Numerical Simulation in Astrophysics and Cosmology

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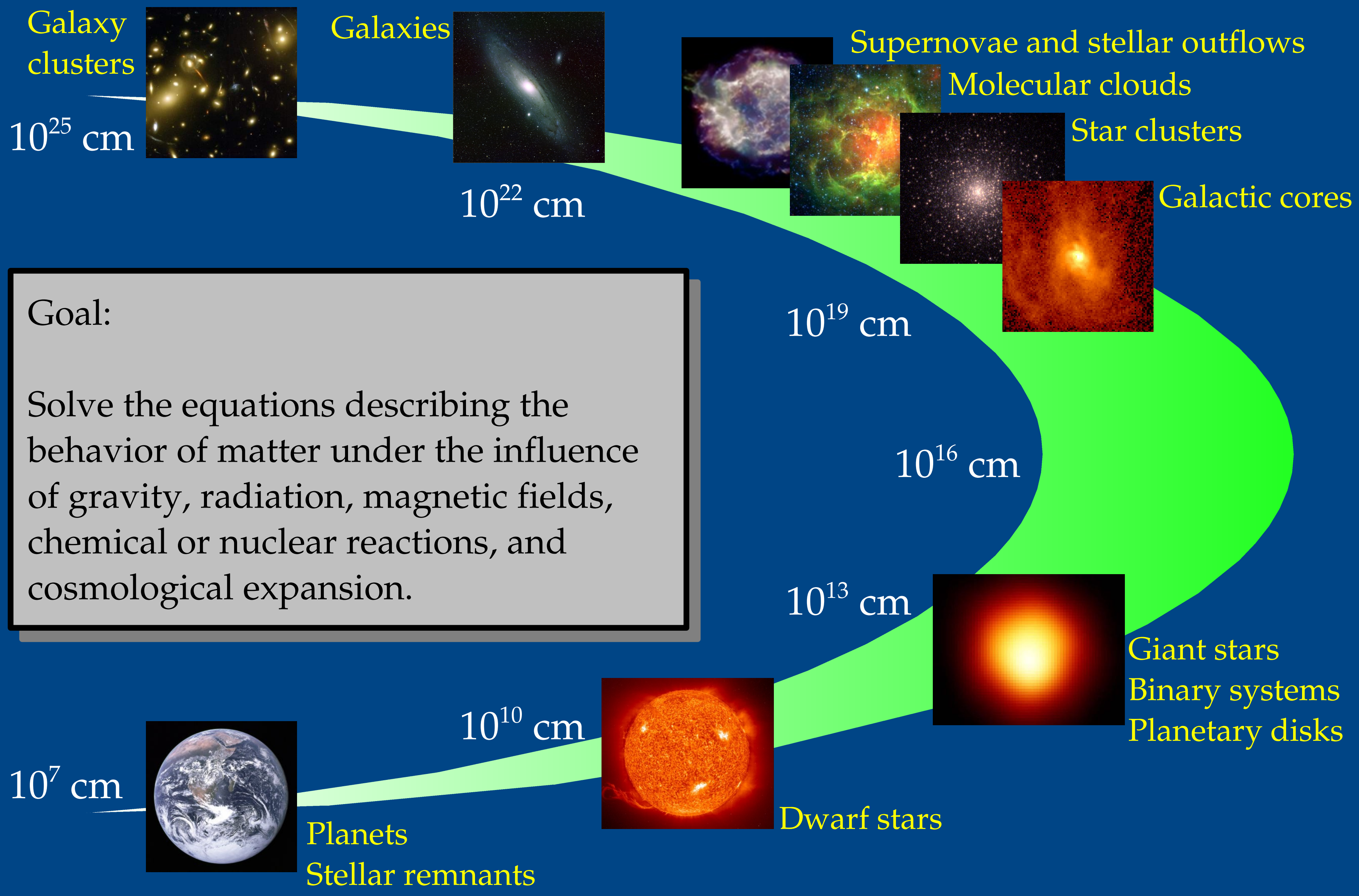
Scope of the problem



Goal:

Solve the equations describing the behavior of matter under the influence of gravity, radiation, magnetic fields, chemical or nuclear reactions, and cosmological expansion.

Physics: equations

- Hydrodynamics
  - Euler equations
  - Magnetohydrodynamics
  - Multifluid advection

$$\frac{\partial U}{\partial t} + \nabla \cdot \boldsymbol{F}(U) = 0$$

- Reactions
  - Coupled ODE

$$\frac{\partial U}{\partial t} + R(U) = 0$$

- Gravity
  - Poisson equation

$$\nabla^2 V = S(U)$$

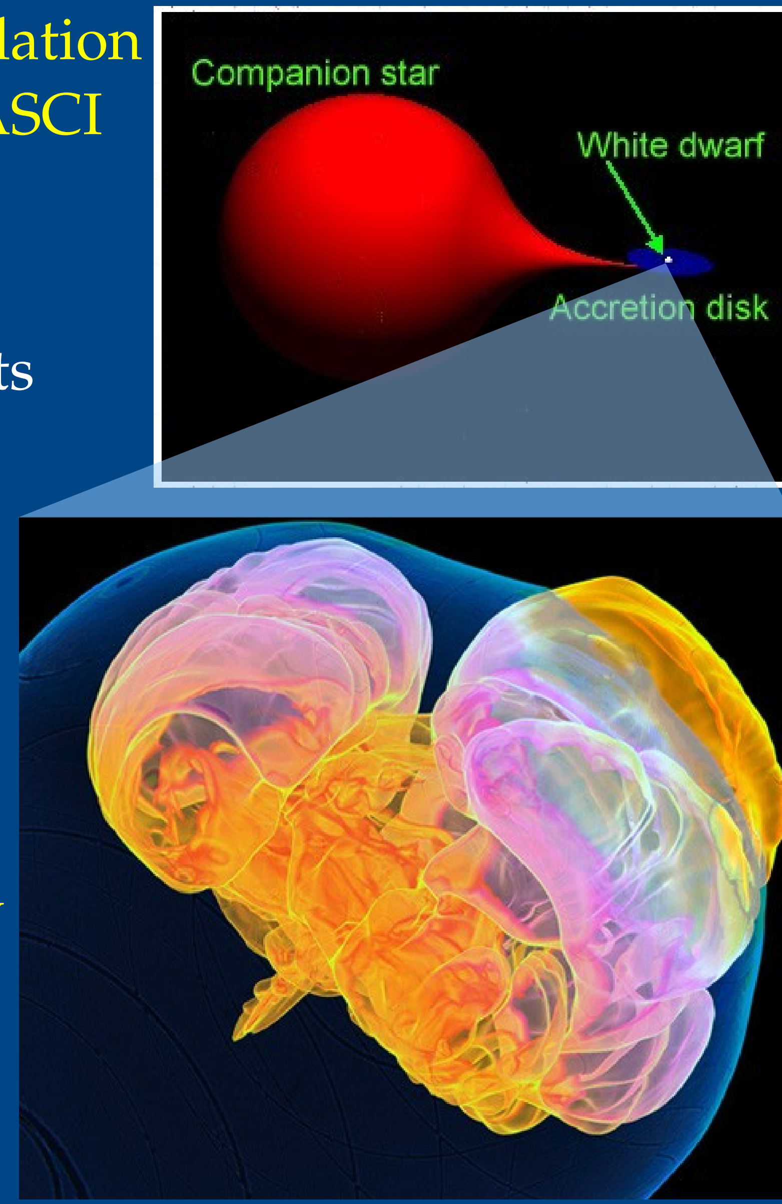
$$\frac{\partial U}{\partial t} + G(U, V) = 0$$

- Particles
  - Vlasov-Boltzmann equation

$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \nabla_x f + \boldsymbol{g} \cdot \nabla_v f = 0$$

FLASH

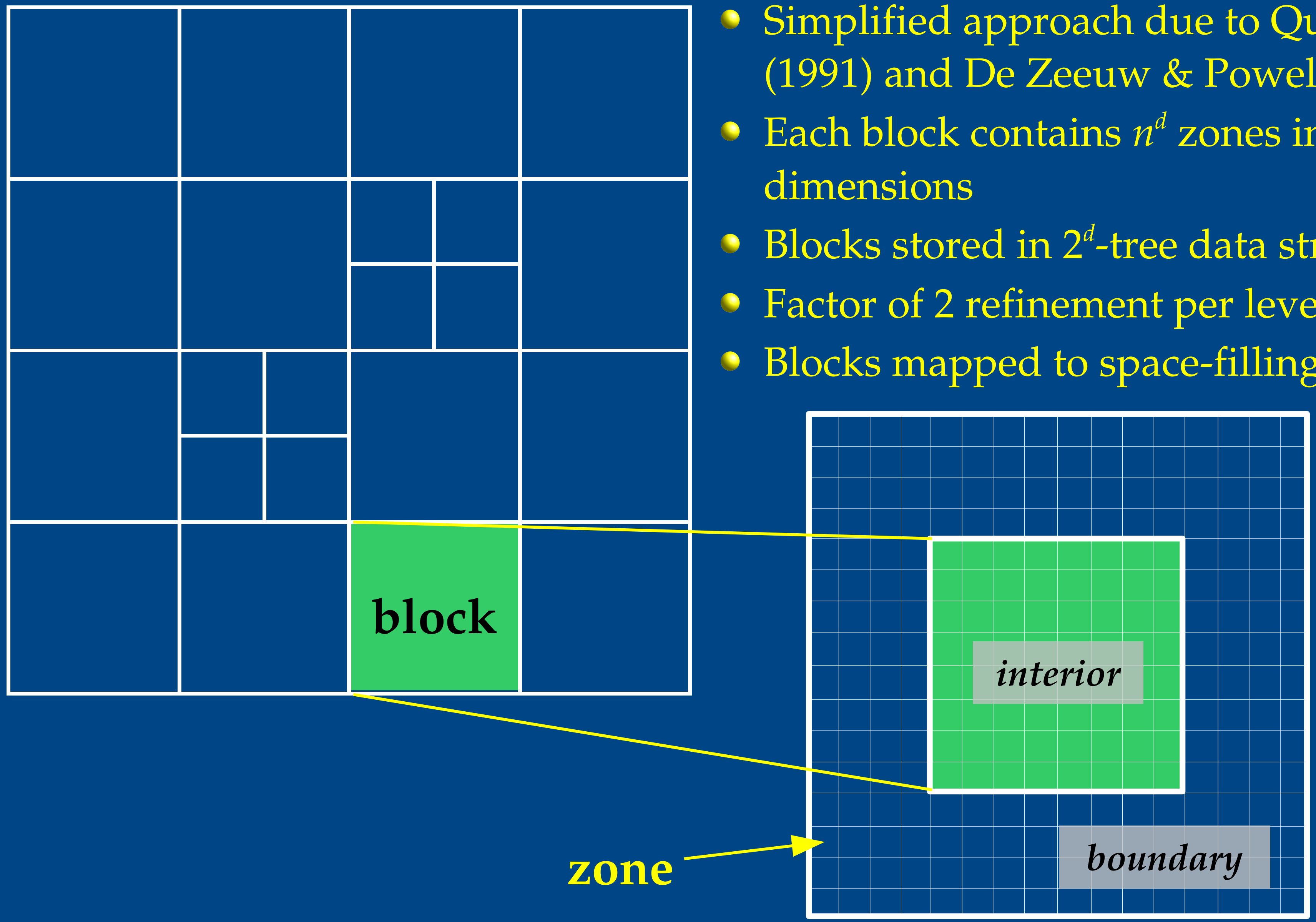
- Adaptive mesh refinement (AMR) simulation code originally developed under DOE ASCI program at the University of Chicago
- Original science targets
  - Type Ia supernovae, novae, X-ray bursts
- Code targets
  - Performance and scalability
  - Modularity and ease of use
  - Verification and validation
  - Portability
- Publicly available and used for a variety of problems
  - > 300 users (as of mid-2007)
  - > 250 refereed publications



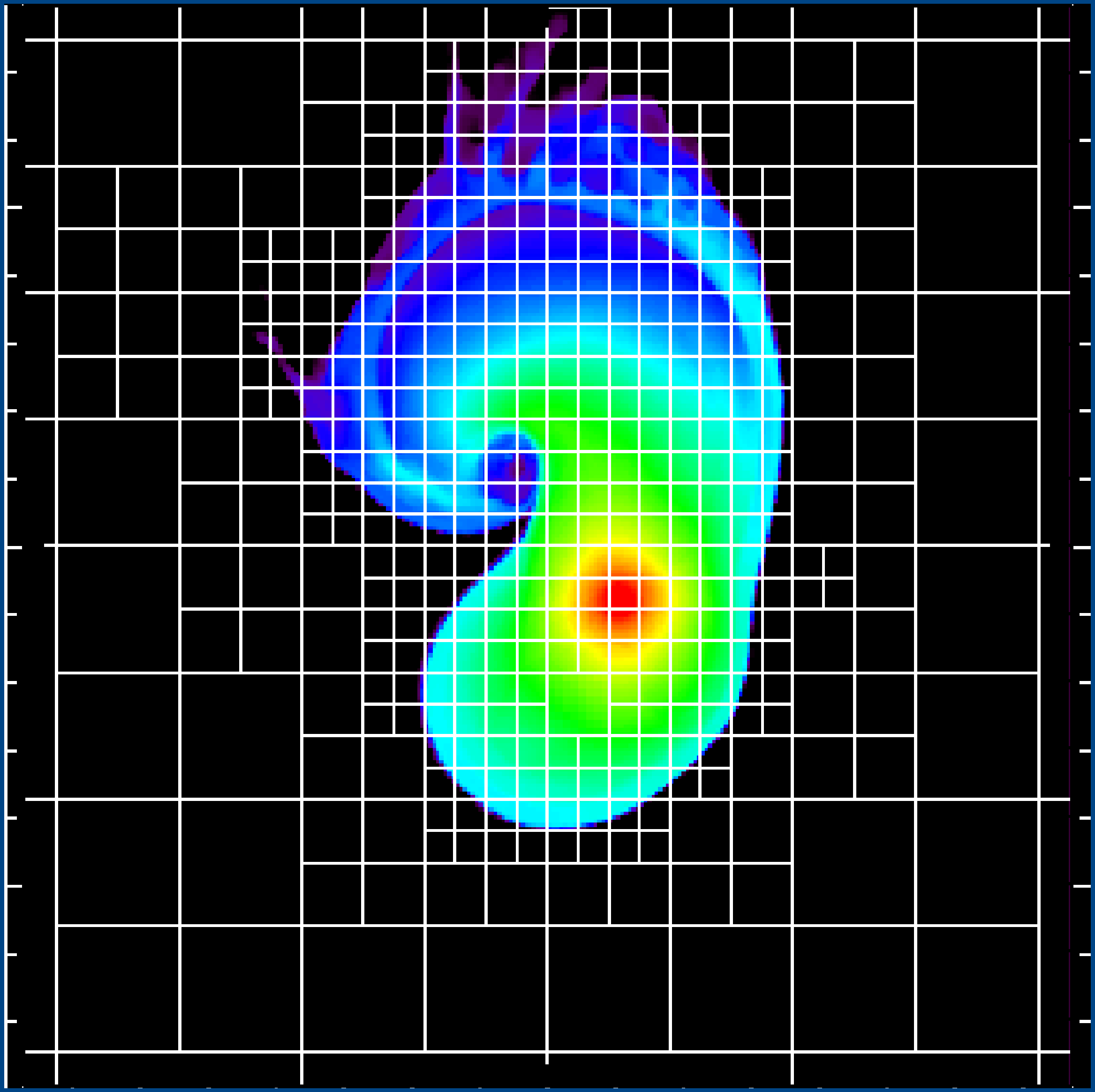
A. Calder (Stonybrook)

Adaptive mesh – PARAMESH library (MacNeice et al. 2000)

- Simplified approach due to Quirk (1991) and De Zeeuw & Powell (1993)
- Each block contains n^d zones in d dimensions
- Blocks stored in 2^d-tree data structure
- Factor of 2 refinement per level
- Blocks mapped to space-filling curve

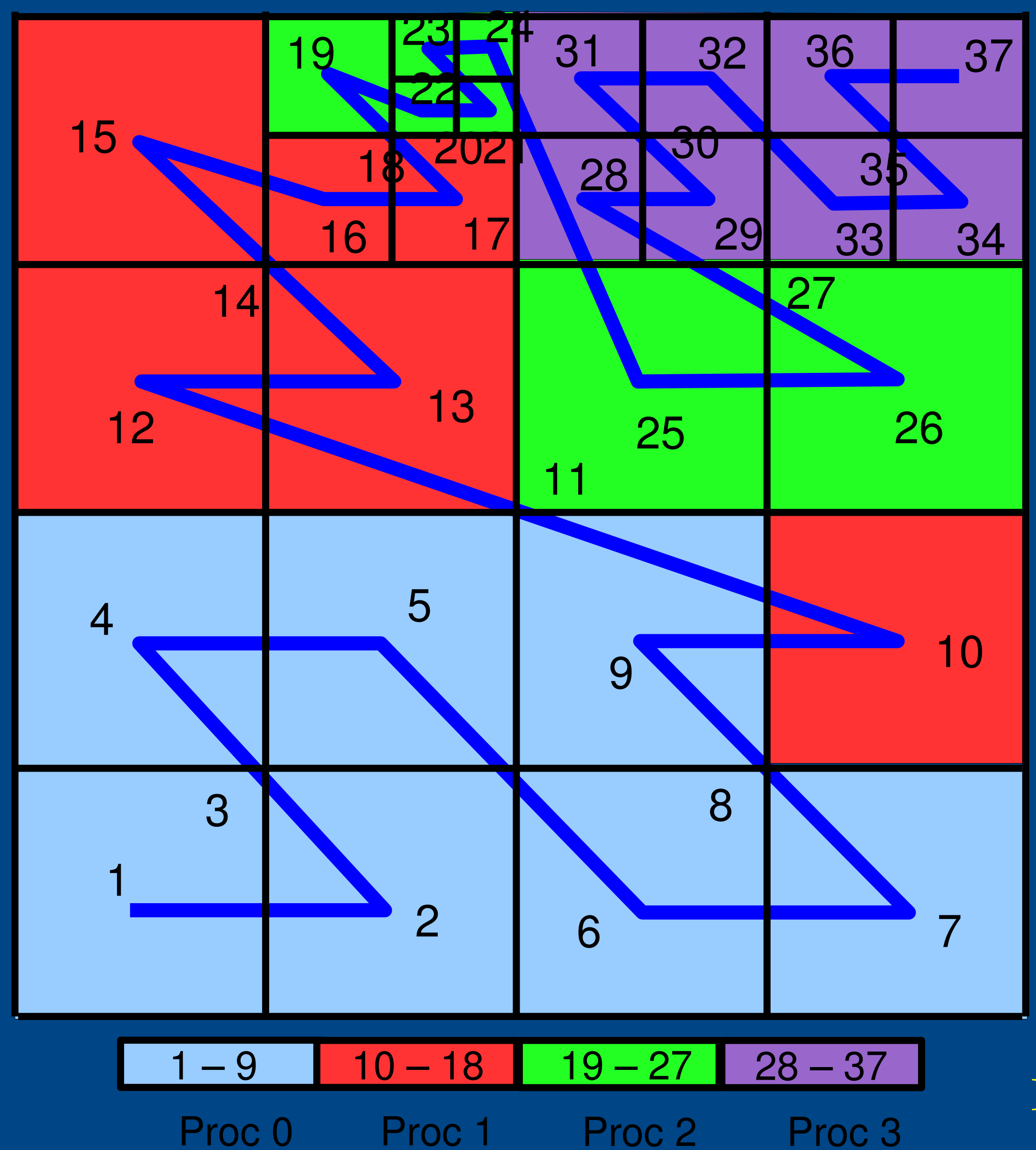


Example refinement pattern



Taam & Ricker (2004)

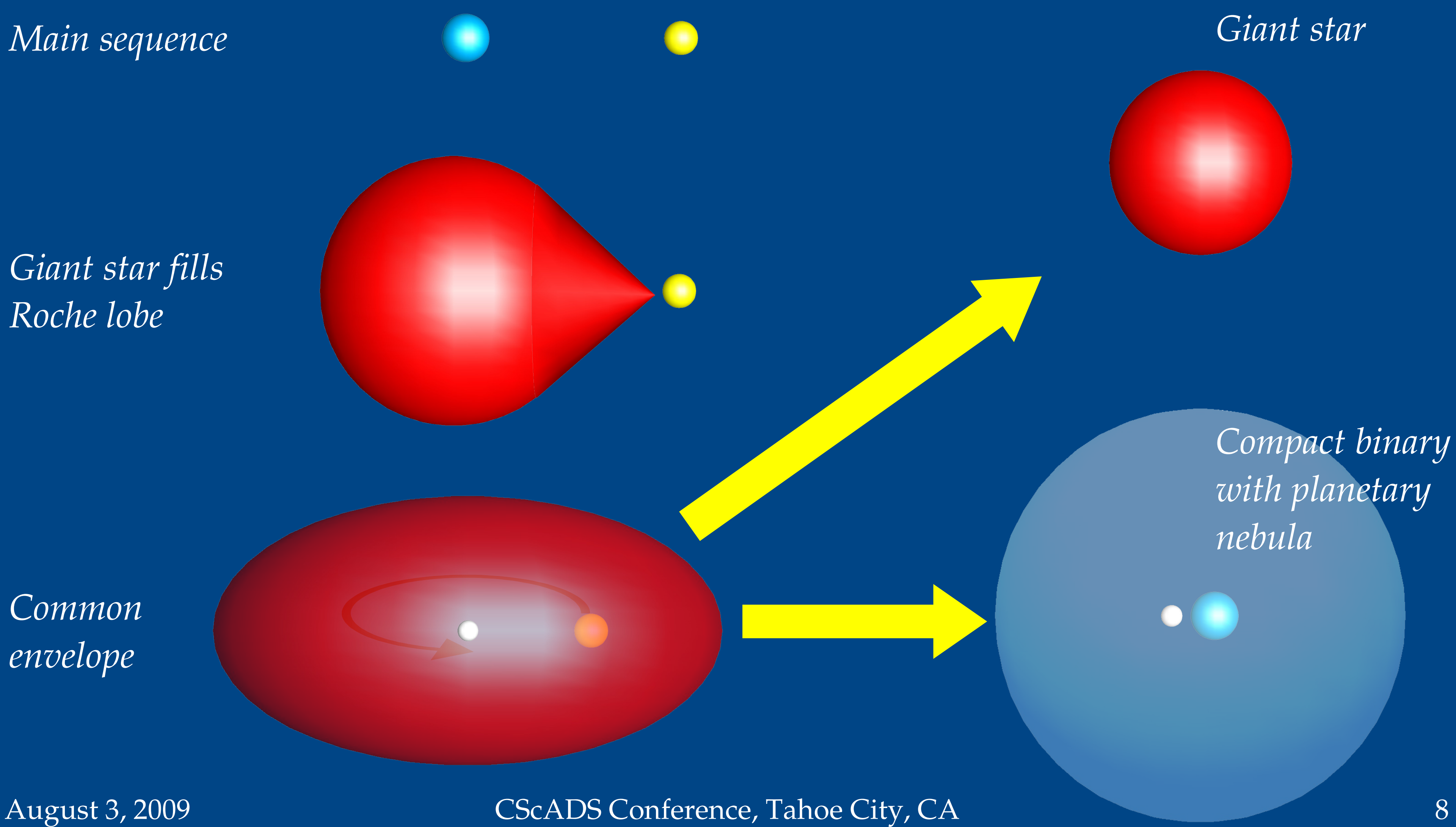
Adaptive mesh – load balancing



Fryxell et al. (2000)

Common envelope evolution

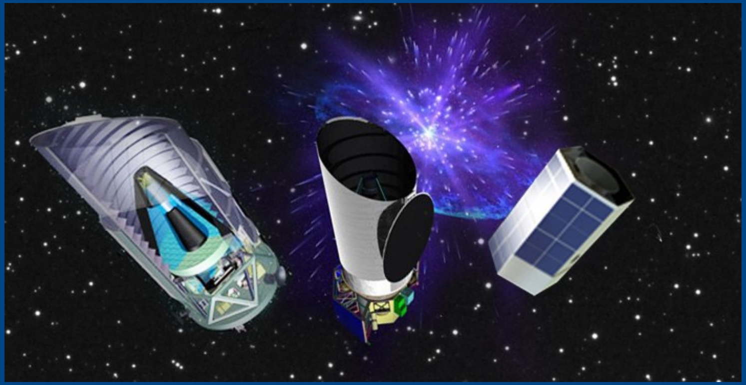
How to form low angular momentum binary stars with compact members?
Paczynski (1976): differentially rotating common envelopes



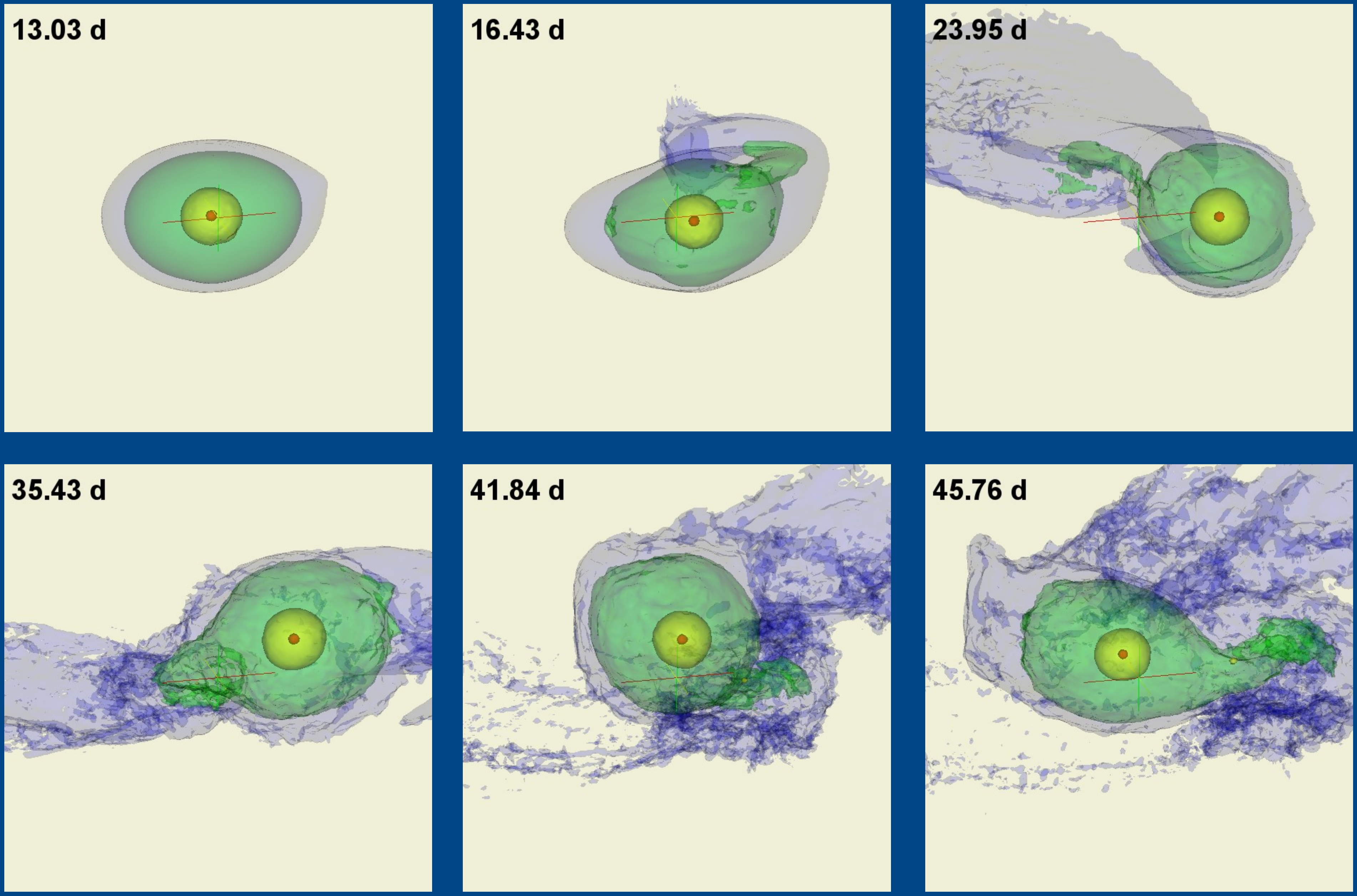
Observational drivers (close binary stars) – 2010 to 2020+

- Gravitational waves: *LIGO*
  - Number of gravitational wave-producing mergers of compact binaries depends on how many common-envelope systems survive as binaries

- Optical/IR: *Joint Dark Energy Mission*
  - Large survey of Type Ia supernova to probe accelerated expansion of Universe
  - Need to understand progenitors of these systems to characterize systematics

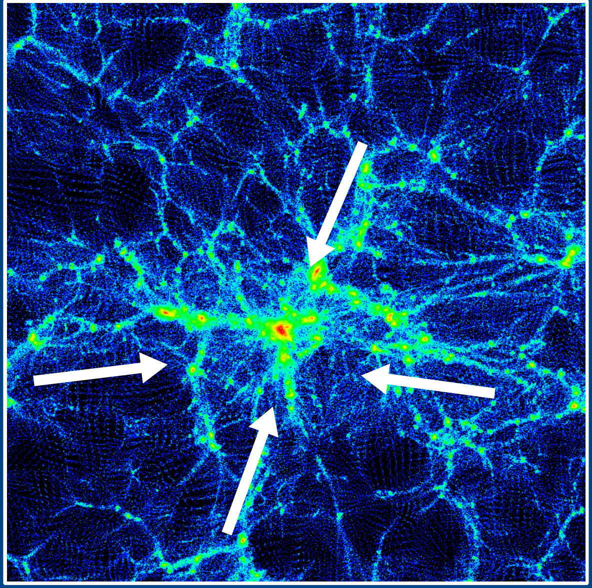


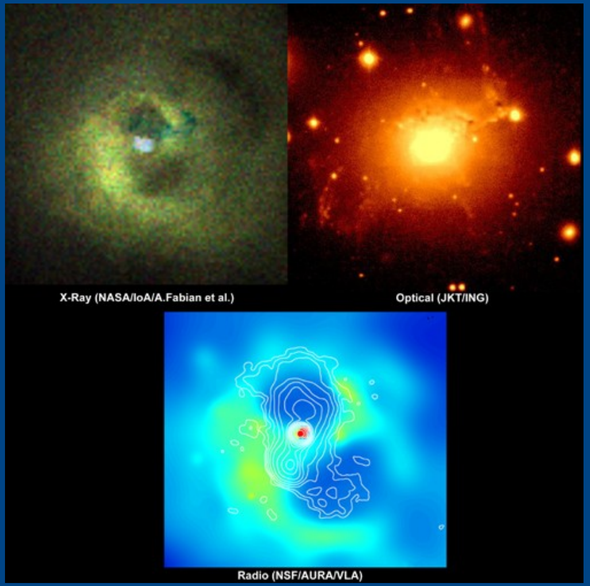
Red giant with degenerate core (Ricker & Taam 2008)



Galaxy cluster evolution

- What is a galaxy cluster?
  - 85% dark matter, 14% diffuse plasma, 1% galaxies
  - Form via gravitational instability
- Influences on structure
  - Merger-driven shock waves and turbulence
  - Collisionless relaxation of dark matter
  - Magnetic fields (collisionality and transport)
  - Radiative cooling
  - Jets and bubbles from active galaxies
  - Galaxy wakes

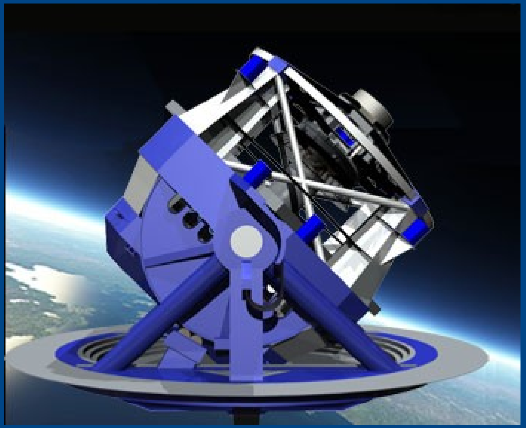


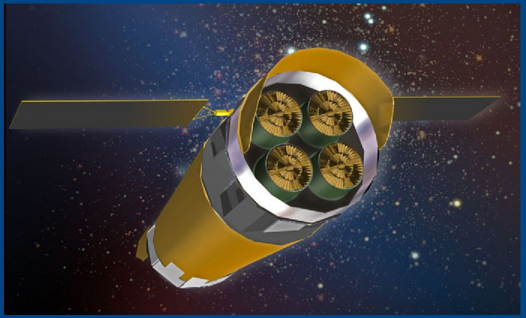


Perseus A (z = 0.018)

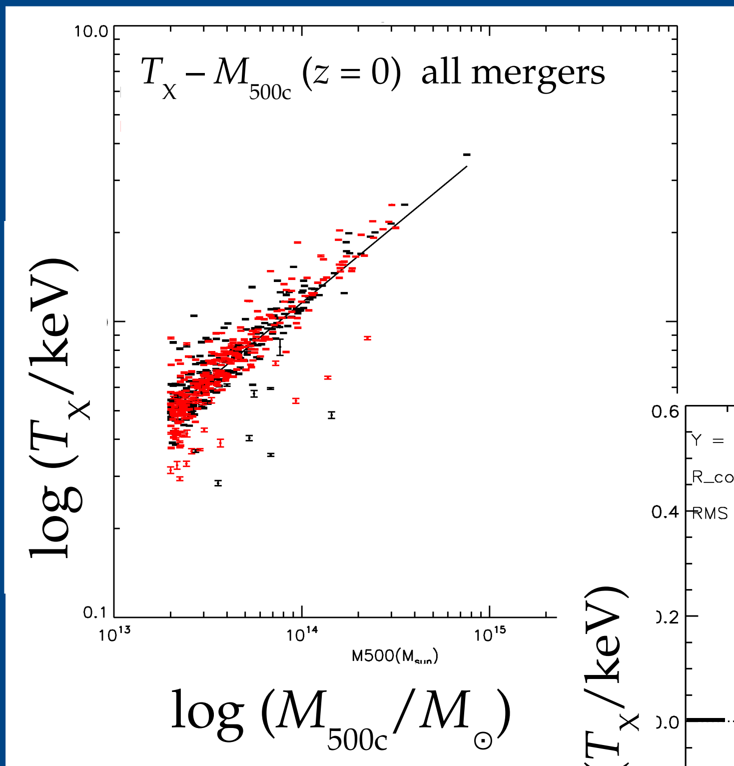
Observational drivers (cosmology) – 2010 to 2020+

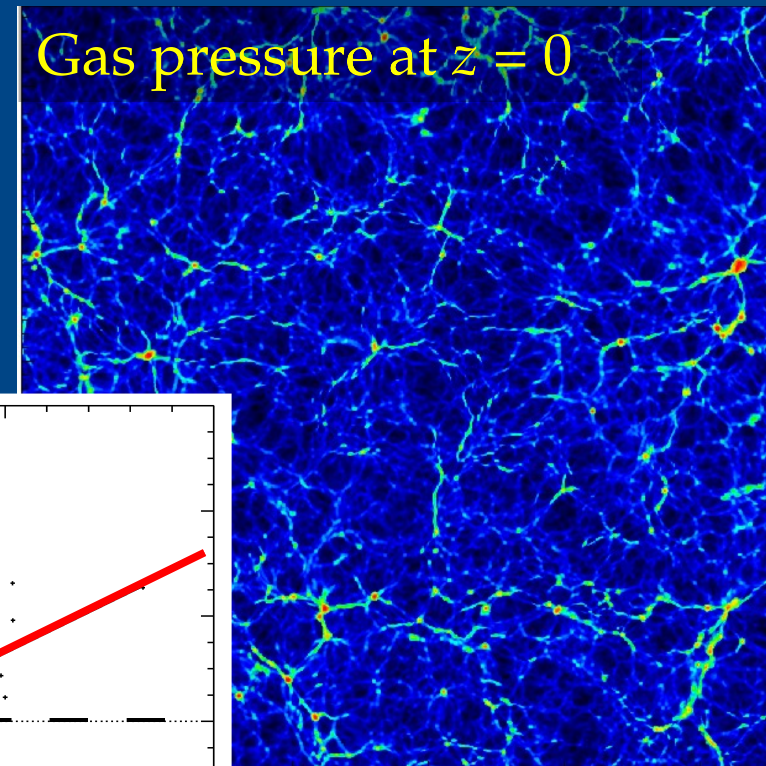
- Millimeter: *Atacama Large Millimeter Array*
  - Star formation and gas dynamics in galaxies up to high redshift
- Optical: *Large Synoptic Survey Telescope*
  - Huge optical galaxy samples to redshifts ~ 6
  - Sensitive imaging, variability, transient data
- Radio: *Square Kilometer Array*
  - Imaging of active galaxy bubbles and jets
  - 21 cm mapping of structure during Dark Ages
- X-ray: *International X-Ray Observatory*
  - High-resolution imaging and spectroscopy of active galaxies and galaxy clusters

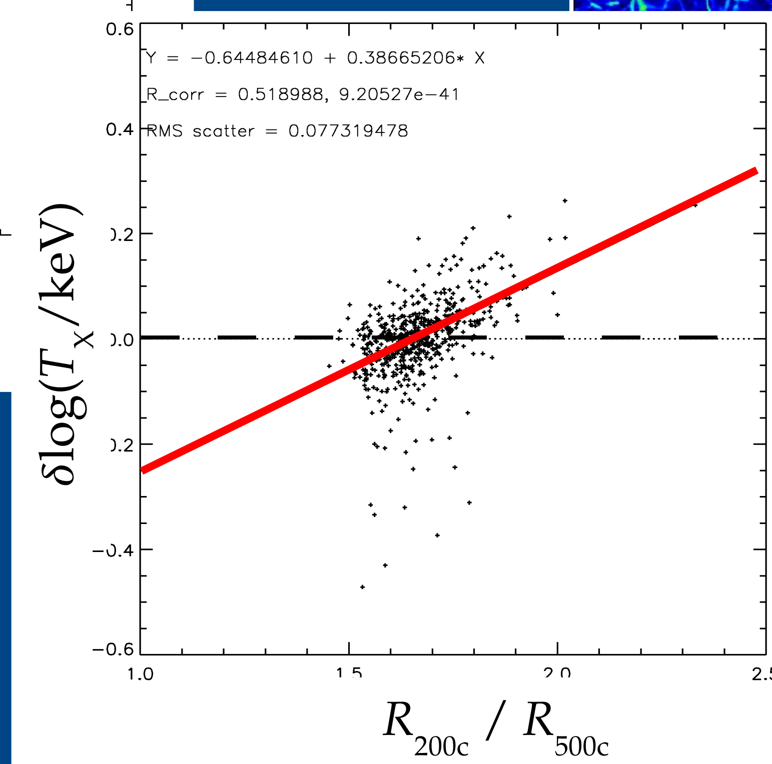




Mergers and mass-temperature scatter (Yang, Ricker, & Sutter 2009)







Conclusions

- Astrophysical problems are multi-physics, multi-scale
  - Drives us toward AMR and particle techniques
- Large multiwavelength observational datasets now the norm
  - Major emphasis on generating realistic simulated observations from simulation data
- Needs for simulation data analysis
  - Need for data management tools and frameworks
  - Analysis tools must be parallel and must be brought to the data
  - Some analysis (halo finding) needs to be done on-the-fly