The Internal Structure of Galaxy Clusters

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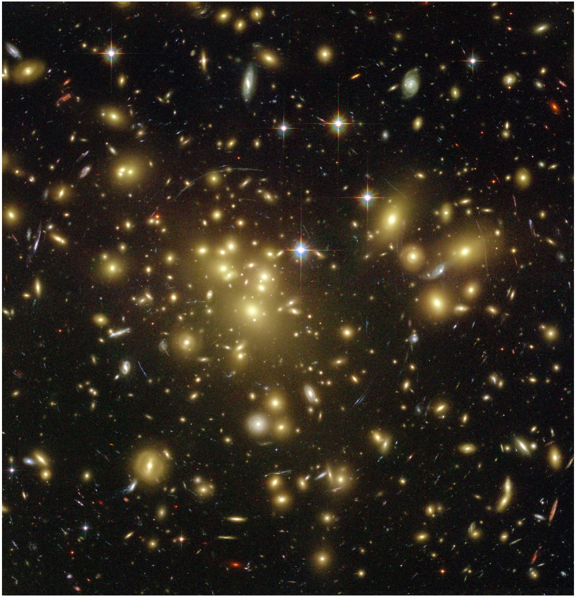
Galaxy Clusters



Structure of Simulated Clusters

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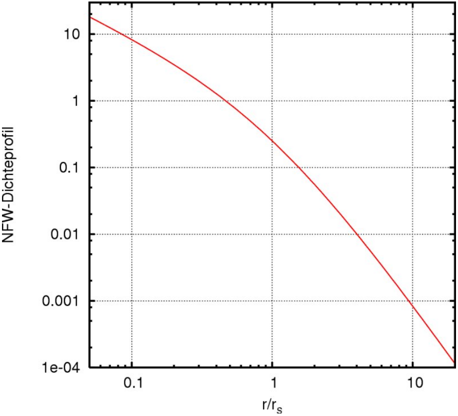
Springel et al.

Structure of Simulated Clusters

Springel et al.

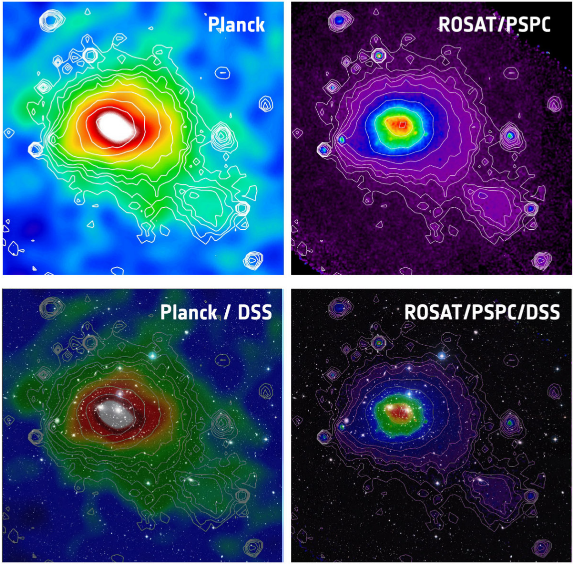


Navarro, Frenk & White 1996/97

Cluster Observables

(Umetsu et al. 2012)

Cluster Observables



(Coma cluster as seen by the Planck satellite)

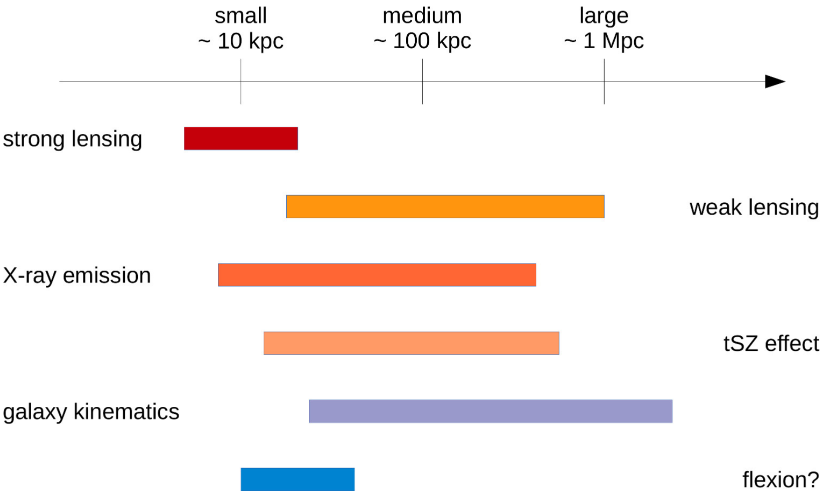
Question

Given the main observables provided by galaxy clusters:

- Gravitational lensing,
- X-ray emission,
- Thermal Sunyaev-Zel'dovich effect,
- Galaxy kinematics,

how is the cluster mass distributed?

Scales


small
~ 10 kpc
medium
~ 100 kpc
large
~ 1 Mpc
strong lensing
weak lensing
X-ray emission
tSZ effect
galaxy kinematics
flexion?

Observables: Gravitational lensing

All lensing effects given by effective lensing potential:

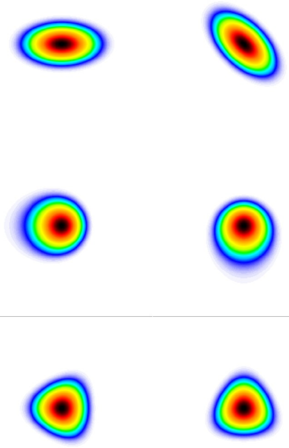
$$\psi = \frac{2}{c^2}\frac{D_{\mathrm{ds}}}{D_{\mathrm{d}}D_{\mathrm{s}}}\int \Phi \mathrm{d}z$$

(Potential) observables:

- Surface-mass density: $\kappa = \eth^\dagger \eth \psi$
- Shear: $\gamma = \eth^2 \psi$
- Critical curves:
  $\det\left(\delta_{ij} - \partial_i \partial_j \psi\right) = 0$
- Flexion: $\mathcal{F} = \eth\kappa$, $\mathcal{G} = \eth\gamma$

(“Edth” operator: $\eth = \partial_1 + \mathrm{i}\partial_2$)

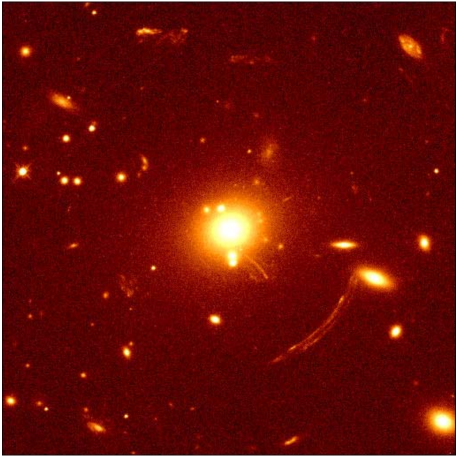
(e.g. MB 2010)



Gravitational lensing: Potential reconstruction

Procedure:

- Cover cluster with adaptive grid
- Vary lensing potential at grid points
- Until lensing observables are best reproduced



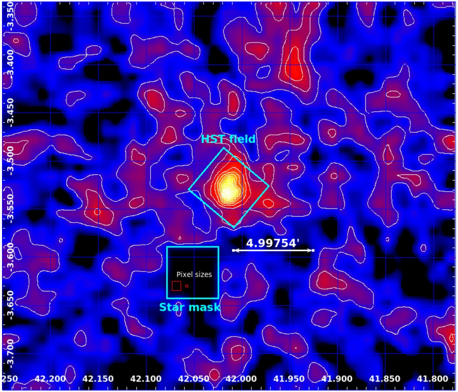
(Gavazzi 2005)

Gravitational lensing: Potential reconstruction

Procedure:

- Cover cluster with adaptive grid
- Vary lensing potential at grid points
- Until lensing observables are best reproduced

Essential quantity is the lensing (projected) Newtonian potential
(MB et al. 1996, Bradač et al. 2005, Cacciato et al. 2006, Merten et al. 2009)



Clash: Abell 383

The Clash project

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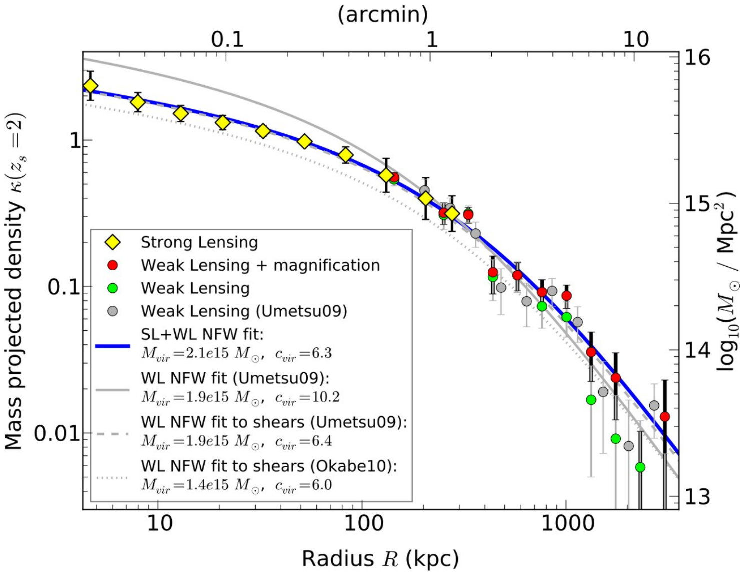
- Cluster Lensing And Supernovae with Hubble
- 25 hand-picked clusters observed with 524 Hubble orbits in 16 bands
- Additional data in optical, X-ray, and Sunyaev-Zel'dovich regimes
- Goals: internal cluster structure, galaxy evolution, high-redshift supernovae

Clash: MACS J 1206

Gravitational lensing: Potential reconstruction



Clash: Abell 2261

Observables: X-ray emission

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- Thermal bremsstrahlung:
  $j_X = C\rho^2\sqrt{T}$
- Hydrostatic equilibrium:
  $\nabla P = -\rho\nabla\Phi$
- Polytropic gas: $P/P_0 = (\rho/\rho_0)^\varkappa$

Leads to:

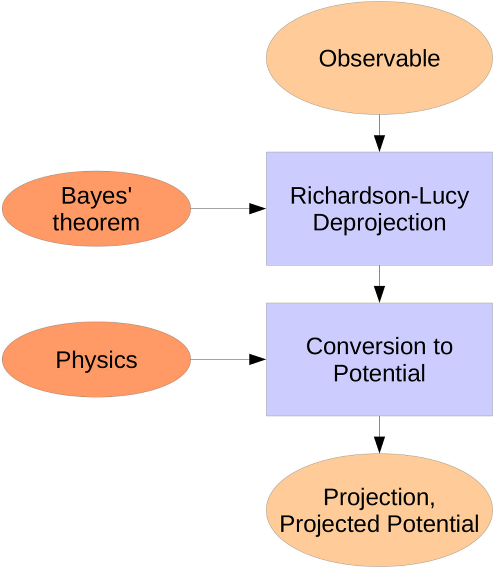
$$\frac{j_X}{j_{X,0}} = \left(-\frac{\varkappa - 1}{\varkappa}\frac{\rho_0}{P_0}(\Phi - \Phi_0)\right)^\alpha$$

with

$$\alpha = \frac{\varkappa + 3}{2(\varkappa - 1)} \approx 10$$

(Briel et al. 1992)

Joint Reconstruction Scheme



Observables: Thermal Sunyaev-Zel'dovich Effect

- Compton parameter:

$$y = \frac{k_\mathrm{B} T}{m_\mathrm{e} c^2} \sigma_\mathrm{T} n_\mathrm{e}$$

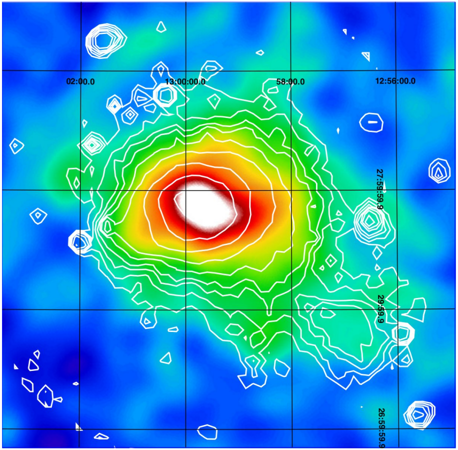
- Hydrostatic equilibrium:
  $\nabla P = -\rho \nabla \Phi$
- Polytropic gas: $P/P_0 = (\rho/\rho_0)^\varkappa$

Leads to:

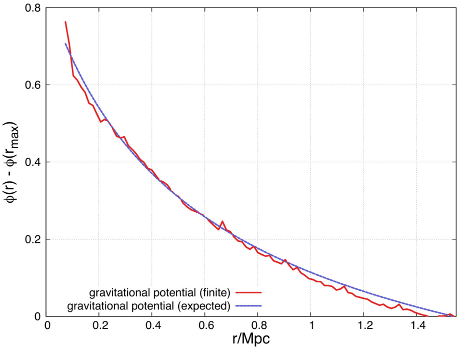
$$\frac{y}{y_0} = \left(-\frac{\varkappa - 1}{\varkappa} \frac{\rho_0}{P_0} (\Phi - \Phi_0) \right)^\beta$$

with

$$\alpha = \frac{\varkappa}{\varkappa - 1} \approx 6$$

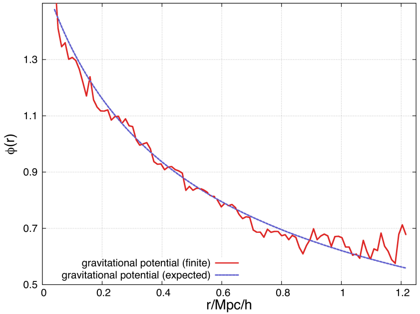


Potential from X-ray Emission and SZ Effect



X-ray emission

(Konrad et al. 2013)



thermal Sunyaev-Zel'dovich effect

(Majer et al. 2013, submitted)

Galaxy cluster assumed at $z = 0.2$ with $M = 5 \times 10^{14}\, h^{-1} M_{\odot}$

Observables: Galaxy Kinematics

- Jeans equation:

$$\frac{\partial(n\sigma_r^2)}{\partial r} + \frac{2\beta(r)}{r}(n\sigma_r^2) = -n\frac{\partial\Phi}{\partial r}$$

- Anisotropy parameter:

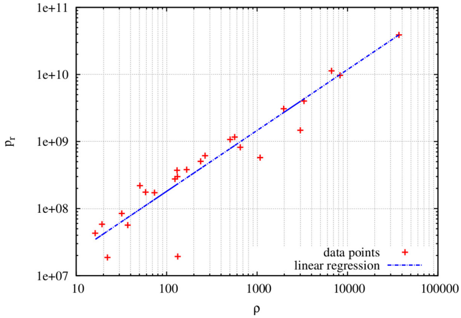
$$\beta(r) = 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$$

- Effective galaxy pressure

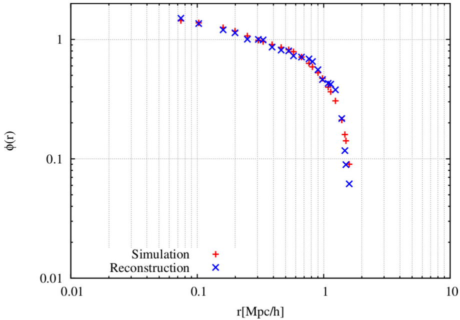
$$n\sigma_r^2 = P_\mathrm{gal} = P_\mathrm{gal,0}\left(\frac{n}{n_0}\right)^\varkappa$$

- Relation between pressure and potential: Volterra-type integral equation relating P_gal and Φ

Potential from Galaxy Kinematics



polytropic relation between galaxy pressure and density



gravitational potential recovered

Galaxy cluster assumed at $z = 0.2$ with $M = 5 \times 10^{14}\, h^{-1} M_{\odot}$

(Sarli et al. 2013, submitted)

Reconstruction of Abell 1689

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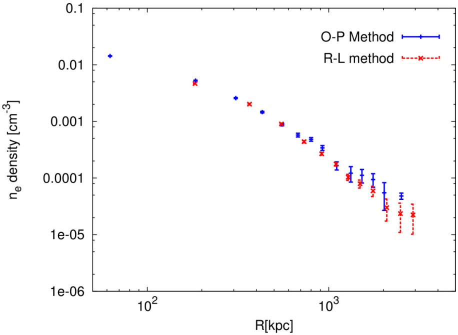
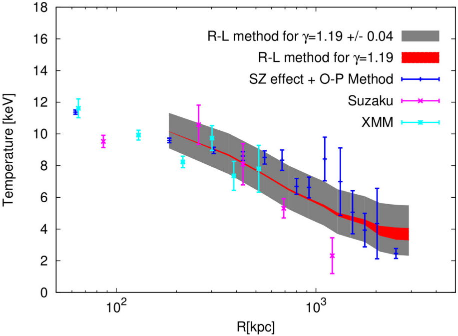


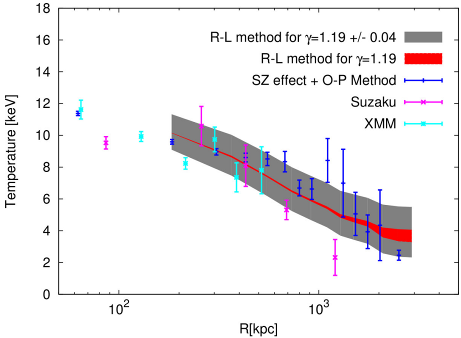
deprojected electron density in Abell 1689

Reconstruction of Abell 1689

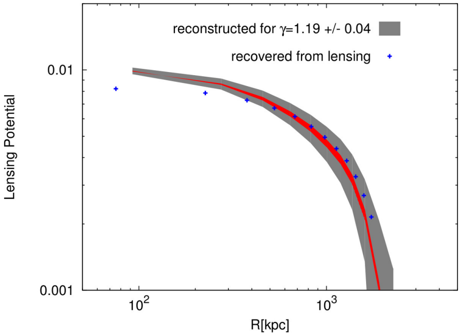


temperature profile recovered

Reconstruction of Abell 1689



temperature profile recovered



gravitational potential from X-ray emission, compared to lensing

(Tchernin et al., submitted)

Summary

- The internal structure of galaxy clusters is important for our understanding of dark matter
- All cluster observables (gravitational lensing, X-ray emission, thermal Sunyaev-Zel'dovich effect, galaxy kinematics) are determined by the gravitational potential, if equilibrium assumptions are being made
- Joint cluster reconstruction is possible combining all observables in one step
- Observables probe lensing potential on different scales
- Results seem to confirm cold dark matter