Exploring the first generation of galaxies with Blue Waters and the James Web Space Telescope

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With:
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Special thanks to:

Manisha Gajbe (Blue Waters technical POC)
Bill Kramer and all of the Blue Waters team
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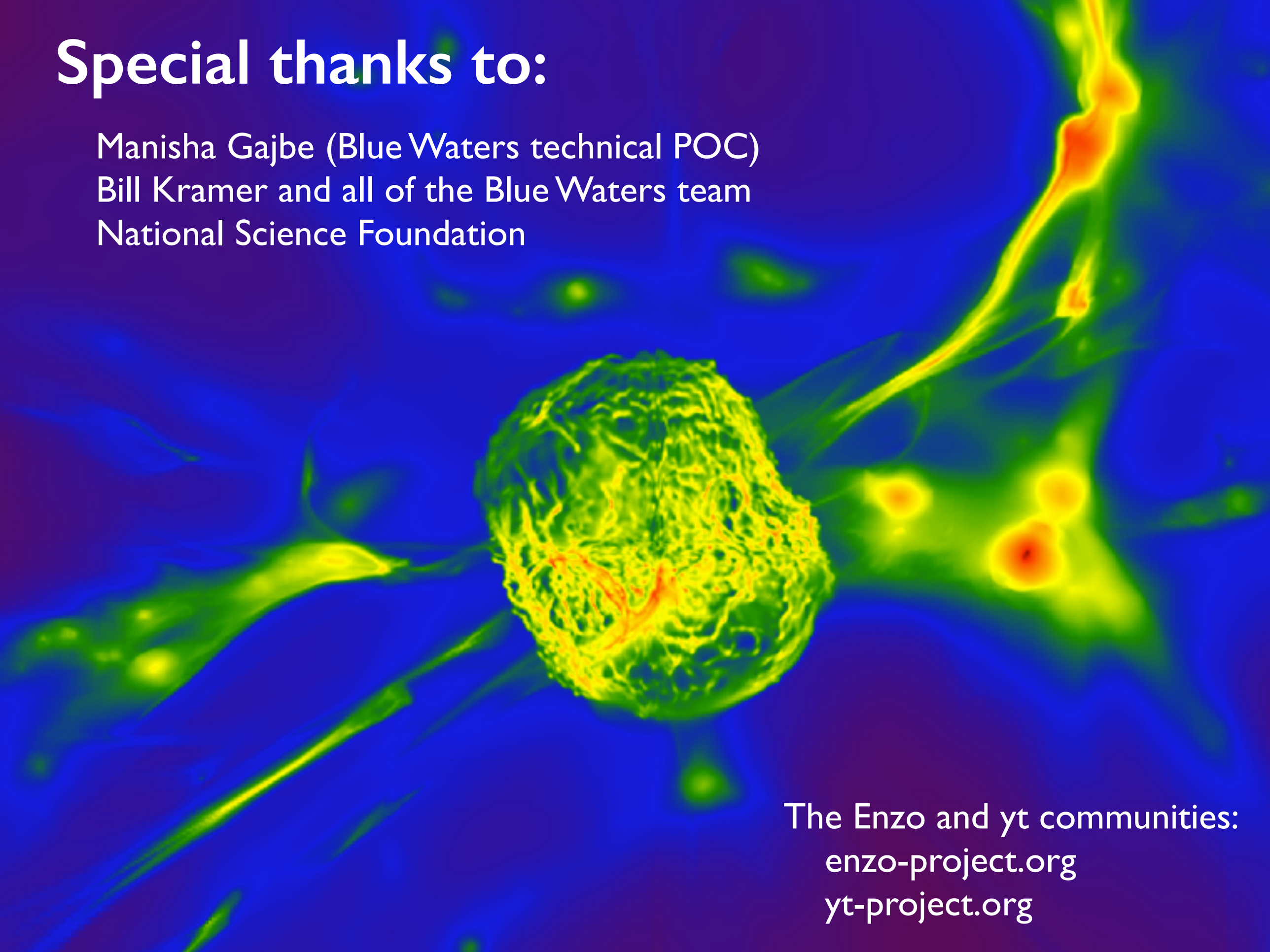
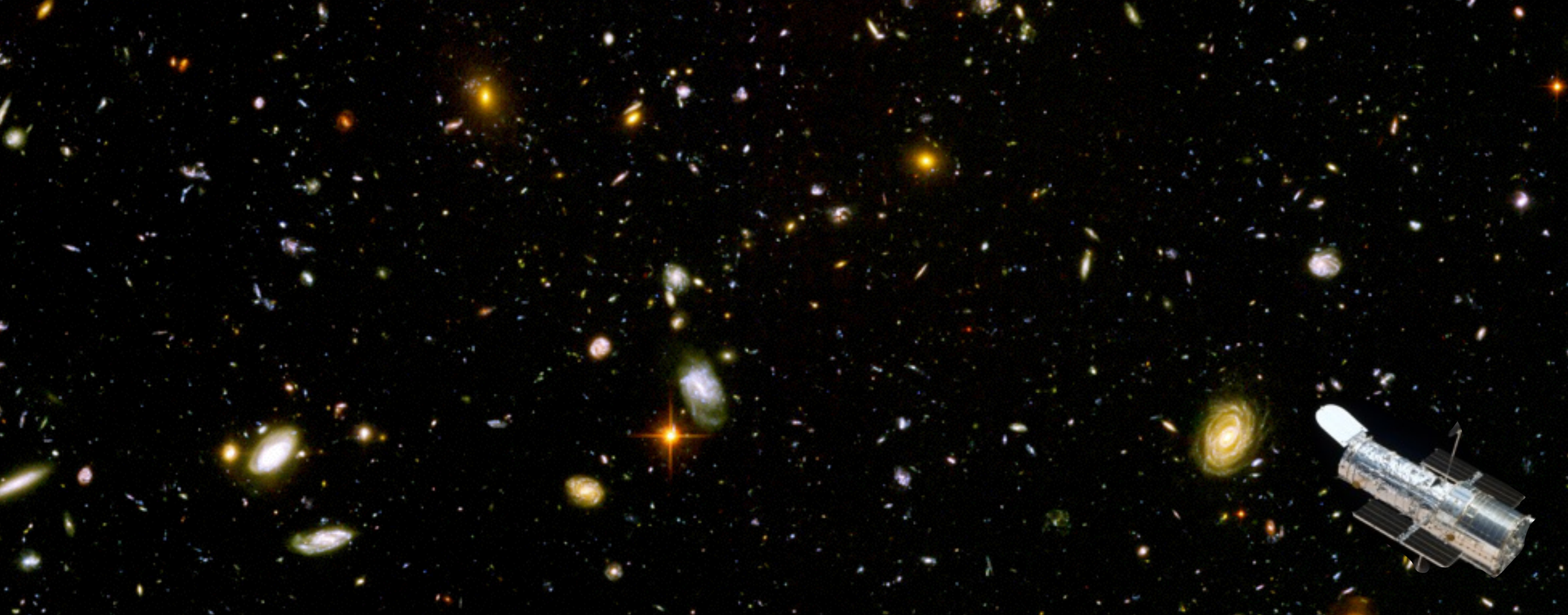
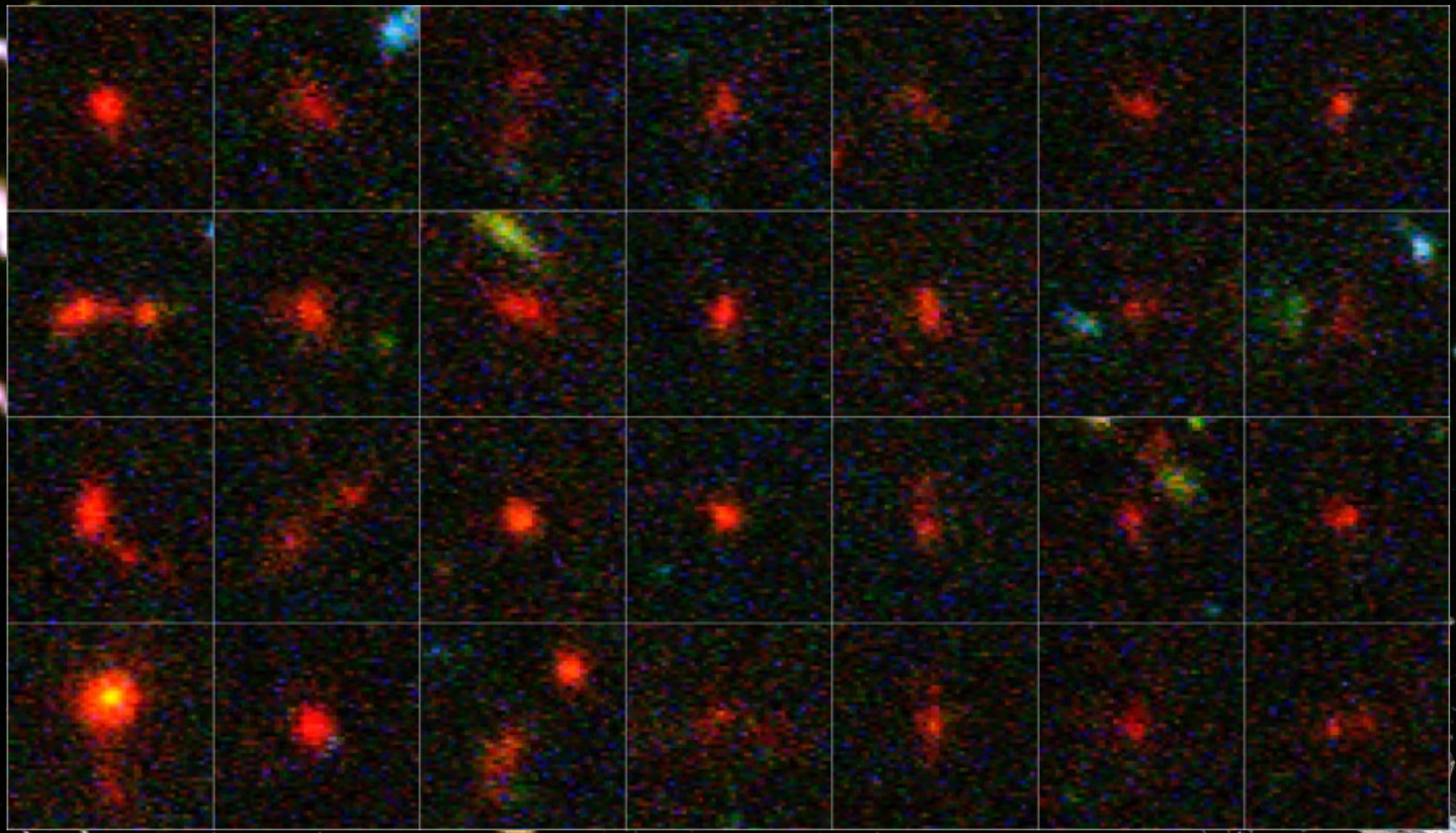


The Enzo and yt communities:
enzo-project.org
yt-project.org





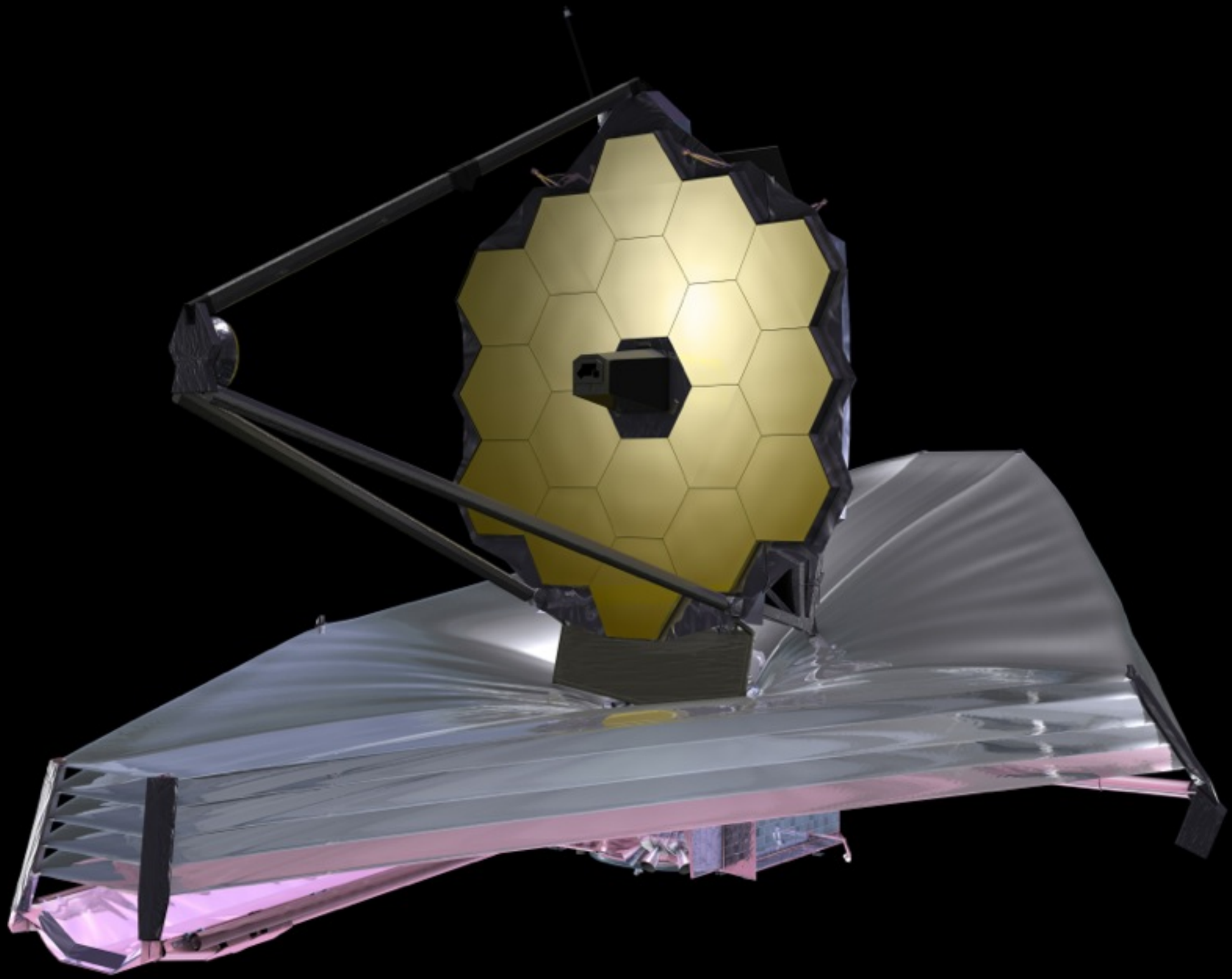


Image c/o NASA

Our goal:

Understanding the first generations of galaxy formation

Why is studying galaxy formation challenging?

Our simulation tool:

Bryan et al. 2014, ApJS, 211, 19
http://enzo-project.org

Our analysis/viz tool:

Turk et al. 2011, ApJS, 192, 9
http://yt-project.org

Lots of results!

- Xu et al., "Heating the Intergalactic Medium by X-Rays from Population III Binaries in High-redshift Galaxies," 2014, ApJ, 791, 110
- Chen et al., "Scaling Relations for Galaxies Prior to Reionization," 2014, ApJ, 795, 144
- Ahn et al., "Spatially Extended 21 cm Signal from Strongly Clustered UV and X-Ray Sources in the Early Universe", 2015, ApJ, 802, 8
- O'Shea et al., "The ultraviolet luminosity function of the earliest galaxies," 2015, ApJ submitted (arXiv:1503.01110)
- Smith et al., "The First Population II Stars Formed in Externally Enriched Mini-halos," 2015, ApJ submitted (arXiv:1504.07639)
- Xu et al., "Ionising Photons From Faint Galaxies During the Epoch of Reionization," 2015, ApJ, in prep (submitting ~June 1st)
- Shi et al., "The Dynamics of Seed Black Holes in the First Galaxies," 2015, ApJ, in prep. (submitting ~July)

And much more to come!

Focus areas

The transition to metal-enriched star formation: Britton Smith*, John Wise*, BWO

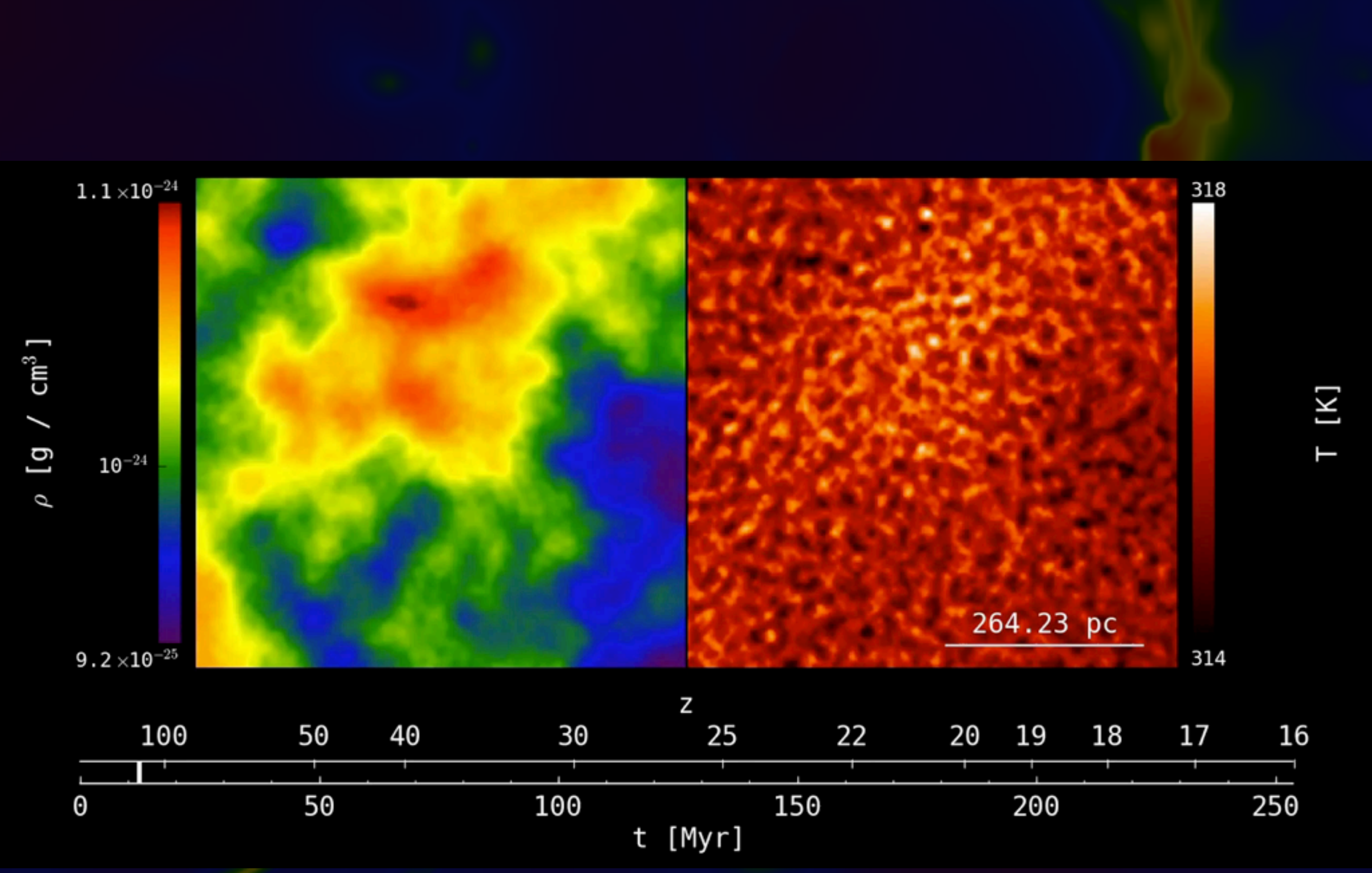
Evolution of early galaxy populations: Hao Xu*, Pengfei Chen, Mike Norman, Kyungjin Ahn, BWO

* Ran the simulations

The transition to metal-enriched star formation

- **Small volume:** 0.5 Mpc/h box
- ***Extremely* high resolution:** 15 levels of AMR prior to explosion (0.029 pc comoving max); 30 after (~1 au comoving); ~0.19 $M_\odot$ gas, 0.92 $M_\odot$ dm mass resolution
- **Sophisticated physics:**
  - Primordial gas + **metal + dust chemistry** & cooling
  - Radiation transport for Pop III stars; core-collapse supernovae w/11.2 $M_\odot$ of metals

Smith et al. 2015 (submitted; arXiv:1504.07639)



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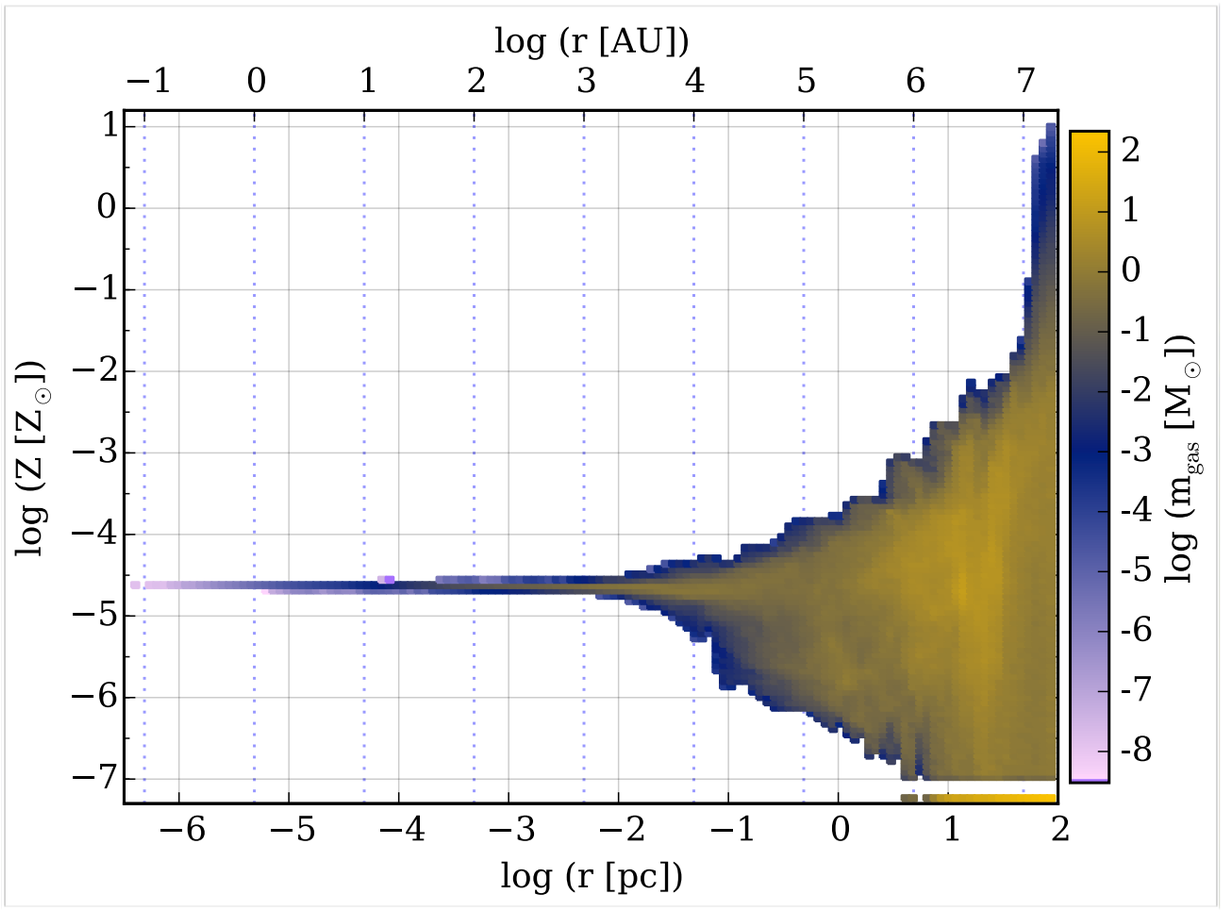
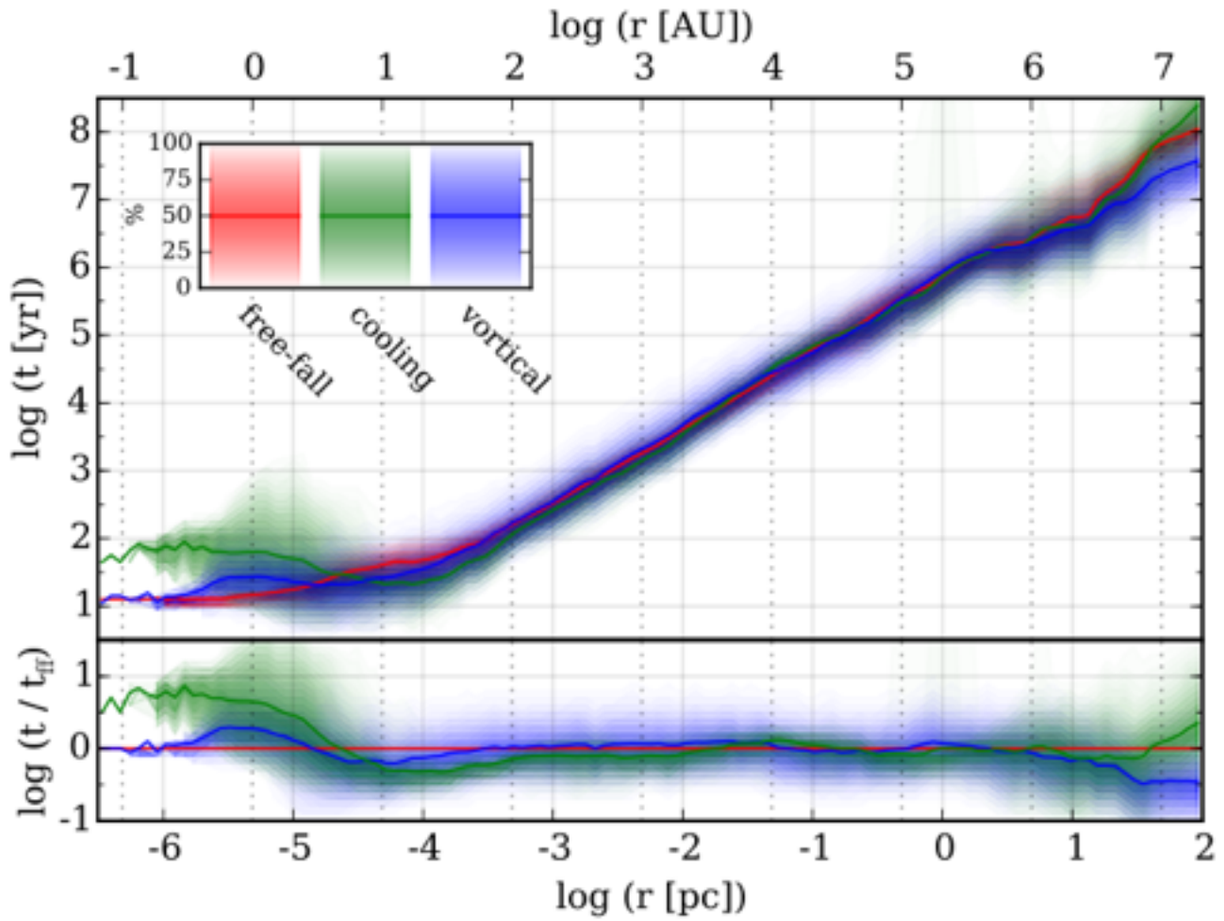
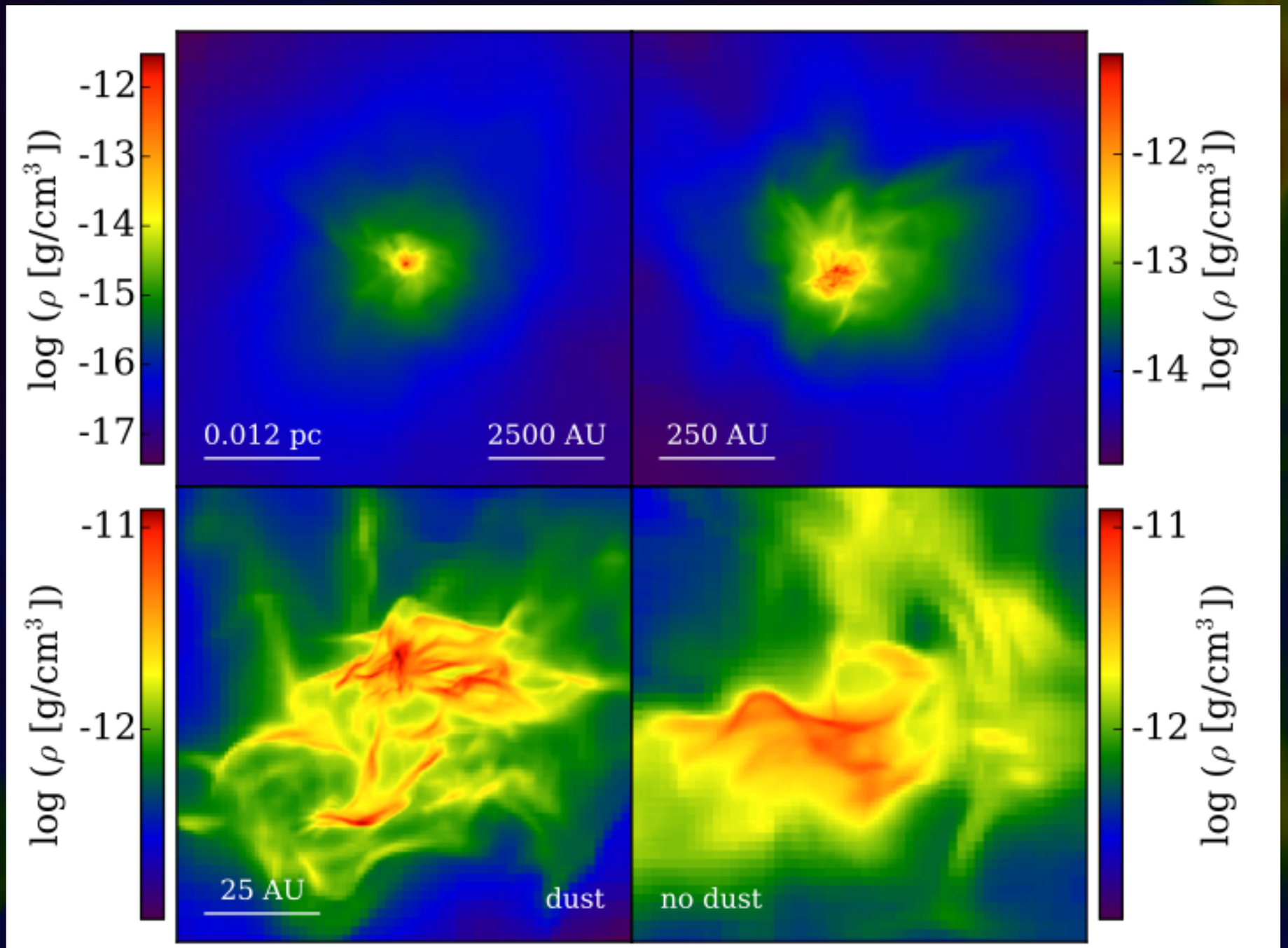


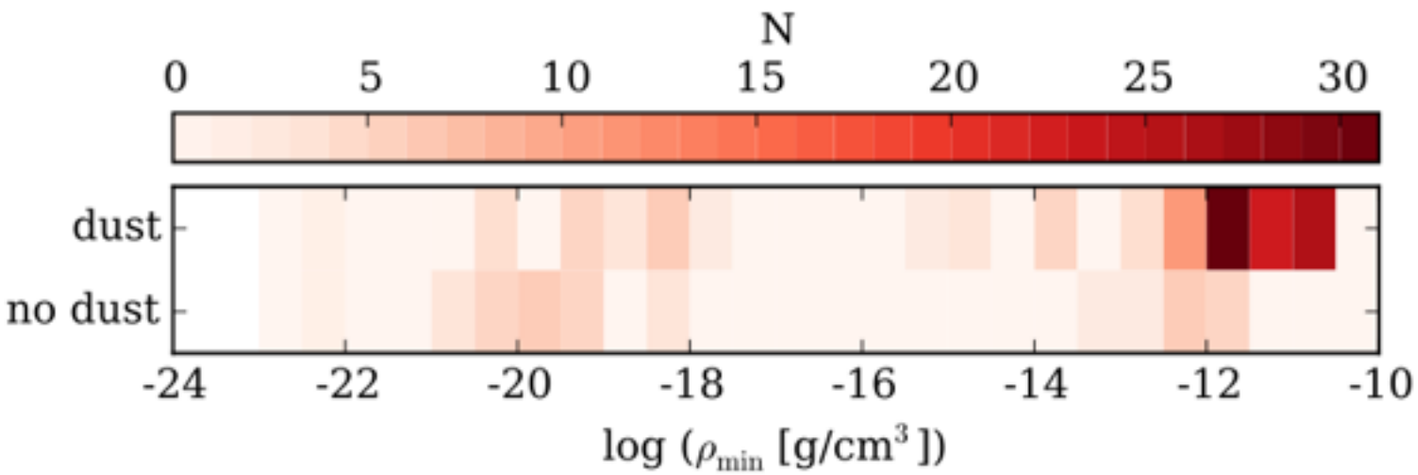


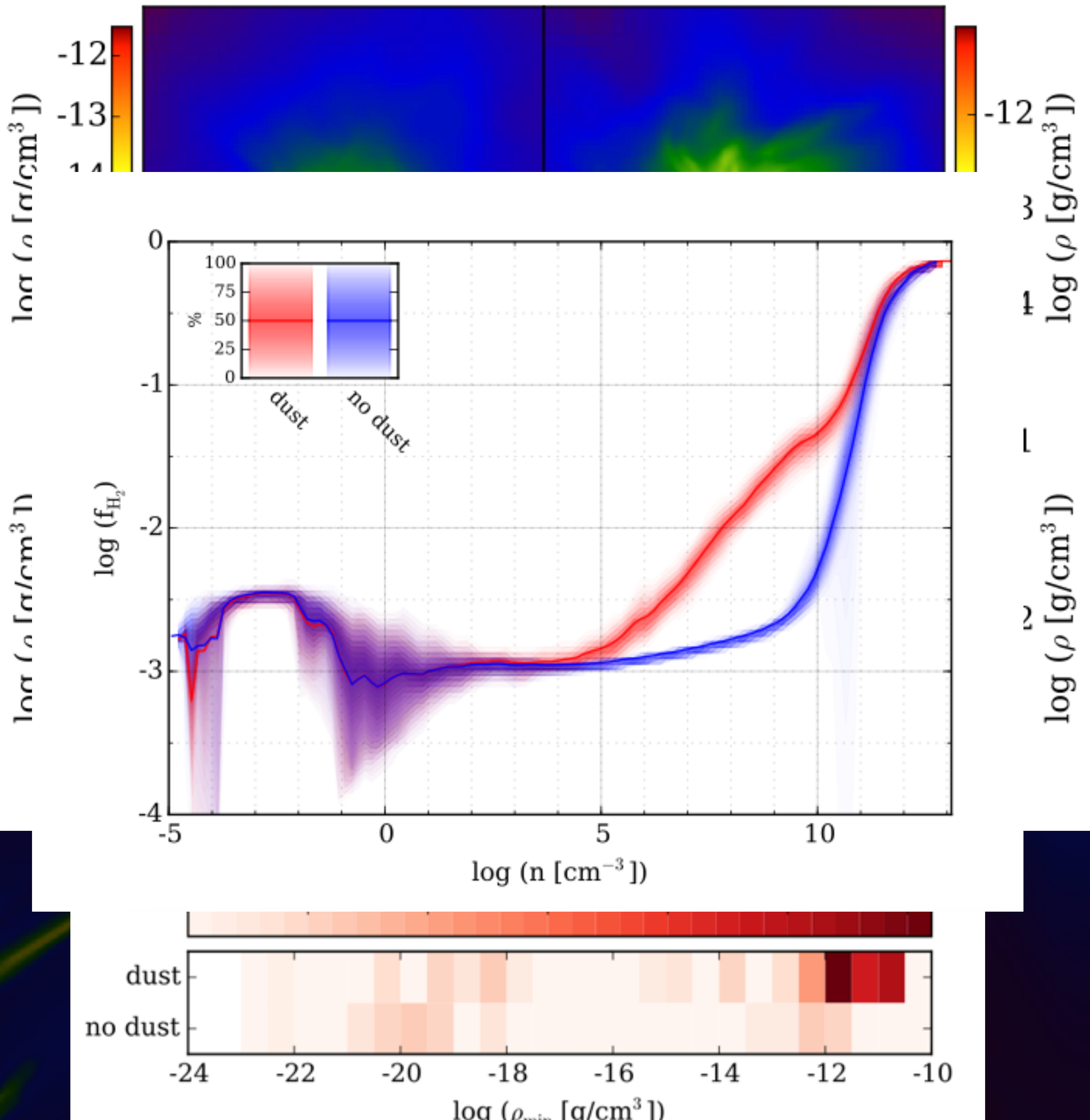
Metal mixing

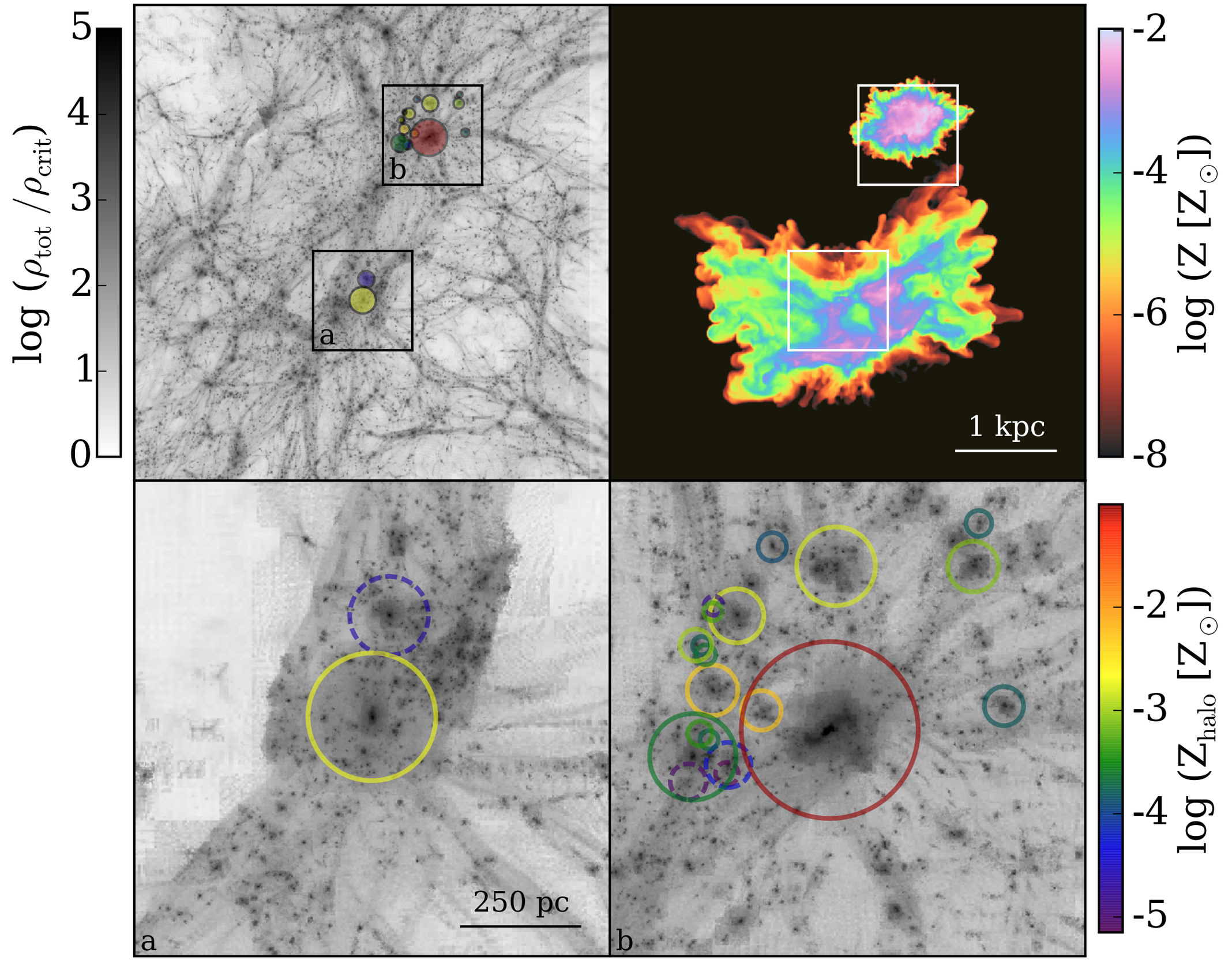
Physical timescales

Smith et al. 2015 (submitted; arXiv:1504.07639)


log (ρ [g/cm^3])
-12
-13
-14
-15
-16
-17
0.012 pc
2500 AU
250 AU
log (ρ [g/cm^3])
-11
-12
25 AU
dust
no dust


N
0
5
10
15
20
25
30
dust
no dust
-24
-22
-20
-18
-16
-14
-12
-10
log (ρ_{min} [g/cm^3])

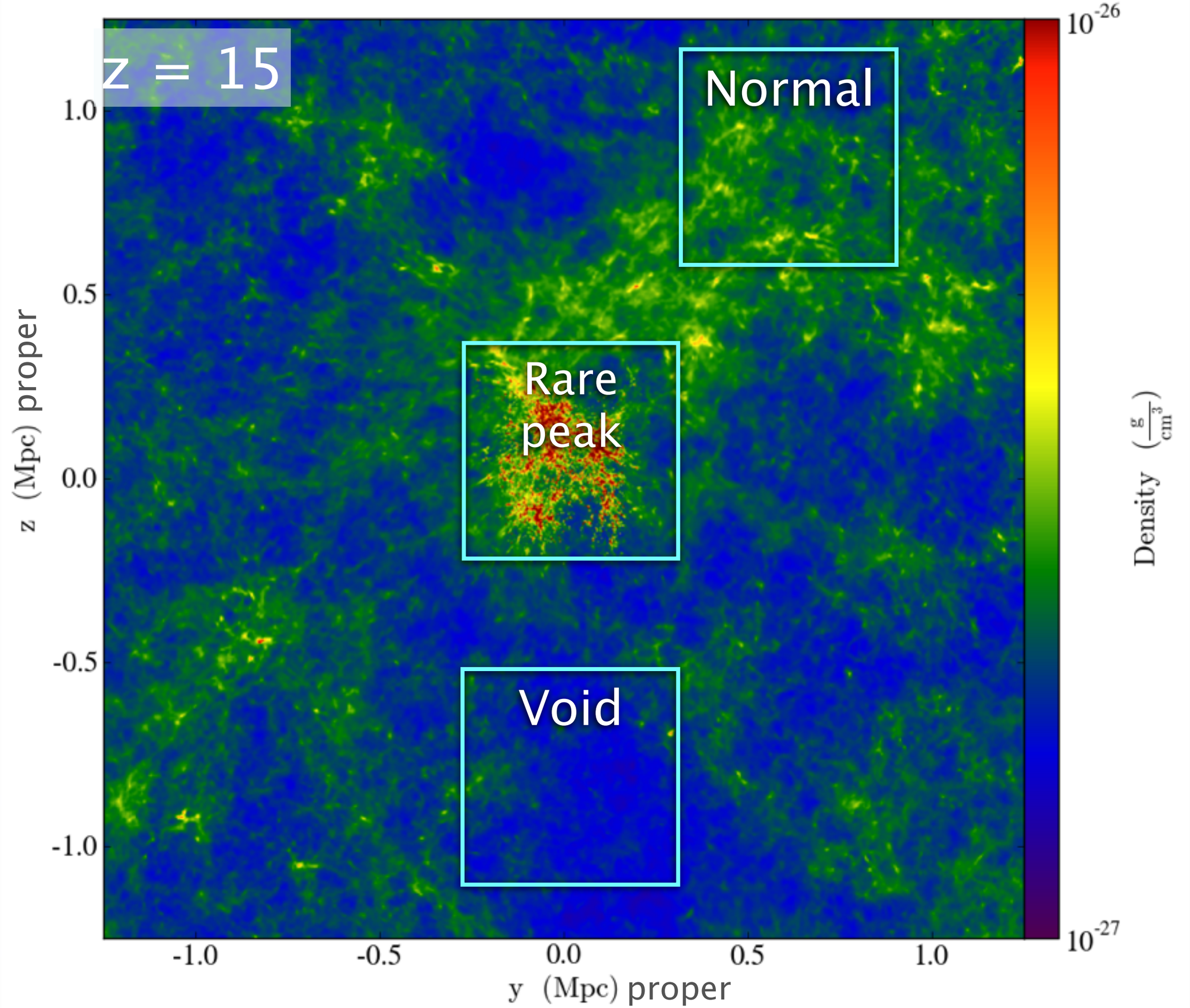

-12
-13
-14
log (ρ [g/cm³])
-12
log (ρ [g/cm³])
0
-1
-2
-3
-4
log (f_H2)
100
75
50
25
0
%
dust
no dust
-5
0
5
10
log (n [cm⁻³])
dust
no dust
-24
-22
-20
-18
-16
-14
-12
-10
log (ρ_min [g/cm³])


log ($\rho_{\rm tot}$ / $\rho_{\rm crit}$)
5
4
3
2
1
0
b
a
1 kpc
log (Z [$Z_\odot$])
-2
-4
-6
-8
250 pc
a
b
log ($Z_{\rm halo}$ [$Z_\odot$])
-2
-3
-4
-5

Evolution of early galaxy populations

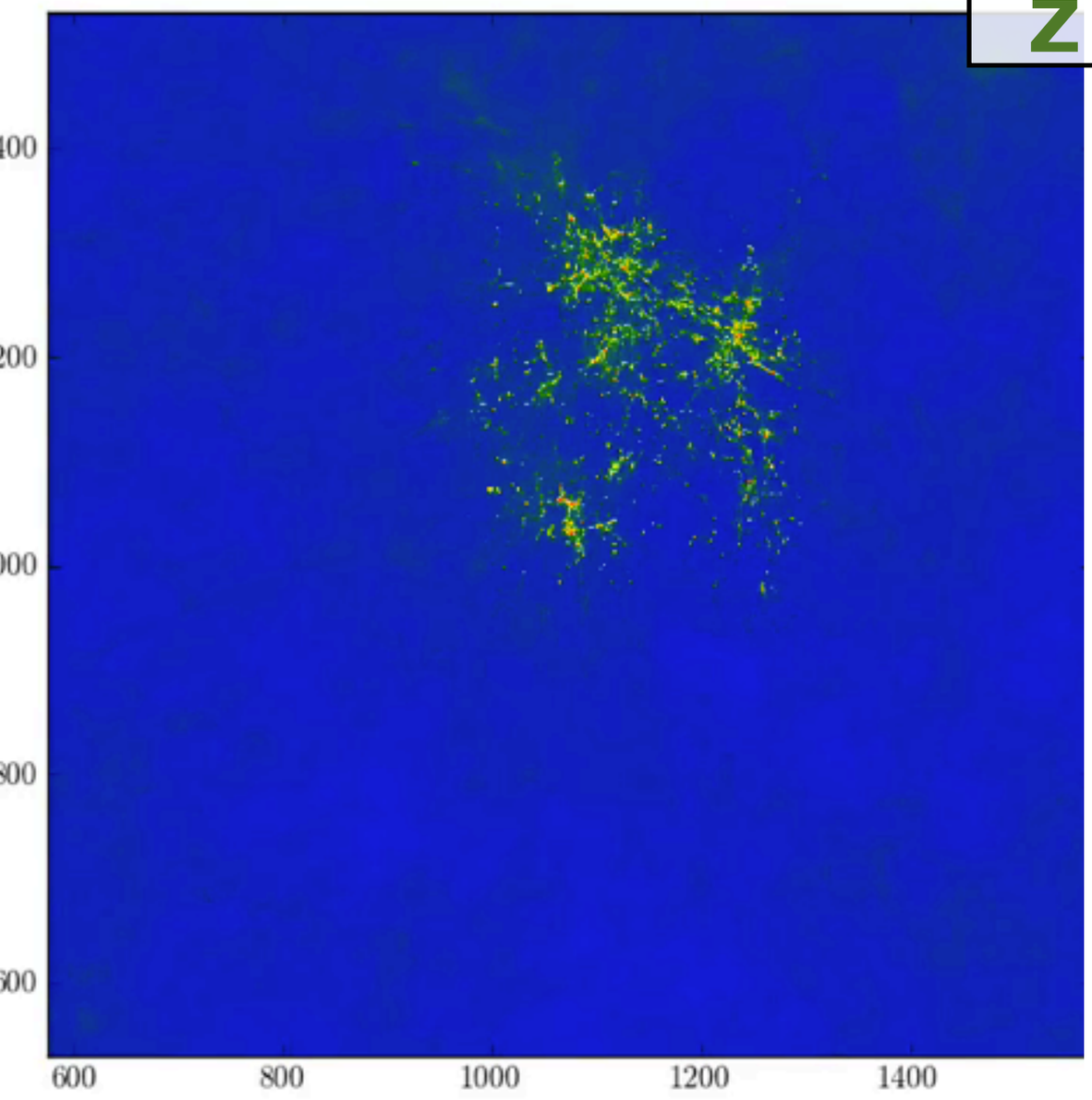
- **Large volume:** 40 Mpc box, refine on three separate ~300 Mpc^3 regions (overdense, average, low density)
- **High resolution:** Simulation at 12 levels of AMR (19 comoving pc), primordial + metal-enriched chemistry, Pop III and metal-enriched SF
- **Lots of galaxies:** 13,000 Pop III stars formed, ~3,000 halos > 10^7 $M_\odot$ (with star formation) by end of simulations

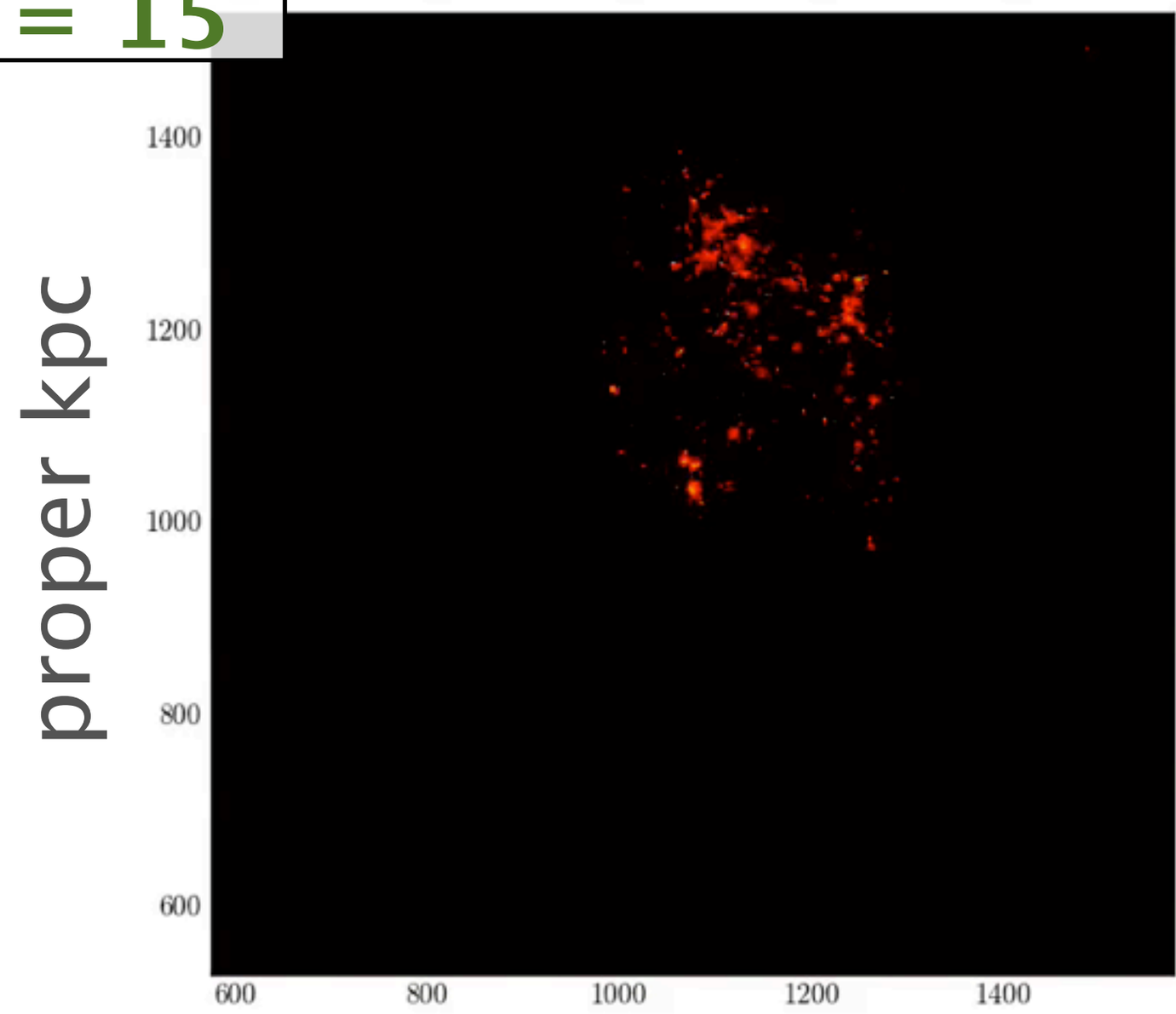
Xu et al. 2014, 15; Ahn et al. 2015;
Chen et al. 2014; O'Shea et al. 2015


z = 15
Normal
Rare peak
Void
1.0
0.5
0.0
-0.5
-1.0
z (Mpc) proper
-1.0
-0.5
0.0
0.5
1.0
y (Mpc) proper
10^{-26}
10^{-27}
Density $\left(\frac{g}{cm^3}\right)$

What's in the "rare peak" region?

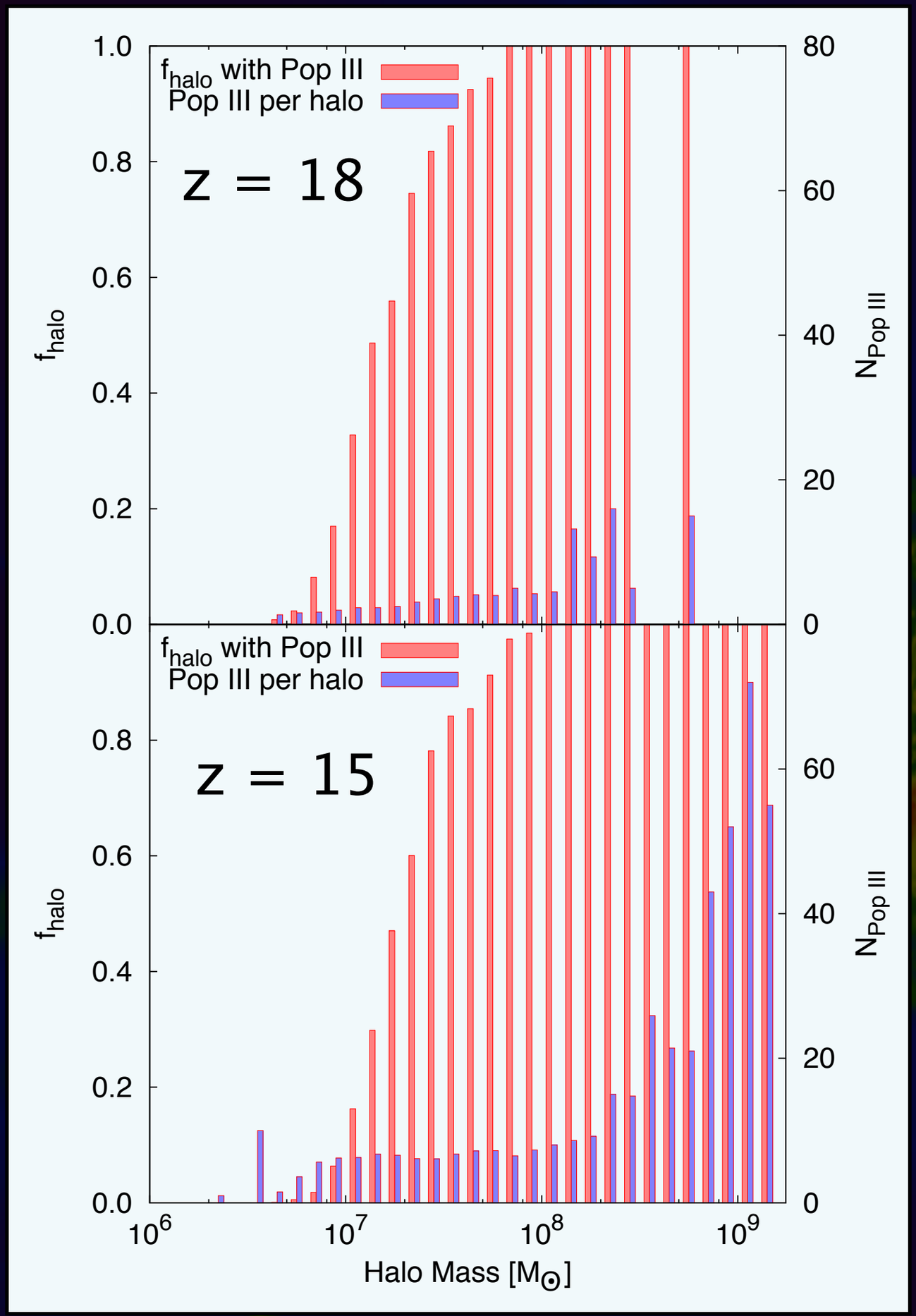
z = 15

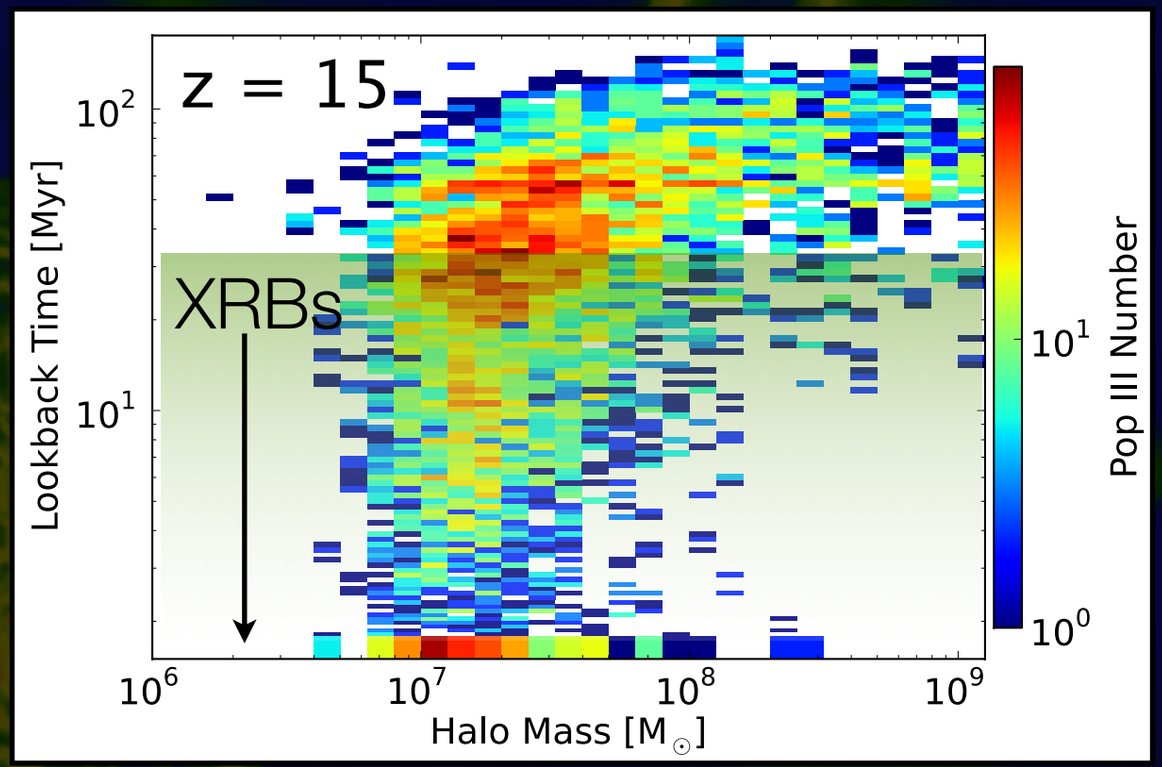




Projected Density
(scale: 3 x 10^{-28} – 3 x 10^{-24} g/cm^3)

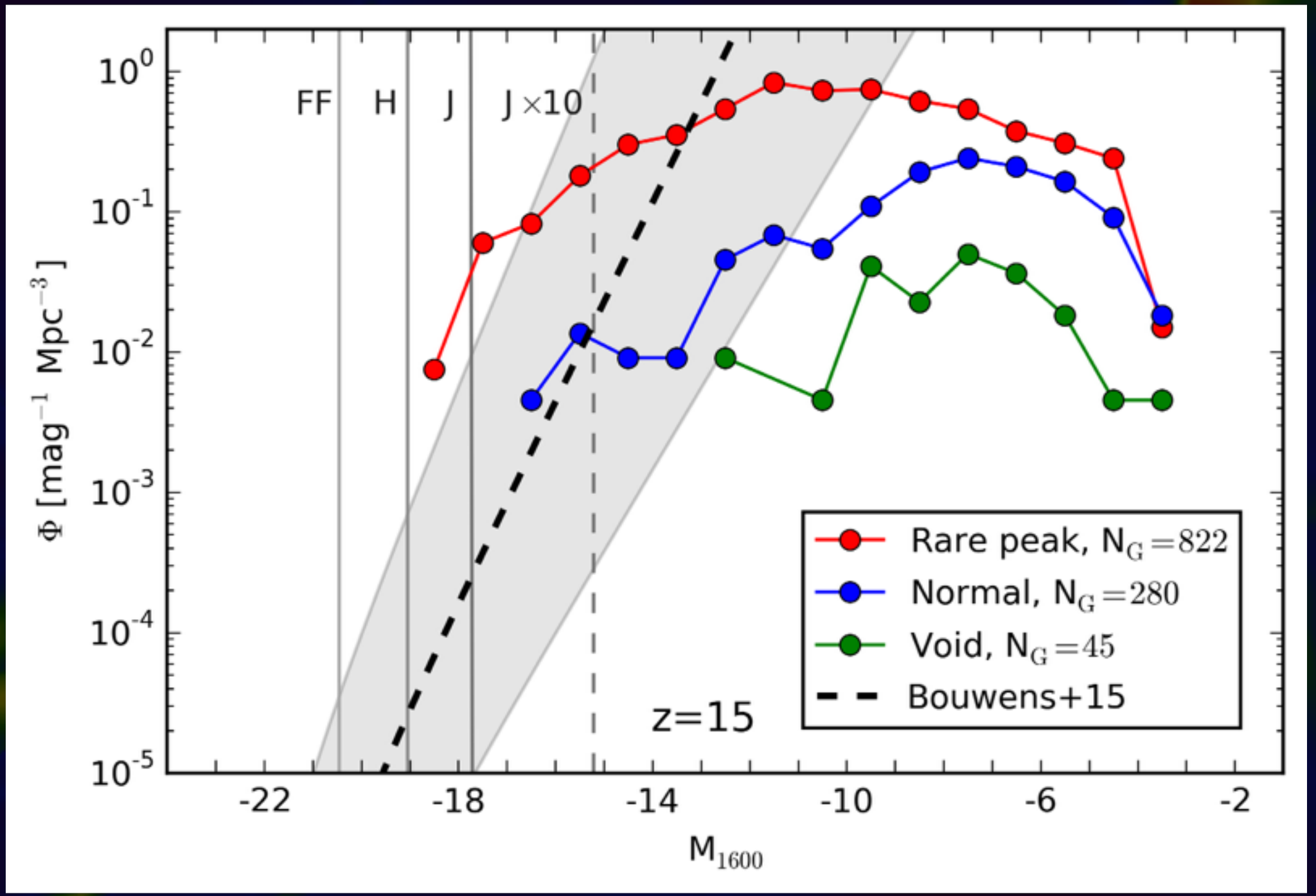
Projected Temperature
(scale: 10^3 – 3 x 10^4 K)





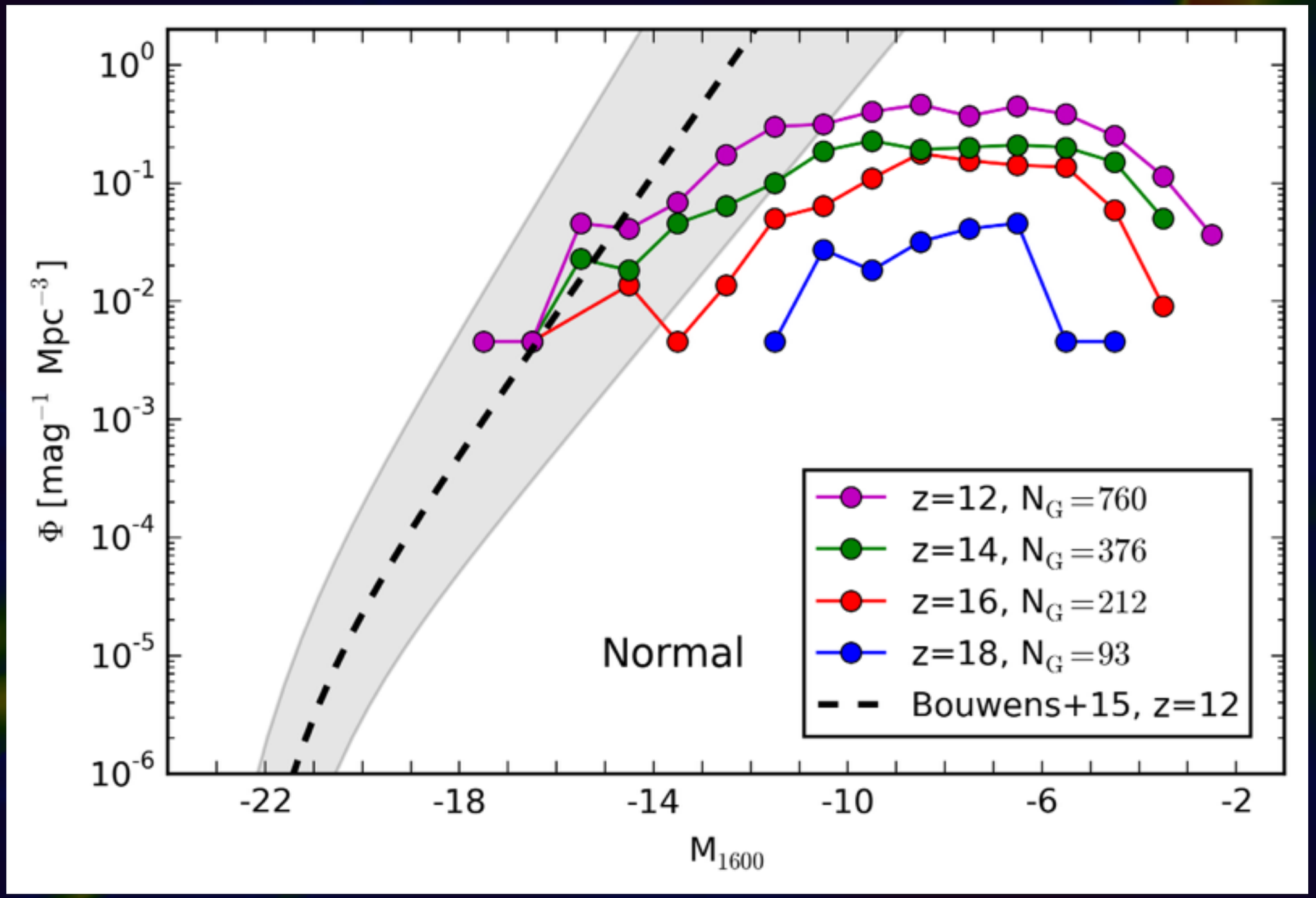
Xu et al. 2014,
ApJ, 791, 110

Luminosity function of early galaxies



O'Shea et al. 2015, ApJ, submitted (arXiv:1503.01110)

Luminosity function of early galaxies



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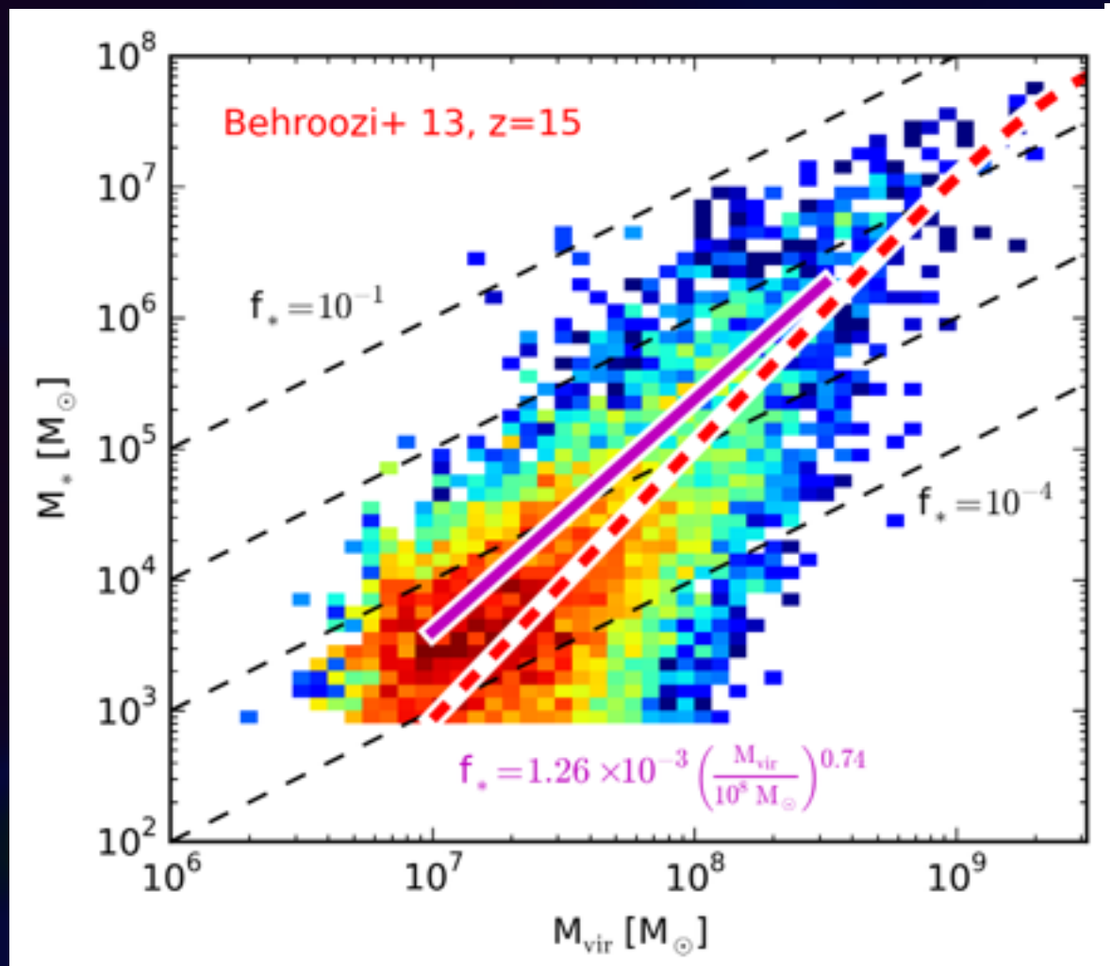
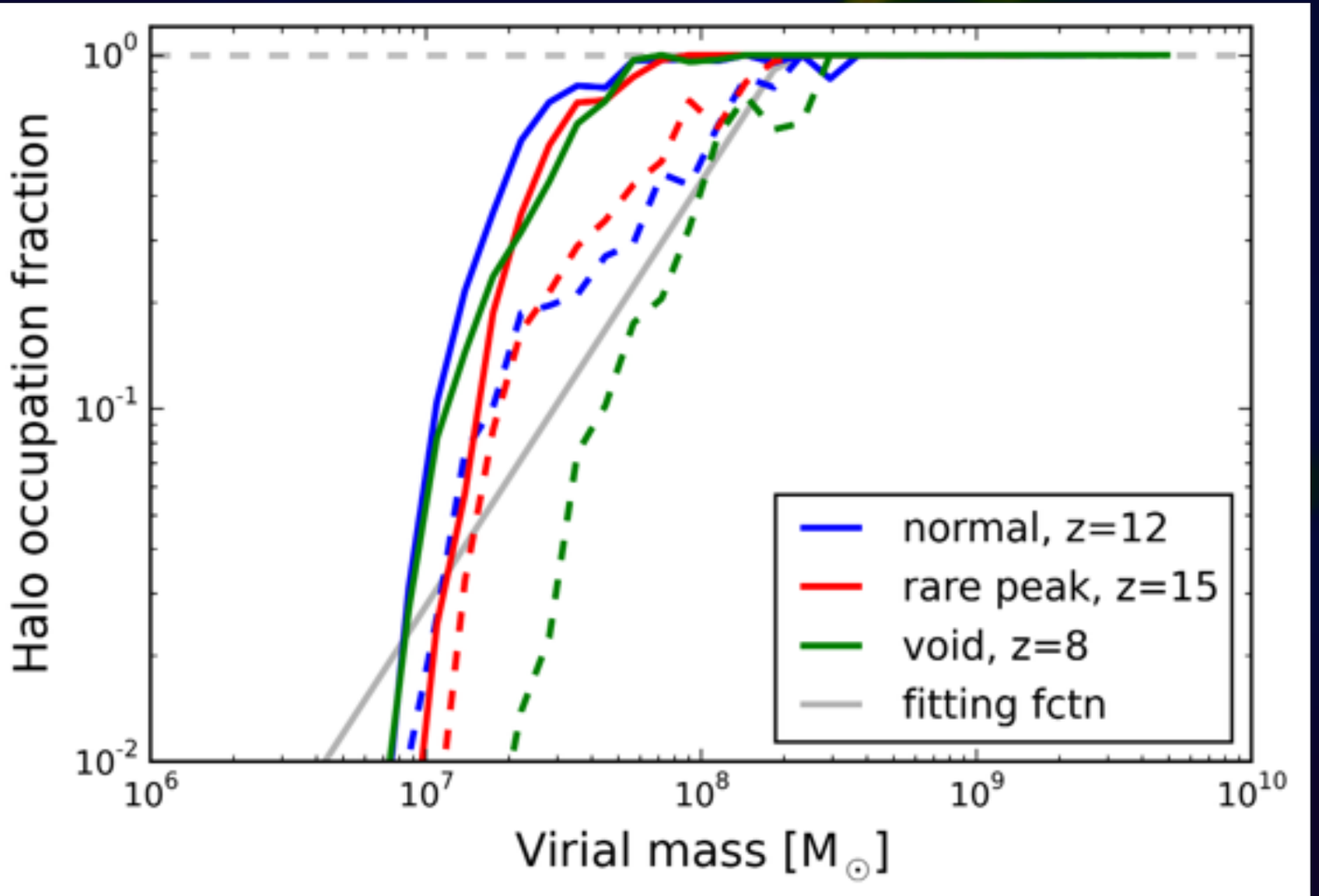
Luminosity function of early galaxies





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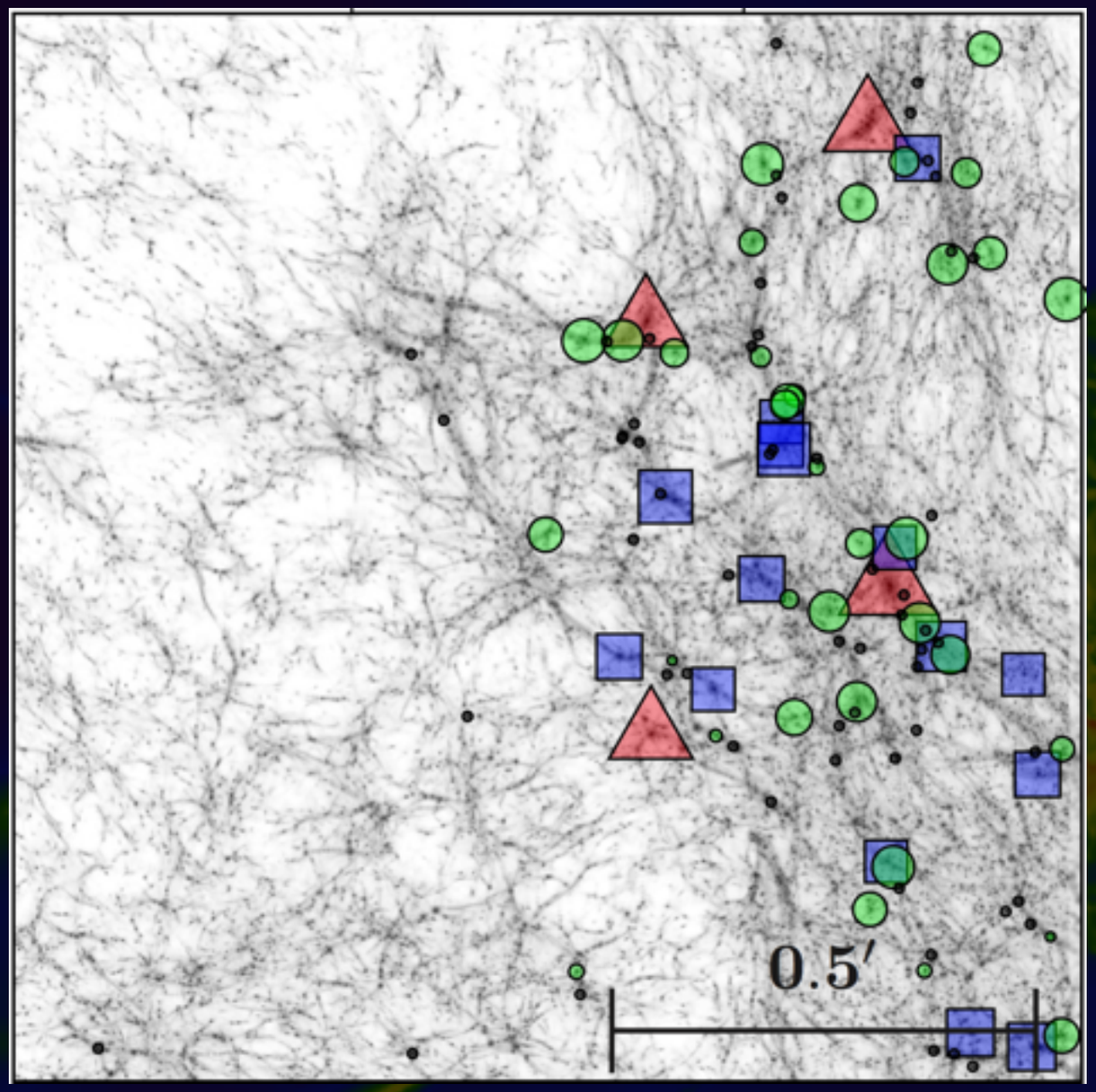
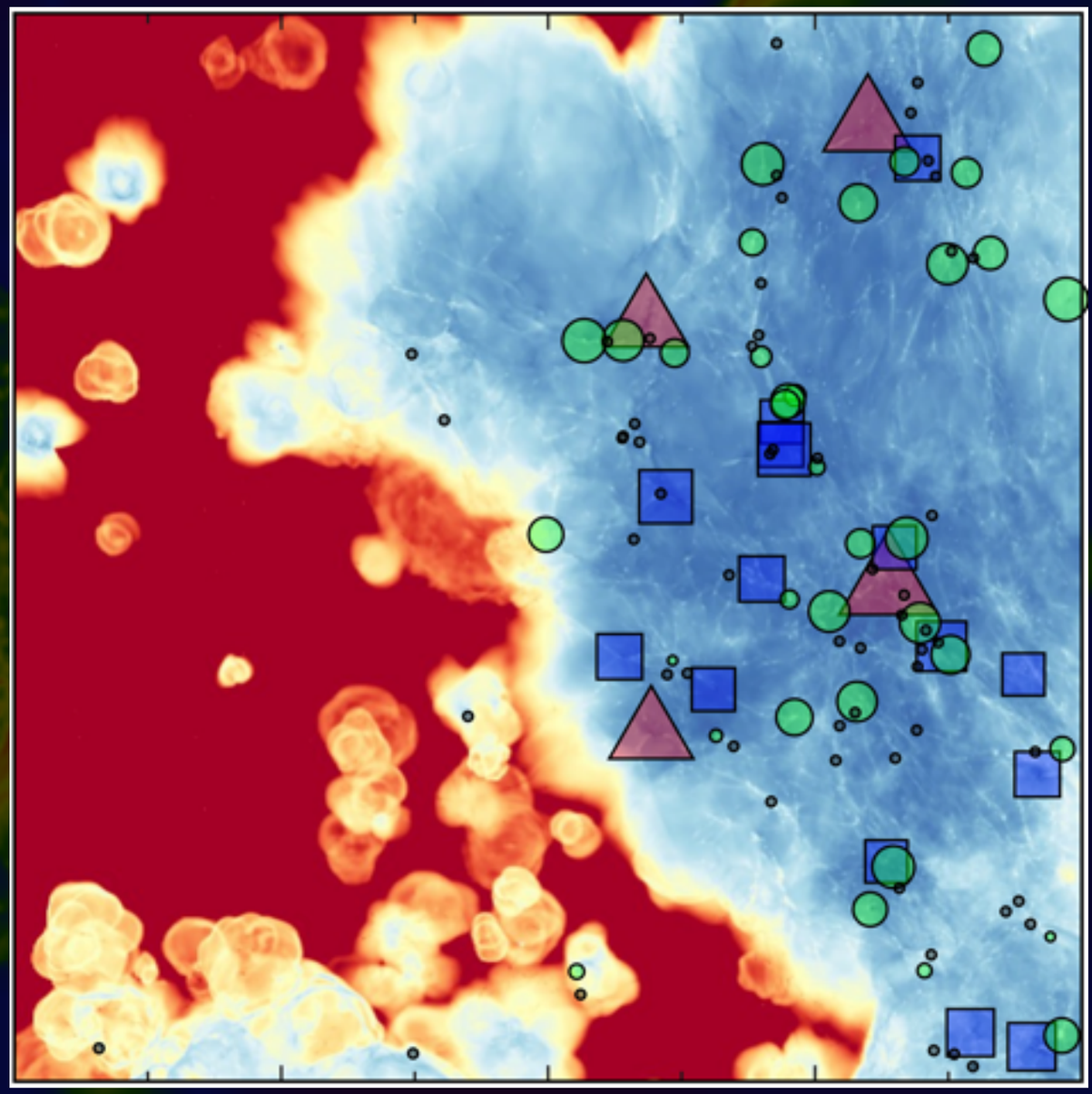
Luminosity function of early galaxies



Density



Electron fraction
(ionizing radiation)

Simulation data as a community resource

- Simulation tool (Enzo) and analysis/viz tool (yt) are open-source community codes.
- We are making all of our datasets (and resulting data products) publicly available via the National Data Service and NDS Labs.
- These simulations were very expensive and will be a community resource for years to come!

Cutting-edge simulations have a long tail of utility!

Takeaways

- The transition between primordial and metal-enriched star formation is locally complex, and the outcome is strongly affected by the presence of dust.
- Multiple Pop III stellar remnants wind up in each high-sigma halo: X-ray binaries? SMBH progenitors?
- Star formation is inefficient (and sometimes suppressed entirely) in small, high-z galaxies - turnover in UV luminosity function predicted.
- This would have been undoable without a machine like Blue Waters: memory, interconnect, fast IO.