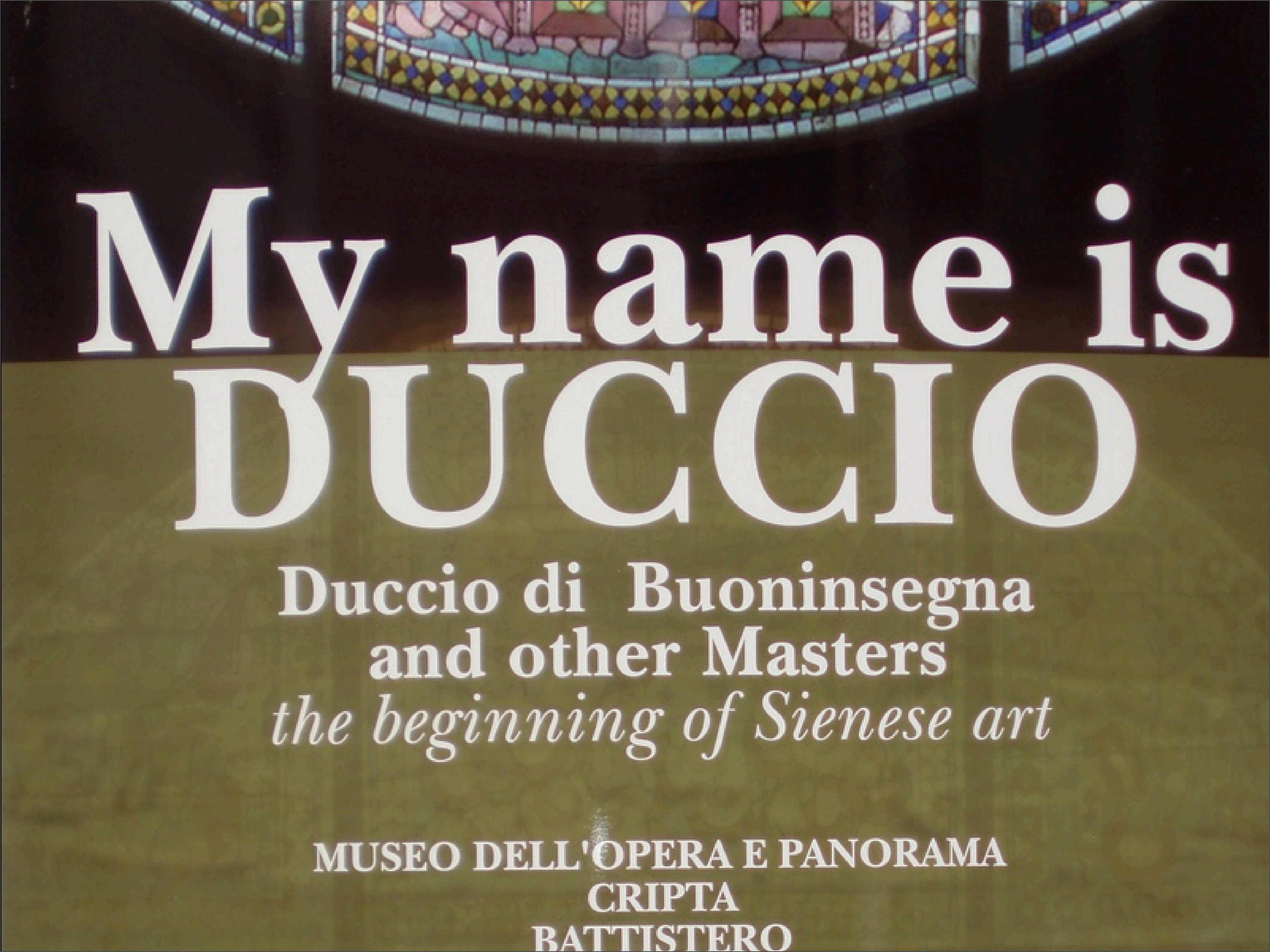
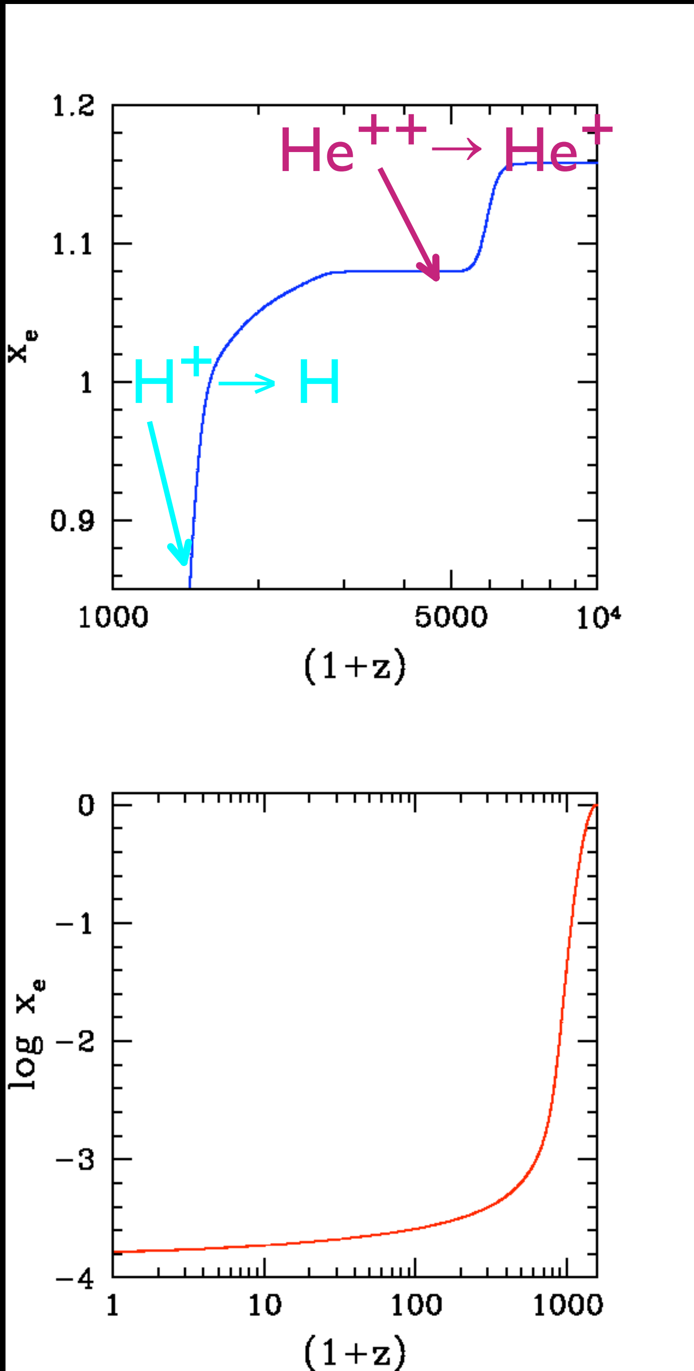
Galaxy Formation, Halo Substructure, and Reionization

Piero Madau (UCSC)

ESTEC 07


My name is
DUCCIO
Duccio di Buoninsegna
and other Masters
the beginning of Sienese art
MUSEO DELL'OPERA E PANORAMA
CRIPTA
BATTISTERO

post-recombination Universe

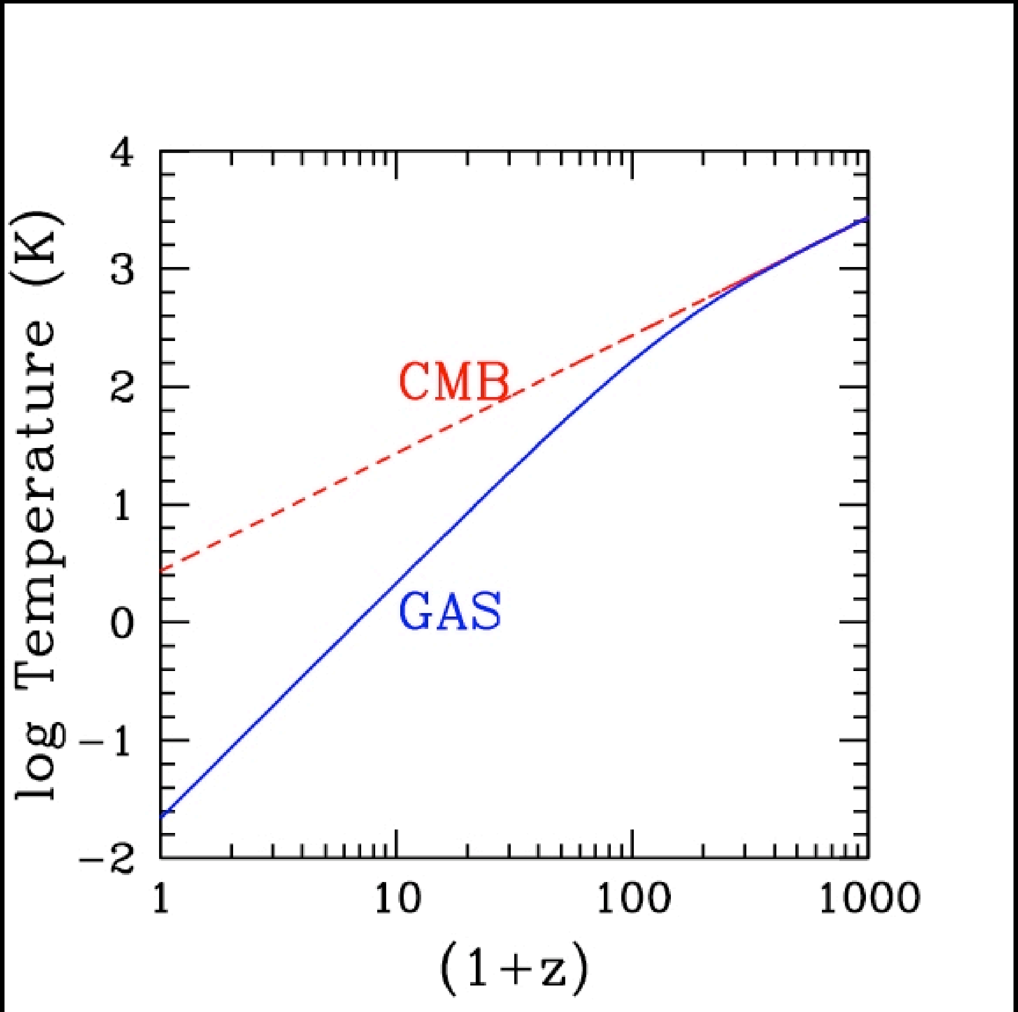


H and He recombination with RECFAST

- @ z_{dec}=1088±1, t_{dec}=(372±14) kyr after the big bang, Universe becomes optically thin to Thomson scattering
- at this epoch the electron fraction x drops below 13% and CMB cools below 3000 K
- we understand the microphysics of the post-recombination Universe well: recombination freezes out with

$$\frac{n_e}{n_H} \equiv x \approx 10^{-5}\,\Omega_M^{1/2}/h\Omega_b$$

Cosmic Dark Ages



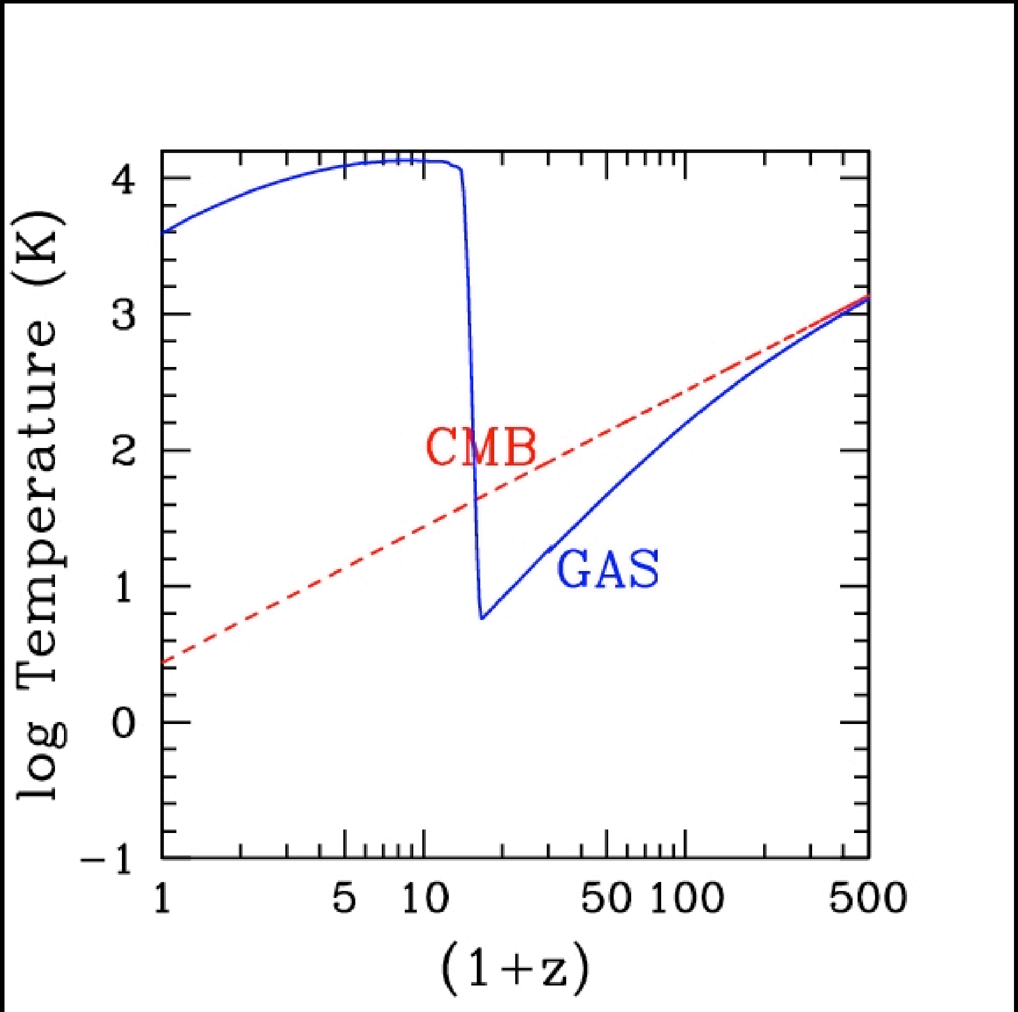
- residual free electrons keeps $T_{IGM}=T_{CMB}$ until thermalization redshift:

$$z_{th}=750\ (\Omega_b\ h)^{2/5}\approx 150$$

- Universe becomes semi-opaque again after reionization. Third-year WMAP measurement of electron scattering optical depth $\tau_e=0.09 \pm 0.03$ implies $z_{rei}=11\pm 2.5$

$$\tau_e = \int_0^{z_{rei}} \frac{cdz}{(1+z)H(z)} \sigma_T n_e(z) \approx 0.002\ x\left[(1+z)^{3/2}-1\right]$$

Cosmic Dark Ages



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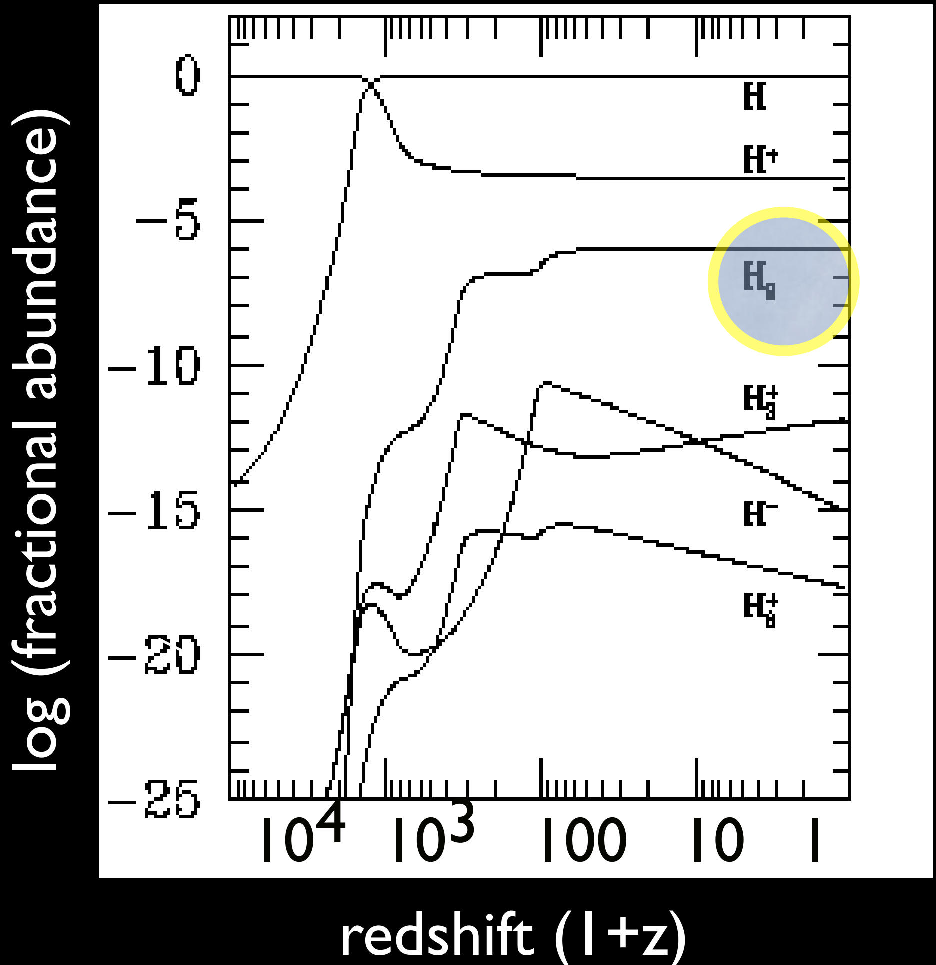
H_2 molecules



free electrons serve as catalysts for the formation of H_2 through the negative ion H^-

$$H + e^- \leftrightarrow H^- + \gamma.$$

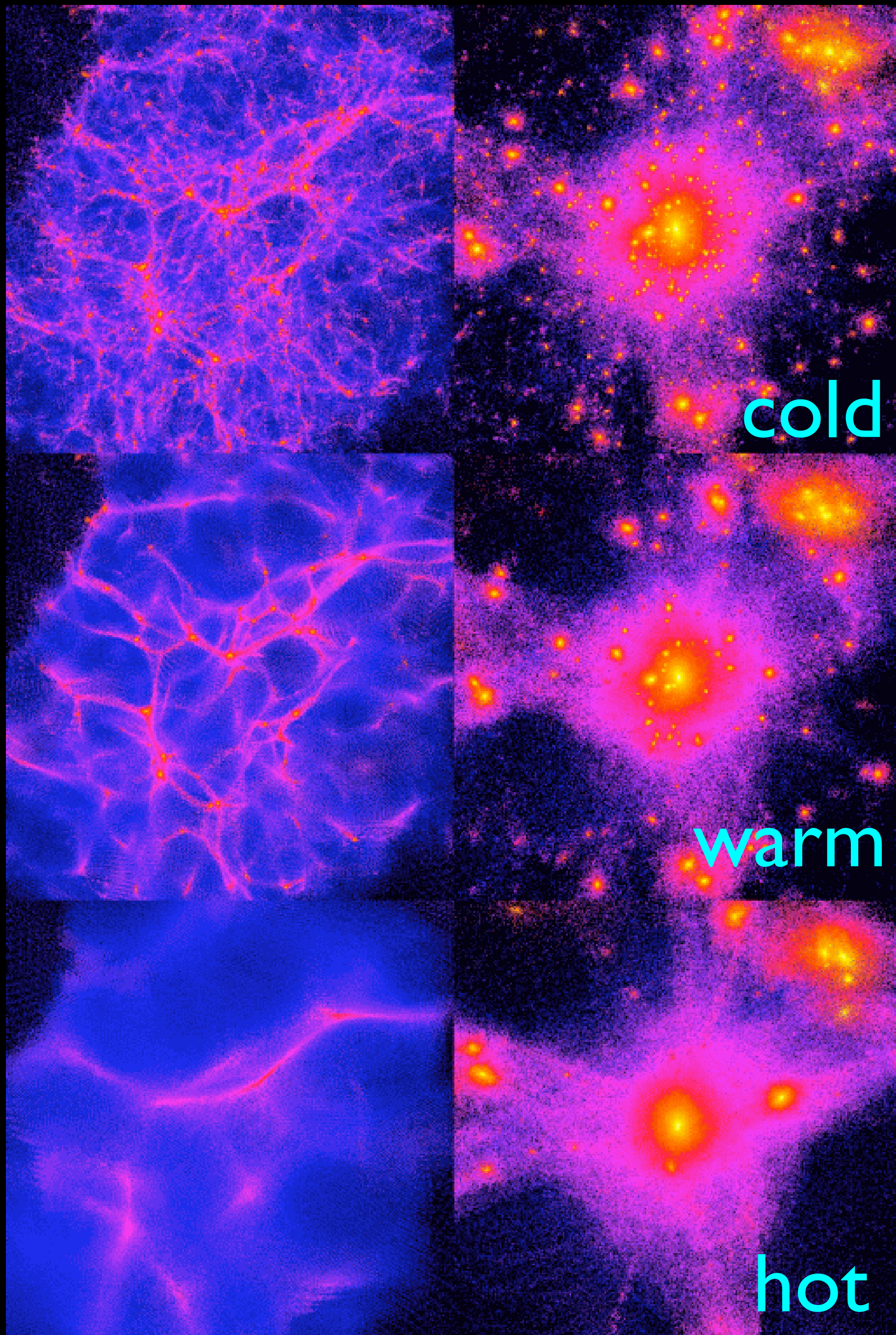
$$H^- + H \leftrightarrow H_2 + e^-$$

$$\frac{dx_{\mathrm{H}_2}}{dt} \propto x_e n_{\mathrm{HI}} T^{0.9}$$

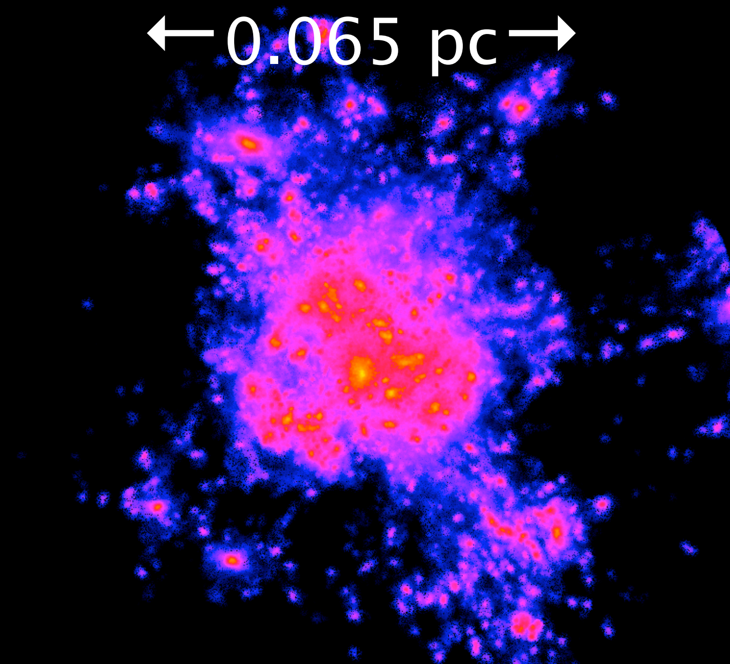
H_2 is the main source of cooling in the first generation of gravitationally bound gas clouds

$x_{H2}(\mathrm{IGM}) \sim 10^{-6} \Rightarrow t_{cool} \gg H^{-1}$

Some like it cold



B. Moore's Nbody site

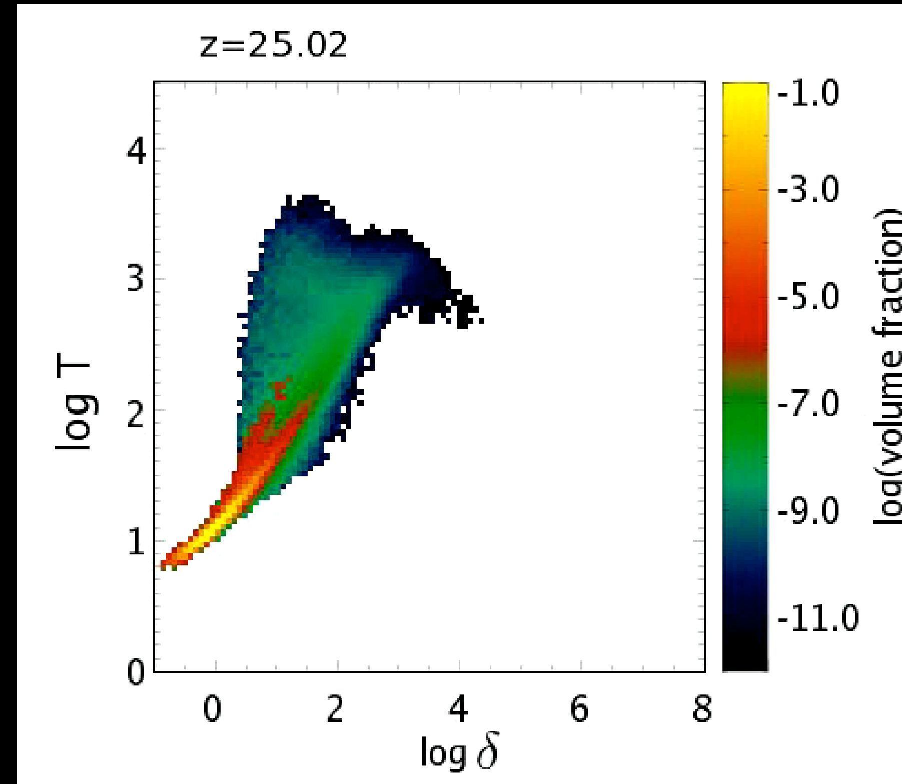


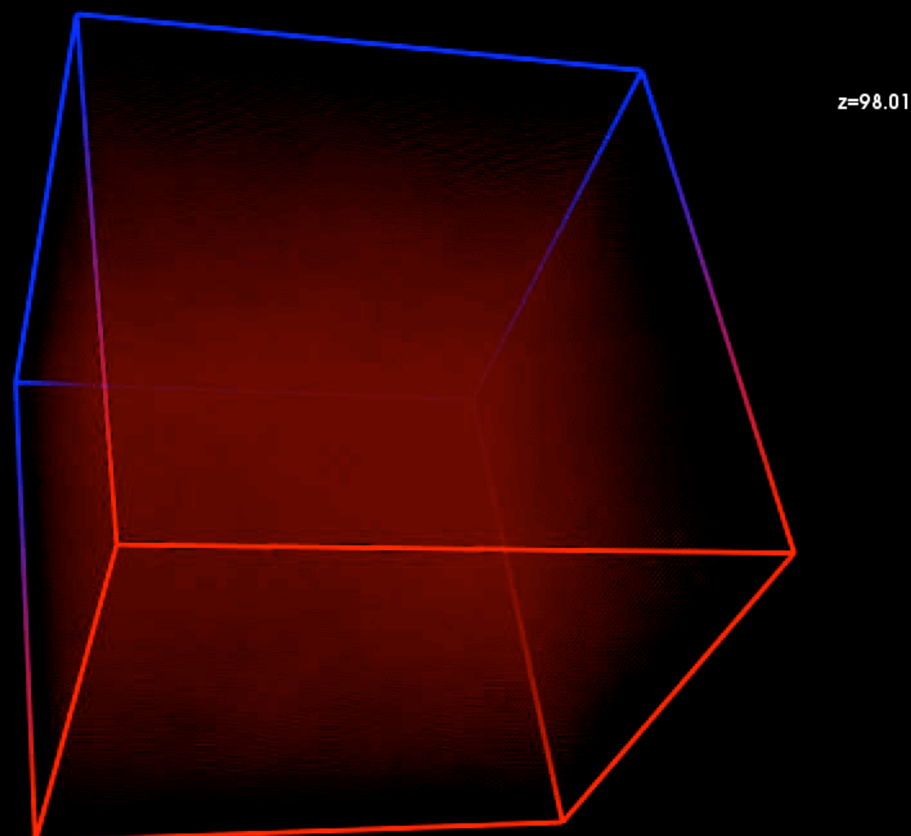
$z=86$ $M_{vir}=0.005\ M_{\odot}$

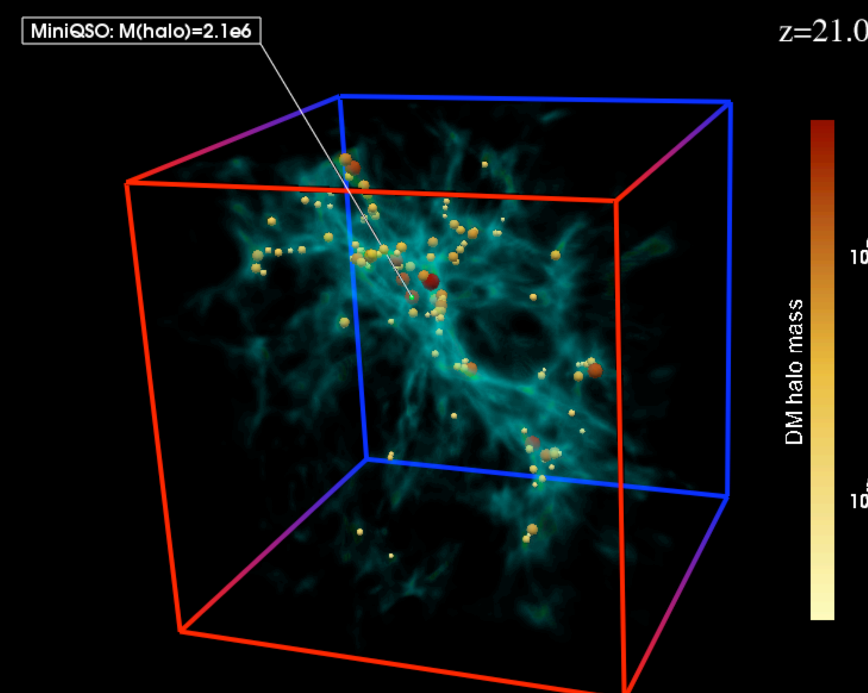
- no minimum scale for the gravitational aggregation of collisionless cold dark matter (CDM)

$$\sigma^2_M = \langle (\delta M / M)^2 \rangle = \frac{1}{2\pi^2} \int_0^\infty dk k^2 P(k) T^2(k) W^2(kR)$$

From dark halos to the first galaxies

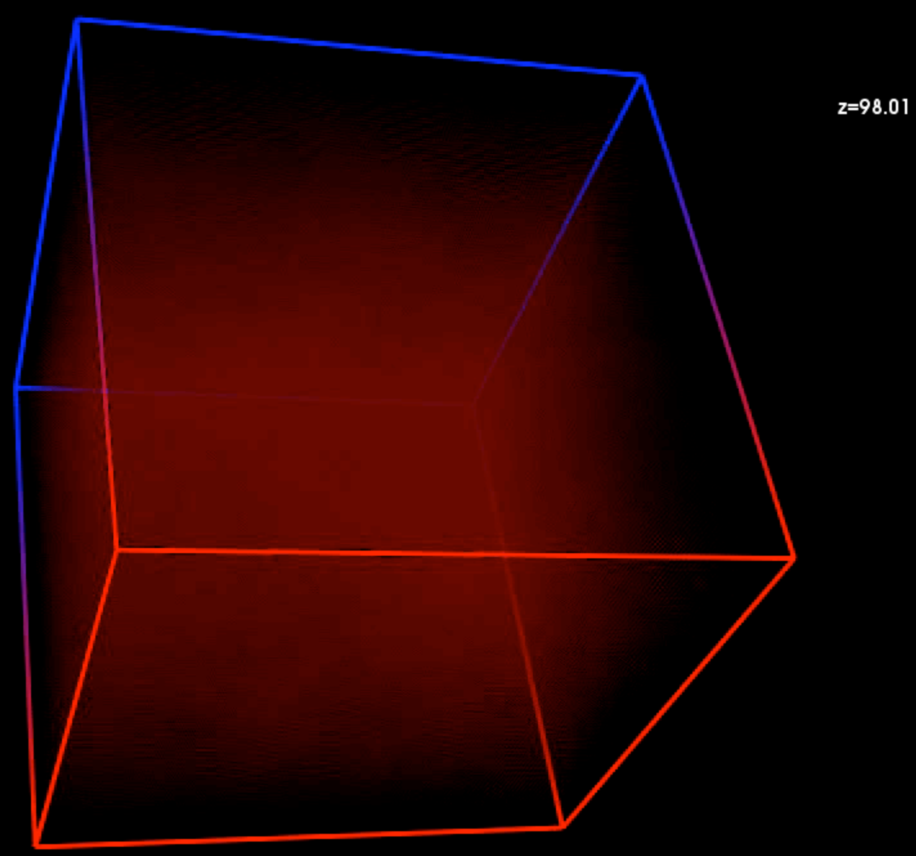


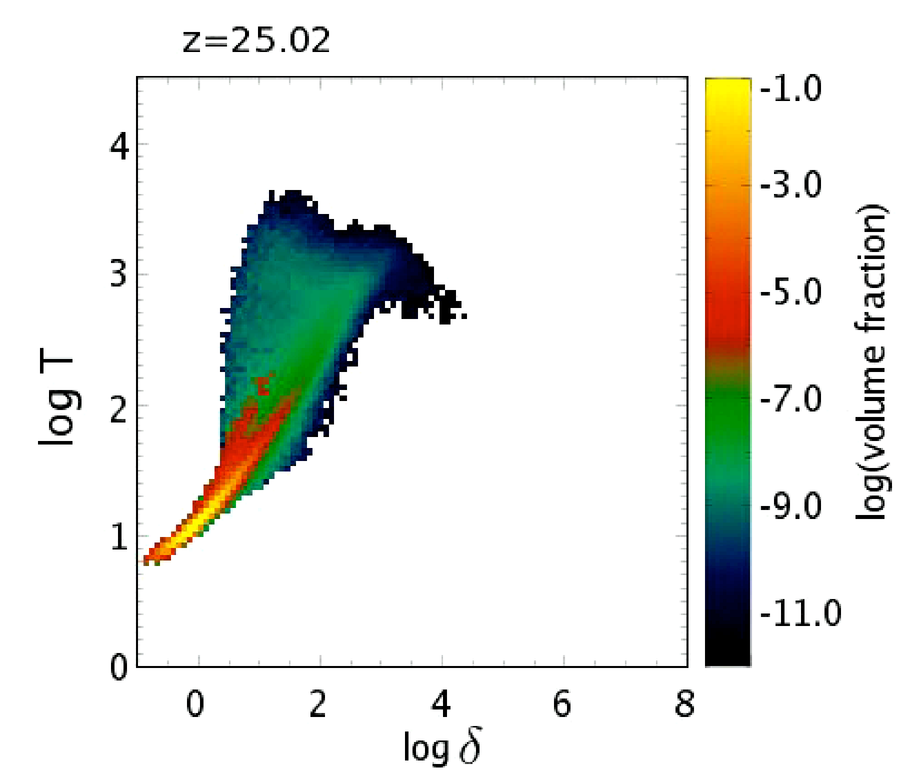


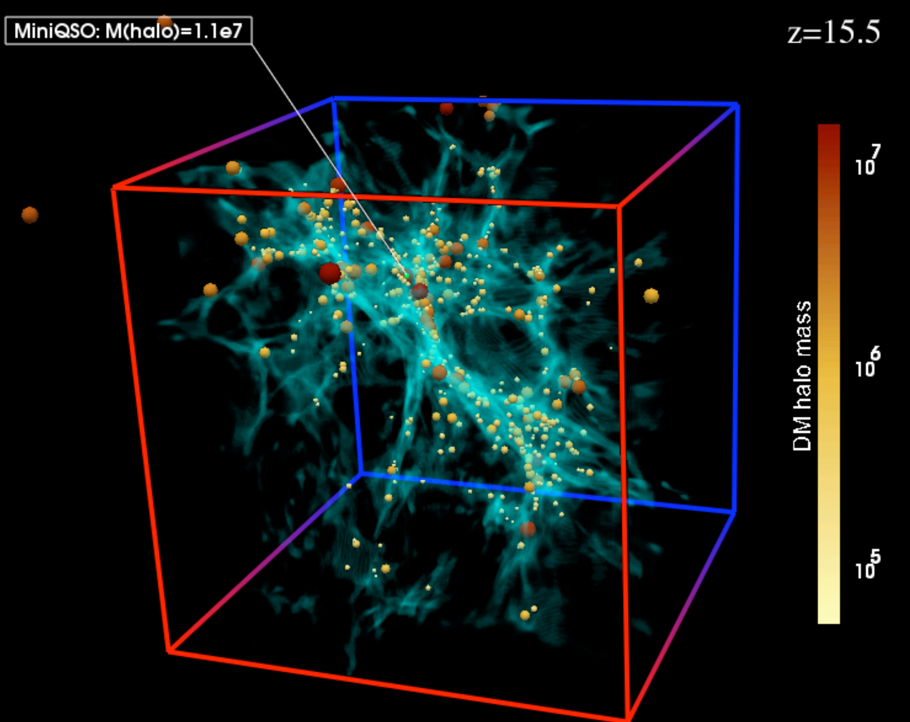


Kuhlen & PM 05

From dark halos to the first galaxies







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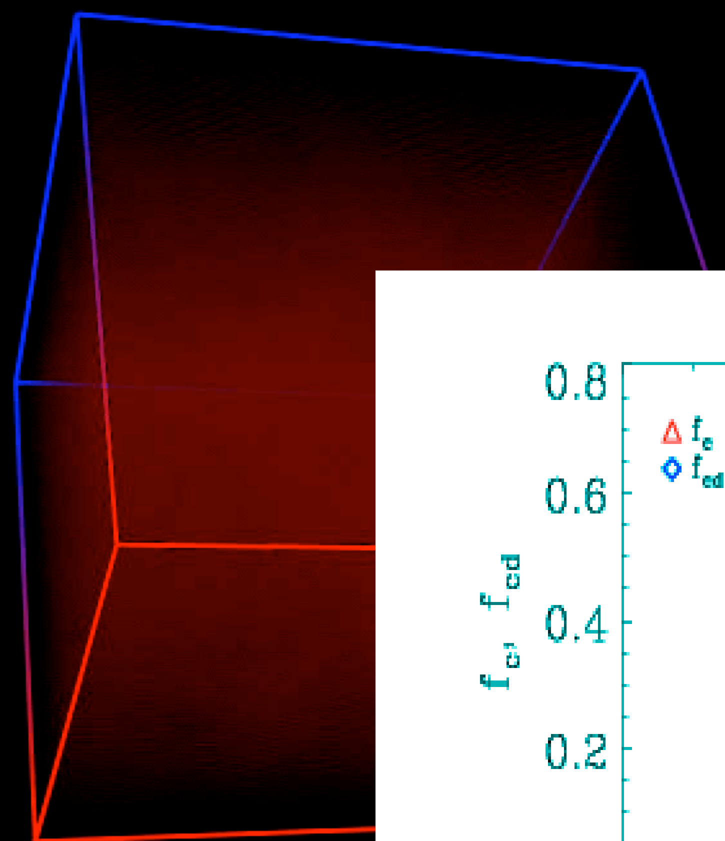
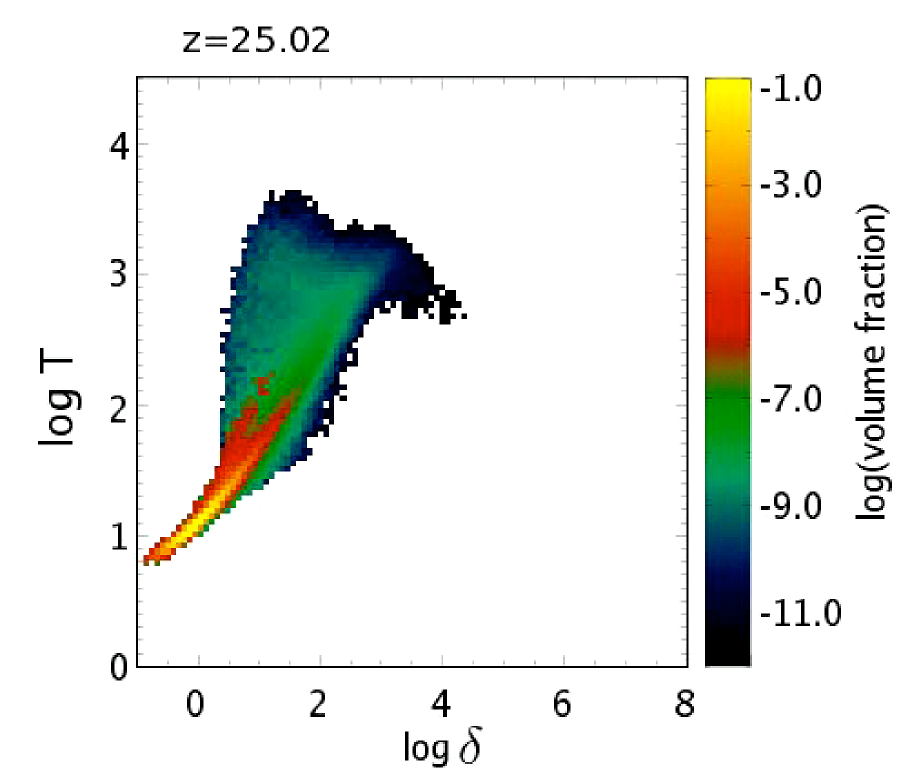
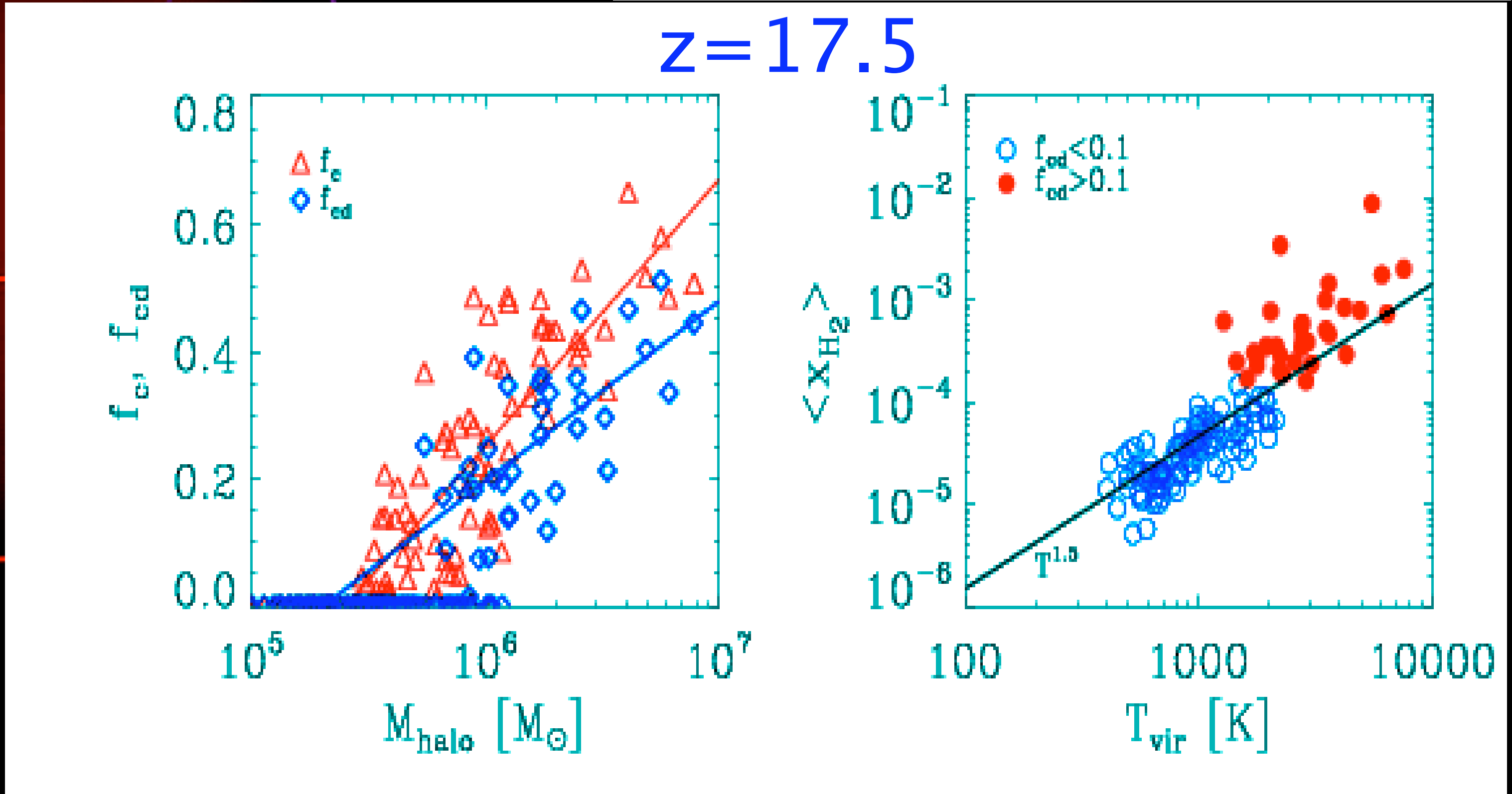
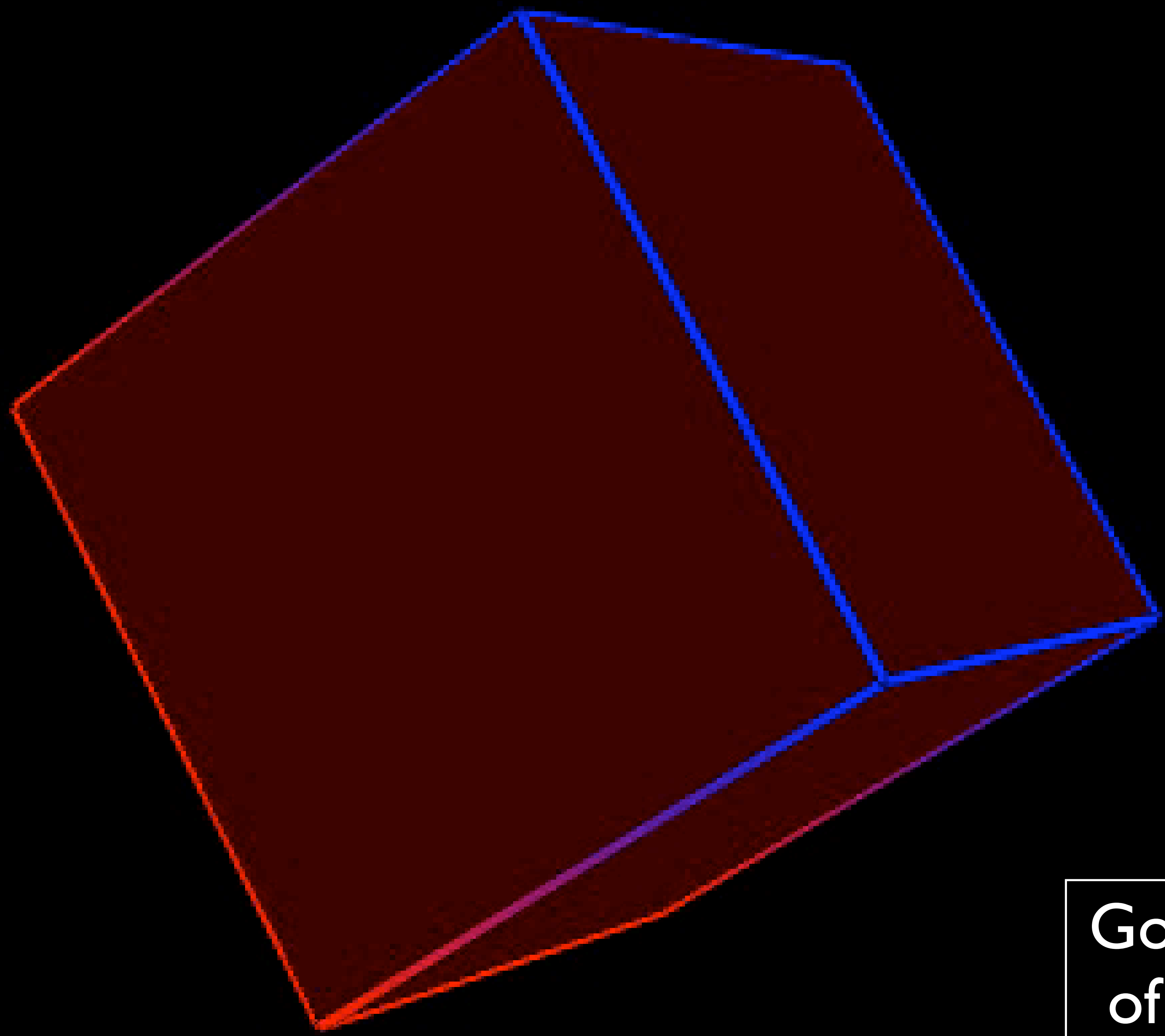






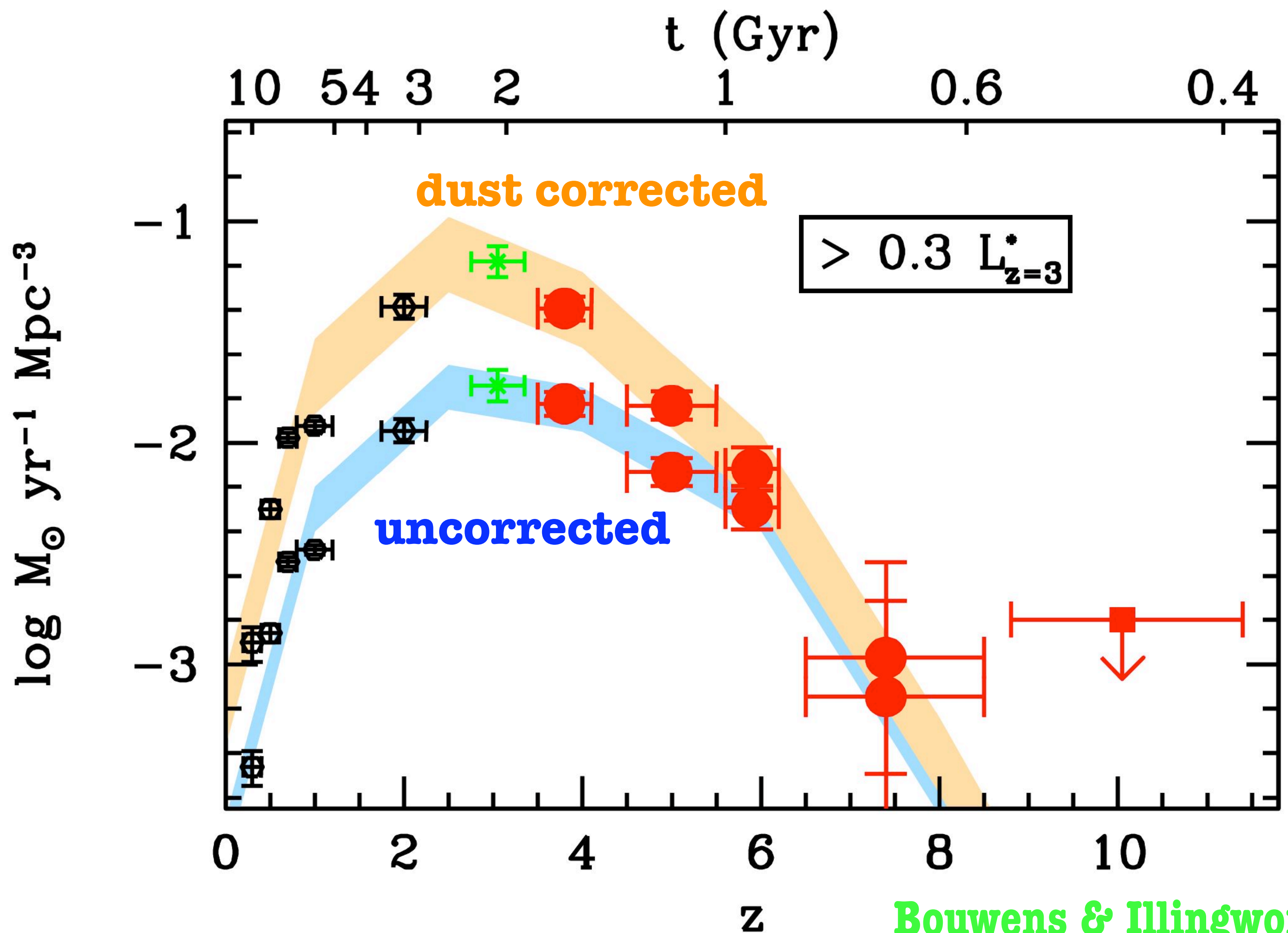
Kuhlen & PM 05

N. Gnedin



God's view of cosmic reionization

Star Formation Rate (SFR) History to z~7

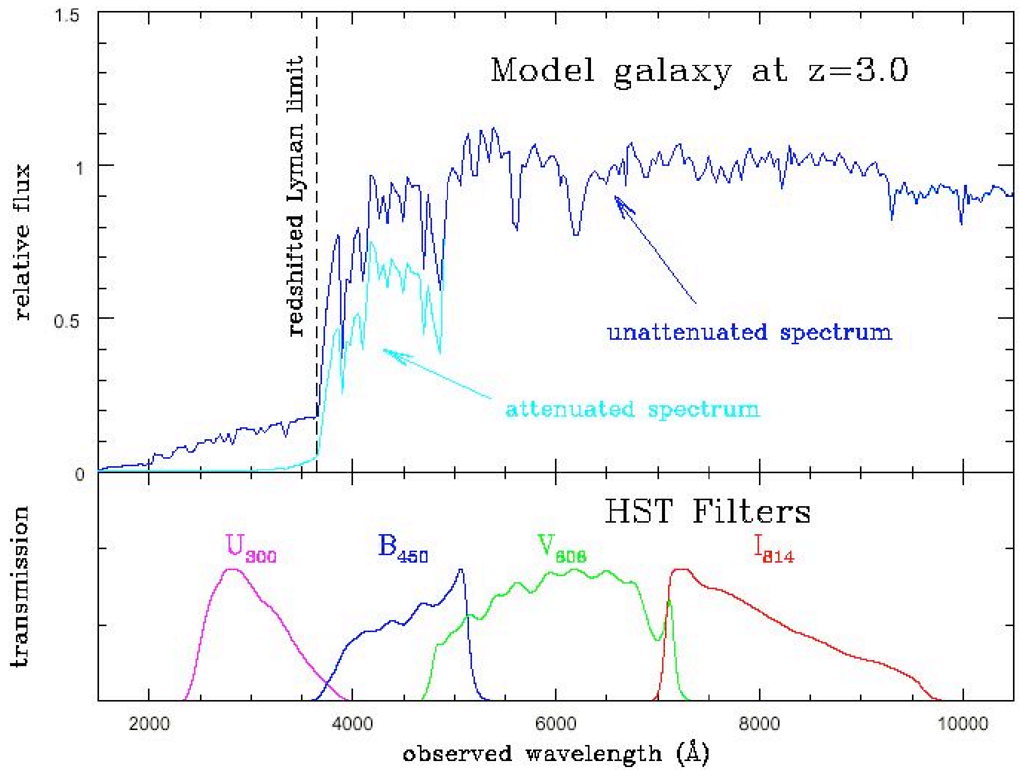


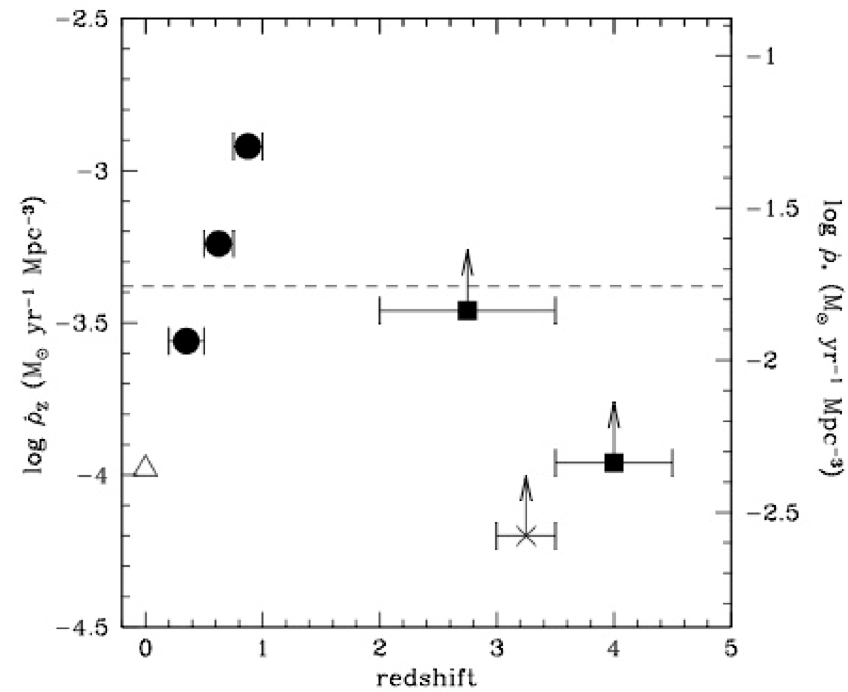
Bouwens & Illingworth 2006

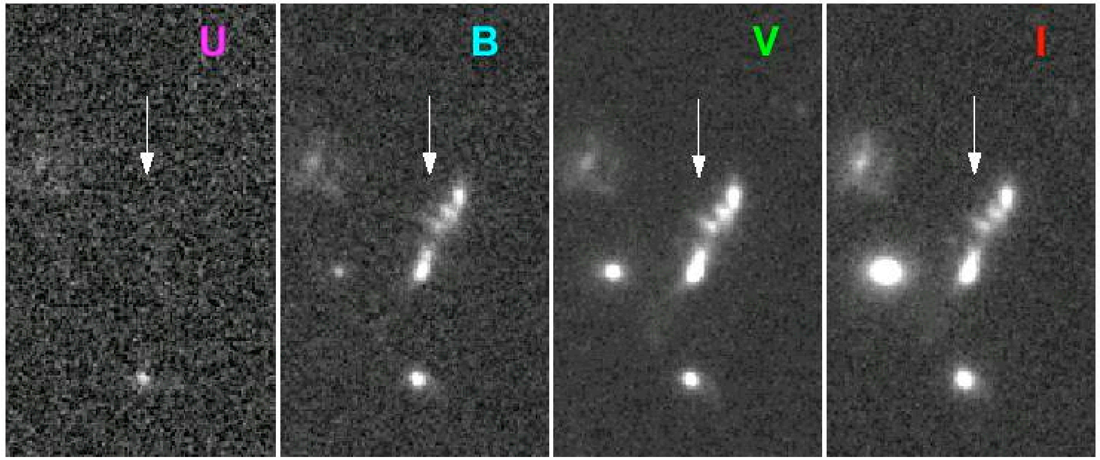
Large drop at z~7-8 for luminous (more massive?) galaxies

12 years ago...

Mark Dickinson: *Color–Selected High Redshift Galaxies*

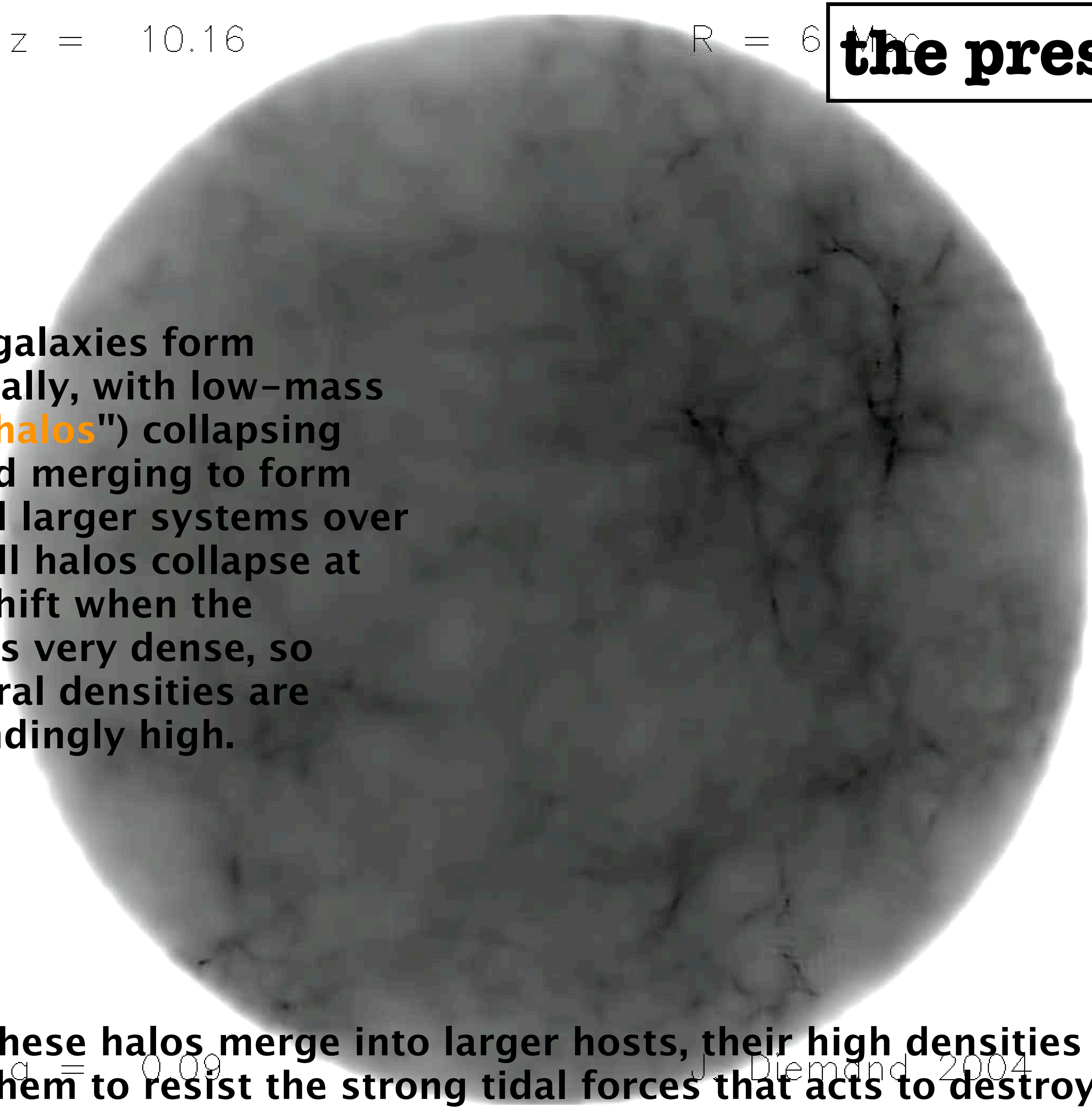






PM+ 1996
70 z~2.5 U-drops
15 z~4 B-drops

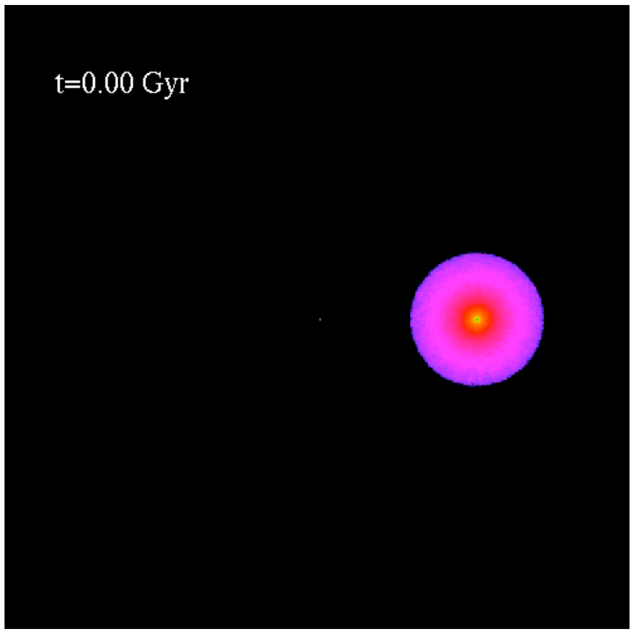
the present...

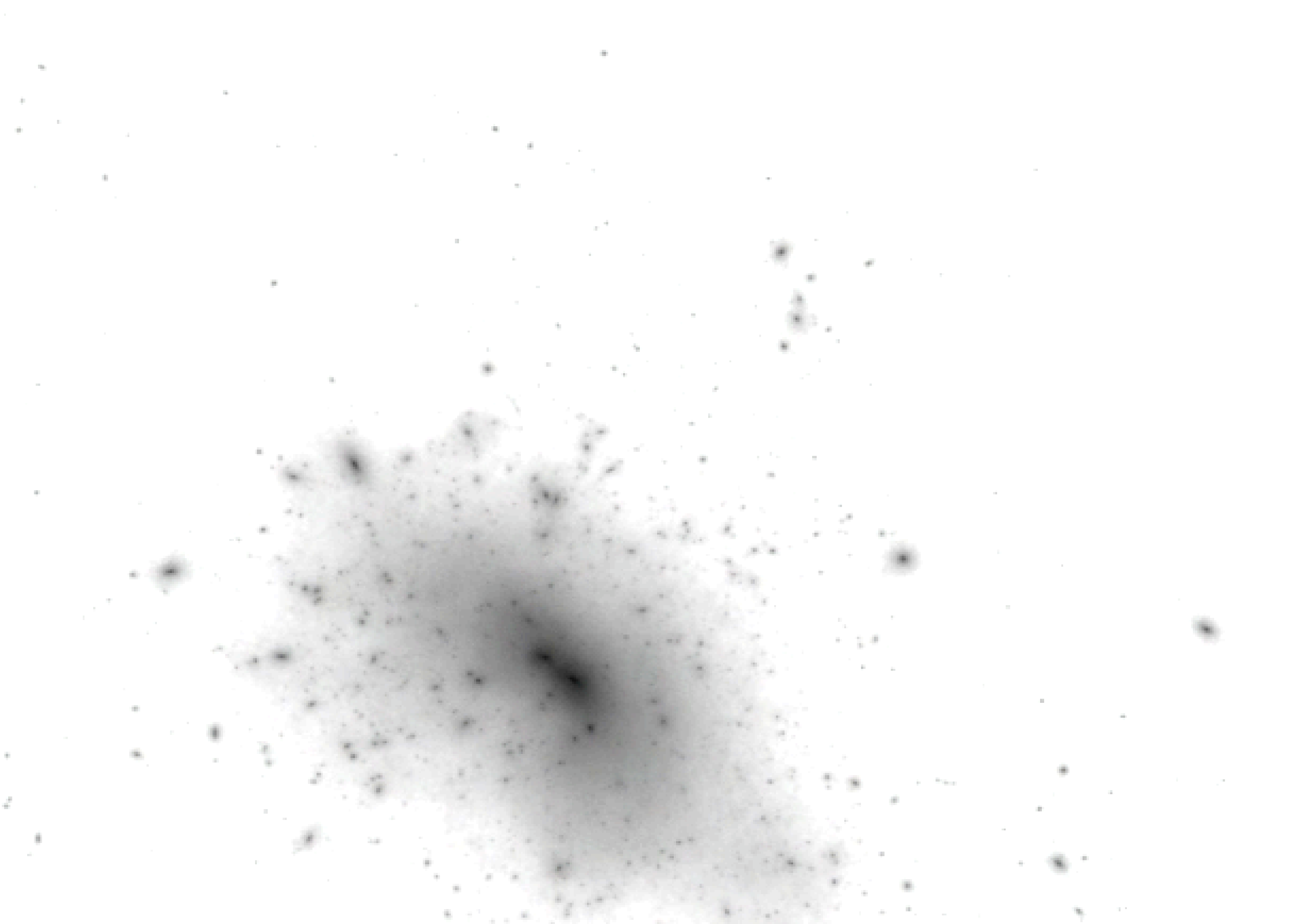


In ΛCDM galaxies form hierarchically, with low-mass objects (“halos") collapsing earlier and merging to form larger and larger systems over time. Small halos collapse at high redshift when the universe is very dense, so their central densities are correspondingly high.

When these halos merge into larger hosts, their high densities allow them to resist the strong tidal forces that acts to destroy them.

Gravitational interactions appear to unbind most of the mass associated with the merged progenitors, but a significant fraction (f_{sub}~5–10%) of these small halos is expected to survive as distinct substructure.



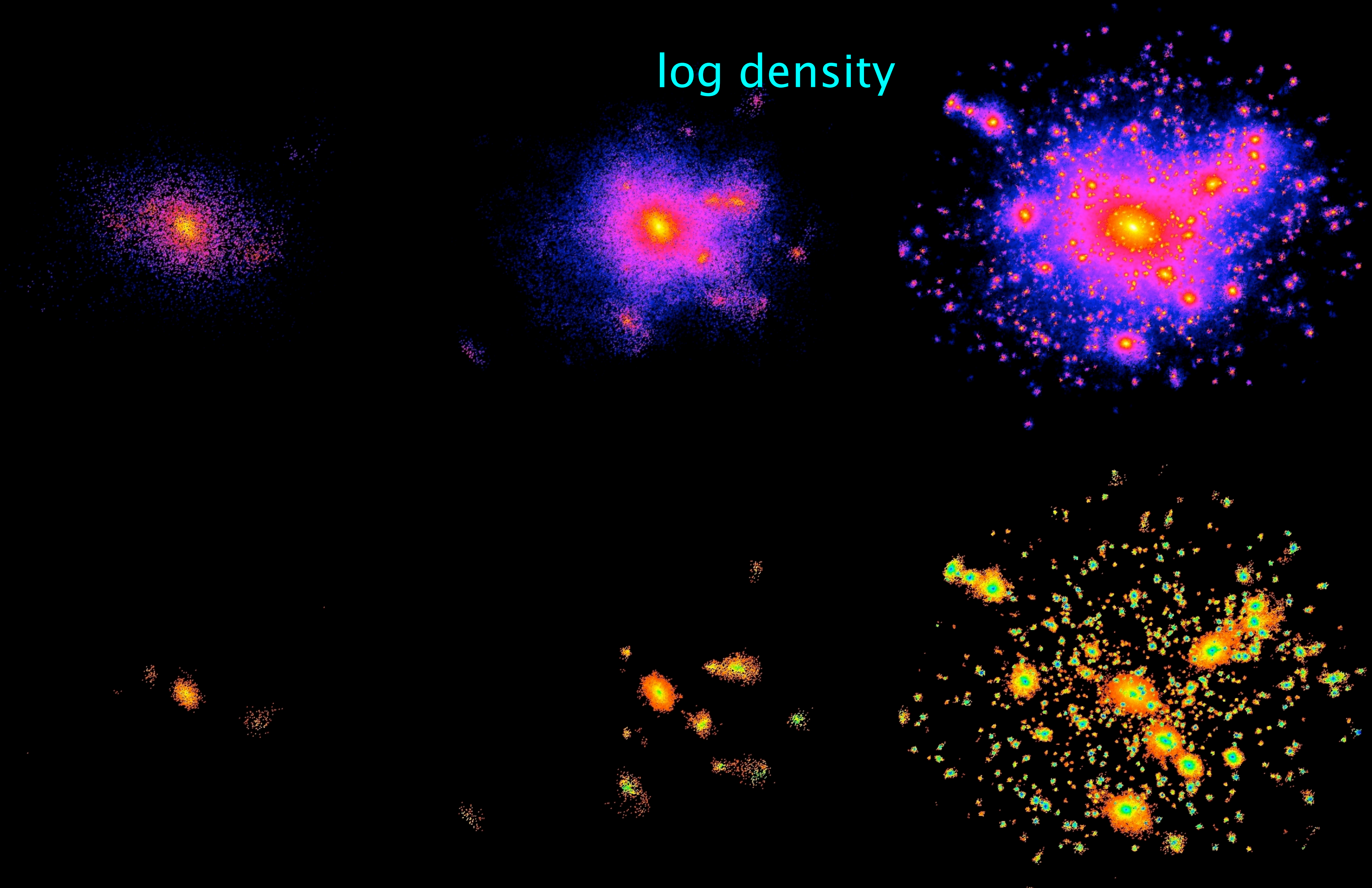


It is therefore a clear, unique prediction of CDM that galaxies are embedded in massive, extended dark matter halos teeming with self-bound substructure or “subhalos". High resolution N-body simulations have confirmed that CDM halos both on cluster and galaxy scales are not smooth but have a wealth of substructure on all resolved mass scales.

Simulating structure formation

A brief history of simulating CDM halos (about 1995 to 2000)

log density



log phase space density

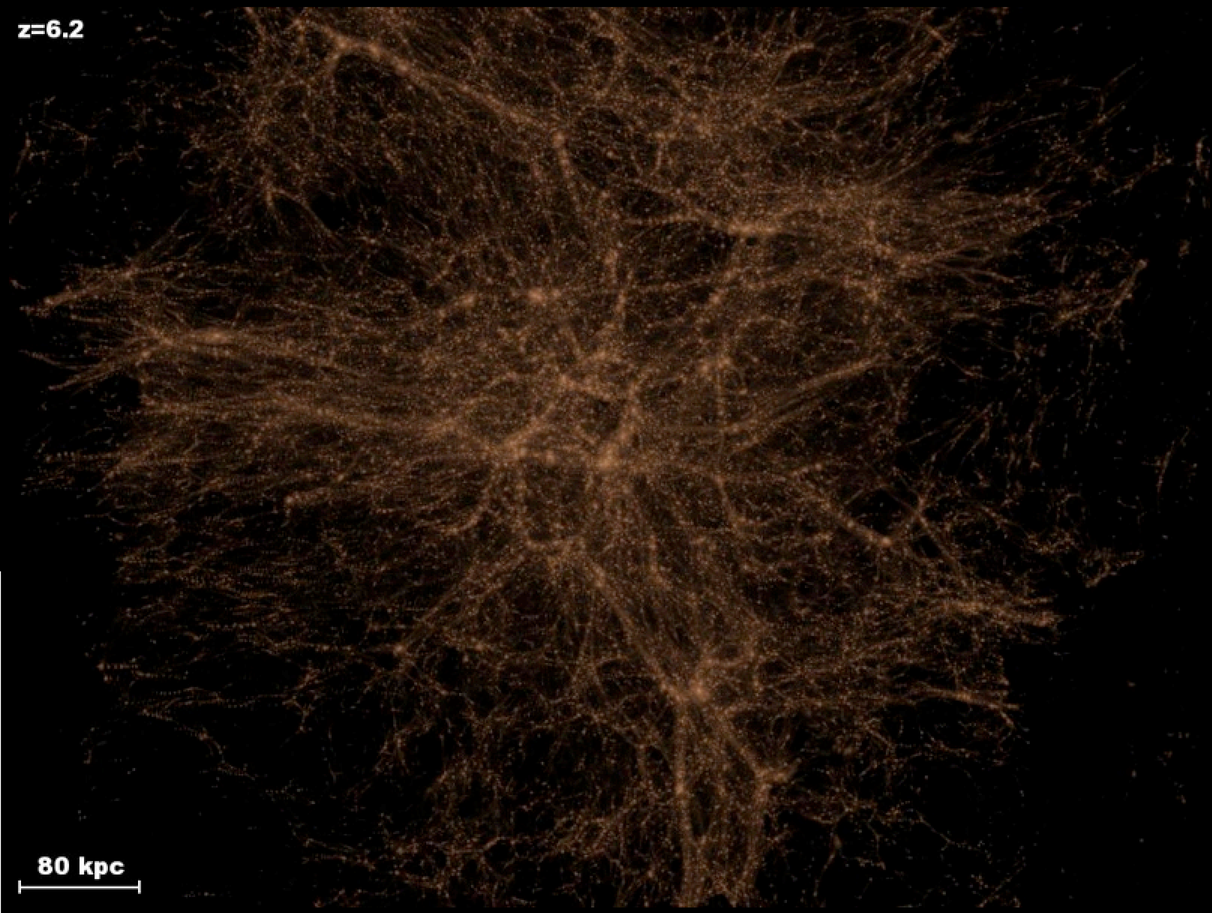
from B. Moore : www.nbody.net

"VIA LACTEA": a new N-body simulation of unprecedented dynamic range

Largest DM simulation to date at these scales. 320,000 cpu hours (36.5 cpu yrs) 213,217,920 high res particles embedded in a periodic 90 Mpc box sampled at lower resolution to account for tidal field.

M_{halo}=1.8e12 $M_{\odot}$
$r_{vir}=r_{200}$=390 kpc
softening length=90 pc
m_p=2e4 $M_{\odot}$

A Milky Way-sized DM halo simulated with 234 million particles on NASA's Project Columbia supercomputer



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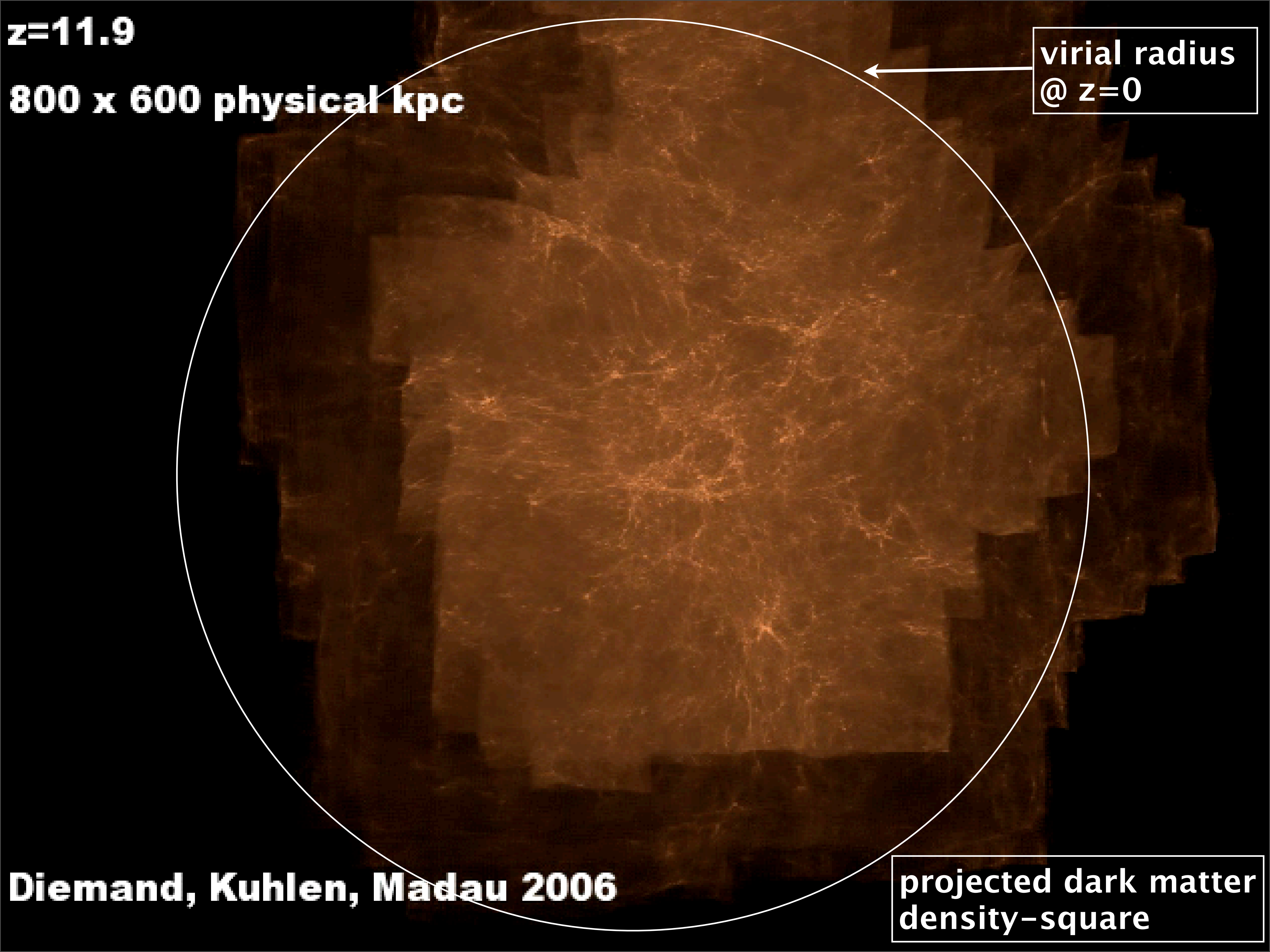
time resolution: adaptive
timesteps as short as
68,500yr=Hubble time/200,000

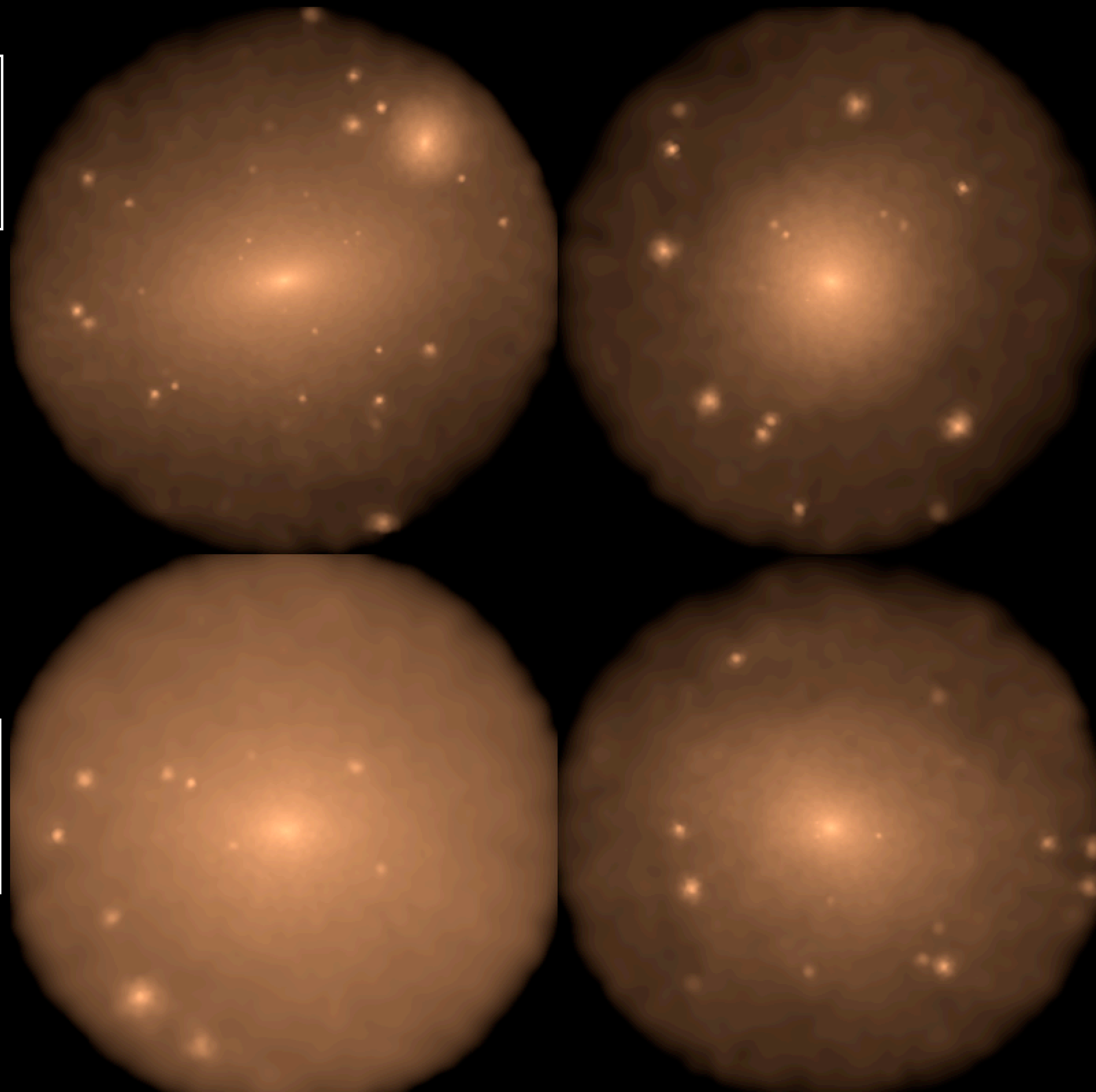
WMAP 3-year cosmology:
Ω_M=0.238, Ω_Λ=0.762, h=0.73, n=0.951, σ_8=0.74


z=11.9
800 x 600 physical kpc
virial radius
@ z=0
Diemand, Kuhlen, Madau 2006
projected dark matter
density-square

Resolve sub-subhalos in most massive satellites!

M_{sub} =9.8e9 $M_\odot$
r_t=40.1 kpc
D=345 kpc

M_{sub} =3.7e9 $M_\odot$
r_t=33.4 kpc
D=374 kpc

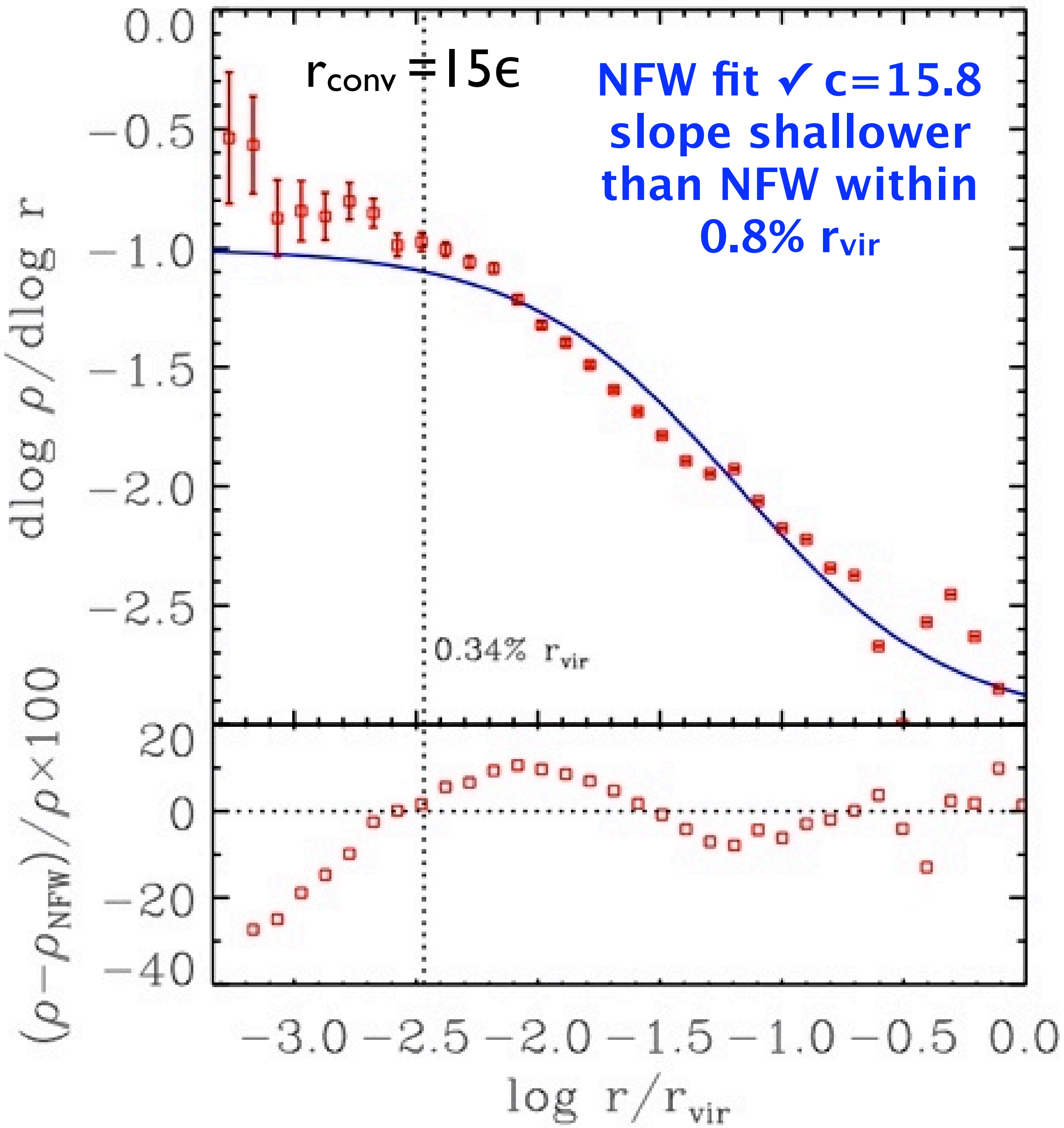


M_{sub} =3.0e9 $M_\odot$
r_t=28kpc
D=280 kpc

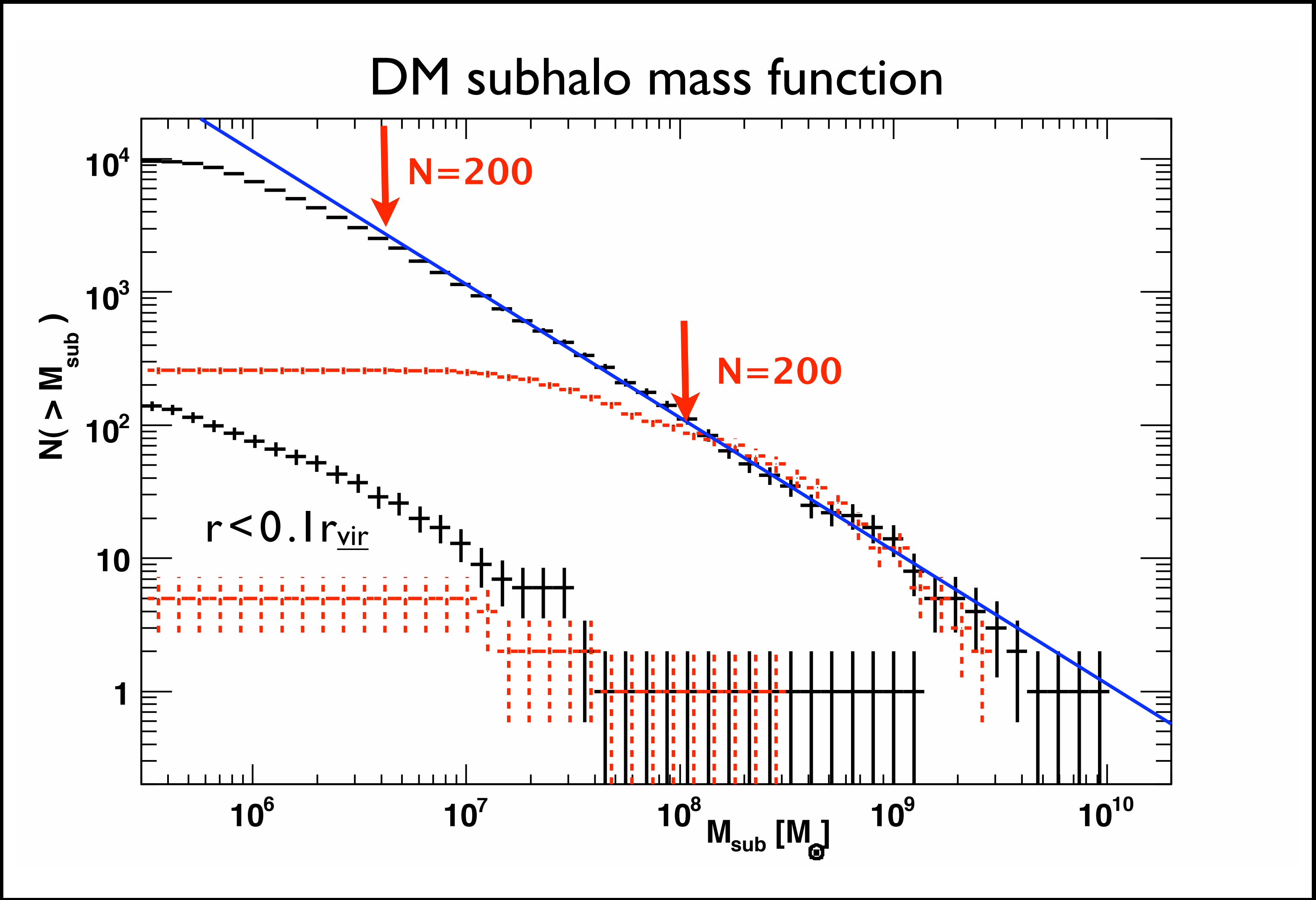
M_{sub} =2.4e9 $M_\odot$
r_t=14.7 kpc
D=185 kpc

subhalo density (tidal radius) = 2 background density
subhalo tidal mass = total mass (< tidal radius) ≤bound mass

Logarithmic slope of density profile



6102 (11400 if $N \propto 1/M_{sub}$) subhalos above $10^6\,M_\odot$



$N(>M_{sub}) \propto 1/M_{sub}$

➡ equal mass per subhalo mass decade

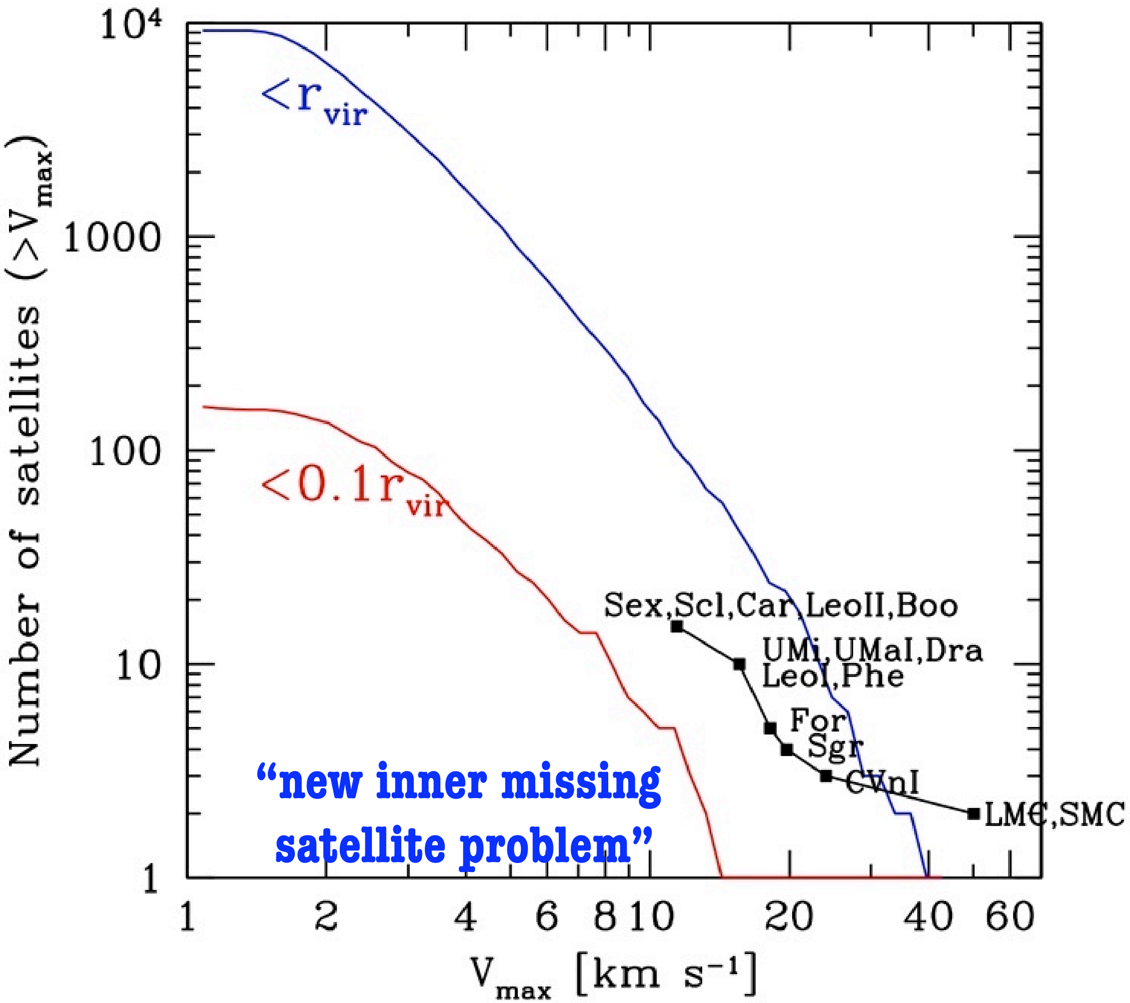
best-fit slope 0.9-1.1, depending on mass range used

mf steeper at high M due to dynamical friction/tidal mass losses

shallower at low M due to numerical limitations

resolution effects start to flatten the mass function below ~200 particles

124 (812) sats V_{max} >10 (5)km/s

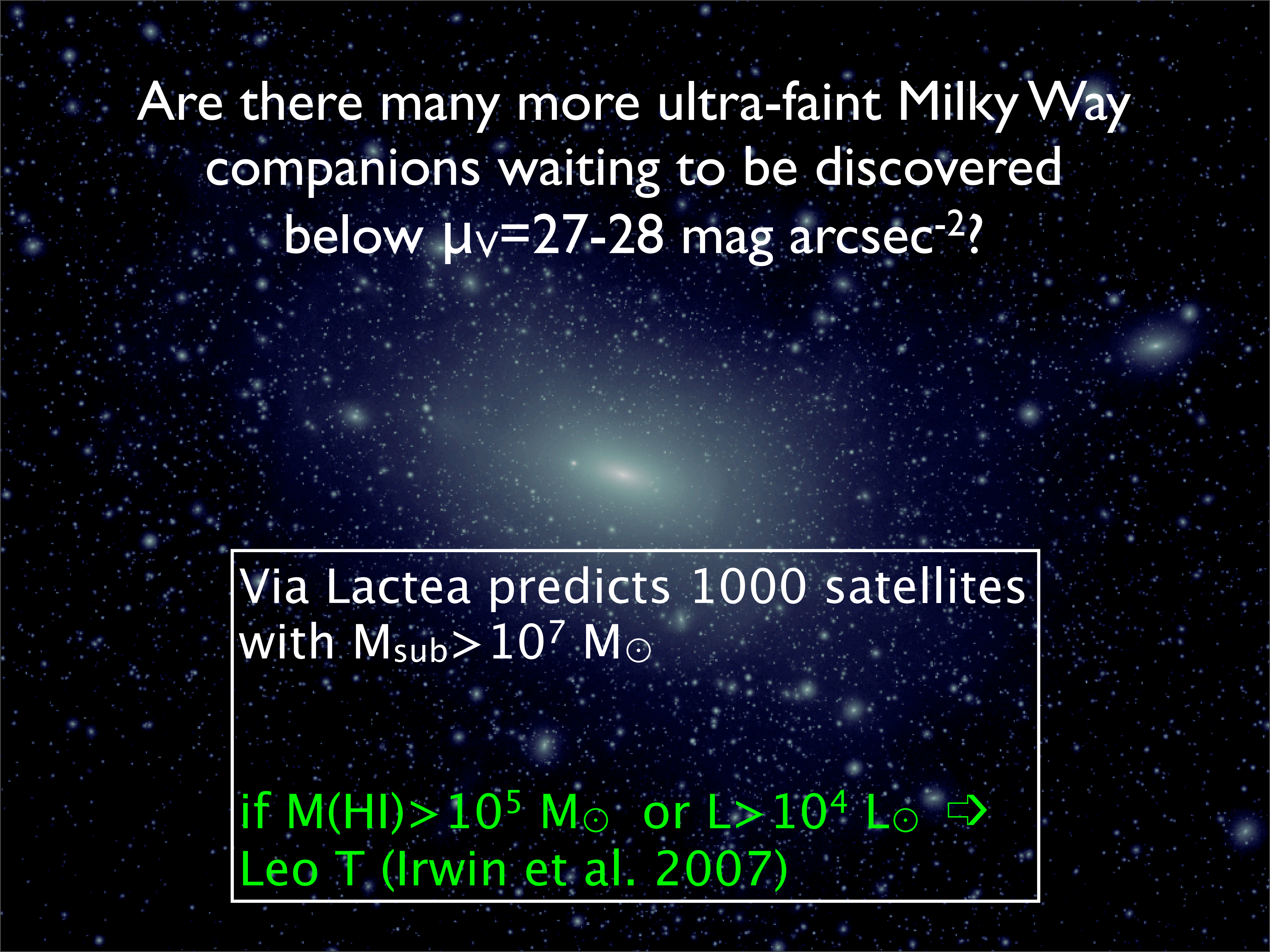


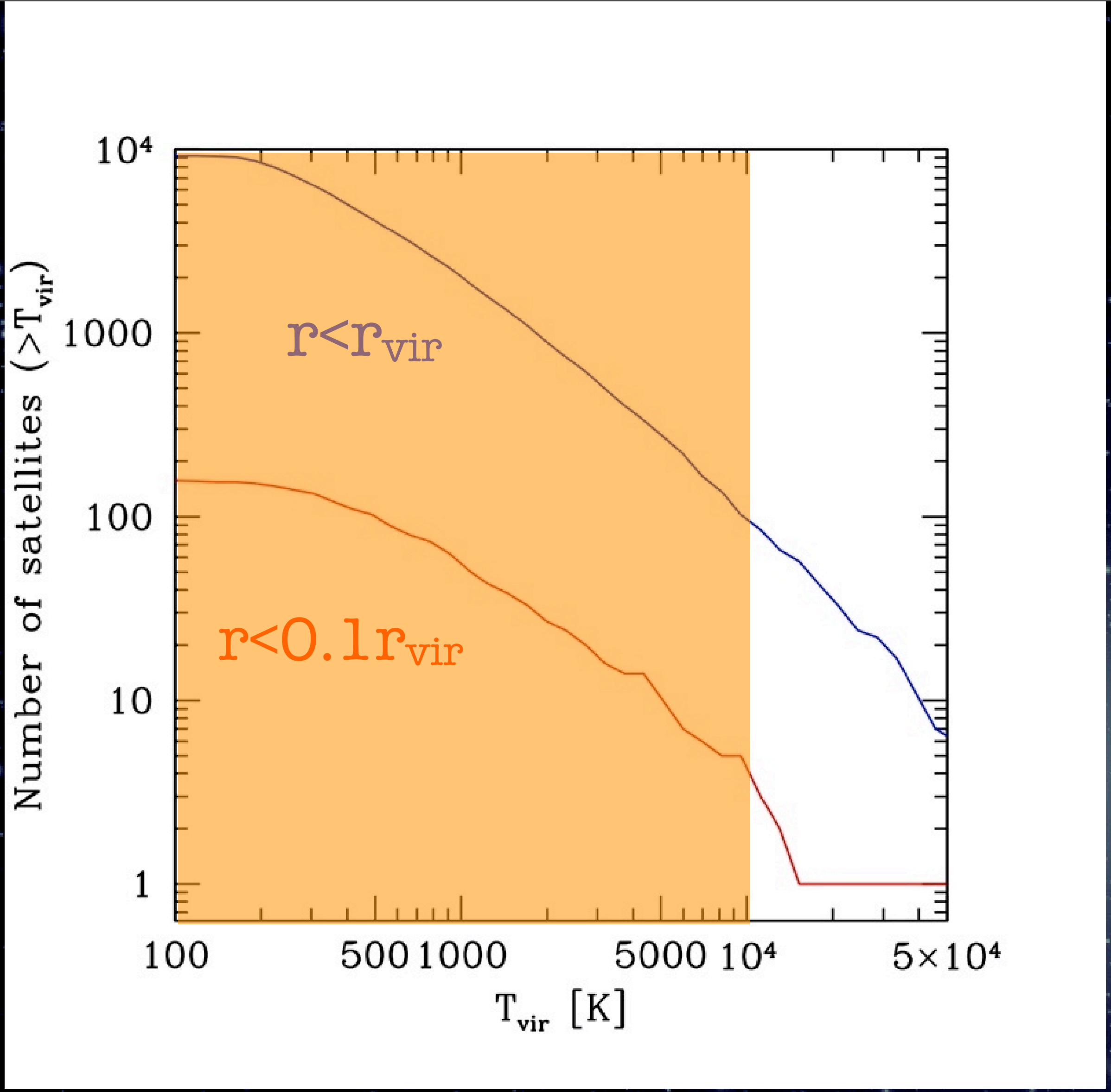
before SDSS: 9 dSphs + Phoenix,SMC,LMC
N(r<0.1 r_{vir})=1 (Sagittarius)

SDSS (Belokurov+ 07): 10 new dwarfs UMaI, CVnI, Boo,UMaII, CVnII, Her,Com,LeoIV, Leo T,WillmanI
+ Canis Major (CMa, Martin + 04)

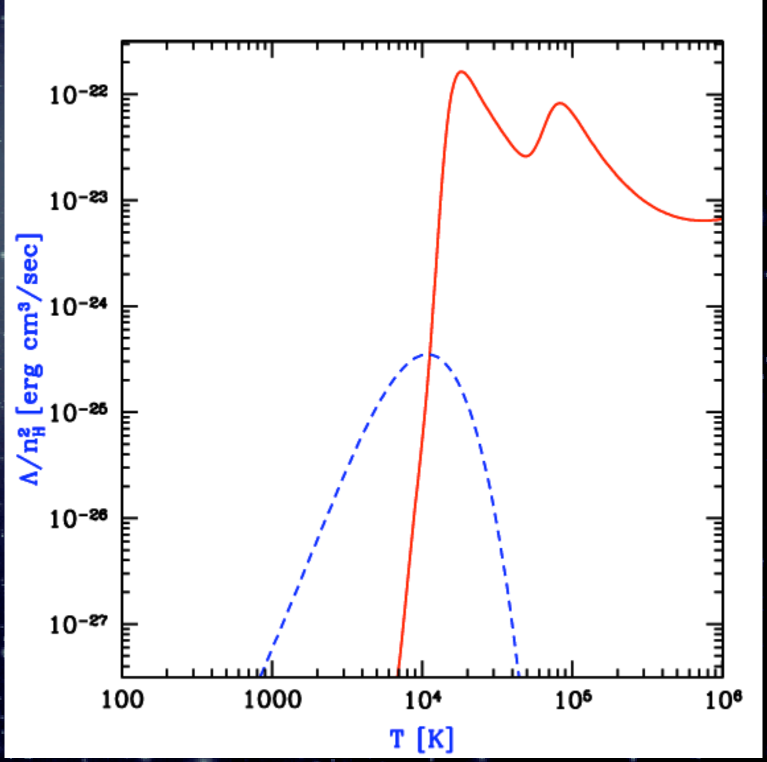
N(r<0.1 r_{vir})=1+1 (Sgr +CMa)

NB comparsion traditionally assumes $\sqrt{3}\sigma_*=V_{max}$. Dark halos extend well beyond the stellar radius of a satellite ⇨ stellar kinematics alone provide only a lower limit on the halo V_{max} value.


Are there many more ultra-faint Milky Way companions waiting to be discovered below μ_V=27-28 mag arcsec^{-2}?
Via Lactea predicts 1000 satellites with $M_{sub}>10^7\ M_\odot$
if $M(HI)>10^5\ M_\odot$ or $L>10^4\ L_\odot$ ⇨
Leo T (Irwin et al. 2007)

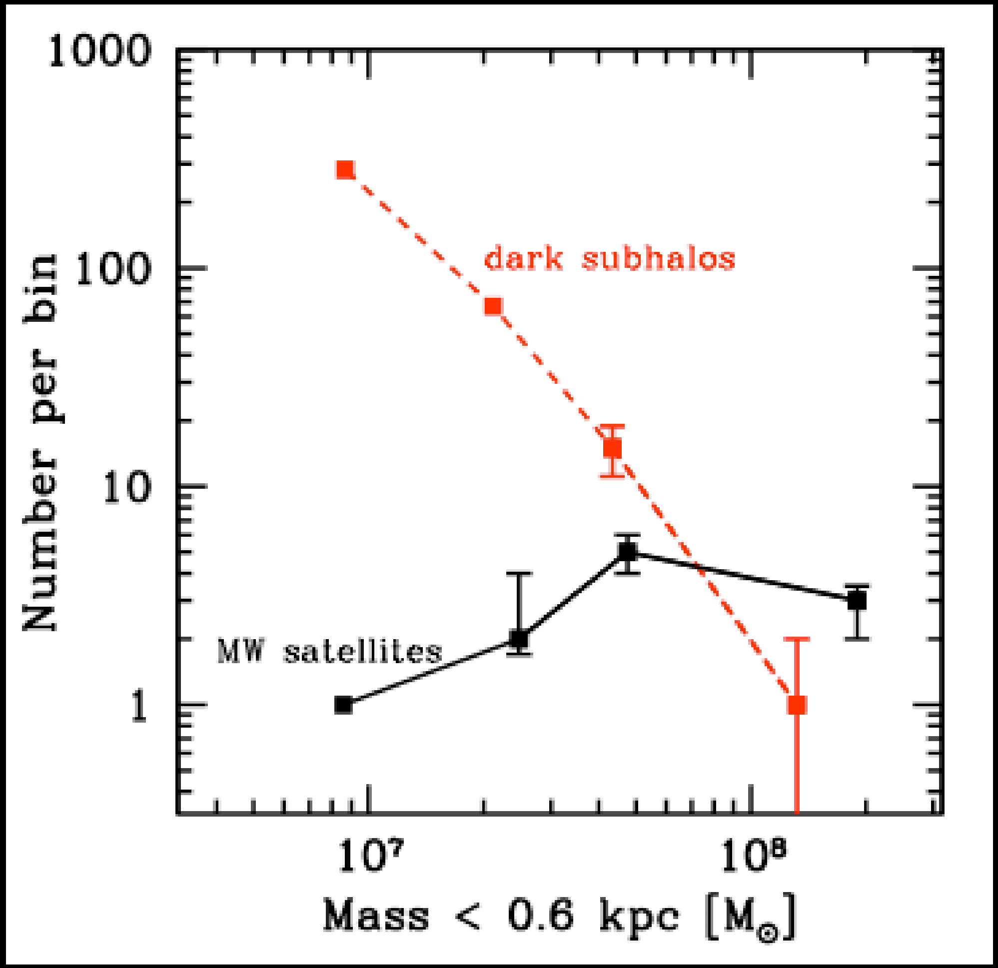


What's happening in subhalos with T_{vir} <10,000 K?

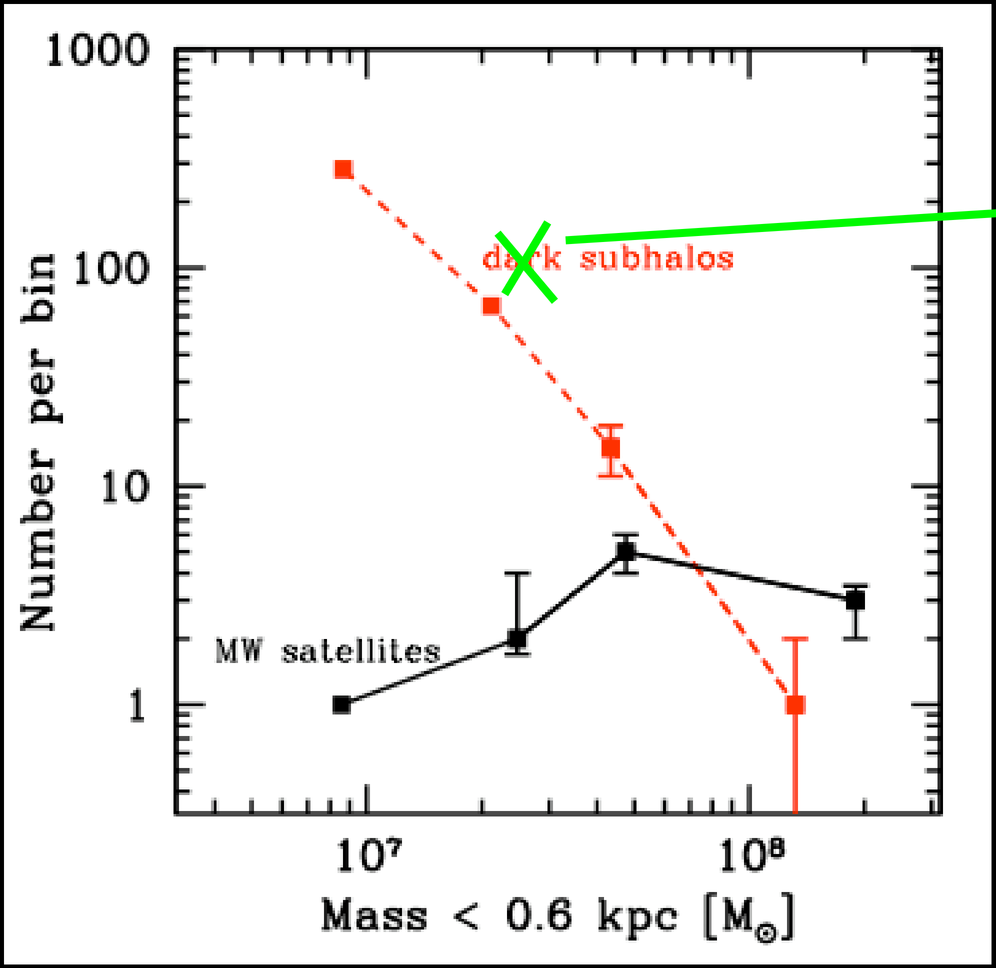


Needs a very efficient feedback mechanism quenching SF below atomic cooling mass

DM annihilation and GLAST



DM annihilation and GLAST



maybe we just need a different telescope?

glast.gsfc.nasa.gov

Annihilation flux for a distant spherically symmetric system:

annihilation cross-section
x thermal velocity

γ-photons produced
per annihilation

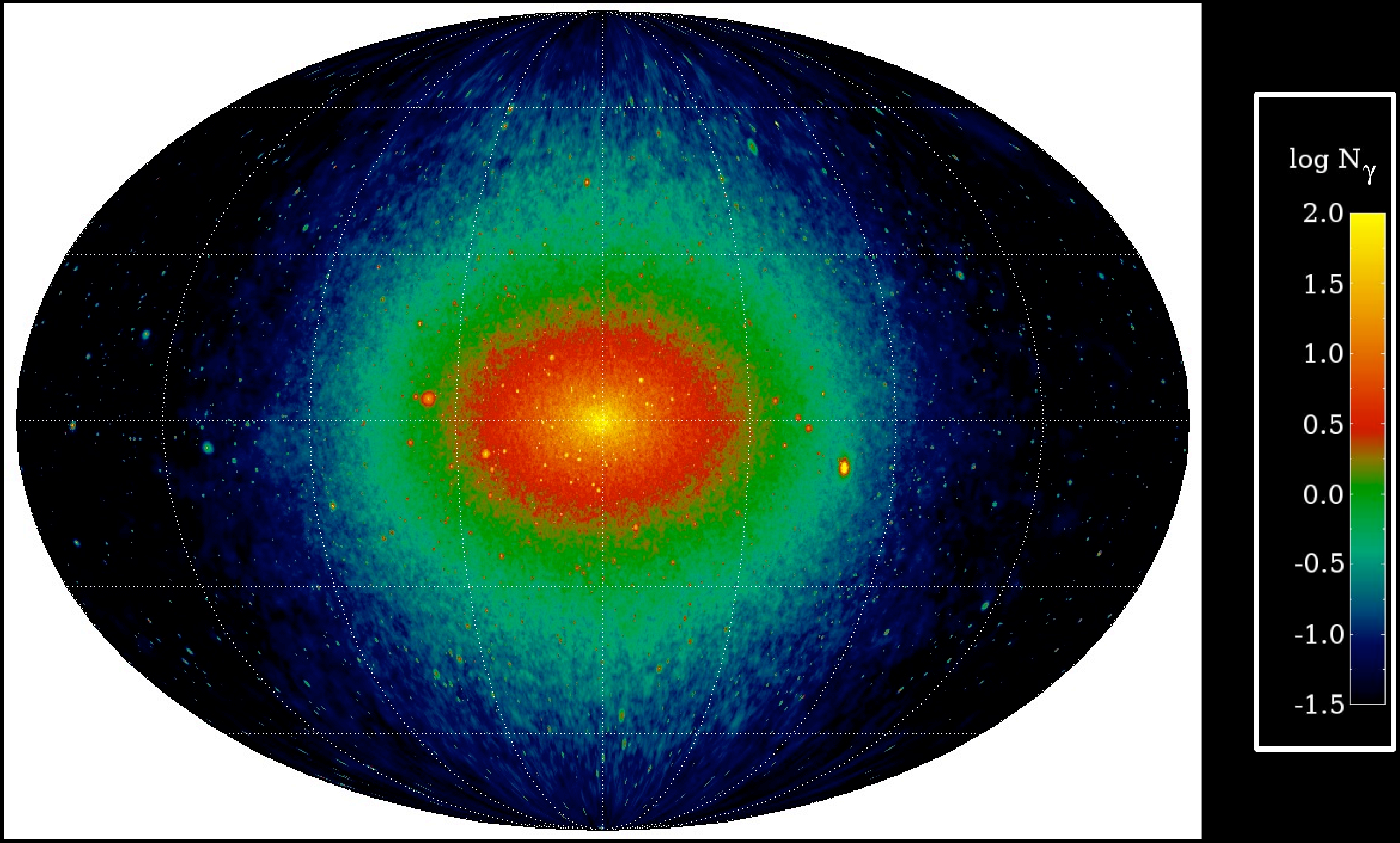
$$F = \frac{N_\gamma \langle \sigma v \rangle}{2\, d^2 m_\chi^2} \int_0^{r_{\mathrm{vir}}} \rho_{DM}^2(r) r^2 dr$$

mass of DM particle

The density squared weighting of the integrand results in most of the flux in dark DM halos being produced by a small fraction of their mass in the densest regions: (1) galactic center and (2) halo substructure

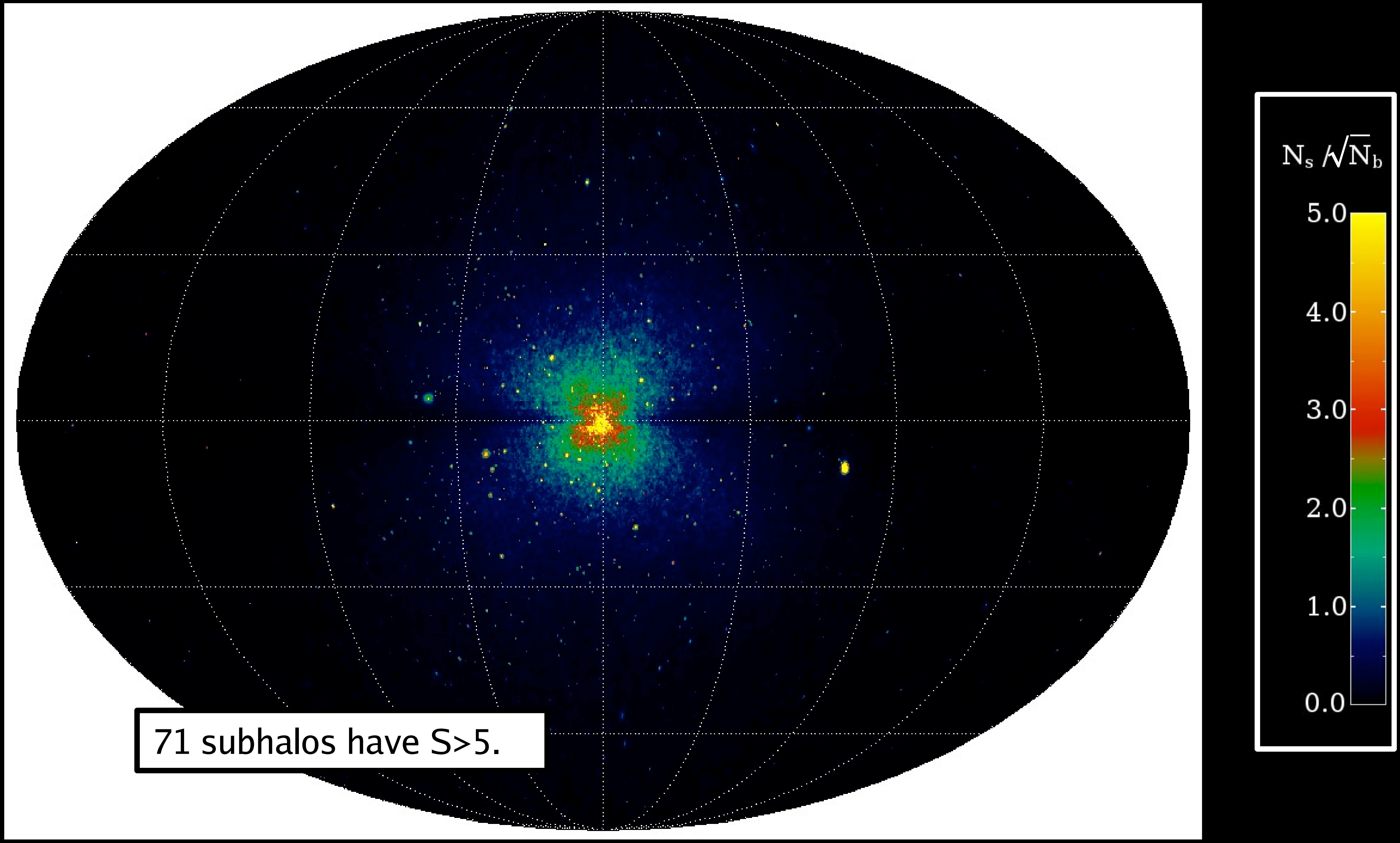
Simulated Maps

Signal with subhalo boost factor = 10 (strong boost)



Simulated Maps

Detection significance with subhalo boost factor = 10 (strong boost)



THE END