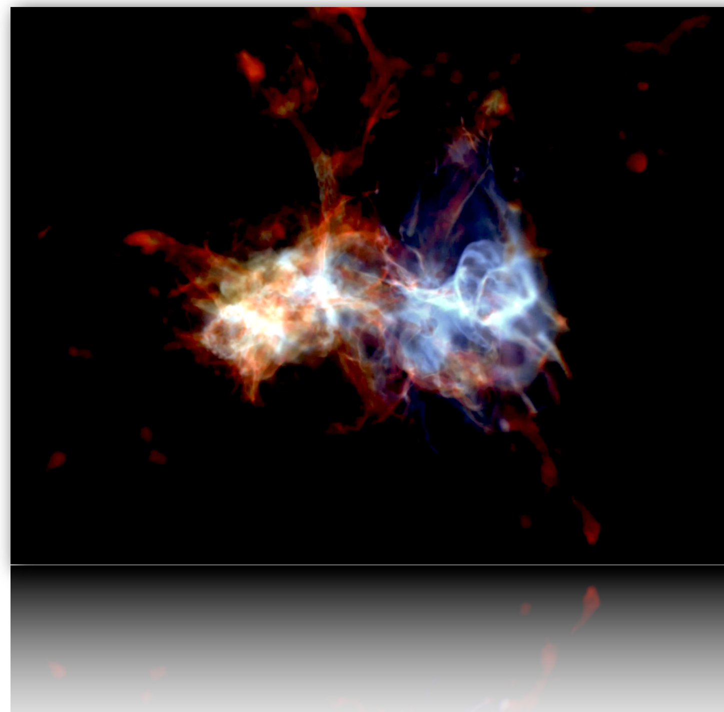
Studying Star Formation from First Principles?

Tom Abel
KIPAC/Stanford

mostly work with
Marcelo Alvarez, Matt Turk, Ji-hoon Kim,
Peng Wang, John Wise, Fen Zhao KIPAC

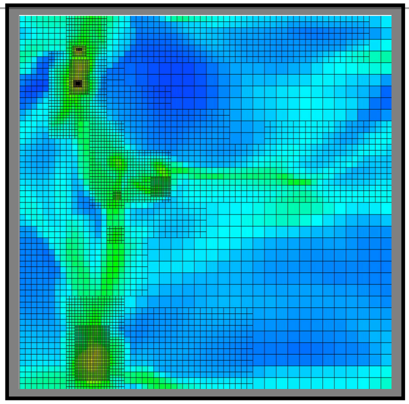
Greg Bryan, Mike Norman,
Brian O'Shea, Naoki Yoshida

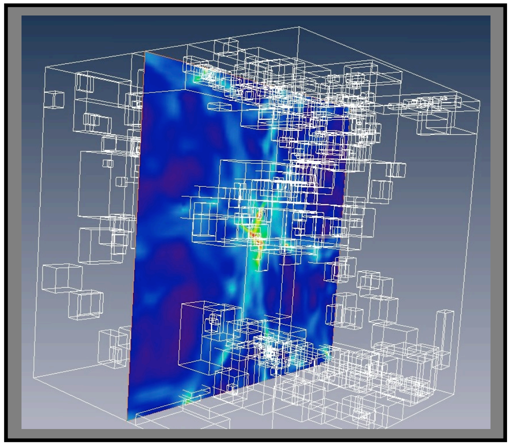
Ralf Kähler (Scientific Visualization)



Talk Outline

- First Objects are very massive isolated stars
- First stars: HII regions, Supernovae, BH accretion
- Properties of First Galaxies
- ISM and molecular cloud formation
- Making Galaxies one star at a time
    - Star formation in general
    - Physics Challenges
    - Computational Challenges
- public version of enzo at: http://lca.ucsd.edu/portal/software/enzo





Recap

First Stars are isolated and very massive

- Theoretical uncertainty: 30 - 300 solar mass

  Many simulations with **four very different numerical techniques** and a large range of numerical resolutions have **converged** to this result. Some of these calculations capture over 20 orders of magnitude in density!

  Non-equilibrium chemistry & cooling, three body H2 formation, chemical heating, H2 line transfer, collision induced emission and its transport, and sufficient resolution to capture chemo-thermal and gravitational instabilities.
  Stable results against variations on all so far test dark matter variations, as well as strong soft UV backgrounds.

- Perfectly consistent with observations!
  Could have been a real problem!

cosmological: Abel 1995; Abel et al 1998; Abel, Bryan & Norman 2000, 2002; O'Shea et al 2006; Yoshida et al 2006; Gao et al 2006,
idealized spheres: Bodenheimer 1986; Haiman et al 1997; Omukai & Nishi 1998; Bromm et al 1999,2000,2002; Ripamonti & Abel 2004
other talks at this conference: Volker Bromm, Brian O'Shea, Naoki Yoshida

Tumultuous Life

- Entire mass range are strong UV emitters
- Live fast, die young. (2.7 Myr)
- Fragile Environment
    - Globular Cluster mass halo but ~100 times as large -> small v_{esc} ~ 2 km/s
    - Birth clouds are evaporated

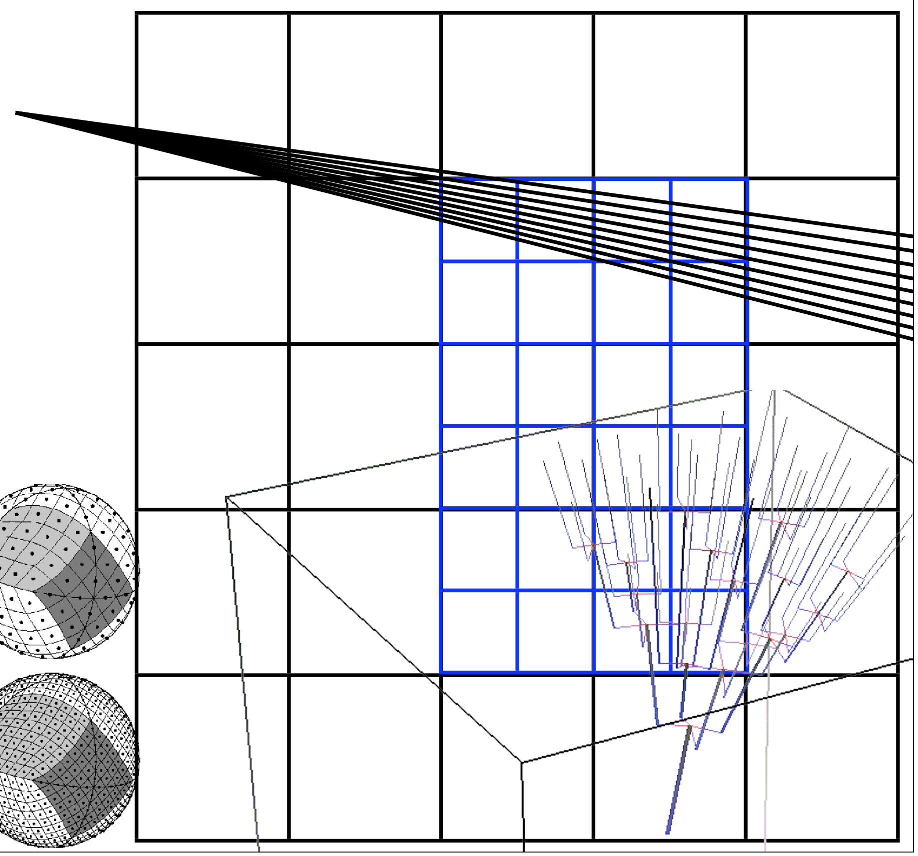

CALIFORNIA NEBULA, NGC1499
500 pc = 1,500 light years away
30 pc long
Xi Persei, منكب mankib, Shoulder of Pleiades:
O7.5III
330,000 solar luminosities
~40 solar masses, Teff=3.7e4K

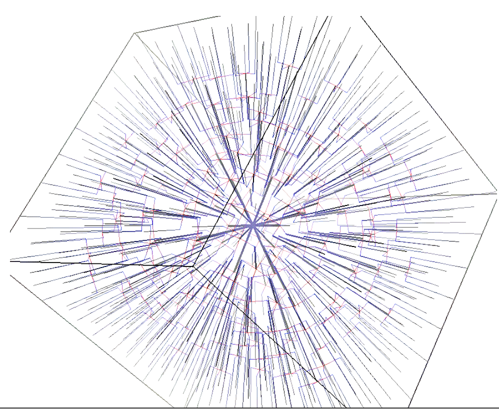
3D Cosmological Radiation Hydrodynamics

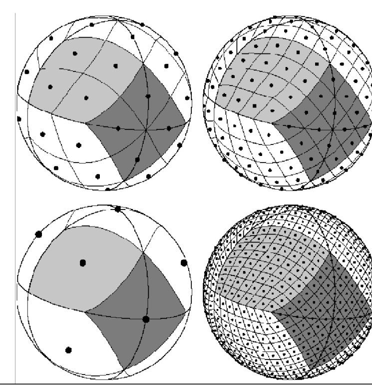
- Focus on point sources
- Early methods: Abel, Norman & Madau 1999 ApJ; Abel & Wandelt 2002, MNRAS; Variable Eddington tensors: Gnedin & Abel 2001, NewA
- Latest: Abel, Wise & Bryan 06 ApJL
  Keeps time dependence of transfer equation
- Adaptive ray-tracing of PhotonPackages using HEALPIX pixelization of the sphere. Photon conserving at any resolution.
- Parallel using MPI and dynamic load balancing.

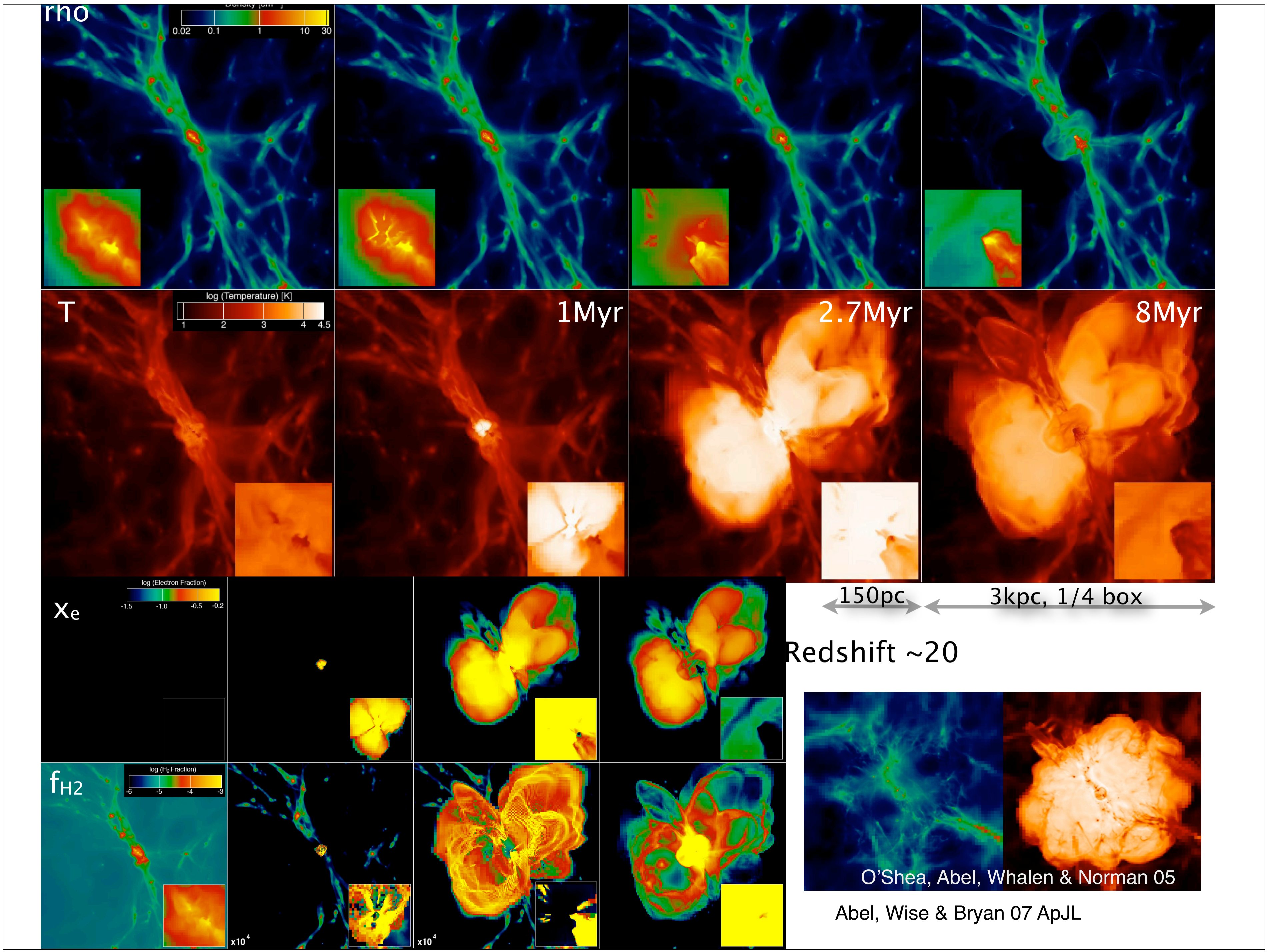
$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\partial I_\nu}{\partial r} = -\kappa I_\nu$$

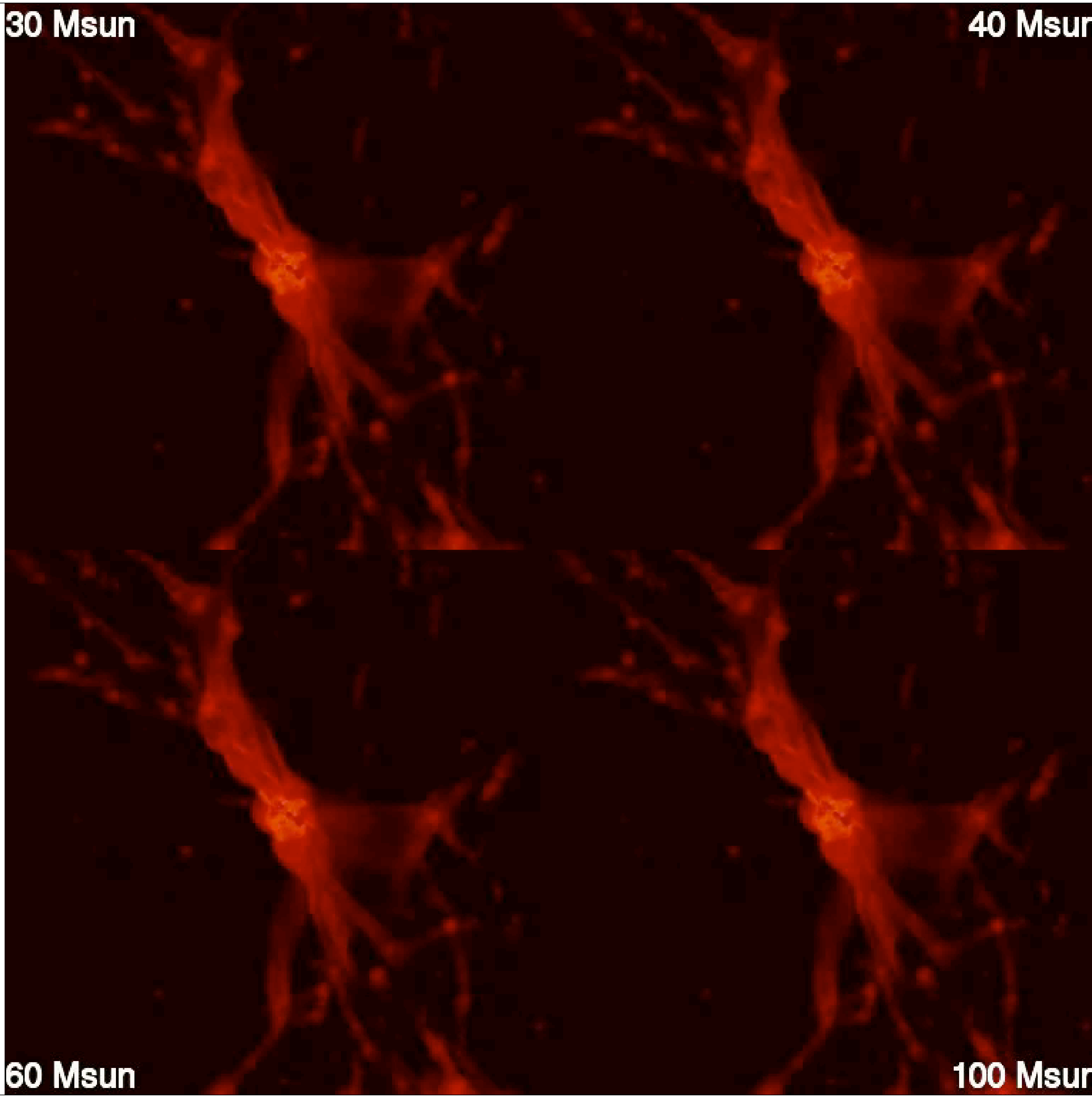
Transfer done along adaptive rays
Case B recombination





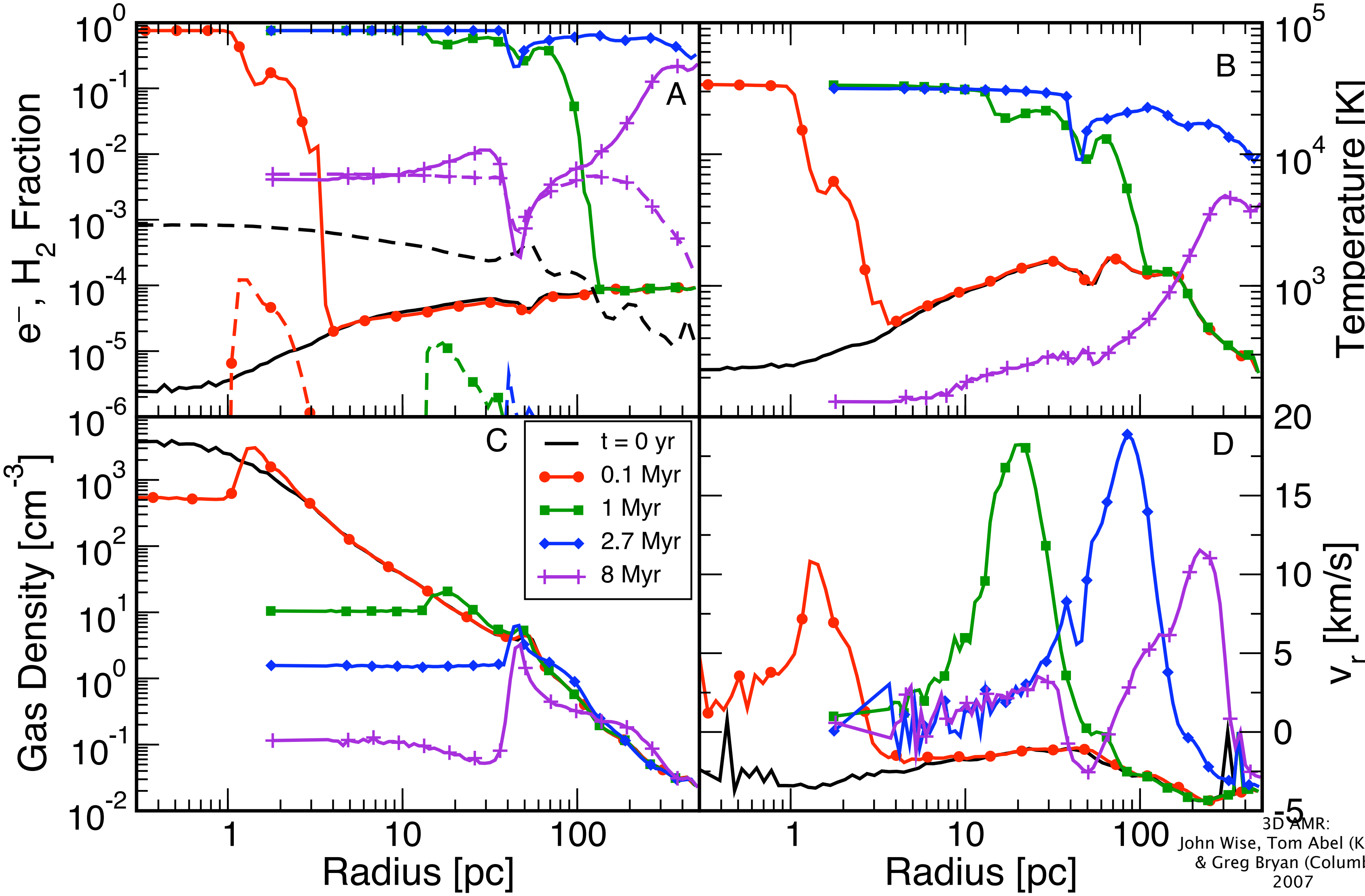



rho
0.02 0.1 1 10 30
T
log (Temperature) [K]
1 2 3 4 4.5
1Myr
2.7Myr
8Myr
x_e
log (Electron Fraction)
-1.5 -1.0 -0.5 -0.2
f_H2
log (H2 Fraction)
-6 -5 -4 -3
x10^4
x10^4
150pc
3kpc, 1/4 box
Redshift ~20
O'Shea, Abel, Whalen & Norman 05
Abel, Wise & Bryan 07 ApJL


30 Msun
40 Msun
60 Msun
100 Msun

The First HII Regions

1D spherical:
Whalen, Abel & Norman 05;
Kiteyama &Yoshida 05

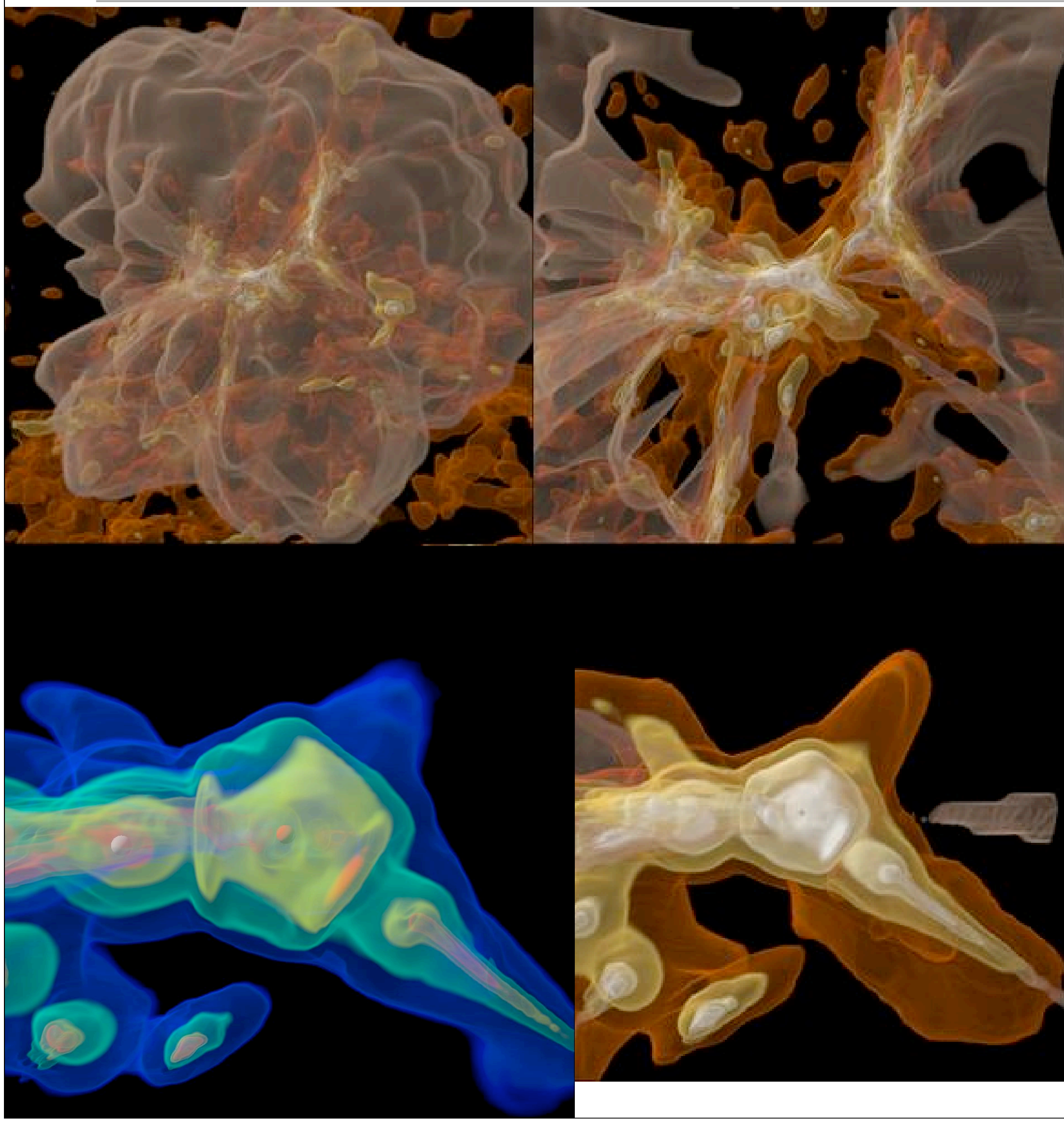


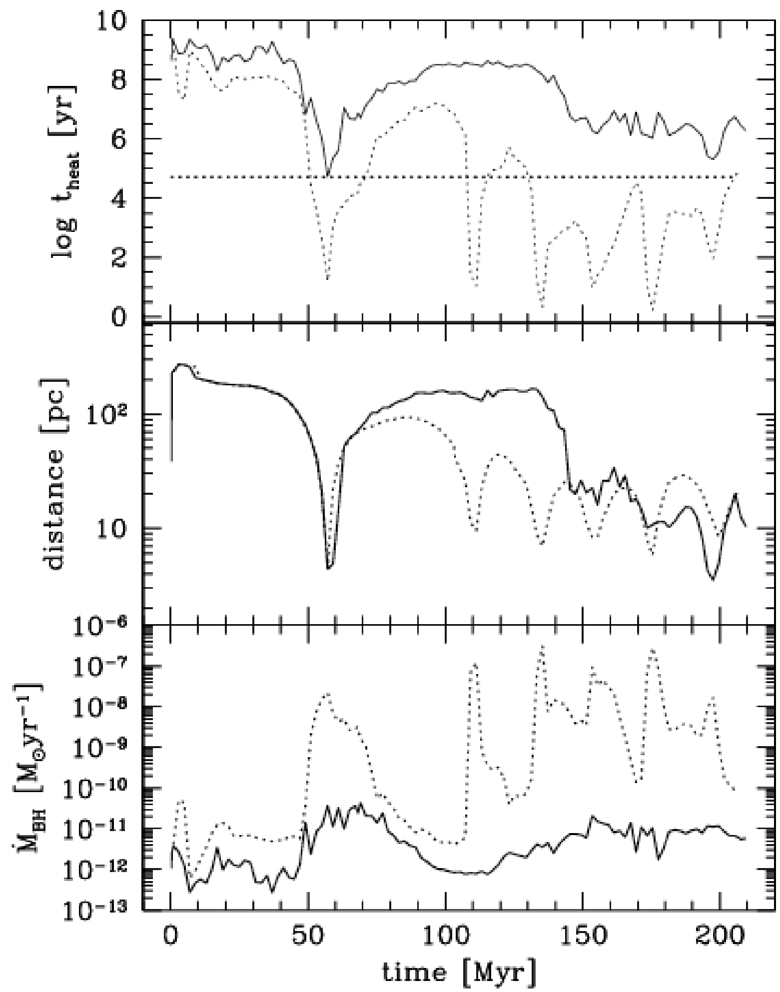
3D AMR:
John Wise, Tom Abel (KIPAC)
& Greg Bryan (Columbia)
2007

Surprising Life - Many uncertainties from inaccurate stellar evolution predictions!

- No three dimensional stellar evolution calculations feasible. No ab initio predictions possible at present.
  - Angular momentum transport
  - Mixing from core, mixing into the atmosphere?
  - Stellar winds, as well as episodic mass loss?
  - Magnetic dynamo? At proto-stellar densities: guaranteed seed field of ~ 4 $\times 10^{-10}$ Gauss from recombination. Larger contribution from Biermann battery plausible
- Can do:
  - Proto-stars (1st & 2nd generation)
  - HII regions (HeII & HeIII regions)
  - Metal enrichment & potential GRB remnants
  - Beginning of Cosmic Reionization
- Relevant mass range : PopIII-1: 30 - 300 solar mass and PopIII-2: 10 - 100

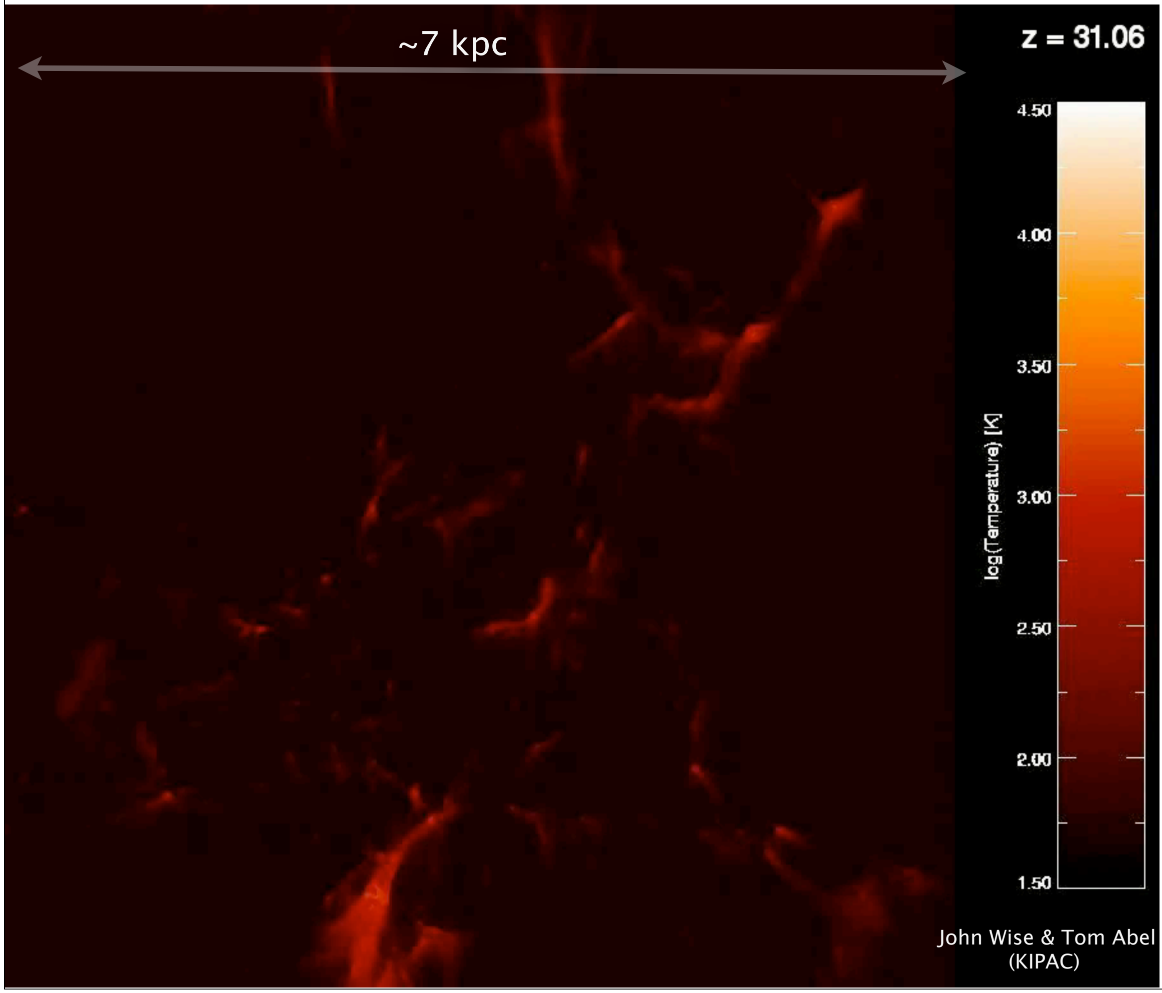
Insignificant BH accretion – no mini quasars through this process.

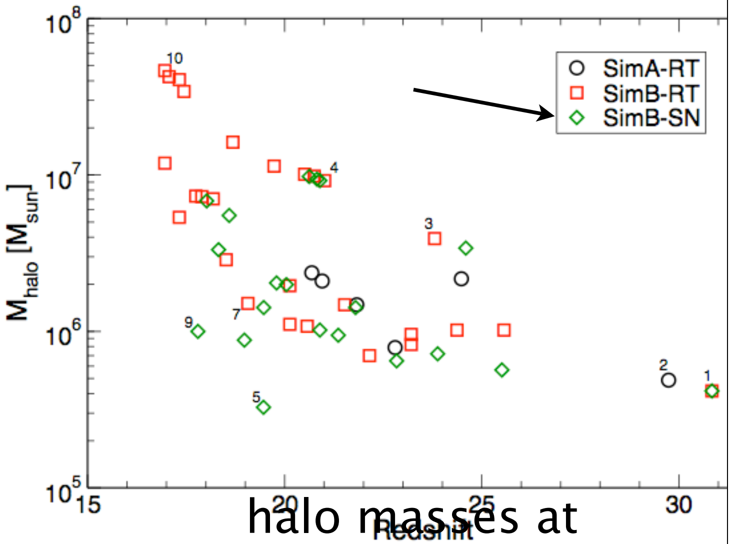




Alvarez, Wise & Abel in prep.

First few hundred million years: Cosmic

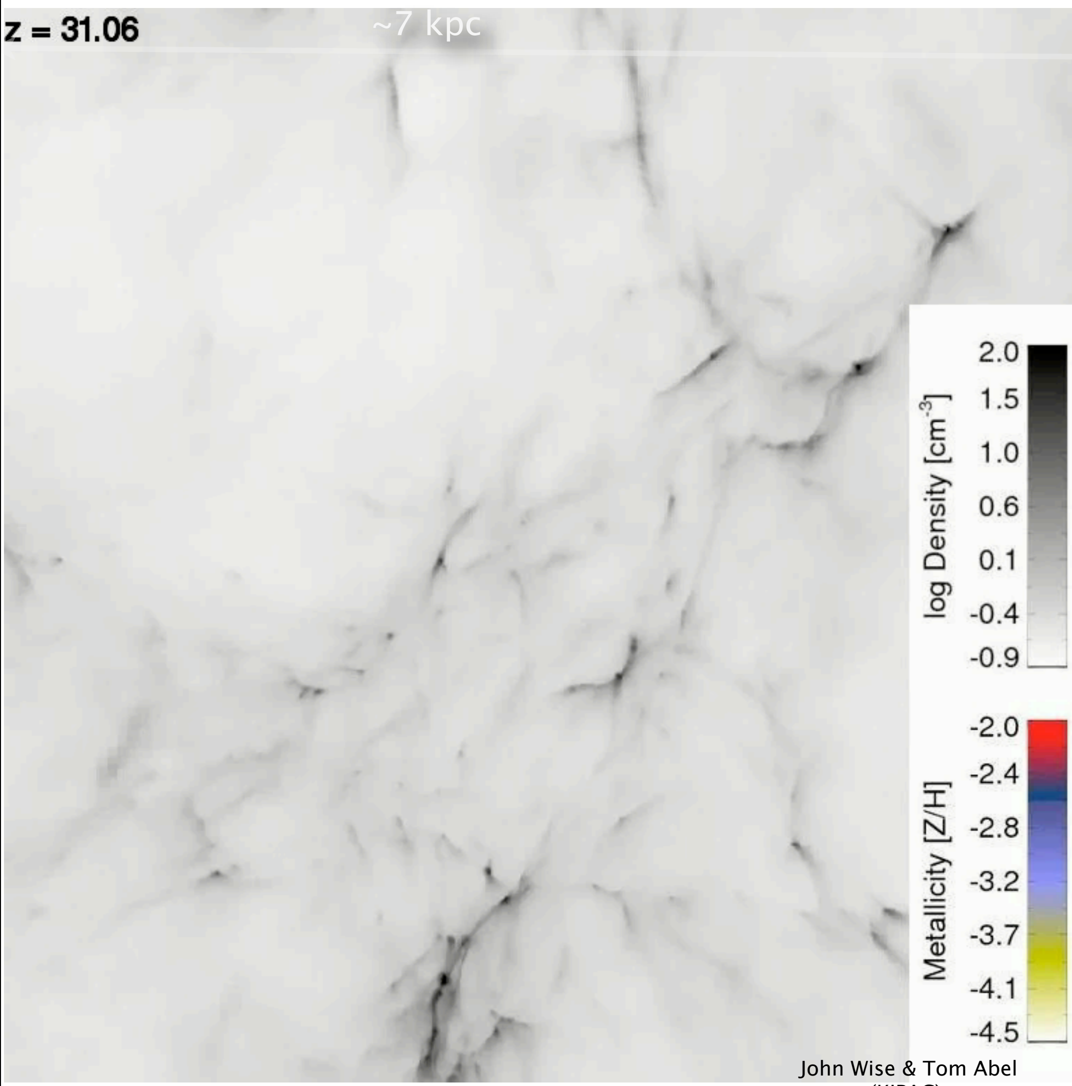




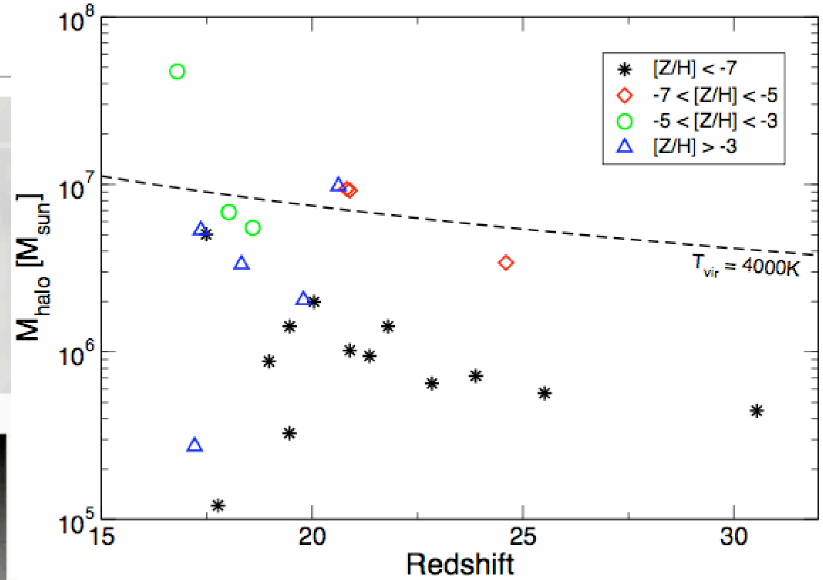
halo masses at redshift stars form within them

10,000 such patches make
Milky Way
~ 1e5 popIII remnants
early metal enrichment

First few hundred million years: Cosmic

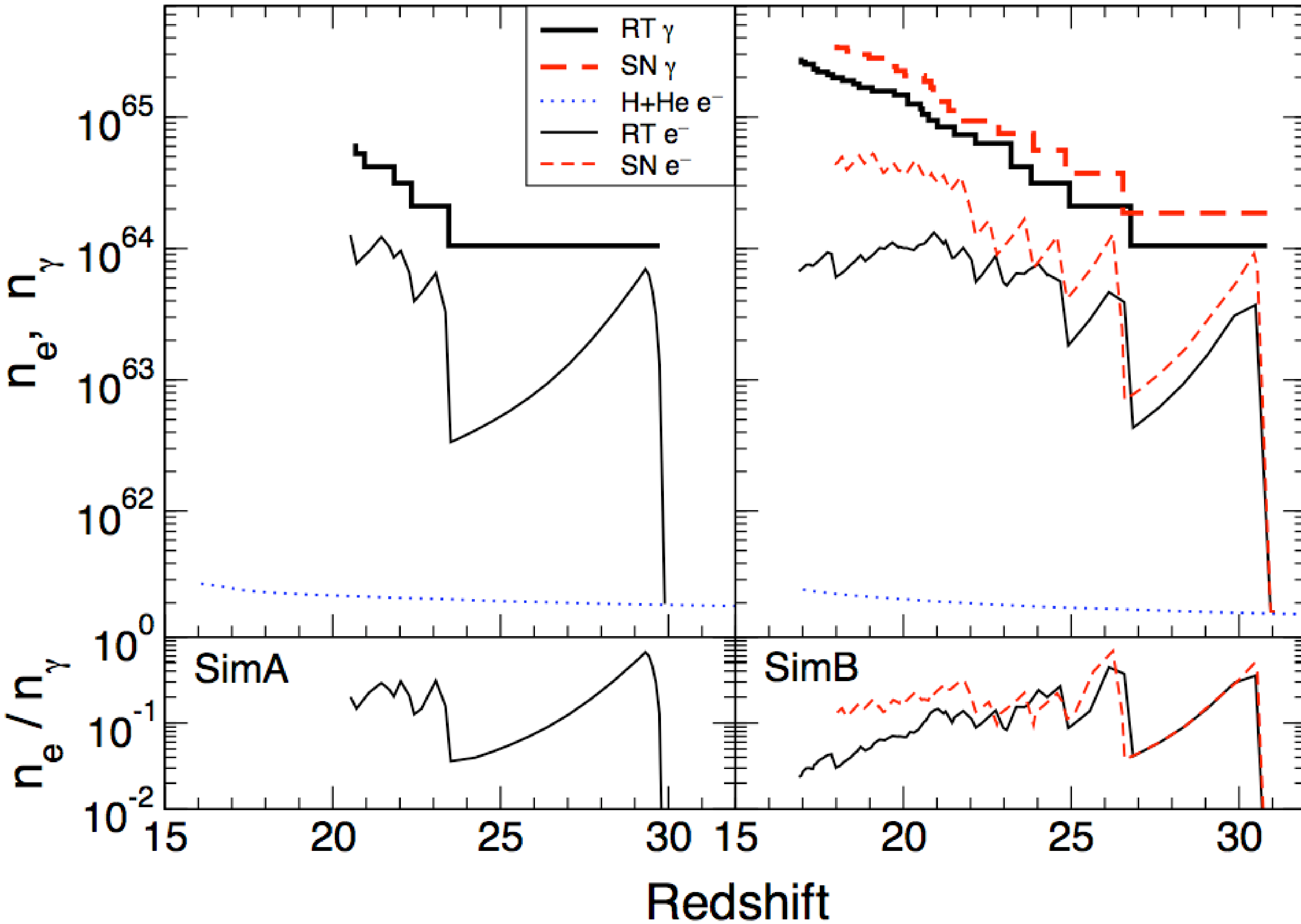


John Wise & Tom Abel
(KIPAC)

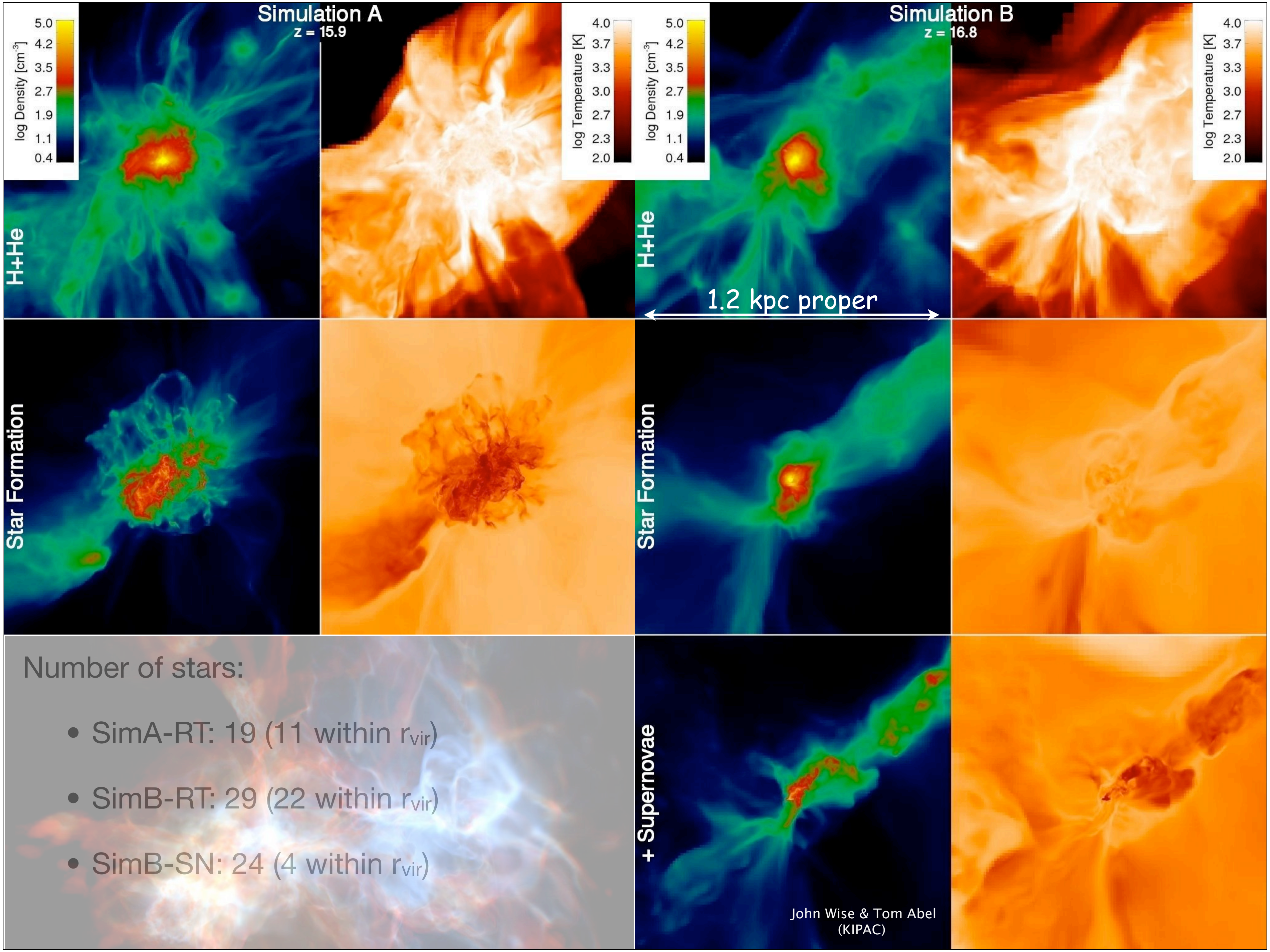


10,000 such patches make
Milky Way
~ 1e5 popIII remnants
early metal enrichment

Beginning of cosmic reionization



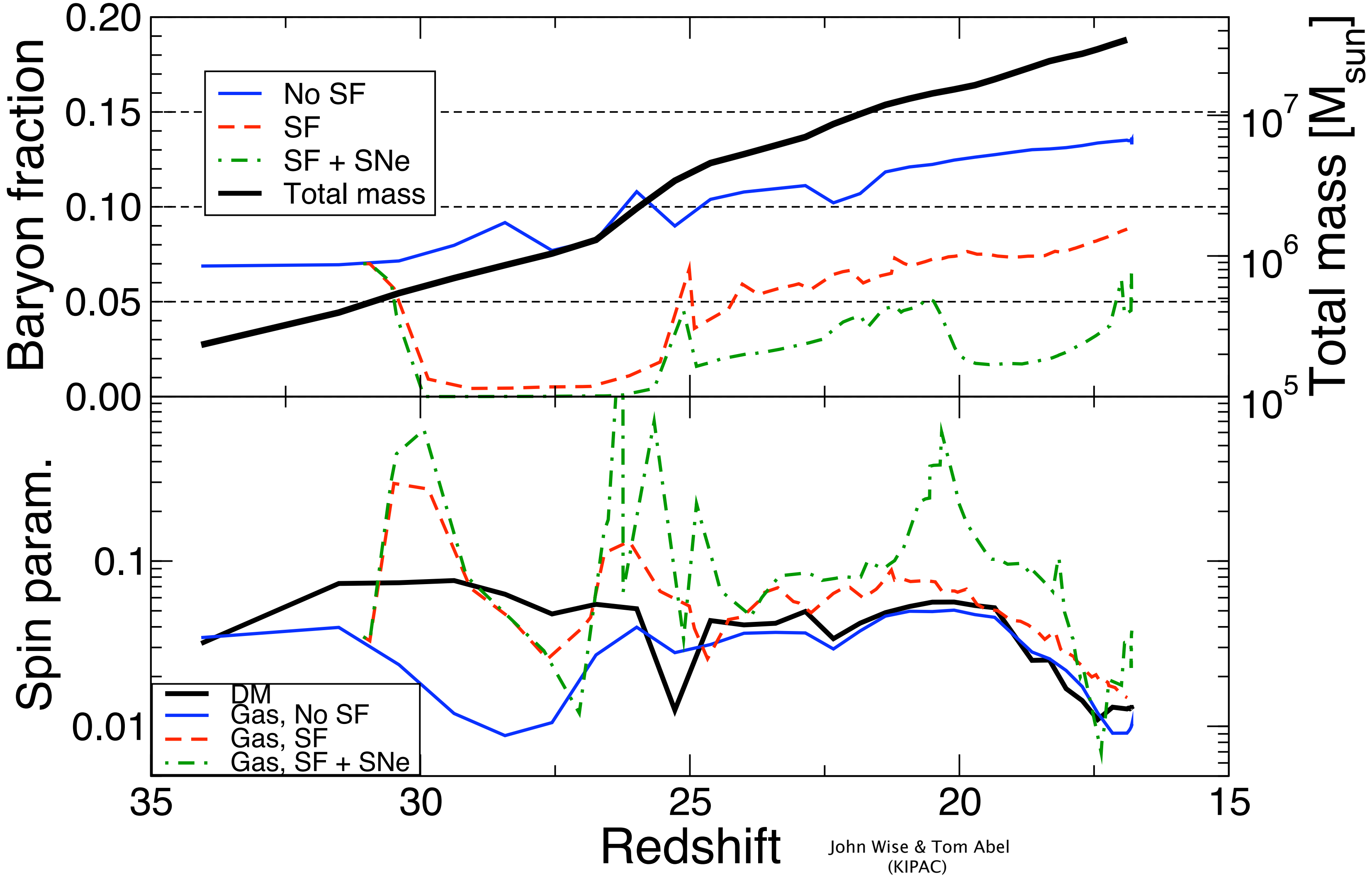
electrons/
UV
photon



Number of stars:

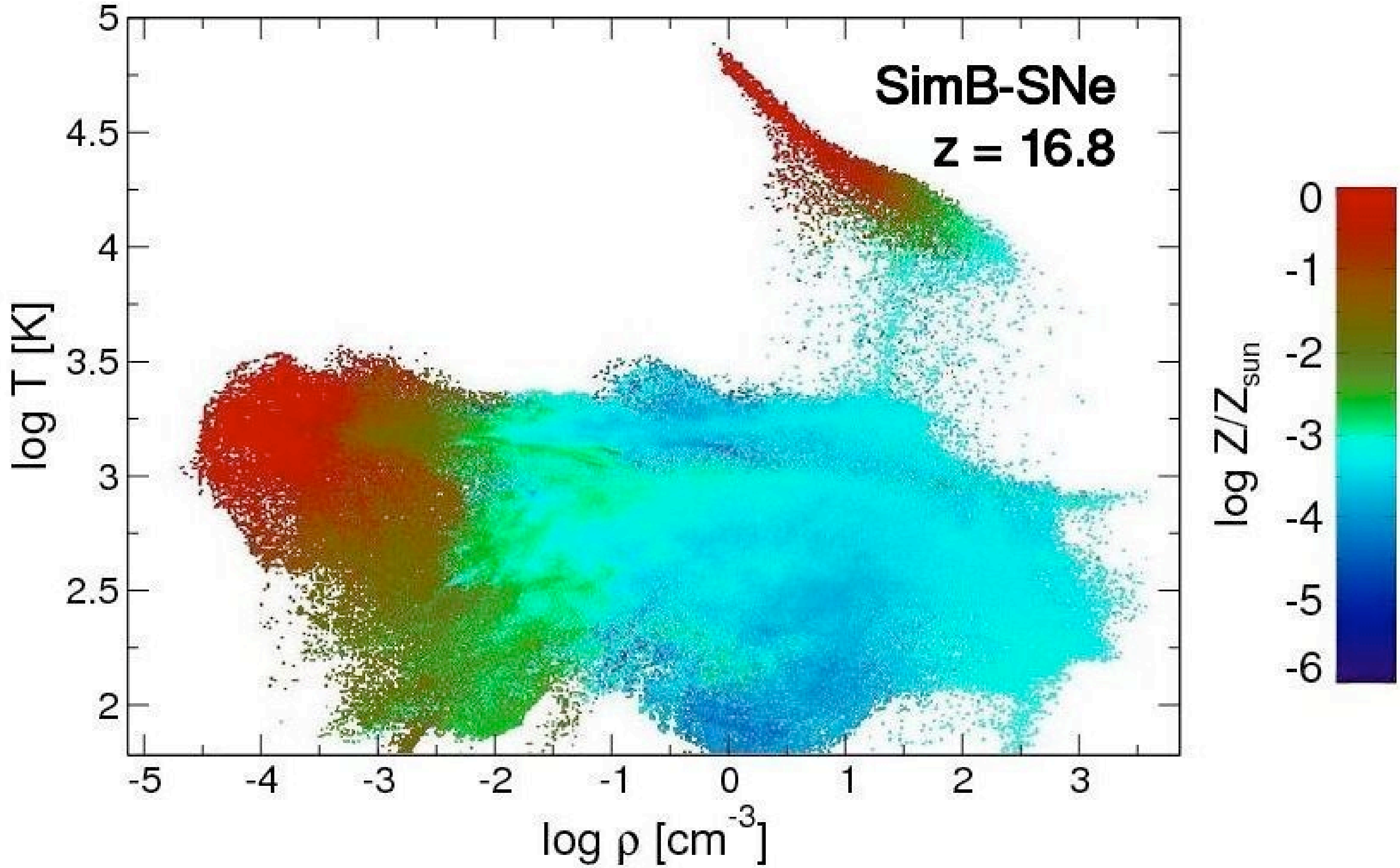
- SimA-RT: 19 (11 within r_{vir})
- SimB-RT: 29 (22 within r_{vir})
- SimB-SN: 24 (4 within r_{vir})

Baryon Fraction & Angular Momentum



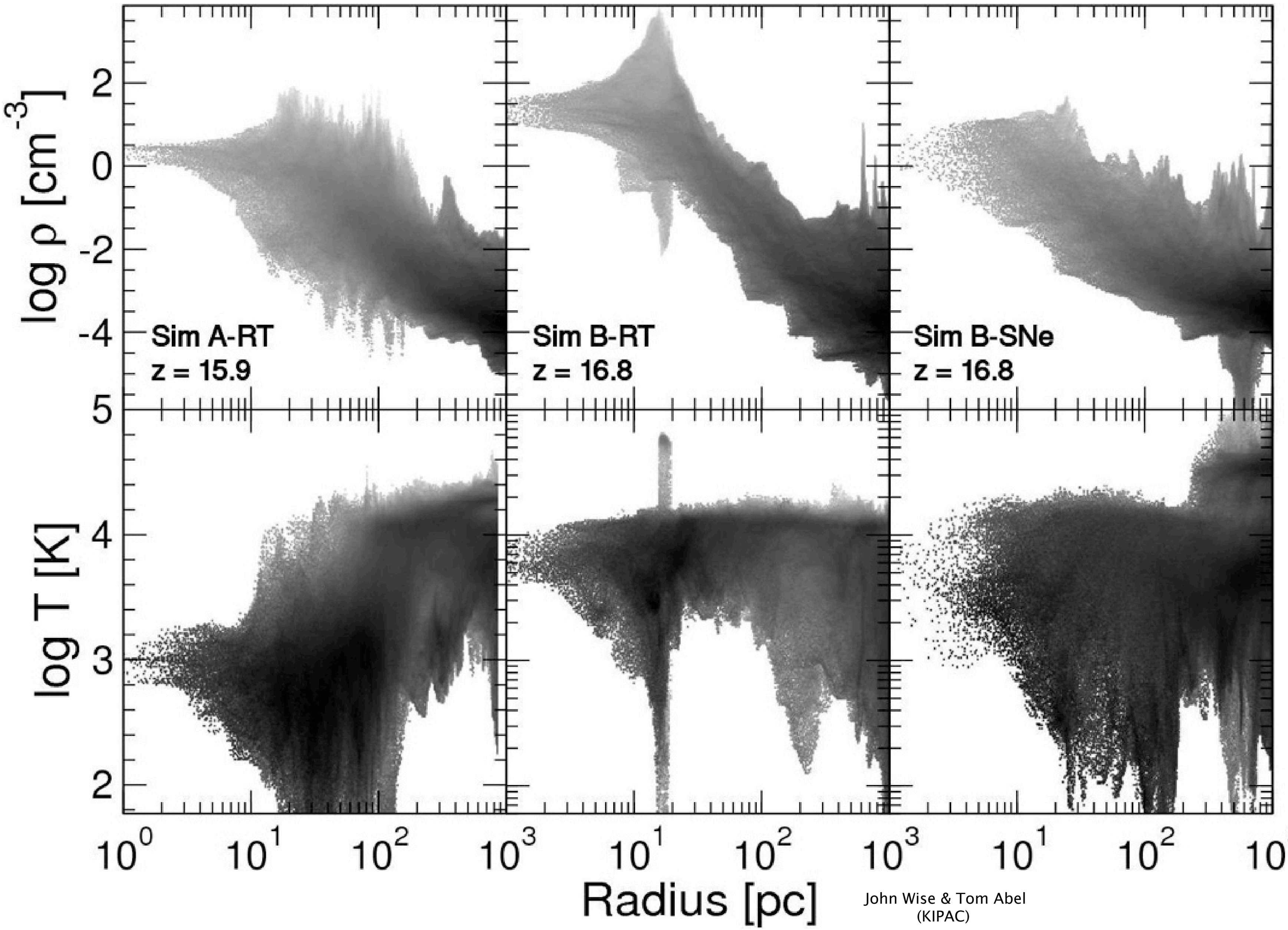
John Wise & Tom Abel
(KIPAC)

Developing an ISM



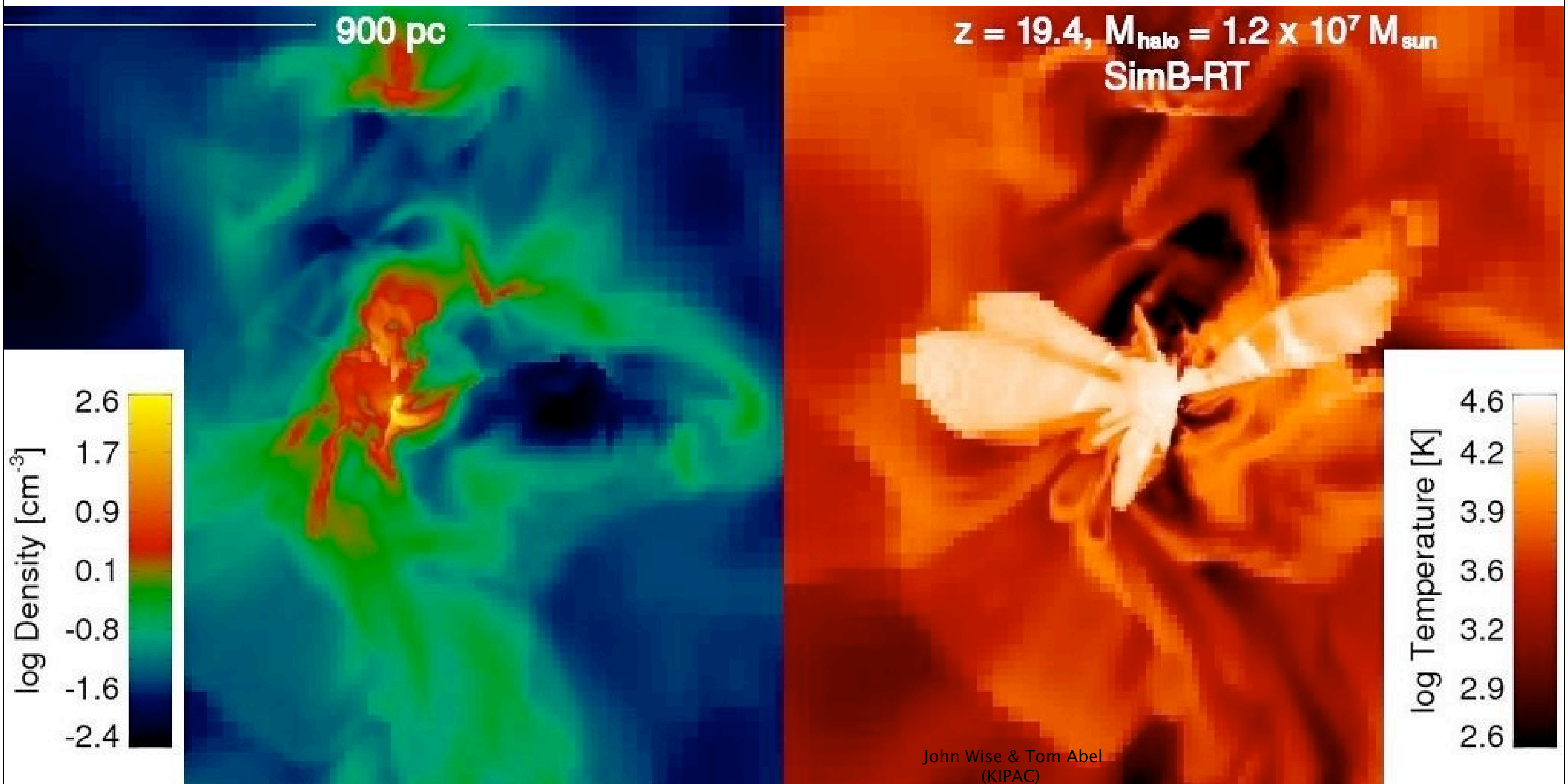
John Wise & Tom Abel
2007 (KIPAC)

Radial Profiles – Multi-phase ISM



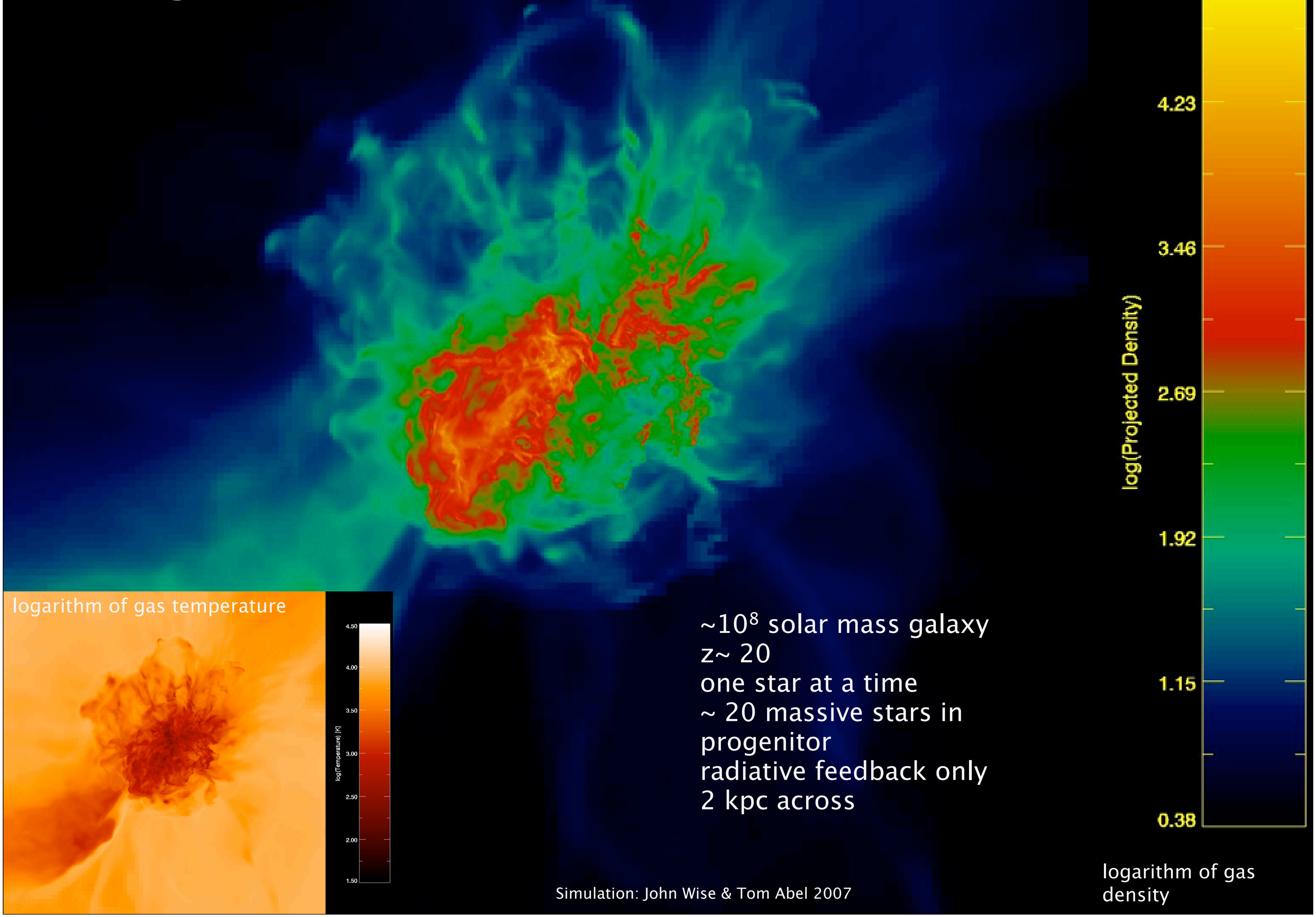
John Wise & Tom Abel
(KIPAC)

HII regions starting to be confined inside galaxies



John Wise & Tom Abel
(KIPAC)

Making Galaxies one Star at a Time



~10^8 solar mass galaxy
z~ 20
one star at a time
~ 20 massive stars in progenitor
radiative feedback only
2 kpc across

Simulation: John Wise & Tom Abel 2007

Application to present day star formation:

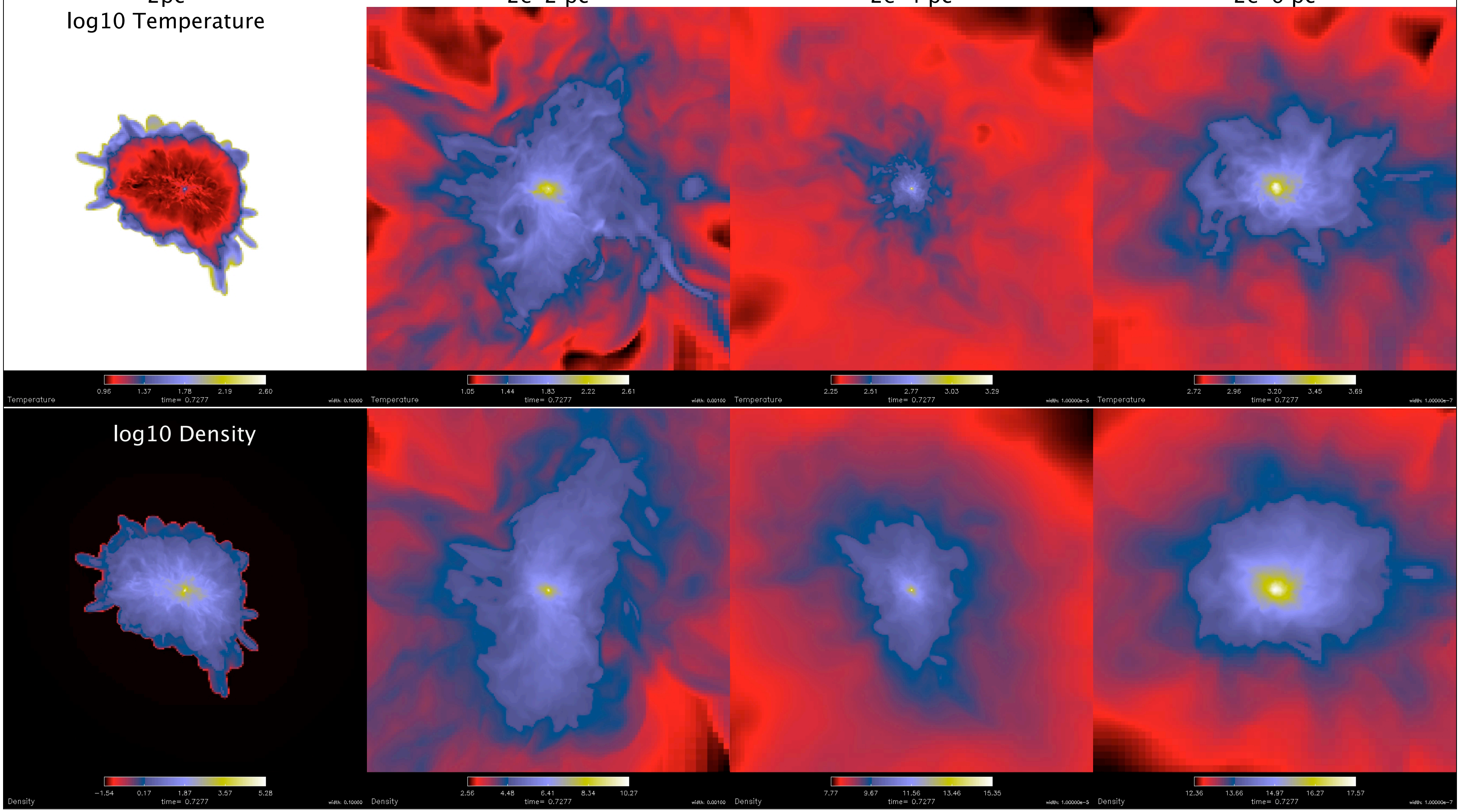
30 solar mass cloud
jeans number ~ 1
Mach 2 decaying turbulence
thermal + turbulent pressure equilibrium with ambient medium
31 levels of refinement: 11 orders of magnitude in length dynamic range: dx ~ 5e8 cm
64 cells per jeans length corresponds to 1e6 SPH particles per jeans mass or ~ 1e13 SPH particles for traditional (non-splitting) scheme
This run takes a few days on 16 (old) processors

Mass = 30 Msun
Density = 5.65e-22 g/cm^3
Radius = 2.932e18 cm = 0.95 pc
Temperature = 10 K, Mu = 2, Gamma = 1.4
Initial isothermal sound speed=0.203192 km/s
Surface density = 2.21e-3 g/cm^2
Medium Density = 5.65e-23 g/cm^3
The time unit is such that t=1 is exactly one initial free fall time

New version of enzo:
Hydro: RK2, HLL+PLM
MHD with Dedner formalism
Neufeld et al. cooling, EOSs
Multi-species chemistry
Radiation transport

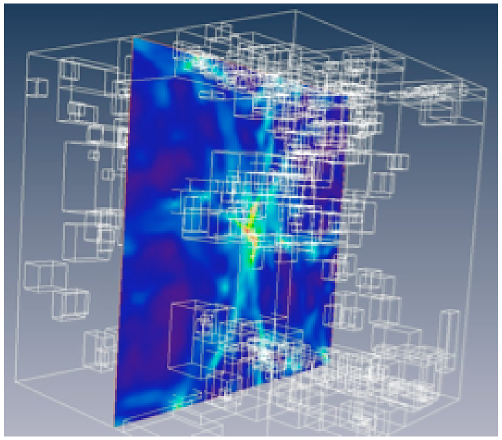
Wang & Abel 2007

2pc | 2e-2 pc | 2e-4 pc | 2e-6 pc



Physics and algorithmic challenges

- MHD
- Microphysics: first and foremost: Dust physics, molecules and ions affecting the thermal state of the gas
- Radiation transport of cooling radiation
- Cosmic ray acceleration, transport and pressure
- Subgrid models of B-field dynamos and stellar evolution



Computational Challenges

- With 1000 resolution elements per jeans mass we currently can follow galaxies that contain 10^5 local jeans masses. Current maximum galaxy that can be hoped to be simulated today ~ 1e10 solar masses.

$$\int_{MW} l_J^{-3} dV = ?$$

- HII region dynamics requires resolution ~ 0.01 - 0.1 pc around massive star forming regions

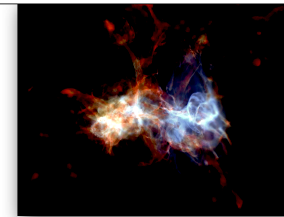
- Effective load balancing for tens of thousands of processors

- Effective data mining and analysis framework

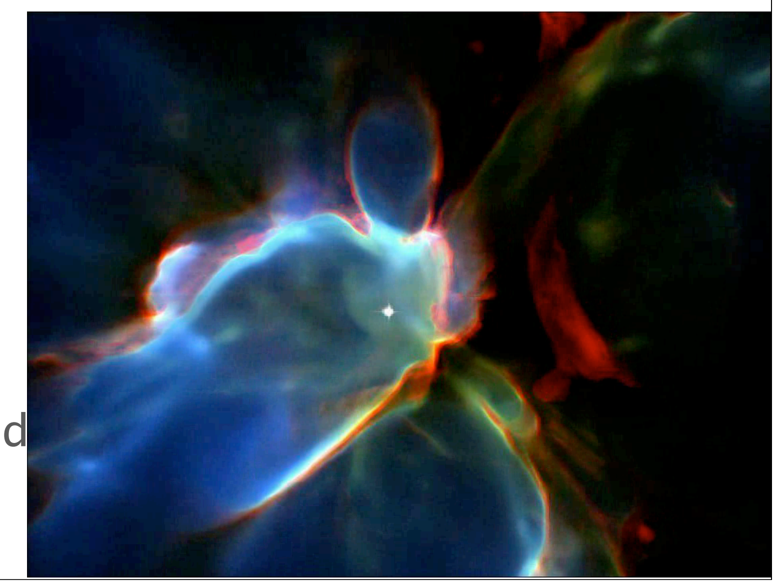
Building galaxies one star at a time. Why now?

- JWST, ALMA, LOFAR, MWA, etc. will not be able to observe individual stars but the smallest high redshifts galaxies as yet.
- Target dates: 2013
- We can and should predict the properties of these first galaxies to unprecedented detail:
  – metals, stellar content, Lyman alpha strengths, nebular emission lines, etc.
  before they are seen.
- Compare with nearby fossil record in

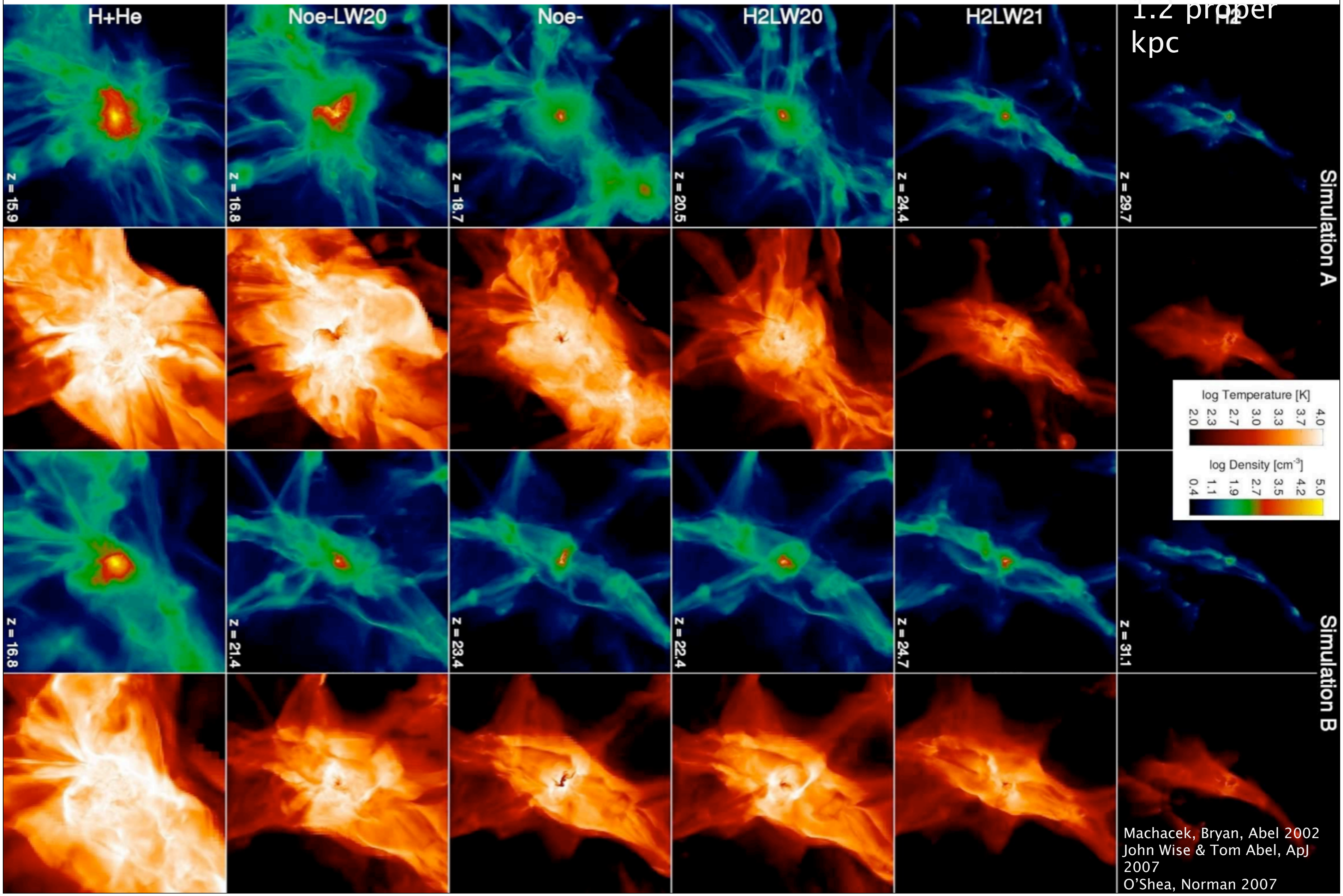
Summary



- Wide range of birth, life & death of the first massive stars are being explored on super computers. Second generation primordial stars have lower mass than the first ones.
- HII regions of the first stars evaporate their host-halos leave a medium with ~ 1 cm^{-3} density but can we really assume no winds? Need better 3D stellar evolution calc.
- Enormous impact on subsequent structure formation
  - different angular momentum of gas vs. dark matter in first galaxies
  - turbulence/ISM
  - Black hole accretion limited
  - seed the first magnetic fields
  - etc ....
- Developed methods are very well suited to stud
  star formation through cosmic time



Strong H_2 suppression from dissociating UV



Machacek, Bryan, Abel 2002
John Wise & Tom Abel, ApJ 2007
O'Shea, Norman 2007