The Center for Astrophysical Thermonuclear Flashes

Simulating Everything:
Galaxy Cluster Mergers in a Supercomputer

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Why Are Galaxy Clusters Interesting?

❑ **Fascinating objects!**

   ❑ Galaxies: star formation, supernovae, active galactic nuclei

   ❑ Intracluster medium: diffuse ($n \sim 10^{-4}$ -10^{-2} cm^{-3}), hot ($T \sim 10^7$-10^8 K), magnetized plasma emits X-rays

   ❑ Dark matter: collisionless particles that interact only by gravity comprise vast majority of the mass in clusters

❑ **Probes of cosmology**

   ❑ Can use distribution of cluster masses as a function of redshift to determine cosmological parameters

   ❑ Can determine cluster masses from "scaling relations" (mass-temperature, mass-luminosity, etc.) under the assumption of hydrostatic equilibrium


Abell 1689 (Credit: NASA)

Cluster Collisions and Mergers

- Cosmological structure formation proceeds in a "bottom-up" fashion
- There are thus lots of mergers!
- Why is it important to understand mergers?
  - Mergers reveal the different physical properties of the different components of the cluster, and may reveal new physics (e.g., properties of the dark matter)
  - Understanding the merging process and its effects on global cluster properties (temperature, luminosity, etc.) helps to calibrate and constrain cluster scaling relations and therefore improves the estimates of cosmological parameters
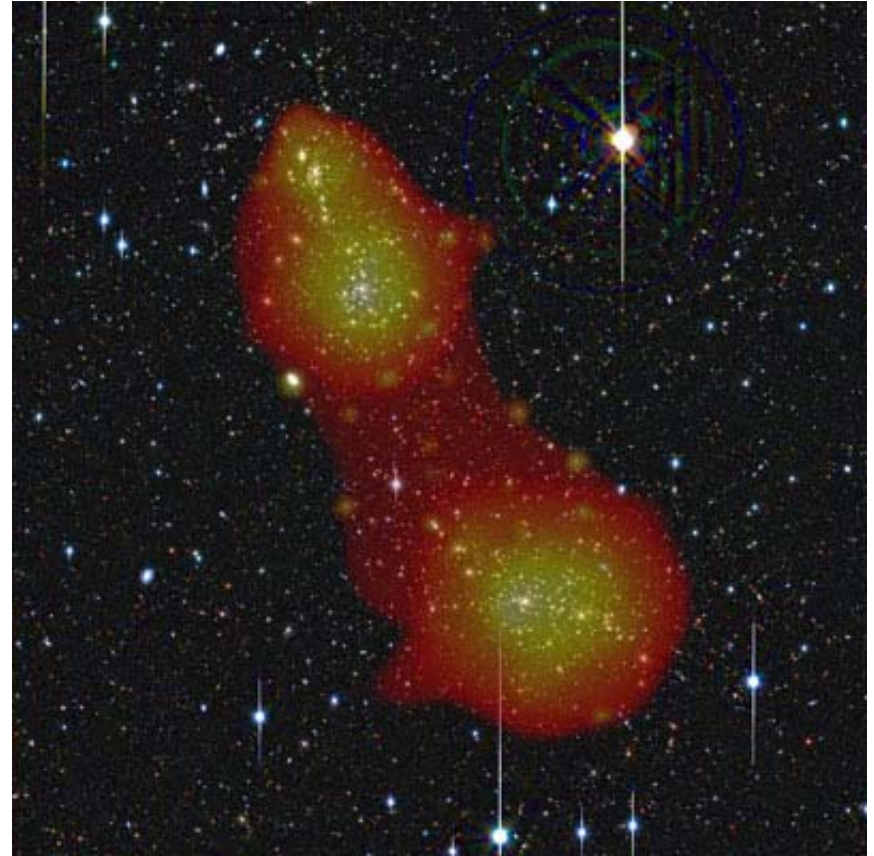
Abell 222 and Abell 223 (Credit: ESA)

Cluster Collisions and Mergers
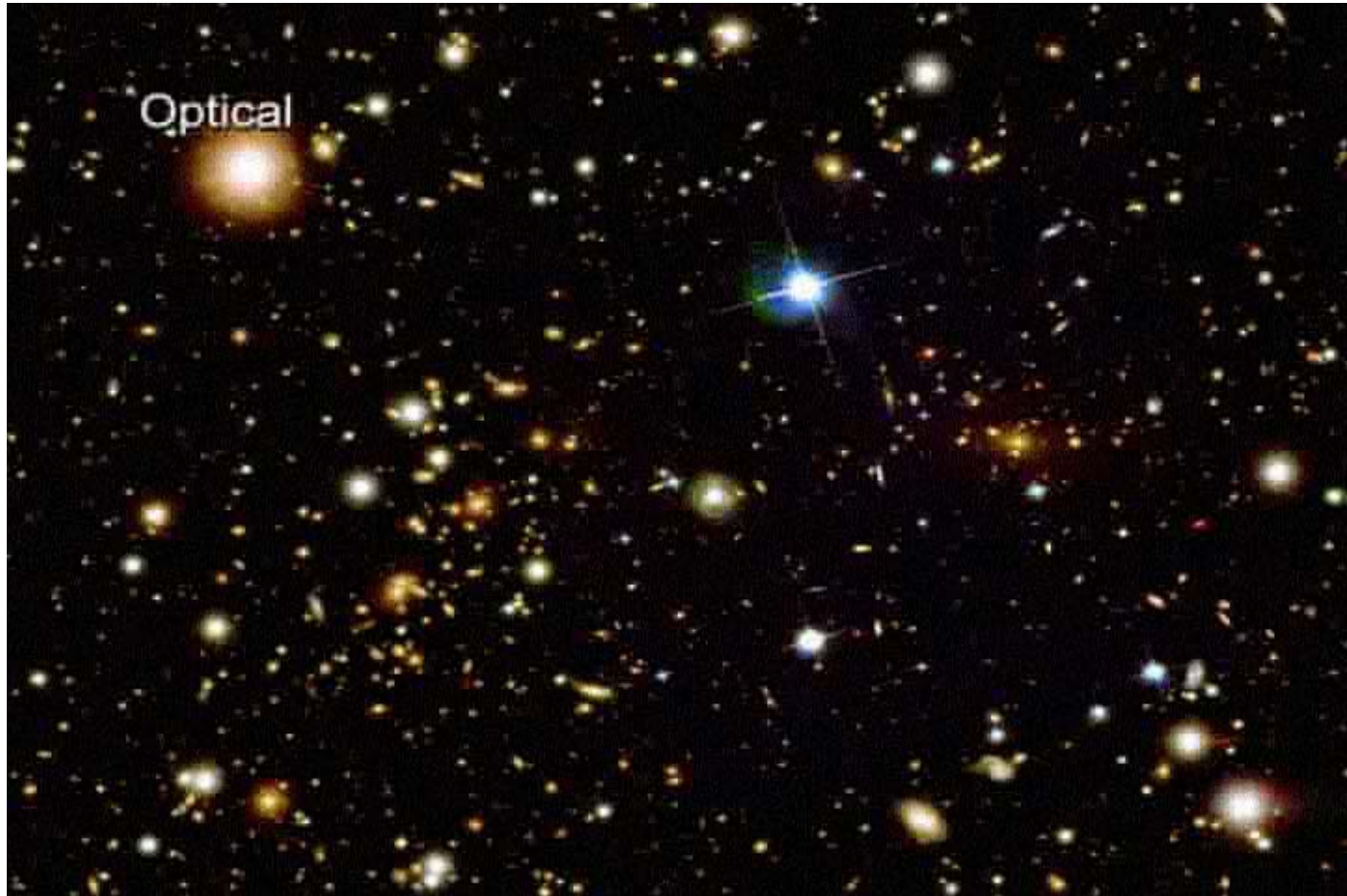
1E 0657-56, "The Bullet Cluster" (Credit: Chandra X-Ray Center)

Galaxy Cluster Cl 0024+17

- Galaxy Cluster Cl 0024+17
    - Rich cluster of galaxies at a redshift of z = 0.4 (~5 billion light-years away)
    - One of the best examples of gravitational lensing of distant galaxies by a cluster
- Indications of Two Clusters Colliding Along the Line of Sight?
    - Bimodal galaxy velocity distribution
    - Unusual mass profile derived from gravitational lensing
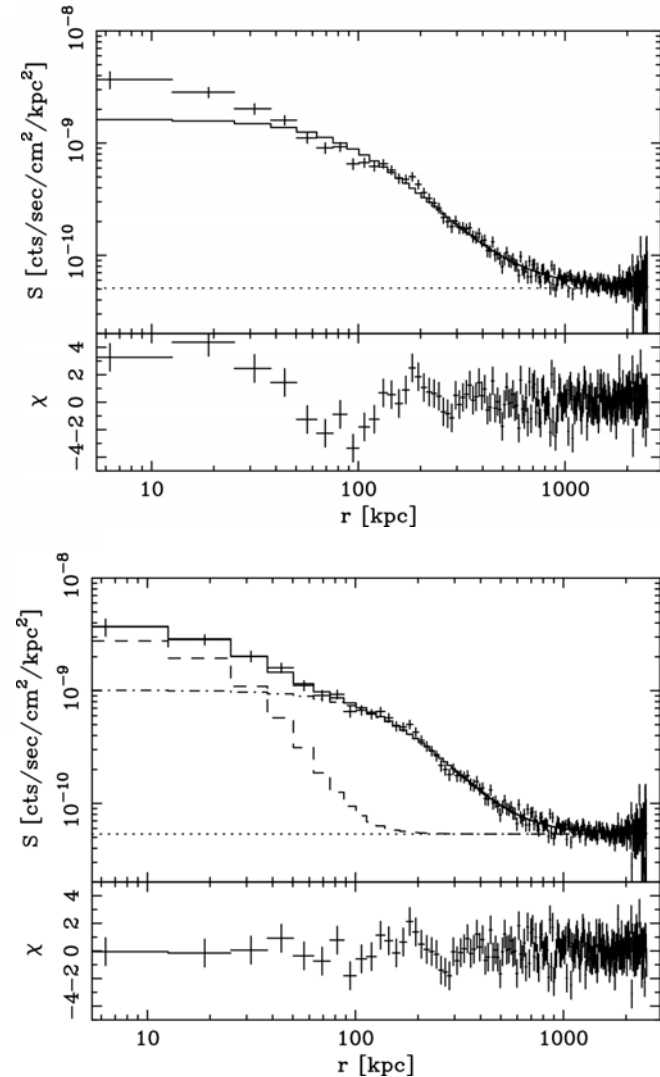   - X-ray surface brightness analysis indicates the existence of two components co-aligned along our line of sight
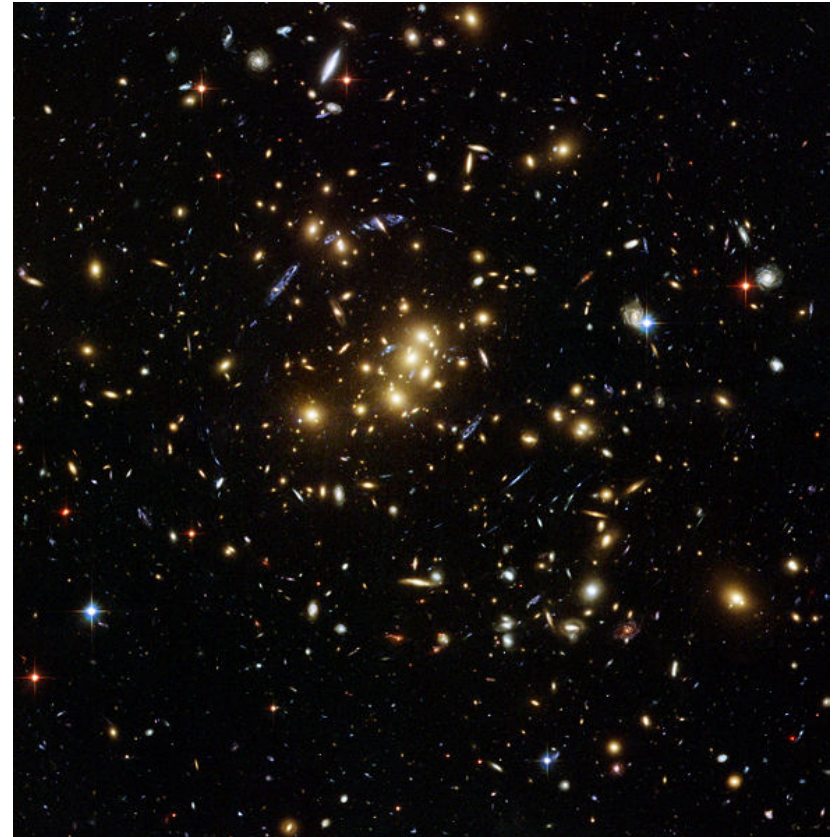
Credit: NASA
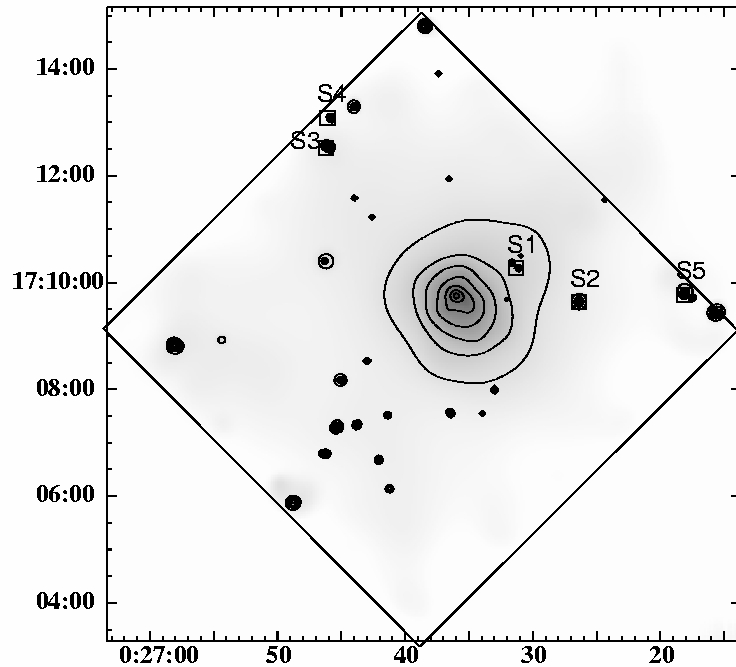
Ota et al. 2004

Questions Concerning Cl 0024+17

❑ Can we detect there are two clusters colliding along our line of sight, rather than just a single cluster?

❑ Assuming hydrostatic equilibrium, how accurate is the mass estimate assuming there is one cluster? Two clusters?

❑ What does this system tell us about whether we can detect there are two clusters colliding along our line of sight in other systems?

The FLASH Code

❑ FLASH: A highly capable, fully modular, extensible community code

❑ Essential components:

   ❑ Block-Structured Adaptive Mesh Refinement (PARAMESH library)

      ❑ Octree(s) of blocks make up the mesh

      ❑ Refine the mesh on built-in or user-specified criteria

      ❑ Can go to higher resolution using less memory and less time

   ❑ Eulerian Hydrodynamics

      ❑ Piecewise-Parabolic Method (PPM, Woodward & Colella 1984)

      ❑ Higher-order Godunov method

      ❑ Well-suited to capture sharp features like shocks and contact discontinuities

   ❑ *N*-body

      ❑ Particle-based systems, e.g. dark matter, stars, cosmic rays

      ❑ Map particles to mesh (particle mass to grid density)

      ❑ Map mesh to particles (grid forces to particle accelerations)

Simulating a Cluster Collision

- ❑ Physics Modules
  - ❑ Massive particles representing dark matter
  - ❑ PPM solver for hydrodynamics
  - ❑ Ideal gamma-law equation of state with $\gamma = 5/3$
  - ❑ Multigrid solver for gravitational potential (Ricker 2008)
- ❑ Initial Conditions
  - ❑ 2:1 mass ratio, $M_1 = 6 \times 10^{14}$ M$_\odot$, $M_2 = 3 \times 10^{14}$ M$_\odot$
  - ❑ Relative velocity: $v_{rel} = 3000$ km/s, derived from redshift data
  - ❑ Ratio of gas mass to total mass: $f_{gas} = 0.12$
  - ❑ Temperature profile derived assuming hydrostatic equilibrium
- ❑ Simulation Parameters
  - ❑ ~3 million particles
  - ❑ Refine mesh on sharp features in fluid and on matter density
  - ❑ Box size: $L = 10h^{-1}$ Mpc
  - ❑ Finest AMR resolution: $\Delta x = 9.77h^{-1}$ kpc

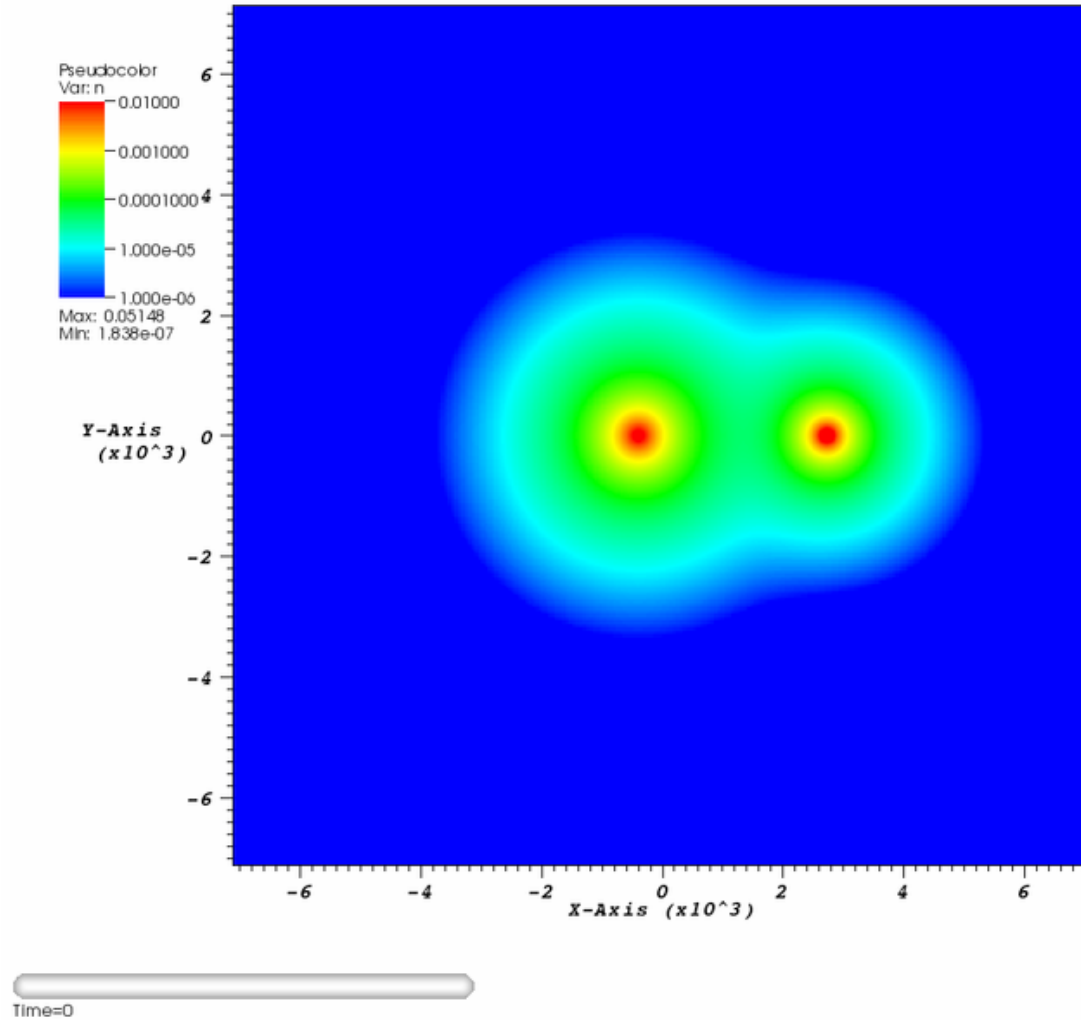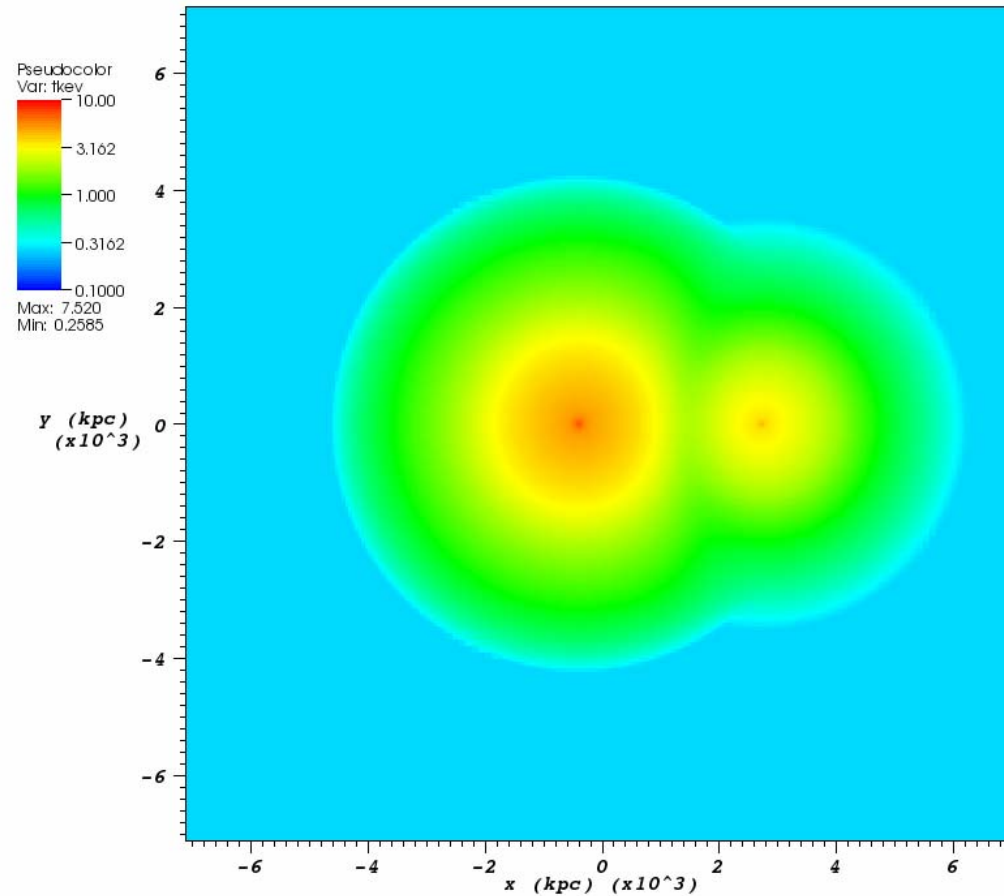# Dark Matter Density (M$_\odot$ kpc^{-3})
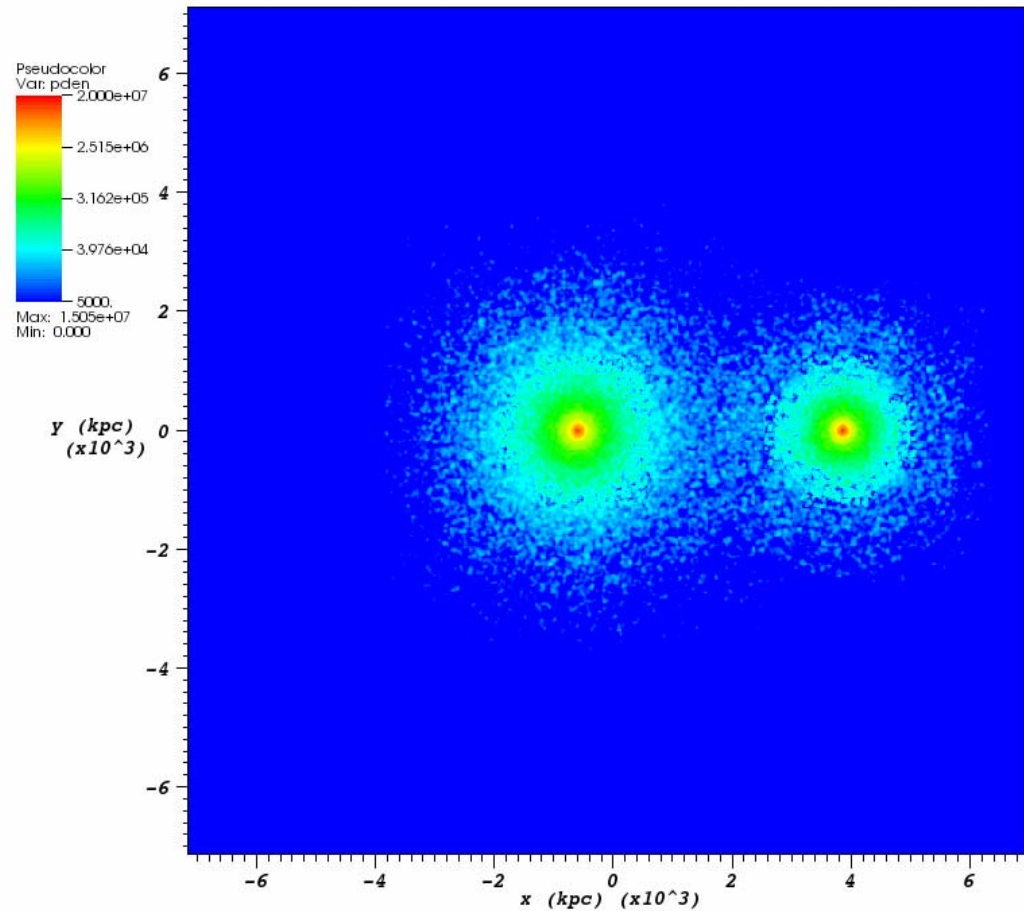
Gas Density (cm^{-3})

Gas Temperature (keV)

Comparing Simulations and Observations

❑ Observations of galaxy clusters don't give us physical quantities directly, as in simulations; all of our information comes from photons

❑ Physical quantities like density, temperature, and metallicity must be *derived* from fitting the spatial and energy distributions of photons to physically motivated models

❑ The information we are able to get from observations depends heavily on our instrument:

  ❑ Resolution of the detector(s) (both in position and energy space)

  ❑ Exposure time (how long can we observe?)

  ❑ Ability to account for and model extraneous influences

❑ Creating synthetic X-ray observations of simulated cluster collisions helps to determine what information we can get, and therefore what scientific questions we can answer, from the observations

Simulating X-Ray Observations

- Chandra X-Ray Telescope
    - Launched by NASA in 1999
    - Has observed planets, compact objects, supernovae, galaxies, and galaxy clusters
    - High resolution CCDs (0.5 seconds of arc on the sky per pixel)
- MARX
    - Simulates on-orbit performance of Chandra
        - Mirror, detectors, gratings
        - Quantum efficiency, aspect motion
    - Variety of models
        - Point sources, disk models, cluster models
   - User-generated models

Credit: Chandra X-Ray Center

Verification Study

□ **Is our procedure for generating synthetic observations correct?**

-- reproduce simple test cases:

  □ Case 1: Isothermal, "β-model" cluster

  □ Case 2: Two isothermal β-model clusters

□ **Is our procedure for fitting to the synthetic observations correct?**
-- check that our fitting procedure recovers X-ray radial surface brightness distribution and gas temperature
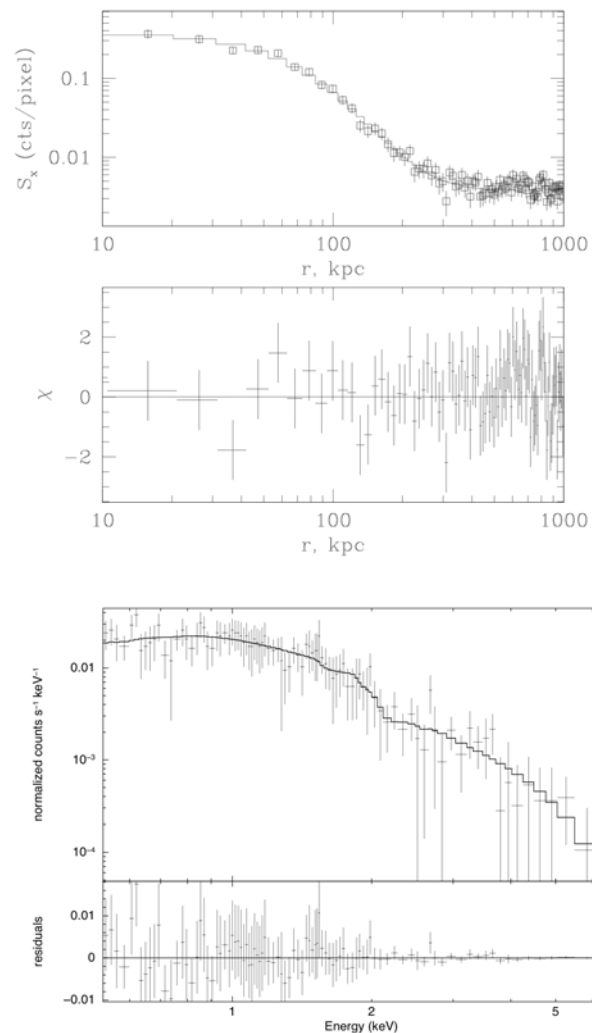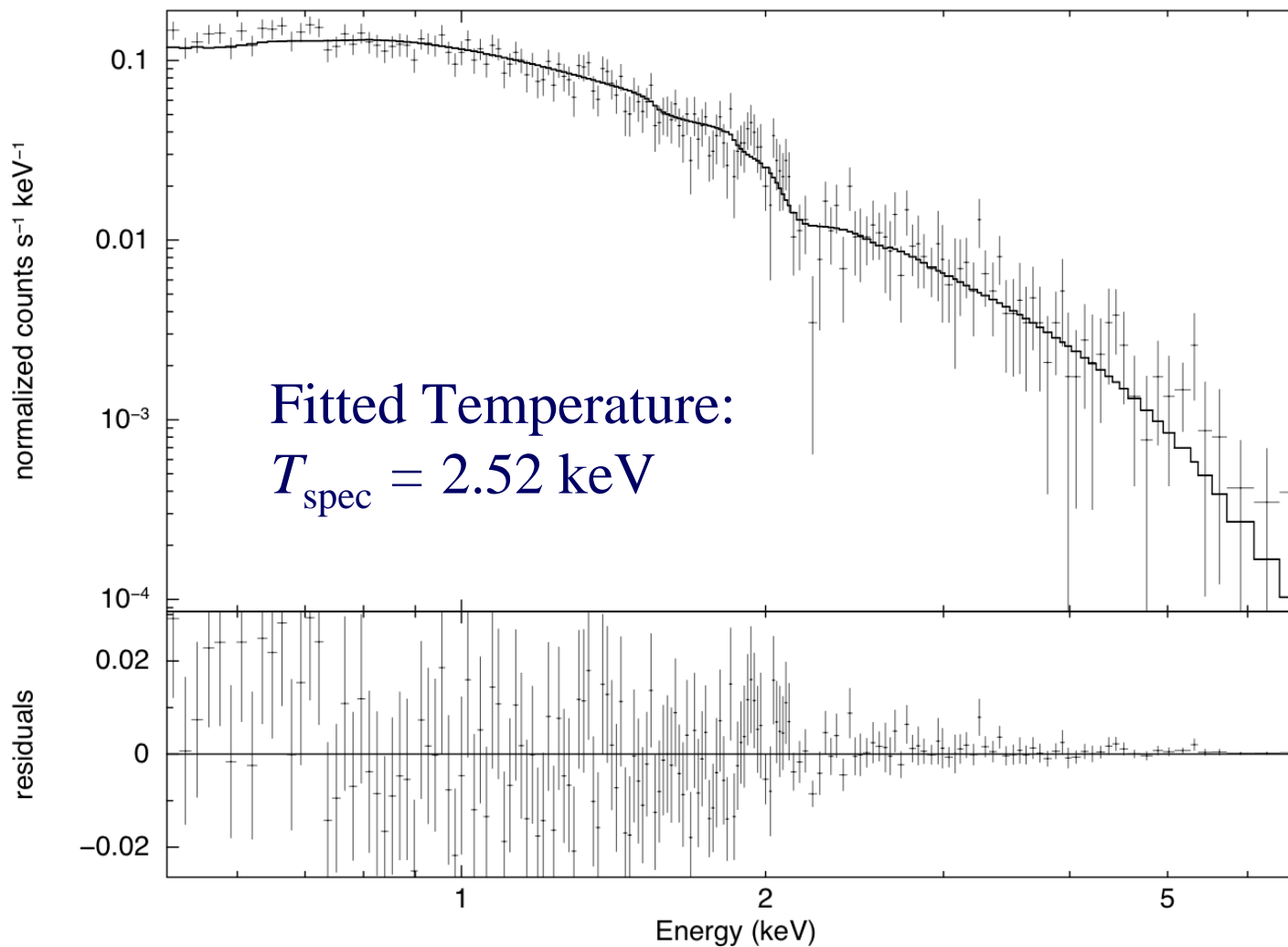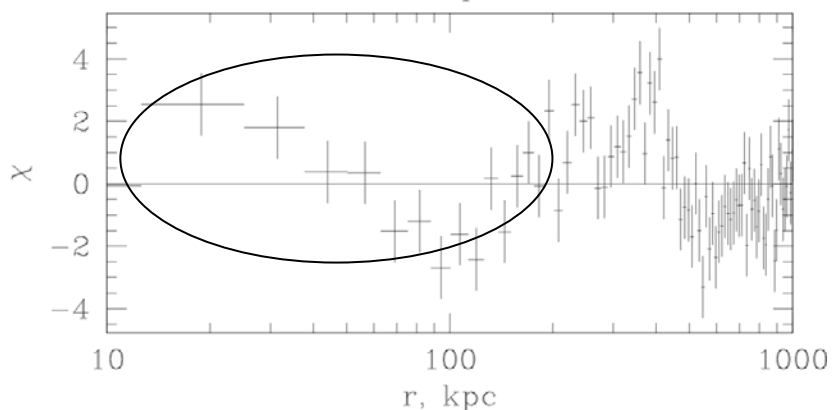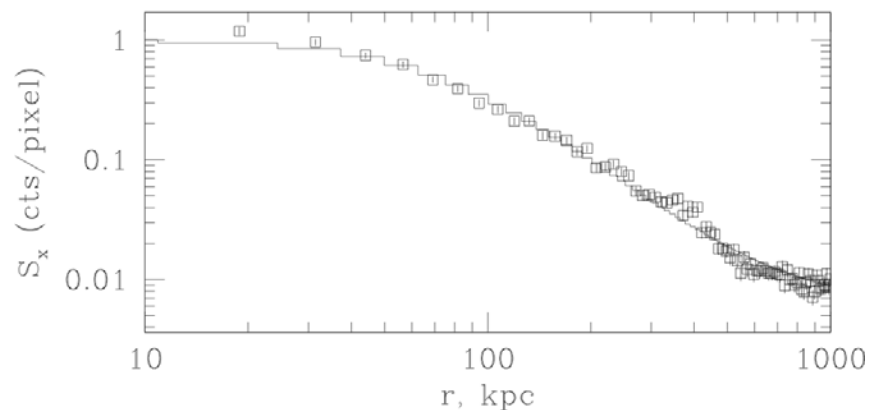
Simulated Chandra X-Ray Image

100 kpc
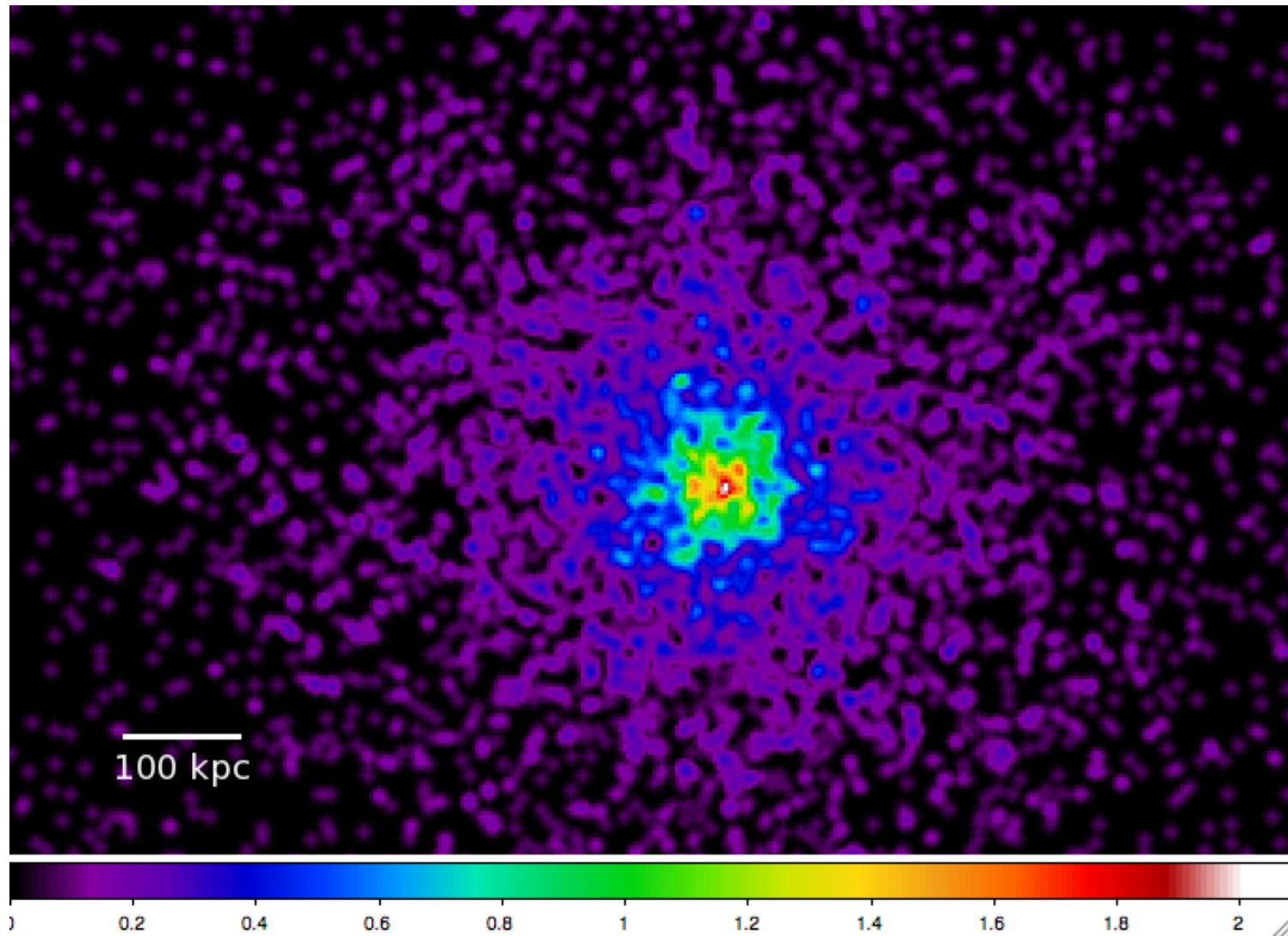
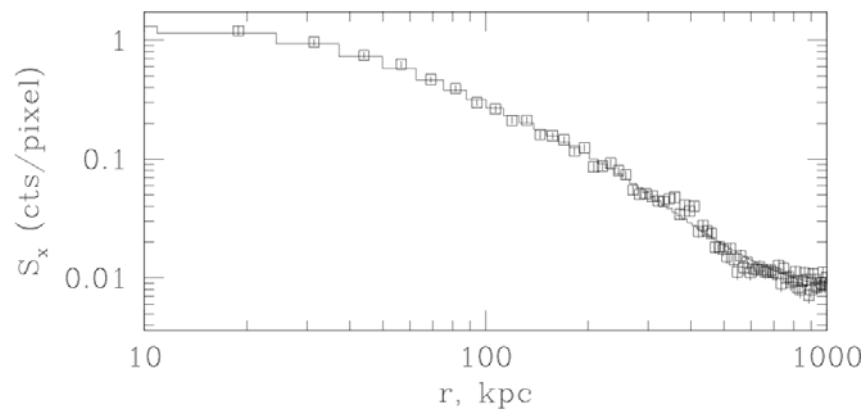# Simulated X-Ray Spectrum
and Best-Fit Model

Fitted Temperature:
$T_{\text{spec}} = 2.52$ keV

Simulated Surface Brightness Profiles and Best-Fit Models
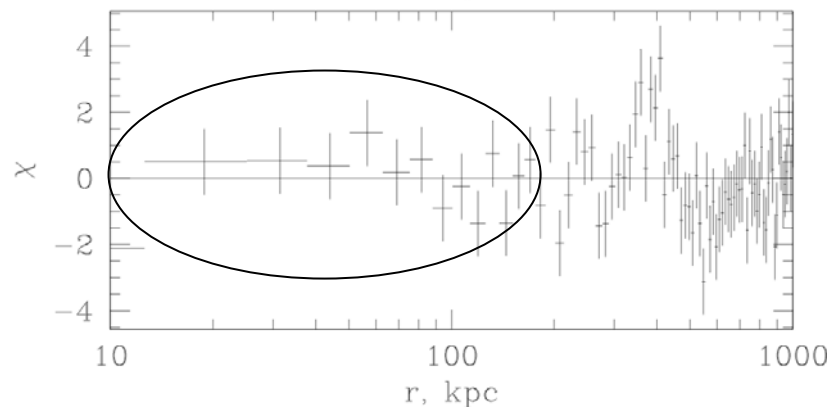
Significant improvement in χ^2!

Implications for Cosmology

- ❑ X-ray surveys of large areas of the sky look for galaxy clusters at a wide range of redshifts (distances) to determine the cluster mass function and constrain cosmological parameters

- ❑ Colliding clusters mis-identified as a single cluster give an incorrect mass estimate and therefore incorrect cosmological parameters;

- ❑ Is it possible to detect there are two colliding clusters aligned along the line of sight, rather than a single cluster?

- ❑ In X-ray surveys, the exposure time for each area is much shorter than in observations of a single galaxy cluster, which makes doing this more difficult

- ❑ Even so, we find it is possible to detect two clusters colliding along the line of sight out to a redshift $z \sim 1$ by fitting single cluster and two cluster models to the X-ray surface brightness distribution and using the likelihood ratio test

- ❑ Therefore, it may be possible to remove this systematic effect in determining the masses of clusters, and so improve the accuracy with which X-ray cluster surveys can determine cosmological parameters

Conclusions

❑ Comparing simulations of galaxy cluster collisions and high-quality observations is essential to validating the simulations and improving our understanding of these astrophysical objects

❑ Bridging the gap: synthetic X-ray observations of a simulated galaxy cluster collision

❑ Implications for Cl 0024+17:

  ❑ Statistical analysis of the X-ray surface brightness profile indicates that two clusters are colliding along the line of sight

  ❑ Even shortly after the collision, an estimate of the cluster mass based on the assumption of hydrostatic equilibrium can be made that is accurate to within ~10% if a two-cluster model is used

  ❑ Even for short exposure times and clusters at high redshifts, it may be possible to detect the existence of two clusters colliding along the line of sight, removing an important systematic error in the use of X-ray cluster surveys to determine cosmological parameters

Acknowledgements

❑ Don Lamb (advisor)

❑ ASC FLASH Center team

    ❑ http://flash.uchicago.edu/

❑ Collaborators at the University of Illinois at Urbana-Champaign:

    ❑ Paul Ricker

    ❑ Karen Yang (developed synthetic X-ray pipeline)

    ❑ http://www.astro.uiuc.edu/~pmricker/research/codes/flashcosmo/

❑ Practicum Advisor: Bronson Messer

❑ Krell Institute and DOE

THANKS!