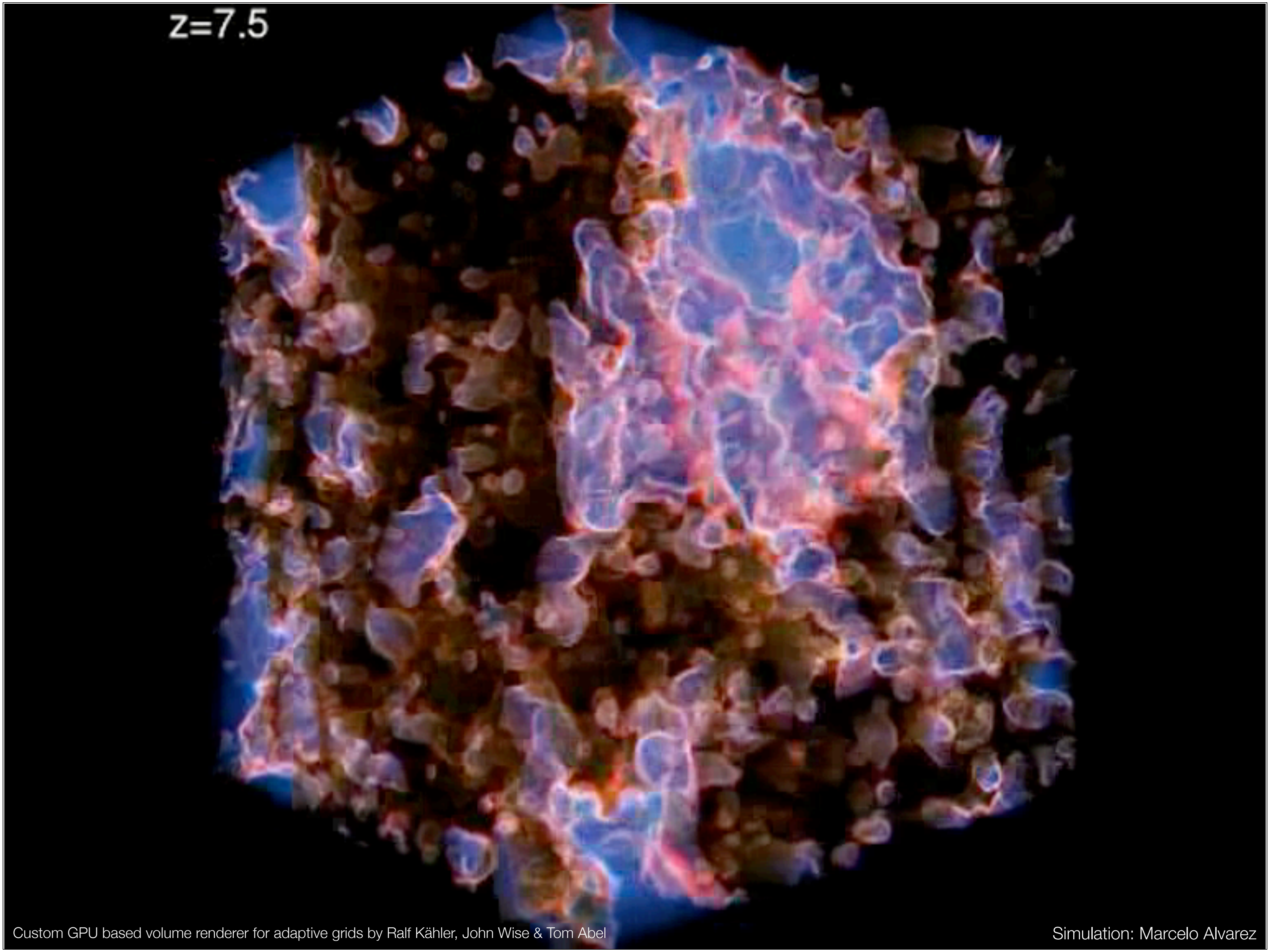
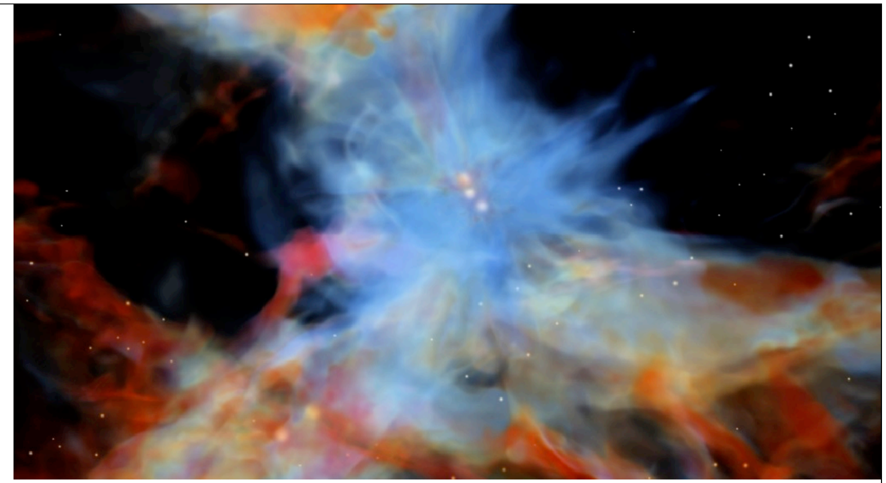

z=7.5
Custom GPU based volume renderer for adaptive grids by Ralf Kähler, John Wise & Tom Abel
Simulation: Marcelo Alvarez

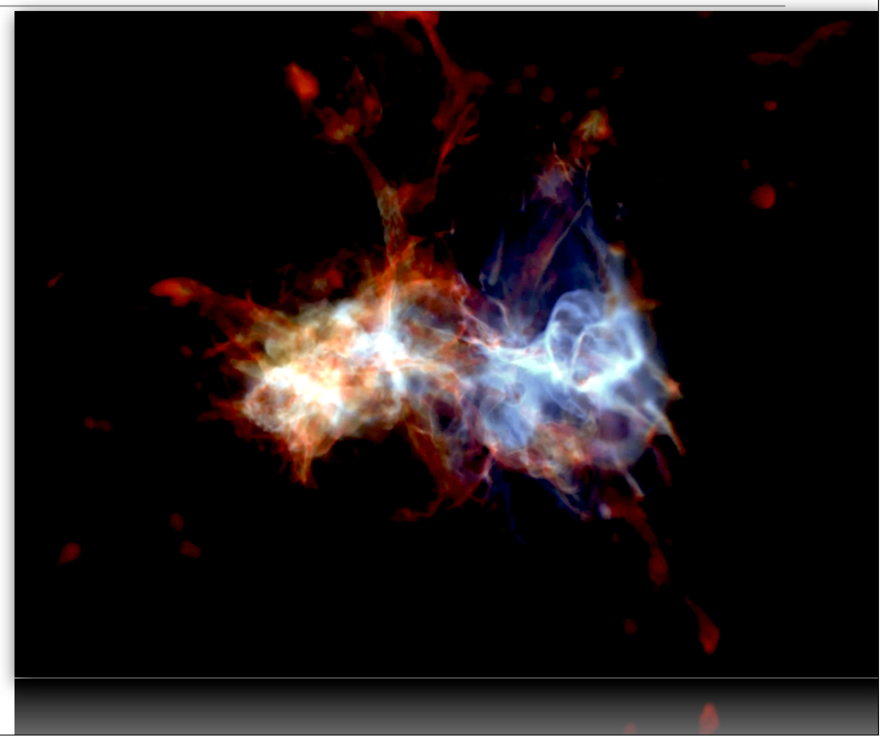


How the First Stars start Reionization

Tom Abel
KIPAC/Stanford

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

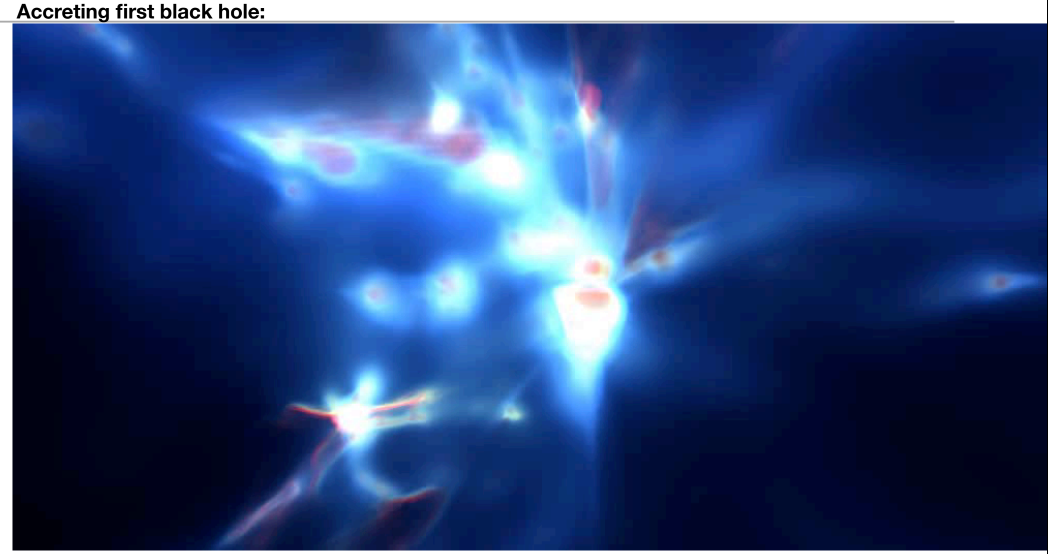
Ralf Kähler (Scientific Visualization)



Some questions

- How do Pop III stars form?
- Do Pop III stars re-ionize the Universe?
- Do Pop III stars make the seeds of the supermassive black holes that are found in almost all galaxies?

Accreting first black hole:



Simulation: Marcelo Alvarez, John Wise & Tom Abel 2007 Visualization: Ralf Kähler, Alvarez & Abel

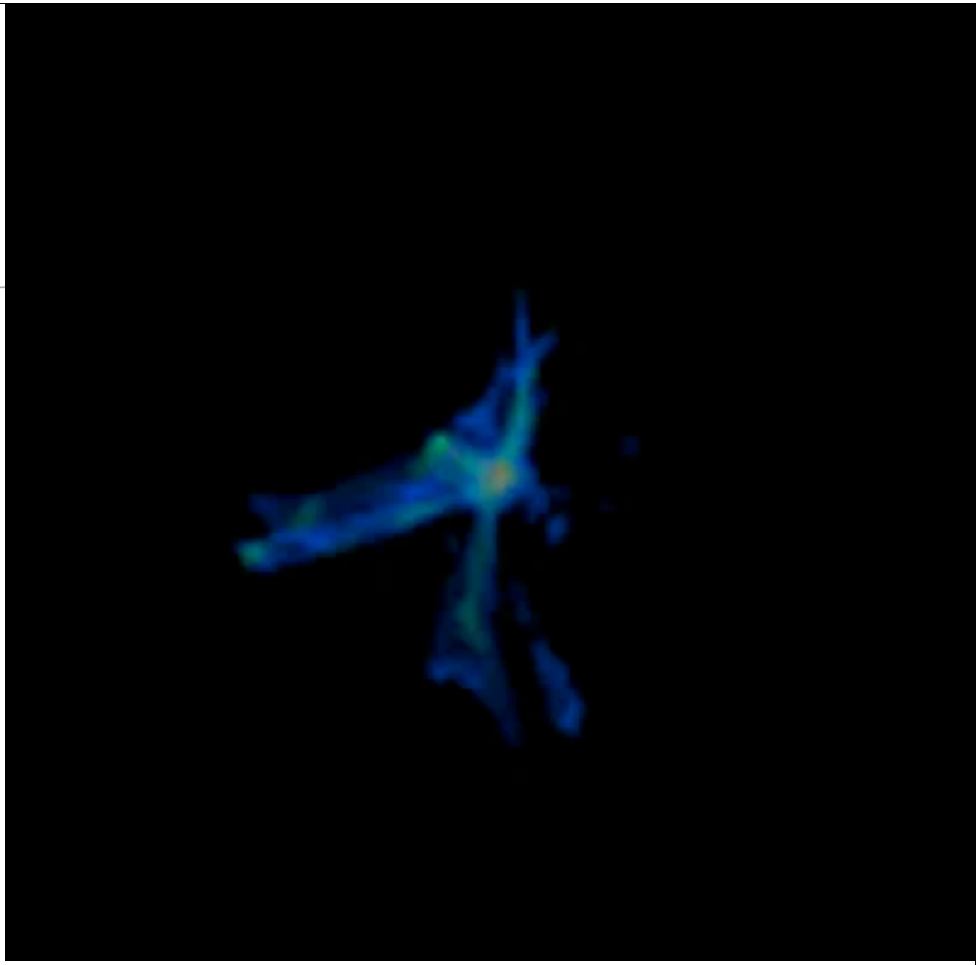
- Do Pop III stars affect galaxy formation?
- How does primordial star formation differ from star formation in the Galaxy?
- What do the first galaxies look like in 21 emission?
- Can Pop III stars be observed with any next generation telescopes?
- Can we understand Galaxies one star at a time?
- Ab initio understanding of star formation?

Informed answers are derived most reliably with ab initio numerical simulations.

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

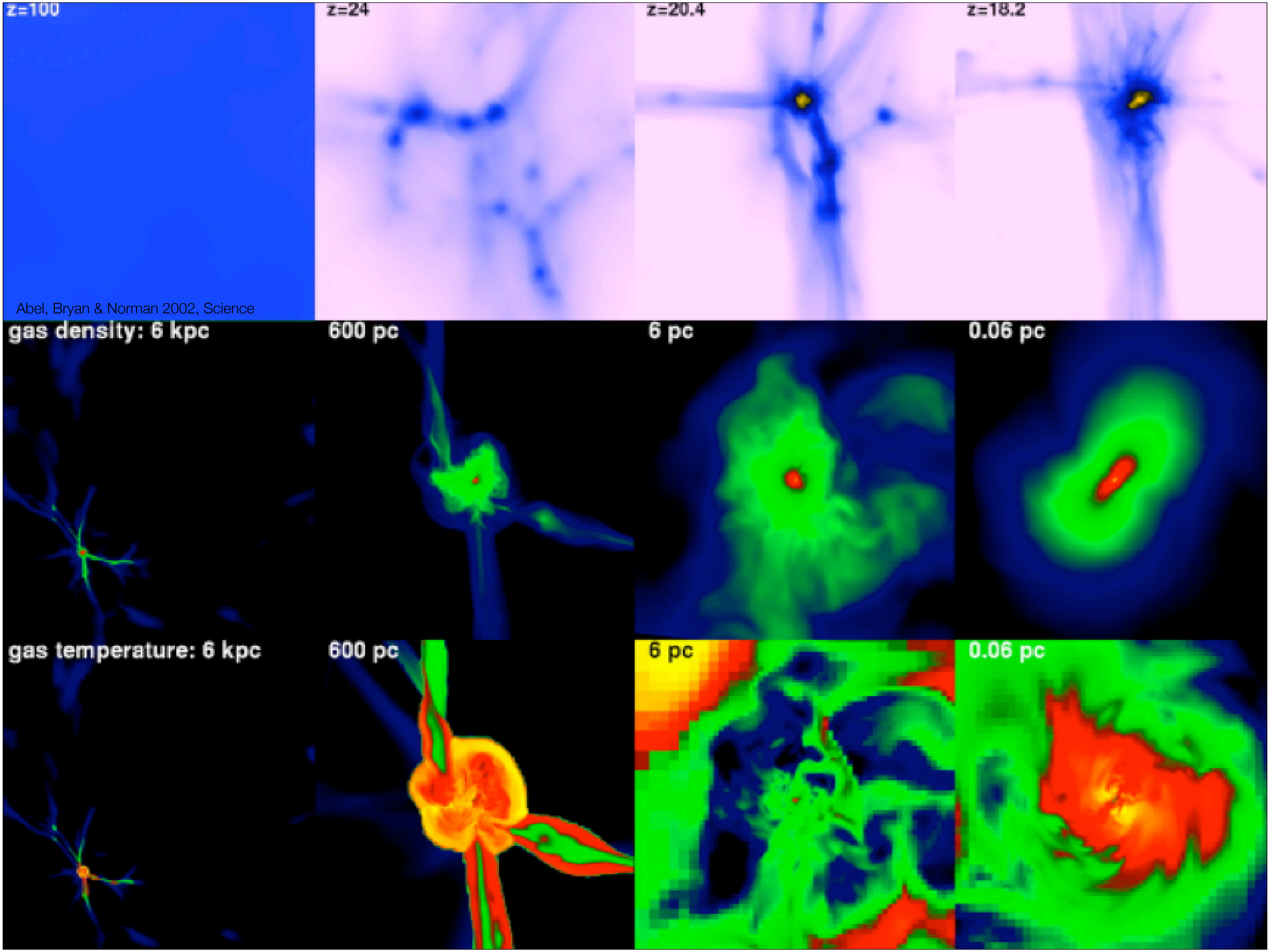
- Differs from current day star formation:
- Complete ICs are known
- Chemistry, cooling, B, known

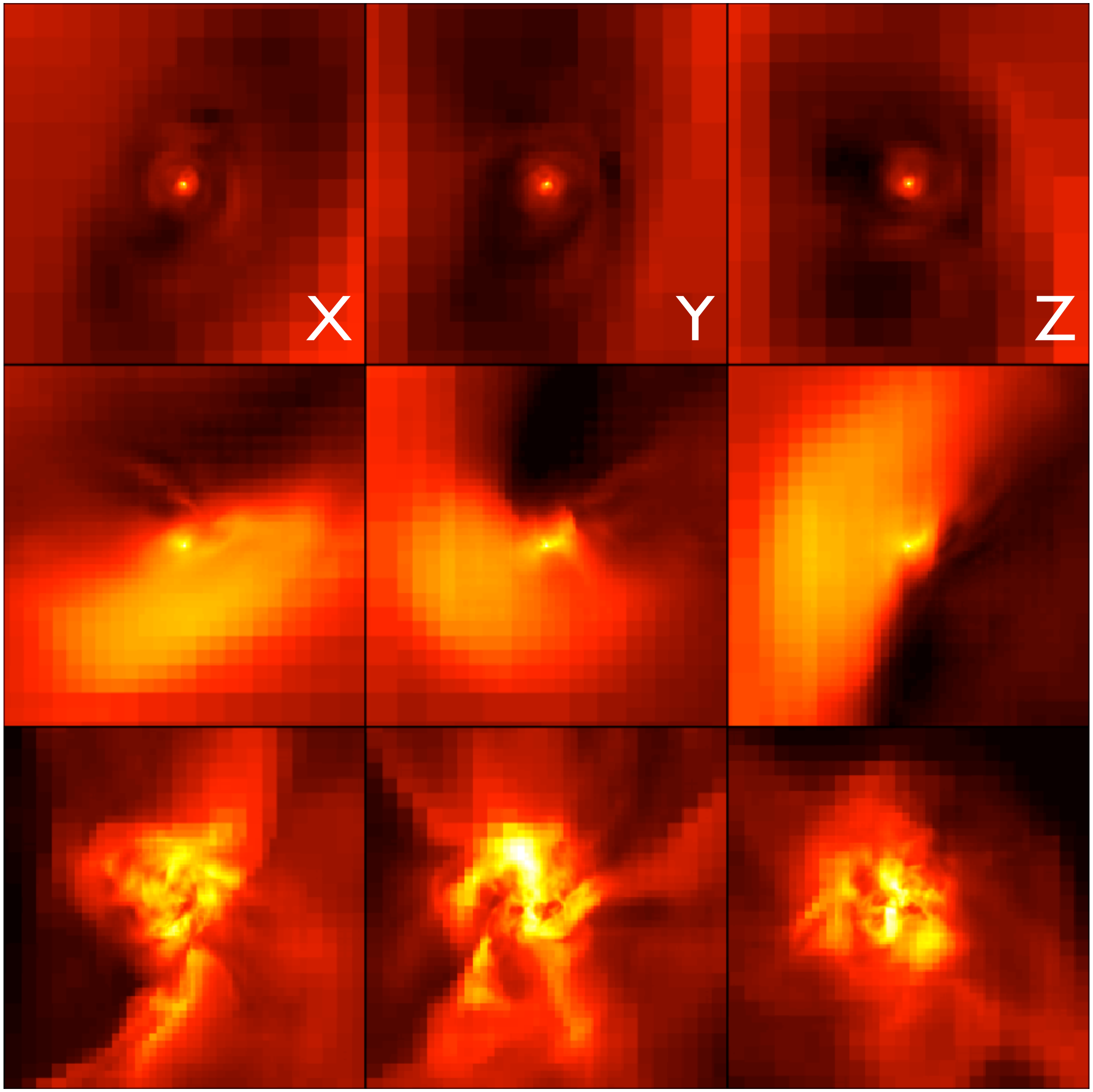


Ralf Kähler & Tom Abel for PBS Origins. Aired Dec 04

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

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


z=100
z=24
z=20.4
z=18.2
Abel, Bryan & Norman 2002, Science
gas density: 6 kpc
600 pc
6 pc
0.06 pc
gas temperature: 6 kpc
600 pc
6 pc
0.06 pc

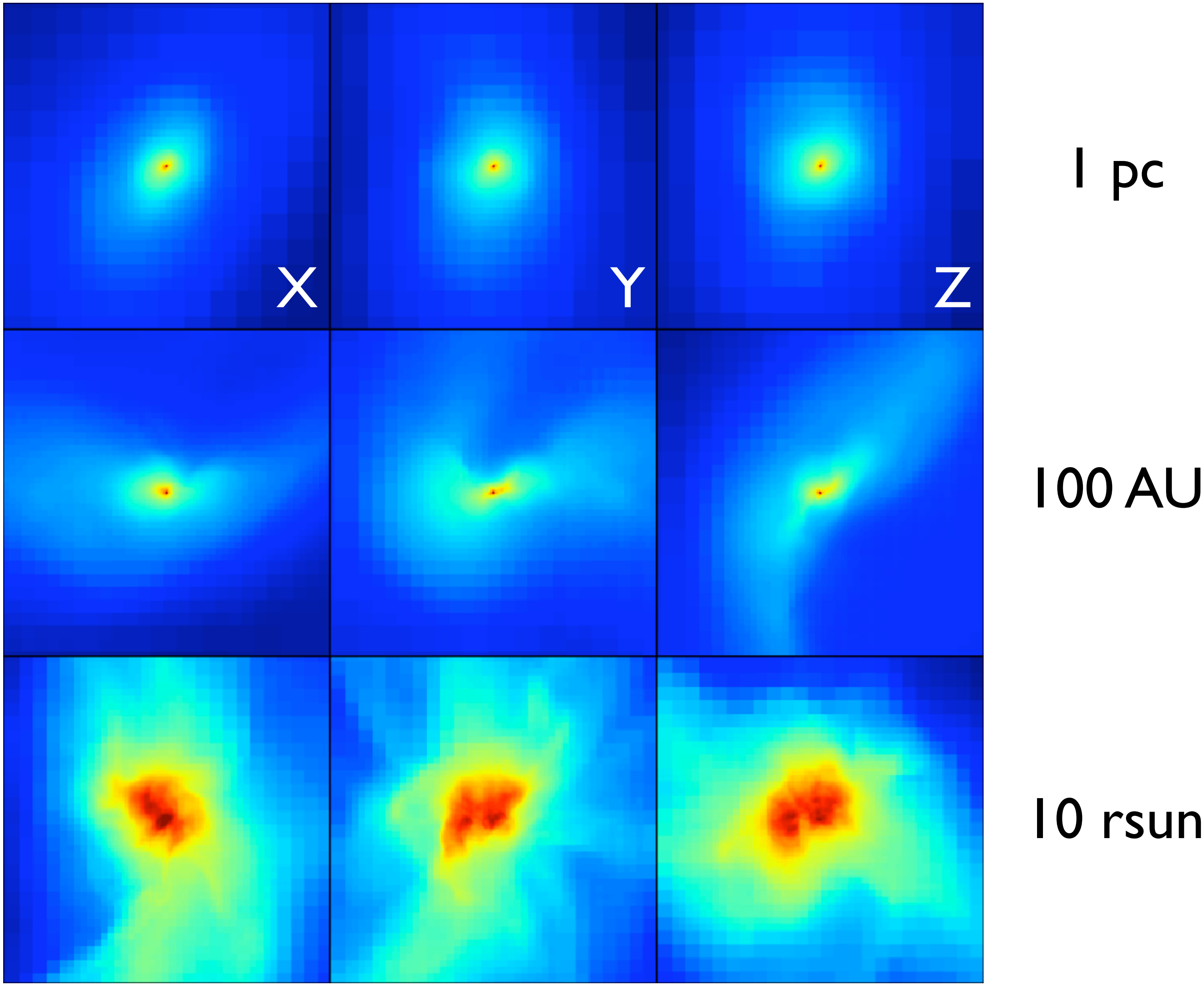


1 pc

100 AU

10 rsun

Turk, Abel & O'Shea 2008 in prep



Turk, Abel & O'Shea 2008 in prep

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!

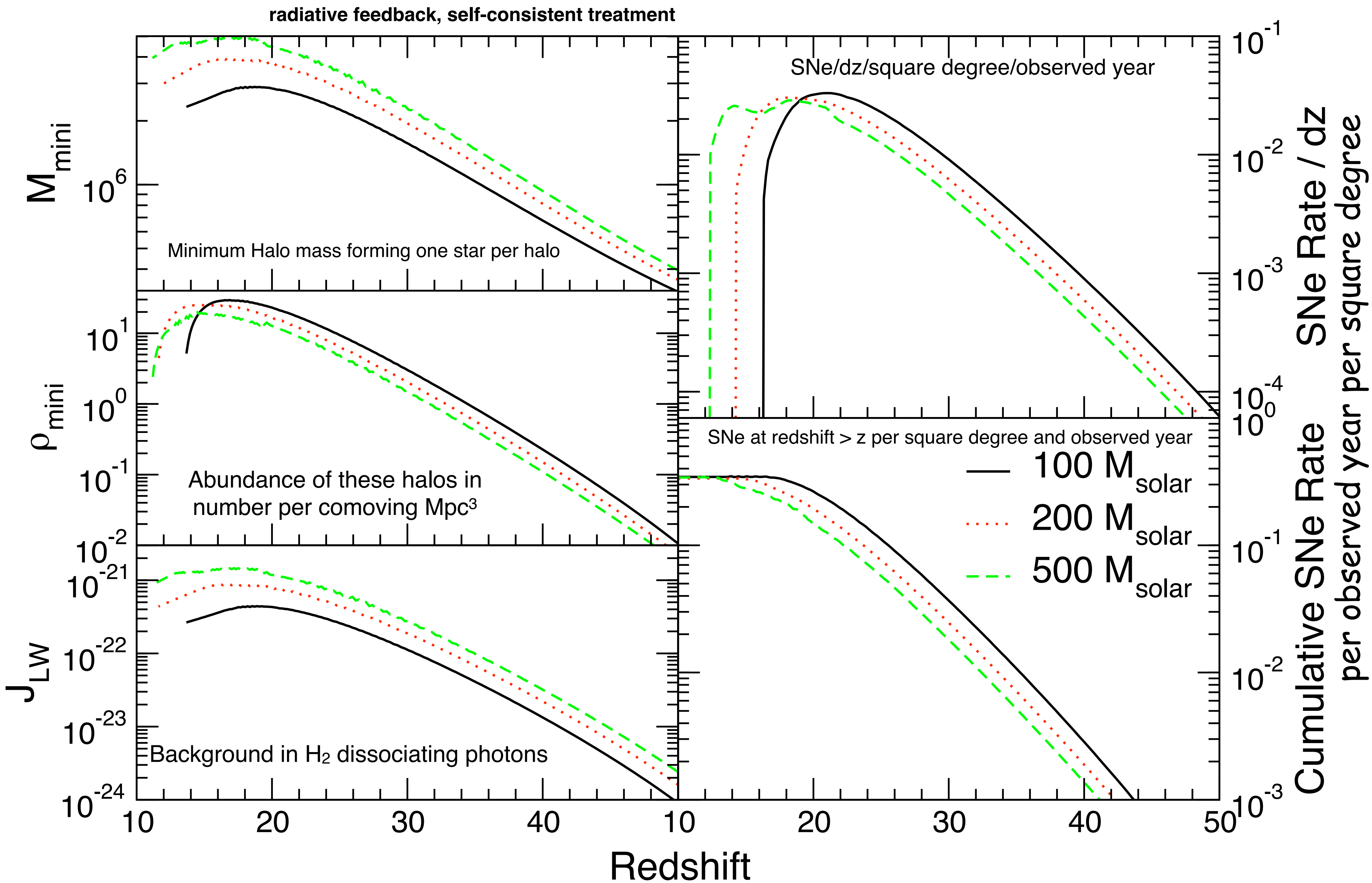
Non-equilibrium chemistry & cooling, three body H2 formation, chemical heating, H2 line transfer, collision induced emission and its transport, and sufficient resolution to capture chemo-thermal and gravitational instabilities. Stable results against variations on all so far test dark matter variations,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

Perfectly consistent with observations!
Could have been a **large problem**!

- New: Proto-stellar densities. First 10 Jupiter masses understood. Another ~13 mass doublings to go...

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 2008 in prep; Turk, Abel & O'Shea 2008 in prep
idealized spheres: Bodenheimer 1986; Haiman et al 1997; Omukai & Nishi 1998; Bromm et al 1999,2000,2002; Ripamonti & Abel 2004

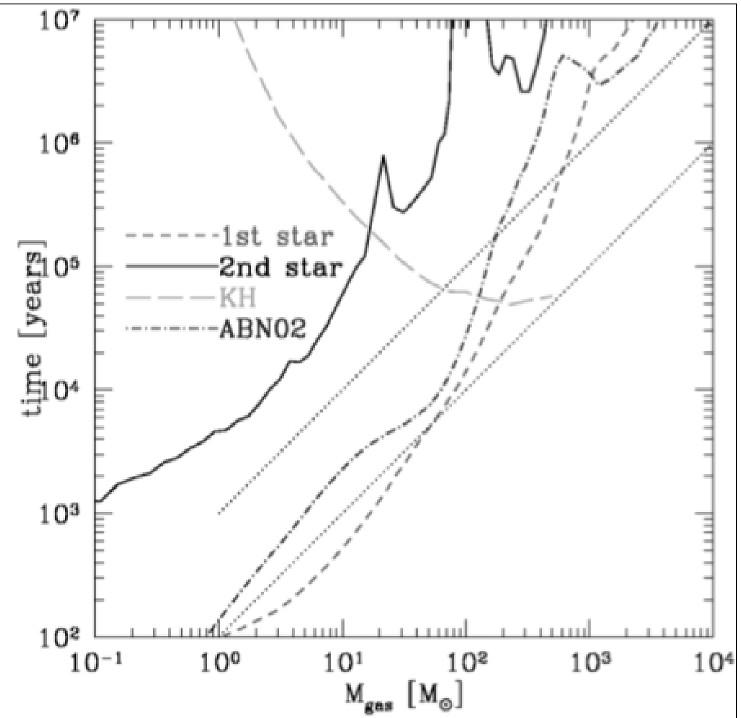
Supernovae & GRBs at high redshift?

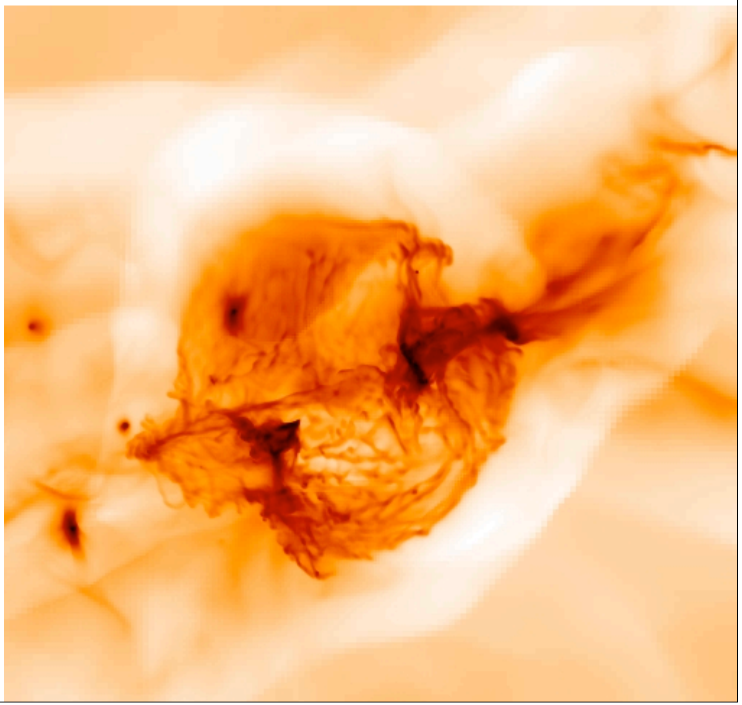


Wise & Abel 2005, ApJ

Pop III.2

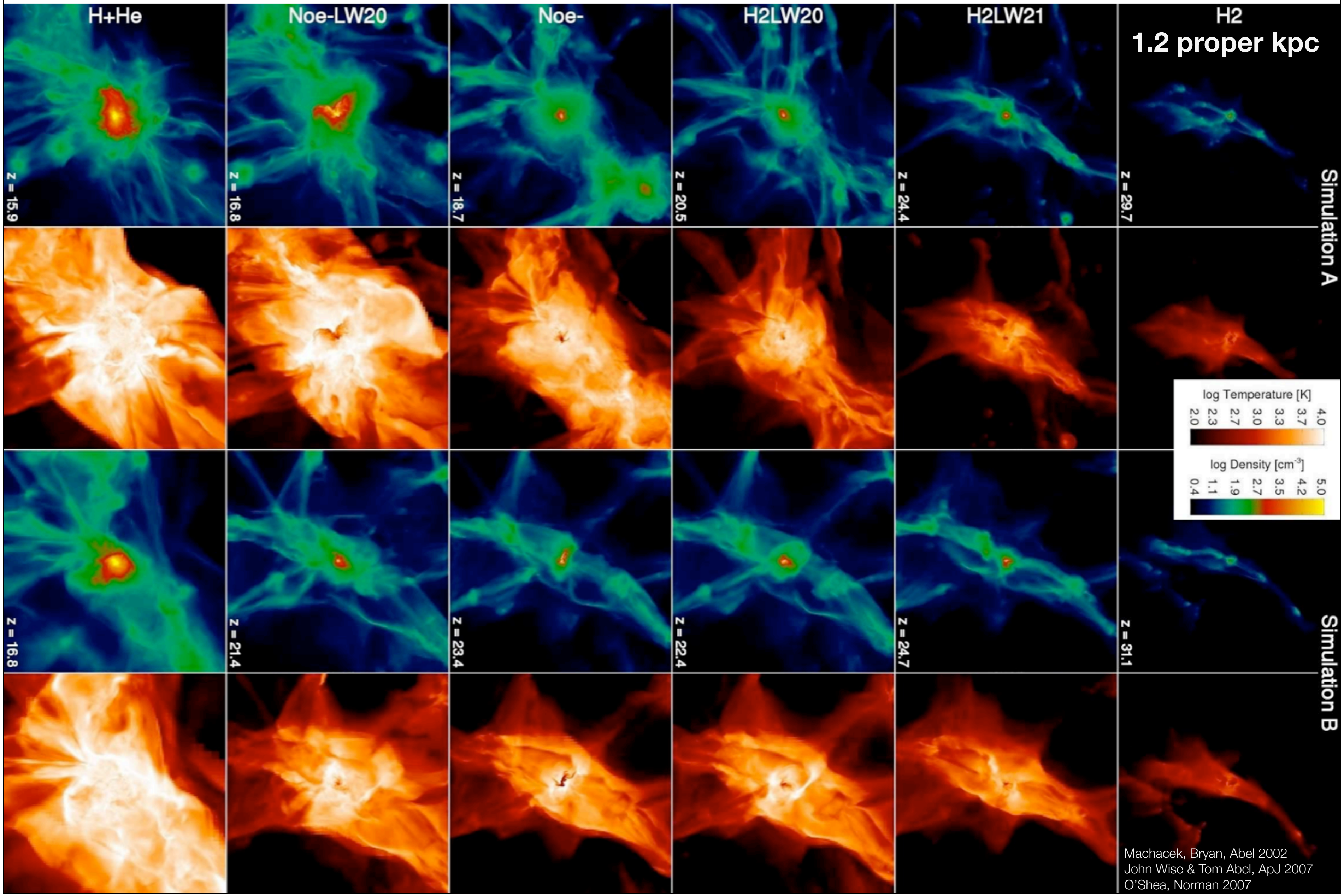
- Exciting development over past three years.
- Stars forming from previously ionized yet not metal enriched material typically will give a factor of a few lower masses.
- Profound consequences for metal enrichment and studying the fossil record.
- Can no longer neglect e- and proton collisions for H_2 cooling (Glover & Abel 2008)





3D simulations: O'Shea et al 2005, Yoshida et al 2007

Strong H_2 suppression from dissociating UV background? No!



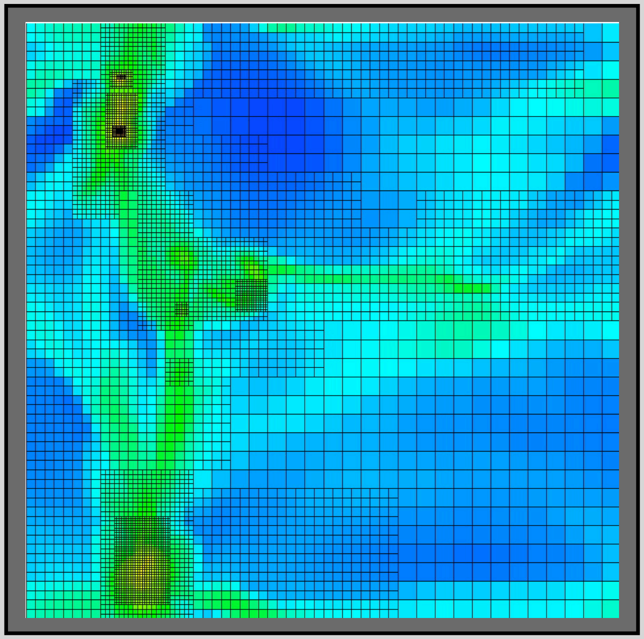
Machacek, Bryan, Abel 2002
John Wise & Tom Abel, ApJ 2007
O'Shea, Norman 2007

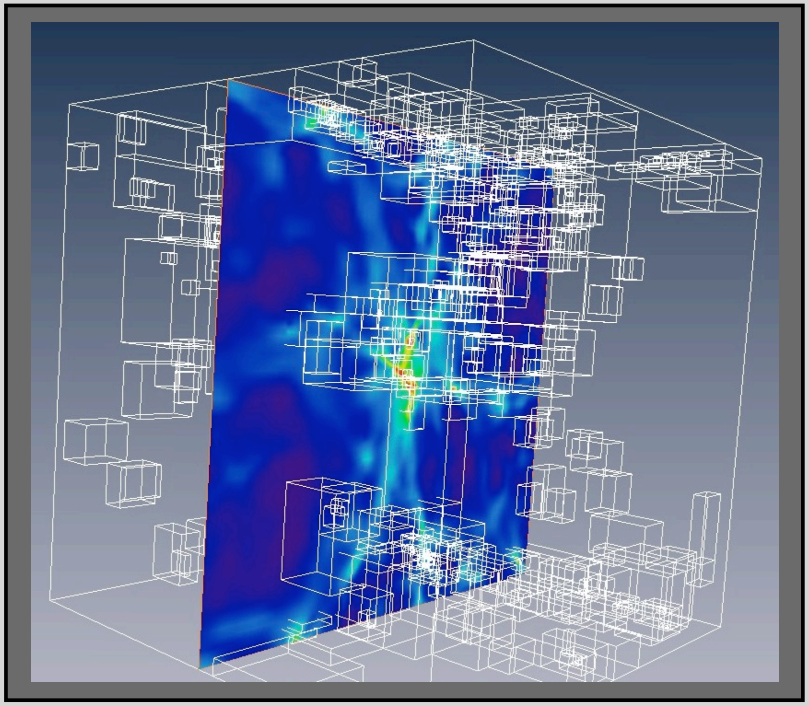
Clear consequences of very massive first stars:

- 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

Cosmological Adaptive Mesh Refinement

- **Enzo:** Bryan and Norman 1997-; Abel et al 97; Anninos et al 97; Bryan, Abel & Norman 2002; O'Shea et al; Abel, Wise & Bryan 2006
  - ~90,000 lines of code in C++ and F77
  - Cosmological Radiation Hydrodynamics adapting in space and time
  - Dynamic range up to 1e15 using quadruple precision coordinates in space and time
  - Dynamically load balanced parallel with MPI
  - Gravity, DM, Gas, Chemistry, Radiation, star formation & feedback
  - Current **new** Developments **@ KIPAC**: completely new dimensionally unsplit hydro algorithms, higher order time updates, exact **3D radiation transport**, very high density chemistry, HD & fine structure line cooling, relativistic hydro, **MHD**, new visualization toolkits





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, Wise & Abel 2007 and Wise, Abel, Wang 2008 in prep.

Keeps time dependence of transfer equation

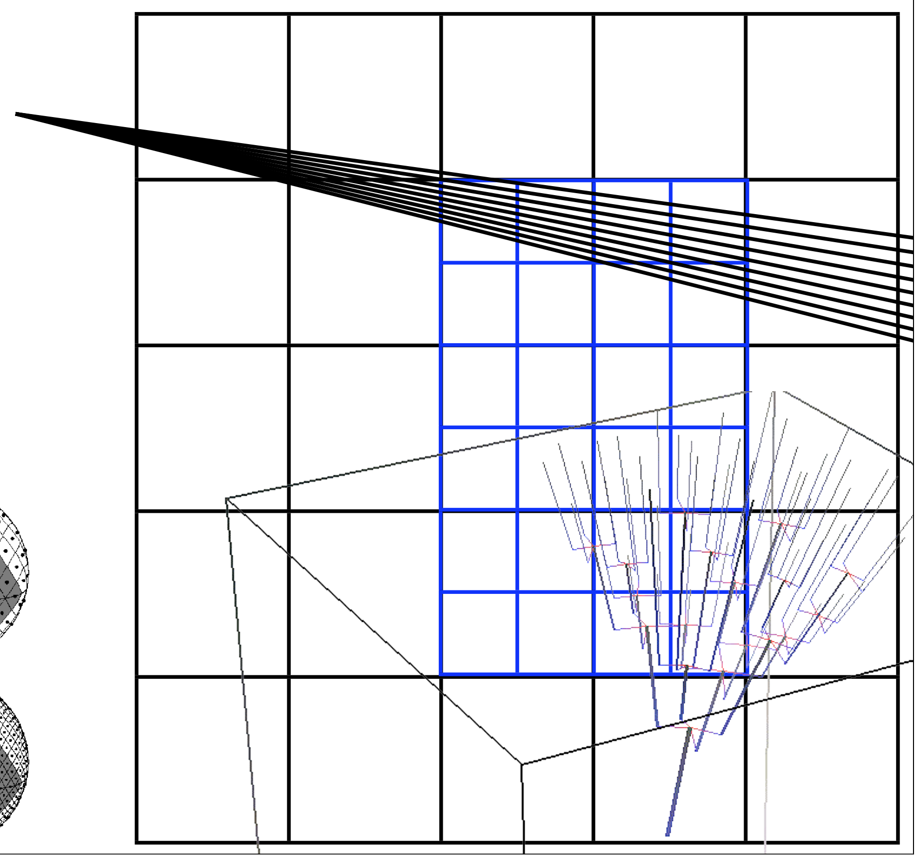
Exact Adaptive ray-tracing of PhotonPackages using HEALPIX pixelization of the sphere. Photon conserving at any resolution.

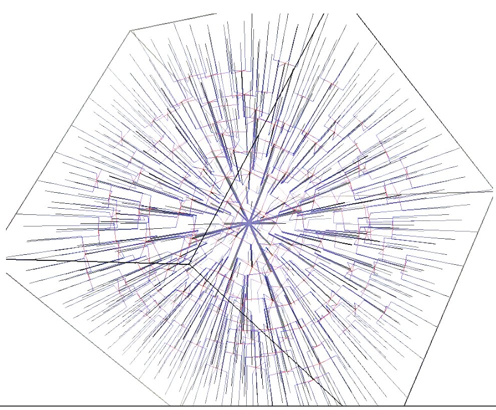
Parallel using MPI and dynamic load balancing.

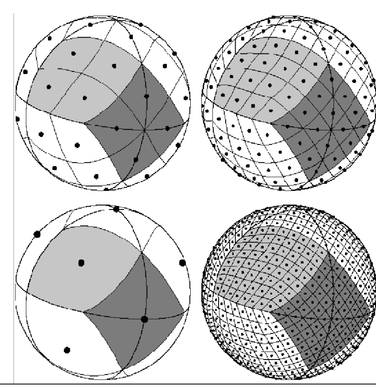
Fully coupled with non-equilibrium chemistry and hydrodynamics.

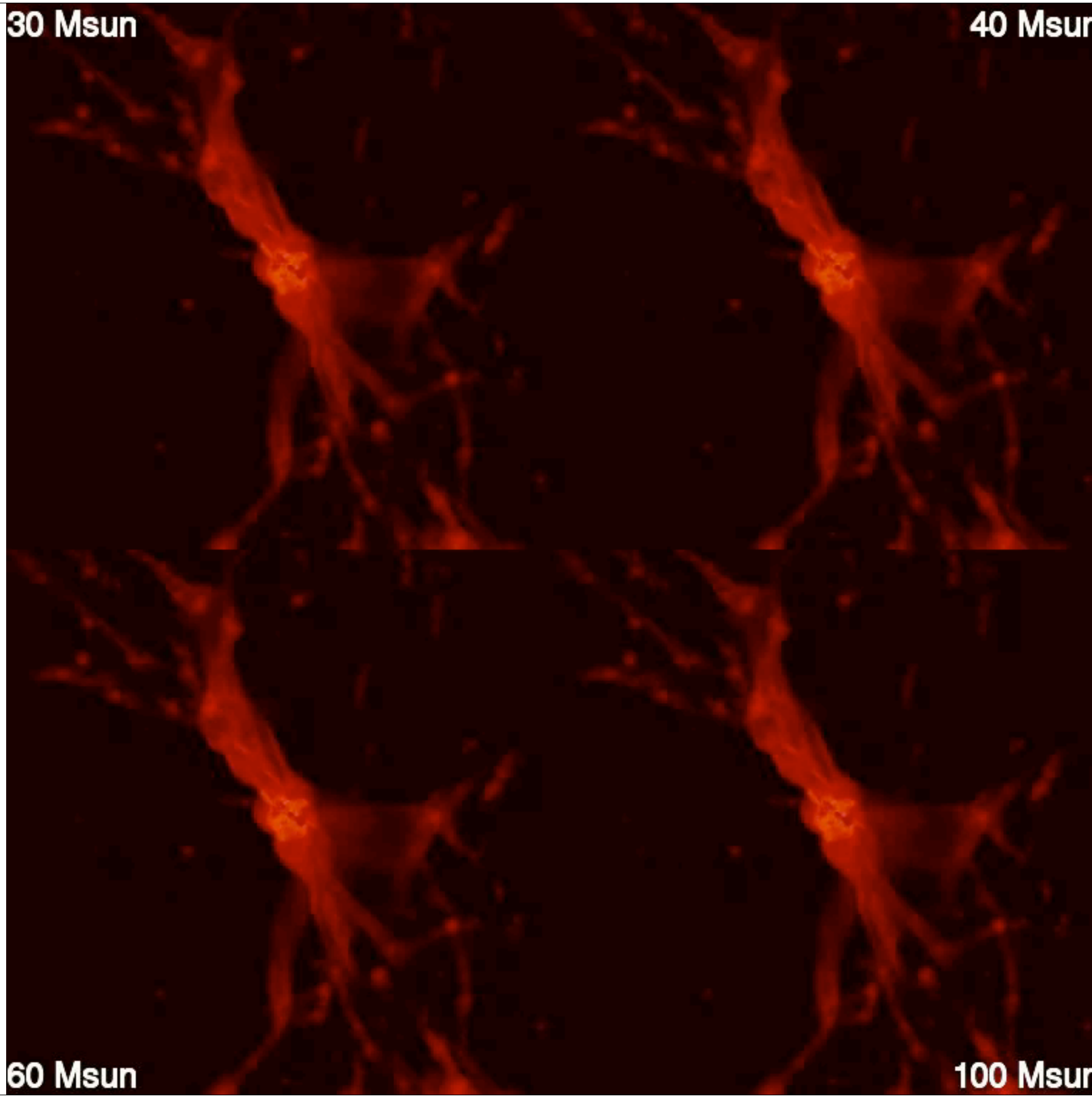
$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\partial I_\nu}{\partial r} = -\kappa I_\nu$$

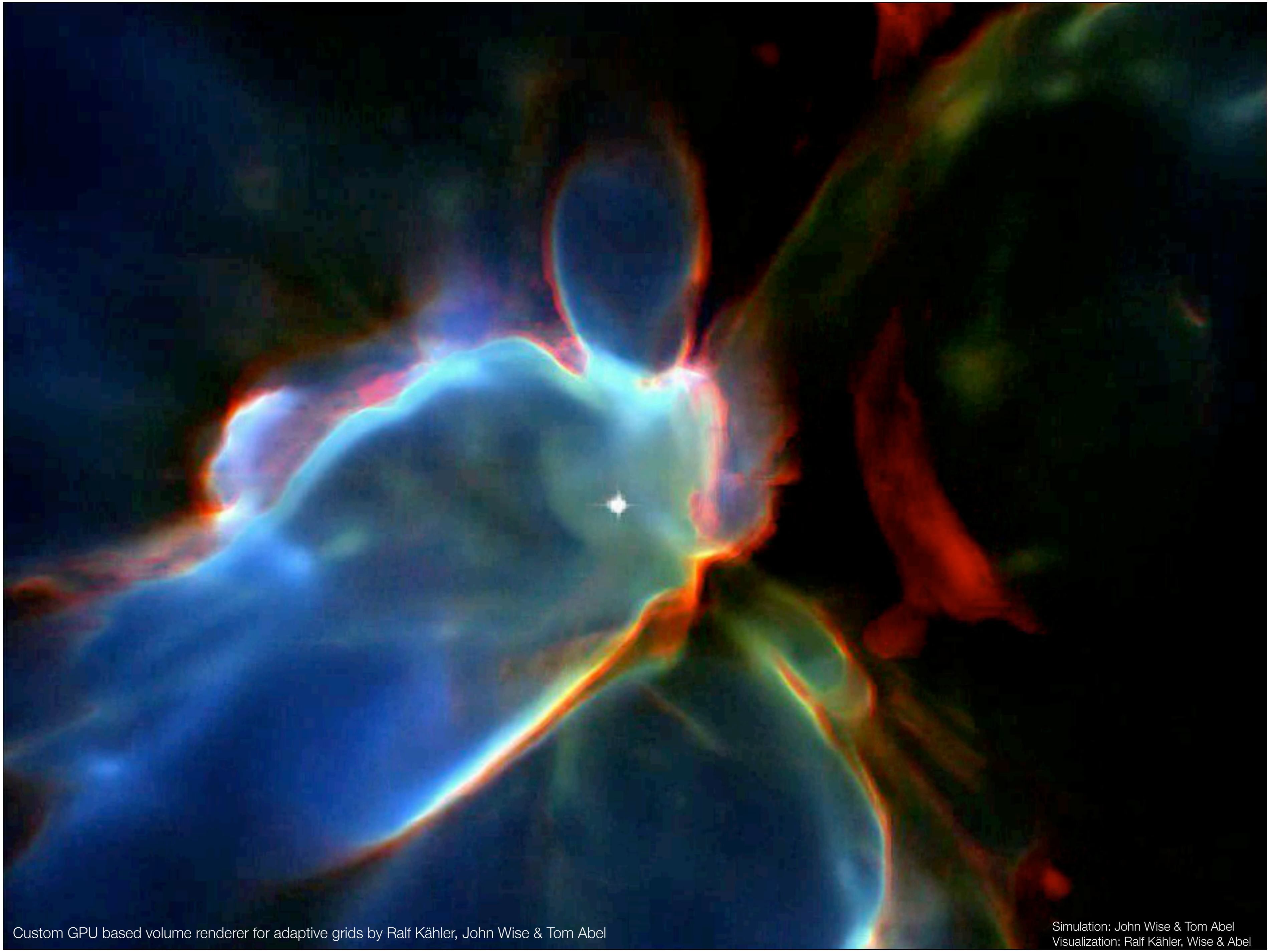
Transfer done along adaptive rays
Case B recombination



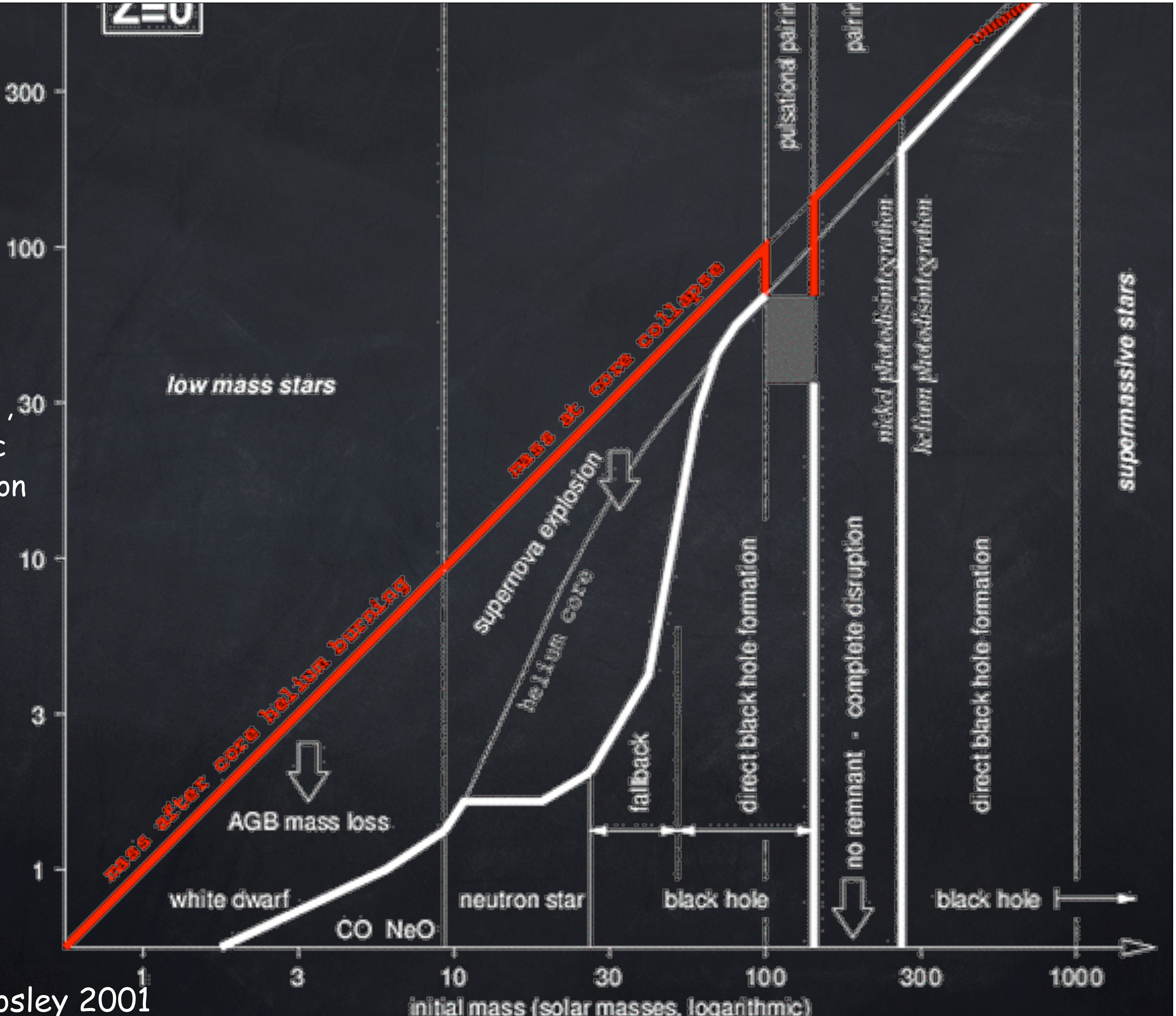





30 Msun
40 Msun
60 Msun
100 Msun

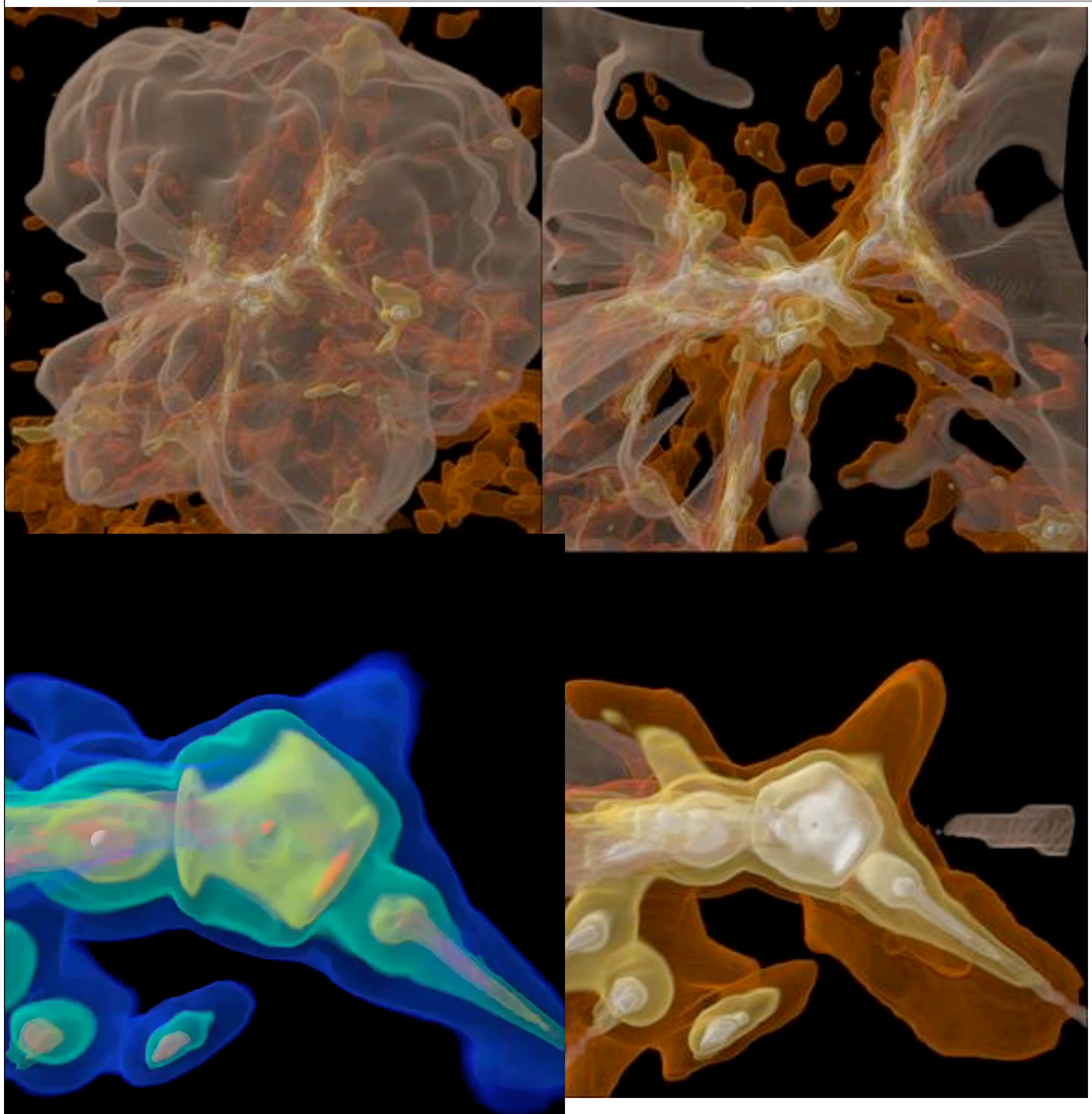

Custom GPU based volume renderer for adaptive grids by Ralf Kähler, John Wise & Tom Abel
Simulation: John Wise & Tom Abel
Visualization: Ralf Kähler, Wise & Abel

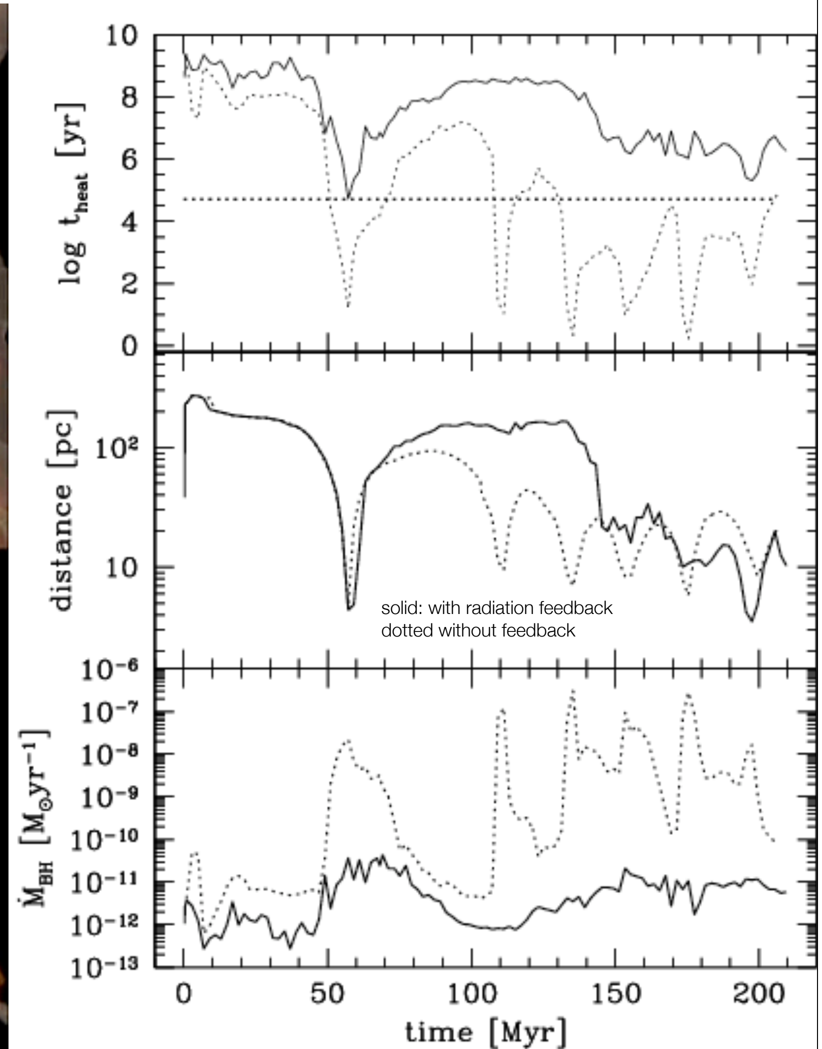
Non-rotating , non-magnetic stellar evolution models ...



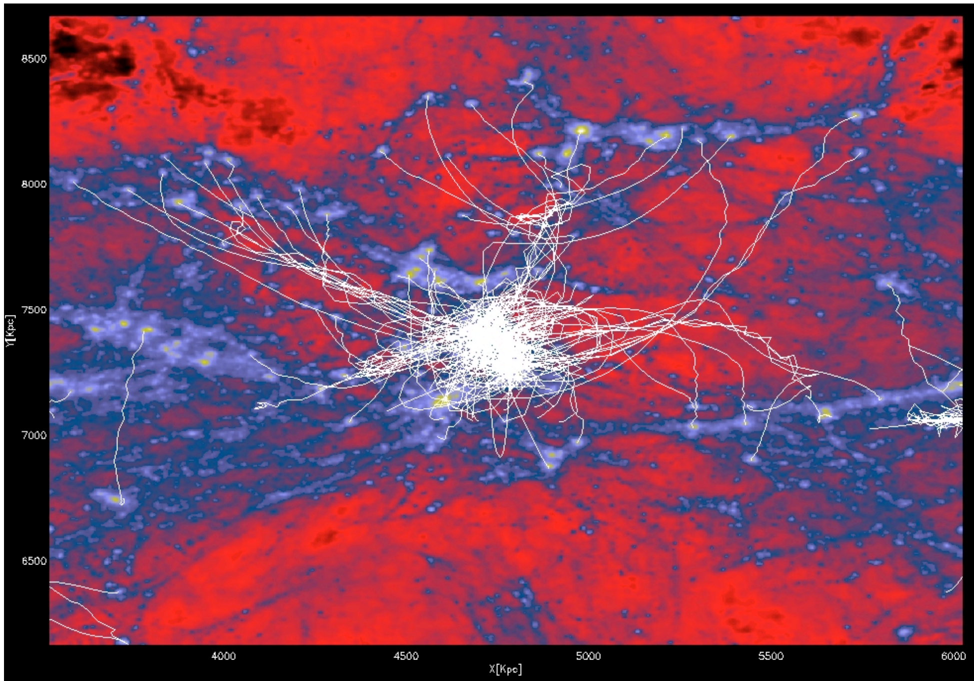
Heger &Woosley 2001

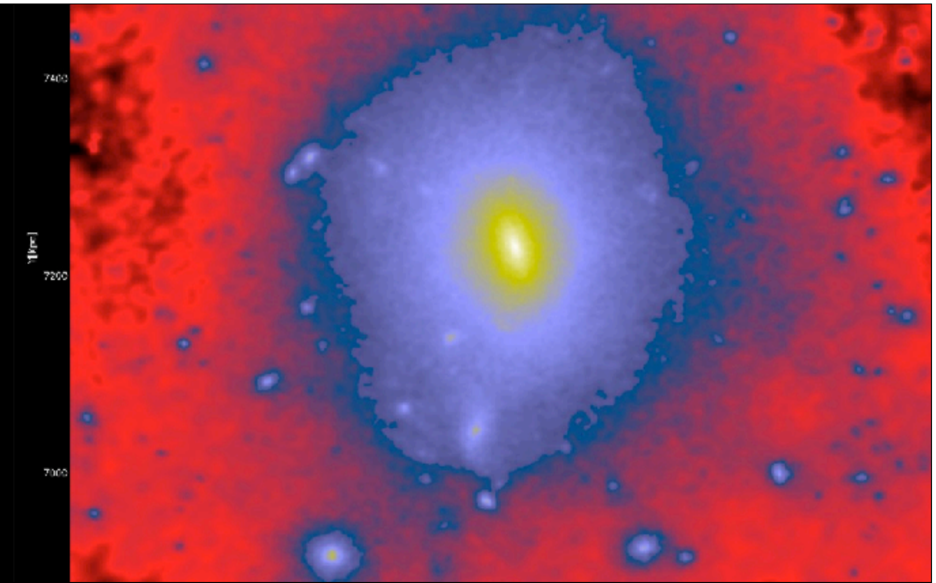
Insignificant BH accretion - no mini quasars through this process, nor pre-cursors of Quasars.





Alvarez, Wise & Abel in prep.



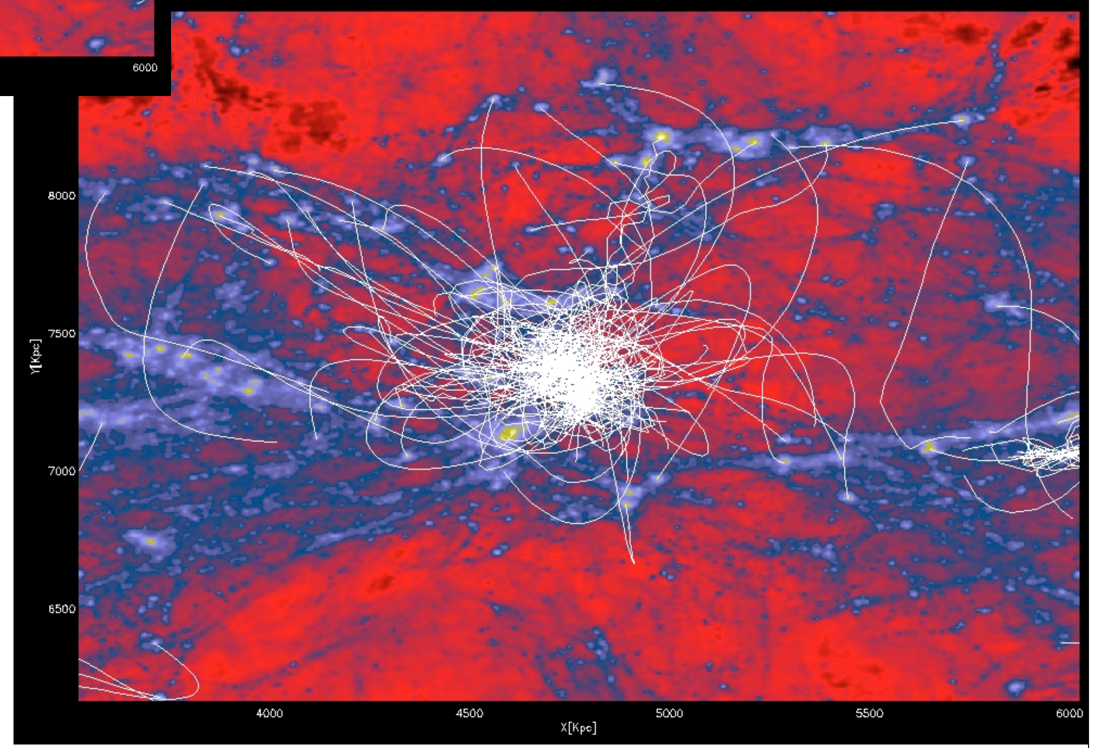


$2e12M_{\odot}$ object at

z=1, resolved with
2e6 particles

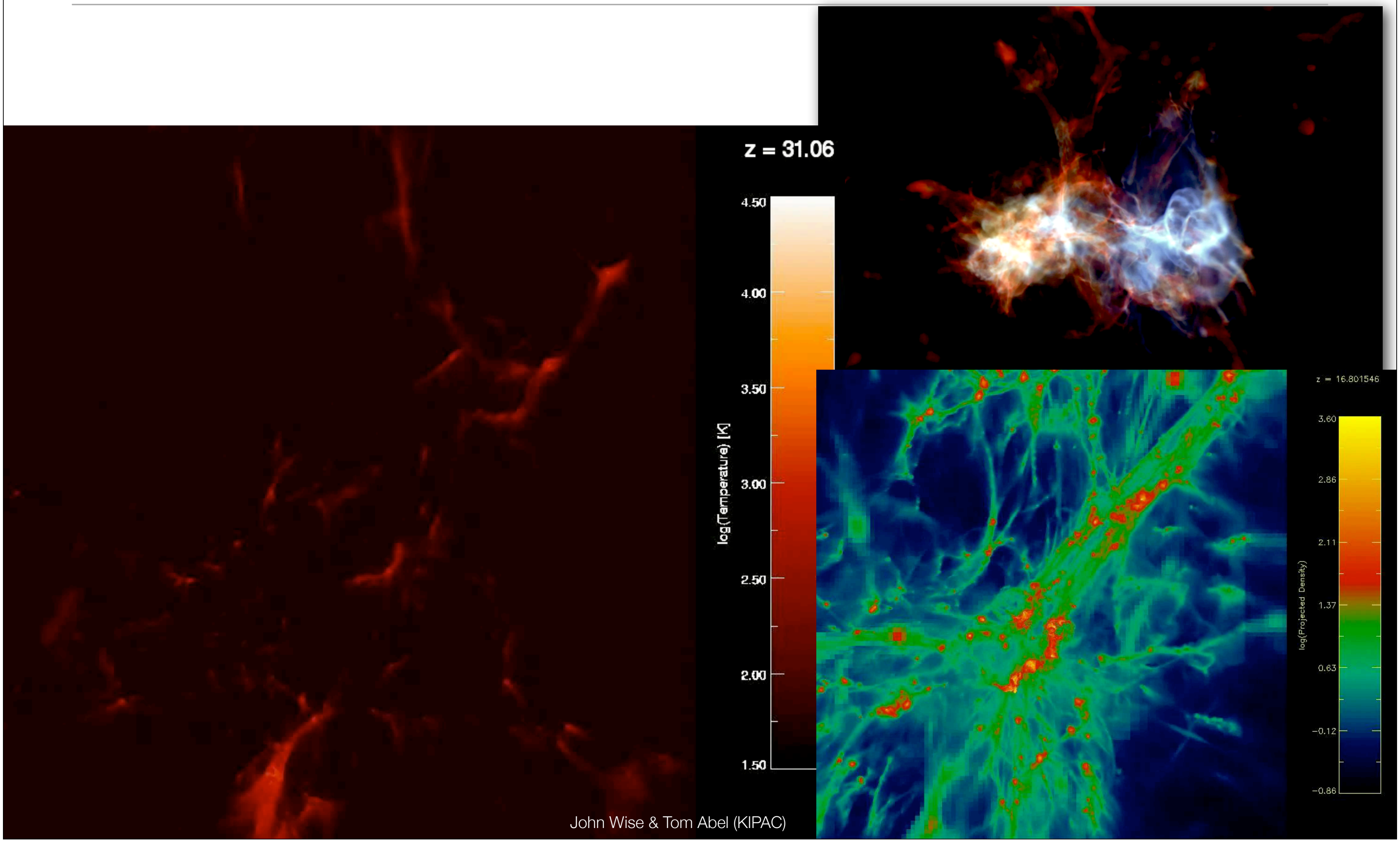
Two interesting facts:

- Approximately as many BHs kicked in as out.
- Dynamical friction time changes dramatically if BH leaves its host halo

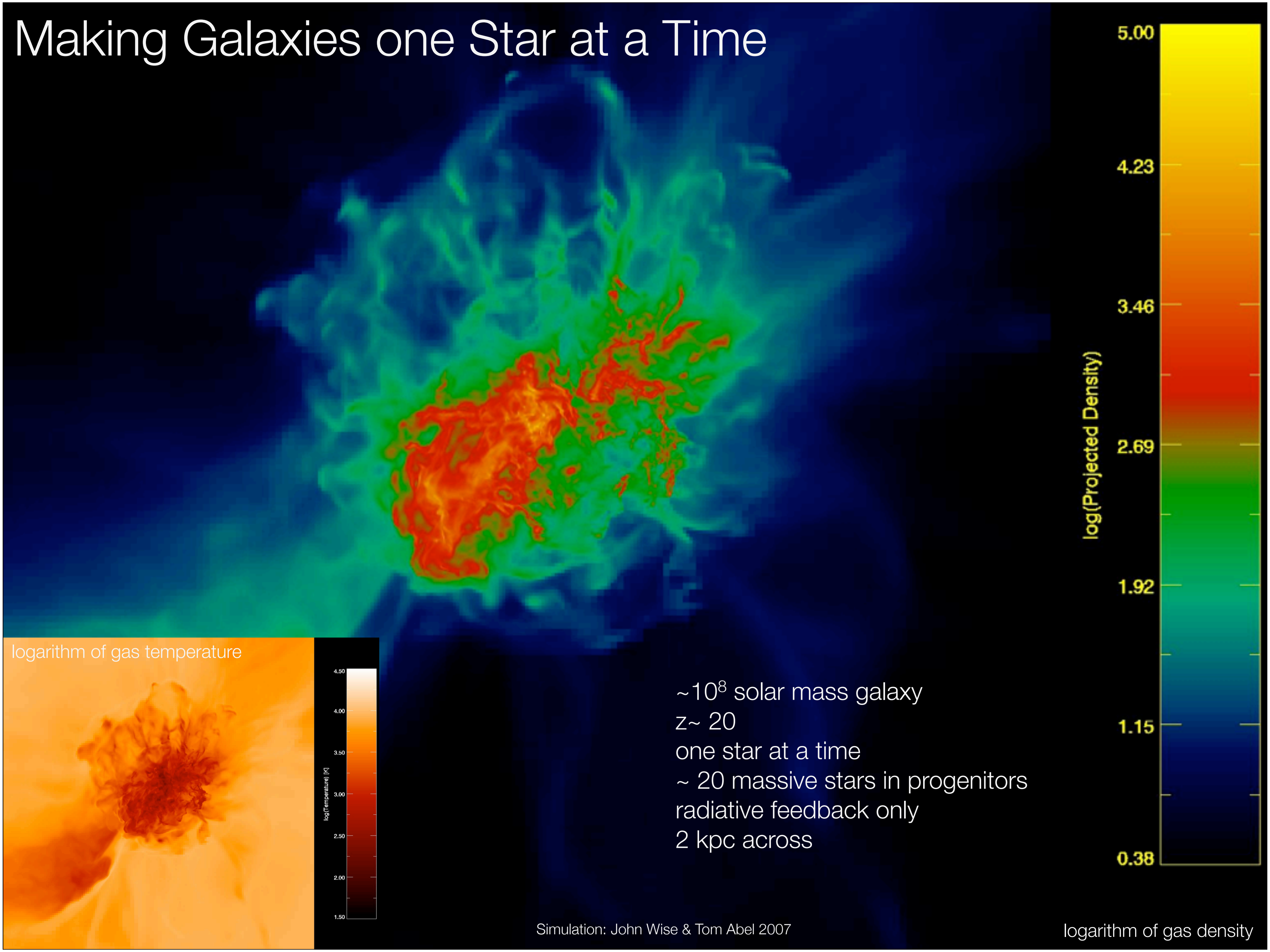


Micic, Abel & Sigurdsson 2006

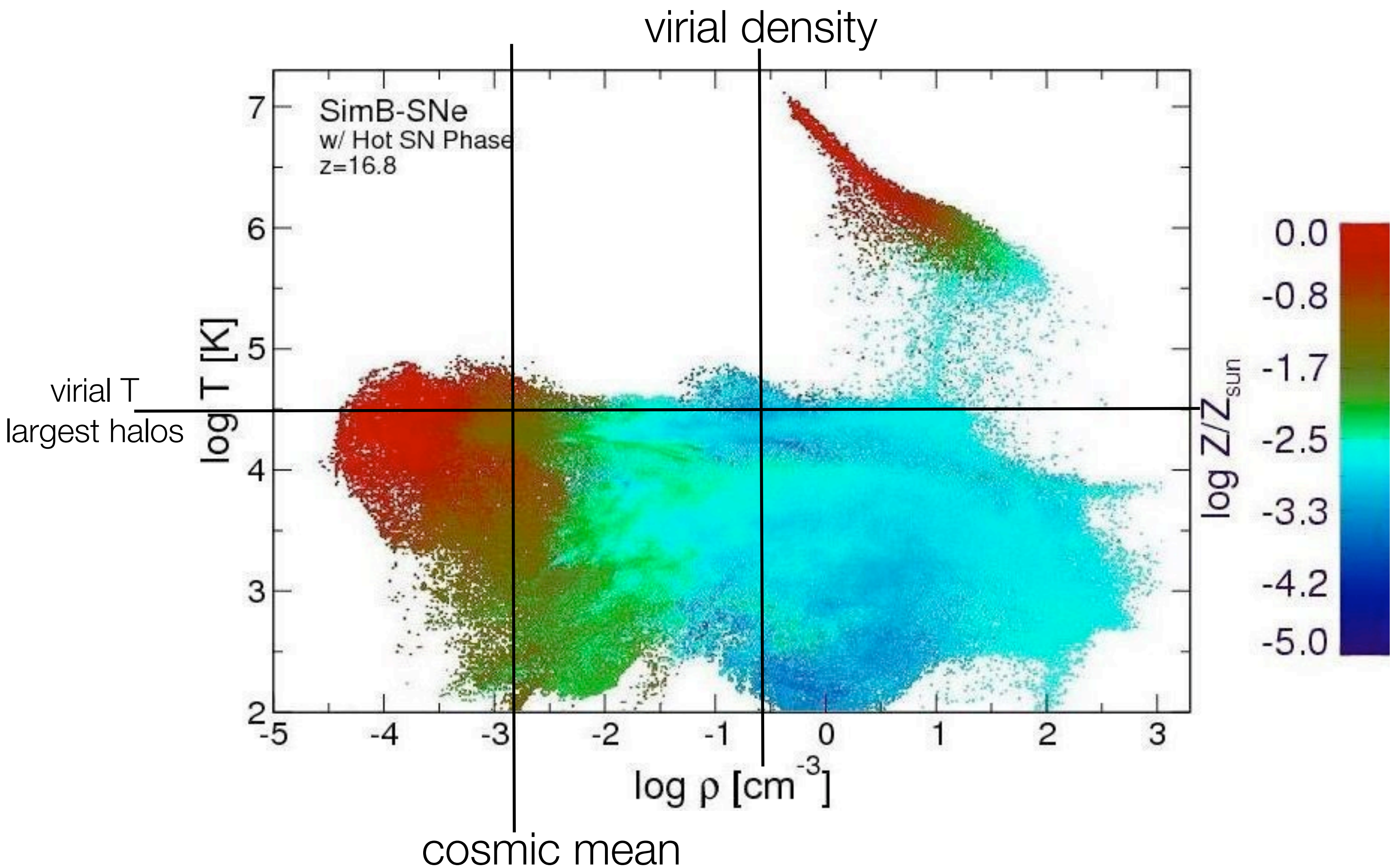
Galaxies, one star at a time



John Wise & Tom Abel (KIPAC)


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
4.50
4.00
3.50
3.00
2.50
2.00
1.50
~10^8 solar mass galaxy
z~ 20
one star at a time
~ 20 massive stars in progenitors
radiative feedback only
2 kpc across
Simulation: John Wise & Tom Abel 2007
logarithm of gas density

Phase diagram



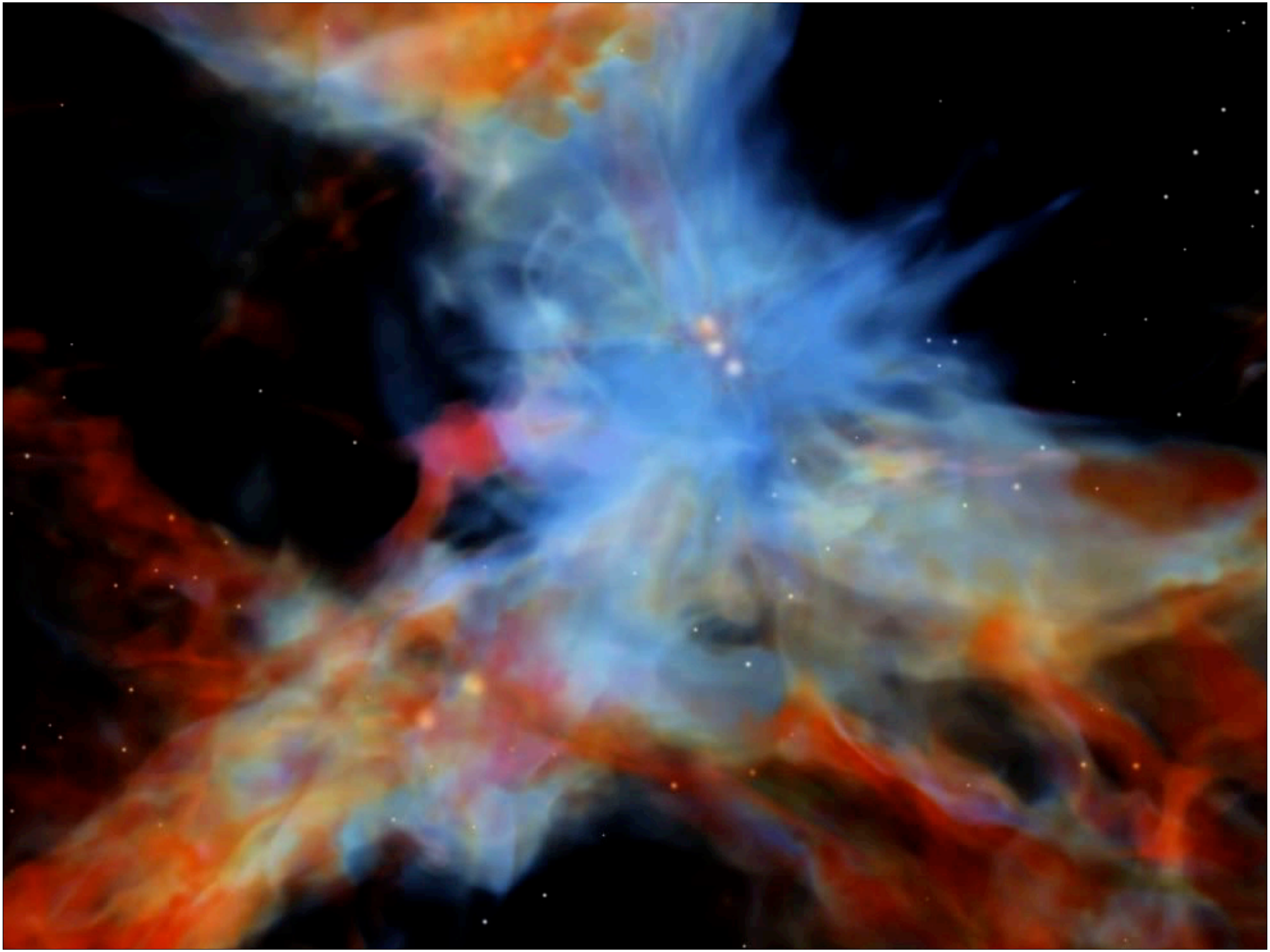
How big of a difference do Pop III stars make for the first galaxies?

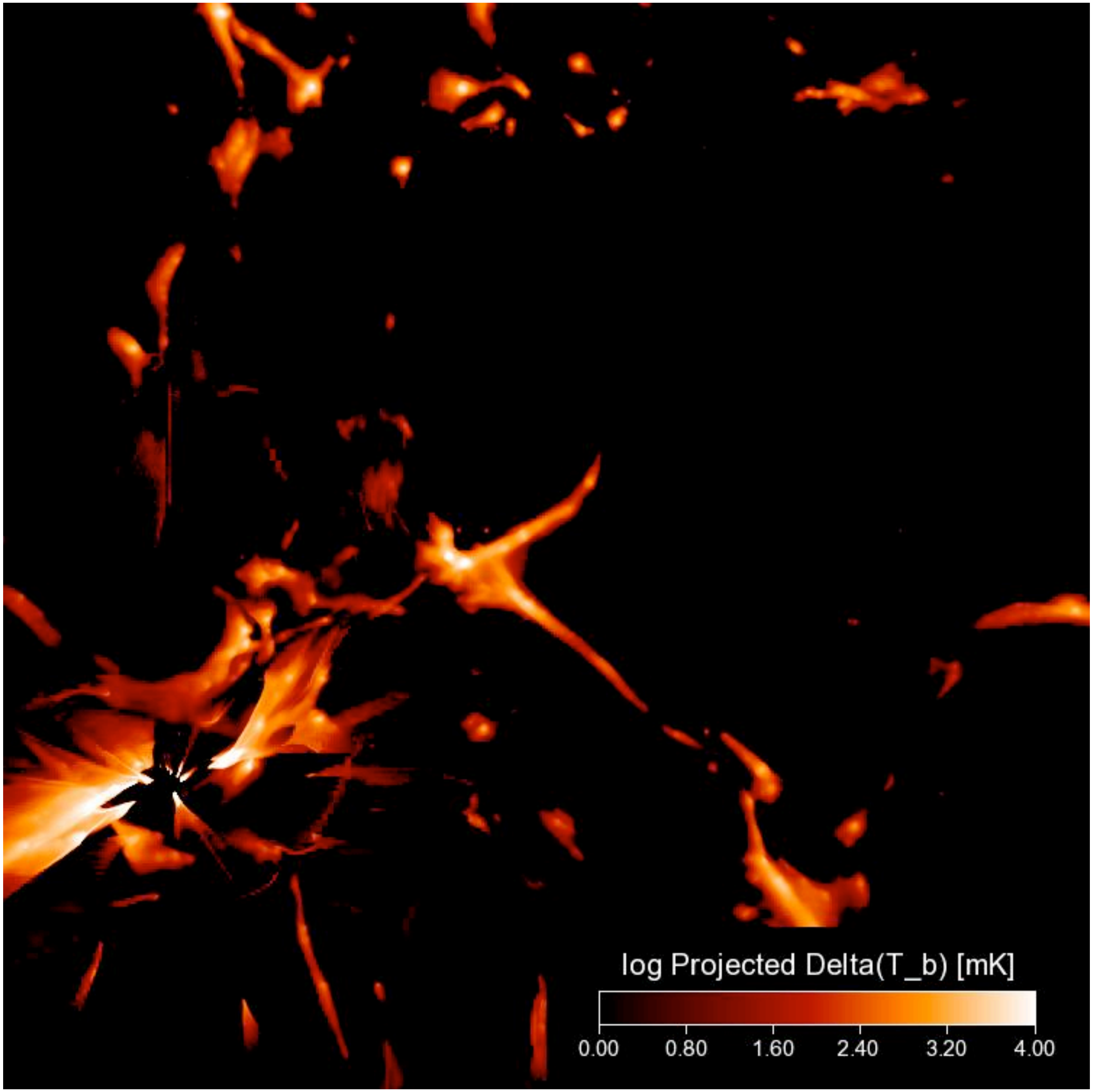
- Feedback is different from an effective equation of state

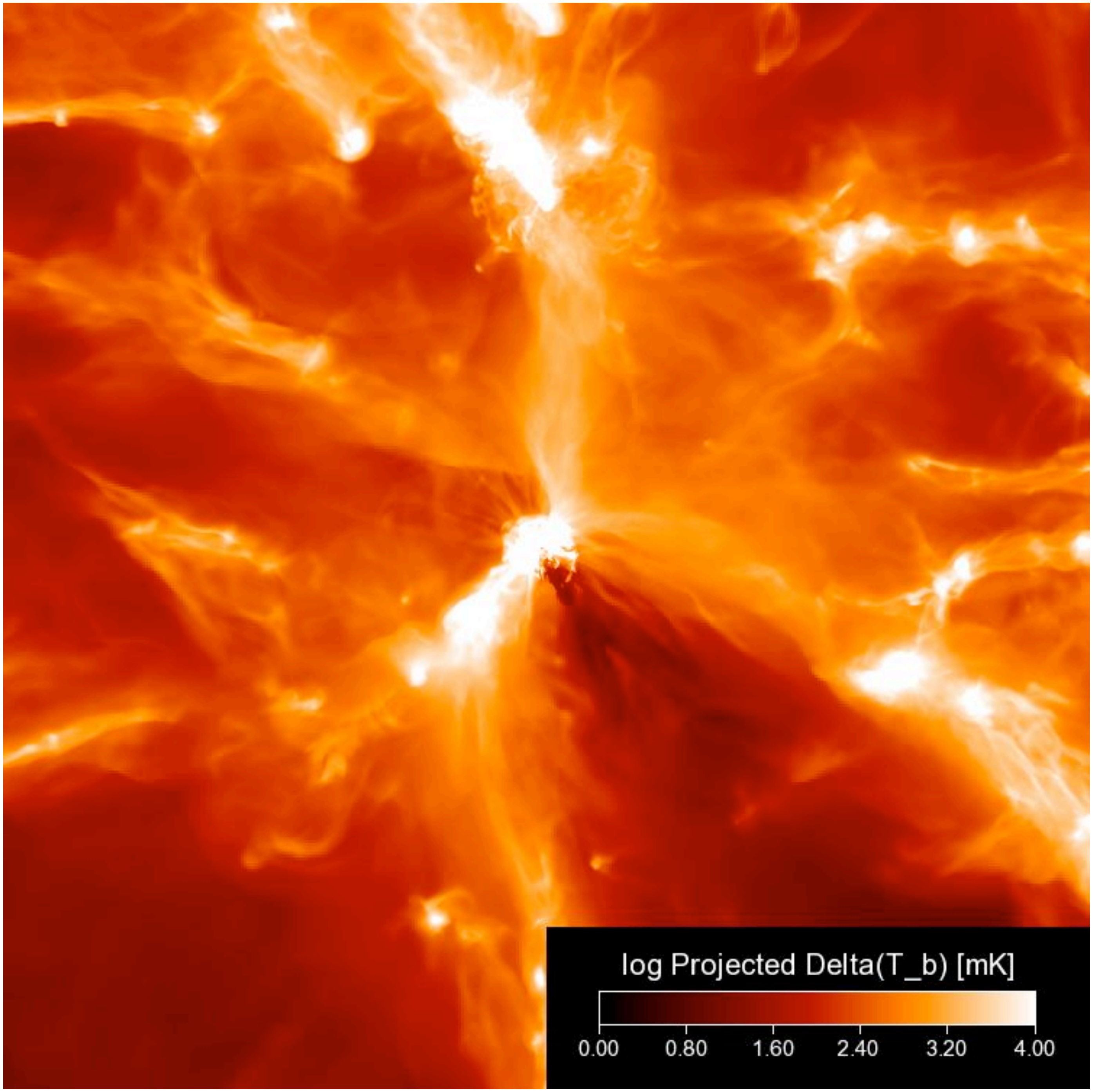
	Halo Mass $[M_\odot]$	Spin Parameter
Simulation A	3.47×10^7	0.030
Simulation B	3.50×10^7	0.022

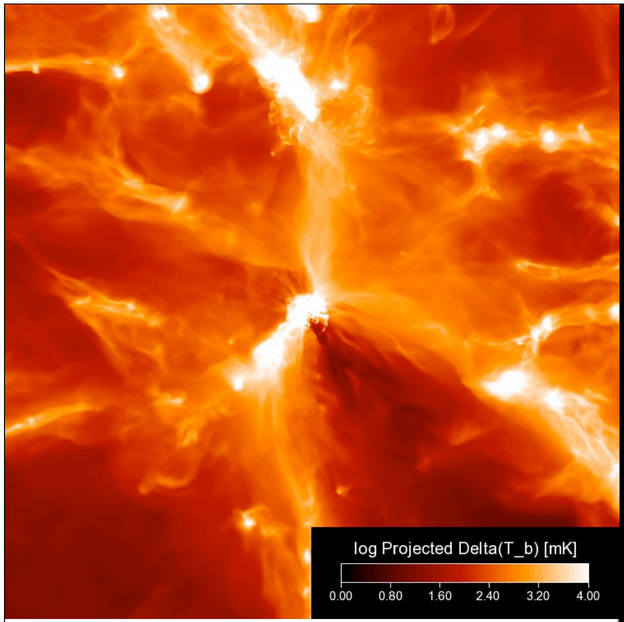
	N★ (< rvir)	N★ (< 3rvir)	Mgas / Mtot	λgas	
SimA-Std H+He cooling	…	…	0.14	0.010	
SimA-SF transfer only	14	16	1/2 0.081	0.053	5
SimB-Std H+He cooling	…	…	0.14	0.010	
SimB-SF transfer only	13	19	4/5 0.11	0.022	2
SimB-SNe full	7	13	1/3 0.049	0.097	10

Wise & Abel 2007

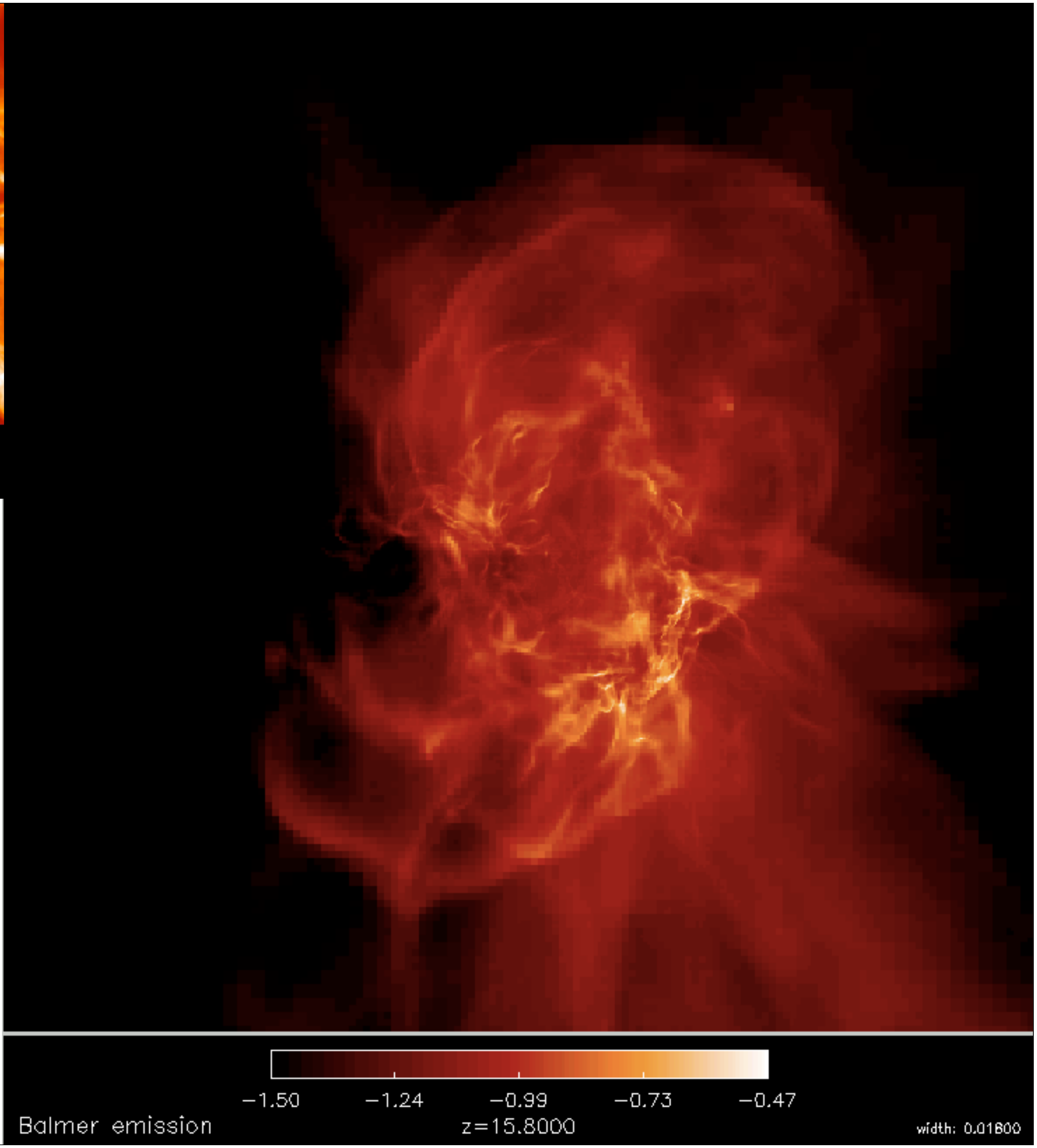



log Projected Delta(T_b) [mK]
0.00
0.80
1.60
2.40
3.20
4.00


log Projected Delta(T_b) [mK]
0.00
0.80
1.60
2.40
3.20
4.00



log Projected Delta(T_b) [mK]
0.00
0.80
1.60
2.40
3.20
4.00

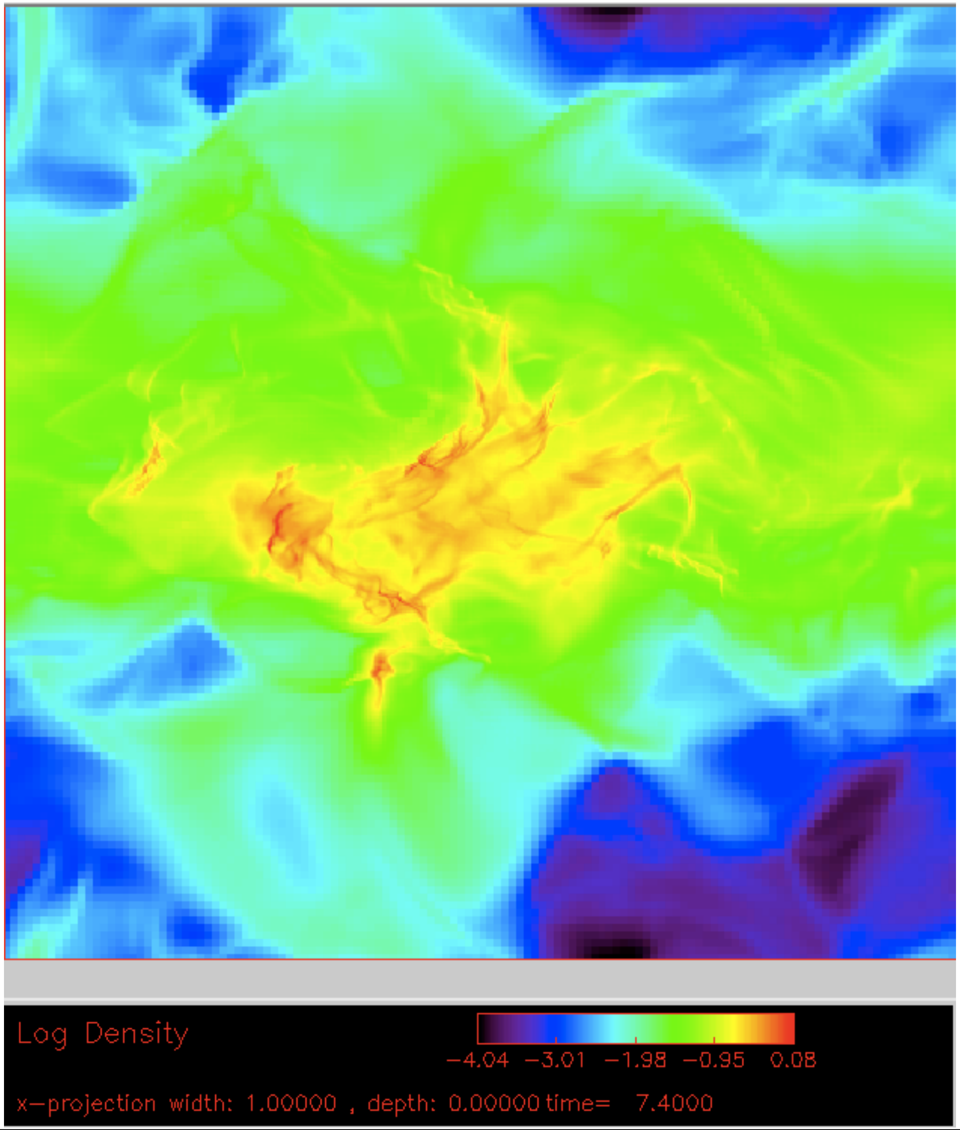


−1.50
−1.24
−0.99
−0.73
−0.47
Balmer emission
z=15.8000
width: 0.01800

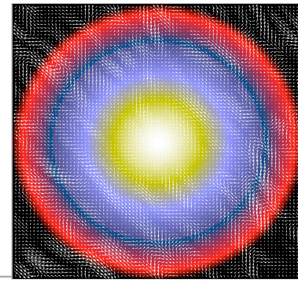

CALIFORNIA NEBULA, NGC1499
500 pc = 1,500 light years away
30 pc long
Xi Persei, منكب mankib, Shoulder of Pleiades:
O7.5III
330,000 solar luminosities
~40 solar masses, Teff=3.7e4K

Initial Conditions for Star Formation

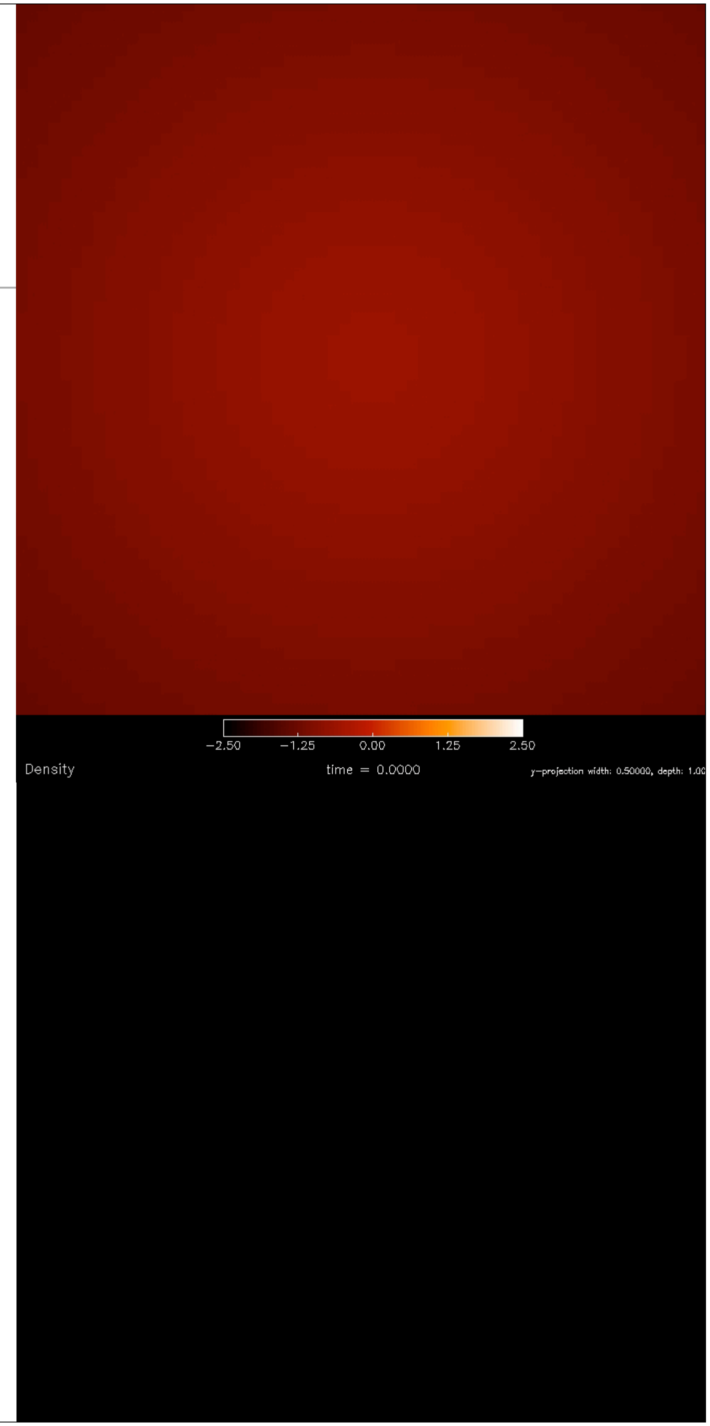
- Force driving with fixed pattern
- Shaped force to mimic central concentrated conditions
- 5 levels of refinement
- Jeans length at least resolved by 8 cells
- In present day star formation the level of turbulence and feedback are thought to determine the initial mass function. Metallicity alone may not be what determines the transition from Pop III to Pop II ....



Local Star Formation



- A 1e4 Msun cloud, radius 3.6 pc with central flat core (~1000 Msun) and r^{-2} envelope, central density ~ 10^4 /cm^3.
- Initial Kolmogorov turbulent velocity spectrum with Mach 10.
- We model proto-stellar growth by Bondi-Hoyle accretion.
- Cooling down to 10 K using a fitted cooling function, which essentially keeps gas isothermal.
- Top grid resolution 128^3. Four level of AMR level using Jeans refinement criterion (Jeans number 4), corresponding to 1000 AU best resolution.
- Adaptive ray tracing for UV ionizing radiation coupled with HLL-PLM Hydro/MHD solver.
- Main sequence luminosity for radiating stars (>10 Msun).

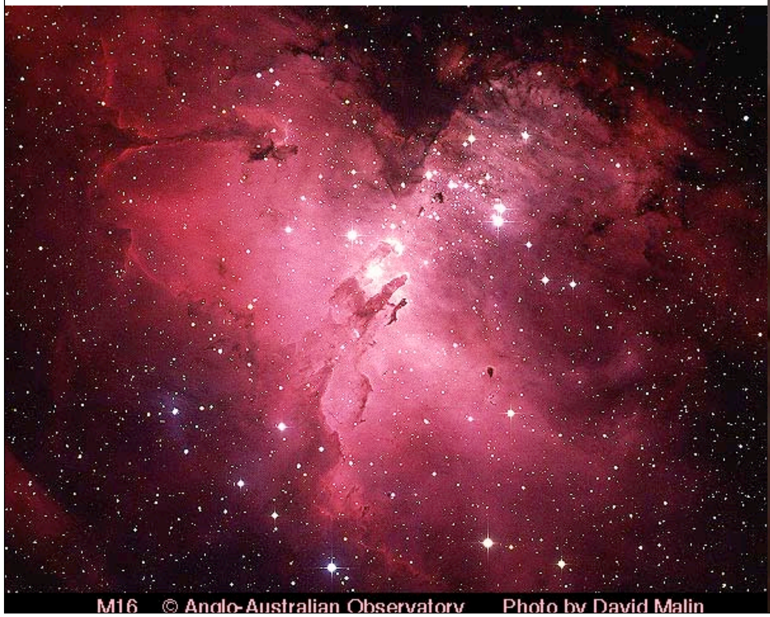


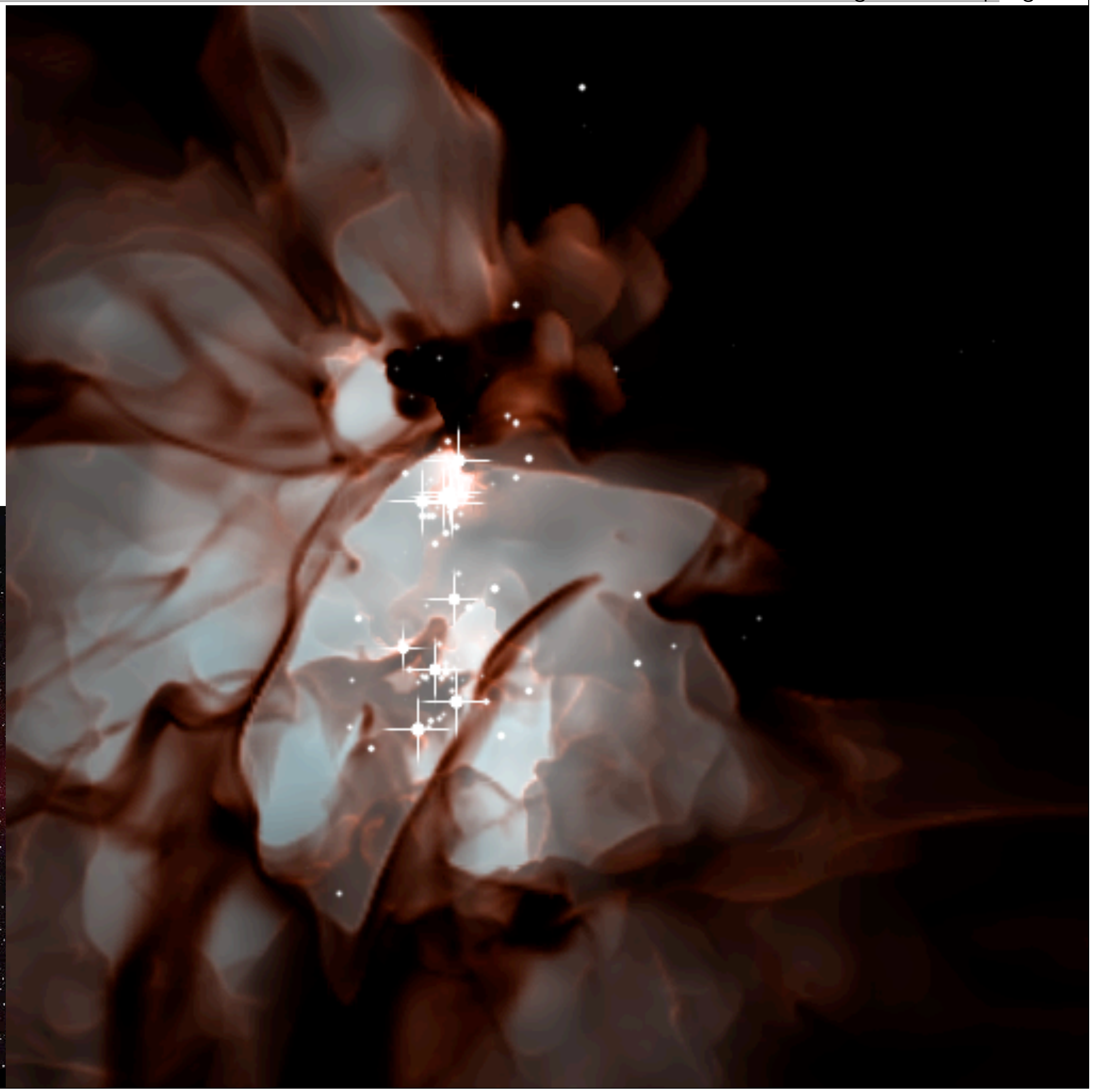
Wang & Abel 2008, in preparation.

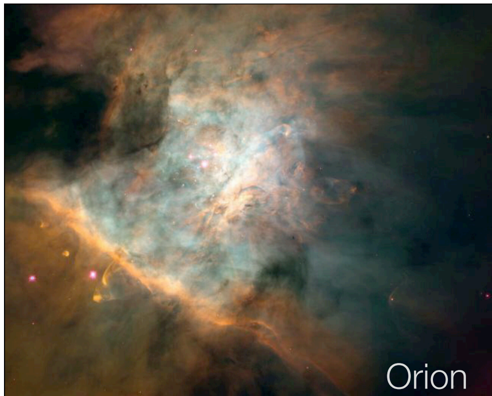
Using local HII regions as Laboratory for Star Formation

Ianucci, Wang & Abel in progress

- Massive Stars light up initial conditions
- IFU spectroscopy possible in many lines
- Radio - Xrays







Galaxy Formation models: a friendly reminder

missing:

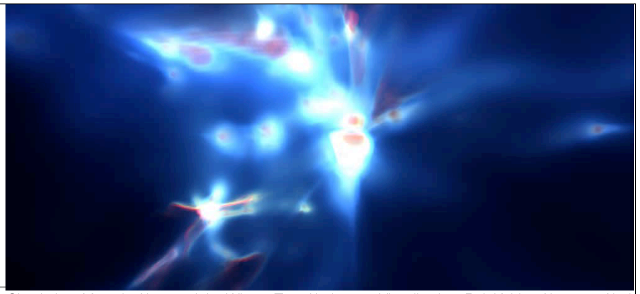
- B field
- Cosmic Rays
- Radiation Transport & Physics
- Molecules
- Dust
- Radiation Pressure on Dust & Lyman alpa
- HII regions

included:

- DM dynamics
- “Hydrodynamics”
- Some cooling
- “Star formation”
- “Supernova feedback”
- “AGN feedback”

Not ab initio

Summary



Simulation: Marcelo Alvarez, John Wise & Tom Abel 2007 Visualization: Ralf Kähler, Alvarez & Abel

- Wide range of birth, life & death of the first massive stars are being explored on super computers.
- HII regions of the first stars evaporate their host-halos leave an expanding medium with ~ 1 cm^{-3} density. This fact and small amounts of radiation feedback limits black hole accretion and growth.
- Ab initio calculations of galaxy formation: one Star at a Time
  - Enormous impact from early feedback: f_B, spins, etc.
  - kpc scales predicted with great confidence. Larger scales require more a priori phenomenological inputs.
  - An ab initio understanding of star formation at all epochs is a key missing “ingredient” in understanding structure formation
  - Still more physics we need to implement ...
- What is computable from first principles and what is observable is getting closer...