The next quasars and massive galaxies frontier:

The bluetides simulation

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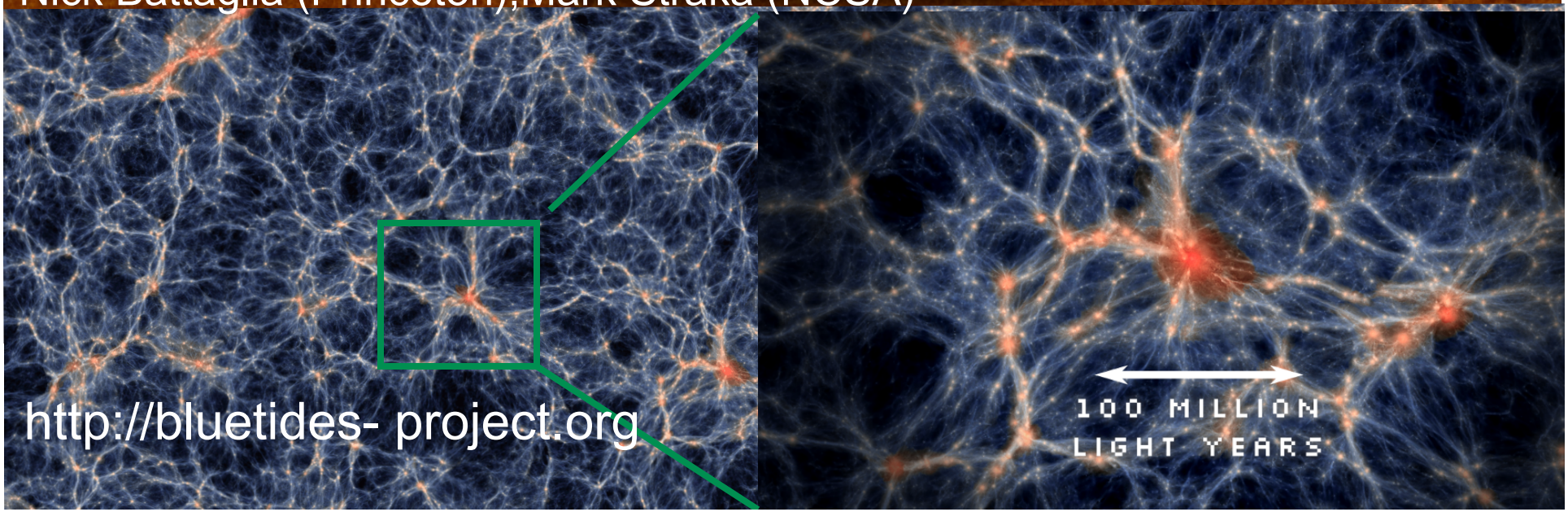
Simeon Bird (CMU), Steve Wilkins (Sussex),Ananth Tenneti (CMU)
Nick Battaglia (Princeton),Mark Straka (NCSA)



$z > 7$

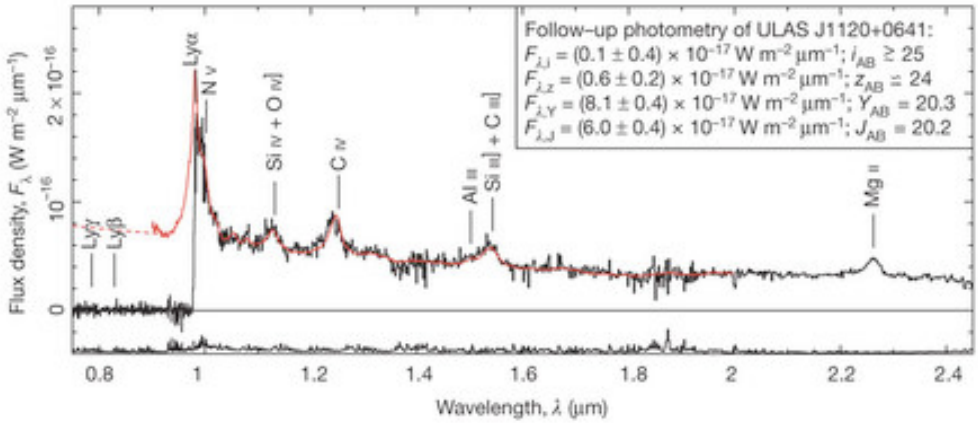
Observations

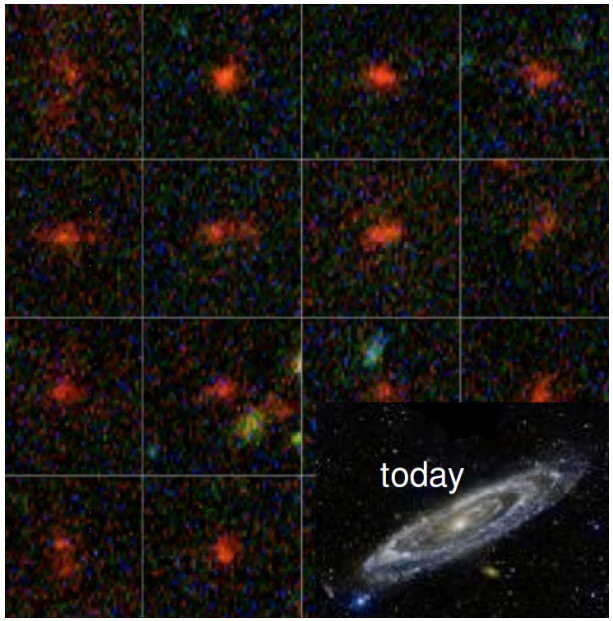
The first 800 million years

$z > 7$

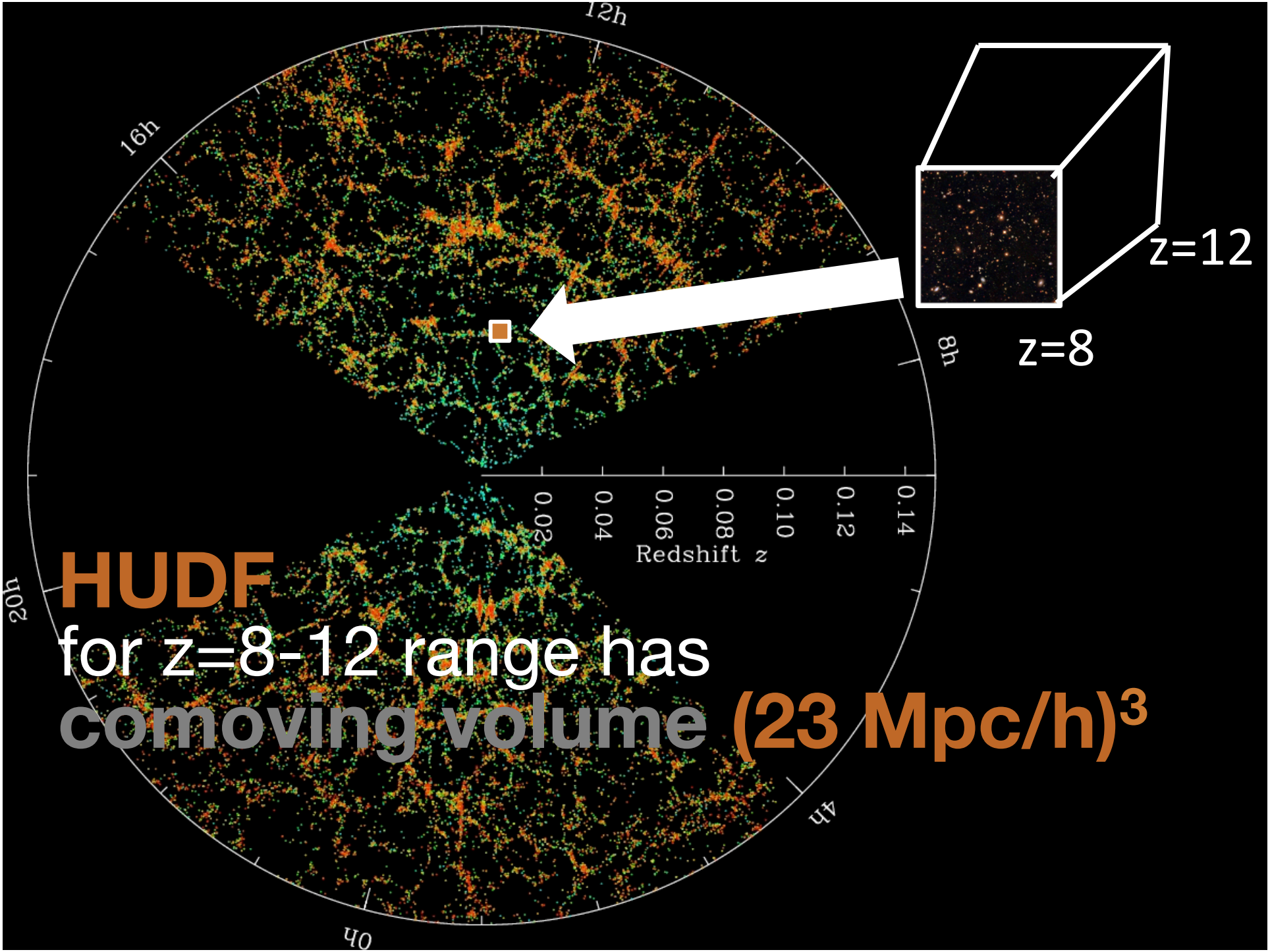
a few (tens) of compact, clumpy irregular galaxies

One quasar

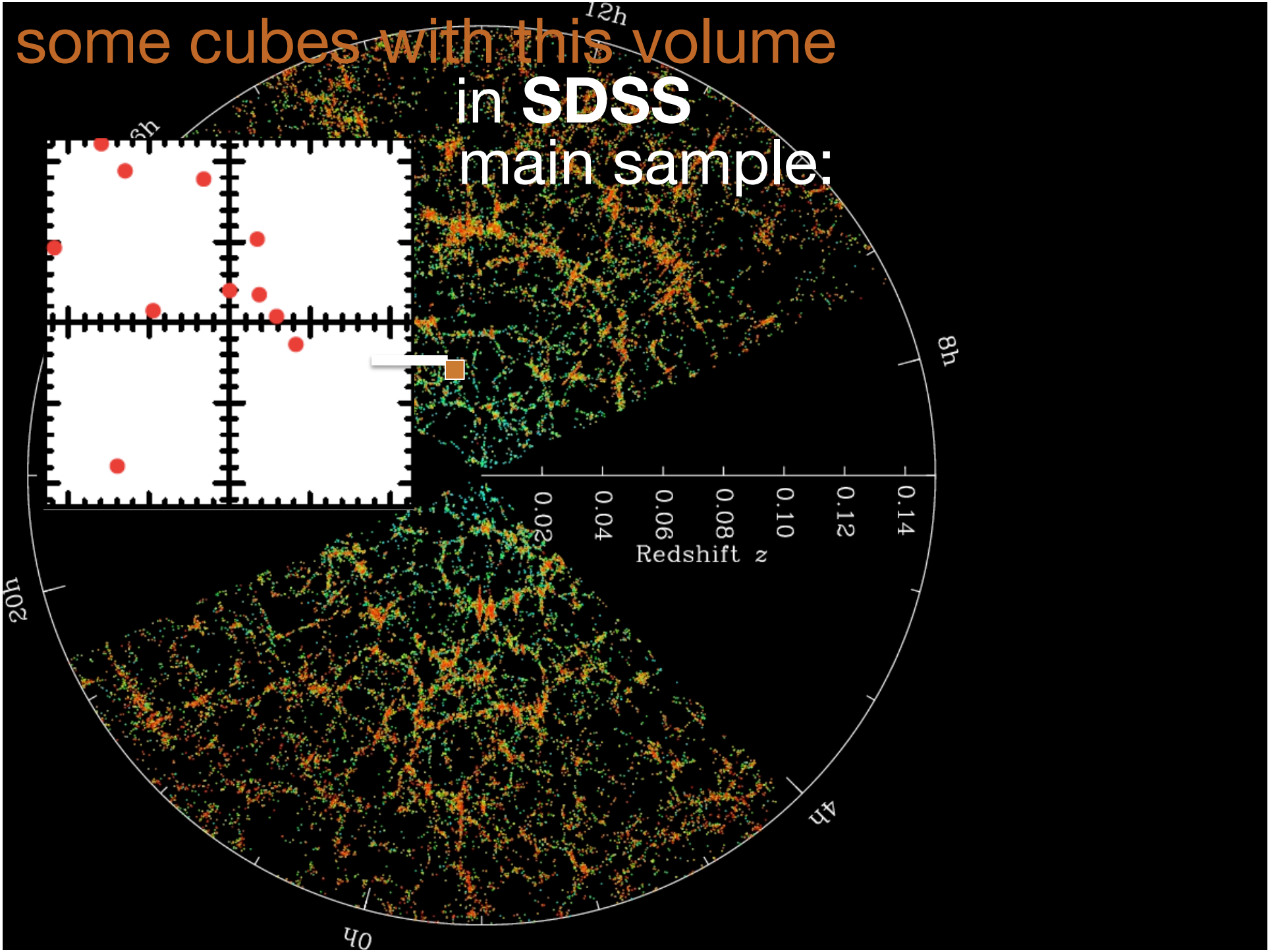


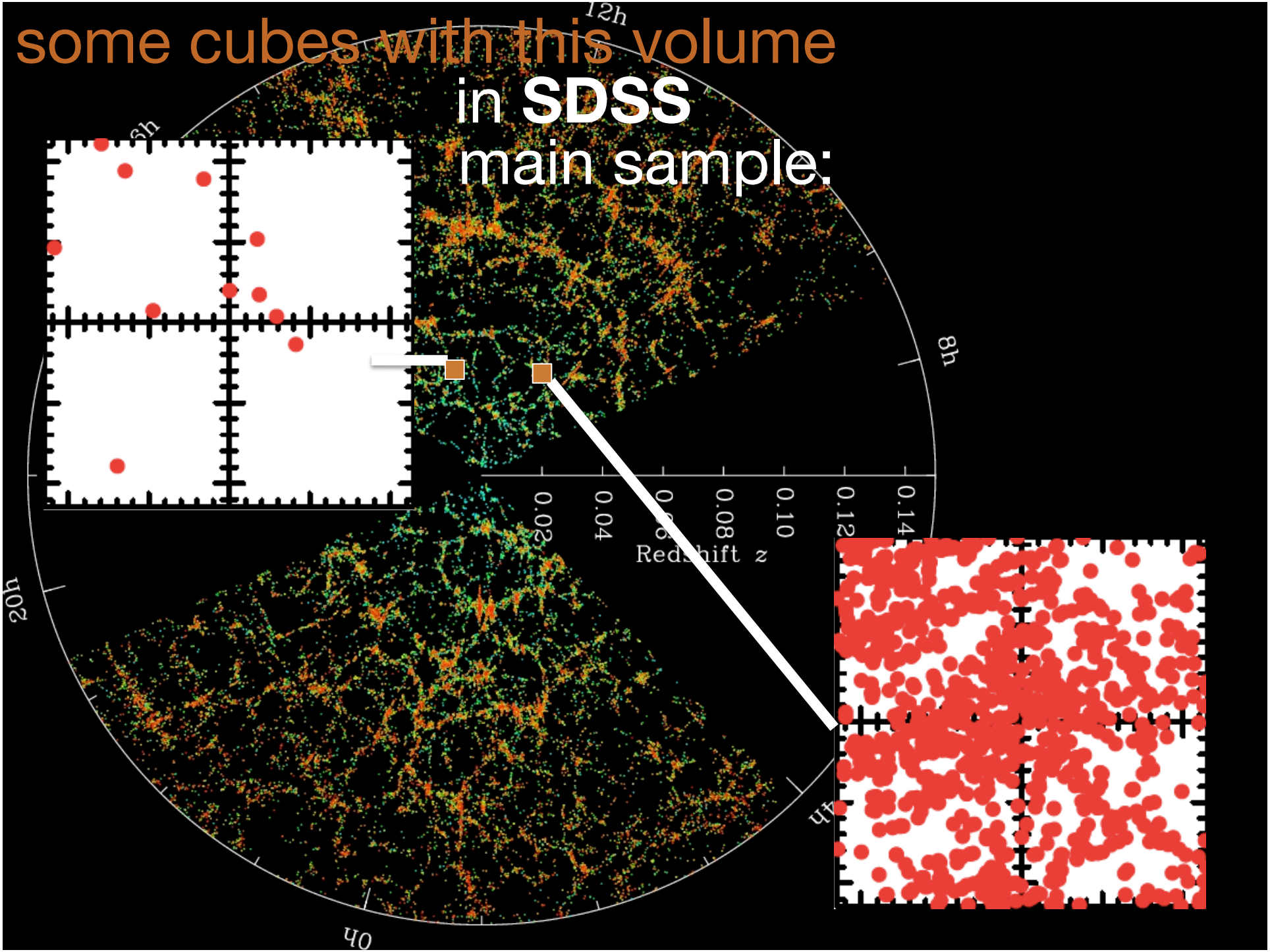


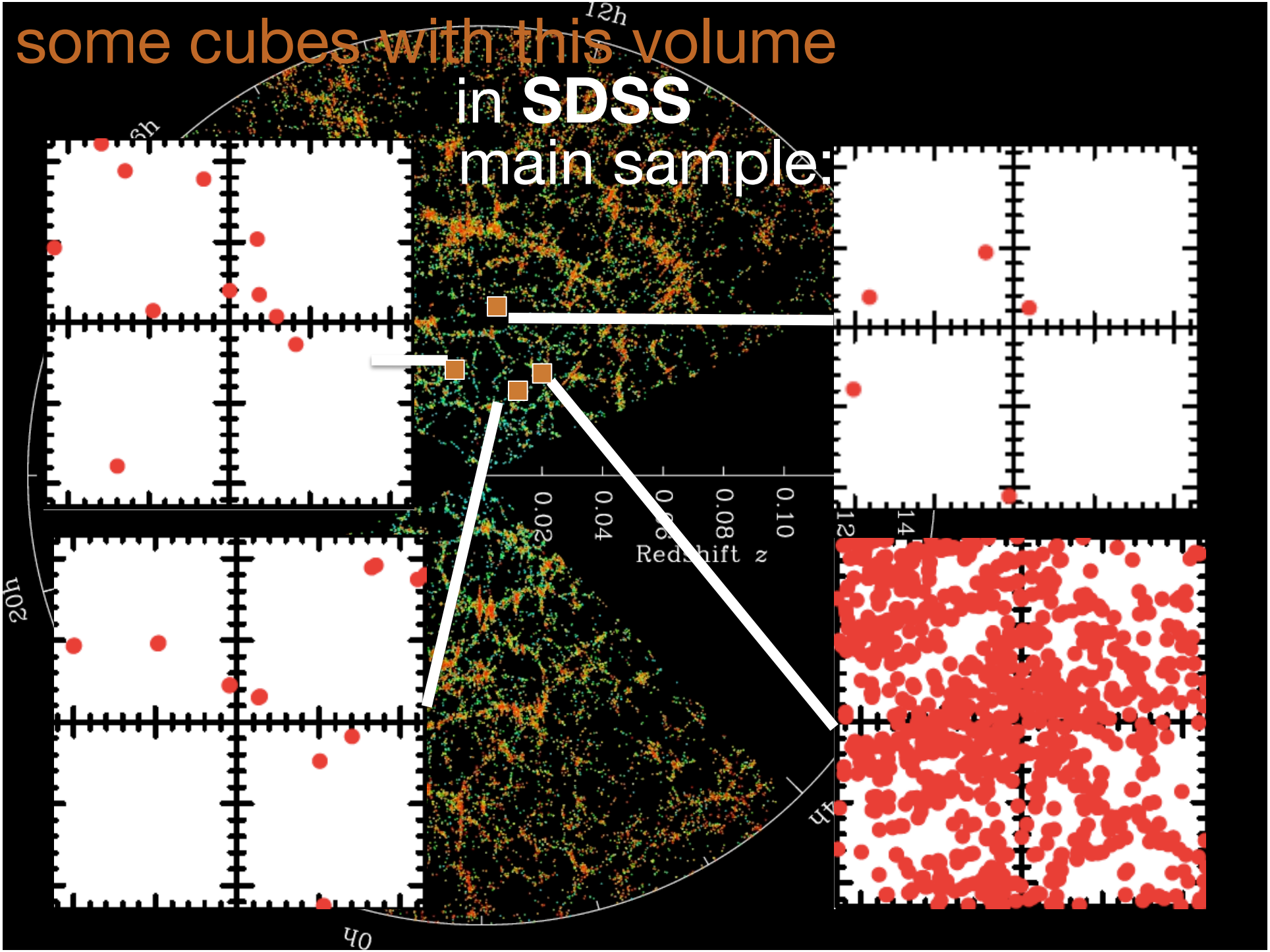
Z > 7


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

some cubes with this volume in **SDSS** main sample:

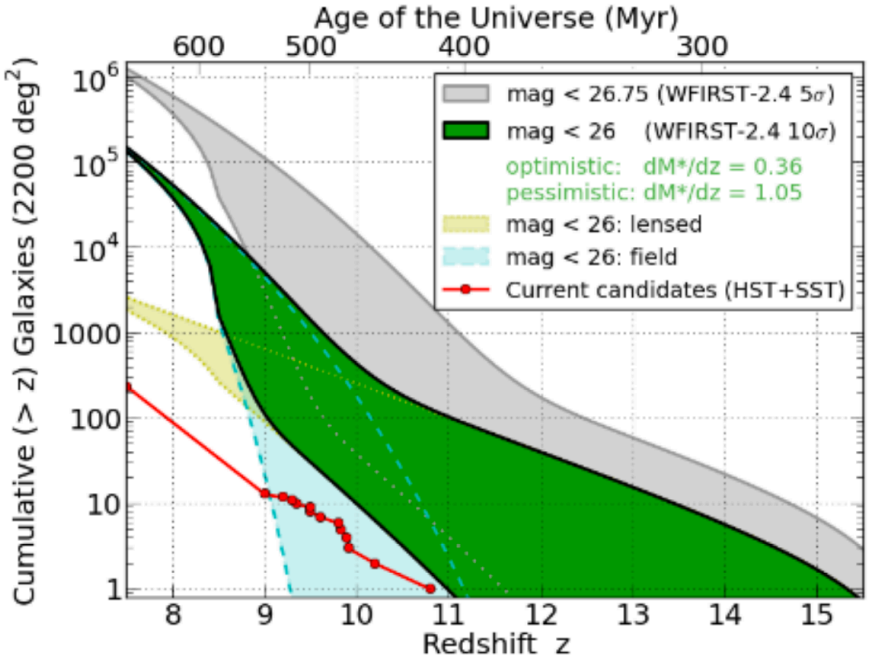



some cubes with this volume
in SDSS
main sample:
12h
8h
4h
0h
20h
0.02
0.04
0.08
0.10
0.12
0.14
Redshift z


some cubes with this volume
in SDSS
main sample:
12h
6h
20h
0h
4h
0.02
0.04
0.08
0.10
Redshift z

Z > 7

room for discovery

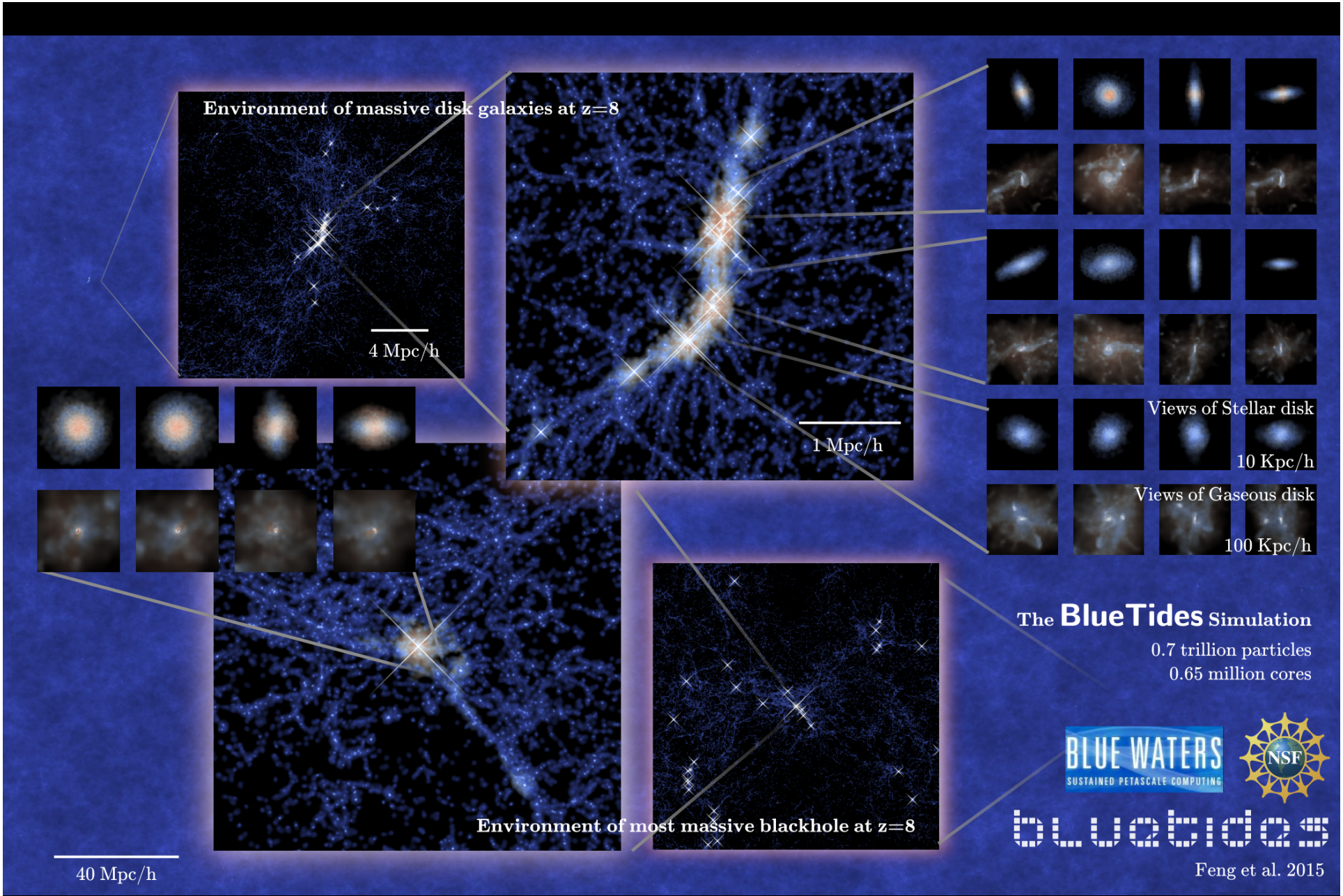


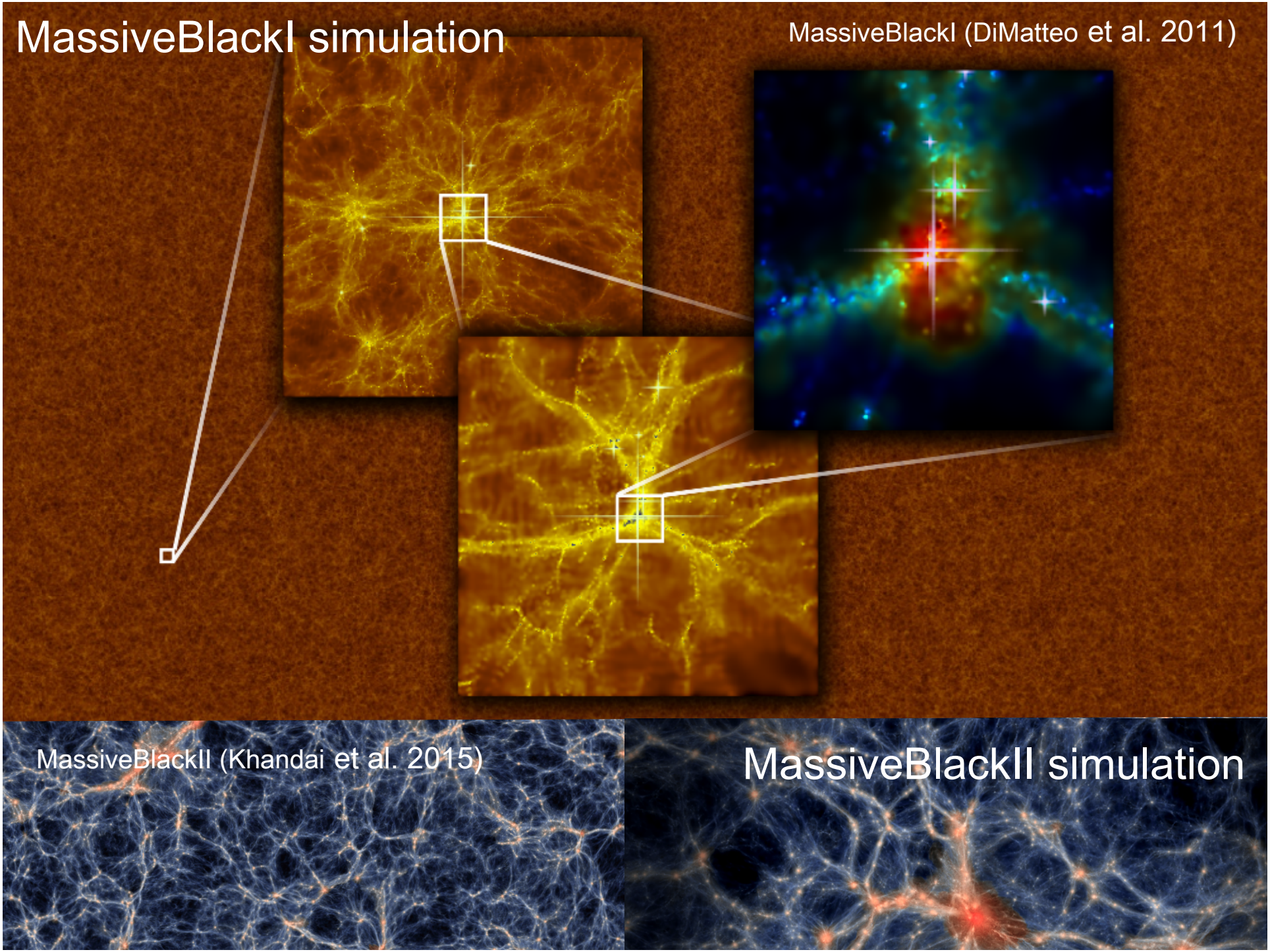
$z > 7$

Predictions:

The first 800 million years

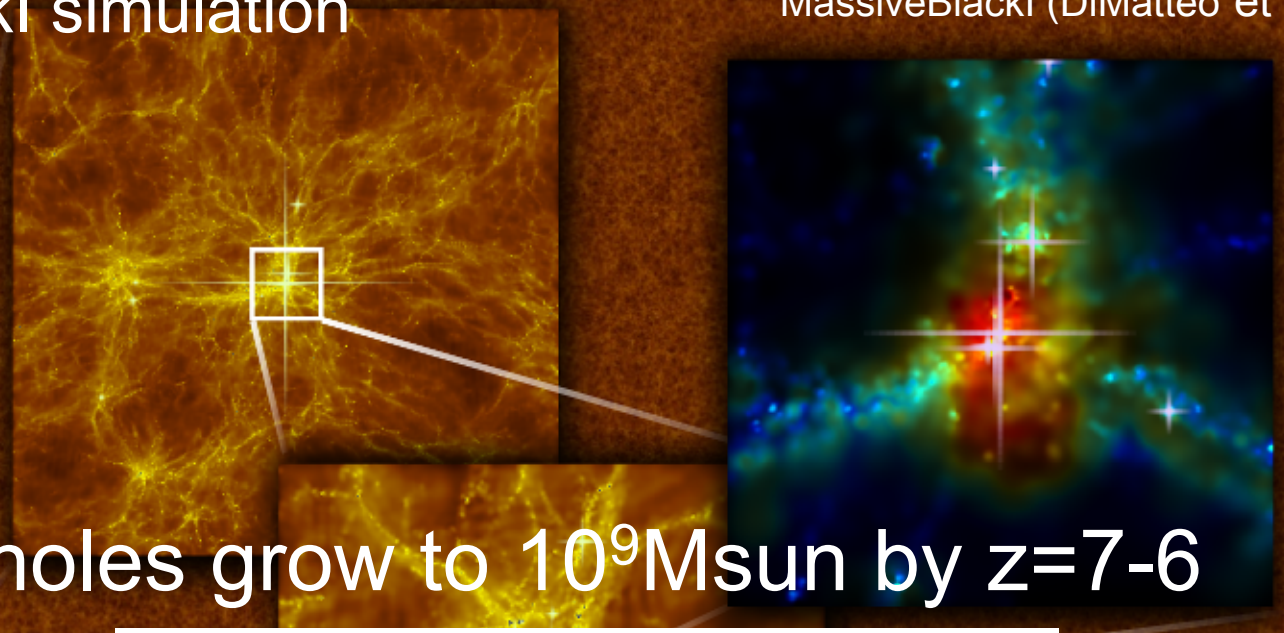
http://bluetides-project.org/


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

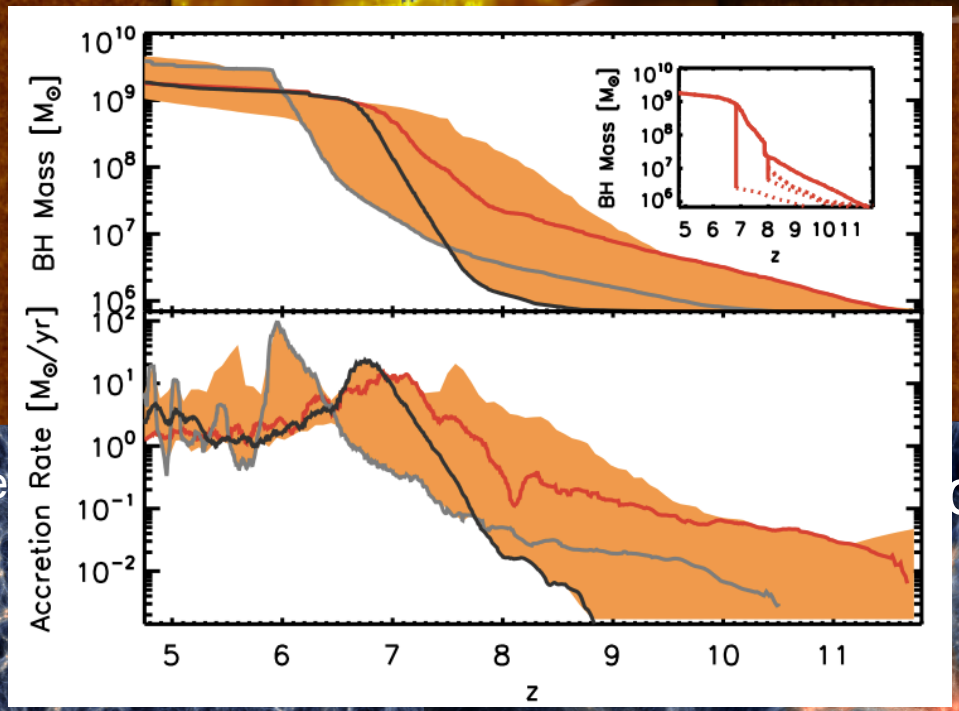

MassiveBlackI simulation
MassiveBlackI (DiMatteo et al. 2011)
MassiveBlackII (Khandai et al. 2015)
MassiveBlackII simulation

MassiveBlackI simulation

MassiveBlackI (DiMatteo et al. 2012)

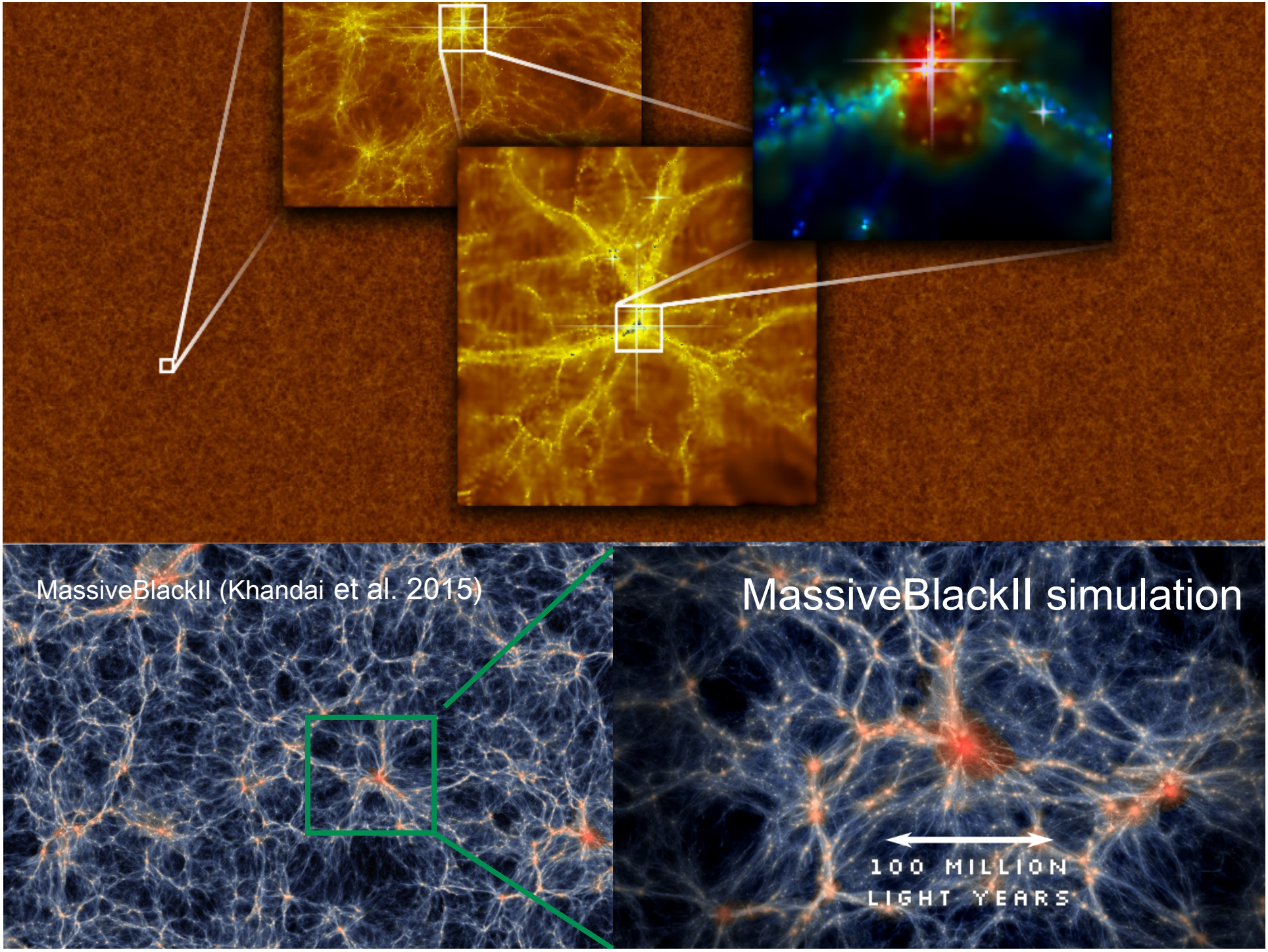


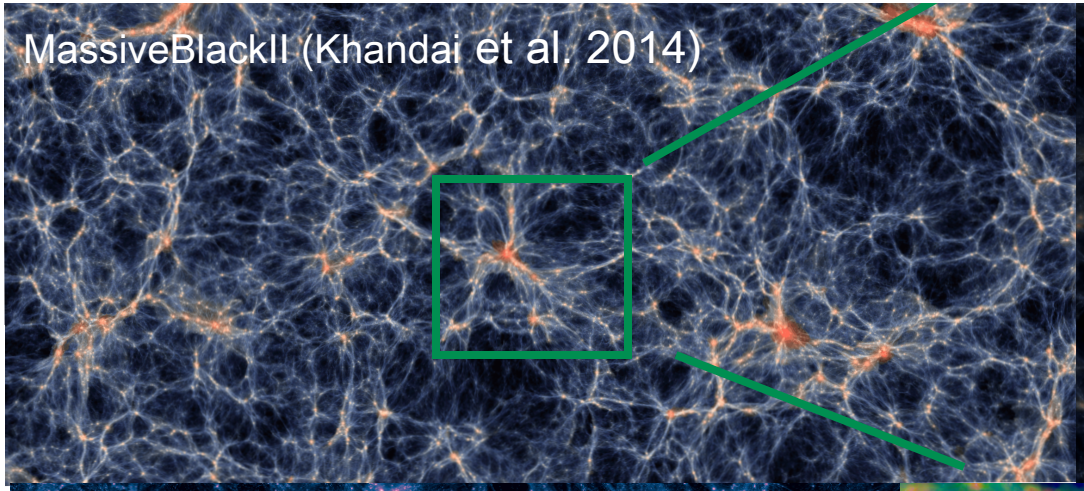
Black holes grow to 10^9Msun by z=7-6

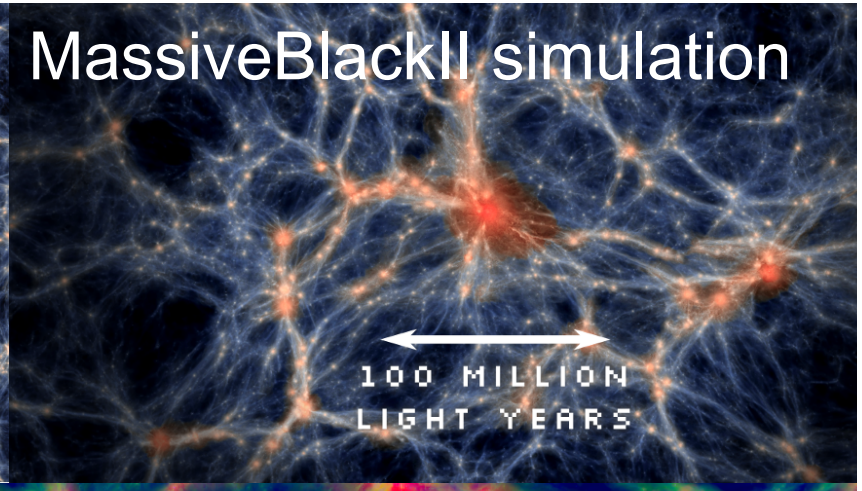


MassiveBlackII (Khandai e

ckII simulation


MassiveBlackII (Khandai et al. 2015)
MassiveBlackII simulation
100 MILLION
LIGHT YEARS


MassiveBlackII (Khandai et al. 2014)


MassiveBlackII simulation
100 MILLION
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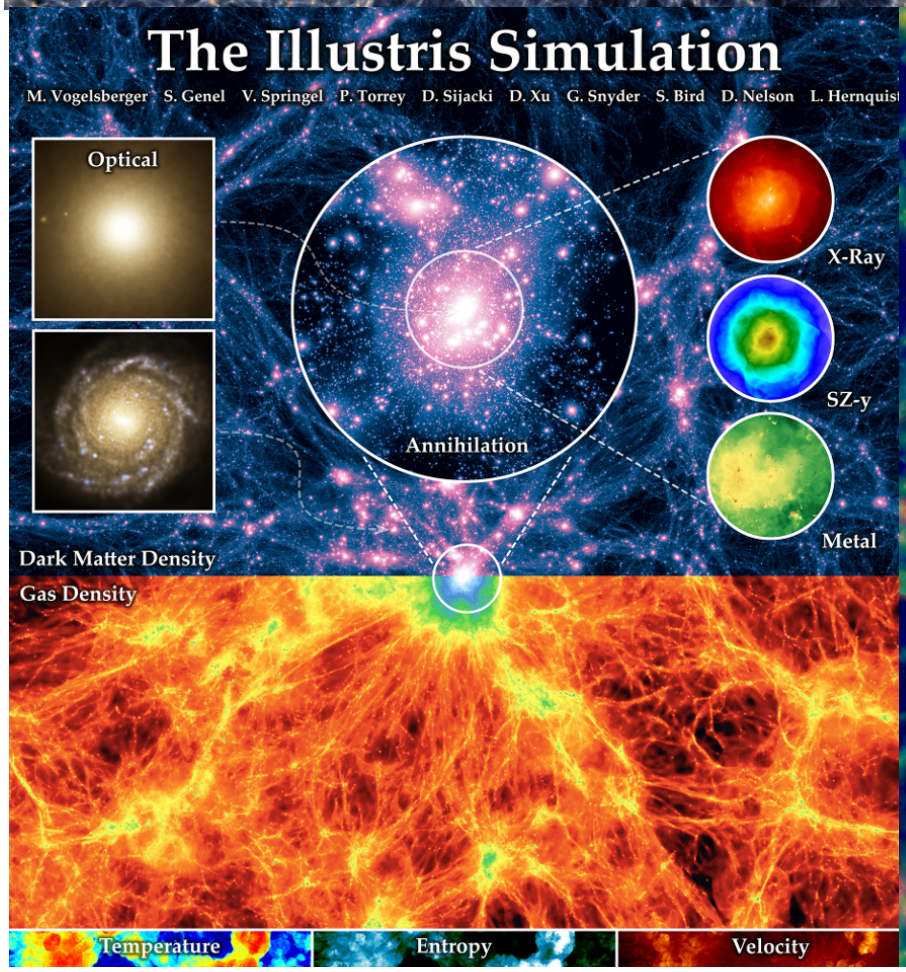
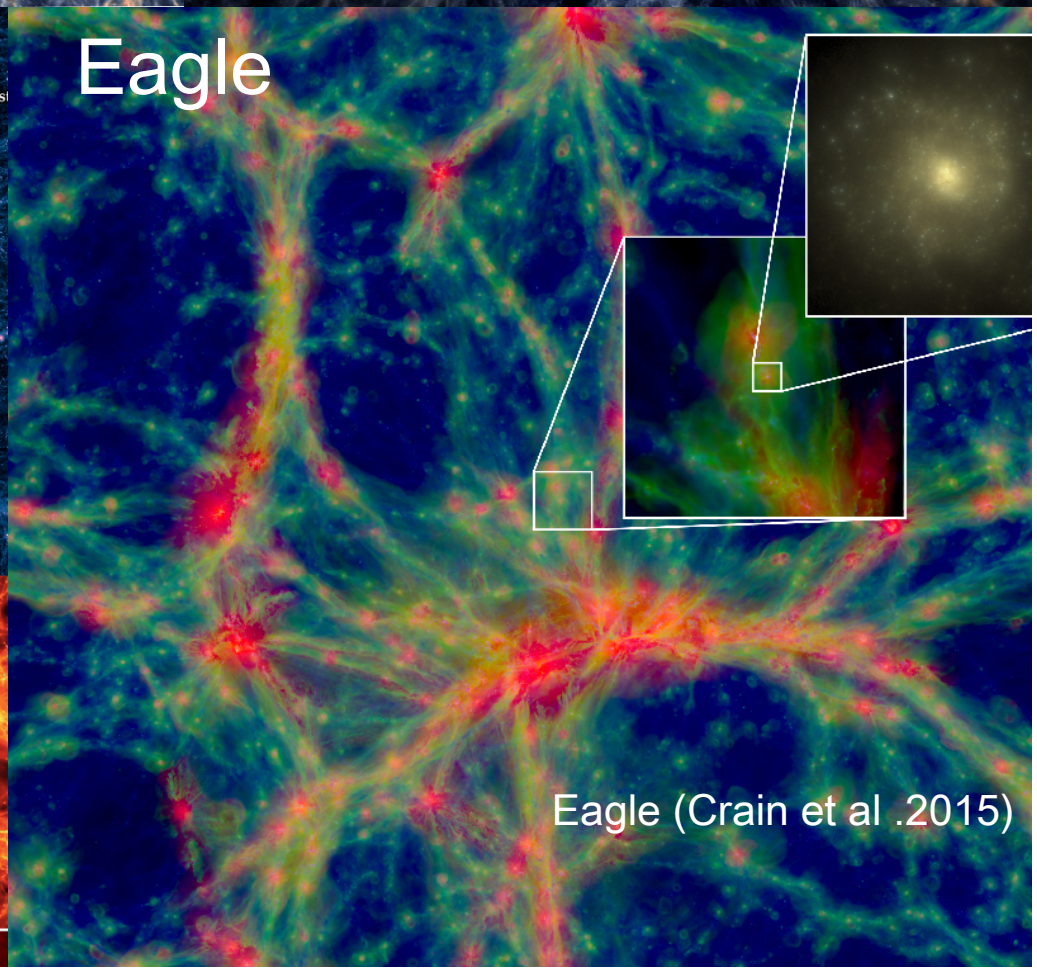
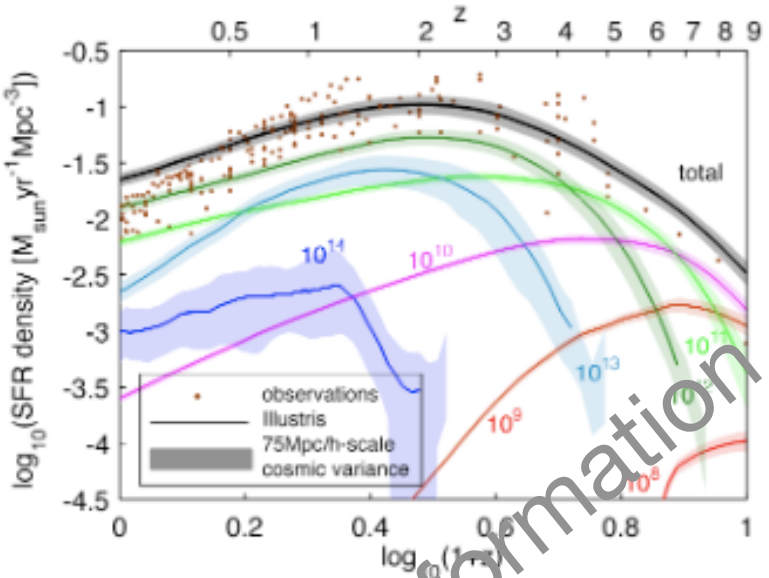
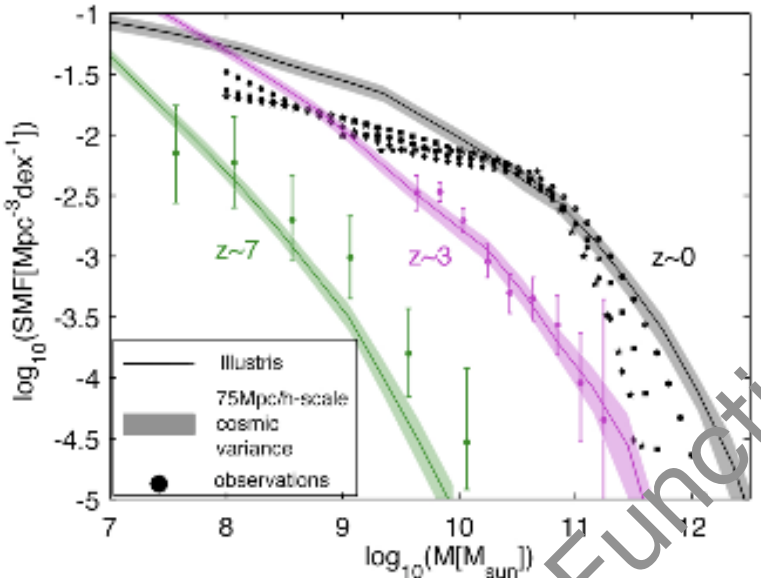

The Illustris Simulation
M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist
Optical
X-Ray
SZ-y
Metal
Annihilation
Dark Matter Density
Gas Density
Temperature
Entropy
Velocity


Eagle
Eagle (Crain et al .2015)

Simulations reproduce statistics of galaxy formation



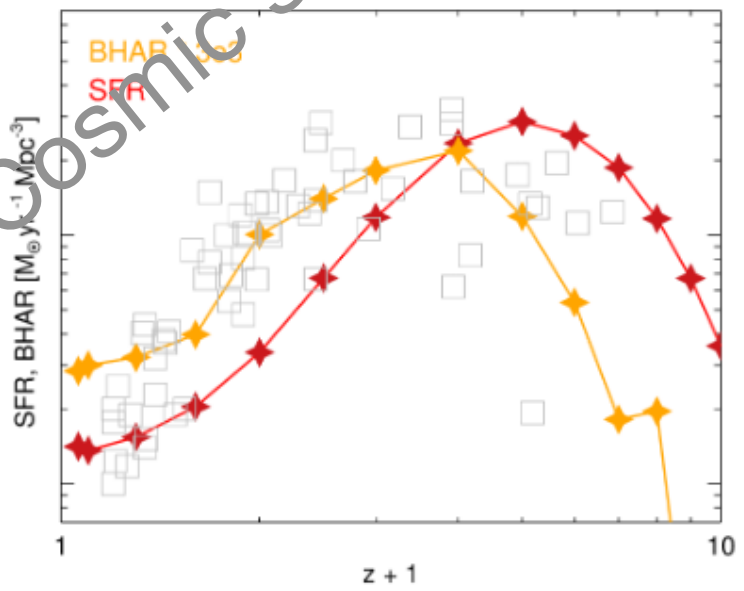
(c) Cosmic SFR density, 106.5 Mpc cosmic variance

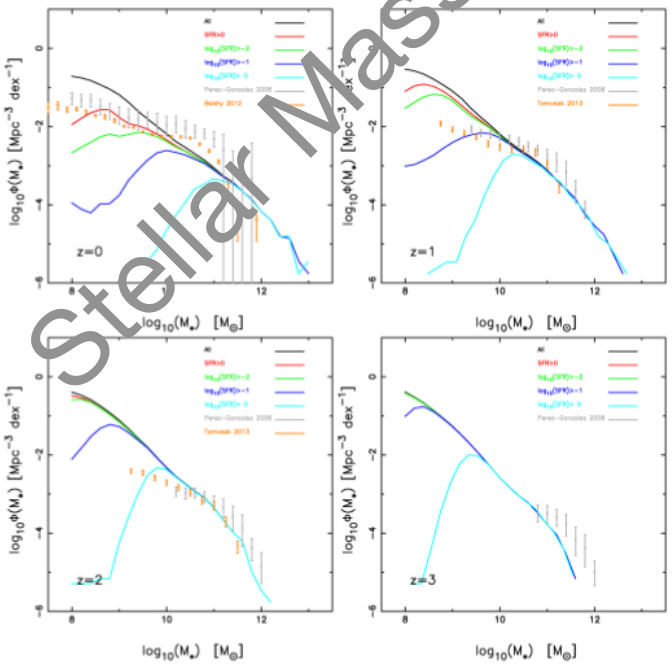


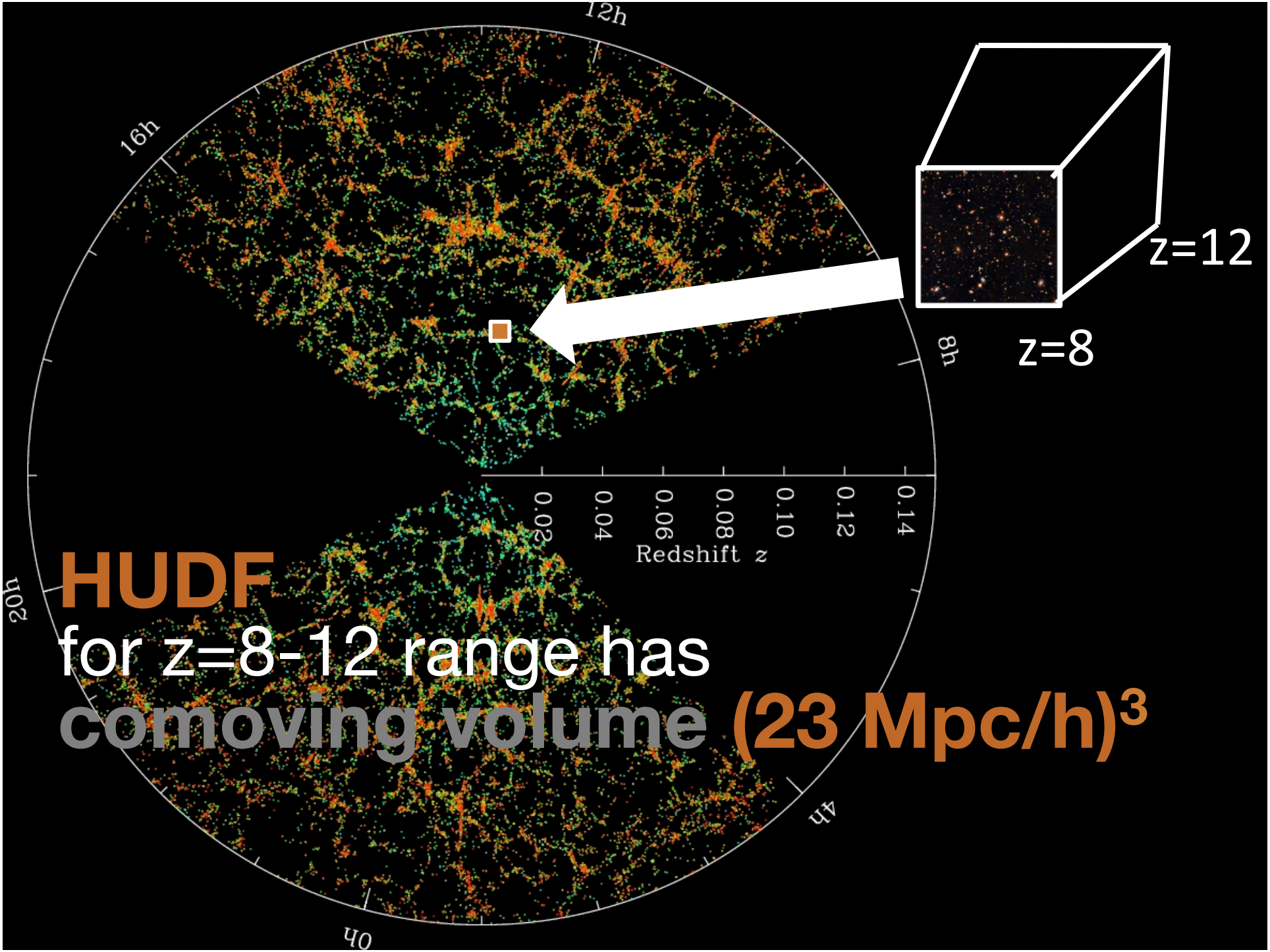
(d) Stellar mass functions, 106.5 Mpc cosmic variance

Cosmic star formation

Stellar Mass Functions






12h
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Redshift z
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for z=8-12 range has
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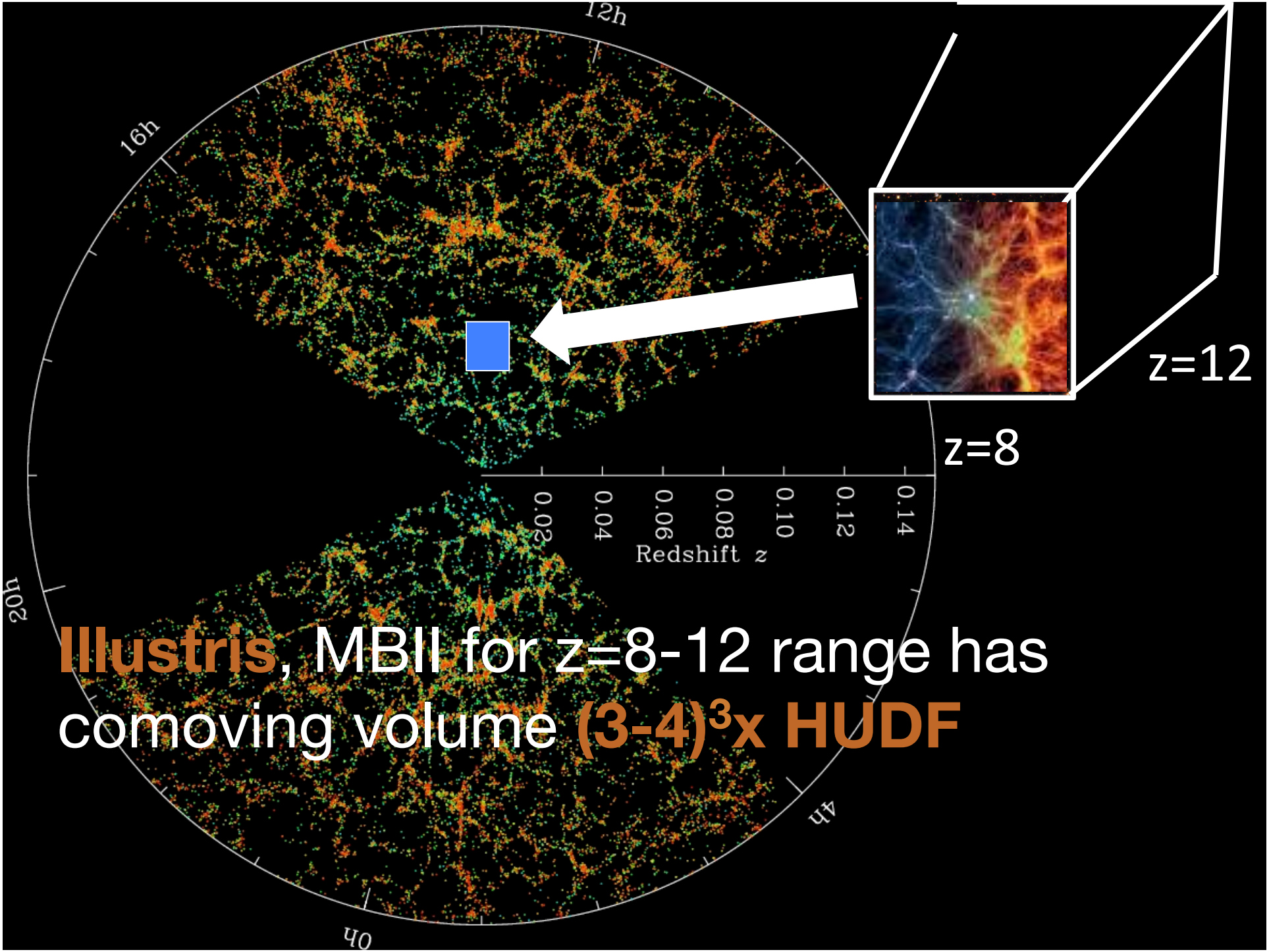
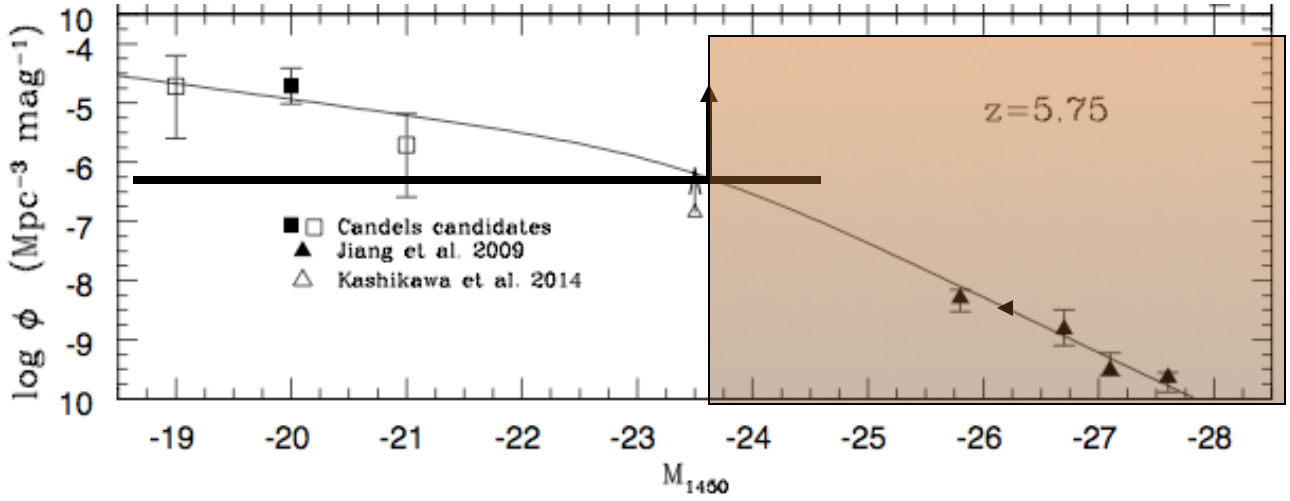


Illustris, MBII for z=8-12 range has comoving volume **(3-4)^{3}x HUDF**

Theoretical predictions lacking at z=7+
simulations have either:
insufficient resolution or too small volumes for massive objects/high density regions

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

Illustris



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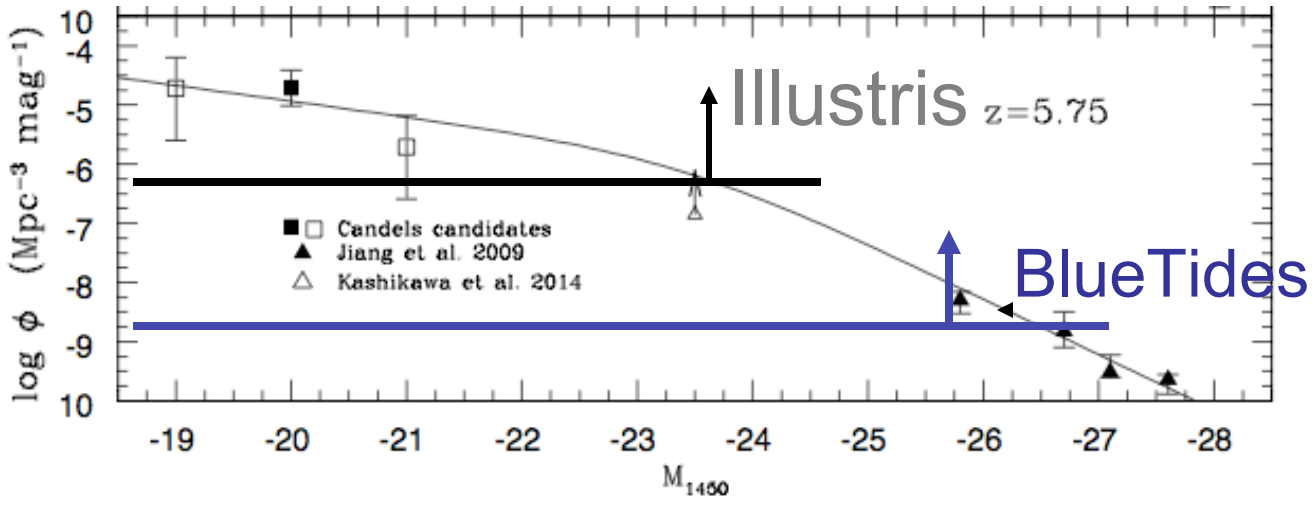


BlueTides Simulation:

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
$2x7040^3$ (0.7 trillion) particles
Star formation/ AGN model compatible with Illustris

50 times bigger volume with highest resolution

BlueTides Simulation: Technology

Current MP-Gadget: 22,000 lines
much leaner code base
flatter, low redundancy code
for better sustainability/future
developments.

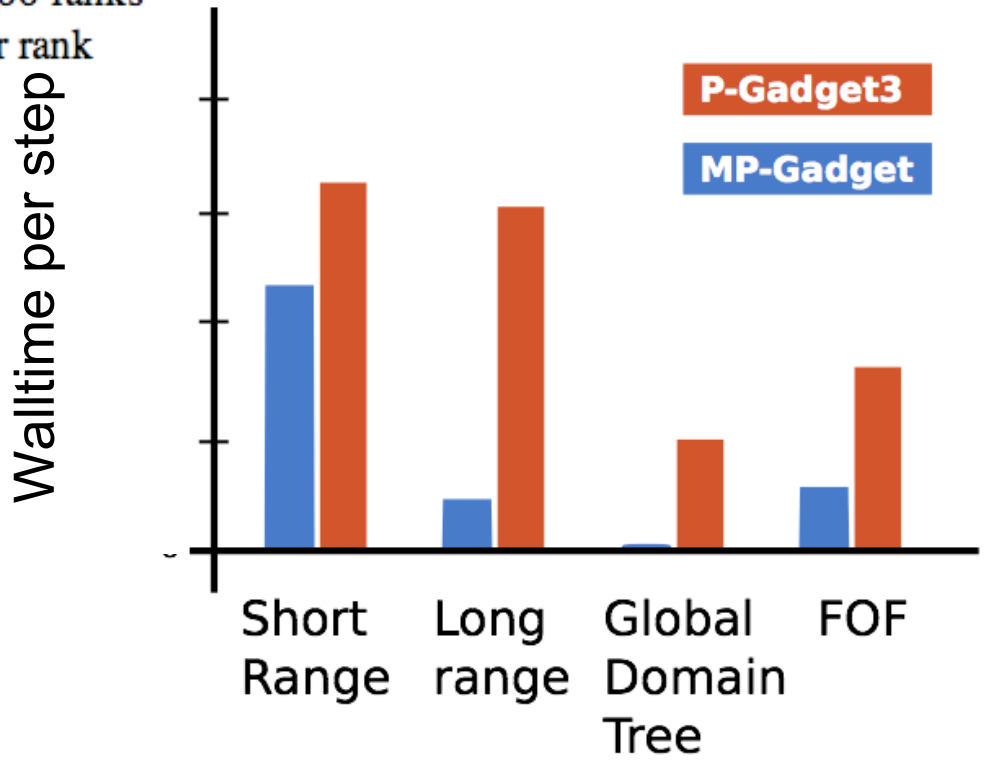
Gadget3+ MPGadget

BlueTides Simulation: Technology

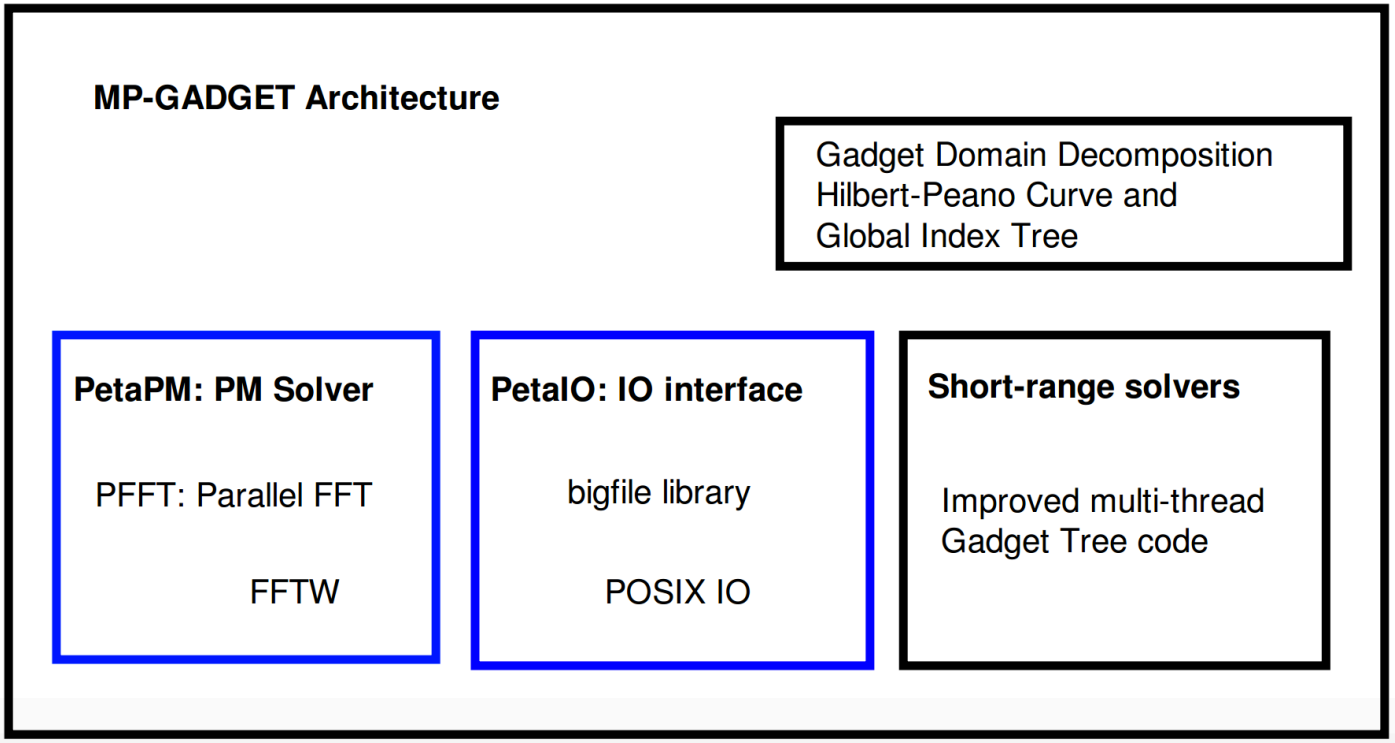
Technology Path-Finder:
- From P-Gadget to MP-Gadget
- 81000 MPI ranks, 8 OpenMP threads per rank
- Large, distributed FFT: 10,000 mesh on 81000 ranks
- Efficient thread parallism up to 32 threads per rank

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

- PFFT : large-scale distributed FFT



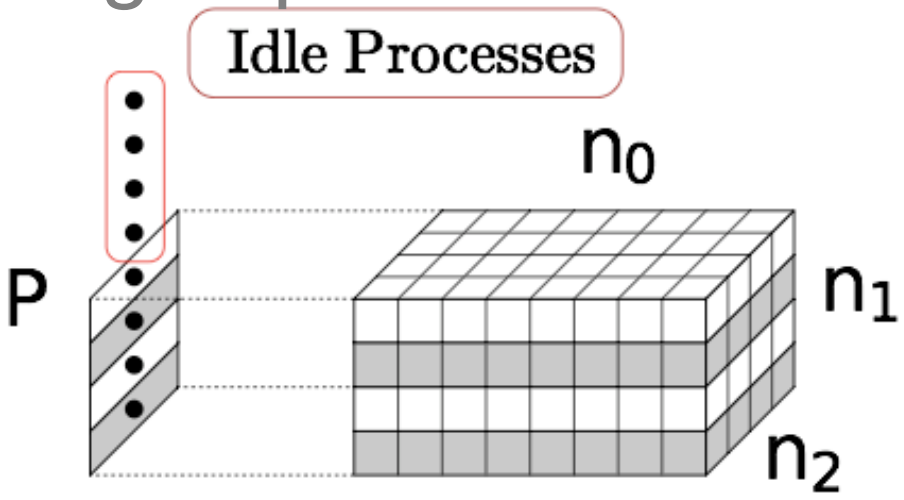
BlueTides Simulation: Technology



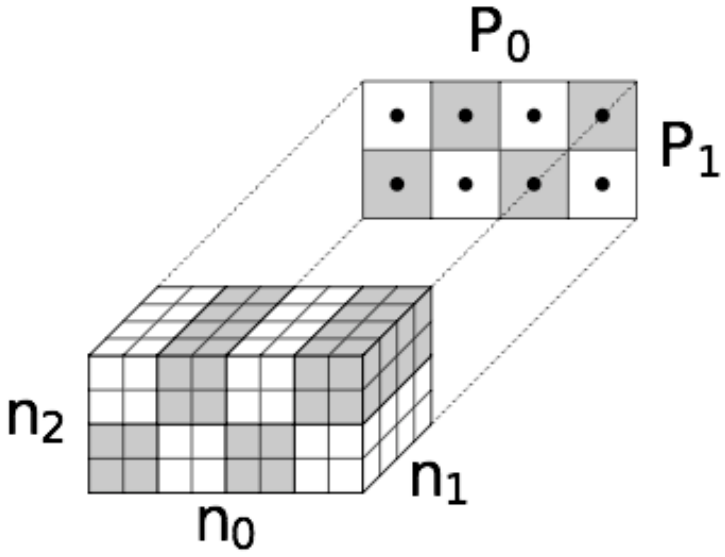
- Exposed data to avoid container overhead
- Splicing
- Plain text meta data
- Increased threading effciency (several threads interfere)
- Replaced critical sections with spinlocks

Long range force calculation (PM): New solver

E.g. 8 processes:



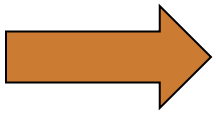
FFTW/P-Gadget3



PFFT/MP-Gadget

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

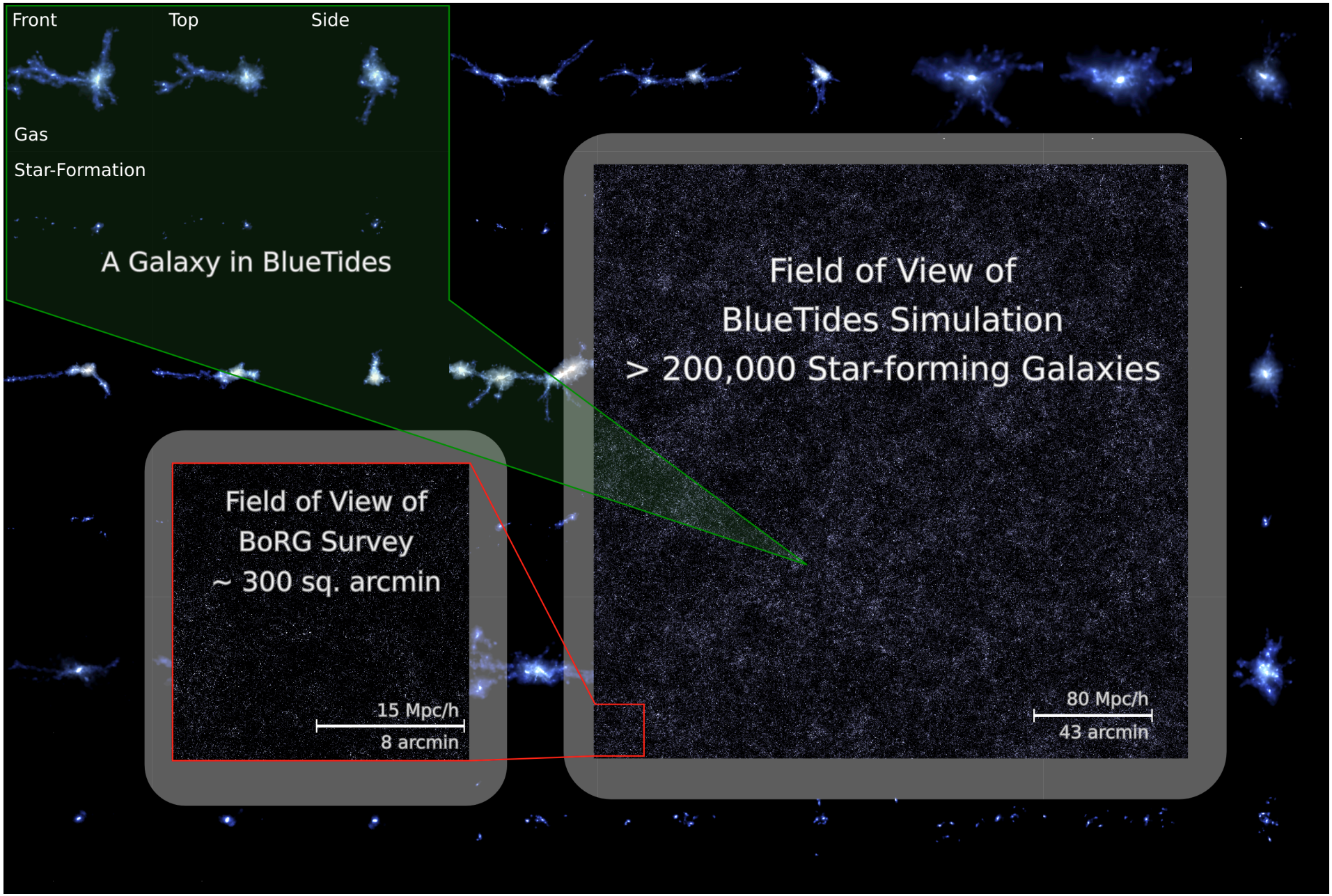
Physics modelling in BlueTides

- 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)

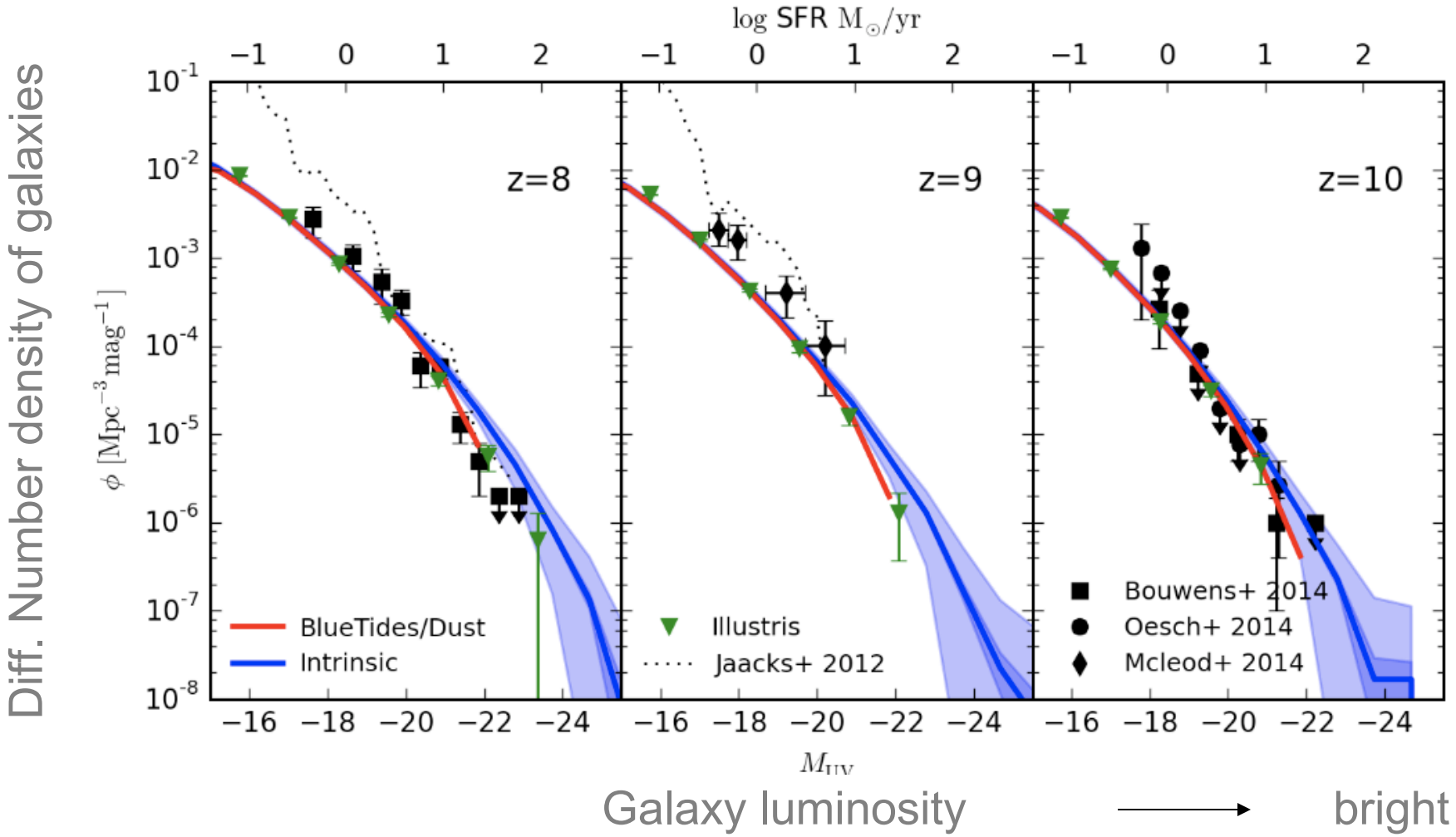
Science of high redshift galaxy

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

BlueTides 400 x volume of HUDF



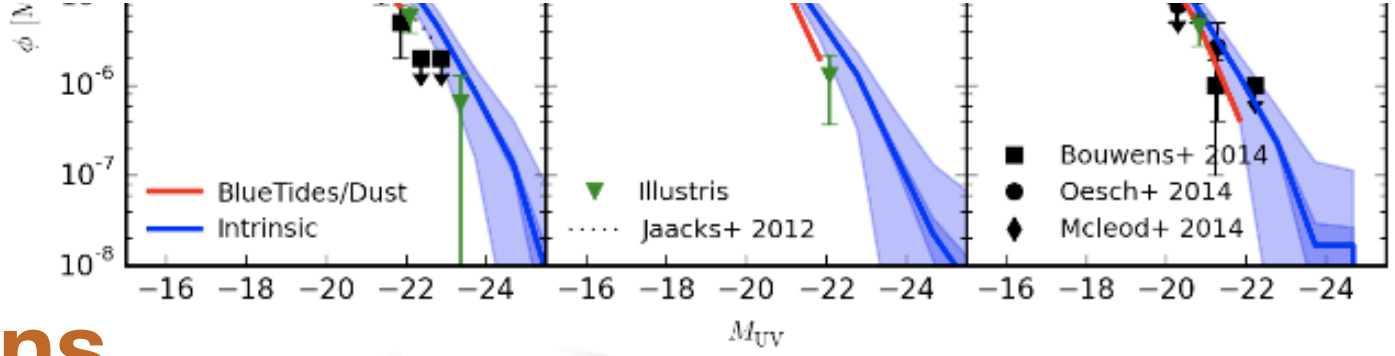
Galaxy Luminosity Function in BlueTides
consistent with Hubble Legacy Fields

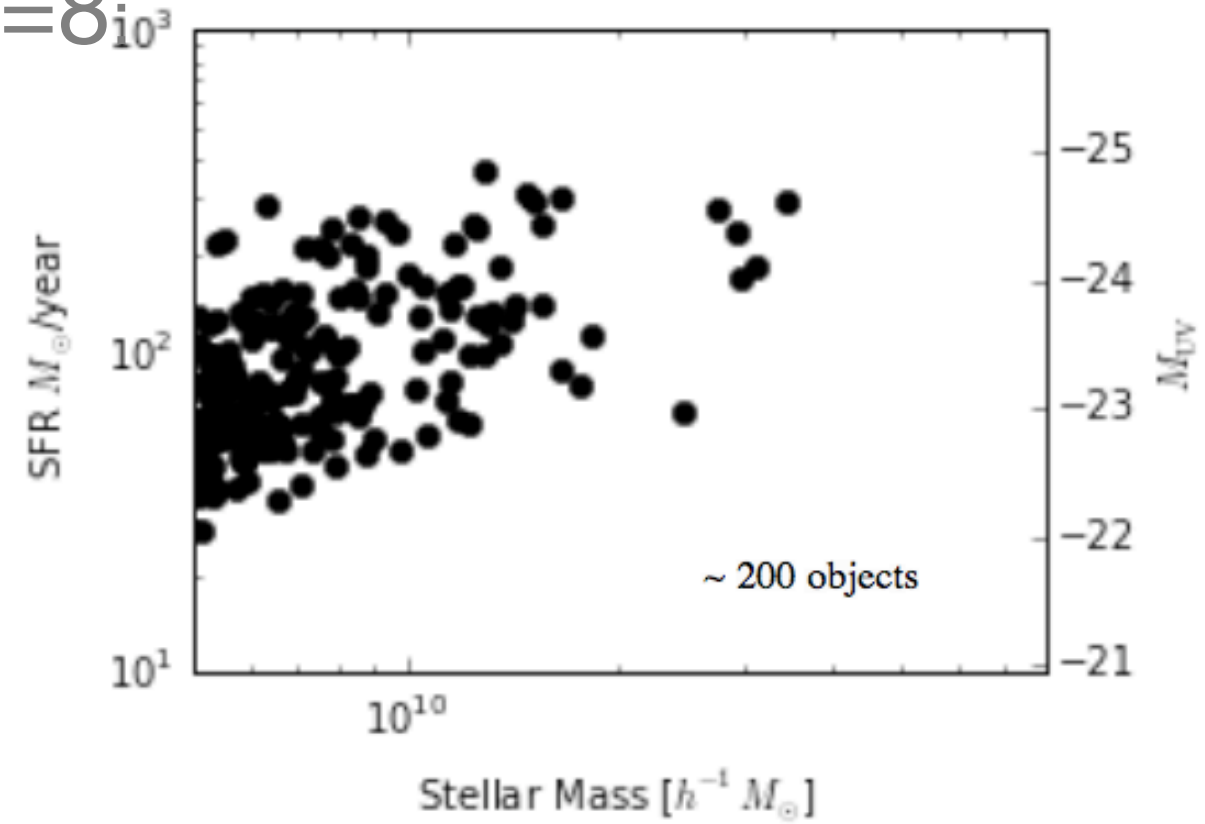


Feng et al., 2015a

Predictions

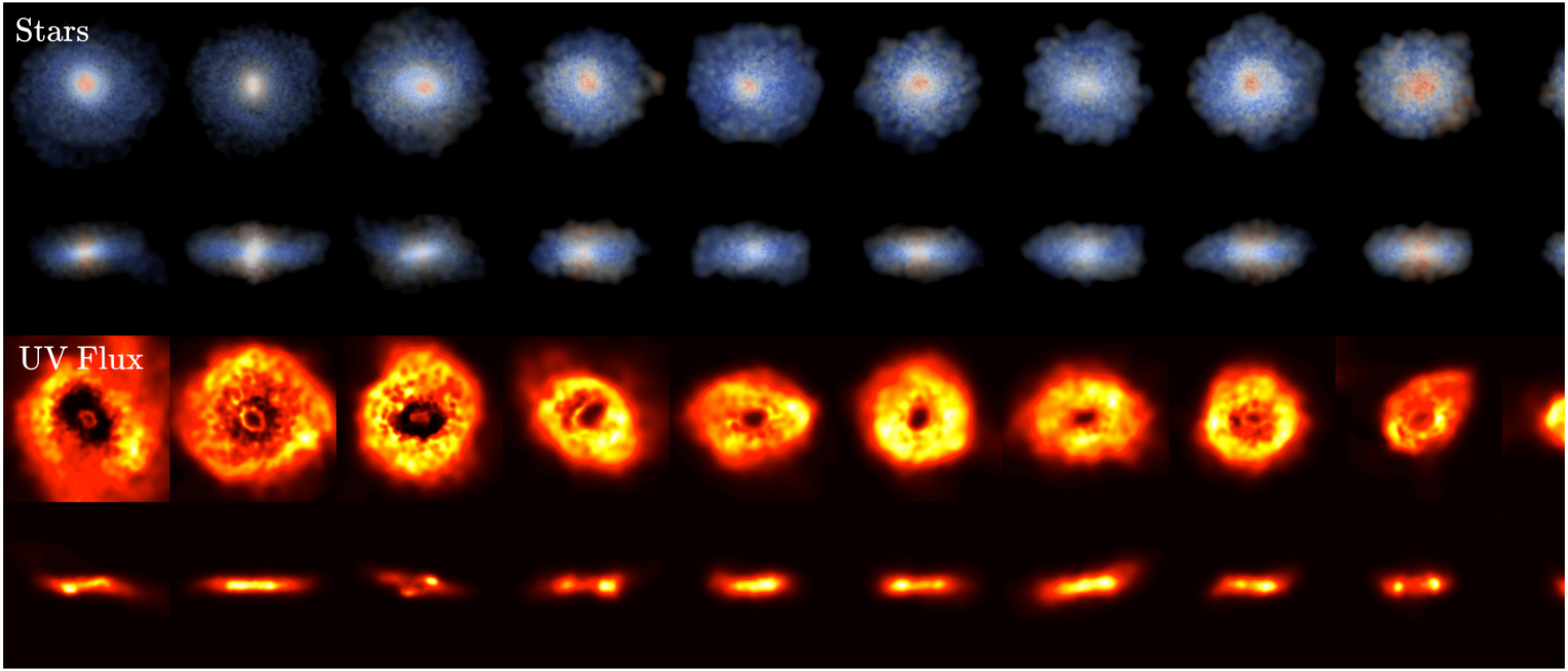
for the brightest galaxies at z=8





Example I:

z=8, Milky Way(Mass) galaxies are disks!



Feng, TDM et al., 2015

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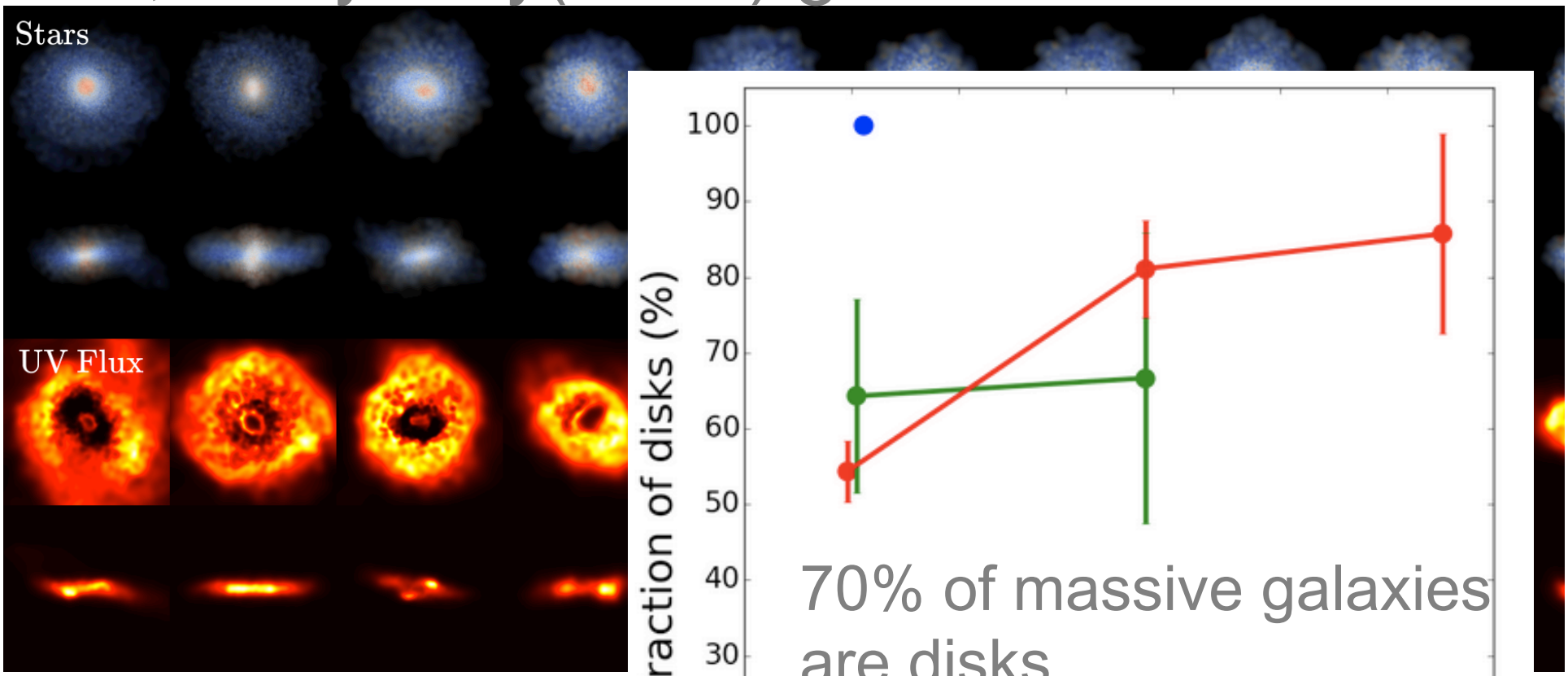
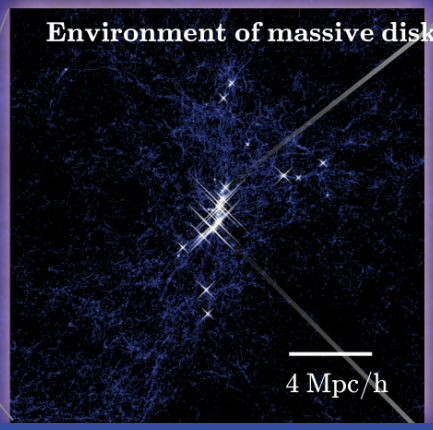
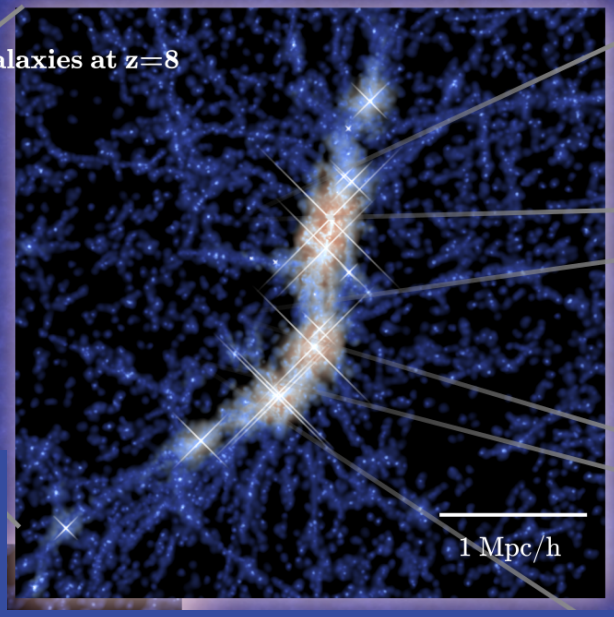
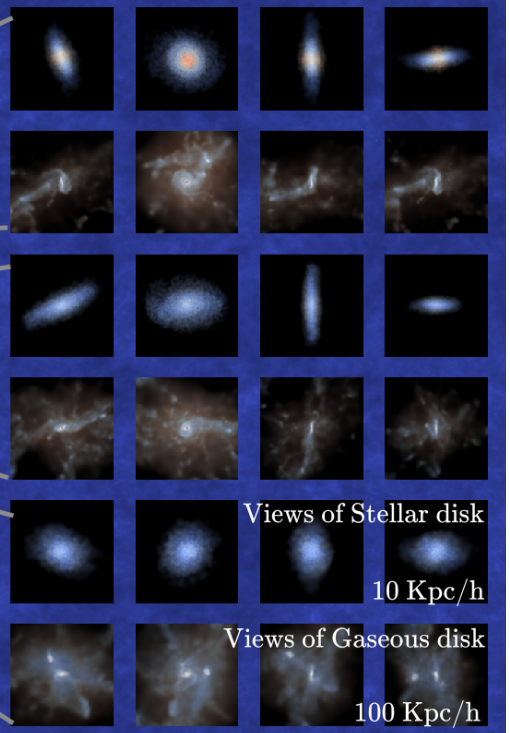








WFIRST
should detect
~ 8000 Milky Way
mass disks
at z=7-8

The **BlueTides** Simulation
0.7 trillion particles
0.65 million cores

BLUE WATERS
SUSTAINED PETASCALE COMPUTING

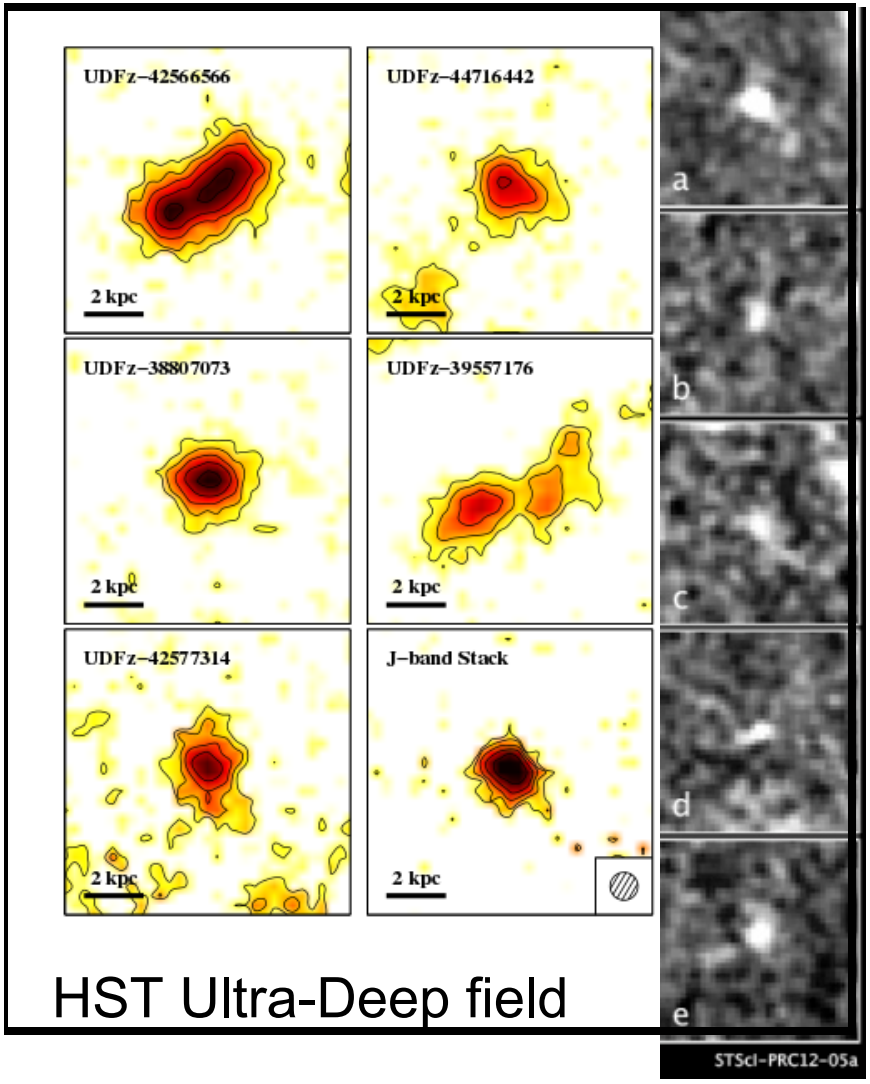
NSF

bluetides

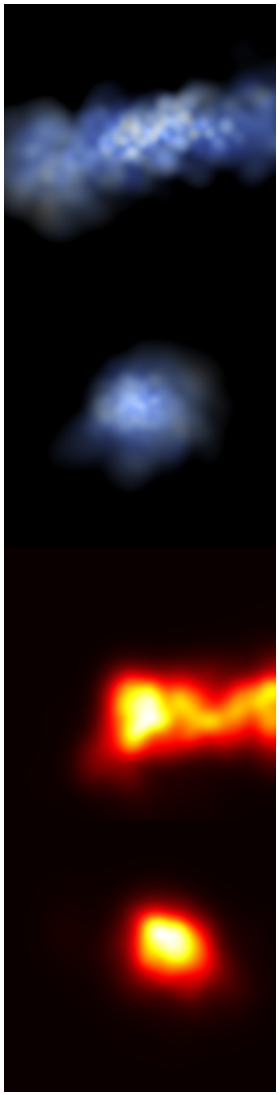
Feng et al. 2015

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

But small faint galaxies are irregular



HST Ultra-Deep field

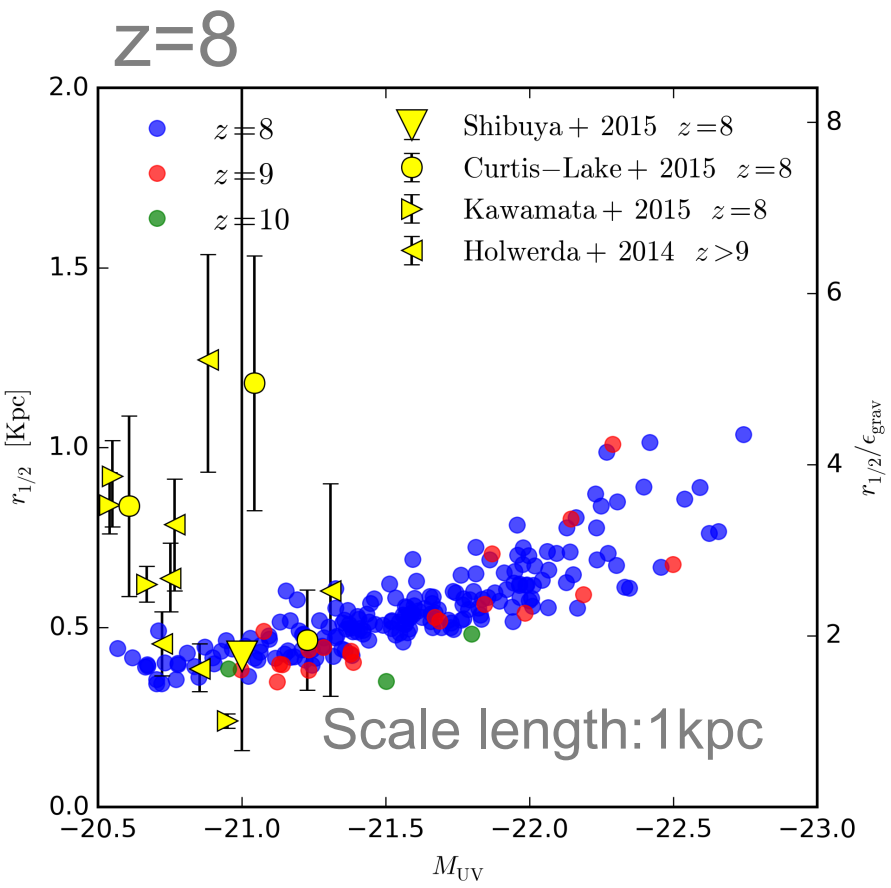


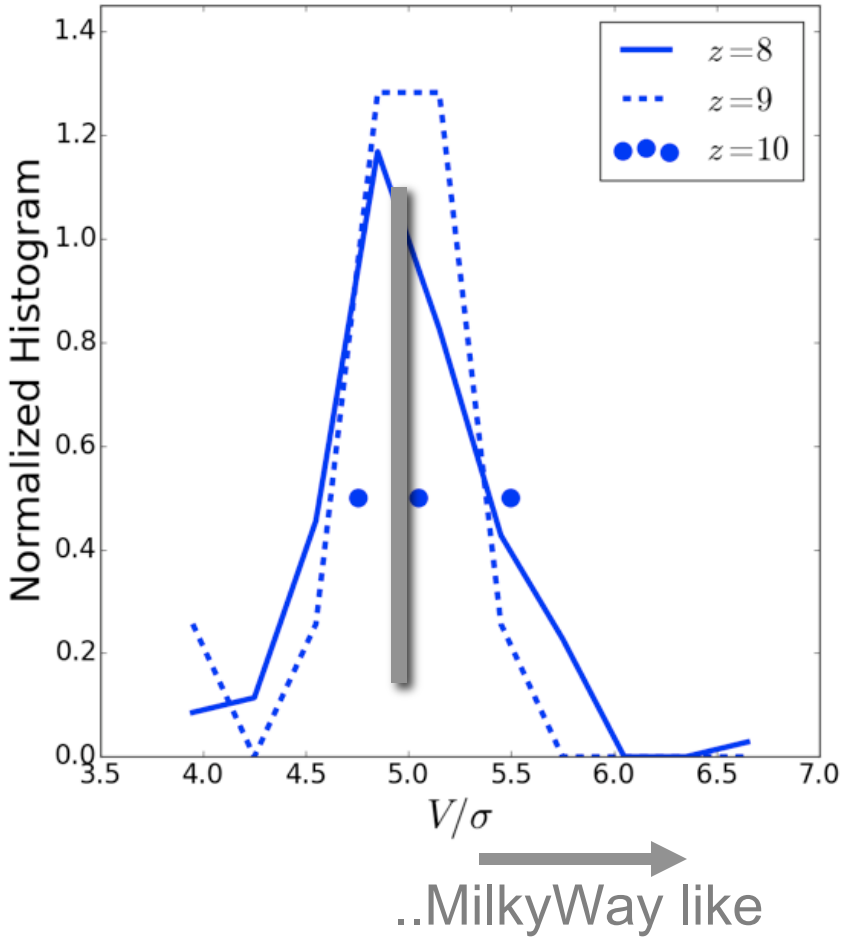
Bluetides

small galaxies

Feng et al., 2015b

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



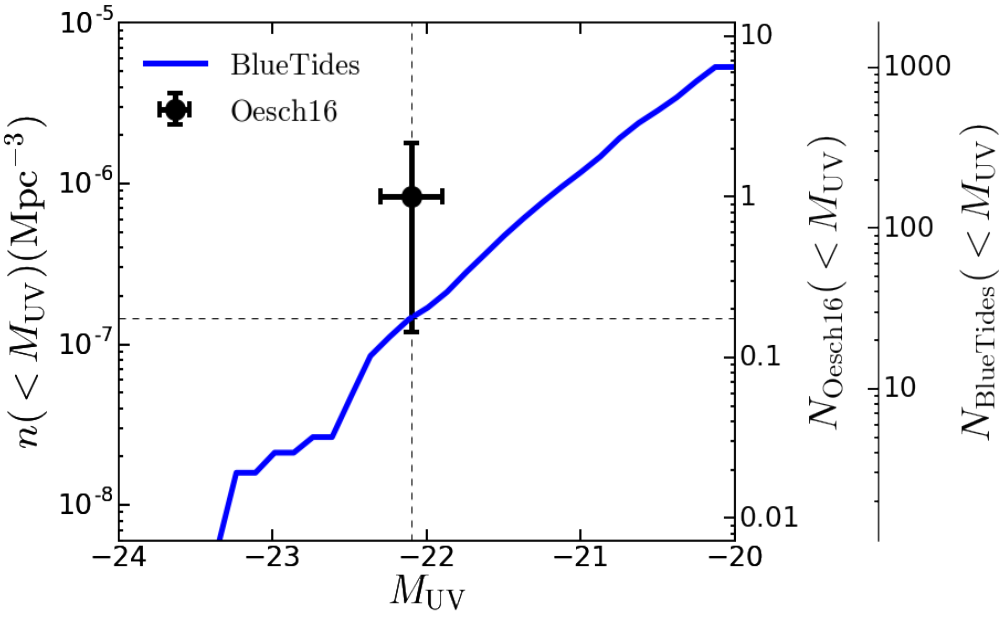


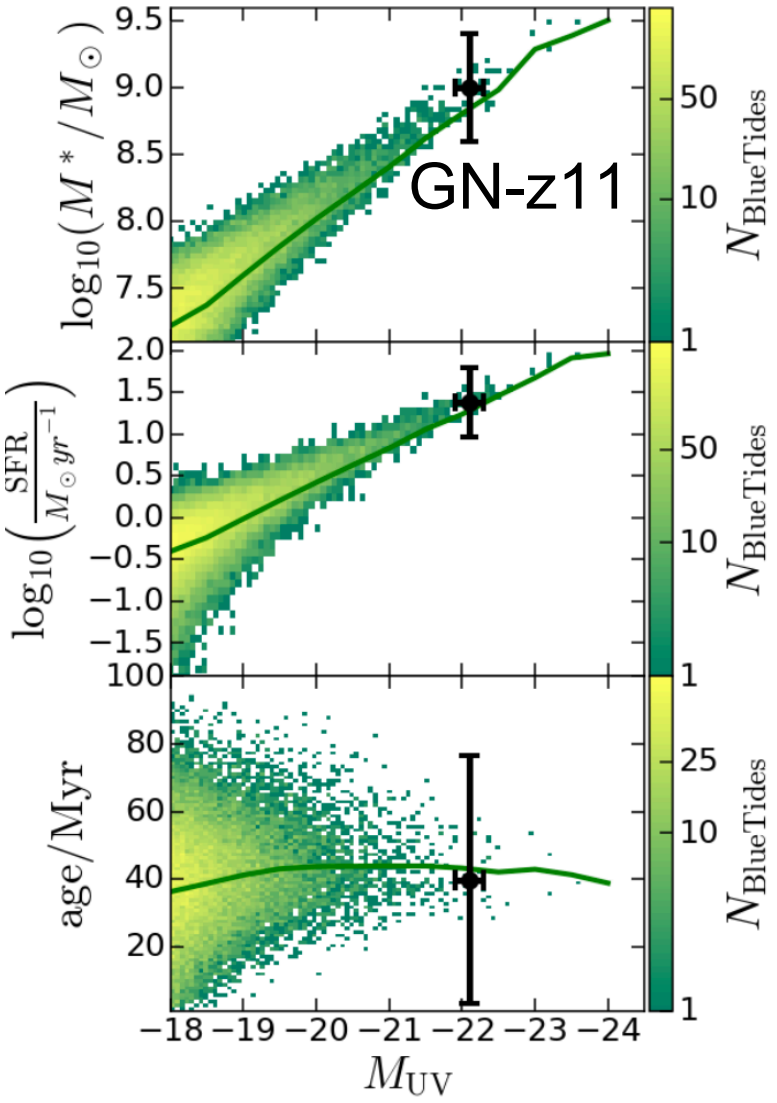
..MilkyWay like

Feng et al., 2015a

Example II:

Z=11, GN-z11 cosmic distance record is in Bluetides.





Example III:
First quasars beyond z=7

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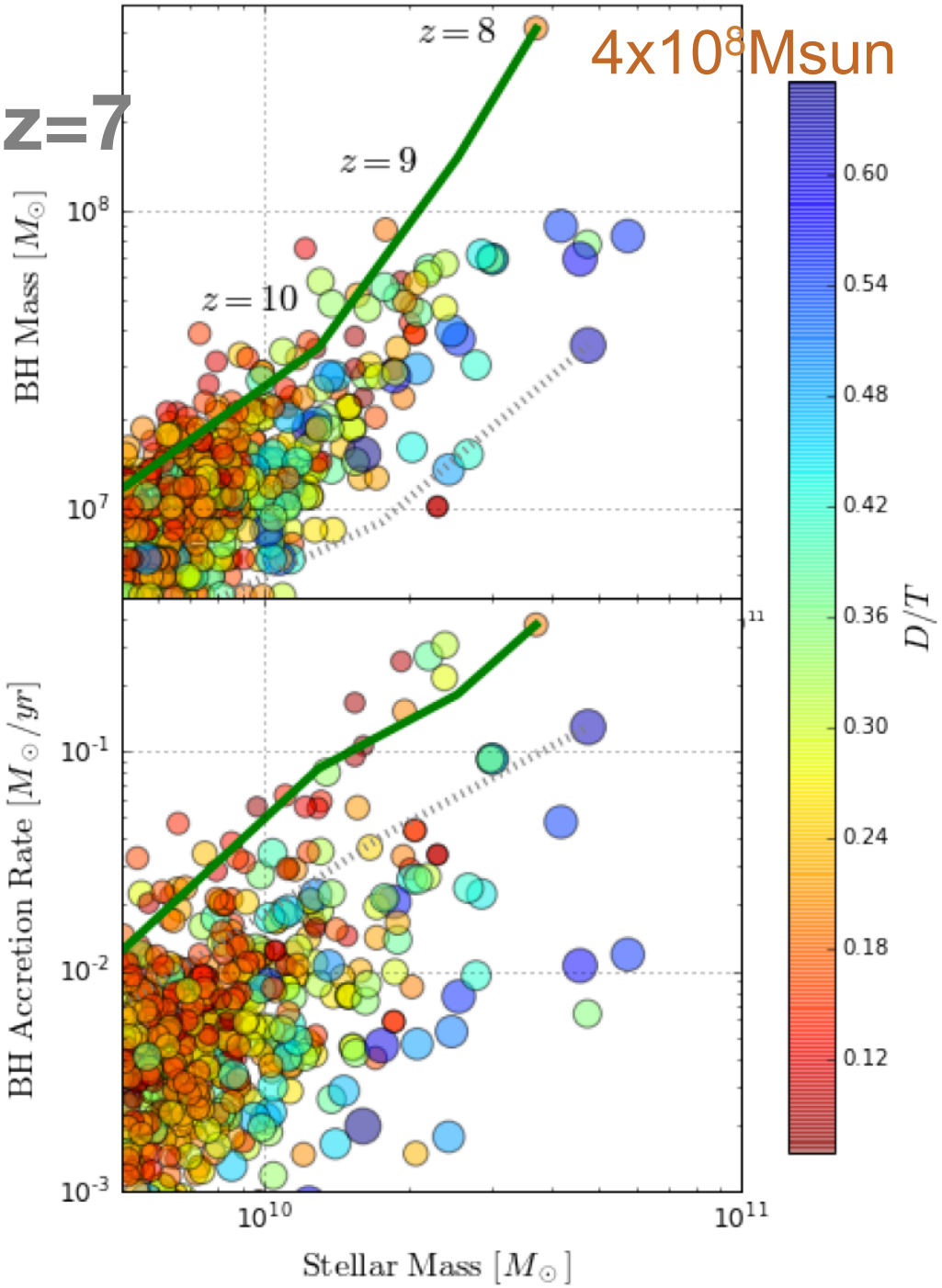
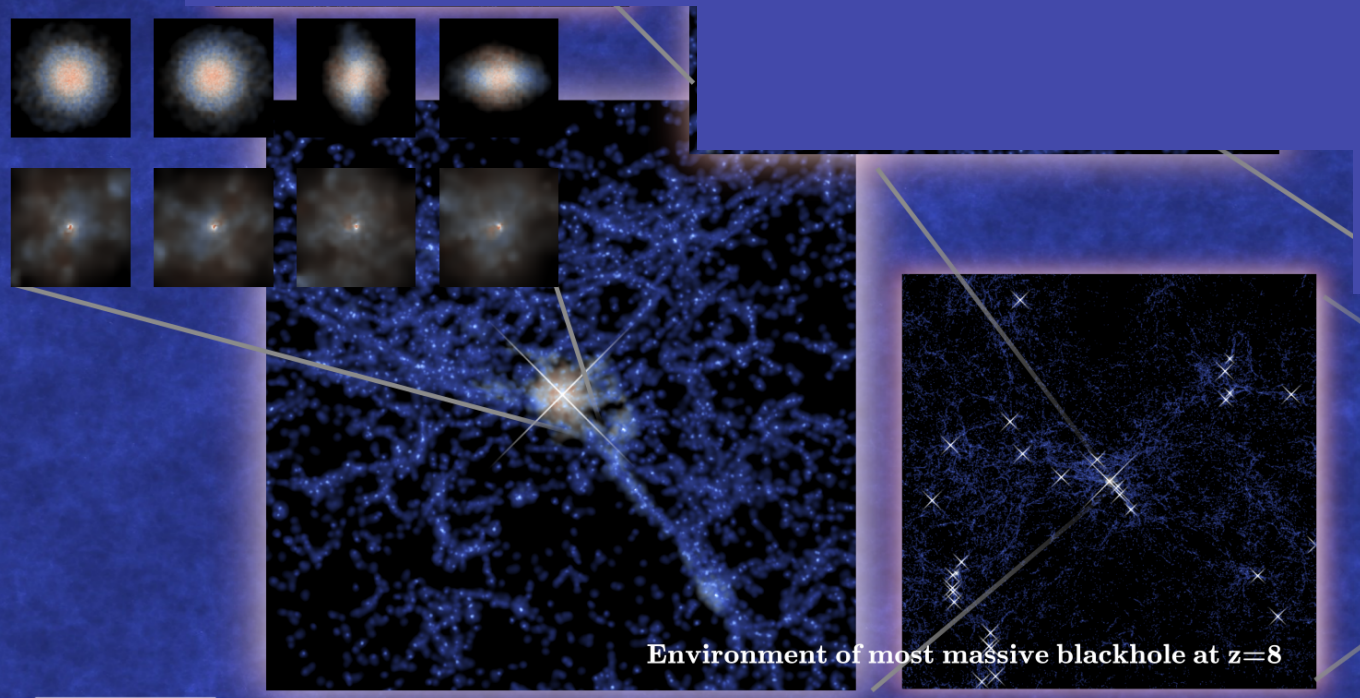
First quasars beyond z=7

Most massive BHs
at z=8, M ~ $10^8 M_{sun}$

Fastest growing,
massive black holes
are not in disky galaxies!



The environment of the most massive BH: compact, spheroidal host galaxy with strong radial inflows



Environment of most massive blackhole at z=8

40 Mpc/h

The **BlueTides** Simulation

0.7 trillion particles

0.65 million cores

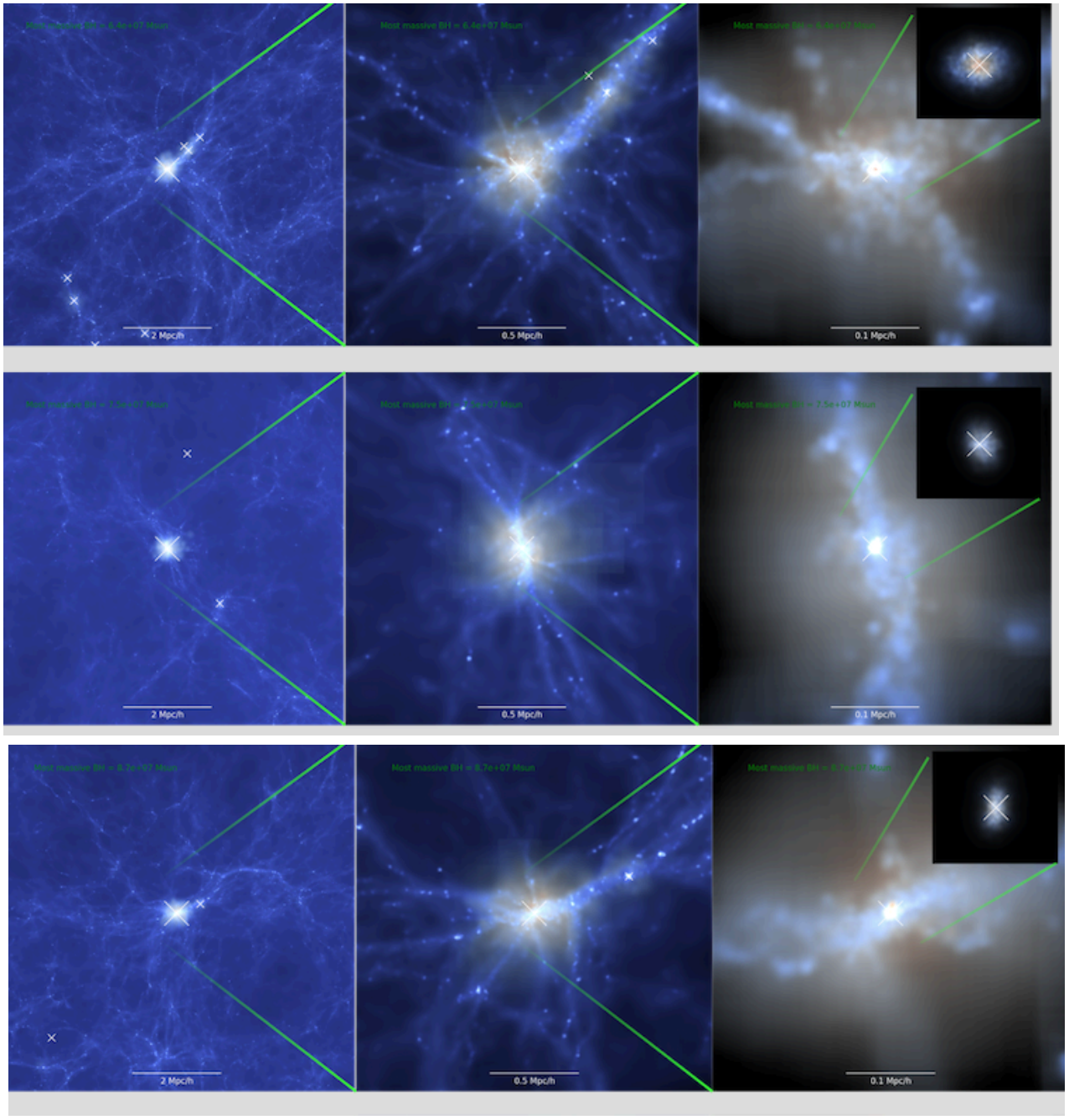
BLUE WATERS
SUSTAINED PETASCALE COMPUTING

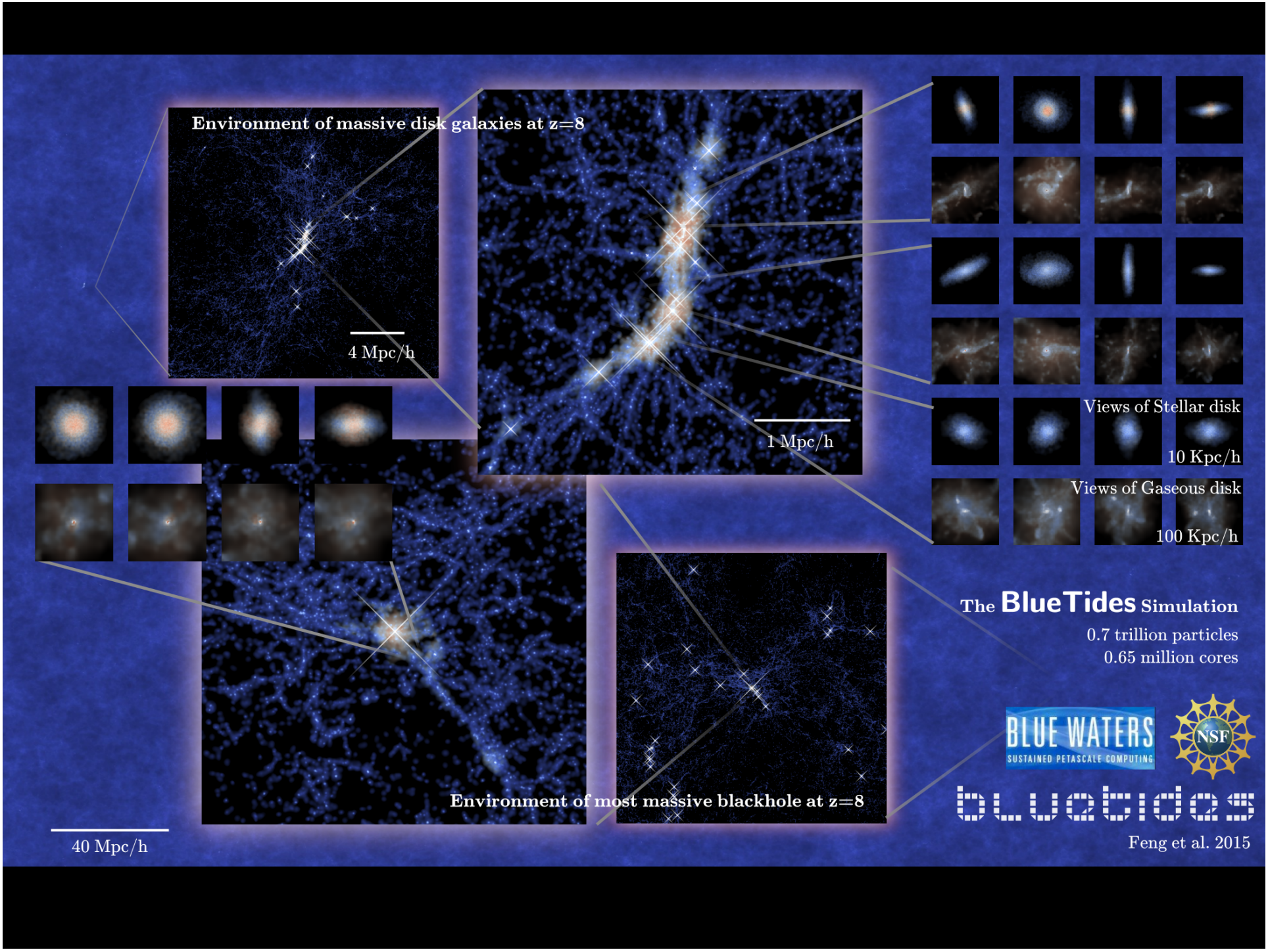
NSF

bluetides

Feng et al. 2015

Massive BHs reside 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
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bluetides
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40 Mpc/h
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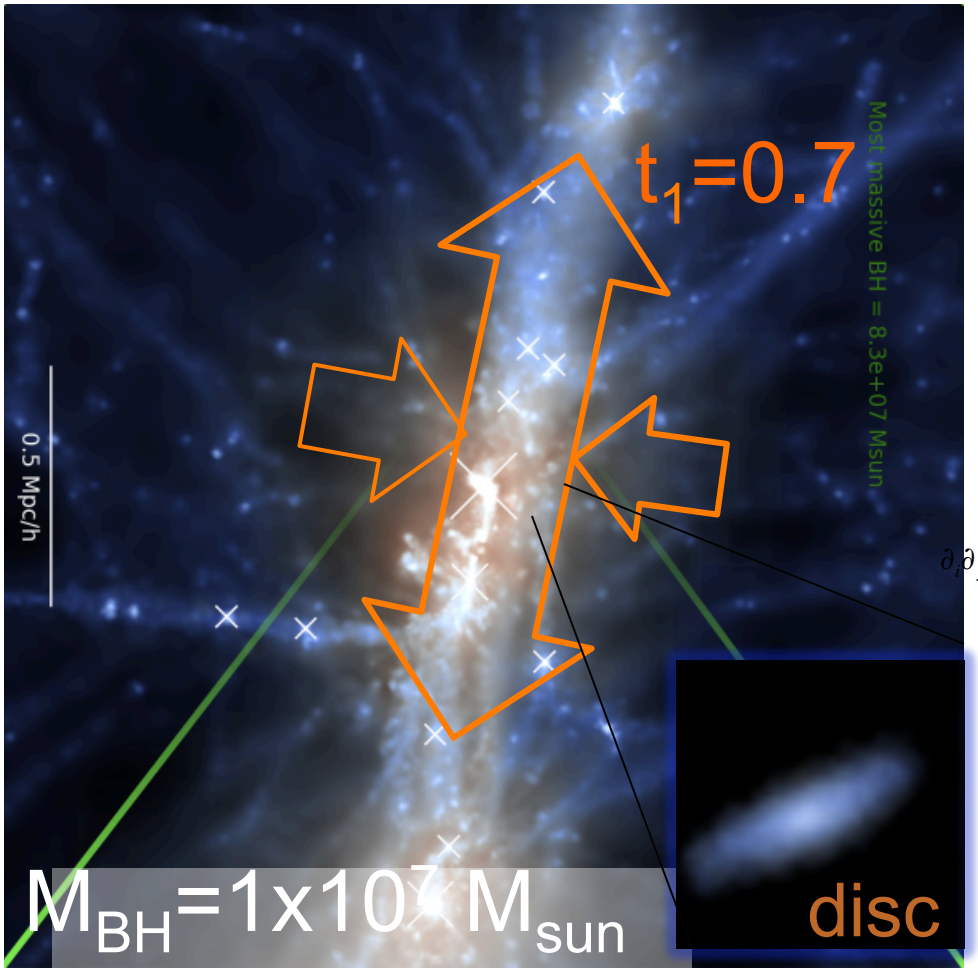
tidal tensor

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

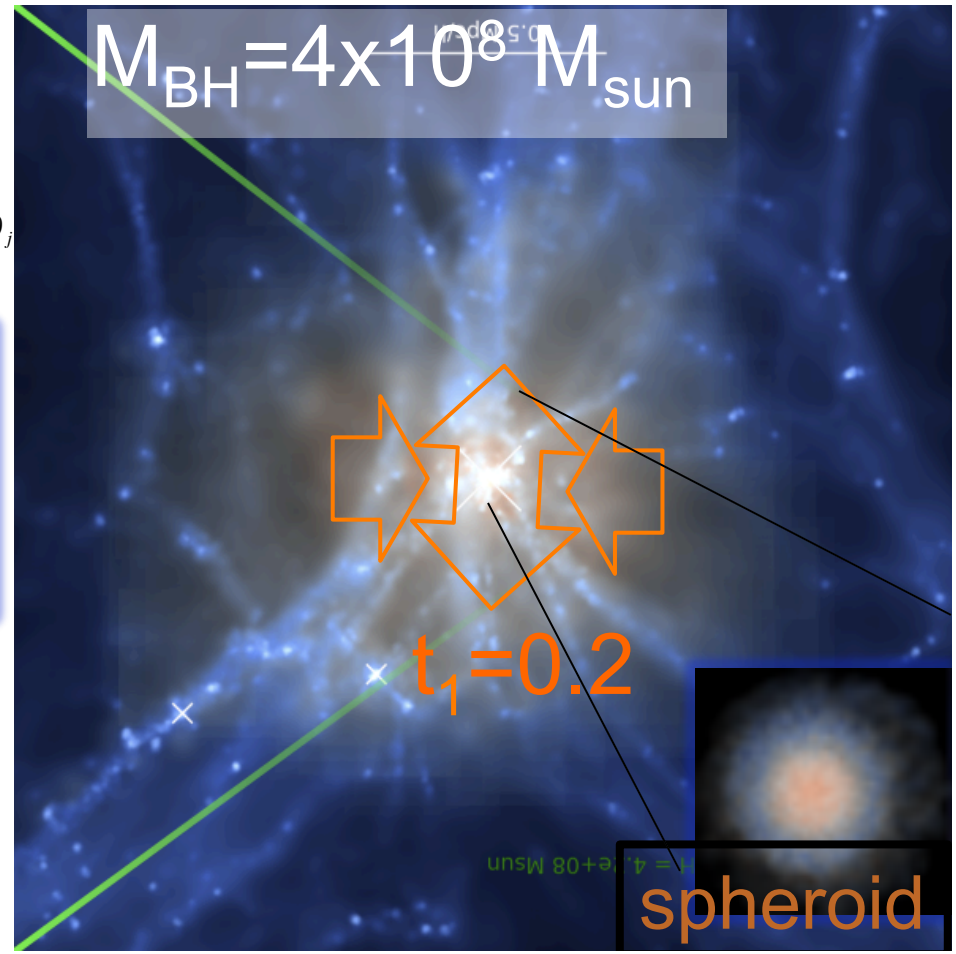


weak tidal field:

Thin filaments

radial motions along t1,

cold accretion



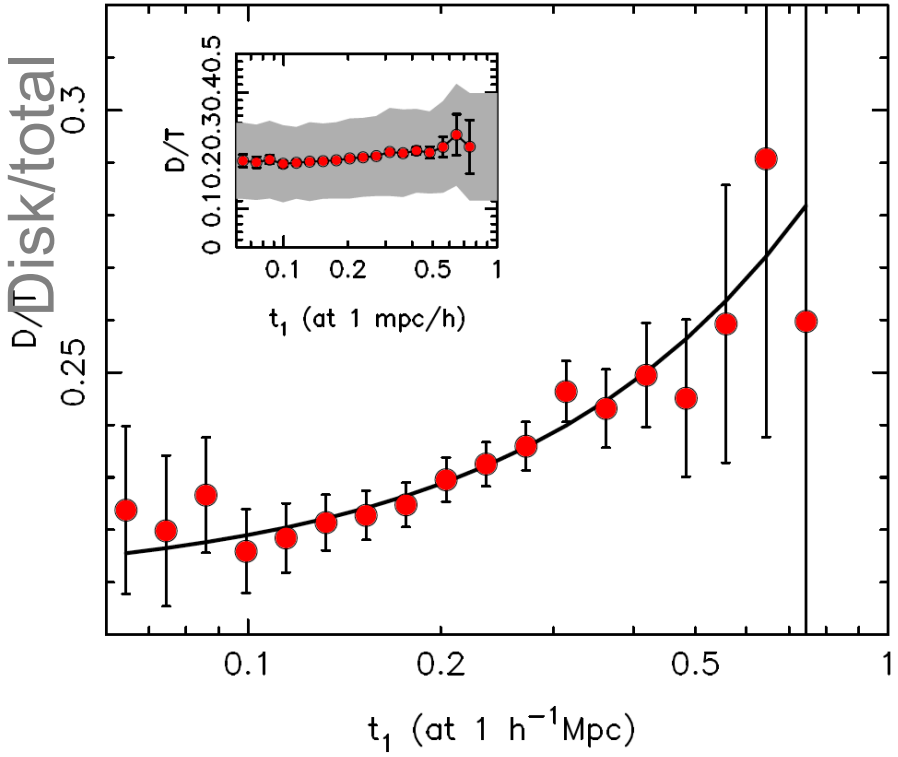
Large tidal field:

Large filaments,

Accretion perp. to t1, /coherent ang. momentum

Large tidal field:

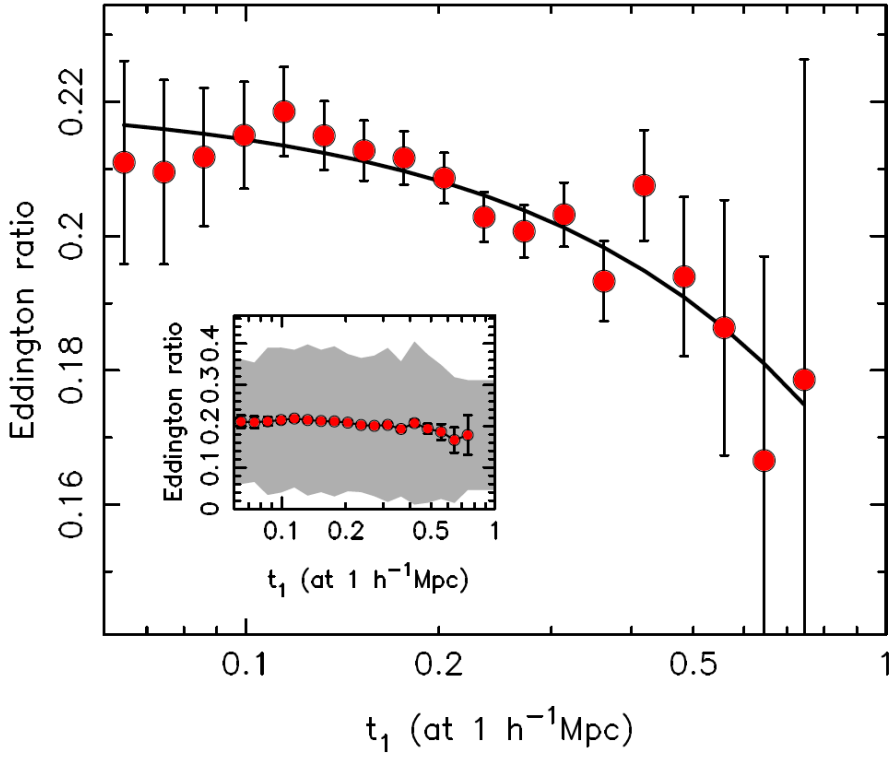
→discs



Tidal field strength

weak tidal field:

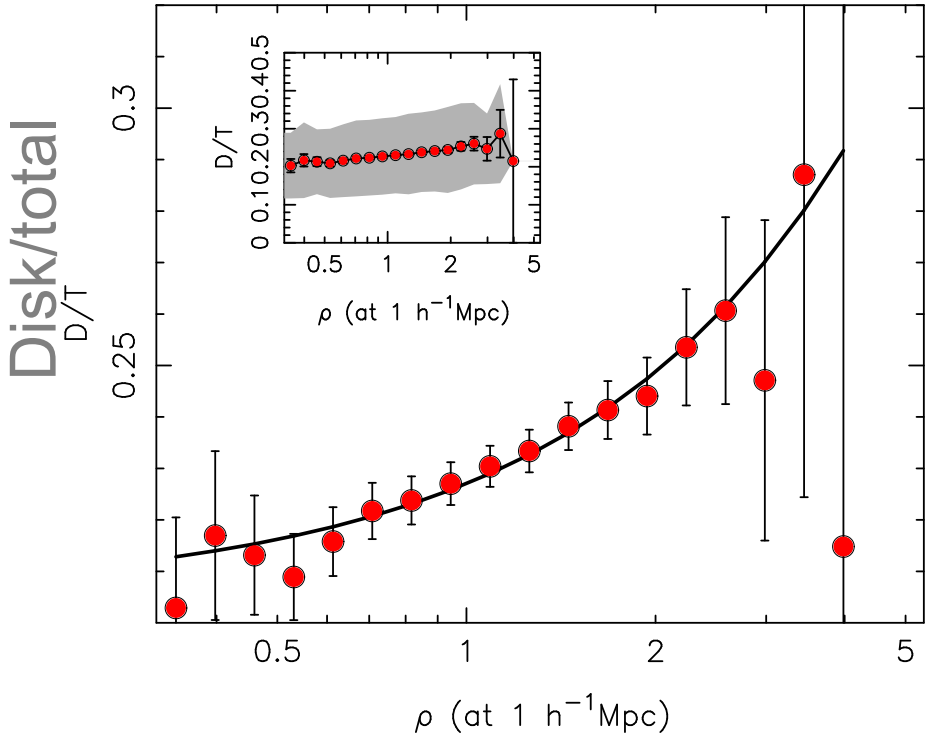
→massive BHs in spheroids



Tidal field strength

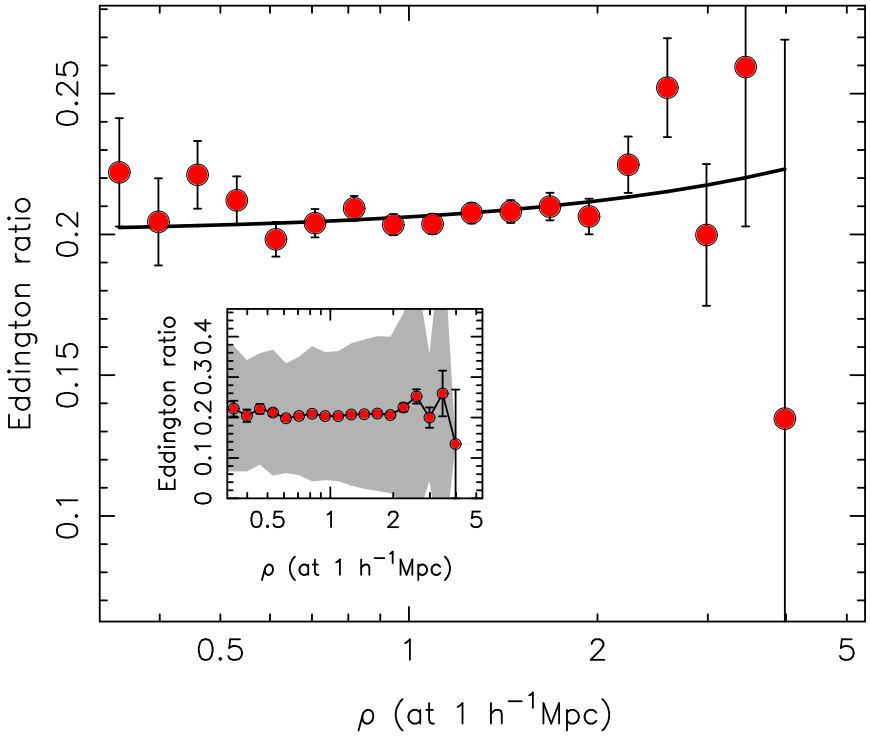
TDM et al. 17

→discs



Density field

→massive BHs in spheroids



Density field

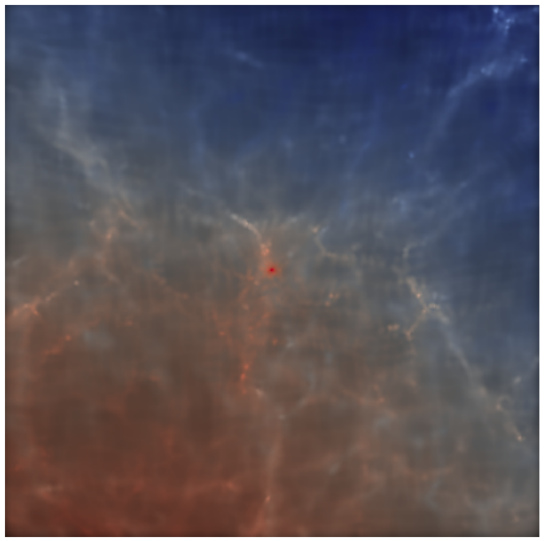
Not correlated to density

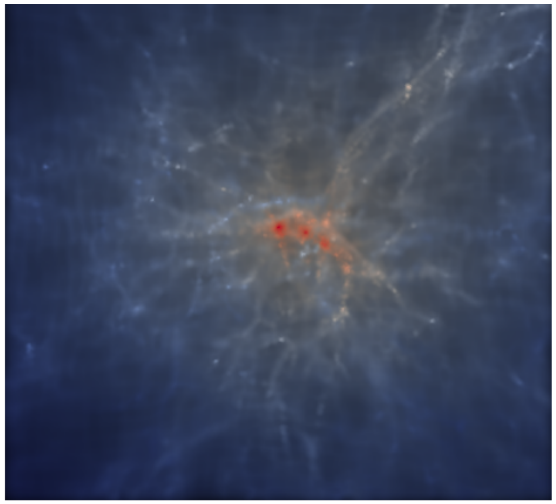
TDM et al. 17

The descendants of the most black hole at z=2 is not amongst the most massive DM Halo

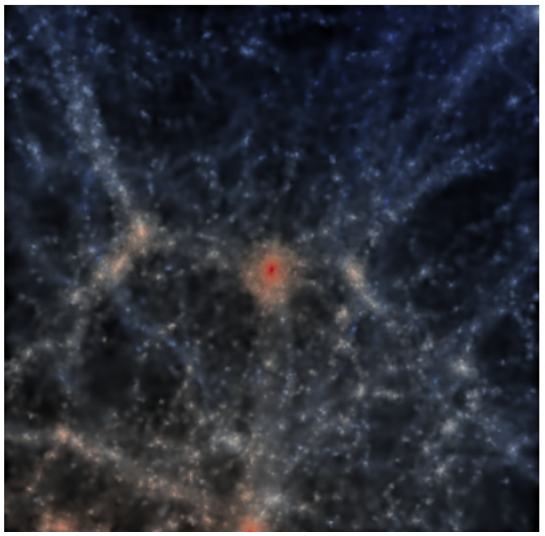
M_{halo} for most massive BH at z=2.5
< 8 times than most massive halo
(BH halo is 500th)

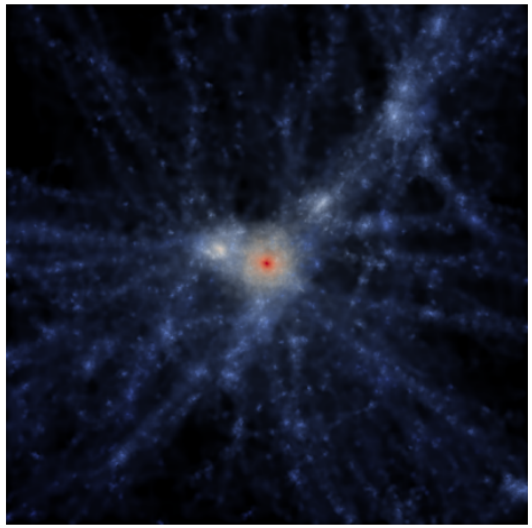
z=8





z=2.5

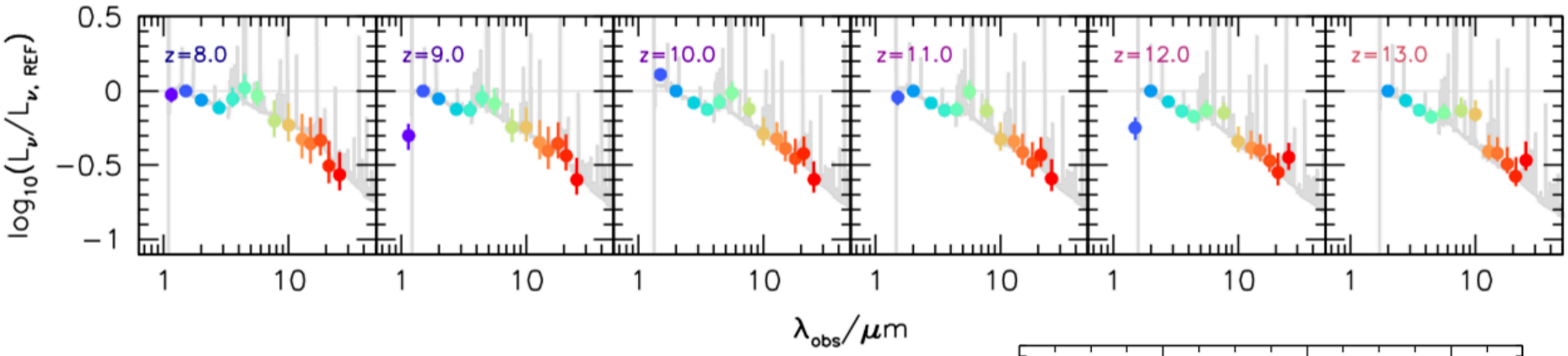




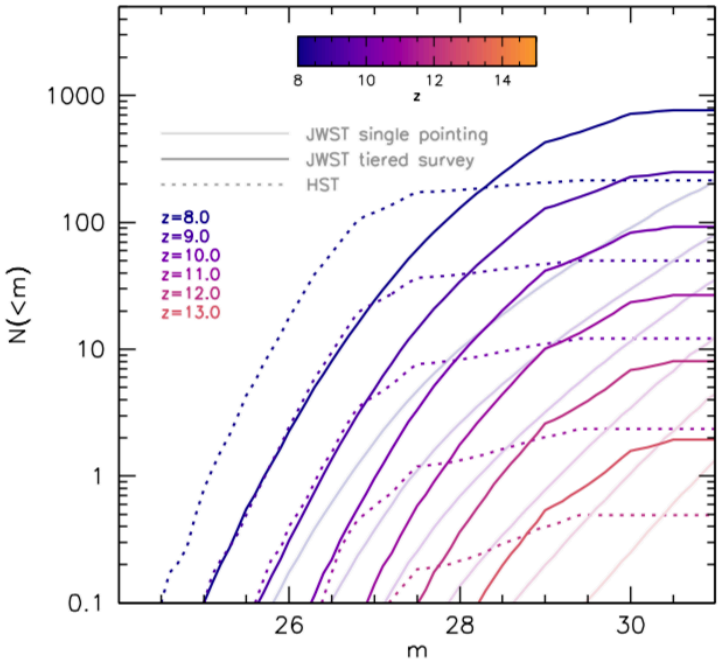
Example IV:

The next frontier: JWST, WFIRST

Predictions for JWST

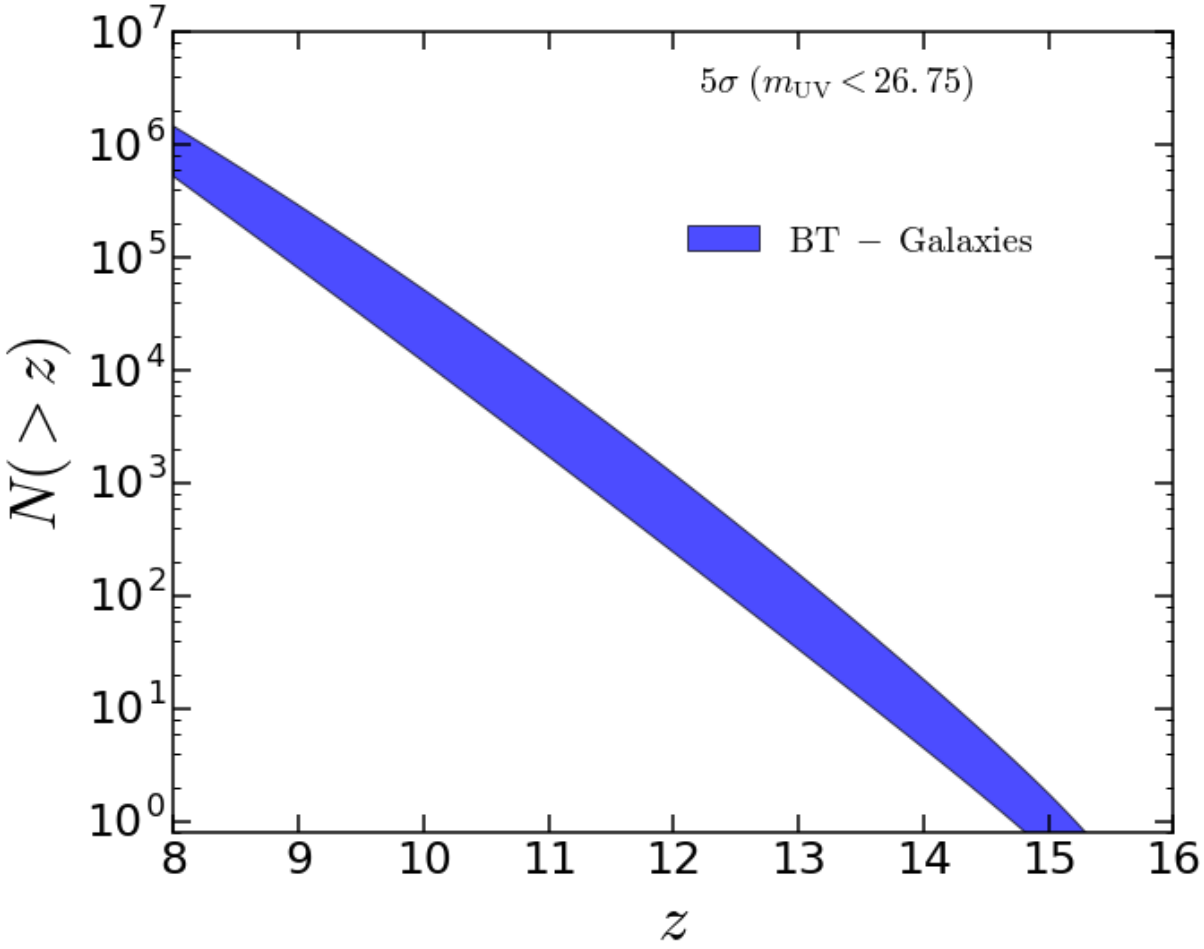


4 times as many galaxies as in current HST fields



The end of the dark ages is bright!

HLS 2200 sq degrees



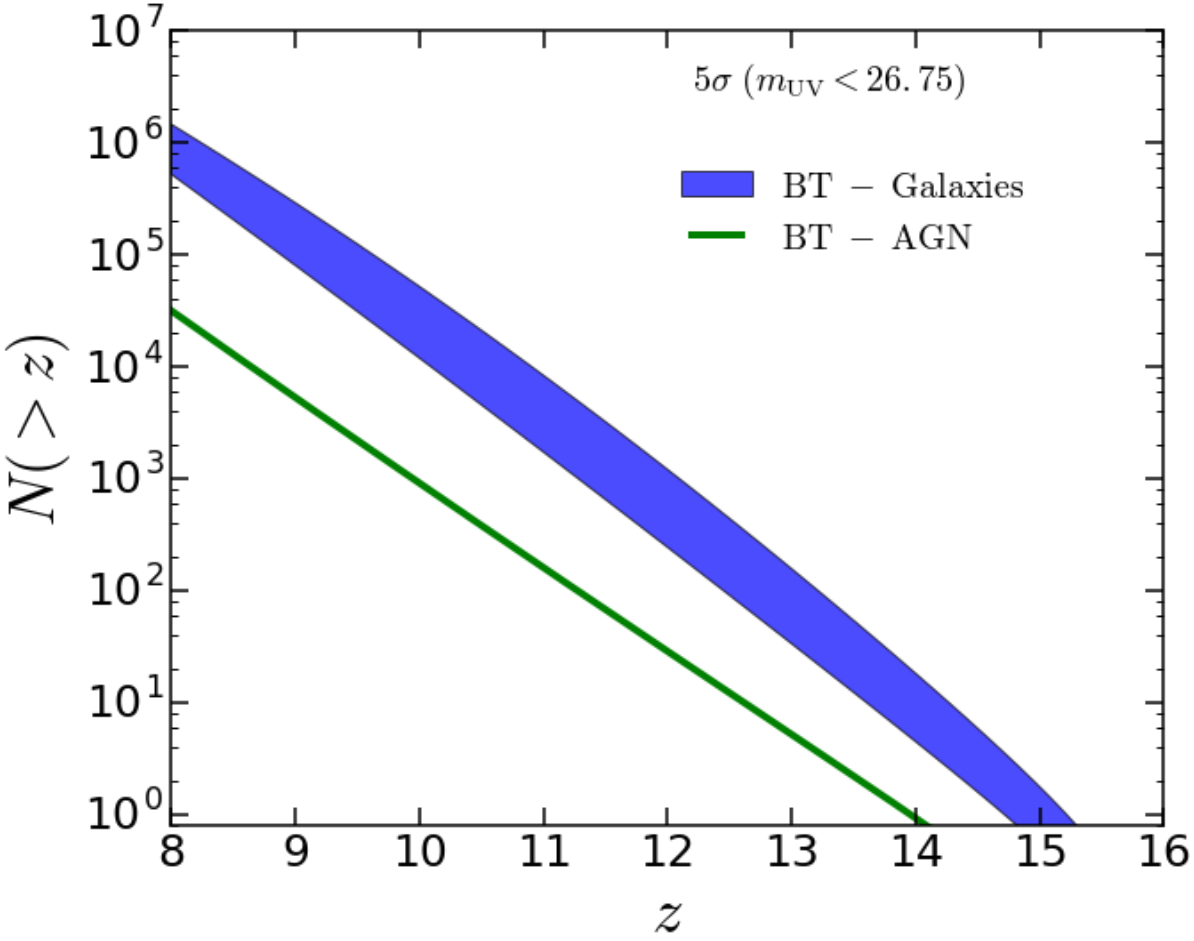
Waters, DM+, 16

Up to 1M galaxies,

First galaxies at z=15; t=300Myr

The end of the dark ages is bright!

HLS 2200 sq degrees



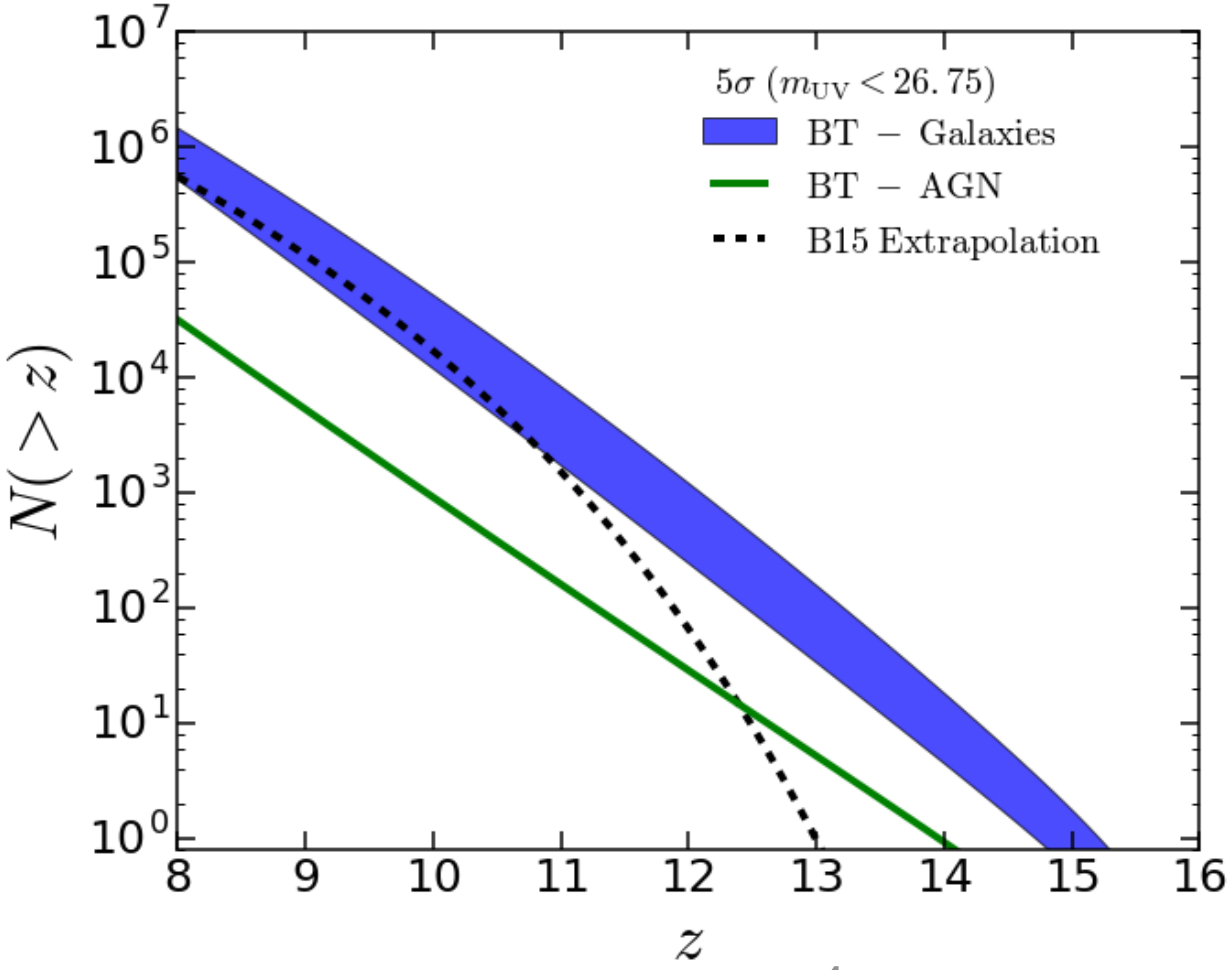
Waters, DM+, 16

Up to 1M galaxies, 10^4 AGN

First AGN at z=14

The end of the dark ages is bright!

HLS 2200 sq degrees



Waters, DM+, 16

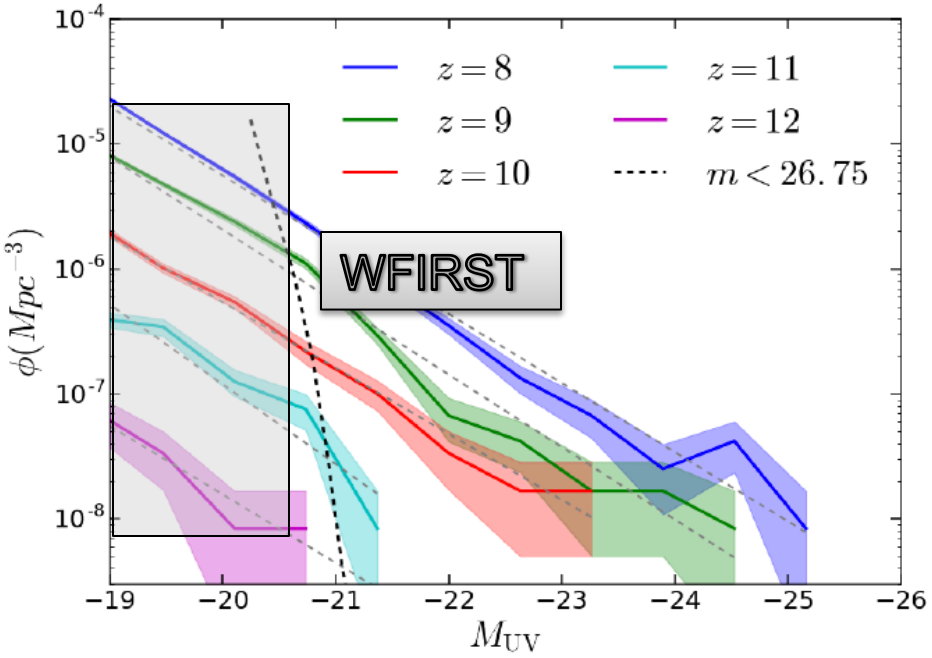
Up to 1M galaxies, 10^4 AGN

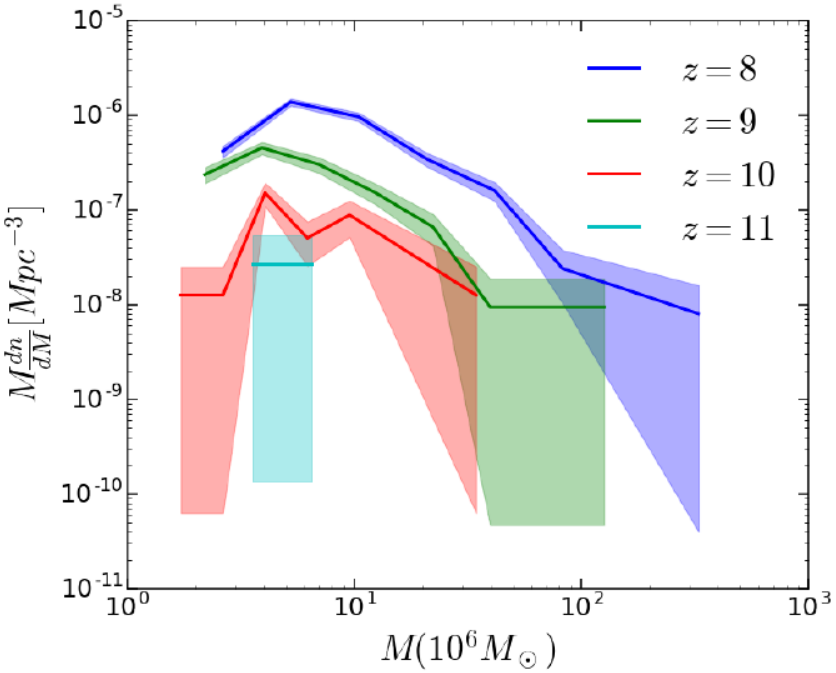
First galaxies at z=15, First AGN at z=14

The end of the dark ages is bright!

HLS 2200 sq degrees

AGN LF



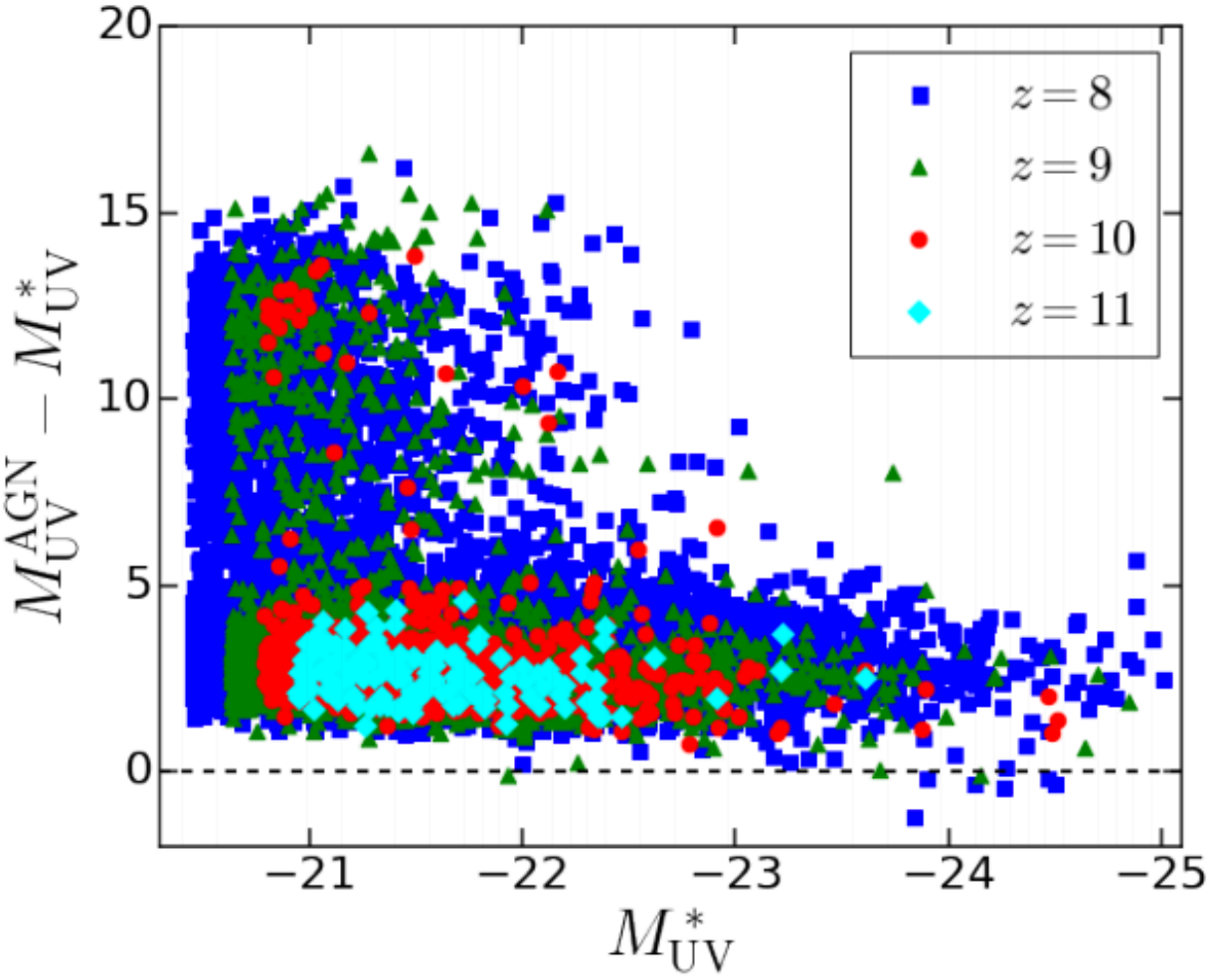


First quasars up to at z=13-14

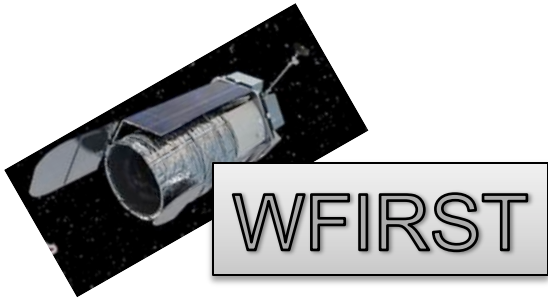
Bulk of black hole mass function >10^6 M_{sun}

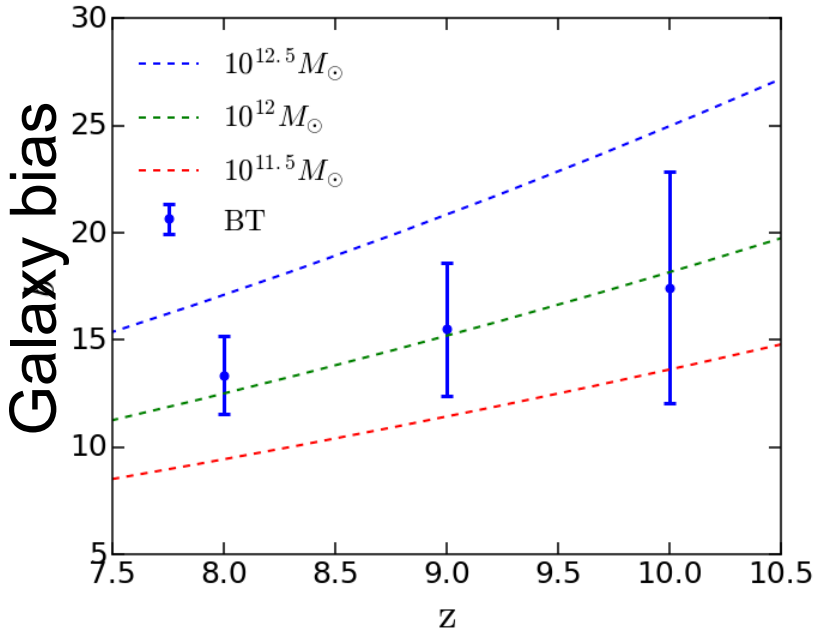
Quasars, beyond z>7 are about **2 mag fainter than their hosts**

apart from handful of very bright AGN



Cosmology with galaxies at z>7 !

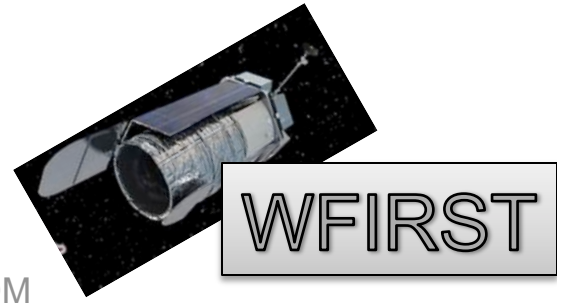




Waters, DM+, 16

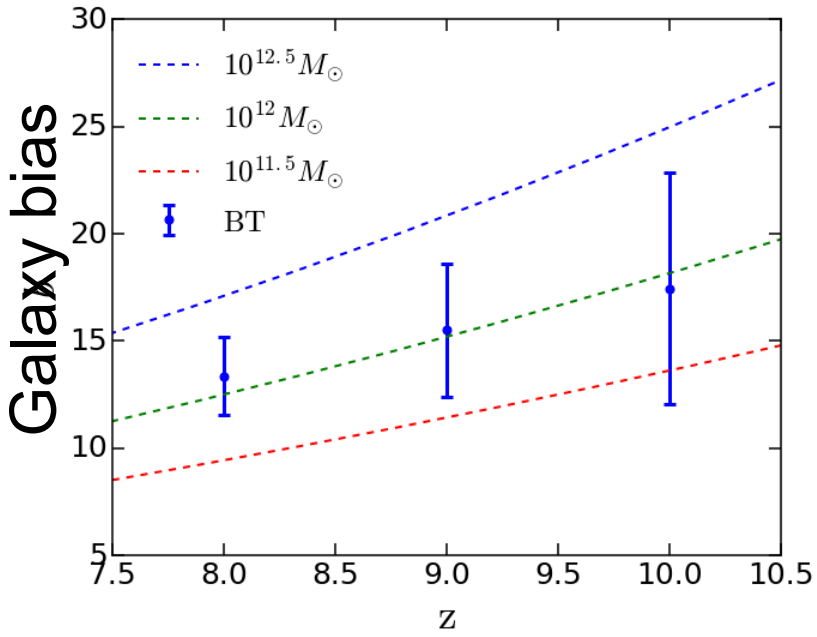
WFIRST galaxies, bias ~ 10-15

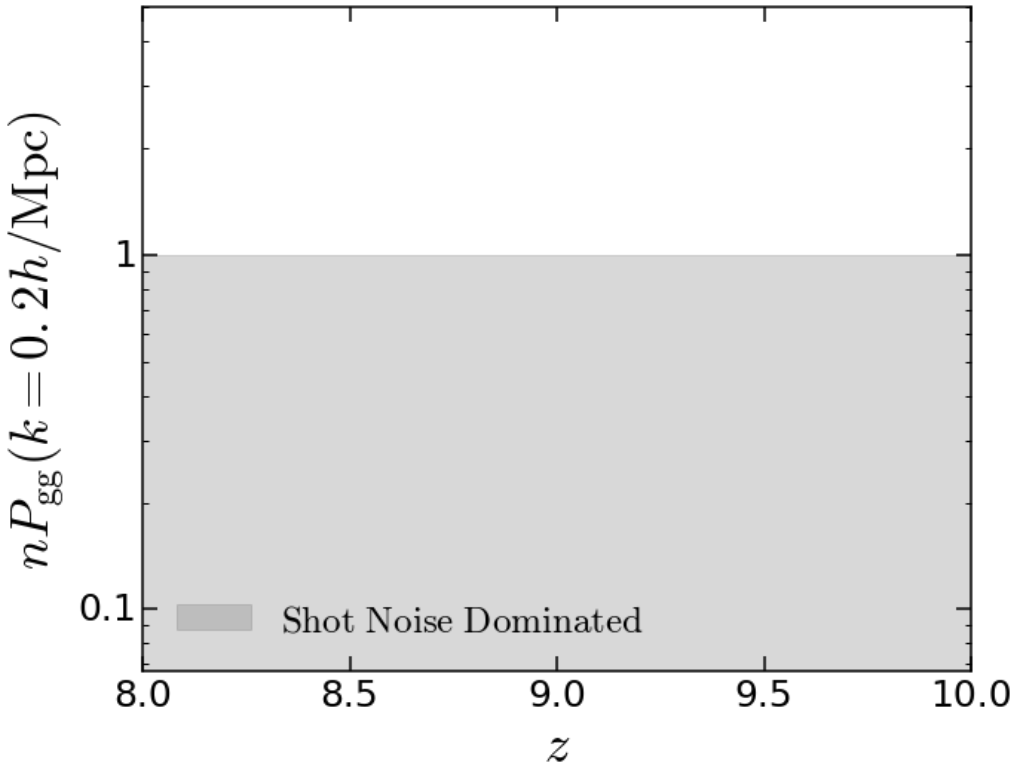
Cosmology with galaxies at z>7 !



$n \sim 10^{-3}$

P_{gg}=bias x P_{DM}



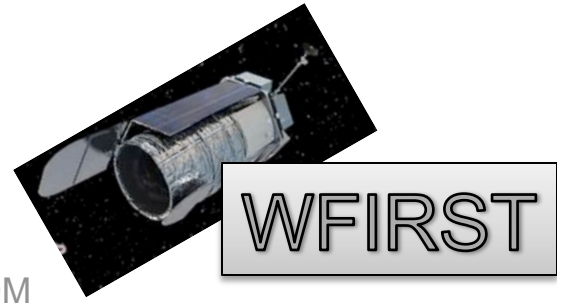


WFIRST galaxies, bias ~ 10-15

Waters, DM+, 16

BAO detection feasible?

Cosmology with galaxies at z>7 !



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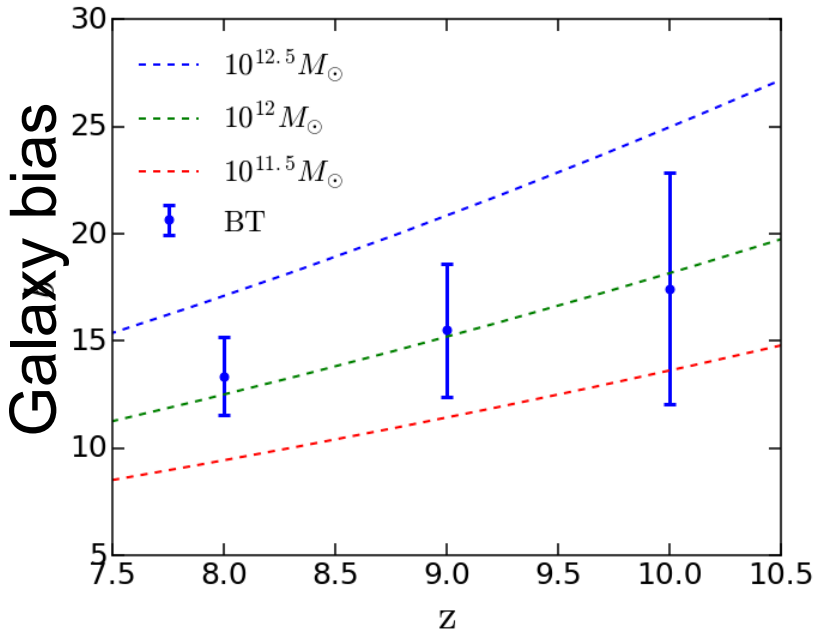

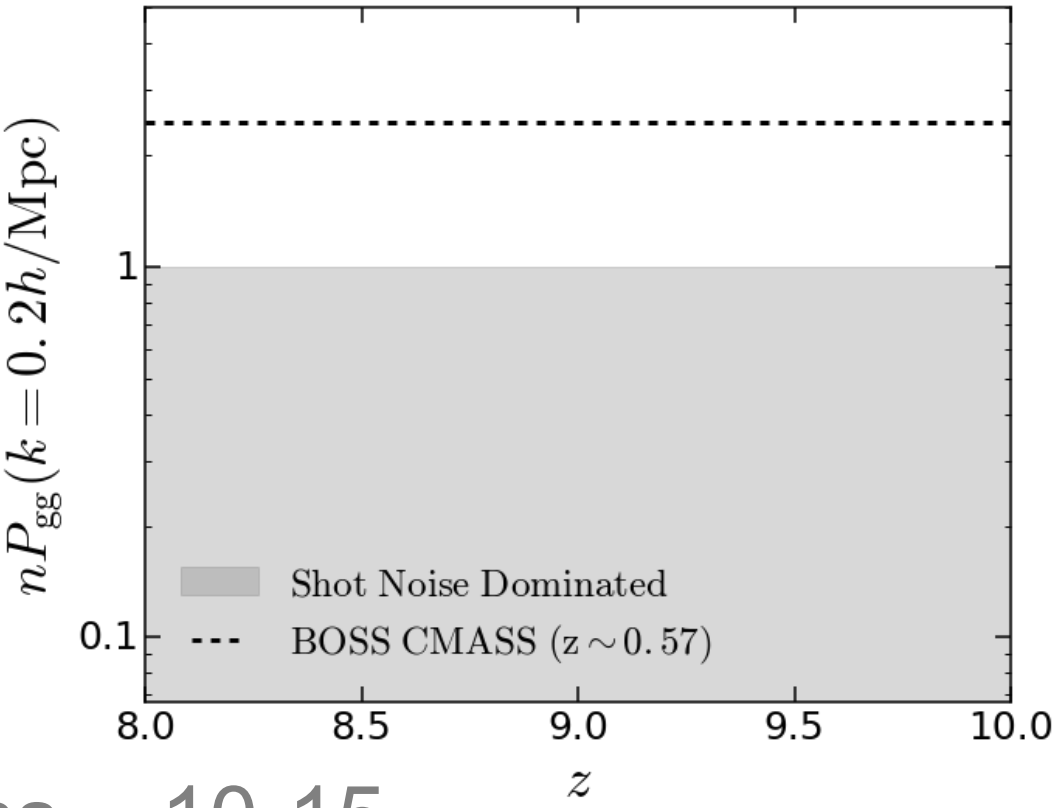

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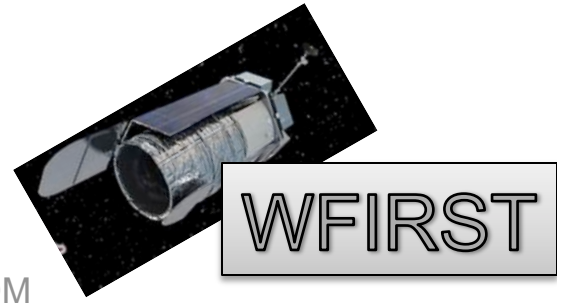

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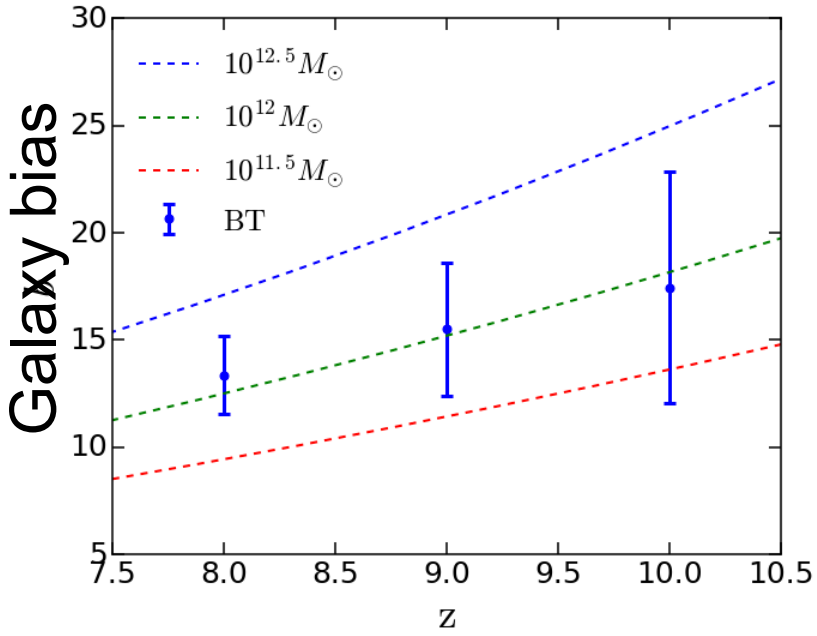
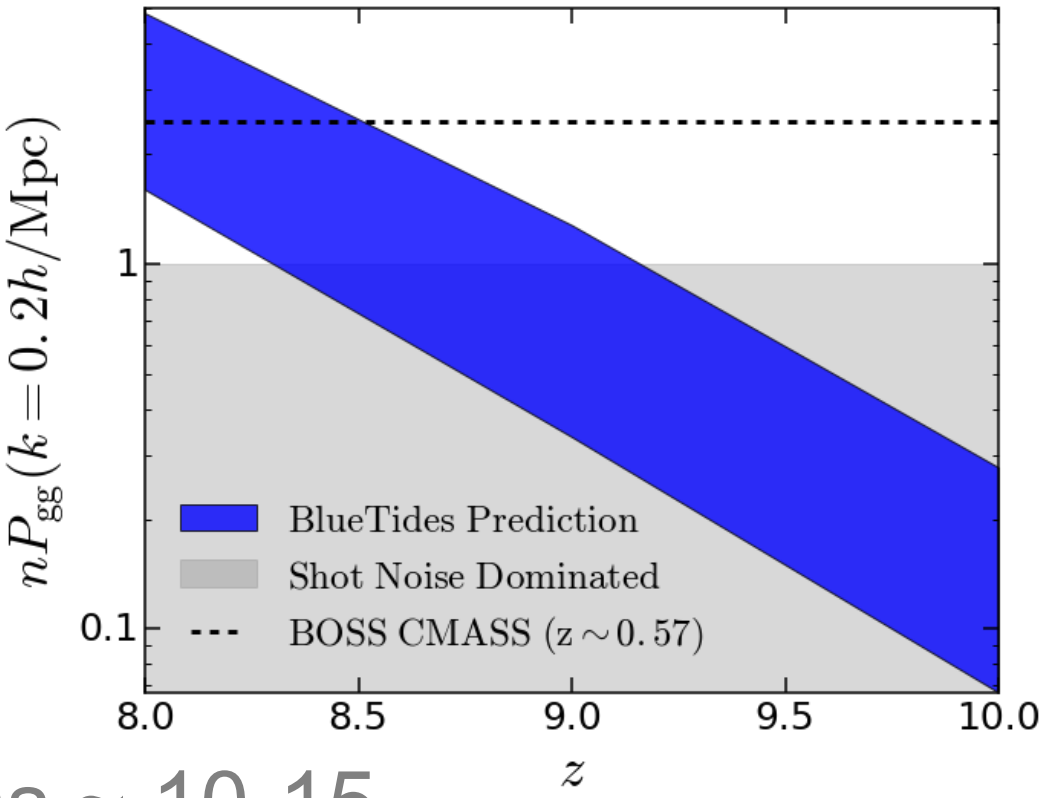


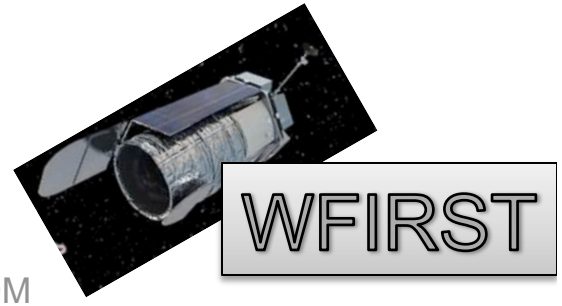


WFIRST galaxies, bias ~ 10-15

Waters, DM+, 16

BAO detection feasible up to z=8-9

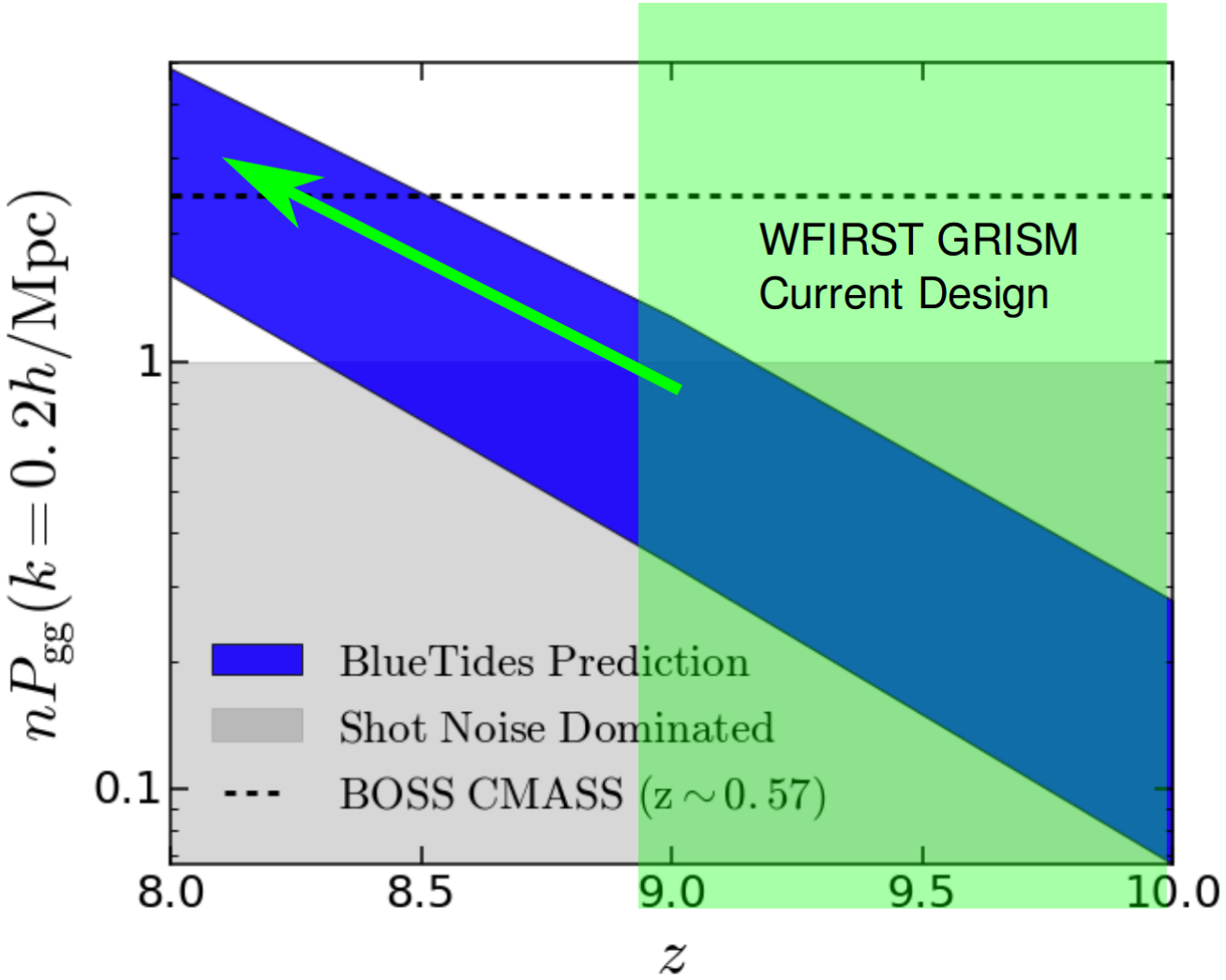
Cosmology with galaxies at z>7 !



$n \sim 10^{-3}$

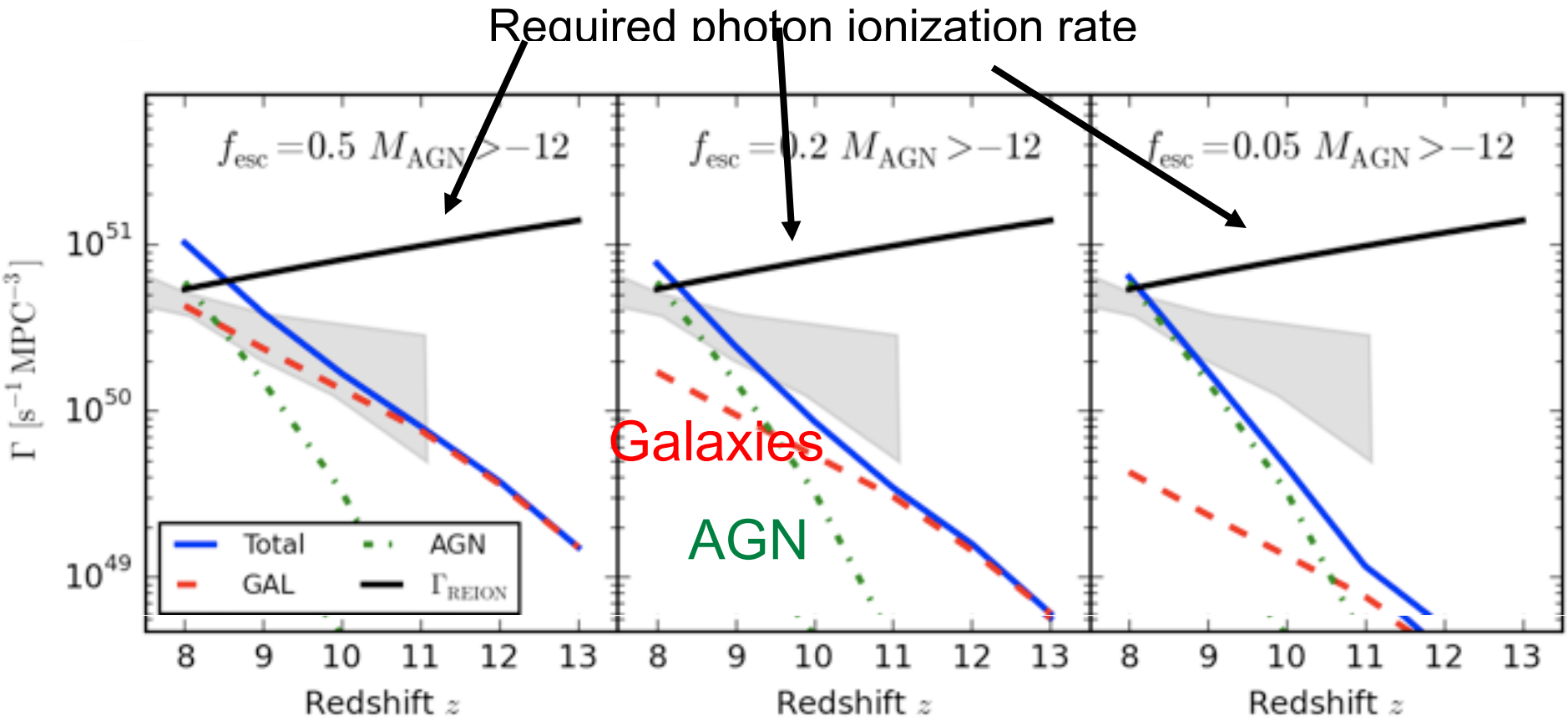
P_{gg}=bias x P_{DM}

First BAO detection in first half of Universe (at z=8-9)



BlueTides and Re-ionization history of the Universe

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



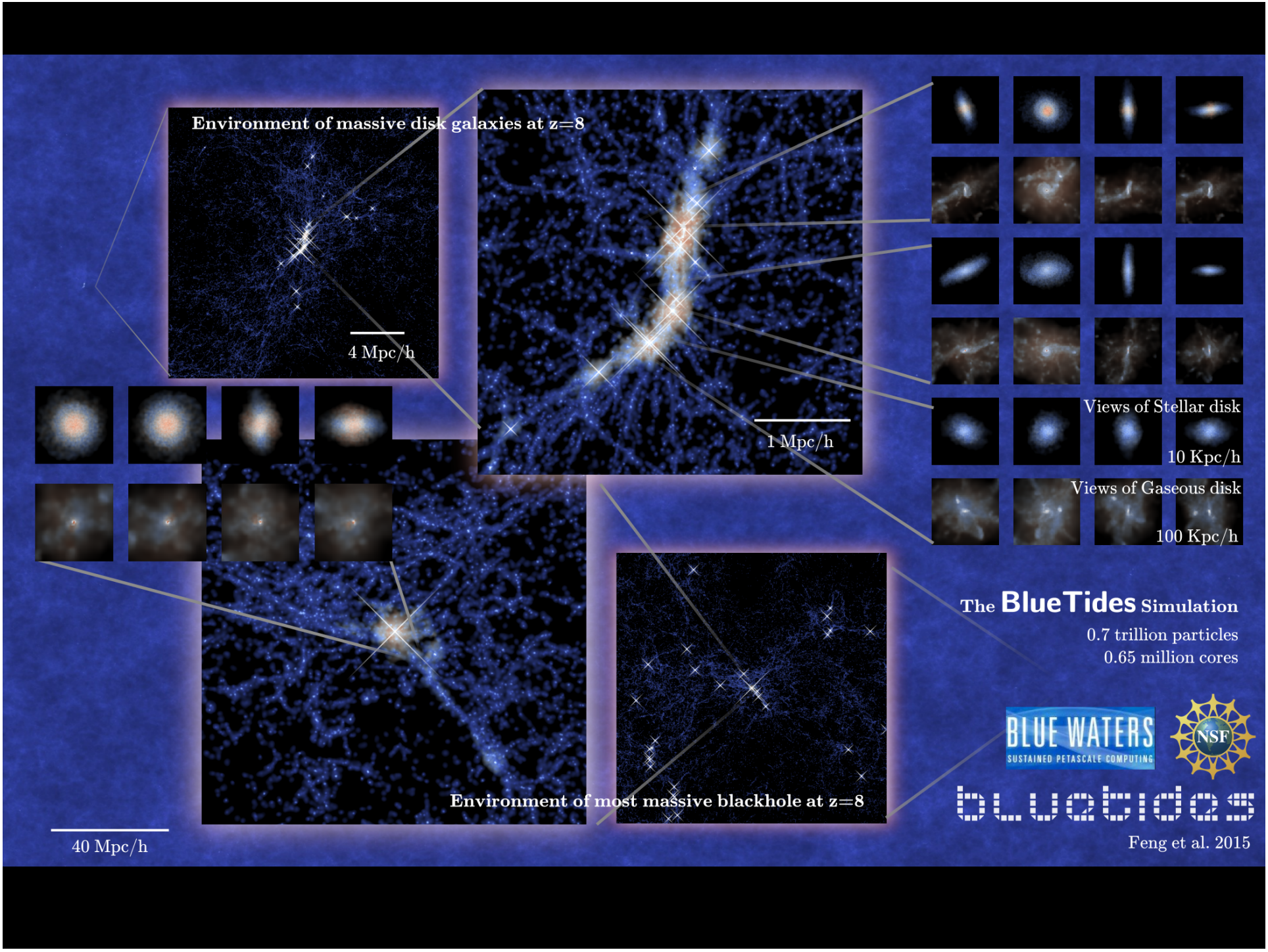
Summary:

New large volume high res BlueTides Simulation

predictions

for the next frontier of high-z surveys (WFIRST, JWST)

- statistical properties of BH and galaxy populations
- probe physics/origin of first black holes and galaxies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