How the first stars shaped the first galaxies

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mostly work with
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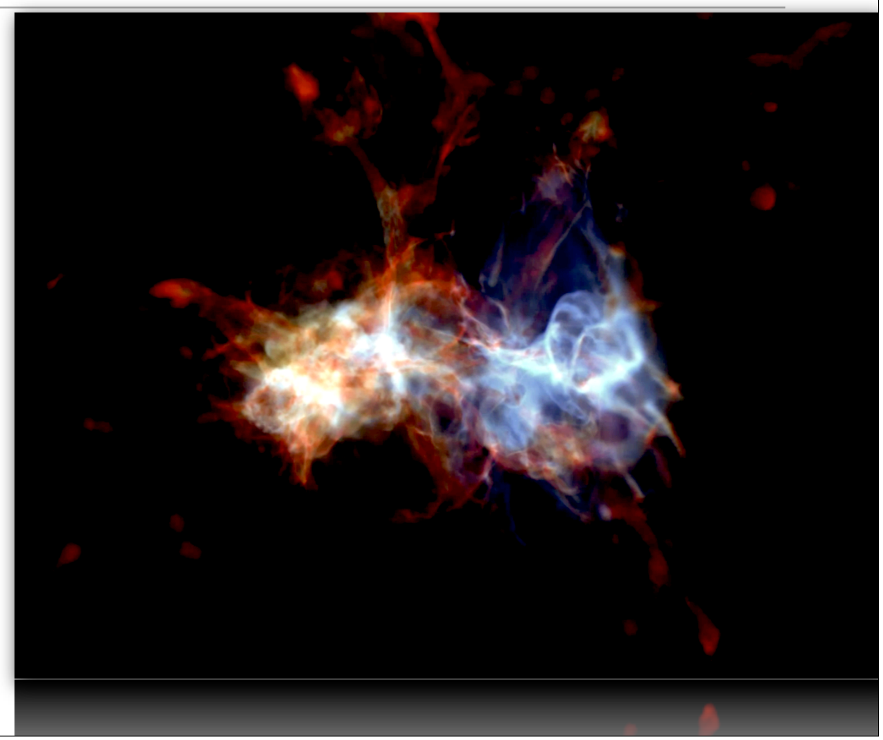
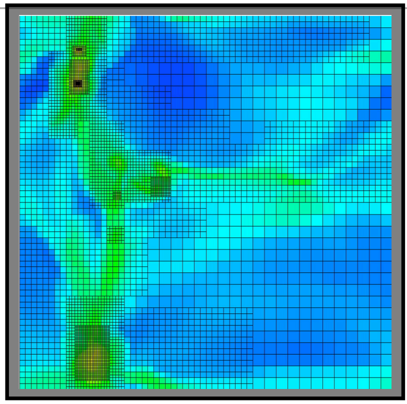
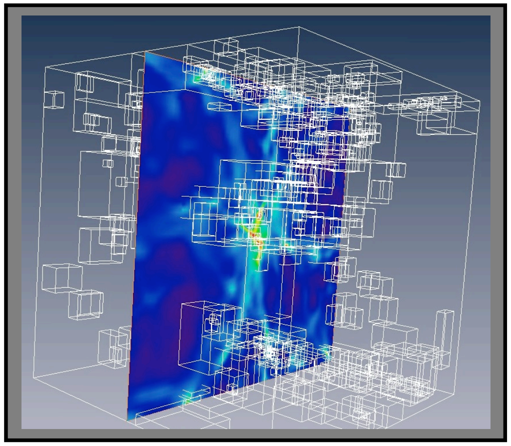
Ralf Kähler (Scientific Visualization)



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
- Why making Galaxies one star at a time?



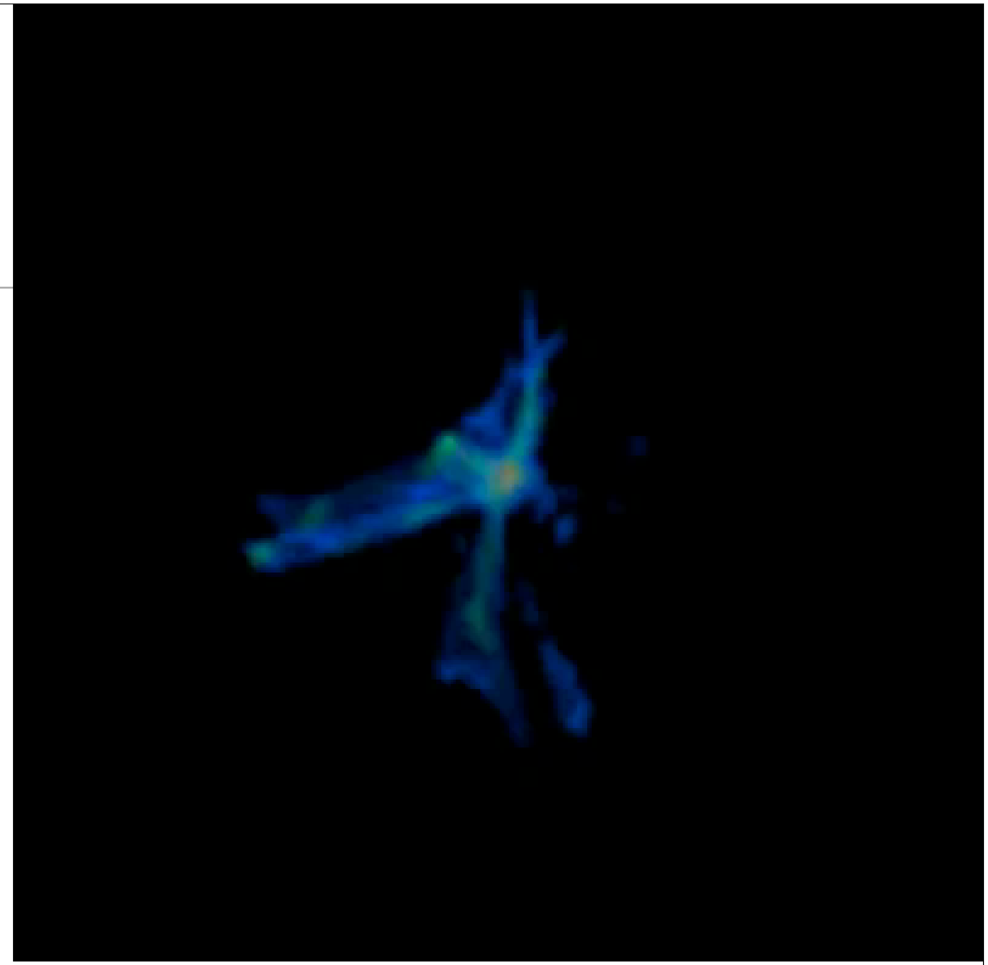


- public version of enzo at:
  http://lca.ucsd.edu/portal/software/enzo

Initial Value Problem

- Initial Conditions: COBE/ACBAR/ Boomerang/WMAP/CfA/SDDS/2DF/ CDMS/DAMA/Edelweiss/... + Theory: Constituents, Density Fluctuations, Thermal History
- Physics: Gravity, MHD, Chemistry, Radiative Cooling, Radiation Transport, Cosmic Rays, Dust drift & cooling, Supernovae, Stellar evolution, etc.
- Transition from Linear to Non-Linear:
- Using patched based structured adaptive (space & time) mesh refinement

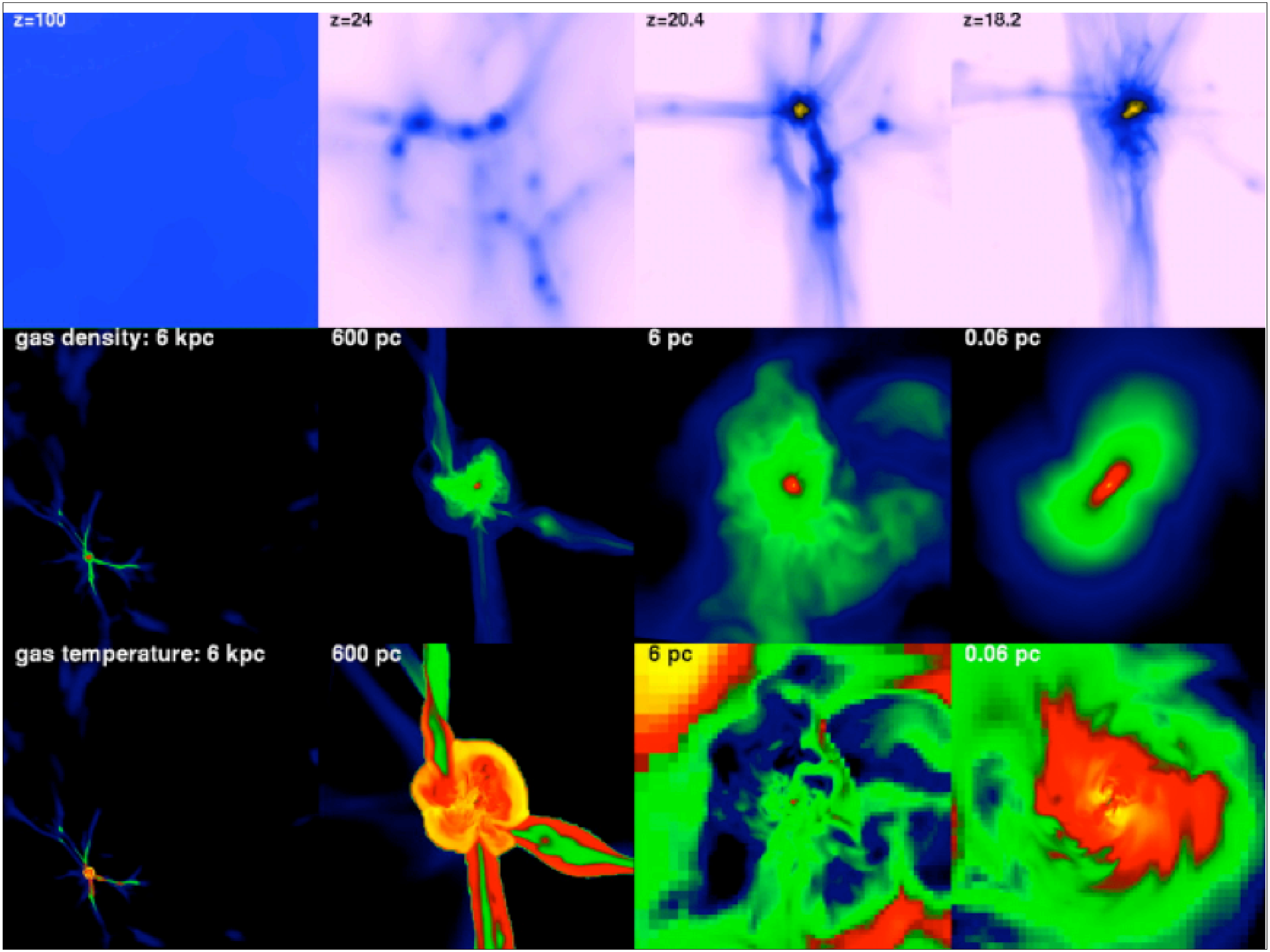
- Differs from current day star formation:
- Complete ICs are known
- Chemistry, cooling, B, known



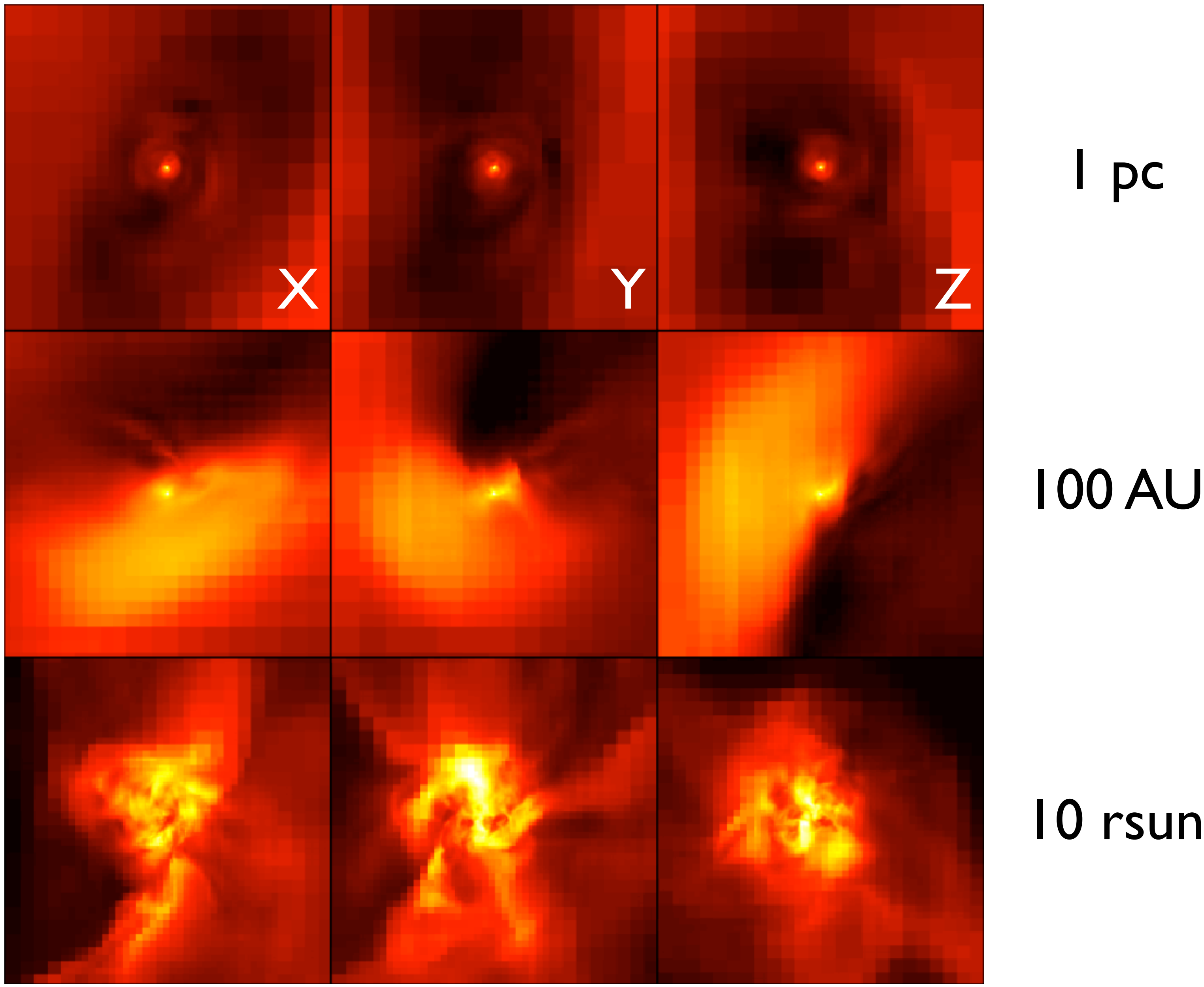
Ralf Kähler & Tom Abel for PBS Origins. Aired Dec 04

$$\frac{R_\odot}{R_{\rm Milky Way}} \approx 10^{-12}$$

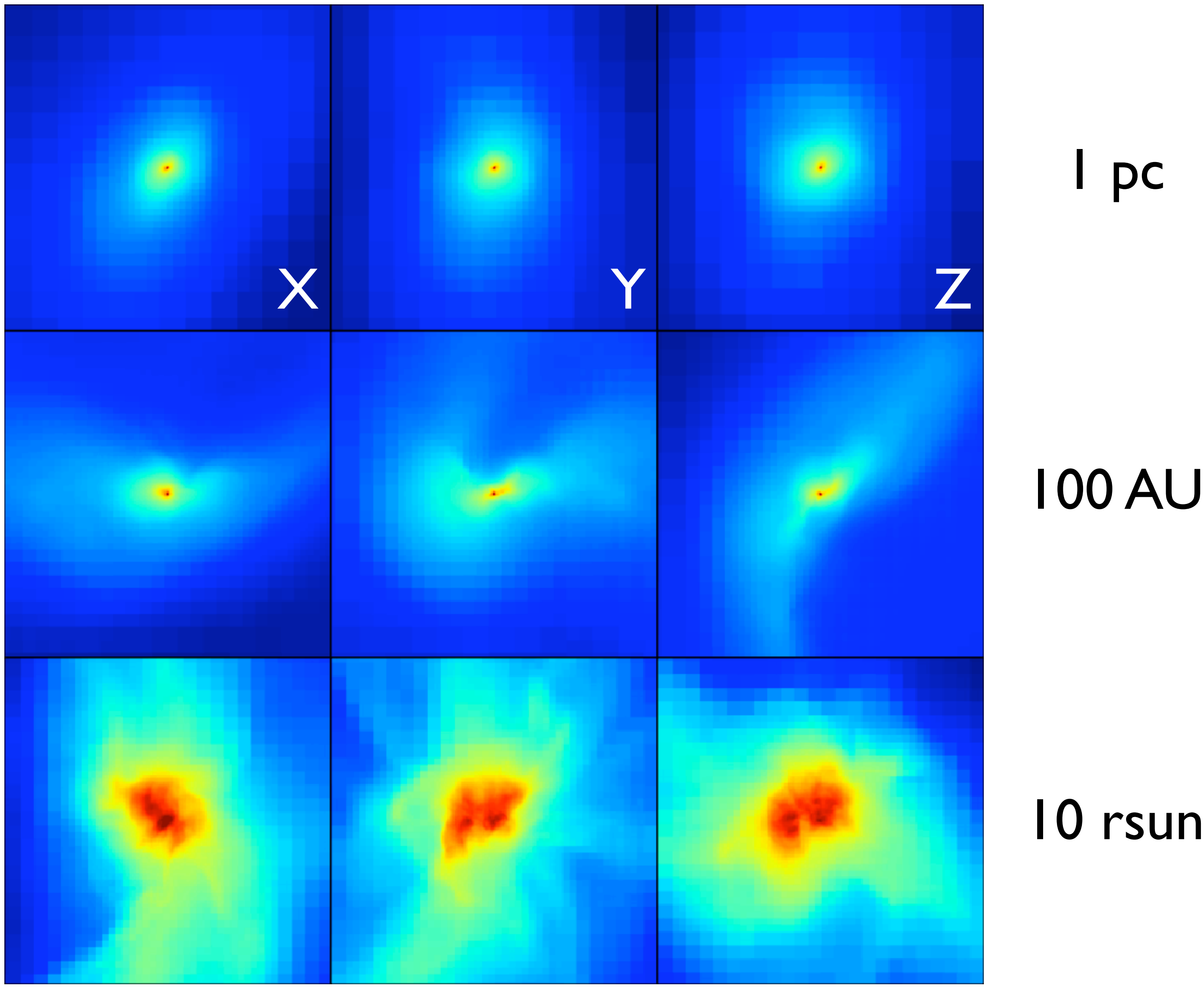
$$\frac{P_{\odot,\rm Kepler}}{t_{\rm Hubble}(z=30)} \approx 10^{-12}$$



z=100
z=24
z=20.4
z=18.2
gas density: 6 kpc
600 pc
6 pc
0.06 pc
gas temperature: 6 kpc
600 pc
6 pc
0.06 pc



Turk, Abel & O'Shea 2007 in prep



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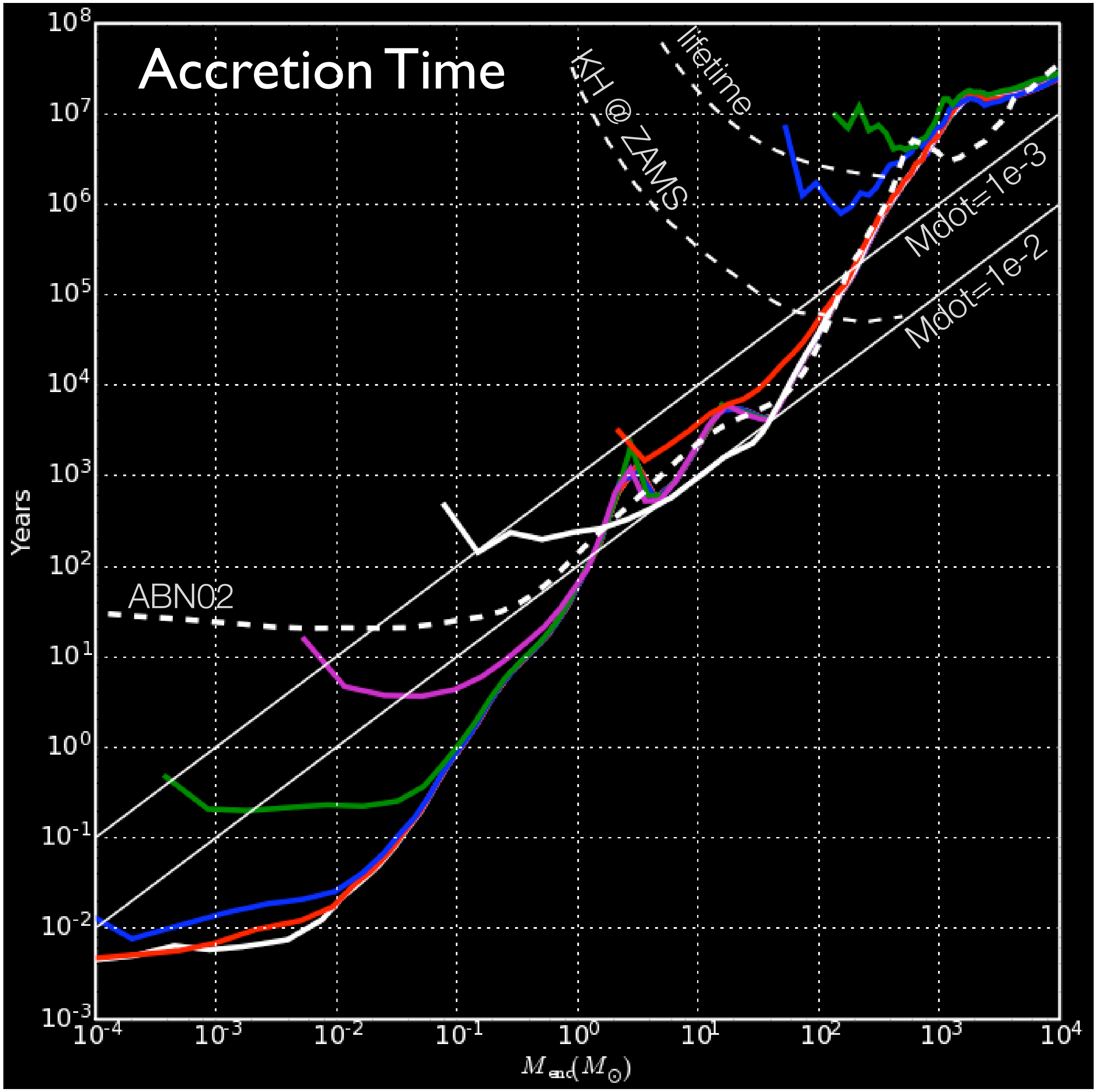


Turk, Abel & O'Shea 2007 in prep

dynamic range: 2e13
min dx = 0.1 R_{sun}
16 cells per jeans length

High density, temperature, equation of state, radiation transport corrections, collision induced emission.

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 and reach the proto-stellar accretion phase!

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, Yoshida et al 2007 in prep; Turk, Abel & O'Shea 2007 in prep
idealized spheres: Bodenheimer 1986; Haiman et al 1997; Omukai & Nishi 1998; Bromm et al 1999,2000,2002; Ripamonti & Abel 2004

Immediate consequences

- 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

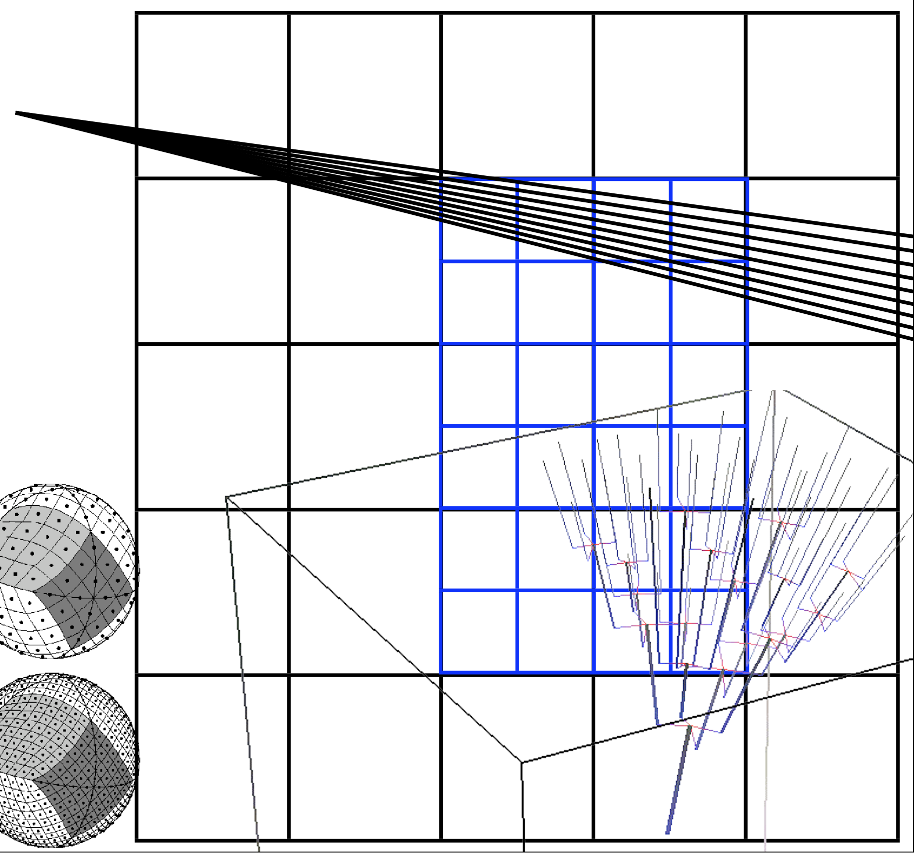
Adaptive ray-tracing of PhotonPackages using HEALPIX pixelization of the sphere. Photon conserving at any resolution.

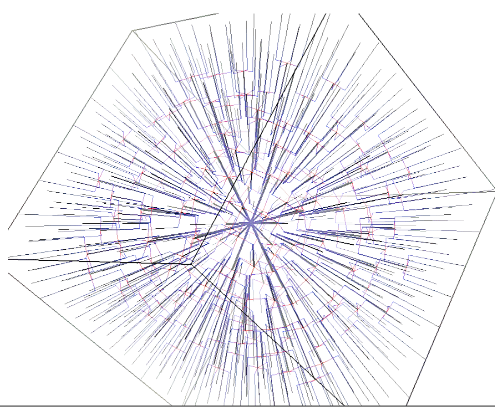
Parallel using MPI and dynamic load balancing.

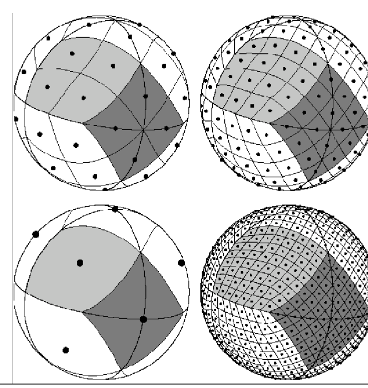
Fully coupled with non-equilibrium chemistry and hydrodynamics.

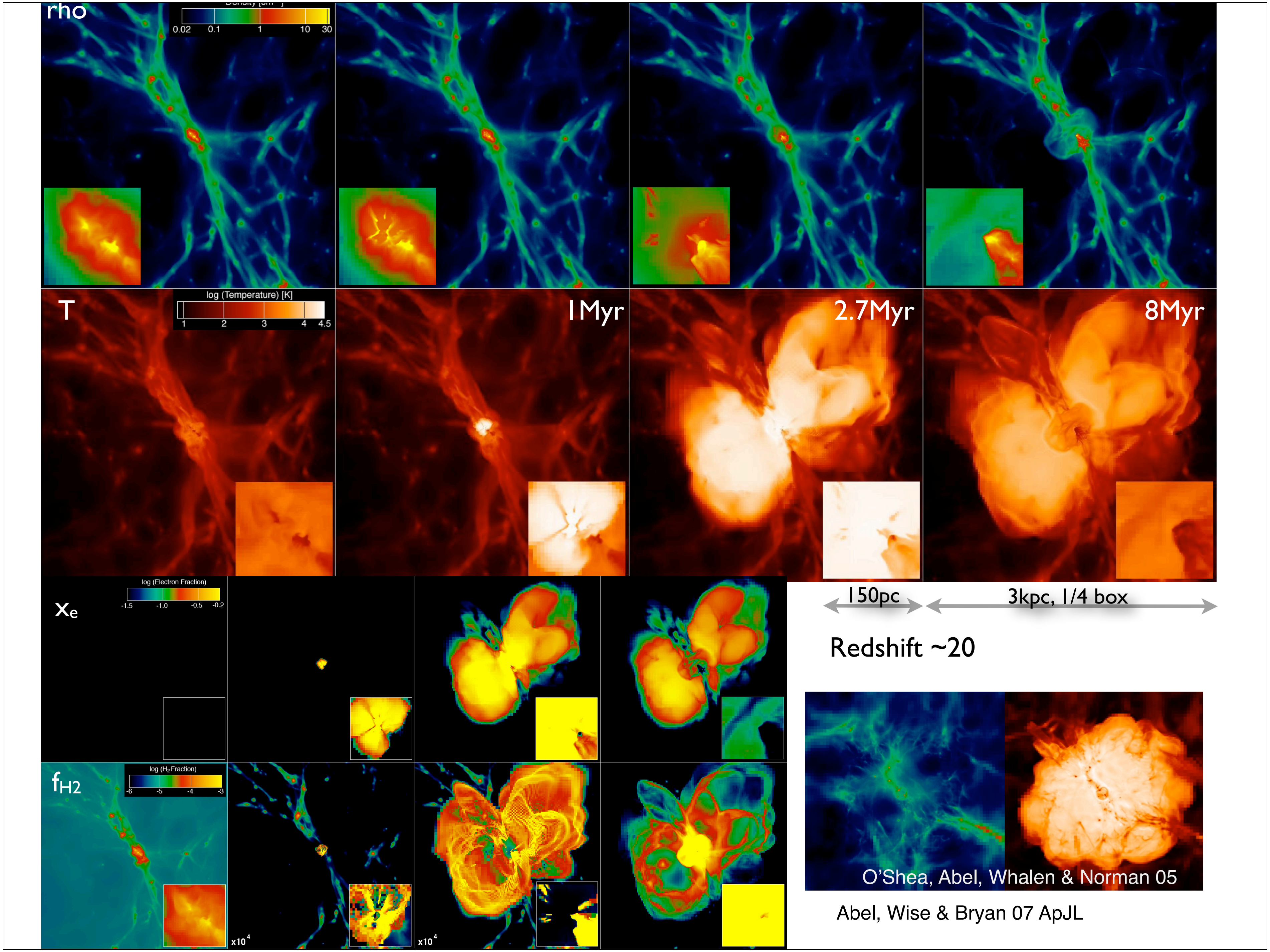
$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\partial I_\nu}{\partial r} = -\kappa I_\nu$$

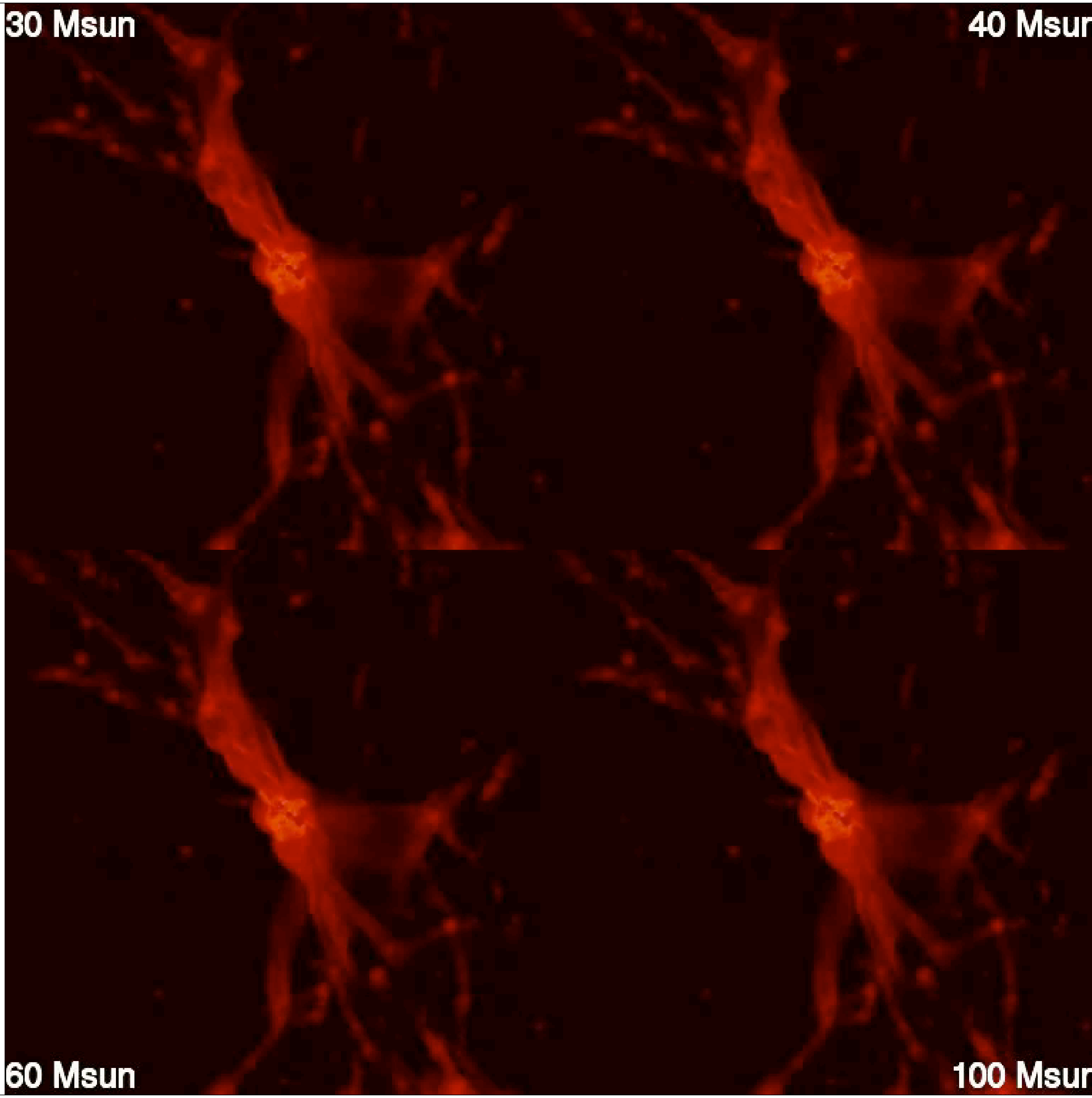
Transfer done along adaptive rays
Case B recombination



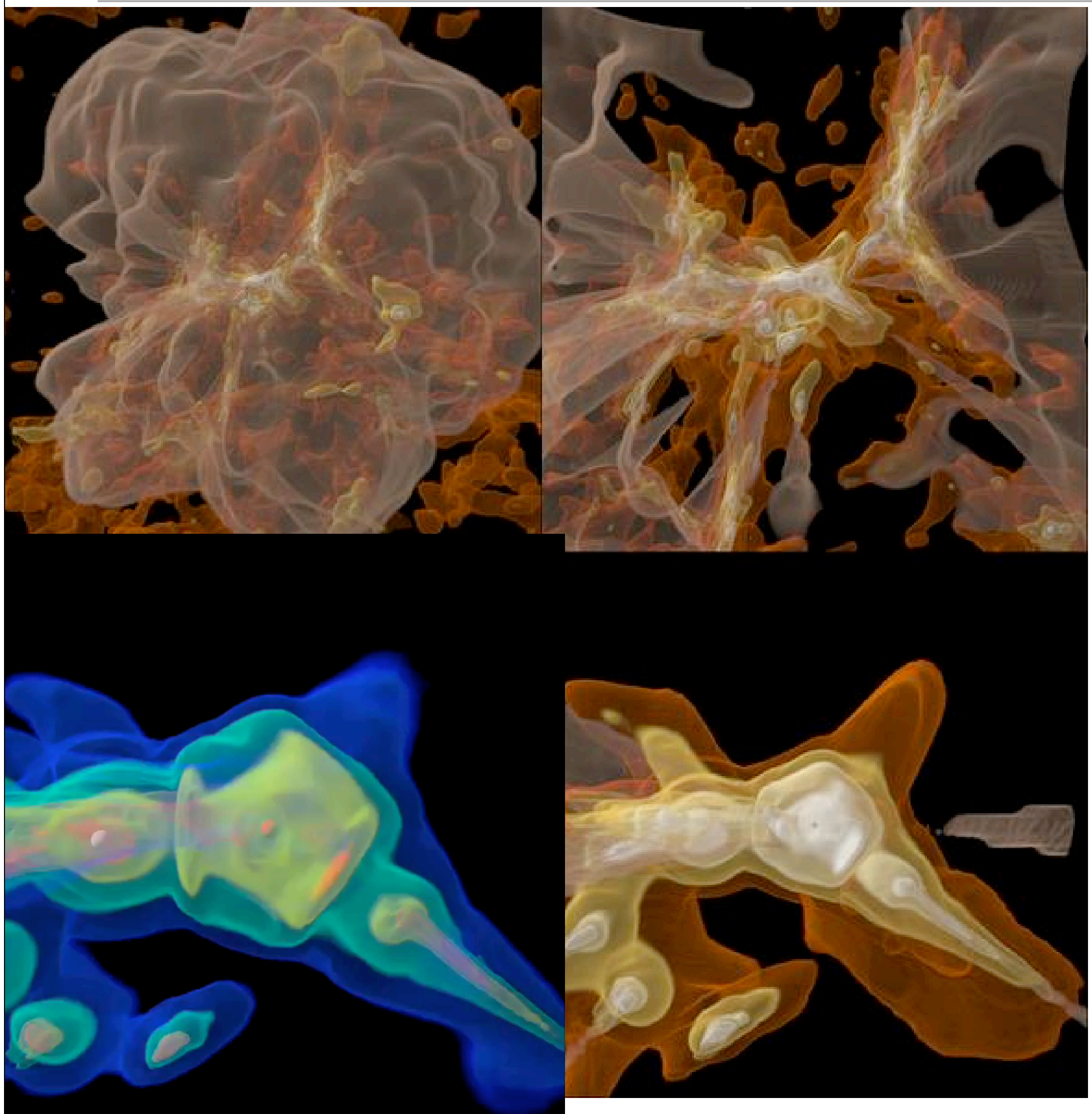


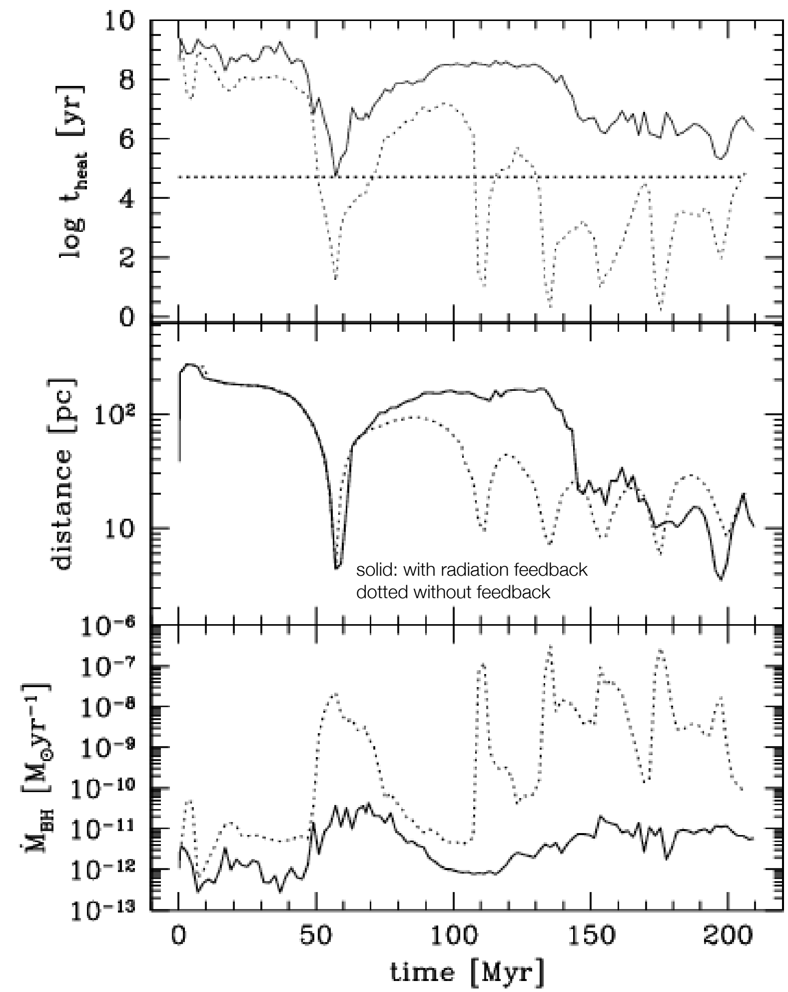



rho
0.02
0.1
1
10
30
T
log (Temperature) [K]
1
2
3
4
4.5
1Myr
2.7Myr
8Myr
x_e
log (Electron Fraction)
-1.5
-1.0
-0.5
-0.2
f_{H2}
log (H_2 Fraction)
-6
-5
-4
-3
x10^4
x10^4
150pc
3kpc, 1/4 box
Redshift ~20
O'Shea, Abel, Whalen & Norman 05
Abel, Wise & Bryan 07 ApJL


30 Msun
40 Msun
60 Msun
100 Msun

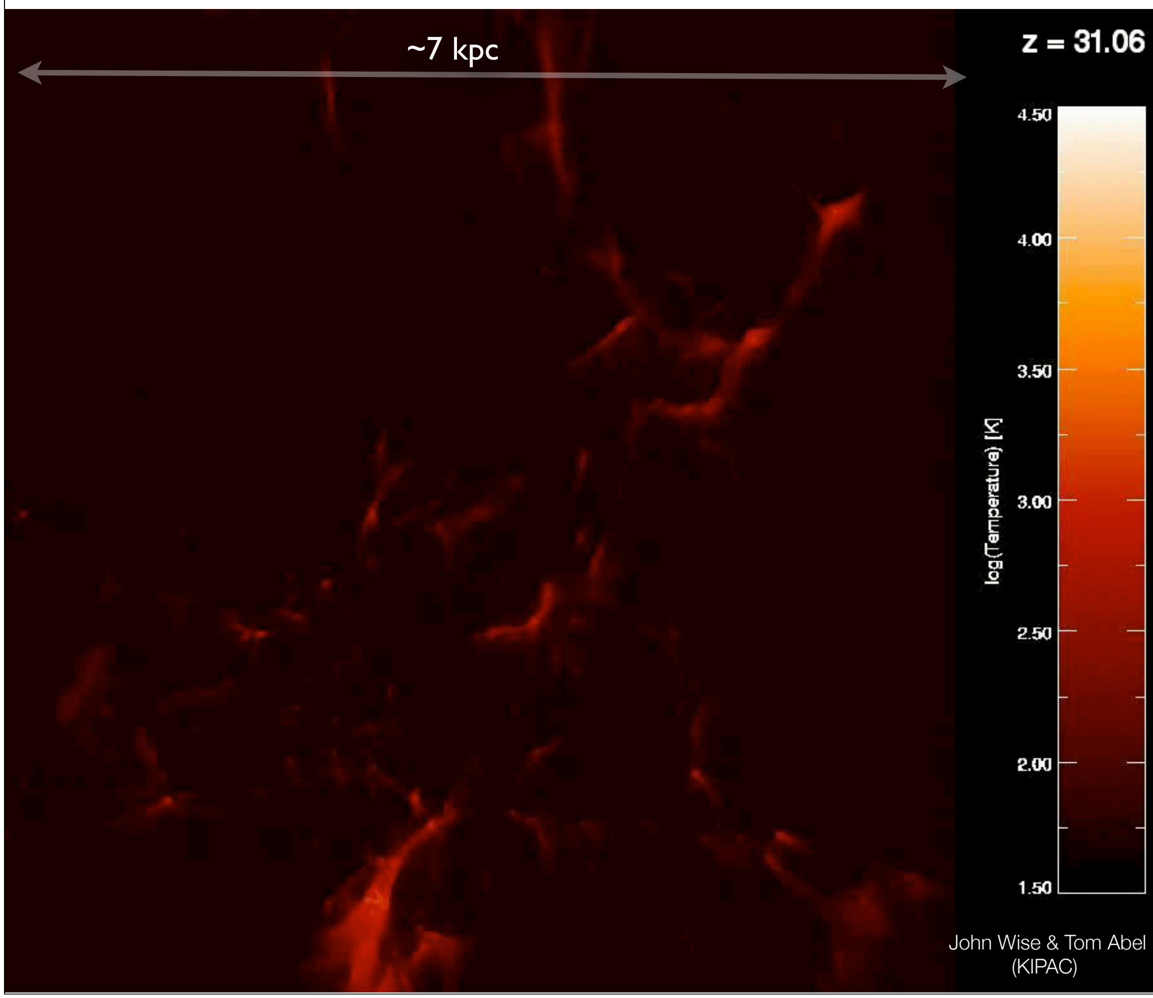
Insignificant BH accretion - no mini quasars through this process, nor pre-cursors of Quasars.

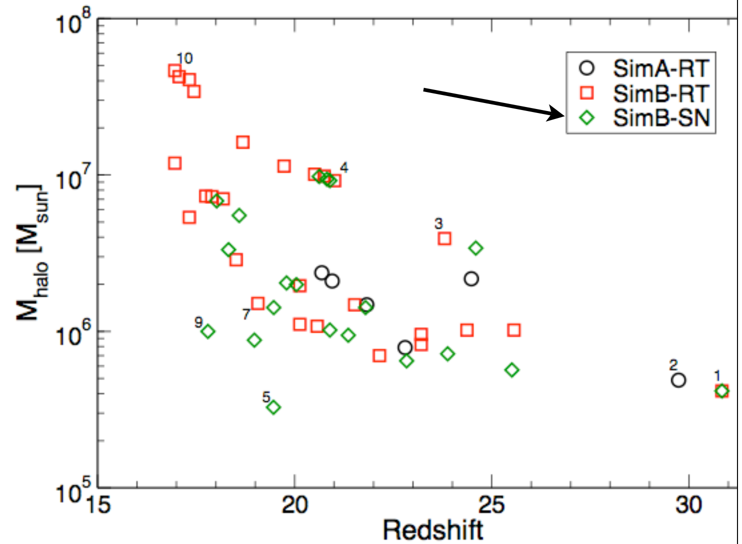




Alvarez, Wise & Abel in prep.

First few hundred million years: Cosmic Fireworks

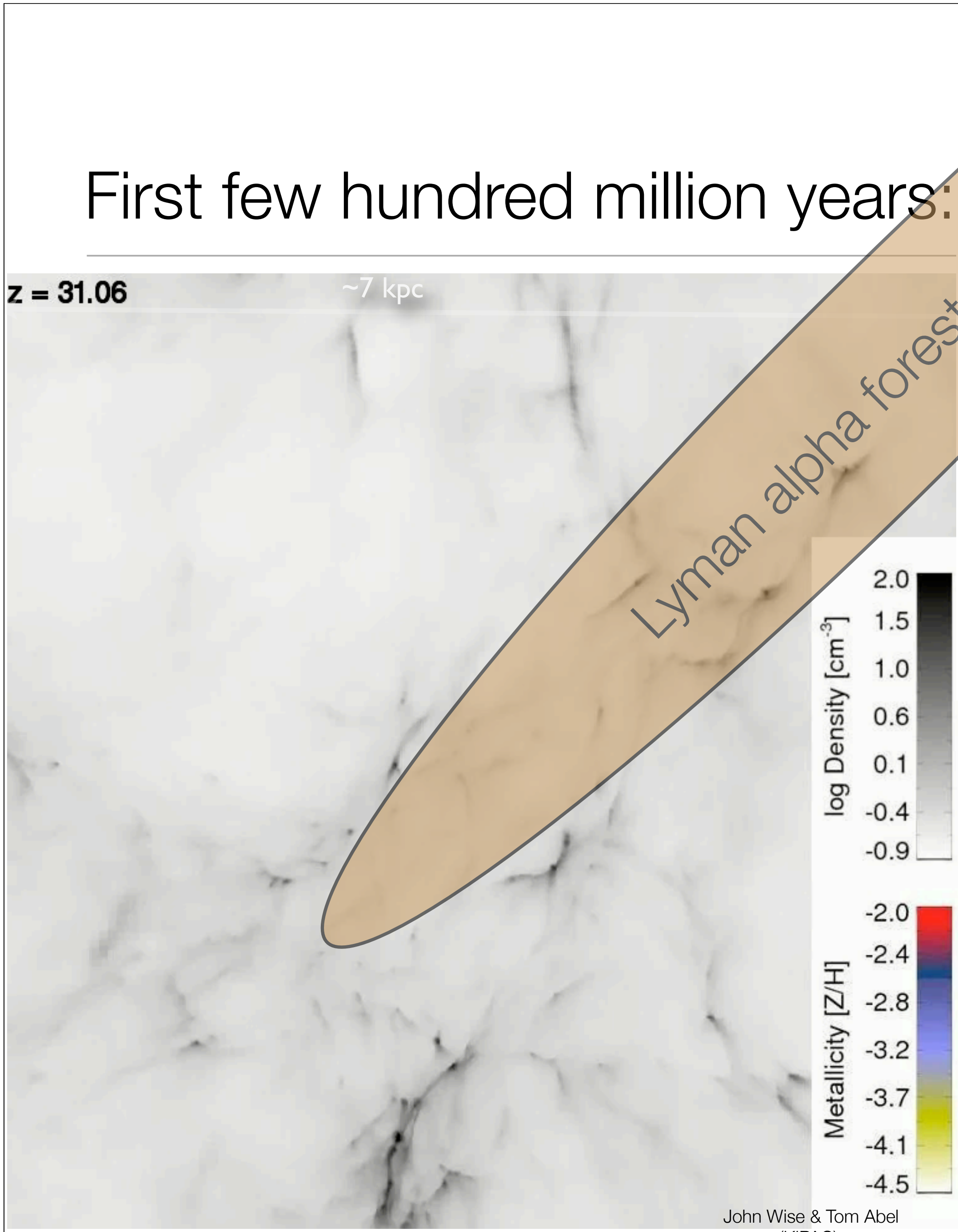




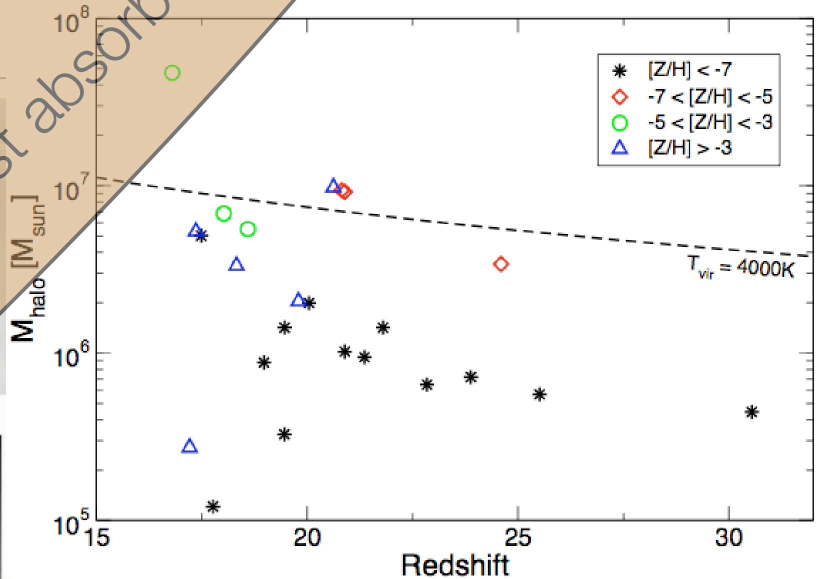
halo masses at redshift stars form within them

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

First few hundred million years:



John Wise & Tom Abel
(KIPAC)

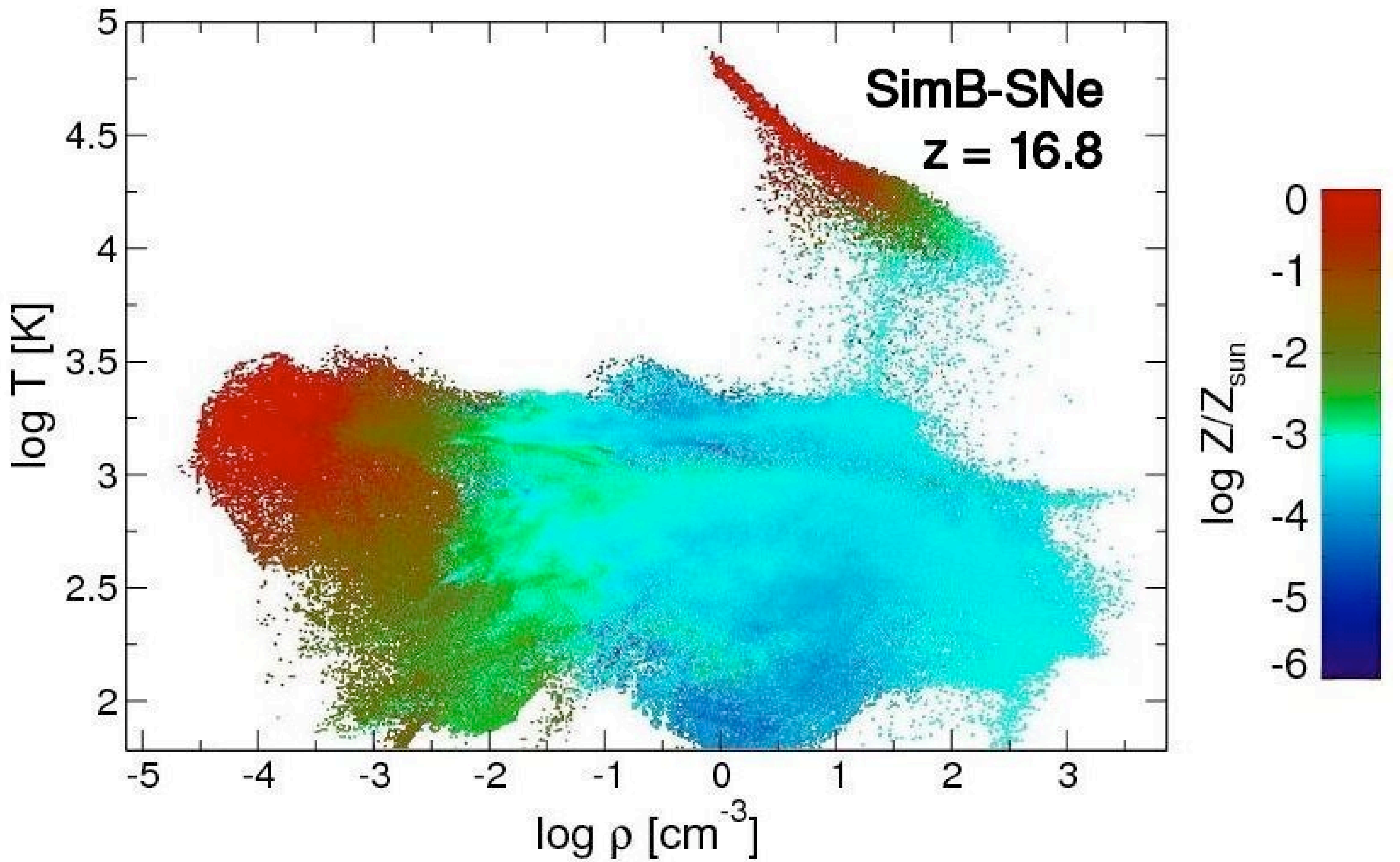


10,000 such patches make Milky Way

~ 1e5 popIII remnants

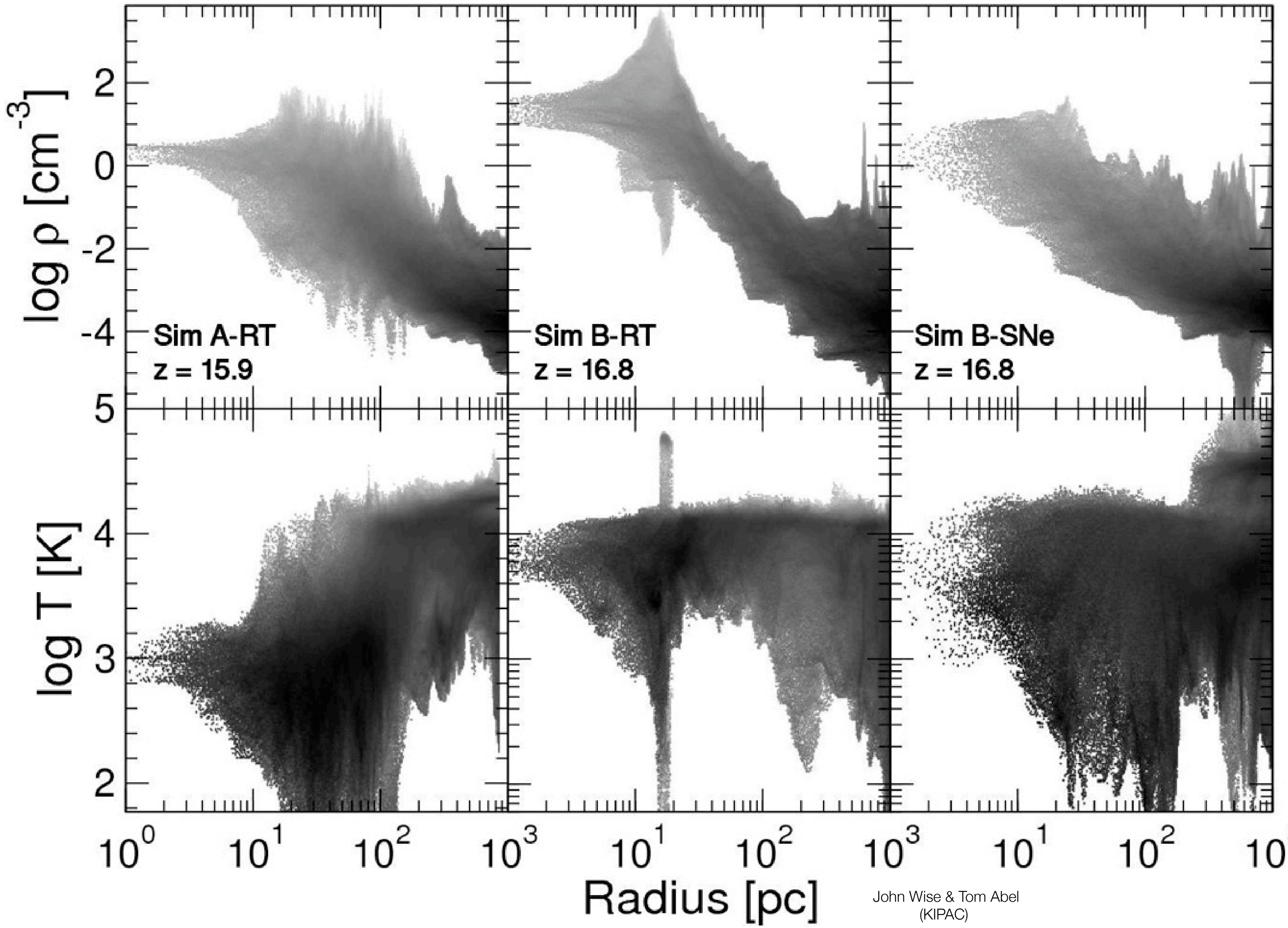
early metal enrichment

Developing an ISM



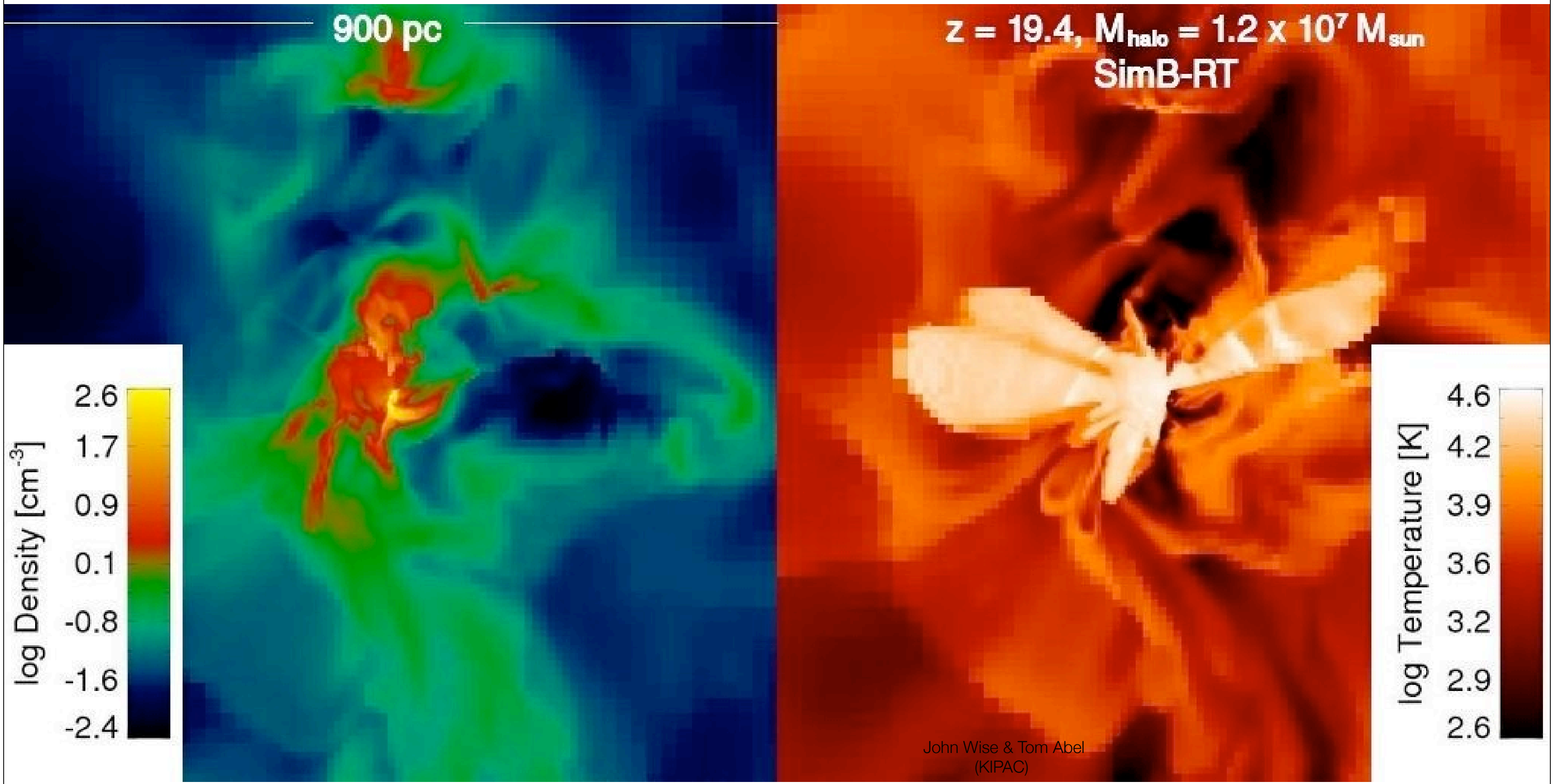
John Wise & Tom Abel 2007
(KIPAC)

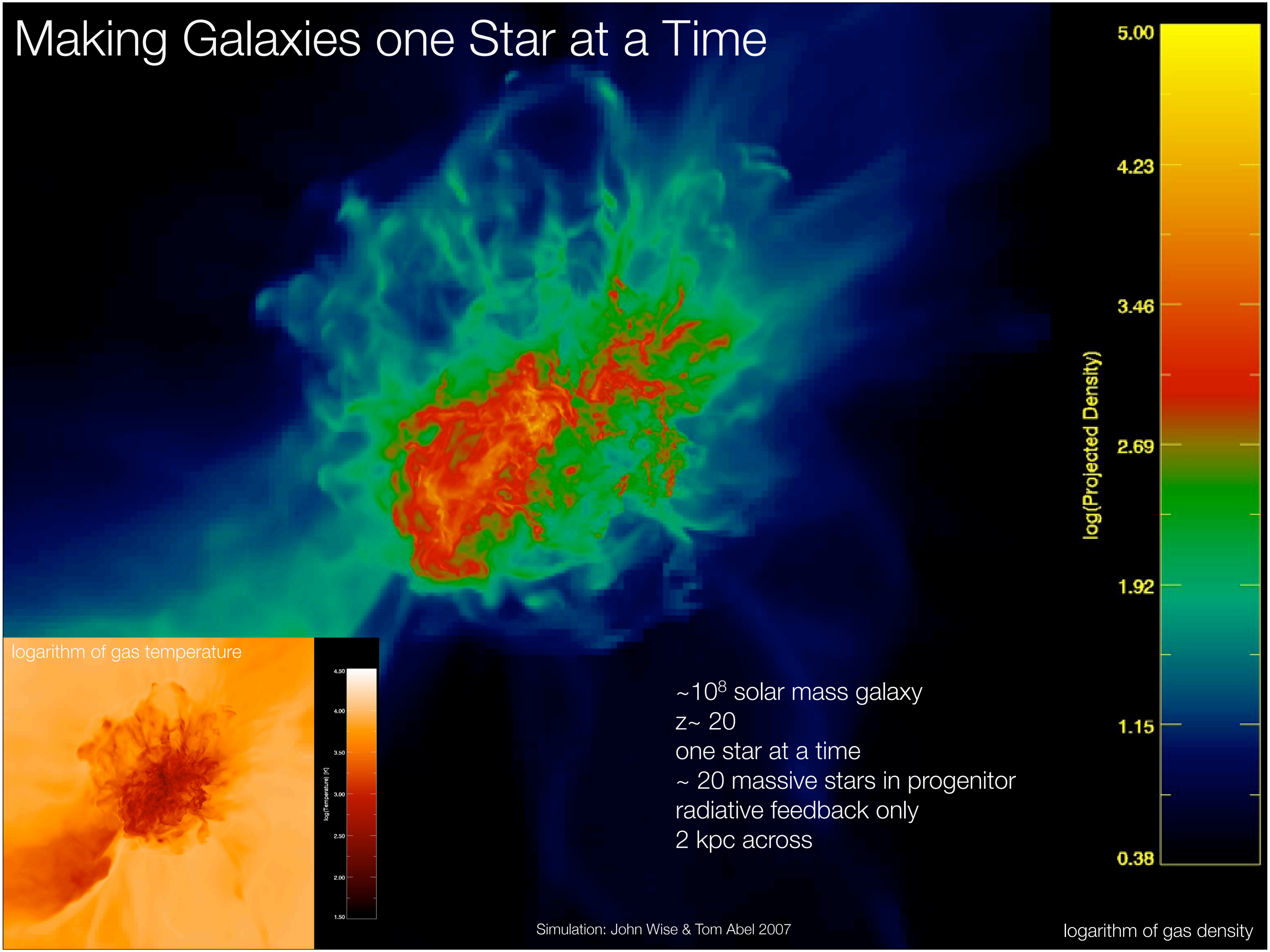
Radial Profiles – Multi-phase ISM

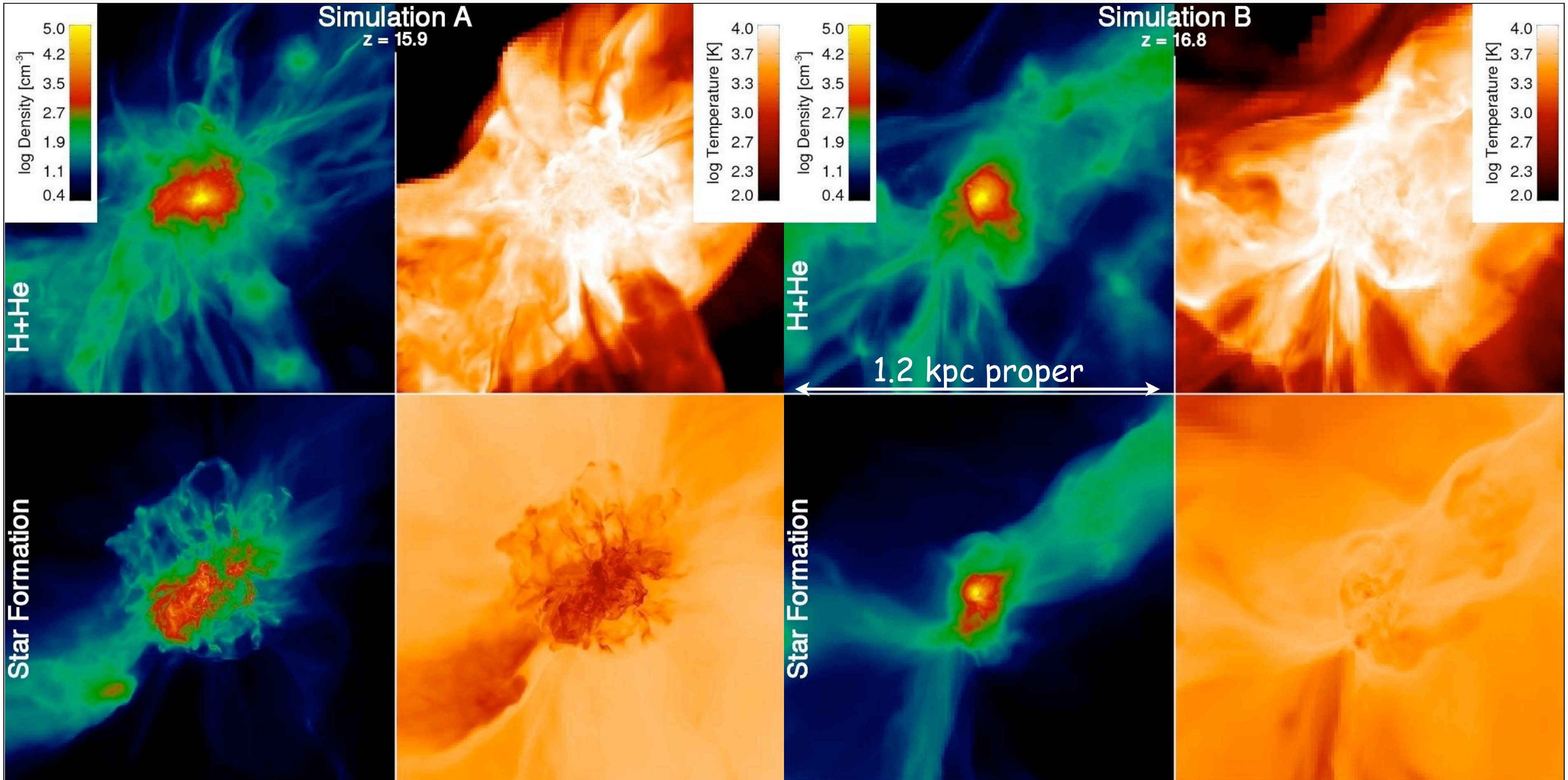


John Wise & Tom Abel
(KIPAC)

HII regions starting to be confined inside galaxies

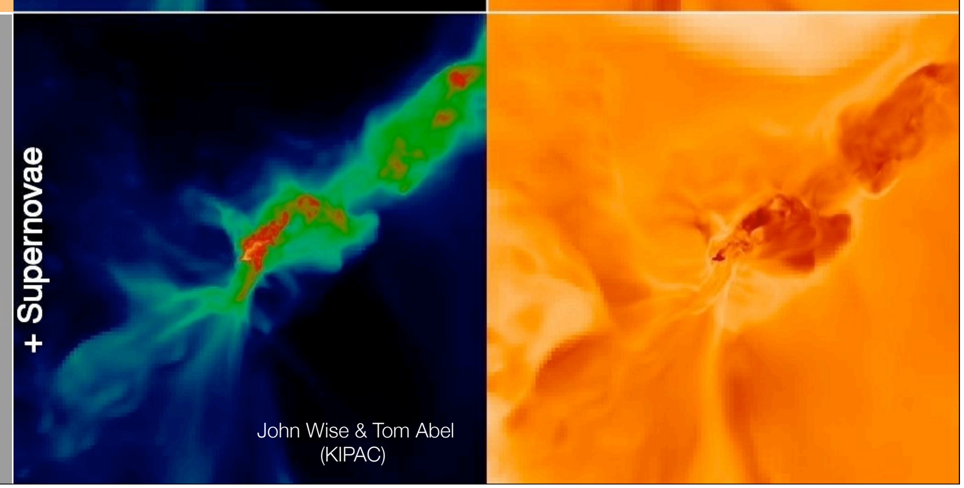



Making Galaxies one Star at a Time
5.00
4.23
3.46
2.69
1.92
1.15
0.38
log(Projected Density)
logarithm of gas temperature
~10^8 solar mass galaxy
z~ 20
one star at a time
~ 20 massive stars in progenitor
radiative feedback only
2 kpc across
Simulation: John Wise & Tom Abel 2007
logarithm of gas density

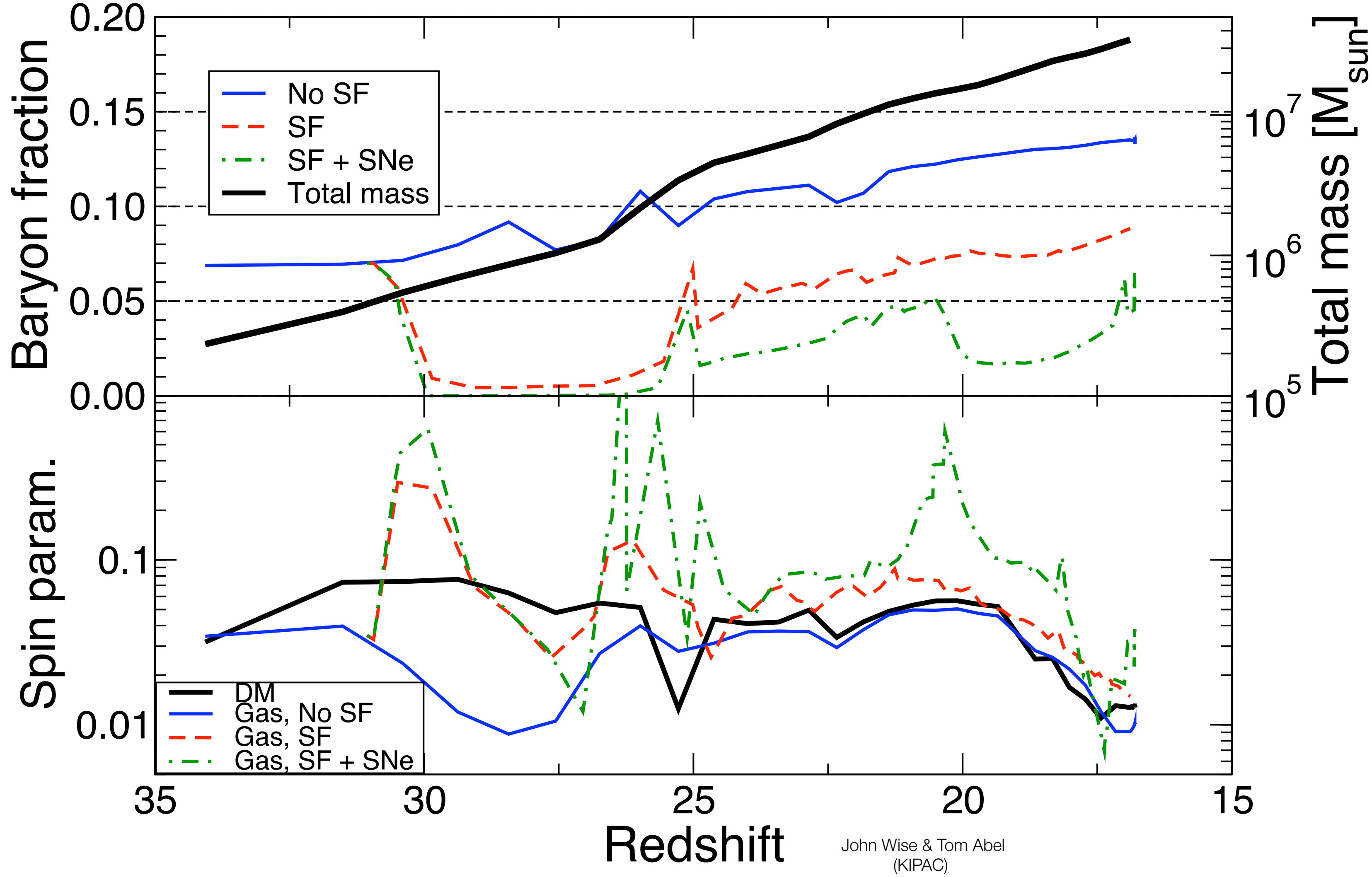


Number of stars:

- 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

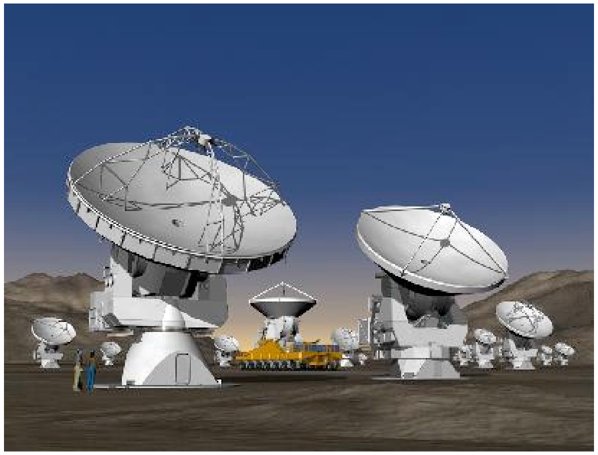


John Wise & Tom Abel
(KIPAC)

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.
- Elucidate first galaxies-Lyman alpha forest connection
- Compare with nearby fossil record in the meantime

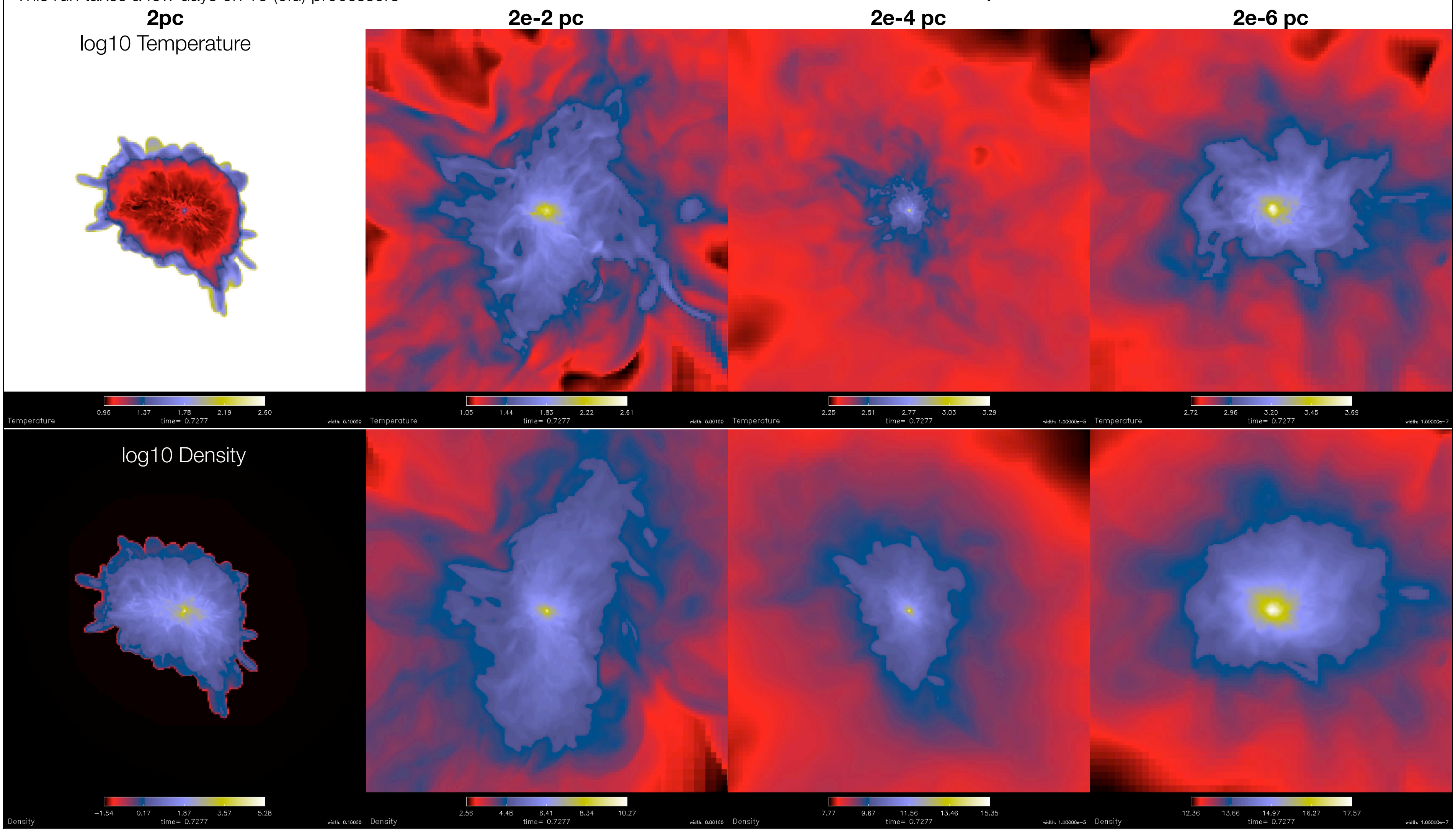


Application to present day star formation: very promising!

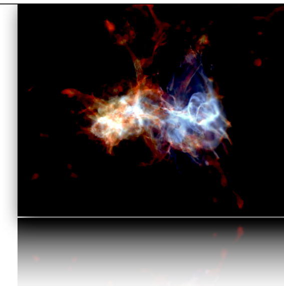
30 solar mass cloud
jeans number ~ 1
Mach 2 decaying turbulence
thermal + turbulent pressure equilibrium with ambient medium
31 levels of refinement: 11 orders of magnitude in length dynamic range: dx ~ 5e8 cm
64 cells per jeans length corresponds to 1e6 SPH particles per jeans mass or
~ 1e13 SPH particles 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



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
  - may provide a lot of the metalicity in quasar absorption systems
  - etc ....
- Developed methods are very well suited to **create star formation theories that will eventually confront observations**