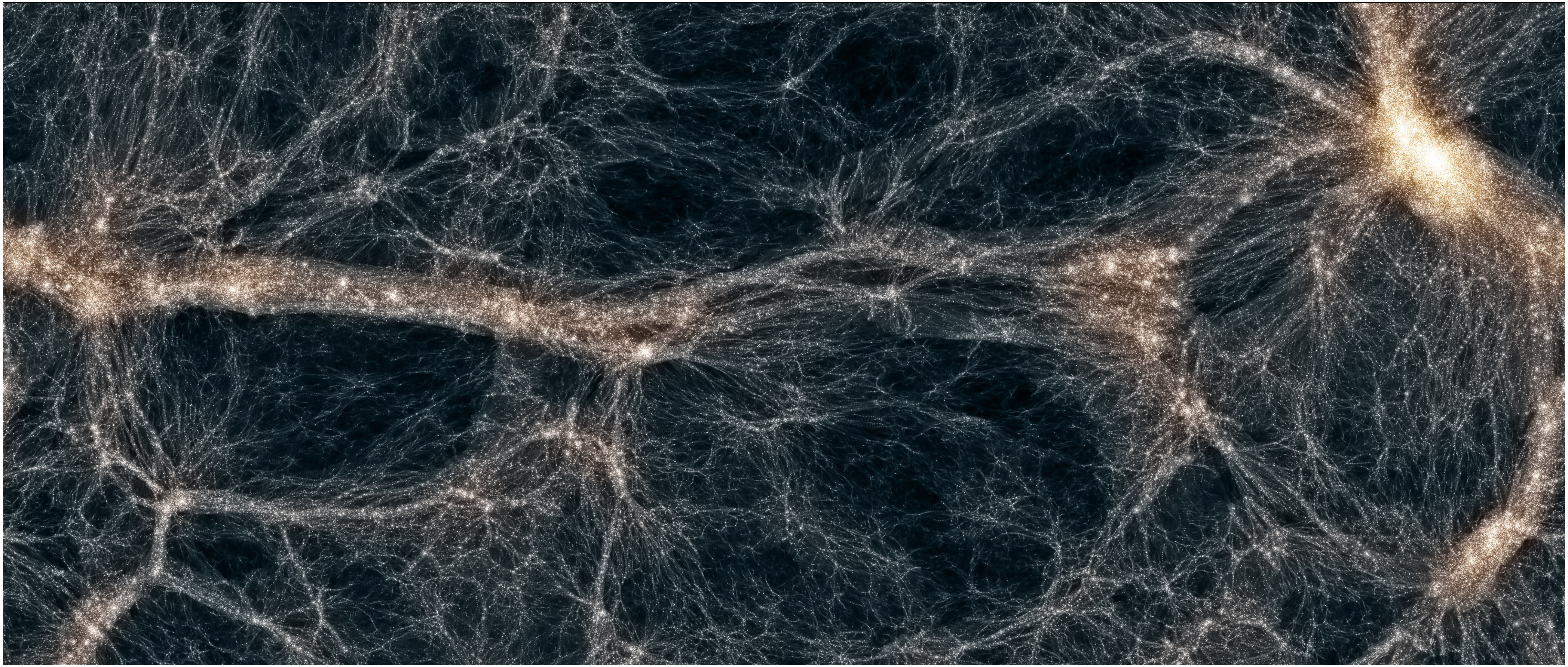
# ChaNGa: from cosmology to a flexible, parallel tree-code framework



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Others:
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# Dark Matter in the Universe

- Cosmic Microwave Background (Gigapc)
- Galaxy Rotation Curves (Kilopc)

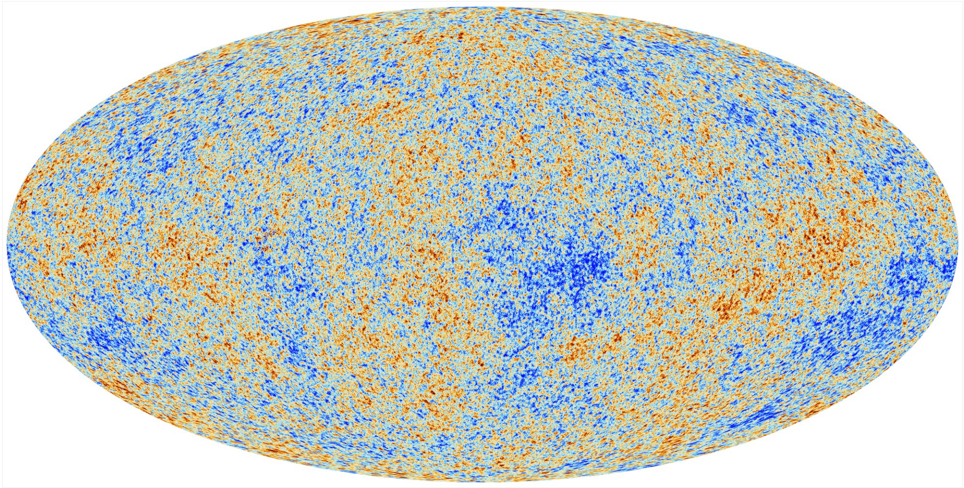
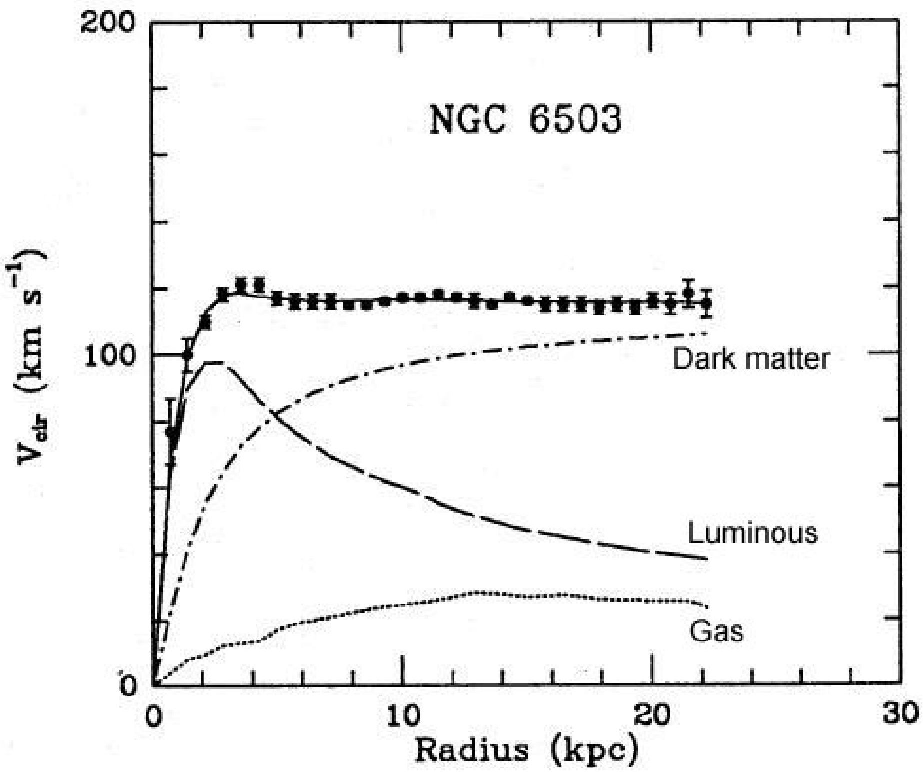


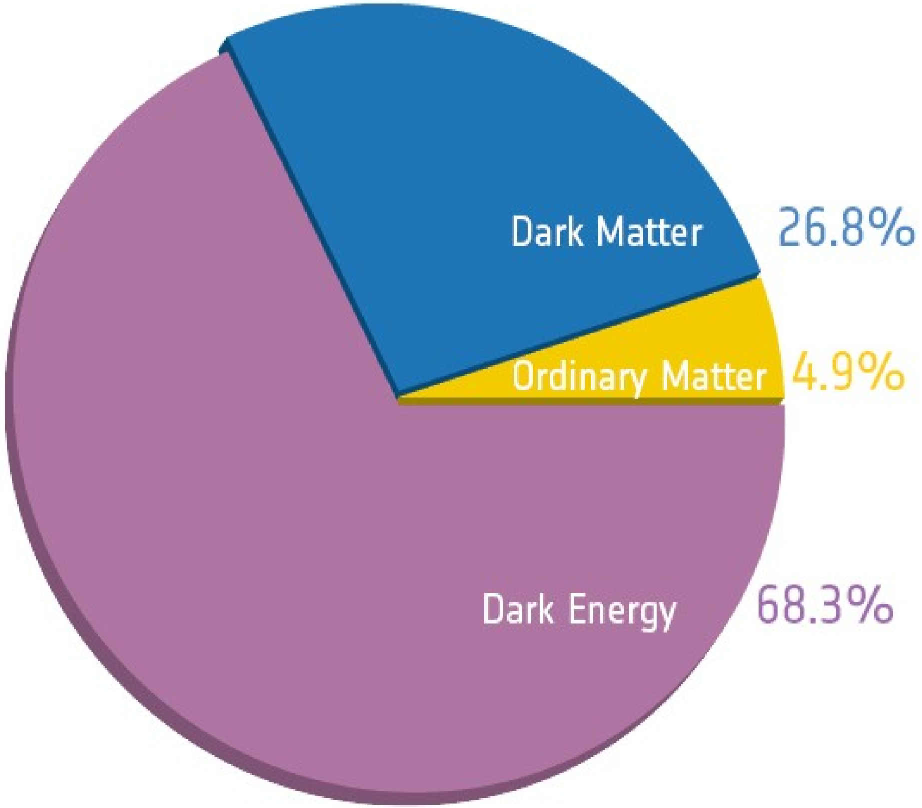
Image courtesy ESA/Planck




Begeman, Broels & Sanders, 1991

# 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)

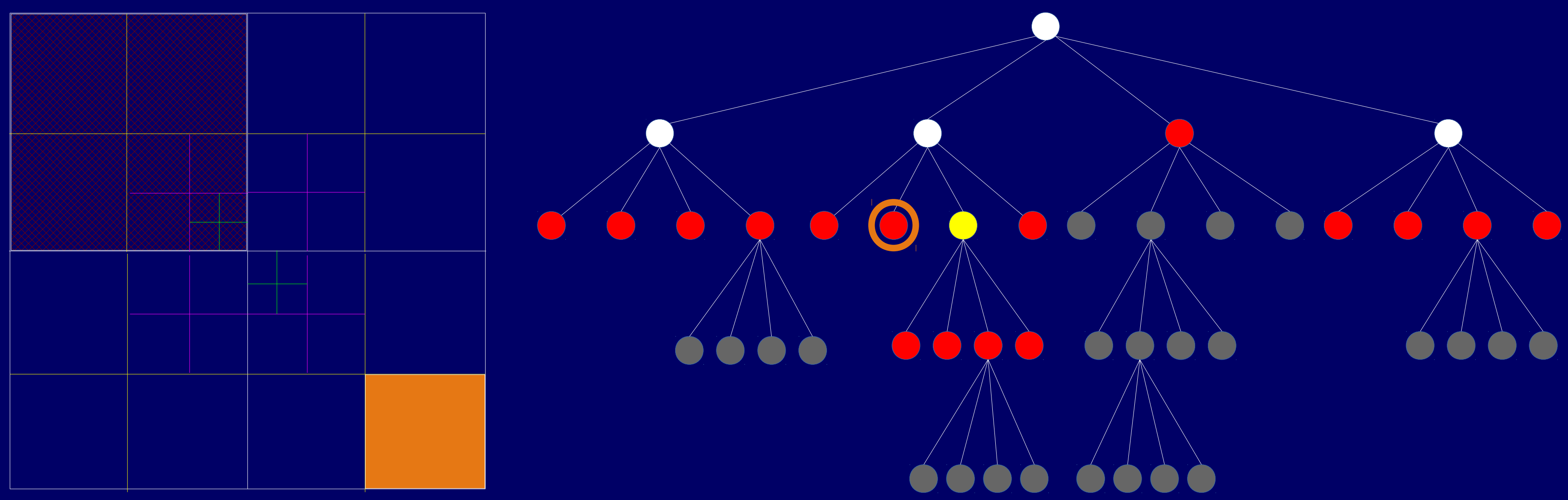


# Modeling Dark Matter

- 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

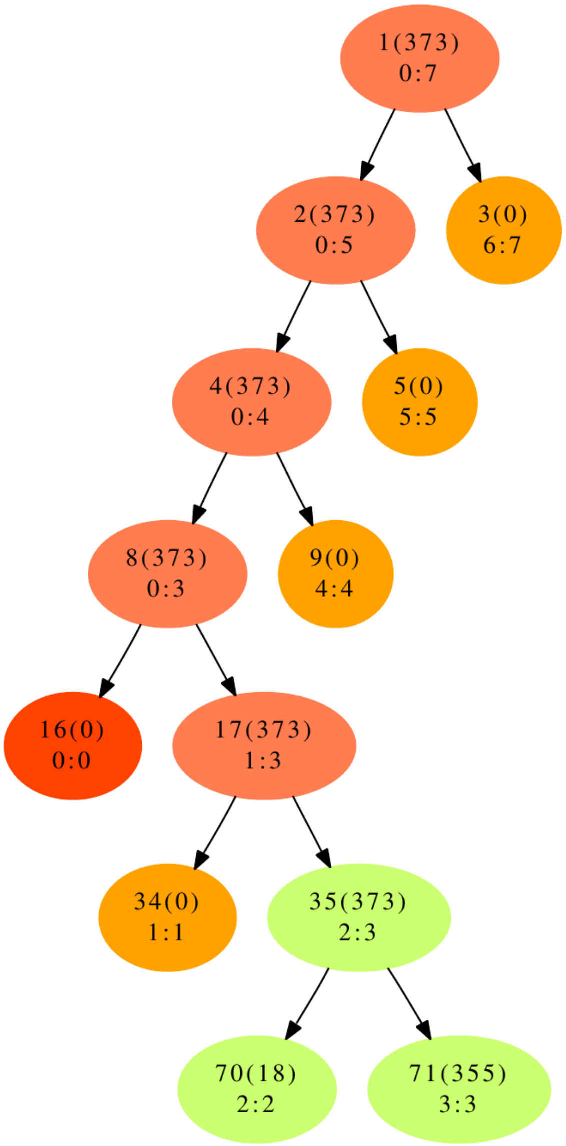
# Basic Gravity algorithm ...

- 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

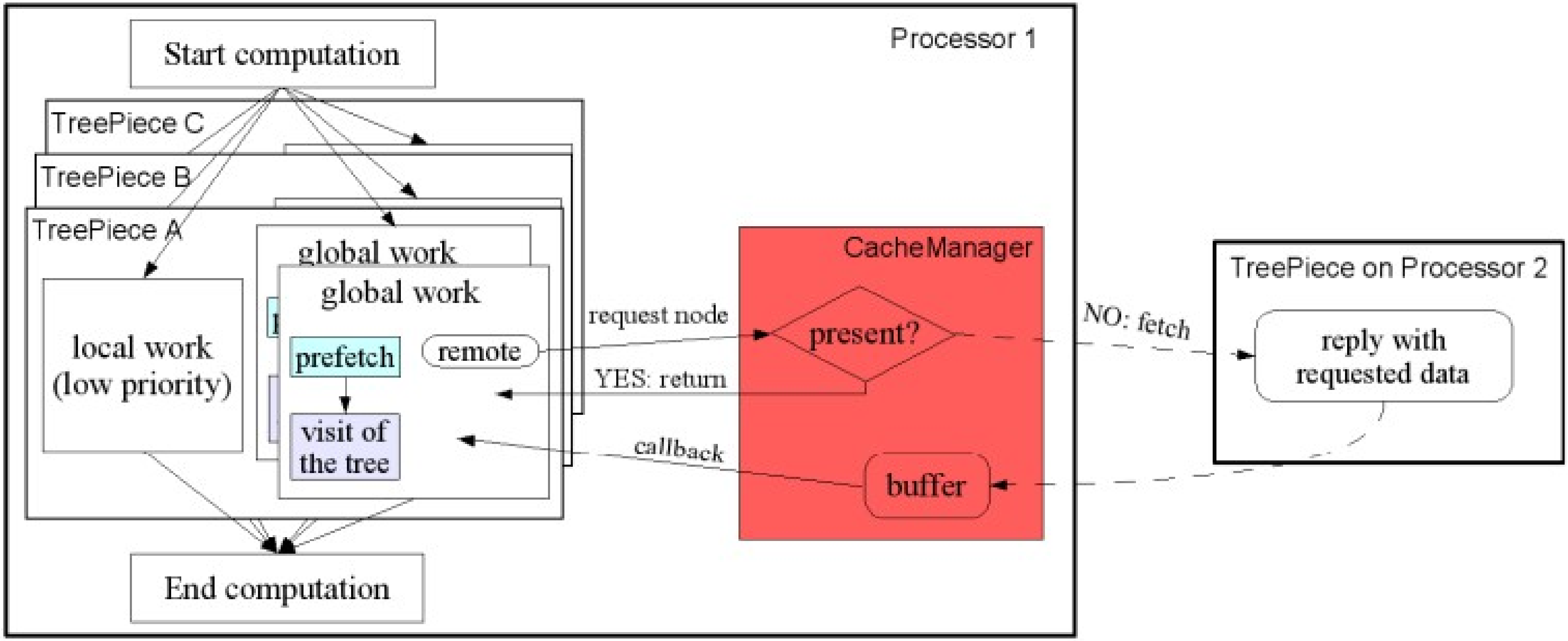


# TreePiece: basic data structure

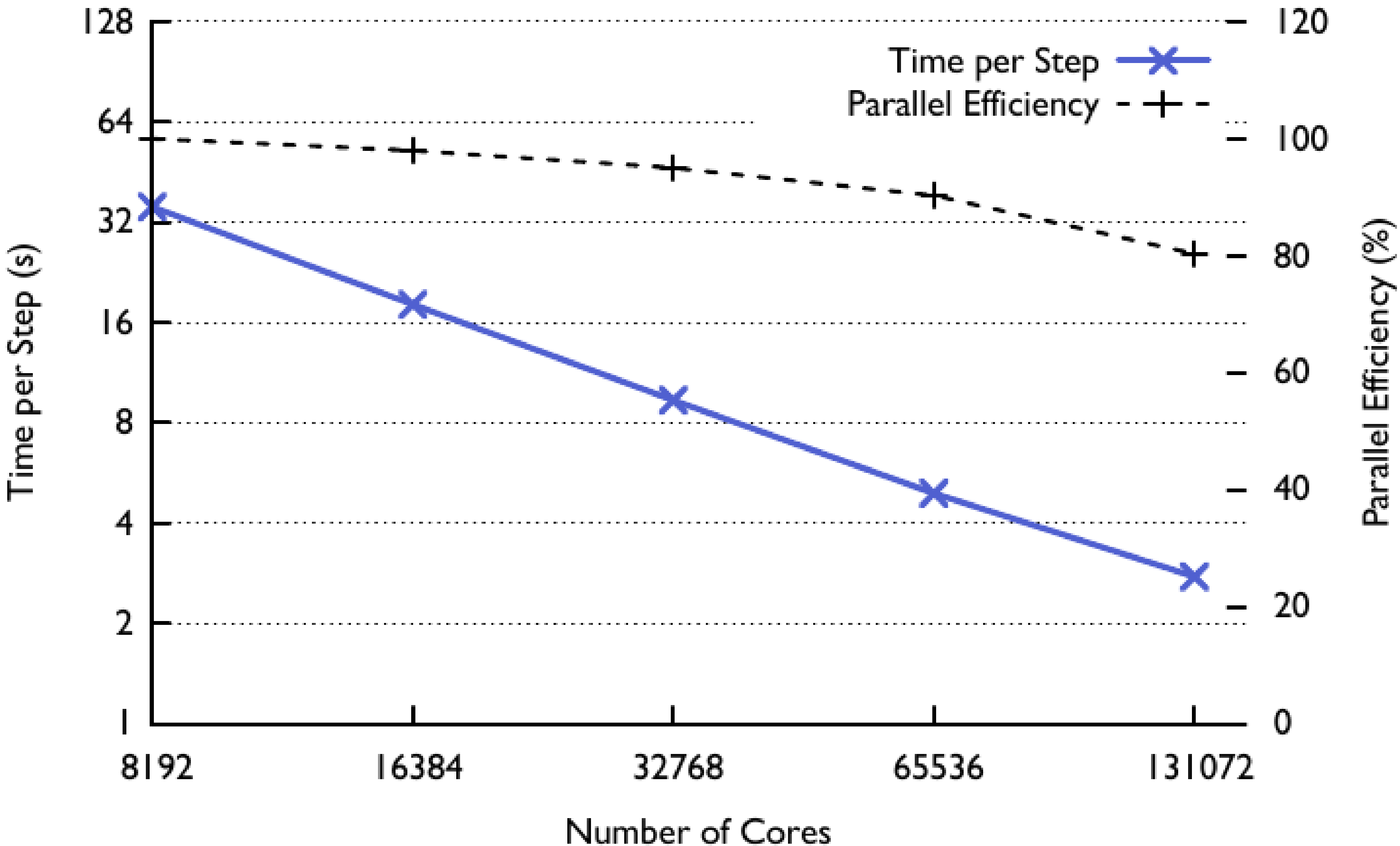
- A "vertical slice" of the tree, all the way to the root.
- Nodes are either:
  - Internal
  - External
  - Boundary (shared)

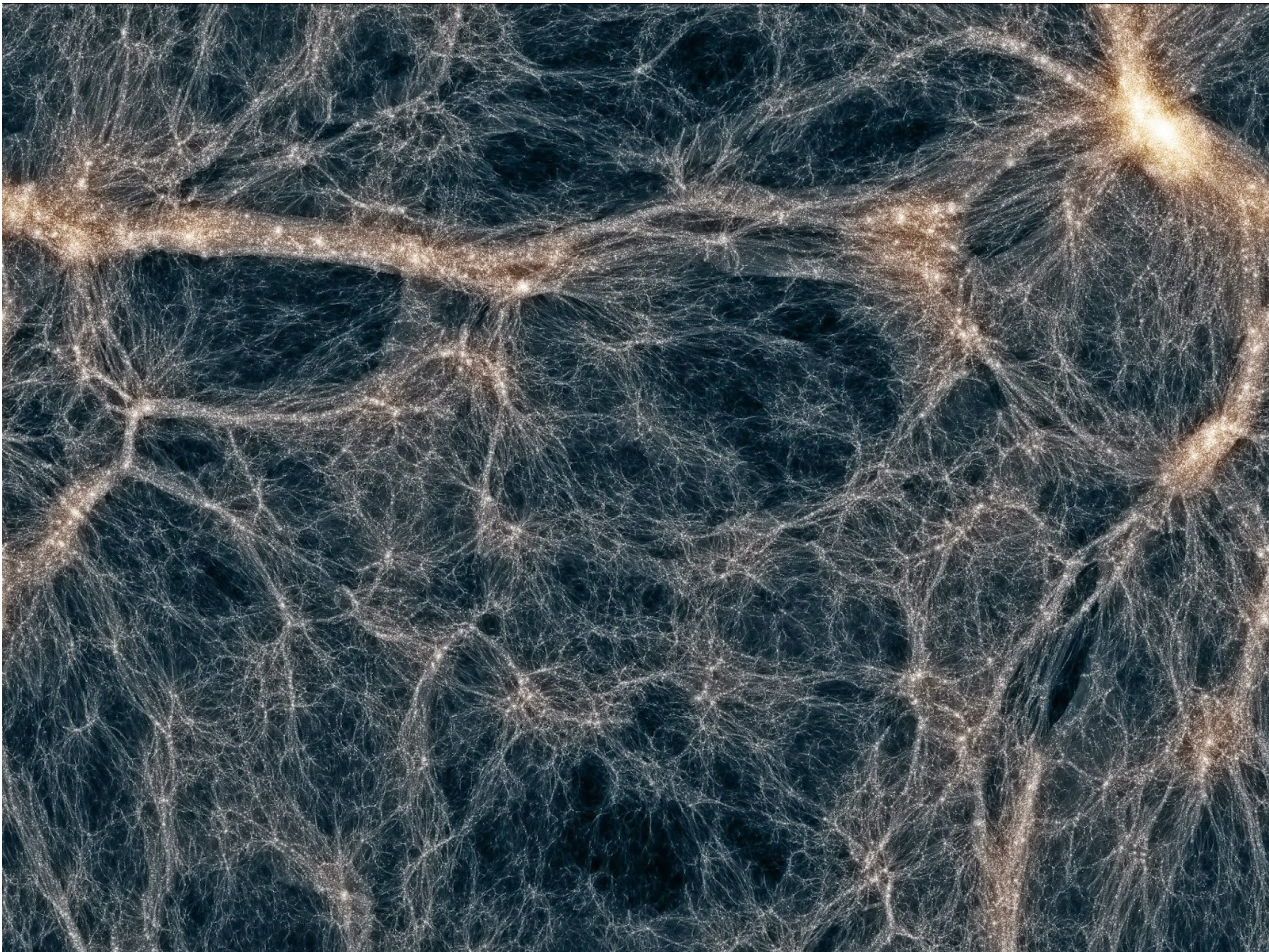


# Overall treewalk structure

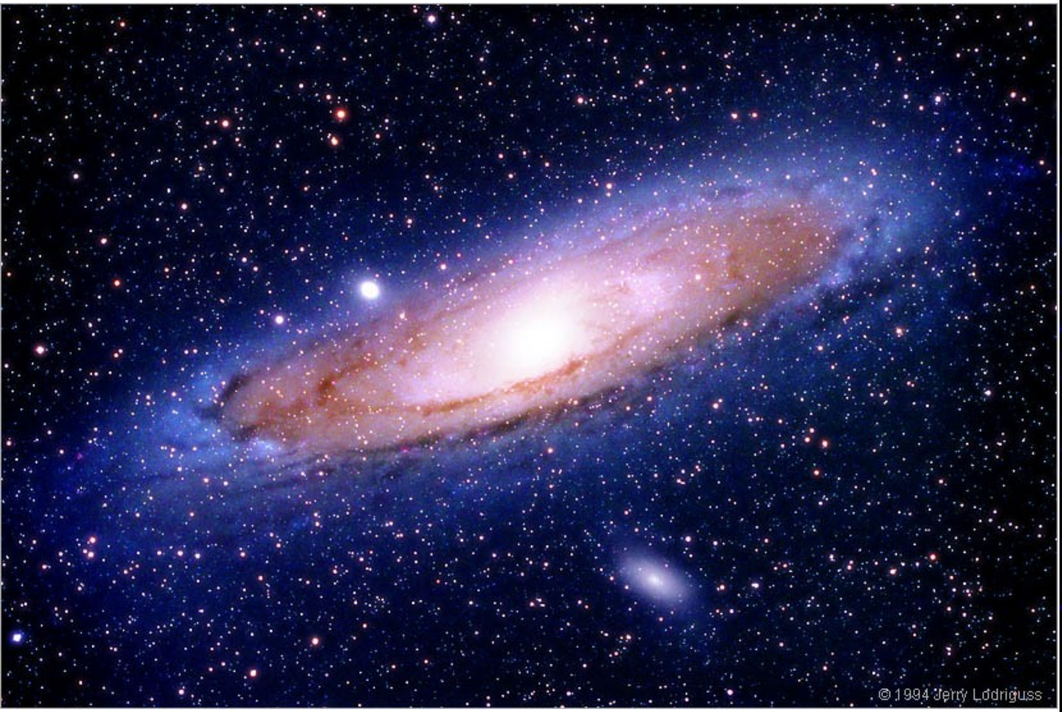


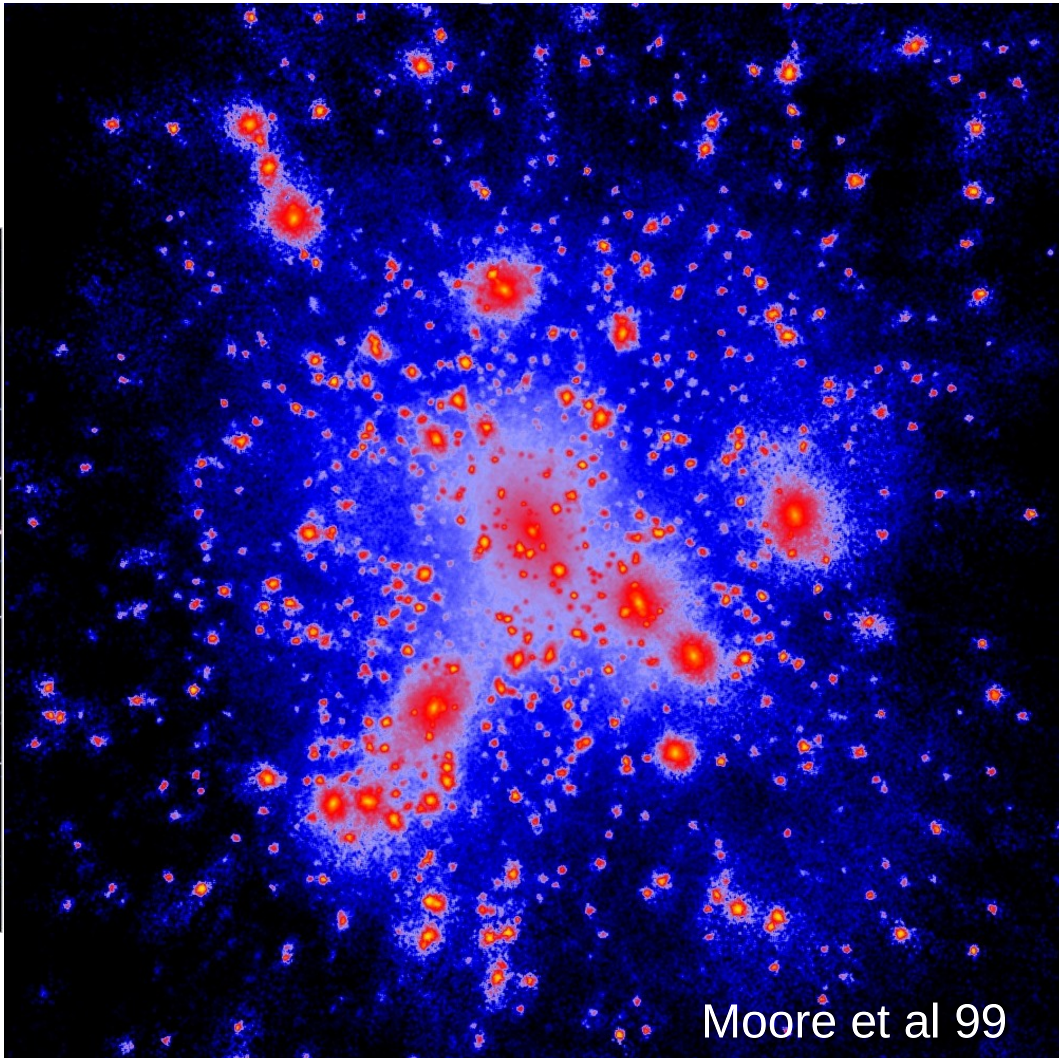
# Speedups for 2 billion clustered particles





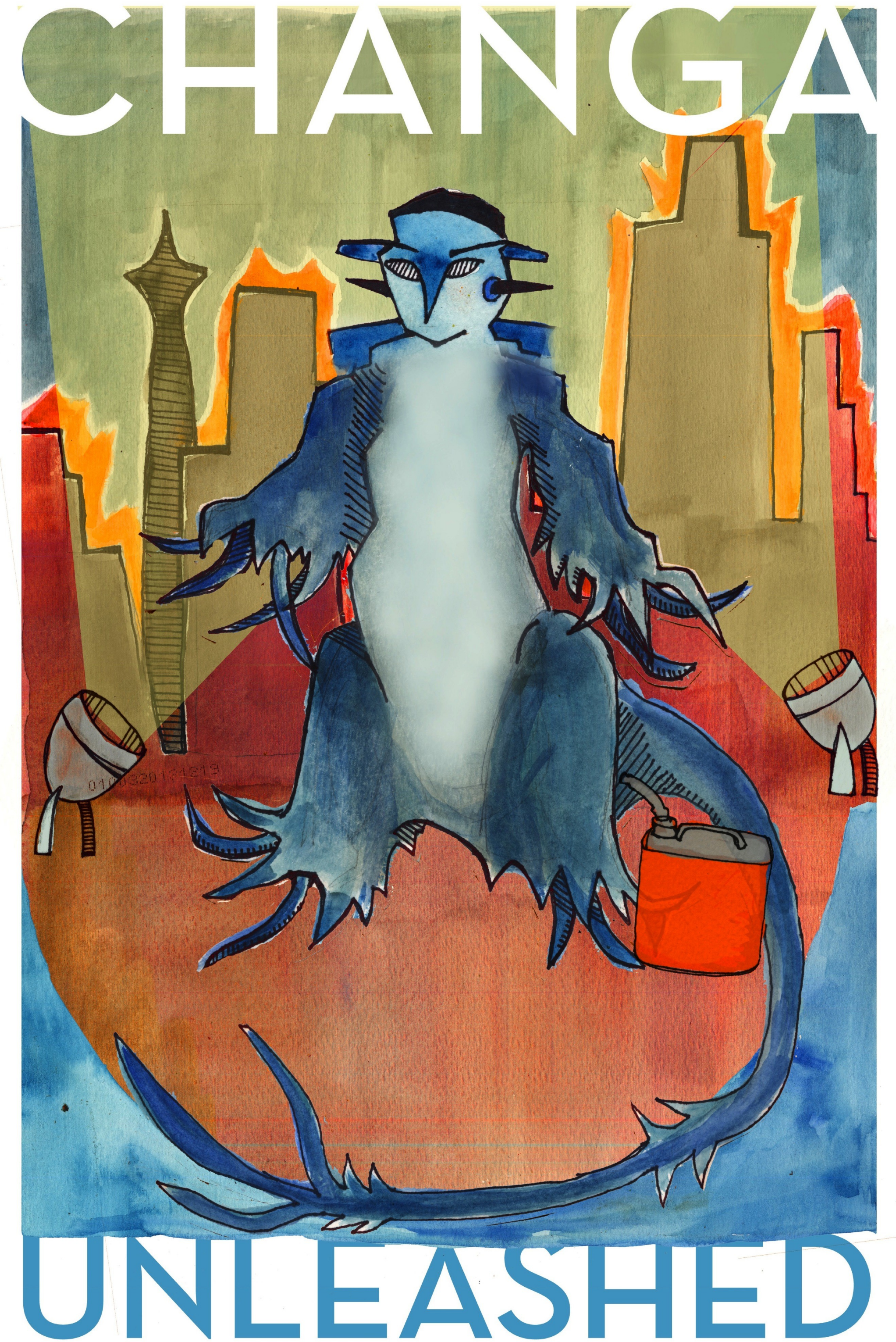
# Light vs. Matter



# Smooth Particle Hydrodynamics

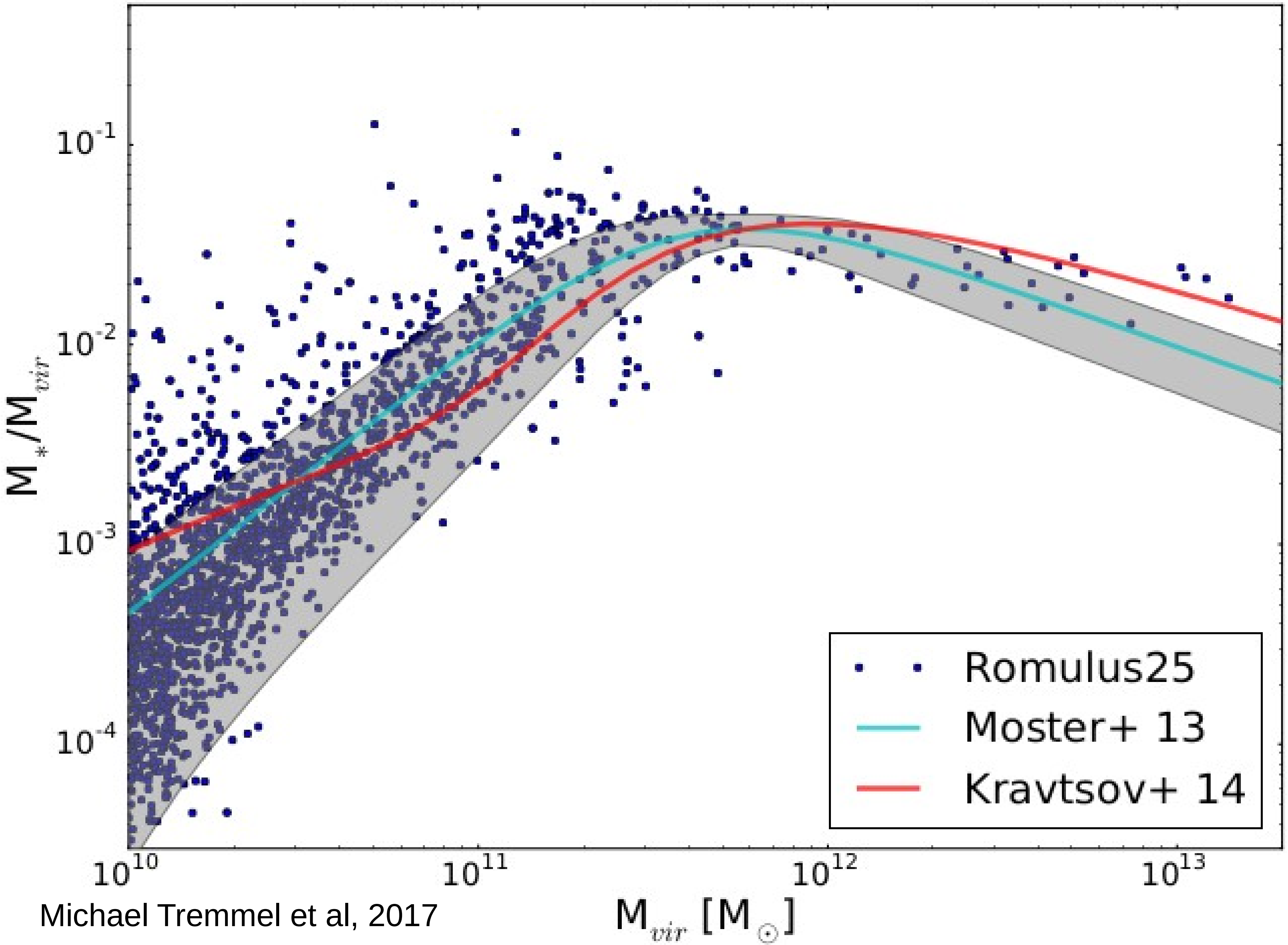
- Making testable predictions needs Gastrophysics
  - High Mach number
  - Large density contrasts
- Gridless, Lagrangian method
- Galilean invariant
- Monte-Carlo Method for solving Navier-Stokes equation.
- Natural extension of particle method for gravity.




# 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




Michael Tremmel et al, 2017

# Fundamental Origins Questions:

How did the Universe begin?

How did stars form?

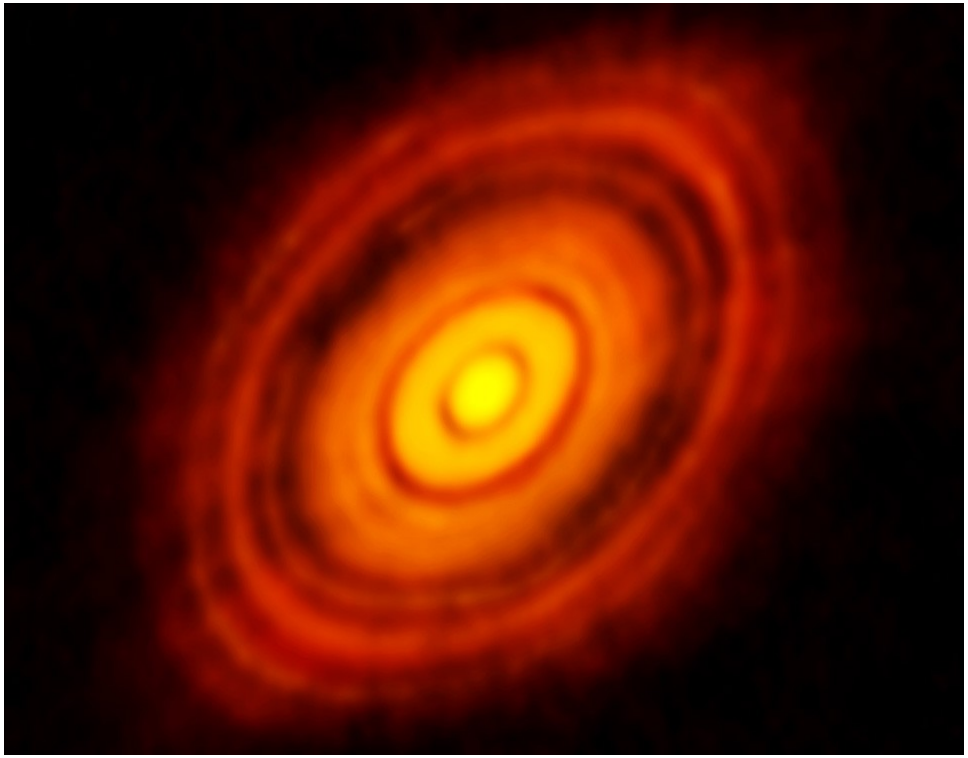
**How did planets form?**

How did life begin?

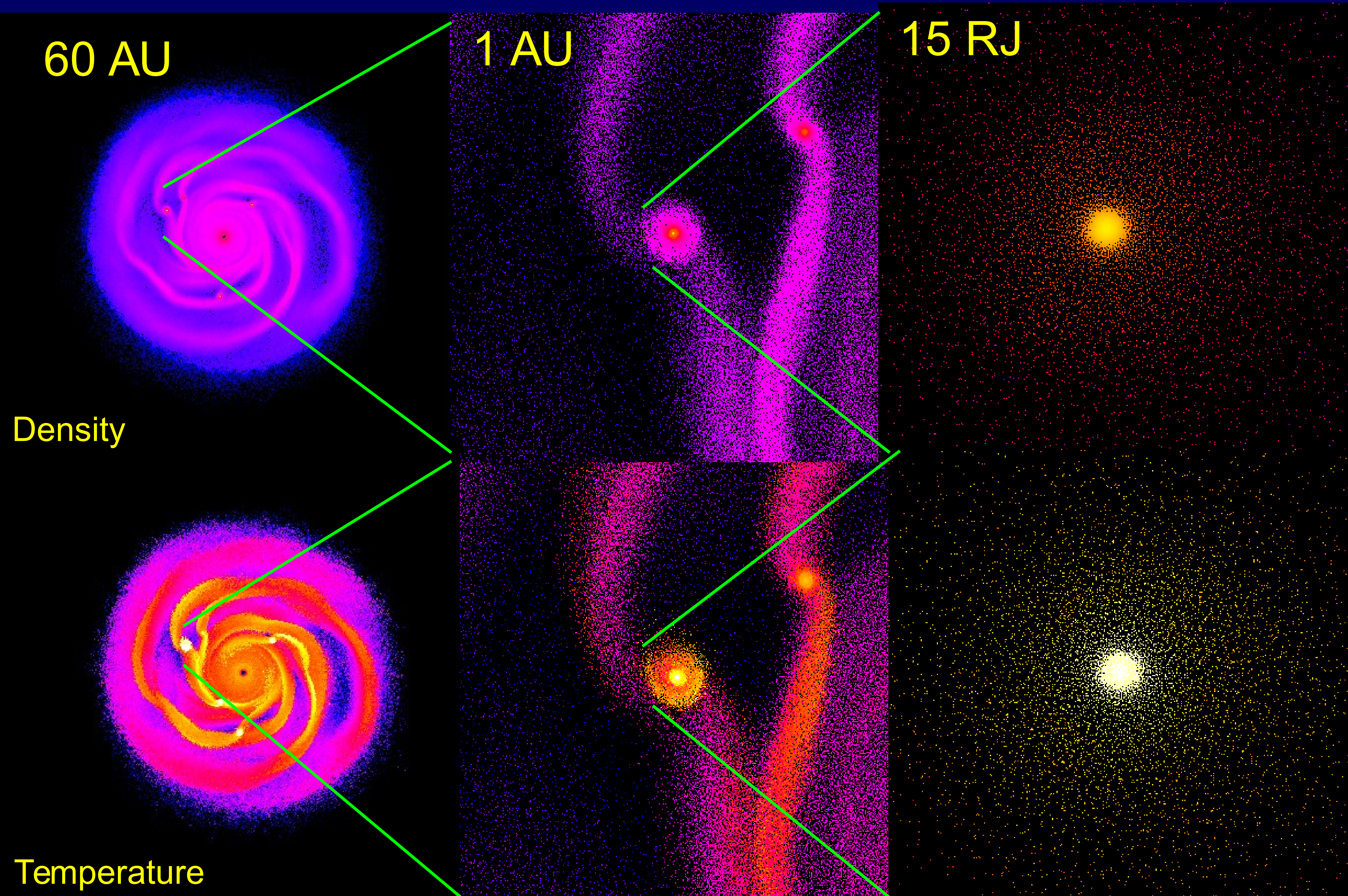
How did intelligent life develop?

# Protoplanetary Disks

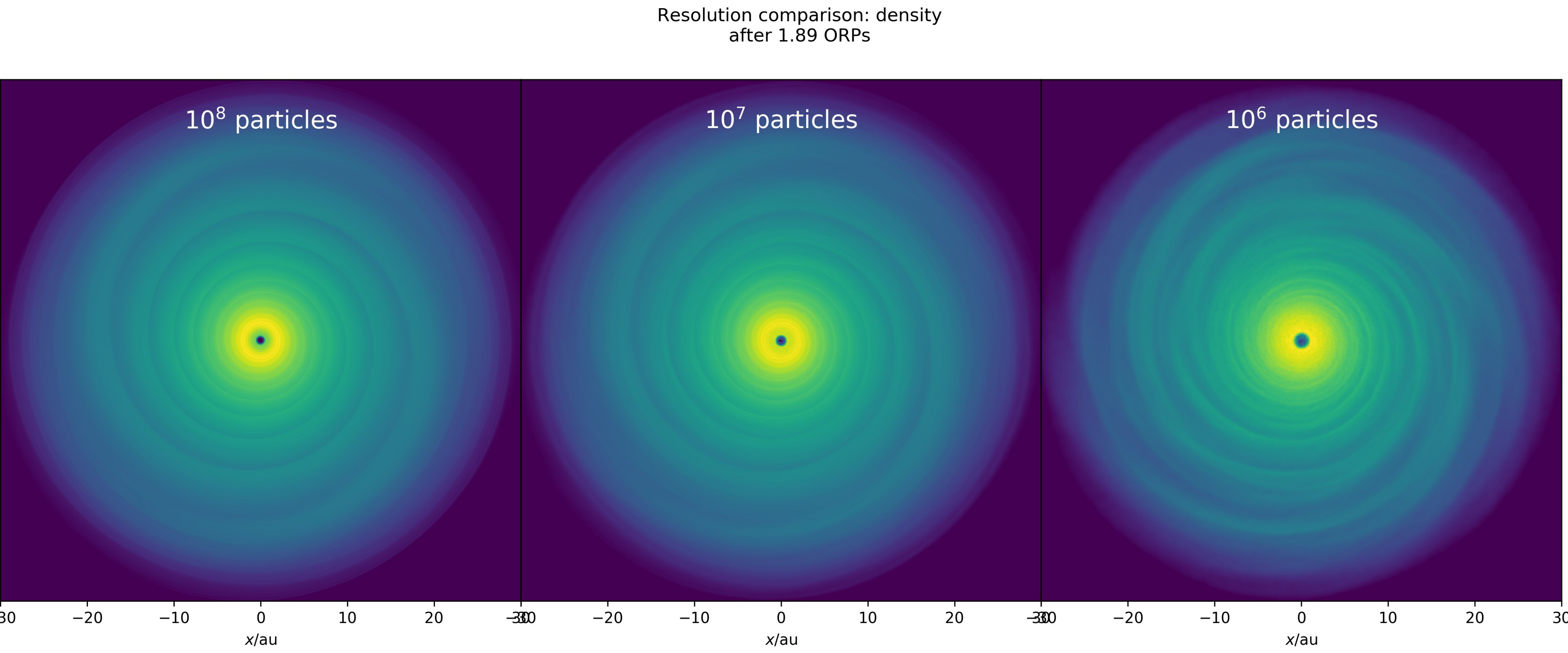
- Likely result of cloud collapse with conserved angular momentum
- Disks can be gravitationally unstable
- Fragmentation depends on details of gas dynamics



# Planet Formation Resolution



# ChaNGa: unprecedented resolution




Isaac Backus, Ph. D. Thesis

# 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)

# The simulation model

Planetesimals represented by spherical particles.

Particles gravitationally interact with each other, planets and Sun.

*Heuristic collision model:* particles stick or bounce when they collide.

Particles acquire spin through collisions.

Need a fast collision finder: ChaNGa

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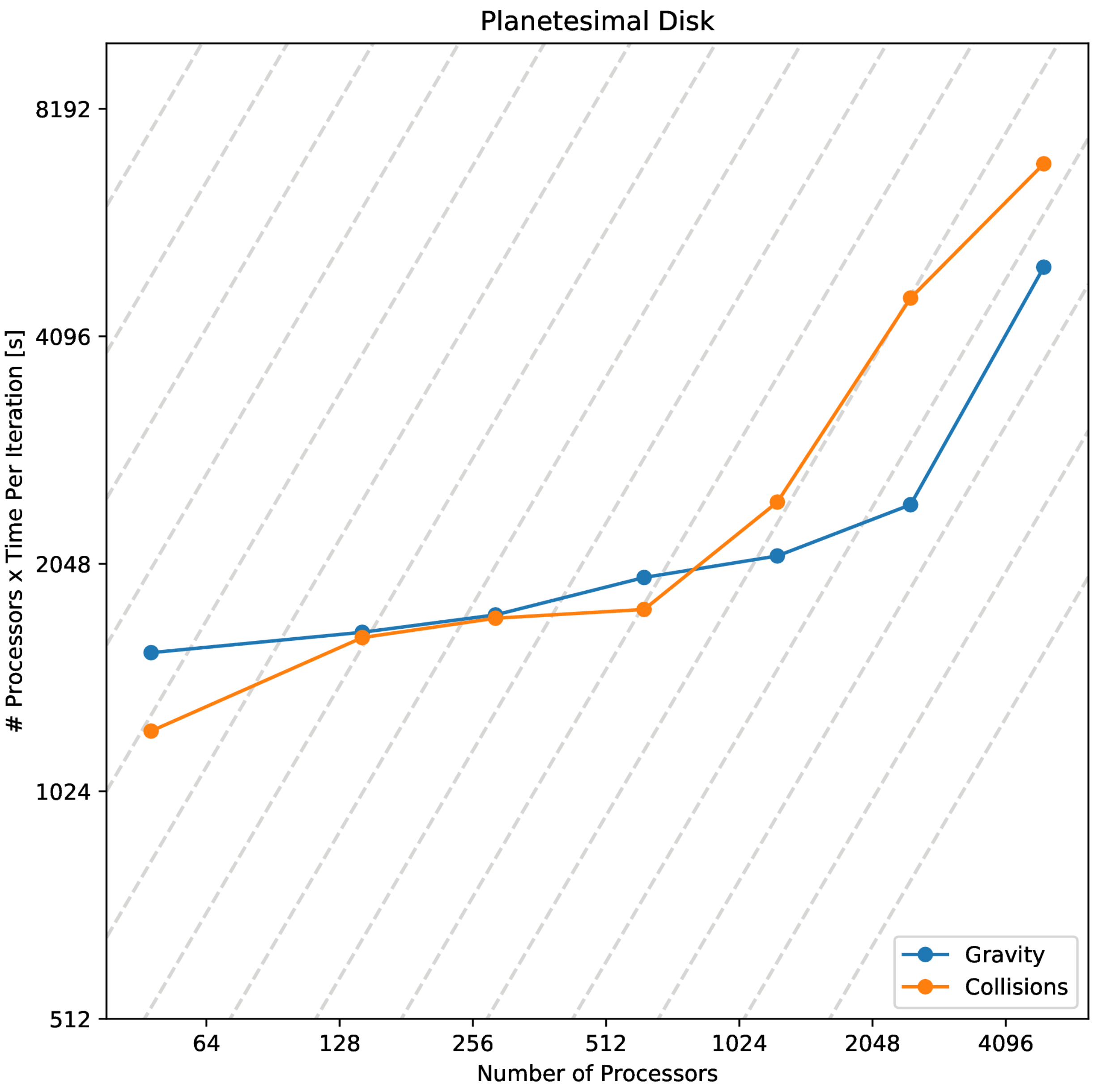
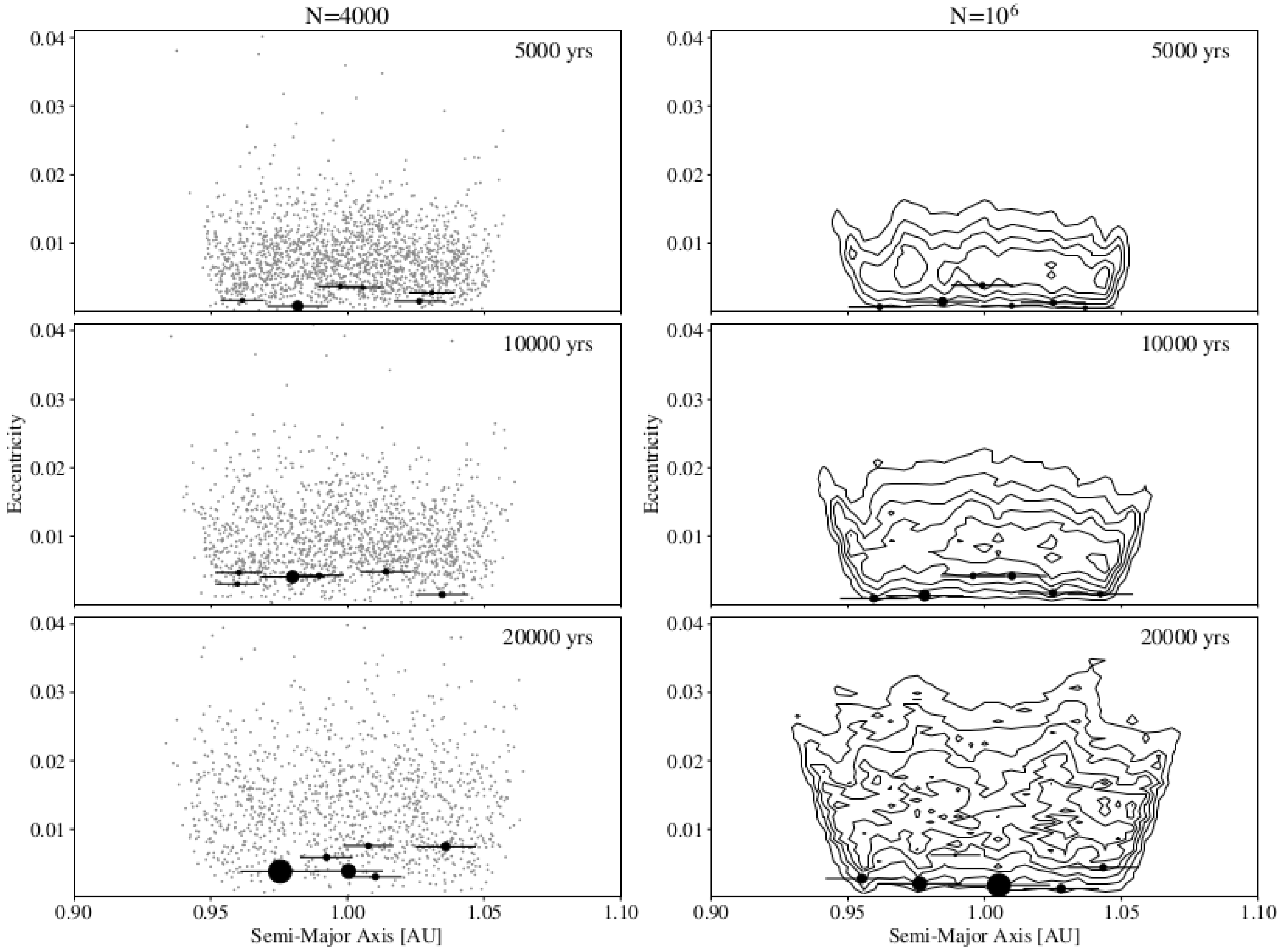
# Collision scaling: 50M particles



# Orders of magnitude better resolution

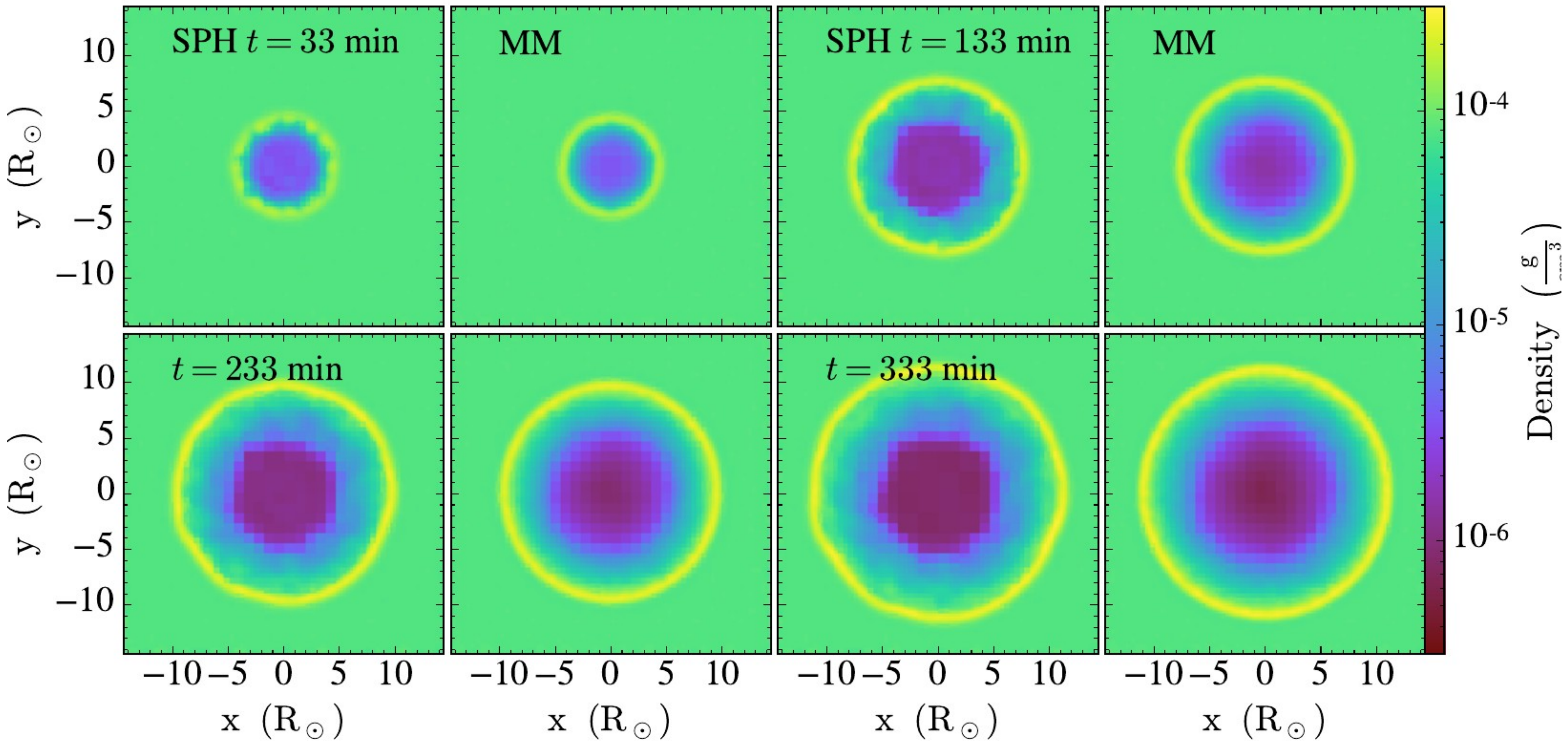



Spencer Wallace

# 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)

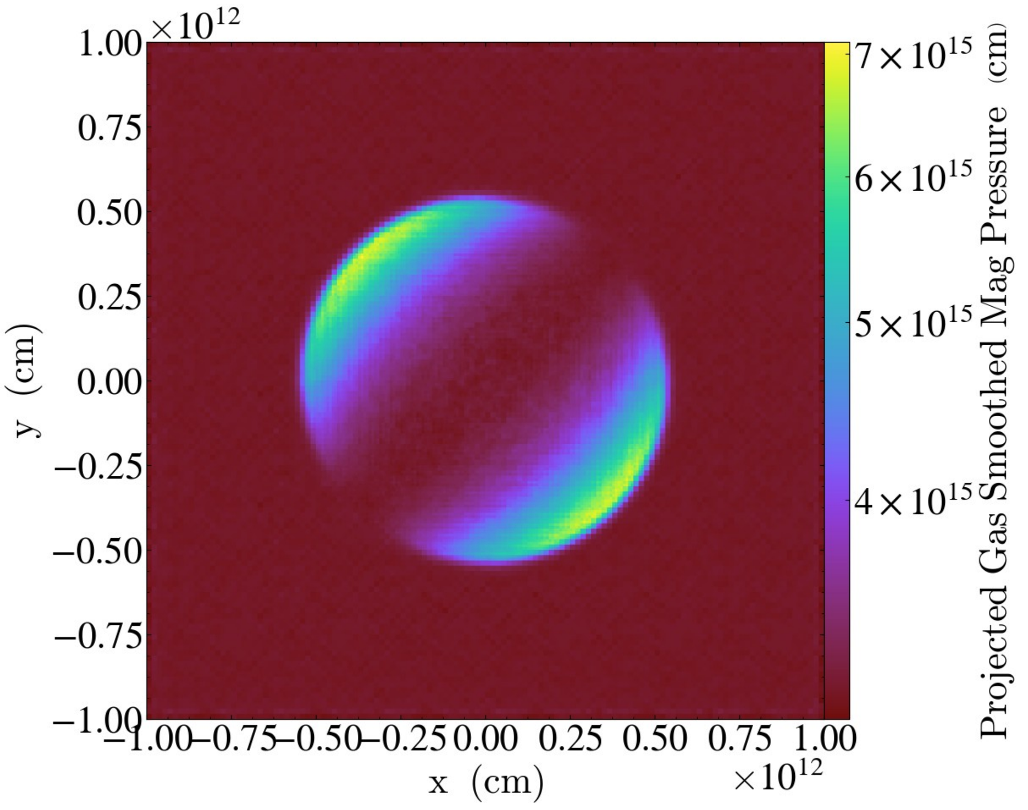
# Sedov Test



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

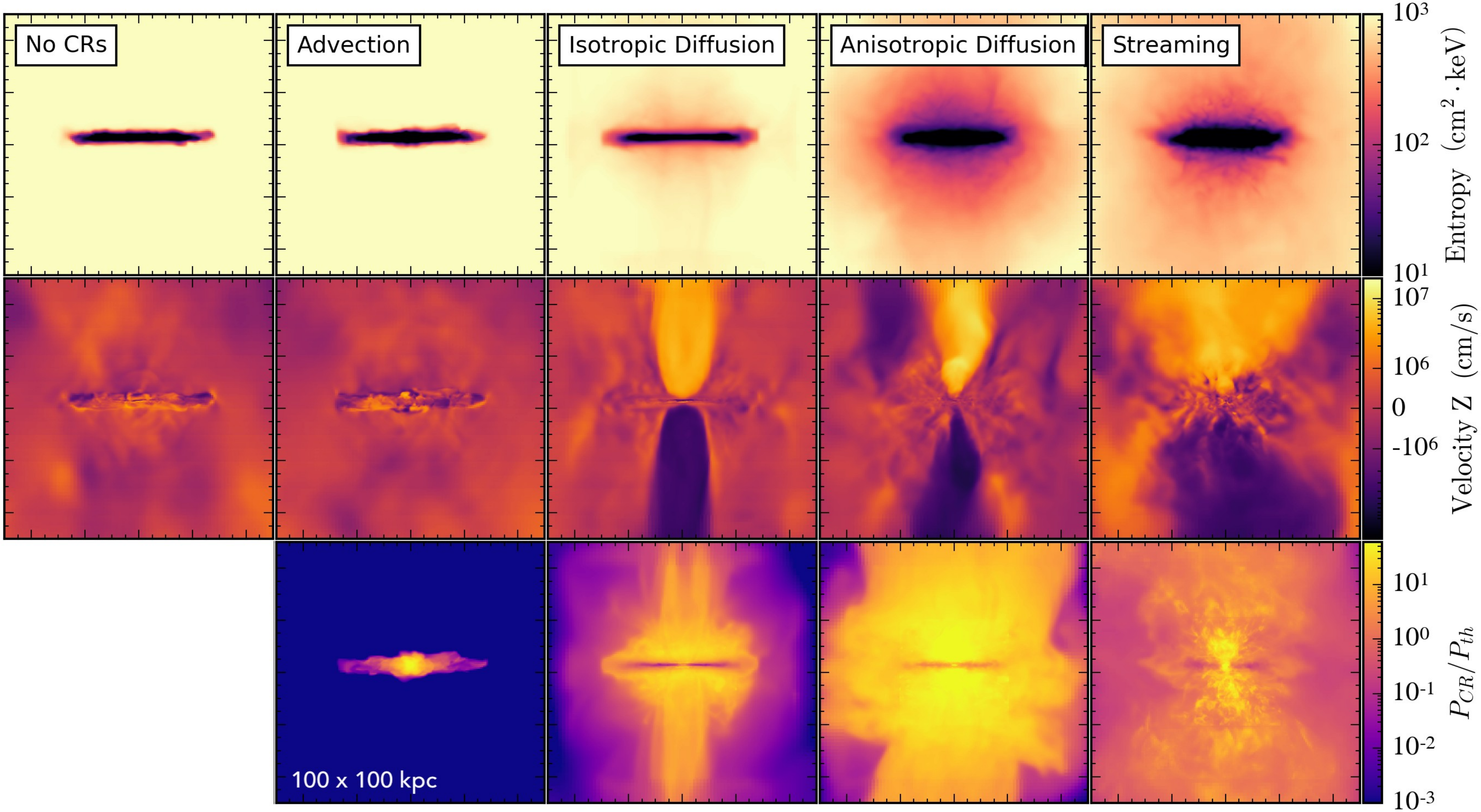
# More Physics

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



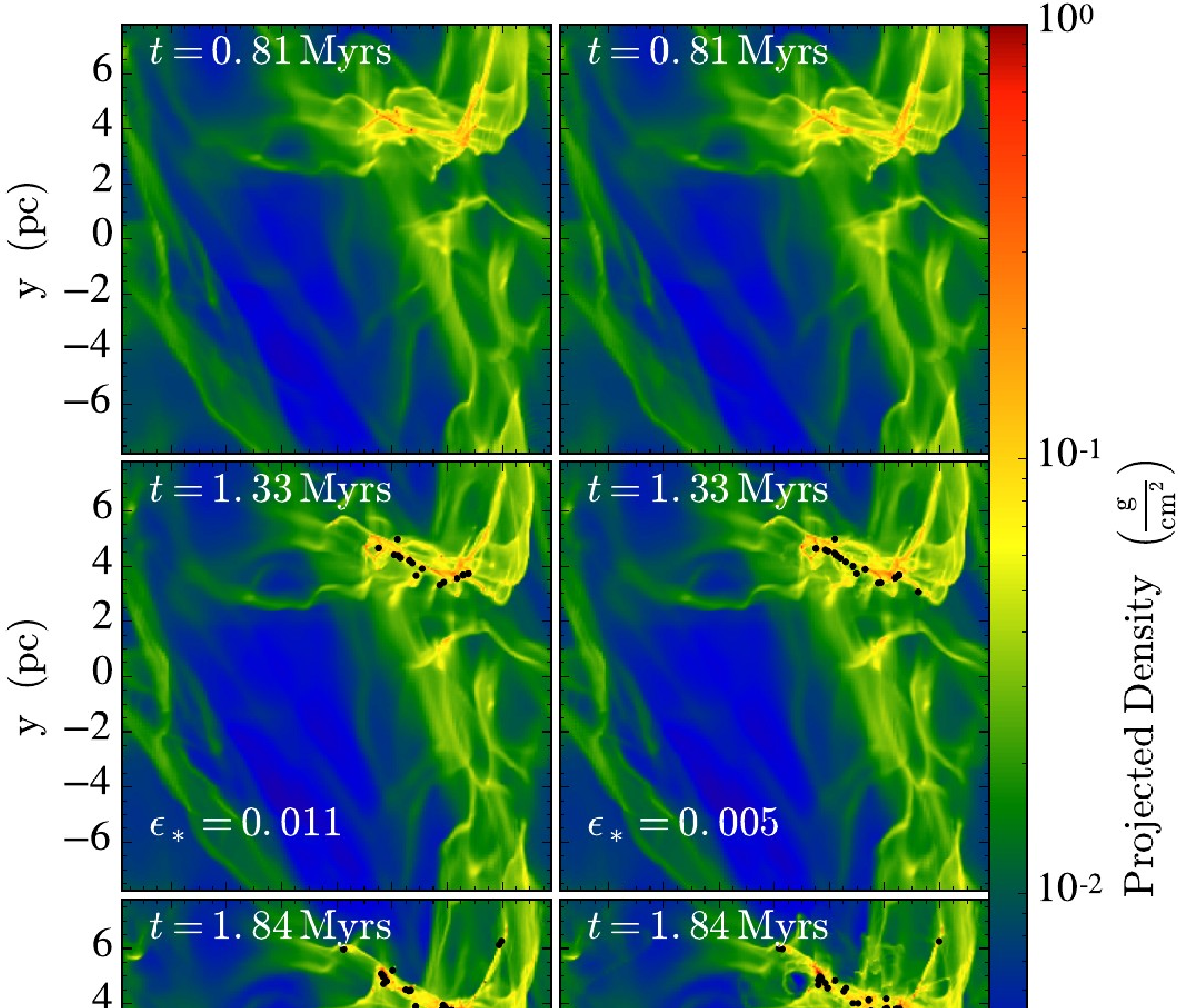

Phil Chang, UW-Milwaukee

# Magnetic fields and outflows




Iryna Butsky

# Simulations of Star Formation

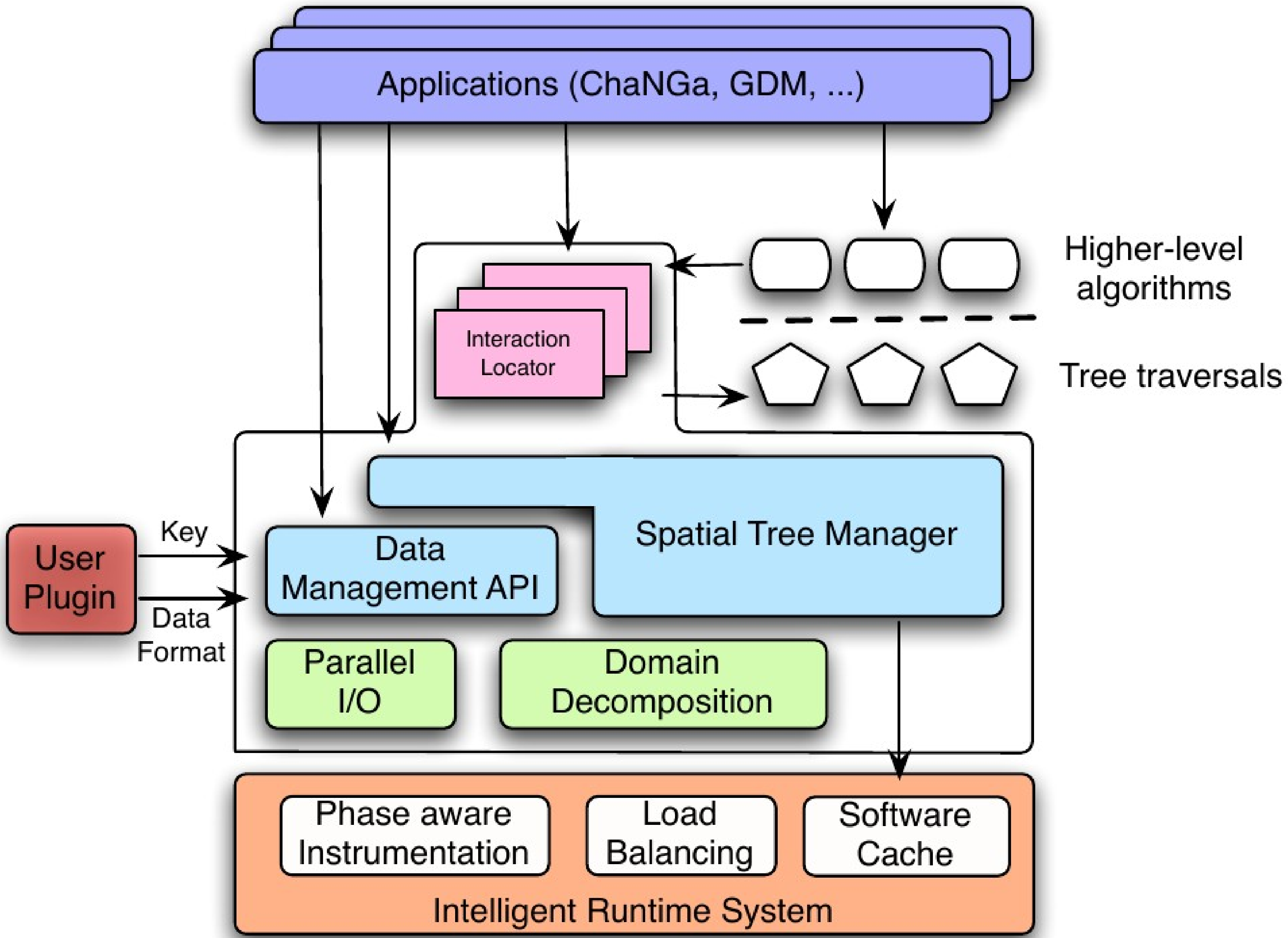



Norm Murray, 2018

# 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



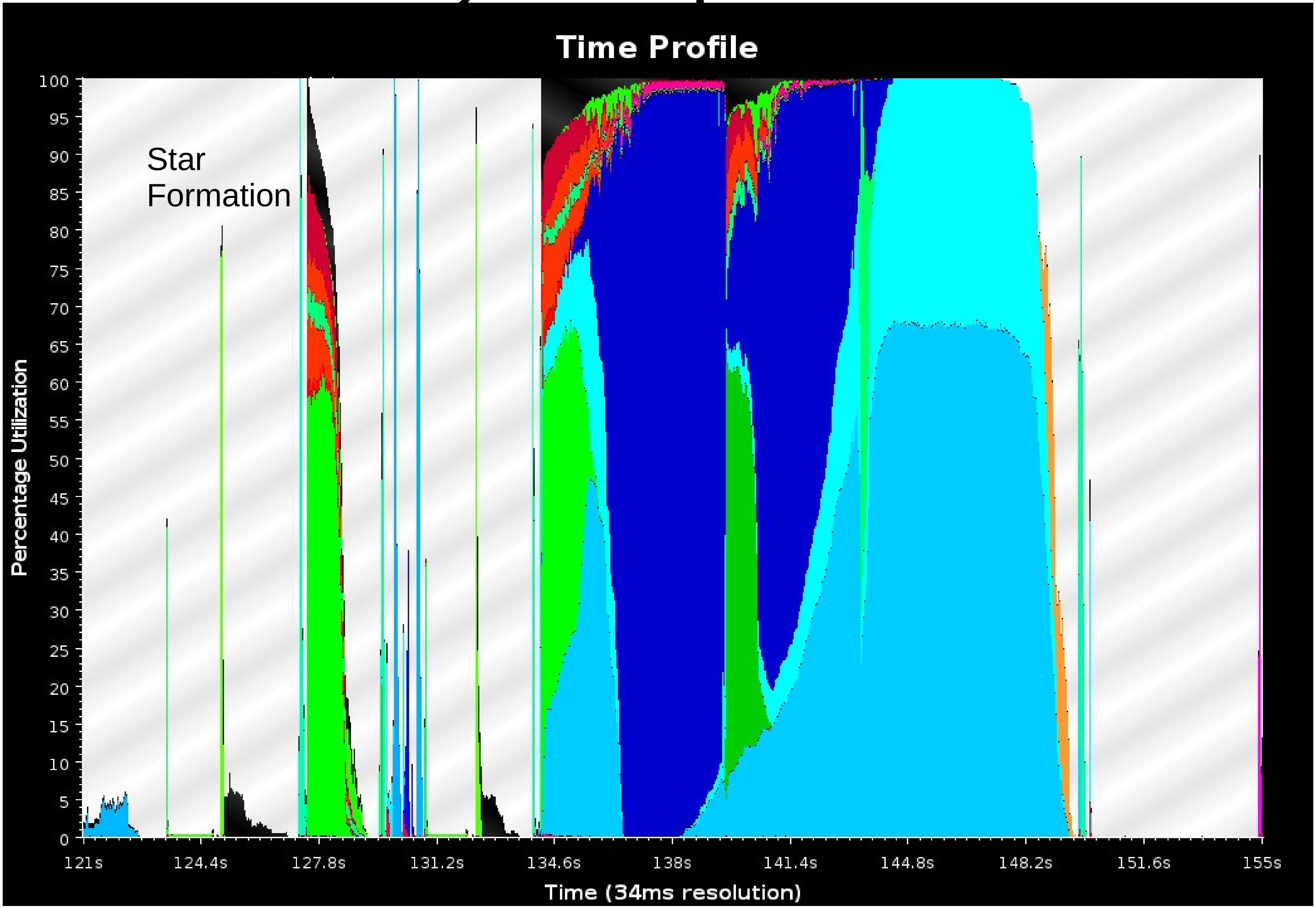
# Availability

- 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

# LB by Compute time




15.8 seconds

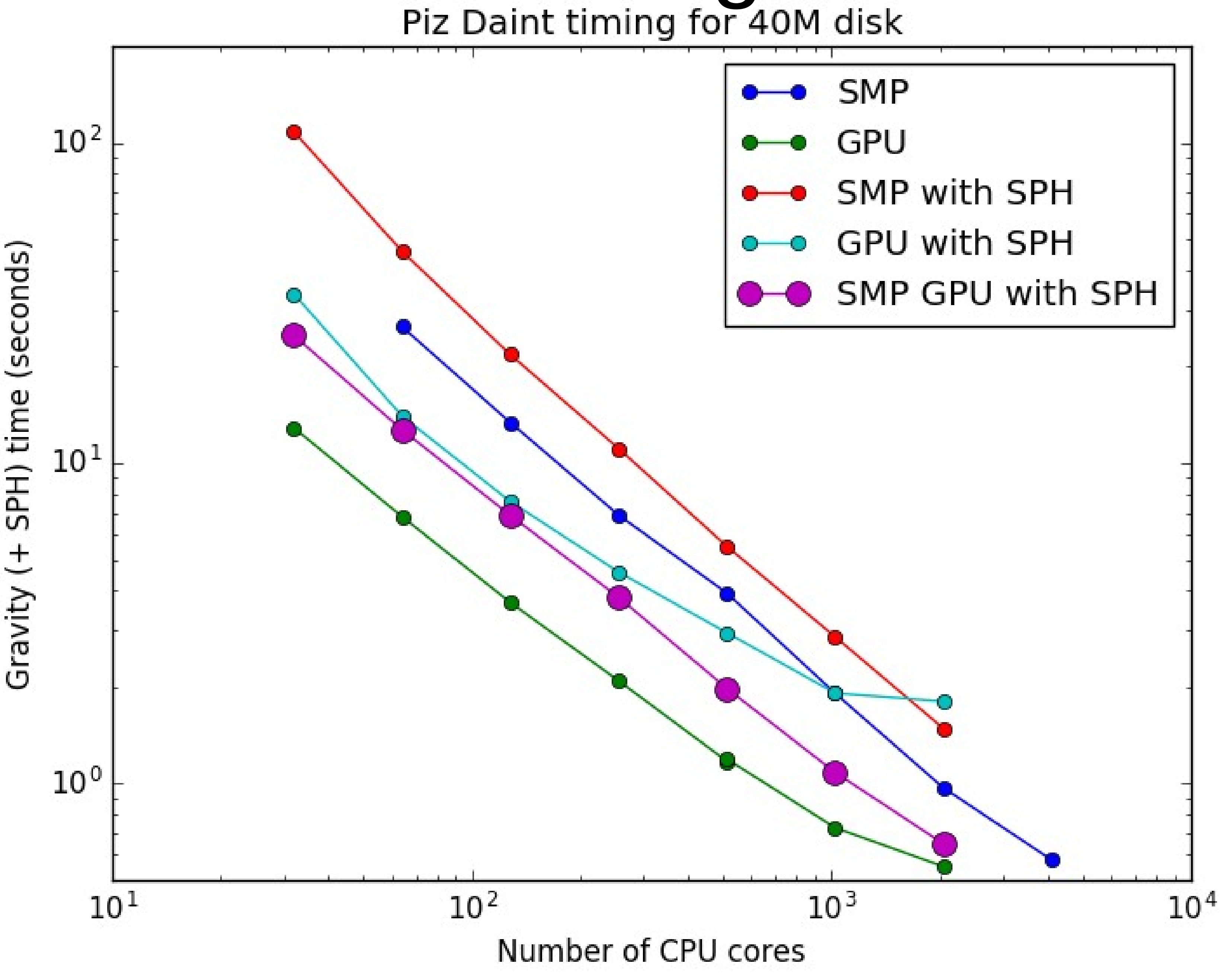
# CPU Scaling Summary

- 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

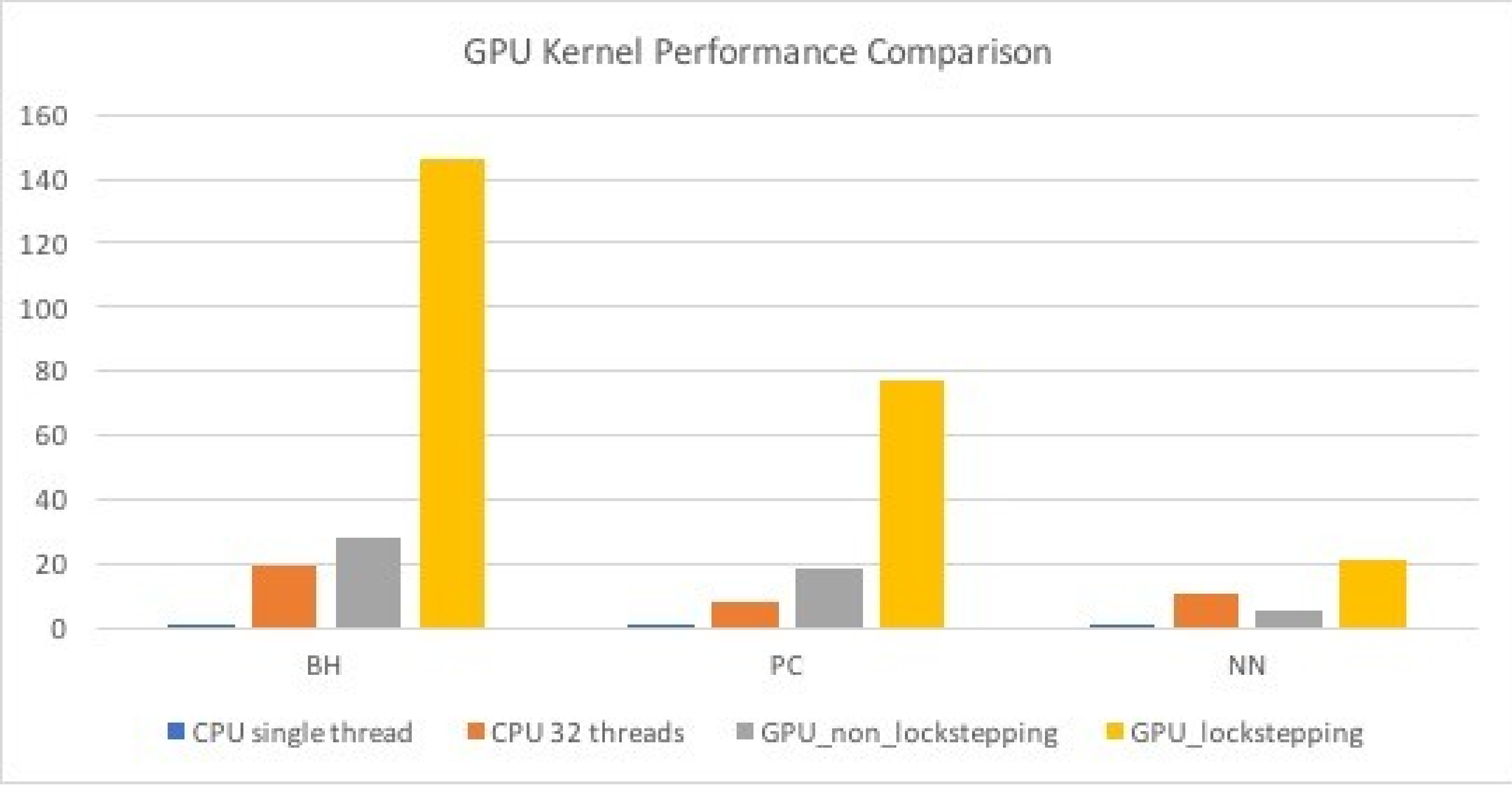
# GPU Implementation: Gravity Only

- 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