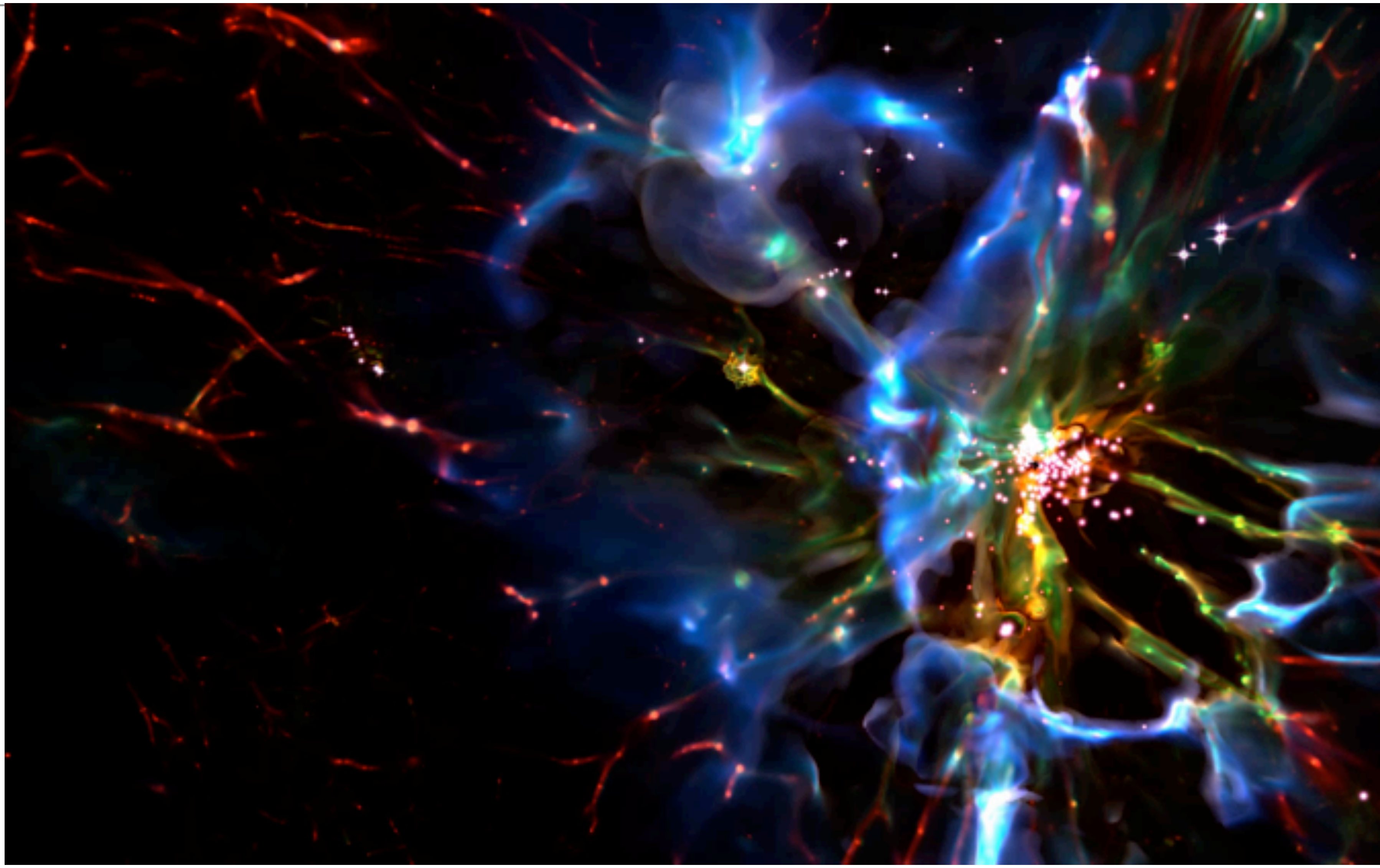
The First Stars and Black Holes

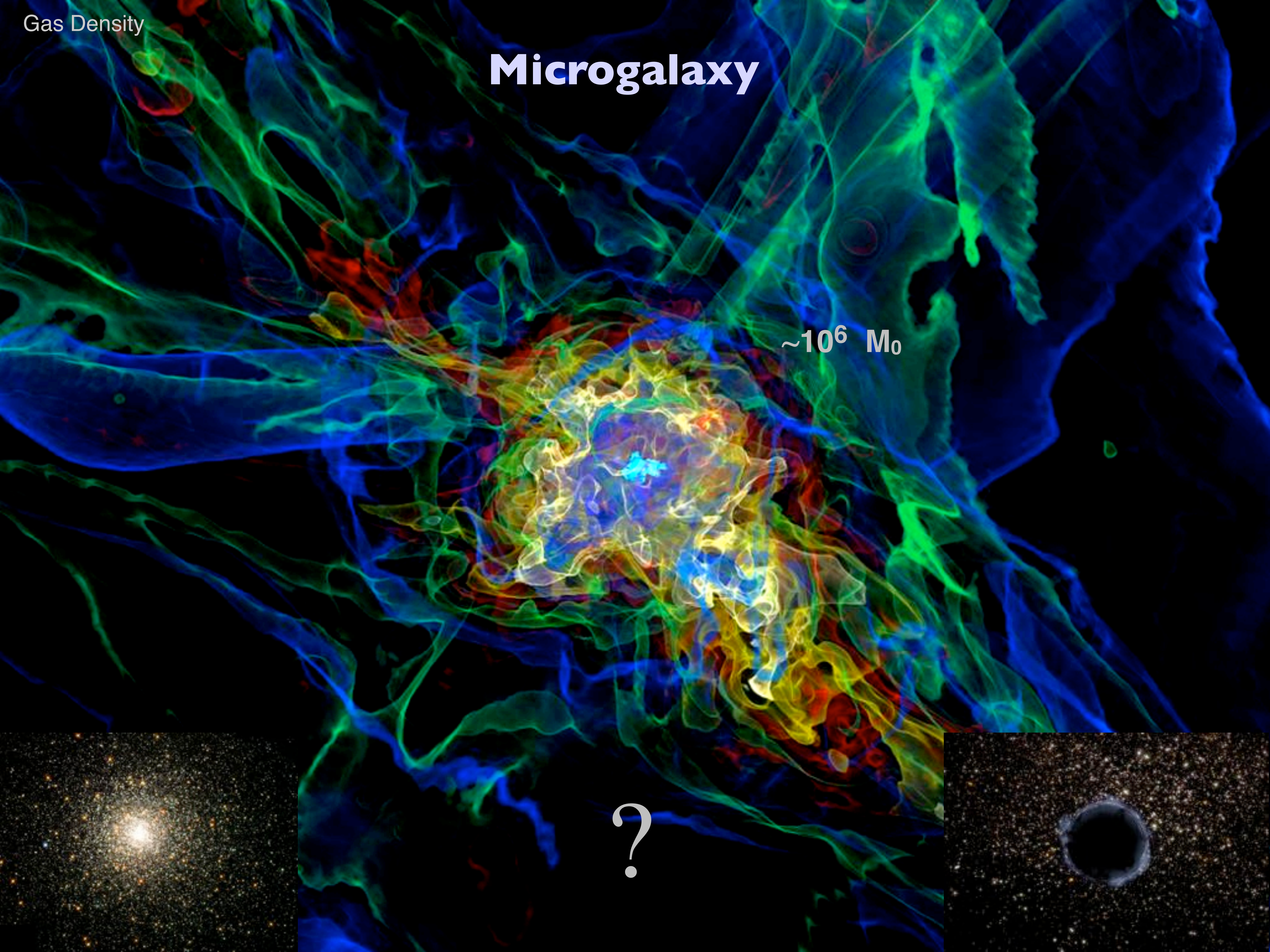


Simulation: John Wise & Tom Abel 2011
Visualization: Ralf Kähler & Abel (KIPAC)

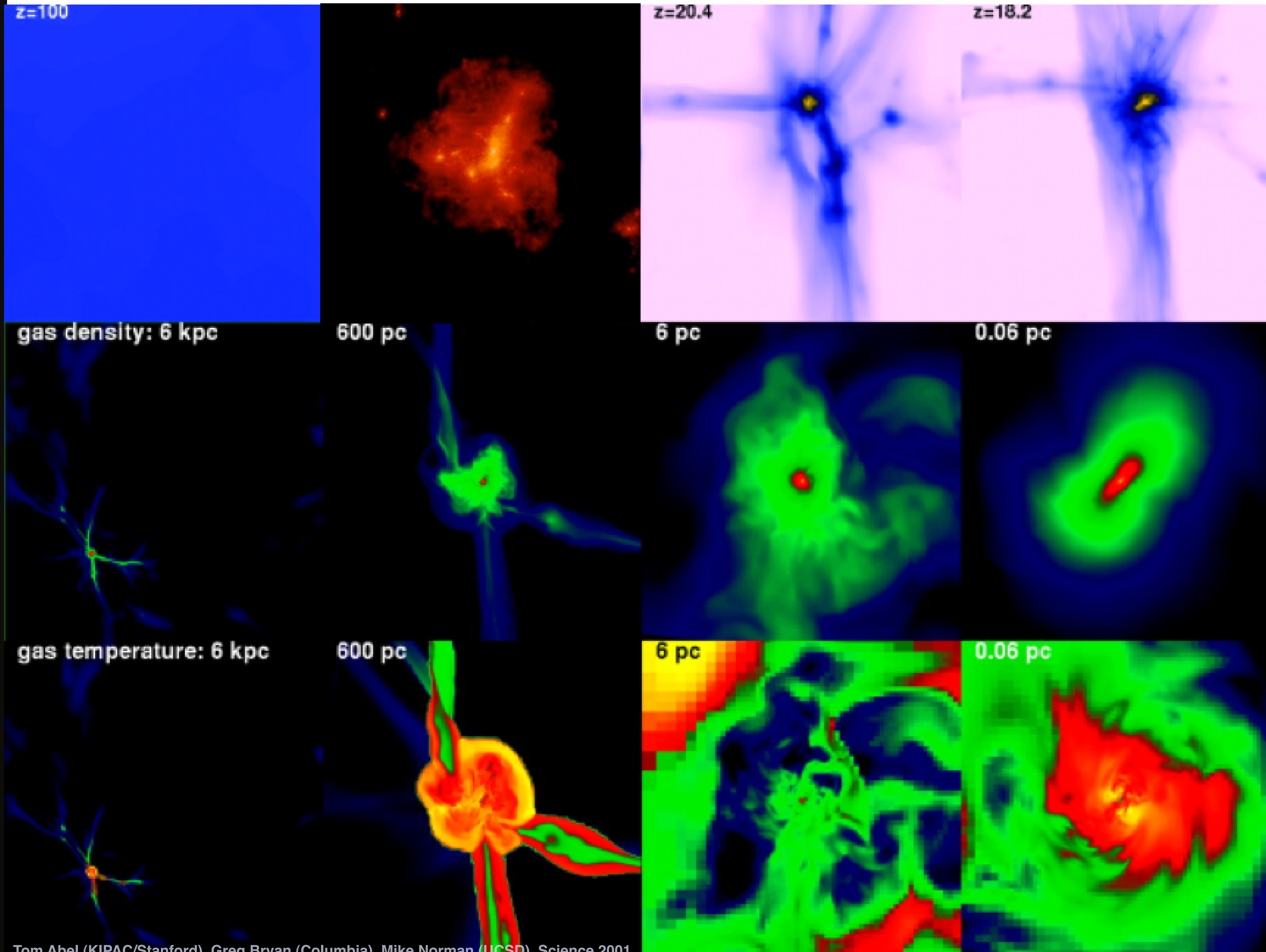
- Nature of First Stars
- Early black hole formation scenarios

With: Matthew Turk, John Wise, Jeff Oishi, Ji-hoon Kim, Peng Wang, Marcelo Alvarez.
Vis: Ralf Kaehler

Tom Abel
Kavli Institute for Particle Astrophysics and Cosmology
SLAC National Accelerator Laboratory & Physics Department, Stanford University
Institute for Theoretical Astrophysics and Heidelberg Institute of Theoretical Studies (HITS)

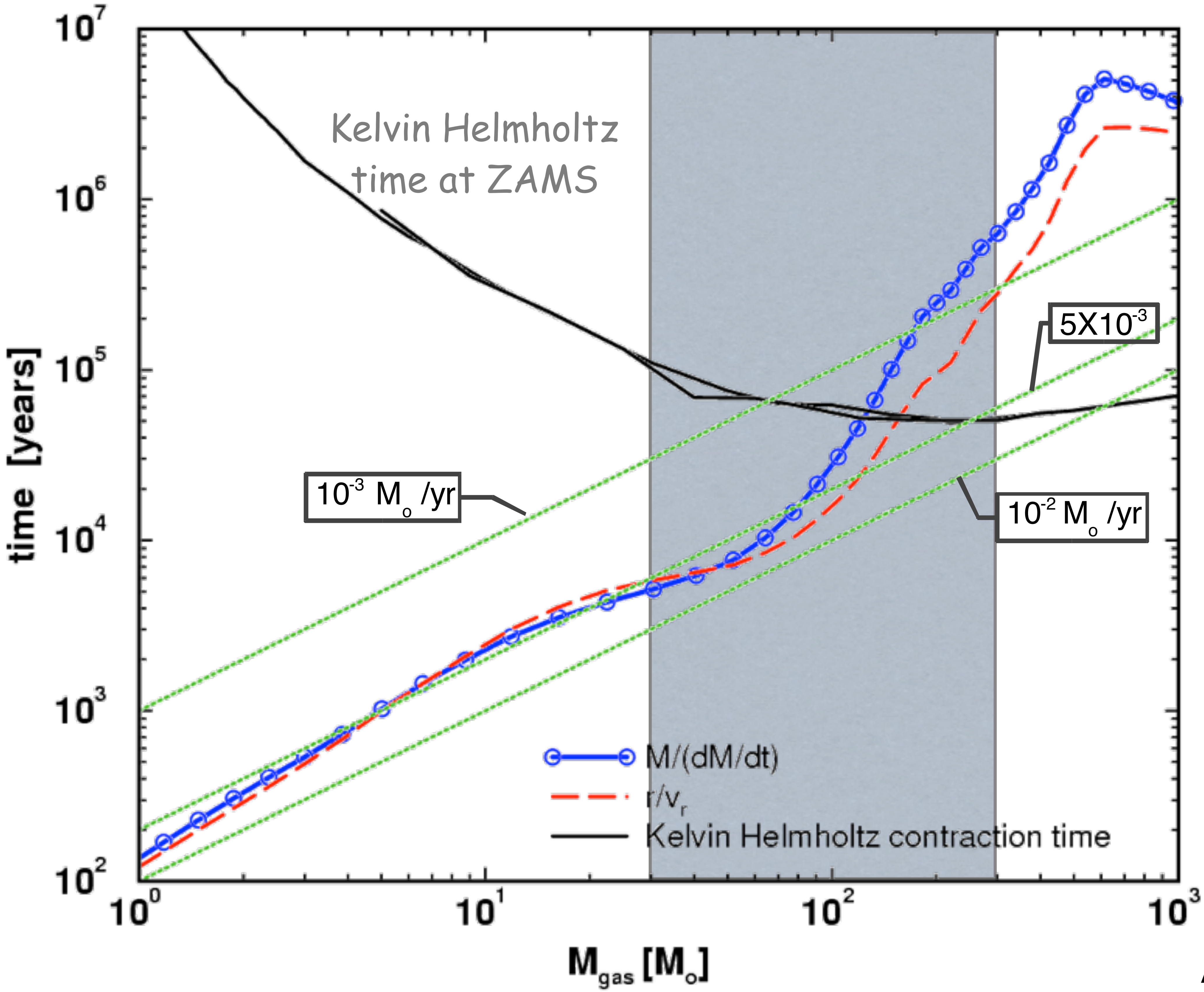

Gas Density
Microgalaxy
~10^6 M0
?

First cooling objects



Tom Abel (KIPAC/Stanford), Greg Bryan (Columbia), Mike Norman (UCSD), Science 2001

If angular momentum transport is fast then Accretion Time -> Mass Scale of FS?



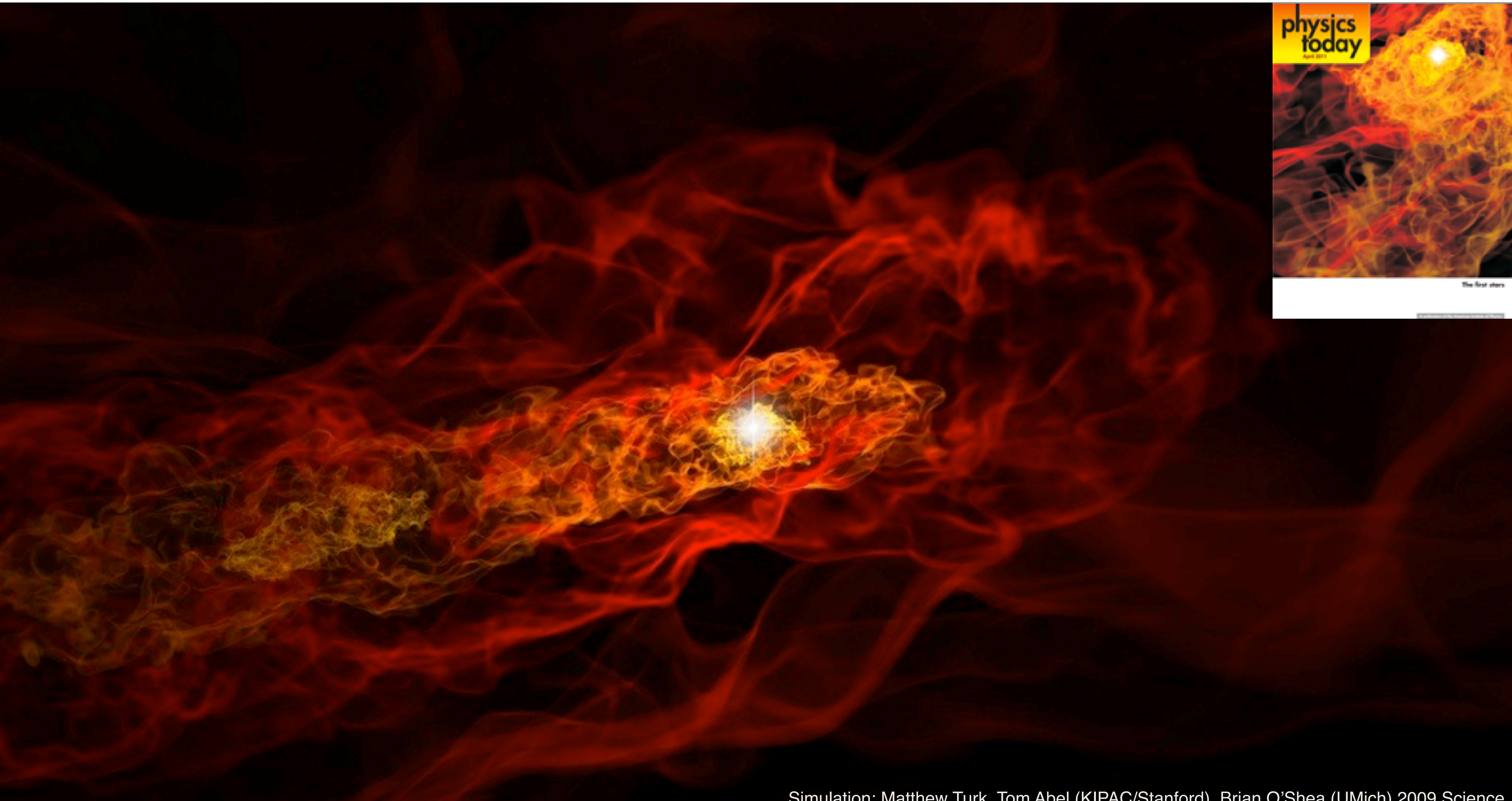
ABN02

Tom Abel
KIPAC/Stanford

~30 high res sims of different environments

One out of five cases

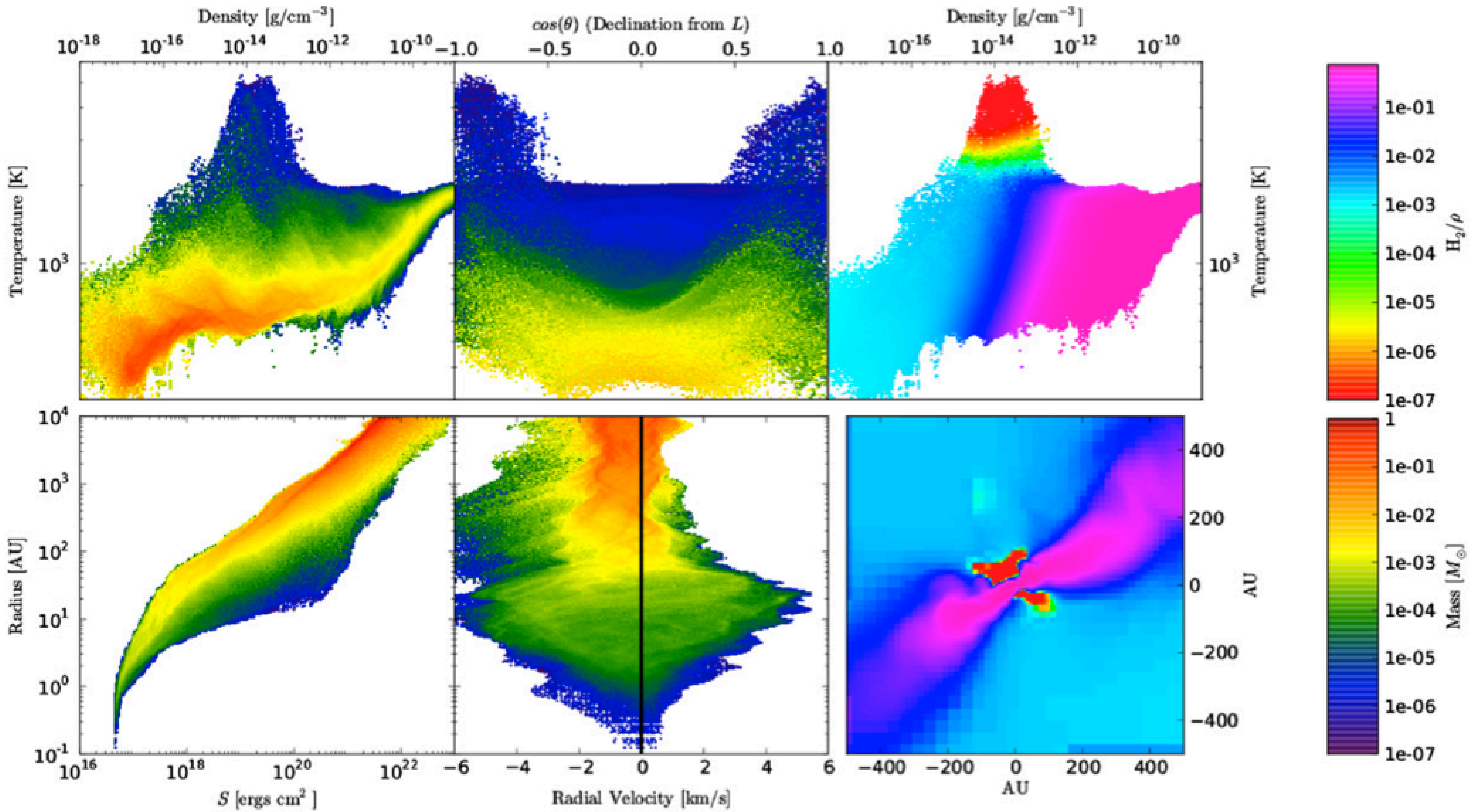
Binaries and even triple systems made in first collapse.



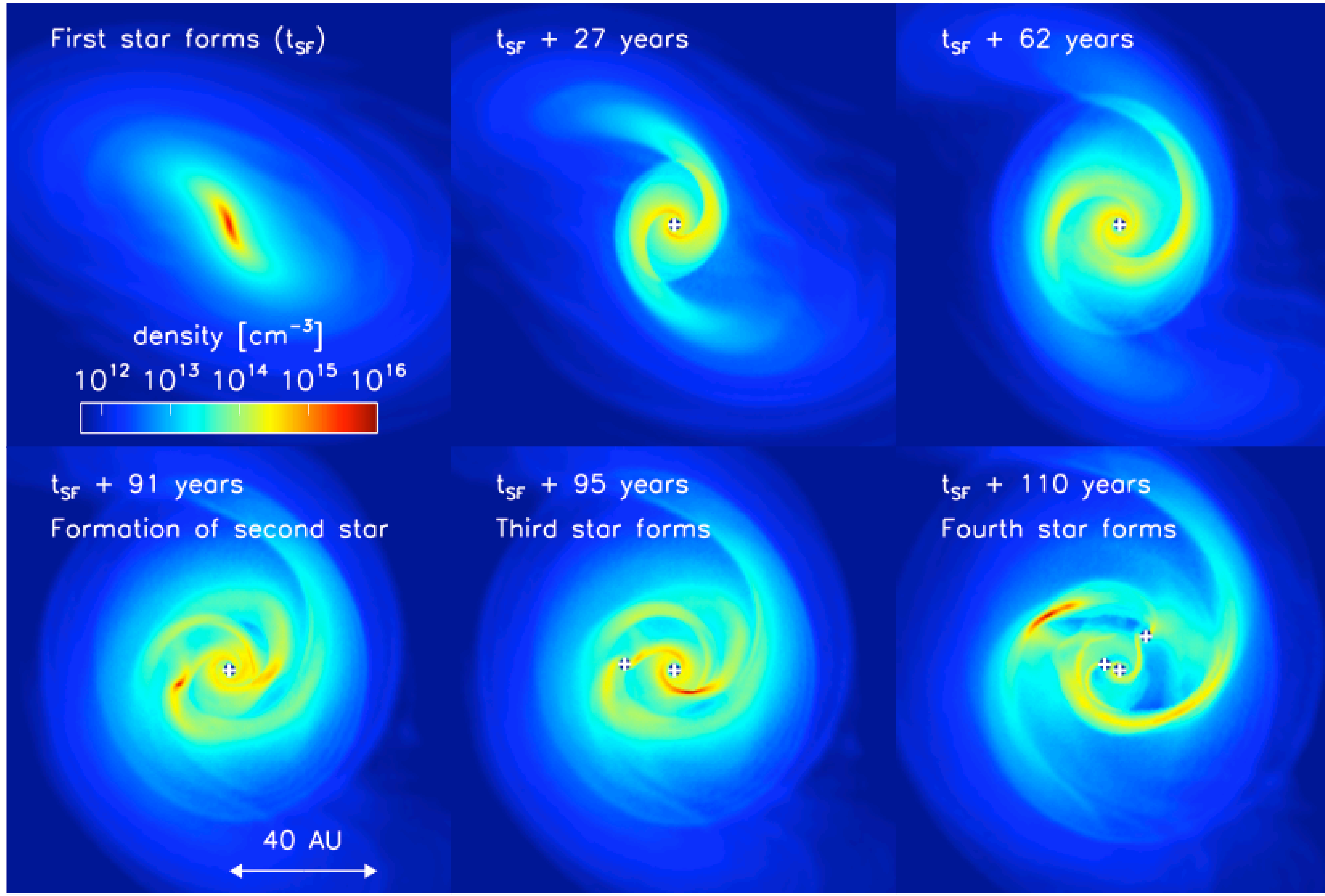
Simulation: Matthew Turk, Tom Abel (KIPAC/Stanford), Brian O'Shea (UMich) 2009 Science
Viz: Ralf Kähler, Tom Abel
See in Physics Today April 2011 article

Complex accretion disks around the first proto-stars

Turk, Norman & Abel 2010, ApJL



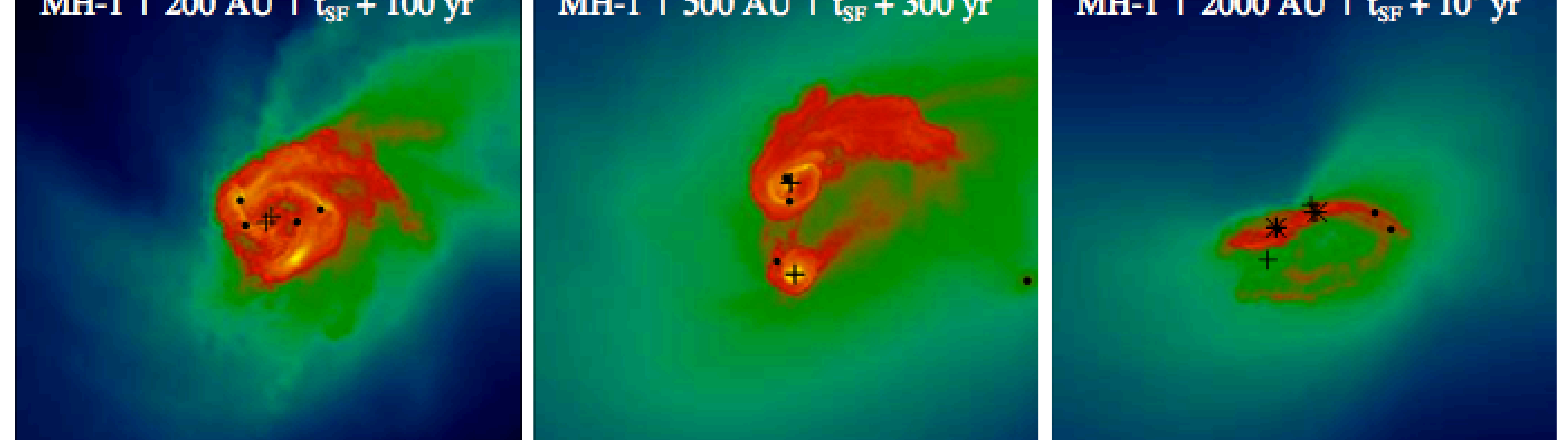
100 yrs ~ 0.1 % of relevant accretion time



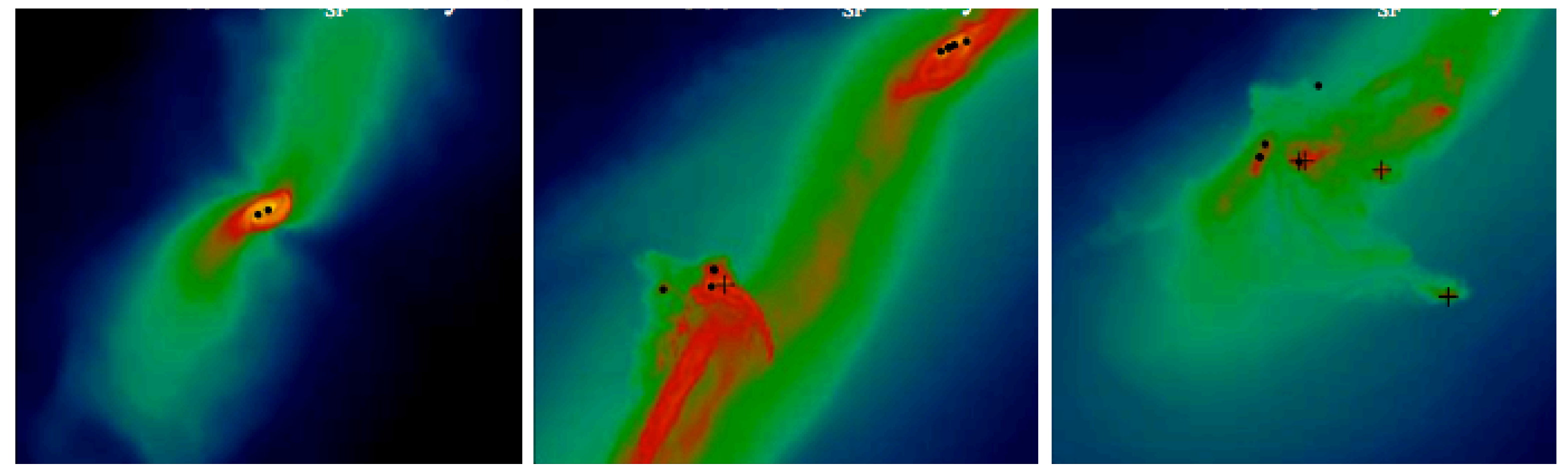
Our results show that the disks that formed around the first young stars were unstable to gravitational fragmentation, possibly producing small binary and higher-order systems that had separations as small as the distance between the Earth and the Sun.

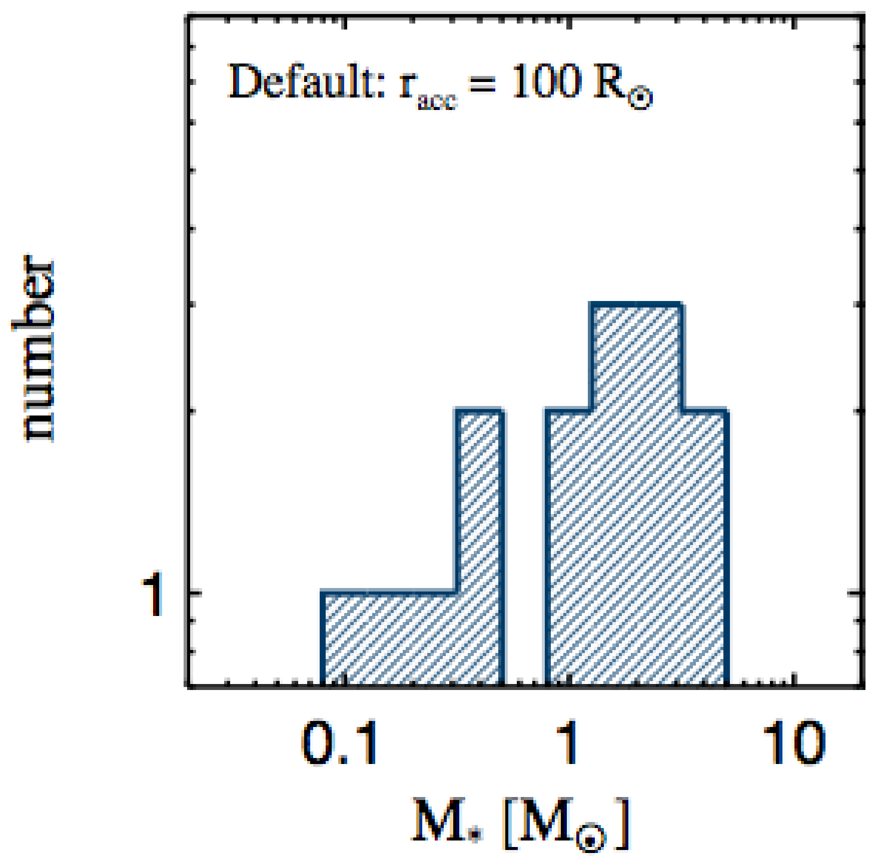
Paul C. Clark,[1*] Simon C.O. Glover,[1] Rowan J. Smith,[1] Thomas H. Greif,[2]
Ralf S. Klessen,[1,3] Volker Bromm[4]

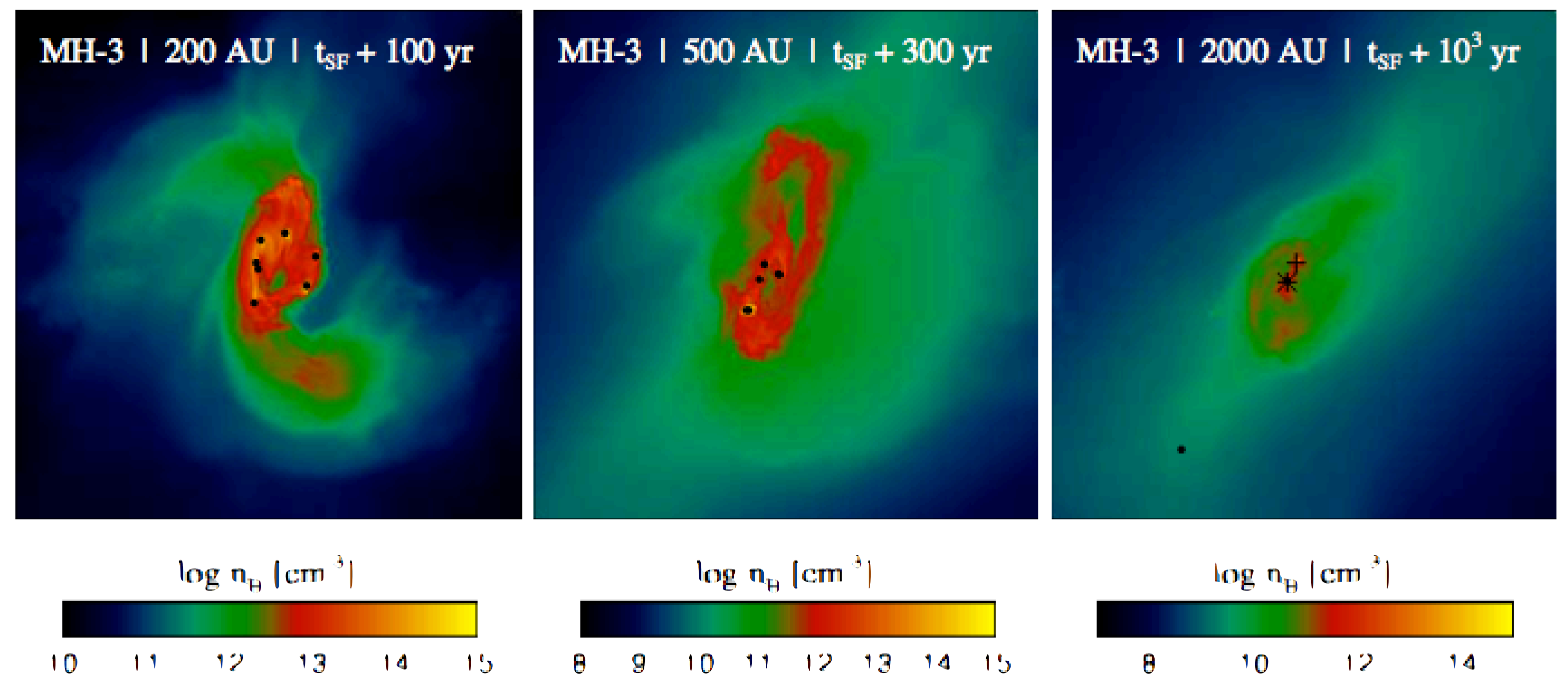
1000 yrs ~ 1 % of relevant accretion time.
All the mass in most massive objects.



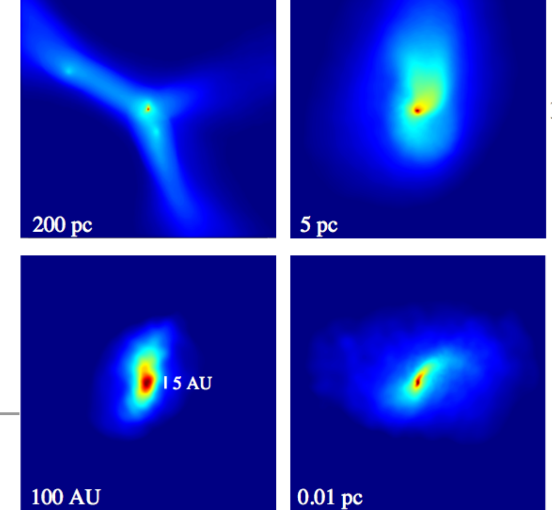
Thomas H. Greif[1], Volker Springel[2,3], Simon D. M. White[1], Simon C. O. Glover[4], Paul C. Clark[4]
Rowan J. Smith[4], Ralf S. Klessen[4] & Volker Bromm[5]

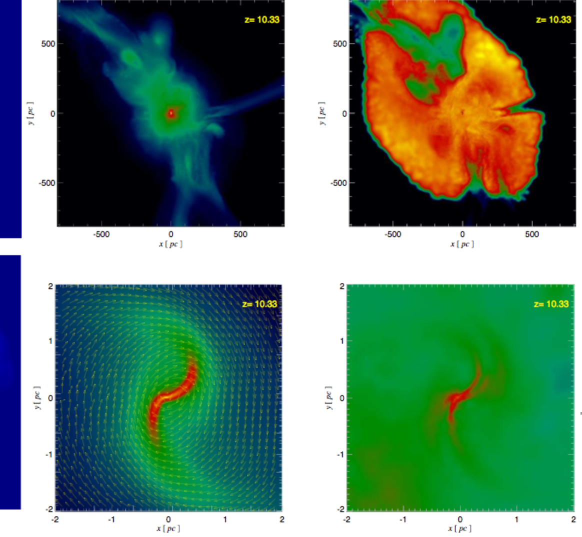


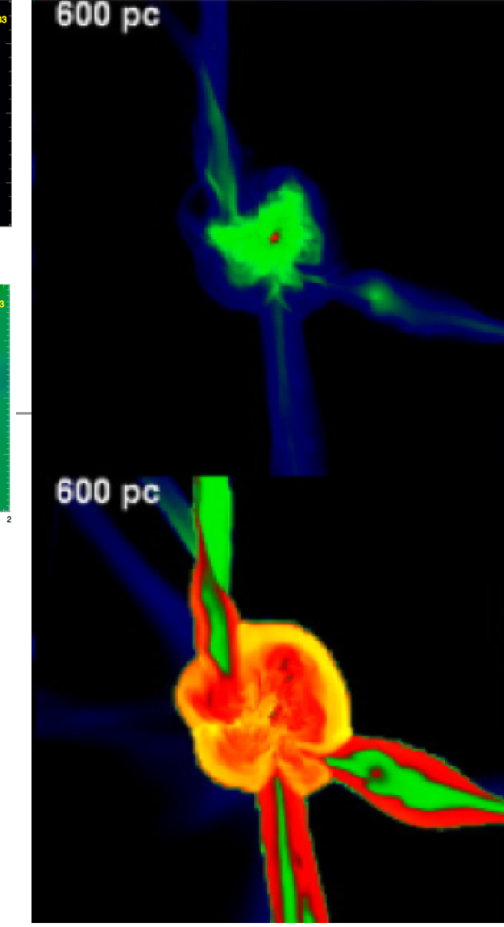




After an initial burst, gravitational instability recurs periodically, forming additional protostars with masses ranging from ~ 0.1 to 10 M_sun. Although the shape, multiplicity, and normalization of the protostellar mass function depend on the details of the sink-particle algorithm, fragmentation into protostars with diverse masses occurs in all cases, confirming earlier reports of Population III stars forming in clusters. **Depending on the efficiency of later accretion and merging**, Population III stars may enter the main sequence in clusters and with much more diverse masses than are commonly assumed.







Recap

Formation of the first stars

- 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! (AMR-ppm, AMR-zeus, AMR-Muscl, SPH, rpSPH, ALE-Arepo)

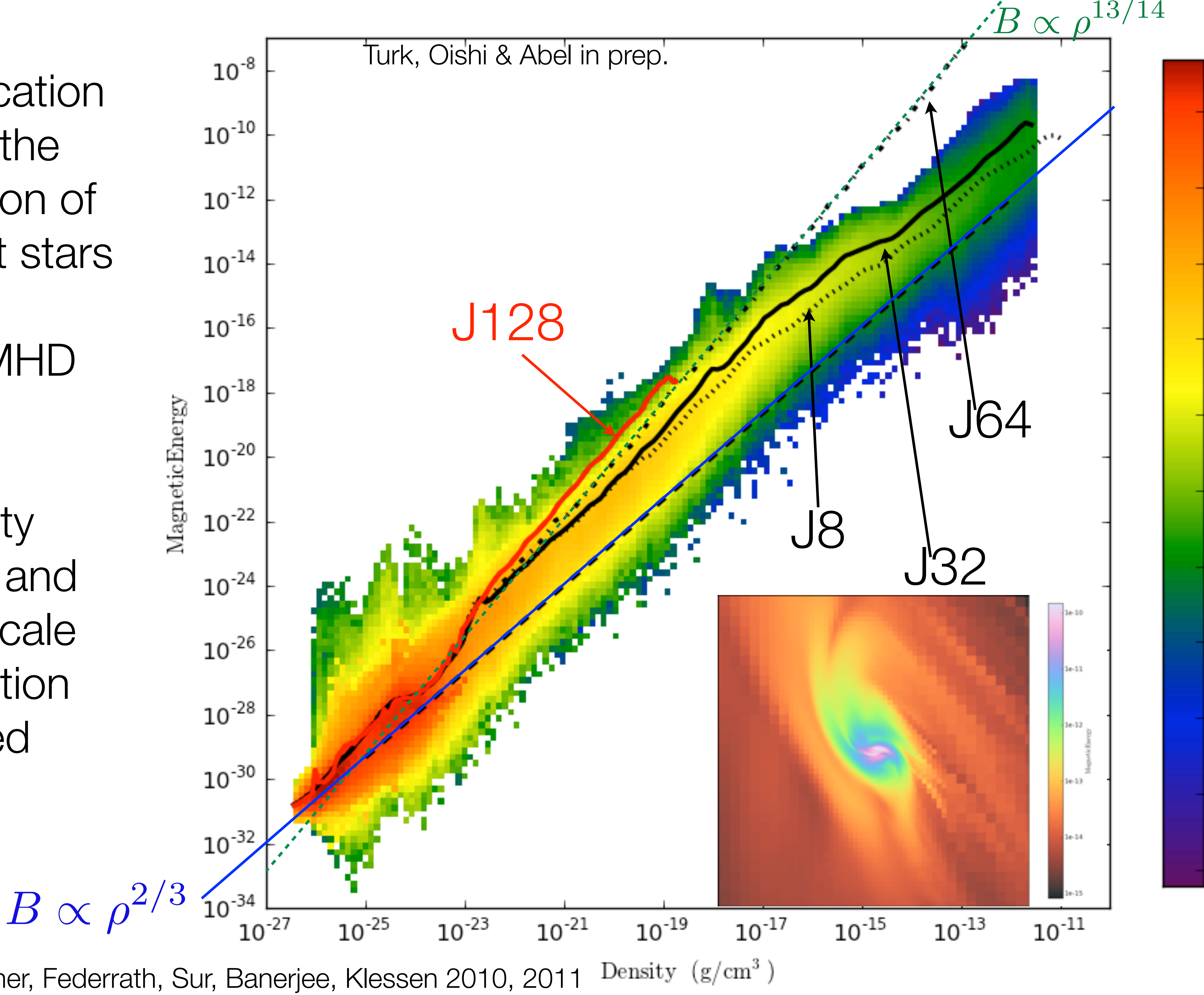
  Non-equilibrium chemistry & cooling, three body H2 formation, chemical heating, H2 line transfer, collision induced emission and its transport, and sufficient resolution to capture chemo-thermal and gravitational instabilities. Stable results against variations on all so far test dark matter variations, as well as strong soft UV backgrounds.
- Will this continue to hold at higher resolutions?
- **Pop III stars are very massive > 30 solar mass but less than 300**
- Disk fragmentation possible. Most fragments merge very rapidly due to the enormous gas drag and loss of angular momentum. Do a few have a chance to survive? Binary fraction could be large.

cosmological: Abel 1995; Abel, Zhang, Anninos & Norman1998; Abel, Bryan & Norman 2000, 2002; O'Shea et al 2006; Yoshida et al 2006; Gao et al 2006, O'Shea & Norman 2007, Yoshida et al 2009; Turk, Abel & O'Shea 2009, Science. With re-griding: Greif et al 2011; Clark et al 2011
idealized spheres: Bodenheimer 1986; Haiman et al 1997; Omukai & Nishi 1998; Bromm et al 1999,2000,2002; Ripamonti & Abel 2004;

B-field amplification during the formation of the first stars

Enzo/MHD

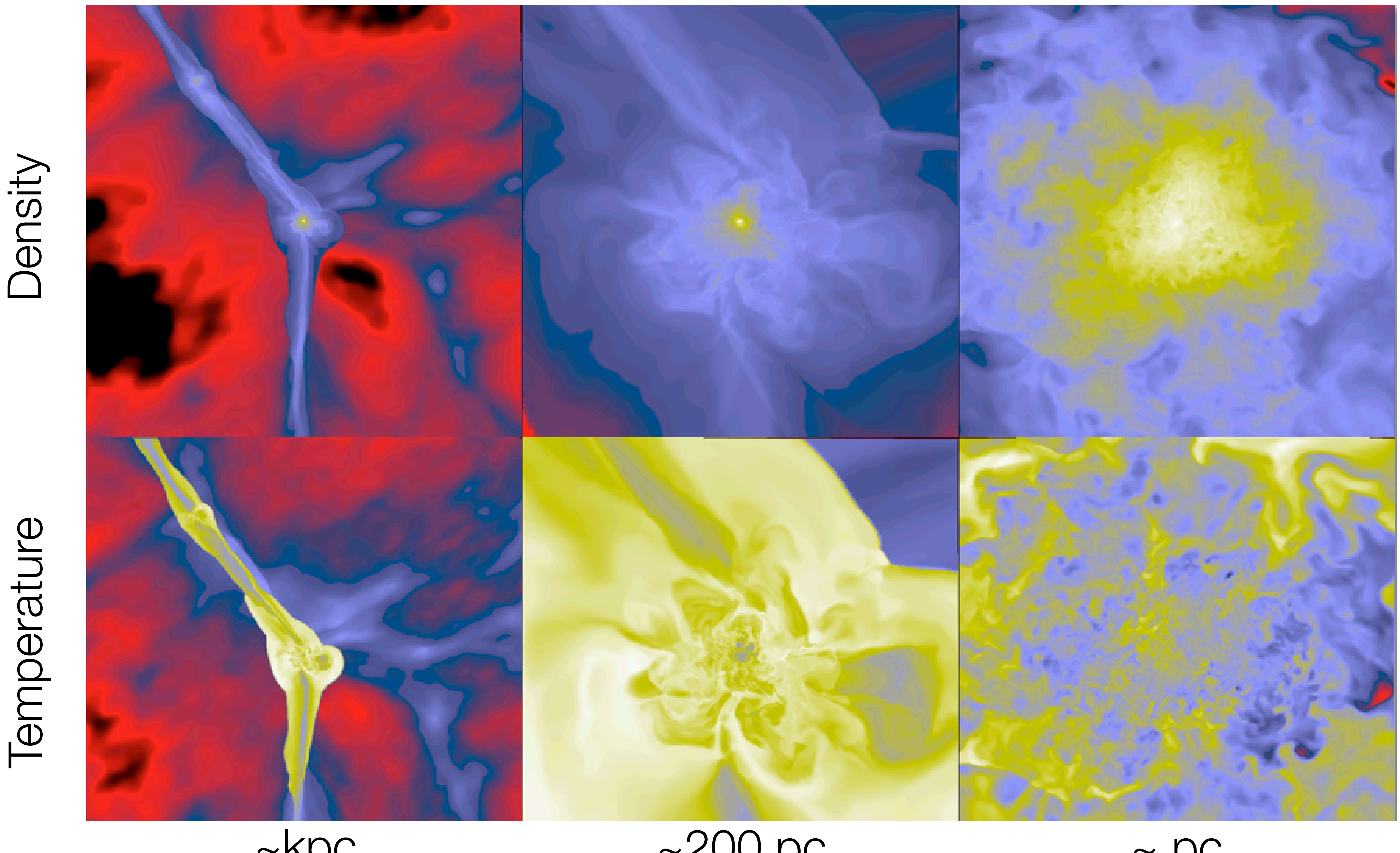
Viscosity of fluid and small scale dissipation modified



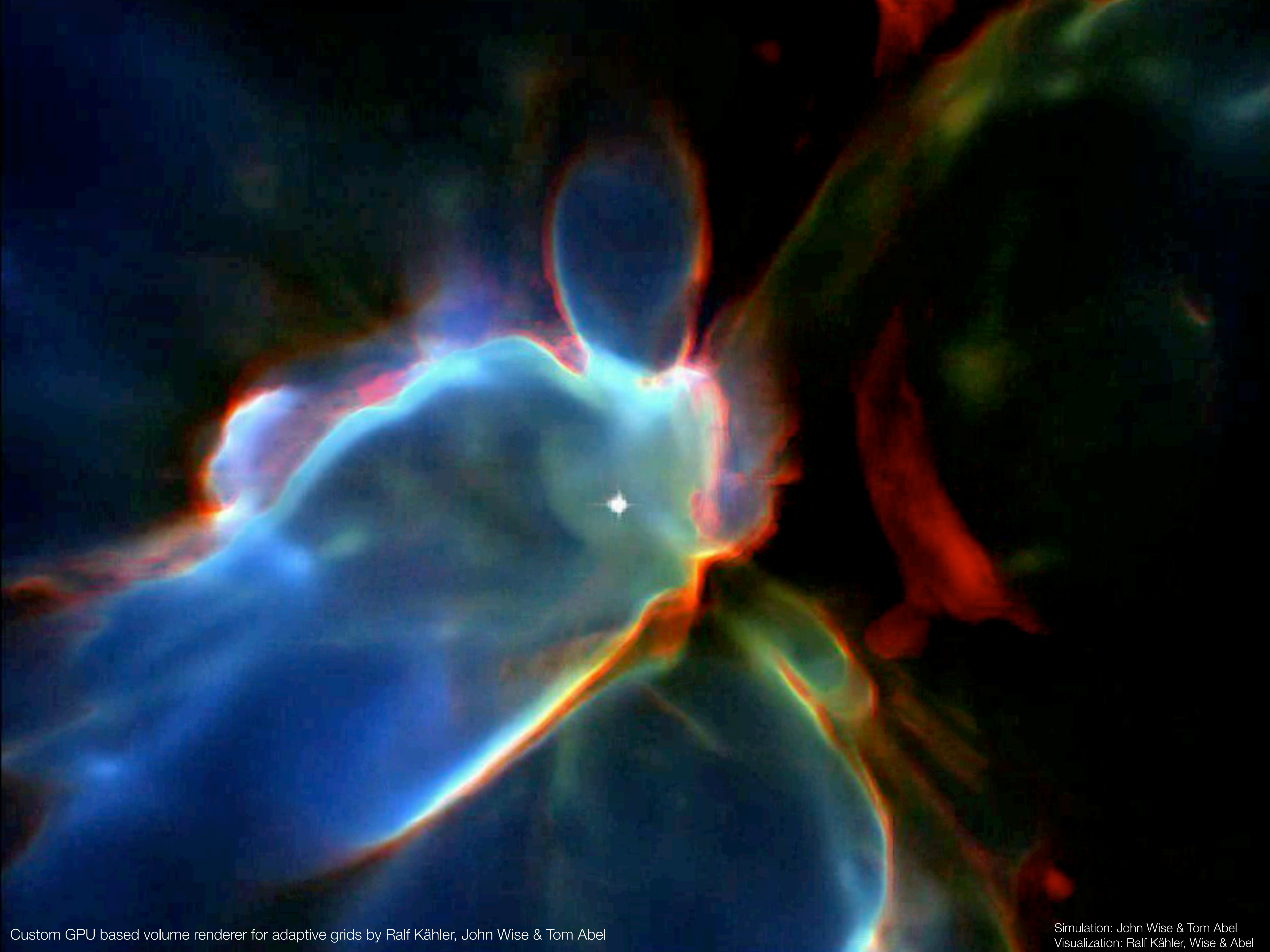
Schleicher, Federrath, Sur, Banerjee, Klessen 2010, 2011

One billion resolution elements afforded by the hard and software improvements.

A critical Reynolds number at which our results change qualitatively?



Turk & Abel, ongoing


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

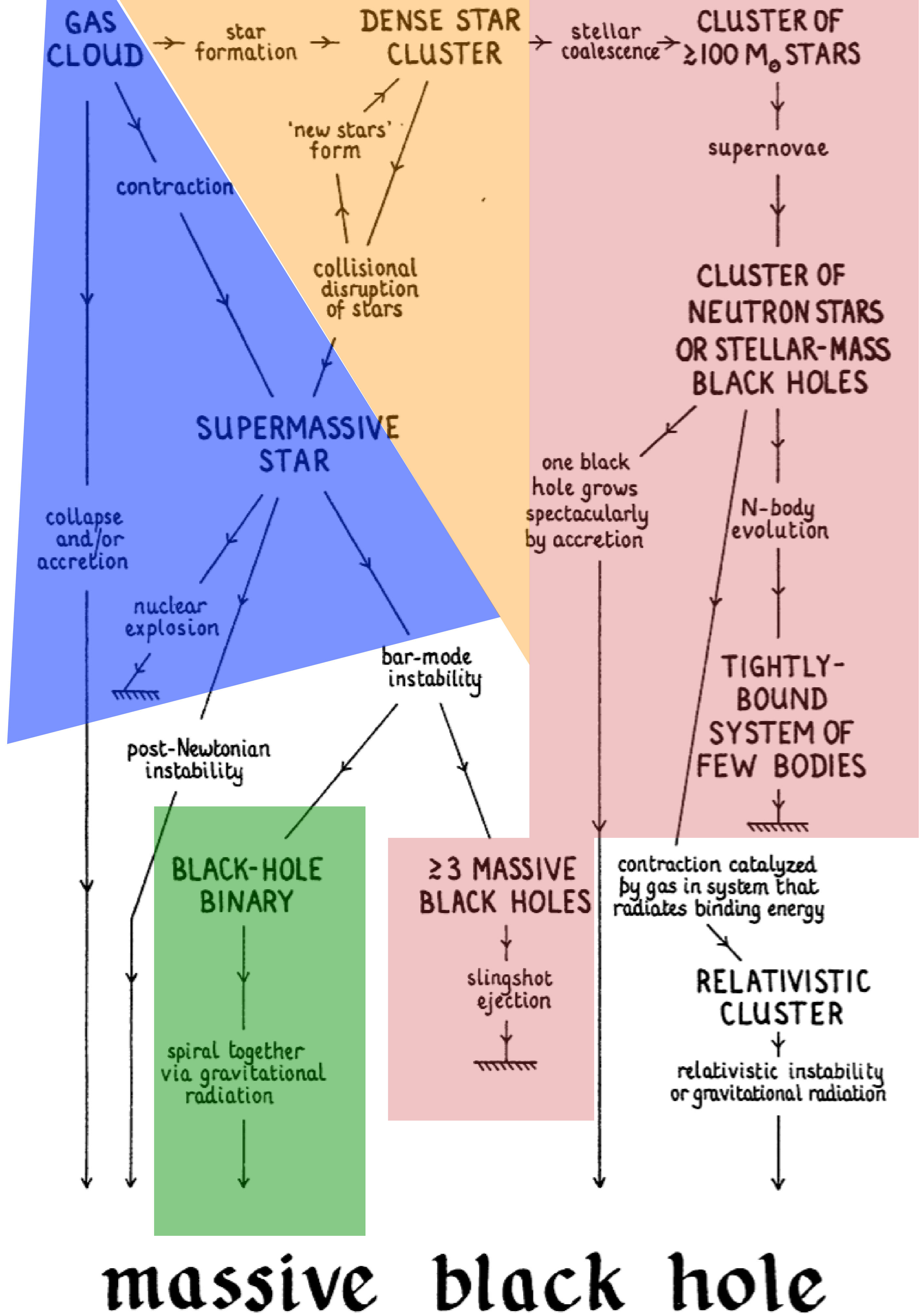
First Black Holes

Accessible to direct simulations in hydrodynamic and MHD limits
Dynamic range > 1e10
+
subgrid modeling

Accessible to direct simulations in N-body limit
> 1e6 particles

Numerical Relativity

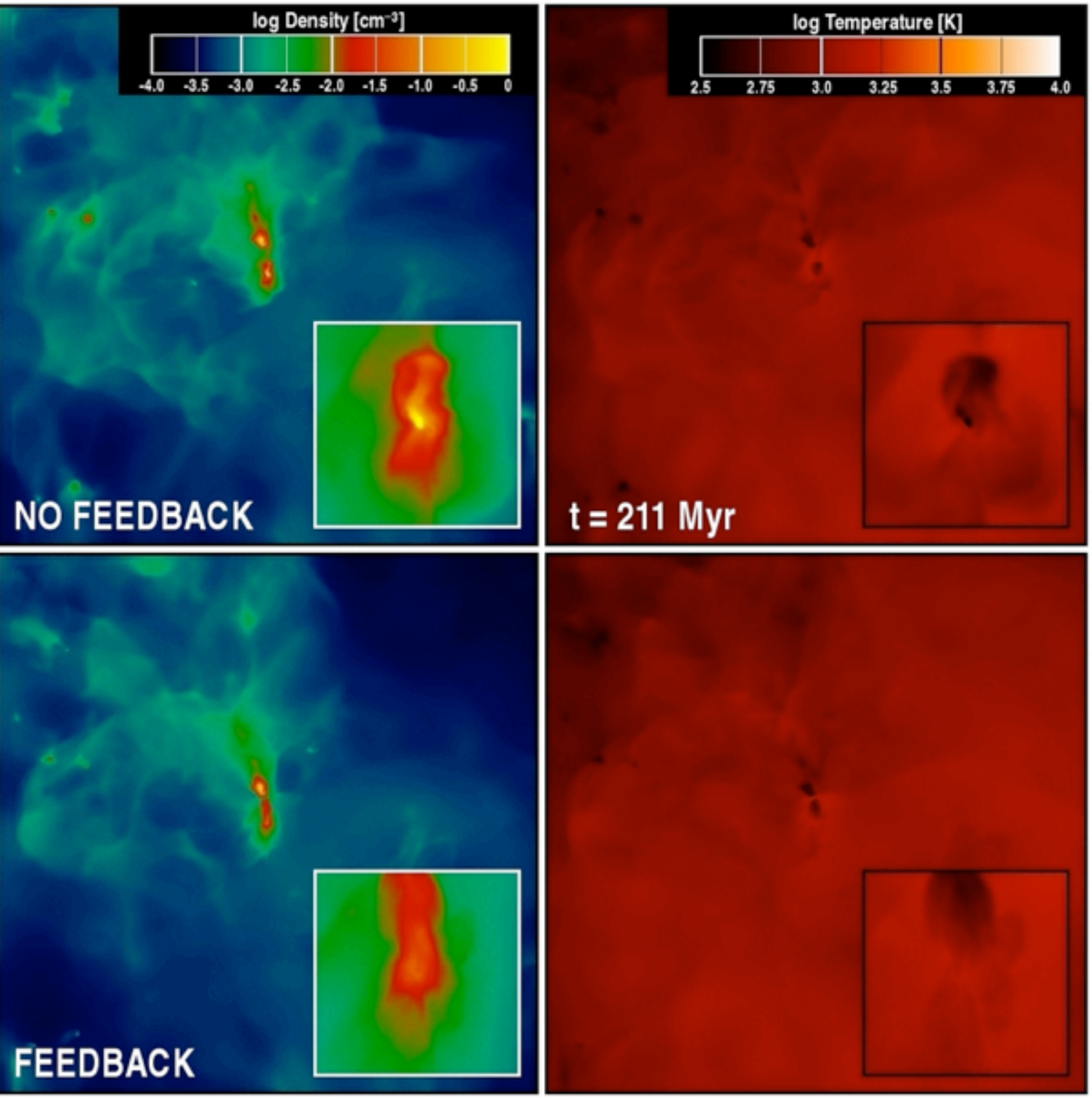
An old subject which modern simulations are poised to make substantial progress on.

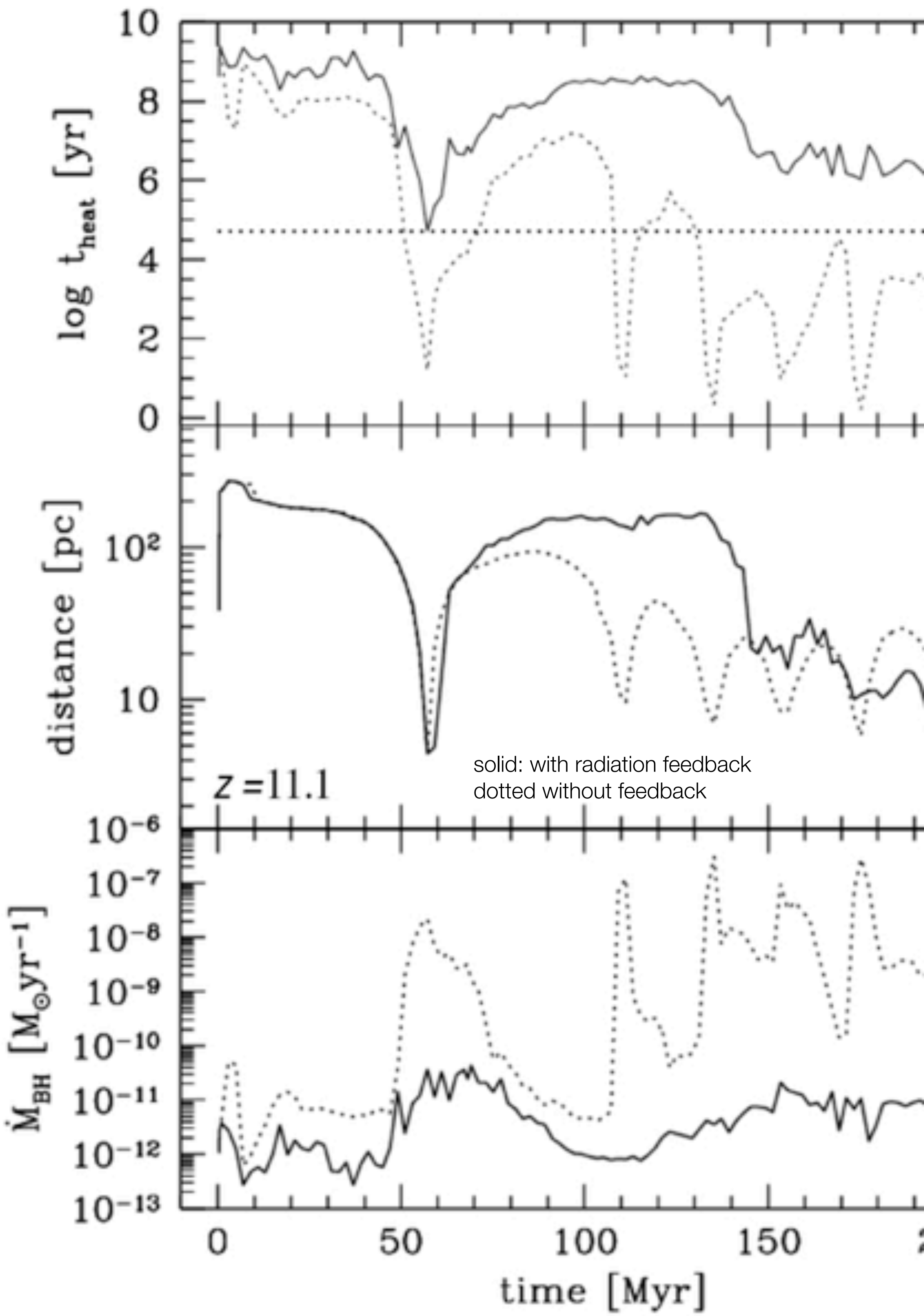


Martin Rees 1980

Do the first black holes grow rapidly?

Insignificant BH accretion - no mini quasars because of internal photo-evaporation, nor pre-cursors of Quasars, large local feedback.

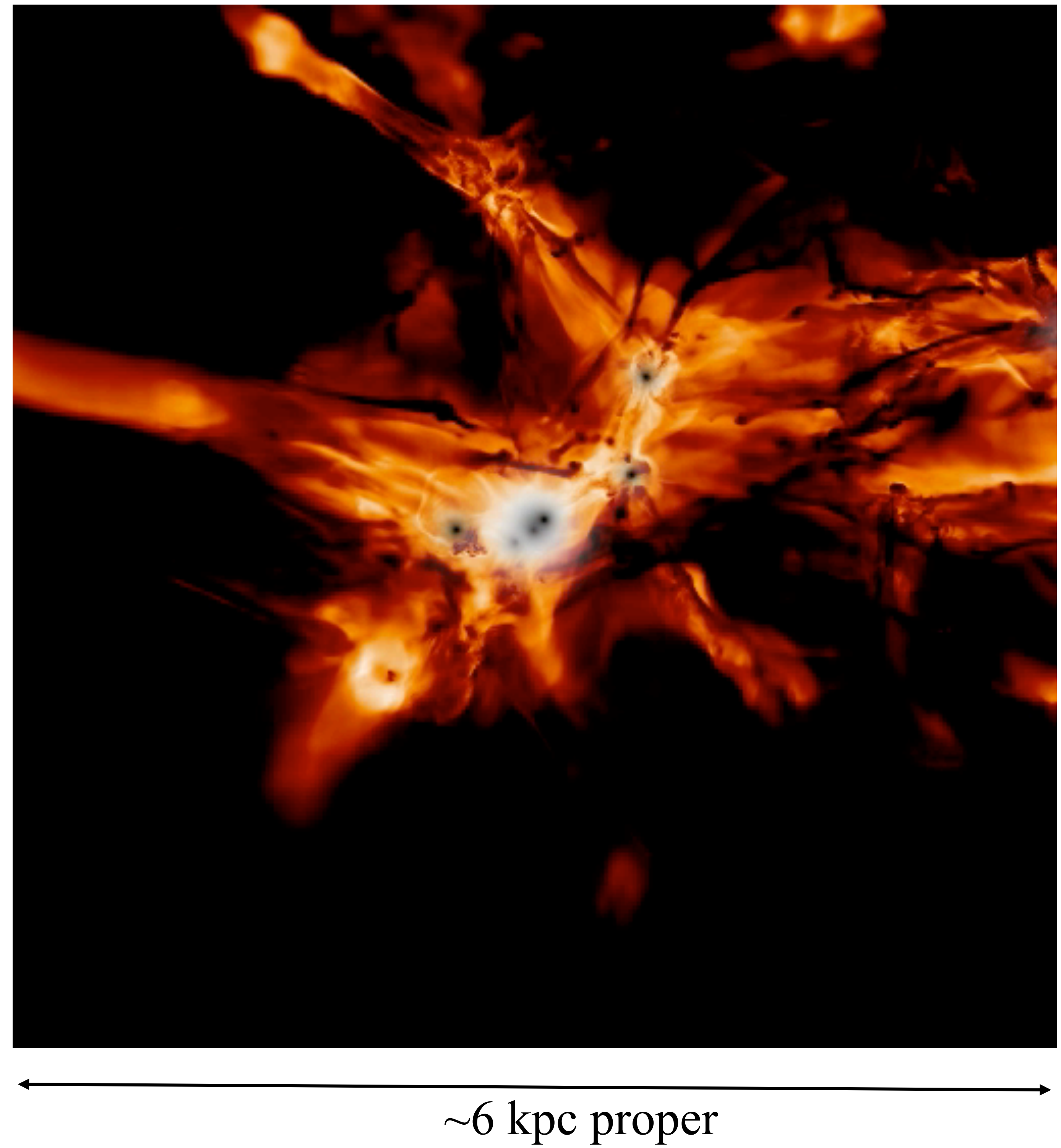




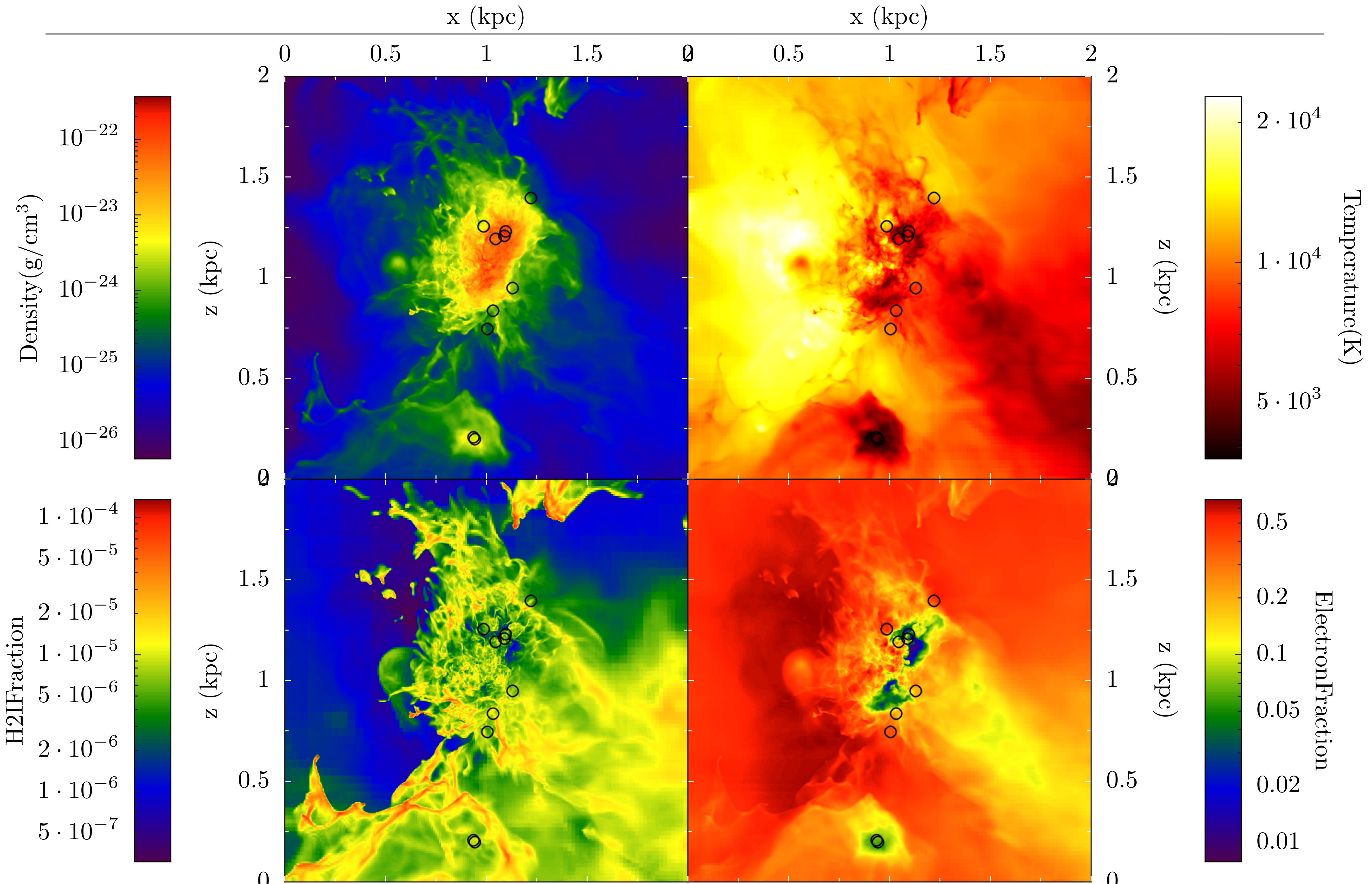
Alvarez, Wise & Abel ApJL, 2008

Yes! But how about the small seeds falling into rapidly growing galaxies. Surely they must grow then, isn't it?

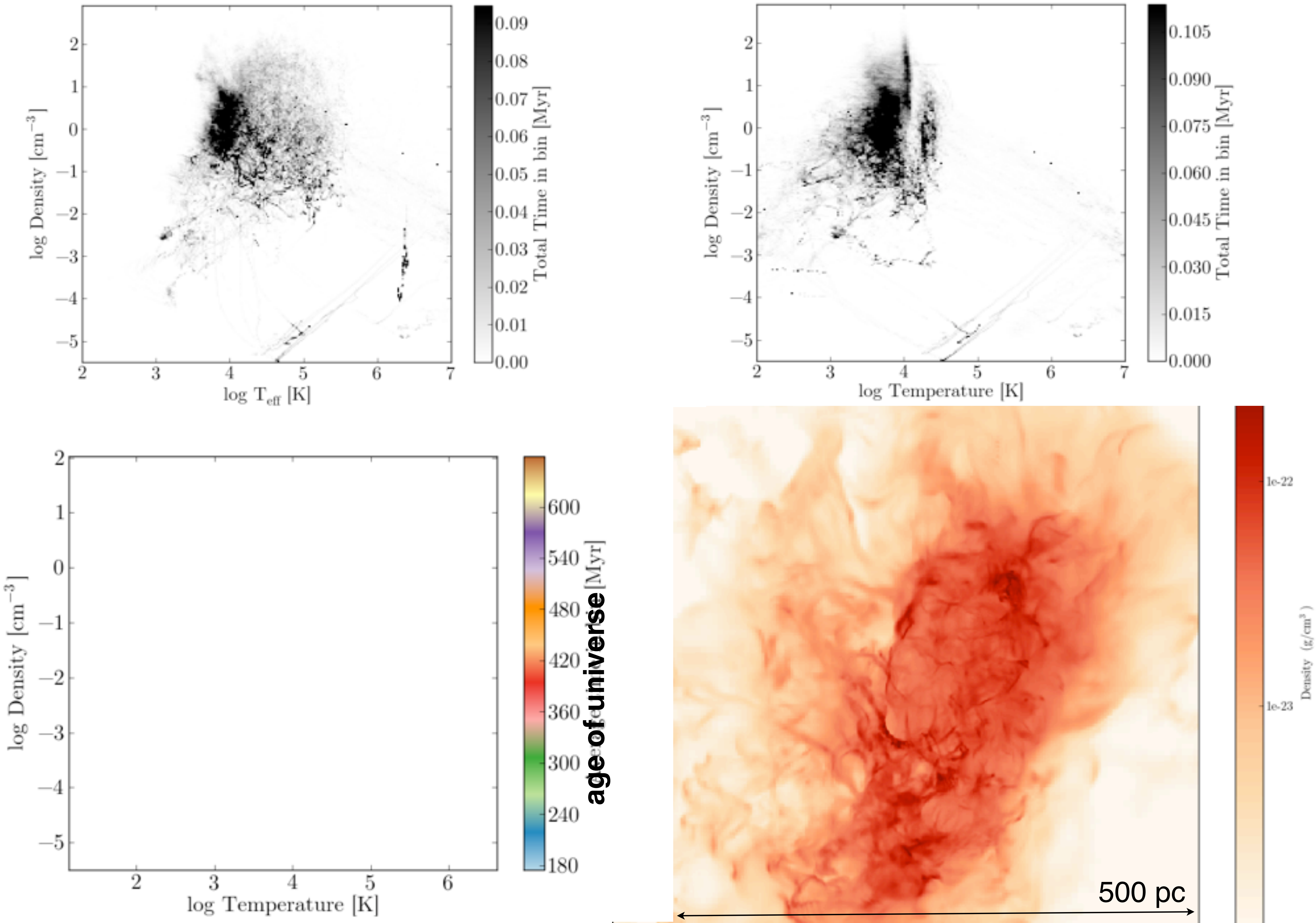
- **Same initial conditions as "Simulation B" of *Wise et al (2008abcd…)***
  - **1.5 Mpc periodic box**
  - **1024^3 effective resoltution**
  - **0.3 pc resolution**
  - **H_2 chemistry, pop III and pop II star formation, full radiative transfer,**
  - **First star forms at z~30**
  - **Ionizing radiation from 100 $M_\odot$ stars coupled to hydro**
  - **Remnant black hole accretion and radiative feedback treated including secondary ionization *Alvarez, Wise & Abel (2009)***



z=8.2 still no further growth. Halo: 2×10^8 solar mass
3 solar masses total on 25 black holes

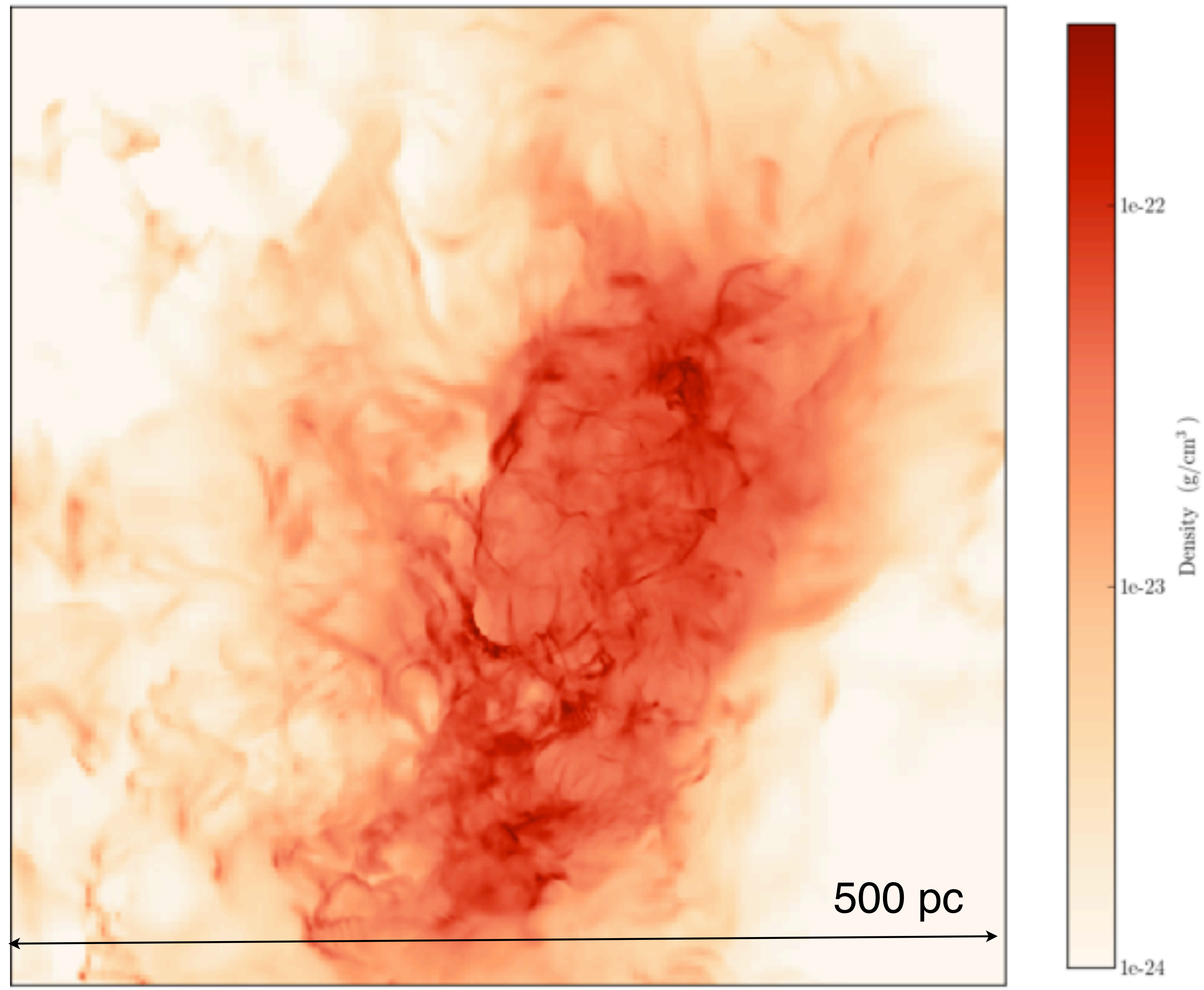


Black holes spend almost all their time in the wrong places



Most Pop III stellar seed black holes do not grow.

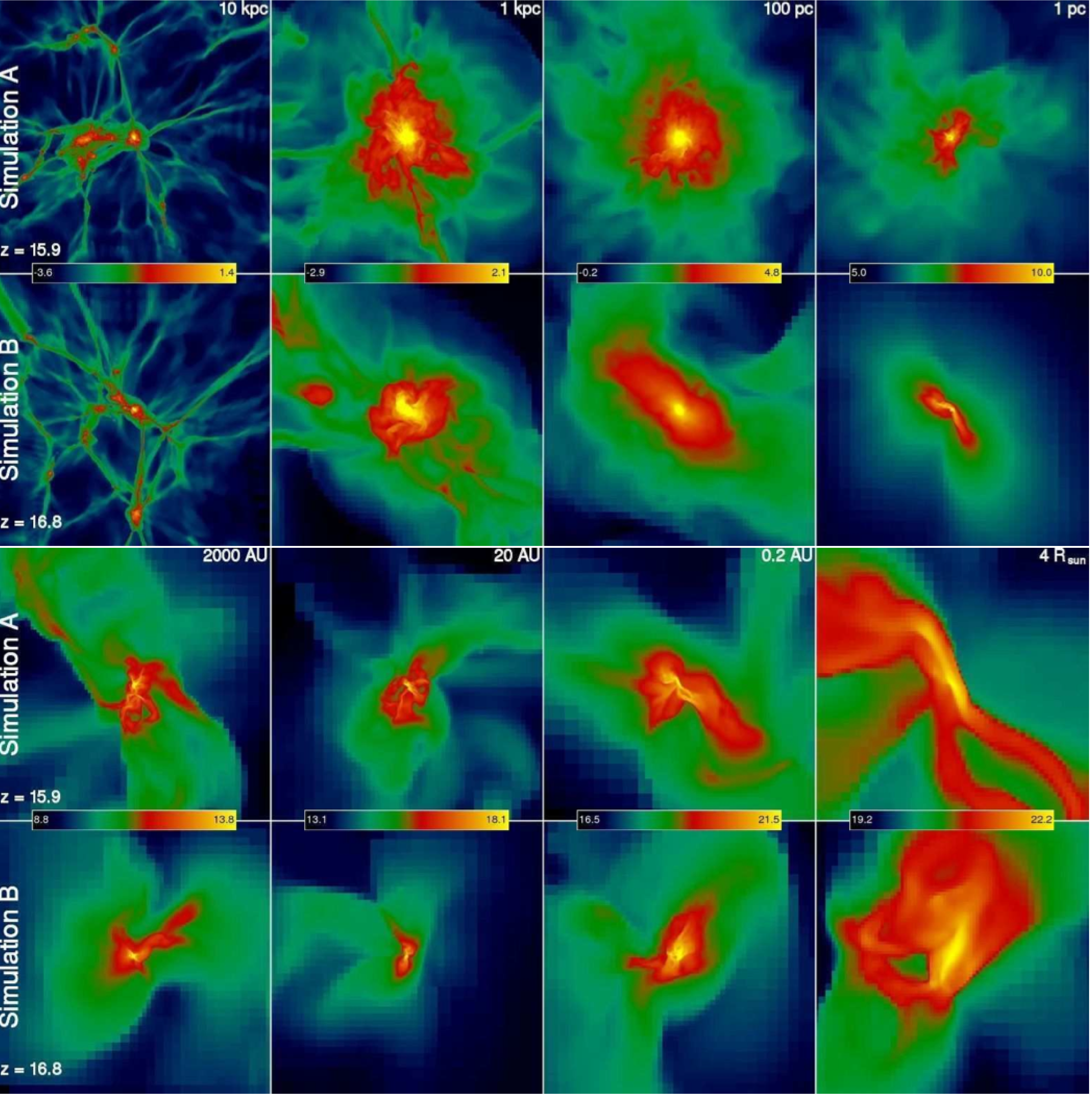
- Only need to make one bright high-z quasar per comoving Gpc. So only one of hundreds of thousands potential pop III remnant black holes has to experience runaway growth.
  - Why that one?
  - How does kpc scale gas know to keep being available for accretion onto it?



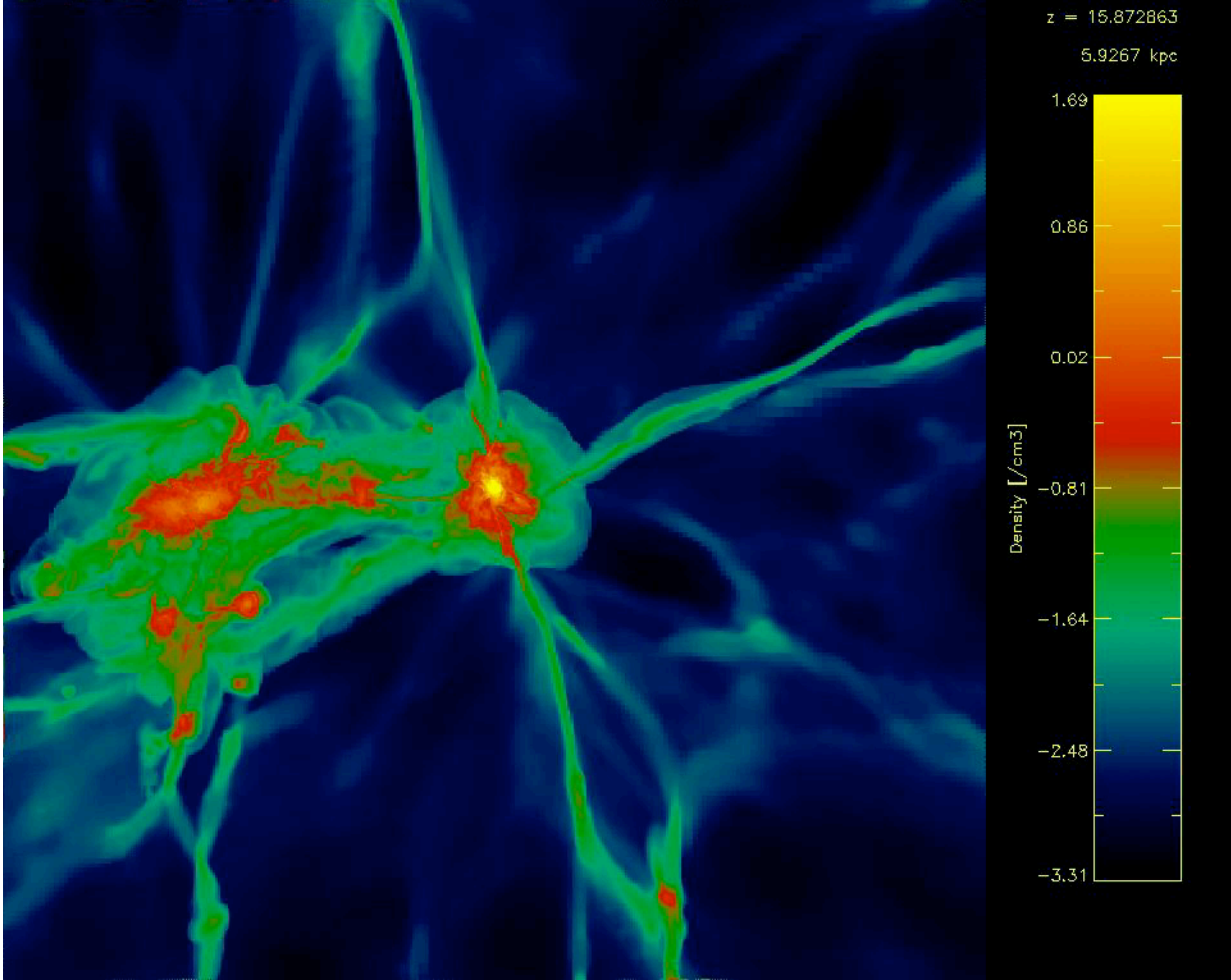
Wise, Alvarez, Abel in prep.

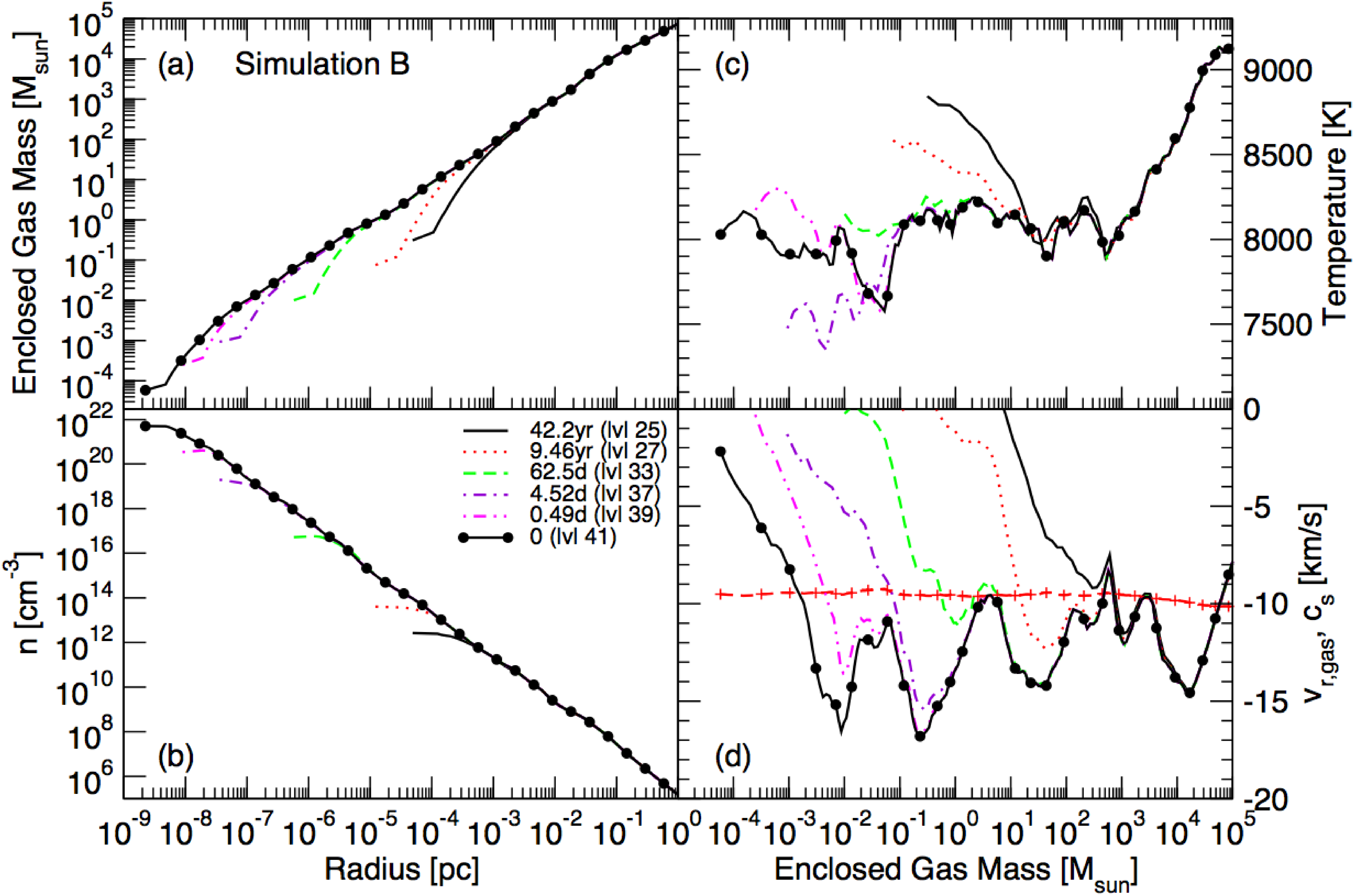
SMBH from direct gaseous collapse?

- Perhaps some halos with 10^4K can have central cores that collapse directly? (e.g. Koushiappas et al. 2004; Volonteri & Rees 2005; Begelman et al 2006; Spaans & Silk 2006; Lodato & Natarajan 2006; Wise & Abel 2007; Regan & Haehnelt 2008)
- Numerical experiment
  - Assume no molecules can be formed (actually very bad assumption ... see John Wise' talk this afternoon)
  - Only H, He cooling leads to the first cooling objects to be ~ 1e8 solar masses which have a central 1e5 solar mass cloud contract fast.
  - See it as a numerical experiment to study the collapse of a turbulent isothermal cloud formed form cosmological initial conditions
  - Interesting also as a model to start studying the role of turbulence in galaxy formation
  - Dynamic range of 10^{15} which is by far the highest resolution simulation carried out. Beat our own record by 5 order of magnitude ...



Wise, Turk & Abel 2008, ApJ

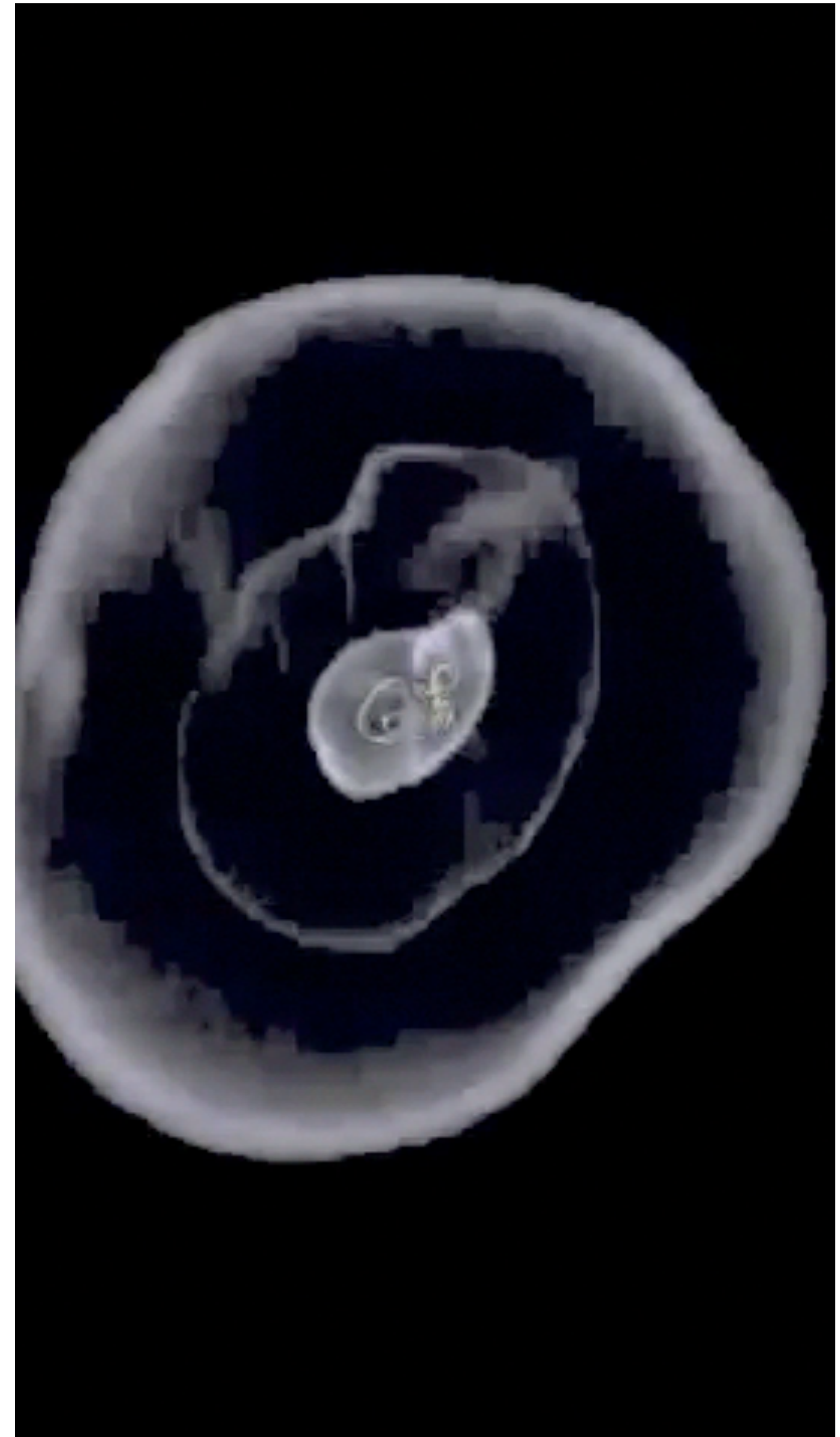

z = 15.872863
5.9267 kpc
1.69
0.86
0.02
−0.81
−1.64
−2.48
−3.31
Density [/cm3]



(a) Simulation B
(b)
(c)
(d)
Enclosed Gas Mass [M_sun]
n [cm^-3]
Radius [pc]
Enclosed Gas Mass [M_sun]
Temperature [K]
v_r,gas, c_s [km/s]
42.2yr (lvl 25)
9.46yr (lvl 27)
62.5d (lvl 33)
4.52d (lvl 37)
0.49d (lvl 39)
0 (lvl 41)

Bars within Bars (and disks) are misaligned

- Turbulent viscosity sufficient.
- Angular momentum may be transported quickly.
- Is this scenario realized when halo forms next to a bright source? (Shang, Bryan & Haiman 2010)
    - Lyman Werner band H_2 dissociation so strong that during collapse no molecules can form
    - Need to have such a high flux for the entire time the progenitors grow from 10^5 to 10^8 solar mass.



Summary

- First star formation simulations study now not only proto-stars but also binaries and multiples formed prior to and after the appearance of accretion disks.
- B-fields are amplified from the start. Relevant on small scales quickly. Viscous scale, Reynolds number and small scale dissipation are affected first.
- Radiation and supernovae feedback severe for early small galaxies.
- Early black holes barely grow.
- Key in evaluating whether the direct collapse scenario is viable will be to simultaneously and believably model star formation.