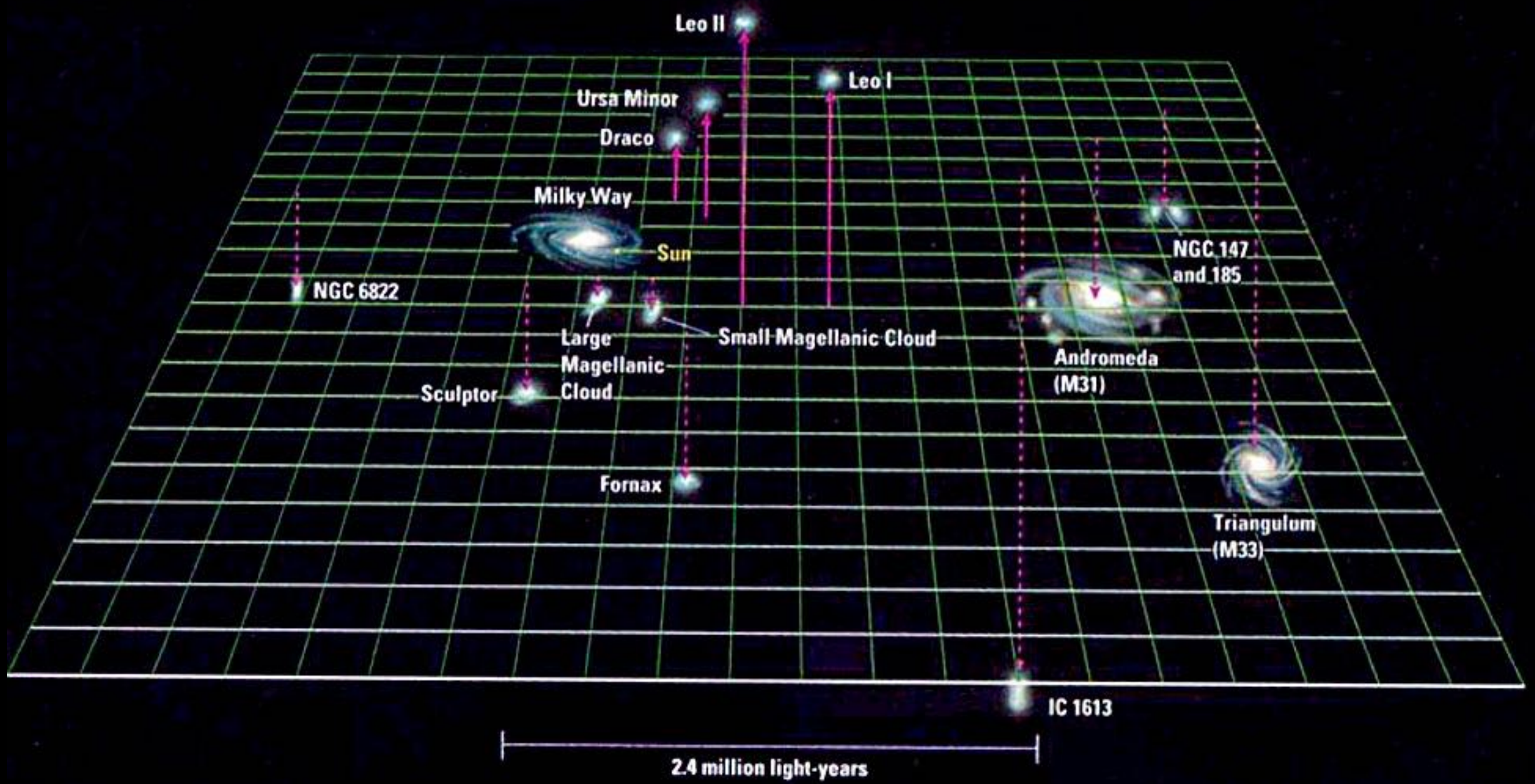
Building up on Zwicky

Clusters dunkle (kalte) materie

Local Group Of Galaxies



Kahn & Woltjer (1956)

$$M_{MW} + M_{M31} \geq 2\ 10^{12}\ M_{\odot}$$

$$IGM\ \ N = 10^{-4}\ cm^{-3}\ \ T = 5\ 10^{5}\ \ ^{\circ}K$$

Sandage (1986) $\quad M_{LG} \approx 4\ 10^{11}\ M_{\odot}$ ..... *possible* $2.9\ 10^{12}\ M_{\odot}$

Watkins et al. (2010)

$$M_{300,\,MW} = 0.9 \pm 0.3\ 10^{12}\ M_{\odot}$$

$$M_{300,\,M31} = 1.4 \pm 0.4\ 10^{12}\ M_{\odot}$$

Goanzales et al. (2014)

$$M_{MW} + M_{M31} = 2.40^{+1.95}_{-1.05}\ M_{\odot}$$

$$M_{LG}\left(R \prec 1\ Mpc\right) = 4.2^{+3.4}_{-2.0}\ 10^{12}\ M_{\odot}$$

Van der Marel et al. (2012)

$$M_{LG} \equiv M_{MW} + M_{M31} = 4.93 \pm 1.63\ 10^{12}\ M_{\odot}$$

$$M_{LG} = 3.17 \pm 0.57\ 10^{12}\ M_{\odot}$$

Add eventually deceleration analysis

And ....

here the observer

1936
Zwicky observing at the Schmidt 18 inch

The size of the Coma Cluster

Add a few slides and written discussion later on. For now talk

1. *Discussion with Zwicky*
2. *Schmidt & counts of galaxies*
3. *Observation with Rood*
4. *Superclustering & Ref.*

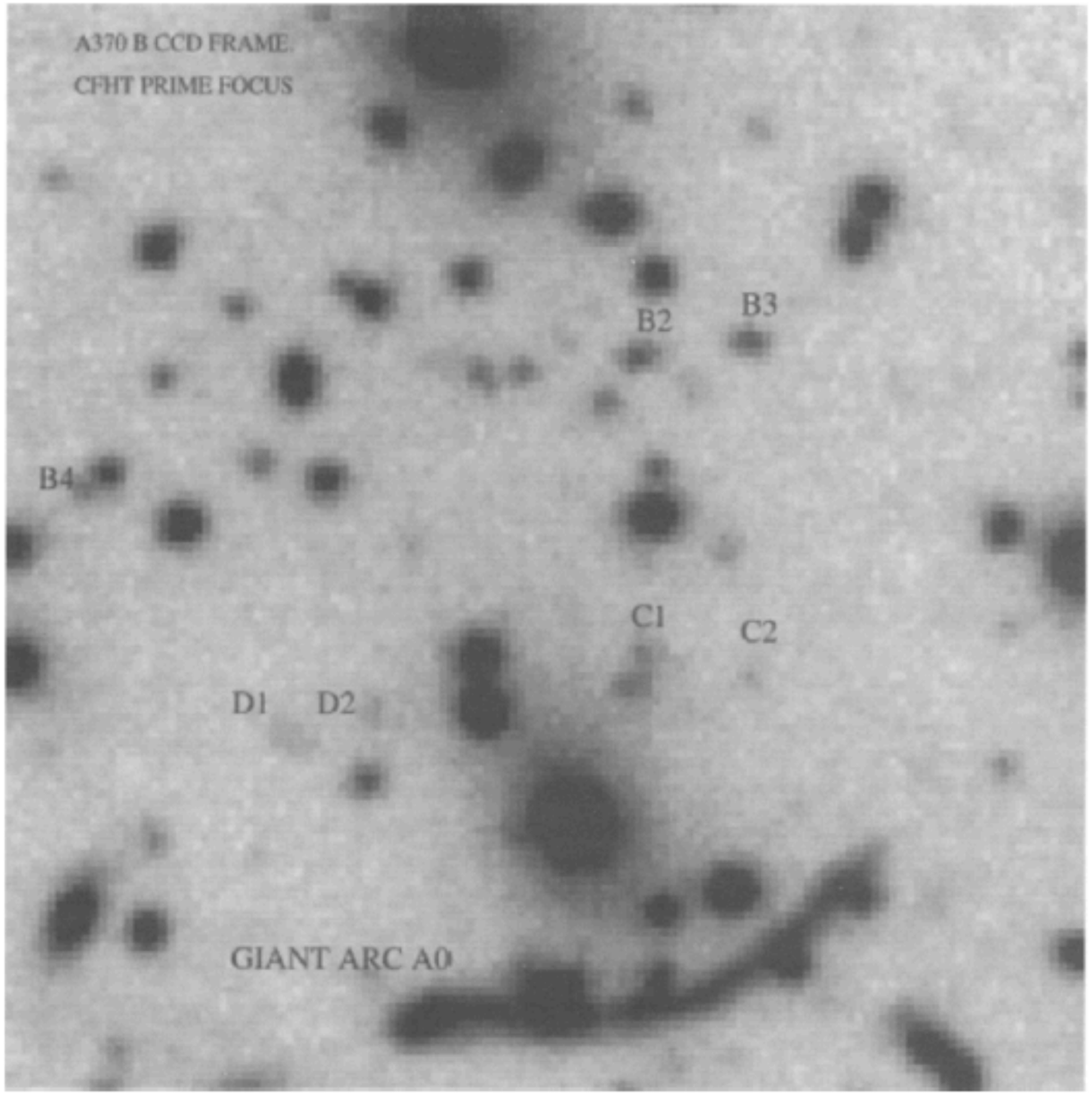
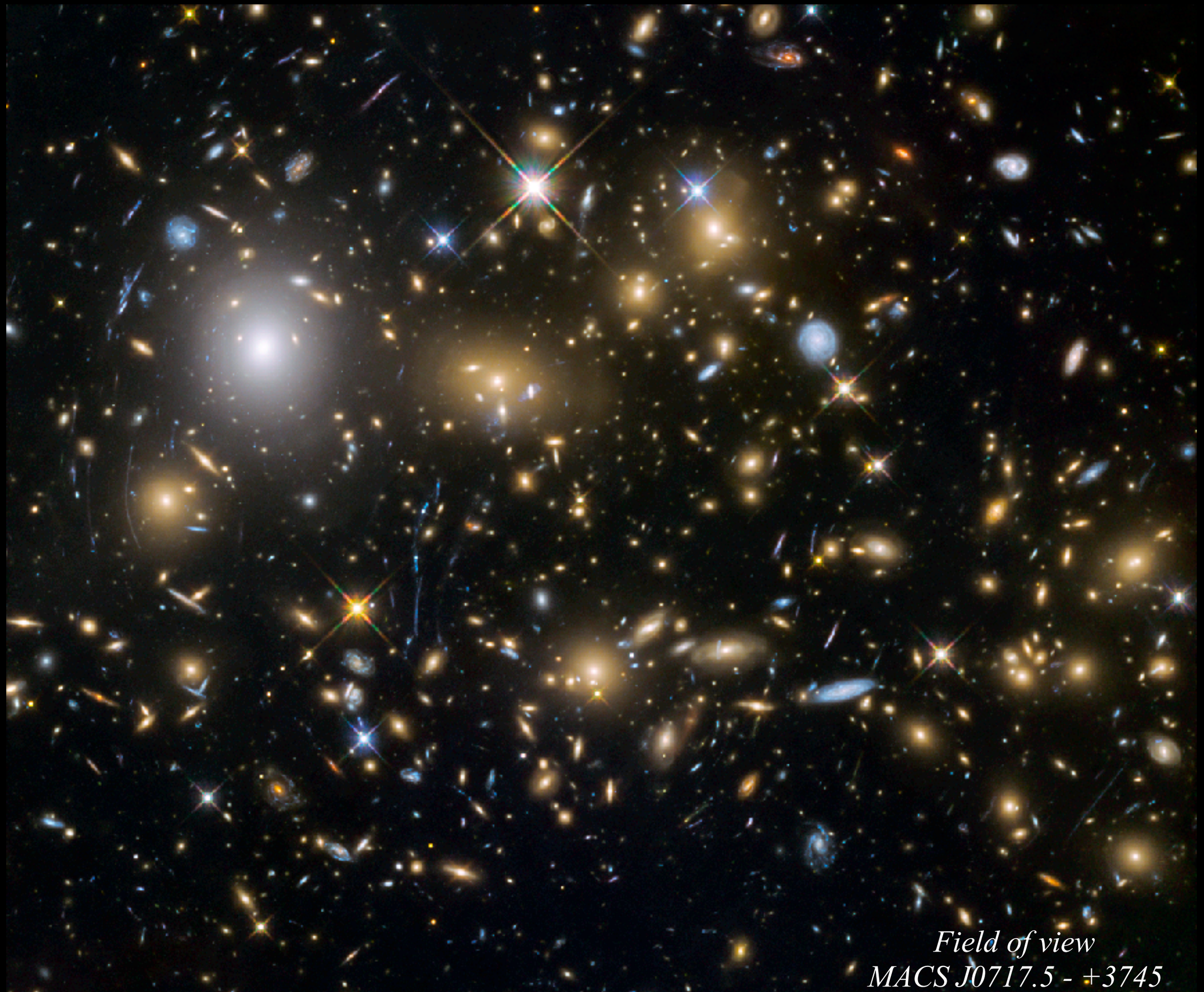
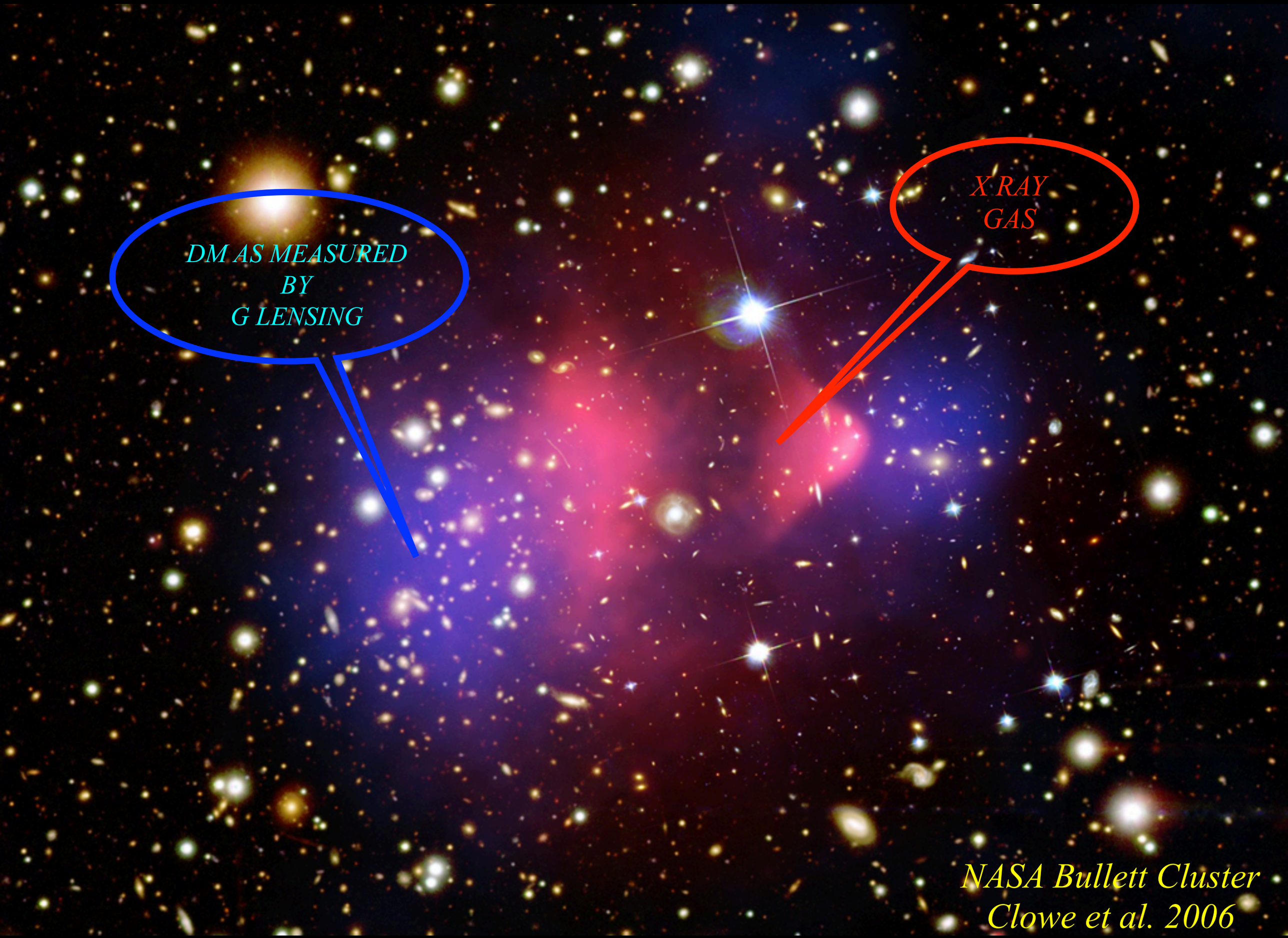


Fig. 1. Deep CCD image of the giant arc discovered in A370. The arc extends over 25 arcsec, and is actually a merging of three images of a background source at $z = 0.725$. The other galaxies are cluster members at redshift $z = 0.375$. A370 appears as a bimodal cluster dominated by two very luminous galaxies. One is visible at the top of the image, while the other one lies close to the arc. Note also the faint pairs (B2-B3), (C1-C2) and (D1-D2), which are multiple images of other background sources (Kneib et al. 1993; see Sect. 2). The notation (B2-B3) come from Fort et al. (1988). Kneib et al. predicted that B4 must be the third image associated with (B2-B3)

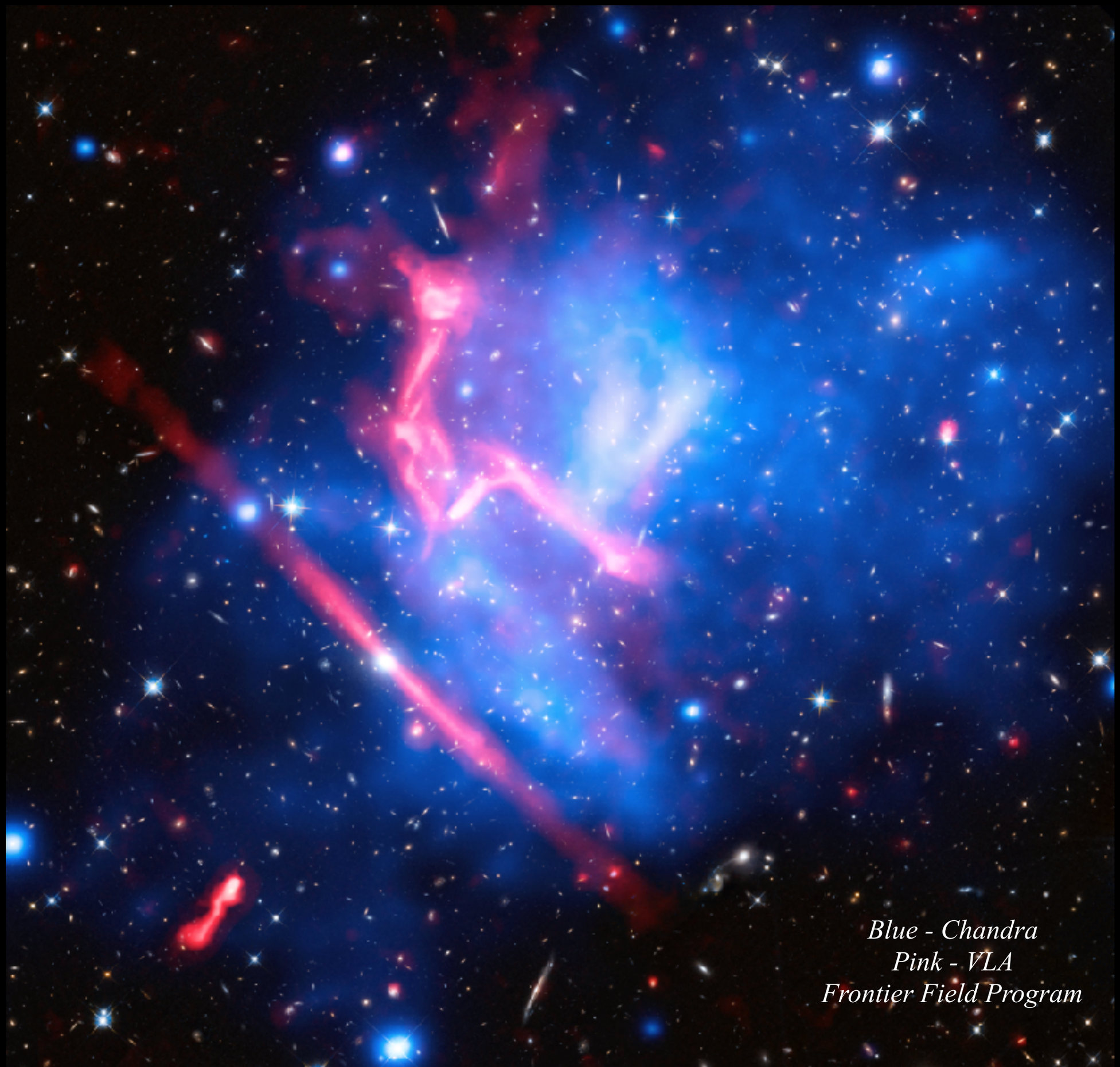


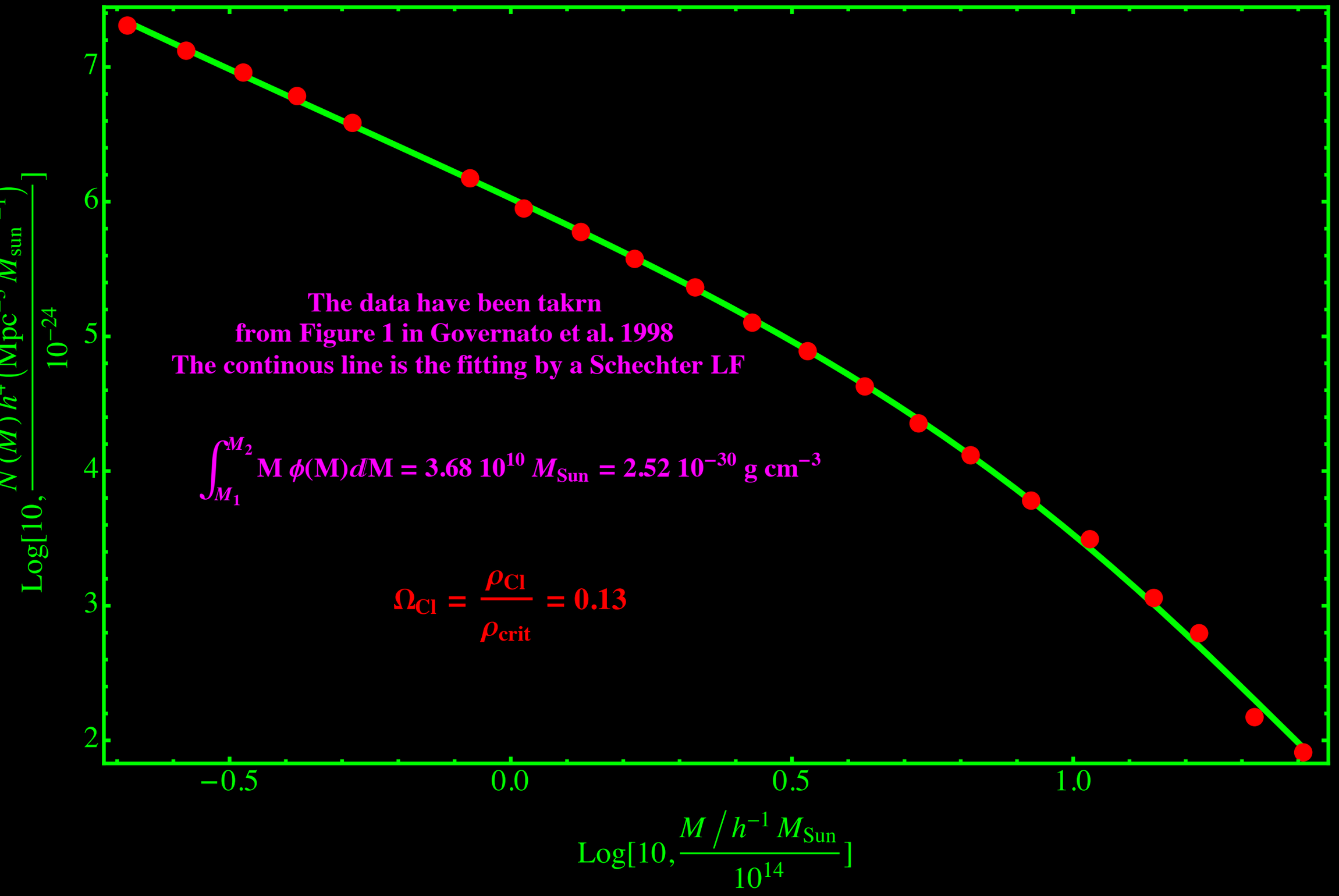
Field of view
MACS J0717.5 - +3745

Abel 1689
lens


DM AS MEASURED
BY
G LENSING
X RAY
GAS
NASA Bullett Cluster
Clowe et al. 2006

Dark Matter Blue
Chandra - Pink


Blue - Chandra
Pink - VLA
Frontier Field Program


The data have been takrn
from Figure 1 in Governato et al. 1998
The continous line is the fitting by a Schechter LF
$\int_{M_1}^{M_2} \mathrm{M}\,\phi(\mathrm{M})d\mathrm{M} = 3.68\ 10^{10}\ M_{\mathrm{Sun}} = 2.52\ 10^{-30}\ \mathrm{g\ cm^{-3}}$
$\Omega_{\mathrm{Cl}} = \frac{\rho_{\mathrm{Cl}}}{\rho_{\mathrm{crit}}} = 0.13$
$\mathrm{Log}[10, \frac{N(M)\,h^4\,(\mathrm{Mpc}^{-3}\,M_{\mathrm{sun}}{}^{-1})}{10^{-24}}]$
$\mathrm{Log}[10, \frac{M\,/\,h^{-1}\,M_{\mathrm{Sun}}}{10^{14}}]$
7
6
5
4
3
2
−0.5
0.0
0.5
1.0

$$\sum \overline{v}_i \cdot \partial T \big/ \partial v_i = 2\,T; \quad \partial T \big/ \partial \overline{v}_i = \overline{p}_i \quad 2T = \sum\nolimits_i \overline{p}_i \cdot \overline{v}_i = \frac{d}{dt}\left(\sum\nolimits_i \overline{p}_i \cdot \overline{r}_i\right) - \sum\nolimits_i \overline{r}_i \cdot \dot{\overline{p}}_i$$

$$f = \lim_{\tau\to\infty} \frac{1}{\tau}\int_0^\tau \frac{dF}{dt}\,dt = \lim_{\tau\to\infty} \frac{F(\tau) - F(0)}{\tau} = 0$$

$$\frac{d}{dt}\left(\sum\nolimits_i \overline{p}_i \cdot \overline{r}_i\right) \quad \& \quad \dot{\overline{p}} = -\partial\Omega \big/ \partial \overline{r} \quad \Rightarrow 2\langle T\rangle = \left\langle \sum\nolimits_i \overline{r}_i \cdot \partial\Omega \big/ \partial \overline{r}_i \right\rangle$$

$$\Omega\left(\alpha\overline{r}_1, \alpha\overline{r}_2, \ldots, \alpha\overline{r}_n\right) = \alpha^k \Omega\left(\overline{r}_1, \overline{r}_2, \ldots, \overline{r}_n\right) \quad \sum_i^n \frac{\partial f}{\partial x_i} x_i = k\, f\left(x_i\right)$$

$$2\langle T\rangle = k\langle\Omega\rangle \quad (k=1) \quad \langle 2\,T\rangle = -\langle\Omega\rangle \quad E = -\langle T\rangle$$

$$\& \quad or$$

$$\frac{1}{2}\frac{d^2}{dt^2} I_{jk} = 2K_{jk} + W_{jk}$$

$$\frac{d^2}{dt^2} I_{jk} = 0 \quad \ldots\ldots\ldots\ldots$$

$$\langle v_r \rangle = \langle v_\theta \rangle = 0$$

$$\frac{d}{dr}\left(\rho \langle v_r^2 \rangle\right) + \frac{\rho}{r}\left[2\langle v_r^2 \rangle - \left(\langle v_\theta^2 \rangle + \langle v_\varphi^2 \rangle\right)\right] = -\rho \frac{d\Phi}{dr}$$

$$\langle v_\theta^2 \rangle = \langle v_\varphi^2 \rangle$$

$$\frac{1}{\langle v_r^2 \rangle}\frac{d}{dr}\left(\rho \langle v_r^2 \rangle\right) + 2\frac{\rho}{r}\left[1 - \frac{\langle v_\theta^2 \rangle}{\langle v_r^2 \rangle}\right] = -\frac{\rho}{\langle v_r^2 \rangle}\frac{d\Phi}{dr}$$

$$\beta \equiv 1 - \frac{\langle v_\theta^2 \rangle}{\langle v_r^2 \rangle} \qquad \frac{d\Phi}{dr} = \frac{GM(r)}{r^2}$$

$$M(<r) = -\frac{r\langle v_r^2 \rangle}{G}\left(2\beta + \frac{d\,ln\rho}{d\,ln\,r} + \frac{d\,ln\langle v_r^2 \rangle}{d\,ln\,r}\right)$$

$$I = \sum_{i=1}^{N} m_i r_i^2 = \sum_{1=1}^{N} m_i \left(x_i^2 + y_i^2 + z_i^2 \right)$$

$$\frac{1}{2}\frac{d^2}{dt^2} I = \sum_{i=1}^{N} m_i \left(\dot{x}_i^2 + \dot{y}_i^2 + \dot{z}_i^2 \right) + \sum_{i=1}^{N} m_i \left(x_i \ddot{x}_i + y_i \ddot{y}_i + z_i \ddot{z}_i \right) = 0$$

$$\Omega = -G \sum_{i=1}^{N} \frac{m_i m_j}{r_{ij}}$$

$$r_{ij} = \sqrt{\left(x_i - x_j \right)^2 + \left(y_i - y_j \right)^2 + \left(z_i - z_j \right)^2} \qquad m_i \ddot{x}_i = -\frac{\partial \Omega}{\partial x_i} \quad m_i \ddot{y}_i = -\frac{\partial \Omega}{\partial y_i} \quad m_i \ddot{z}_i = -\frac{\partial \Omega}{\partial z_i}$$

$$\sum_{i=1}^{N} m_i \left(x_i \ddot{x}_i + y_i \ddot{y}_i + z_i \ddot{z}_i \right) = -\sum_{i=1}^{N} \left(x_i \frac{\partial \Omega}{\partial x_i} + y_i \frac{\partial \Omega}{\partial y_i} + z_i \frac{\partial \Omega}{\partial z_i} \right)$$

$$\textit{Euler's Theorem} - \sum_{i=1}^{N} \left(x_i \frac{\partial \Omega}{\partial x_i} + y_i \frac{\partial \Omega}{\partial y_i} + z_i \frac{\partial \Omega}{\partial z_i} \right) = -\Omega$$

If the potential energy is a homogeneous function of the coordinates, that is if $\Omega(\alpha\overline{r}_1, \alpha\overline{r}_2, \ldots, \alpha\overline{r}_n) = \alpha^k \Omega(\overline{r}_1, \overline{r}_2, \ldots, \overline{r}_n)$ where k is called the degree of homogeneity, using Euler's theorem $[\sum_i^n \frac{\partial f}{\partial x_i} x_i = k\, f(x_i)]$ we have $2\langle T\rangle = k\langle\Omega\rangle$. For a Newtonian interaction the potential energy is proportional to $\mathbf{r}^{-1}$ so that k= -1 and $\langle 2T\rangle = -\langle\Omega\rangle$ and $E = \langle T\rangle + \langle\Omega\rangle = \langle T\rangle - \langle 2T\rangle = -\langle T\rangle$ with these mean values intended over time, Landau & Liftshitz Vol. I. The derivation of the tensor viral theorem is given in all details by Binney and Tremaine (1987).

$$\sum_{i=1}^{N} m_i \left(\dot{x}_i^2 + \dot{y}_i^2 + \dot{z}_i^2 \right) = 2\,T$$

$$2\,T + \Omega = 0$$

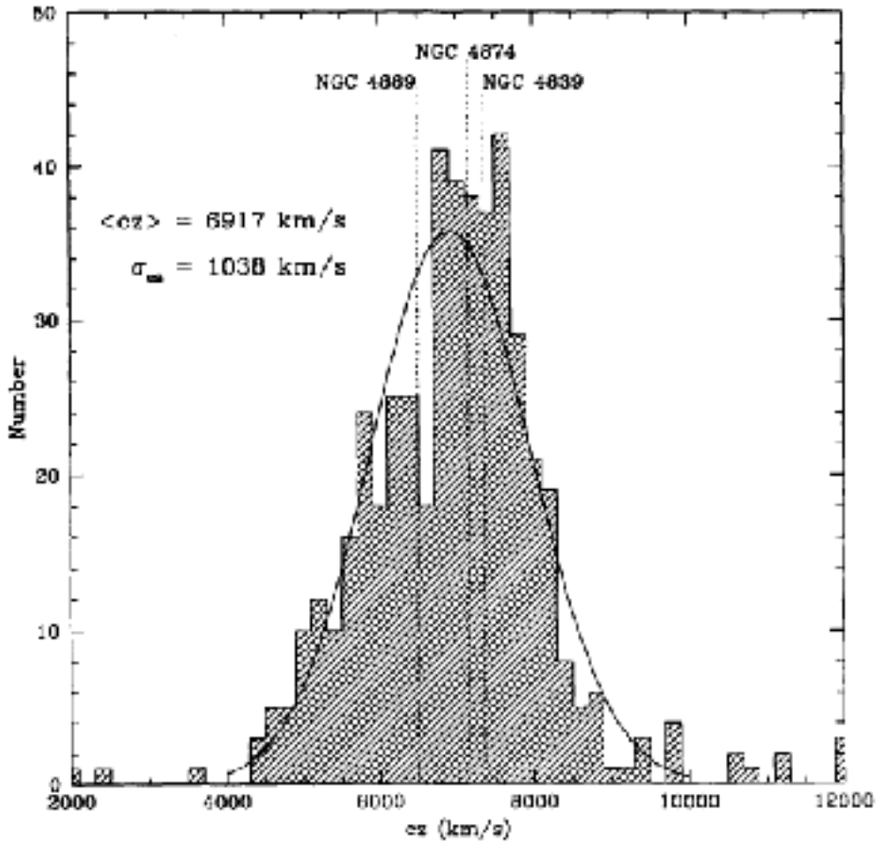
$$\sum m_i v_i^2 = -G \sum \frac{m_i m_k}{r_{ik}} \qquad M = \sum m_i \qquad \frac{1}{M} \sum \frac{m_i}{M} V_D^2 = \sum \frac{m_i}{M} v_i^2$$

$$v_i^2 = -G \sum \frac{m_i}{M} \frac{m_k}{M} \frac{1}{r_{ik}} \qquad V_D^2 = \sum \frac{m_i}{M} v_i^2 \qquad R = \sum \frac{M^2 r_{ij}}{m_i m_k}$$

$$M_{Cl} = \frac{V_D^2\, R}{G}$$

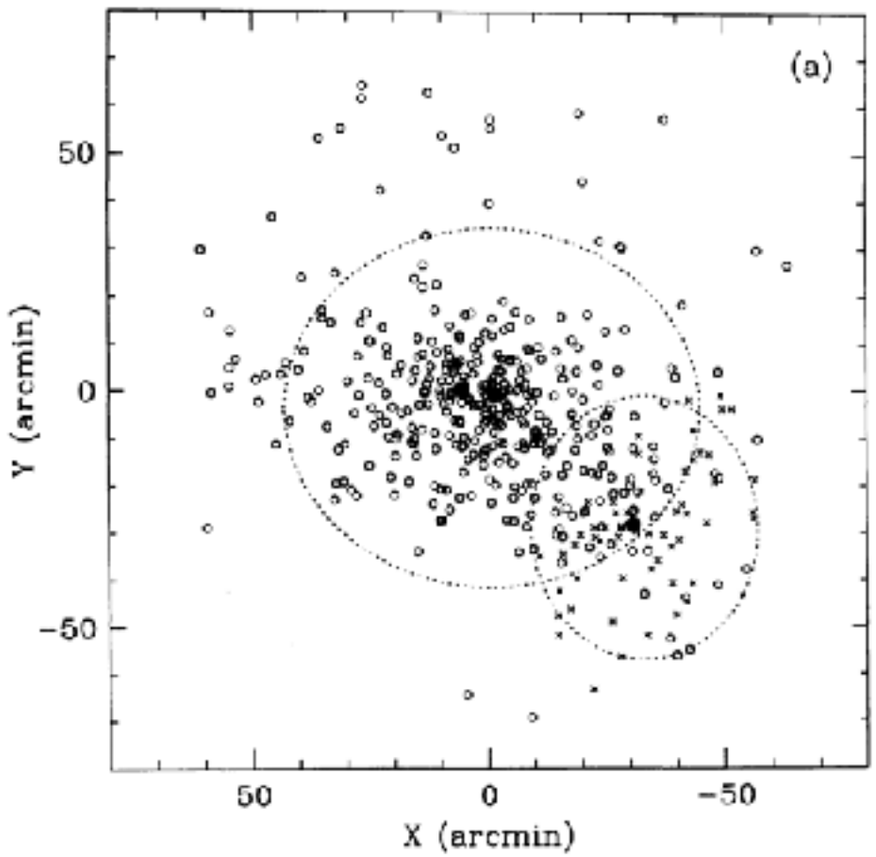
$$V_D^2 = 3 \left\{ \frac{\sum m_i \left(V_i - V_{cm} \right)^2}{M} - \frac{\sum m_i \sigma^2 \left(V_i \right)}{M} \right\}$$

$$V_{cm} = \frac{\sum m_i V_i}{M} \qquad R = \frac{\pi\, M^2 / 2}{1/2 \sum \sum m_i m_j / r_{ij}} \qquad M = \sum m_i = \sum L_i f_i$$



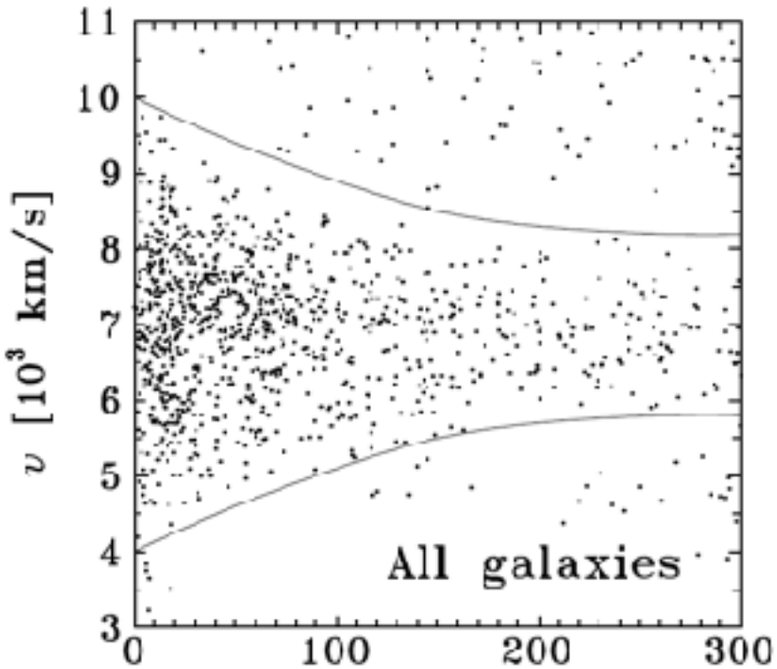
Coma Cluster

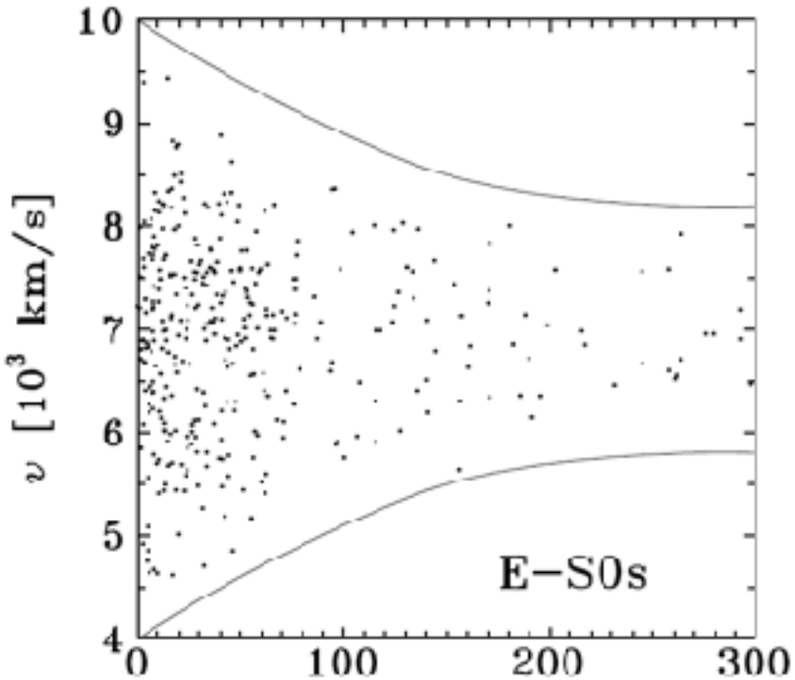
Colless & Dunn 1996

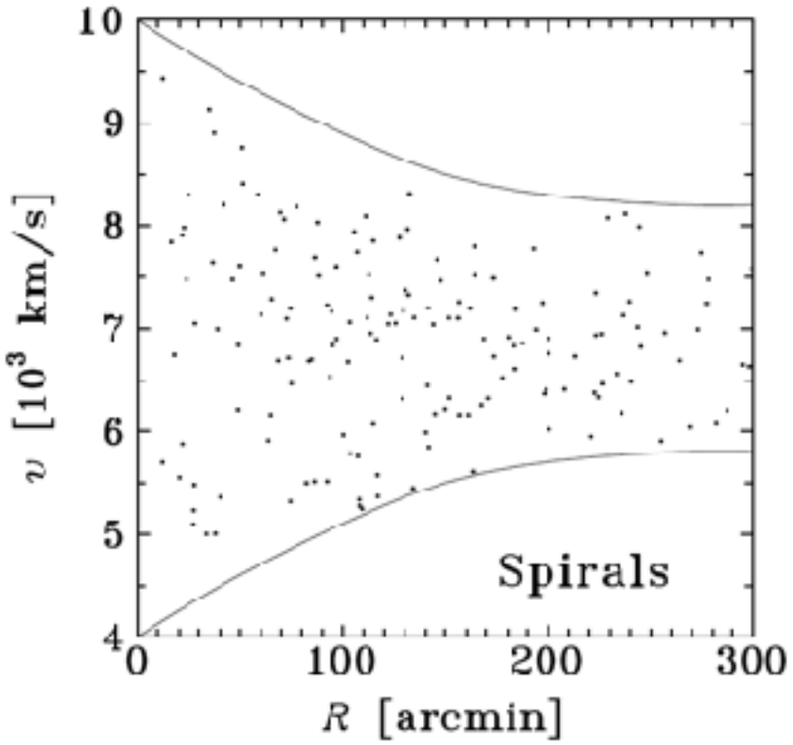


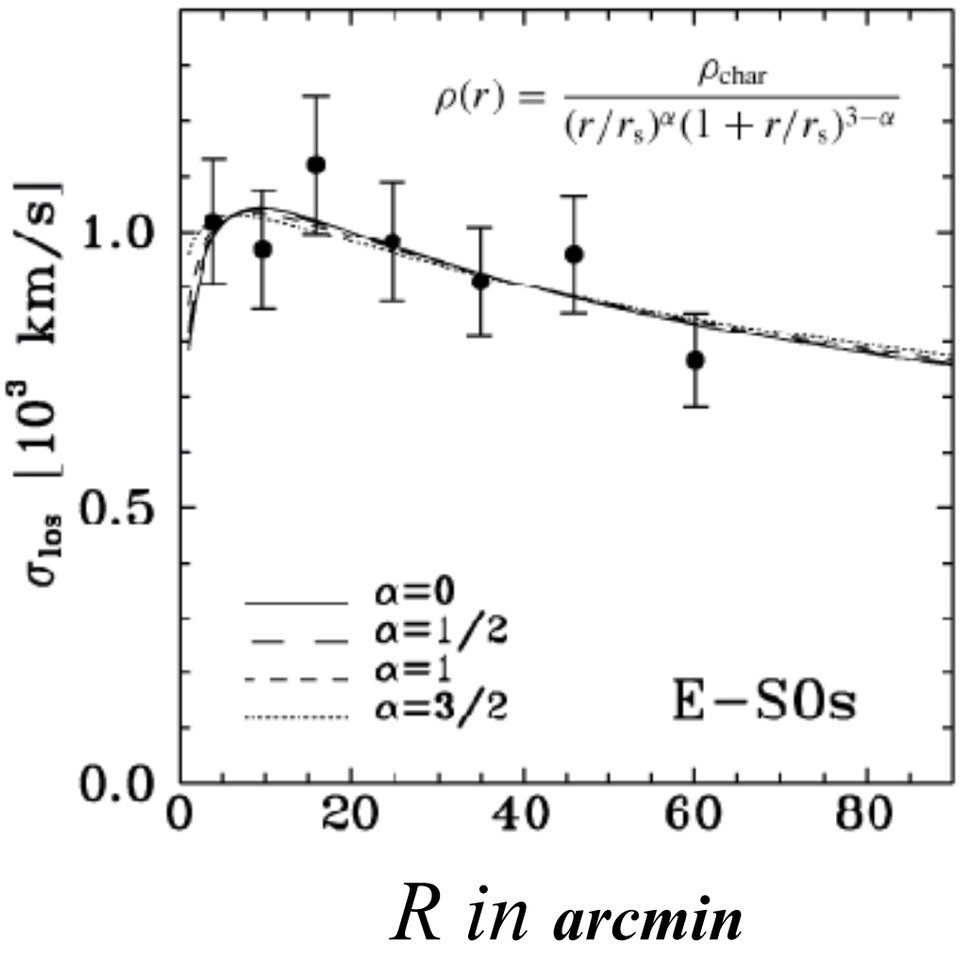
$$Colless\ \&\ Dunn(1996) \quad M_{Coma,vir} = 0.9\,10^{15}\,h^{-1}M_{\odot}$$

$$Carlberg\ et\ al.(1996\text{-}97)\begin{cases} \left\langle M/L \right\rangle_{16\,Clusters,vir} = 289 \pm 5\ h\ M_{\odot}/L_{\odot} \\ \left\langle M/L \right\rangle_{field} = 215 \pm 59\ h\ M_{\odot}/L_{\odot} \\ \Omega_0 = 0.19 \end{cases}$$









$For\ R \prec 2.\,Mpc \quad M_{Cl} = 0.98\, h_{100}^{-1} M_{\odot}$

$DM \approx 85\%$

$\left(M/L\right)_{Blue} = 250\, M_{\odot}/L_{\odot}$

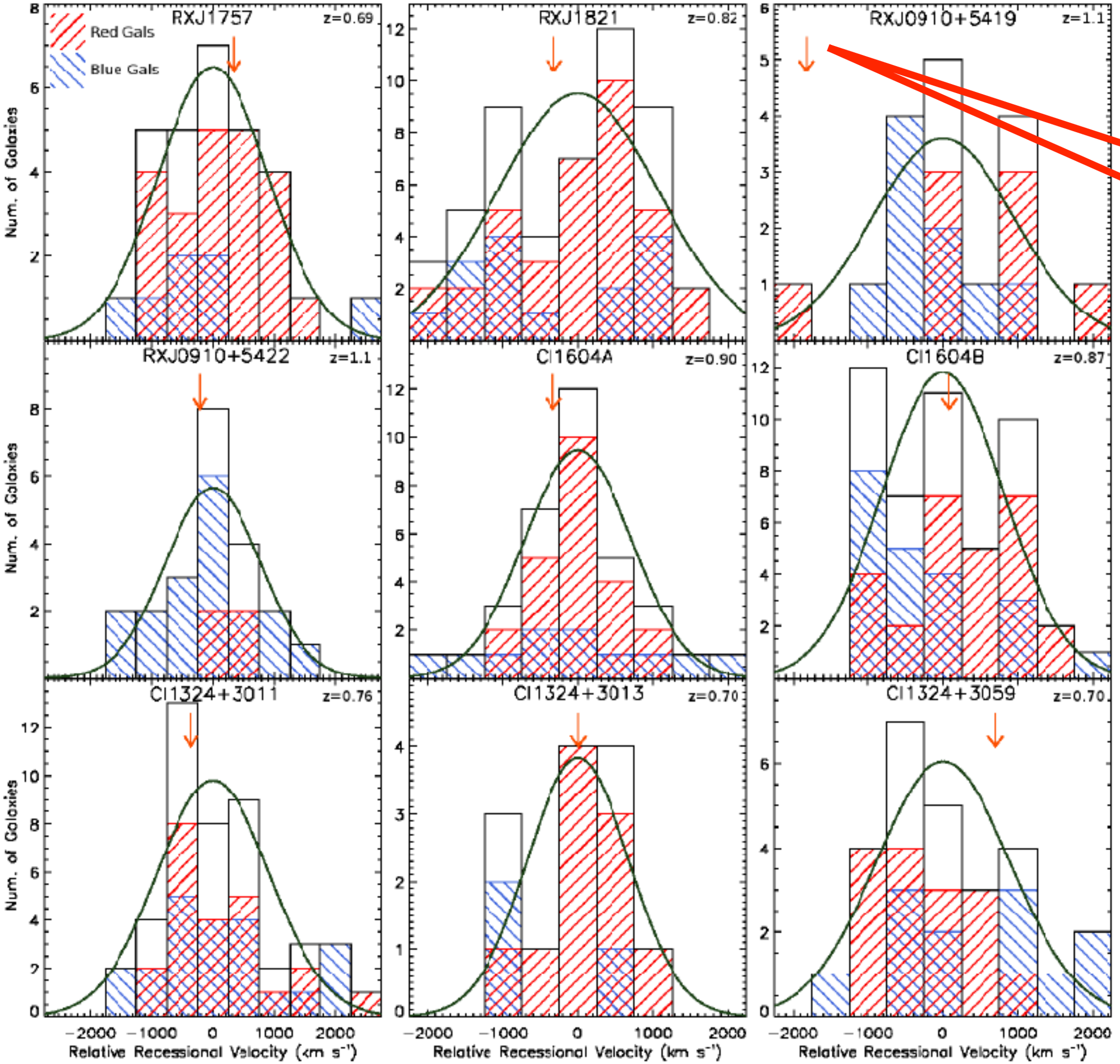
$\Omega_0 = 0.29$ .....*see however derivation*

Geller et al.1999

Method Diaferio 1999

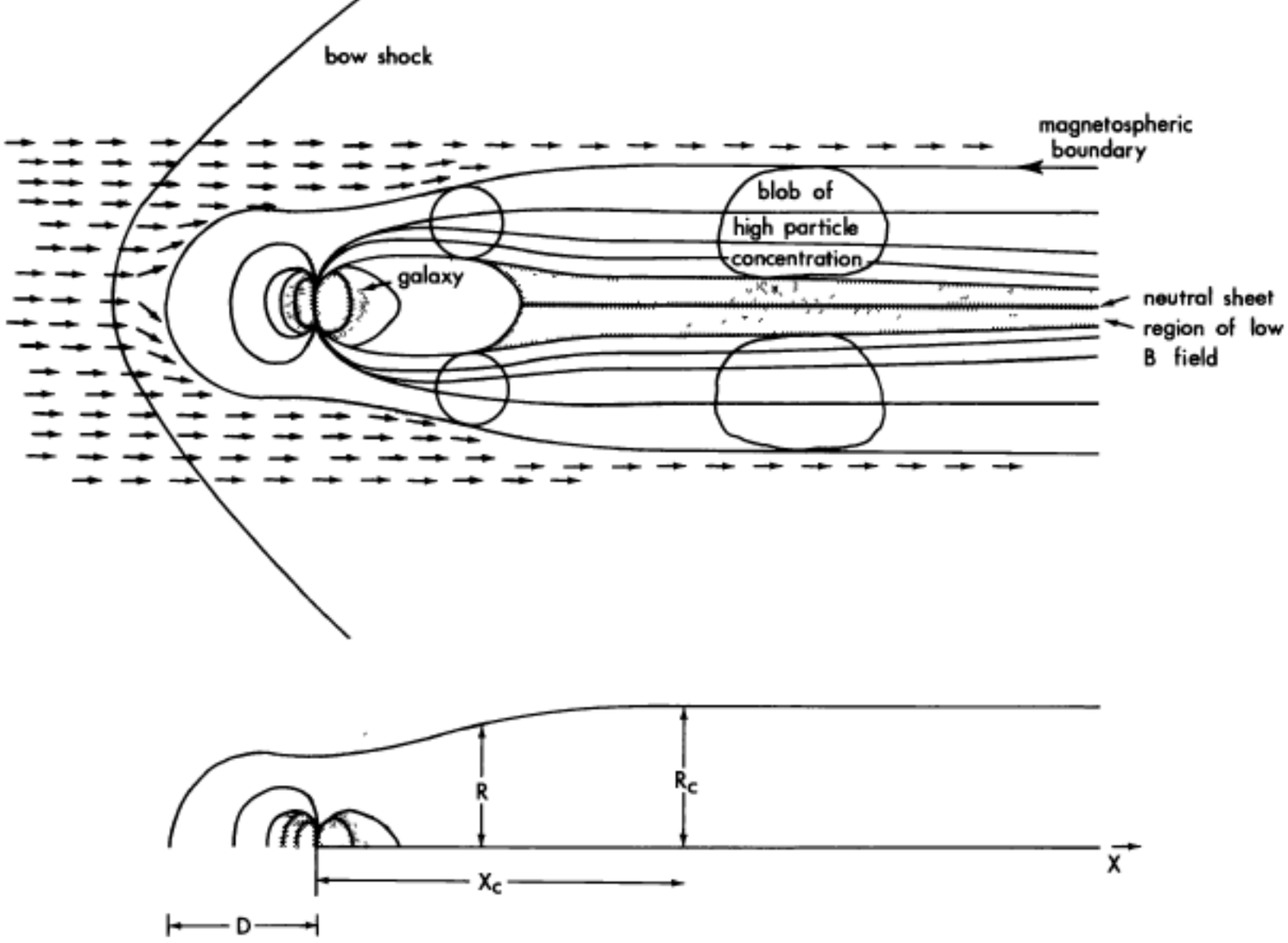
$M \leq 10\, h^{-1} Mpc = 1.65 \pm 0.41\, 10^{15}\, M_{\odot}$

Lokas 2003



Velocity Bright Cluster galaxy

Rumbaugh et al. 2013



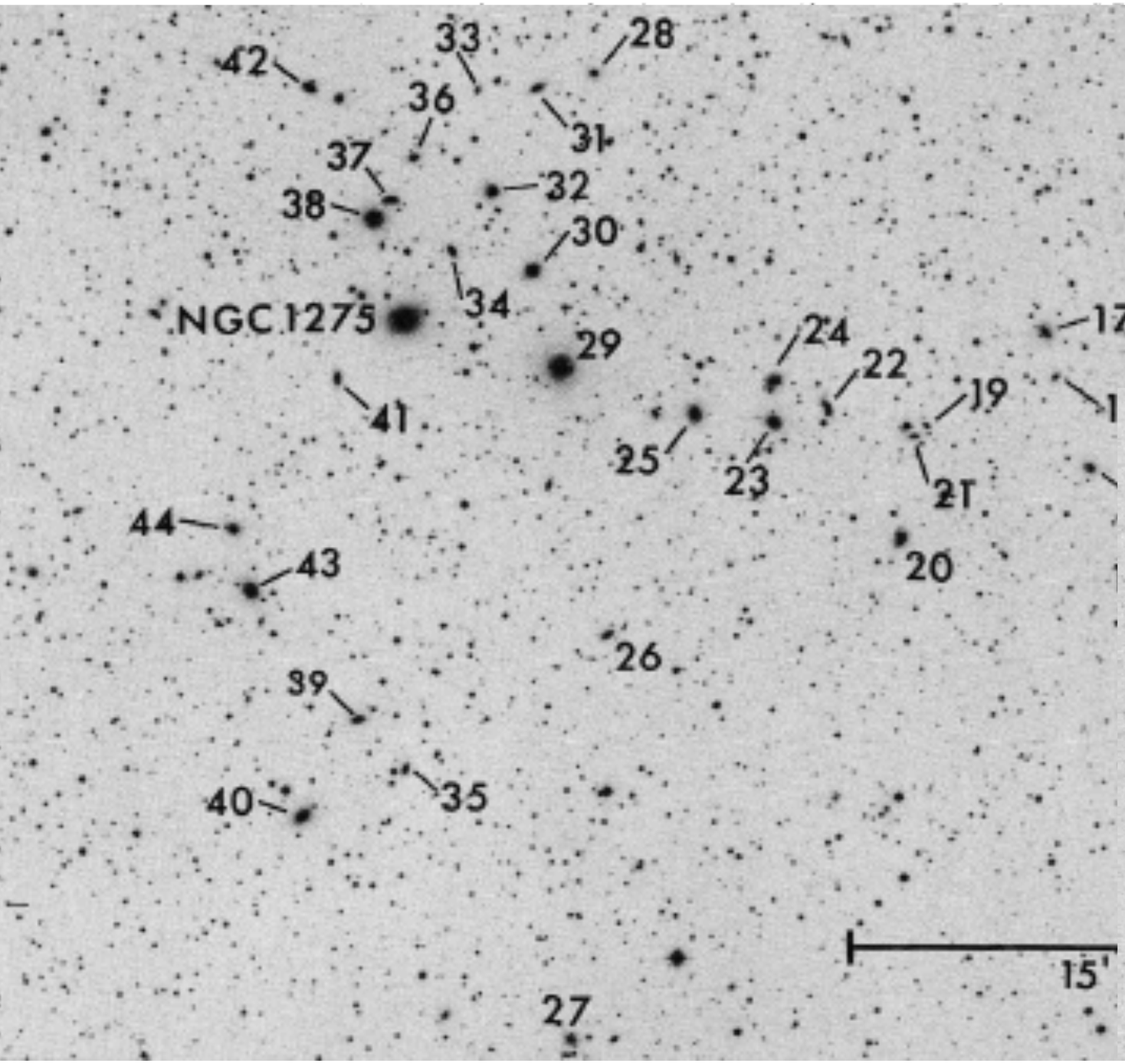
For the temperatures we find we expect the gas to be observable in the X-ray region, and it is important to compare our results with the estimates of ϱ_{ic} and the temperature that can be obtained by interpreting the X-ray flux from rich clusters such as Coma and Perseus (Gursky *et al.*, 1972b) as due to free-free transitions in a hot gas. The temperatures derived by fitting the X-ray spectral data, are typically several times 10^7 K (Gursky *et al.*, 1972a) and the densities about 10^{-27} g cm^{-3}, which are indeed close to our estimates. If the bremsstrahlung origin of the X-rays were confirmed, this could serve as a test of our models and give an extra constraint very useful for fixing the internal conditions of the radio sources and the character of the flow.

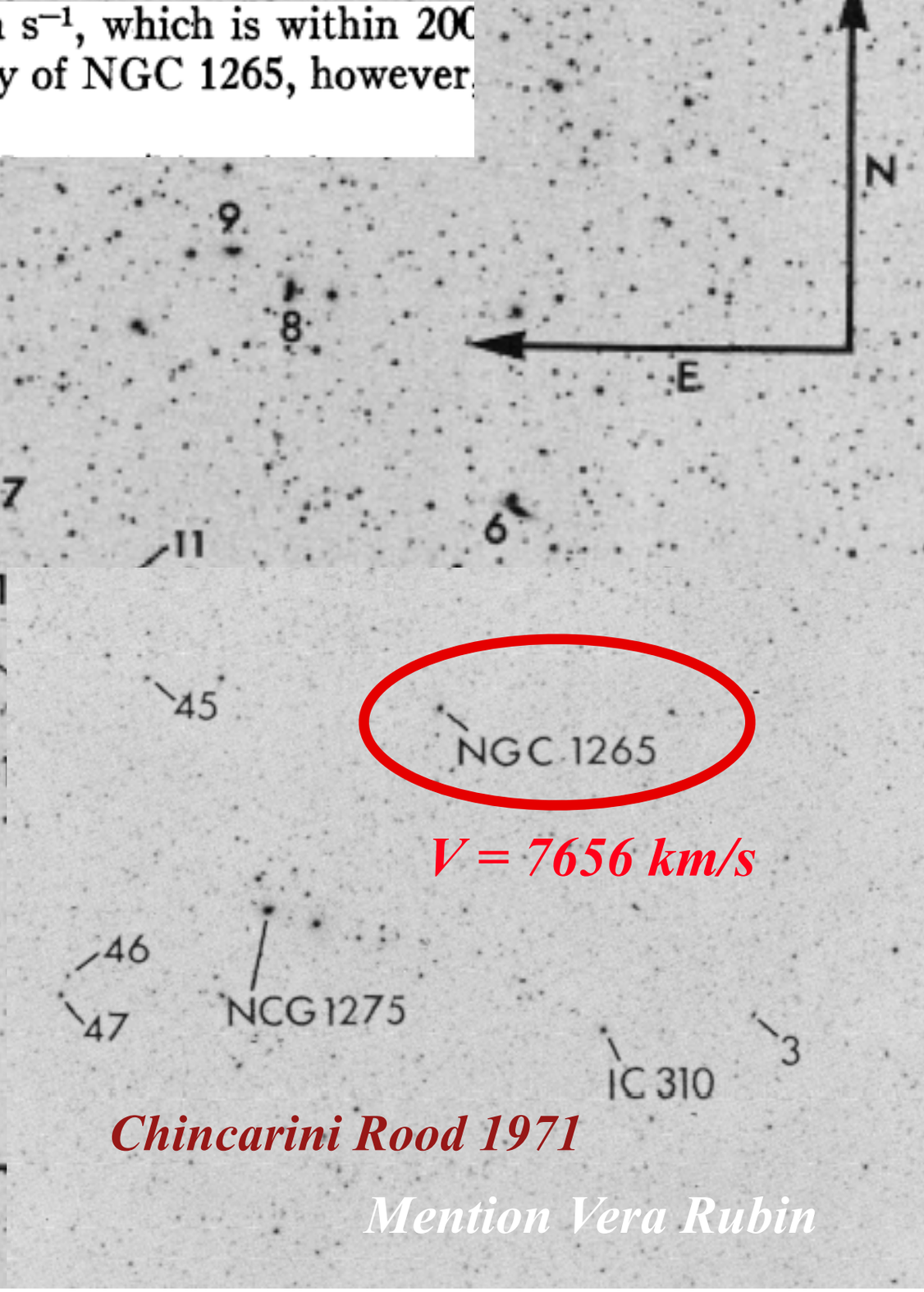
In conclusion, we have shown that the peculiar structures observed in this kind of sources can be attributed to the action of an intracluster gas on a radio galaxy moving through it at supersonic speed. Of the two

We assume that the velocity of the galaxy $v_g = 3000\,\mathrm{km\,s^{-1}}$. This is a relatively high value, but we use it because the velocity of NGC 1265, a tailed source similar to 3 C 129, is of this order with respect to the Perseus Cluster, and because in the case of

Jaffe & Perola 1973

The mean velocity of the cluster is $\langle V_0 \rangle = 5460 \pm 200$ km s^{-1}, which is within 200 km s^{-1} of the velocities of NGC 1275 and IC 310. The velocity of NGC 1265, however, is 2200 km s^{-1} larger than the cluster mean!

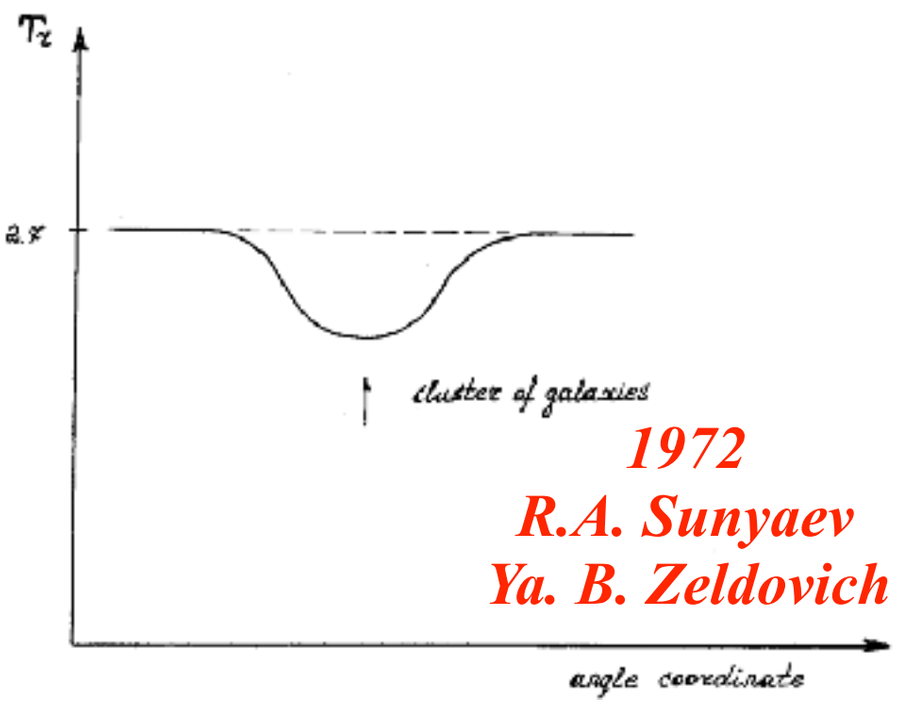




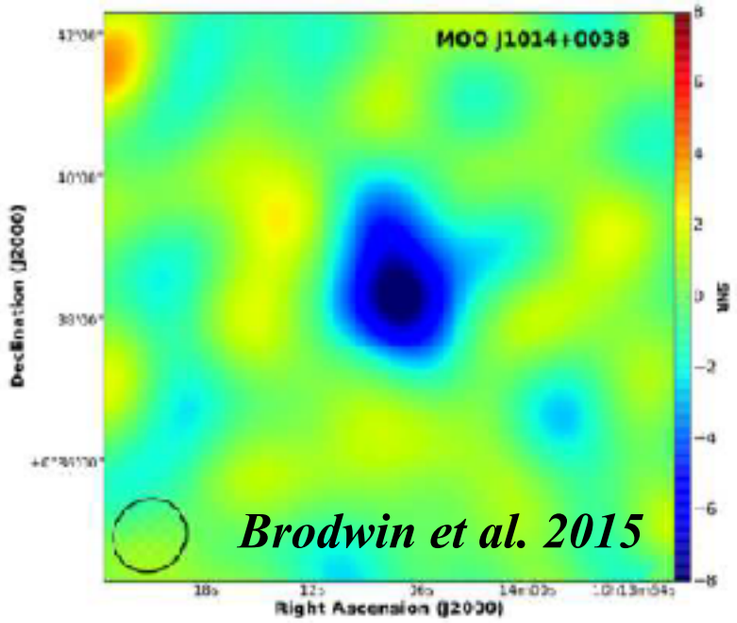
Gursky et al. 1972 Uhuru sat.

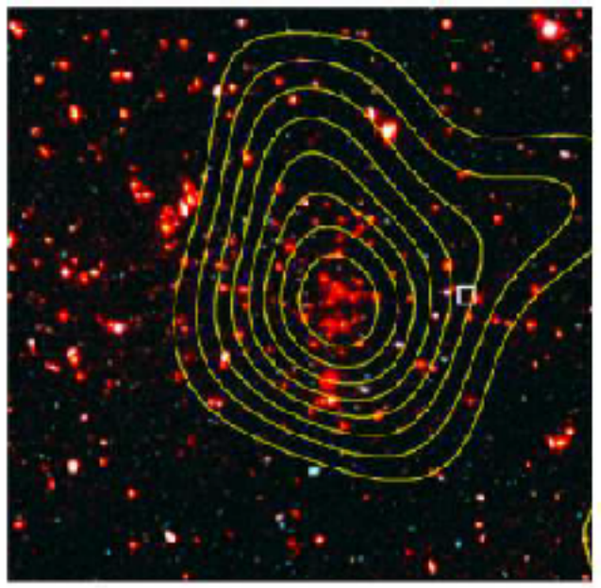
the present data are consistent with all the clusters of richness class 2 being X-ray sources within the range of X-ray luminosities indicated (i.e., 0.5–6 $\times$ 10^{44} ergs s^{-1}).

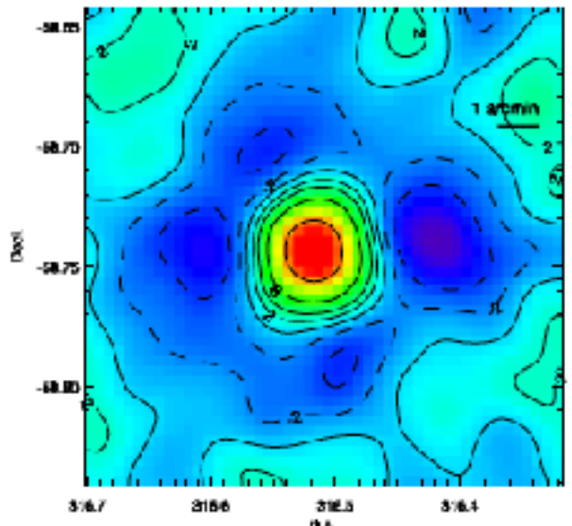
This latter statement forms the principal conclusion of this paper, namely, that there is an extended region of very high X-ray luminosity associated with the richest clusters of galaxies, and that this is a phenomenon common to most such clusters. This conclu-



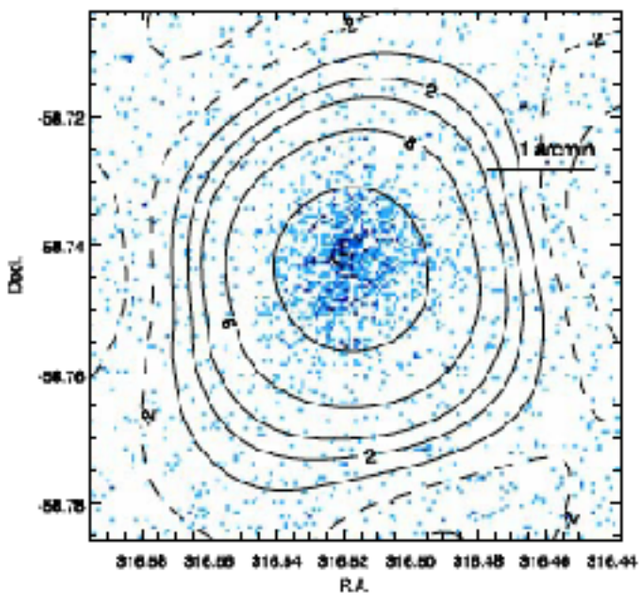
1972
R.A. Sunyaev
Ya. B. Zeldovich







Foley et al. 2011 (z =1.13)



If hot intergalactic gas really exists in clusters of galaxies, there are all the conditions for action of the proposed effect. Thus, for example, the x-ray radiation of the Coma cluster of galaxies is interpreted as the bremsstrahlung radiation of a hot intergalactic gas having $T_e \sim 7 \times 10^7$ °K and the density $N_e \sim 10^{-3}$ cm^{-3}. The linear dimension of the source is estimated to be $l \sim 10^{25}$ cm^{-3}. Multiplying these figures, we find

$$\frac{\Delta T_r}{T_r} = -2y = -2\sigma_T N_e l \frac{kT_e}{m_e c^2} \sim 2 \times 10^{-4},$$

the value accessible for observations. Namely, such effect was recently discovered in Coma by Pariysky.[11]

The deficit of brightness (hole) in the Coma is difficult to understand by any other mechanism! The radiation temperature is 2.7 °K; an arbitrary absorption of radiation is always accompanied by spontaneous emission. If the temperature of the absorber is higher than 2.7 °K, the net result would be an increase of radiation, instead of the observed deficit.

SAN MARCO

The access to the platform San Marco is from the boat via the cage you see.

Every thing on the platform is clean and it is the way to was even if it is not used any more.

Marg
Chester
Patrizia
Caraveo
Monica
Sperandio

Likewise
if
we have a gas

$$\frac{1}{\rho_{gas}}\frac{dP}{dr} = -\frac{\partial\phi}{\partial r} = -\frac{G\,M}{r^2}\,; \quad P = kTMN_e$$

This is equivalent to (*See next slide*)

$$\frac{\partial\, ln\, N_e}{\partial\, ln\, r} + \frac{\partial\, ln\, T_{gas}}{\partial\, ln\, r} = -\frac{G\,M(r)\,\mu\, m_p}{r\,k\,T_{gas}}$$ *Therefore*

$$M(r) = -\frac{r\,k\,T_{gas}}{G\ \ \mu\, m_p}\left\{\frac{\partial\, ln\, N_e}{\partial\, ln\, r} + \frac{\partial\, ln\, T_{gas}}{\partial\, ln\, r}\right\}$$

$$\rho_{gas} = N_e \, \mu \, m_p$$

$$\frac{\partial \ln N_e}{\partial \ln r} + \frac{\partial \ln T_{gas}}{\partial \ln r} = \frac{\partial \ln \left(T_{gas} \; N_e \right)}{\partial \ln r} = - \frac{G \, M(r) \mu \, m_p}{k \, r \, T_{gas}}$$

$$\frac{1}{Ne \, T_{gas}} \partial \left(T_{gas} \; N_e \right) \frac{1}{\frac{1}{r} \partial r} = - \frac{G \, M(r) \mu \, m_p}{k \, r \, T_{gas}}$$

$$\frac{1}{\mu \, m_p \; Ne \, T_{gas}} \partial \left(k \, T_{gas} \; N_e \right) \frac{1}{\partial r} = - \frac{G \, M(r)}{r^2 \; T_{gas}}$$

$$\frac{1}{\rho_{gas}} \frac{\partial P}{\partial r} = - \frac{G \, M(r)}{r^2}$$

$$\Sigma(r) = \Sigma(0)\left(1+\left(\frac{r}{r_c}\right)^2\right)^{-3\beta+1/2}$$

$$\rho(r) = \rho(0)\left(1+\left(\frac{r}{r_c}\right)^2\right)^{-3\beta/2}$$

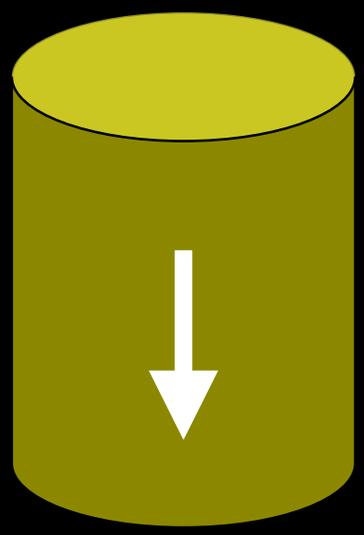
$$M(r) = -\frac{r\,kT}{\mu\, m_p\, G}\left(\frac{d\,ln\rho}{d\,ln\,r}+\frac{d\,\ln T}{d\,ln\,r}\right)$$

$$\varepsilon^{ff} = 1.4\,10^{-27}\,\bar{g}\,T_g^{1/2} n_e \sum_i Z_i^2 n_i$$

I stopped at the Ni

$$\sum_i Z_i^2 n_i n_e = 1.4\,n_e^2 \quad \bar{g} \approx 1/2 \quad \varepsilon^{ff} = 2.4\;10^{-27} T_g^{1/2} n_e^2$$

$$t_{cooling} = \frac{3\,k\,n\,T_g}{1.97\,10^{-27}\,T_g^{1/2} n_p^2} = 6.67\,10^3\,T_g^{1/2}\,n_p^{-1}$$



$$mg = \rho_{gal}\frac{GM_{Cl}(r)}{r^2}$$

$$\left(\frac{dP}{dr}\right)_{gal} = -\rho_{gal}\frac{GM_{Cl}(r)}{r^2}$$

$$\left(\frac{dP}{dr}\right)_{gas} = -\rho_{gas}\frac{GM_{Cl}(r)}{r^2}$$

$$P_{gal} = nkT_{gal} = \frac{\rho_{gal}}{\langle M_{gal}\rangle}\frac{\langle M_{gal}\rangle}{3}\sigma_v^2 \quad \& \quad P_{gas} = nkT_{gas} = \frac{\rho_{gas}}{\mu m_p}kT_{gas}$$

$$-\frac{GM_{Cl}(r)}{r^2} = \frac{1}{\rho_{gal}}\left(\frac{dP}{dr}\right)_{gal} = \frac{1}{\rho_{gal}}\frac{1}{3}\left(\frac{d\rho}{dr}\right)_{gal} \quad \sigma_v^2 = -\frac{GM_{Cl}(r)}{r^2} = \frac{1}{\rho_{gas}}\left(\frac{d\rho}{dr}\right)_{gas}\frac{kT_{gas}}{m_p\mu}$$

$$\frac{1}{\rho}\left(\frac{d\rho}{dr}\right) = \frac{d\,ln\rho}{dr} \Rightarrow (d\,ln\rho)_{gal}\frac{1}{3}\sigma_v^2 = (d\,ln\rho)_{gas}\frac{kT_{gas}}{m_p\mu}$$

$$ln\left[\frac{\rho_{gal}(r)}{\rho_{gal}(0)}\right] = \frac{kT_{gas}}{m_p\mu}\frac{3}{\sigma_v^2}ln\left[\frac{\rho_{gas}(r)}{\rho_{gas}(0)}\right]$$

see Cavaliere Fusco Firmiano 1978

$$ln\left[\frac{\rho_{gal}(r)}{\rho_{gal}(0)}\right]=\frac{k\,T_{gas}}{m_p\mu}\frac{3}{\sigma_v^2}ln\left[\frac{\rho_{gas}(r)}{\rho_{gas}(0)}\right]$$

$$Define \quad \beta=\frac{m_p\mu\sigma_v^2}{3k\,T_{gas}}$$

$$\frac{\rho_{gas}(r)}{\rho_{gas}(0)}=\left(\frac{\rho_{gal}(r)}{\rho_{gal}(0)}\right)^{\beta} \qquad \frac{\rho_{King(1966)-gal}(r)}{\rho_{gal}(0)}=\left(1+\left(\frac{r}{r_c}\right)^2\right)^{-3/2}$$

$$\frac{\rho_{gas}(r)}{\rho_{gas}(0)}=\left(1+\left(\frac{r}{r_c}\right)^2\right)^{-3/2\beta}$$

$$\Sigma(r) = \Sigma(0)\left(1+\left(\frac{r}{r_c}\right)^2\right)^{-3\beta+1/2}$$

$$\rho(r) = \rho(0)\left(1+\left(\frac{r}{r_c}\right)^2\right)^{-3\beta/2}$$

$$M(r) = -\frac{r\,kT}{\mu\, m_p\, G}\left(\frac{d\,ln\rho}{d\,ln\,r}+\frac{d\,\ln T}{d\,ln\,r}\right)$$

$$\varepsilon^{ff} = 1.4\,10^{-27}\,\bar{g}\,T_g^{1/2} n_e \sum_i Z_i^2 n_i$$

I stopped at the Ni

$$\sum_i Z_i^2 n_i n_e = 1.4\,n_e^2 \quad \bar{g} \approx 1/2 \quad \varepsilon^{ff} = 2.4\;10^{-27} T_g^{1/2} n_e^2$$

$$t_{cooling} = \frac{3\,k\,n\,T_g}{1.97\,10^{-27}\,T_g^{1/2} n_p^2} = 6.67\,10^3\,T_g^{1/2}\,n_p^{-1}$$

Isothermal and NFW

$$dP = -\rho\, d\phi = \rho(r)\, g(r)\, dr \;\&\; g(r) = \frac{G}{r^2}\int_0^r 4\pi r^2 \rho(r)\, dr$$

$$dP + \rho(r)\, dr\, \frac{G}{r^2}\int_0^r 4\pi r^2 \rho(r)\, dr = 0 \qquad G\int_0^r 4\pi r^2 \rho(r)\, dr + \frac{dP}{dr}\frac{r^2}{\rho(r)}$$

$$G\, 4\pi r^2 \rho(r) + \frac{d}{dr}\left(\frac{dP}{dr}\frac{r^2}{\rho(r)}\right) = 0 \qquad 4\pi G r^2 \rho(r) = -\frac{d}{dr}\left(\frac{d\left(\frac{\rho kT}{\mu}\right)}{dr}\frac{r^2}{\rho(r)}\right)$$

$$\frac{d}{dr}\left(r^2\frac{d\,ln\rho}{dr}\right) + \frac{4\pi G\mu}{kT} r^2 \rho(r) \qquad \rho = \rho_0\, e^{\psi} \quad r = r_0\, \xi \quad \frac{4\pi G\mu}{kT} r_0^2 \rho_0 = 1$$

$$\frac{d}{d\xi}\left(\xi^2\frac{d\psi}{d\xi}\right) + \xi^2 e^{\psi} = 0$$

$$\frac{d^2\psi}{d\xi^2} + \frac{2}{\xi}\frac{d\psi}{d\xi} = e^{\psi}$$

The Lane - Emden equation has to be integrated numerically, however Ivan King (1962) give an excellent approximation and physical reasoning for a cut off distance. Liu (1996) propose a formula that may be convenient to use since it is rather accurate. Here a = 0.551 and b = 3.84 10^{-4}.

$$\frac{\left(1+\frac{x^2}{3^{1/a}\,12\,e}\right)^a}{\left(1+\frac{x^2}{6}\right)^{1+a}\left(1+\left(2^{-a}-1\right)\left(\frac{b\,x^2}{1+b\,x^2}\right)\right)}\,Exp\left[\frac{a\left(\frac{x^2}{6}\right)}{\left(1+\frac{x^2}{6}\right)}\right]$$

Selermitsos et al. 1977

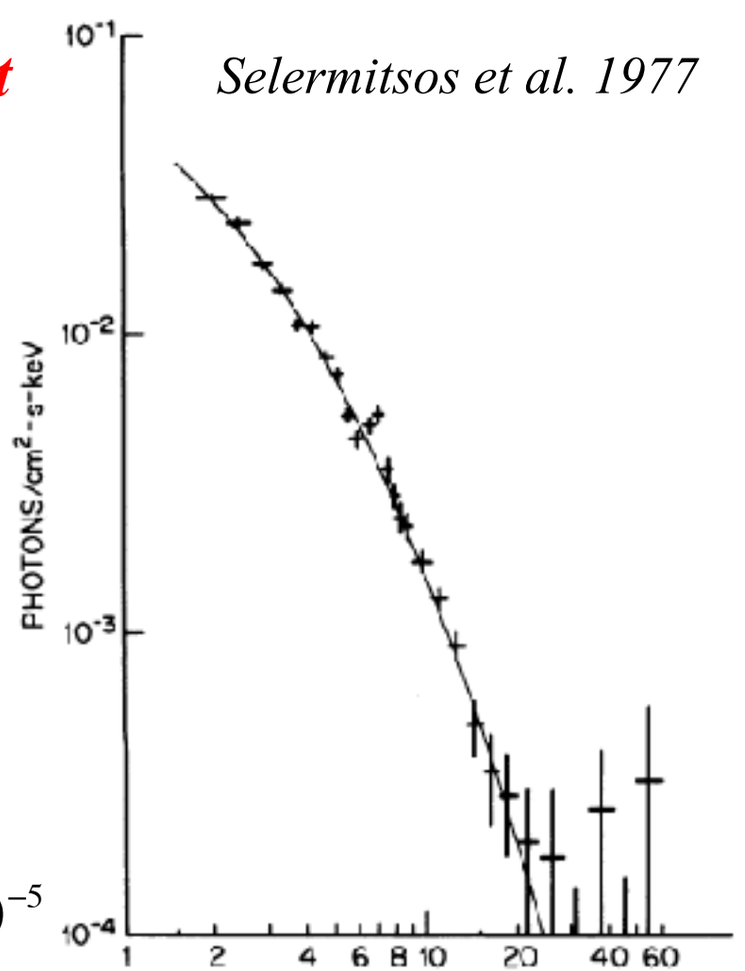
TABLE 1

SUMMARY OF RESULTS

Parameter	Virgo	Perseus	Coma
	Thermal§		
kT (keV)	2.85 ± 0.25	6.95 ± 0.35	9.3 ± 1.3
$N_H (\times 10^{21})$	≤ 3.2	≤ 1.8	$3.3 \pm 2 \times 10^{21}$
2–6 keV intensity* (ergs cm^{-2} s^{-1})	$3.53 \pm 0.05 \times 10^{-10}$	$6.62 \pm 0.05 \times 10^{-10}$	$2.55 \pm 0.04 \times 10^{-10}$
Line strength* (photons cm^{-2} s^{-1})	0.0021 ± 0.0006	0.0044 ± 0.0008	0.0012 ± 0.0007
Equivalent width (eV)	850 ± 250	490 ± 88	280 ± 170
Fe abundance relative to cosmic†	$0.40 \pm$ .12	0.45 ± 0.08	0.38 ± 0.23
χ^2‡	37.5	20.5	23.8

Inverse Compton out

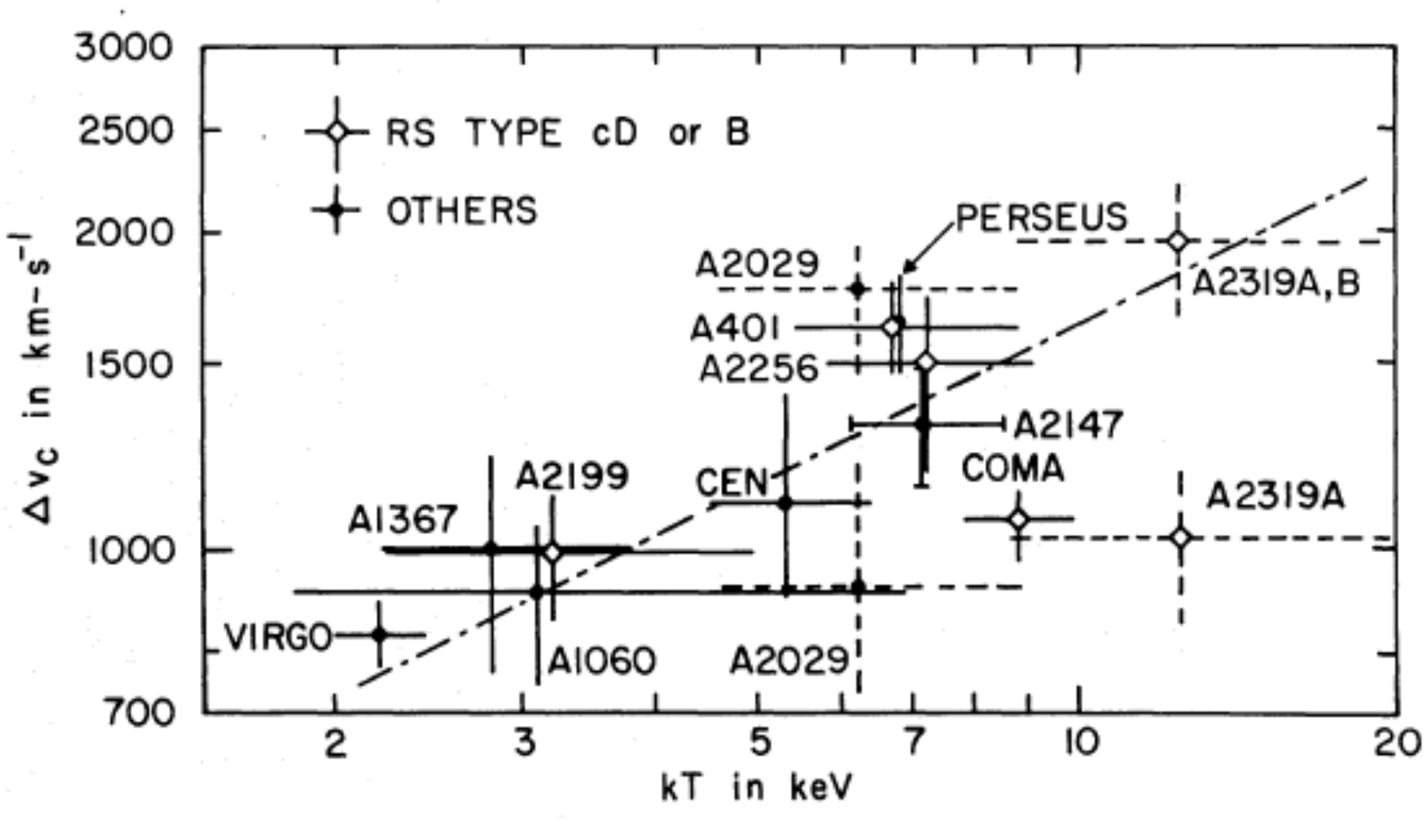
Selermitsos et al. 1977

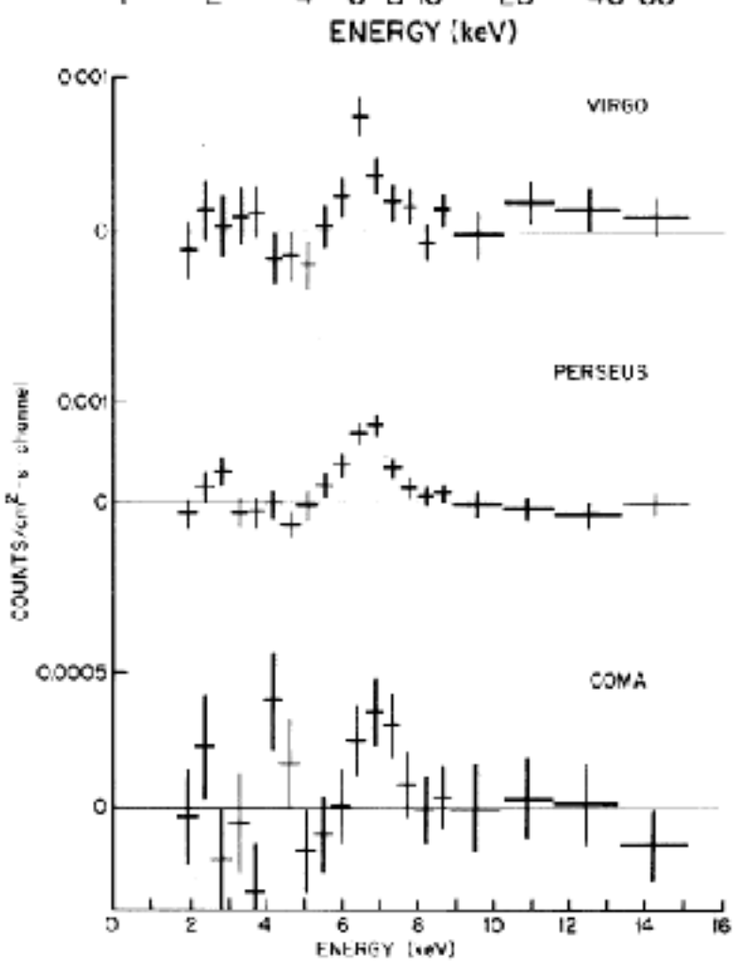


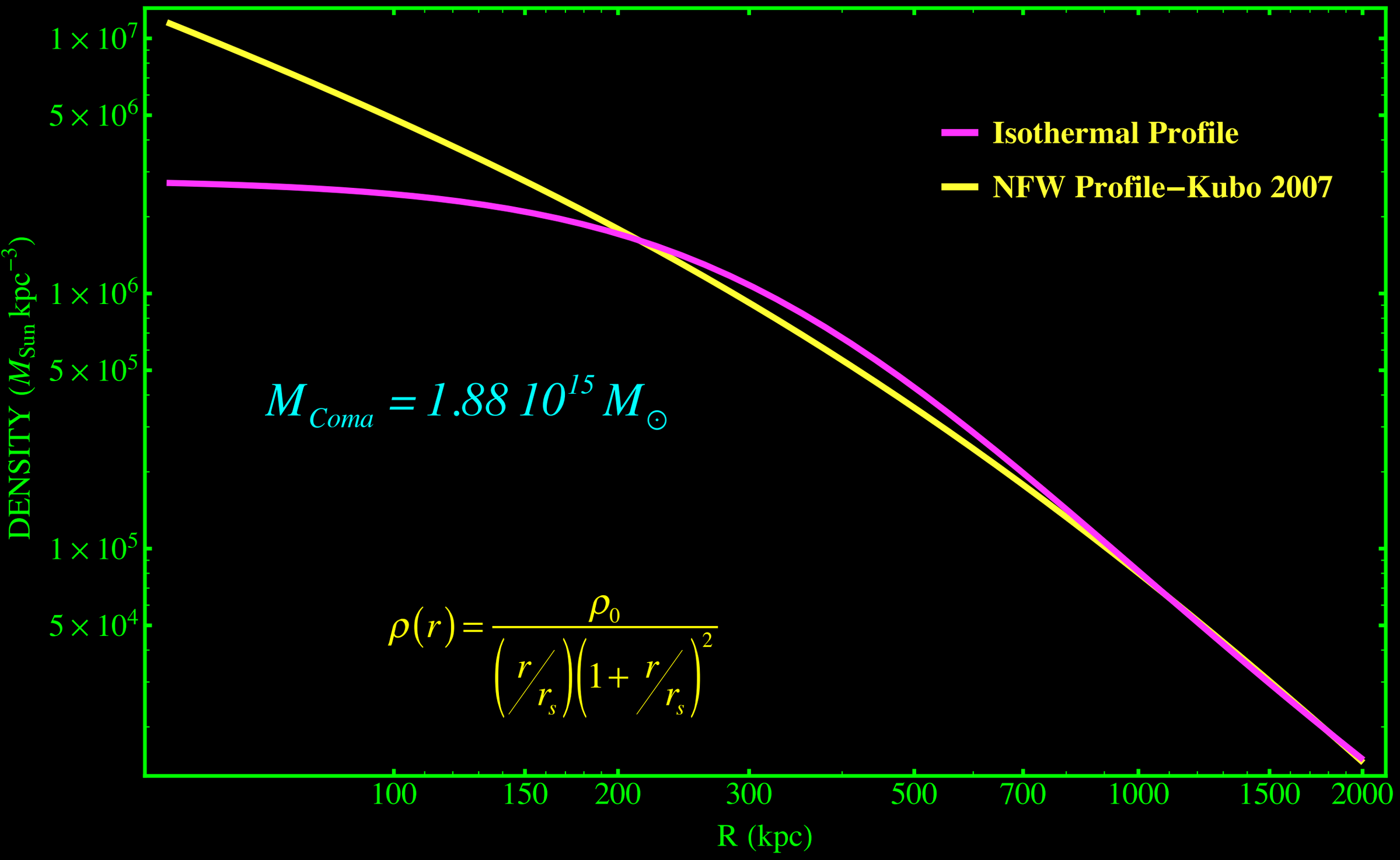
Mushotzsky et al. 1978

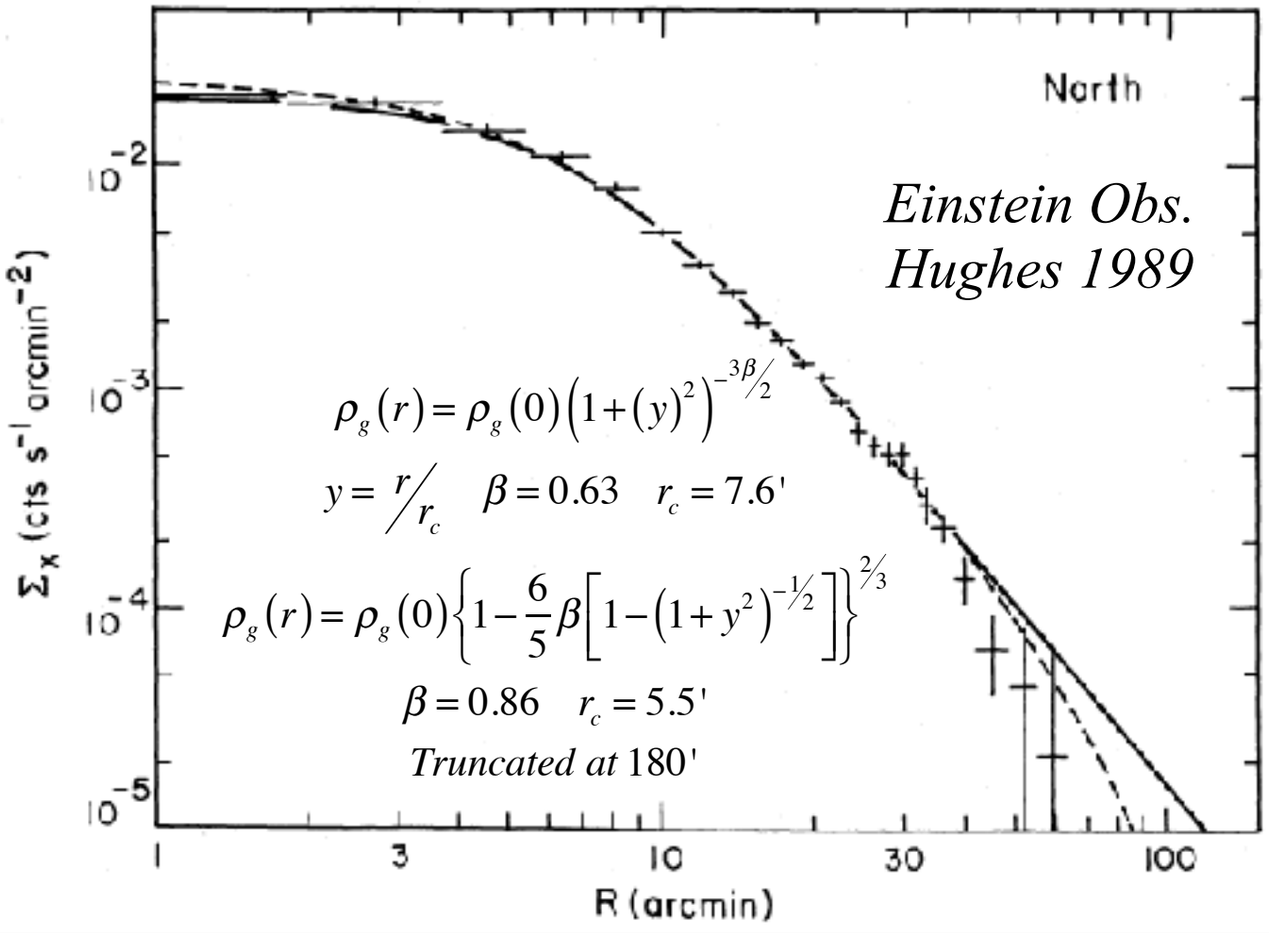
$$\frac{Fe}{H} \sim (1.4 \pm 0.1) \times 10^{-5}$$

$$0.4\,10^{7.6-12} = 1.6\,10^{-5}$$






Isothermal Profile
NFW Profile−Kubo 2007
$M_{Coma} = 1.88\ 10^{15}\ M_{\odot}$
$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2}$
DENSITY (M_{Sun} kpc^{-3})
1×10^7
5×10^6
1×10^6
5×10^5
1×10^5
5×10^4
100
150
200
300
500
700
1000
1500
2000
R (kpc)



Mass distribution follows
the distribution of optical light

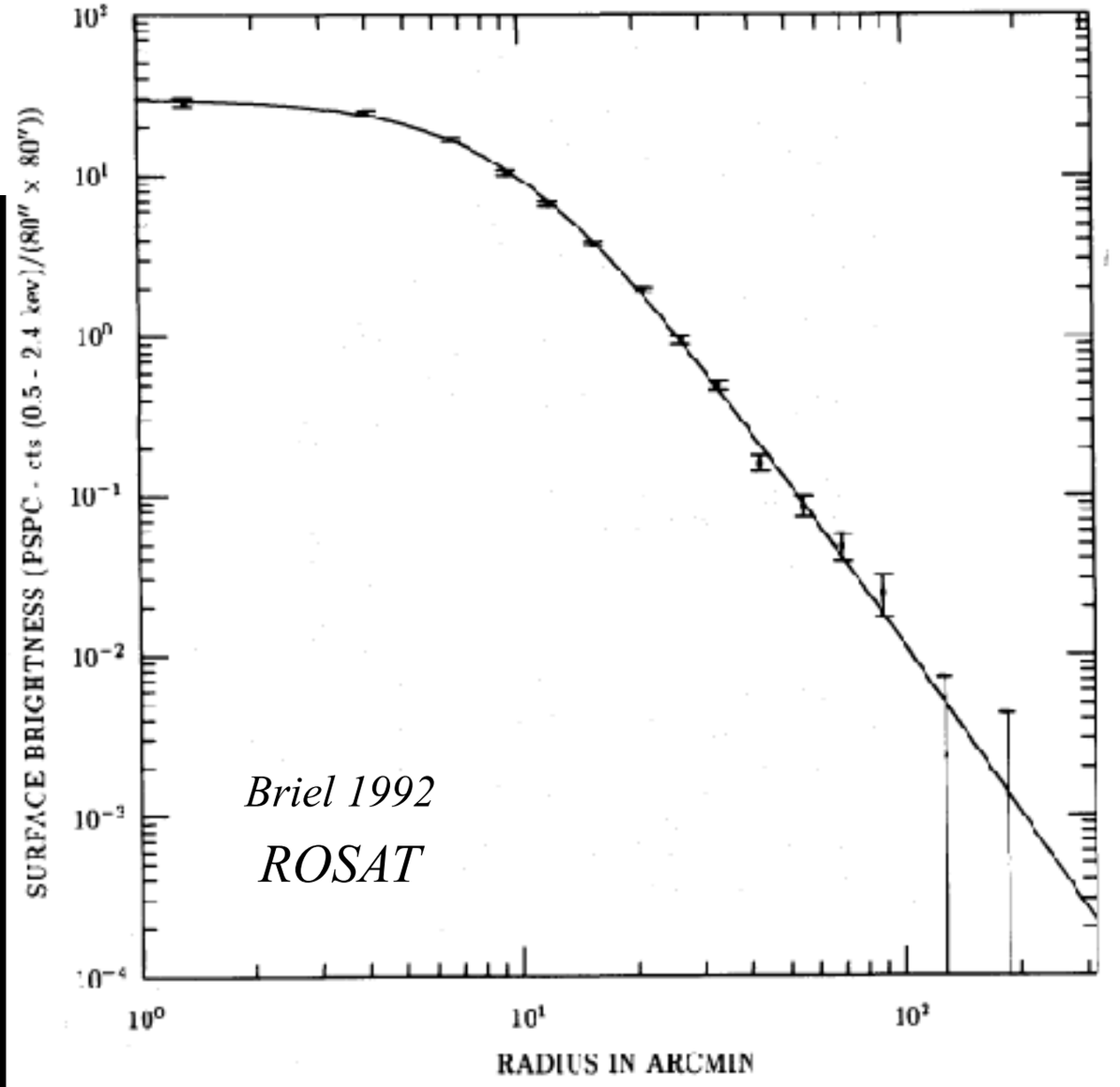
$R<2.5\,h_{100}^{-1}\ M_{pc}\ M=0.93\pm0.12\,10^{15}\,h_{100}^{-1}M_{\odot}$

$M/L=330\pm50\,h_{100}$

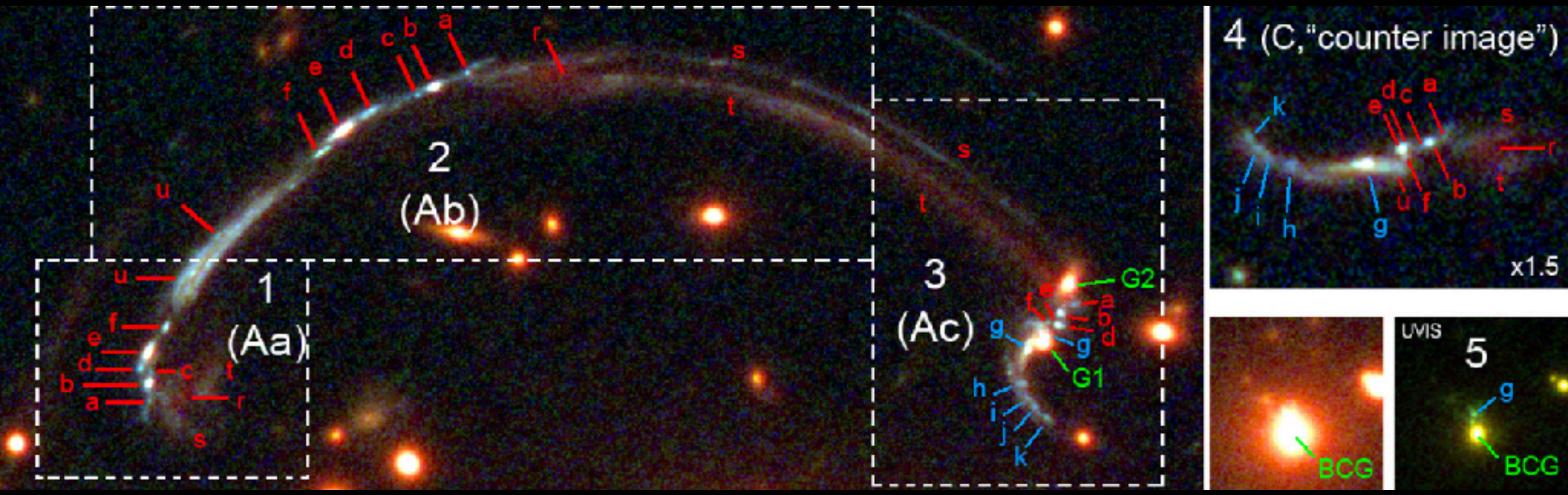
Coma Cluster

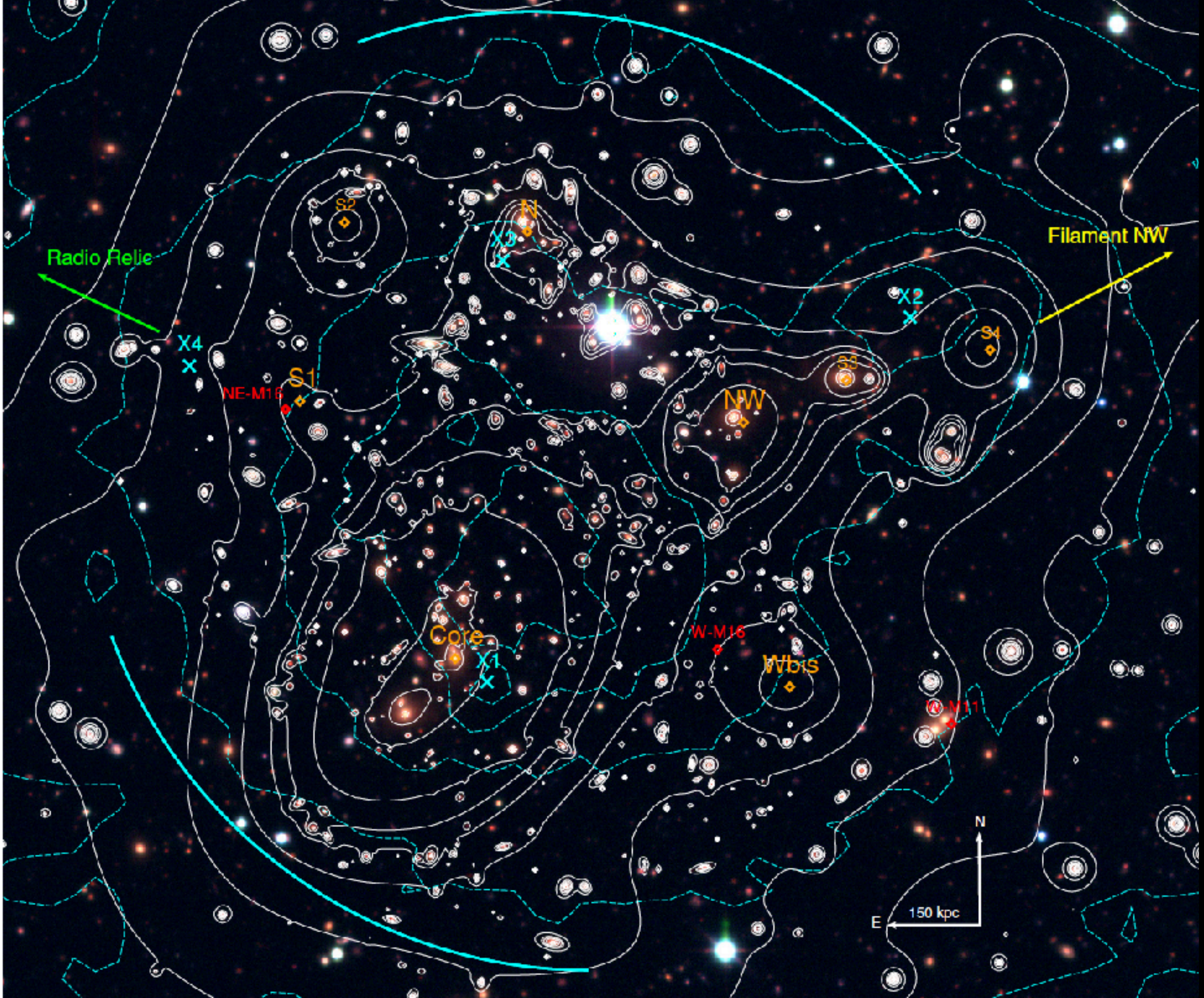
$R<2.5\,h_{100}^{-1}\ M_{pc}\ M=0.9\pm0.310^{15}\,h_{100}^{-1}M_{\odot}$

$Gas=0.92\pm0.27\,h_{100}^{-5/2}$

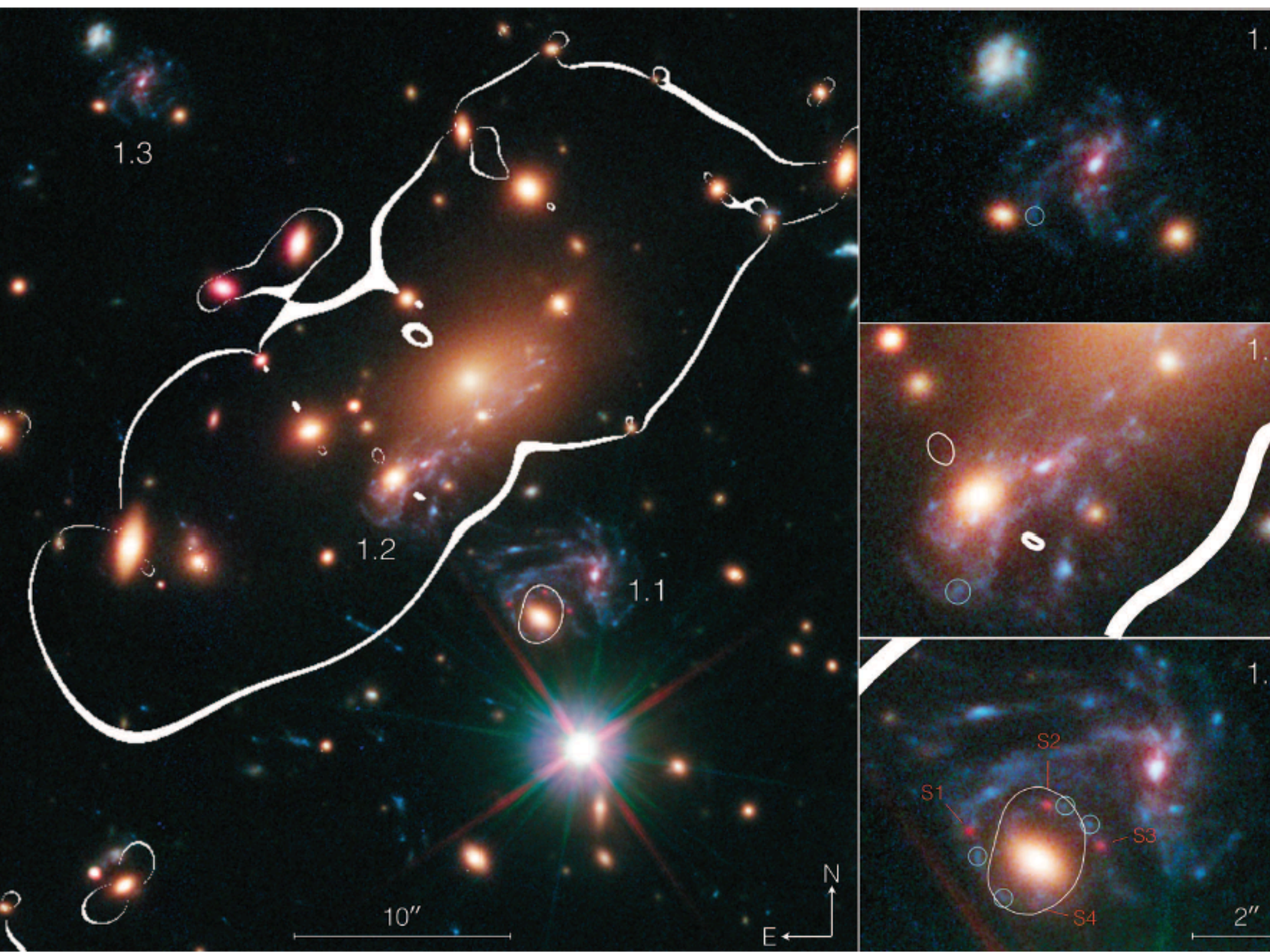


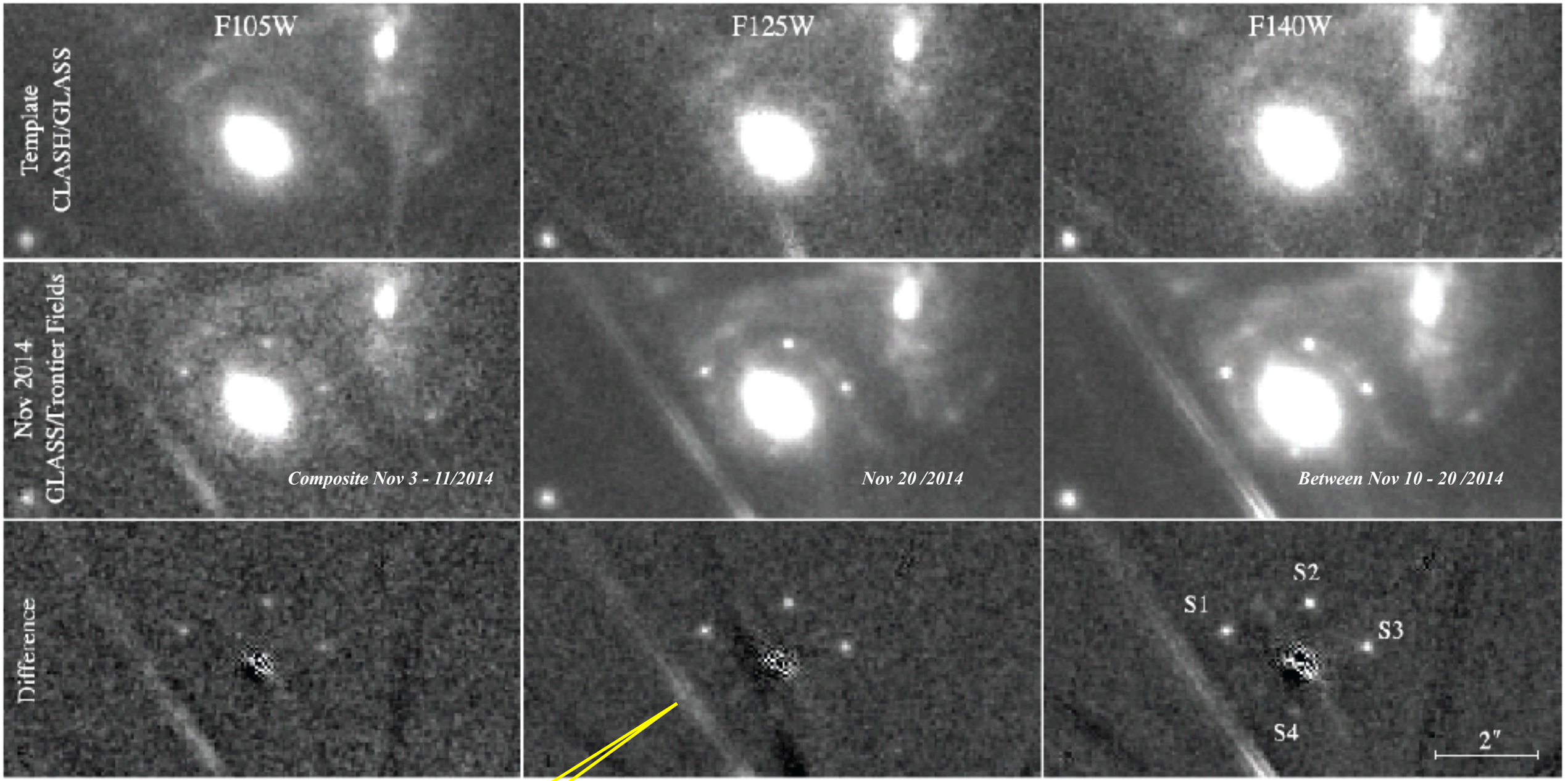
Strong & Weak Lensing The state of the art


2
(Ab)
1
(Aa)
3
(Ac)
4 (C,"counter image")
x1.5
UVIS
5
BCG
BCG
G1
G2



JAUZAC et al. 2016 - Abell 2744


1.3
1.2
1.1
10″
N
E
S1
S2
S3
S4
2″

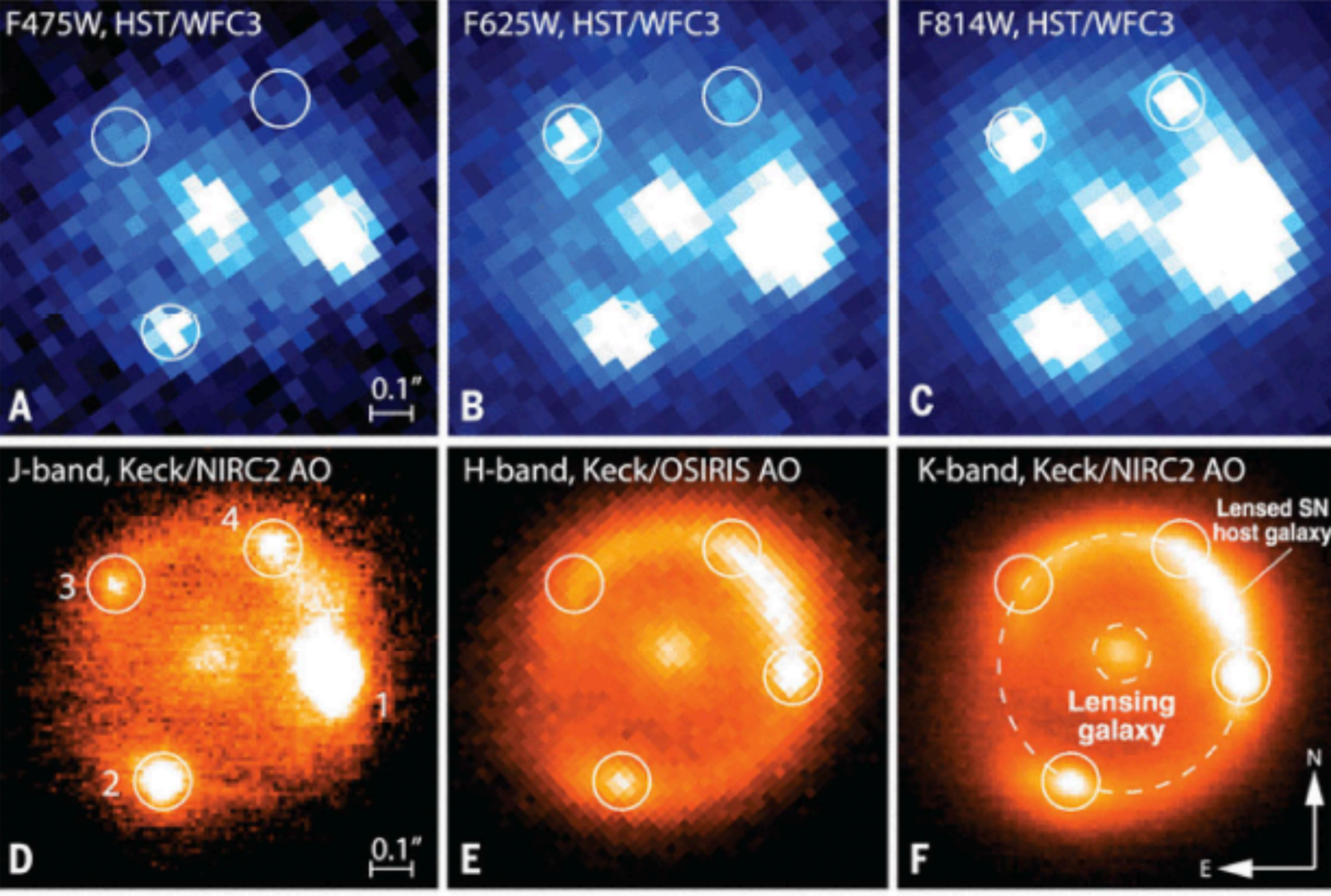


Kelly et al. 2015

Diffraction Spikes

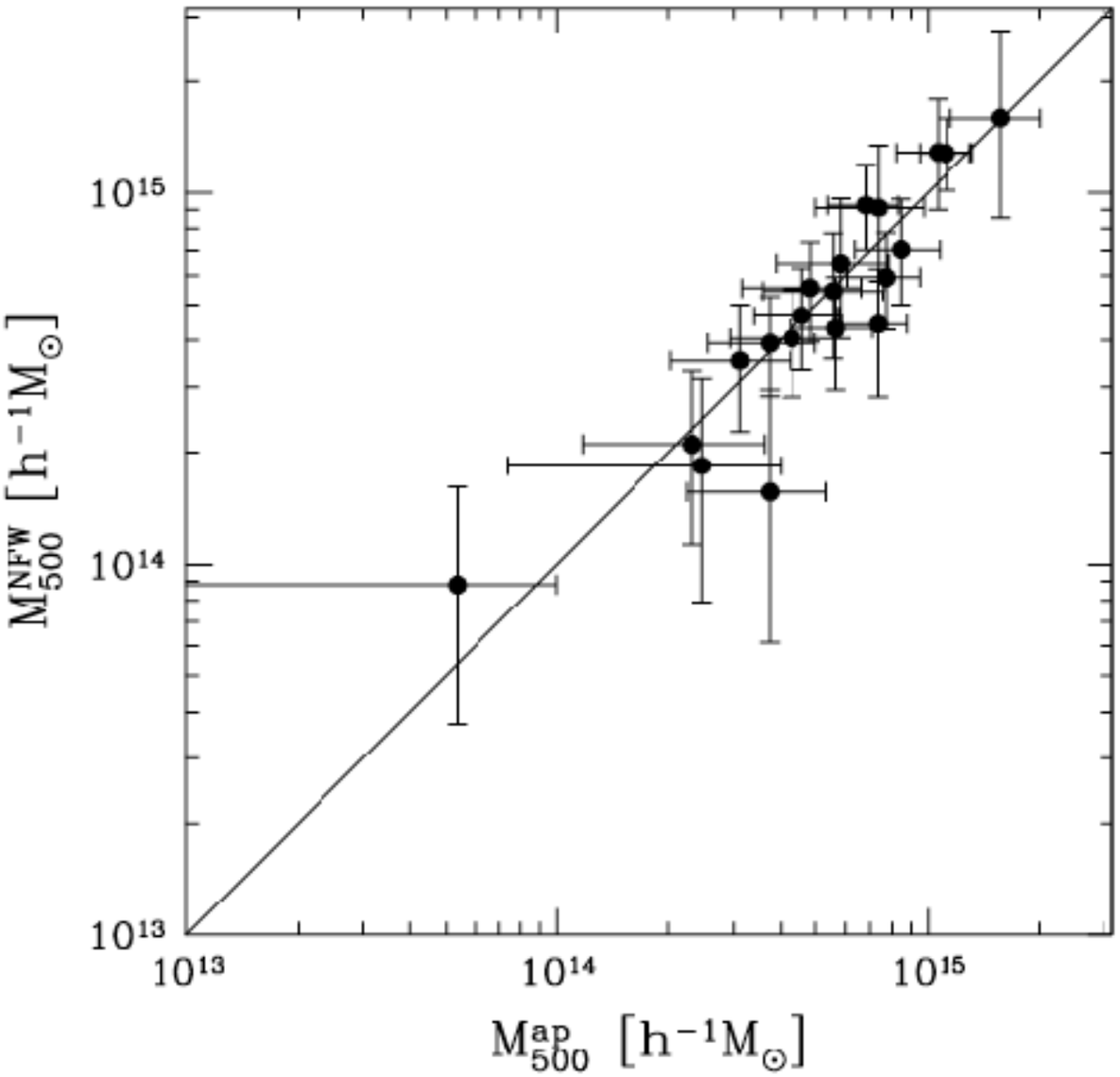
The last row is the subtraction between the second and the first row.

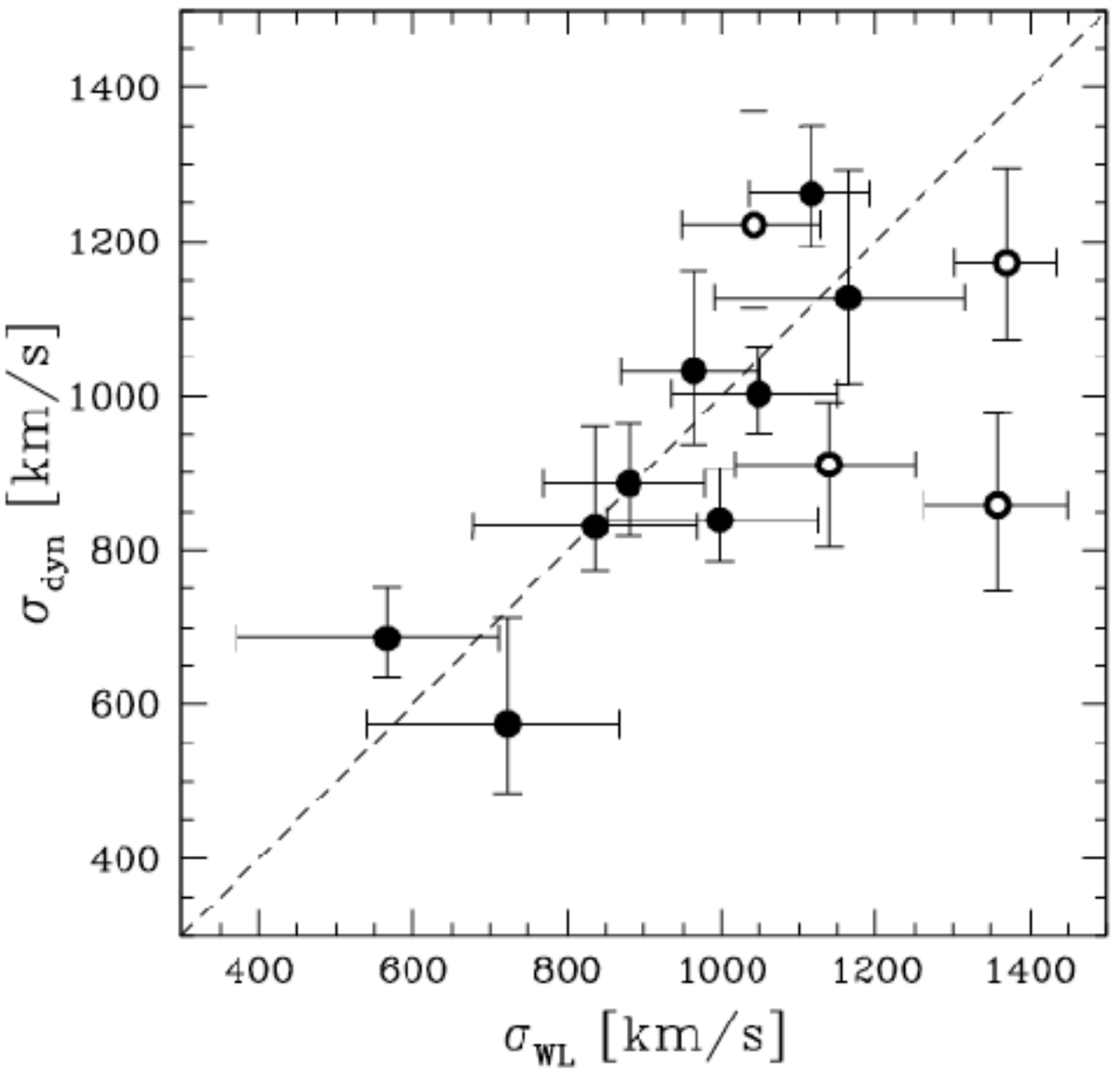
Cluster - Elliptical z = 0.54 // Spiral SN z= 1.49



SN (iPTF16ge) z=0.409

Goobar et al. 2017 Science 356, 291





Hoekstra et al. (2007) derive WL masses that are essentially model independent and find that they agree well with measurements of the velocity dispersion of cluster galaxies and with the results of X ray studies.

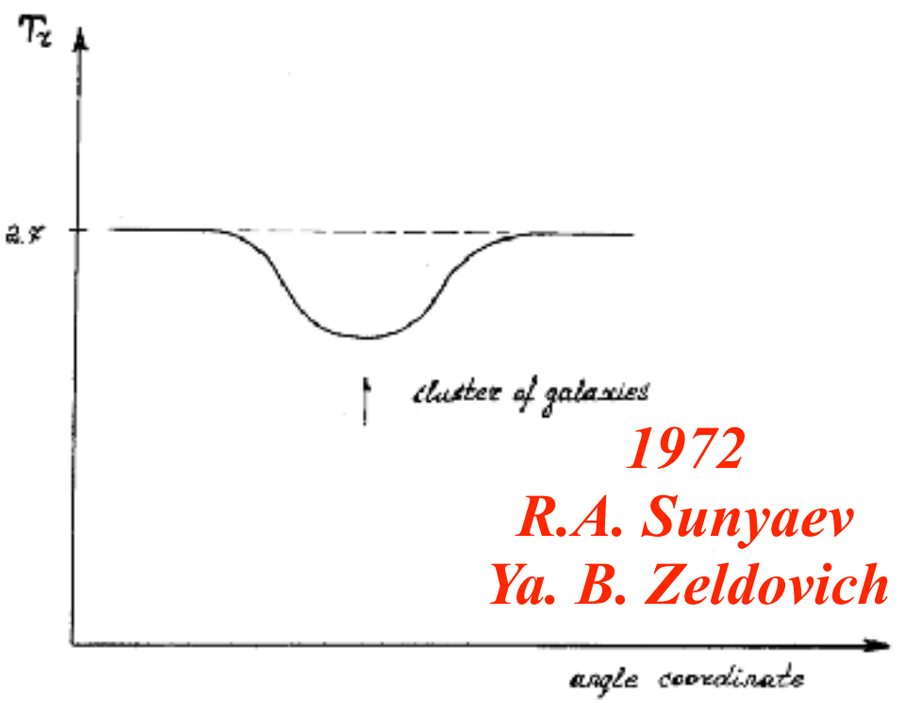
Conclusions

- *various mass estimates give similar results so that the estimates are very robust.*
- *The dynamical mass is much larger than the visible mass.*

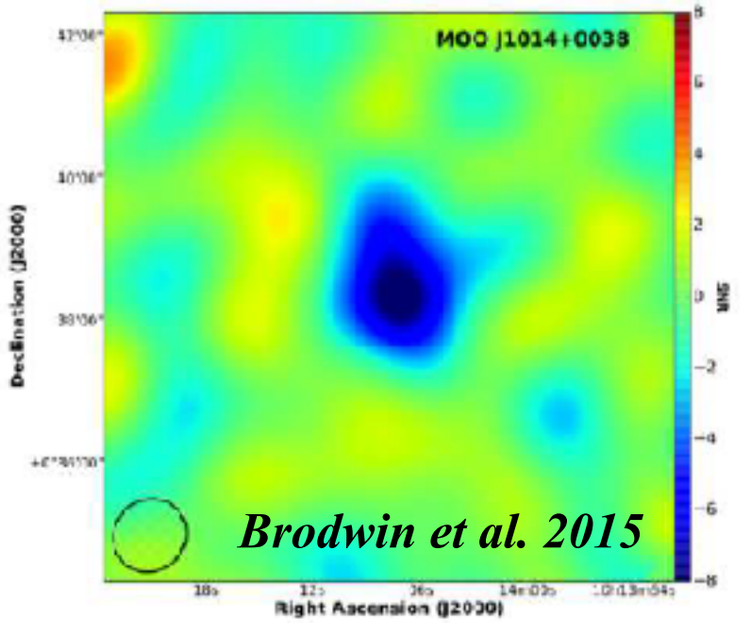
And more

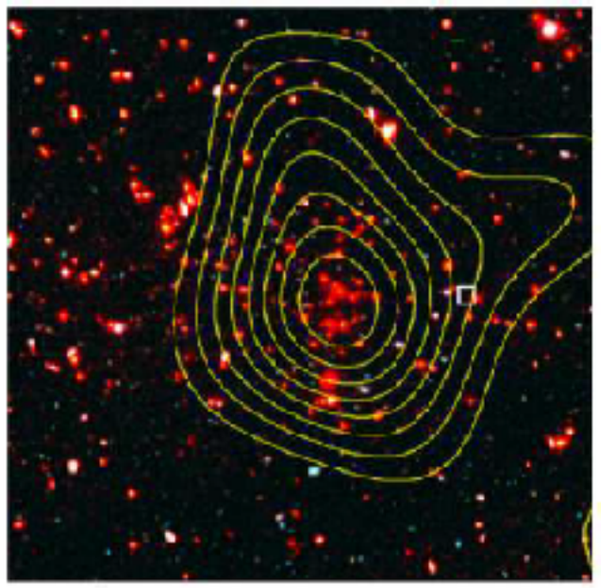
The Sunyaev & Zelovich

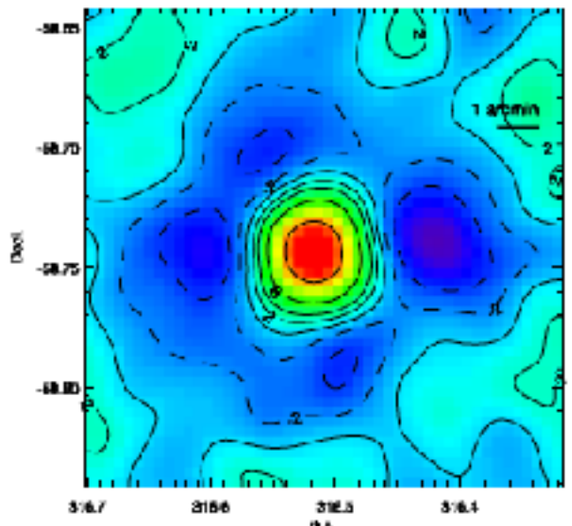
effect



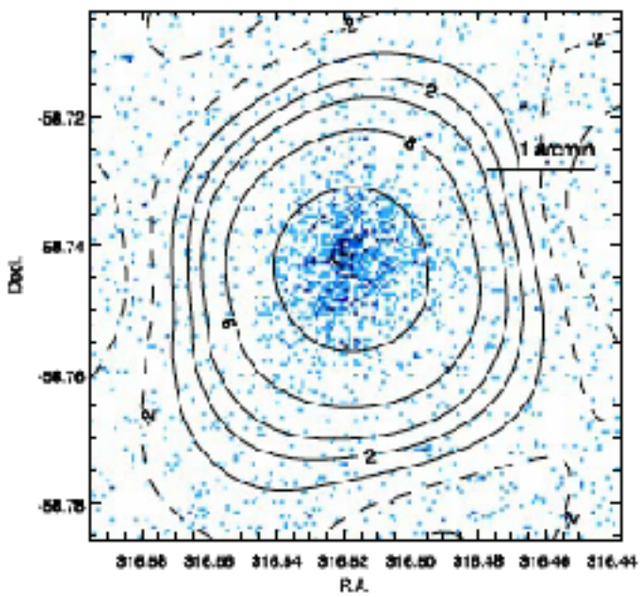
1972
R.A. Sunyaev
Ya. B. Zeldovich







Foley et al. 2011 (z =1.13)



If hot intergalactic gas really exists in clusters of galaxies, there are all the conditions for action of the proposed effect. Thus, for example, the x-ray radiation of the Coma cluster of galaxies is interpreted as the bremsstrahlung radiation of a hot intergalactic gas having $T_e \sim 7 \times 10^7$ °K and the density $N_e \sim 10^{-3}$ cm^{-3}. The linear dimension of the source is estimated to be $l \sim 10^{25}$ cm^{-3}. Multiplying these figures, we find

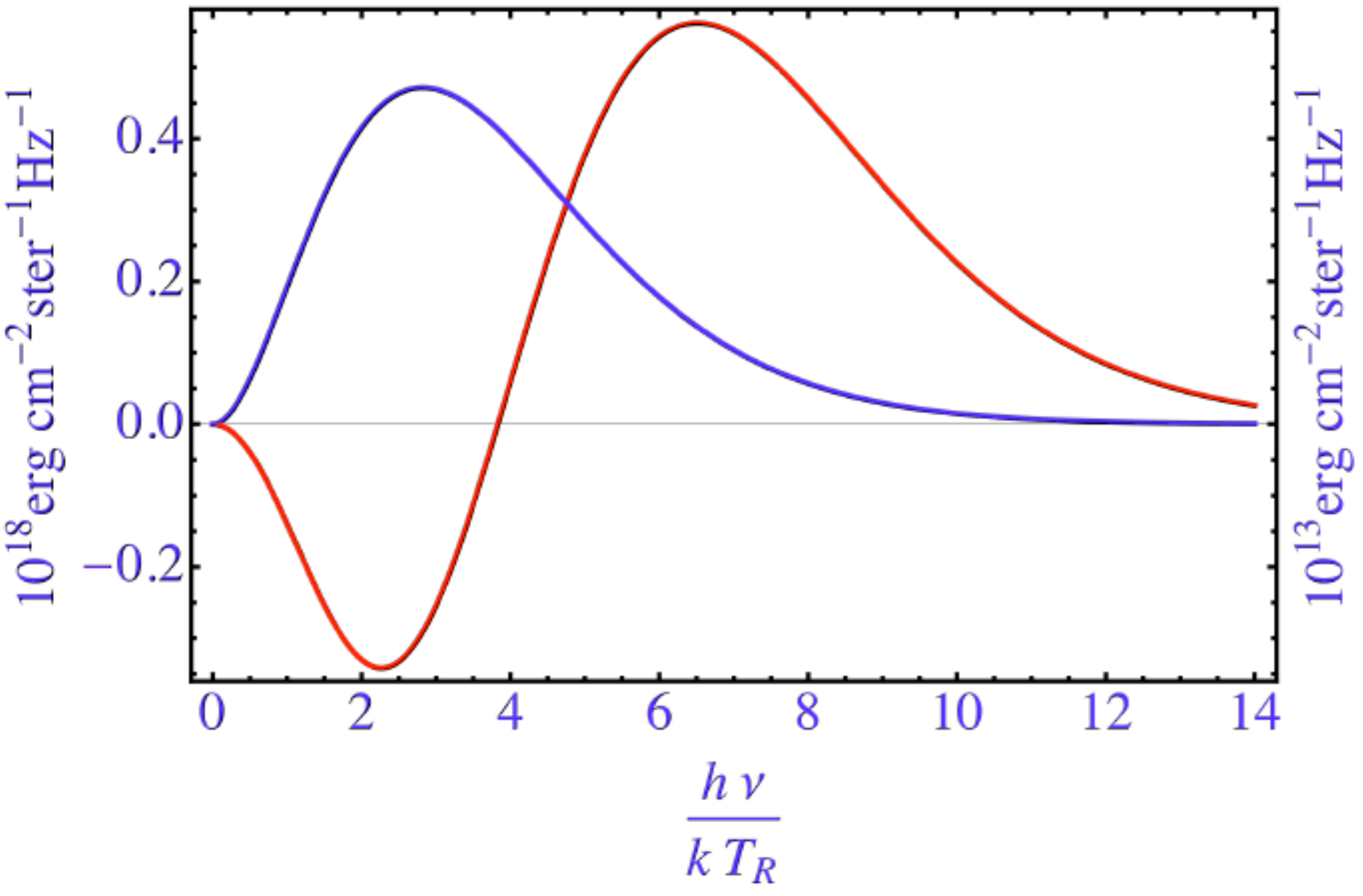
$$\rho_c(z) = \rho_c(0)(1+z)^3$$
$$\rho_\gamma(z) = \rho_\gamma(0)(1+z)^3$$

$$\frac{\Delta T_r}{T_r} = -2y = -2\sigma_T N_e l \frac{kT_e}{m_e c^2} \sim 2 \times 10^{-4},$$

the value accessible for observations. Namely, such effect was recently discovered in Coma by Pariysky.[11]

The deficit of brightness (hole) in the Coma is difficult to understand by any other mechanism! The radiation temperature is 2.7 °K; an arbitrary absorption of radiation is always accompanied by spontaneous emission. If the temperature of the absorber is higher than 2.7 °K, the net result would be an increase of radiation, instead of the observed deficit.

SZ effect scale larger by a factor 10^5



$$\textit{Similar to Vikhlinin et al. 2009 where } \frac{M_{500}}{10^{14} M_{\odot} / h} = A_x h^{3/2} \left(\frac{Y_x}{3\,10^{14} M_{\odot} keV} \right)^{B_x} \left(\frac{H(z)}{H_0} \right)^{C_x}$$

$$\textit{we define } \zeta = A_{SZ} \left(\frac{M_{500}}{5\,10^{14} M_{\odot} h^{-1}} \right)^{B_{SZ}} \left(\frac{1+z}{1.6} \right)^{C_{SZ}}$$

See Vanderlinde 2010
A_{SZ} , B_{SZ} , C_{SZ} from simulations
Williamson 2011

ς (unbiased significance) is related to the average detection significance of a given cluster across many noise realization for which the symbol ξ is used.

Planck
Beam diluition

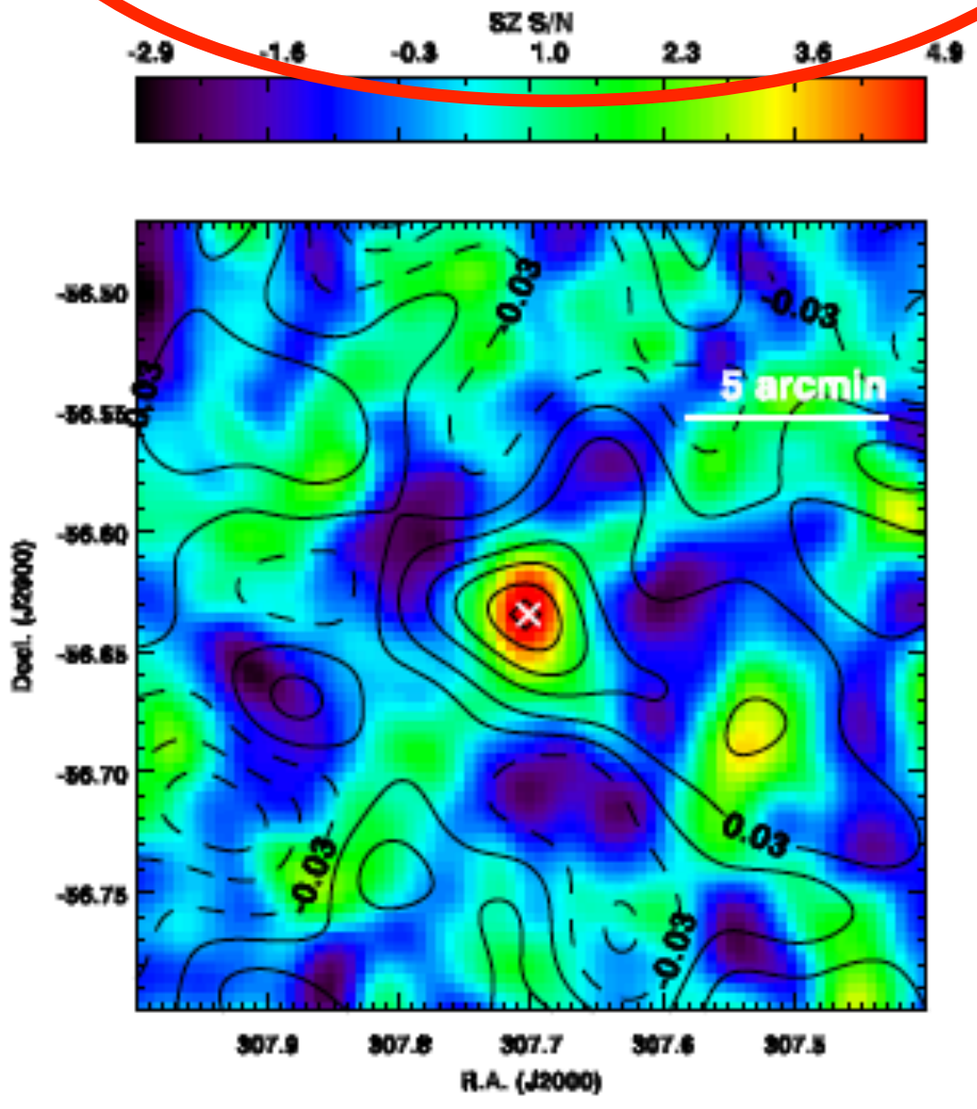
ROSAT
Cosmo dimming

No z dependence
high z

$$\zeta = \sqrt{\langle \xi \rangle^2 - 3}$$

High et al 2012

"In conclusion we find statistically consistency between masses derived from WL data and those derived from SZ and X ray data at the ~ 20% level."



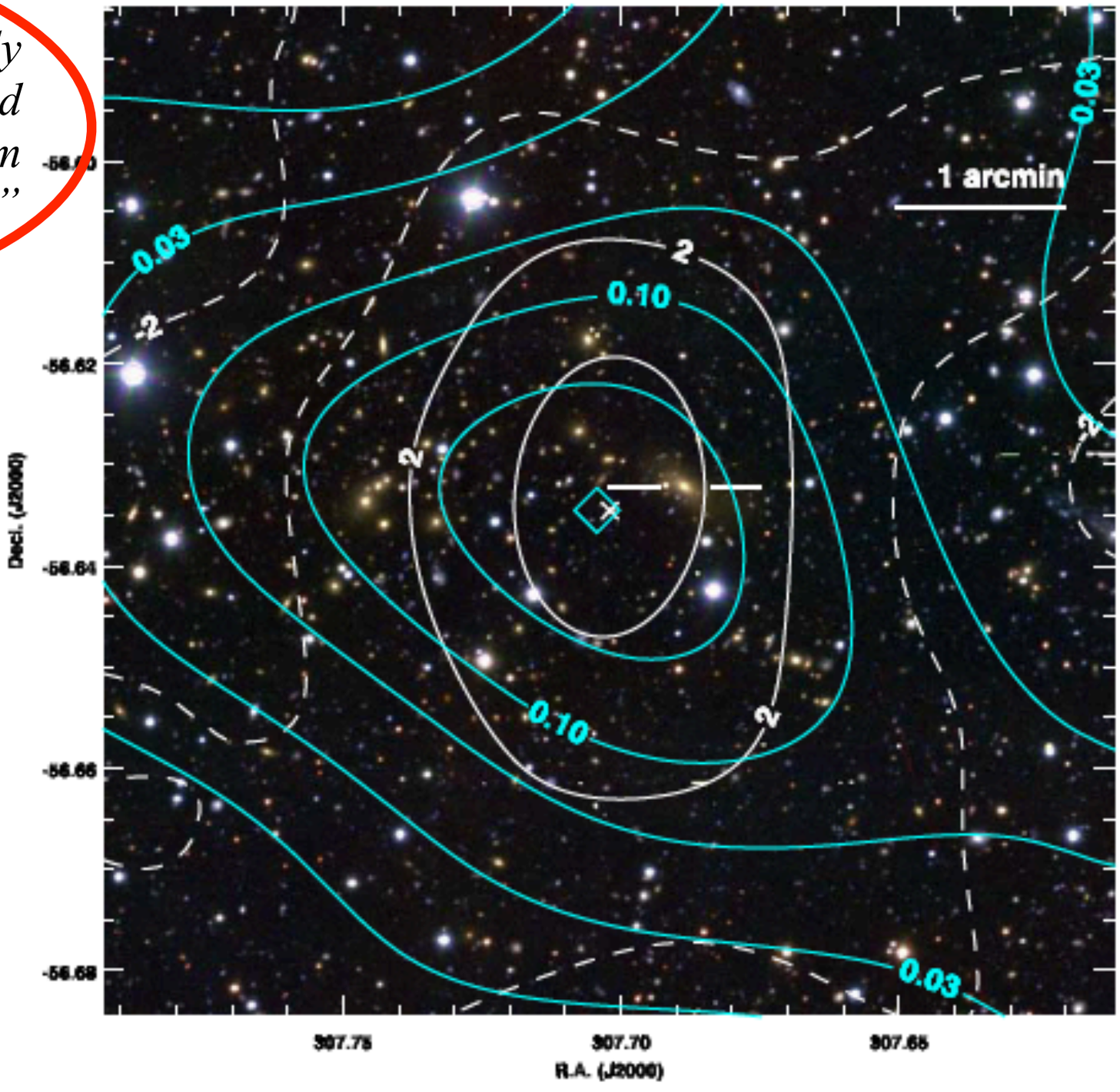


TABLE 3
MASS RATIO RESULTS AND CONSISTENCY TESTS

Procedure	Aperture Masses		Spherical Masses at $R_{500,\mathrm{SZ}}$		Spherical Masses at $R_{500,\mathrm{WL}}$	
	Mean Ratio	Total Scatter (%)	Mean Ratio	Total Scatter [%]	Mean Ratio	Total Scatter (%)
Baseline results	1.04 ± 0.18	33	1.07 ± 0.18	33	1.10 ± 0.24	58
$i_{\mathrm{CFHT}} < 24.5$	1.05 ± 0.20	37	1.05 ± 0.19	37	1.08 ± 0.25	65
$i_{\mathrm{CFHT}} < 24.0$	1.07 ± 0.23	34	1.07 ± 0.21	35	1.12 ± 0.29	60
Conservative color cuts	1.07 ± 0.19	35	1.12 ± 0.18	35	1.16 ± 0.23	58

To be done

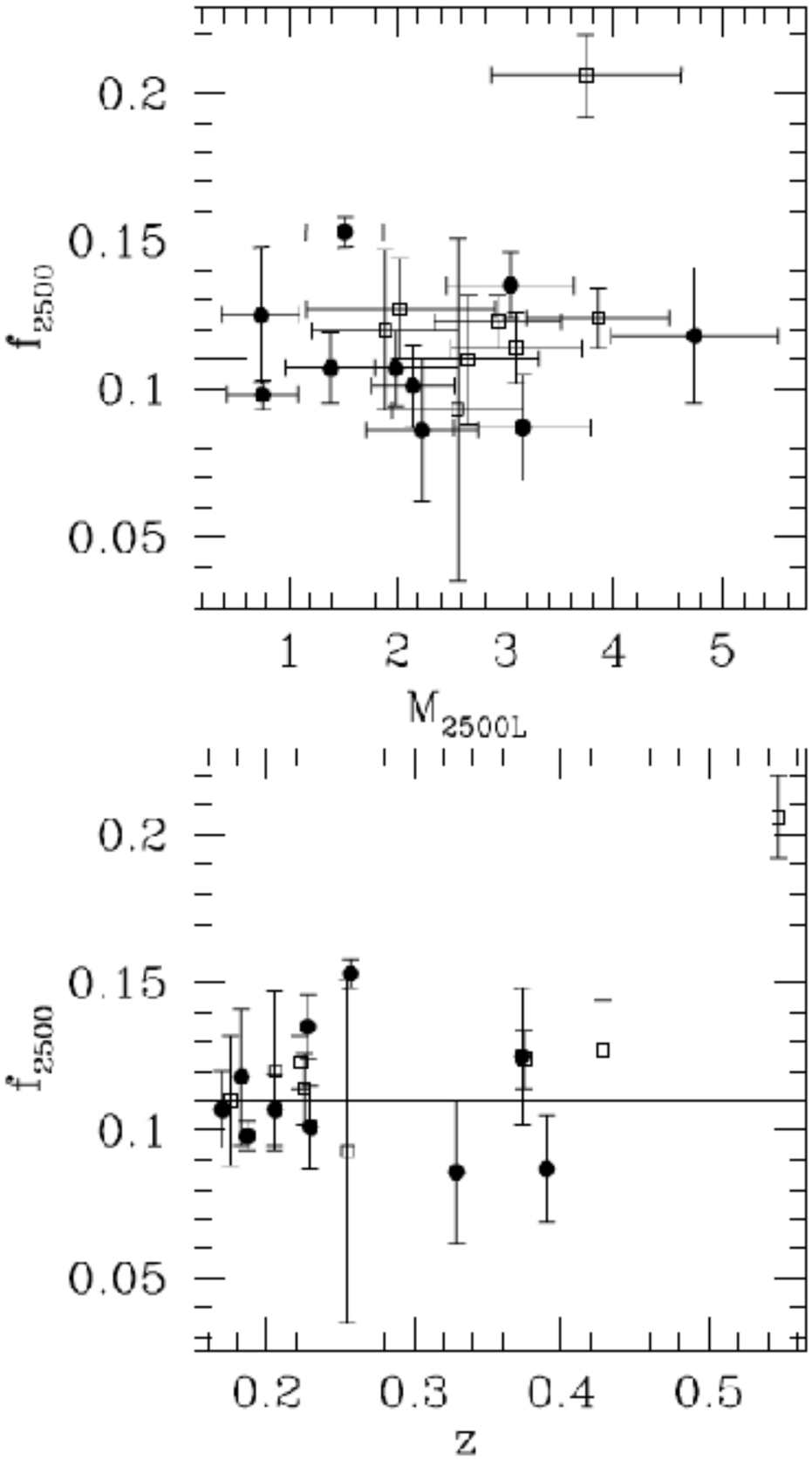


Figure 5. The X-ray gas fraction as a function of (*top*) weak lensing mass at r_{2500} and (*bottom*) redshift. There is no evidence of a trend with mass or redshift. Filled circles and unfilled squares show systems with and without cool cores, respectively. The solid horizontal line shows the Allen et al. (2007) value.

MAHDAVI ET A. 2007

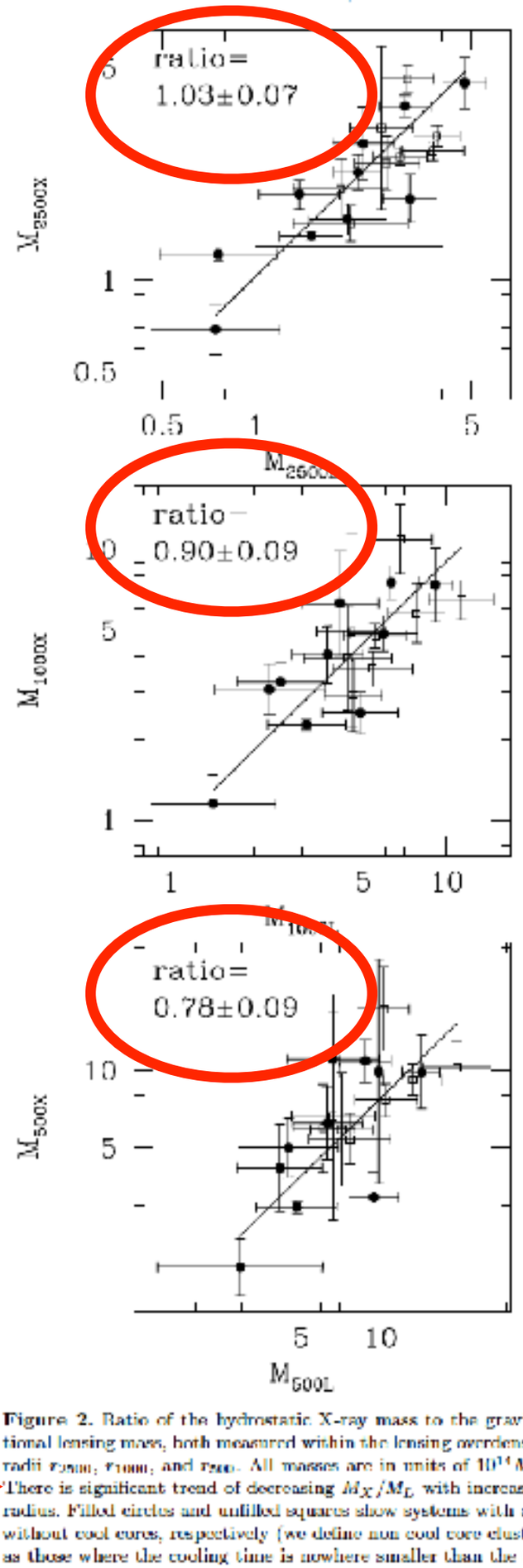
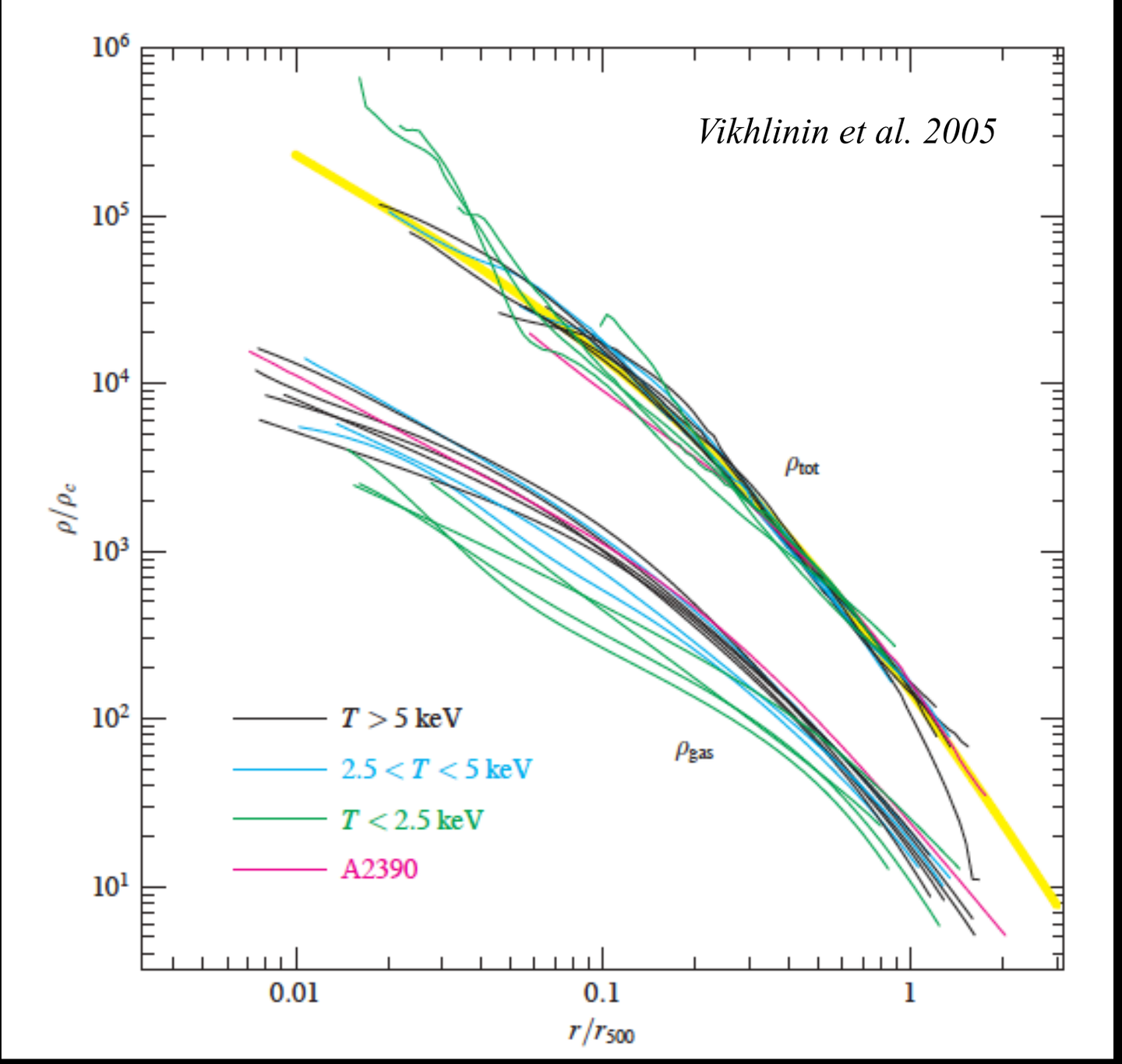


Figure 2. Ratio of the hydrostatic X-ray mass to the gravitational lensing mass, both measured within the lensing overdensity radii r_{2500}, r_{1000}, and r_{500}. All masses are in units of $10^{14}\,M_{\odot}$. There is significant trend of decreasing M_X/M_L with increasing radius. Filled circles and unfilled squares show systems with and without cool cores, respectively (we define non cool core clusters as those where the cooling time is nowhere smaller than the age of the universe at the redshift of the cluster).

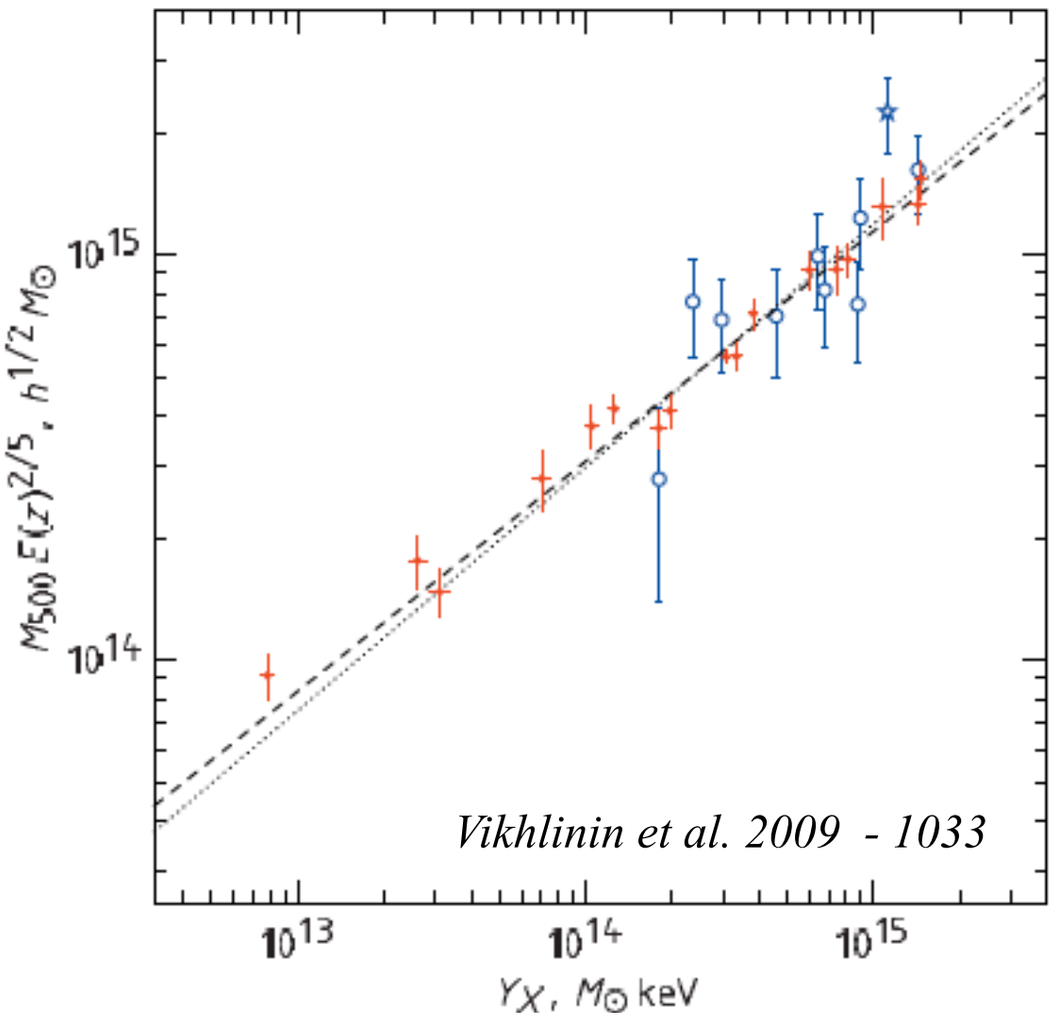


$$f_{gas} = 0.06 \pm 0.02 \; for \; r < r_{2500}$$

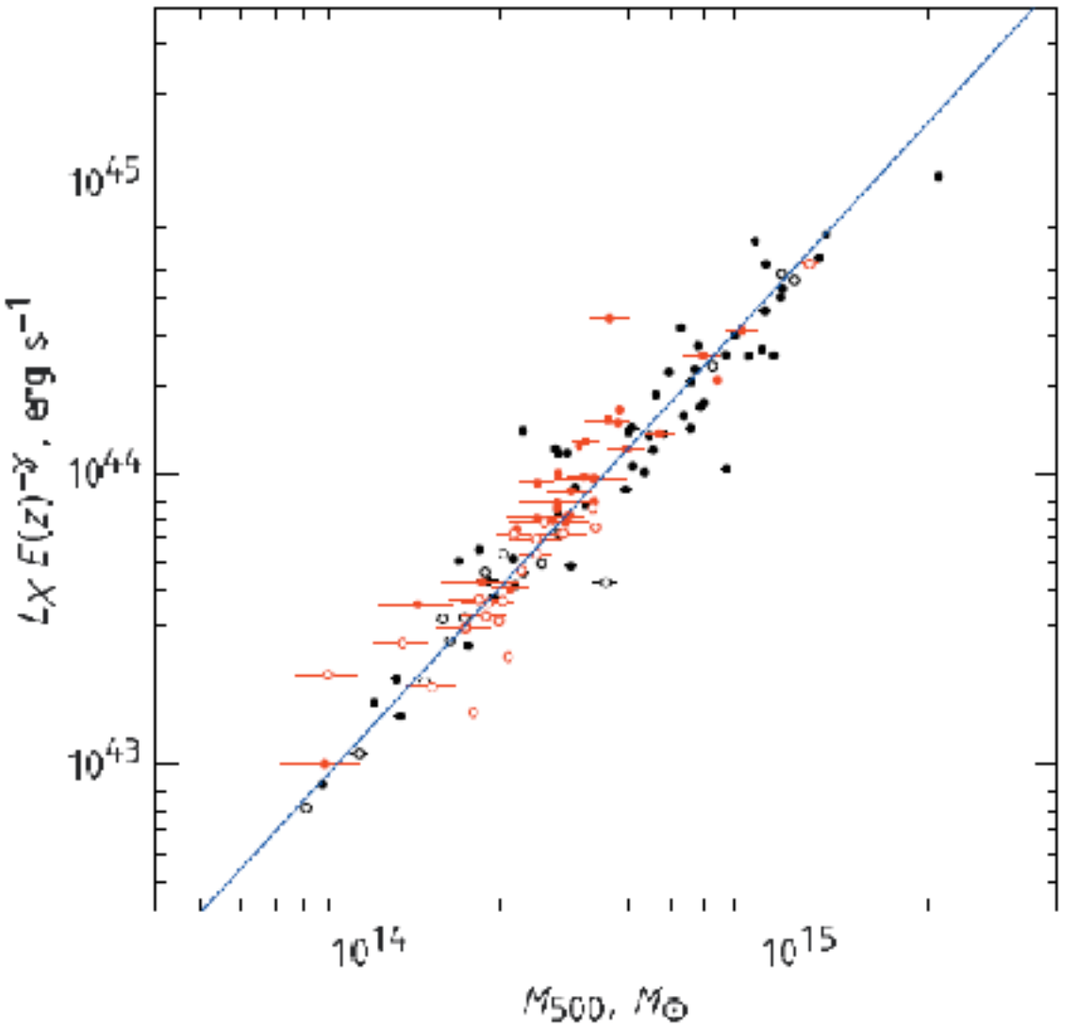
$$f_{gas} = 0.10 \pm 0.02 \; for \; r < r_{500}$$

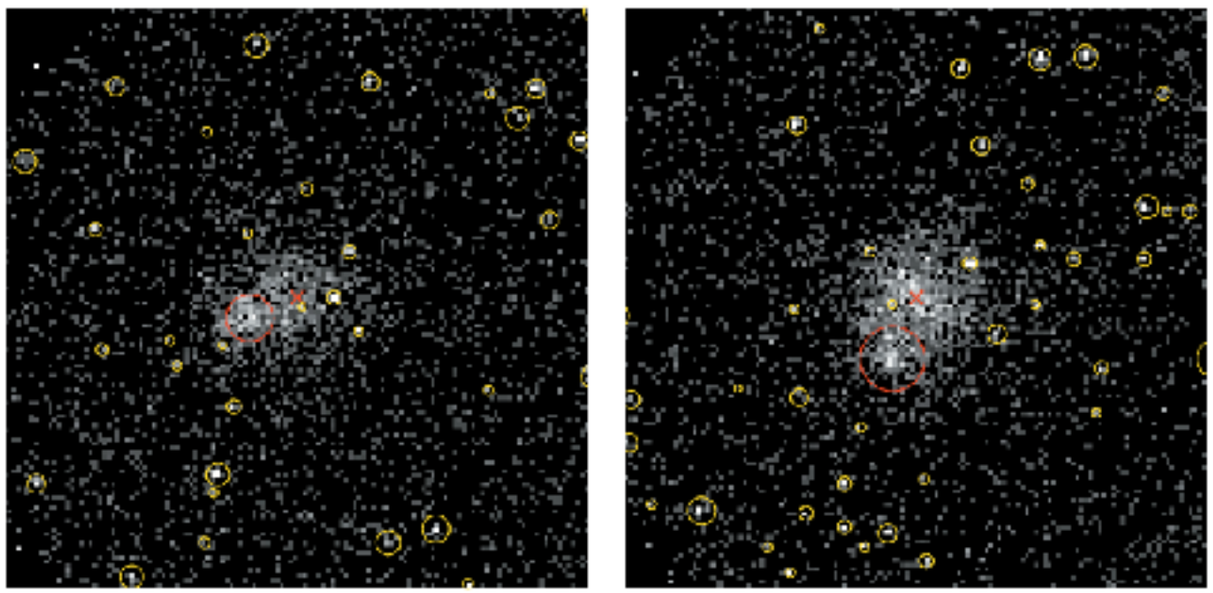
$$\left\langle \frac{f_{2500}}{f_{500}} \right\rangle_{Vikhlinin\ 2006} = 0.84$$

$$f_g \left(h / 0.72 \right)^{1.5}_{Vikhlinin\ 2009} = 0.125 + 0.037 \; Log \; M_{15}$$



Vikhlinin et al. 2009 - 1033





(0230+1836, $z = 0.80$ and cl1120+2326, $z = 0.56$)

The estimate of M_{Tot}

$$\begin{cases} T_x \\ M_{gas} \\ Y_x = T_x * M_{gas,x} \end{cases}$$

& opening to baryonic fraction to be discussed later

$$Y_X = T_X\, M_{gas} \qquad M_{500} \propto T^{3/2}\, E(z)^{-1} \qquad E(z) = H(z)/H_0$$

$$\begin{cases} T_x \propto E_{Kin} \propto \Omega \propto M/R \\ M^{1/3} \propto R \quad T_x \propto M^{2/3} \end{cases}$$

$$M_{Tot\ at\ \delta\ overdensity} = f_g^{-1}\, M_{gas} \qquad \delta = \frac{M_g(r)\, f_g^{-1}}{4/3\, \pi\, r^3 \rho_c(z)} \qquad f_g \sim 25\%\ lower\ than \left(\frac{\Omega_b}{\Omega_m}\right) = 0.165 \pm 0.005$$

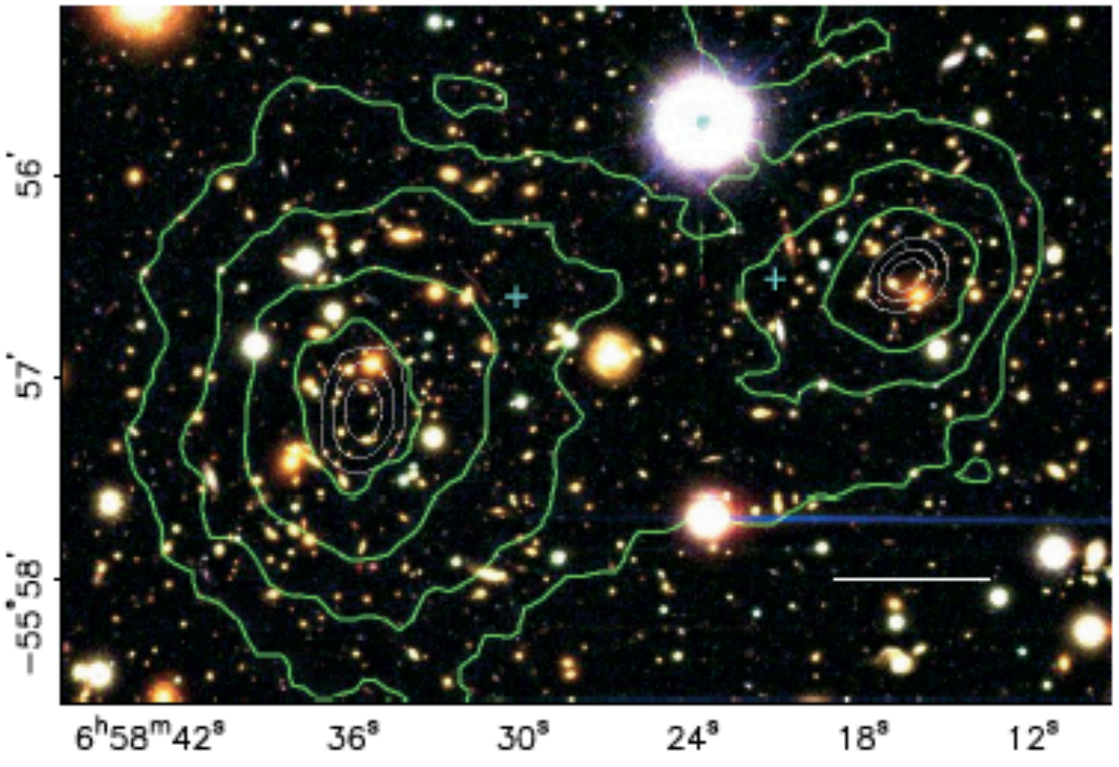
$$M_{500}\, E(z)^{2/5} \propto Y_x^{0.57\pm0.05}$$

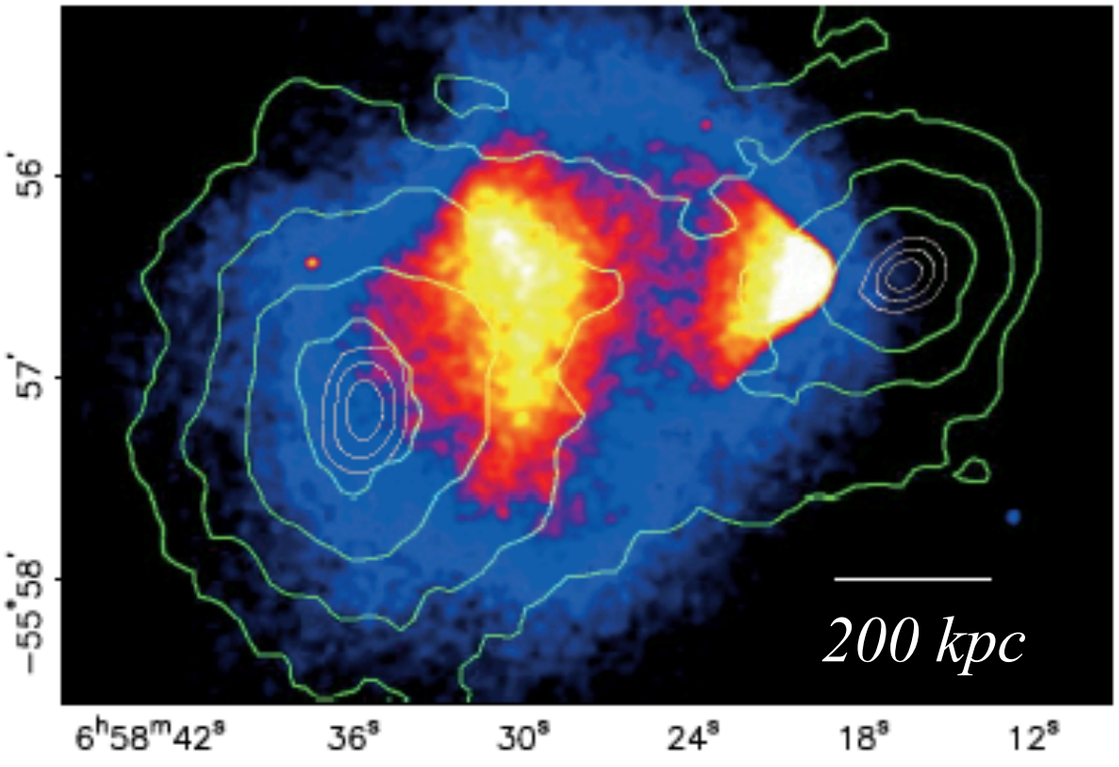
Vikhlinin et al. 2009

Calibration of Mass-observable Relations

Relation	Form	$M_0, f_{g,0}$	α
$M_{500} - T_X$	$M_{500} = M_0 (T/5\,\mathrm{keV})^{\alpha}\, E(z)^{-1}$	$(3.02 \pm 0.11) \times 10^{14}\, h^{-1}\, M_\odot$	1.53 ± 0.08
$M_{500} - T_X$	$M_{500} = M_0 (T/5\,\mathrm{keV})^{\alpha}\, E(z)^{-1}$	$(2.95 \pm 0.10) \times 10^{14}\, h^{-1}\, M_\odot$	1.5, fixed
$M_{500} - M_{\mathrm{gas}}$	$f_g = f_{g,0} + \alpha \log M_{15}$	$(0.0764 \pm 0.004)\, h^{-1.5}$	0.037 ± 0.006
$M_{500} - Y_X$	$M_{500} = M_0 (Y_X/3 \times 10^{14}\, M_\odot\,\mathrm{keV})^{\alpha}\, E(z)^{-2/5}$	$(5.77 \pm 0.20) \times 10^{14}\, h^{1/2}\, M_\odot$	0.57 ± 0.03
$M_{500} - Y_X$	$M_{500} = M_0 (Y_X/3 \times 10^{14}\, M_\odot\,\mathrm{keV})^{\alpha}\, E(z)^{-2/5}$	$(5.78 \pm 0.30) \times 10^{14}\, h^{1/2}\, M_\odot$	0.6, fixed

Notes. To apply the relations, measure the mass proxy for your h of choice, and scale the normalization factor in Column 2 according to the h-dependence given in Column 3. $M_{\mathrm{tot}} - Y_X$ relation should be applied according to Equation (14). The f_g trend is used in the $M_{\mathrm{tot}} - M_{\mathrm{gas}}$, Equations (8) and (7); the z-dependence of this relation is discussed in Section 4.2.2.





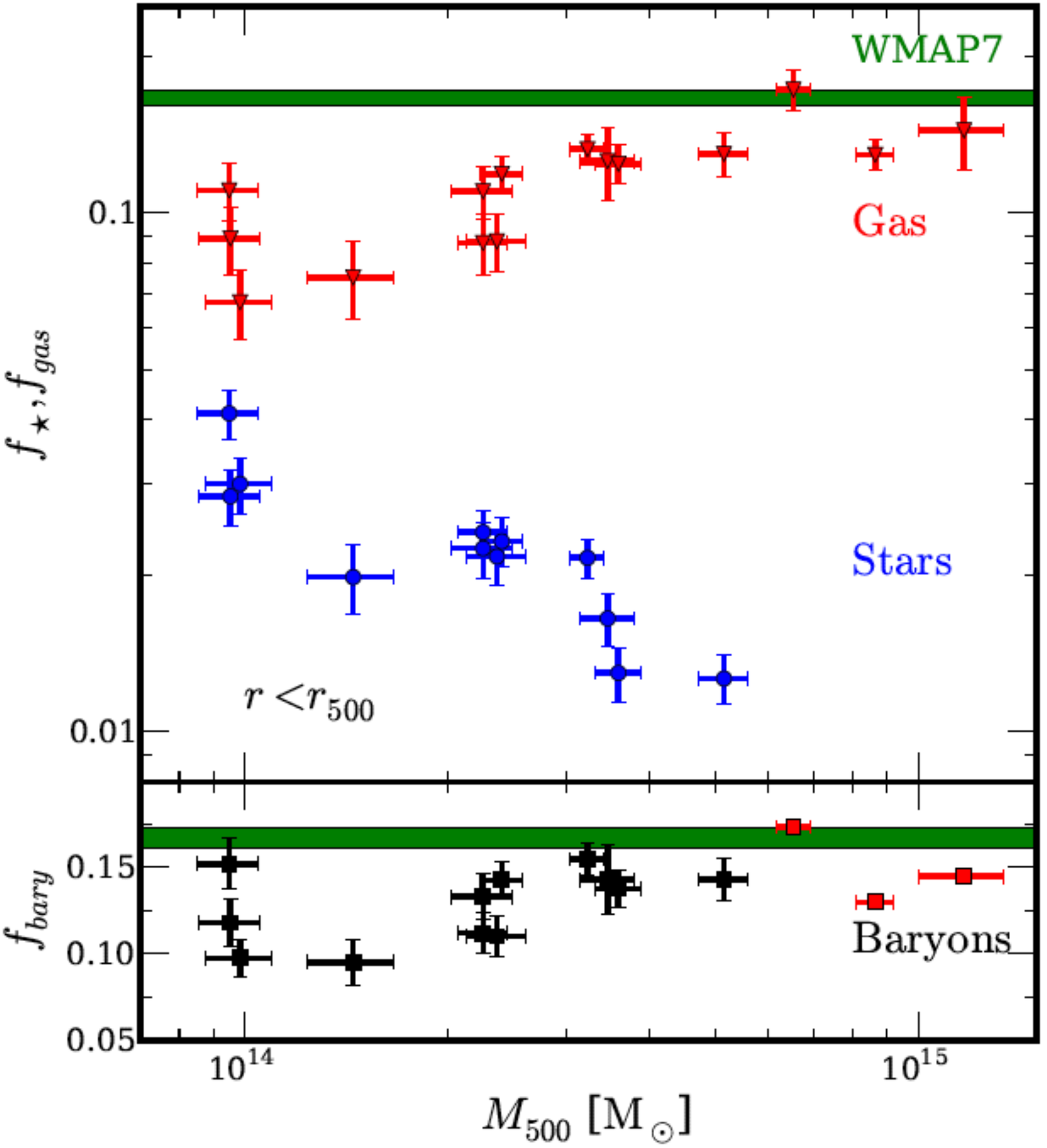
Chiu et al. 2015

Clowe et al. 2006

ID	Percentage (%)	Error (%)
f^* (M^*/M_{500})	1.1	0.1
f_{ICM} (M_{ICM}/M_{500})	9.6	0.5
f_c $(M^*/M_{baryons})$	10.7	1.1
f_b $(M_{baryons}/M_{500})$	10.7	0.6

Conclusions

- *The mass of clusters is on robust grounds and the estimates by various methods concorde.*
- *The presence of DM at these scales is on solid grounds.*
- *SZ clusters fascinating tool for cosmology*
- Ω_b / Ω_m *clusters about 25% less than cosmic (0.165* $\pm$ *0.005)*
- *Hunt for baryons is open?. See next slides however.*



Gonzales 2015

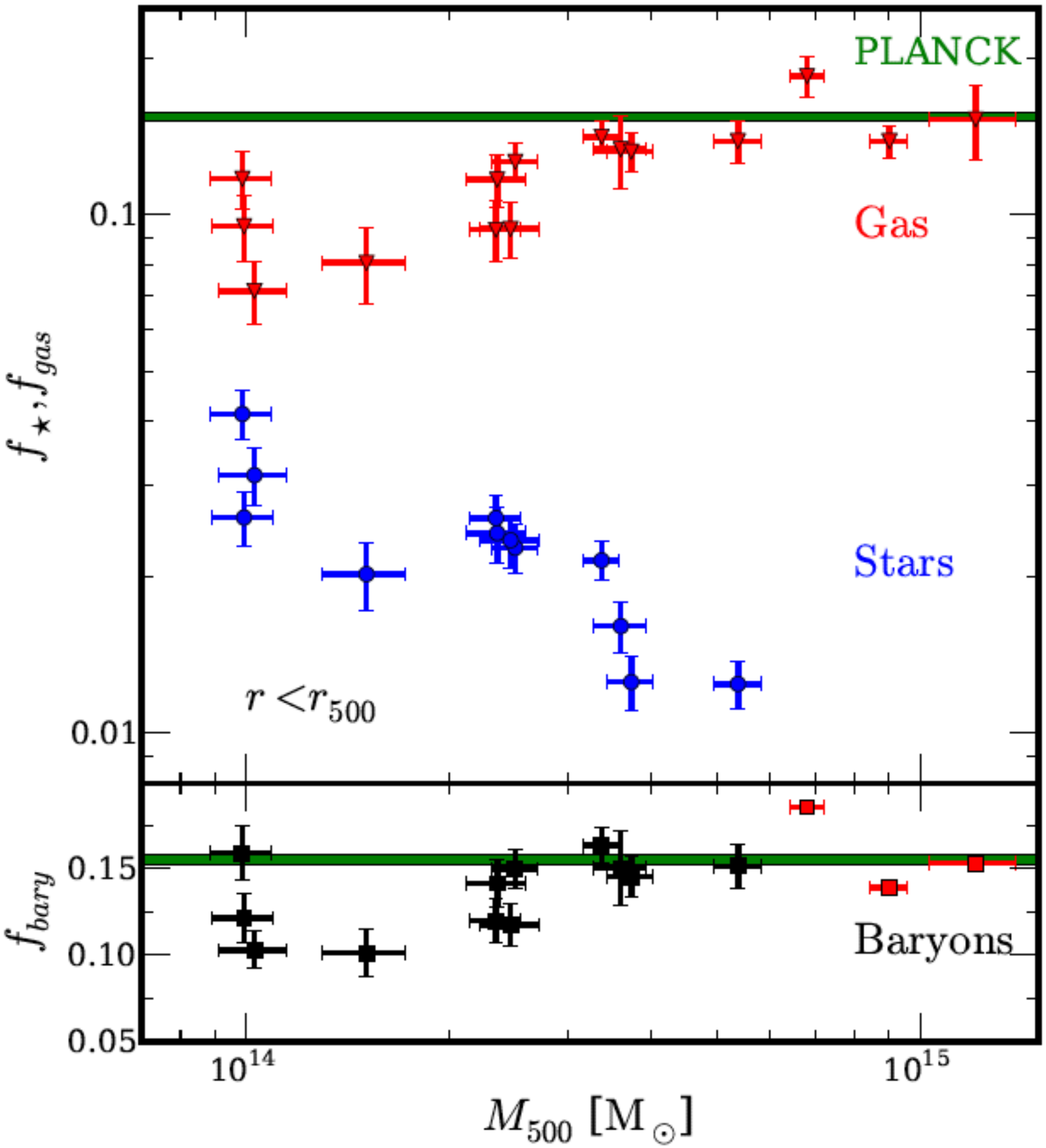
$M_* \propto M_{500}^{-0.52\pm0.04}$

$f_* \propto M_{500}^{-0.45\pm0.04}$

$f_{gas} \propto M_{500}^{0.26\pm0.03}$

$f_{bary} \propto M_{500}^{0.16\pm0.04}$

f_{bary_Tot} {
- *18% below* Ω_b/Ω_m *WMAP*
- *7% below* Ω_b/Ω_m *Planck*
}



baryon fraction closer to the Universal value using the parameters from the Planck Coll. 2013.

$f_{bary} = 0.144 \pm 0.005$

This is 7% only below the Universal value.

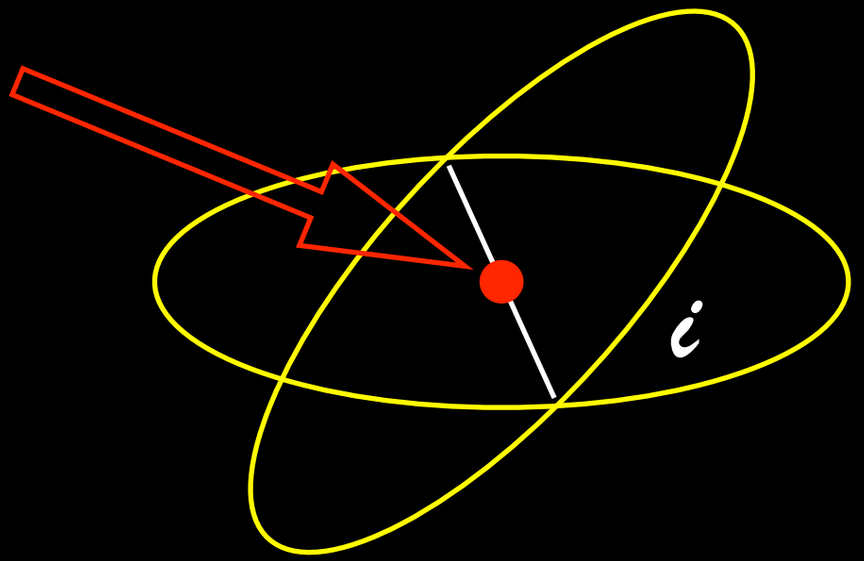
Non tutti quelli che vagano si sono persi

NOT ALL THOSE WHO WANDER ARE LOST

[J.R.R. Tolkien]

But first

The local Group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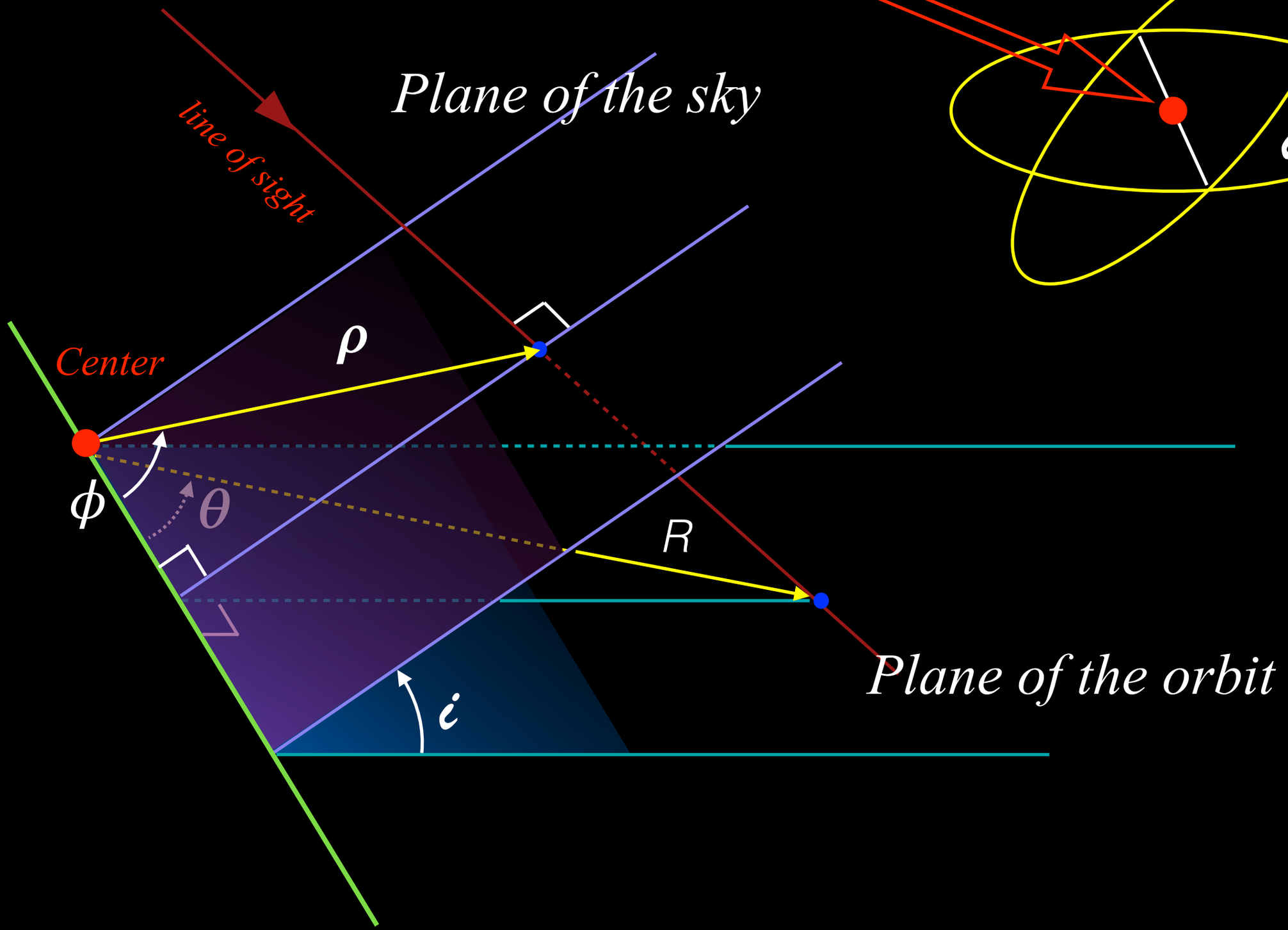

Plane of the sky
line of sight
Center
ρ
ϕ
θ
R
i
Plane of the orbit

$$M_1 + M_2 = \frac{V^2\ R}{G} \qquad R^2 = \rho^2\left(\cos\phi^2 + {\sin\phi^2}\Big/{\cos i^2}\right) \qquad \rho^2 = R^2\left(\cos i^2 + \cos\theta^2\right)$$

$$V_R(\rho,\phi) = V_{c.m.} + \Pi(R,\theta)\sin\theta\sin i + \Theta(R,\theta)\cos\theta\sin i + Z(R,\theta)\cos i =$$

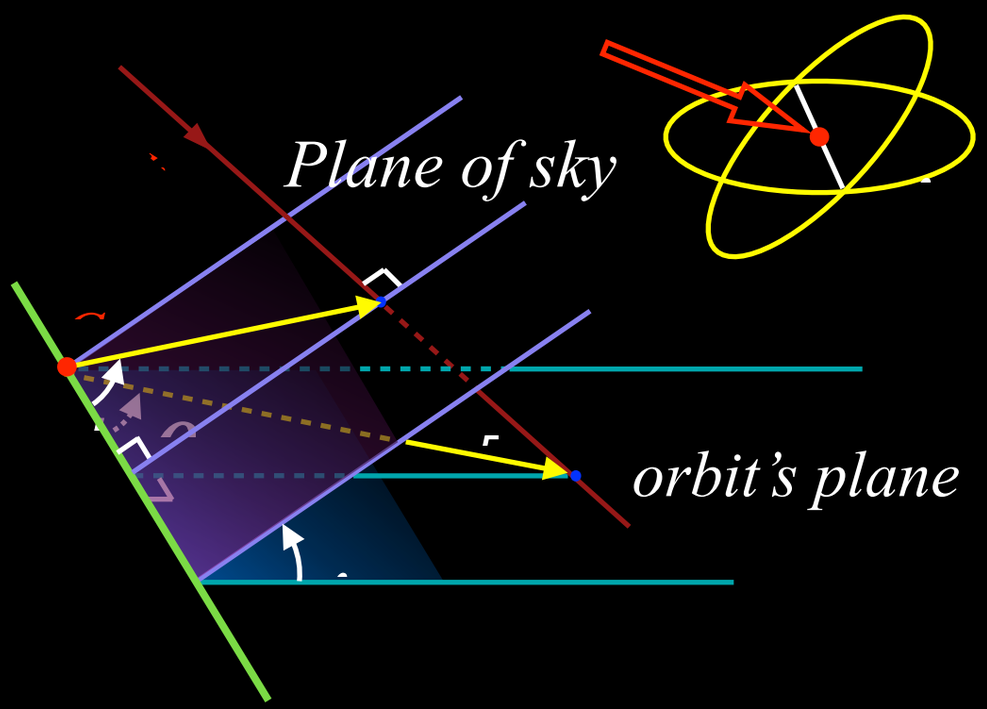
$$V_{c.m.} + \Theta(R,\theta)\cos\theta\sin i$$

or

$$\Delta V_{obs} = V\left(\equiv \Theta(R,\theta)\right)\cos\psi \qquad R_{obs} = R\sin\chi$$

$$f(M_1 + M_2) = \frac{\Delta V_{obs}^2\ R_{obs}}{G} = (M_1 + M_2)\, f(i,\theta)$$

$$\langle M_1 + M_2\rangle = \frac{\langle f(M_1 + M_2)\rangle}{\langle f(i,\theta)\rangle}$$



Likewise
if
we have a gas

$$\frac{1}{\rho_{gas}}\frac{dP}{dr} = -\frac{\partial\phi}{\partial r} = -\frac{G\,M}{r^2}\,; \quad P = kTMN_e$$

This is equivalent to (*See next slide*)

$$\frac{\partial\, ln\, N_e}{\partial\, ln\, r} + \frac{\partial\, ln\, T_{gas}}{\partial\, ln\, r} = -\frac{G\,M(r)\,\mu\, m_p}{r\,k\,T_{gas}}$$ *Therefore*

$$M(r) = -\frac{r\,k\,T_{gas}}{G\ \ \mu\, m_p}\left\{\frac{\partial\, ln\, N_e}{\partial\, ln\, r} + \frac{\partial\, ln\, T_{gas}}{\partial\, ln\, r}\right\}$$

$$\rho_{gas} = N_e \, \mu \, m_p$$

$$\frac{\partial \ln N_e}{\partial \ln r} + \frac{\partial \ln T_{gas}}{\partial \ln r} = \frac{\partial \ln \left(T_{gas} \; N_e \right)}{\partial \ln r} = - \frac{G \, M(r) \mu \, m_p}{k \, r \, T_{gas}}$$

$$\frac{1}{Ne \, T_{gas}} \partial \left(T_{gas} \; N_e \right) \frac{1}{\frac{1}{r} \partial r} = - \frac{G \, M(r) \mu \, m_p}{k \, r \, T_{gas}}$$

$$\frac{1}{\mu \, m_p \; Ne \, T_{gas}} \partial \left(k \, T_{gas} \; N_e \right) \frac{1}{\partial r} = - \frac{G \, M(r)}{r^2 \; T_{gas}}$$

$$\frac{1}{\rho_{gas}} \frac{\partial P}{\partial r} = - \frac{G \, M(r)}{r^2}$$