The Intra Cluster Medium in Dark Matter Halos

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OUTLINE

1) The ICP: the best Plasma in Universe, archive of the rich cluster history, Baryons & DM over ~ 10 Gyr

2) In DM halos, ICP equilibrium under DM gravity vs. thermal pressure related to baryon entropy:

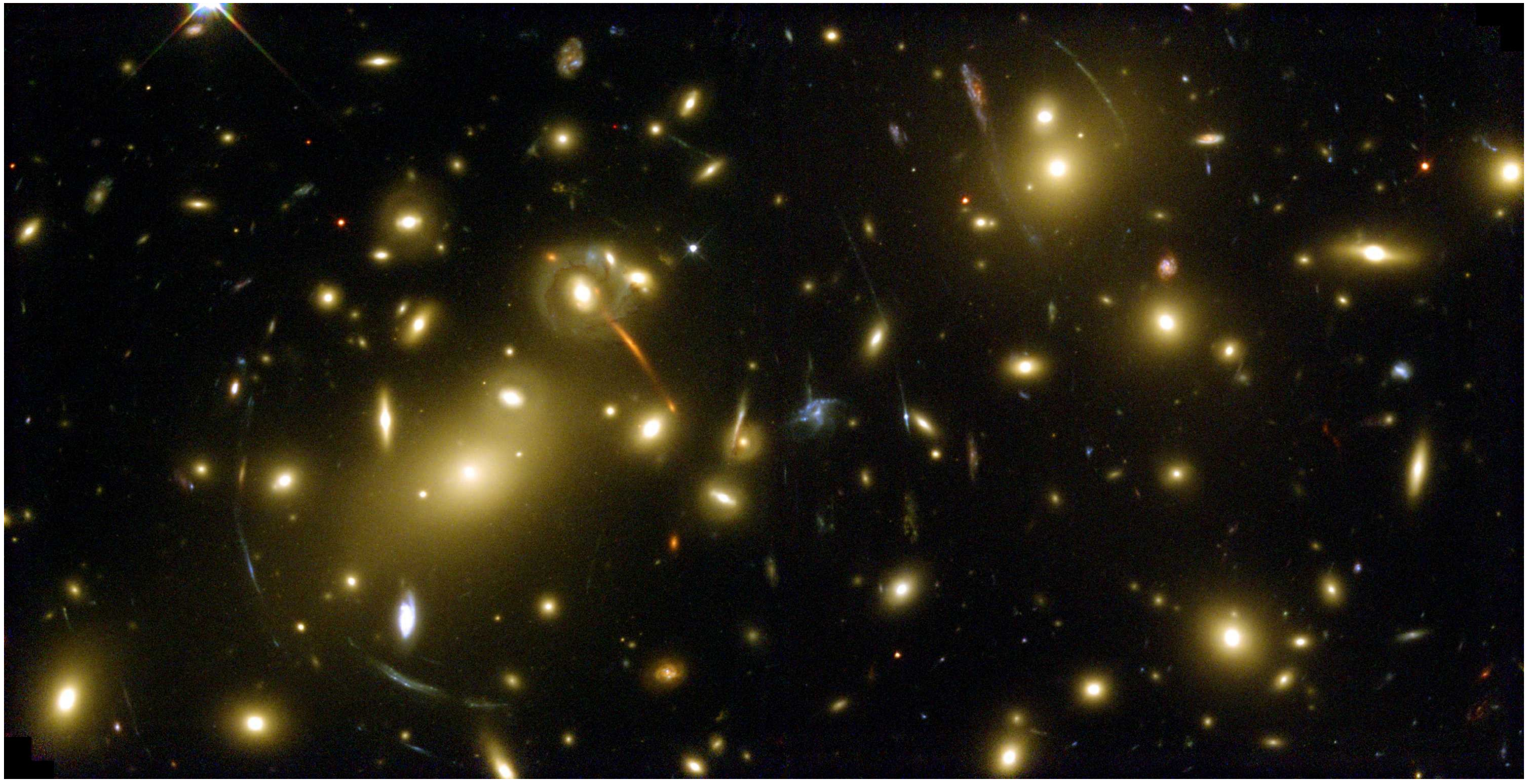
   conserved on compressions, raised by shocks (central AGN or deep mergers + boundary accretion); eroded by cooling

3) Entropy -> ICP Supermodel, compared with data: central cores, CCs vs. NCCs; halo shapes/ages, a Grand Design

4) Outskirts: accretion demise and T(r) decline, non-thermal pressure and its effects

-> ICP as a probe of structure/development of DM halos.

Clusters of galaxies



Abell 2218 z = 0.17, the Optical view

The Optical view:

observed 1-D $\sigma \sim 10^3$ km/s

$\sim 10^3$ galaxies (rich cl.)

Virial theorem --> $M \sim 10^{15}\ M_{sun} \sim 10^2\ M_*$

within v. radii $R \sim 2$ Mpc

$$\sigma^2 \sim \frac{GM}{5R}$$

crossing time $R/\sigma \sim$ 1 Gyr

The IntraCluster Plasma

UHURU: A.C., Gursky & Tucker 1971 → new class of powerful **X-ray** sources ⟺ galaxy **associations**

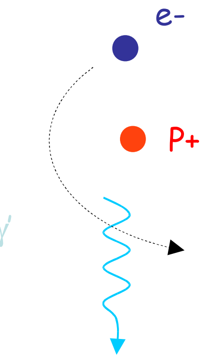
→ all Clusters,
most Groups

$$5\,\mathrm{keV} \sim kT = \frac{GM}{10R}\,m_p = \frac{\sigma^2}{2} \qquad \sigma \sim 10^3\ \mathrm{km/s}$$

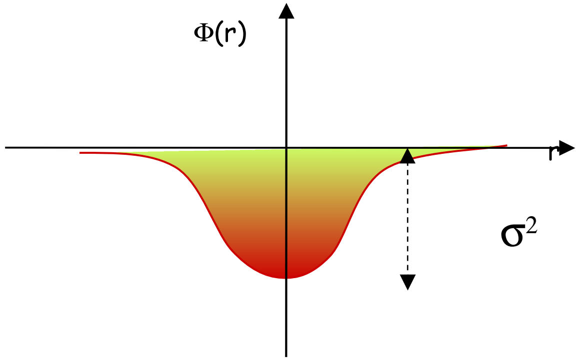
L_X by thermal o. thin Bremsstrahlung, $h\nu \sim kT$

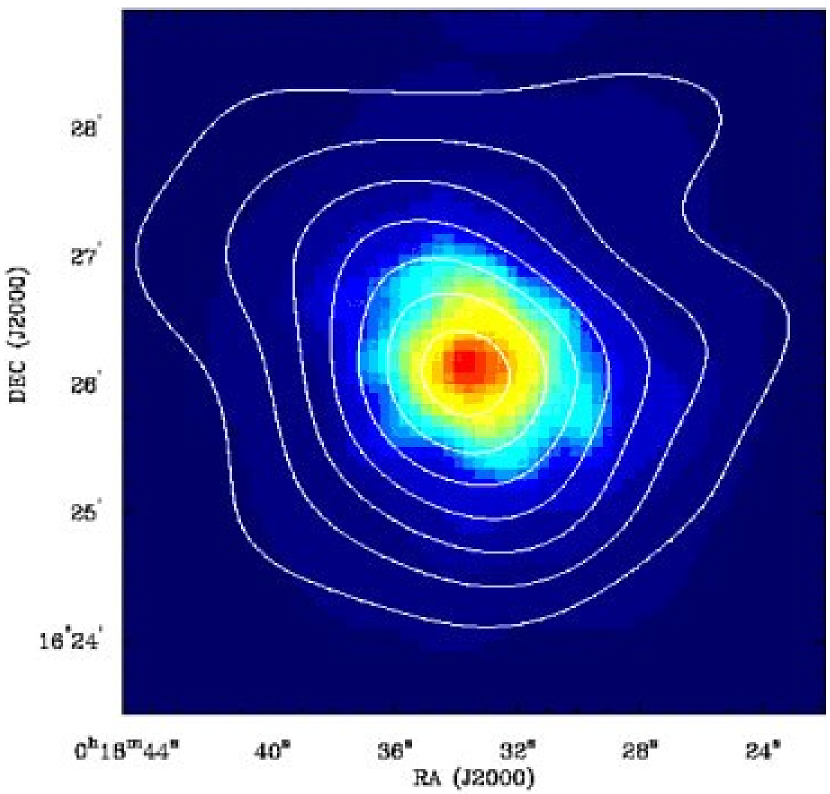
$$L_X = A\,n^2 R^3 \sqrt{T} \approx 10^{44\div 45}\ \mathrm{erg\,s^{-1}}$$

+ high excitation em. lines 1976-77



Hot, thin medium $n \approx 10^{-3}\ \mathrm{cm^{-3}}$
within DM gravitational well





CL 0016+16 z=0.54, X + SZ views

→ ICP, best Plasma in Universe !

free p+, e⁻ kinetic >> electrostatic energy at average $d = n^{-1/3} \sim 10$ cm

In fact

$$\frac{kT}{e^2 n^{1/3}} \sim 10^{12}$$

>> star interiors 10^3 or
cosmological Plasma 3 10^5

Despite feeble gravity $G\, m^2_p/e^2$ d/10 R N_{DM}

10^{-36} 10^{-25} 10^{73} Or $n\, \Lambda^3_D = (r/4\pi)^{3/2} \sim 10^{16}$

→ ICP = fluid with 3 degrees of freedom, effective $\mu \sim 0.6\, m_p$, in thermal equilibrium by collisions: $\lambda_{ii} \sim 10\,(k_B T_{5\,\mathrm{keV}})^2/n_{-3}$ kpc, $\lambda_{ei} \sim 40 \times$. Makes up baryonic mass $m \approx 1/6\, M$ ~ cosmic fraction (metals Z ~ 1/3 Solar).

ICP confined/heated up by DM gravity: simple fluid amenable to precise modeling

Based on ICP entropy $kT/n^{2/3}$ that provides the archive for conserving energy discharged into cluster center//outskirts over radiative cooling t ~ 0.1 //10 Gyr

DM halos

lecture by A. Lapi

Jeans eq. ~ hydrostatic $$\frac{1}{\rho}\frac{d(\rho\sigma^2)}{dr} = -\frac{G\,M(<r)}{r^2}$$ under same DM gravity

DM $P = \rho\,\sigma^2 = \rho^{5/3}\,K$ i. t. o. convenient 'entropy' $K \equiv \sigma^2/\rho^{2/3}$ though collisionless & self-gravitating !

N-body simulations prove in the halos' body $K \propto r^\alpha$ $\alpha = 1.27 \pm 0.02$

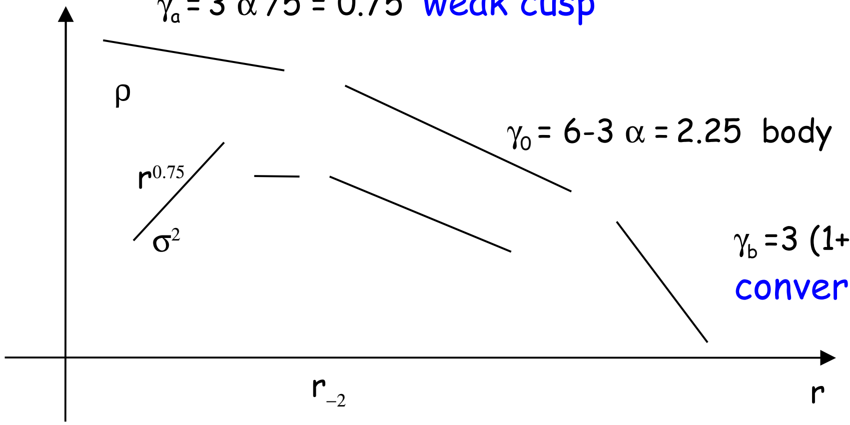
Thus Jeans reads $$\frac{d\ln\rho}{d\ln r} = -\frac{3}{5}\frac{d\ln K}{d\ln r} - \frac{3}{5}\frac{v_c^2}{\sigma^2}$$ $$v_c^2(r) \equiv \frac{G\,M(<r)}{r}$$

or in compact form
$\rho \sim r^{-\gamma}$

$$\boxed{\gamma(r) = \frac{3}{5}\alpha + \frac{3}{5}\kappa(r)}$$ ⇒ α-profiles

e.g., $\alpha = 1.25$
Taylor & Navarro 01
≠ from NFW!

concentration $c = R/r_{-2}$
outskirts/body from
G. Lensing or X rays



$\gamma_a = 3\,\alpha/5 = 0.75$ weak cusp

$\gamma_0 = 6-3\,\alpha = 2.25$ body

$\gamma_b = 3\,(1+\alpha)/2 = 3.38$
converging M

ICP in hydrostatic equilibrium, DM gravity vs. thermal $p = n\,k_B\,T/\mu$

$$\frac{1}{m_p\,n}\,\frac{dp}{dr} = -\frac{G\,M(<r)}{r^2}$$

on sound crossg. $R/c_s \leq R/\sigma$ dyn. time

e.g., β-model: T = const, $d\ln n/dr = -\beta\, d\varphi/dr$ → $n = n_2 \exp(-\beta\,\Delta\varphi)$ $(\beta \doteq \mu\, m_H \sigma^2/k_B T)$

Use ICP entropy $k \equiv k_B\,T/n^{2/3}$ (adiabat) dependg. only on energy addition/loss

→ $p = n^{5/3}\,k$

$$\frac{d\ln n}{d\ln r} = -\frac{3}{5}\frac{d\ln k}{d\ln r} - \frac{3}{5}\,b(r)$$

$b(r) \equiv \mu\, m_p\, v_c^2/k_B\, T$

running β

This simple 1st order differential eq. + 1 boundary condition integrates to

normd. k/k_2 , T/T_2 , n/n_2

➡

$$T(r) = k^{3/5}(r)\left[1 + \frac{2}{5}\,b_2 \int_r^1 dr'\,\frac{v_c^2(r')}{r'}\,k^{-3/5}(r')\right] = k(r)\,n(r)^{2/3}$$

AC, Fusco, Lapi 09

http://people.sissa.it/Supermodel/

→ Supermodel, w. entropy run κ (r) physically given, yields precision Cluster description to match rich observations:

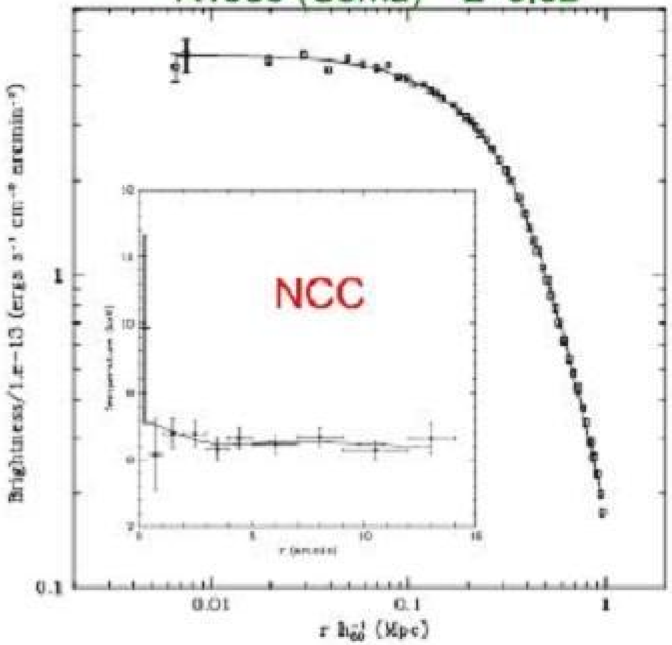
X-ray brightness $\propto n^2\,T^{1/2}$ + spectral temperature T, μw SZ scattering $y \propto p_e \propto n\,T$

X-ray obs.: Surface brightness & Temperature (insets)

from XMM, Chandra, Suzaku 0.5 – 10 keV

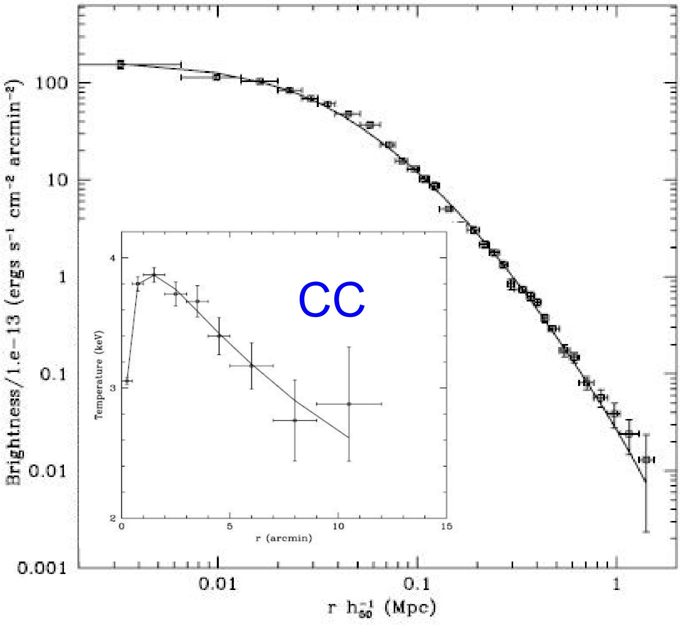
Mohr al. 99

A1656 (Coma) z=0.02



A2597 z=0.08

Xue, Wu 00



Supermodel links n(r) & T(r) in terms of k(r)
yields for T(r) shapes: peaked Cool Core vs. flat NCC

Molendi Pizzolato 01, Pratt al. 10

based on entropy production/erasure -->

ICP entropy, produced by shocks, conserved over cooling t

Eroded by radiative cooling on scale $t_{cool} = 3\, k_B\, T/l_x \sim 10\, T_8^{1/2}/n_{-3}$ Gyr

Raised by shocks converting bulk into thermal energy on dyn. t ~ 0.1 Gyr,
(over λ_{ii} , equipartition takes longer λ_{ei}) Bower 97, AC Lapi Menci 05, Voit 05

Rankine-Hugoniot shock jumps: conservation of mass, momentum, energy across layer yield for strong shocks (supersonic flows, maximal thermalization)

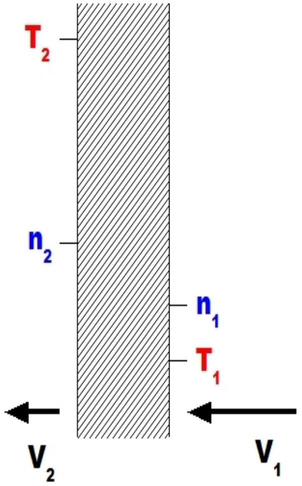
$n_2/n_1 = 4$

$k_B\, T_2 = \mu\, m_p\, v^2_f\, /3$

$\propto Mach^2 = (v_1/c_s)^2$

$\rightarrow \boxed{k_2 = k_B\, T_2/\, n_2^{2/3}}$

+ residual bulk $v_2 = v_1/4$
(shock frame)



Shocks thermalize flows from:

- grav. infall across cl. boundary of cold IGM at Mach ~ 10^2
- blasts/shocks into ICP from:
  central AGNs Mach ~ 1.5 – 2
  deep mergers Mach ~ 5

→ k(r) = floor + ramp

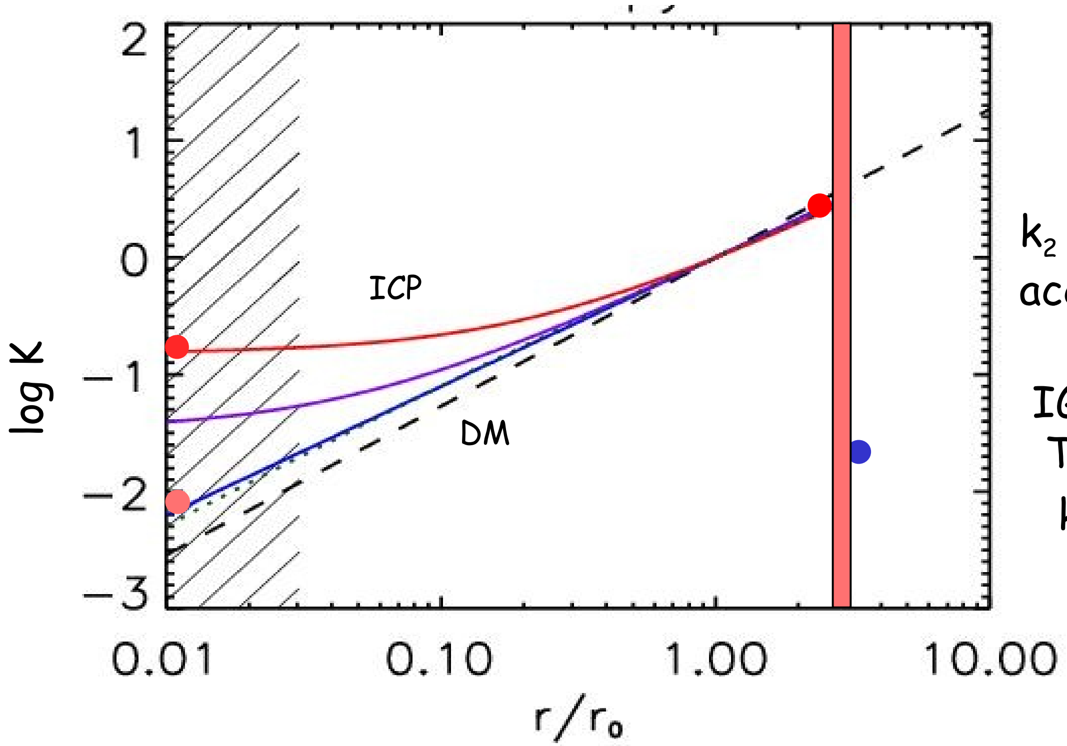
Entropy floor + ramp

$k = k_0 + k_2\,(r/R)^a$

Voit 05, Arnaud al. 2009

in SModel
3 parameters:

k_0, k_2, $a \sim 1.1$



$k_2 \sim 3\ 10^3$ keV cm^2
accr. shock at R

IGM:
$T_1 <$ 0.1 keV,
$k_1 \sim 0.1$ keV cm^2

Pivotal values:

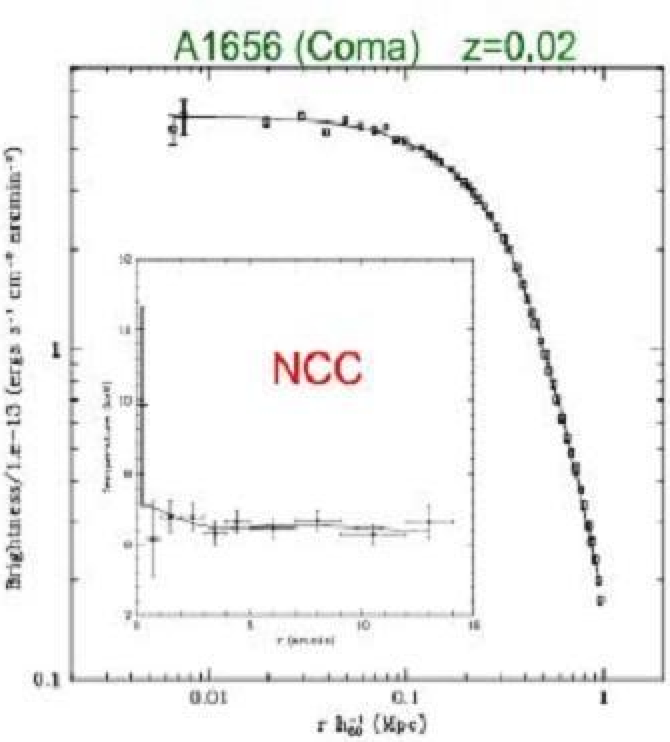
central floor, AGN/merger *shocks*: $\Delta E \rightarrow k_0 \sim 1$ keV/part$(10^{-3})^{-2/3} \sim 10\text{-}10^2$ keV cm^2

boundary infall, strong accr. *shock*: $k_2 \sim 5$ keV / $(10^{-5}\ \mathrm{cm}^{-3})^{2/3} \sim 3\ 10^3$ keV cm^2

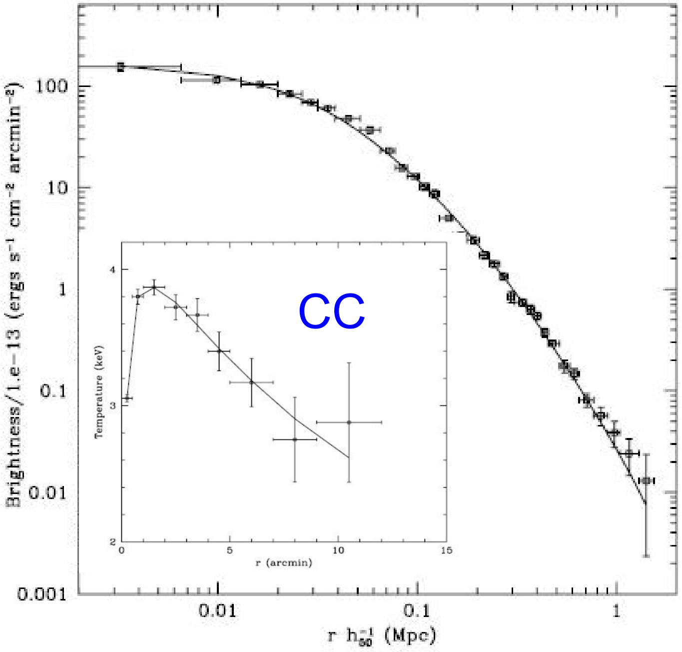
ramp: stratified $k(r) \sim r^{1.1}$, see later

X-ray Brightness & Temperature

Fusco-Femiano, Lapi, AC 09


A1656 (Coma) z=0.02

A2597 z=0.08



SModel fits n(r) & T(r), in terms of entropy floor + ramp

$k(r) = k_0 + k_2 (r/R)^a$ w. 3 specific params.: k_0 , k_2 a, with $\chi^2_n \sim 1$

→ $T_0 \sim k_0^{3/5 - 0.35 \sim 0.3}$, $n_0 \sim k_0^{-1}$ → $t_{co} \sim 10\,(k_o/100)^{1.1}$ Gyr short/long

+ concentration $c = R/r_{-2}$ (if not known from Grav. Lensing)

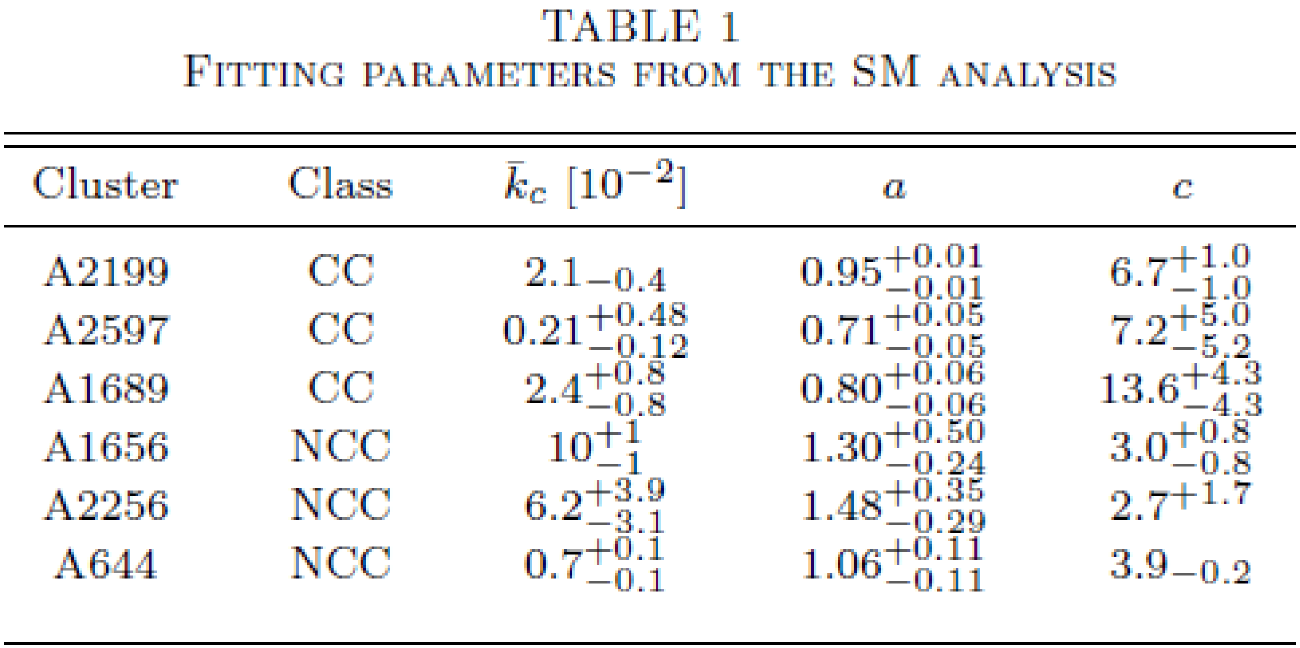


TABLE 1
FITTING PARAMETERS FROM THE SM ANALYSIS

Cluster	Class	$\bar{k}_c$ $[10^{-2}]$	a	c
A2199	CC	$2.1_{-0.4}$	$0.95^{+0.01}_{-0.01}$	$6.7^{+1.0}_{-1.0}$
A2597	CC	$0.21^{+0.48}_{-0.12}$	$0.71^{+0.05}_{-0.05}$	$7.2^{+5.0}_{-5.2}$
A1689	CC	$2.4^{+0.8}_{-0.8}$	$0.80^{+0.06}_{-0.06}$	$13.6^{+4.3}_{-4.3}$
A1656	NCC	10^{+1}_{-1}	$1.30^{+0.50}_{-0.24}$	$3.0^{+0.8}_{-0.8}$
A2256	NCC	$6.2^{+3.9}_{-3.1}$	$1.48^{+0.35}_{-0.29}$	$2.7^{+1.7}$
A644	NCC	$0.7^{+0.1}_{-0.1}$	$1.06^{+0.11}_{-0.11}$	$3.9_{-0.2}$

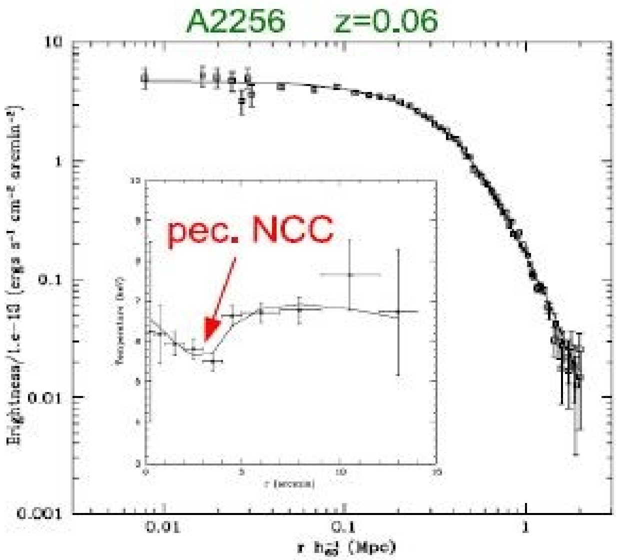
ICP – DM connection: basic T(r) shapes: CC – NCC related to central k_0

Also related to large-scale halo concentration $c = R/r_{-2} = 10 - 4$ (from X rays or G Lensing), in turn linked to ages (outskirts) $z_t = 2 - 0.2$

lecture by A. Lapi

→ Grand Design: CC central ICP = cold; DM = extended, old $z_t \sim 2$
NCC central ICP = hot; DM = compact, young $z_t \sim 0.5$

Next:



Snowden al. 08

Fusco-Femiano, Lapi, AC 09

blast/shock stalls at r_f ~ 250 kpc

inner entropy flat before ramp,
T(r) ~ k(r) $n^{2/3}$ dips then recovers

Focus on Center

Deep mergers
or
AGNs/QSOs → inject energy pulses

$\Delta E \sim 10^{63}$ erg

$\Delta E \sim 3\ 10^{61}$ erg

Launch blastwaves w. leading shocks, spread energy ΔE into ICP E,

when continuously driven Mach > 1 out to 200 kpc

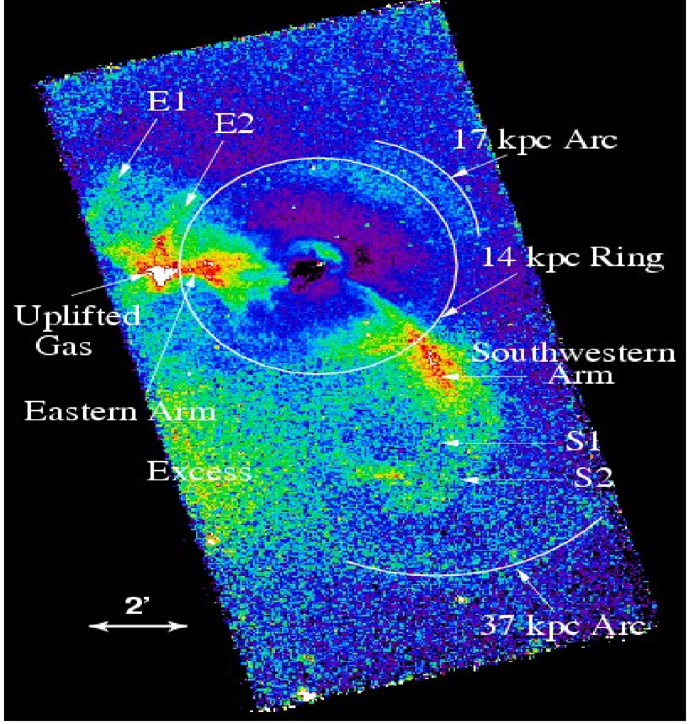
Raise etropy to $k_2 = k_B T_2 / n_2^{2/3} \propto \mathit{Mach}^2 \propto \Delta E/E$

Also deplete/eject ICP → $m \sim (1 - \Delta E/2E)$ AC, Lapi 07

Deep mergers, simulations Markevitch Vikhlinin 07, McCarthy al. 08;

see lectures by Gottloeber, Hoffman, Klypin

AGNs w. $L \sim 2\ 10^{46}$ erg/s, direct evidence in nearby clus./groups



M87 (Virgo Cluster), shocks on 15 -30 kpc scales

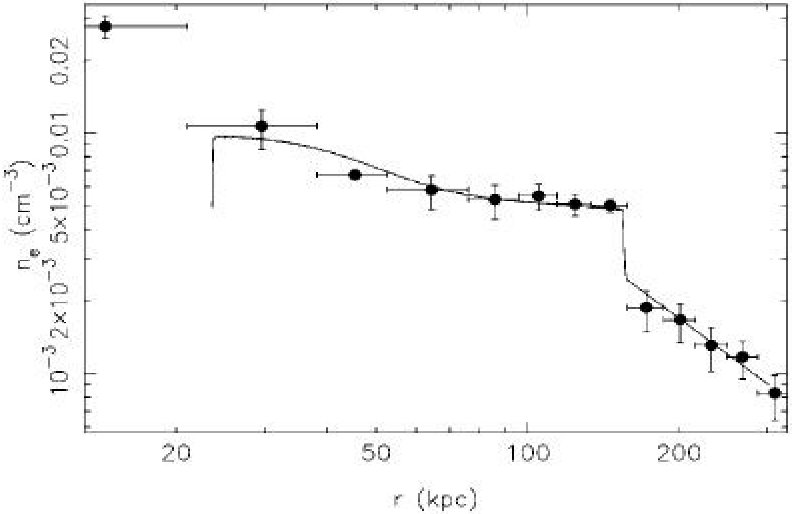
14 kpc ring in

- Seen over nearly 360^0

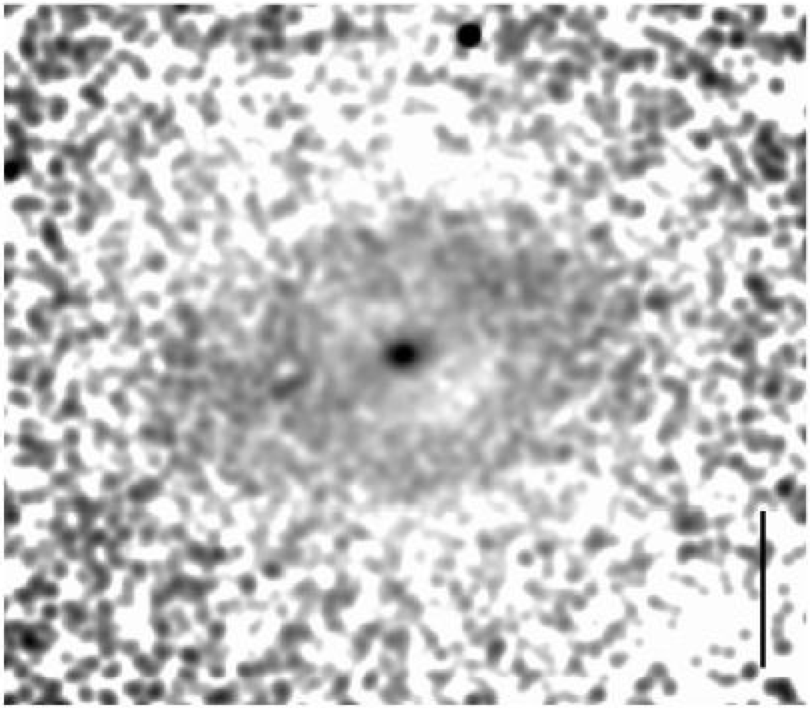
Symmetry naturally explained as a shock explosion of 10^{58} ergs about 10^7 years ago.

- Mildly supersonic (Mach=1.2, v=950 km/s).
- Up to Mach 8 Forman al. 06

McNamara & Nulsen 08



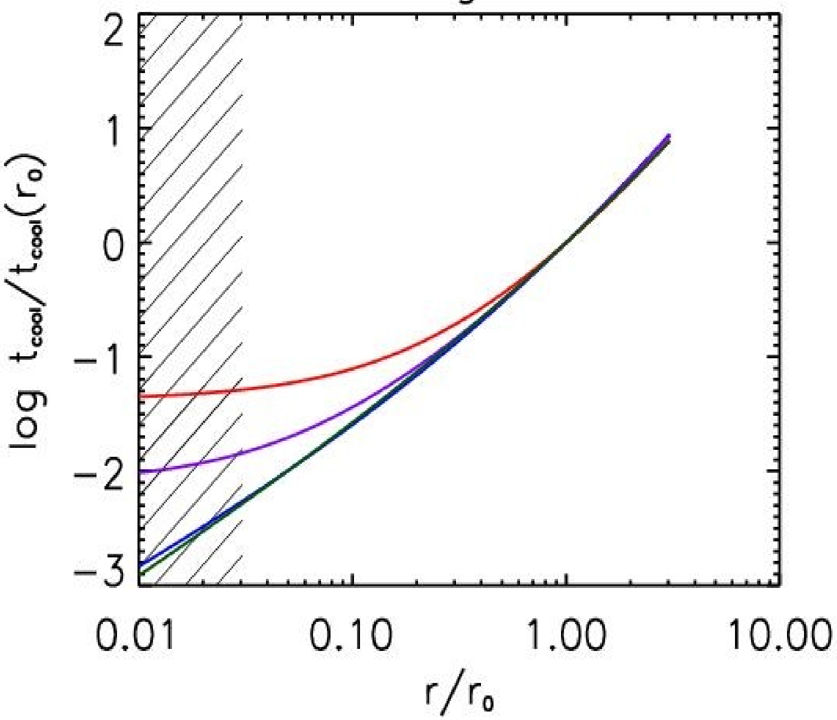
200 kpc shocks in Hercules A Cluster



Central ICP, snapshots w. SModel

NCCs $k_o/k_2 > 3\ 10^{-2}$: hot, stable to both new shocks and cooling $t_{c0} \sim$ Gyrs; flat brightness requires weak DM halo cusps

CCs $k_o/k_2 < 10^{-2} \sim$ 10 keV cm^2: low but finite $T_0 \sim 1$ keV, spiky central n^2



For both:

$T_0 \sim k_0^{3/5-1/3\,=\,0.27}$ $n_0 \sim k_0^{-1}$

with cooling times

$t_{co} \sim T_o^{1/2}/n_o \sim 10\ (k_0/100)^{1.1}$ Gyr

→ 10 - 0.1 Gyr

Cool Cores will trigger radiative cooling; $dk/dt \sim - k/t_c$ may start in central E galaxy a recurrent loop: see Voit Donahue 05; Ciotti Ostriker 07 ..

BH fueling, frequent AGN outbursts raise k_0 (A.C. & Lapi 08), stabilize catastrophic cooling (Tabor Binney 98), lead to an average balance ?

Next

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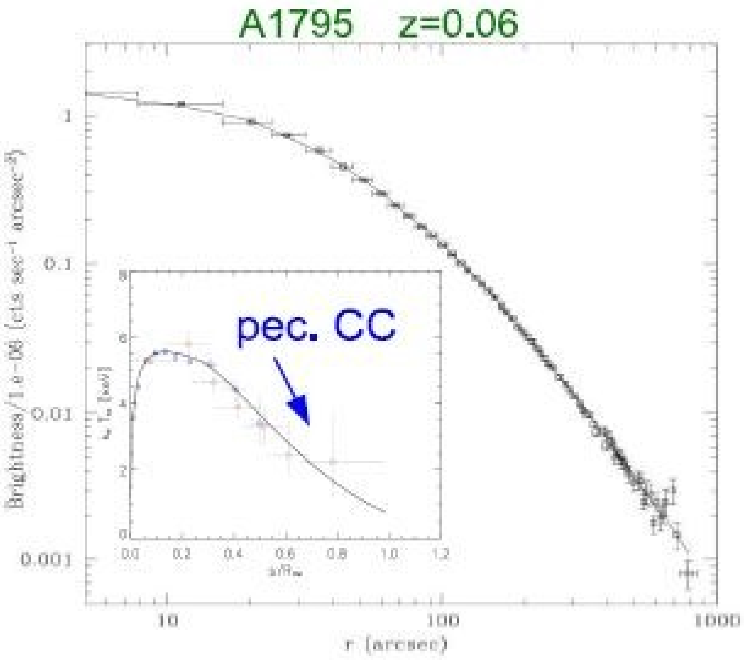


Bautz al. 09

Lapi, Fusco, AC 10

+ boundary/outskirts:

gravitational accretion and entropy production on their demise?

Focus on boundary & outskirts

Deposition at r=R of infall kinetic energy → k_2 . For **strong** accretion shocks recall

$$\begin{cases} kT_2 = \mu\, m_p v_{\inf}^{2}/3 \\ n_2 = 4n_1 \end{cases} \quad \rightarrow \quad k_2 = k_B\, T_2\, n_2^{-2/3}$$

DM sets $v_1^2 = 2\, v_c^2 = 2\,\Delta\Phi$ infall to R → $b_2 = \mu\, m_p v_c^2/kT_2 = 3/2\,\Delta\Phi \sim 2.7$ ($\alpha \sim 1.27$)

Scaling yields $k(m) \propto K \propto m^{1.5}$

$$K \propto \frac{M^{4/3}}{\dot{M}^{2/3}} \propto M^{2\,(1+\epsilon/d)/3}$$

A.Lapi lecture

as outskirts grow after $m \propto M \propto t^{d/\epsilon}$ ($d = 2/3 \rightarrow 1/2$ in Concordance Cosmology) from perturbations with shape ruled by $\epsilon > 1$ for slow accretion.

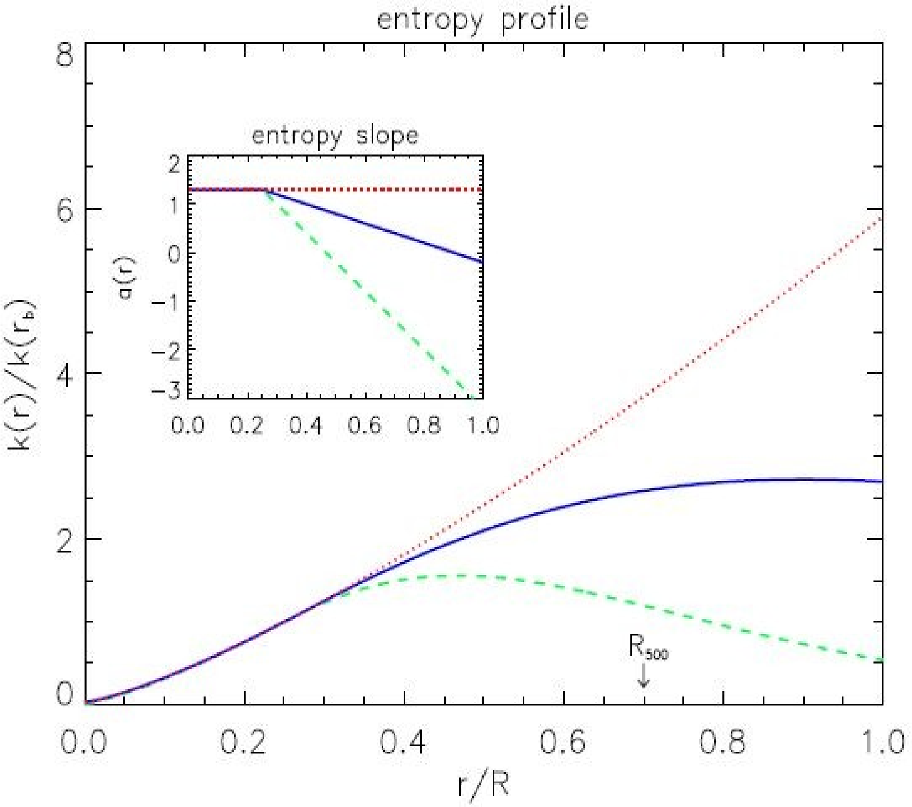
But at r = R equilibrium density $n \propto r^{-g}$ with $g = 3\,(a + b_2)/5$, so $k \propto r^{a} \propto m^{a/(3-g)}$

On equating → $a = 2.4 - 0.47\, b_2 \sim 1.1$ (+ variance)

Tozzi & Norman 01,

Note $k \propto r^a$ throughout outskirts by stratification in relaxed Cls. (adiabatic compression, no other sources down to 1/2 Mpc) and conservation (long t_c)

But for $z < 0.5$ expect: accretion & related entropy production slow down, slope a of $k \propto r^a$ saturates/declines



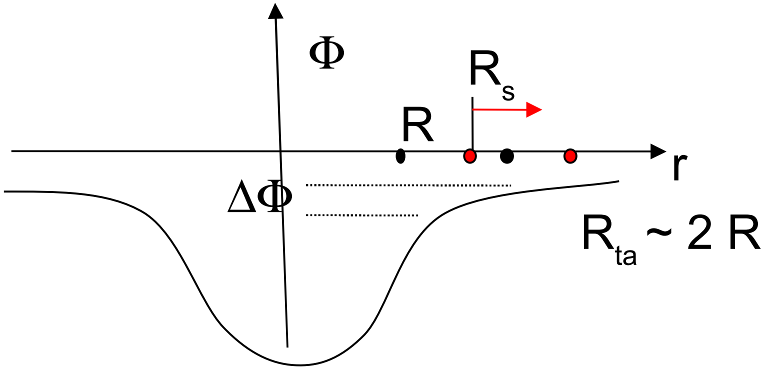
Then from

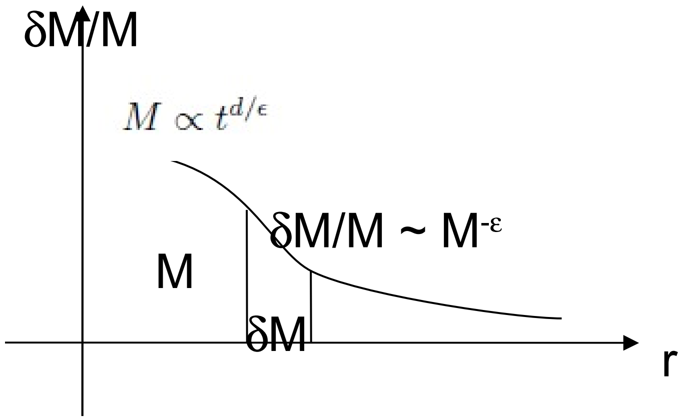
$$T(r) \propto n^{2/3}(r) \quad k(r)$$

expect $T(r) \propto n^{2/3}(r)$ to decline steeply outwards

In detail -->

Outskirts development M $\sim t^{d/\varepsilon}$ modulated by: decreasing perturbation wings ($\varepsilon > 1$) + accelg. cosmology ($d < 2/3$)





shape of
initial pert.

$$\Delta\Phi = \int_R^{R_{ta}} dr\, \frac{G\delta M}{r^2} = \frac{1}{3\epsilon - 2}\left[1 - \left(\frac{R}{R_{ta}}\right)^{3\epsilon-2}\right]$$

late z: shallow outer potential wells from perturbation wings

$$v_1^2 \propto \frac{M}{R_s}\Delta\phi$$

cause slower infall

$$\frac{R_s}{R_{ta}} \propto \frac{M^{2/3-\epsilon}}{\dot{M}^{2/3}}(\Delta\phi)^{1/3}$$

shock moves out, weakens

→ lower k(r)

- steeper T(r)
- larger residual v_2

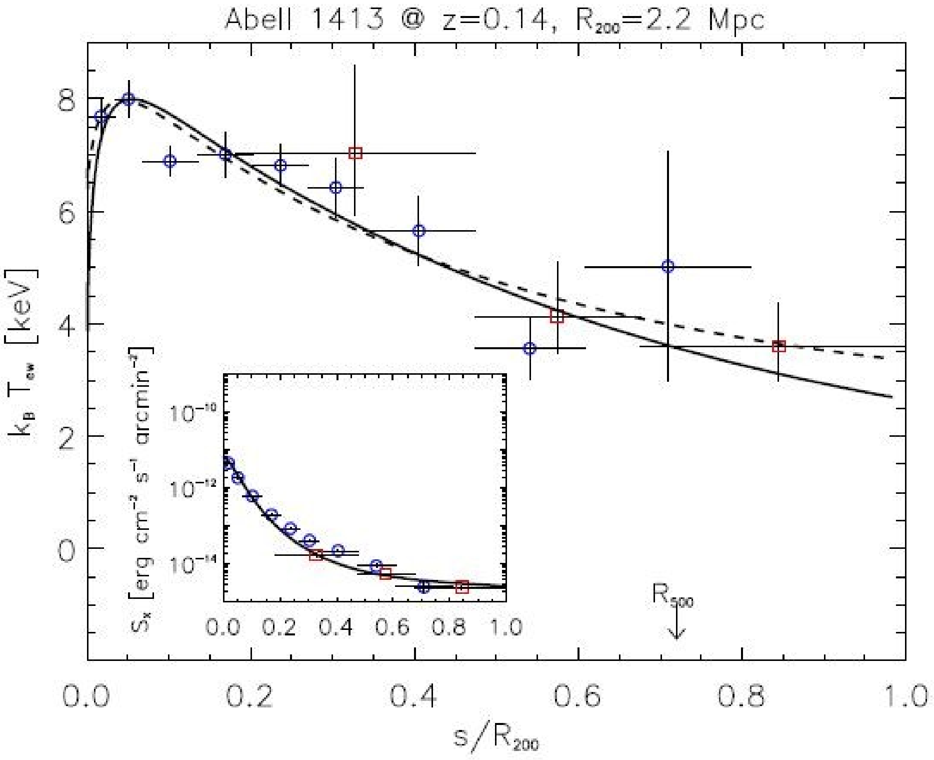
Several Clusters observed >2009

XMM, Suzaku: T(r) declines

SModel: Lapi, Fusco, AC 2010

--> k(r) bends ar r/R = 0.3 +/- 0.02
gradient a' = 1.8 +/- 1.3

T(r) steep at low z

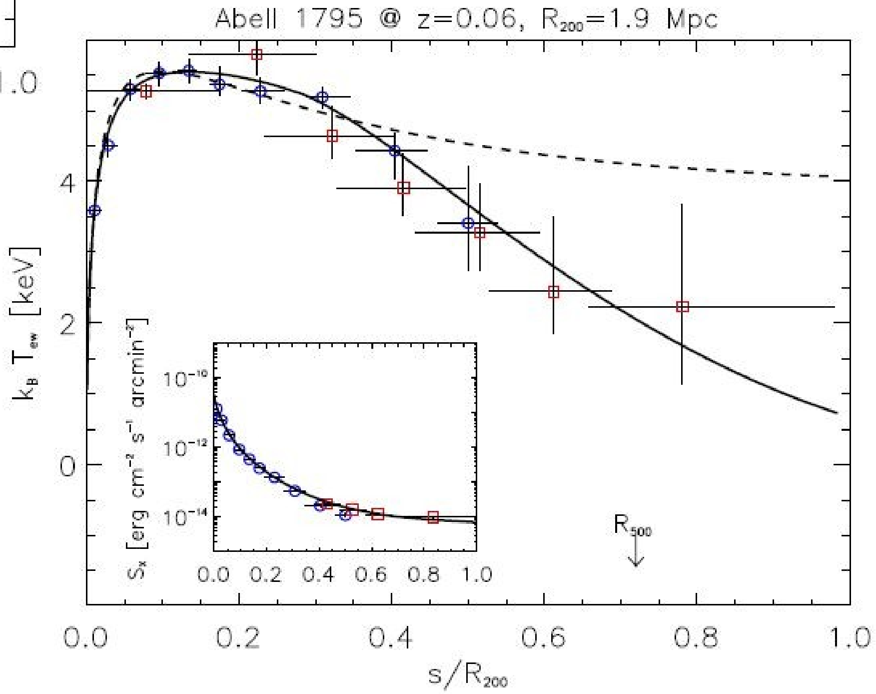


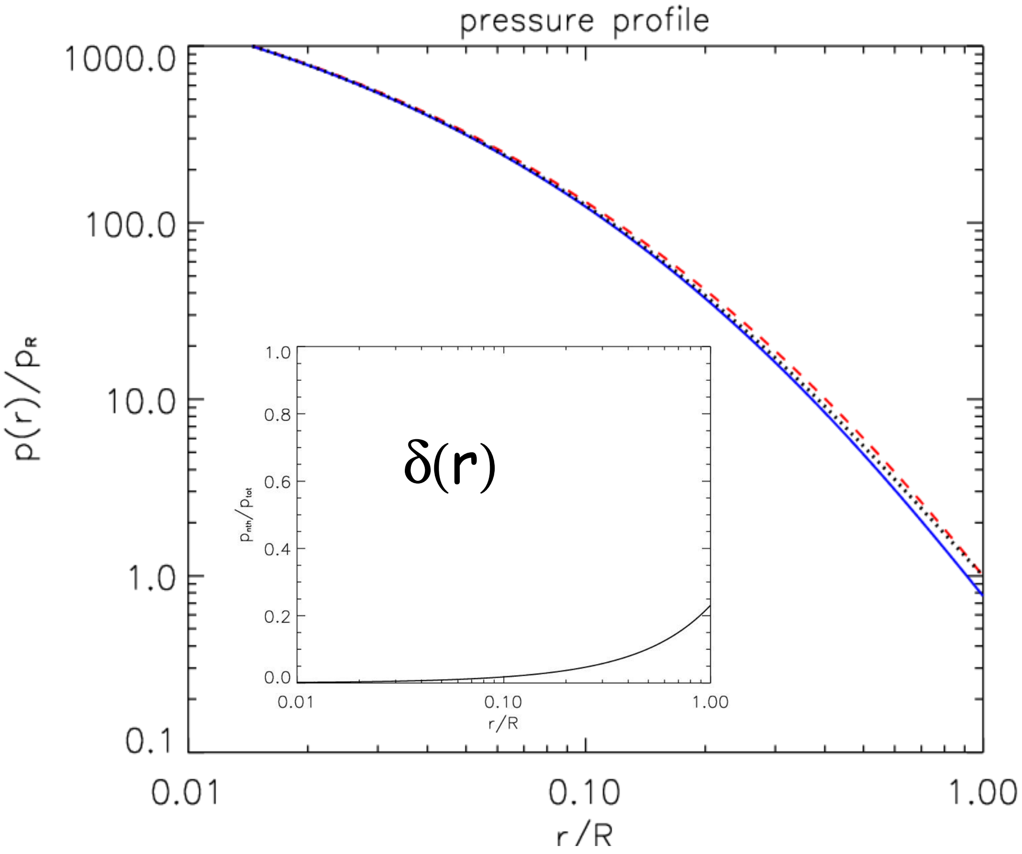
high z

Reiprich al. 09

Bautz al. 09

also George al. 09, Kawaharada al. 10 ..





But then non-thermal, turbulent δp from residual bulk flow past shock will contribute to hydrostatic support even in relaxed Clusters

Turbolence, wide interest:
Vikhlinin al. 09, Lau al. 10, Molnar al. 10 ..

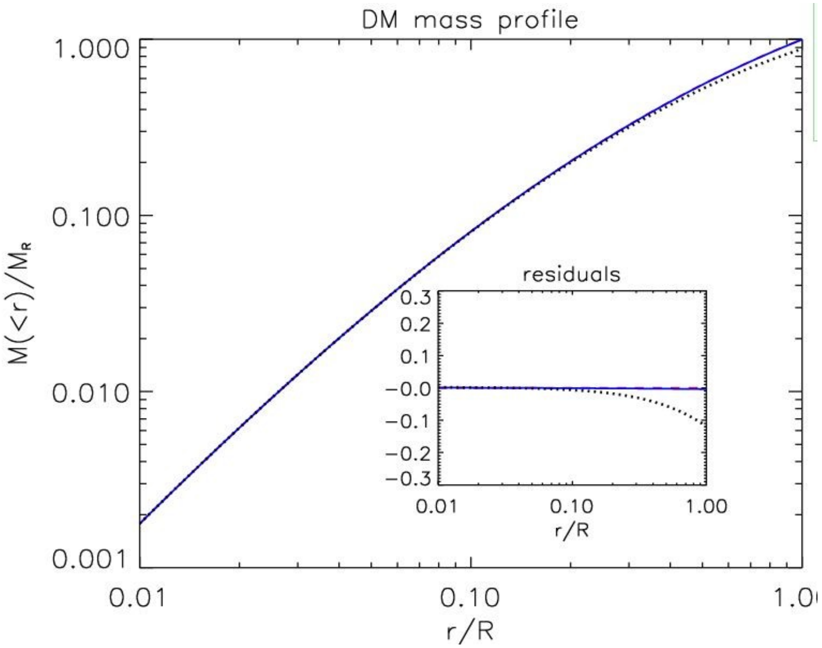
┈┈┈ p_{th} $\delta = 0$

$$\left.\begin{array}{l} \text{—— } p_{th} \\ \text{■■■ } p_{tot} \end{array}\right\} \delta_2 = 30\%$$

$\delta p/p = \delta(r)$ in SModel: levels at shock
$\delta_2 \sim (v_2/v_1)^2 > 1/16 =$ 9% from resid. v_2;
dissipated on scale $R/Re^{3/4} \sim$ ½ Mpc

Inogamov Sunyaev 03

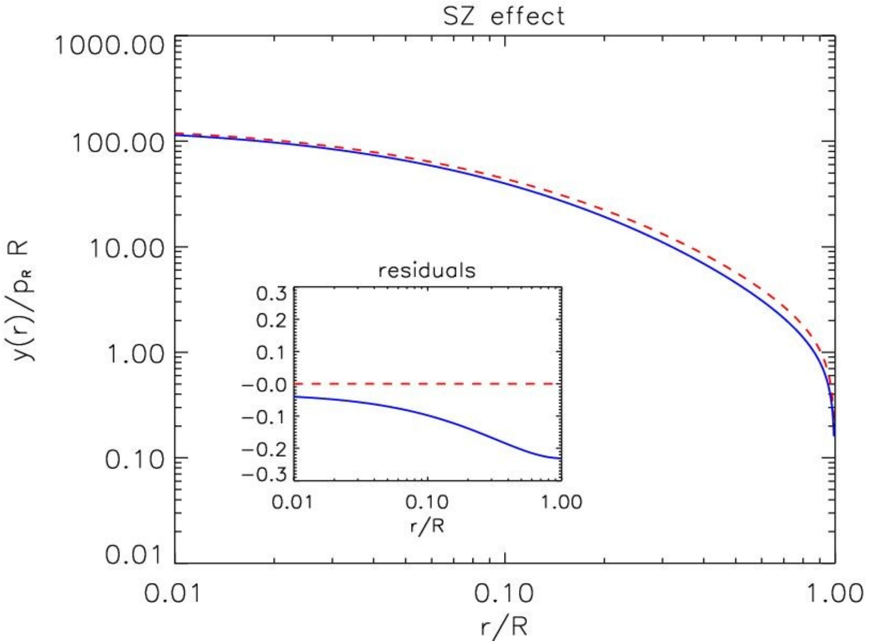
→ $T \propto (1+\delta)^{-2/5} \sim 0.9$ decreases weakly,
entropy saturation & a(r) dominate



But signature: in X rays, pure thermal support would cause DM M(<r) to attain only 85 % of true value

$$M(<r) = -\frac{rT(r)}{G}\frac{d\log p}{d\log r}$$

δp → full DM masses from fast X rays? key issue for Cosmology from statistics of DM halos.



Check w. SZ scattering

$y \propto p_e \propto (1 + \delta)^{-1}$

higher by 25 % with δp

Probe turbulent δp, input level & scale

AC, Lapi, Fusco in prep.

Conclusions

DM halos probed in terms of ICP, with X rays (brems. : $n^2 T$, T) and microwaves (SZ scattering: $p_e \propto n T_e$)

ICP represented by effective yet simple Supermodel: hydrostatic equilibrium under thermal p, 3 specific parameters, based on entropy (// simulations)

Entropy deposited/stratified at center and outskirts, conserved over a cooling time; thus radius r records history t.

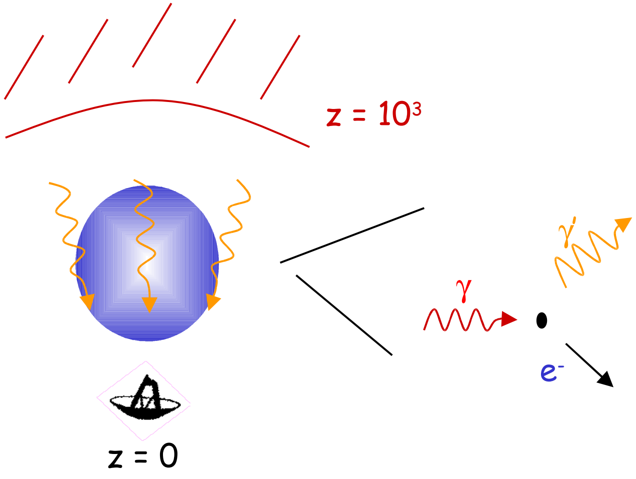
SModel snapshots provide info. to retrieve evolution of ICP: central events over r ~ 0.3 Mpc, t ~ 0.1 Gyr; outskirts, r ~ 2 Mpc, t ~ 10 Gyr

Inner CC -- NCC shapes of ICP relate to large-scale DM halo shape c ~ 10 – 4, formation (transition) ages $z_t \sim 2$ -- 0.5 of DM halos → Cluster Grand Design

For $z_{obs} < 0.5$ expect: accretion demise, increasing turbulent contribution δp to HE driven by smooth mass inflow past the shock → from fast X rays (+SZ), assess bias in masses of DM halos

SZ: i. Compton scattering of CMB photons by thermal electrons

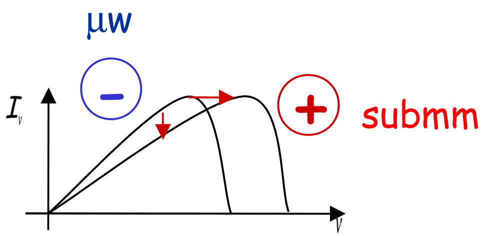
Sunyaev Zel'dovich 1972



$$y \equiv 2\frac{\sigma_T}{m_e c^2}\int_0^R kT_e\, n\, d\ell$$

Compt. parameter along l.o.s.

$$\left(\frac{\Delta T}{T}\right)_{CMB} \rightarrow -2y \sim \underset{\frac{\Delta h\nu}{h\nu}}{10^{-2}} \times \underset{\tau}{10^{-2}} \sim 10^{-4}$$

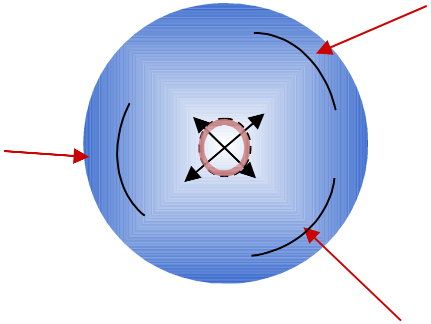


a "cold shadow" cast by a hot plasma cloud

SModel:

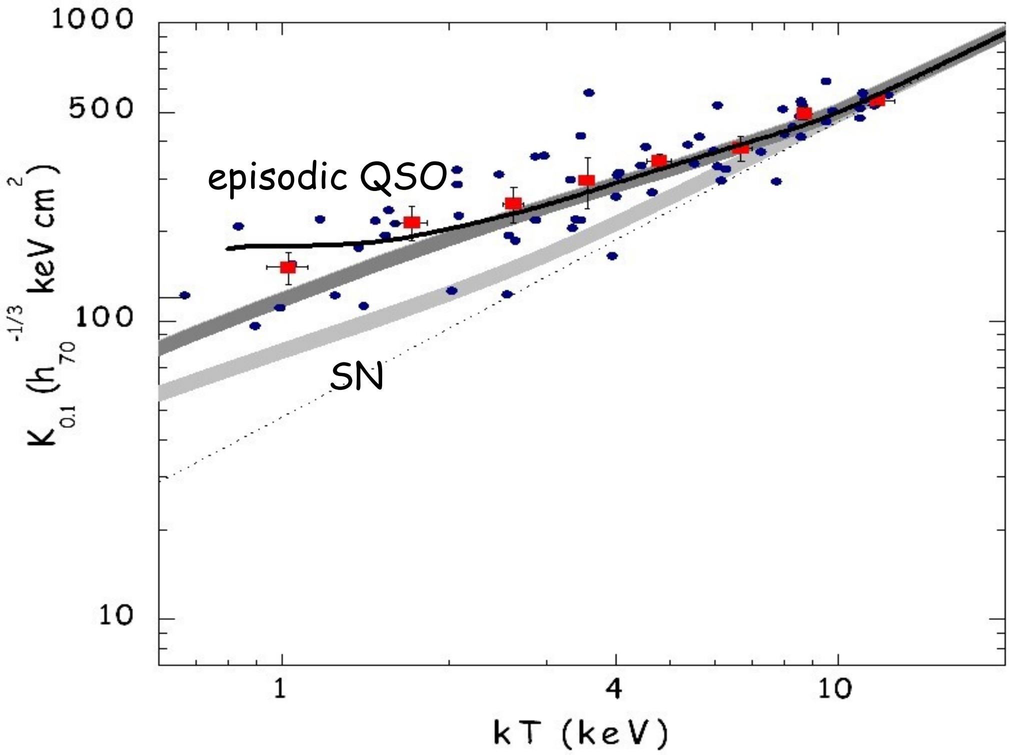
$$y(\bar{r}) \propto \left[1 + 2/5\, b_R \int_{\bar{r}}^{1} d\bar{r}'\,\bar{k}^{-3/5}(\bar{r}')\,\bar{v}_c^2(\bar{r}')/\bar{r}'\right]^{5/2}$$

Central AGN feedback → $k_0 = k_B T_0 / n_0^{2/3}$



entropy k - T correlation

A.C., Lapi & Menci 02,
Lapi, A.C., & Menci 05

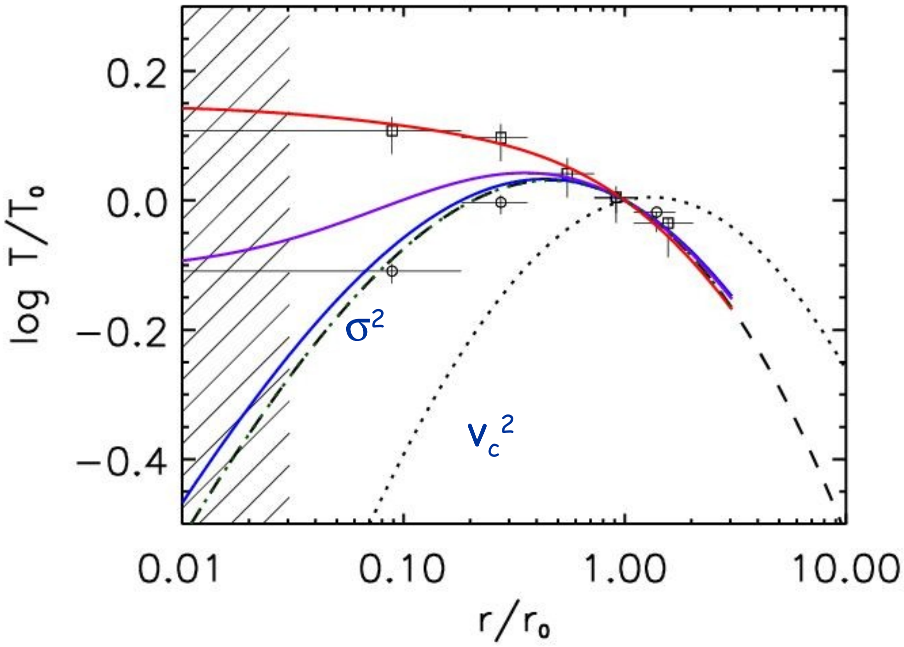


groups

clusters

Connection to simple models

Average NCC and CC
from Leccardi & Molendi 08



A) β - model, central region NCCs

B) CCs: SModel yields $k_0 \sim 10^{-3}$ (blue)
→ T(r) follows $\sigma^2(r)$, not $v_c^2(r)$.

This suggests trying the simple
model (cf. A.C. & Fusco-Femiano 81)

$$T(r) \sim \sigma^2(r) \quad \rightarrow \quad n(r) \sim \rho^{\beta} \ \sigma^{2(\beta-1)}$$

OK for CCs !
Consistent with non-radiative sims. (see Borgani 04)

→ Prediction: peaks of T should move left
in poor clusters and groups, w. lower DM
a and decreasing σ^2_M positions (cf. A Lapi)

Consistent with obs. Nagai al. 07
(recalibrated Chandra)