Population III stars and the formation of the first protogalaxies

Brian O’Shea
Theoretical Astrophysics Group
Los Alamos National Laboratory
bwoshea@lanl.gov

Image (c) Matt Hall, NCSA

Some big questions

- How do the first stars form and evolve? (Part 1)
- What is the mass distribution (IMF) of Population III stars? (Part II)
- What are the cosmological consequences of feedback from the first generation of stars? (Part III)

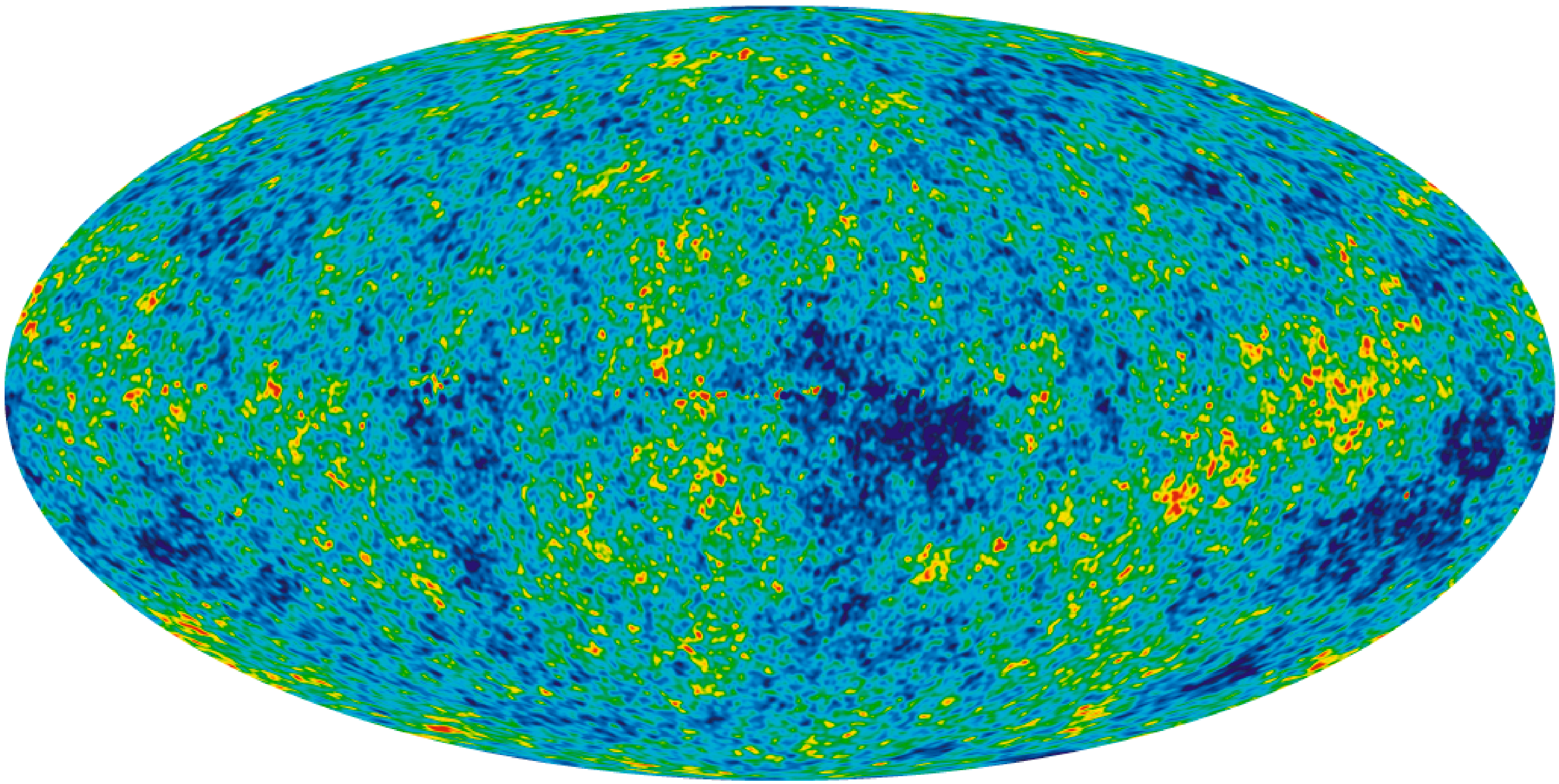
Los Alamos NATIONAL LABORATORY EST. 1943

Who cares about Pop III stars?

- First bright objects to form in the universe
- Mark a fundamental change from linear to nonlinear
- These objects affect all later generations of structure formation (reionization, metal enrichment, black hole formation, etc.)
- Necessary to understand Pop III stars if we want to understand galaxy formation from first principles

Los Alamos
NATIONAL LABORATORY
EST. 1943

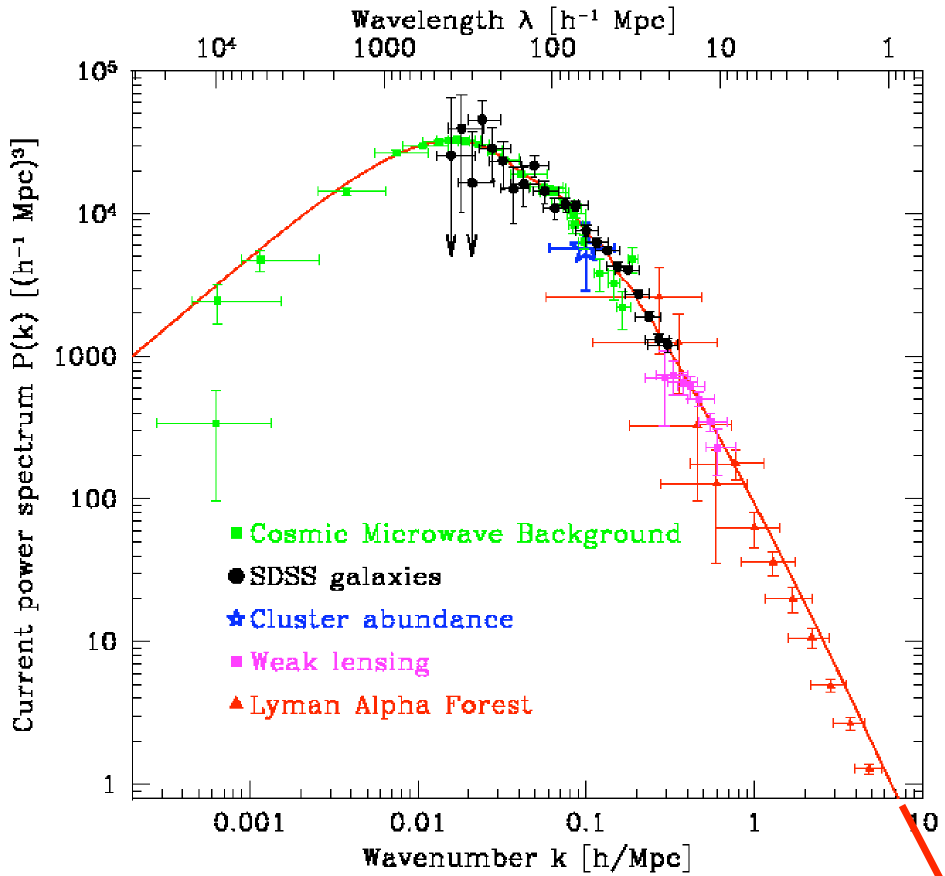
ICs for large scale structure are specified from observation



WMAP Year 3 data release

(courtesy of NASA/WMAP science team)

ICs for large scale structure are specified from observation



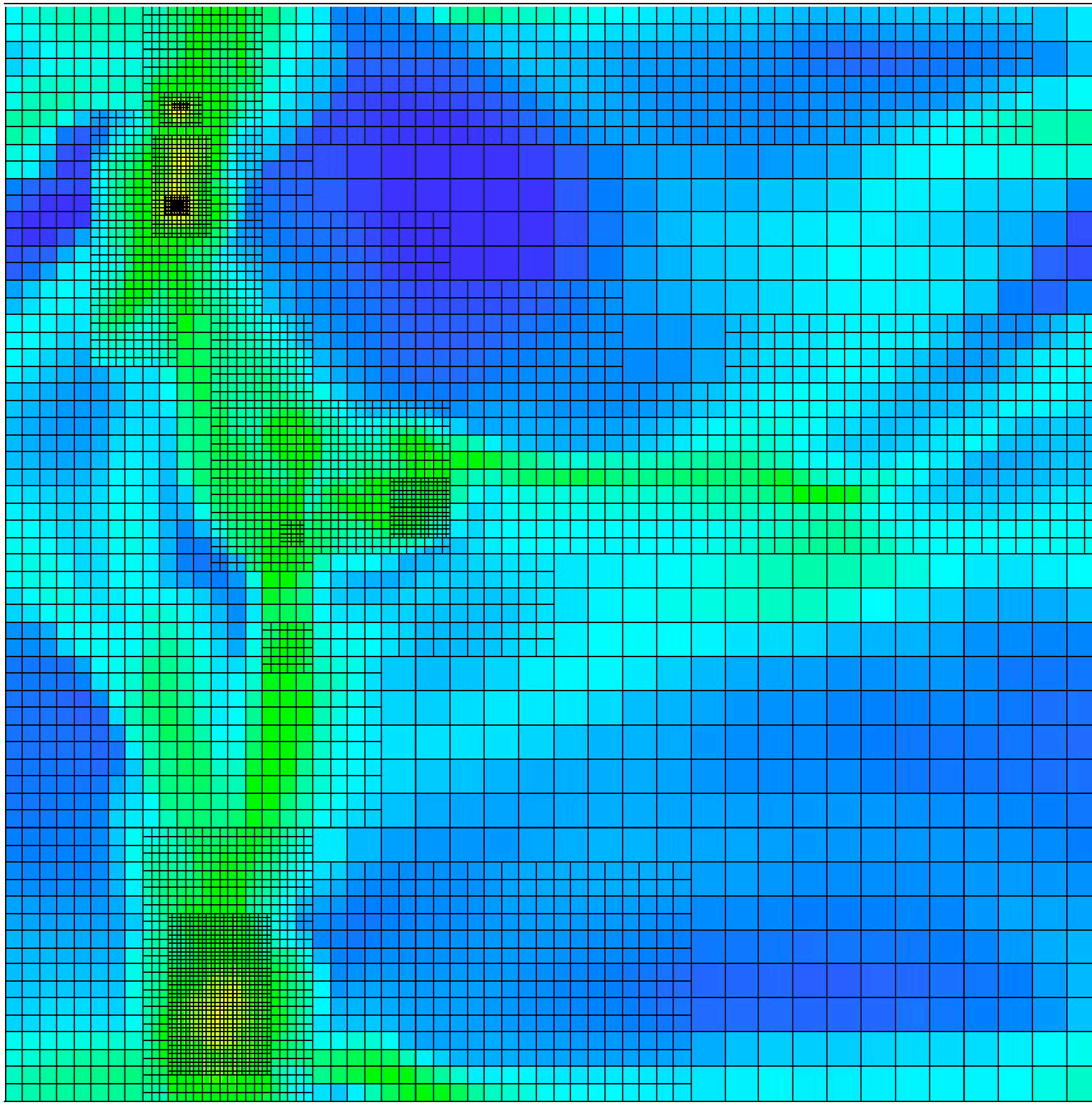
Pop III

from Tegmark et al. 2003

Population III Star Formation

- A well-posed problem
  - Initial conditions can be taken from cosmology (CMB, LSS)
  - Simple but nonlinear physics - gravity, hydrodynamics
  - Simple non-equilibrium chemistry and optically thin radiative cooling - no dust or metals, just H, He (and H_2)
  - No dynamically important B-fields (we believe)
- Complexity due to large range of scales involved
  - $R_\odot/L_{LSS}$ (z = 20) ~ 10^{-12}
  - $P_\odot/t_{hubb}$ (z = 20) ~ 10^{-12}

Los Alamos NATIONAL LABORATORY EST.1943



)

ve

Los Alamos
NATIONAL LABORATORY
EST. 1943

H_2 chemistry and Pop III Stars

- H_2 is primary coolant - no metals!

- Low density ($n \leq 10^8$ cm^{-3}) - residual electrons catalyze H_2 formation via H^- channel:

$$H + e^- \Rightarrow H^- + \gamma$$
$$H^- + H \Rightarrow H_2 + e^-$$

- High density ($n \geq 10^8$ cm^{-3}) - formation of H_2 via 3-body process:

$$H+H+H \Rightarrow H_2 + H$$

- Pop III: $T_{min} \sim 200$ K, Galaxy: $T_{min} \sim$ few K

$$M_J \sim \frac{T^{3/2}}{\rho^{1/2}}$$

Los Alamos
NATIONAL LABORATORY
EST. 1943

Part 1

How do the first stars form and evolve?

O'Shea & Norman 2007, ApJ, 654, 66-92
and
Turk, O'Shea & Abel 2007, in prep.
(watch astro-ph next month!)

Los Alamos
NATIONAL LABORATORY
EST. 1943

Numerical Experiment

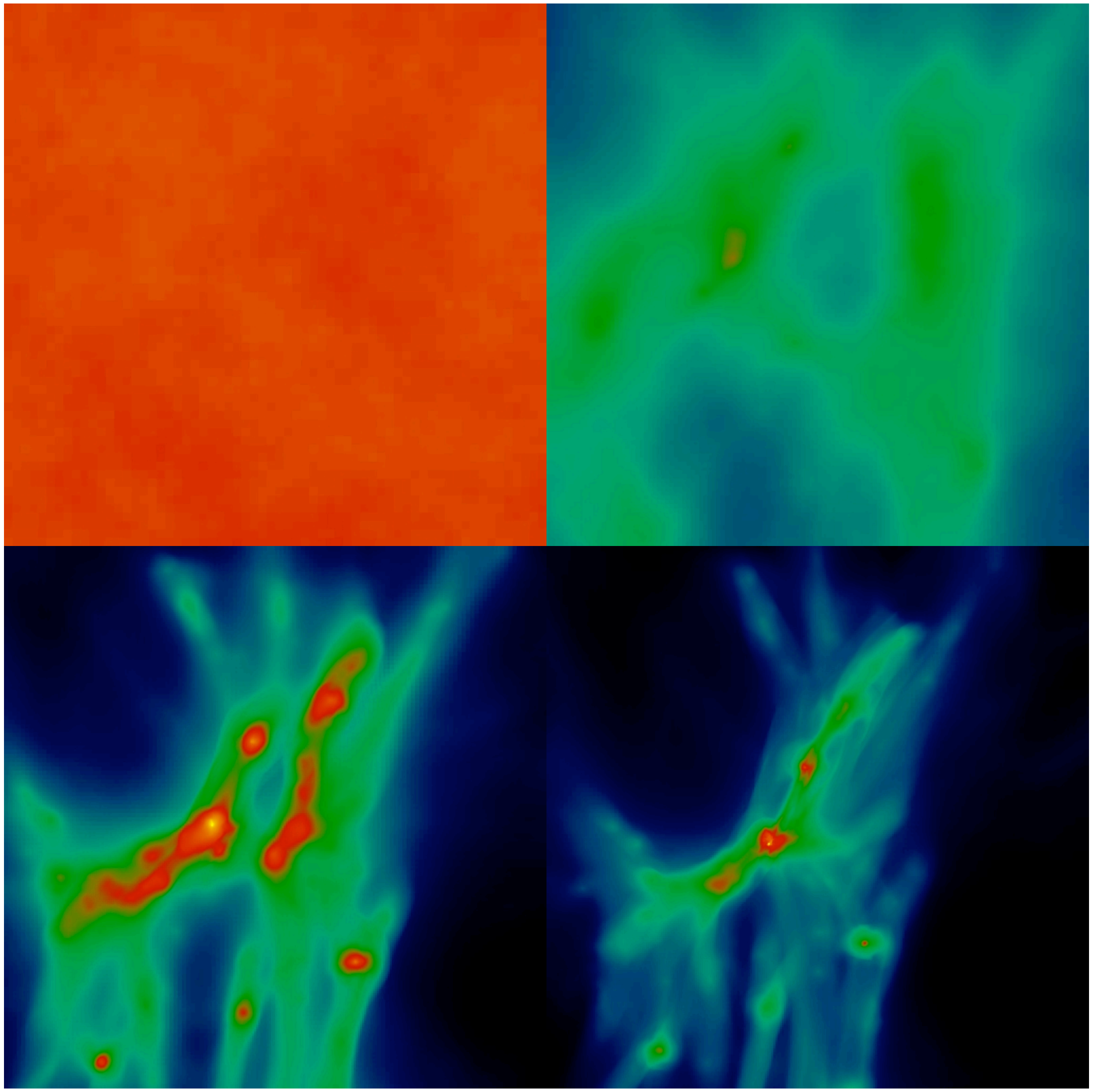
- Set up AMR hydro + N-body calculation with concordance cosmology and $L_{box} = 0.3\ h^{-1}$ Mpc, initialized at z ~ 170 with a nested-grid setup, ΛCDM cosmology (WMAP Year 1)
- Use nonequilibrium primordial chemistry, 42 maximum levels of AMR, refine on baryon and dark matter overdensity, Jeans length (Truelove), cooling time, shocks, etc.
- Evolve simulation until collapse of gas in the core of the most massive halo - follow up to densities of $\sim 10^{21}\ cm^{-3}$ (protostellar densities!)

Los Alamos NATIONAL LABORATORY EST. 1943

Pop III star formation: current paradigm

z=99

z=25

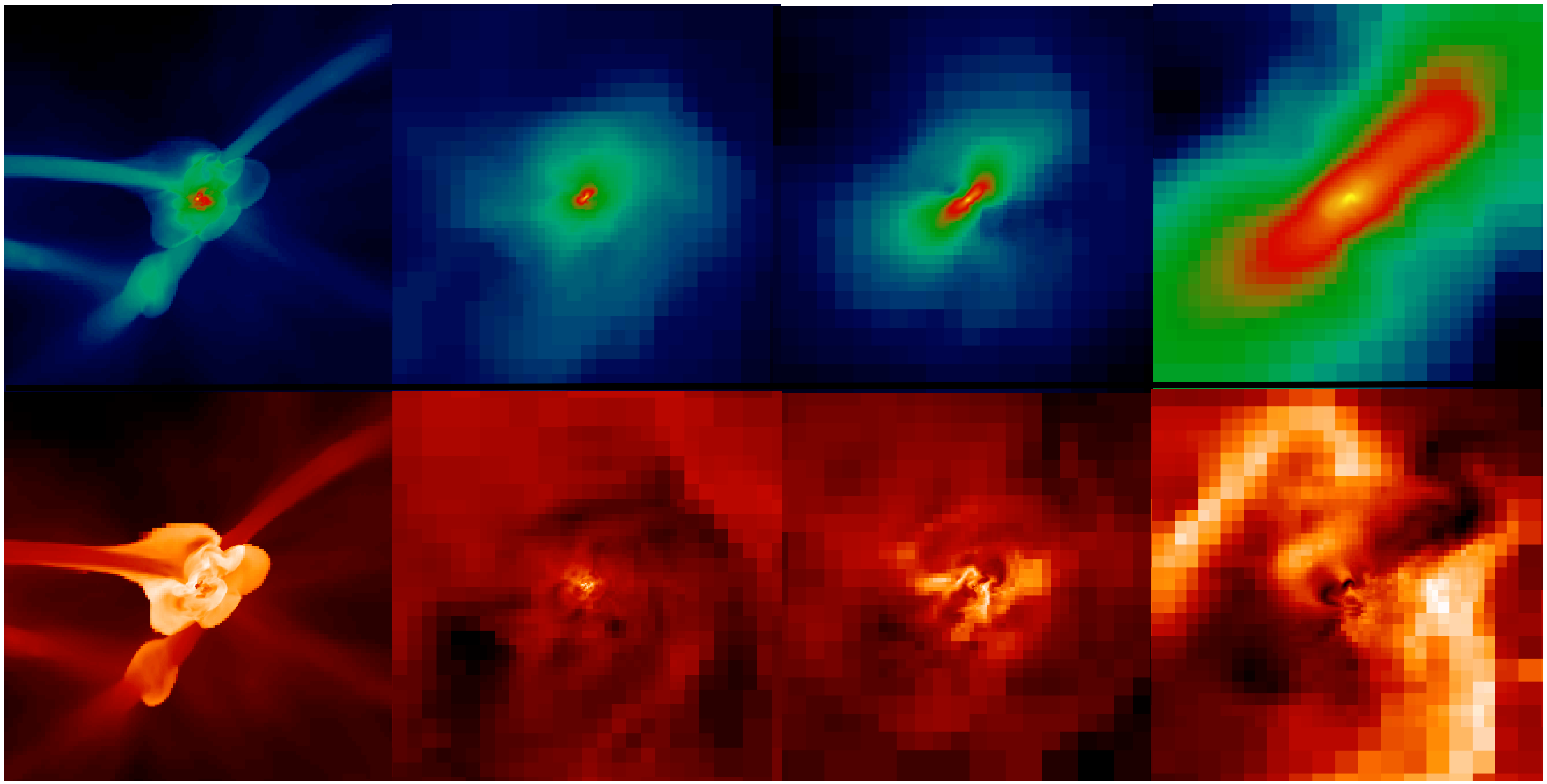


z=20

z=18

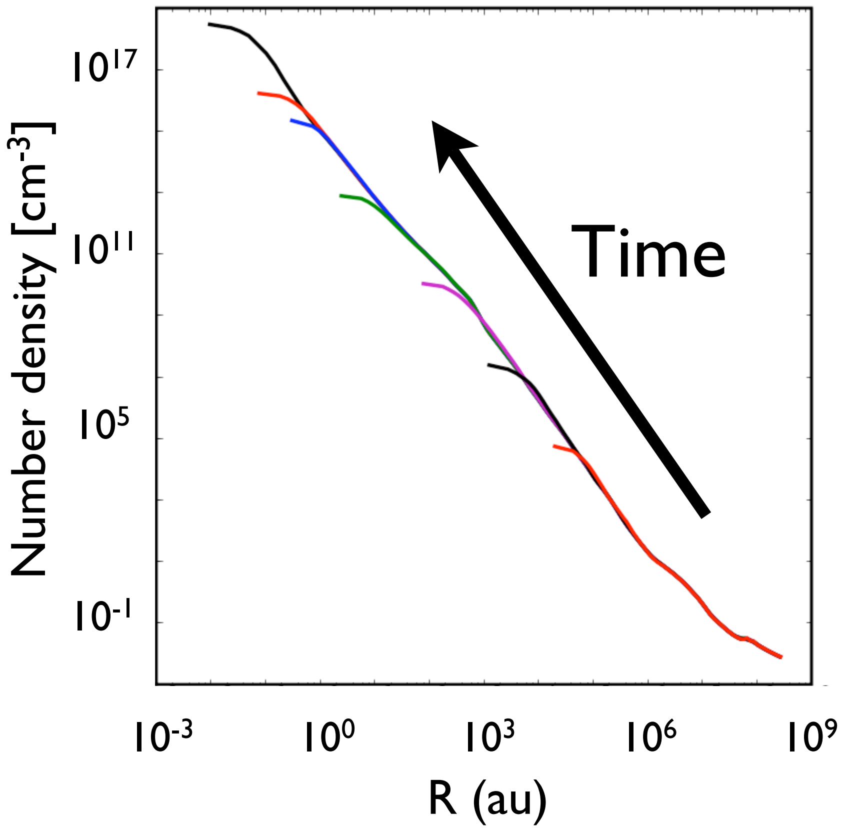
FOV: 26.8 comoving kpc
(1.41 prop. kpc @ z=18)

Pop III star formation: current paradigm

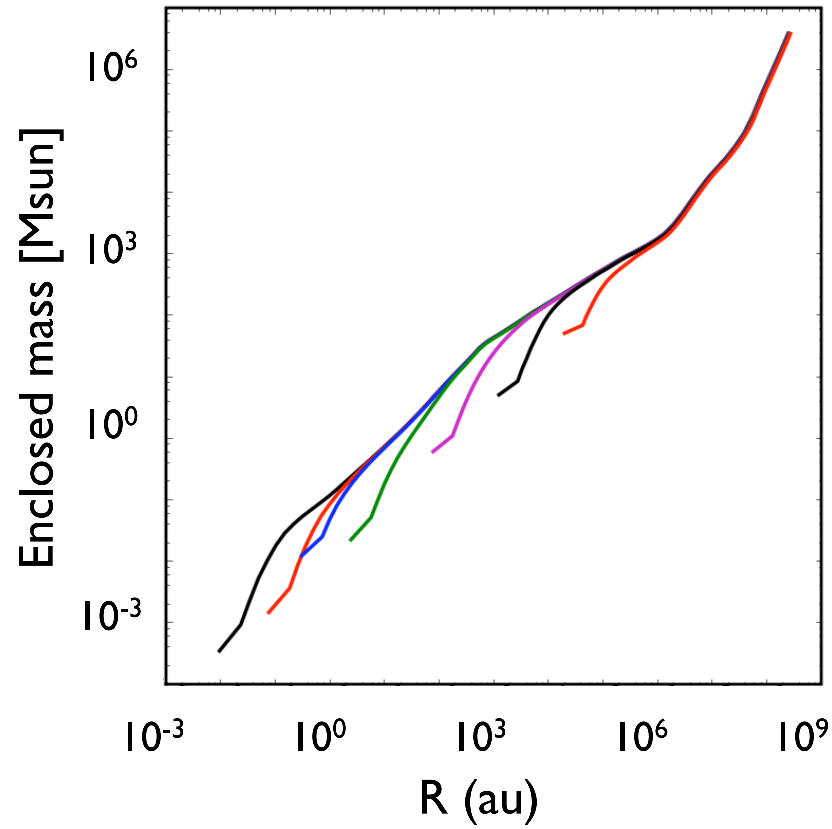


1 kpc	5 pc	0.5 pc	0.05 pc

Pop III star formation: current paradigm



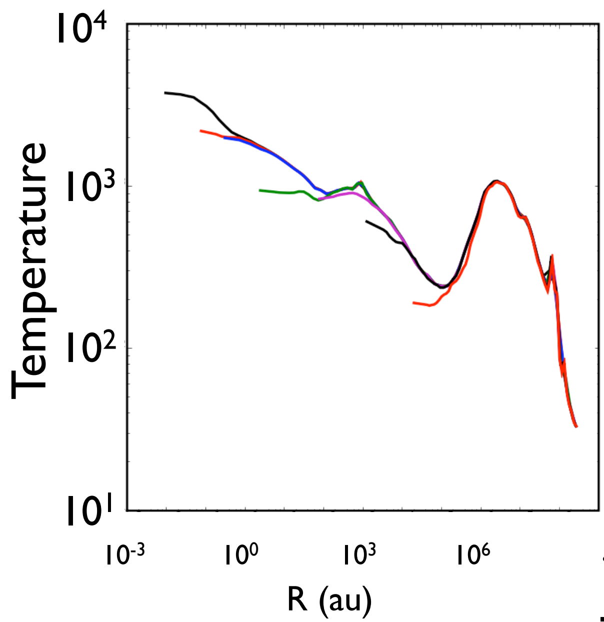
Number density

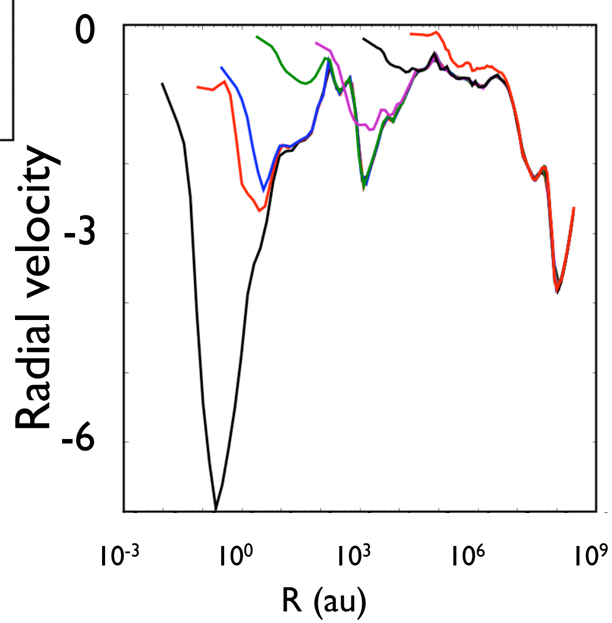


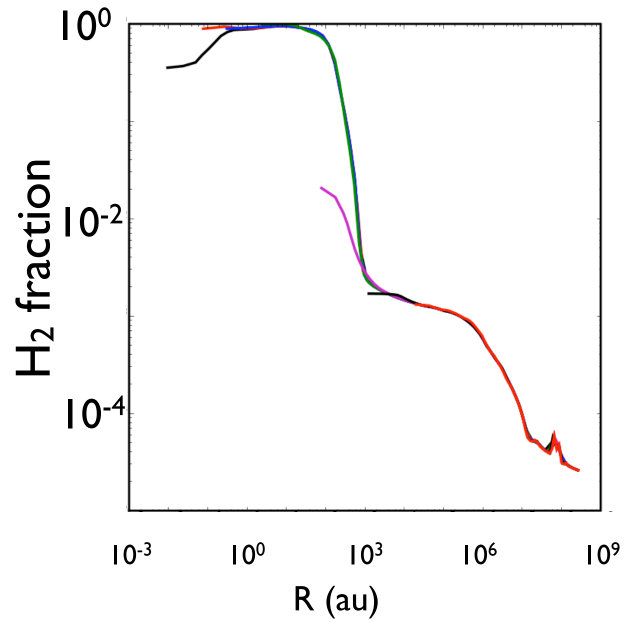
Enclosed mass

Turk, O'Shea & Abel 2007 (in prep)

Pop III star formation: current paradigm



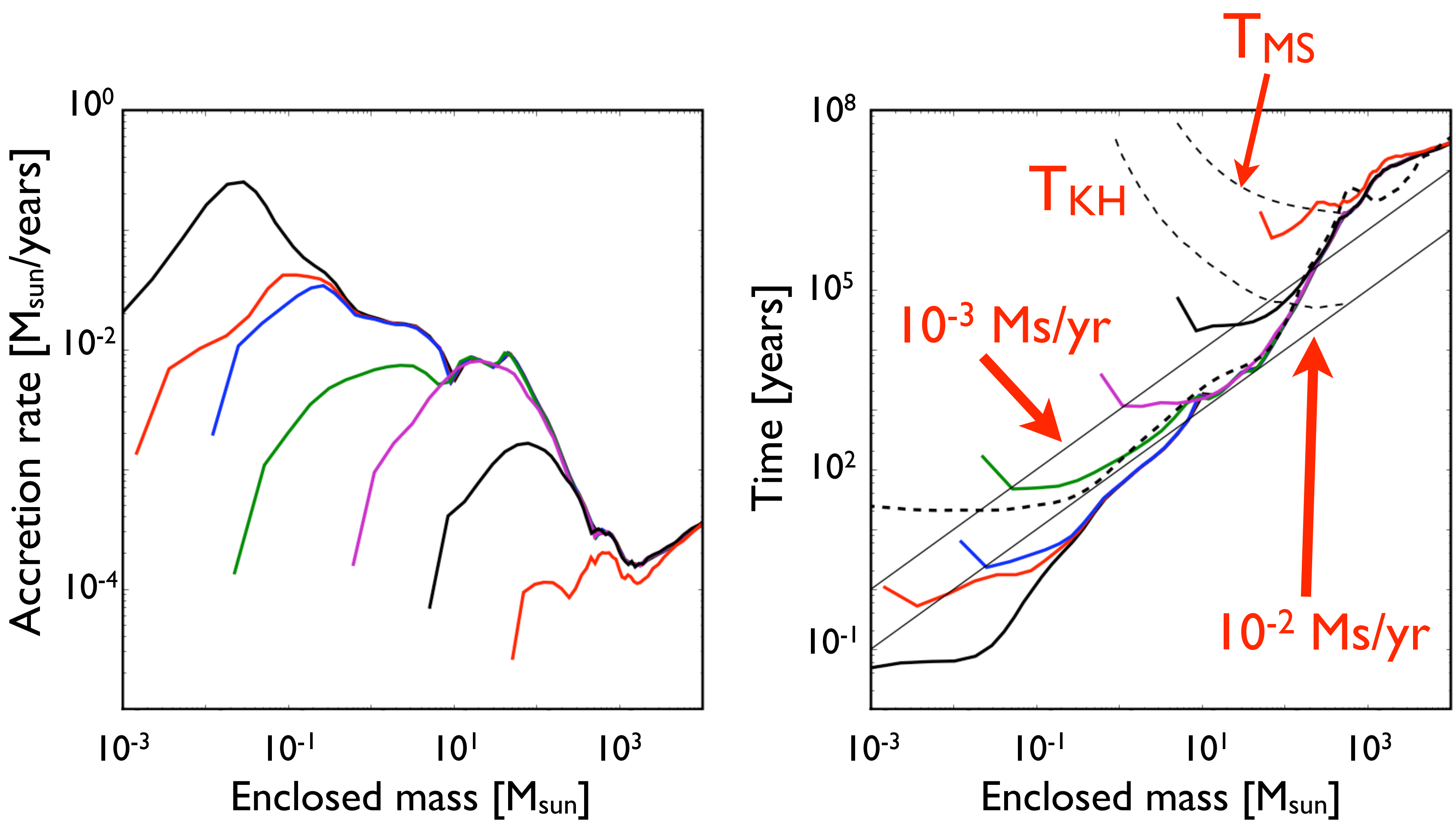




Turk, O'Shea & Abel 2007 (in prep)

Los Alamos
NATIONAL LABORATORY
EST. 1943

Pop III star formation: current paradigm



Turk, O'Shea & Abel 2007 (in prep)

Los Alamos NATIONAL LABORATORY EST.1943

Part 1: Conclusions

- H_2 chemistry sets the mass scales/accretion rates in Pop III star formation
- Poor H_2 cooling leads to high temperatures, large overall clumps, massive stars!
- Exact stellar masses are still undetermined due to complicated accretion physics (but we're working on this)

Part II

What is the IMF of Pop III stars?

(O'Shea and Norman 2007, ApJ, 654, 66-92)

Key questions:

1. Robustness of Part I result?
2. Environmental effects?
3. Are Pop III stars at different redshifts different?

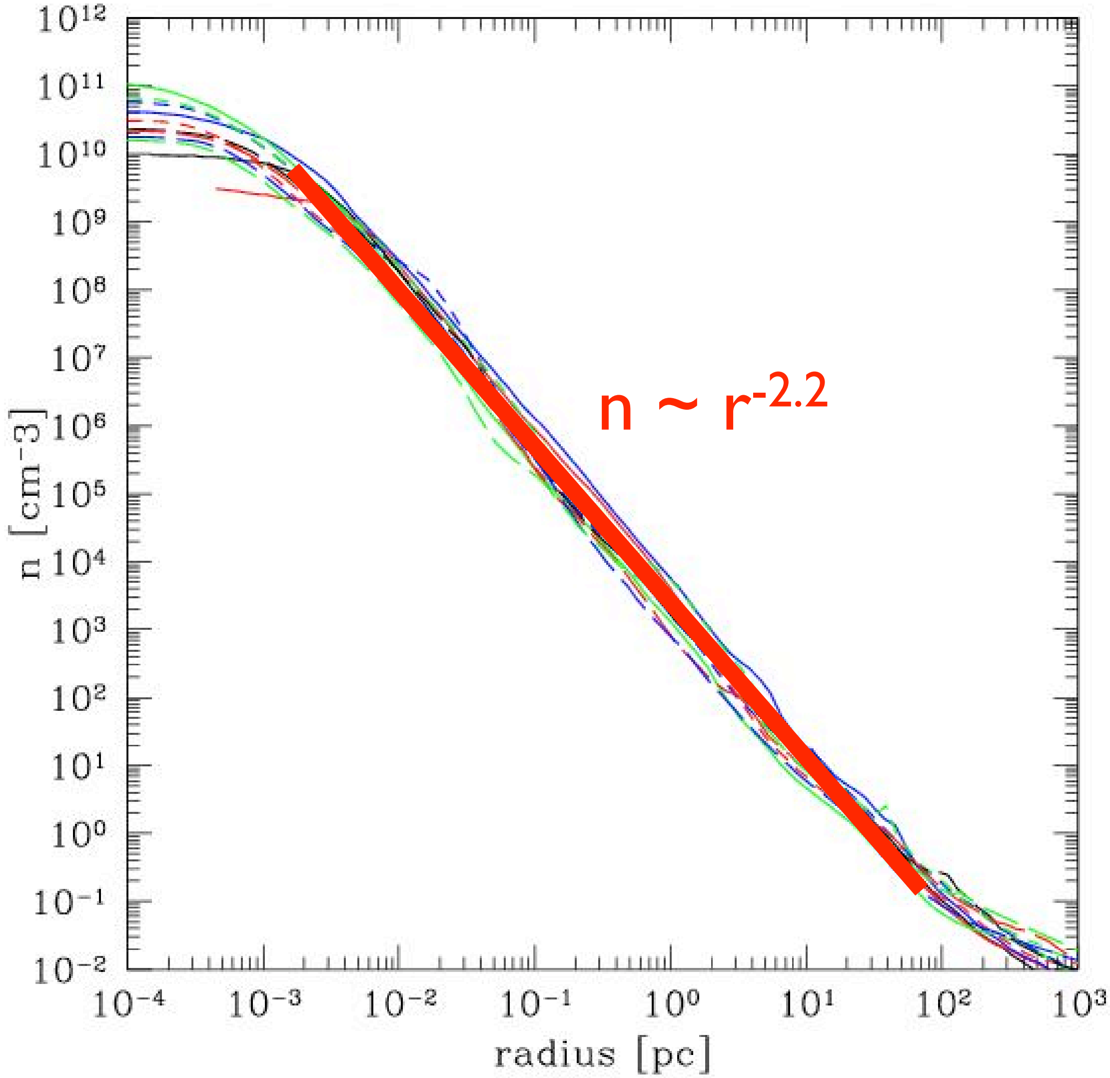
The simulations

- Twelve simulations using WMAP Year 1 concordance cosmology
- Three sets of four simulations in boxes of 0.3, 0.45 and 0.6 h^{-1} Mpc
- Each simulation has a different random seed (varied large-scale cosmological structure)
- Evolve until collapse of first halo in each calculation, analyze when core reaches $n \sim 10^{10}$ cm^{-3}

O'Shea & Norman 2007, ApJ, 654, 66-92

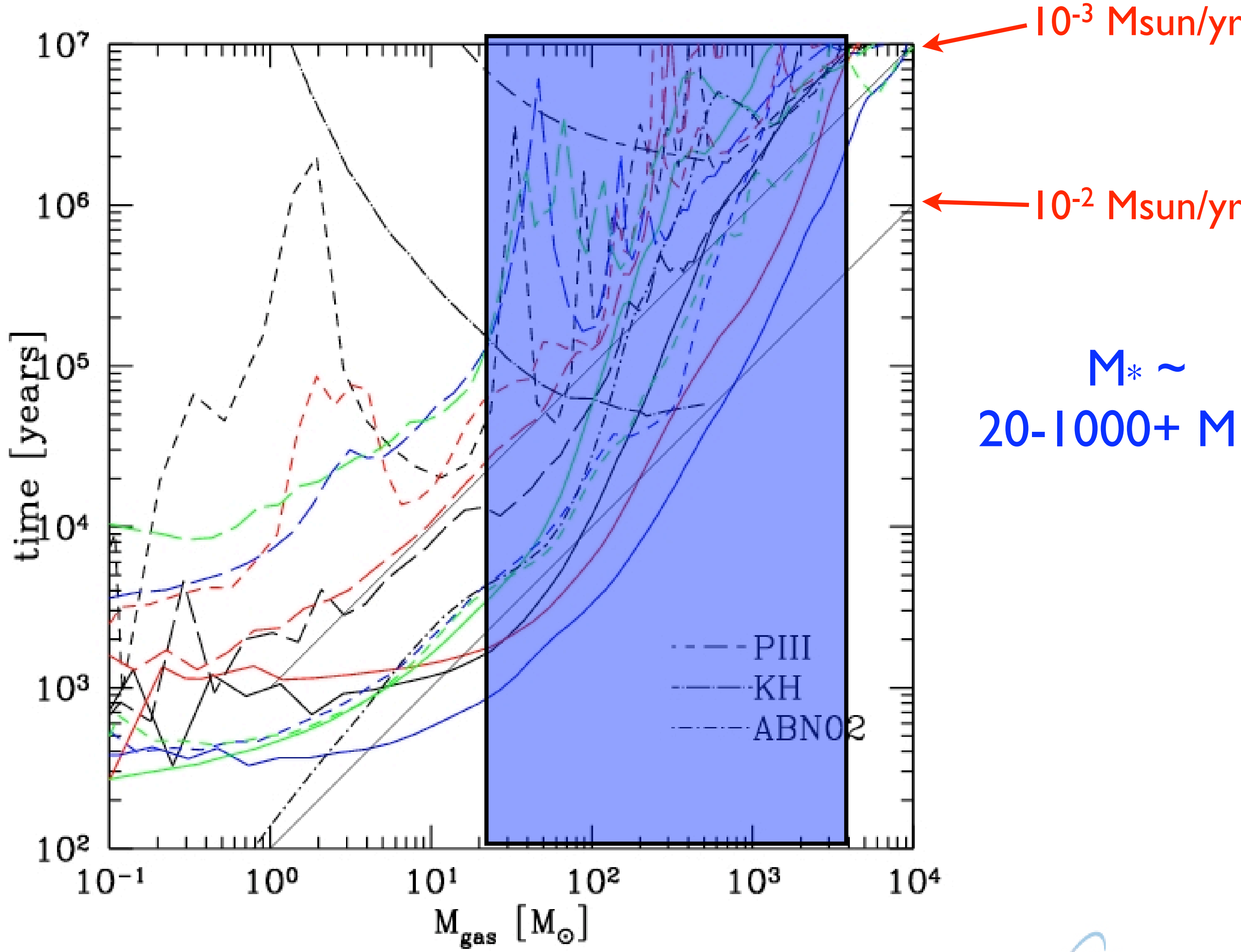
Los Alamos NATIONAL LABORATORY EST. 1943

Baryon number density, all simulations



O'Shea & Norman 2007, ApJ, 654, 66-92

Accretion time, all simulations

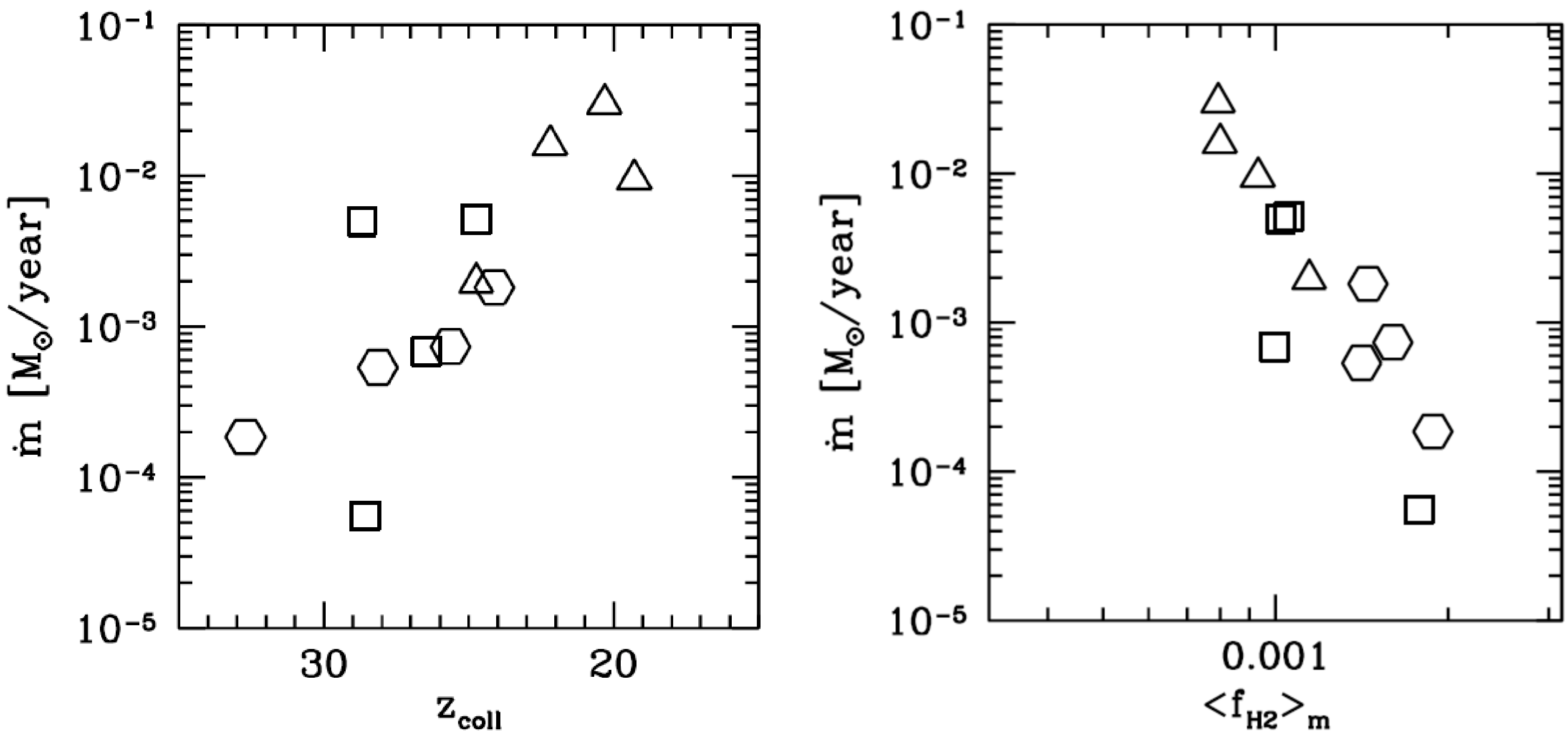


M* ~
20-1000+ M☉?

O'Shea & Norman 2007, ApJ, 654, 66-92

Los Alamos NATIONAL LABORATORY EST. 1943

Variation in accretion rates



O'Shea & Norman 2007, ApJ, 654, 66-92

Part II: Conclusions

- Pop III halos to form at higher redshifts (earlier times) have:
  - Higher overall temperatures
  - Higher core H_2 fraction
  - Lower core temperature
  - Lower accretion rates!
- The first Pop III stars to form may have smaller masses than later-forming stars (but still very large!)
- Pop III epoch may start small and build up (but relation b/w accretion and mass is complicated...)

Los Alamos
NATIONAL LABORATORY
EST. 1943

Part III

What are the cosmological consequences of feedback from the first stars?

O'Shea & Norman 2007, ApJ, accepted (FUV; astro-ph/0706.4416)

Whalen, **O'Shea**, Smidt & Norman 2007, ApJ, submitted (Halo photoevaporation; astro-ph/0708.1603)

O'Shea, Norman & Whalen 2007, ApJ, in prep. (Supernovae; in ~October)

Los Alamos
NATIONAL LABORATORY
EST.1943

If Pop III stars are very massive, they will...

- Produce tremendous amounts of photodissociating (Lyman-Werner) radiation
- Create very large HII regions ($r_{HII} >> r_{halo}$) which will interact with nearby halos
- Explode in Type II or (possibly) pair instability supernovae - metal enrichment!

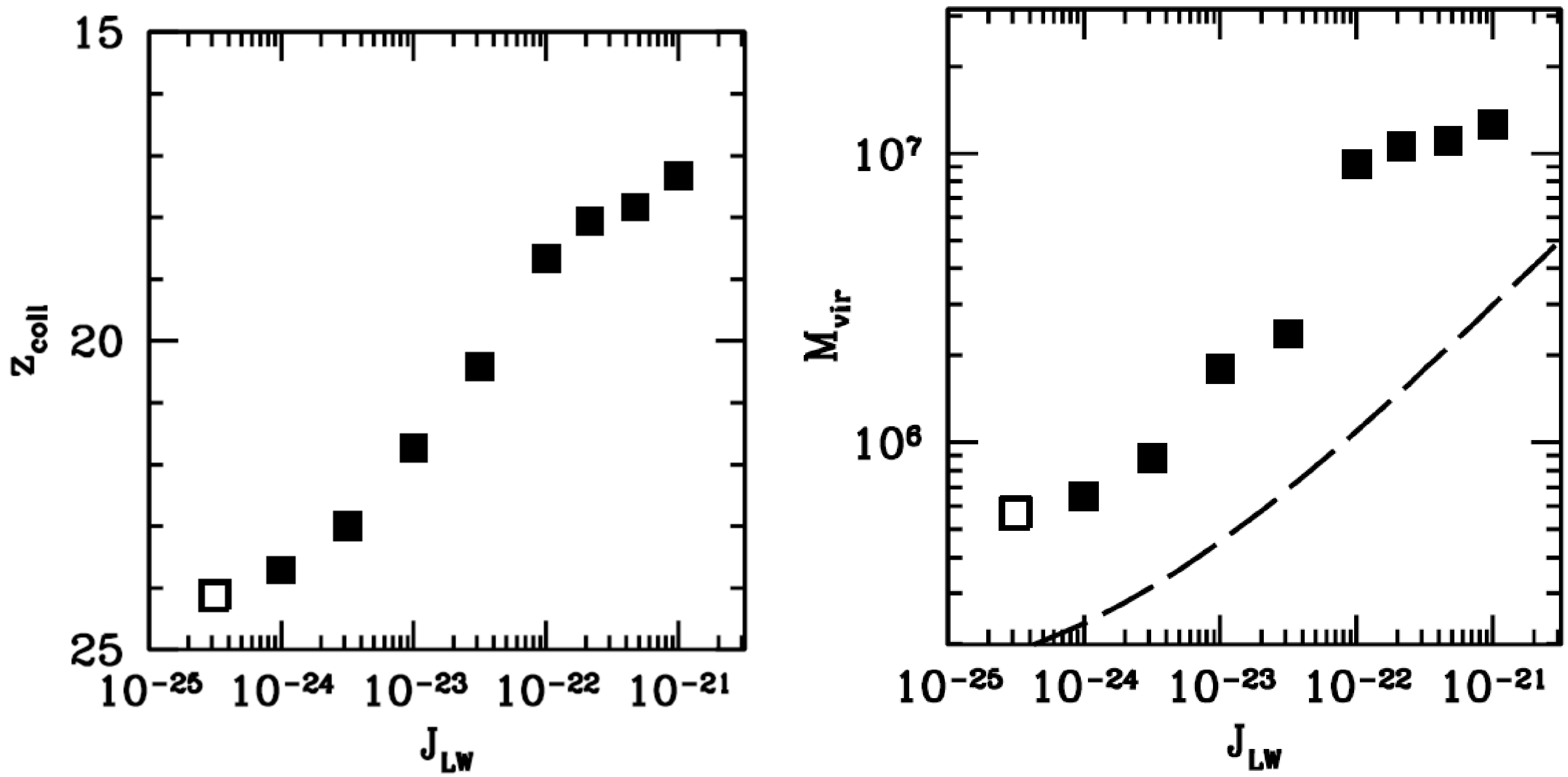
Los Alamos
NATIONAL LABORATORY
EST. 1943

Effect of a soft UV background

- Photodissociation region around a Pop III star is much larger than the HII region (see Whalen et al., astro-ph/0708.1603 [up tomorrow] for more information)
- Takes relatively few stars to build up a far-UV background which suppresses H_2 formation
- Most Pop III stars will form in the presence of some sort of radiation background ("Pop III.2 stars")
- How does the destruction of H_2 affect properties of primordial stars?
- See O'Shea & Norman 2007, ApJ accepted (astro-ph/0706.4416)

Los Alamos
NATIONAL LABORATORY
EST. 1943

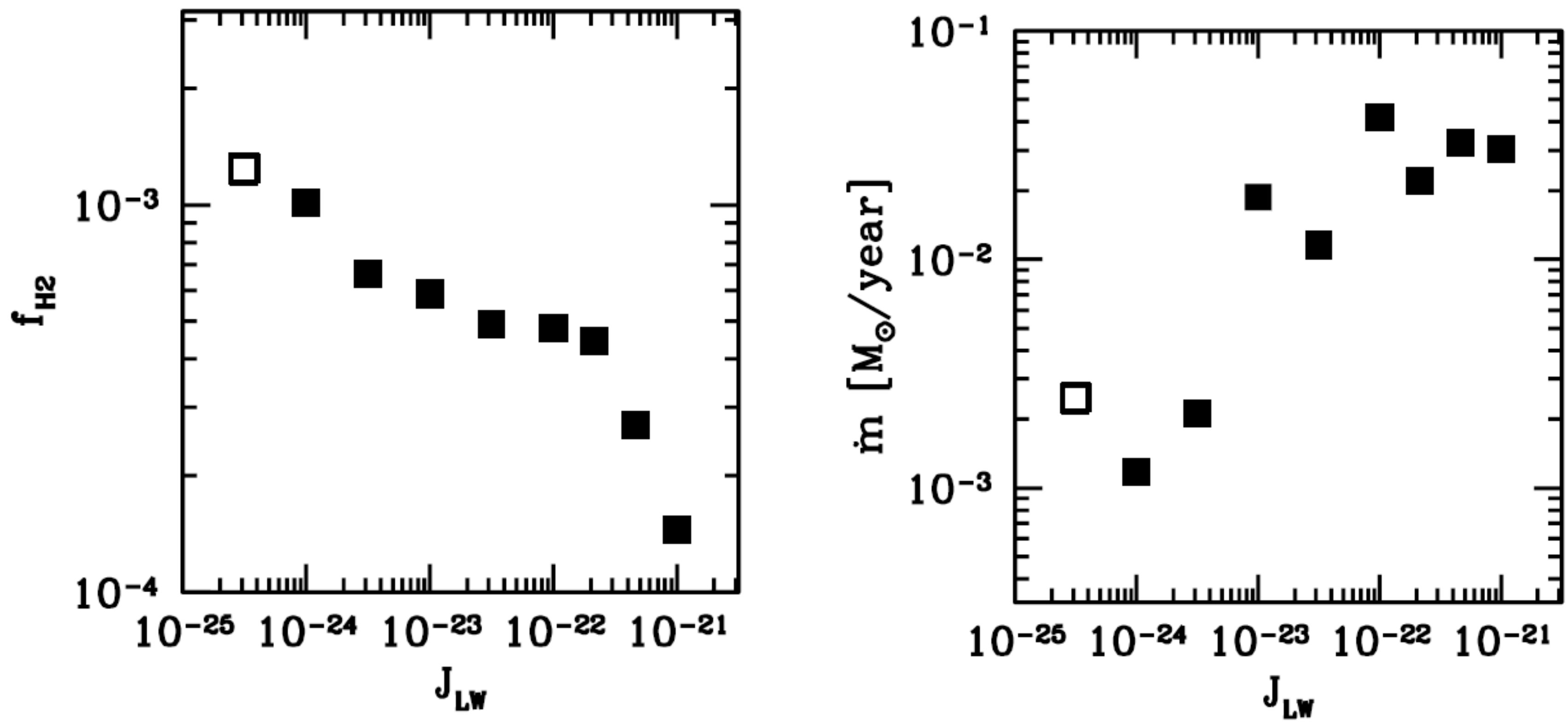
Effect of a soft UV background



O'Shea & Norman 2007, ApJ accepted (astro-ph/0706.4416)

Los Alamos NATIONAL LABORATORY EST. 1943

Effect of a soft UV background



O'Shea & Norman 2007, ApJ accepted (astro-ph/0706.4416)

Effects of Pop III HII regions on neighboring halos

- Use ZEUS-MP 2.1w/photon-conserving, multifrequency rad'n transport algorithm (400 groups, based on Whalen & Norman 2006 scheme) coupled directly to 9-species nonequilibrium chemistry (species include H, H_2, He, but no D)
- Halo properties taken from O'Shea & Norman 2006: single halo at a range of evolutionary states (central densities)
- I-front from 120 M_{sun} star propagates in along z-axis, $T_{sim} = 2\,T_{ms}$ (radiation source turns off halfway through simulation)
- Examine how this effects chemodynamical evolution of halo
- See Whalen, O'Shea, Smidt & Norman, ApJ submitted (astro-ph/0708.1603)

Los Alamos
NATIONAL LABORATORY
EST. 1943

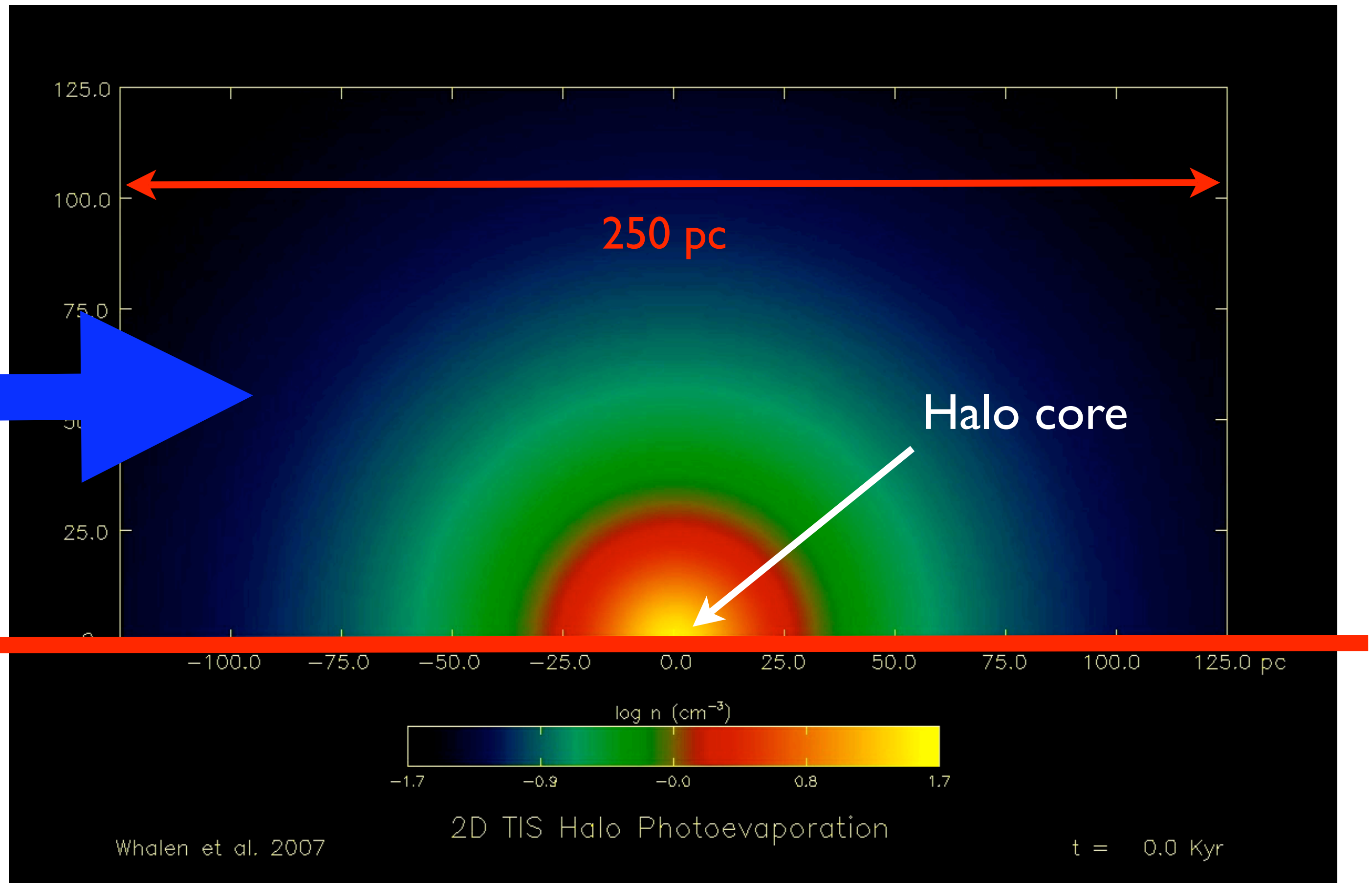
Simulation ICs and setup

2D, cylindrical (r,z) symmetry

Gas in hydrostatic equilibrium

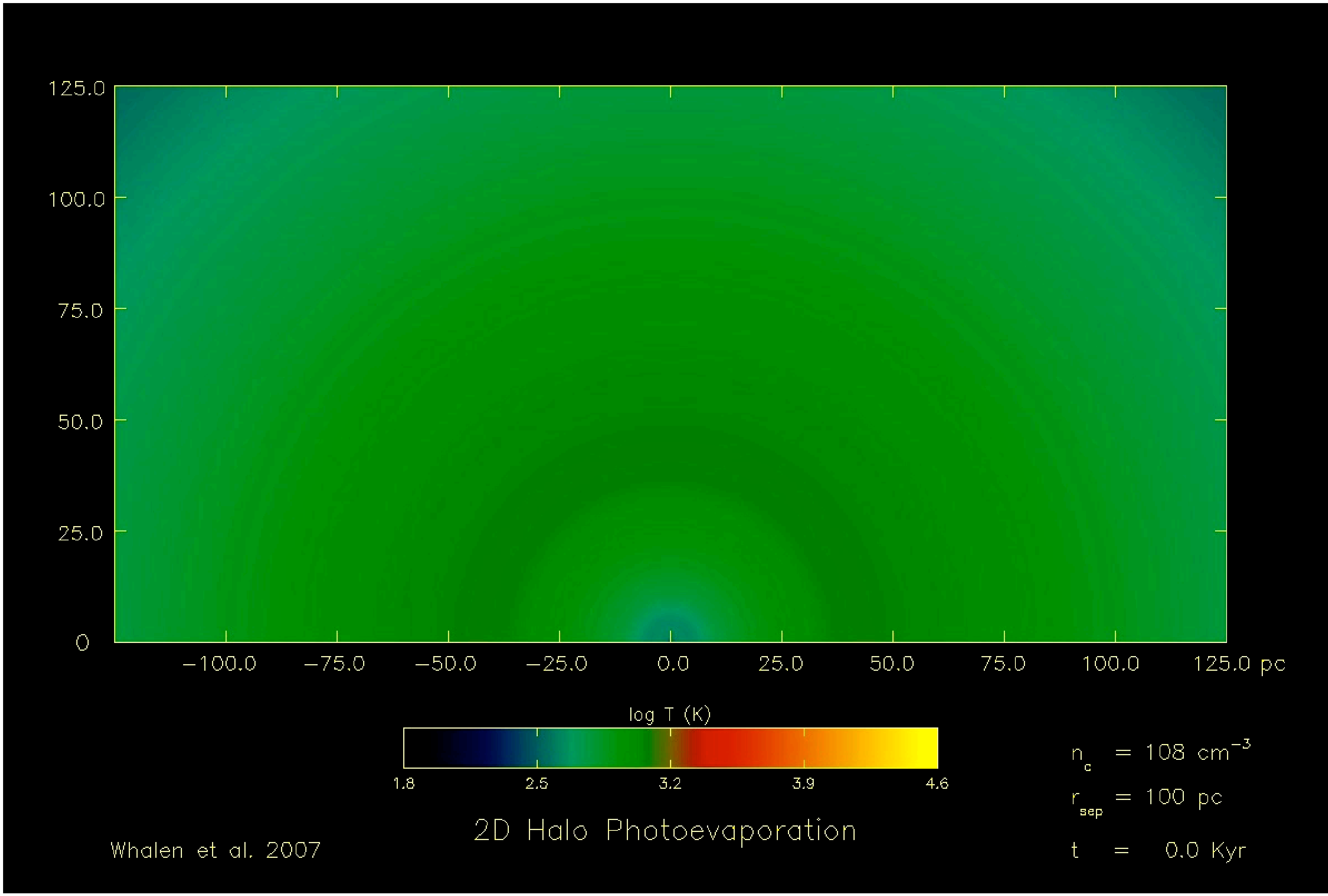
I-front propagates in from left to right:
$M_{*} = 120\ M_{sun}$
$T_{eff} = 10^5$ K

Axis of symmetry (z-axis)

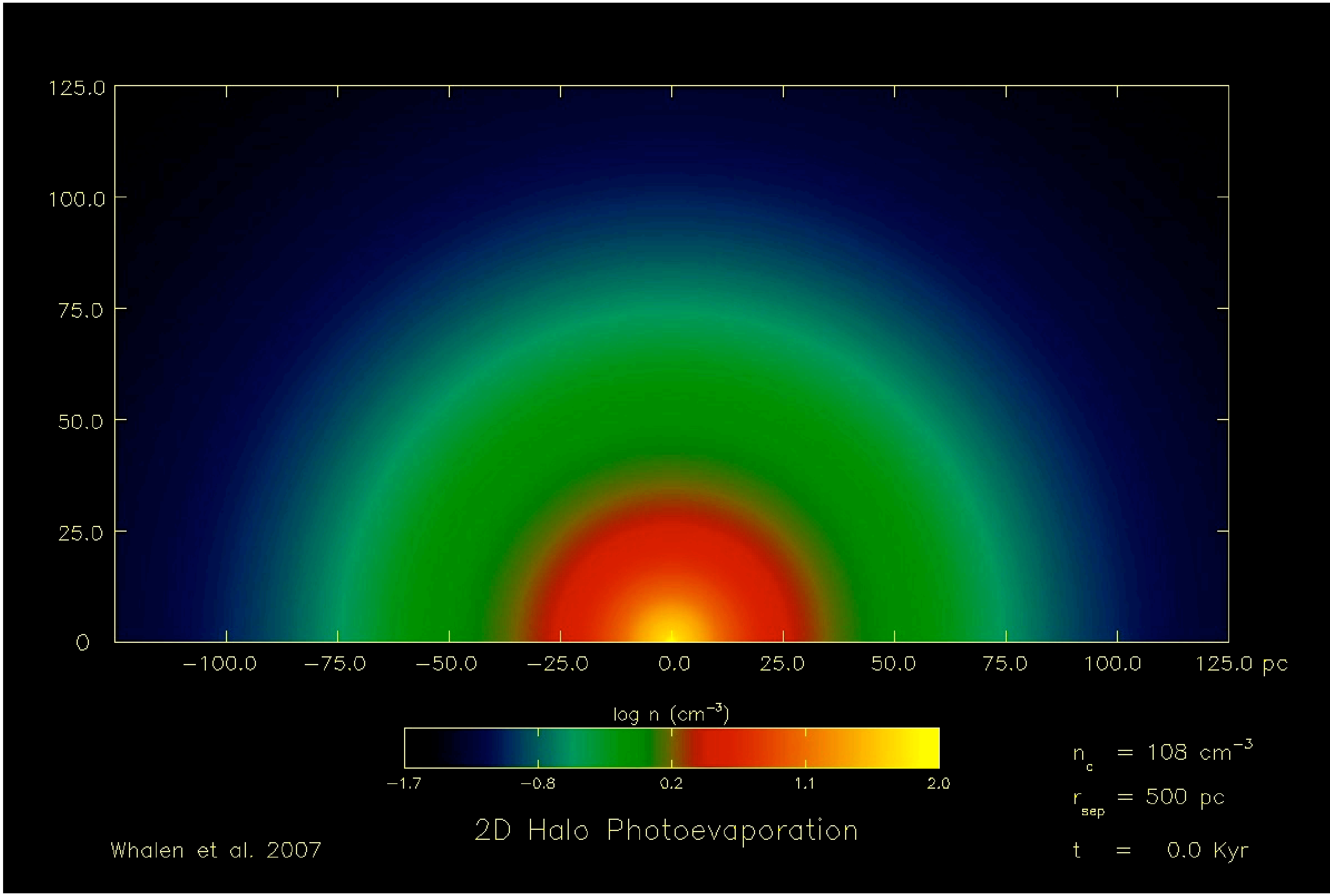


Los Alamos NATIONAL LABORATORY EST.1943

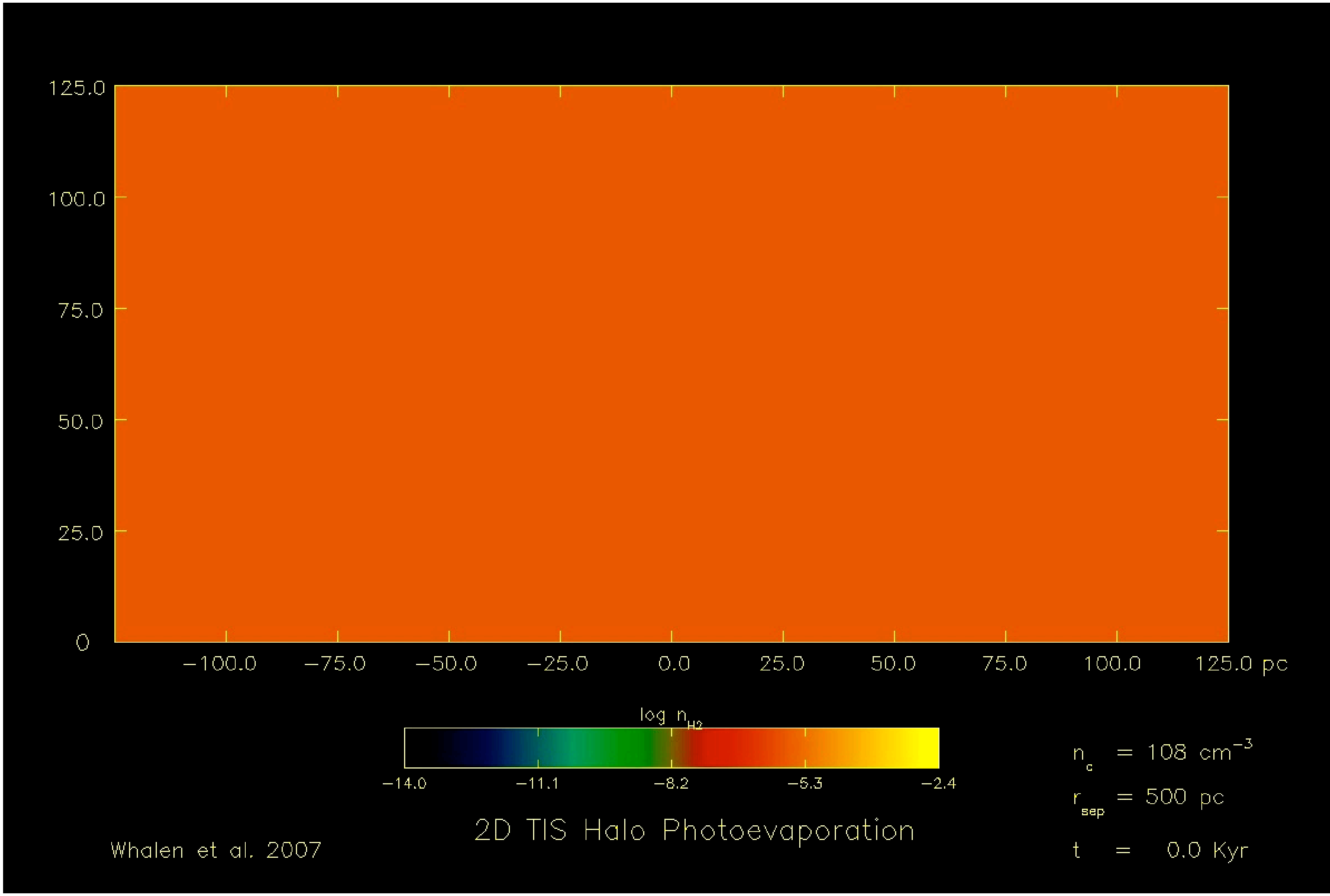
Net positive effect on SF



Net positive effect on SF



Net positive effect on SF



Metal enrichment from Pop III supernovae

- Choose representative Population III star formation simulation from O'Shea & Norman 2006
- Assume $M_* = 30\ M_\odot$, $E_{SN} = 10^{51}$ ergs, $M_z = 10\ M_\odot$
- Put in Sedov blast model w/ $R_{Sedov} = 0.5$ pc
- Evolve until metal-enriched gas collects in a next generation halo
- O'Shea, Norman & Whalen 2007, ApJ, in prep (October)

Los Alamos
NATIONAL LABORATORY
EST. 1943

Population III Supernovae

- A crude estimate of relative energies:

  E_{bind} (M_{halo} ~ 5 x 10^5 $M_\odot$) ~ $10^{50}/10^{49}$ ergs ttl/gas

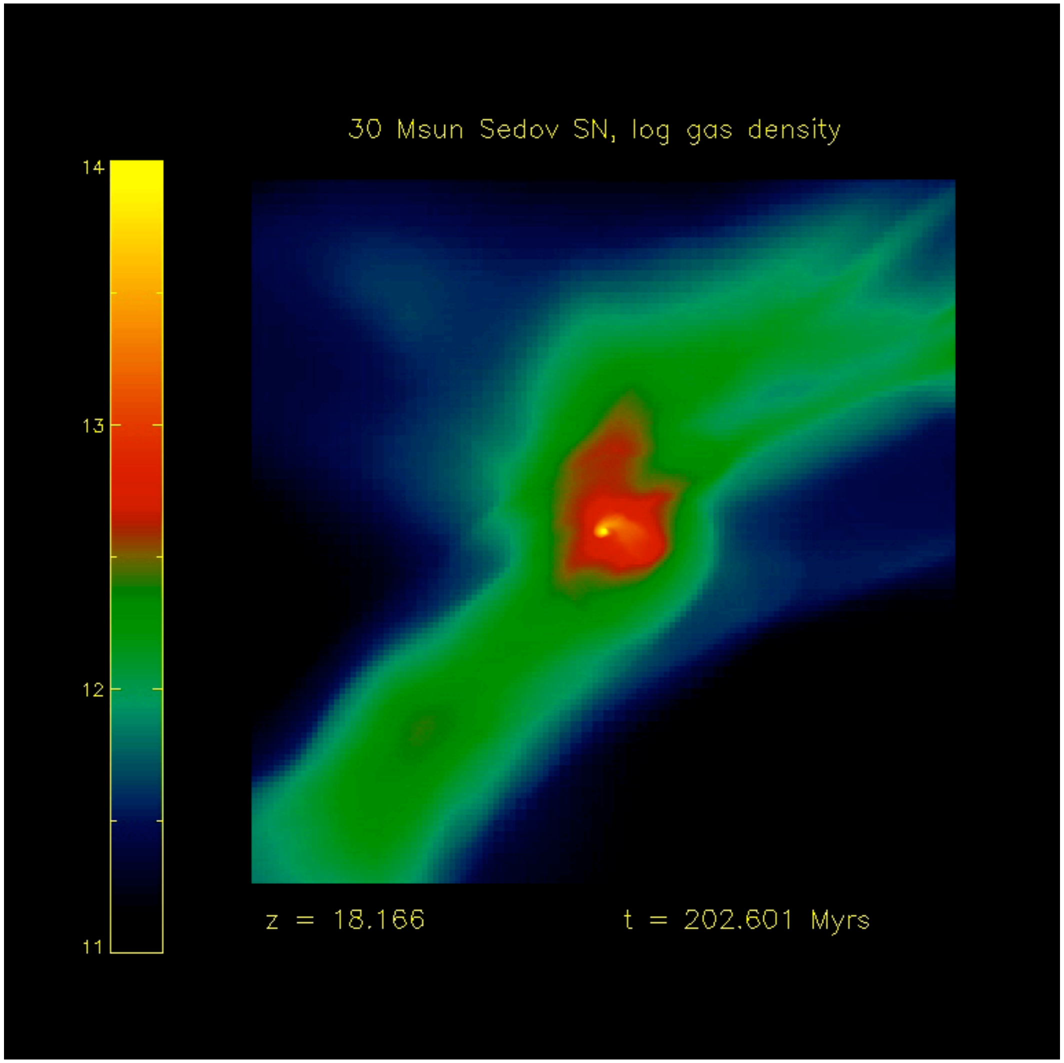
  E_{SN} (M_{PopIII} ~ 30 $M_\odot$) ~ 10^{51} ergs

  E_{SN} (M_{PopIII} ~ 250 $M_\odot$) ~ PISN: 10^{53} ergs >> E_{bind}!

- Population III supernovae may completely disrupt their parent halos! (metal propelled to large distances)

- Population III stars: nucleosynthetic signatures in second-generation stars?

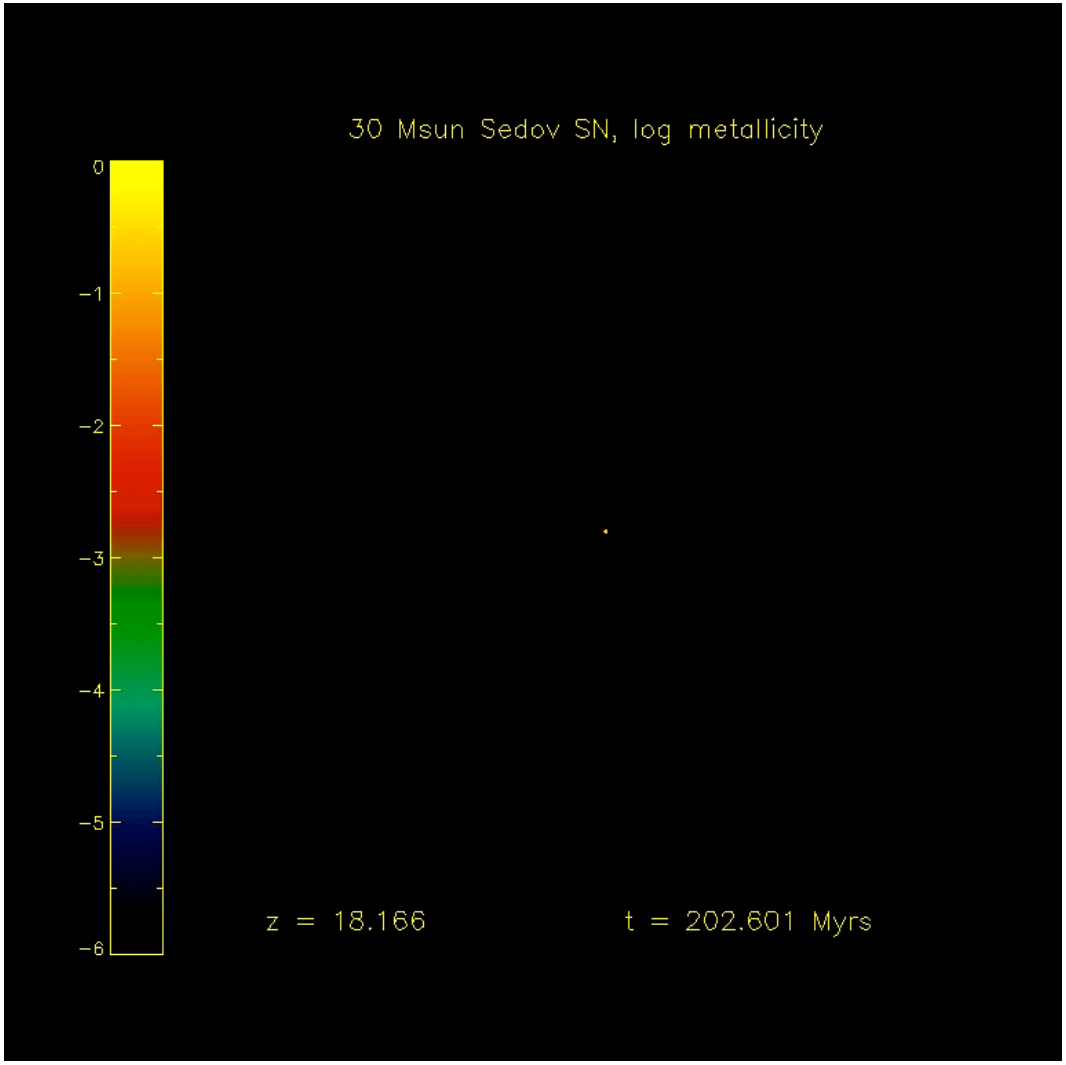
Projected log baryon density



~350 pc (proper)

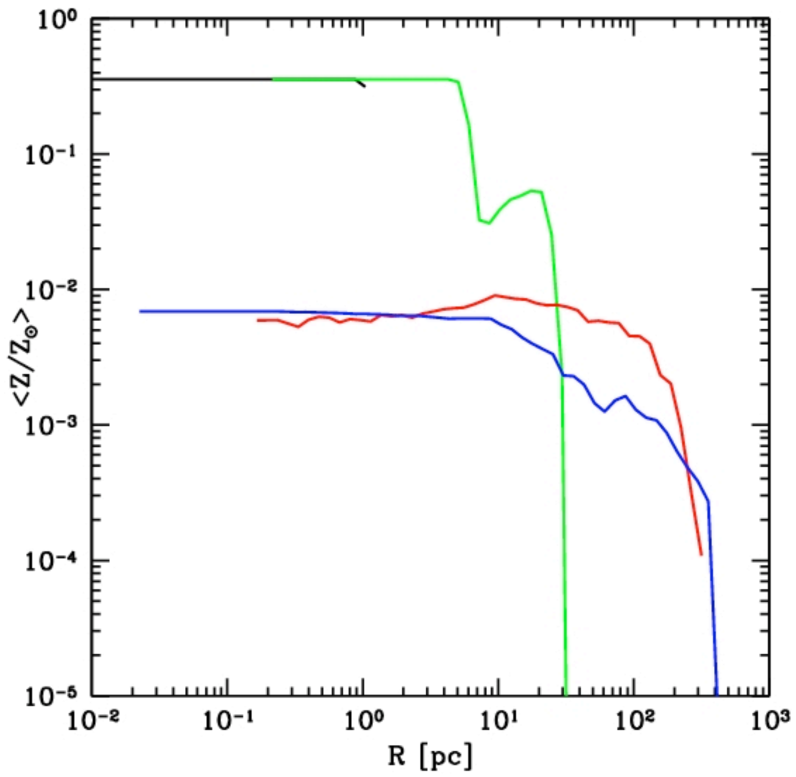
Los Alamos
NATIONAL LABORATORY
EST.1943

Projected log metallicity



~350 pc (proper)

Supernova remnant evolution: metallicity



$t = t_{SN}$

$t = t_{SN} + 4 \times 10^5$ yrs

$t = t_{SN} + 3 \times 10^7$ yrs

$t = t_{SN} + 7 \times 10^7$ yrs

Final polluted gas mass is $\sim 2 \times 10^5\, M_\odot$, $\langle Z \rangle \simeq 0.003\, Z_\odot$

Part III: conclusions

- Photodissociating UV background delays halo collapse, increases accretion rate onto primordial protostellar core
- HII regions from Pop III stars can have positive or negative effects: increase the amount of H_2 in nearby halos by increasing the e- fraction or completely disrupt halo
- Population III supernovae can eject metals out to a significant distance from the parent halo (a few hundred proper pc for a 30 M_{sun} SN) and enrich ~few x 10^5 M_{sun} of gas
- Gas is enriched by this supernova to a wide range of metallicities, but always higher than the Bromm & Loeb "critical" metallicity

Overall conclusions

- The mass scales related to the formation of Pop III stars and their accretion rates are fundamentally regulated by H_2 chemistry
- Accretion rates onto Pop III protostars evolves strongly with redshift: wider range of stellar masses?
- The presence of a strong UV background (photodissociating or photoionizing) can strongly affect halo evolution
  - LW background delays collapse and increase protostellar accretion rates
  - HII regions cause chemical and dynamical changes - direction of feedback depends strongly on secondary halo state and distance
- Pop III stars can rapidly enrich their surroundings to above the "critical" metallicity - rapid change from Pop III to galactic IMF?

Los Alamos
NATIONAL LABORATORY
EST. 1943

Extra slides

Why only one Pop III star per halo?

- Shallow DM potential drives cold gas to center: cooling flow rather than standard "molecular cloud"
- Cooling time > Dynamical time (quasistatic contraction) for most of the evolution
- Inefficient H_2 cooling ➔ pressure smoothing of density perturbations
- $3H \rightarrow H_2$ doesn't lead to fragmentation (poor cooling, no independent Jeans unstable fragments)
- Feedback from first star destroys H_2; star formation immediately "quenched" in the halo

See Ripamonti & Abel (2004)

The varied fates of Population III Stars

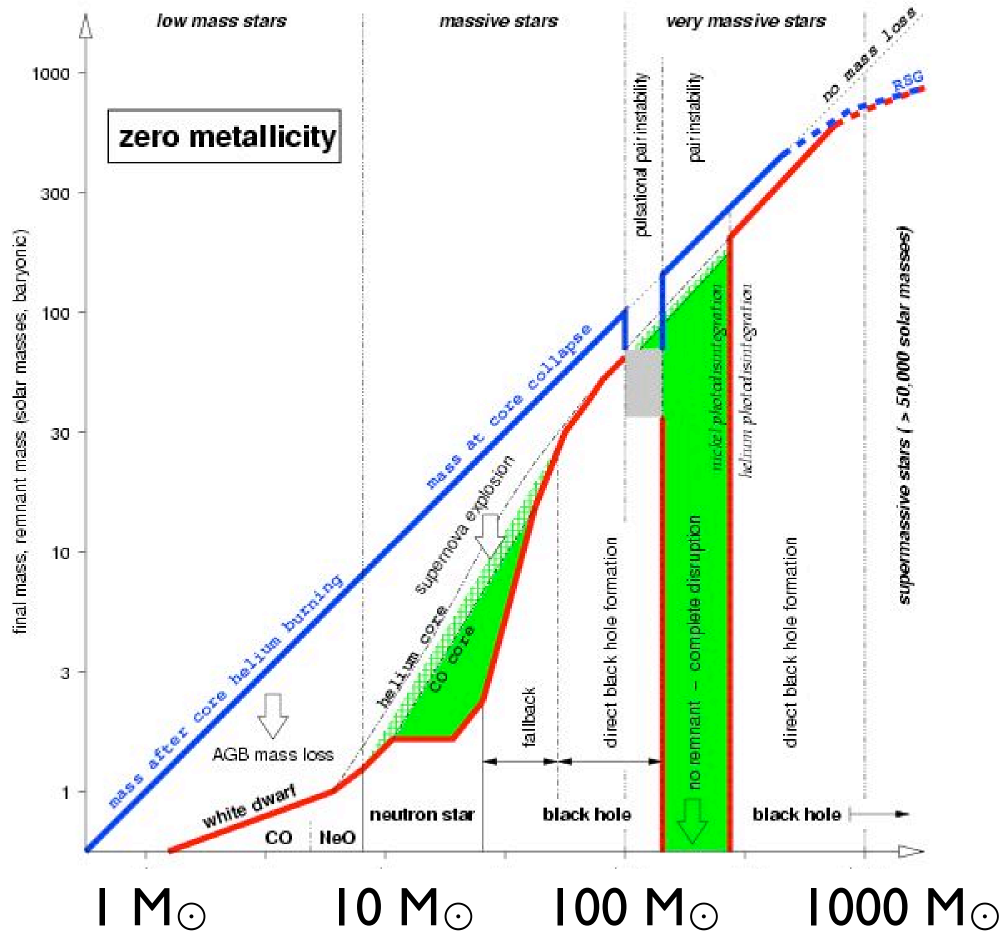
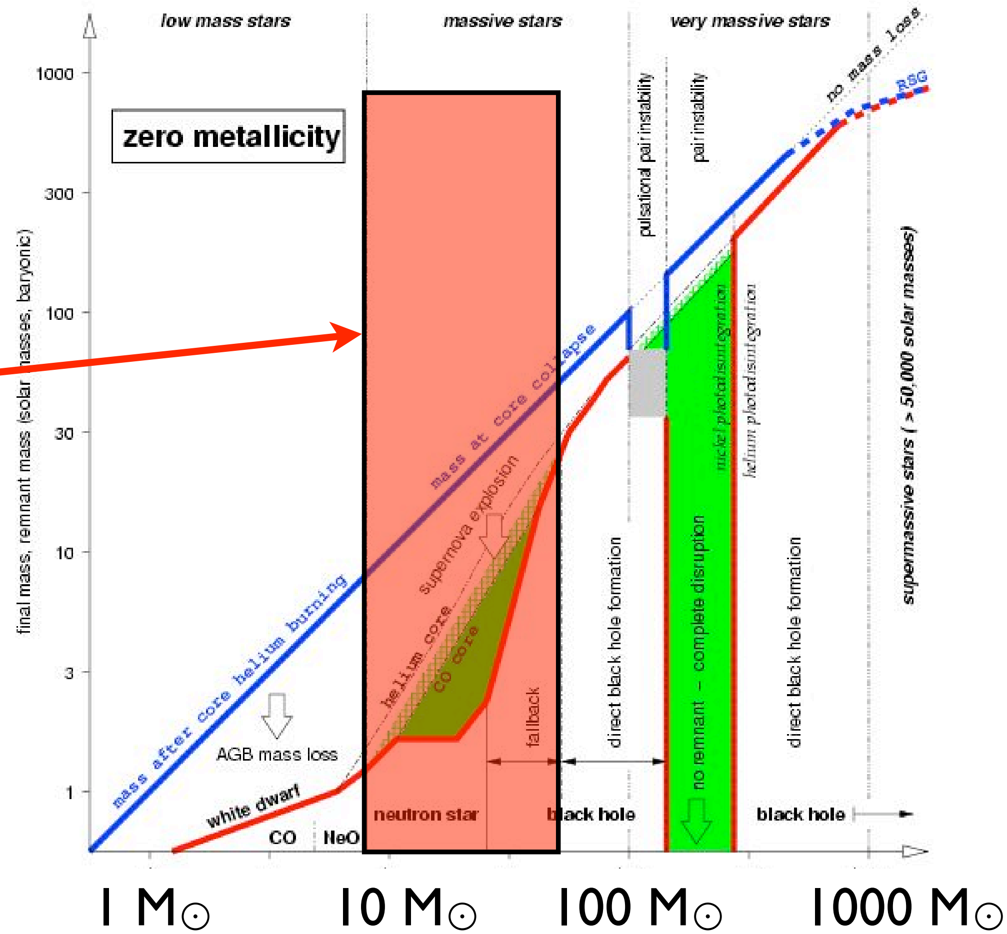


Image courtesy Alex Heger

The varied fates of Population III Stars

Type II SNae

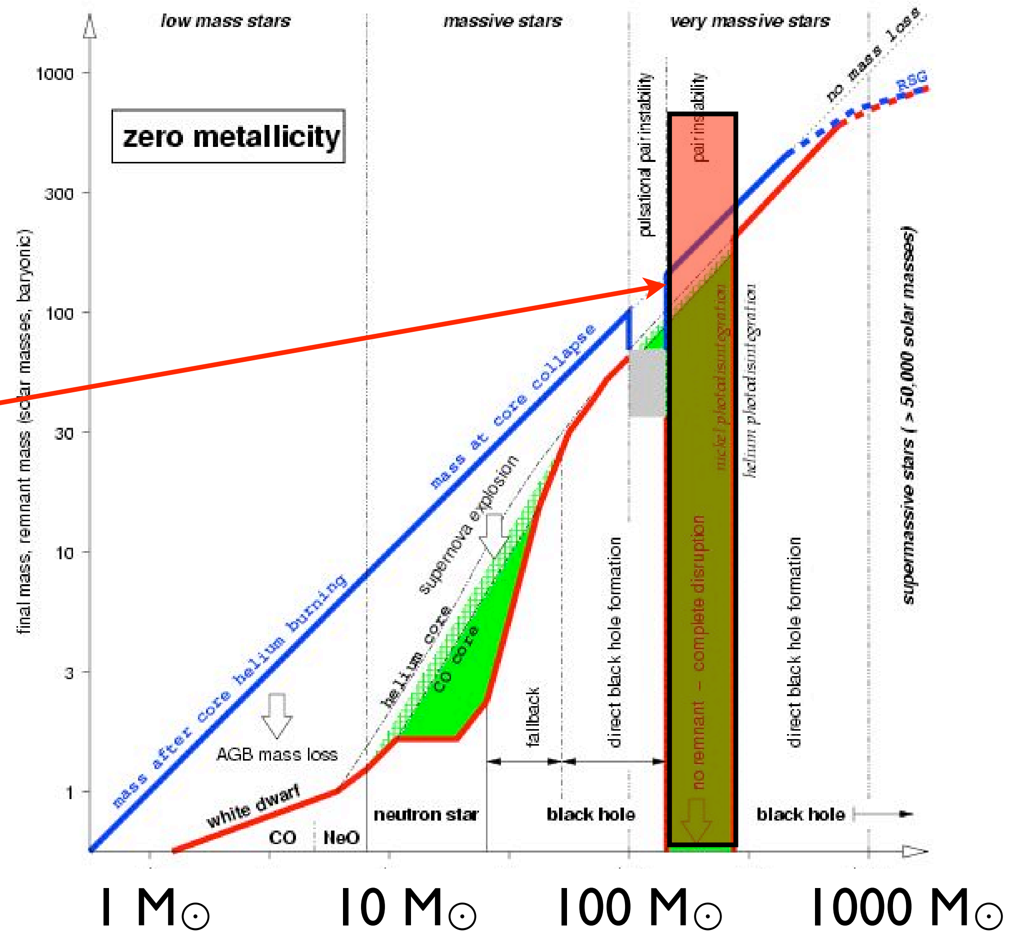


Type II
$E_{SN} \sim 10^{51}$ ergs

Image courtesy Alex Heger

The varied fates of Population III Stars

Pair instability supernovae (PISN)



PISN
$E_{SN} \sim 10^{52}$ - 10^{53} ergs

Image courtesy Alex Heger

The varied fates of Population III Stars

No supernova: direct collapse to black hole!

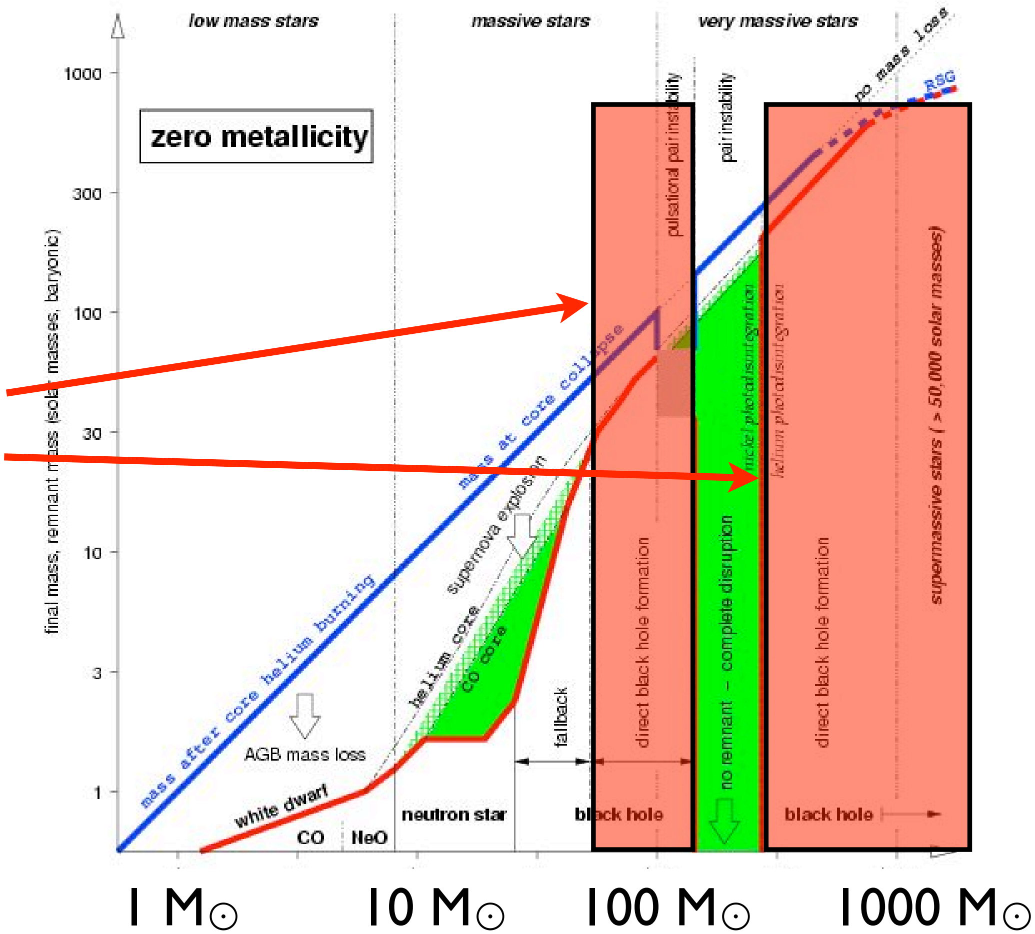


Image courtesy Alex Heger