# Fitting thermodynamic profiles of galaxy clusters from SZ and X-ray measurements

*Castagna Fabio, Andreon Stefano, Trombetta Alberto, Landoni Marco*

*Observing the millimeter Universe with the NIKA2 camera*

Sapienza University, Rome - 28 June 2021

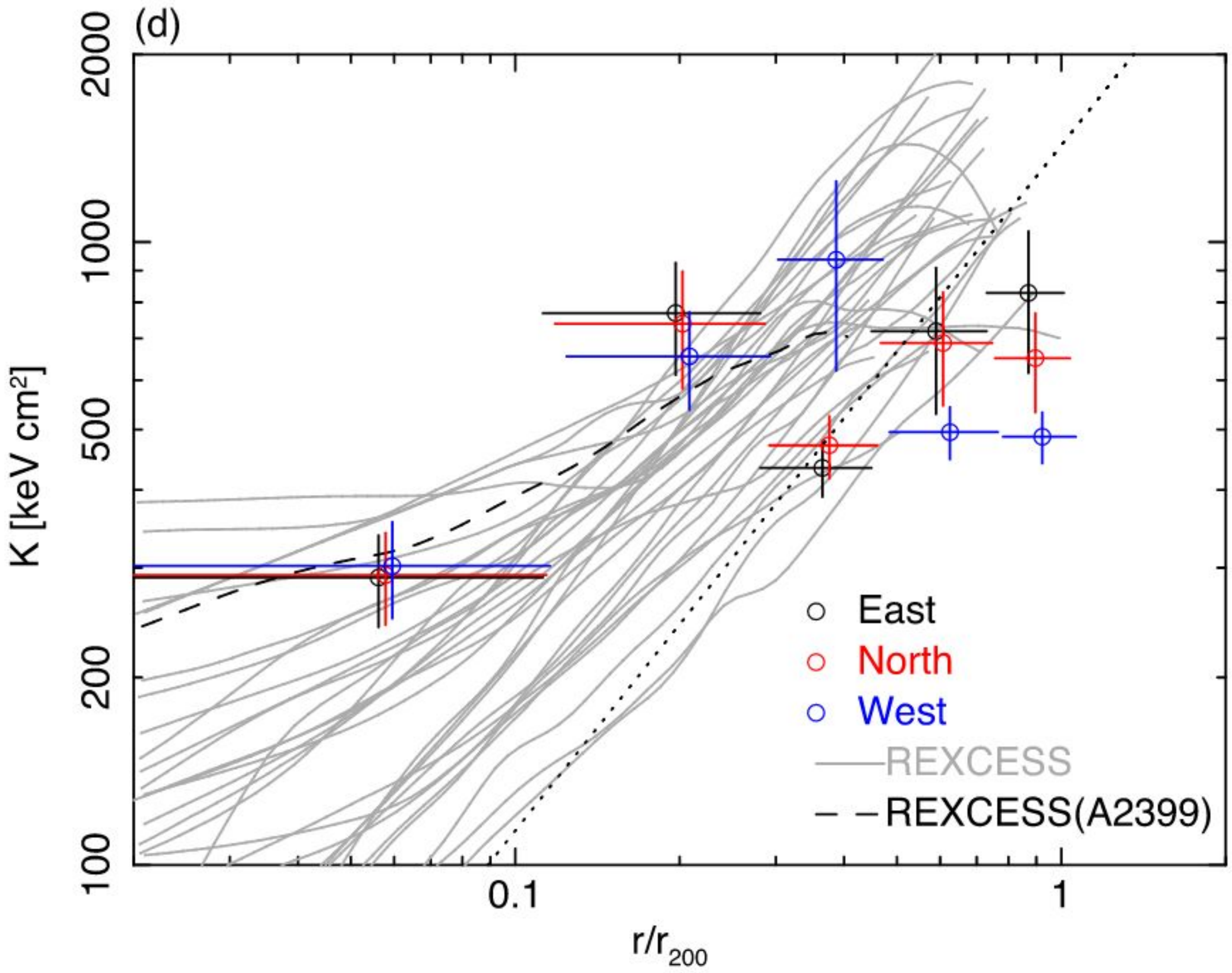
# Outline

- Why is it interesting to measure thermodynamic profiles?
- How do we derive them from SZ and X-ray measurements?
- *PreProFit* - Pressure Profile Fitting code from SZ data
- *JoXSZ* - Joint X-ray and SZ fitting code for galaxy clusters
- Future developments

# Thermodynamic profiles

➢ Give insights into the ICM **dynamical state**

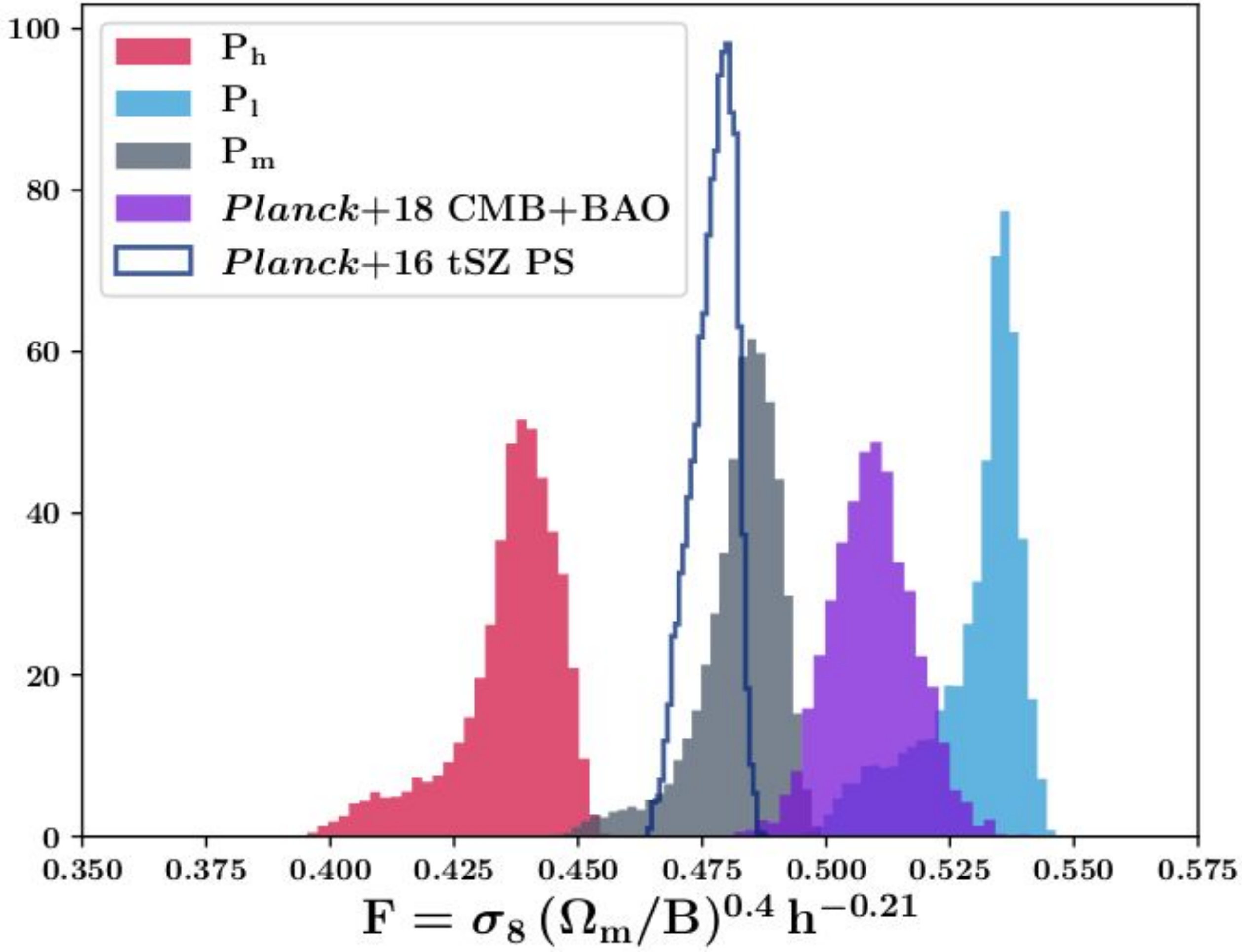
→ merger activity, shock fronts, etc.




*Mitsuishi et al. 2018*

# Cosmological applications

- ➢ Mass derivation
  - → improve constraints on cosmological parameters estimation (e.g. $\Omega_m$, $\omega$, $\sigma_8$)




*Ruppin et al. 2019*

# Thermodynamic profiles: which is our target?

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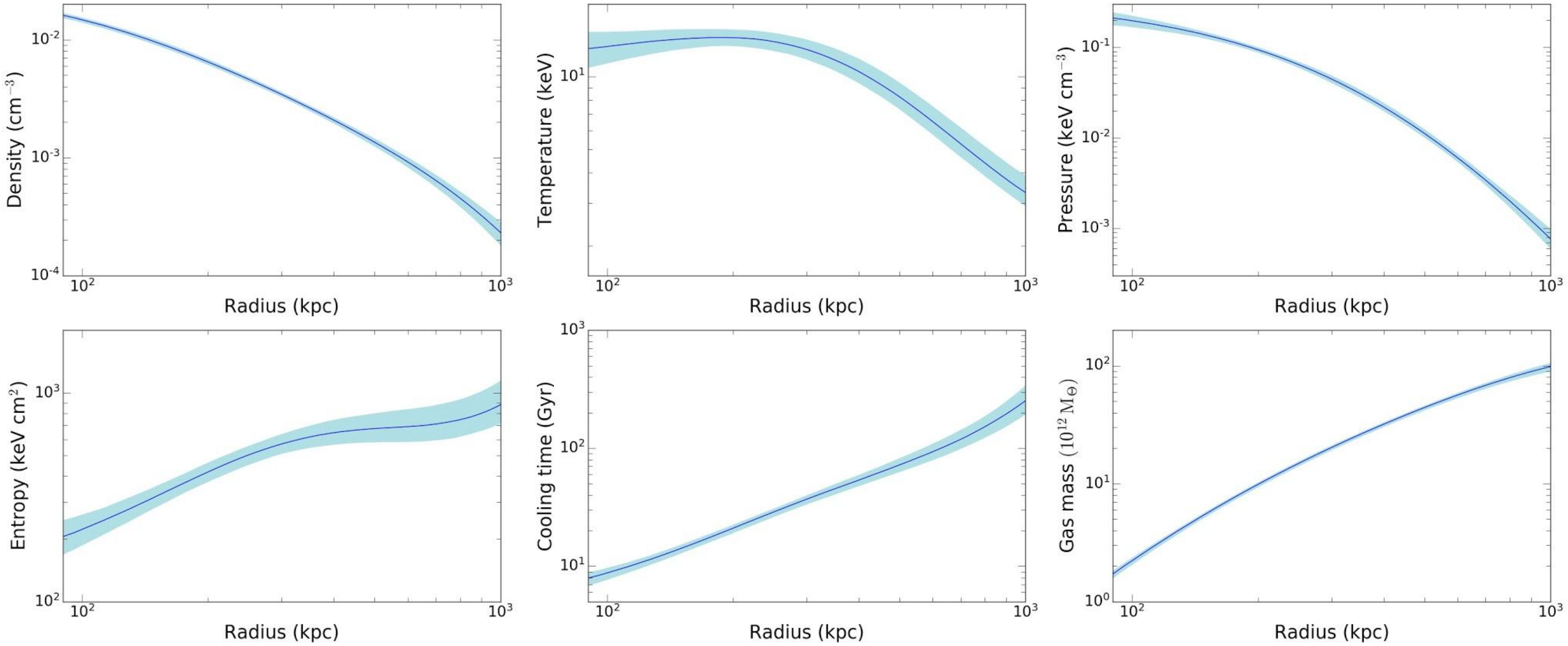


# Thermodynamic profiles derivation from multiwavelength observations

$$\begin{cases} S_X \propto \int n_e^2 T_e^{1/2} \partial \ell \\ y \propto \int n_e T_e \partial \ell \end{cases}$$

spherical symmetry

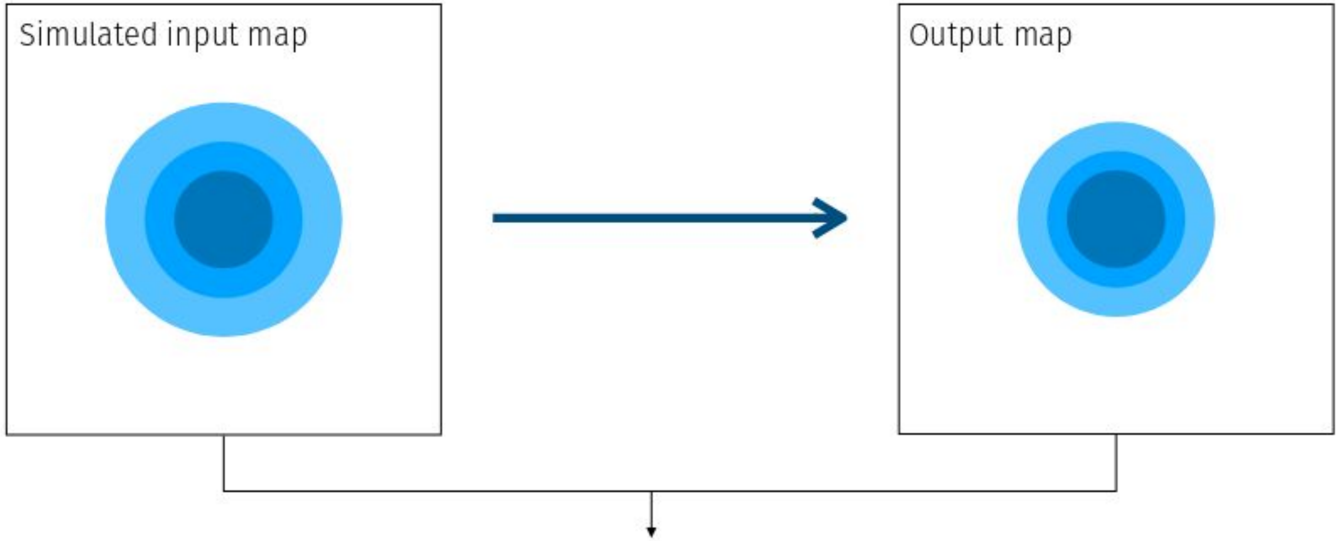
$$\Rightarrow n_e, T_e, P_e$$

$$\Rightarrow K, t_{cool}, M_{gas}$$

hydrostatic equilibrium

$$\Rightarrow M_{tot}, f_{gas}$$

# Transfer function




$$tf = \sqrt{\frac{\hat{P}_{input}(k)}{\hat{P}_{output}(k)}}$$

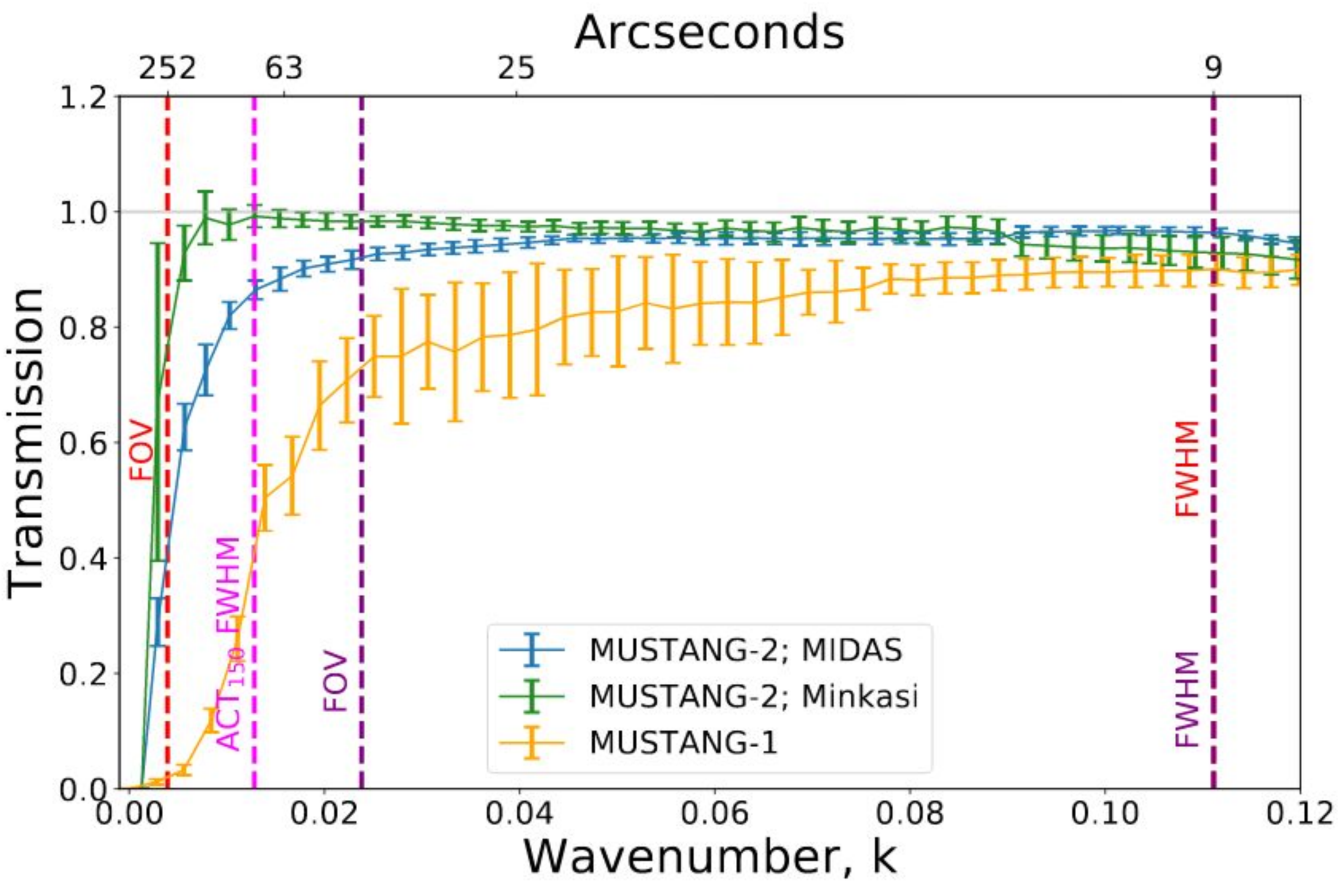
The recorded image is a **filtered** view of the true image because part of the **signal is lost** in SZ data processing.

How much? At which angular scales?

*Credit: Kéruzoré 2019*

# Transfer function

Each camera requires **its own** transfer function




*Credit: Romero 2019*

# *PreProFit*

# Pressure Profile Fitting code for galaxy clusters from SZ data

# PreProFit

- SZ-only analysis

A&A 632, A22 (2019)
https://doi.org/10.1051/0004-6361/201936487


Astronomy & Astrophysics

## PreProFit: Pressure Profile Fitter for galaxy clusters

Fabio Castagna and Stefano Andreon

INAF-Osservatorio Astronomico di Brera, via Brera 28, 20121 Milano, Italy
e-mail: fabio.castagna@inaf.it

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**ABSTRACT**

Galaxy cluster analyses based on high-resolution observations of the Sunyaev–Zeldovich (SZ) effect have become common in the last decade. We present PreProFit, the first publicly available code designed to fit the pressure profile of galaxy clusters from SZ data. PreProFit is based on a Bayesian forward-modelling approach, allows the analysis of data coming from different sources, adopts a flexible parametrization for the pressure profile, and fits the model to the data accounting for Abel integral, beam smearing, and transfer function filtering. PreProFit is computationally efficient, is extensively documented, has been released as an open source Python project, and was developed to be part of a joint analysis of X-ray and SZ data on galaxy clusters. PreProFit returns $\chi^2$, model parameters and uncertainties, marginal and joint probability contours, diagnostic plots, and surface brightness radial profiles. PreProFit also allows the use of analytic approximations for the beam and transfer functions useful for feasibility studies.

**Key words.** methods: data analysis – methods: numerical – methods: statistical – galaxies: clusters: intracluster medium – cosmic background radiation

### 1. Introduction

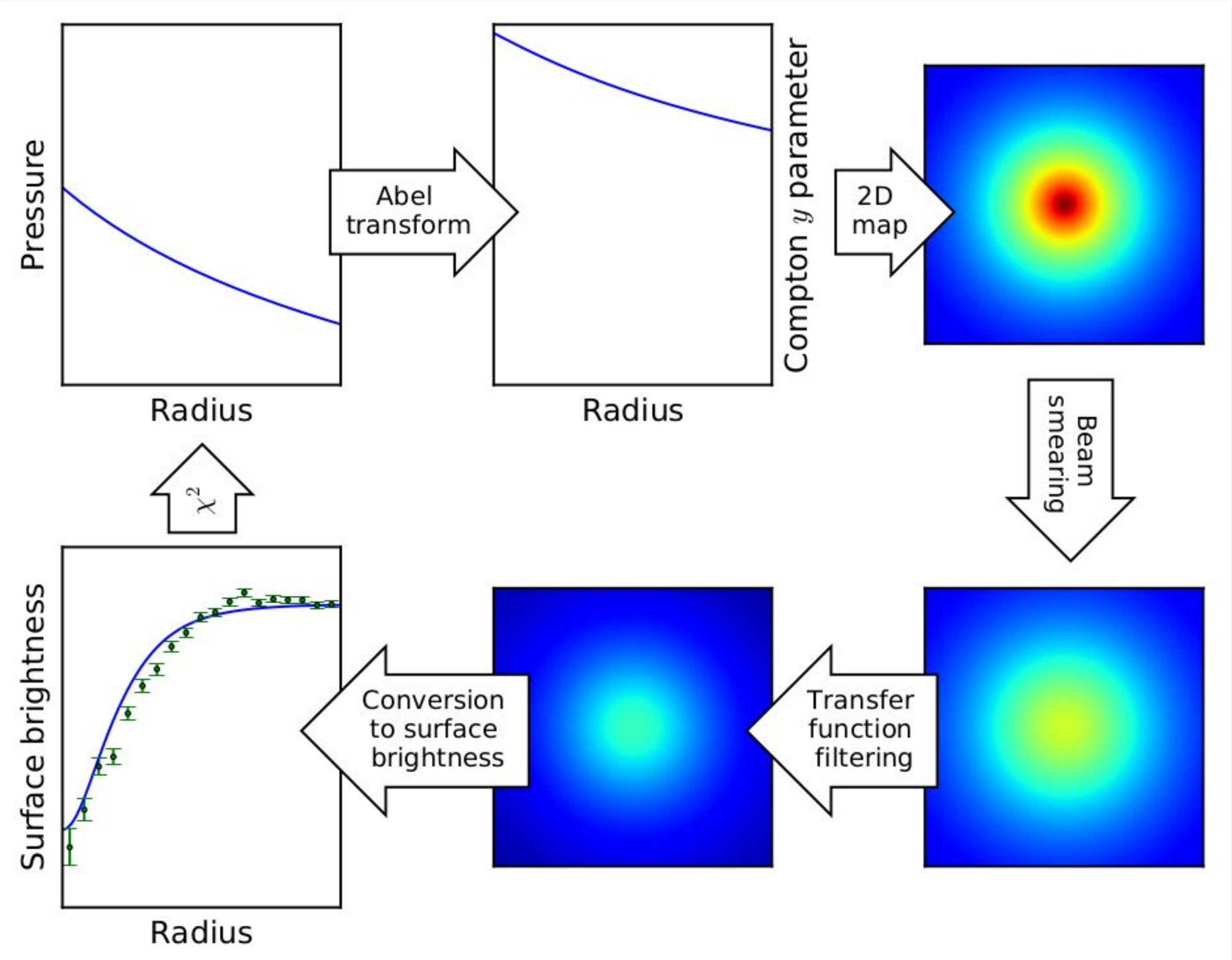
Galaxy clusters are the largest and most massive gravitationally bound objects in the Universe, and thus they offer a unique tracer of cosmic evolution. The thermodynamic properties of

2011; Sayers et al. 2013; Adam et al. 2015; Romero et al. 2017) and the methodologies for operating with these data are constantly evolving. In most cases, the SZ data analysis improves in order to meet the specific demands of each analysis (e.g. using

https://github.com/fcastagna/preprofit

# Program flow

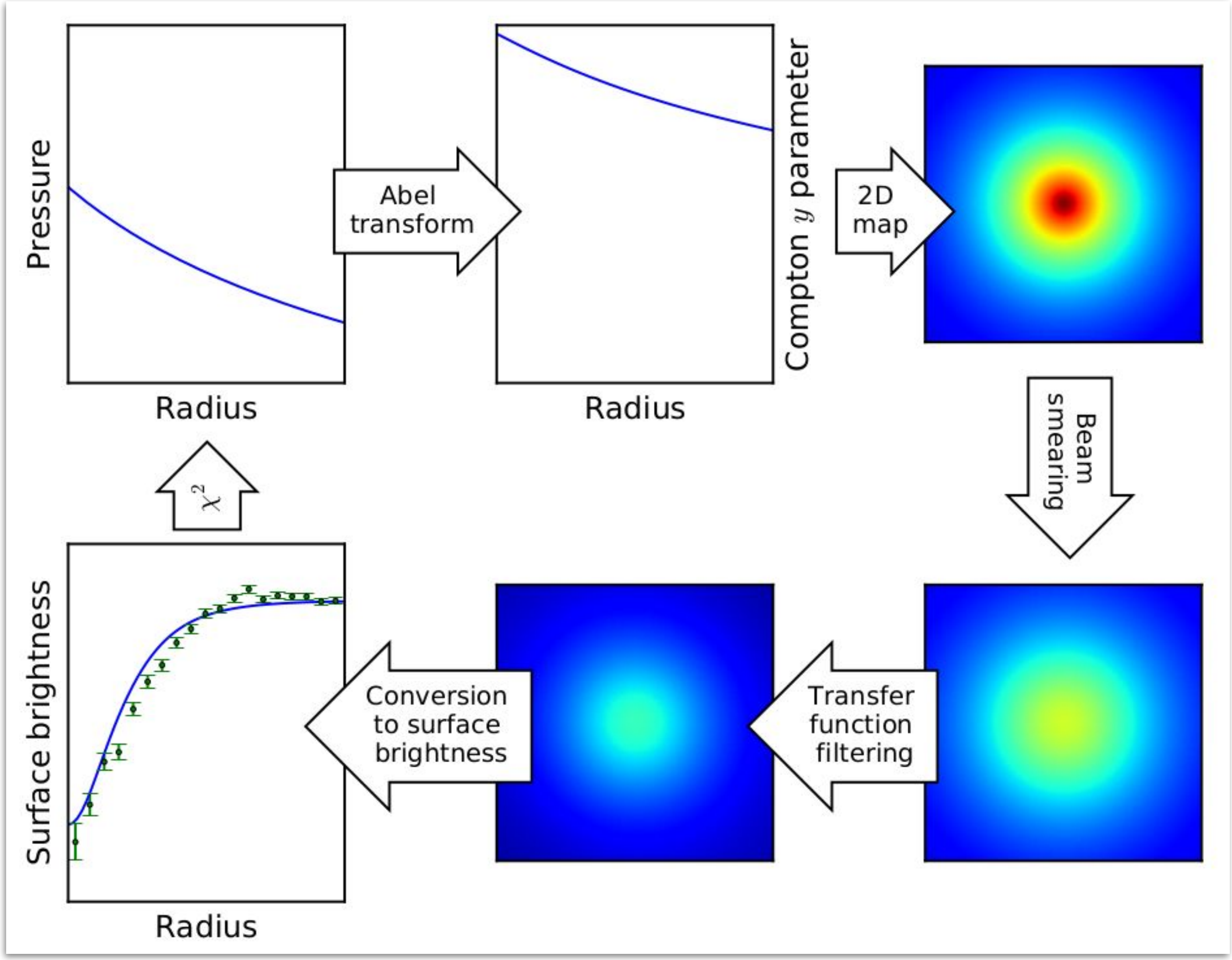
- ➢ Forward-modelling
- ➢ Bayesian estimation



# Program flow

➢ Forthcoming version

→ 1D Hankel transforms



# *JoXSZ*

# Joint X-ray data cube and SZ fitting code for galaxy clusters

# *JoXSZ*

➢ Joint analysis

A&A 639, A73 (2020)
https://doi.org/10.1051/0004-6361/202037543


Astronomy & Astrophysics

## JoXSZ: Joint X-SZ fitting code for galaxy clusters

Fabio Castagna and Stefano Andreon

INAF-Osservatorio Astronomico di Brera, Via Brera 28, 20121 Milano, Italy
e-mail: fabio.castagna@inaf.it

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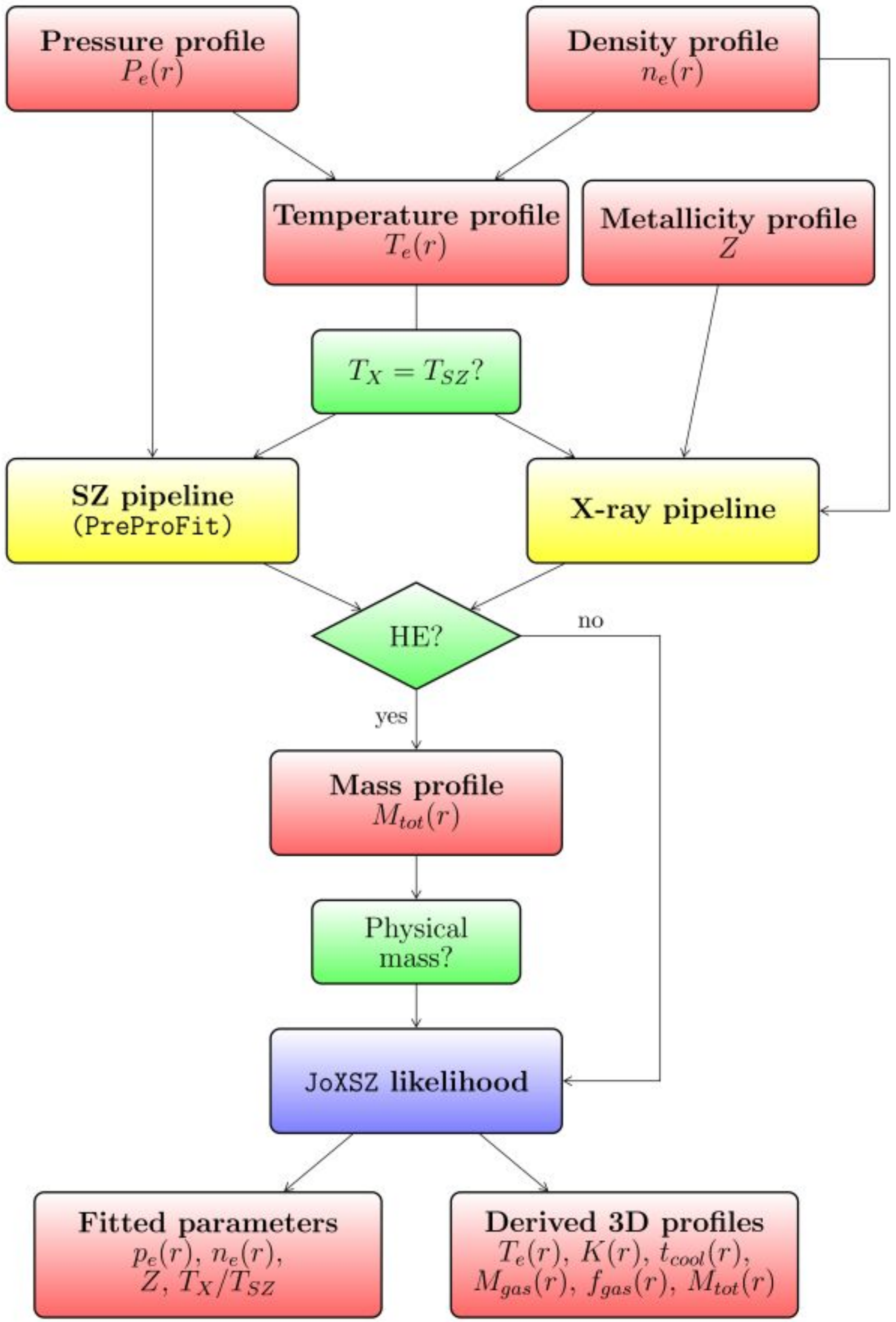
**ABSTRACT**

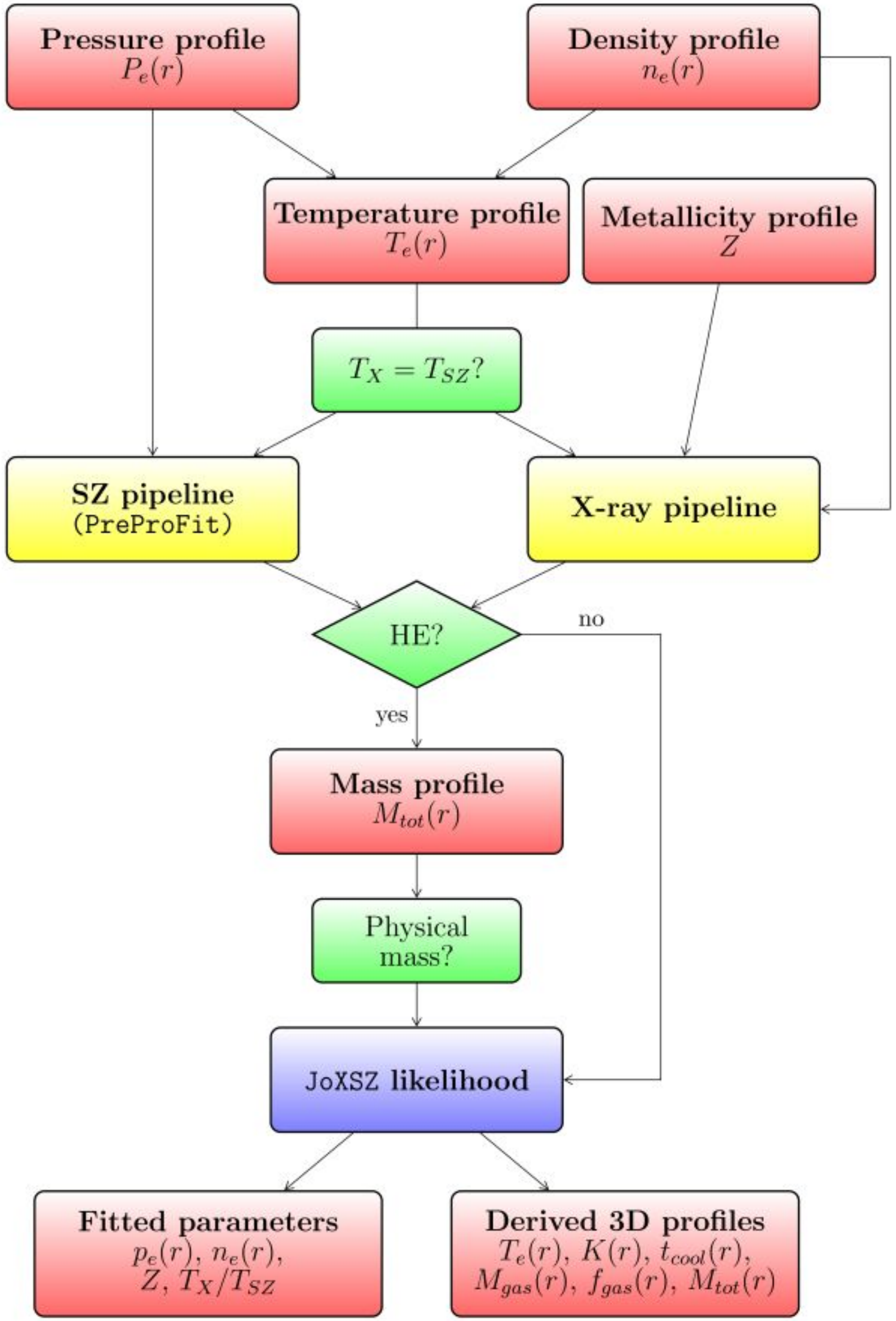
The thermal Sunyaev-Zeldovich (SZ) effect and the X-ray emission offer separate and highly complementary probes of the thermodynamics of the intracluster medium. We present JoXSZ, the first publicly available code designed to jointly fit SZ and X-ray data coming from various instruments to derive the thermodynamic profiles of galaxy clusters. JoXSZ follows a fully Bayesian forward-modelling approach, accounts for the SZ calibration uncertainty, and for the X-ray background level systematic. It improves upon most current and not publicly available analyses because it adopts the correct Poisson-Gauss expression for the joint likelihood, makes full use of the information contained in the observations, even in the case of missing values within the datasets, has a more inclusive error budget, and adopts a consistent temperature in the various parts of the code, allowing for differences between X-ray and SZ gas-mass weighted temperatures when required by the user. JoXSZ accounts for beam smearing and data analysis transfer function, accounts for the temperature and metallicity dependencies of the SZ and X-ray conversion factors, adopts flexible parametrisation for the thermodynamic profiles, and on user request, allows either adopting or relaxing the assumption of hydrostatic equilibrium (HE). When HE holds, JoXSZ uses a physical (positive) prior on the radial derivative of the enclosed mass and derives the mass profile and overdensity radii $r_\Delta$. For these reasons, JoXSZ goes beyond simple SZ and electron density fits. We illustrate the use of JoXSZ by combining Chandra and NIKA data of the high-redshift cluster CL J1226.9+3332. The code is written in Python, it is fully documented, and the users are free to customise their analysis in accordance with their needs and requirements. JoXSZ is publicly available on GitHub.

**Key words.** methods: data analysis – methods: numerical – methods: statistical – galaxies: clusters: intracluster medium – cosmic background radiation – X-rays: galaxies: clusters

https://github.com/fcastagna/joxsz




- **Joint** and **consistent** use of information encoded in the data
- **Flexible** parametrization
- Correct **Poisson-Gauss** expression for the joint likelihood
- **Bayesian** forward-modelling approach

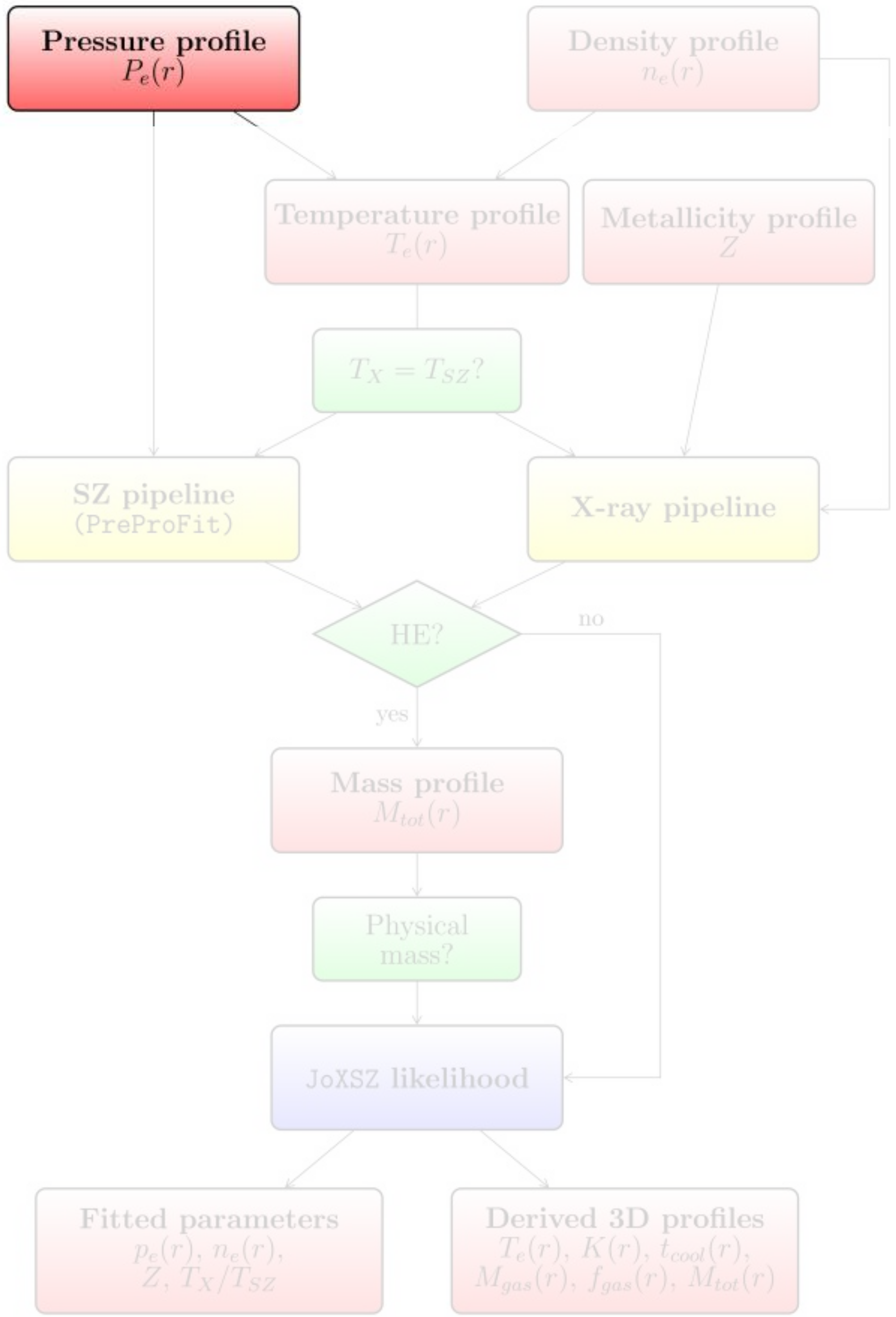



⇐ Prior knowledge:
**P (param)**

Bayes theorem:
**P (param | data) ∝ P (data | param) * P (param)**

⇐ Likelihood evaluation:
**P (data | param)**

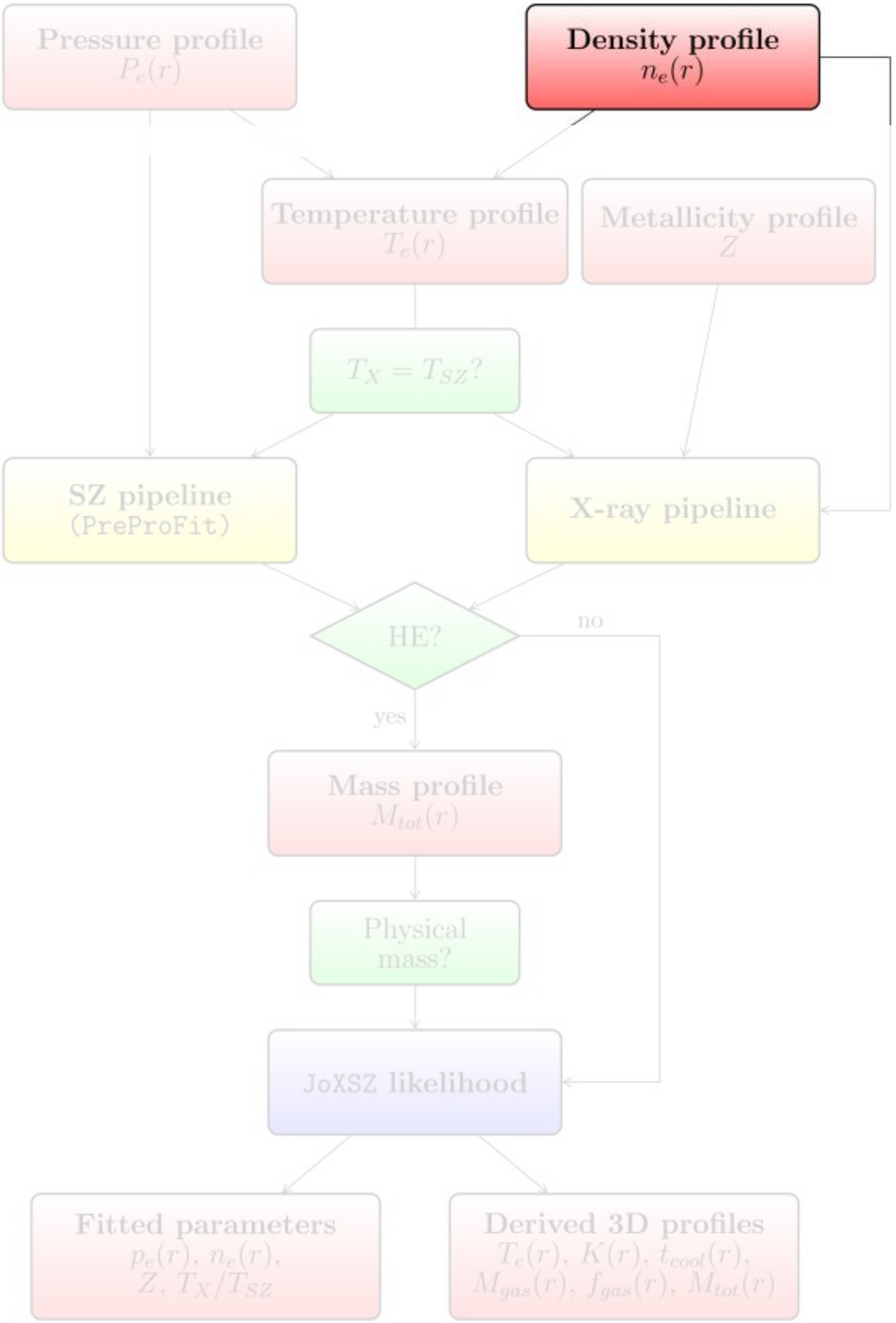
⇐ Posterior knowledge:
**P (param | data)**




- ➢ Currently
  - → parametric profile: **gNFW** (generalised Navarro, Frenk & White)

$$P_e(r) = \frac{P_0}{\left(\frac{r}{r_p}\right)^c \left(1 + \left(\frac{r}{r_p}\right)^a\right)^{\frac{b-c}{a}}}$$

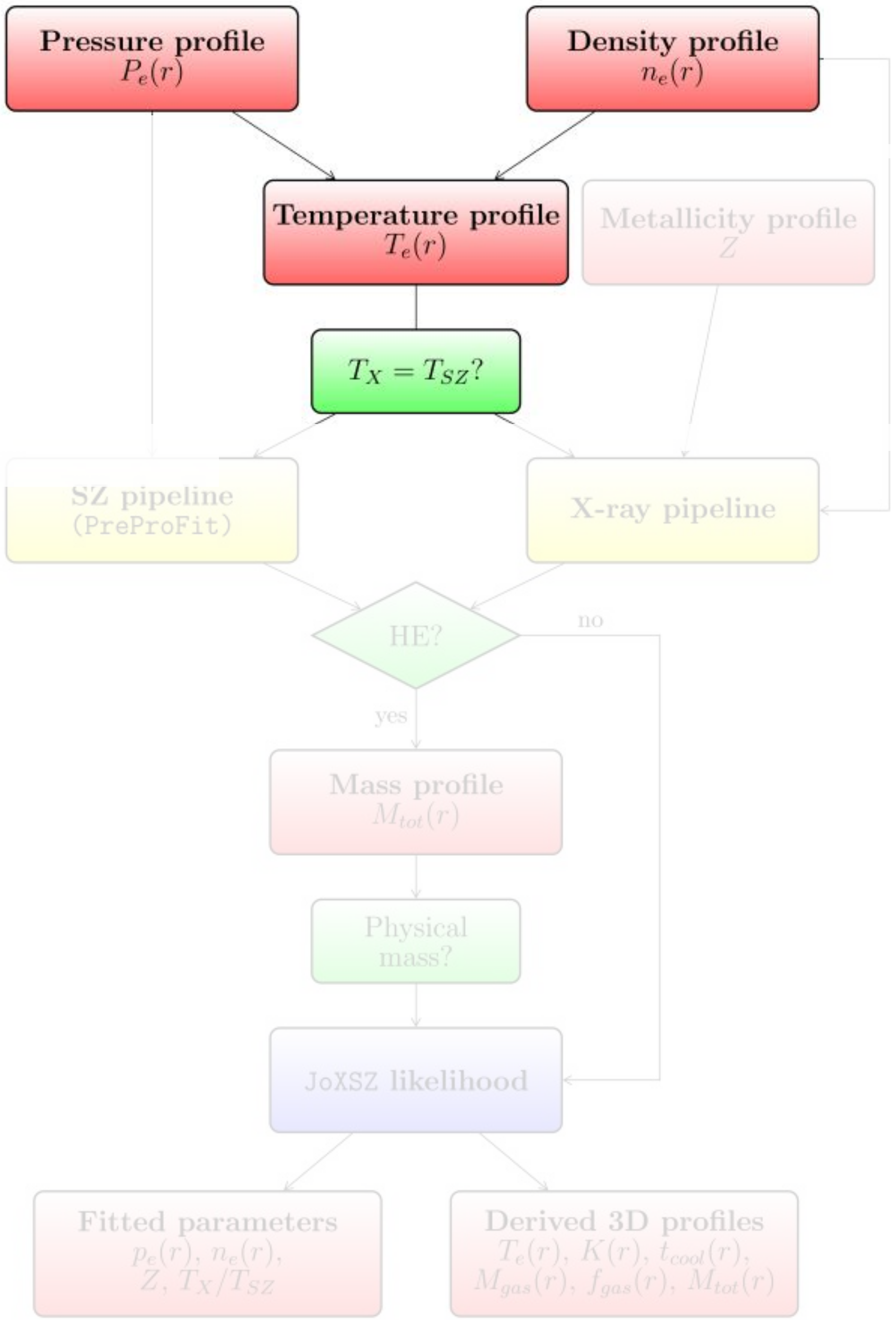
- ➢ Forthcoming version
  - → allows alternative modelization including **non parametric** profiles (e.g. cubic spline, power-law interpolation model)
  - → optionally adds prior constraint on the **outer slope**




➢ **Vikhlinin** model

$$n_e^2(r) = \frac{n_{e0}^2}{\left(\frac{r}{r_c}\right)^{\alpha}\left[1+\left(\frac{r}{r_c}\right)^2\right]^{3\beta-\frac{\alpha}{2}}\left[1+\left(\frac{r}{r_s}\right)^{\gamma}\right]^{\frac{\epsilon}{\gamma}}} + \frac{n_{e02}^2}{\left[1+\left(\frac{r}{r_{c2}}\right)^2\right]^{3\beta_2}}$$

Highly **flexible** parametrization with many parameters involved



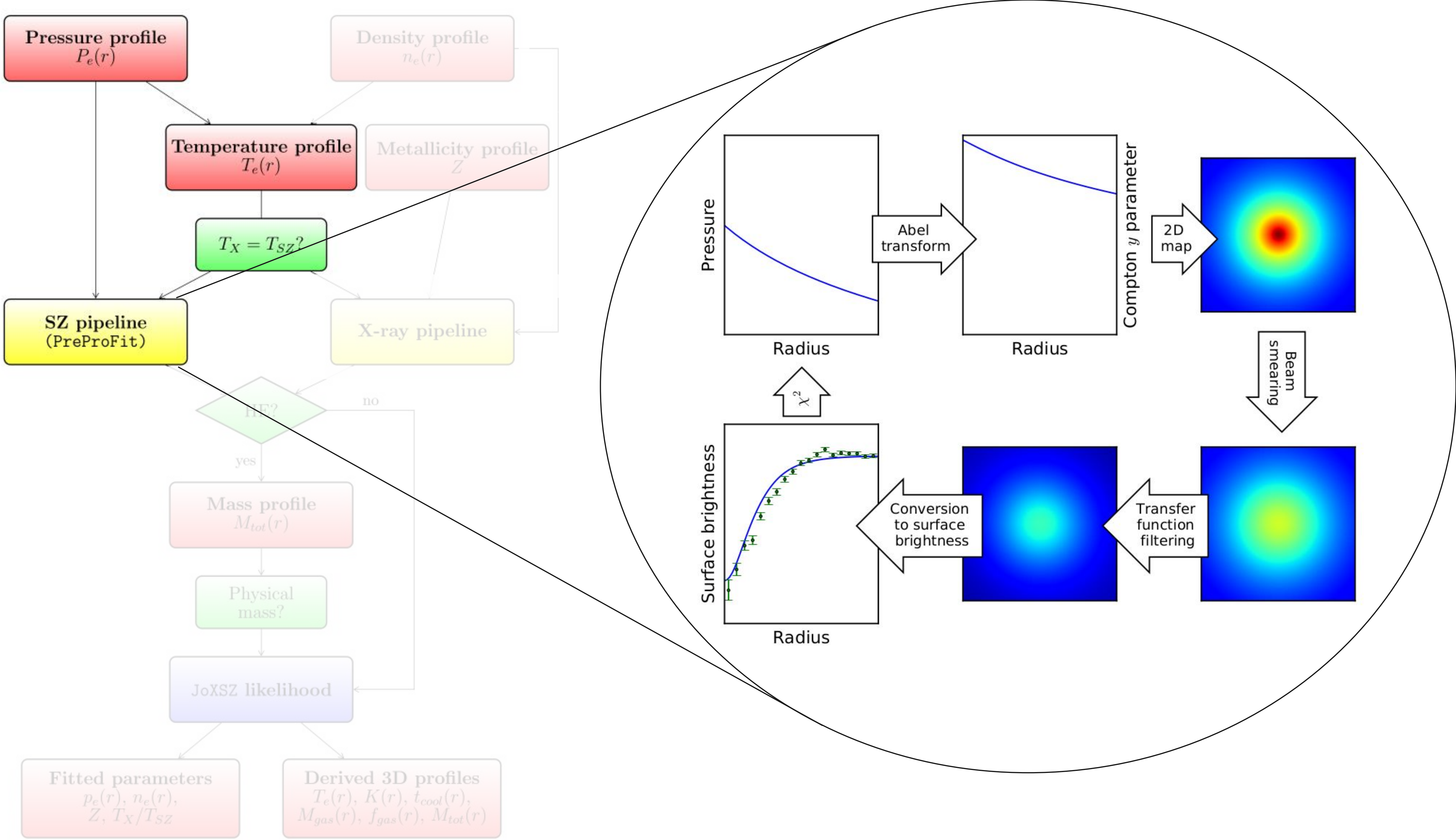

$$k_B T_e(r) = \frac{P_e(r)}{n_e(r)}$$

➢ $T_{SZ}$ → **gas-mass** weighted temperature

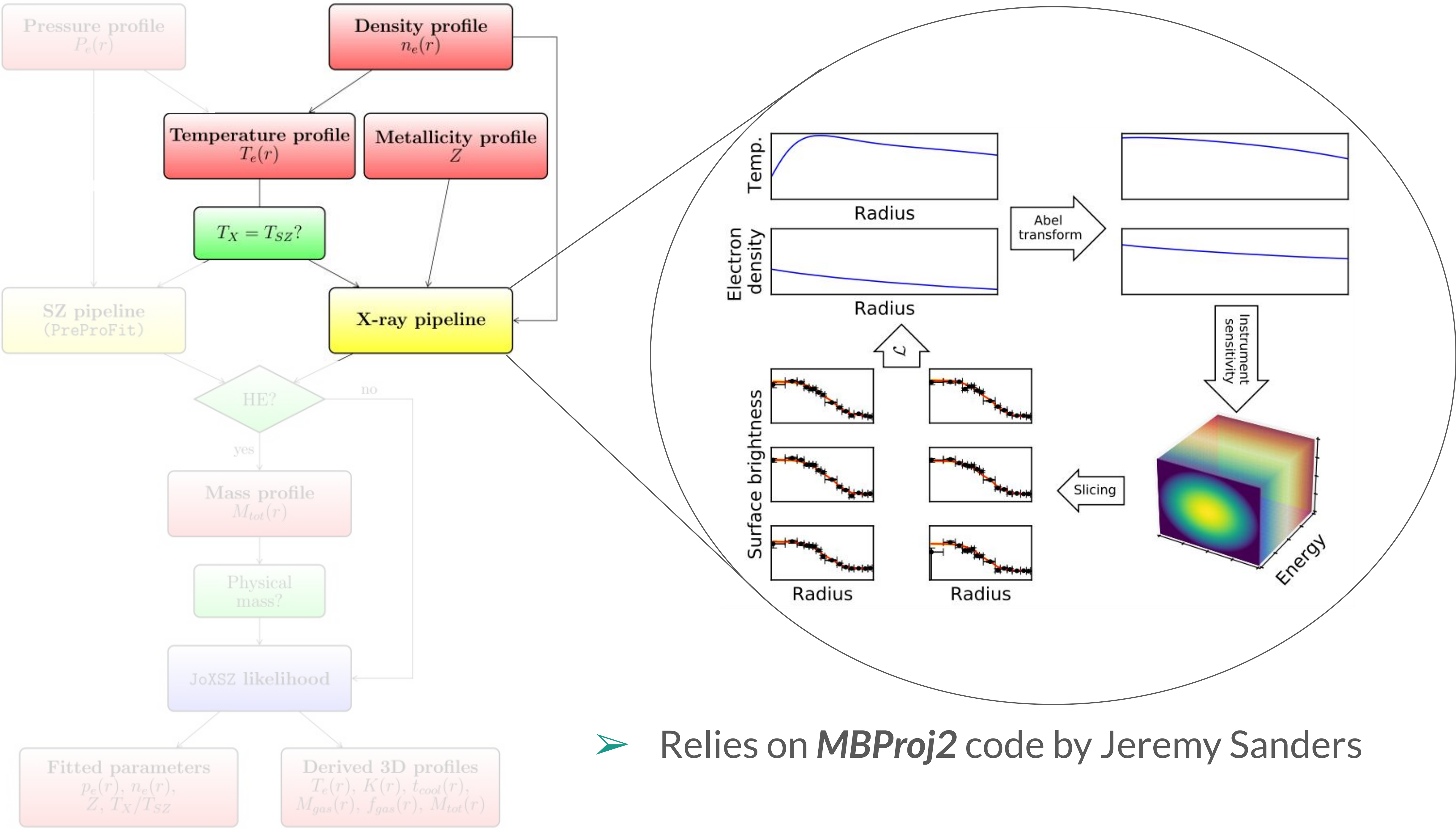
➢ $T_X$ → **spectroscopically** derived temperature

Both **intrinsic** differences (e.g. gas clumping) and instrument-specific **calibration systematics**

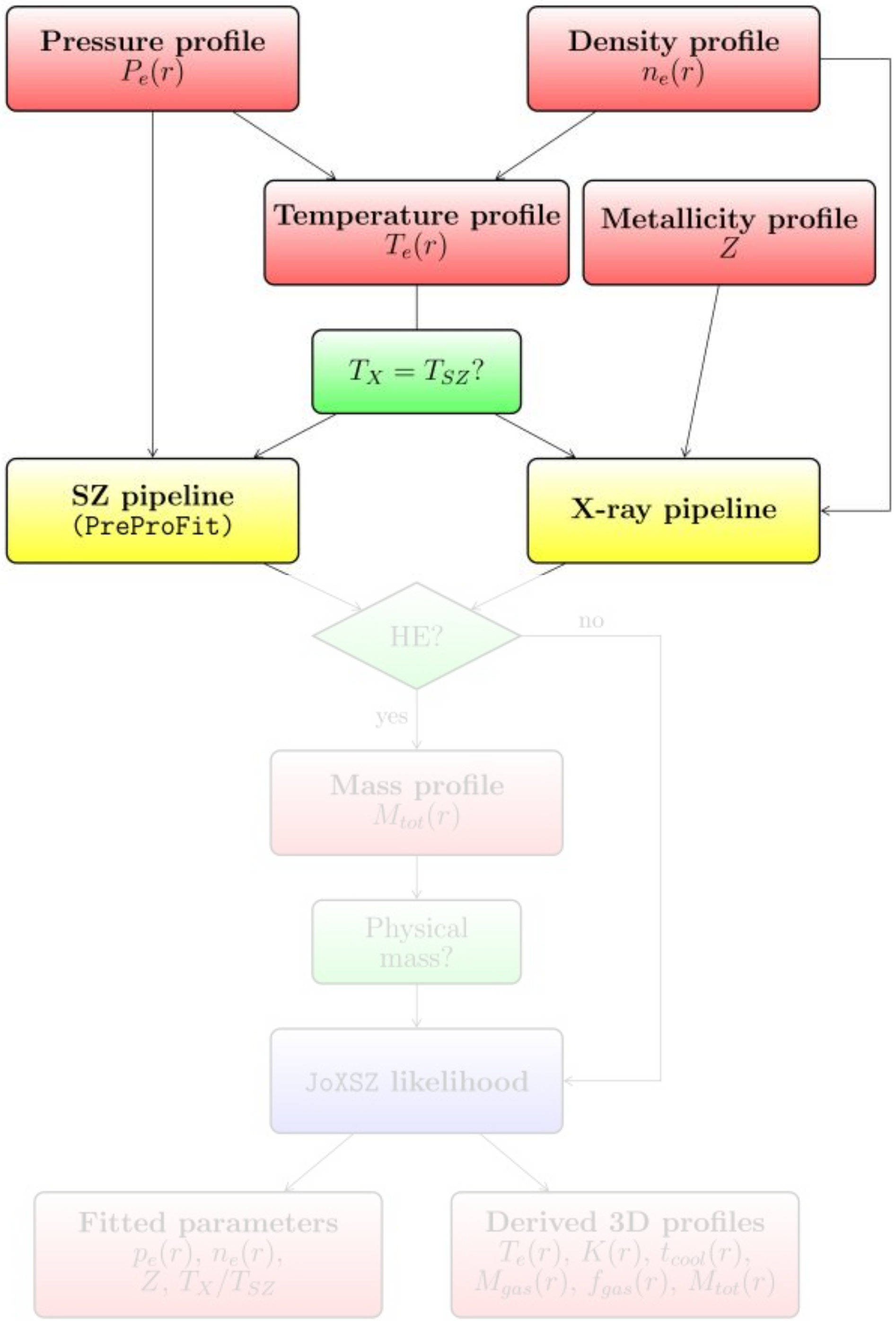
→ optional multiplicative parameter **log($T_X$ / $T_{SZ}$)** distinguishes between the two temperatures



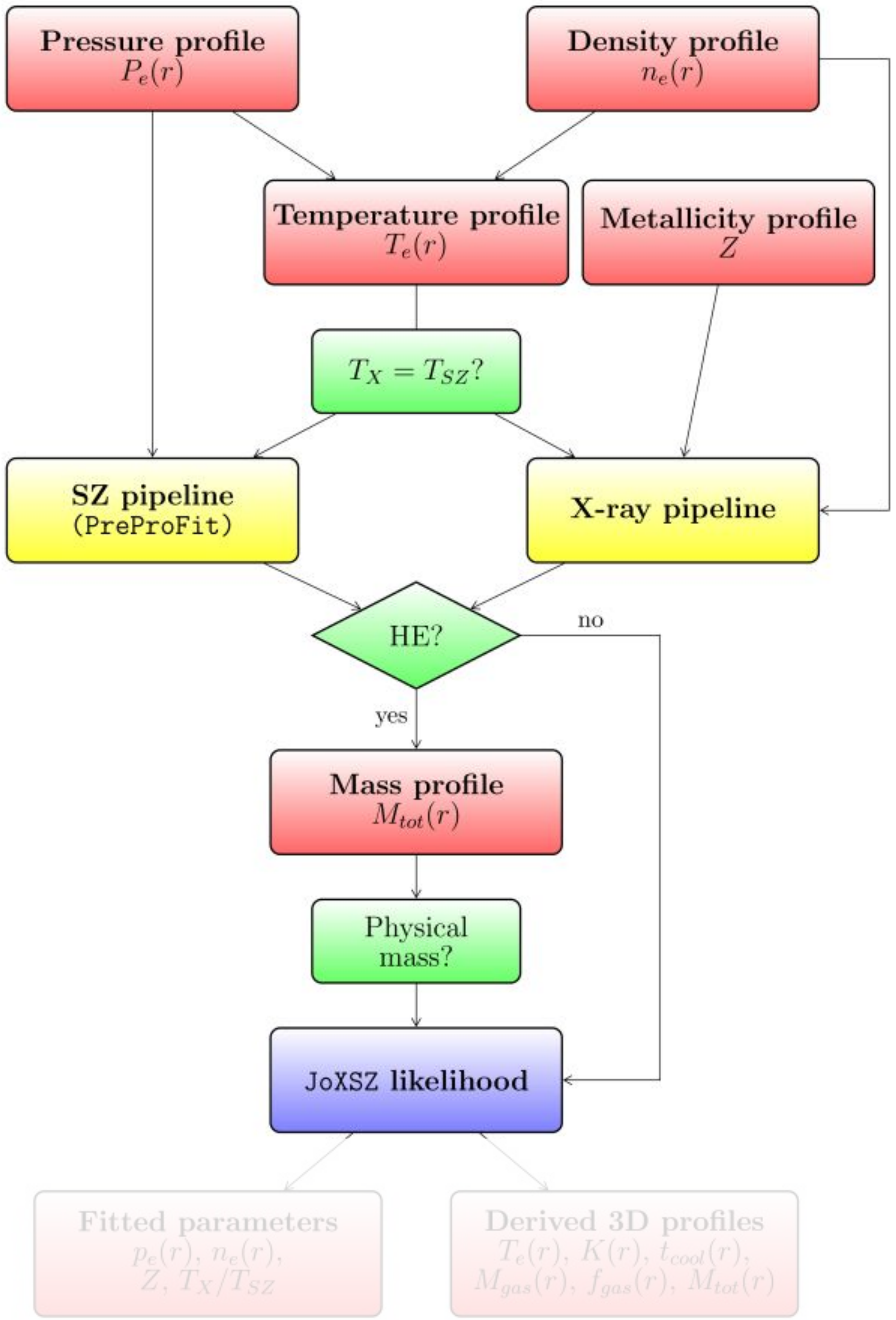
Pressure profile
$P_e(r)$
Density profile
$n_e(r)$
Temperature profile
$T_e(r)$
Metallicity profile
$Z$
$T_X = T_{SZ}$?
SZ pipeline
(PreProFit)
X-ray pipeline
HE?
no
yes
Mass profile
$M_{tot}(r)$
Physical mass?
JoXSZ likelihood
Fitted parameters
$p_e(r)$, $n_e(r)$, $Z$, $T_X/T_{SZ}$
Derived 3D profiles
$T_e(r)$, $K(r)$, $t_{cool}(r)$, $M_{gas}(r)$, $f_{gas}(r)$, $M_{tot}(r)$
Pressure
Radius
Abel transform
Compton $y$ parameter
Radius
2D map
Beam smearing
Transfer function filtering
Conversion to surface brightness
Surface brightness
Radius
$\chi^2$



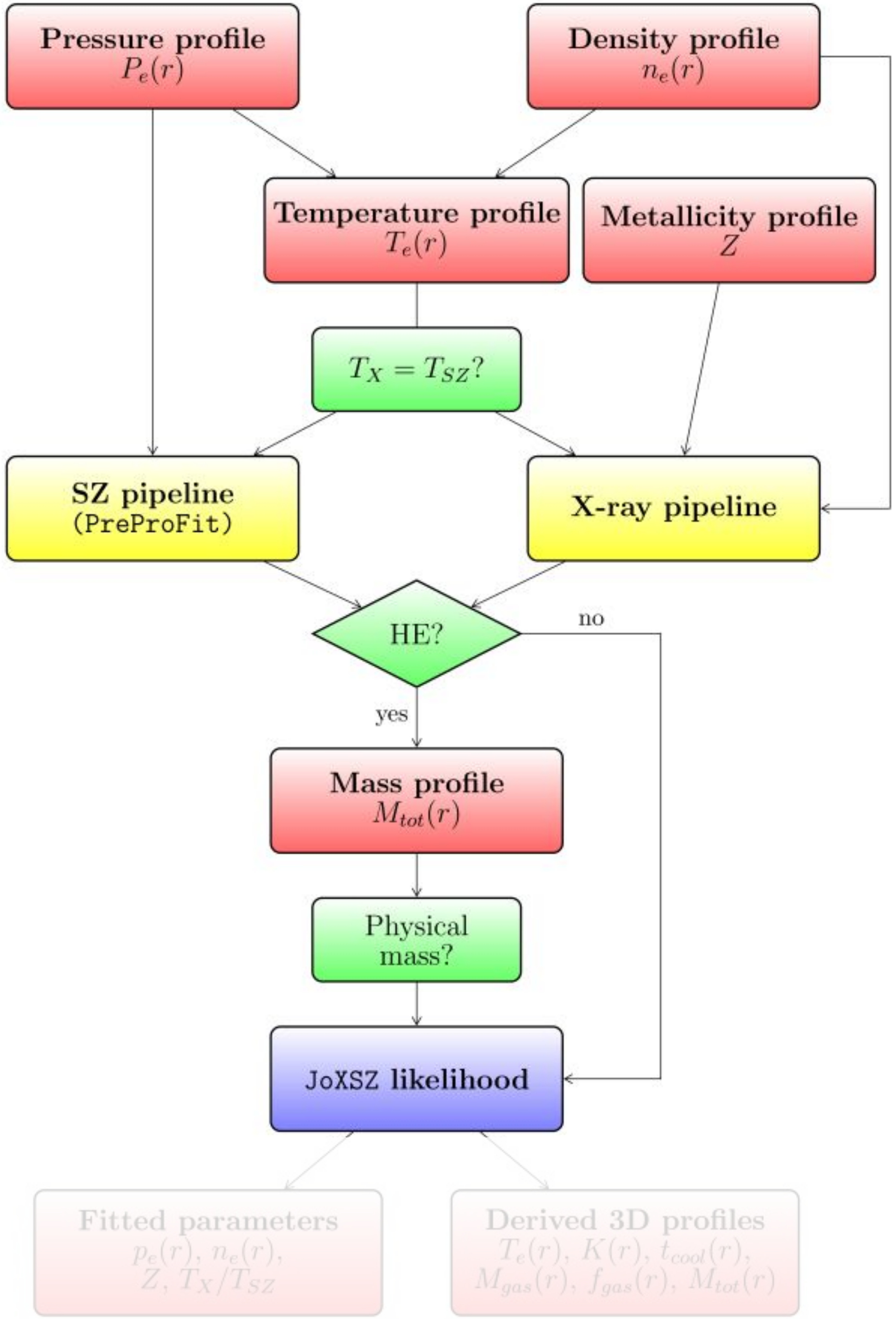

- Relies on ***MBProj2*** code by Jeremy Sanders




- Additional parameters accounting for **systematics**
  - → **SZ calibration** parameter: accounts for uncertainty in the SZ measurement
  - → **X-ray background** scaling parameter: accounts for differences in background level between the cluster and control fields
- Forthcoming version
  - → includes **pedestal parameter** for non-zero level in SZ maps




$$M_{tot}(< r) = -\frac{r^2}{\mu_{gas} m_p G n_e(r)} \frac{dP_e(r)}{dr}$$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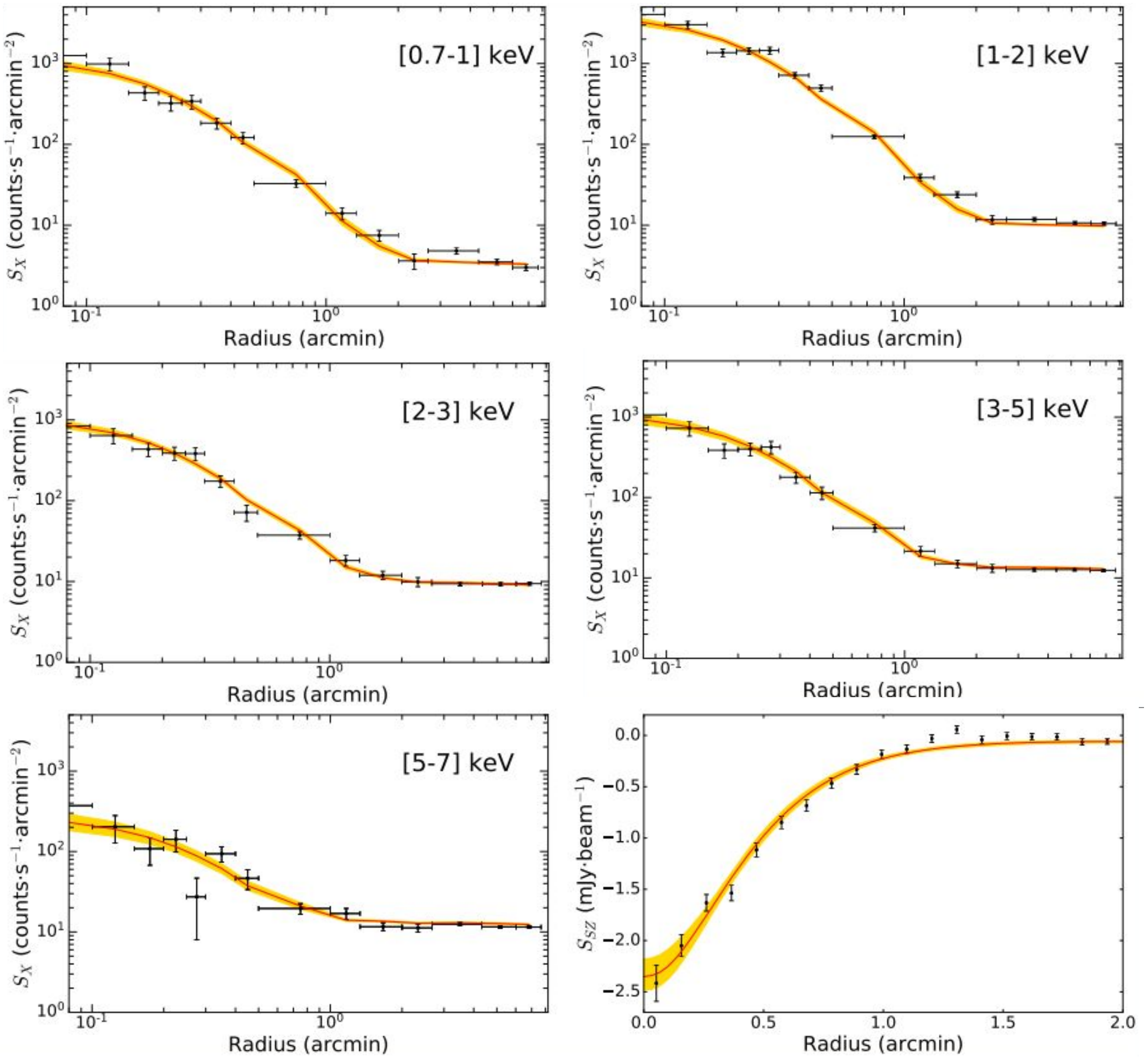
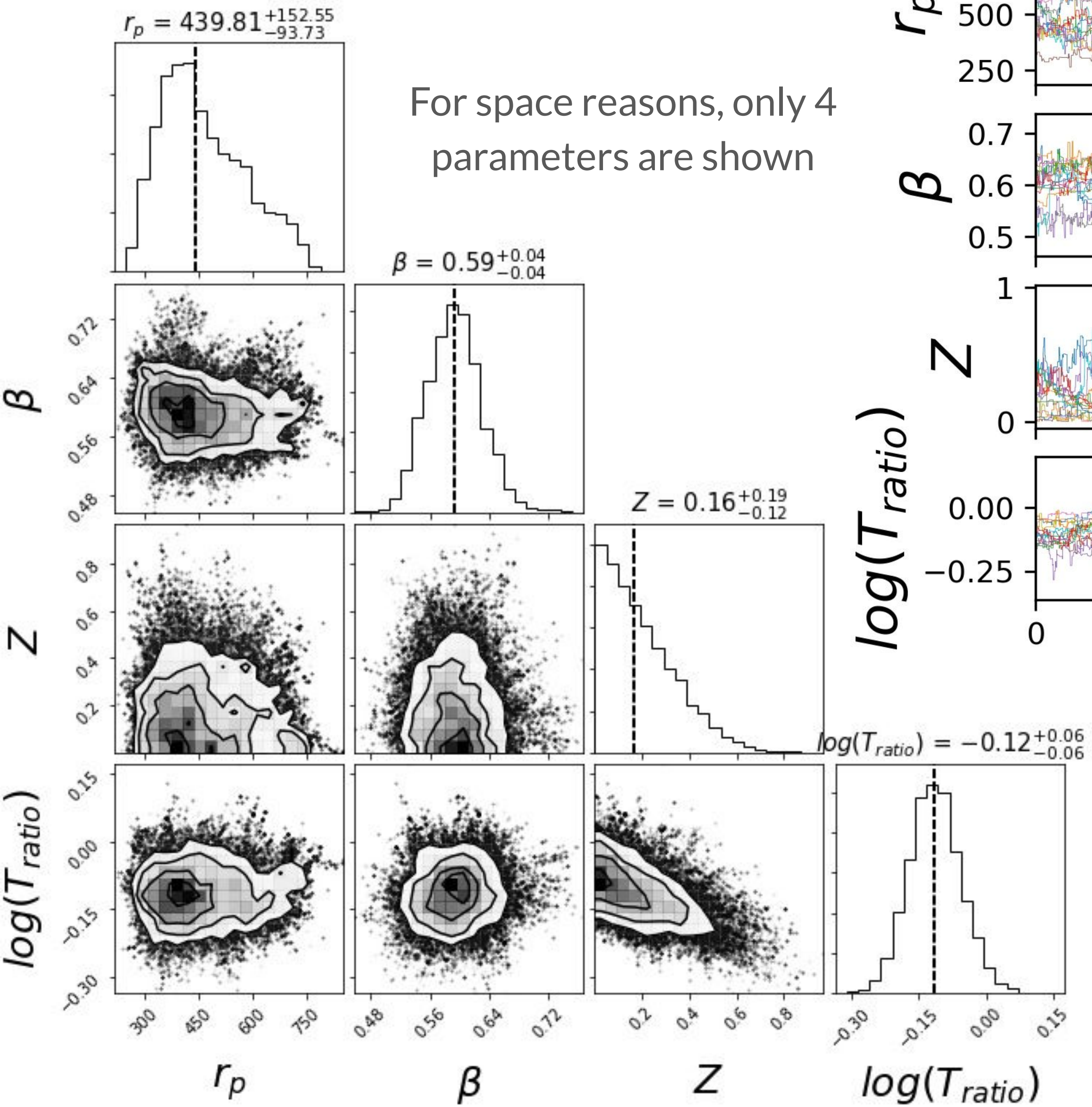
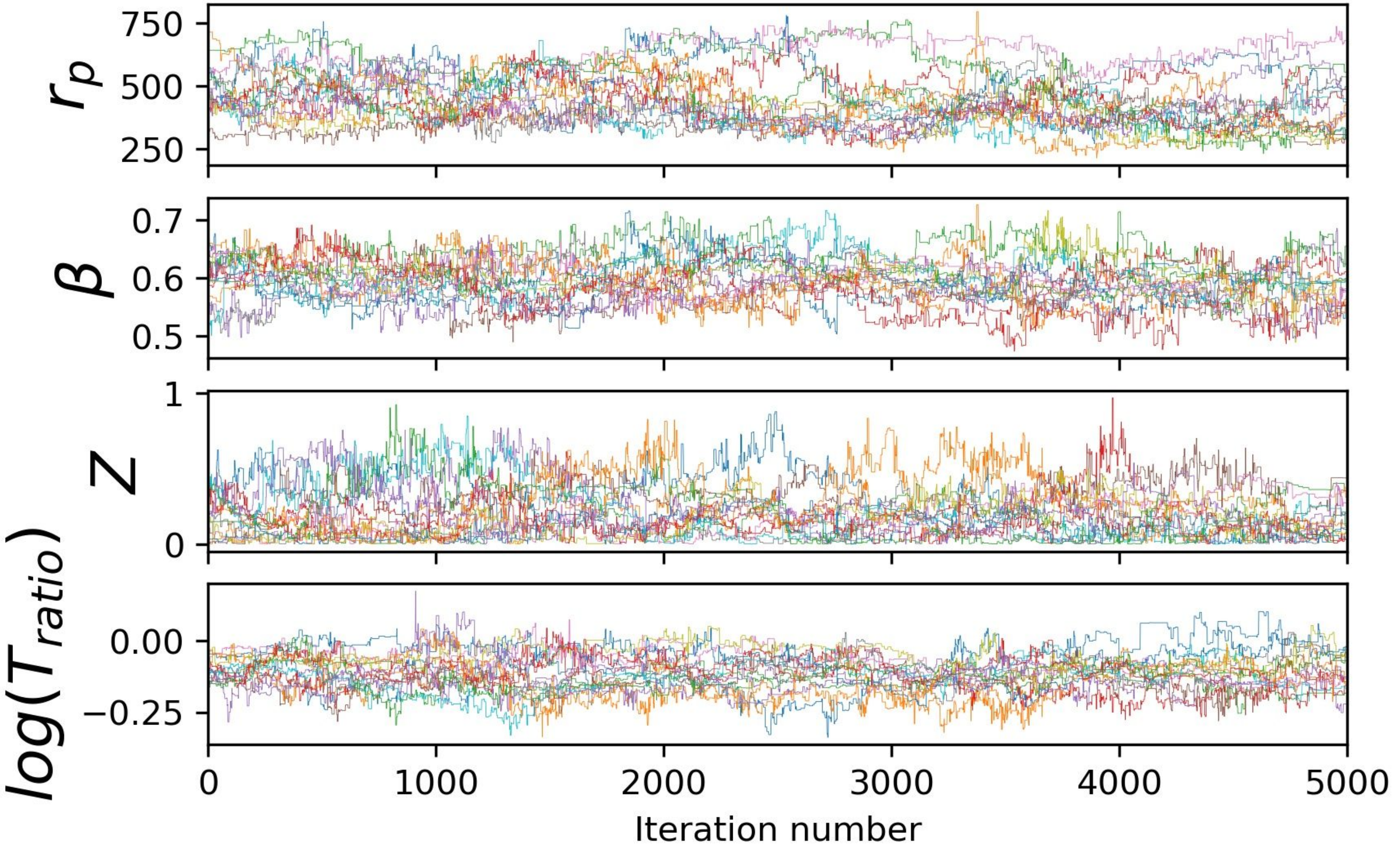
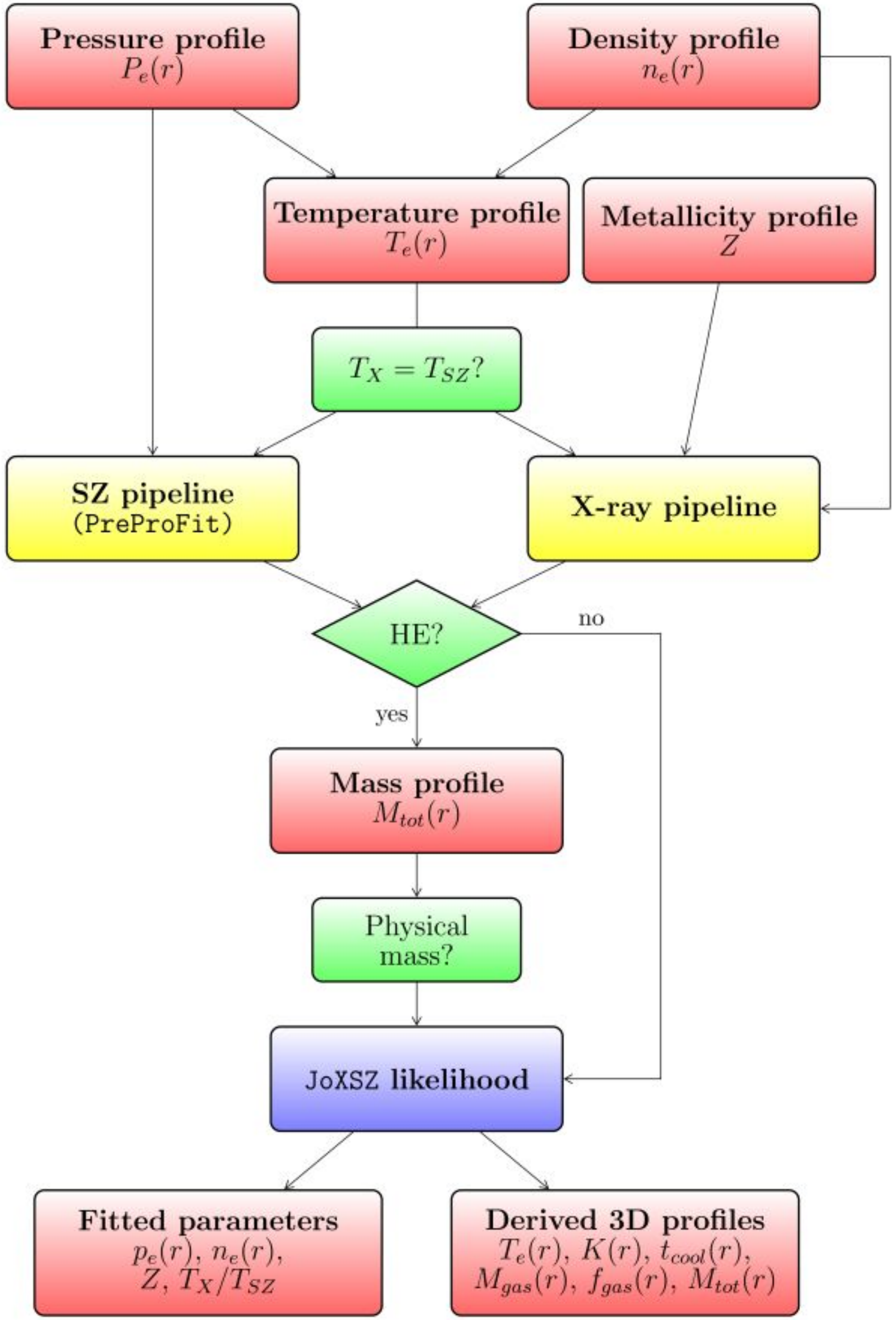

[0.7-1] keV
[1-2] keV
[2-3] keV
[3-5] keV
[5-7] keV
$S_X$ (counts·s$^{-1}$·arcmin$^{-2}$)
$S_{SZ}$ (mJy·beam$^{-1}$)
Radius (arcmin)




For space reasons, only 4 parameters are shown




**Markov Chain Monte Carlo algorithm**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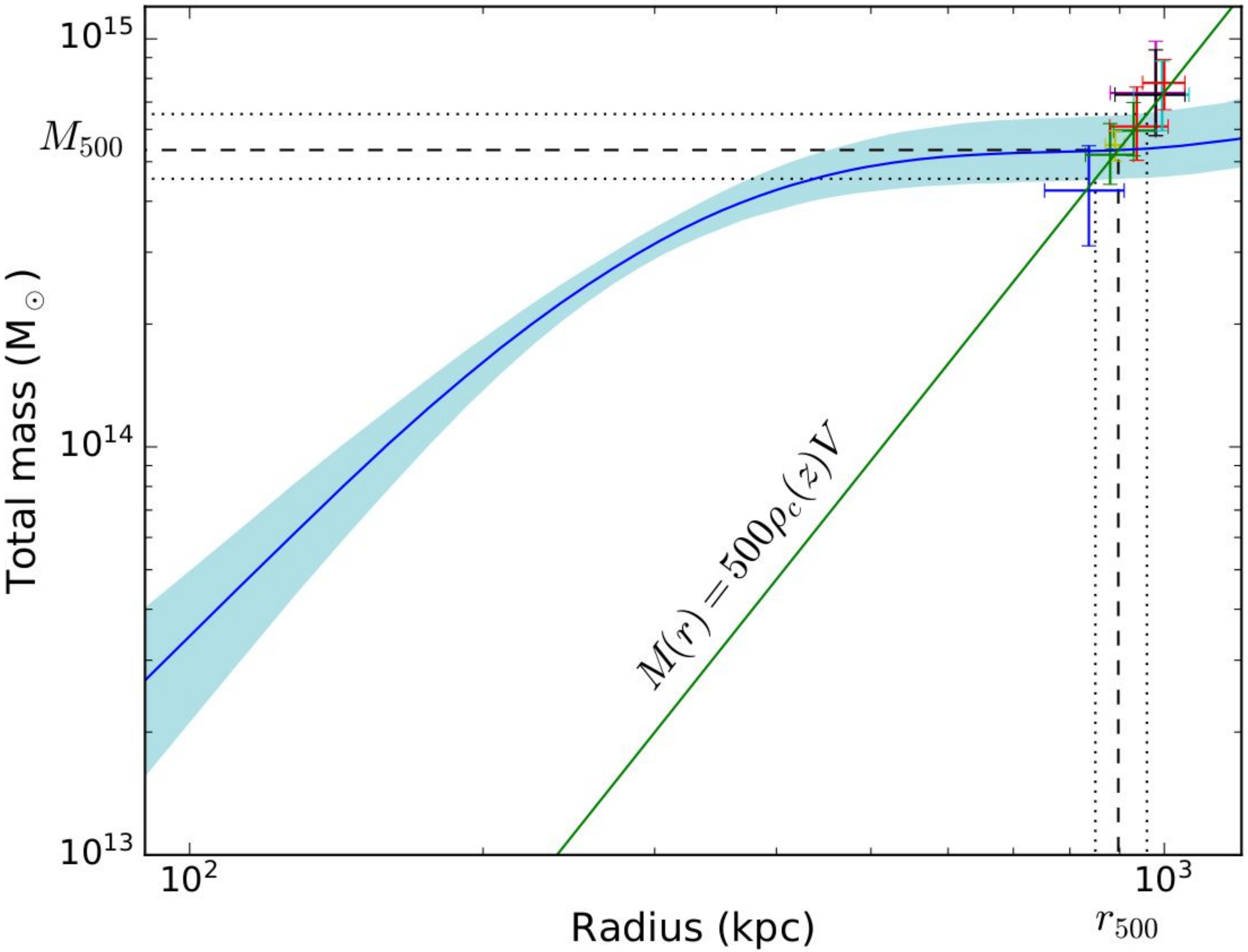

$10^{15}$
$10^{14}$
$10^{13}$
$M_{500}$
Total mass ($M_\odot$)
$M(r) = 500\rho_c(z)V$
$10^2$
$10^3$
Radius (kpc)
$r_{500}$

# *JoXSZ - Additional functionalities*

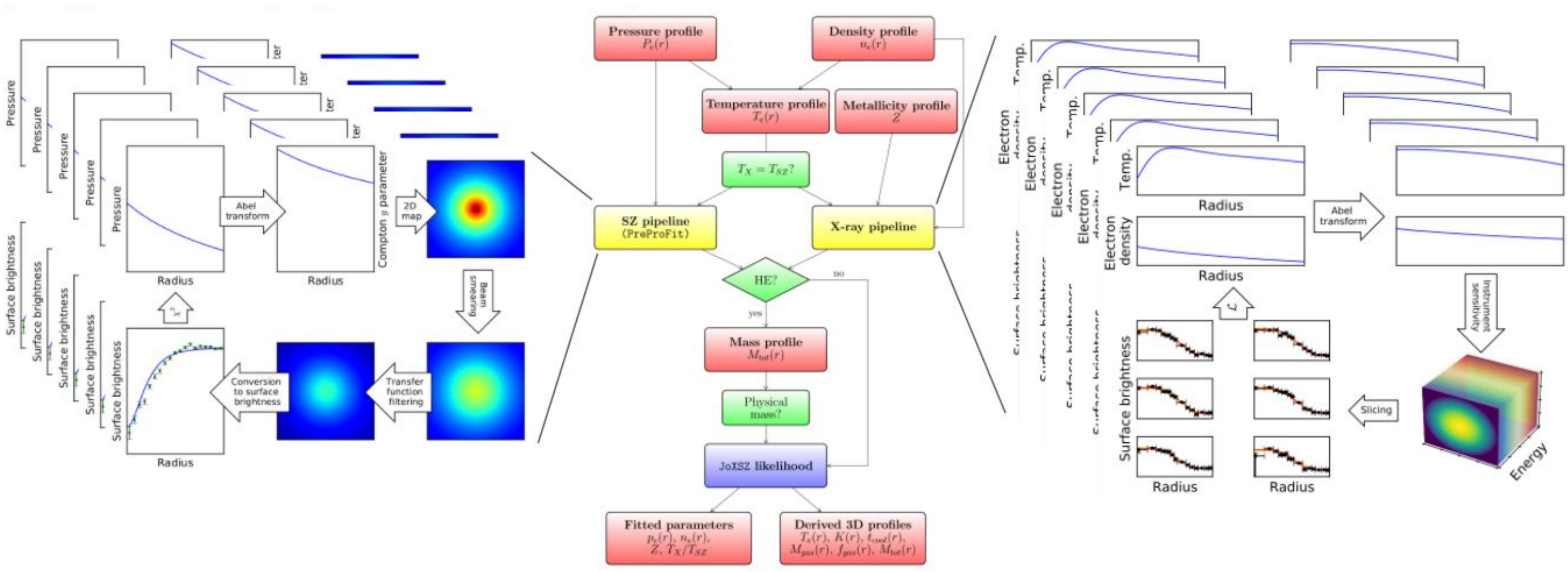
- Adopt **approximated** values for PSF and transfer function

  → **feasibility study**

- Prior constraint on the **integrated Compton parameter**

# JoXSZ - Limitations and possible countermeasures

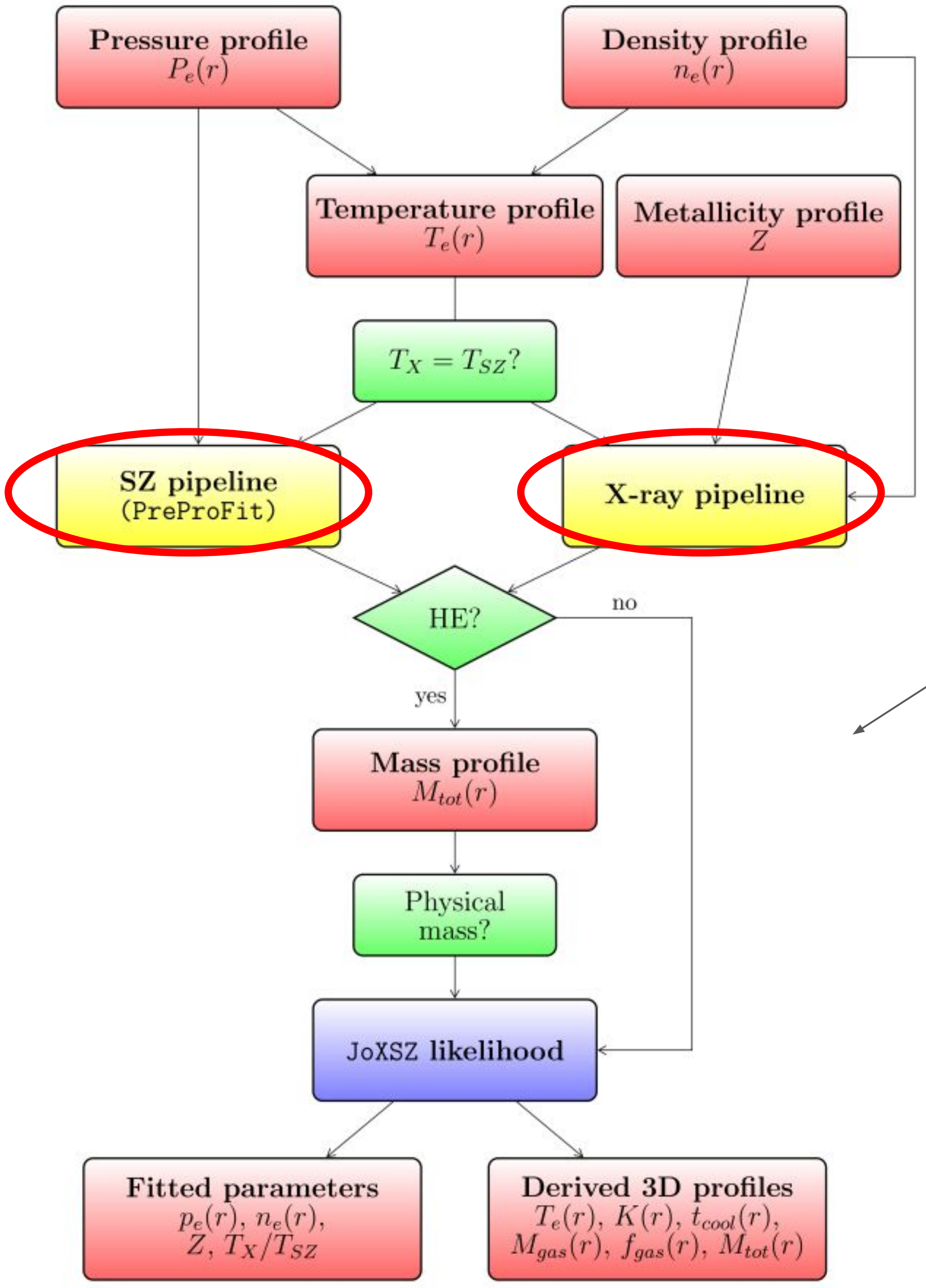
- ➢ **Spherical** symmetry assumption
  - → possible switch to **elliptical** symmetry
- ➢ **Fixed** centre of the cluster
  - → include the **coordinates** of the center in the fit



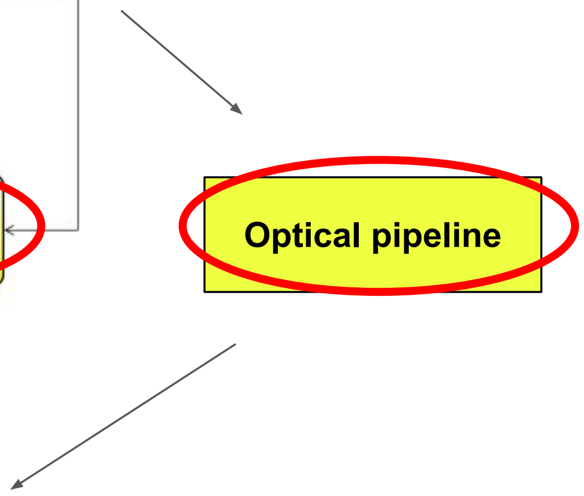

➢ Highly **time-consuming** operations (integrations, convolutions)

→ exploit **parallel** computing techniques to speed up the computation

# *Future developments*

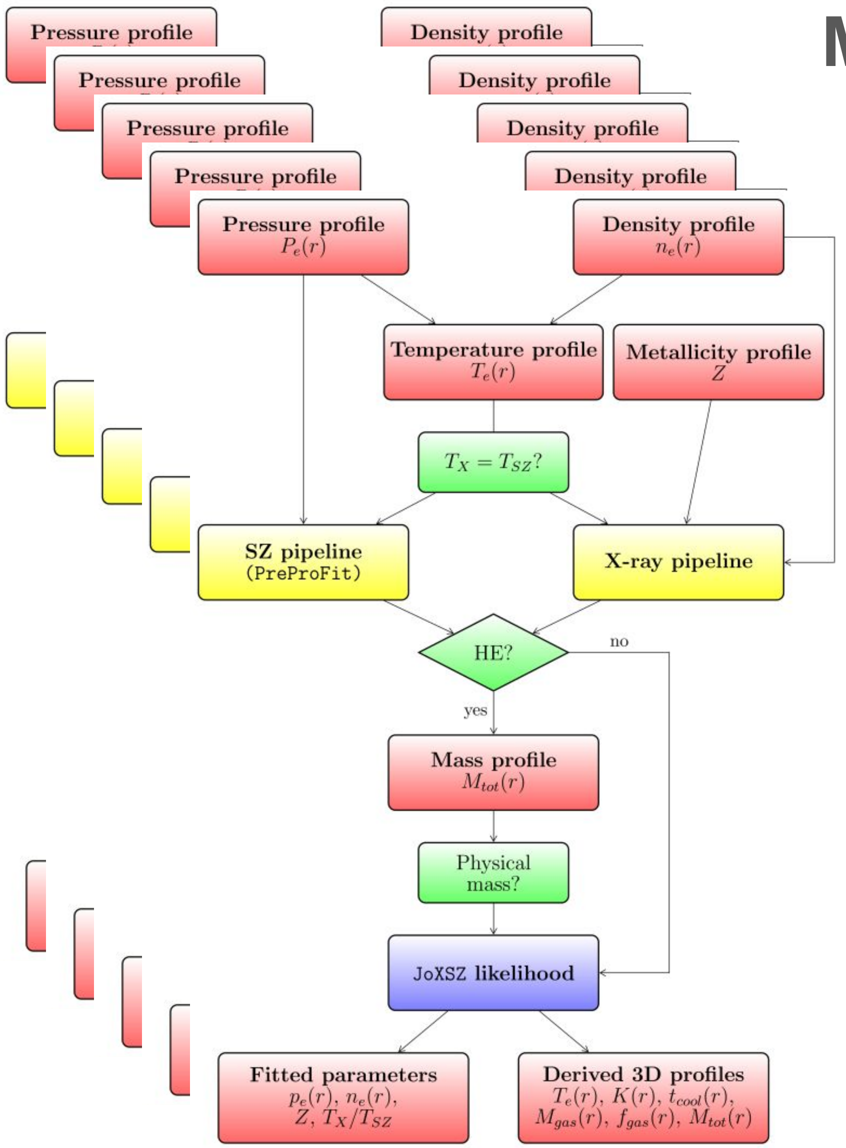


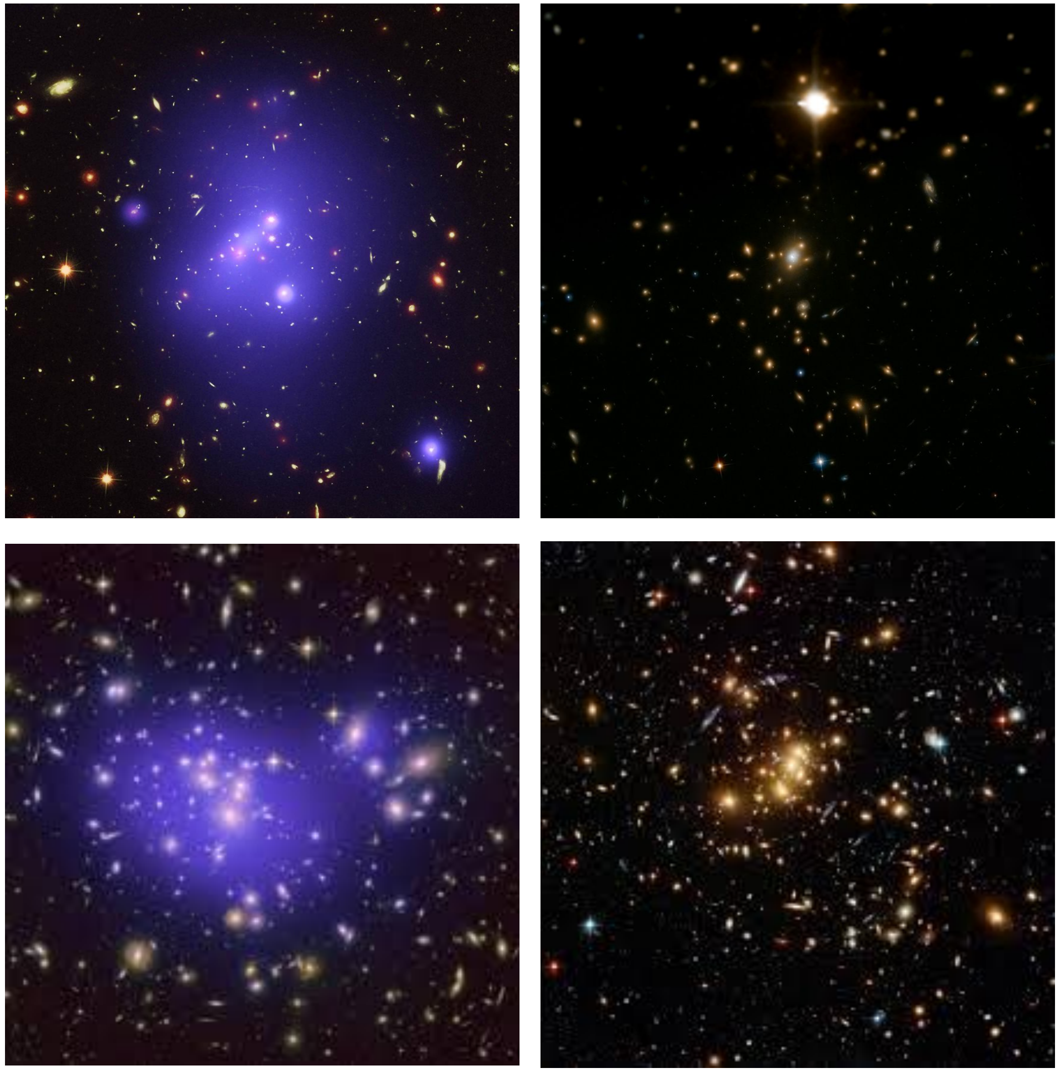

# SZ + X-ray + optical analysis

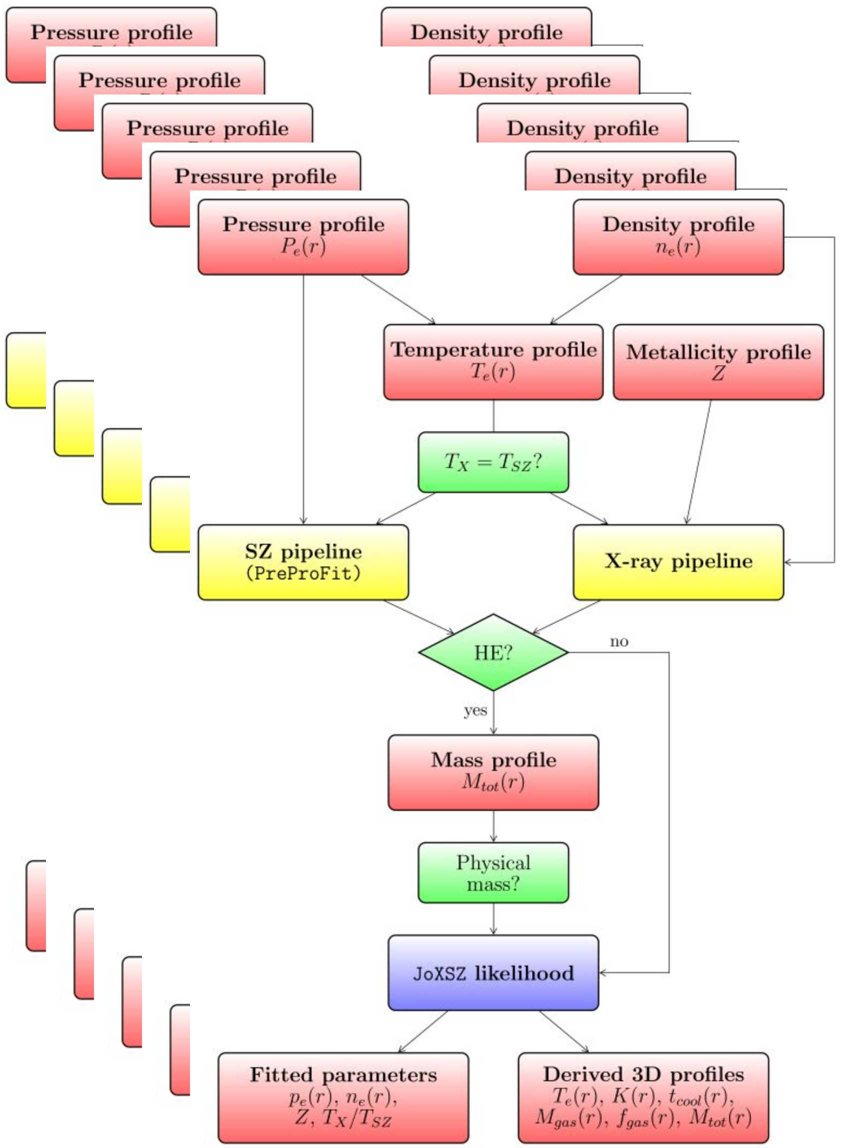



- **Avalanche** of data from both already operative and forthcoming **facilities** (e.g. SPT, ACT, Euclid, eROSITA, Vera Rubin, wFIRST)

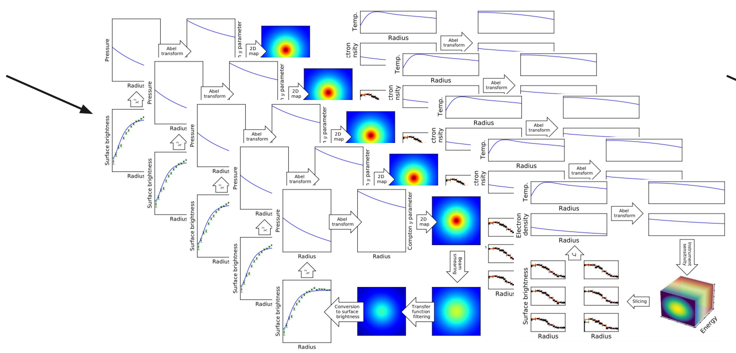
# Multiwavelength analysis on multiple clusters

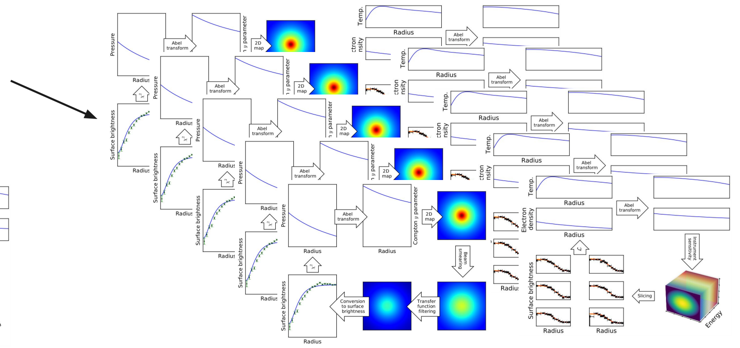


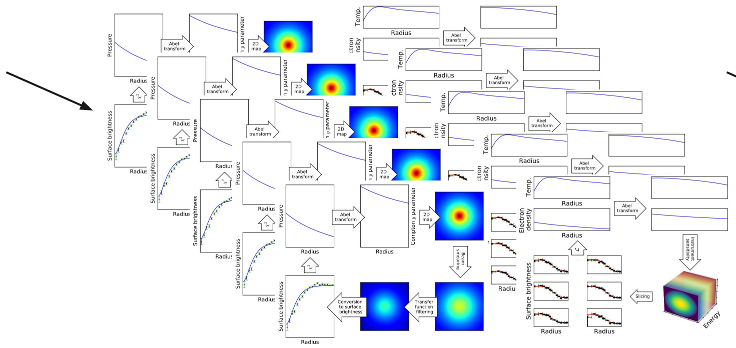



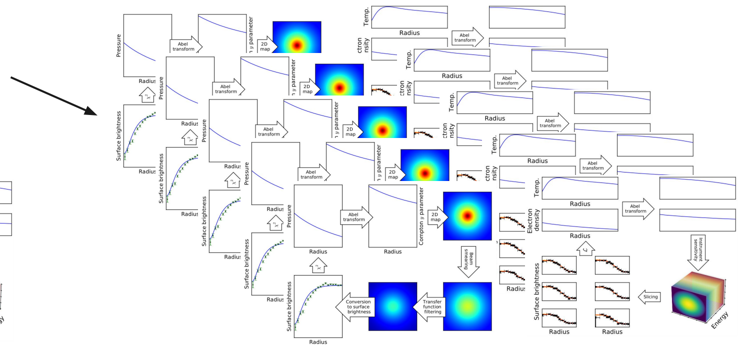


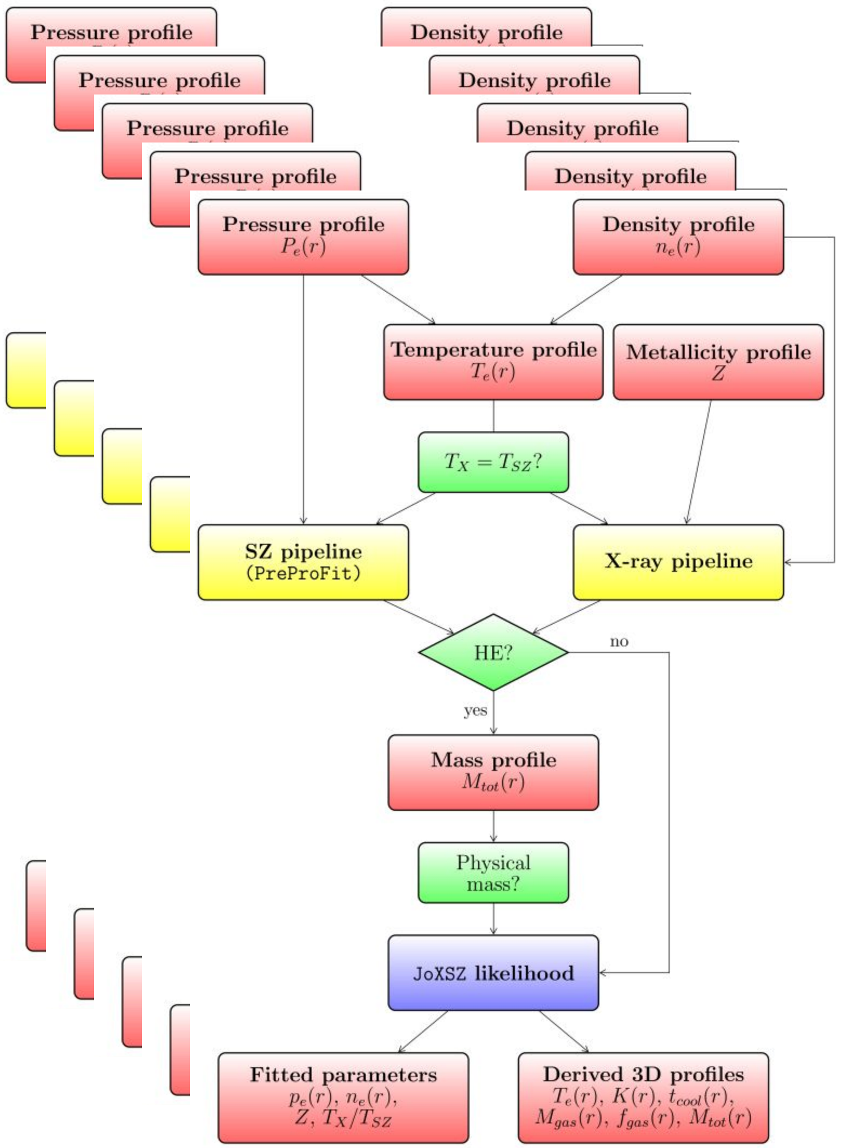

- ➢ Fit on a population of clusters at the same time
  → parameter estimation at both individual level and population level












# Multiwavelength analysis on multiple clusters

- ➢ Statistics POV
  - → Bayesian hierarchical model
- ➢ Computer Science POV
  - → distributed/parallel frameworks for (horiz/vert) scalability (Spark/MPI/GPUs)
  - → Cloud Computing tools
- ➢ Astrophysics POV
  - → address more complex questions (e.g. testing General Relativity)

# *Any questions?*

*Castagna Fabio* - fabio.castagna@inaf.it
*Andreon Stefano* - stefano.andreon@inaf.it
*Trombetta Alberto* - alberto.trombetta@uninsubria.it
*Landoni Marco* - marco.landoni@inaf.it