Andrewsarchus

83 cm

Eocene (~ 55 – 34 Myr ago)

Simulating the structural evolution of galaxy clusters

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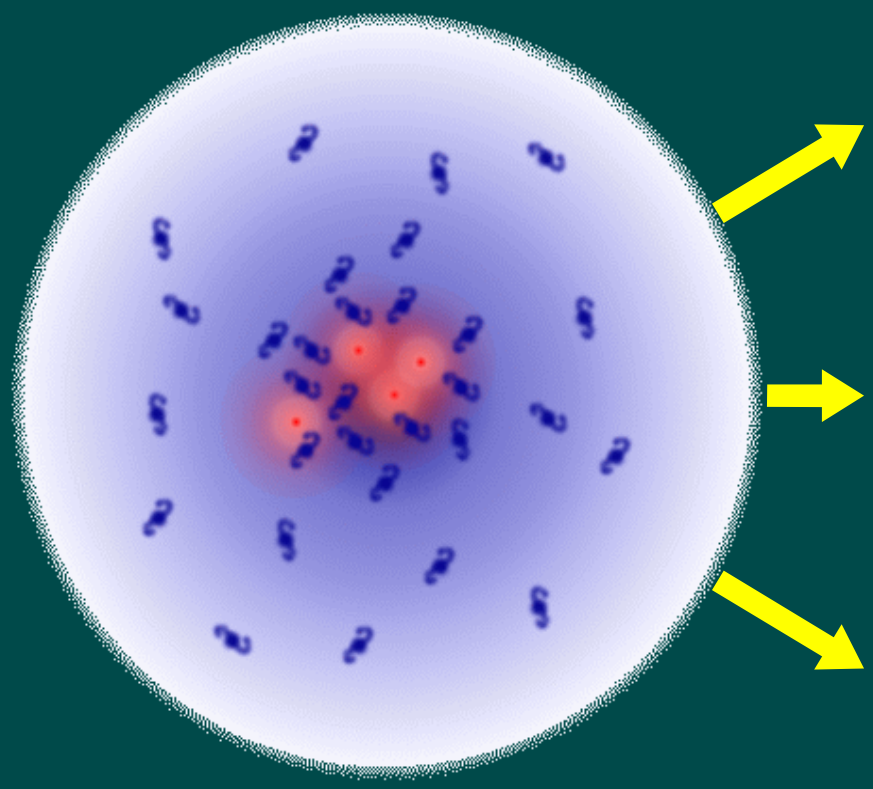
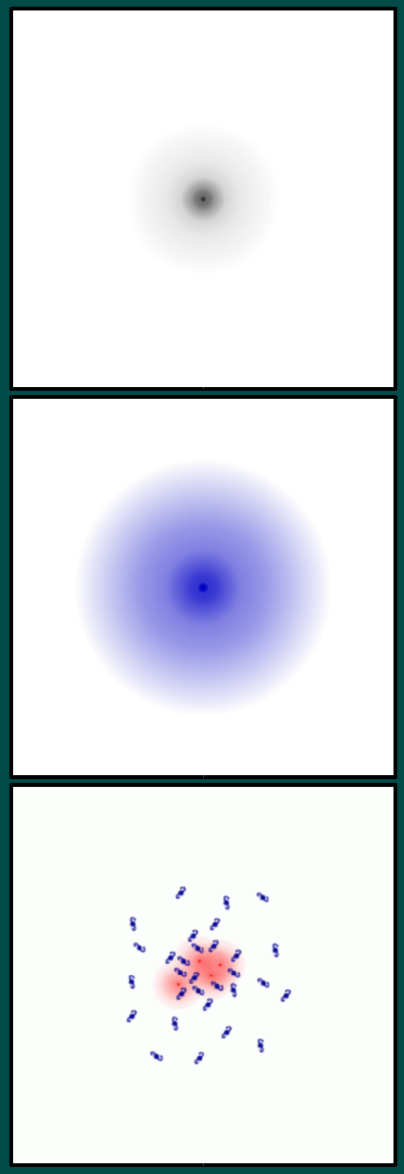
Santa Fe Cosmology Workshop, July 11, 2005

Clusters of galaxies

Size: ~ 1-10 Mpc



Mass: $10^{14} – 10^{15}\ M_{\odot}$

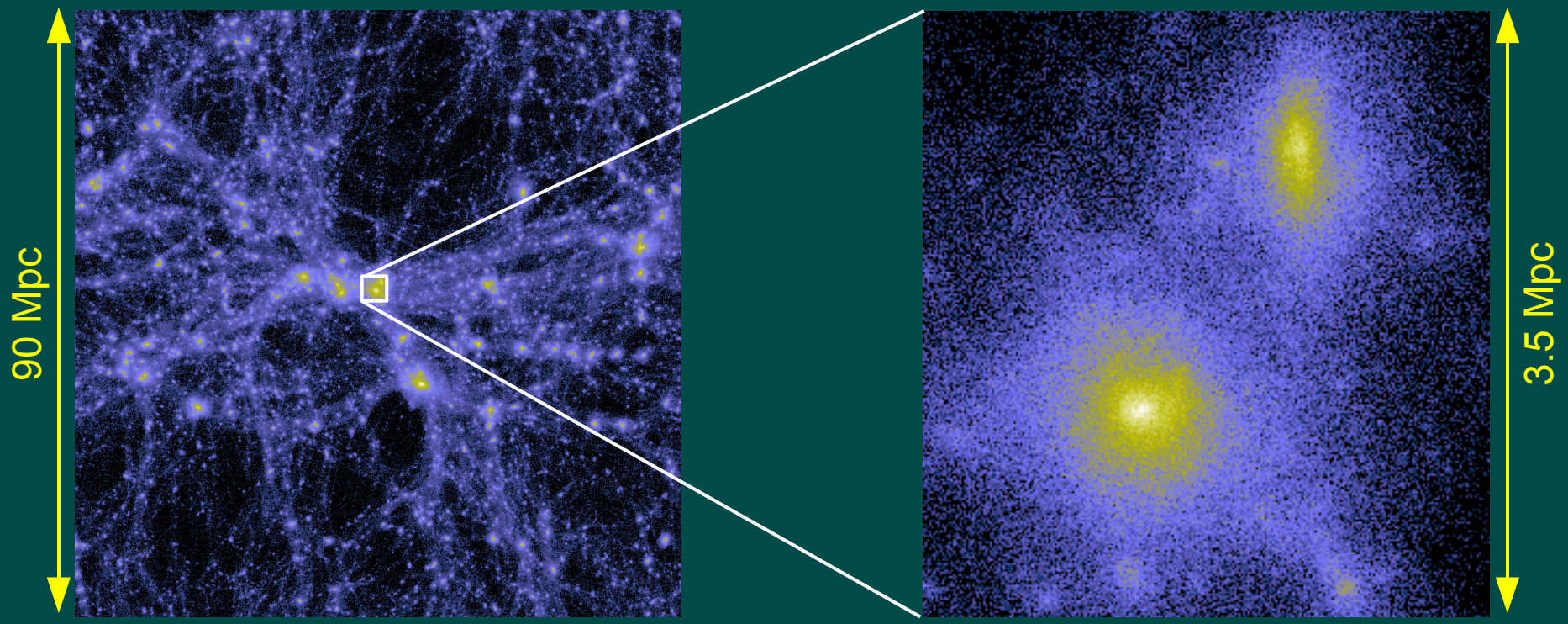


Dark matter: 89%
???

Gas: 10%
$n_{e0} \sim 10^{-3}\ \mathrm{cm}^{-3}$
$kT \sim 1 - 10$ keV

Galaxies: 1%
$N \sim 50 - 1000$
$v_{rms} \sim 200 - 1000\ \mathrm{km\ s}^{-1}$

Clusters and hierarchical structure formation



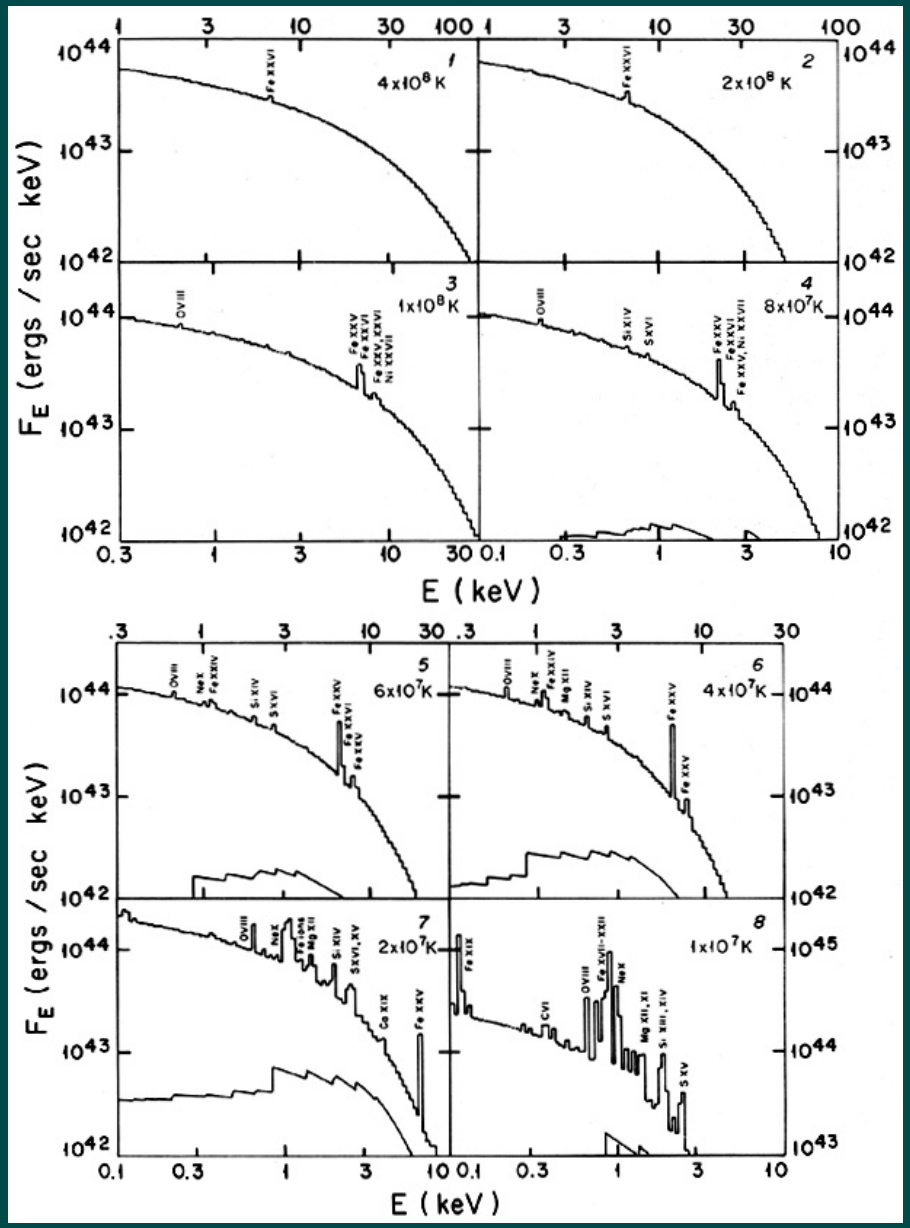
Heitmann et al. (2005)

- In hierarchical models:
  - Clusters form through mergers of subunits
  - Richest clusters form at intersections of filaments
- In ΛCDM 20-40% of clusters have experienced a major (1:5 – 1:1) merger in last 2.5 Gyr (Cohn et al. 2001; Cohn & White 2005)

The intracluster medium (ICM)

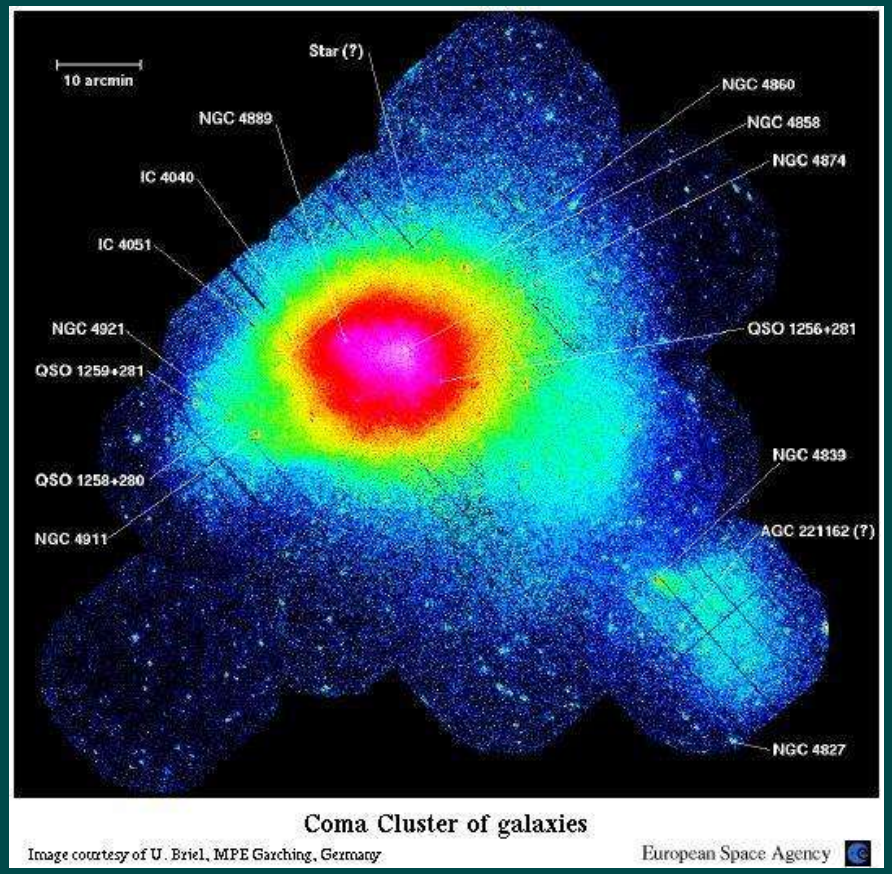
- Collisionally ionized plasma
  - $n_e \sim 10^{-3}$ cm^{-3}
  - $T \sim 10^7 - 10^8$ K (1 – 10 keV)
- Heavy element abundance ~ 0.3 – 0.5 solar
- Optically thin emission
  - Thermal bremsstrahlung ($T > 10^7$ K)
  - Recombination and line emission ($T < 10^7$ K)
- Isobaric cooling time

$$t_{\rm cool} = 8.5\times10^{10}\left(\frac{n_e}{10^{-3}\,{\rm cm}^{-3}}\right)^{-1}\left(\frac{T}{10^8\,{\rm K}}\right)^{1/2}\ {\rm yr}$$



Model spectra (Sarazin & Bahcall 1977)

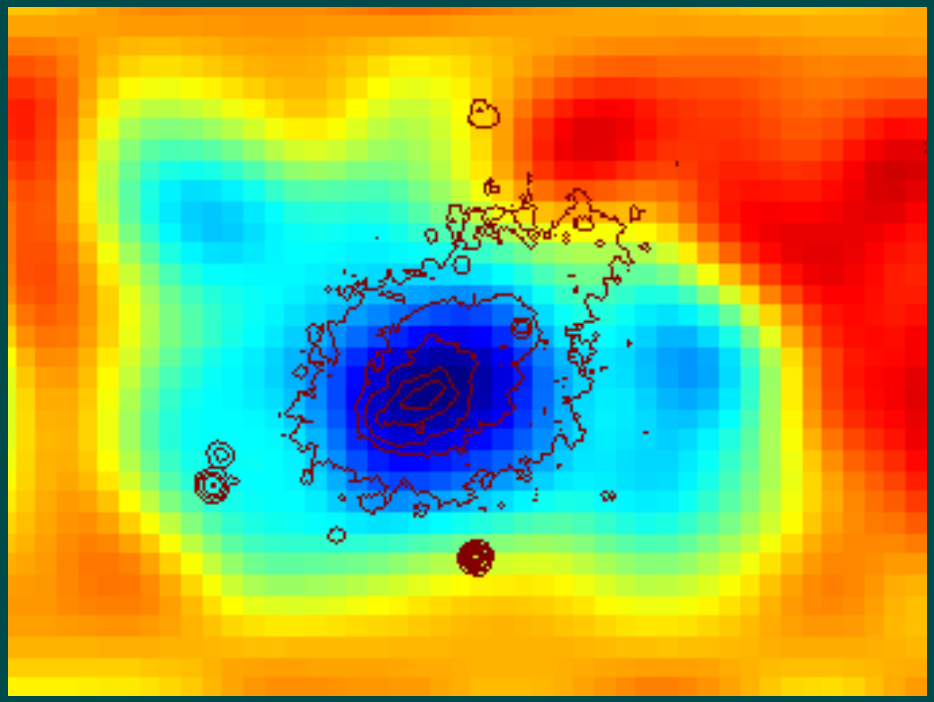
Observing the ICM



X-ray imaging

Coma Cluster
(z = 0.023)

Abell 3667
(z = 0.053)

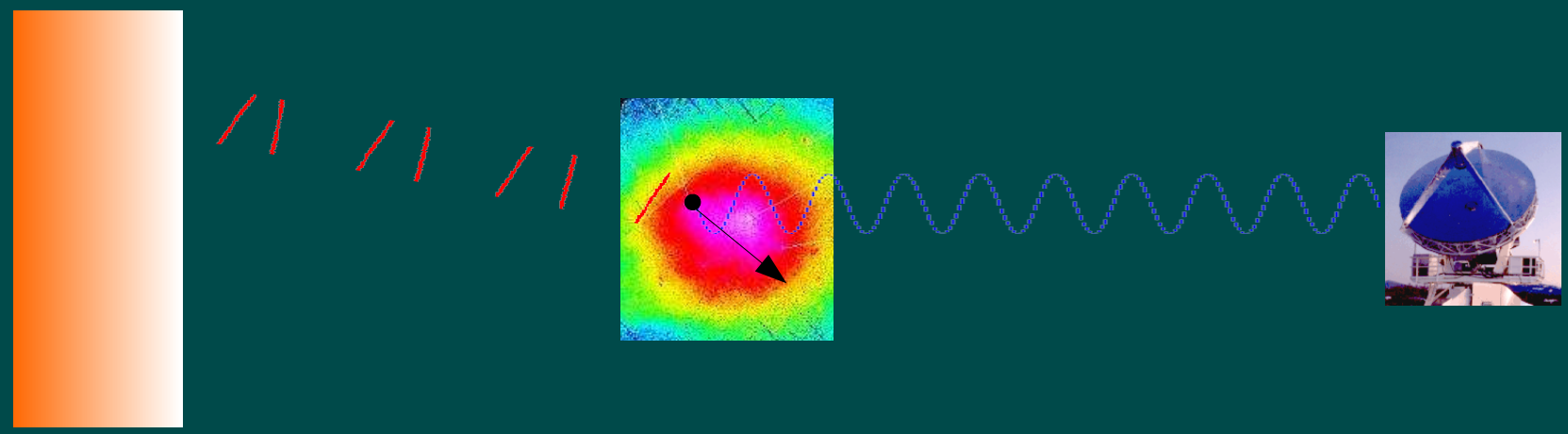


Sunyaev-Zel'dovich effect

(Viper SZ map; K. Romer et al.)

Sunyaev-Zel'dovich effect

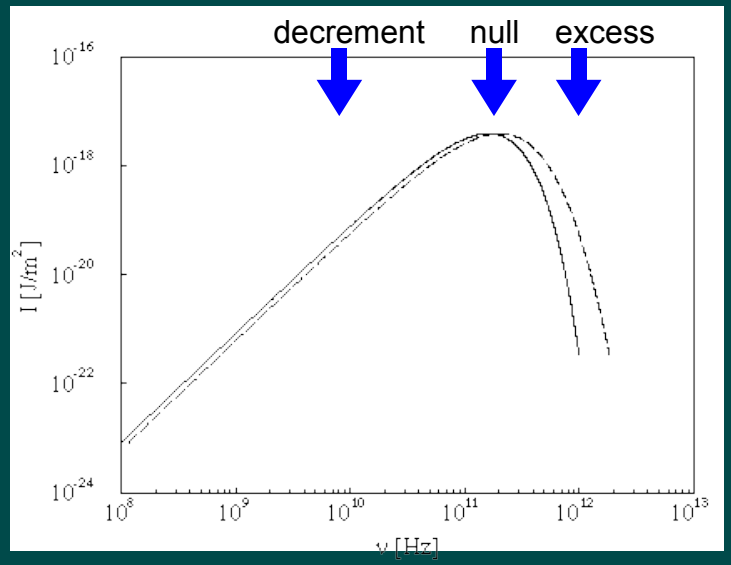
About 1% of cosmic background photons scatter from hot electrons in ICM



Last scattering surface

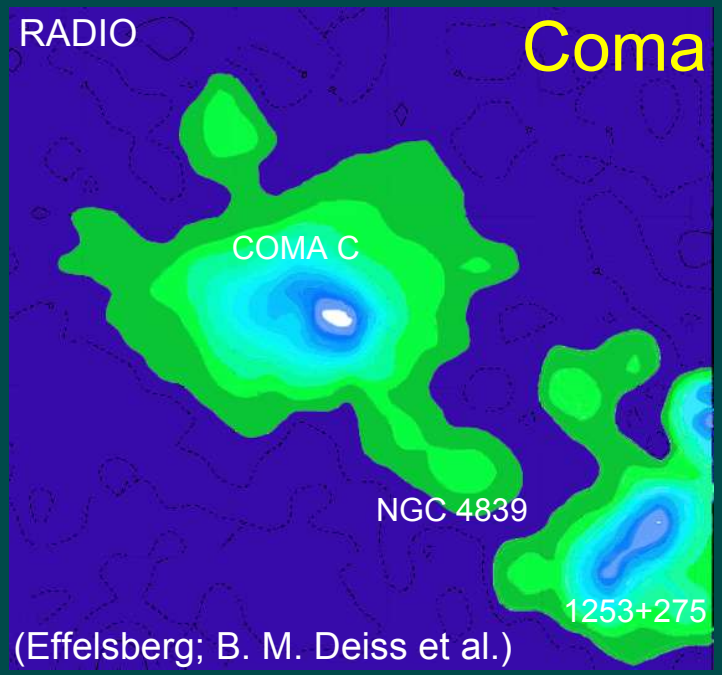
Hot, ionized gas in a galaxy cluster

Photons tend to gain energy
Background temperature changes by ~ 1 mK

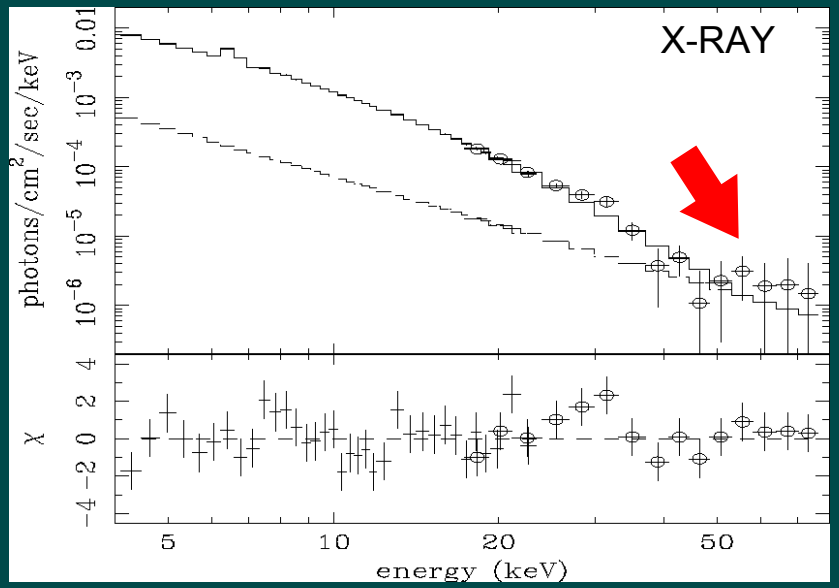


Nonthermal particles

- Evidence
  - Diffuse radio synchrotron emission (radio halos)
    - Steep spectrum ($S_\nu \sim \nu^\alpha$, $\alpha < -1$)
    - Low polarization (< 5%)
  - Nonthermal X-ray emission
- Acceleration models
  - Primary
    - Merger shocks (1st order)
    - Turbulence (2nd order)
  - Secondary



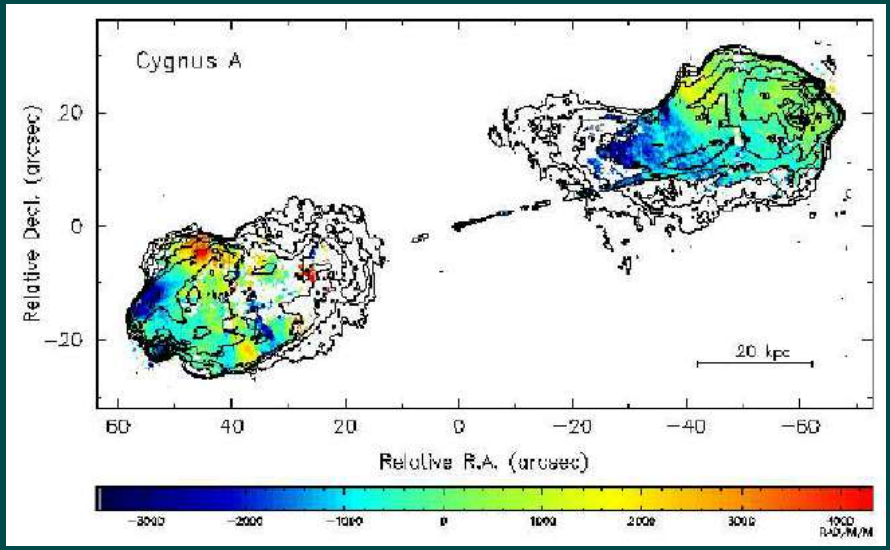
(Effelsberg; B. M. Deiss et al.)



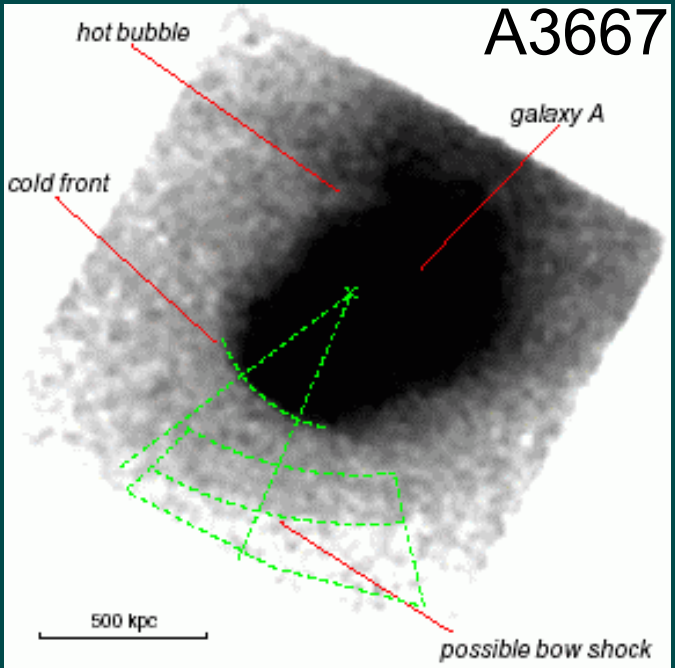
RXTE spectrum of Coma (Rephaeli & Gruber 2002)

Magnetic fields

- Evidence
  - Faraday rotation measures
  - Synchrotron/inverse Compton
  - Cold fronts
- Characteristics
  - $B_{rms} \sim 1 - 10\ \mu G$
  - Up to ~ 50 μG in cooling cores
  - Coherence length 5 – 10 kpc
  - Electron gyroradius ($10^8 - 10^9$ cm) << collision mean free path (kpc)
    - Thermal conduction suppressed?



Dreher et al. (1987)



Vikhlinin et al. (2001)

Simulating cluster evolution

Increasing realism

Gaussian random field initial conditions

Comoving 3D space

Spherical, virialized initial conditions

Fixed 3D space

Spherically symmetric

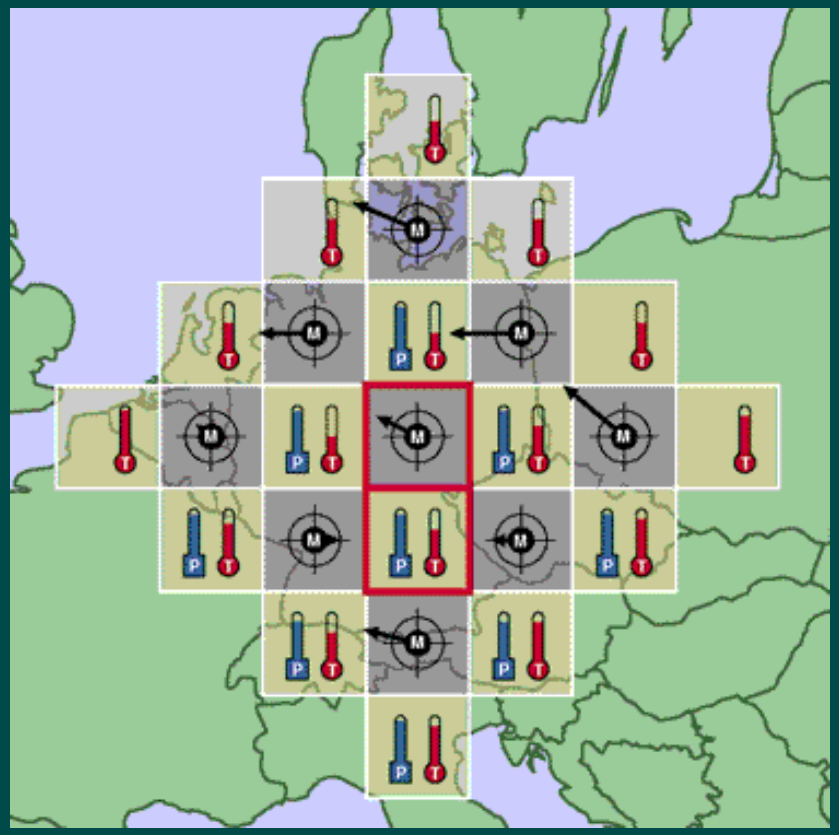
Fixed 1D space

Increasing complexity & cost

Basic physics inputs

- Minimum
  - Dark matter (*Vlasov equation*)
  - Gasdynamics (*Euler equations*)
  - Gravity (*Poisson equation*)
- Additional physics
  - Radiative cooling (*Local energy sink term*)
  - Thermal conduction (*Energy diffusion term*)
  - Galactic feedback (*Local energy/momentum source terms*)
  - Magnetic fields (*MHD?*)
  - Cosmic-ray particles (*Advection-diffusion equation*)
- Resolution is less and less of an issue
  - $> 10^7$ dark matter particles per cluster
  - Spatial dynamic range $> 10^4$
  - Spatial resolution ~ few kpc

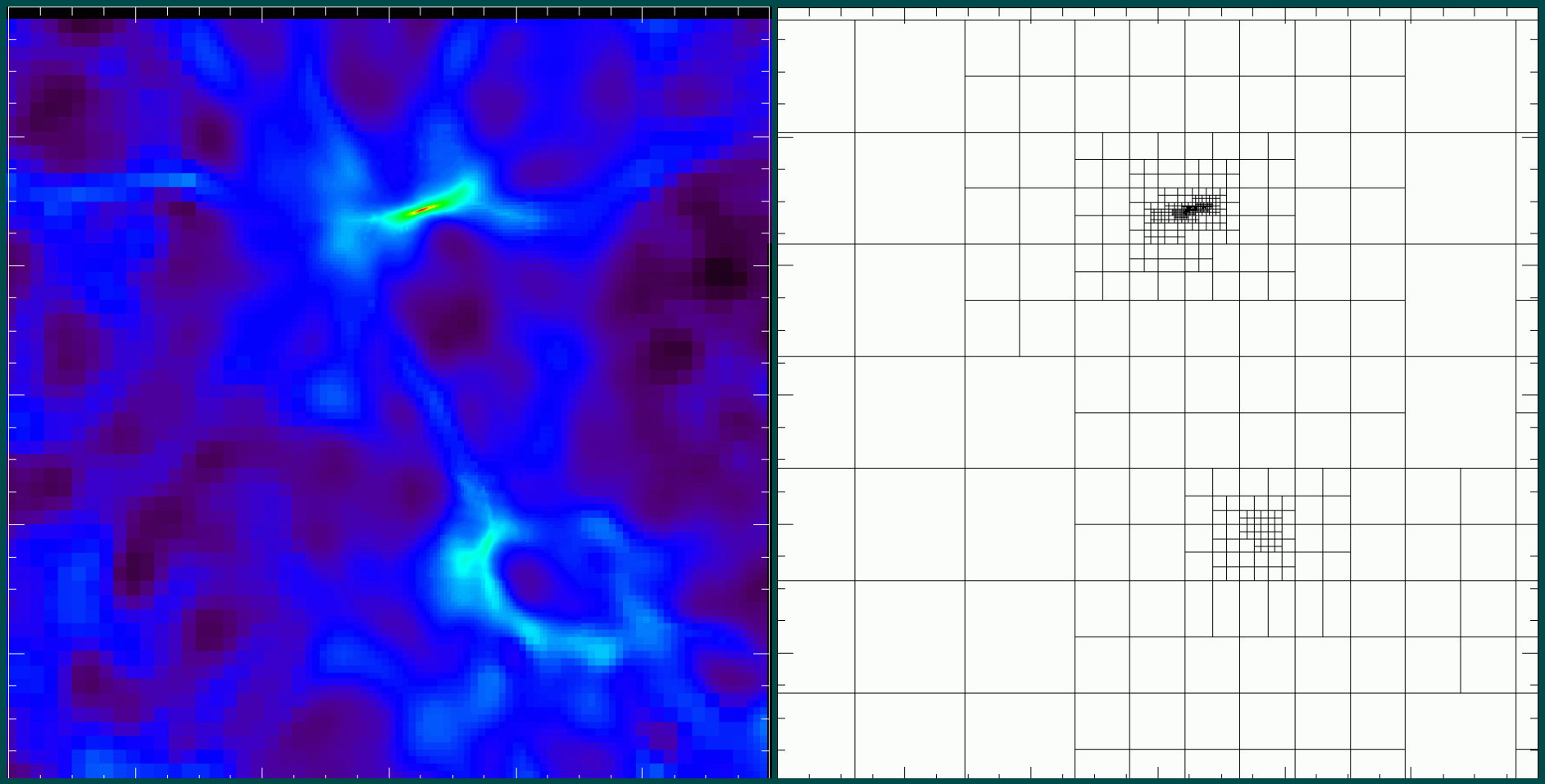
Our debt to meteorology



Lewis Fry Richardson
Weather Prediction by Numerical Process
(1922)

Adaptive mesh refinement

- FLASH (Fryxell et al. 2000)
  - Eulerian AMR + particle-mesh
  - Oct-tree refinement



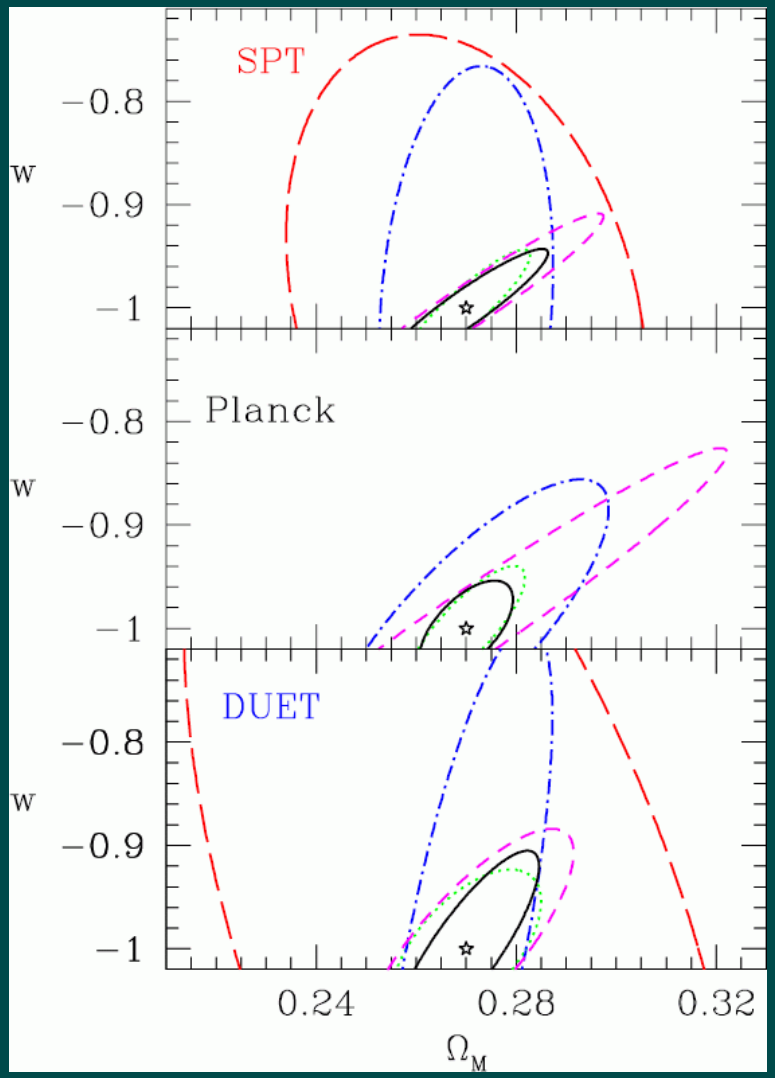
Ricker (2005)

Why are clusters interesting to cosmologists?

- Largest collapsed objects
  - Internal structure nonlinear, statistics ~ linear
  - Evolution timescales comparable to age of Universe
  - Detectable to high *z*, especially using SZ effect
- Lots of information available
  - Mass function d*N*/d*M*
  - Power spectrum *P*(*k*)
  - Merger rate evolution
  - Redshift distribution d*N*/d*z*
- Independent source of constraints
  - Power spectrum normalization σ_8
  - Matter density parameter Ω_m
  - Dark energy parameters *w*, d*w*/d*z*
  - Dark matter self-interaction (Markevitch et al. 2004)

Self-calibration of cluster surveys

- Recent/forthcoming large surveys
  - Optical: SDSS, DES, LSST, ...
  - SZ: SZA, SPT, Planck
  - X-ray: ?!
- Crucial elements for cosmological constraints from clusters
  - Selection function
  - Mass-observable relation
  - Redshift estimates
- Self-calibration (Levine et al. 2002, Majumdar & Mohr 2004, Hu 2003, Lima & Hu 2003)
  - With enough clusters (> 10^4), can parametrize cluster physics and fit it along with cosmology (with some loss of information about cosmology)



Majumdar & Mohr (2004)

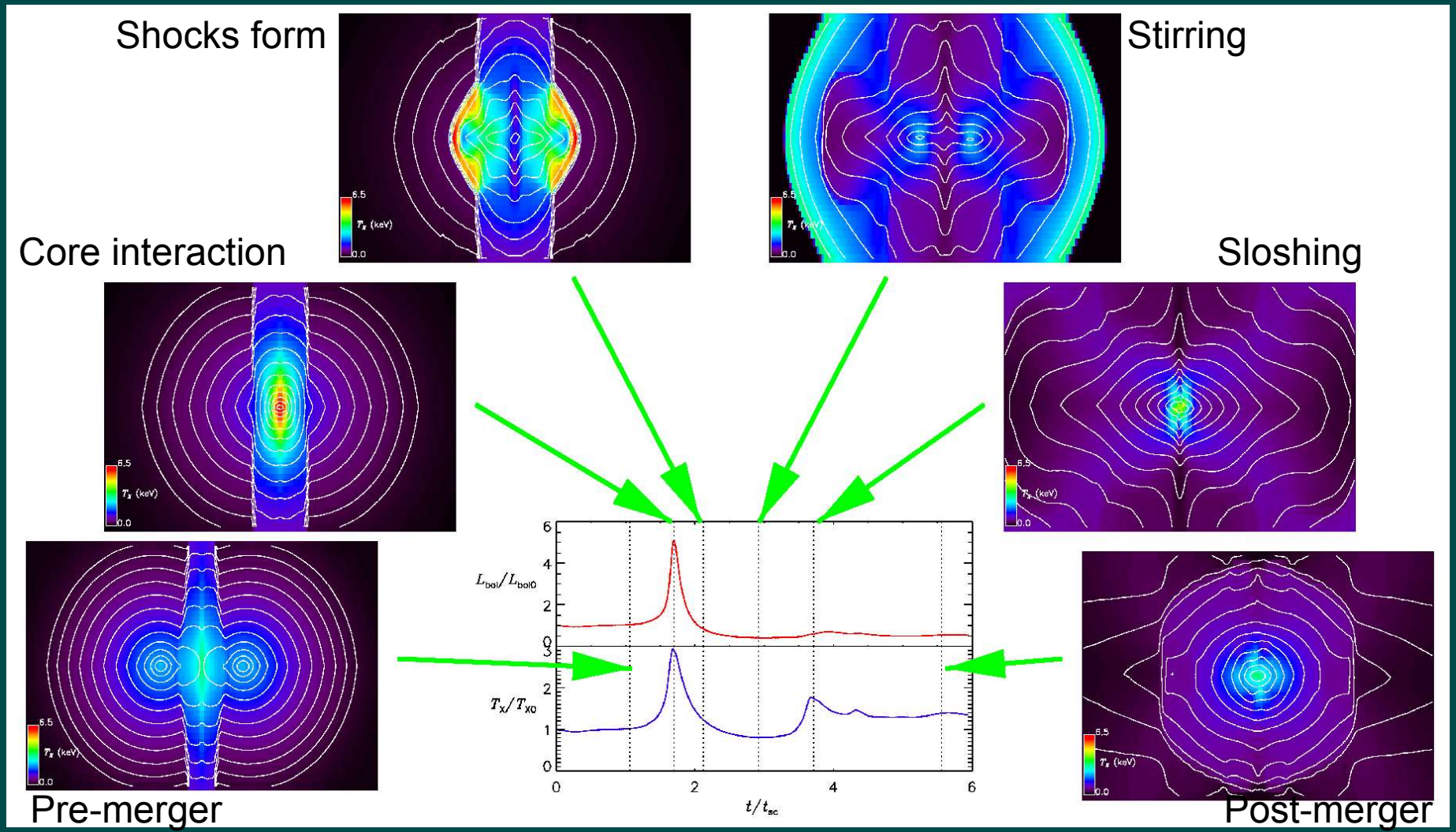
The role of simulation

- Direct simulation of cluster formation
  - What is important nonlinear/nongravitational physics?
  - How good is “spherical cow” approximation?
  - Systematic effects on mass-observable relations?
- Direct simulation of survey volumes
  - All systematics built in
  - Apply observational tools directly to theory predictions
  - Test cluster detection methods
  - Test self-calibration assumptions

Mergers

Progress of a merger

Ricker & Sarazin (2001)

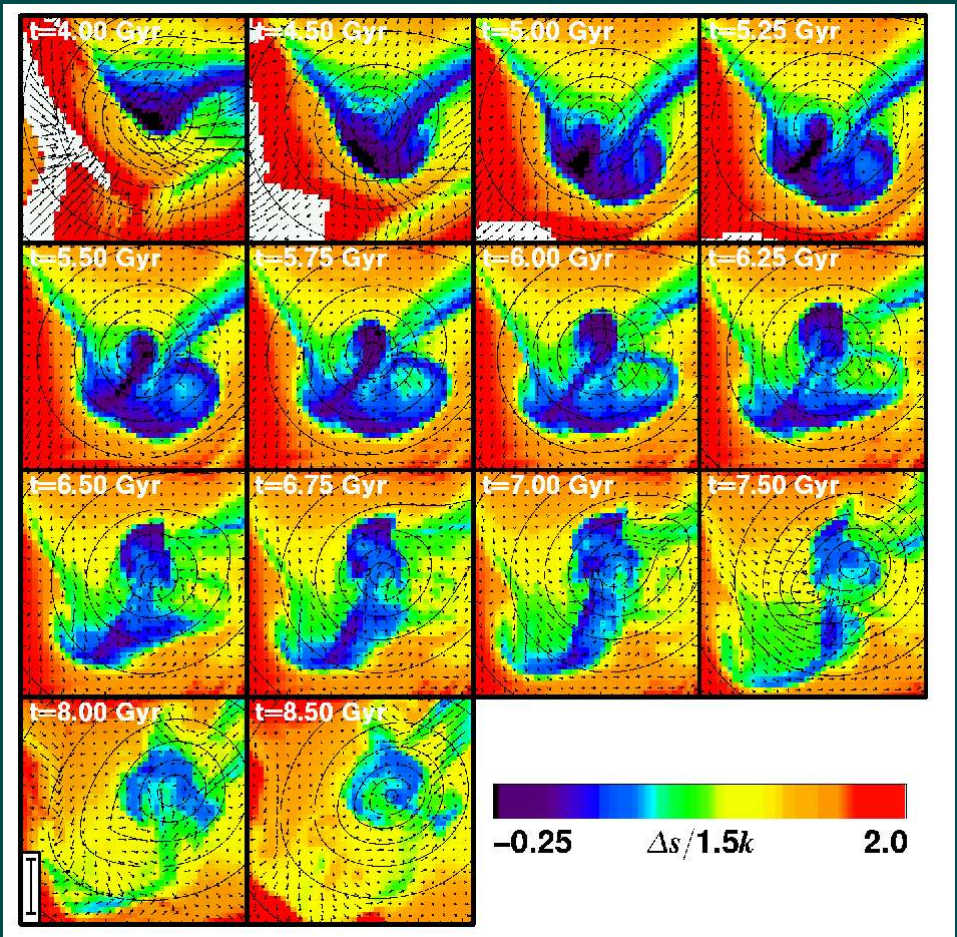


Several x 10^9 yr

Mixing

- Mergers do not leave a cluster well-mixed after several Gyr
- Offset mergers drive fluid instabilities with long growth times (Ricker & Sarazin 2001)
- More important than shocks in raising core entropy
- *Detectability of instabilities and limits on ICM turbulence?*
- *Importance of bulk transport effects relative to local sources and sinks?*

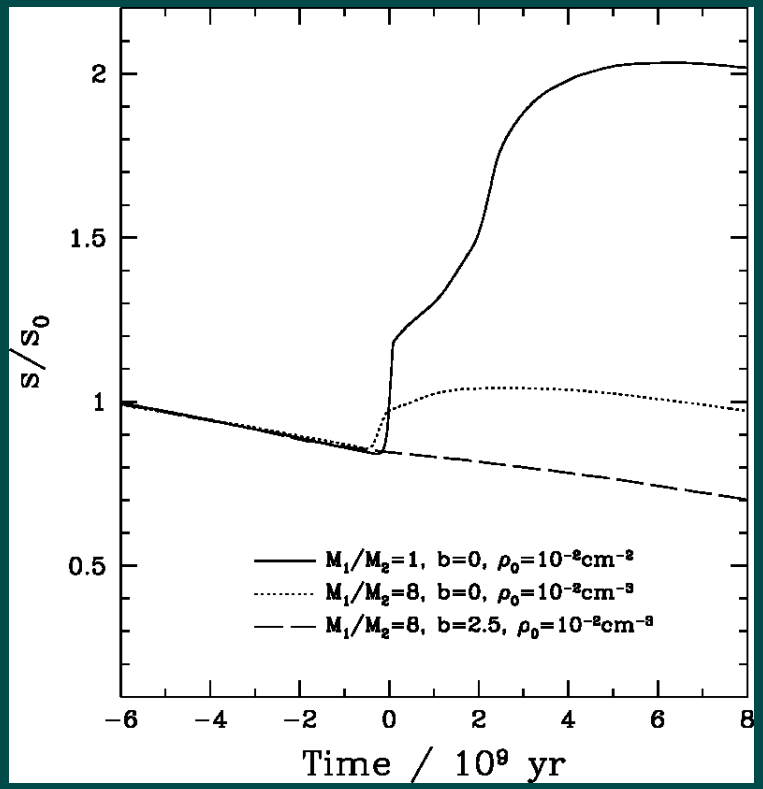
Ricker & Sarazin (2001)



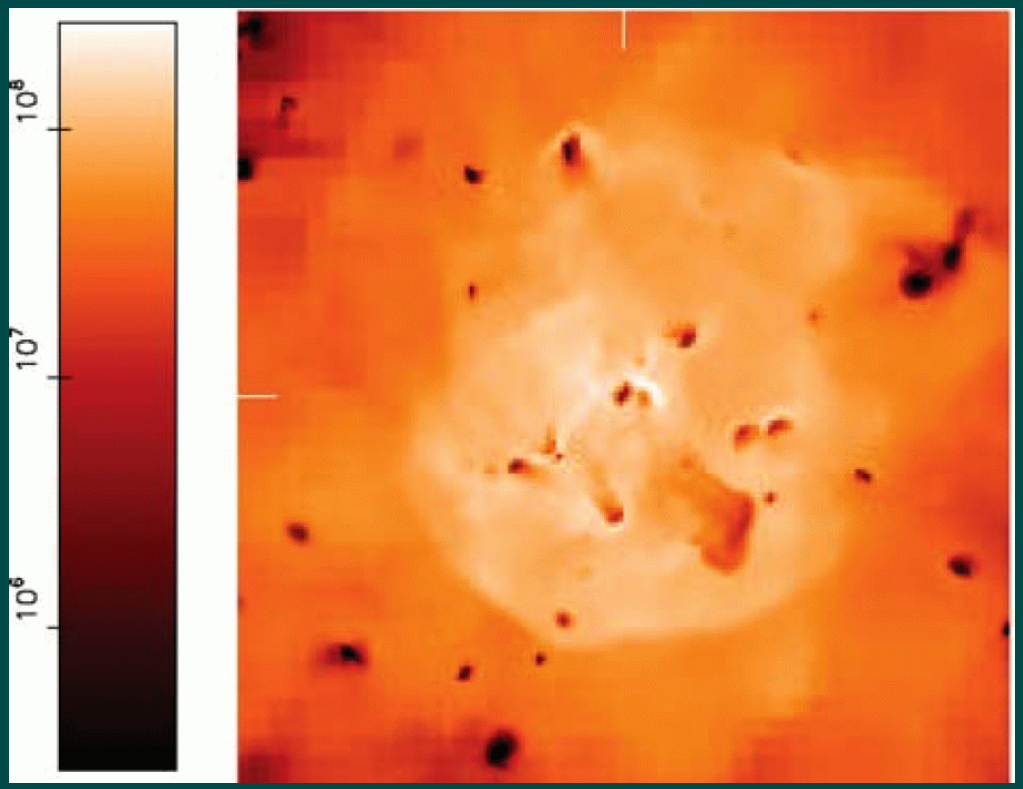
Gas specific entropy (color); gravitational potential (contours)

The cold regions formerly known as cooling flows

- Cold cores robust against high mass-ratio or offset mergers
  Gomez et al. (2002); Ritchie & Thomas (2002); Motl et al. (2004)
- Readily destroyed by equal-mass, head-on mergers
- *Effects when internal heating sources and multi-phase gas are included?*



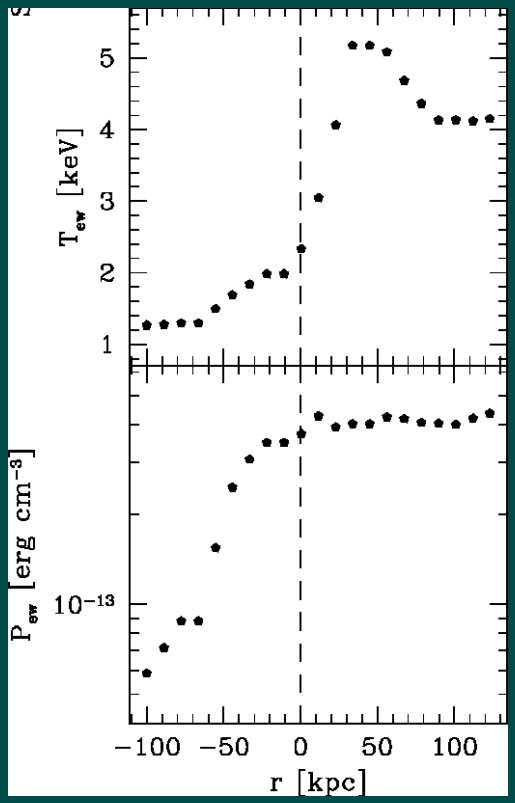
Ritchie & Thomas (2002)

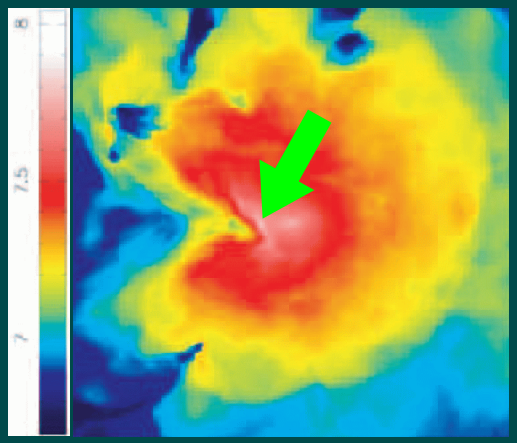


Motl et al. (2004)

Cold fronts

- Short-lived (~ 1 Gyr) contact discontinuities
- Major or minor mergers
- Mechanisms
  - Expansion of gas out of tidally disrupted subclumps (Bialek et al. 2002)
  - Contact discontinuity behind bow shock driven by confined gas (Nagai & Kravtsov 2003)
  - Radiative cooling not necessary!
- Internal motions may enhance temperature contrasts (Heinz et al. 2003; Mathis et al. 2004)
- |**B**| stretching allows conductivity constraints even in complex flow fields (Asai et al. 2004)
- *Statistics? Necessary conditions?*

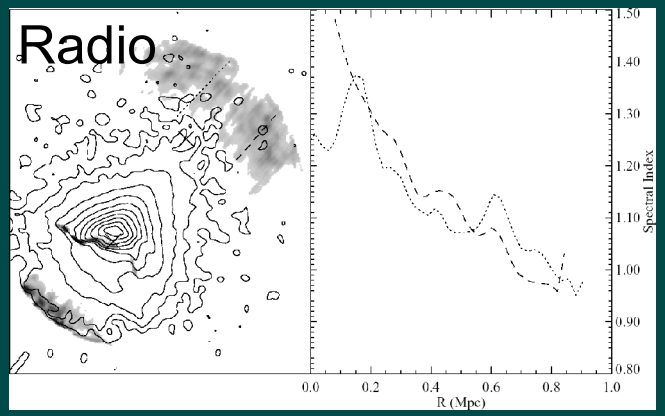




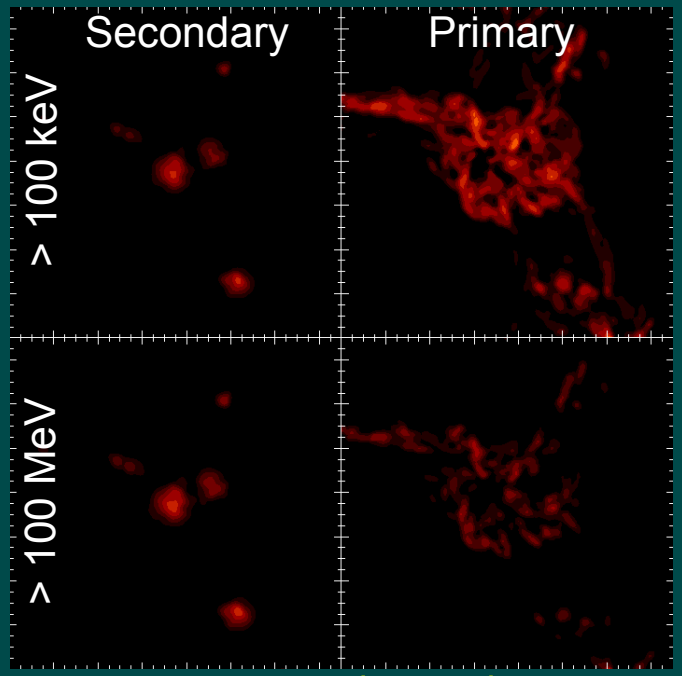
Nagai & Kravtsov (2003)

Radio sources from merger shock acceleration

- Relics (*gischt*; Kempner et al. 2004)
  - Simple 3D shock acceleration models reproduce shape and aging (Roettiger et al. 1999)
  - Diffusive models predict large cosmic-ray pressures (>10%) (Miniati et al. 2001)
  - Major merger shocks too weak? (Gabici & Blasi 2004)
- Halos
  - Secondary electrons can reproduce many halo features (Dolag & Ensslin 2000)
  - Gamma-ray imaging distinguishes from turbulent reacceleration model (Miniati 2002)
- *More groups need to include acceleration models in 3D simulations*
- *More detailed comparisons of 3D simulations with real clusters*



Roettiger et al. (1999)

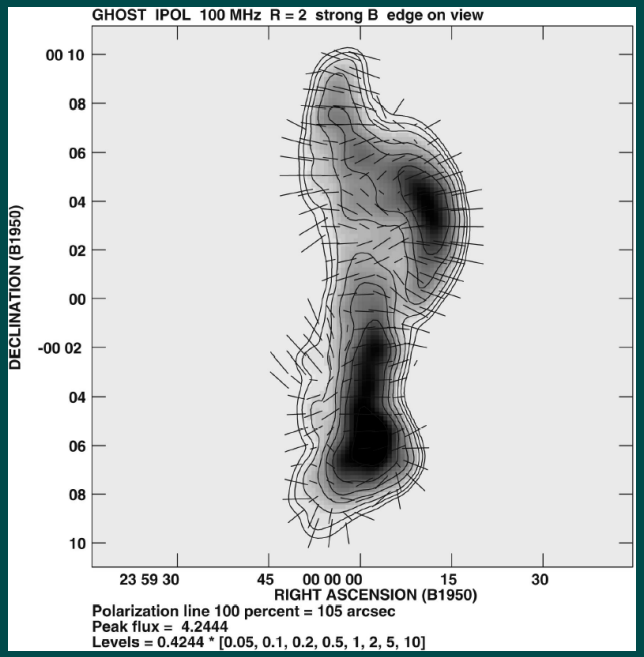


Miniati (2002)

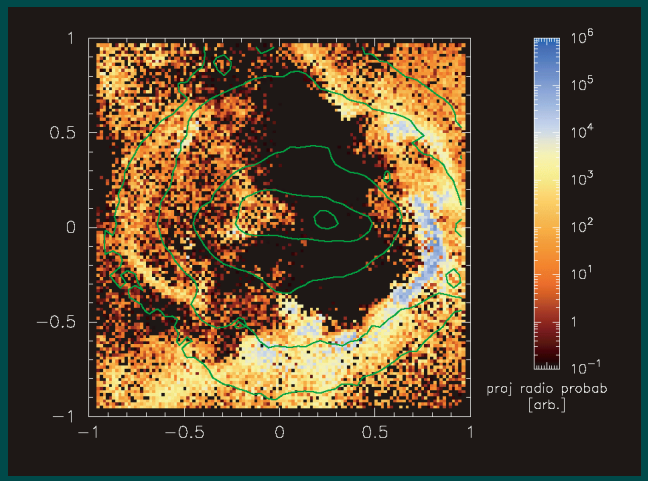
Radio sources from merger shock compression

Radio *phoenixes* (Kempner et al. 2004)

- Like gischt, but not in pairs
- Re-energization of fossil radio plasma? Ensslin & Gopal-Krishna (2001); Ensslin & Brüggen (2002); Hoeft et al. (2004)
  - Reproduces observed morphologies and spectra
  - Require P_{mag}/P_{therm} ~ 1%, radio plasma age ~ 1 Gyr
  - Relics > 100 kpc from center:
    - Shocks weaker in core
    - |**B**| larger in core (synchrotron losses)
- *Actual distribution of fossil plasma ages and resulting frequency of relics?*



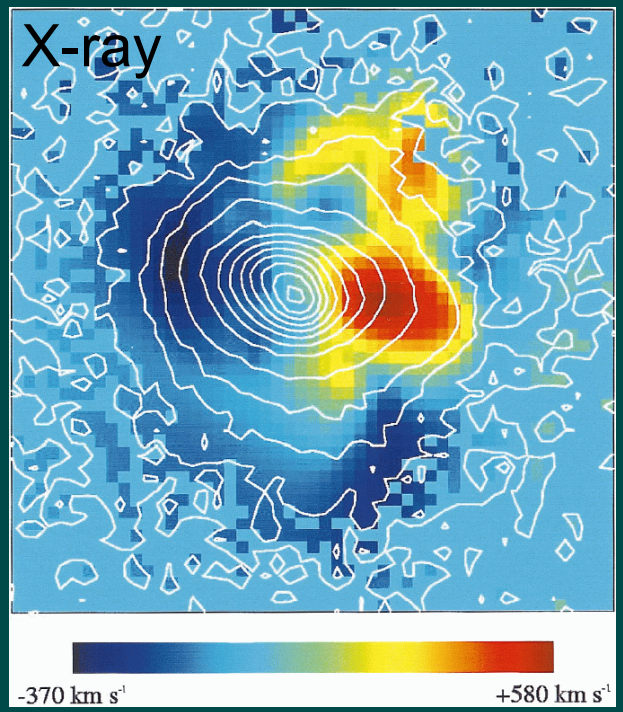
Ensslin & Brüggen (2002)



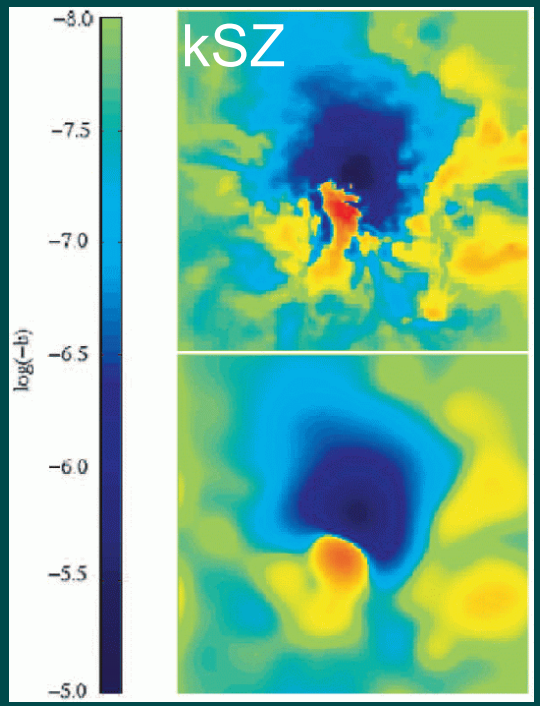
Hoeft et al. (2004)

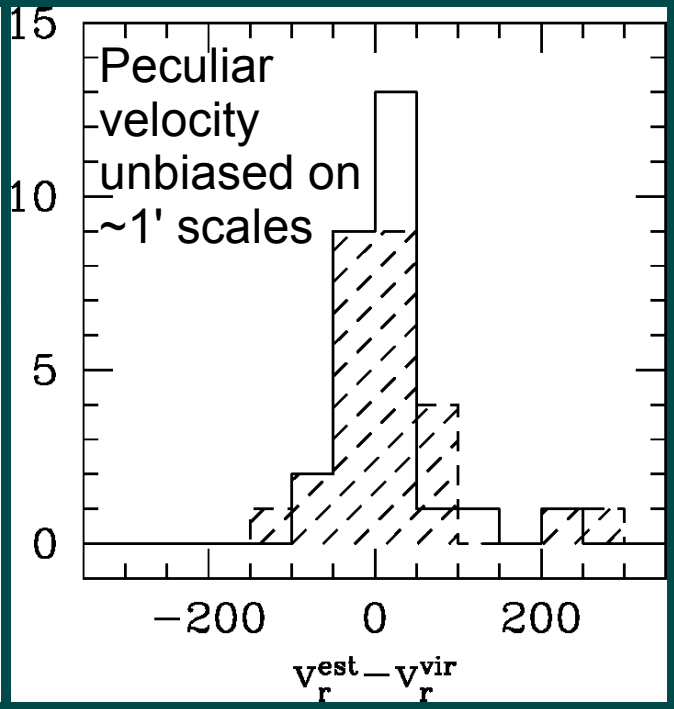
Detectability of merger-induced gas flows

- X-ray emission line shifts and Doppler broadening
  - Detectable with Astro-E2 ΔE ~ eV (Roettiger & Flores 2000; Sunyaev et al. 2003)
- Kinetic Sunyaev-Zel'dovich effect
  - Detectable in near future with $\Delta T/T \sim 10^{-5}$ on scales < 1', ignoring other sources of error (Dupke & Bregman 2002; Nagai et al. 2003; Sunyaev et al. 2003)



Roettiger & Flores (2000)

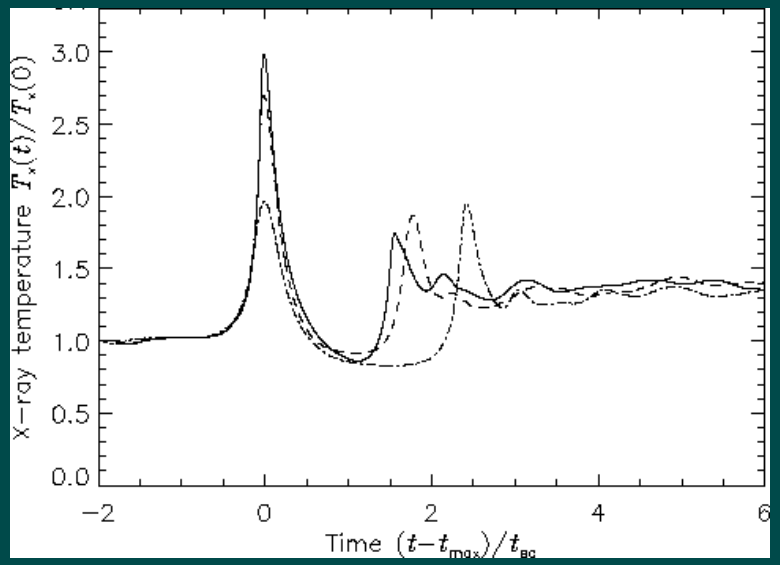




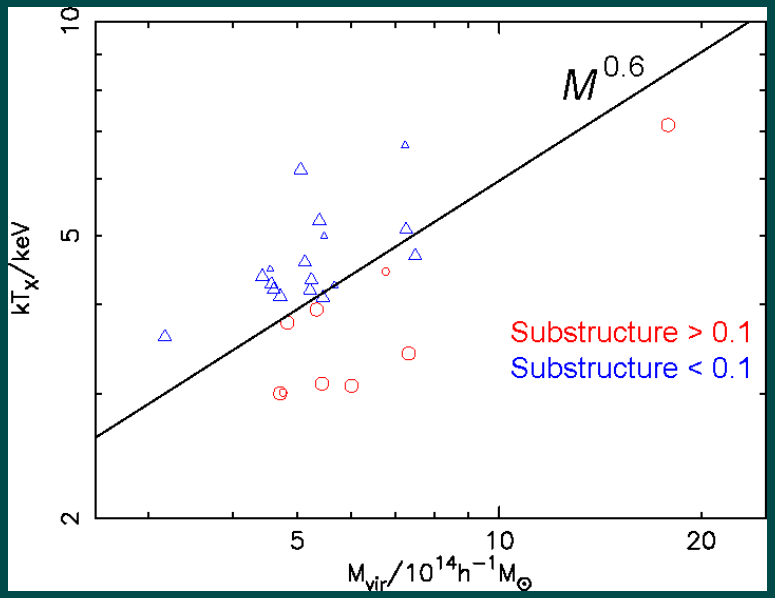
Nagai et al. (2003)

Mergers and X-ray statistics

- X-ray temperatures and luminosities
  - Mass function derived assuming hydrostatic equilibrium
  - Mergers temporarily boost *L* and *T*, biasing mass estimates
  - ~ 10% systematics in σ_8 and Ω_m (Randall et al. 2002)
  - Scatter in *M-T* correlated with substructure (Rowley et al. 2004)
  - *Need large sample of simulated and observed clusters with lensing and hydrostatic masses*



Ricker & Sarazin (2001)



Rowley et al. (2004)

Mergers and Sunyaev-Zel'dovich statistics

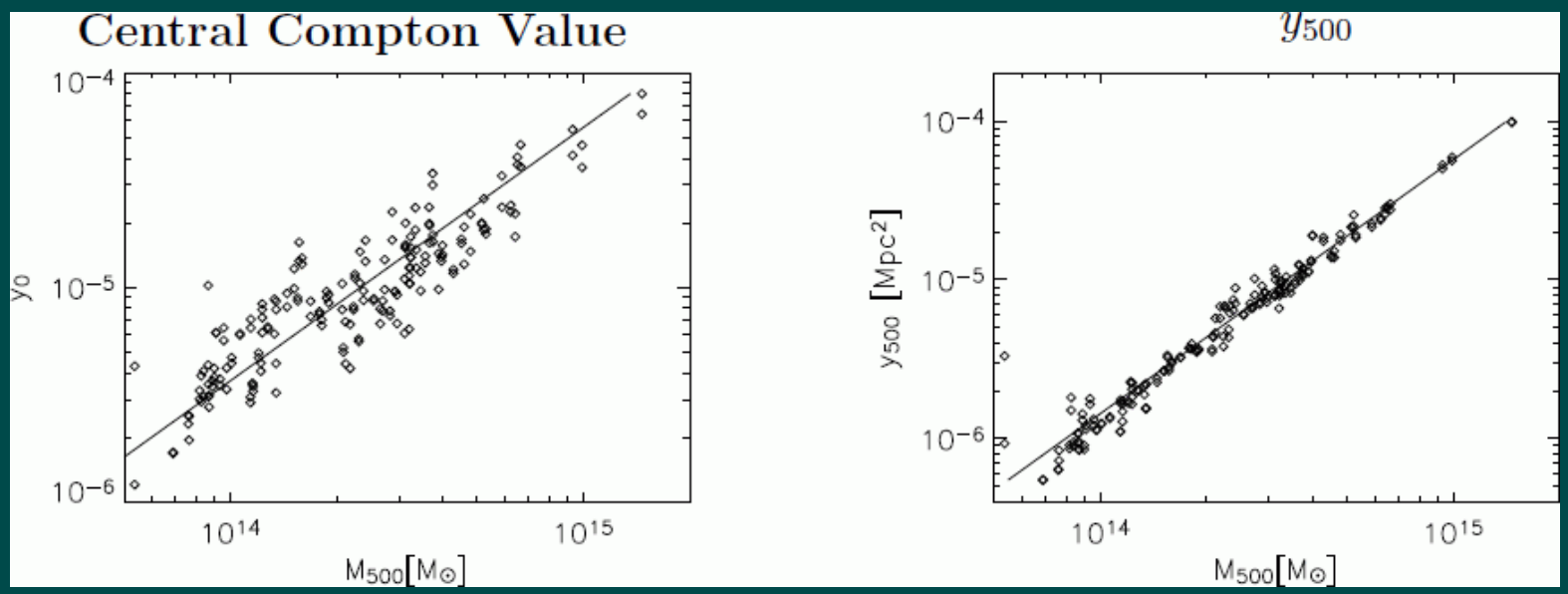
- Effects on thermal SZ observables (Motl et al. 2005)
  - Significant transient boosts (2-20) in central decrement
  - Integrated SZ decrement within r_{500} relatively insensitive to mergers or to entropy-producing processes

TABLE 1
SCALING EXPONENT FOR $y_{500} - M$ RELATION, z=0

Simulation	α	σ_α
Adiabatic	1.59	0.021
Radiative Cooling	1.71	0.031
Star Formation	1.60	0.027
Star Formation with Feedback	1.61	0.024

TABLE 2
ACCURACY OF MASS ESTIMATION, z=0

Method	Median M_{est}/M_{true}	$+1\sigma$	-1σ	+80%	-80%
$y_{500} - M$	0.97	1.00	0.93	1.13	0.86
$T_X - M$	1.04	1.11	0.92	1.33	0.74
$L_{X,500} - M$	0.87	1.03	0.75	1.46	0.62
$y_0 - M$	0.96	1.14	0.82	1.53	0.67



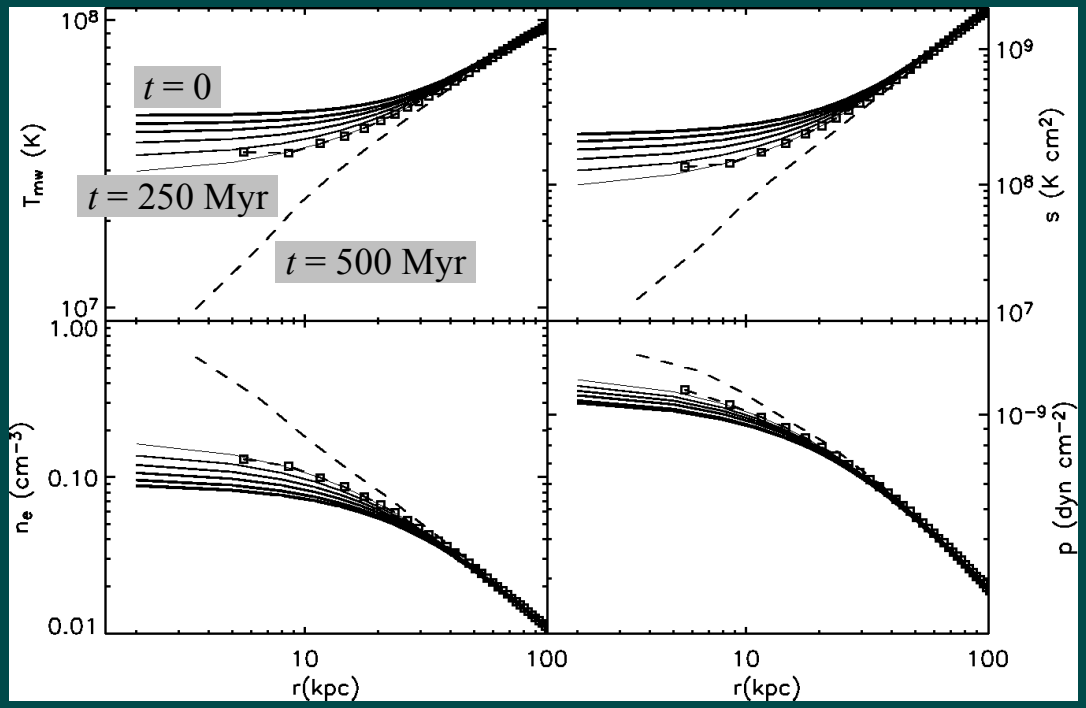
Mergers summary – cosmology effects

- Relaxation timescales and ICM state
  - "Obvious" effects (bimodality, etc.) last ~ 1 – 2 Gyr
  - "Non-obvious" effects (nonthermal support) last much longer
  - Direct measurement of turbulence will tell us how bad the "non-obvious" effects are
- Mass-observable relationships
  - X-ray: biased if "messy" clusters included; hard to get better than ~ 15% spread even if "smooth" clusters only
  - SZ: averaging within r_{500}, can overcome X-ray limitations, achieve unbiased estimator with ~ 4% errors
  - Weak lensing: serious systematic effects (M. White, SF04)
- Other
  - Strong lensing: arc frequency sensitive to merger rate
  - Cosmic rays: potentially an important (~ 10%) contributor to cluster energy content

Bubbles

Cooling flows

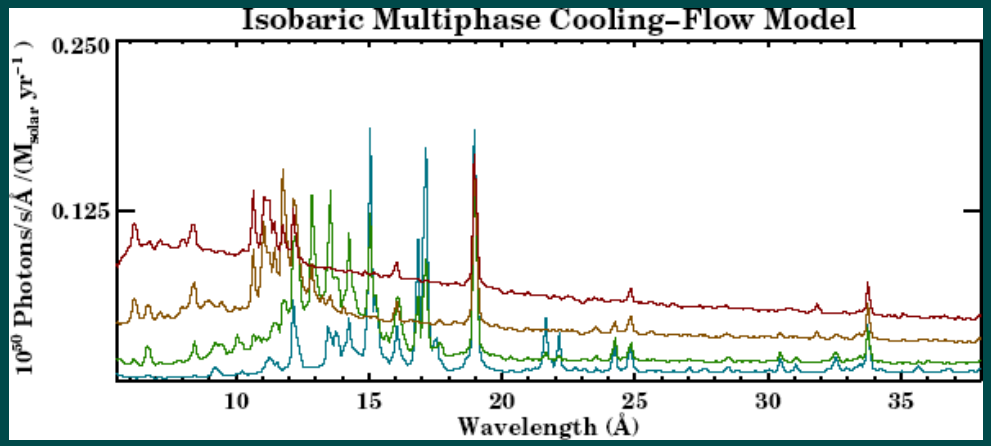
- If $t_{\rm cool} < t_{\rm Hubble}$, expect cooling to be important
  - Loss of pressure support against gravity
  - Slumping of gas toward cluster center
  - X-ray luminosity spike at center
  - Runaway cooling ⇒
    - Thermal instability
    - Multiphase medium
    - Star formation (1 – 100 $M_\odot$ yr^{-1})
- Review: Fabian (1994)

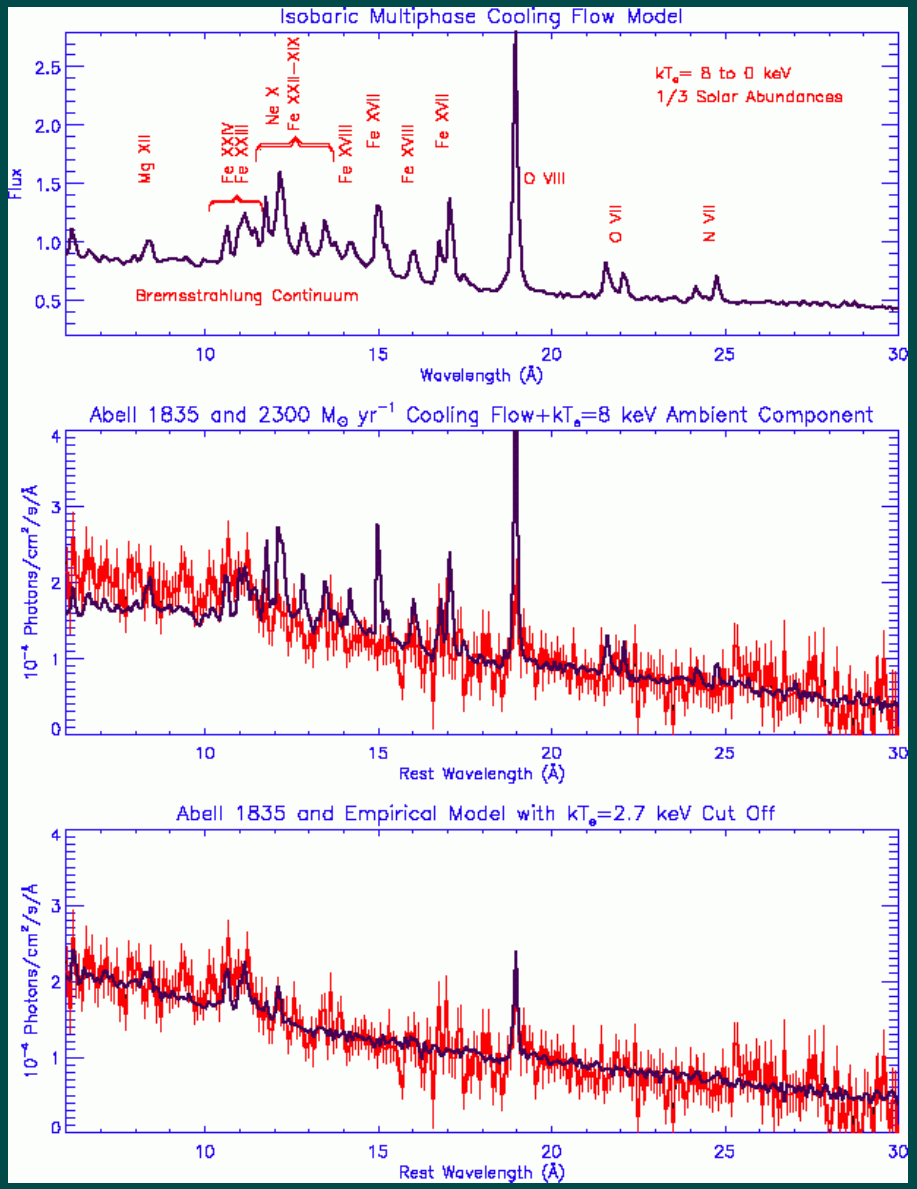


Gardini & Ricker (2005)
Cooling-only reference cases
(single phase)

Where is the cold gas?

- Expect strong X-ray emission lines from gas cooling below ~ 1 keV
- New instruments (ASCA, Chandra, XMM) have energy sensitivity and spectral resolution to detect them
- Not seen !!

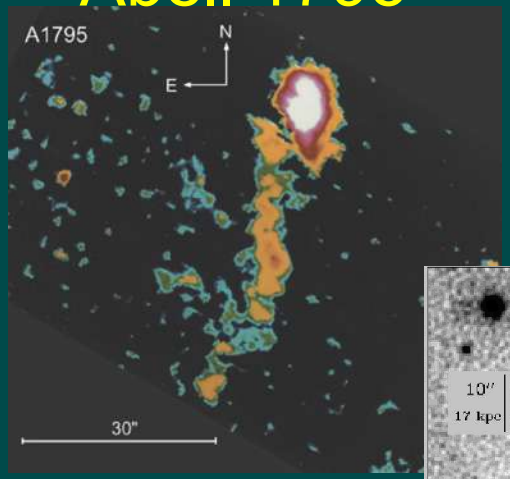




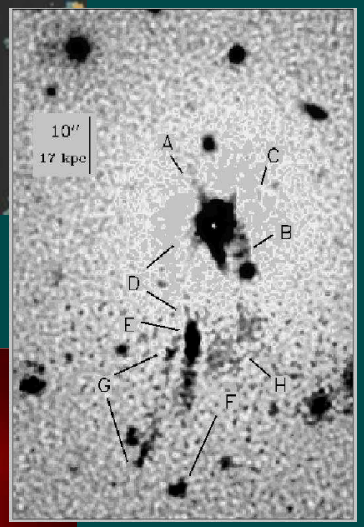
Petersen et al. (2003)

Star formation in cooling flows

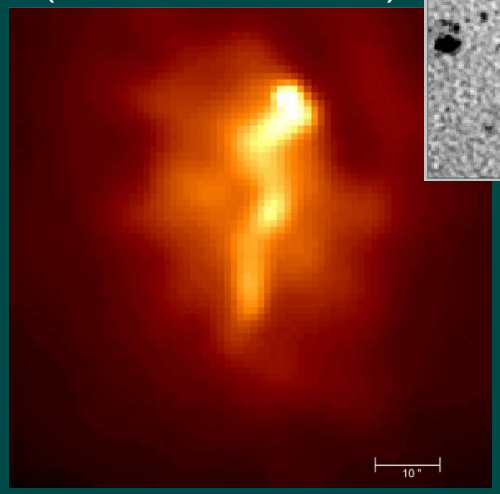
Abell 1795



Hα
(Cowie et al. 1983)

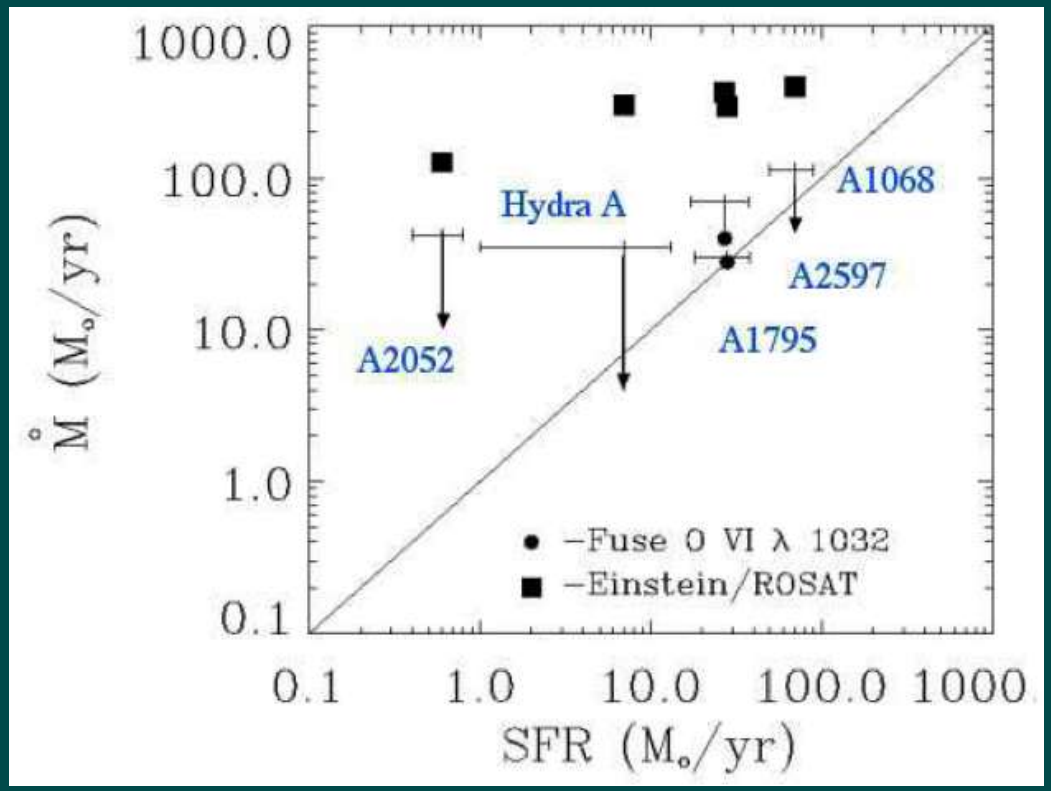


U band
(McNamara et al. 1997)



X-ray (Fabian et al. 2001)

Revised cooling mass accretion rates now consistent with star formation rates determined from optical filaments



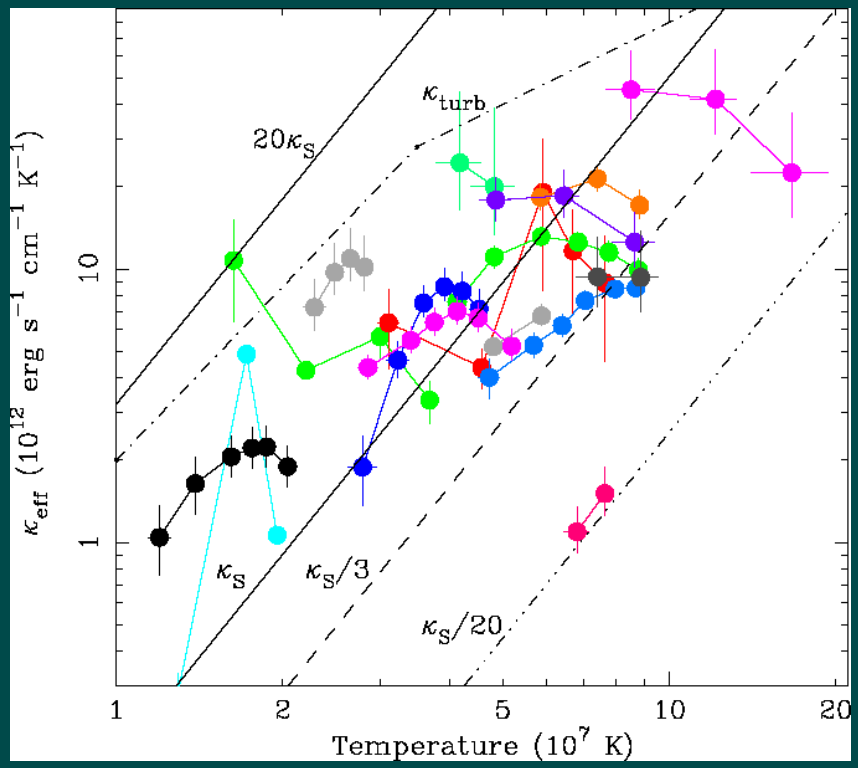
McNamara 2004 (astro-ph/0402081)

Thermal conduction

- Magnetic field previously thought to suppress thermal conduction to << Spitzer (1962) value

$$\kappa_S \approx 5.0 \times 10^{-7} T^{5/2} \text{erg s}^{-1} \text{ cm}^{-1} \text{ K}^{-7/2}$$

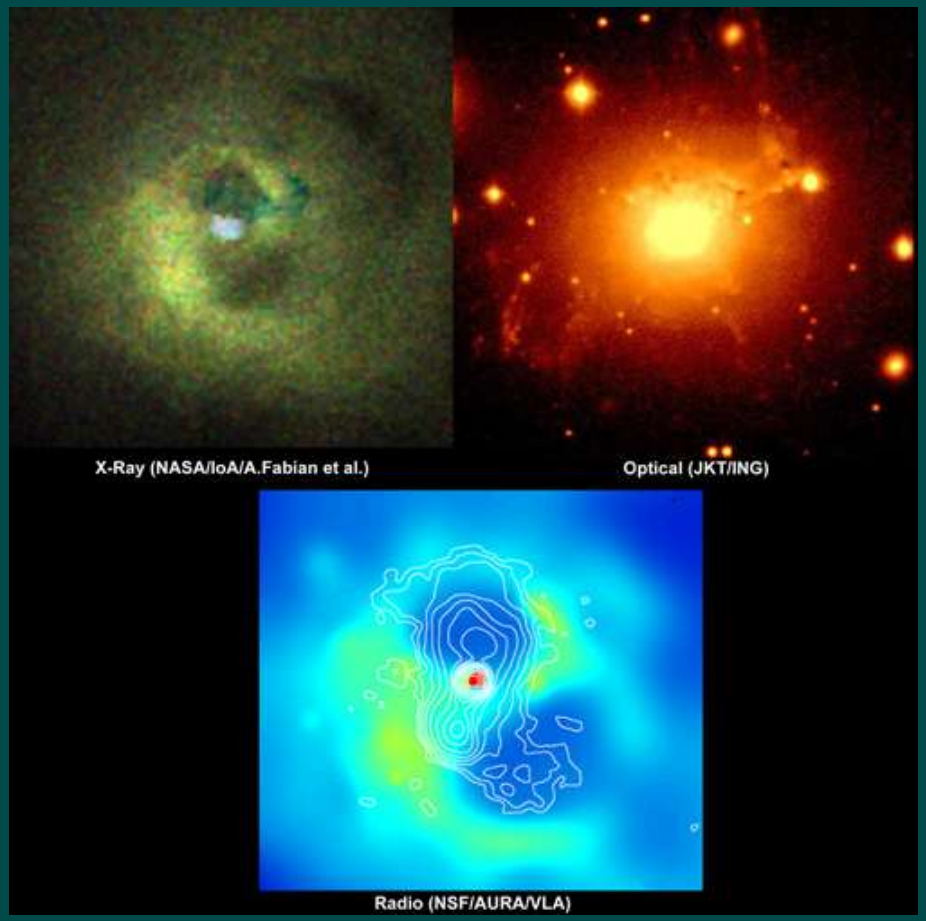
- Chaotic B-field gives less suppression: 0.1 – 0.4 (Narayan & Medvedev 2001) or ~ 0.02 (Maron et al. 2002)
- Conductivity required to balance cooling (Voigt & Fabian 2003):
  - > κ_S near center
  - < κ_S outside few x 10 kpc
- Problems
  - Too much needed near center
  - Fine tuning



Voigt & Fabian (2003)

Buoyant bubbles in the ICM

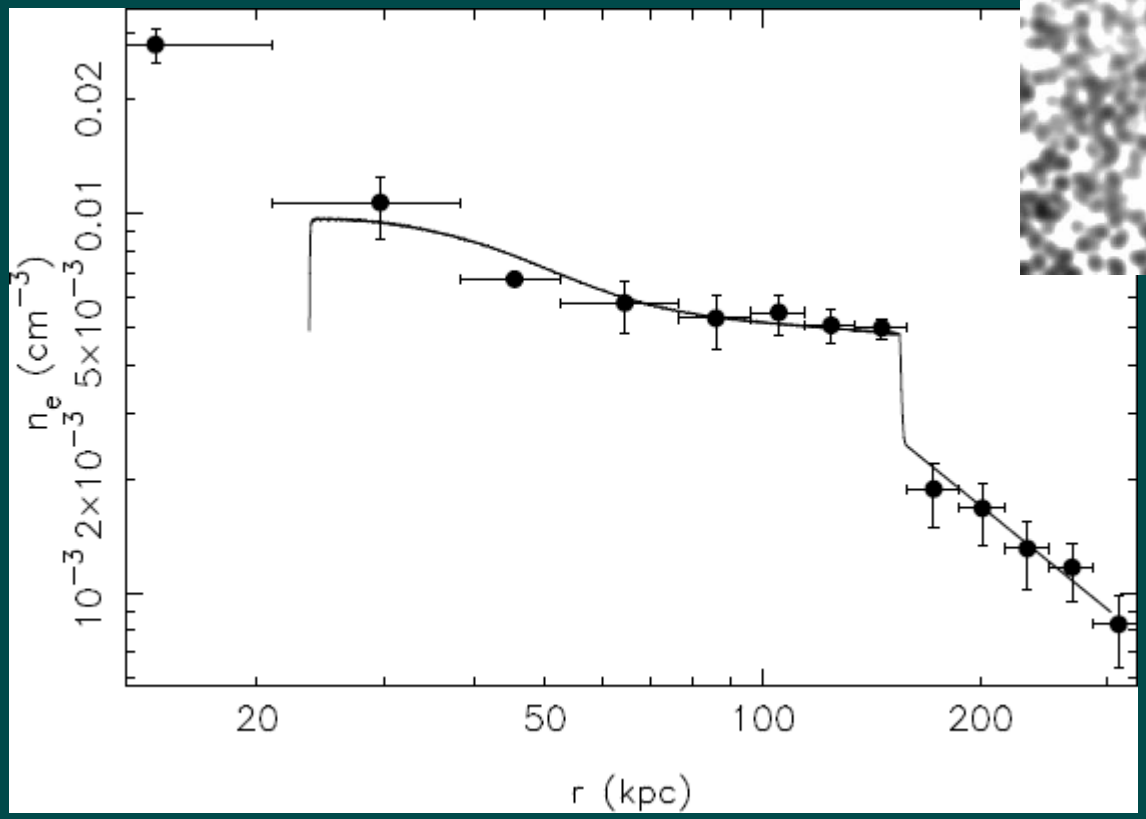
- Cavities in X-ray emission seen in ~ 16 Chandra clusters since 2000 (Birzan et al. 2004)
  - Associated with radio galaxies
  - Radii ~ 2 – 60 kpc
  - Buoyant rise times ~ 10 – 100 Myr
  - Multiple cavities in some clusters
  - Pressure equilibrium (some edge brightening though)
  - Often coincide with radio emission
  - Most subsonic

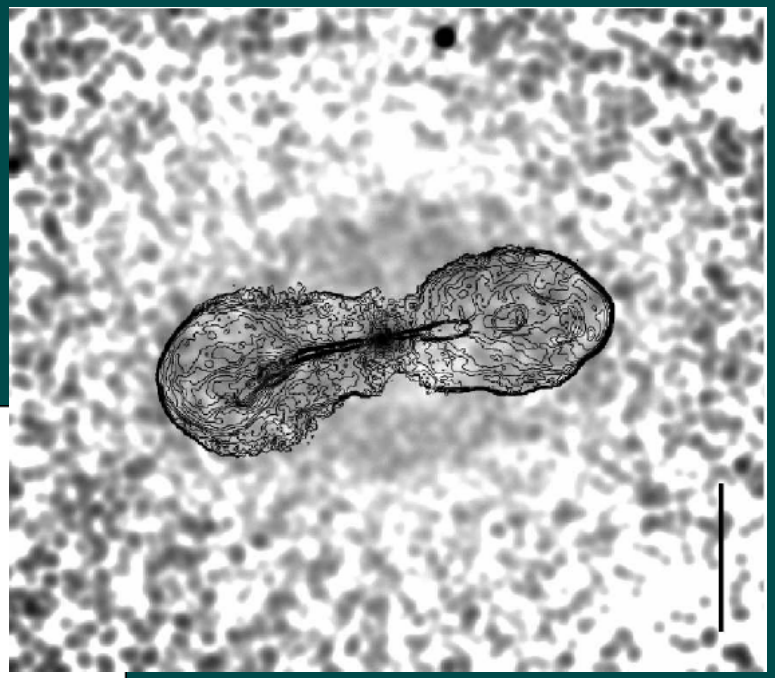


Perseus A
(z = 0.018)

Supersonic bubbles (Nulsen et al. 2005)

- Hydra A (z = 0.154)
  - Mach 1.65 shock – cocoon of radio lobes?
  - Energy > 100x radiative cooling losses

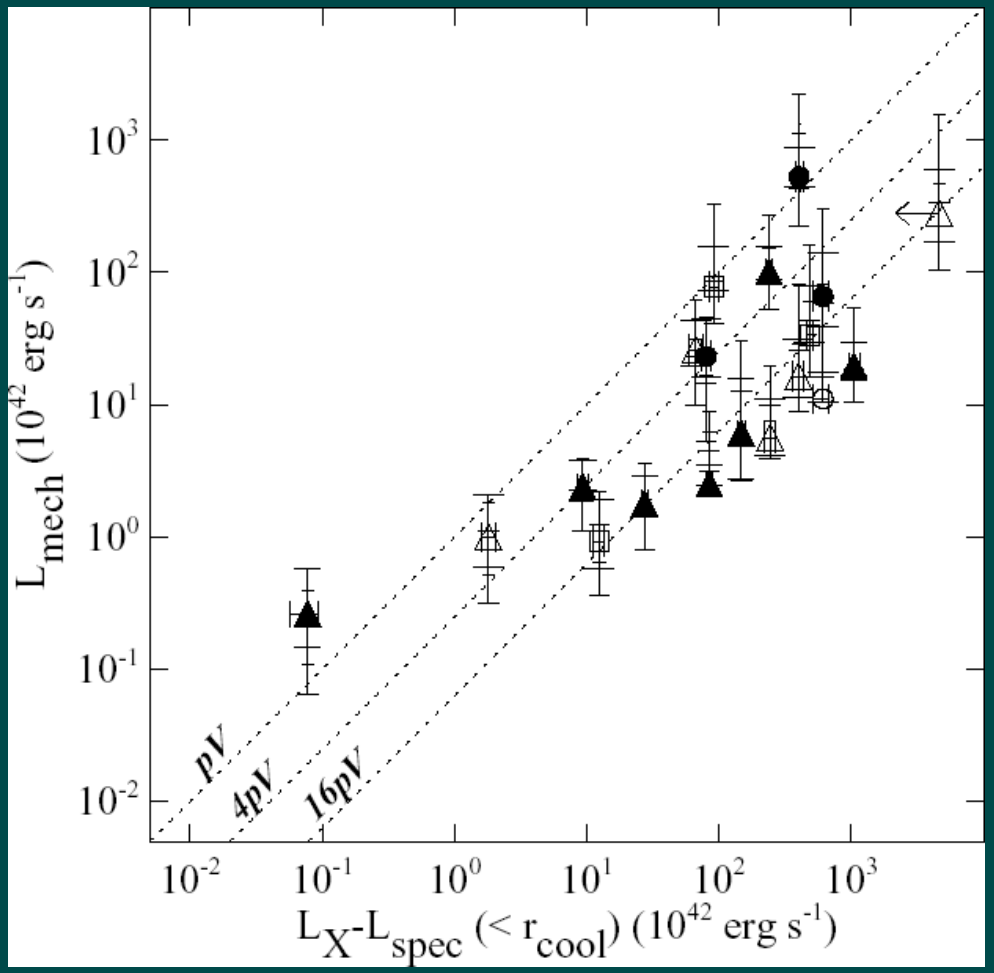




Chandra X-ray (gray) + 1.4 GHz radio (contours)

Bubble heating

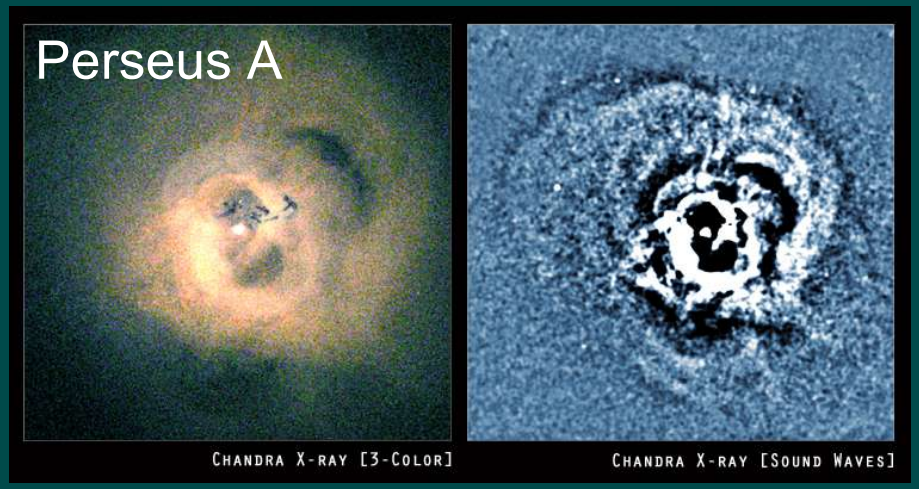
- Problems with bubble heating:
  - Not uniform
  - Convectively unstable
    - Could mix efficiently, but then problems with abundance gradients (Boehringer et al. 2004)
  - Fine tuning
  - Generally not enough
- Mechanical energy in bubbles does seem to go up with ICM X-ray luminosity
  - Feedback mechanism?



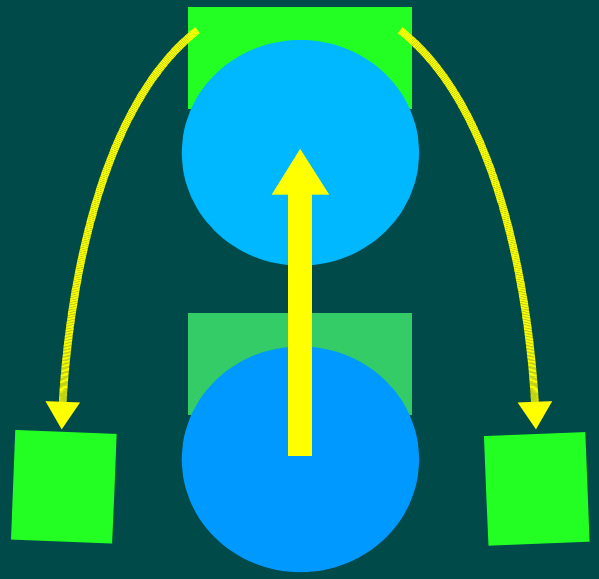
Birzan et al. (2004)

Possible bubble heating mechanisms

- *P*d*V* work as bubble expands
- Sound waves with viscous damping
- Shocks (into ICM or interacting with bubbles)
- Diffusive mixing of hot bubble plasma with ICM
- Diffusive mixing of ICM with hotter ICM at larger radii
- Lifting of ICM followed by potential energy release

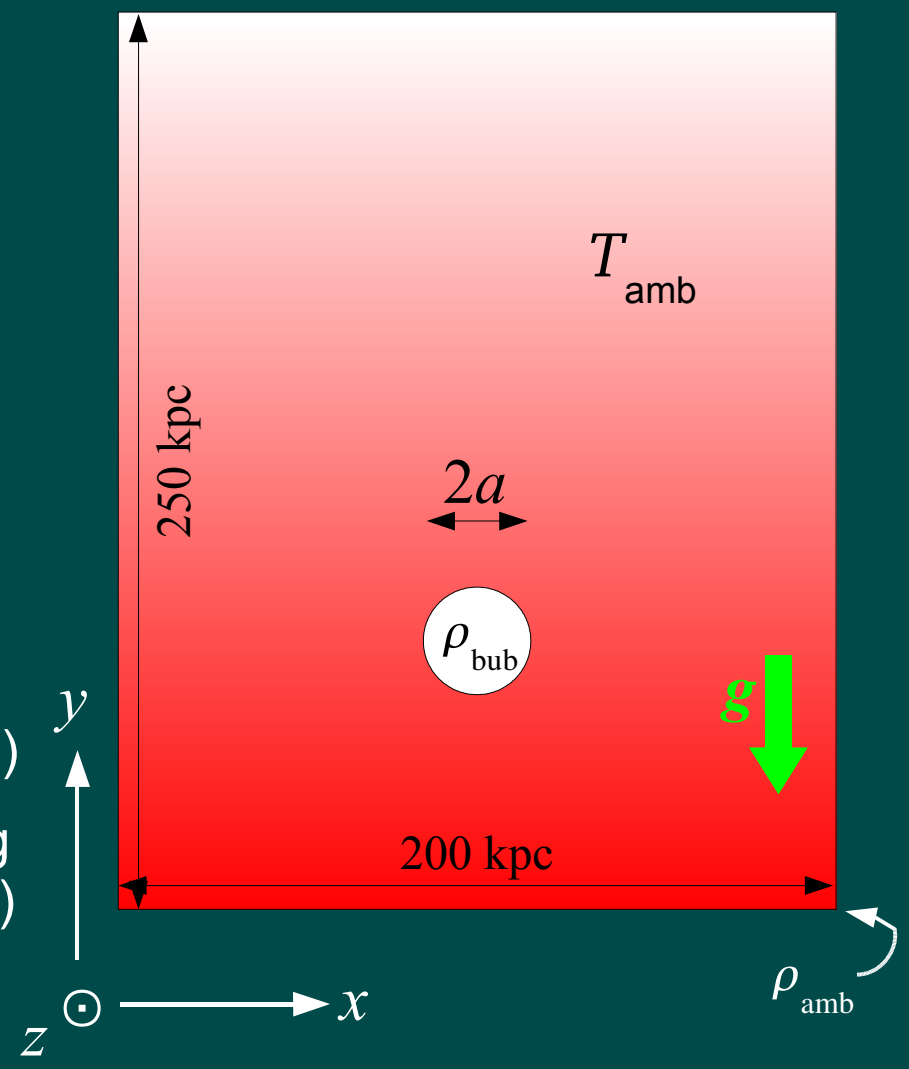


Fabian et al. (2003)



FLASH simulations of bubbles (Robinson et al. 2004)

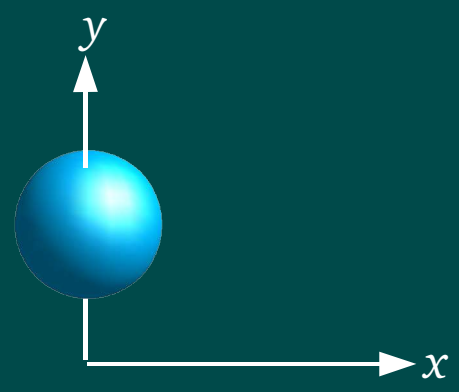
- Initial conditions:
  - Plane-parallel stratified atmosphere
  - Buoyant bubble in horizontal pressure (thermal + magnetic) equilibrium
- Domain:
  - 200 × 250 kpc (2D)
  - About 3 pressure scale heights
  - AMR with effective 512 × 640 mesh
- Solvers:
  - PPM with hydrostatic modifications for hydrodynamic cases (Zingale et al. 2002)
  - TVD MHD solver using diffusive cleaning to enforce $\nabla \cdot \mathbf{B}=0$ (Marder & Barry 1987)



FLASH simulations of bubbles (Robinson et al. 2004)

Vary:

- Density contrast: 10:1 and 100:1 ($n_{e,amb}$ = 5×10^{-3} cm^{-3}, T_{amb} = 8.9 keV)
- Geometry: planar and axisymmetric
- Bubble size: a = 15 kpc and 25 kpc
- Stratification: g = (5,1.25)×10^{-8} cm s^{-2}) (field of 10$^{14}M_\odot$ point mass @ 170 kpc)
- Physics: hydrodynamic and MHD (MHD in planar geometry only)
- Magnetic field with varying $\beta \equiv 8\pi P/B^2$ (β = 460, 0.19, 0.046, 0.012)
  - Horizontal (z)
  - Horizontal (x)
  - Vertical (y)
  - Force-free field with background horizontal z field (Cargill & Chen 1996)



Axisymmetric geometry

"Flux rope" field configuration

$$B_\theta = \begin{cases} B_b \dfrac{r}{a} & r < a \\ 0 & r \geq a \end{cases}$$

$$B_z = \begin{cases} B_b \left[4 - 2(r/a)^2\right]^{1/2} & r < a \\ B_{z0} & r \geq a \end{cases}$$

$$B_b \equiv \frac{1}{\sqrt{3}} \sqrt{8\pi(P_{amb} - P_{bub}) + B_{z0}^2}$$

Nonmagnetized bubbles (Robinson et al. 2004)

Results:

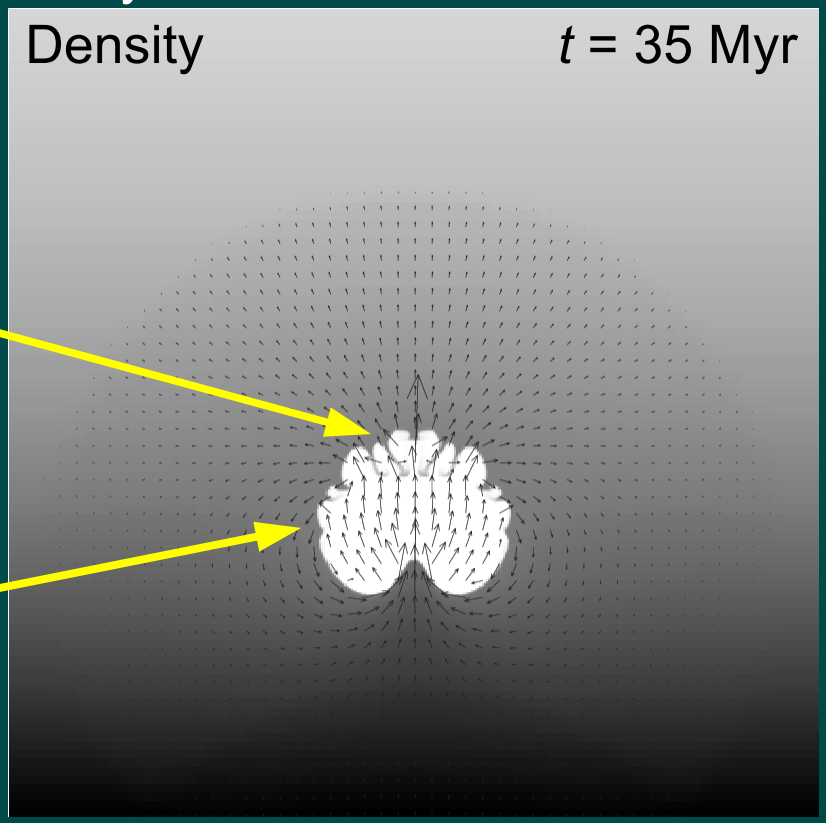
- Purely hydrodynamic bubbles are disrupted by fluid instabilities

Rayleigh-Taylor at top

Growth time $t_{\mathrm{RT}} = \sqrt{\frac{a}{2\pi g}} \sim 10\ \mathrm{Myr}$

Rise time $t_{\mathrm{rise}} = \sqrt{\frac{4a}{g}} \sim 60\ \mathrm{Myr}$

Kelvin-Helmholtz along sides



- Instability growth rate controlled by Atwood number

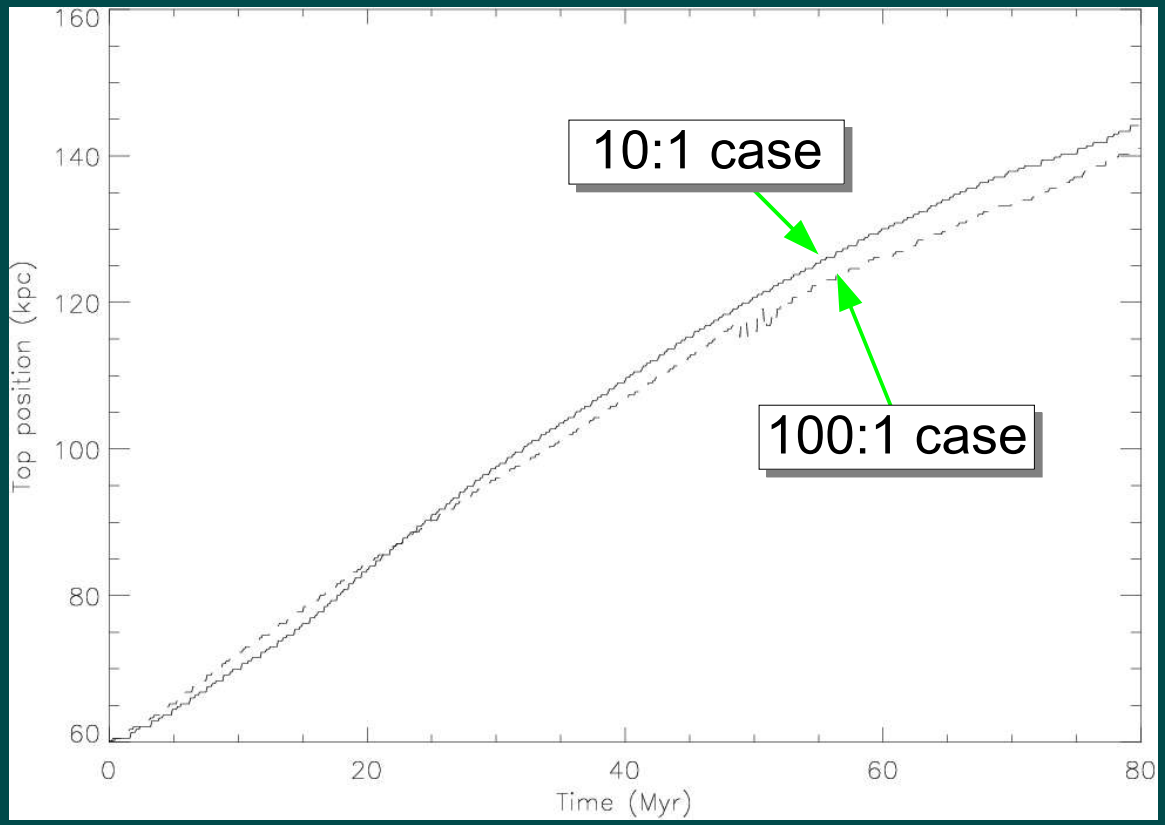
$$A \equiv \frac{\rho_{\mathrm{amb}} - \rho_{\mathrm{bub}}}{\rho_{\mathrm{amb}} + \rho_{\mathrm{bub}}}$$

⇒ changes only from 0.82 (10:1) to 0.98 (100:1)

Nonmagnetized bubbles (Robinson et al. 2004)

Vertical position of top of bubble vs. time

- Relatively insensitive to density contrast (denser bubble entrains less ambient fluid)

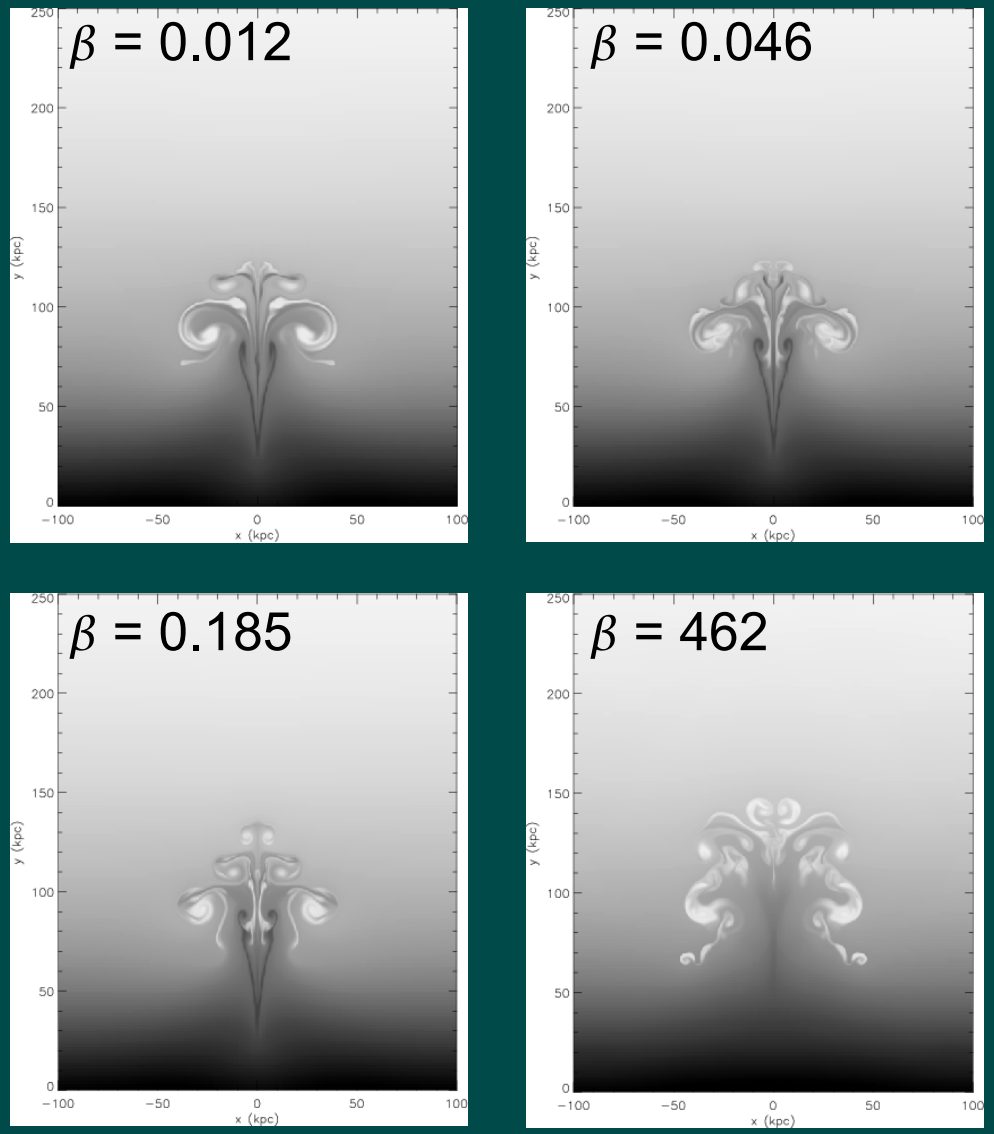


Magnetized bubbles (Robinson et al. 2004)

- Pressure-supported bubbles, external magnetic fields
- Horizontal (*z*) field acts to reduce effective stratification

$$\frac{\nabla P}{P} \rightarrow \frac{\beta}{\beta+1}\frac{\nabla P}{P}$$

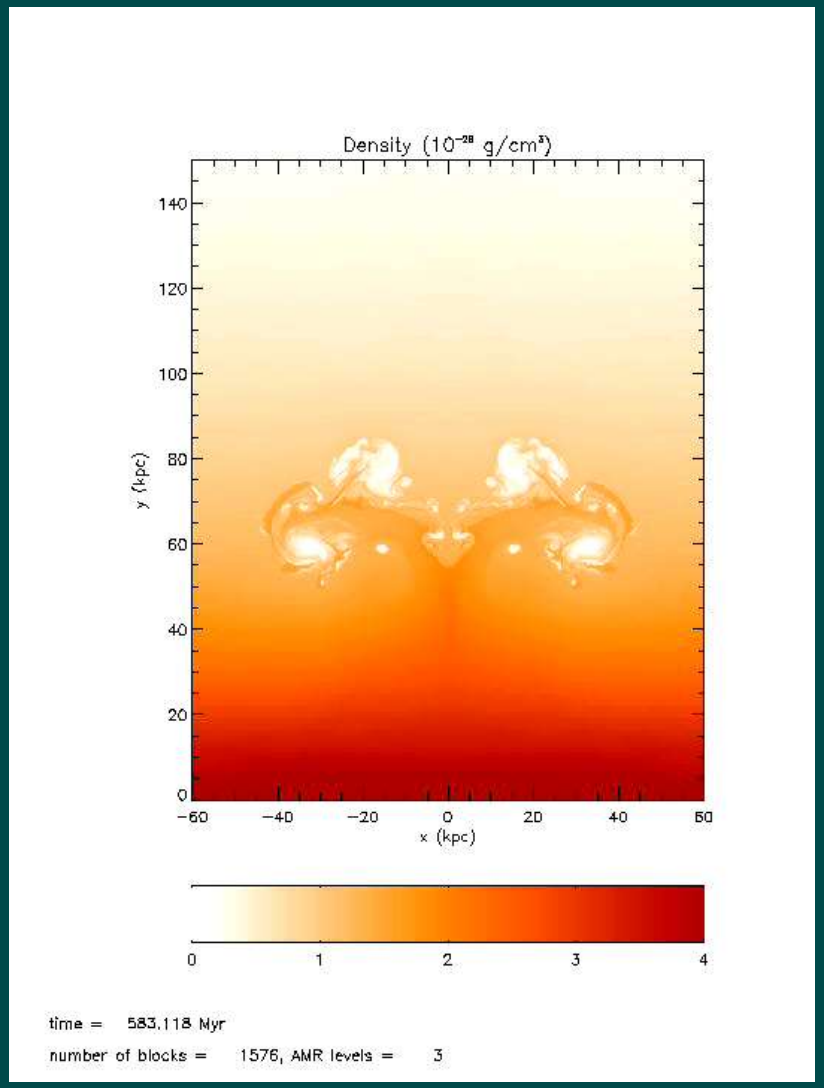
- Decreasing β acts to tighten vortical structures
- Horizontal (*x*) field completely contains bubble – acts as surface tension
- Artifact of geometry
- Vertical (*y*) field helps to suppress KH instability along sides
- Sufficiently strong field (β=0.019) can prevent disruption (probably unrealistic)



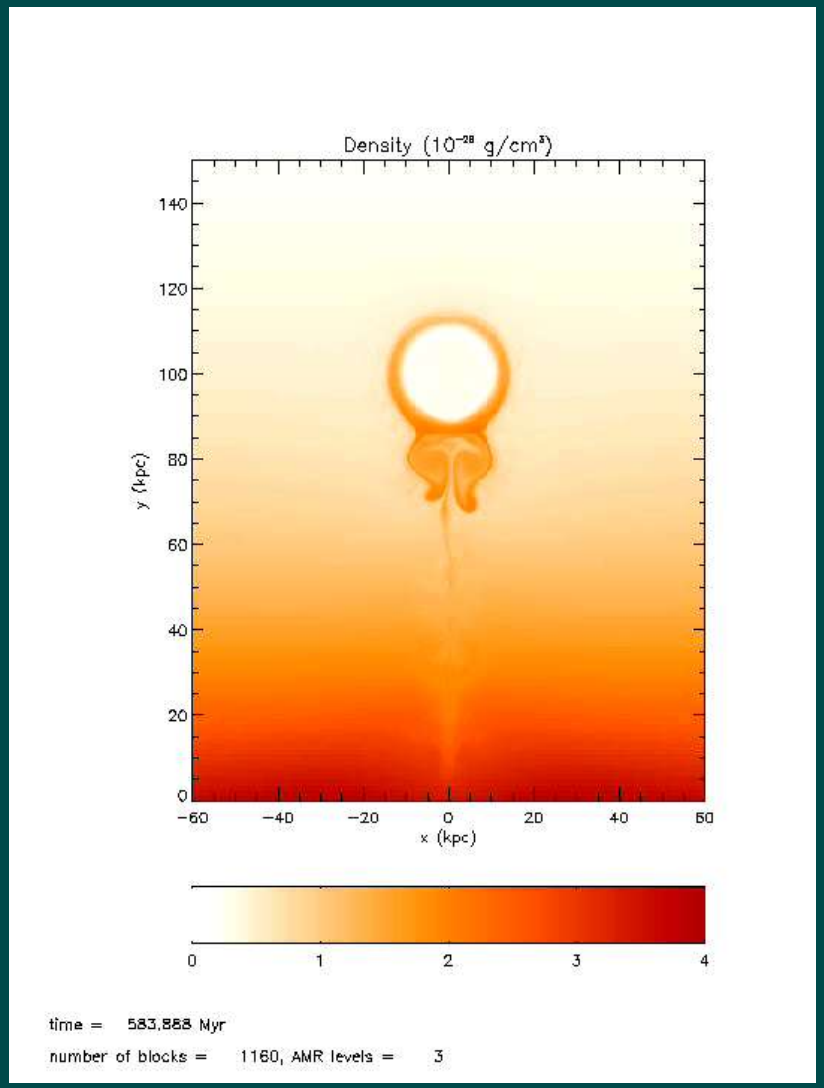
Gas density at *t* = 250 Myr for horizontal *z* field configurations

Magnetized bubbles (Robinson et al. 2004)

No magnetic field



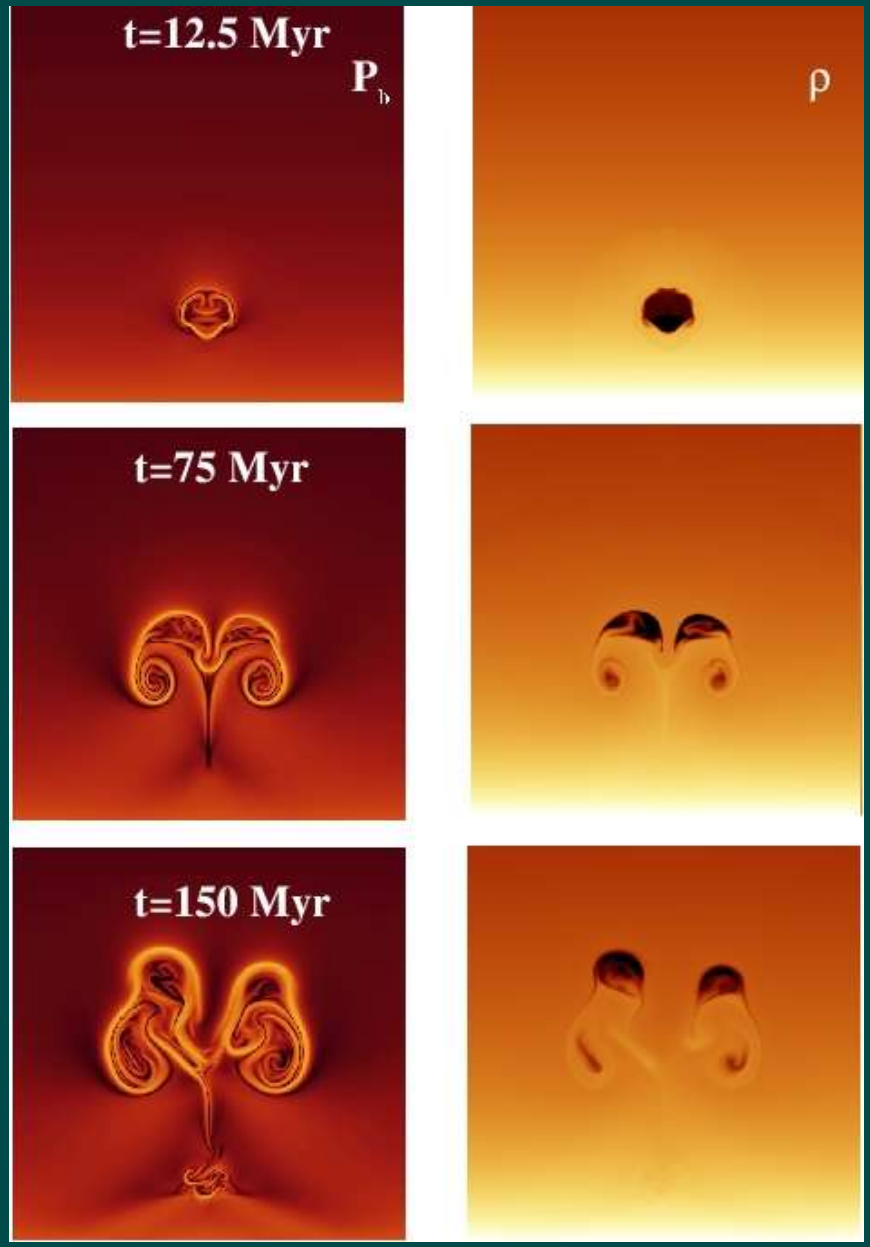
Force-free field, $\beta \simeq 0.9$



Density (g cm^{-3})

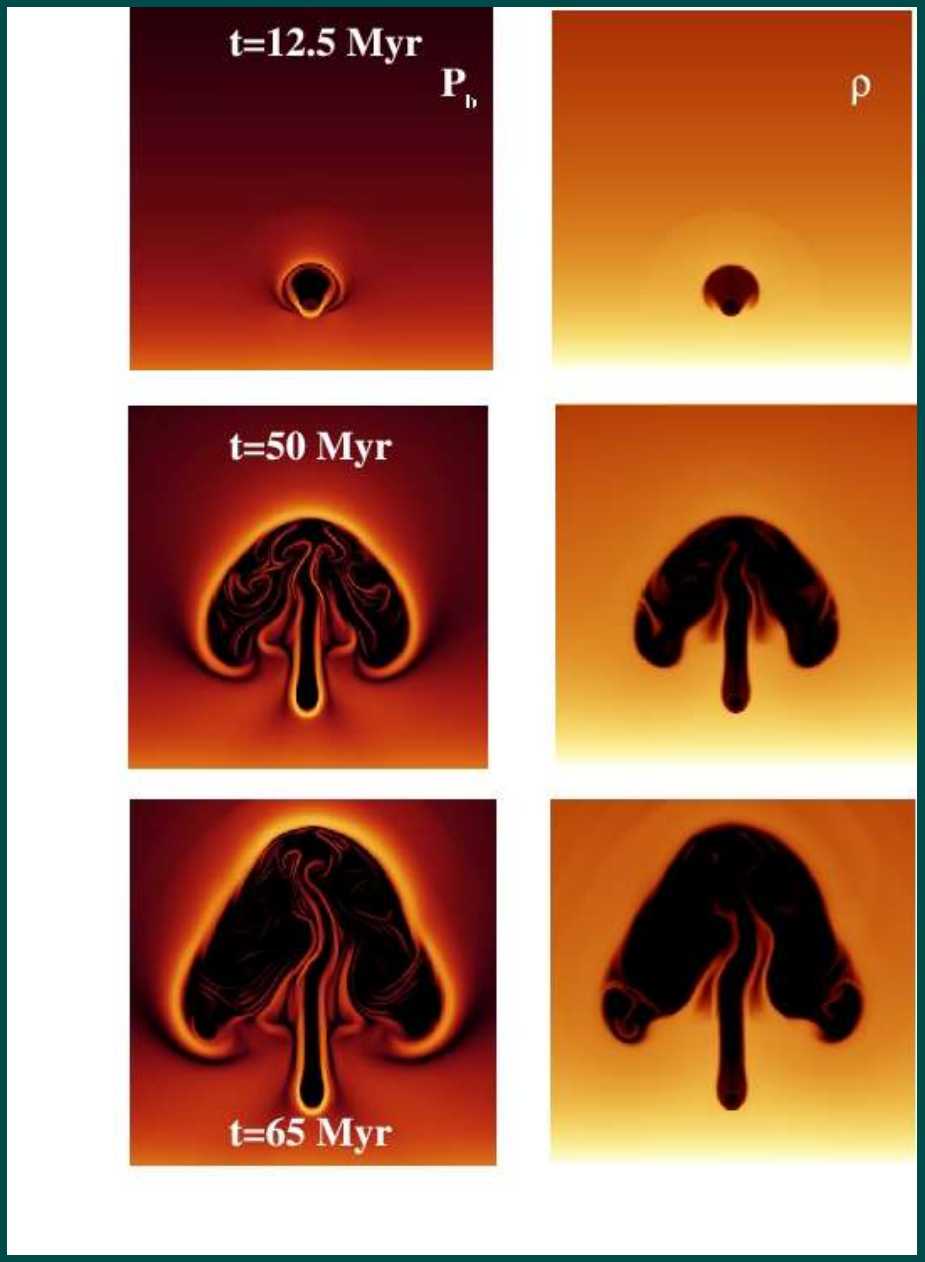
2D magnetized bubbles (Jones & De Young 2005)

- More realism...
  - Cluster + galaxy potential
  - Bubble inflation
  - Initially small bubble field, isolated from ICM field
- Results consistent with Robinson et al.:
  - **B** suppresses bubble deformation
- Also:
  - Internal bubble shear quickly amplifies magnetic field to ~ 20 μG on bubble surface



2D magnetized bubbles (Jones & De Young 2005)

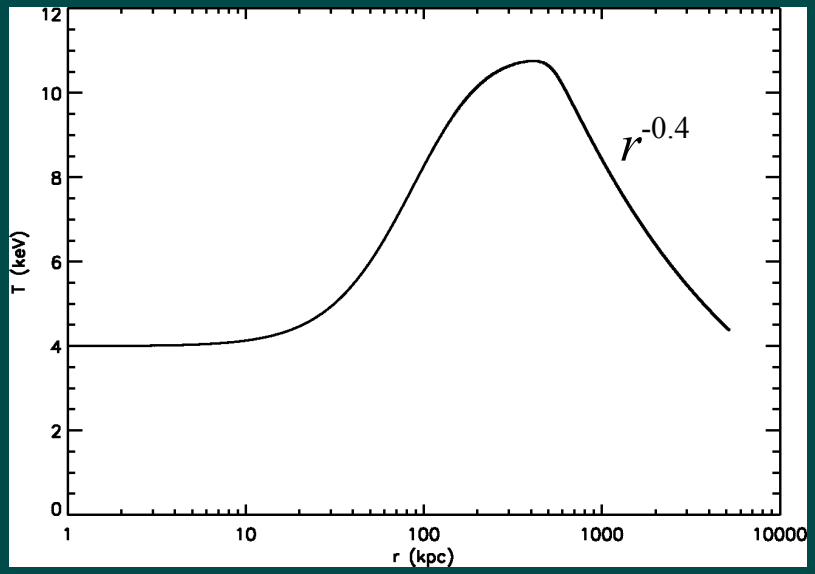
- Duration of inflation matters:
  - Compare to bubble rise time through one ICM scale height (~ 20 Myr)
  - Slower bubble inflation creates mildly supersonic internal motions (crude de Laval nozzle)

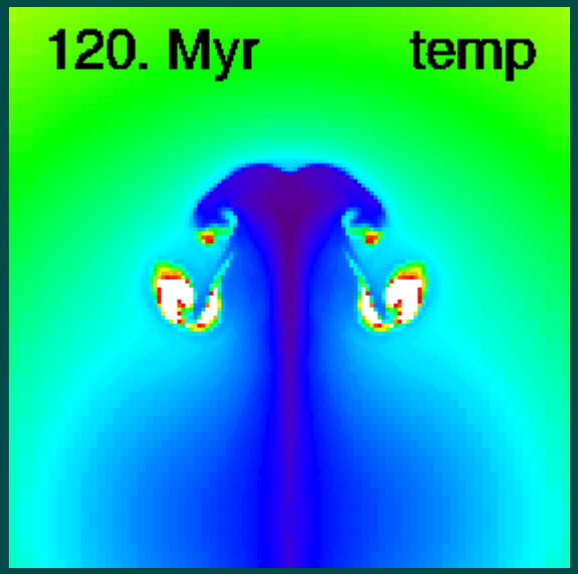


Hydrodynamic bubbles in 3D (Gardini & Ricker 2005)

- More realistic environment
  - 3D with fixed NFW potential
  - L = 600 kpc, Δx = 586 pc
  - Temperature profile from observations
  - Relativistic equation of state for bubble plasma
  - Radiative cooling
  - Reference against cooling-only case
- Objectives
  - Varied bubble size, radius
  - Investigate effect on cooling flow and heating mechanism

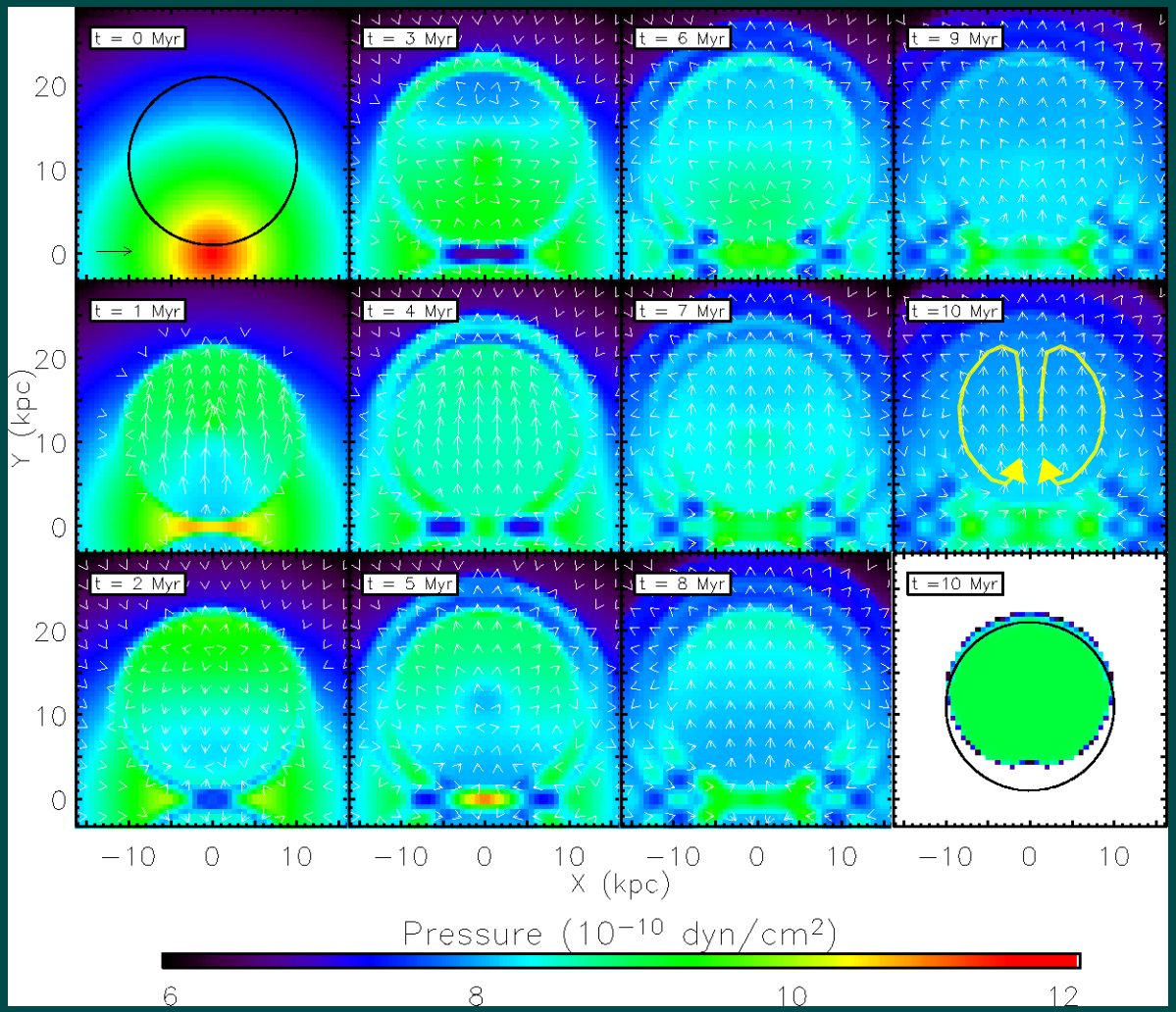
Initial temperature profile





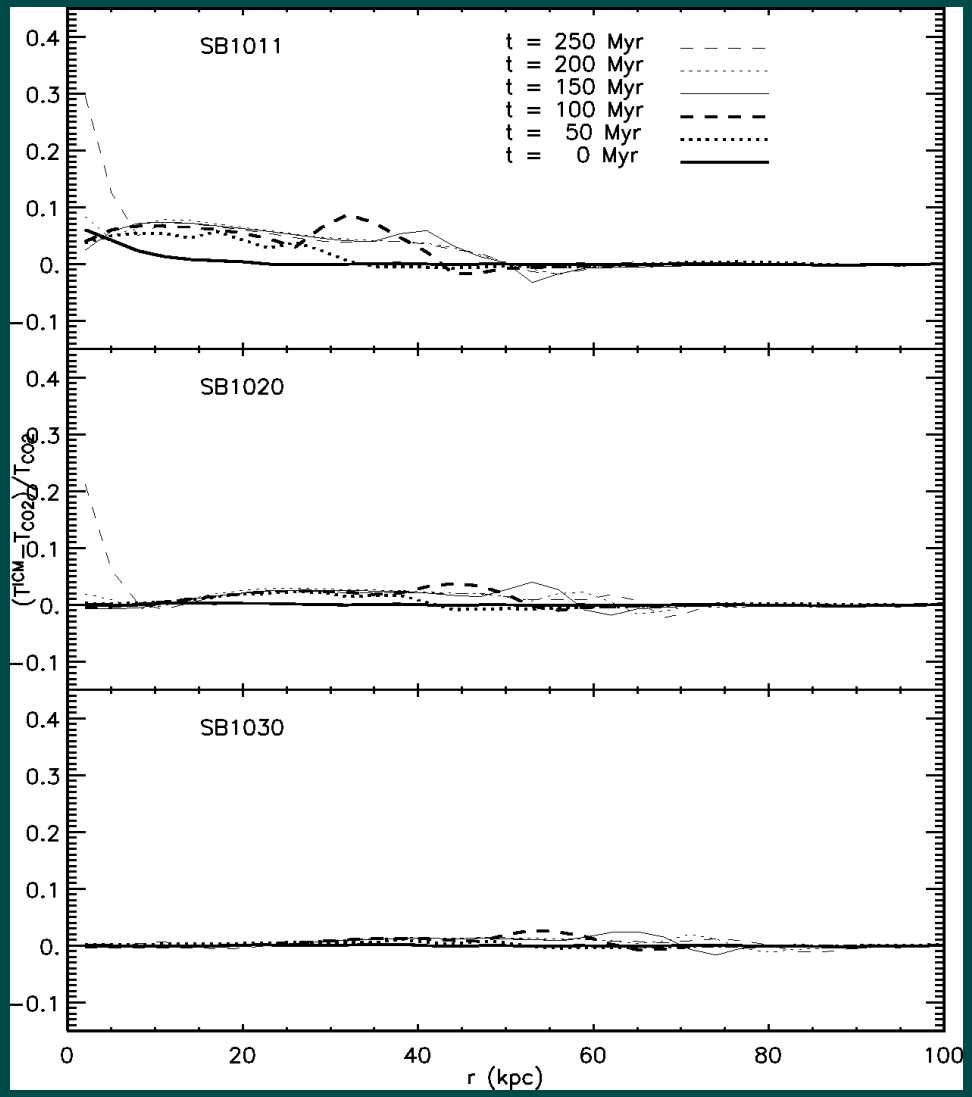
Hydrodynamic bubbles in 3D (Gardini & Ricker 2005)

- Results
  - Establishment of Hill (1894) circulation



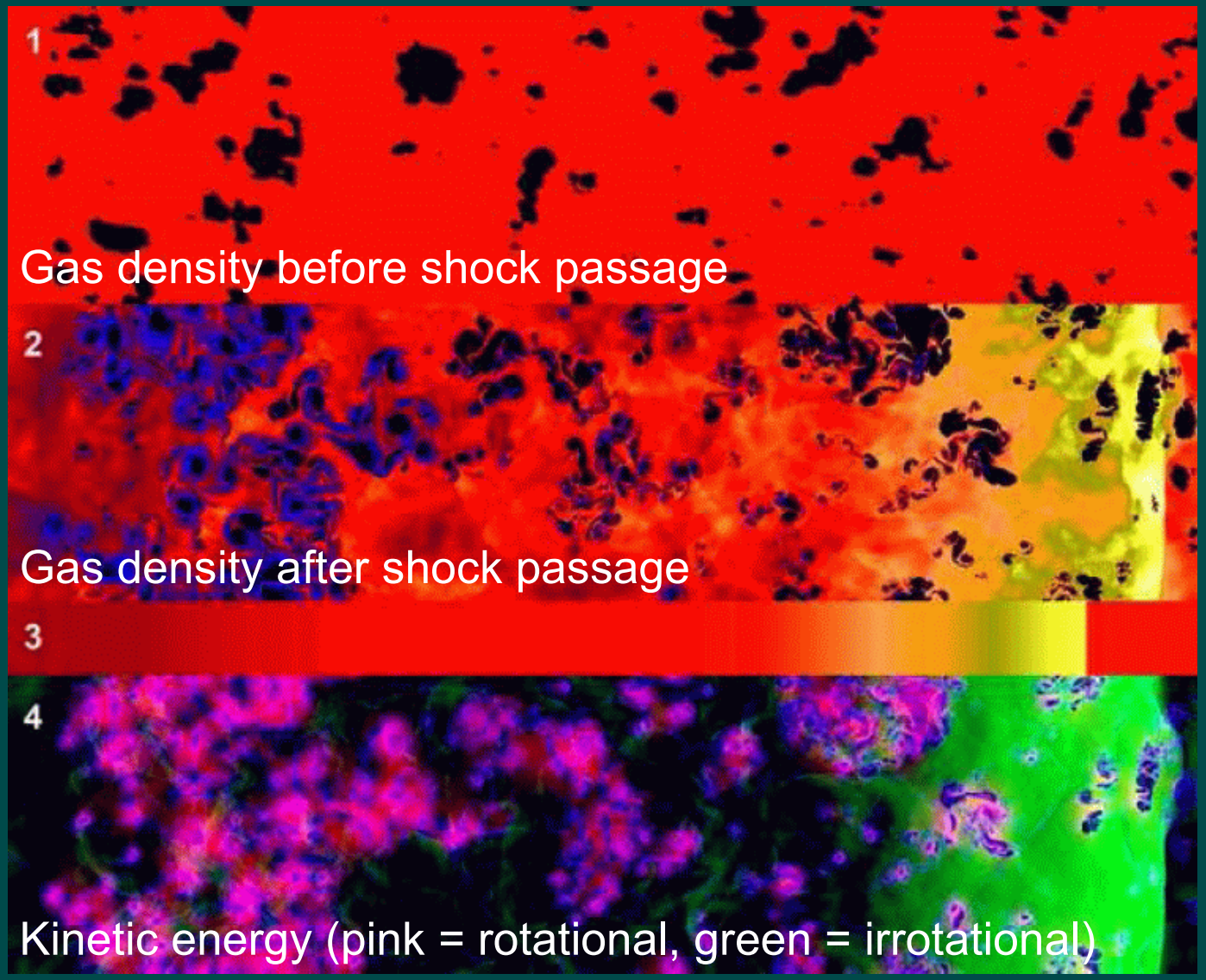
Hydrodynamic bubbles in 3D (Gardini & Ricker 2005)

- Results
  - Most influential bubbles stay close to center (lower jet speeds, shorter inflation period)
  - ICM heating is more due to lifting and dropping rather than mixing (either of ICM with bubble plasma or cooler with hotter ICM)

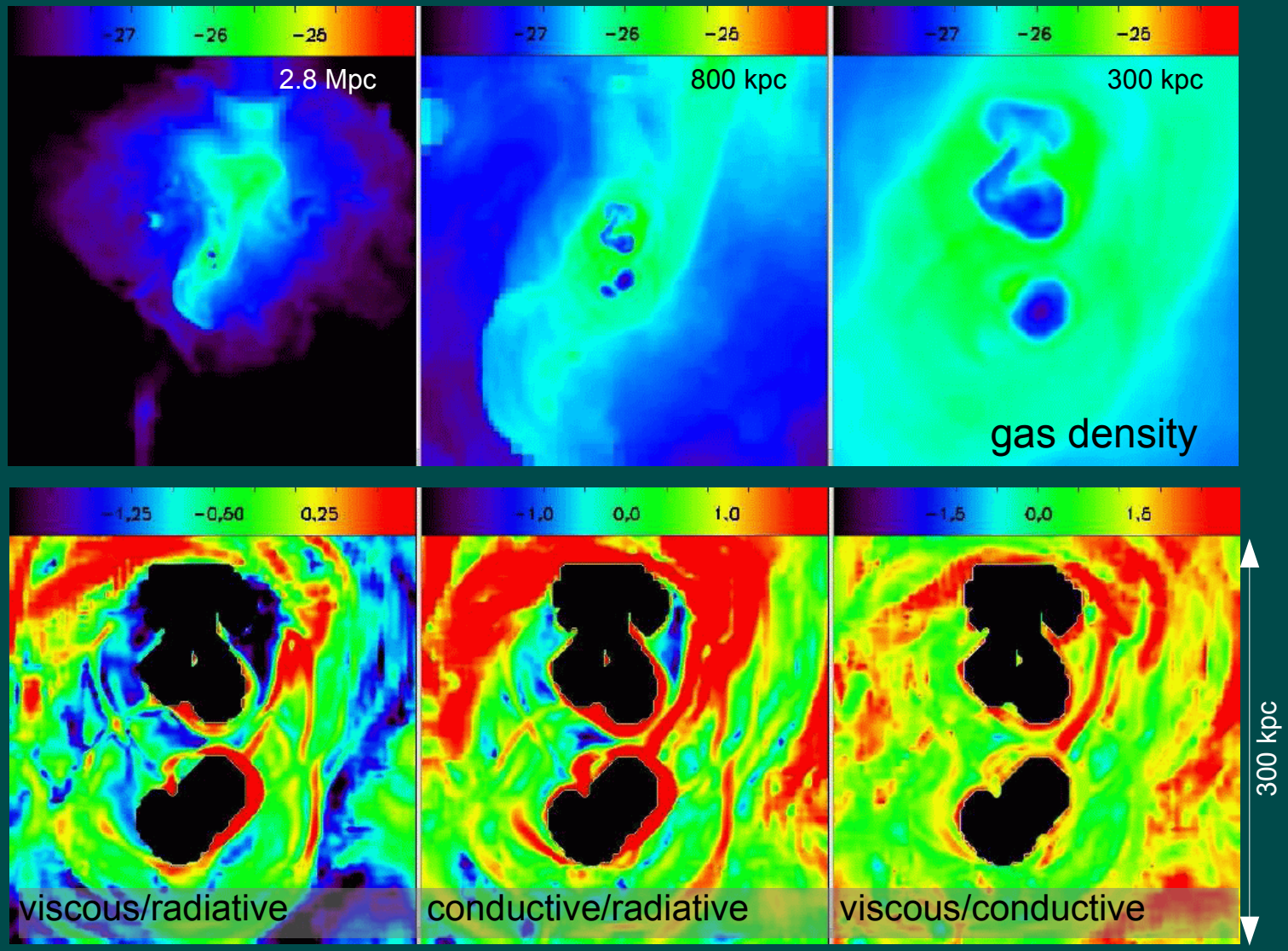


Shock-bubble interactions (Heinz & Churazov 2005)

- Heating via Richtmyer-Meshkov instability



Cosmological bubbles (Brüggen et al. 2005)



140 Myr after AGN outburst

Bubbles summary – cosmology effects

- What bubbles tell us about ICM state and physics
  - Bubbles must have interior B ~ μG if they are long-lived
  - If they don't have it, they will generate it
  - Numerous means of heating “work”
  - Much depends on nature of transport coefficients
- Effects of AGN on clusters
  - Significant source of entropy and energy
  - Can shut off cooling flows, but usually not by themselves
- Questions
  - Effect on self-similarity breaking?
  - Feedback mechanism?
  - Relationship of presence of active AGN to cluster merger history?

The important questions

- Can we understand the energetics of the ICM at the few-percent level?
  - YES, given time and faster/bigger/better computers.
- With this understanding, can we use clusters as cosmological probes yielding 1% constraints on w, σ_8, etc.?
  - What day is today?
- Do we need this understanding to use clusters for "precision" cosmology?
  - HOPEFULLY NOT. But need to combine our detailed understanding of ICM dynamics with statistically significant samples of simulated clusters to be sure.