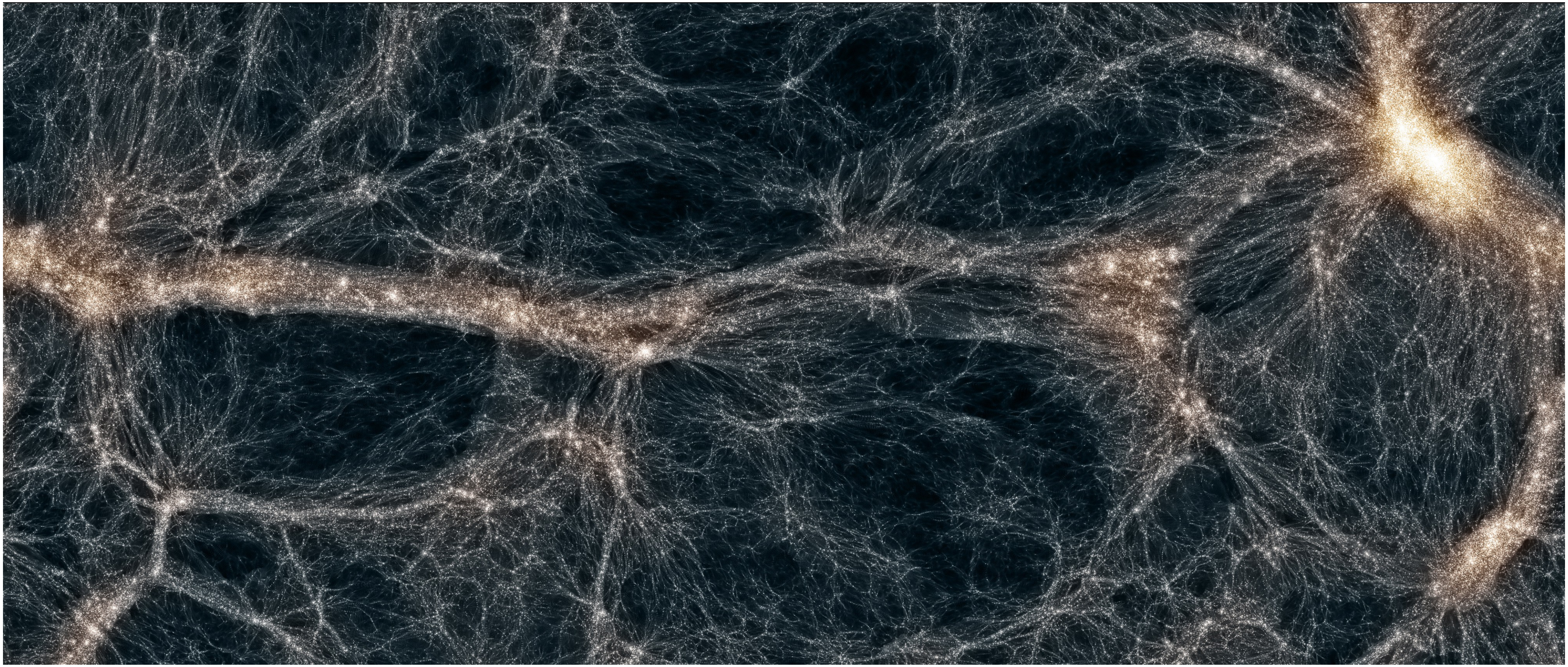
From Cosmology to Planets:
the ChaNGa N-body/Hydro Code



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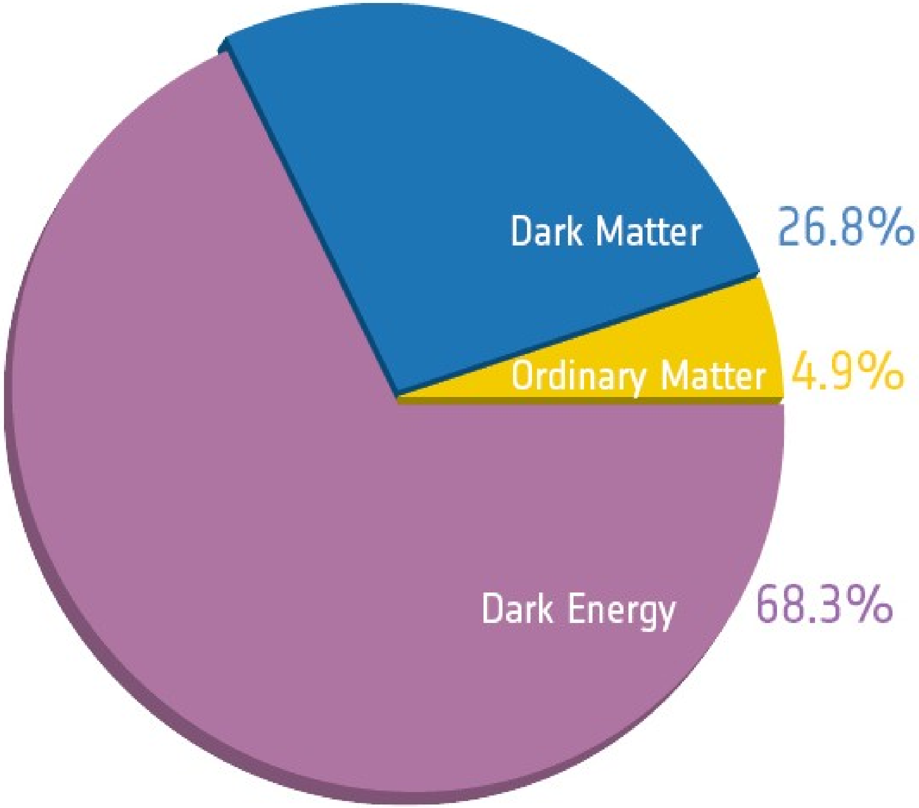
The Hierarchy

- Cosmology
- Galaxy Clusters
- Galaxies
- Stars
- Planets
- You

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

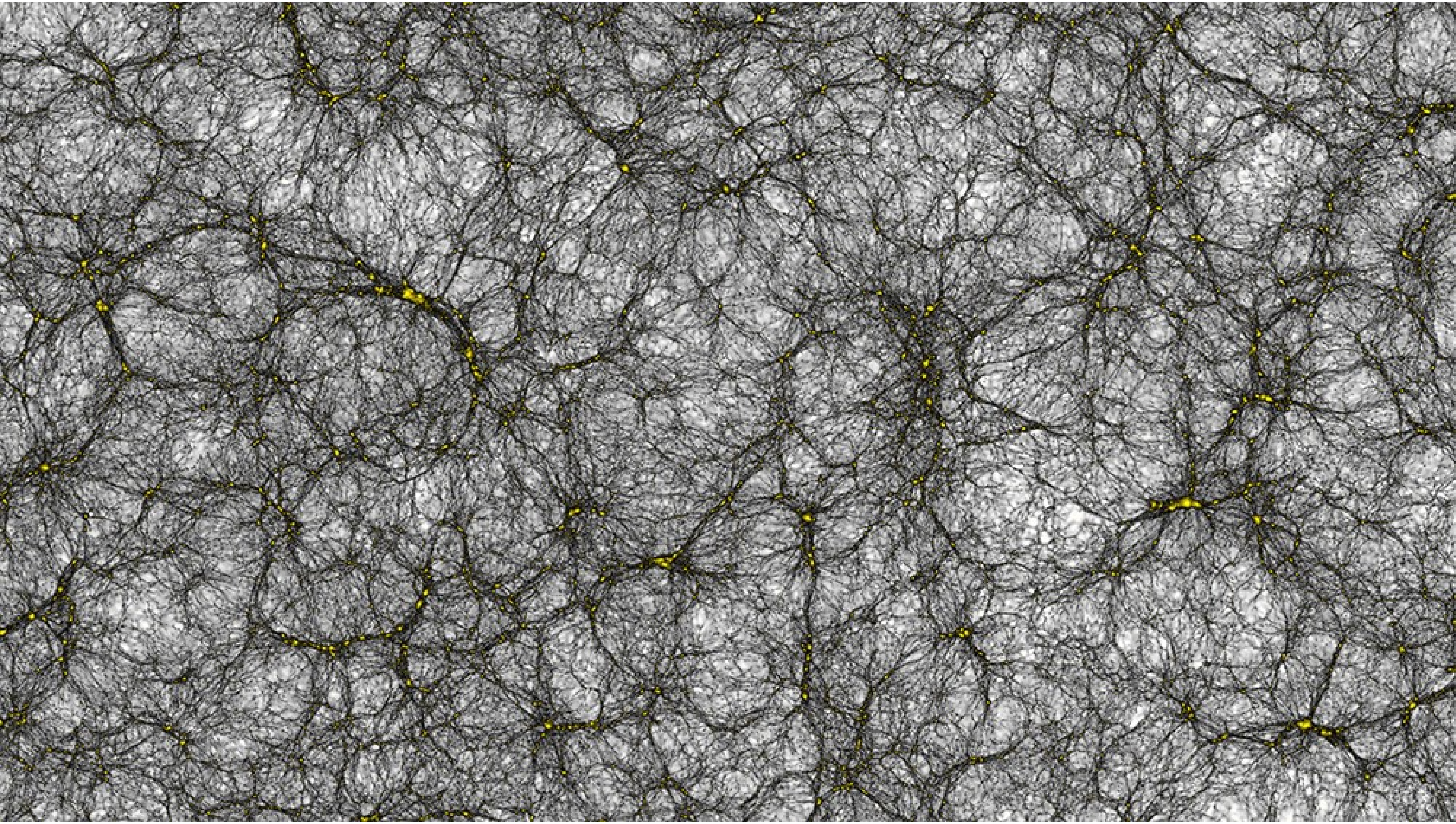
- Not baryons
- Gravitates!
- Simulations show: not known neutrinos
- Candidates:
  - Sterile Neutrinos
  - Axions
  - Lightest SUSY Particle (LSP)



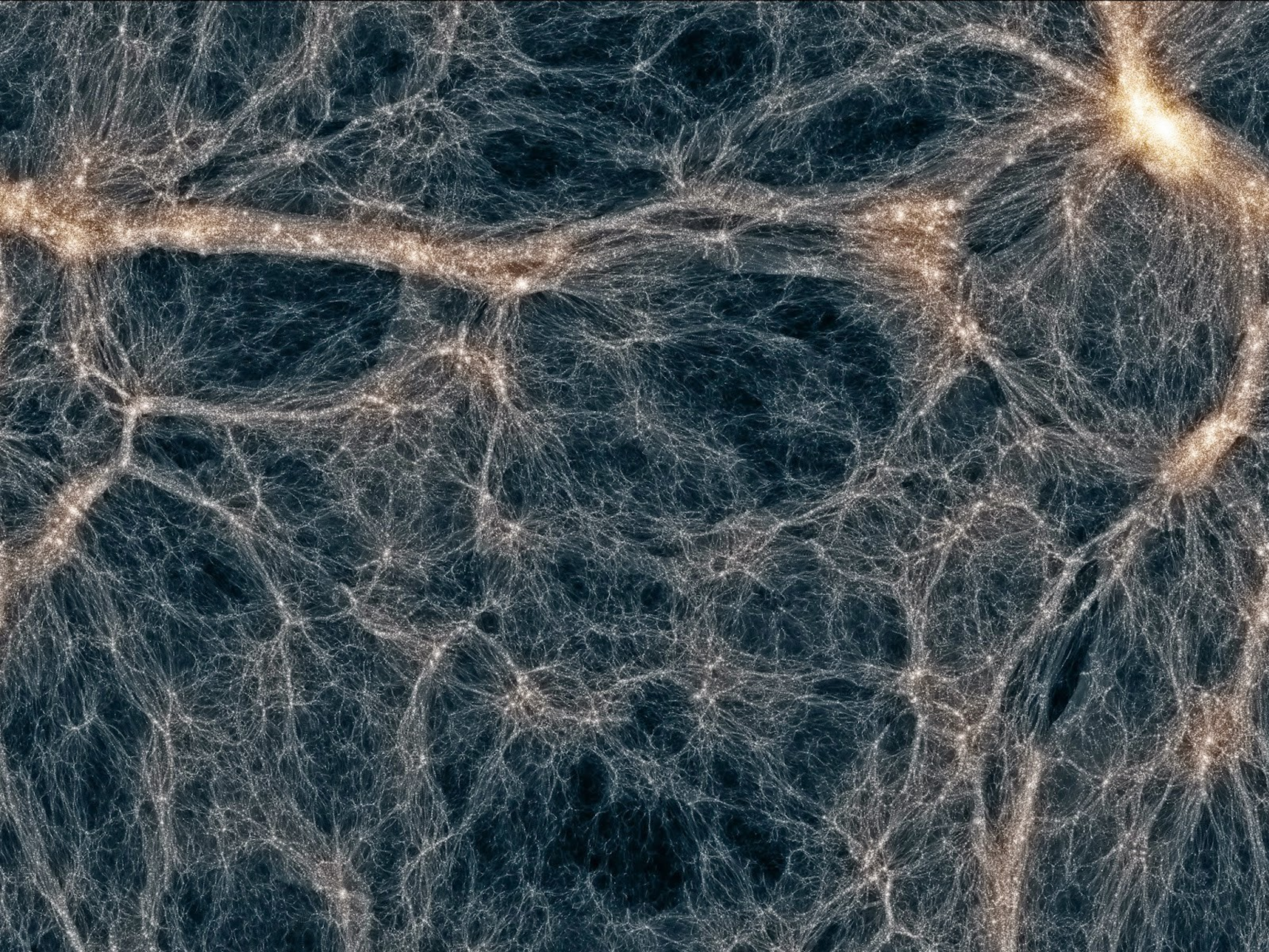
Modeling Dark Matter

- Physics is simple: Newton’s Laws
- Computation is challenging: Naively order N^2
- 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

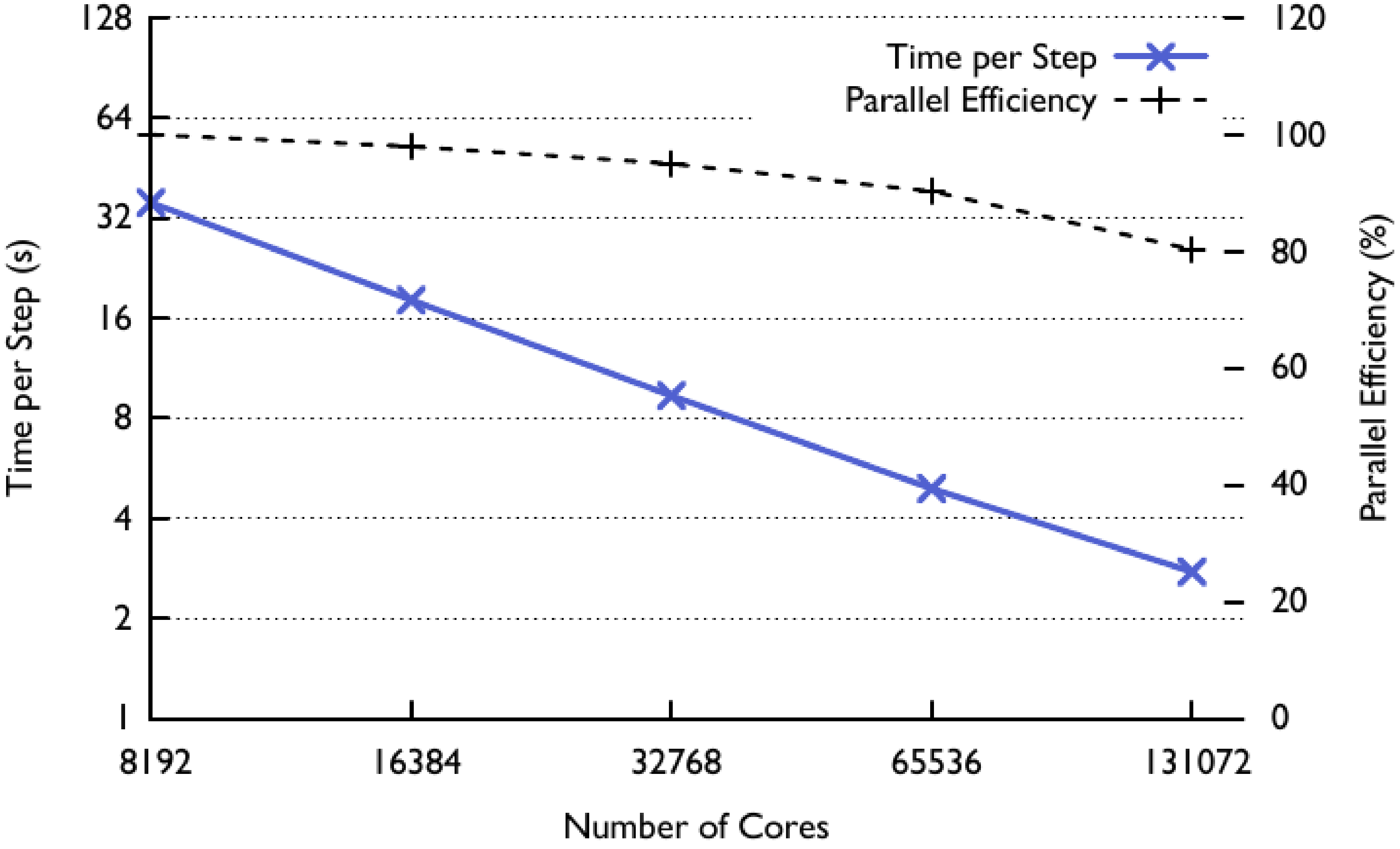
Gigaparsecs: the Cosmic Web



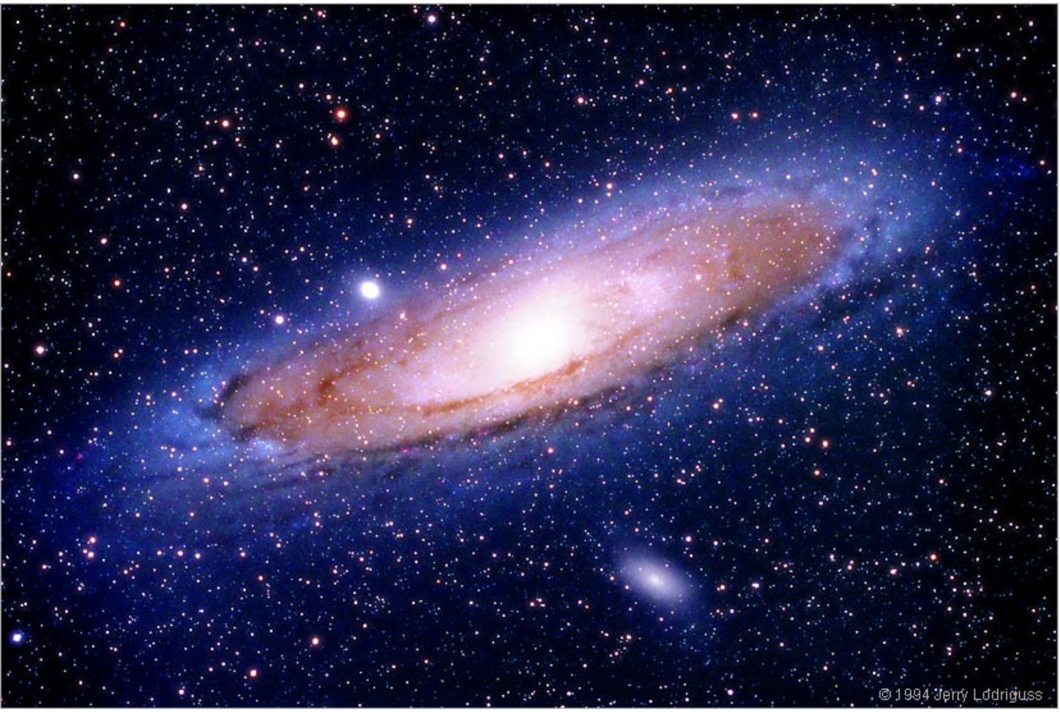
Potter & Stadel, 2017

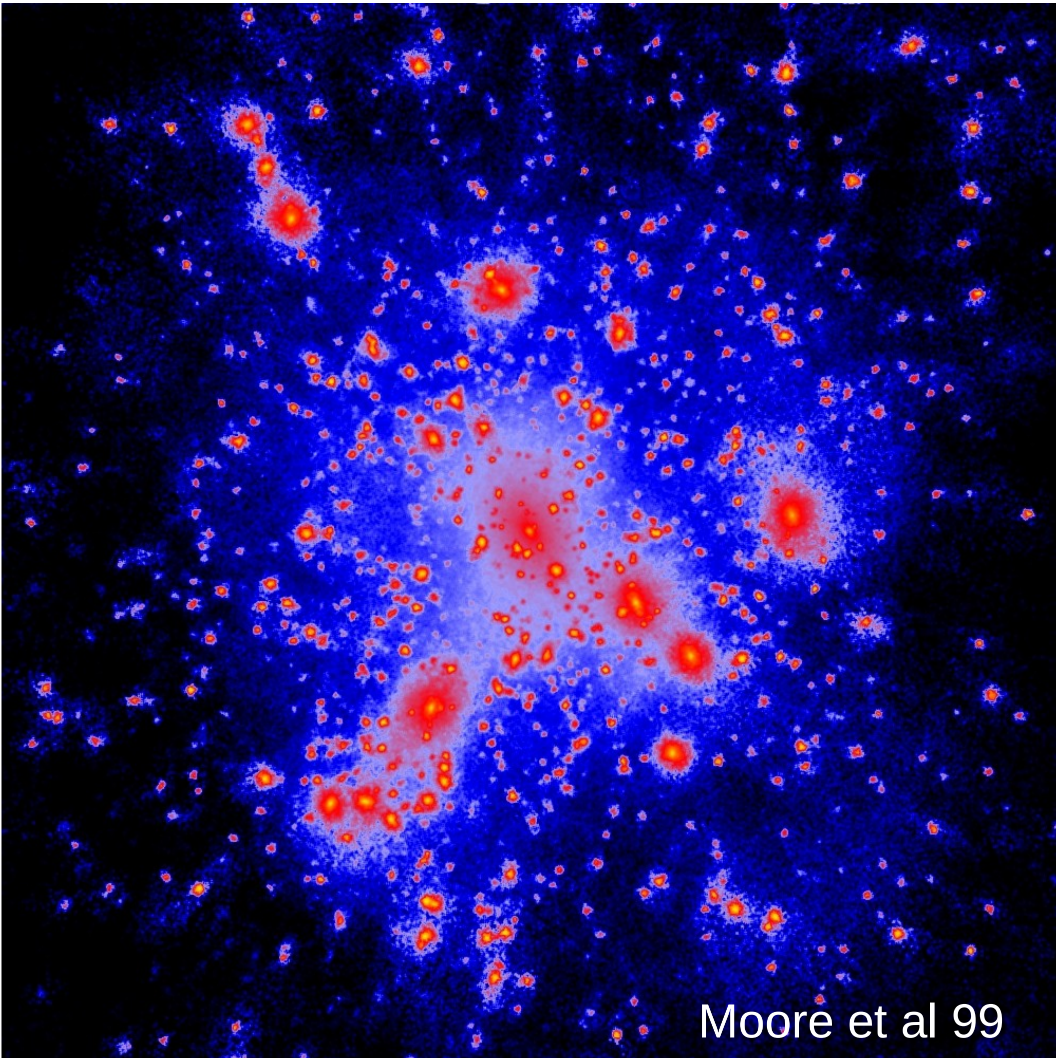


Speedups
for 2 billion clustered particles



Light vs. Matter

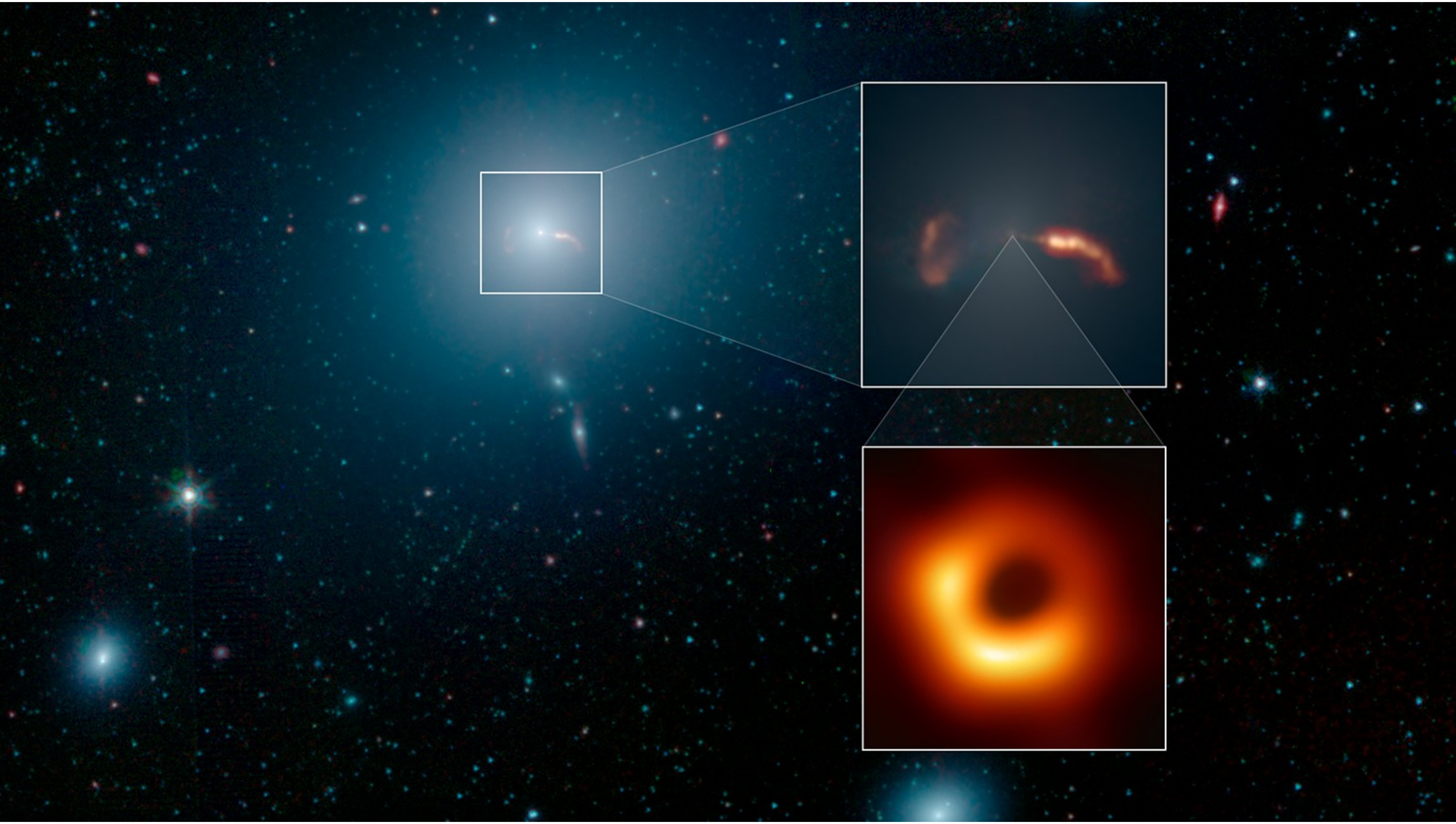



Moore et al 99

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.

Black Holes!



NASA, JPL, Event Horizon Telescope

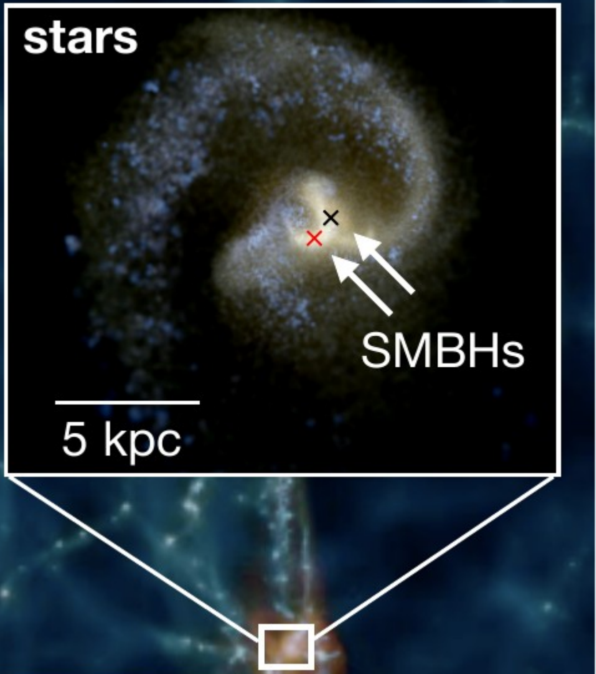
The ROMULUS Simulations

Certified organic, free-range, locally grown supermassive black holes

- ✓ Early Seeding in low mass halos
- ✓ Self-consistent and physically motivated dynamics, growth, and feedback
- ✓ Naturally produces large-scale outflows
- ✓ **No unnecessary additives or assumptions**

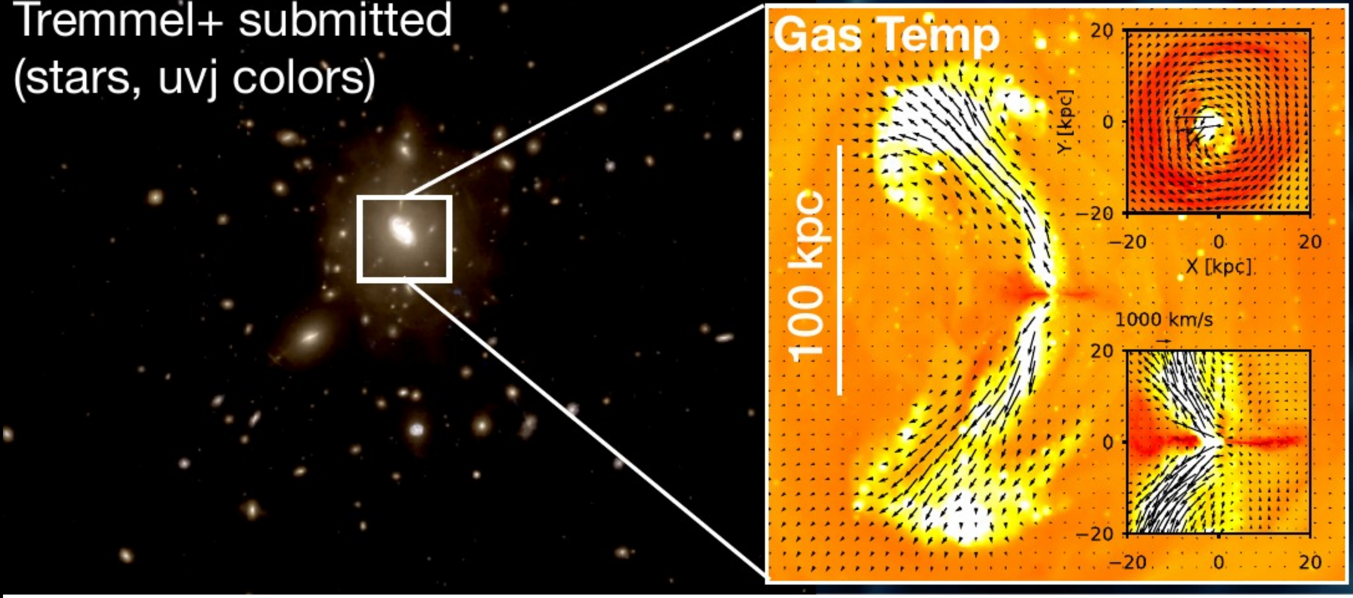
ROMULUS25

25 Mpc Volume
Tremmel+ 2017
(gas temp)



ROMULUSC

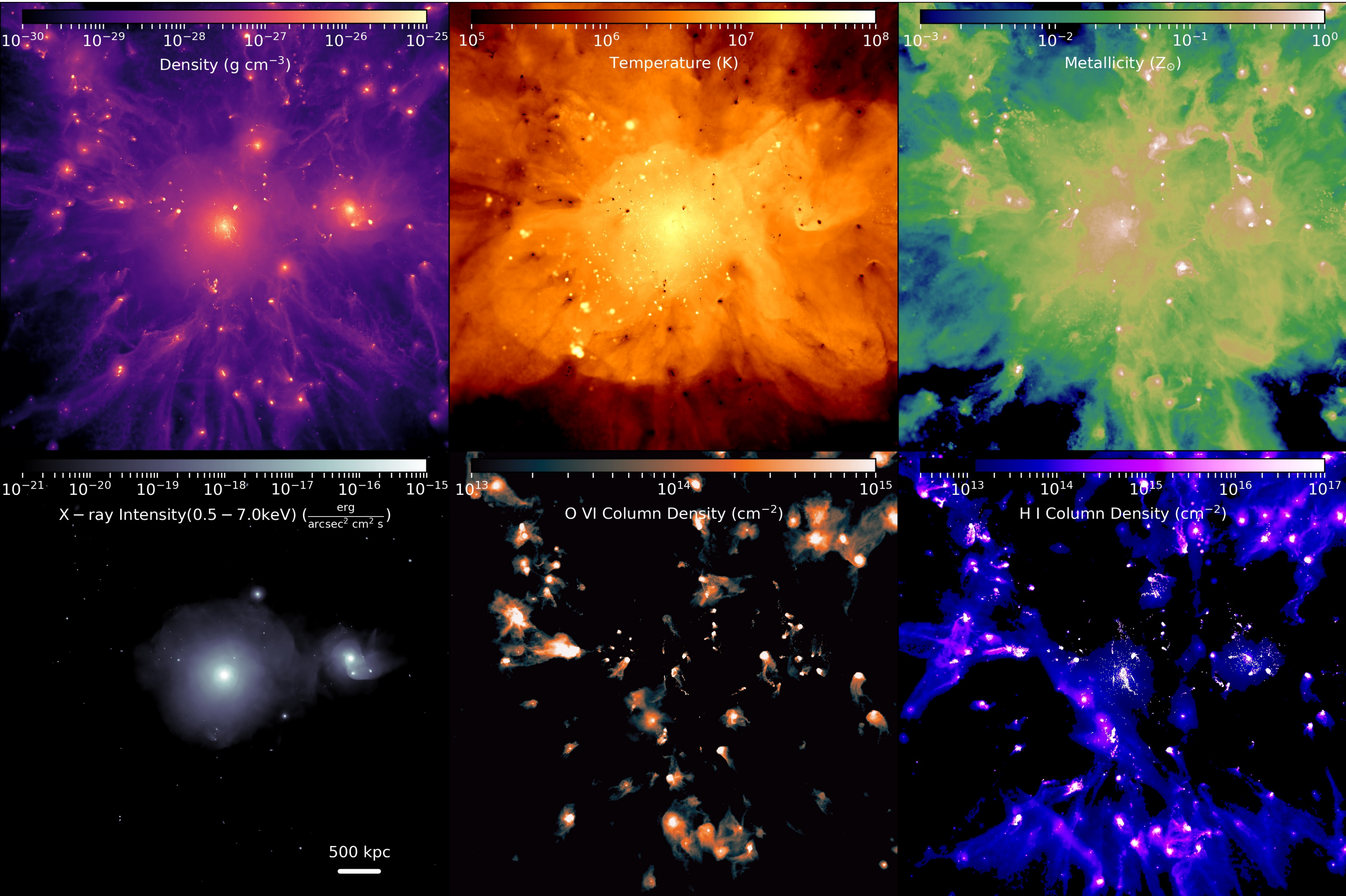
10^{14} M_{sun} Galaxy Cluster
Tremmel+ submitted
(stars, uvj colors)



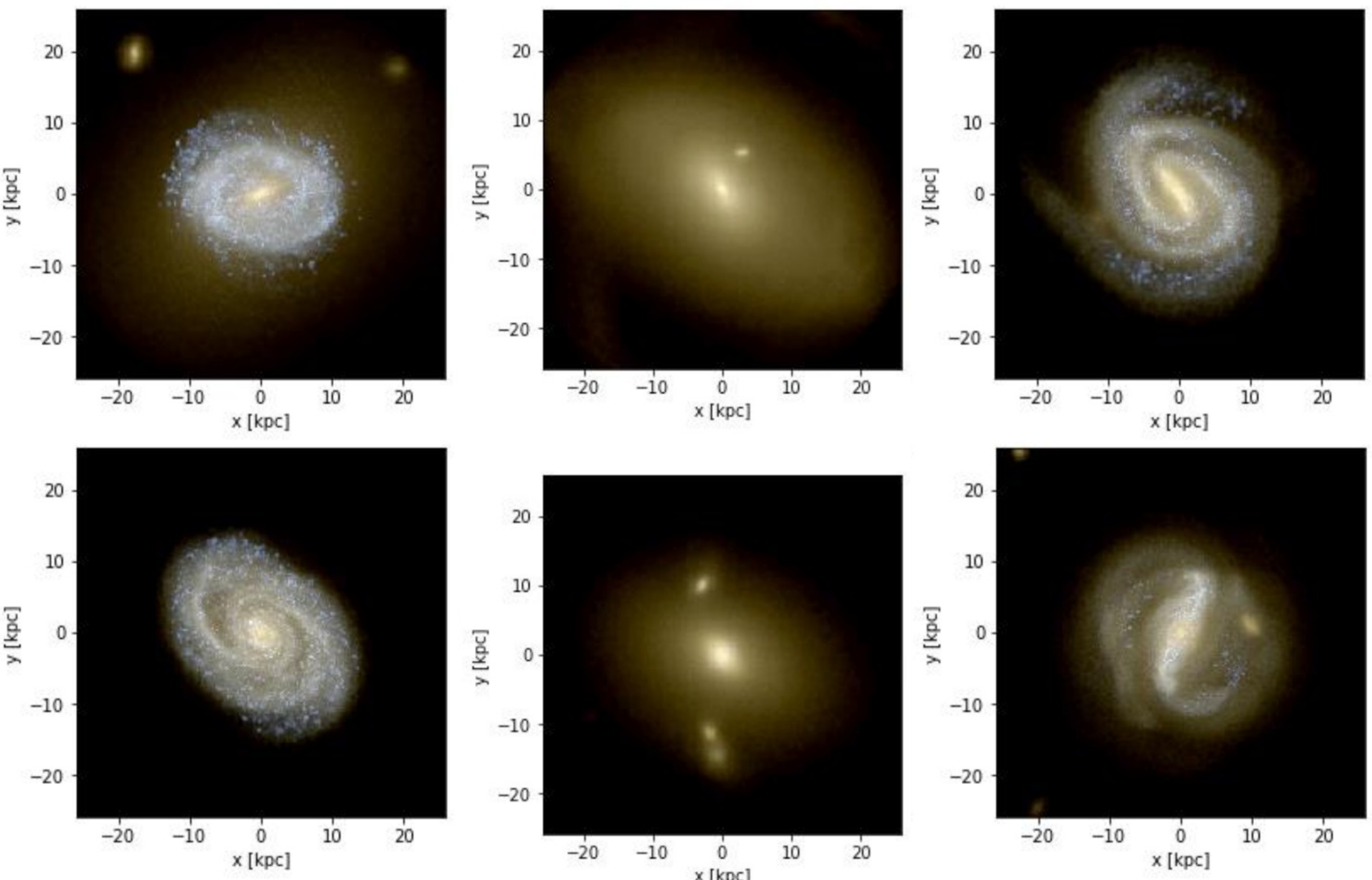
Resolution:
250 pc (grav)
50 pc (hydro)
~1e5 M_{sun}

CHANGA

Galaxy Cluster



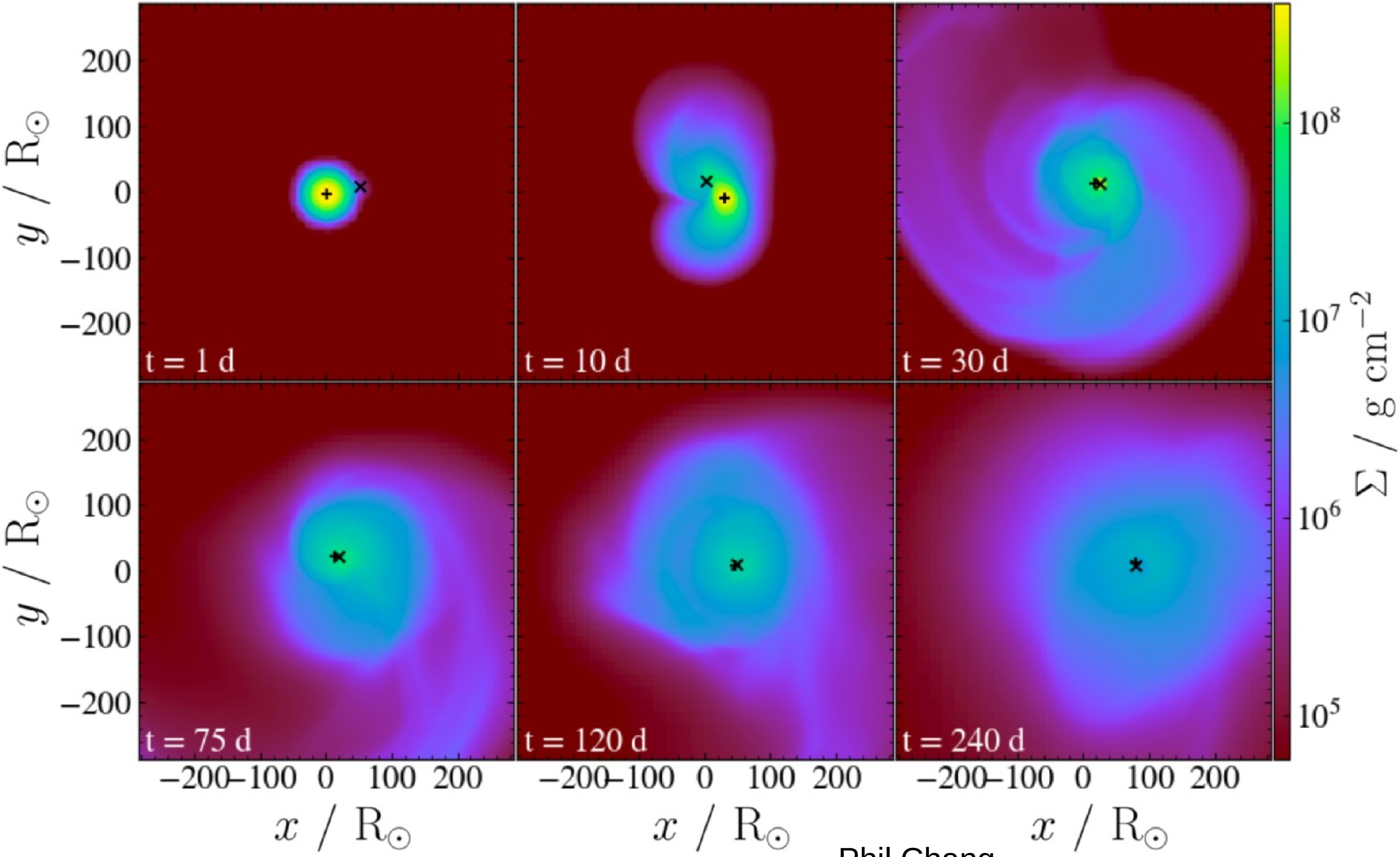
Galaxy populations



Moving Mesh Hydrodynamics

- More accurate hydrodynamics requires Riemann solvers
- Galilean invariance: mesh needs to follow the fluid flow
- Mesh needs to have arbitrary geometry
- Need a fast Voronoi mesh generator: ChaNGa (MANGA)

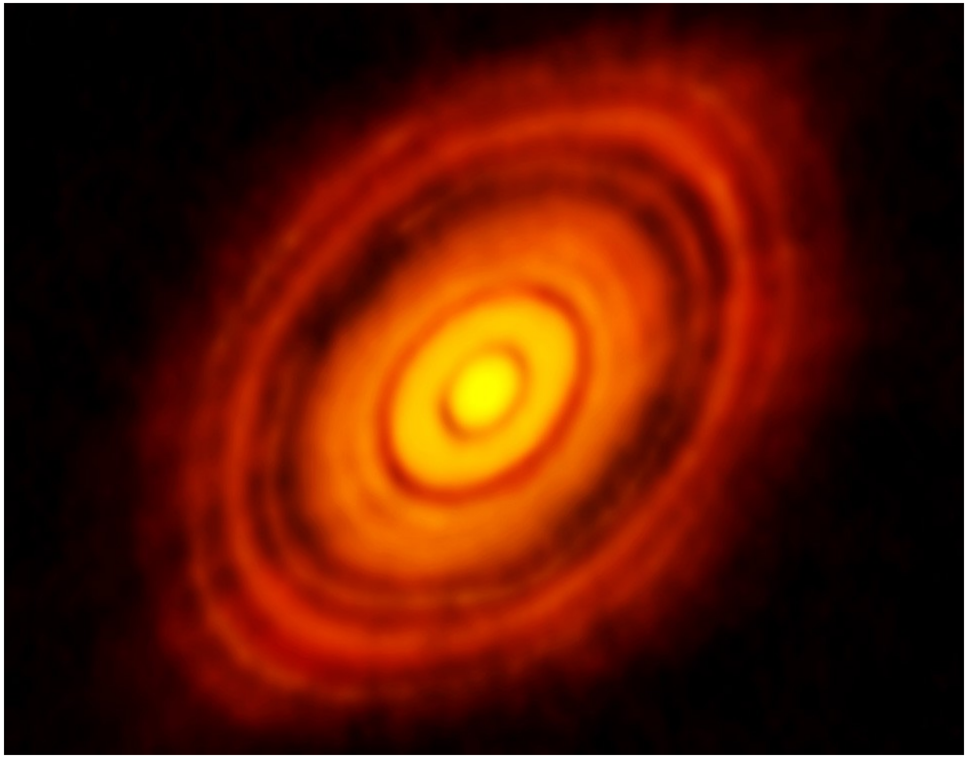
Binary Stars with MaNGa



Phil Chang

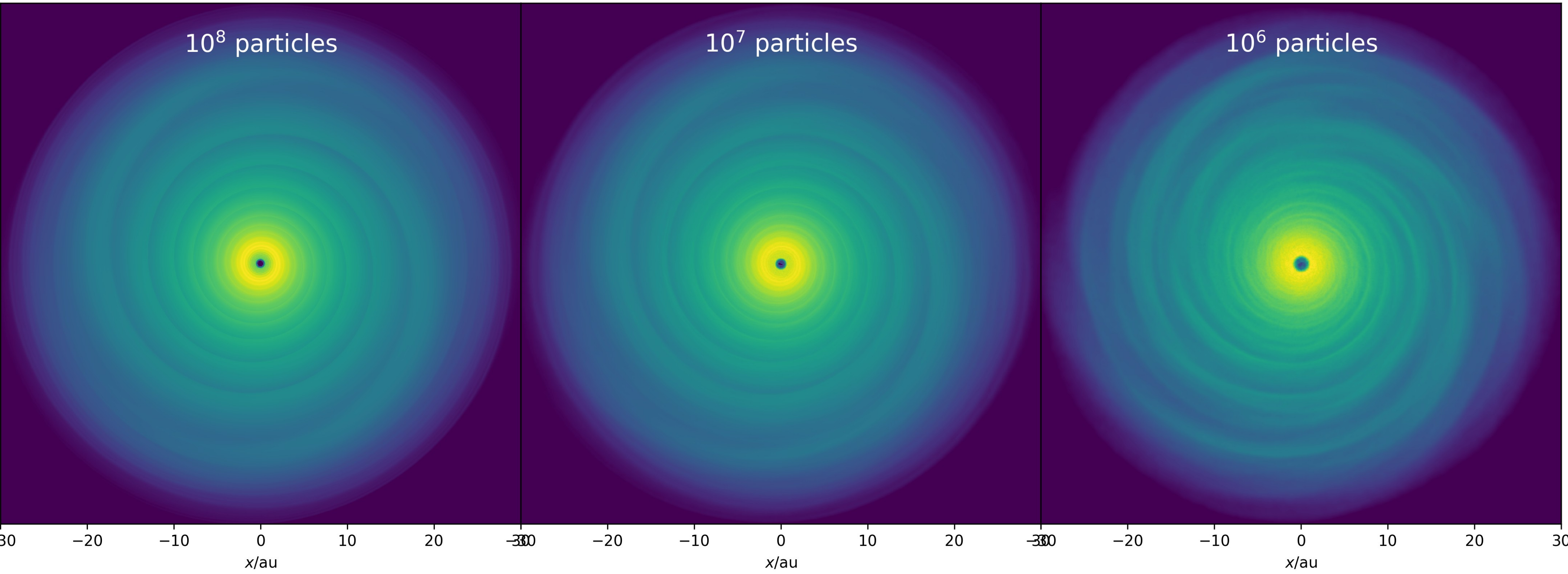
Protoplanetary Disks

- Likely result of cloud collapse with conserved angular momentum
- Disks can be gravitationally unstable
- Fragmentation depends on details of gas dynamics



Resolution and Disks

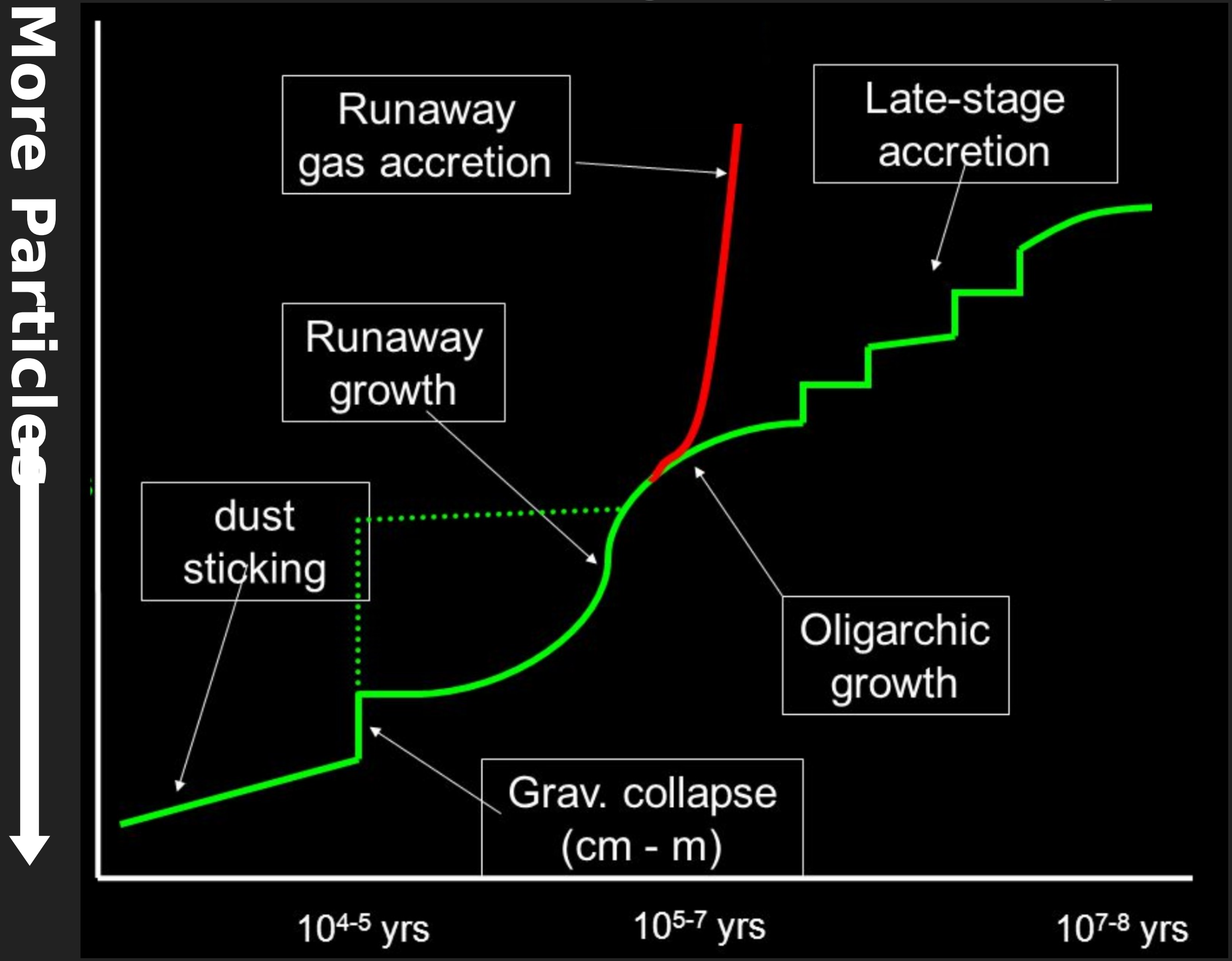
Resolution comparison: density
after 1.89 ORPs

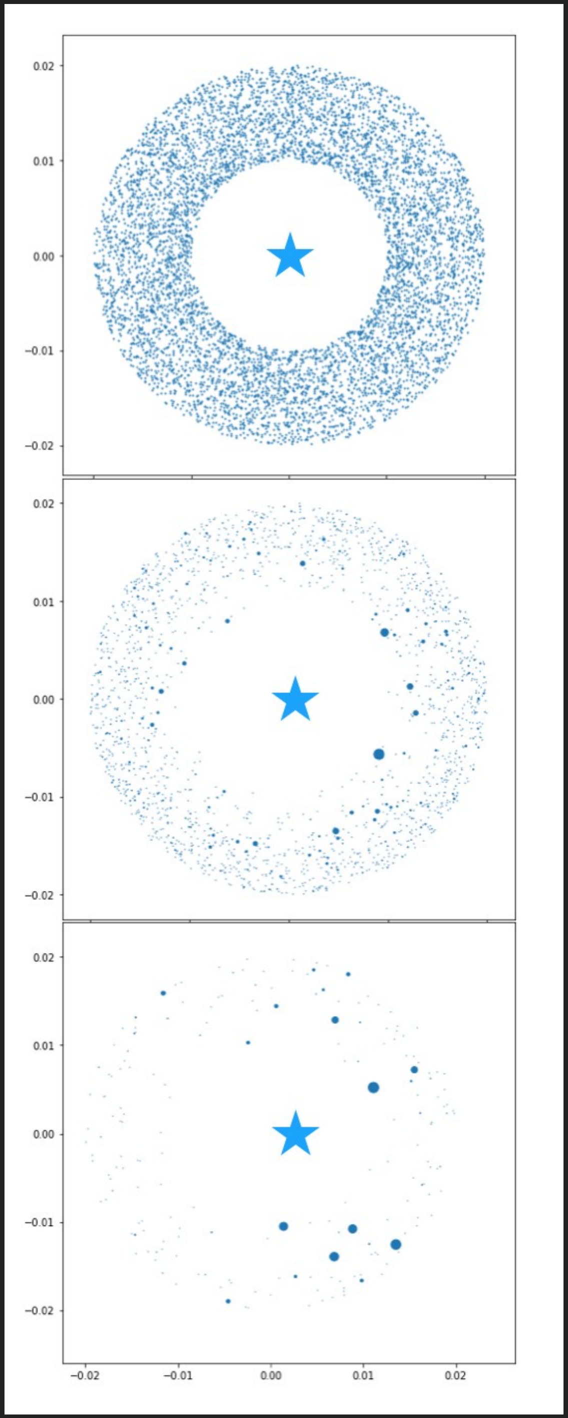


Isaac Backus, Ph. D. Thesis

FROM DUST TO PLANETS

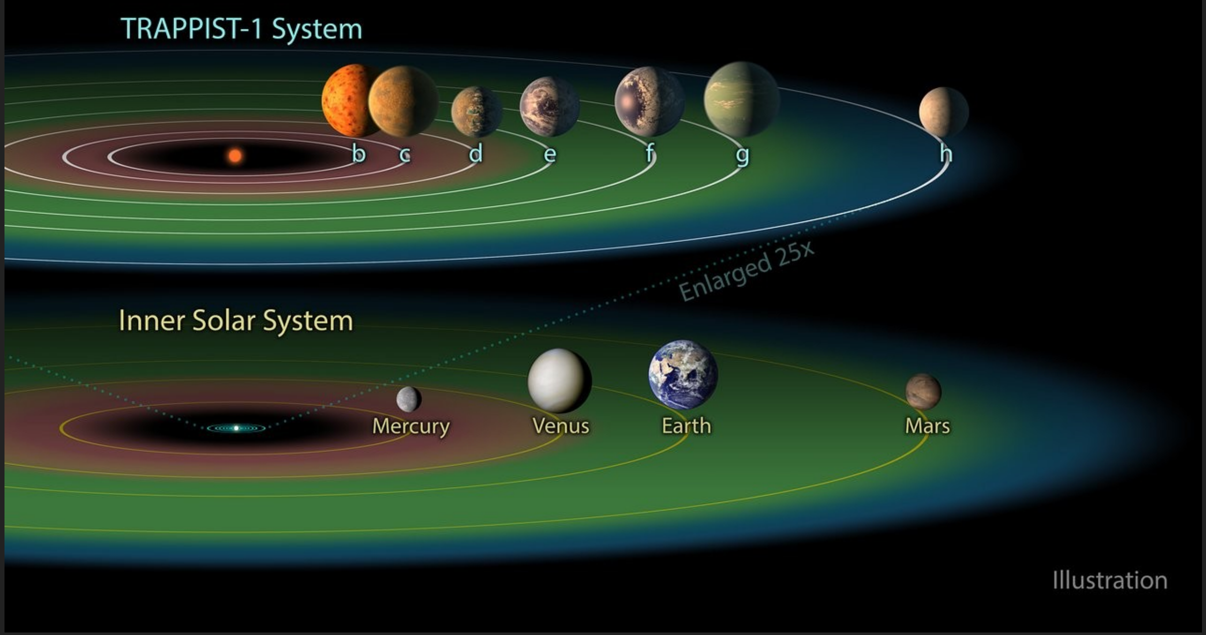
Image credit: Sean Raymond

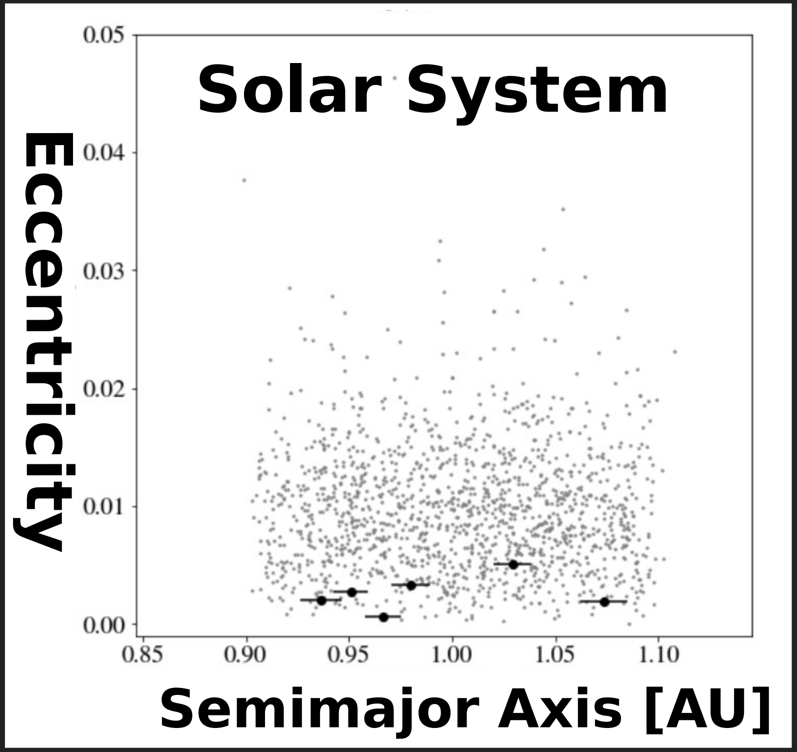


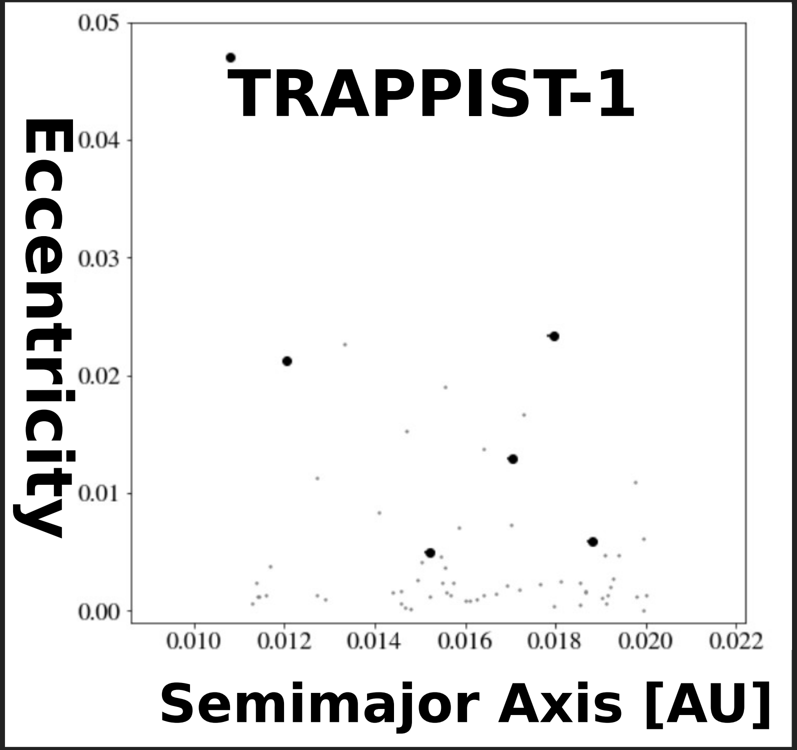


- ChaNGa can directly simulate accretion of planetesimals, test planetesimal formation models

SYSTEMS OF TIGHTLY PACKED INNER PLANETS

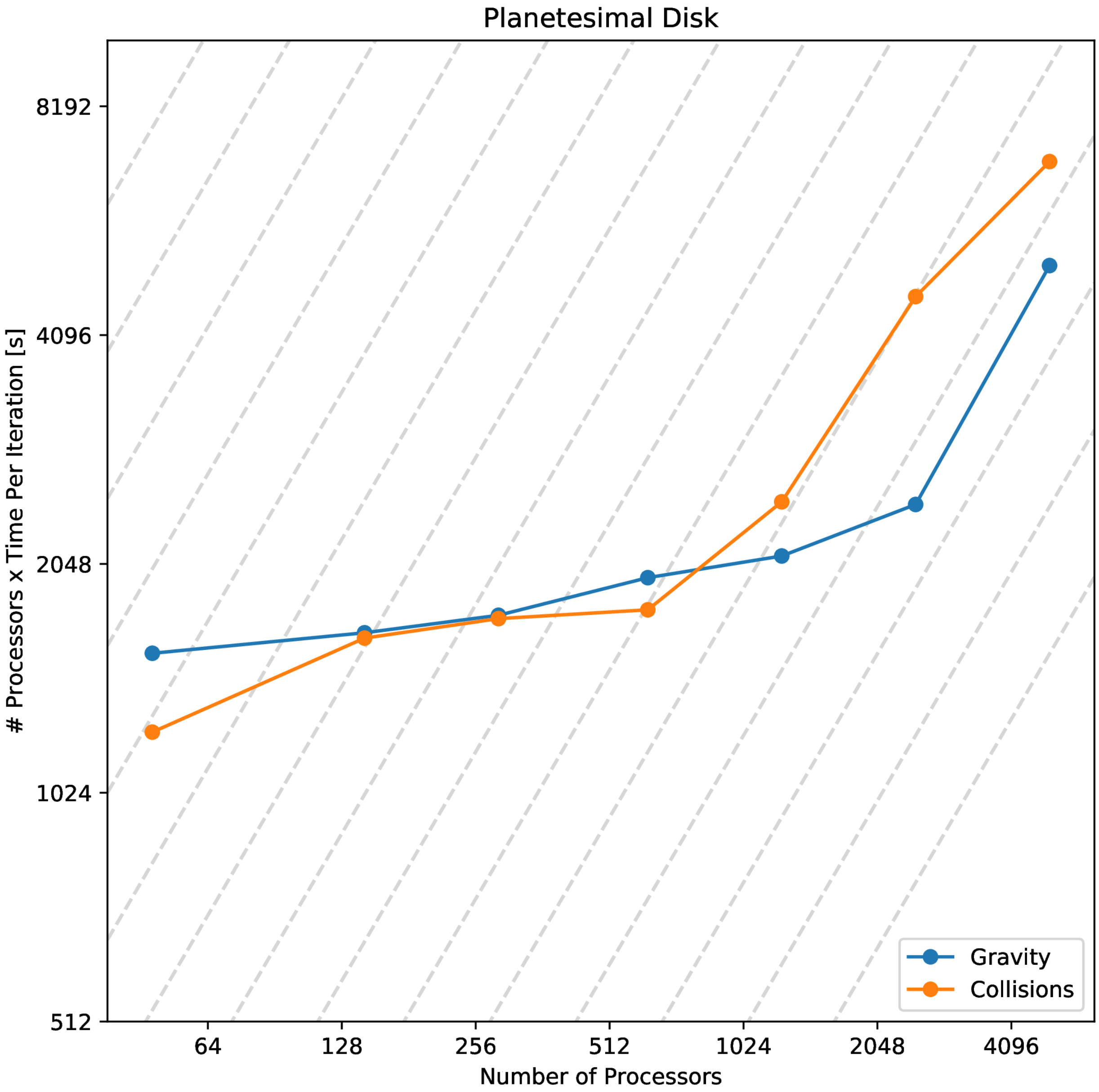






- High surface density, short dynamical timescale close to star
- Does the runaway + oligarchic growth model still apply?

Collision scaling: 50M particles



Summary

- Astrophysical simulations provide a challenges to parallel implementations
  - Non-local data dependencies
  - Hierarchical in space and time
- ChaNGa has been successful in addressing these challenges using Charm++ features
  - Computation/Communication overlap
  - Message priorities
  - Load Balancing
  - Modularity to add new Physics

Availability

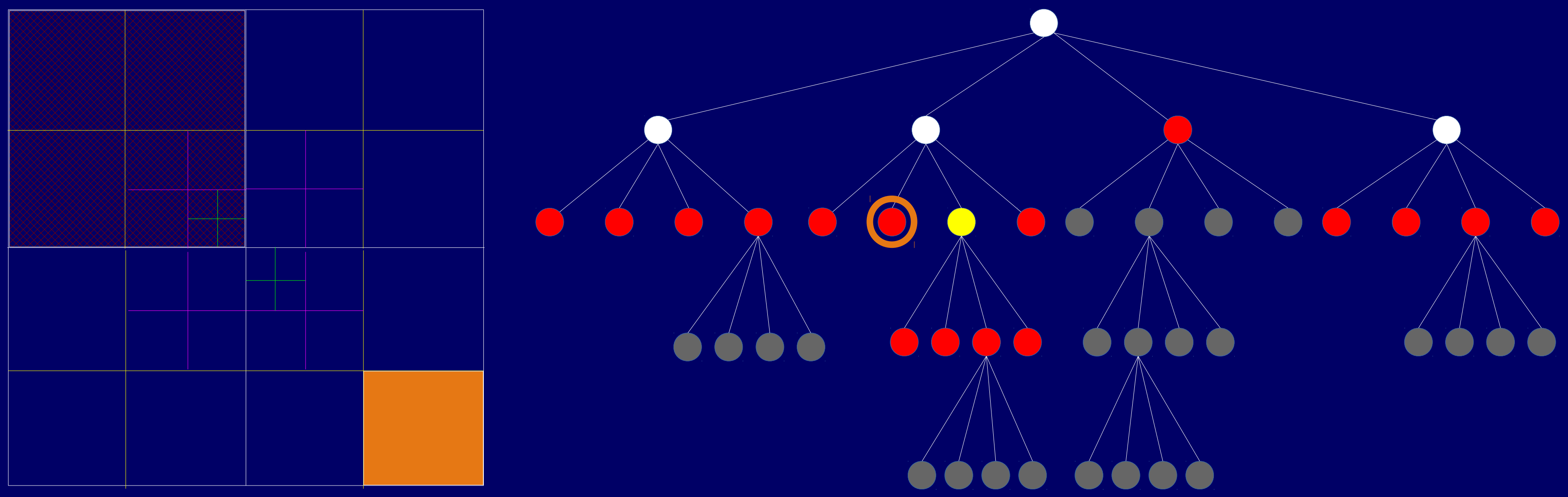
- ChaNGa: http://github.com/N-bodyShop/changa
  - See the Wiki for a developer's guide
- Paratreet: http://github.com/paratreet
  - Some design discussion and sample code

Acknowledgments

- NSF ITR
- NSF Astronomy
- NSF SSI
- NSF XSEDE program for computing
- BlueWaters Petascale Computing
- NASA HST
- NASA Advanced Supercomuting

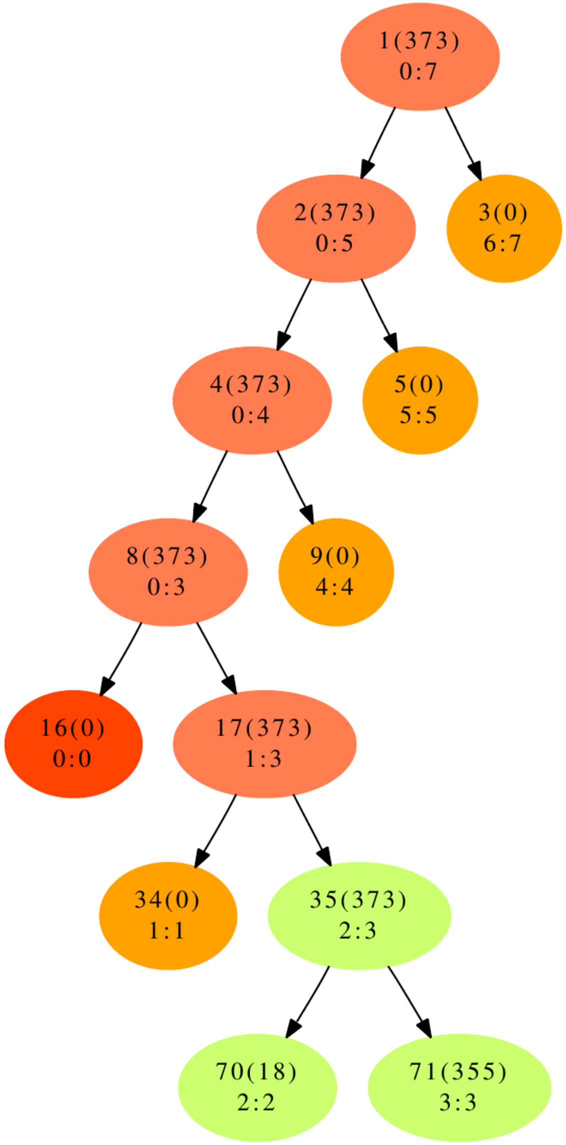
Basic Gravity algorithm ...

- Newtonian gravity interaction
  - Each particle is influenced by all others: O(n^2) algorithm
- Barnes-Hut approximation: O($n$log$n$)
  - Influence from distant particles combined into center of mass

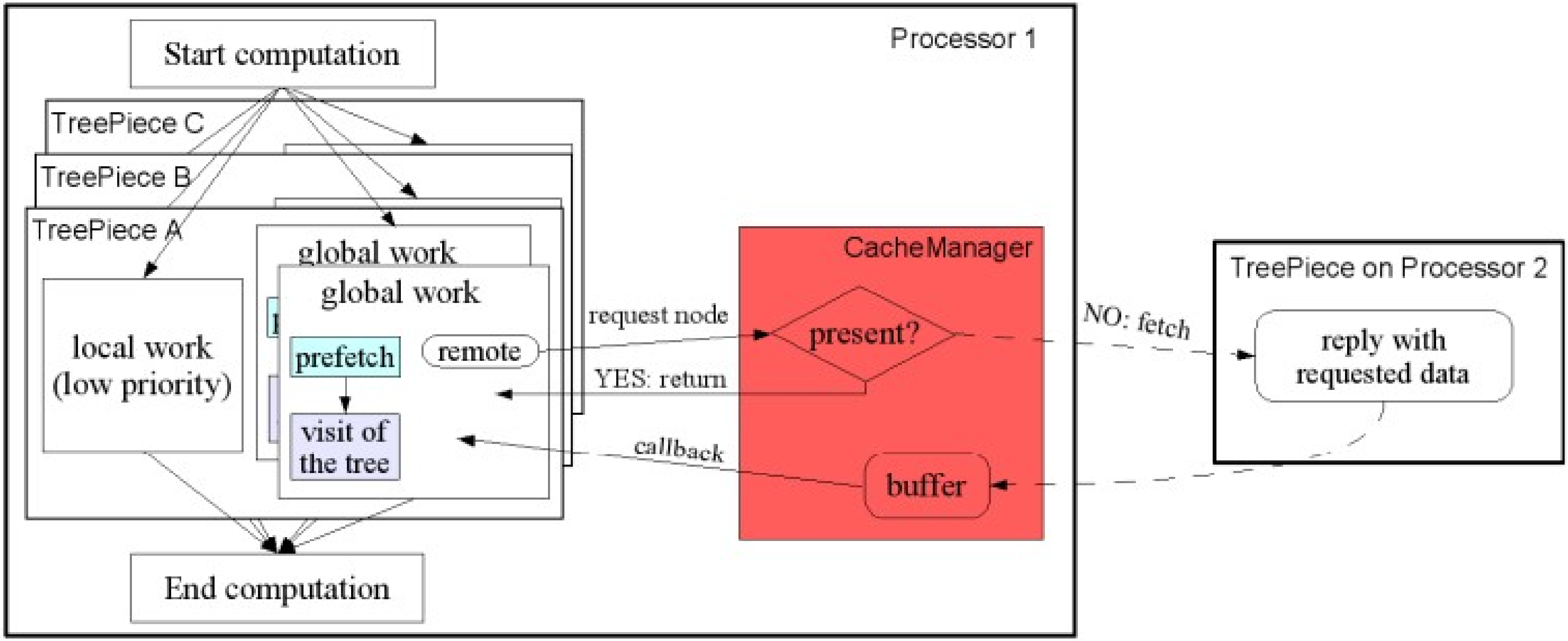


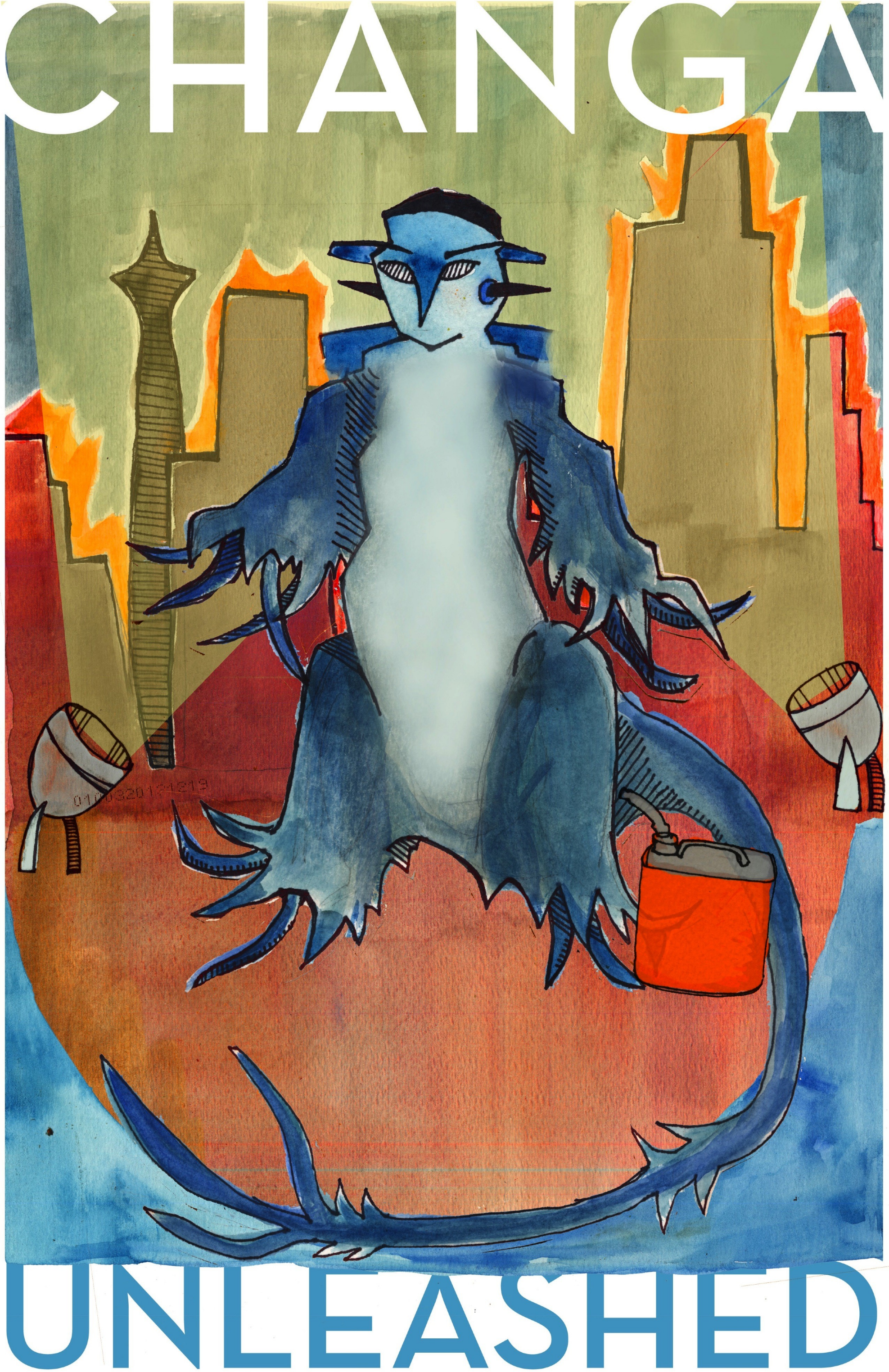
TreePiece: basic data structure

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



Overall treewalk structure





Charm Nbody GrAvity solver

- Massively parallel SPH
- SNe feedback creating realistic outflows
- SF linked to shielded gas
- SMBHs
- Optimized SF parameters
- AGORA participant

Menon+ 2015, Governato+ 2014

Fundamental Origins Questions:

How did the Universe begin?

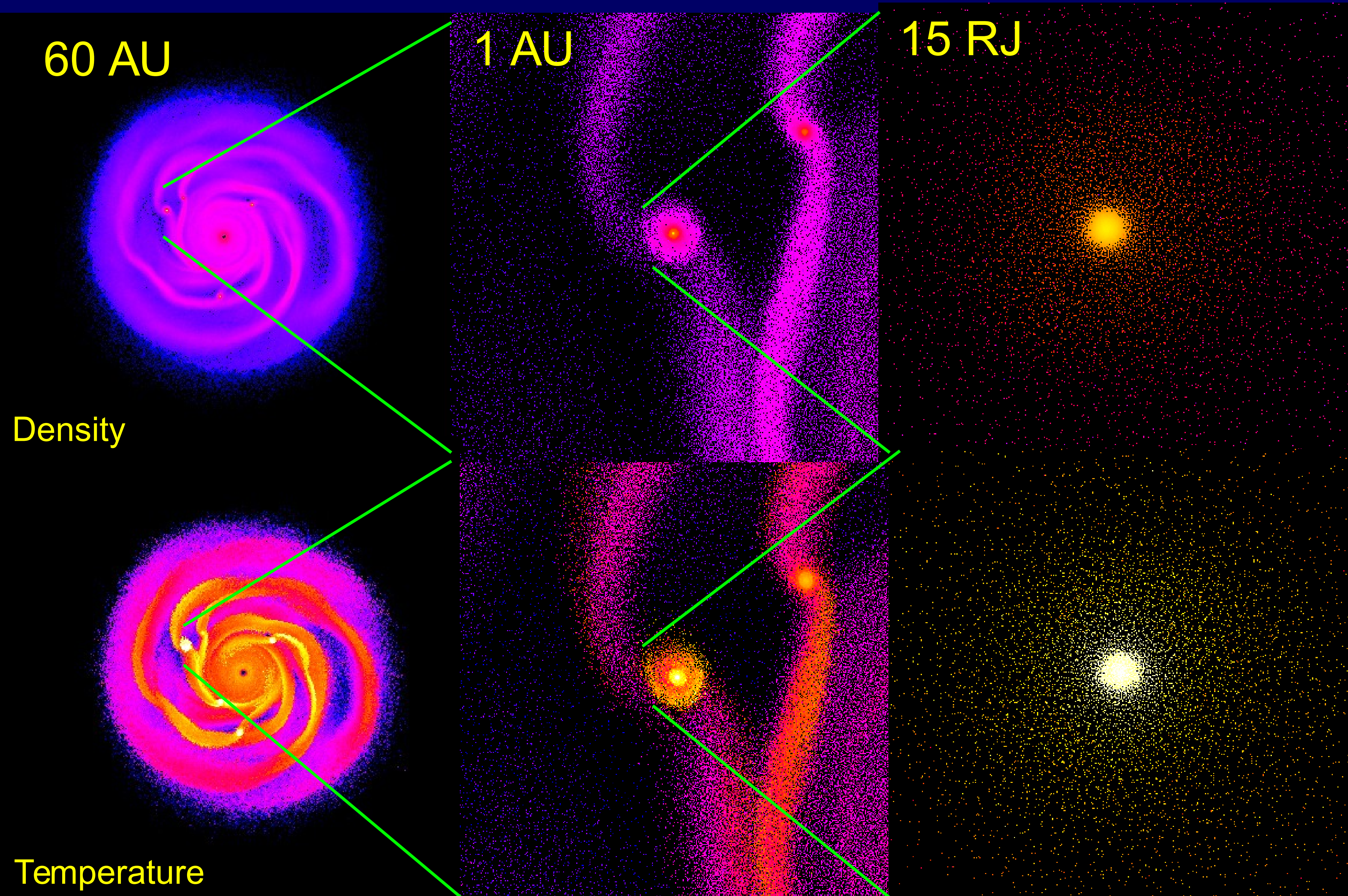
How did stars form?

How did planets form?

How did life begin?

How did intelligent life develop?

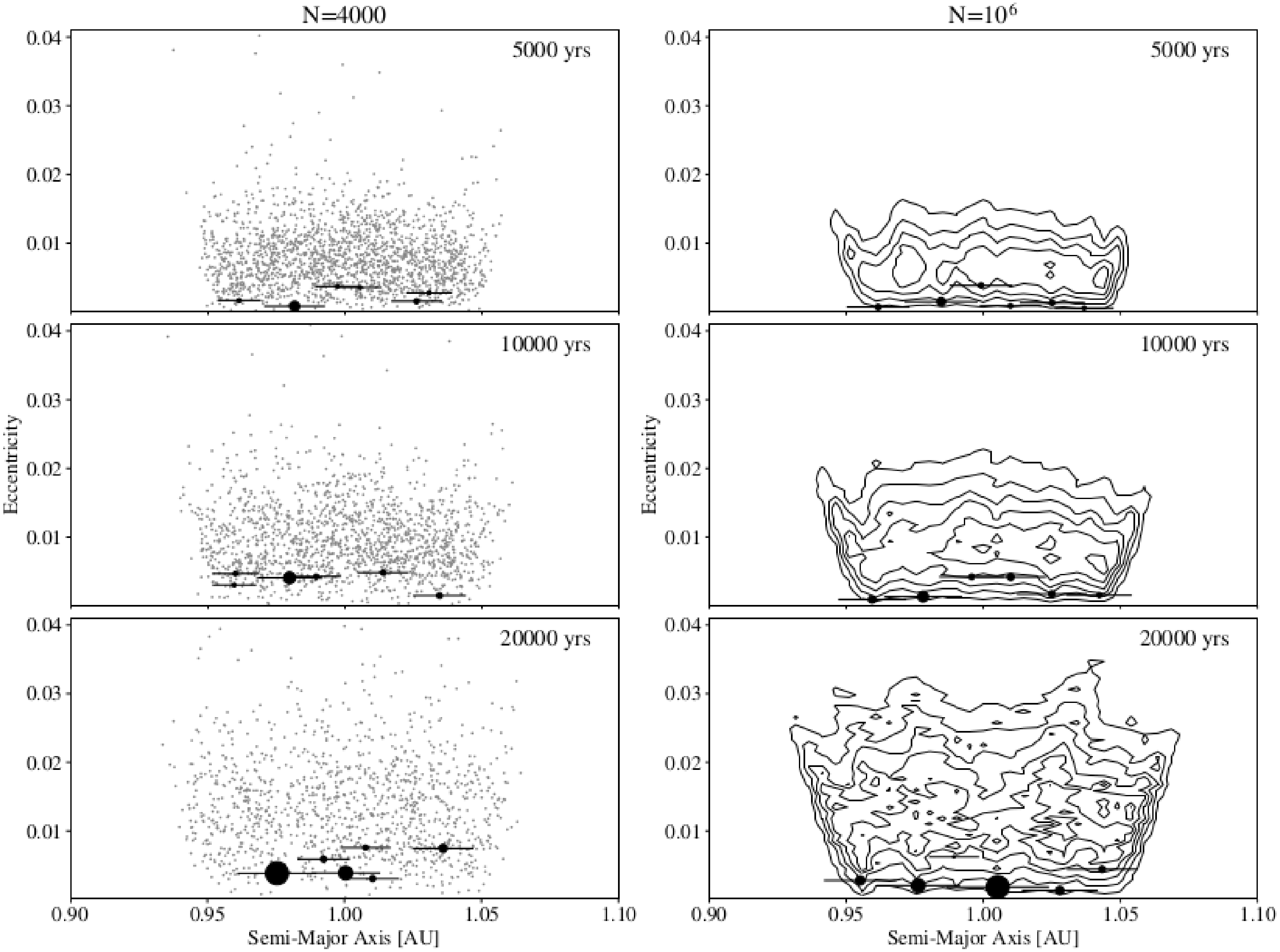
Planet Formation Resolution



Terrestrial Planet Formation

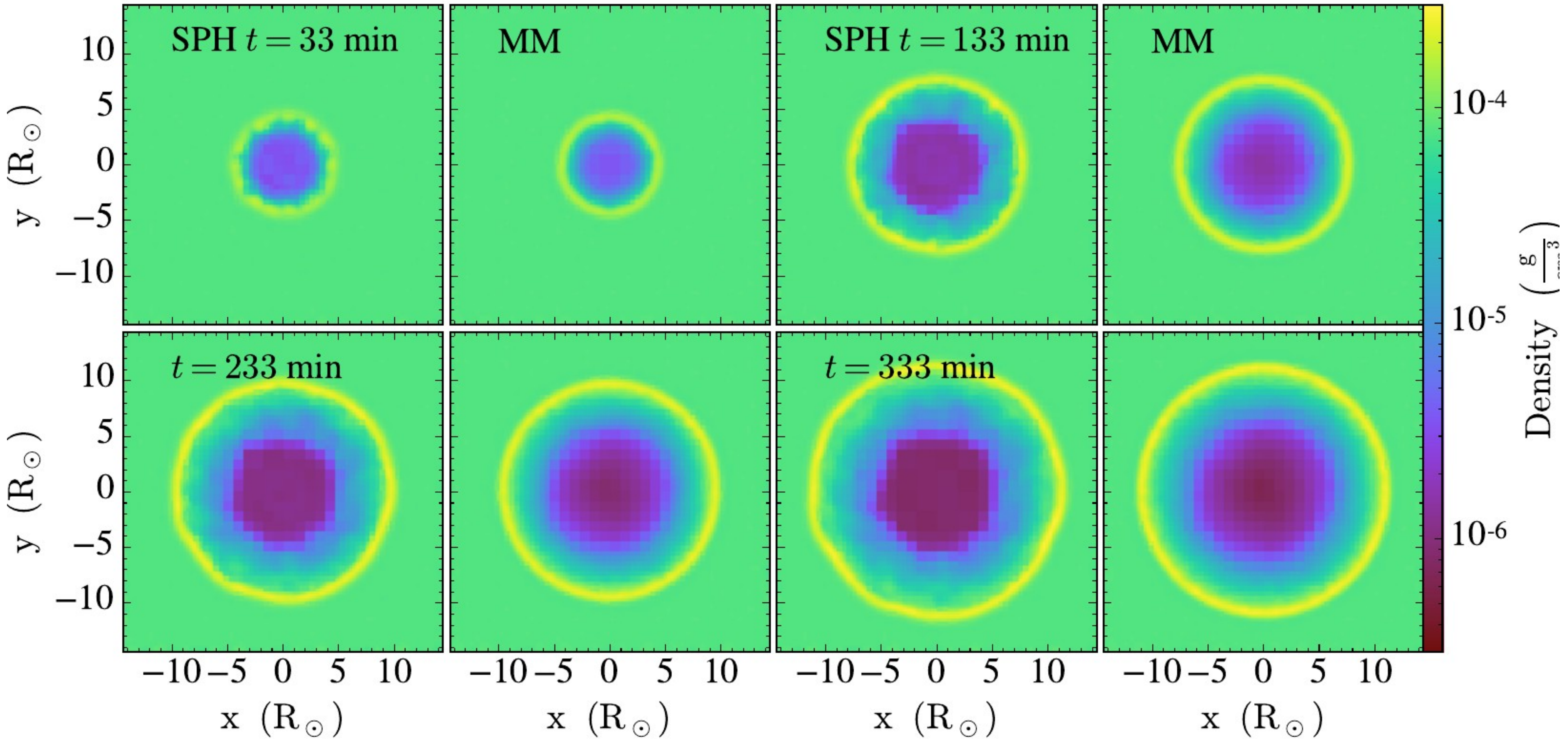
- Terrestrial planets are enhanced in refractory elements
- Elements initially condense into grains out of the protoplanetary nebula
- Grains grow (quickly) to ~kilometer size bodies (planetesimals)
- Planetesimals collide to build larger bodies (protoplanets)
- Left over planetesimals remain as small bodies (asteroids, comets, and minor moons)

Orders of magnitude better resolution



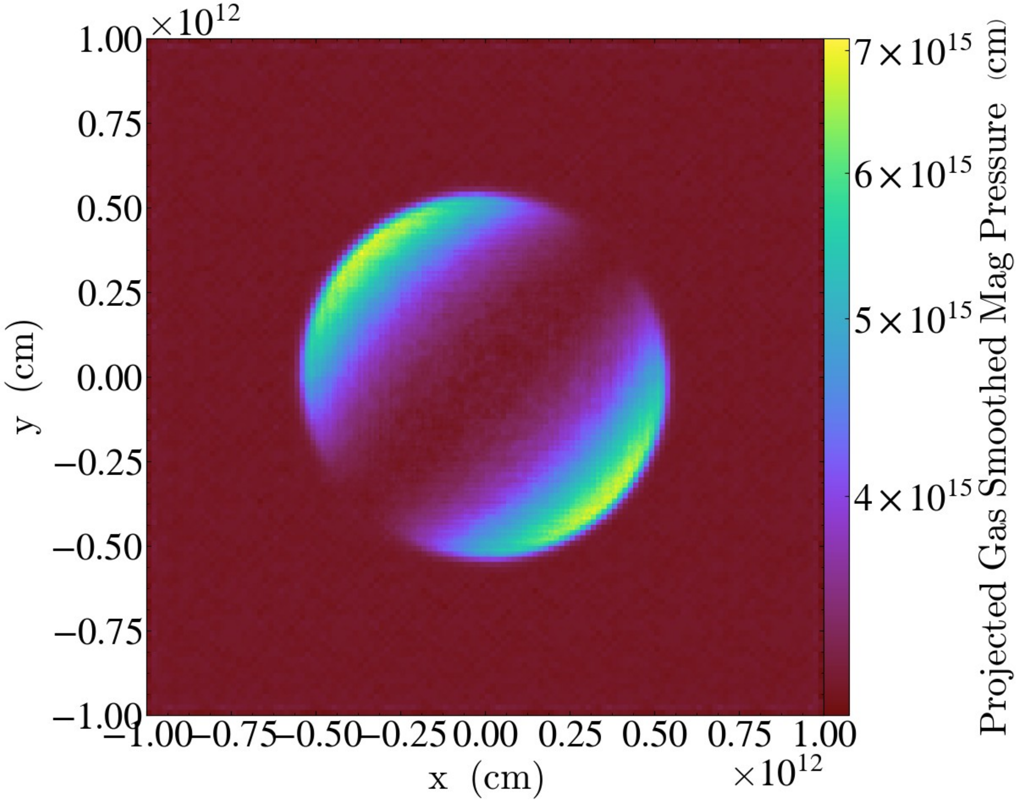
Spencer Wallace

Sedov Test


SPH $t = 33$ min
MM
SPH $t = 133$ min
MM
$t = 233$ min
$t = 333$ min
y ($R_\odot$)
x ($R_\odot$)
10
5
0
−5
−10
Density ($\frac{g}{cm^3}$)
10^{-4}
10^{-5}
10^{-6}

More Physics

- Magnetic fields (with constrained transport)
- Radiative Transfer (Flux limited diffusion and ray tracing)

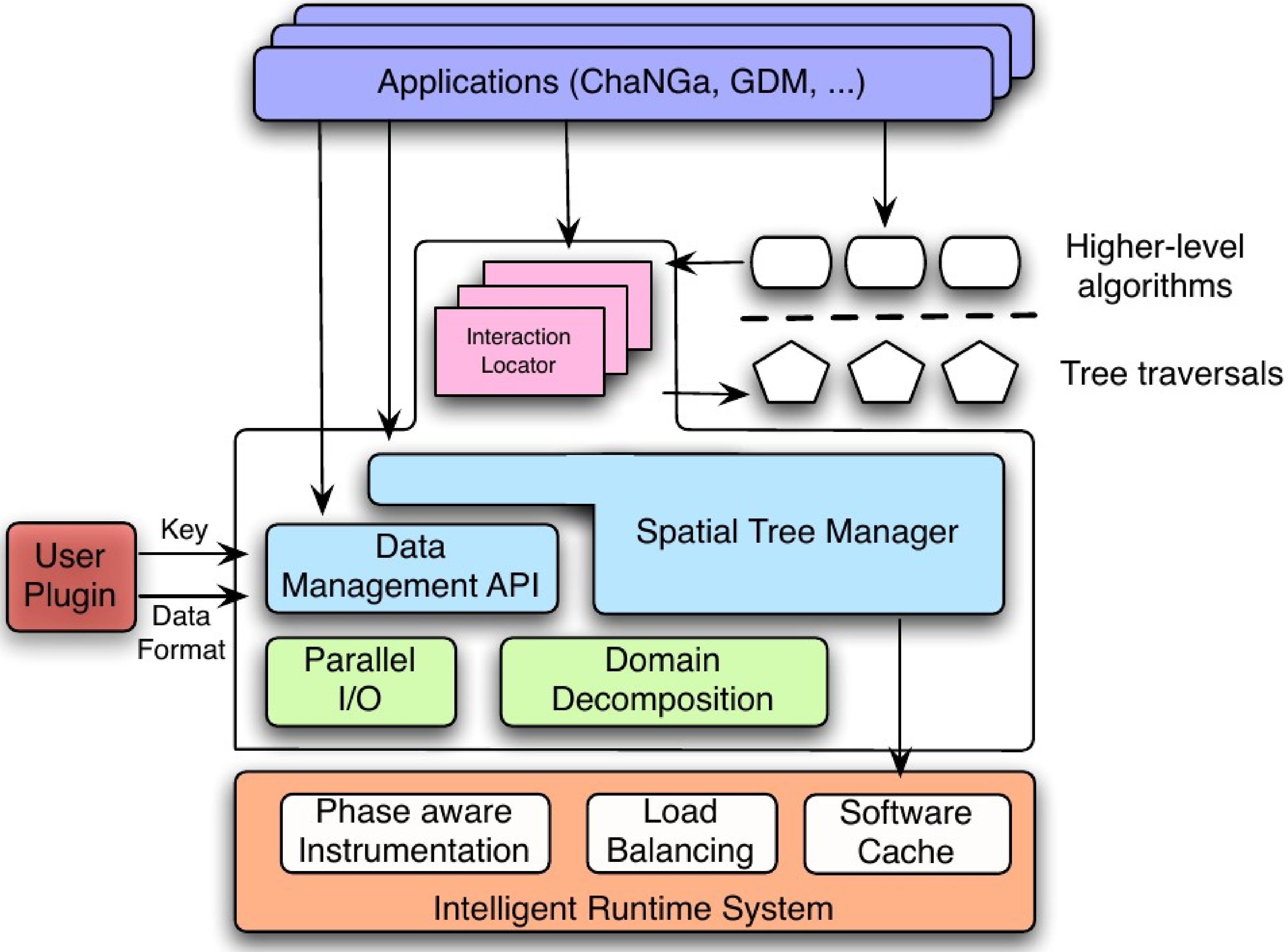


Phil Chang, UW-Milwaukee

Other Applications

- N-point correlation functions
- Gravitational Lensing maps
- Granular Dynamics
- Cluster finding
- High dimensional classification
- Identification of cytoskeletal structures
- Ray tracing
- Surface reconstruction

Paratreet: parallel framework for tree algorithms



Applications (ChaNGa, GDM, ...)

Interaction Locator

Higher-level algorithms

Tree traversals

User Plugin

Key

Data Format

Data Management API

Spatial Tree Manager

Parallel I/O

Domain Decomposition

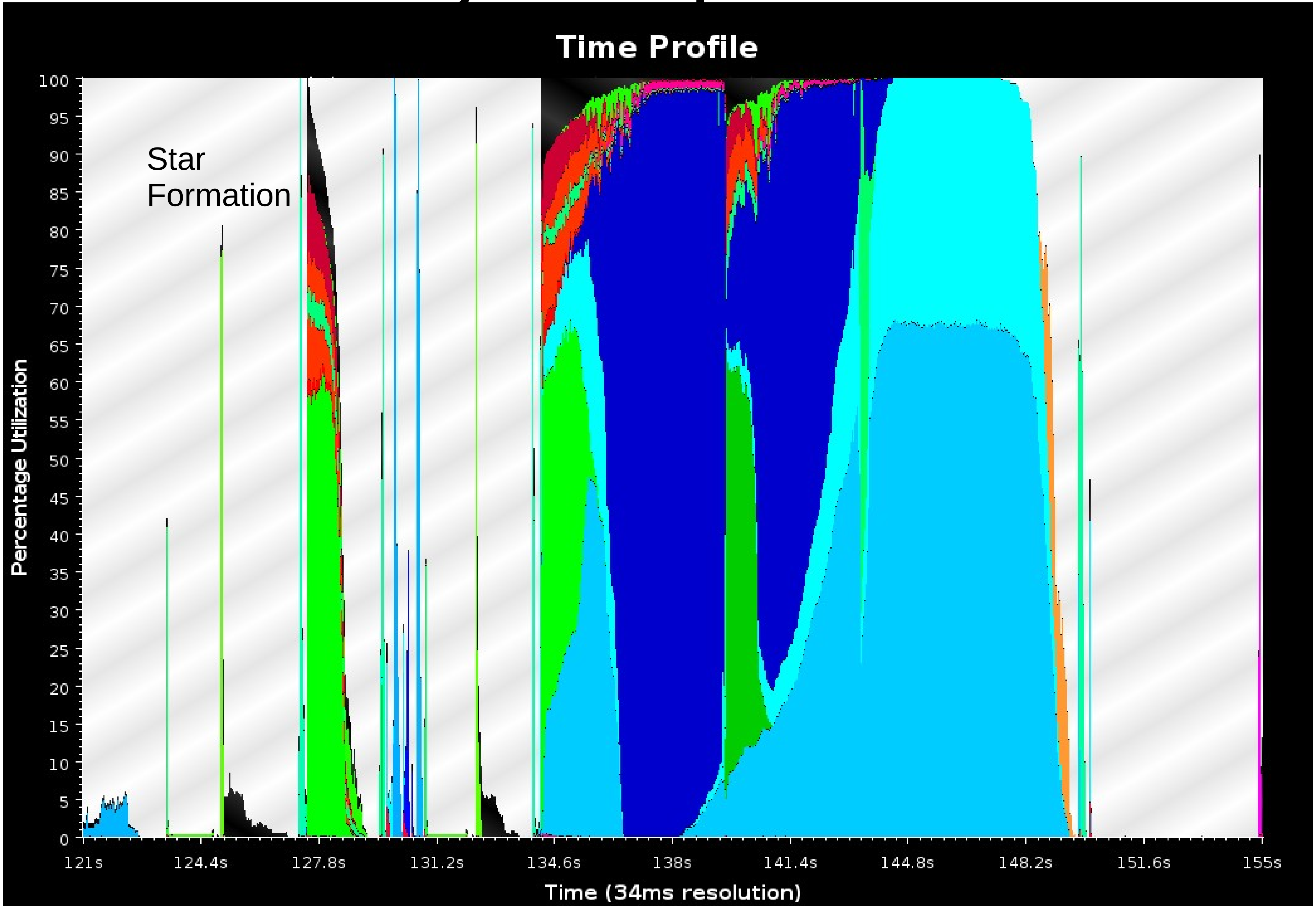
Phase aware Instrumentation

Load Balancing

Software Cache

Intelligent Runtime System

LB by Compute time



Star Formation

15.8 seconds

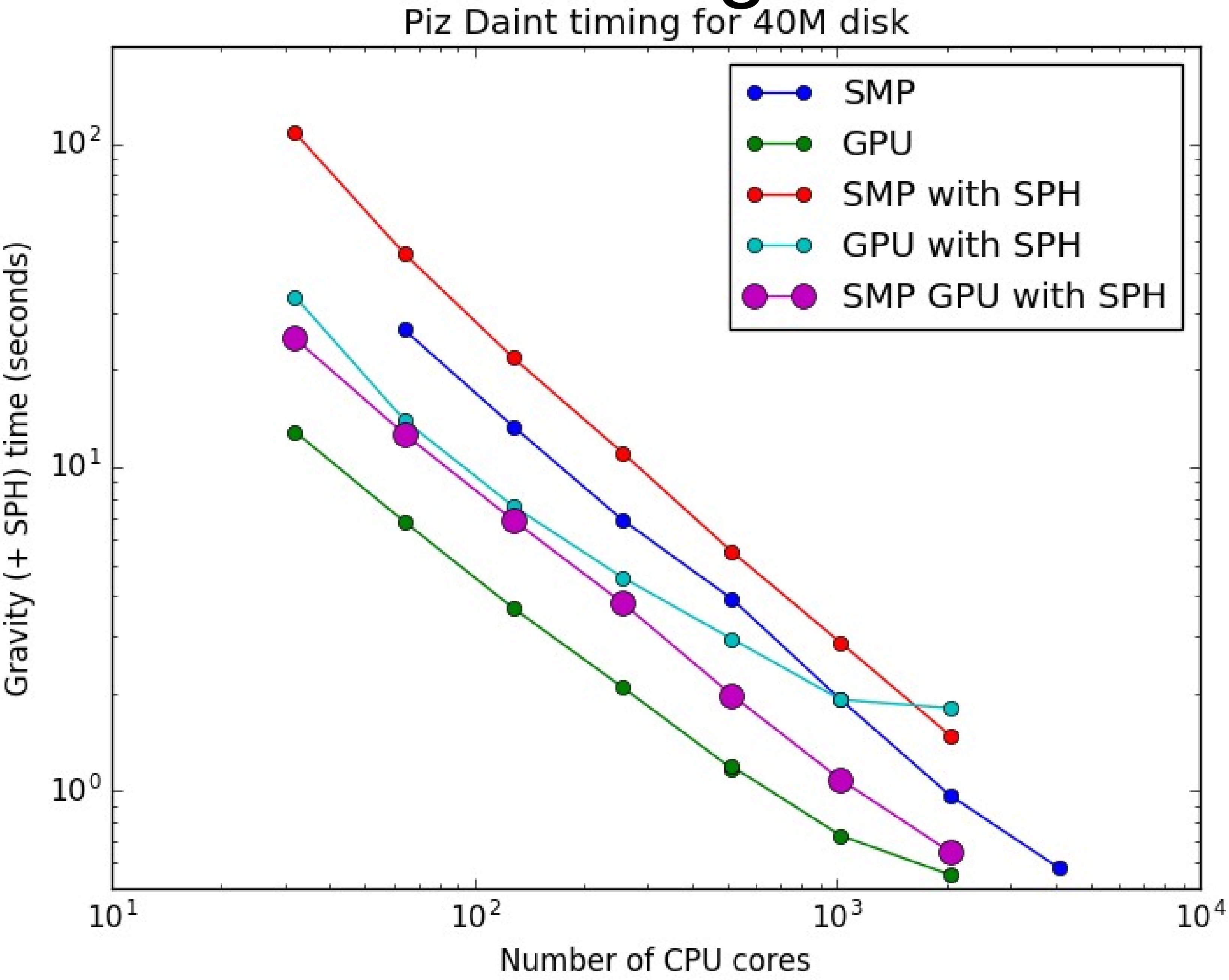
CPU Scaling Summary

- Load balancing the big steps is (mostly) solved
- Load balancing/optimizing the small steps is what is needed:
  - Small steps dominate the total time
  - Small steps increase throughput even when not optimal
  - Plenty of opportunity for improvement

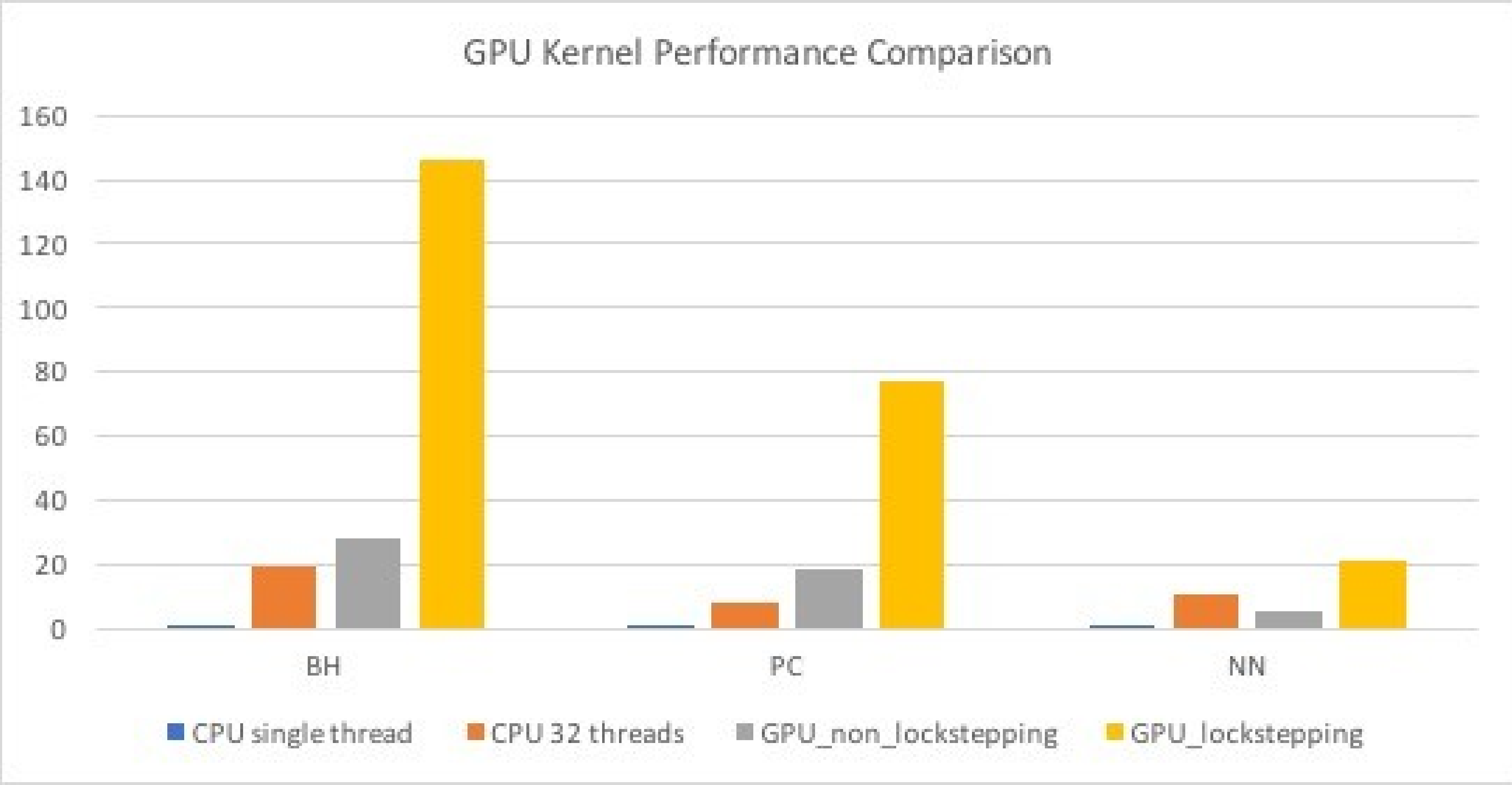
GPU Implementation: Gravity Only

- Load (SMP node) local tree/particle data onto the GPU
- Load prefetched remote tree onto the GPU
- CPUs walk tree and pass interaction lists
  - Lists are batched to minimize number of data transfers
- “Missed” treenodes: walk is resumed when data arrives: interaction list plus new tree data sent to the GPU.

Grav/SPH scaling with GPUs



Tree walking on the GPU



Jianqiau Liu, Purdue University