

Combining Lensing, X-ray, and galaxy dynamic Measurements in Clusters

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Step 1: Combining lensing and X-ray measurements

Lemze, Barkana, Broadhurst, & Rephaeli 2008

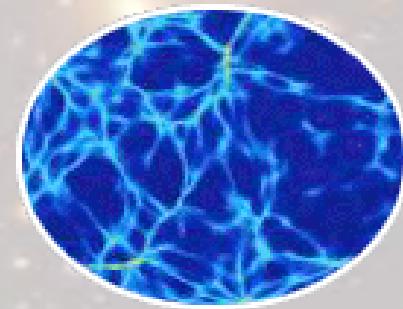
Objectives

To obtain accurate 3D ρ_{DM} , ρ_{gas} , and inferred T, and M profiles.

Motivation:

Clusters are a major probes of:

- Structure formation
- Global cosmological models



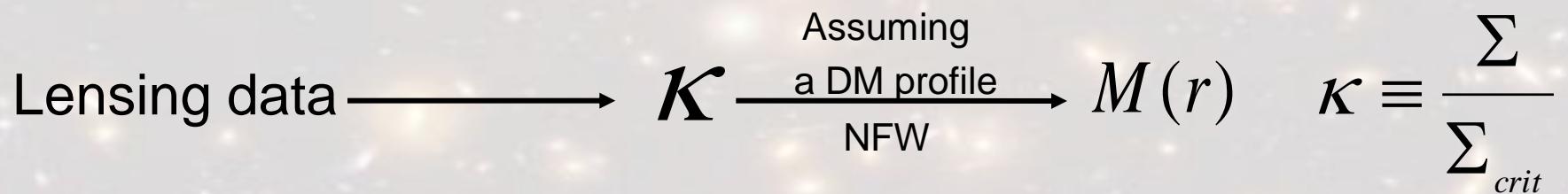
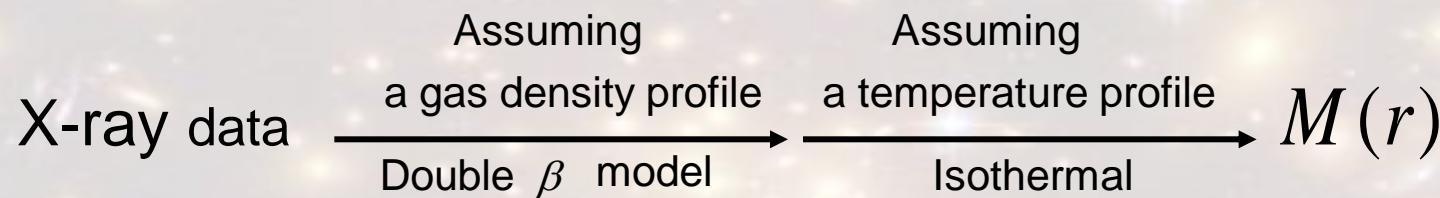
$$\Omega_\Lambda = 0.3$$

$$\Omega_m = 0.3$$

$$\Omega_\kappa = 0.0$$

What has been done previously?

For obtaining the mass profile:



The problems that emerge from this methodology:

- Discrepancy between the mass inferred by X-ray surface brightness and lensing, e.g. for A1689 a factor of ~2 (Xue & Wu 2002).
- Simple formulae are of limited use.

What do we do differently?

- We use data from X-ray surface brightness and lensing simultaneously.
- We do not adopt simplified expressions for the DM, gas, and temperature profiles.

The measuring instruments



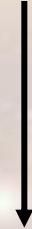
Hubble



Strong lensing



Subaru



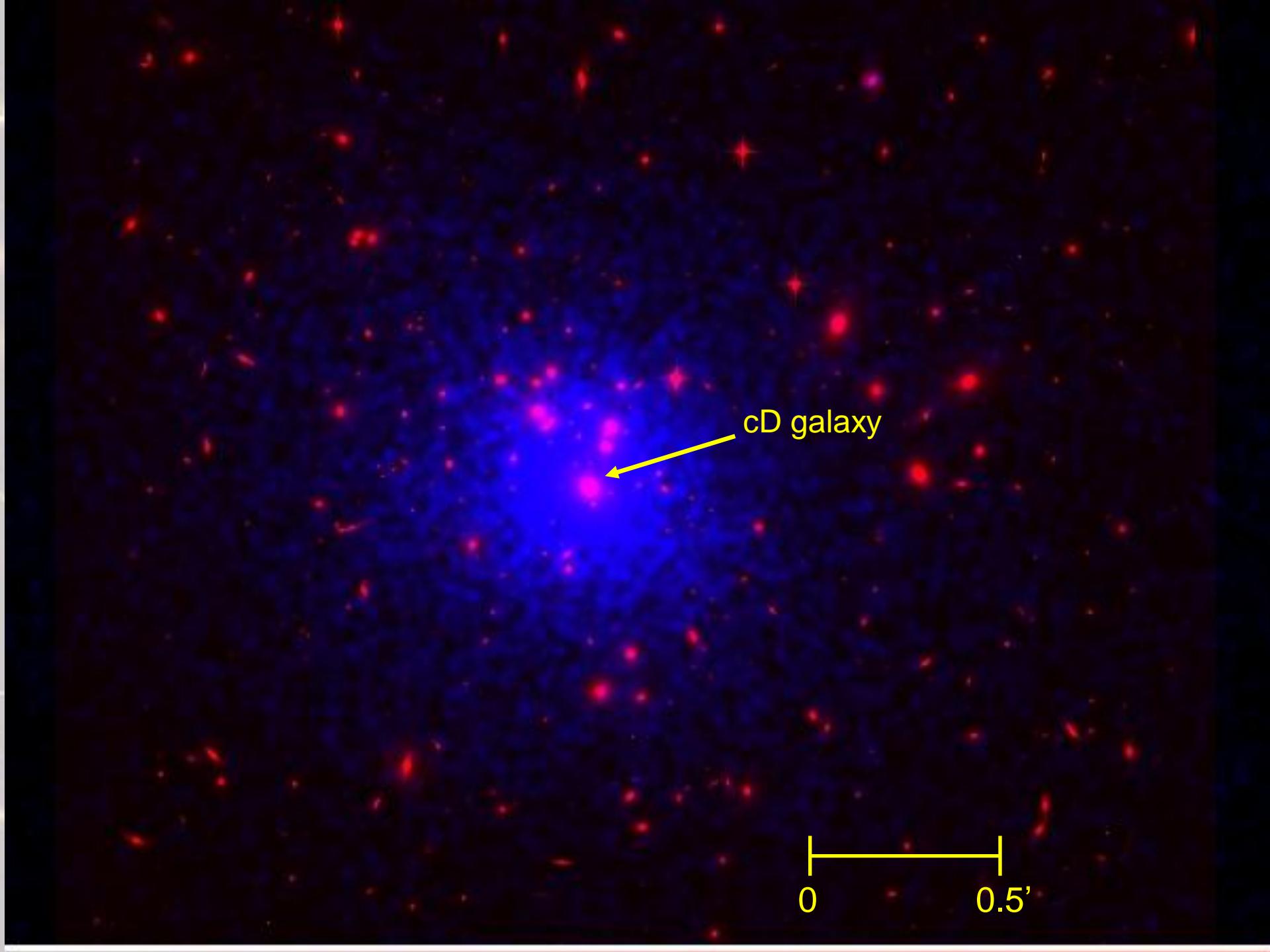
Weak lensing



Chandra



X-ray data

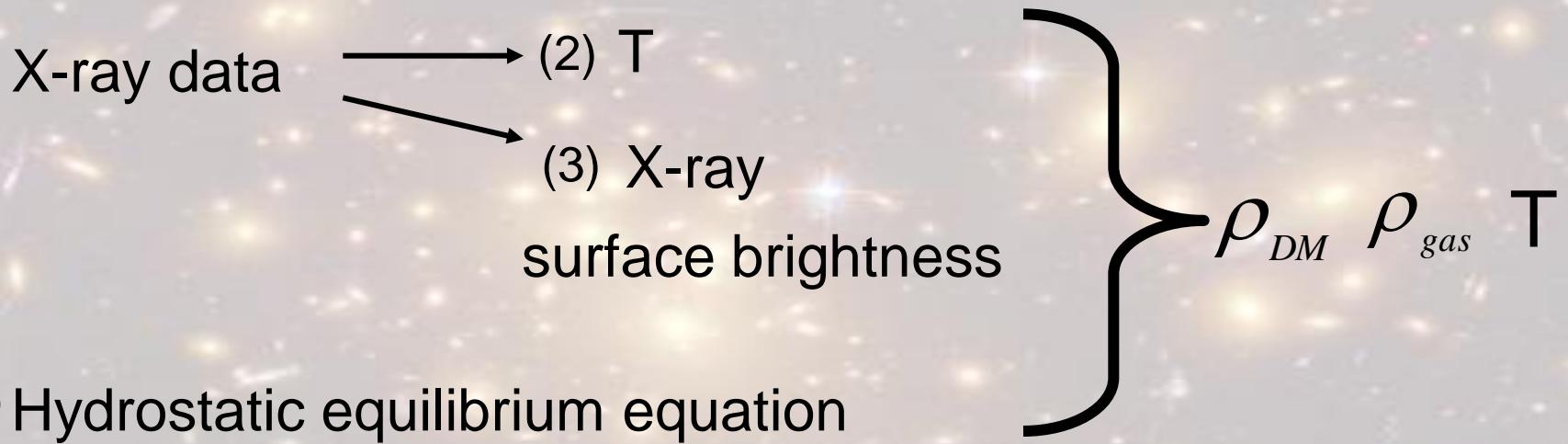


cD galaxy

0 0.5'

Our methodology

(1) Lensing (strong and weak) $\longrightarrow \rho_{total} (= \rho_{DM} + \rho_{gas})$



3 unknown profiles and 4 constraints
 \implies no model is needed

We used (1), (3), and (4) in order to find our 3 unknown profiles.
Constraint (2) is used in order to check our results.

Using general profiles

We take $\rho_{total}(r_i)$ and $\rho_{gas}(r_j)$ to be free parameters, where $\rho_{total}(r_i)$ and $\rho_{gas}(r_j)$ are equally logarithmically spaced in their data ranges.

The steps taken:

(1) For given assumed $\rho_{total}(r_i)$ and $\rho_{gas}(r_j)$

(2) $\rho_{total} \rightarrow M$

$$M(r) = 4\pi \int_0^r \rho_{total}(r') r'^2 dr'$$

(3) $\rho_{gas}, M \rightarrow T$

$$(\rho_{gas}(r)T(r)) \Big|_{\infty}^r = \int_r^{\infty} \frac{GM(\leq r') \mu m_p \rho_{gas}(r')}{k_B r'^2} dr'$$

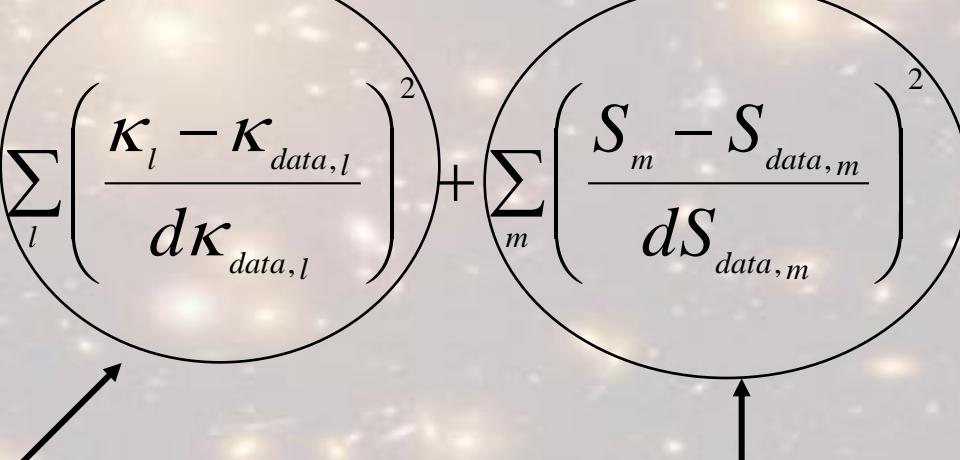
(4) $\rho_{gas}, T, A \rightarrow \varepsilon$

Projecting

$$\kappa(R_l) = \int_R^{\infty} \frac{\rho_{total}(r)r}{\sqrt{r^2 - R_l^2}} dr$$

$$S(R_m) = \int_R^{\infty} \frac{\varepsilon(r)r}{\sqrt{r^2 - R_m^2}} dr$$

And minimizing

$$\chi^2 = \chi_{\kappa}^2 + \chi_S^2 = \sum_l \left(\frac{\kappa_l - \kappa_{data,l}}{d\kappa_{data,l}} \right)^2 + \sum_m \left(\frac{S_m - S_{data,m}}{dS_{data,m}} \right)^2$$


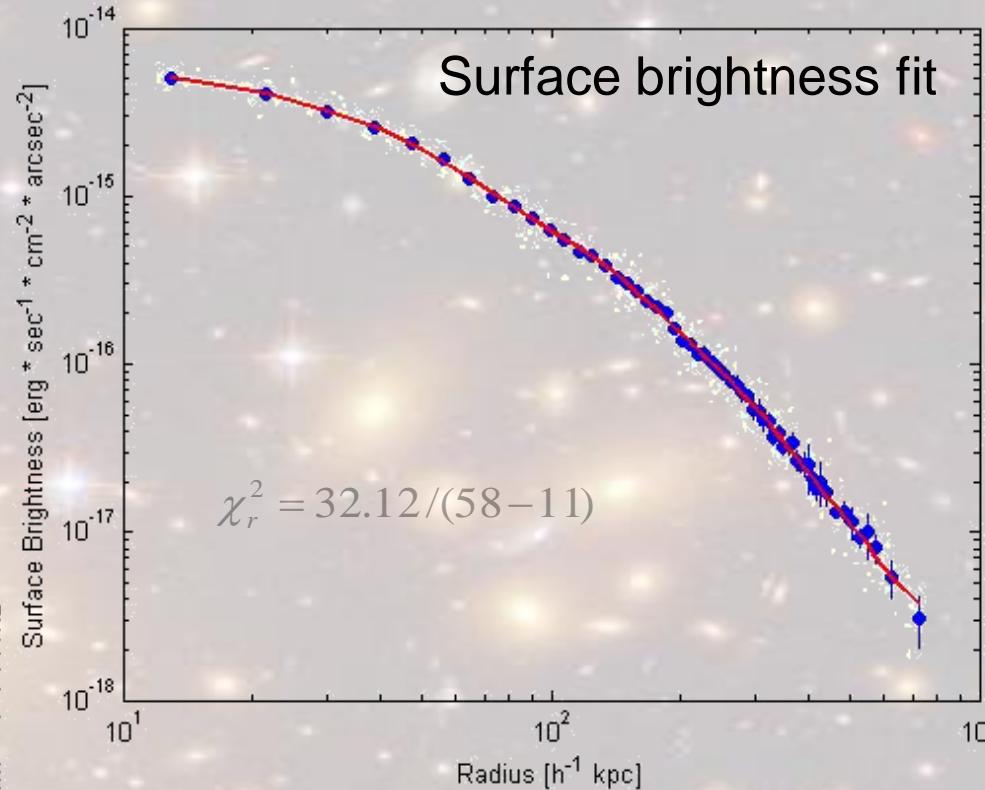
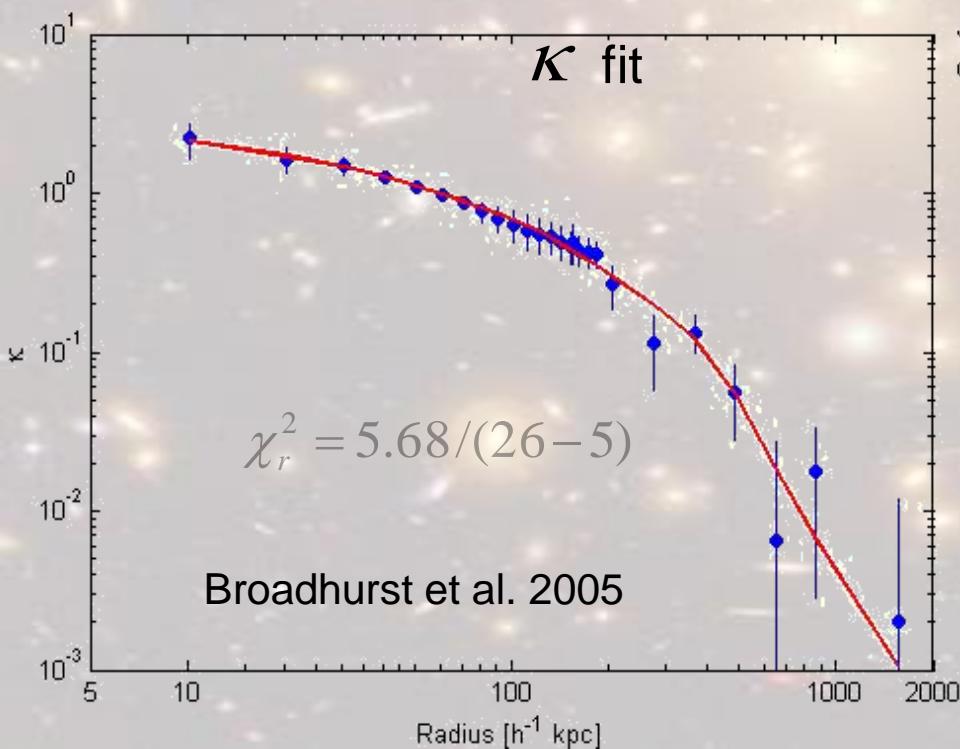
Using lensing data

Using X-ray data

The fit results for A1689

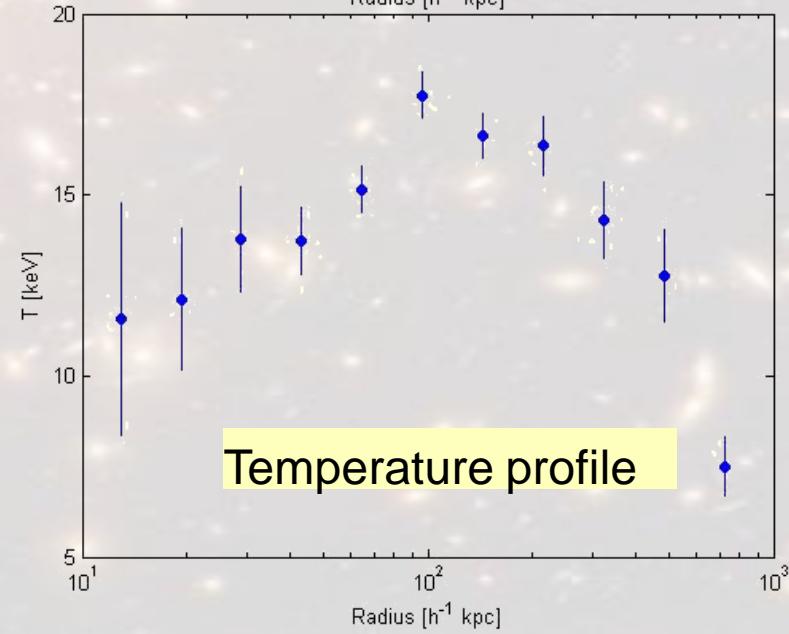
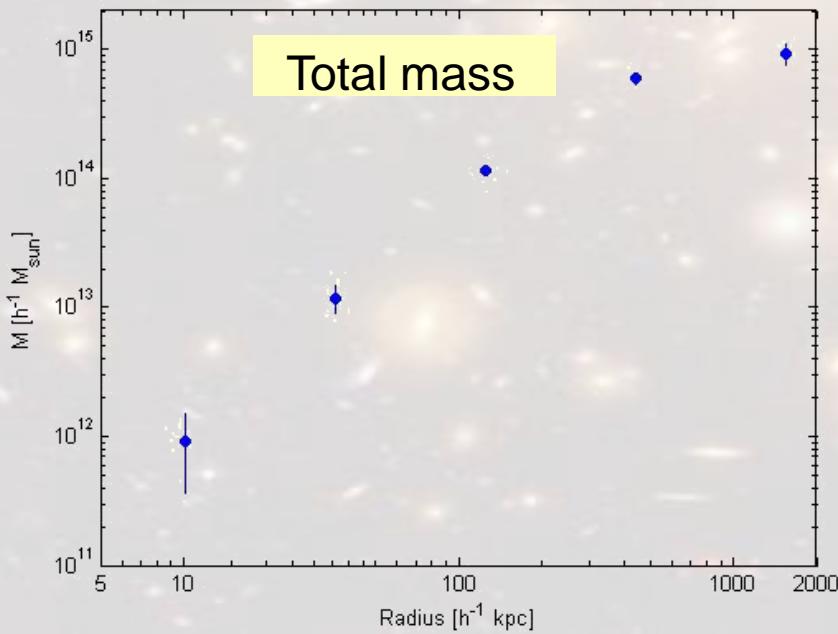
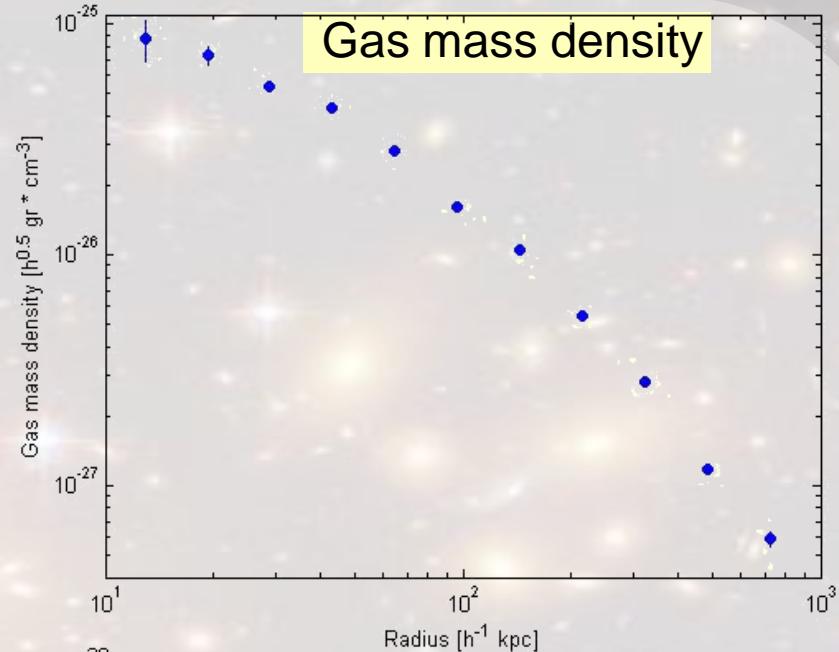
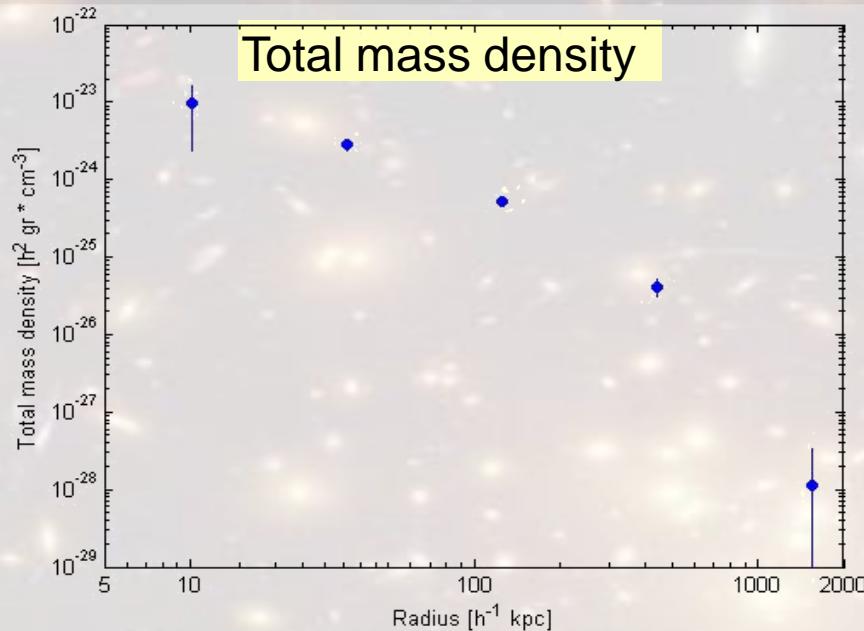
X ray data points : 58
Lensing data points : 26
The number of free parameters of $\rho_{total}(r_i)$: 5
The number of free parameters of $\rho_{gas}(r_j)$: 11

dof : 68

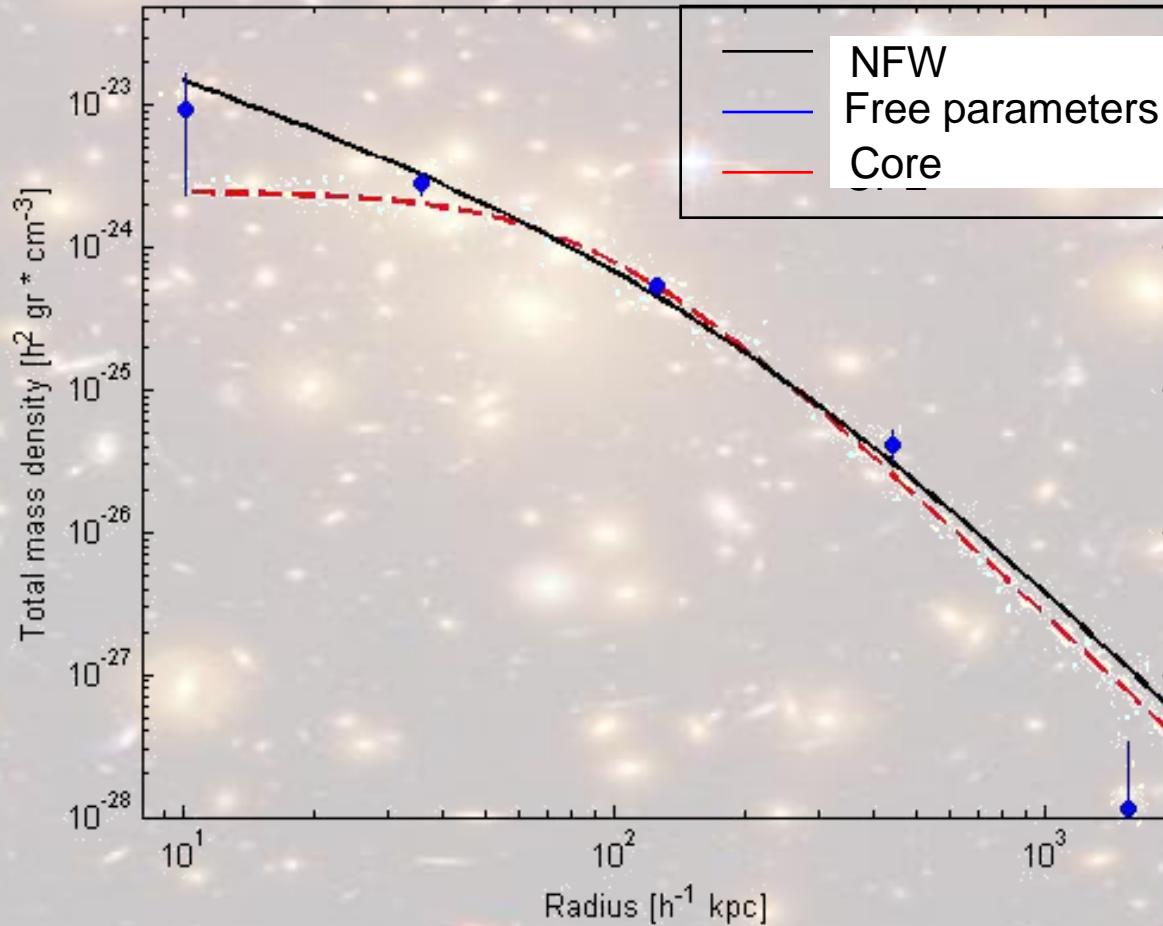


$$\chi^2_r = \chi^2 / dof = 37.8 / 68$$

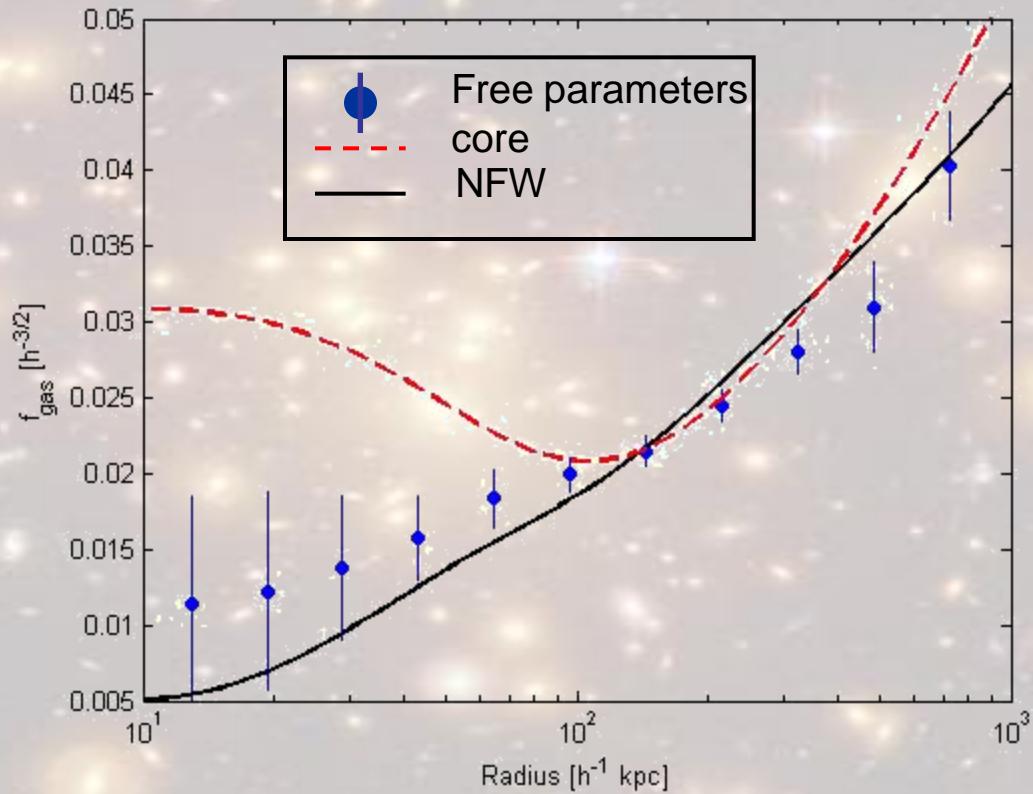
The 3D profiles



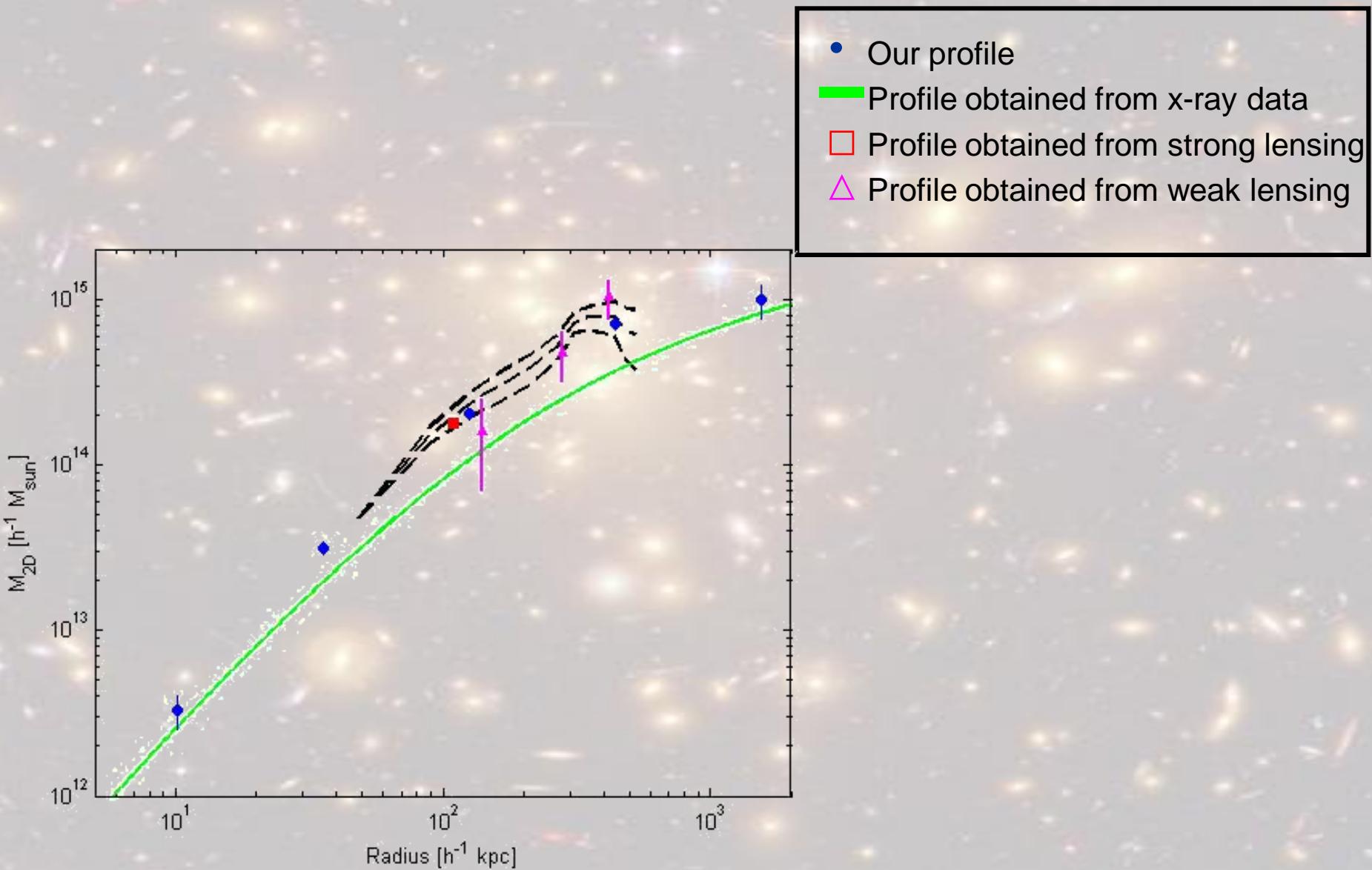
Comparing the results of the general total (mostly DM) mass density profile to other profiles



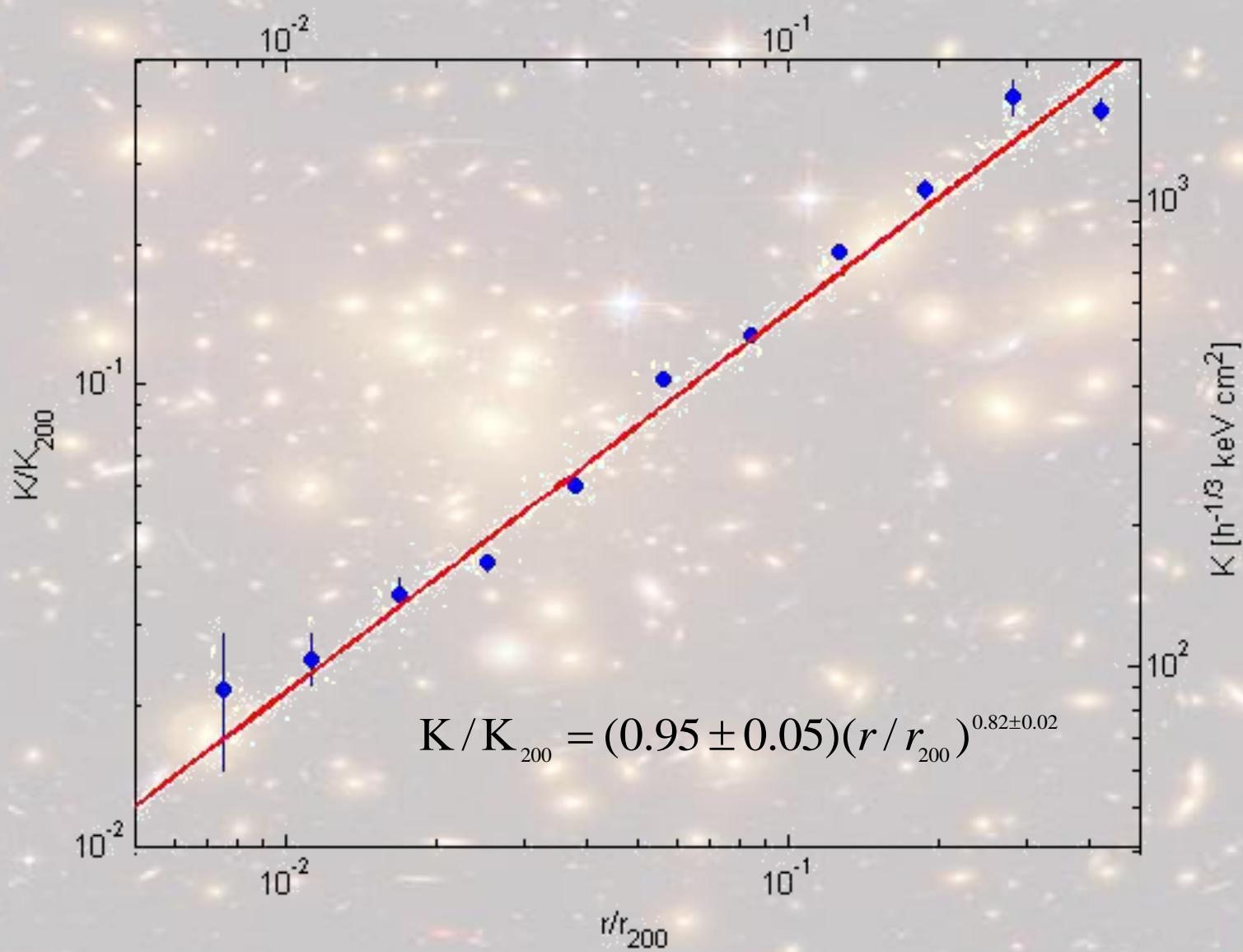
The 3D gas fraction



Resolving the mass discrepancy

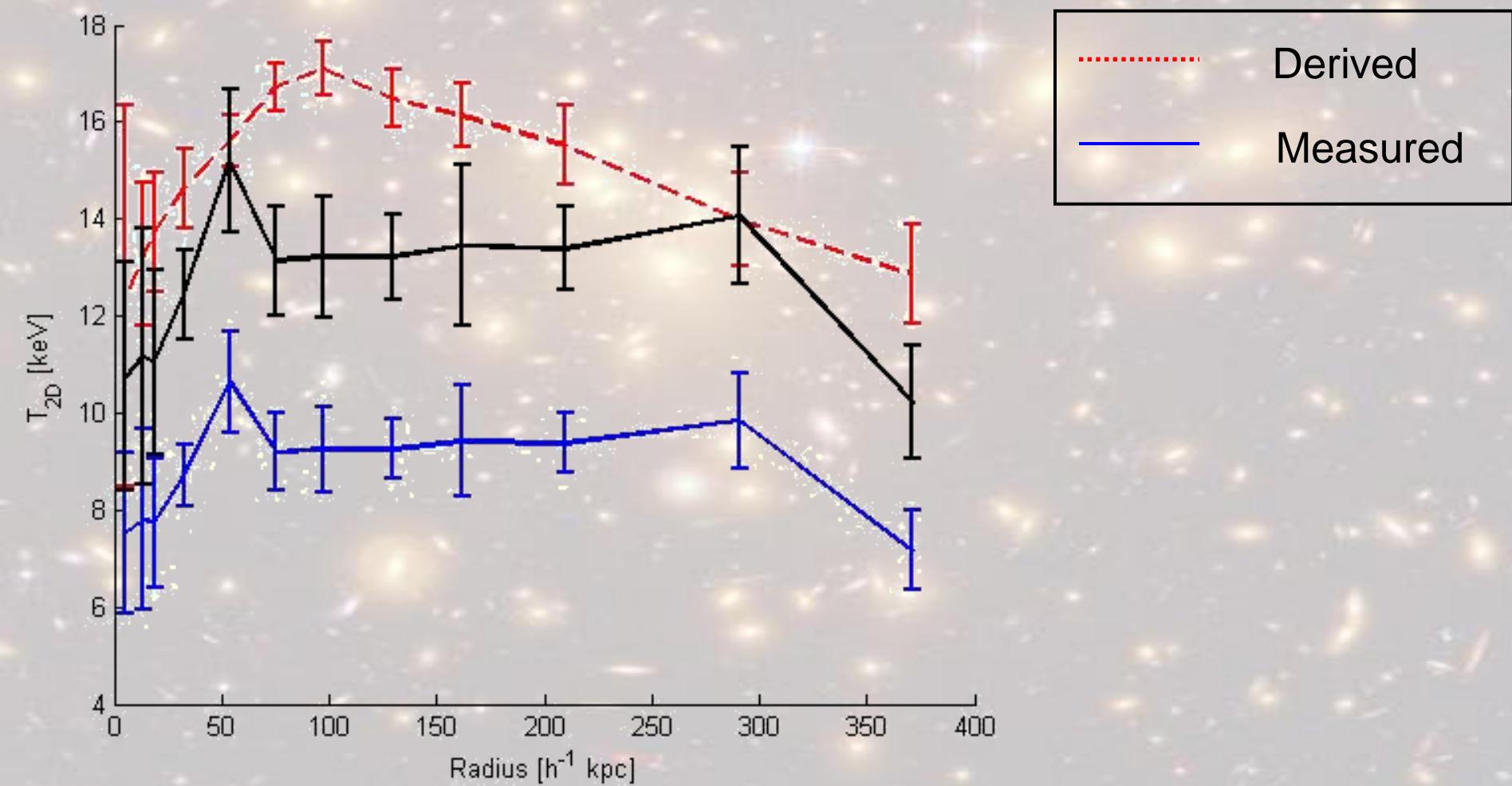


The 3D entropy profile



Checking consistency of the 2D temperature

2D Temperature profile



The temperature discrepancy

$$T_{ew} = \frac{\int T \varepsilon(A, n, T) dr}{\int \varepsilon(A, n, T) dr} \quad \text{Naively}$$

The discrepancy: $T_{ew} \neq T_{sl}$

The problem: a bias due to the radial temperature gradient

$$\begin{aligned} & n_1^2 G_c(Z, T_1, E) \frac{1}{\sqrt{T_1}} \exp\left(-\frac{E}{kT_1}\right) \\ & + n_2^2 G_c(Z, T_2, E) \frac{1}{\sqrt{T_2}} \exp\left(-\frac{E}{kT_2}\right) \\ & \neq n_e^2 G_c(Z, T_3, E) \frac{1}{\sqrt{T_3}} \exp\left(-\frac{E}{kT_3}\right), \end{aligned}$$

Mazzota et al. 2004

Solutions to the temperature discrepancy

$$T_{sl} = \frac{\int T \varepsilon(A, n, T) T^\alpha dr}{\int \varepsilon(A, n, T) T^\alpha dr} \quad \text{Mazzotta et al. -- for } T \geq 3 \text{ keV scaling}$$

For $T < 3 \text{ keV}$ line emission is important!

Vikhlinin 2006 algorithm ...still limited to $T > 0.5 \text{ keV}$

More biases to the 2D temperature profile?!

Local inhomogeneities

Kawahara et al. 2007

$$\kappa \equiv \frac{T_{sl}}{T_{ew}} = \kappa^{RP} \kappa^{LI}$$

Conclusions

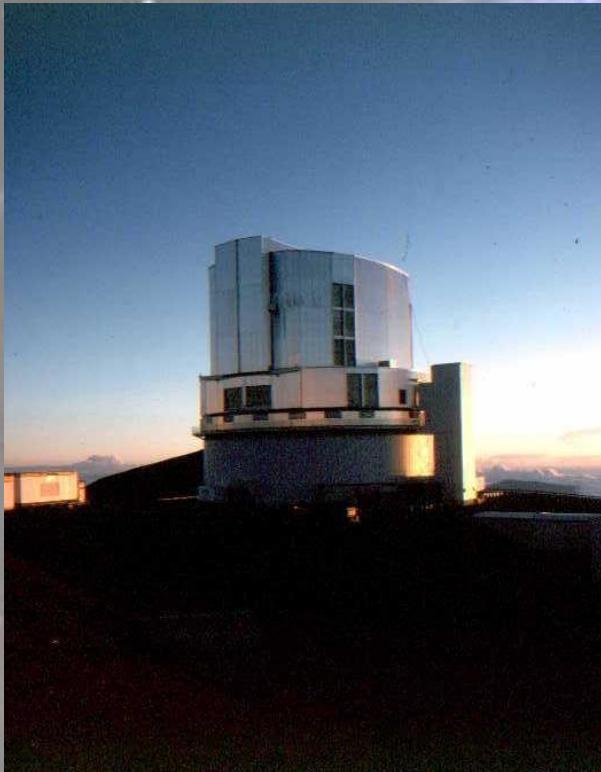
- We resolved the mass discrepancy.
- We have determined the “real” DM and gas density profiles.
- We have a tool which can help pinpoint the right model, especially when better data become available.



Step 2: Adding dynamical data

Lemze, Broadhurst, Rephaeli, Barkana,
Czoske, Umetsu (in preparation)

The measuring instruments

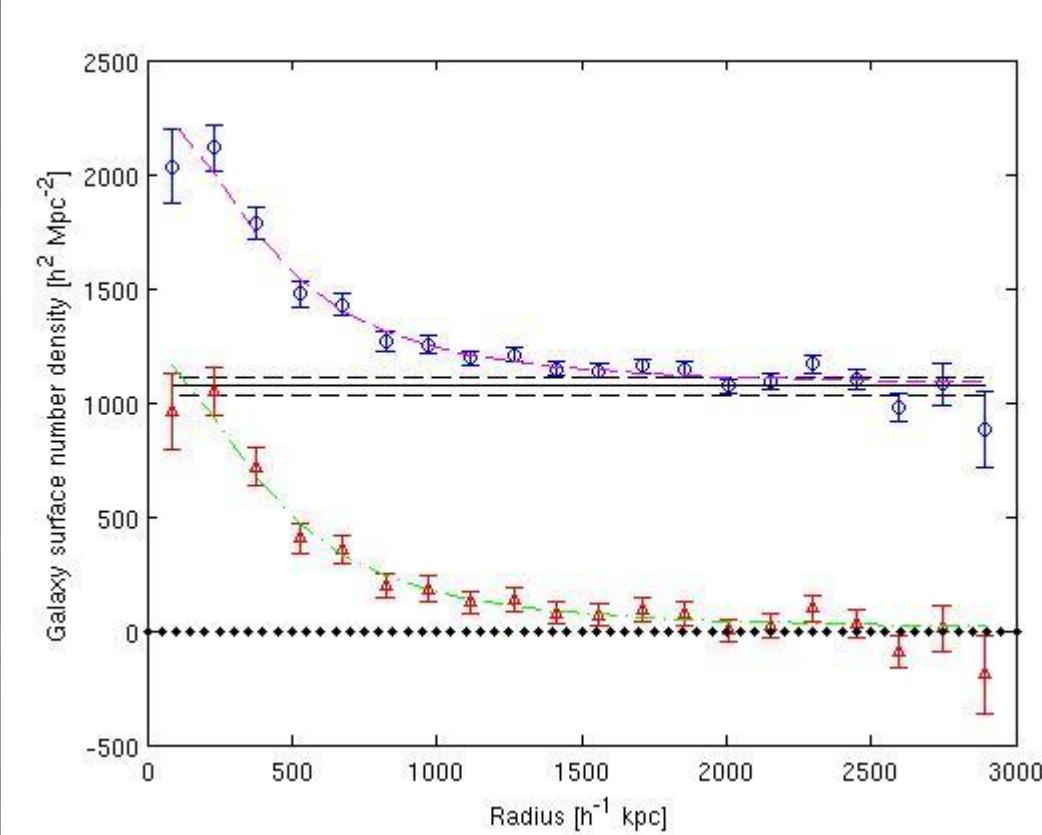


Subaru/suprime-cam

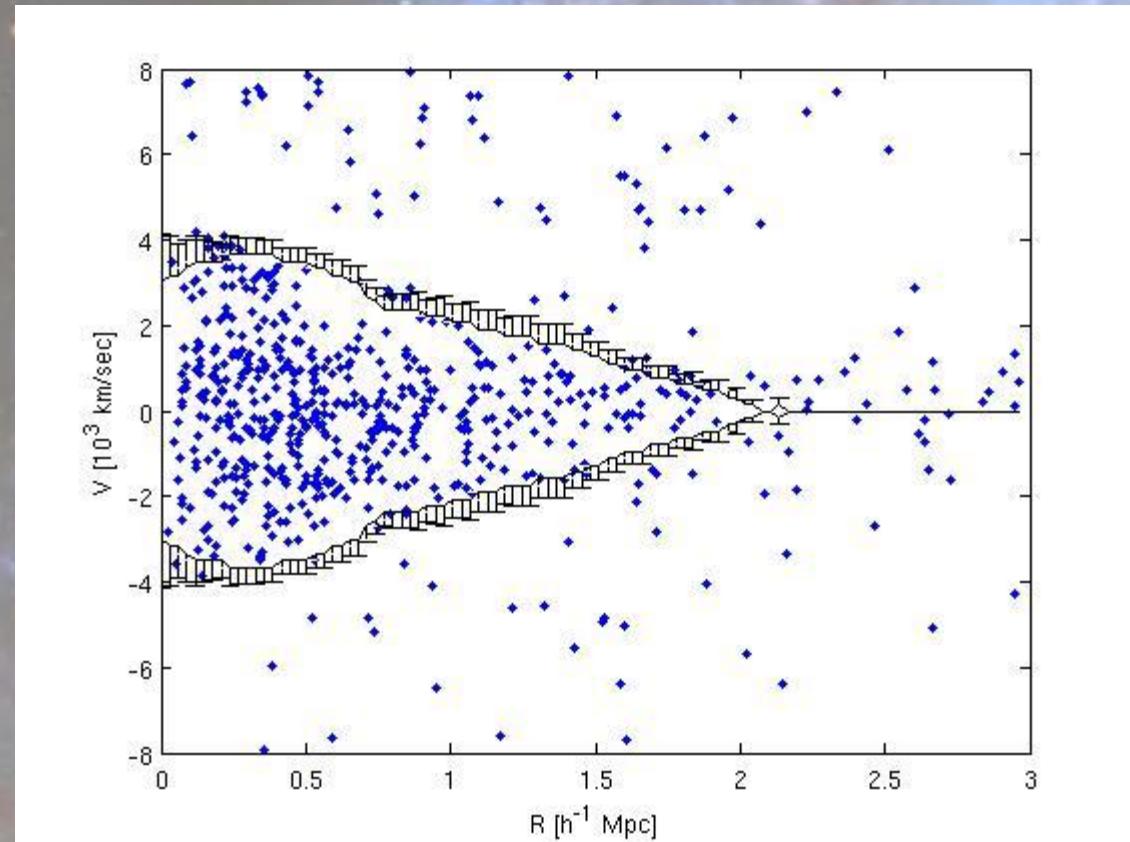


VLT/VIMOS

Galaxy surface number density



Velocity-Space Diagram



Diaferio 1999

About 500 cluster members.

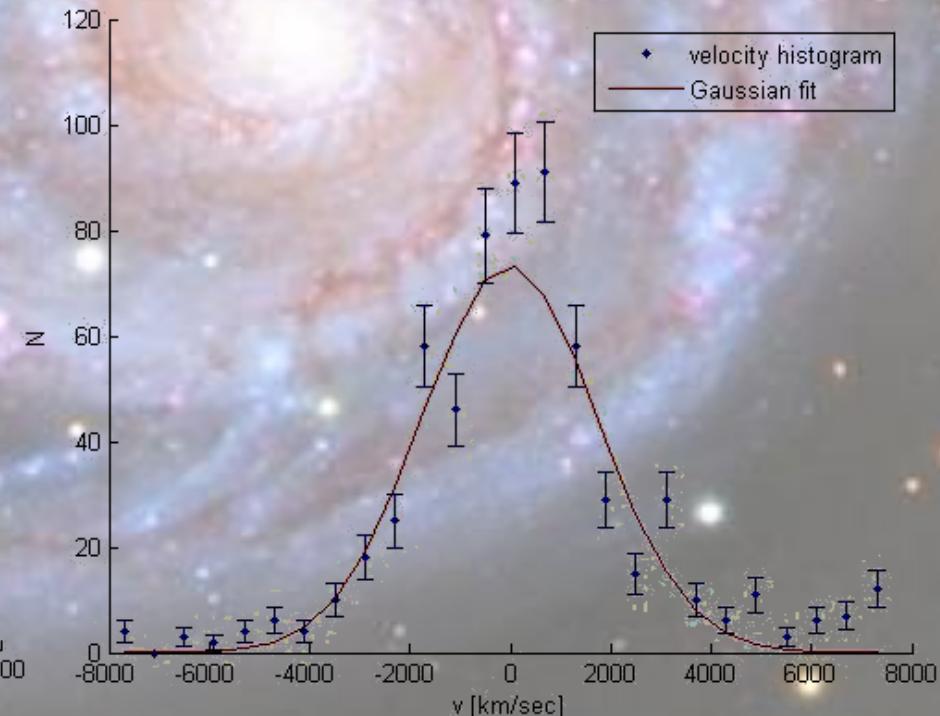
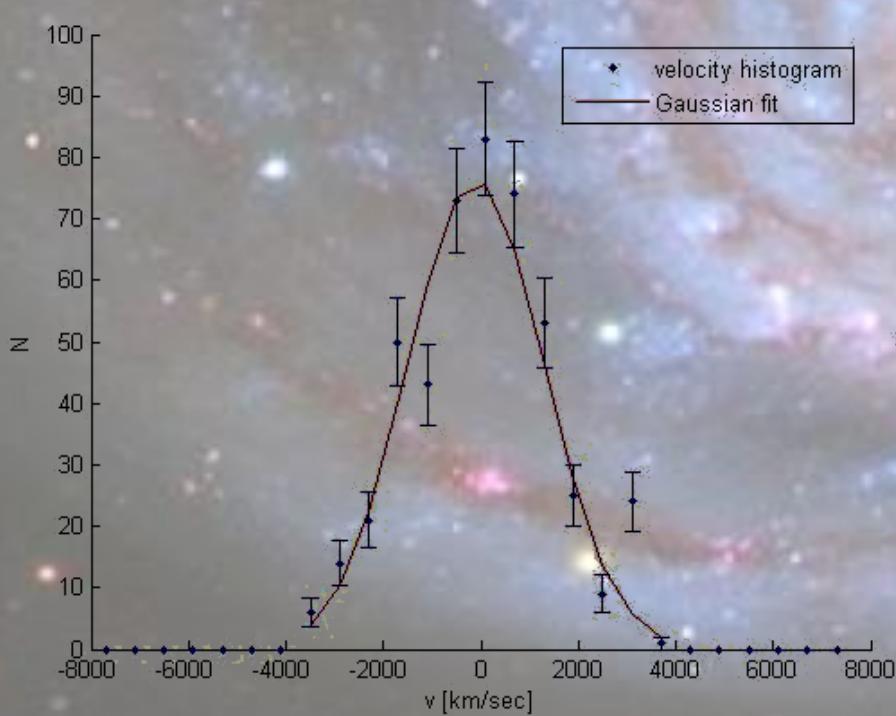
Galaxy number Vs. (peculiar) velocity distribution

Cluster members

$$\chi^2_r = 1.7$$
$$\sigma_p = (1.4 \pm 0.06) \cdot 10^3 \text{ km/sec}$$

All galaxies

$$\chi^2_r = 2.5$$
$$\sigma_p = (1.75 \pm 0.08) \cdot 10^3 \text{ km/sec}$$



Methodology

$$\frac{d}{dr} \left(\rho_{gal}(r) \sigma_r^2(r) \right) + \frac{2\beta(r)}{r} \rho_{gal}(r) \sigma_r^2(r) = - \frac{GM(\leq r) \rho_{gal}(r)}{r^2} \quad \text{Jean's eq.}$$

$$\beta(r) \equiv 1 - \frac{\sigma_t^2}{\sigma_r^2}$$

Velocity anisotropy

$$\sigma_{gal}(R) = 2 \int_R^\infty \frac{\rho_{gal}(r) r dr}{\sqrt{r^2 - R^2}}$$

Galaxy surface number density

$$\sigma_p^2(R) = \frac{2}{\sigma_{gal}^2(R)} \int_R^\infty \frac{\rho_{gal}(r) \sigma_r^2(r) (1 - \beta(r) \frac{R^2}{r^2}) r dr}{\sqrt{r^2 - R^2}}$$

Projected velocity dispersion

Galaxy surface number density

data points : 20

Projected velocity dispersion

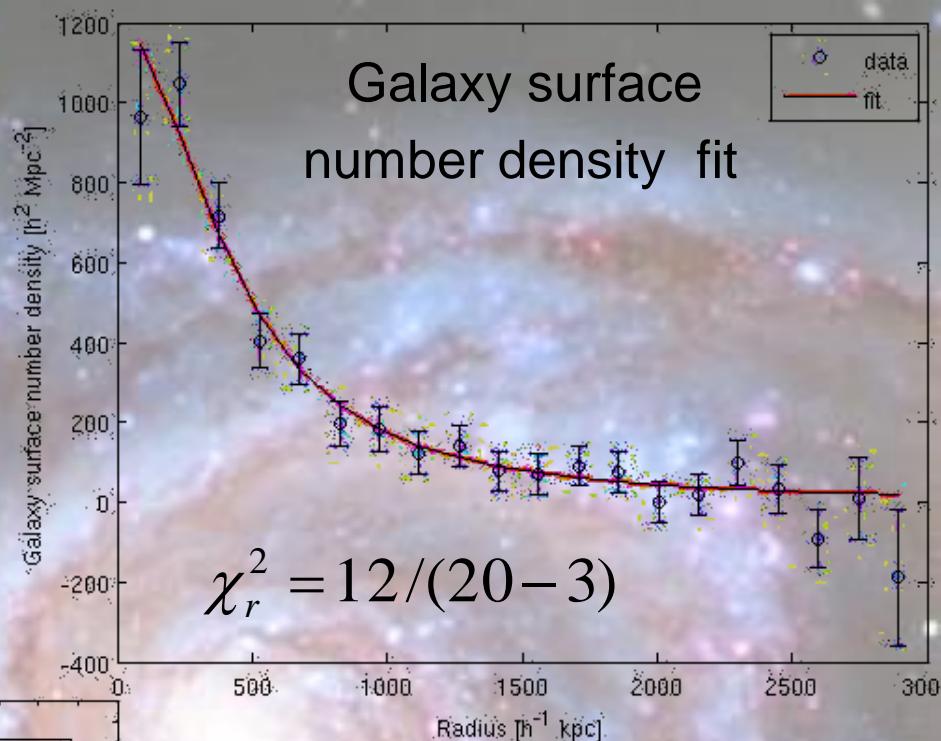
data points : 10

The number of free

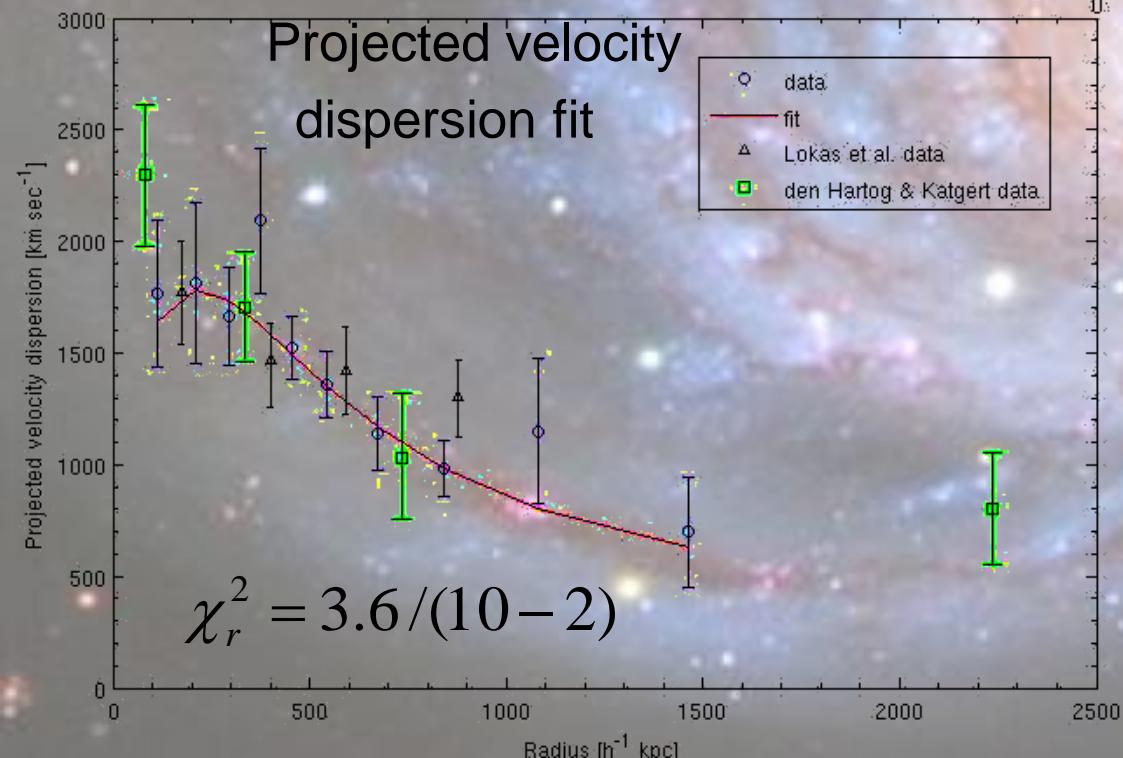
parameters : 5

dof : 25

Galaxy surface
number density fit

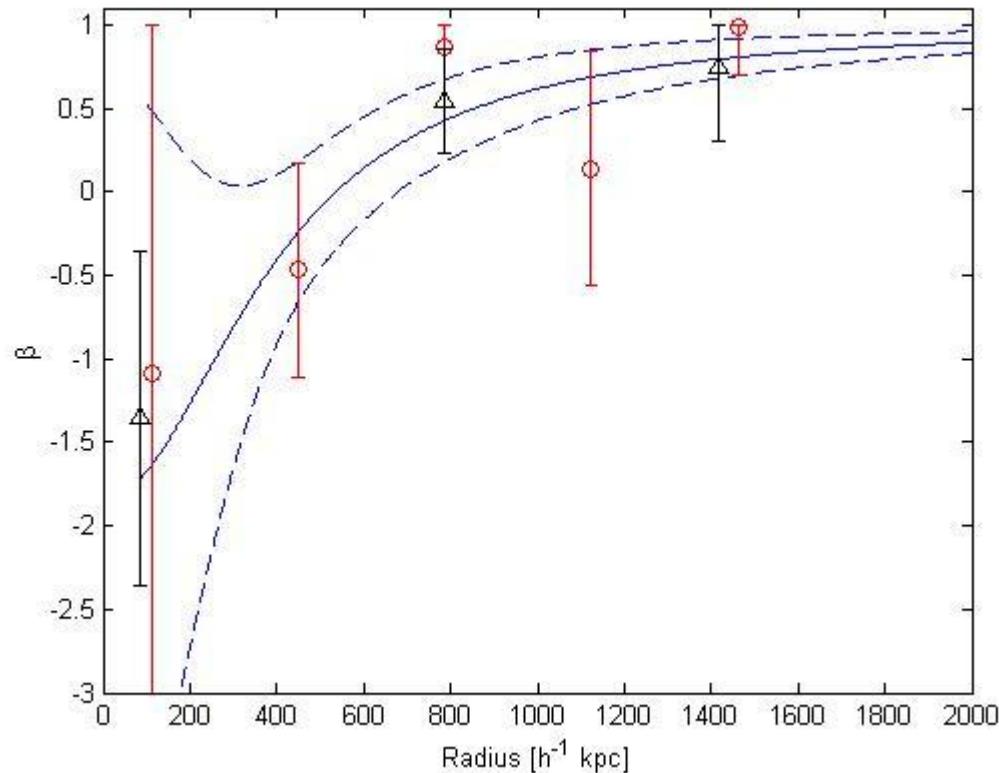


Projected velocity
dispersion fit

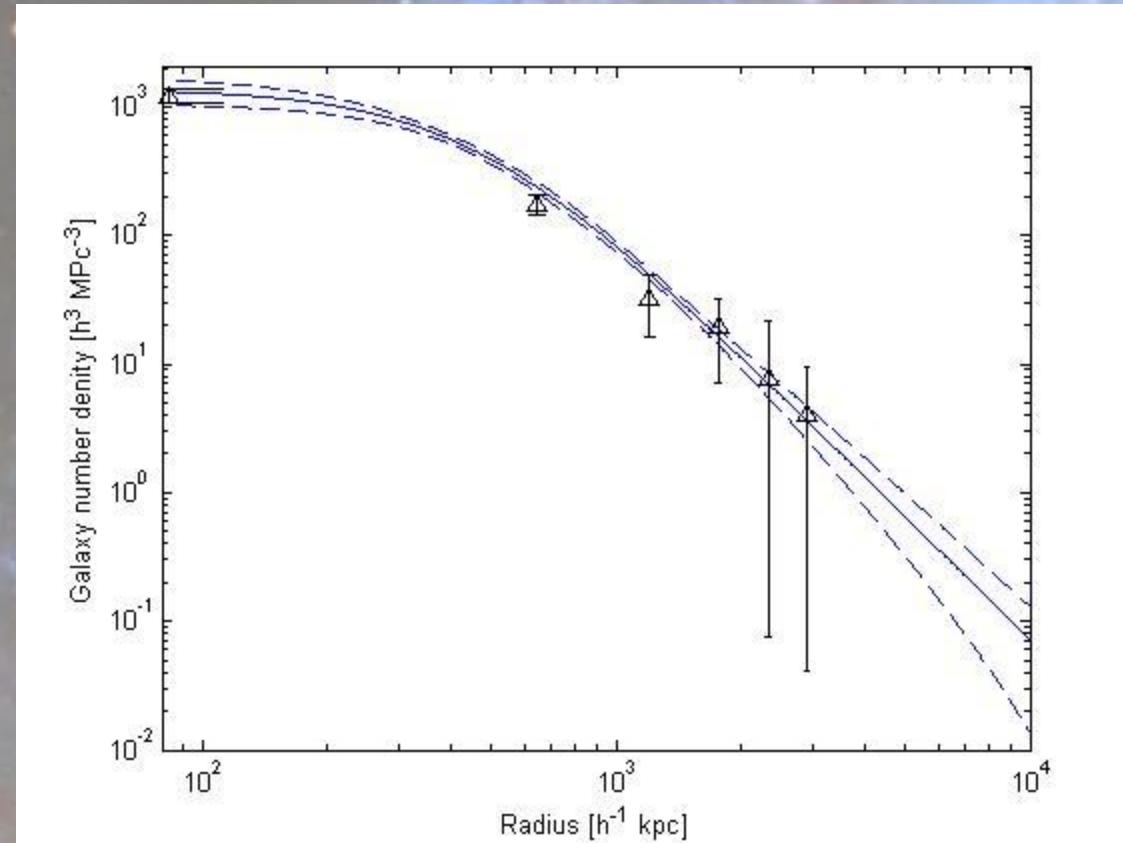


$$\chi^2_r = \chi^2 / dof = 15.6/(30-5)$$

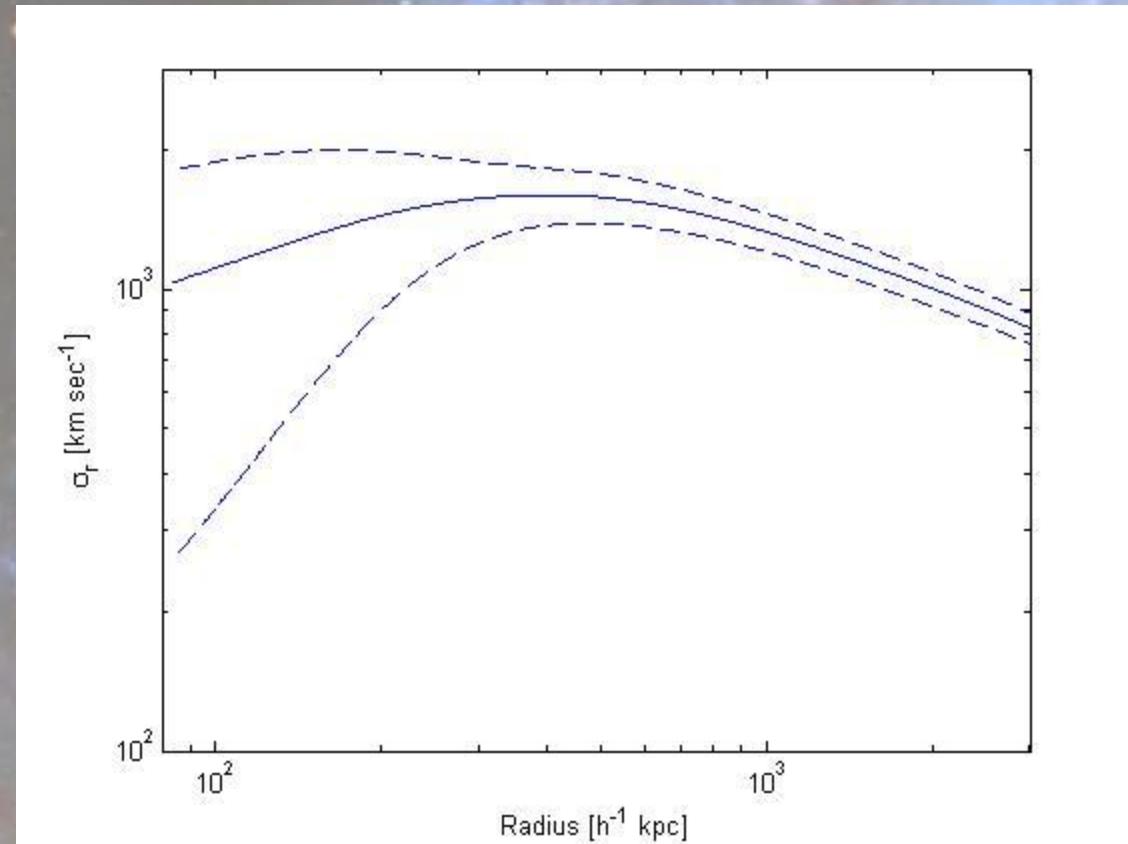
Velocity anisotropy profile



Galaxy number density profile

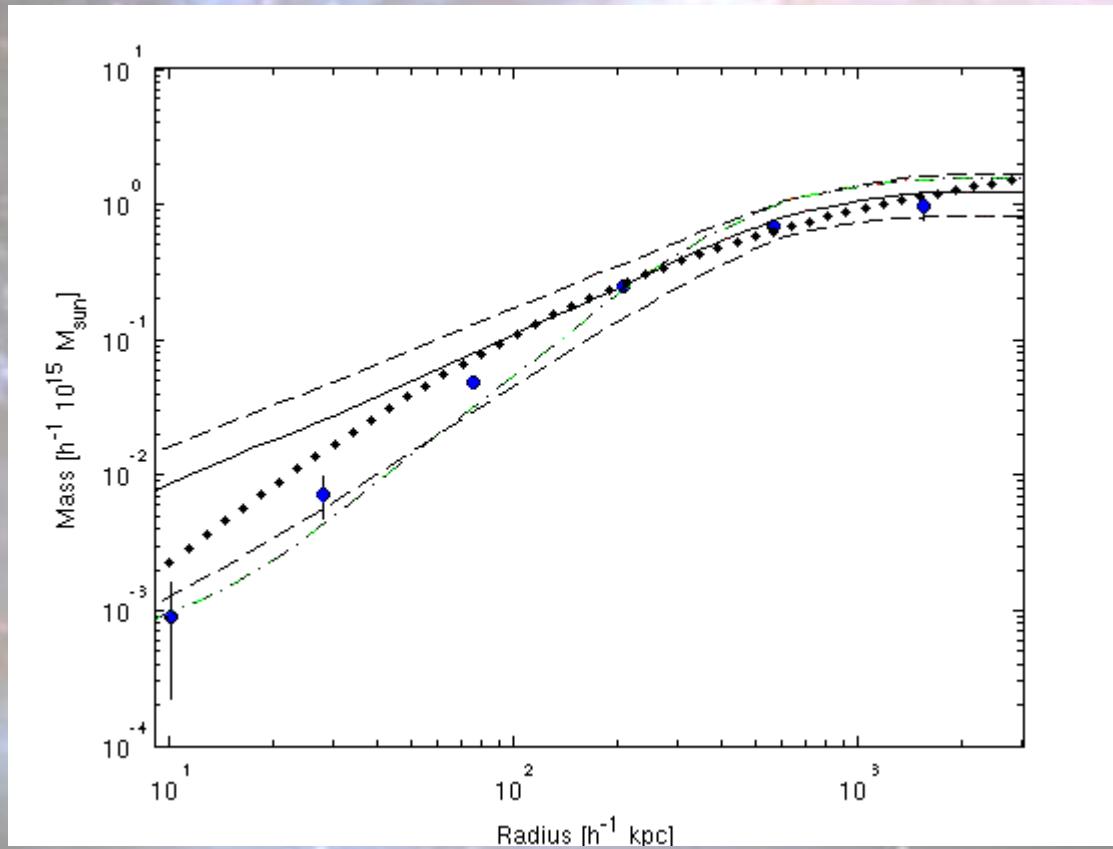


Radial velocity dispersion profile

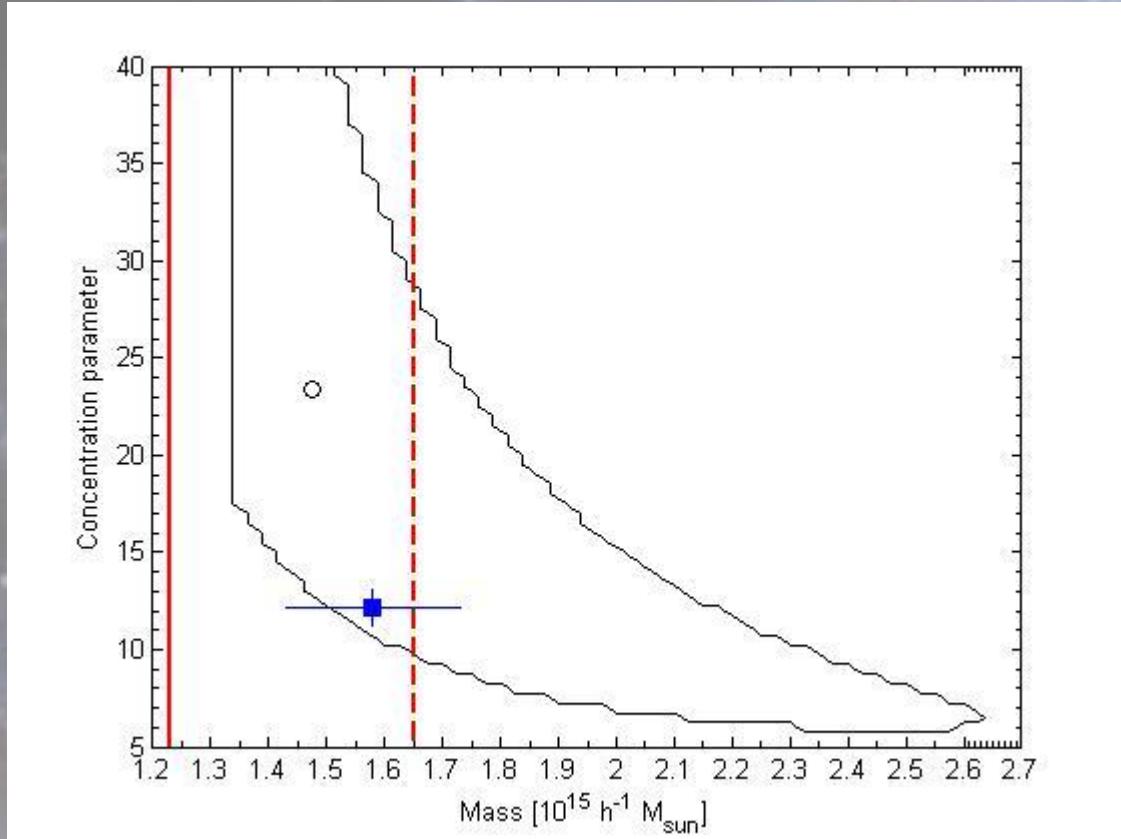


Mass profiles

$$M_{caustics}(r) = 1/G \int_0^r A^2(x) F_\beta(x) dx$$



Virial mass Vs. concentration parameter



$$1.5 < \frac{M_{vir}}{10^{15} h^{-1} M_{sun}} < 1.65$$

$$c_{vir} > 9.75$$

Conclusions

- We estimated for the first time a detailed 3D velocity profile.
- We found that the caustic mass is a good estimation for the mass profile. And we made a correction which makes this method used in all radii.
- We made three independent estimations for the mass profile. We found them consistent with each other.
- We found a very constrained estimation for the virial mass
- We showed from two independent methods that high concentration values exist.

A dense field of galaxies against a dark background.

The End