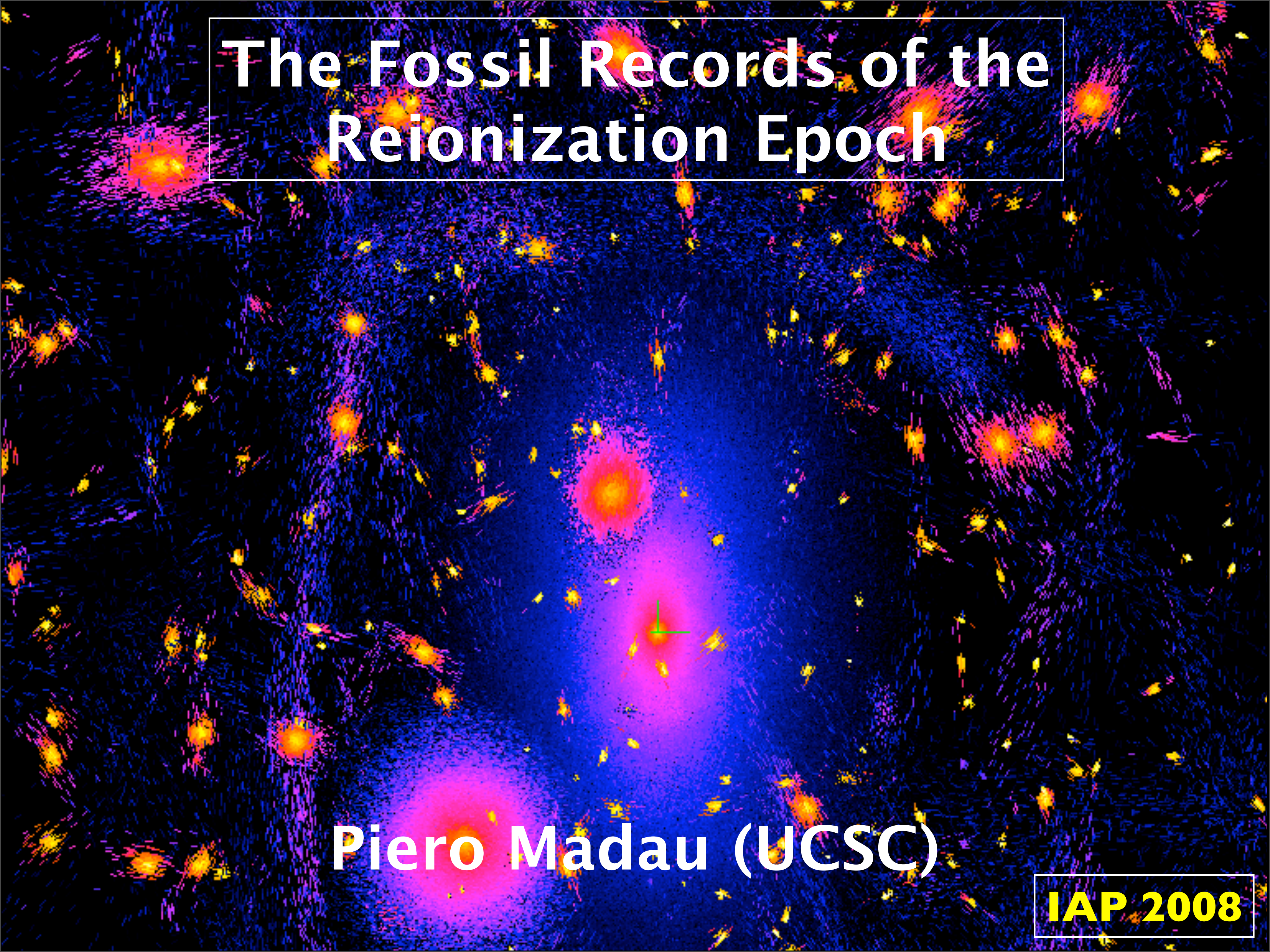
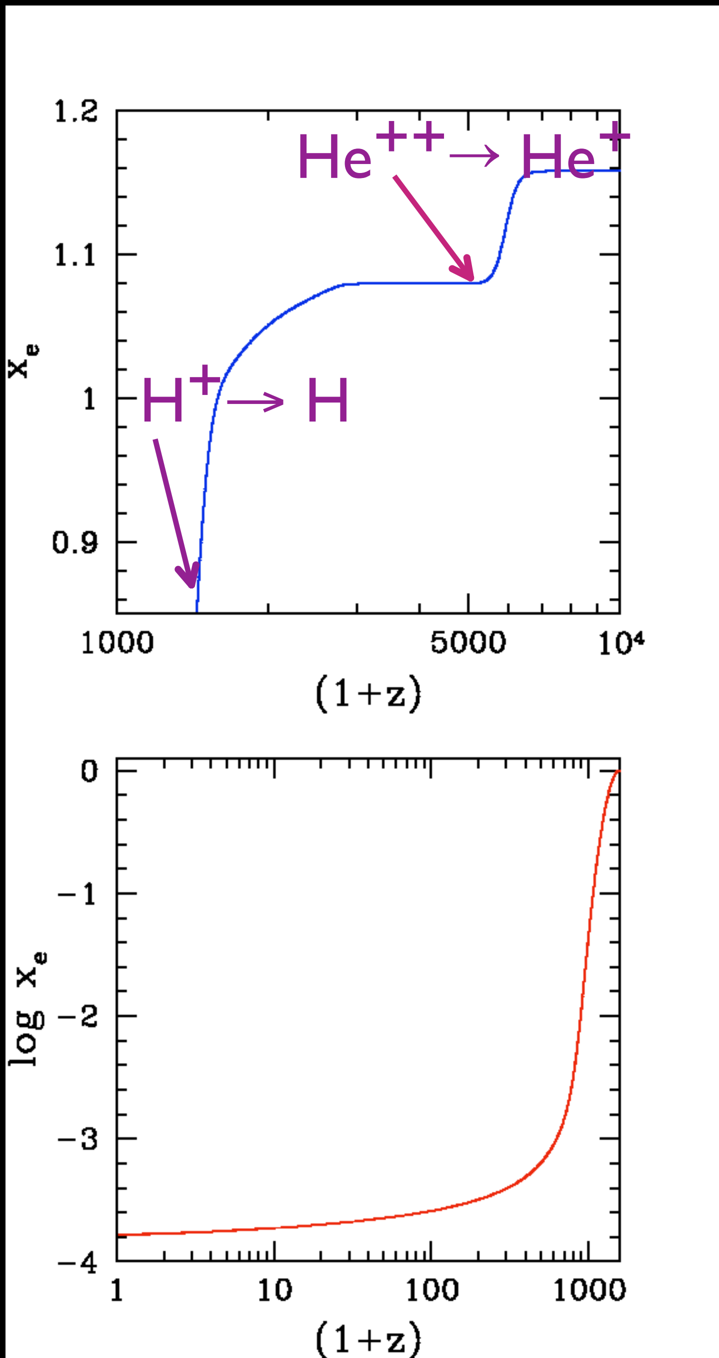


The Fossil Records of the Reionization Epoch

Piero Madau (UCSC)

IAP 2008

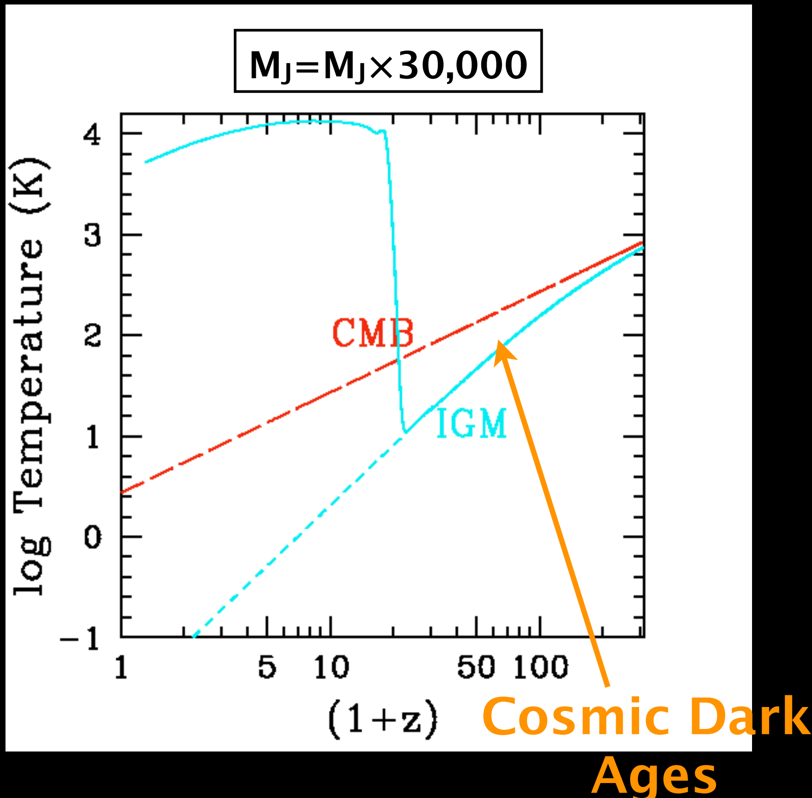
The post-recombination Universe

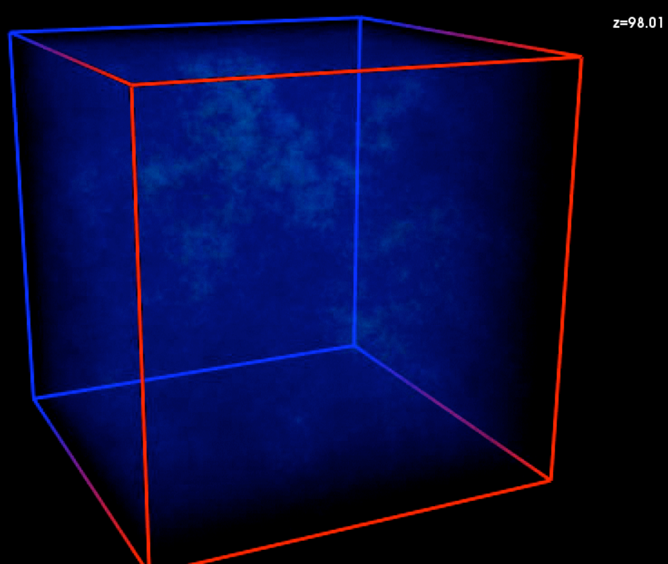


@ z=1090, t=370,000 yr after big bang, Universe becomes optically thin to Thomson scattering

at this epoch the electron fraction x_e drops below 13% and CMB cools below 3000 K

we understand the microphysics at these very early stages well: recombination freezes out with $x_e \approx 2x10^{-4}$





After recombination residual e^- keep $T_{IGM}=T_{CMB}$ until $z_{th}\approx150$ (age=10 Myr)

$T_{IGM}(z<z_{th})\propto(1+z)^2$

Universe becomes semi-opaque again after reionization. WMAP data imply scattering opacity $\tau_e=0.09$ ⇨ $z_{rei}=11\pm1.4$ (age=400 Myr)

⇨ significant star-formation activity at very early times!!

unique prediction of CDM: first stars formed @ z>15 in shallow potential wells (“minihalos” with $M\gtrsim10^6\ M_\odot$, gas coolant=H_2)

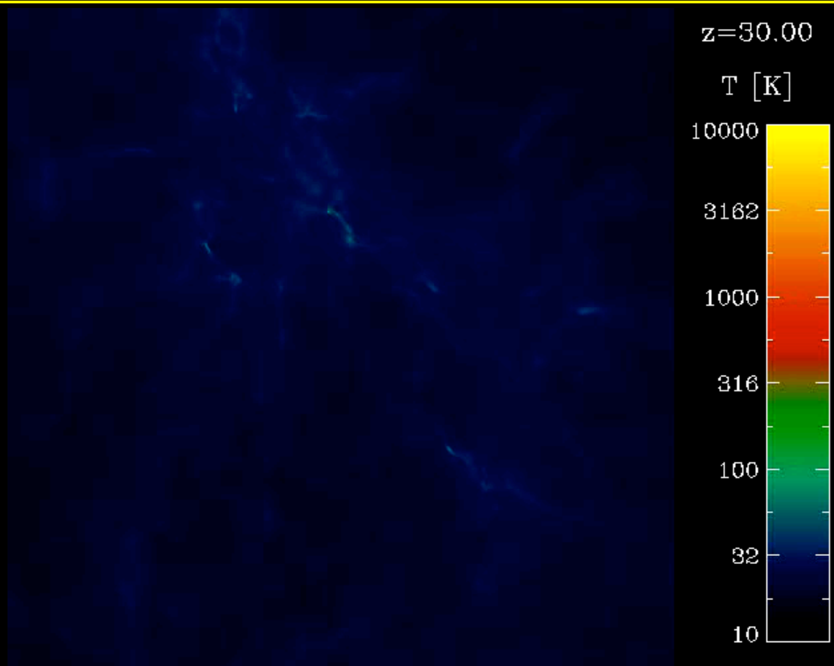
$$H+e^-\rightarrow H^-+\gamma$$
$$H^-+H\rightarrow H_2+e^-$$

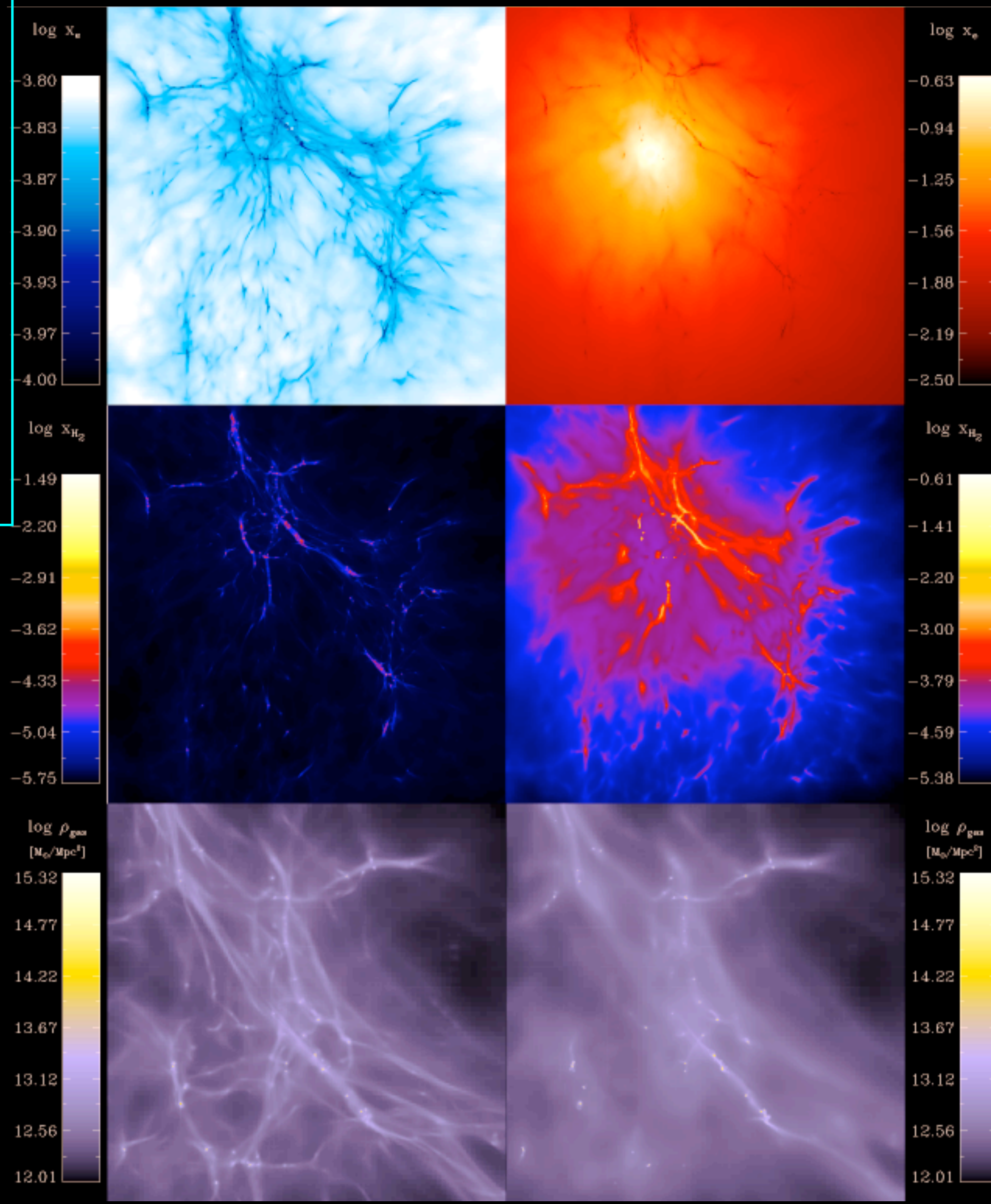
$$\frac{dx_{\rm H_2}}{dt}\propto x_e n_{\rm HI}T^{0.9}$$

Q: Were Z=0 very massive (Pop III) stars in minihalos the dominant source of reionizing photons? Or was it low Z stars in more massive "dwarf" galaxies (gas coolant=H+He)?

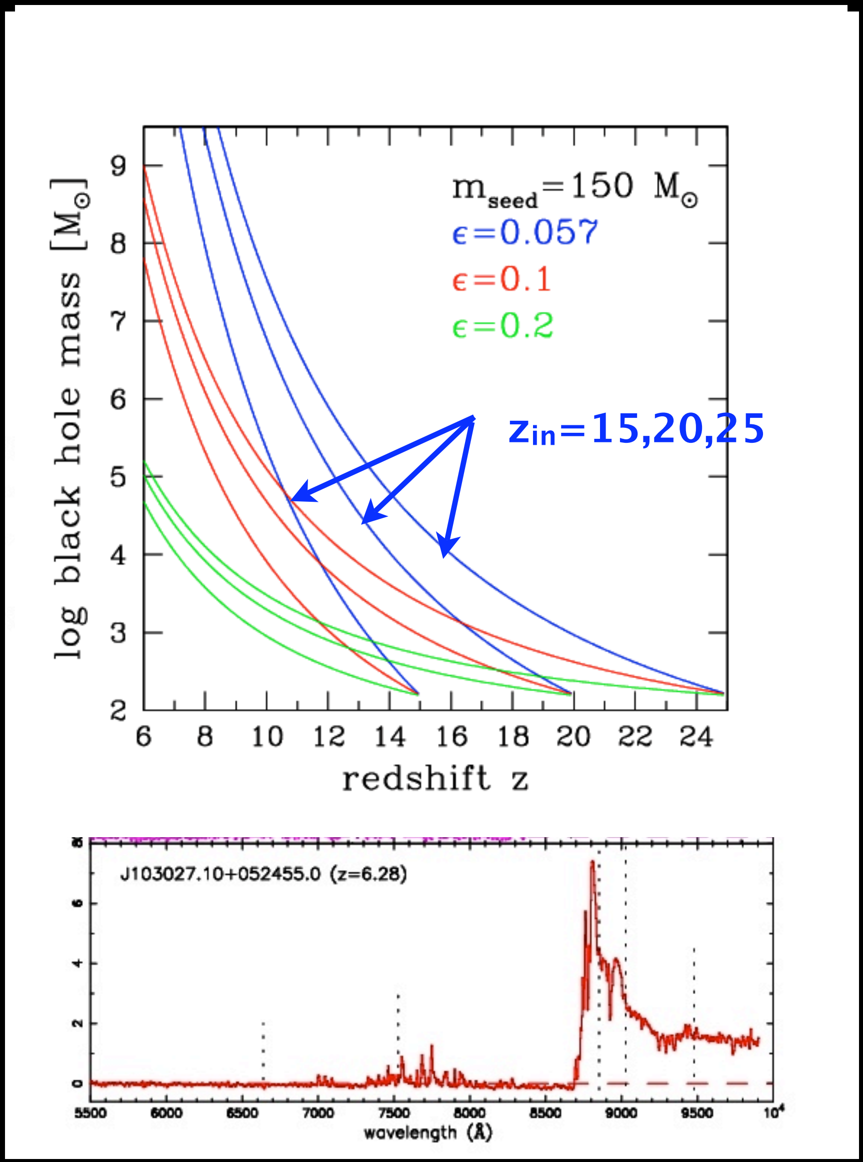
What was the role of "mini-QSOs" (active nuclei powered by IMBHs) in structuring the all-pervading IGM and regulating star formation in their hosts?

z=21 turn on 150 $M_\odot$ MBH accreting at Eddington rate and shining for a Salpeter timescale at 200eV-10KeV





SDSS z≈6 QSOs as fossil records of the EoR



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

ε=radiation efficiency

$$M_{\rm BH} = m_{\rm seed} e^{t/t_{\rm Edd}}$$

$$t_{\rm Edd} \equiv 450\,{\rm Myr}\,\frac{\epsilon}{1-\epsilon}$$

$\ln(M_{BH}/m_{seed})$= $\ln(3\times10^9/150)=17$ e-foldings

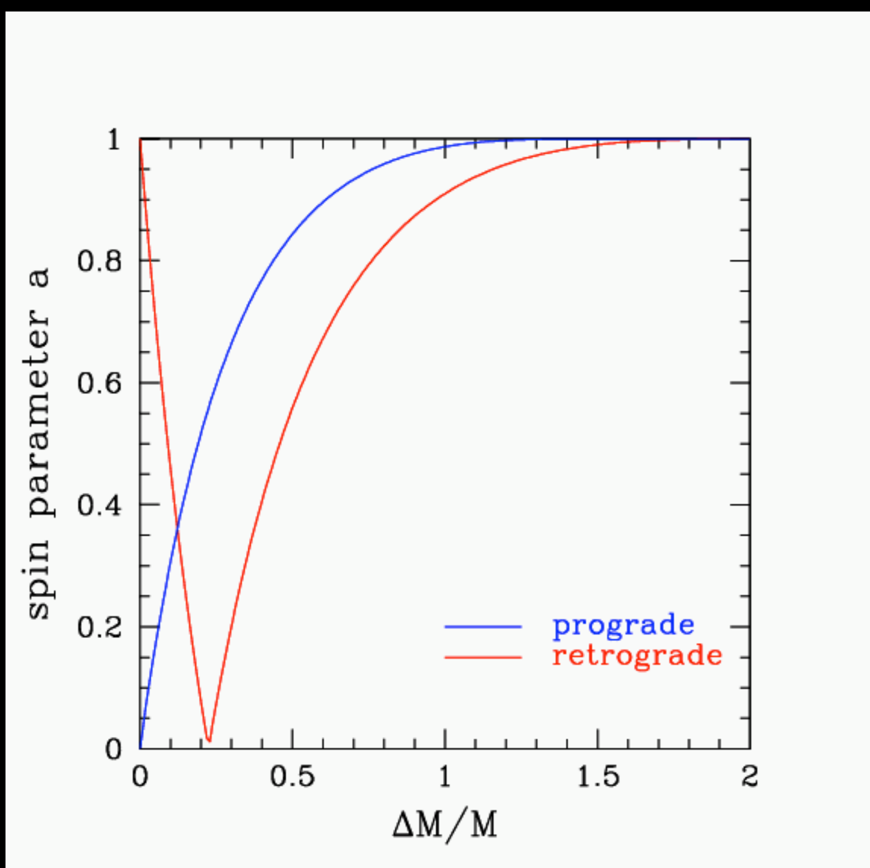
small "seed" rotating holes would have grown only to $\lesssim 10^5$ M⊙ by redshift 6

☞ **Q: Is there a large population of faint mini-QSOs at z»6?**

$$S = aGM_{\rm BH}^2/c, \qquad 0 \le a \le 1.$$

black hole spin a_*	thin disk radiation efficiency (corrected for capture by hole) $\epsilon = L_{\rm disk}/(\dot{M}c^2)$
0[a]	0.057
0.7[b]	0.133
0.9[c]	0.151
0.998[d]	0.308
1[e]	0.400

[a] result of isotropic accretion of small bodies.
[b] result of collapse or equal mass merger.
[c] approx equilibrium spin in magnetised disk accretion.
[d] equilibrium spin in unmagnetised disk accretion.
[e] maximal rotation before naked singularity appears.



$$M_{\rm BH} \to M_{\rm BH} + dm$$

(in equatorial plane)

$$\frac{da}{d\ln m} = \frac{L_{\rm ISCO}}{M_{\rm BH}E_{\rm ISCO}} - 2a.$$

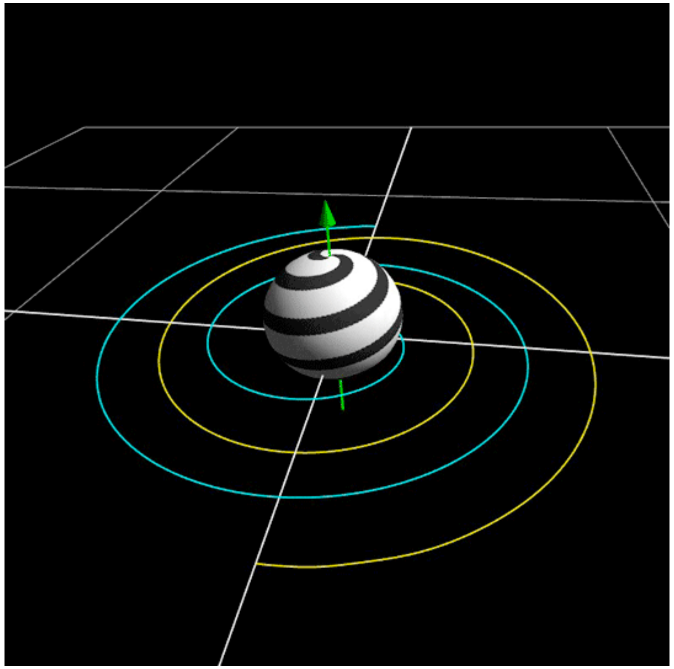
hole that is initially nonrotating ($r_{\rm isco}$=6$M_{\rm BH}$) gets spun up to a=1 after a modest amount of accretion, ΔM/M=1.4

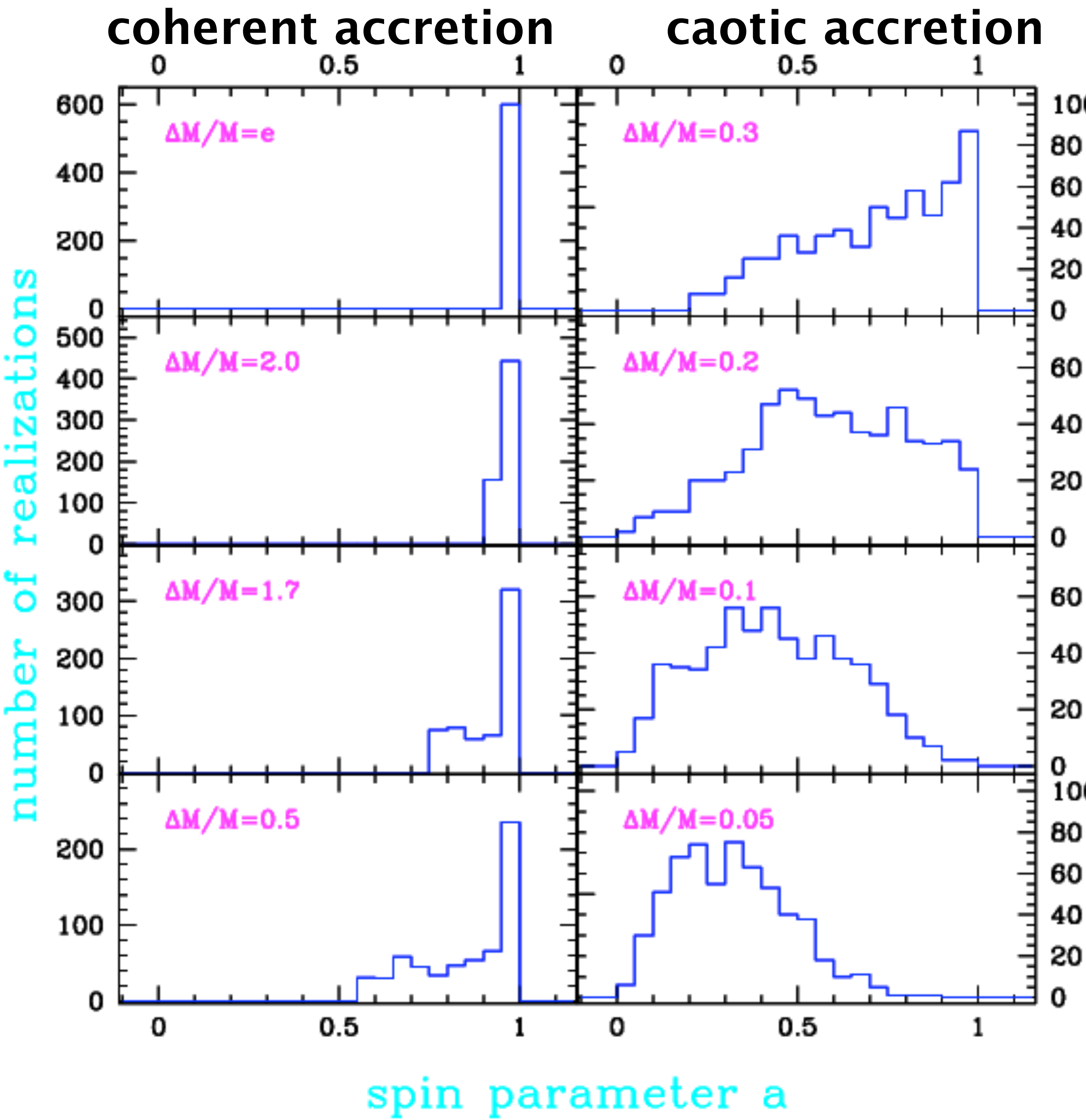
a=1 hole spun down by retrograde accretion ($r_{\rm ISCO}$ =9 $M_{\rm BH}$) to a=0 after ΔM/M=0.225

a=1 hole does a 180° flip after ΔM/M=2

Monte Carlo realizations of hole spin distribution when matter ΔM added at random orientations

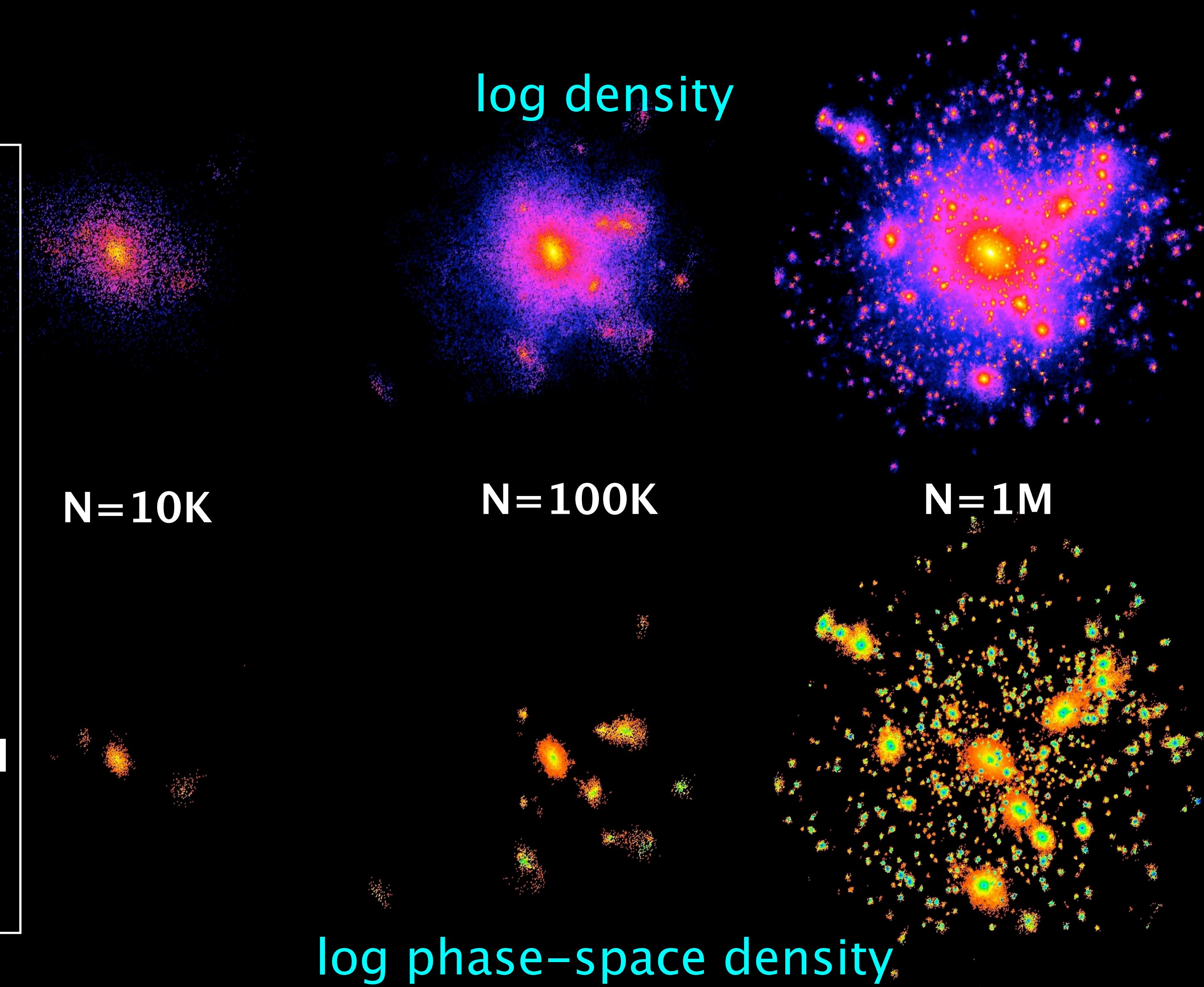
Spin distribution of MBHs provides information on large scale “coherence” of accretion flow





A brief history of N-body simulations of CDM halos

Also unique prediction of CDM: galaxies form “bottom-up”, with low-mass sub-units (**“halos"**) collapsing earlier and merging to form larger and larger systems over time. Hierarchical assembly of galaxy halos preserves memory of the initial stages. **Q: where are the first stars and their hosts today?**



ability of subhalos to survive as substructure within the host is clearly sensitive to resolution issues

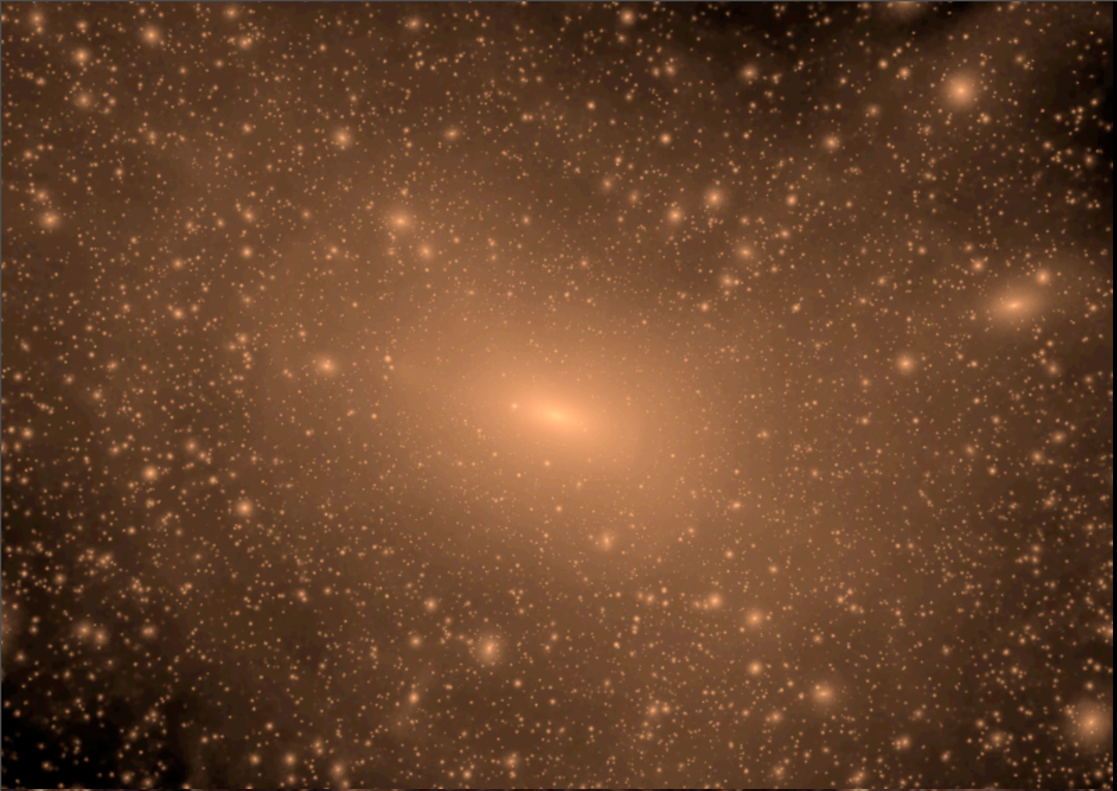
The "VIA LACTEA Project"

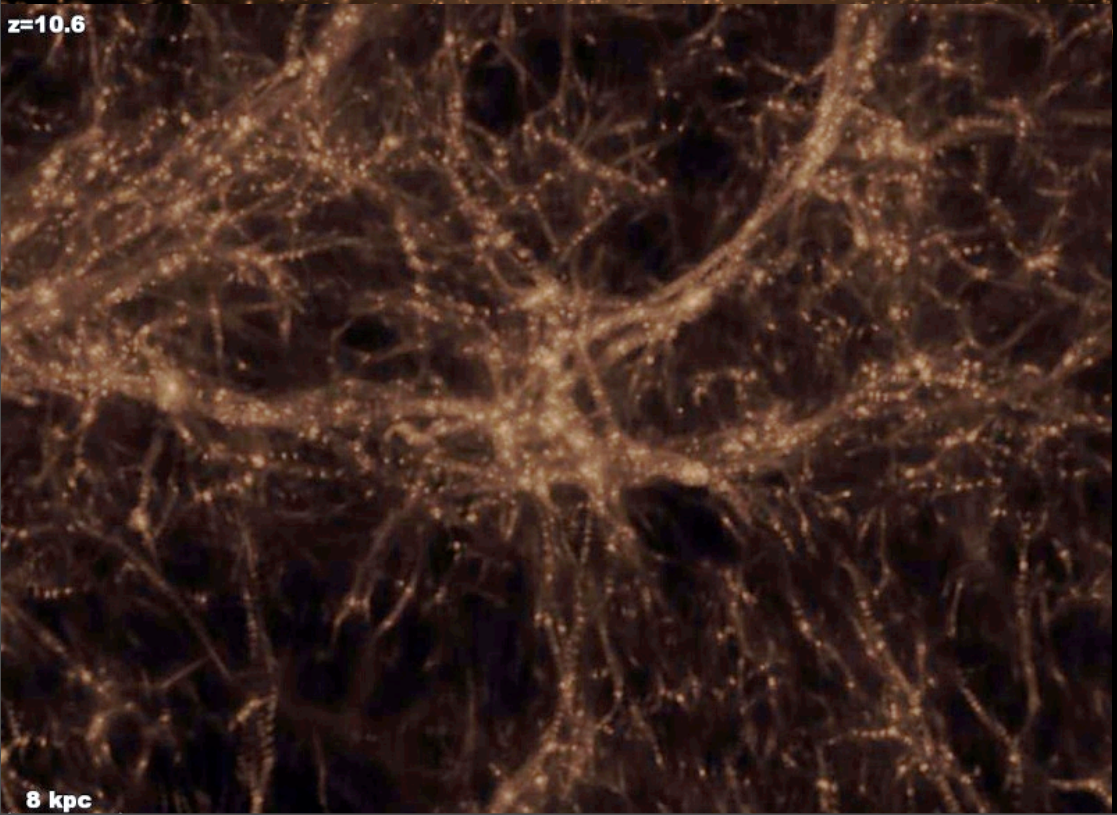
A suite of the largest cosmological simulations to date of the assembly of the $2\times10^{12}\ M_{\odot}$ DM halo of the MW in ΛCDM/WMAP3 [NB: if m_{DM} ~100 GeV/c2 $O(10^{67})$ particles in MW!]

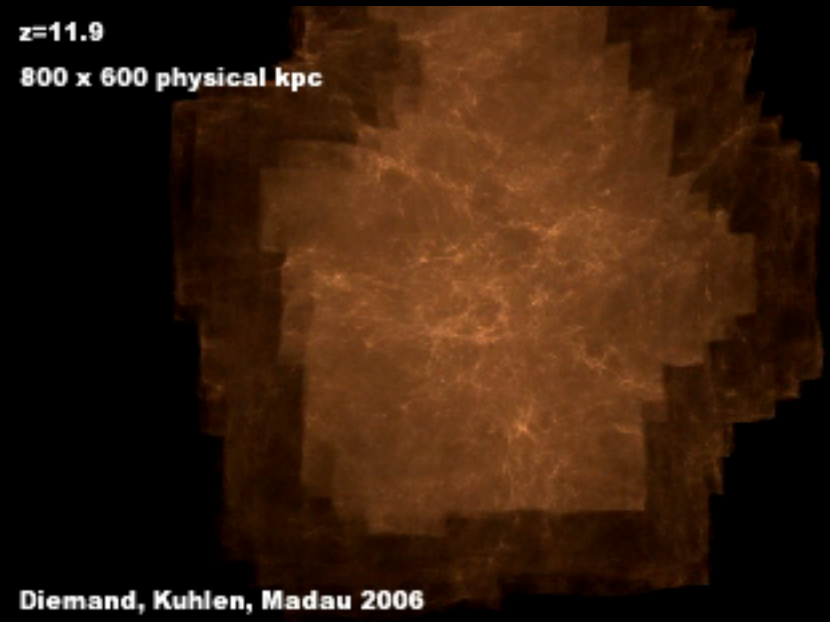
2007: VL, N_{halo}=85M (N_{tot}=213M), m_p=2.1e4 $M_{\odot}$, ε=90 pc, 320K CPUh on Columbia @ NASA Ames

2008: VLII, N_{halo}=500M (N_{tot}=1.1B), m_p=4100 $M_{\odot}$, ε=40 pc, 1M CPUh on Jaguar @ ORNL (DOE INCITE)

First cosmological simulations that resolve building blocks of massive galaxies down to z=0

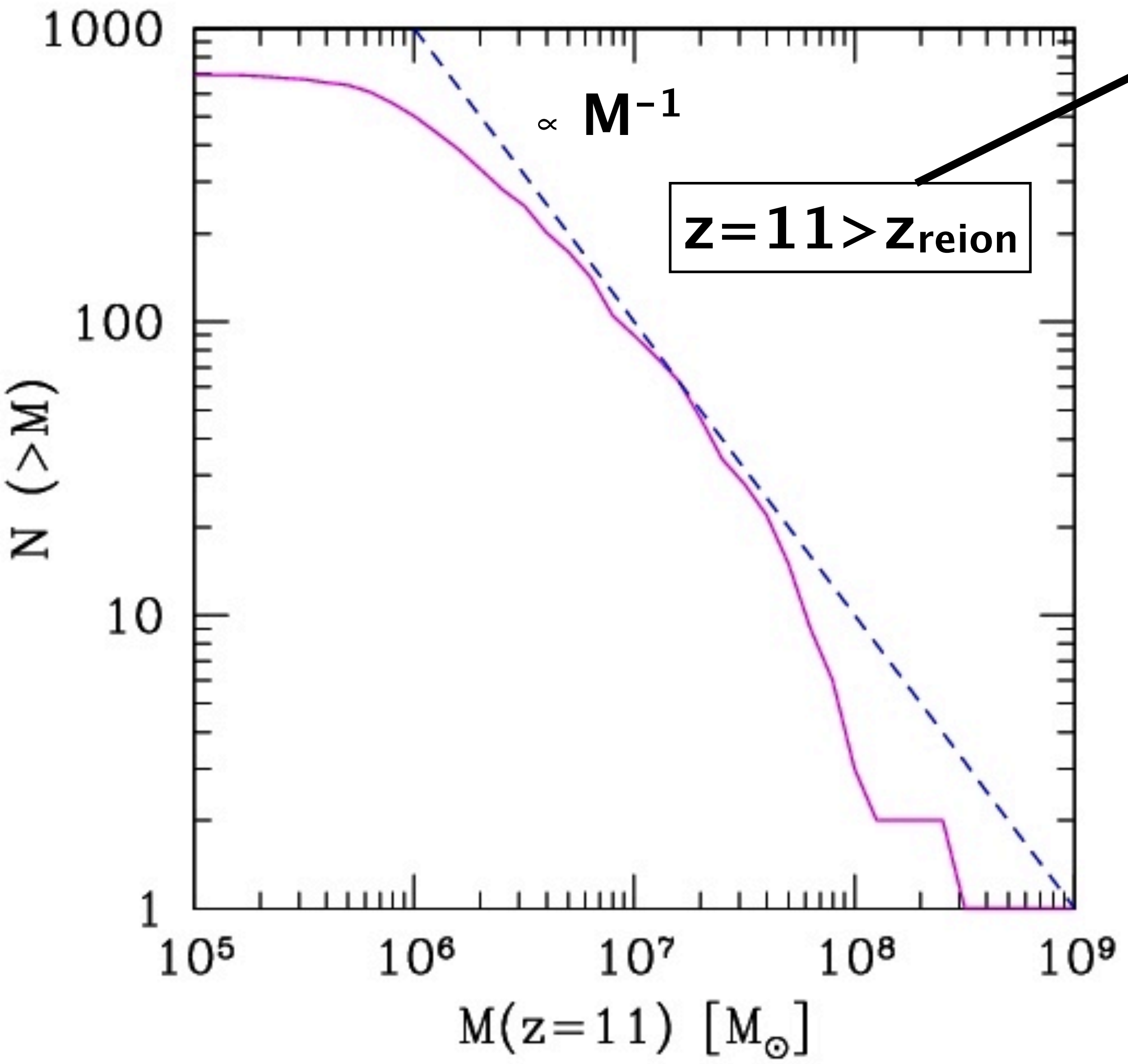






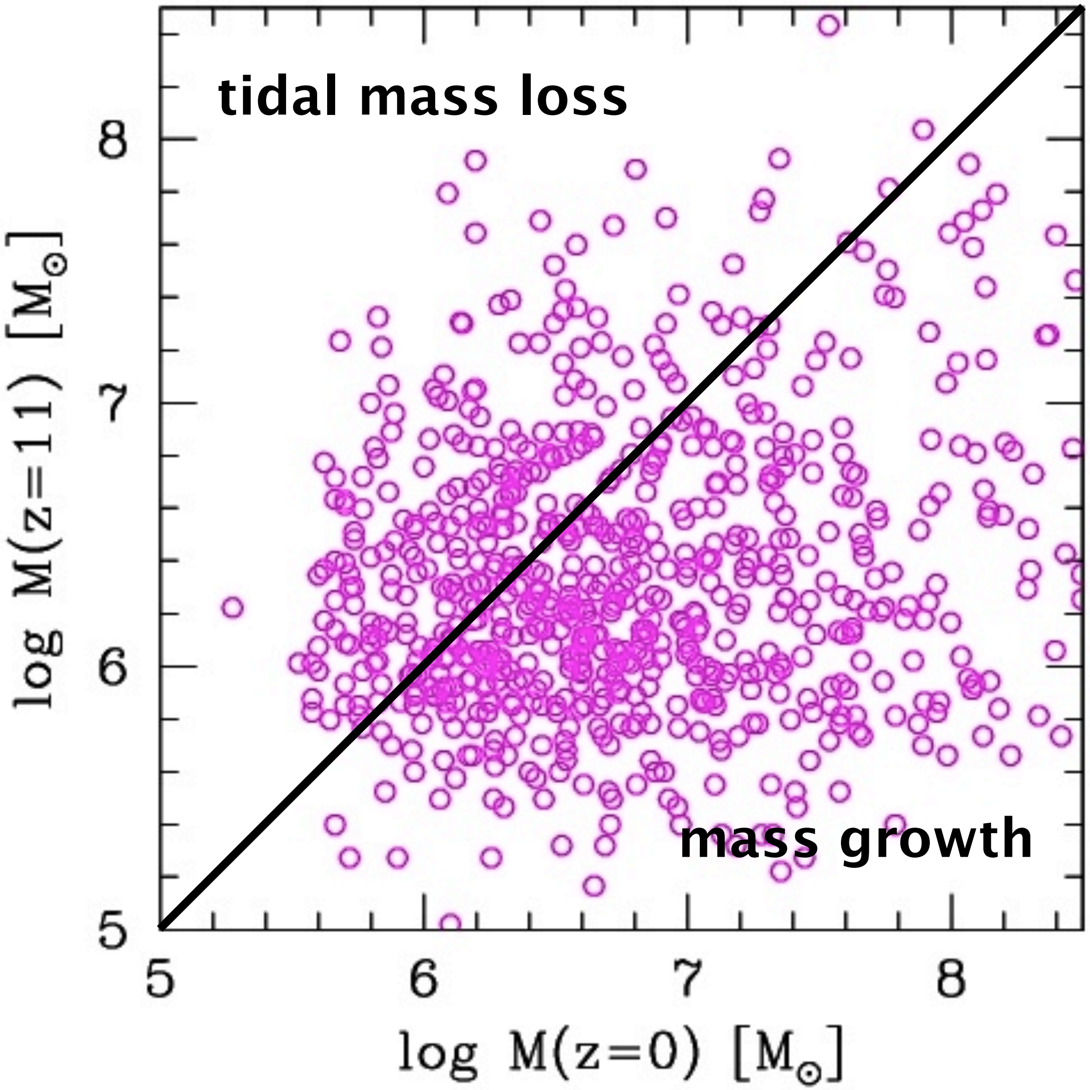
Do some of the protogalaxies that reionized the “MW volume” survive to z=0?

Mass function of early, resolved (V_{max}>2.5 km s^{-1}) (sub)halos that have a surviving remnant today within 280 kpc from GC



No external feedback!

As many as ~10^3 (sub)halos that may be shining "prior" to the EoR



tidal mass loss
mass growth
log M(z=11) [M☉]
log M(z=0) [M☉]
5
6
7
8
5
6
7
8

Let $M_{gas}=(\Omega_b/\Omega_M)M_{halo}$

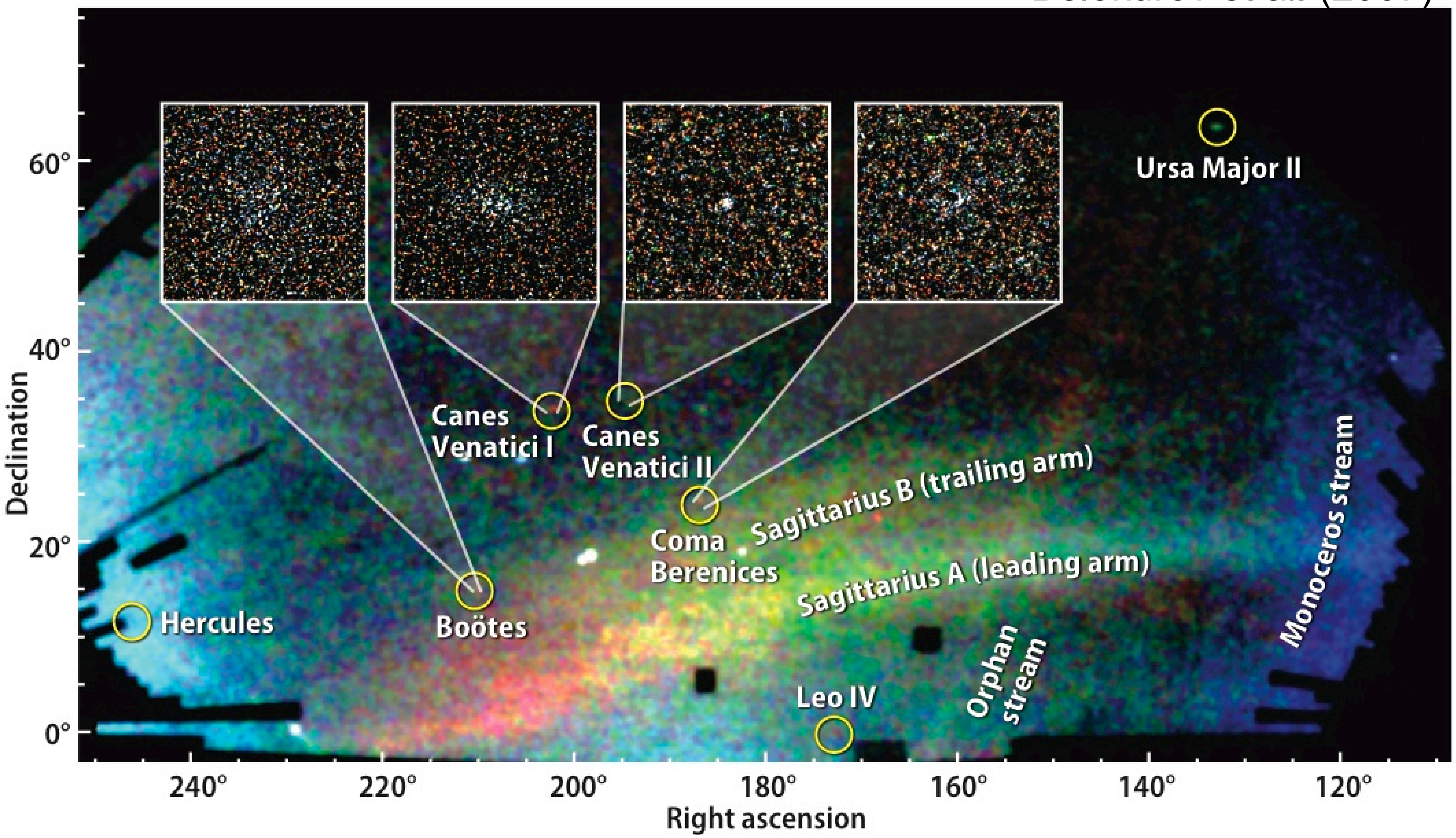
Let $M_*=f_*M_{gas}$ be the mass turned into stars with a Salpeter IMF (0.1–100$M_\odot$) @ $z>11\equiv z_{reion}$

After 13–13.5 Gyr [$t_{look}(z=11)=13.2$ Gyr], $M_*=1\ M_\odot$

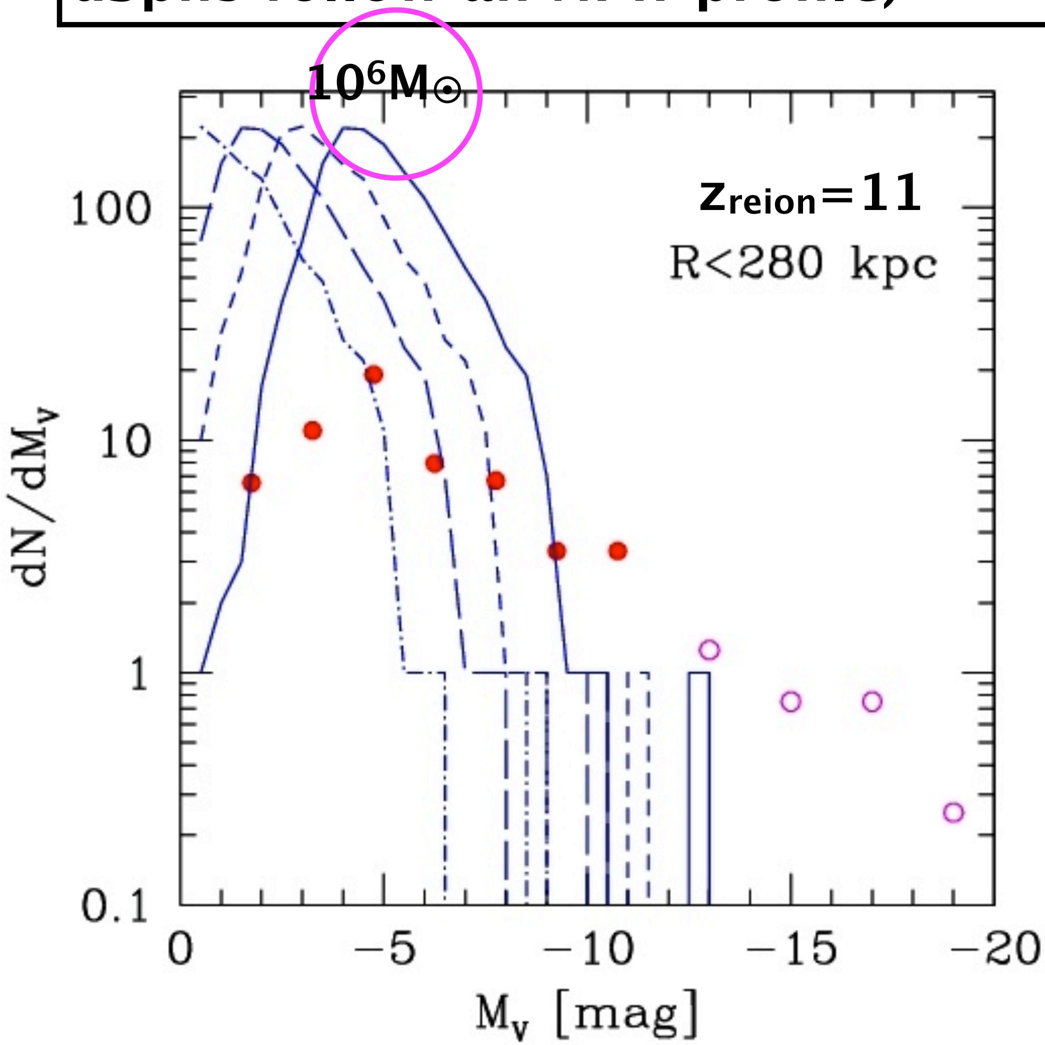
⇨ $M_V=6.6$ (BC03, Z=0.0001)

$M_*=3000\ M_\odot$ ⇨ $M_V=-2.1$

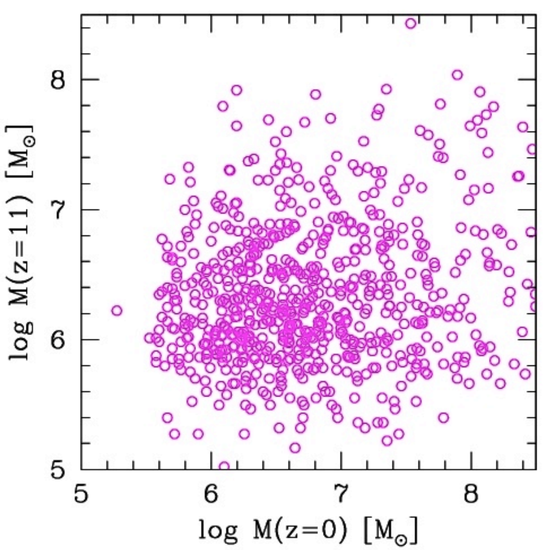
Belokurov et al. (2007)



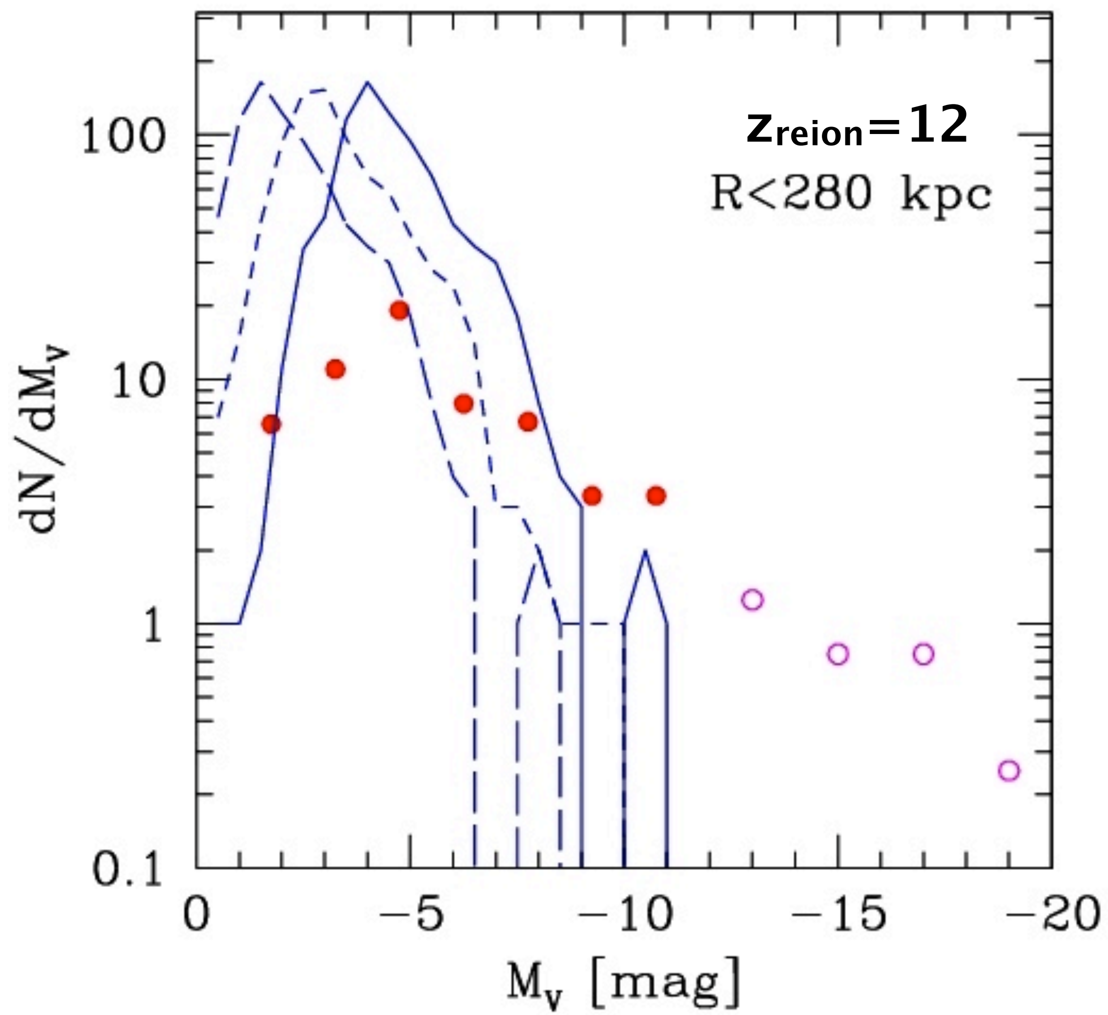
The LF of Milky Way's satellites after SDSS (data points from Koposov 2008, corrected assuming dSphs follow an NFW profile)

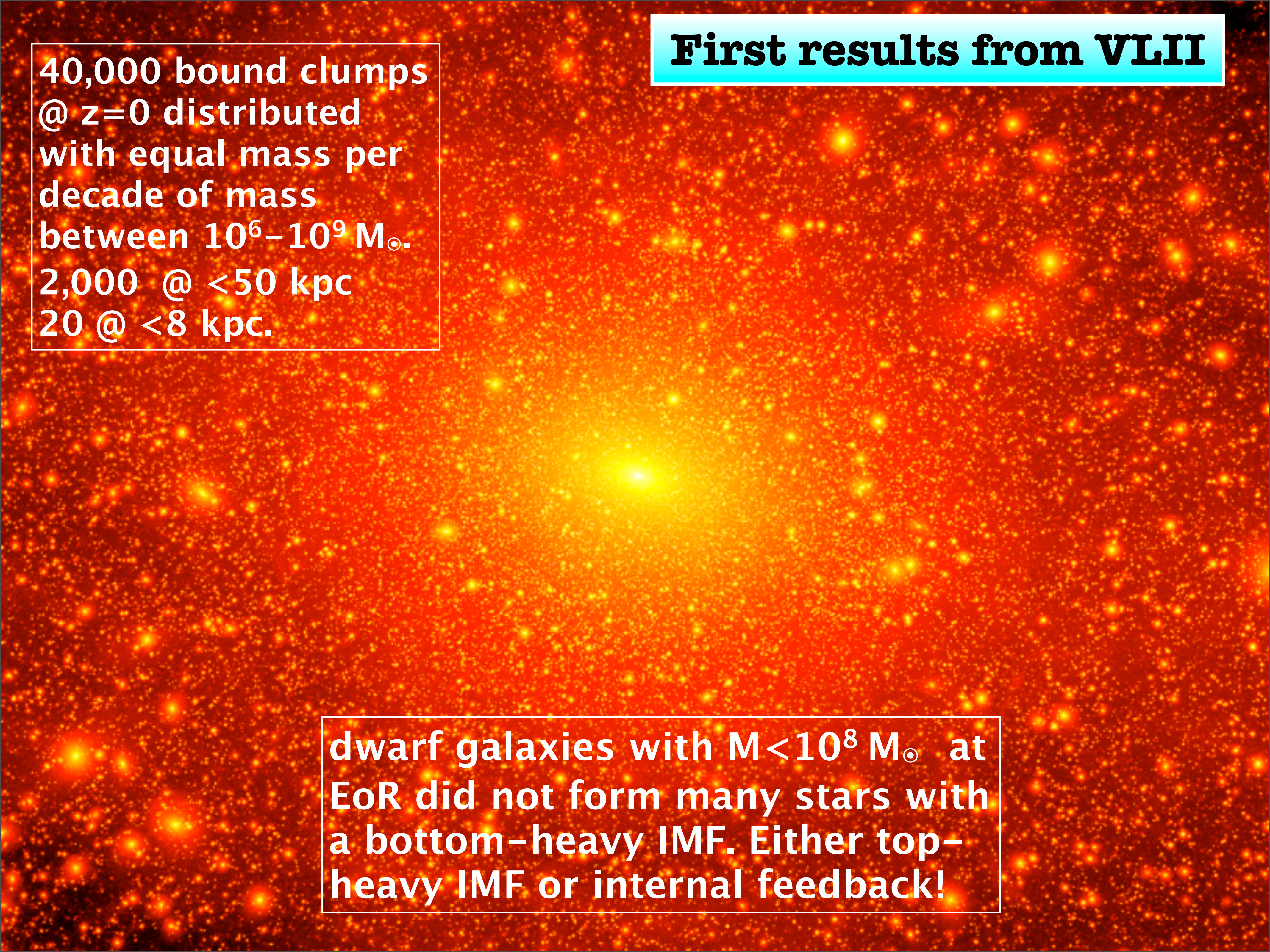


f_*=0.1
f_*=0.03
f_*=0.01
f_*=0.003

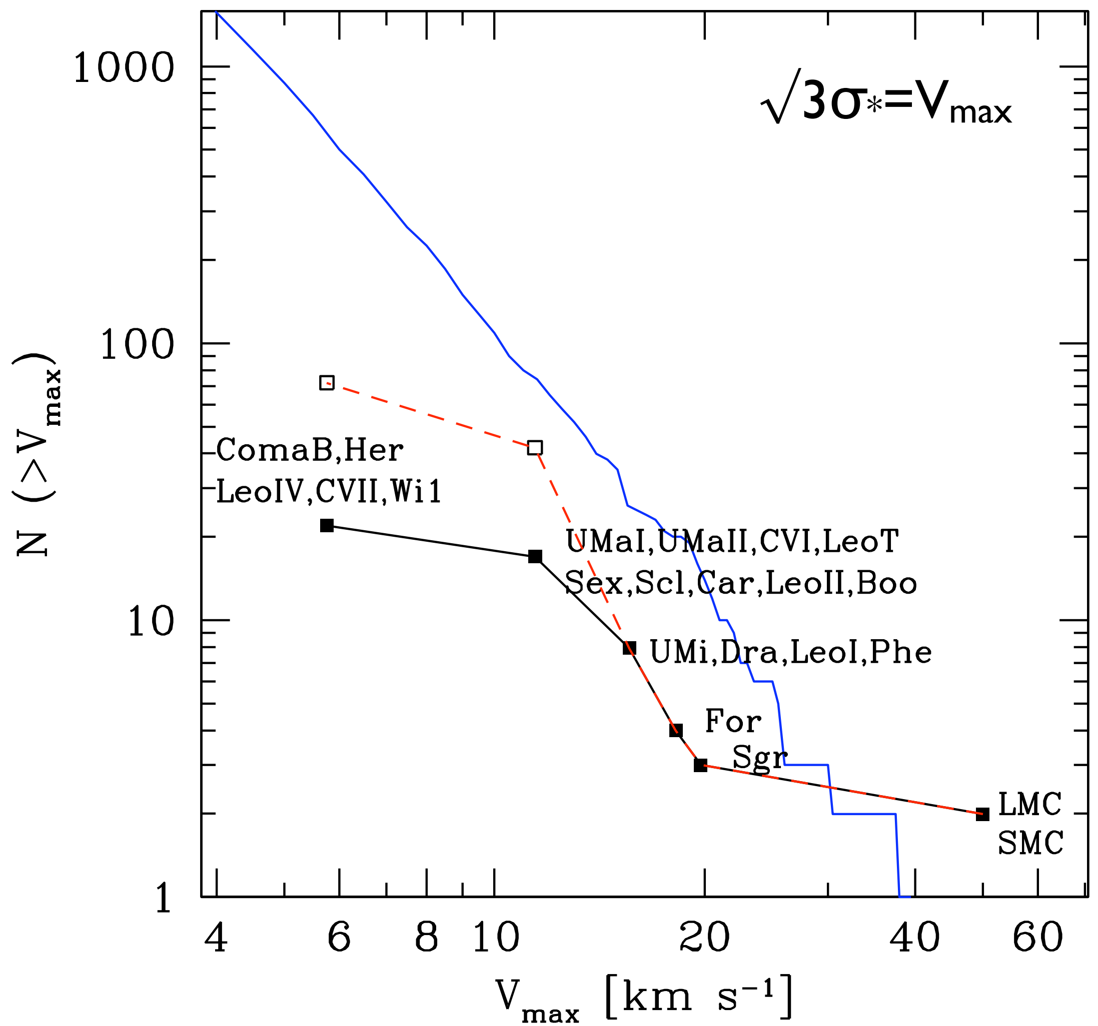


Not very sensitive to the exact EoR redshift




First results from VLII
40,000 bound clumps @ z=0 distributed with equal mass per decade of mass between 10⁶-10⁹ M☉. 2,000 @ <50 kpc 20 @ <8 kpc.
dwarf galaxies with M<10⁸ M☉ at EoR did not form many stars with a bottom-heavy IMF. Either top-heavy IMF or internal feedback!

The "substructure problem"



Only 1/5-1/10 subhalos with Vmax>20 km/s today appear to be luminous

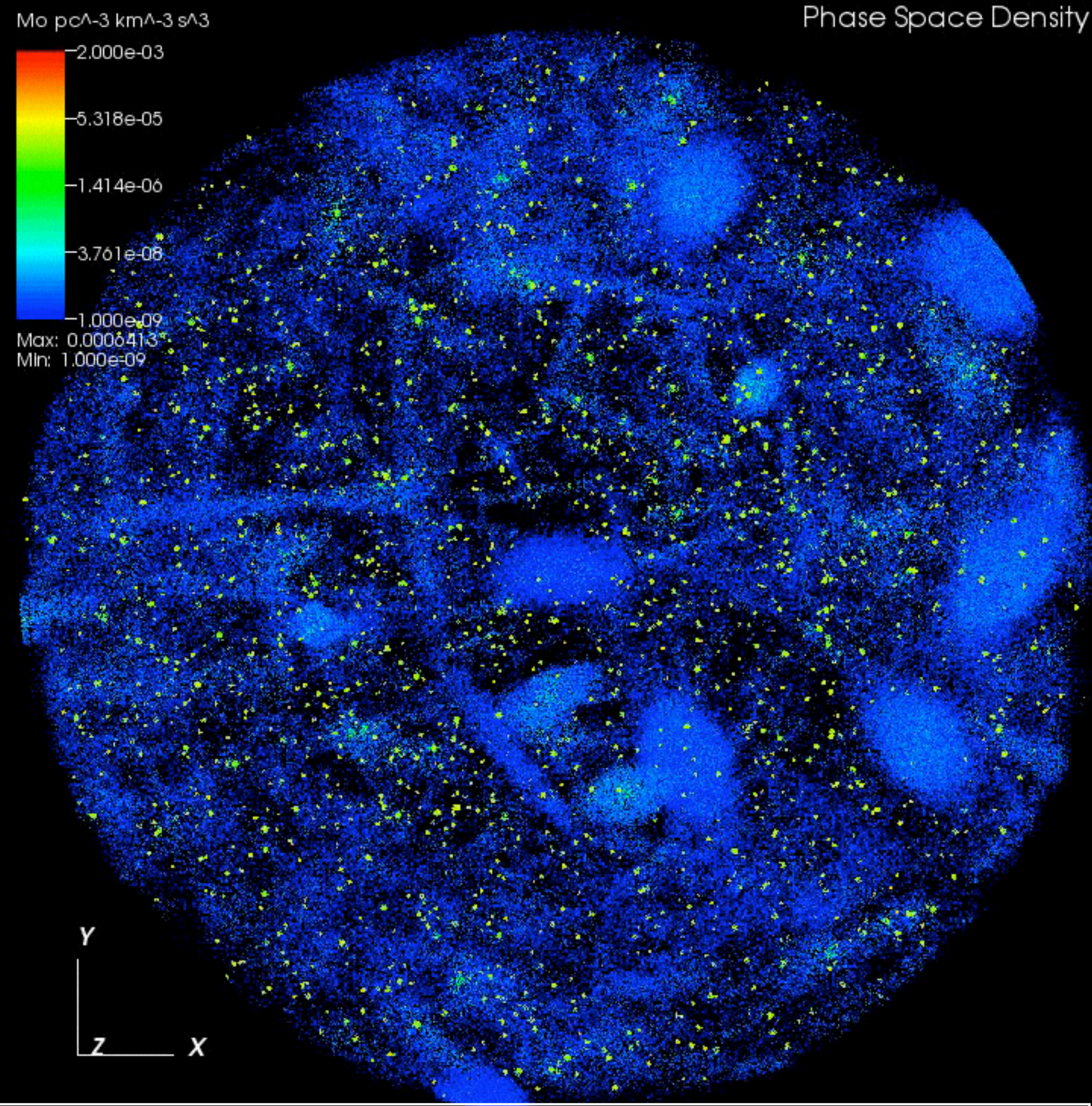
Are there many more ultra-faint Milky Way companions waiting to be discovered below μ_V=28 mag arcsec^{-2}?

Via Lactea predicts 2000 satellites with $M_{sub}>10^7\ M_\odot$ (> Leo T, Leo IV, Coma B, CVII)

Leo T (Irwin et al. 2007)
$M(H\ I)>10^5\ M_\odot$ and $L>10^3\ L_\odot$

Need a very efficient feedback mechanism quenching SF for $V_{max}<$ 20 km/s (today)
$V_{max,p}<$35 km/s (past)

Subhalos have very large inner phase-space densities ~10^{-5} $M_\odot$ pc^{-3} km^{-3} s^3 due to their relatively small internal velocity dispersions.



<u>coherent elongated features</u>: streams that form out of material removed from accreted and disrupted subhalos. The visible streams are underdense relative to the background but owing to their low velocity dispersion they manage to stand out in local phase space density.

The End