X-ray analyses of clusters of galaxies

- Imaging
- Spatially resolved spectroscopy
- Mass analysis

Cluster mass modeling

- Hydrostatic equilibrium

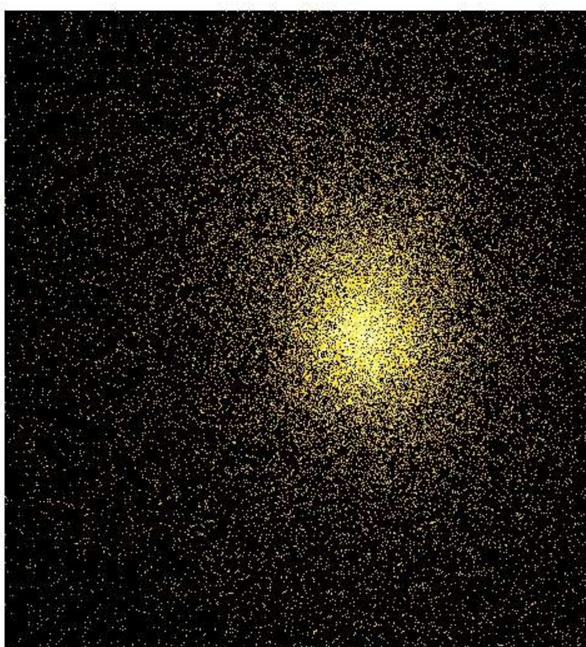
$$M_{tot}(<r) = -\frac{k}{\mu m_p G} T_g(r)\, r \left(\frac{d \ln \rho_g(r)}{d \ln r} + \frac{d \ln T_g(r)}{d \ln r} \right) \qquad \text{Eq. 1}$$

- ρ_g from image analysis
- T(r) from spatially resolved spectroscopy

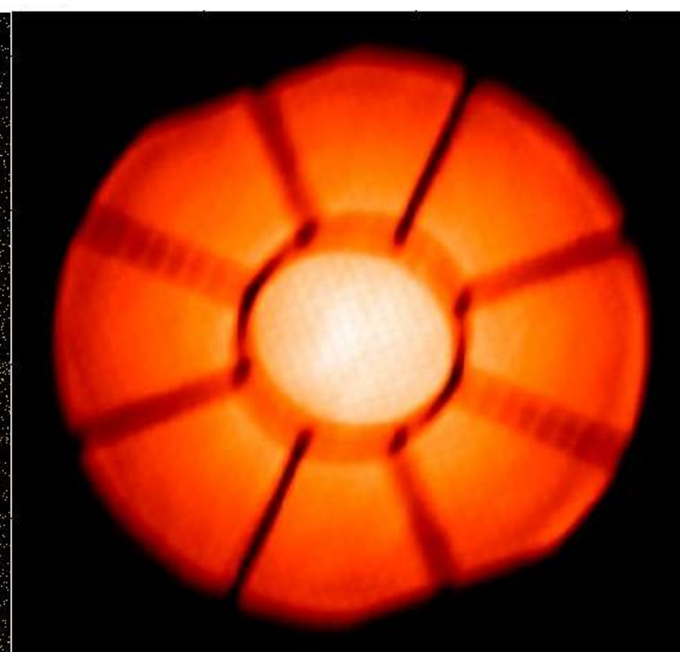
Imaging data

- FITS table recording 1) energy, 2) arrival time , 3) X and Y coordinate of each event (event list)
- Integrate data over time and energy for each pixel → raw image [c pixel^{-1}]
- instrument background subtraction (sky bkg constant so leave it in)
- Vignetting correction by dividing with the exposure map [s] → rate map [c s^{-1} pixel^{-1}]

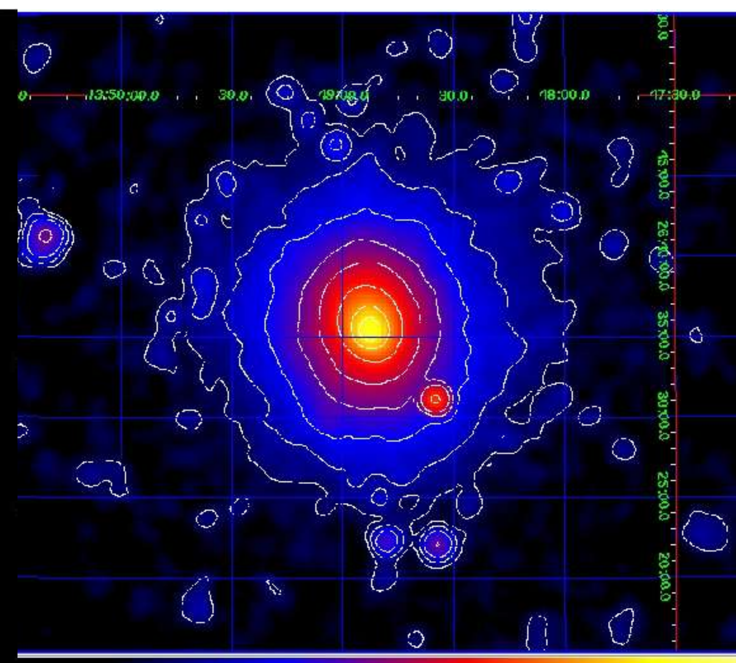
raw image



exposure map



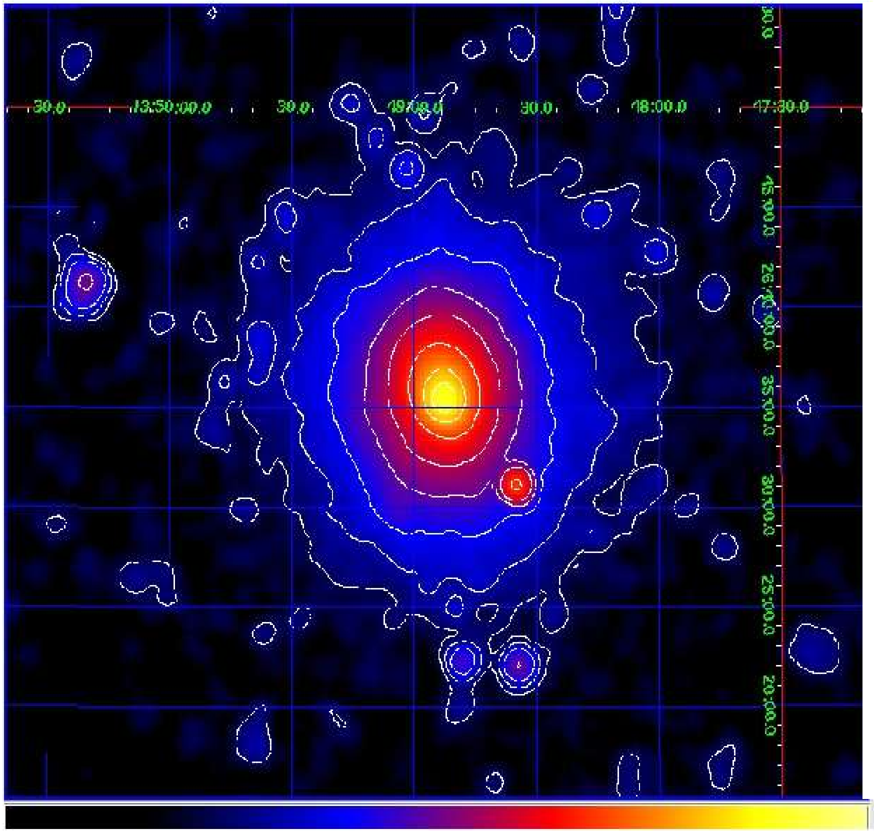
rate map



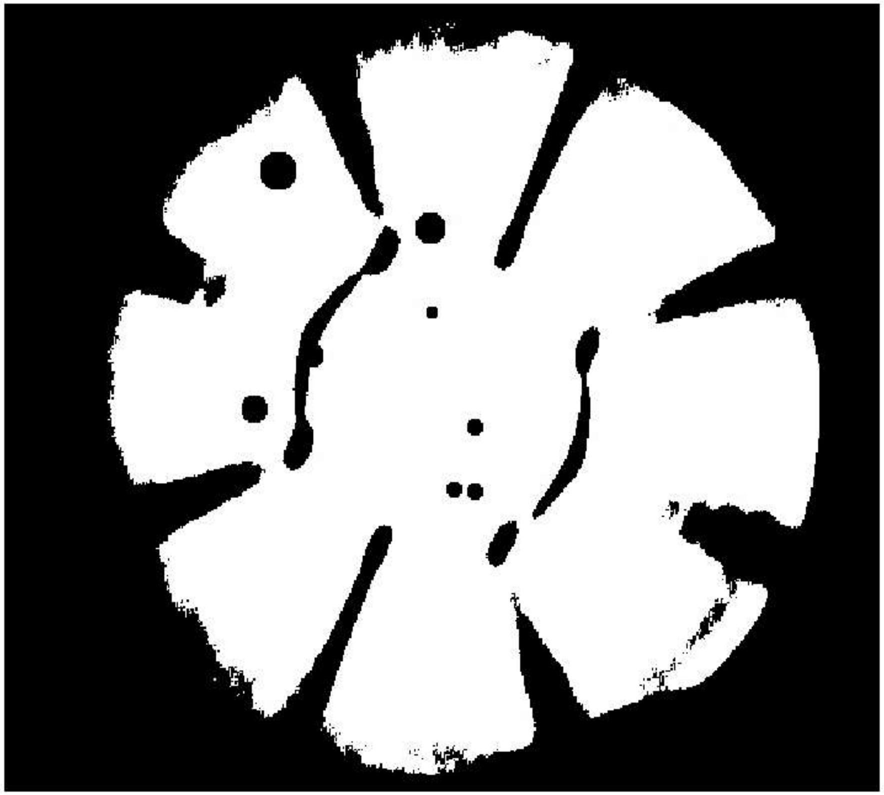
Imaging data

- mask out point sources and detector artifacts
- in the mask image, the excluded pixels have a value of 0, others 1

rate image



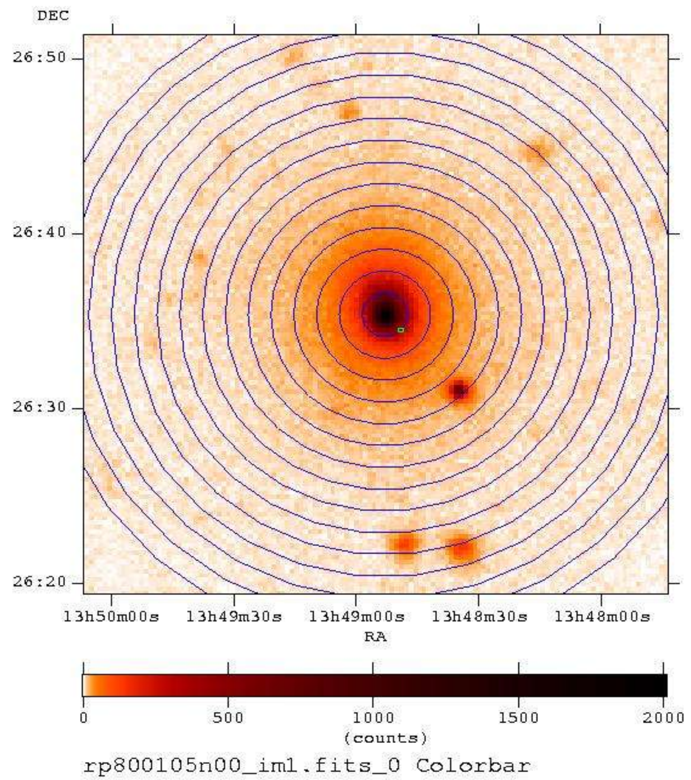
mask image



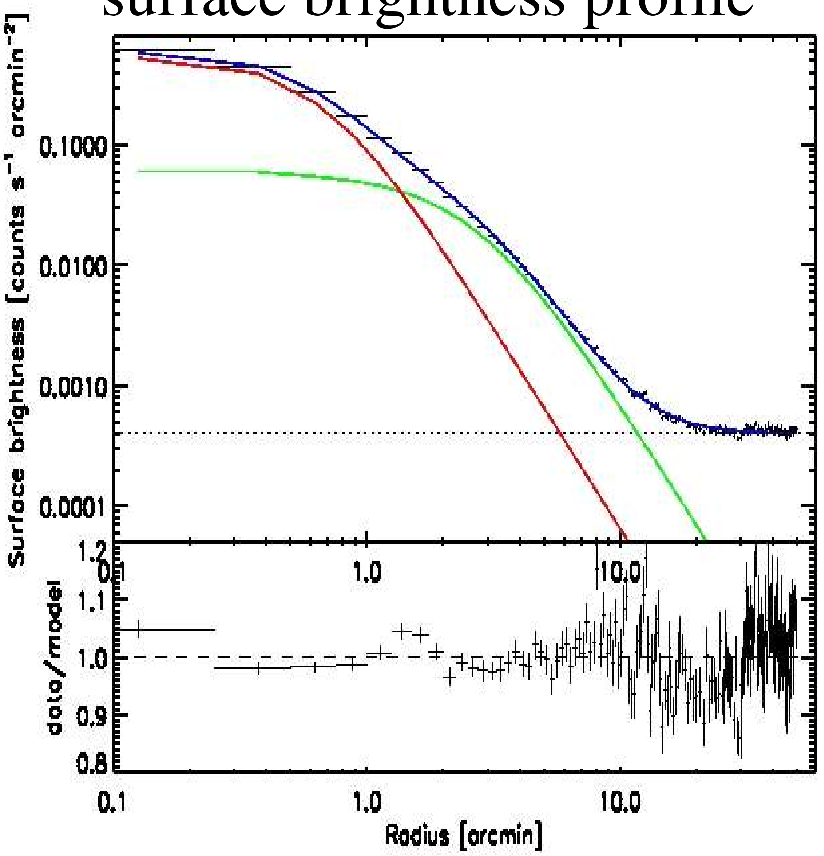
Surface brightness profile

- add up the count rates of each pixel of rate image (where mask value = 1) in concentric annuli
- divide by the (number × size) of pixels in the annulus [arcmin^2] → surface brightness [c s^{-1} arcmin^{-2}]
- plot with distances of annuli → surface brightness profile

rate image



surface brightness profile



Modeling the surface brightness profile

- X-ray imaging → surface brightness I (x,y) [c s^{-1} $arcmin^{-2}$]
- azimuthal symmetry → surface brightness profile I (b)

$$I(b)=I_0\left[1+\left(\frac{b}{r_{core}}\right)^2\right]^{(-3\beta+0.5)}$$

β profile (Cavaliere & Fusco-Femiano, 1976, A&A, 49, 137

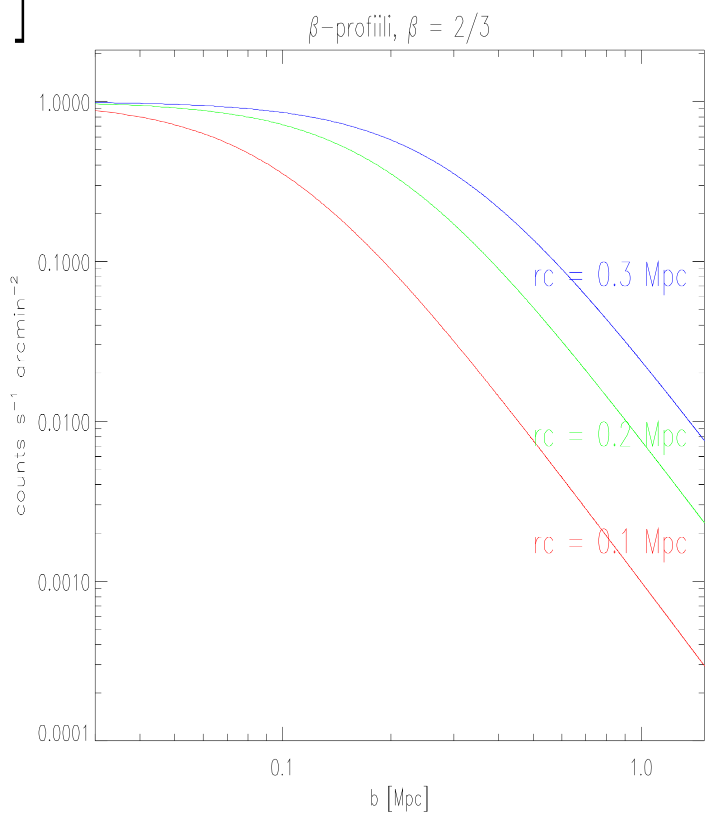
b = projected radius

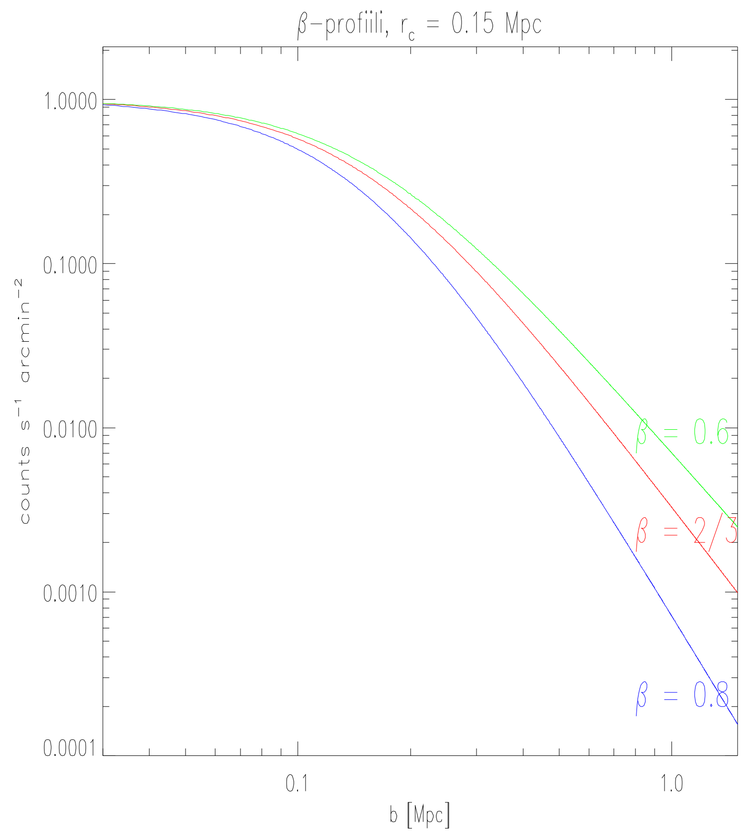
β = index

r_{core} = core radius

typically: β ~ 0.6-0.8

r_c ~ 100 kpc





Cooling Sarazin 5.3.1

- Clusters radiate energy away, so they cool
- Bremsstrahlung cooling time scale (over which the cluster looses a significant amount of thermal energy:

$$t_{cool} \equiv \left(\frac{d \ln T_g}{dt} \right)^{-1} \approx 8.5 \times 10^{10} \text{ yr} \left(\frac{T_g}{10^8 K} \right)^{1/2} \left(\frac{n_p}{10^{-3} \text{cm}^{-3}} \right)^{-1}$$

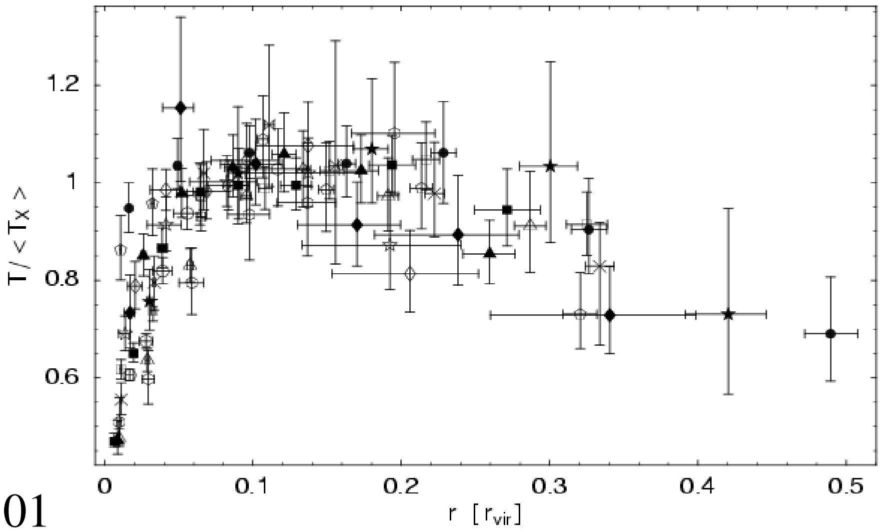
- Typically no problem $T \approx 10^8 K, n_e \approx 10^{-3} \rightarrow t_{cool} \approx 10^{11} \text{yr} > t_{Hubble}$
- Some cluster centers are so dense that

  t_{cool} is shorter than the cluster age ➔ cooling happens

- Gas pressure (P = knT) decreases and the gas flows

  into the center ➔ gas density increases in the center ➔

  brightness peak



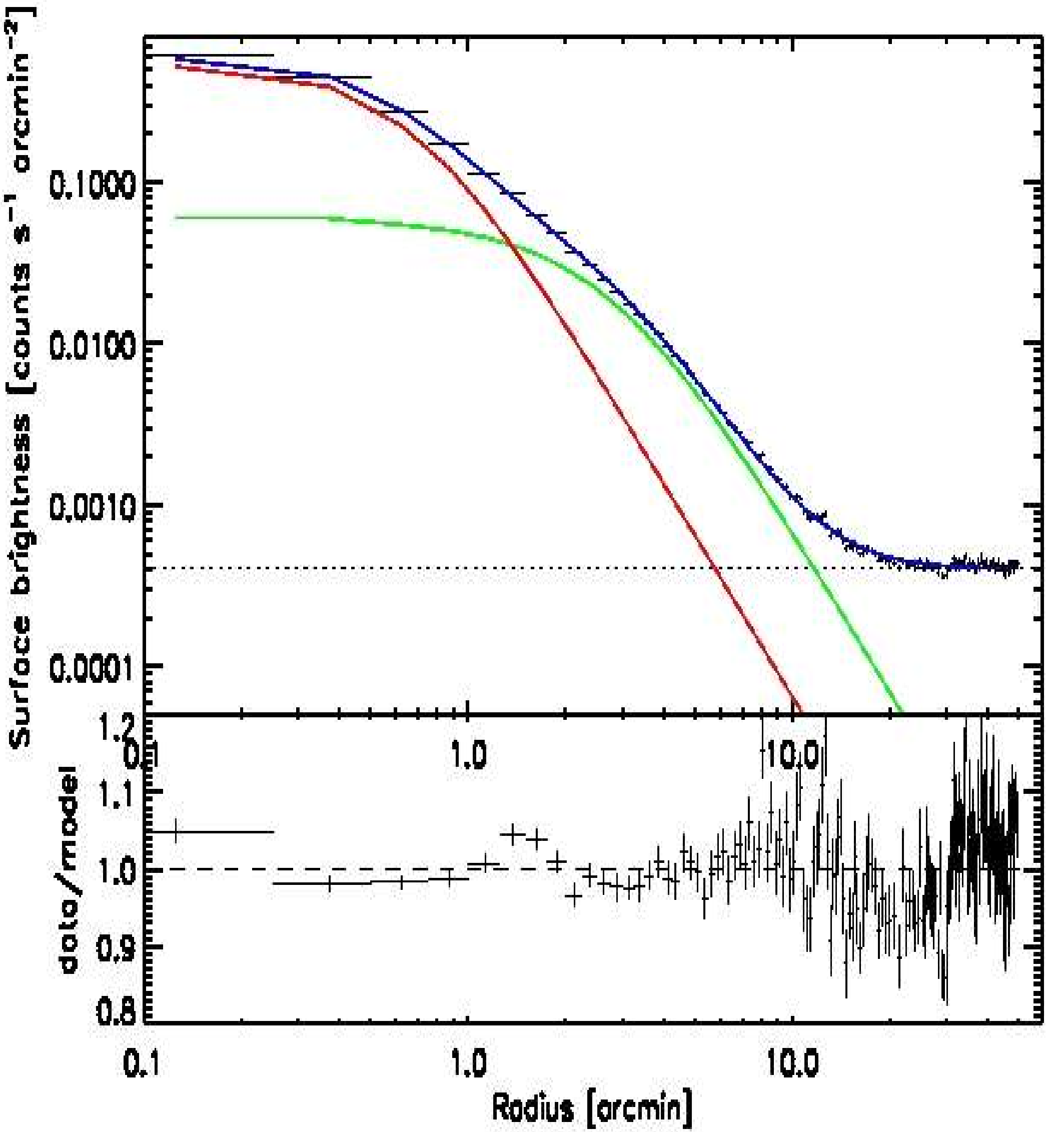
Piffaretti et al., 2005, A&A 433, 101

Modeling the surface brightness profile

double β profile

$$I(b)=I_{0,1}\left[1+\left(\frac{b}{r_{core,1}}\right)^2\right]^{(-3\beta+0.5)} +$$

$$I_{0,2}\left[1+\left(\frac{b}{r_{core,2}}\right)^2\right]^{(-3\beta+0.5)}$$



2D to 3D Sarazin 5.5.4

Bremsstrahlung emissivity $\varepsilon_\nu \propto n_e^2 \rightarrow I_\nu(b) = f(\varepsilon_\nu(r)) = f(n_e^2)$ (T dependence negligible)

$$I_\nu(b) = const \times \int_{b^2}^{\infty} \frac{\varepsilon_\nu(r)\, dr^2}{\sqrt{r^2 - b^2}} \quad \text{(spherical symmetry, const instrumental)}$$

$$\rightarrow \varepsilon_\nu(r) \propto -\frac{1}{2\pi r} \frac{d}{dr} \int_{r^2}^{\infty} \frac{I_\nu(b)\, db^2}{\sqrt{b^2 - r^2}}$$

$$(\beta \;\; profile) \qquad I(b) = I_0 \left[1 + \left(\frac{b}{r_{core}} \right)^2 \right]^{(-3\beta + 0.5)} \rightarrow$$

$$n_e(r) = n_e(0) \left[1 + \left(\frac{r}{r_{core}} \right)^2 \right]^{(-\frac{3}{2}\beta)} \qquad \text{Eq. 2}$$

r_{core} and β (= gas density profile shape) from surface brightness profile fit

Central density

$n_e / n_p = 1.17$ (for typical cluster mix, $n_p =$ H density, n_e contains He) Eq. 3

$\rho_g = 1.35\, m_p n_p$ Eq. 4

$$EM\,(= emission\, measure) \equiv \int n_e n_p\, dV = \int n_e \frac{n_e}{1.17}\, dV = \frac{1}{1.17} \int n_e^{\,2}\, dV \quad (\beta\ profile\ for\ n_e \rightarrow)$$

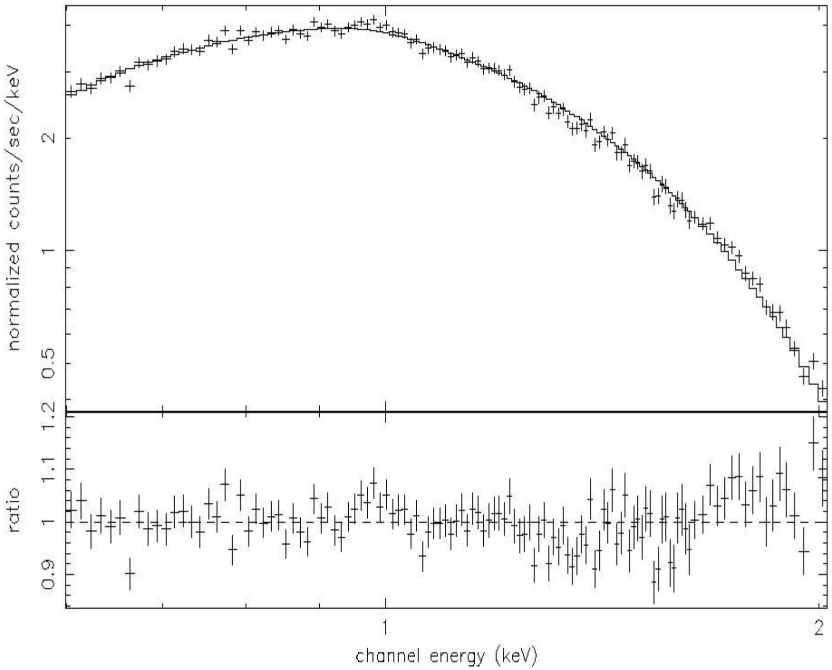
$$EM = \frac{1}{1.17}\, n_e(0)^2 \int \left[1 + \left(\frac{r}{r_{core}} \right)^2 \right]^{-3\beta} dV \rightarrow$$

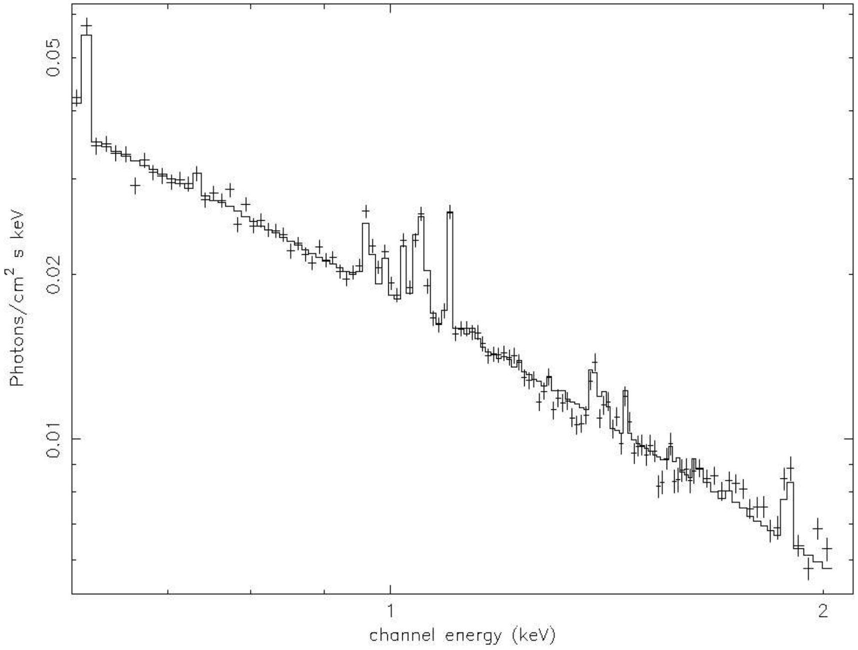
$$n_e(0) = \sqrt{1.17 \times EM / \int \left[1 + \left(\frac{r}{r_{core}} \right)^2 \right]^{-3\beta} dV}$$ Eq. 5

EM from spectral analysis

A1795 15 arcmin circle spectra

Data and folded model **unfolded model**





Spectral fit yields: T = 4.1 keV, norm = 8.21 x 10^{-2}

$$EM\,[cm^{-3}] = norm_{MEKAL}[cm^{-5}] \times 10^{14} \times 4\pi \left[D_A \times (1+z)\right]^2 [cm^2] \qquad \text{Eq. 6}$$

EM → n_0: example calculation

- A1795 is a cluster at z = 0.062, i.e. a distance DA = 233 Mpc (=7.20 x 10^{26} cm)
- Imaging has yielded: r_{core} = 2.9 arcmin, β = 0.7
- Spectral analysis has yielded MEKAL norm = 8.21 x 10^{-2} within 15 arcmin
- What is the central electron density $n_e(0)$?
- Use Eq. 5 (repeat) $$n_e(0)=\sqrt{1.17\times EM/\int\left[1+\left(\frac{r}{r_{core}}\right)^2\right]^{-3\beta}dV}$$
- EM using Eq. 6:

$$EM[cm^{-3}]=norm_{MEKAL}[cm^{-5}]\times 10^{14}\times 4\pi\left[D_A\times(1+z)\right]^2[cm^2]=$$

$$8.21\times 10^{-2}\,cm^{-5}\times 10^{14}\times 4\times\pi\times(7.20\times 10^{26}\,cm)^2\times(1+0.062)^2=\underline{6.0\times 10^{67}\,cm^{-3}}$$

EM → n_0: example calculation

- The integral in Eq. 5:

$$\int \left[1+\left(\frac{r}{r_{core}}\right)^2\right]^{-3\beta} dV \rightarrow 4\pi \int_0^{15\,arcmin} \left[1+\left(\frac{r}{2.9}\right)^2\right]^{-2.1} r^2\,dr = \ldots numerically \ldots\, 1.60\times 10^{72}\,cm^3 \rightarrow$$

$$n_e(0)=\sqrt{\frac{1.17\times 6.0\times 10^{67}\,cm^{-3}}{1.60\times 10^{72}\,cm^3}}=6.6\times 10^{-3}\,cm^{-3}\rightarrow$$

- Using Eq. 3 $\quad n_p(0)=n_e(0)/1.17=5.6\times 10^{-3}\,cm^{-3}$
- Using Eq. 4

$$Mpc=3.086\times 10^{24}\,cm \qquad \rho_g(0)=1.35\times m_p\times n_p(0)=1.35\times 1.6725\,10^{-24}\,g\times 5.6\times 10^{-3}\,cm^{-3}=1.3\times 10^{-26}\,g\,cm^{-3}$$

$$M_\odot=1.989\times 10^{33}\,g$$

$$\rightarrow$$

$$\rho_{gas}(0)=\underline{1.9\times 10^{14}\,M_\odot\,Mpc^{-3}}$$

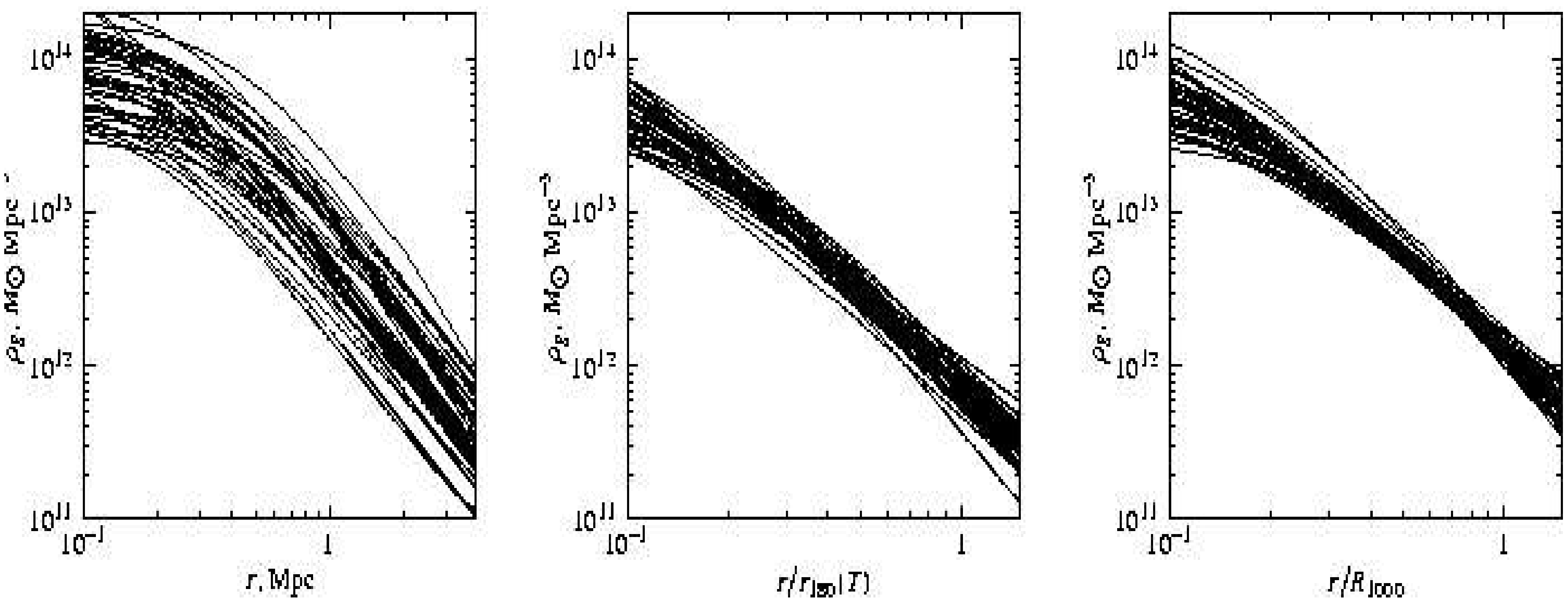
- Now you know the gas density at any radius by Eq. 2

Gas density profiles

- $\rho_{g,0} \sim 10^{14}\ M_\odot\ \mathrm{Mpc}^{-3} \sim 10^{-3}\ \mathrm{cm}^{-3}$ $\quad \beta \sim 0.6 - 0.7 \rightarrow n_e(r) \propto r^{-2}$, when $r \rightarrow \infty$
- $M_{gas}(< 1\ \mathrm{Mpc}) \sim 10^{14}\ M_\odot$

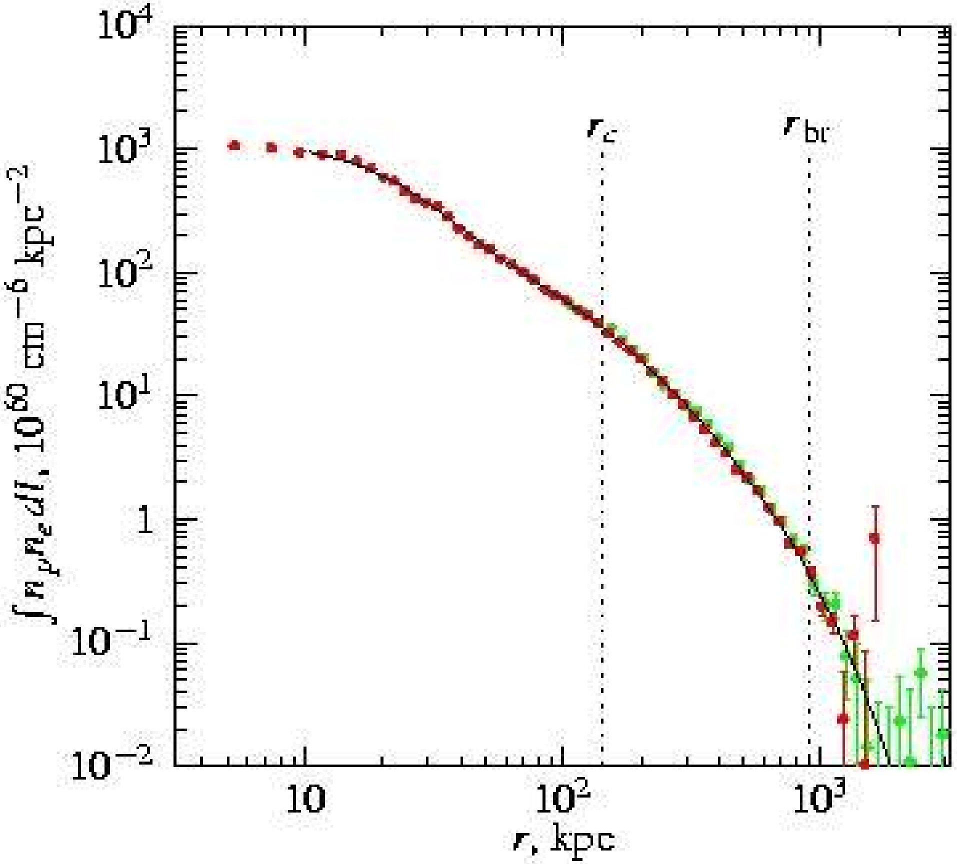
Vikhlinin et al., 1999, ApJ, 525, 47

ROSAT PSPC data



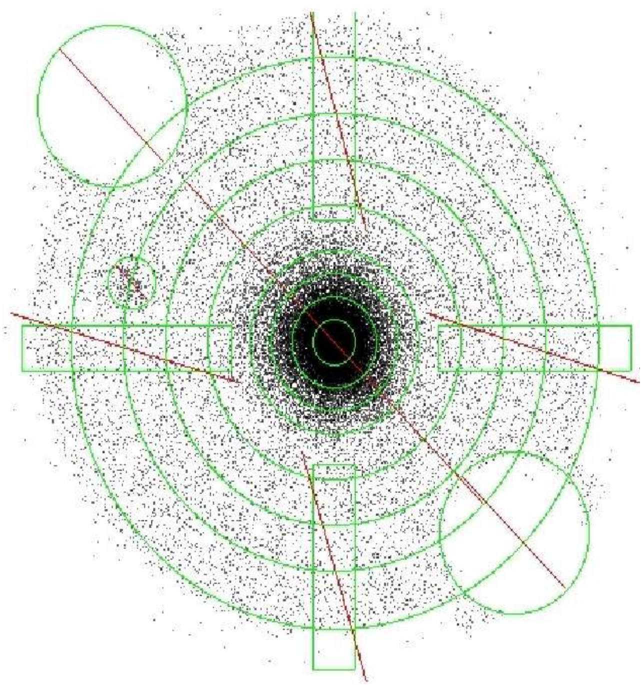
Gas density profiles

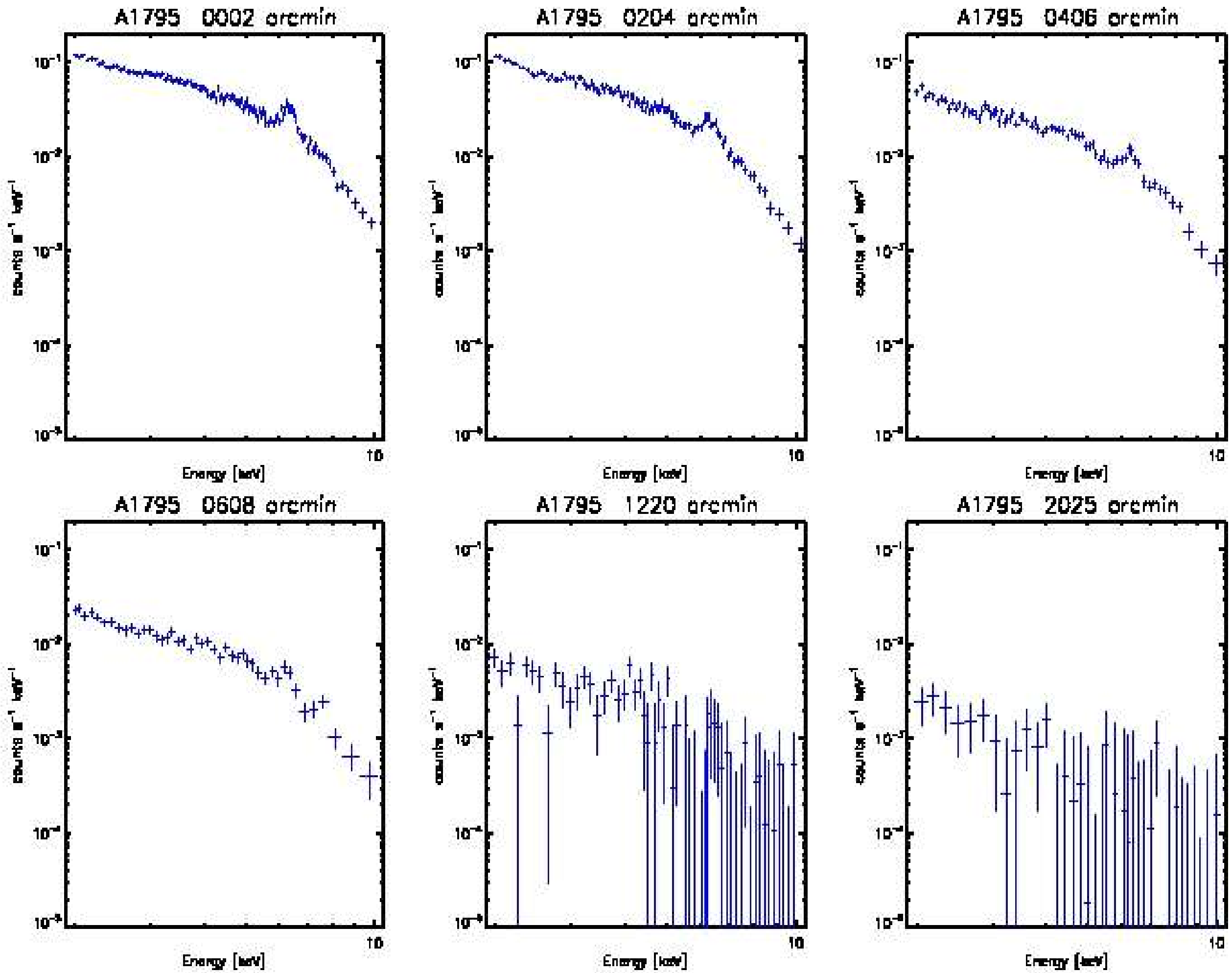
- surface brightness steeper than beta model beyond r_{br} (Vikhlinin et al, 2006, ApJ, 640, 691)



Spectroscopy

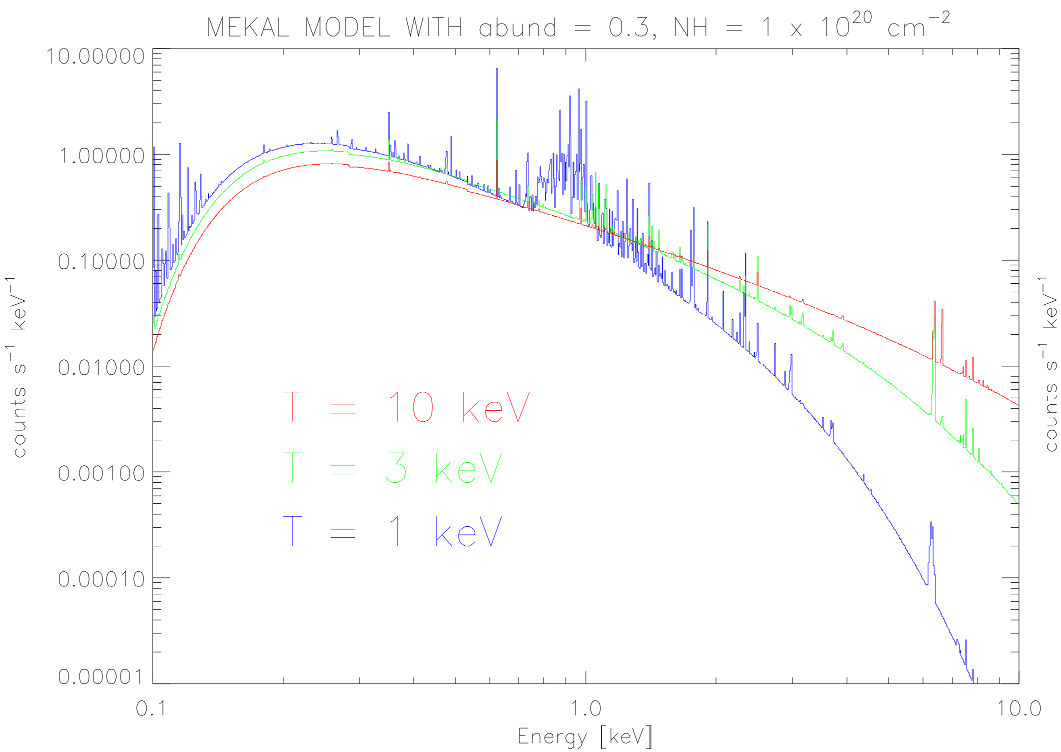
- extract spectra in concentric annuli (= integrate events over time, chosen area (X,Y) and sort by energy bins)

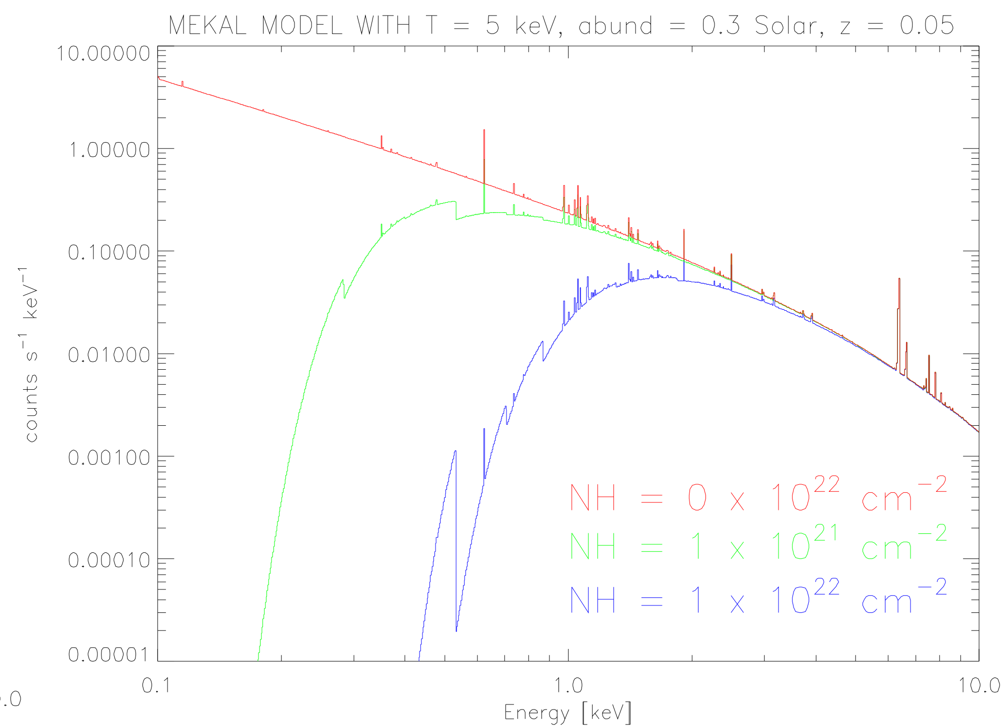




Spectral modeling

- MEKAL model (T, abund, redshift) for emission
- WABS model (NH) for Galactic absorption





Spectral fit

- **RMF** (= Redistribution Matrix File):

- contains dE/E (energy resolution) information of the instrument

- convolution of the model $\mathbf{S}_{\mathbf{model}}$(E) with RMF approximates the spreading of counts

- **ARF** (= Auxiliary Response File)

- contains mirror effective area, filter transmission and detector quantum efficiency

- $\mathbf{S}_{\mathbf{model}}(E) \times \mathbf{ARF}(E)$: [photons s^{-1} cm^{-2} keV^{-1}] → [counts / channel]

- $\mathbf{S}_{\mathbf{pred}}$ (= model prediction) = $[\mathbf{S}_{\mathbf{model}}(E) \otimes \mathbf{RMF}(E,channel)] \times \mathbf{ARF}(E)$

- **bkg** (= background = CXRB + Galactic emission + CR induced detector background)

- must be removed from the total observed signal : $\mathbf{S}_{\mathbf{data}}(E) = \mathbf{S}_{\mathbf{total\ obs}}(E) - \mathbf{bkg}(E)$

Spectral fit

- background subtracted data is compared with the model prediction
- model parameters varied until best match between background subtracted data and model prediction found, i.e χ^2 minimisation

$$\chi^2 = \Sigma \frac{\left(S_{data}(E) - S_{pred}(E)\right)^2}{\sigma(E)^2}$$

where

$$S_{data}(E) = S_{total\,obs}(E) - bkg(E)$$

$$S_{pred}(E) = \left[S_{model}(E) \otimes RMF(E, channel)\right] \times ARF(E)$$

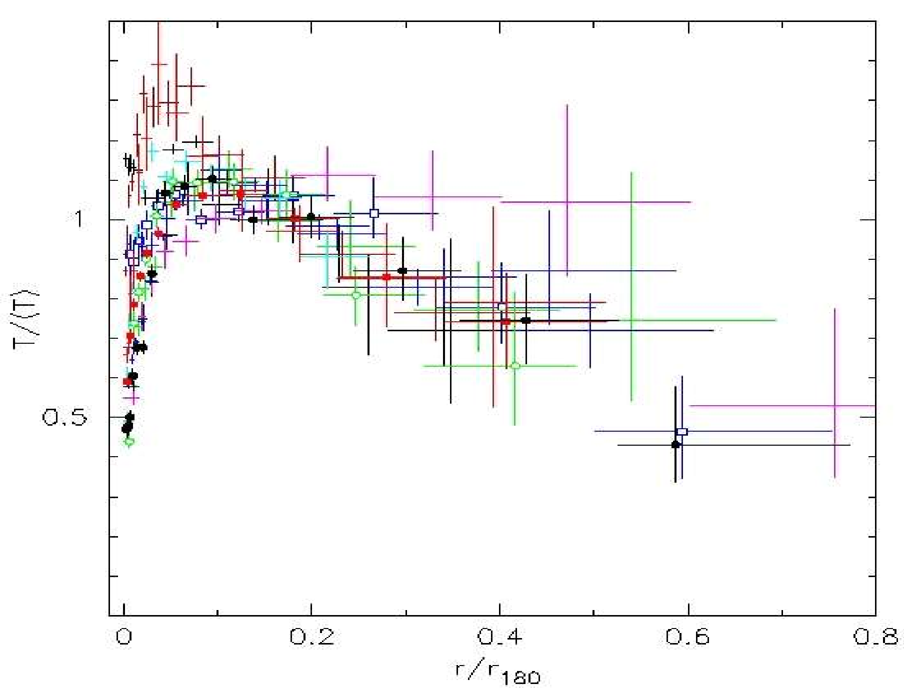
$\sigma(E)$ are the statistical uncertainties

T-profile results

- similar shape with scaled radius: factor of 2 variations inside a given cluster
- Cool core = relaxed cluster, merger destroys cool core
- T gradient at large radii

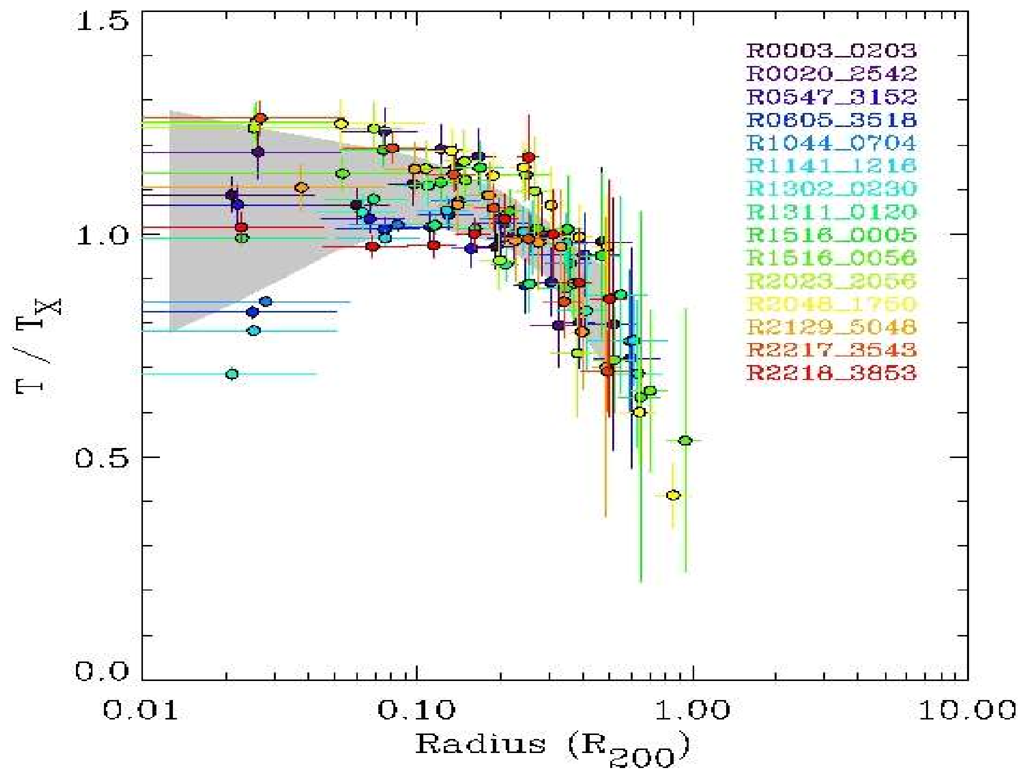
Chandra

Vikhlinin et al., 2005, ApJ 628, 655



XMM-Newton

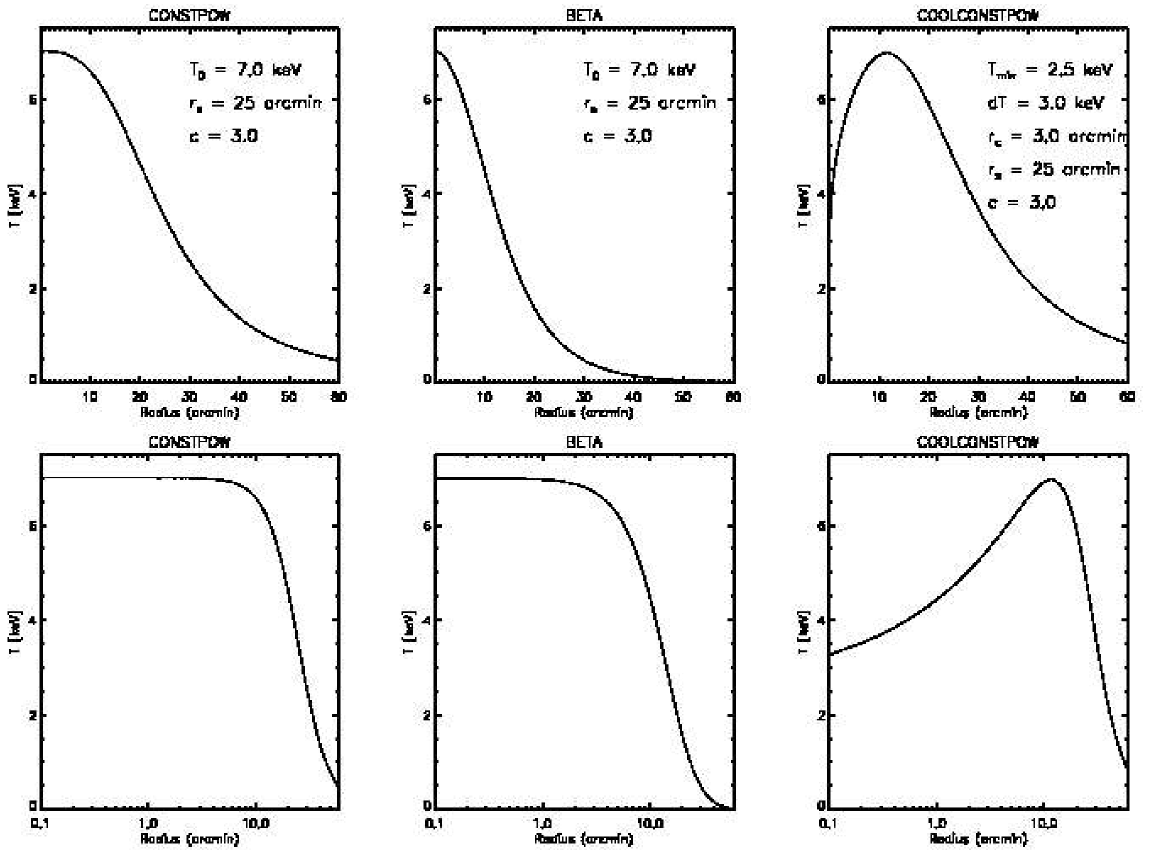
Pratt et al, 2006, A&A, 446, 429



3D temperature profile models T(r)

- 2D observations → 3D physics
- use 3D T(r) model and project

  along the line-of-sight



CONSTPOW: $$T(r)=T_0\times\left[1+\left(\frac{r}{r_s}\right)^c\right]^{-1}$$

BETA: $$T(r)=T_0\times\left[1+\left(\frac{r}{r_s}\right)^2\right]^{-c}$$

COOLCONSTPOW: $$T(r)=\left[T_{min}+dt\times\left(\frac{r}{r_c}\right)^{0.4}\right]\times\left[1+\left(\frac{r}{r_s}\right)^c\right]^{-1}$$

T profile projection and fit

- $T_{mod}(r)$ = 3D T profile model
- $T_{mod,\, proj}(b)$ = model T projection to 2D detector plane

$$T_{\mathrm{mod,proj}}(b) = \frac{\int_V \rho(r)^2 \times T_{mod}(r)\,\mathrm{dV}}{\int_V \rho(r)^2\,\mathrm{dV}}$$ (Emission weighted)

$$T_{\mathrm{mod,proj}}(b) = \frac{\int_V \rho(r) \times T_{mod}(r)\,\mathrm{dV}}{\int_V \rho(r)\,\mathrm{dV}}$$ (Mass weighted)

$$\chi^2 = \Sigma \frac{\left(T_{data}(b) - T_{mod,\, proj}(b)\right)^2}{{\sigma_T}^2}$$

$T_{mod}(r)$ parameters varied, χ^2 minimum gives best fit parameters

T profile projection and fit

- COOLCONSTPOW model (simulated data)

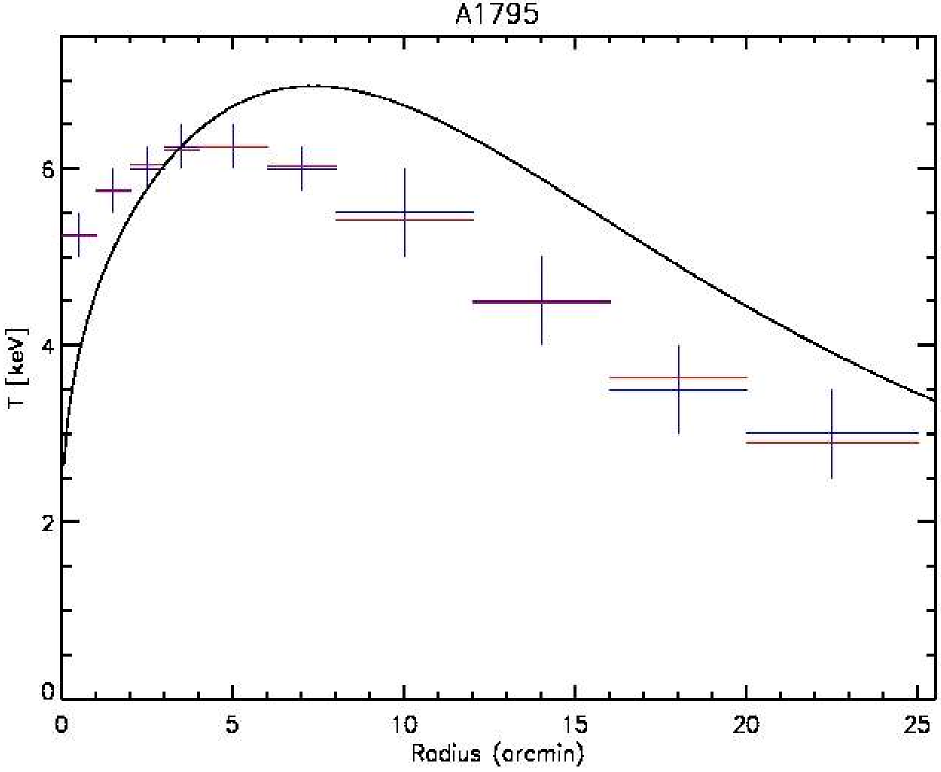
  T_{min} = 1.8 keV

  dT = 3.1 keV

  r_c = 1.3 arcmin

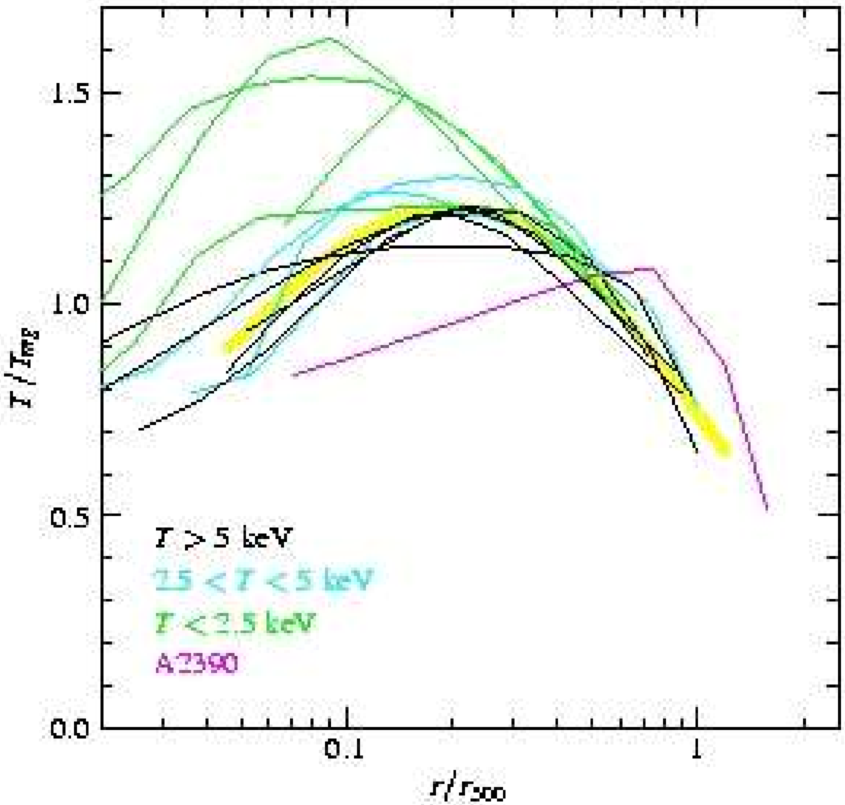
  r_s = 16.6 arcmin

  c = 2.2



Results:

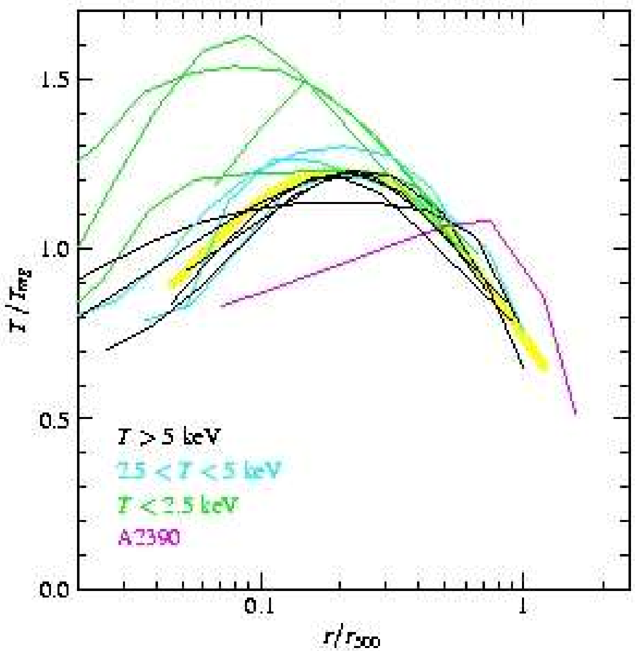
Chandra data (Vikhlinin et al., 2005, ApJ 628, 655)

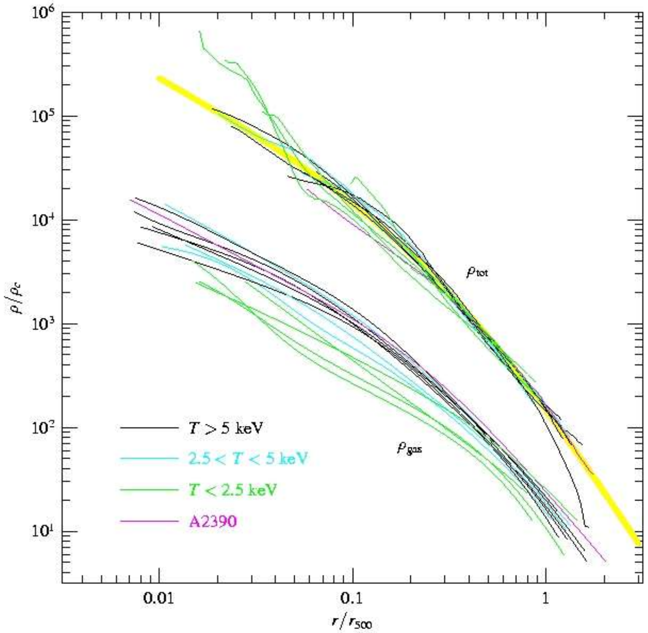


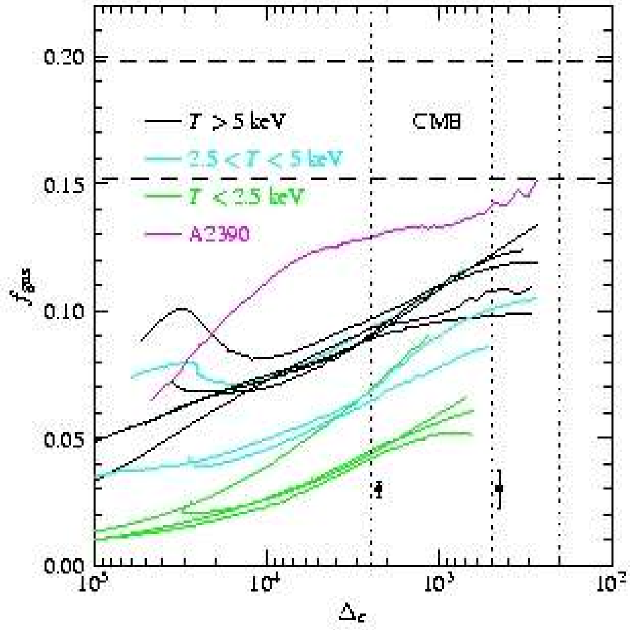
3D profile results

- Now we have ρ_g(r) and T(r) for the evaluation of hydrostatic equation (Eq. 1) → total mass profile
- similar T profiles (and similar gas density profiles) → similar DM profiles

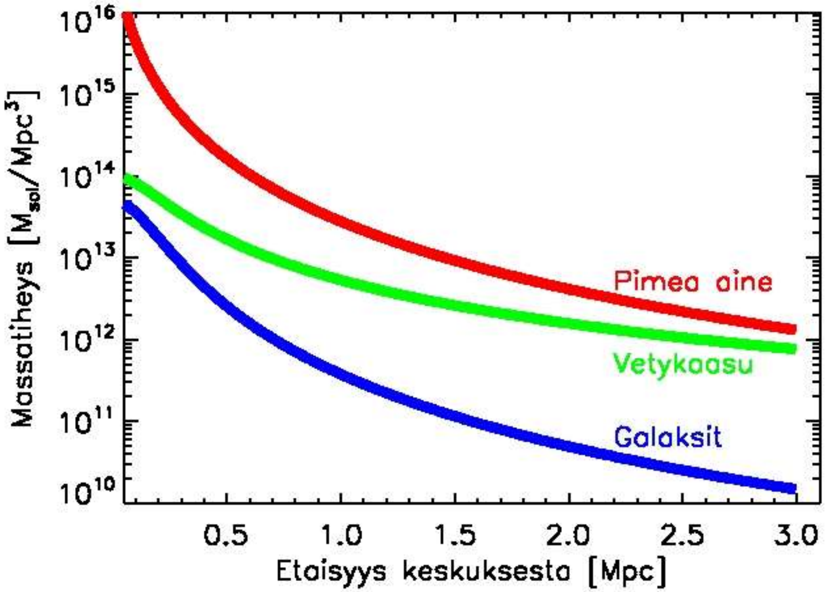
Chandra data (Vikhlinin et al., 2005, ApJ 628, 655)

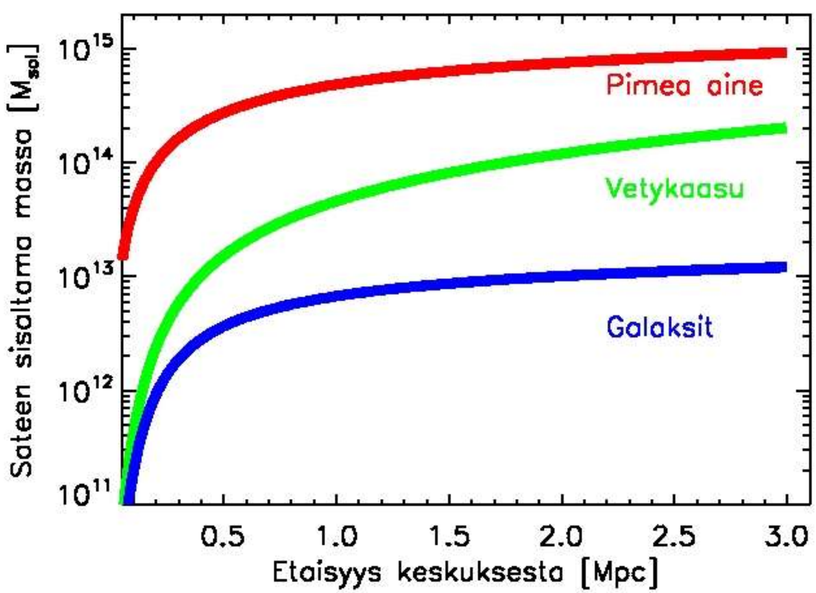






Mass components





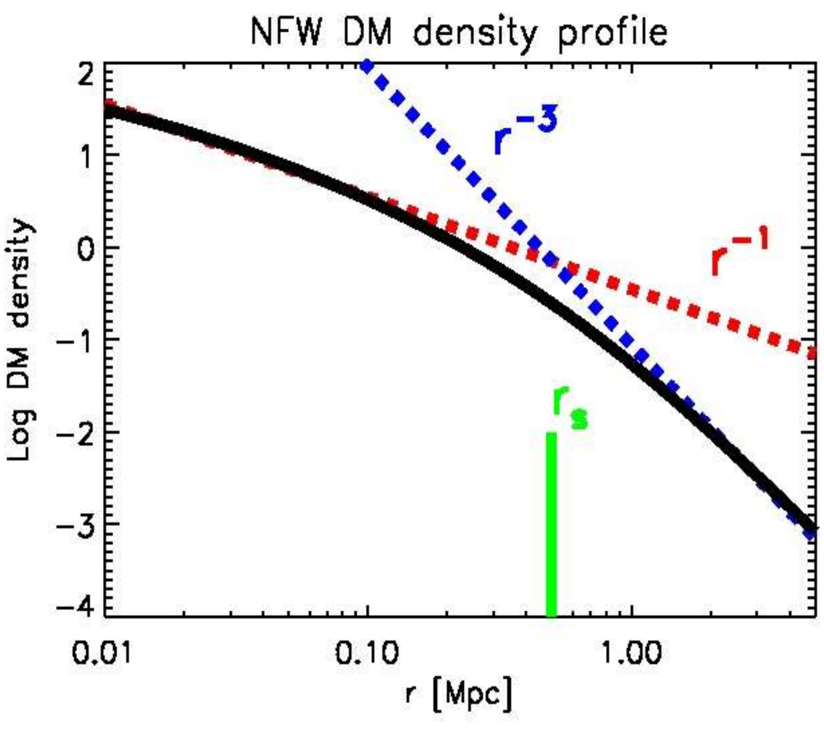
- gas density $\rho_{gas} \propto r^{-2}$
- galaxy mass $M_{gal} \sim 10^{13}\, M_{\odot} \sim 1\ \%$
- gas mass $M_{gas} \sim 10^{14}\, M_{\odot} \sim 10\%$
- dark matter $M_{DM} \sim 10^{15}\, M_{\odot} \sim 90\%$

NFW

- Universal NWF (Navarro-Frenk-White) dark matter density profile from simulations (Navarro et al, 1997, ApJ, 490, 493)

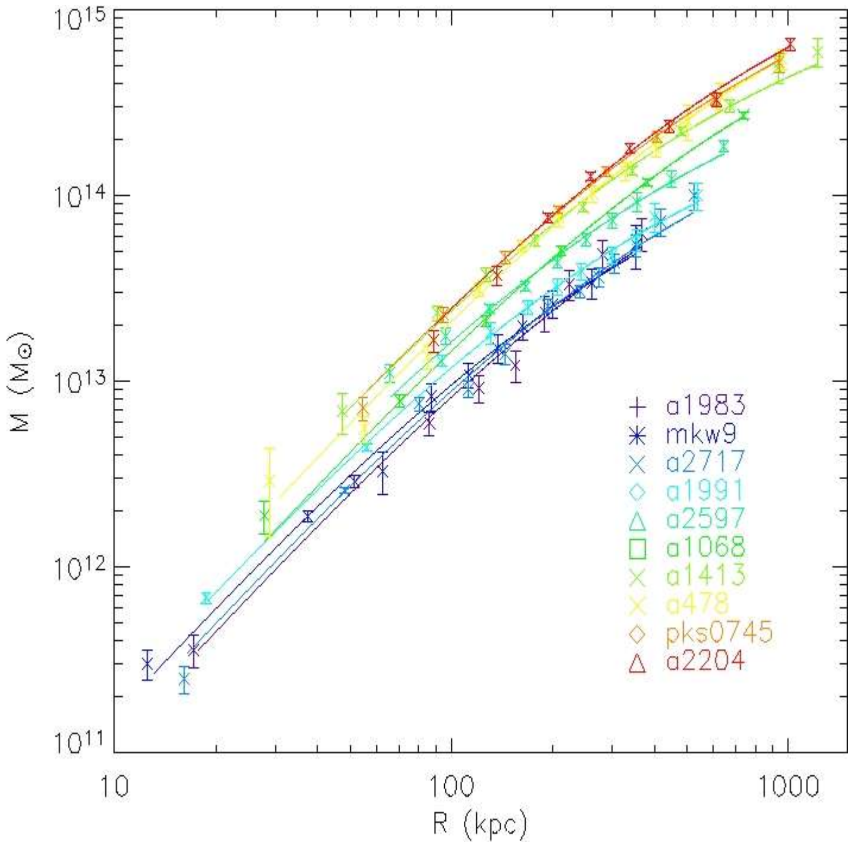
$$\rho_{DM}(r) \propto \left(\frac{r}{r_s}\right)^{-1} \times \left(1+\frac{r}{r_s}\right)^{-2}$$

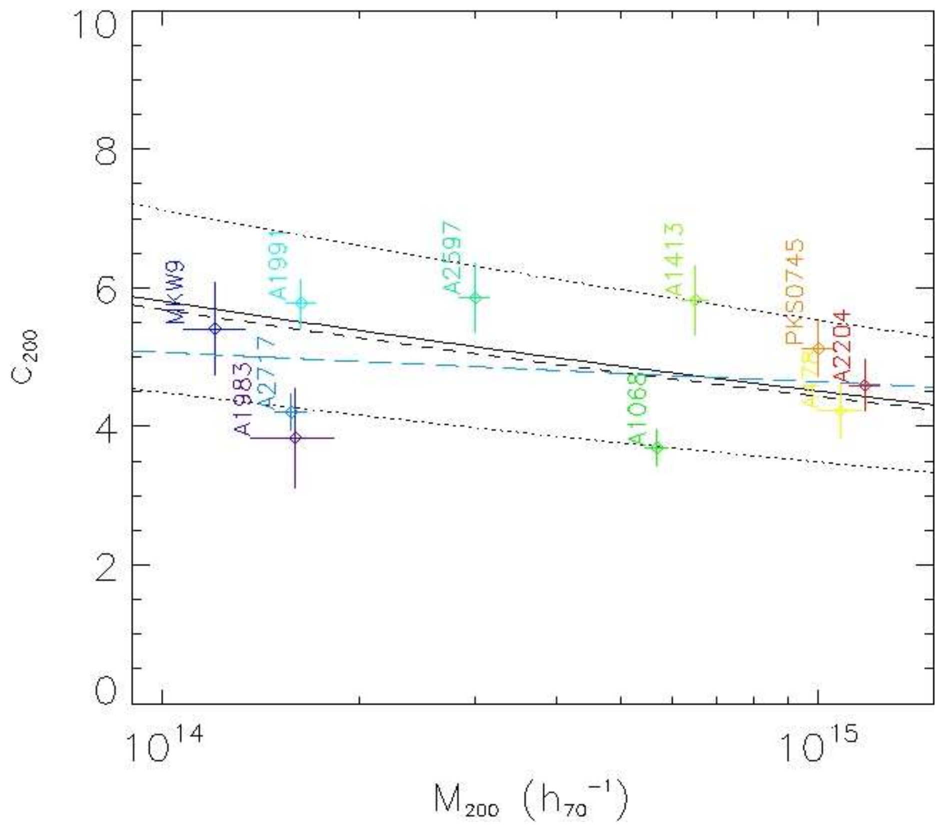
- central cusp $\rho_{DM}(r) \propto r^{-1}$
- steepening towards $\rho_{DM}(r) \propto r^{-3}$ beyond r_s



NFW modeling

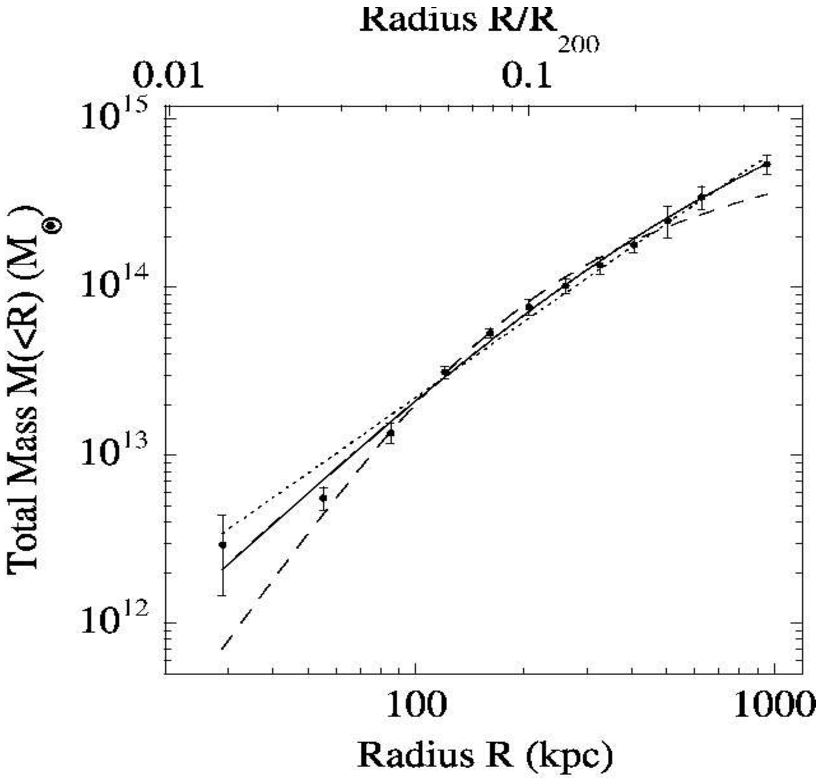
- Pointecouteau, 2005A&A...435: XMM

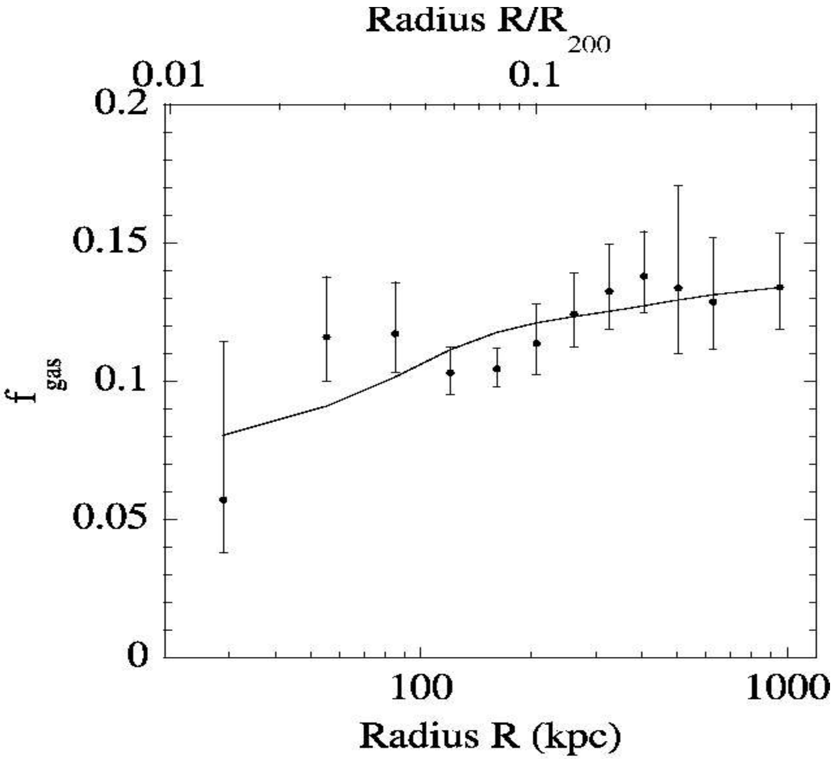




NFW modeling

- A&A., 2002, 423, 33: A478 with XMM-Newton





Gas mass fraction results

- with gas and total mas profile, we get the gas mass fraction profile:

$f_{gas}(r) = M_{gas}(r) / M_{tot}(r)$

- recent analyses yield: $f_{gas}(r_{vir}) \sim 15\%$ ($H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$)

Vikhlinin et al., 2006, ApJ, 640, 691

f_{gas} $(r < r_{500})$