Enzo Lectures

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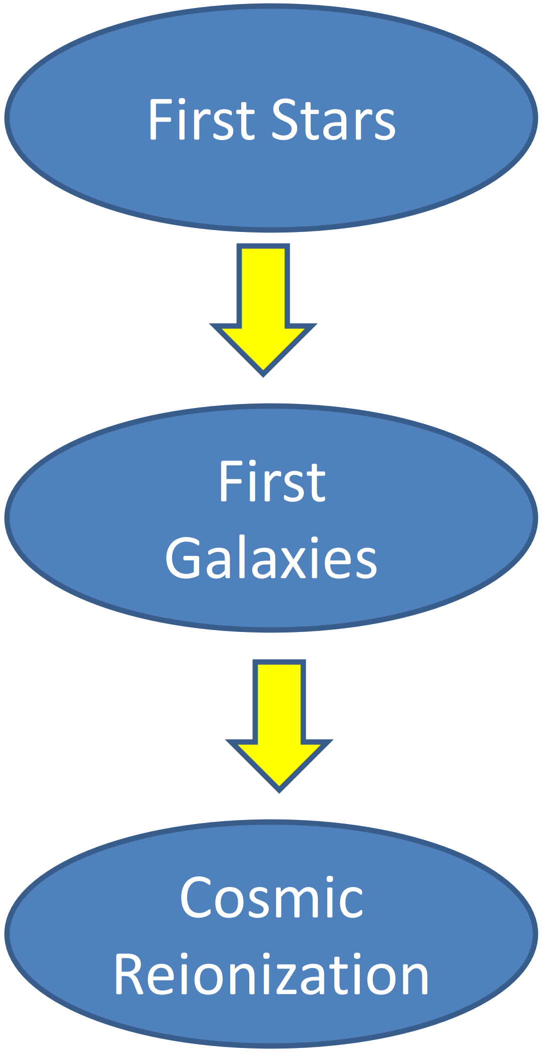
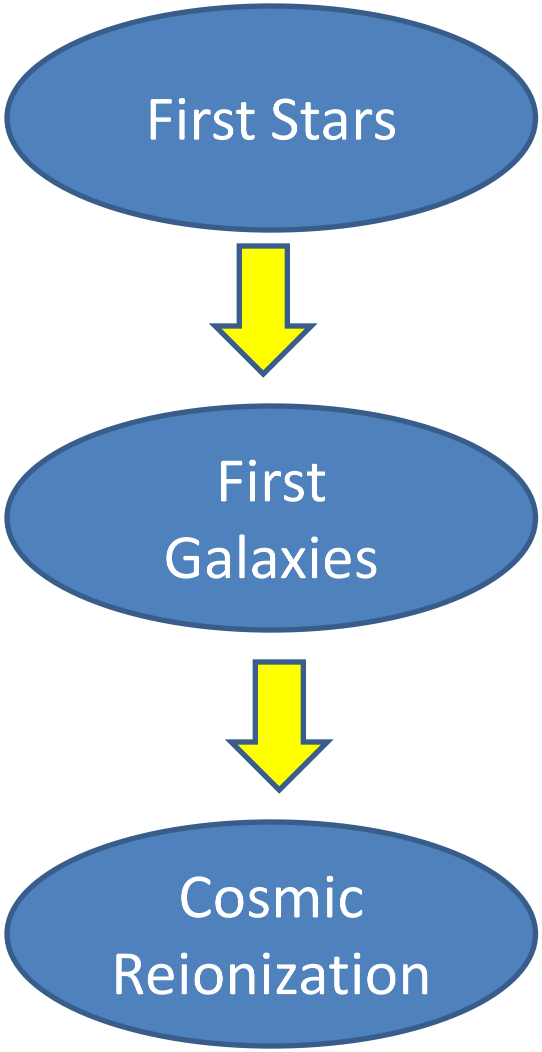
	Morning	Afternoon
Mon.	Introduction to Enzo	
Tue.	1. Setting Up and Running Enzo 2. Enzo Projects	Introduction to YT
Wed.	Basic Enzo Algorithms	Lab session
Thu.	Applications to First Stars, First Galaxies, and Reionization	Lab session
Fri.	What's New in Enzo 2.0?	Q & A



First Stars

First Galaxies

Cosmic Reionization



$$M_{vir} = 10^{5-6} M_s$$

$$R_{vir} \approx 100\ pc$$

$$T_{vir} \approx 10^3 K$$

First Stars

- First luminous objects
- Massive stars (OB)
- Form via H2, HD cooling
- Preprocess gas for FG

$$M_{vir} = 10^{8-9} M_s$$

$$R_{vir} \approx 10 kpc$$

$$T_{vir} \approx 10^4 K$$

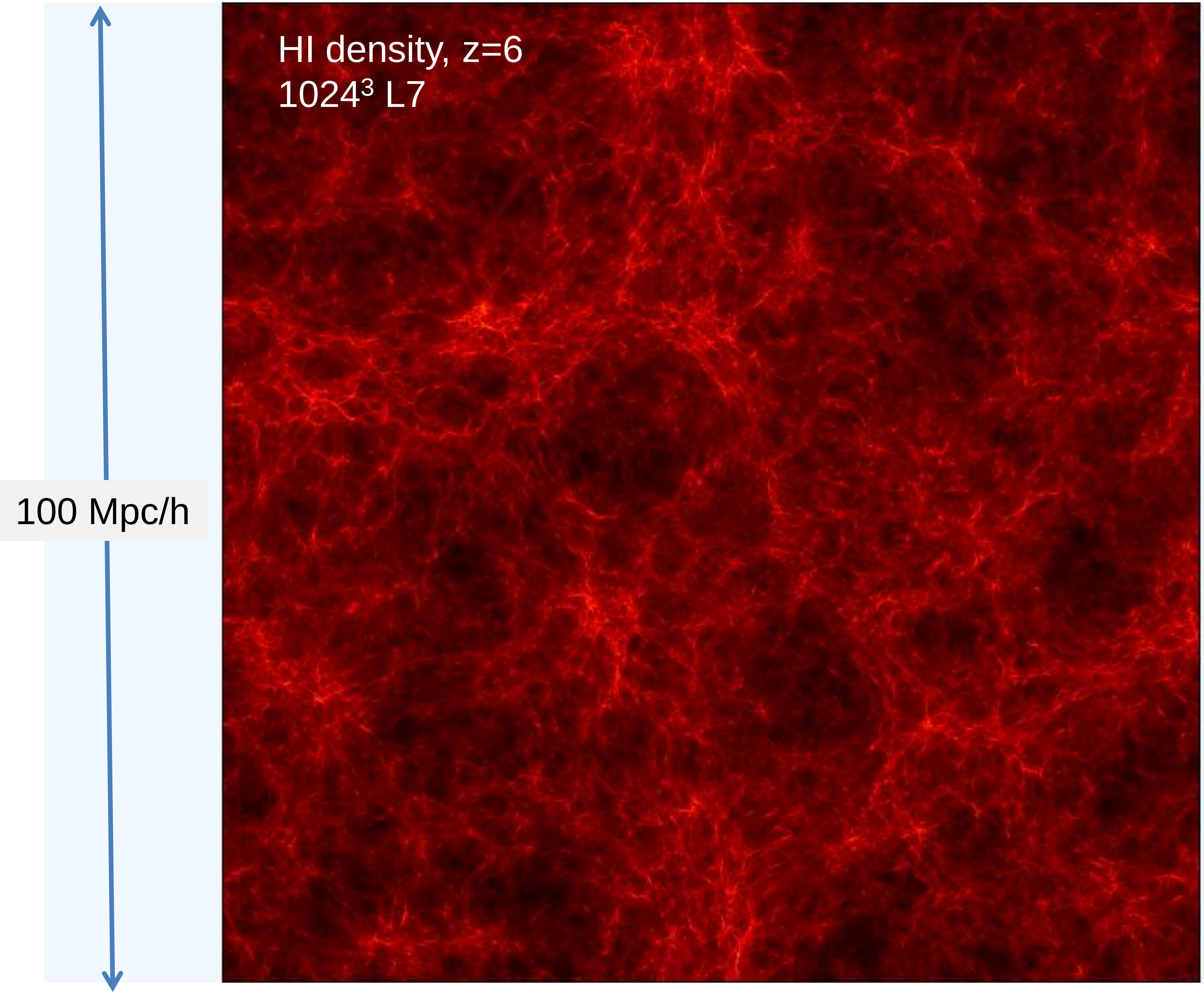
First Galaxies

- Galaxy building blocks
- Normal stellar populations
- Ly α cooling
- Thought to reionize U.

- Global!
- IGM mass density variations on all scales to > 100 Mpc/h
- Source clustering

Cosmic Reionization

- Percolation of HII regions of individual galaxies
- Low mass G's may dominate
- Observations constrain when, not how

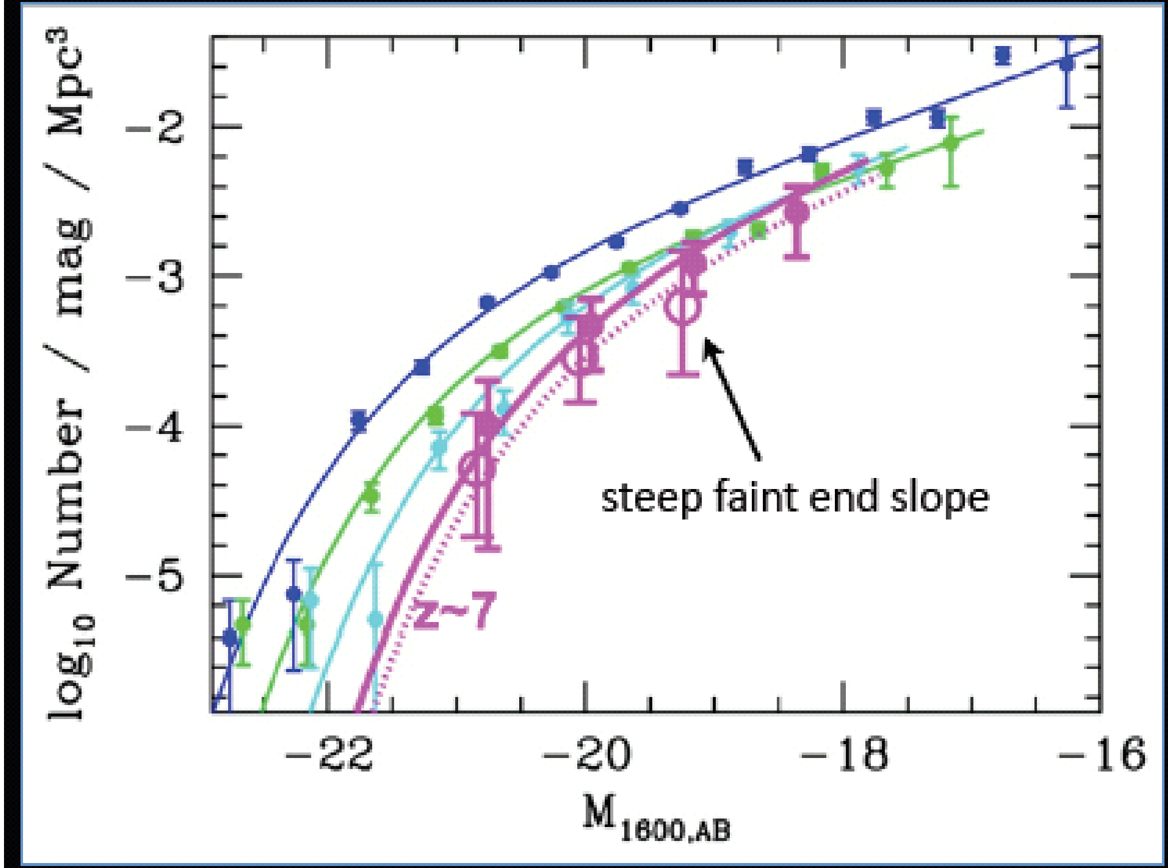


HI density, z=6

1024^3 L7

100 Mpc/h

luminosity functions



luminosity functions (LF) are key for determining the UV luminosity density and star formation rate densities

existing z~4-6 luminosity functions show that the slope is very steep at the faint end below L* (α ~ -1.75)

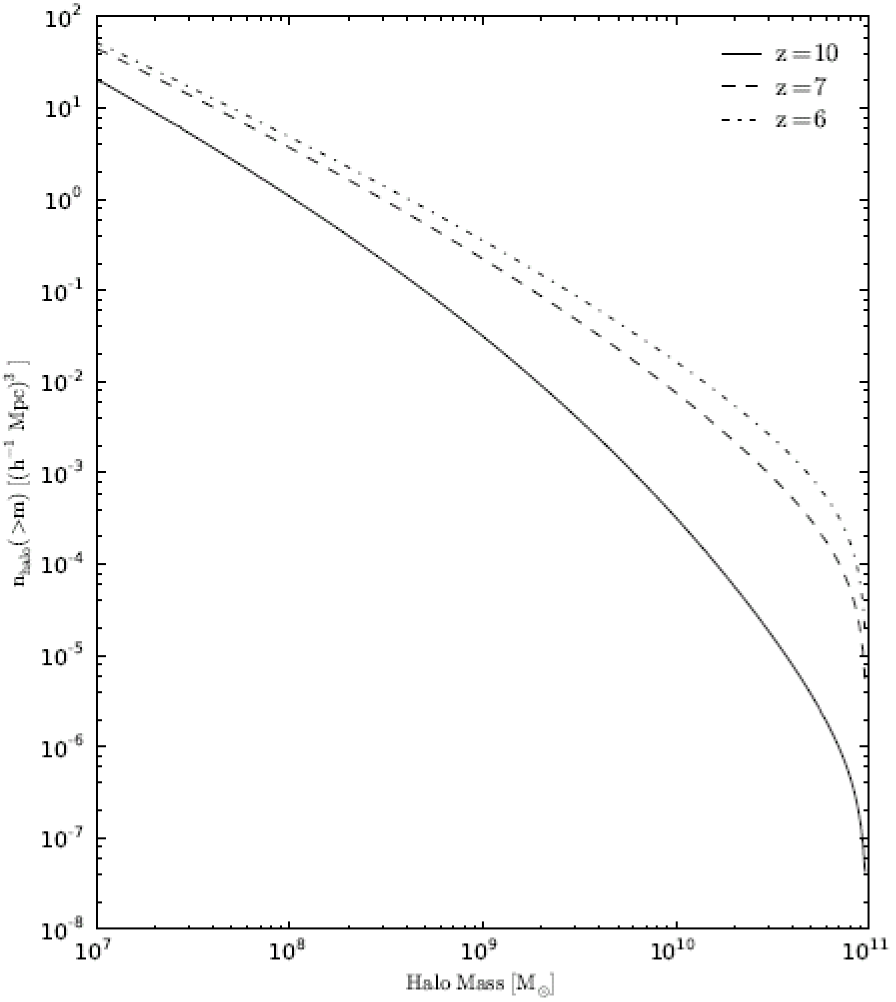
the bulk of the integrated UV flux at high-redshift comes from sub-L* low luminosity galaxies

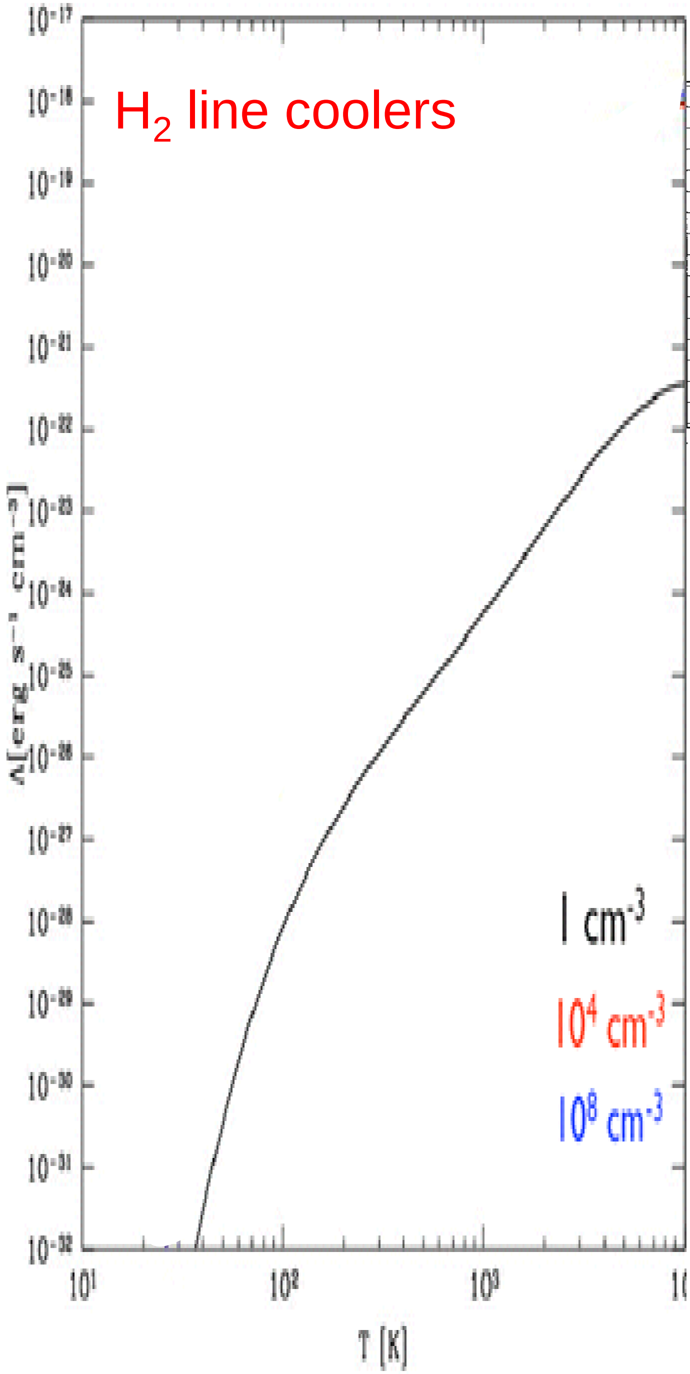
the changes in the LF with redshift are primarily at the bright end.

G. Illingworth

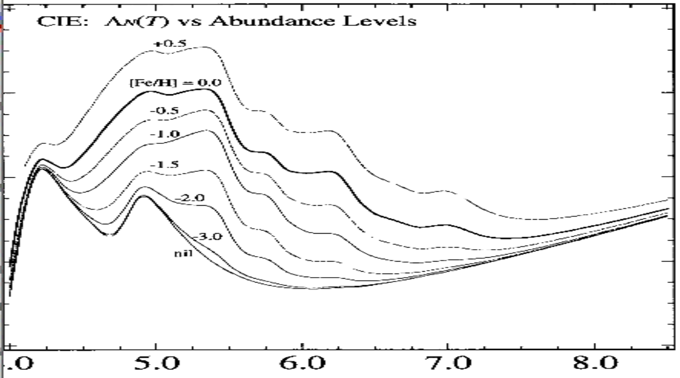
Halo Mass Function

- About 10 galaxies >= 10^8 M_s per $(Mpc/h)^3$ @z=6
- 100 Mpc/h box would have 10^7 sources!
- Need a radiative transfer method whose cost/source is ~independent of N(source)
- Such a method is in Enzo 2.0





H_2 line coolers



Atomic line coolers

$$T_{vir} \approx 10^4 K \Rightarrow M_{vir} \approx 10^8 M_s$$

First Stars

Nomenclature

- Pop III.1
  - Gas of primordial composition
  - Initial conditions purely cosmological
- Pop III.2
  - Gas of primordial composition
  - Initial conditions modified by radiative or kinetic feedback of Pop III.1 stars, but not chemical feedback

– Pop II
  - Stars formed from metal enriched gas
  - $Z > Z_{crit} \sim 10^{-3.5} Z_s$ (Bromm & Loeb 2005; Smith et al. 2008, 2009)

Formation of Pop III.1 protostars

Bromm et al. 1999, 2002; Abel et al. 2000, 2002; Yoshida et al. 2003, 2006, 2008, 2009; O’Shea & Norman 2006, 2007, 2008; Turk et al. 2008, 2009

primordial matter power spectrum

➔hierarchical structure formation

➔DM minihalo (${M_{dyn}} \sim 10^6$ $M_{s,}$ z~20)

➔primordial cloud ($M_{cl} \sim 10^4$ M_s)

➔H_2 formation and cooling

➔collapsing core ($M_{core} \sim 10^3$ M_s)

➔accreting protostar ($M_{ps} \sim 10^{-2}$ M_s, m*~ 10^{-2} M_s/yr)

➔stellar evolution, accretion, and radiative feedback

➔endpoints (supernovae and black holes)

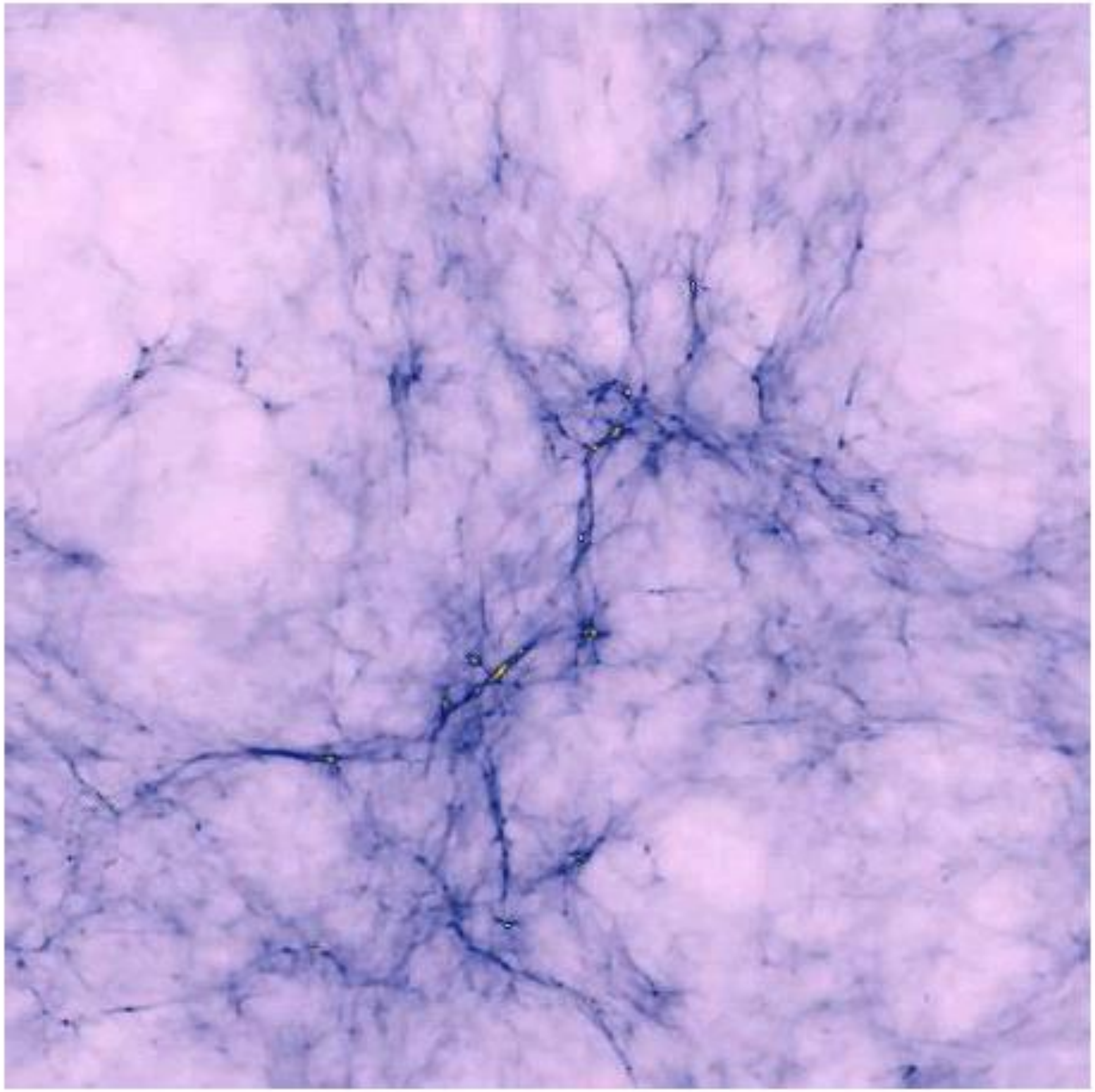


Figure 2: The projected gas distribution at $z = 17$ in a cubic volume of $600h^{-1}$kpc on a side. The cooled dense gas clouds appear as bright spots at the intersections of the filamentary structures. From Ref. (17).

Yoshida et al. (2003)

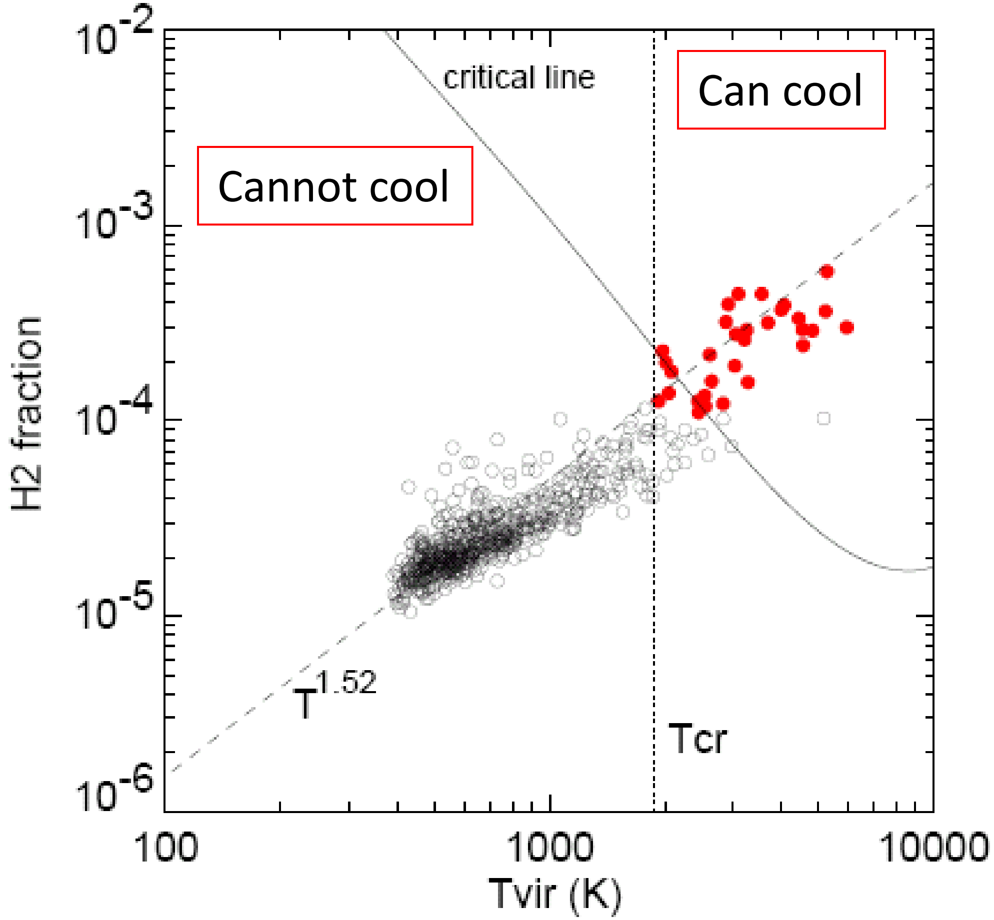
H_2 formation: the key to Pop III star formation

$$\mathrm{H} + e^- \rightarrow \mathrm{H}^- + \gamma,$$

$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + e^-.$$

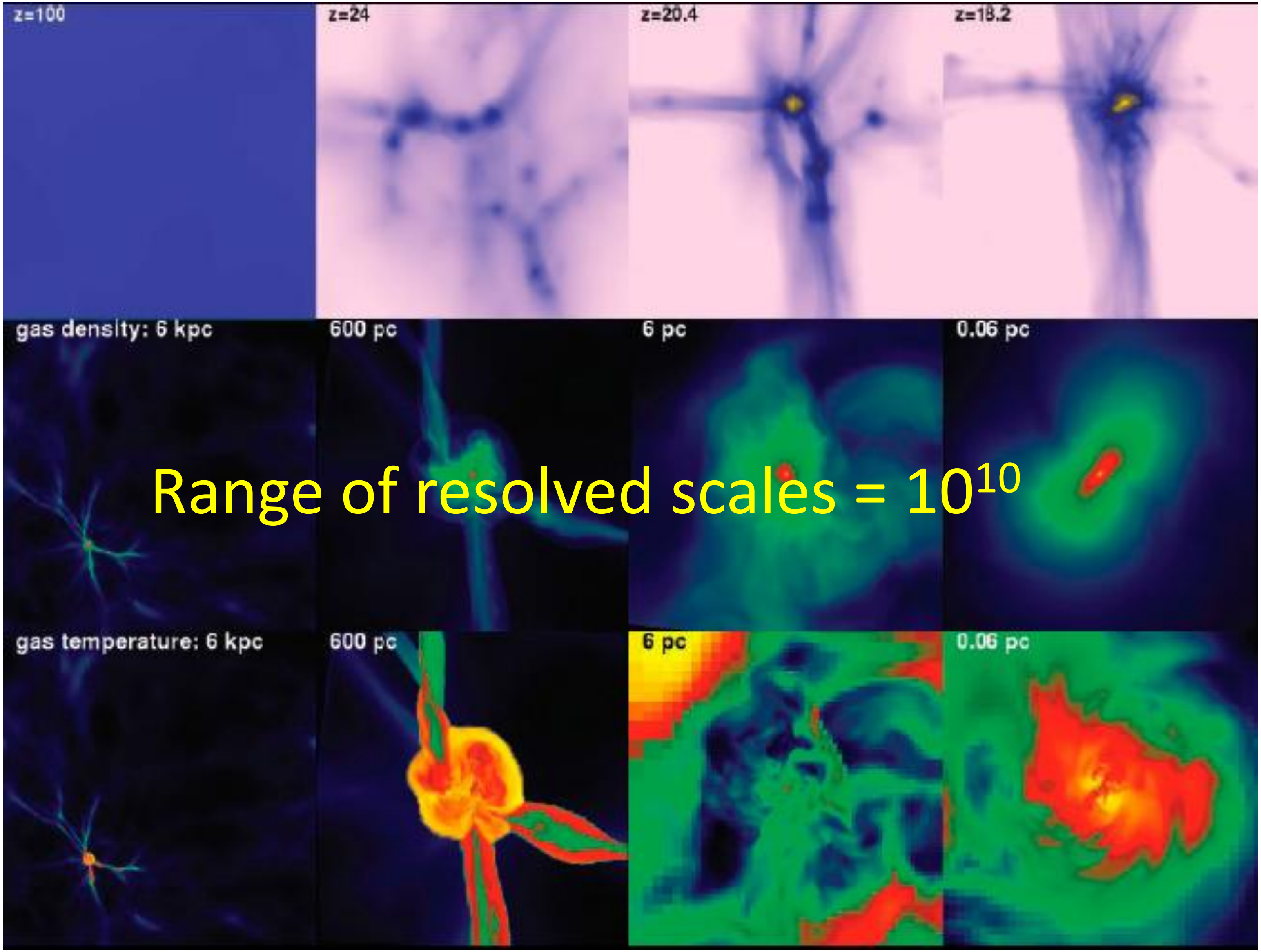
Catalytic reaction becomes efficient above 2000K

Cooling becomes efficient above $f(H2) \sim 10^{-4}$



Yoshida et al. (2003)

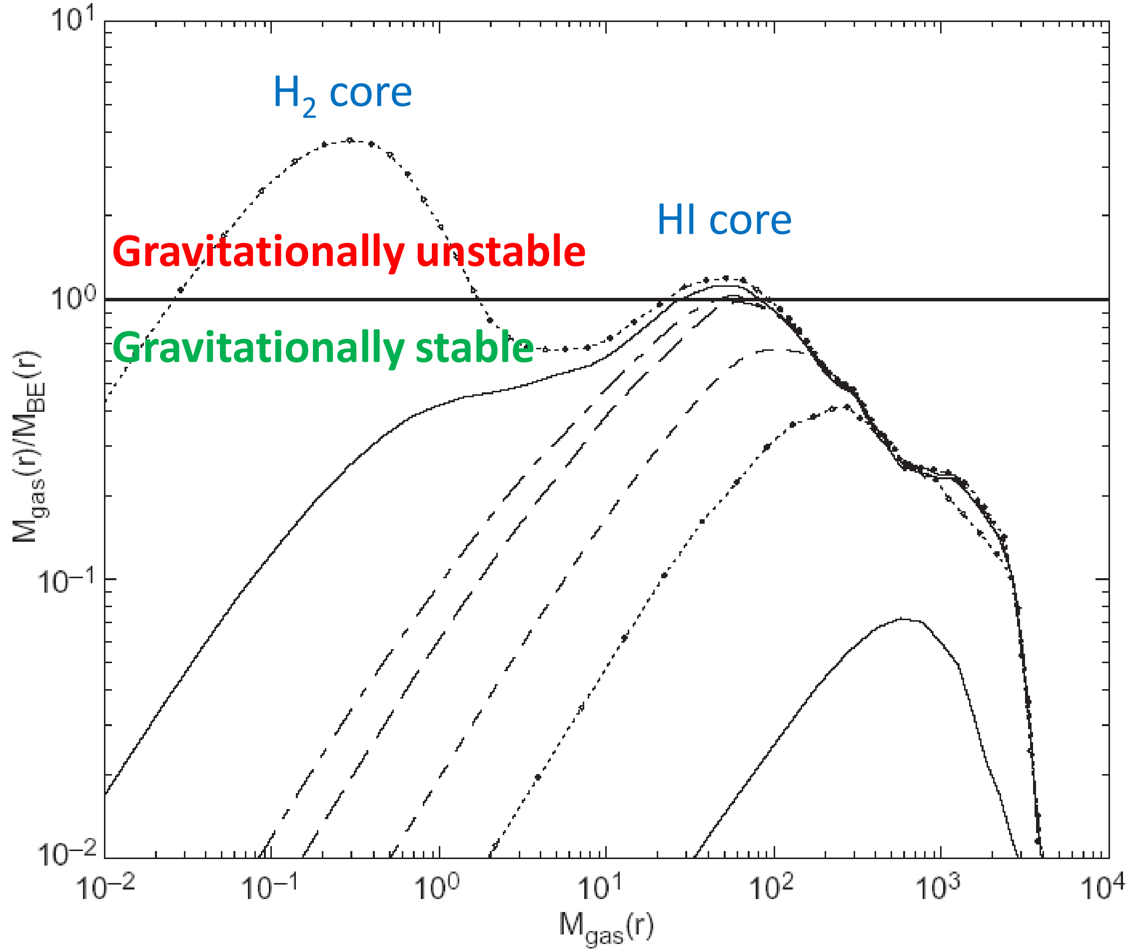
Pop III Star formation: the current paradigm



Range of resolved scales = 10^{10}

From Abel, Bryan and Norman 2002, Science, 295, 93

Evolution of cloud core



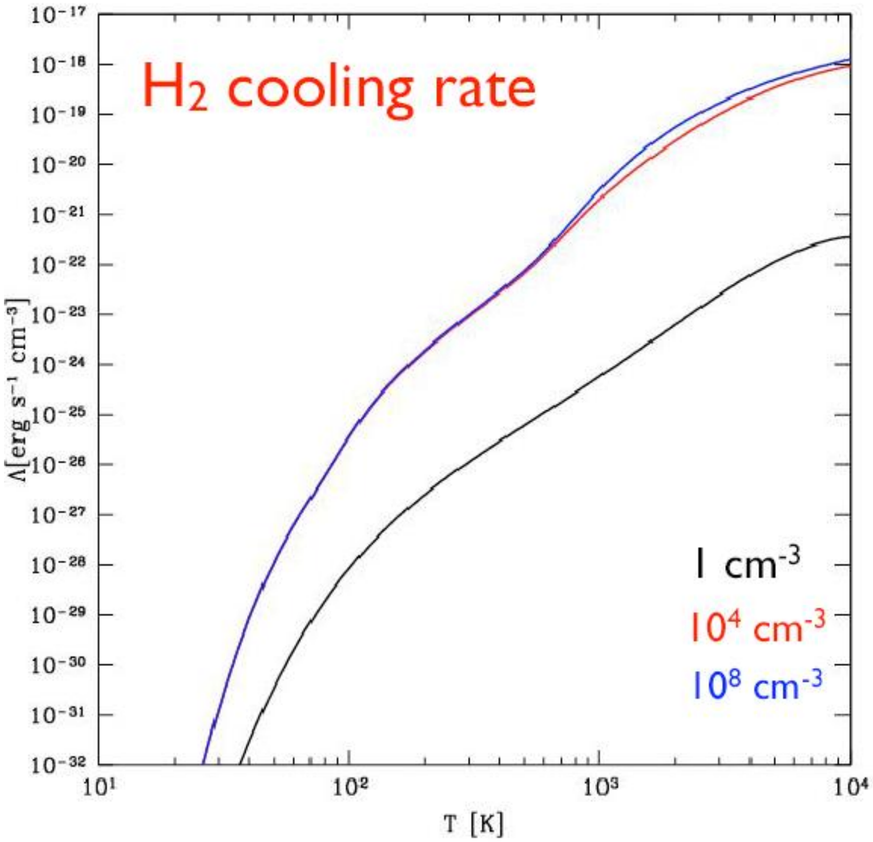
Z=19
+ 9 Myr
+ 300 Kyr
+ 30 Kyr
+ 3 Kyr
+ 1.5 Kyr
+ 200 yr (z=18.18)

Abel, Bryan & Norman (2002)

Origin of mass scale: H_2

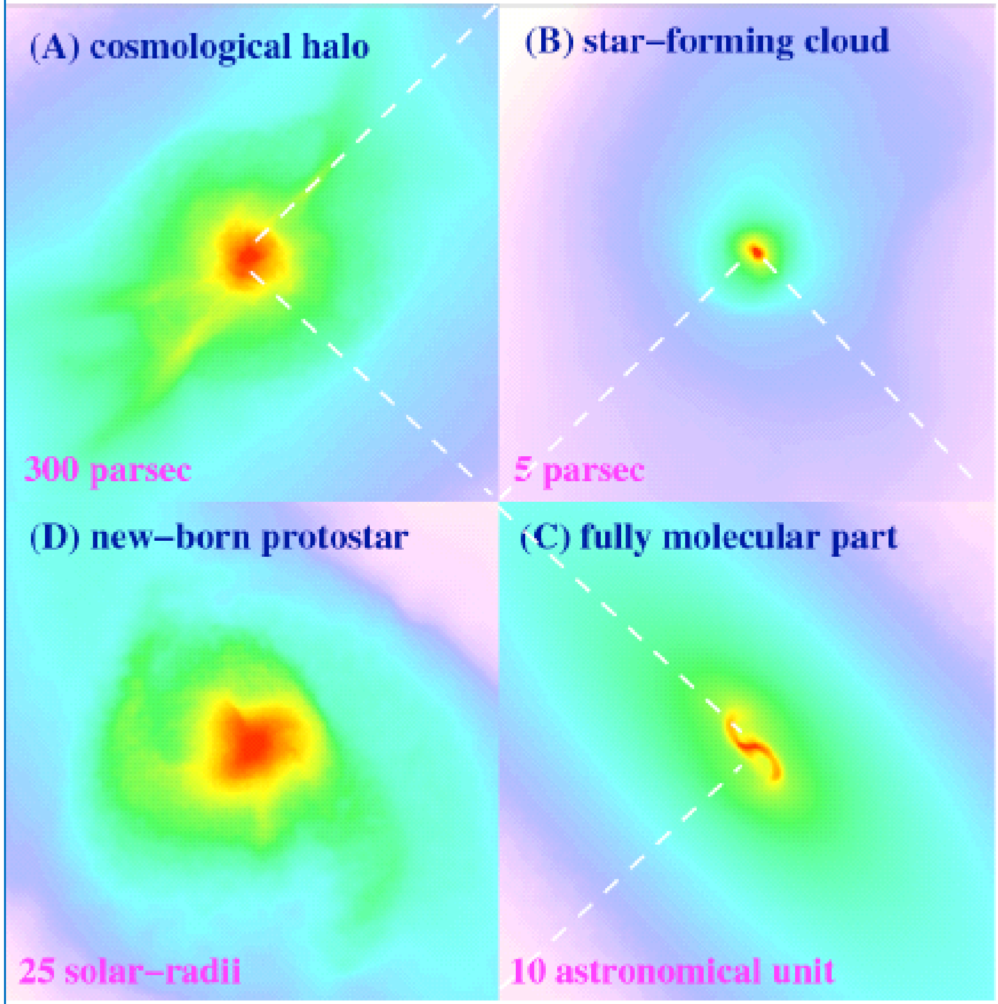
- H_2 cooling rate (per particle) becomes independent of density above $n=10^4$ cm^{-3} (“critical density”)
- 0-1 ro-vib. excitation temperature =590K
  - T_{min}~200K
- Cloud core “loiters” at these conditions until a Jeans mass of gas accumulates, and then it collapses

$$M_J \approx 500 M_\odot \left(\frac{T}{200}\right)^{3/2} \left(\frac{n}{10^4}\right)^{-1/2}$$



Stellar Density Achieved!

Yoshida et al. (2008), Turk et al. (2008)



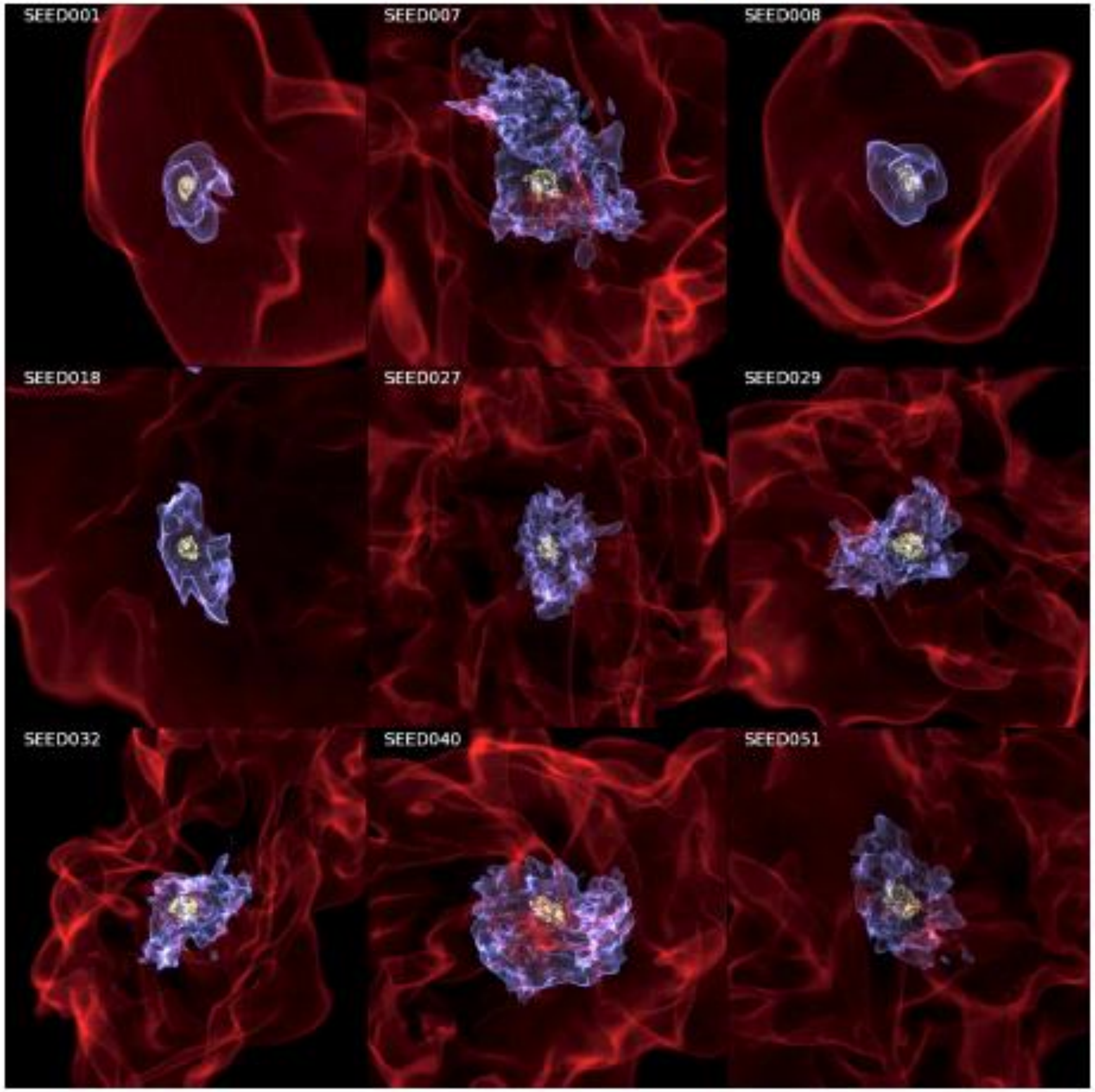
A complete picture of the formation process of a primordial protostar.

Dynamic range 10^{13}
Resolving planetary scale structures in a cosmological volume!

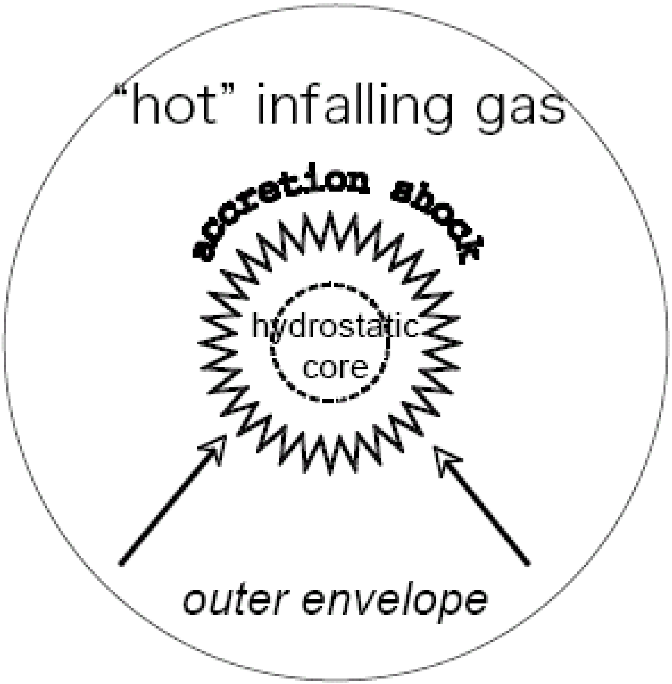
NY, Omukai, Hernquist
Science 2008

Pop III Binarity: *Princeton Twist* Survey

Turk et al. in prep



A hyper-accreting protostar



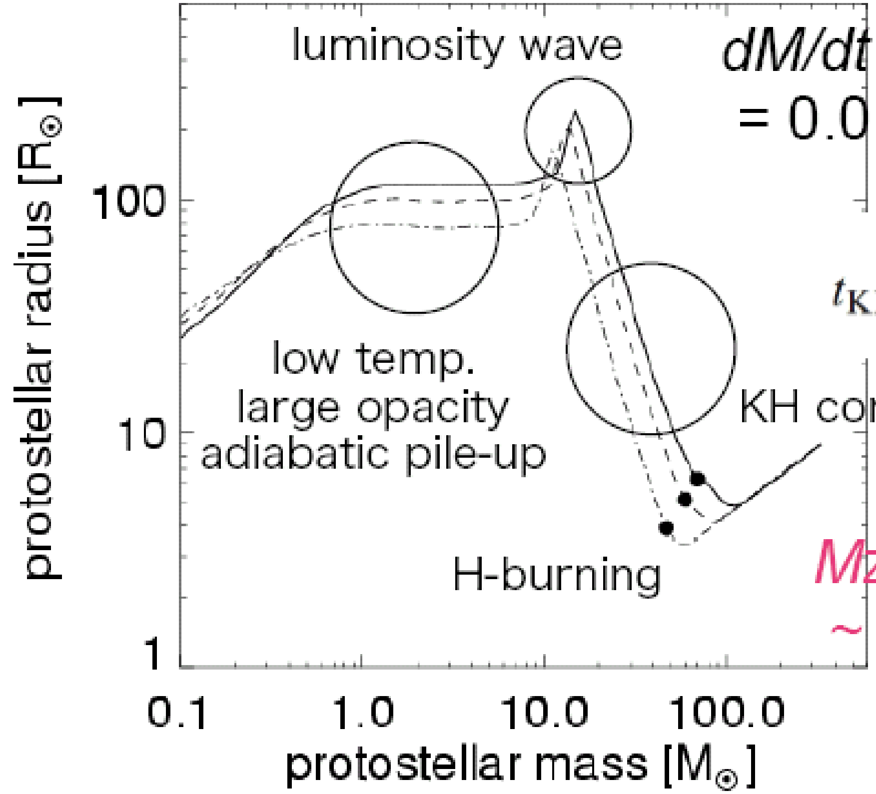
T ~ 1000-10000K

Re-formulate the problem as gas accretion onto a hydrostatic core, using the mass accretion rate from our simulation.

Compute the evolution of the mass and radius.

slide courtesy N. Yoshida

Protostellar evolution



dM/dt = 0.01-0.1 *M*sun/yr

$$t_{\rm KH} = \frac{GM_*^2}{R_* L_*} \propto \frac{1}{M_* R_*}$$

*M*ZAMS ~ 100 *M*sun

NY+ 2006, ApJ

slide courtesy N. Yoshida

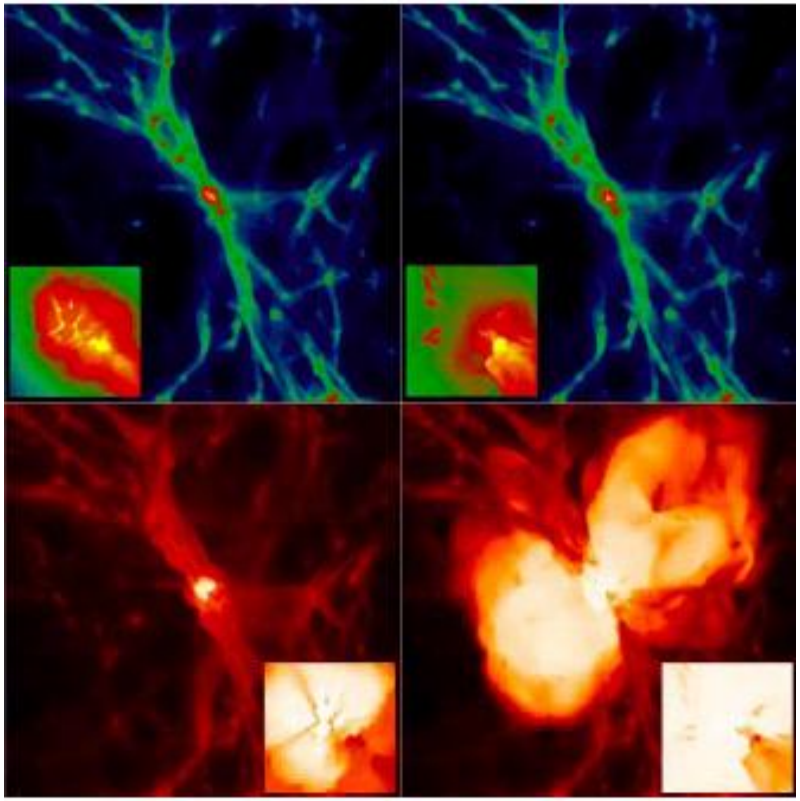
Formation of Pop III.2 protostars

Machacek et al. 2001, 2003; O’Shea et al. 2005; Ahn & Shapiro 2006; Yoshida et al. 2007; Wise & Abel 2008; Whalen et al. 2008

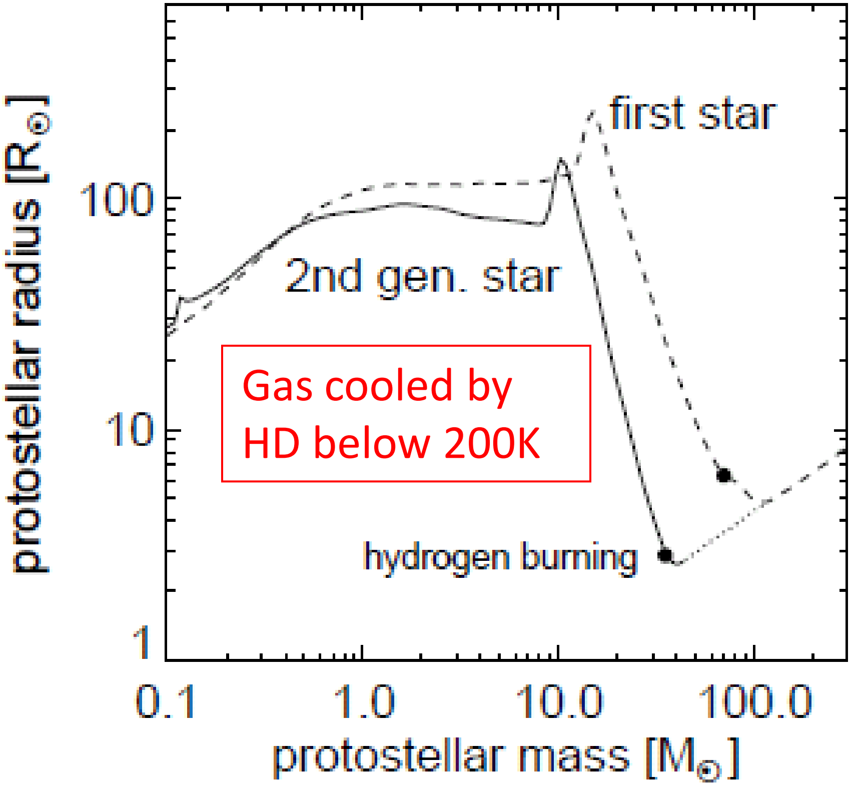
- Initial conditions disturbed by radiative feedback from a Pop III.1 star
  - EUV radiation pre-ionizes gas, which recombines and cools via H_2 and HD
    - local
  - FUV radiation photodissociates H_2, delays cooling and collapse
    - local or global (Lyman-Werner background)

Pop III star formation in a relic HII region

(O'Shea et al. 2005, Yoshida et al. 2007)



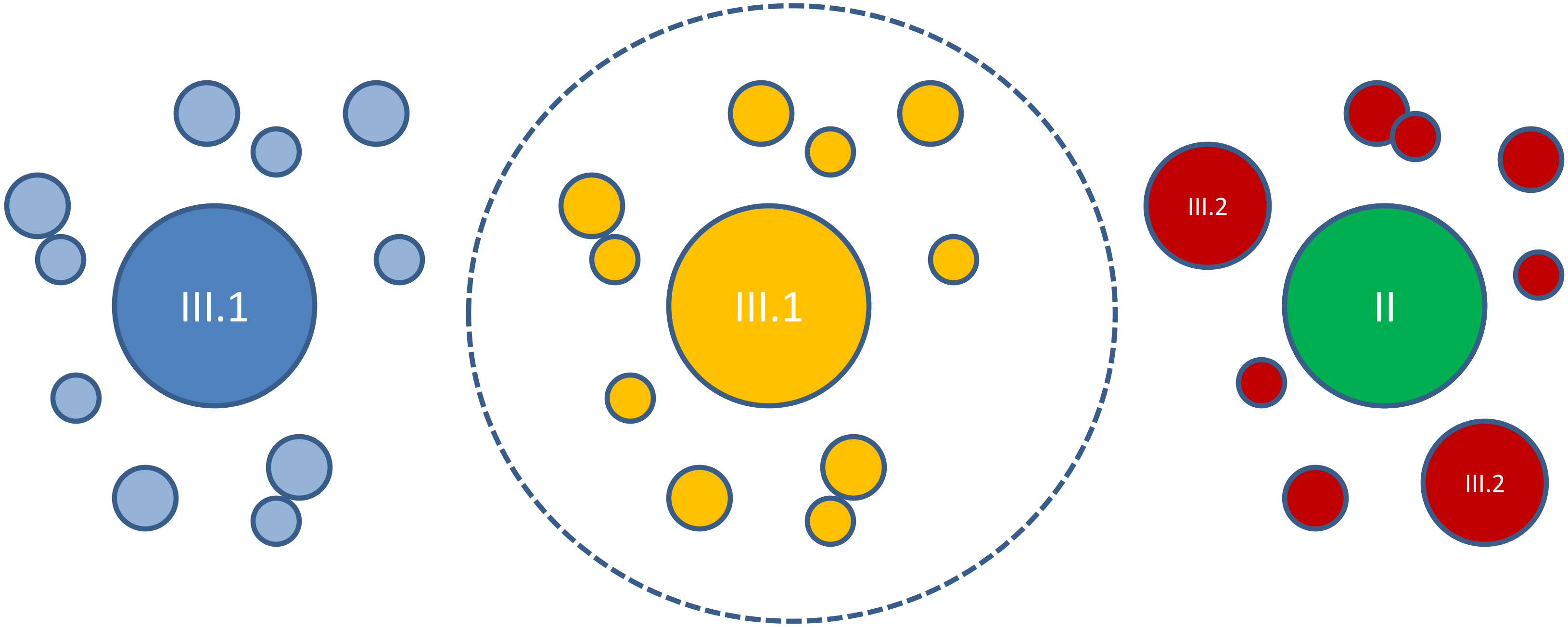
Abel, Wise & Bryan (2007)



Gas cooled by HD below 200K

Yoshida et al. (2007)

Origin of Pop III.2



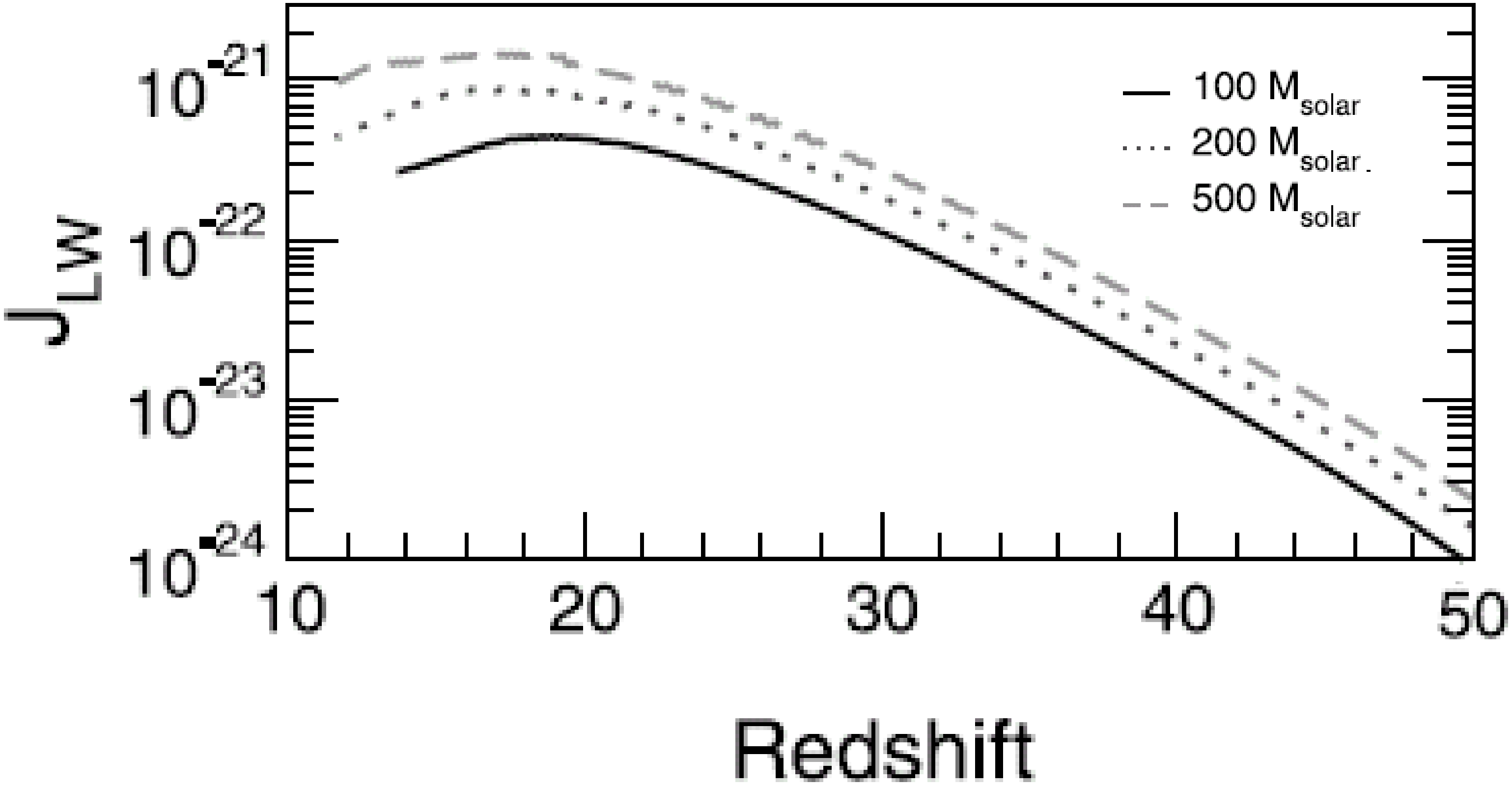
Neutral
H_2 formation

ionized
H_2 destruction

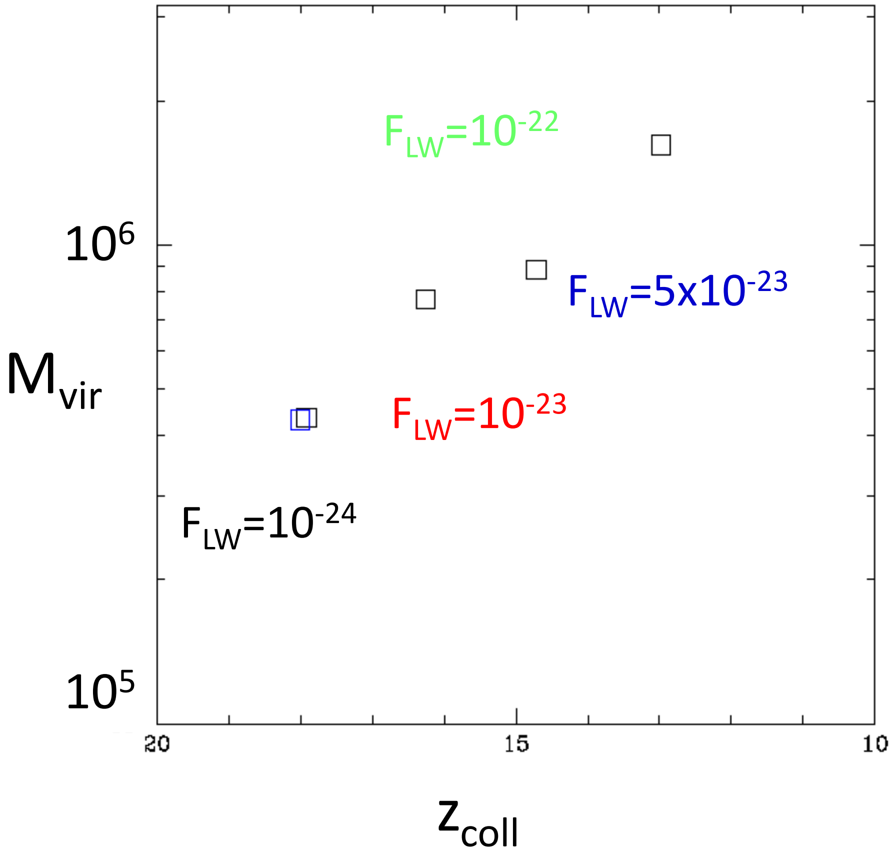
recombining
H_2 & HD formation

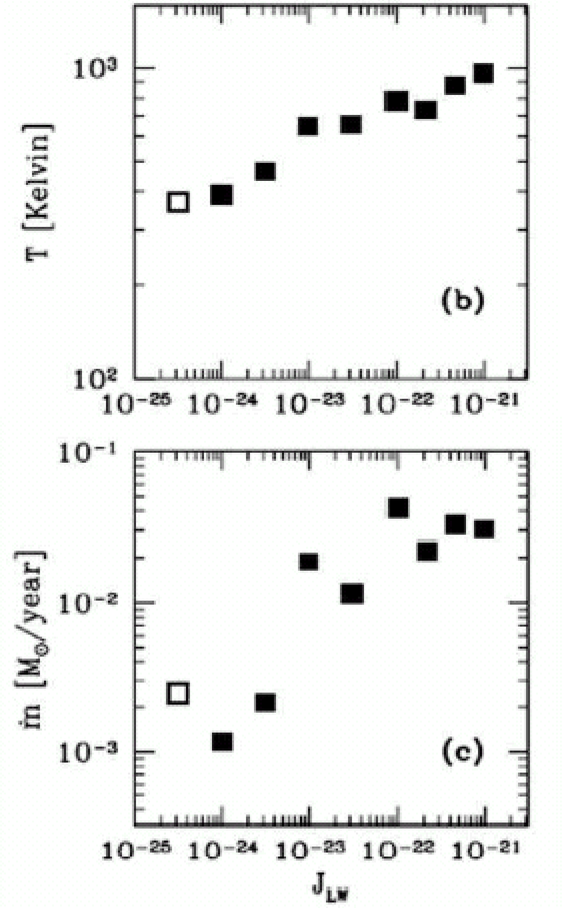
Evolution of the FUV background

Wise and Abel (2005)



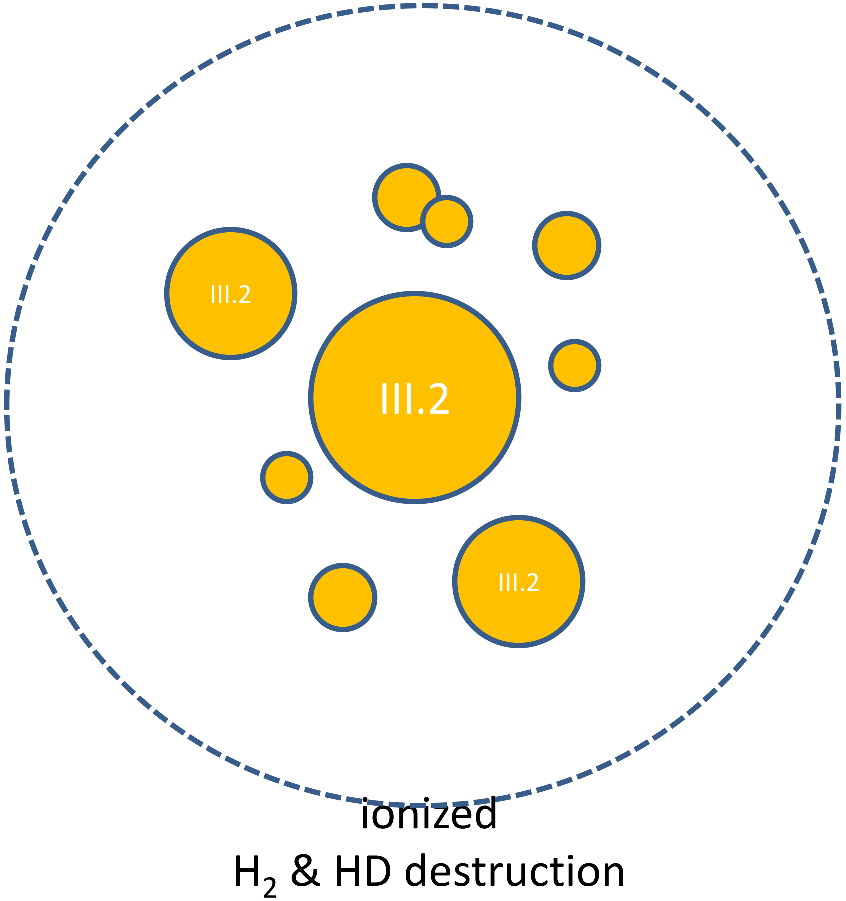
FUVB delays collapse, and raises core temperature and accretion rate (O'Shea & Norman 2008)



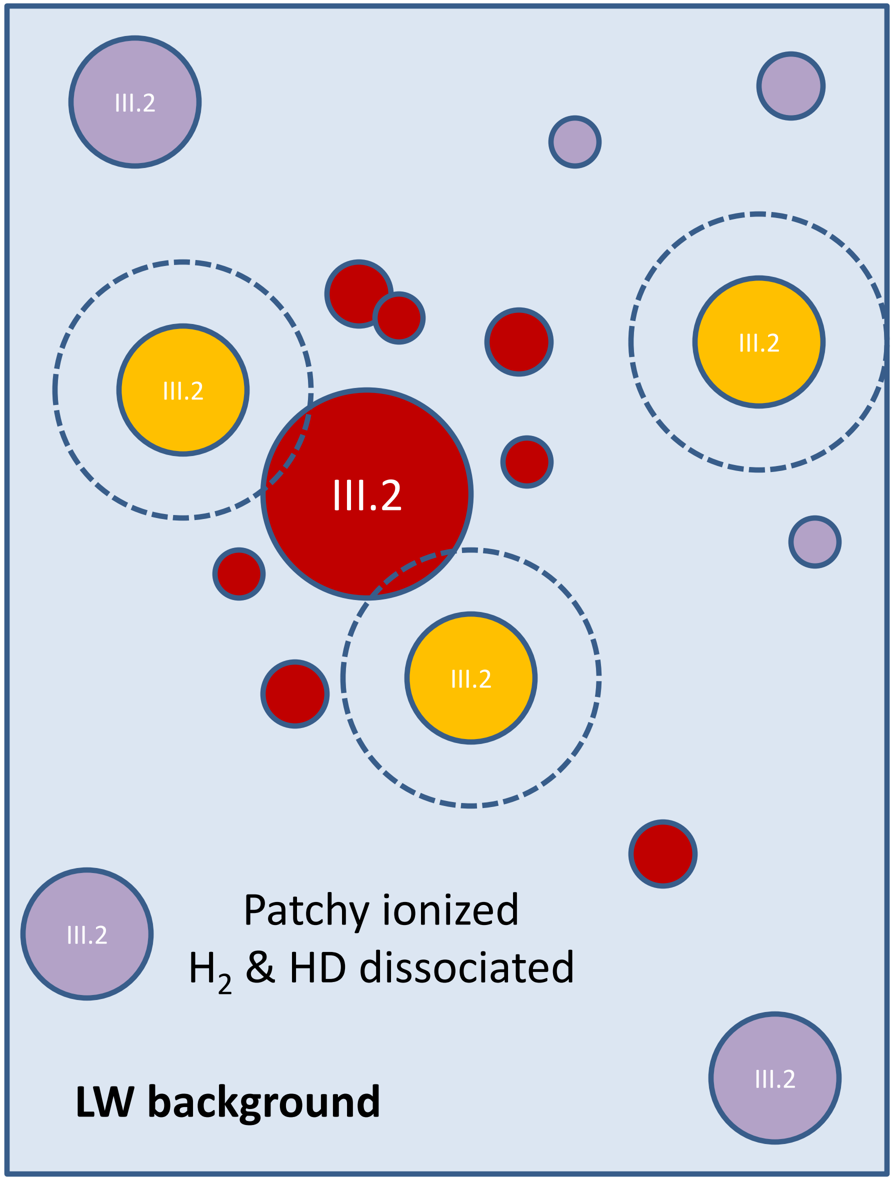


Implies Pop III stars formed at lower redshift are more massive

Origin of Pop III.2



ionized
H_2 & HD destruction



Patchy ionized
H_2 & HD dissociated

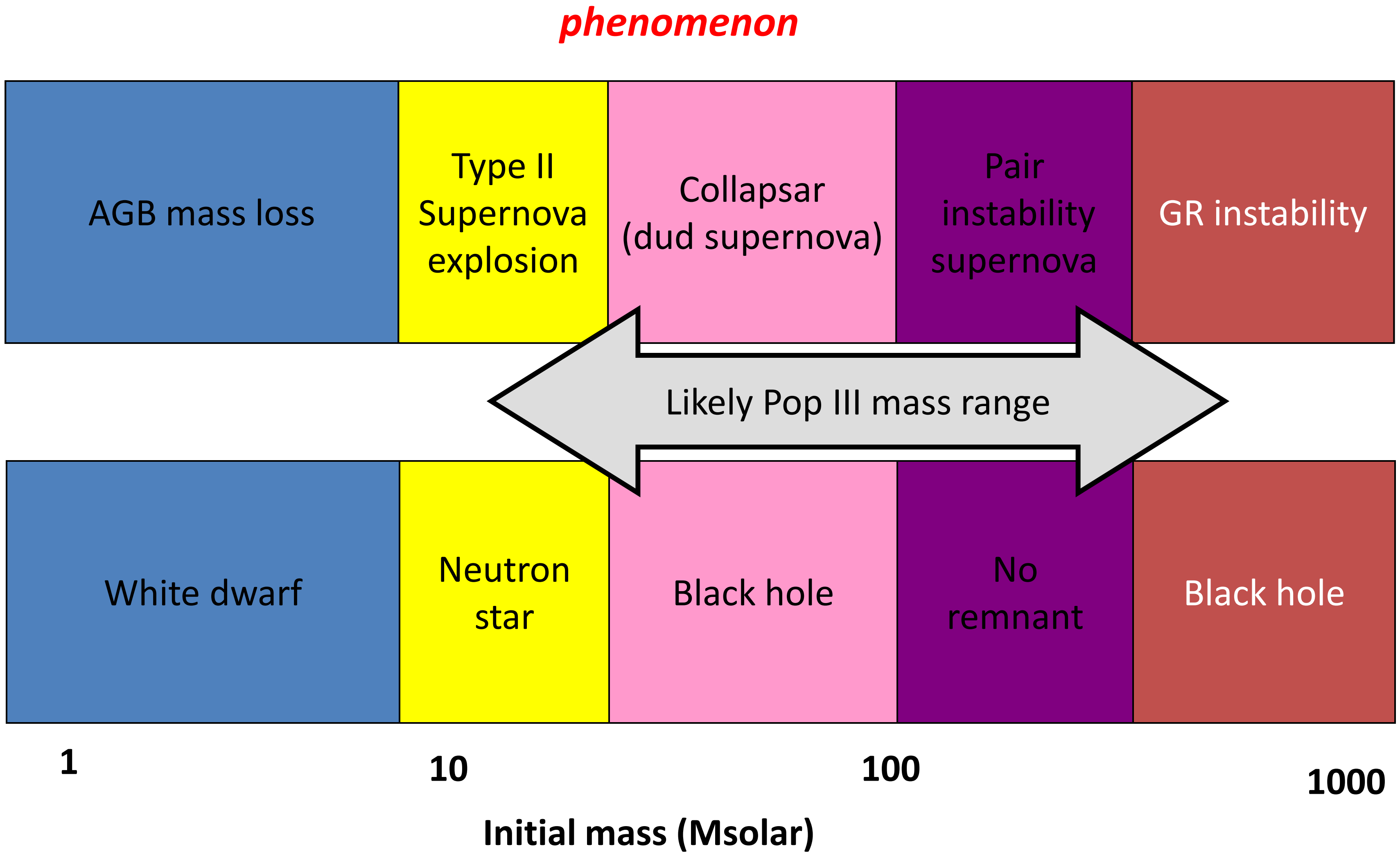
LW background

Final Stellar Masses

- Pop III.1 (III.2) stars enter main sequence at M~100 (40) Ms while they are still accreting mass from their birth cloud (~1000 Ms)
- How massive can they become?
  - Mass loss due to stellar winds presumed negligible (Baraffe et al. 2001, Kudritzki 2002)
  - Radiation pressure on grains not a factor
  - Consider other radiative feedback effects

Fate and Remnants of Pop III Stars

non-rotating models (Heger & Woosley 2002)



phenomenon

AGB mass loss

Type II Supernova explosion

Collapsar (dud supernova)

Pair instability supernova

GR instability

Likely Pop III mass range

White dwarf

Neutron star

Black hole

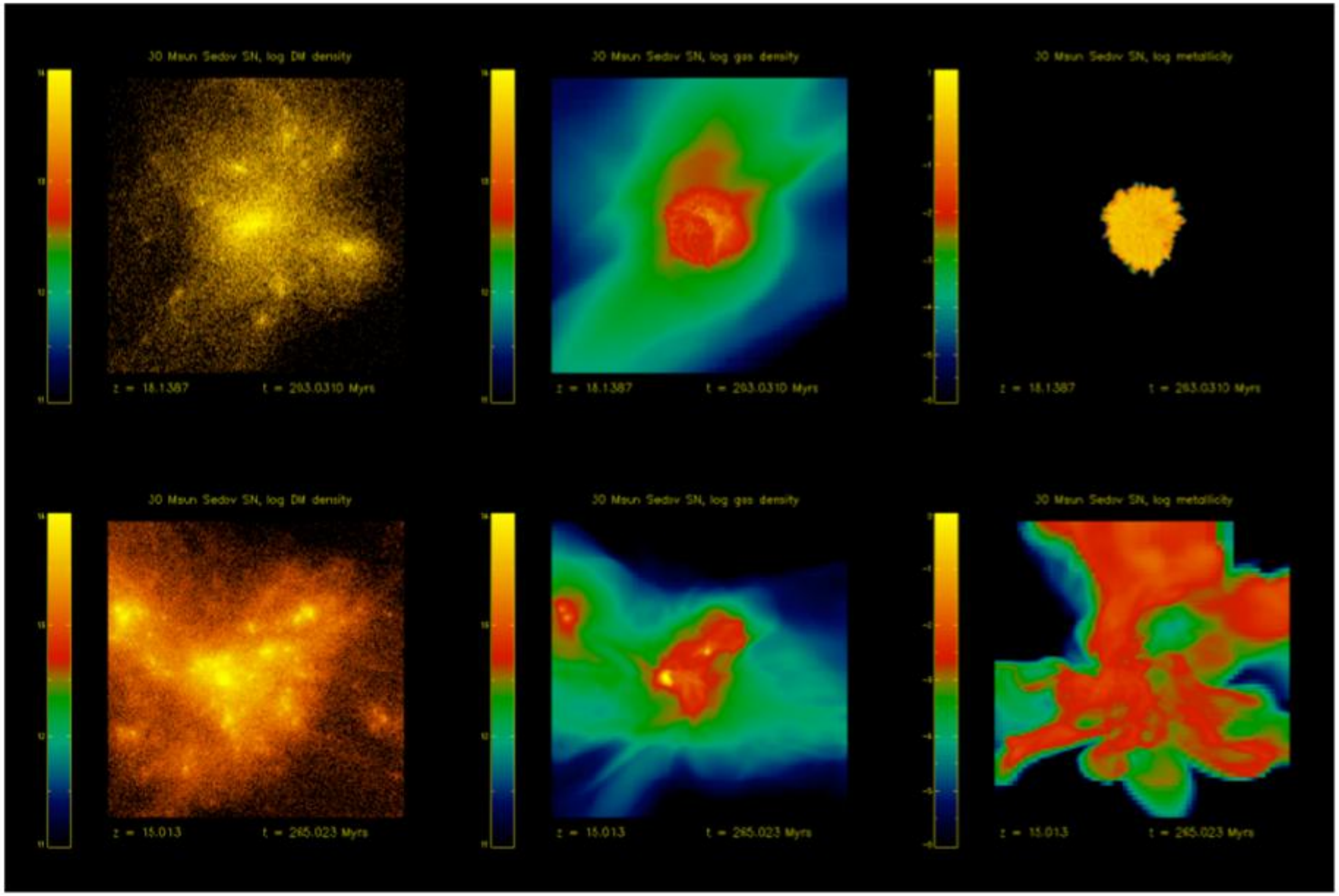
No remnant

Black hole

Initial mass (Msolar)

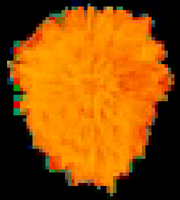
Chemical Feedback from Pop III SN

(O'Shea 2005)

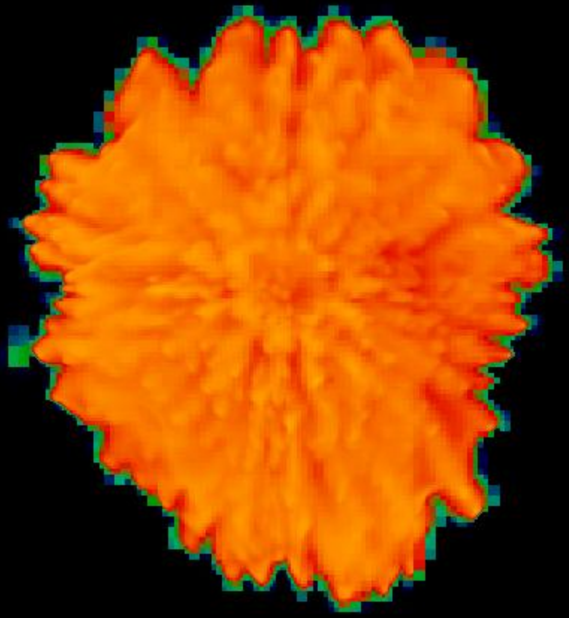


$4x10^5$ yr

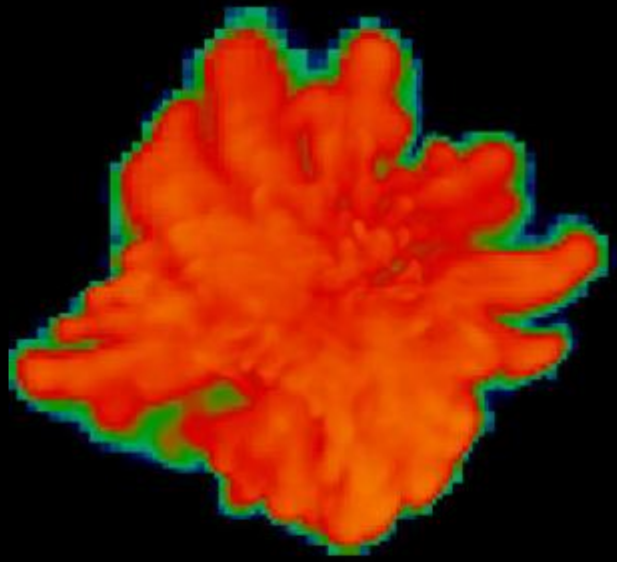
$6x10^7$ yr



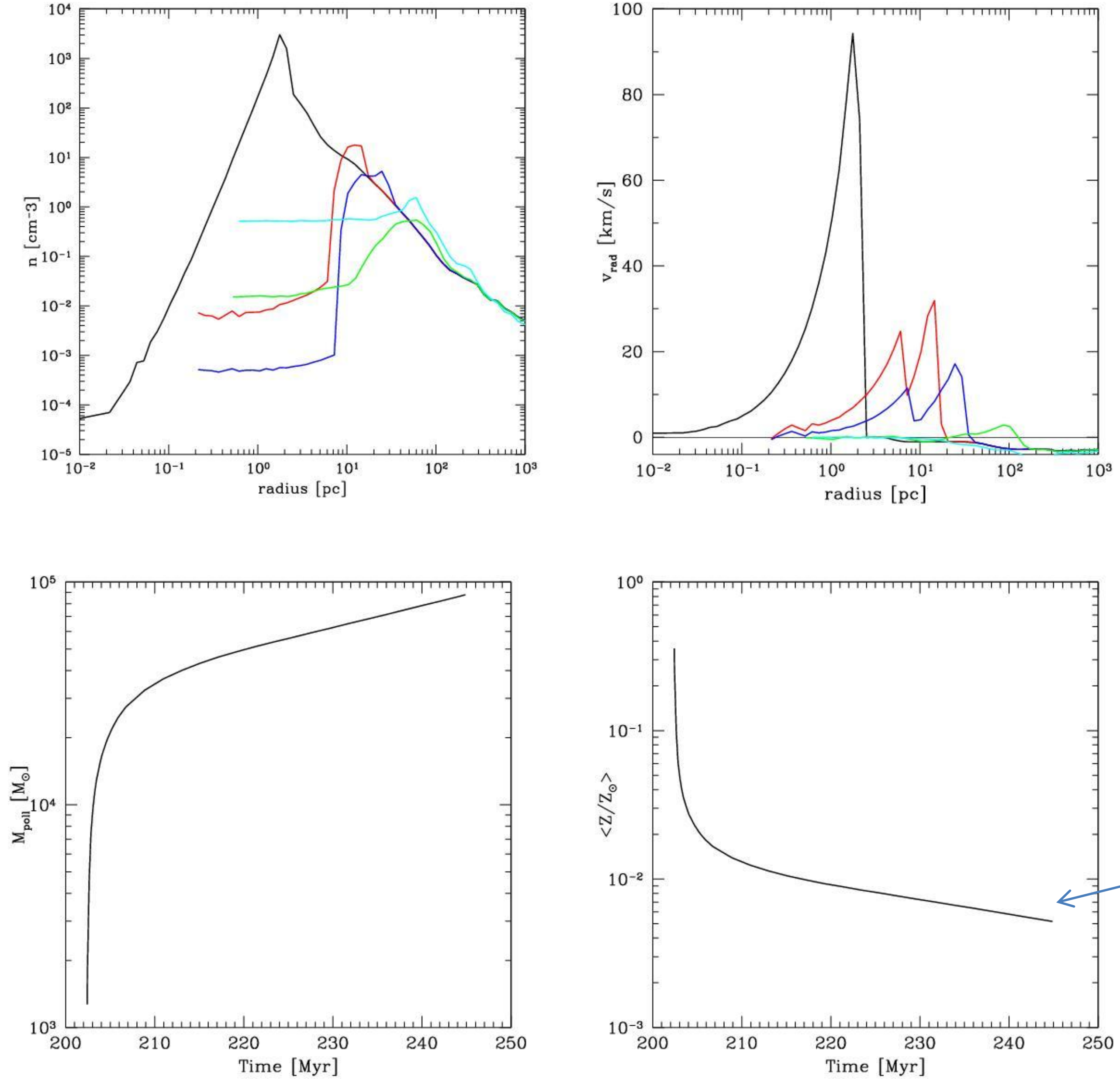
10 pc



50 pc



500 pc

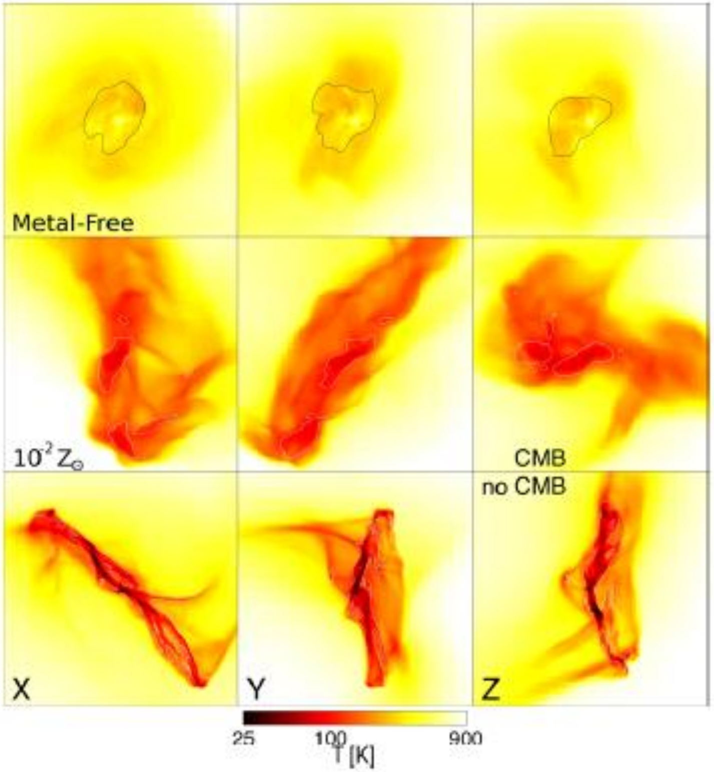


Z/Z_s=5x10^{-3}

Transition to Pop II Stars

Smith, Turk, Sigurdsson & MN (2009)

Metallicity and CMB temperature determine how cool gas gets, and characteristic fragment mass



METAL-ENRICHED STAR FORMATION IN THE EARLY UNIVERSE

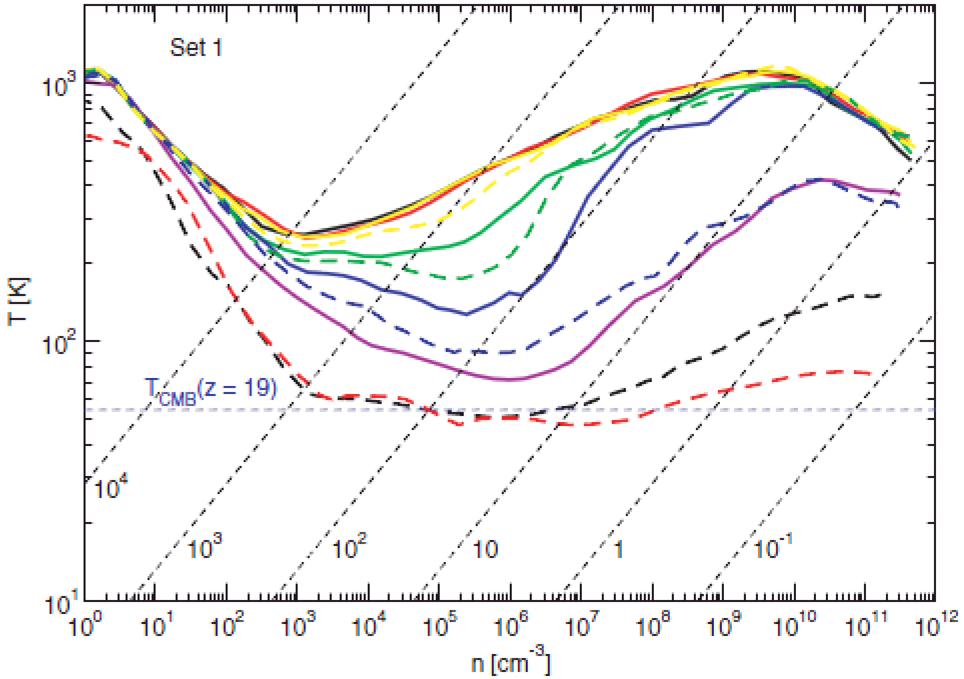
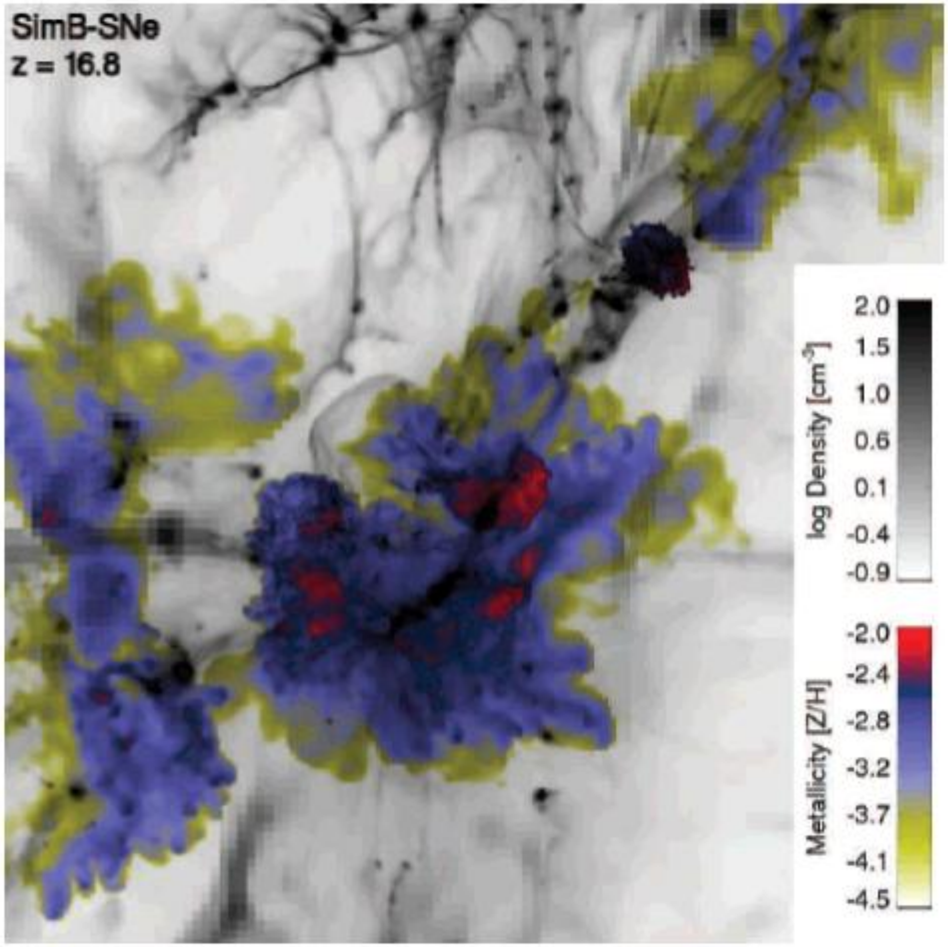


Figure 5. Mass-weighted, average temperature as a function of number density for all runs in Set 1. The colors are the same as in Figure 2, including the runs with metallicities $Z = 10^{-4.25}\ Z_\odot$ (dashed-yellow), $10^{-3.75}\ Z_\odot$ (dashed-green), and $10^{-3.25}\ Z_\odot$ (dashed-blue). The thin, black, dashed lines indicate lines of constant Jeans mass in $M_\odot$. The horizontal, blue, dashed line denotes the temperature of the CMB at $z = 19$, the approximate redshift of collapse for runs r1_Z-2.5 and r1_Z-2. The central cores in these two runs were both able to cool to the temperature of the CMB.

First
Galaxies

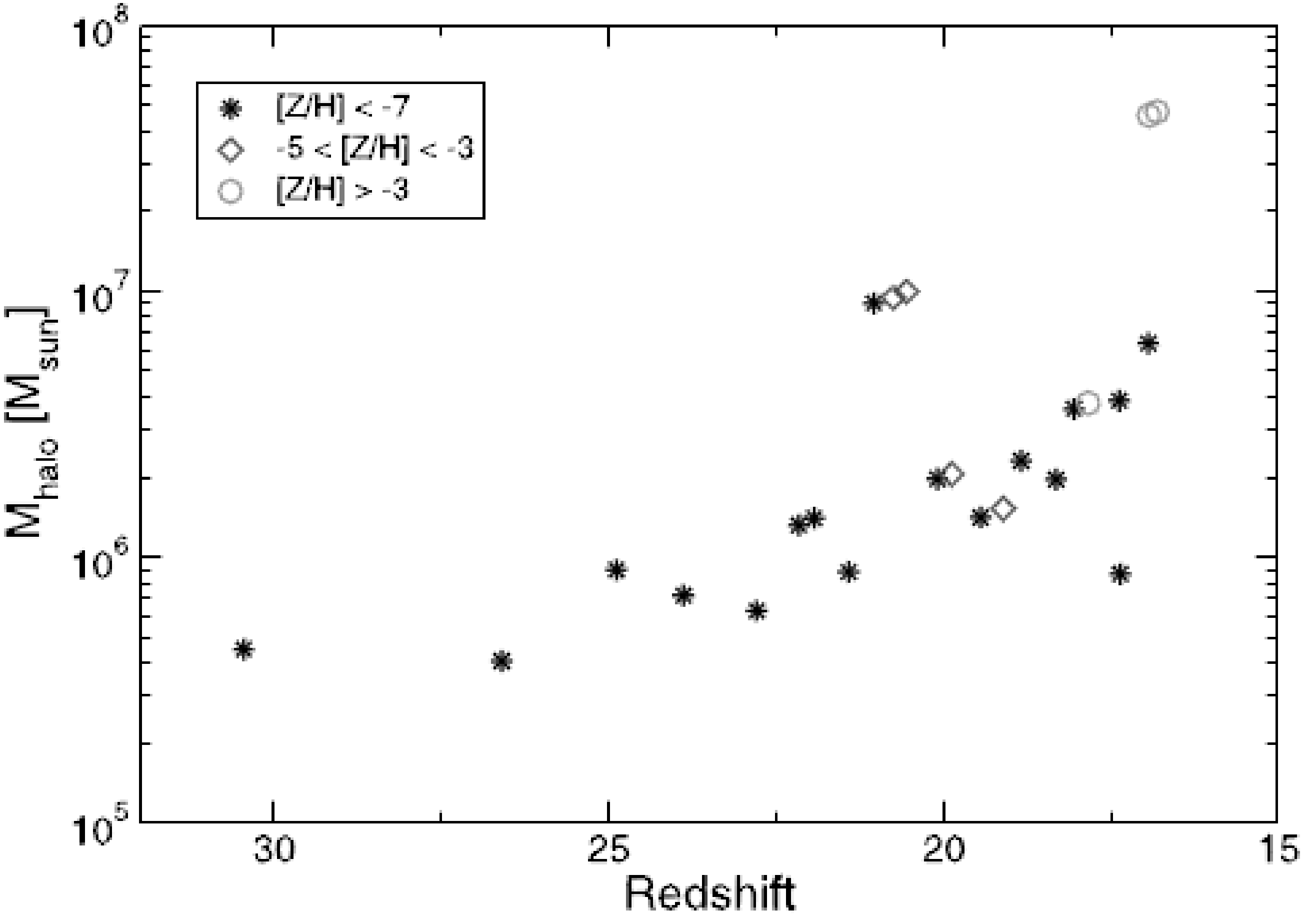
First Galaxies (Protogalaxies)

- A 10^8 Ms galaxy will form from DM and gas pre-processed by multiple Pop III SF episodes
- Strong radiative feedback, SN feedback, and shallow potential wells deplete 1st galaxies of baryons



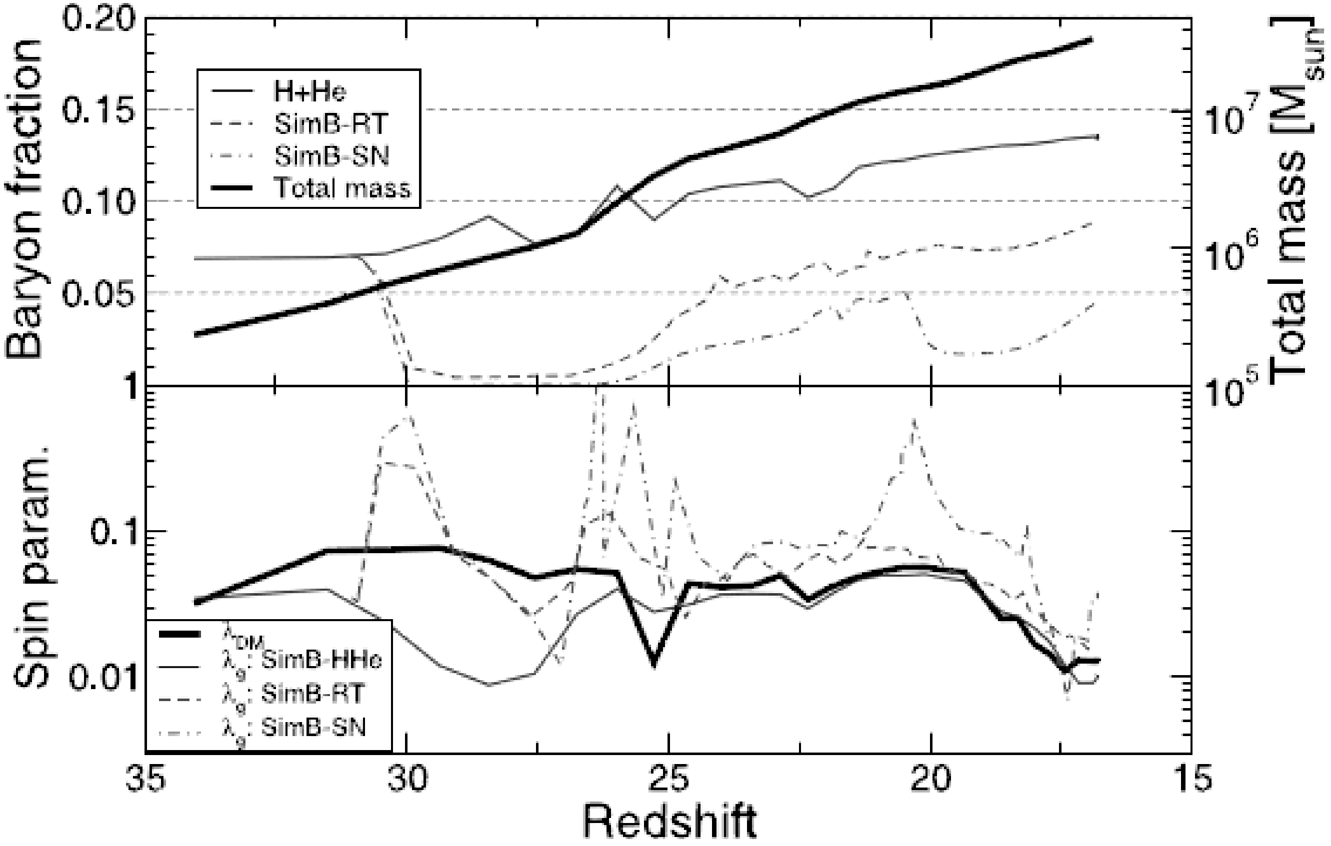
Wise & Abel 2008

Pop III Star Formation Events



Wise & Abel 2008

Baryons Depleted 3x



Wise & Abel 2008

Test Run Including Pop III➔II Transition

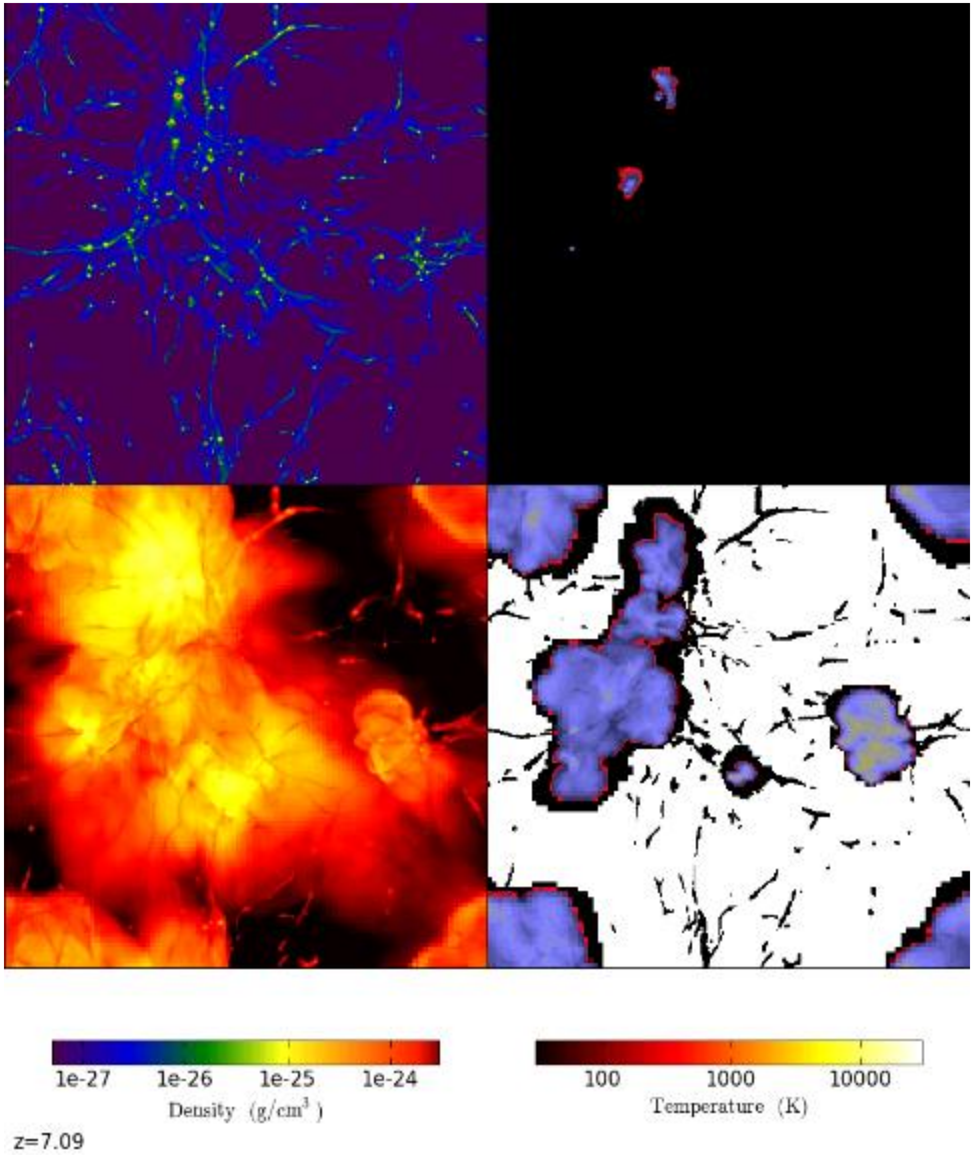
Wise, Abel & Norman (in prep)

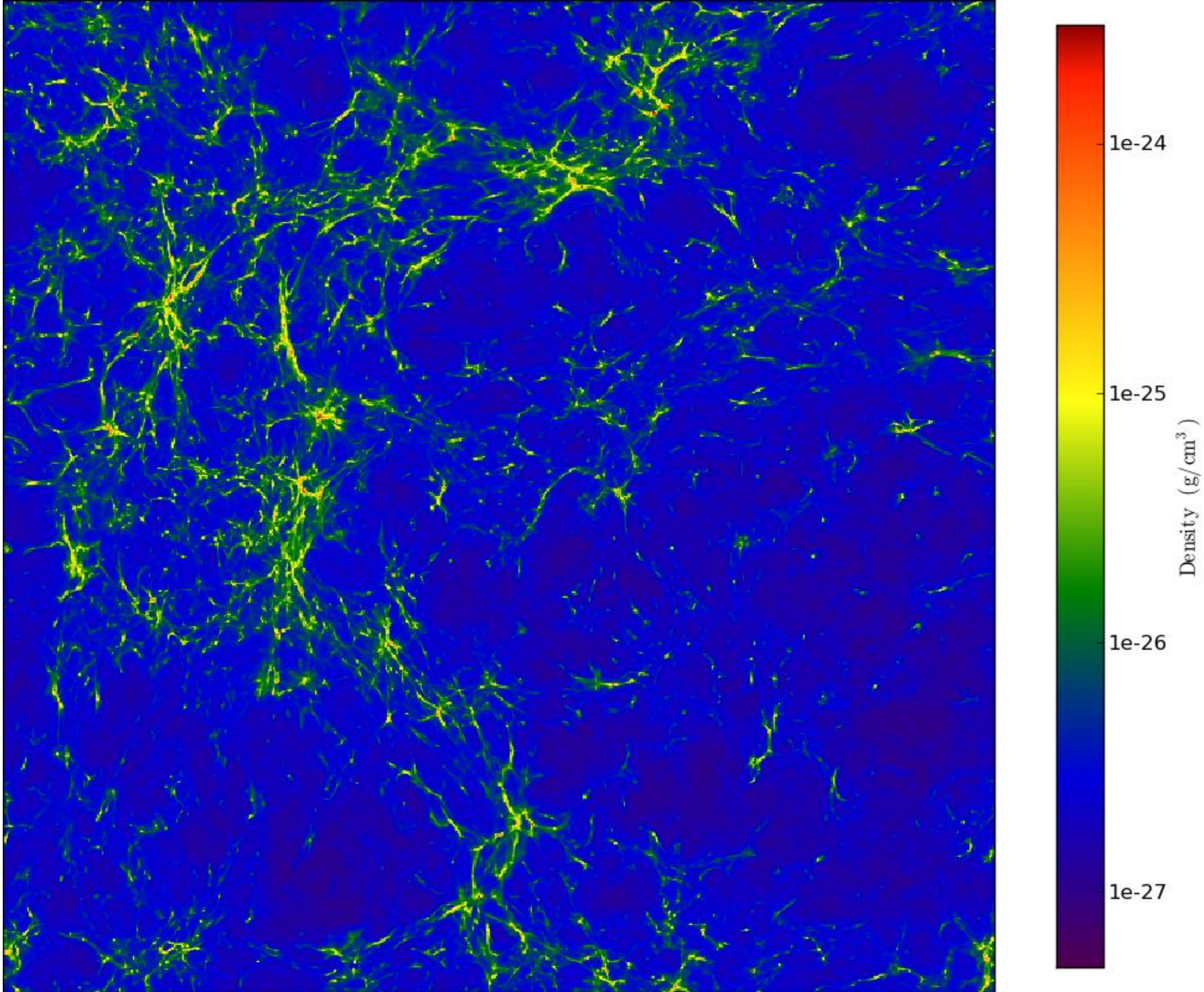
- Pop III model
  - Wise & Abel (2008)
  - Mass drawn from a top-heavy IMF
  - UV luminosities and lifetimes drawn from Schearer (2002)
  - Endpoints and SN yields taken from Heger & Woosley
- Pop II model
  - Wise & Cen (2009)
  - “star cluster particle” created if Z>Zcrit (10^{-4} Zs)
  - 104 Ms
  - Salpeter IMF
  - EUV emitted 40 Myr
  - Standard SN yields

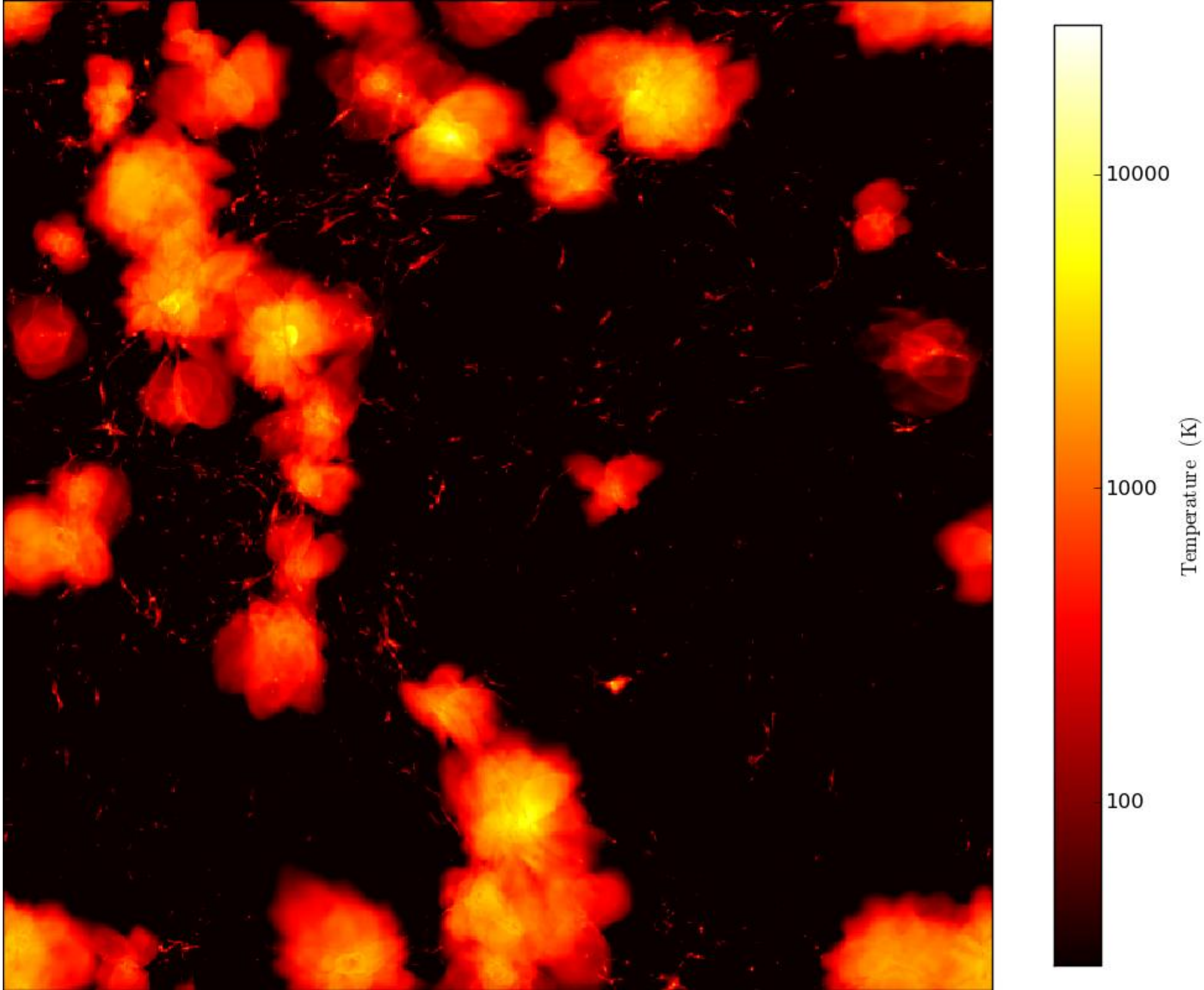
Test Run Including Pop III→II Transition

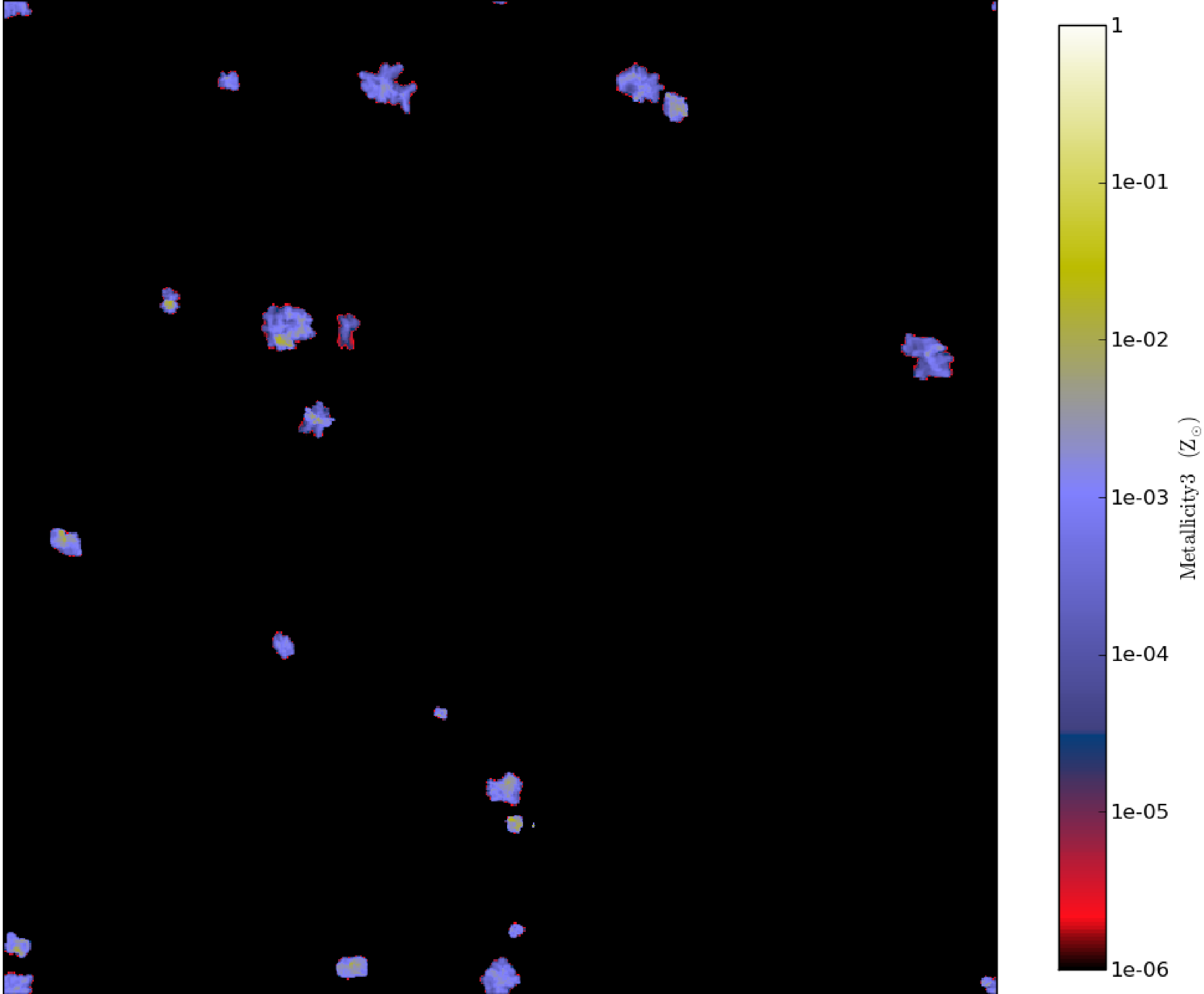
Wise, Abel & Norman (in prep)

- L_{box}=600 kpc/h
- 96^3 root grid and particles
- 10 levels of refinement
- $M_{dm} = 10^3$ Ms
- $\Delta x(min)$=1pc




1e-24
1e-25
1e-26
1e-27
Density $(\mathrm{g/cm^3})$


10000
1000
100
Temperature (K)


1
1e-01
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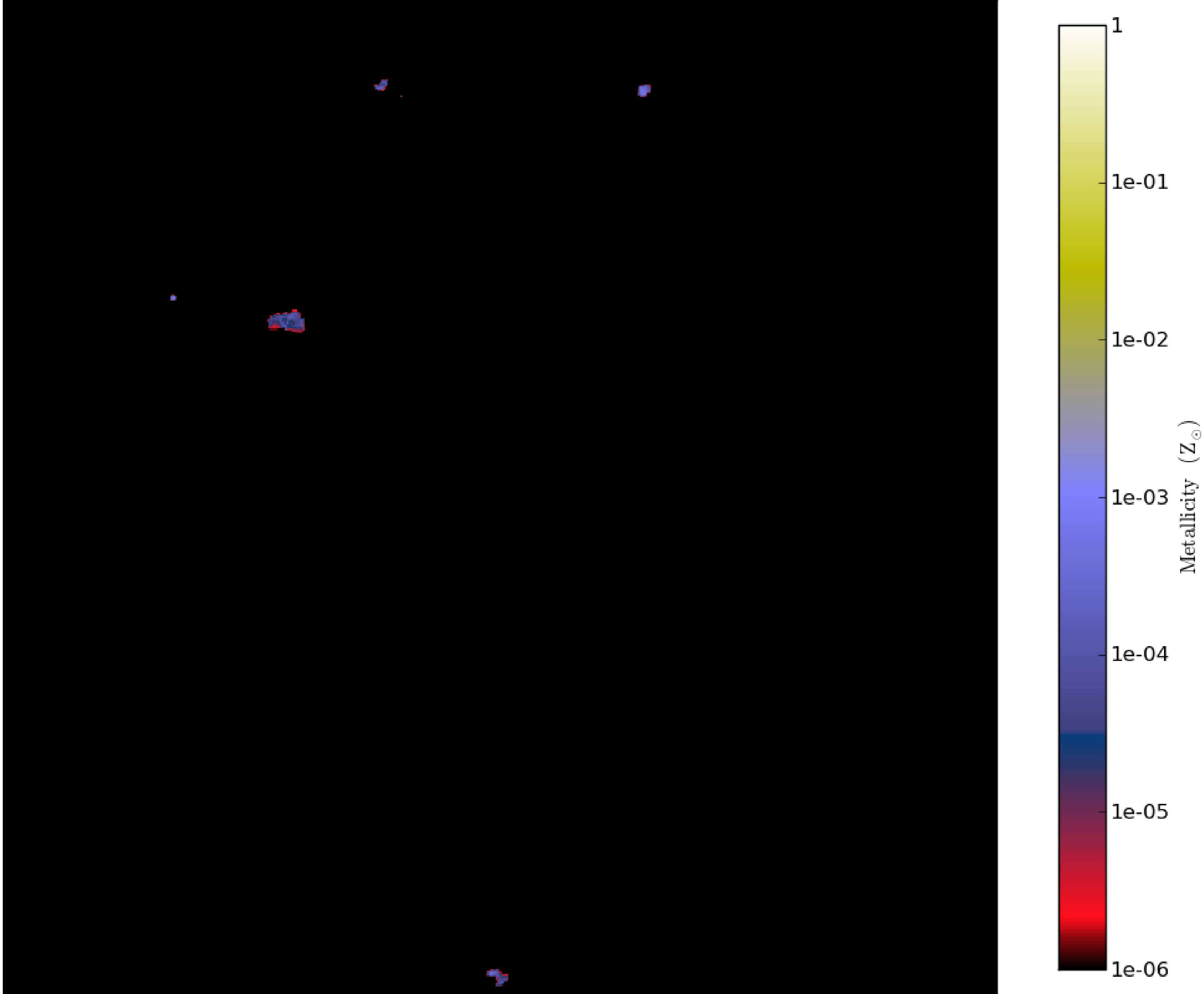
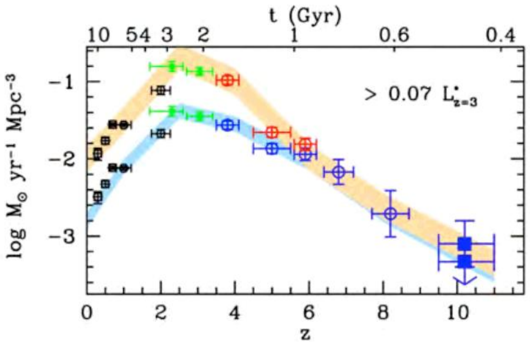
1e-03
1e-04
1e-05
1e-06
Metallicity3 (Z$_\odot$)


1
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
Metallicity $(Z_\odot)$

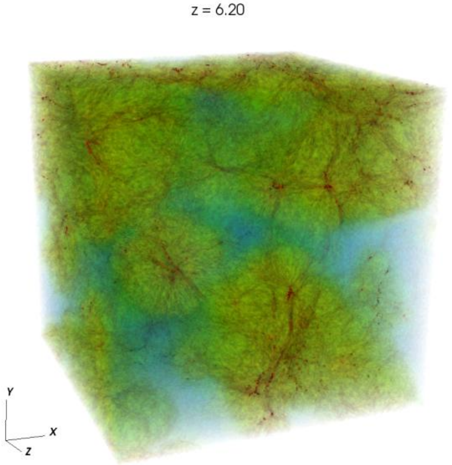
Cosmic Reionization

Connecting first galaxies with cosmic reionization via self-consistent cosmological RHD simulations

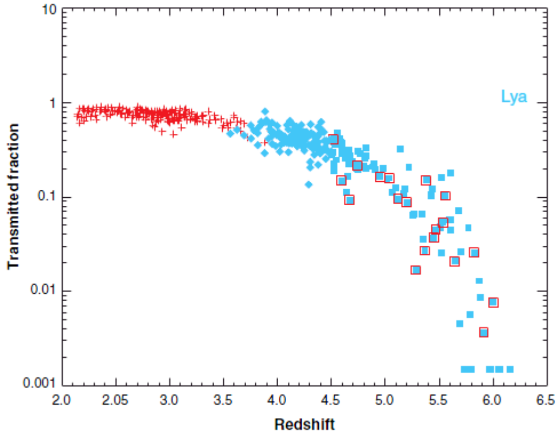
Michael Norman, Pascal Paschos, Geoffrey So, Matt Turk, Robert Harkness, UCSD
Dan Reynolds, SMU
John Wise, Jerry Ostriker, Princeton
Massimo Ricotti, U Maryland



Bouwens et al. (2010)



Norman et al. (2010), in prep



Fan, Carilli & Keating (2006)

…or, what can you do with a Petaflop?

NICS Kraken, ORNL

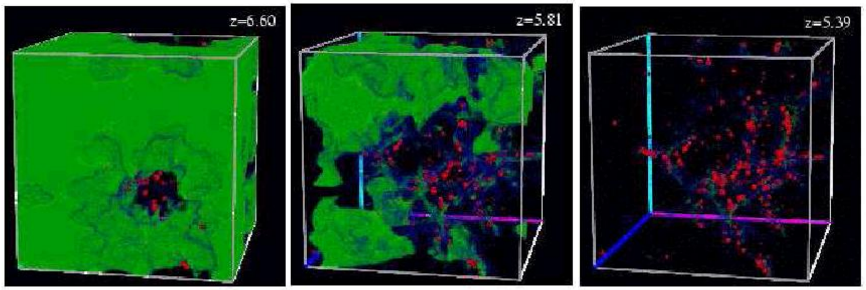
100,000 cores, >1 Pflops peak

Science Motivations

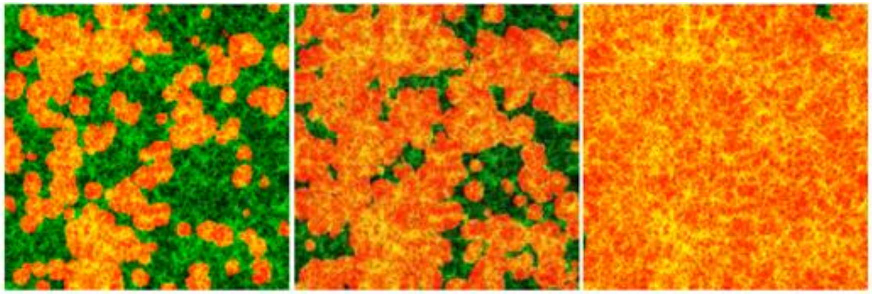
- Want to connect first galaxies to reionization in a self-consistent (i.e. predictive) way
  - Mass scale of reionizers
  - radiative feedback effects on self and nearest neighbors
    - High-z galaxies highly biased and clustered
  - Internal physical properties of FLOs
  - Evolving stellar populations of FLOs
  - Predictions for JWST and ALMA

Three generations of cosmological reionization simulations

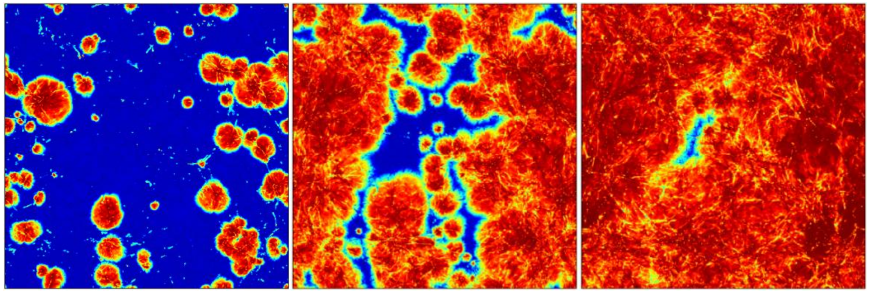
- 1. Local self-consistent
  - (small boxes < 10 Mpc)
  - CRHD+SF+ionization+heating
  - e.g., Razoumov et al. 2002



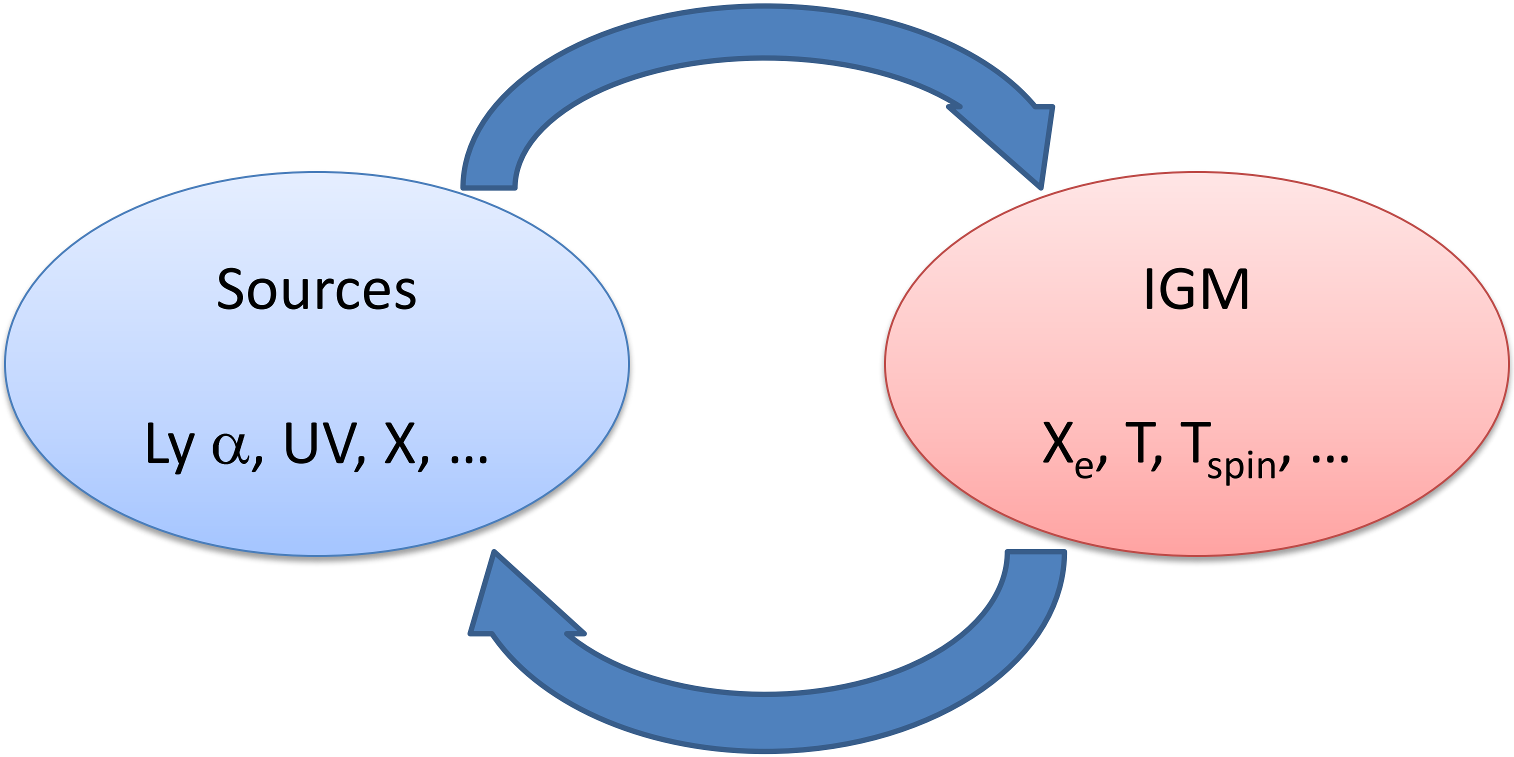
- 2. Global post-processing
  - (large boxes > 100 Mpc)
  - N-body + RT
  - e.g., Iliev et al. 2006



- 3. Global self-consistent
  - (large boxes > 100 Mpc)
  - CRHD+SF+ionization+heating
  - Norman et al. 2010, in prep.



Self-consistent evolution of sources, IGM, and radiation backgrounds



Radiation backgrounds

Sources

Ly α, UV, X, …

IGM

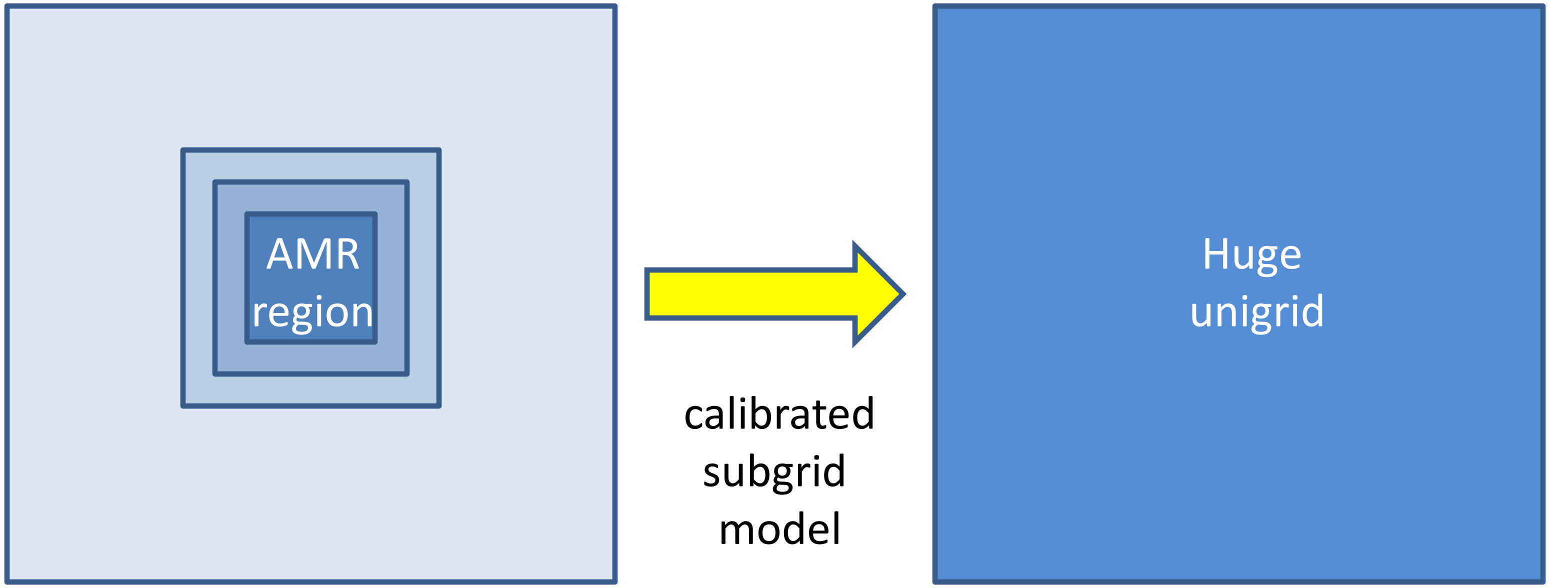
X_e, T, T_{spin}, …

Cosmological hydro/N-body dynamics

What’s the difficulty?

- Tremendous range of scales
  - Global reionization: >100 Mpc
  - First galaxies scale lengths: < 1 kpc
  - Ratio: $>10^5$ *achievable with AMR*
- Large number of emitting sources
  - 10^6 – 10^8 depending on box size and lower mass cutoff
  - Need O(N) scalable radiation solvers
- Uncertain star formation physics
  - HST, JWST, ALMA to the rescue

Our strategy



Go deep

AMR
region

Cosmological volume
> 100 Mpc/h

- RHD with adaptive ray tracing
- Sub-kpc resolution
- John Wise (Princeton)

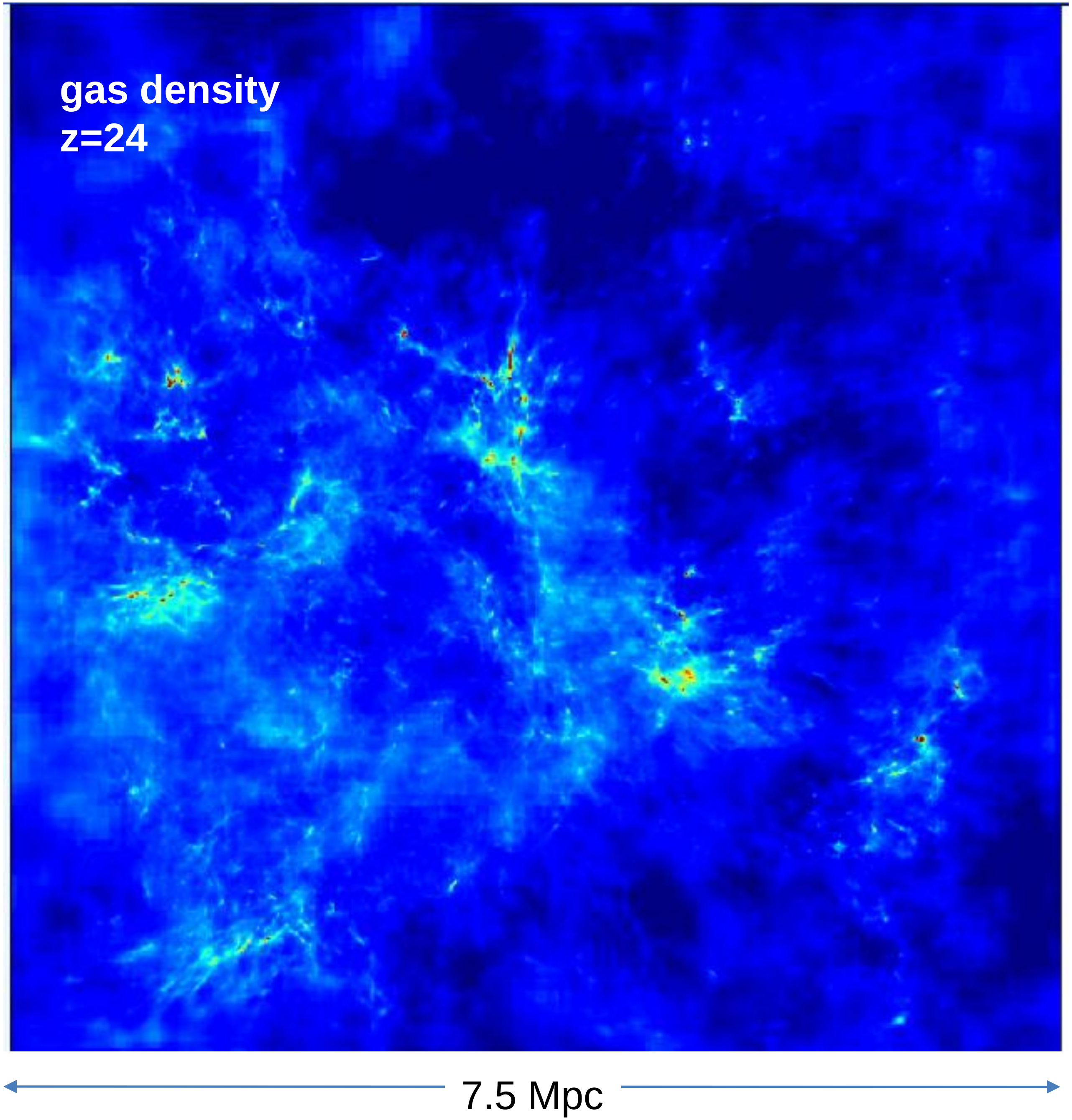
calibrated
subgrid
model

Go wide

Huge
unigrid

Cosmological volume
> 100 Mpc/h

- RHD with implicit FLD
- Sub- 100 kpc resolution
- Dan Reynolds (SMU)



Deep AMR simulation of highly biased region inside 30 Mpc box

$M_{dm} = 3 \times 10^4$ Ms

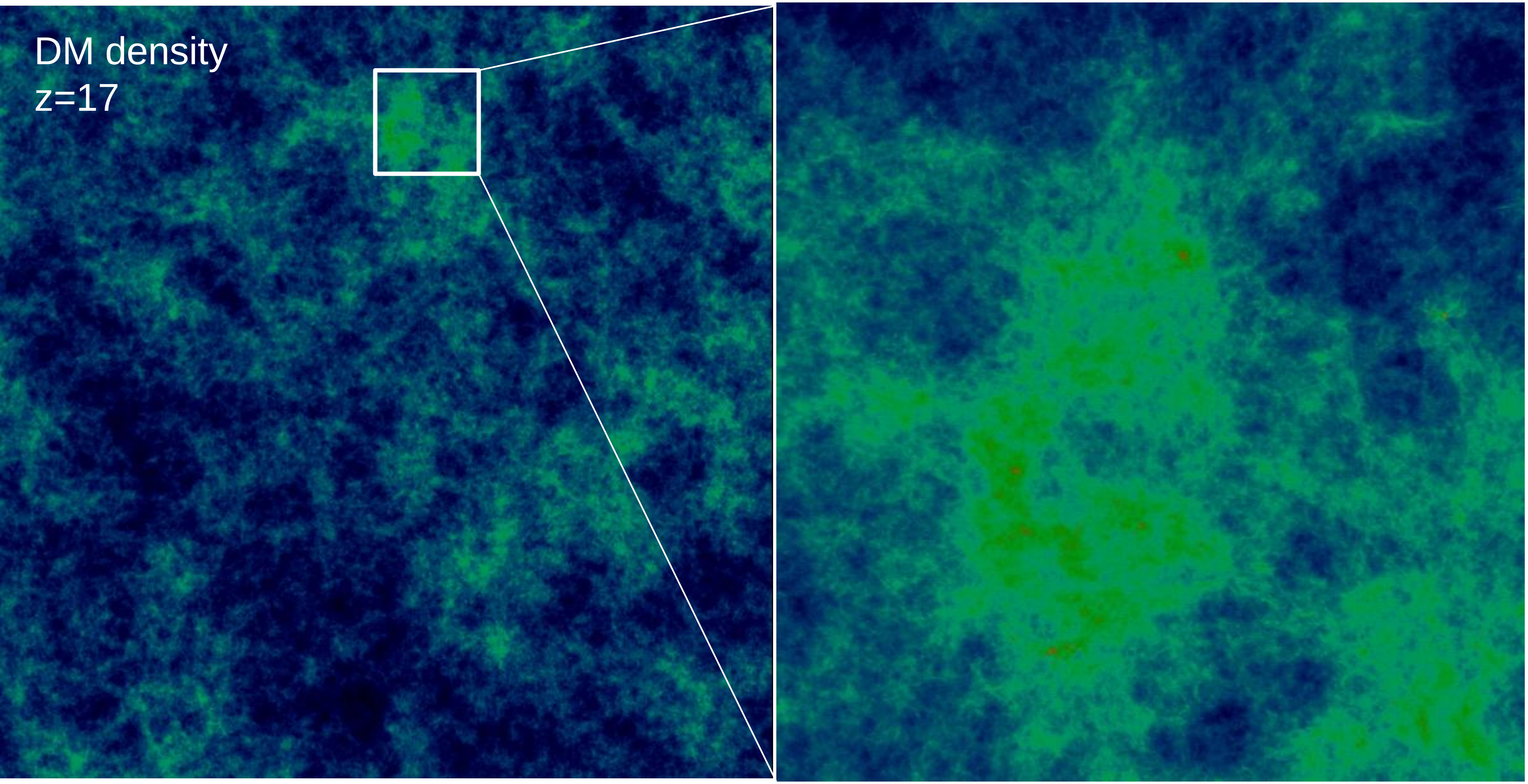
Min(Δx)= 11pc@z=6

Pop II SF/FB model of Wise & Cen (2009)

Metal enrichment and metal-dependent cooling

adaptive ray tracing radiative transfer

A Huge Unigrid: 6400^3 *Enzo*



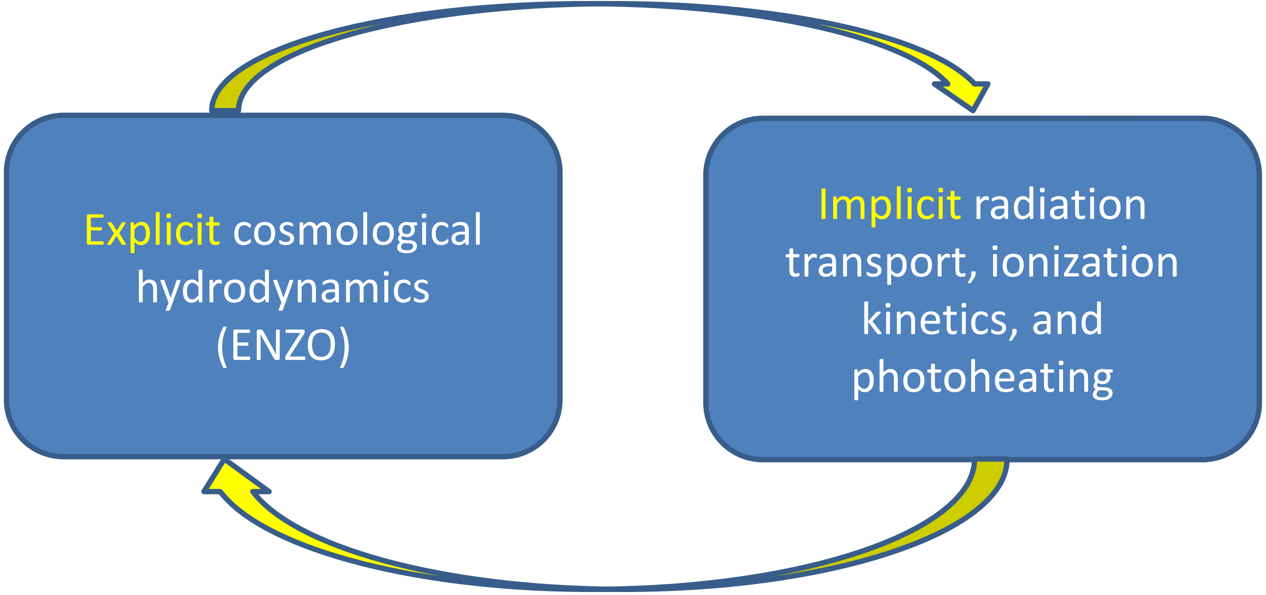
6400^3 cells/particles, 80 Mpc box, DM+Gas+SF/FB

93,000 cores, Kraken

Self-consistent Cosmological Radiation Hydrodynamics/Ionization

Reynolds et al. (2009), JCP

- Goal
  - Create a parallel scalable solver that couples cosmological hydrodynamics, radiation transport, chemical ionization, and gas photoheating self-consistently



Explicit cosmological hydrodynamics (ENZO)

Implicit radiation transport, ionization kinetics, and photoheating

Implicit Coupled System

- non-equilibrium multispecies model

$$\partial_t e_c = -\frac{2\dot{a}}{a} e_c + G - \Lambda, \tag{19}$$

$$\partial_t \mathrm{n}_i = \alpha_{i,j} \mathrm{n}_e \mathrm{n}_j - \mathrm{n}_i \Gamma_i^{ph}, \tag{20}$$

$$\partial_t E = \nabla \cdot (D \nabla E) - m \frac{\dot{a}}{a} E + 4\pi\eta - c\kappa E, \tag{21}$$

- Optimally scalable Newton-Krylov-Schur-Multigrid nonlinear solver for resulting system of equations (Reynolds et al. 2009)
  - Cost independent of the number of sources
  - Cost scales linearly with number of processors
- Easily generalized to multi-frequency/group and variable tensor Eddington factors

Scalability, algorithmic and parallel

Weak scaling test: lattice of HII regions

Geometric multigrid is optimally scalable

HYPRE parallel implemenation also scalable

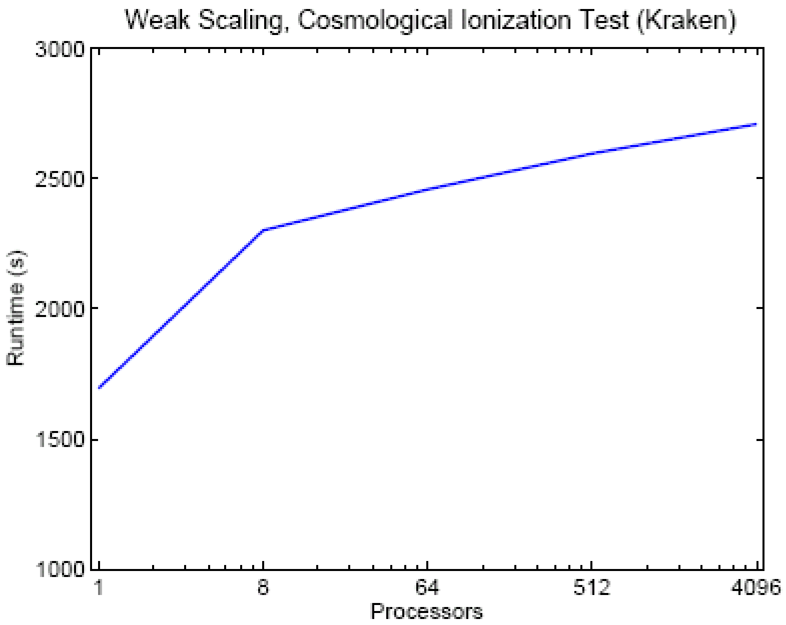
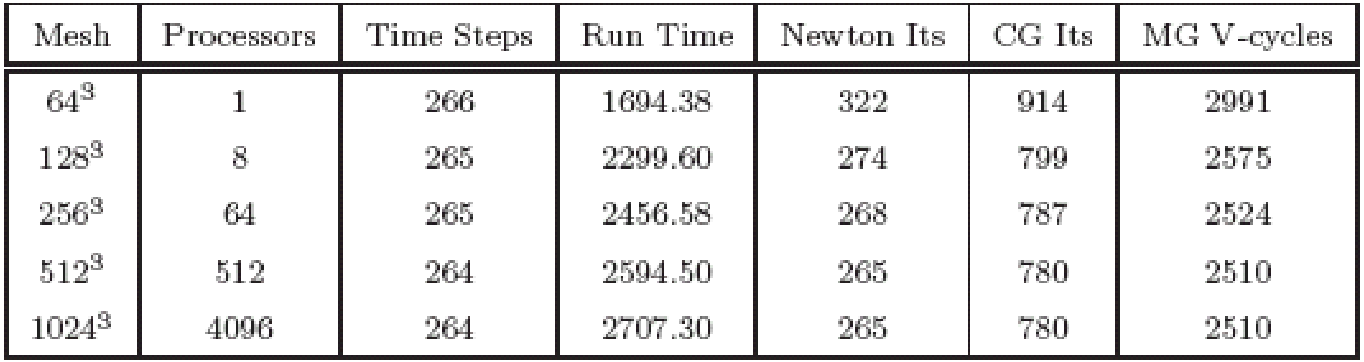
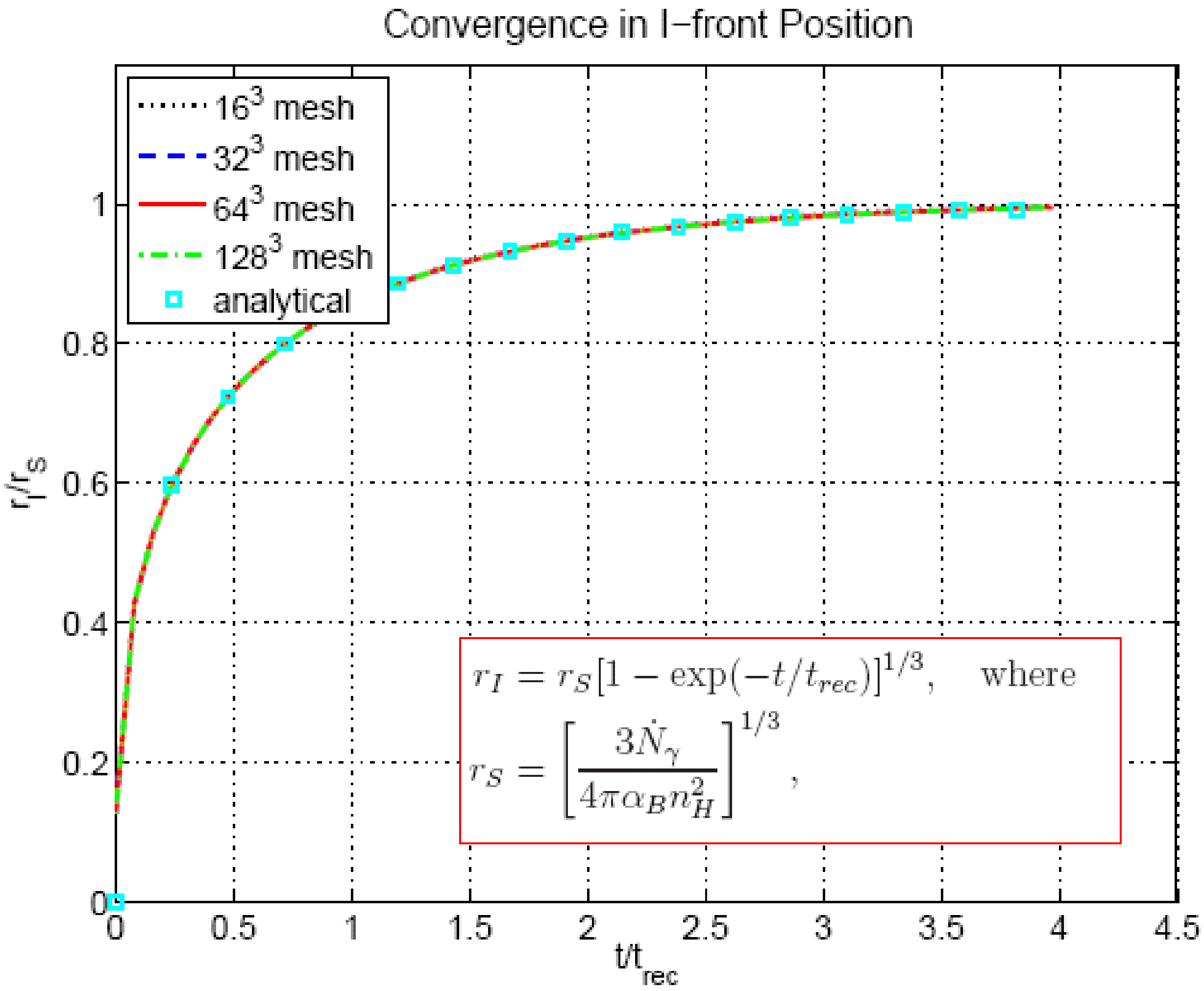


Fig. 13. Weak scaling results for the cosmological HII-region expansion test.



Mesh	Processors	Time Steps	Run Time	Newton Its	CG Its	MG V-cycles
64^3	1	266	1694.38	322	914	2991
128^3	8	265	2299.60	274	799	2575
256^3	64	265	2456.58	268	787	2524
512^3	512	264	2594.50	265	780	2510
1024^3	4096	264	2707.30	265	780	2510

HII Region Expansion in static, homogeneous, isothermal medium (Stromgren sphere test)


Convergence in I−front Position

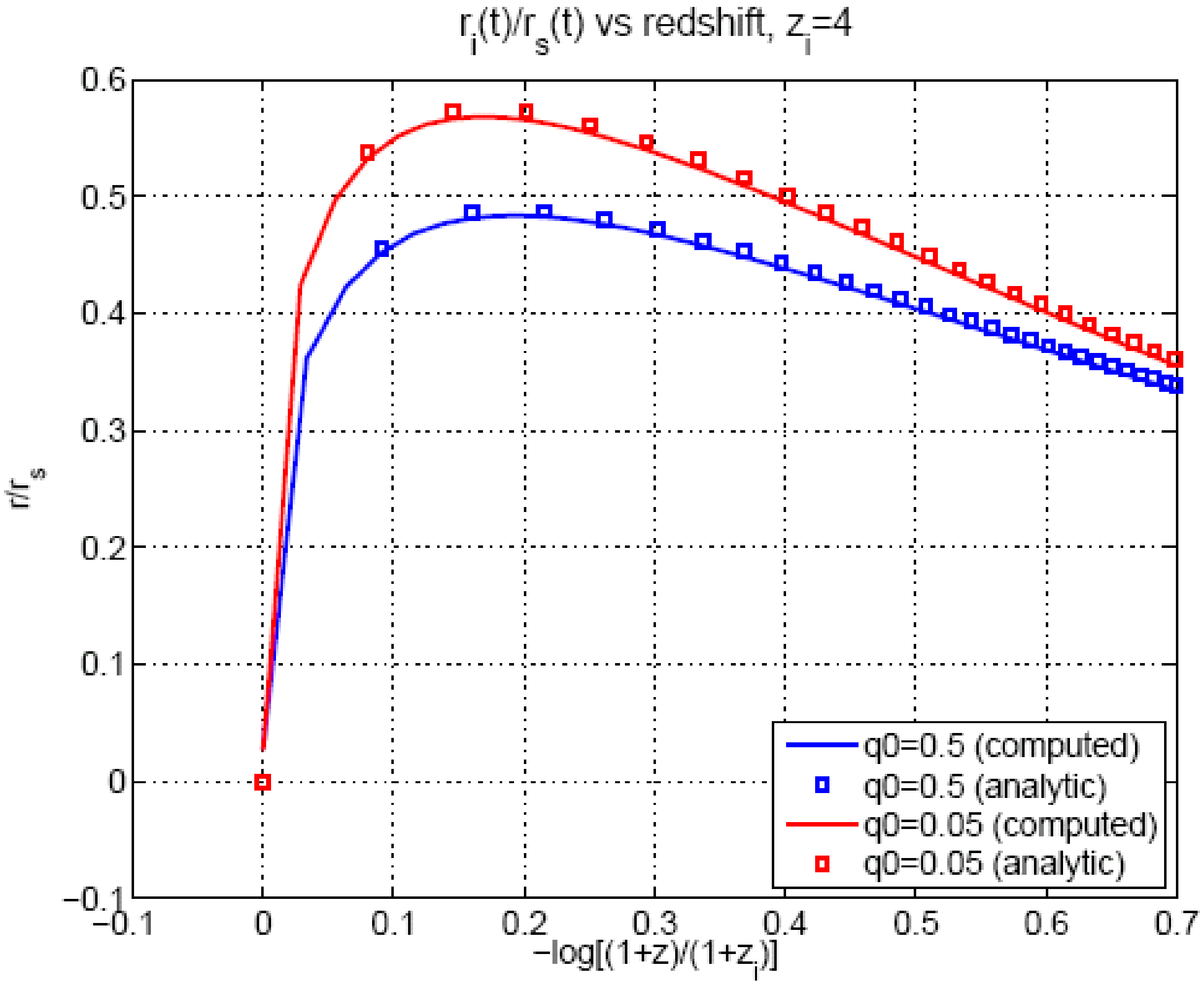
$$r_I = r_S[1 - \exp(-t/t_{rec})]^{1/3}, \quad \text{where}$$

$$r_S = \left[\frac{3\dot{N}_\gamma}{4\pi\alpha_B n_H^2}\right]^{1/3},$$

Reynolds+2009, JCP

Cosmological HII Region Expansion

(Shapiro & Giroux test problem)



Reynolds+2009, JCP

RHD Solver Commissioning Test

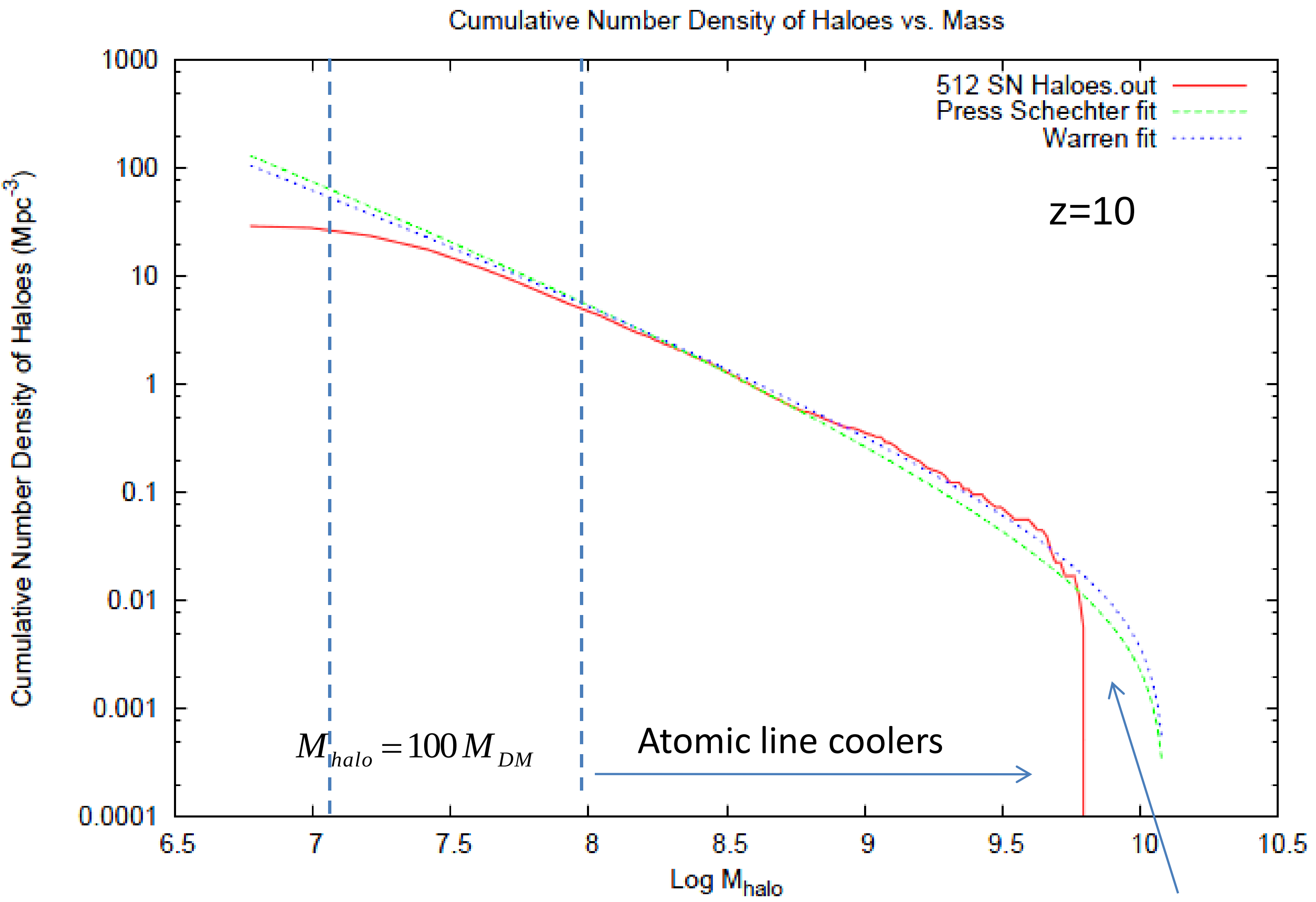
➔*uncalibrated SF/FB*

- ΛCDM WMAP3 cosmology
- 8 Mpc box, 512^3 grid, Δx=16 kpc comoving
  - ~ 1.5 kpc proper at z=10
- $M_{dm} = 1.2\text{x}10^5\ M_{sol}$
  - $10^8\ M_{sol}$ halos well resolved by mass, marginally resolved spatially
- Pure hydrogen ionization (no He)
- Cen & Ostriker (1992) star formation/feedback recipe
- optional X-ray background (Ricotti, Gnedin & Ostriker 2005)

$$\dot{E}_{UV} = \varepsilon_{UV}\dot{M}_{SF}c^2$$

$$\dot{E}_{SN} = \varepsilon_{SN}\dot{M}_{SF}c^2$$

$$\dot{E}_{X} = \varepsilon_{X}\dot{M}_{SF}c^2$$



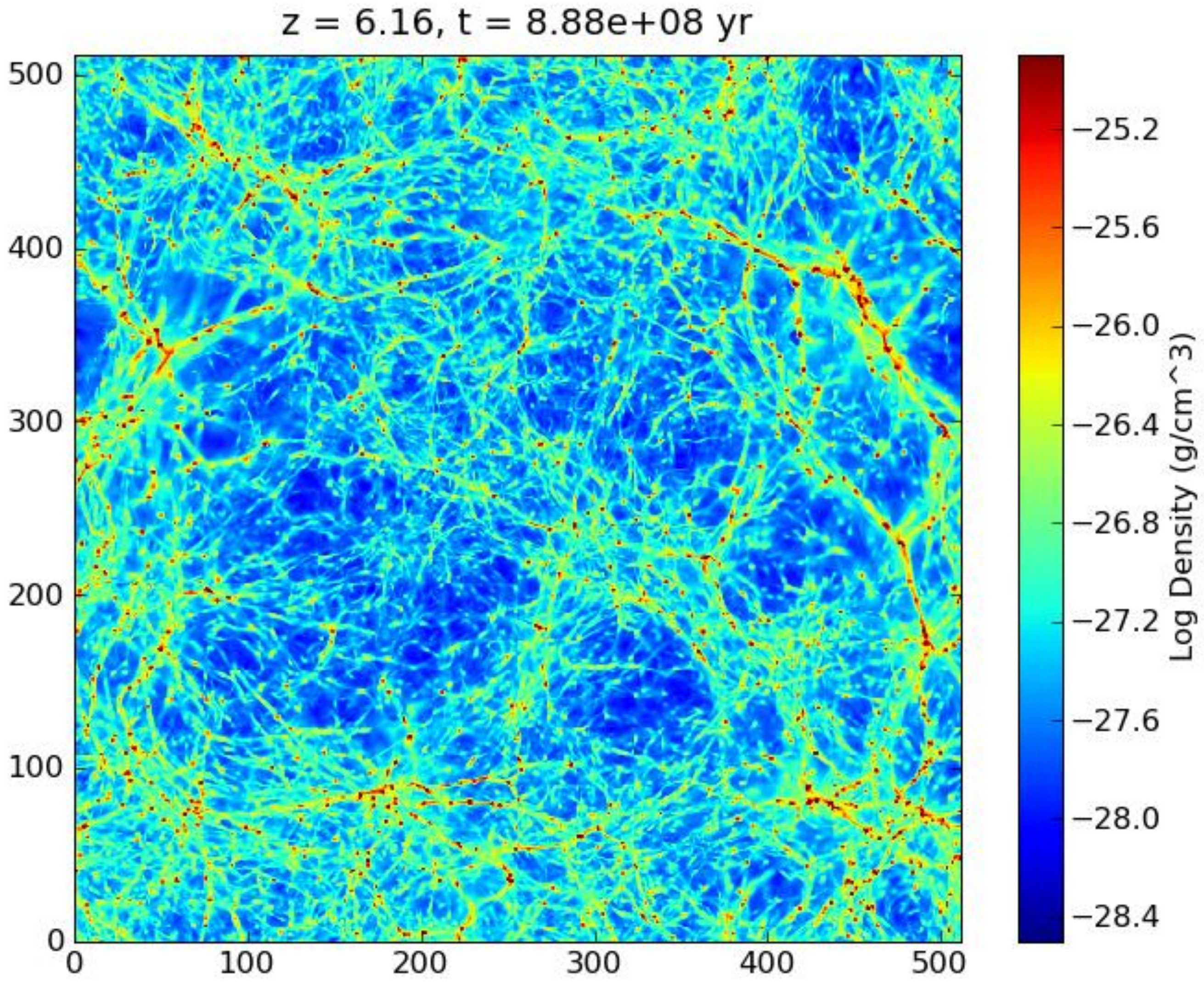
z=10

$M_{halo} = 100\, M_{DM}$

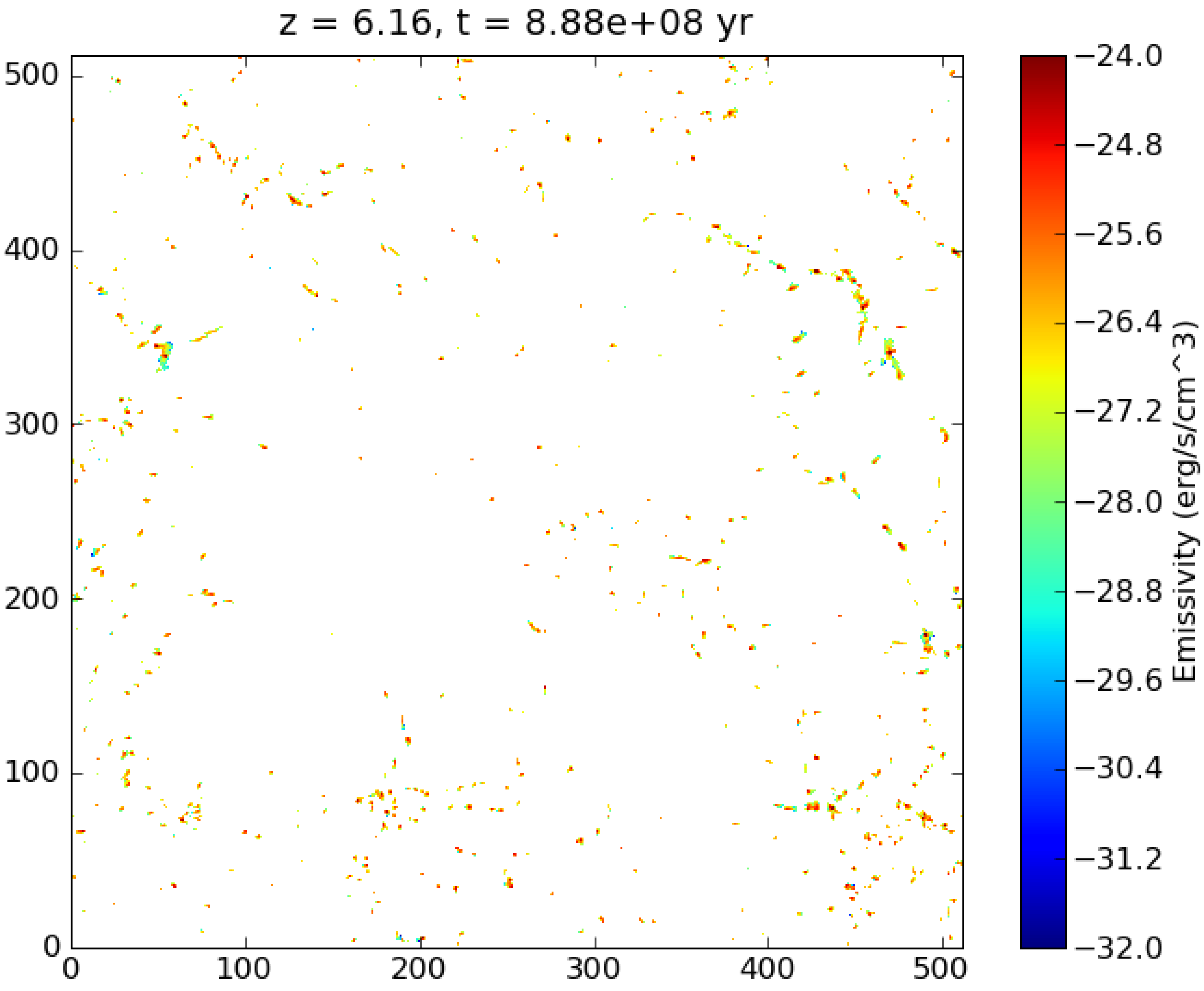
Atomic line coolers

box-size truncation

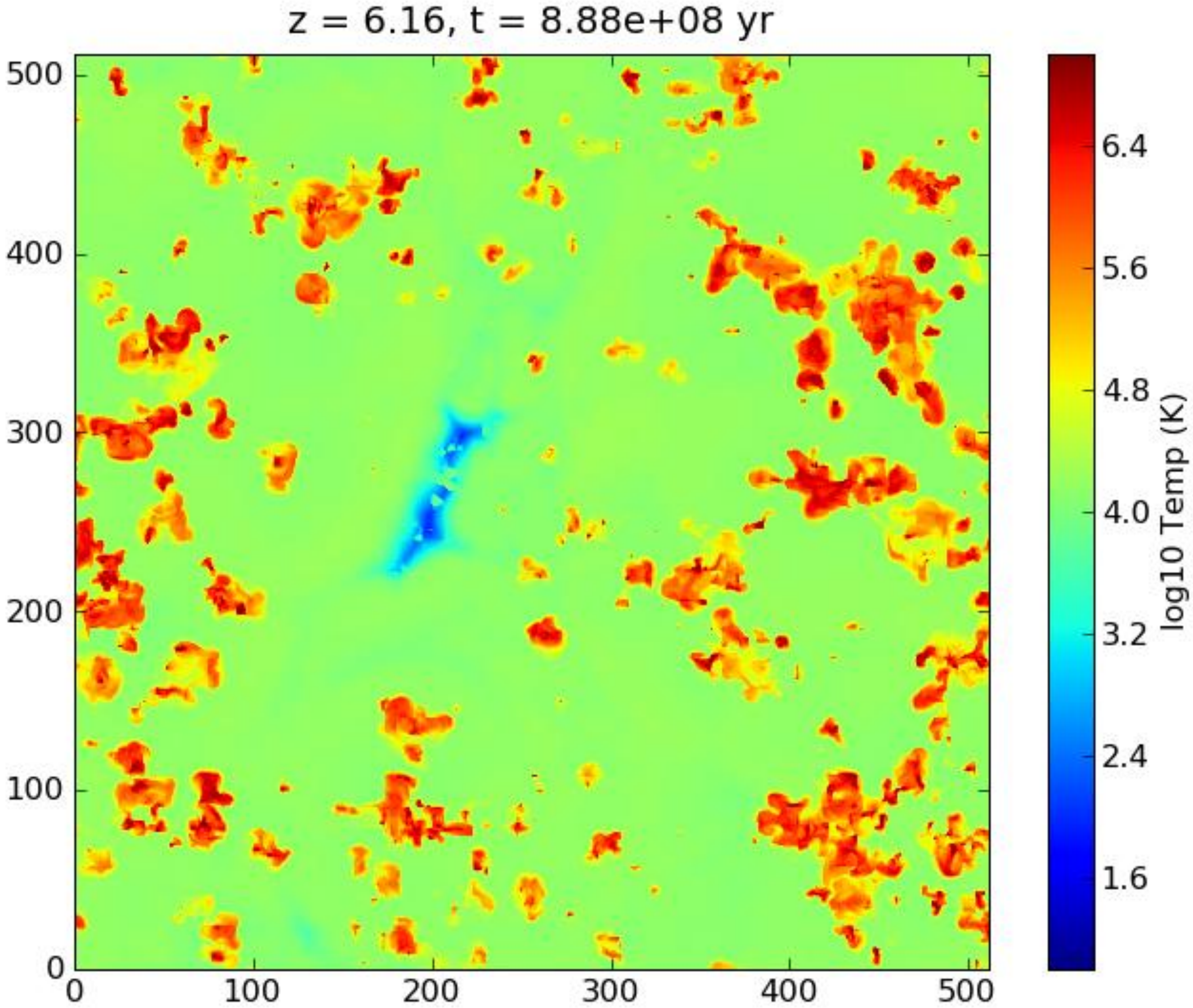
Proper baryon density



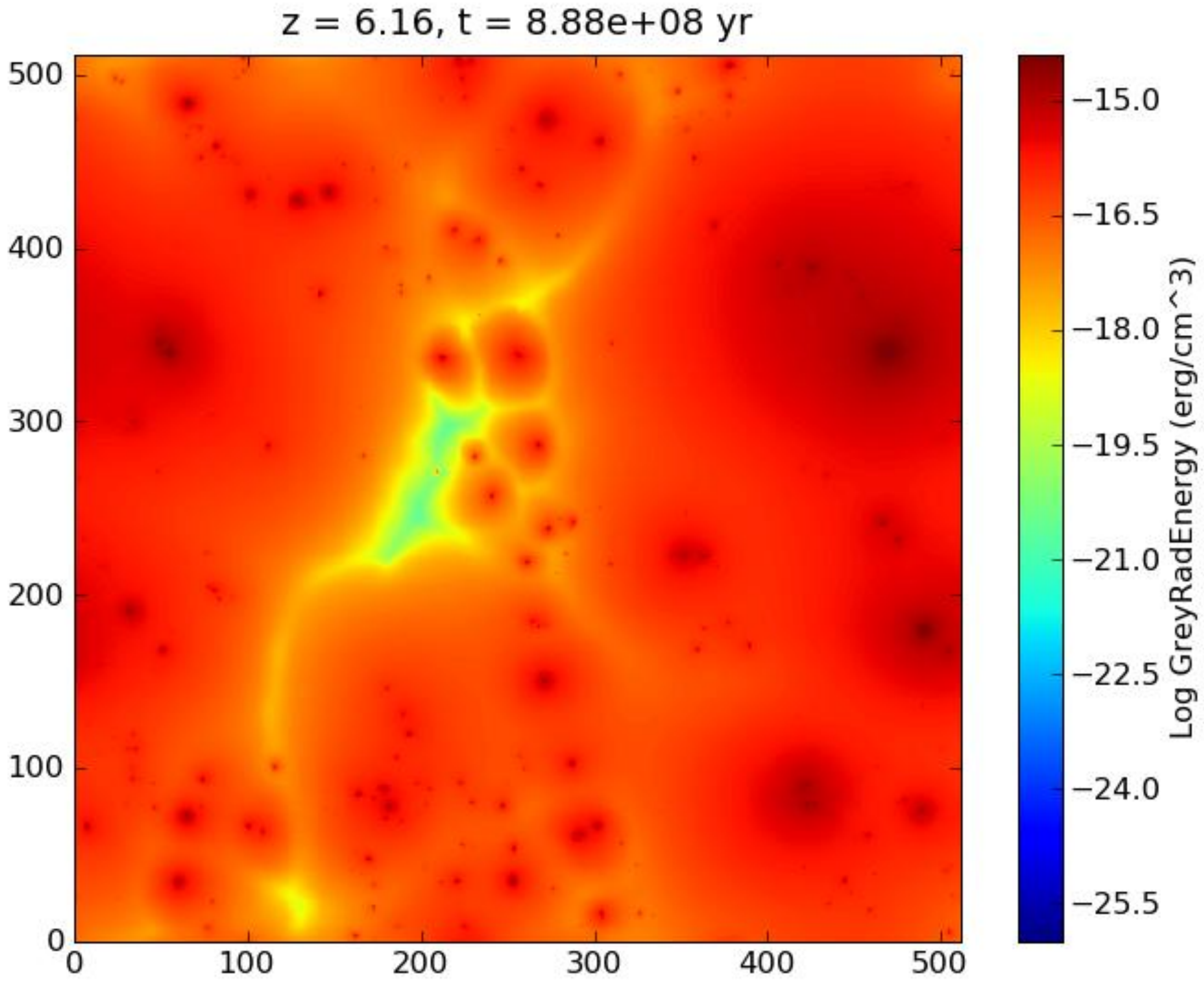
ionizing emissivity



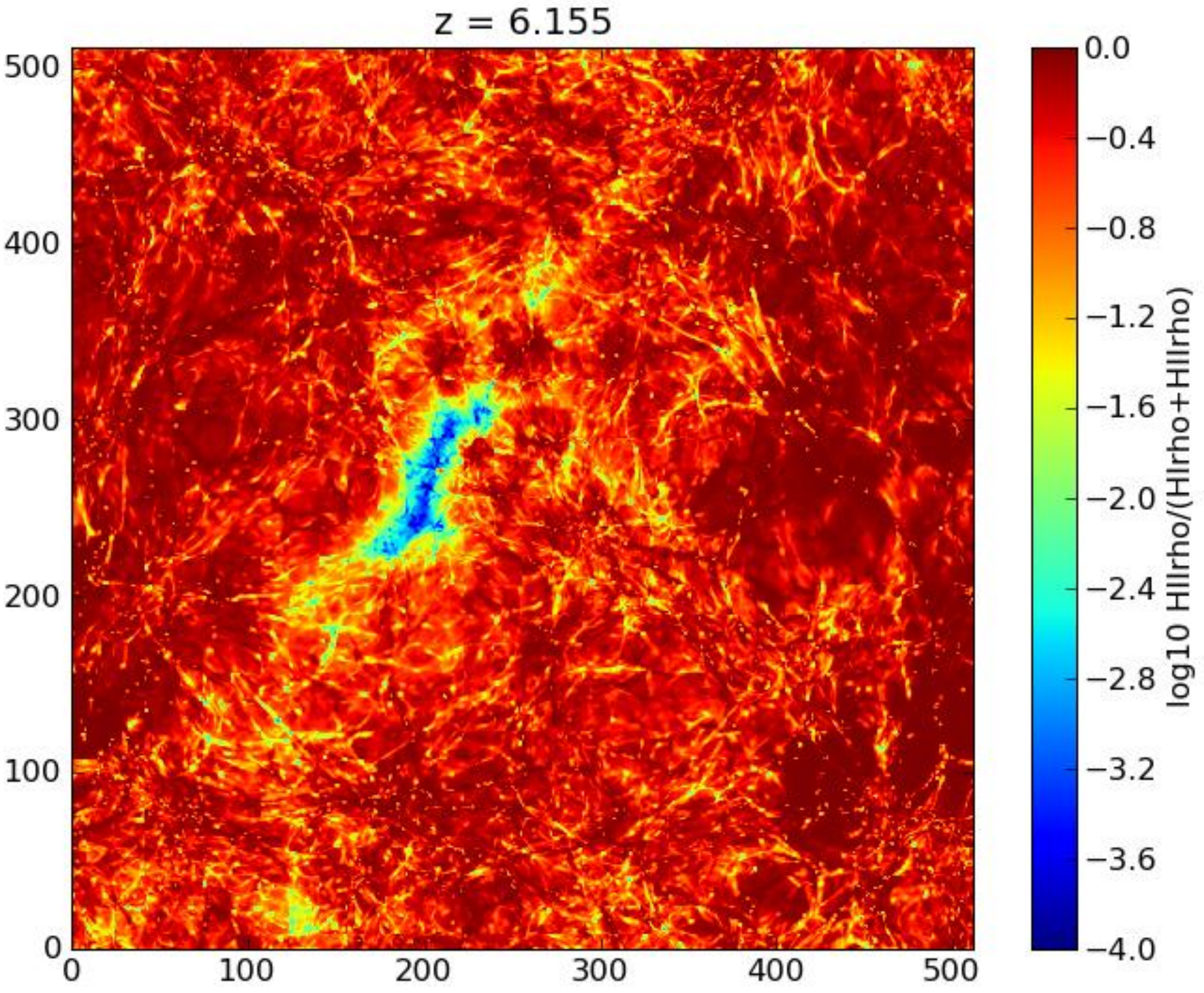
Gas temperature



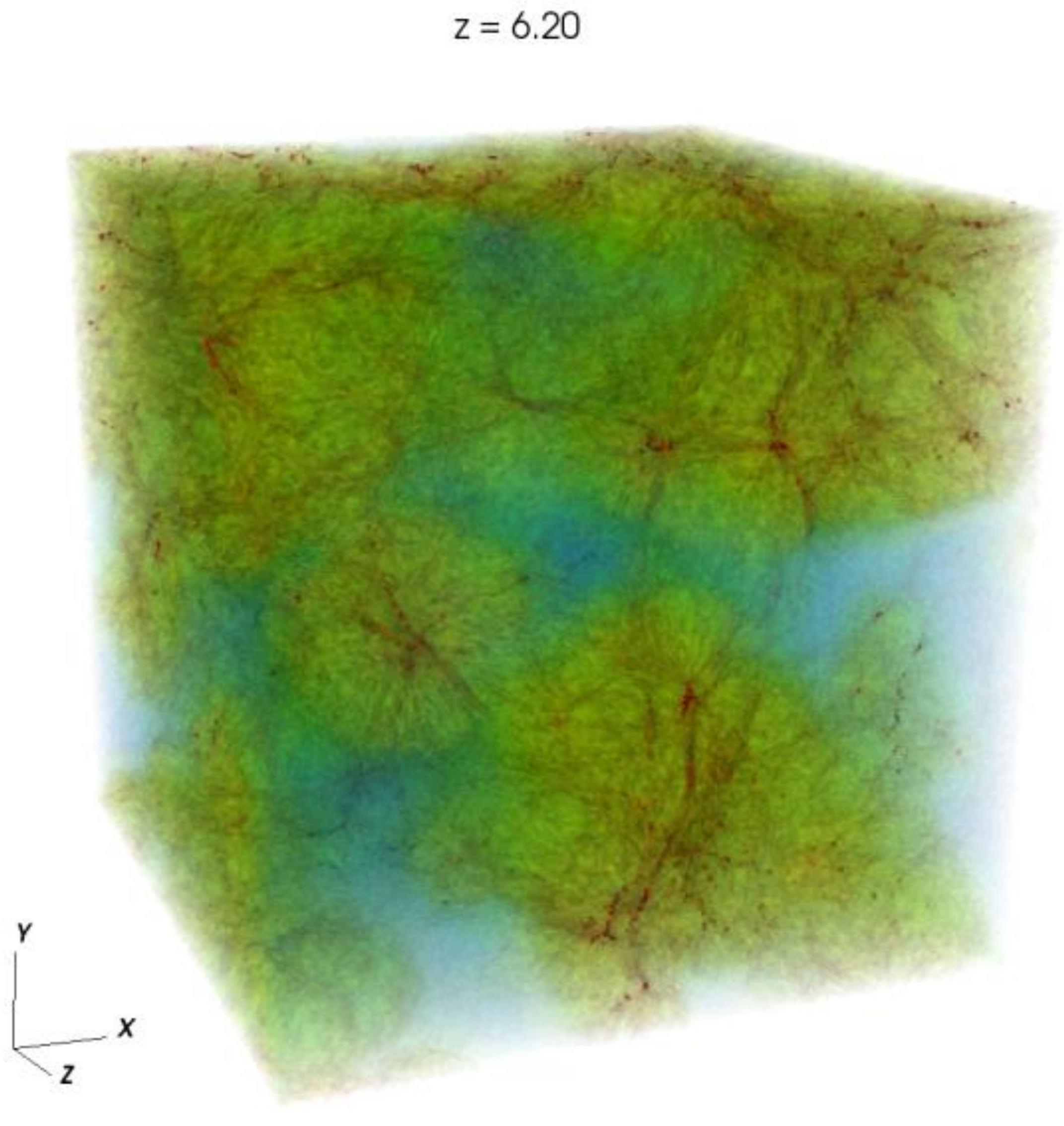
Radiation energy density

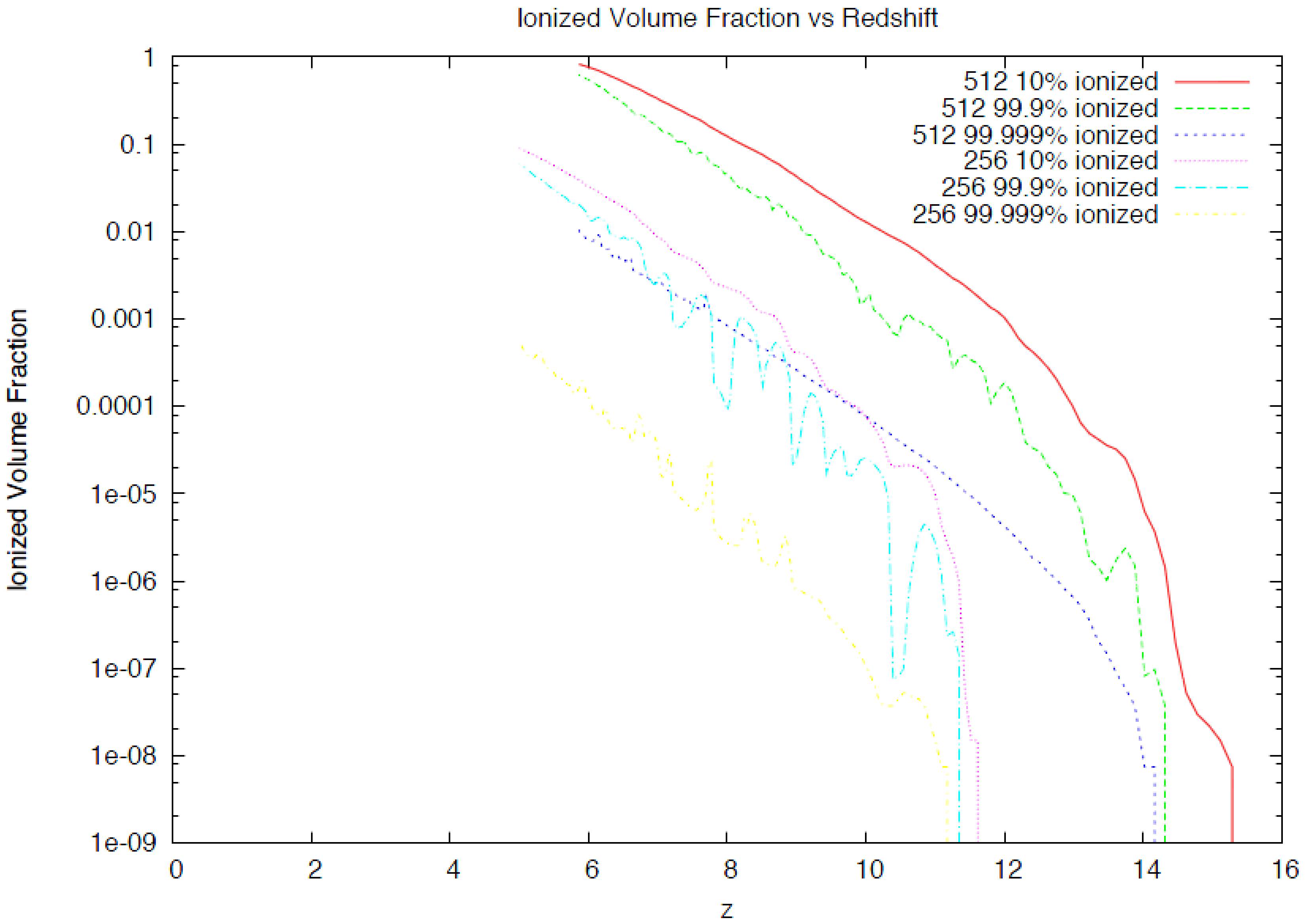


Ionized fraction

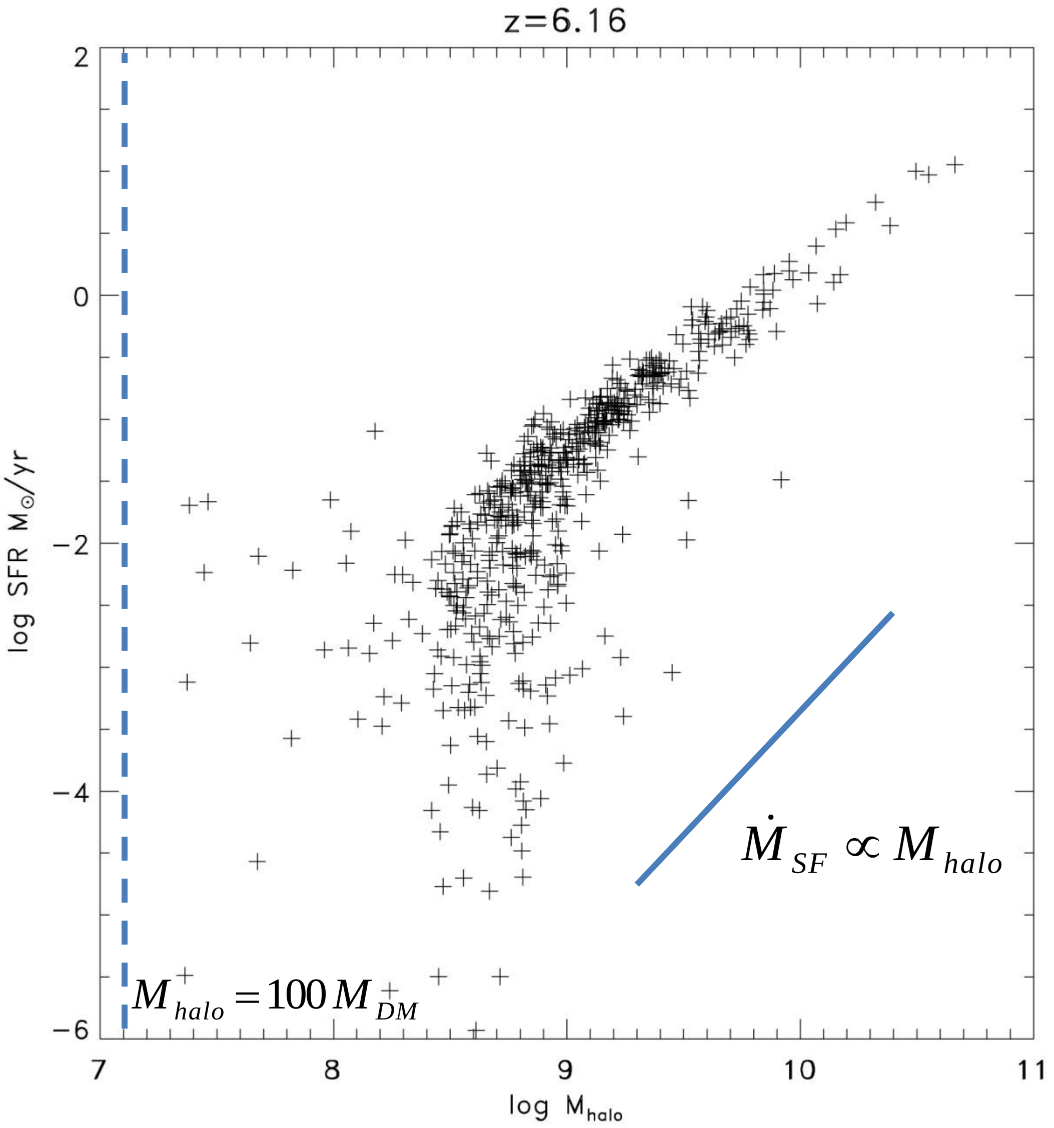


Volume rendering of ionization fraction

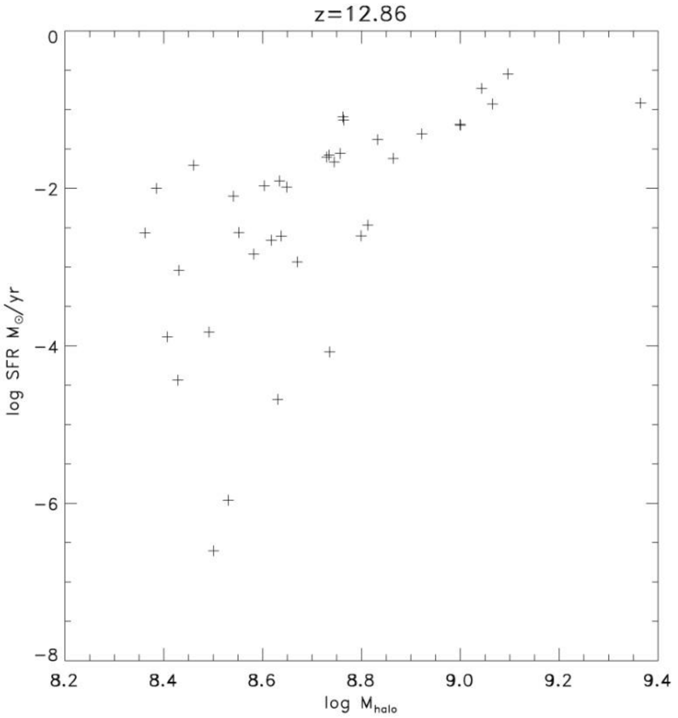


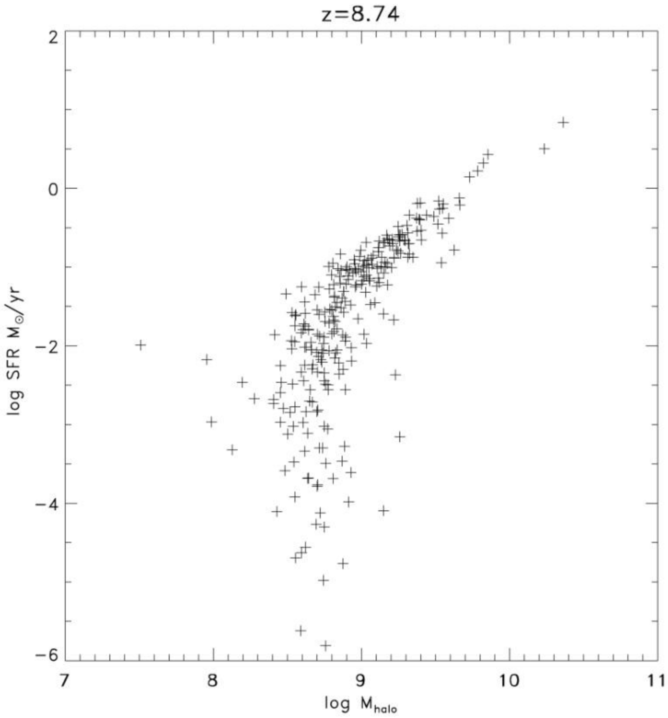

Ionized Volume Fraction vs Redshift
Ionized Volume Fraction
z
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
0
2
4
6
8
10
12
14
16
512 10% ionized
512 99.9% ionized
512 99.999% ionized
256 10% ionized
256 99.9% ionized
256 99.999% ionized

SFR vs M_{halo}


z=6.16
log SFR $M_\odot$/yr
log M_{halo}
2
0
−2
−4
−6
7
8
9
10
11
$\dot{M}_{SF} \propto M_{halo}$
$M_{halo} = 100\, M_{DM}$

Strong Suppression of SF below $M_{halo} = 10^{8.5}$ M_{sol}

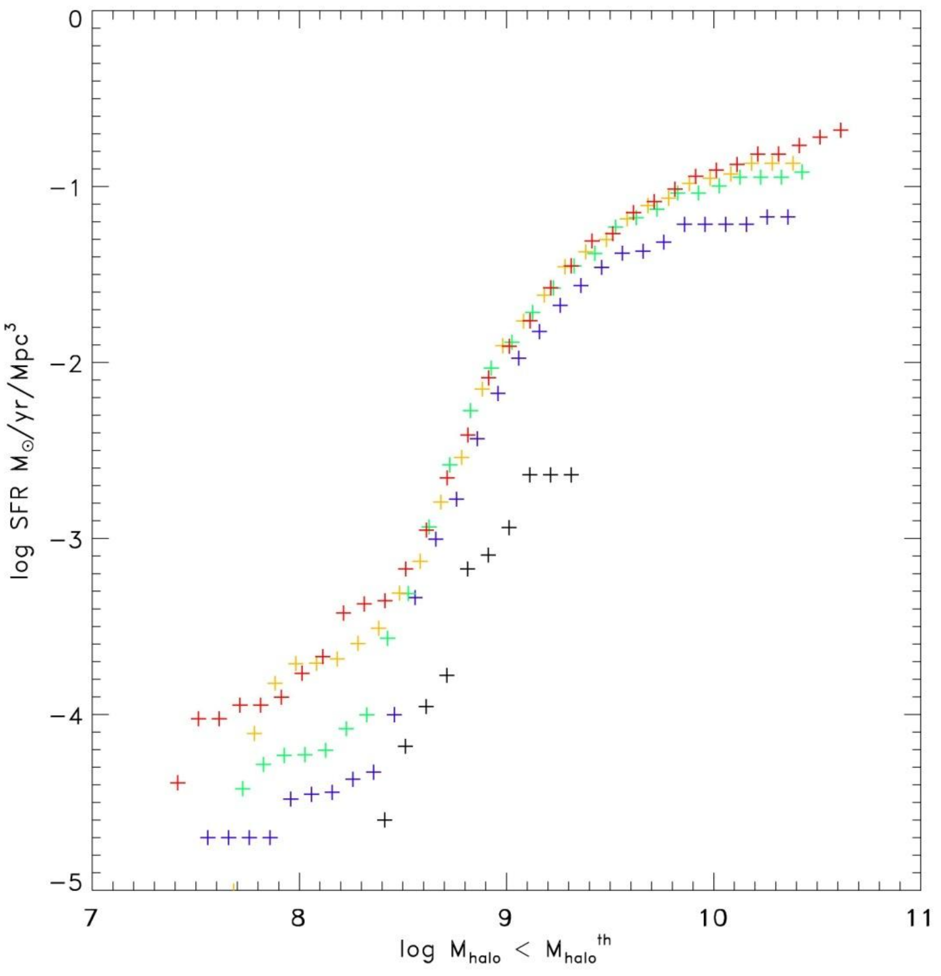




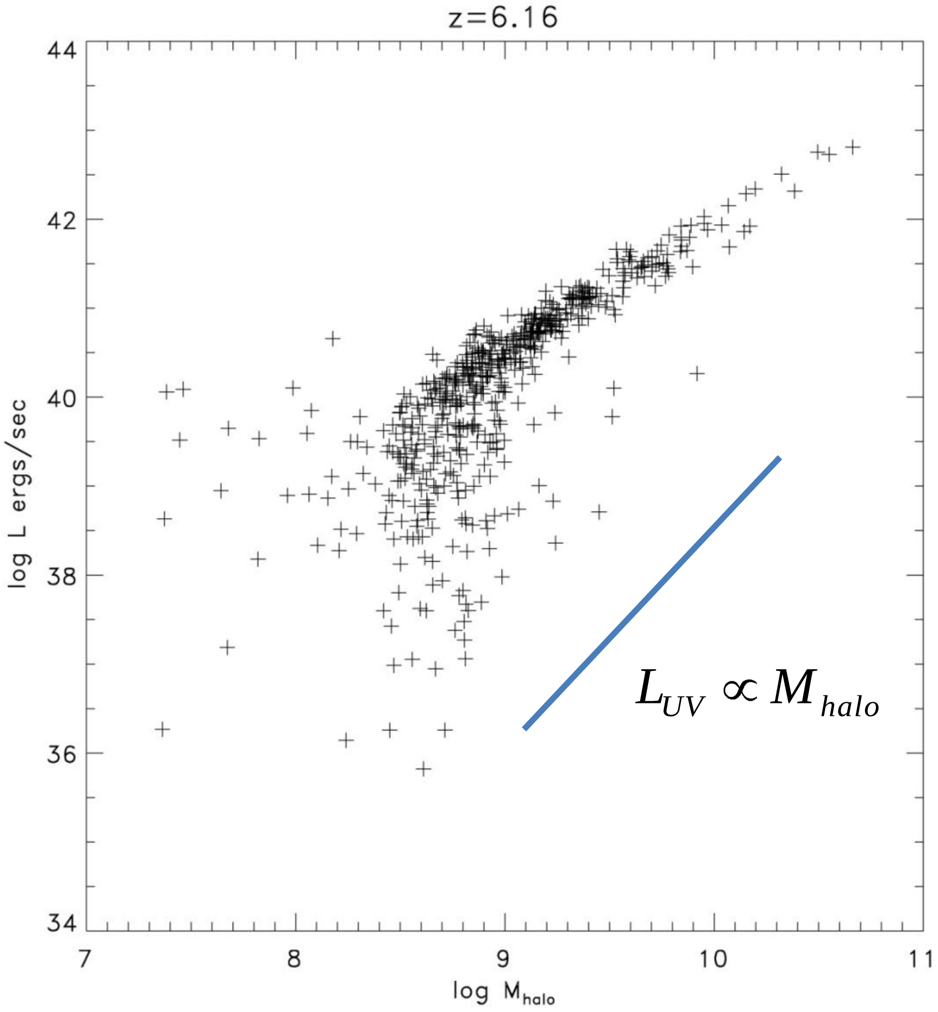
Strong Suppression of SF below $M_{halo} = 10^{8.5}$ M_s

Cumulative SFR below a given mass

Redshifts : black=12.86, blue = 8.74, green=7.45, orange=7, red = 6.16

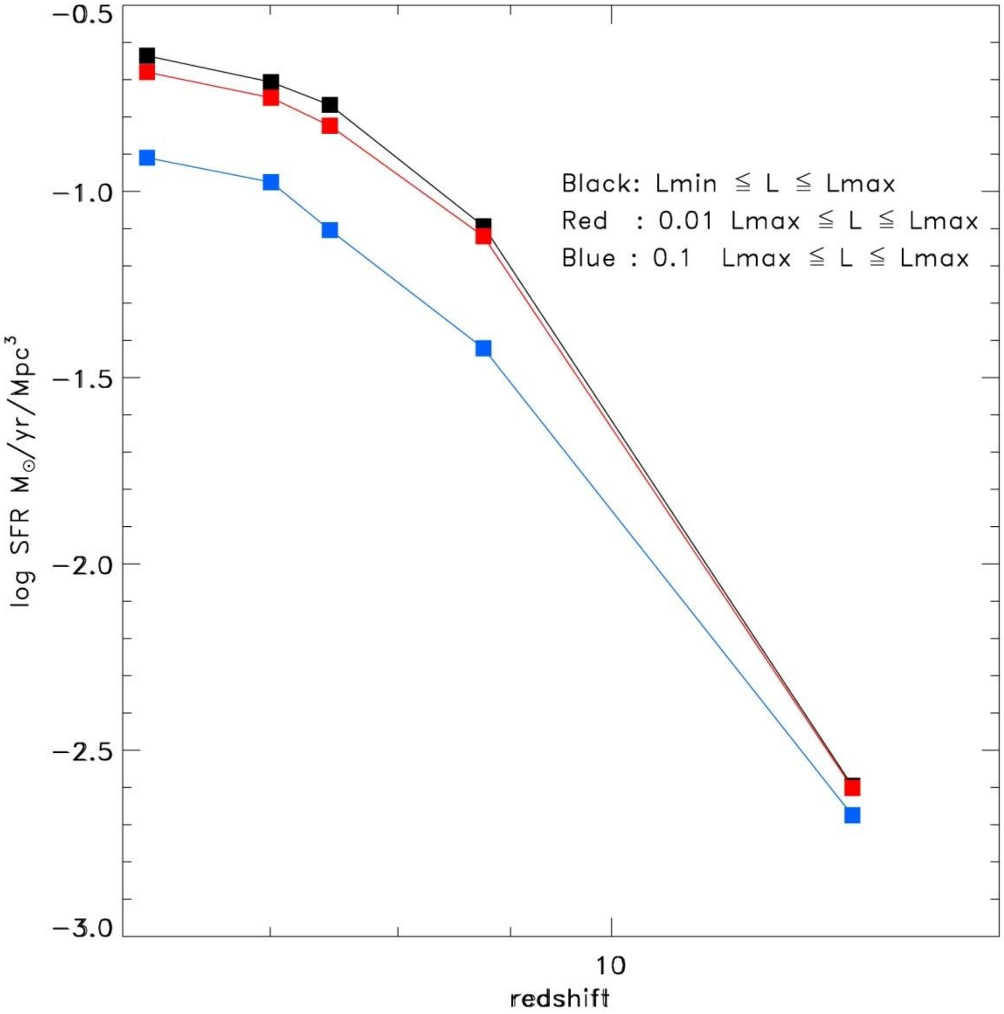


$$L_{uv}/10^{38}=A(\varepsilon_{uv}/10^{-5}) \text{ x } (SFR/0.1)$$



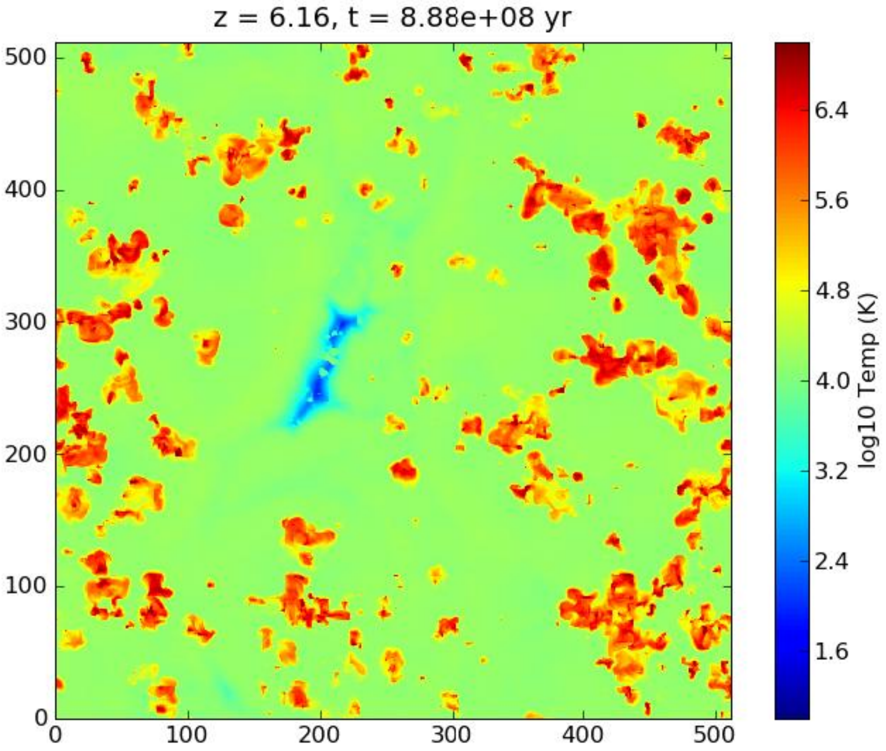
$L_{UV} \propto M_{halo}$

SF Density vs. Luminosity Threshold

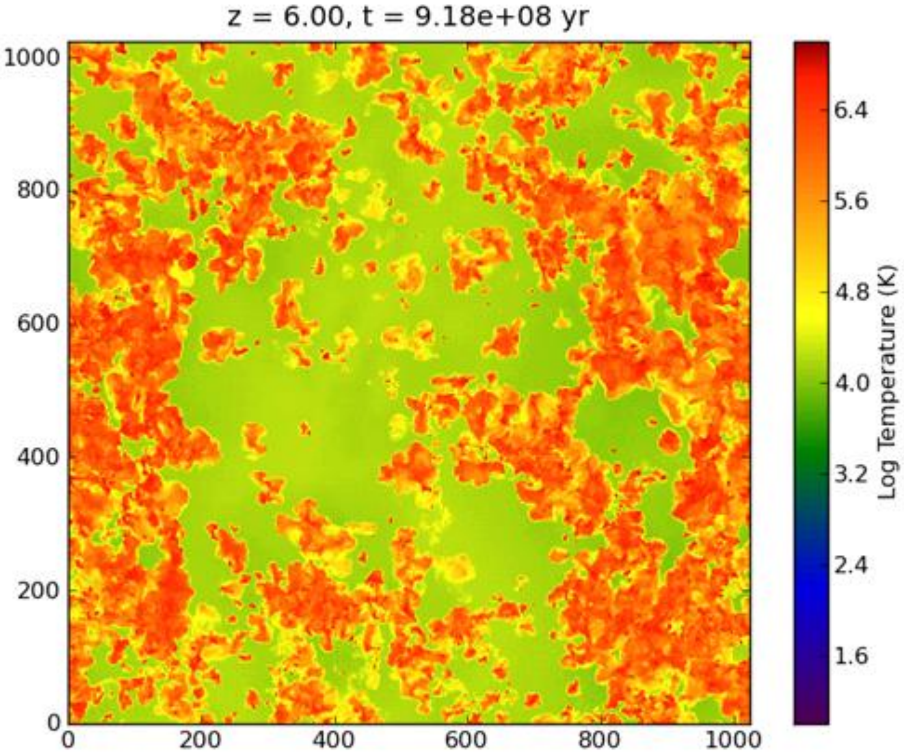


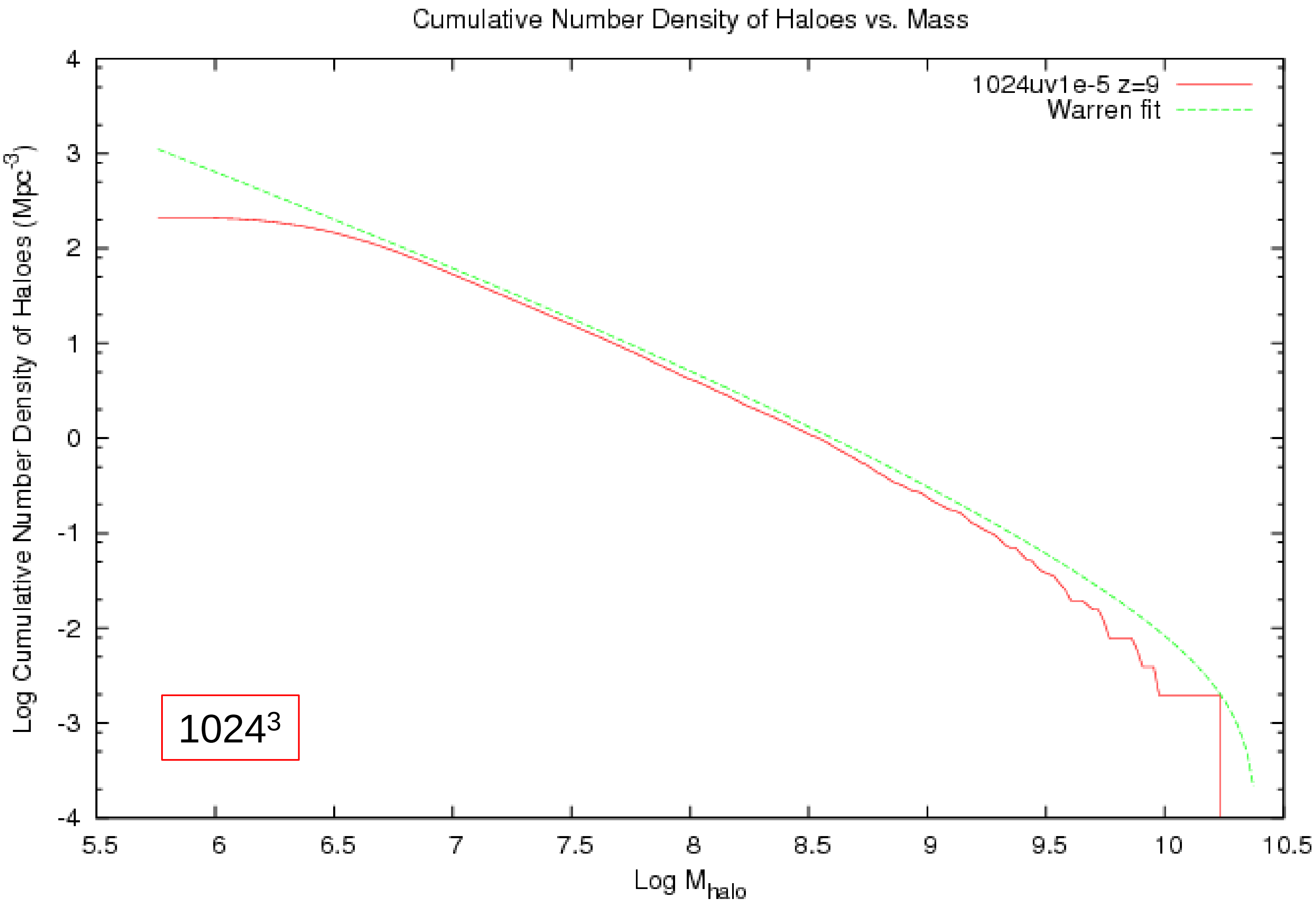
Effect of Resolution

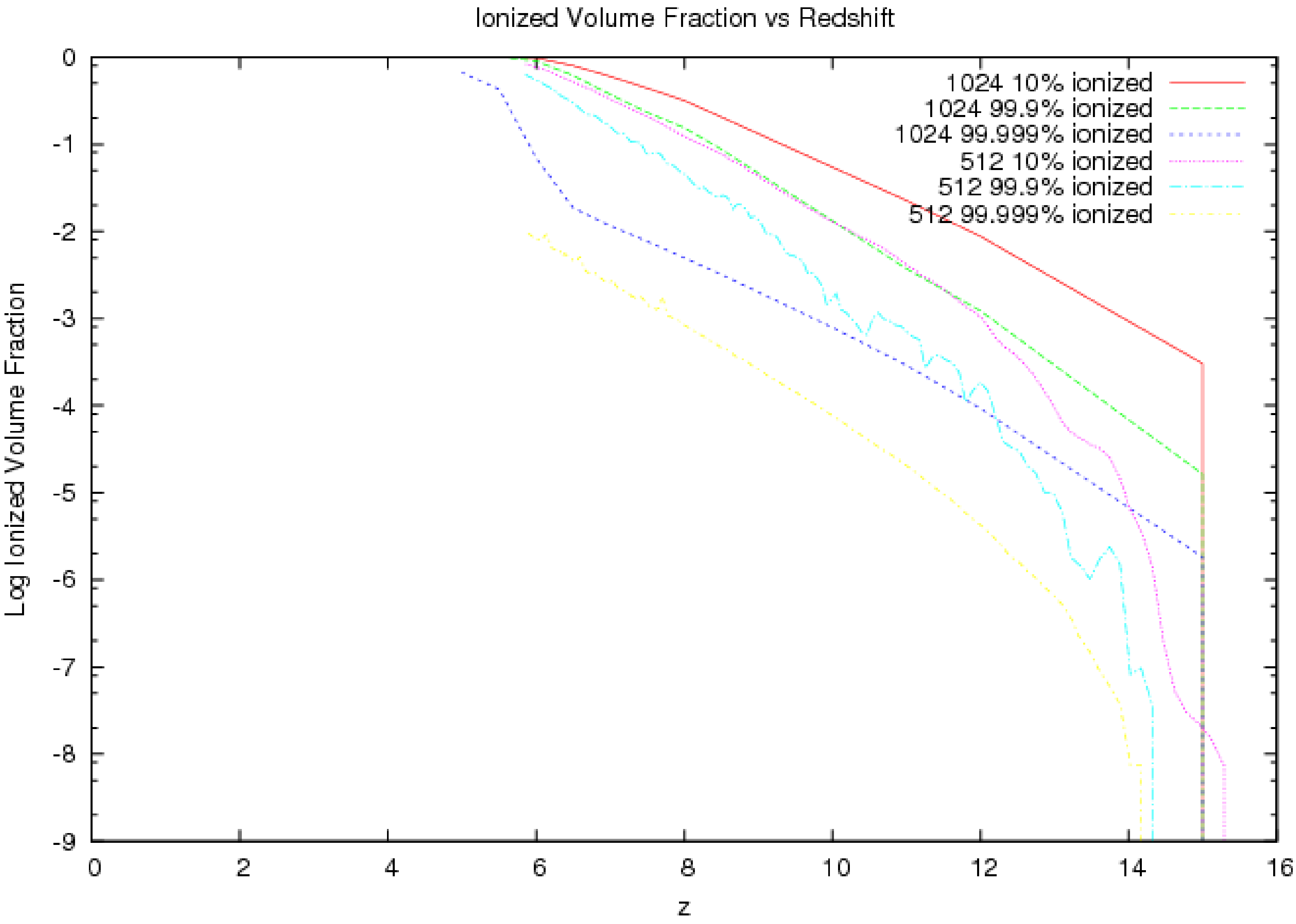
512^3

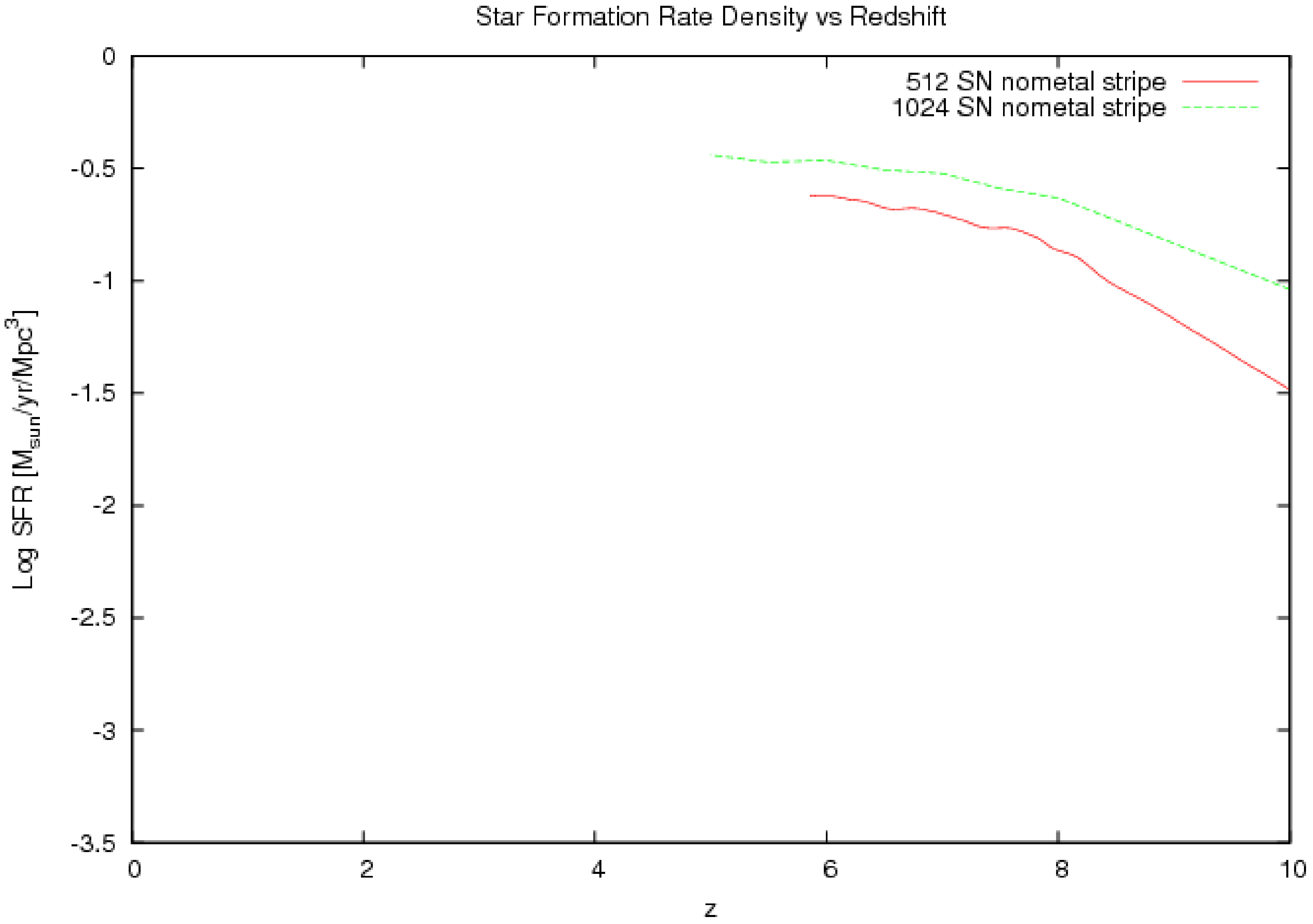


1024^3




Cumulative Number Density of Haloes vs. Mass
1024uv1e-5 z=9
Warren fit
Log Cumulative Number Density of Haloes (Mpc^{-3})
4
3
2
1
0
-1
-2
-3
-4
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
Log M$_{halo}$
1024^3


Ionized Volume Fraction vs Redshift
Log Ionized Volume Fraction
z
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
2
4
6
8
10
12
14
16
1024 10% ionized
1024 99.9% ionized
1024 99.999% ionized
512 10% ionized
512 99.9% ionized
512 99.999% ionized


Star Formation Rate Density vs Redshift
512 SN nometal stripe
1024 SN nometal stripe
Log SFR [M_{sun}/yr/Mpc^3]
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0
2
4
6
8
10
z

Where do we go from here?

- Uniform grid runs (reionization)
  - Larger boxes to sample high-mass galaxies, galaxy clustering, and global reionization process
  - Higher resolution to check for convergence
  - Effect of X-ray background generated by stellar sources (SNR, X-ray binaries) and AGN
- AMR runs (first galaxies)
  - Evolution of stellar populations, gas metallicity, and ionizing escape fraction in resolved halos
  - Effect of environment (e.g., clustering in rare peaks) on radiative feedback and SFR

Where do we go from here [2]?

- “self-consistent” global reionization simulations
  - AMR sims used to calibrate SF/FB model for a global reionization simulation
  - Targeted for Blue Waters sustained petascale supercomputer at NCSA in 2011

IBM 5 GHz Power7
>200,000 cores
800 TB RAM
6 PF peak
>1 PF sustained on real applications

A Blue Waters compute drawer on display in the IBM booth at SC09.