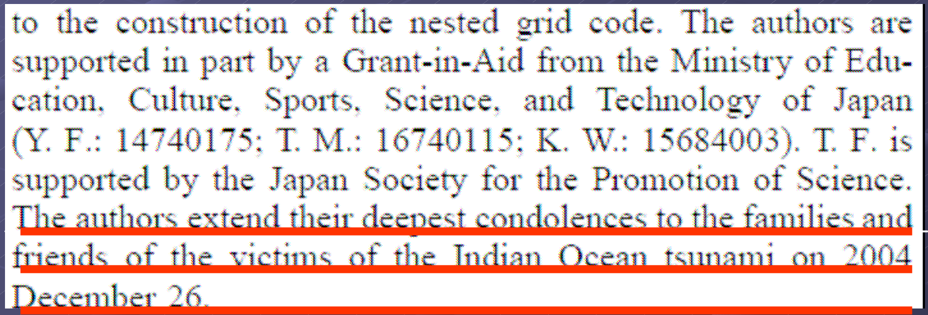
The cooling flow problem and the tsunami model



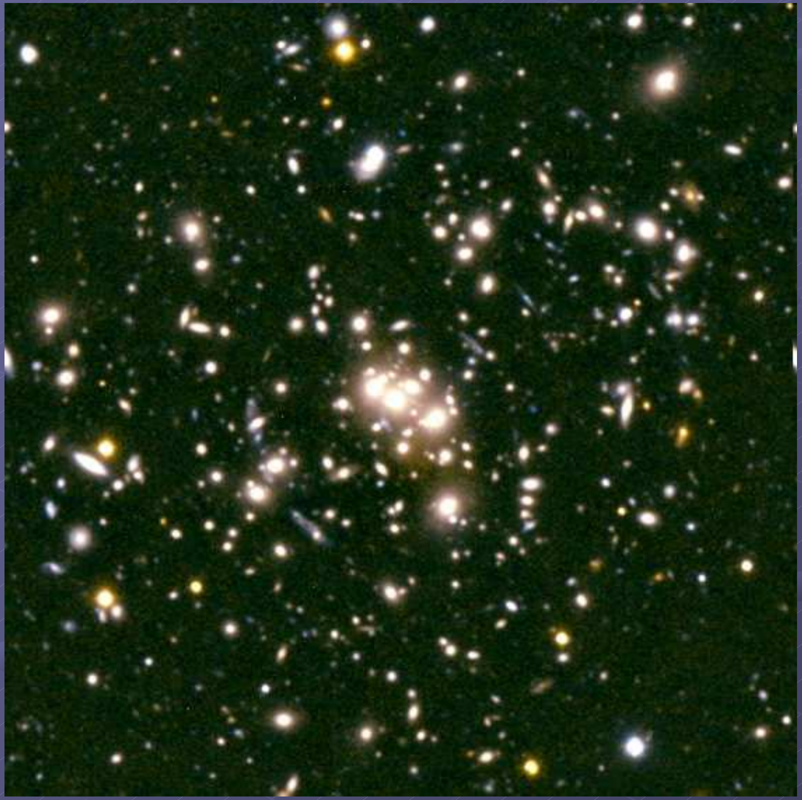
to the construction of the nested grid code. The authors are supported in part by a Grant-in-Aid from the Ministry of Education, Culture, Sports, Science, and Technology of Japan (Y. F.: 14740175; T. M.: 16740115; K. W.: 15684003). T. F. is supported by the Japan Society for the Promotion of Science. The authors extend their deepest condolences to the families and friends of the victims of the Indian Ocean tsunami on 2004 December 26.

Fujita et al. (2005)

Yutaka Fujita (Nat. Astron. Obs., Japan)

Fujita, Matsumoto, & Wada 2004, ApJ, 612, L9
Fujita, Matsumoto, Wada, & Furusho 2005, ApJ, 619, L139

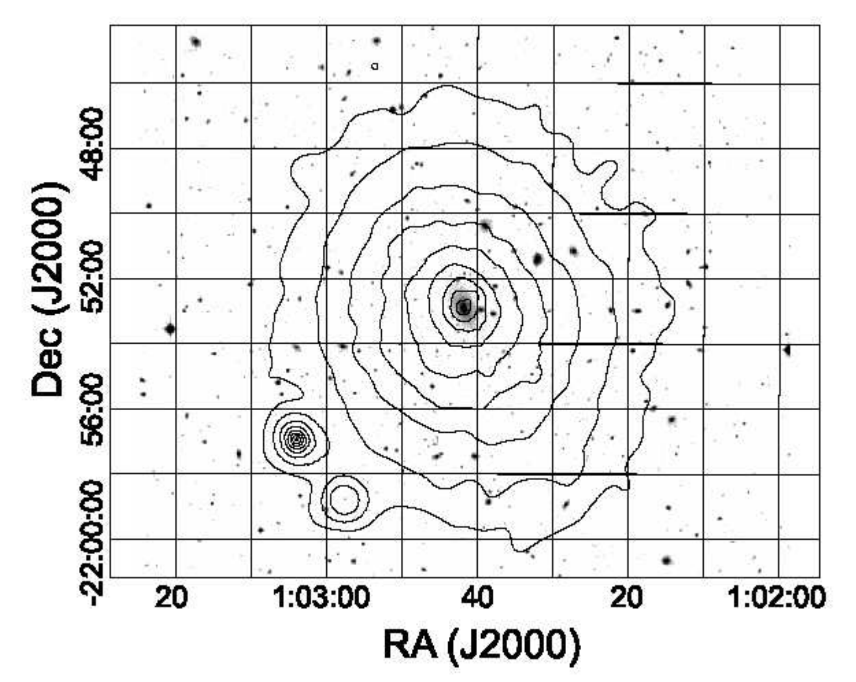
Introduction



Cl0024+1654

- Clusters of galaxies
  - Mass ～$10^{13\text{-}15}$ $M_\odot$
  - Number of galaxies ～100-1000
  - Size～Mpc
- The most massive gravitationally bounded objects

Cluster observed in X-Ray



A133
X-ray contours are overlaid on an optical image
(Fujita et al. 2004)

- The diffuse X-ray emission comes from Intracluster medium (ICM)
- Most baryon in a cluster is in the form of ICM.
  - ICM is mainly thermal hot gas (~2-10 keV).

Intracluster medium (ICM)

- Mass
  - 4-10 × total galaxy mass of a cluster
  - 1/4 -1/10 × gravitational mass of a cluster
- Temperature (2-10 keV)
  - Depth of the potential well
- X-ray emission mechanism
  - Bremsstrahlung

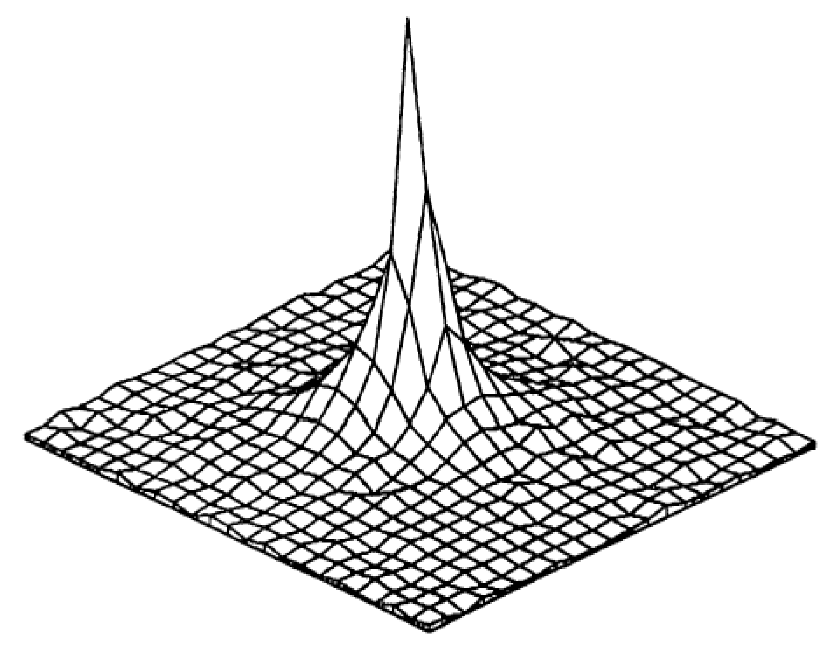
The Cooling Flow Problem

- Cooling time

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

  - Larger than the age of the universe
  - Generally, the ICM does not cool
- The cluster core ($r \lesssim 100$ kpc) is the exception
  - High density ($n \sim 0.1$ cm^{-1}), small cooling time ($\sim 10^{8\text{-}9}$ yr)
  - Cooling should be effective

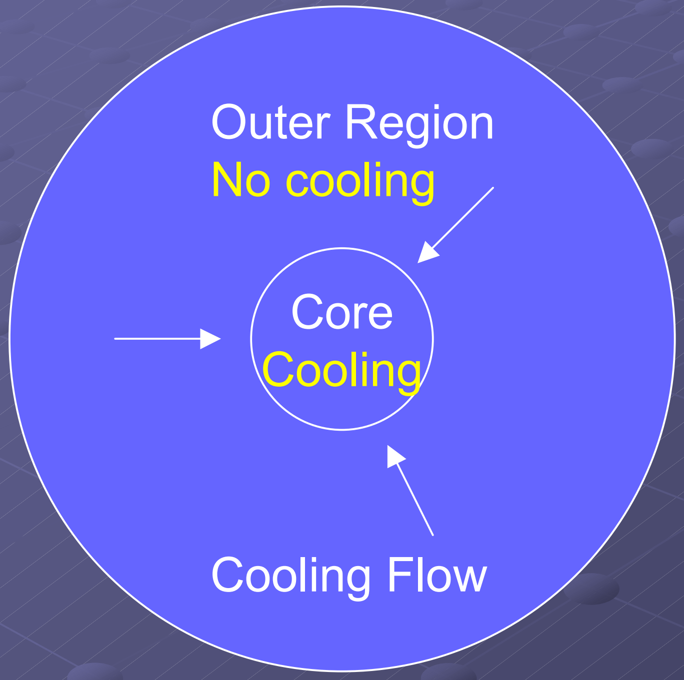
Strong X-ray Emission from Cluster Cores



3D representation of the X-ray surface brightness of A478 (White et al. 1994)

- X-ray luminosity of a core
  - $\sim 10^{42\text{-}45}$ ergs s^{-1}
  - The ICM loses its thermal energy in $\sim 10^{8\text{-}9}$ yr

Cooling Flows



Cluster

- Because of cooling, gas pressure in the core decreases
  - Gas pressure in the core cannot sustain pressure from the outer region
  - Cooling flows were thought to be established

Galaxy Formation?

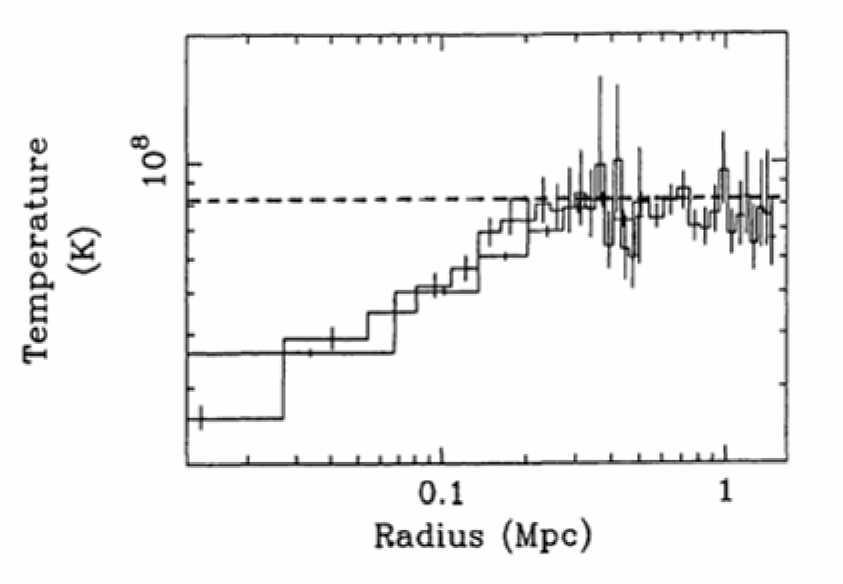
- Expected mass deposition (inflow) rate is huge

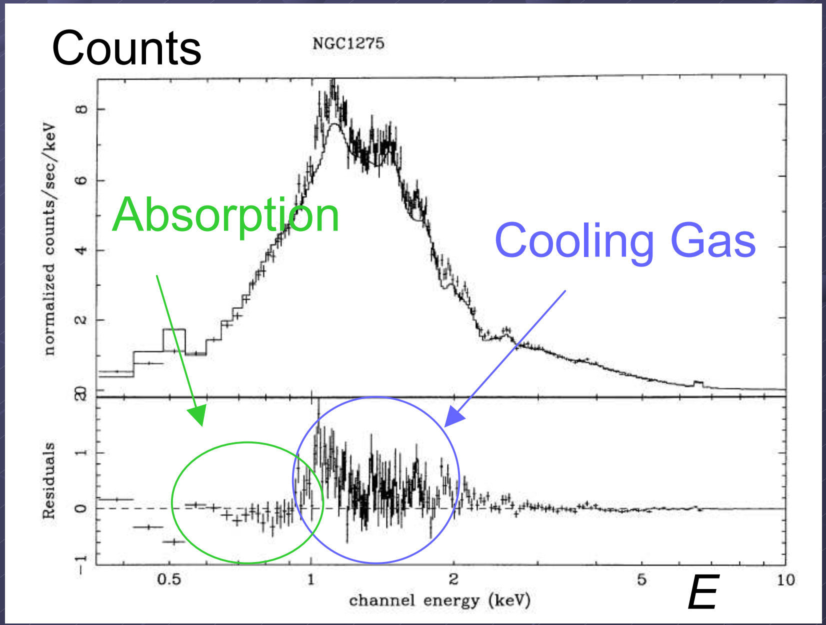
$$L_X \sim \frac{k_B T}{\mu m_p} \dot{M}$$

  - X-ray luminosity L_X and temperature T can be observed
    - $\dot{M}$ ~100 $M_\odot$ yr^{-1}
  - ~10^{12} $M_\odot$ for 10^{10} yr
    - Comparable to galaxy mass
- Some people thought that cooling flows are laboratories of galaxy formation
  - In fact, cD galaxies are located at cluster centers

Evidence of Cooling Flows?

- Temperature decrease toward the cluster center
- Metal emission from cooling gas
- Absorbing material





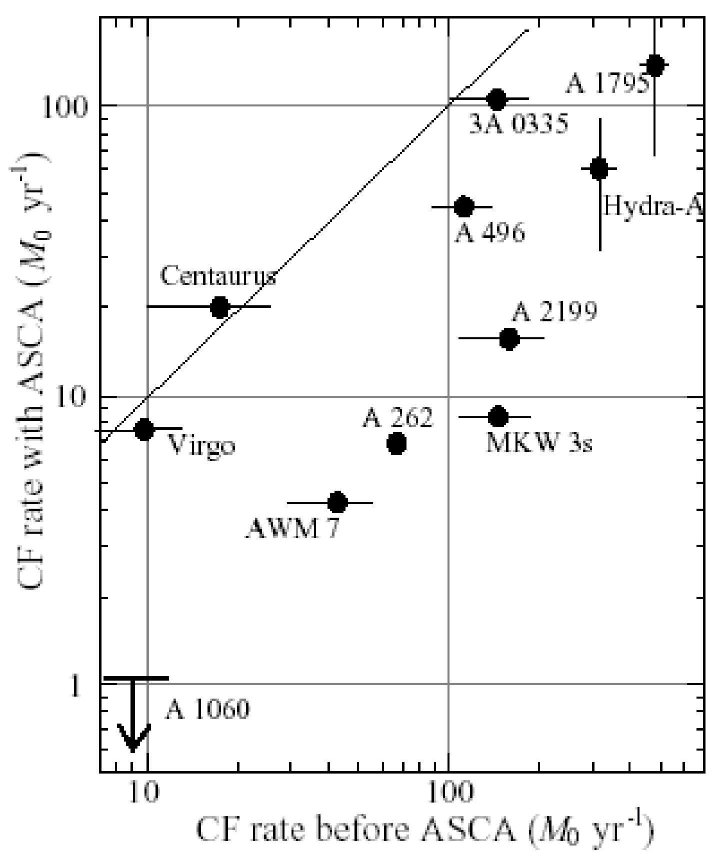
Fabian et al. (1994)

The Most Serious Problem of the Cooling Flow Model

- Where has the cooling gas gone?
  - $\dot{M} \sim 100\ M_\odot\ \mathrm{yr}^{-1}$
  - $\sim 10^{12}\ M_\odot$ for 10^{10} yr
- Star Formation?
  - Star formation rate at cluster centers is $\sim 10\ M_\odot\ \mathrm{yr}^{-1}$
- Cold Gas?
  - The mass of HI or H_2 gas at cluster centers is $\lesssim 10^{10}\ M_\odot$

I must comment on ASCA results…

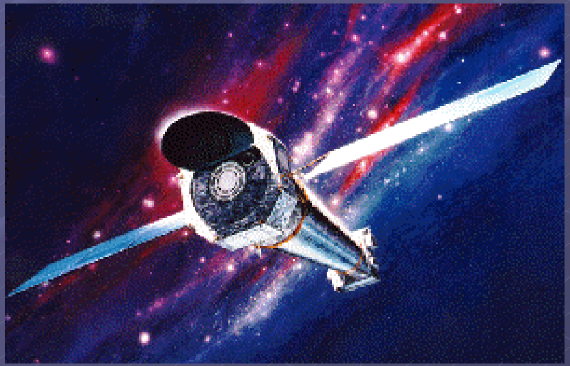
- During 80s and 90s, the cooling flow model was supported by most researchers
- However, the Japanese ASCA team indicated that the model was not correct even at that time
  - Emission from cooling gas is not strong



Review by Makishima et al. (2001)

Chandra and XMM-Newton Results

- Chandra
  - High angular resolution
- XMM-Newton
  - Large collective area



Chandra

XMM-Newton

- Cooling Flow problem has been widely recognized

Performance

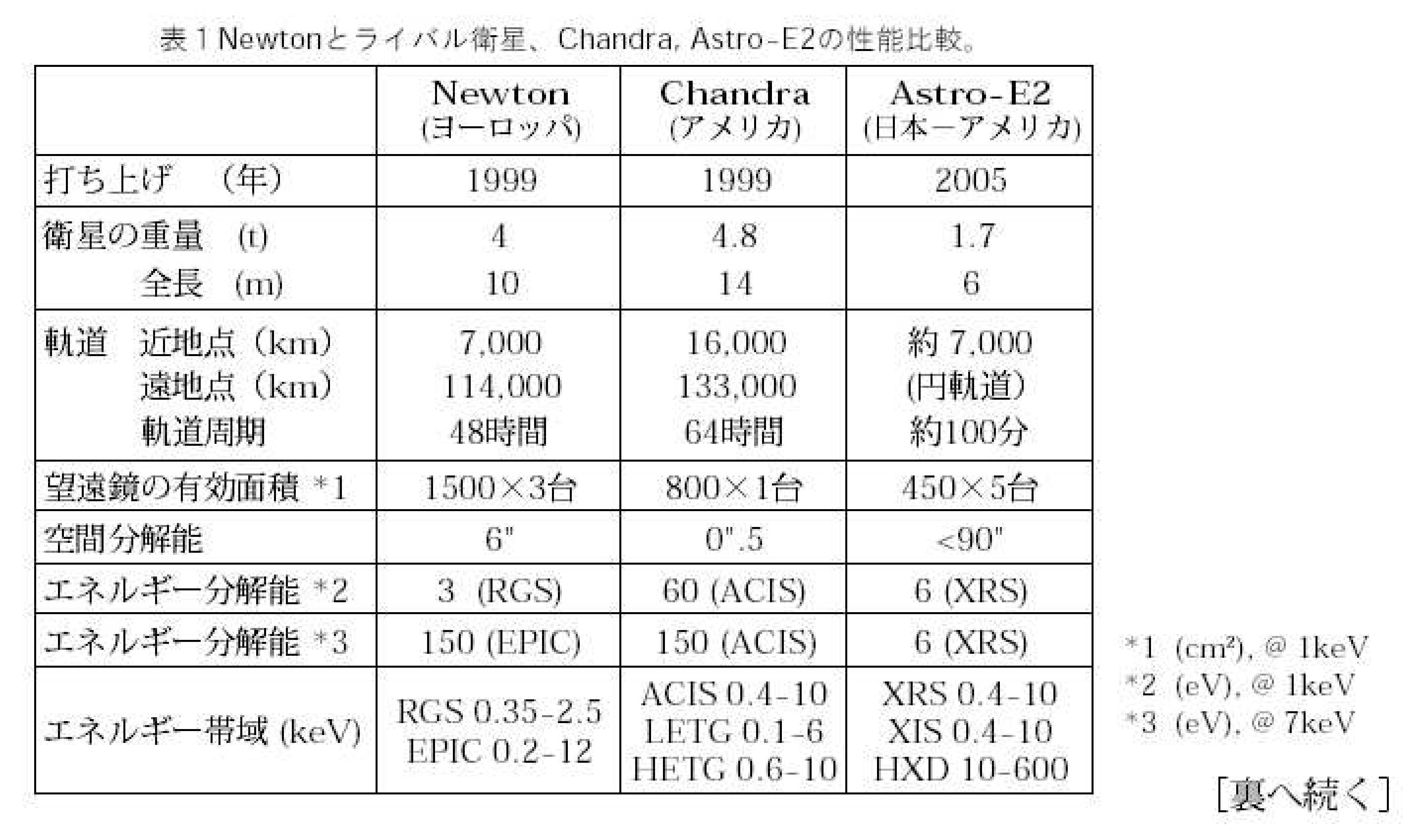


表 1 Newtonとライバル衛星、Chandra, Astro-E2の性能比較。

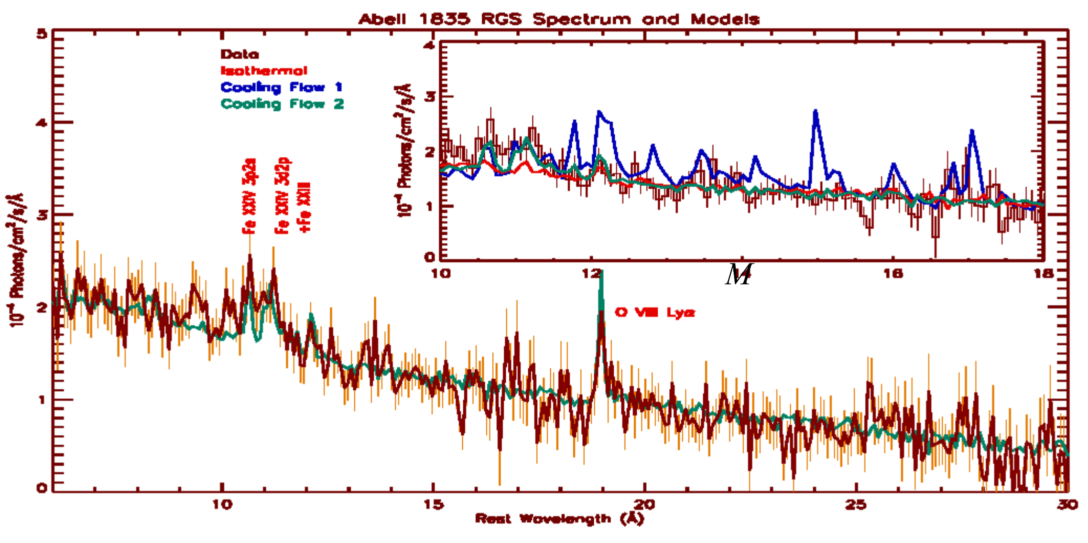
	Newton (ヨーロッパ)	Chandra (アメリカ)	Astro-E2 (日本ーアメリカ)
打ち上げ　（年）	1999	1999	2005
衛星の重量　(t) 全長　(m)	4 10	4.8 14	1.7 6
軌道　近地点（km） 遠地点（km） 軌道周期	7,000 114,000 48時間	16,000 133,000 64時間	約 7,000 (円軌道） 約100分
望遠鏡の有効面積 *1	1500×3台	800×1台	450×5台
空間分解能	6"	0".5	<90"
エネルギー分解能 *2	3 (RGS)	60 (ACIS)	6 (XRS)
エネルギー分解能 *3	150 (EPIC)	150 (ACIS)	6 (XRS)
エネルギー帯域 (keV)	RGS 0.35-2.5 EPIC 0.2-12	ACIS 0.4-10 LETG 0.1-6 HETG 0.6-10	XRS 0.4-10 XIS 0.4-10 HXD 10-600

*1 (cm^2), @ 1keV
*2 (eV), @ 1keV
*3 (eV), @ 7keV

[裏へ続く]

Little Cooling Gas in Cores!

- XMM-Newton Observations

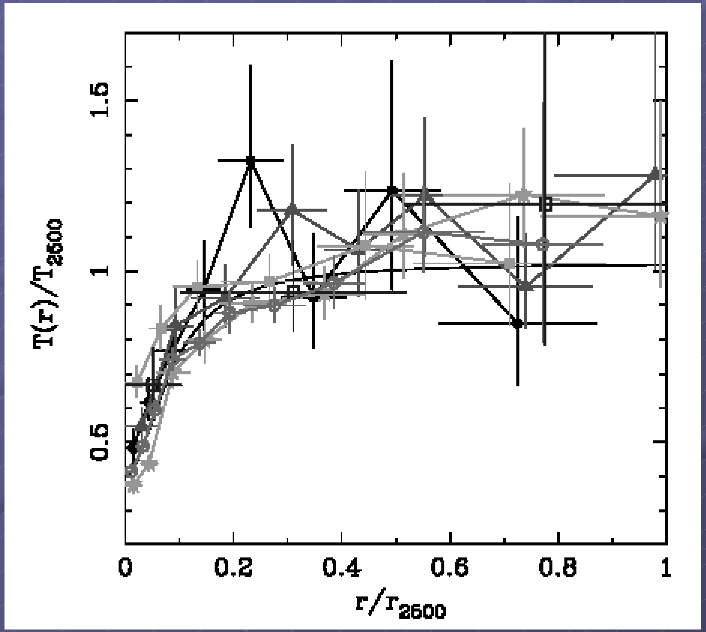


A1835
(Peterson et al. 2001)

  - Little metal line emissions from low temperature gas
  - This is the same for most clusters
  - $\dot{M}_{\mathrm{XMM}}$ ~0.1$\dot{M}_{\mathrm{Classical}}$ $(\dot{M}_{\mathrm{Classical}} \propto L_{\mathrm{X,Core}} / kT)$

Something Stops Gas Cooling

- Chandra observations



T_{out} →

6 clusters
(Allen, Schmidt & Fabian 2001)

  - Gas cooling is stopped at $T \sim 1/2\ T_{\mathrm{out}}$
    - Inconsistent with the classical cooling flow model ($T \to 0$ as $r \to 0$)

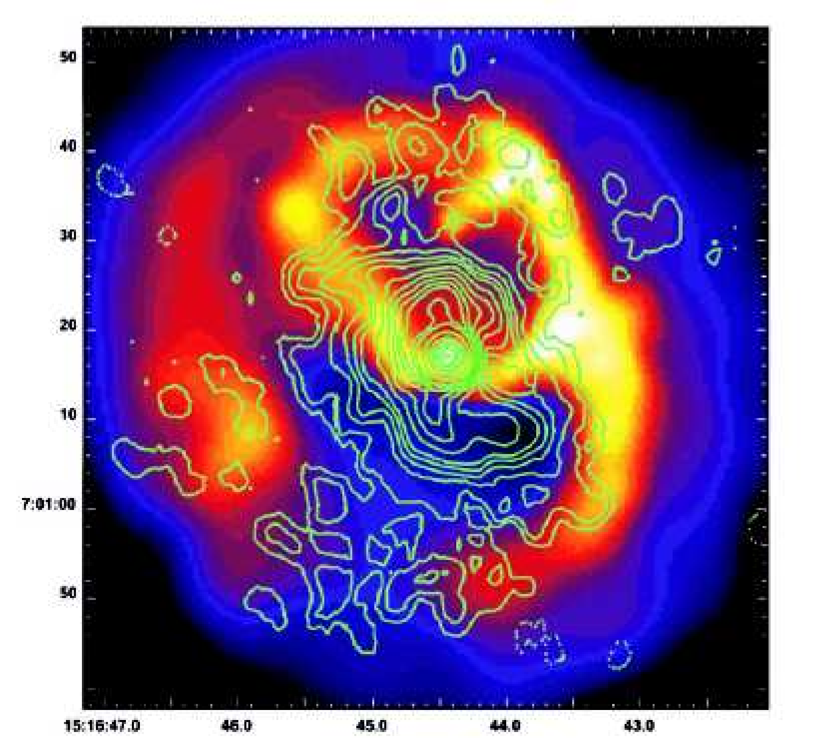
Heating Sources

- There must be heating sources to prevent cores from radiative cooling
- Popular ideas
  - AGNs (Tucker & Rosner 1983)
  - Thermal conduction (Takahara & Takahara 1981)

AGNs

- AGN activities are often observed in cluster cores
  - Heating Source?
- Bubbles
  - AGNs in cluster cores can inflate bubbles of nonthermal plasma, which displace X-ray-emitting gas

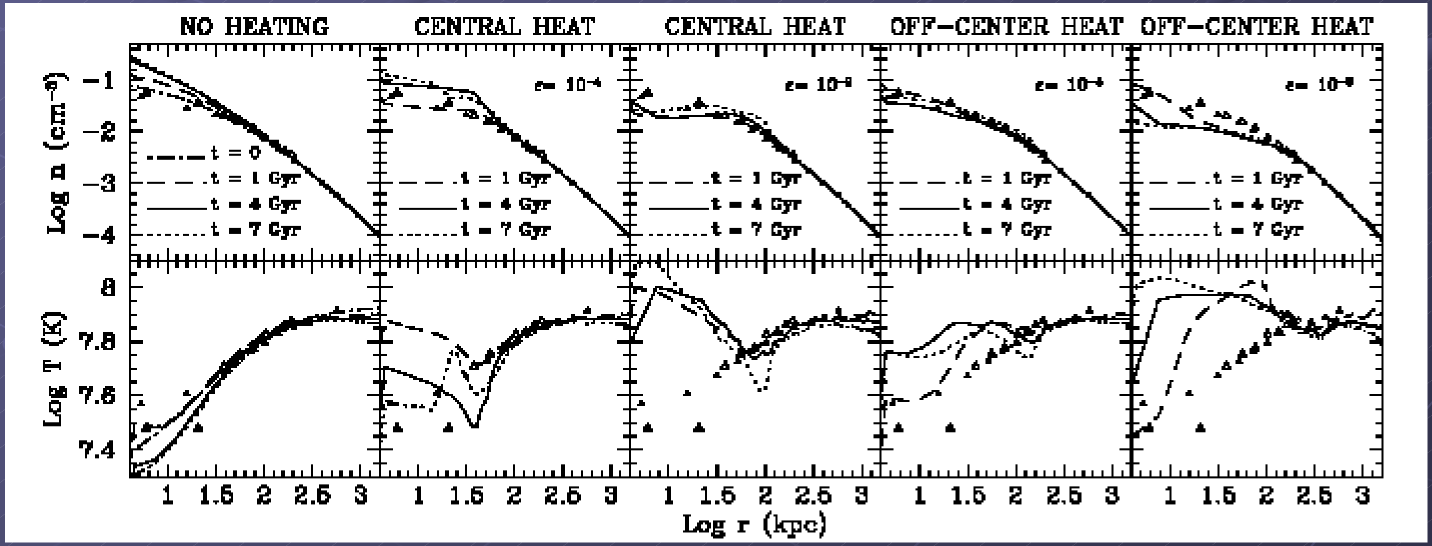
A2052



Color: X-ray
Contours: Radio
(Blanton et al. 2001)

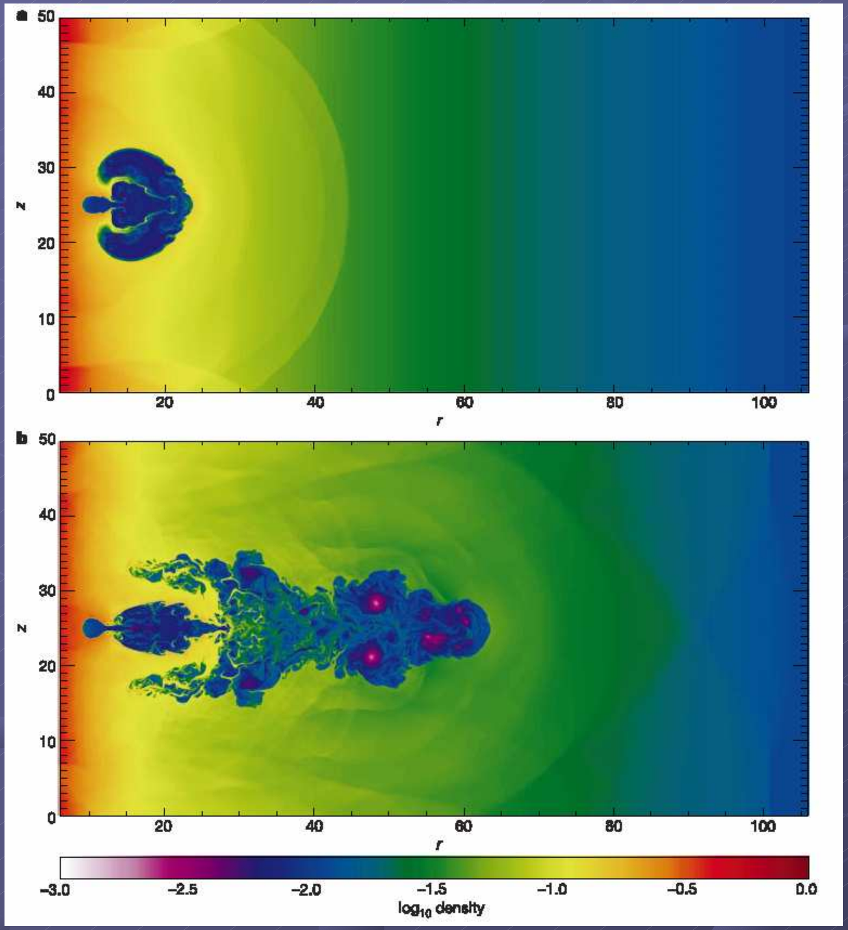
Problems of AGN Heating

- Observation
  - Gas temperature around the AGNs and bubbles is not large, etc.
- Theory
  - Generally, it is difficult to balance heating with cooling, etc.



Brighenti & Mathews (2003)

Mixing by Bubble Motions?

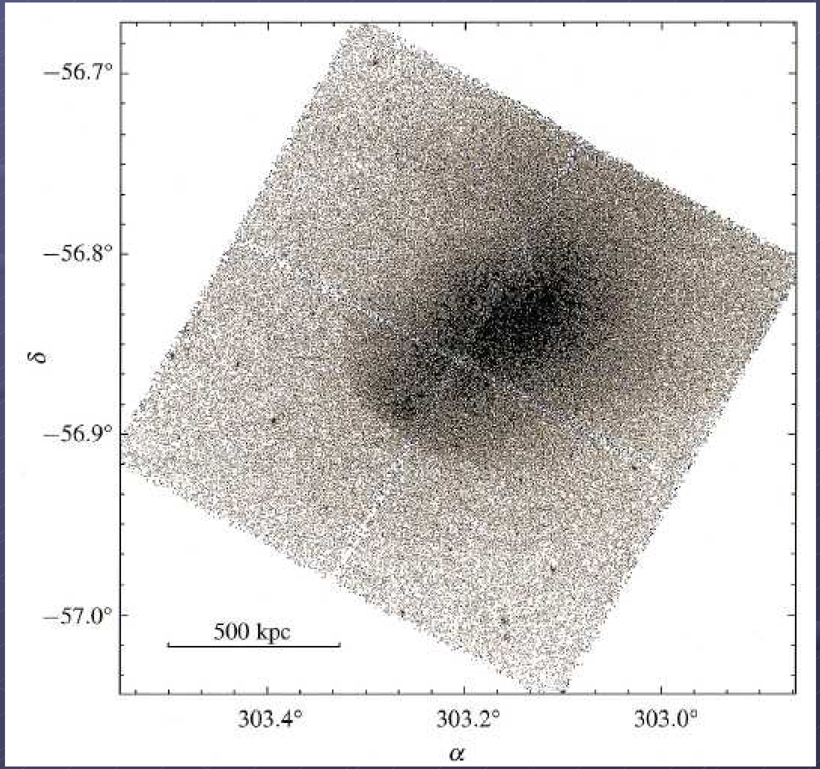


Brüggen & Kaiser (2002)

- Bubbles move in the ICM via buoyancy
- The motions mix the surrounding ICM
  - Hot gas in outer regions is brought to the cluster center (heating)

Problems of Thermal Conduction

- Observation
  - Fine structures are often found in ICM
  - Conduction rate must be low
    - If so, cores cannot be heated
- Theory
  - It does not work in low temperature clusters
    - Conduction rate $\propto T^{2.5}$



Vikhlinin, Markevitch & Murray (2001)

Problems

- AGN
  - Tuning between heating and cooling is very difficult
    - AGN’s power changes ~4 orders of magnitude
- Thermal conduction
  - Conduction rate must be tuned
  - It is ineffective for low temperature clusters

- These problems have been recognized for a long time
  - Is it time to propose a new idea?

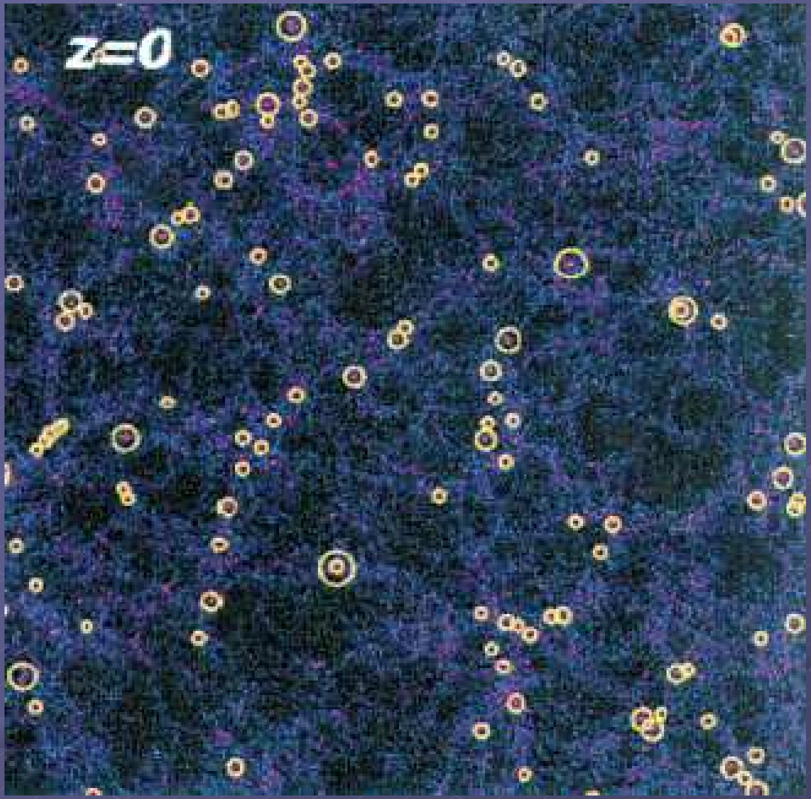
Tsunami Model

- Collaborators
  - Tomoaki Matsumoto (Hosei U.)
  - Keiichi Wada (NAOJ)
  - Takeru Ken Suzuki (Kyoto U.)
  - Tae Furusho (JAXA)

Tsunami Model

- Basic Idea
  - In clusters, large scale bulk motions of gas should prevail
    - Large scale structure formation of the universe
  - The bulk motions may affect the cluster cores

The origin of the bulk gas motions

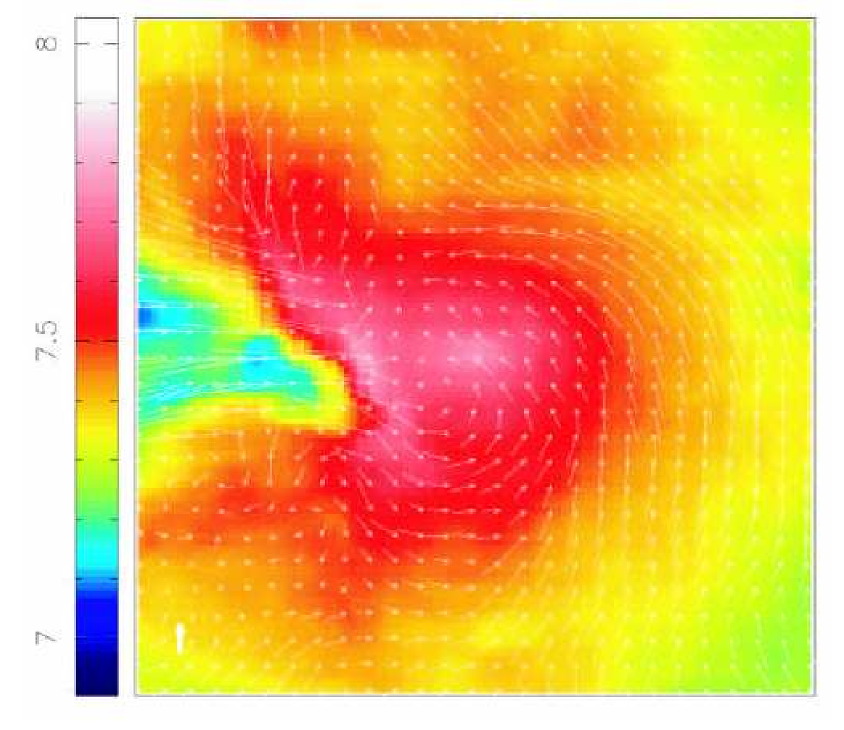


Circles are clusters
(Borgani & Guzzo 2001)

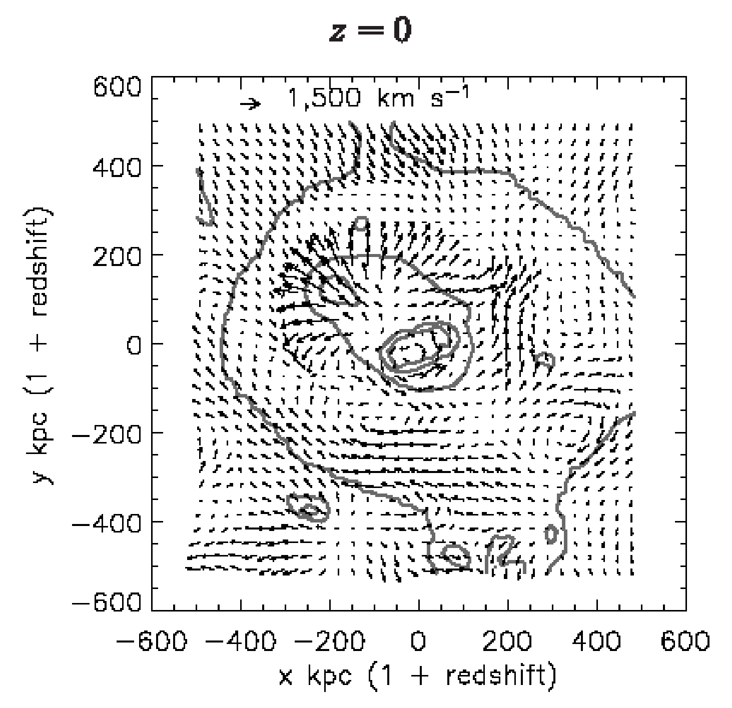
- Large scale structure of the universe
  - Clusters are knots of filaments
- Small clusters and galaxies fall into clusters along the filaments
  - Velocity > 1000 km s^{-1}
  - Gas motions in the clusters

Cosmological Numerical Simulations

- Velocity fields in the ICM of a cluster (Arrows)
  - $\gtrsim$20-30% of the sound velocity



Nagai et al (2003)



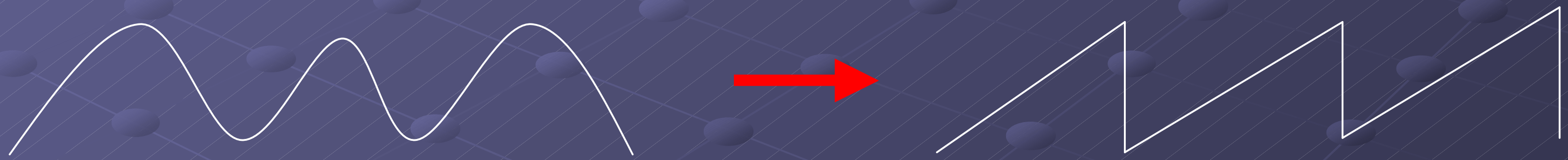
Motl et al. (2004)

Tsunami Models

- Old Tsunami (One dimension)
  - Fujita, Suzuki, & Wada 2004, ApJ, 600, 650
- New Tsunami (Two dimension)
  - Fujita, Matsumoto, & Wada 2004, ApJ Letters submitted

Old Tsunami

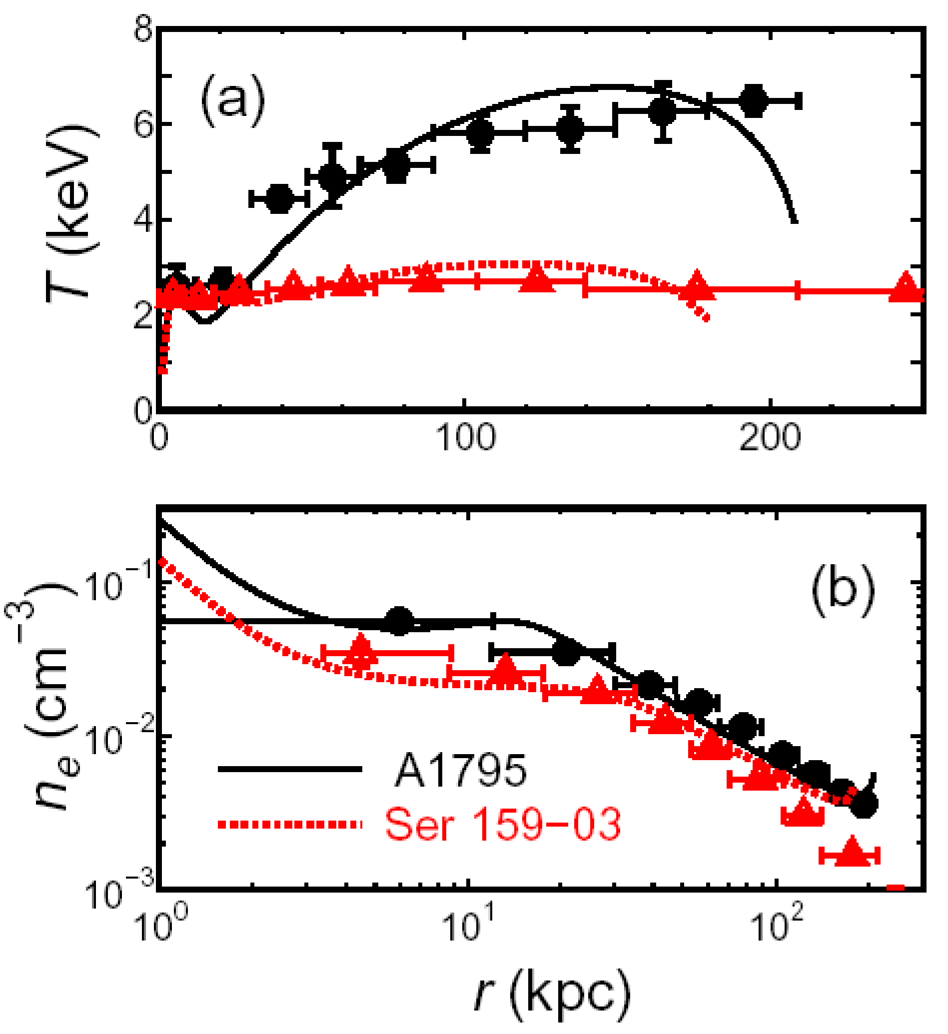
- A cluster is spherically symmetric
- Bulk gas motions are approximated by acoustic-gravity waves (`tsunamis')
- These waves with relatively large amplitude eventually form shocks to shape sawtooth waves (N-waves)



  - Shocks directly heat the surrounding ICM by dissipation of their wave energy
- Analytical approach (weak shock theory)
- Numerical simulation

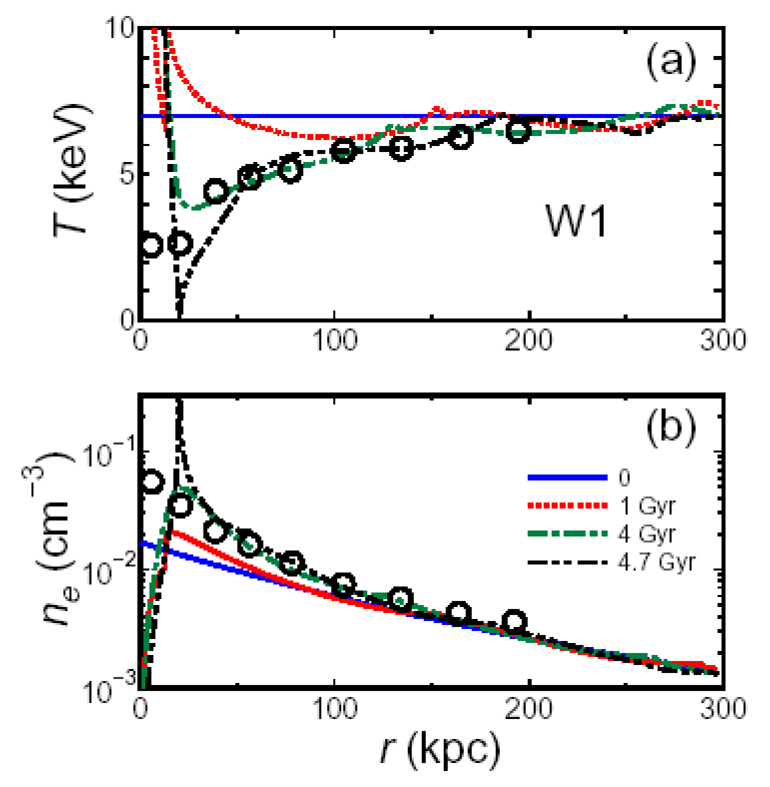
Results of Analytical Approach

- Time independent
- Velocity amplitude
  - ~10-20% of the sound velocity
- *T*, n_e profiles
- Comparison with observations
  - A1795
    - Ettori et al. (2002), Tamura et al. (2001)
  - Ser159-03
    - Kaastra et al. (2001)
- Consistent
- The core can be effectively heated



Results of One-Dimensional Simulations

- We needed to confirm the results of analytical approach
- Velocity perturbations of 10-20% of the sound velocity are given
- Cooling time is 2-∞ times increased, compared with the case of no waves



A Defect of One-Dimensional Study

- One-dimensional study showed that the bulk gas motions in a cluster could heat the core
- However, in the one-dimensional study, the heating efficiency could be overestimated
  - Waves are automatically focus on the cluster center
  - Multi-dimensional study is required

2D Hydrodynamic Simulations

- We focus on a cluster core
  - $\lesssim$300 kpc from the center
- Reproduction of fine structures
  - Nested grid code
  - Resolution of 22 pc at the center
- Gas cooling is included
- Gravitational potential is fixed (NFW)
- This is the first time to follow the evolution of the core in `a stormy cluster‘ with multi-dimensional high-resolution hydrodynamic simulations

Bulk Gas Motions

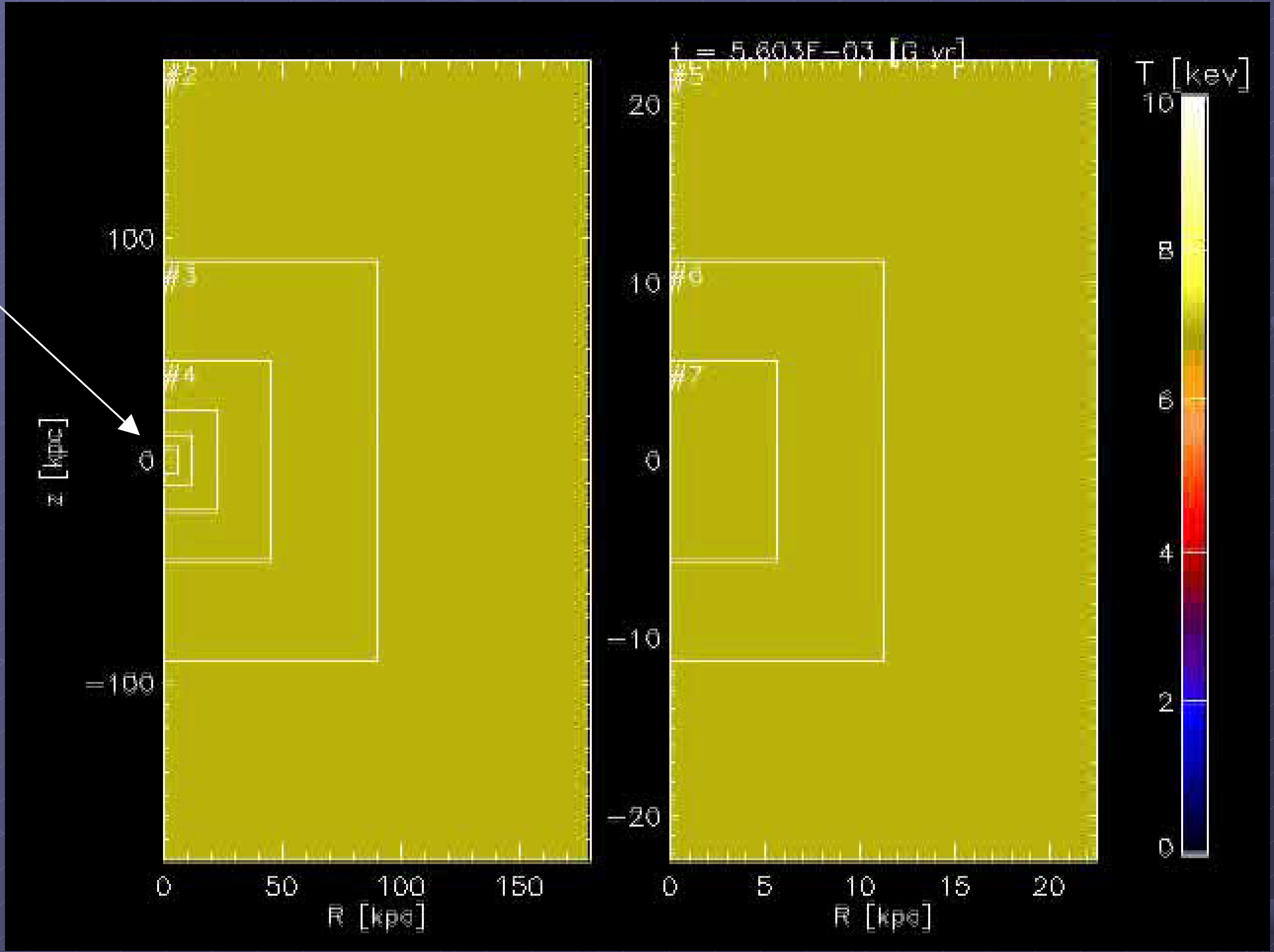
- Plane waves are considered (Tsunamis)
- Injection of waves
  - ~300 kpc from the cluster center
  - Wave velocity ($\alpha \times$sound velocity)
    - $\alpha = 0\text{-}0.5$
  - Wave length (λ)
    - 100-1500 kpc
- These parameters are based on results of cosmological numerical simulations
  - e.g. Nagai et al. (2003), Motl et al. (2004)

Movie (α=0.3, λ=100 kpc)

Temperature

Cluster Center

Filament of LSS



≲200 kpc

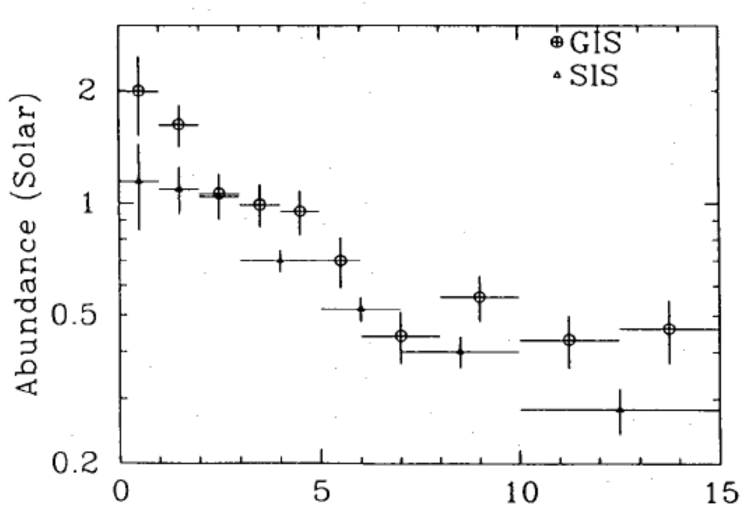
≲20 kpc (zoomed up)

Results 1

- Rayleigh-Taylor (RT) and Kelvin-Helmholtz (KH) instabilities
  - Formation of turbulence
- Mechanisms
  - → The core cools through radiative cooling
  - → The core becomes denser
  - → Waves cannot move the core
  - → Relative motion between the core and the surrounding gas
  - → RT and KH instabilities
  - → Turbulence

Results 2

- Turbulence is spatially limited to the cluster core
  - The turbulence does not completely erase metal abundance excess observed in cores
    - If turbulence developed in the entire cluster, the excess would be erased

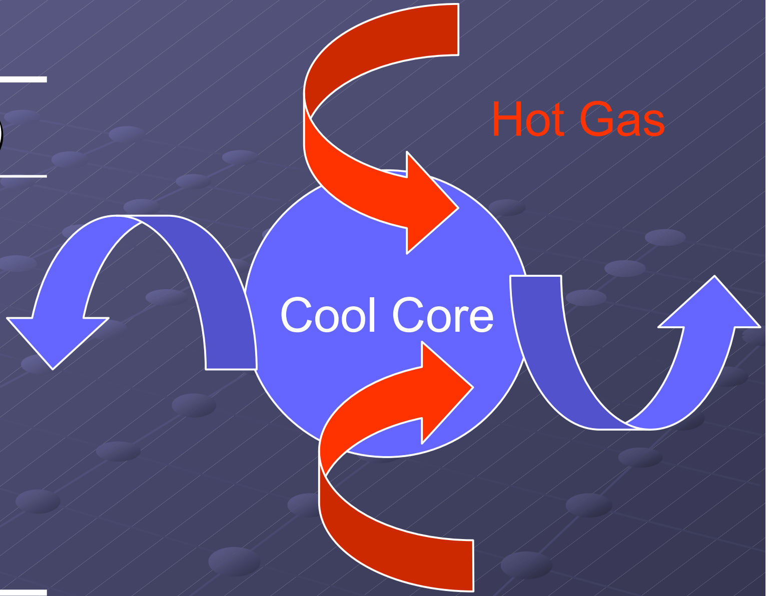


Fukazawa et al. (1994)

Results 3

- Typical cooling time of the core

α	λ(kpc)	t_{cool} (Gyr)
0	*...*	*2.2*
0.3	100	3.3
0.5	500	4.7
0.3	1000	6.2
0.3	1500	>6.2



- The cooling time is increased by heat transport through turbulent mixing (cf. Cho et al. 2003, Kim & Narayan 2004, Voigt & Fabian 2004)
- We found an possible origin of turbulence that is responsible for core heating

Predictions

- The turbulence in a core should be developed only in cool cores (`cooling flow clusters')
  - If a core is not much cooled, waves pass the core without changing the structure
  - No overheating
    - Self-regulated
- The turbulent heating could work in groups of galaxies and elliptical galaxies
  - This is in contrast with heating through thermal conduction, which works only in high temperature clusters
    - Conduction rate $\propto T^{5/2}$

Structures of Dark Halos

- Dark matter structures are not much different between clusters and galaxies
  - Bulk gas motions and turbulence should be excited in smaller objects

Cluster

Galaxy

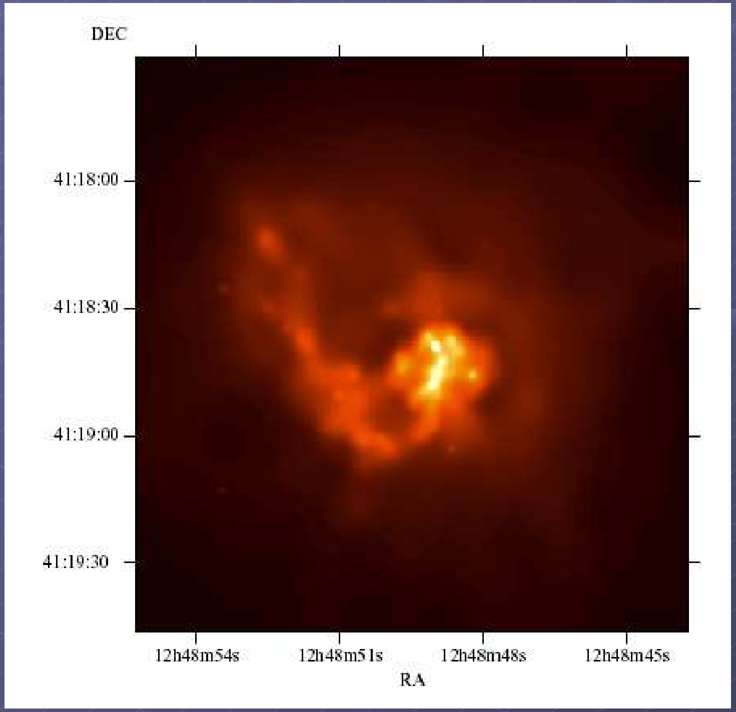
Moore et al. (1999)

Comparison with Observations

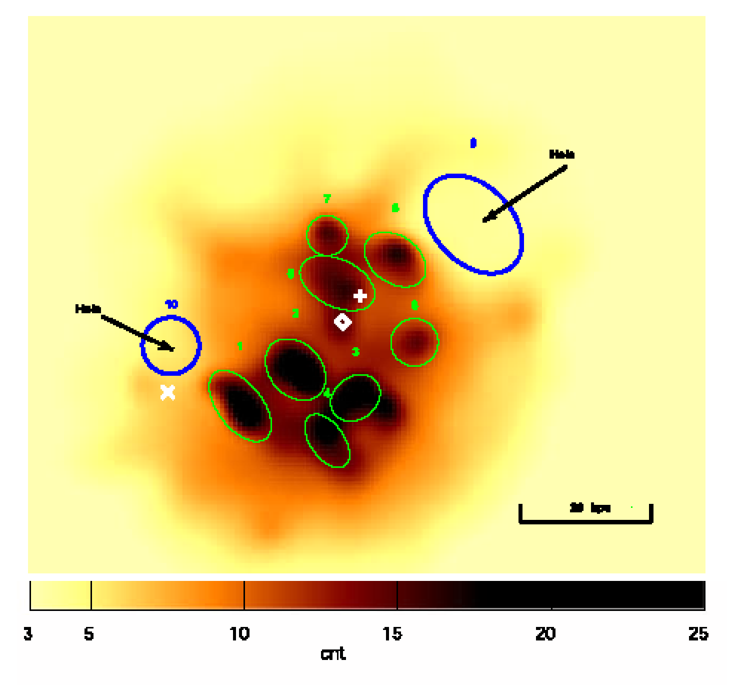
- Image
  - Chandra, XMM-Newton
- Spectra
  - XMM-Newton, ASTRO-E2

Irregular Gas Distribution 1

- Observations of Cluster Cores ($\lesssim$100 kpc)



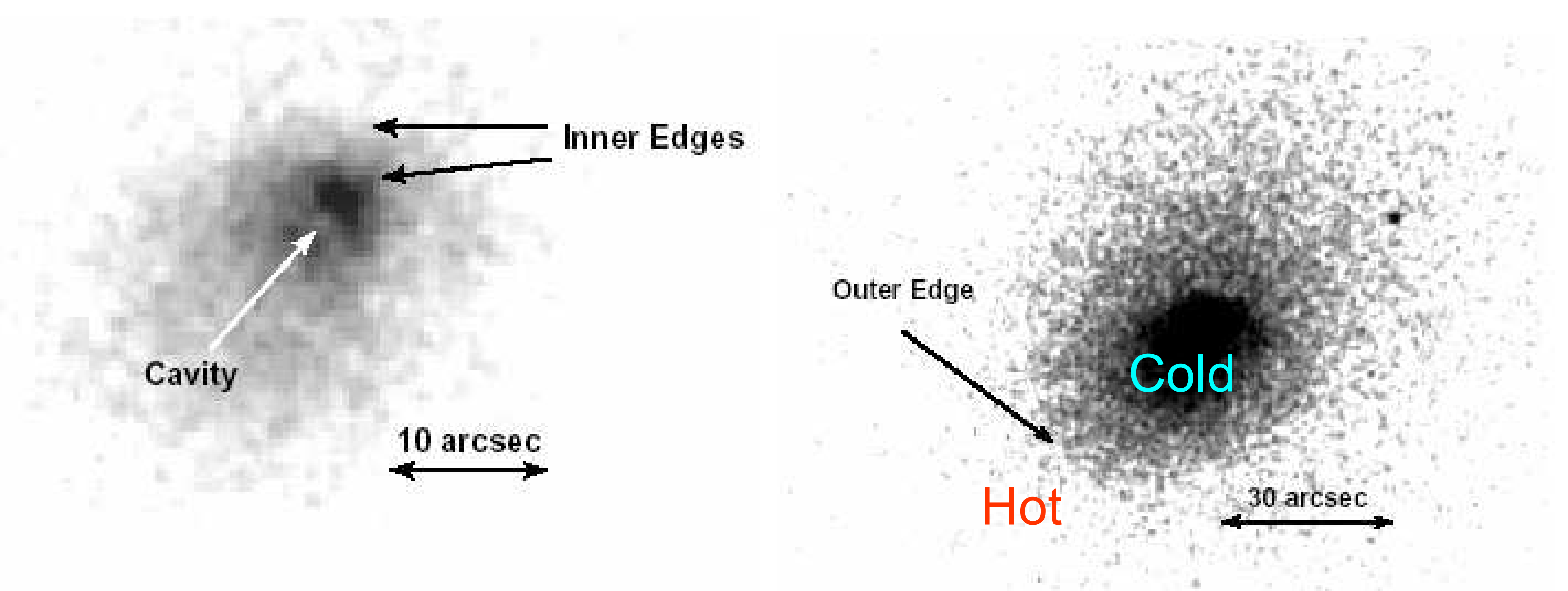
Centaurus
(Sanders & Fabian 2002)



2A 0335+096
(Mazzotta et al. 2003)

Irregular Gas Distribution 2

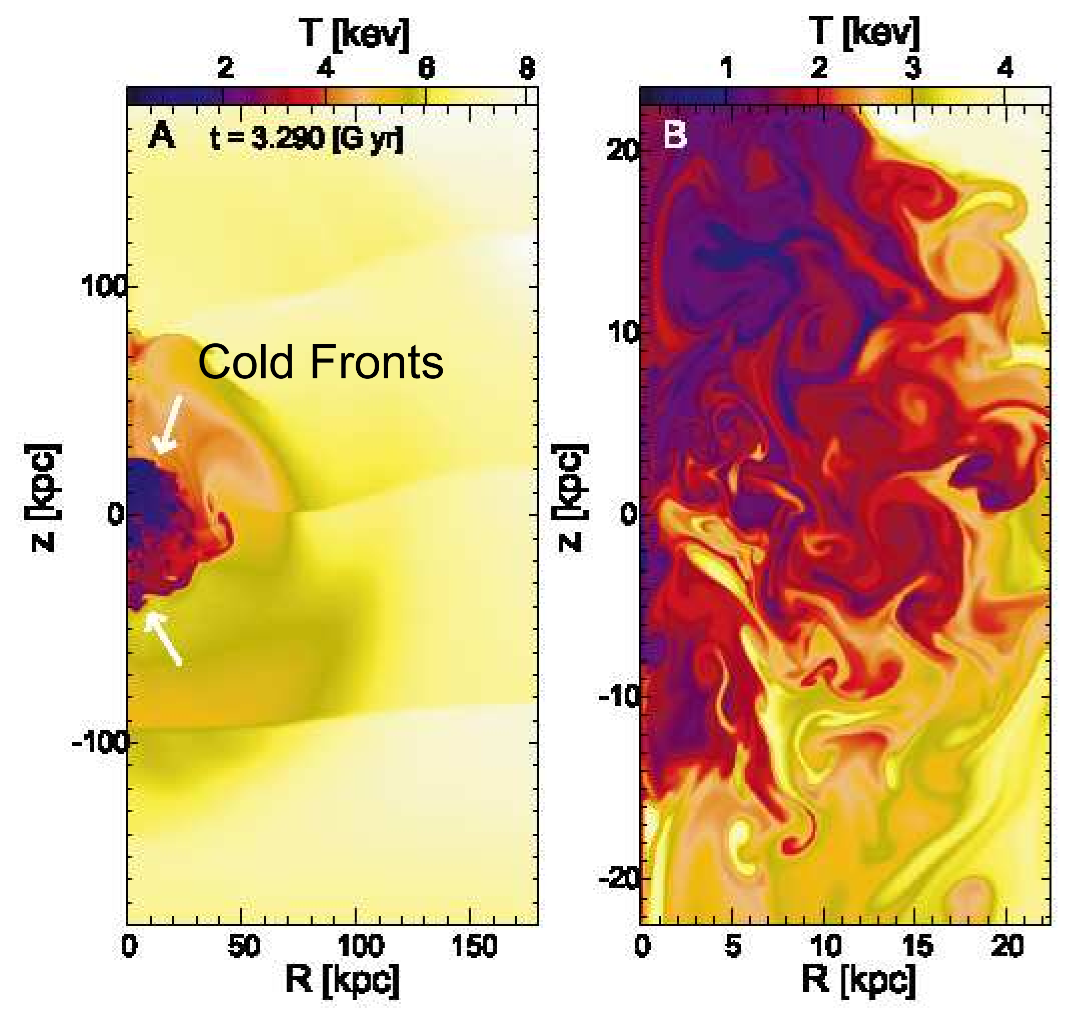
- Cold Fronts (`Sloshing' type)
  - e.g. A1795 (Markevitch et al. 2001)



ZW3146
(Forman et al. 2003)

Our Predictions

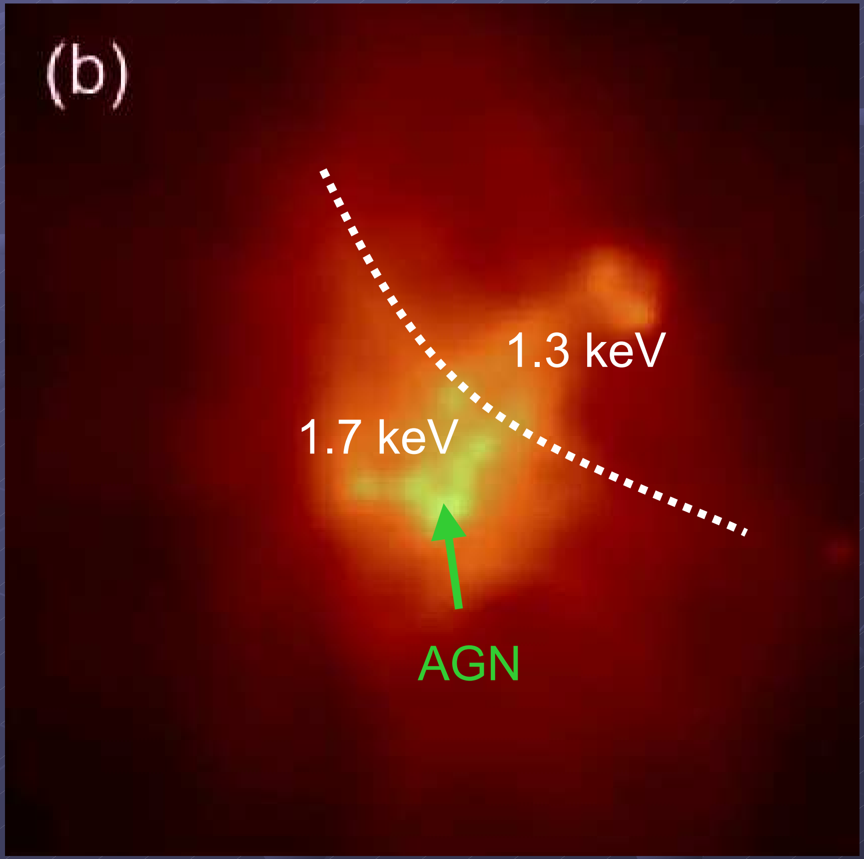
- Turbulence creates very complicated structures
  - Not steady
- Filaments and cold fronts can be reproduced



≲200 kpc ≲20 kpc (zoomed up)

Can we observe the waves?

- Generally difficult
  - Wave amplitude is not large
  - Angle between wave fronts and the line of sight
- But yes

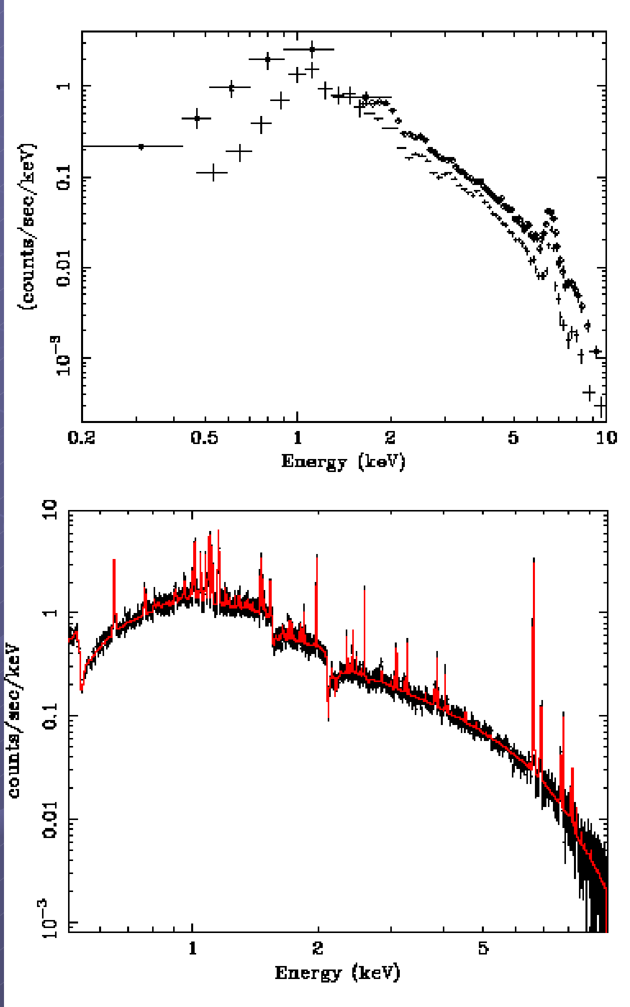


The core of A133 (Fujita et al. 2002, 2004)

ASTRO-E2

- ASTRO-E2 will be launched in 2005
  - Superb energy resolution
    - ~100 km s^{-1}
  - Metal lines can be investigated in detail
  - We will be able to directly observe the velocity fields in the ICM for the first time
- Bulk gas motion
  - Doppler shift
- Turbulence
  - Doppler Broadening

Predicted X-ray Spectra

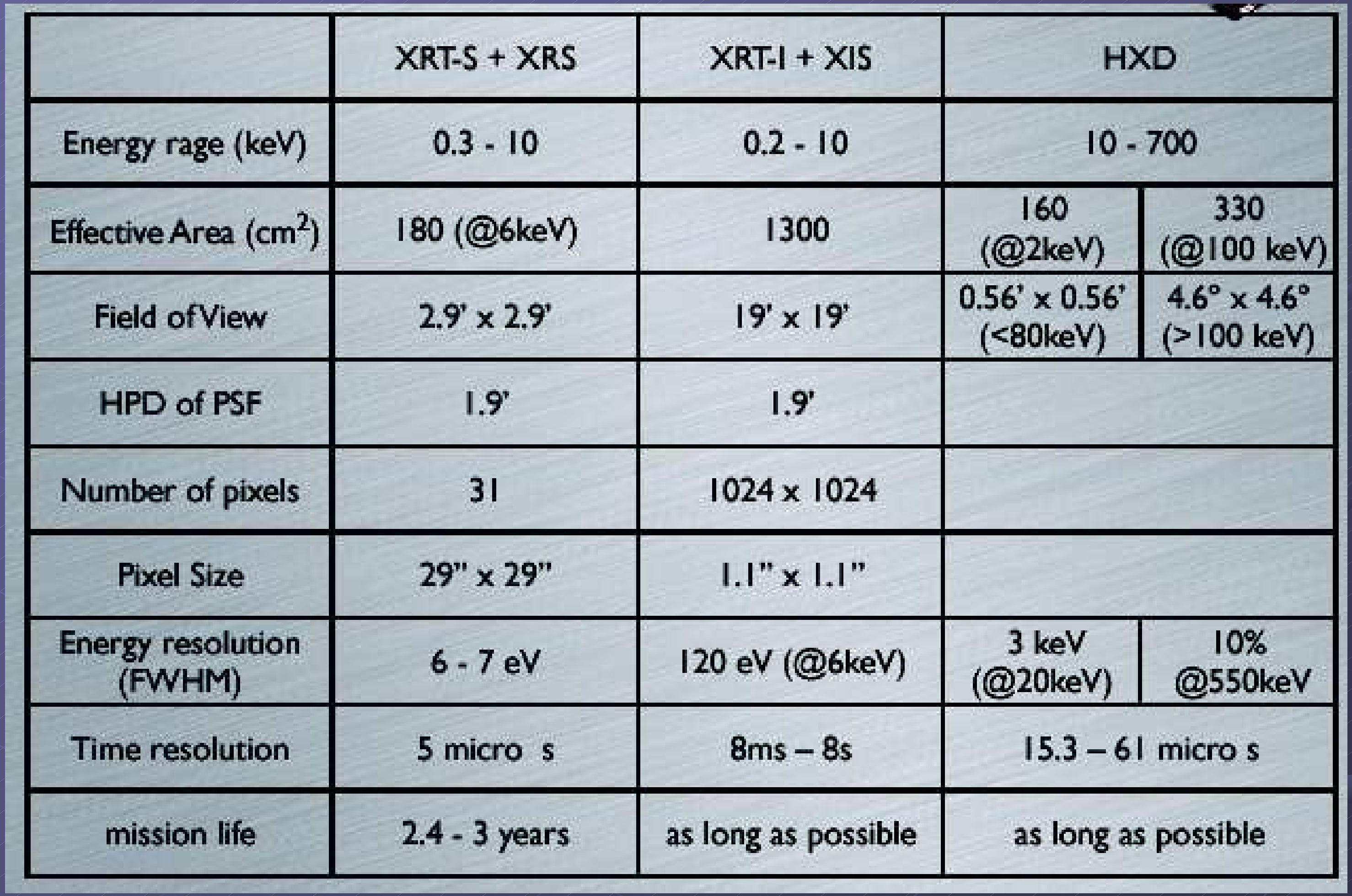


Centaurs Cluster

ASCA

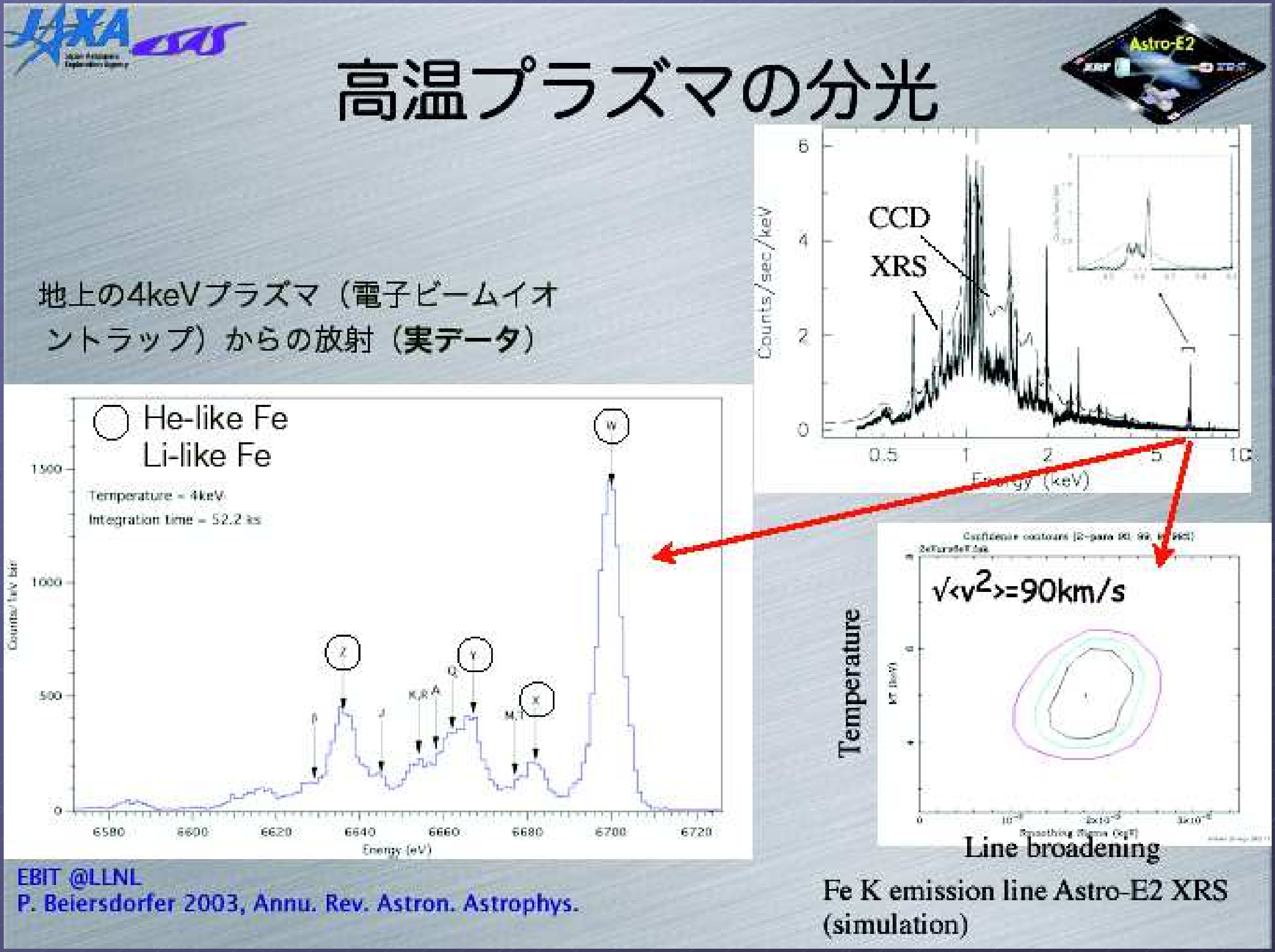
ASTRO-E2

Performance



	XRT-S + XRS	XRT-I + XIS	HXD	
Energy rage (keV)	0.3 - 10	0.2 - 10	10 - 700	
Effective Area (cm^2)	180 (@6keV)	1300	160 (@2keV)	330 (@100 keV)
Field of View	2.9' x 2.9'	19' x 19'	0.56' x 0.56' (<80keV)	4.6° x 4.6° (>100 keV)
HPD of PSF	1.9'	1.9'		
Number of pixels	31	1024 x 1024		
Pixel Size	29" x 29"	1.1" x 1.1"		
Energy resolution (FWHM)	6 - 7 eV	120 eV (@6keV)	3 keV (@20keV)	10% @550keV
Time resolution	5 micro s	8ms – 8s	15.3 – 61 micro s	
mission life	2.4 - 3 years	as long as possible	as long as possible	

by JAXA



高温プラズマの分光

地上の4keVプラズマ（電子ビームイオントラップ）からの放射（**実データ**）

EBIT @LLNL
P. Beiersdorfer 2003, Annu. Rev. Astron. Astrophys.

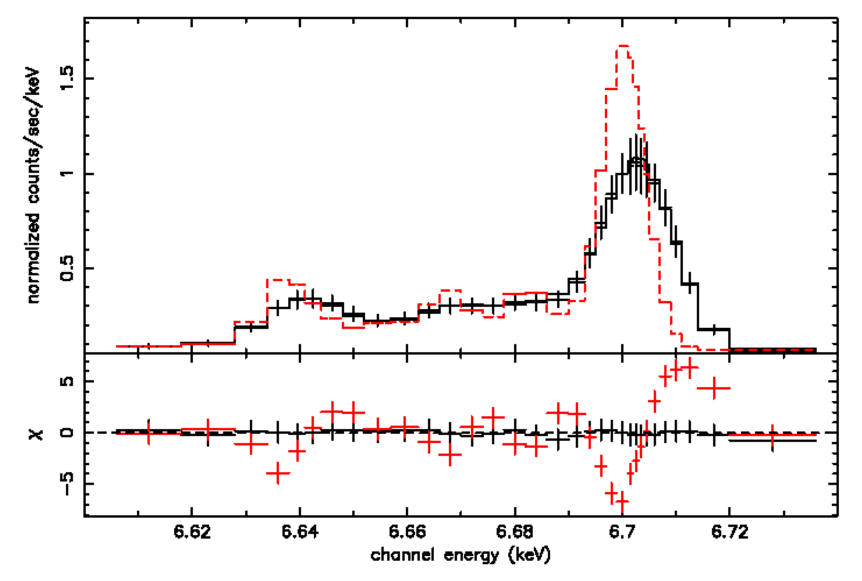
Fe K emission line Astro-E2 XRS
(simulation)

by JAXA

Mock observations

- We summed up the spectra of individual computational grid points
  - This is the first time to construct detailed X-ray spectra from numerical simulation results
- ASTRO-E2 XRS response file is used
  - We made mock observations with ASTRO-E2
  - Fe lines at ~6.7 keV

Results



Black: Tsunami
Red: No Tsunami

- Fe lines are broadened by turbulence
- Lines are shifted by tsunamis
  - Bulk motion of the cluster core
    - Asymmetric injection of waves (e.g. cluster mergers)
  - Line shifts are unlikely to occur for turbulence induced by symmetric jets accompanied by AGN activities

Summary

- Cooling flow problem
  - Little cooling gas has been observed in cluster cores
  - There must be a heating source in a cluster core
- Popular solutions
  - AGNs
  - Thermal conduction
  - Both have serious problems

Summary

- Tsunami model
    - Hierarchical clustering scenario predicts bulk gas motions in clusters
    - The cores should be affected by the motions
- Two-dimensional simulations showed that local but strong turbulence is created in a core
    - The turbulence suppresses radiative cooling
    - Complicated X-ray structures observed in cores can be reproduced
    - Turbulence could be observed with ASTRO-E2

The Future

- 3D ultra-high resolution cosmological simulations
  - Structure of turbulence is different between 2D and 3D
  - Heat transfer could be more efficient in 3D turbulence
  - Wave injection from various directions
  - Change of gravitational potential well
- Particle acceleration by turbulence
  - Radio mini-halos?
- Magnetic fields
  - Amplification of magnetic fields
  - Thermal conduction
- Turbulent dissipation