Supernova Explosions and the First Galaxies

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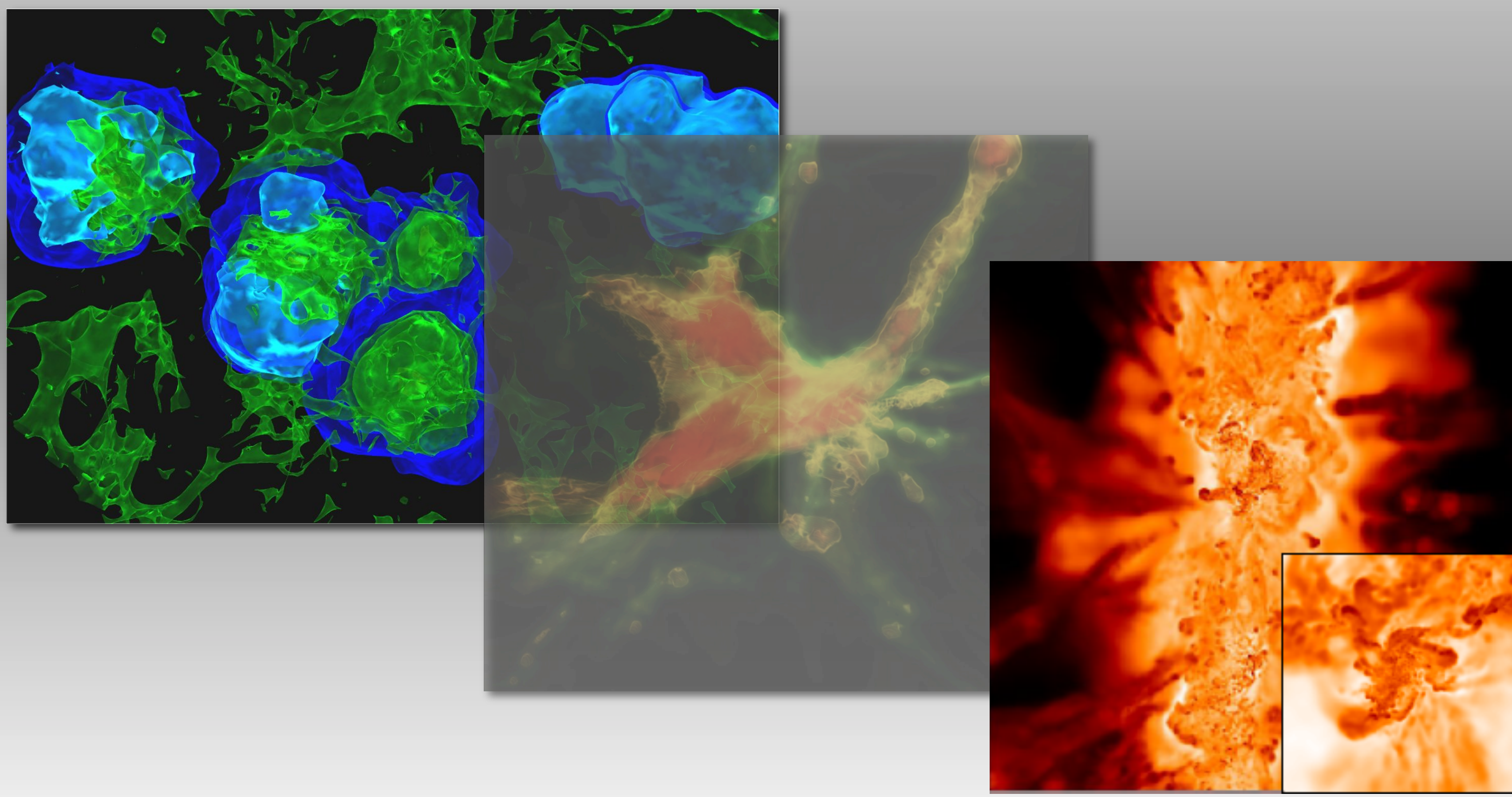


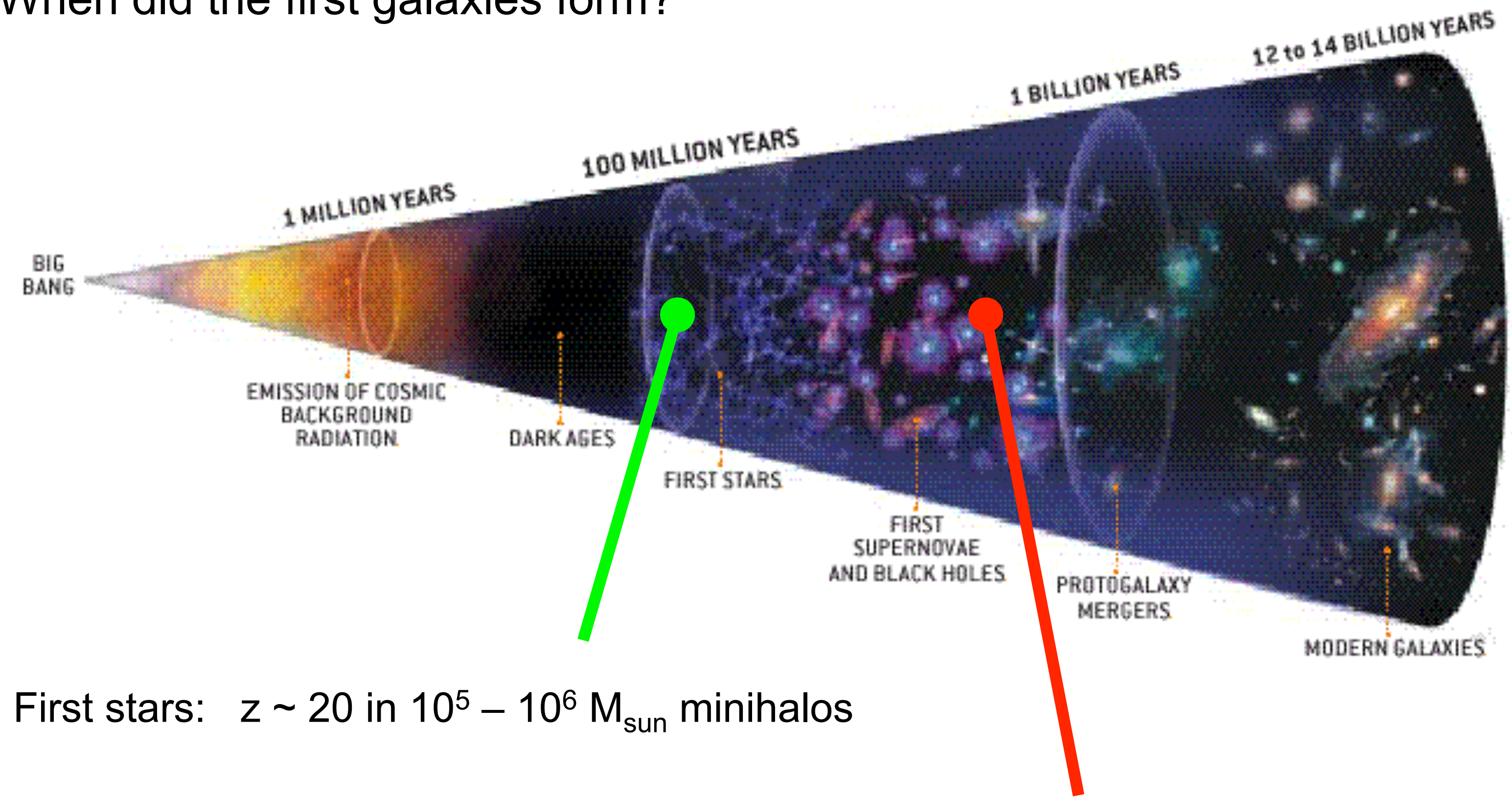
FSGCON, March 2010

TexPoint fonts used in EMF

Cosmological Context

Larson & Bromm (2001), Scientific American

When did the first galaxies form?



First stars: z ~ 20 in 10^5 – 10^6 M_{sun} minihalos

First galaxies: z ~ 10 in ~ 10^8 M_{sun} halos via minihalo mergers

Motivation

Why do we need to understand the formation of the first galaxies?

- Likely major contributors to reionization *Trac et al. (2008); Wise & Cen (2008)*
- Possible formation sites of SMBH`s *Fan et al. (2006); Li et al. (2008)*
- Initial enrichment of the Universe with metals *Madau et al. (2002)*
- Transition from primordial to present-day star formation

Preferred tool: numerical simulations (Gadget, Arepo)

Complicating factor: previous star formation in minihalos

→ Need to include radiation transport and chemical mixing

Recent Work

Greif, Glover, Bromm & Klessen 2010, ApJ, submitted

Cosmological simulation:

- SPH + N-body for DM: Gadget-2 — *Springel et al. (2001); Springel (2005)*
- Cosmological initial conditions: $z_{init} = 100$
- Multiple levels of refinement: 1 Mpc → 300 kpc (comoving)
- Diffusion-based model for chemical mixing — *Greif et al. (2009a)*
- Radiation transport for star formation in minihalos — *Greif et al. (2009b)*
- Full primordial chemistry network — *Glover & Jappsen (2007)*
- Fine-structure and metal line cooling for C, Si and O

The Simulation

Greif, Glover, Bromm & Klessen 2010, ApJ, submitted

- Includes radiation from all Pop III stars in minihalos

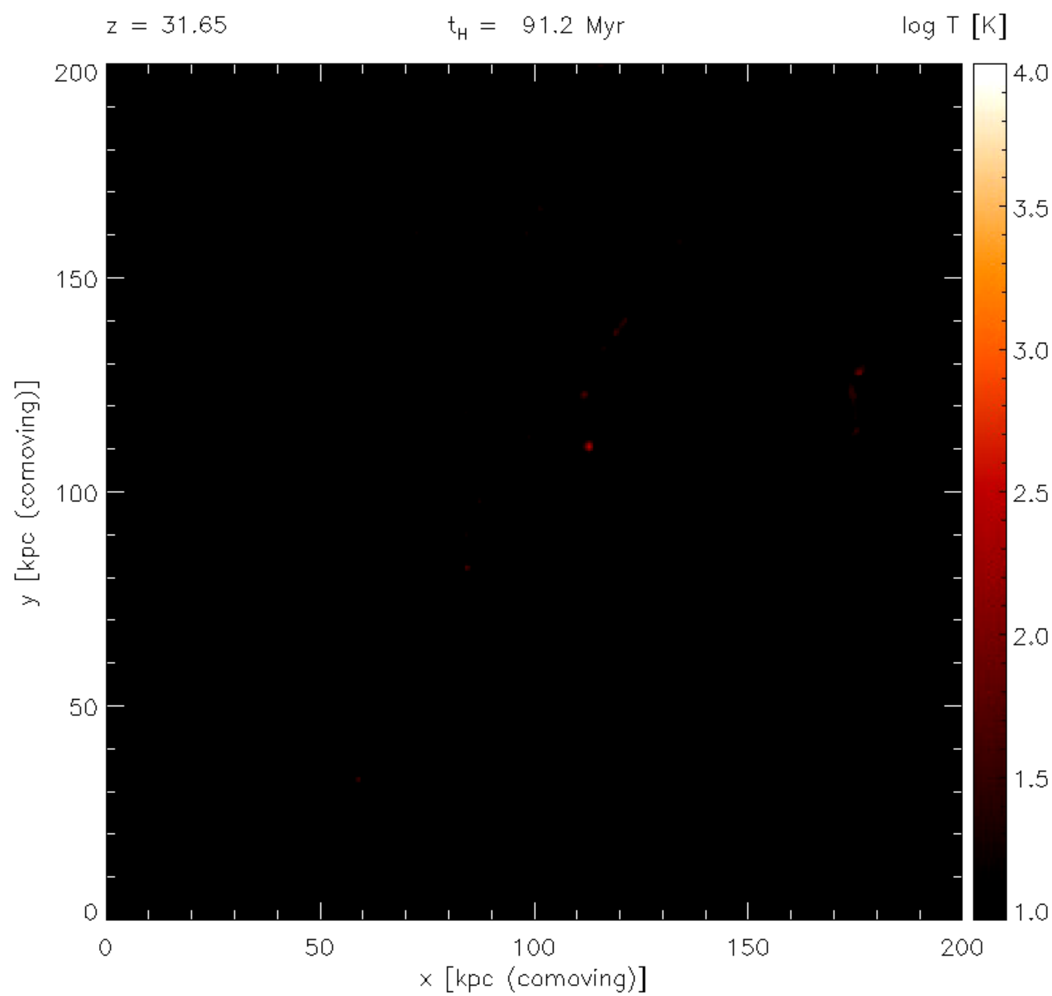
- First star explodes as PISN:

  - Kinetic energy: 10^{52} ergs

  - Metal yield: 50%

  - C, Si and O

All other stars → BH`s



Multi-phase Medium

Greif, Glover, Bromm & Klessen 2010, ApJ, submitted

- Cold Neutral Medium (CNM):

  Adiabatic IGM gas, dense halo gas

- Warm Neutral Medium (WNM):

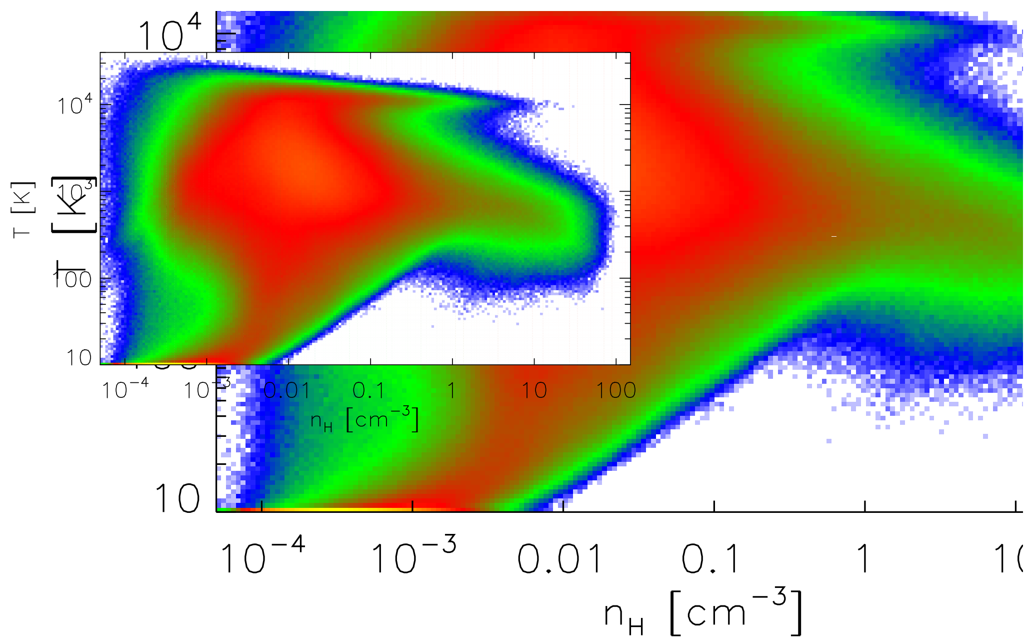
  Shock-heated halo gas

- Warm Ionized Medium (WIM):

  Relic HII region gas

- Hot Ionized Medium (HIM):

  Supernova remnant gas



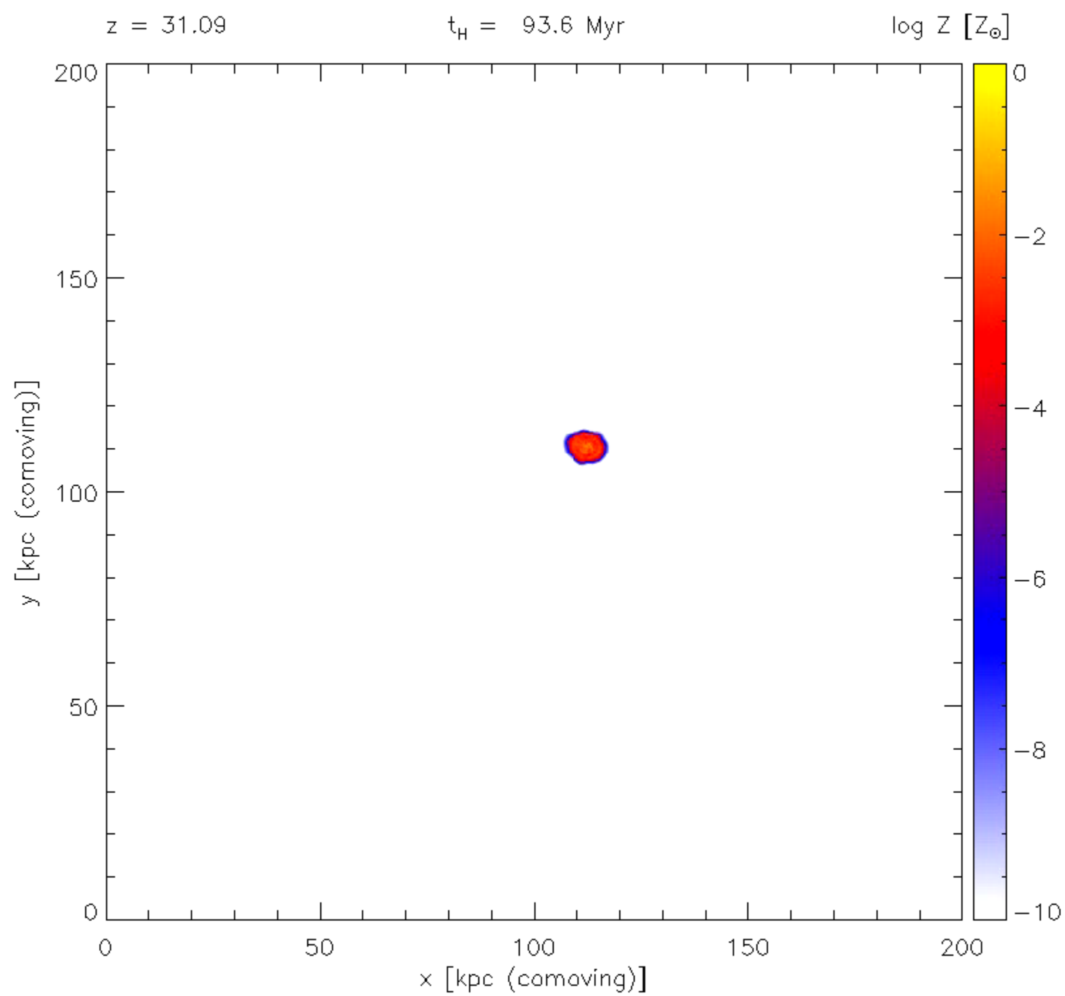
Metal Distribution

Greif, Glover, Bromm & Klessen 2010, ApJ, submitted

- Metals initially distributed by bulk motion of SN remnant

- Later: turbulent mixing by
  - Photoheating
  - Gravitational dynamics

- By z = 10: metal-rich gas recollapses into galaxy

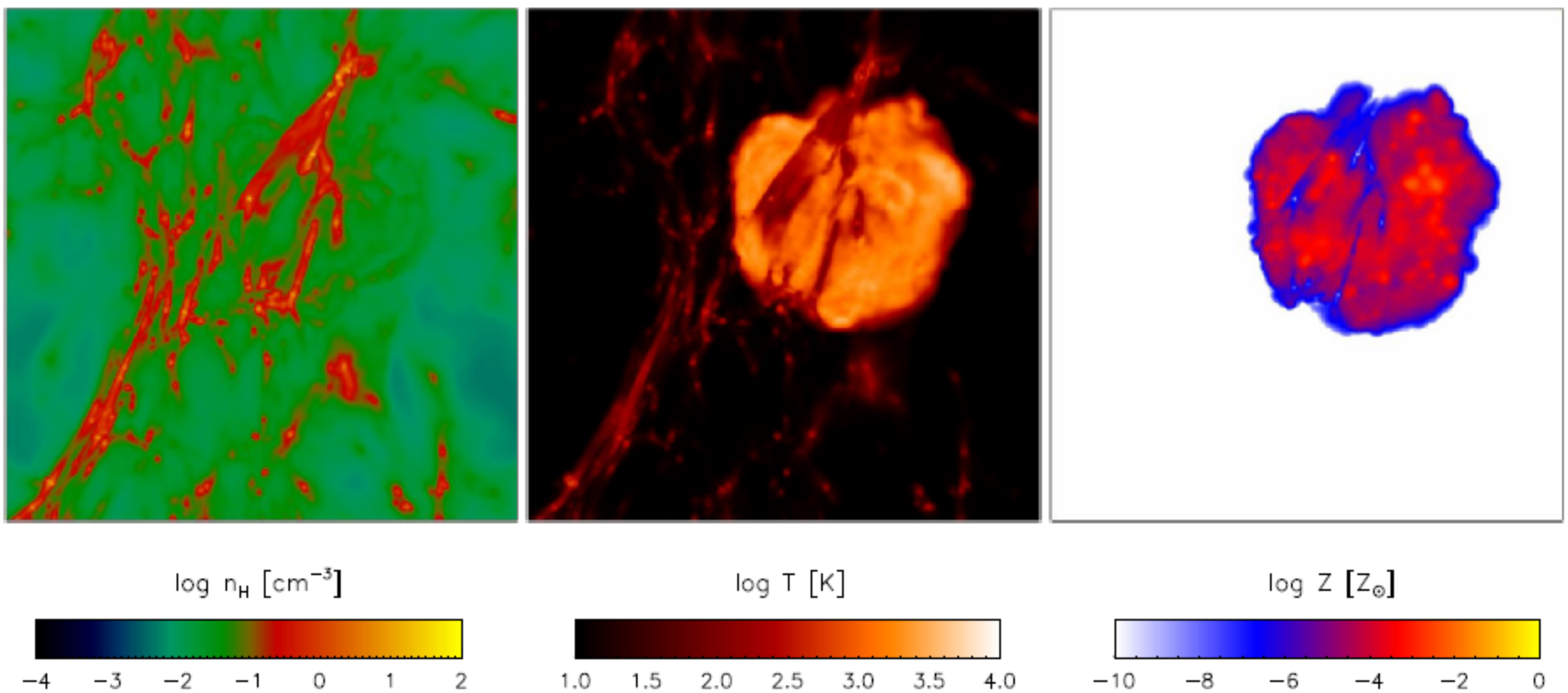


Metal Distribution

Greif, Glover, Bromm & Klessen 2010, ApJ, submitted

t_{sn} = 15 Myr:

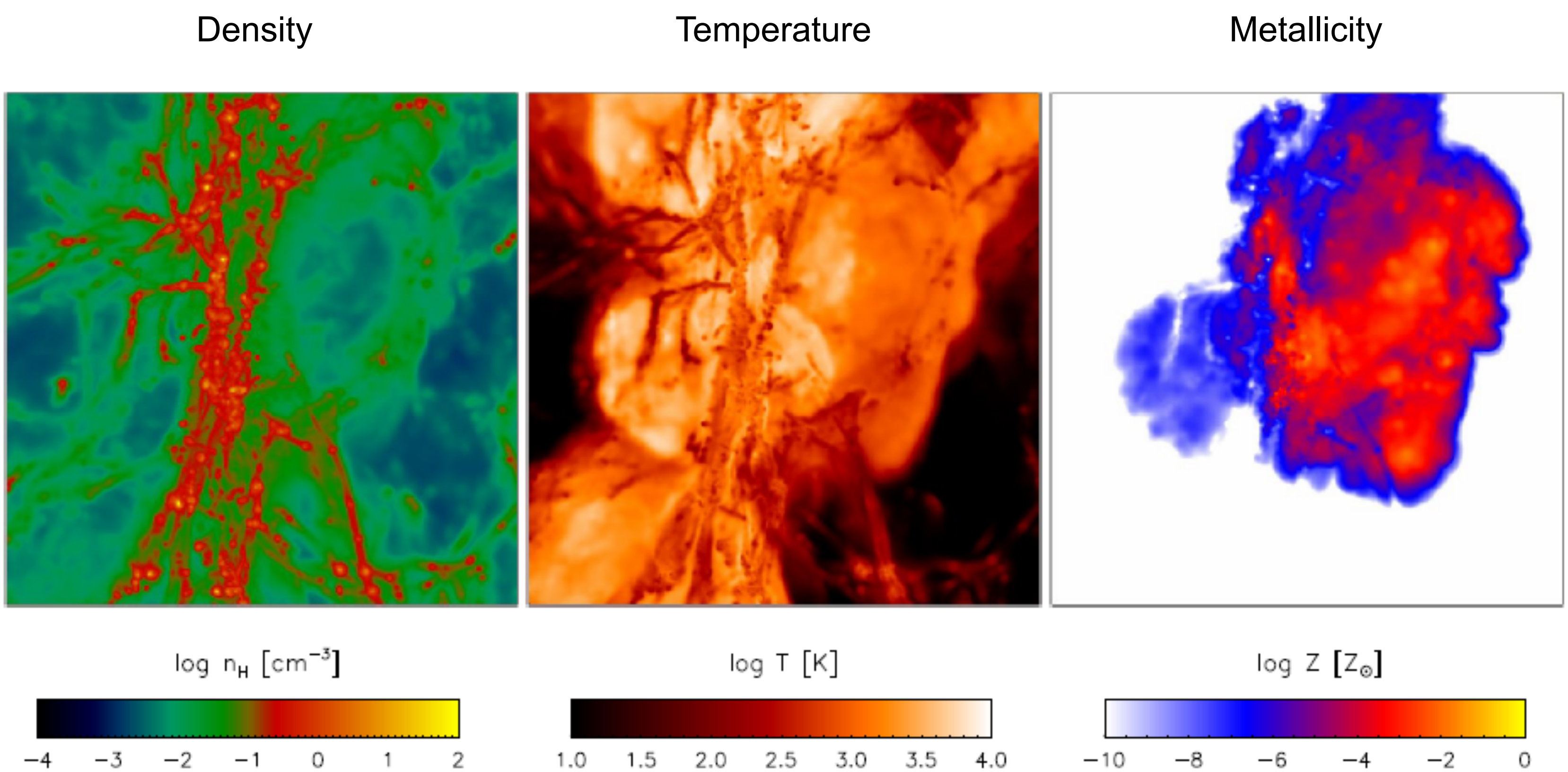
Density | Temperature | Metallicity



Metal Distribution

Greif, Glover, Bromm & Klessen 2010, ApJ, submitted

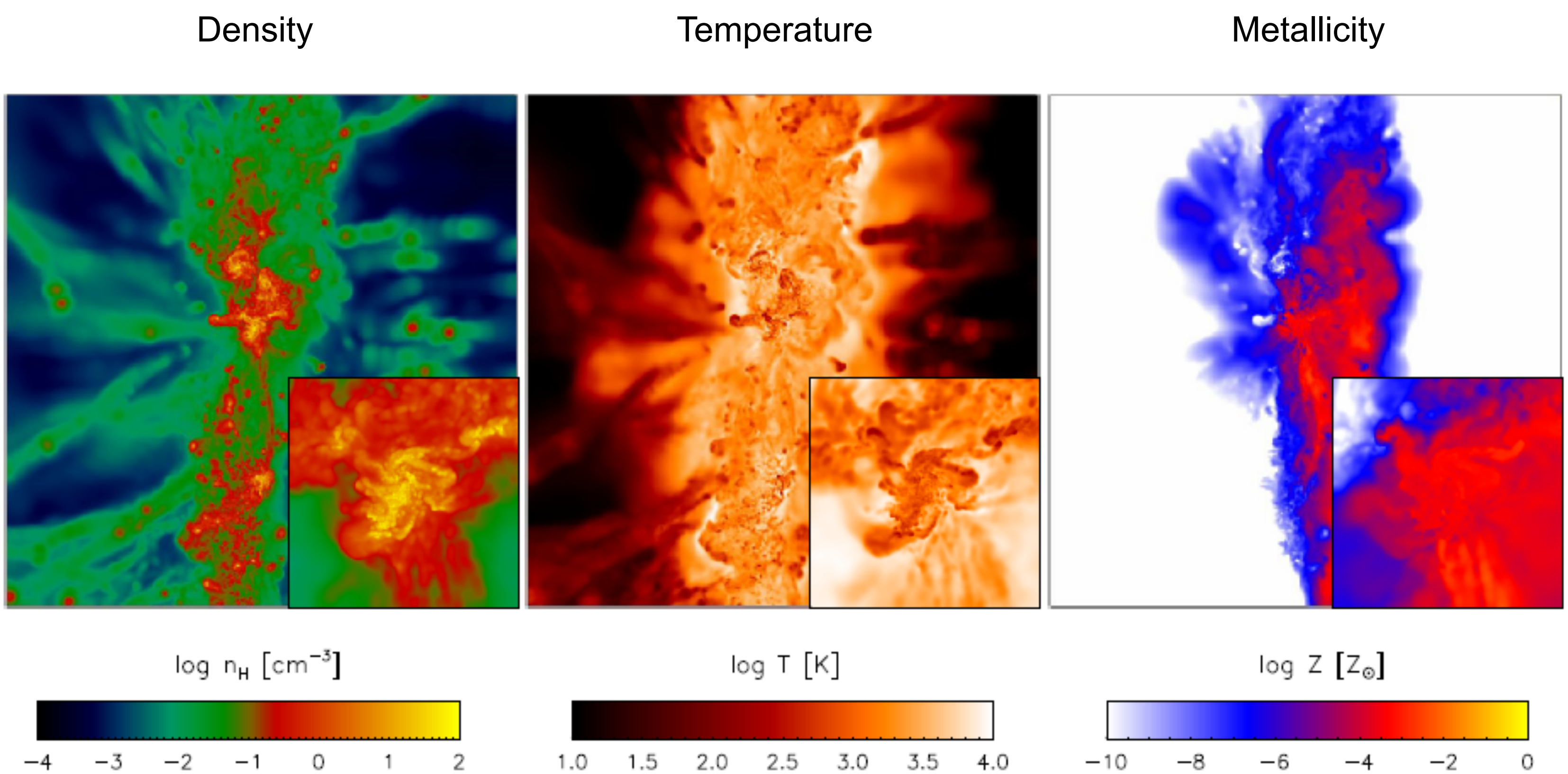
t_{sn} = 100 Myr:



Metal Distribution

Greif, Glover, Bromm & Klessen 2010, ApJ, submitted

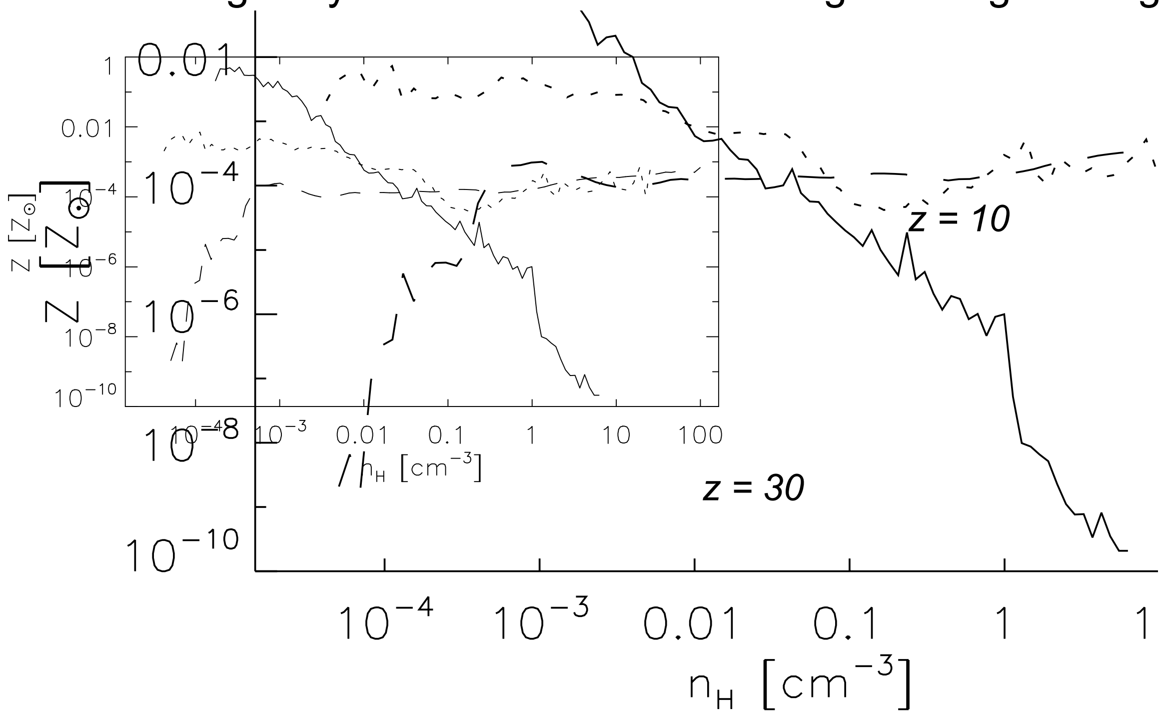
t_{sn} = 300 Myr:



Metal Distribution

Greif, Glover, Bromm & Klessen 2010, ApJ, submitted

- Initially: strong correlation between metallicity and gas density
- Existing halos remain largely pristine, voids become highly enriched
- Turnover once the galaxy assembles → metal-rich gas brought to high densities



Metal Distribution

Greif, Glover, Bromm & Klessen 2010, ApJ, submitted

- Large metallicity spread at high densities

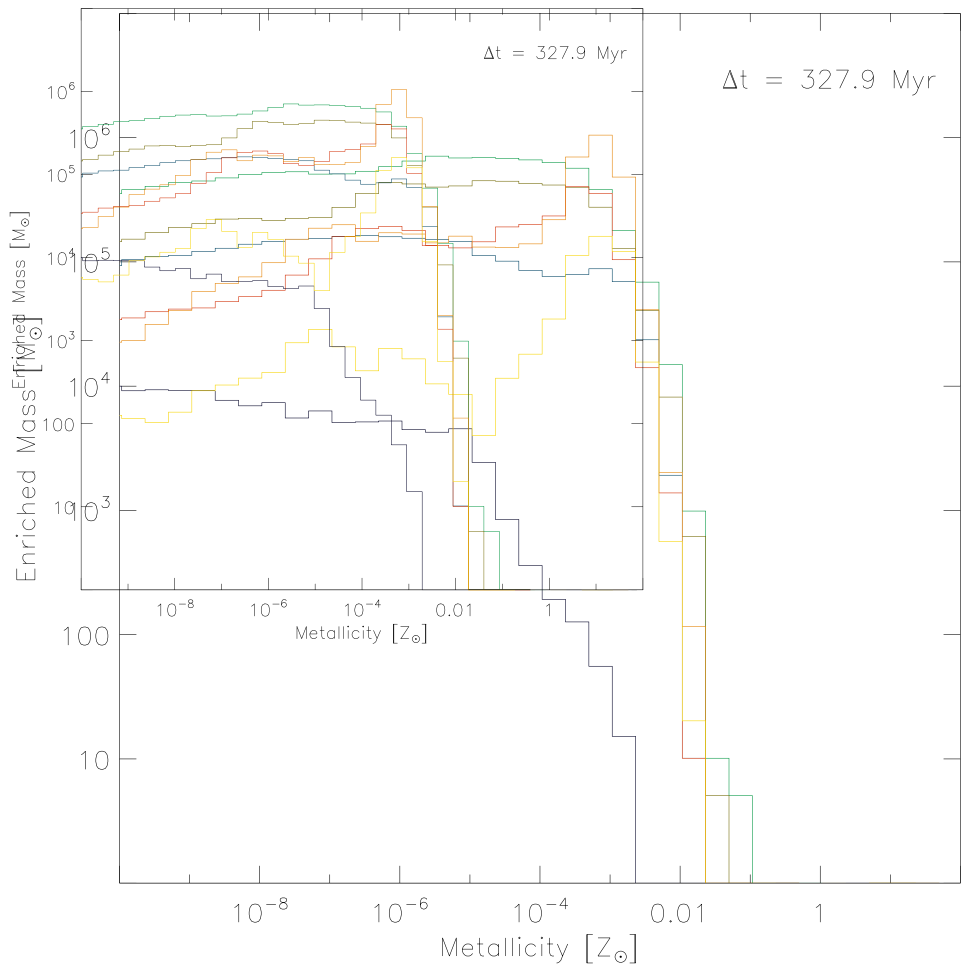
- 10^5 M_{sun} of gas enriched to $Z \sim 10^{-3}$ Z_{sun} in a state of collapse

- Dust-induced cooling at very high densities likely sets fragmentation scale

  Omukai et al. (2005)

- Formation of a cluster of Pop II stars?

  Clark et al. (2008)



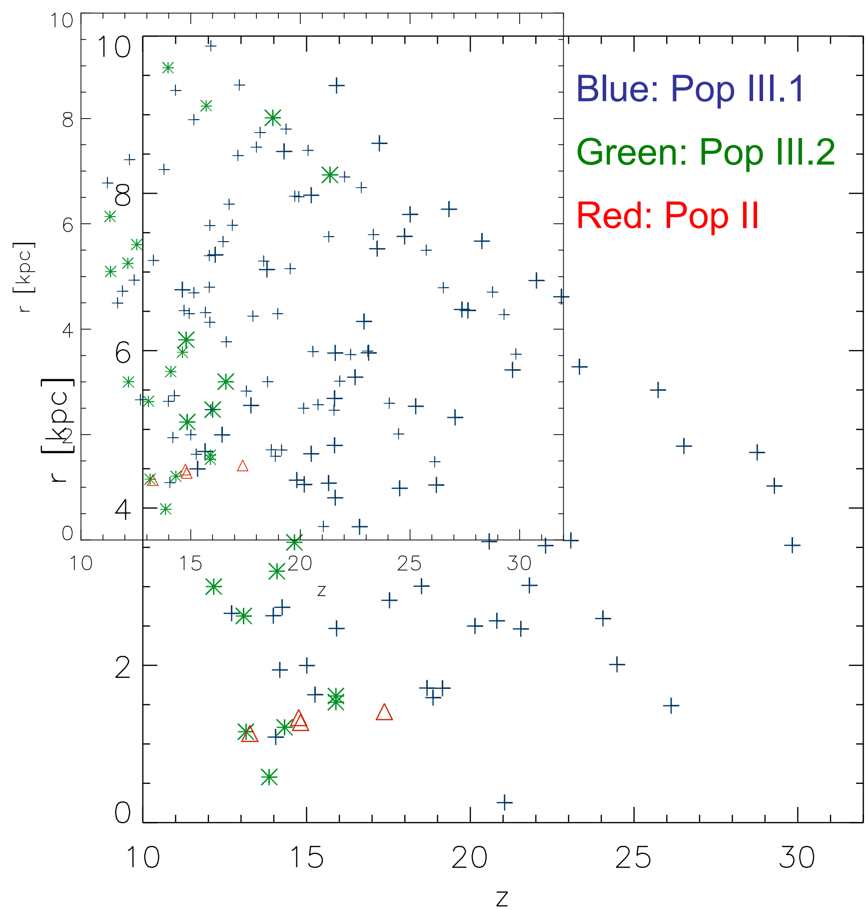
Star Formation in Minihalos

Greif, Glover, Bromm & Klessen 2010, ApJ, submitted

Stellar feedback:

- Photoheating, mechanical feedback, chemical enrichment
- Most halos are dense enough for self-shielding
- Some are photoheated prior to collapse → Pop III.2
- Some are disrupted by the SN remnant and enriched to supercritical levels → Pop II

All star-forming minihalos



Supernova goes Hollywood

Tree of Life (2010)

Director: Terrence Malick (The Thin Red Line)

Tree of Life

Shot :	**DA0100 - Pop III Supernovas**
Filename :	**DA0100_anim_v007.mov**
Vendor :	NCSA, Univ. of Illinois / Volker Bromm, Univ. of Texas at Austin
LUT :	iQ_HD_Kodak_imax_v1_Shake_1D_10.txt
Camera :	v007 camera, 90 fov, with a tansform to adjust to new sim
Comments :	New surrounding volumes added to SN1 and SN2 SN1 has a shell volume, 800 gas and 400 dust volume instances 1400 Dense instance volumes added to SN1 surround environment a point light at each star location, animating up and staying up

frames (1 - 331)

1365 x 1024, 90% photo jpeg, 24fps

07 / 27 / 09

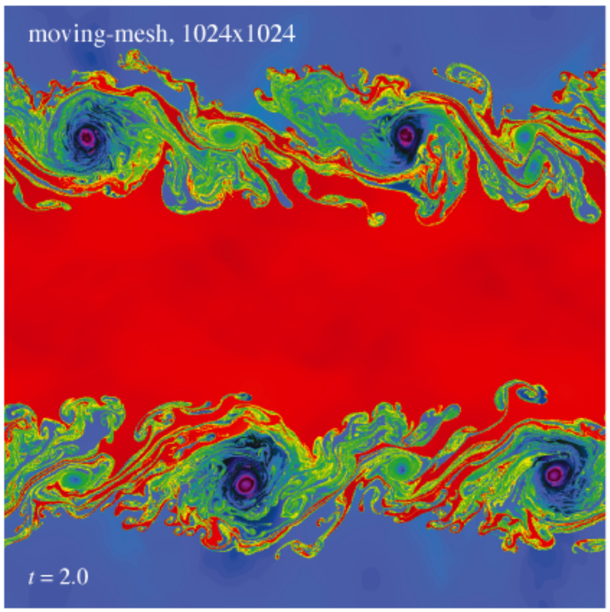
Recent Work at MPA

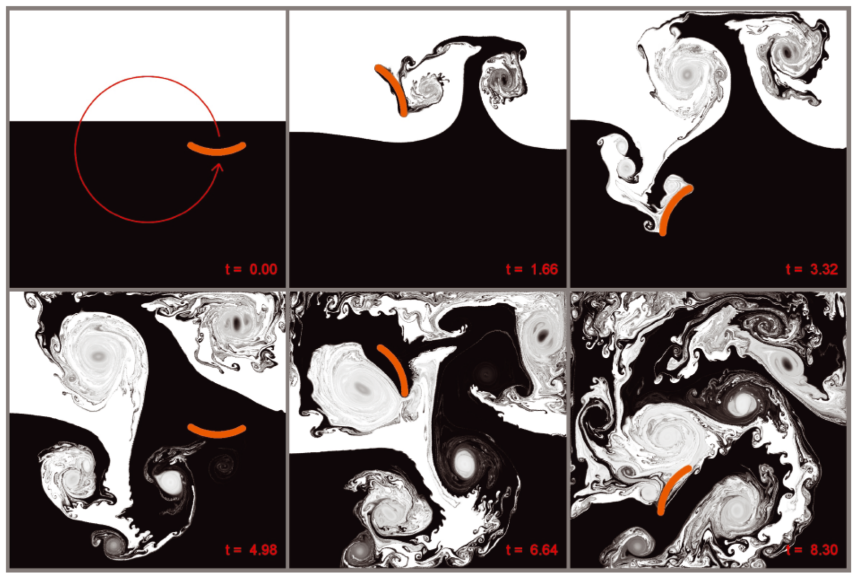
Max Planck Institute
for Astrophysics

Pop III Star Formation with Arepo:

- Galilean-invariant Eulerian code with a Lagrangian mesh
- Based on Voronoi/Delaunay tesselation

Springel (2010)



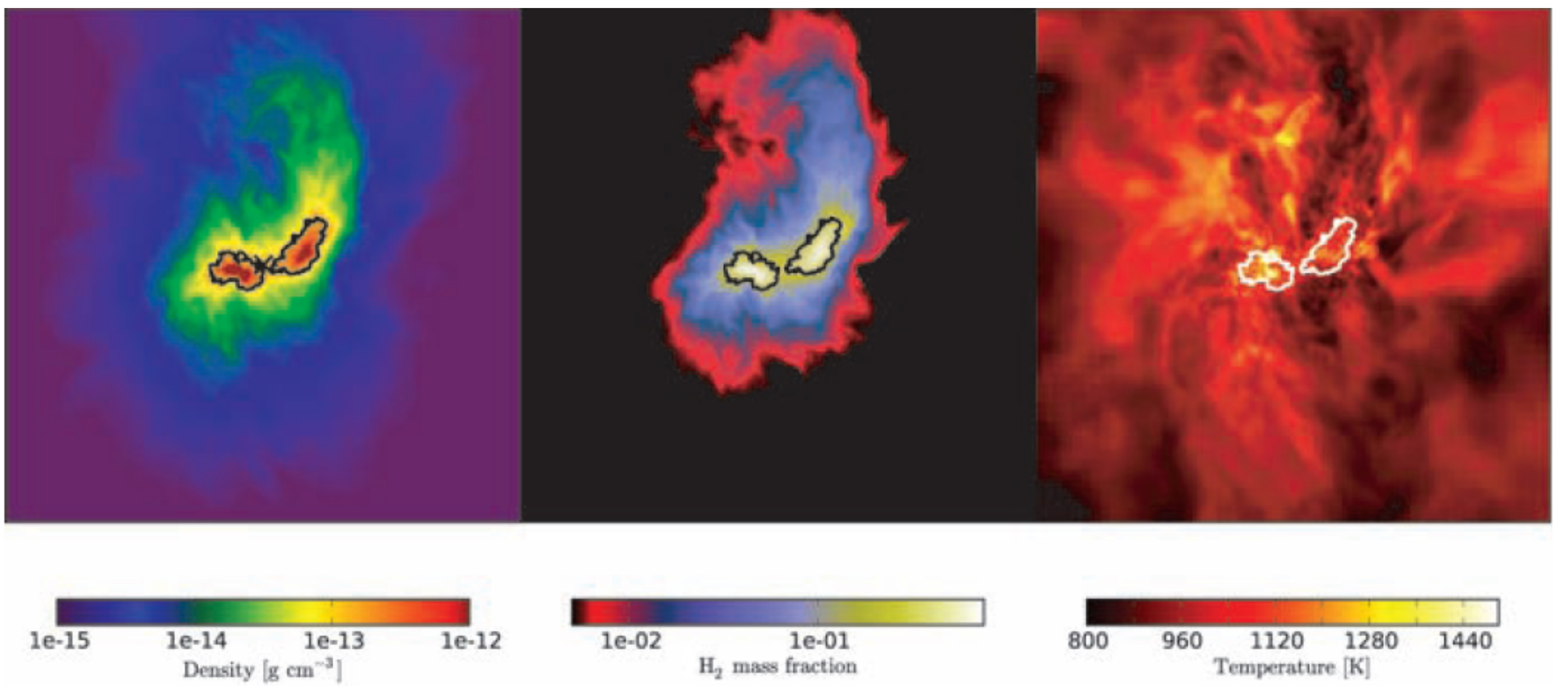


Binary Formation

Greif, Springel & White 2010, in prep.

Recent development: formation of binaries and small multiples

AMR simulation *Turk et al. (2009)*



Two self-gravitating clumps

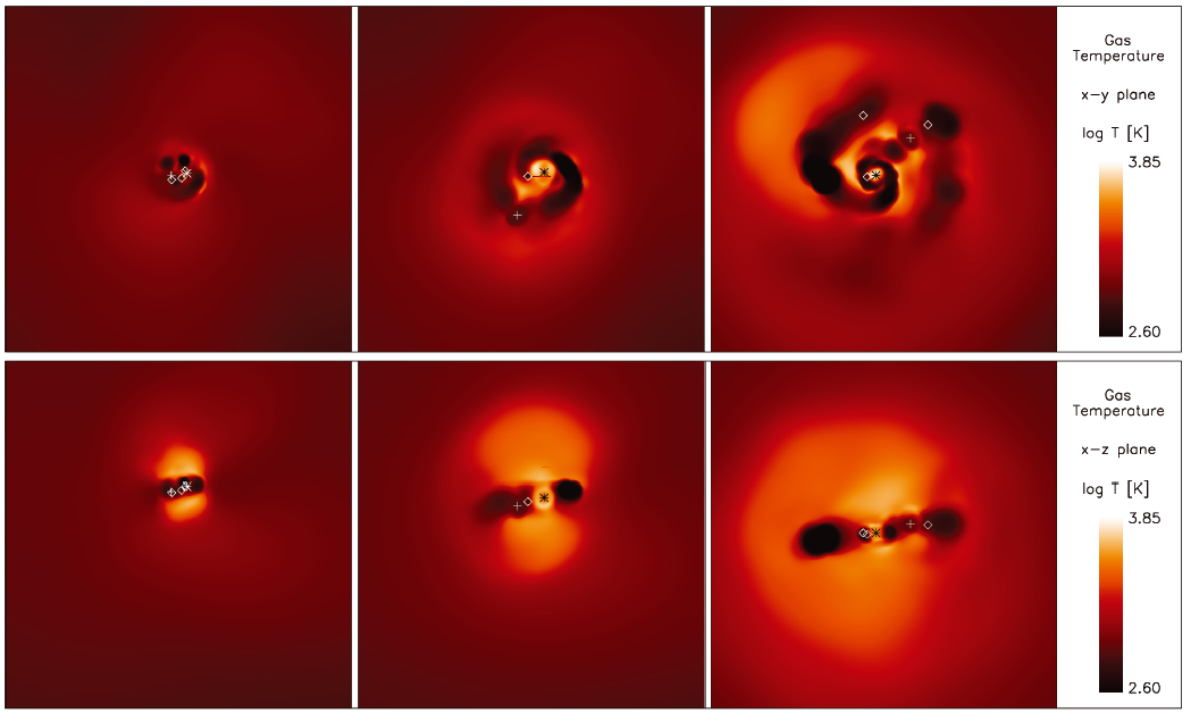
Binary Formation

Greif, Springel & White 2010, in prep.

Recent development: formation of binaries and small multiples

SPH simulation

Stacy, Greif & Bromm (2009)



Small multiple system

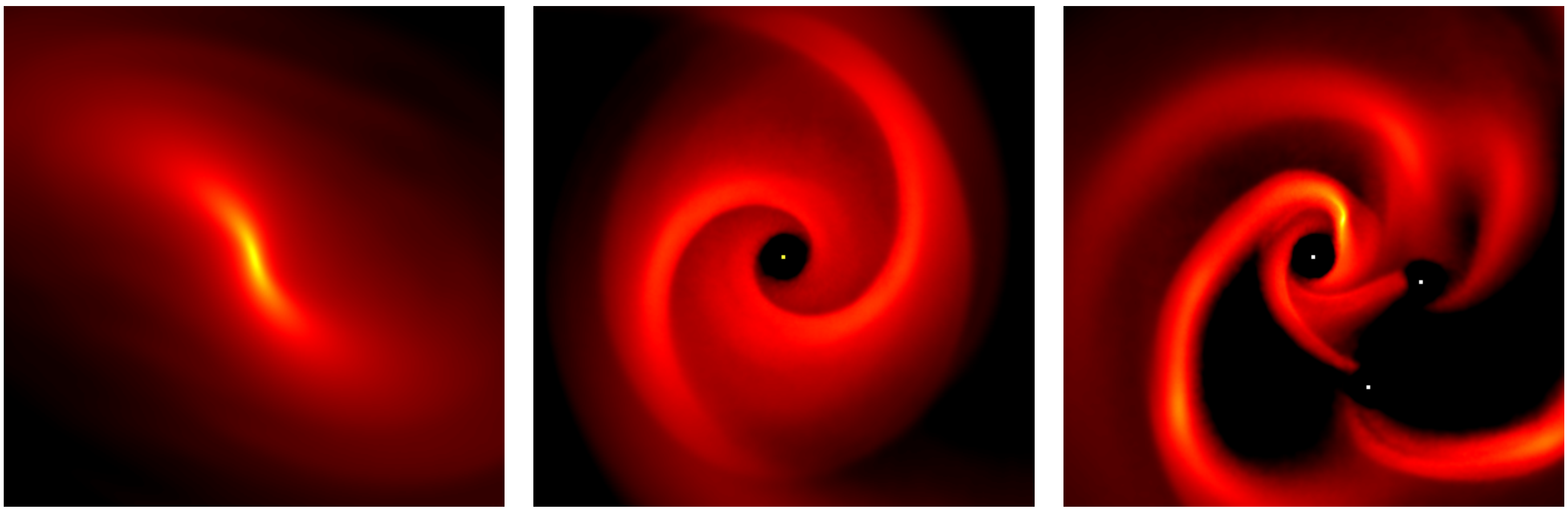
Binary Formation

Greif, Springel & White 2010, in prep.

Recent development: formation of binaries and small multiples

SPH simulation

Clark et al. (2010), in prep.



Small multiple system

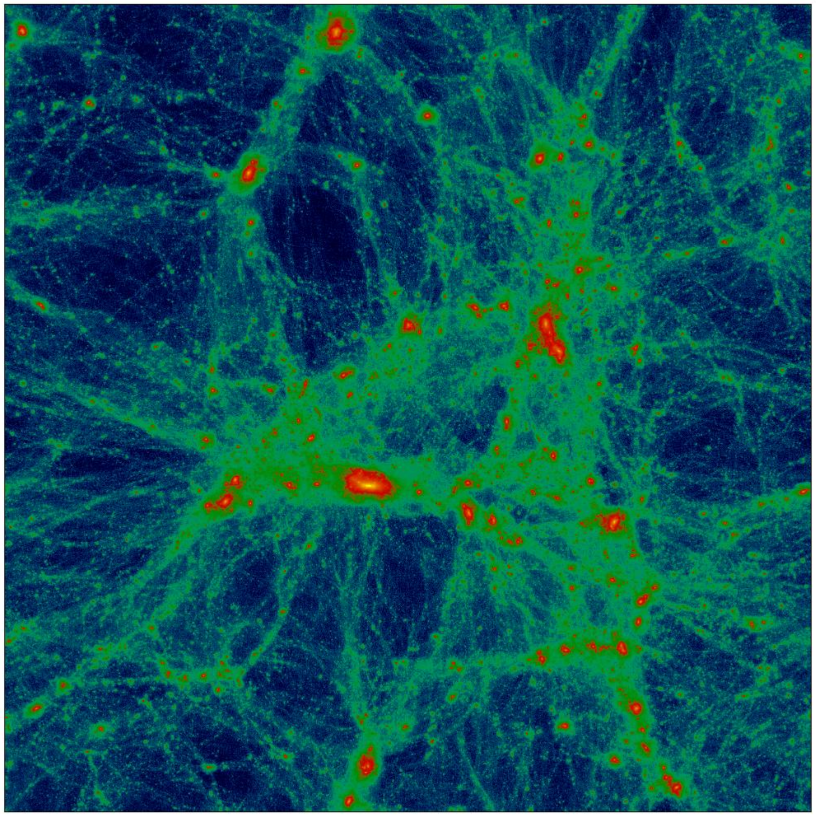
Simulations on a Moving Mesh

Greif, Springel & White 2010, in prep.

Problem: not statistically significant

→ Use much higher efficiency of Arepo to simulate a large number of minihalos

- 1 Mpc box, 512^3 DM particles
- WMAP 5 parameters
- Sophisticated zoom technique
- Random sample of minihalos
- Extremely high resolution: 0.05 M_{sun}
- Only 10 million particles
- Runtime: 24 h on 64 CPU's

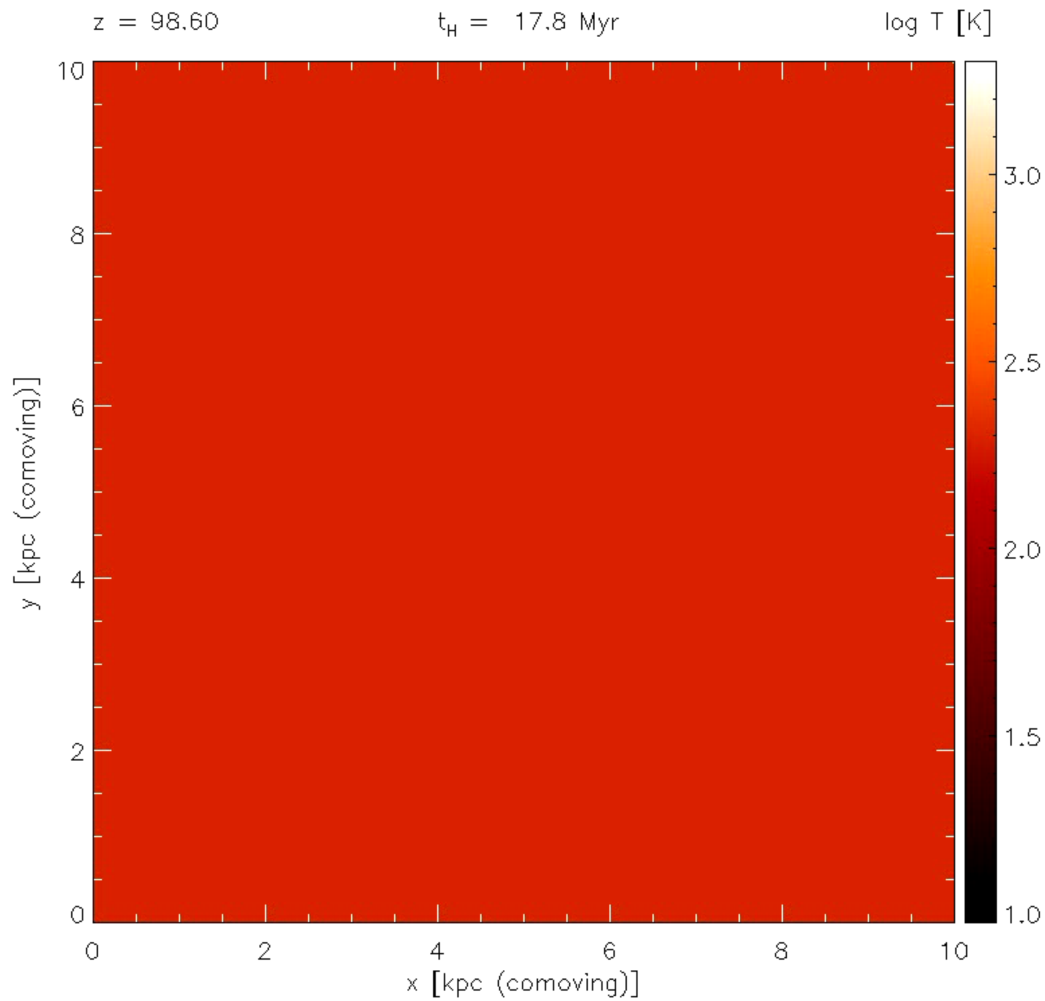


Simulations on a Moving Mesh

Greif, Springel & White 2010, in prep.

Gadget simulation:

- 10^5 particles
- Resolution: 500 M_{sun}

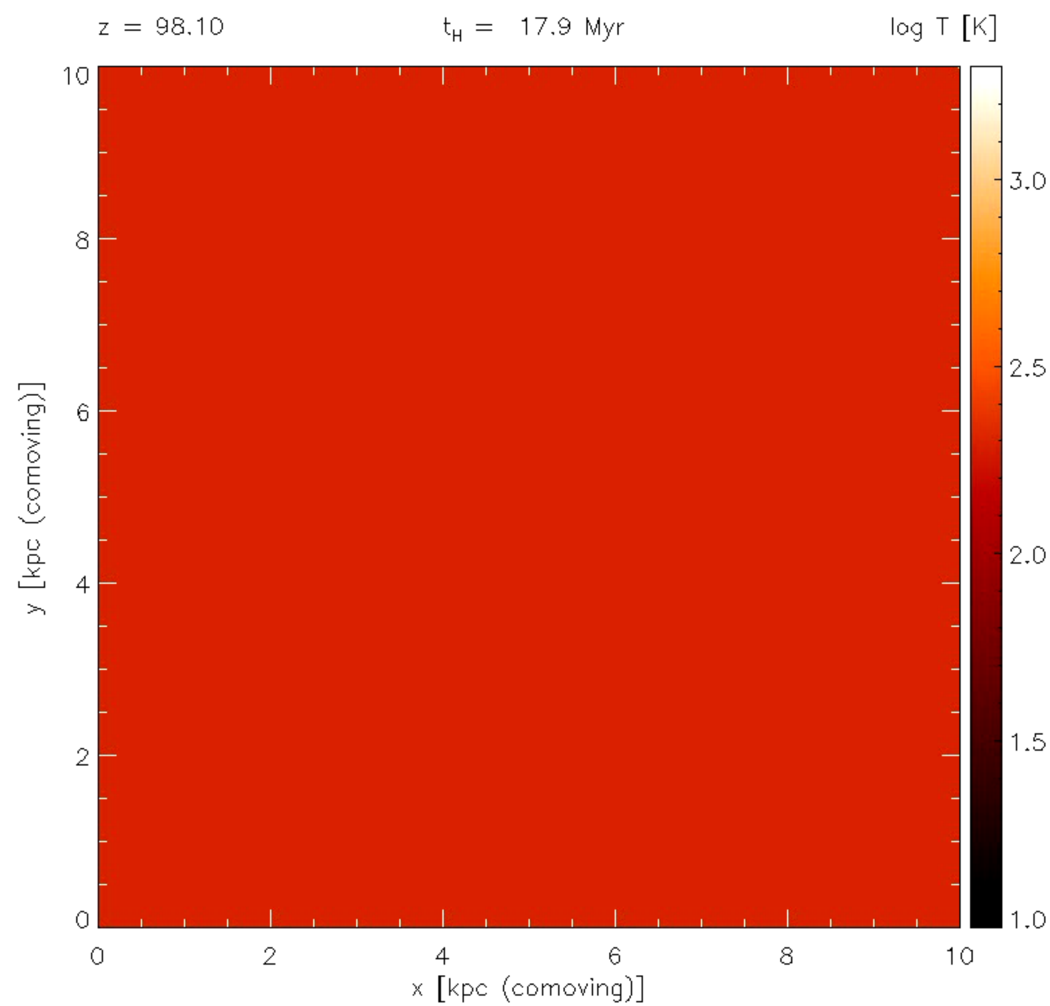


Simulations on a Moving Mesh

Greif, Springel & White 2010, in prep.

Arepo simulation:

- 10^5 particles
- Resolution: 5 M_{sun}



Simulations on a Moving Mesh

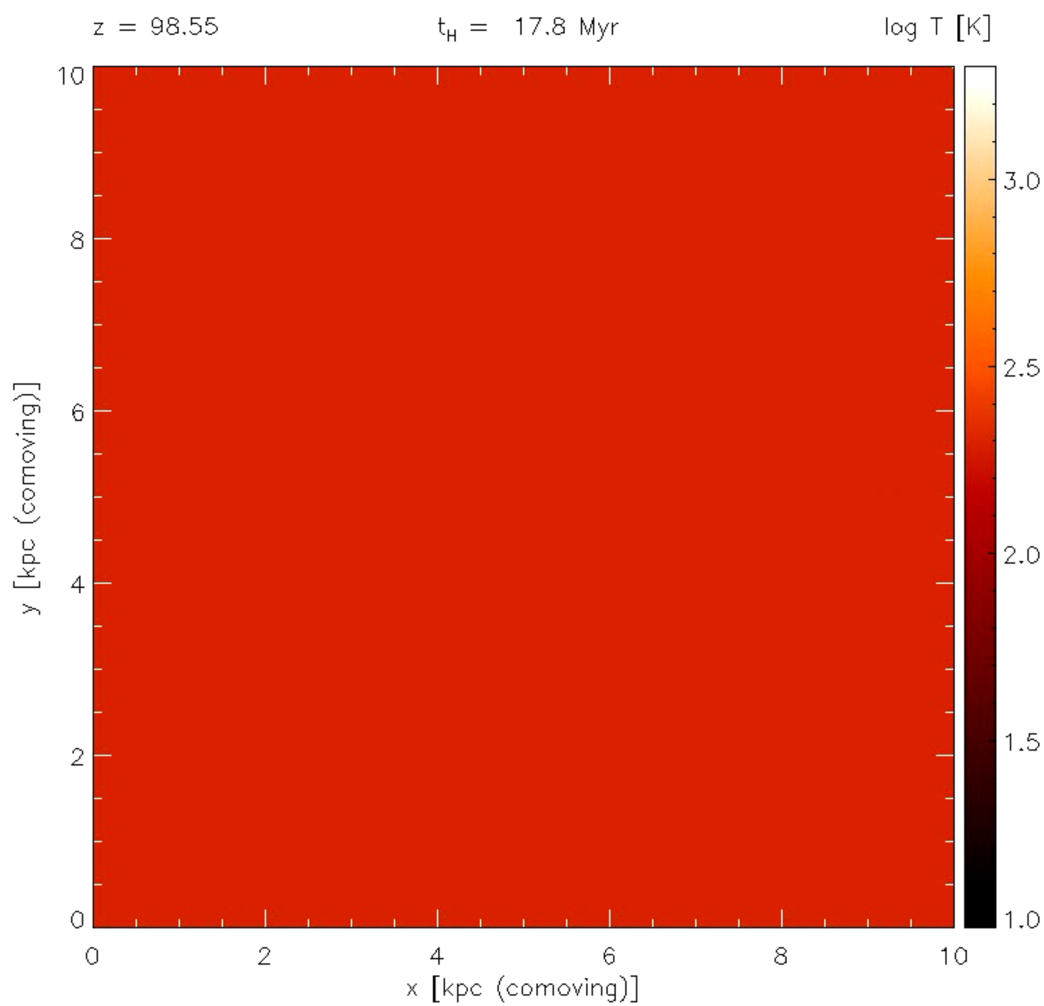
Greif, Springel & White 2010, in prep.

Arepo simulation:

- 100 x 10^5 particles
- Resolution: 0.05 M_{sun}

Likely feasible:

- 10^8 - 10^9 particles
- Resolution: 0.001 M_{sun}
- Resolve DM free-streaming scale: M_J

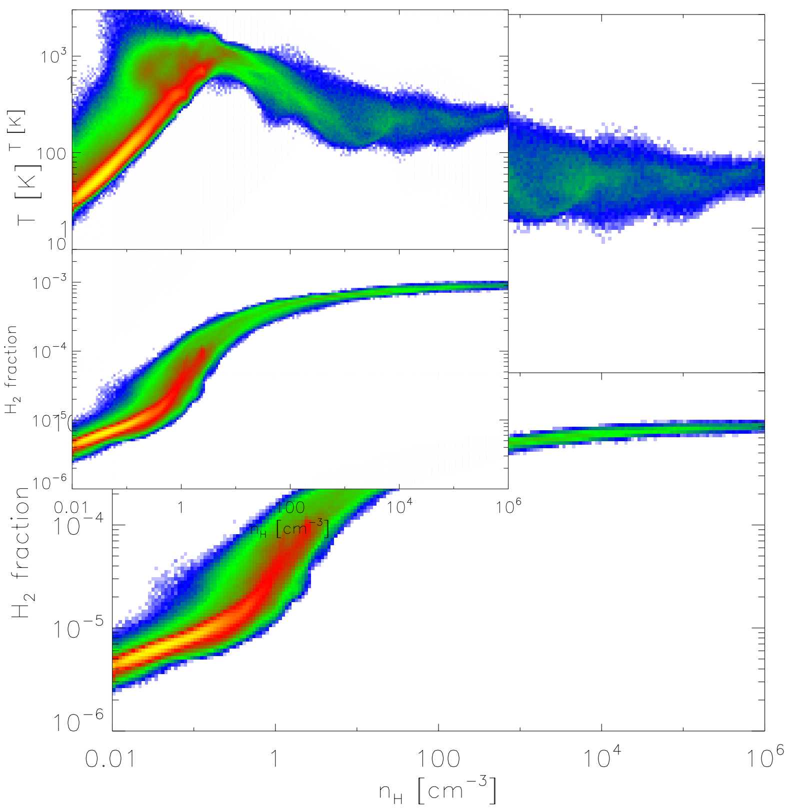


Comparison with SPH

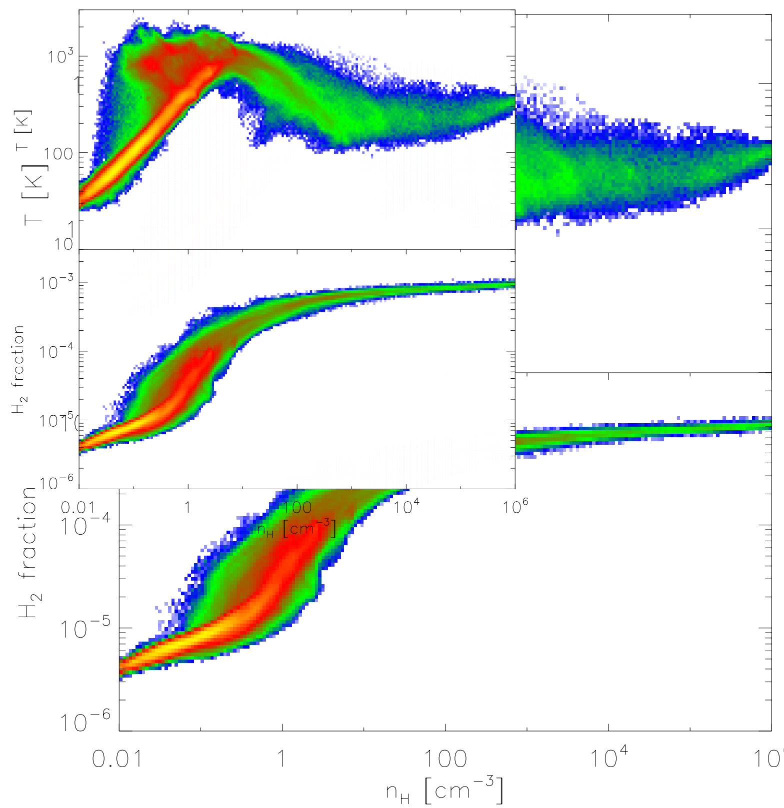
Greif, Springel & White 2010, in prep.

Phase space distribution:

Gadget



Arepo

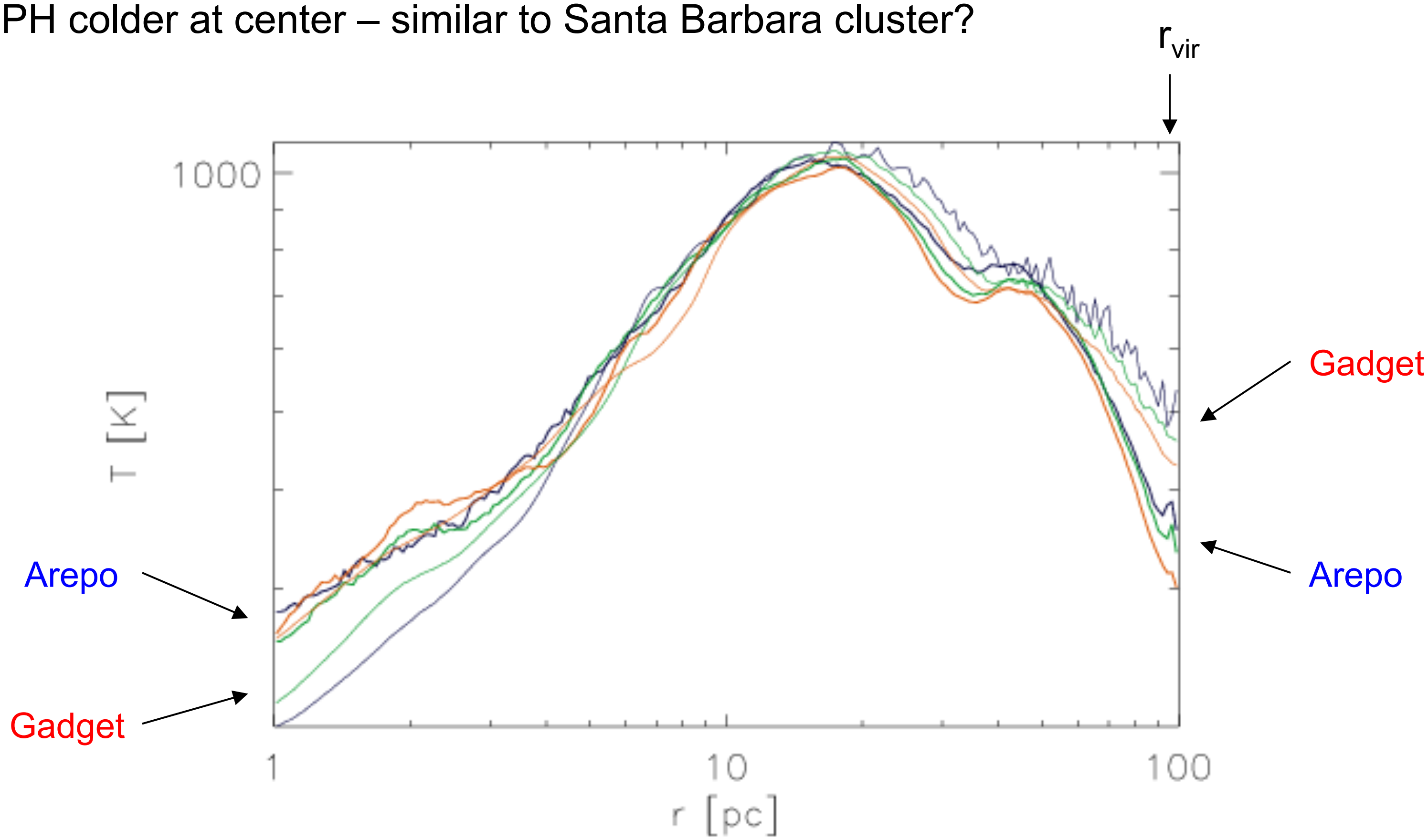


Resolution Study

Greif, Springel & White 2010, in prep.

Temperature:

- SPH colder at center – similar to Santa Barbara cluster?



Summary and Outlook

First Galaxies (Summary):

- Broad metallicity distribution
- Single PISN enriches galaxy to $Z \sim 10^{-3} Z_{sun}$
- Star formation in minihalos not limited to Pop III

First Stars (Outlook):

- Representative sample of minihalos
- Single, extremely high resolution simulation
- Direct code comparison