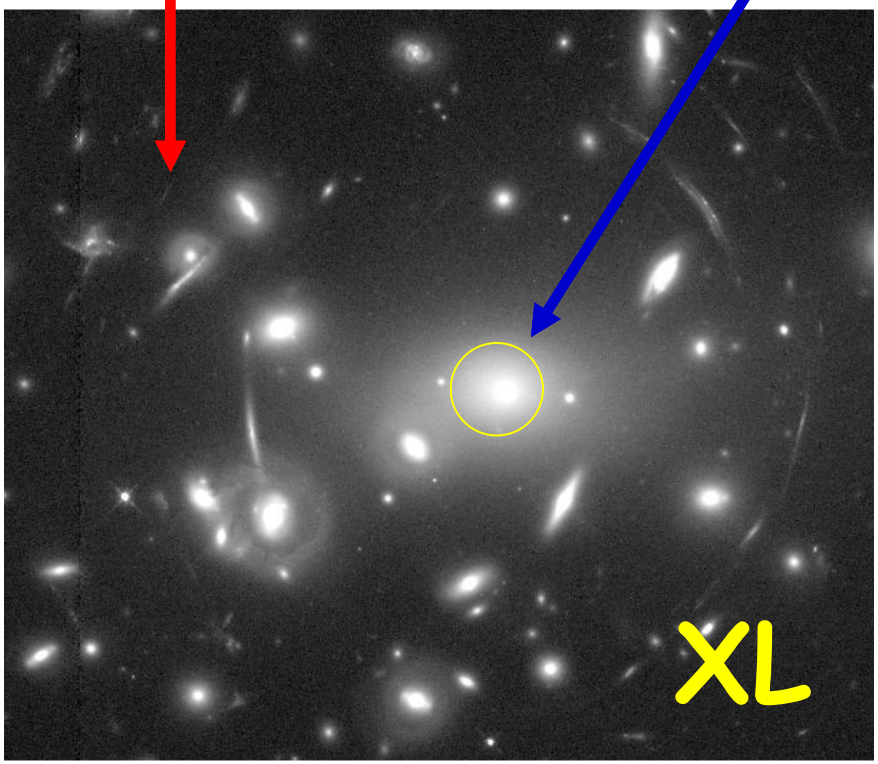
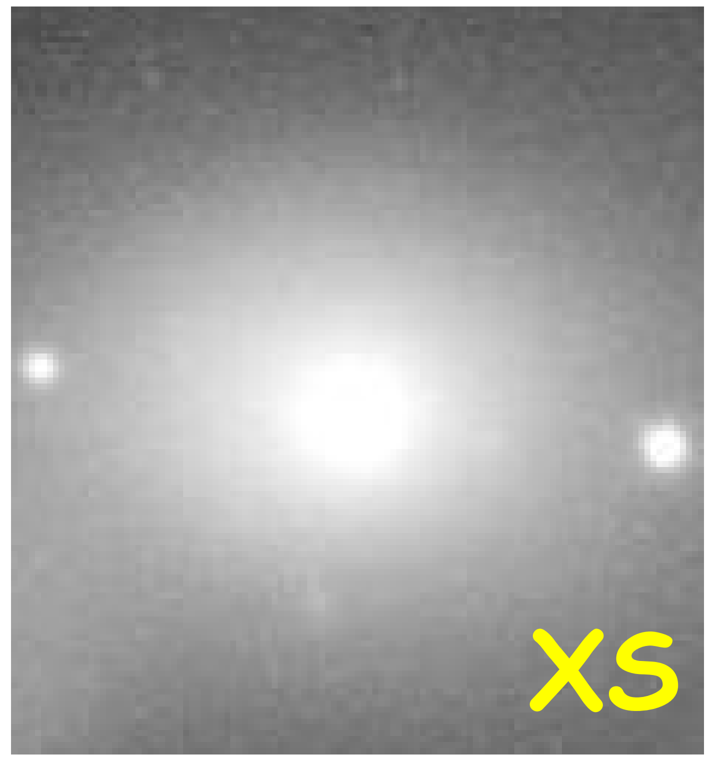
Extra physics (cosmic rays et al.)

E.Churazov, W.Forman, A.Vikhlinin, S.Tremaine, O.Gerhard, C.Jones MNRAS, 2008, v388, p1062

This conference

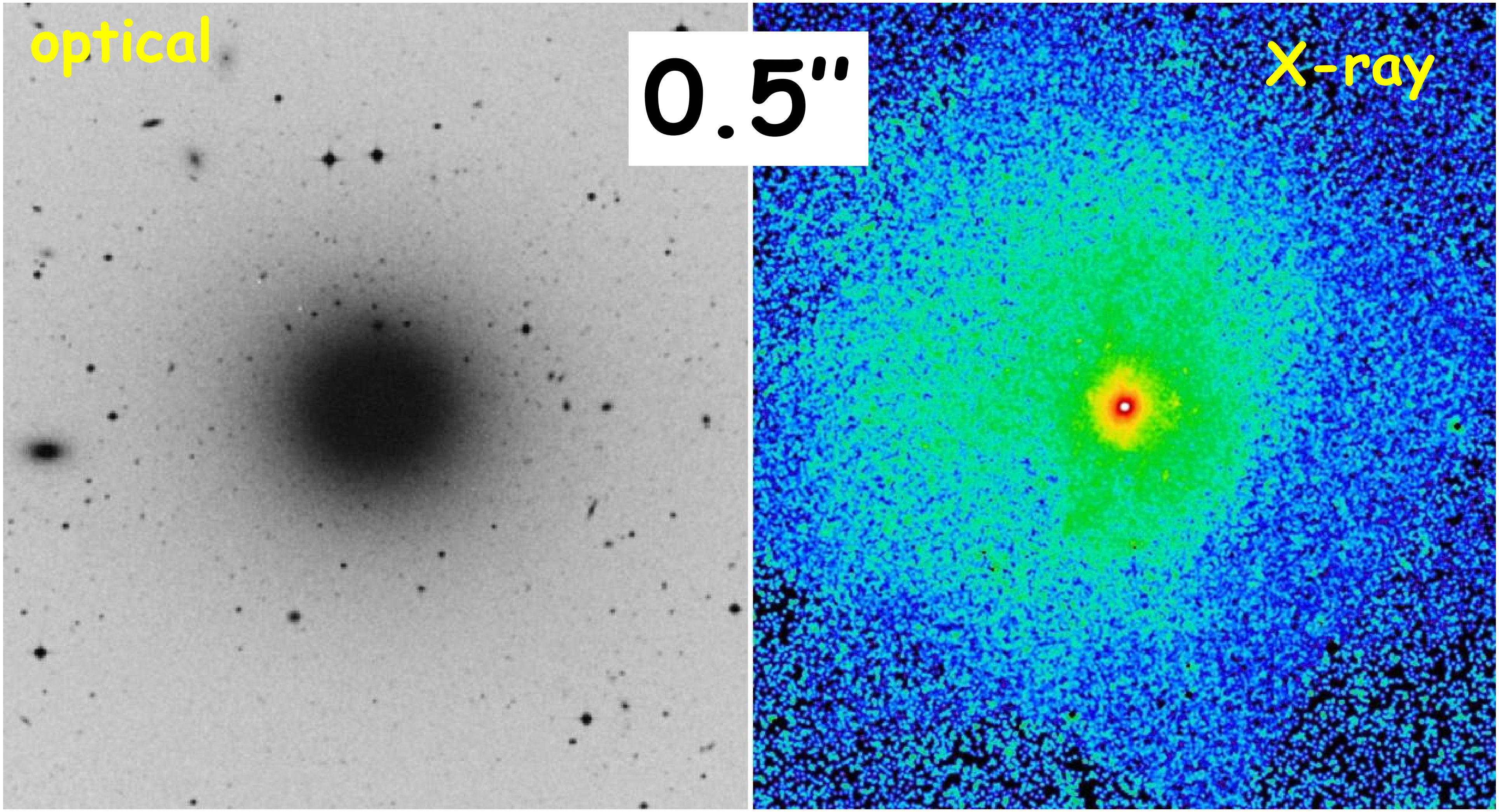
This talk





Goal: not the mass, but constraints on non-thermal pressure and on the deviations from hydrostatic equilibrium

NGC1399 – Fornax cluster



Stars instead of lensing: gravity only

Gas: gravity, magnetic fields, cosmic rays, turbulent motions

Stars: Jeans equation [stationary, spherical system with isotropic velocity dispersion]

$$\frac{1}{n_*}\frac{dn_*\sigma^2}{dr} = -\frac{GM}{r^2}$$

Gas: hydrostatic equilibrium

$$\frac{1}{\rho_{gas}}\frac{dP}{dr} = -\frac{GM}{r^2}$$

$$P_{thermal} = nkT$$ **Gas thermal pressure: can be easily measured**

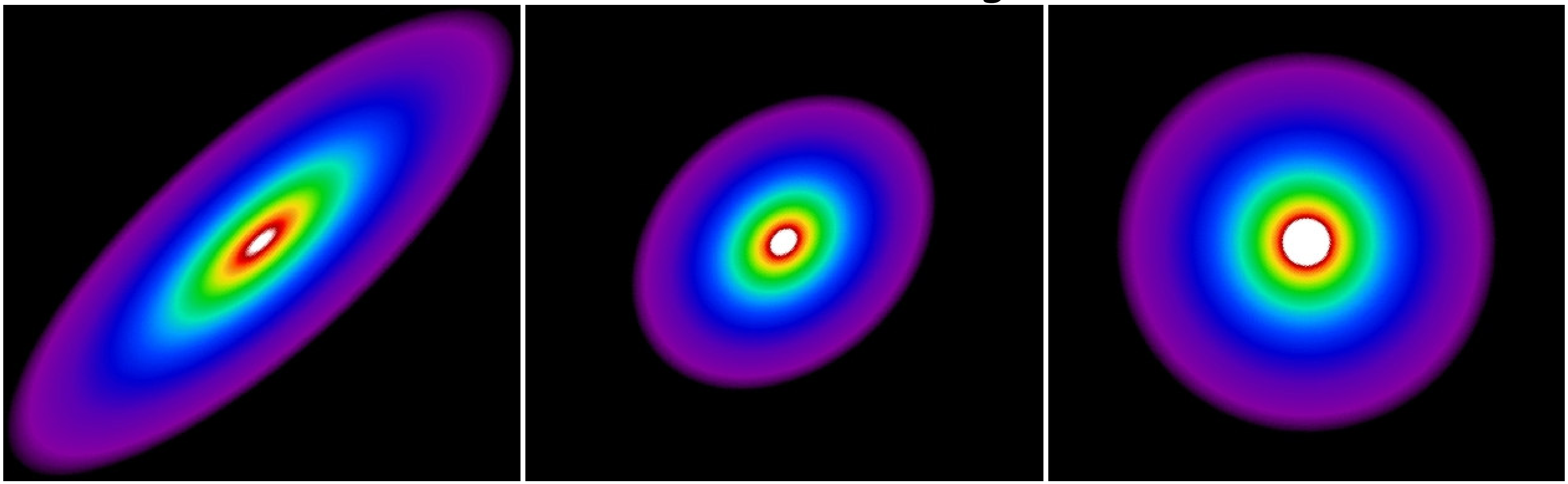
$$P = P_{thermal} + \underbrace{P_{CR} + \frac{B^2}{8\pi} + P_{turb}}_{\text{Non-thermal pressure}}$$

Non-thermal pressure

Goal: to place constraints on the non-thermal pressure and on deviations from the hydrostatic equilibrium

1. (X-ray) Deprojection of non-spherical clusters
2. Using potential instead of mass
3. Impact of non-thermal pressure
4. Results and conclusions

Triaxial β-model, isothermal gas, relaxed

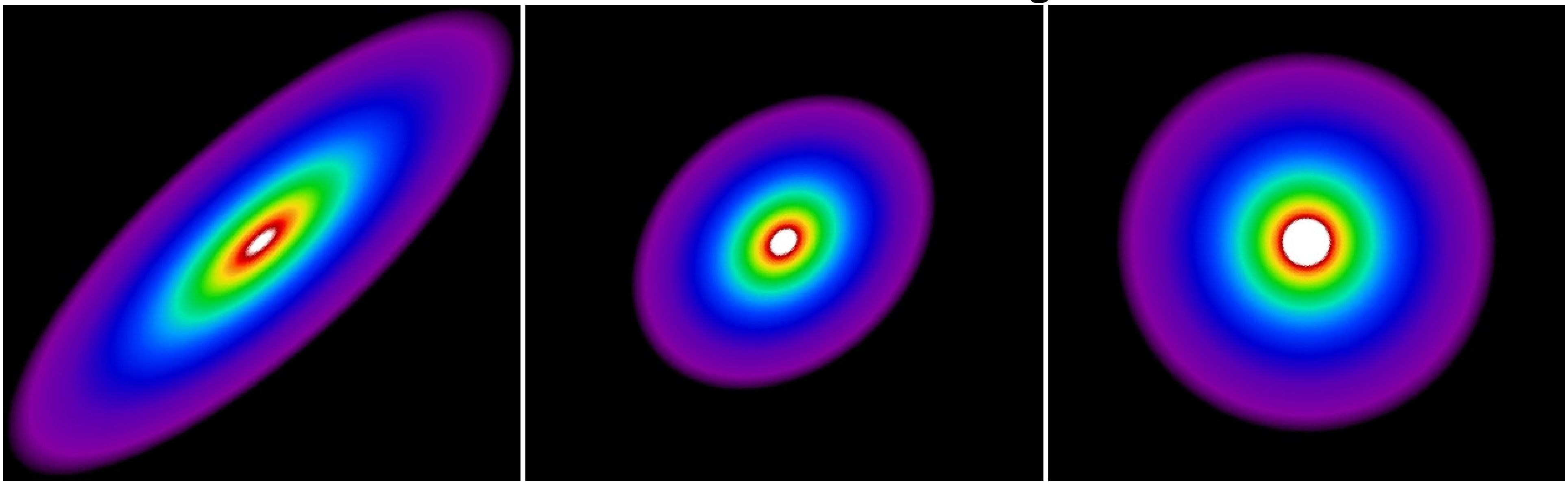


$$n_e = \left[1 + \left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 + \left(\frac{z}{c}\right)^2\right]^{-\frac{3}{2}\beta} \qquad r >> a,b,c \quad n_e = f(\theta,\phi) r^{-\gamma}$$

$$n_e \propto e^{-\frac{\mu m_p \varphi}{kT}} \Rightarrow \quad \varphi = \frac{kT}{\mu m_p}\left[\gamma \ln r - \ln f(\theta,\phi)\right]$$

$$\rho = \frac{kT}{4\pi G \mu m_p}\left[\frac{\gamma}{r^2} - \nabla^2 \ln f(\theta,\phi)\right]$$

Triaxial β-model, isothermal gas



$$M(<R) = \int_{|r|<R} d\vec{r}\,\rho = \frac{kT}{\mu m_p G}\left[\gamma R - \int_{|r|<R} d\vec{r}\,\nabla^2 \ln f(\theta,\phi)\right] = \frac{kT}{\mu m_p G}\gamma R$$

From X-ray analysis: $n_e \propto f(\theta,\phi) r^{-\gamma} \;\Rightarrow\; n_e \propto r^{-\gamma}, \quad T$

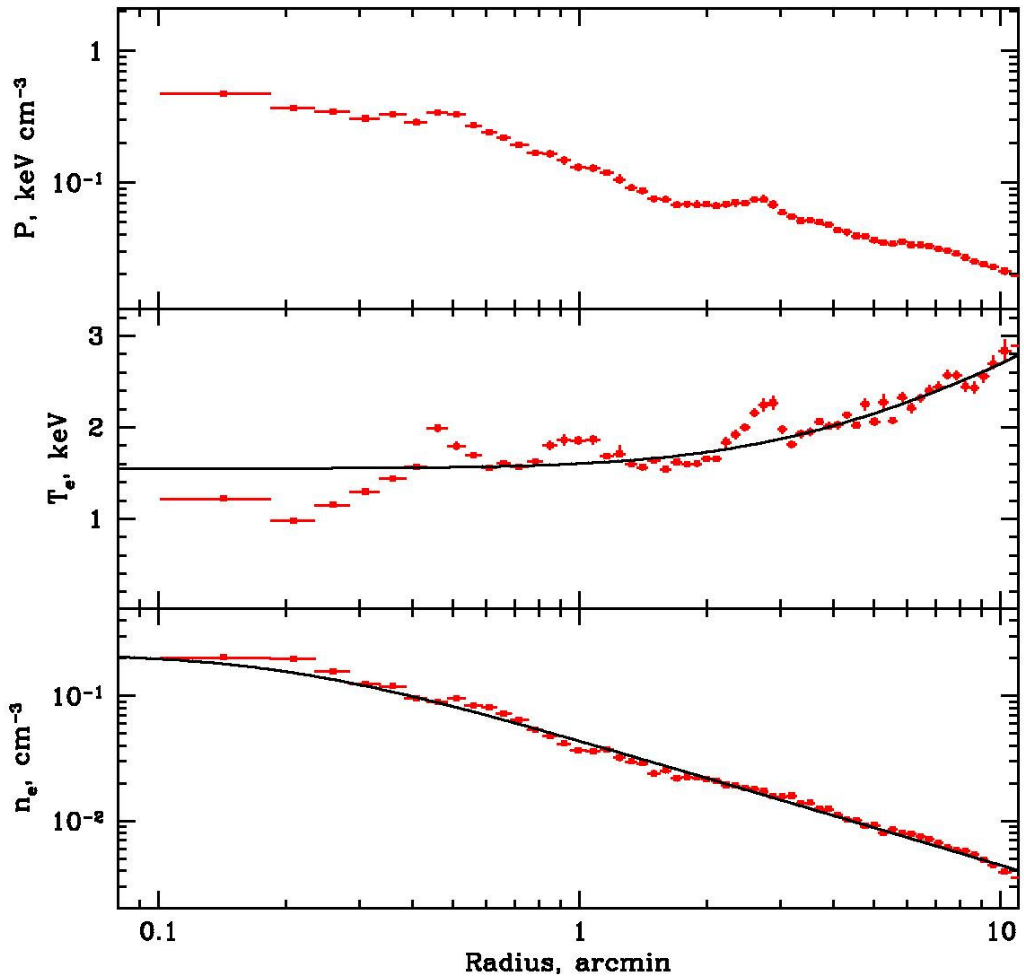
$$M_x(<R) = -\frac{R^2}{G}\frac{1}{\mu m_p n_e}\frac{dP}{dr} = \frac{kT}{\mu m_p G}\gamma R$$

$T; \quad n_e \propto f(\theta,\phi) g(r) \propto f(\theta,\phi) r^{-\gamma}$ **e.g. β_3-model, large r**

Calculate potential rather than mass!

$$\frac{GM}{r^2} = -\frac{1}{\rho}\frac{dP}{dr}$$

$$\frac{d\varphi}{dr} = -\frac{1}{\rho}\frac{dP}{dr}$$



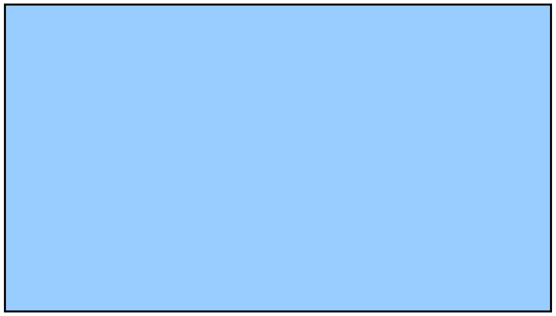
$$\varphi = -\frac{k}{\mu m_p}\left[\int T_e \frac{d\ln n_e}{dr}dr + T_e\right] + C$$

$$\varphi = -\frac{kT_e}{\mu m_p}\ln n_e + C$$

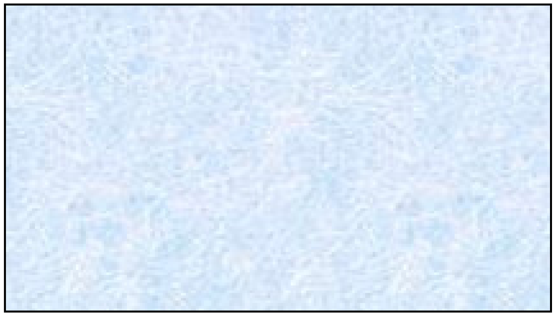
$$\frac{d\varphi_X}{dr} = -\frac{1}{\mu m_p n}\frac{dP}{dr}$$

We measure : $n, T, P = nkT$

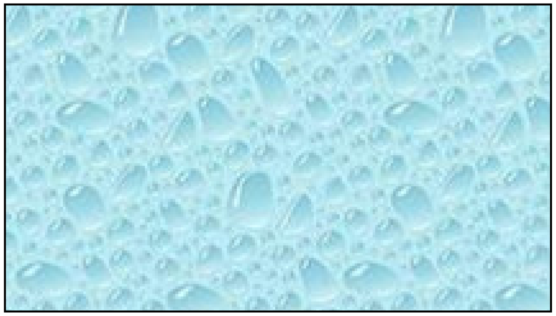
What can be wrong?: $n, T, P = nkT + ..$



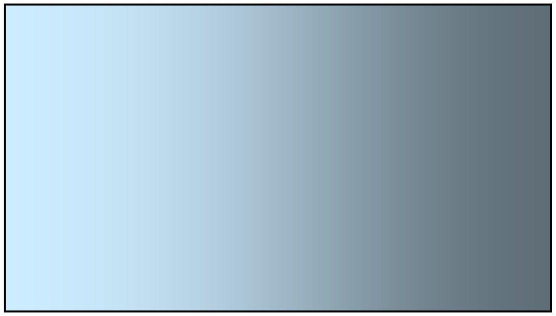
Uniform pure thermal gas
ρ-OK, P-OK



Uniform mixture: thermal + CRs
ρ-OK, P-wrong

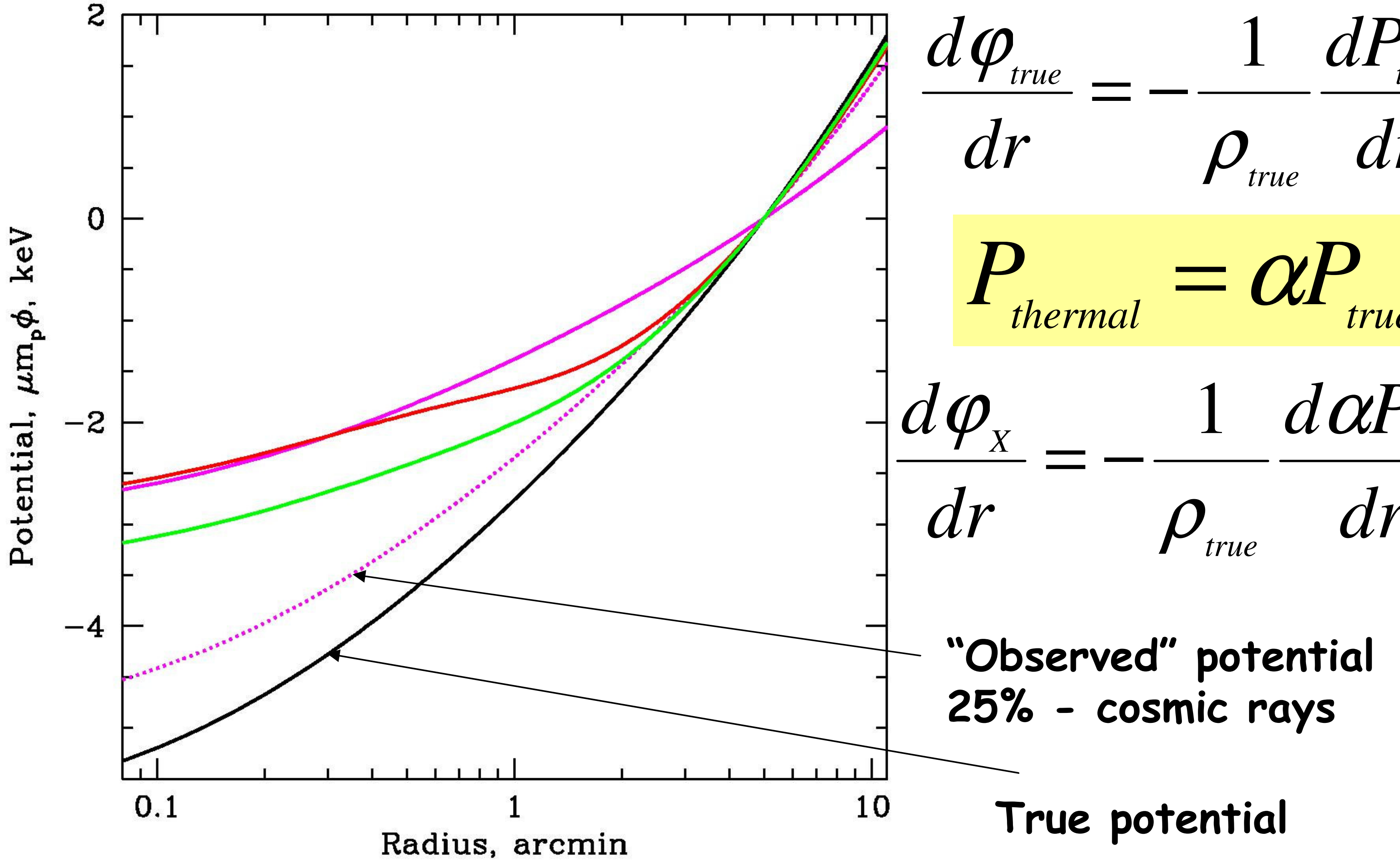


Bubbles of CRs in thermal gas
ρ-wrong, P-wrong



Fraction of CRs varies with radius
ρ-wrong, P-wrong

Impact of non-thermal pressure



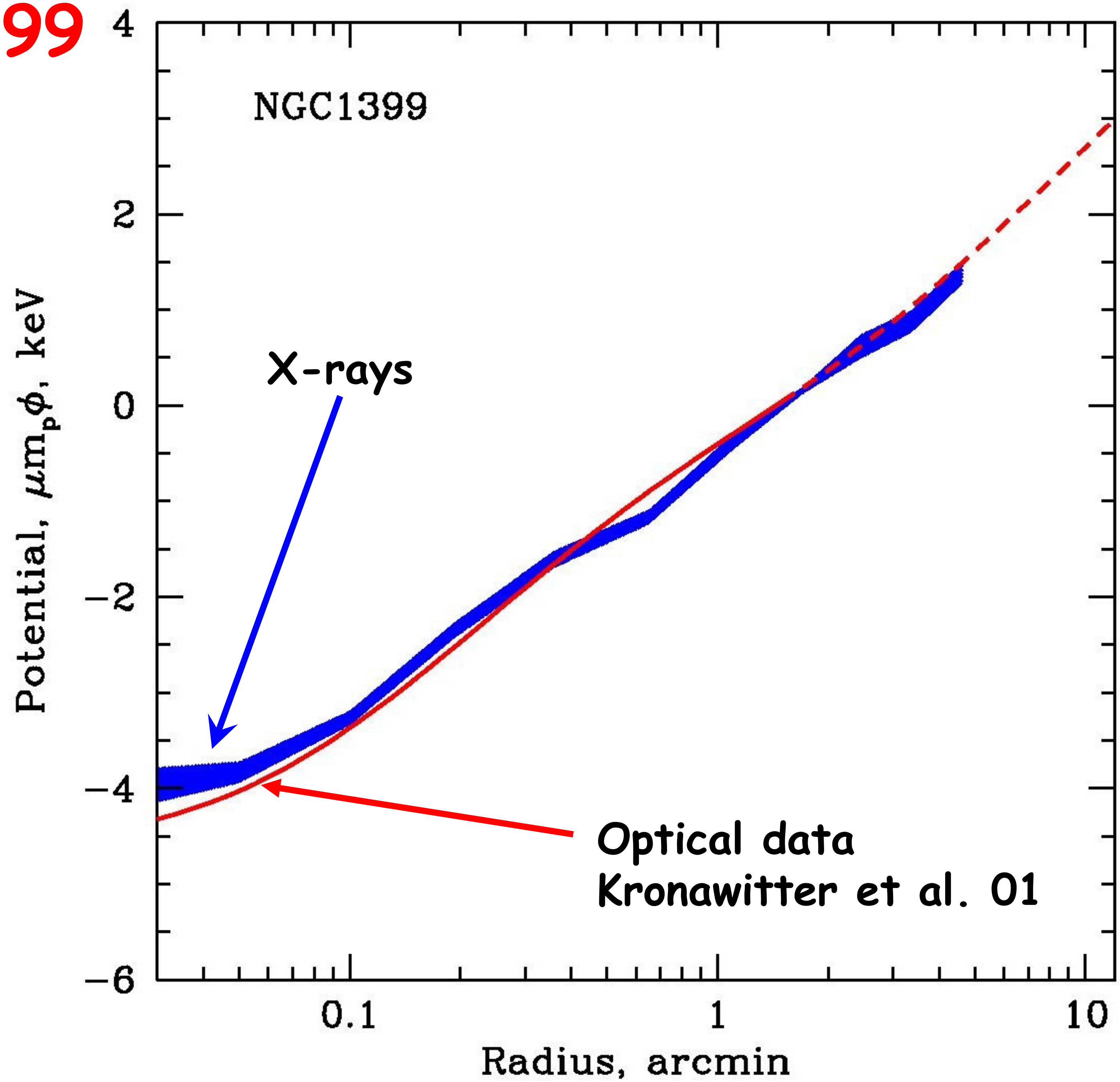
$$\frac{d\varphi_{true}}{dr} = -\frac{1}{\rho_{true}} \frac{dP_{true}}{dr}$$

$$P_{thermal} = \alpha P_{true}$$

$$\frac{d\varphi_X}{dr} = -\frac{1}{\rho_{true}} \frac{d\alpha P_{true}}{dr}$$

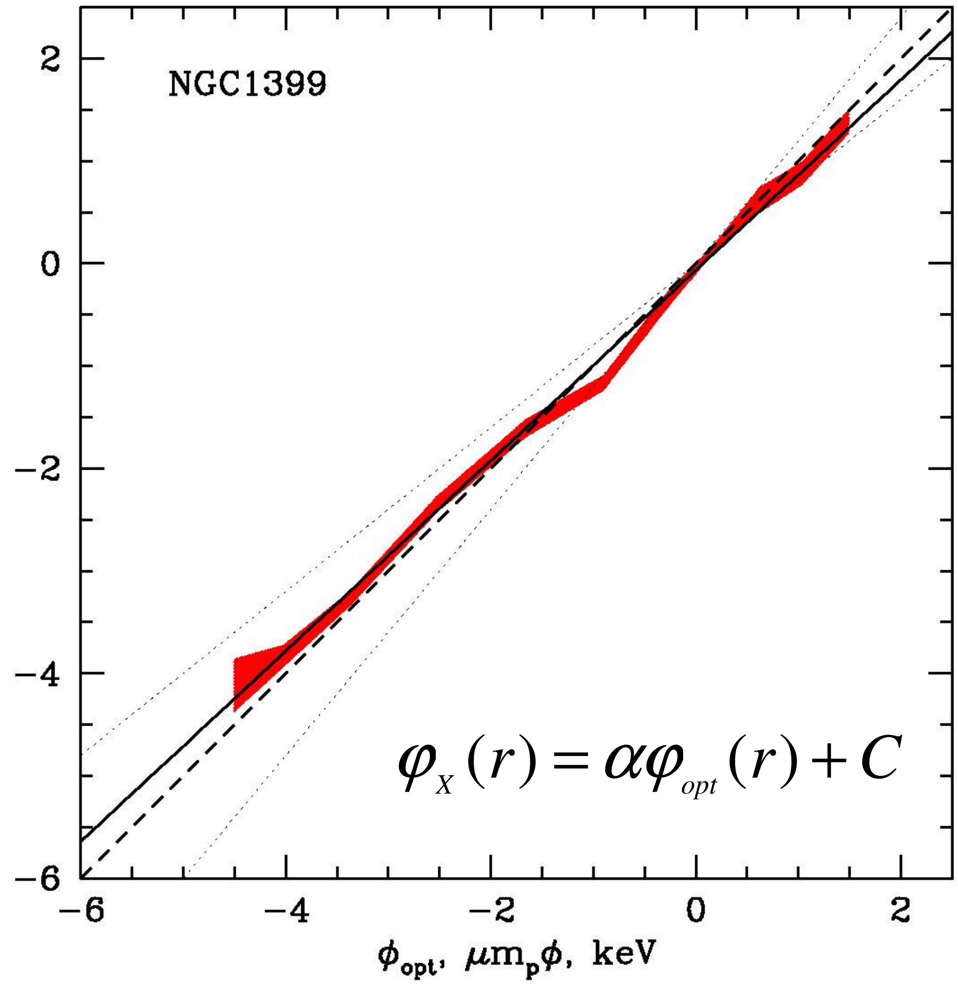
$$\varphi_X(r) \approx \alpha\, \varphi_{true}(r), \qquad \alpha \leq 1$$

NGC1399



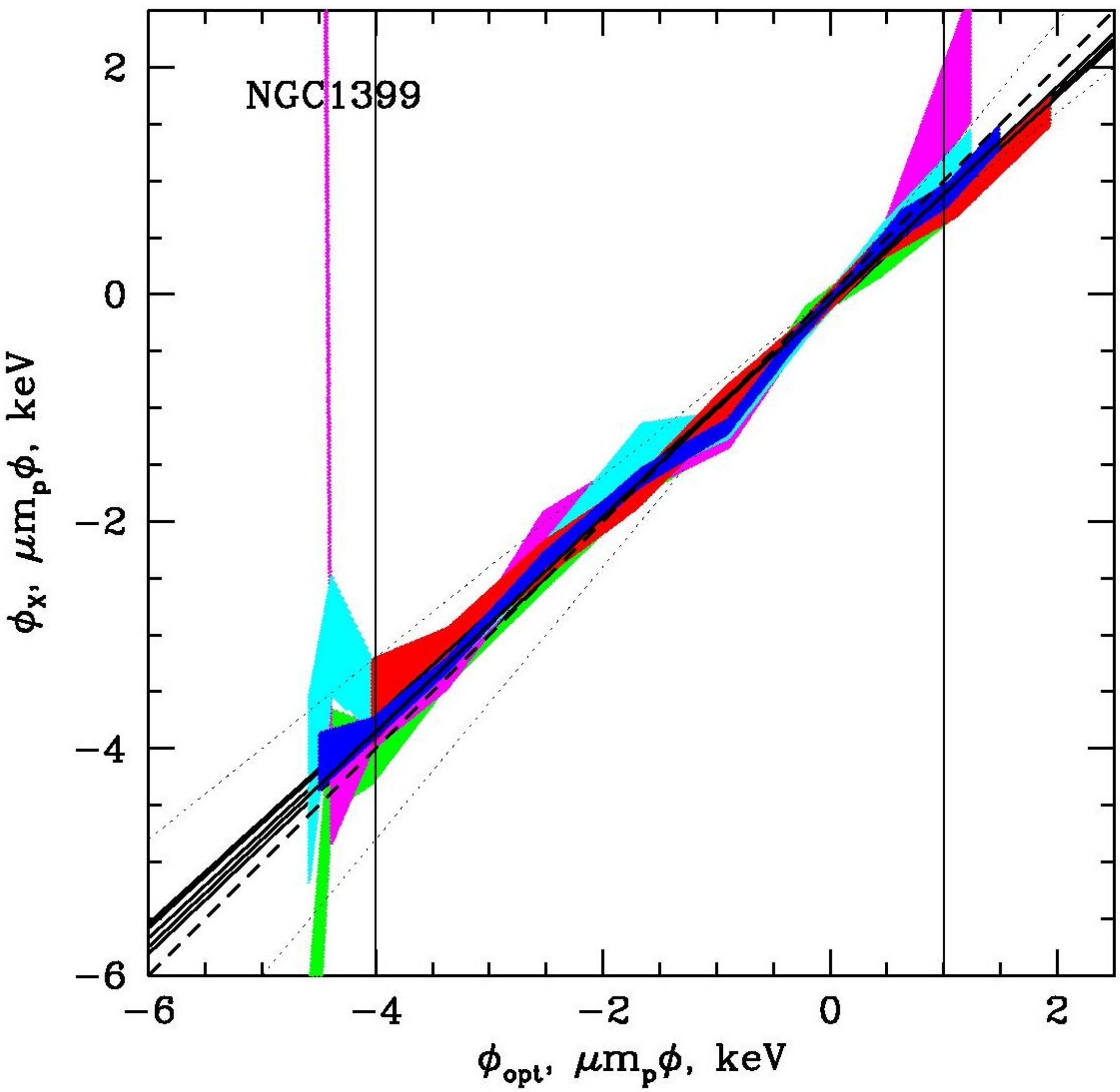
NGC1399
X-rays
Optical data
Kronawitter et al. 01
Potential, $\mu m_p \phi$, keV
Radius, arcmin
4
2
0
−2
−4
−6
0.1
1
10

NGC1399



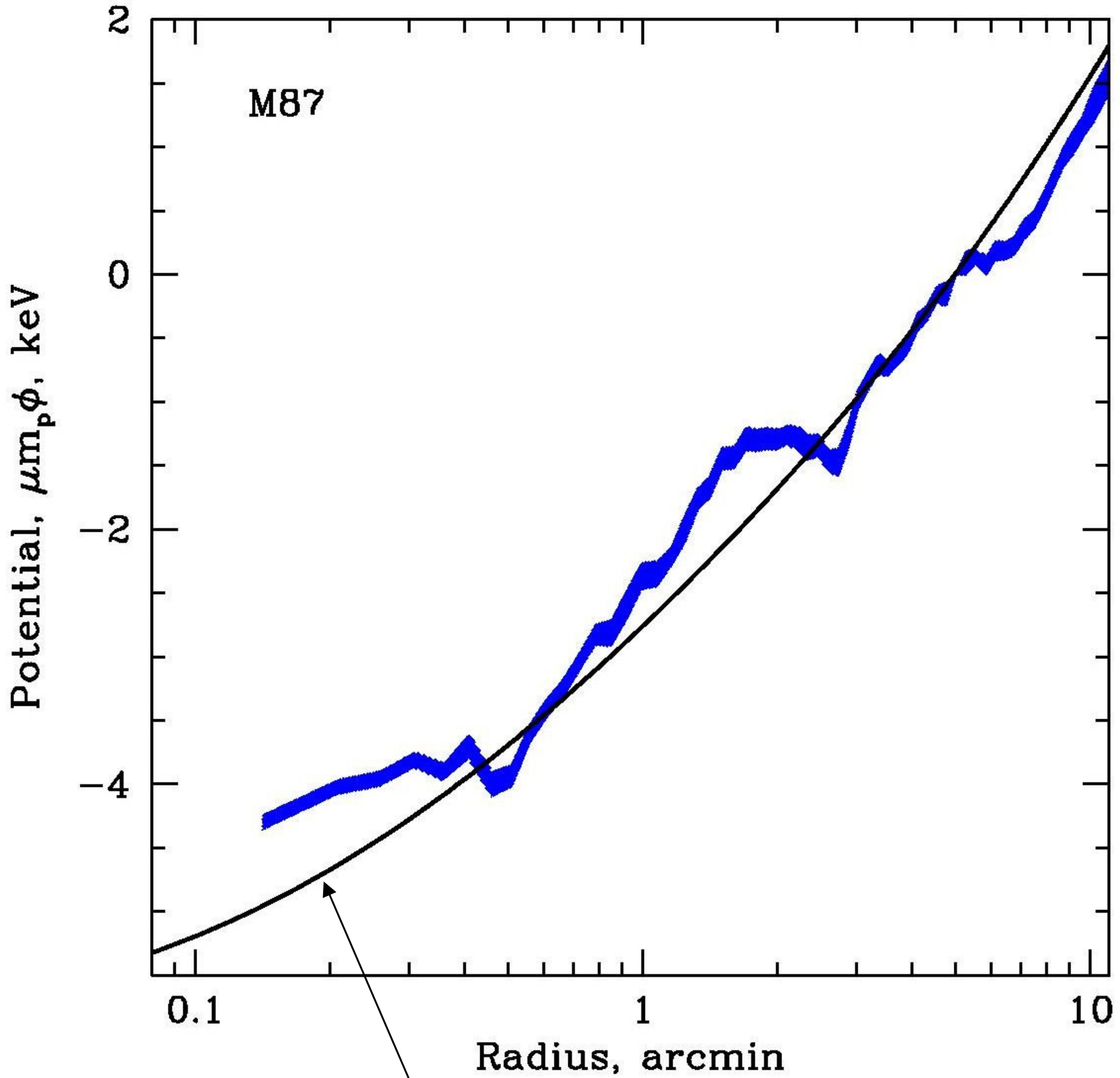
$$\varphi_X(r) \approx 0.93\,\varphi_{opt}(r) + C$$

$$U_{CR} + \frac{H^2}{8\pi} + U_{turb} = 0.07\,U_{thermal}$$



Four 90° wedges={0.95, 0.93, 0.92, 0.95}, averaged over 360°: 0.93

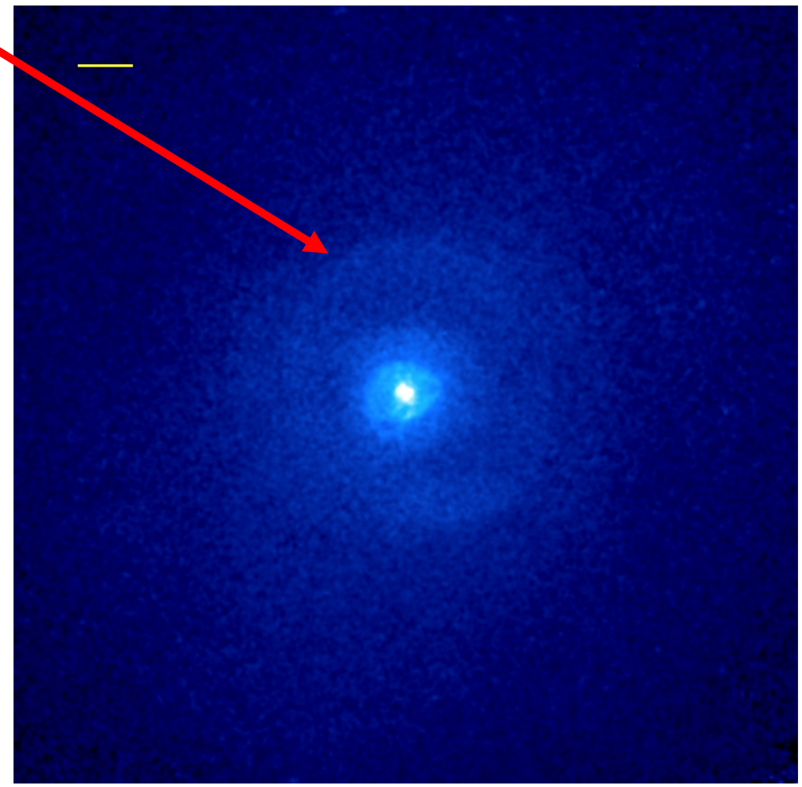
M87



Potential from stellar kinematics [Romanowsky & Kochanek, 2001]

Shock wave in M87 (Forman et al., 2007)

X-ray observations

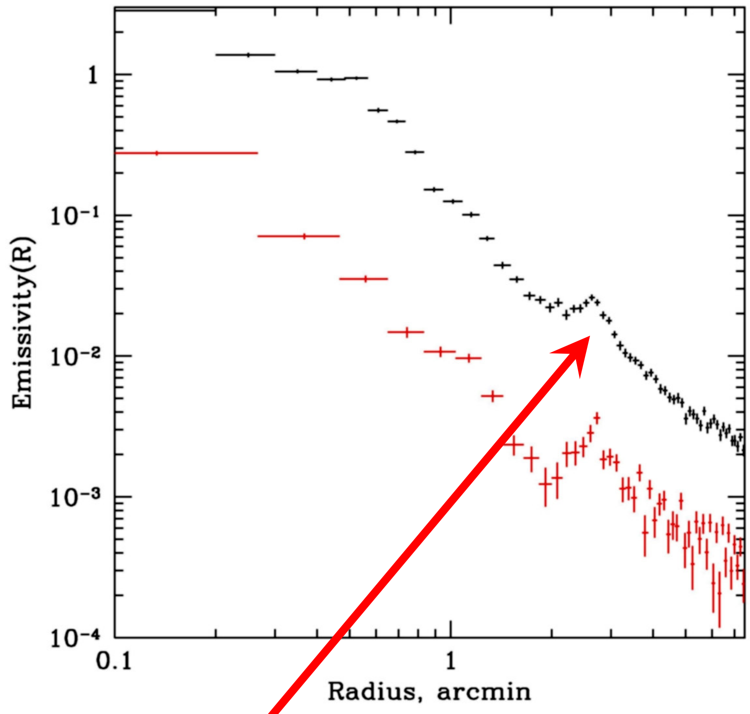


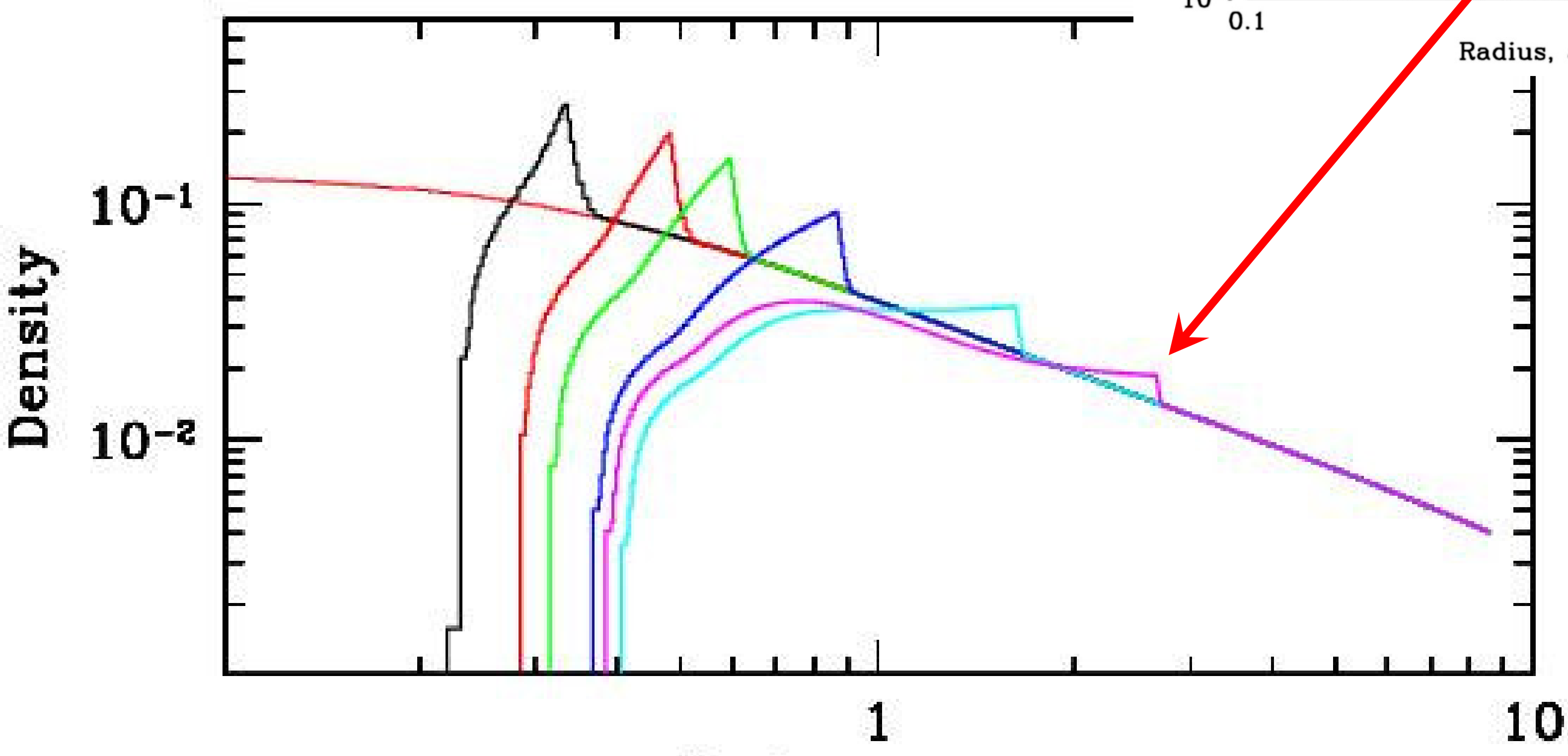
Ruszkowski+, 04

Forman+, 07

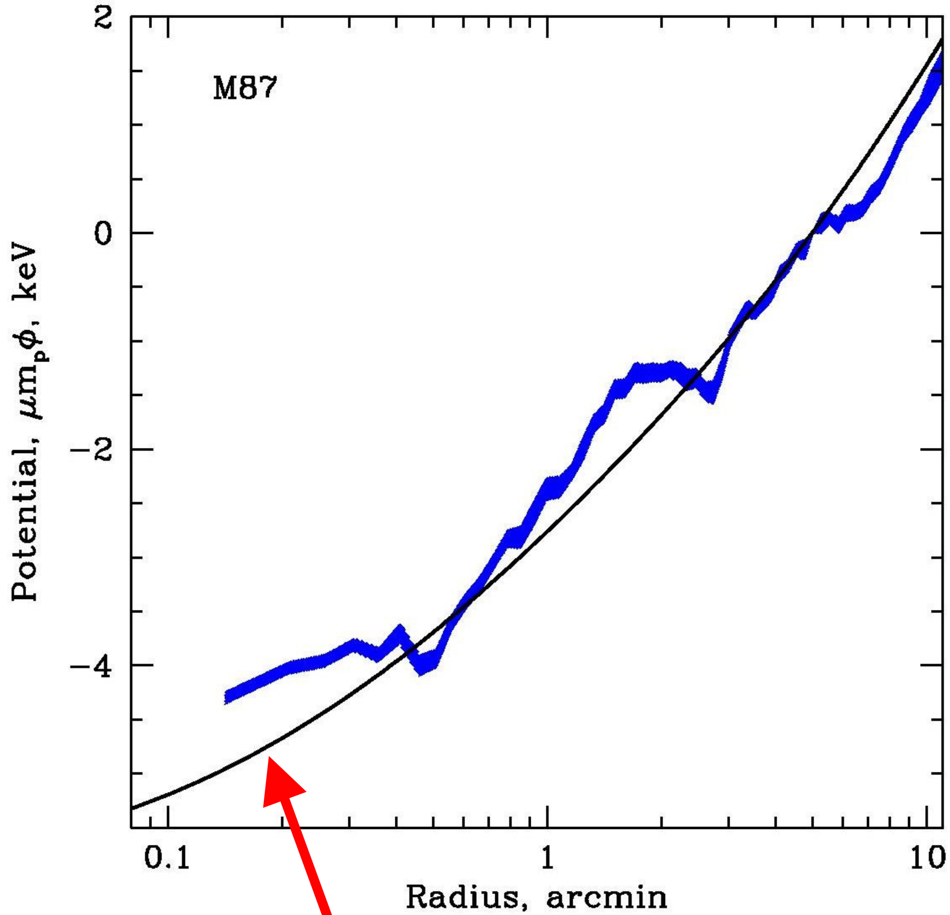
Shock wave in M87

$$E = 5\ 10^{57}\ \text{ergs}$$

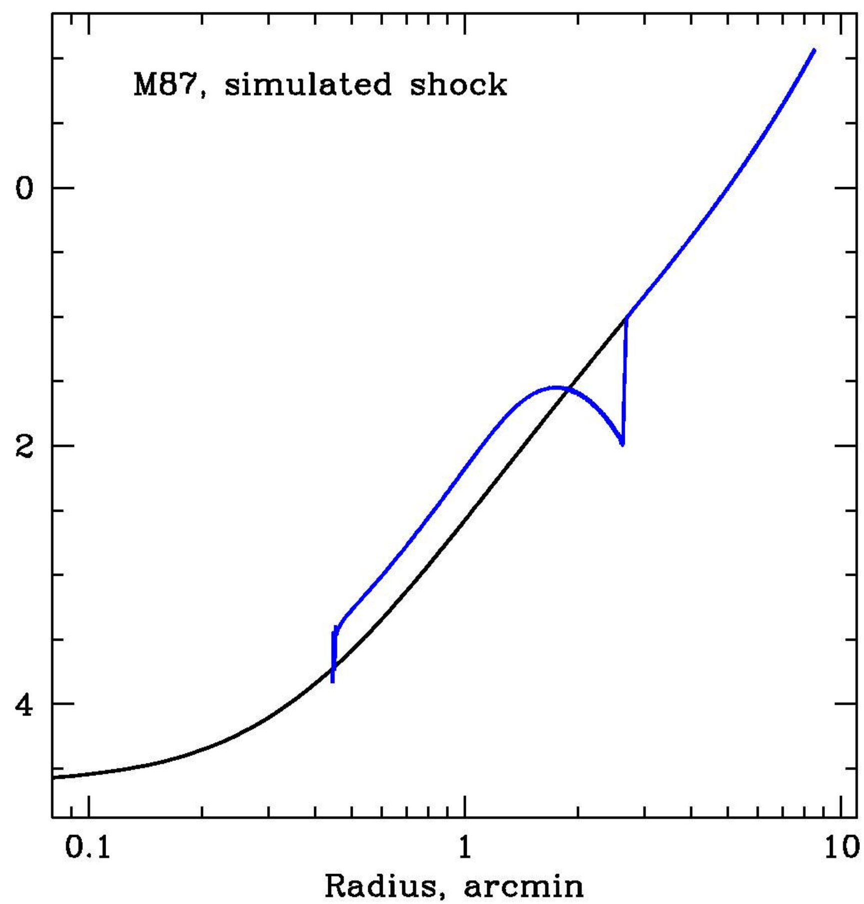




Observations

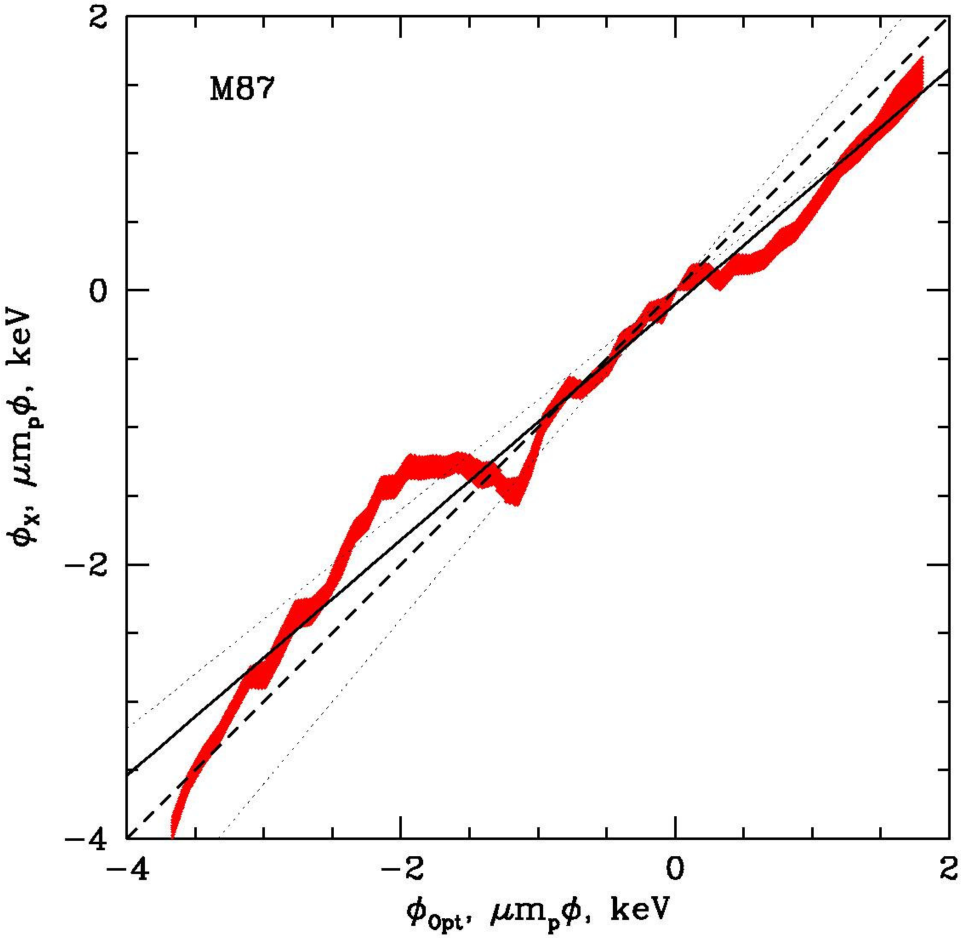


Model predictions



Potential from stellar kinematics [Romanowsky & Kochanek, 2001]

M87



$$\varphi_X(r) \approx 0.85\,\varphi_{opt}(r) + C$$

$$U_{CR} + \frac{H^2}{8\pi} + U_{turb} = 0.15\,U_{thermal}$$

Conclusions

1. Cosmic rays, magnetic fields and microturbulence make ~10% of the total gas pressure in cluster cores
   Mahdavi et al., 2008, Zhang et al. 2008

2. Hydrostatic – (surprisingly) good approximation
   for ICM (in cores)

$$U_{CR} + \frac{H^2}{8\pi} + U_{turb} \approx 0.1 - 0.2 U_{thermal}$$

GLAST (↑ U_{CR})   Faraday (↑ $\frac{H^2}{8\pi}$)   X-ray calorimeters (↑ U_{turb})