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Simulating UV radiative feedback during reionisation

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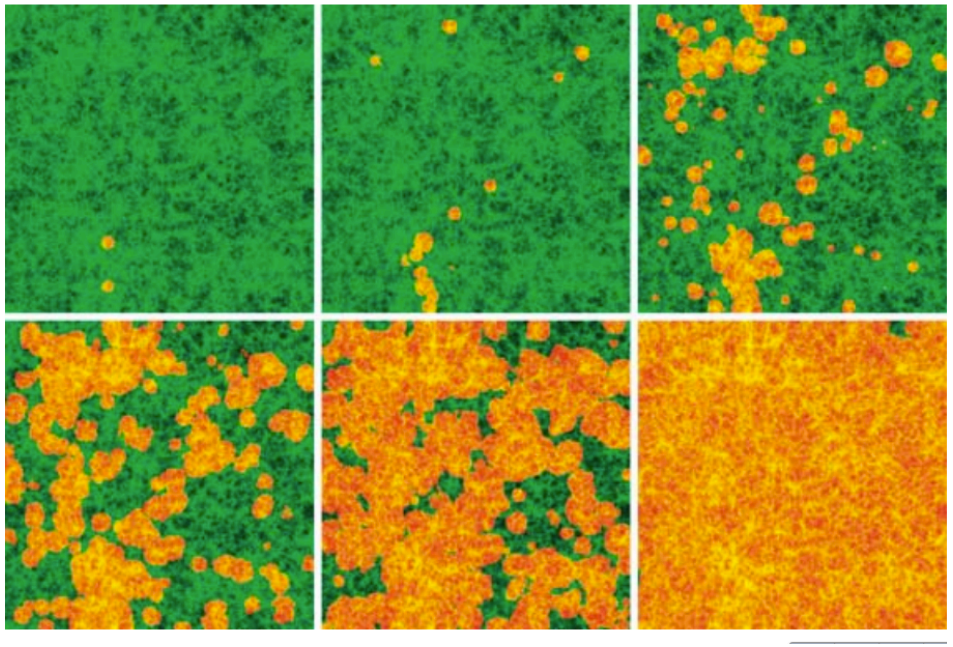
CLUES, Lyon, France

Reionisation

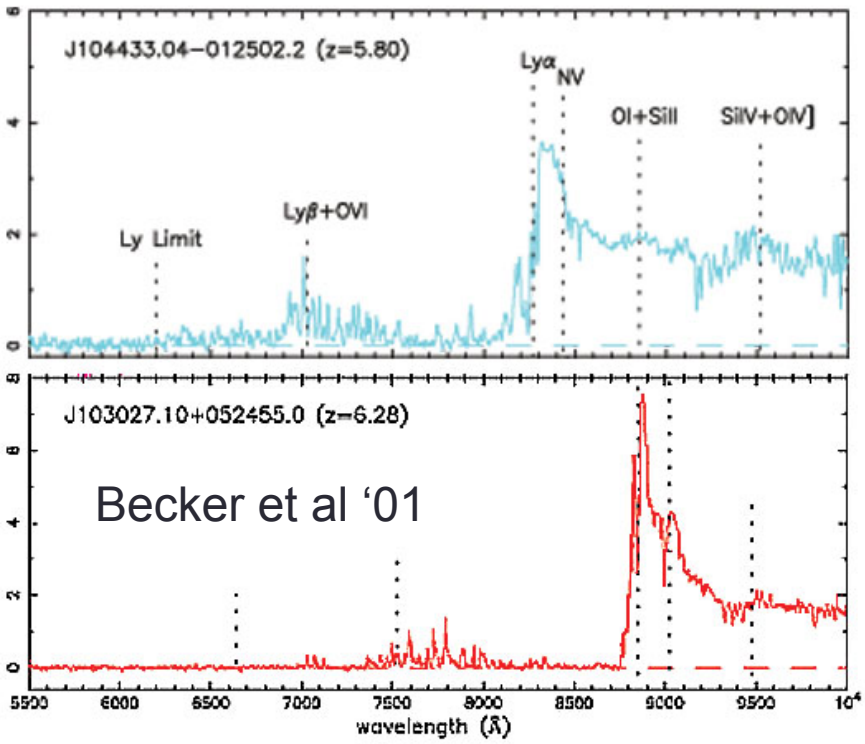
- Ionizing photons must have energies greater than 13.6eV, UV range
- Reionisation occurs “inside-out”, in patches
- Sources (quasars, pop III stars) distributed in DM halos of various size



Iliev et al ‘06: z = 18.5, 16.1, 14.5, 13.6, 12.6 and 11.3. Green H I regions, orange H II regions

Observations

- Gunn-Peterson absorption (Gunn & Peterson ’65)
  - Observed quasar SEDs show Ly-α forest from H I emission very dense at high z
  - Fraction of H I ~ 10^{-5} to 10^{-3} at z ~ 6 (Fan et al ‘06)

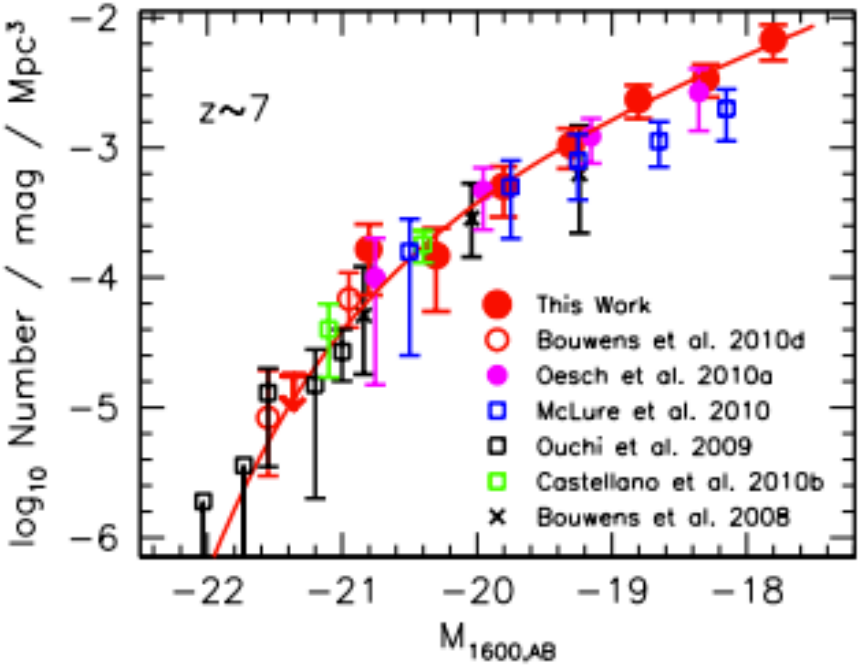


- WMAP-7 constraints (Komatsu et al ‘10)
  - Measurements of anisotropies in CMB polarisation power spectrum imply reionsation starts at z~11

- Future: 21cm line observations by SKA & pathfinders

Constraining Sources of UV Background

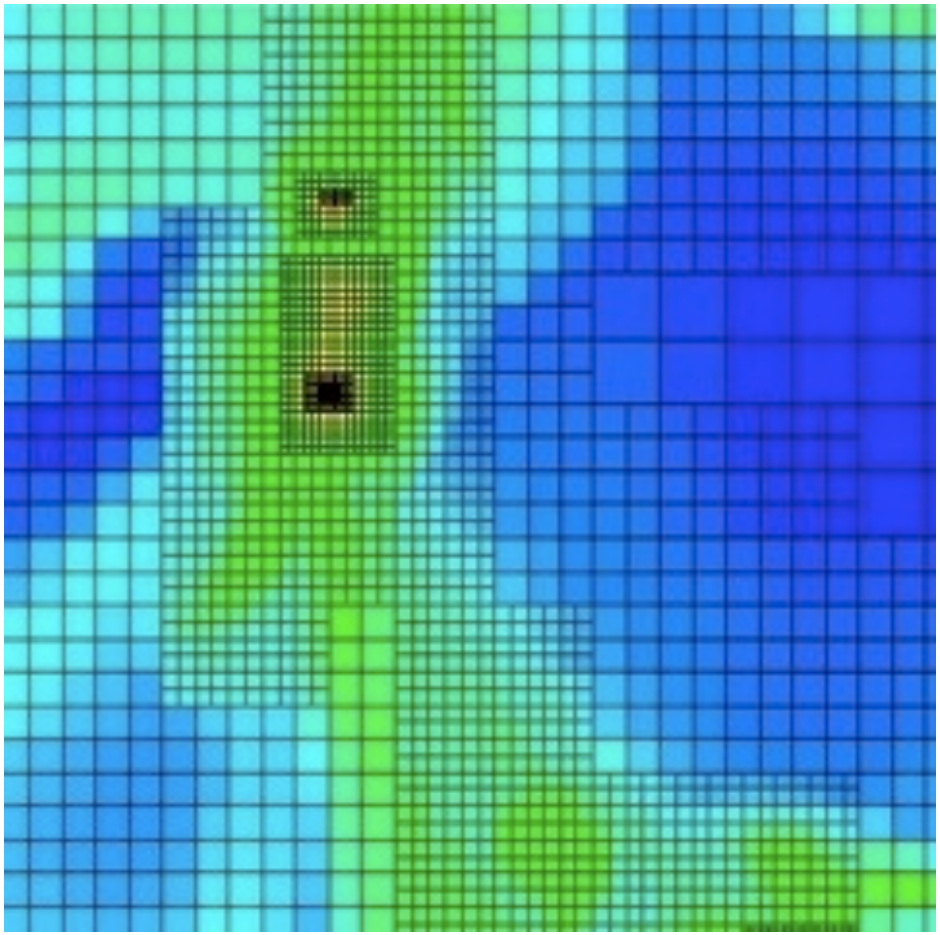
- Majority of UV background from young star-forming galaxies (Robertson et al ‘10) of various sizes
- Only largest galaxies observed at highest redshift
- Smaller galaxies are more prevalent, contribution is more significant
- Need to see inside halos, requires simulation



Bouwens et al ‘11

“Enzo” Adaptive Mesh Refinement

- O’Shea et al (2004), Norman et al (2007)
- Increased resolution in densest *or* user defined volumes
- Solves DM using particle-mesh N-body technique (Hockney & Eastwood 1985)
- Piecewise-Parabolic Method hydro solution (Colella et al (1984))
- Many cooling, UV-bg, stellar formation models, etc
- Analysis with yt (Turk (2008, 2011))



Enzo Parameters and Prescriptions

- WMAP-7 cosmology, z=130 → 5

- Box size: $(8\ \mathrm{Mpc})^3$ (comoving)
- Base grid resolution: $(62.5\ \mathrm{kpc})^3$
- AMR: 6 refinement levels $(0.98\ \mathrm{kpc})^3$ effective resolution

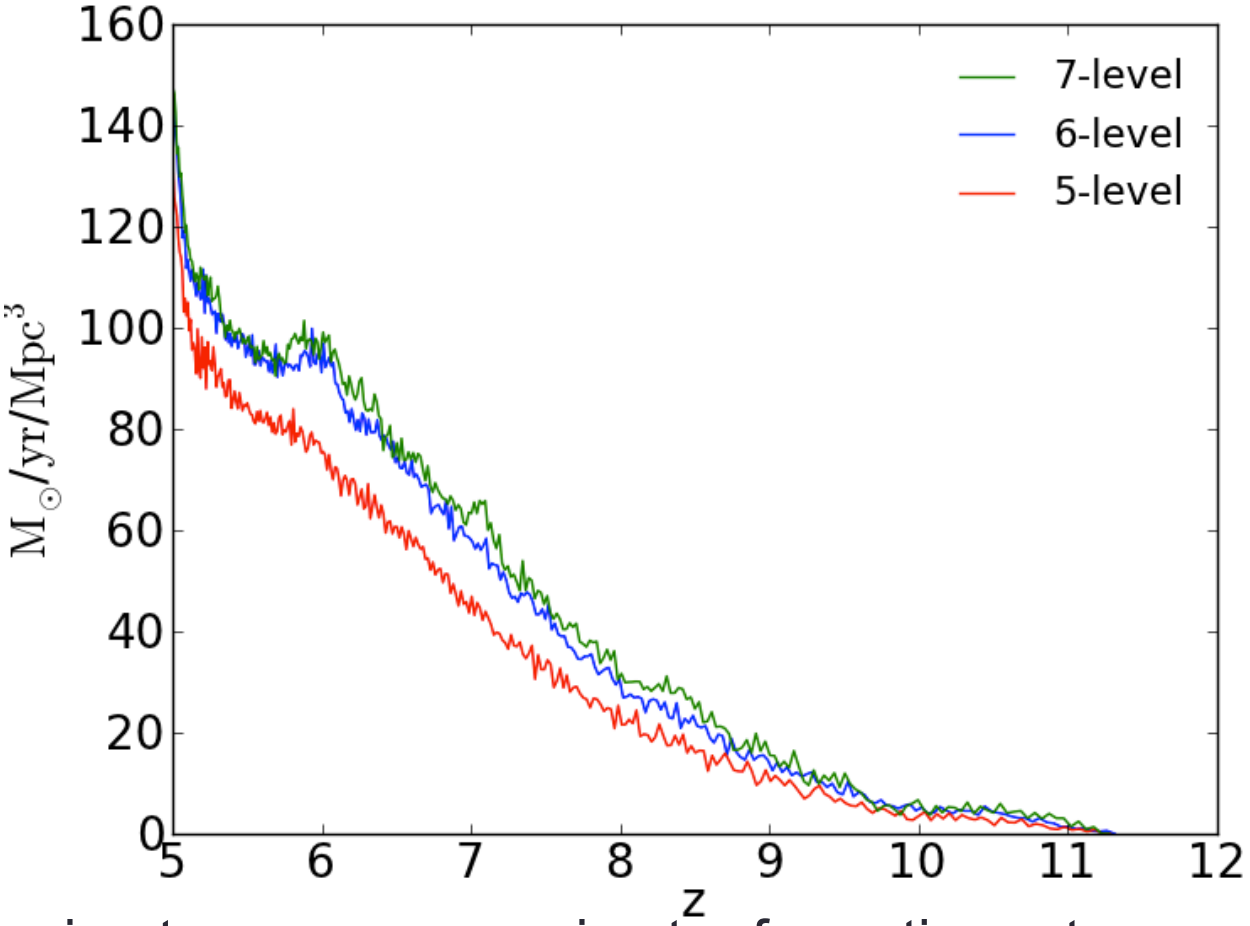
- DM particle size: $2.2 \times 10^7\ M_\odot$

- 9 species cooling (H+, He, H_2, H_2+, H-, He+, He++ ,e) (Abel, Anninos, Zhang '97)

- Star particle model works well at higher redshift, includes feedback (Kravtsov et al '03)

- UV background, Haardt & Madau ('01) using quasar spectra

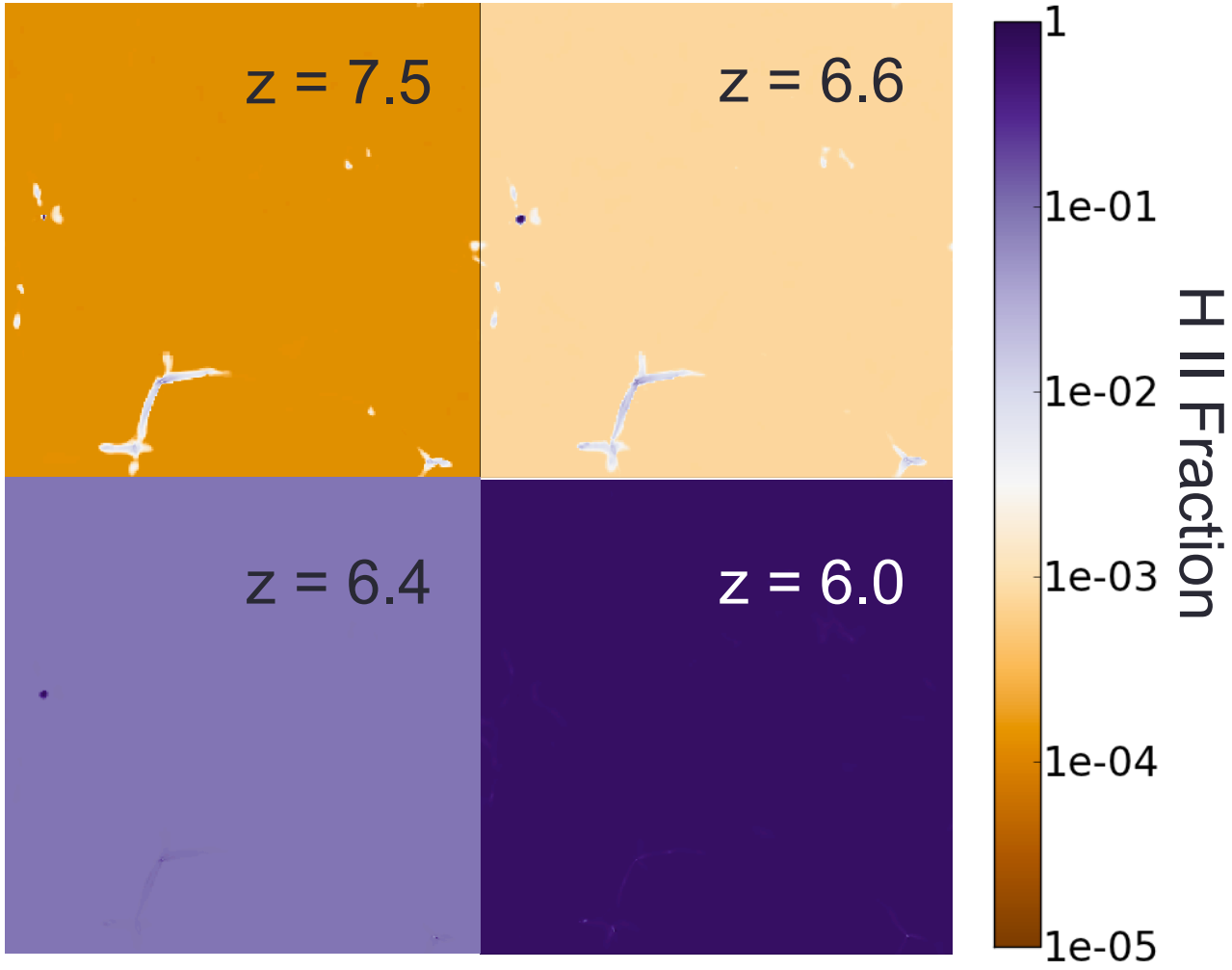
Note on Convergence using SFR



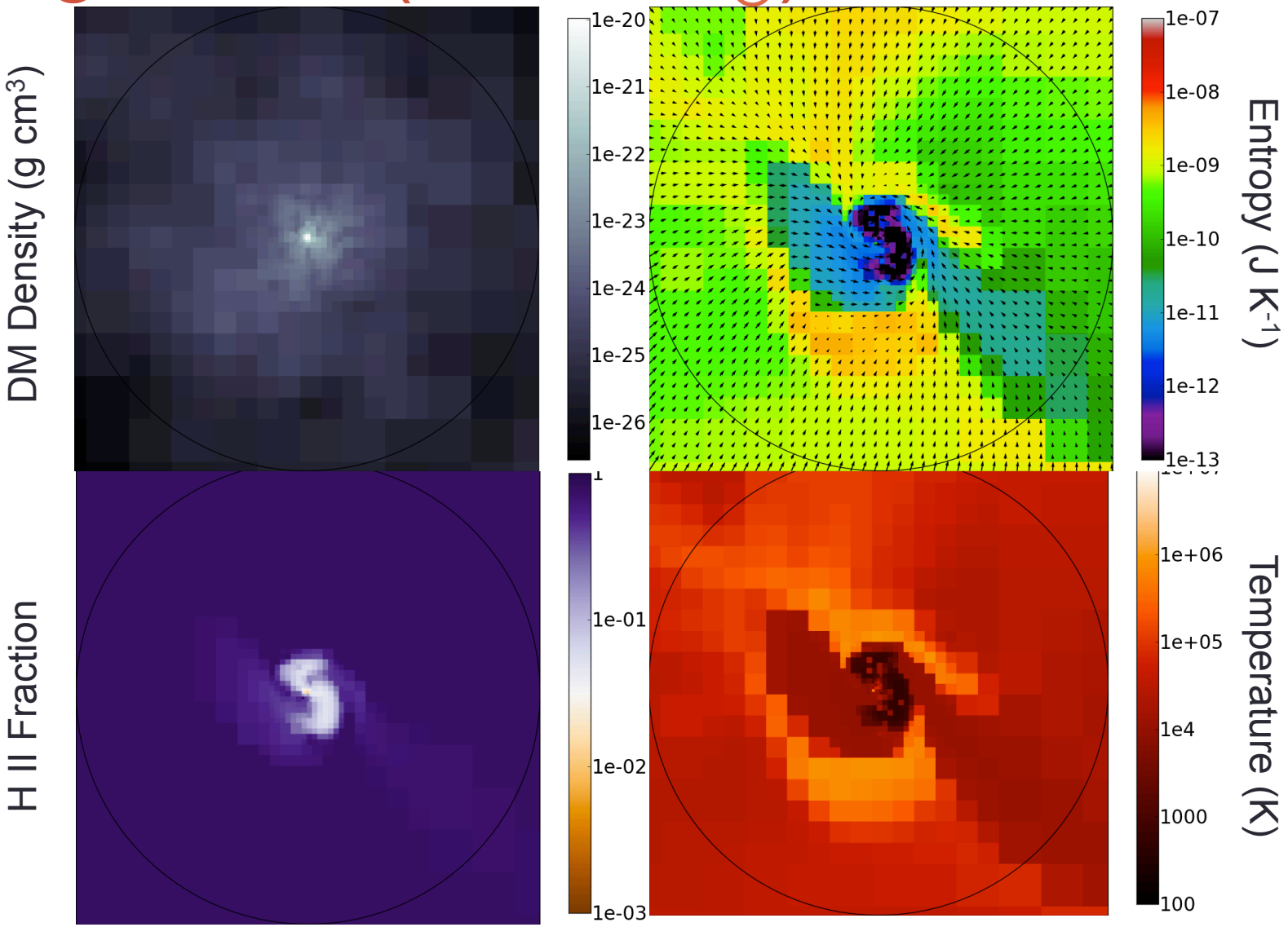
- Approximate convergence in star formation rate over entire box at levels 6 and 7

Progression of Reionisation

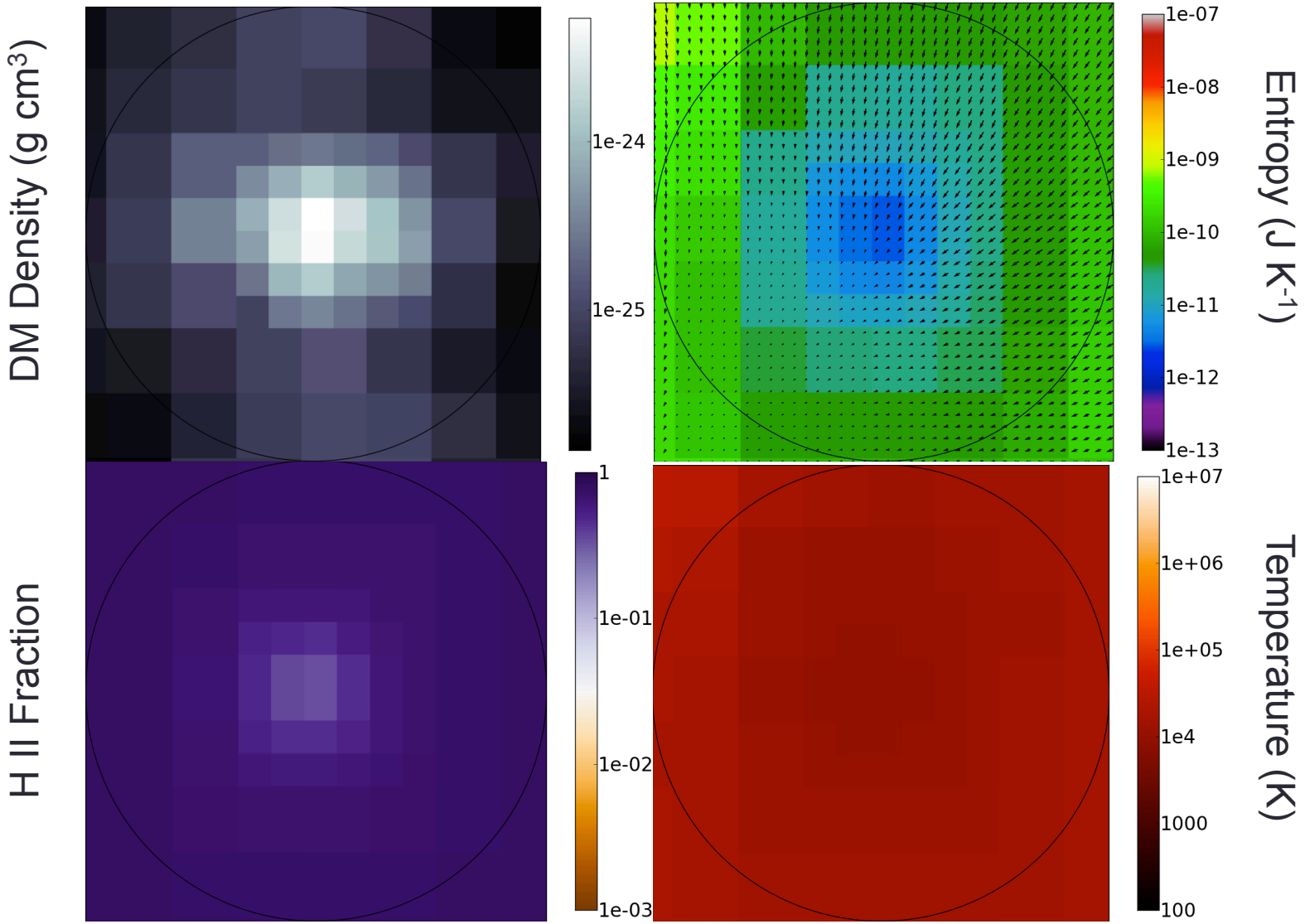
- No reionisation bubbles due to UV prescription used
- Reionisation unfinished, 15% still neutral
- Simulation not perfect, would require explicit sources of UV and radiative transfer



Larger Halo (~ 10^{10} $M_\odot$), z=5

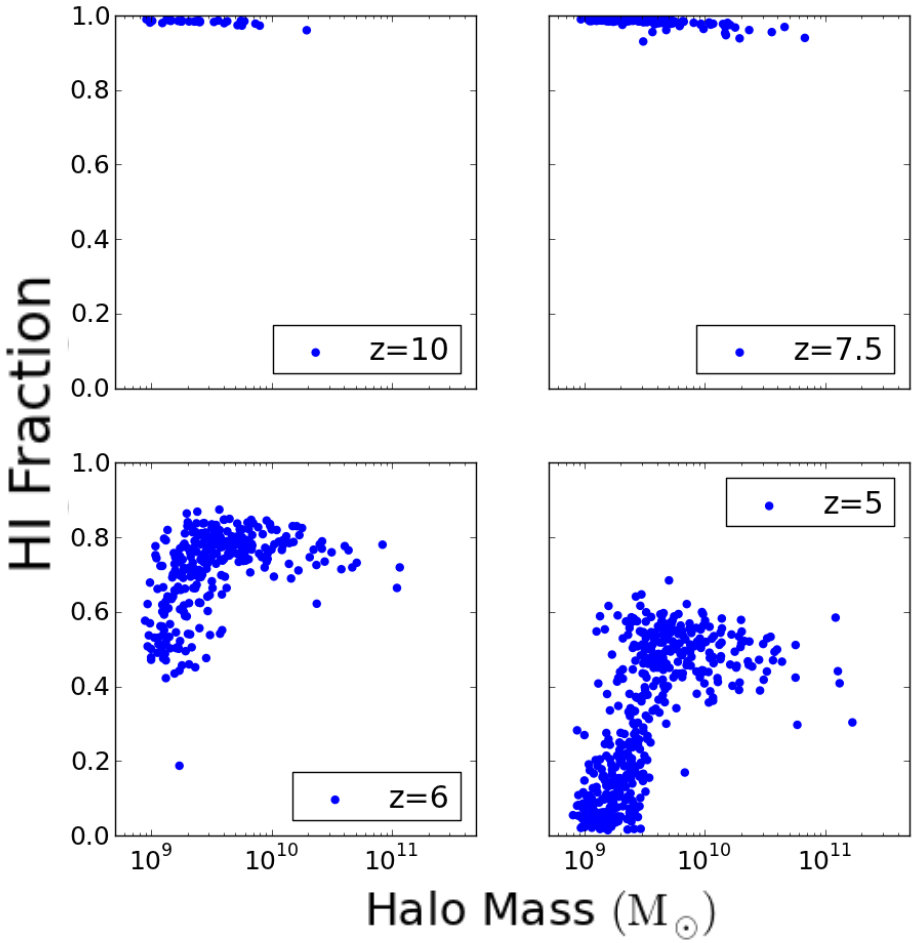


Smaller halo (~10^9 $M_\odot$), z=5

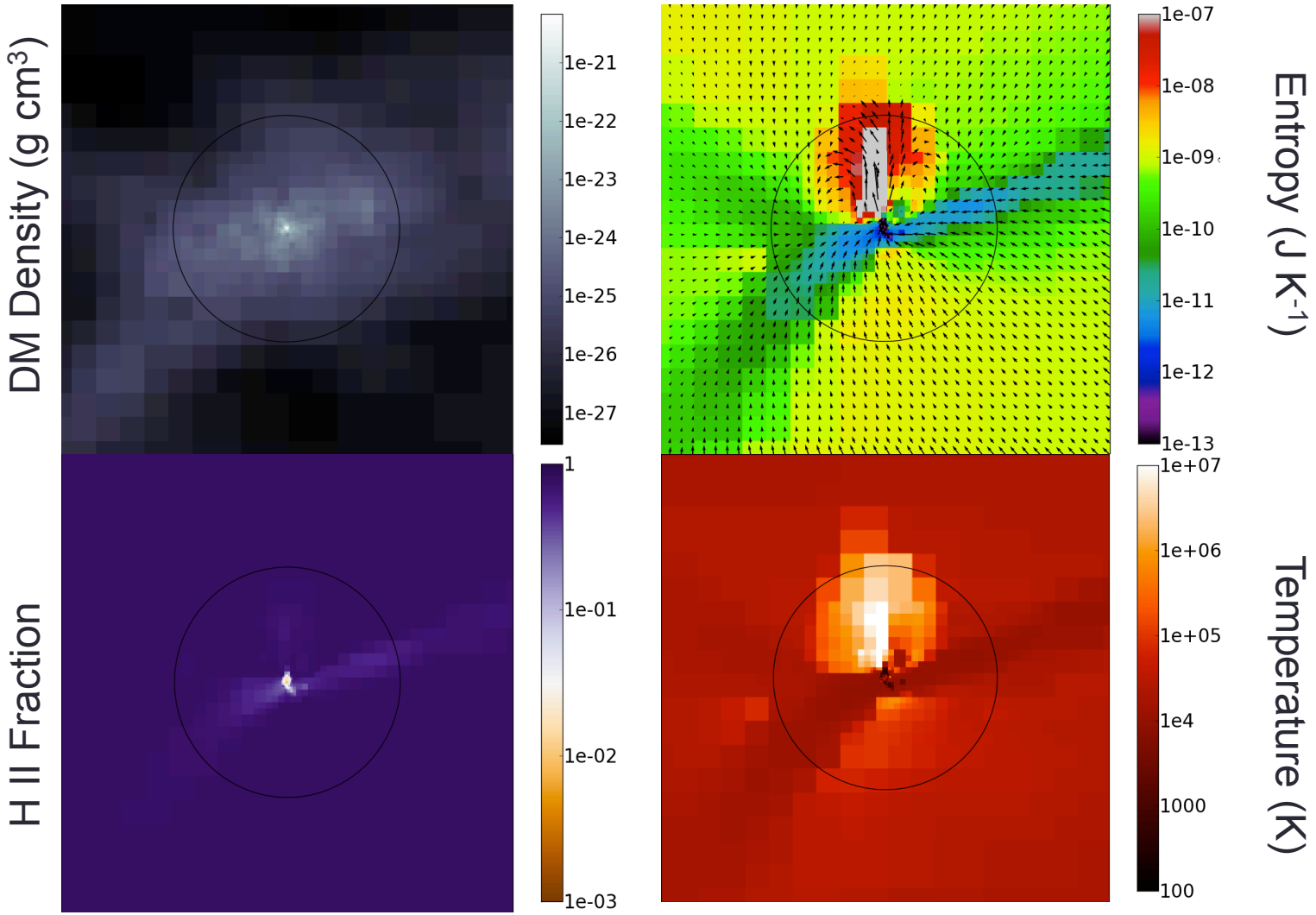


HI Fraction Evolution with UV Background

- Simulation showing evidence of halo mass dependence(!!!)
- Drop at ~$10^{9.1\text{-}9.3}$ solar masses
- H I fraction still decreasing after reionisation within halos



Negative Feedback in halos >10^{11} $M_\odot$



Next steps

- Implement:
  - CLOUDY metal cooling
  - Ray-tracing and/or UV background methods for radiation
- Larger runs:
  - (16 Mpc)^3 volume, 512^3 grid-size, 7 refinement levels
  - Effective resolution of (250 pc)^3
  - DM particle mass of 2.7 x 10^6 $M_\odot$, halo mass of ~10^8 $M_\odot$
- Currently applying for time with Virgo

Summary

- Contribution of UV to UV background from young star-forming galaxies unconstrained during reionisation
- Careful simulations can look at low halo mass range
- Need to simulate sources of UV with background and/or use ray tracing techniques
- Finding how star-formation is suppressed in smaller halos will improve galaxy formation modeling

Outline

- **Reionisation epoch**
  - Cosmology
  - Observations
  - Reasons for study
- **Enzo simulation**
  - What is Enzo?
  - Parameters and prescriptions
- **Preliminary results**
  - With varying UV background
  - Examples of different sized halos
  - Next steps

Recombination

- Universe completely ionised in early times
- Kept ionised by collisions, photons Compton scattered
- Universe expansion reduces rate of ionisation
- Universe neutralised and transparent at z ~ 1100

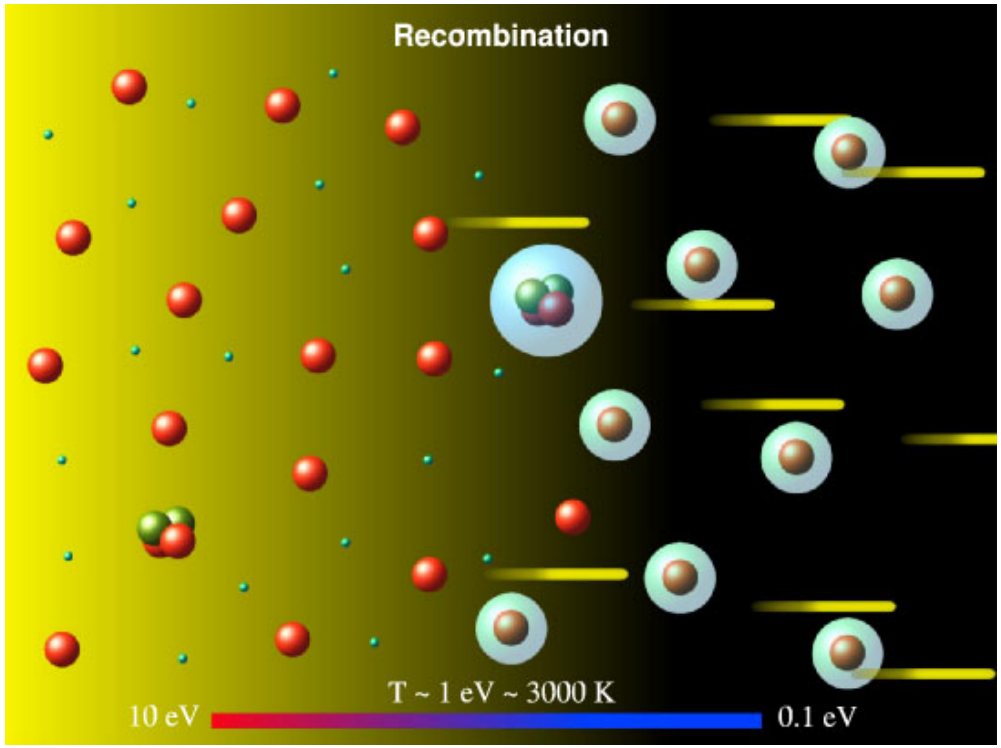
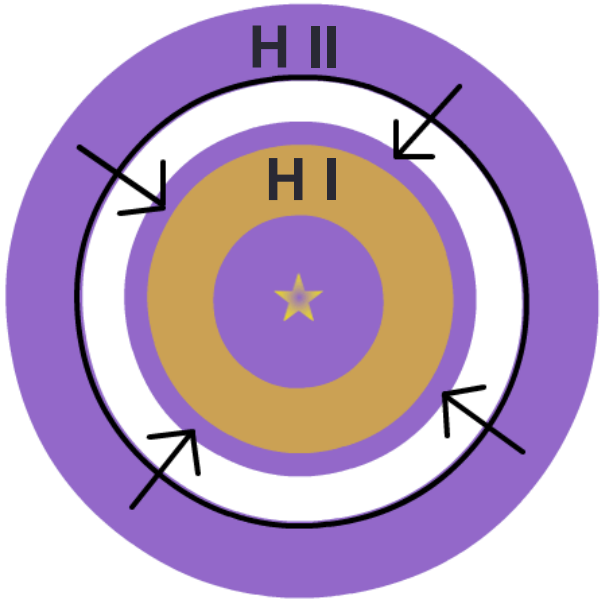
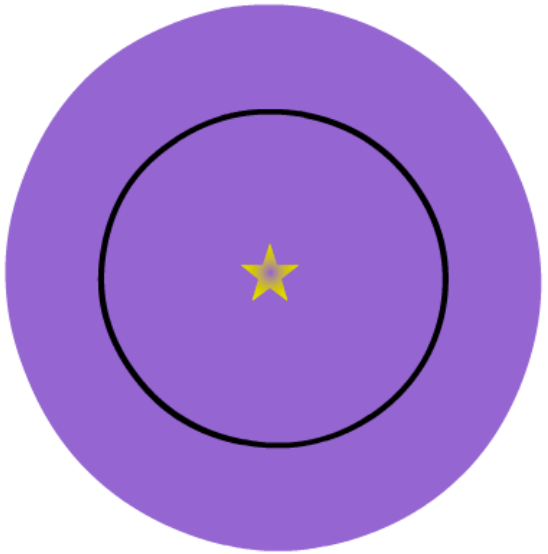


Image: Kinney Cosmology lecture series ‘02

Expected behaviour with varying halo mass





- Halo M>10^{10} $M_{\odot}$
- Some HI ionised internally
- External UV is shielded by large HI regions
- Star formation proceeds unhindered

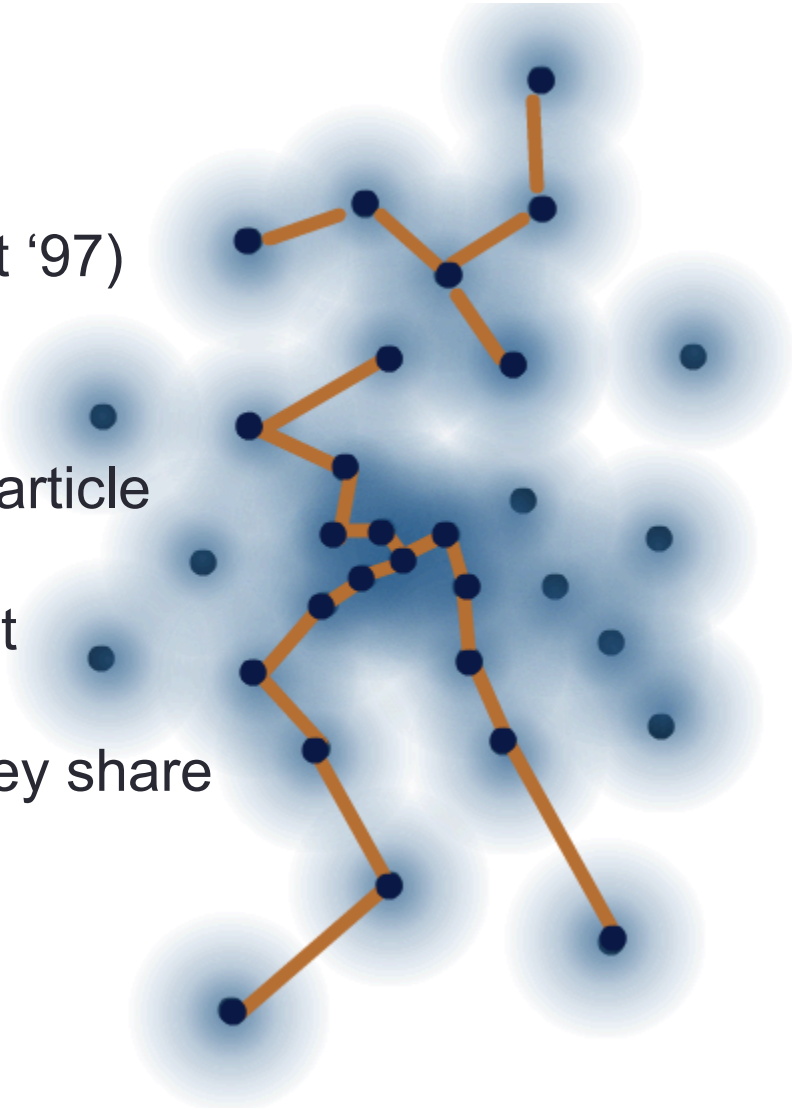
- Halo M<10^{8} $M_{\odot}$
- First stars ionise HI
- External UV penetrates quickly
- Star formation completely suppressed

Modeling Sources: Population III Stars

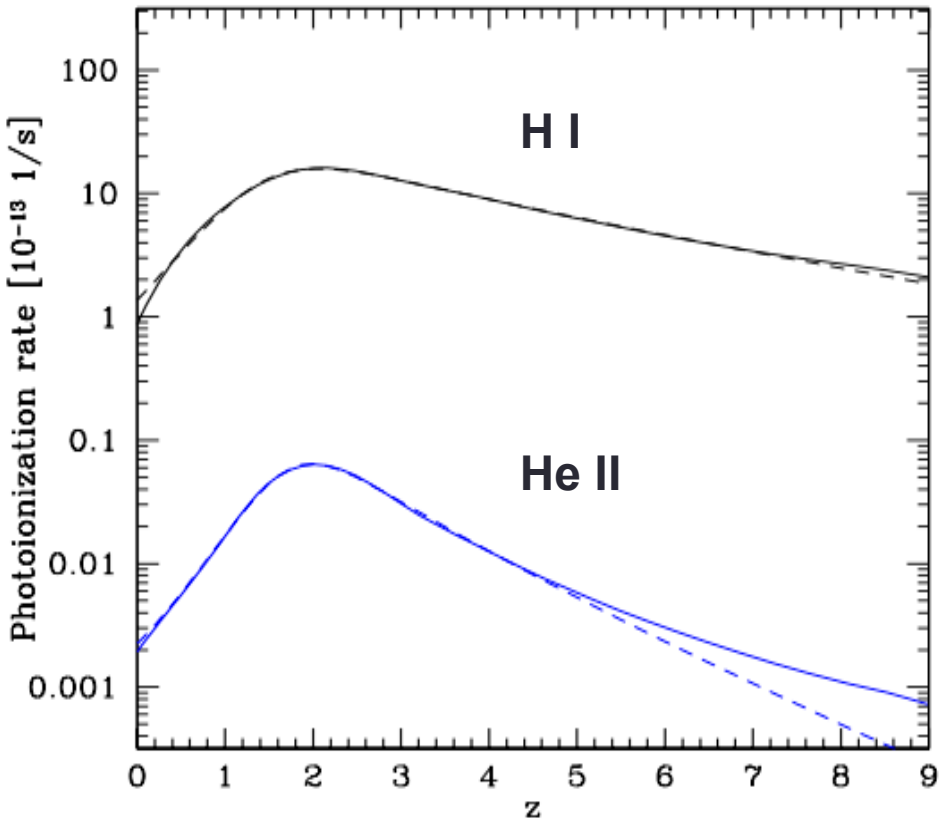
- Pop III stars provide early ionising photons
- Replace UV background with Pop III star prescription (Wise and Abel ’07):
  - Developed for z > 6 epoch
  - Feedback included
  - Phenomenological model “averaging” stars
  - Includes pop II stars
- Prescription uses ray-tracing to calculate UV ionisation!

Dark Matter and Halo Finder

- Particle method for dark matter
- HOP halo finder (Eisenstein & Hut ‘97)
- Particles smoothed with kernel
- Local density estimated at each particle position
- Particles linked to densest nearest neighbour (or self)
- Chains are part of same halo if they share same end of chain
- Find ~300 halos at z=6

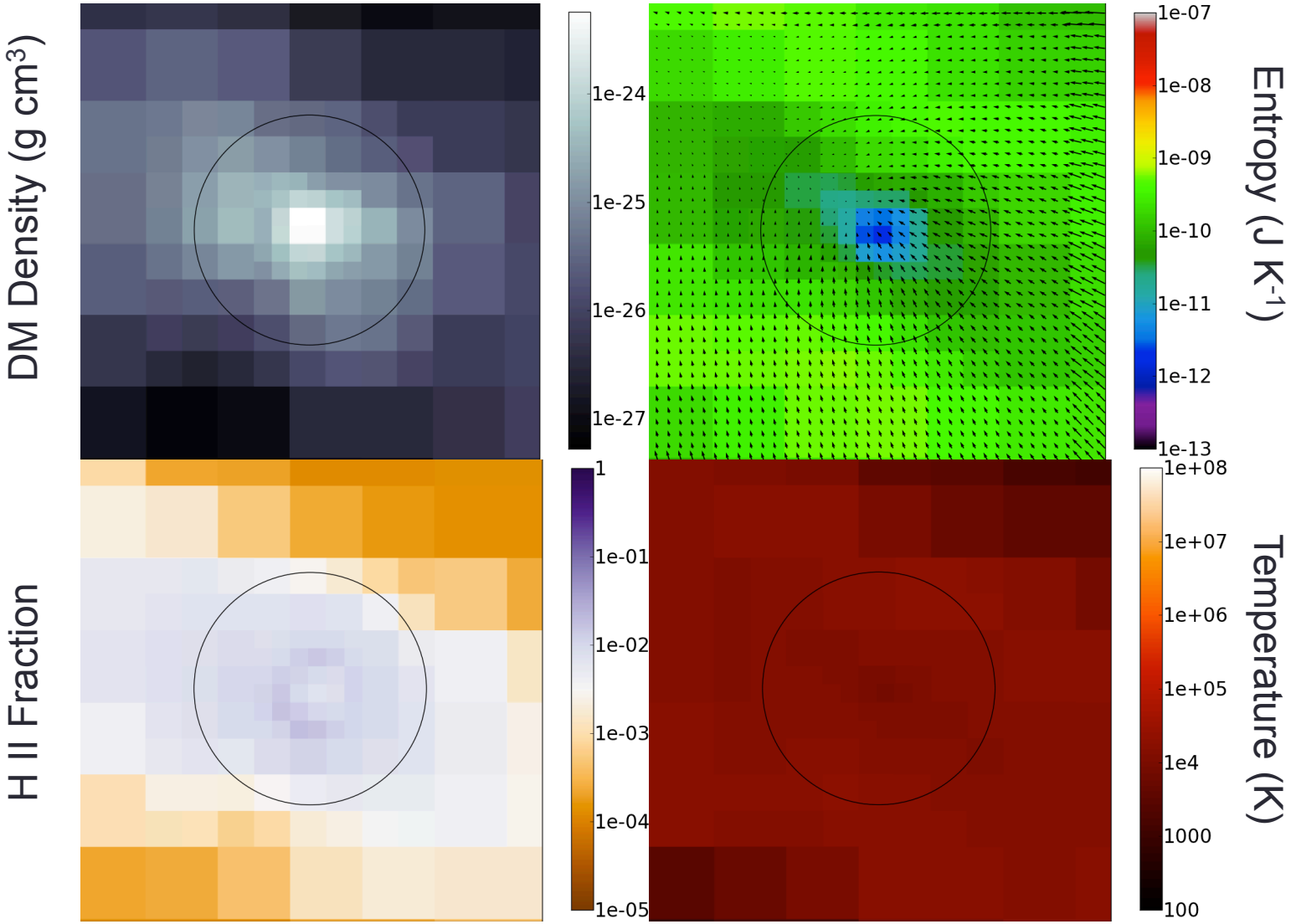


UV Uniform Background



- Modeling sources of UV is difficult, usually done in post-processing
- Haardt and Madau ’01 ionising background; *density*, *species* and *redshift* dependent
- Produces quasar spectrum and X-ray Compton-scattering effects

Smaller Halo (~10^9 $M_\odot$), z=5



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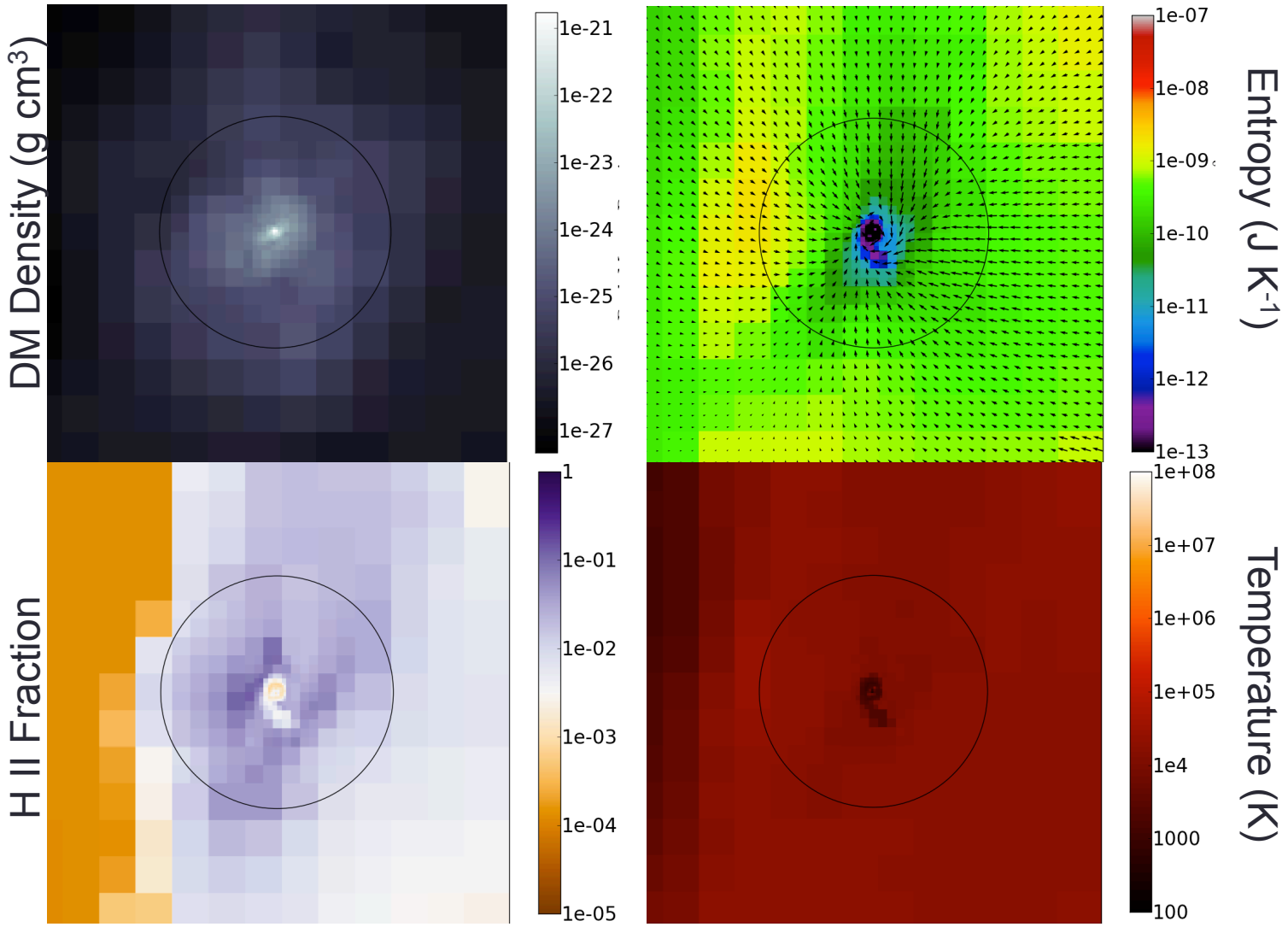
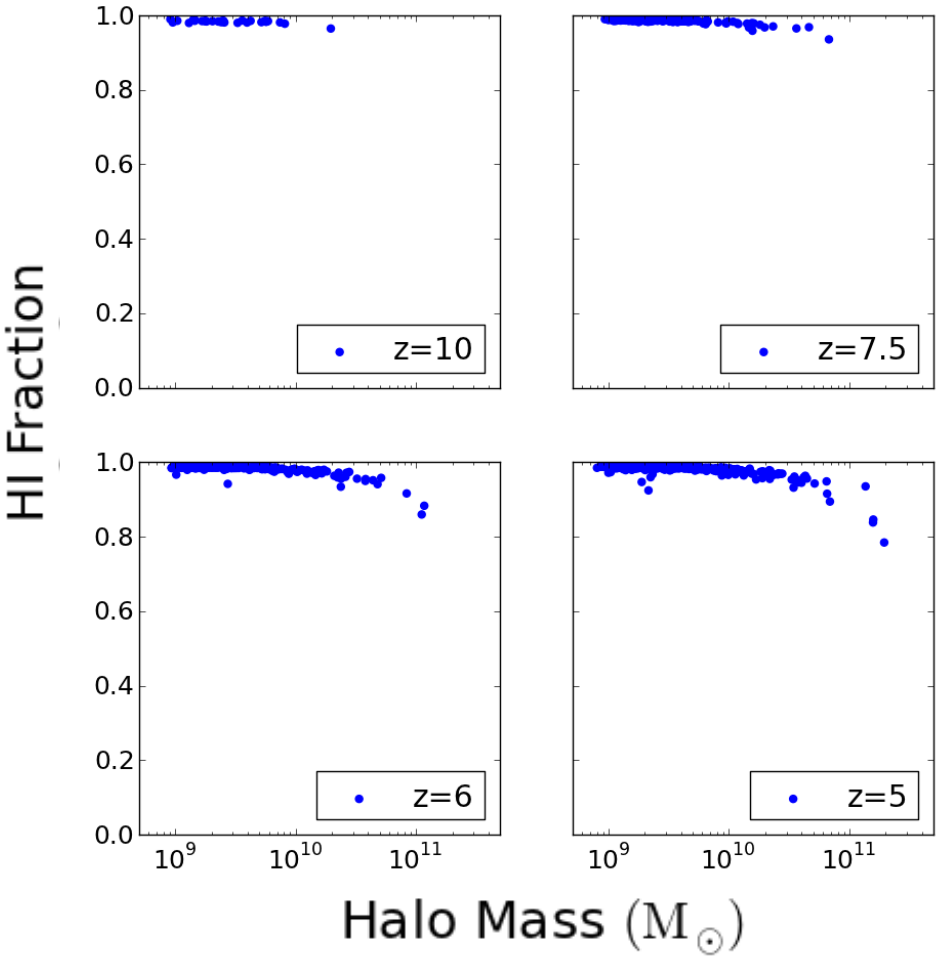


HI fraction with Pop III stars only



- Stellar feedback having no effect at smaller halo masses
- Negative feedback at M > 10^{10} $M_\odot$
- Reionisation barely started, 75% still neutral
- Insufficient in isolation, really needs external UV

Main differences between both

- **UV background**

- **Pros**
  - Fast implementation
  - Fewer parameters

- **Cons**
  - No patchy reionisation
  - Reionsation not finished

- **Pop III stars**

- **Pros**
  - Slower but realistic
  - Can tweak parameters
  - Should give patchy regions

- **Cons**
  - No patchy reionisation
  - Reionsation not started(!)