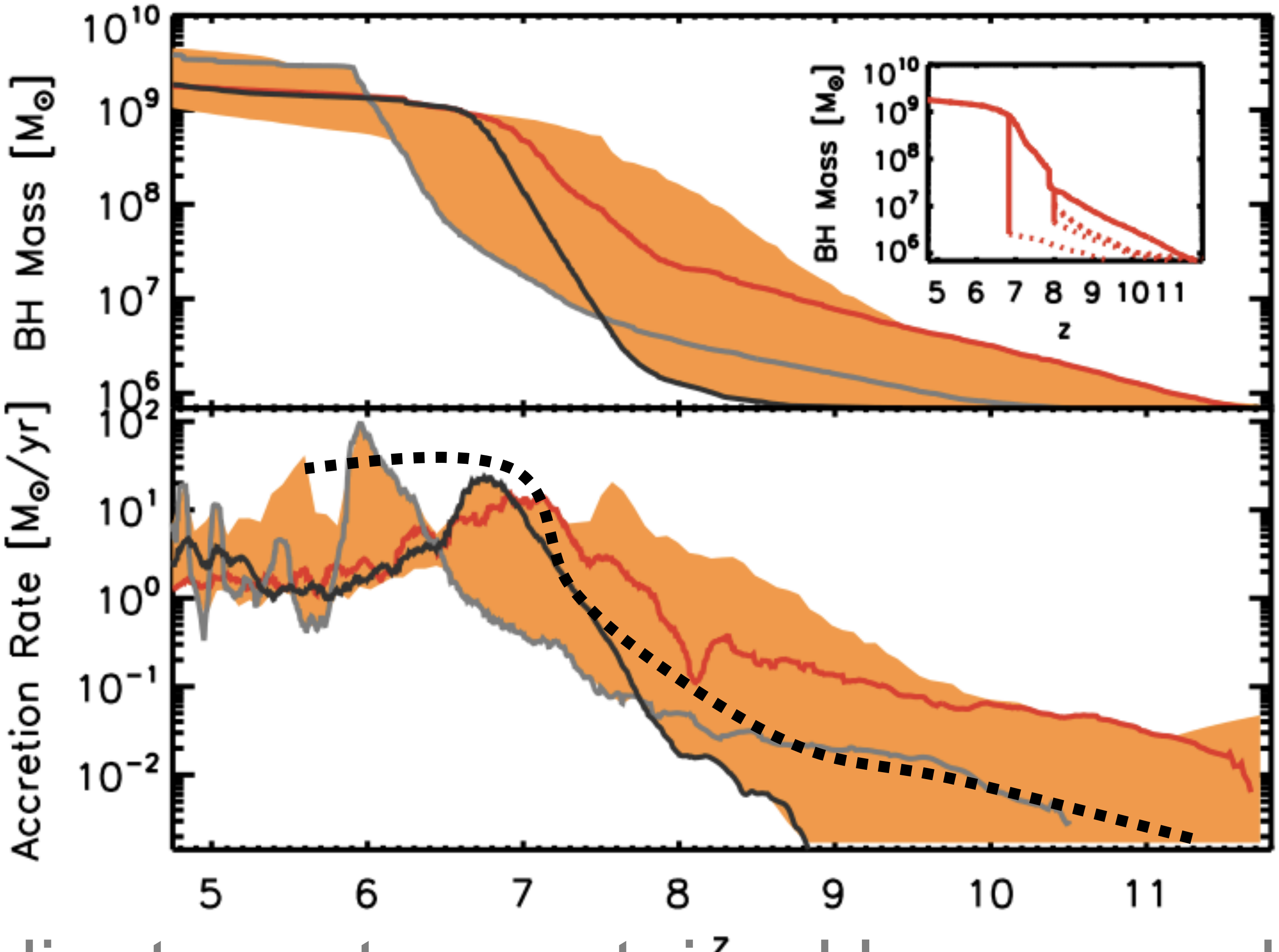
Highest gas inflow rates

Feasible? if so how, where?

Massive Black Simulation, Uniform ~ 1 Gpc^3 Vo



Black holes grow to 10^9Msun by z=7-6

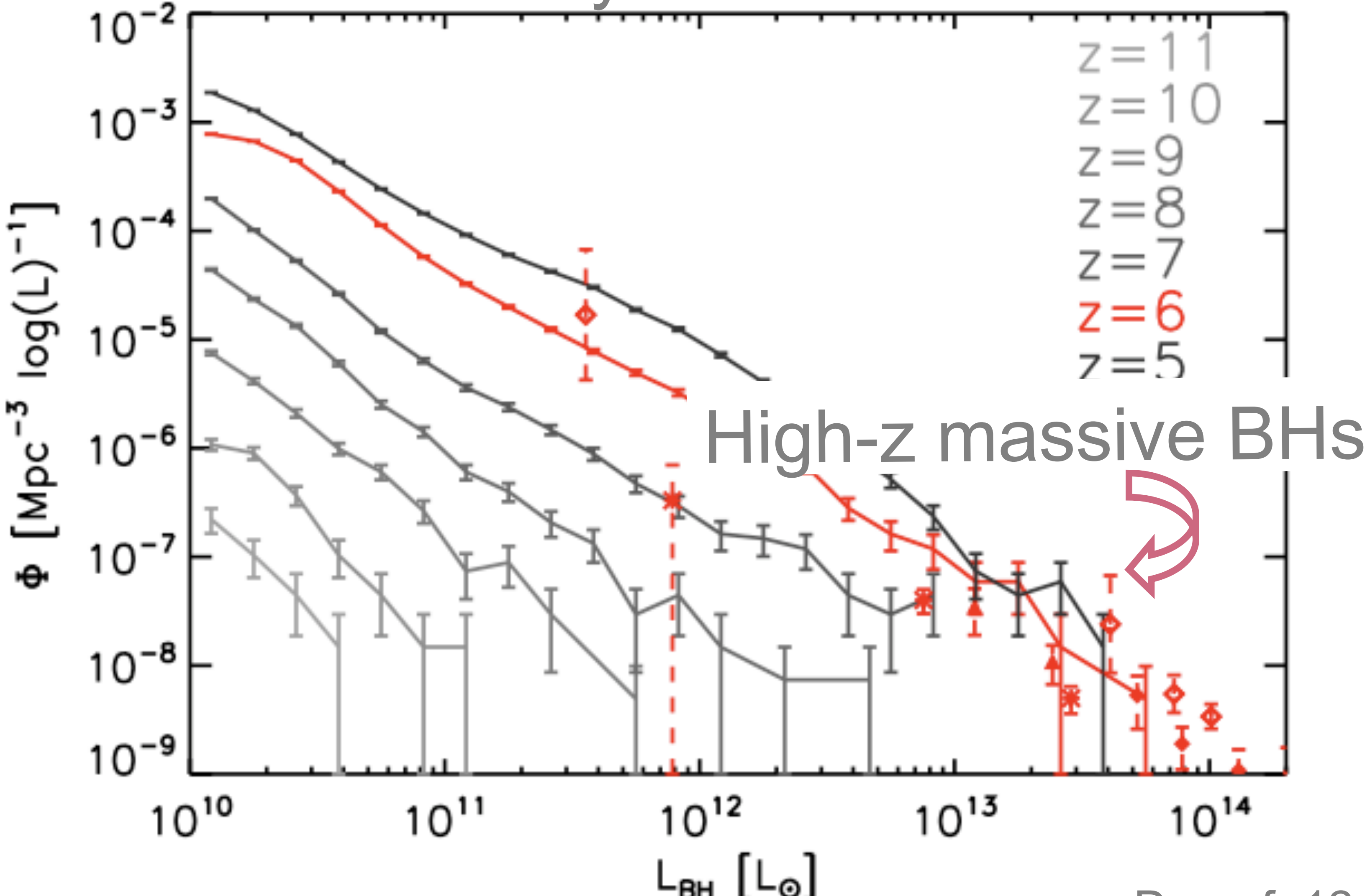


DM et al . 2012

Eddington rates sustained long enough before AGN feedback able to act

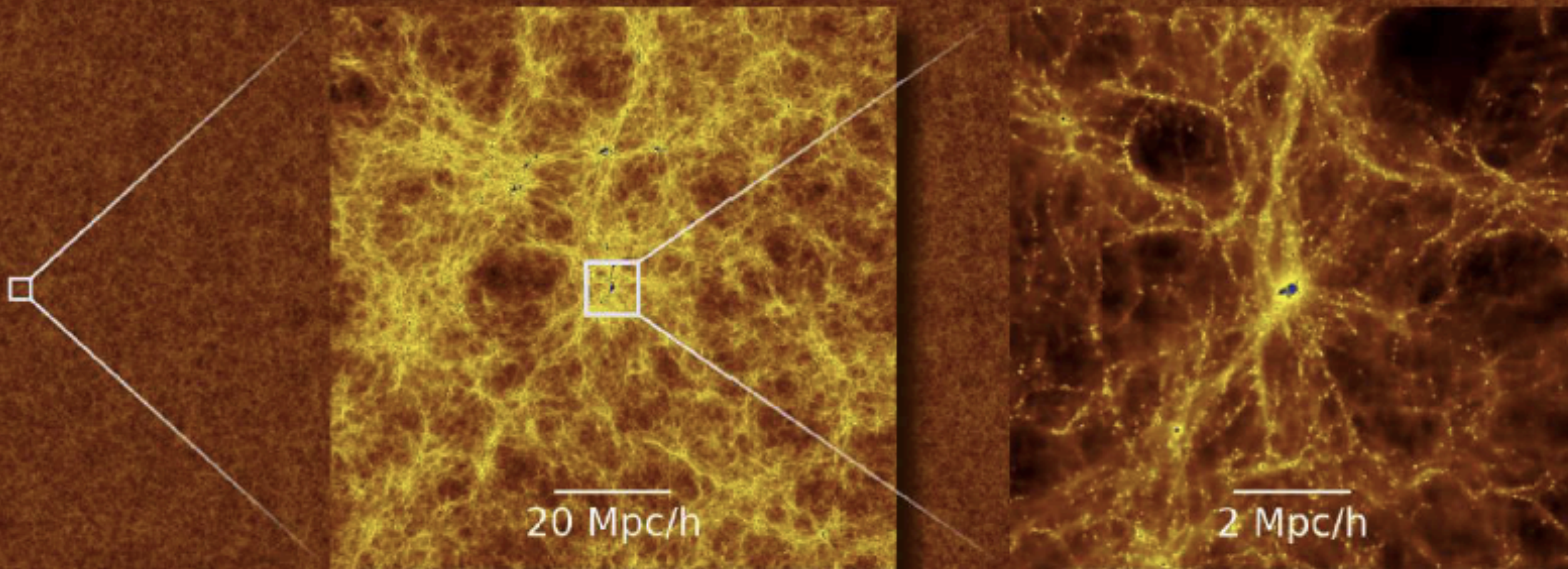
MB cosmological simulation predicts the right number of Sloan Quasars

High-z Quasar LuminosityFunction

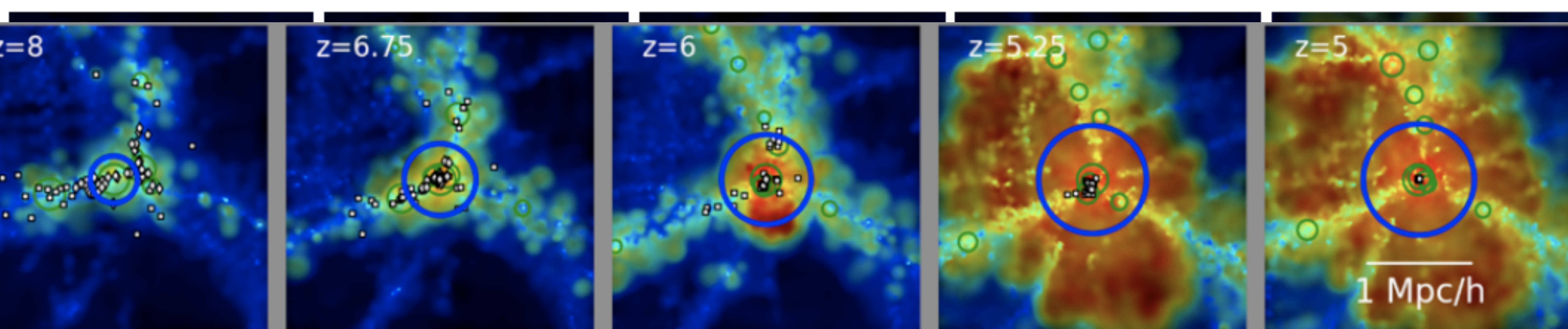


Degraf+12

Simulations show that in high density regions

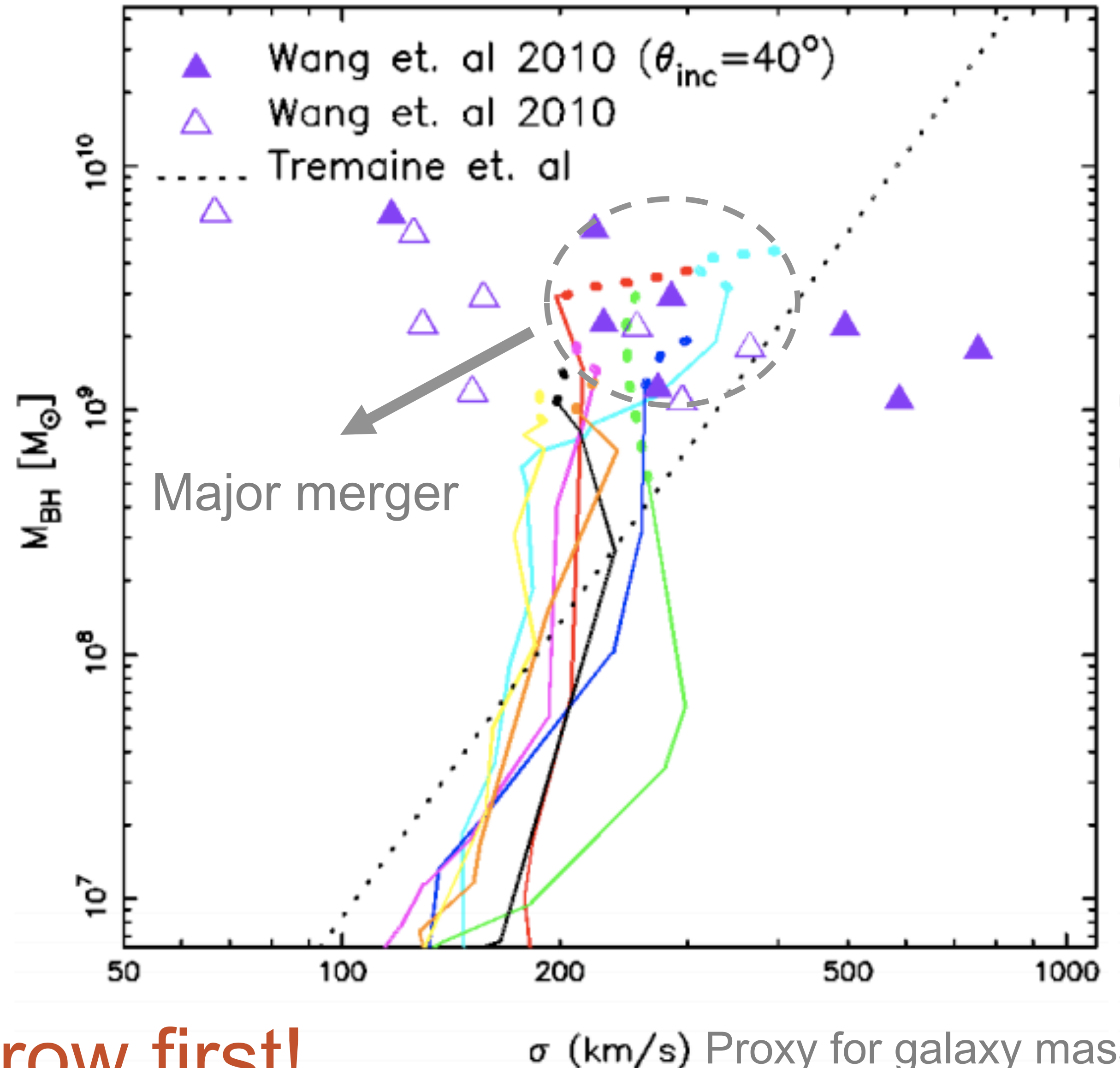


"Cold gas flows" stream to the heart of galaxies and grow black holes



Z=6 Quasar Hosts: The M_{BH}-sigma relation

Khandai et al. 2012



Proxy for galaxy mass

Black Holes grow first!

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

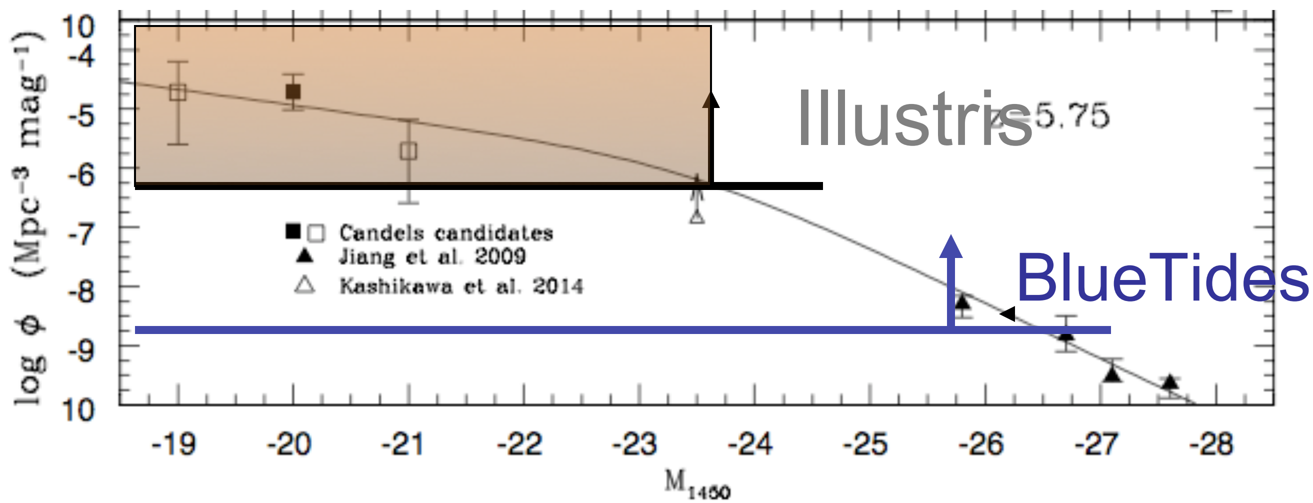
MassiveBlack II (Khandai et al 2014) 100 Mpc/h & 1.8 Kpc/h

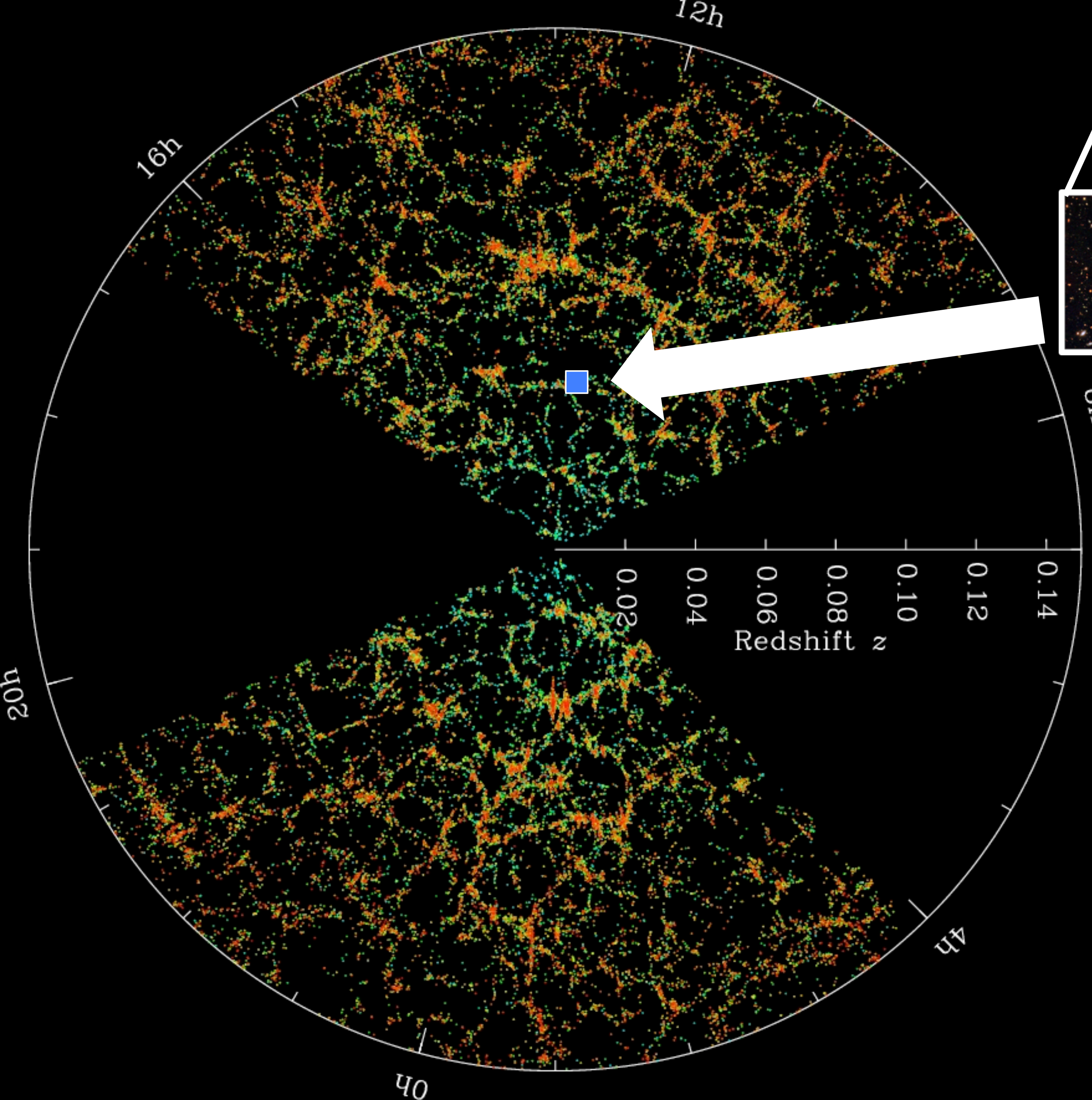
Illustris (Vogelsberger et al 2014) : 72.5 Mpc/h & 1 Kpc/h

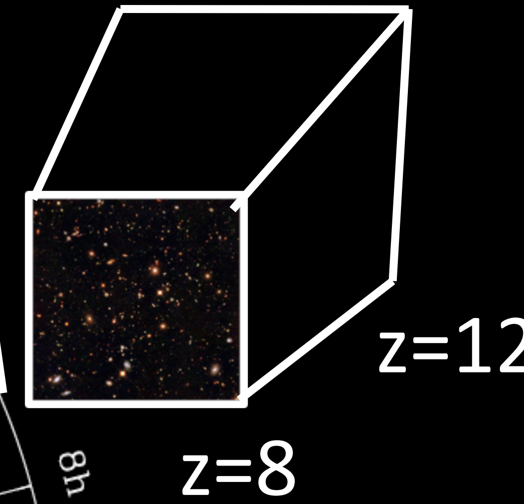
Eagles (Crain et al 2015) : 100 Mpc/h 2.6 Kpc/h

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

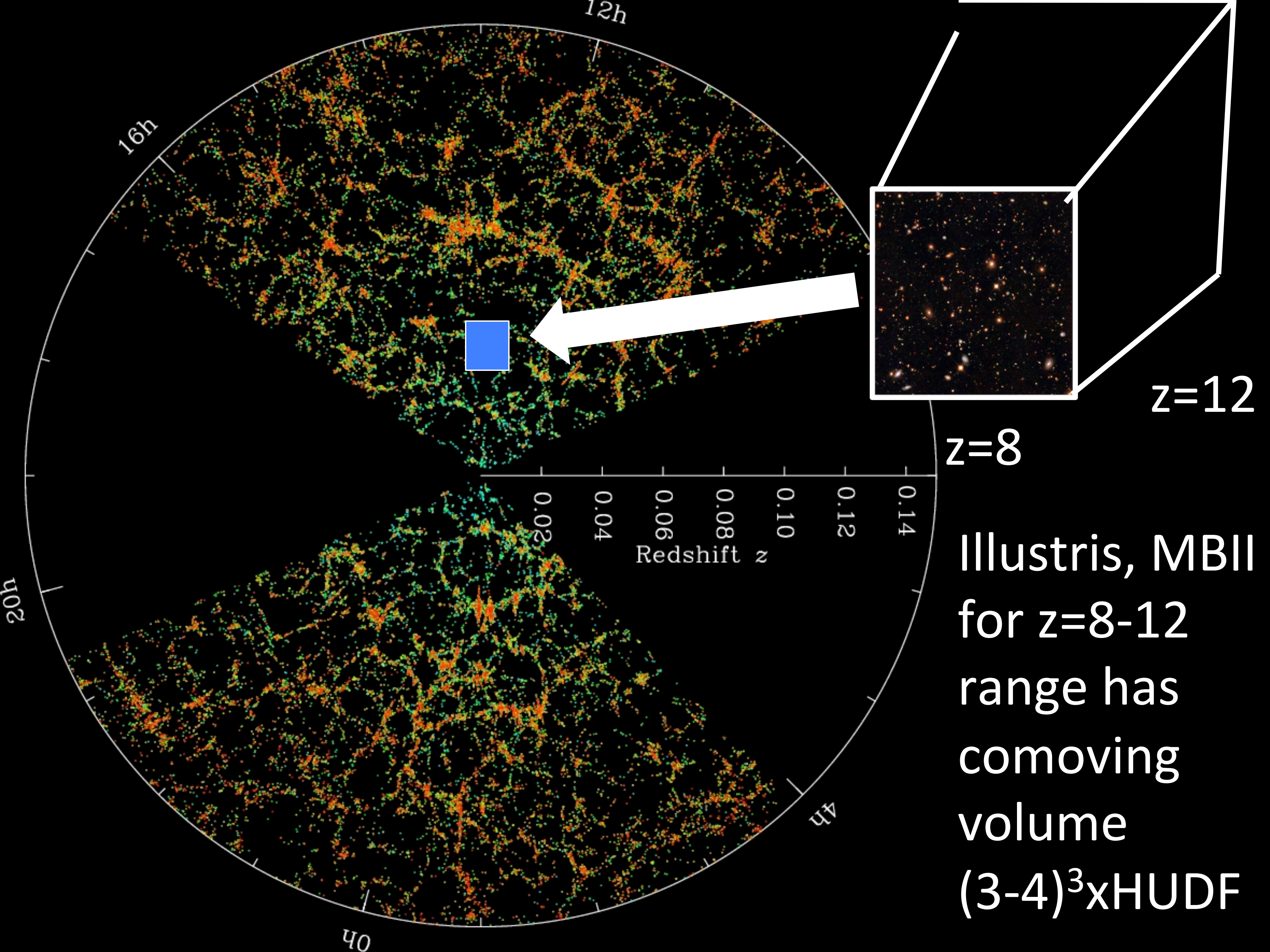
e.g: High-z QSO lum. Function (Giallongo 15)



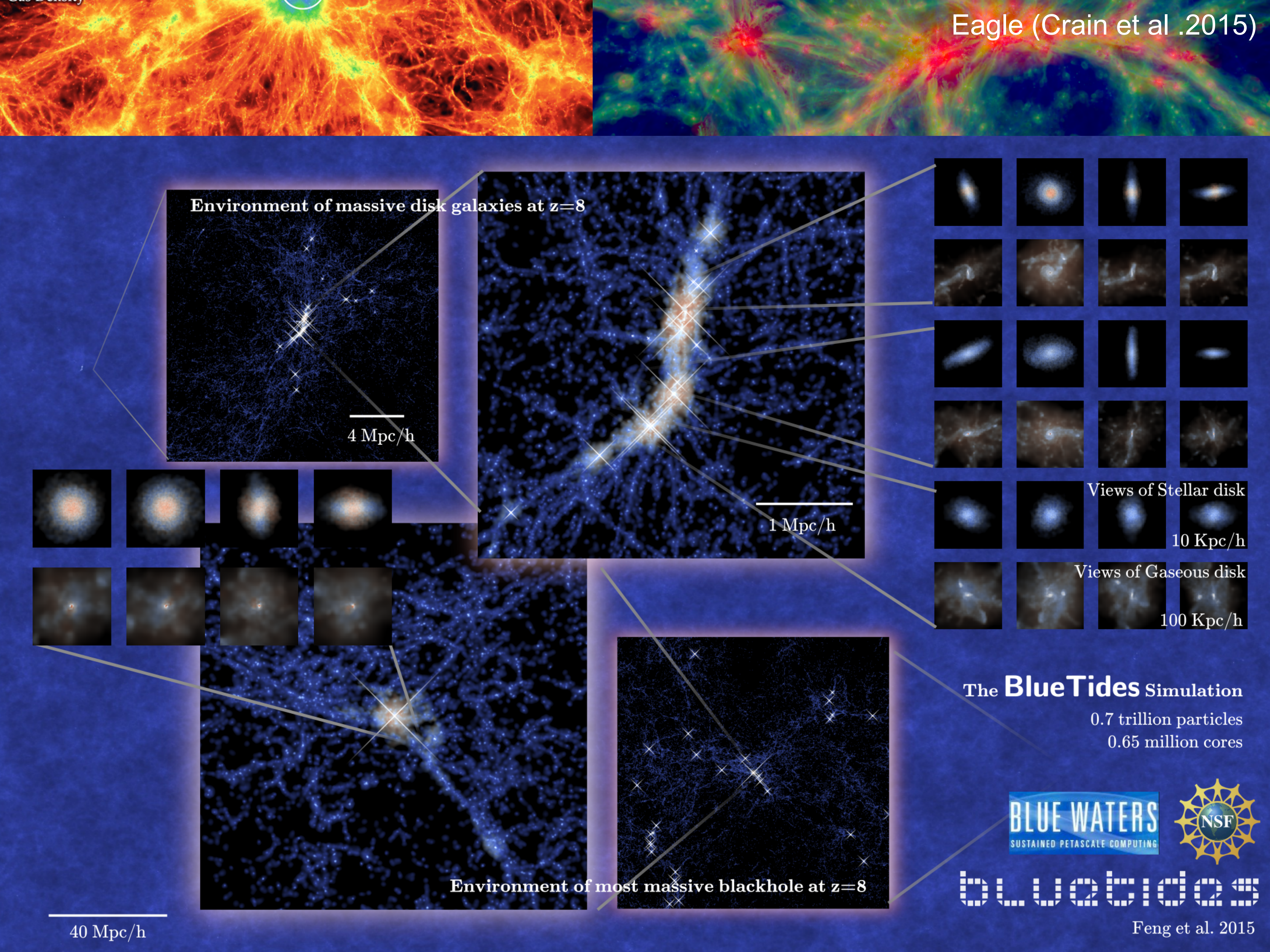




HUDF
for z=8-12
range has
comoving
volume
$(23\ \mathrm{Mpc}/h)^3$



Illustris, MBII for z=8-12 range has comoving volume $(3\text{-}4)^3$xHUDF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0.65 million cores
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NSF
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Environment of most massive blackhole at z=8
40 Mpc/h
Feng et al. 2015

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

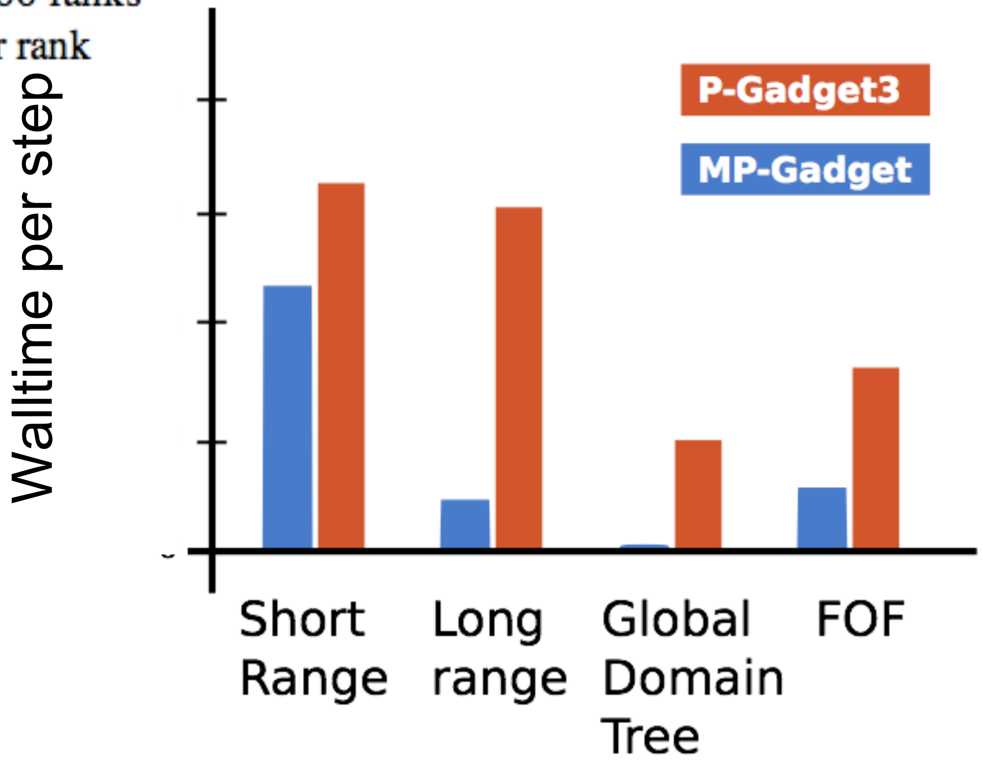
50 times bigger volume with highest resolution

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:

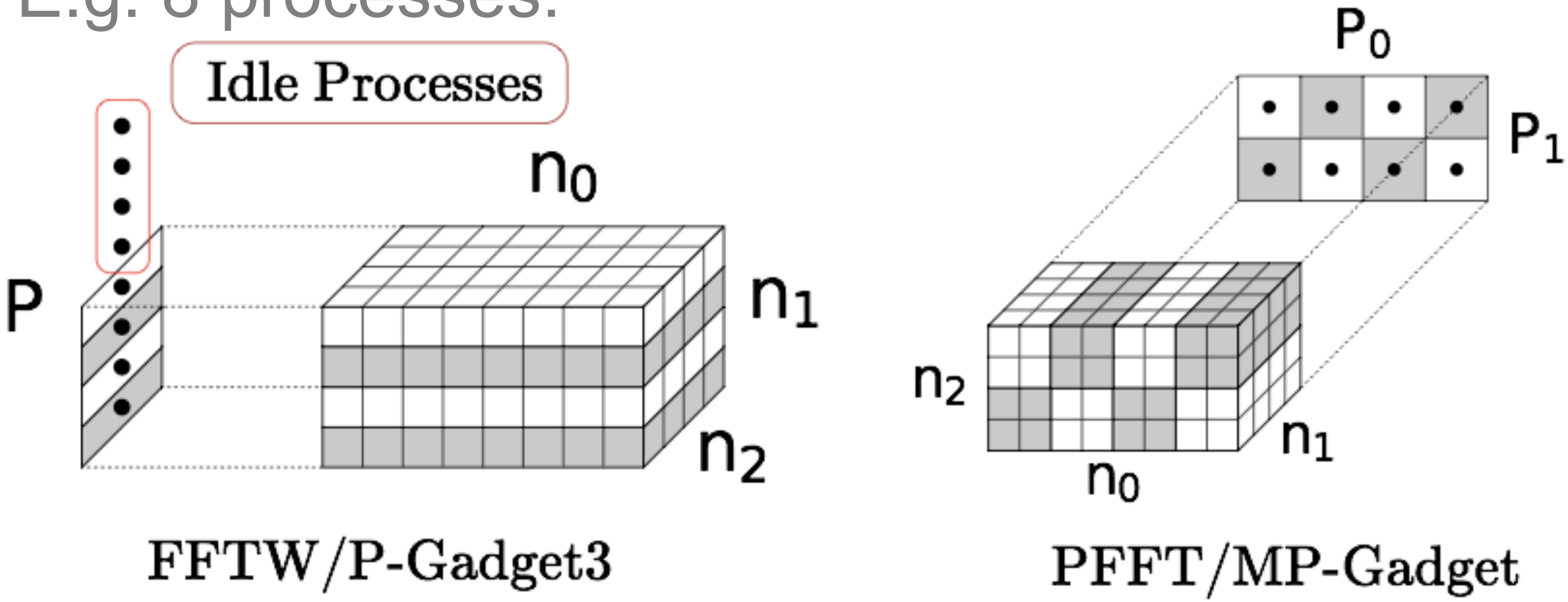


Figure from M.Pippig 2013

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
- ....

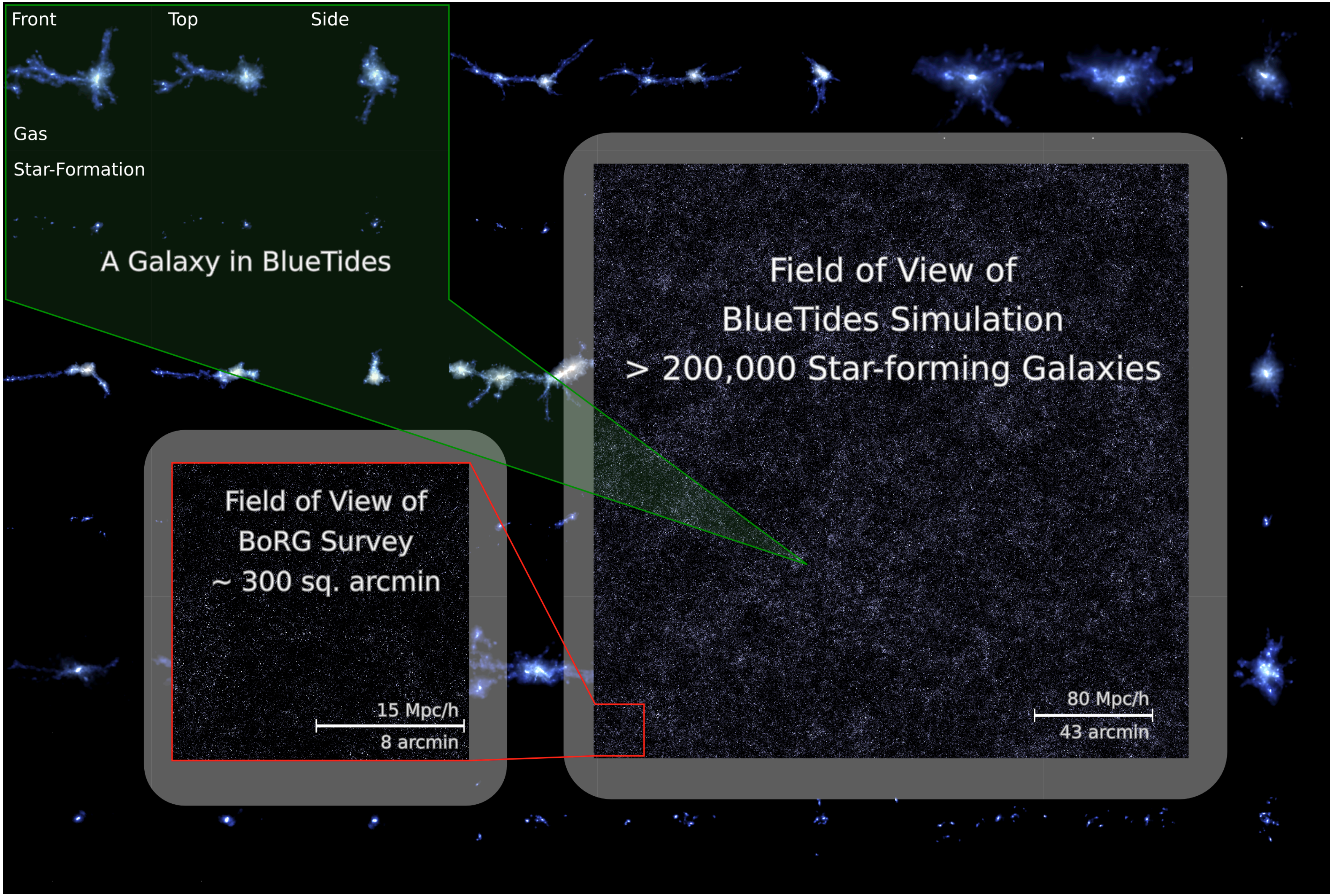
The first 500 million years (z=7+):

What are galaxies like?

Problem 1:

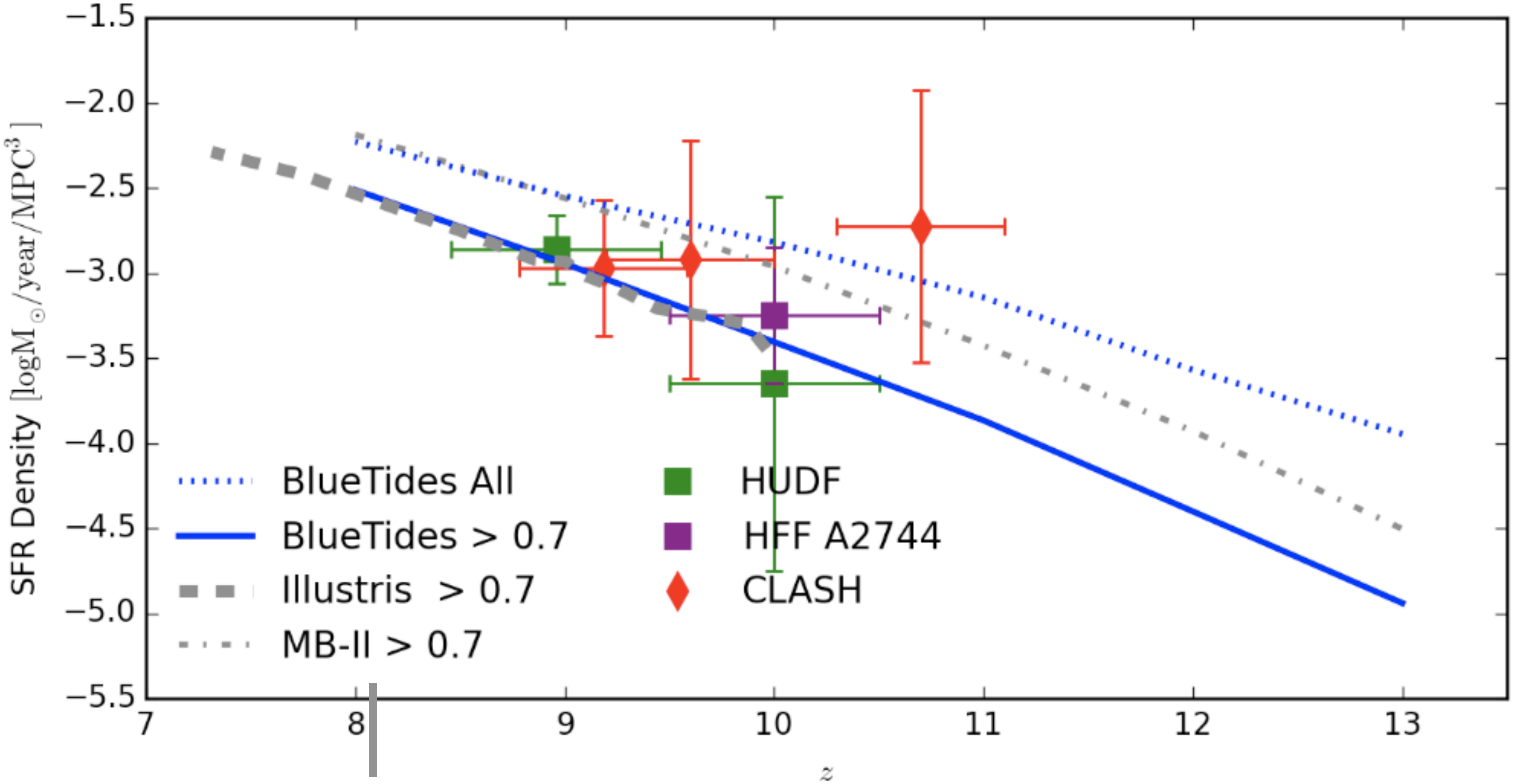
Predictions from BlueTides:

BlueTides 400 x volume of HUDF



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

Star formation rate density



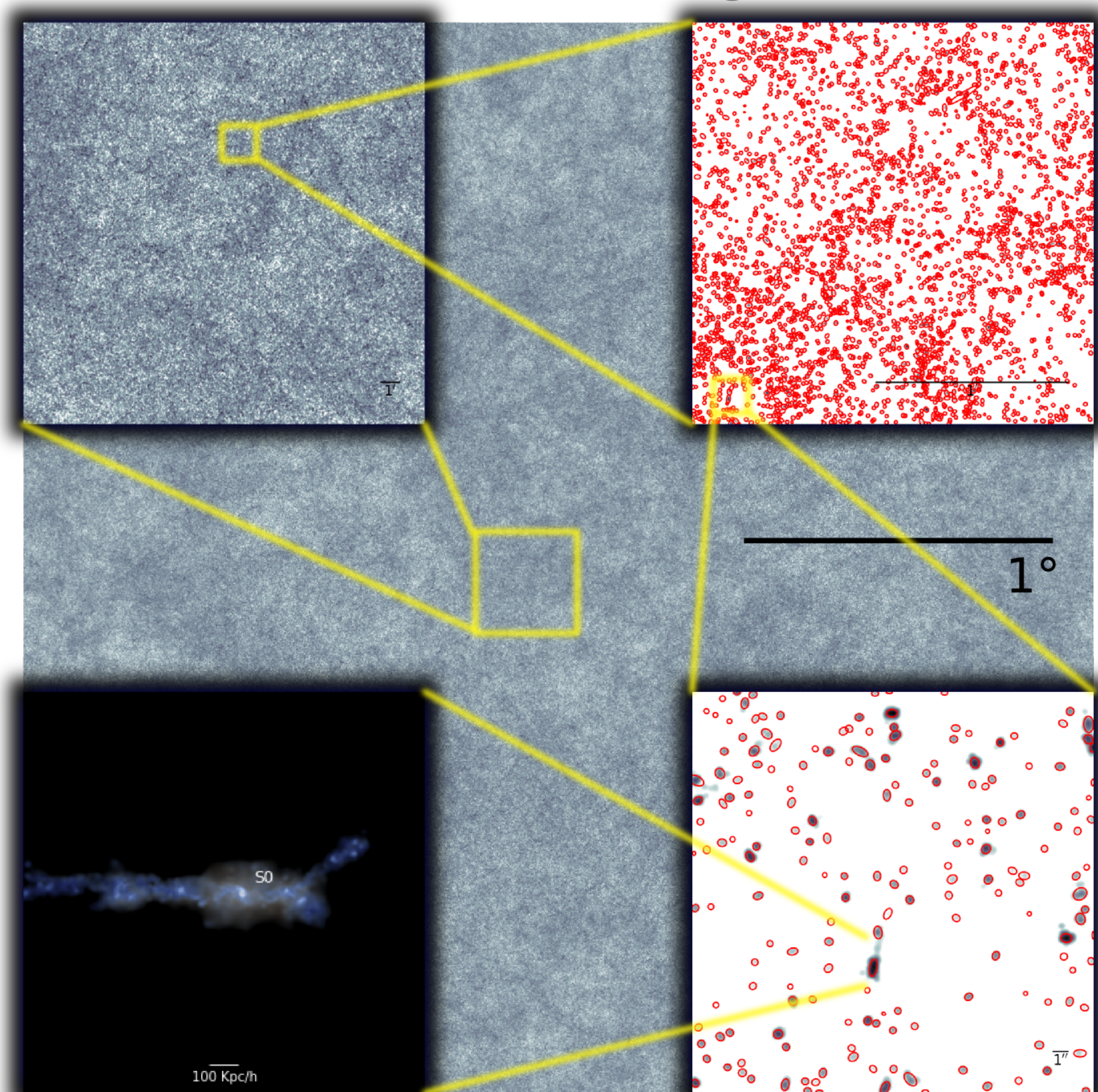
Age: 600 Myrs

redshift

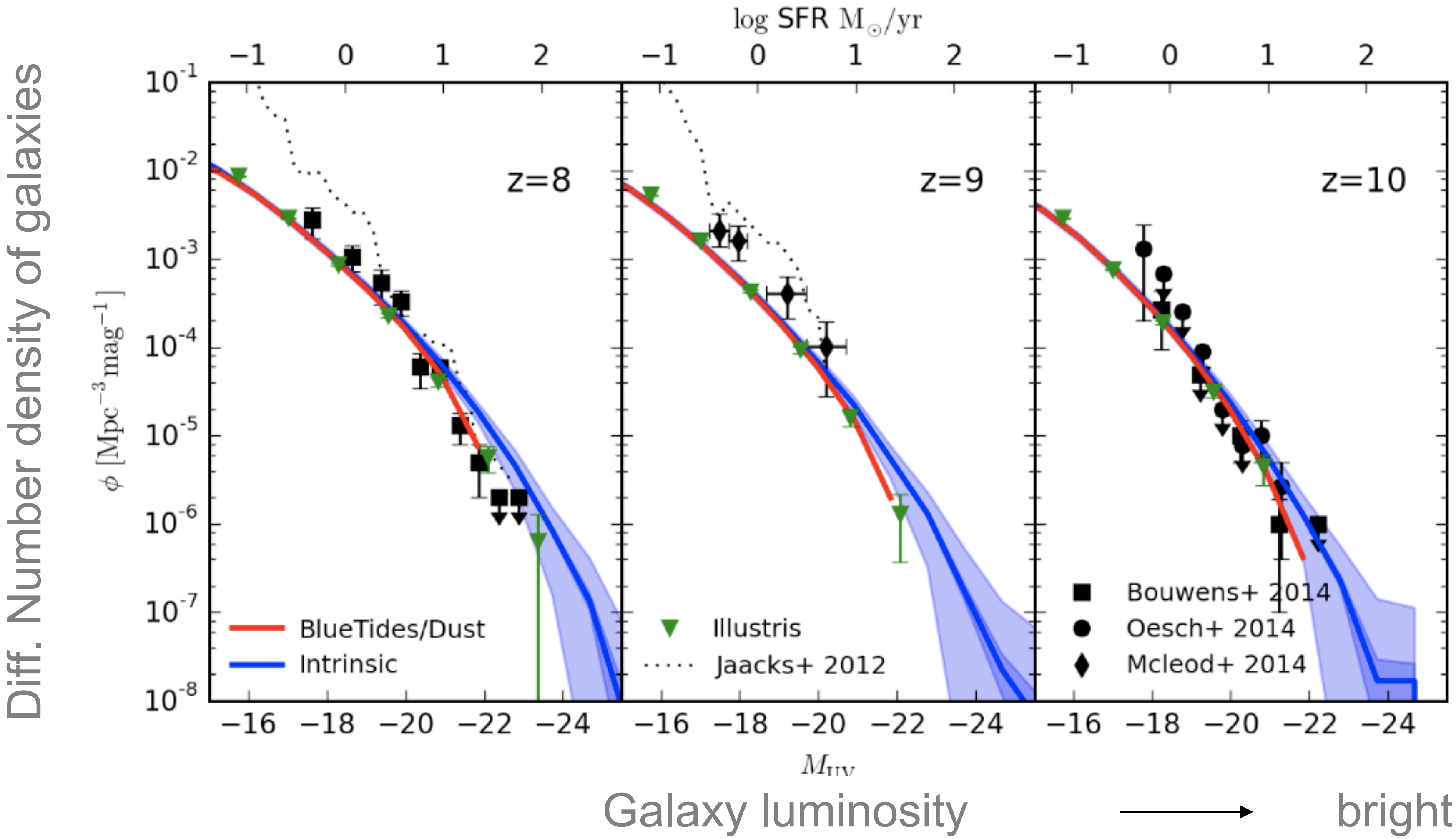
Early universe

Feng et al., 2015a

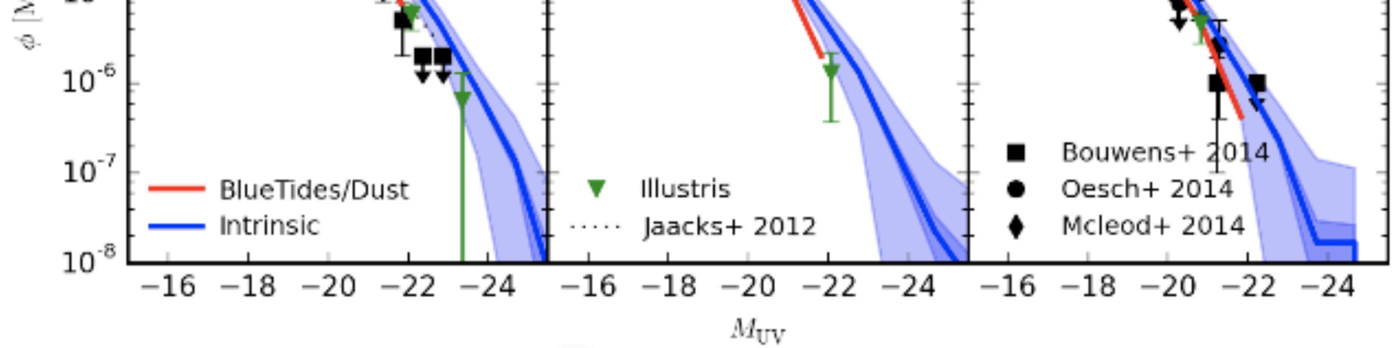
Simulations like Observations: Create Mock Fields. Source extract detection to find galaxies



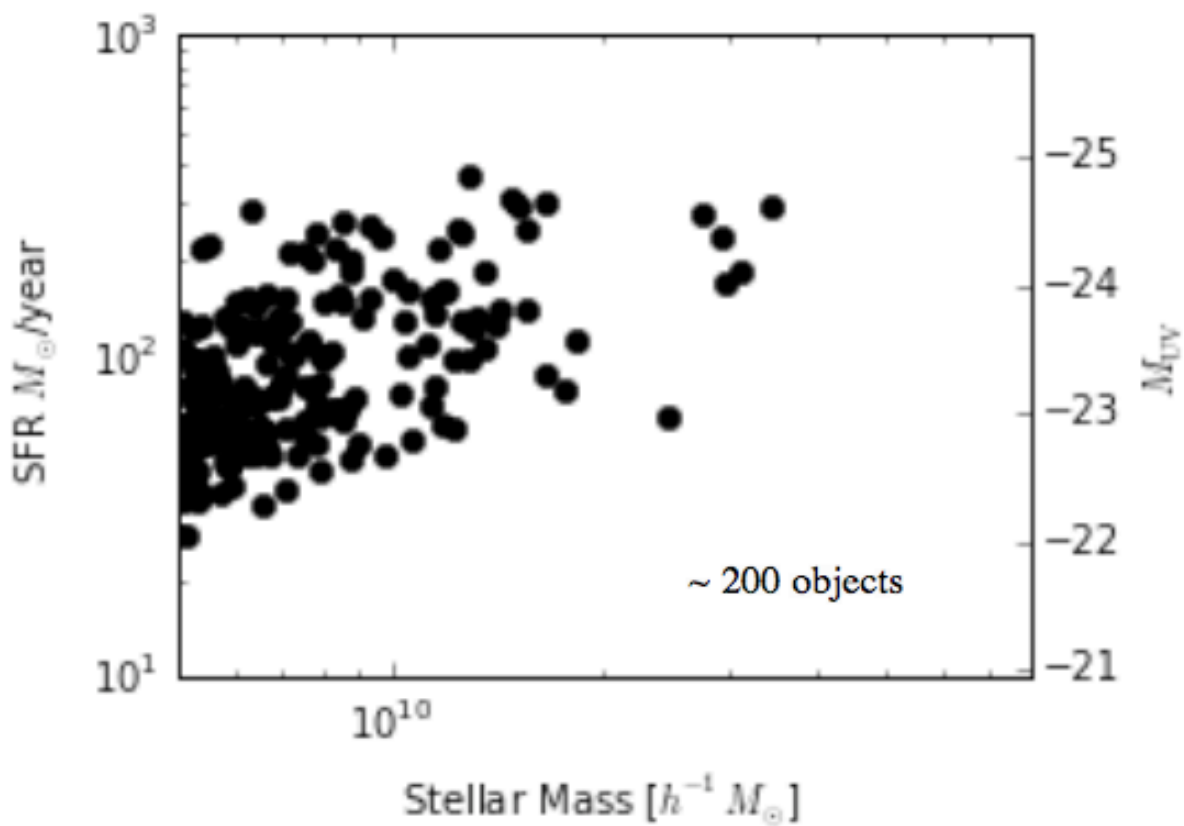
Galaxy Luminosity Function in BlueTides consistent with Hubble Legacy Fields



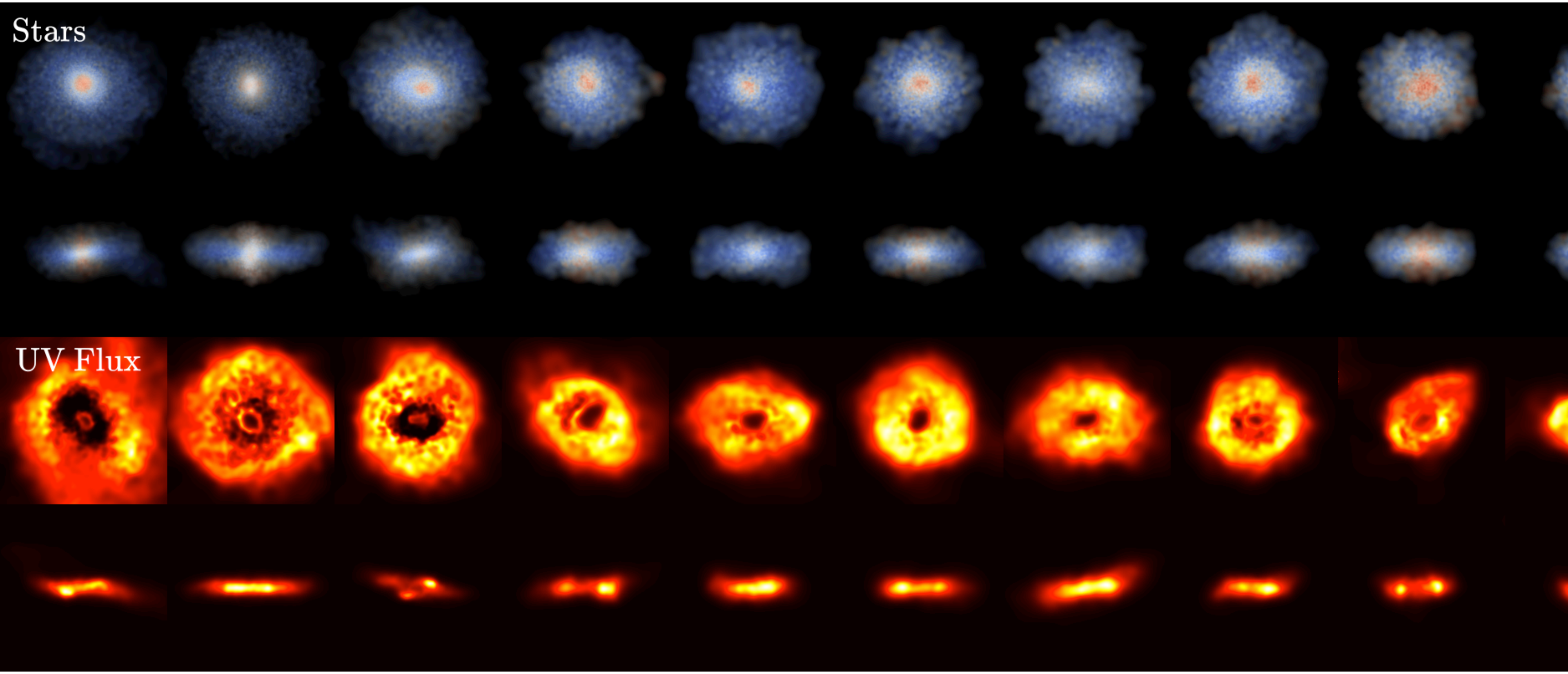
Feng et al., 2015a



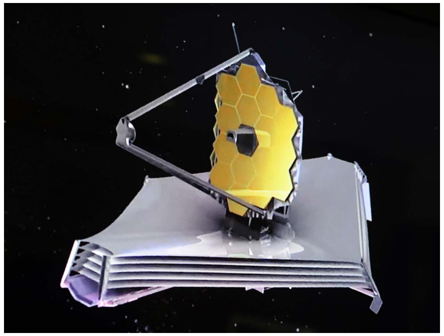
Predictions
for the brightest
Galaxies at z=8:



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

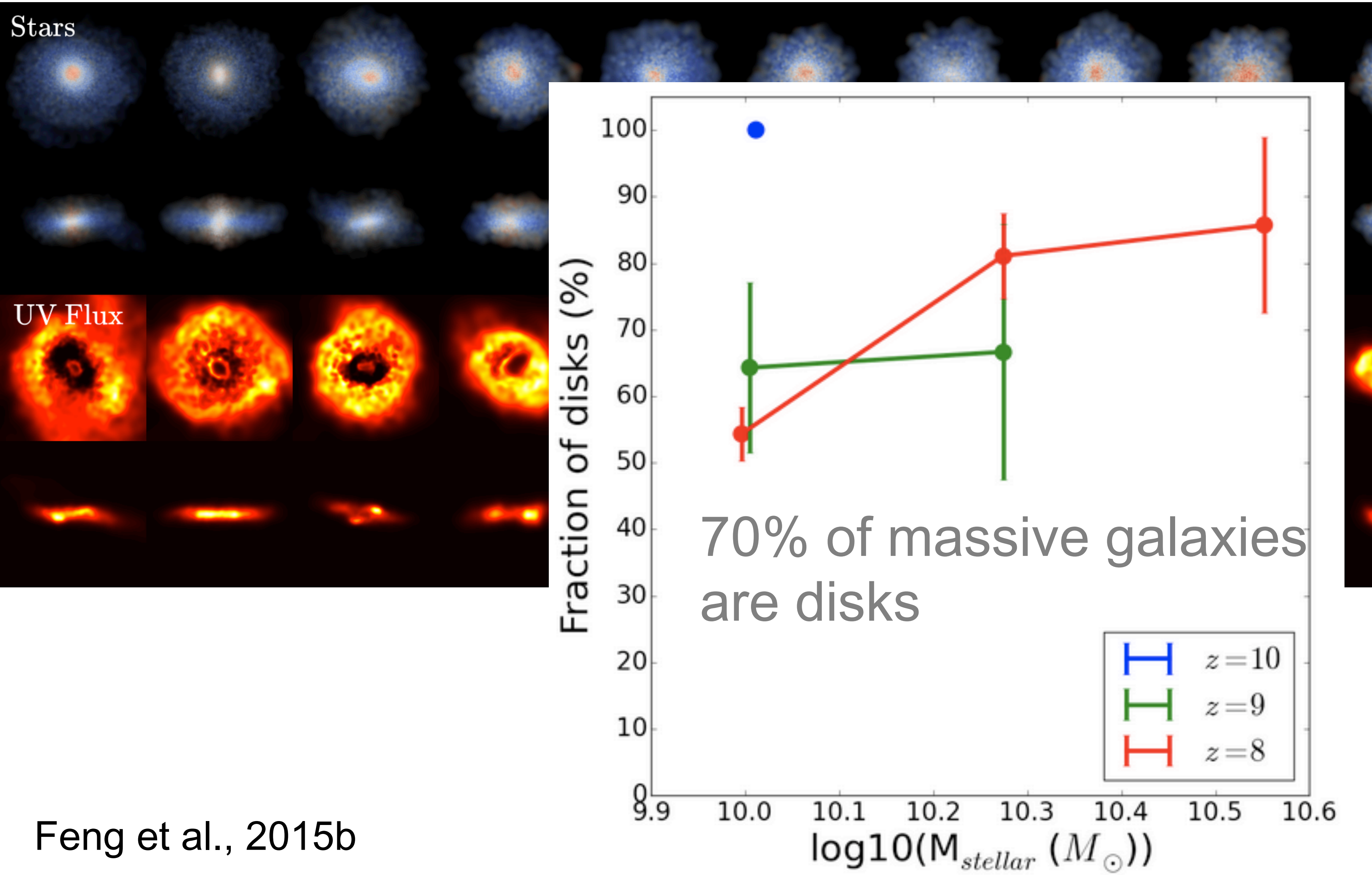


JWST



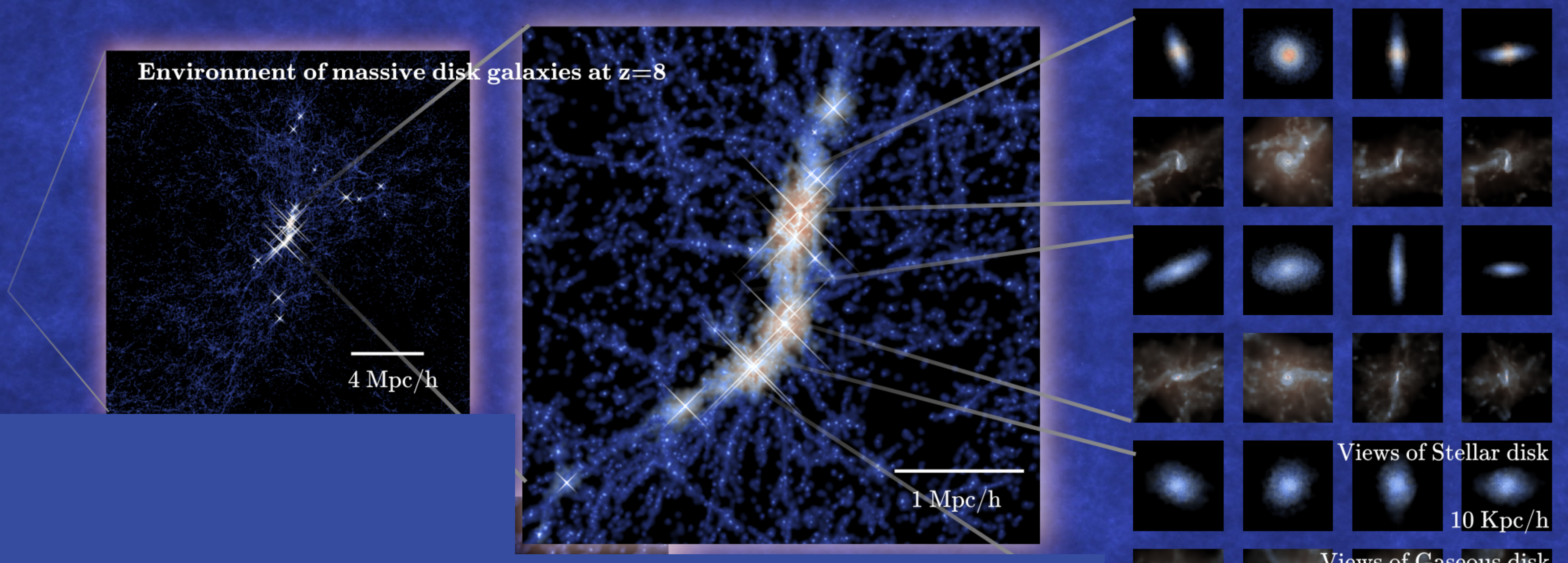
Feng et al., 2015b

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



70% of massive galaxies are disks

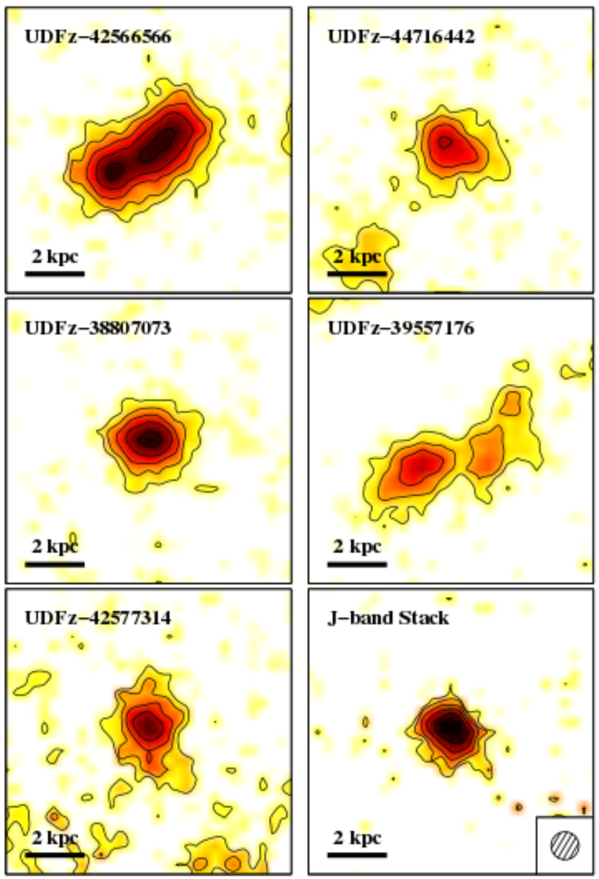
Feng et al., 2015b



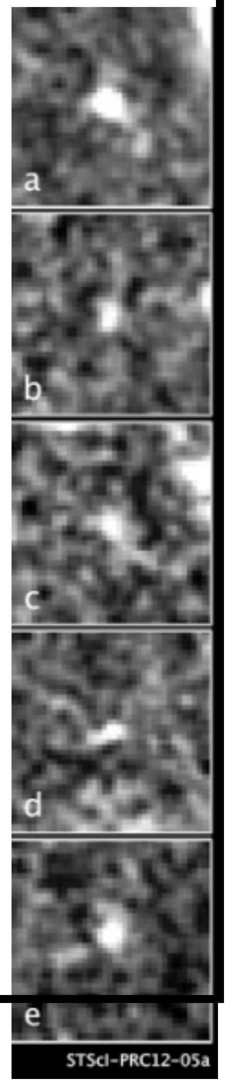
WFIRST
should detect
~ 8000 Milky Way
mass disks
at z=7-8

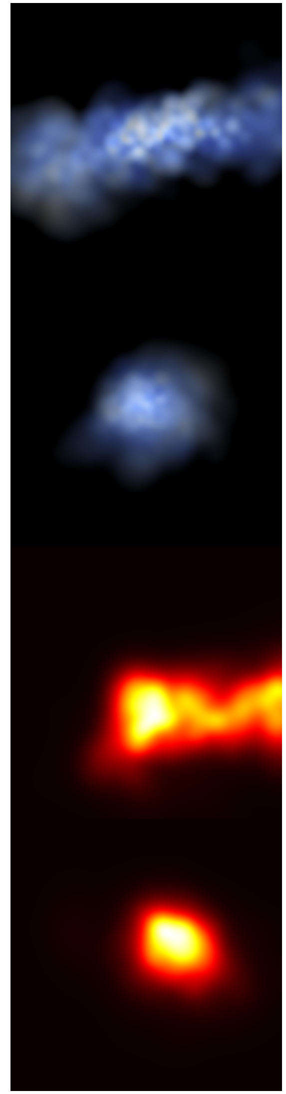
z=8 Milky Way (Massive) galaxies are disks!

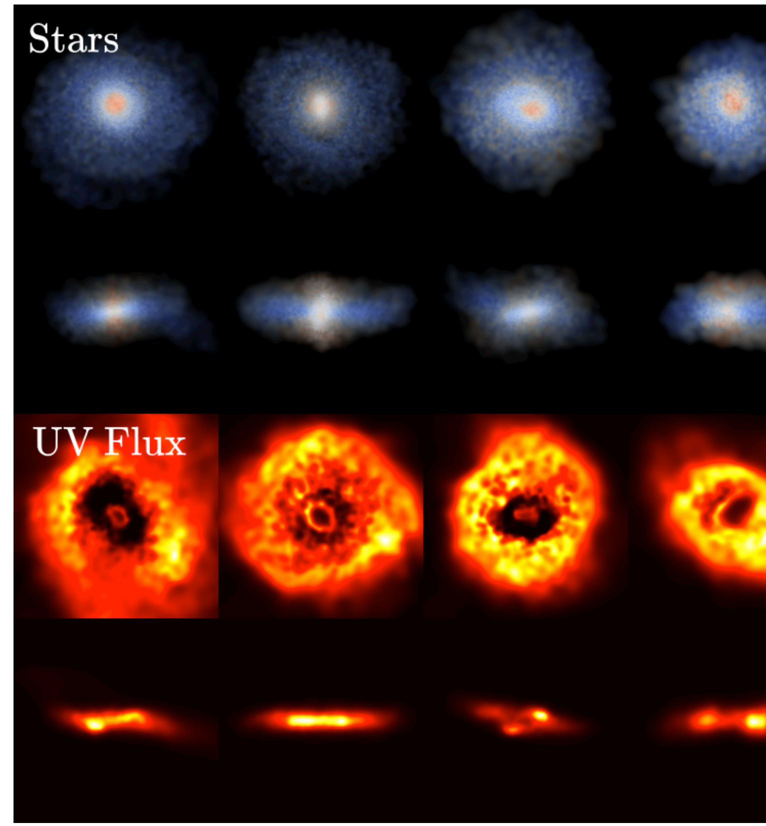
But small faint galaxies are irregular ….



HST Ultra-Deep field



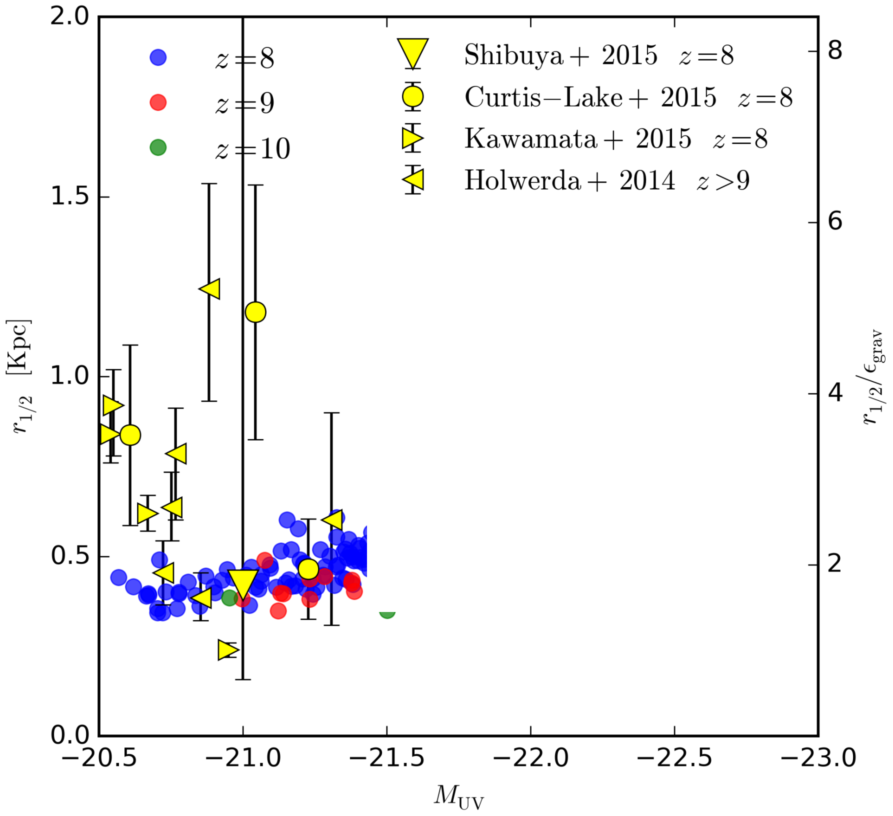




Feng et al., 2015b

The sizes of galaxies in BlueTides are consistent with HST observations

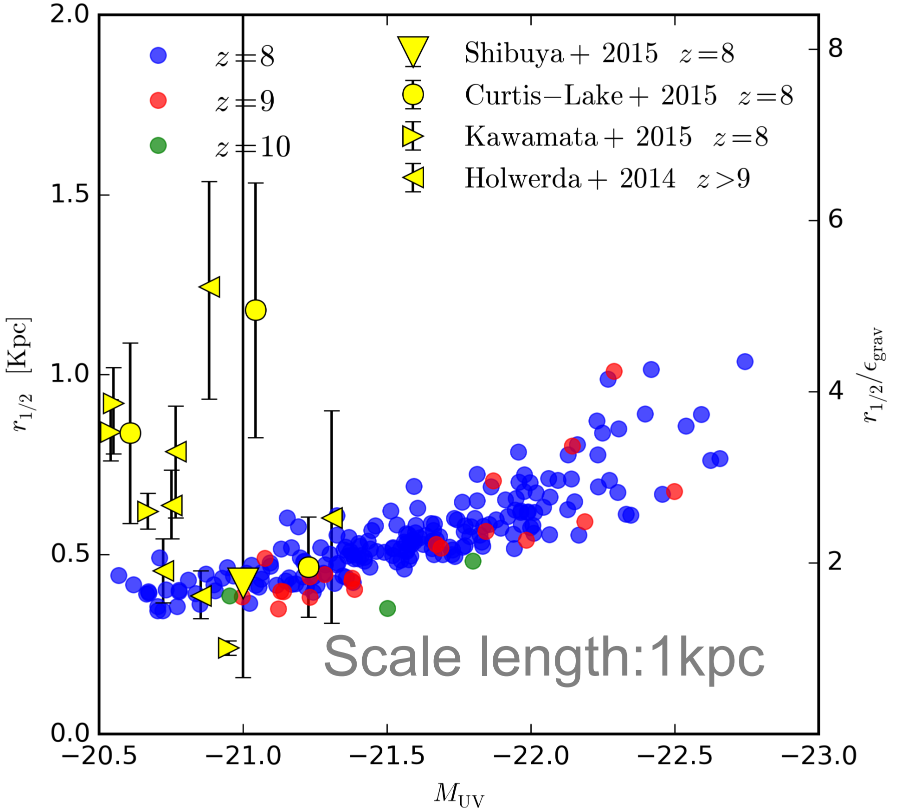
z=8



Feng et al., 2015a

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

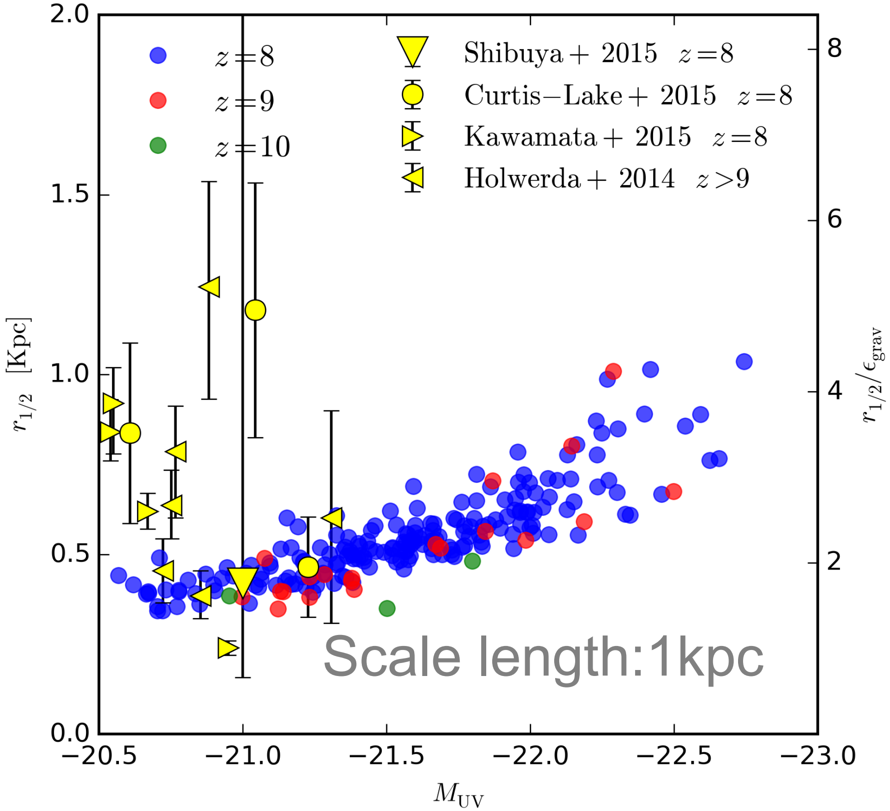
z=8

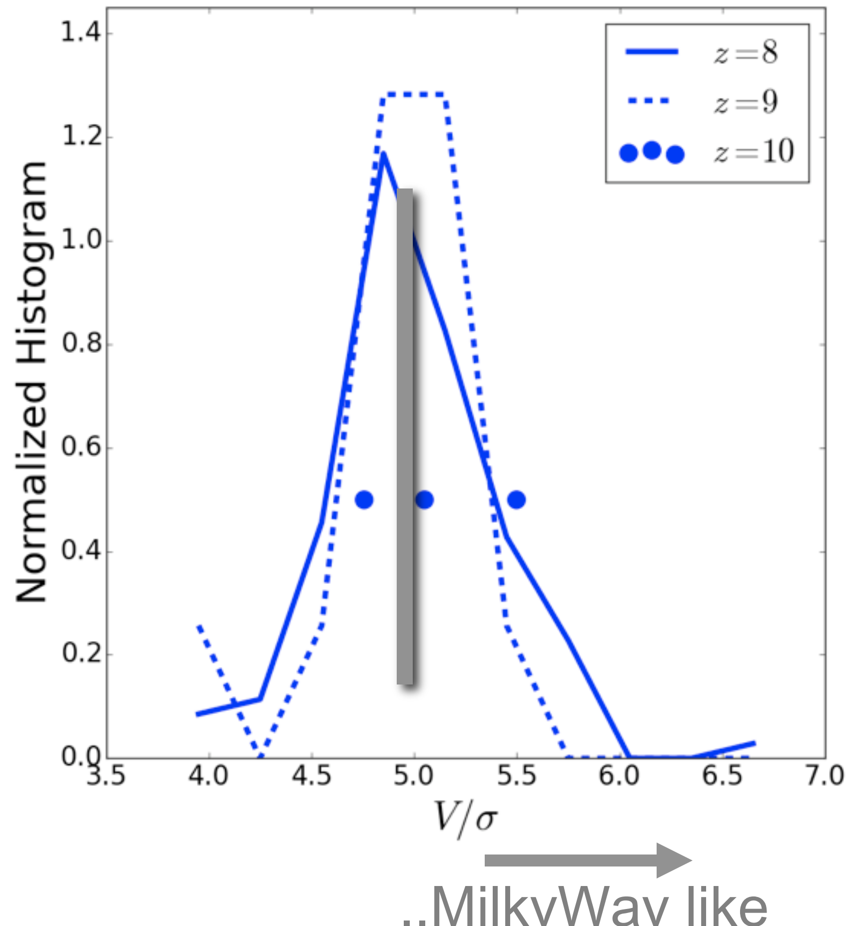


Feng et al., 2015a

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

z=8

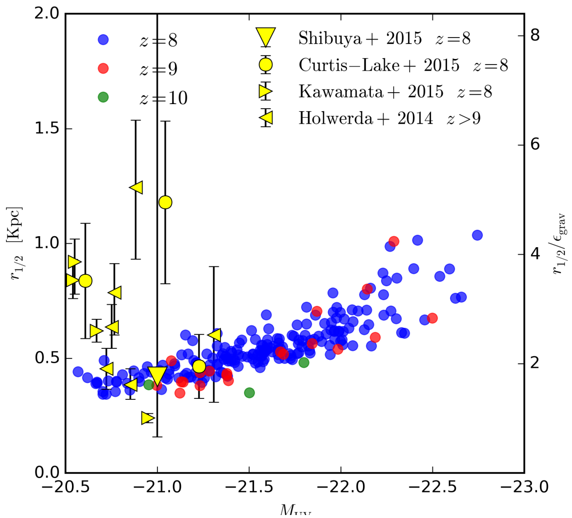


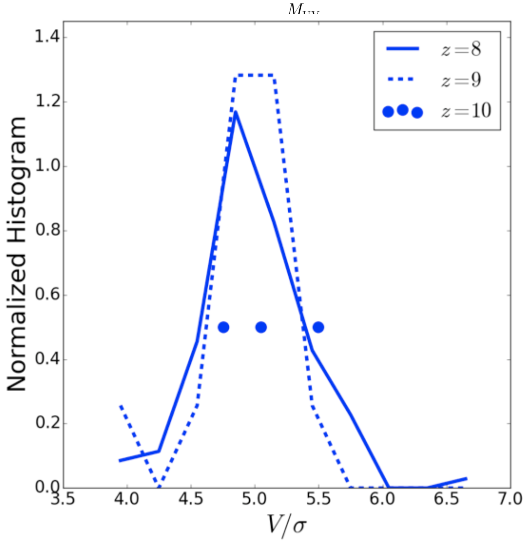


Feng et al., 2015a

Massive Disks at z=8, more compact gas rich

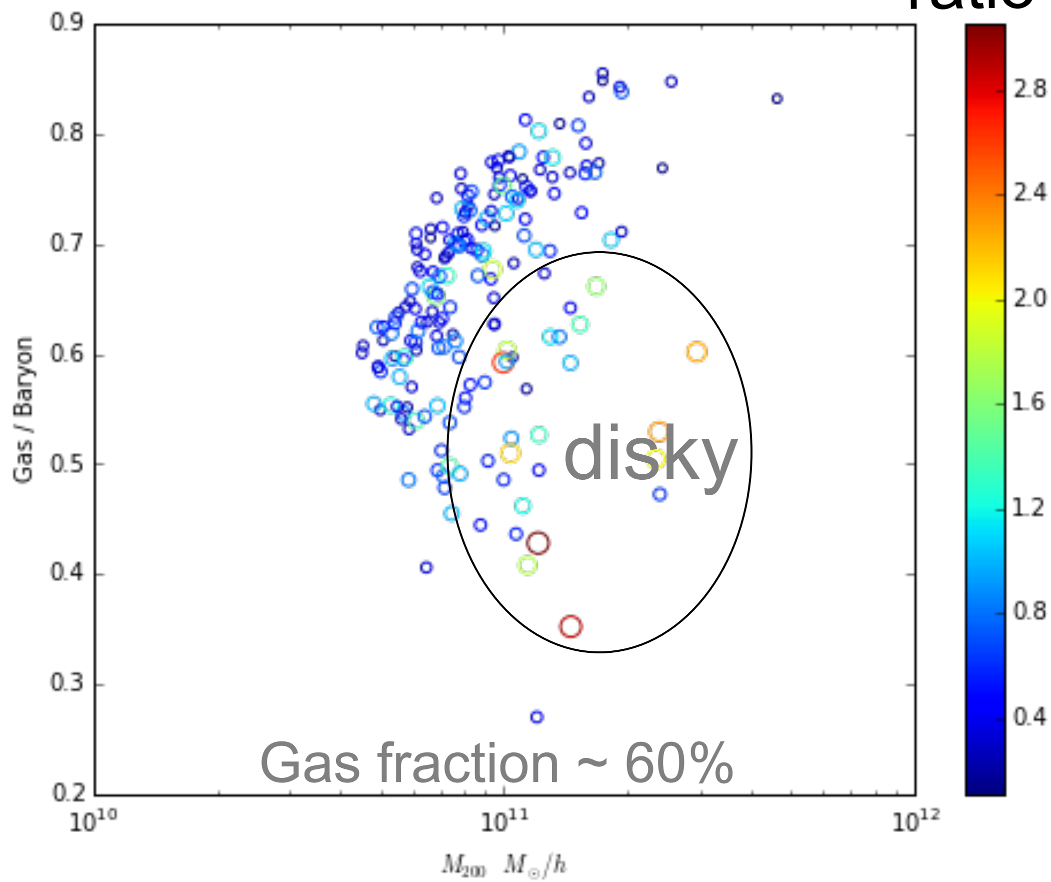
z=8





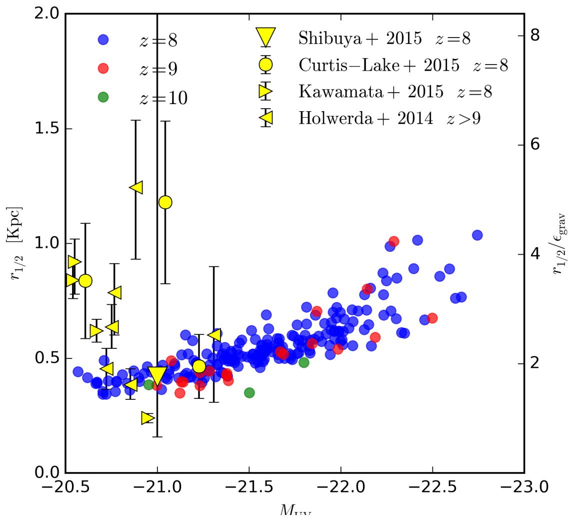
Feng et al., 2015a

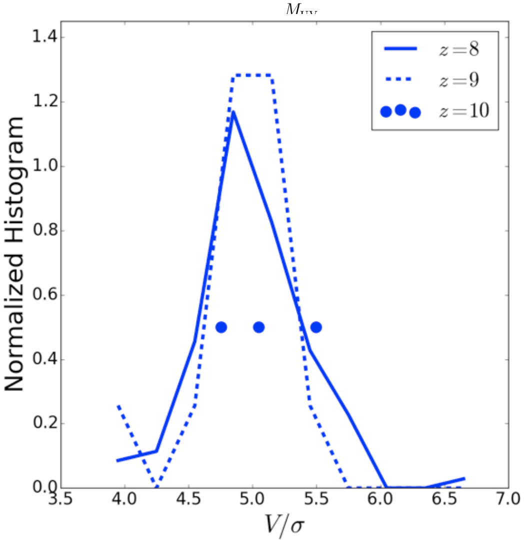
Disk/Bulge ratio



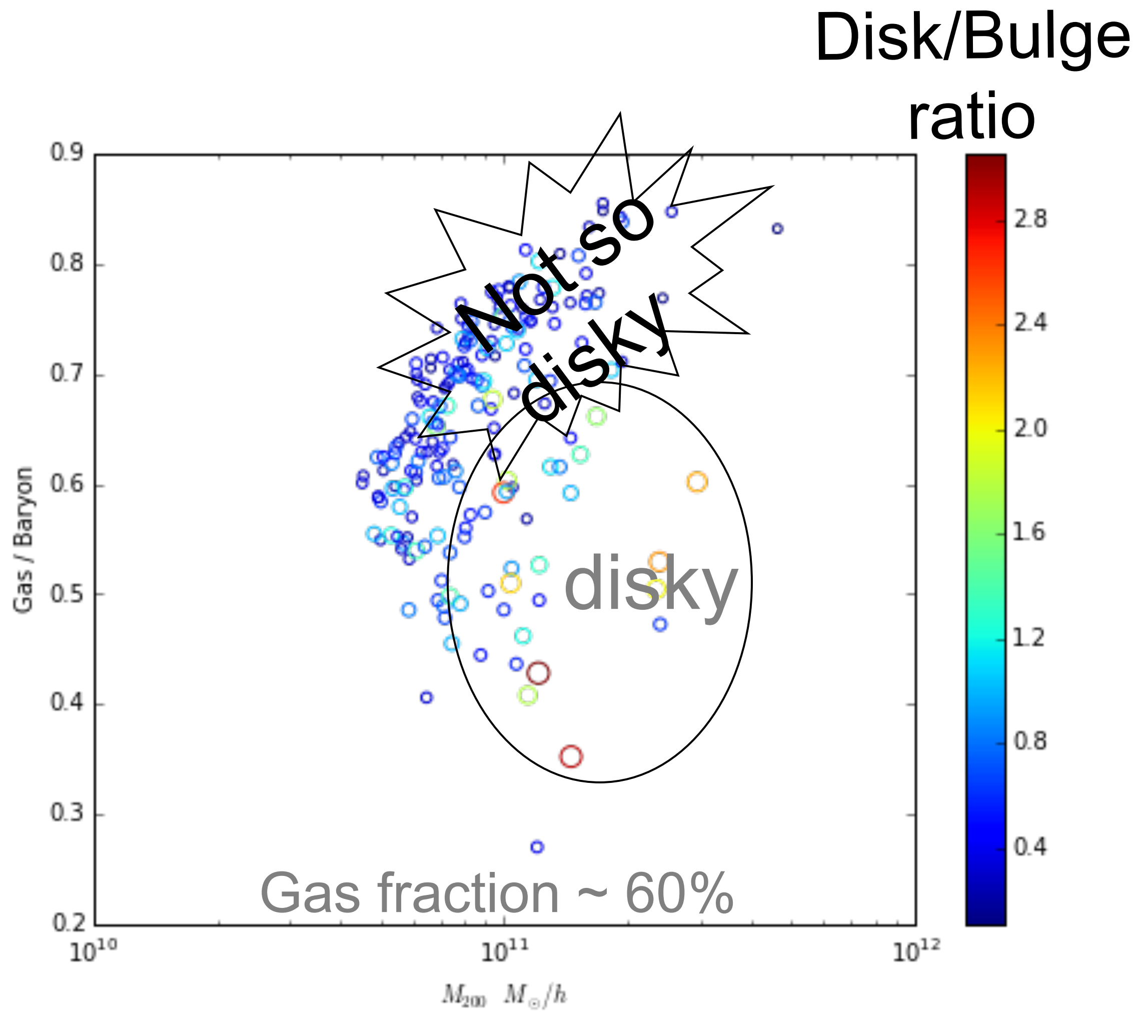
Gas richest systems have less dominant disk….

z=8





Feng et al., 2015a

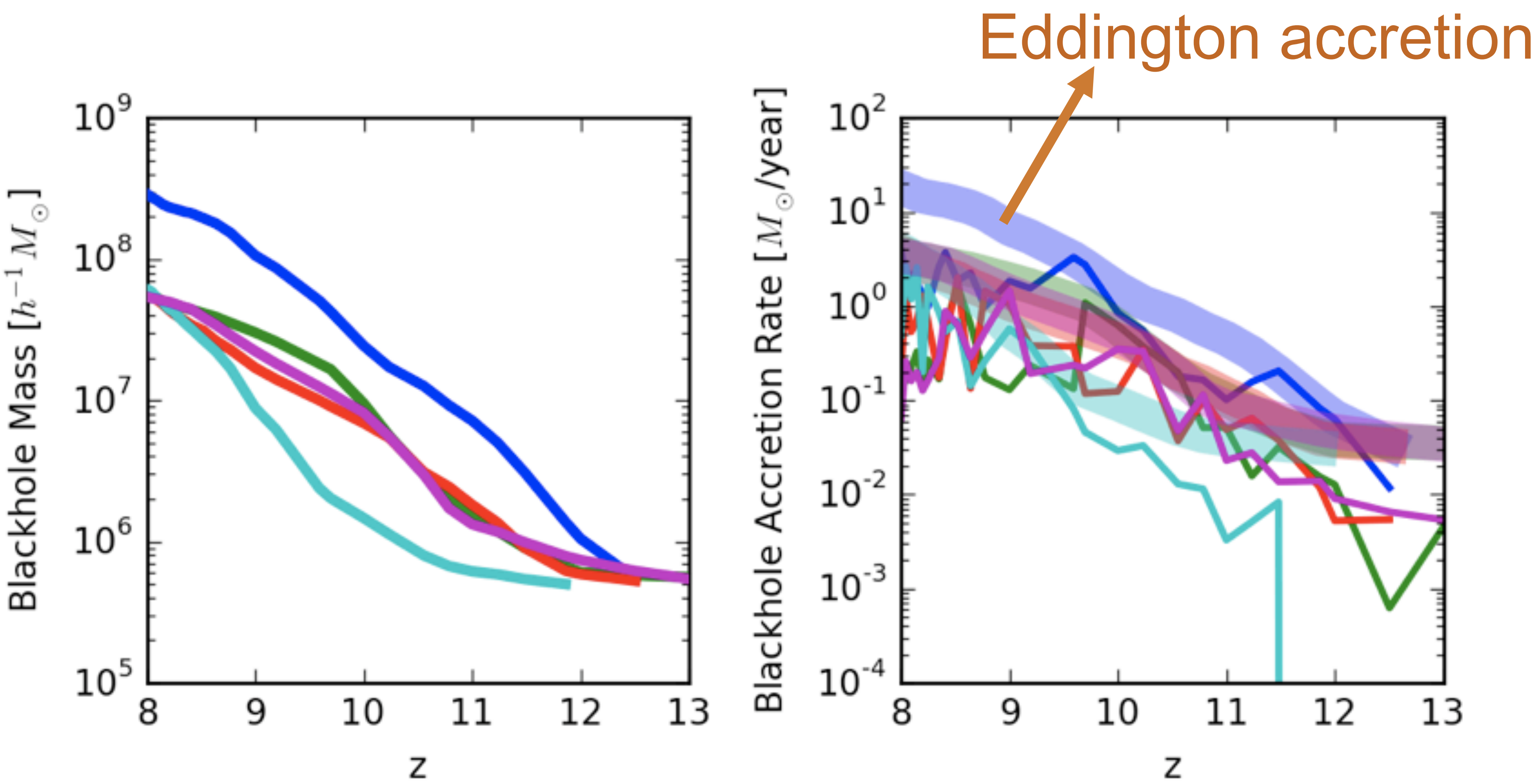


The first 600 million years (z=7+):

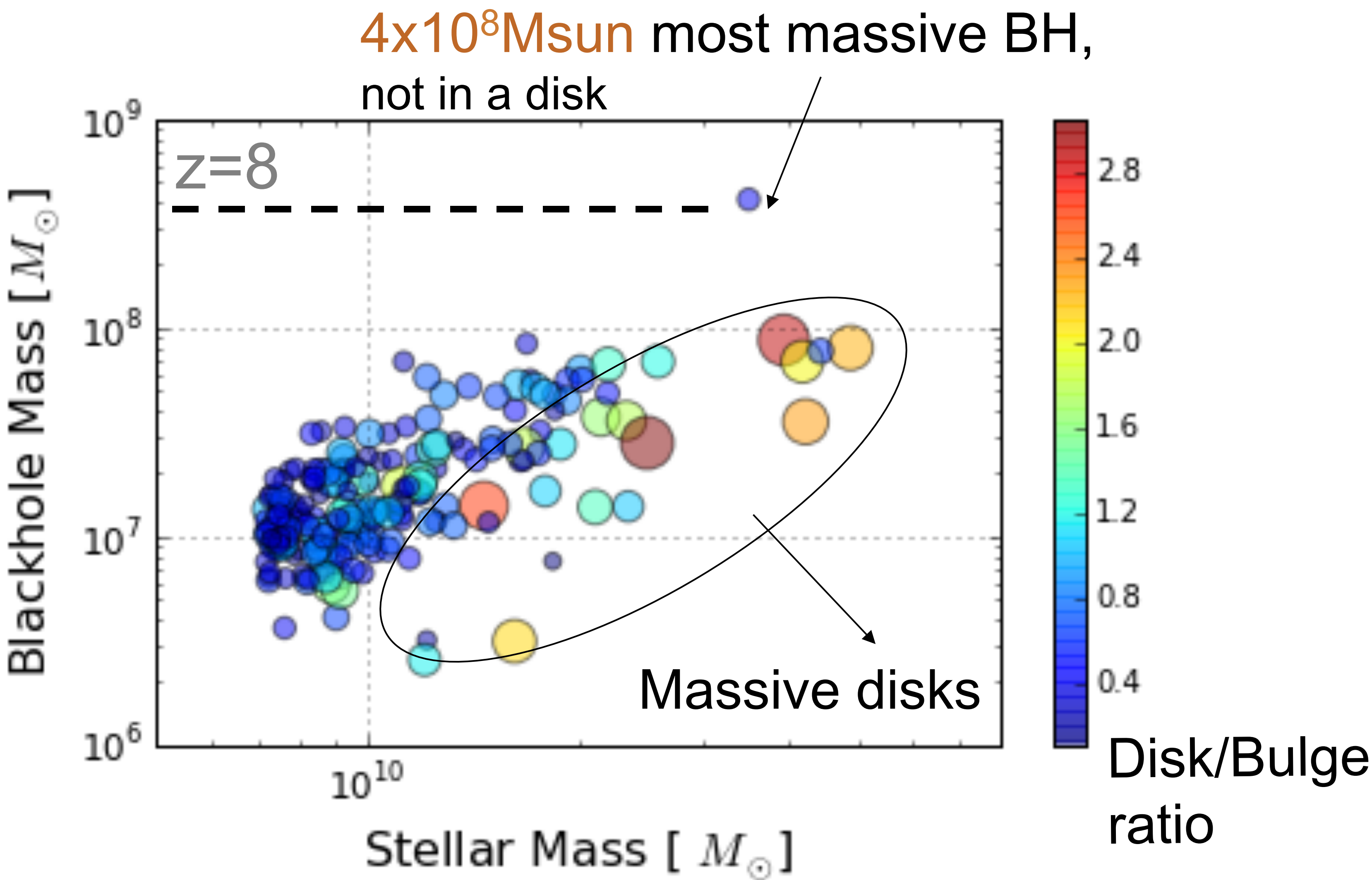
What are the most massive BH/
quasars like?

Predictions from
BlueTides:

Assembly of largest BHs at z=8,

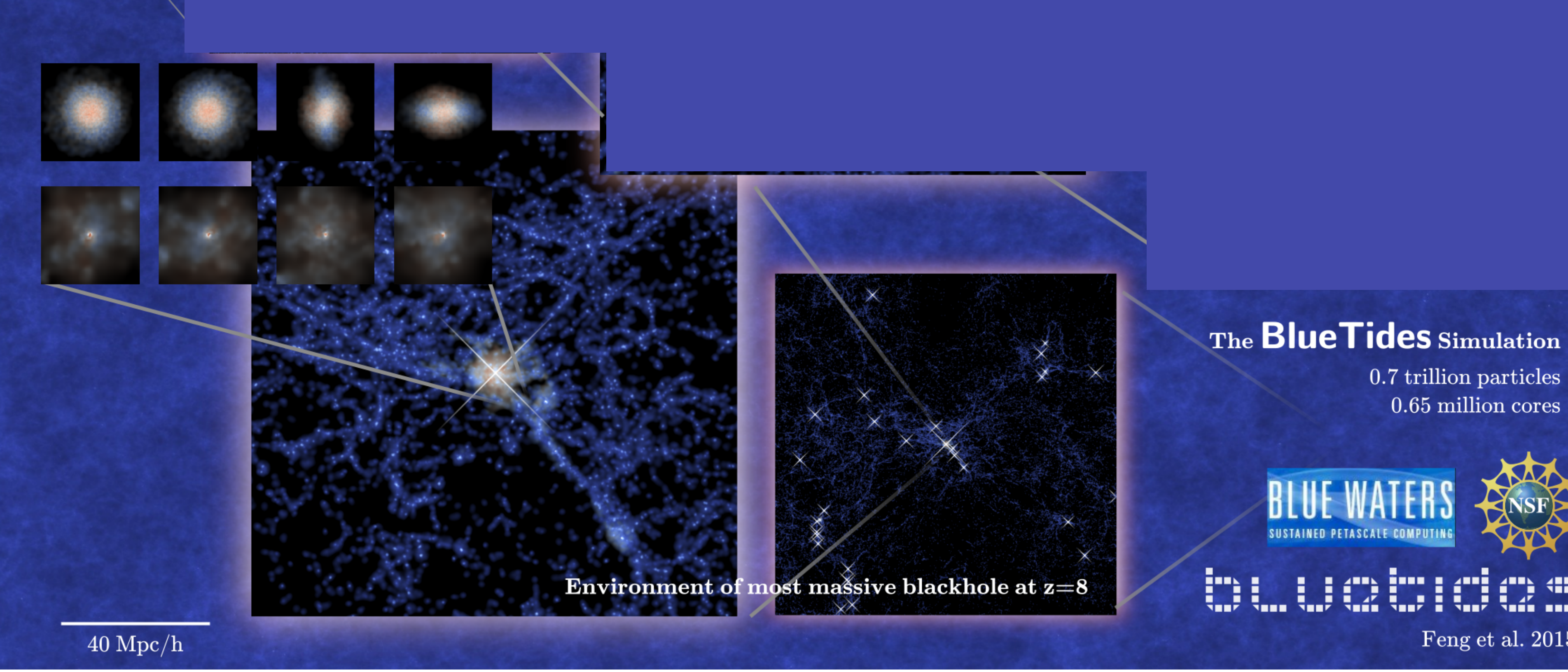


Most massive black holes at z=8, about 10^8Msun

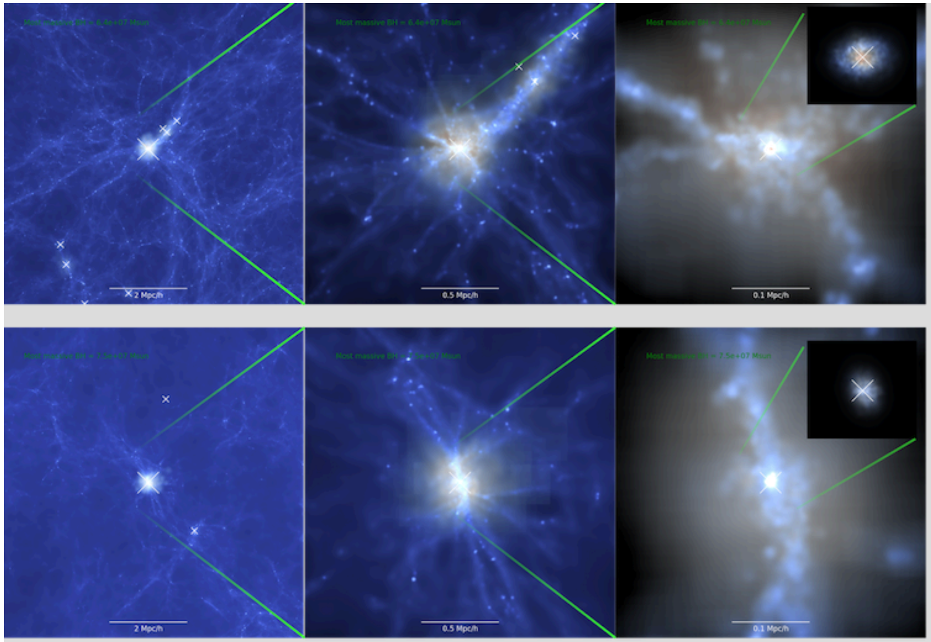


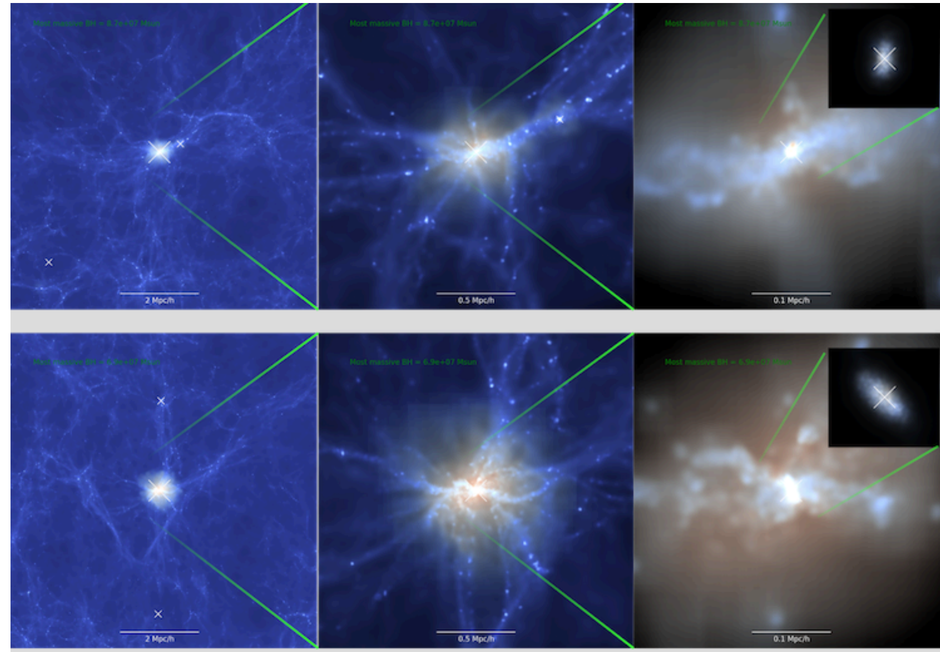
Fastest growing, massive black holes are not found in the massive disk galaxies!

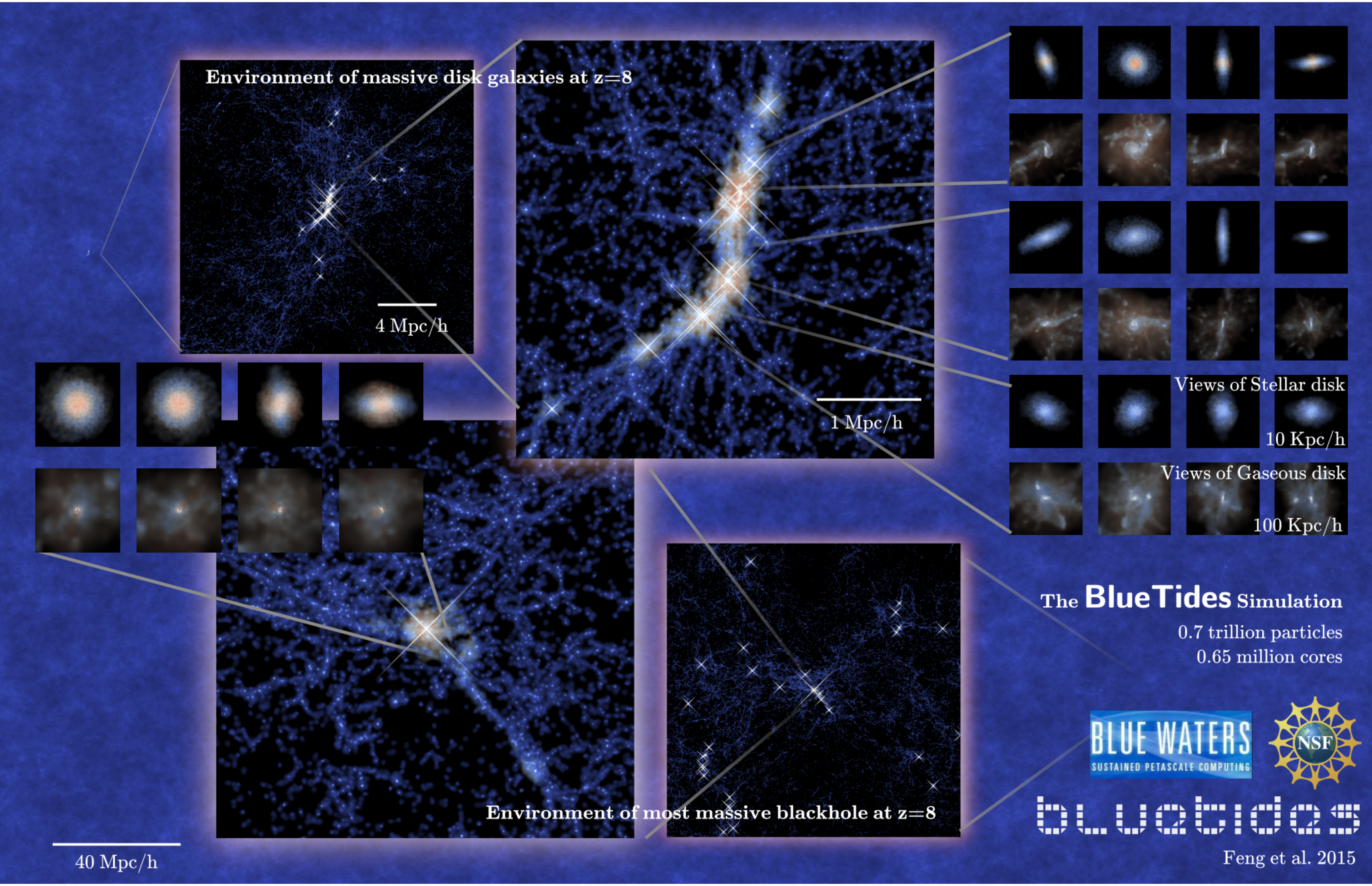
The environment of the most massive black Hole: radial inflow, compact, elliptical host galaxy



The most massive BHs in isolated overdensities in supercompact spheroidal hosts



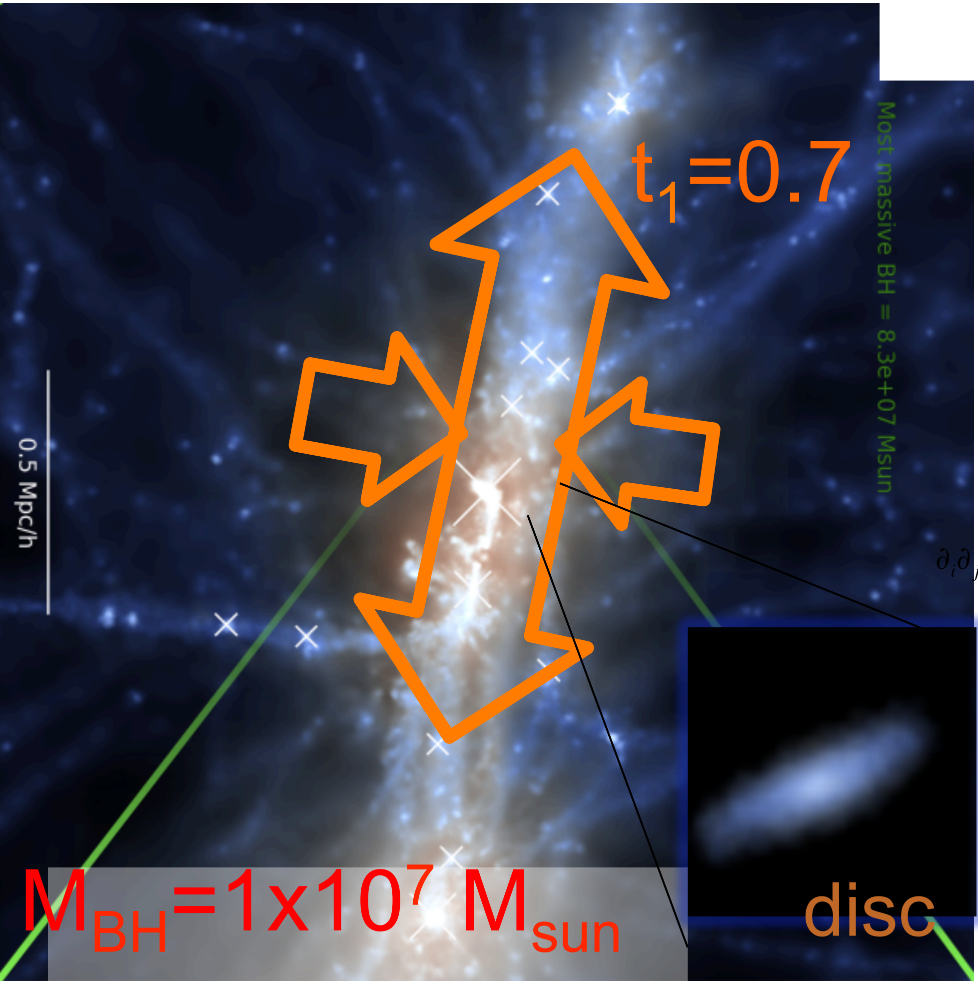




Environment of massive disk galaxies at z=8
4 Mpc/h
1 Mpc/h
Views of Stellar disk
10 Kpc/h
Views of Gaseous disk
100 Kpc/h
The BlueTides Simulation
0.7 trillion particles
0.65 million cores
BLUE WATERS
SUSTAINED PETASCALE COMPUTING
NSF
bluetides
Environment of most massive blackhole at z=8
40 Mpc/h
Feng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

tidal tensor

$$T_{ij}(\boldsymbol{x}) = \frac{\partial^2 \phi}{\partial x_i \partial x_j},$$



Large tidal field:

Large filaments,

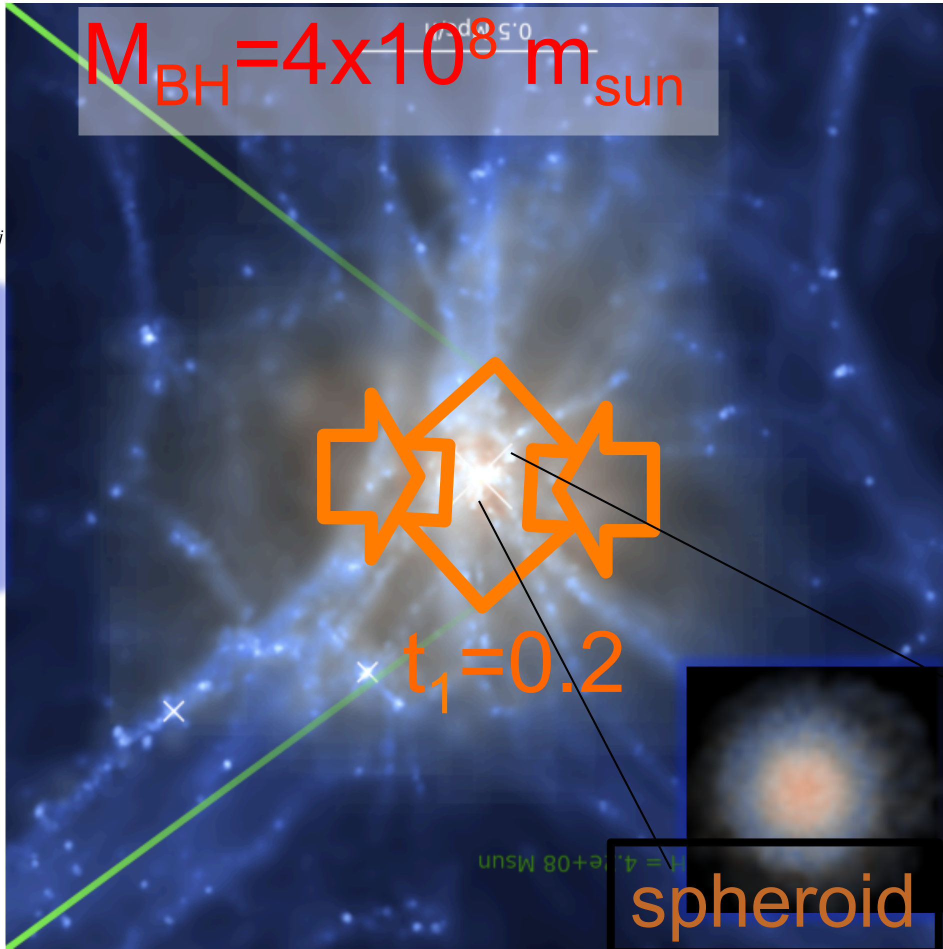
Accretion perp. to t1

weak tidal field:

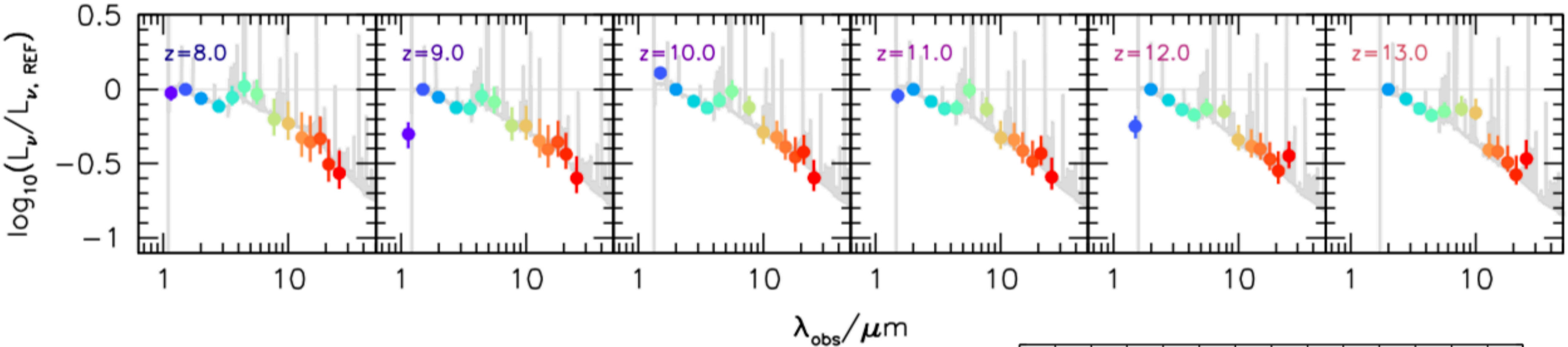
Thin filaments

radial motions,

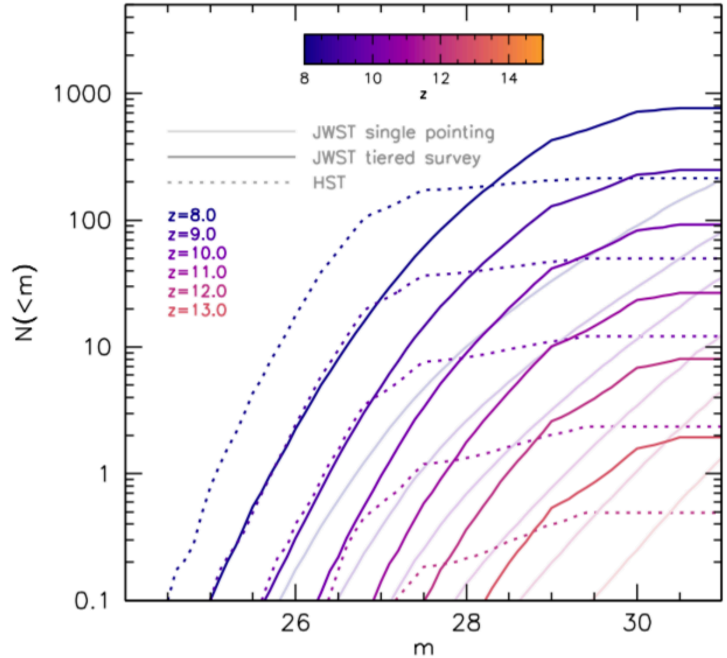
cold accretion



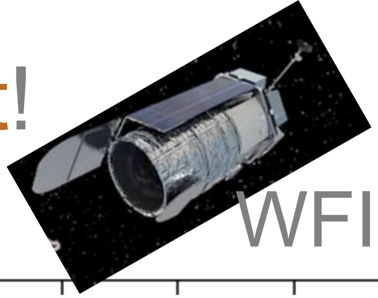
Predictions for JWST

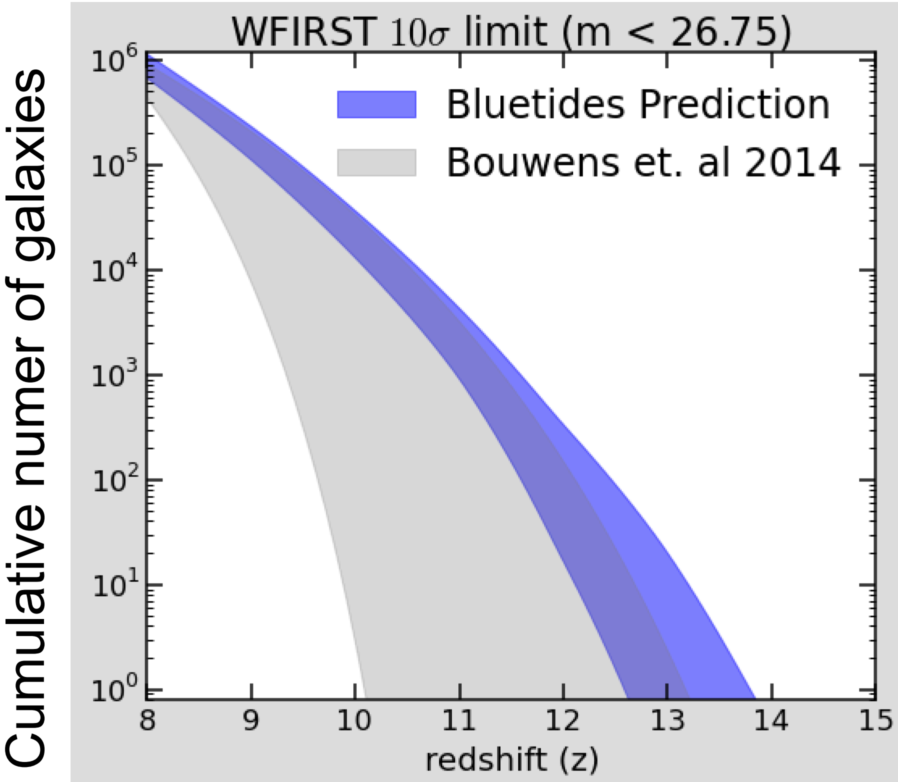


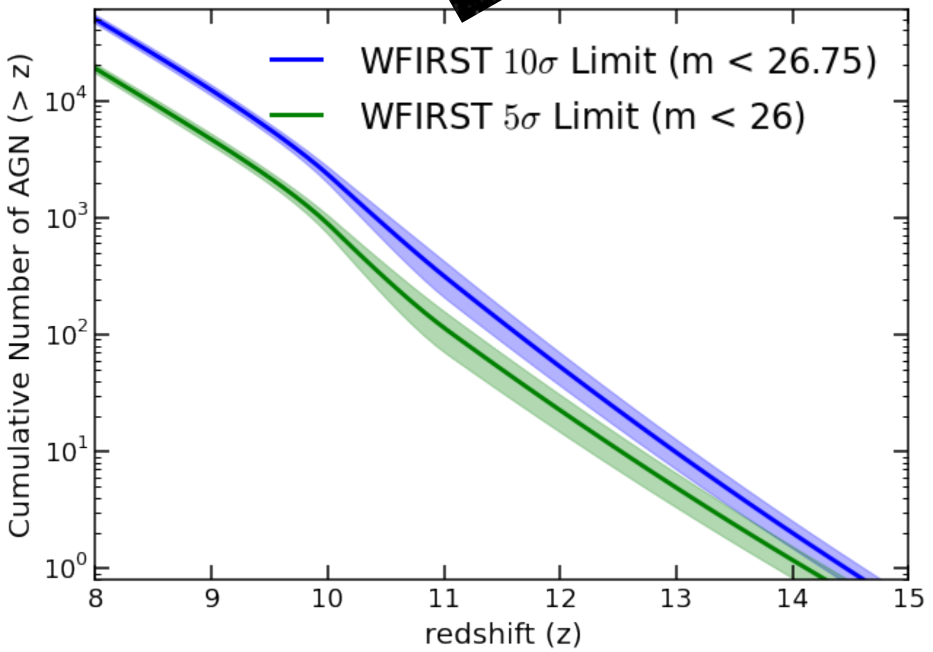
4 times as many galaxies as in current HST fields



The end of the dark ages is bright!



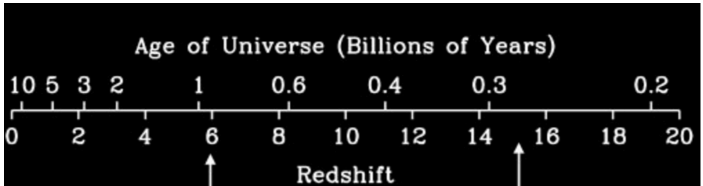




Waters, DM+, 16, in prep

Up to 1M galaxies, 1e4 of quasars at t = 600Myr

First galaxies at t=300Myr



The end of the dark ages is bright!

News Release Number: STScI-2016-07 *March 3, 2016 12:00 PM (EST)*

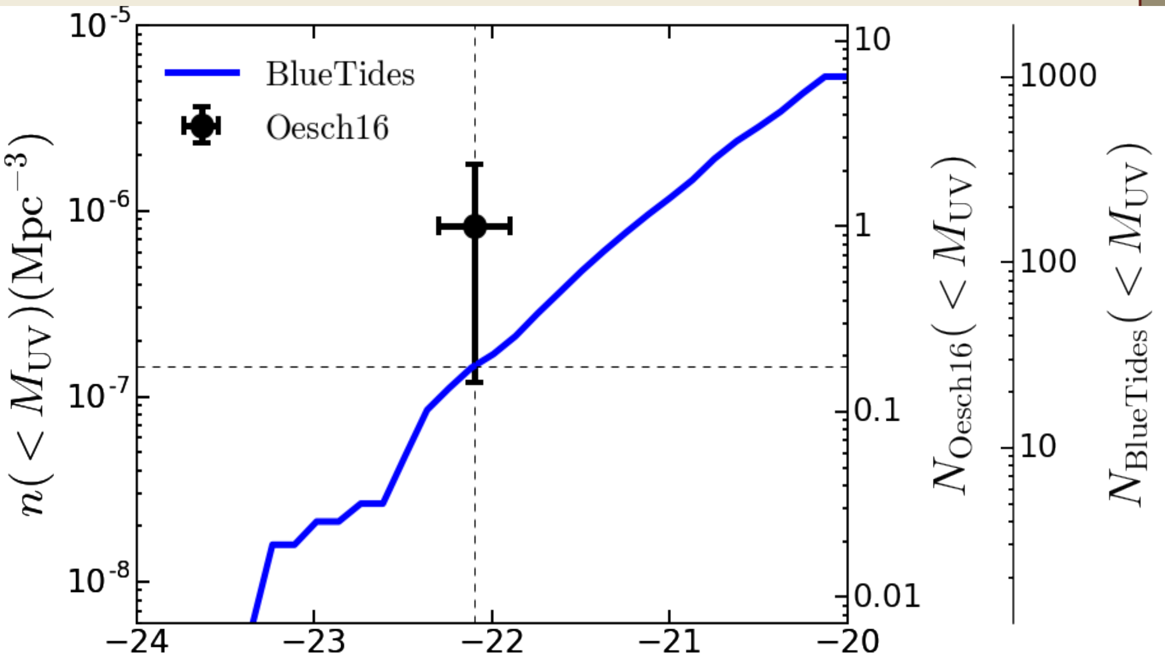
Hubble Team Breaks Cosmic Distance Record

Introduction | The Full Story | Release Images | Release Videos | Fast Facts | Related Links

The full news release story:

By pushing NASA's Hubble Space Telescope to its limits, an international team of astronomers has shattered the cosmic distance record by measuring the farthest galaxy ever seen in the universe. This surprisingly bright, infant galaxy, named GN-z11, is seen as it was 13.4 billion years in the past, just 400 million years after the big bang. GN-z11 is located in the direction of the constellation of Ursa Major.

BlueTides predicts discovery of ‘bright’ 400 million years old galaxy



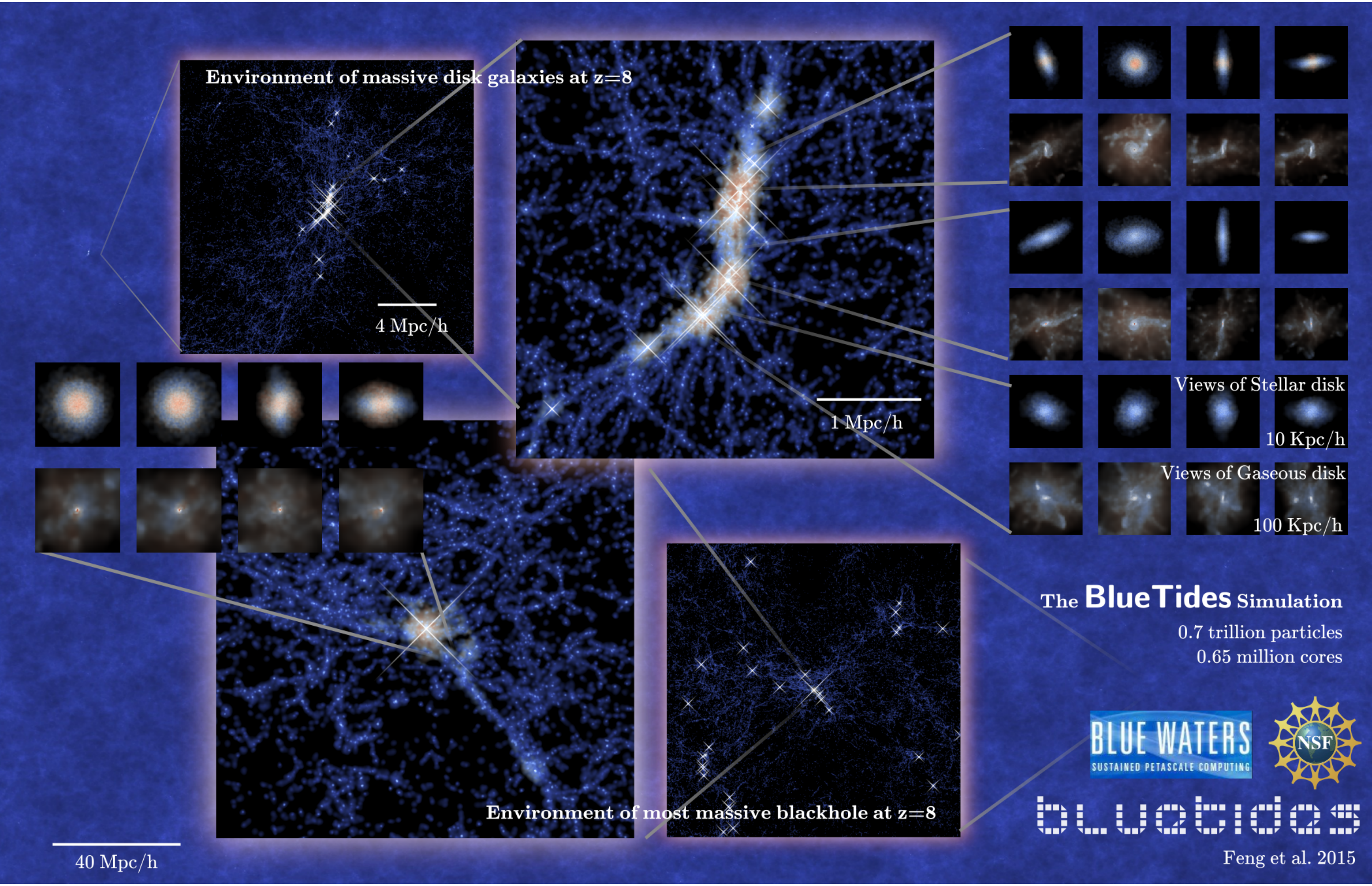
Waters, DM+, 16

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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