Modelling electron clouds of galaxy clusters with strong gravitational lensing

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Goals

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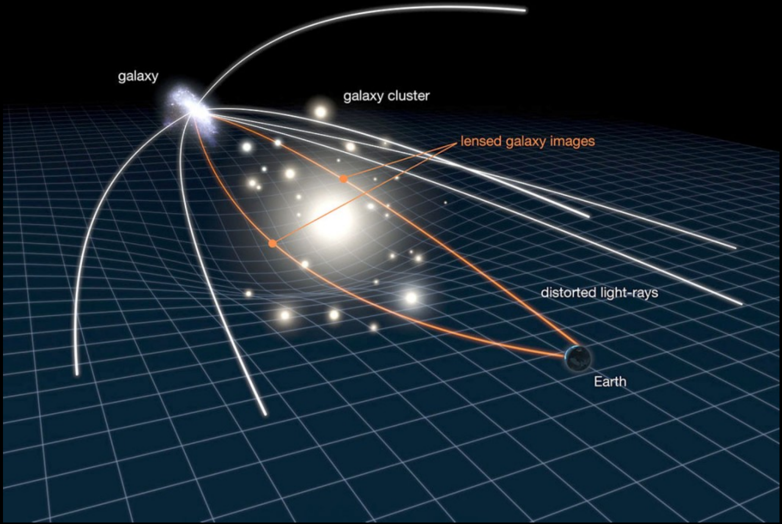
1. Model the density distribution of a galaxy cluster
2. Understand the relationship between electron/gas density and dark matter density
3. **NEW: Model the electron distribution with lensing reconstruction**

Lensing



Credits: NASA/ESA

Data & Mass reconstruction

Data: Lensing: MUSE cube (multiple images of background galaxies), HST, and DES

X-ray: XMM-Newton

Objects: MACS J0242.5-2132: $z = 0.313$, 6 systems of multiple images,

MACS J0949.8+1708: $z = 0.383$, 1 system of multiple images

Density profile: dual Pseudo Isothermal Elliptical Matter Distribution (dPIEMD):

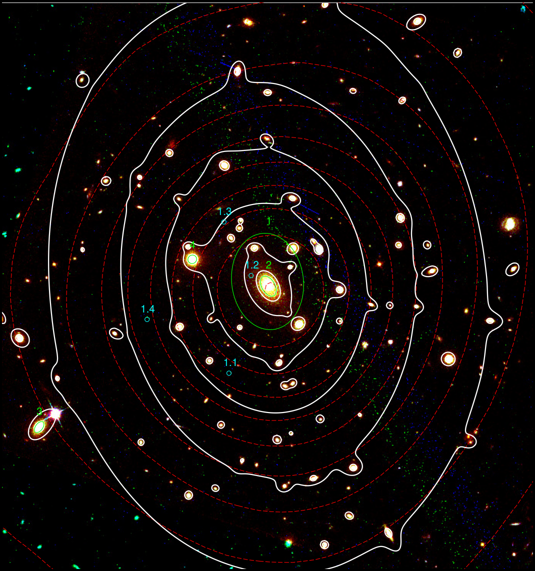
$$\rho(r) = \rho_{0,m} \left\{ \left[1 + \left(\frac{r}{r_{cut}} \right)^2 \right] \left[1 + \left(\frac{r}{r_{core}} \right)^2 \right] \right\}^{-1}$$

Mass reconstruction

DM dominant contributor to lensing

`Lenstool` optimises image plane reconstruction with MCMC

red: X-ray
white: equipotentials



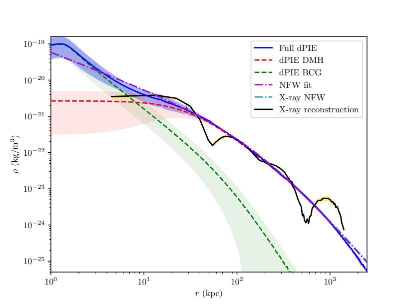
MACS J0949

Lensing results

MACS J0242

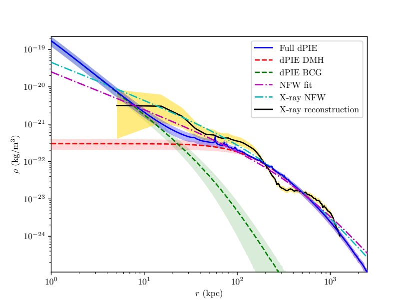
RMS = 0.51 arcsec
Relaxed

Classical cool-core cluster



MACS J0949

RMS = 0.08 arcsec
Post-merger, still relaxing
Not cool-core, not strongly disturbed



<u>Excellent agreement with X-ray and NFW profile</u>
Article in preparation

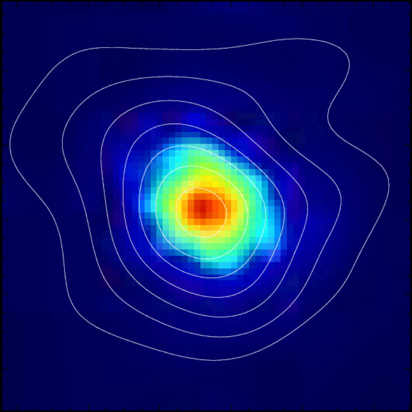
Modelling the electron cloud of clusters

Common assumption: electron cloud of galaxy clusters traces the dark matter halo (DMH).

Typically, e^- cloud of clusters are studied with X-ray and Sunyaev-Zel'dovich (SZ) effect and then compared to lensing.

SZ effect: Inverse Compton scattering of CMB photons on hot electrons in galaxy clusters

Broadens the spectral lines because of Doppler effect
$\implies$ shifts in the CMB frequency



Carlstrom et al. 2000

Modelling the electron cloud of clusters

But we have a "direct" probe of DM $\longrightarrow$ Reverse path: develop a model to reconstruct the e^- cloud and predict X-ray and SZ observations with only the lensing.

Physical interests:

1. Develop a model describing the thermodynamics, baryon and dark matter distribution
2. Relate the baryon distribution to that of DM
3. Test possible deviations to our estimations and challenge DM constraints

Classical electron number density

Usage: DMH represented by β profile on n_e and polytropic law on T_e:

$$n_e(r) = n_{e,0}\left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-\frac{3}{2}\beta}$$

$$T_e(r) = T_{e,0}\left[\frac{n_e}{n_{\mathrm{ref}}}\right]^{(\gamma-1)}$$

Literature $\{\beta;\gamma\} \sim \{0.7;1.2\}$; r_c core radius $\rightarrow$ provided by lensing dPIEMD potentials.

More complex models – derived from Vikhlinin et al. 2006 parametrisation – exist.

X-ray & SZ effect

X-ray surface brightness S_X:

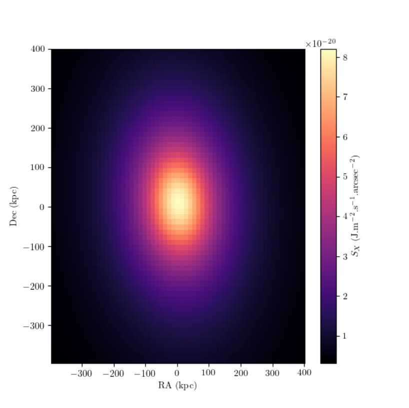
$$S_X = \frac{1}{4\pi(1+z)^3} \int n_e^2 \Lambda(Z, T_e, \Delta E) \mathrm{d}l$$

Sunyaev-Zel'dovich effect:

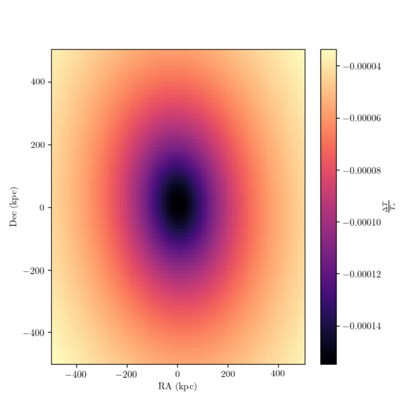
$$\frac{\Delta T}{T_r} = \left[x \coth\left(\frac{x}{2}\right) - 4 \right] \int \frac{k_B T_e}{m_e c^2} \sigma_T n_e \mathrm{d}l$$

with $x = \frac{h\nu}{k_B T_r}$.

An example



X-ray surface brightness



SZ effect

The importance of the gas fraction

To get access to the electron density normalisation through lensing, we need to know the gas fraction (local f_g cumulative F_g):

$$F_g(r) = \frac{\int_0^r \mathrm{d}s\ s^2 \rho_g(s)}{\int_0^r \mathrm{d}s\ s^2 \rho_m(s)} = \frac{M_g(< r)}{M_m(< r)}$$

$$f_g(r) = \frac{\rho_g}{\rho_m} = \frac{\mathrm{d}F_g}{\mathrm{d}r}(r)\frac{\int_0^r \mathrm{d}s\ s^2 \rho_m(s)}{r^2 \rho_m(r)} + F_g(r)$$

ρ_m total matter density (baryons + DM); ρ_g gas density.

$$\boxed{n_e(r) \propto f_g(r)\rho_m(r)}$$

Gas fraction Arctan model

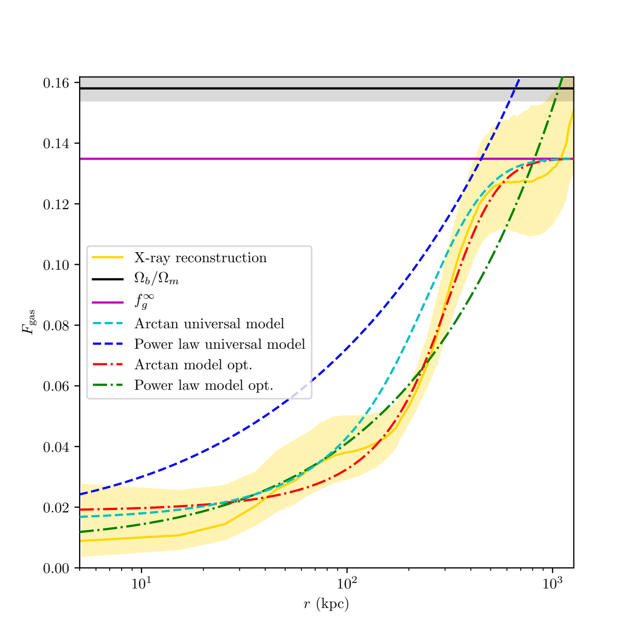
X-COP data & MACS J0242 and MACS J0949 X-ray analysis
$\implies$ First model of gas fraction distribution:

$$\boxed{F_g(r) = a \arctan\left[\exp\frac{r - r_c}{r_f}\right] + b}$$

– all parameters found in data study or depend on lensing

$\rightarrow$ Arctan model converges for $r \rightarrow \infty$, contrarily to power law model

Gas fraction models comparisons

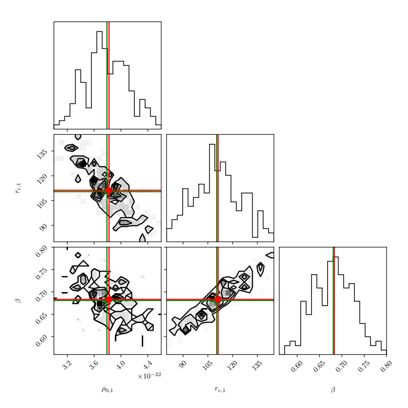


Optimisation in the classical case

Models on $\{n_e; T_e\}$ and $f_g \implies$ prediction full X-ray and SZ effect

Fit model prediction to the X-ray data $\rightarrow$ classical models: 3 parameters $\{\rho_{0,m}; r_c; \beta\}$.

Double-β model proved to be just as efficient as simple-β
$\longrightarrow$ Validates hypothesis "n_e follows the DMH"



n_e, T_e, f_g and our lensing model converge!

Dominique Eckert's universal model of polytropic index

X-COP data $\rightarrow$ universal expression of varying polytropic index:

$$\Gamma(n_e) = \Gamma_0 \left[1 + \Gamma_S \arctan\left(\frac{\ln(n_e/n_{\mathrm{ref}})}{\Gamma_T}\right)\right]$$

where all parameters Γ_0, Γ_S, Γ_T, n_{ref} are known.

$$T = T_0(z) \left(\frac{n_e E(z)^{-2}}{n_{\mathrm{ref}}}\right)^{\Gamma(n_e)-1}$$

Paper in preparation

Full electron density calculation

Poisson equation (hydrostatic equation, hypothesis: virial theorem):

$$\vec{\nabla}\left[\frac{\vec{\nabla}\left(\frac{\rho_g(r)k_B T_g(r)}{\mu_I m_P}\right)}{\rho_g(r)}\right] = -4\pi G \rho_m(r)$$

$$\Longrightarrow \quad \boxed{n_e(r) = \mathcal{J}_z^{-1}\left[\frac{\epsilon}{T_0(z)} \underbrace{\sum_i \rho_{0,m,i} h_i(r)}_{\text{deducted from } \rho_m}\right]}$$

analytically compute n_e from ρ_m!

For those who like maths

$$\boxed{n_e(r) = \mathcal{J}_z^{-1}\left[\frac{\epsilon}{T_0(z)}\sum_i \rho_{0,m,i} h_i(r)\right]}$$

$$\epsilon = -\frac{4\pi G \mu_I m_P}{k_B}$$

$$\text{writing} \quad \rho_m(r) = \sum_i \rho_{0,m,i} f_i(r)$$

$$h_i(r) = \int \mathrm{d}s\ s^{-2} \int \mathrm{d}t\ t^2 f_i(t)$$

and $T_0(z)$ an empirical relationship (Ghirardini et al. 2018) and

$$\mathcal{J}_z(n_e) = \int_0^{n_e} \frac{T_g(x)}{T_0(z)} \mathrm{d}\left[\ln\left(x T_g(x)\right)\right]$$

where $\mathcal{J}_z^{-1}$ is numerically tabulated

Limitations

Only relaxed or relaxing clusters, not yet very perturbed geometries

Only two galaxy clusters so far

Assumptions on metallicity ($Z = 0.3Z_\odot$), and on temperature normalisation

Conclusions

1. Original gas fraction models
2. Fully analytical derivation of the electron/gas density
3. Reasonable agreement between our results and the popular models in X-ray & SZ communities (β distribution and beyond)

Long term: Constrain dark matter models, and more notably IDM.

Two publications to come: lensing reconstruction and e^- clouds models optimised with X-ray.

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