

The Universe in a Box:

Studying galaxies with supercomputers

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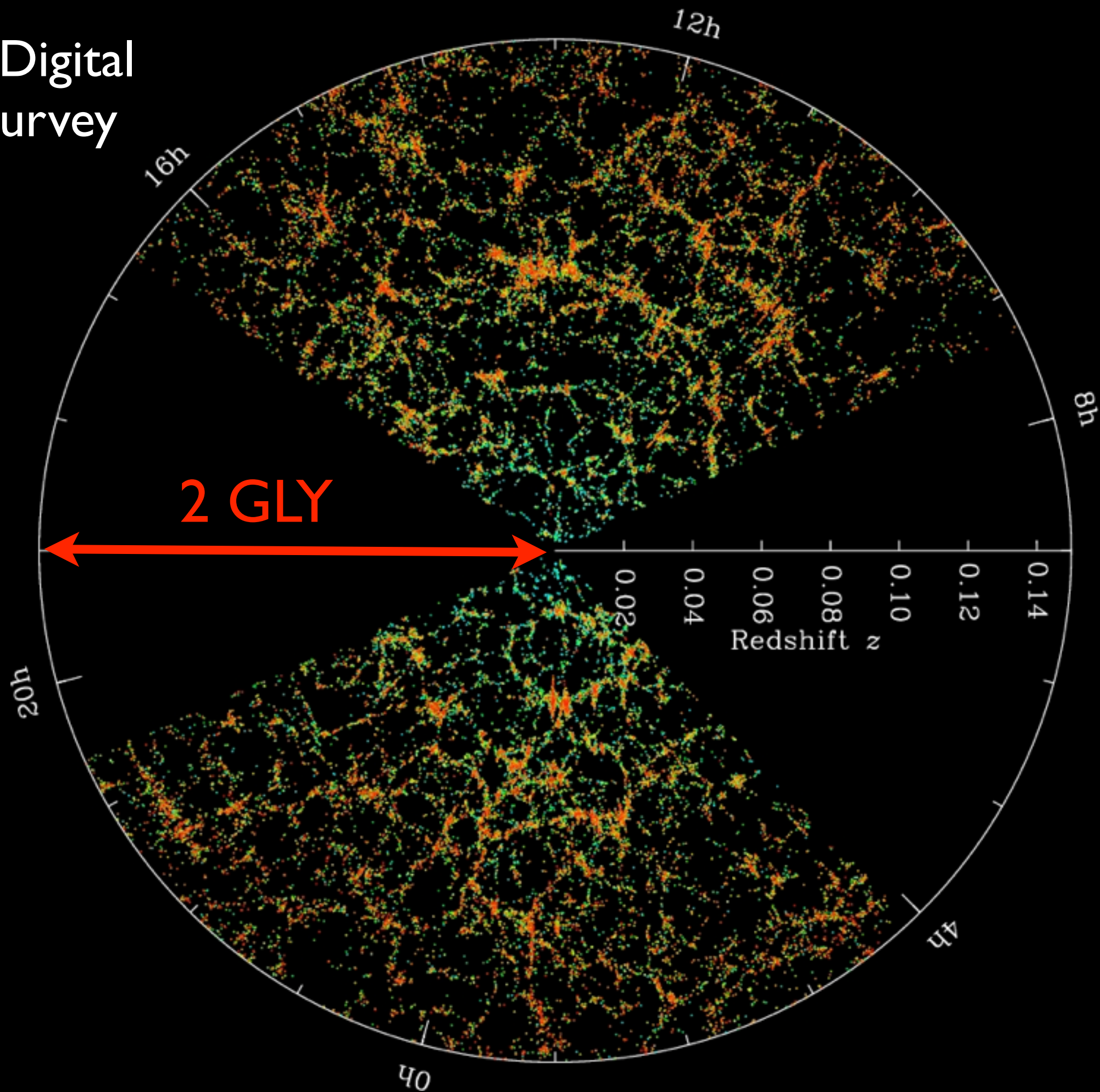
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Big questions

- What do the first stars and galaxies look like?
- How do Milky Way-type galaxies form and evolve?
- How does environment affect galaxy formation (and vice versa)?

What is cosmological structure?

Sloan Digital Sky Survey



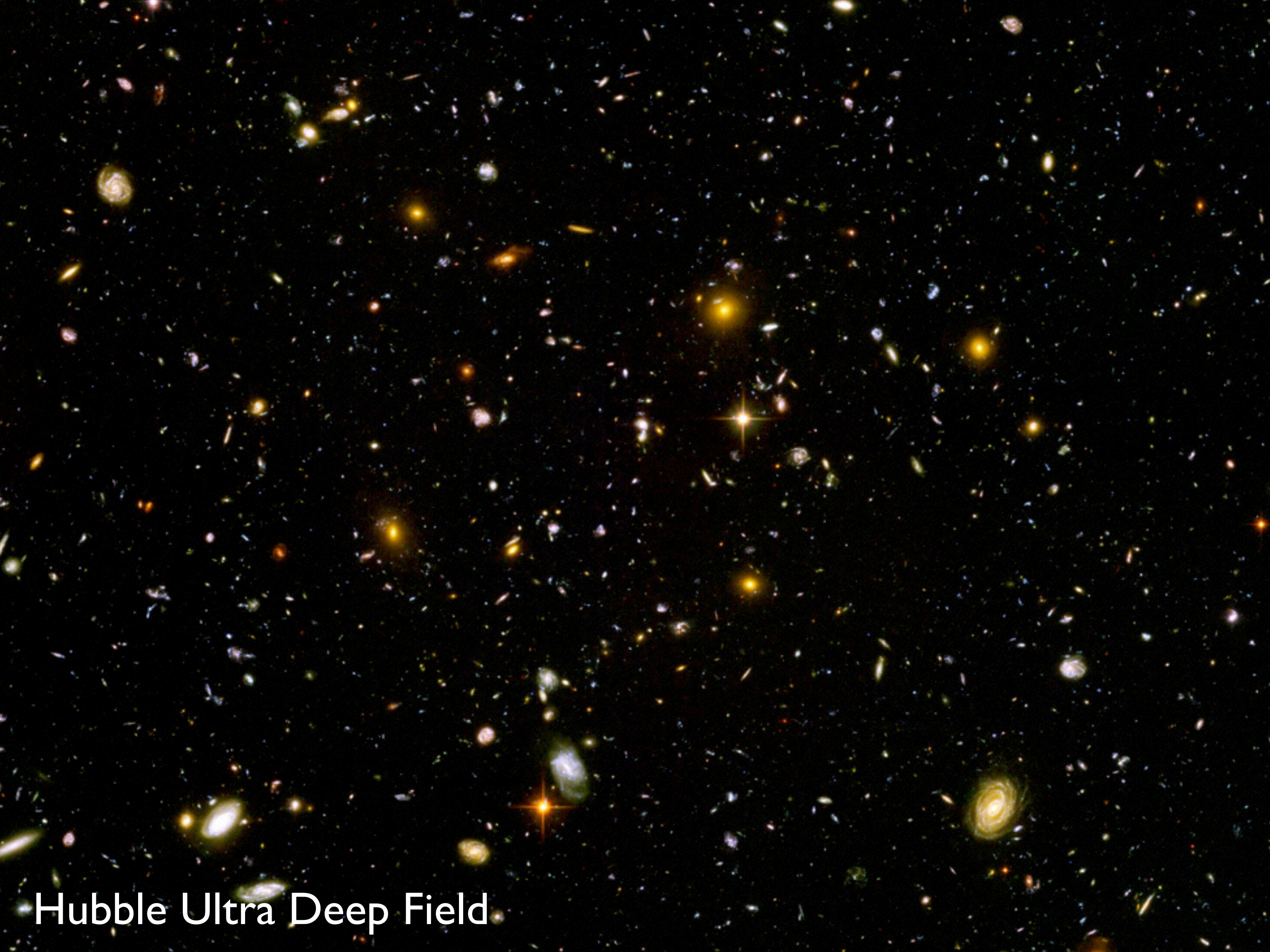




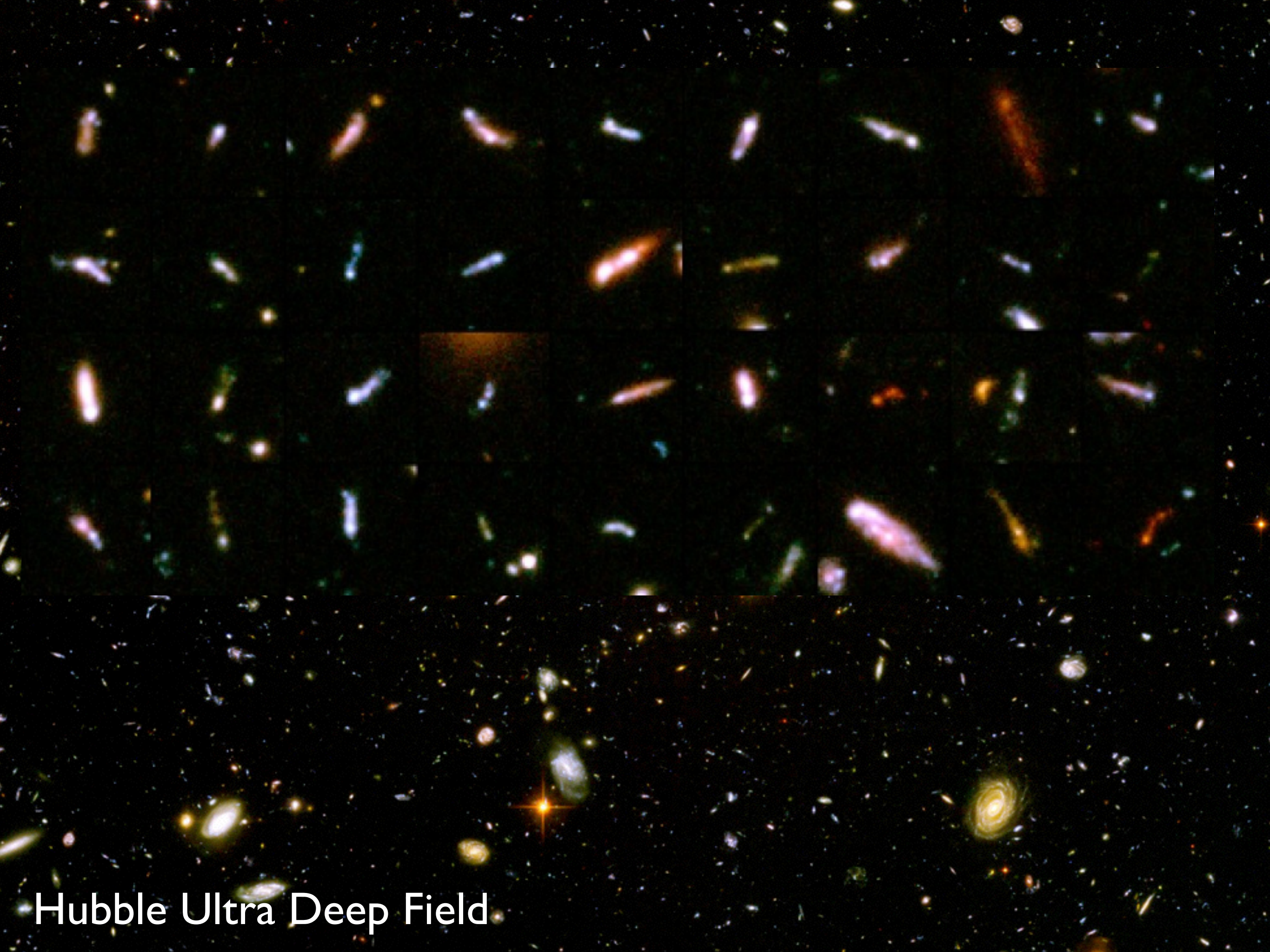
M31/Andromeda



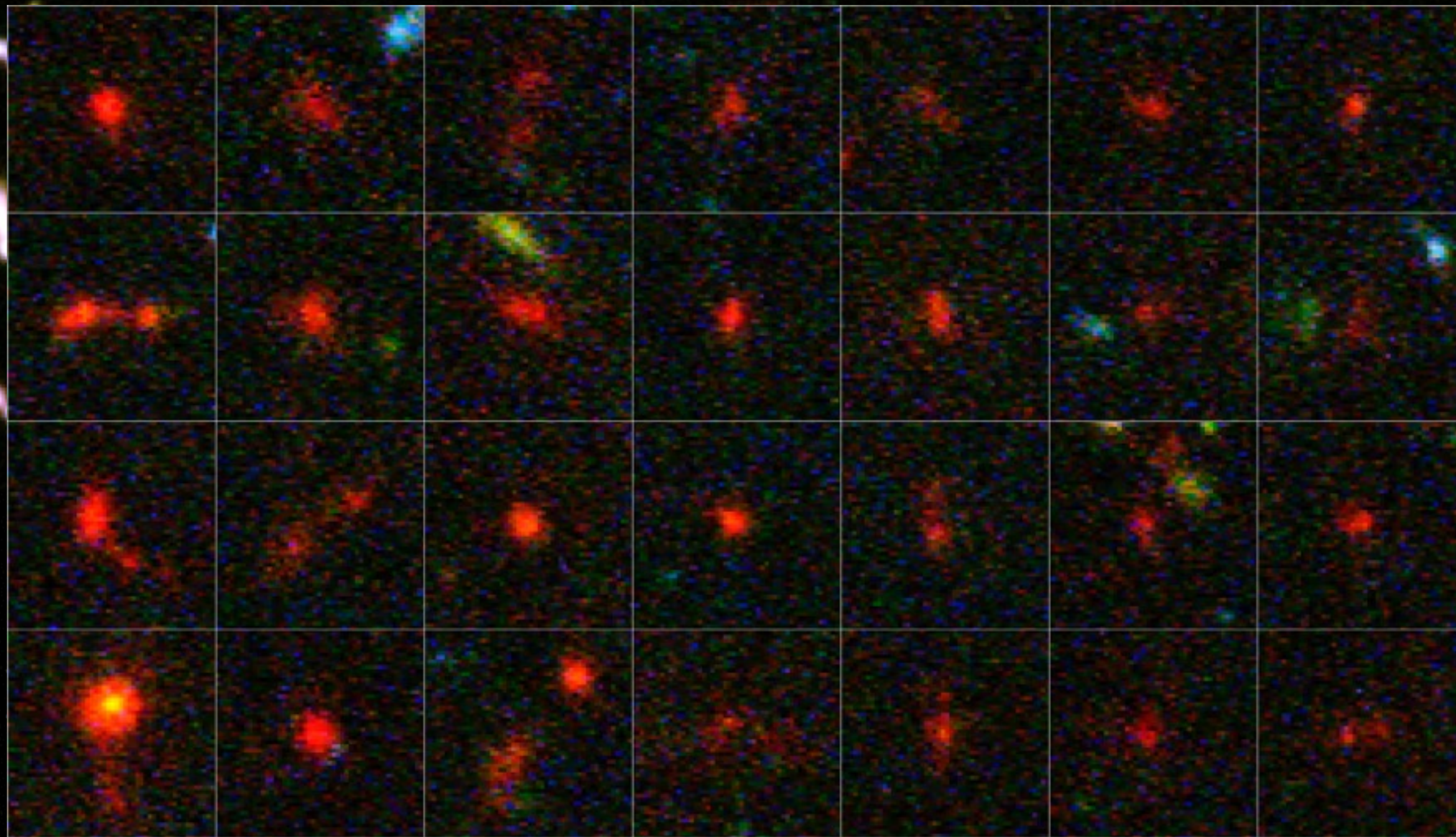
NGC 147



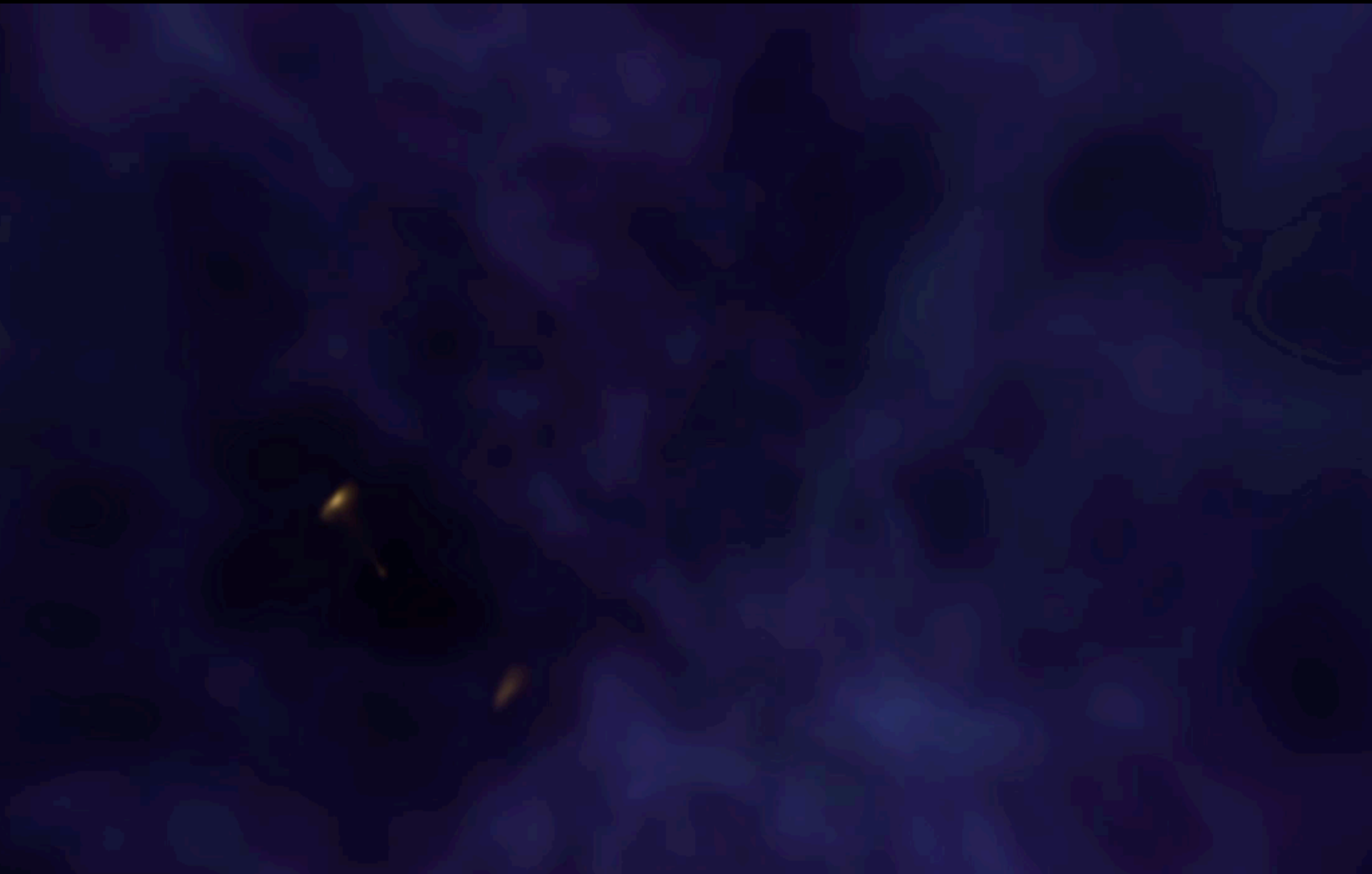
Hubble Ultra Deep Field



Hubble Ultra Deep Field



Hubble Ultra Deep Field



Movie c/o NCSA Advanced Visualization Laboratory

Why is galaxy formation
interesting?

Why is studying galaxy
formation challenging?

Complex physics

- Cosmology
- Gravity
- Hydrodynamics
- Heating and cooling of gas
- Formation and feedback of stars & black holes
- Radiation transport
- Magnetic fields
- Etc...

Dynamic range

“Fair sample” of the universe: 10^8 ly

Milky Way and satellites: 10^6 ly

Star-forming cloud: 10^2 ly

Factor of 10^6 !

Age of universe: $\sim 10^{10}$ years

Evolutionary times for
star-forming regions: $\sim 10^4$ years

Factor of 10^6 !

Statistics and sampling



Outcome: a supercomputer-worthy problem!



Our goal:

Understanding how galaxies
form, evolve, and interact with
their environments

Our simulation tool: The Enzo AMR code

<http://enzo-project.org>



[Intimidating equations slide]

$$\frac{\partial \rho}{\partial t} + \frac{1}{a} \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \frac{1}{a} \nabla \cdot \left(\rho \mathbf{v} \mathbf{v} + \mathbf{I} p^* - \frac{\mathbf{B} \mathbf{B}}{a} \right) = -\frac{\dot{a}}{a} \rho \mathbf{v} - \frac{1}{a} \rho \nabla \phi$$

$$\frac{\partial E}{\partial t} + \frac{1}{a} \nabla \cdot \left[(E + p^*) \mathbf{v} - \frac{1}{a} \mathbf{B} (\mathbf{B} \cdot \mathbf{v}) \right] = -\frac{\dot{a}}{a} \left(2E - \frac{B^2}{2a} \right) - \frac{1}{a} \mathbf{v} \cdot \nabla \phi - \Lambda + \Gamma + \frac{1}{a^2} \nabla \cdot \mathbf{F}_{\text{cond}}$$

$$\frac{\partial \mathbf{B}}{\partial t} - \frac{1}{a} \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

$$\frac{d\mathbf{x}}{dt} = \frac{1}{a} \mathbf{v},$$

$$\frac{d\mathbf{v}}{dt} = -\frac{\dot{a}}{a} \mathbf{v} - \frac{1}{a} \nabla \phi,$$

$$e = p / [(\gamma - 1) \rho]$$

$$\nabla^2 \phi = 4\pi G \rho_{\text{total}}$$

$$E = e + \frac{\rho v^2}{2} + \frac{B^2}{2a}$$

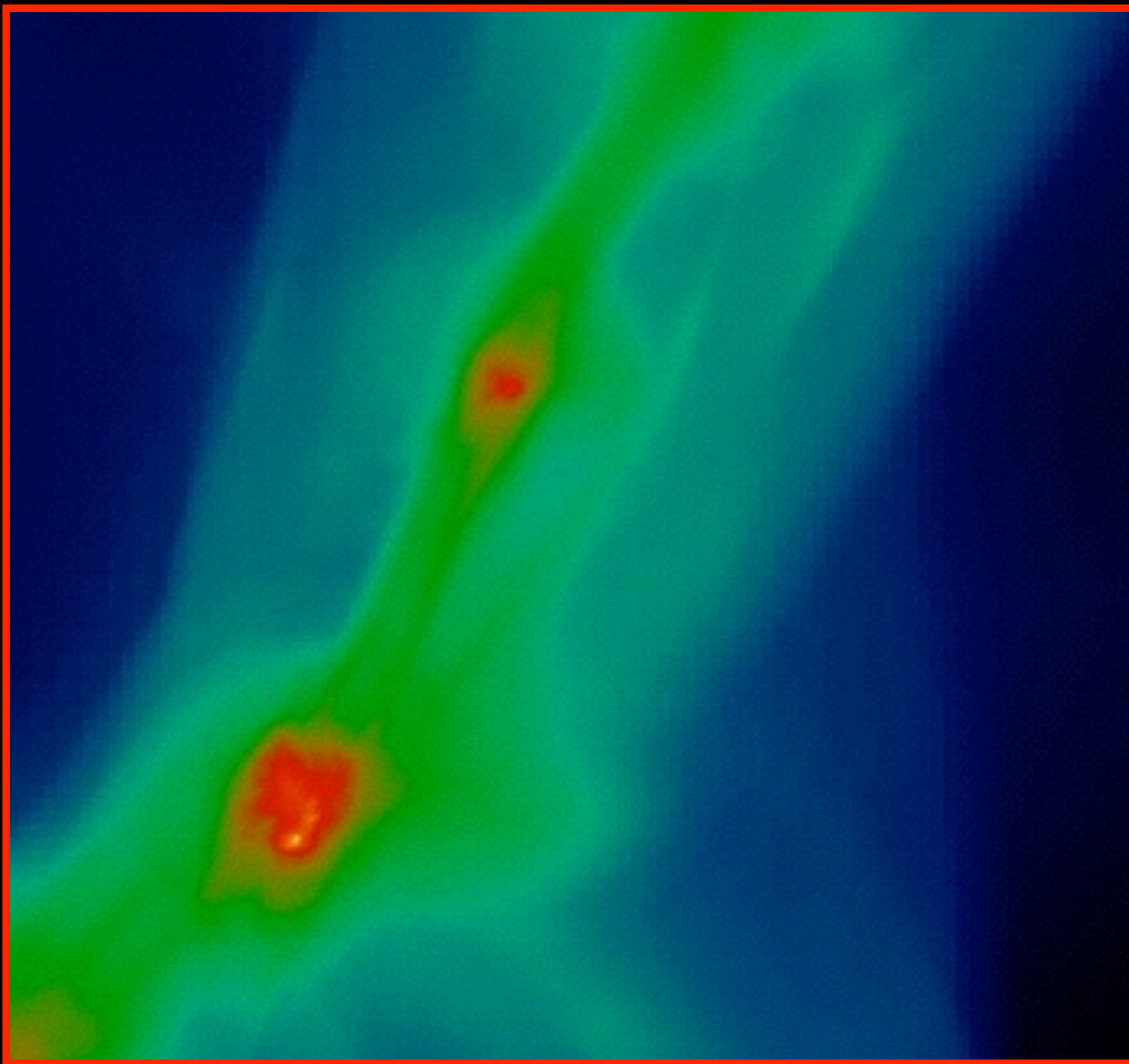
$$\frac{\partial E_r}{\partial t} + \frac{1}{a} \nabla \cdot (E_r \mathbf{v}) = \nabla \cdot (D \nabla E_r) - \frac{\dot{a}}{a} E_r - c\kappa E_r + \eta$$

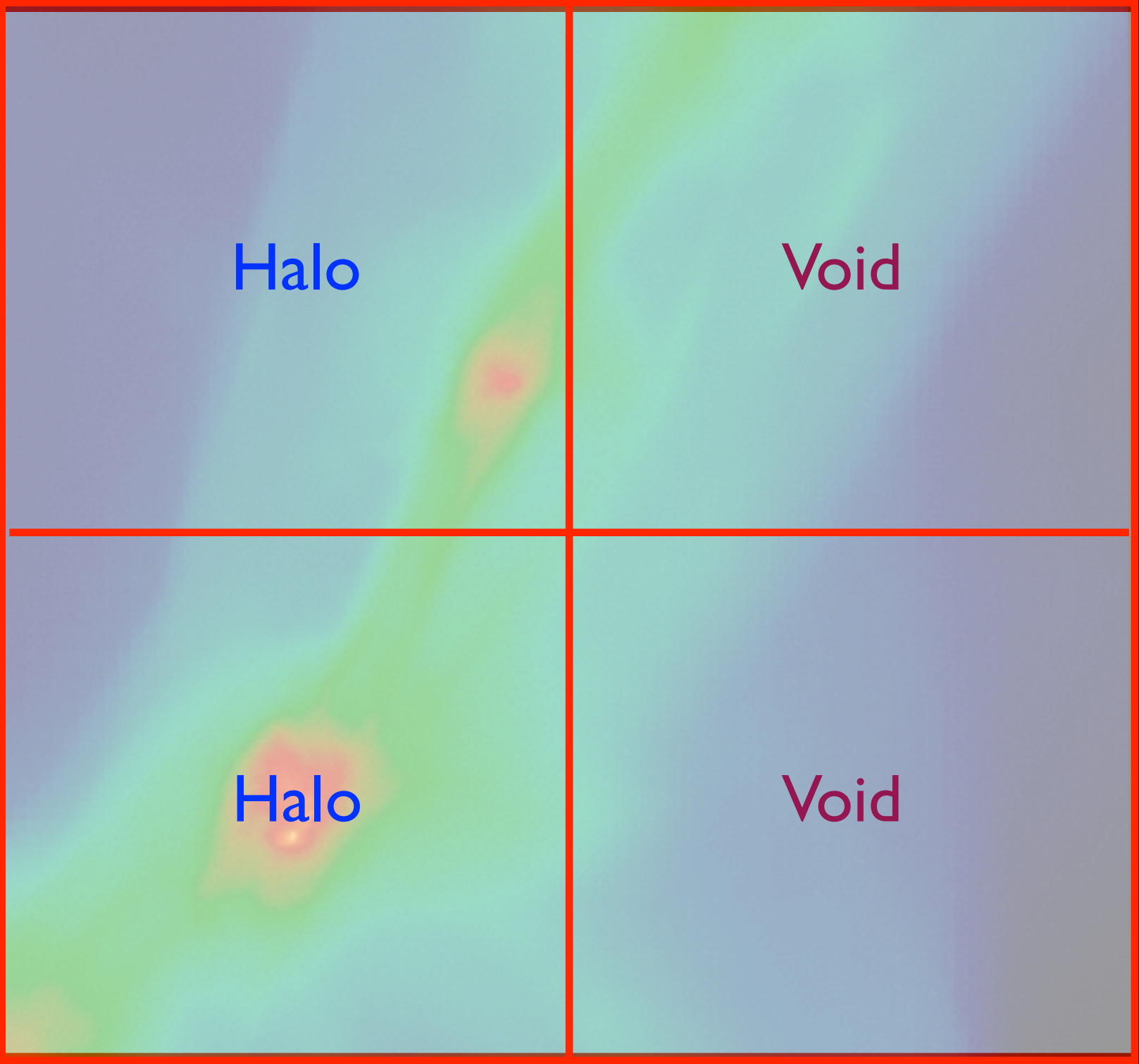
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3a^3} (\rho_0 + 3p_0/c^2) + \Lambda_c/3 \quad p^* = p + \frac{B^2}{2a}$$

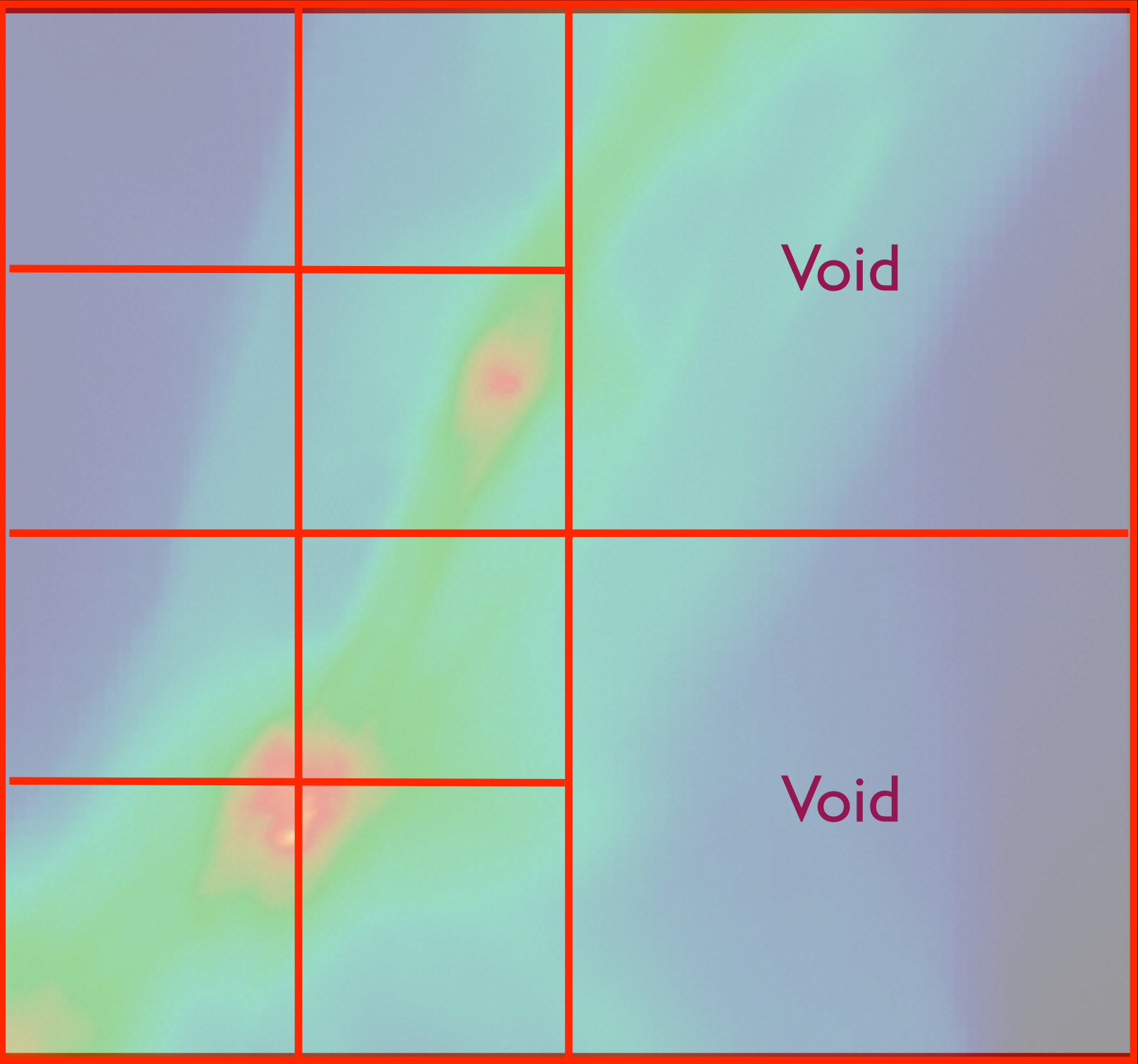
$$\frac{\partial n_i}{\partial t} + \frac{1}{a} \nabla \cdot (n_i \mathbf{v}) = k_{ij}(T) n_i n_j + \Gamma_j^{ph} n_j$$

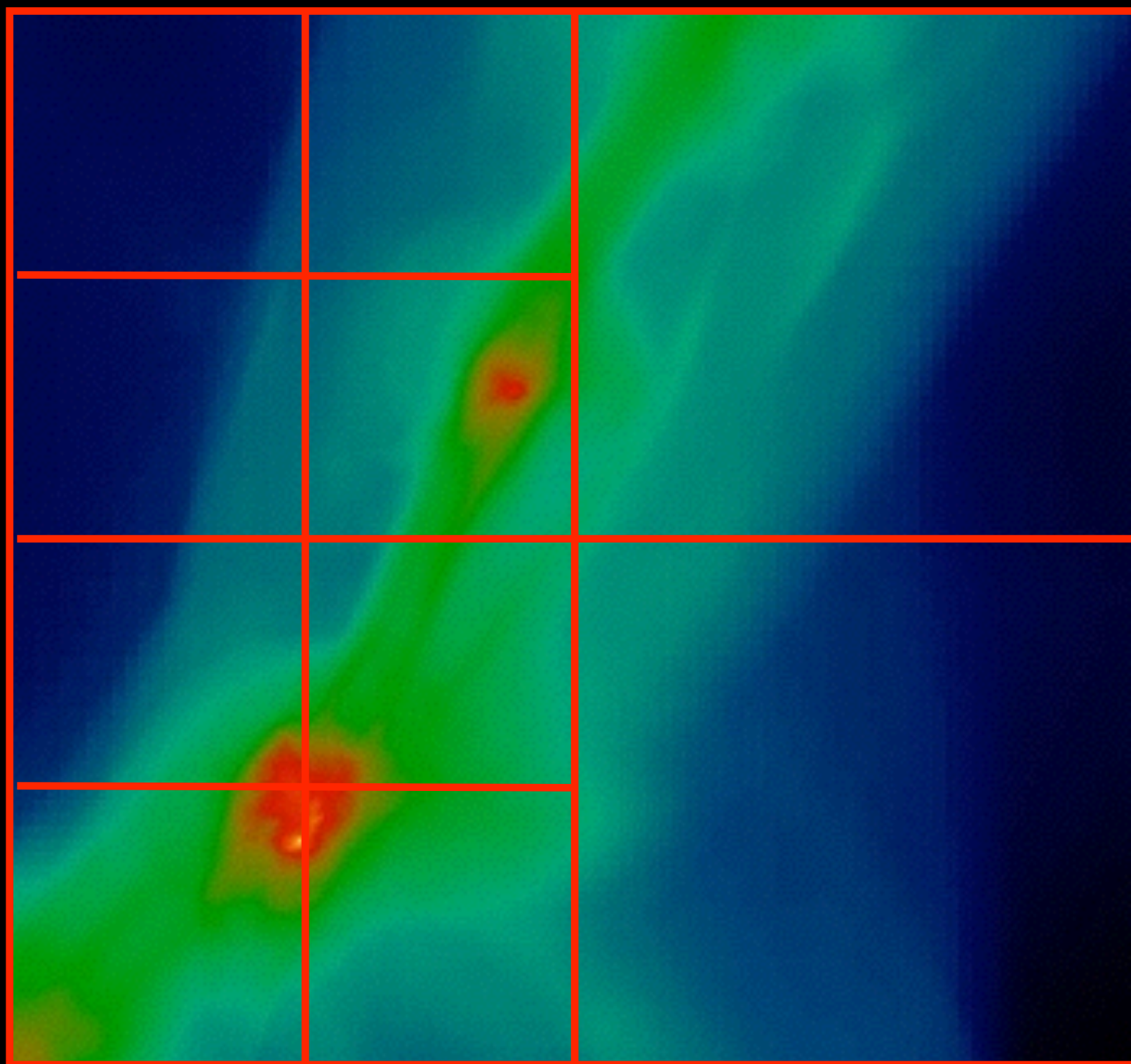
Schematic example of AMR

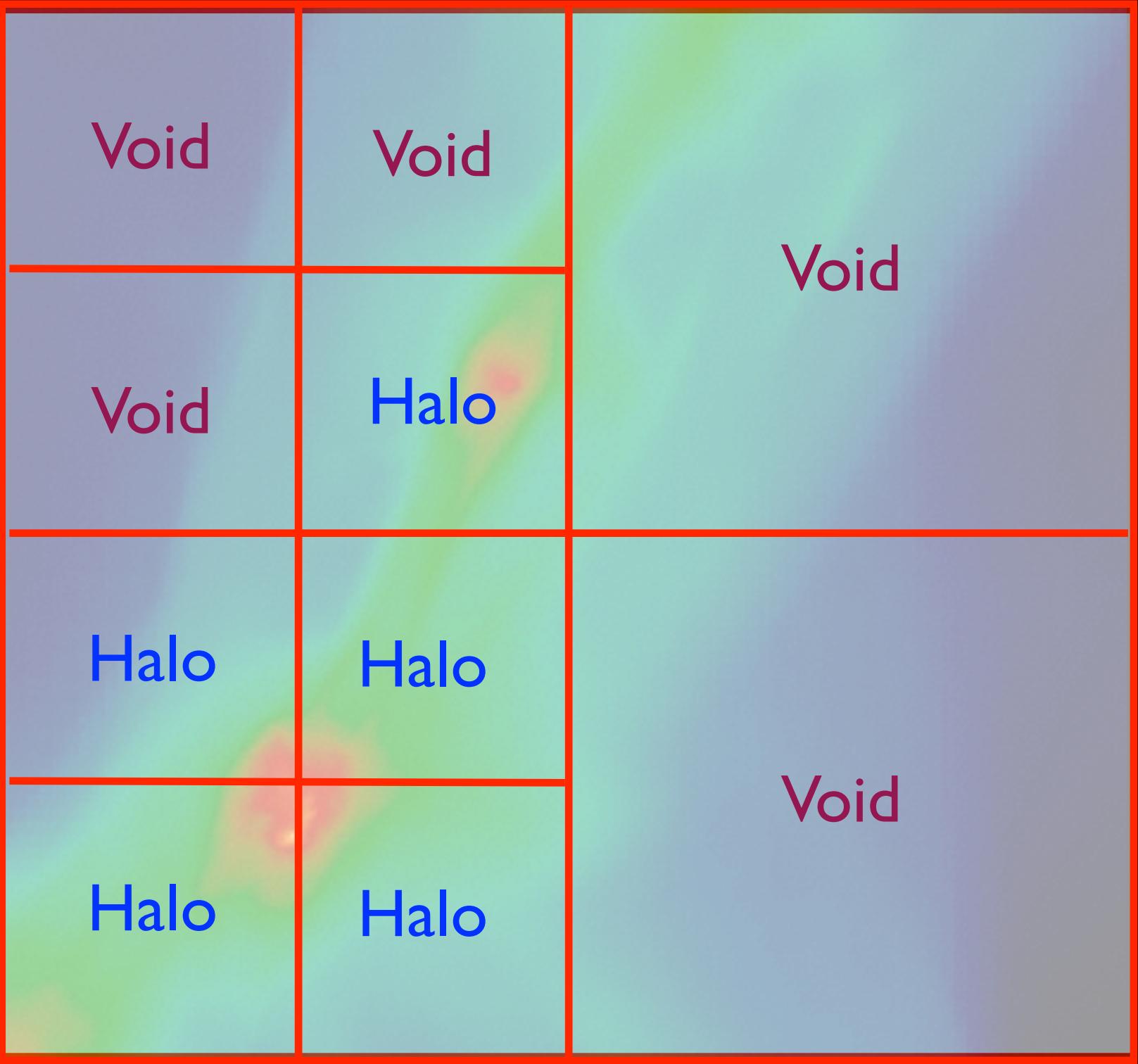
Simulation volume

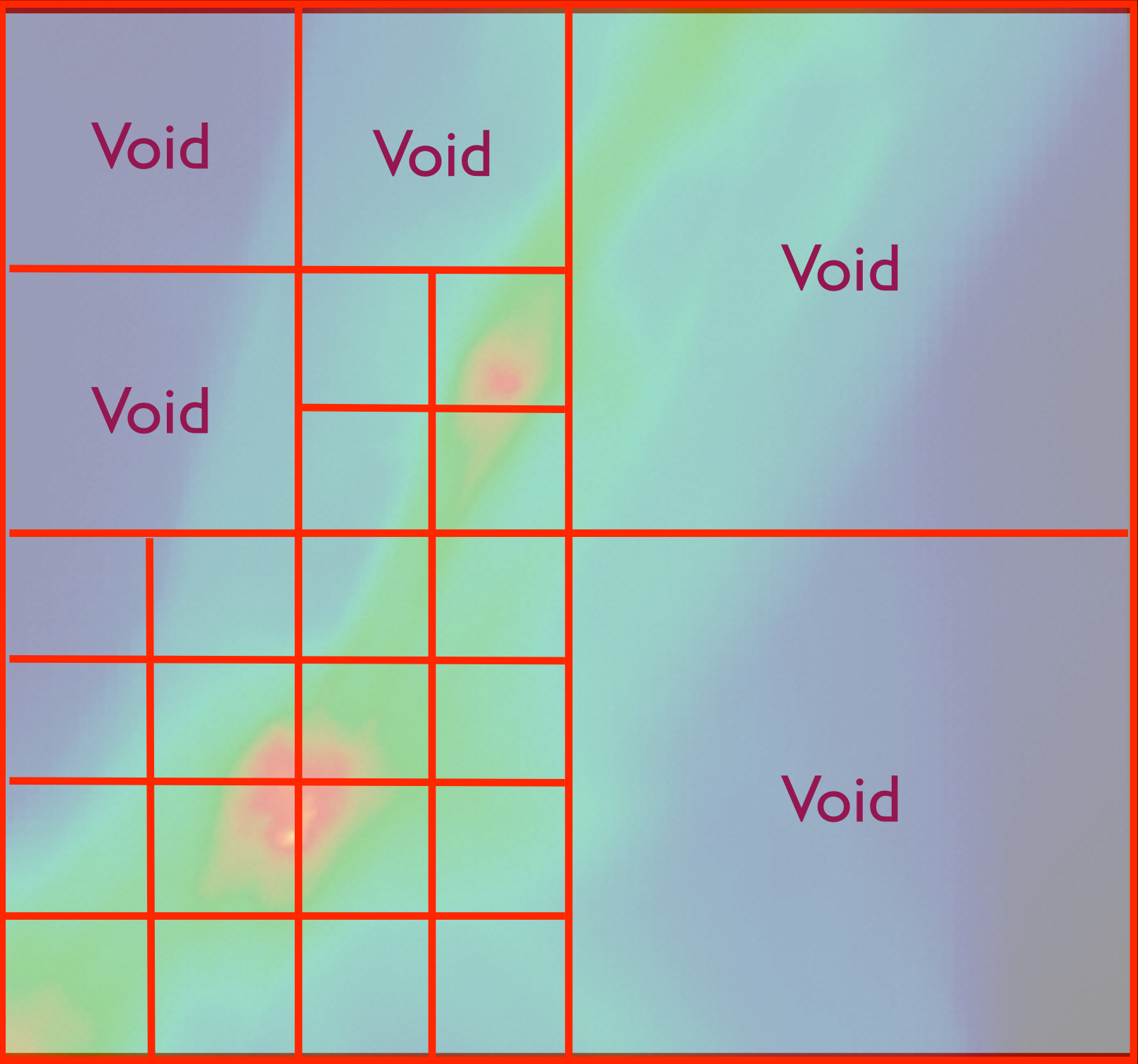


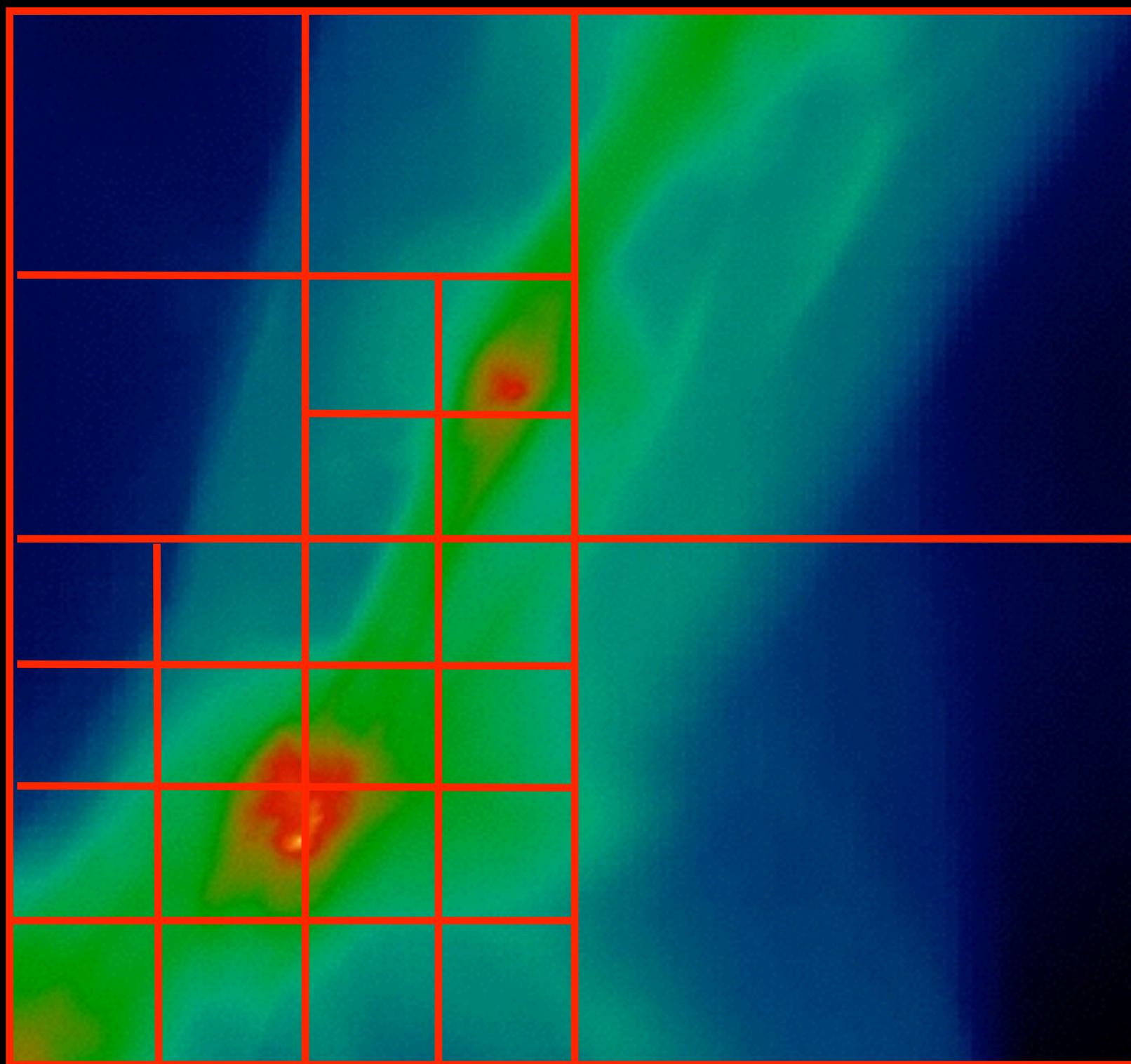


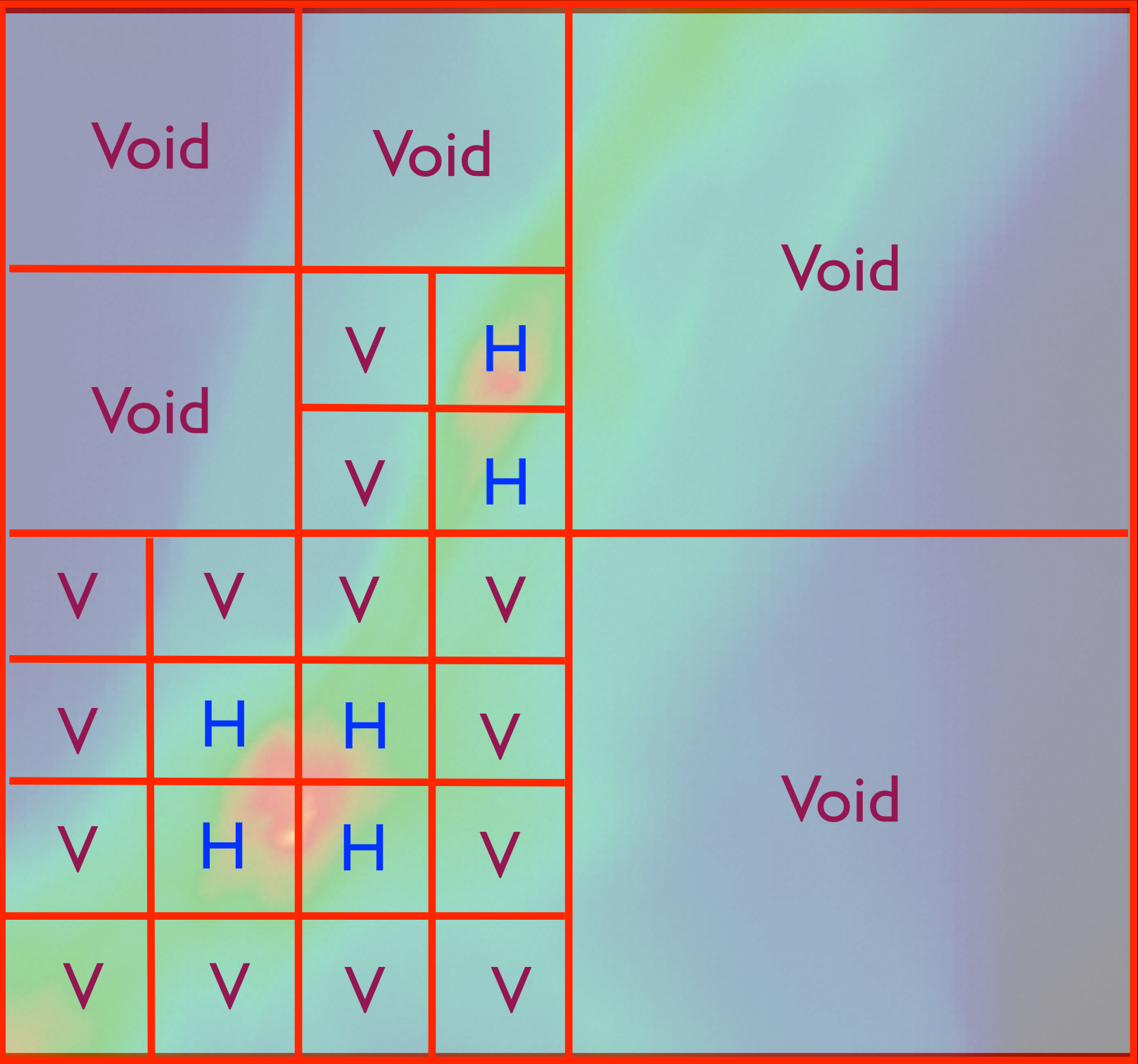


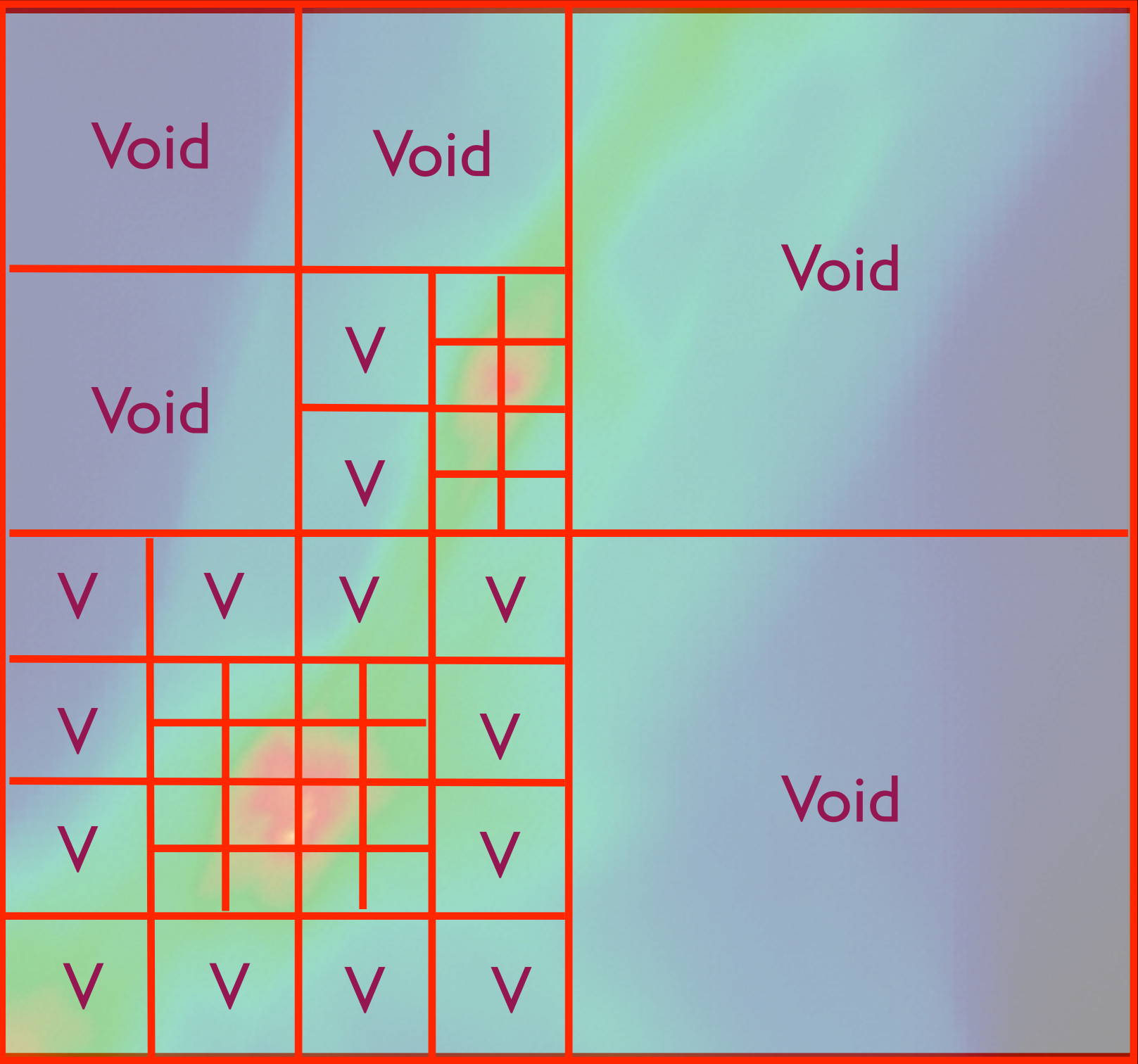


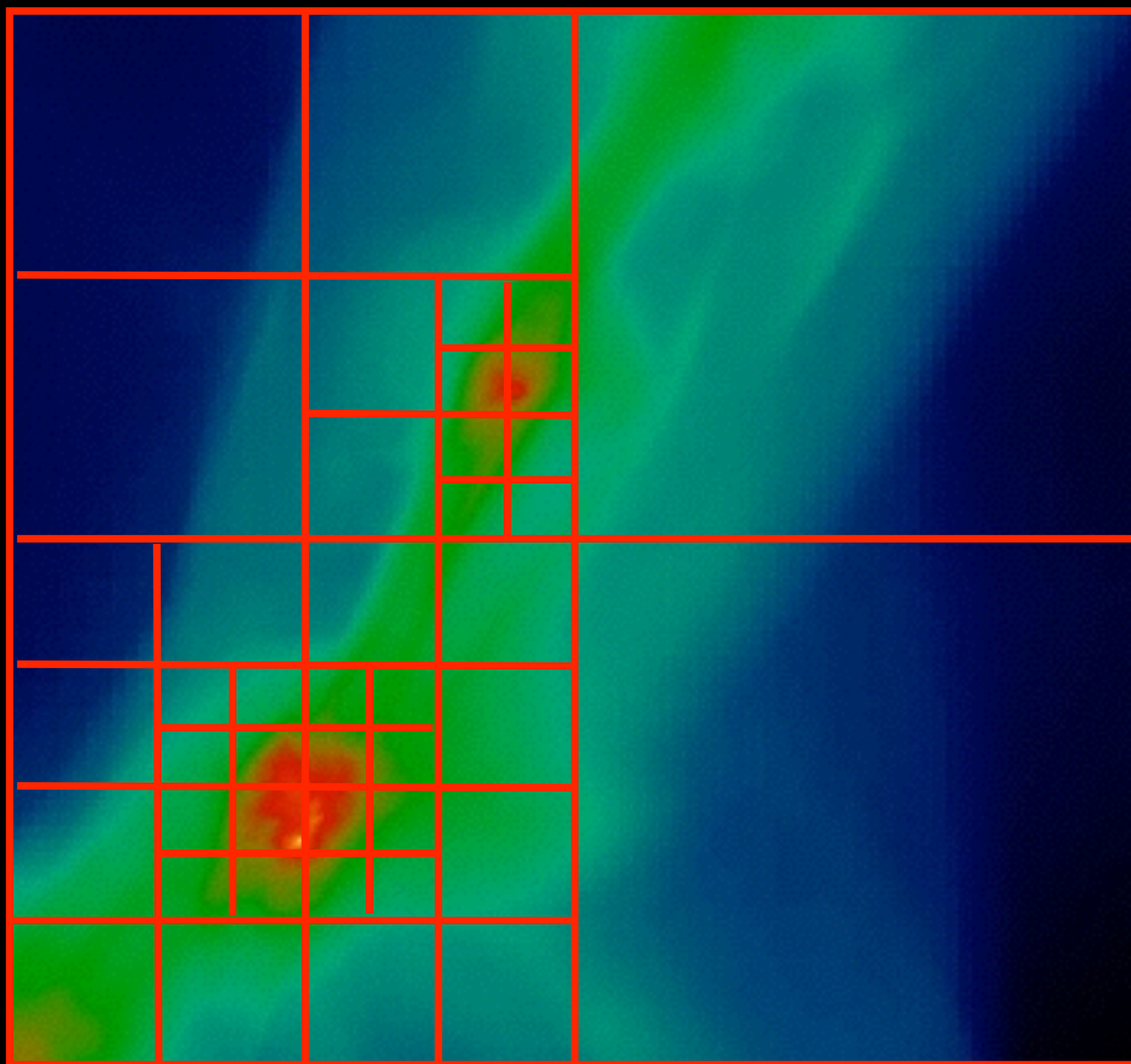


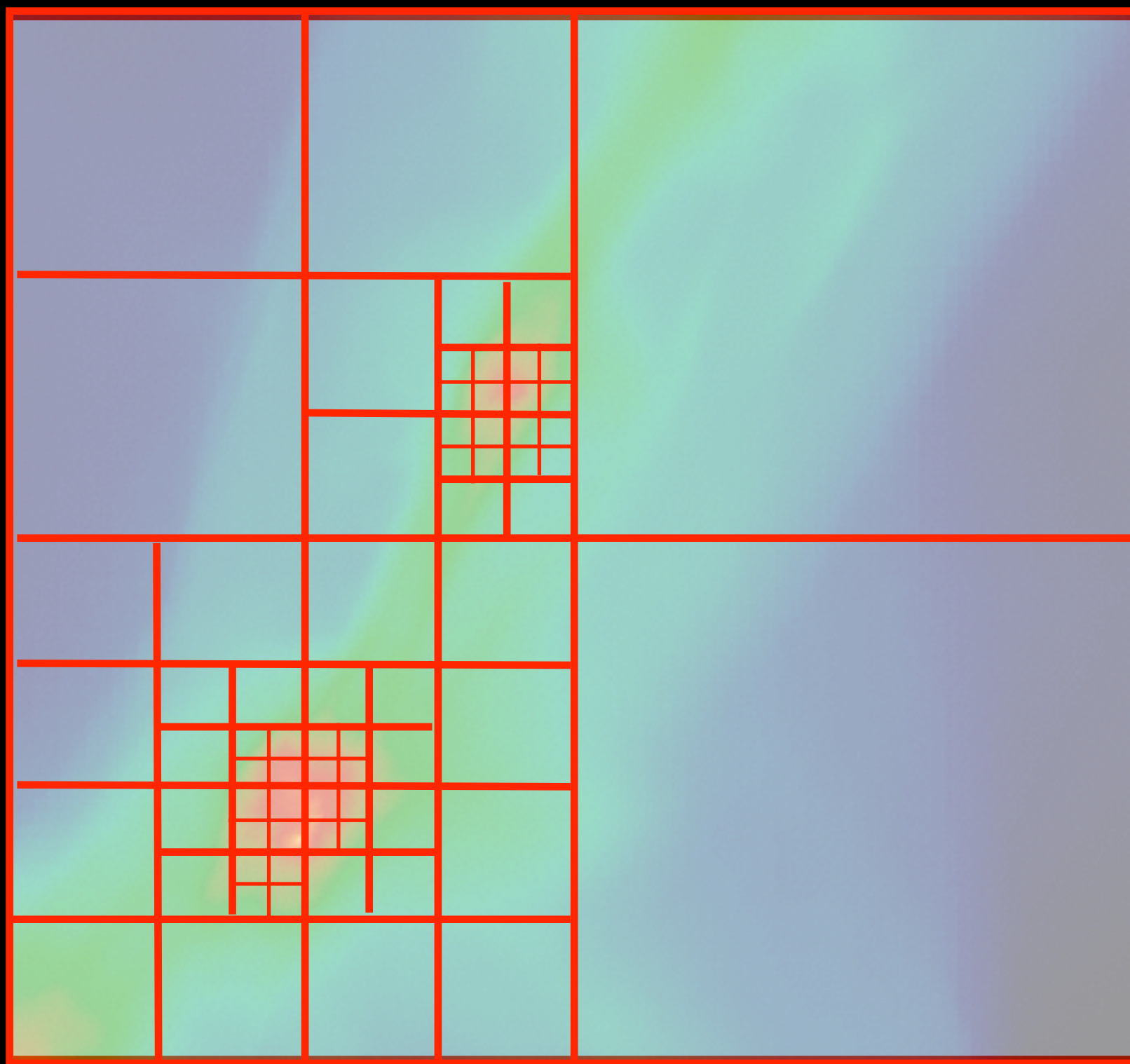


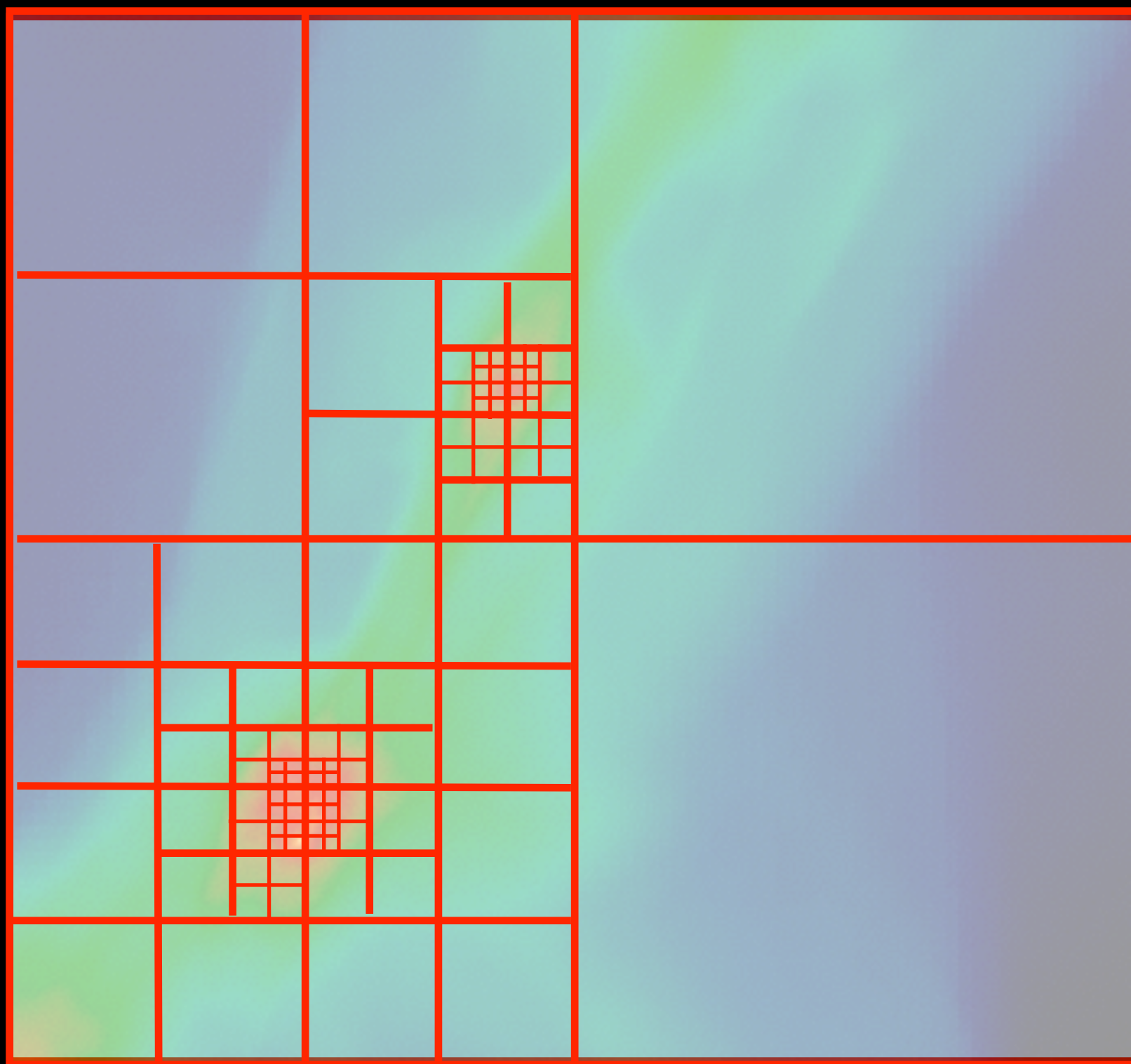


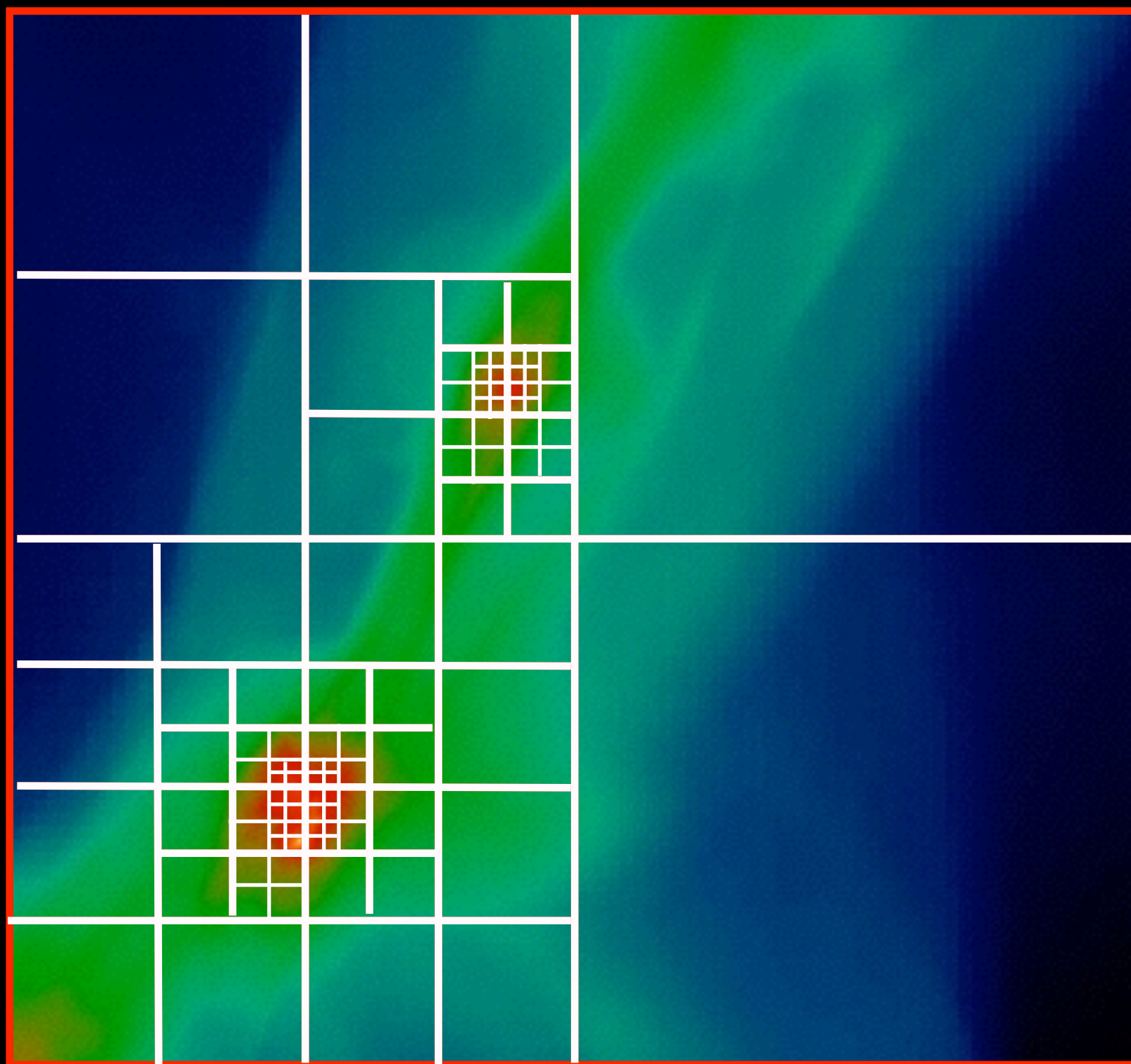






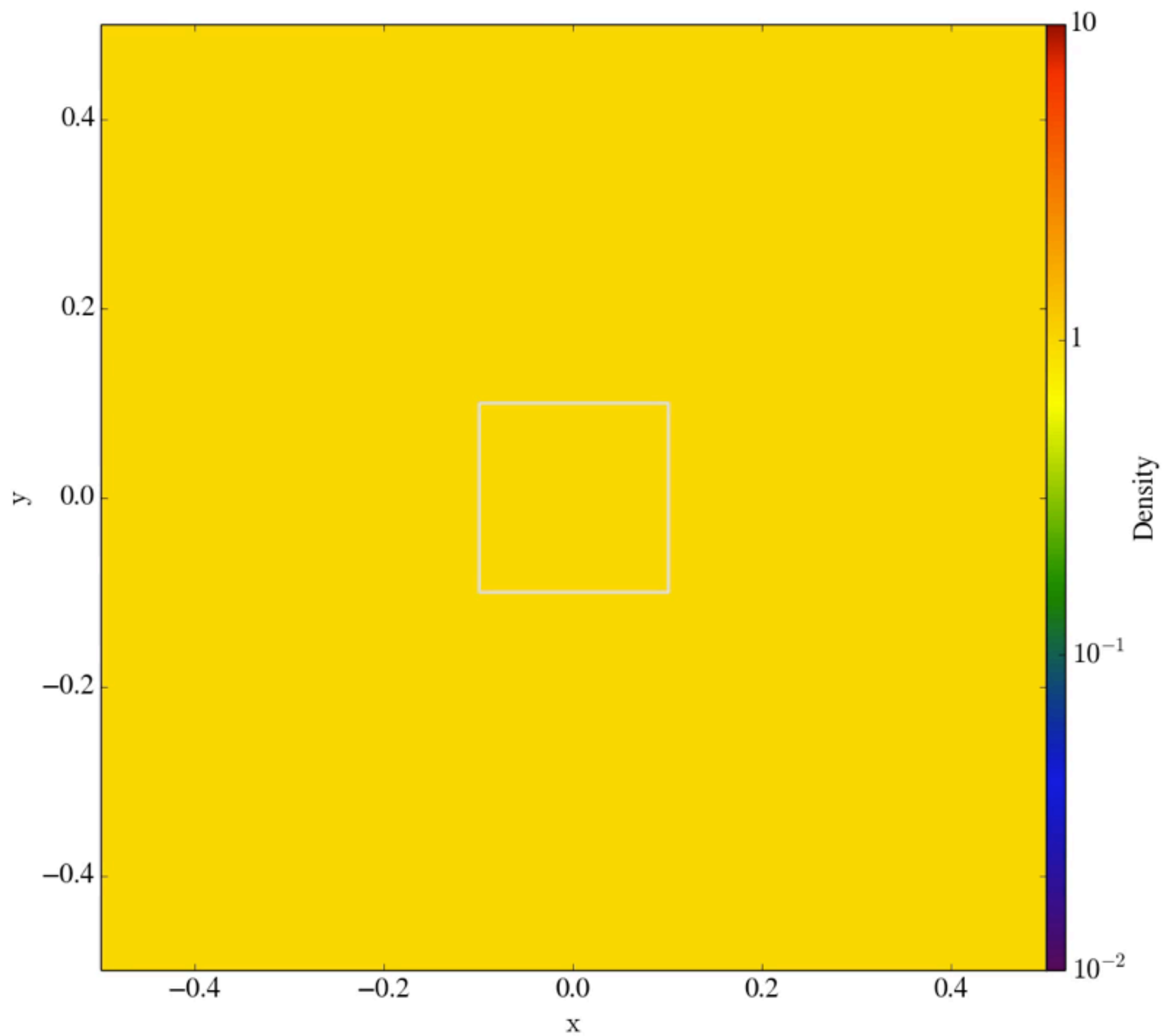


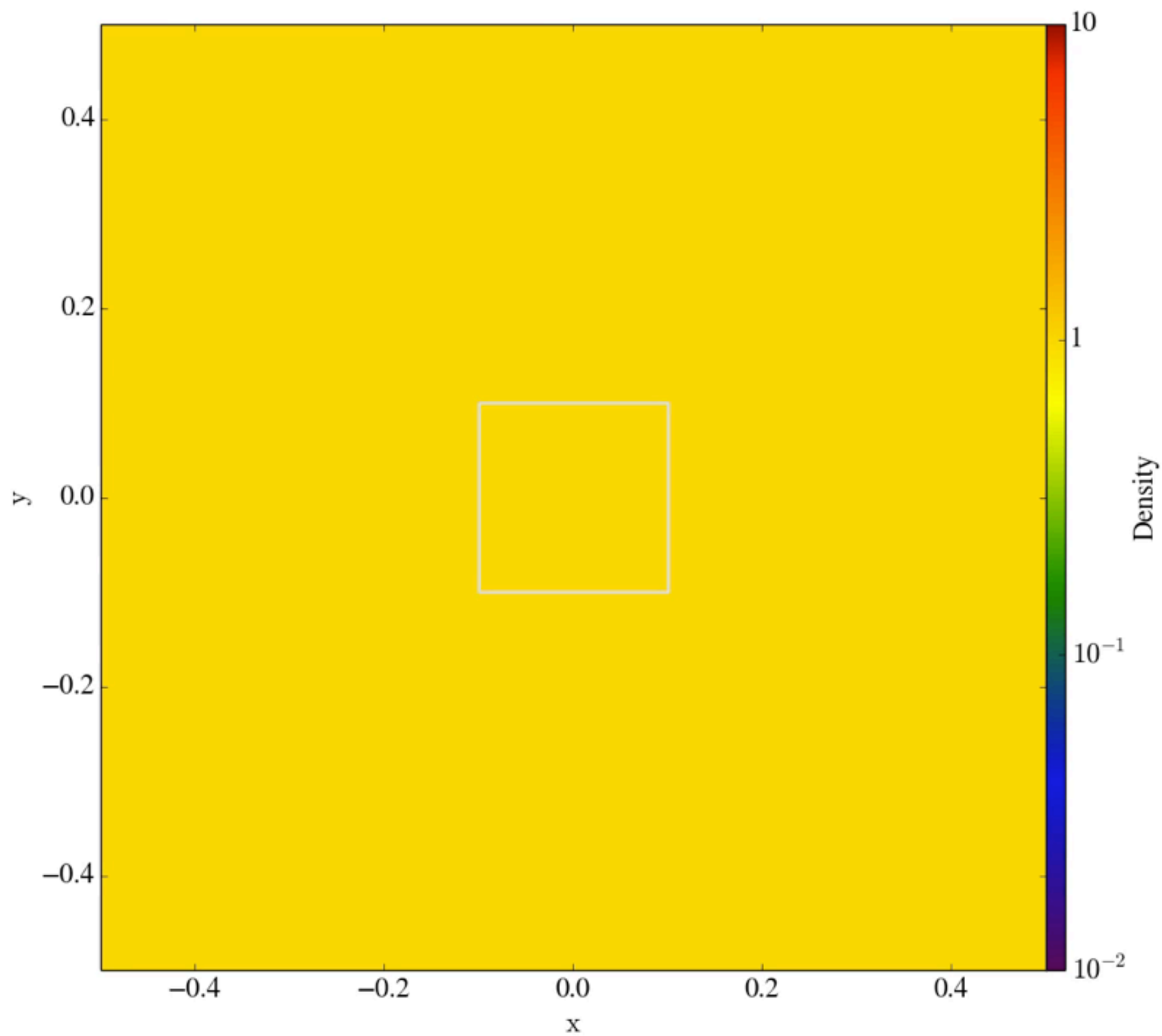


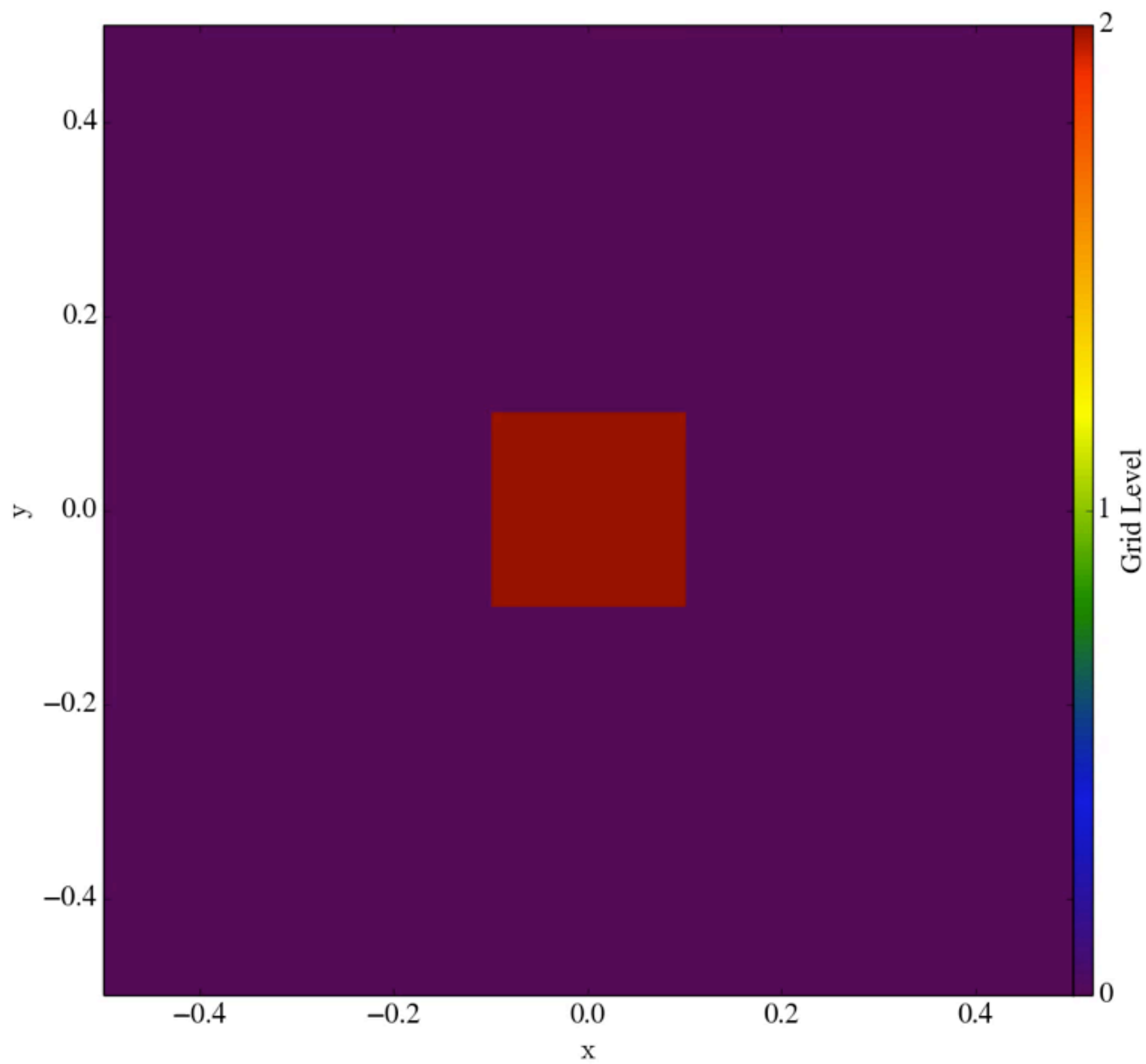


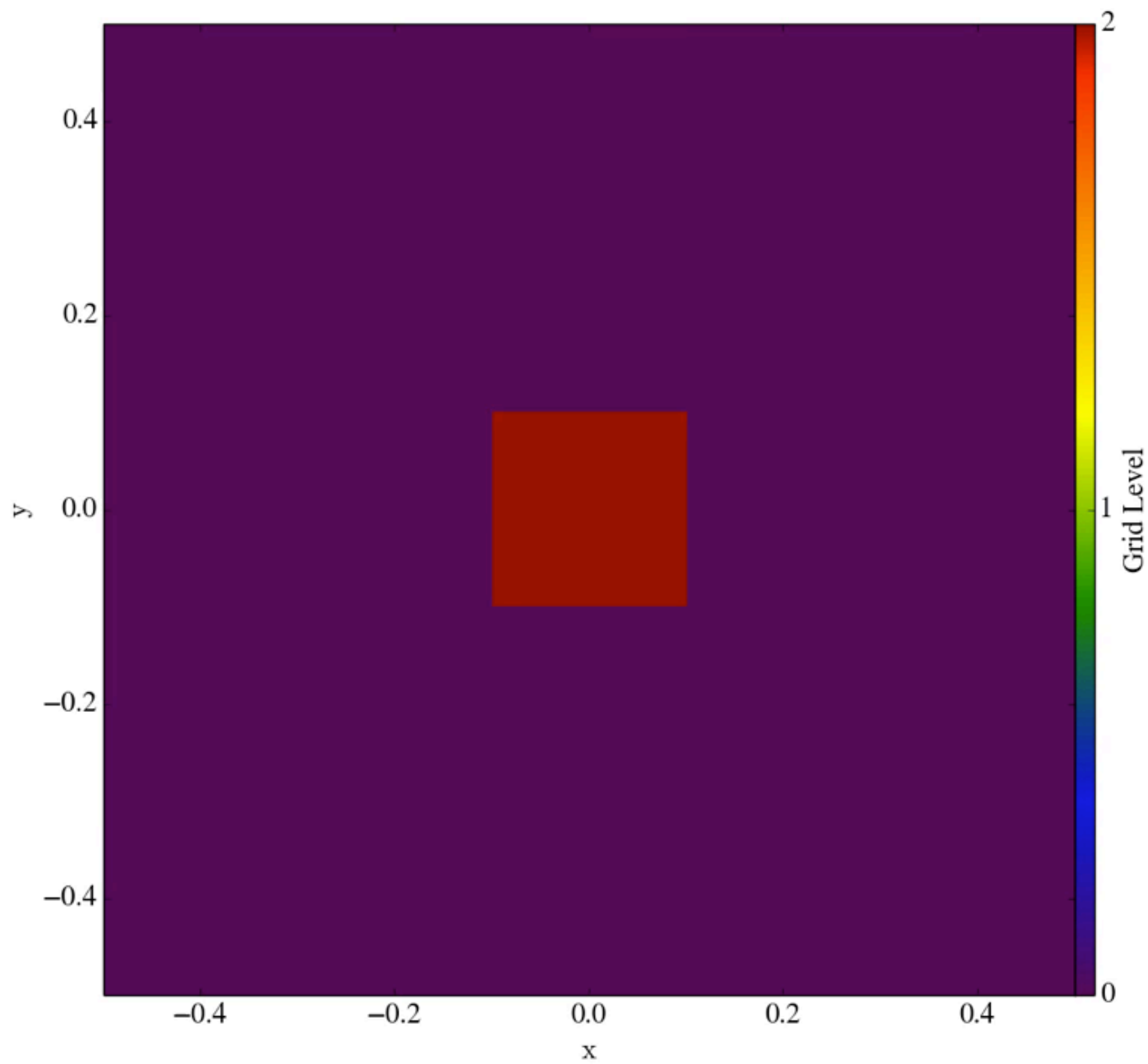
Dynamic example of AMR

Note: movies available at
<http://www.pa.msu.edu/~oshea/>









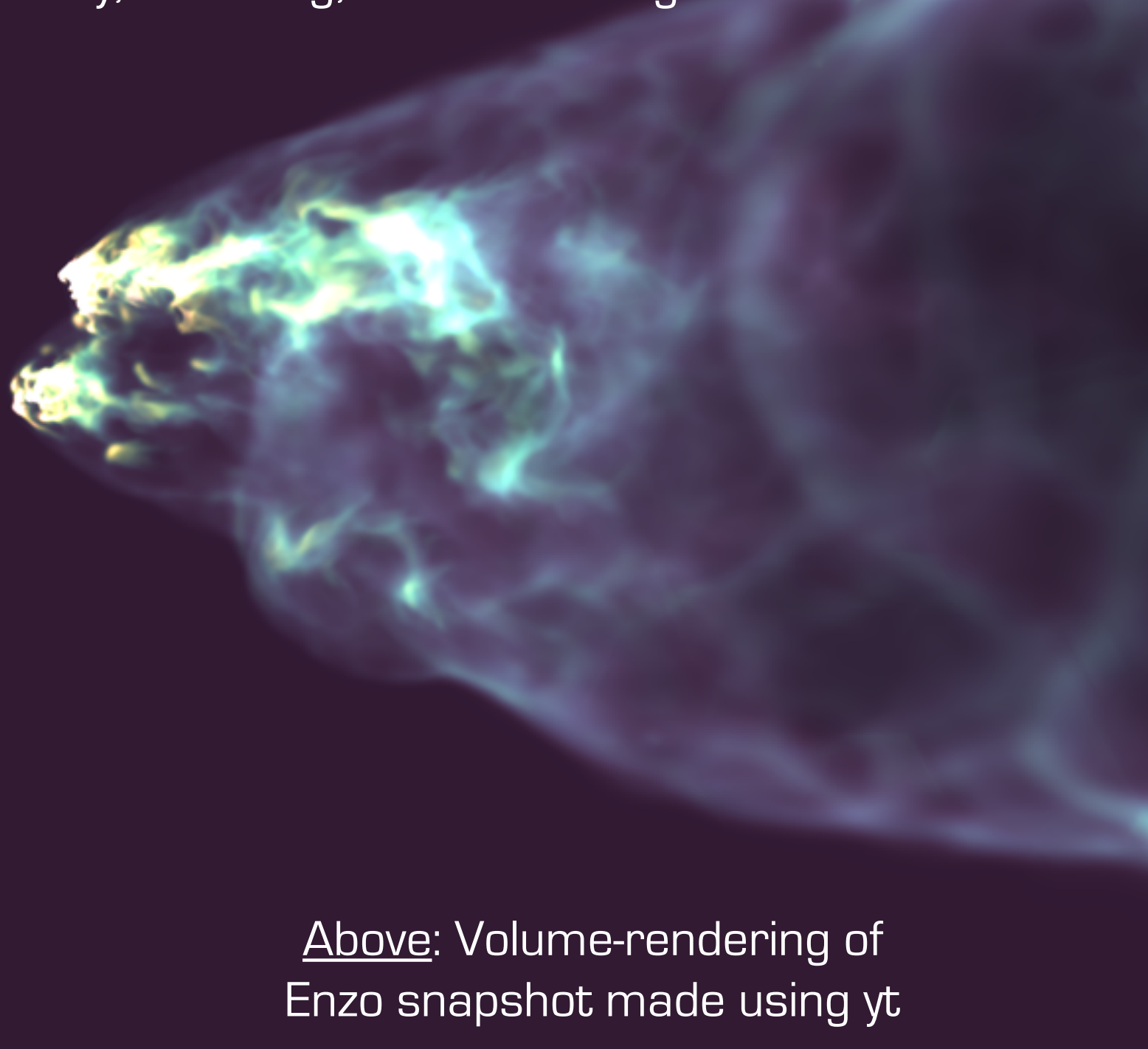
What are the technical challenges that we face?

- Memory
- Computation
- Synchronization
- Data volume

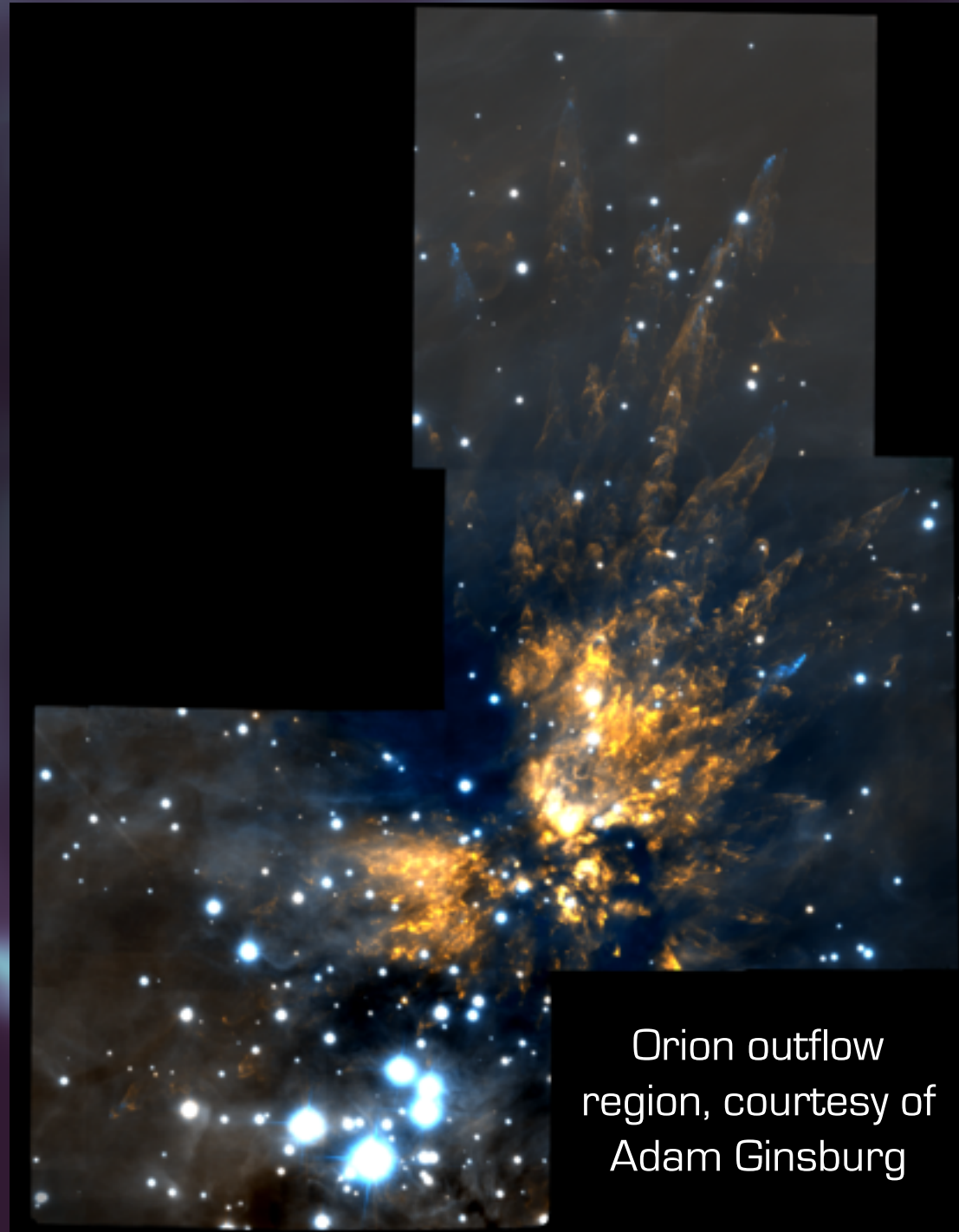
Some example
applications

Understanding outflow morphologies in Orion with simulations

Bally, Ginsburg, **Silvia** & Youngblood 2015

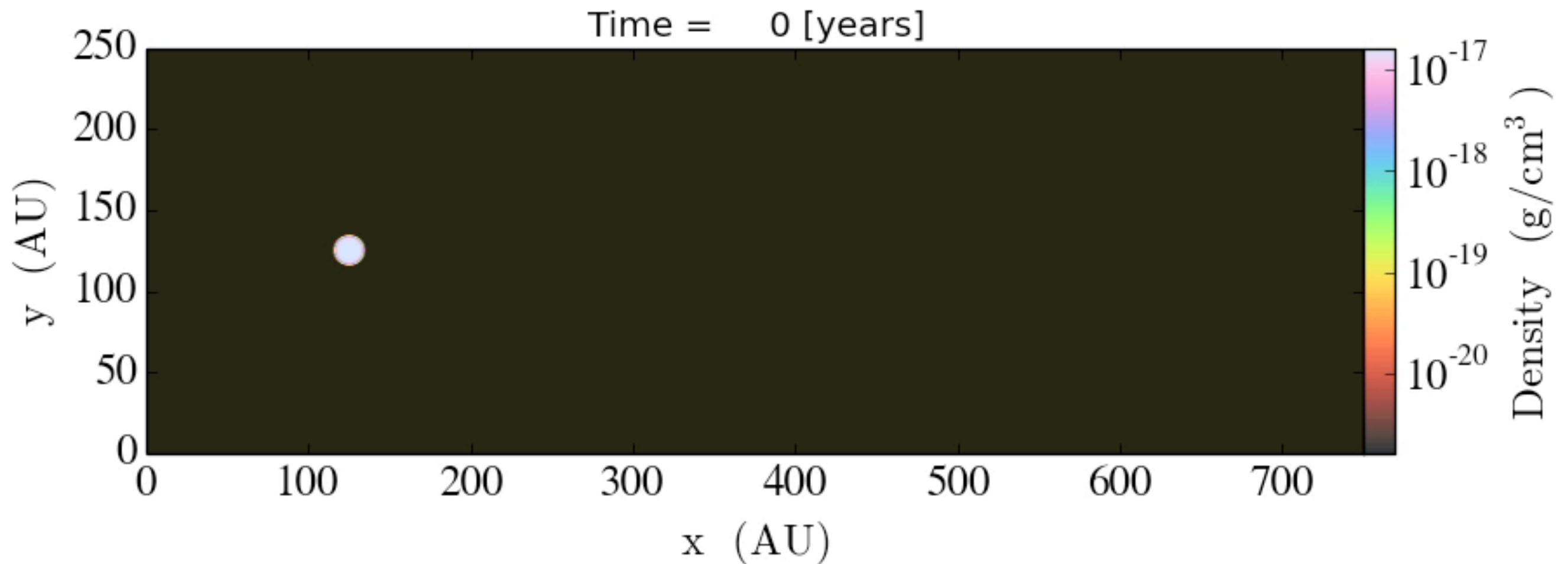


Above: Volume-rendering of
Enzo snapshot made using yt



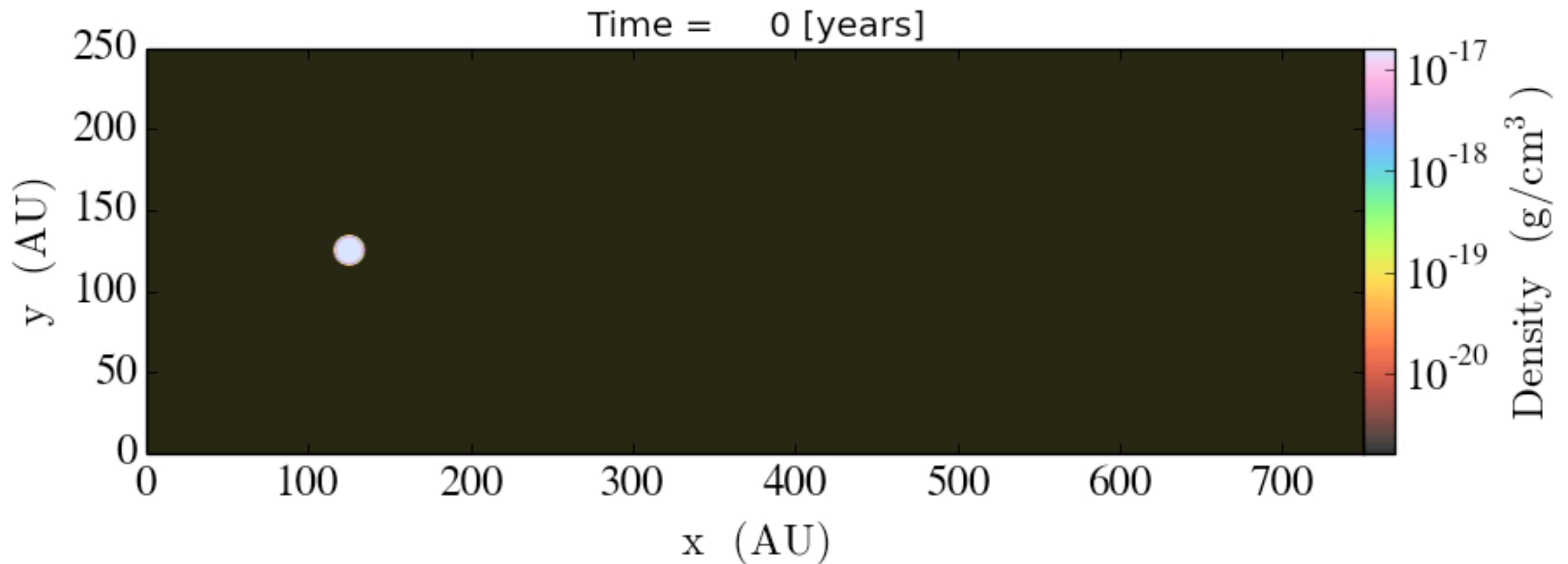
Orion outflow
region, courtesy of
Adam Ginsburg

Exploring bullet evolution



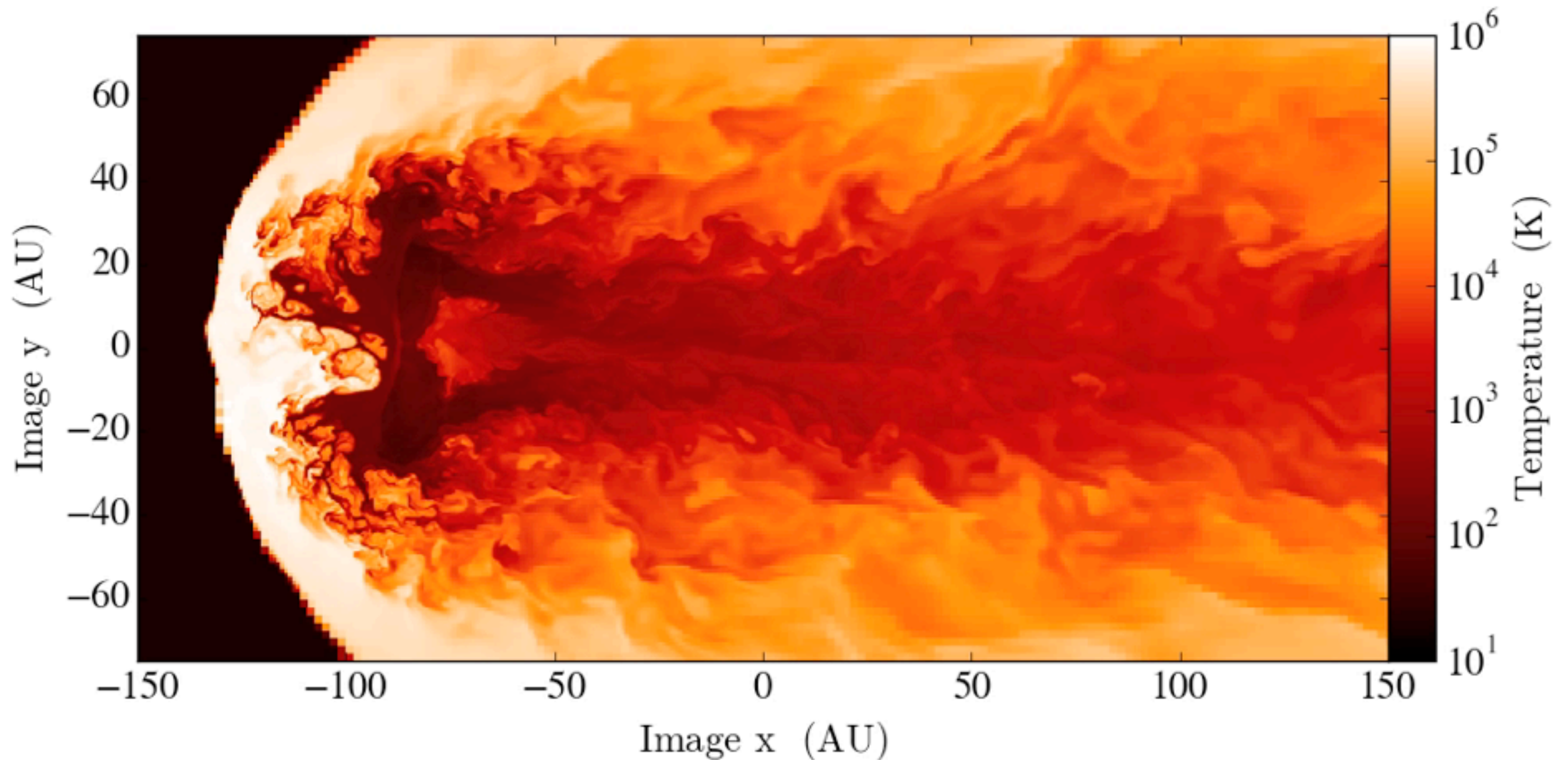
Time evolution of gas density

Exploring bullet evolution



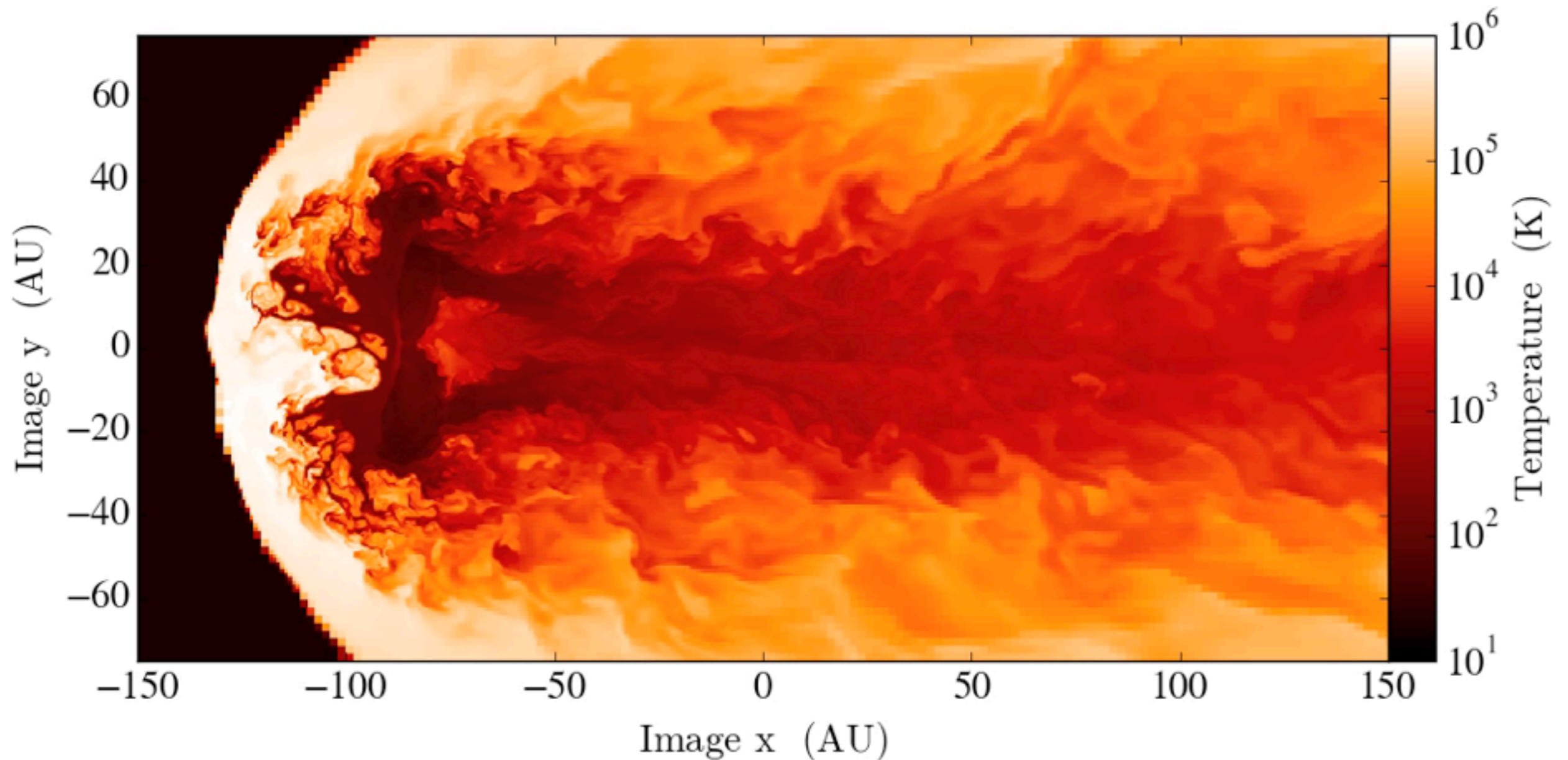
Time evolution of gas density

Probing internal temperature structure



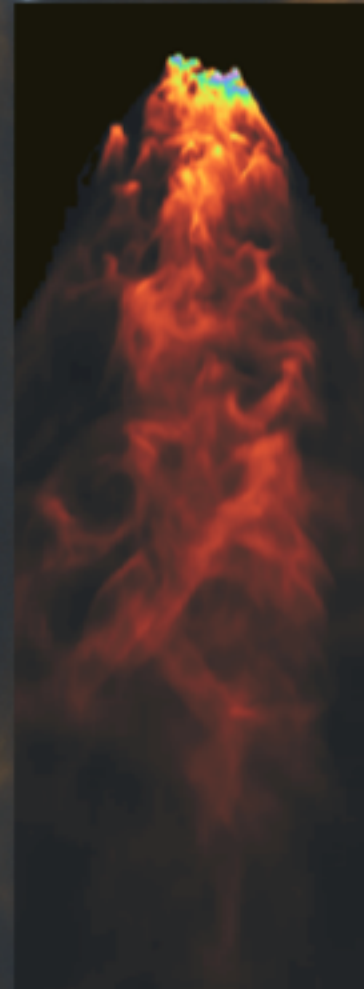
Rotating slices of gas temperature

Probing internal temperature structure



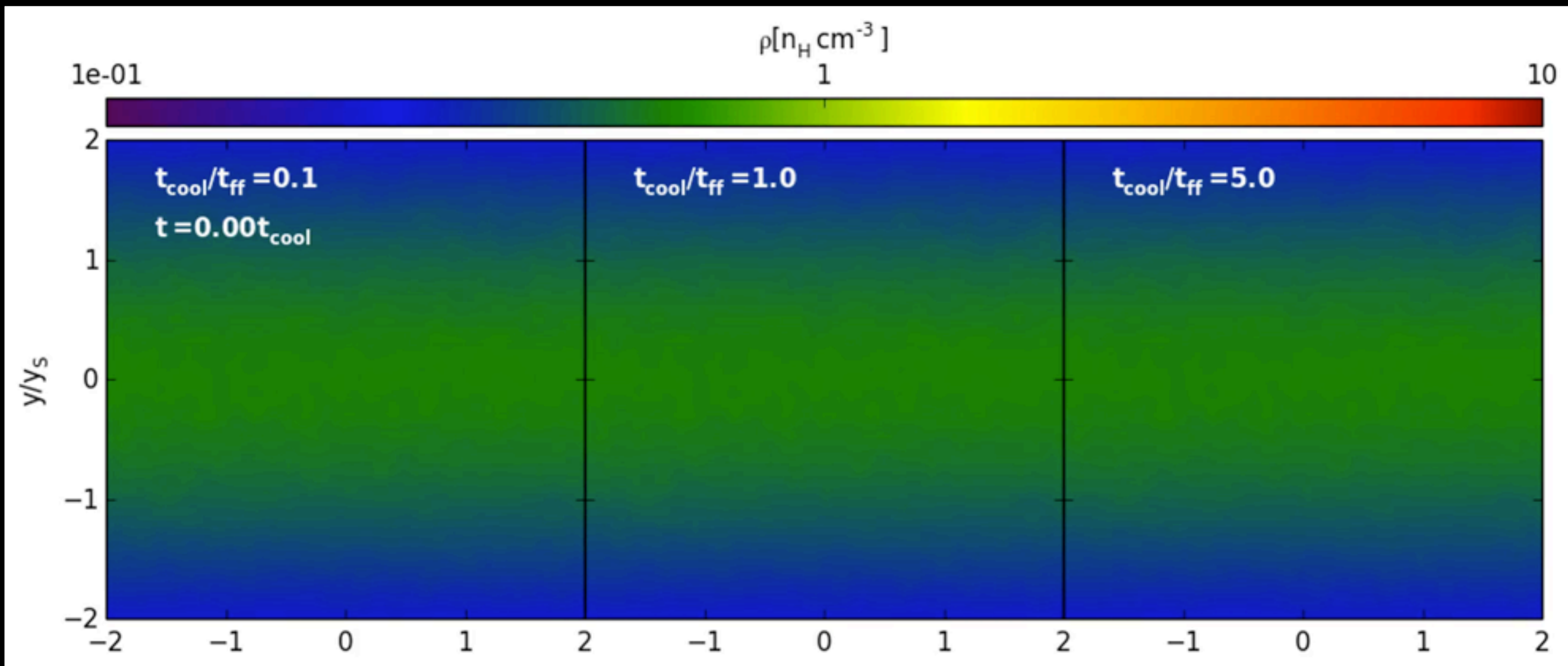
Rotating slices of gas temperature

Striking
similarities



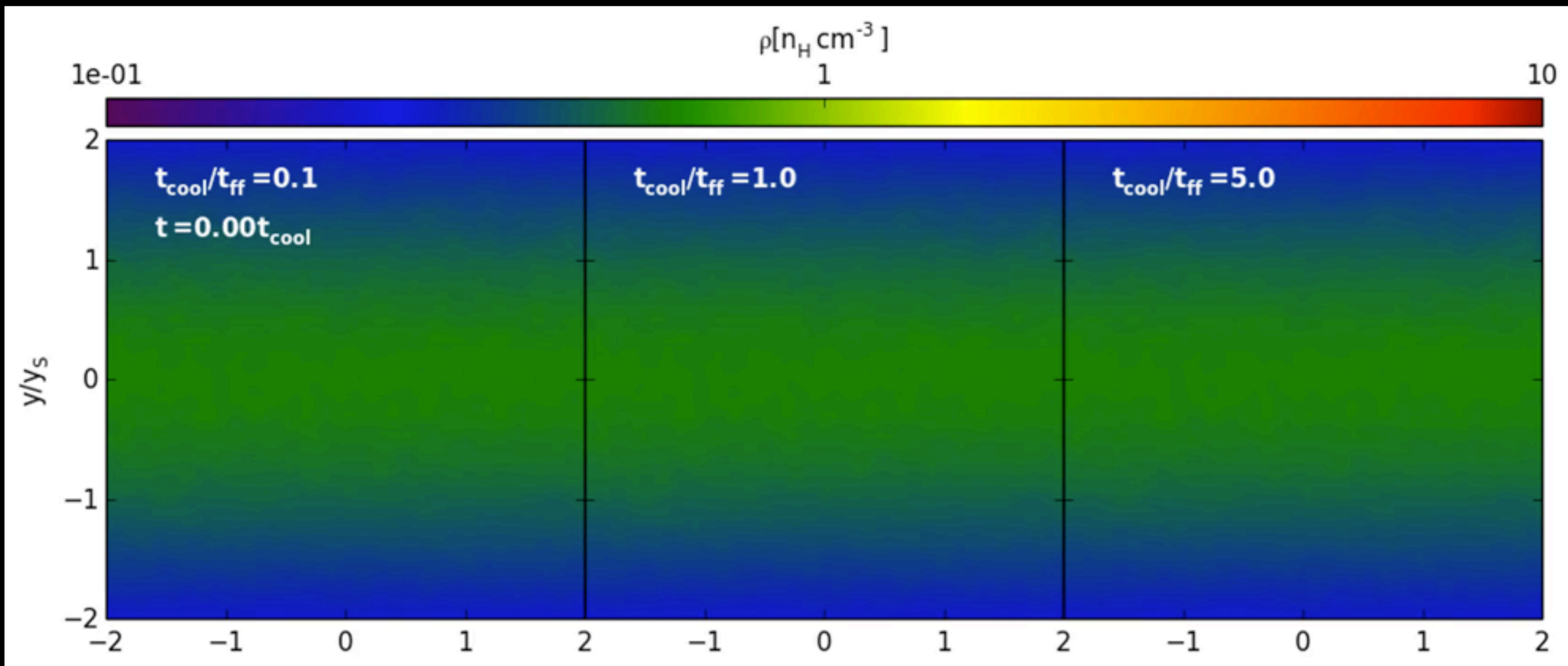
Understanding how galaxy feedback affects environment

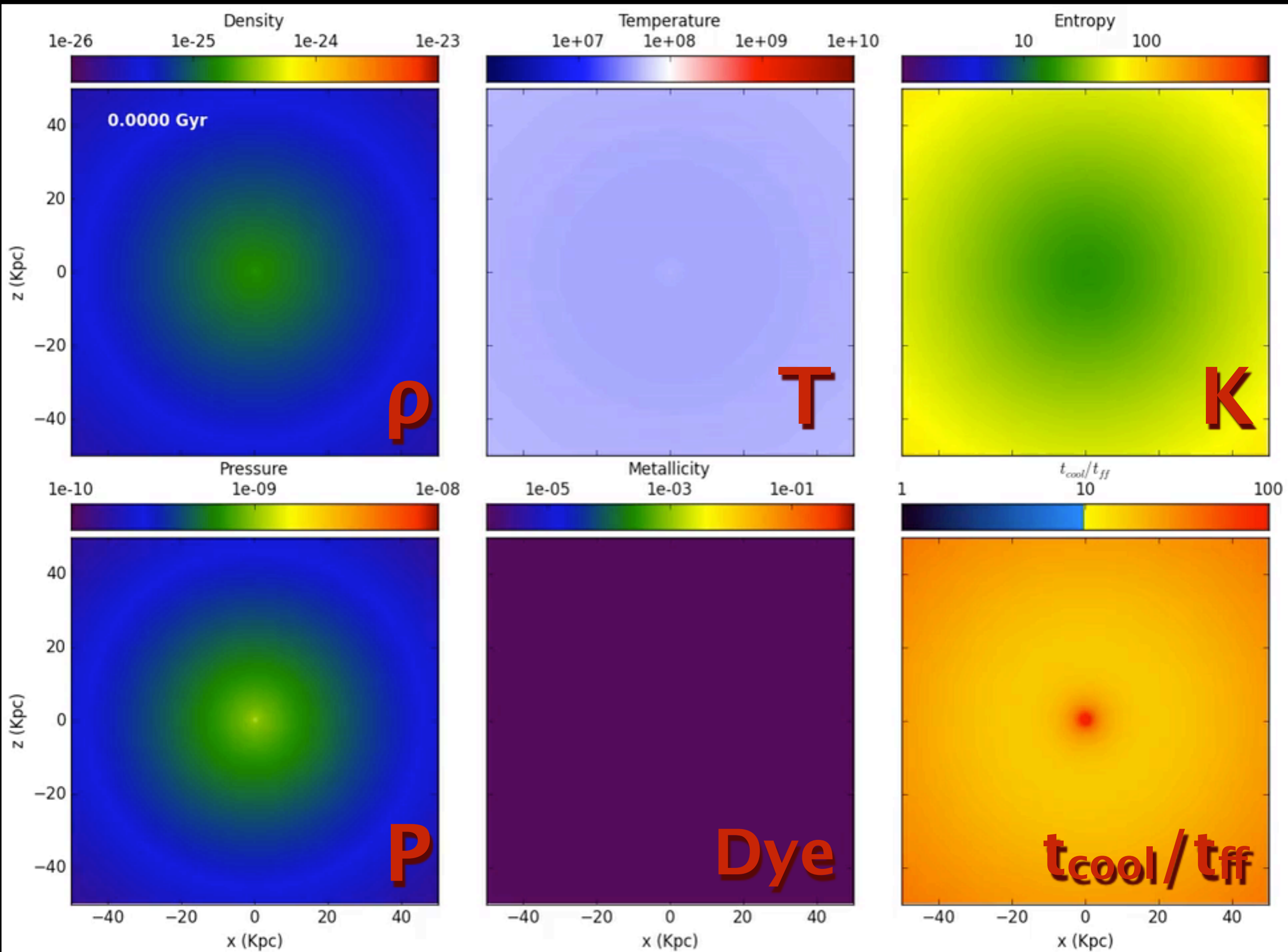
Meece, O'Shea & Voit 2015

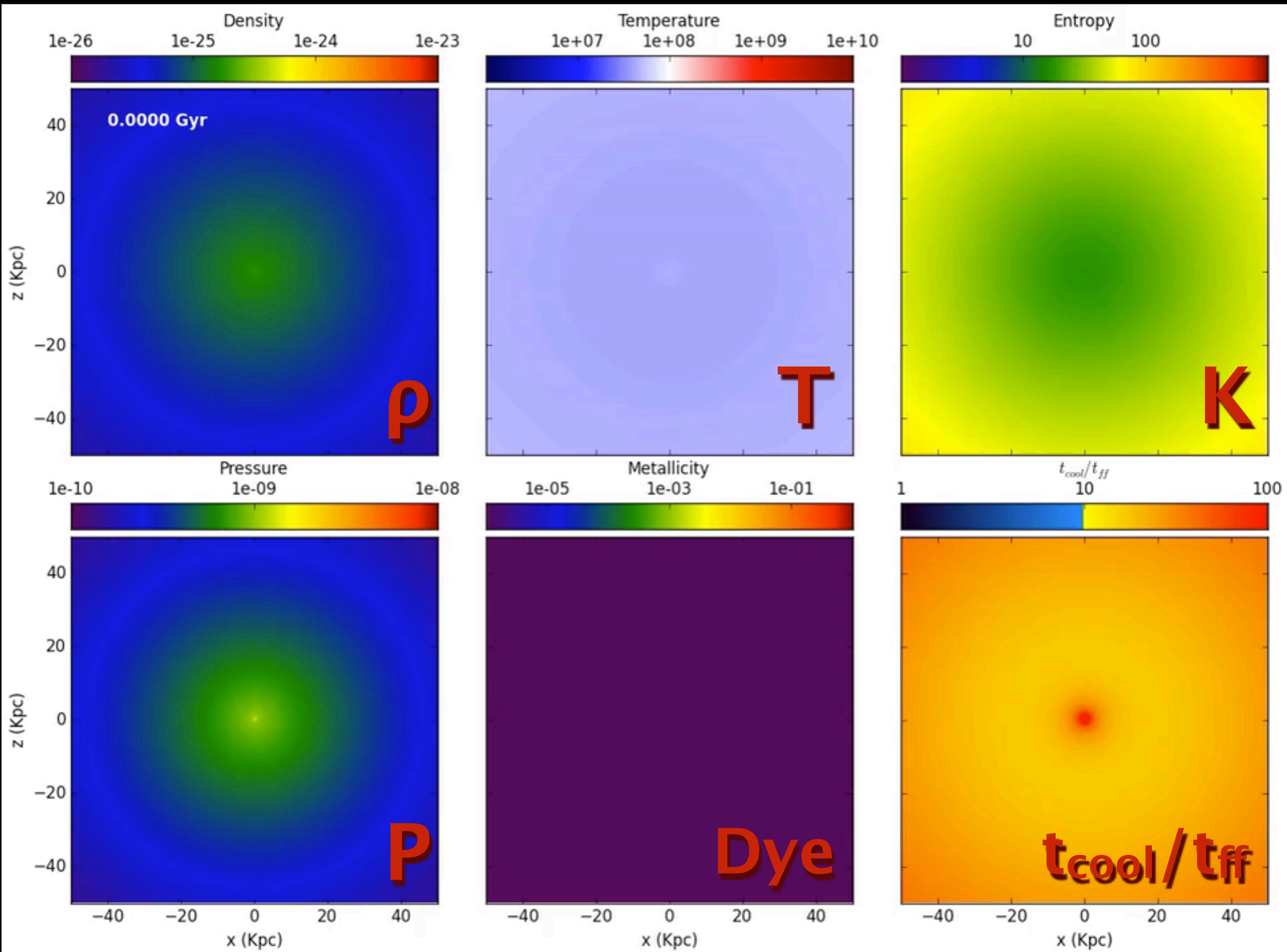


Understanding how galaxy feedback affects environment

Meece, O'Shea & Voit 2015

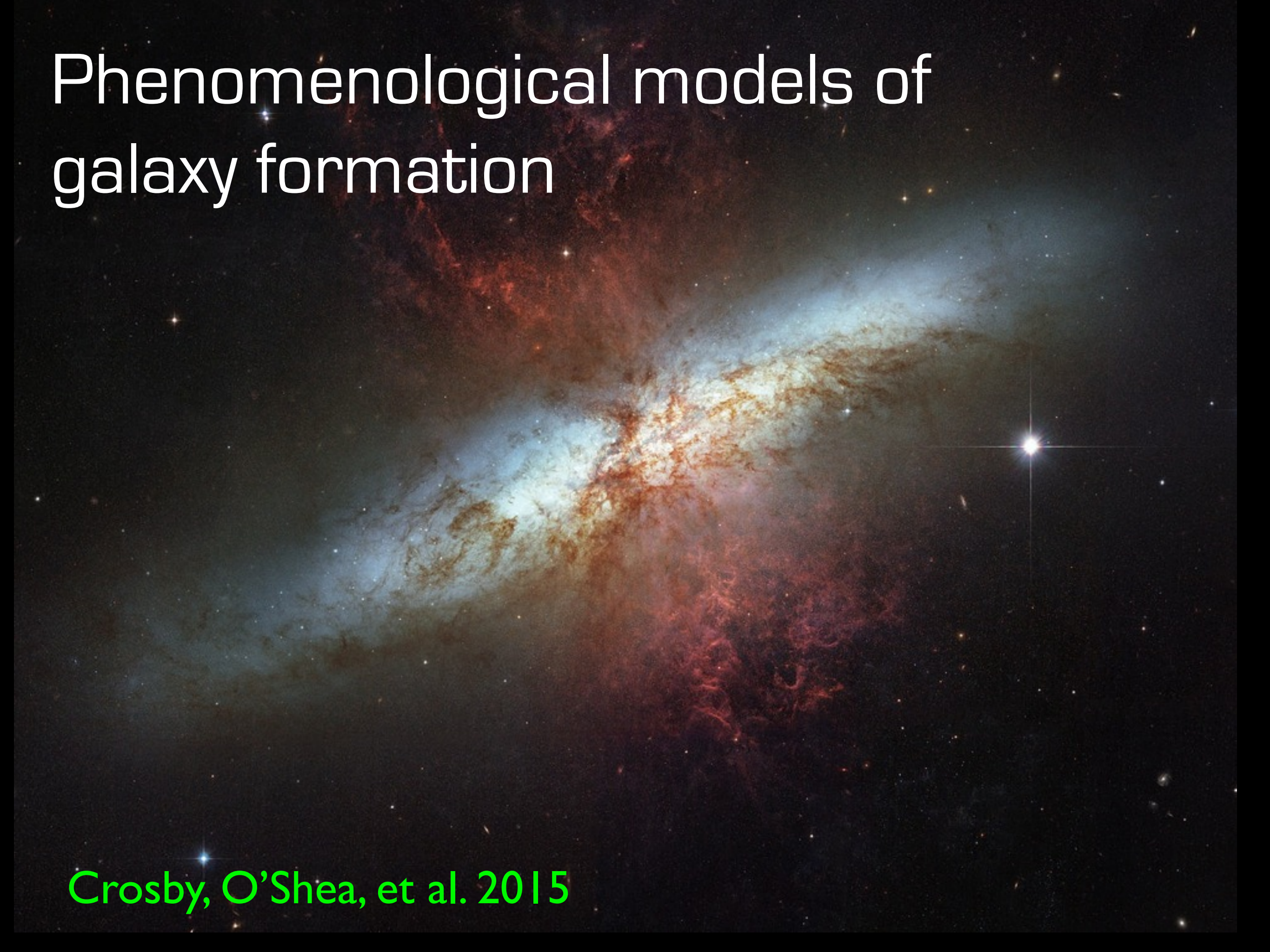


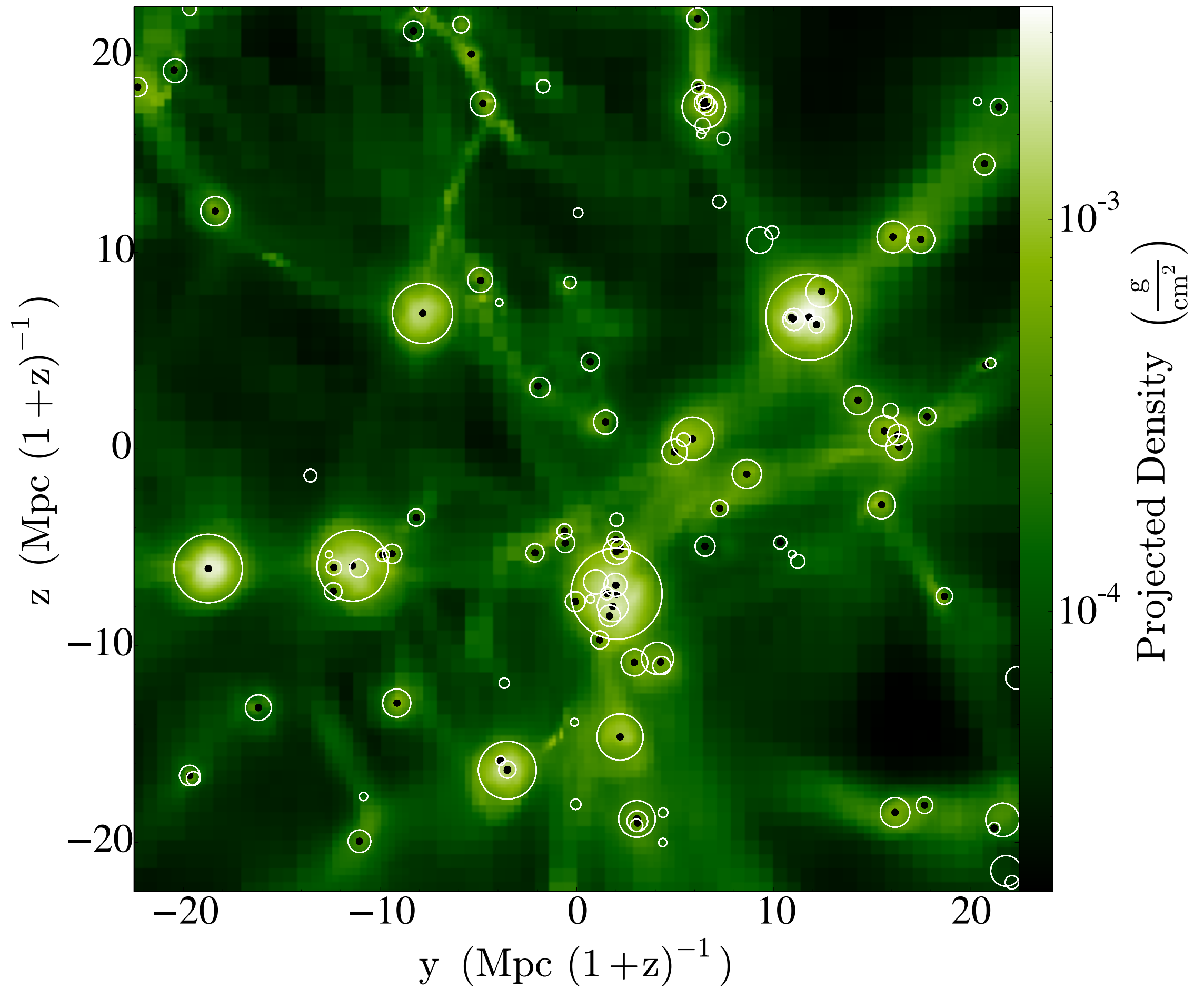


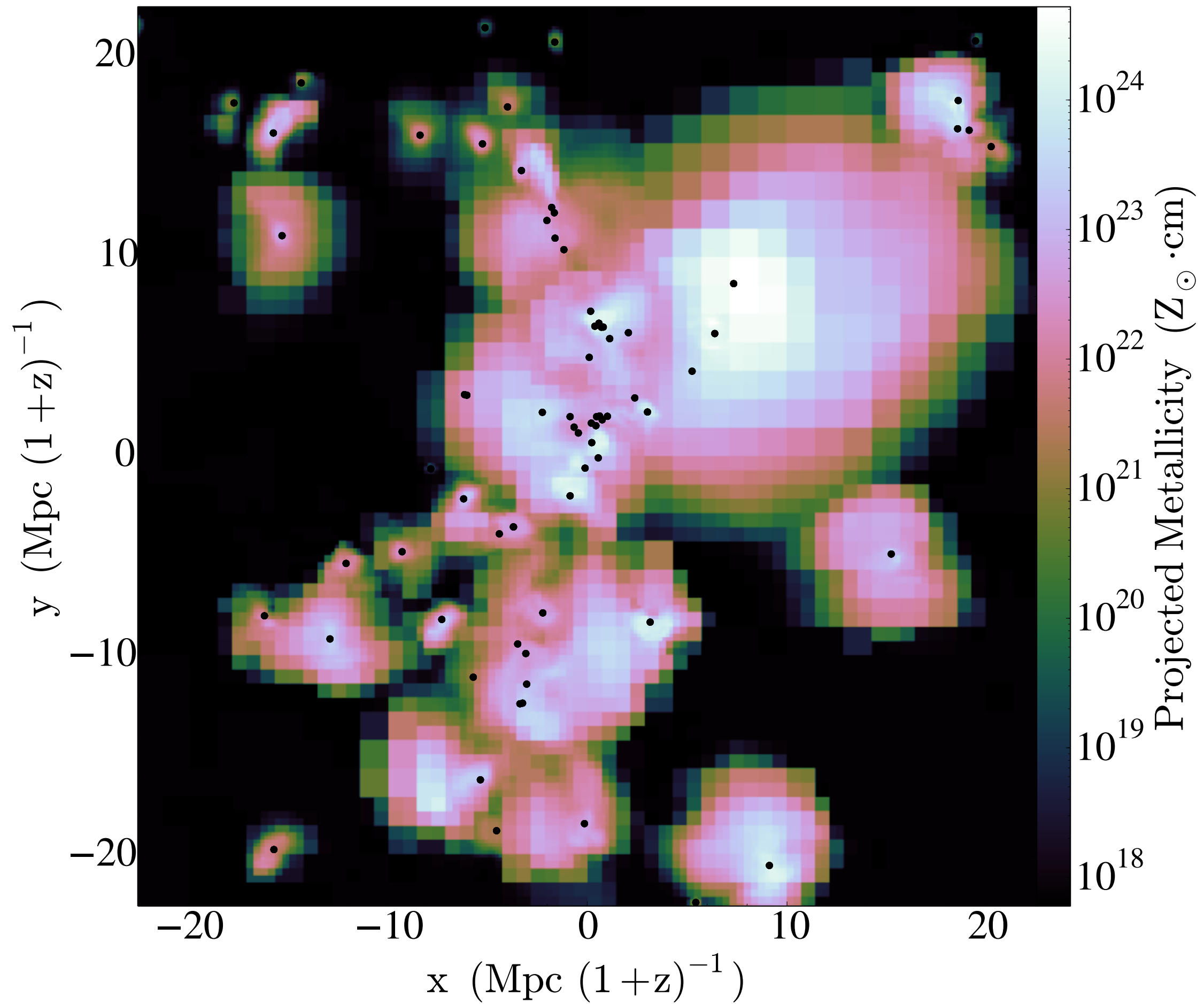


Phenomenological models of galaxy formation

Crosby, O'Shea, et al. 2015



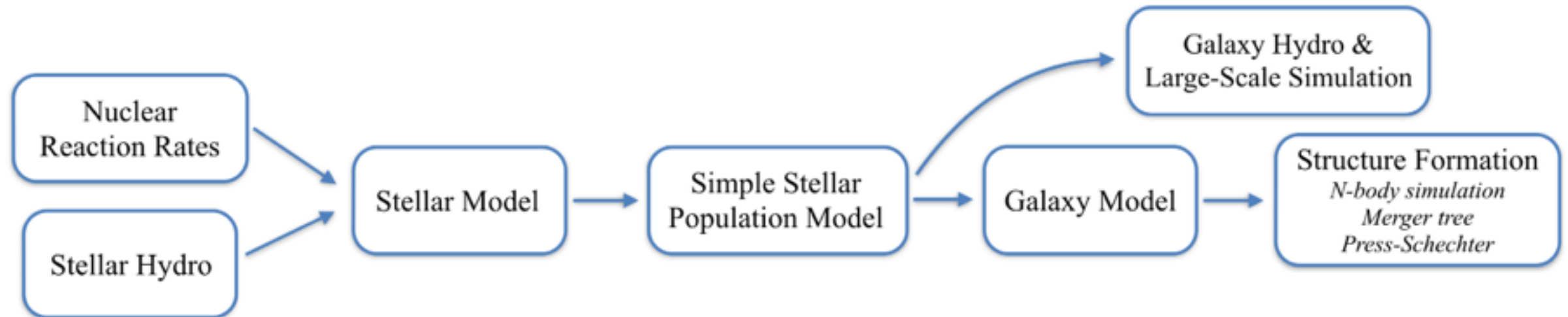




Quantifying uncertainty in galaxy formation models

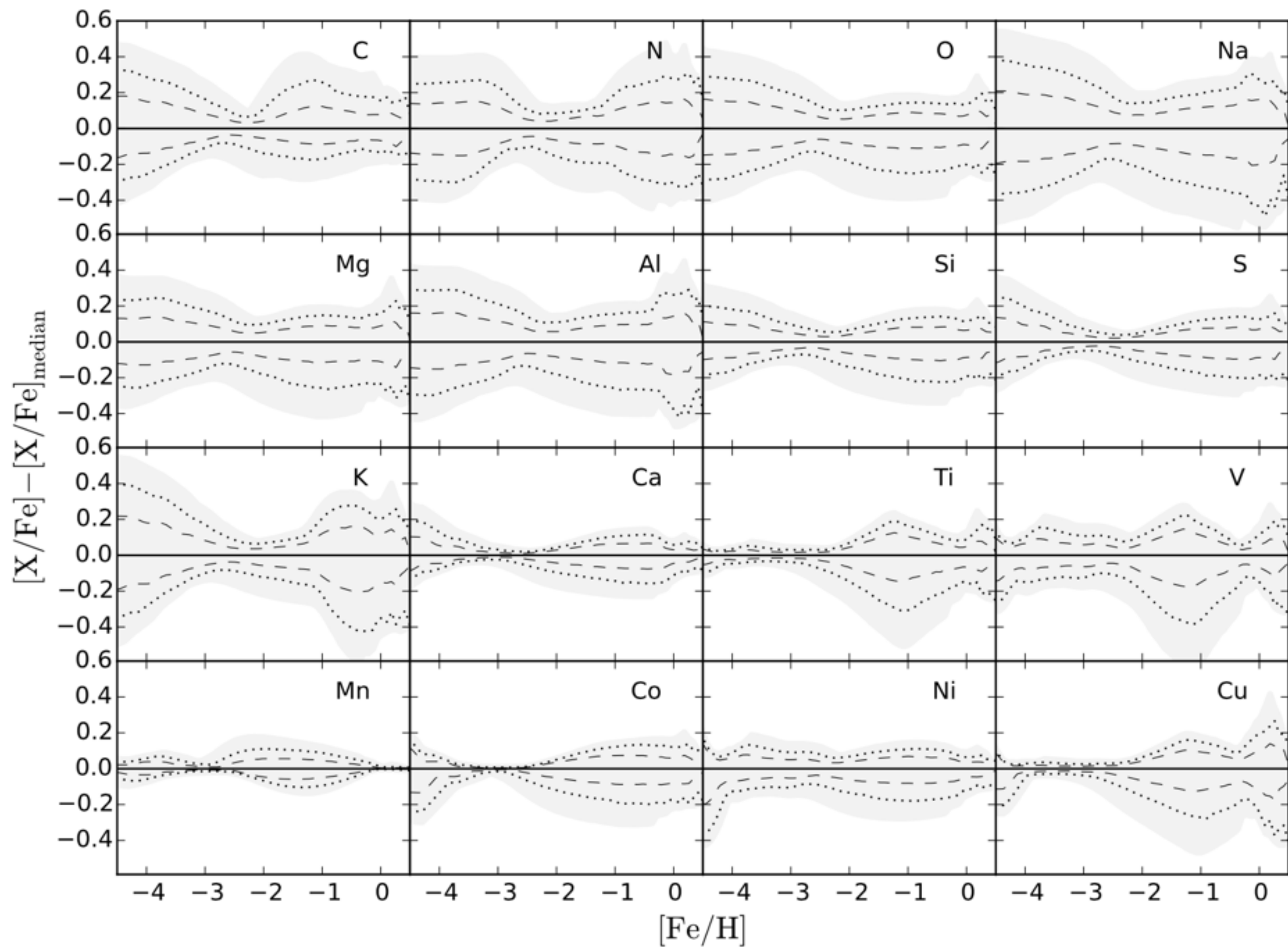
Cote, O'Shea et al. 2015 a,b

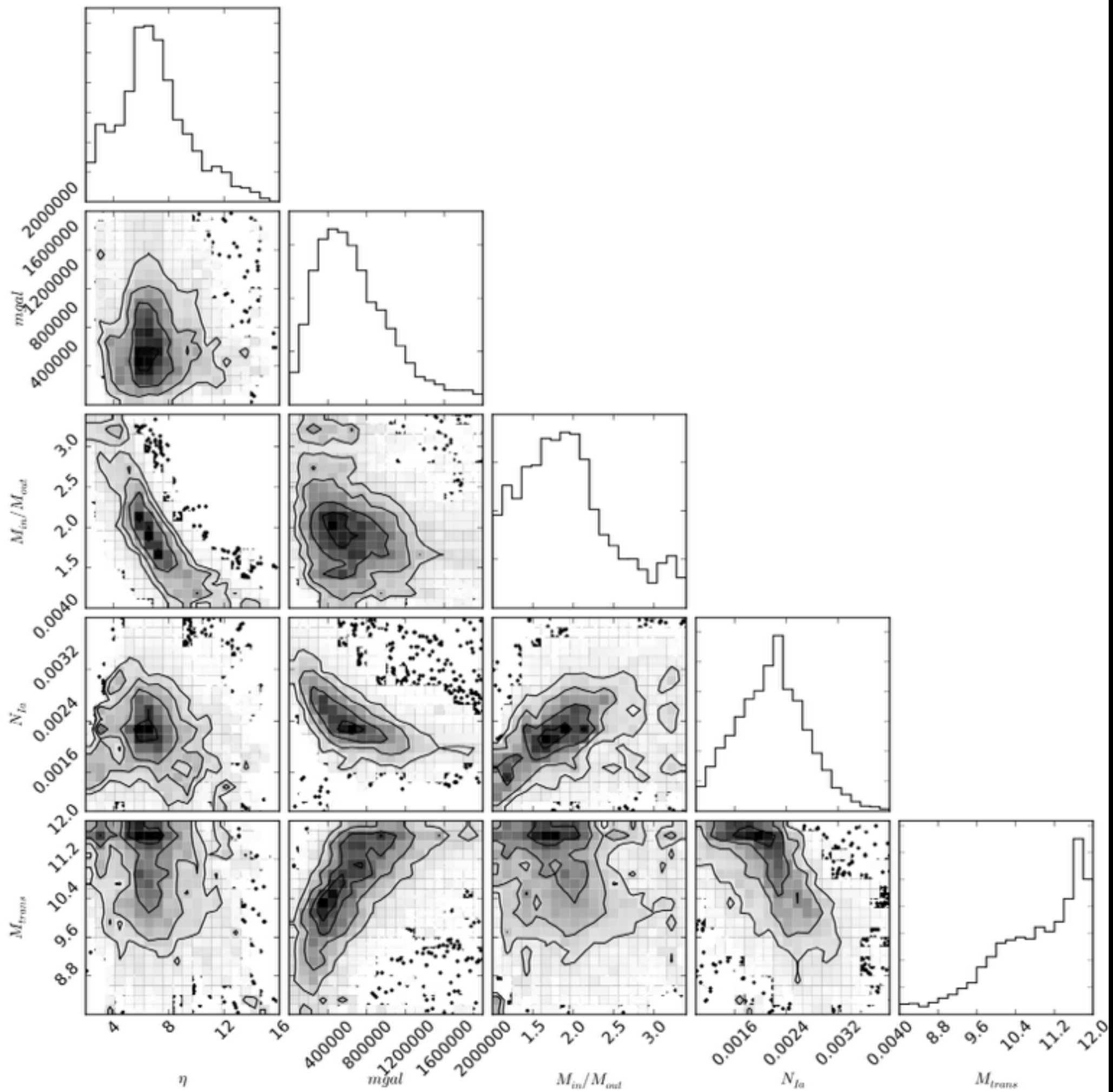
Closer to reality



More accumulated
uncertainty







Conclusions

- Cosmological structure formation is a challenging problem that requires large-scale simulations/modeling for detailed understanding.
- Simulating galaxy formation poses a variety of computational challenges that can only be met with large-scale supercomputers
- A range of interesting problems relating to galaxy behavior have been explored using MSU's HPC resources!

Thank you!

Image c/o
Britton Smith
& Brian O'Shea

