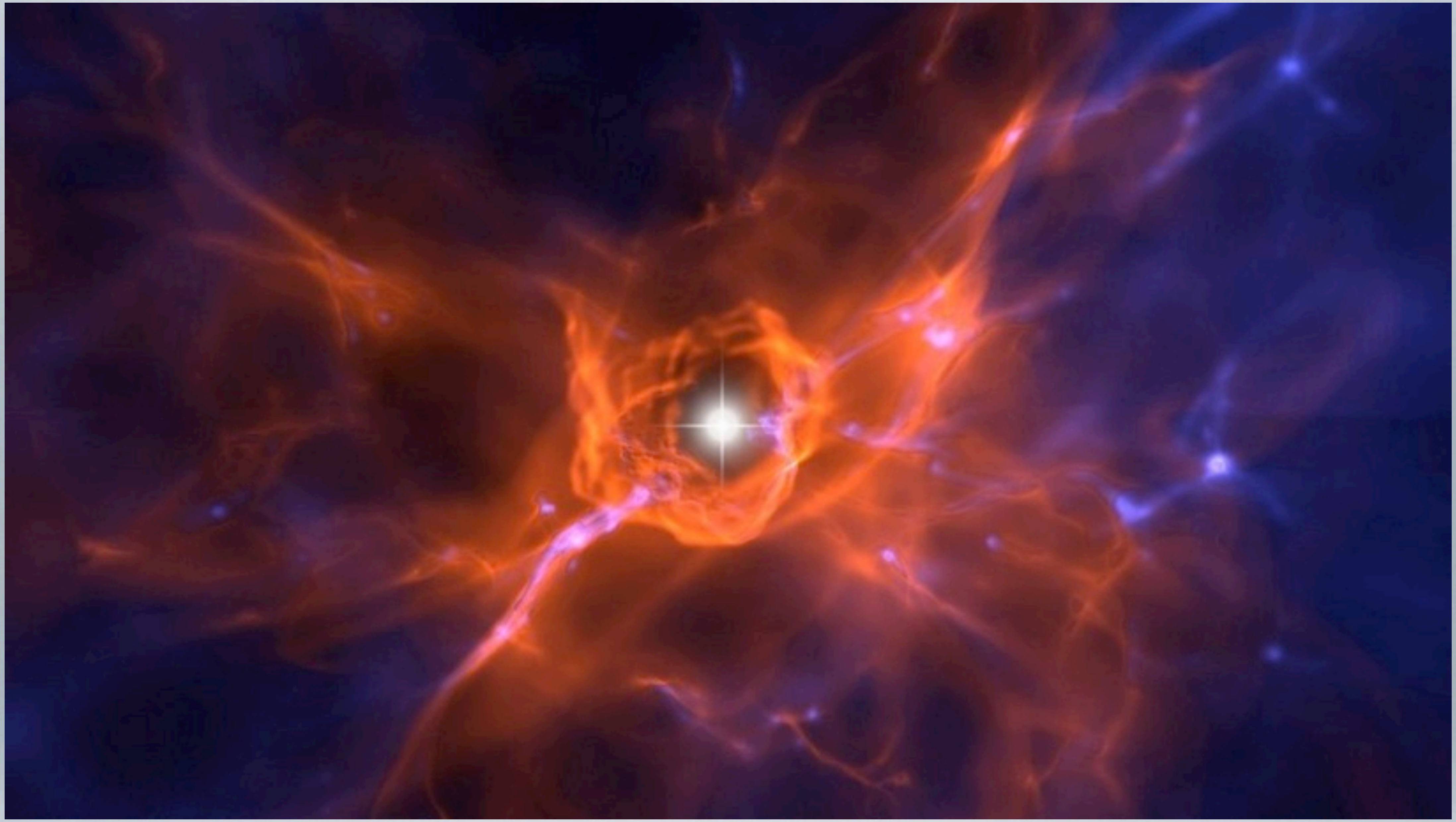
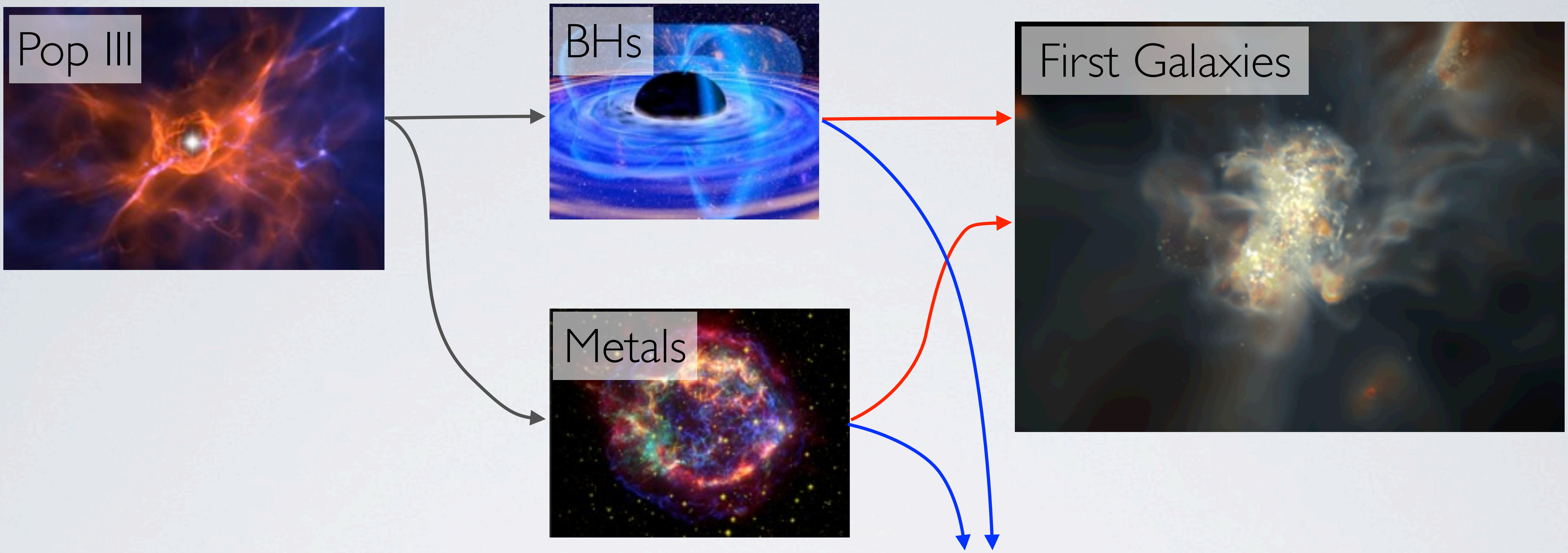


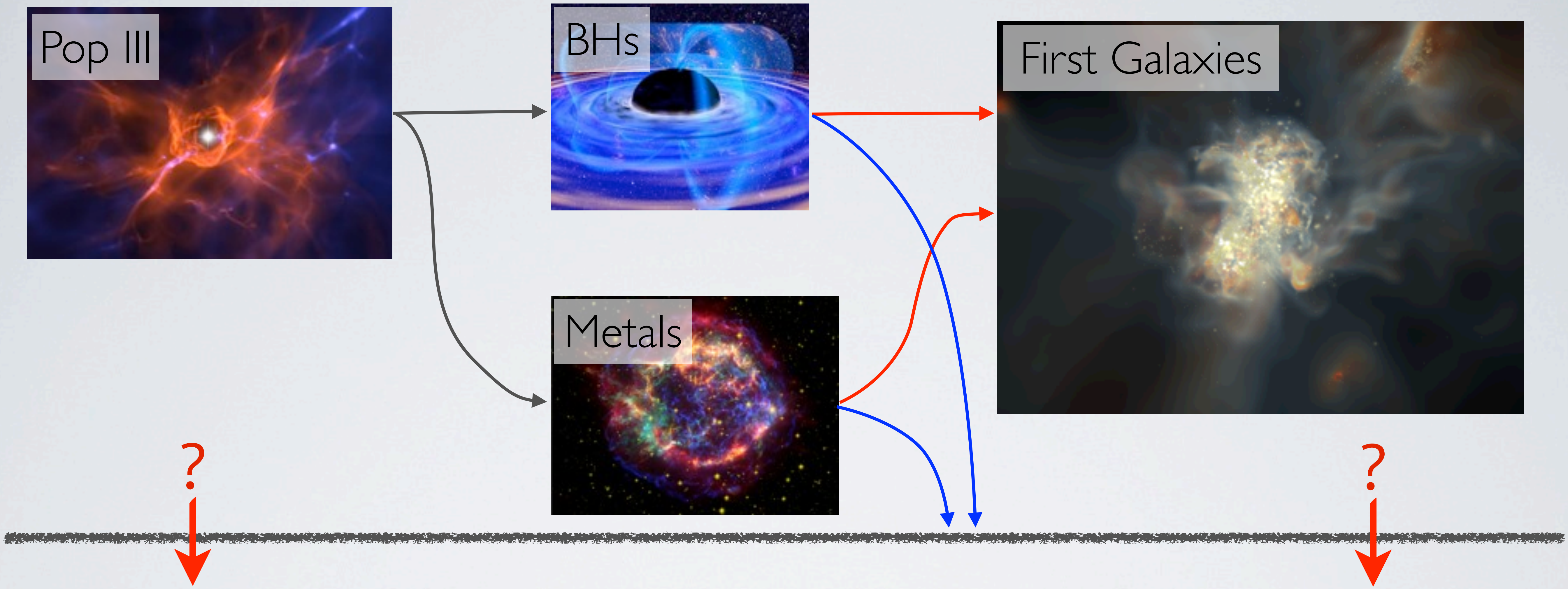
THE BIRTH OF A GALAXY

John Wise (Princeton)
Collaborators: Tom Abel (Stanford), Matthew Turk & Michael Norman (UCSD)

MOTIVATION



MOTIVATION



MOTIVATION

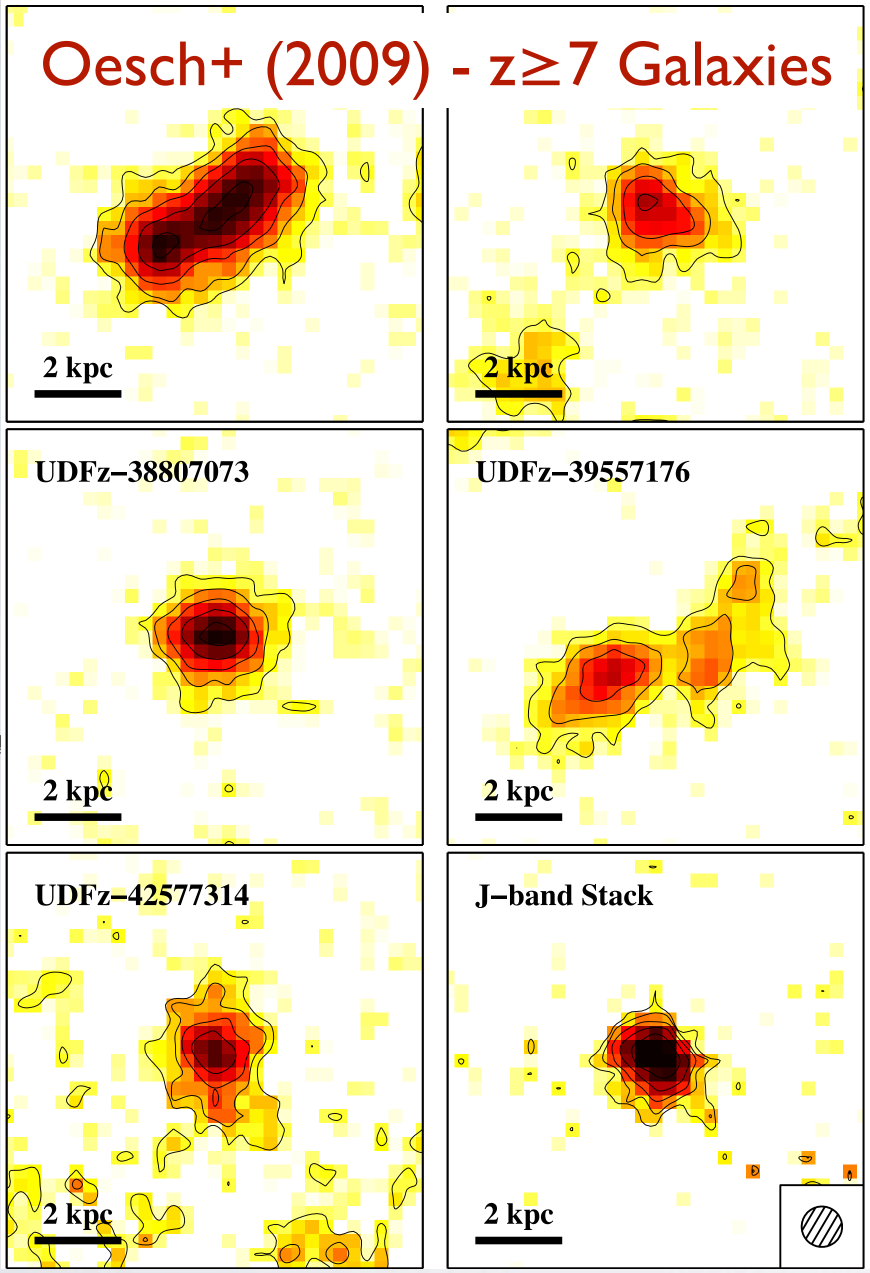
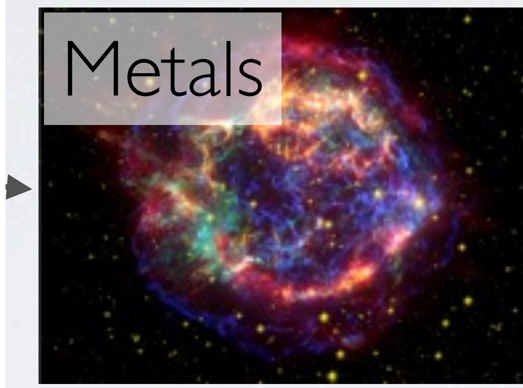
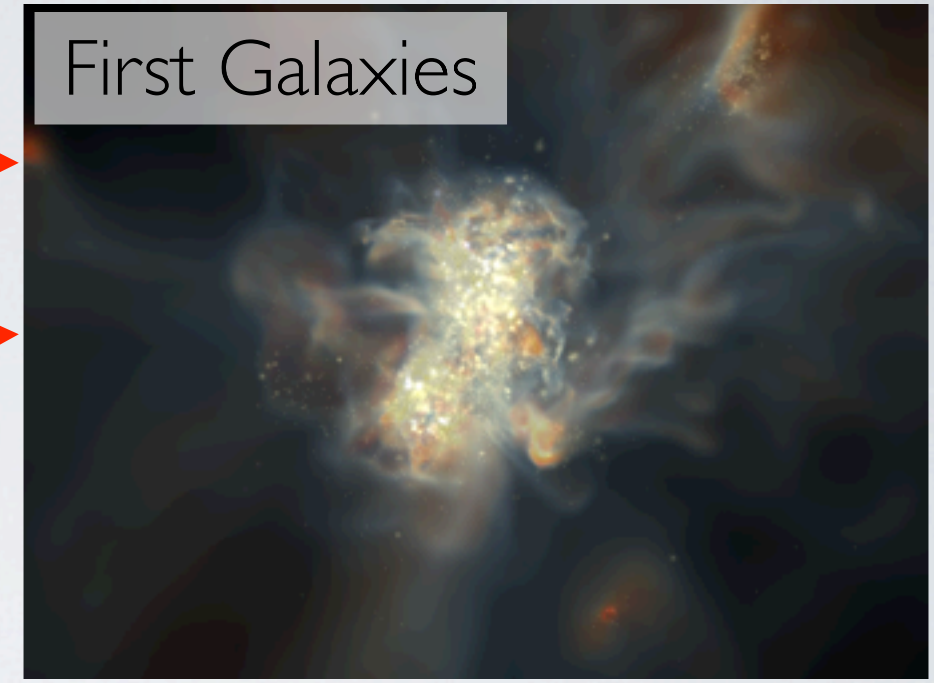


FIG. 1.— Surface brightness contours of the five brightest galaxies in our sample and of a J_{125} stack of the remaining 11 fainter galaxies (last panel in lower right). The first five images are superpositions of Y_{105}, J_{125}, and H_{160} exposures, with the contour lines corresponding to $\mu_{\rm YJH} = 23.5 - 25.5$ mag/arcsec^2 in steps of 0.5 mag/arcsec^2. The bar in the left corner indicates 2 kpc (physical) at $z = 6.8$ the expected mean redshift of these galaxies. All images are $1''\!.8$ on a side. The size (FWHM) of the J_{125} PSF is shown as an inset in the lower right panel for comparison.





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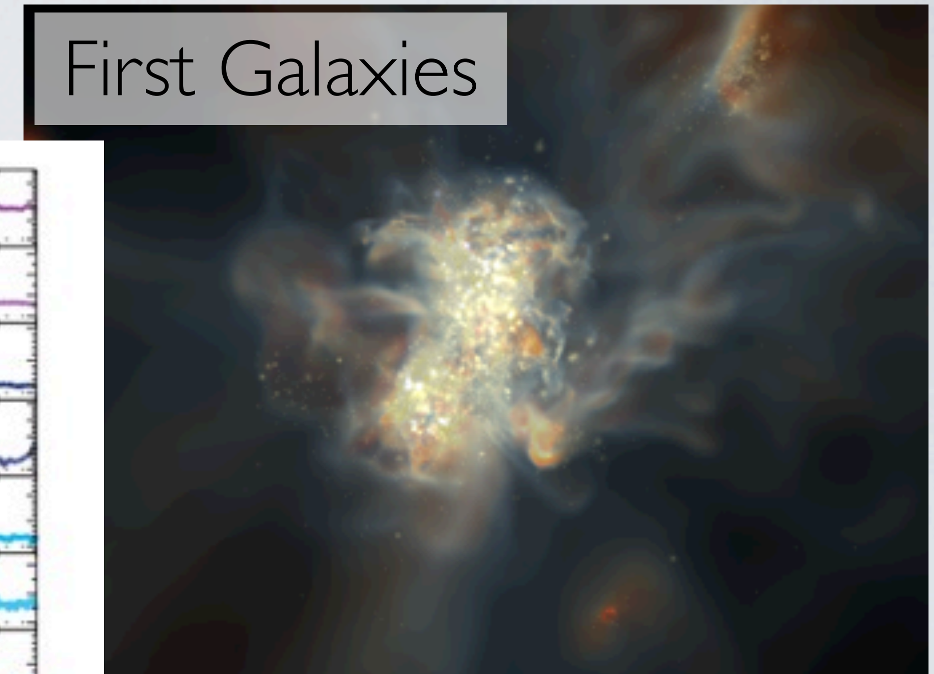
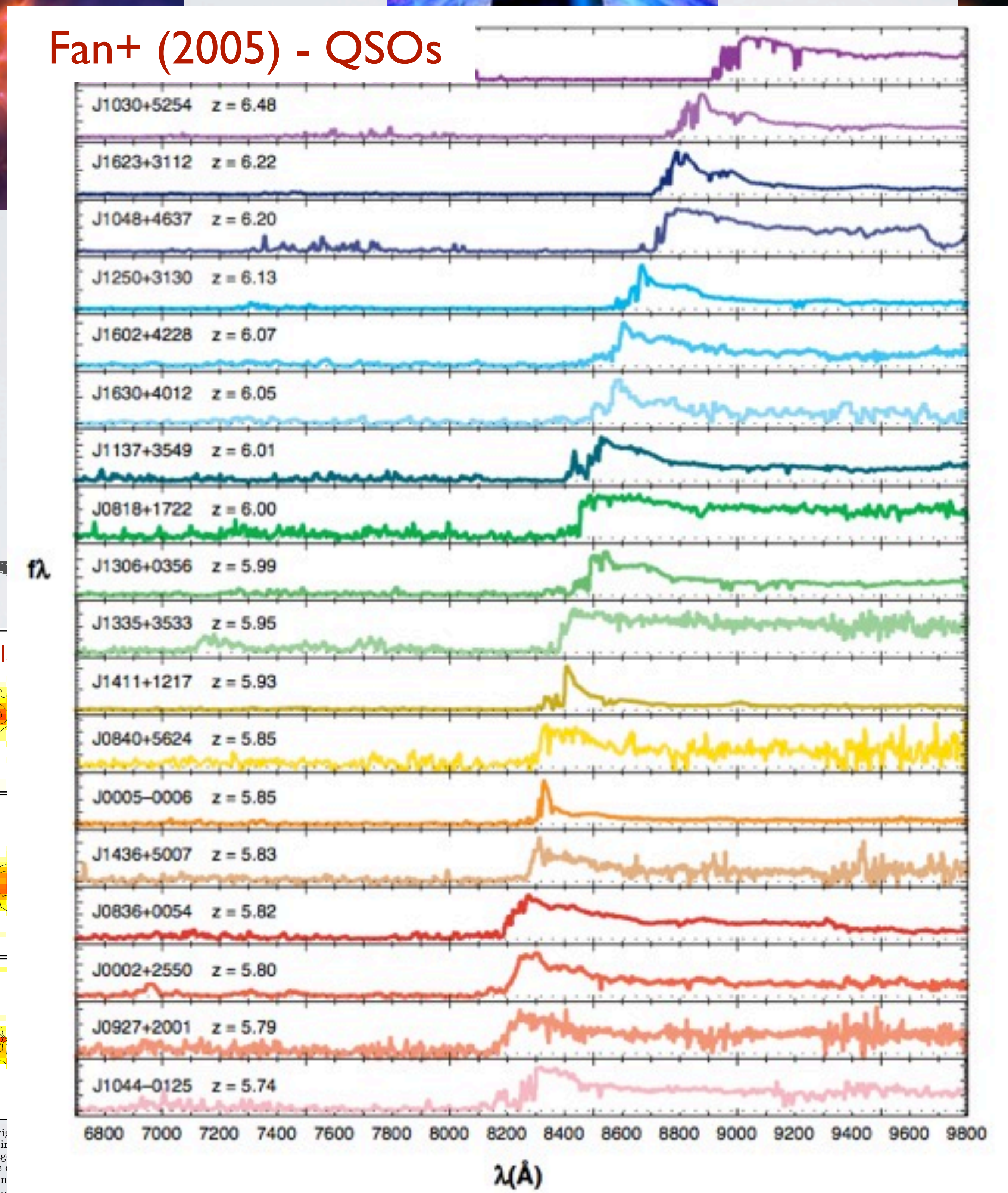
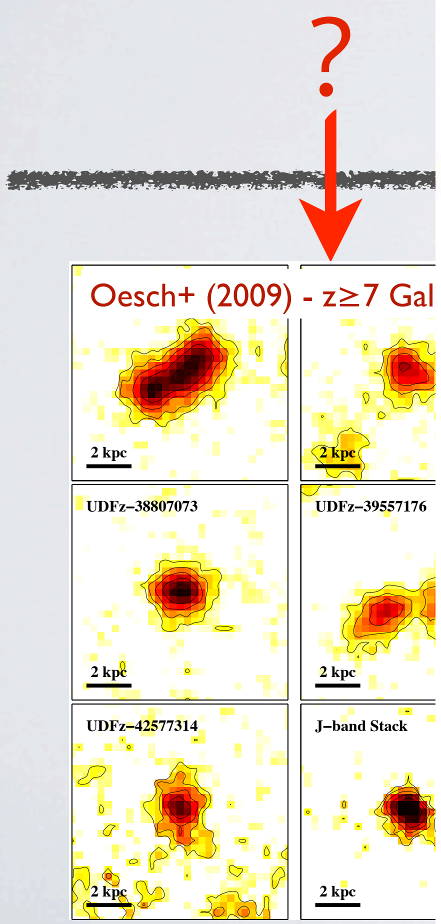
MOTIVATION







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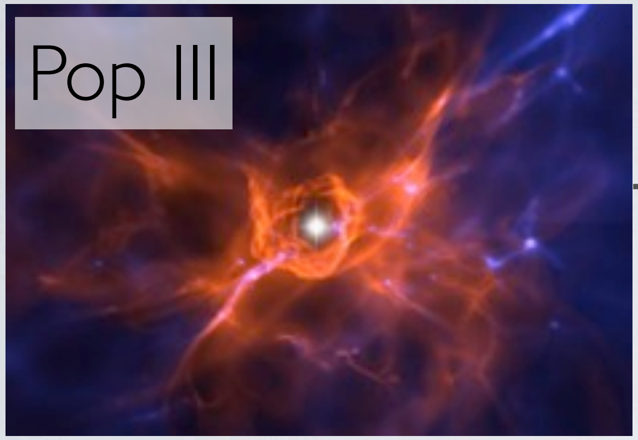
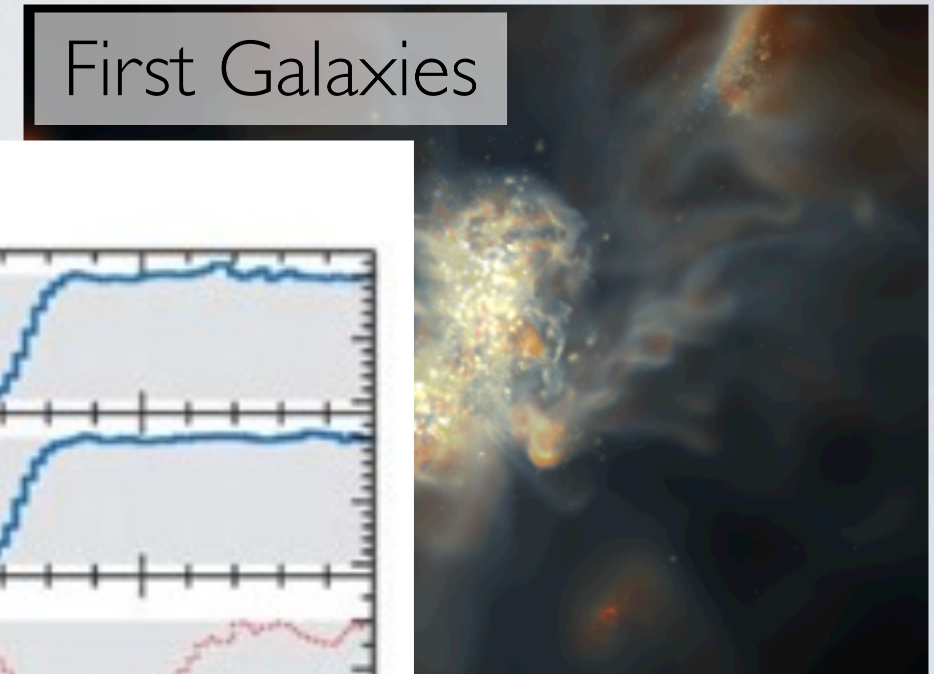
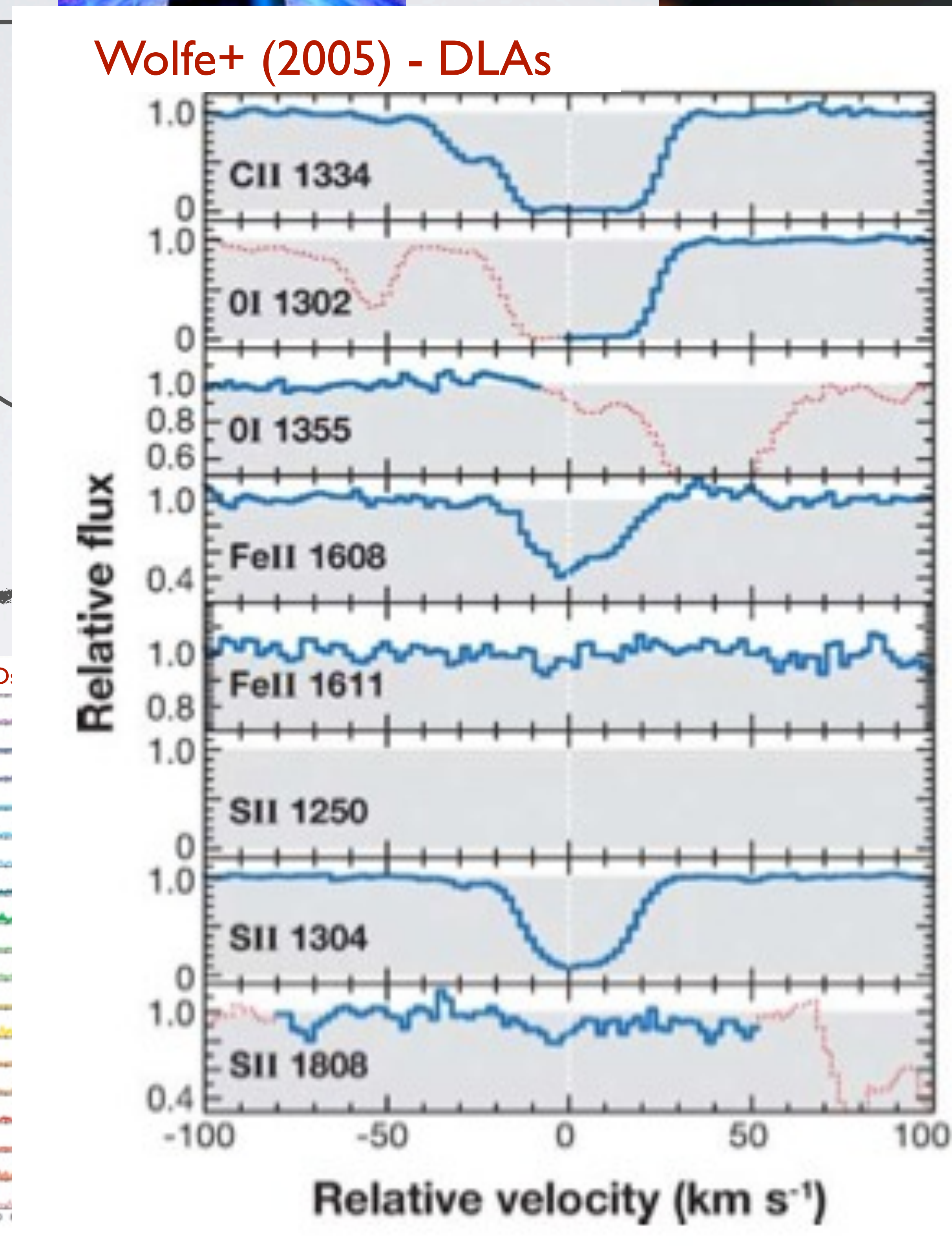
MOTIVATION







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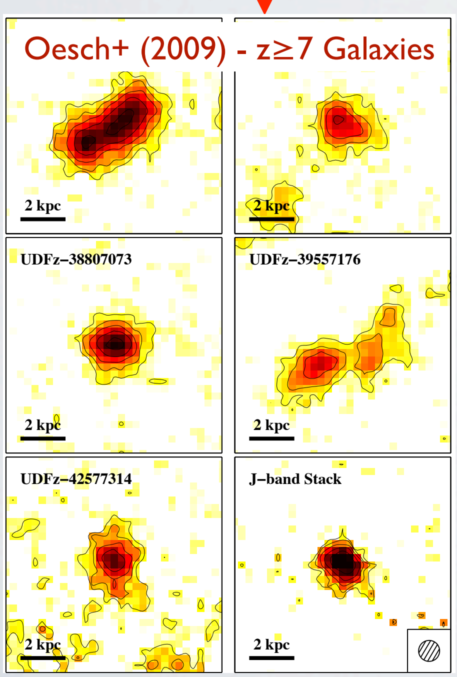

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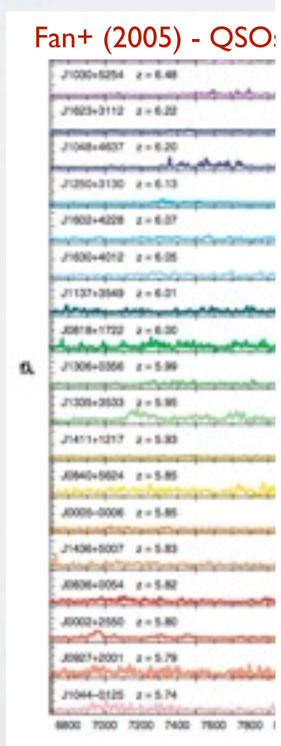
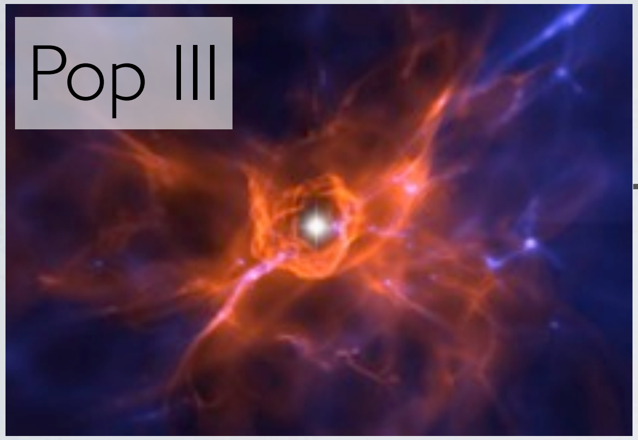
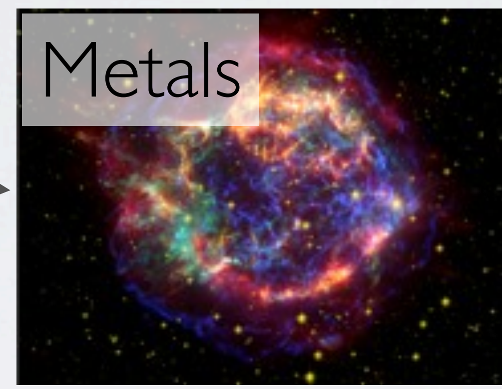
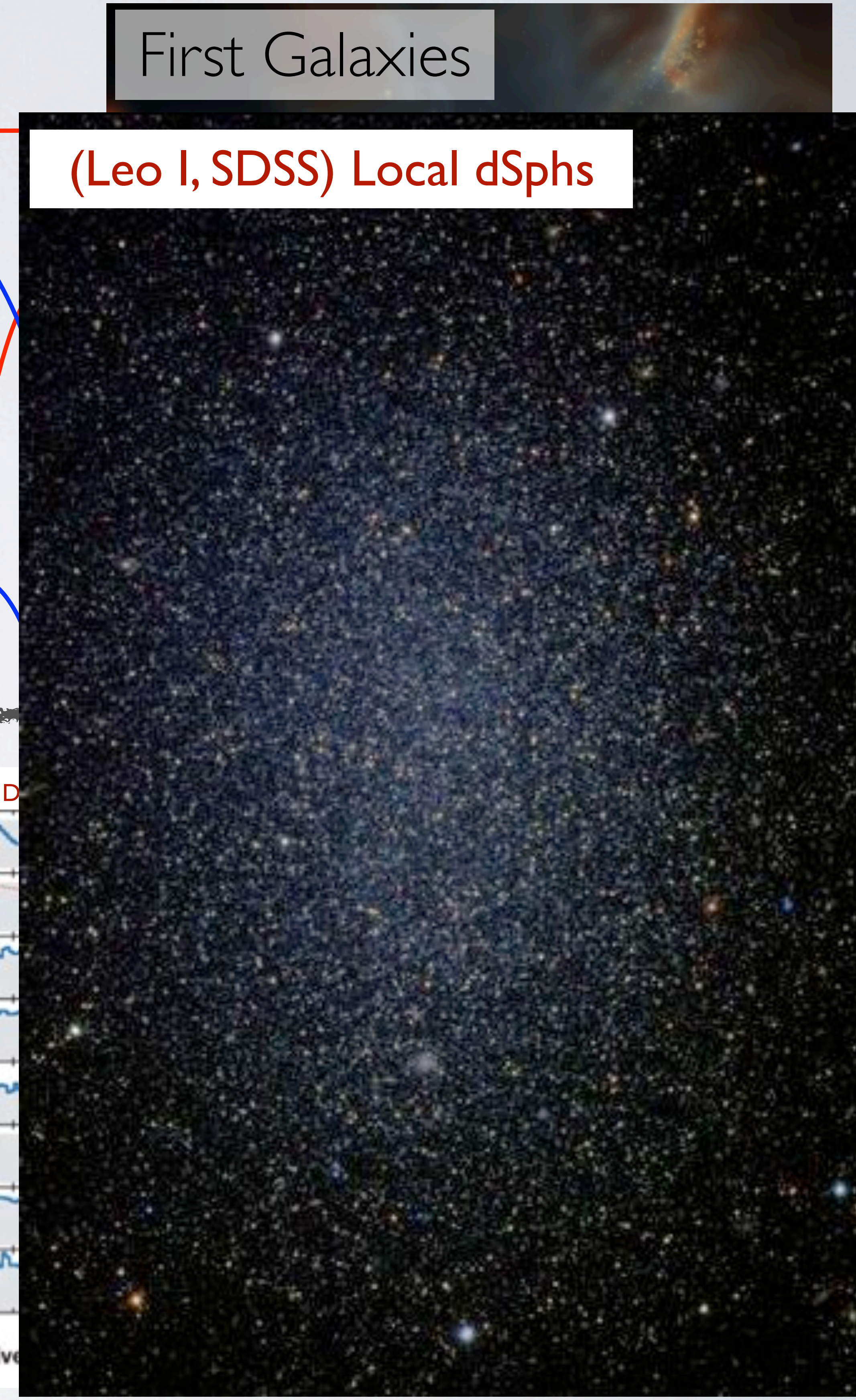


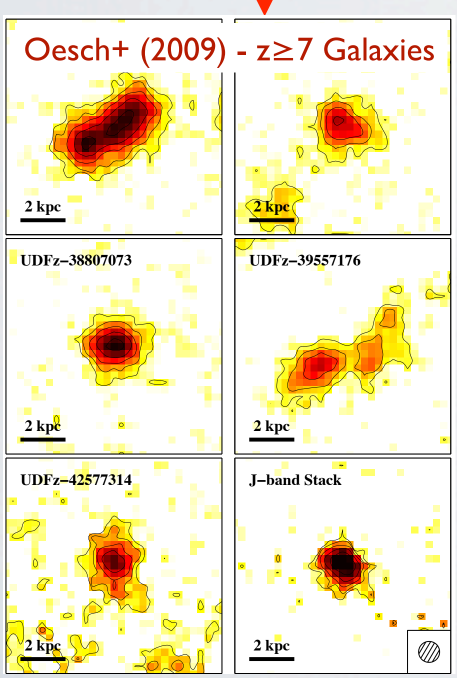
MOTIVATION







?



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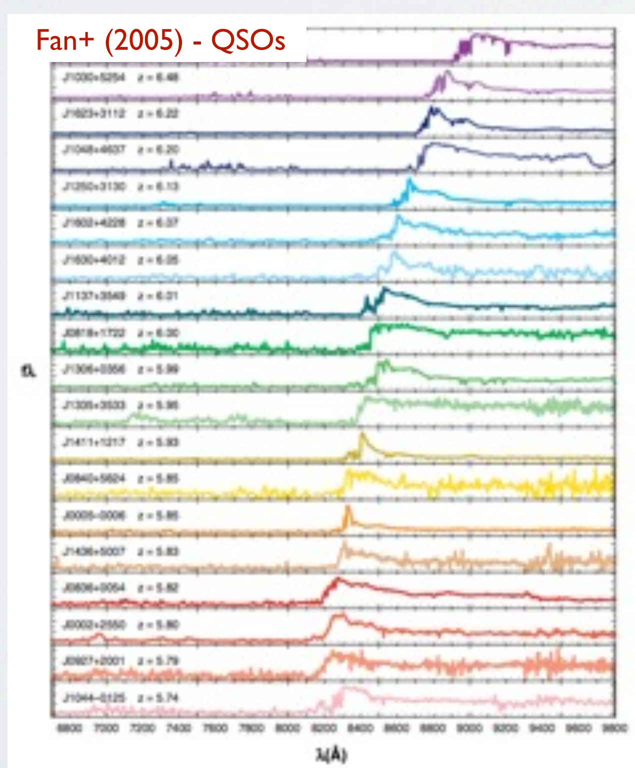
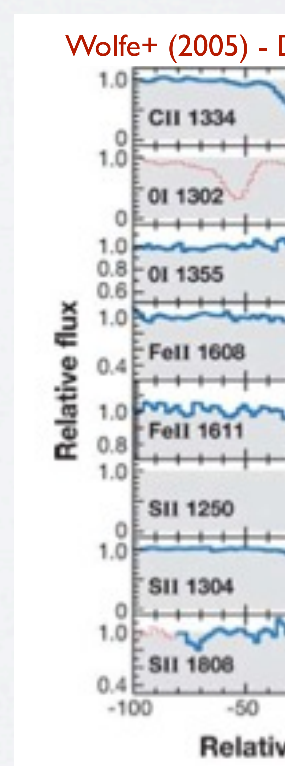
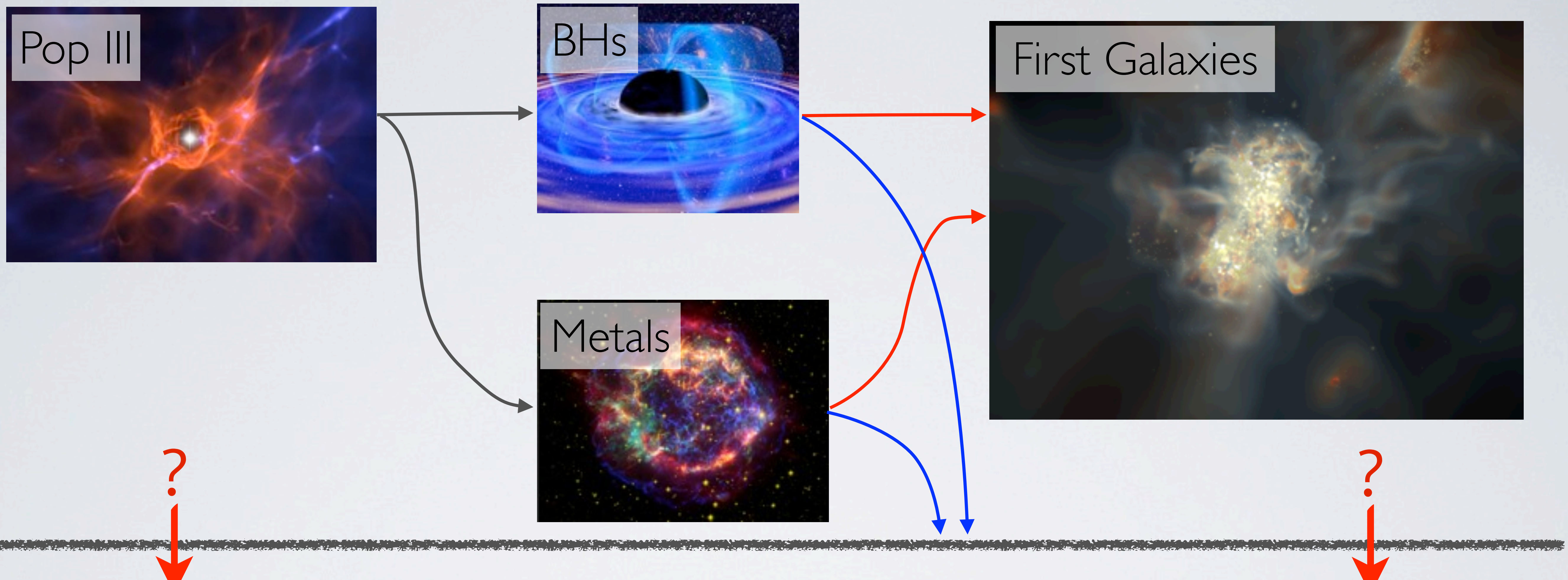
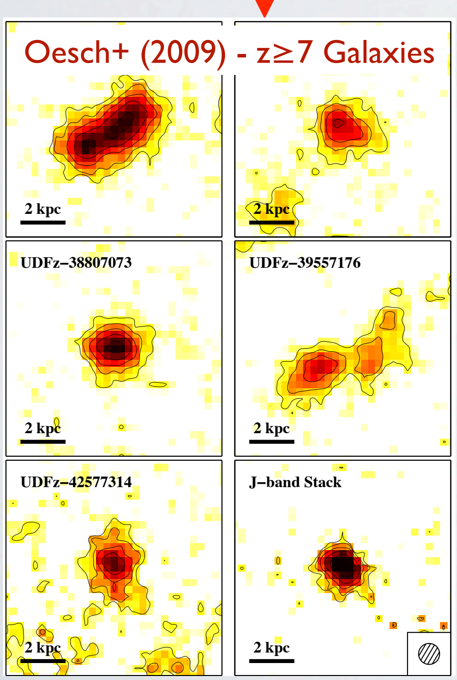




MOTIVATION





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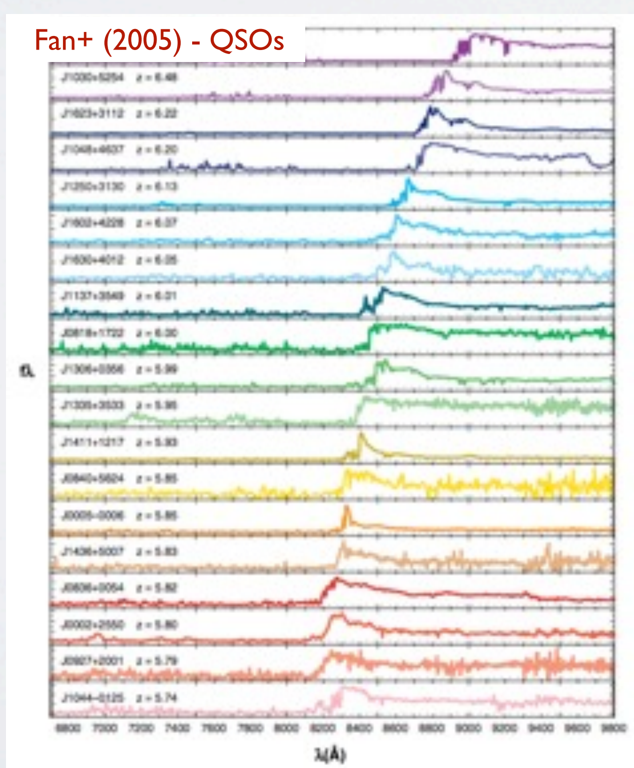

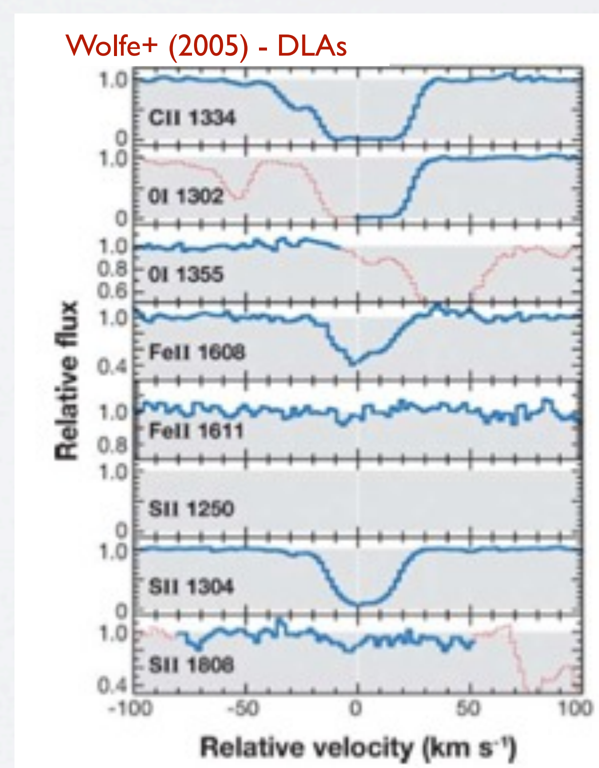

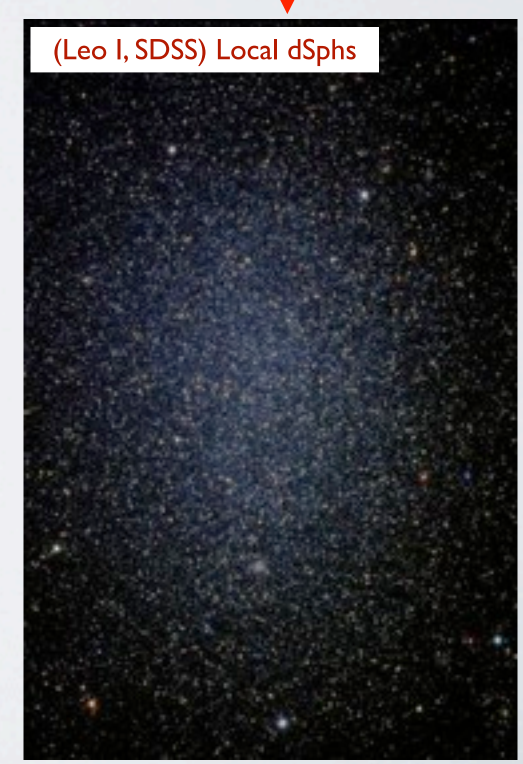

MOTIVATION
FIRST GALAXIES

- Stellar Populations? Remnants?
- Mass to light ratio?
- Gaseous Properties (metallicity, turbulence, etc)?
- Star formation history?
- Morphology?
- Imprint from earlier (Pop III) star formation?

Artist's View of Star Formation in the Early Universe
Painting by Adolf Schaller

MOTIVATION

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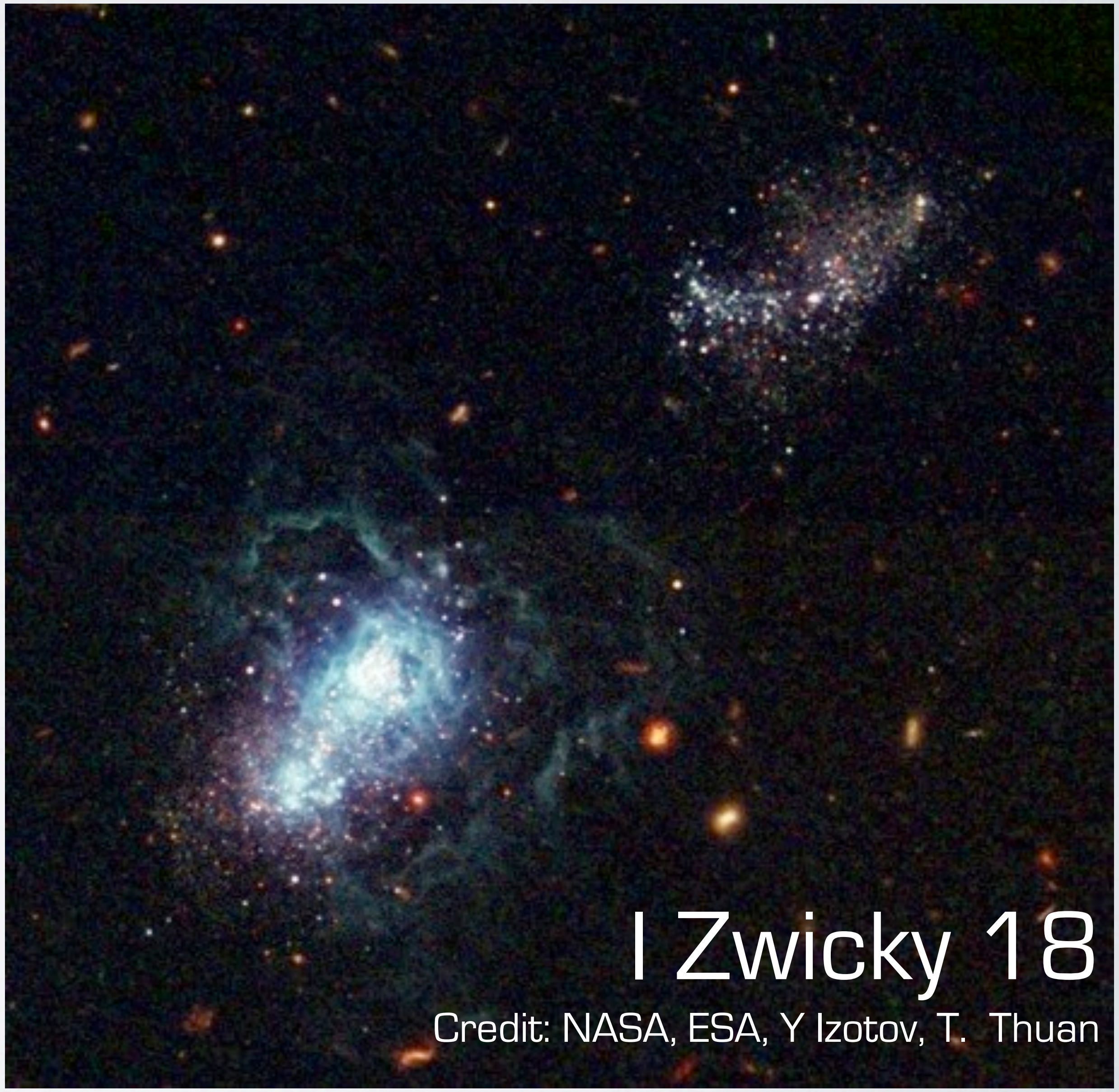
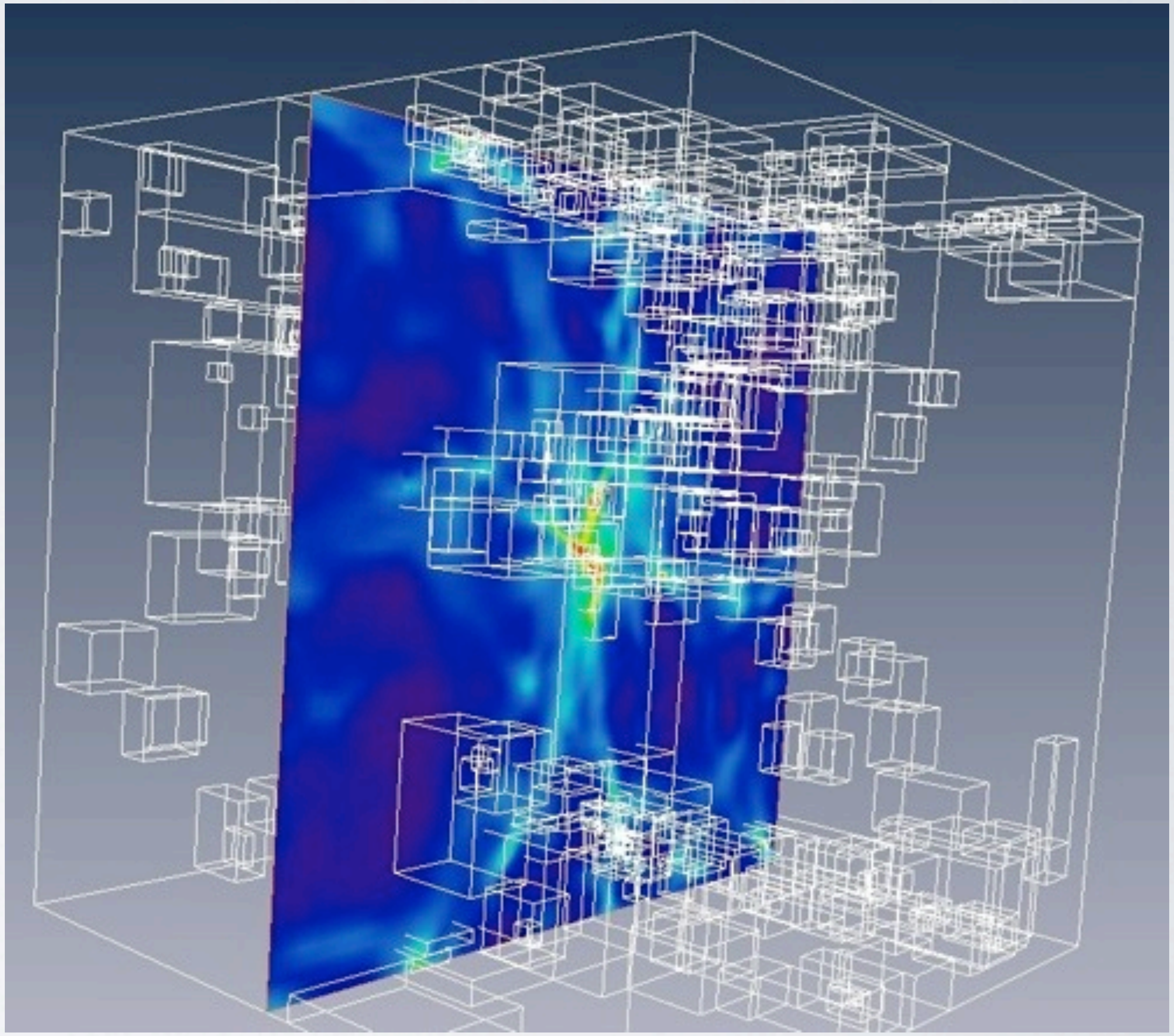


Bryan & Norman (1997)
O'Shea et al. (2004)

ENZO

- **AMR**
- **Physics:** Hydro, Gravity, Non-equilibrium chemistry, MHD, radiation transport
- **Refinement:**
    - DM / Baryon overdensity
    - Jeans length by >4 cells
- Stable to 41 levels (10^{14} dynamical range)



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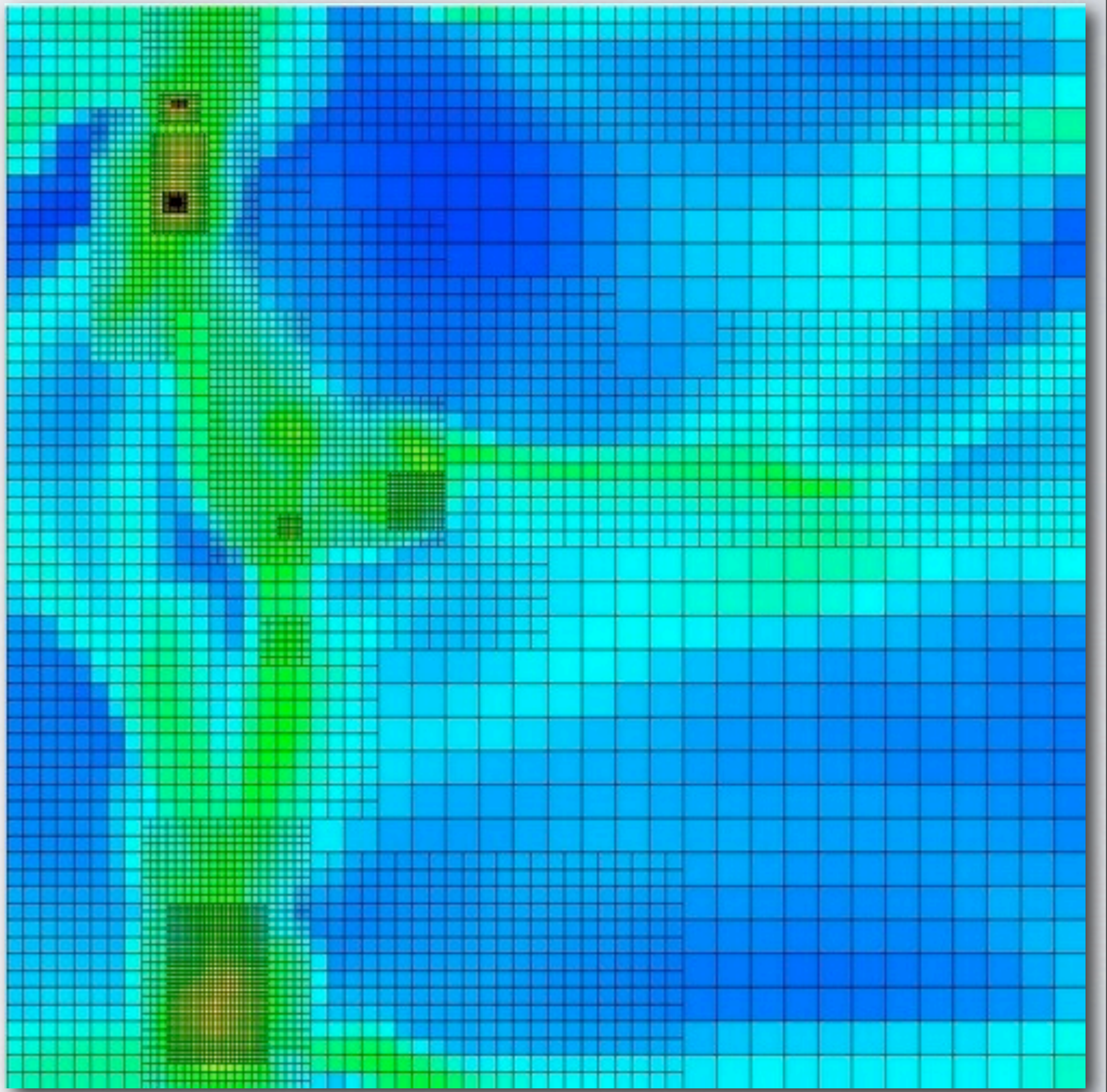
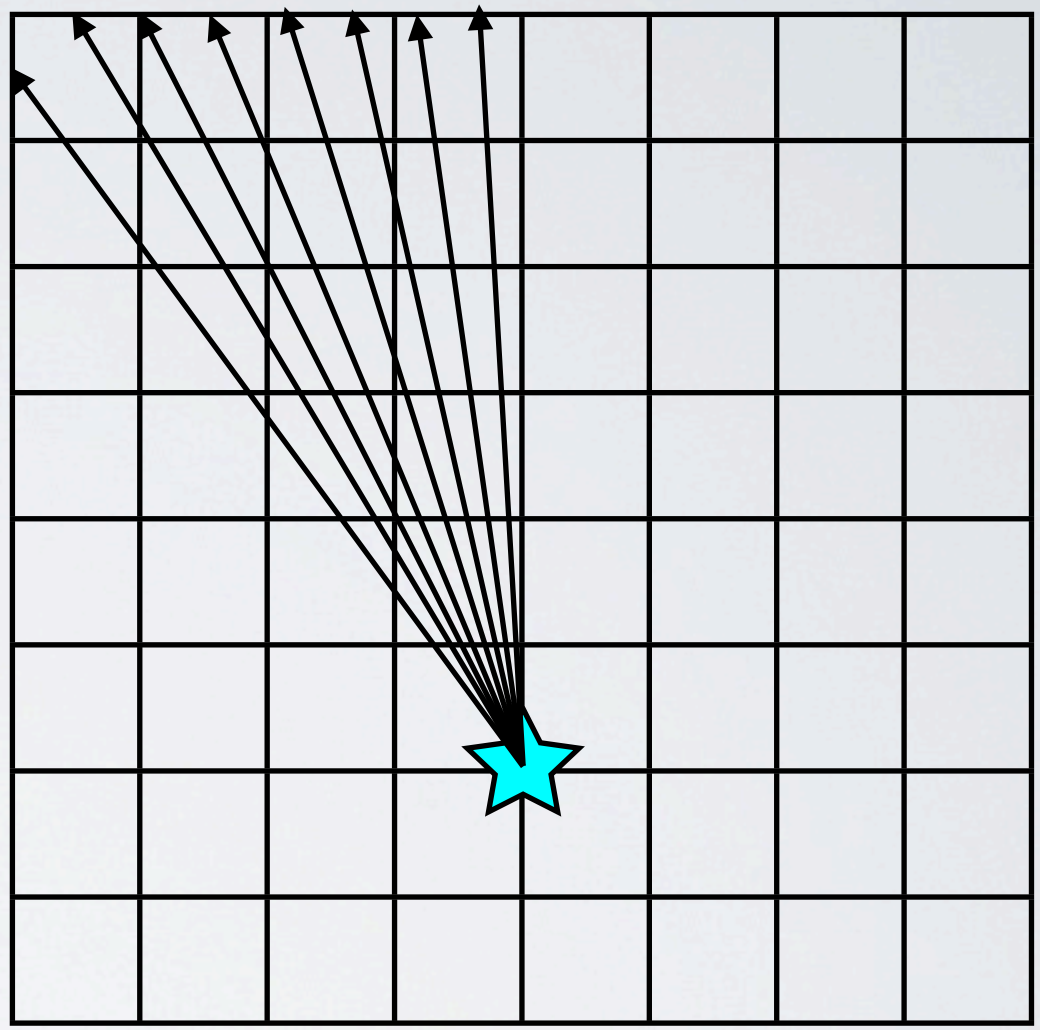


ADAPTIVE RAY TRACING

- Minimize work by splitting photons in high-resolution regions or at large radius.
- Require multiple (3-5) rays per cell.
- Direction of the rays and splitting are determined by HEALPix.
- Fully integrated and coupled with Enzo's hydro, chemistry, and energy solvers.
- MPI parallelized. Scalable (so far) to 512 processors.



Abel & Wandelt (2002)
Wise & Abel (2010); arXiv: 1012.2865

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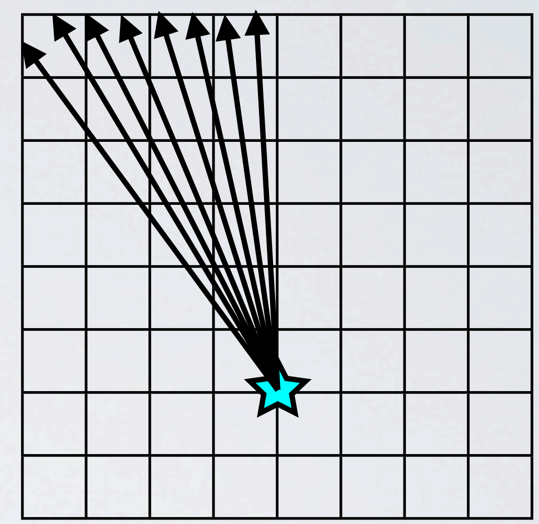
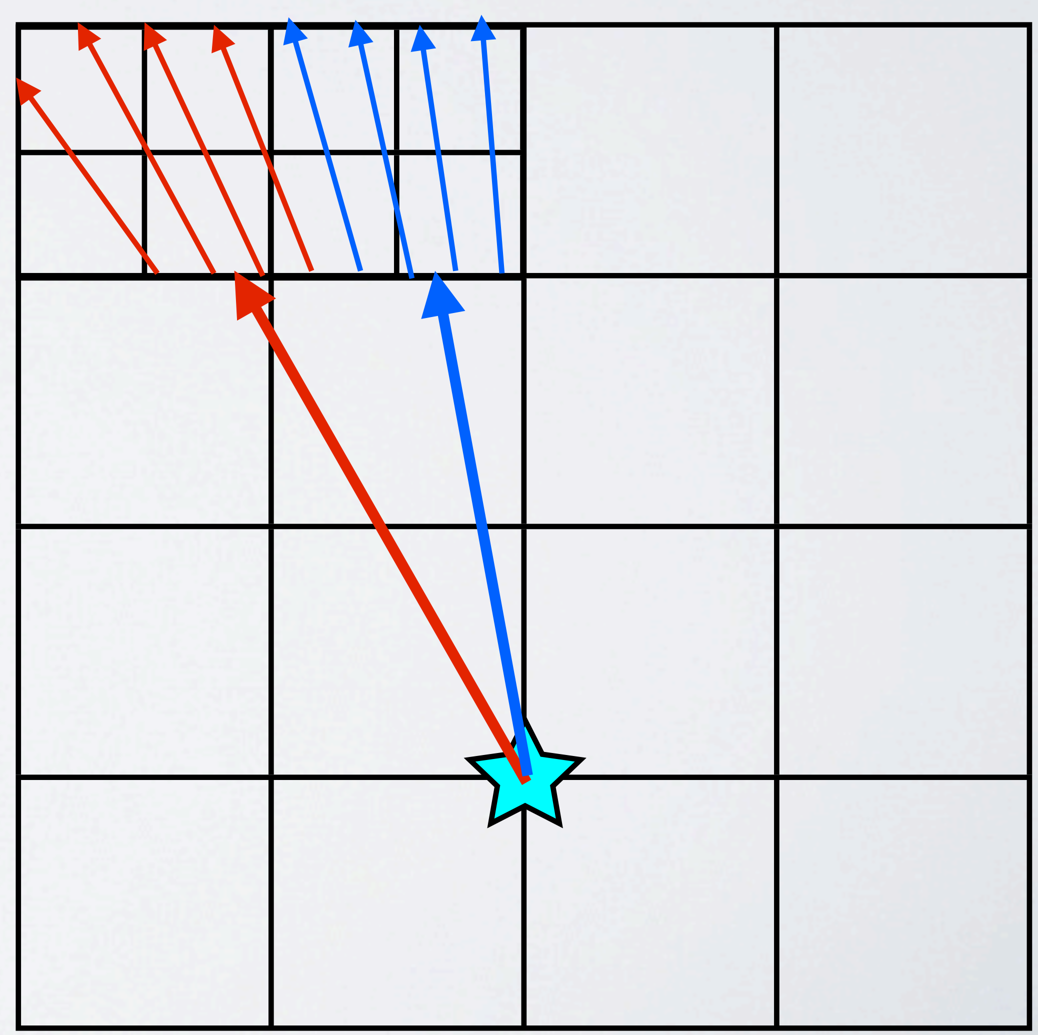


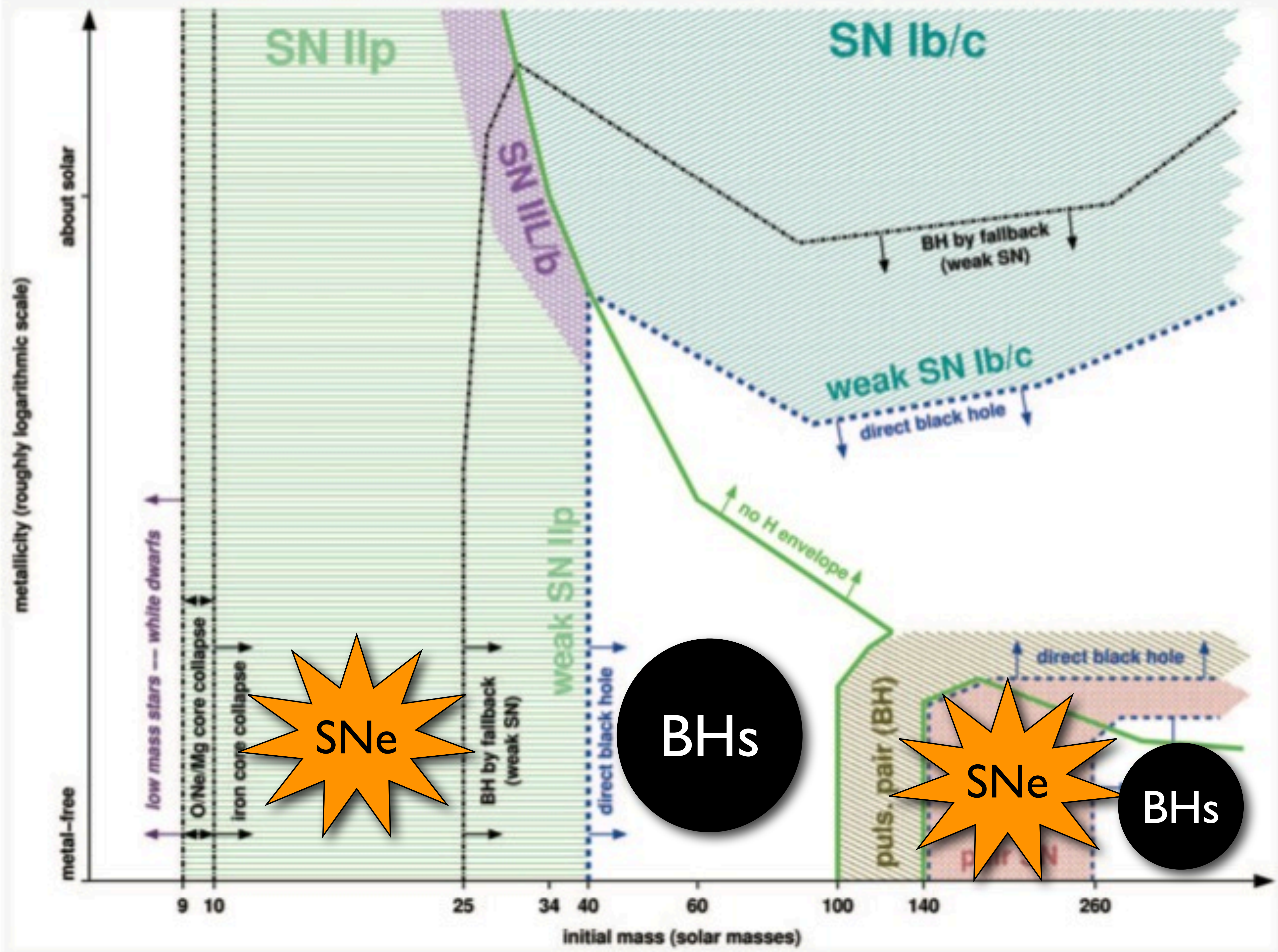


Wise, Turk, Norman, & Abel, arXiv:1011.2632

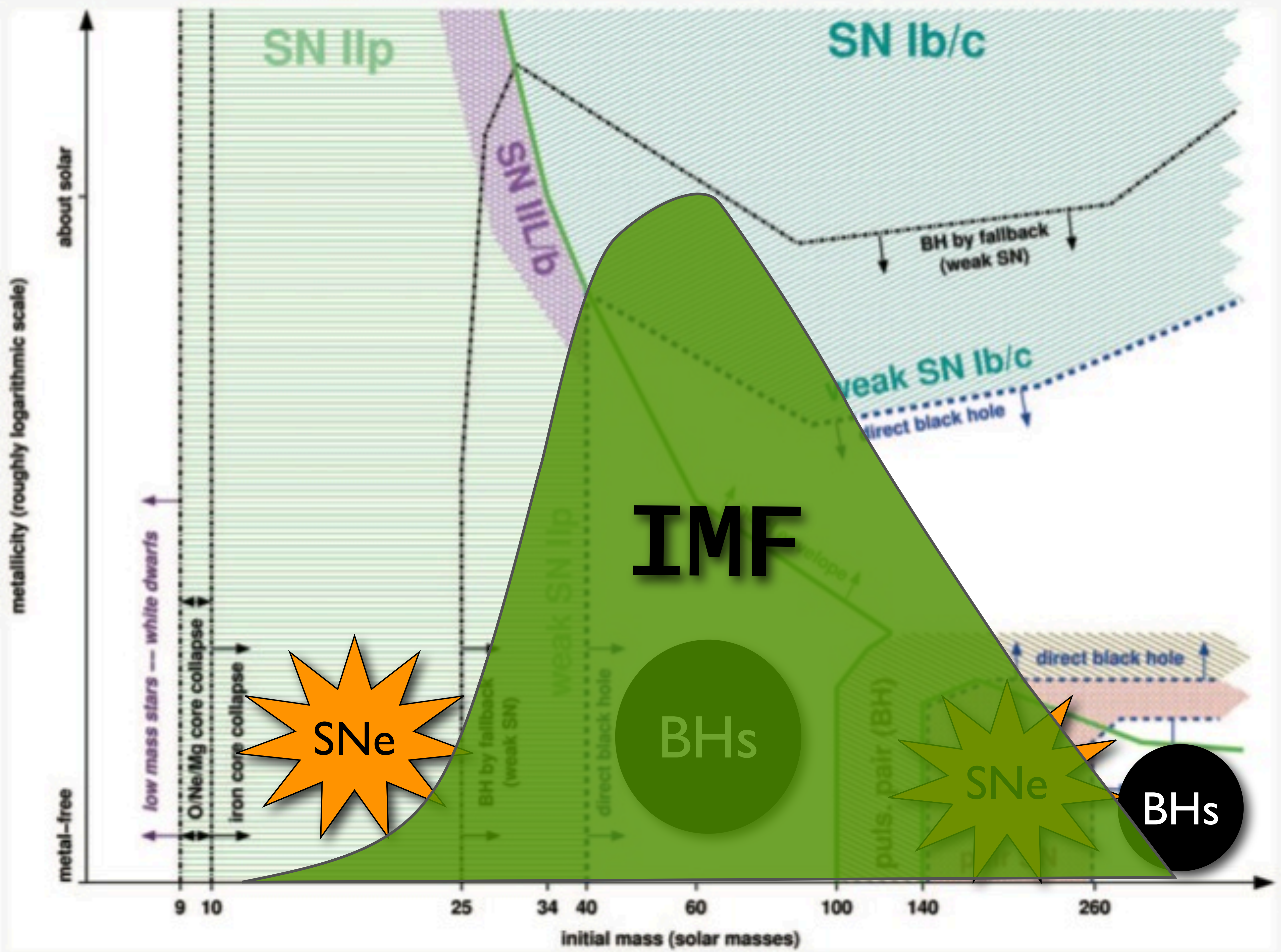
SIMULATION SETUP

- 1 Mpc comoving box, 256^3 resolution, 12 levels of AMR, $z_{\rm final} = 7$
  - 1840 $M_\odot$ dark matter resolution
  - 1 comoving pc spatial resolution
  - 142 million AMR cells ≈ 521^3 cells
  - 512 cores, 500k CPU hours on NASA's Pleiades and Discover
- Primordial non-equilibrium chemistry (metal cooling simulations are underway)
- Radiative feedback; Pop III → II transition at [Z/H] = –4; distinguish metal enrichment from Pop II and III stars
- Assume a Kroupa-like IMF for Pop III stars with mass-dependent luminosities, lifetimes, and endpoints.

$$f(M)dM = M^{-1.3} \exp\left[-\left(\frac{M_{\rm char}}{M}\right)^{-1.6}\right], \quad M_{\rm char} = 100 M_\odot$$



Heger et al. (2003)



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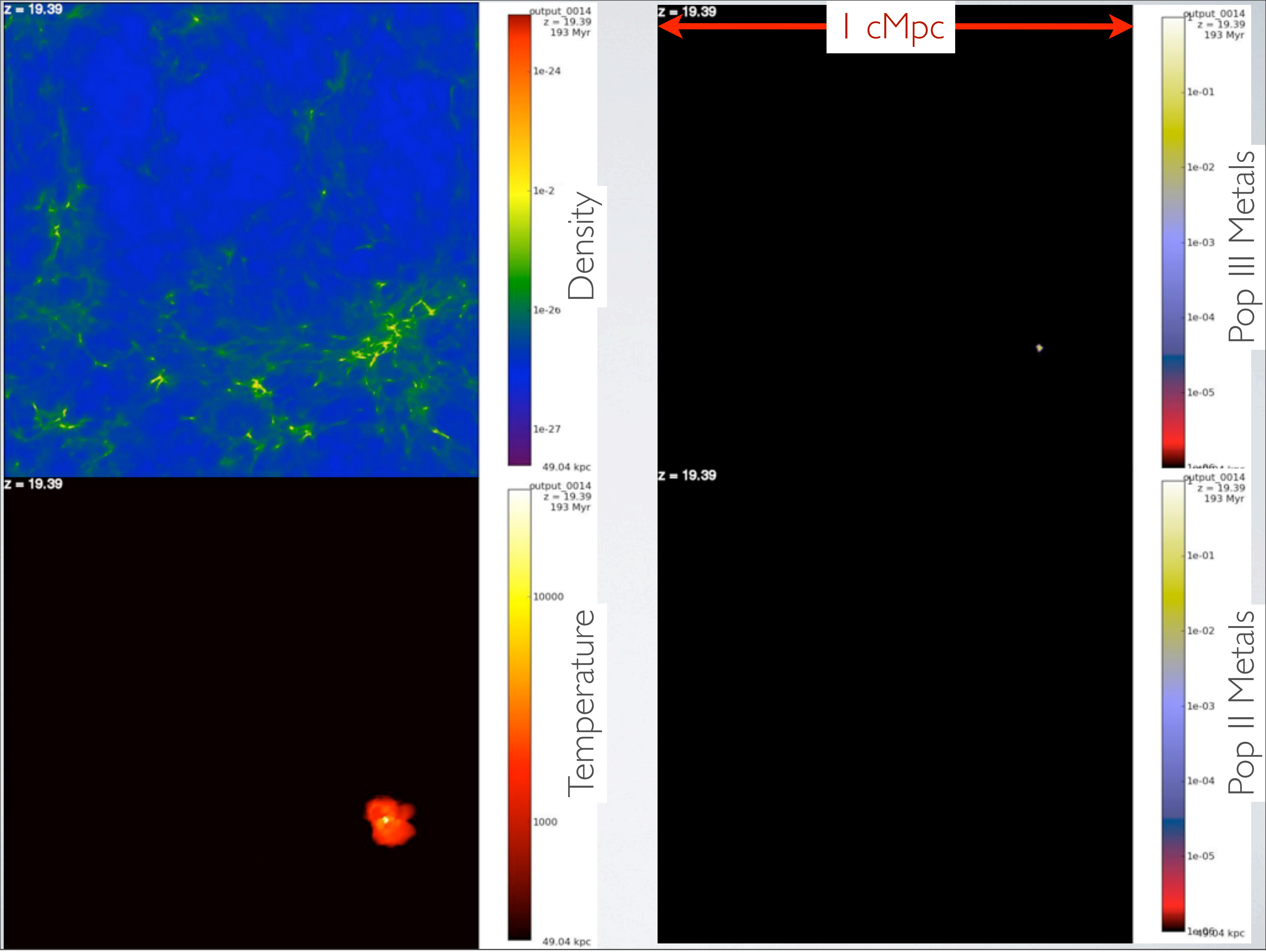
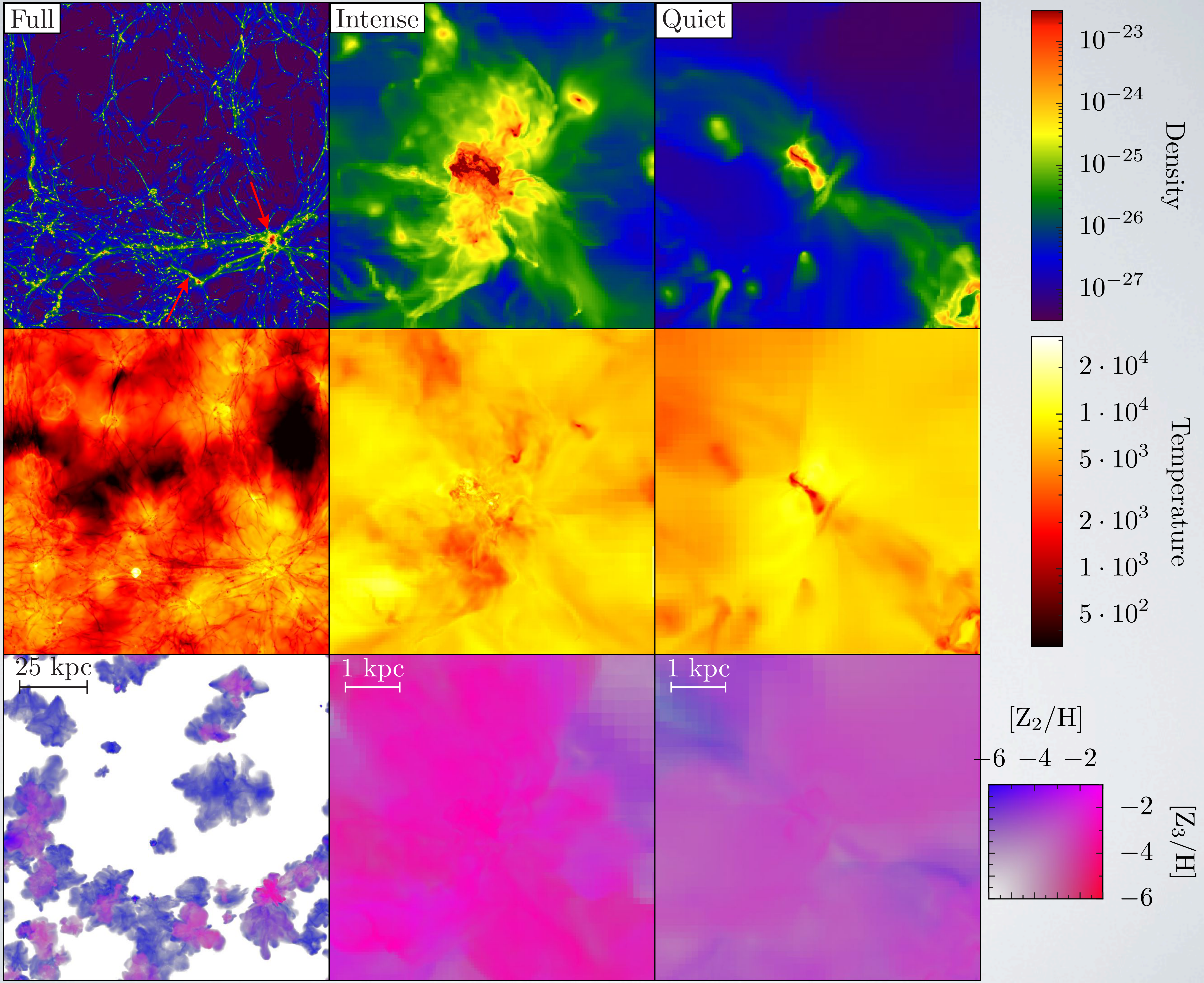
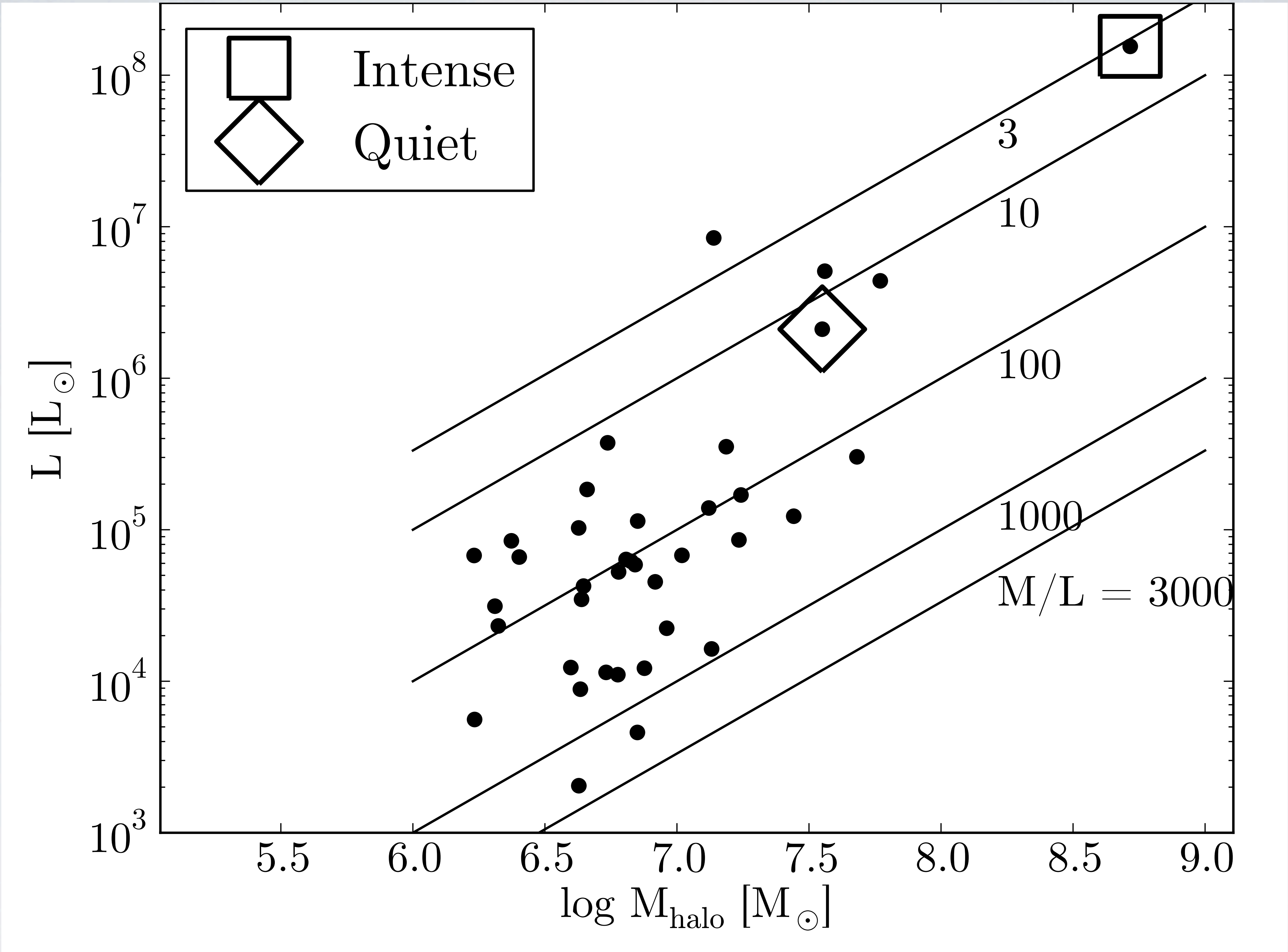

z = 19.39
output_0014
z = 19.39
193 Myr
Density
49.04 kpc
Temperature
1 cMpc
Pop III Metals
Pop II Metals

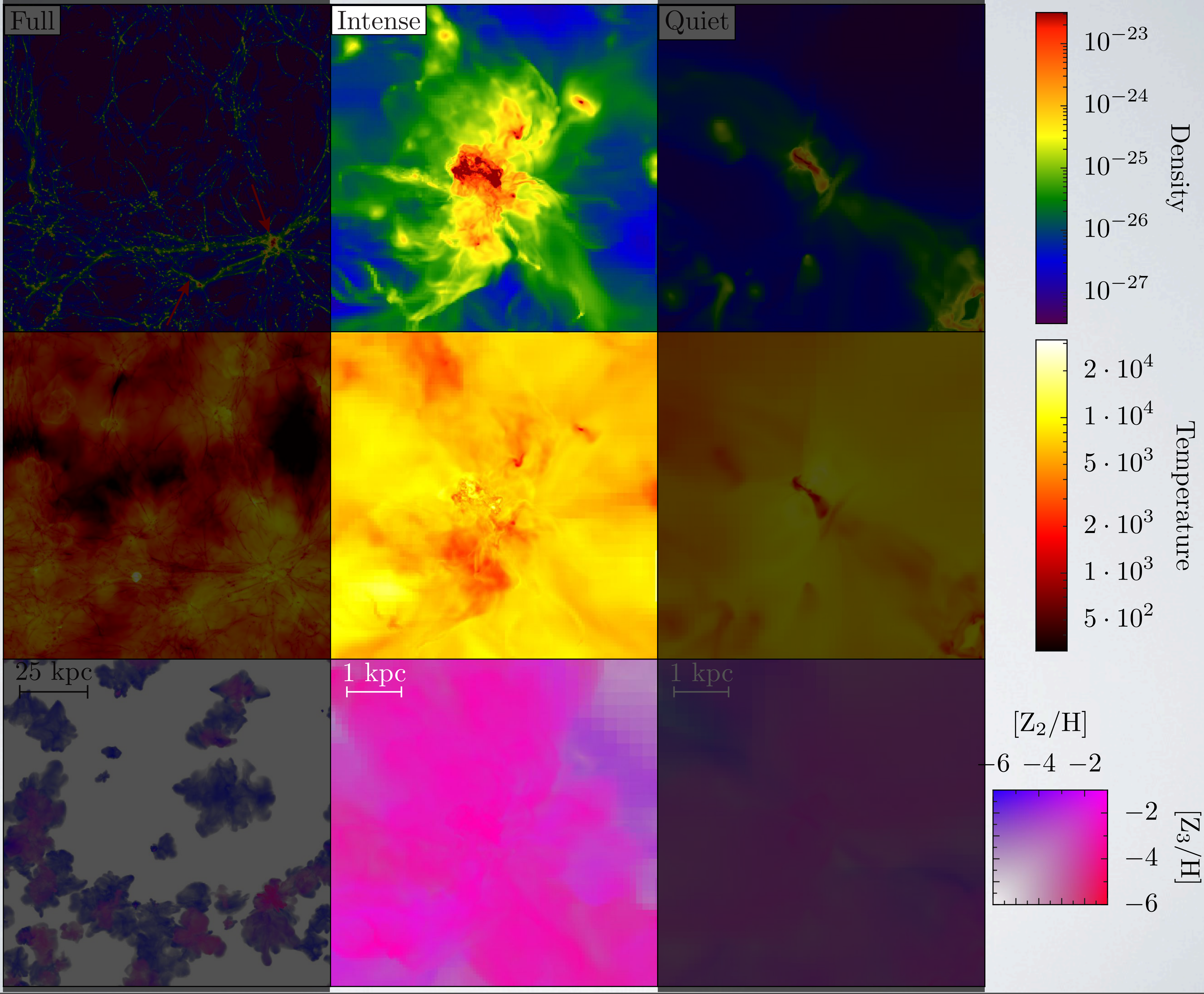

Full
Intense
Quiet
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
Density
$2 \cdot 10^4$
$1 \cdot 10^4$
$5 \cdot 10^3$
$2 \cdot 10^3$
$1 \cdot 10^3$
$5 \cdot 10^2$
Temperature
25 kpc
1 kpc
1 kpc
$[Z_2/H]$
-6 -4 -2
-2
-4
-6
$[Z_3/H]$

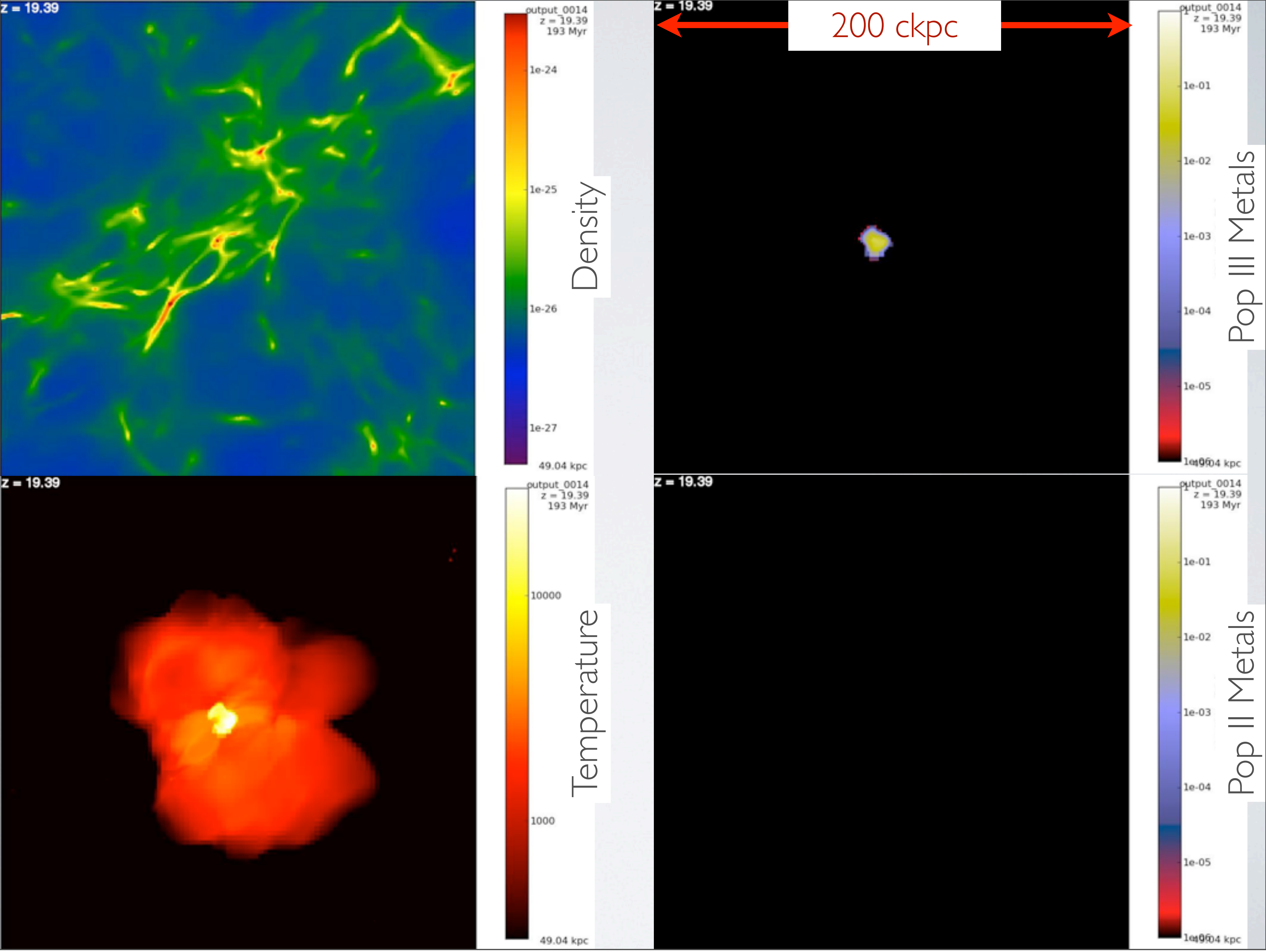


- To form Pop II stars, the halo doesn't necessarily need $T_{vir} > 10^4$ K
- Wide spread in M/L in low-luminosity galaxies, similar to Local Group dSphs

Strigari+ (2008)

- "Intense" galaxy is undergoing a merger-induced starburst, having M/L ~ 3.


Full
Intense
Quiet
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
Density
$2 \cdot 10^4$
$1 \cdot 10^4$
$5 \cdot 10^3$
$2 \cdot 10^3$
$1 \cdot 10^3$
$5 \cdot 10^2$
Temperature
25 kpc
1 kpc
1 kpc
$[Z_2/H]$
-6 -4 -2
-2
-4
-6
$[Z_3/H]$


z = 19.39
output_0014
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193 Myr
1e-24
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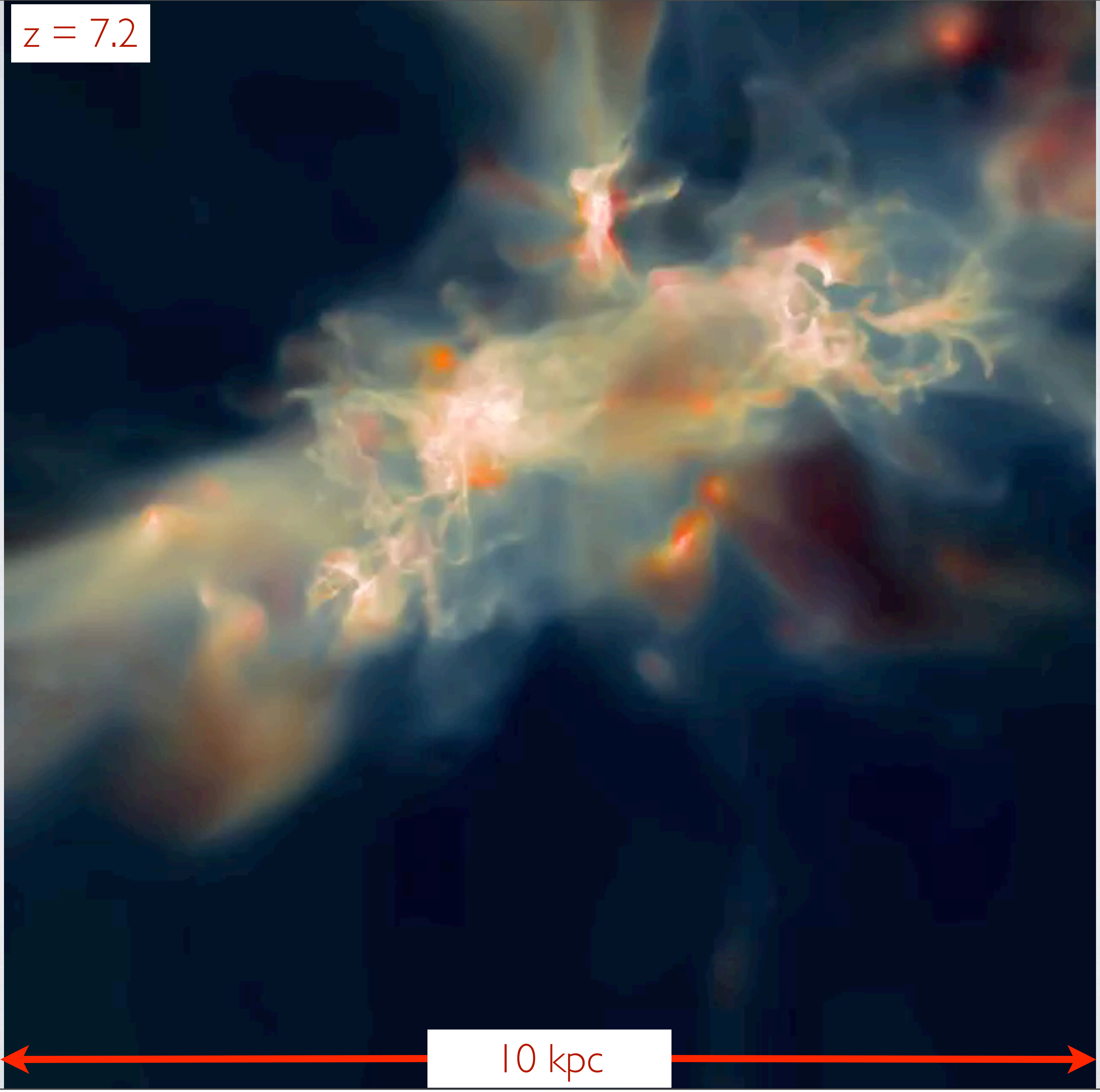
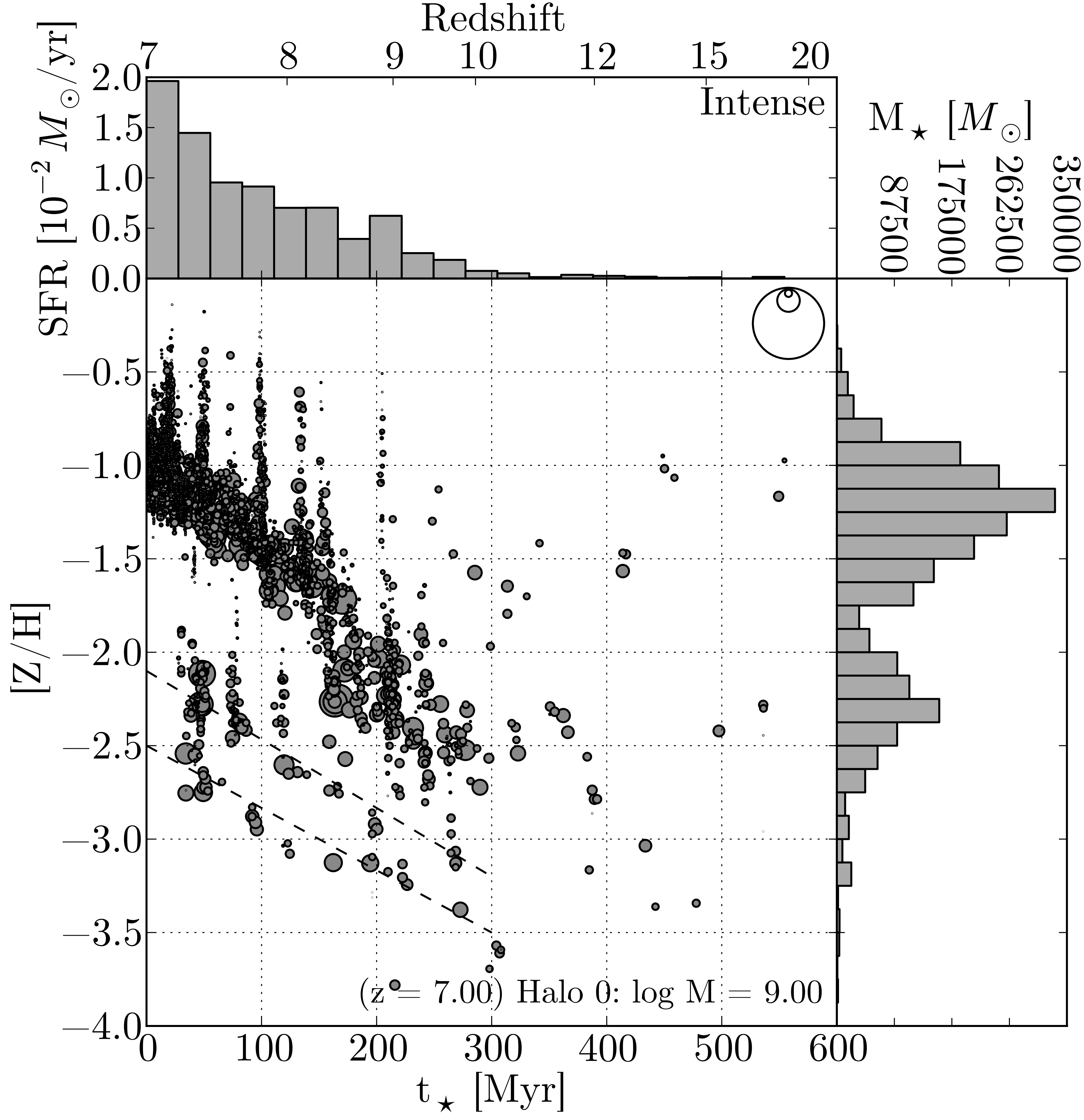
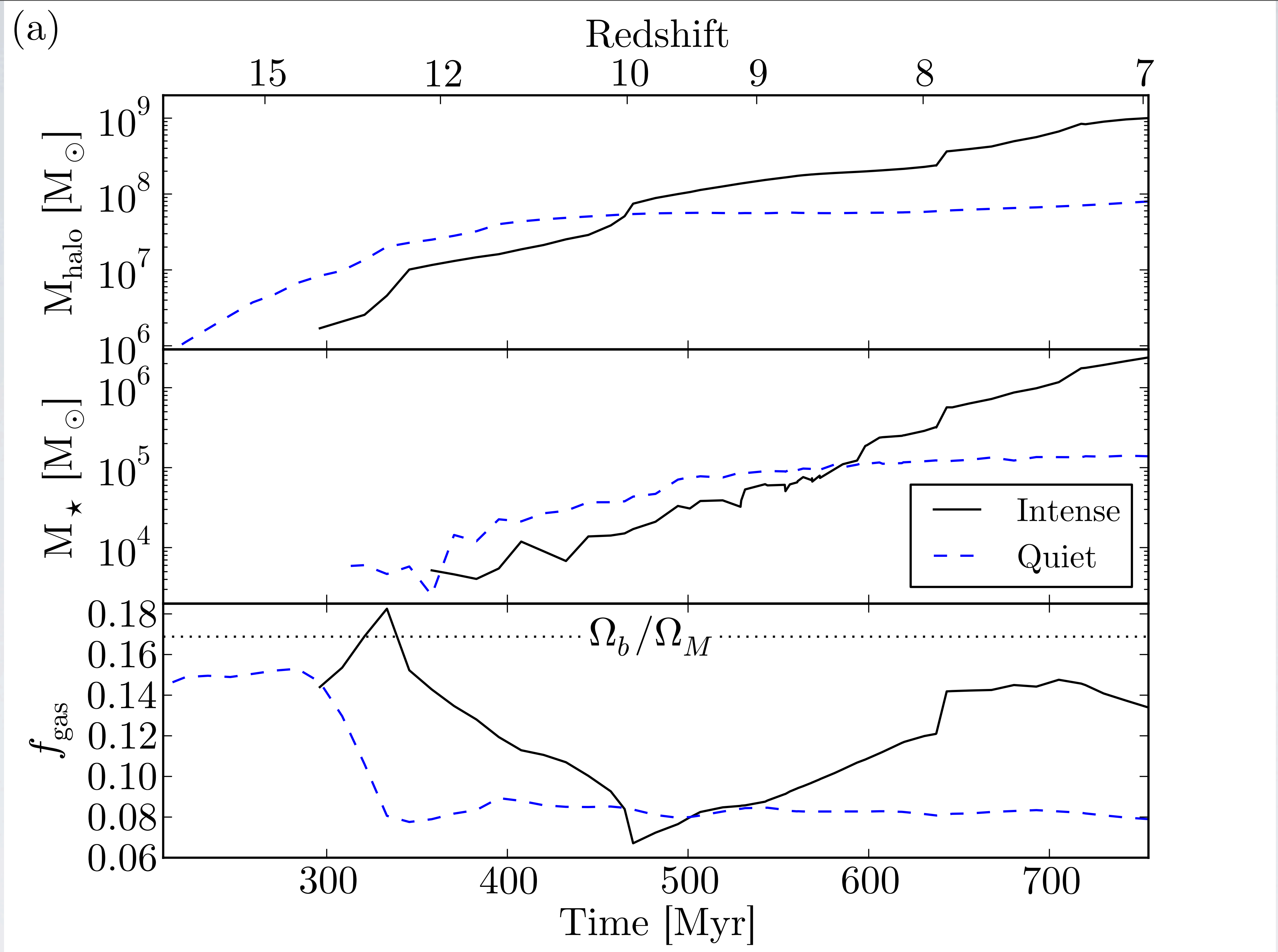
1e-27
49.04 kpc
Density
200 ckpc
1e-01
1e-02
1e-03
1e-04
1e-05
Pop III Metals
10000
1000
Temperature
Pop II Metals

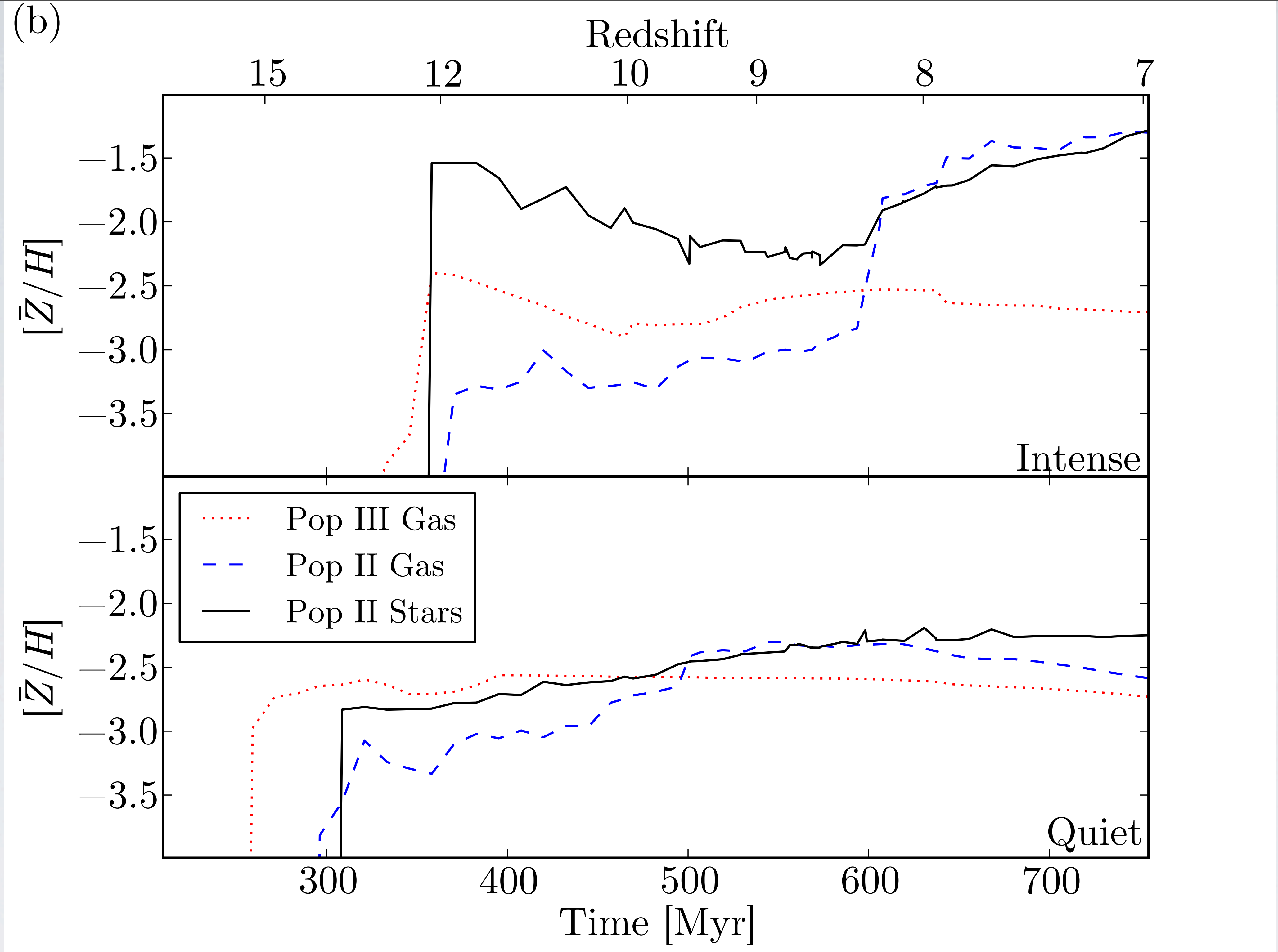

z = 7.2
10 kpc

- Most massive halo (10^9 $M_\odot$) at z=7
- Undergoing a major merger
- Bi-modal [Z/H] originates from progenitors
- Few stars with [Z/H] < -3 from Pop III metal enrichment
- Induced SF makes less metal-poor stars formed near SN blastwaves





- Steadily grows in total and stellar mass with accretion and mergers.
- Gas fraction recovers after initially being gas poor from outflows
- Self-enrichment after starburst when reaching $T_{vir} = 10^4$ K.



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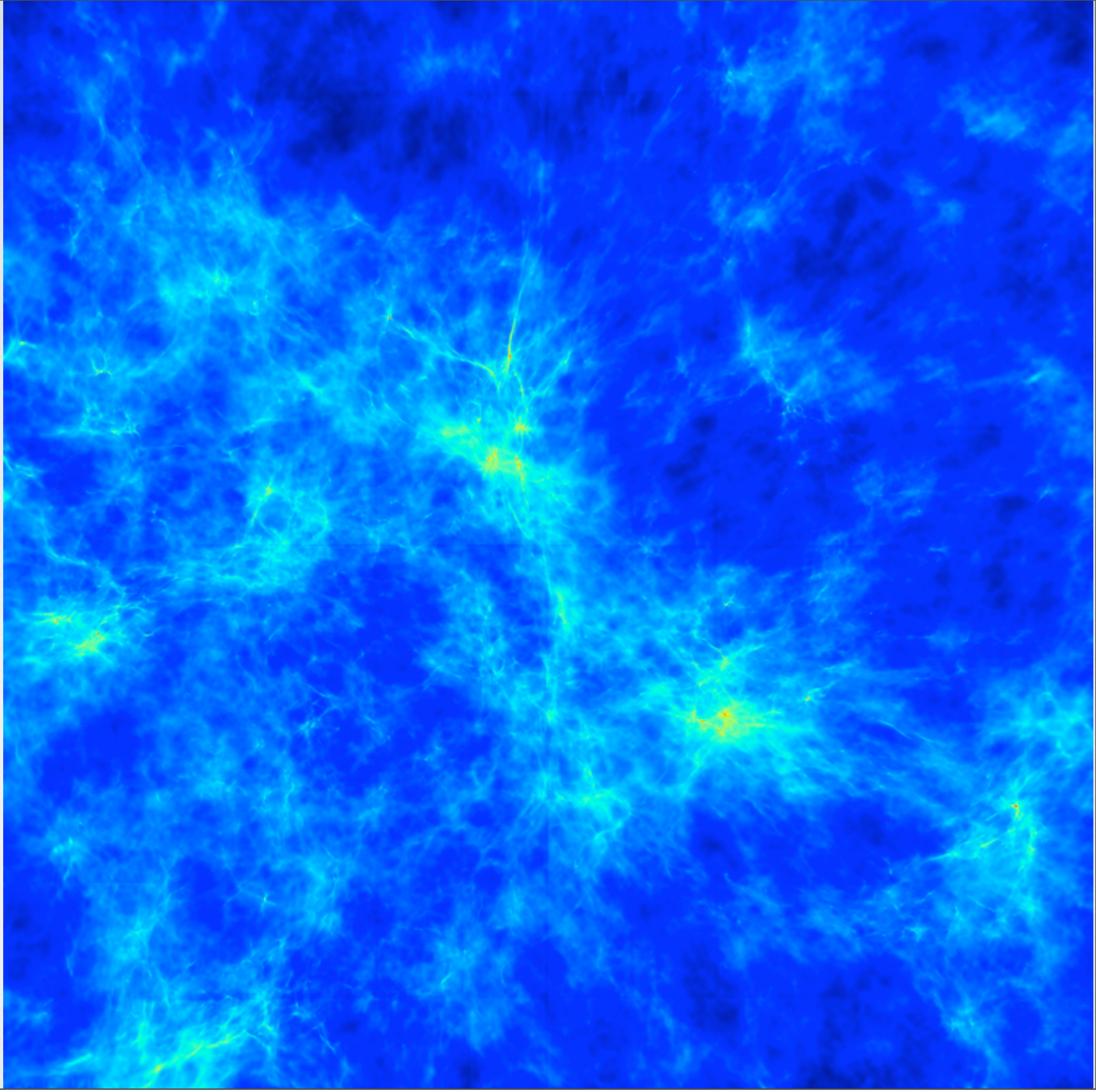
THE NEXT STEP

- Planned simulation: 30 Mpc/h, 3072^3 effective resolution → 10^4 DM mass resolution, 1 pc maximal spatial resolution
- Following the formation of $10^{10\text{-}11}$ $M_\odot$ galaxies at z = 6.
- >50,000 radiation sources, >3 billion AMR cells, >100k AMR grids.
- Need better scalability (i.e. algorithmic development) to run to completion! Running on NICS Kraken.

Projected Gas Density

z = 19

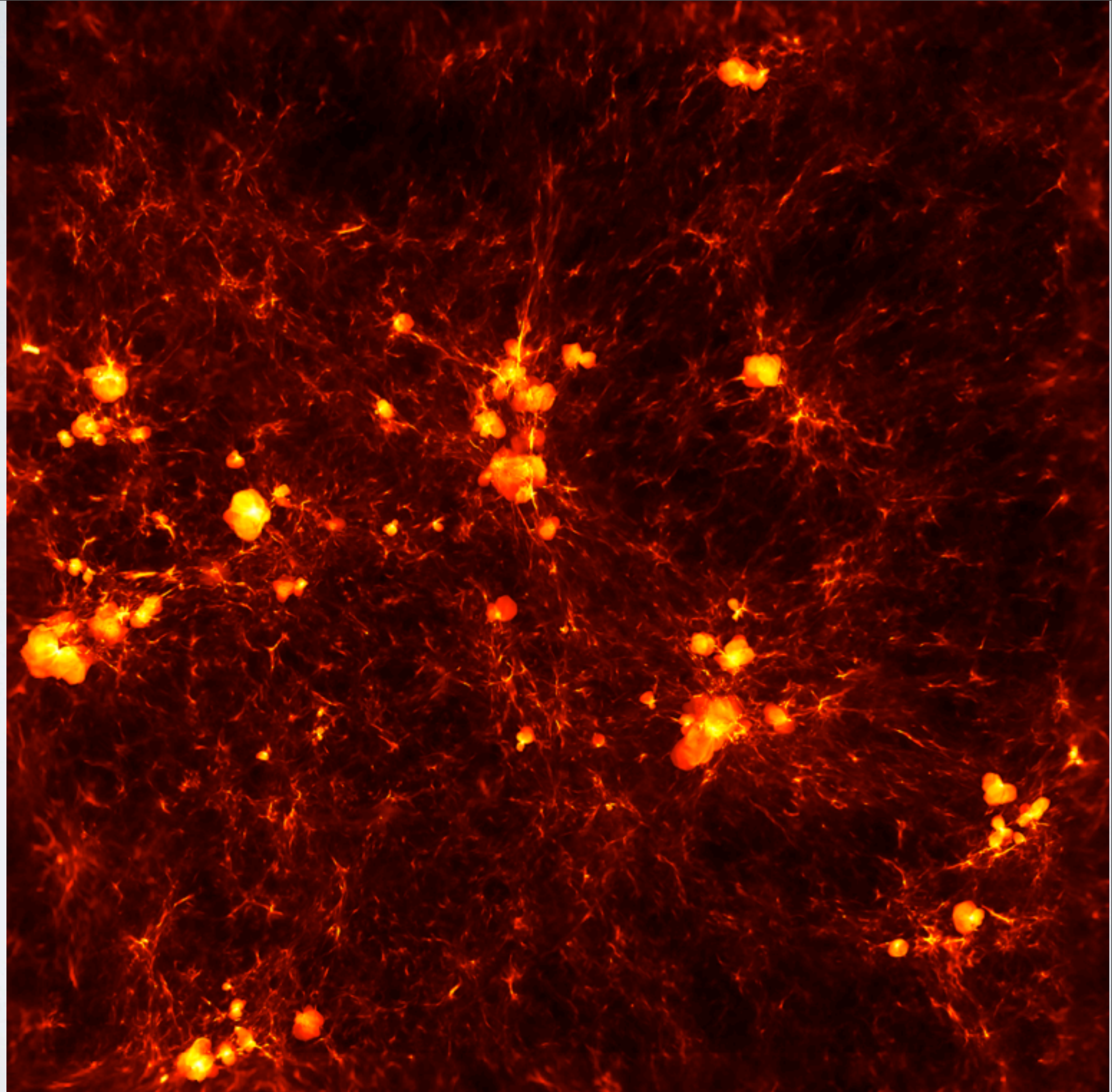


6 comoving Mpc (0.2 of the box)

Projected Temp.

z = 19

6 comoving Mpc (0.2 of the box)



ENZO 2.0 – **RT INCLUDED!**

ENZO.GOOGLECODE.COM

enzo

Astrophysical Adaptive Mesh Refinement

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yipihey
jwise77
Michael.L.Norman
bwoshea

Committers
17 committers

Contributors
0 contributors

People details »

Welcome to Enzo!

This is the development site for Enzo, an adaptive mesh refinement (AMR), grid-based hybrid code (hydro + N-Body) which is designed to do simulations of cosmological structure formation.

Enzo development is supported by grants AST-0808184 and OCI-0832662 from the National Science Foundation.

For more information, see the (older, maintenance-mode) LCA Project Page at http://lca.ucsd.edu/projects/enzo .

How To Get Enzo And Get Started

Documentation

Documentation is provided in every checkout of Enzo. A current build of the documentation is also available online:

http://docs.enzo.googlecode.com/hg/index.html

At the 2010 Enzo Users' Workshop, we also had a number of presentations and tutorials, many of which were recorded. These are all available online.

Enzo Community

Enzo is a community supported code, written by and for active researchers in the field of Astrophysics. Please join the users' mailing list to tell us about interesting things you've done with Enzo, ask for help, and meet the rest of the community.

Enzo 2.0

We are proud to announce the public release of Enzo version 2.0. Enzo is a parallel code for astrophysical and cosmological simulations utilizing adaptive mesh refinement. Enzo 2.0 features many new physics capabilities including ideal MHD, radiation transport (ray tracing and flux limited diffusion), star particle class, metallicity-dependent cooling, and several new hydro solvers. More importantly, we have introduced new software tools to make using and developing Enzo easier. We have adopted distributed version control using Mercurial which supports the growing Enzo developer community. The documentation has been made more accessible and is now distributed with the source code. We have more than doubled the number of test problems and example problems (as well as the number of developers!) In addition, we have added solution testing to the nightly regression tests.

Enzo 2.0 is the product of developments made at UC San Diego, Stanford, Princeton, Columbia, MSU, CU Boulder, CITA, McMaster?, SMU, and UC Berkeley.

Enzo 2.0 now lives at http://enzo.googlecode.com/ to reflect its multi-institutional provenance. Prospective users are also encouraged to view online lectures from the 2010 Enzo Users' Workshop at http://lca.ucsd.edu/workshops/enzo2010.

Enzo development is supported by grants AST-0808184 and OCI-0832662 from the National Science Foundation.

THE ENZO DEVELOPMENT TEAM

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CONCLUSIONS

- Radiative and chemical feedback plays an important role in the formation of the first galaxies and starting reionization
- Further scalability is needed for larger simulations. However more local physics will partially delay this need.
- Established gas metallicity floor of [Z/H] = –3 with a $M_{char} = 100\ M_\odot$ Pop III IMF. Connections to DLAs or metal-poor stars in local dSphs and MW halo?