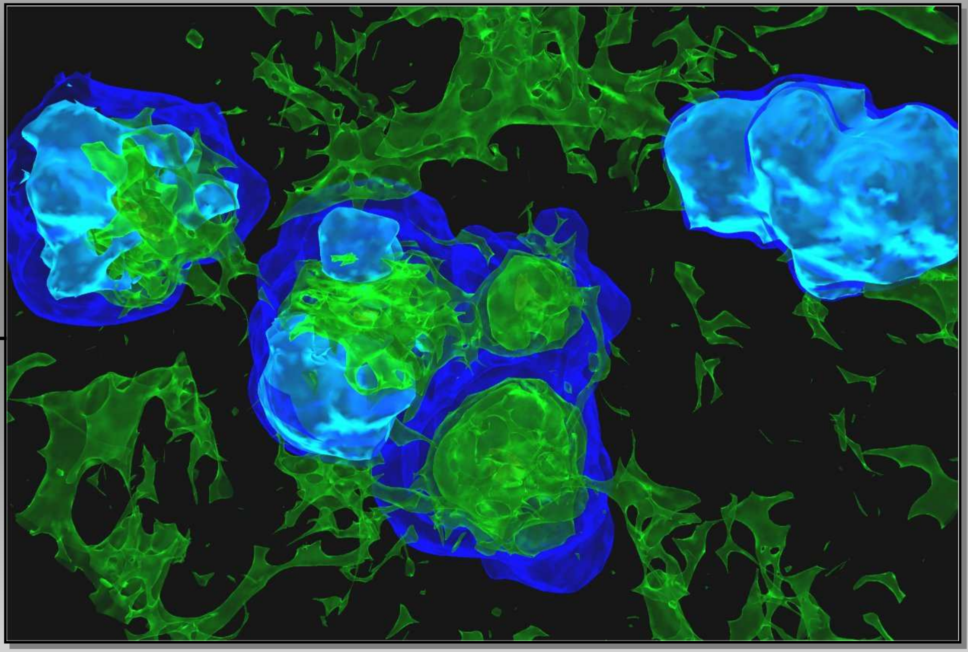
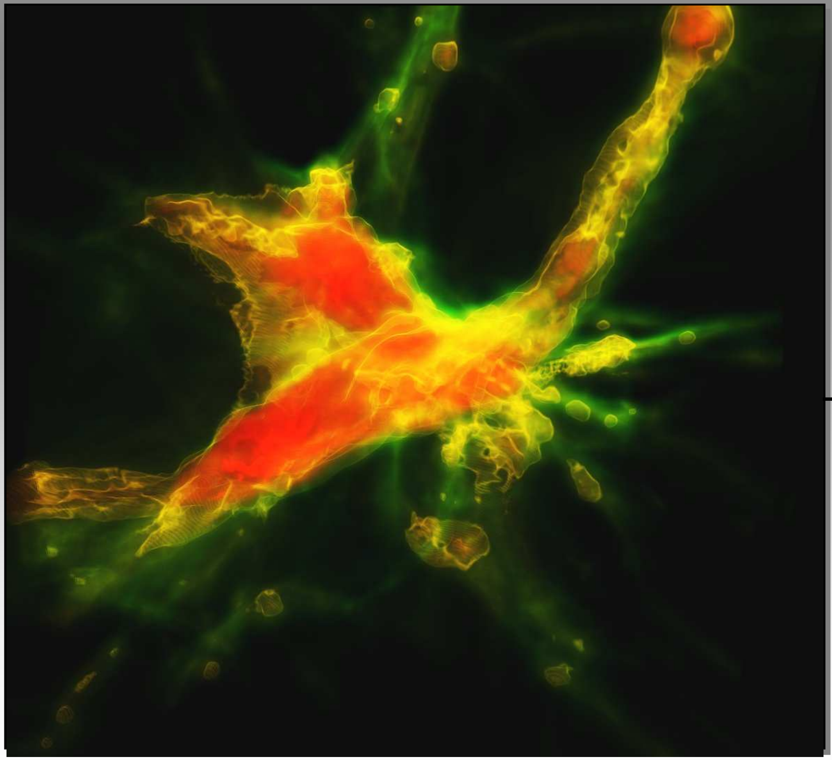
ITA Colloquium
April 2008

The Formation of the First Stars and Galaxies

Thomas Greif





Introduction

What do we do?

- Numerical simulations of cosmological structure formation with GADGET

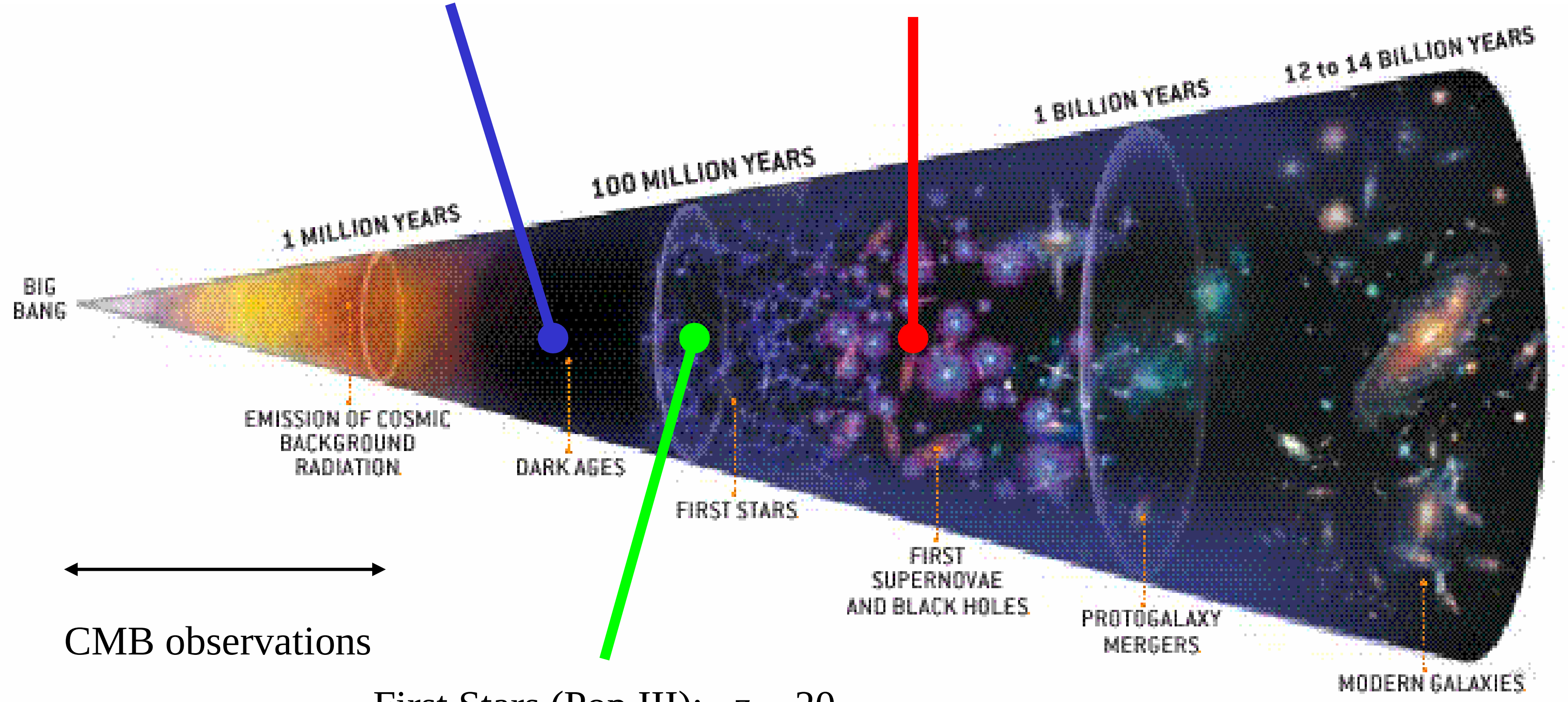
Collaborators:

- Heidelberg: Paul Clark, Ralf Klessen
- Potsdam: Simon Glover
- Austin: Volker Bromm, Jarrett Johnson

Resources:

- Lonestar: ~ 5,000 CPU‘s
- Ranger: ~ 50,000 CPU‘s, world‘s largest open science system

Cosmic Timeline



Dark Ages

First Galaxies: z ~ 10

First Stars (Pop III): z ~ 20

CMB observations

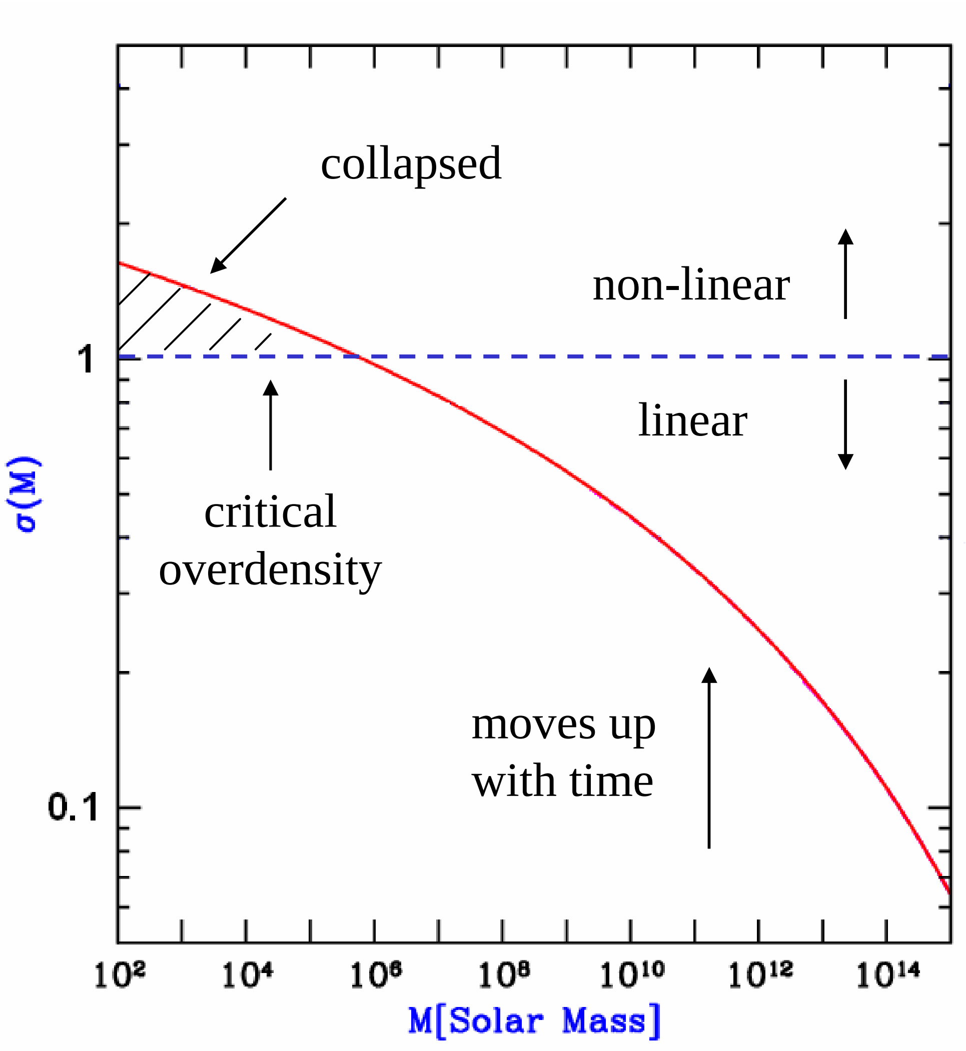
“Direct” observations

Larson & Bromm 01

Review: First Stars

How do the first stars form?

- Primordial quantum fluctuations grow over time
- Dark matter clumps decouple from the Hubble flow once their overdensity approaches unity
- Formation of minihaloes with $M_{vir} \sim 10^5 - 10^6 M_o$

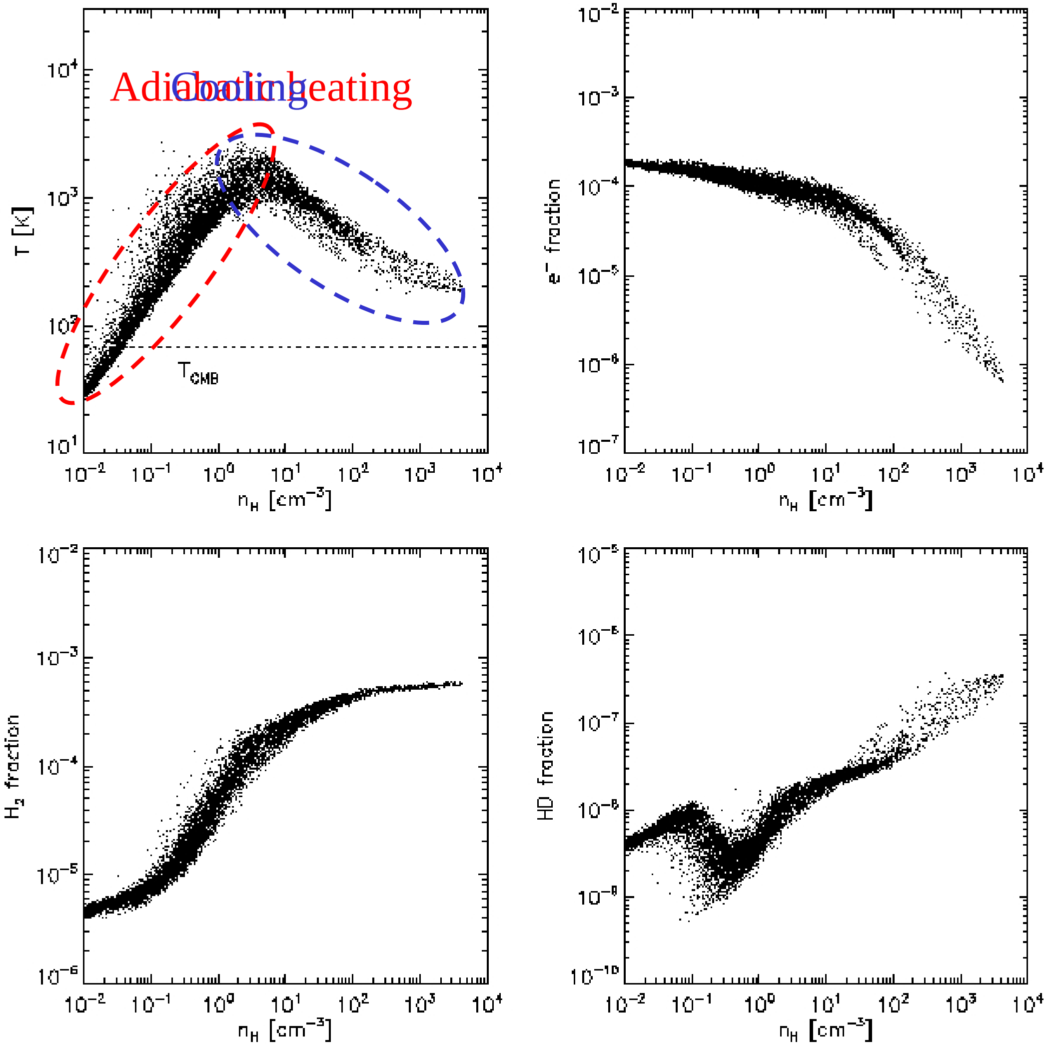


Larson & Bromm 01

Review: First Stars

What does the gas do?

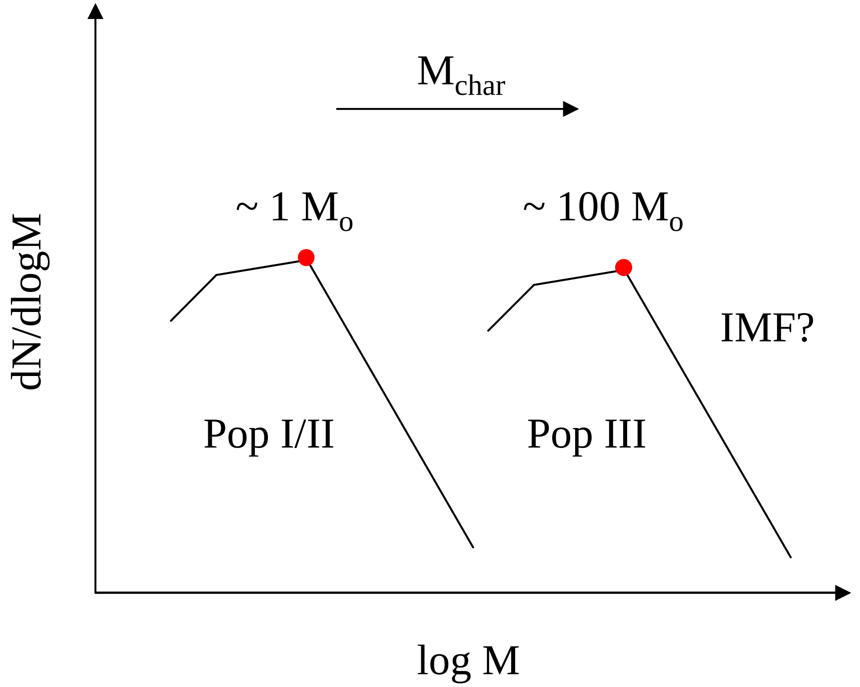
- Gas initially follows the potential set by the dark matter
- Jeans criterion prevents gas from settling into haloes below ~ 10^5 M_o
- Once densities become high enough: formation of H_2 and onset of cooling



Review: First Stars

The final phases:

- Formation of a single protostellar core at very high densities
- Extremely efficient accretion: $dM/dt \propto c_s^3 \propto T^{3/2}$
- Present-day universe: ~ 10 K
- High-redshift universe: ~ 200 K
- Accretion rate ~ 100 times higher!



Pop III stars: ~ 100 M_o

Review: First Stars

Caveats:

- Magnetic fields
- Protostellar accretion phase:
  - Disk formation
  - Radiative feedback on parent cloud
  - Fragmentation?
  - Low-mass primordial stars?
- On main sequence: pulsations, winds

Still many open questions!

Review: First Stars

Simulation setup:

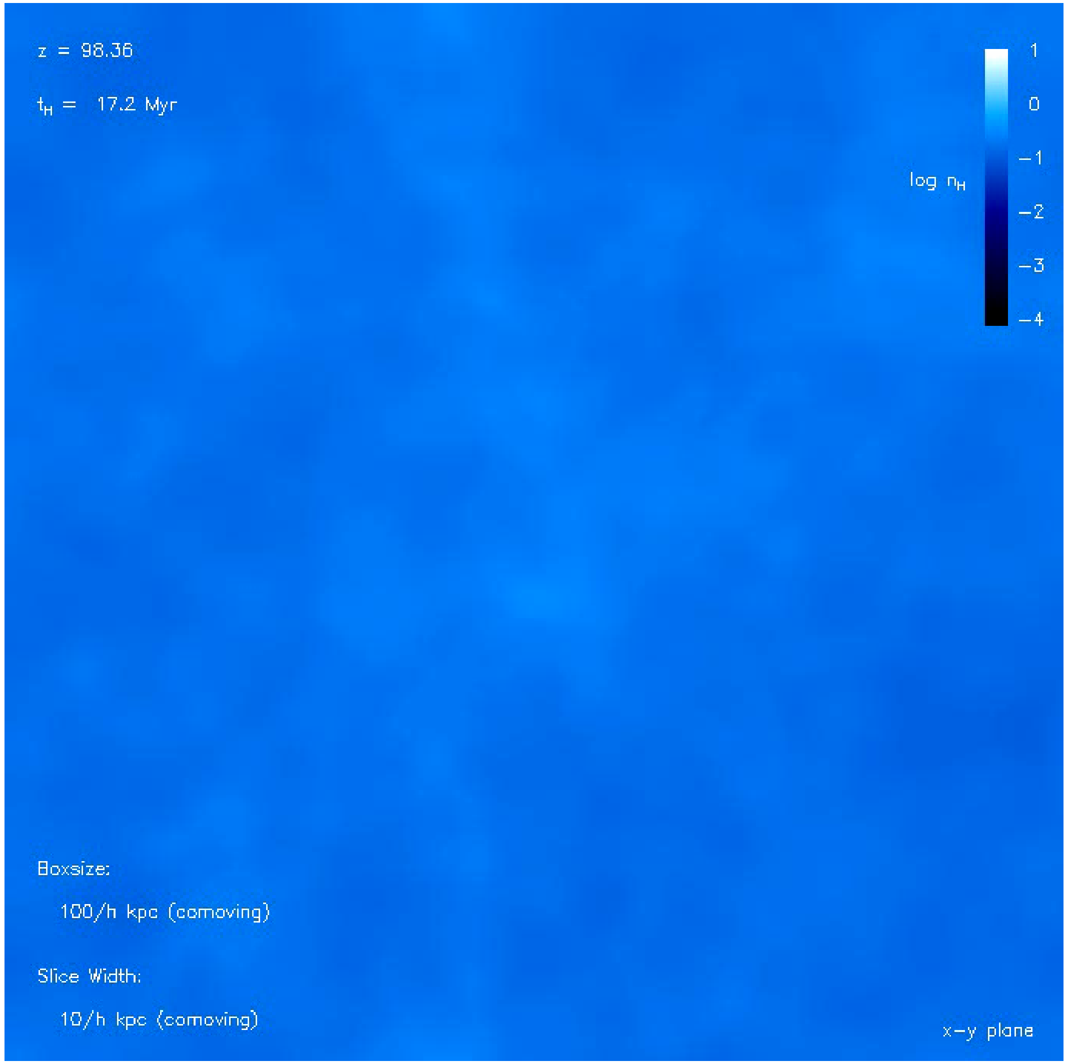
- Fully cosmological initial conditions at z = 100
- Box Size: 150 kpc (comoving)

Result:

- Collapse of first star-forming minihalo at $z \sim 25$ ($\sim 10^6 M_o$)

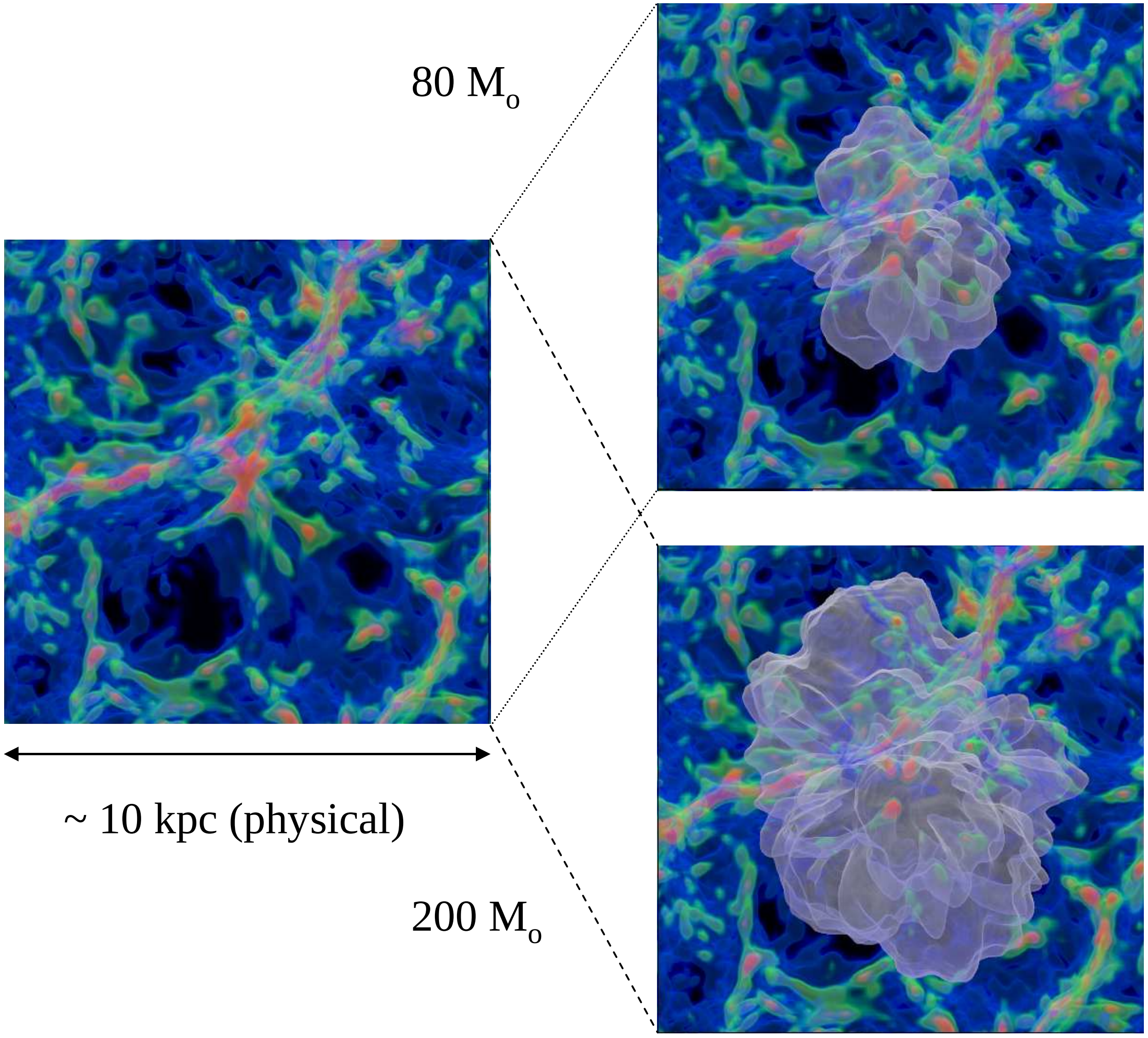
Questions:

- Further evolution?
- Stellar feedback?



Radiative Feedback

- Pop III stars have surface temperatures around 10^5 K
- Ionizing flux ~ 100 times higher than for normal Pop I/II stars
- HII regions extend out to a few kpc

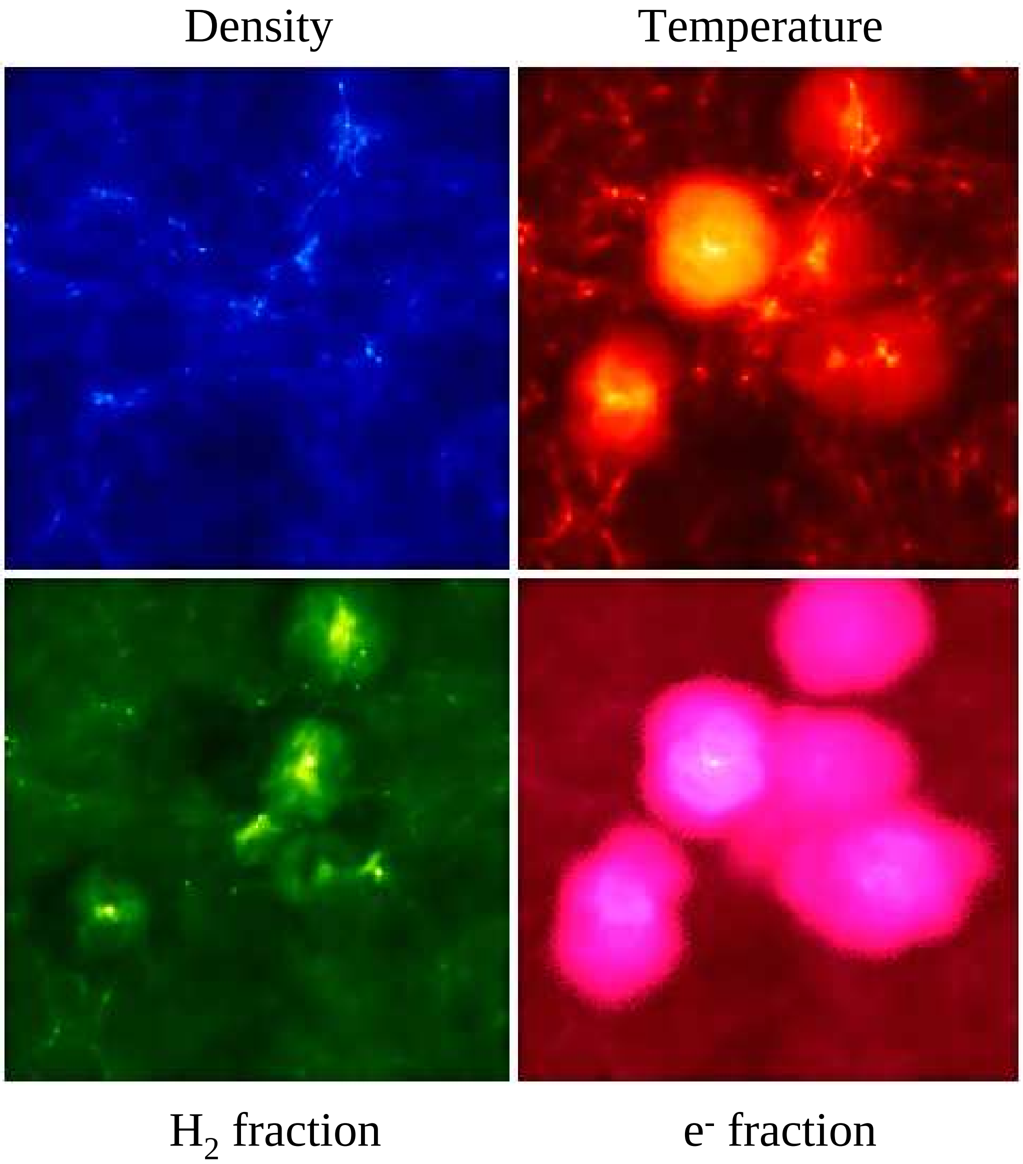


Alvarez, Bromm & Shapiro 06

Radiative Feedback

Recent work:

- Large Box: 500 kpc (comoving)
- Multiple HII regions
- Inclusion of Lyman-Werner radiation

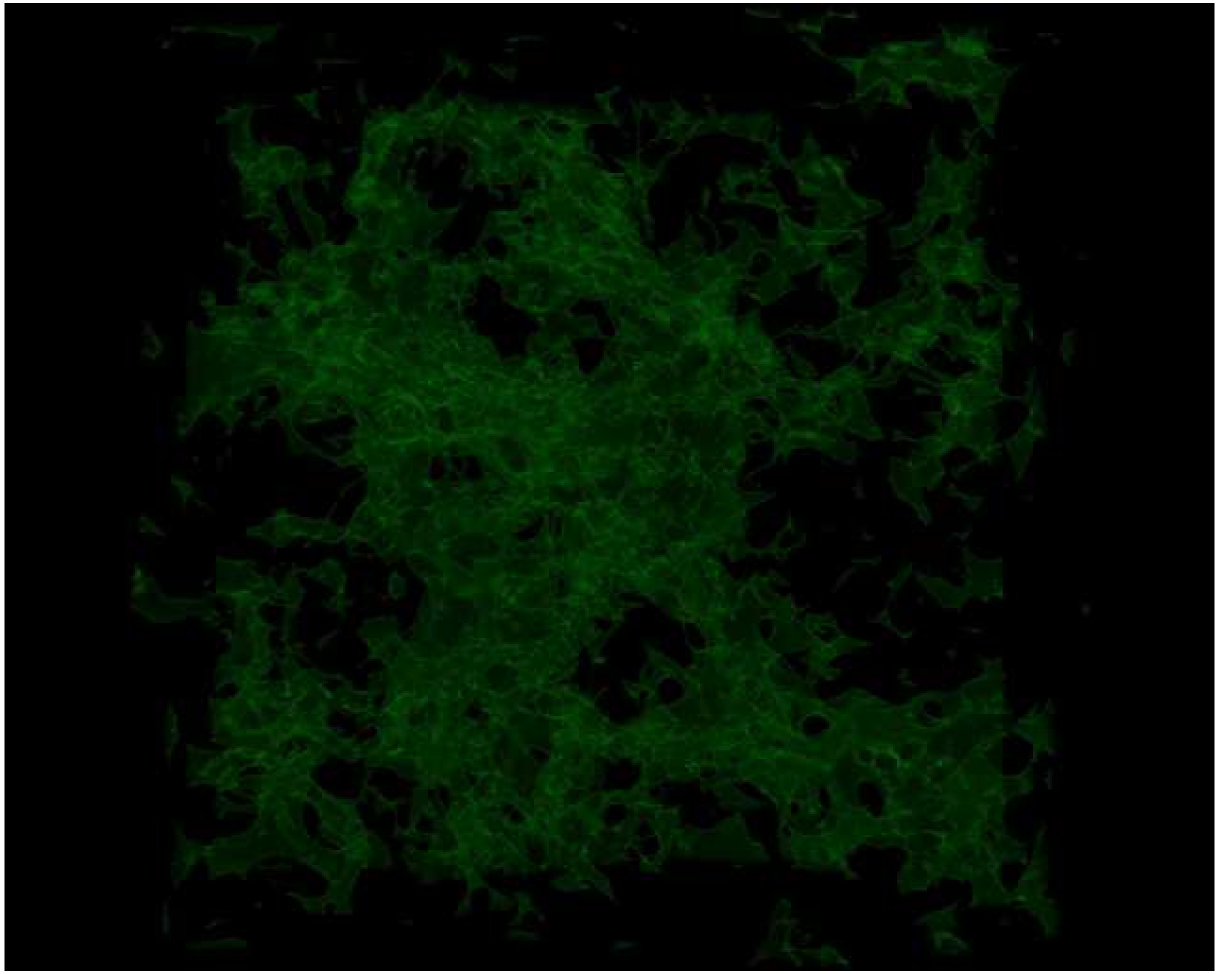


Johnson, Greif & Bromm 07

Radiative Feedback

Crucial:

- Initially radiation destroys molecules
- But: rapid reformation of molecules in relic HII regions
- Cooling to the CMB

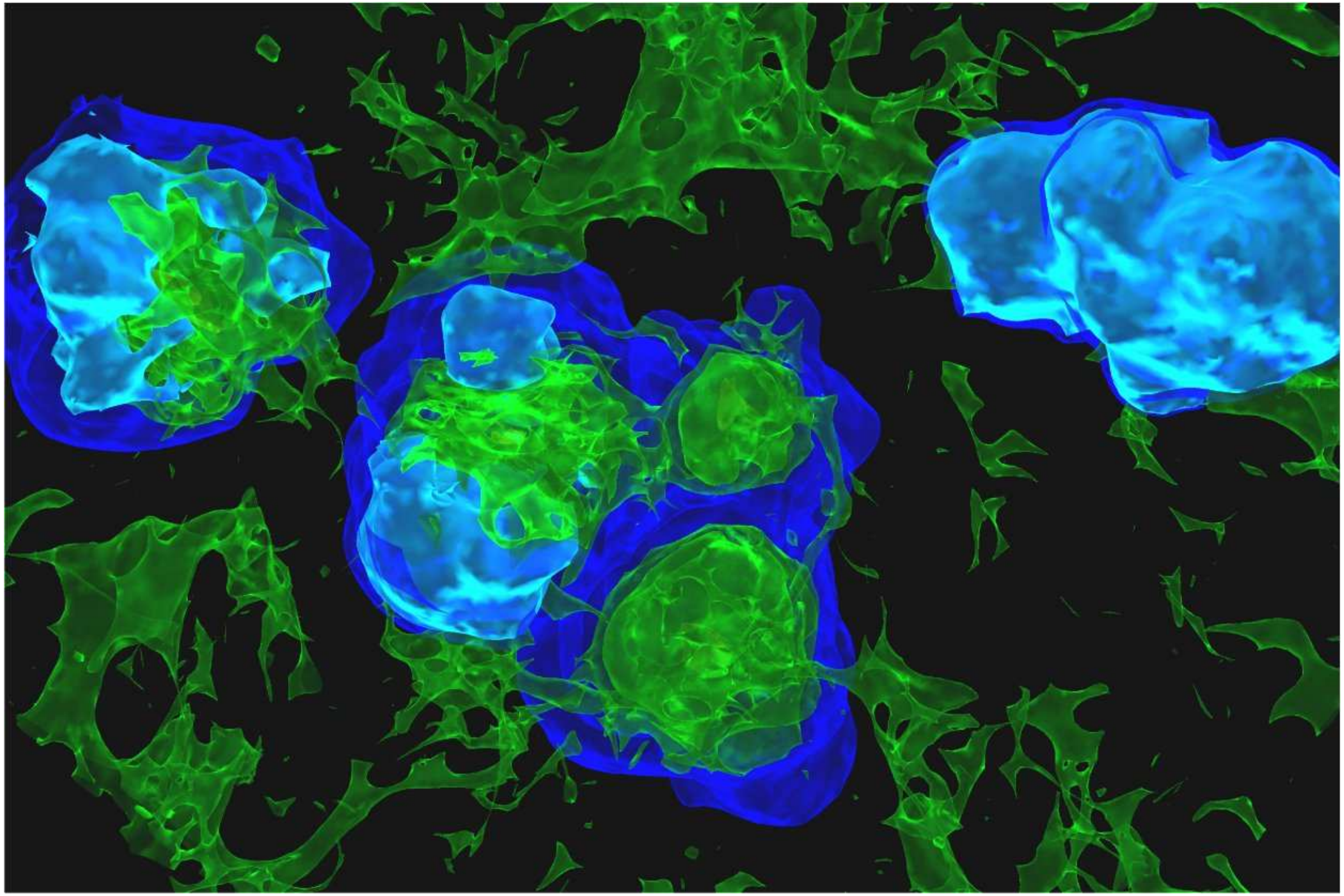


H_2 fraction

Johnson, Greif & Bromm 07

Radiative Feedback

In 3D:



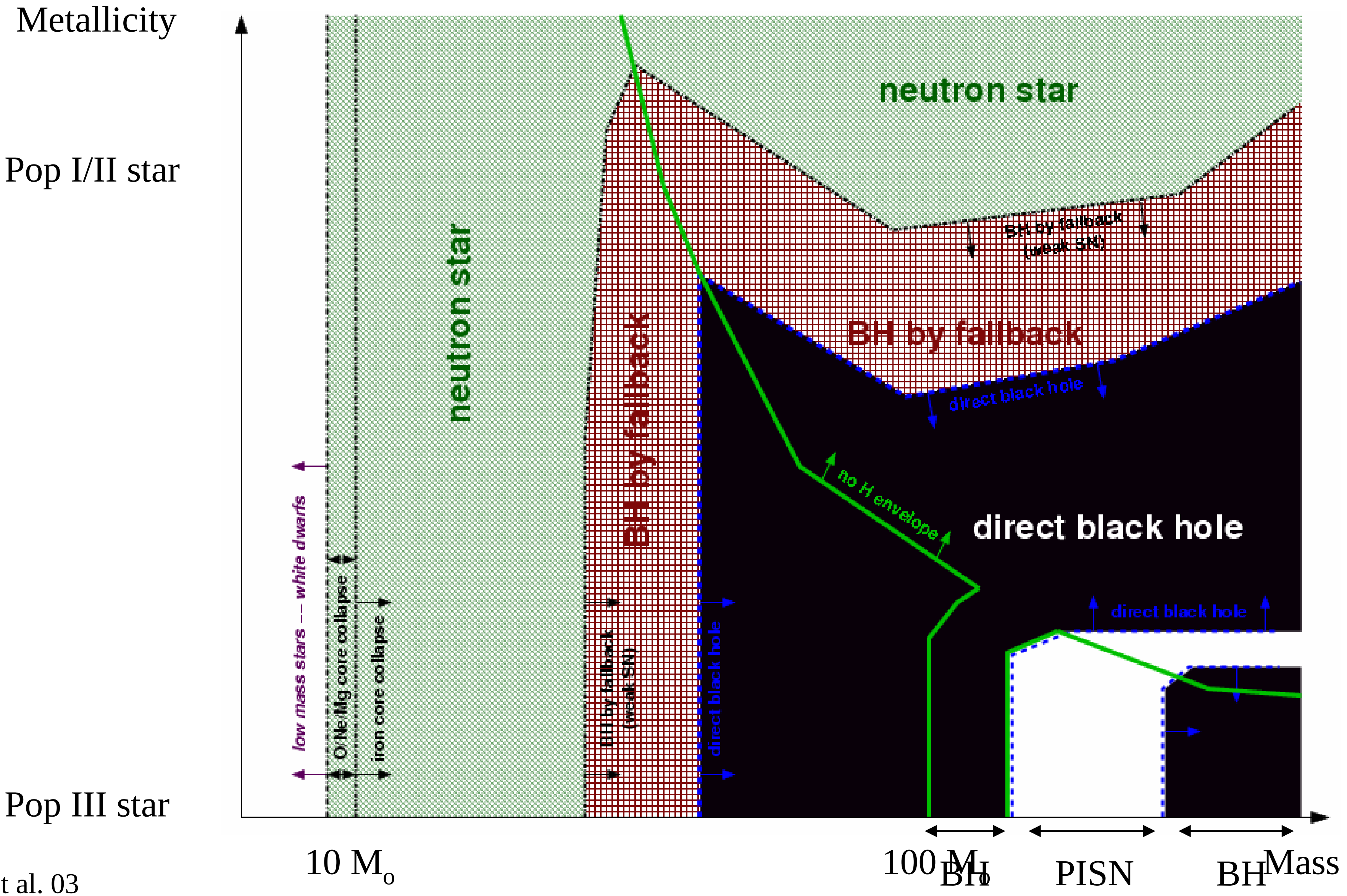
Johnson, Greif & Bromm 07

Radiative Feedback

Implications:

- Relic HII region gas likely forms less massive (~ 10 M_o) primordial stars
- Two populations of metal-free stars:
  - Truly primordial: Pop III.1 with ~ 100 M_o
  - Previous ionization: Pop III.2 with ~ 10 M_o

Fate of Pop III Stars



Heger et al. 03

PISN

Pair-instability supernova:

- Extremely violent explosion: up to 10^{53} ergs of kinetic energy
- Metal yields of order 50%
- Profound impact in terms of dynamics and chemical enrichment

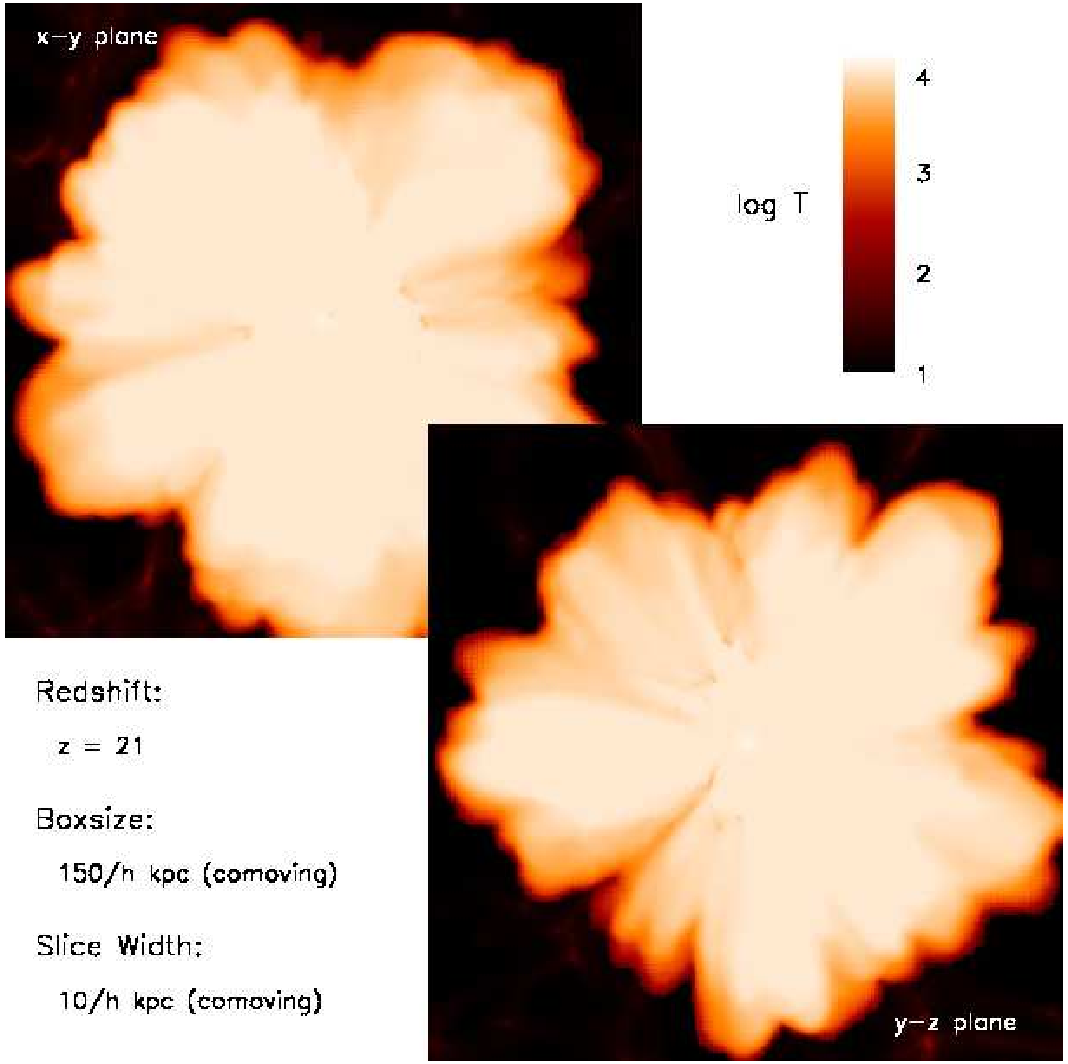
Goal:

- Simulate PISN in cosmological context!

Supernova Explosion

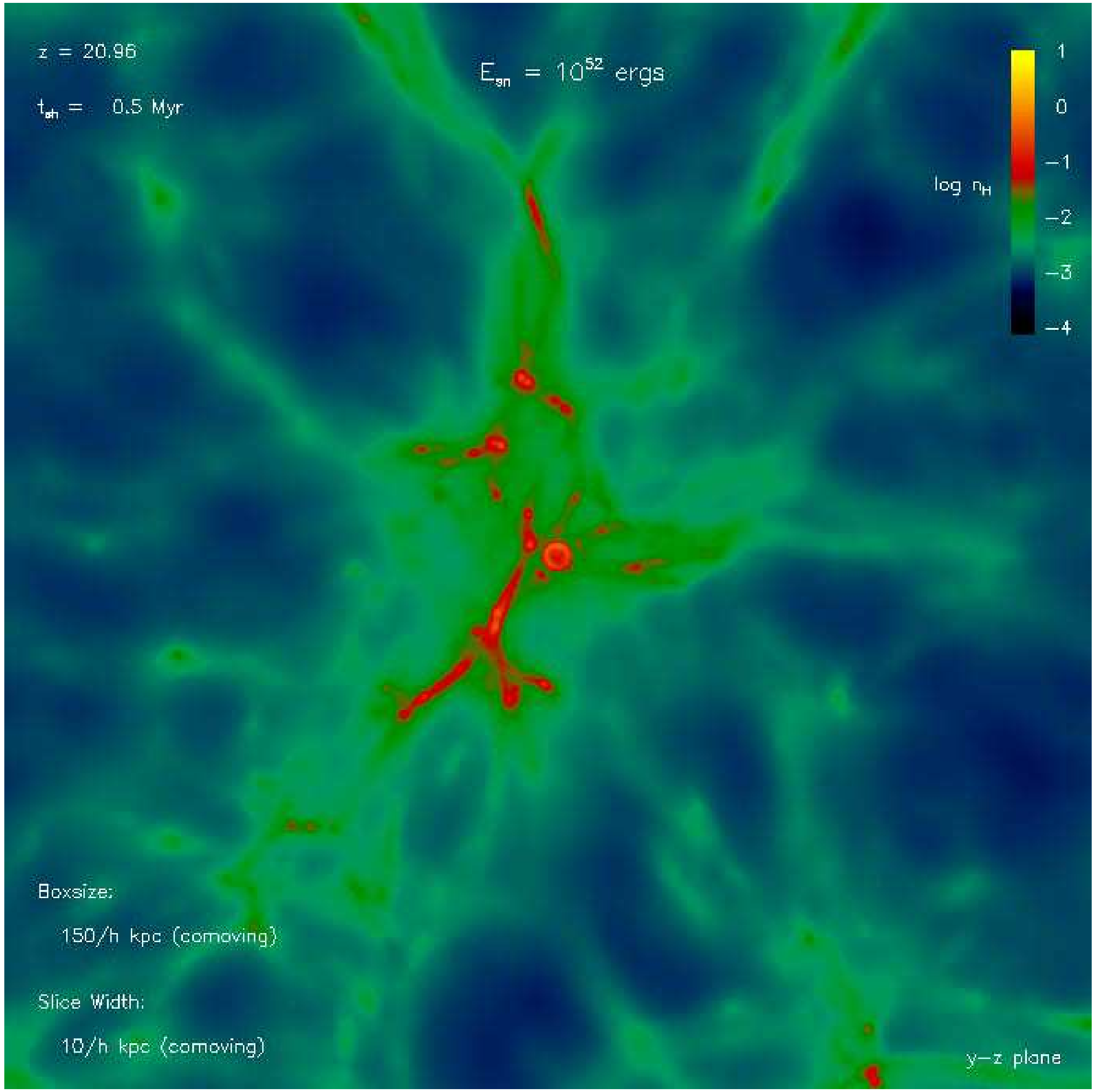
PISN Simulation Setup:

- Cosmological initial conditions
- Box size: 200 kpc (comoving)
- Form Pop III star
- Create HII region
- Inject 10^{52} ergs of kinetic energy



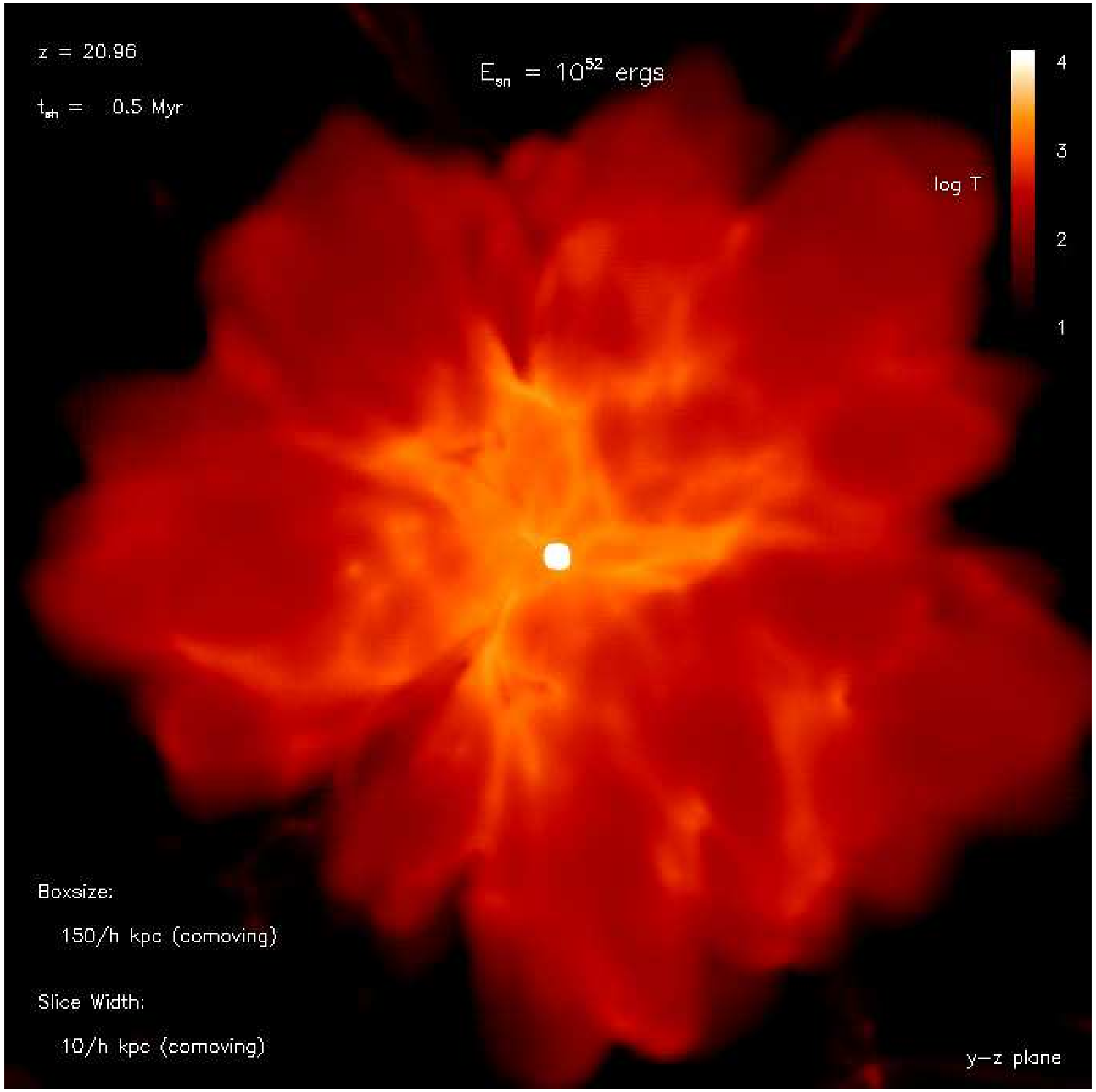
Supernova Explosion

The Simulation:



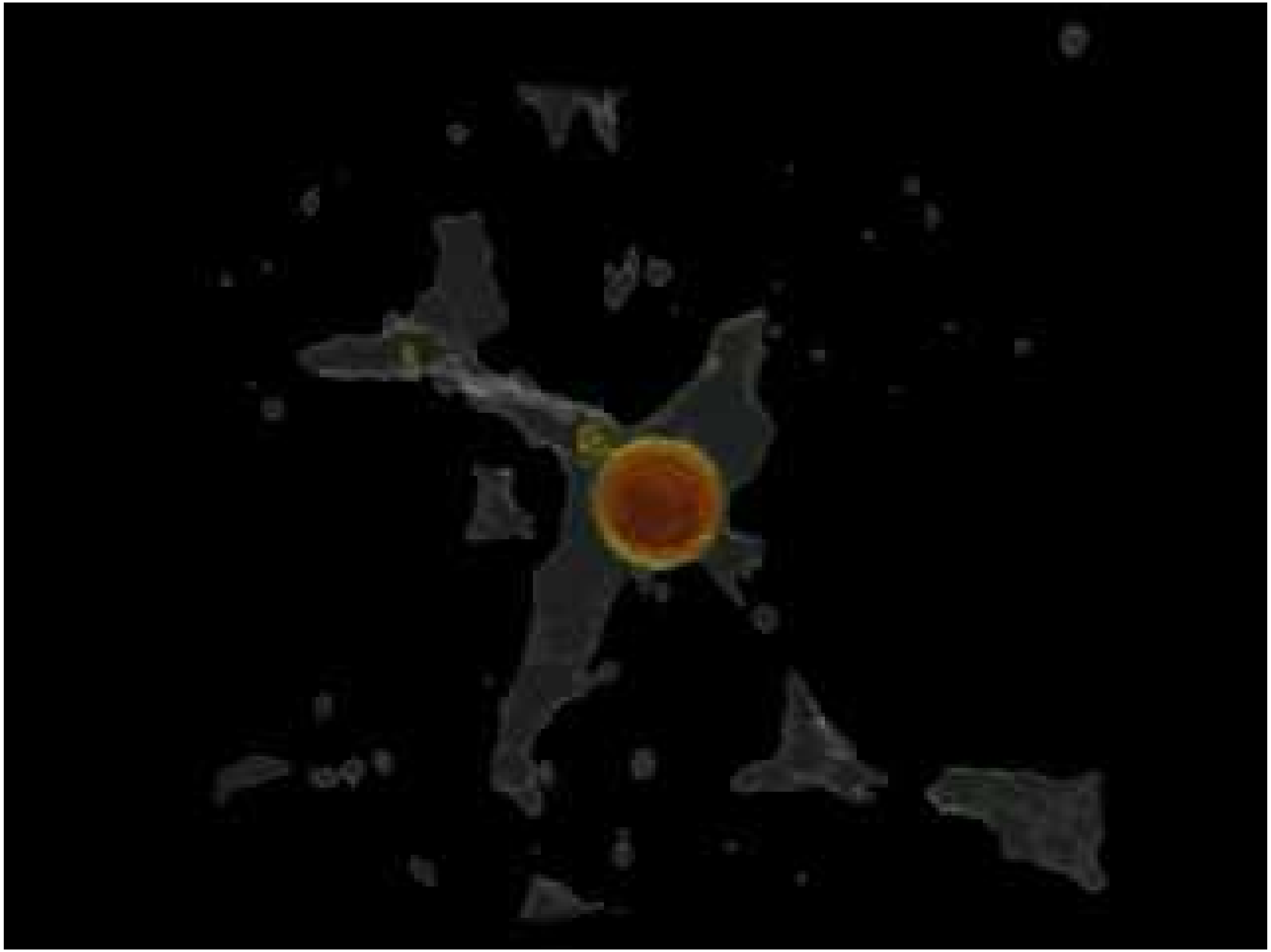
Supernova Explosion

The Simulation:



Supernova Explosion

In 3D:



Supernova Explosion

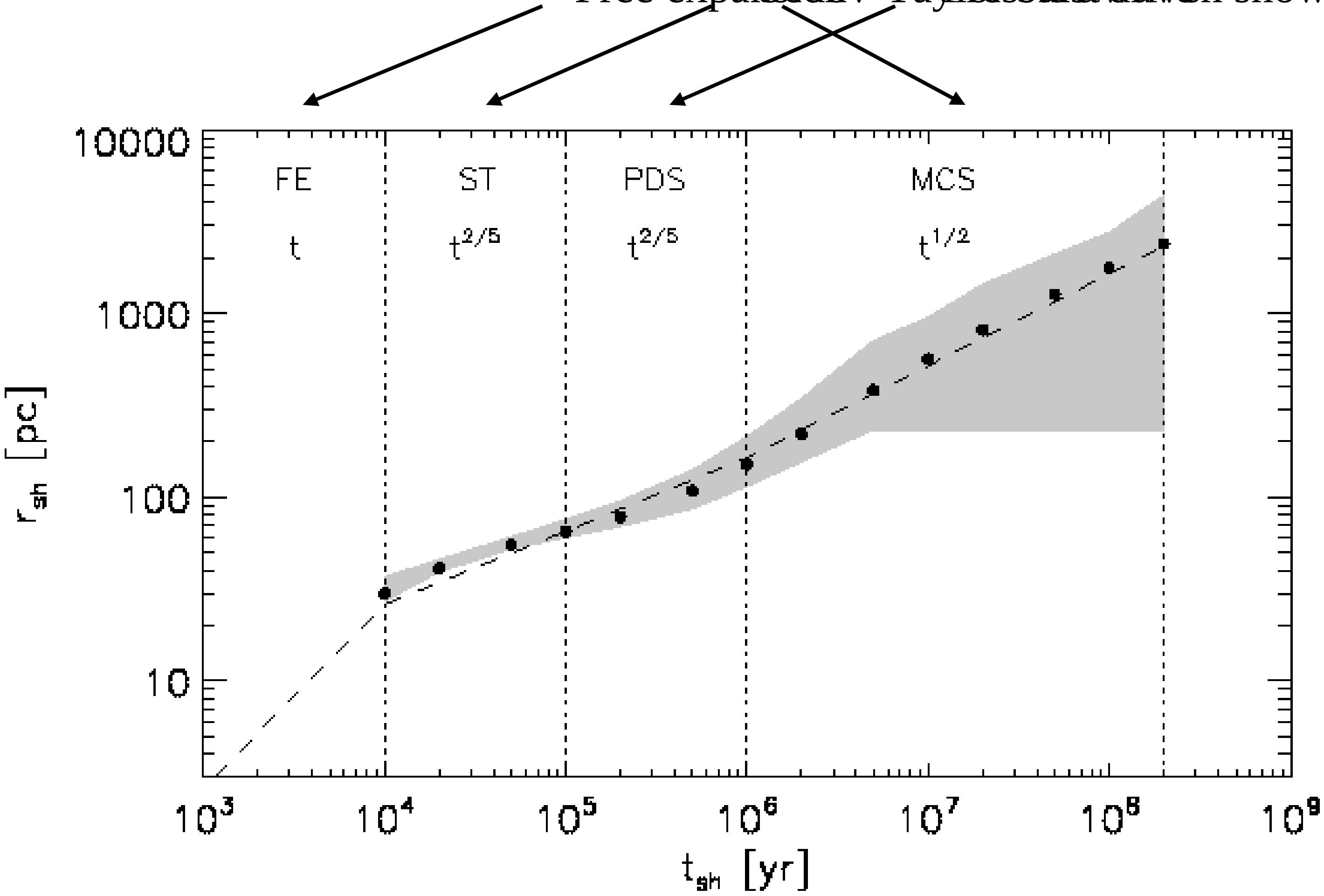
Shock radius:

Momentum-conserving snowplow

Free expansion

Sedov-Taylor blastwave

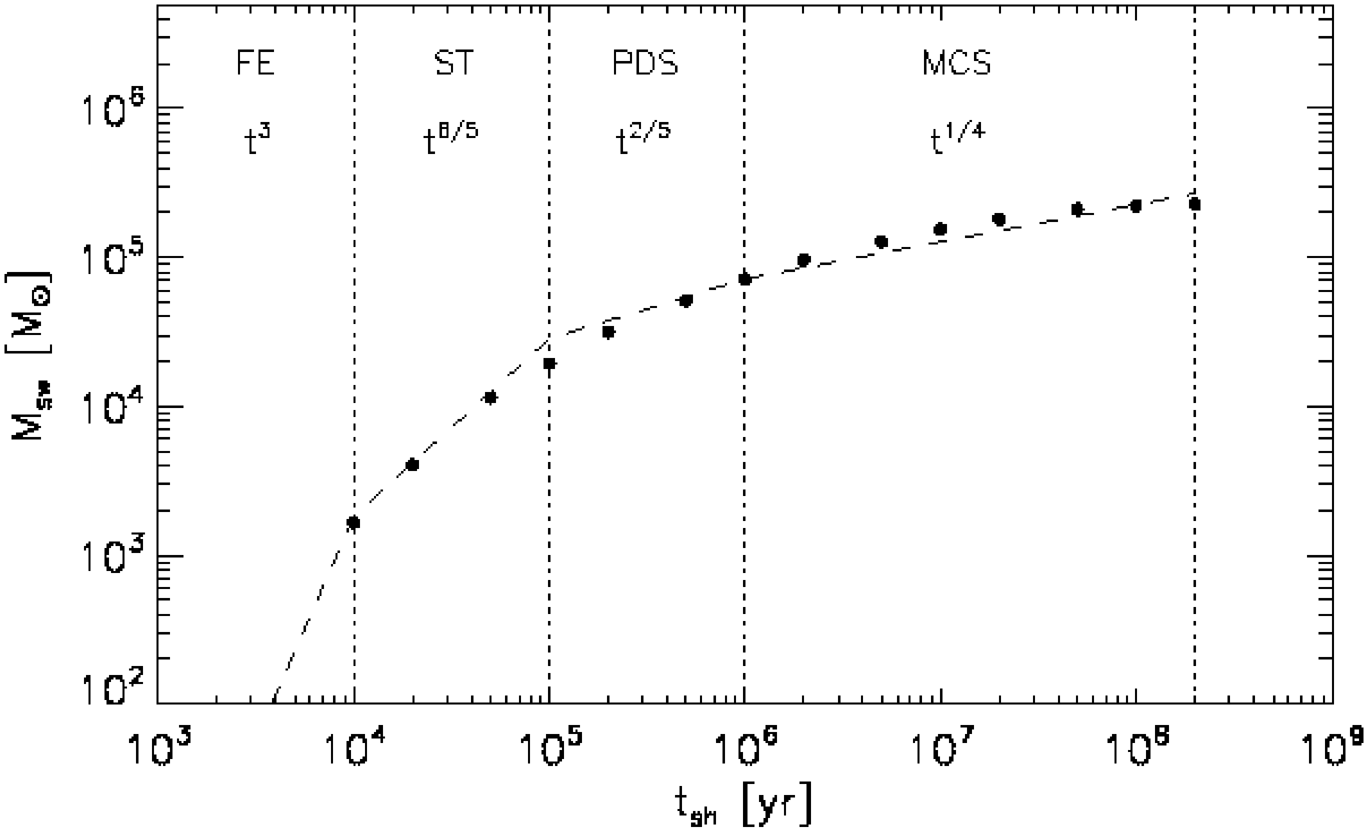
Pressure-driven snowplow



Supernova Explosion

Swept-up mass:

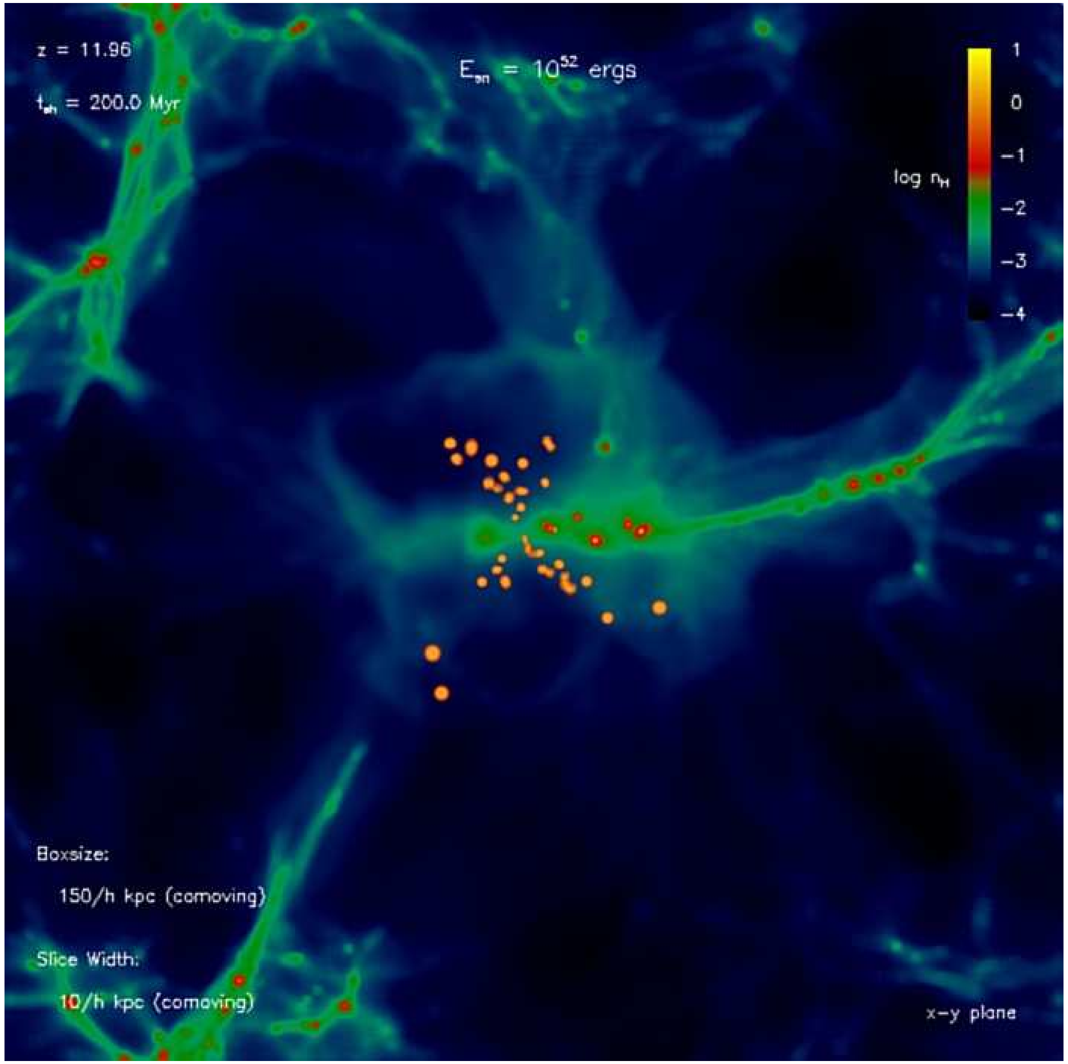
Total swept-up mass: 2.5×10⁵ M_o



Supernova Explosion

Distribution of metals:

- Metals are generally expelled into the voids
- Larger haloes must assemble to recollect the expelled metals
- Nest step: simulate the formation of a first galaxy!



First Galaxies

Definition of a first galaxy:

- Virial temperature exceeds ~ 10^4 K or virial mass exceeds ~ 5×10^7 M_o

Why does this make sense?

- Photoheated gas is retained
- Self-regulated star formation

Remember: onset of atomic hydrogen cooling at ~ 10^4 K!

First Galaxies

Goal:

- Push simulations to $M_{vir} \sim 5\times10^7\ M_o$ (i.e. to $z \sim 10$)

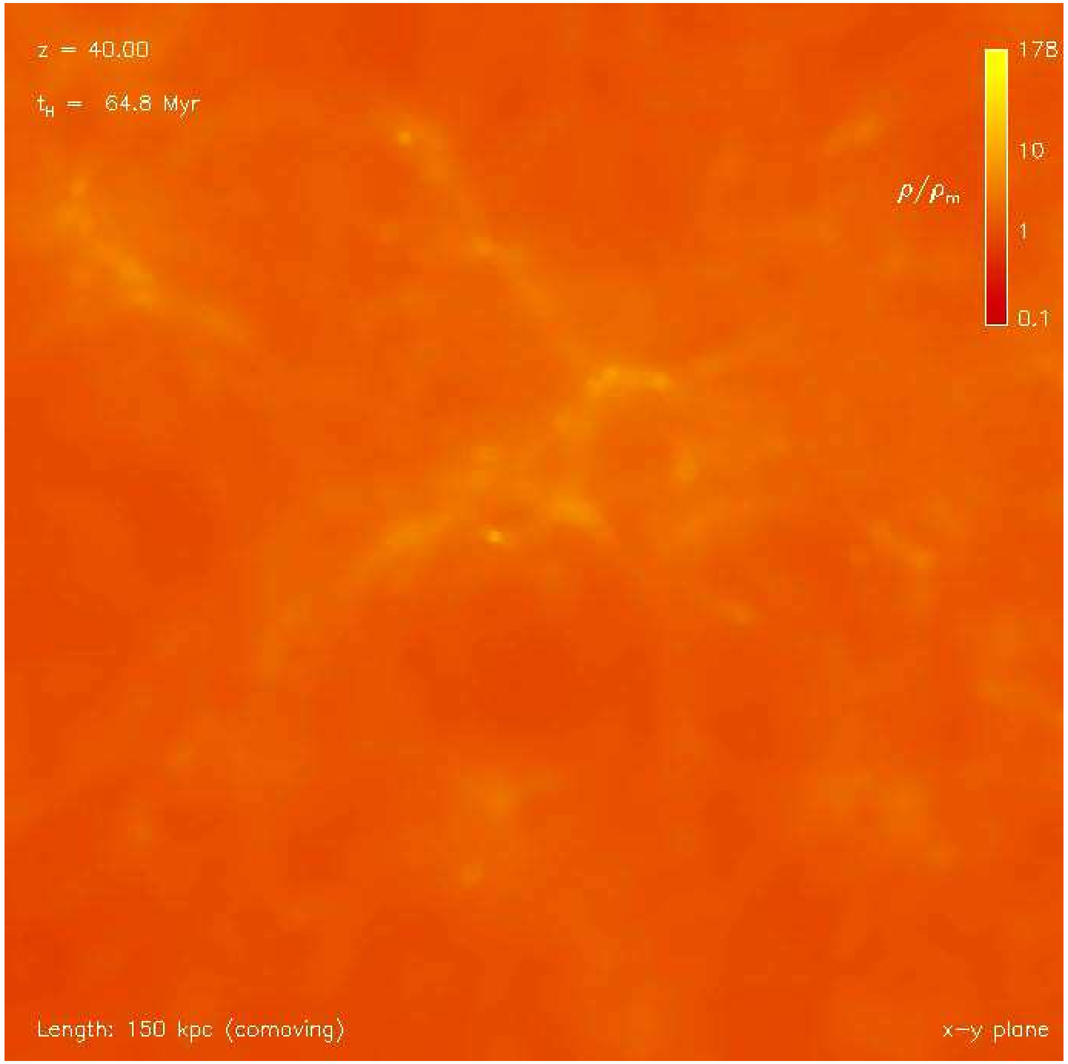
First step:

- Neglect radiative and supernova-driven feedback
- Use primordial chemistry
- Concentrate on consequences of halo collapse on baryonic physics

First Galaxies

Simulation setup:

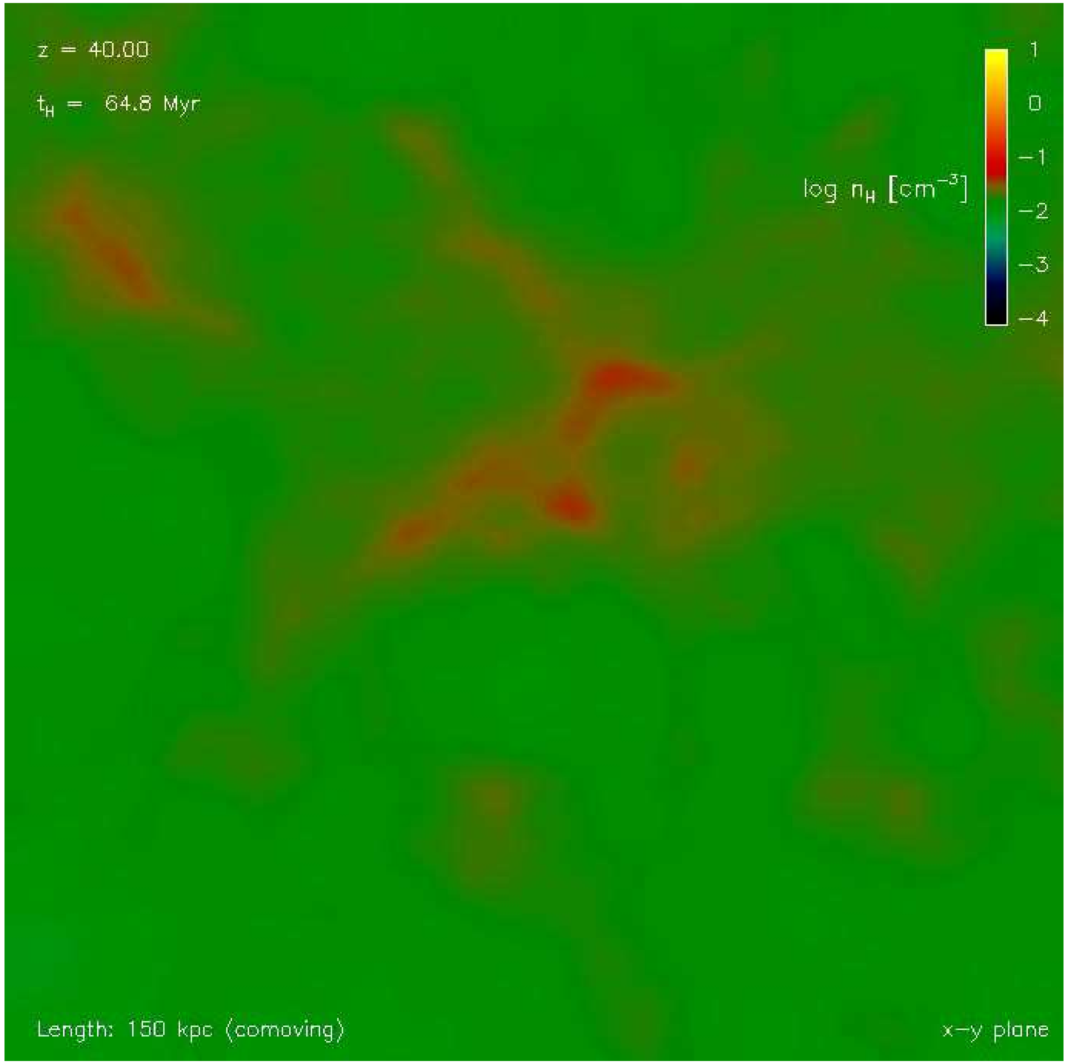
- Cosmological initial conditions
- Box Size: 700 kpc (comoving)
- Create ~ 5×10^7 M_o halo



First Galaxies

Star formation:

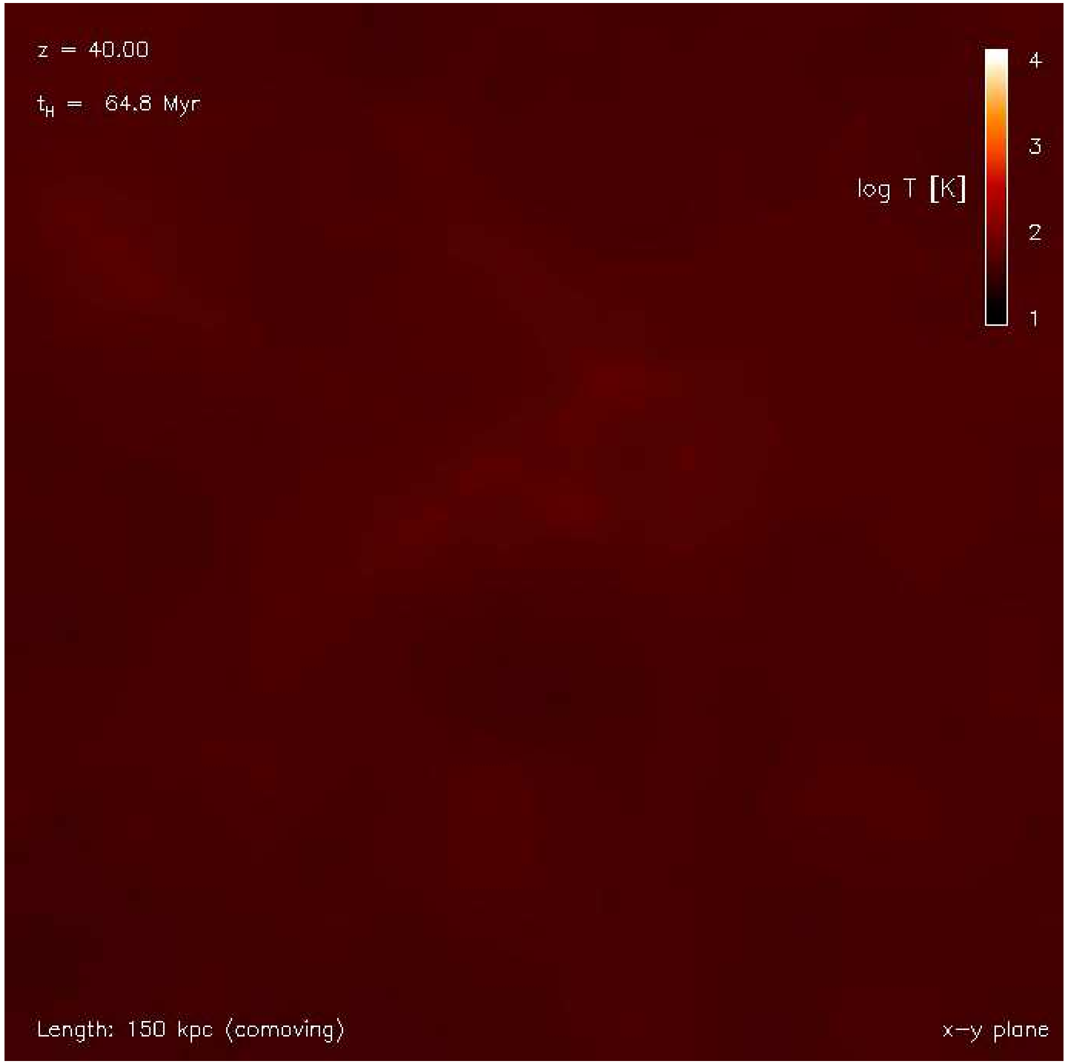
- Individual Pop III stars form, denoted by sink particles (i.e. black holes)
- Of order 10 Pop III stars form prior to the assembly of the galaxy



First Galaxies

Virial heating:

- Virial temperature gradually increases to ~ 10^4 K

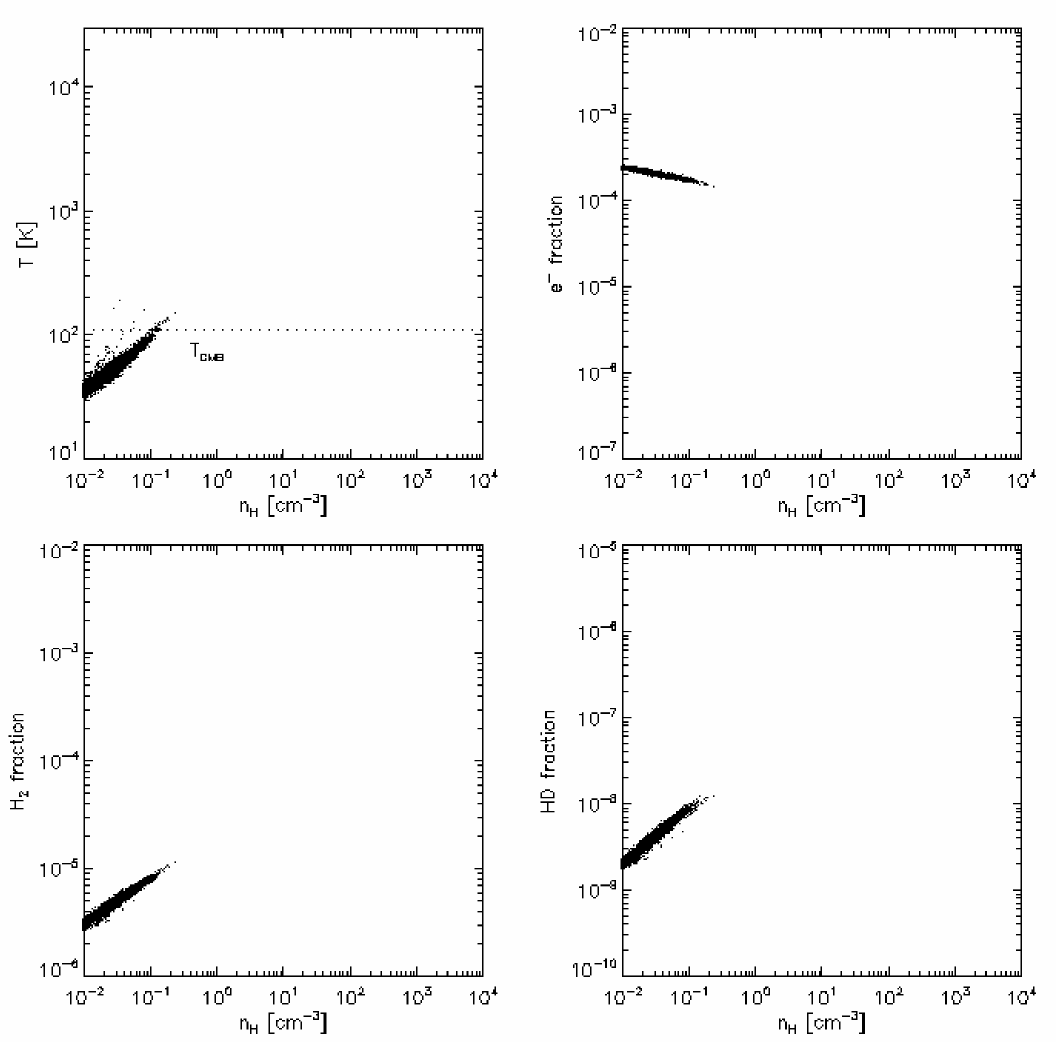


Chemistry and Cooling

Temperature:

- Adiabatic heating to virial temperature followed by onset of H_2 cooling

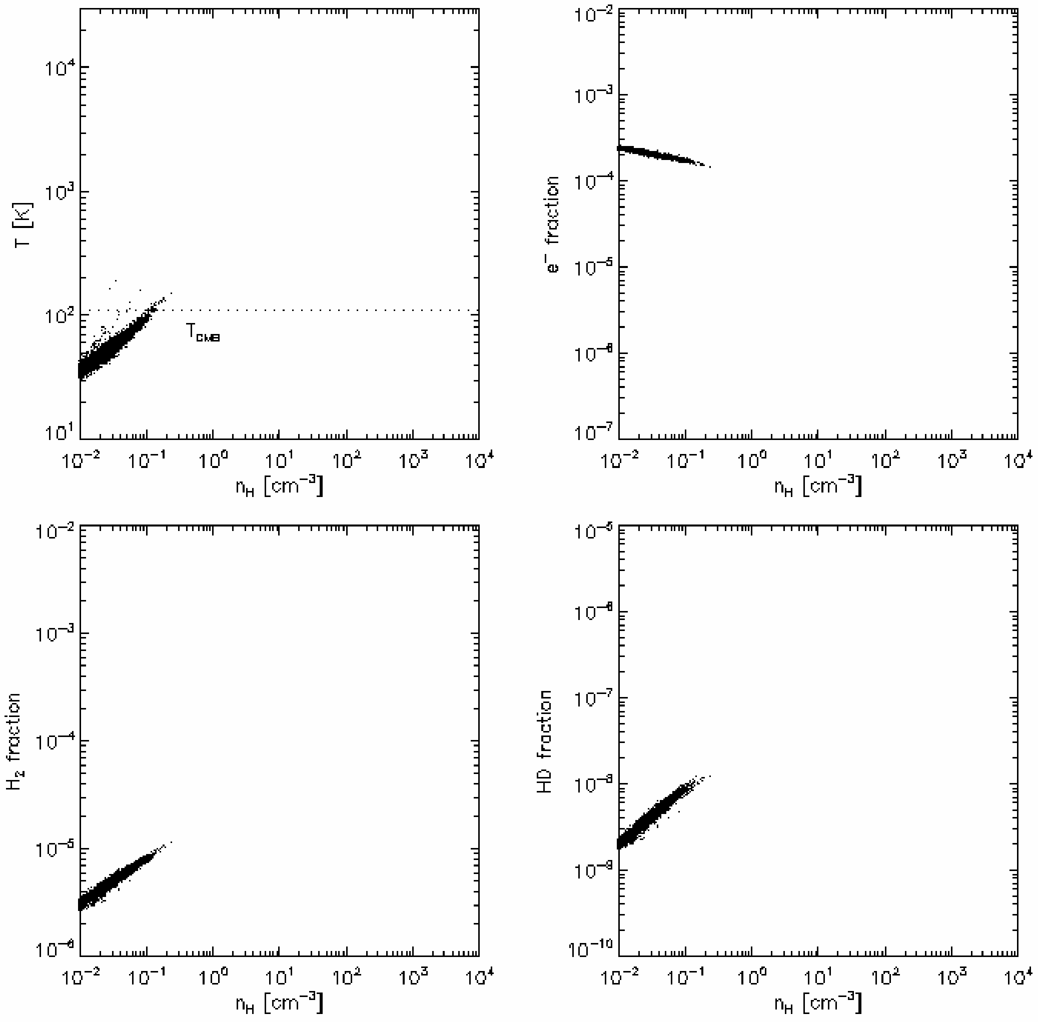
- Isothermality at ~ 10^4 K due to atomic hydrogen cooling



Chemistry and Cooling

Electron fraction:

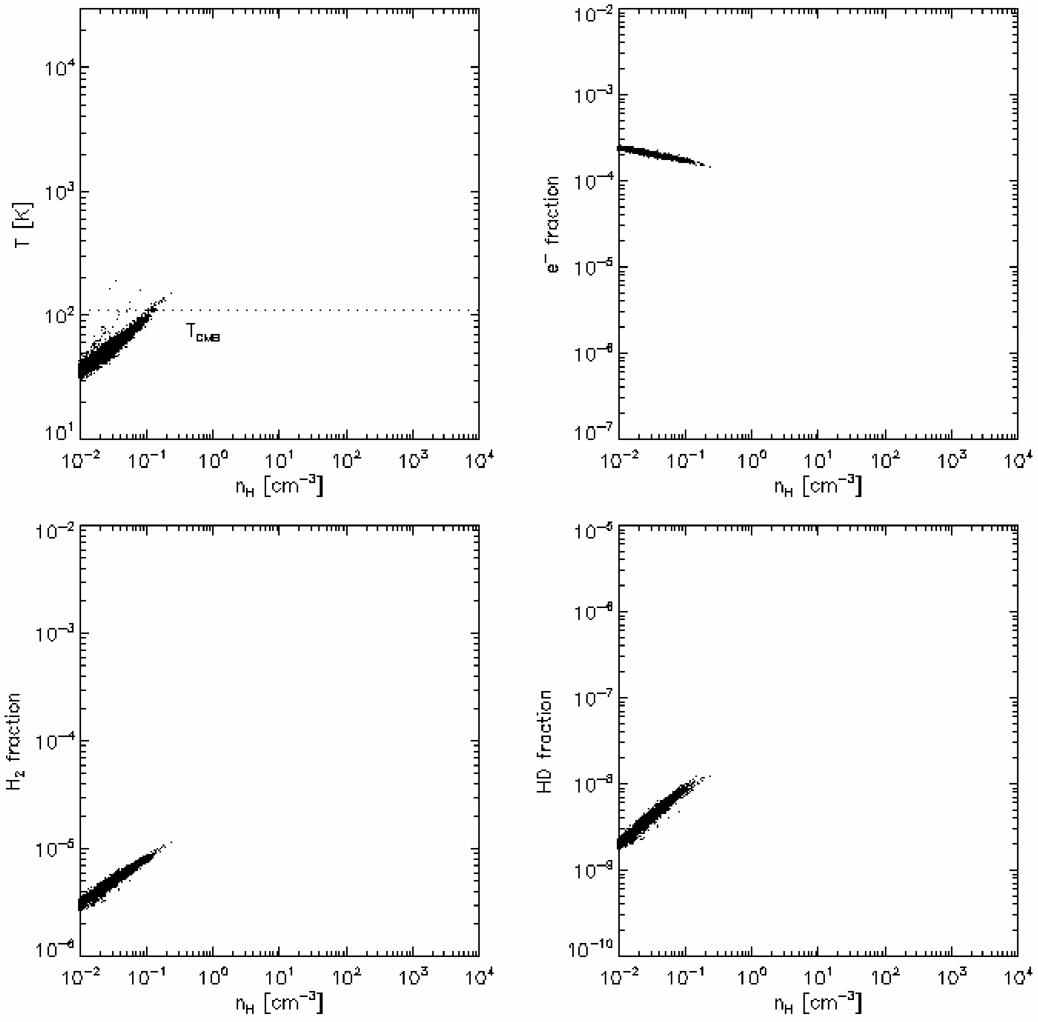
- Elevated electron fraction once virial temperature approaches ~ 10^4 K
- Residual ionization



Chemistry and Cooling

Molecule fractions:

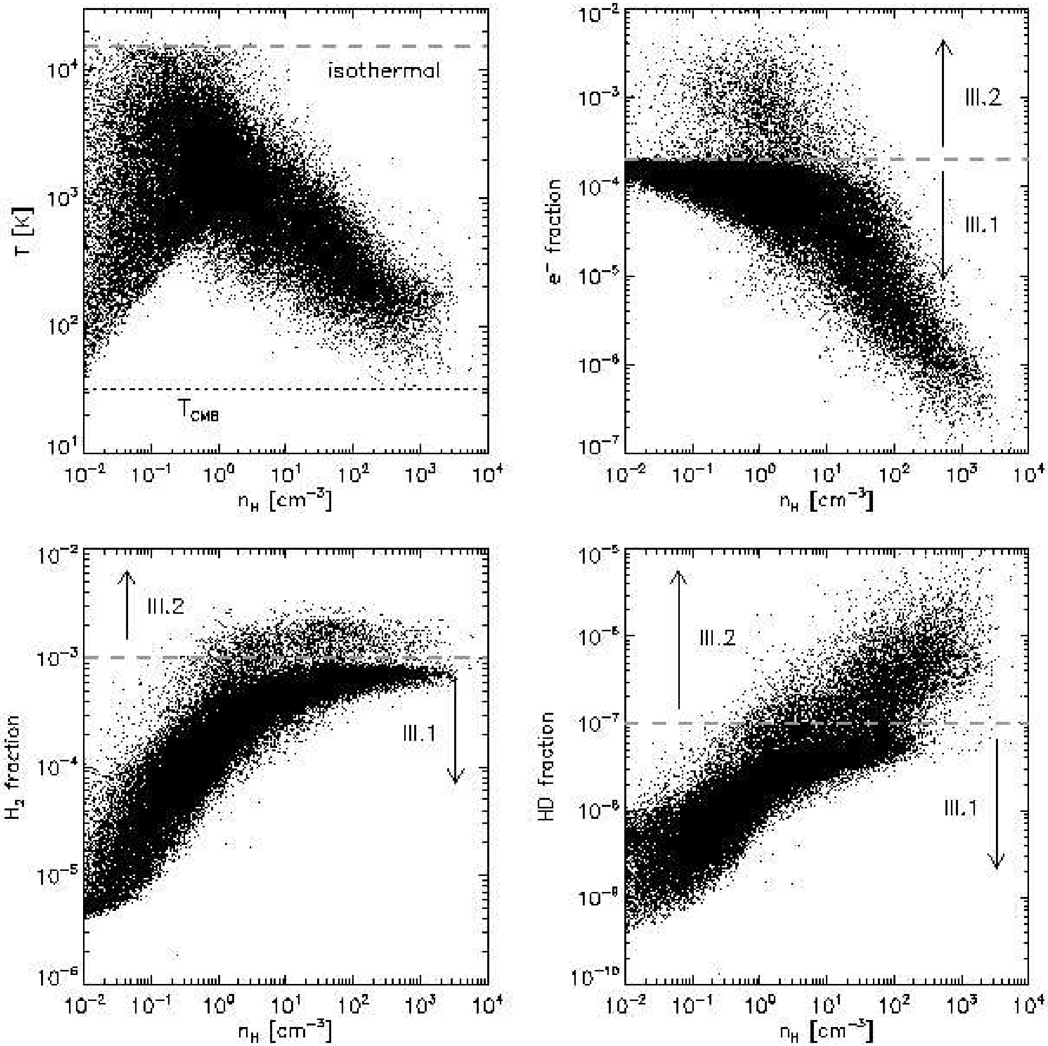
- Elevated H_2 and HD abundances
- Second cooling channel



Chemistry and Cooling

Evolution in phase space:

- Cooling to the CMB?
- Formation of Pop III.2 stars?



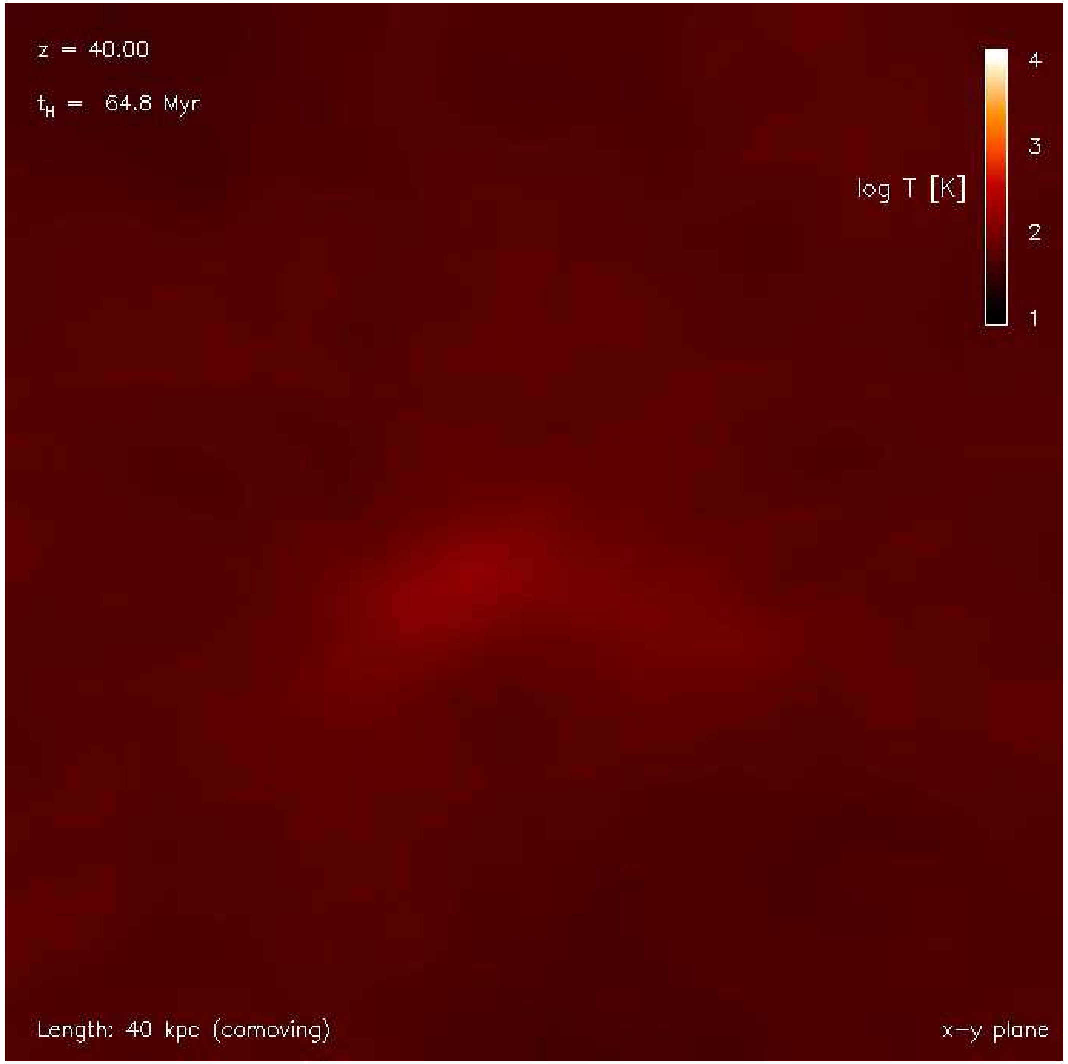
Turbulence

Hot Accretion:

- Accretion of hot gas through the virial shock

Cold Accretion:

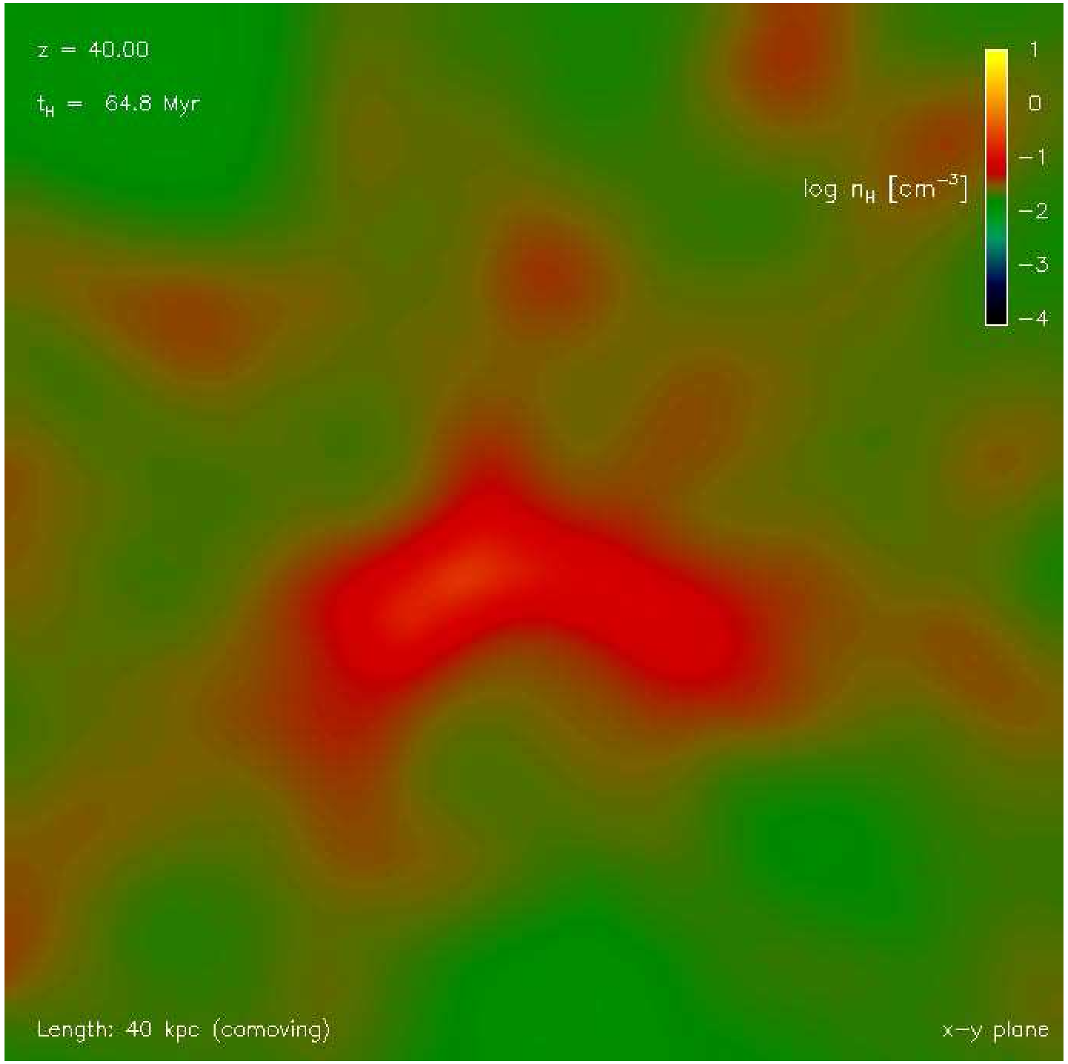
- Accretion of cold gas via filaments



Turbulence

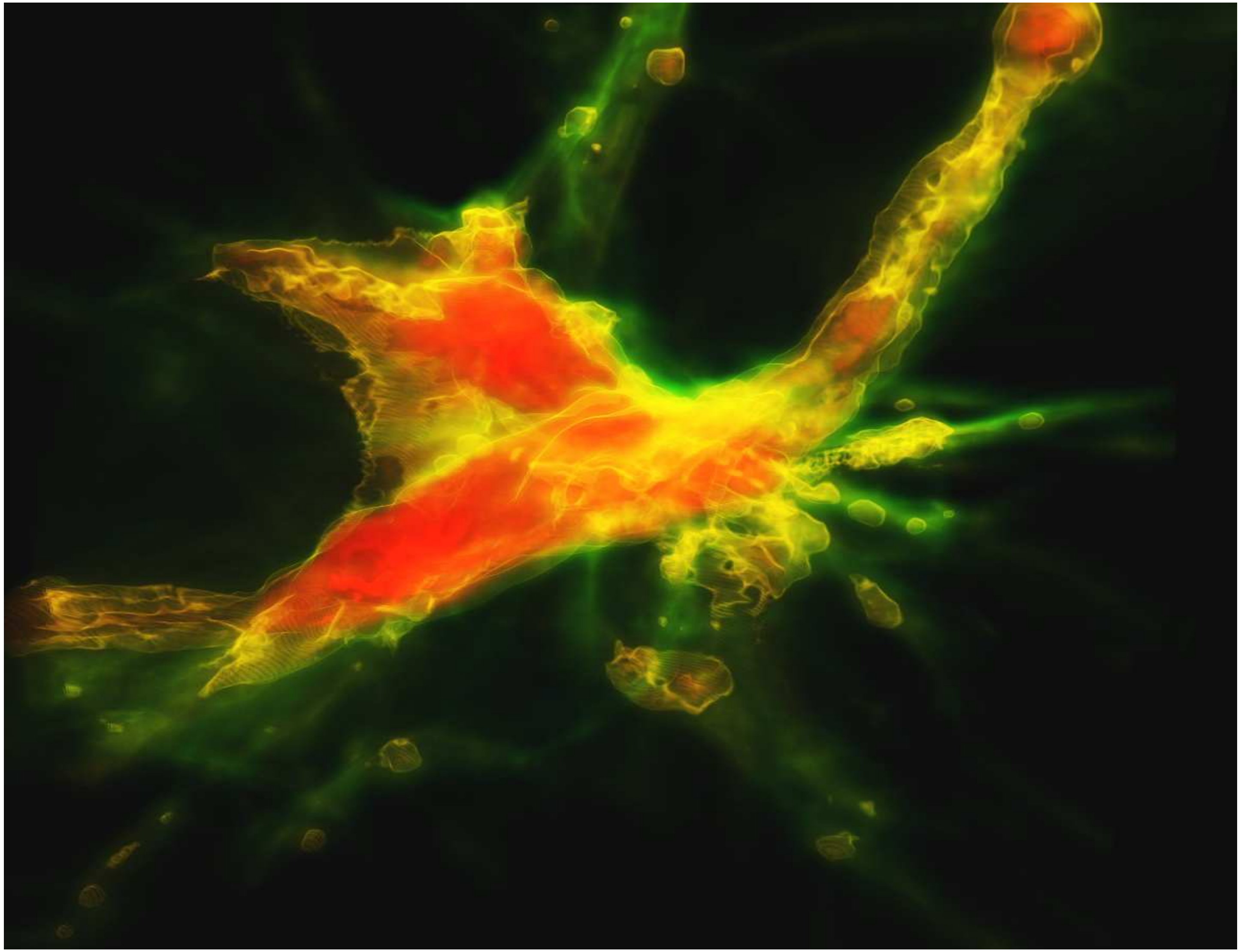
Consequences:

- Cold accretion generates turbulence
- Transitory density perturbations arise that may become Jeans-unstable



Turbulence

In 3D:



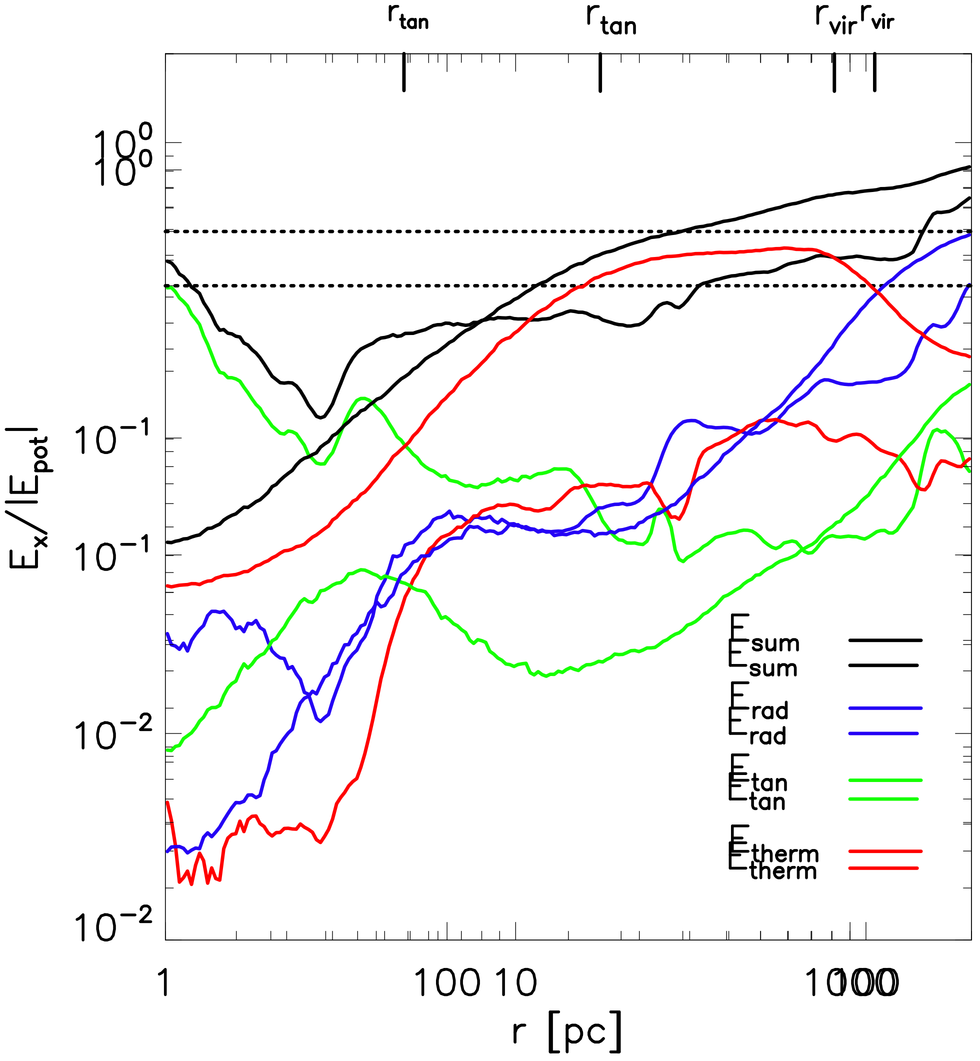
Turbulence

Energy content:

- Dominated by kinetic energy

In minihalo:

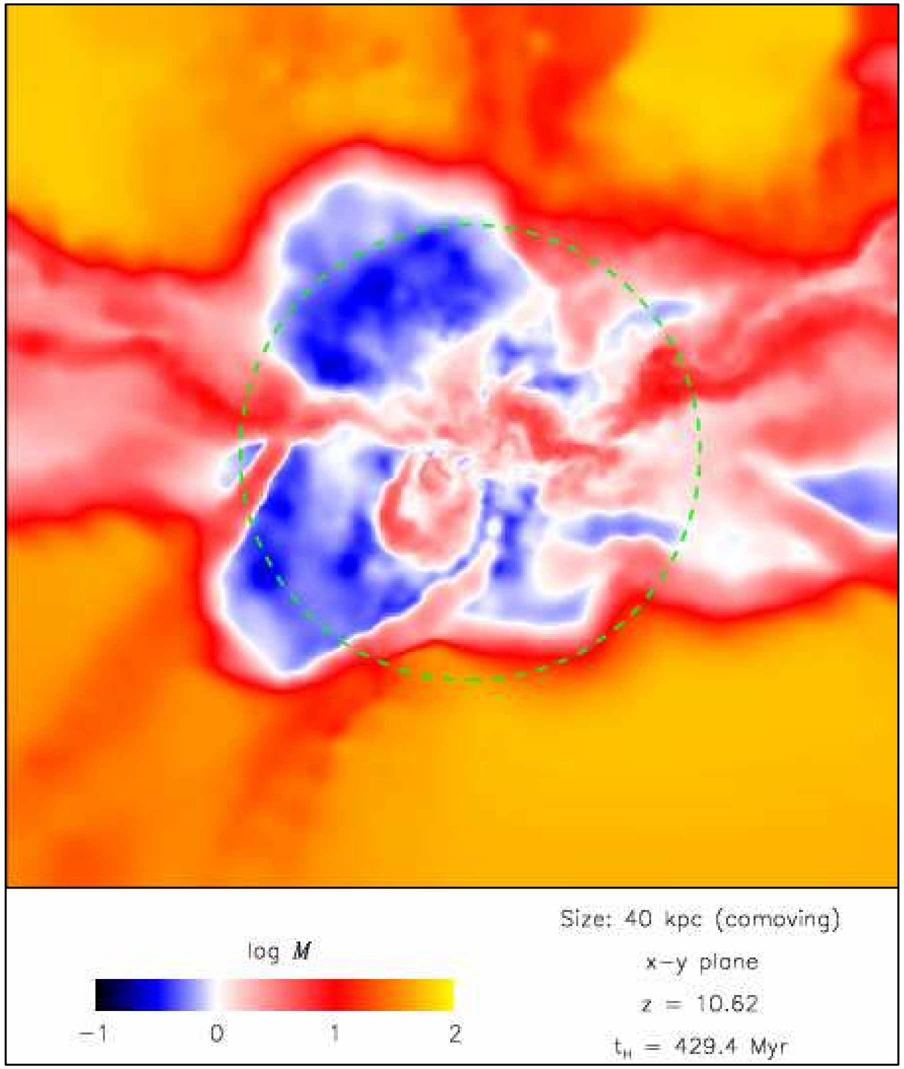
- Dominated by thermal energy



Turbulence

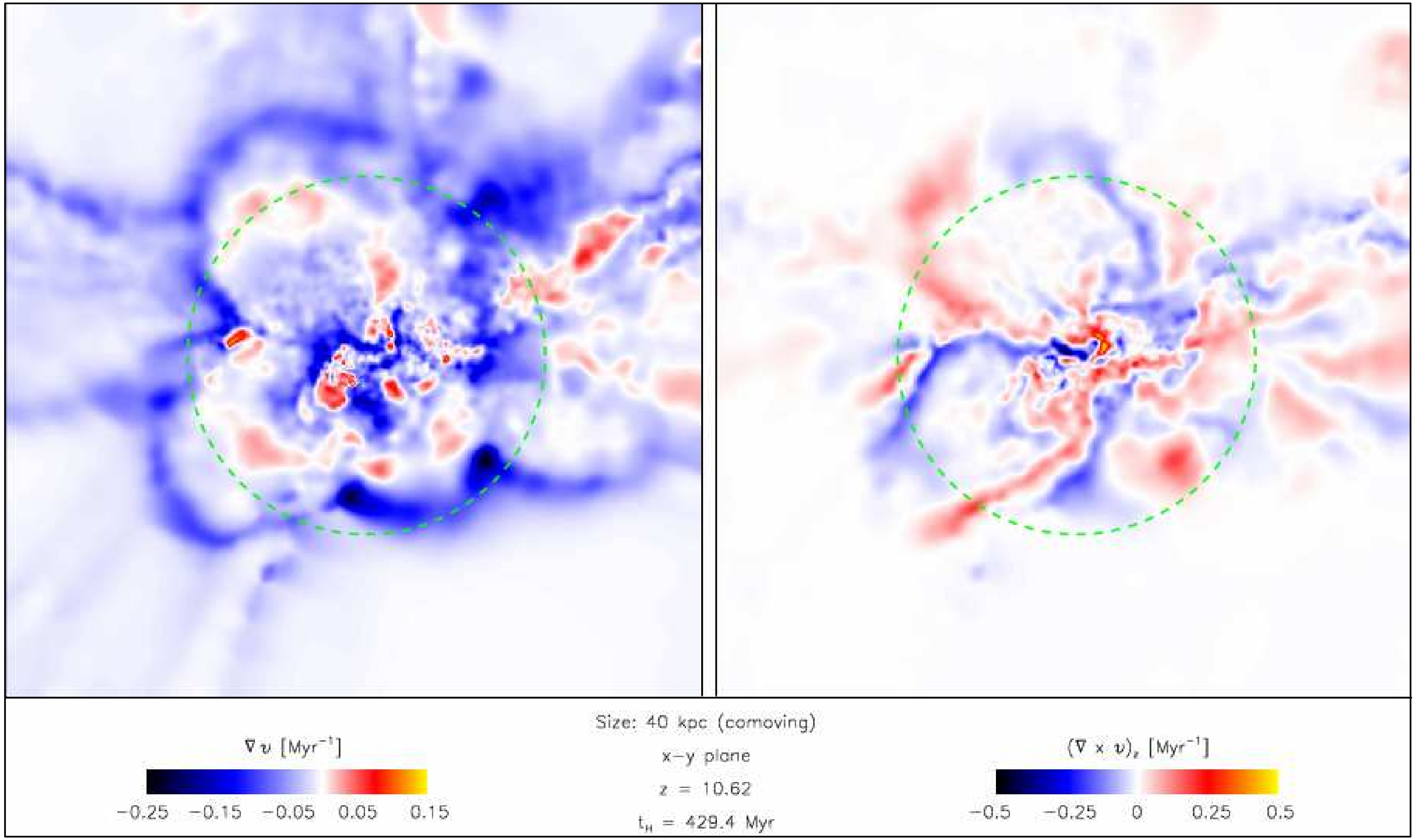
High mach numbers:

- Of order 10 in filaments
- Of order 3 at the center
- Formation of shocks!



Turbulence

Shocks:



Turbulence

Implications:

- First turbulence in first galaxies!
- Fundamental difference to minihaloes
- Signs of transition to present-day star formation?

Future Work:

- Redo supernova simulation in the context of a first galaxy
- Add metal advection and cooling (in progress)

Summary

- Pop III stars form in dark matter minihaloes with ~ 10^5 - 10^6 M_o
- They exert strong radiative and supernova-driven feedback
- Possible existence of two physically distinct populations of metal-free stars:
  - Truly primordial: Pop III.1 with ~ 100 M_o
  - Previous ionization: Pop III.2 with ~ 10 M_o
- Generation of turbulence in the first galaxies by cold accretion
- Transition to present-day star formation?