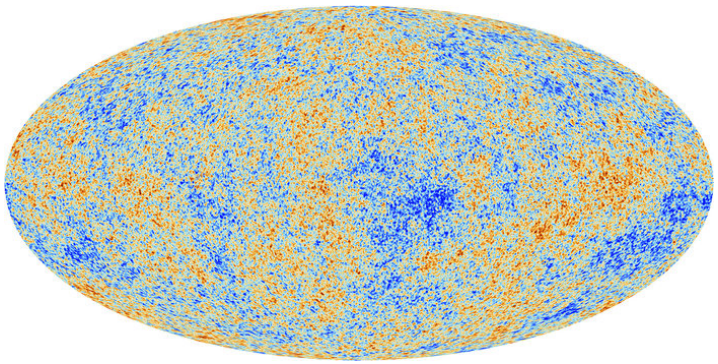
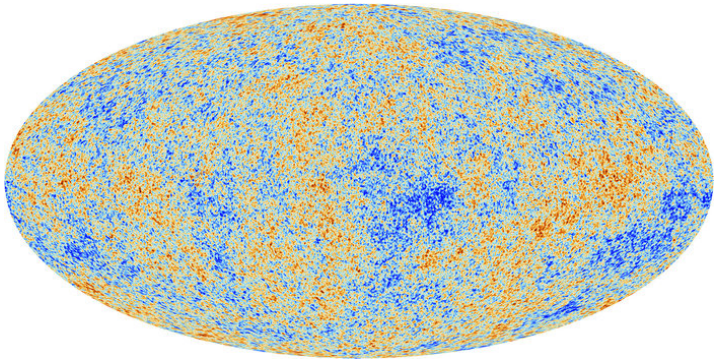
Cosmological structure formation



ESA/Planck Collaboration (2013)

- small fluctuations in cosmic microwave background are initial conditions for structure formation

Cosmological structure formation



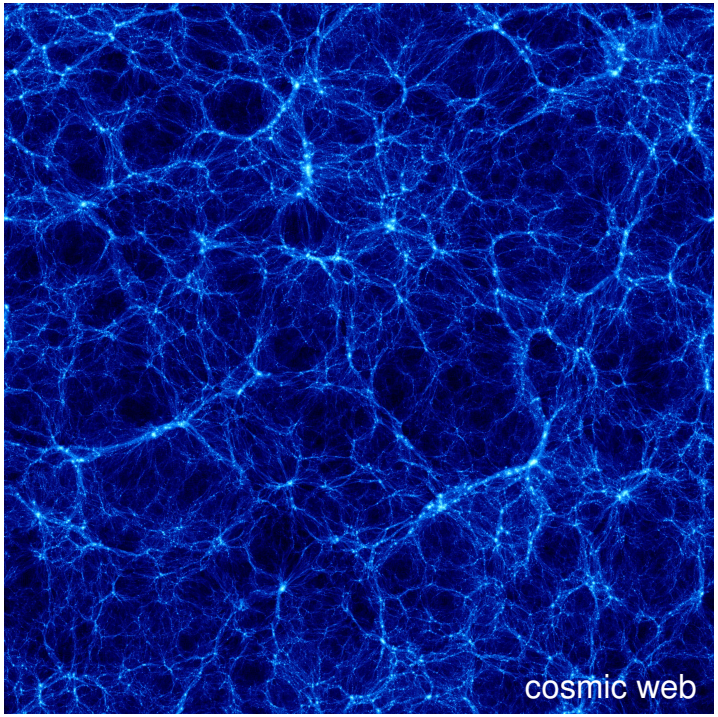
ESA/Planck Collaboration (2013)

dropping pebbles into the pond generates expanding waves that interfere with each other

- small fluctuations in cosmic microwave background are initial conditions for structure formation
- galaxies and clusters form at sites of constructive interference of those primordial waves

AIP

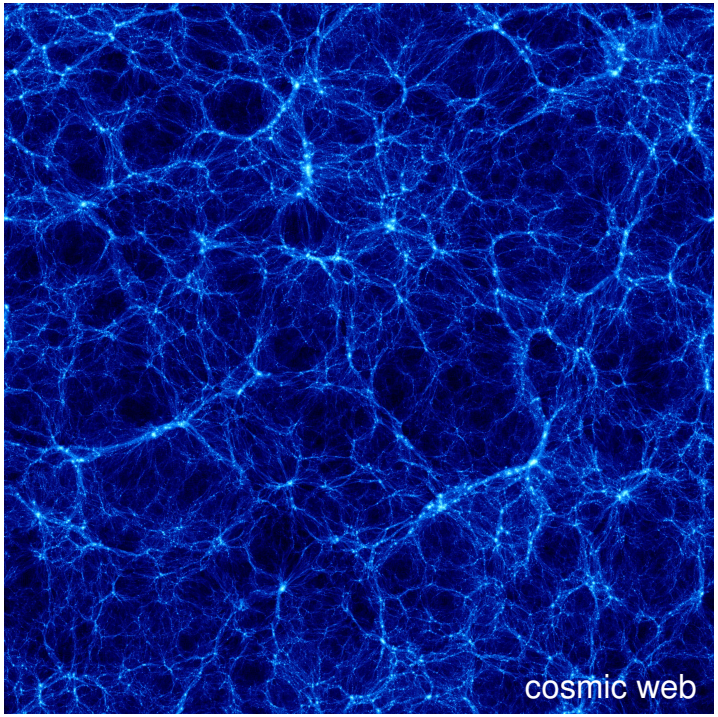
Cosmological structure formation



- small fluctuations in cosmic microwave background are initial conditions for structure formation
- galaxies and clusters form at sites of constructive interference of those primordial waves
- cosmic matter assembles in the "cosmic web" through gravitational instability
- galaxies form as "beats on a string" along the cosmic filaments
- galaxy clusters form at the knots of the cosmic web by mergers of galaxies and galaxy groups

AIP

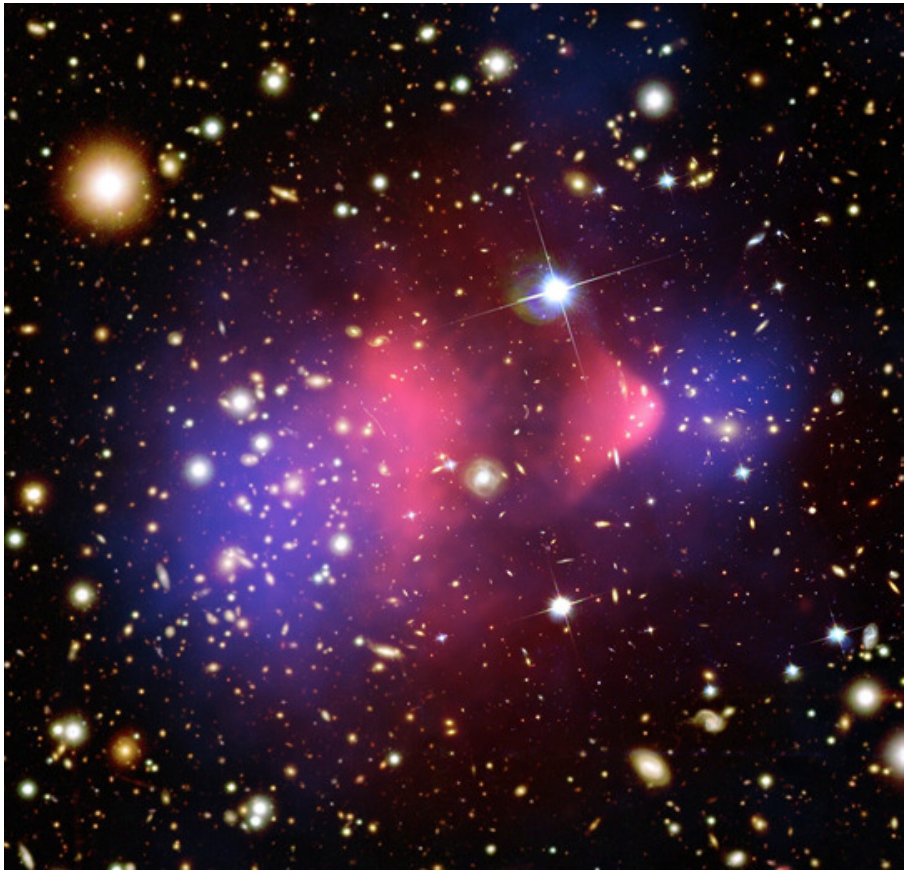
Cosmological structure formation



- small fluctuations in cosmic microwave background are initial conditions for structure formation
- galaxies and clusters form at sites of constructive interference of those primordial waves
- cosmic matter assembles in the "cosmic web" through gravitational instability
- galaxies form as "beats on a string" along the cosmic filaments
- galaxy clusters form at the knots of the cosmic web by mergers of galaxies and galaxy groups

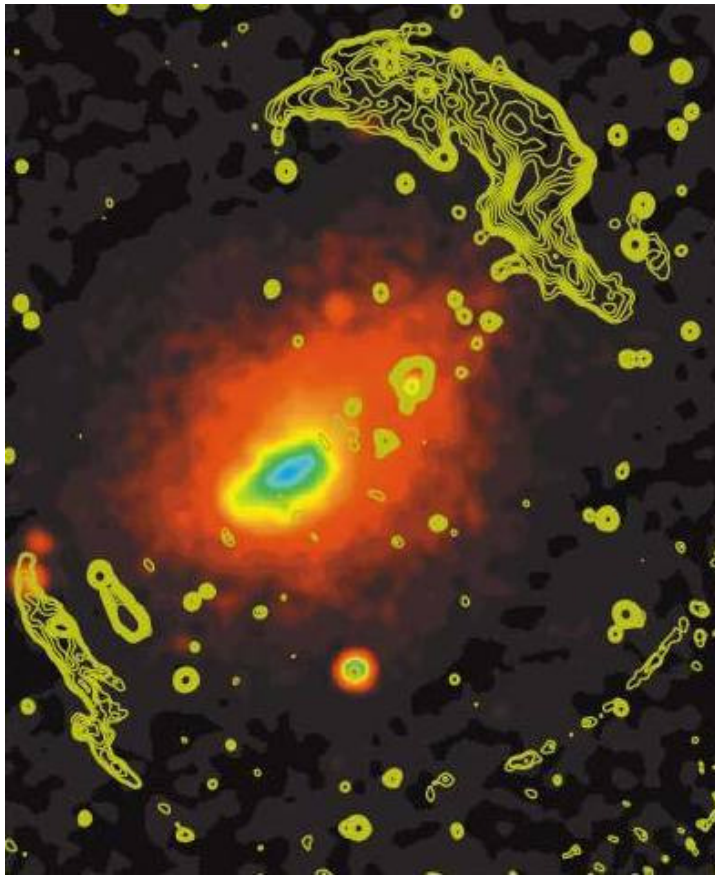
AIP

Cluster mergers: *the* most energetic cosmic events



1E 0657-56 (“Bullet cluster”)

(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)

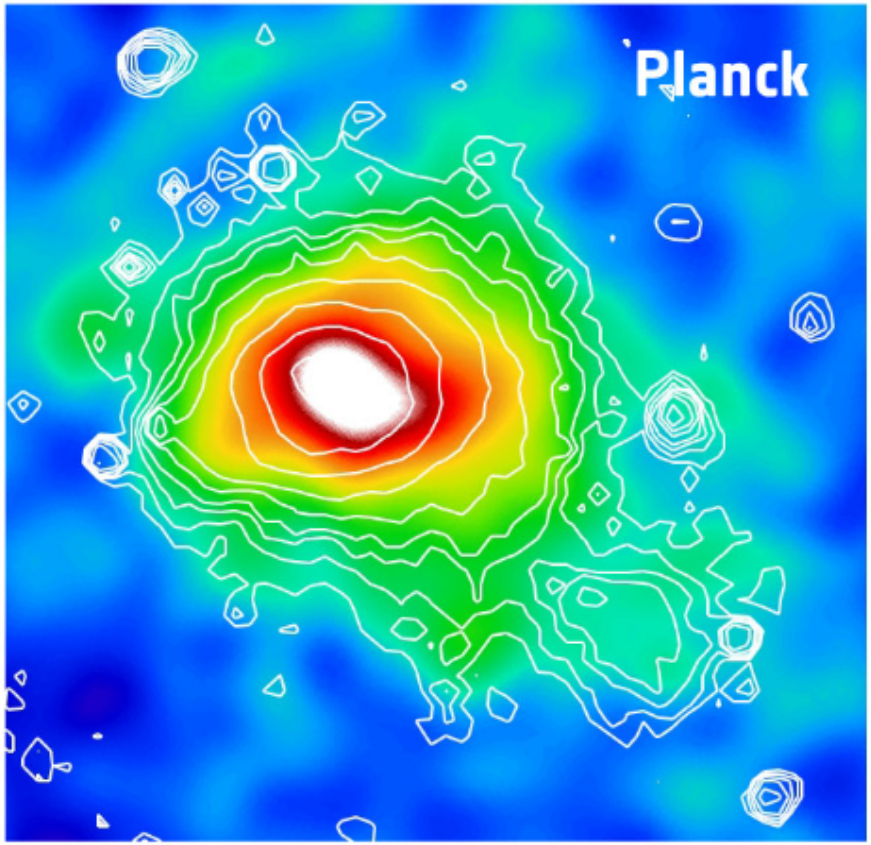


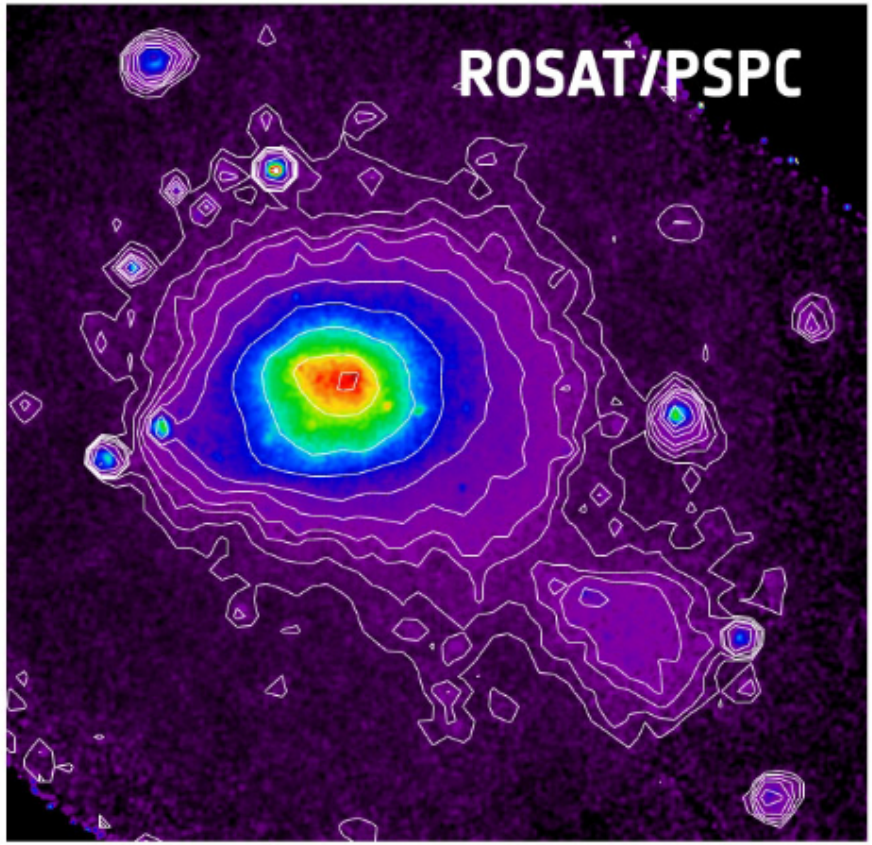
Abell 3667

(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

AIP

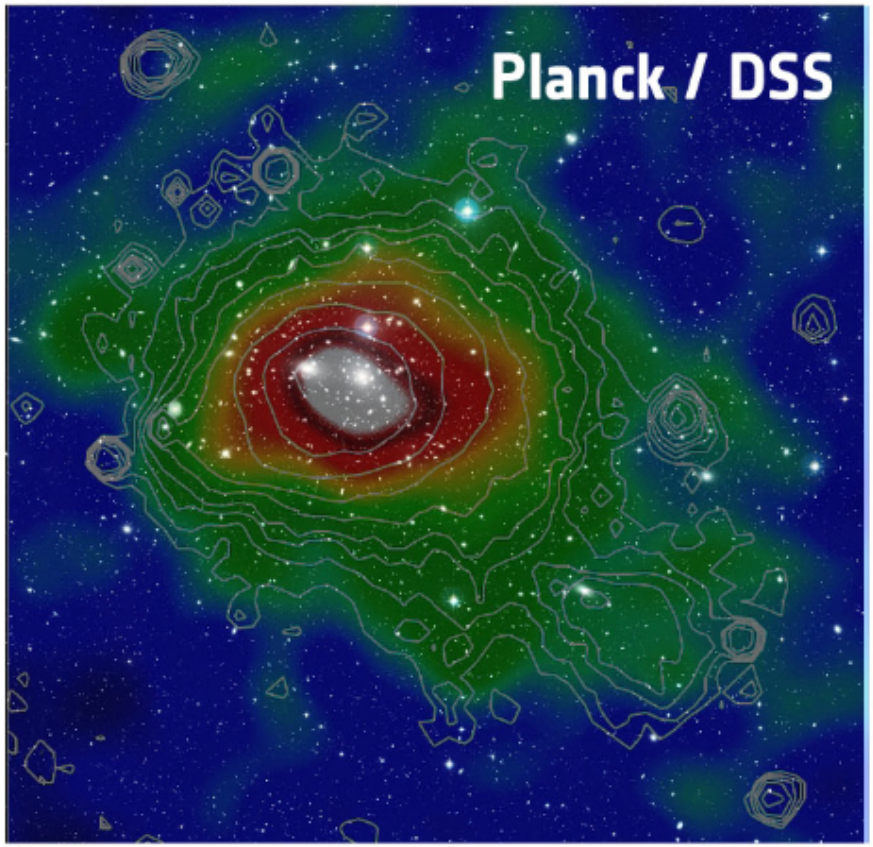
Coma galaxy cluster: Sunyaev-Zel'dovich vs. X-rays

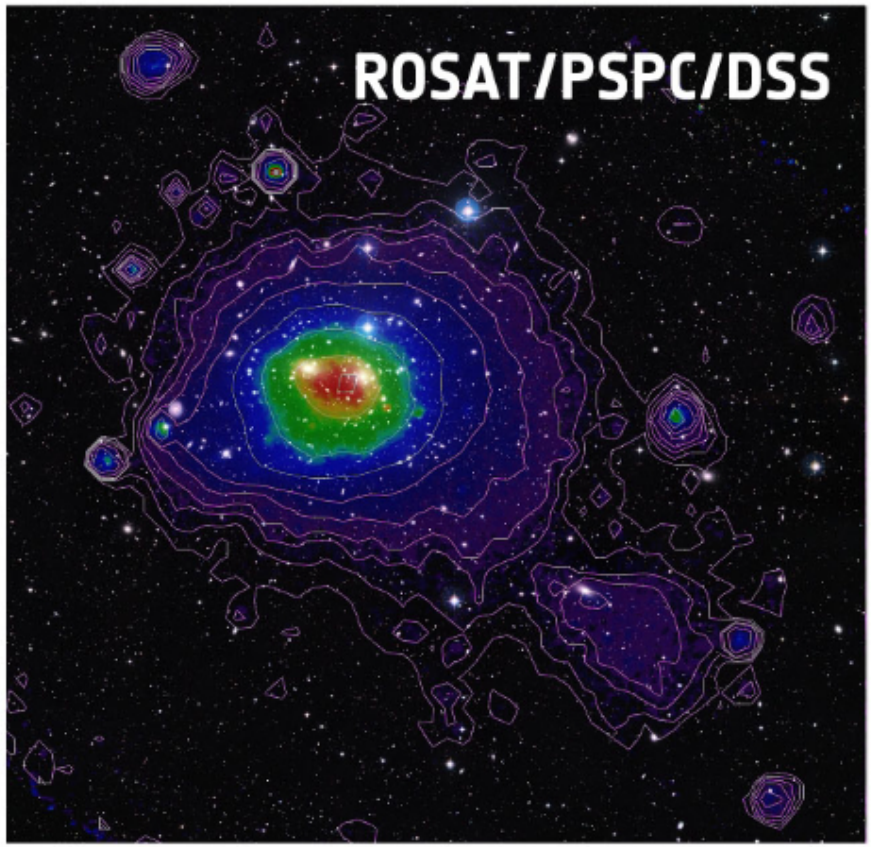




AIP

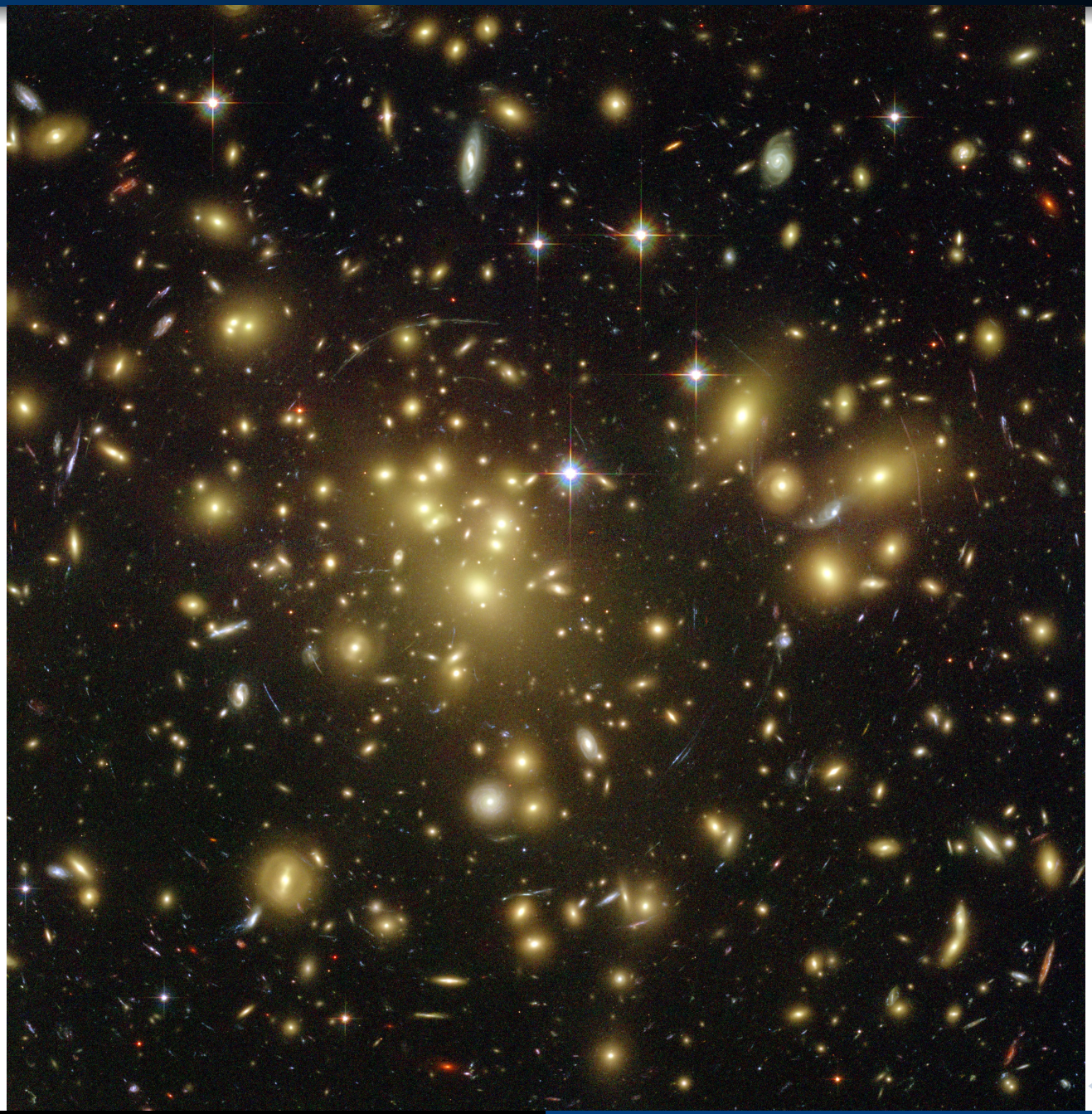
Coma galaxy cluster: SZE/X-rays vs. optical



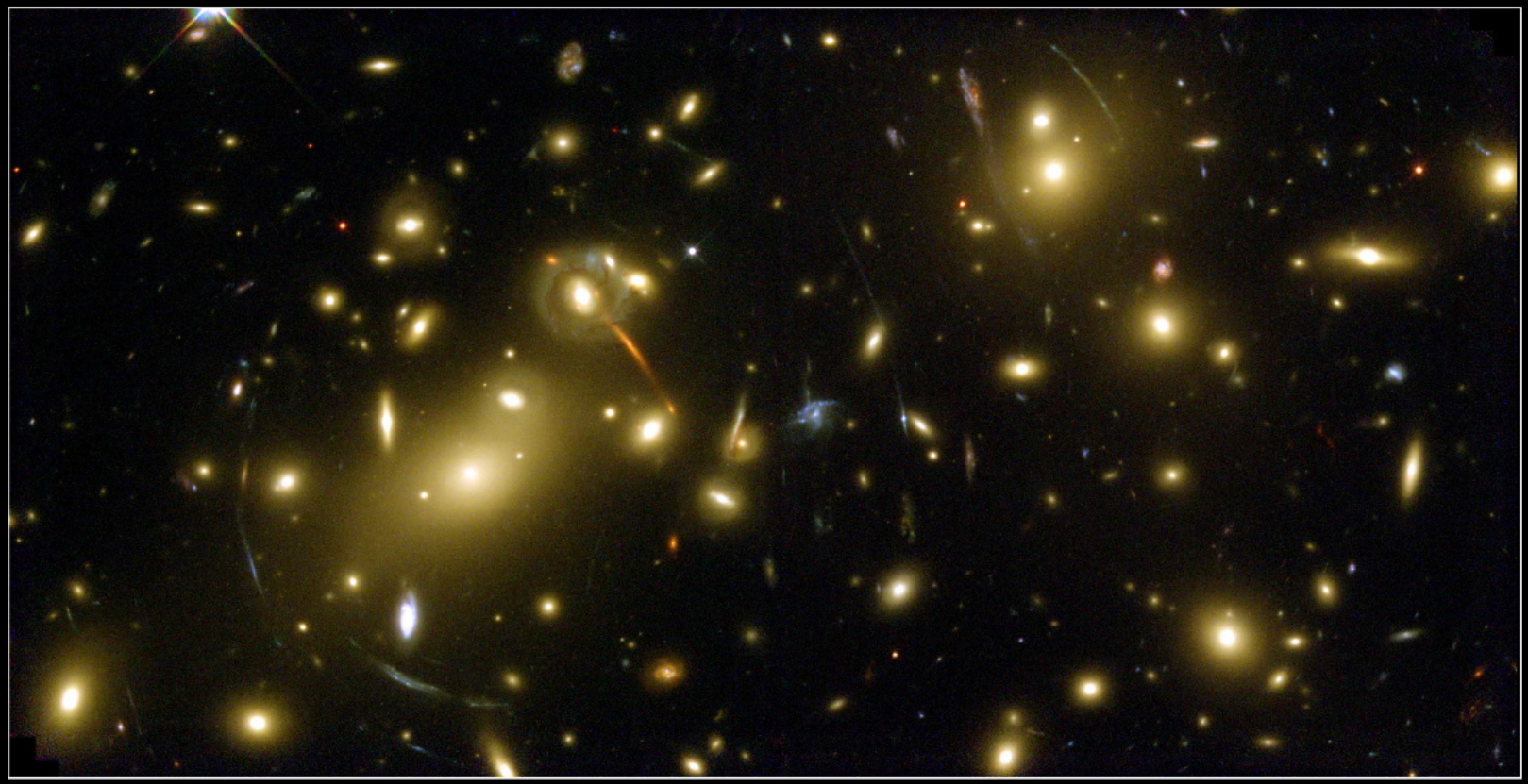


AIP

Gravitational lensing: Abell 1689



Gravitational lensing: Abell 2218



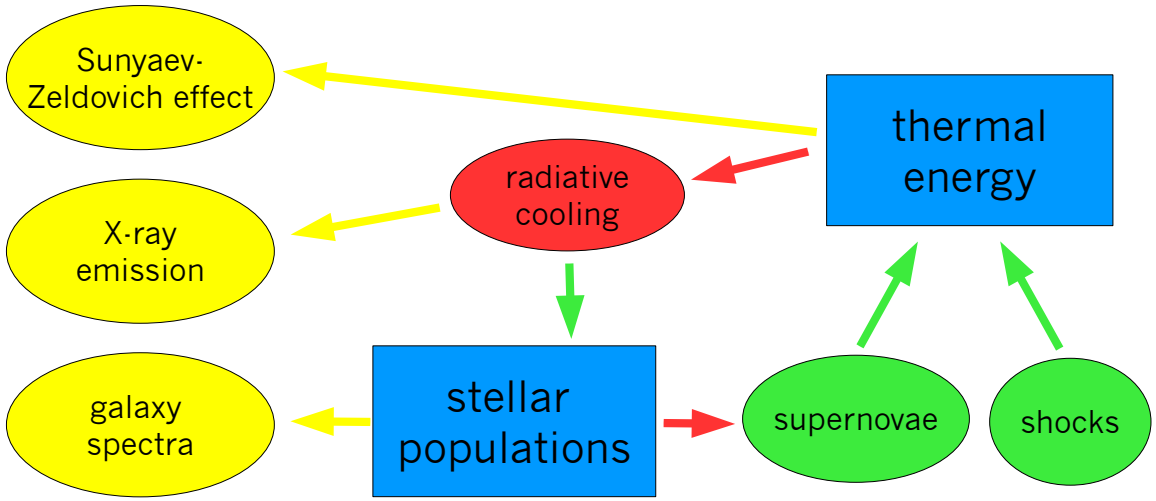
Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

AIP

Cosmological simulations – flowchart

Cluster observables: Physical processes in clusters:

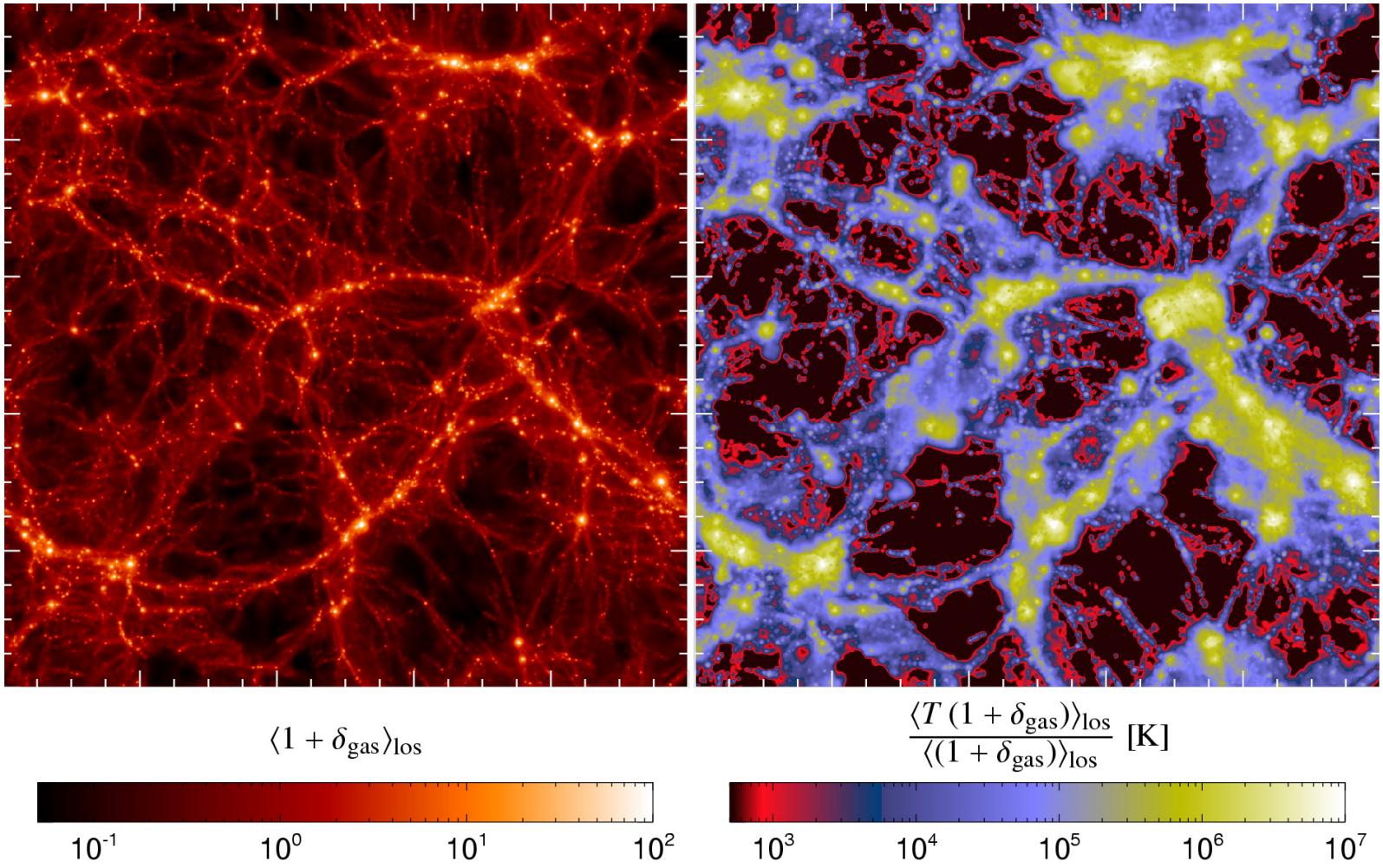


loss processes
gain processes
observables
populations

C.P., Enßlin, Springel (2008)

AIP

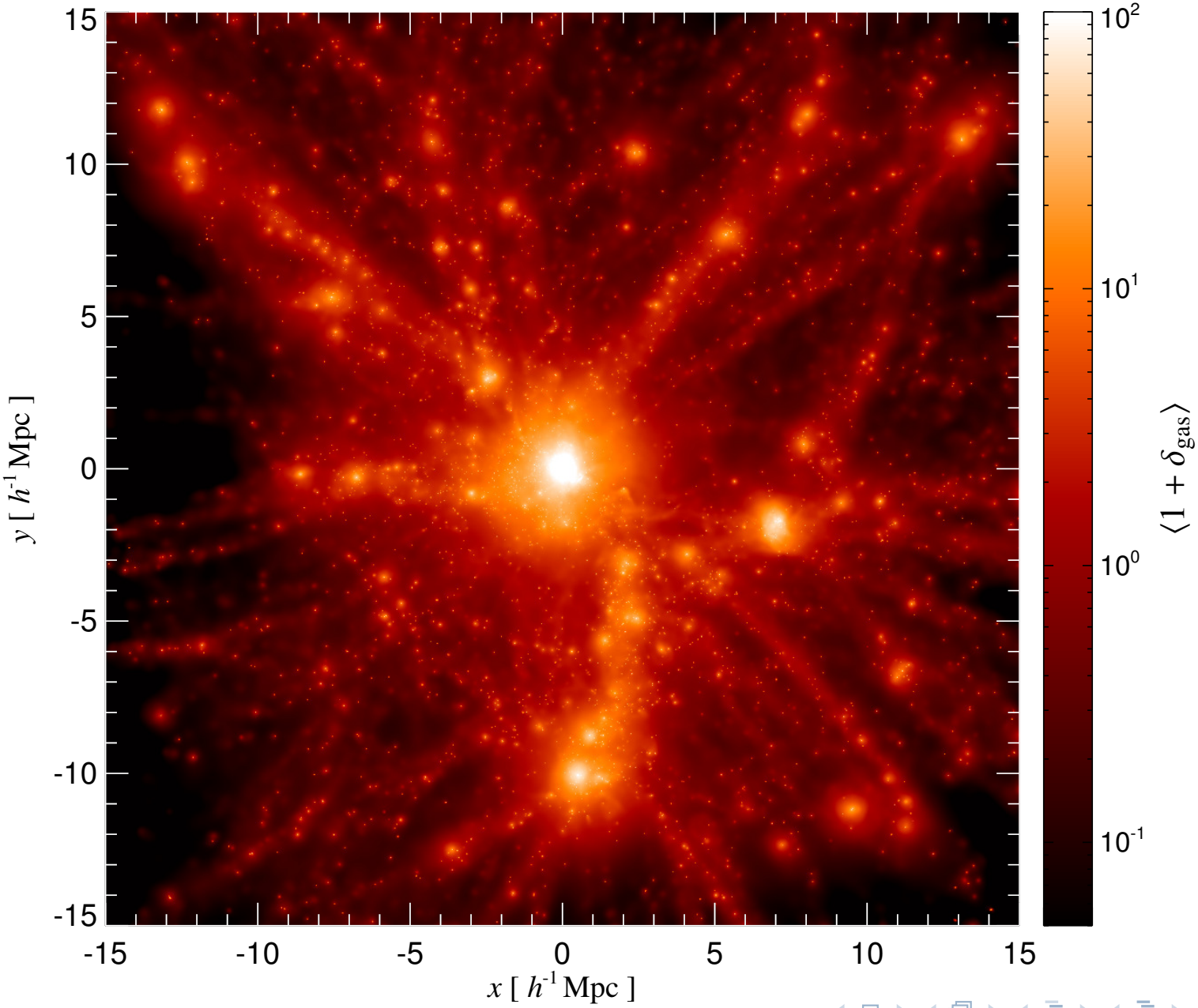
The structure of our Universe



The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intergalactic medium (C.P. et al. 2006).

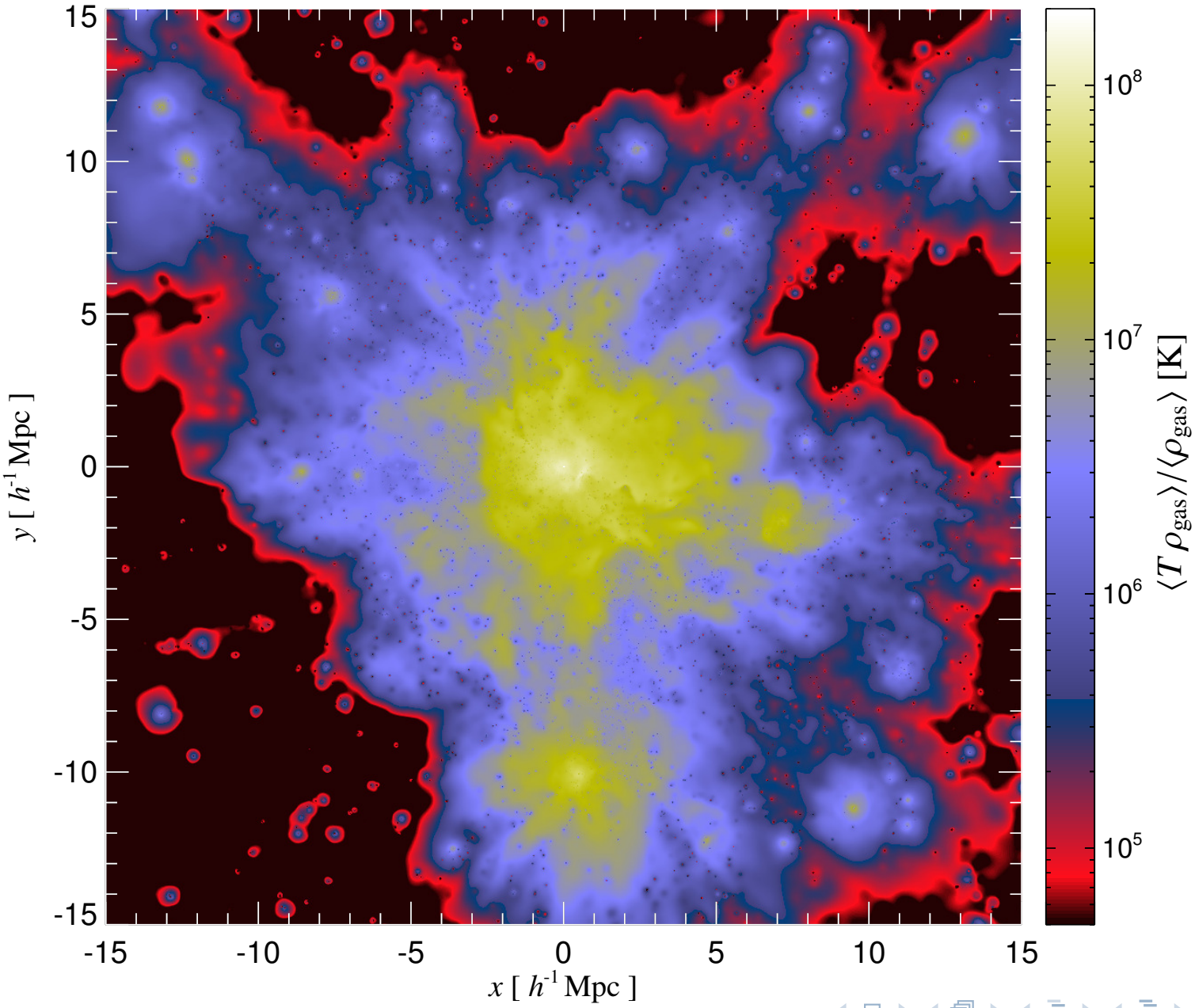
AIP

Cosmological cluster simulation: gas density



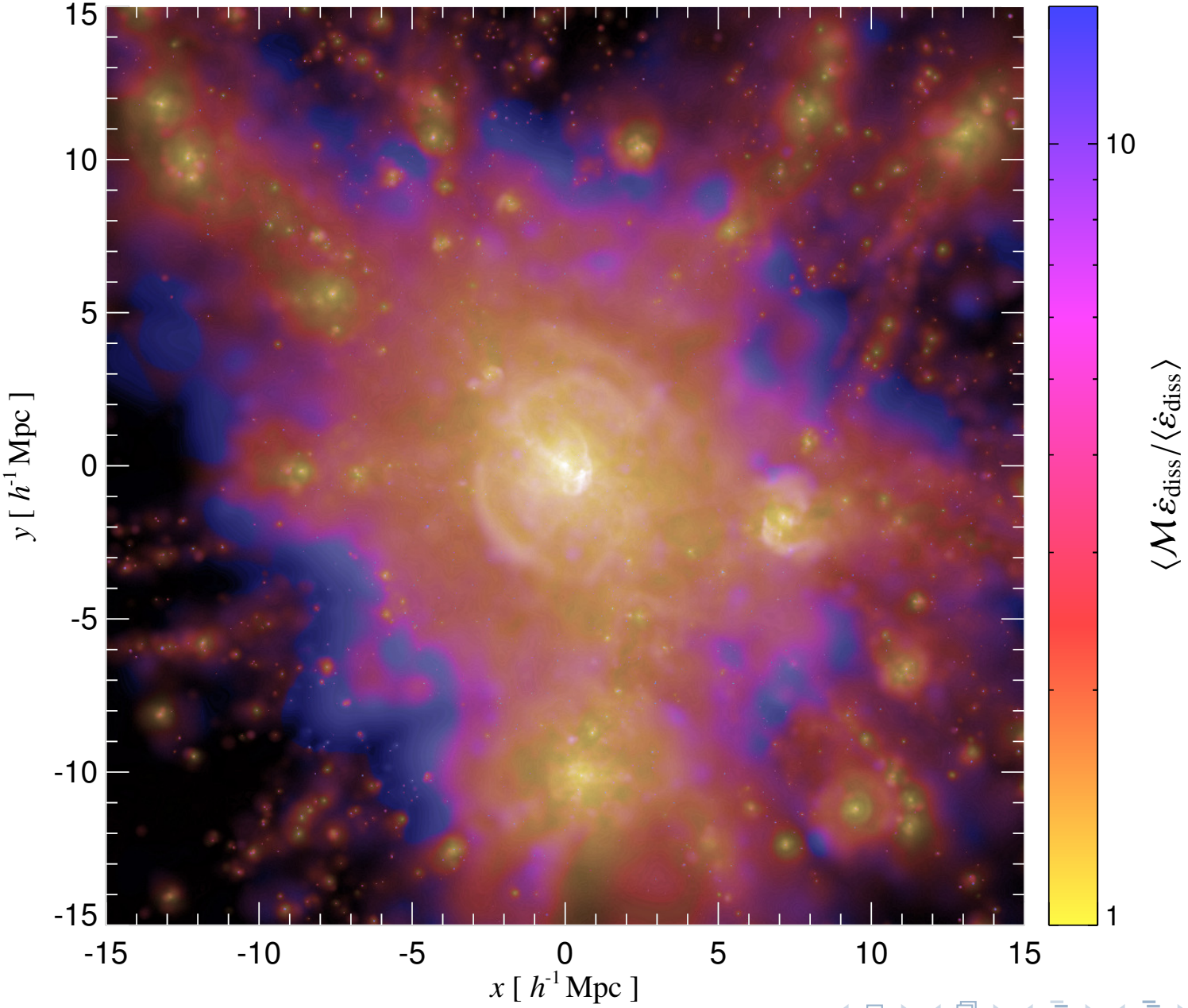
AIP

Mass weighted temperature



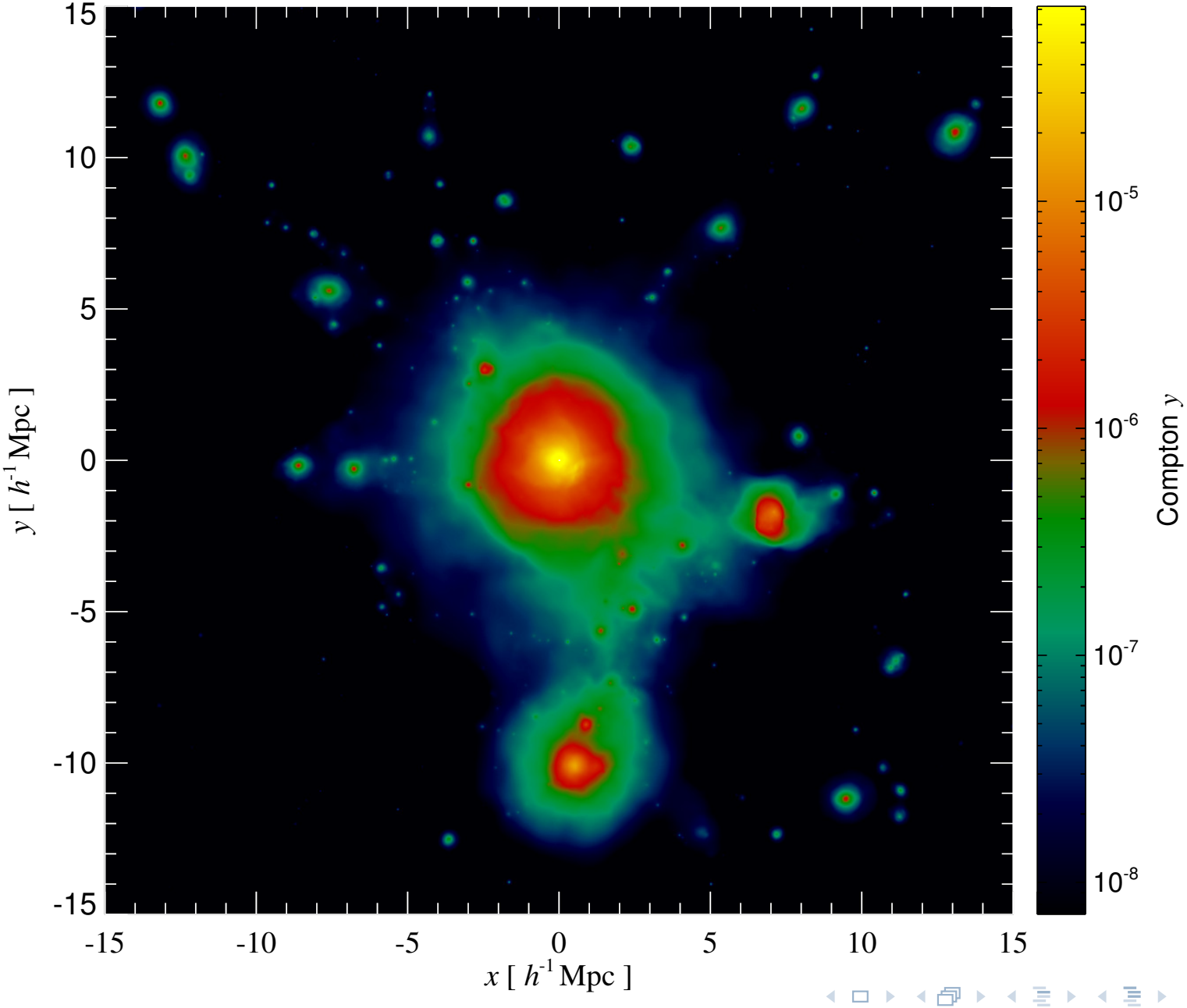
AIP

Shock strengths weighted by dissipated energy



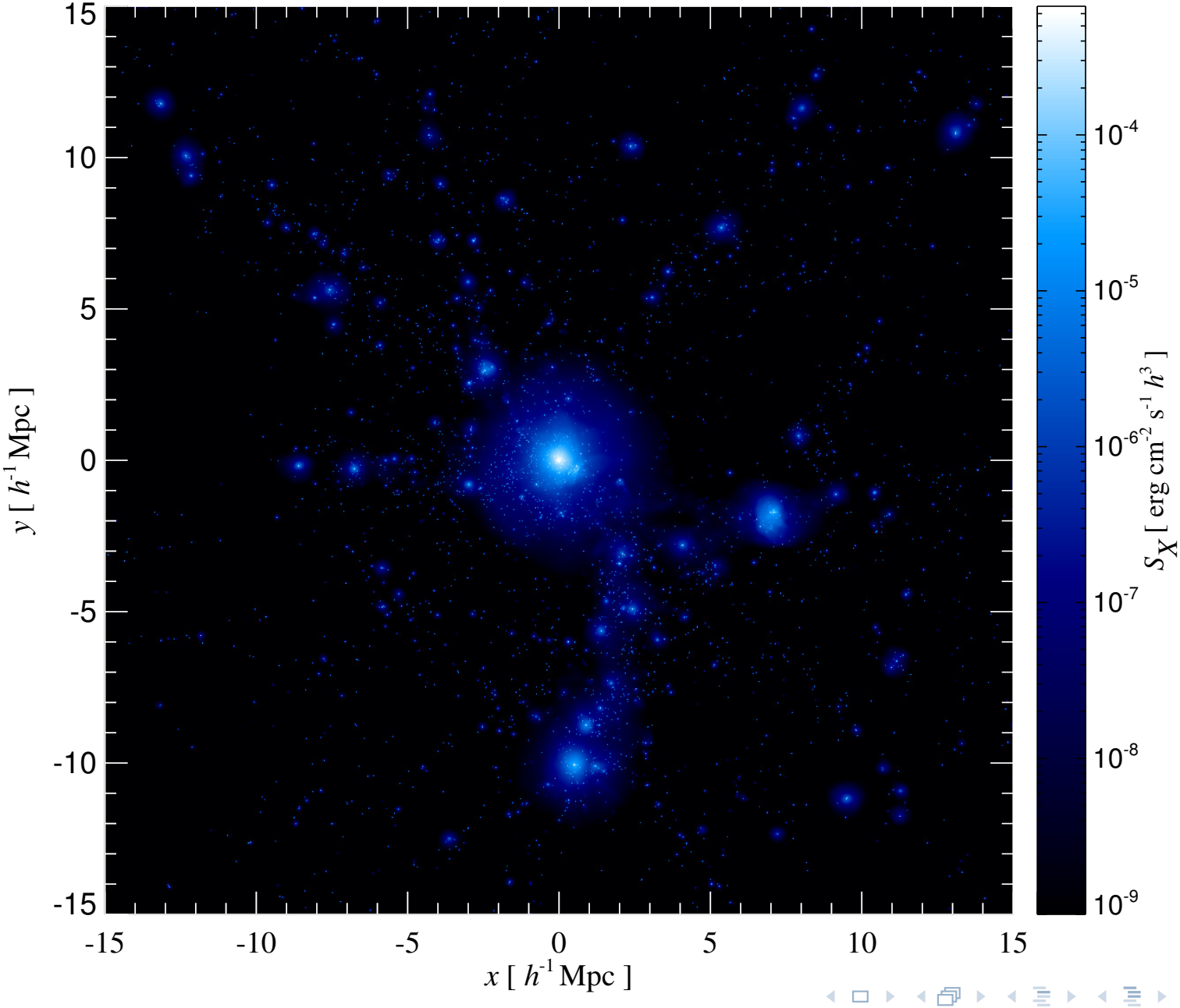
AIP

Sunyaev-Zel'dovich effect: integrated thermal pressure



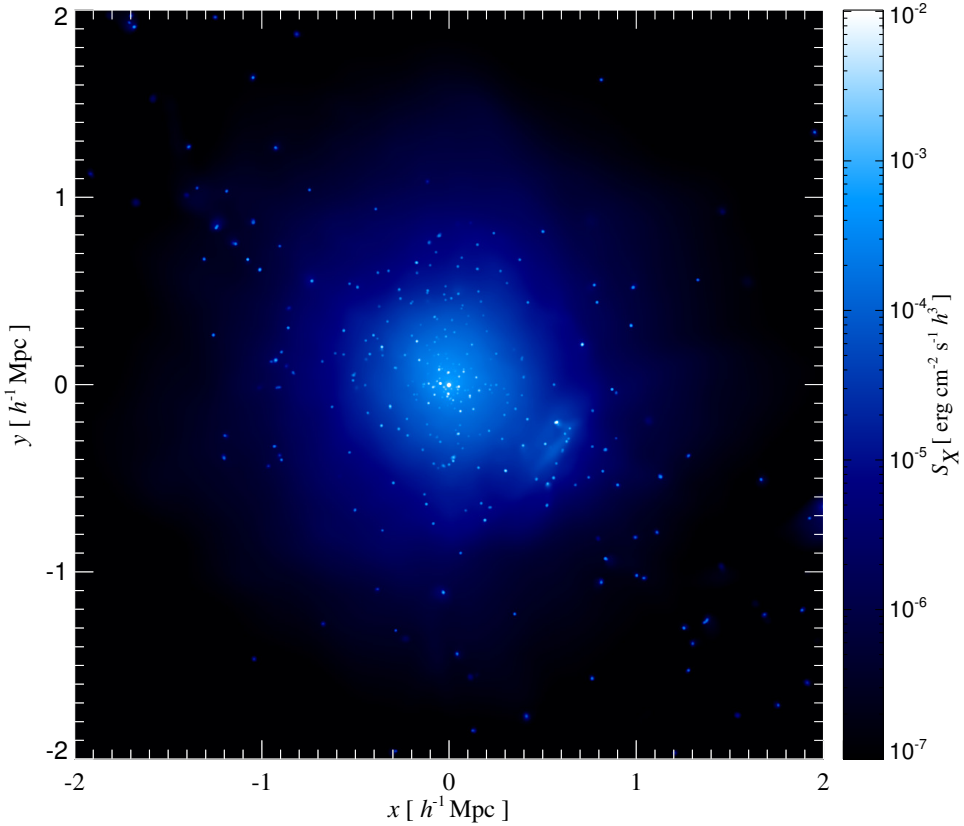
AIP

Thermal X-ray emission: gas density squared



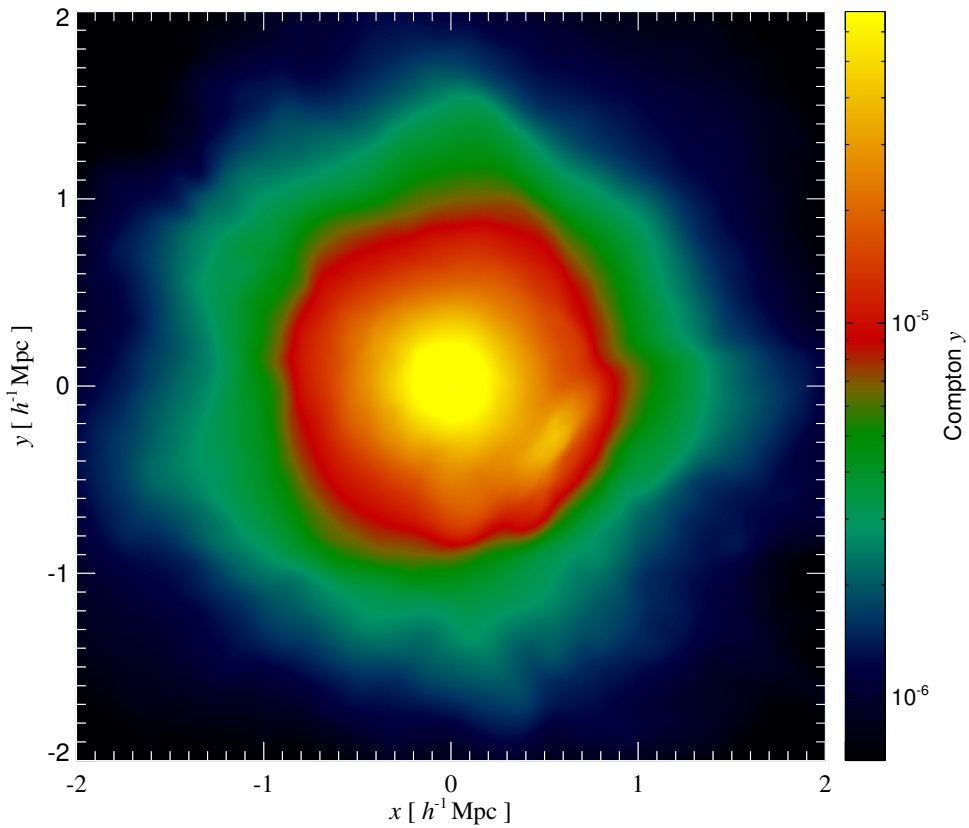
AIP

Zooming on the cluster: thermal cluster gas



Thermal bremsstrahlung emission,

merging cluster, $M_{\mathrm{vir}} \simeq 10^{15} M_{\odot}/h$

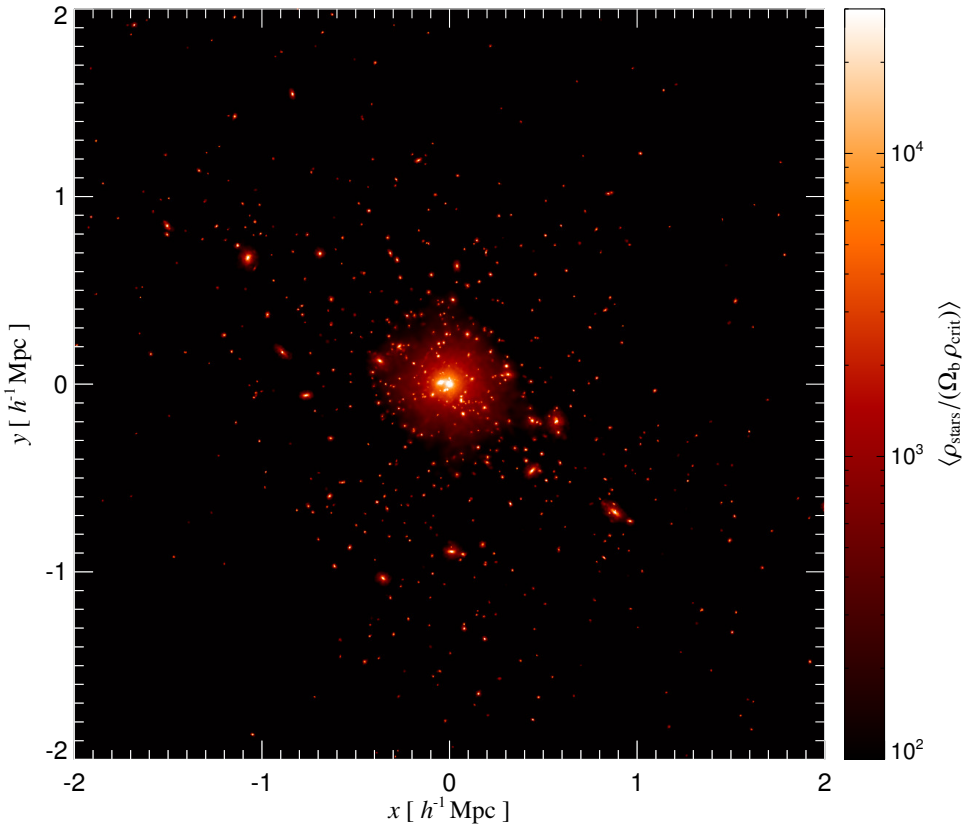


Sunyaev-Zel'dovich effect,

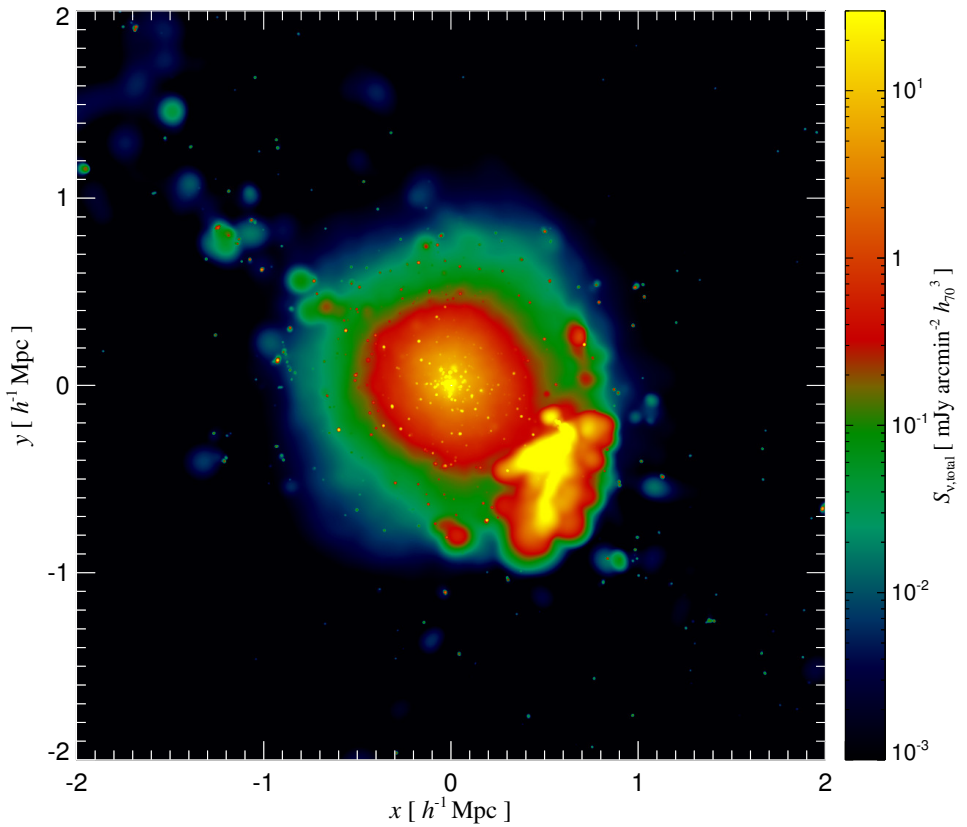
merging cluster, $M_{\mathrm{vir}} \simeq 10^{15} M_{\odot}/h$

AIP

Zooming on the cluster: optical vs. radio synchrotron



Stellar mass density (“cluster galaxies”), merging cluster, $M_{\rm vir} \simeq 10^{15} M_\odot / h$



Radio halo and relic emission, merging cluster, $M_{\rm vir} \simeq 10^{15} M_\odot / h$

AIP