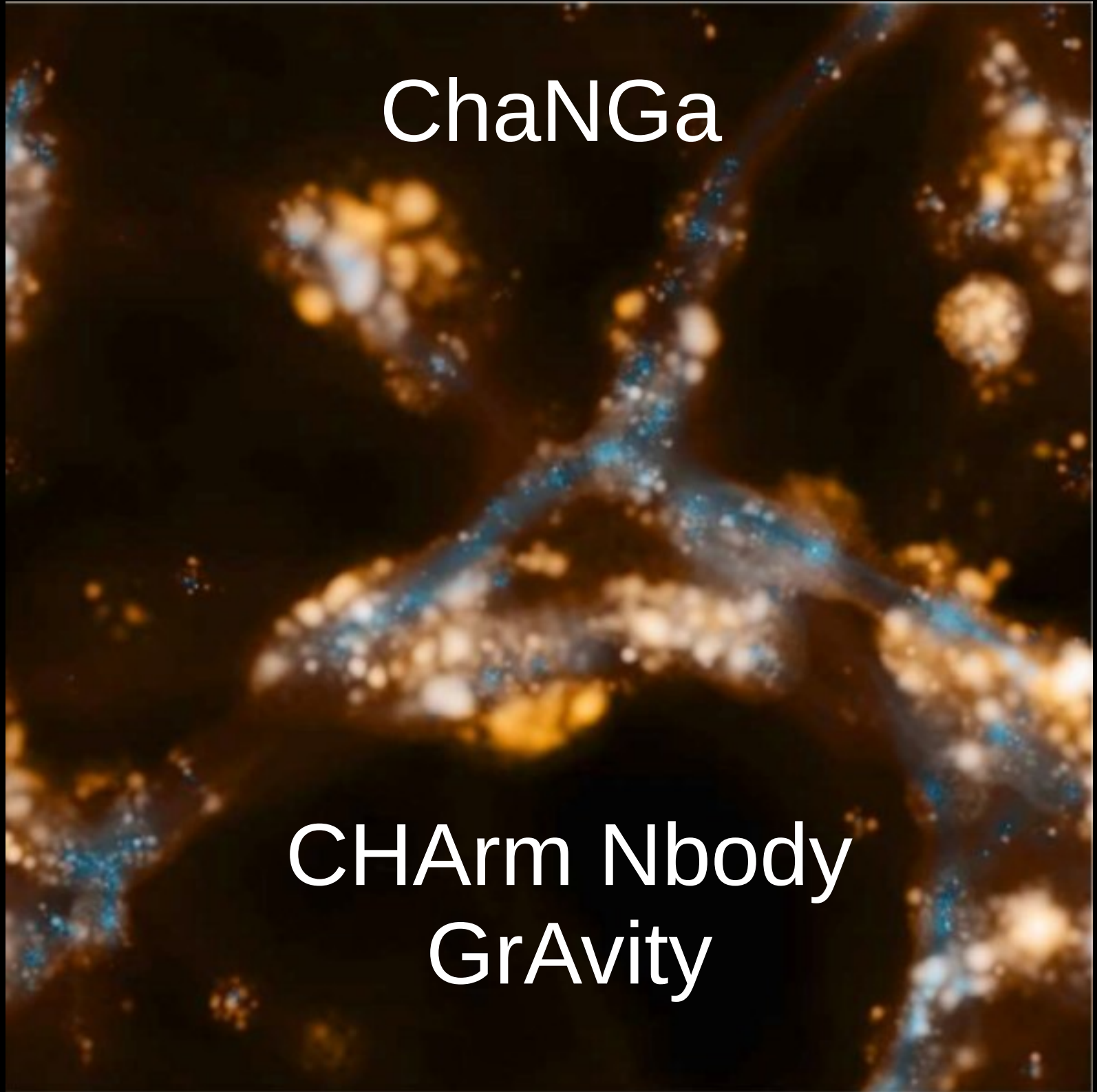
ChaNGa
CHArm Nbody
GrAvity

PPL PARALLEL PROGRAMMING LAB
DEPT OF COMPUTER SCIENCE, UNIVERSITY OF ILLINOIS

Thomas Quinn

Graeme Lufkin

Joachim Stadel

James Wadsley

Greg Stinson

Michael Tremmel

Alex Fry

Lauren Anderson

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Laxmikant Kale

Filippo Gioachin

Pritish Jetley

Celso Mendes

Amit Sharma

Lukasz Wesolowski

Gengbin Zheng

Edgar Solomonik

Harshitha Menon

Orion Lawlor

Outline

- Overview of computational cosmology
- Prelimary Blue Waters Results
- Specific Challenges for Blue Waters
- ChaNGa and Charm features
- Recent science directions
- Future

Cosmology at 380,000 years

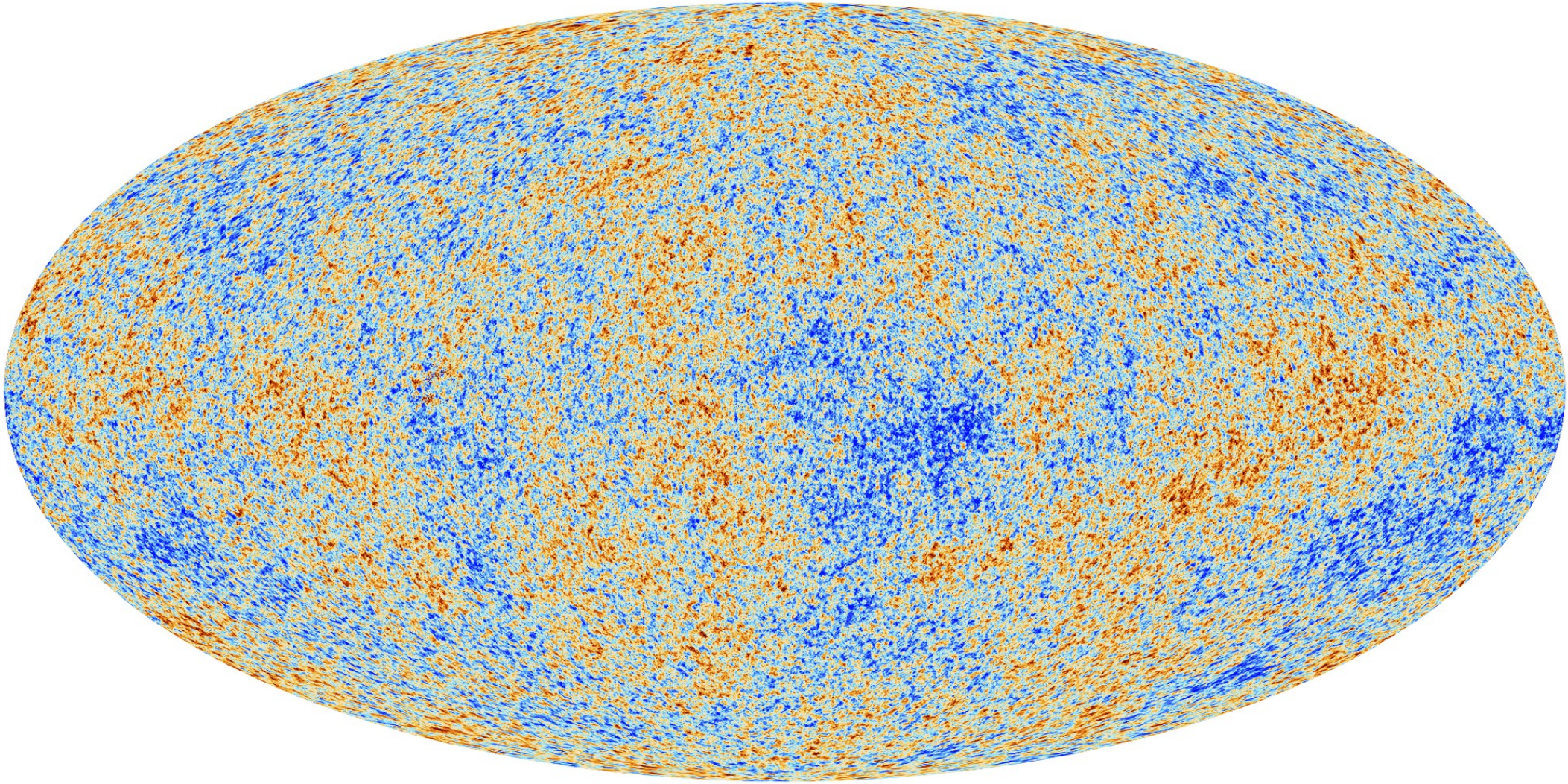
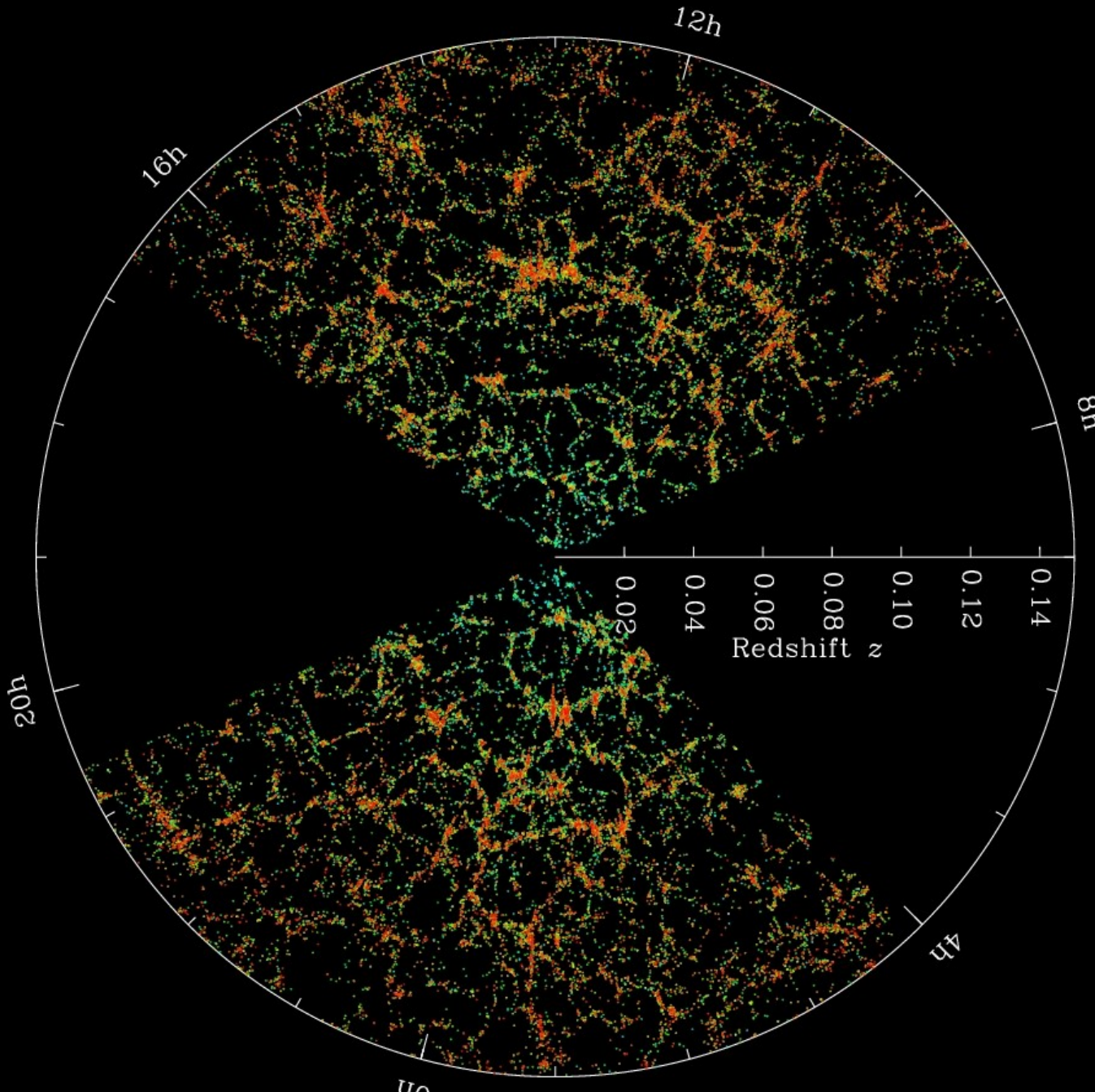


Image courtesy ESA/Planck

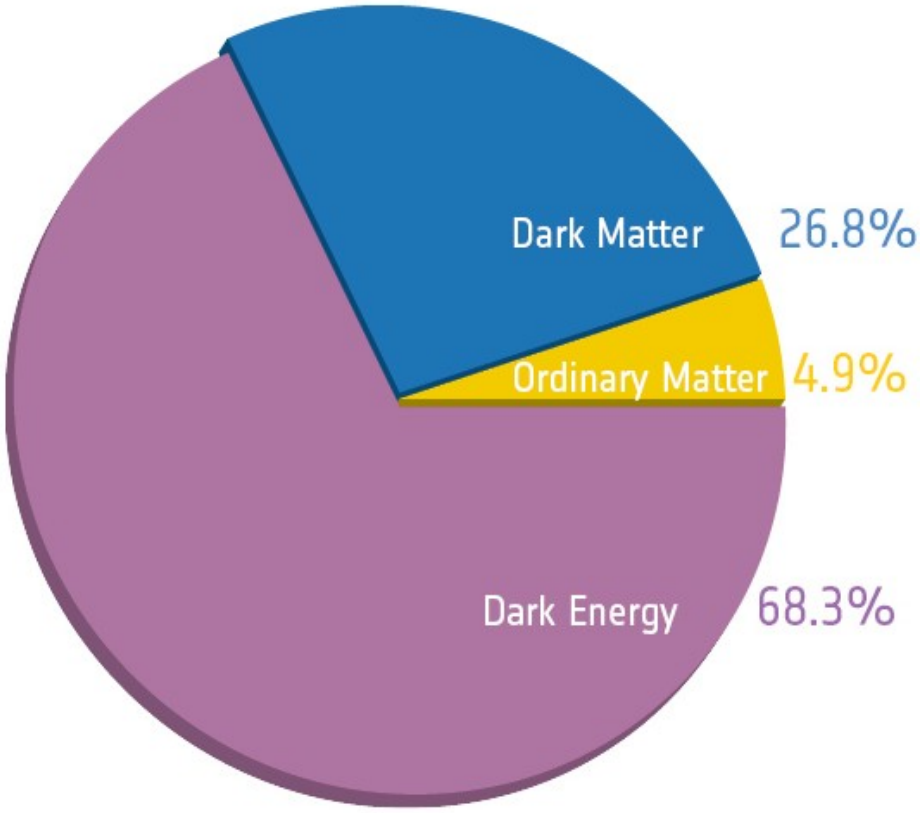
Cosmology at 13.6 Gigayears




... is not so simple

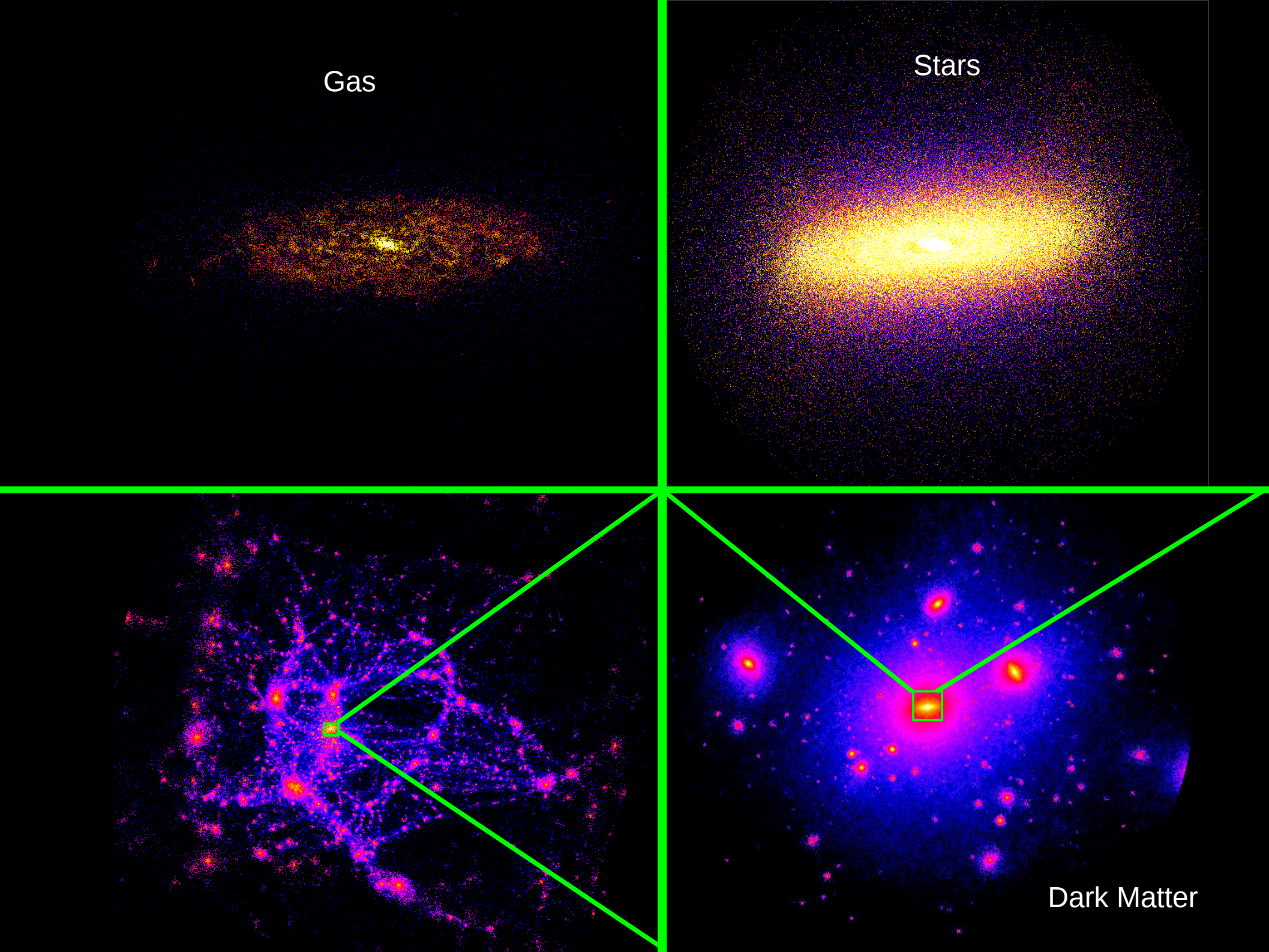
Fundamental Problem: Dark Matter and Energy: What is it?

- Not baryons
- Simulations show: not known neutrinos
- Candidates:
  - Sterile Neutrinos
  - Axions
  - Lightest SUSY Particle (LSP)



Computational Cosmology

- CMB has fluctuations of 1e-5
- Galaxies are overdense by 1e7
- It happens (mostly) through **Gravitational Collapse**
- Making testable predictions from a cosmological hypothesis requires
  - Non-linear, dynamic calculation
  - e.g. **Computer simulation**


Gas
Stars
Dark Matter

Substructure down to 100 pc

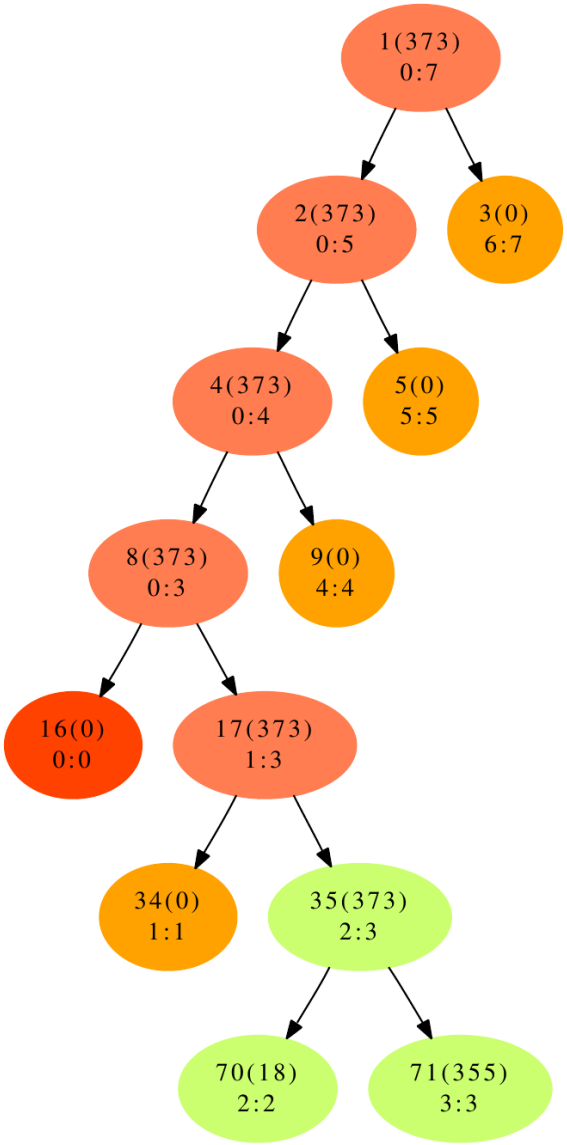
Stadel et al, 2009

Computational Challenges

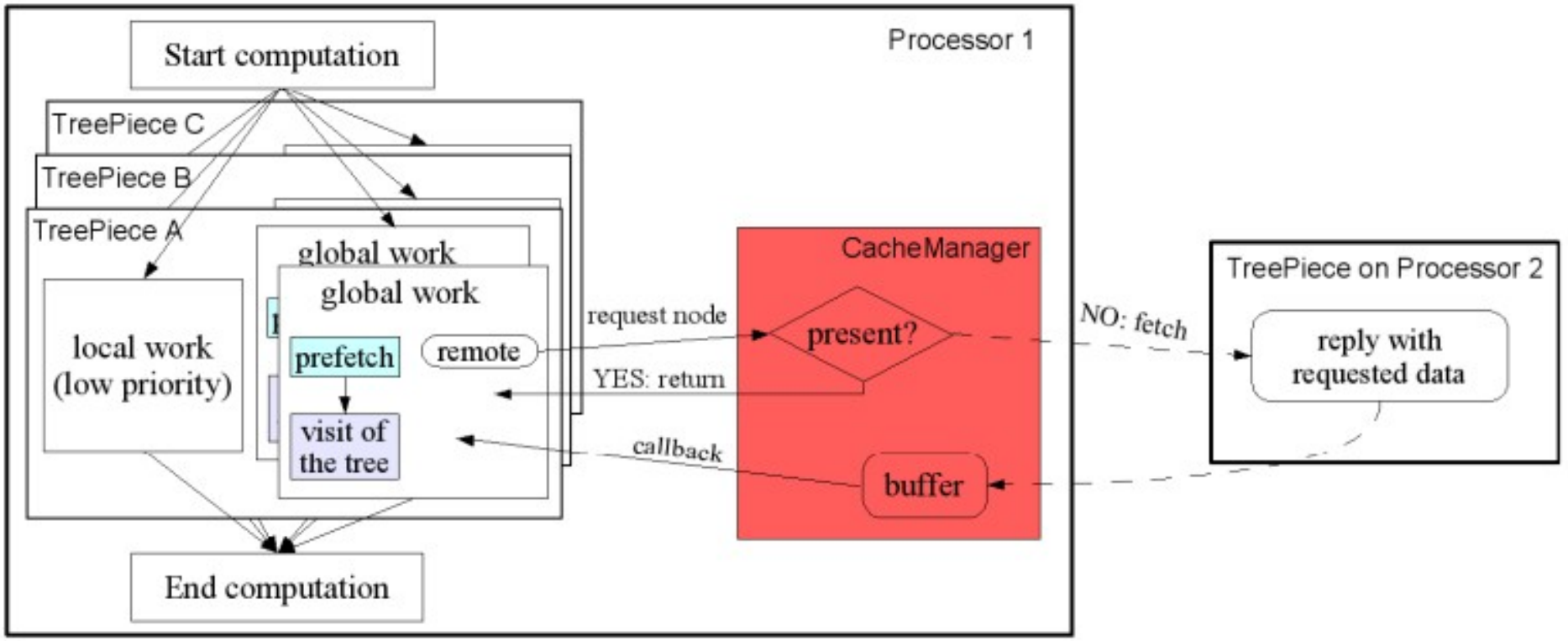
- Large spacial dynamic range: > 100 Mpc to < 1 kpc
  - Hierarchical, adaptive gravity solver is needed
- Large temporal dynamic range: 10 Gyr to < 1 Myr
  - Multiple timestep algorithm is needed
- Gravity is a long range force
  - Hierarchical information needs to go across processor domains

TreePiece: basic data structure

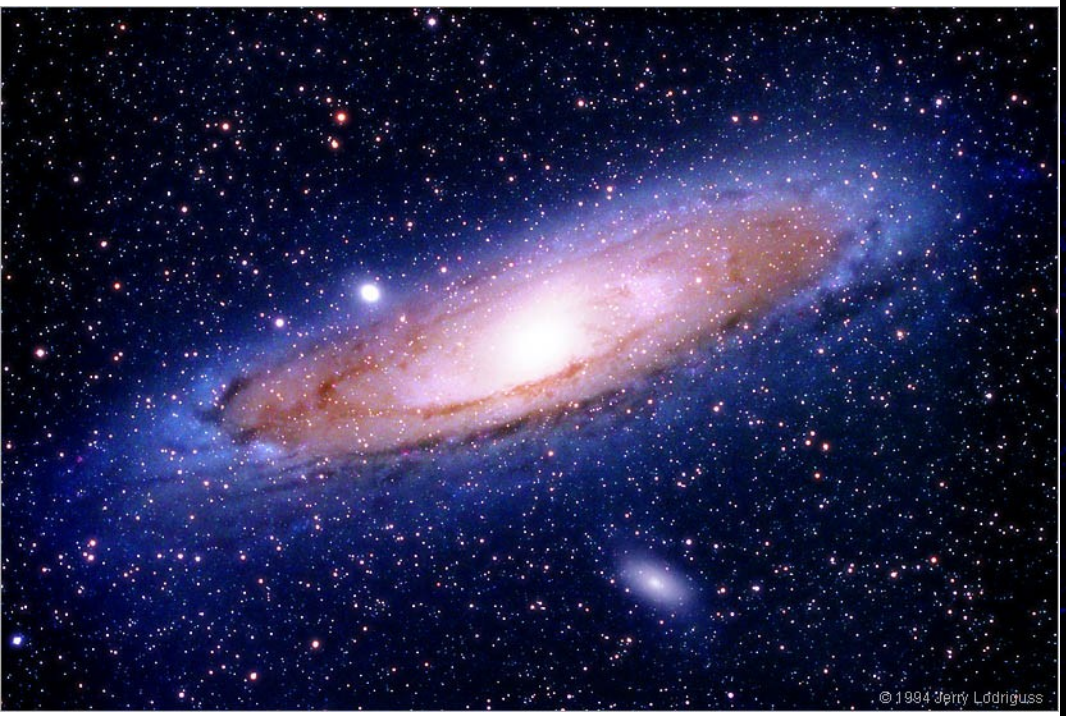
- A “vertical slice” of the tree, all the way to the root.
- Nodes are either:
  - Internal
  - External
  - Boundary (shared)

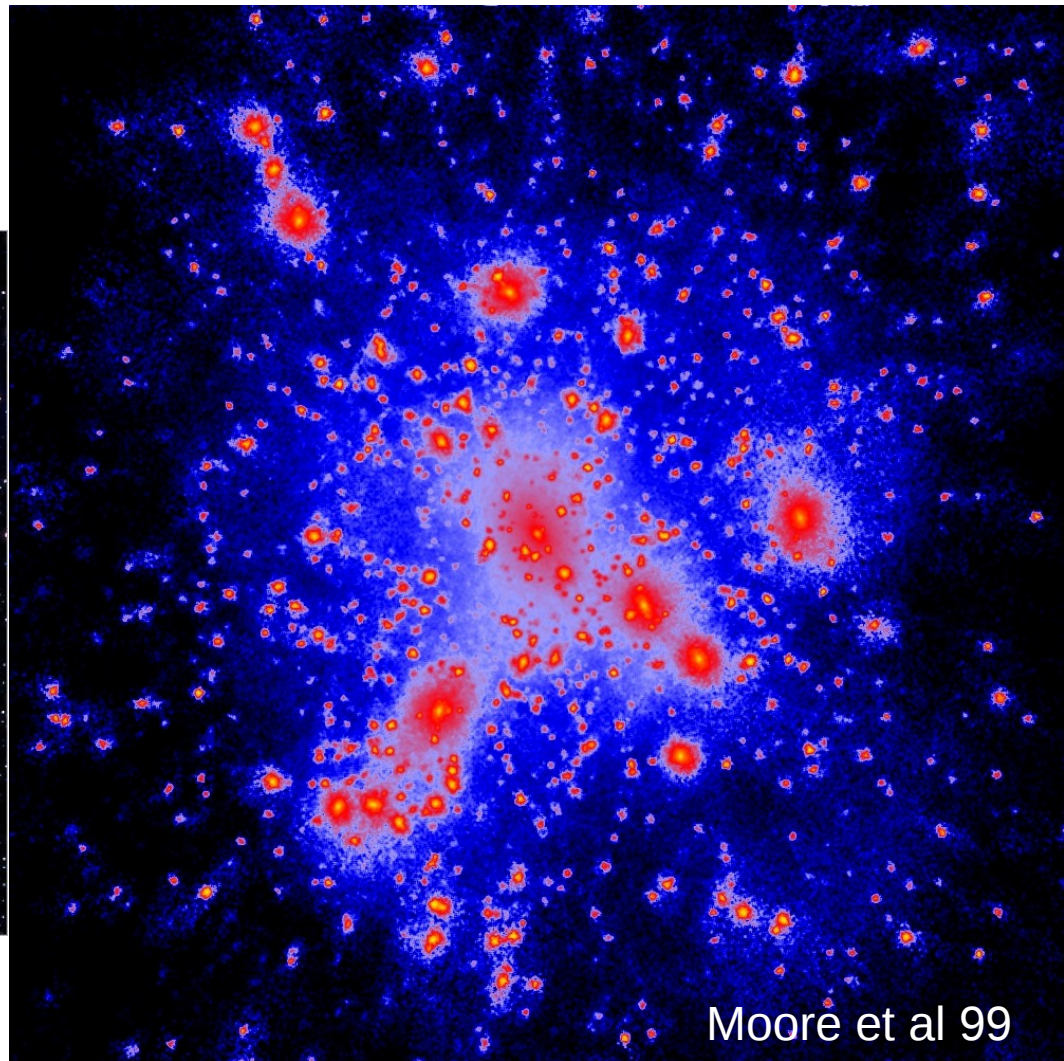


Overall treewalk structure



Light vs. Matter

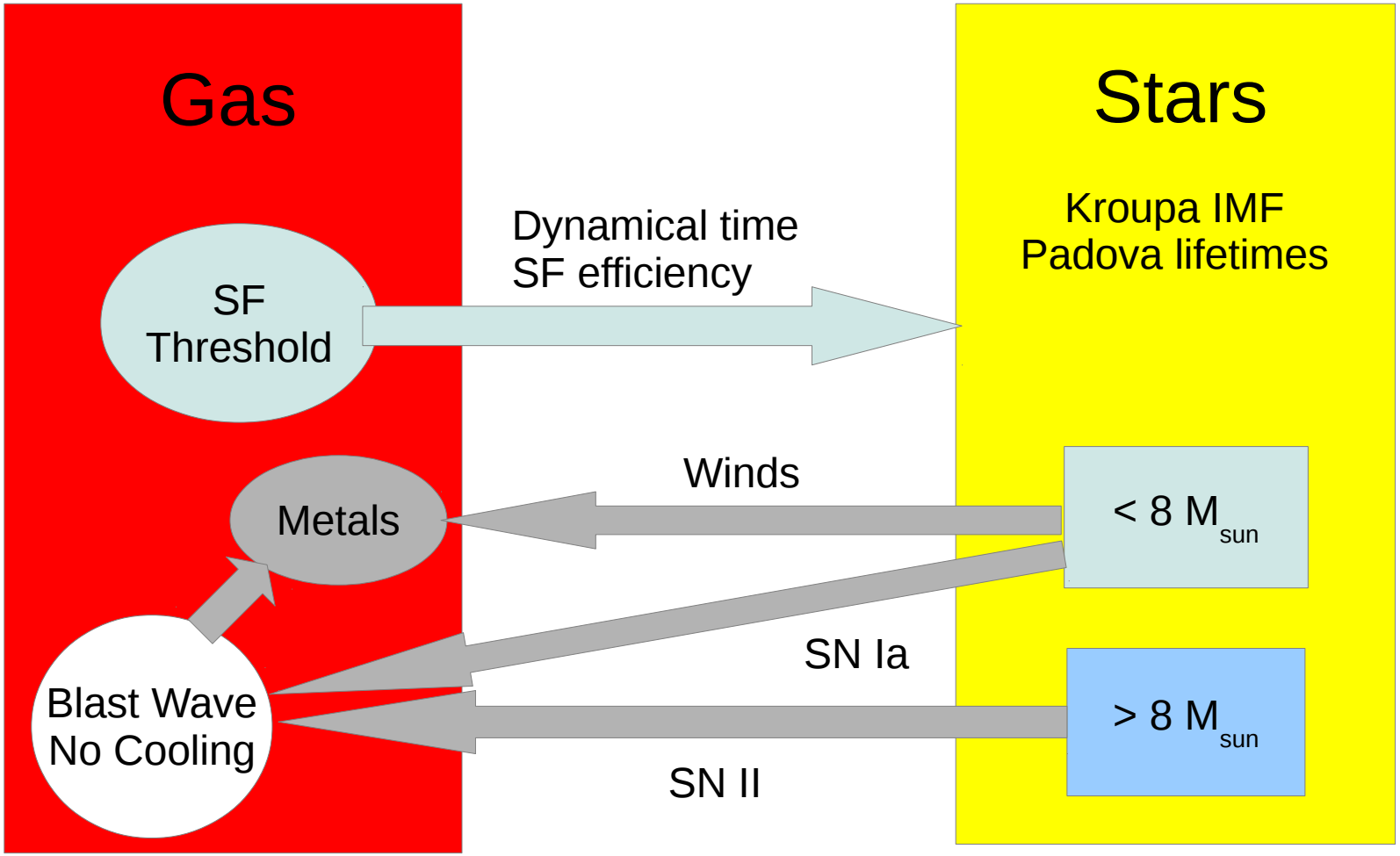




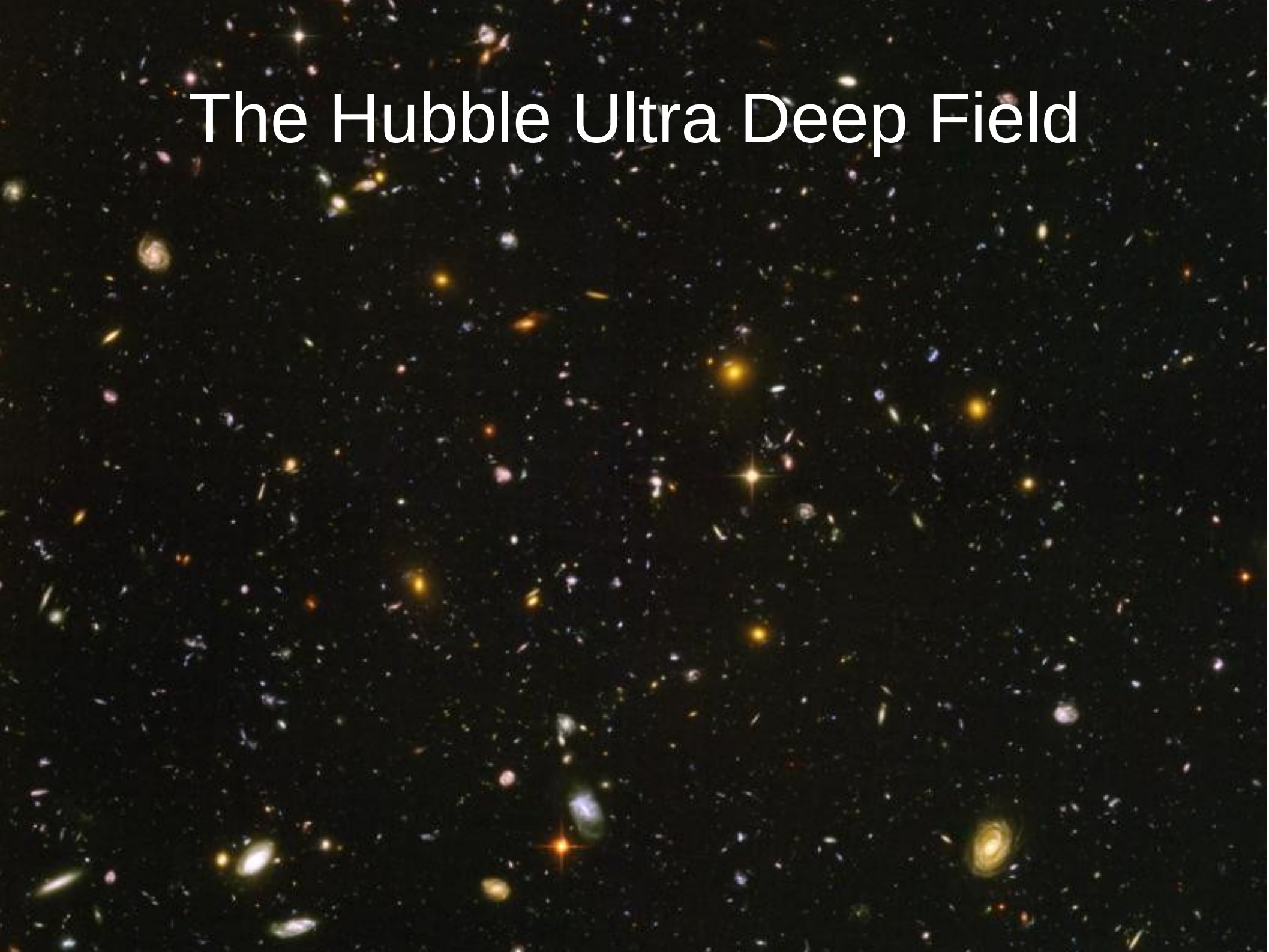
Smooth Particle Hydrodynamics

- Making testable predictions needs Gastrophysics
  - High Mach number
  - Large density contrasts
- Gridless, Lagrangian method
- Galilean invariant
- Monte-Carlo Method for solving Navier-Stokes equation.
- Natural extension of particle method for gravity.

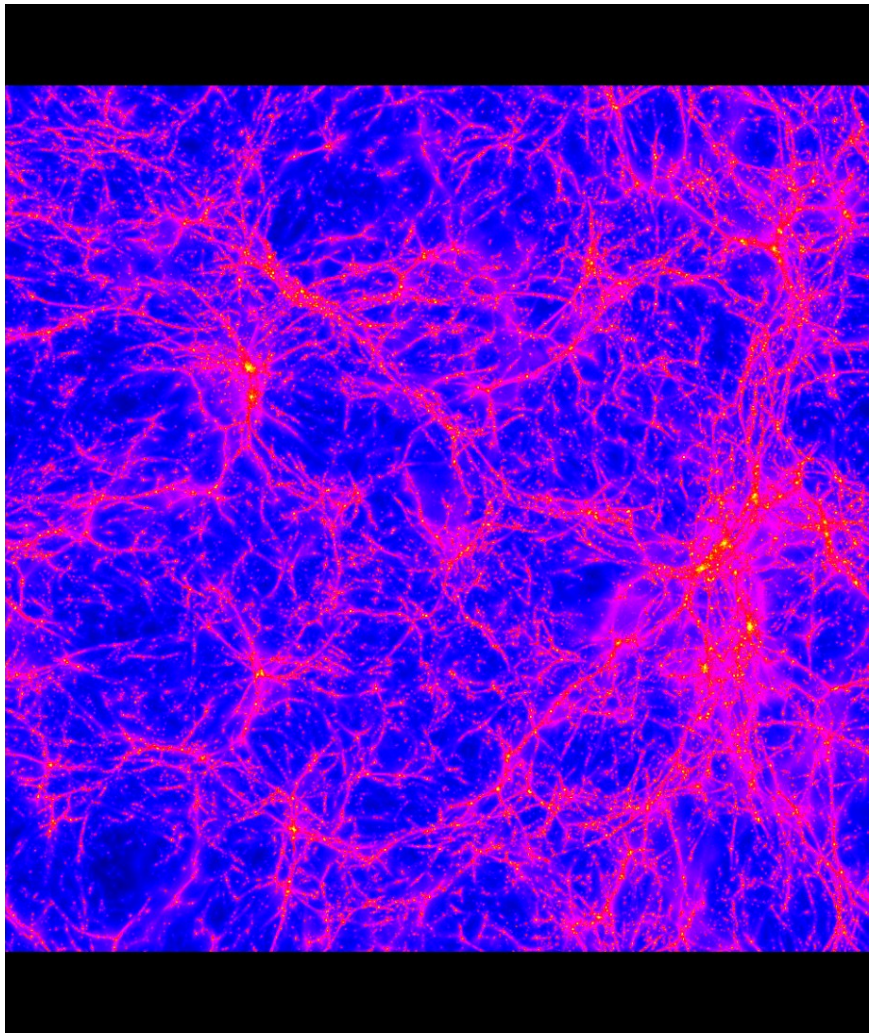
Star Formation/Feedback



Stinson et al 2006


The Hubble Ultra Deep Field

High Redshift Galaxies

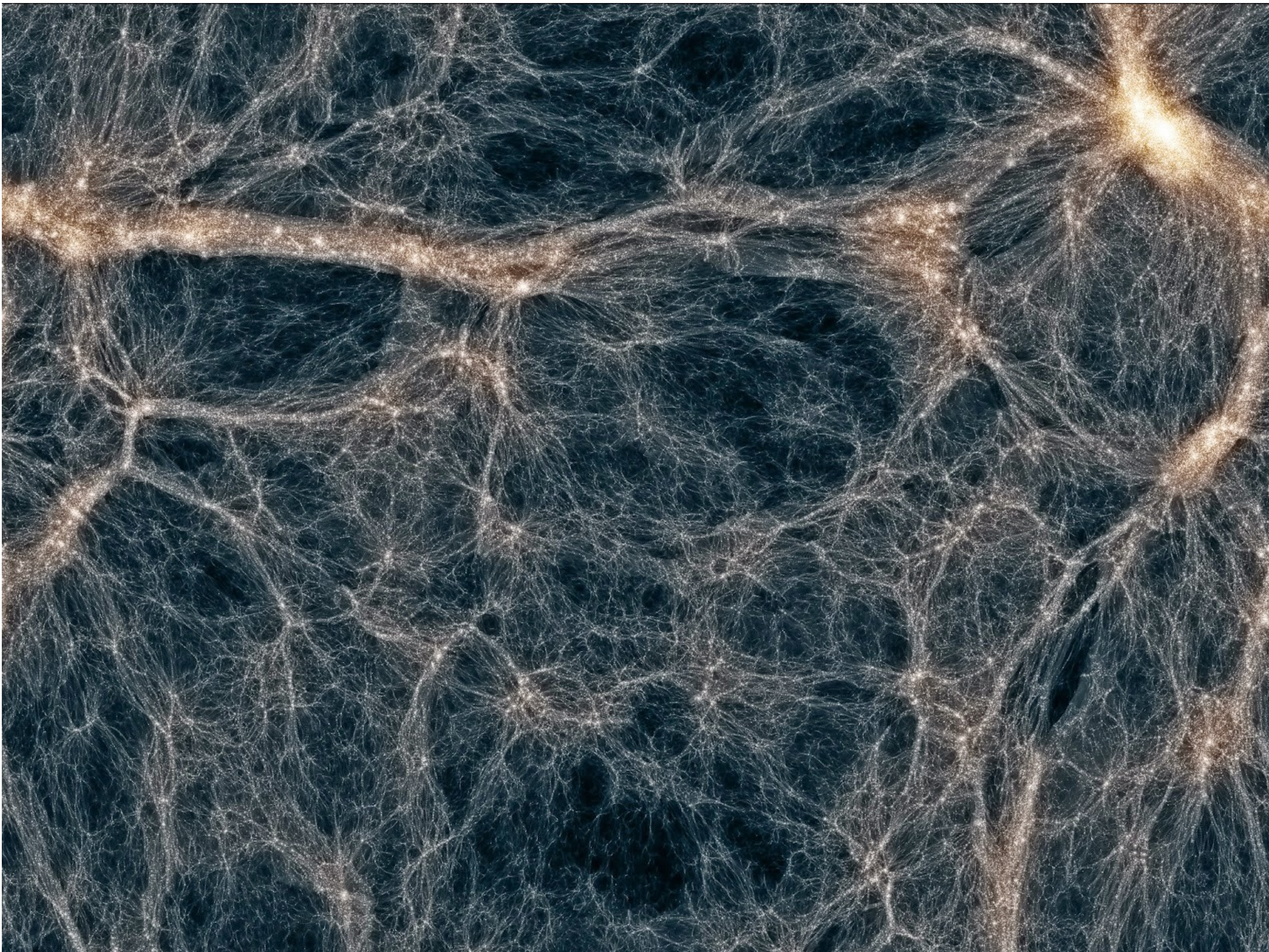


- Galaxies seen by Hubble 12 Gyr ago.
- How do they relate to the Milky Way?
- What is their formation history?
- 300M core-hours on Bluewaters

Charm Nbody GrAvity solver

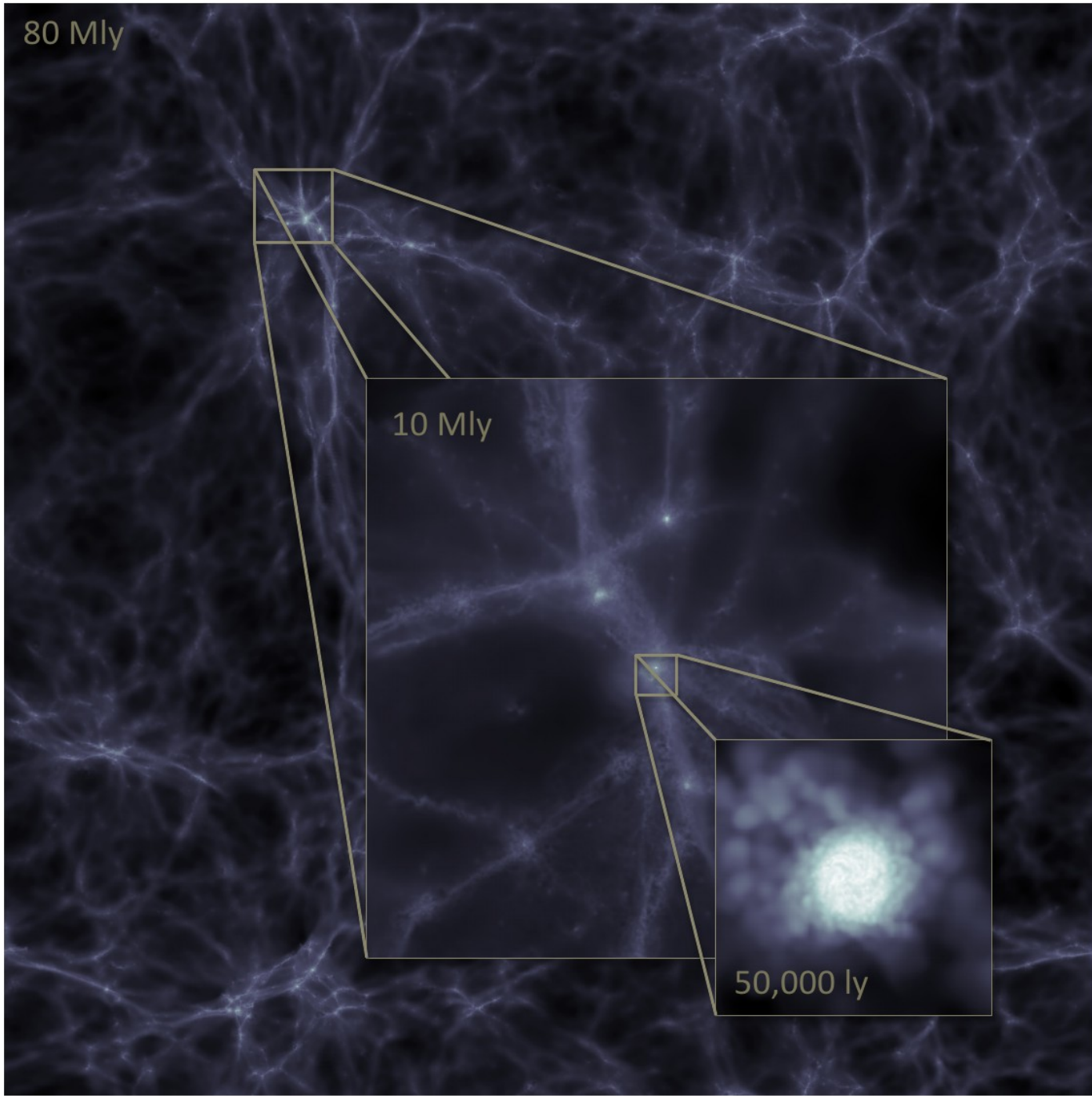
- Massively parallel SPH
- SNe feedback creating realistic outflows
- SF linked to shielded gas
- SMBHs
- Optimized SF parameters (kriging)

Menon+ 2014, Governato+ 2014

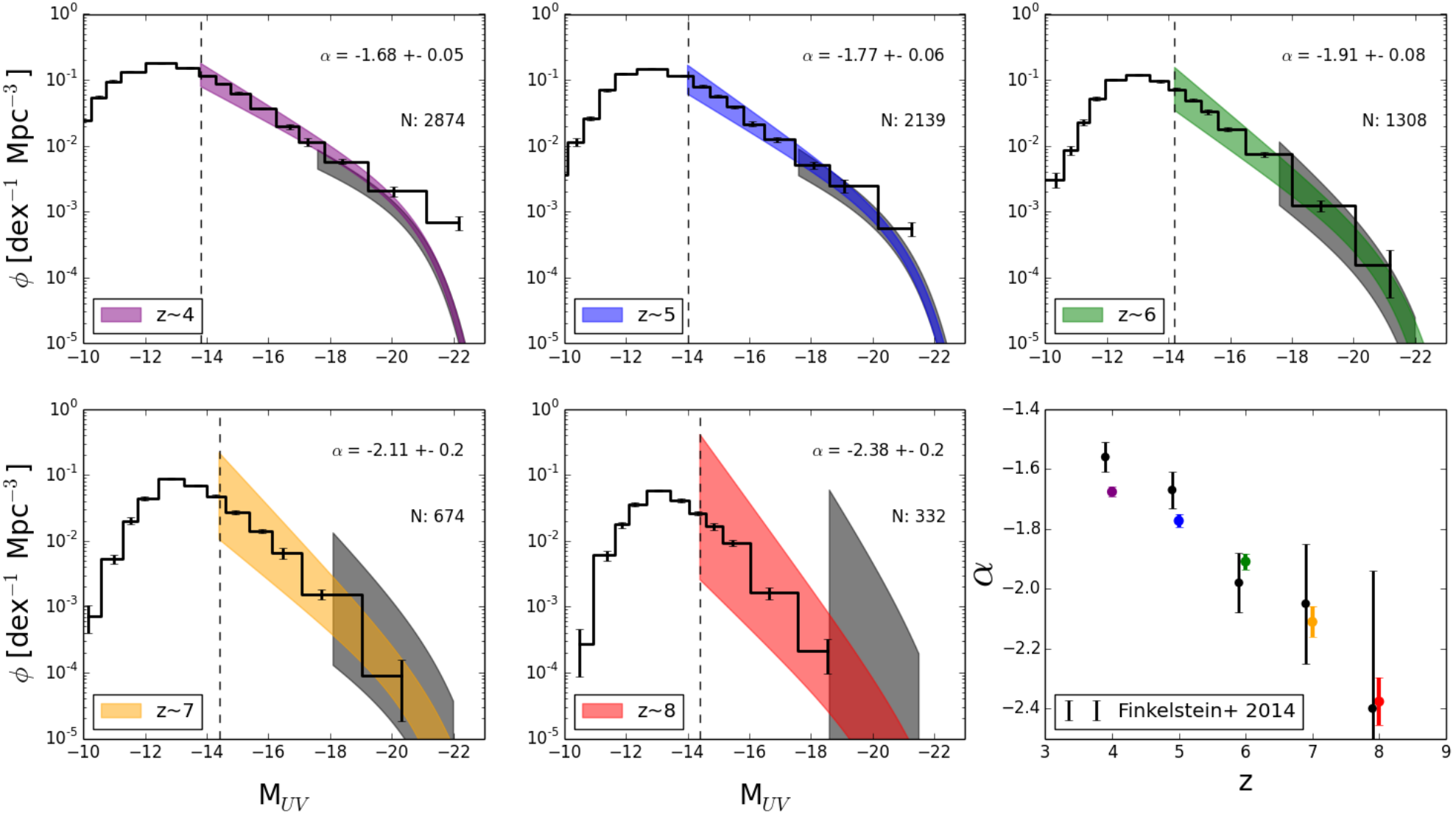


The Vulcan

- 2 billion particles
- (25 Mpc)^3
- Forces ~ 350pc
- SPH ~ 40 pc
- 100s of galaxies
- 5 TB dataset



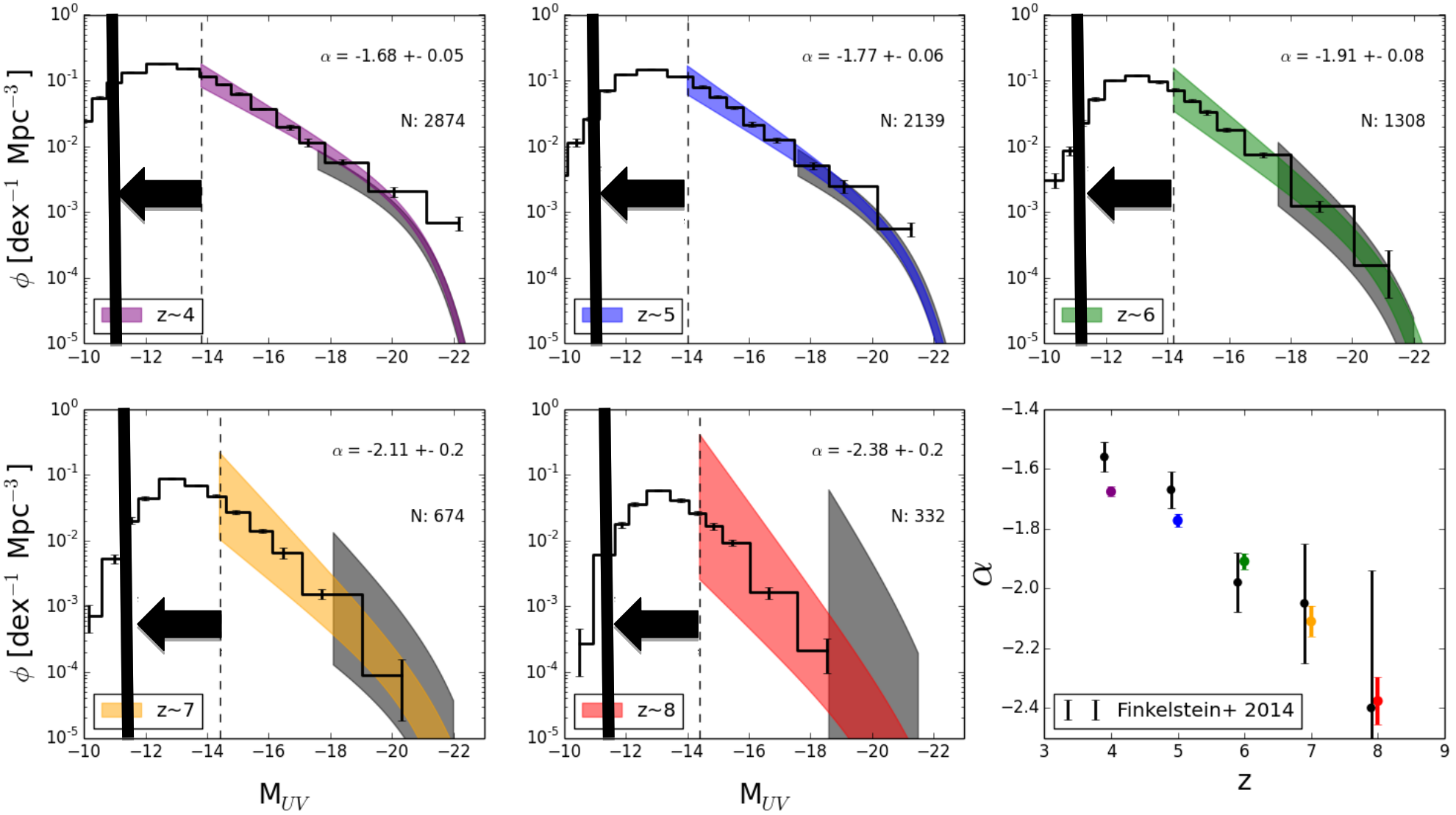
Luminosity Function



Comparison with Finkelstein+ 2014

L. Anderson+ 2015

Luminosity Function: Faint end slope



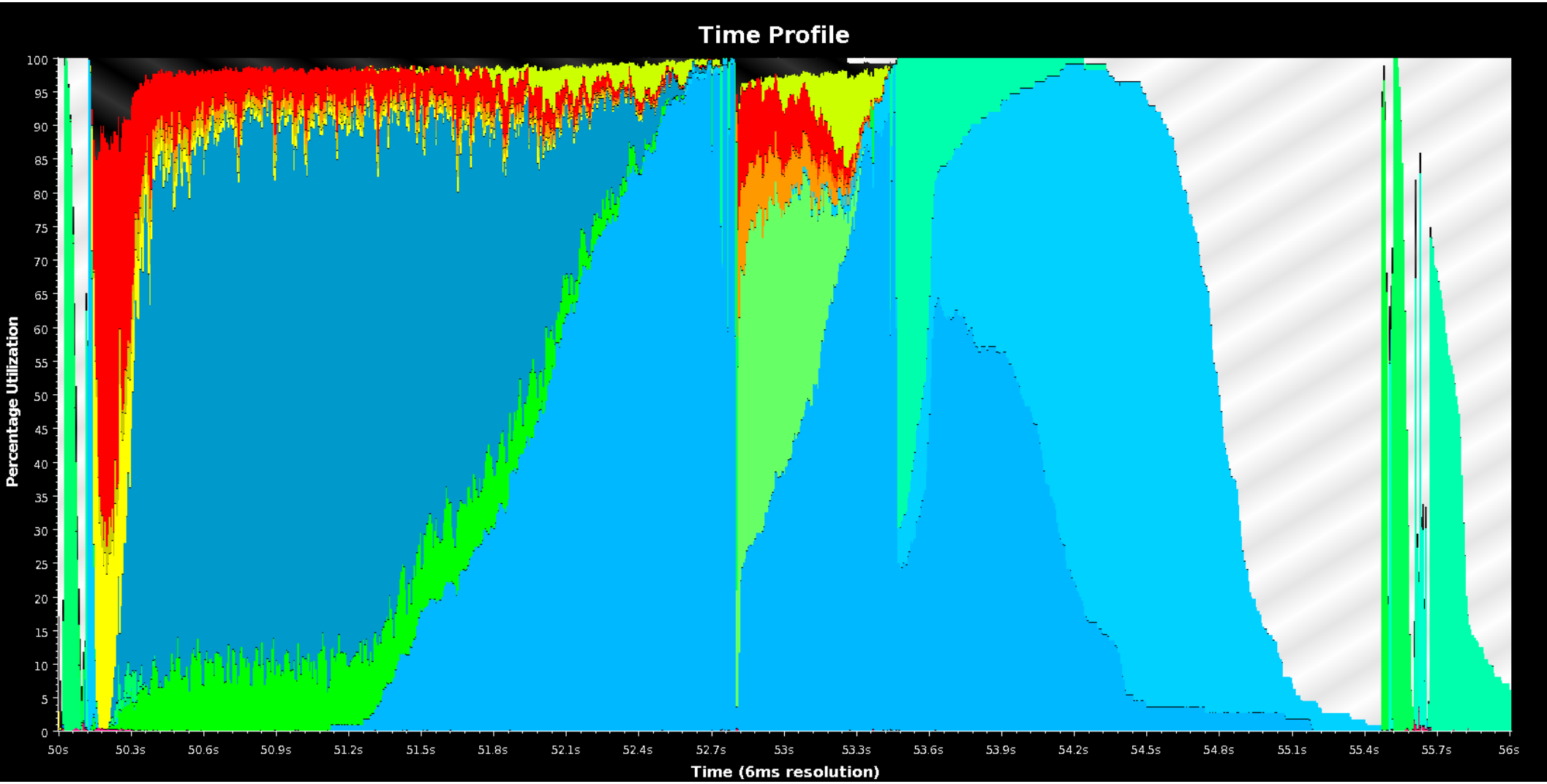
Simulations

	First Stage	Near Future
	Vulcan	Enterprise
Timeline	2014	Autumn 2015
Size	$(25\ \mathrm{Mpc})^3$	$(25\ \mathrm{Mpc})^3$
Nparticles	2 billion	25 billion
Duration in z	100-4	100-0
Force Resolution	350 pc	175 pc
Morphologies	5e10 Mtot	5e9 Mtot
Size	5 TB	100 TB
Extra Physics		Black hole feedback H2 regulated star formation

Latency hiding strategies

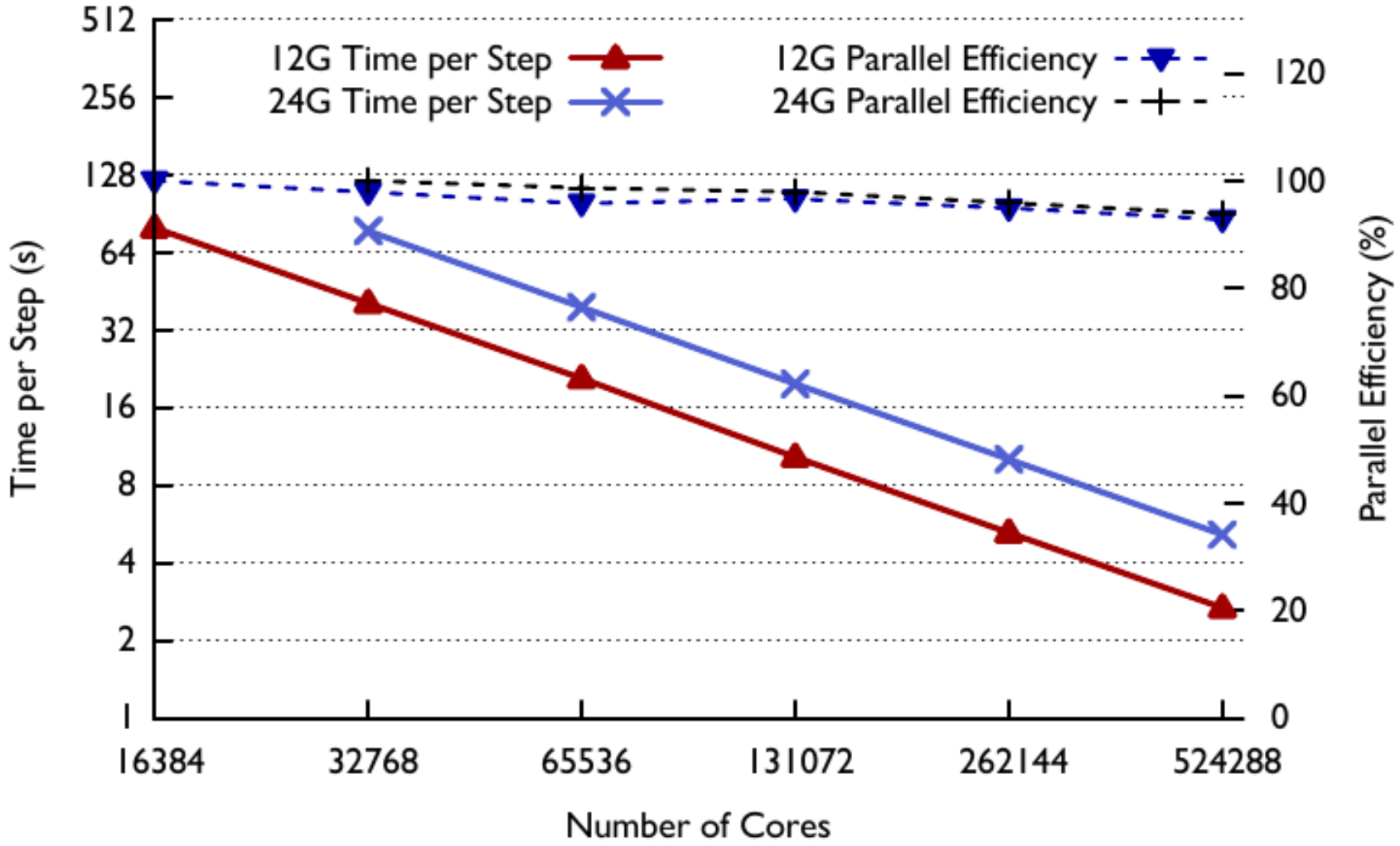
- Multiple “treepieces”/core (over decomposition)
- Division into multiple work units (*all concurrently*)
  - Off processor gravity treewalk
  - SPH treewalk
  - Local gravity treewalk
  - Ewald summation
- Method prioritization
  - Data requests get high priority

Overlap of Phases



Gravity Hydrodynamics

Scaling to .5M cores



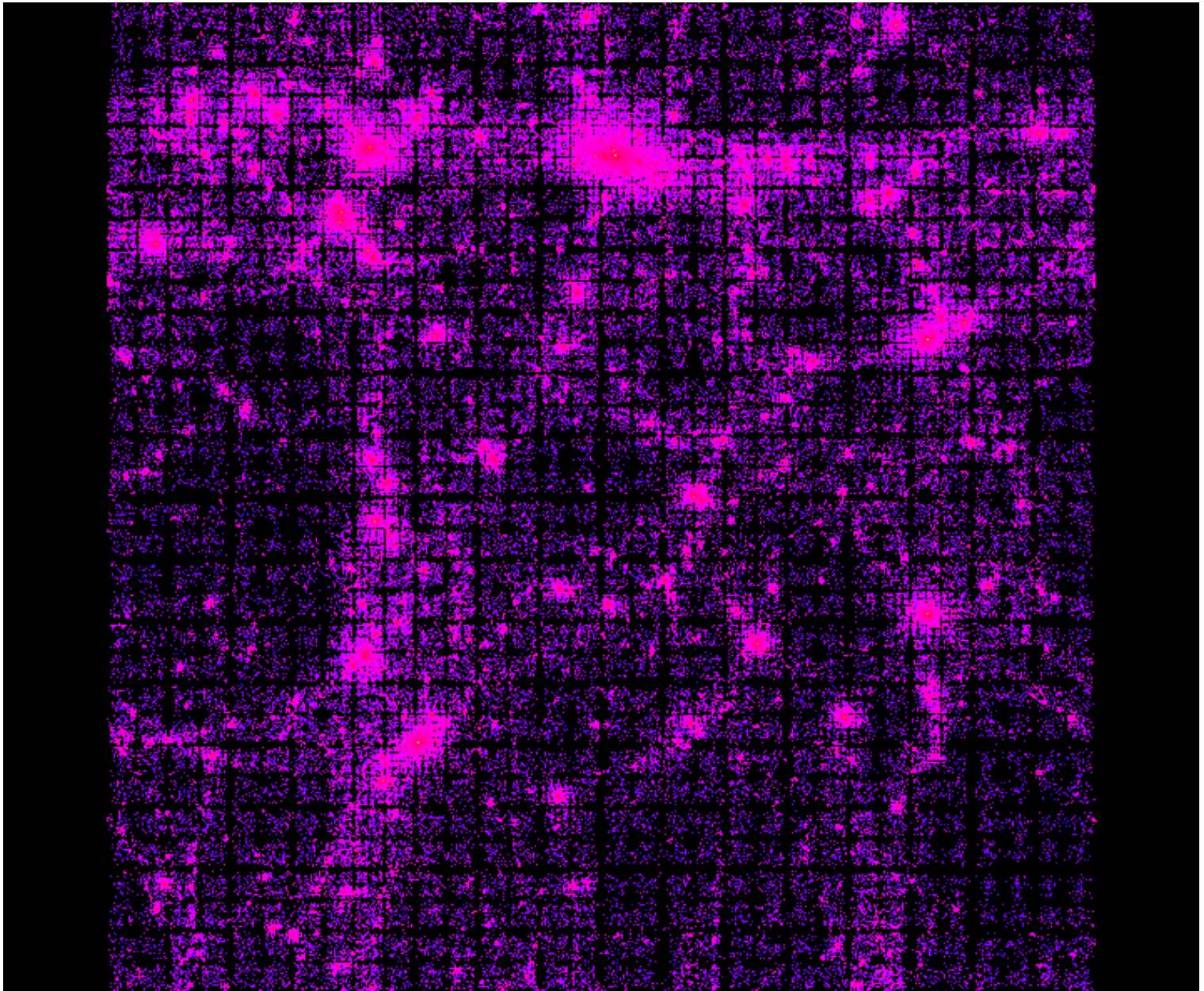
Optimizations for Large Core Count

- Domain Decomposition
  - Reuse previous domain information
  - Only re-decompose when necessary
  - Optimize sort
  - Quiescence detection for particle migration
- Hierarchical Load Balancing
- Treebuilding and approximate remote node location

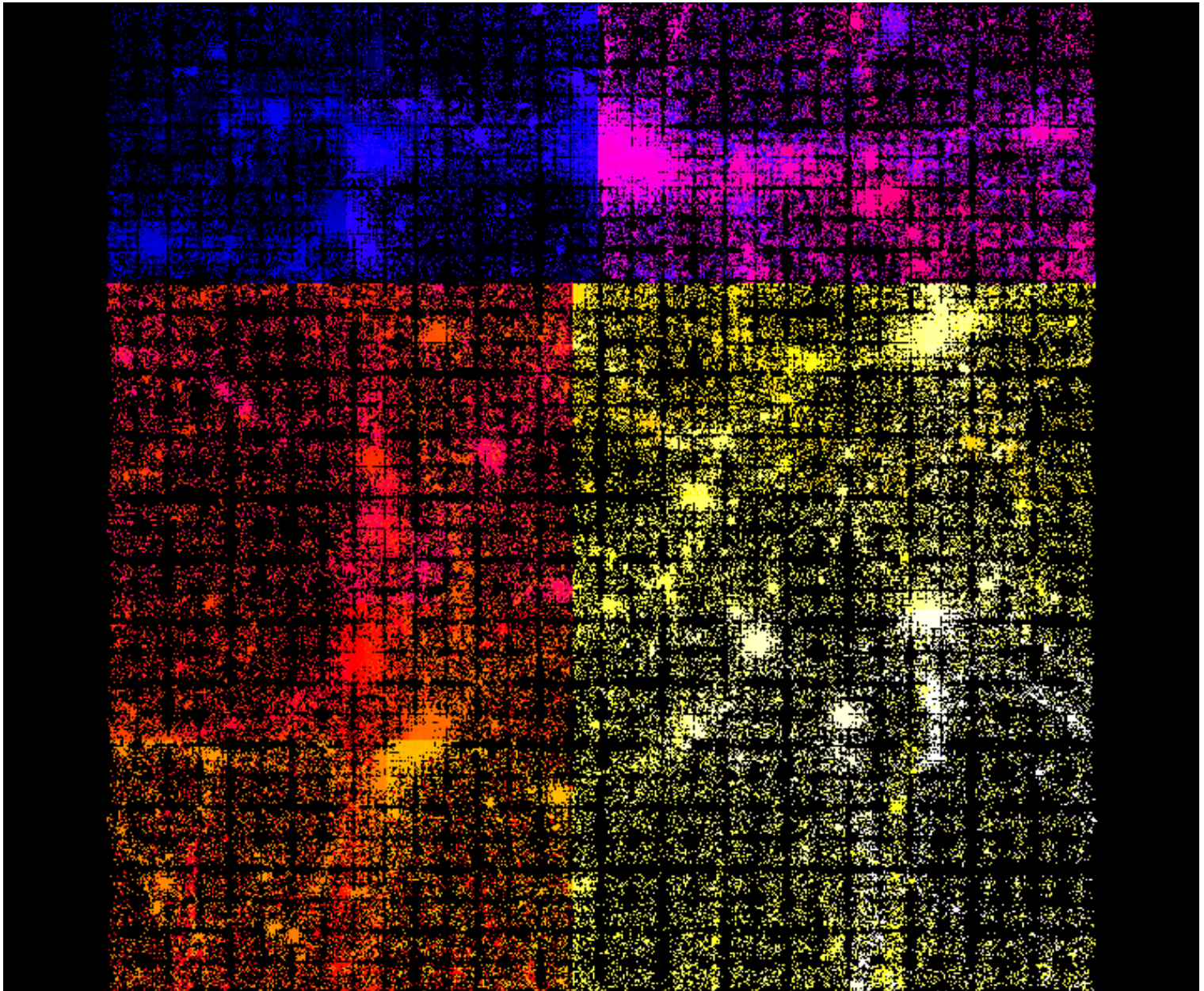
Clustered/Multistepping Challenges

- Load/particle imbalance
- Communication imbalance
- Fixed costs:
  - Domain Decomposition
  - Load balancing
  - Tree build

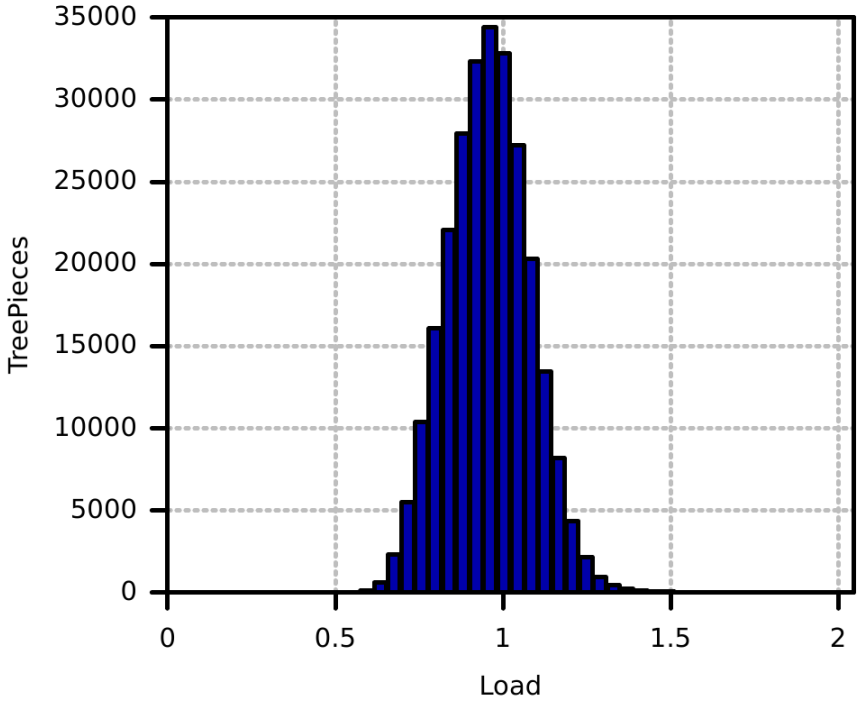
Load Variance

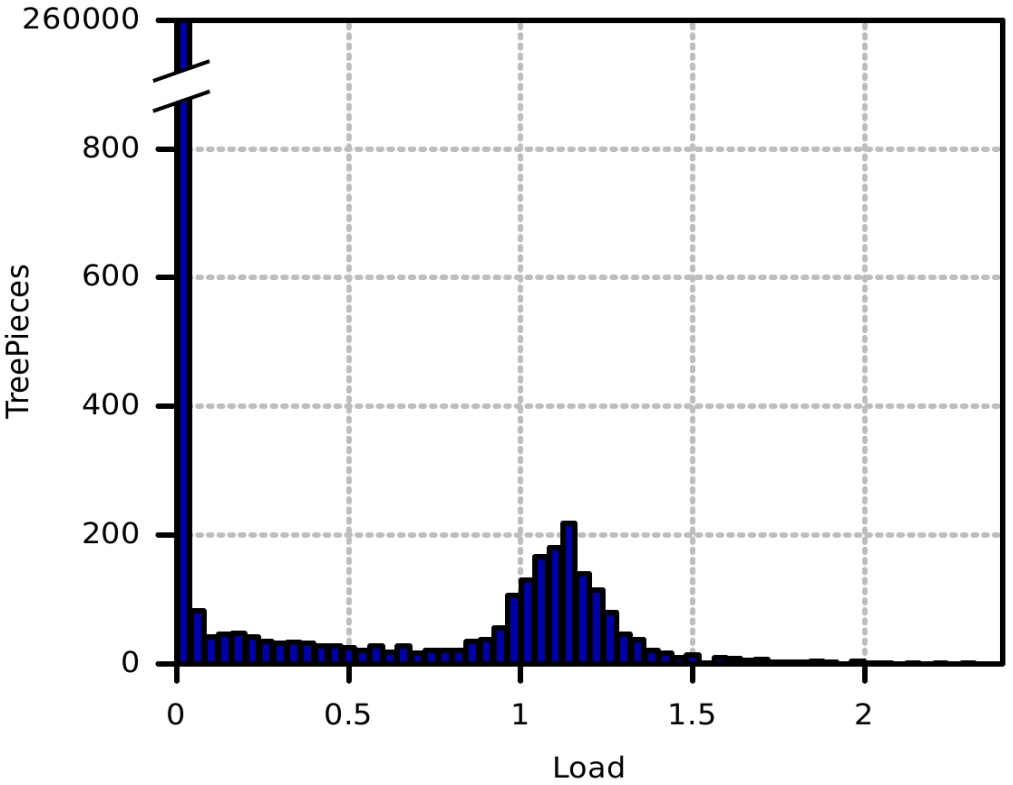


ORB Load Balancing

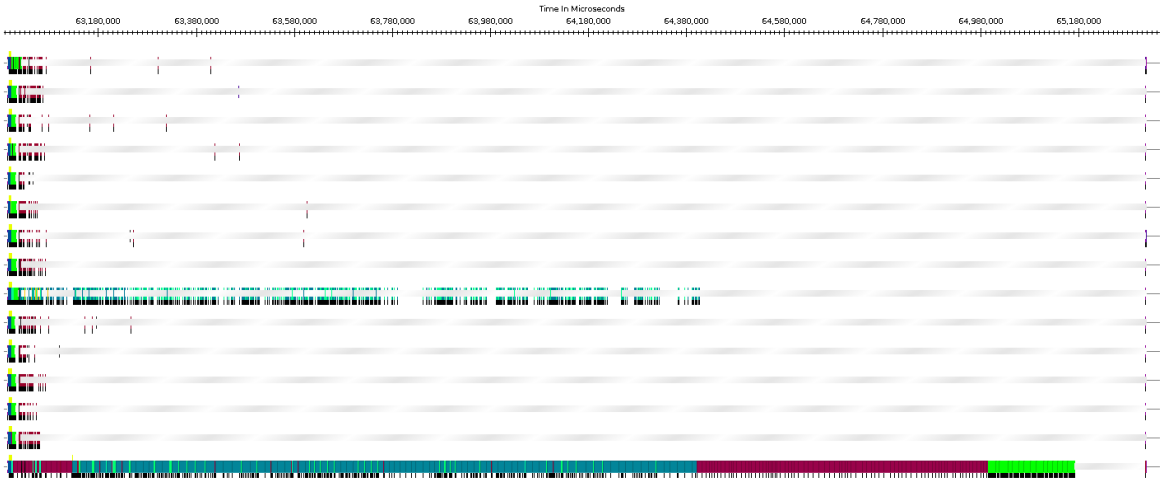


Load distributions

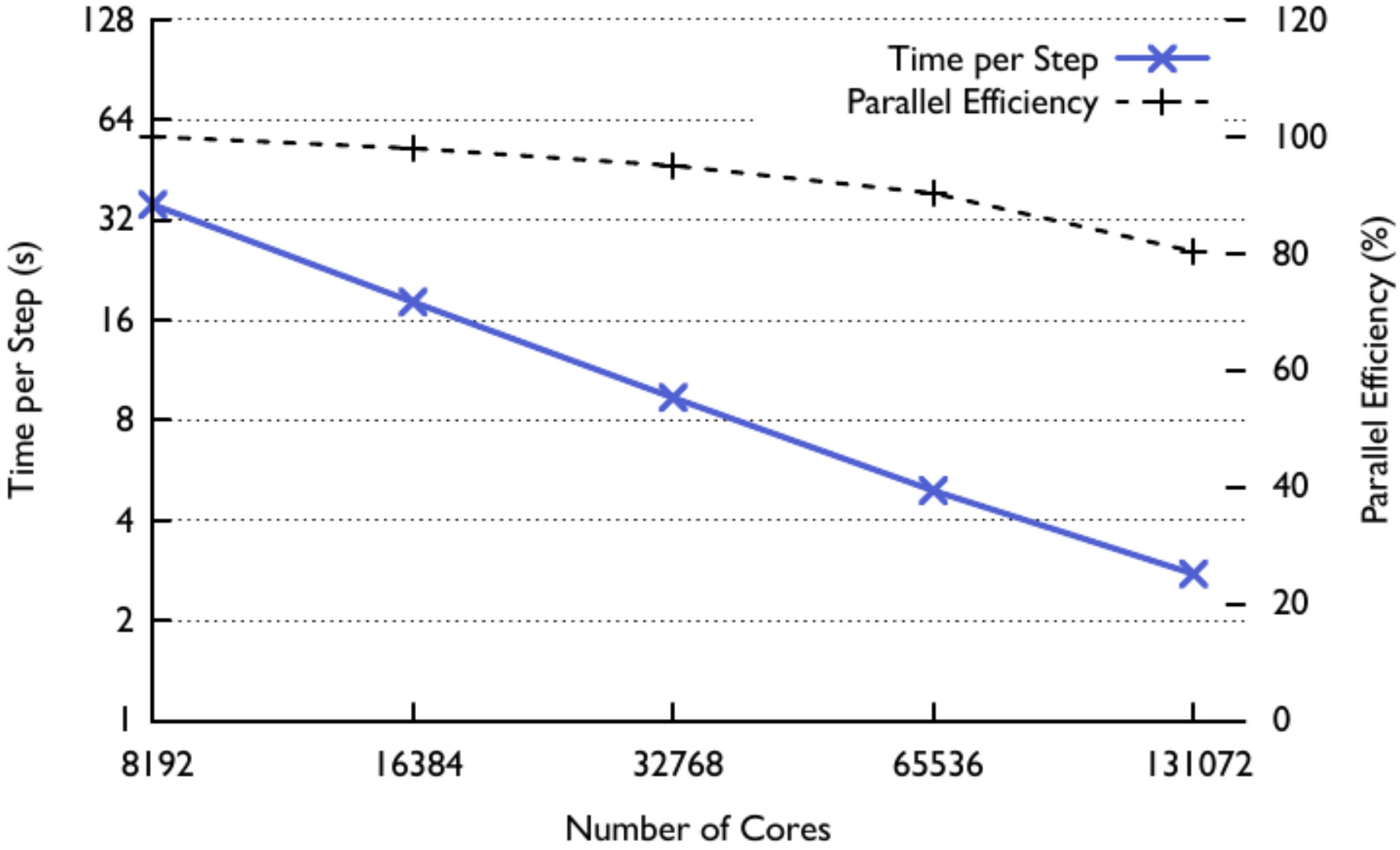




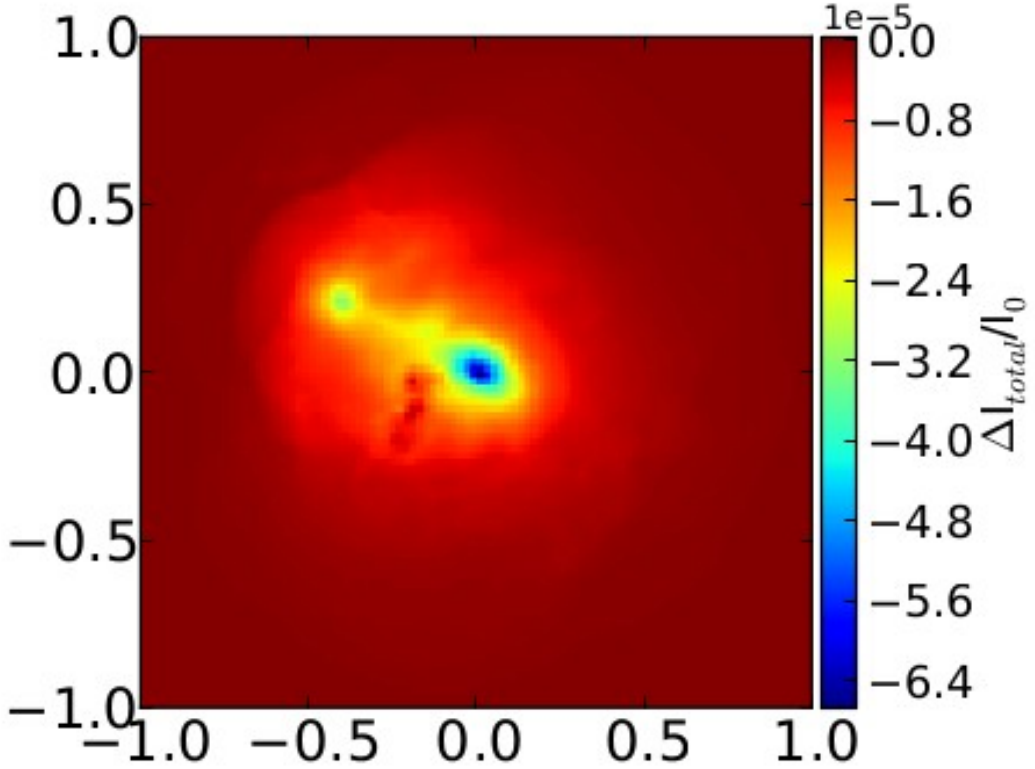
Intra-node work balancing



Multistep speedups



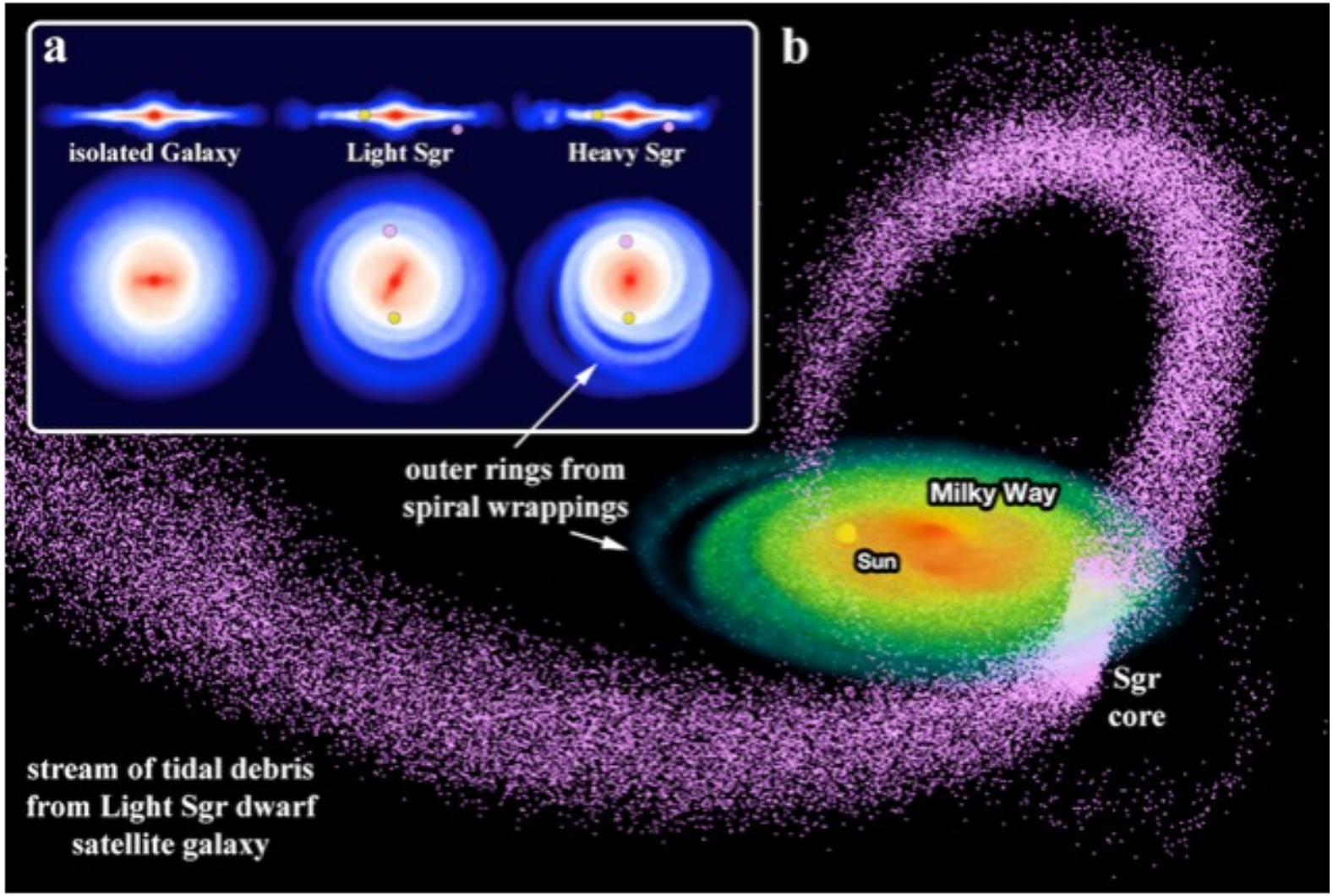
Clusters of Galaxies



- Largest bound objects in the Universe
- Used to study evolution of Dark Energy
- Need 1 kpc resolution in 600 Mpc volume

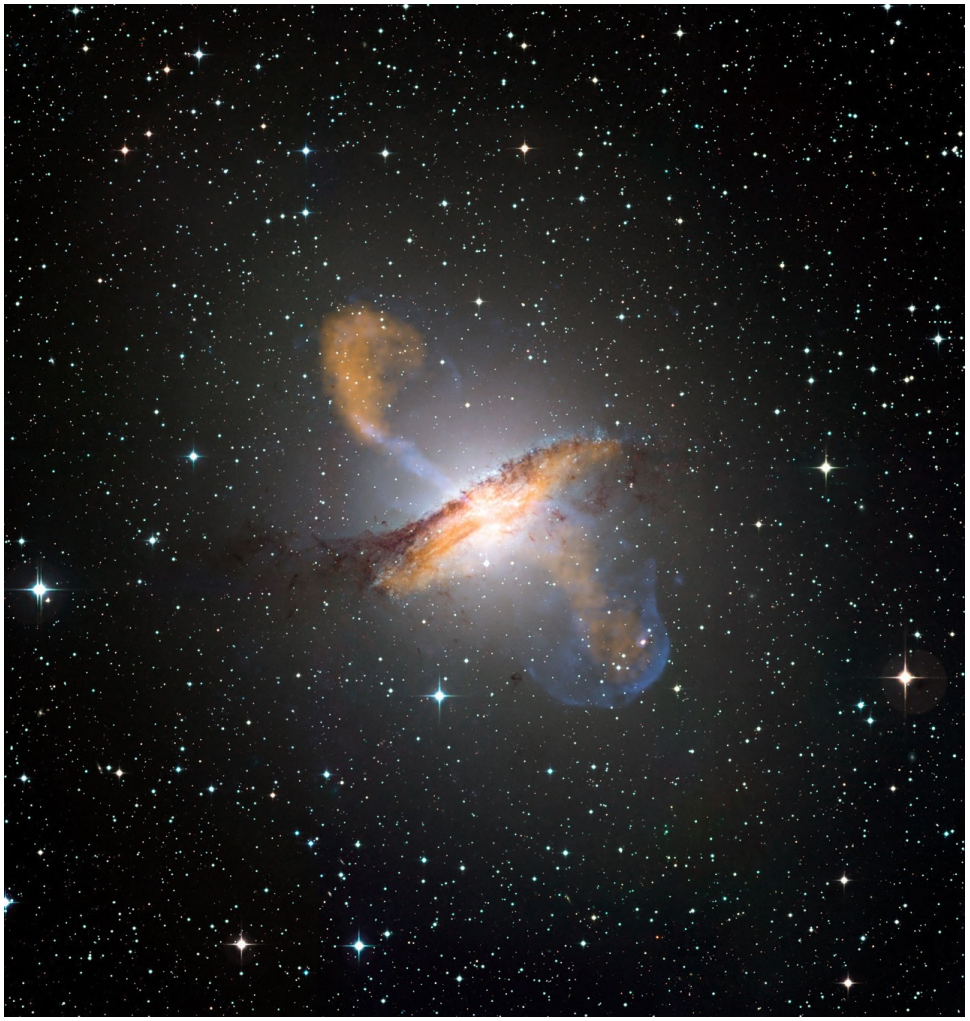
John Ruan, et al 2013

Dwarf Galaxies and the Milky Way Disk



Purcell et al, Nature 2011

Active Galactic Nuclei and Black Holes



- Supermassive Black Holes seem to be at the centers of most galaxies
- Occasionally they become “active”, i.e. energetic.

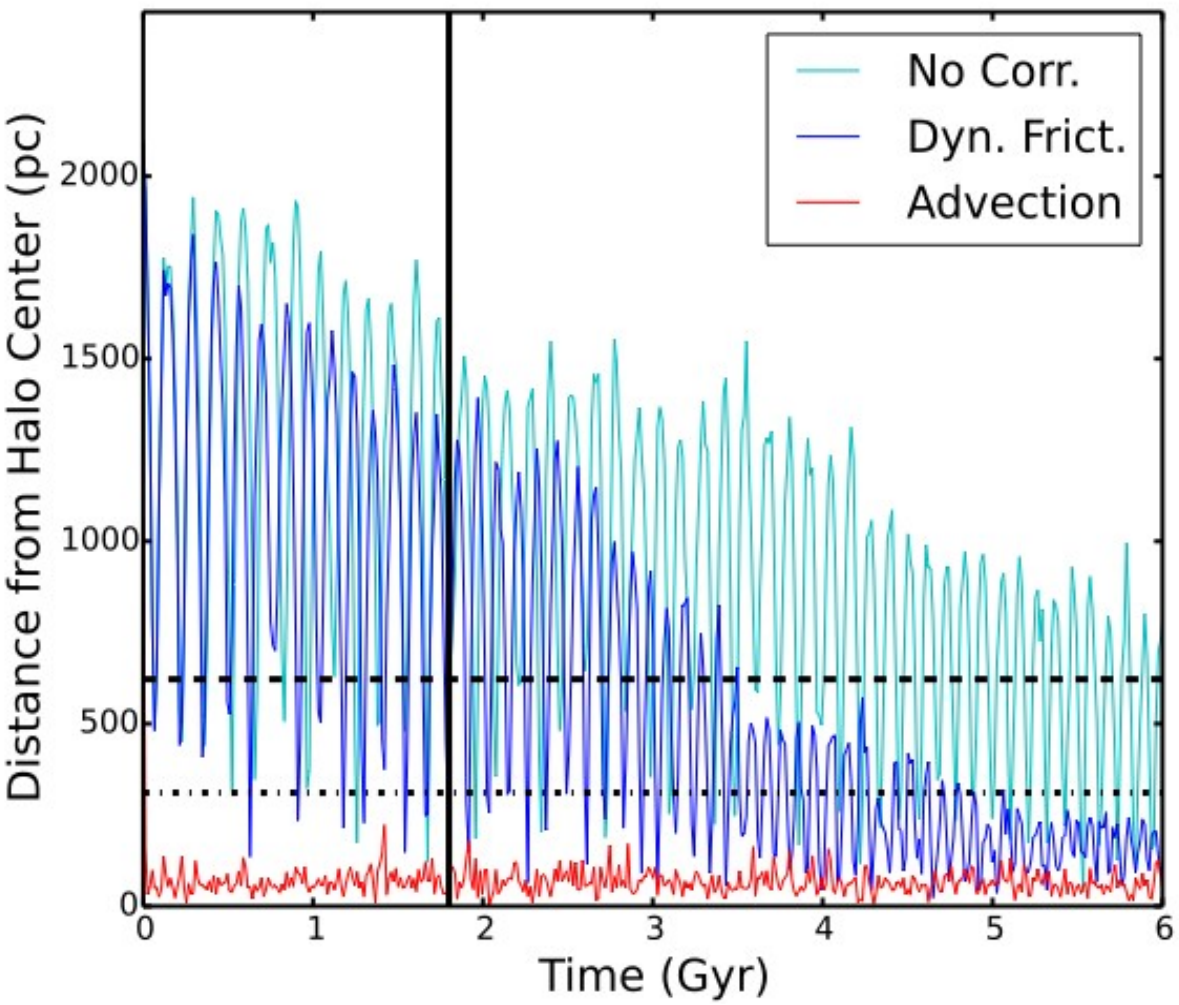
Black Hole Dynamics

- BHs are not assumed to always be stable at the center of their host galaxies

- Unresolved dynamical friction is applied as a sub-grid model
  Tremmel+2015

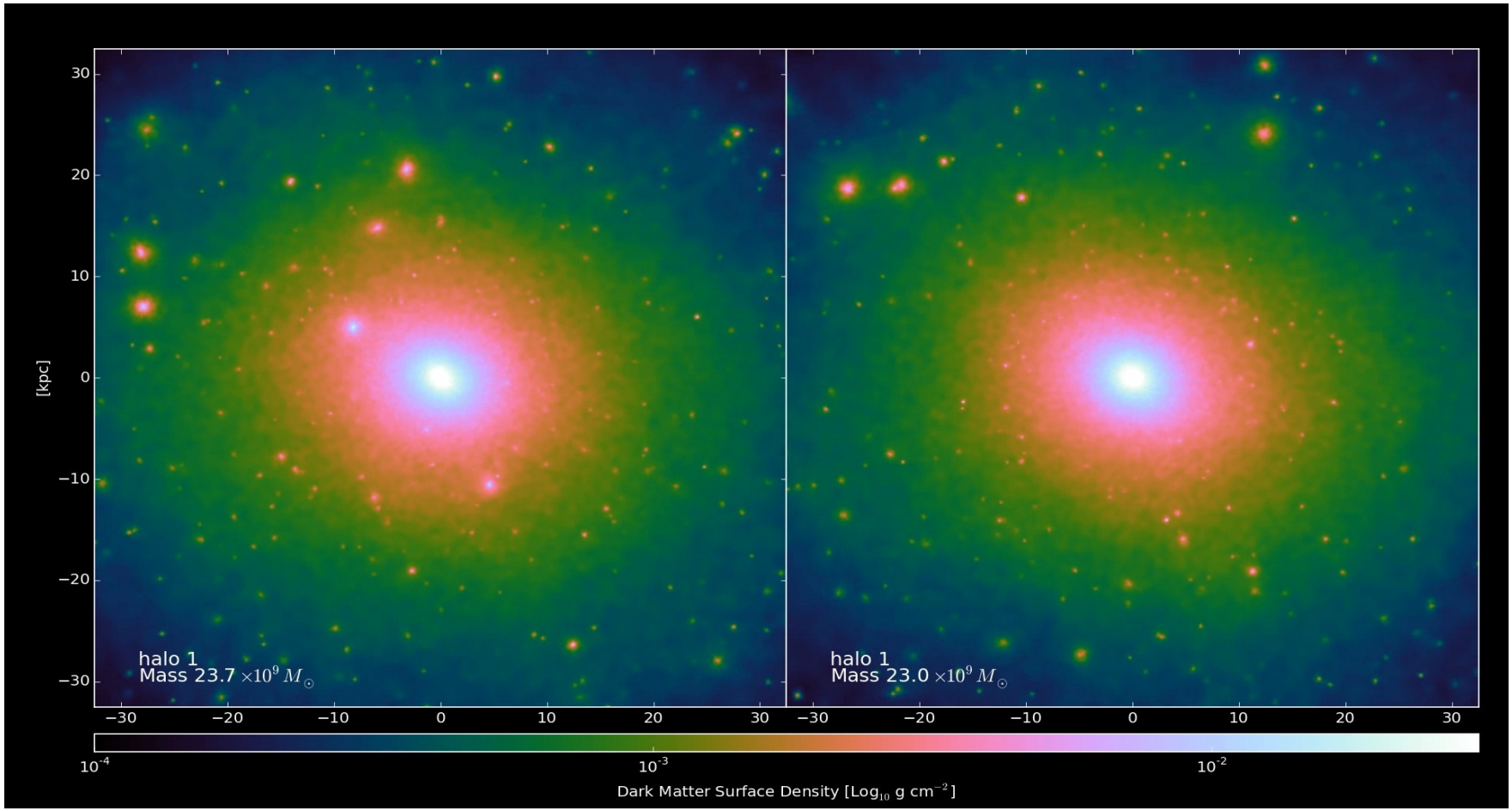
- High DM mass resolution avoids numerical noise
  Bellovary+ 2010, Tremmel+2015

Tremmel+ 2015

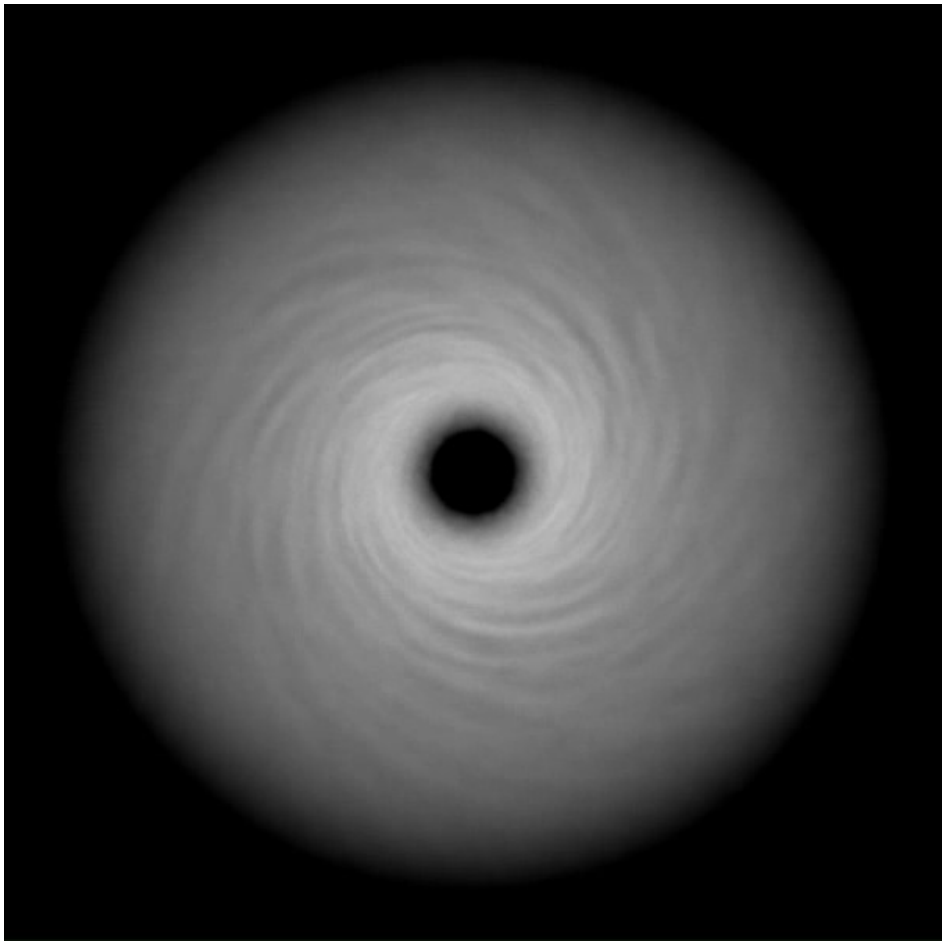


Black Holes and Feedback

Self Interacting Dark Matter



Planet Formation



Future

- More Physics
  - Radiative transfer
  - Collisional dynamics
  - Common Astrophysics modules
- Better gravity algorithms
  - Fast Multipole Method
  - Heterogeneous machines