Biases in the estimation of the hydrostatic mass of the Virgo simulated CLONE

Théo Lebeau

Supervisors : Nabila Aghanim and Jenny Sorce

mmUniverse Conference 2023

Clusters as cosmological probes

- Clusters formed by gravitational collapse, tracers of the matter distribution in the Universe depending on σ_8 and Ω_m

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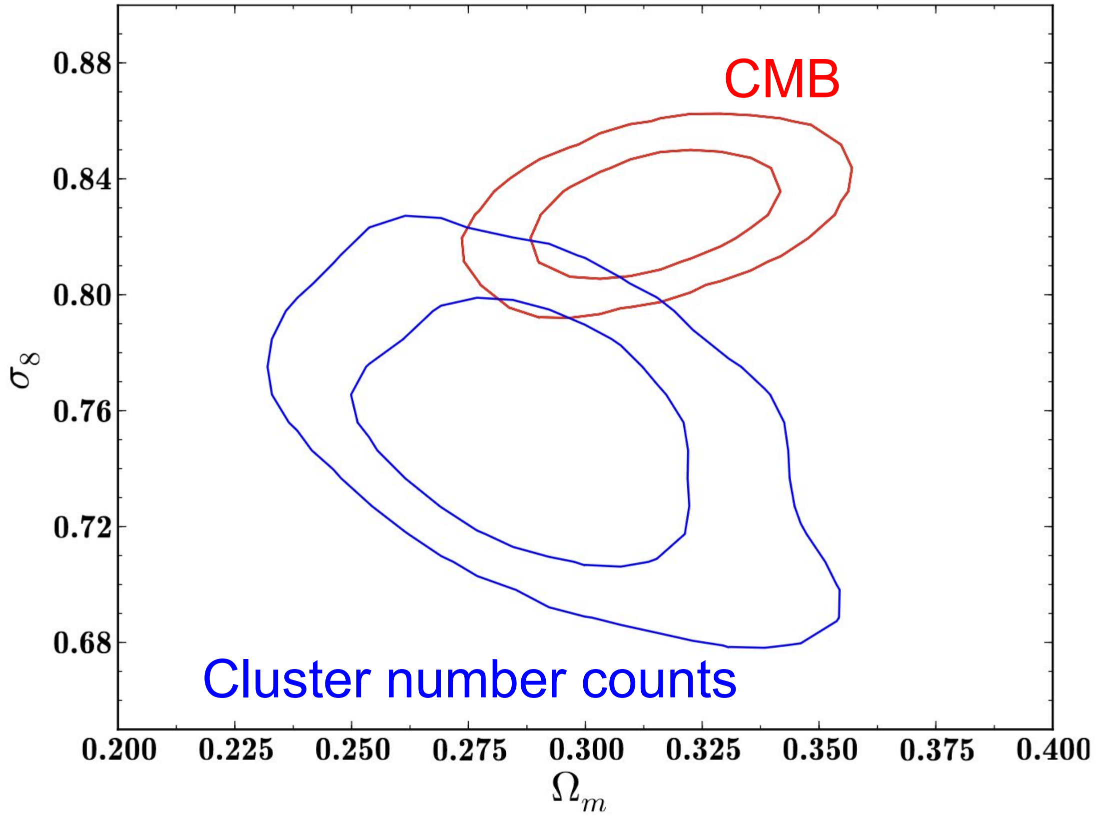

Planck Collaboration 2013

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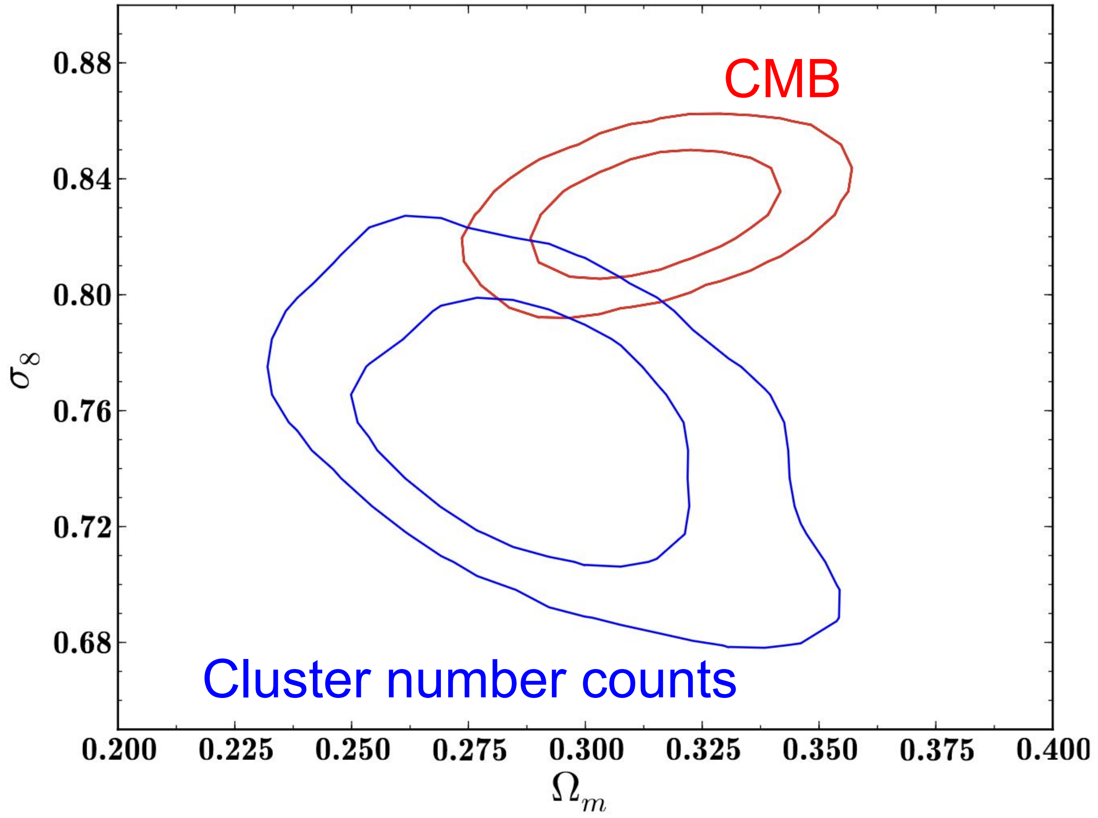

Planck Collaboration 2013

- The tension can be resolved by introducing the mass bias (1-b) ∈ [0.5,1.2]

Calculating cluster masses with the ICM

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$$P = \frac{\rho k_B T}{\mu m_p} = n_e k_B T$$

Equation of state of a perfect gas

Hydrostatic Mass

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$$M_{tot} = \frac{M_{HE}}{(1-b)}$$

Hydrostatic mass bias

Towards bias-free mass calibration of galaxy clusters …

Possible contributions to the mass bias

- Turbulence, magnetic pressure
- Local environnement
- Dynamical state
- **Projection effects**

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The objectives:

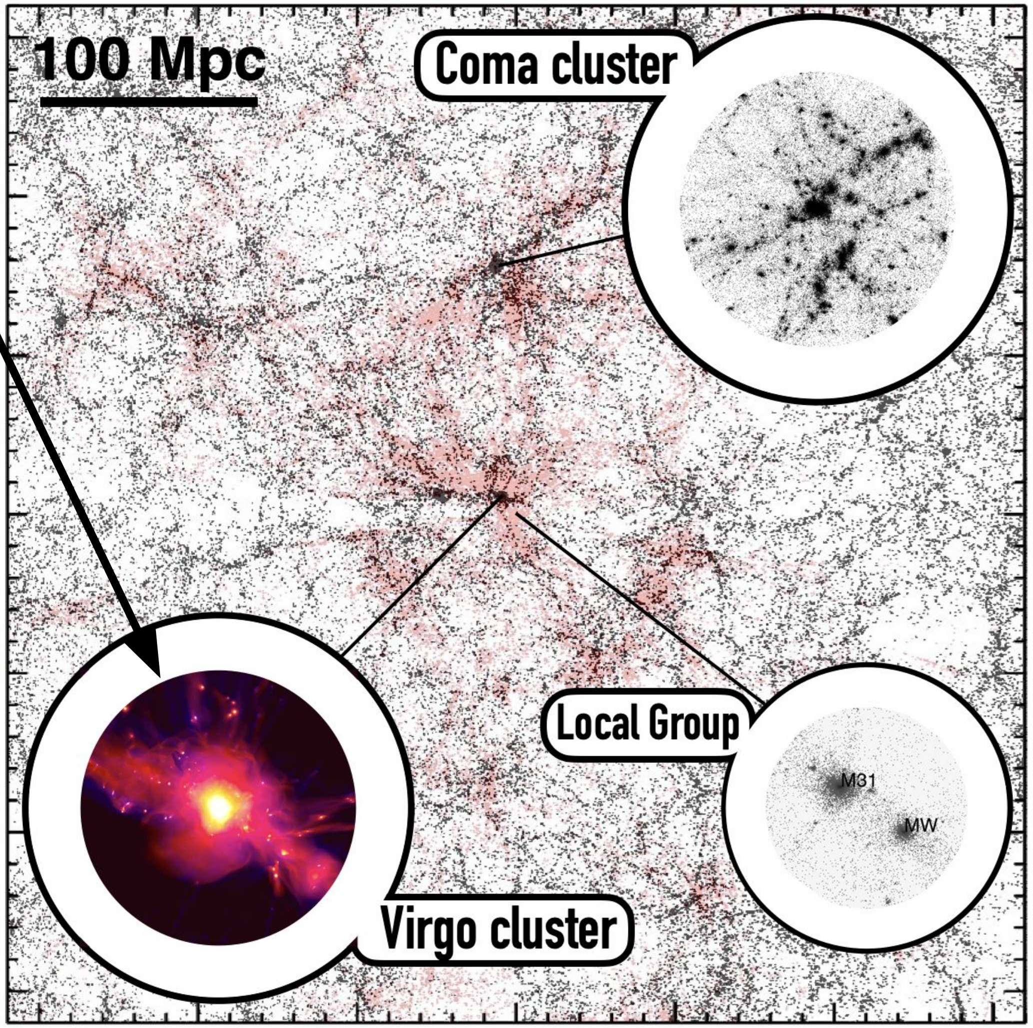
- Quantify contributions to the bias and their impact on cluster mass estimates
- Propose a physically-motivated parametrization of the bias
- Eventually improve constraints on the cosmological parameters using galaxy clusters

…using constrained cosmological simulations

- Cosmological simulation reproducing the Local Universe
  - Dark matter simulation on the full box
  - Hydrodynamical zoom on the Virgo cluster
  - Hydrodynamical simulation on the full box (upcoming)

    Around 1500 cluster with a mass superior to $10^{14}\,M_\odot$ in 300Mpc around the Milky Way

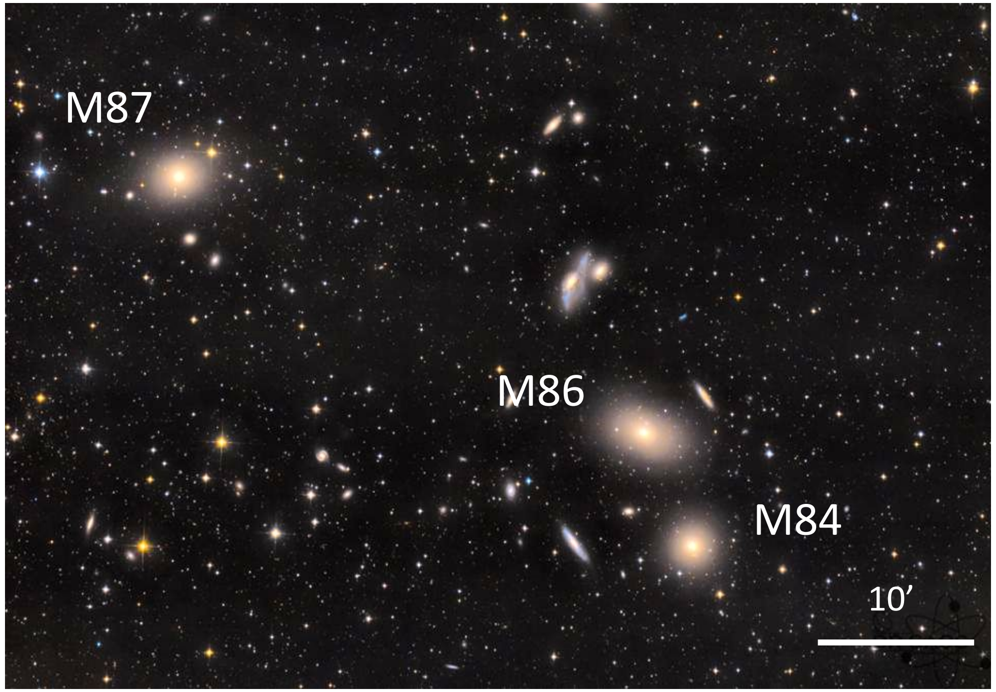
- To be compared to observations and typical cosmological simulations



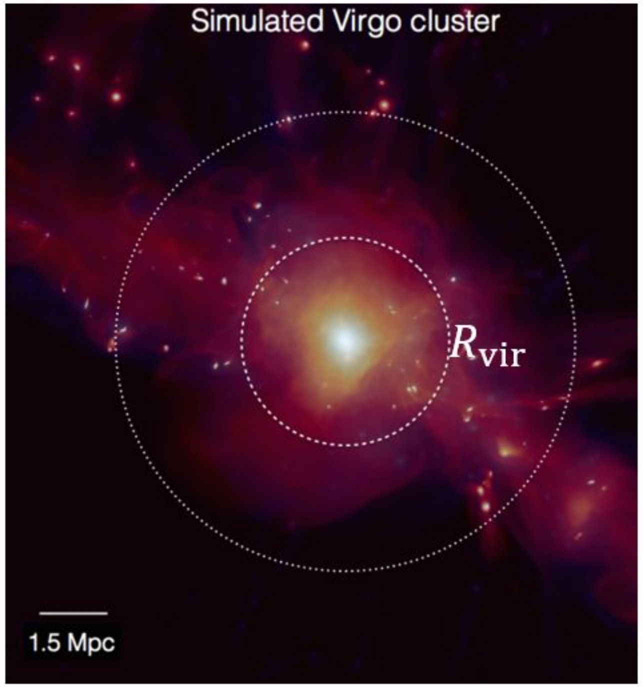
Sorce et al. (2022)

Developing the method with the Virgo cluster

Closest cluster from the Local Group , M_{200}= 5.7 ± 0.6 $10^{14}M_{\odot}$, R_{200}=1.7± 0.2 Mpc, z=0.00428 ± 0.00002 *Sorce et al. (2019)*



Astrophotography of the Virgo Cluster, Fernando Pena

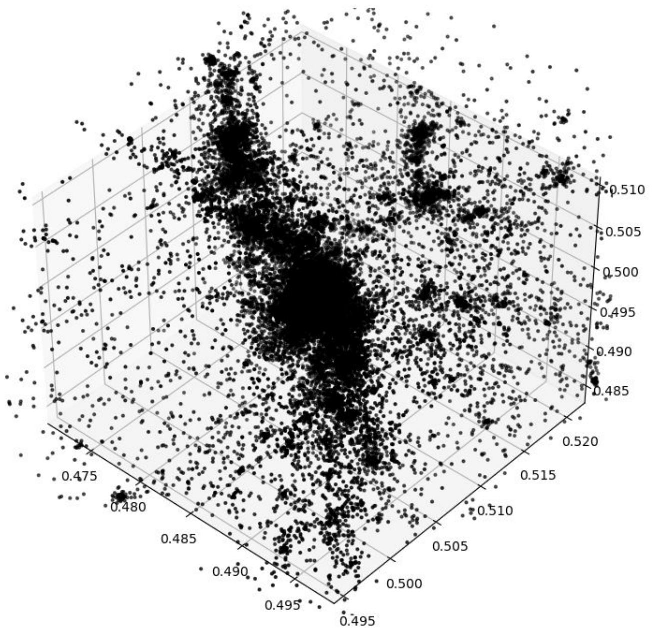


Hydrodynamical simulation of 15 Mpc radius centered on the Virgo Cluster *Sorce et al. (2021)*

Quantify the projection effects on the mass bias

Methodology

- Select the ICM cells in the simulation dataset



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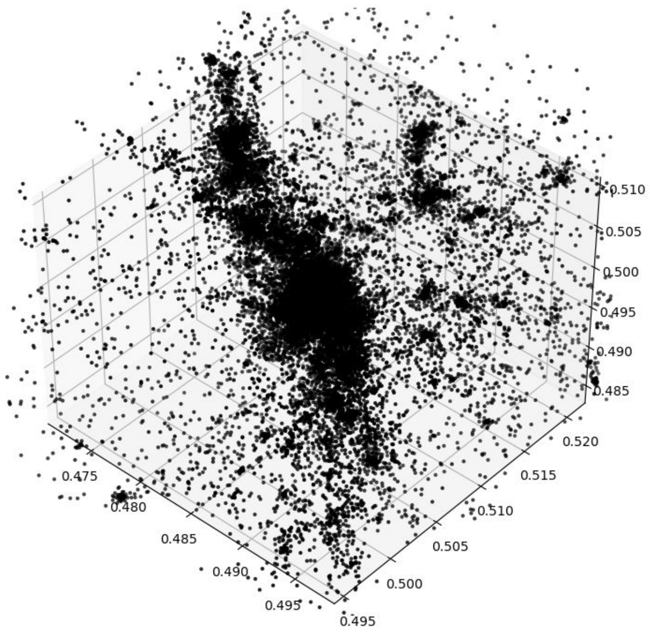
- Select the ICM cells in the simulation dataset
- Compute pressure, electron density and temperature 3D radial profiles



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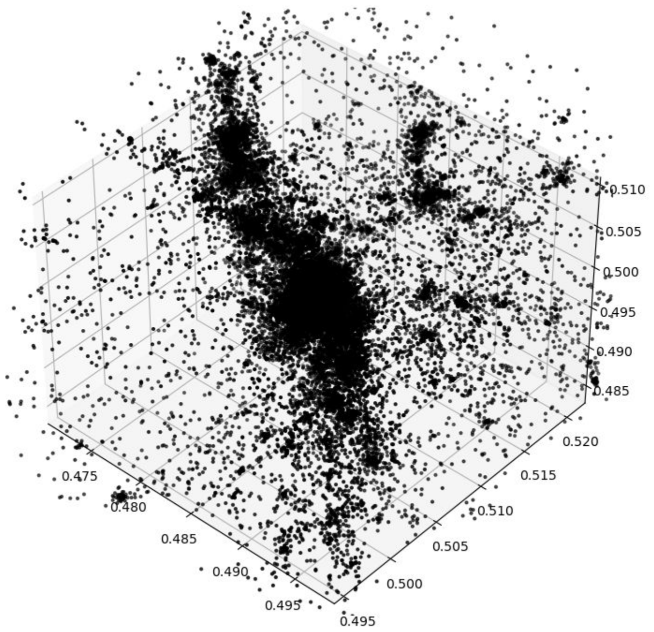

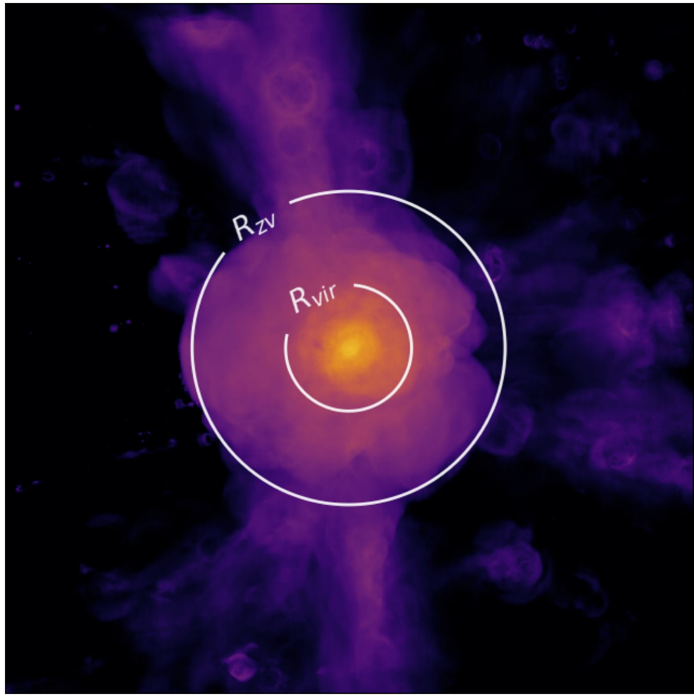

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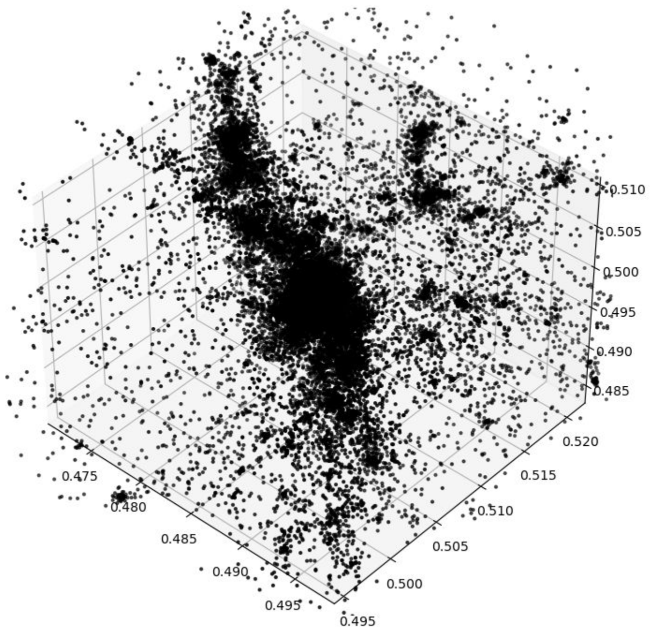
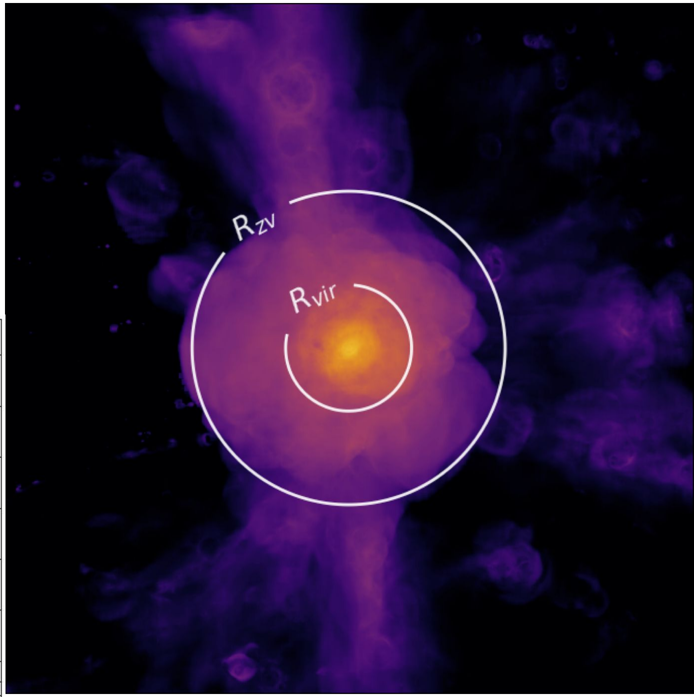
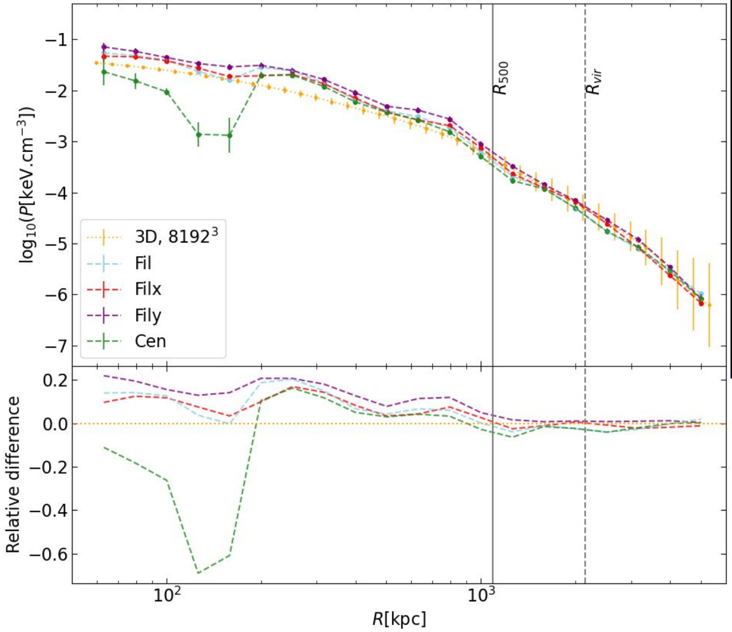
- Use a deprojection method to recover the 3D radial profiles from the 2D projected profile







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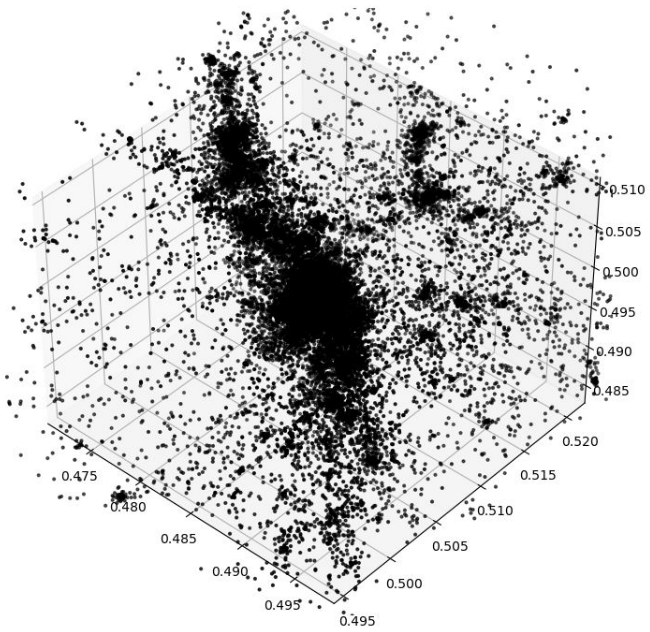
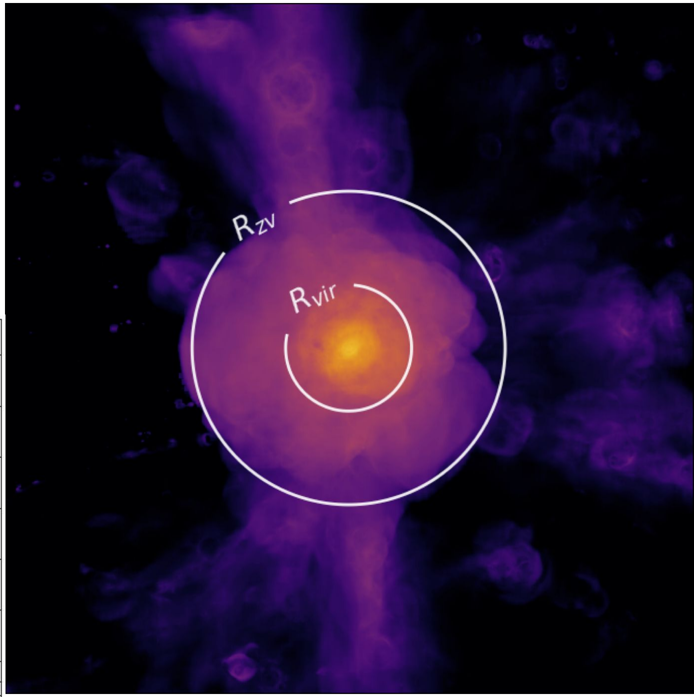
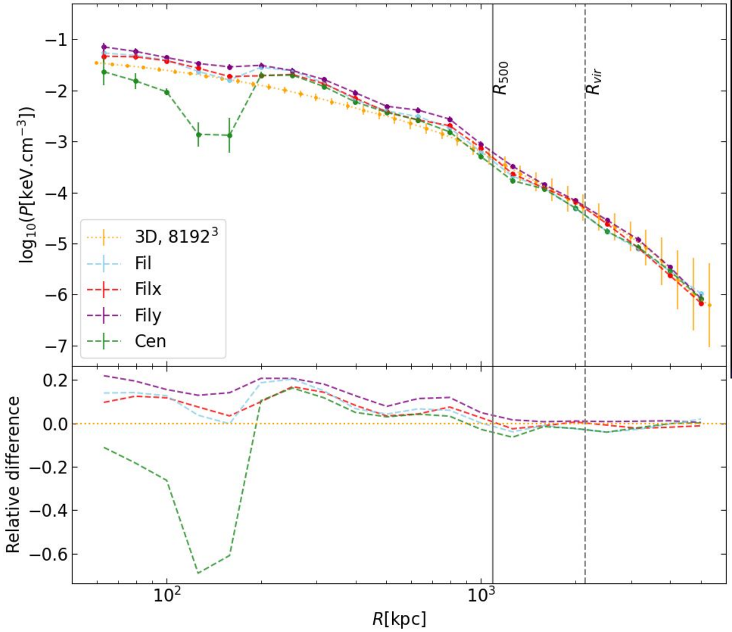


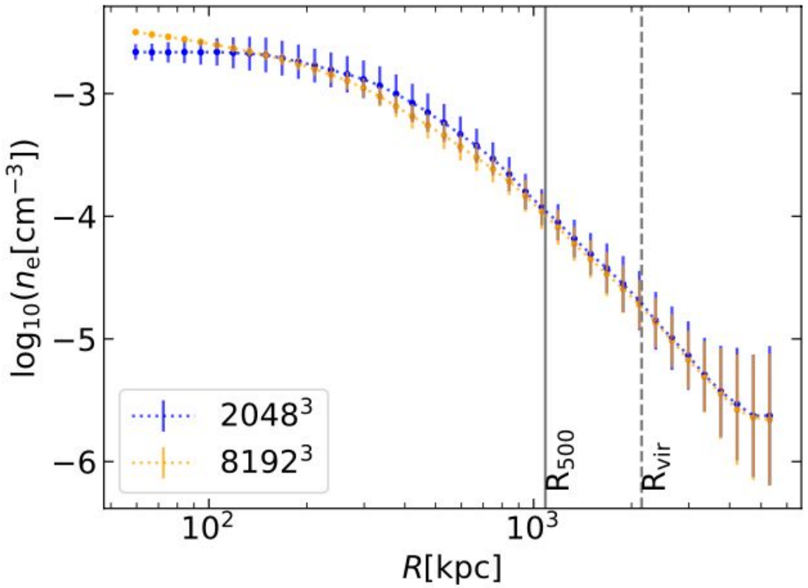


- Use a deprojection method to recover the 3D radial profiles from the 2D projected profile
- Derive the hydrostatic mass bias and compare it to the bias derived from 3D profiles

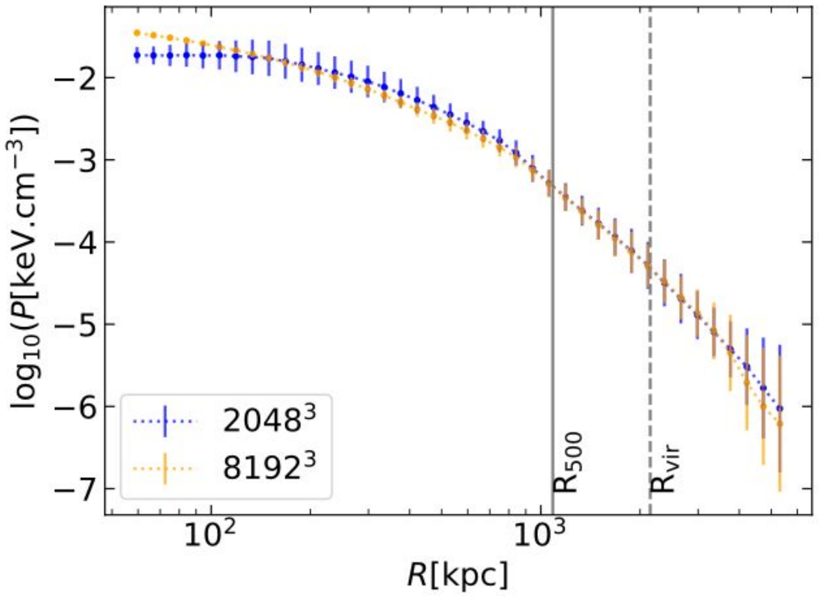


3D profiles

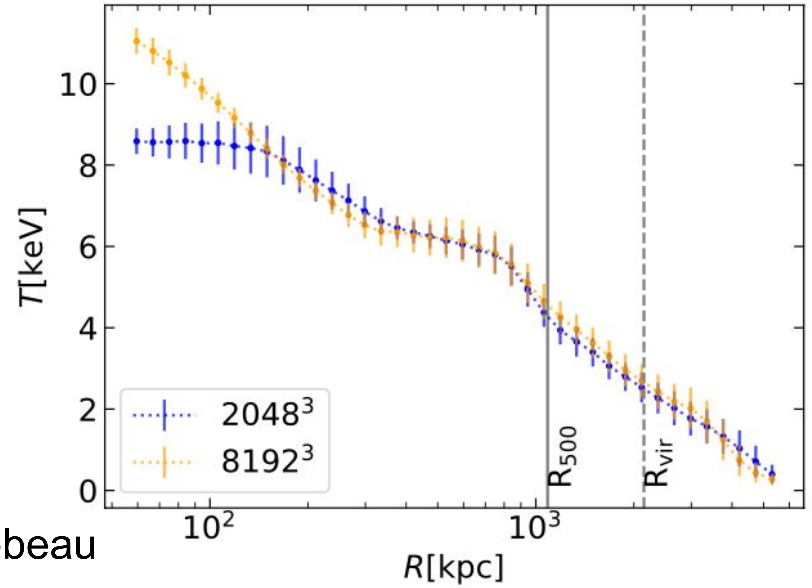
Electron density



Pressure



Temperature



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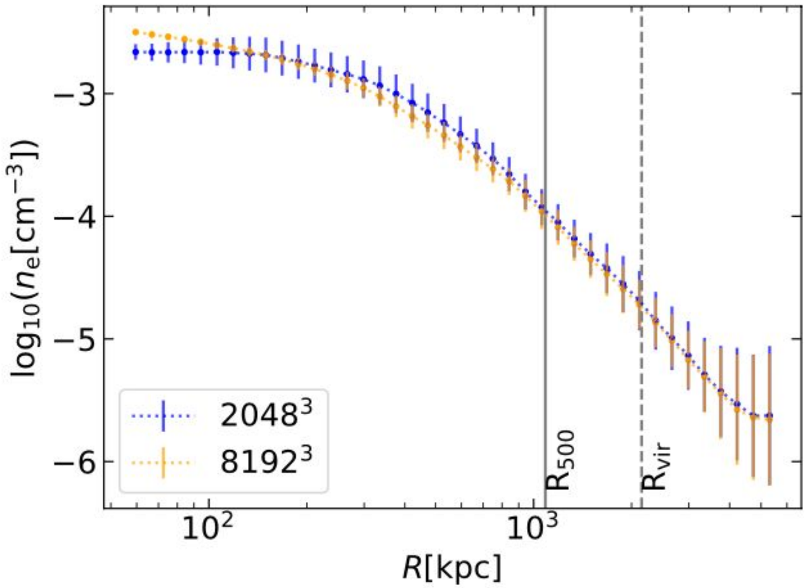

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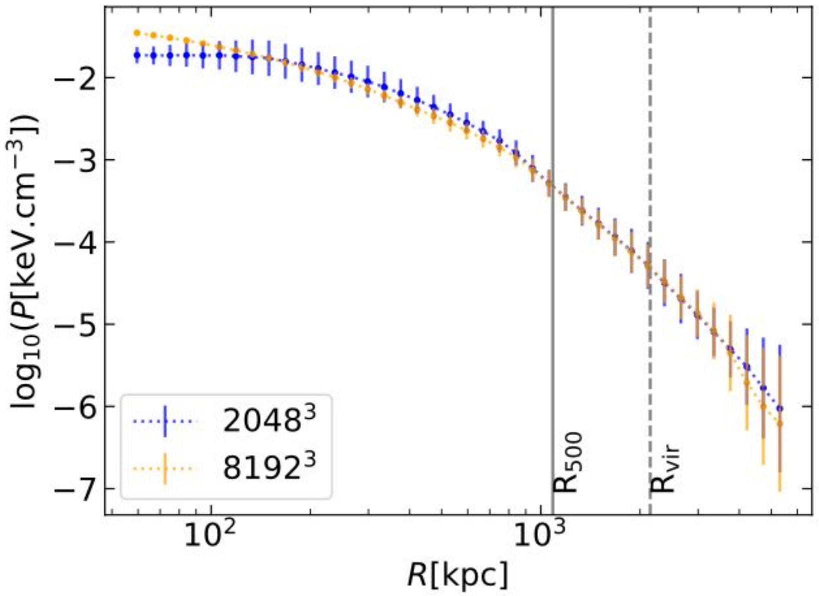

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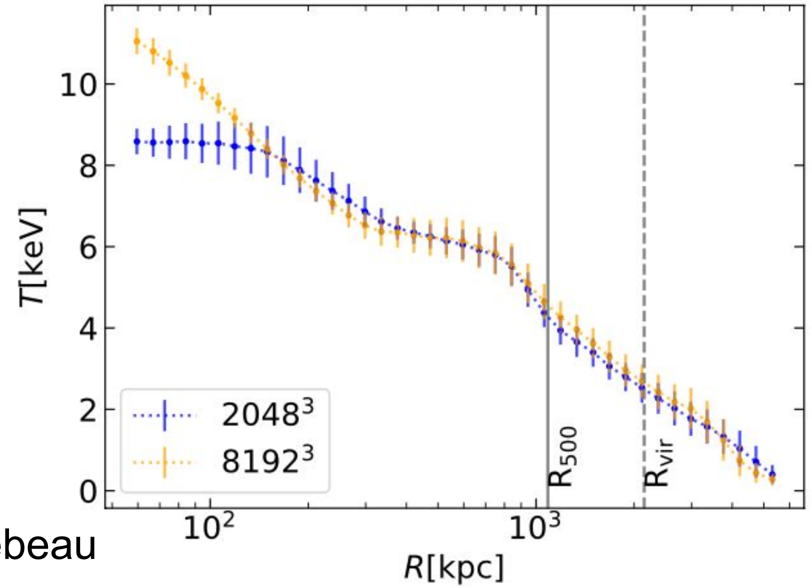
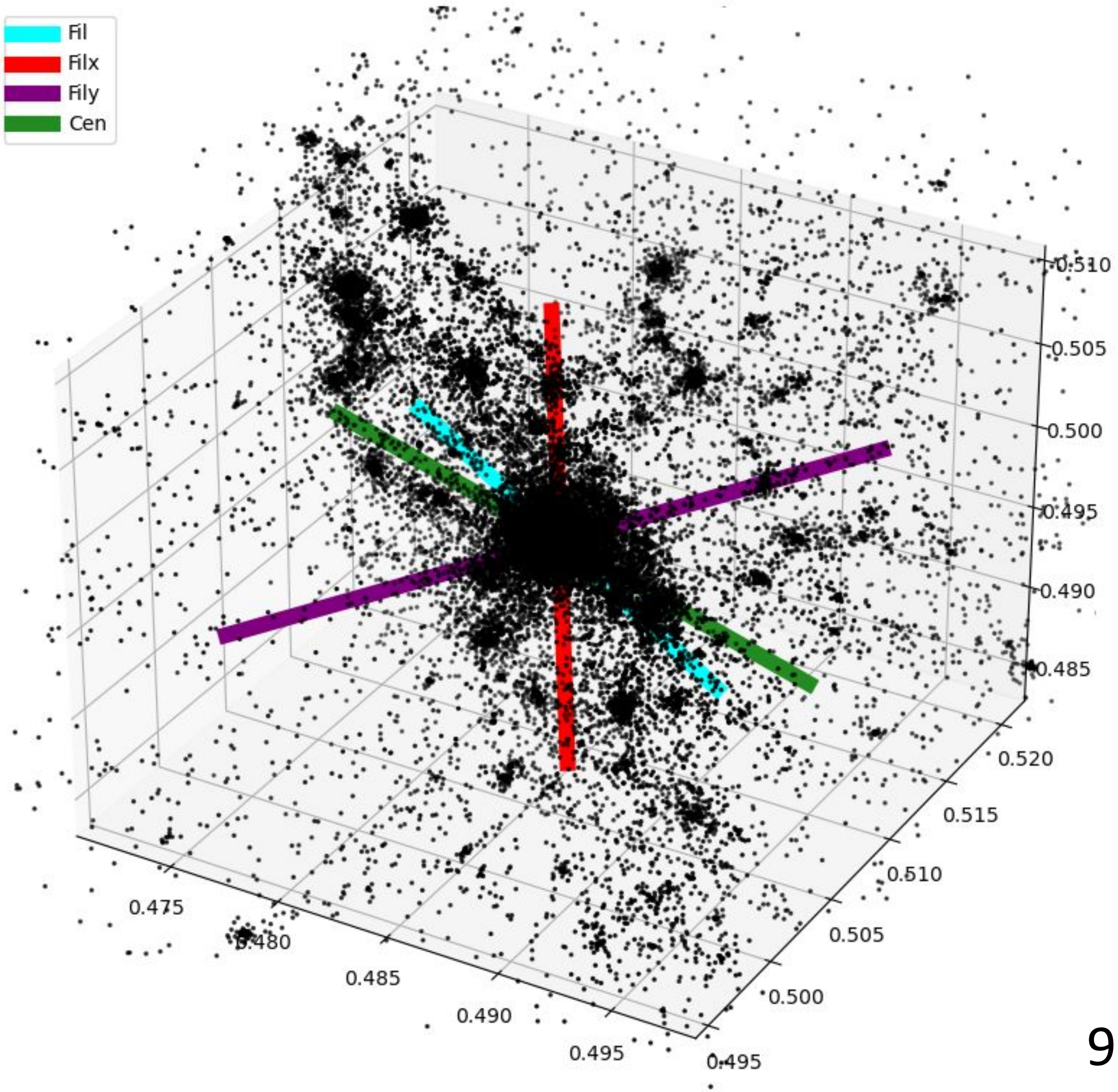


<u>Probe of the convergence of the 2048^3 simulation for future works:</u>
(The large scale hydro simulation will be a 2048^3)

The radial profiles are similar from ~150kpc to the outskirt

The 2048^3 resolution can be used to study the clusters at R_{500} or R_{vir}

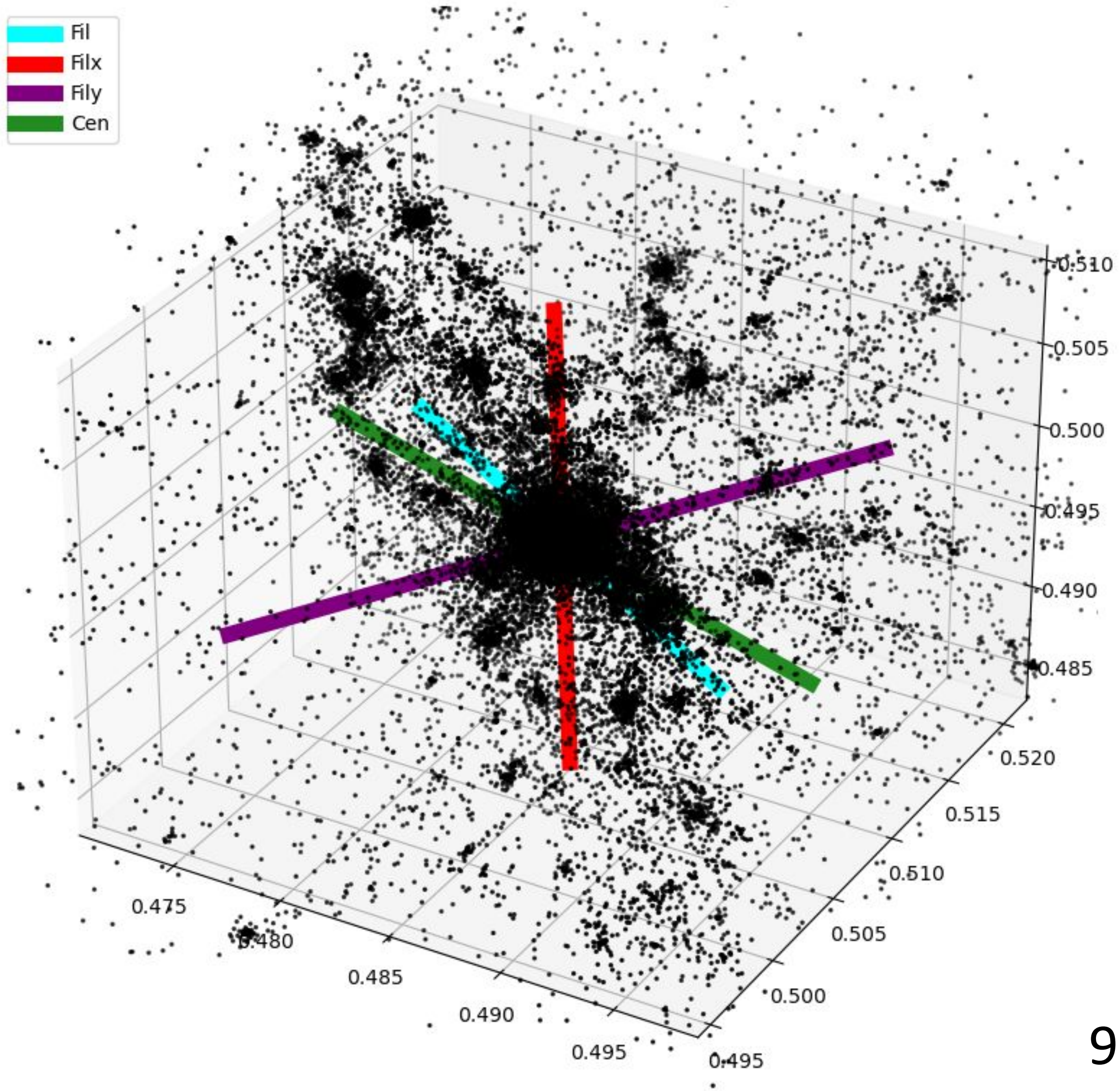
The simulated box



On next slides : LoS = Line of Sight

The simulated box

Main filament axis (**Fil**): *should integrate the most mass*



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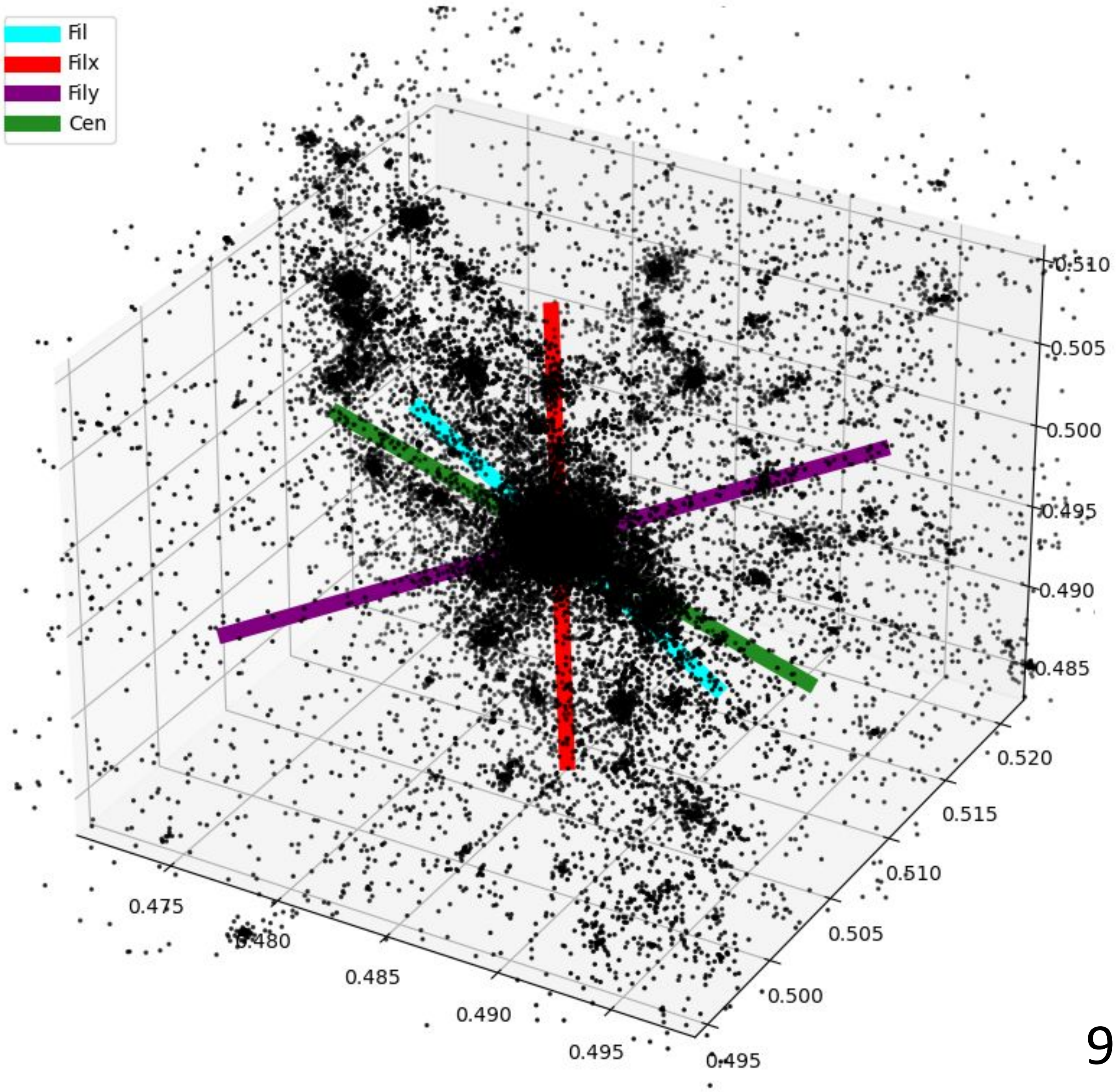

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Perpendicular to the main filament (x axis rotation: **Filx**): *the opposite, should integrate less mass*

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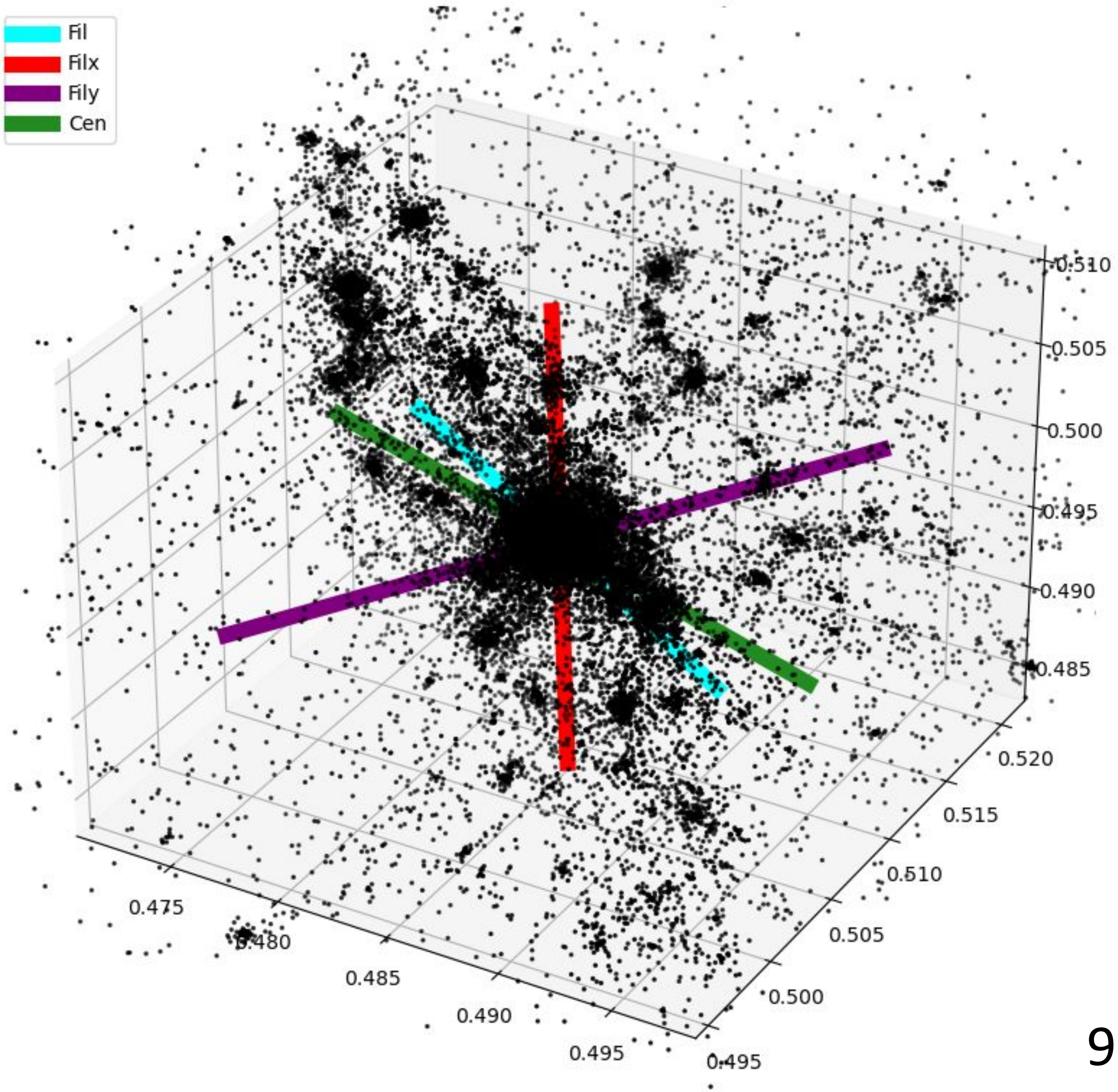

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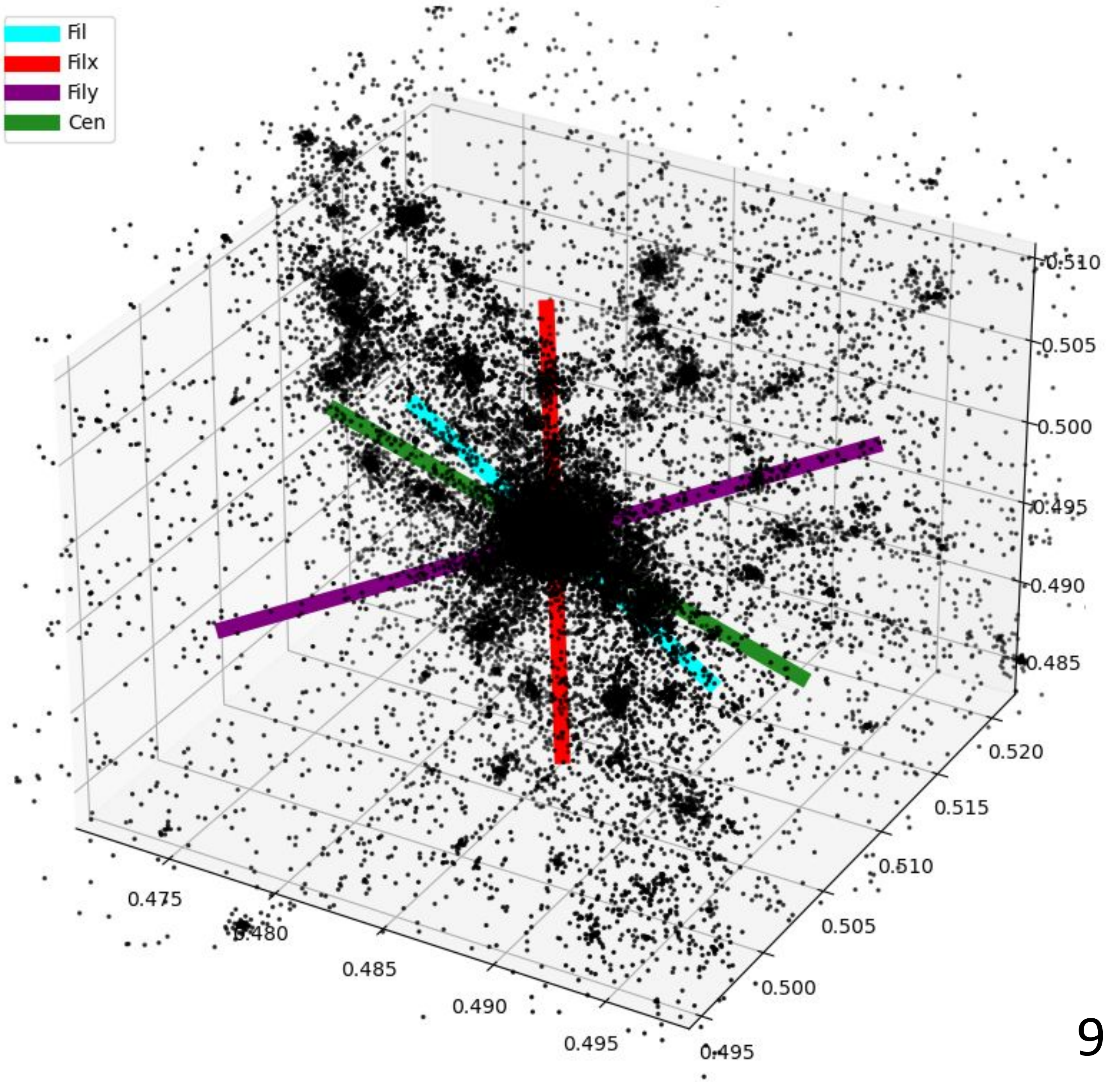
Virgo-center of the box axis (**Cen**): *Assuming it is close to the real line of sight*



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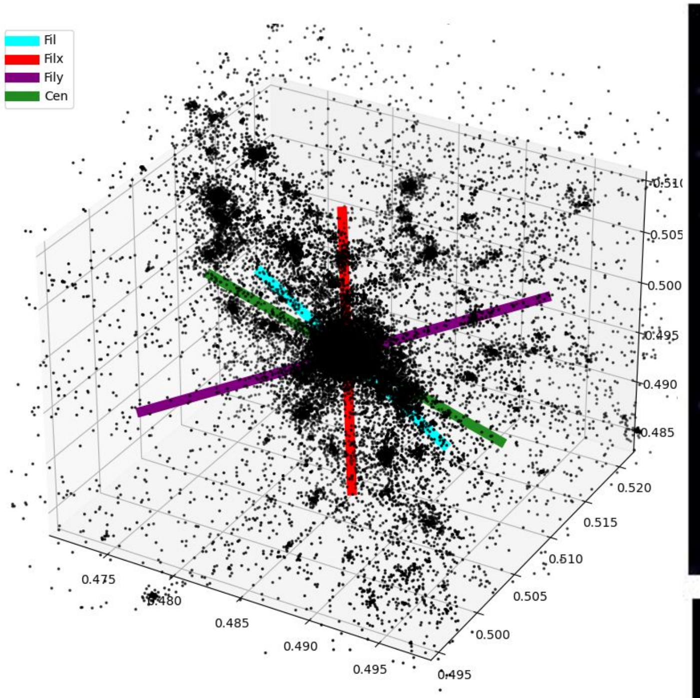
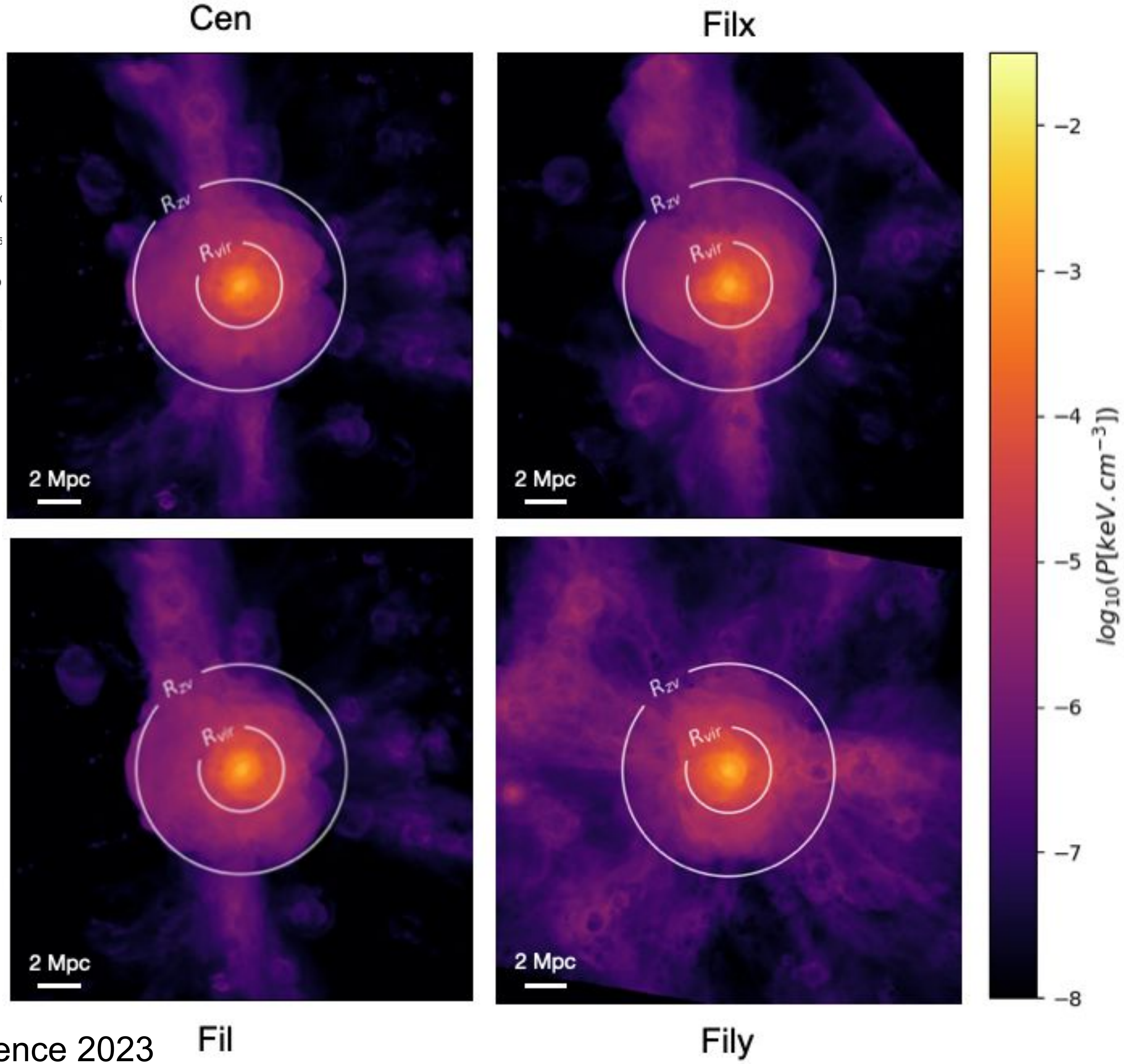
Pressure maps in several projections





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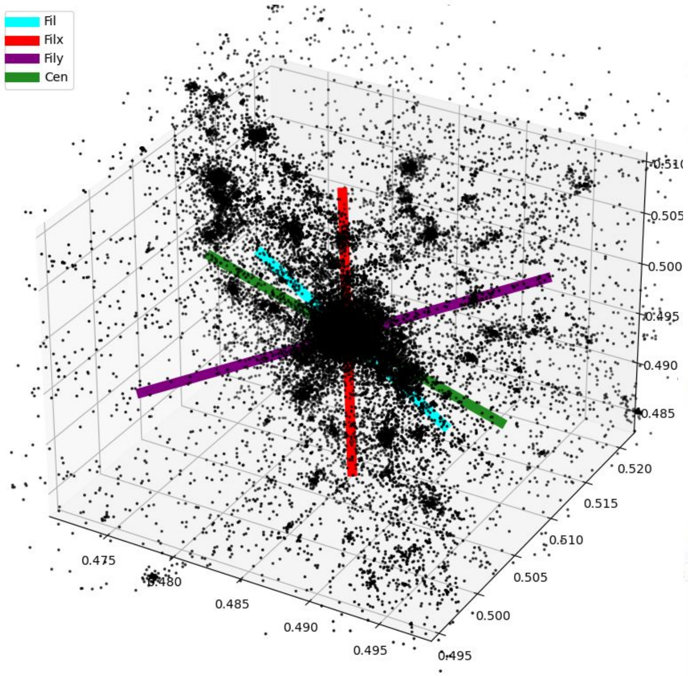
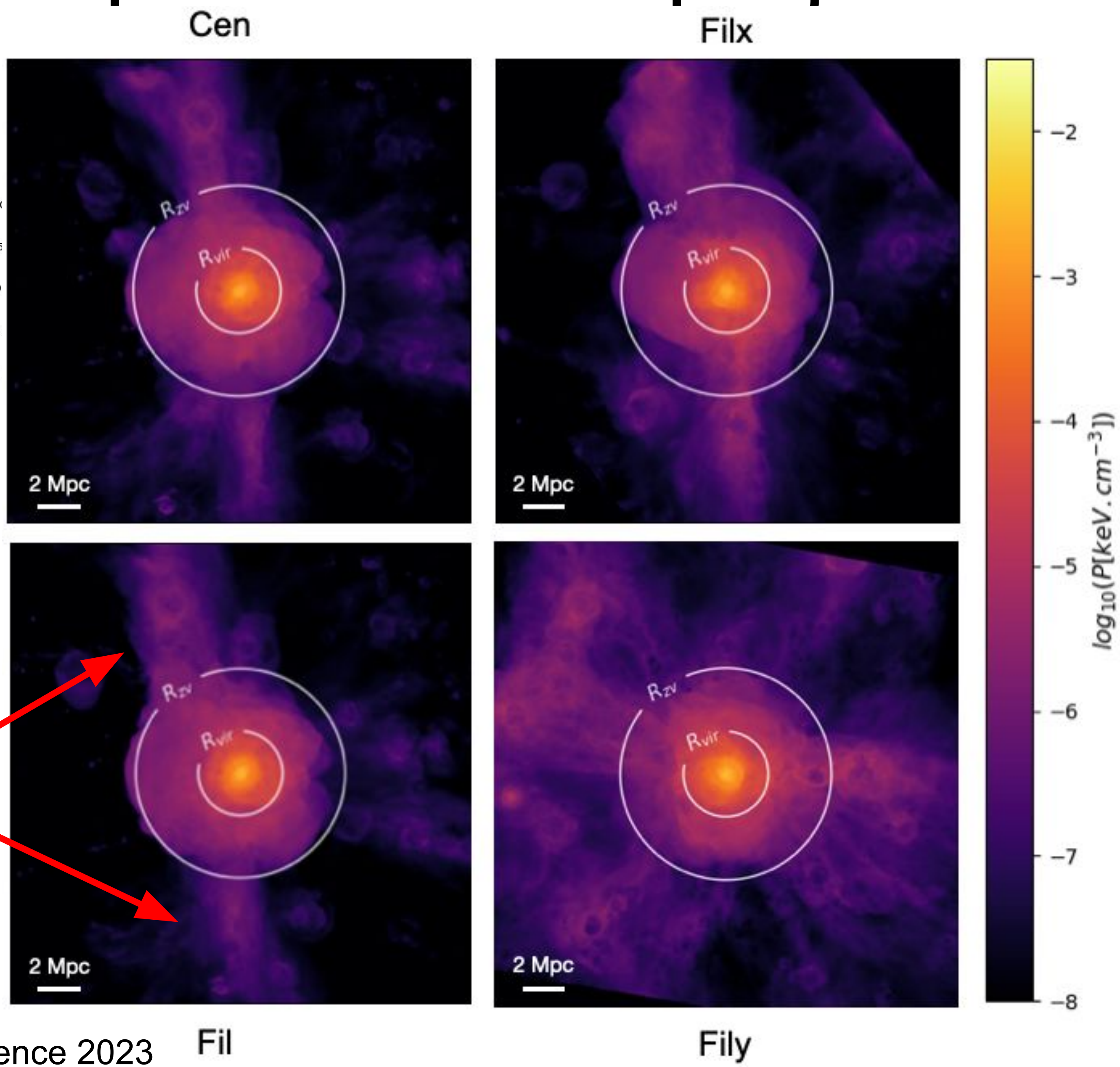
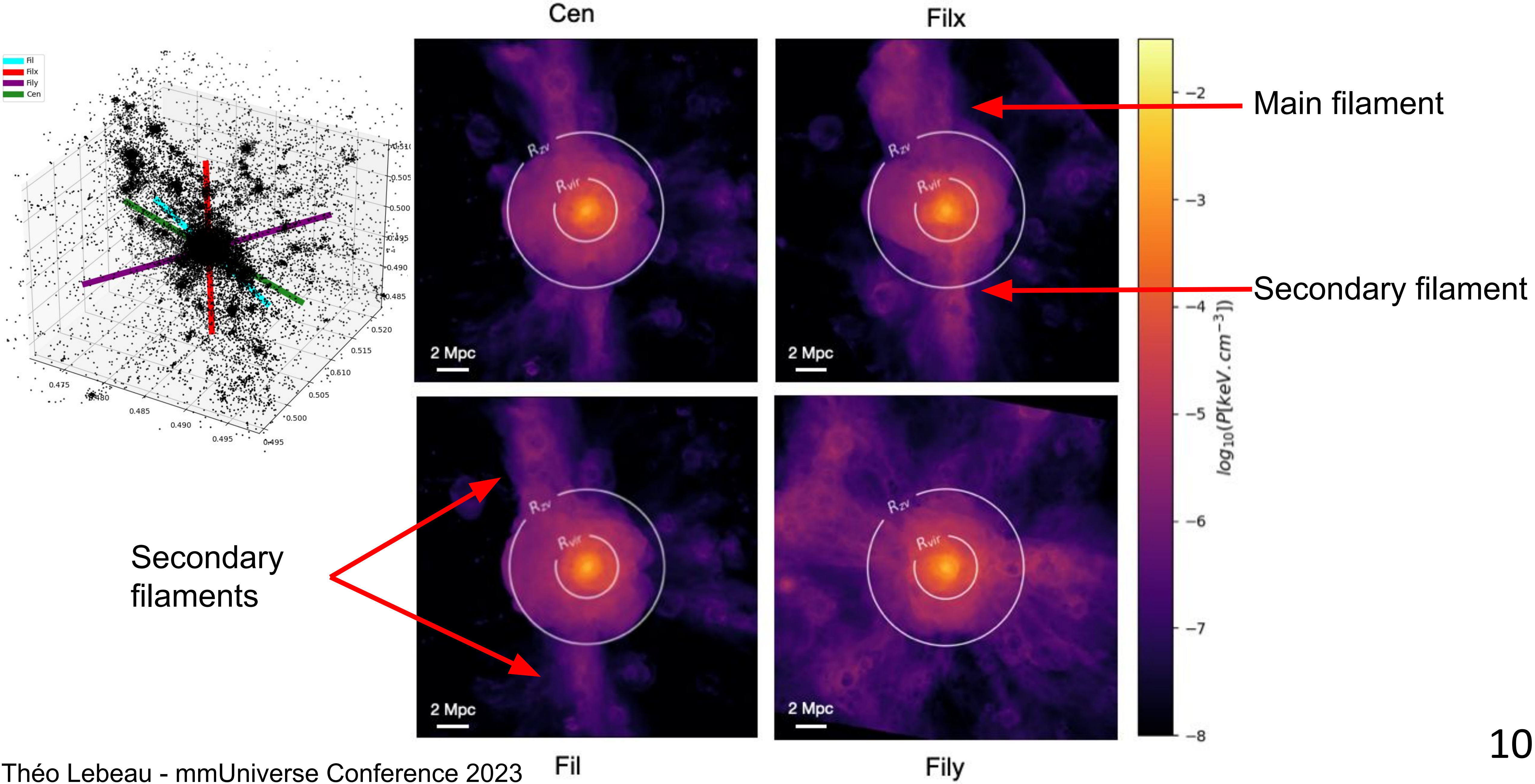




Secondary filaments

Pressure maps in several projections



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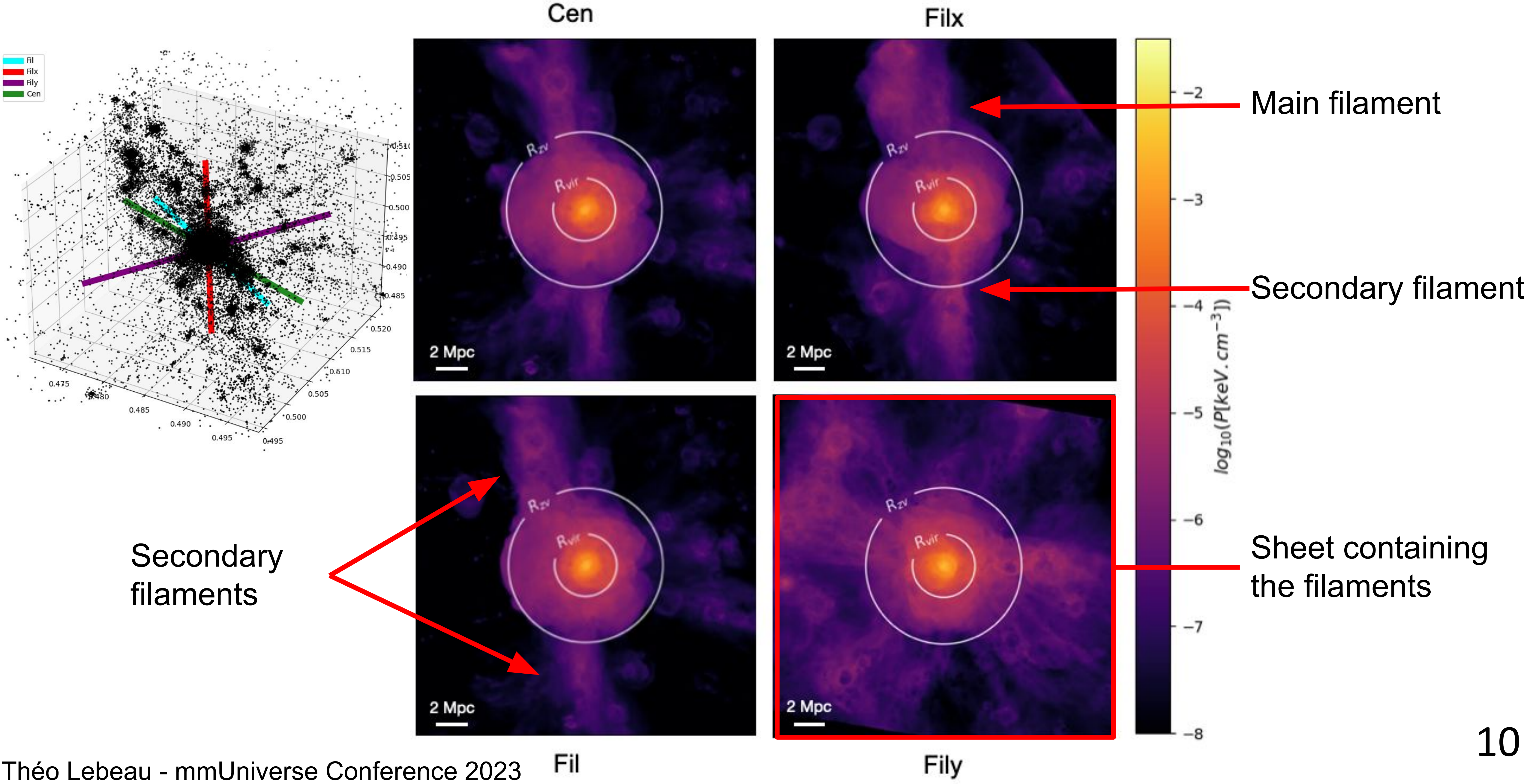
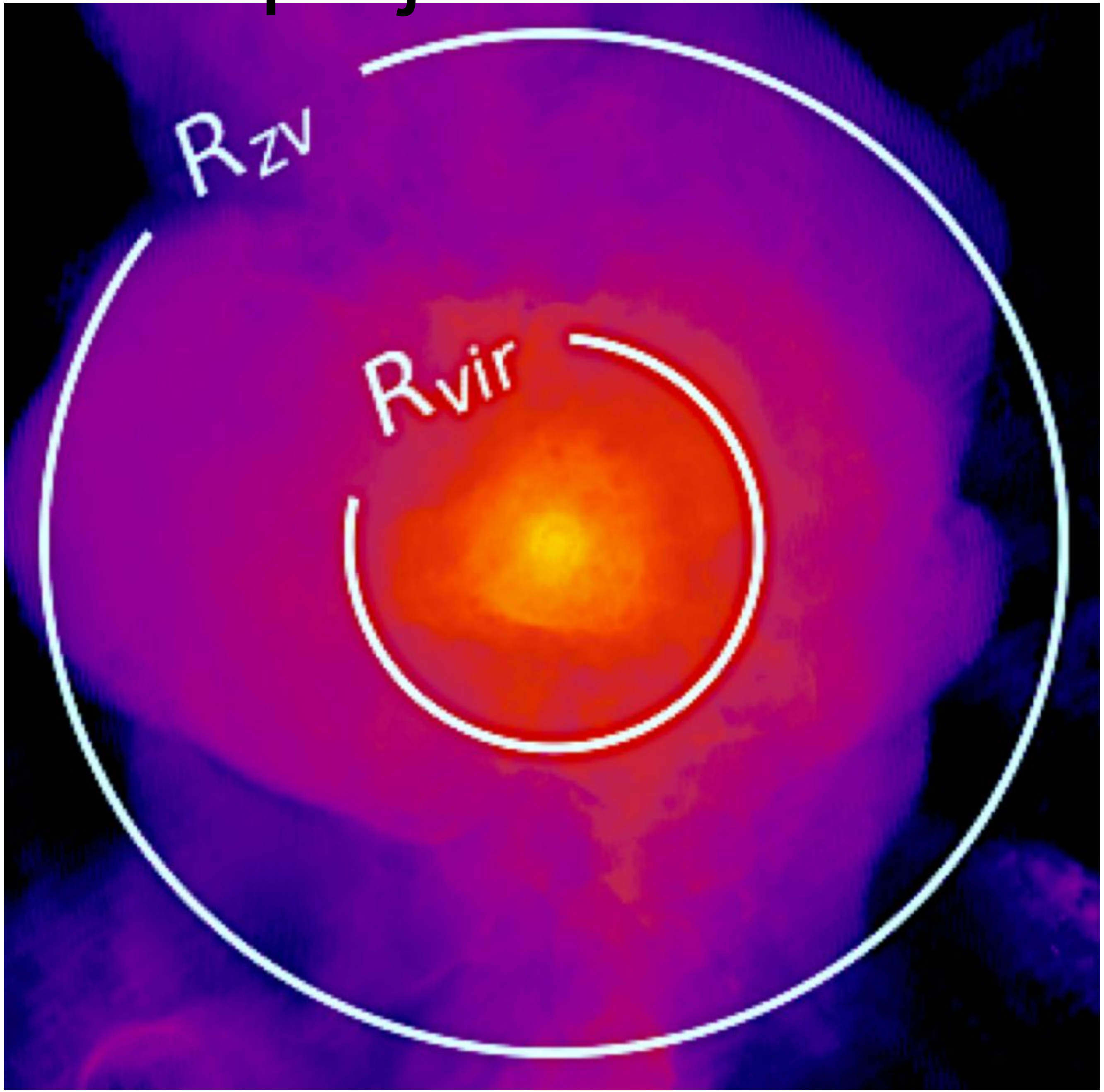


Zoom on the Filx projection



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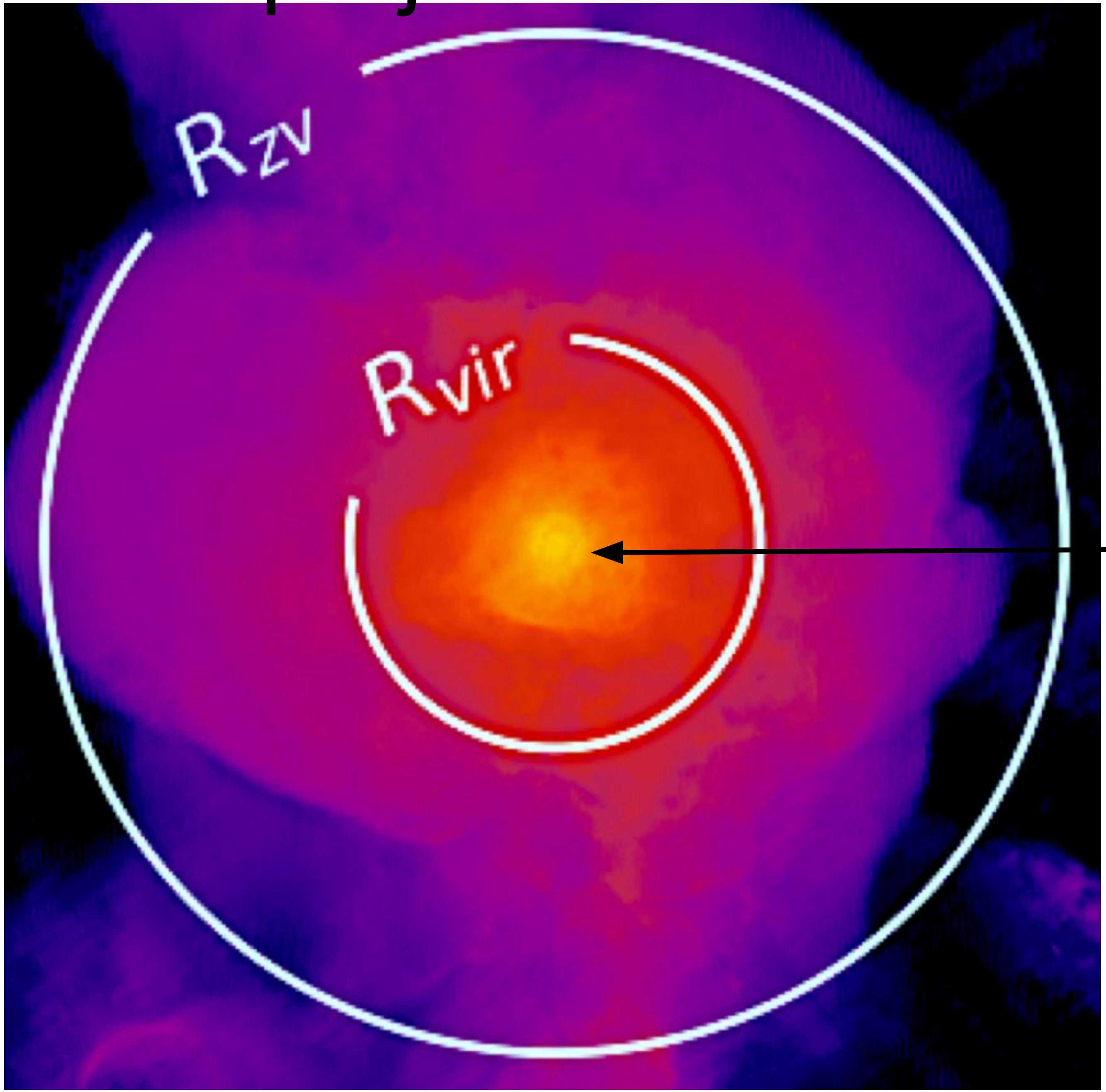

Pressure discontinuities

AGN feedback

Théo Lebeau
mmUniverse Conference 2023

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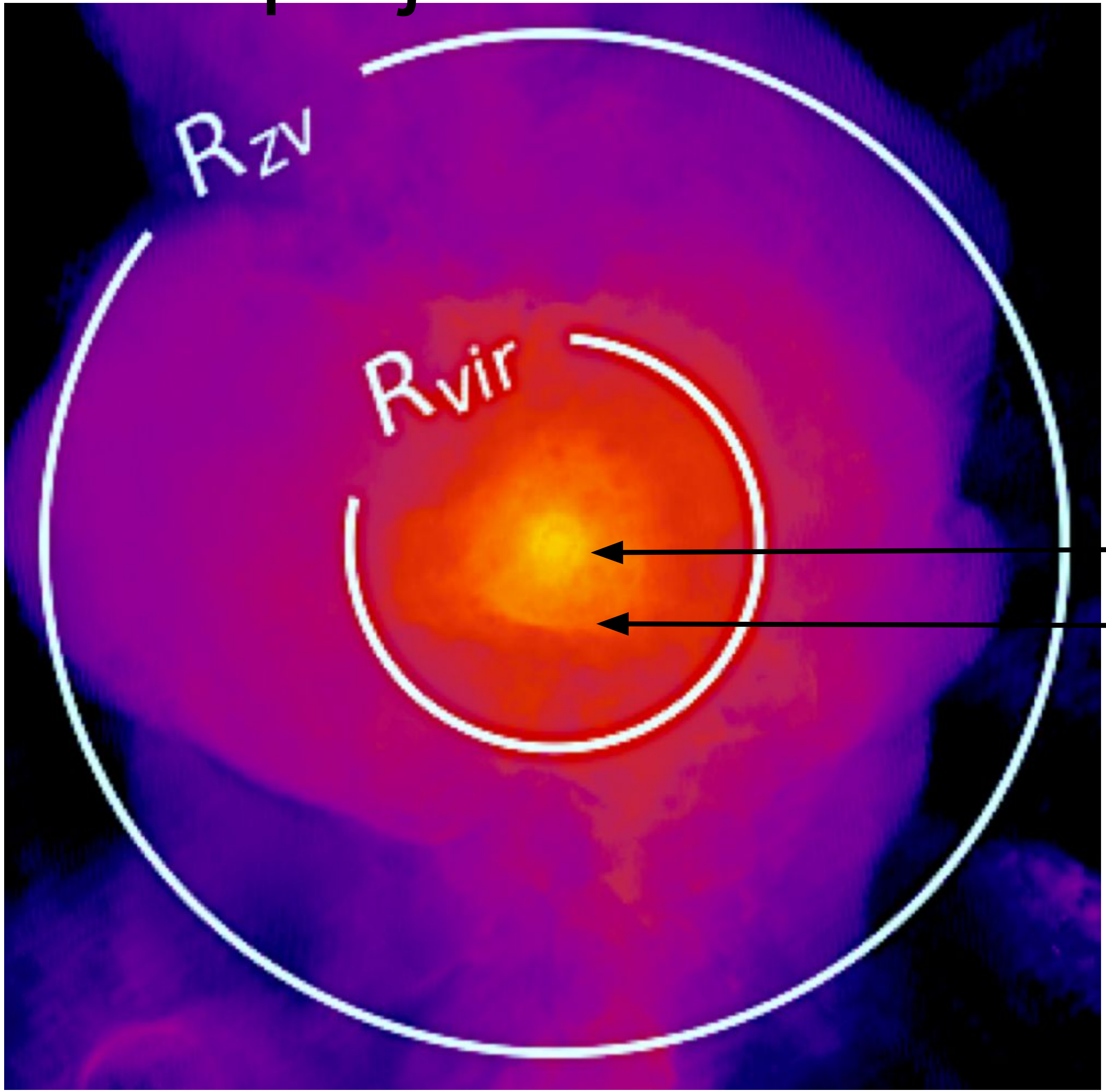

Pressure discontinuities

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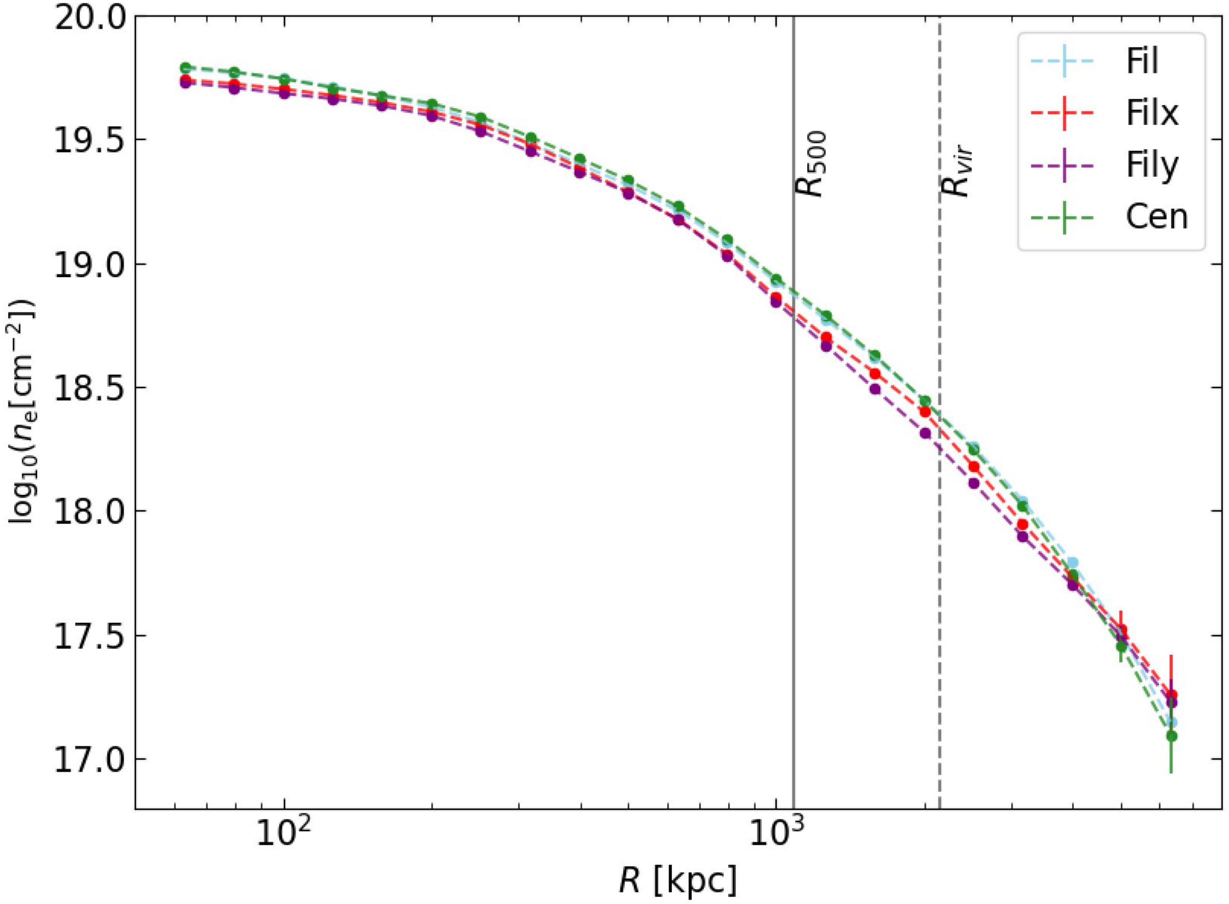
Matter infall from the filament

(see Gouin et al. 2022)

Projected radial profiles

Electron Density (column density)



More mass (associated to hot gas) outside the cluster along the LoS induces **higher column density**

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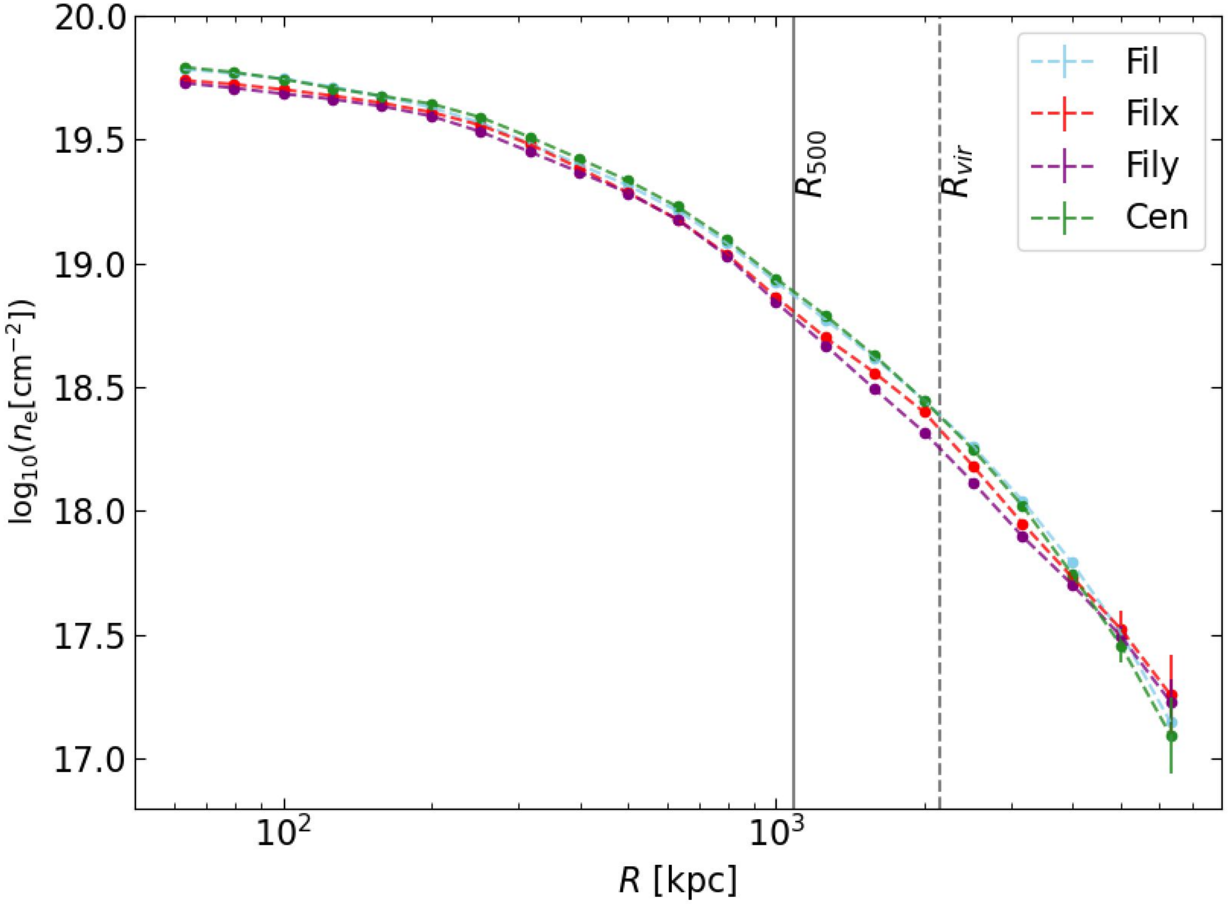

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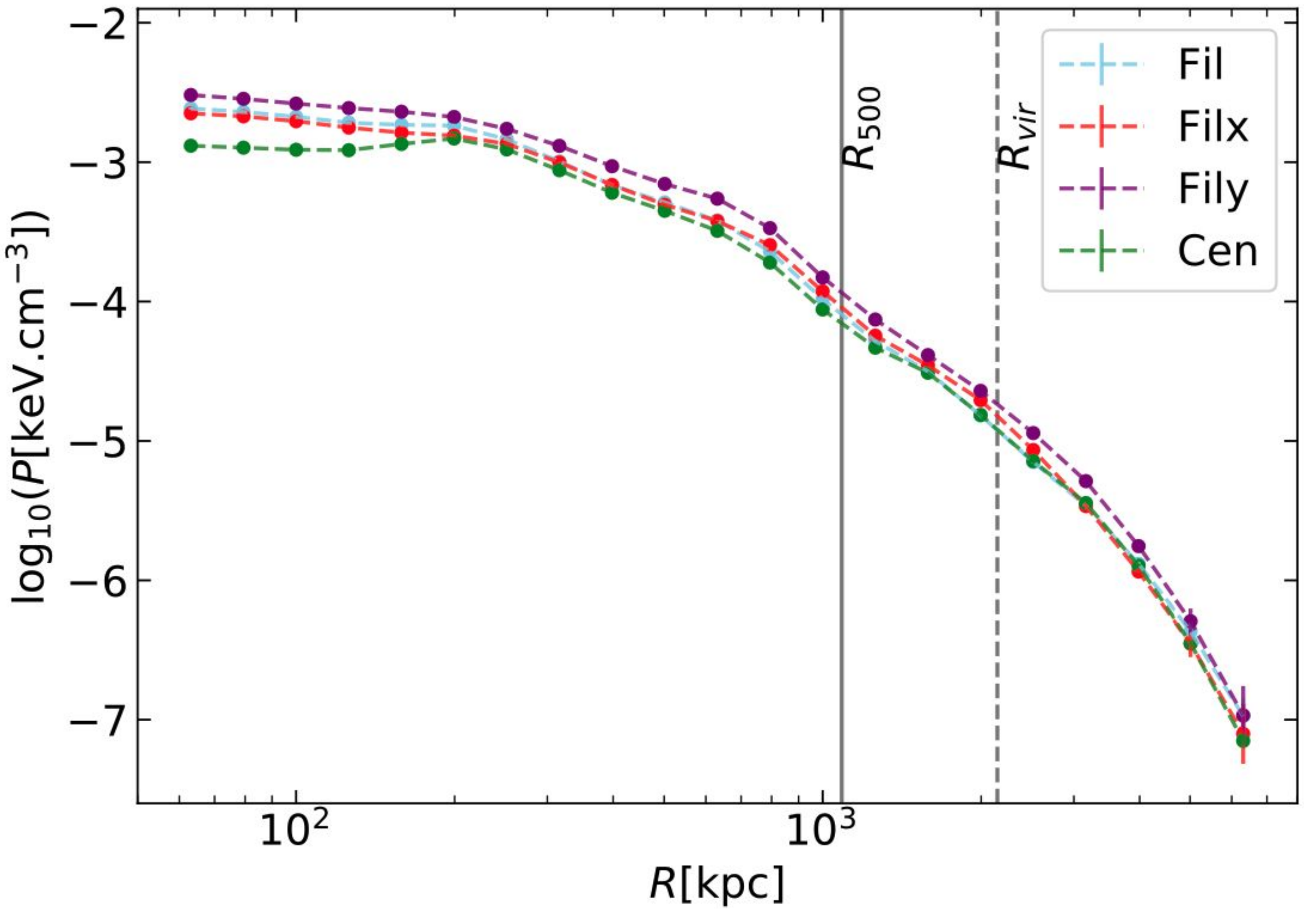
Pressure (mass-weighted mean)



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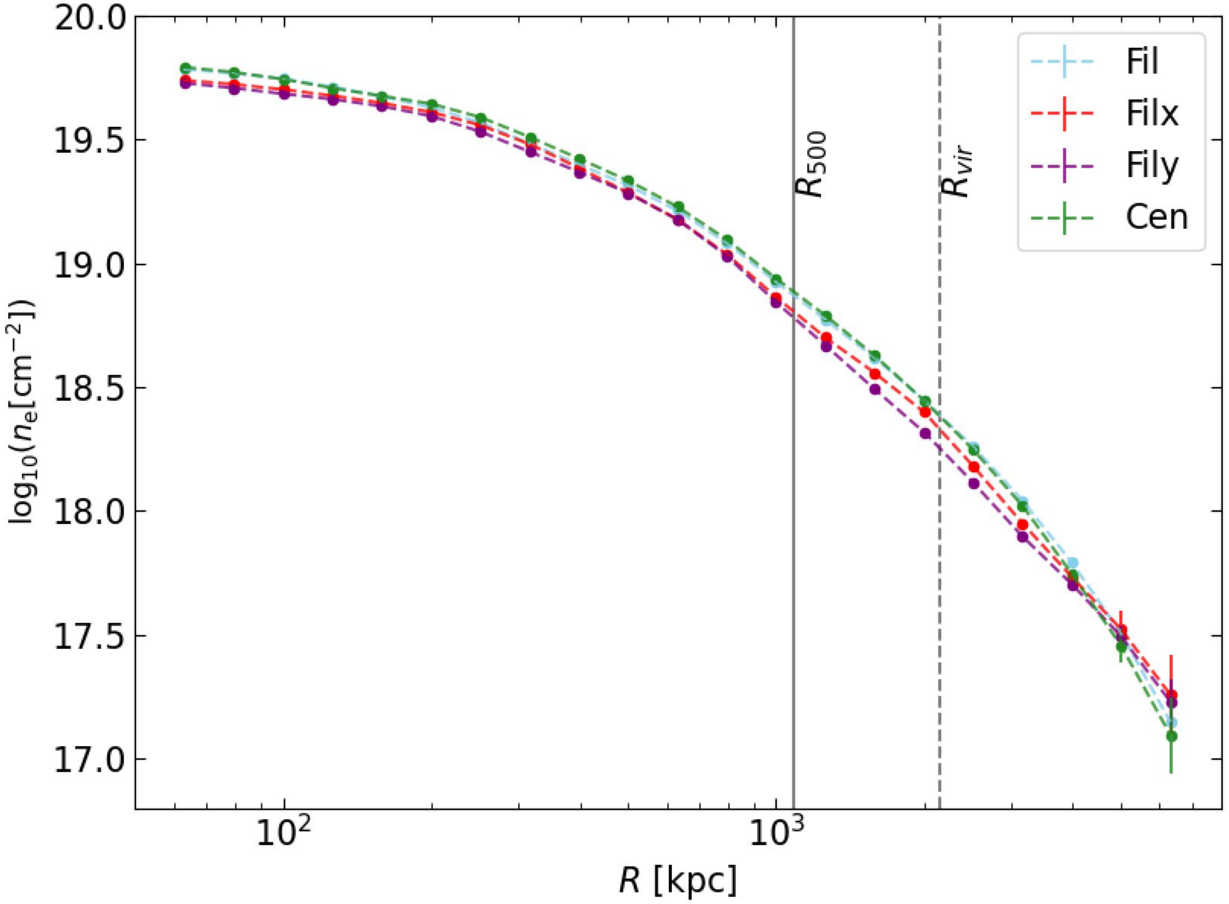

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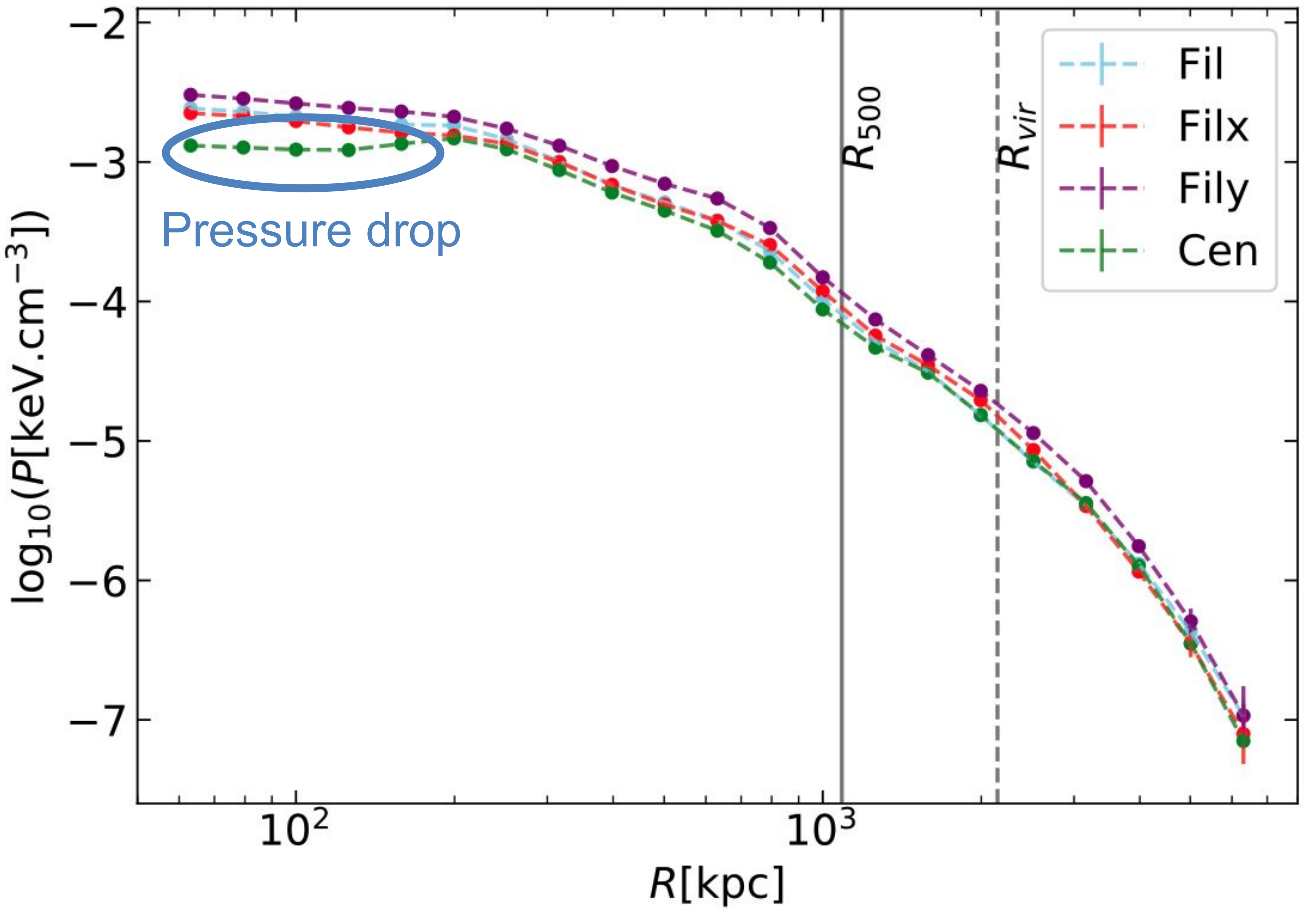

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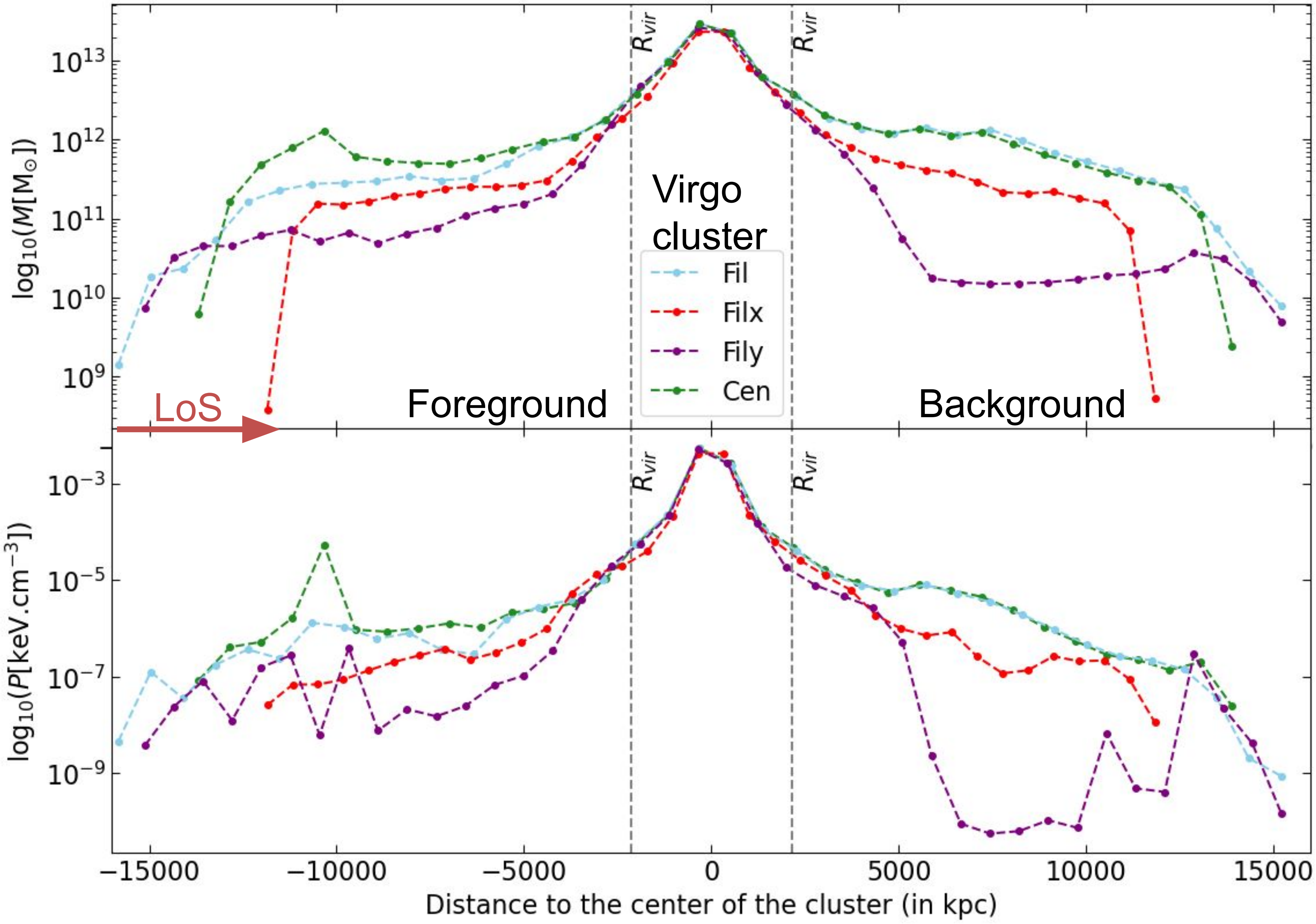
Mass/pressure distribution along the line of sight



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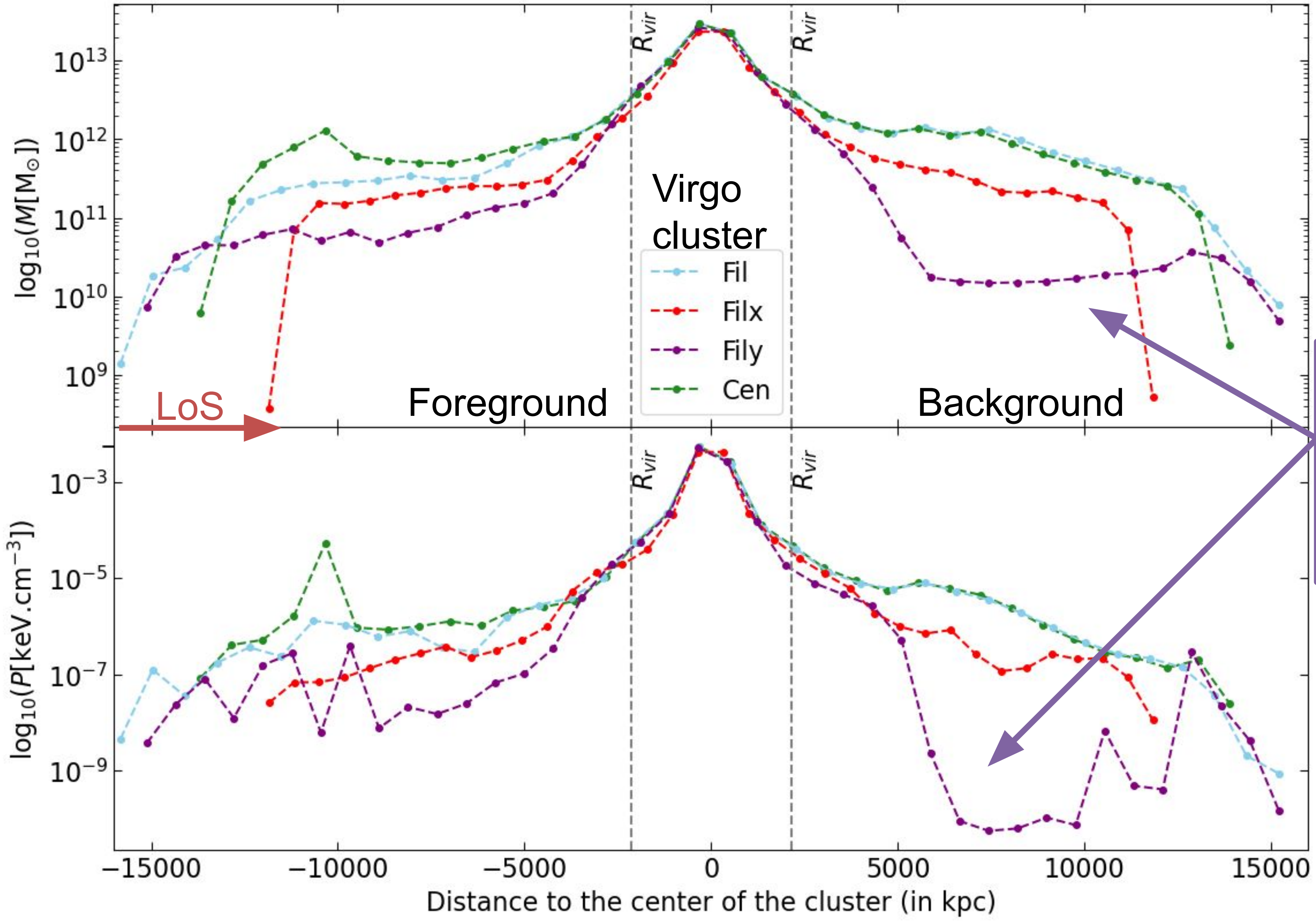

The **Fily** line of sight contains the least mass and pressure outside the cluster

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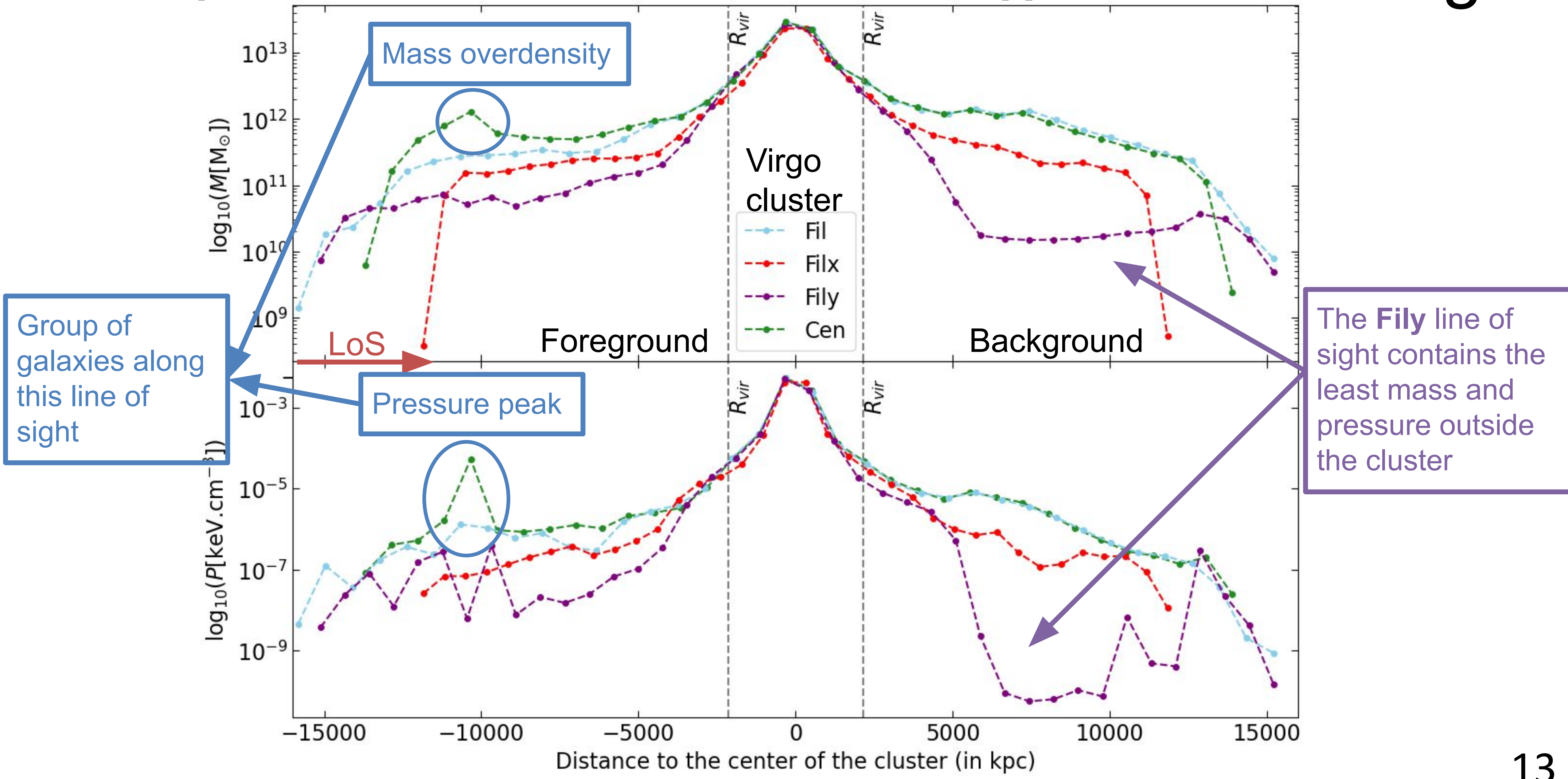
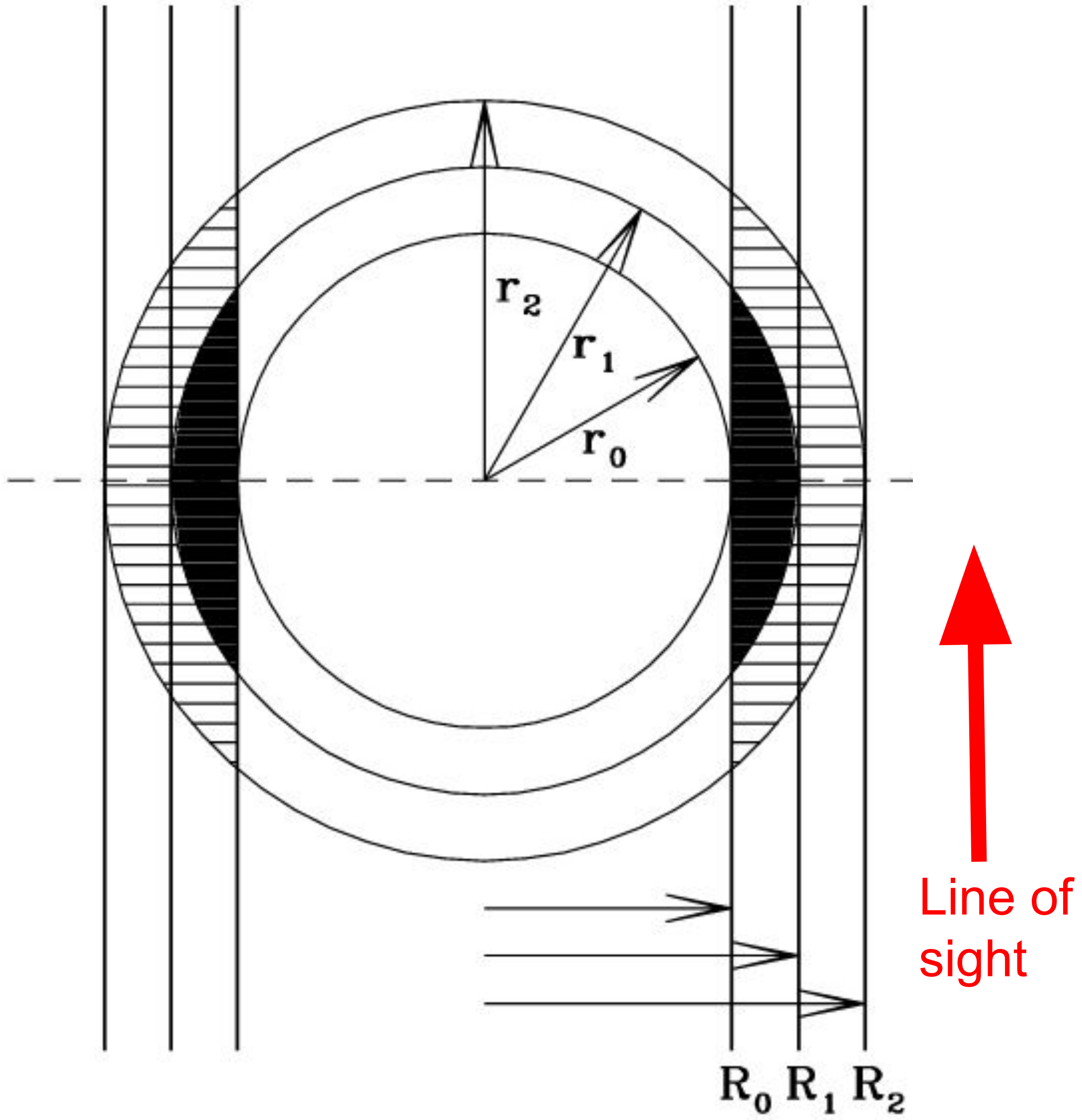


Deprojection method

- Iterative geometrical process ("onion rings method") : from the outskirt to the center of the cluster → model-free



McLaughlin et al. (1999)

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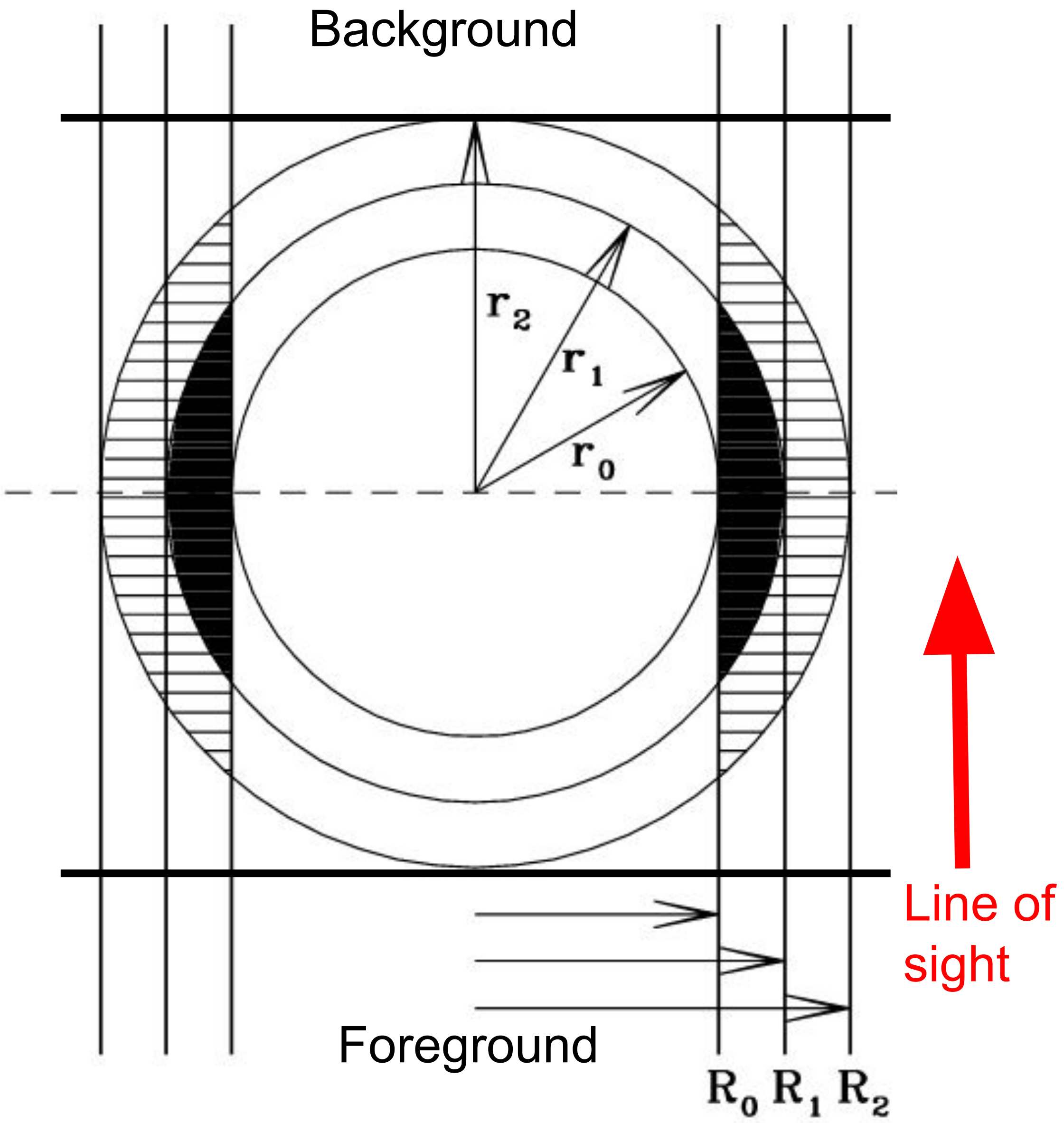

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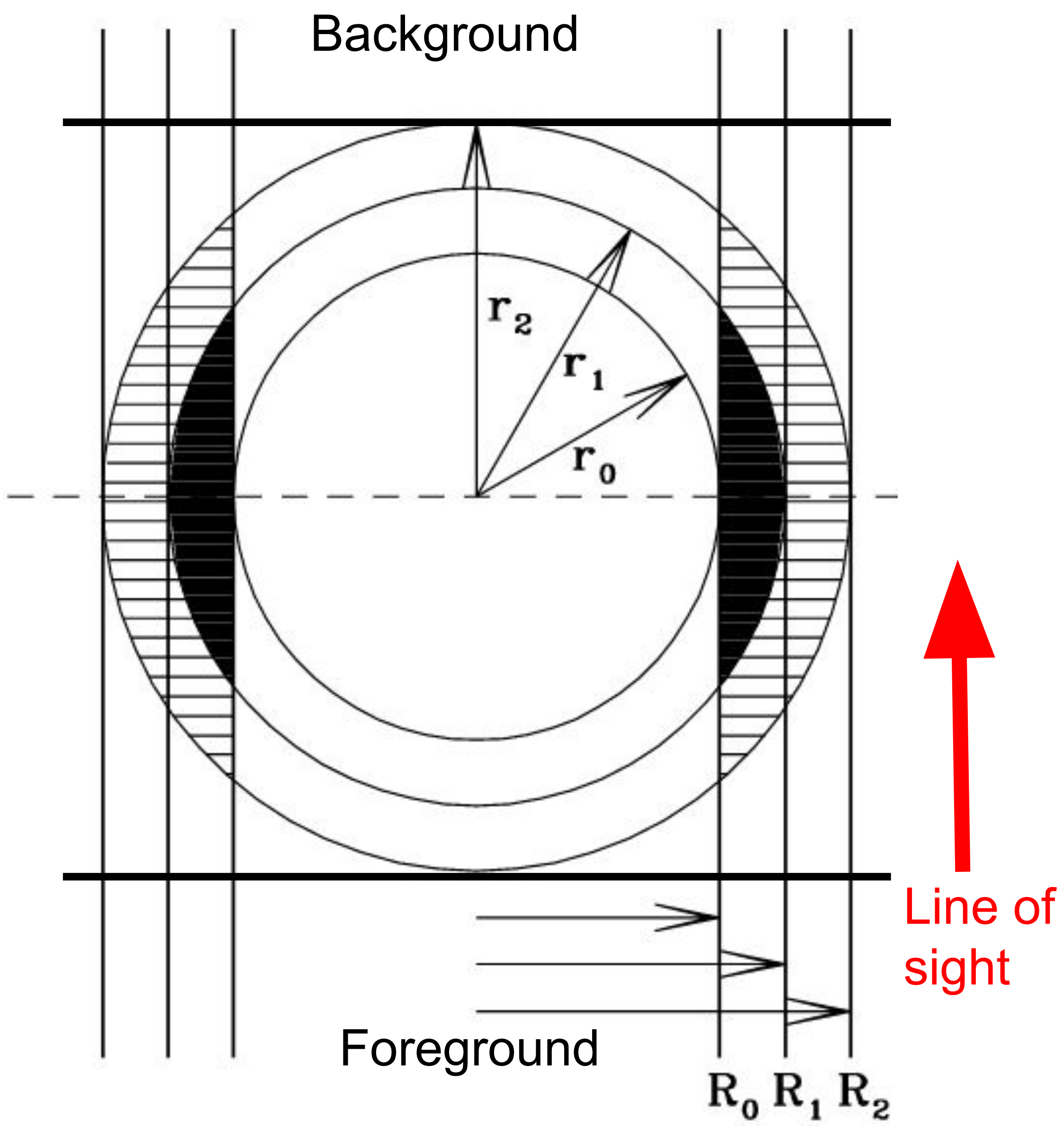

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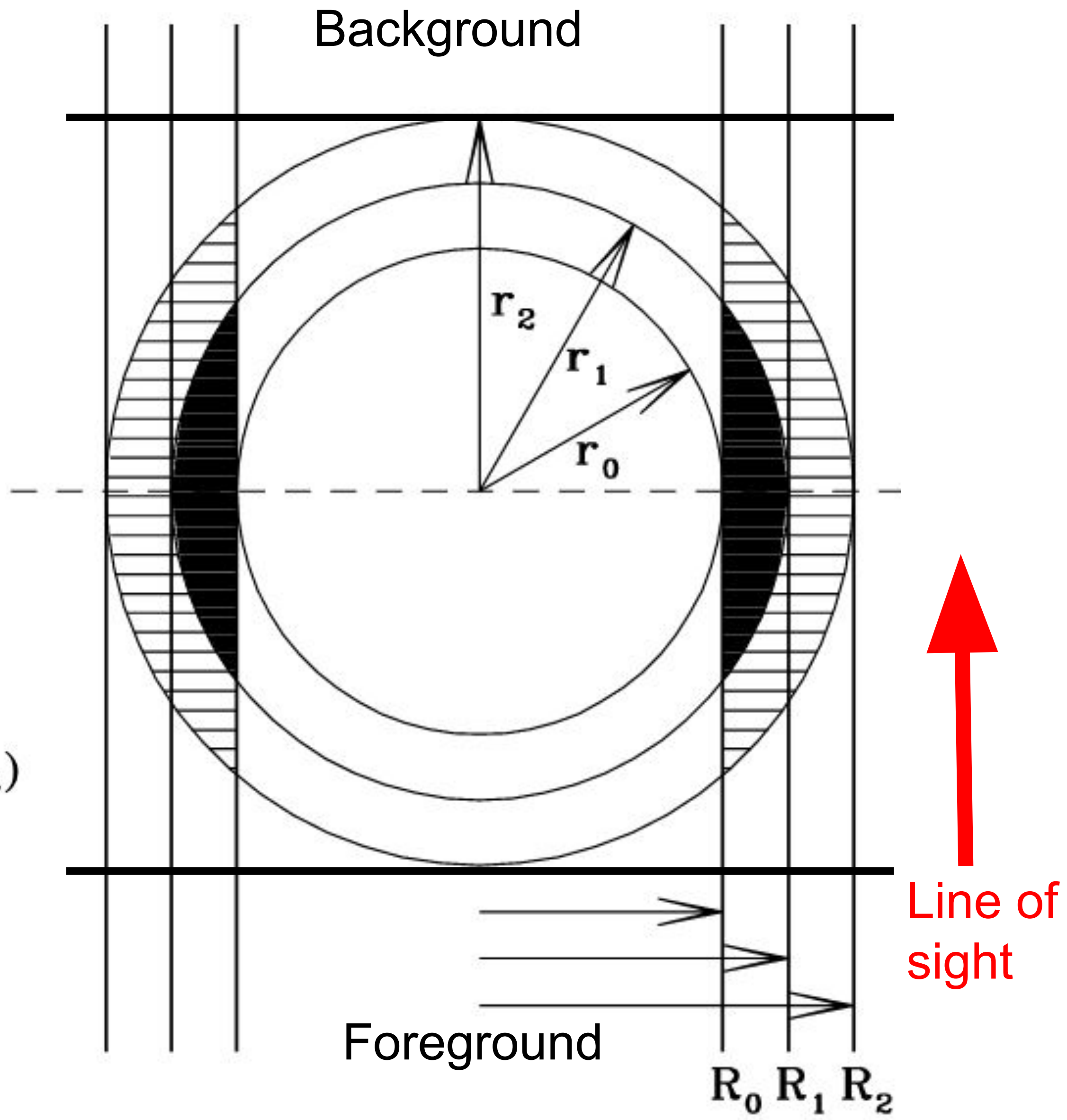

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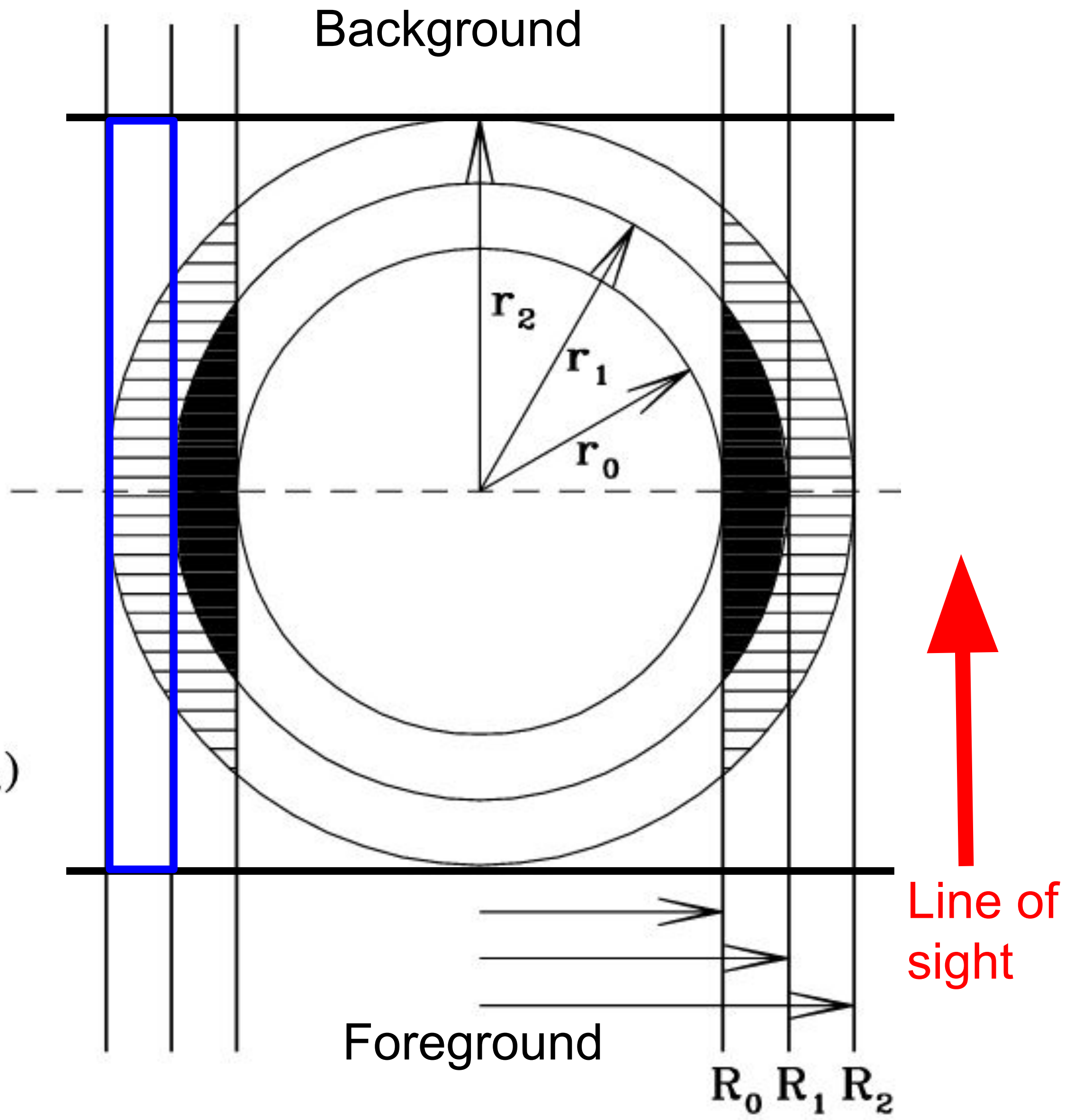

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- Iterative geometrical process ("onion rings method") : from the outskirt to the center of the cluster → model-free
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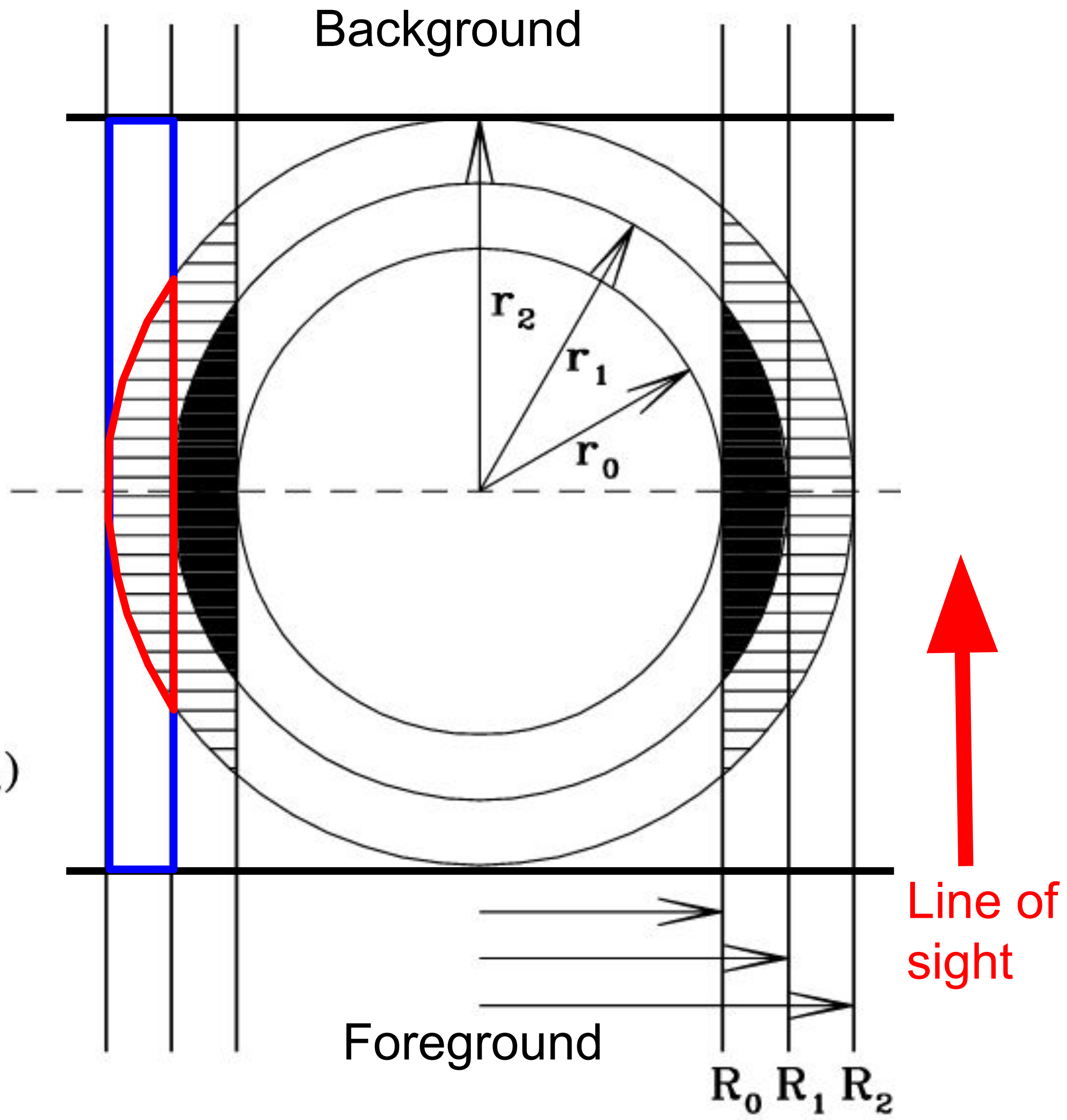
- Signal in circular annulli : contributions of spherical shells along the LoS

P: projected pressure, *P'*: deprojected pressure

Furthest annulus: $\boxed{P(R_1,R_2)} * \pi(R_2^2 - R_1^2)L = \boxed{P'(r_1,r_2)} * V_{int}(r_1,r_2,R_1,R_2)$



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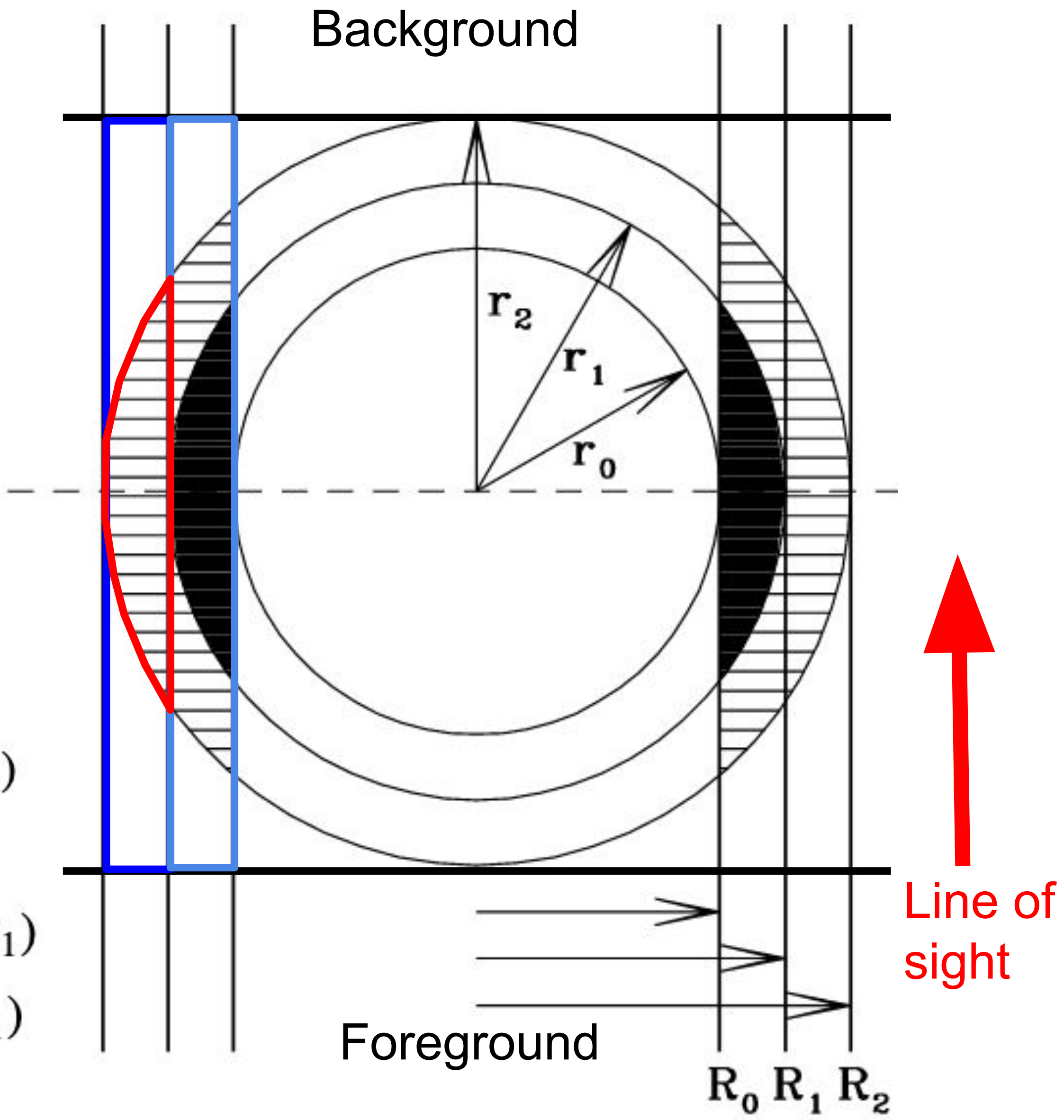

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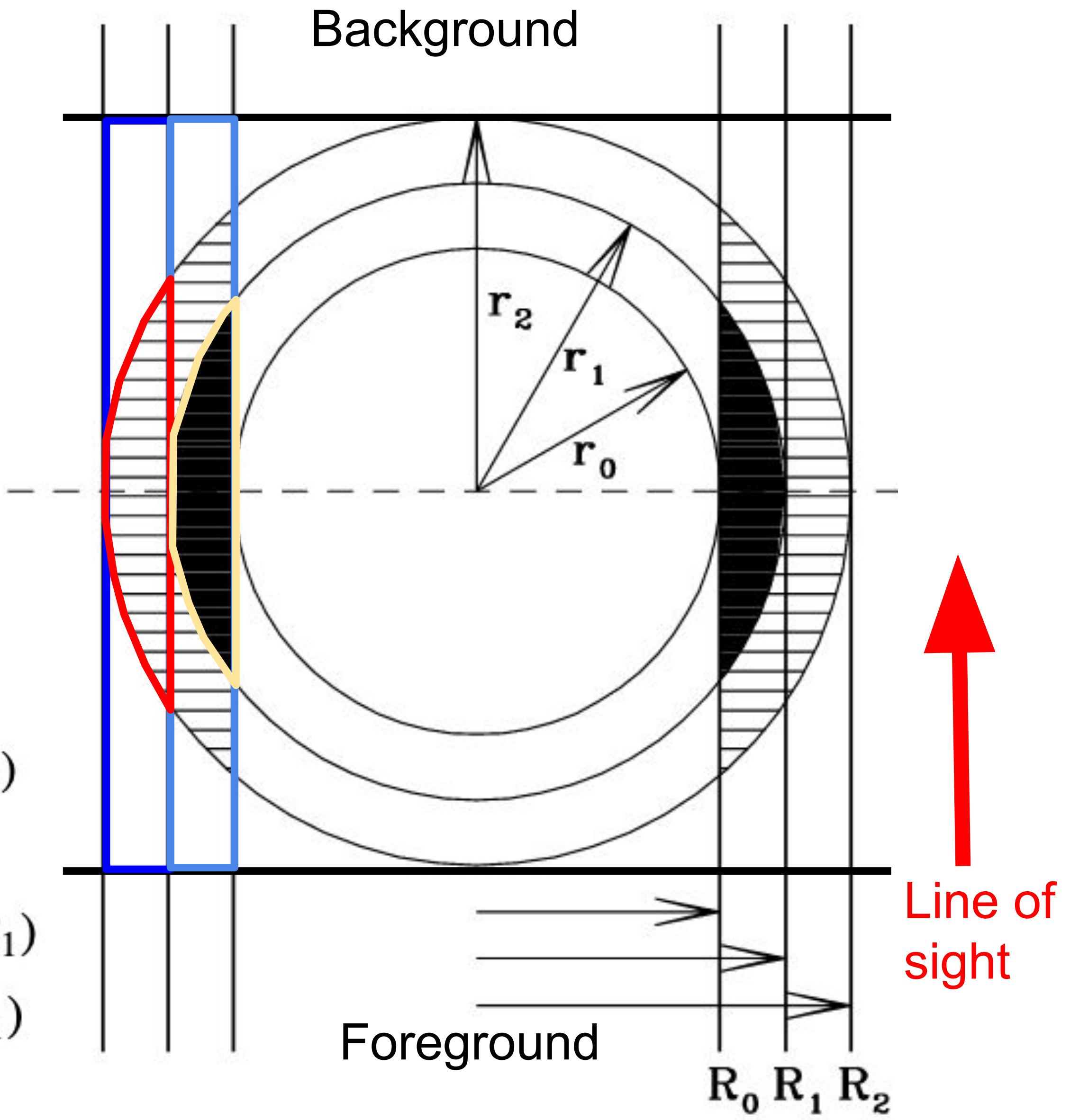

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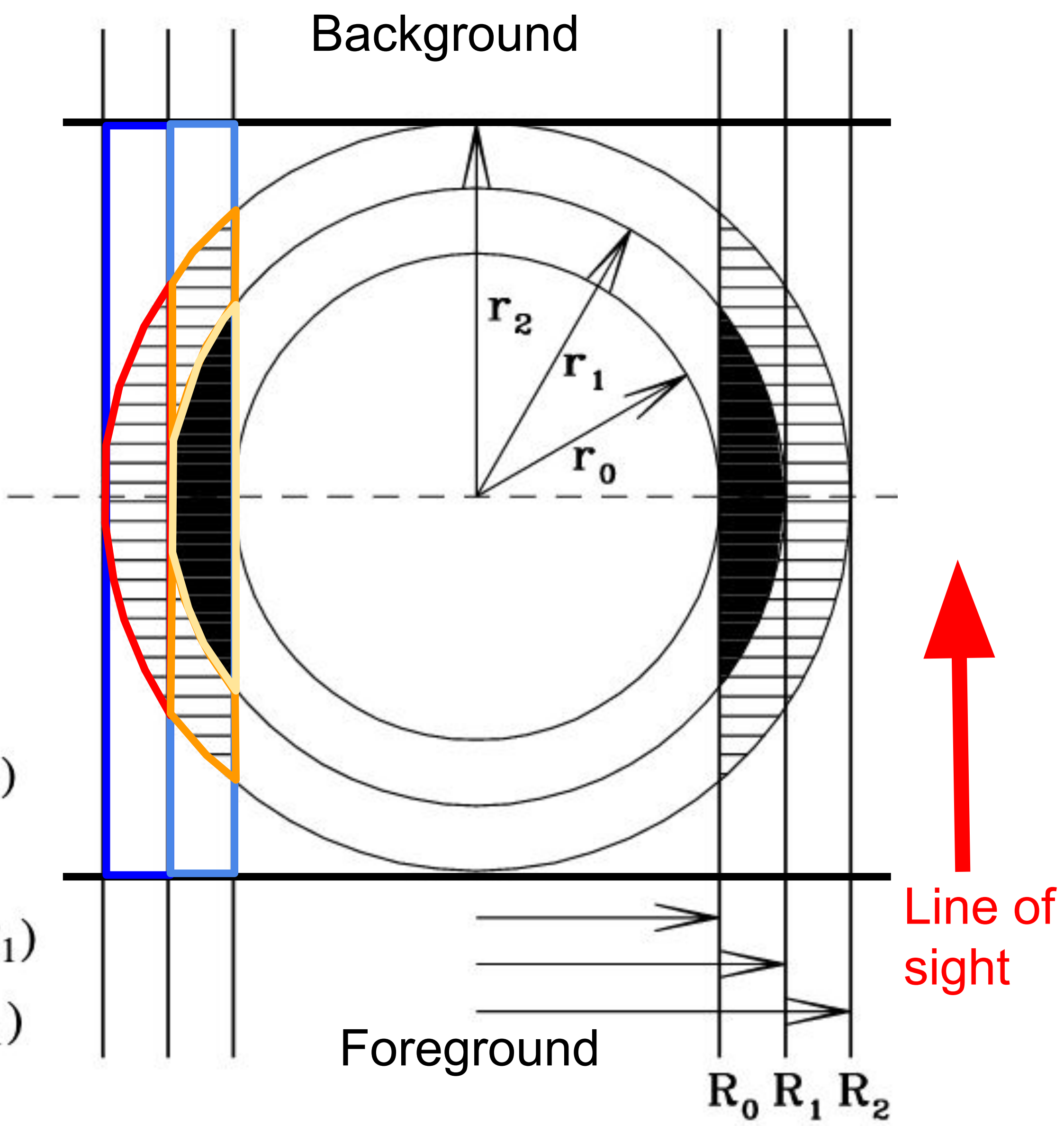

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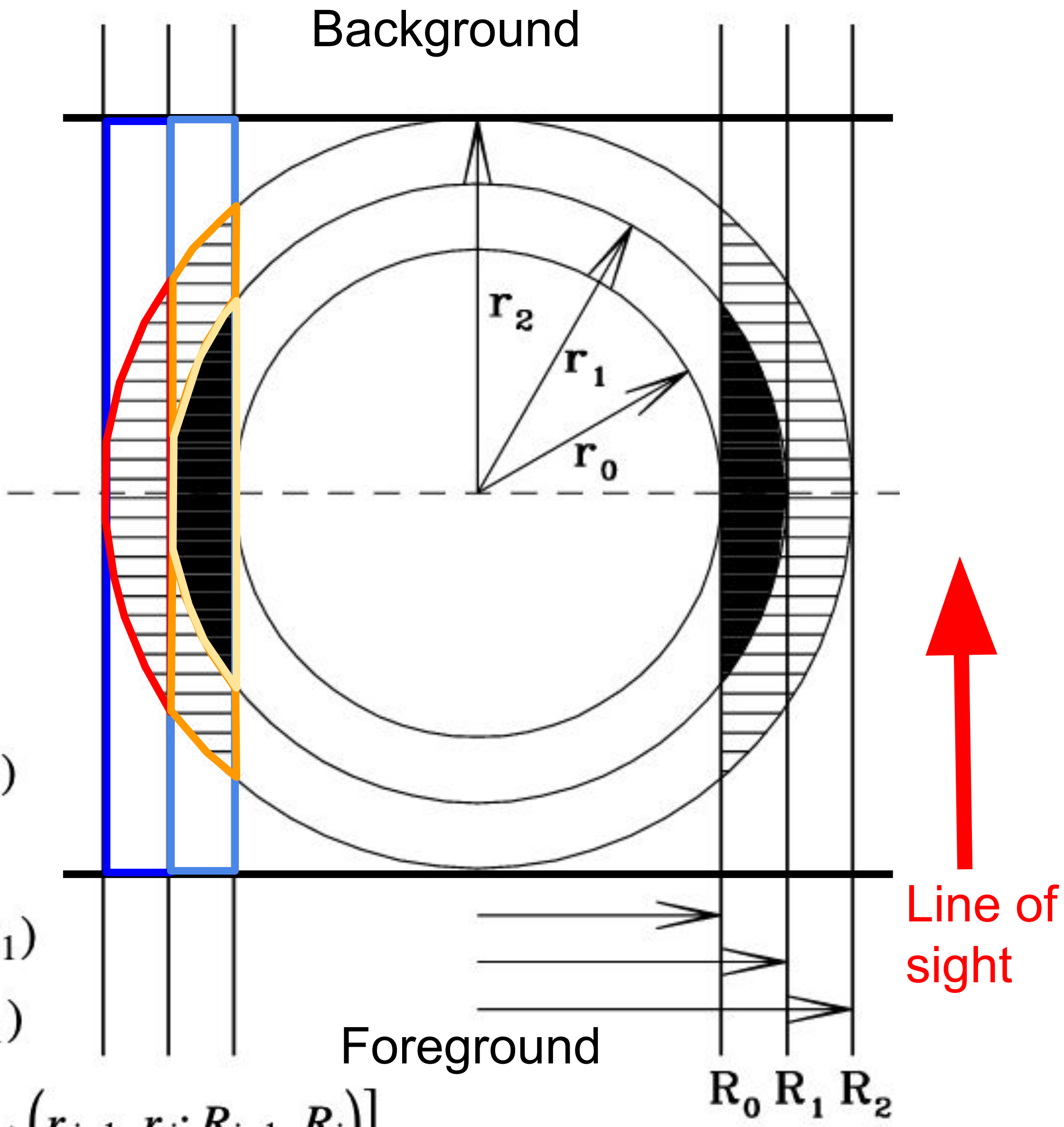

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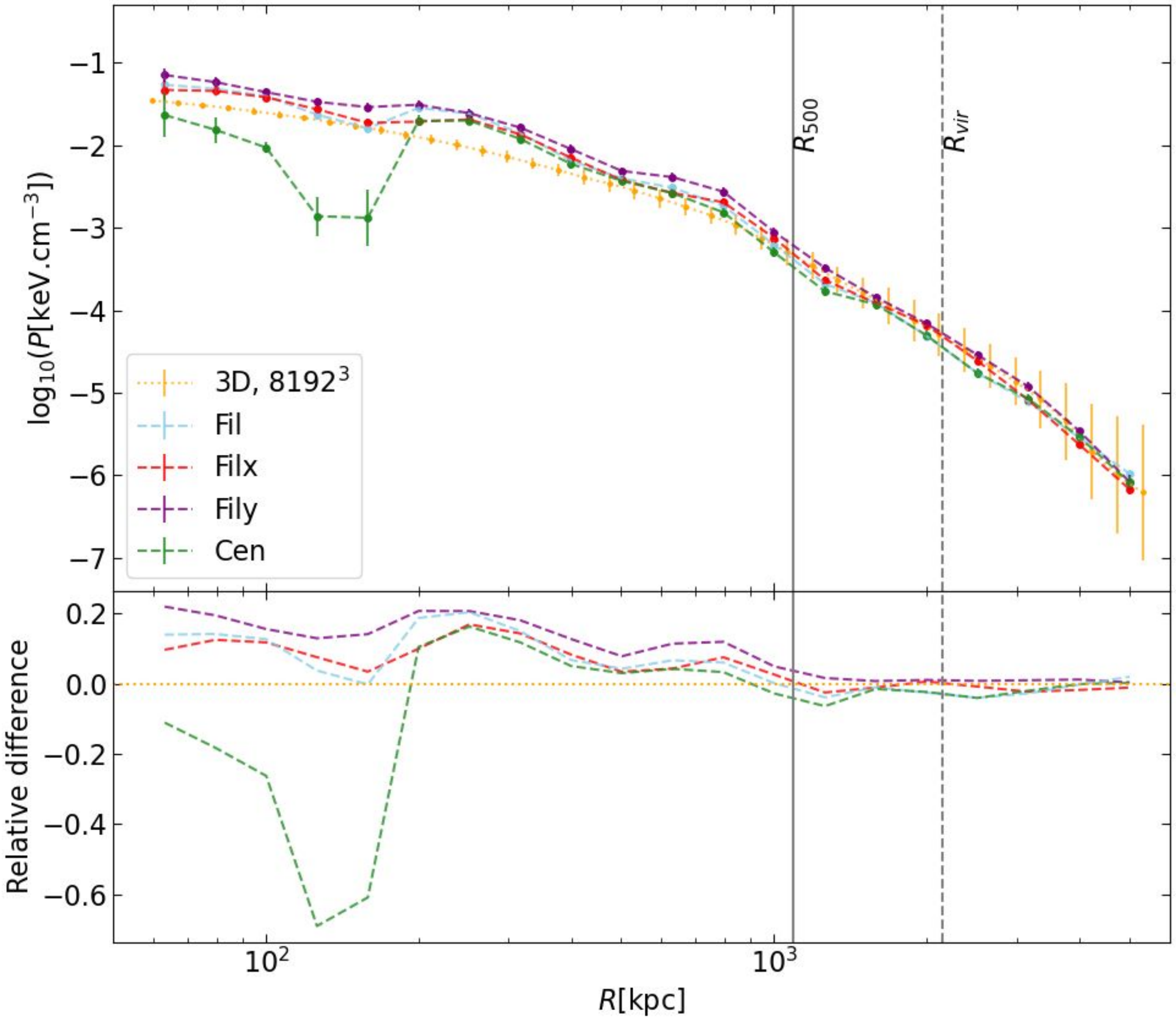
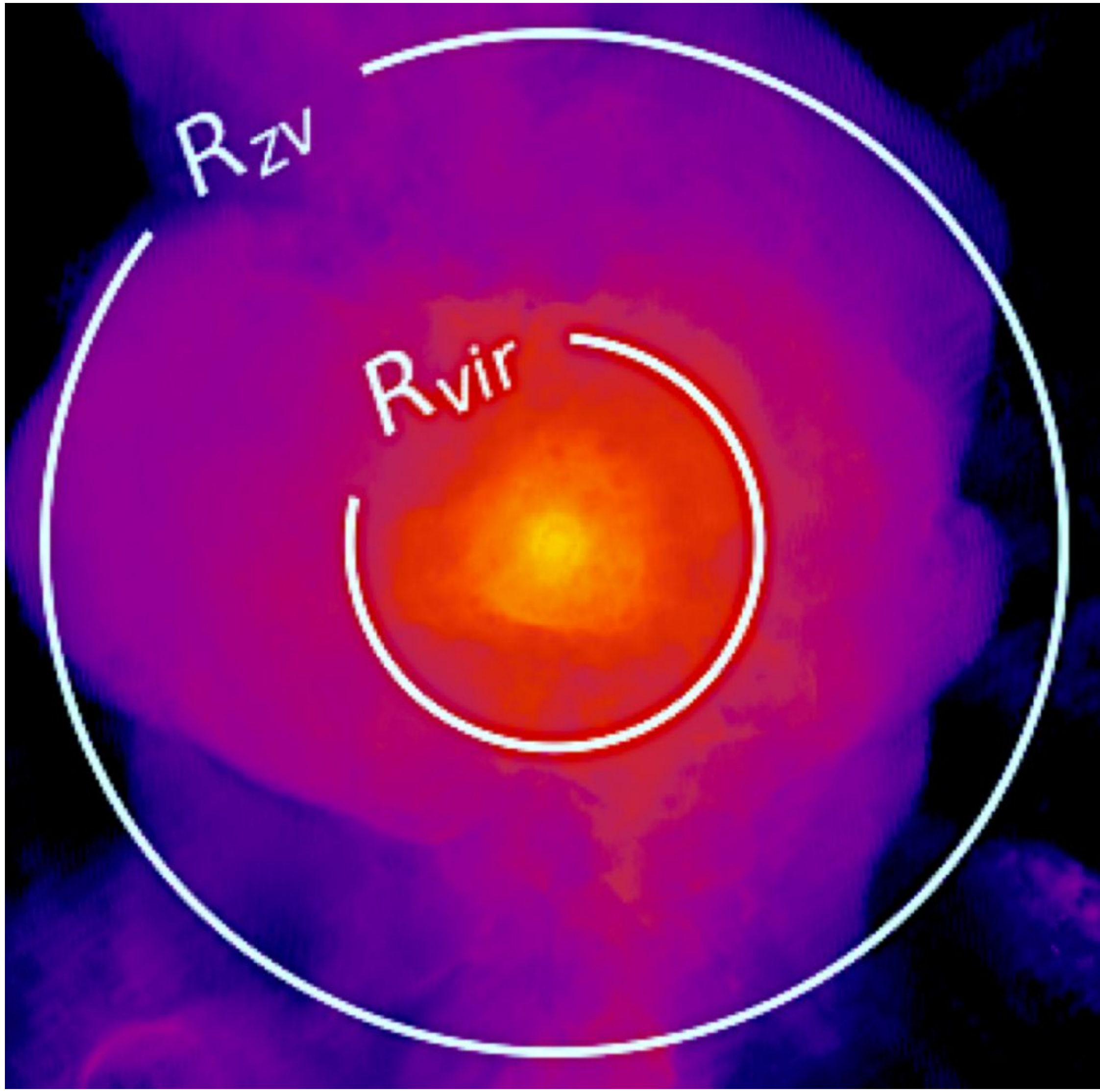
Generalisation :

$$P'(r_{i-1}, r_i) = \frac{P(R_{i-1}, R_i)\,\pi(R_i^2 - R_{i-1}^2)L - \sum_{j=i+1}^{m}\left[P'\left(r_{j-1}, r_j\right) V_{\text{int}}\left(r_{j-1}, r_j; R_{i-1}, R_i\right)\right]}{V_{\text{int}}\left(r_{i-1}, r_i; R_{i-1}, R_i\right)}$$

Deprojected pressure profiles





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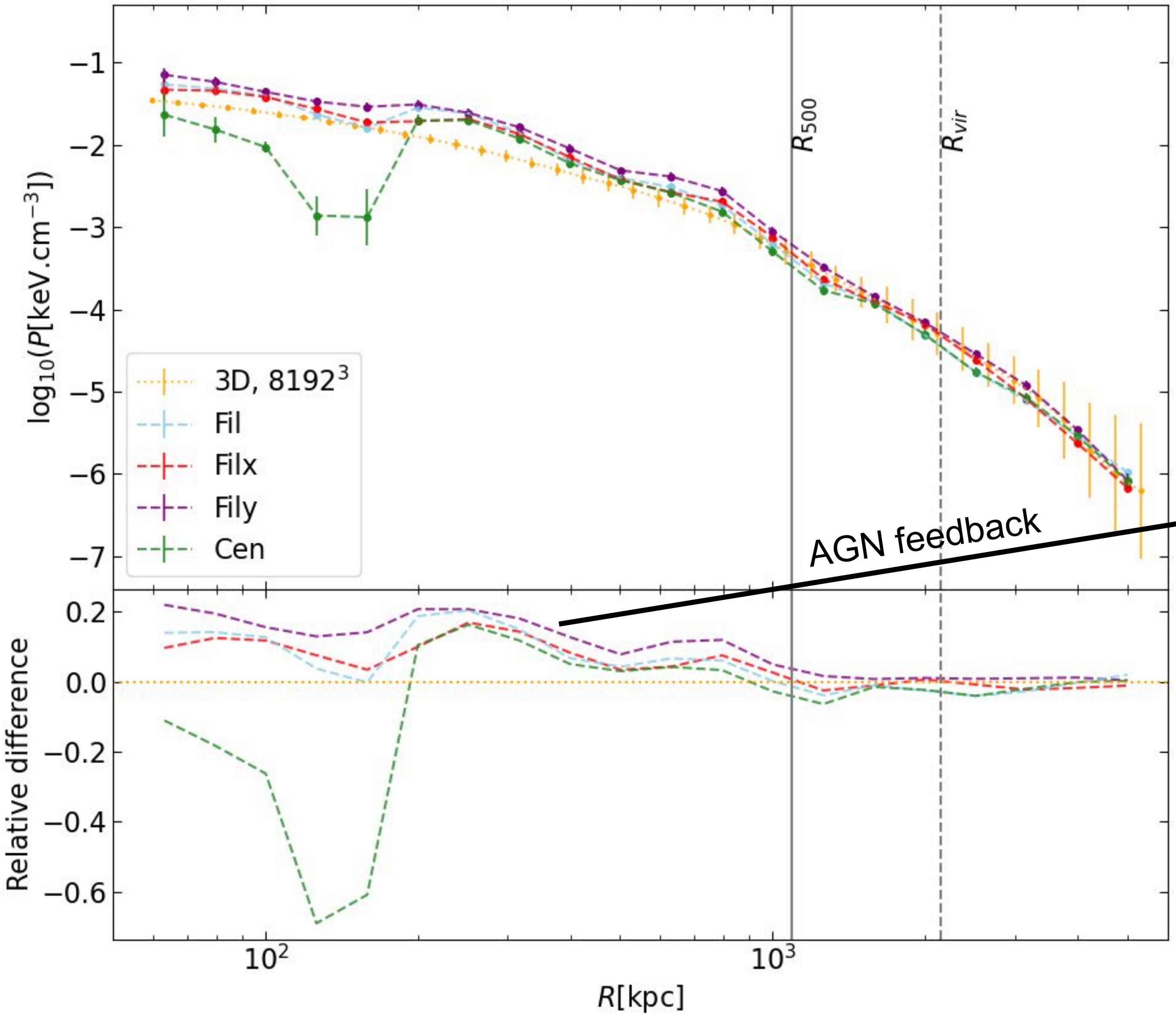

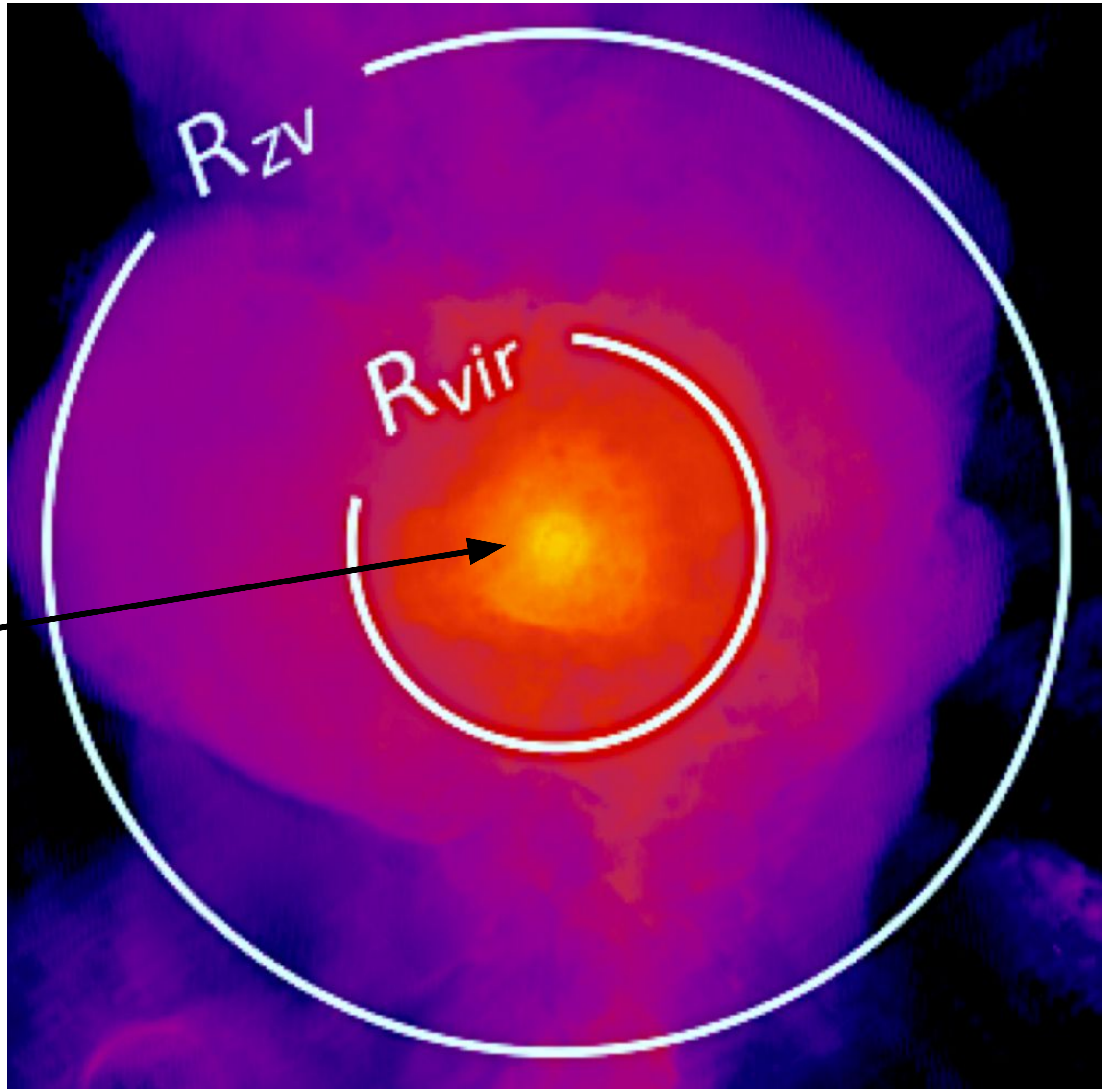

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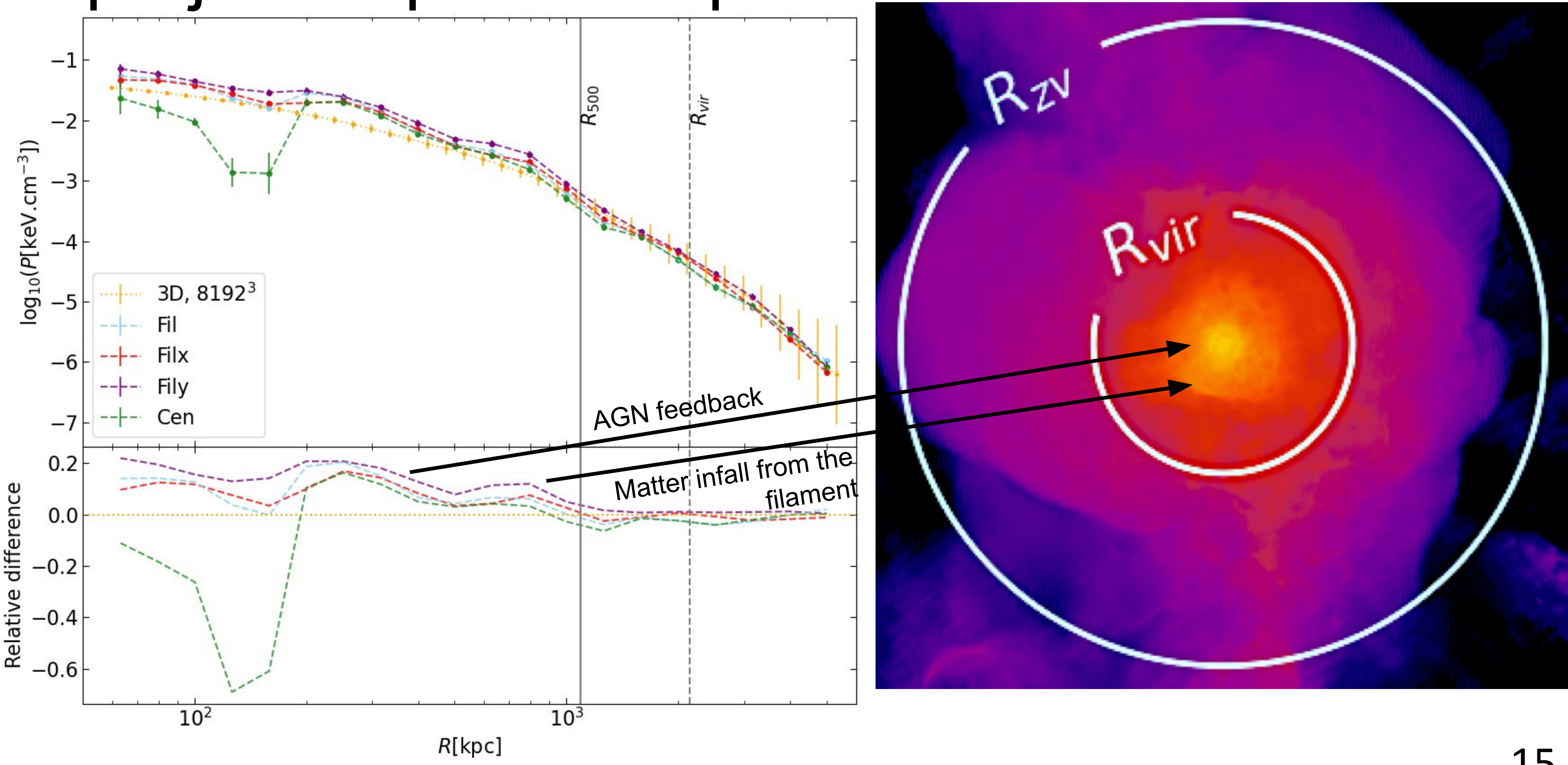

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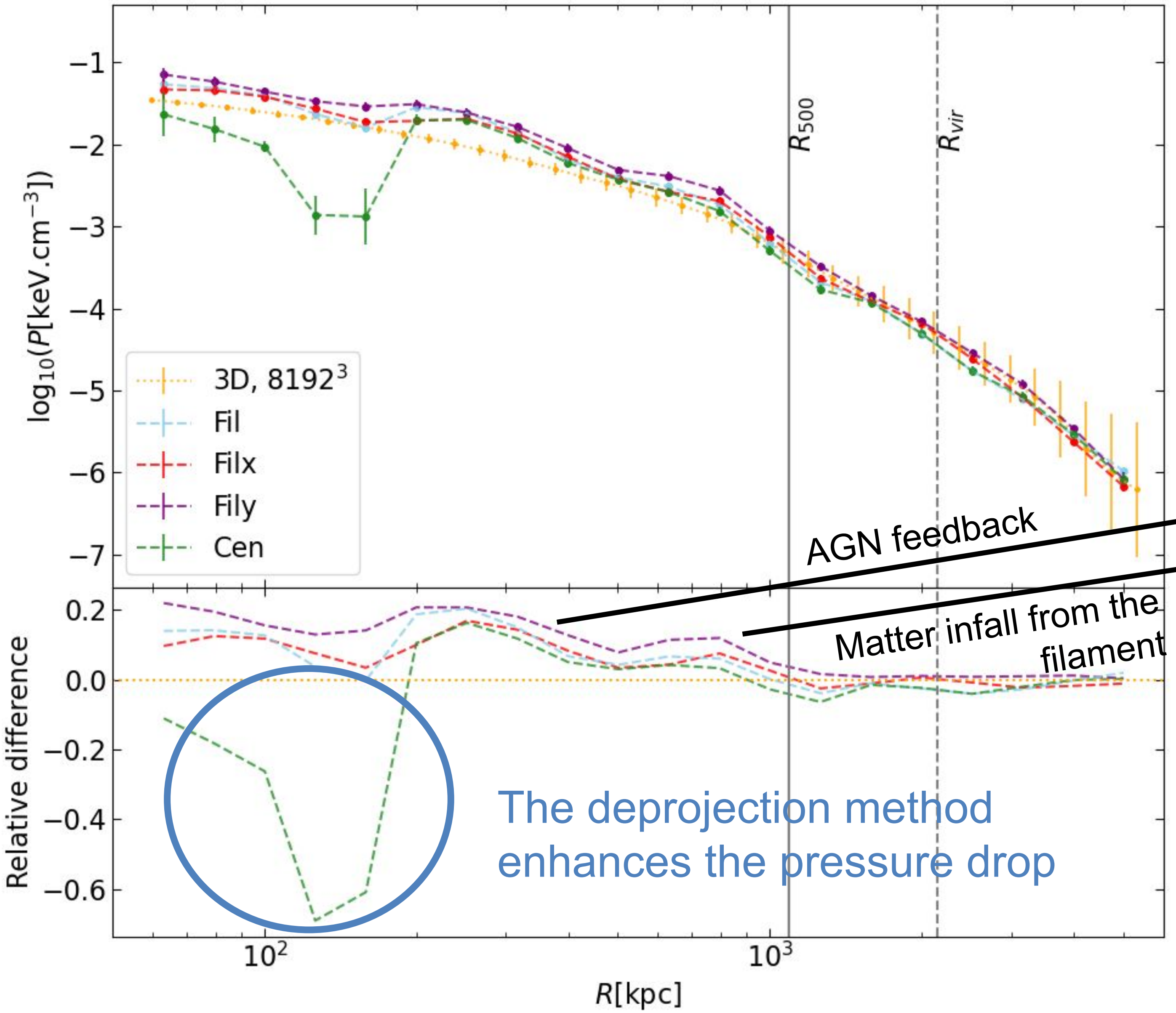
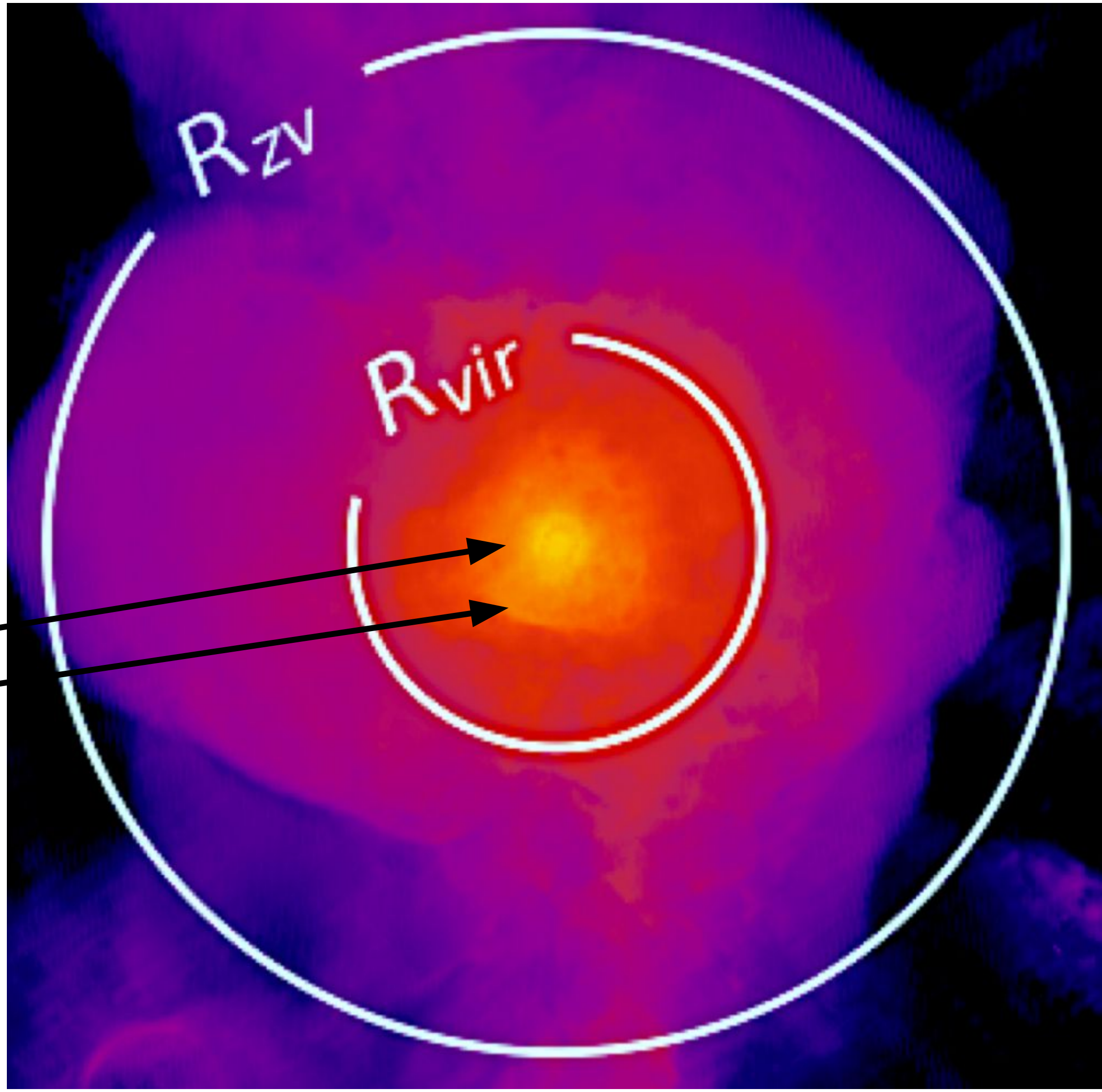
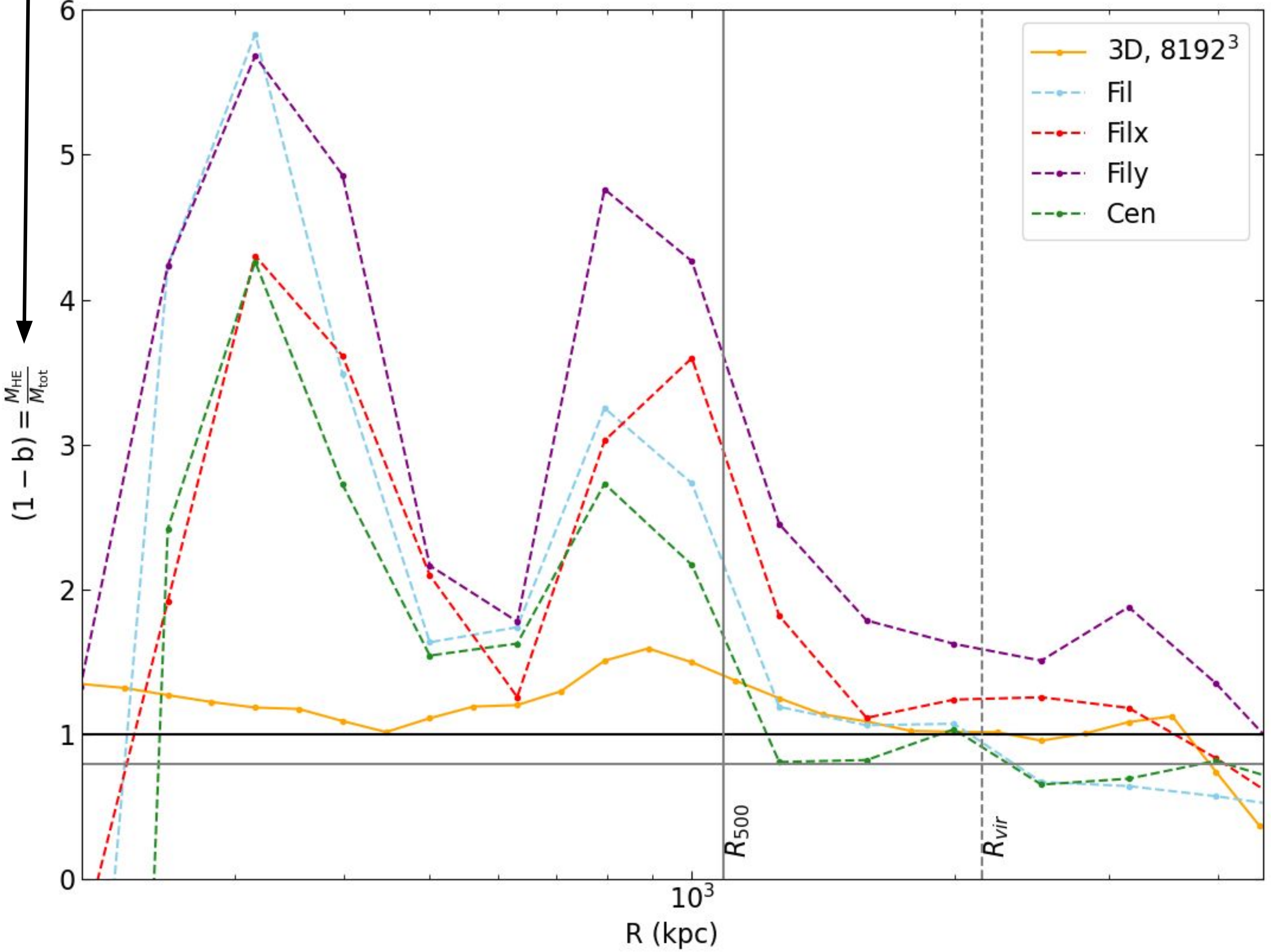
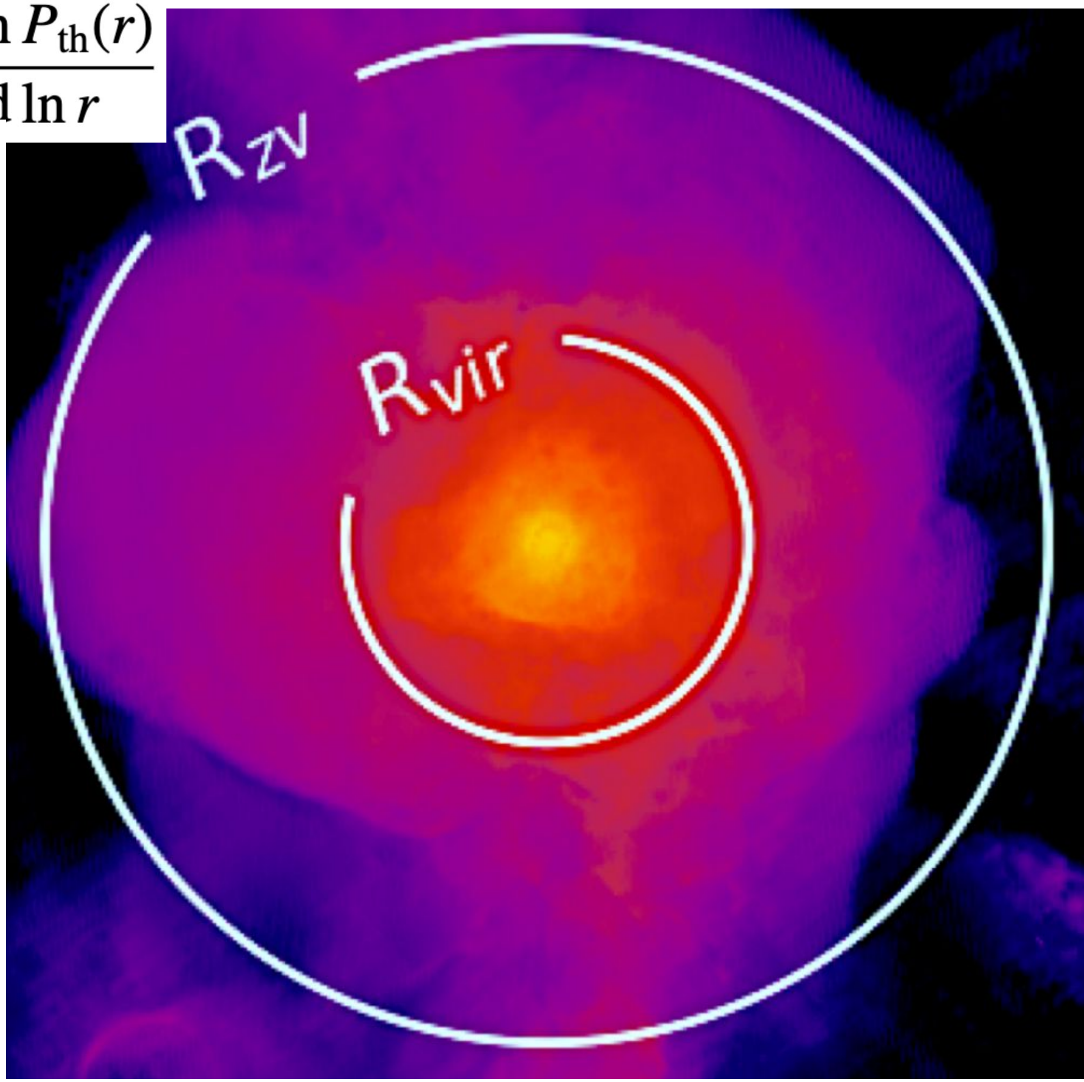




Hydrostatic mass bias from deprojected profiles

$$(1-b) = \frac{M_{HE}(<r)}{M_{tot}(<r)} \qquad M_{\mathrm{HE}}(<r) = -\frac{r P_{\mathrm{th}}(r)}{G \mu m_{\mathrm{p}} n_{\mathrm{e}}(r)} \frac{\mathrm{d} \ln P_{\mathrm{th}}(r)}{\mathrm{d} \ln r}$$





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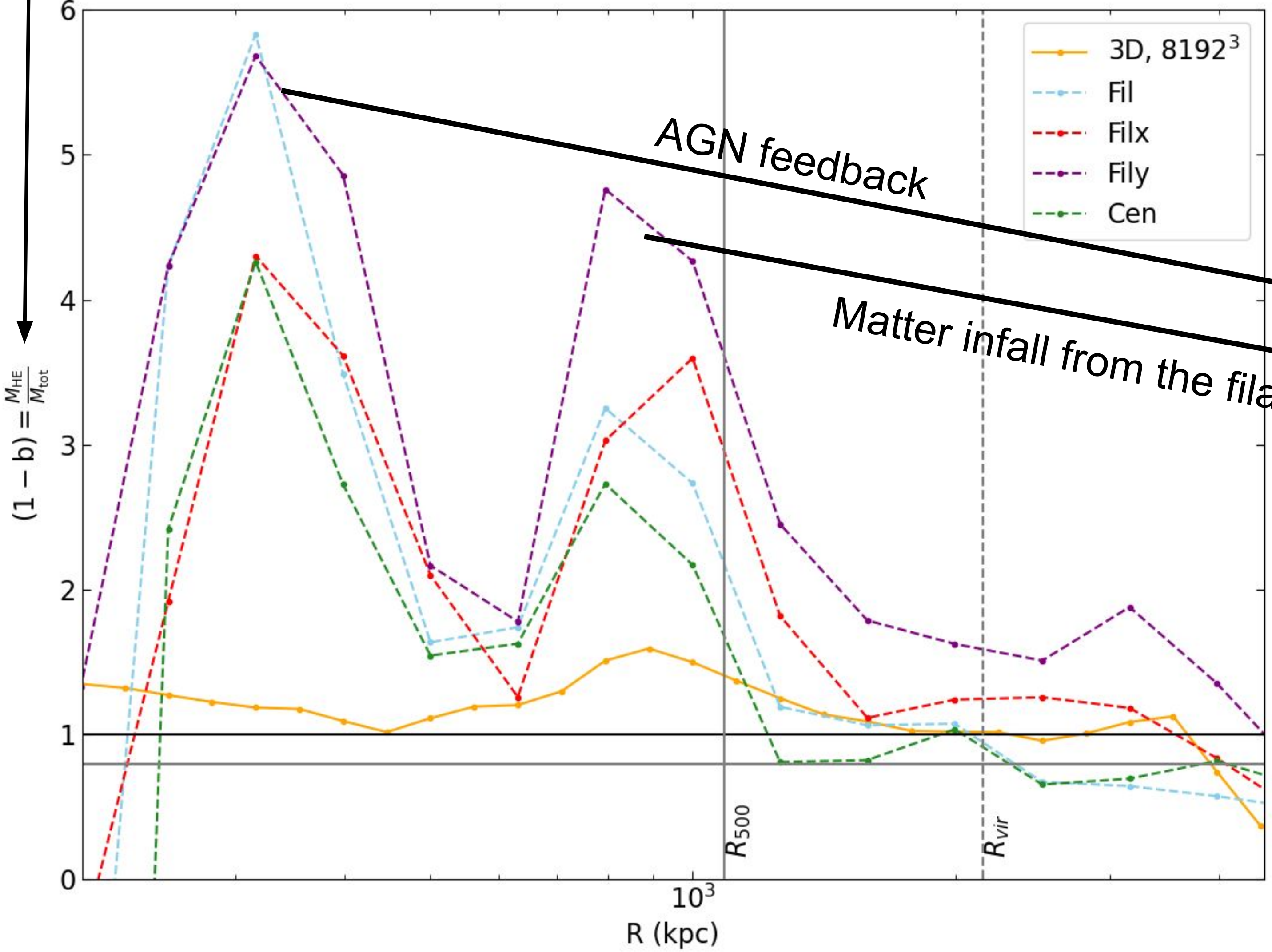

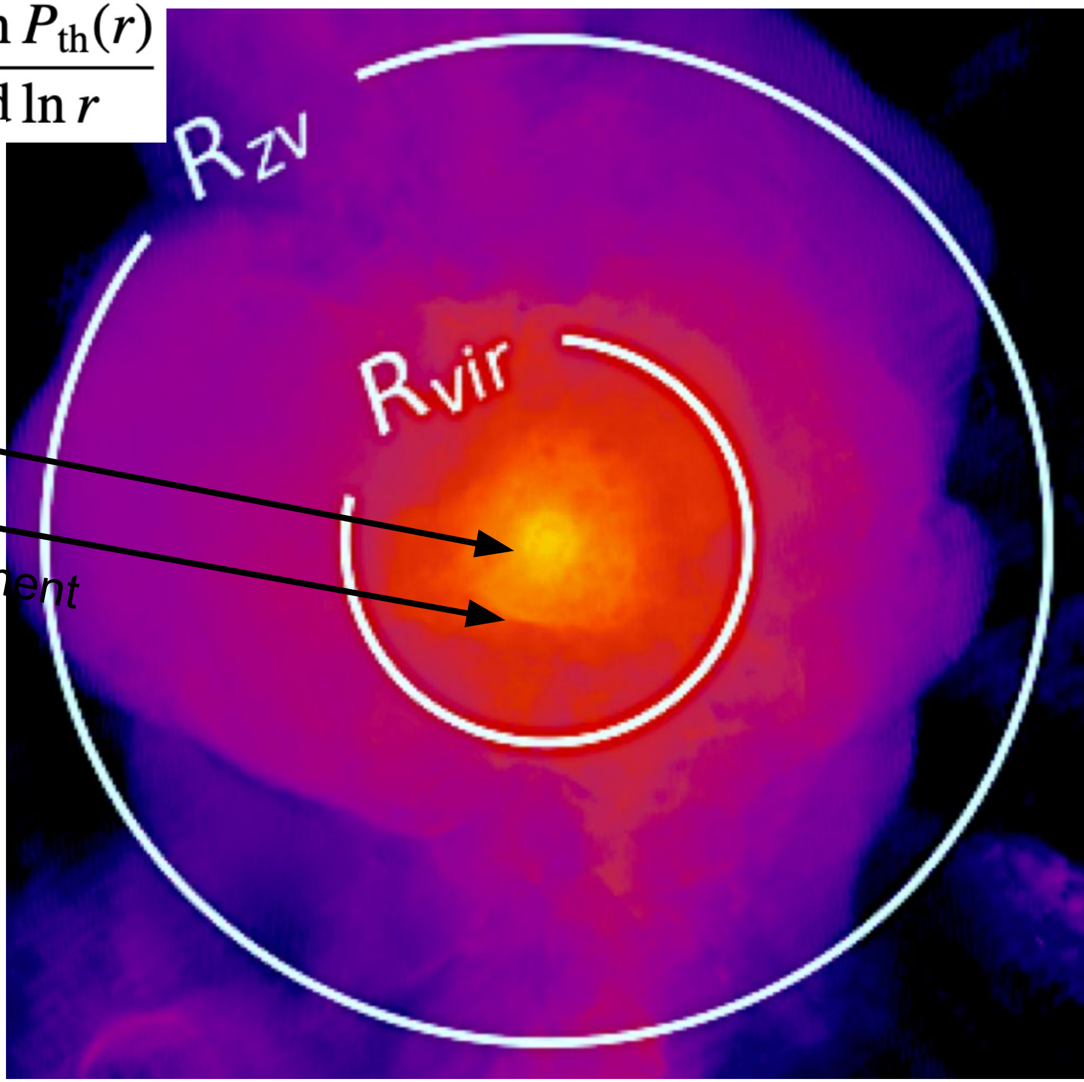

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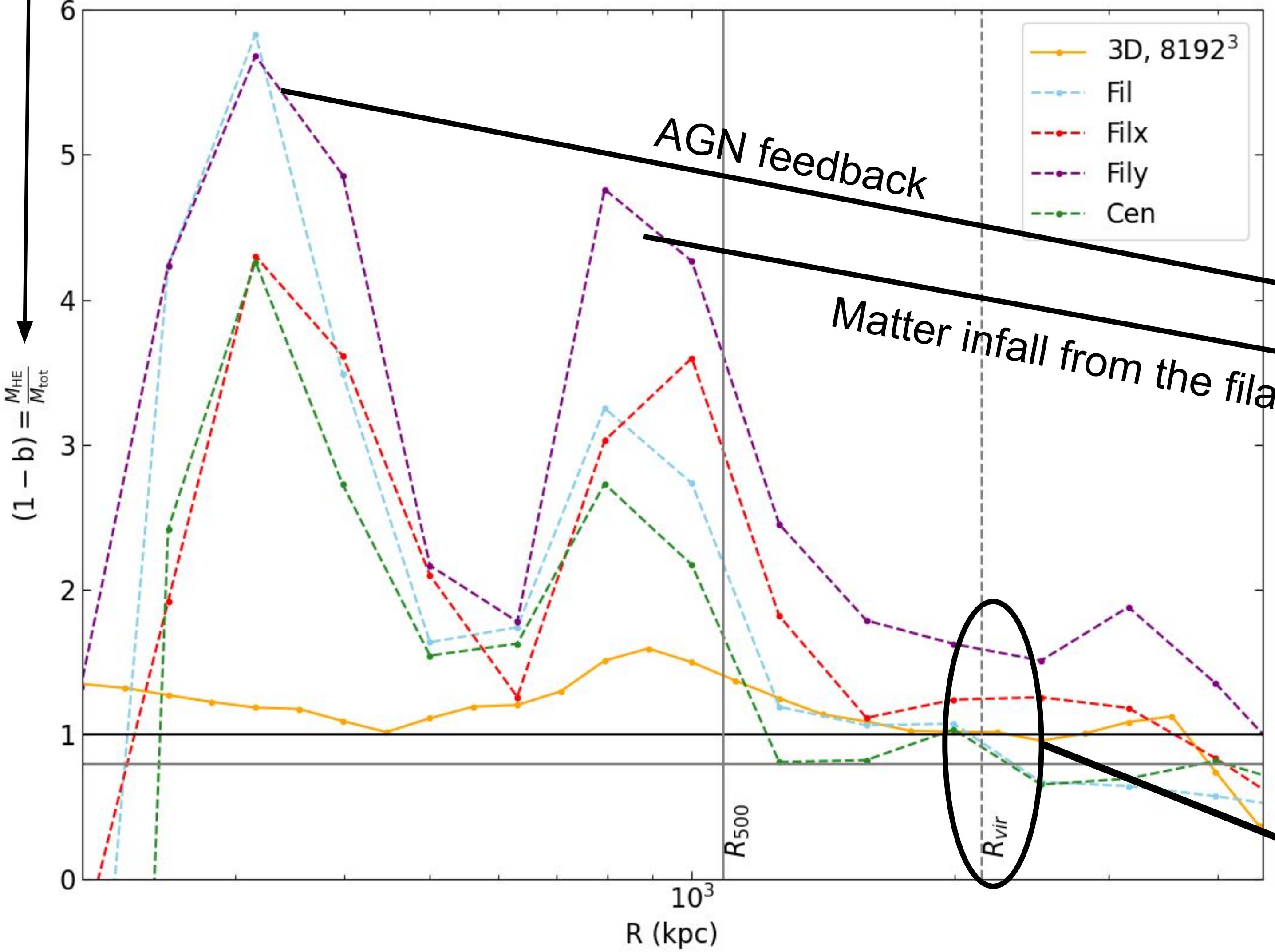

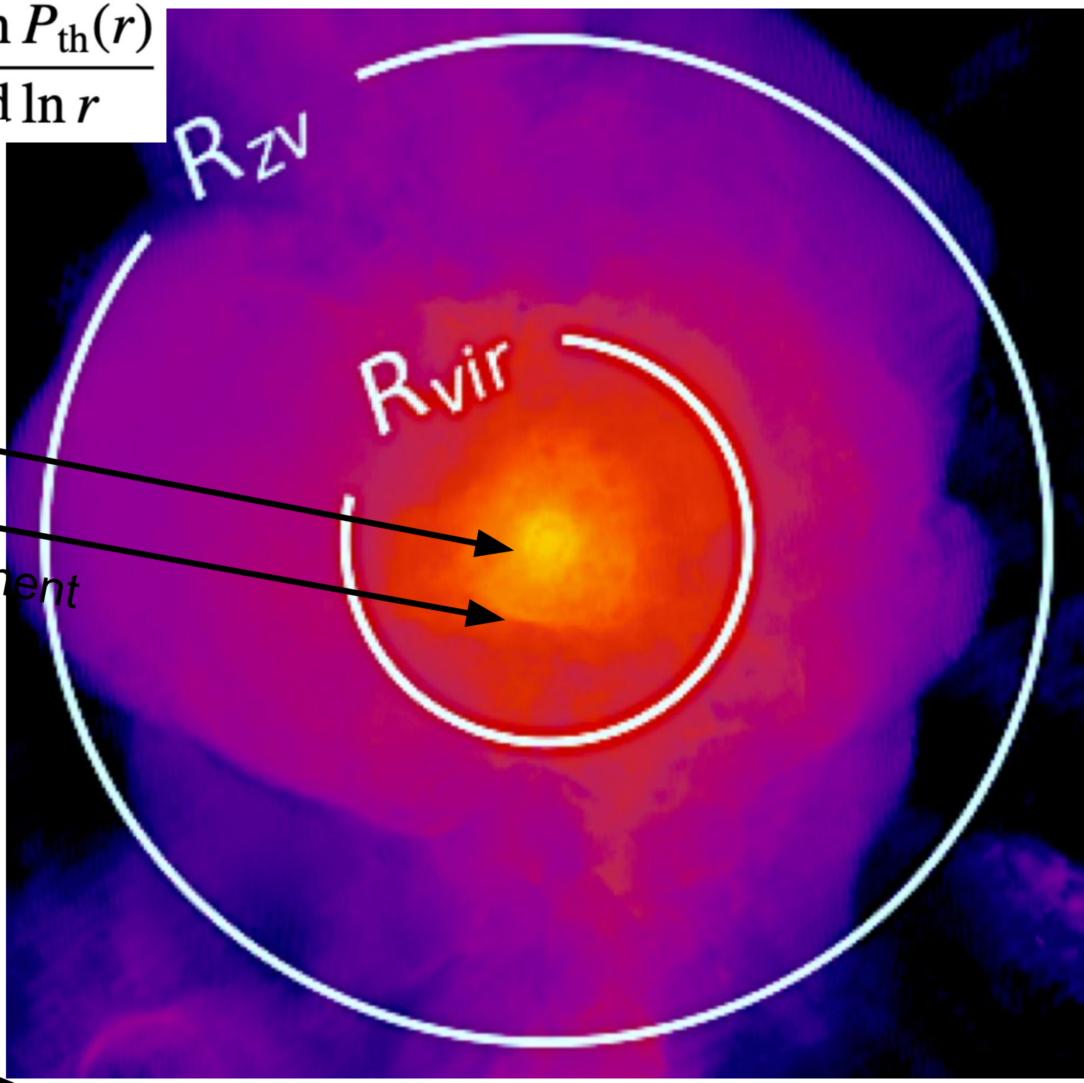

Contribution of the integrated mass to the hydrostatic mass estimation

Conclusions

- Unreliable hydrostatic mass biases derived from deprojected profiles in the cluster core, large scatter at R_{vir}:
  - Major role of the mass along the LoS on derived radial profiles and bias
  - Hydrostatic mass estimation strongly impacted by shocks in the cluster

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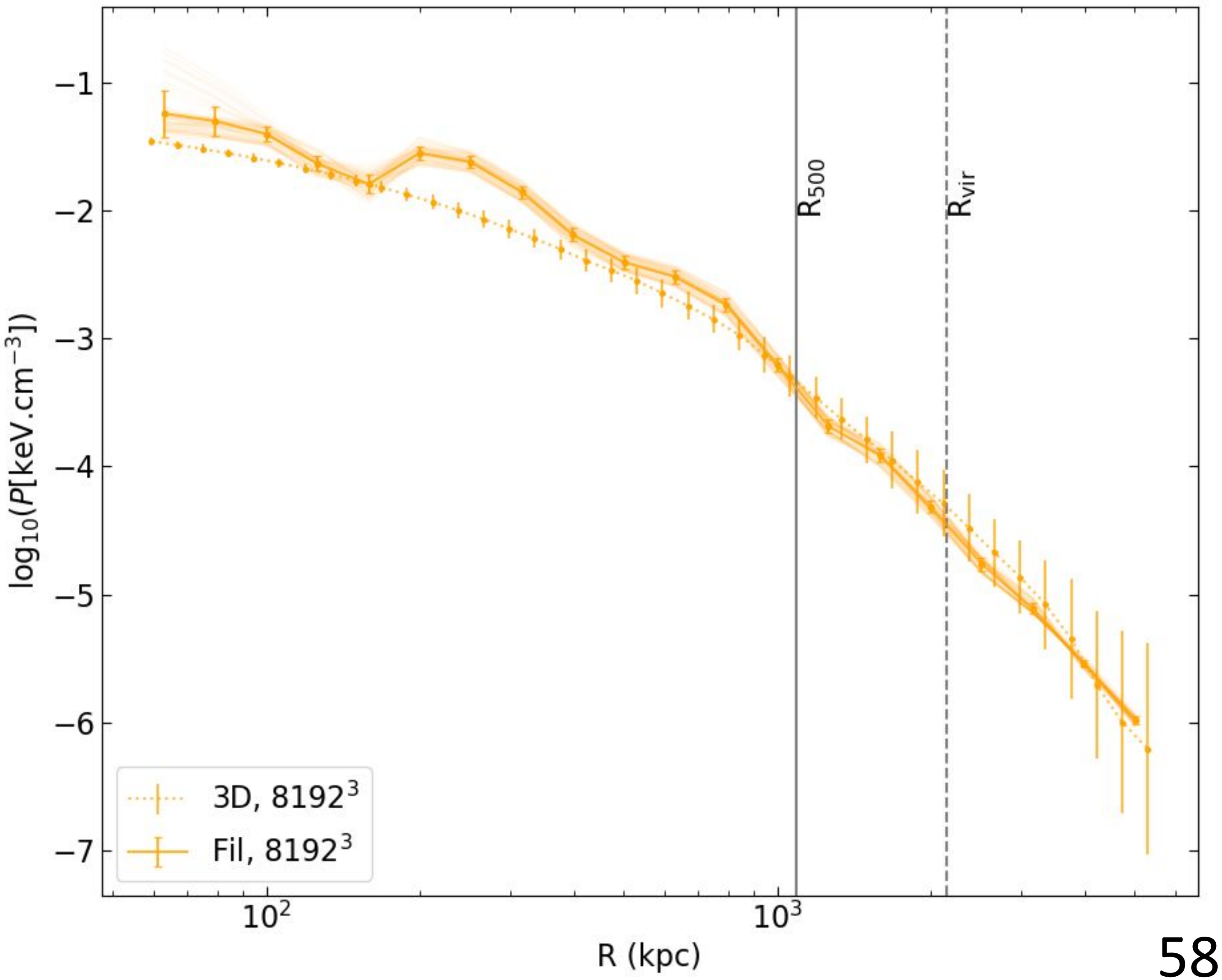
Perspectives and future work:

- The Virgo cluster: physical model of the cluster (shocks, dynamical state,...) and comparison to observations
- The upcoming large scale simulation : statistical study of different sources of bias

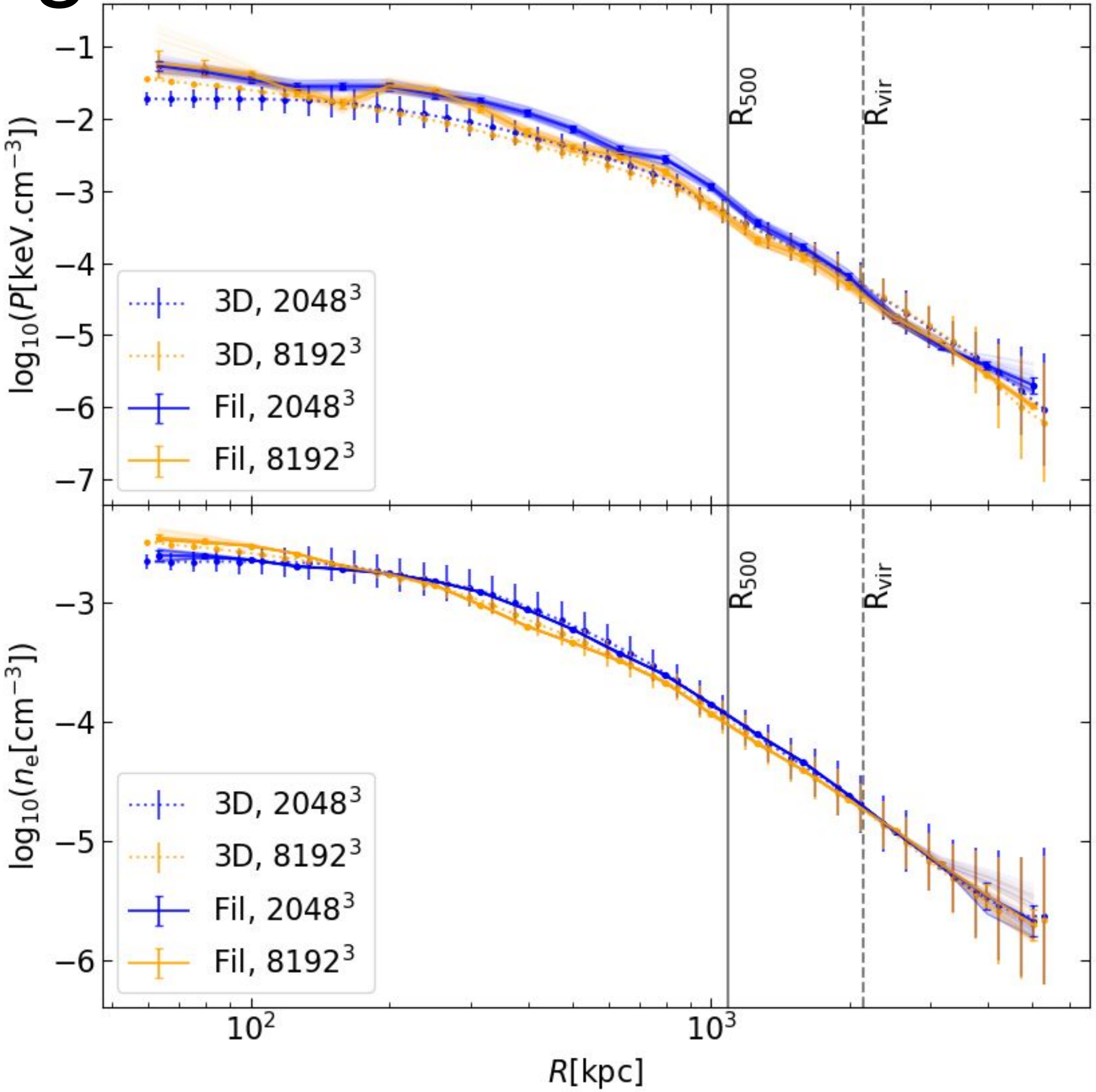
Smoothing the deprojected profiles

- Monte Carlo method: random selection of the lower and upper bounds of the deprojection process
  - Lower limit in the [50,100]kpc range
  - Upper limit in the [4000,6000]kpc range
  - 100 realizations

- Interpolation and extrapolation of the profiles in order to calculate the mean profile



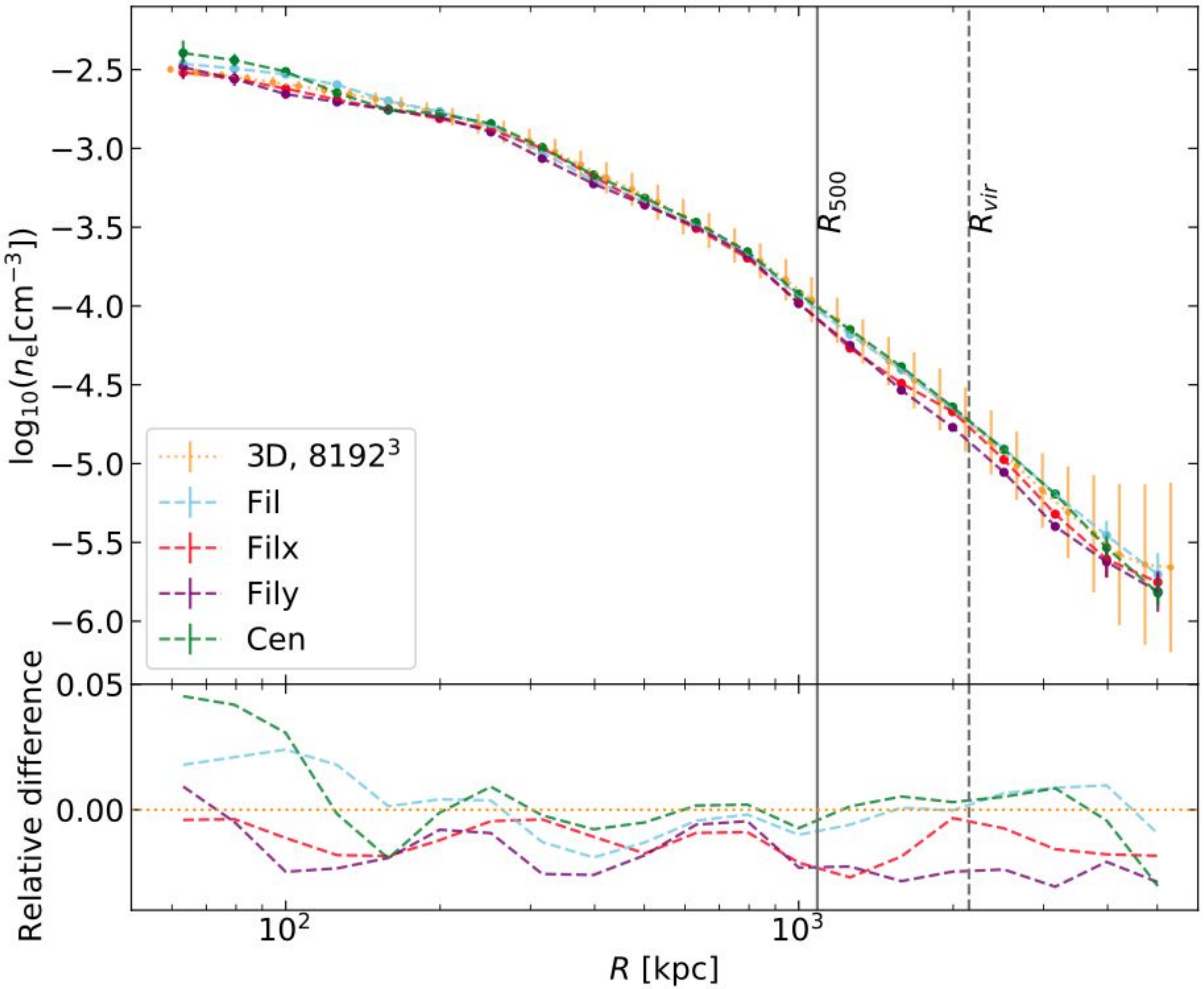
High and low resolution comparisons



The deprojected pressure profiles deviate from the 3D profiles within R_{500}

The deprojected electron density profiles are similar to their respective 3D profiles

Deprojected electron density profiles

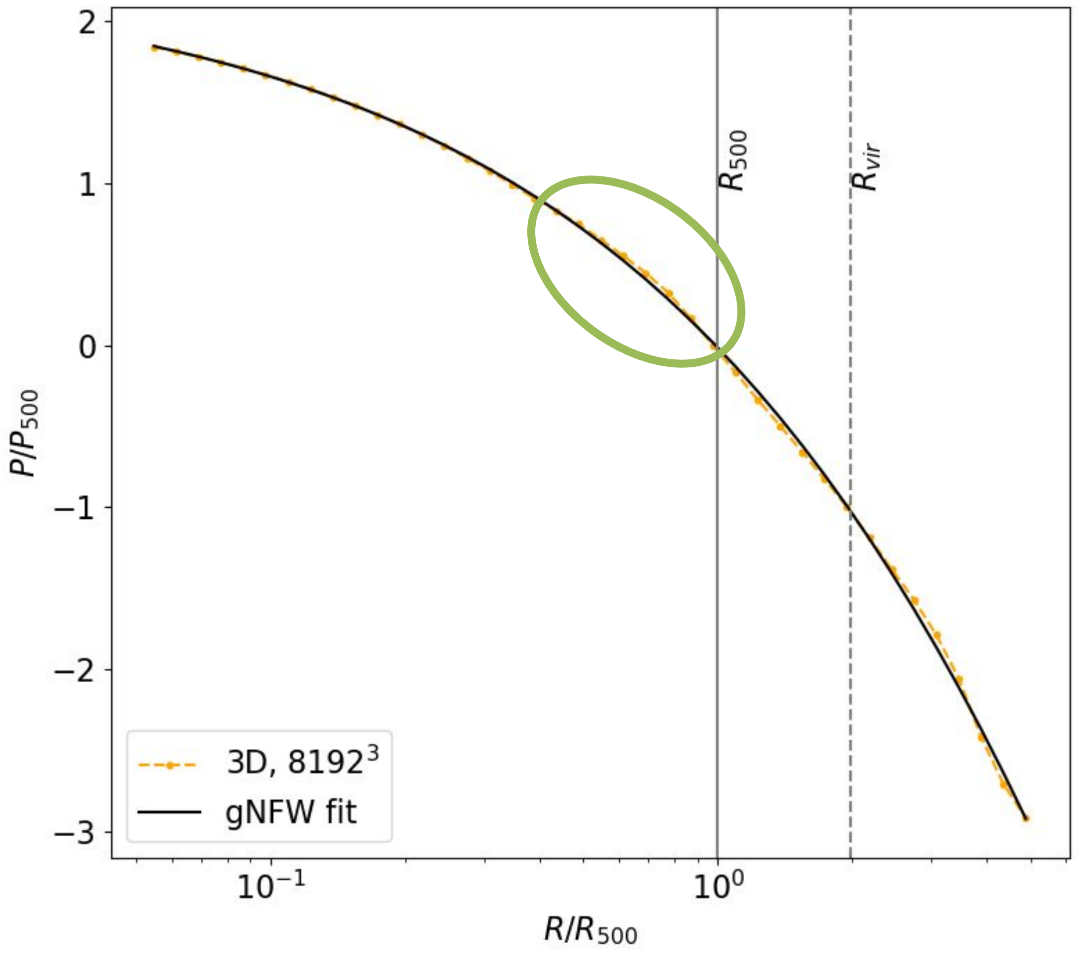


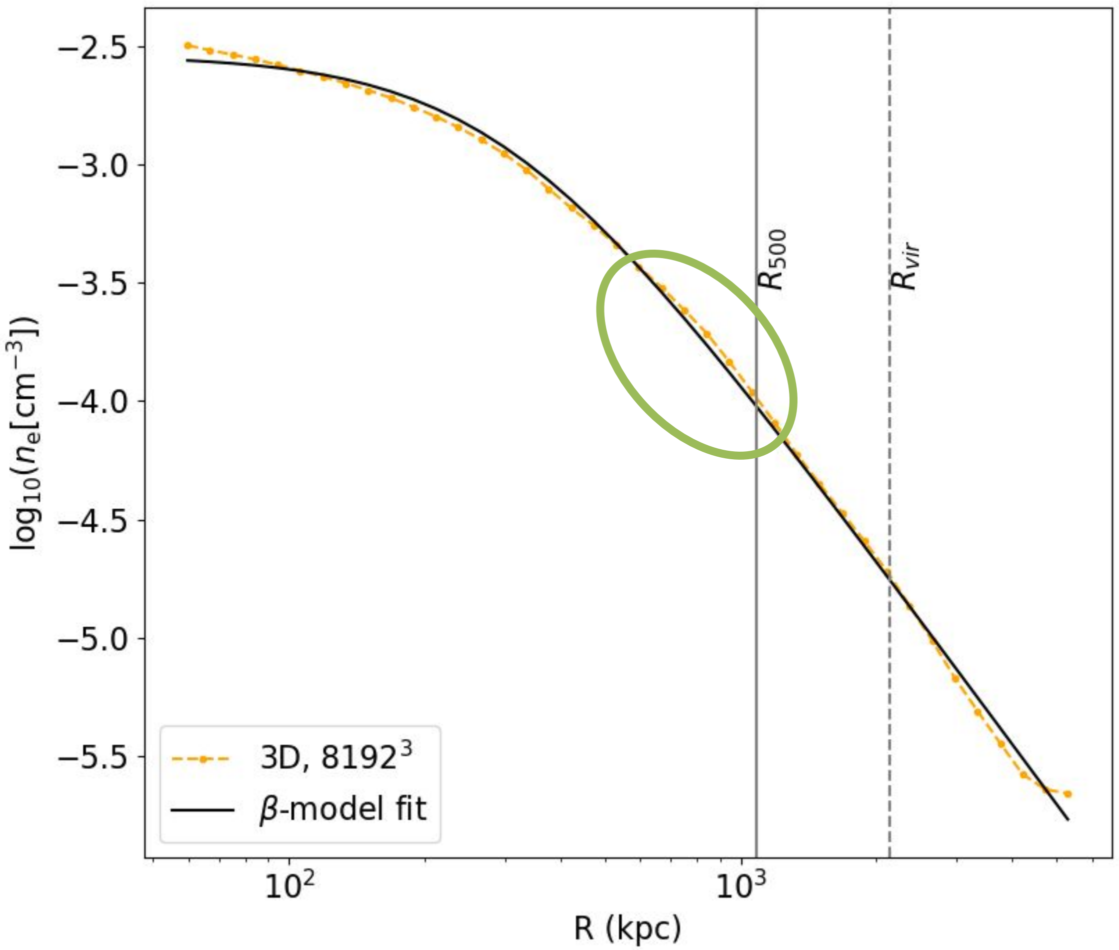
Same trend as for the projected profiles: **more mass** along the line of sight induces **higher** deprojected electron density profile

Numerical VS fitted profiles gradient (*preliminary*)

gNFW : $\frac{P(r)}{P_{500}} = \frac{P_0}{x^c(1+x^a)^{\frac{b-c}{a}}}$

β-model : $n_{\rm gas}(r) = n_{\rm gas}(0)\left[1+\left(\frac{r}{r_{\rm c}}\right)^2\right]^{-3\beta/2}$





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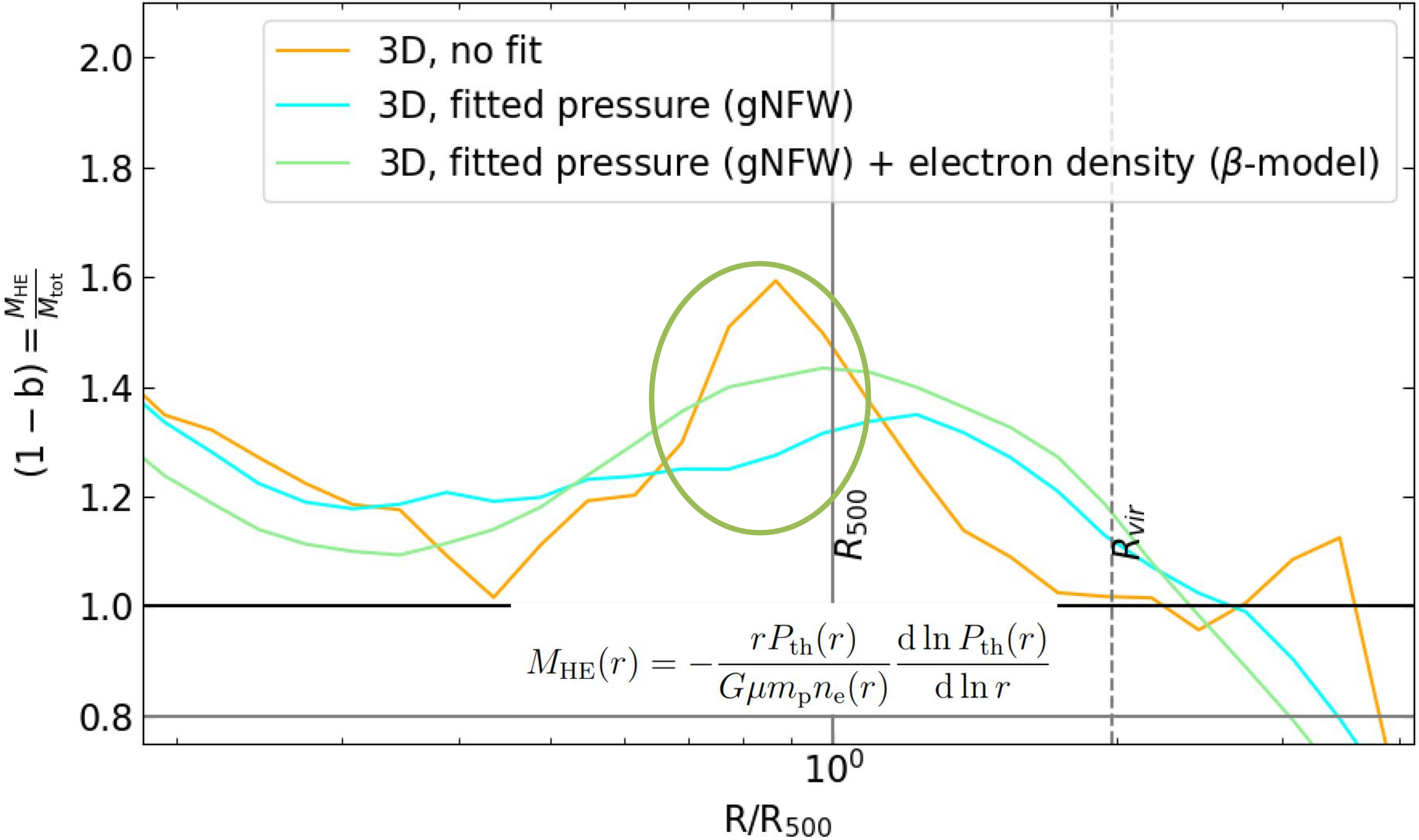
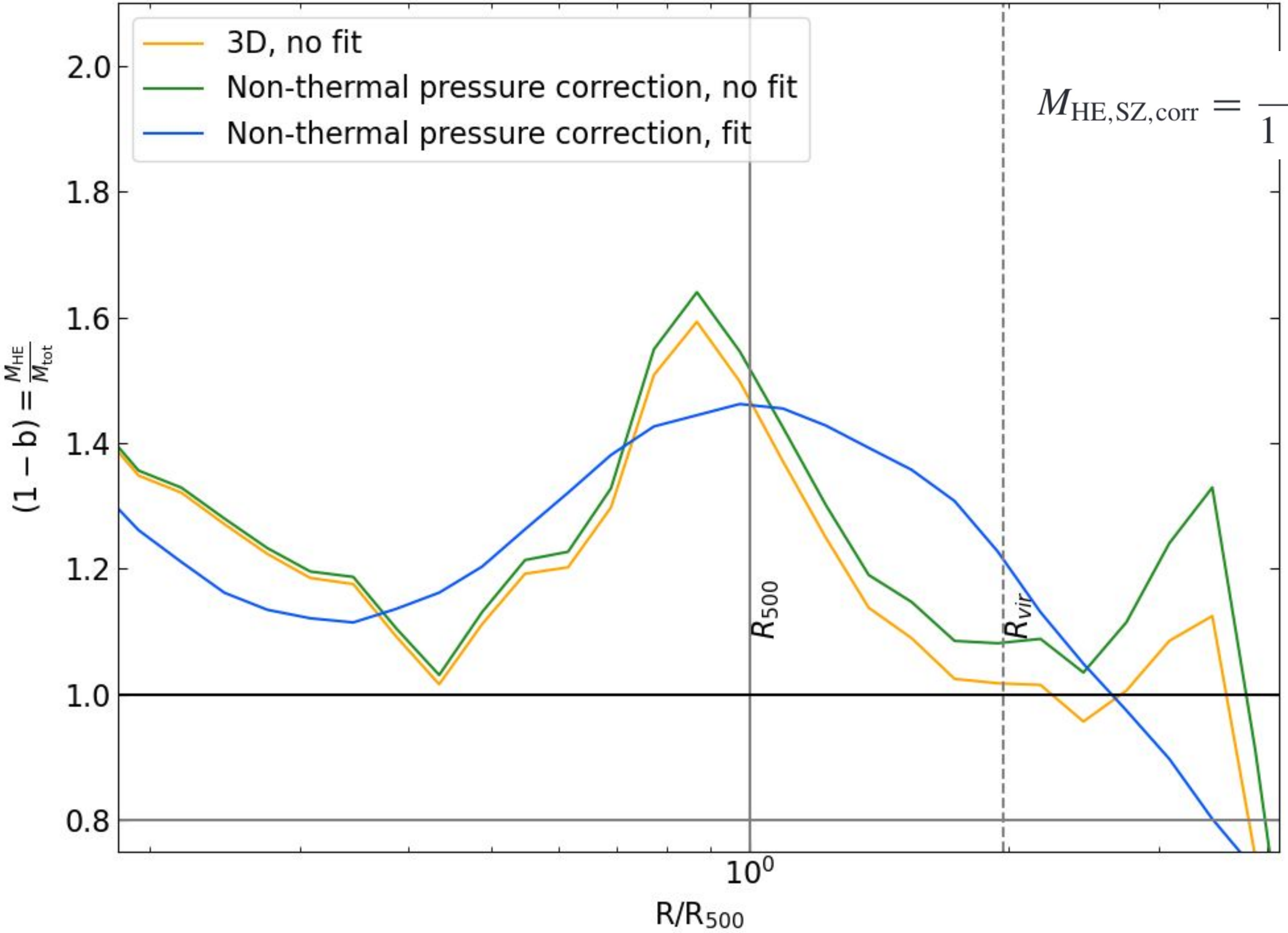


$$M_{\rm HE}(r) = -\frac{r P_{\rm th}(r)}{G\mu m_{\rm p} n_{\rm e}(r)} \frac{{\rm d}\ln P_{\rm th}(r)}{{\rm d}\ln r}$$

Non-thermal pressure correction (*preliminary*)



$$M_{\mathrm{HE,SZ,corr}} = \frac{1}{1-\alpha}\left[M_{\mathrm{HE,SZ}} - \frac{\alpha}{1-\alpha}\frac{r P_{\mathrm{th}}}{G\mu m_p n_{\mathrm{e}}}\frac{\mathrm{d}\ln\alpha}{\mathrm{d}\ln r}\right]$$

Pearce et al. (2020)

$$P_{\mathrm{tot}} = P_{\mathrm{th}} + P_{\mathrm{nth}}$$

$$P_{\mathrm{nth}} = \rho\sigma^2$$

$$P_{\mathrm{nth}} = \alpha(r) P_{\mathrm{tot}}$$

Deprojection method: Electron Density

<u>Basic example:</u>

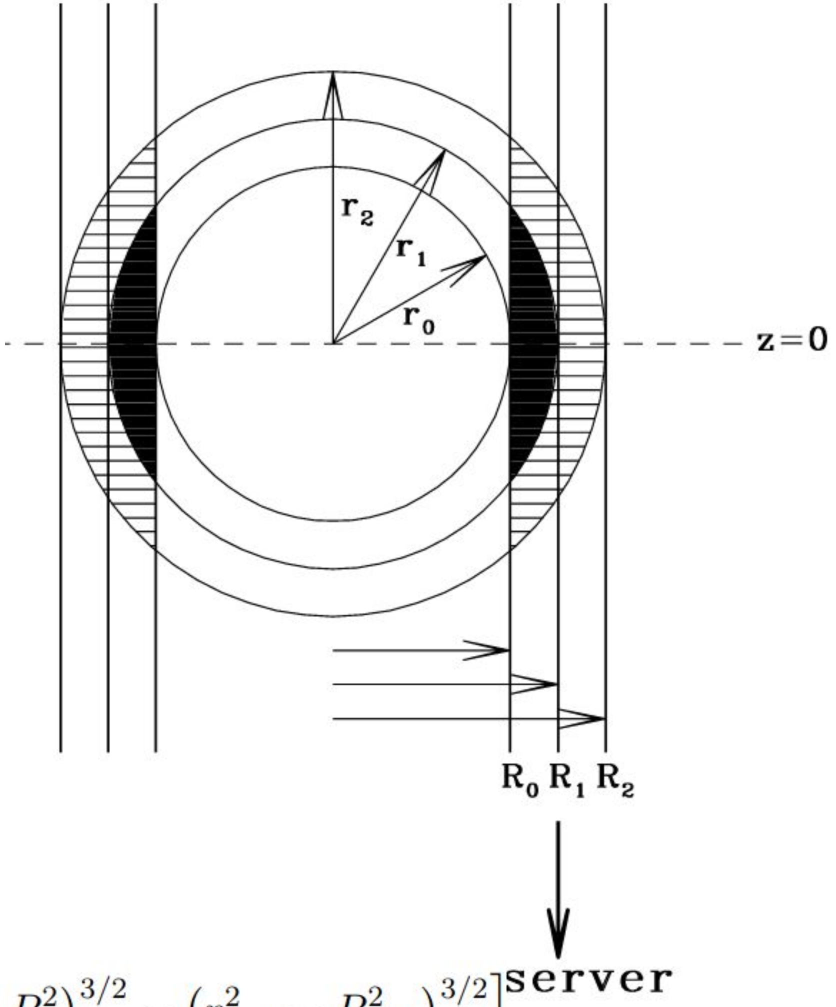
n_e: projected electron density (in cm^{-2})
n_e': deprojected electron density (in cm^{-3})

Furthest annulus:

$$n_e(R_1,R_2)*\pi(R_2^2-R_1^2) = n_e'(r_1,r_2)*V_{int}(r_1,r_2,R_1,R_2) + n_e^{back}*(\pi(R_2^2-R_1^2)*L_{los}-V_{int}(r_1,r_2,R_1,R_2))$$

Second furthest annulus:

$$n_e(R_0,R_1)*\pi(R_1^2-R_0^2) = n_e'(r_0,r_1)*V_{int}(r_0,r_1,R_0,R_1) + n_e'(r_1,r_2)*V_{int}(r_1,r_2,R_0,R_1) + n_e^{back}*(\pi(R_1^2-R_0^2)*L_{los}-V_{int}(r_0,r_2,R_0,R_1))$$



<u>Background :</u> Mean electron density of the local environment (mean electron density in a circular annulus between 8 and 10 Mpc)

<u>Generalisation :</u> $V_{\text{int}}(r_{j-1},r_j;R_{i-1},R_i) = \frac{4\pi}{3}\left[\left(r_j^2-R_{i-1}^2\right)^{3/2}-\left(r_j^2-R_i^2\right)^{3/2}+\left(r_{j-1}^2-R_i^2\right)^{3/2}-\left(r_{j-1}^2-R_{i-1}^2\right)^{3/2}\right]$

$$n_e'(r_{i-1},r_i) = \frac{n_e(R_{i-1},R_i)\,\pi(R_i^2-R_{i-1}^2) - n_e^{back}*(\pi(R_i^2-R_{i-1}^2)*L_{los}-V_{int}(r_{i-1},R_{amas},R_{i-1},R_i)) - \sum_{j=i+1}^{m}\left[n_e'\left(r_{j-1},r_j\right)V_{\text{int}}\left(r_{j-1},r_j;R_{i-1},R_i\right)\right]}{V_{\text{int}}(r_{i-1},r_i;R_{i-1},R_i)}$$

Deprojection method: Pressure

<u>Basic example:</u>

P: projected pressure
P': deprojected pressure

Furthest annulus:

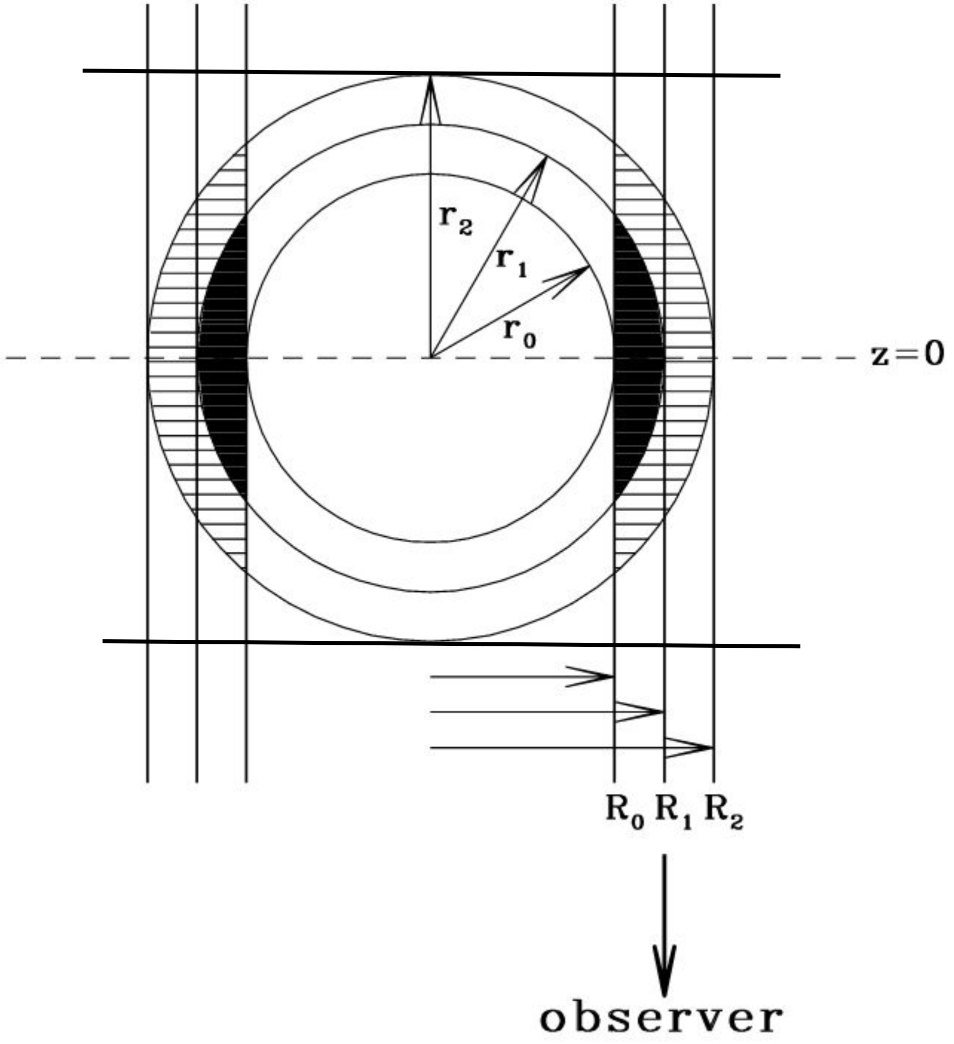
$$P(R_1,R_2) * \pi(R_2^2 - R_1^2)L = P'(r_1,r_2) * V_{int}(r_1,r_2,R_1,R_2)$$

$$\Rightarrow \quad P'(r_1,r_2) = P(R_1,R_2) * \boxed{\frac{\pi(R_2^2 - R_1^2)L}{V_{int}(r_1,r_2,R_0,R_1)}}$$

Ratio of the cylindrical annulus over the fraction of the sphere

Second furthest annulus:

$$P(R_0,R_1) * \pi(R_1^2 - R_0^2)L = P'(r_0,r_1) * V_{int}(r_0,r_1,R_0,R_1) + P'(r_1,r_2) * V_{int}(r_1,r_2,R_0,R_1)$$



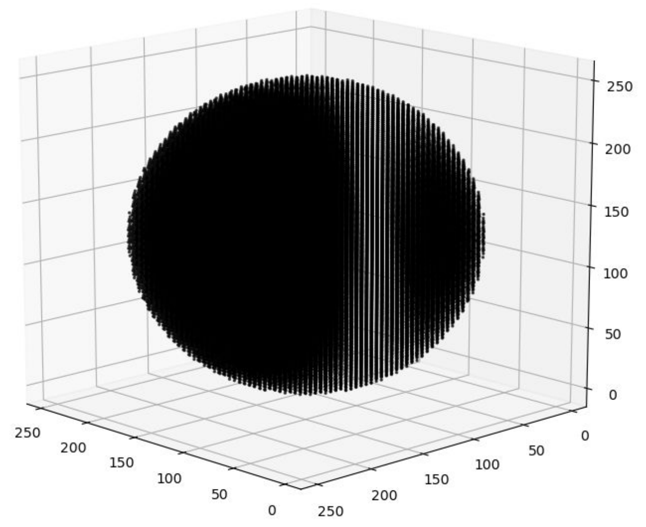
<u>Background subtraction:</u> Subtract the mean pressure of the local environment (mean pressure in a circular annulus between 8 and 10 Mpc)

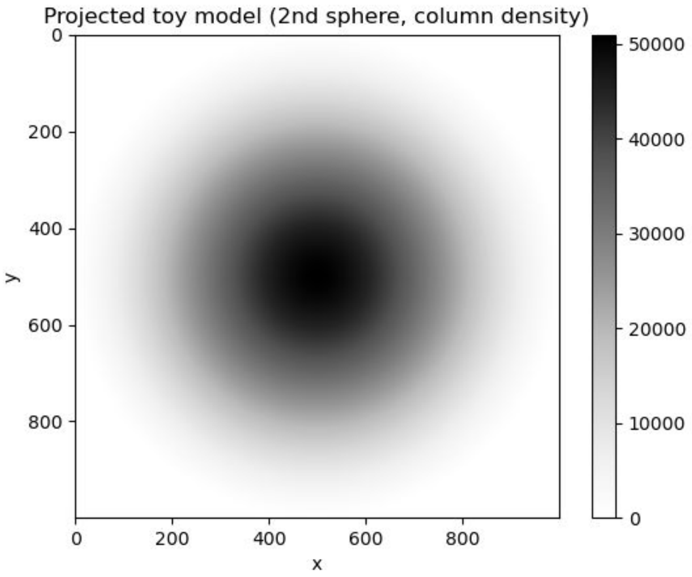
<u>Generalisation :</u>

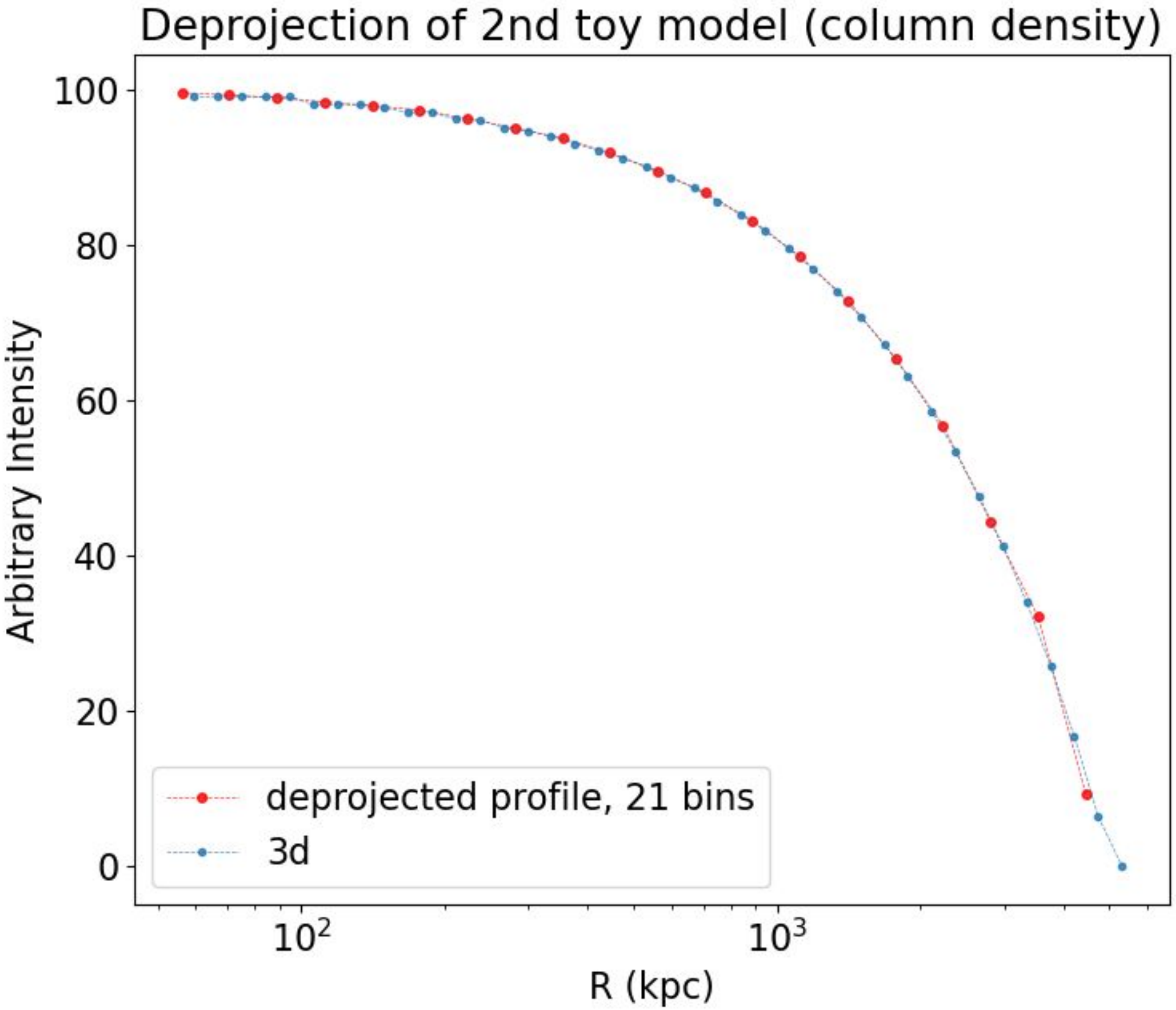
$$P'\left(r_{i-1},r_i\right) = \frac{P\left(R_{i-1},R_i\right)\pi(R_i^2 - R_{i-1}^2)L - \sum_{j=i+1}^{m}\left[P'\left(r_{j-1},r_j\right)V_{\rm int}\left(r_{j-1},r_j;R_{i-1},R_i\right)\right]}{V_{\rm int}\left(r_{i-1},r_i;R_{i-1},R_i\right)}$$

Test of the method: column density maps

Perfect sphere, values in cells varying from 100 in the center to 1 in the outskirt

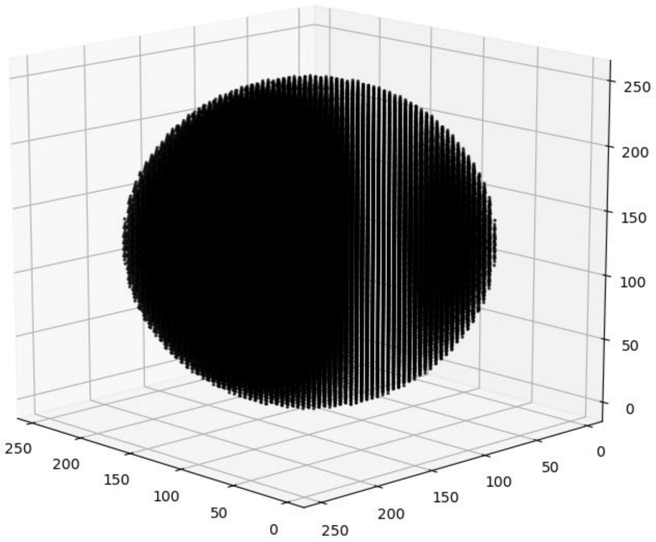


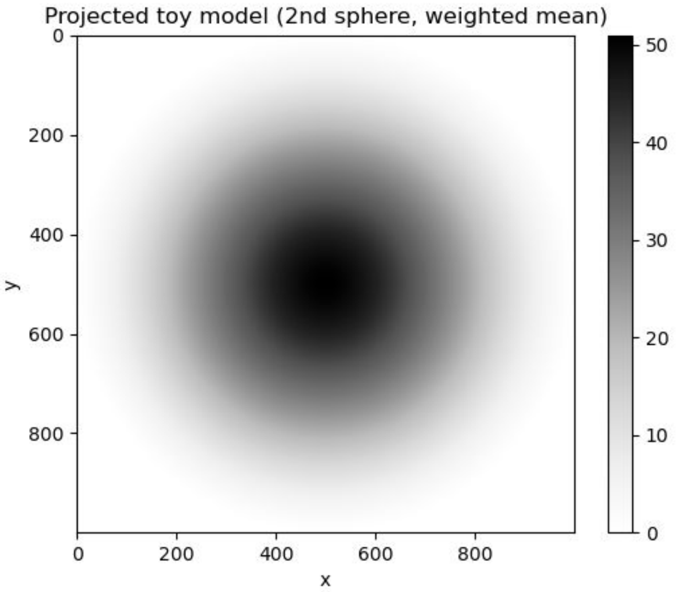


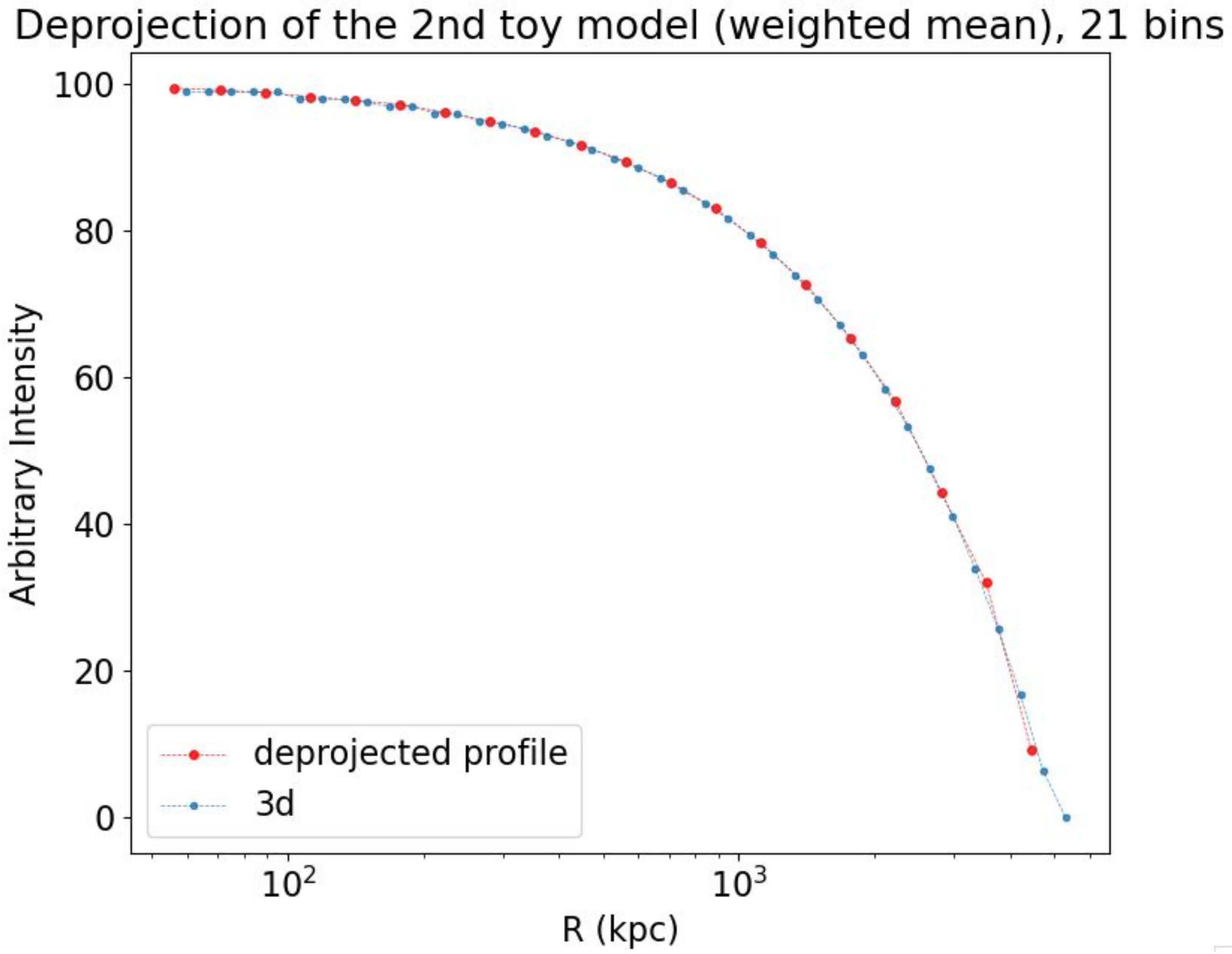


Test of the method: weighted mean maps

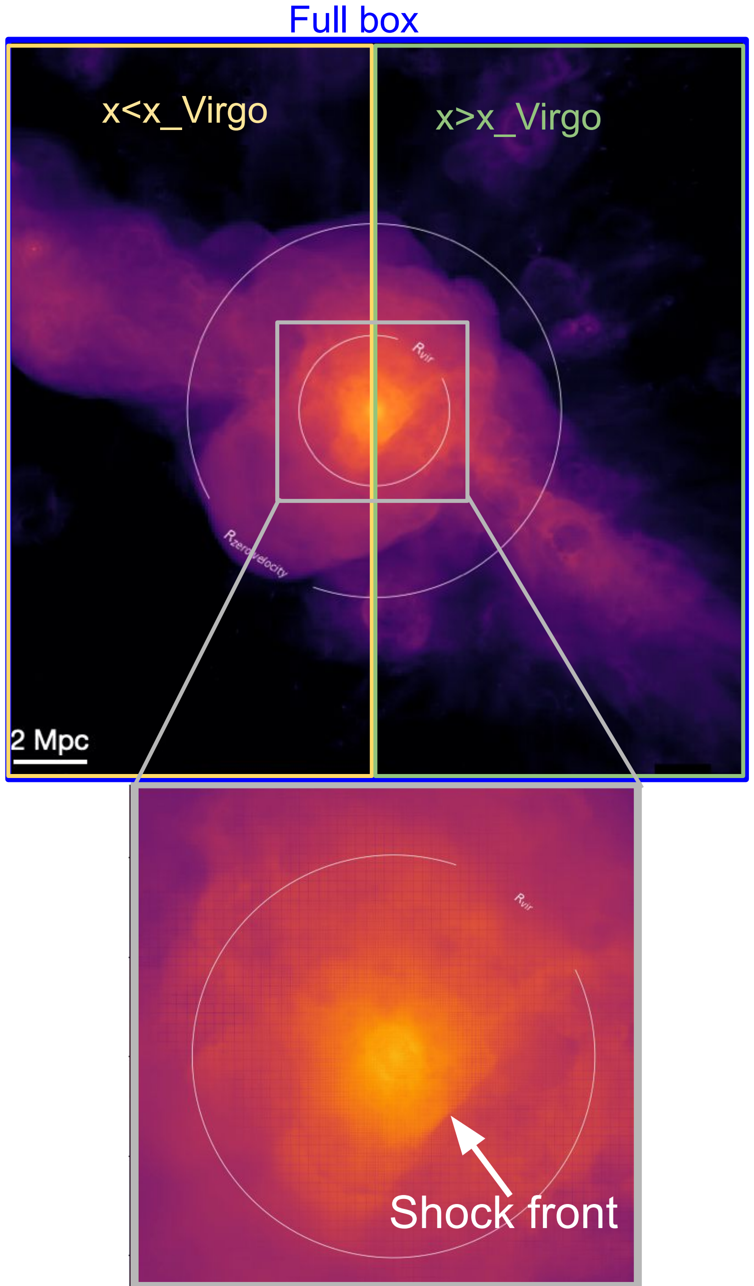
Perfect sphere, values in cells varying from 100 in the center to 1 in the outskirt

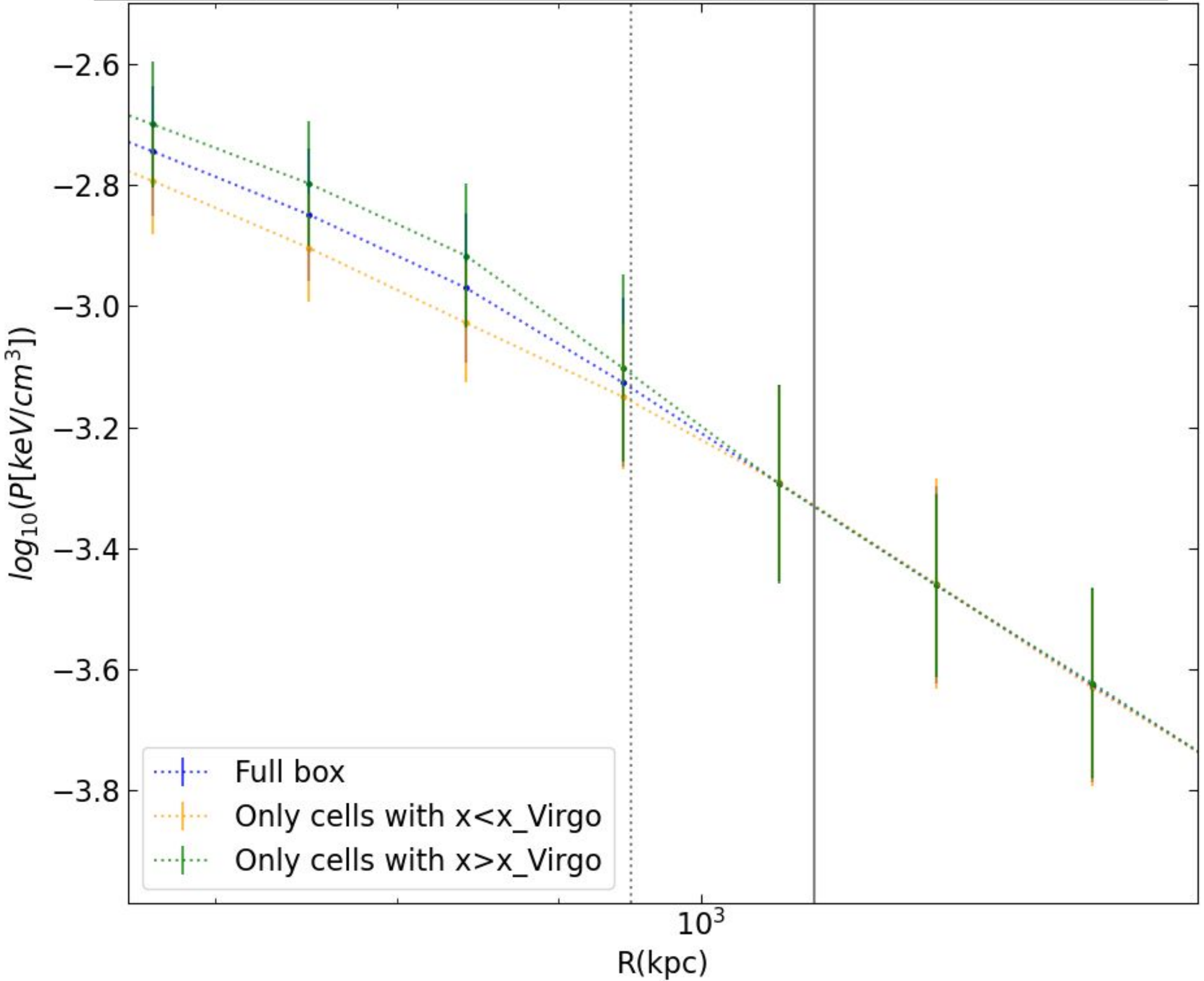






Hydrostatic mass using only a fraction of the simulation box





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