Modelling electron clouds of galaxy clusters with strong gravitational lensing

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Goals

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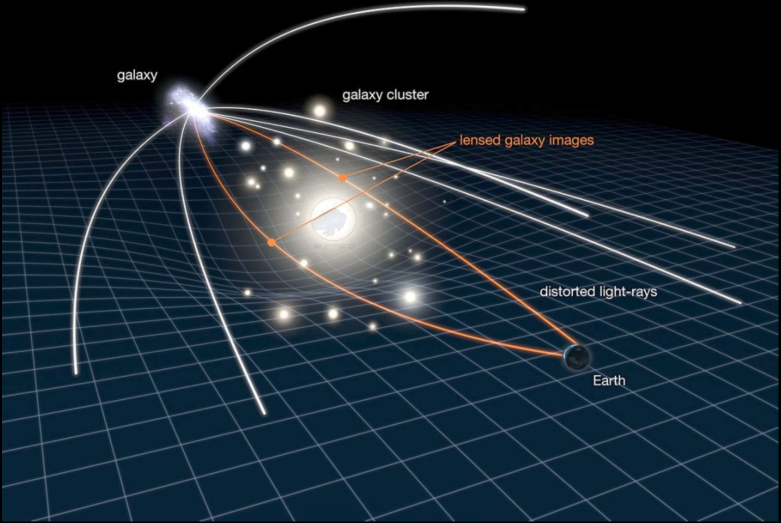
1. Model the density distribution of a galaxy cluster
2. Understand the relationship between electron/gas density and dark matter density
3. **NEW: Model the electron distribution with lensing reconstruction**

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):

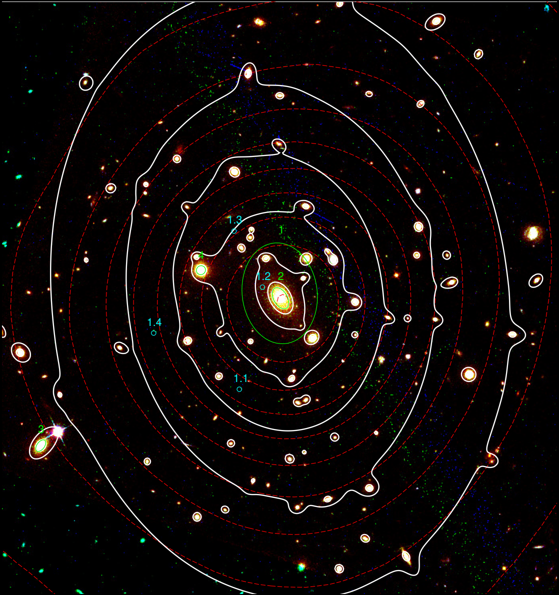
$$\rho(r) = \rho_{0,m} \left\{ \left[1 + \left(\frac{r}{r_{cut}} \right)^2 \right] \left[1 + \left(\frac{r}{r_{core}} \right)^2 \right] \right\}^{-1}$$

Mass reconstruction

MACS J0949

red: X-ray

white: equipotentials

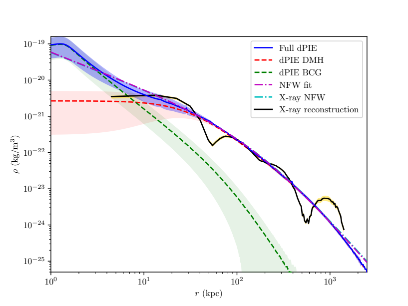


Lensing results

MACS J0242

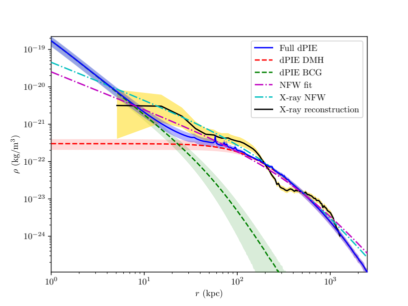
RMS = 0.51 arcsec
Relaxed

Classical cool-core cluster



MACS J0949

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



Excellent agreement with X-ray and NFW profile
Article in preparation

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 from lensing only.

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:

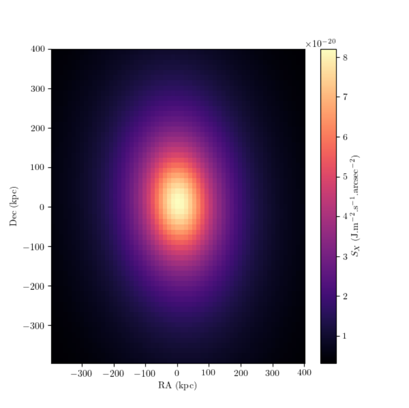
$$n_e(r) = n_{e,0}\left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-\frac{3}{2}\beta}$$

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

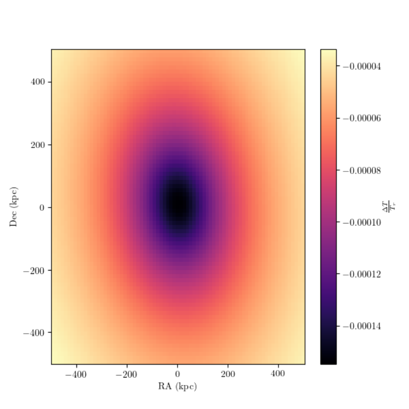
Literature $\{\beta;\gamma\} \sim \{0.7;1.2\}$; r_c core radius $\rightarrow$ provided by lensing dPIEMD potentials.

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

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

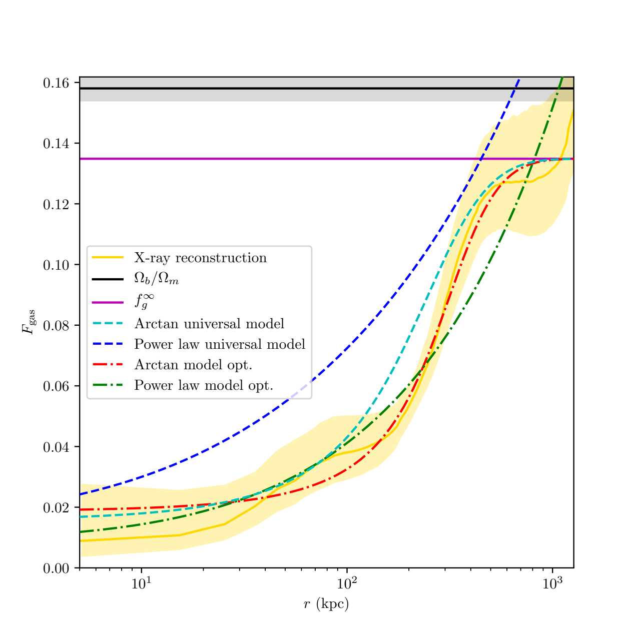
X-COP data & MACS J0242 and MACS J0949 X-ray analysis
$\implies$ First model of gas fraction distribution:

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

– 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

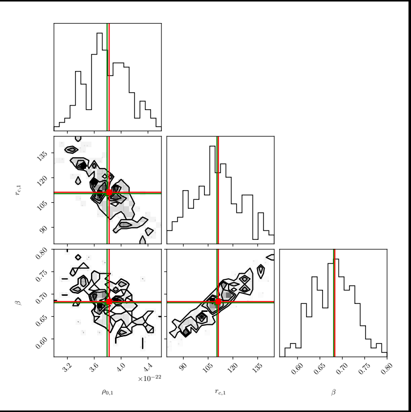


Optimisation in the classical case

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:

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

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

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

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

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

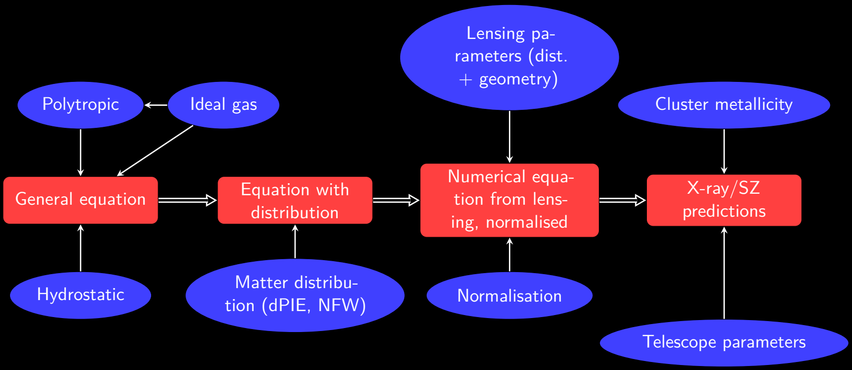
$$h_i(r) = \int \mathrm{d}s\ s^{-2} \int \mathrm{d}t\ t^2 f_i(t)$$

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

Workflow diagram



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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