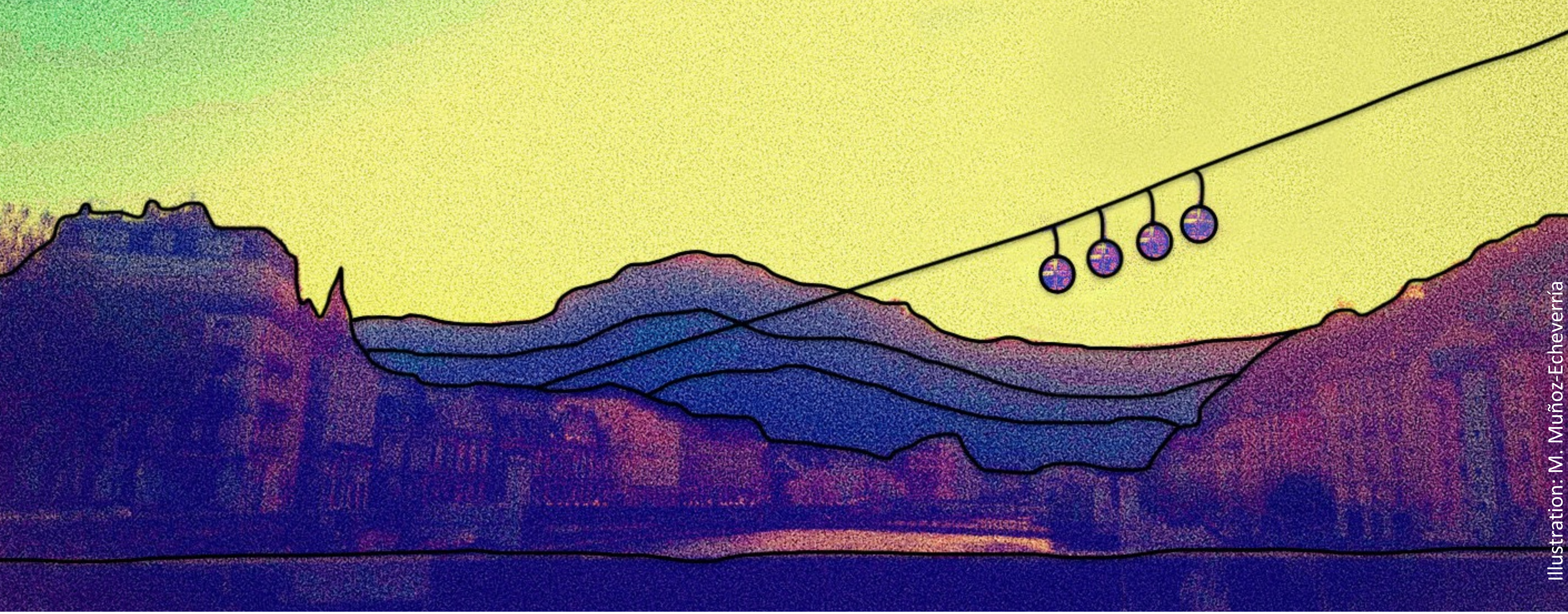

Optimization and quality assessment of baryon pasting for intracluster gas

Florian Kéruzoré, Argonne National Laboratory

mmUniverse23, June 2023

Kéruzoré et al., Submitted to OJA, arXiv:2306.13807 (as of yesterday!)

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Context: Cosmological simulations for cluster science

- **Cluster cosmology needs simulations**

  HMF calibration, accuracy/precision of mass estimates, selection functions, …

- Two types of cosmological simulations:
  - **Hydrodynamic:** Universe with CDM + baryons
  - **Gravity-only (GO):** All matter is CDM

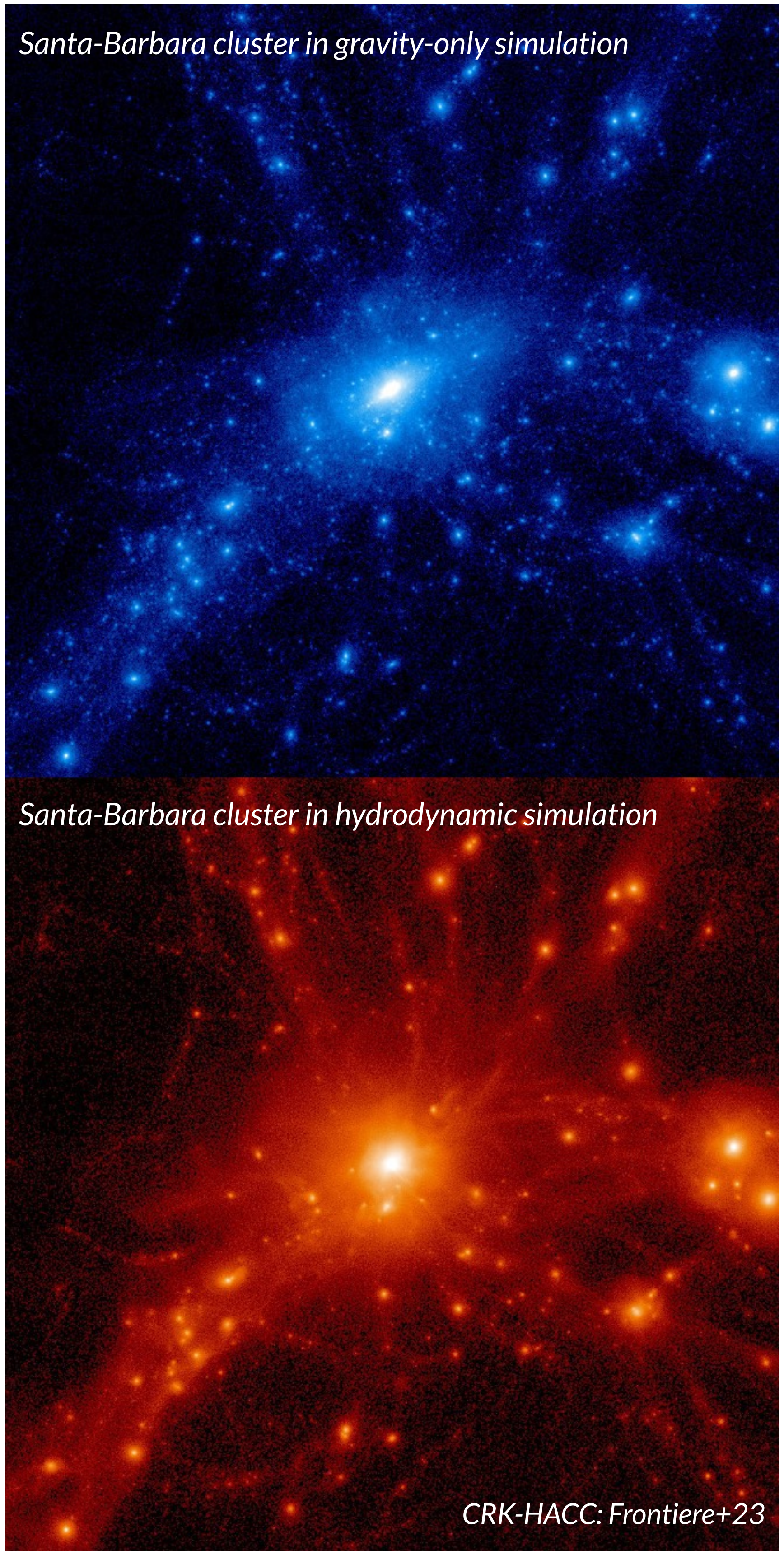
    ☺ **~10x faster than hydro**
    → larger volumes, more cosmologies

    ☹ **No baryons = no SZ** (or X-rays)
    → Can't produce all cluster observables

- **Baryon pasting (BP):** add gas a posteriori to create observables from GO simulations

  → Get the products of a hydro simulation, for the price of a GO simulation

- **This work:** optimize baryon pasting to reproduce results from hydro simulations



- ANL produces state-of-the-art simulations using the HACC solver *(Habib+16, Frontiere+23)*
- **Large variety of available data:**
  - Cutting-edge large boxes *OuterRim, LastJourney, FarPoint*
  - Cosmo params hypercube *Mira-Titan*
  - Volumes simulated in hydro and GO *BorgCube*
- Post-processing pipeline can produce:
  - kSZ / simple tSZ from baryon pasting *(Flender+16)*
  - Galaxies *(LSSTDESC+21)*
  - (CMB) lensing maps *(Larsen+ in prep.)*
- **Widely used for cosmology** *(e.g. LSST DC2)*
- To be improved with DOE's exascale computers *(Aurora, Frontier)*

Year	Simulation	Code, Algorithm	Supercomputer, Location	Cores $[10^3]$	N_p $[10^{12}]$	Box $[h^{-1}\mathrm{Gpc}]$	
2014	Dark Sky (Skillman et al. 2014)	2HOT FMM	Titan USA	20	1.1	8	
2017	TianNu (Emberson et al. 2017)	CUBEP^{3}M PM-PM-PP	Tianhe-2 China	331	2.97	1.2	
2017	Euclid Flagship (Potter et al. 2017)	PKDGRAV3 Tree-FMM	PizDaint Switzerland	4	2.0	3.	
2019	Outer Rim (Heitmann et al. 2019)	HACC Tree-PM	Mira USA	524	1.07	3.0	ANL
2019	Cosmo-π (Cheng et al. 2020)	CUBE PM-PM	π 2.0 China	20	4.39	3.2	
2020	Uchuu (Ishiyama et al. 2021)	GreeM Tree-PM	ATERUI-II Japan	<40	2.0	2.0	
2020	Last Journey (Heitmann et al. 2021)	HACC Tree-PM	Mira USA	524	1.24	3.4	ANL
2021	Far Point (Frontiere et al. 2021)	HACC Tree-PM	Summit USA	?	1.86	1	ANL

Table 1 List of cosmological simulations with a particle number in excess of 1 trillion (10^{12})

Angulo+23

Outline

- Context
- **Optimizing baryon pasting vs hydrodynamic simulations**
  - The Borg Cube simulations
  - Model & Optimization method
  - Results
- **Quality assessment**
  - Gas profiles
  - Preliminary fixed-z tSZ products
- **Conclusions, outlook**

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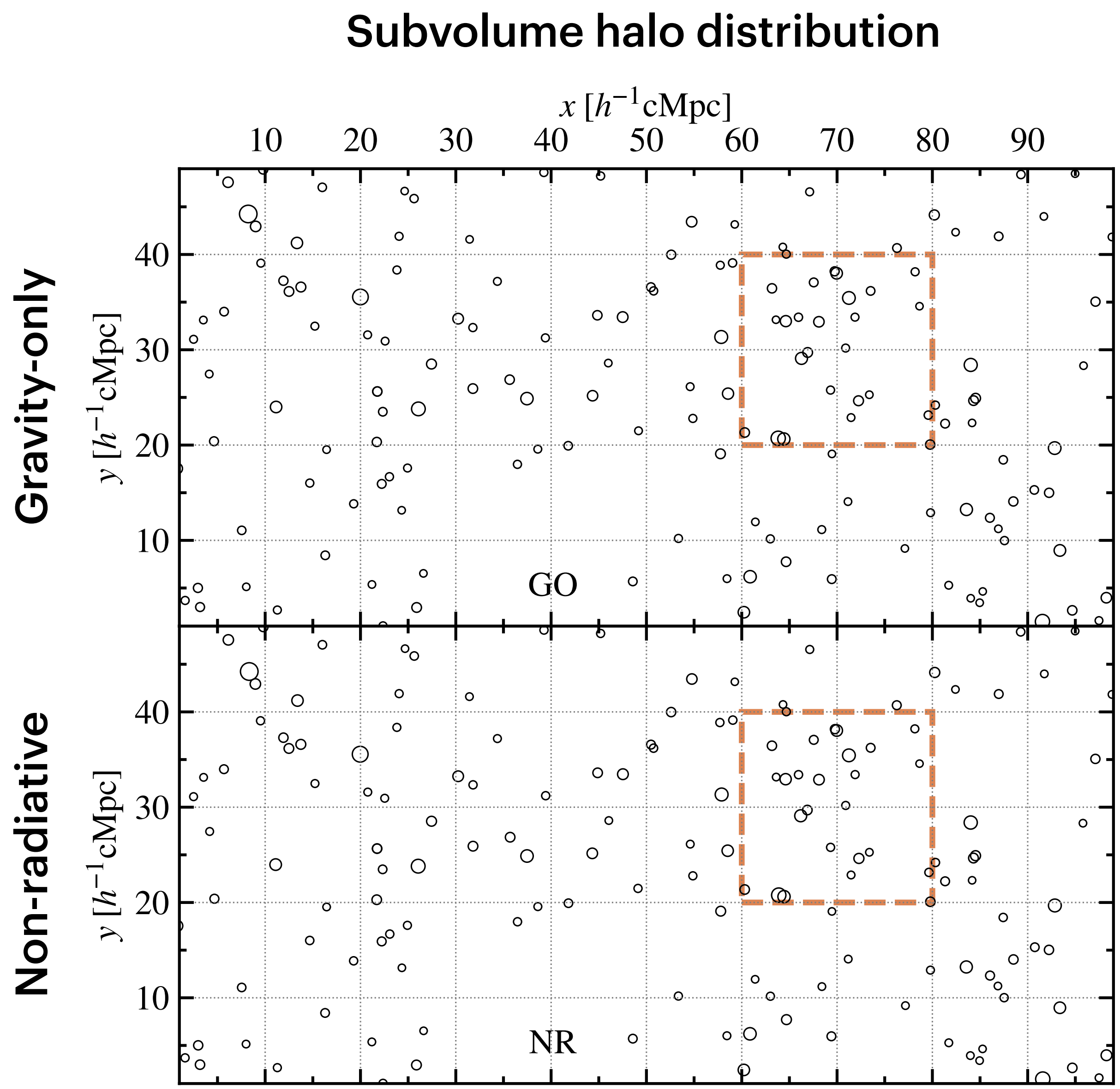
- Volume = $(800\, h^{-1}\mathrm{cMpc})^3$; particle mass $\sim 10^9\, h^{-1} M_\odot$
- **Two simulations** with **same initial conditions:**
  - **GO:** Gravity-only
  - **NR:** Non-radiative hydro
    First CRK-HACC hydrodynamic simulation (Emberson+19)

The Borg Cube simulation(s)

- Volume = $(800\,h^{-1}\mathrm{cMpc})^3$; particle mass $\sim 10^9\,h^{-1}M_\odot$
- **Two simulations** with **same initial conditions:**
  - **GO:** Gravity-only
  - **NR:** Non-radiative hydro
    First CRK-HACC hydrodynamic simulation (Emberson+19)

Same initial conditions → ~ same halos

GO run vs. NR run

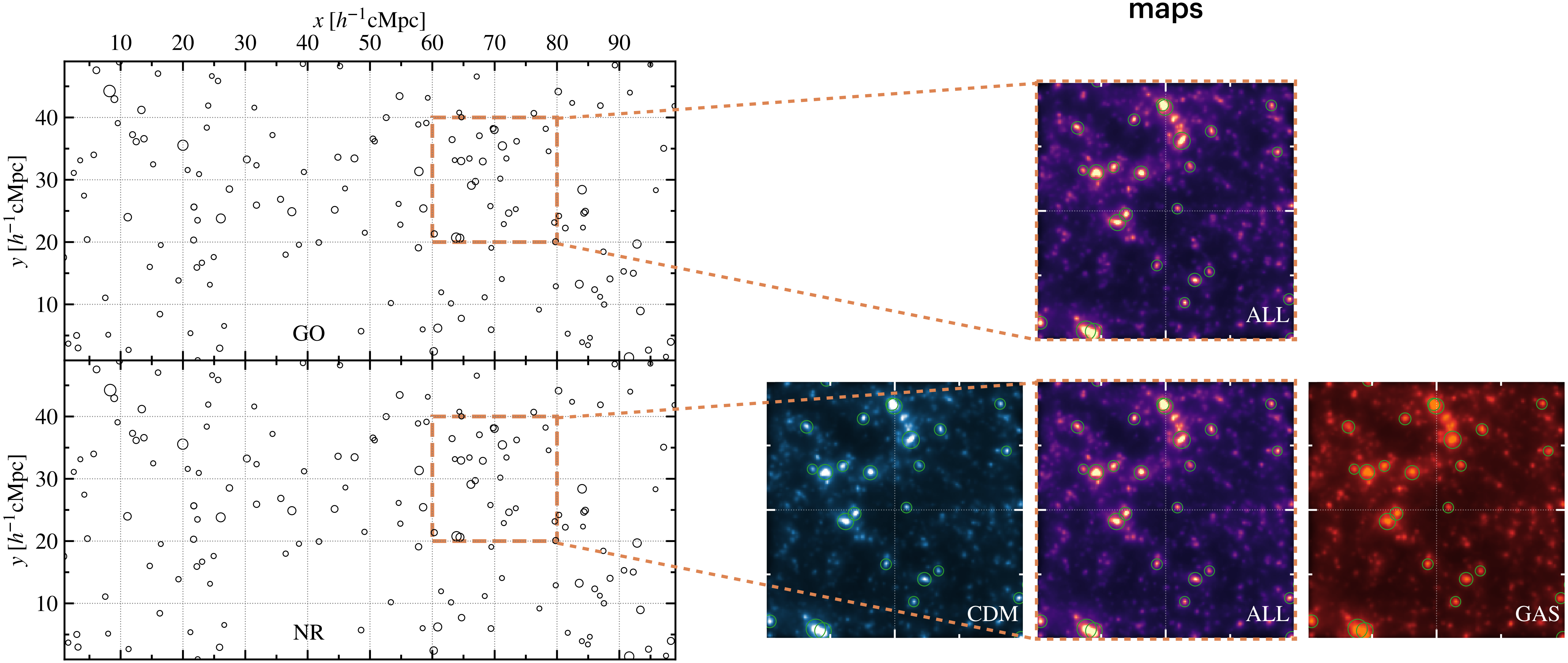


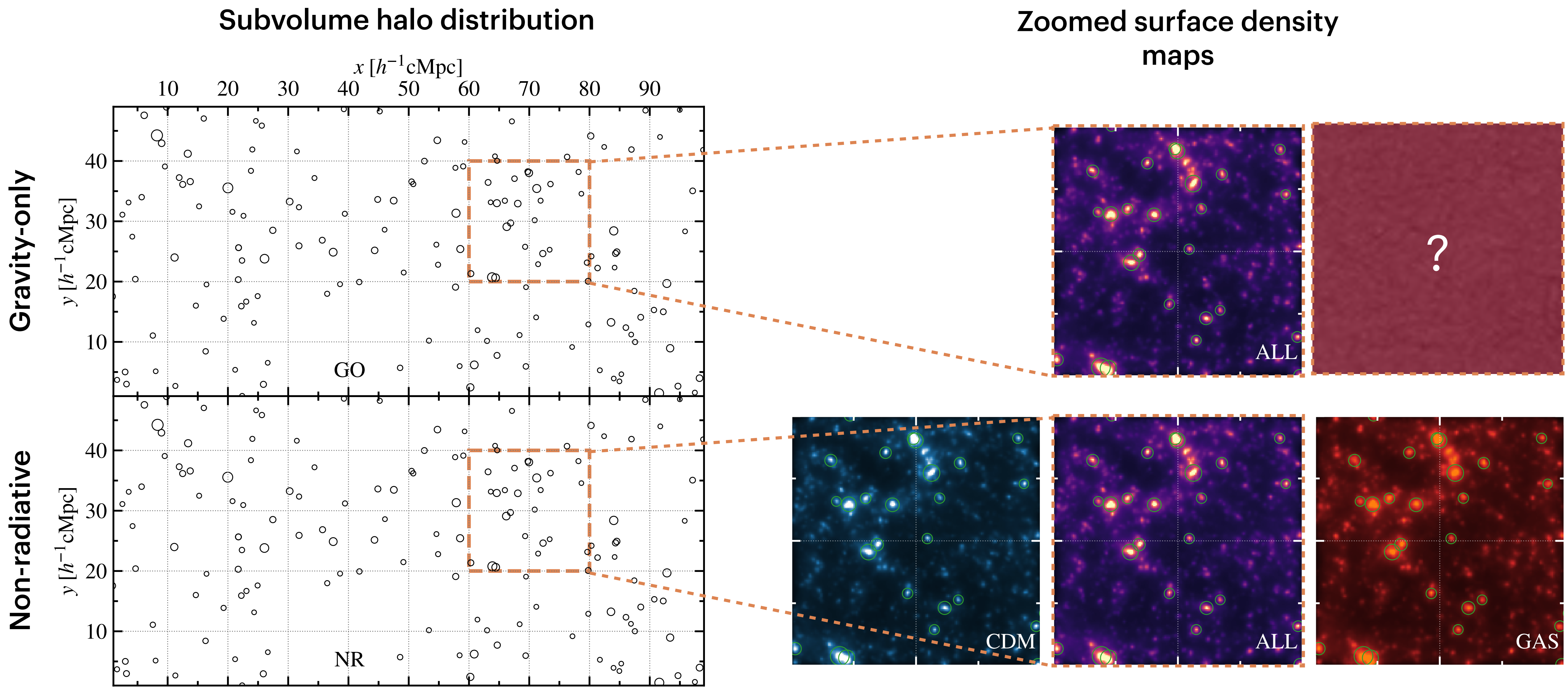
Subvolume halo distribution

Zoomed surface density maps

Gravity-only

Non-radiative





→ **How can we reproduce the NR gas distribution from the GO matter distribution?**

Halo sample: cluster-scale, matched in both runs

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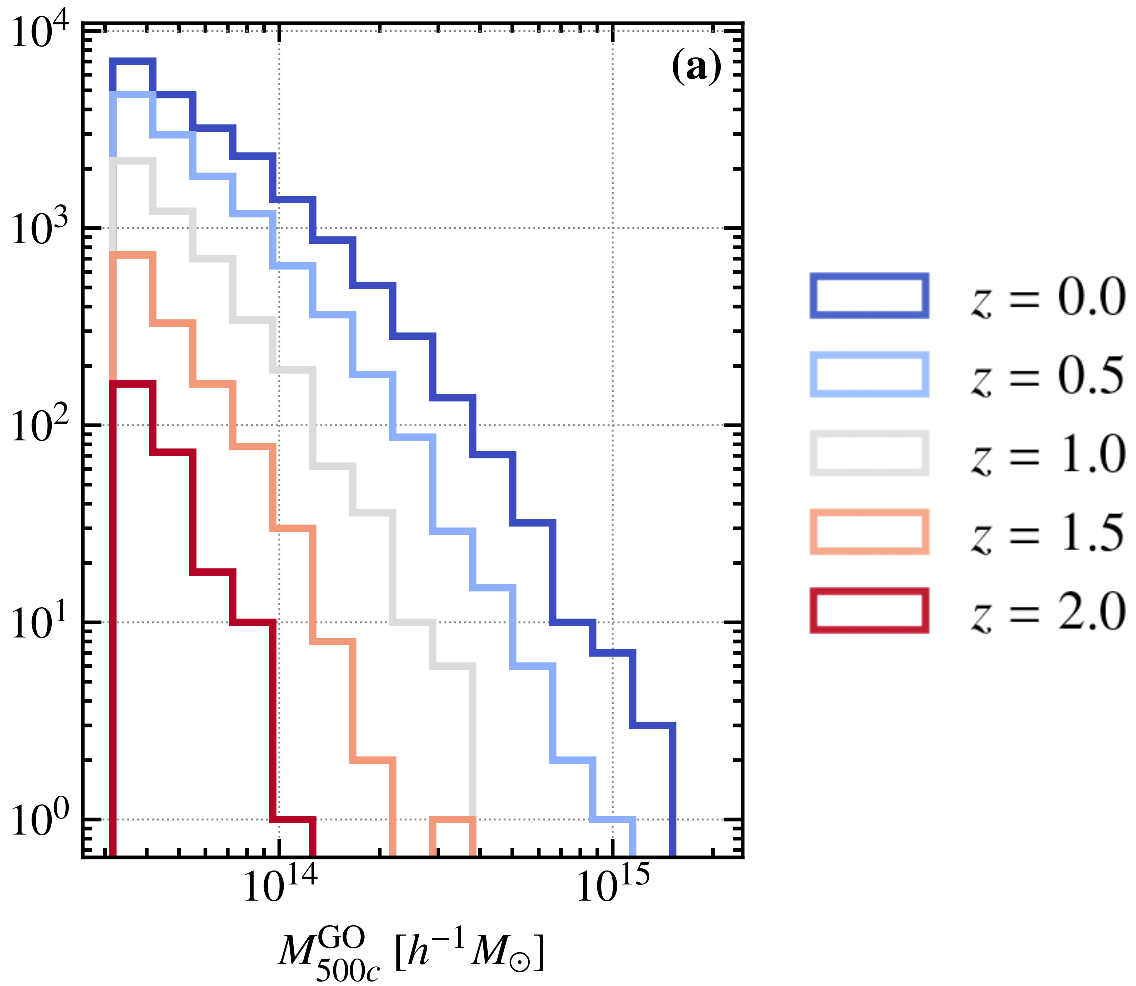
- Study cluster-scale halos: $M_{500c} \geqslant 10^{13.5}\, h^{-1} M_{\odot}$
- Match halos in both runs based on distance + similar mass

  → >98% of GO halos are matched



Redshift	$N_{\rm halos}^{\rm GO}$	$N_{\rm halos}^{\rm both}$
$z = 0$	20458	20120
$z = 0.5$	11880	11703
$z = 1$	4698	4644
$z = 1.5$	1315	1311
$z = 2$	263	260
Total	38614	38038

Baryon pasting model and optimization

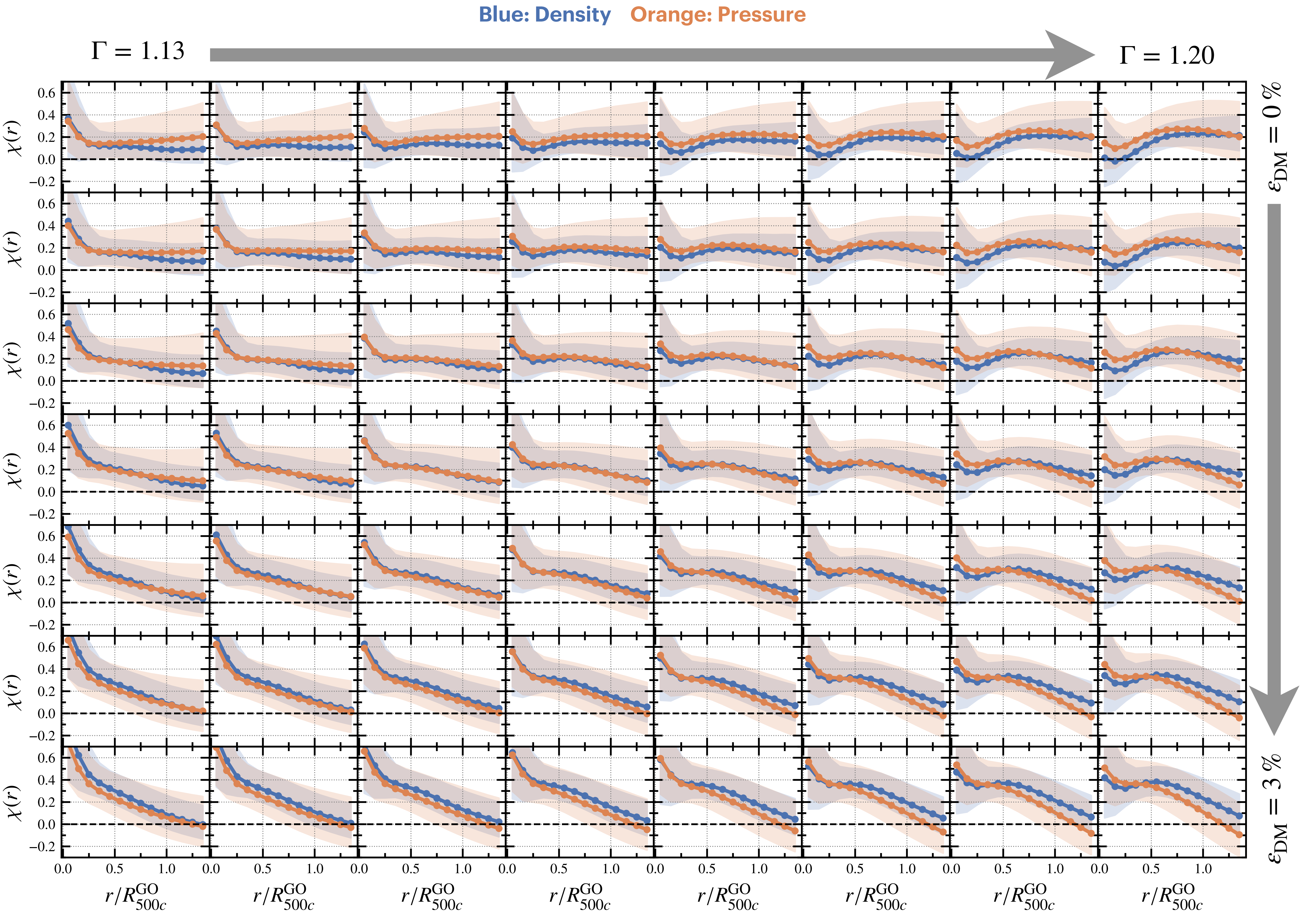
- **Model:** based on Ostriker+05 model: for 1 halo, BP gas density & pressure fixed by:

  (see D. Nagai's talk)
  - GO 3D grav. potential
  - Model parameters:
    - gas polytropic index Γ,
    - fraction of CDM energy transferred to gas $\varepsilon_{\rm DM}$
- **Optimization workflow:**
  - Run baryon pasting on all halos, on a grid of parameter values:
    $\Gamma \in [1.13, 1.20]\ ;\ \varepsilon_{\rm DM} \in [0, 5\%]$
  - For each halo, compare relative difference between BP and NR gas density and pressure,

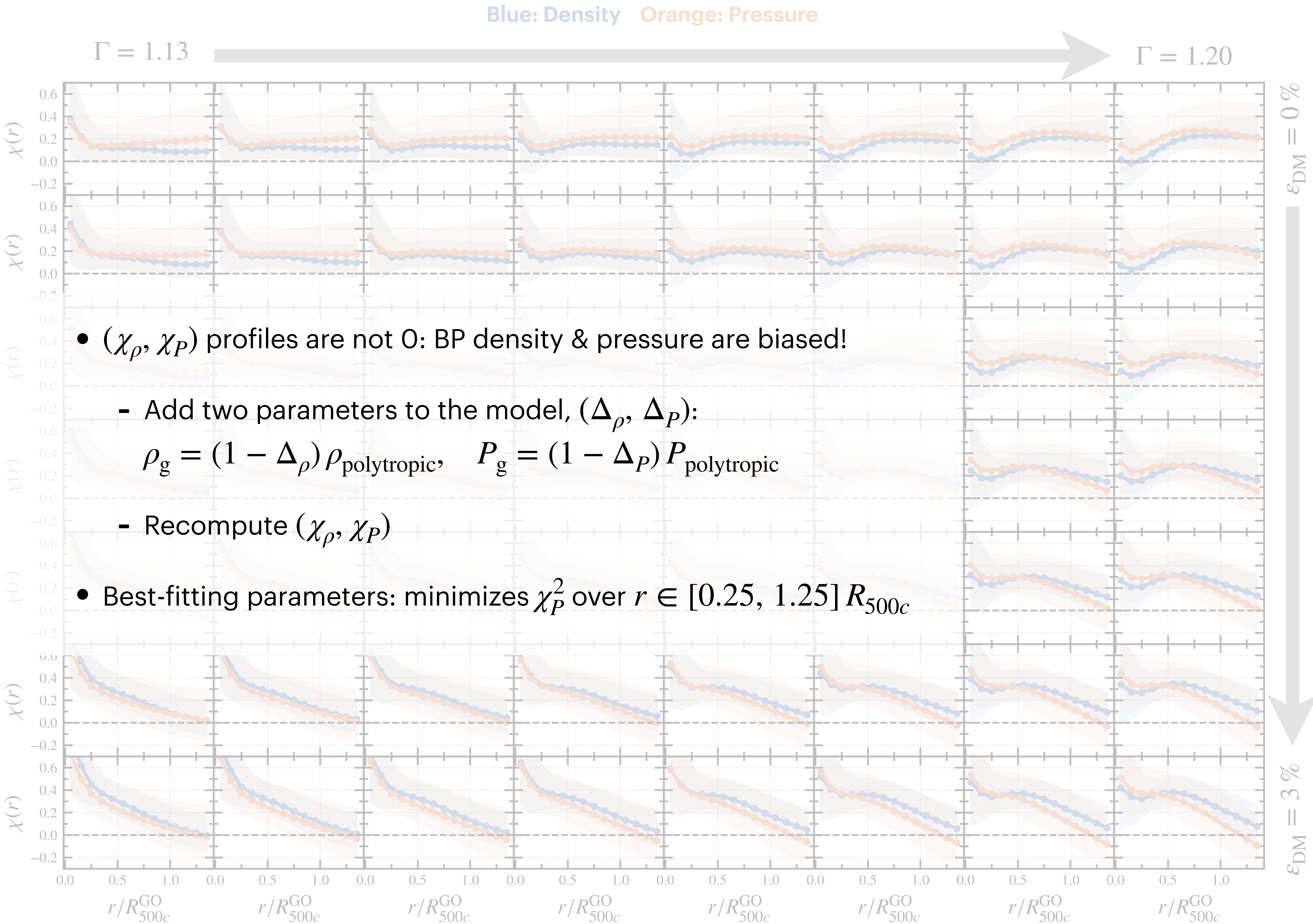
$$\chi_\rho = \frac{\rho_{\rm g}^{\rm BP}}{\rho_{\rm g}^{\rm NR}} - 1, \quad \chi_P = \frac{P_{\rm g}^{\rm BP}}{P_{\rm g}^{\rm NR}} - 1$$

  - Compute the radial profiles of (χ_ρ, χ_P) for all halos
  - Repeat for all redshifts independently

Results: z=0 (n=20,120)



Results: z=0 (n=20,120)

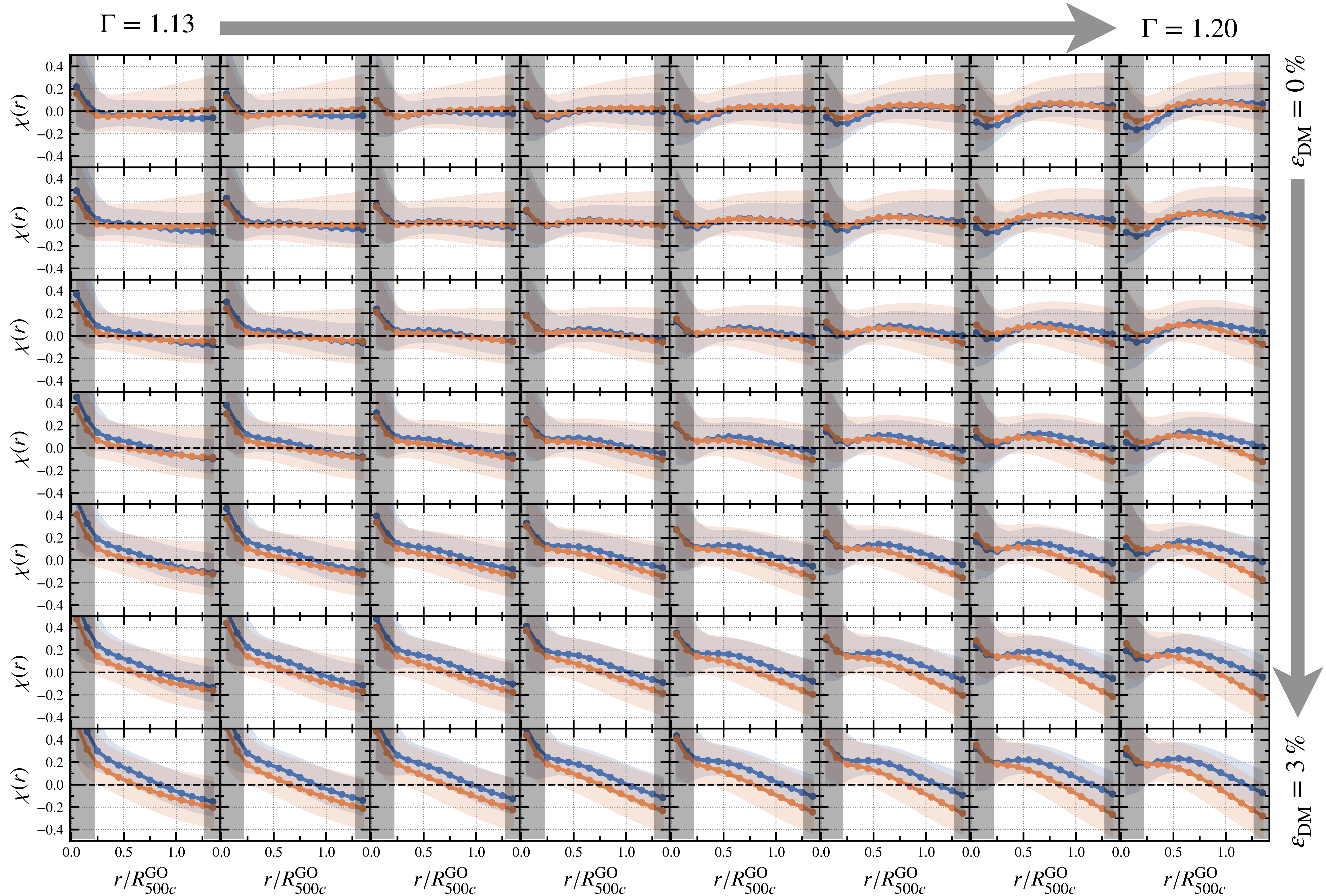


- (χ_ρ, χ_P) profiles are not 0: BP density & pressure are biased!
  - Add two parameters to the model, (Δ_ρ, Δ_P):

    $\rho_{\mathrm{g}} = (1 - \Delta_\rho)\,\rho_{\mathrm{polytropic}}, \quad P_{\mathrm{g}} = (1 - \Delta_P)\,P_{\mathrm{polytropic}}$
  - Recompute (χ_ρ, χ_P)
- Best-fitting parameters: minimizes χ_P^2 over $r \in [0.25,\ 1.25]\,R_{500c}$

Results: z=0 (n=20,120)

Blue: Density   Orange: Pressure



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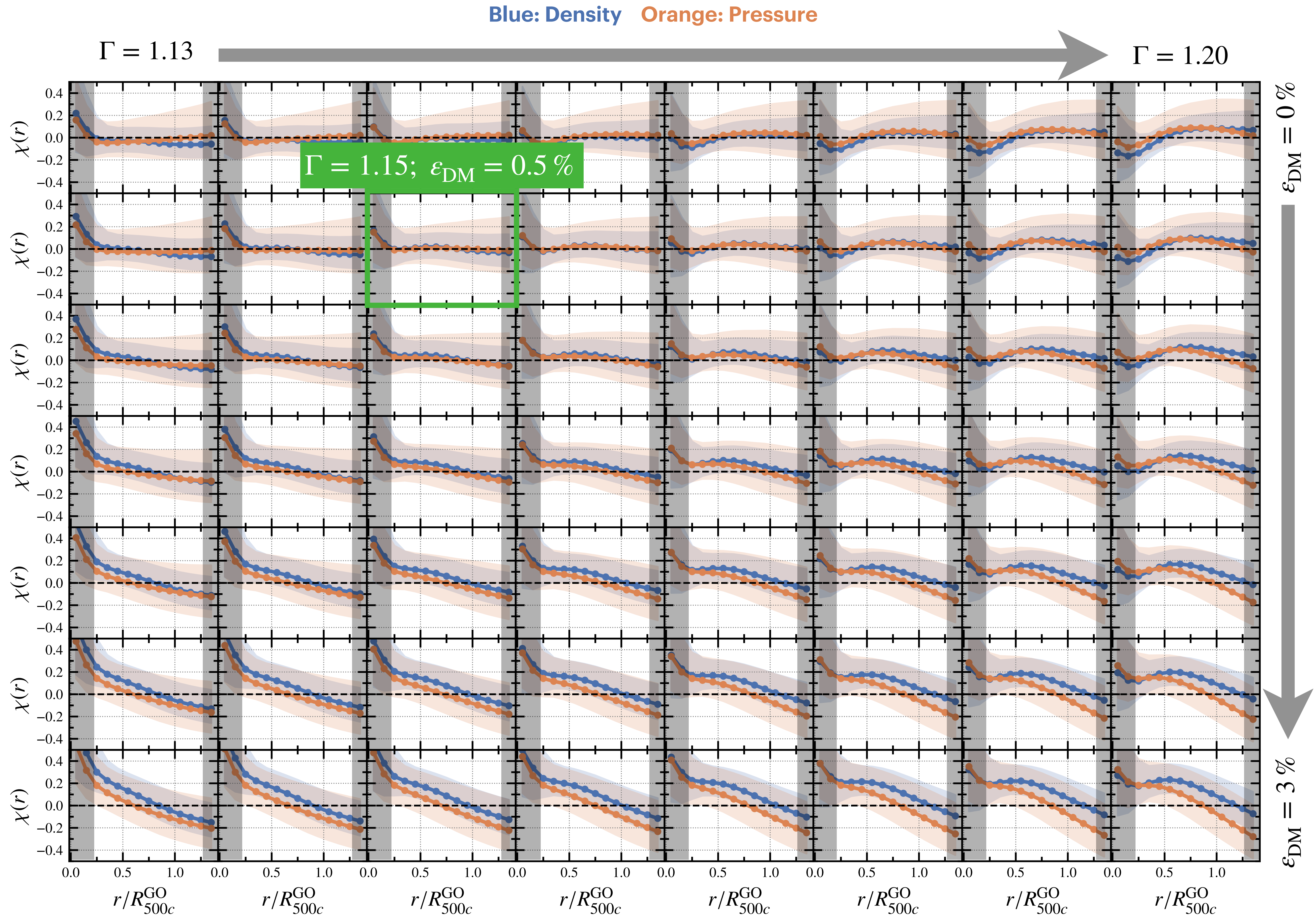
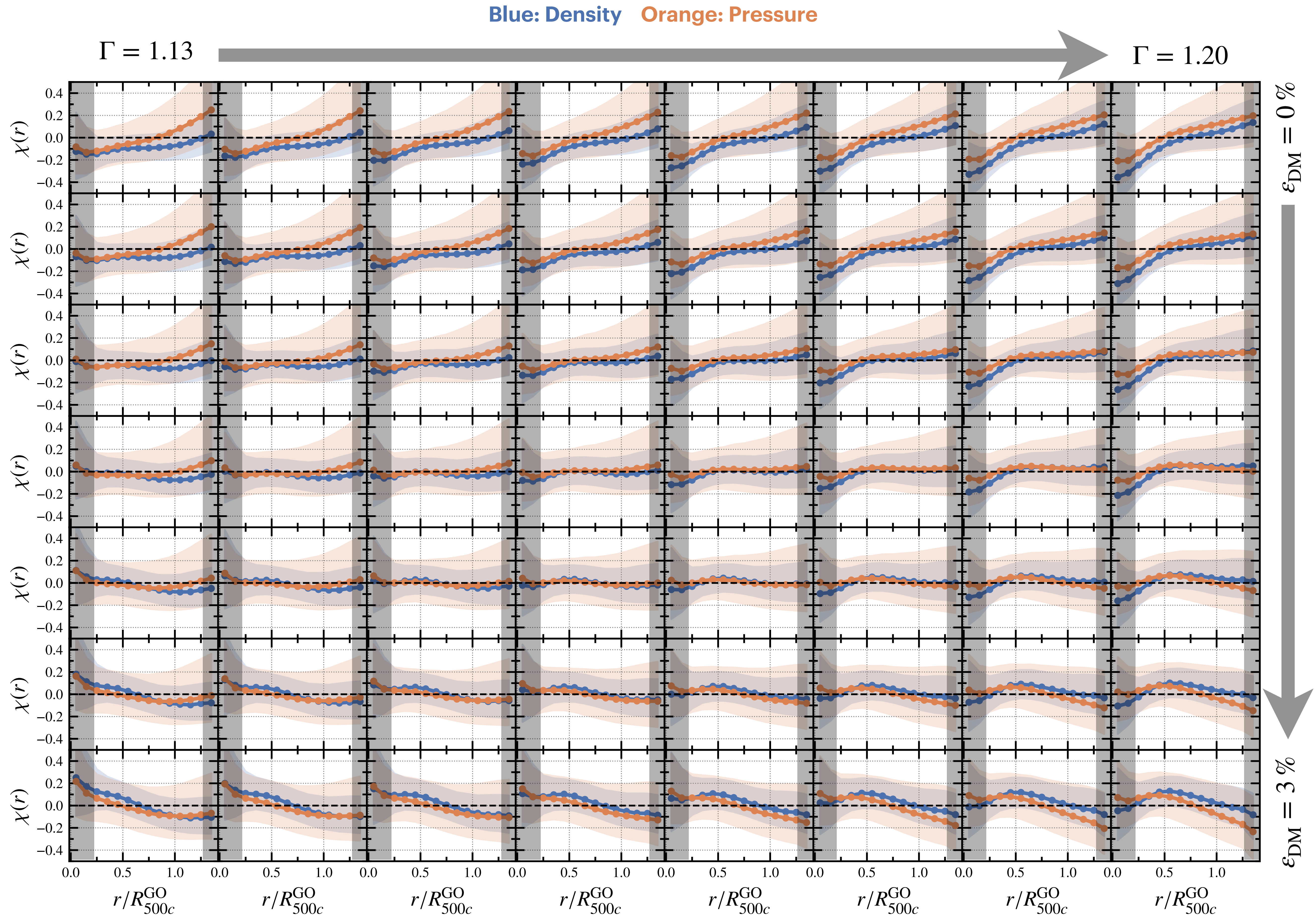


Results: z=1 (n=4,644)



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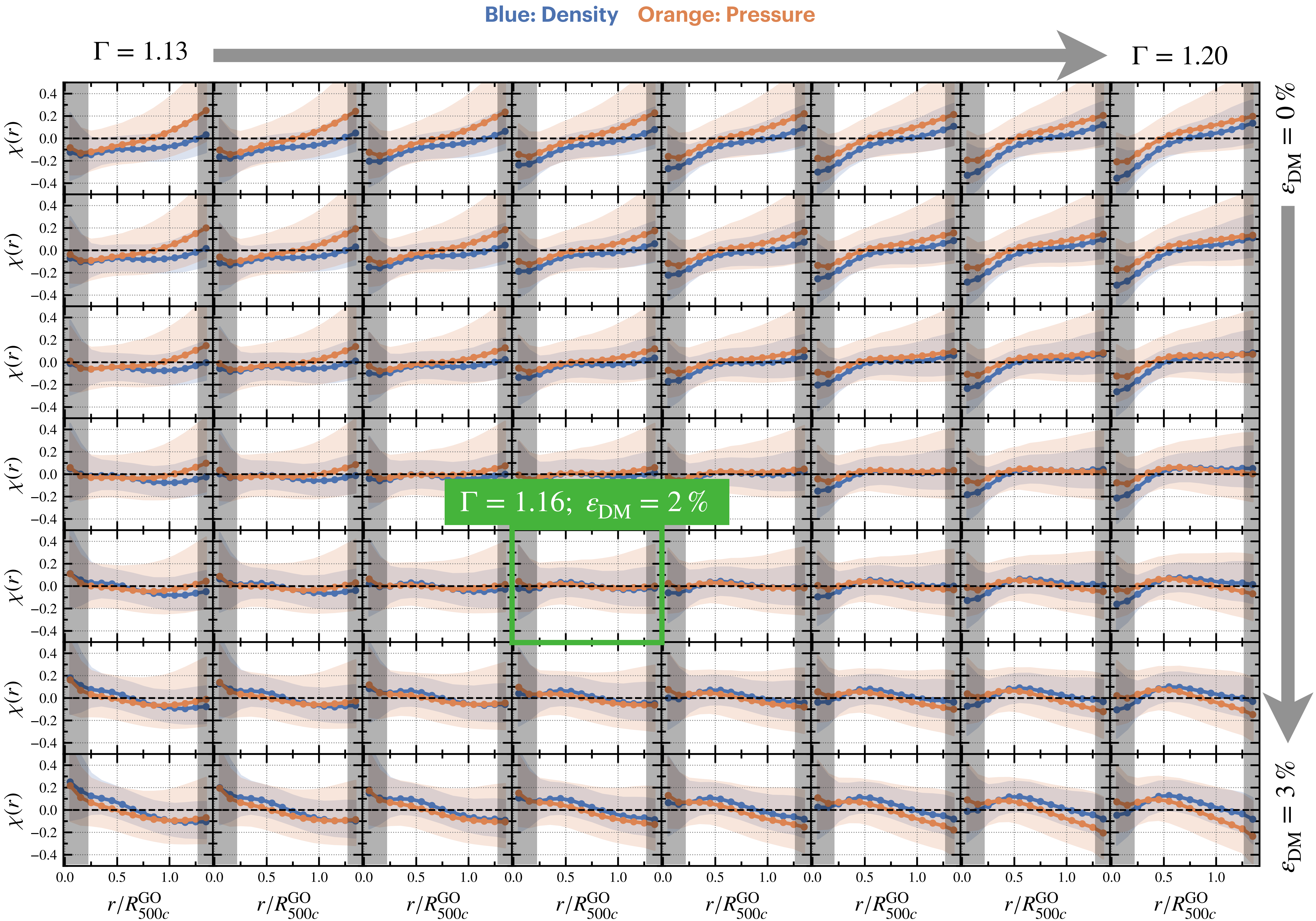
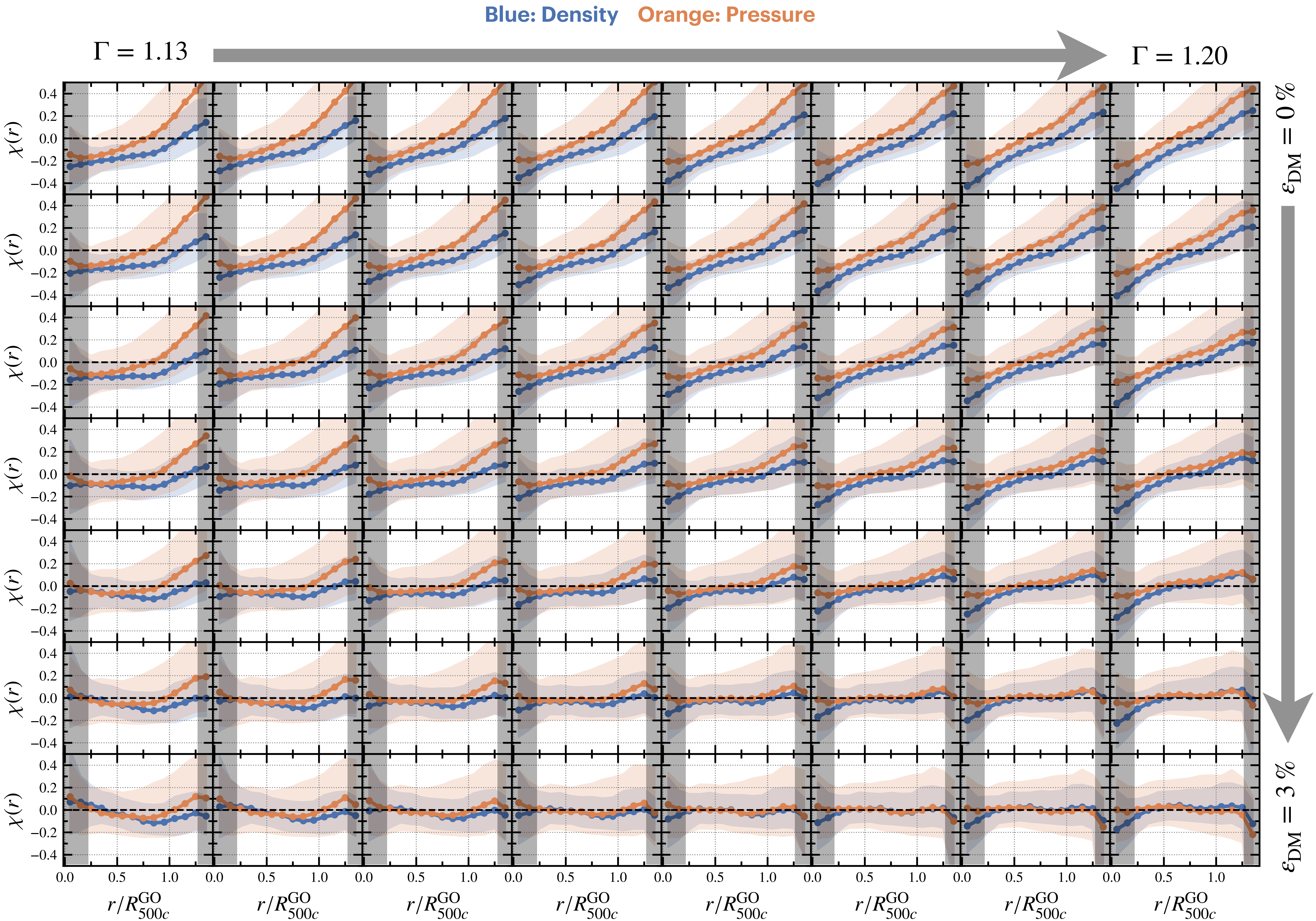
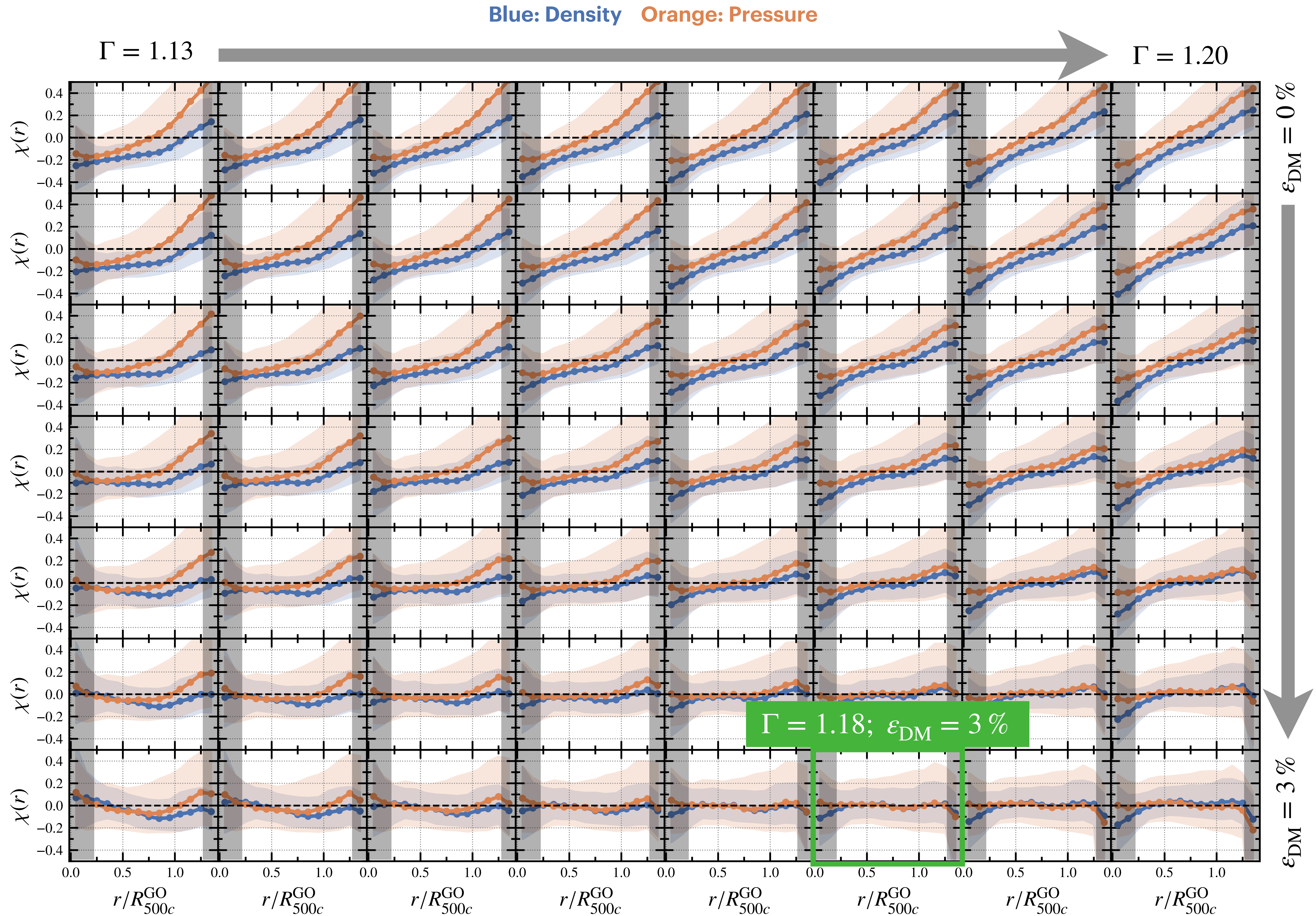


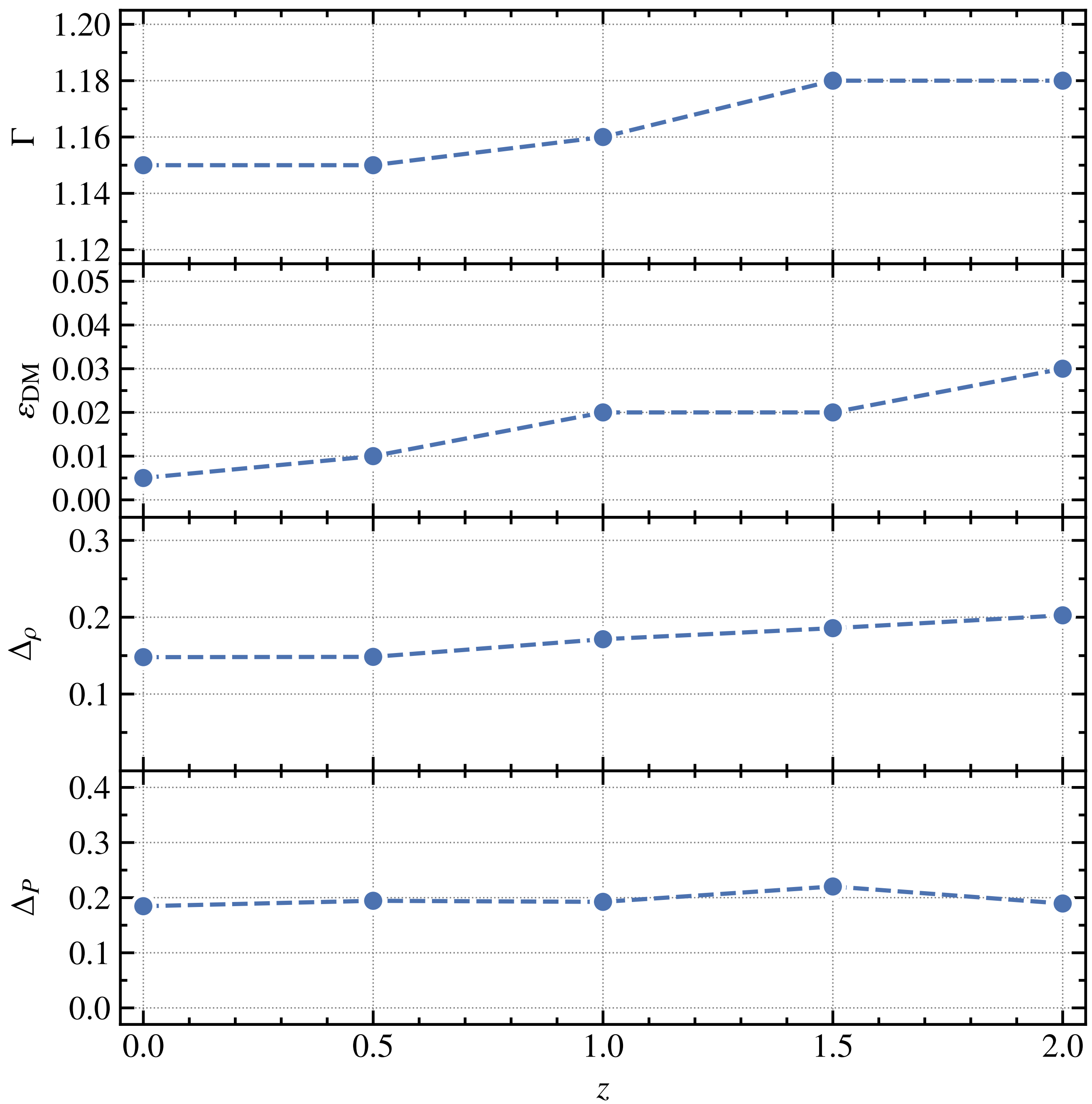
Results: z=2 (n=260)



Results: z=2 (n=260)



Results: params = f(z)



- Measured redshift trend in $(\Gamma, \varepsilon_{DM})$
  - $\Gamma(z=0) = 1.15$
    $\rightarrow \Gamma(z=2) = 1.18$
  - $\varepsilon_{DM}(z=0) = 0.5\,\%$
    $\rightarrow \varepsilon_{DM}(z=2) = 3\,\%$
- Measured bias parameters:
  - Density: $\Delta_\rho \sim 15 - 20\,\%$
  - Pressure: $\Delta_P \sim 20\,\%$

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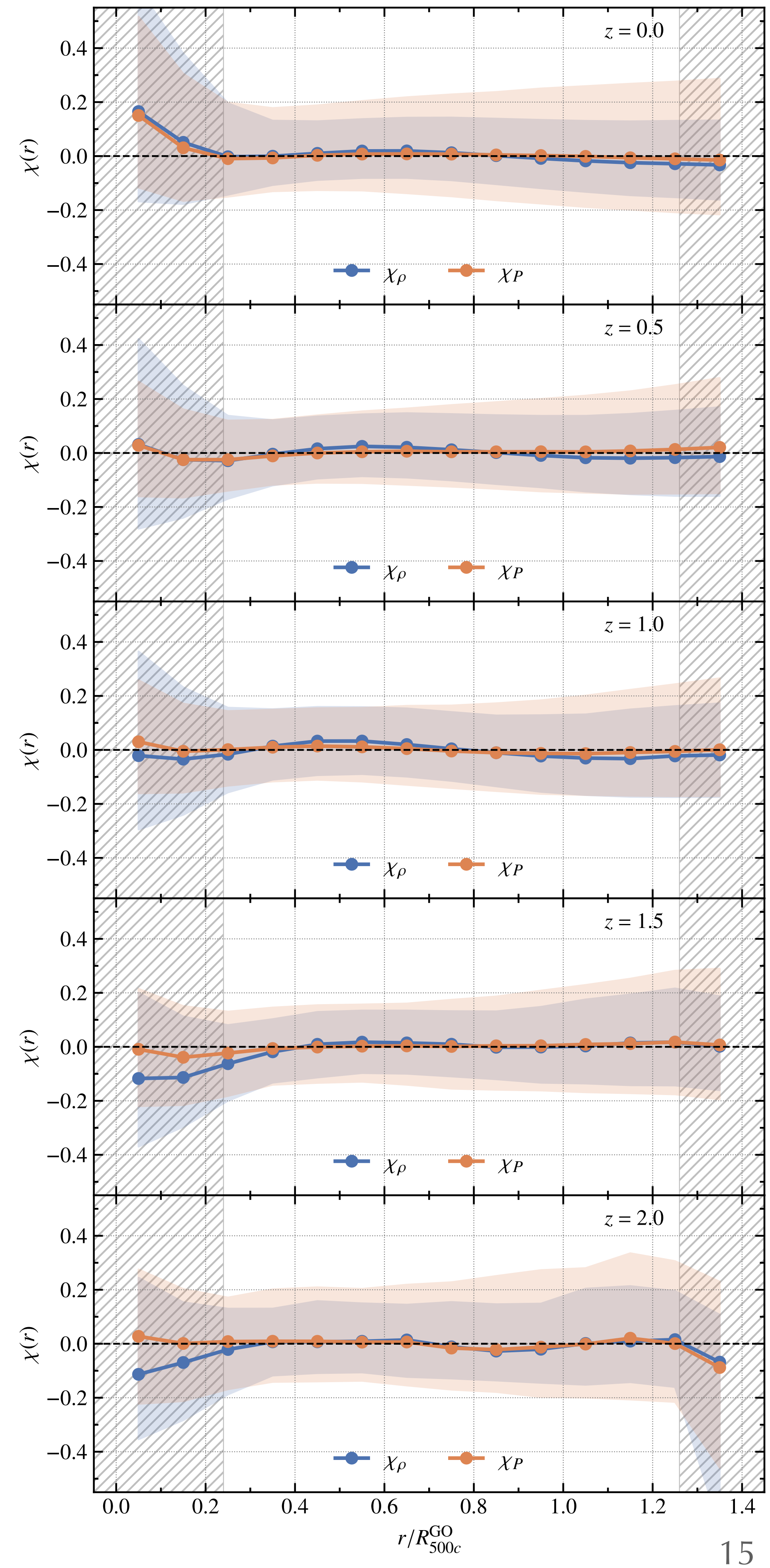
Gas profiles reconstruction: accuracy & precision

- Agreement between density and pressure
- For the best parameters at each z
- Focusing on $r \in [0.25,\ 1.25]\, R_{500c}$
- Accuracy:
  - $< 3\,\%$ on pressure
  - $< 2\,\%$ on density
- Scatter:
  - Radially dependent
  - $\sim 20\,\%$ on pressure
  - $\sim 15\,\%$ on density

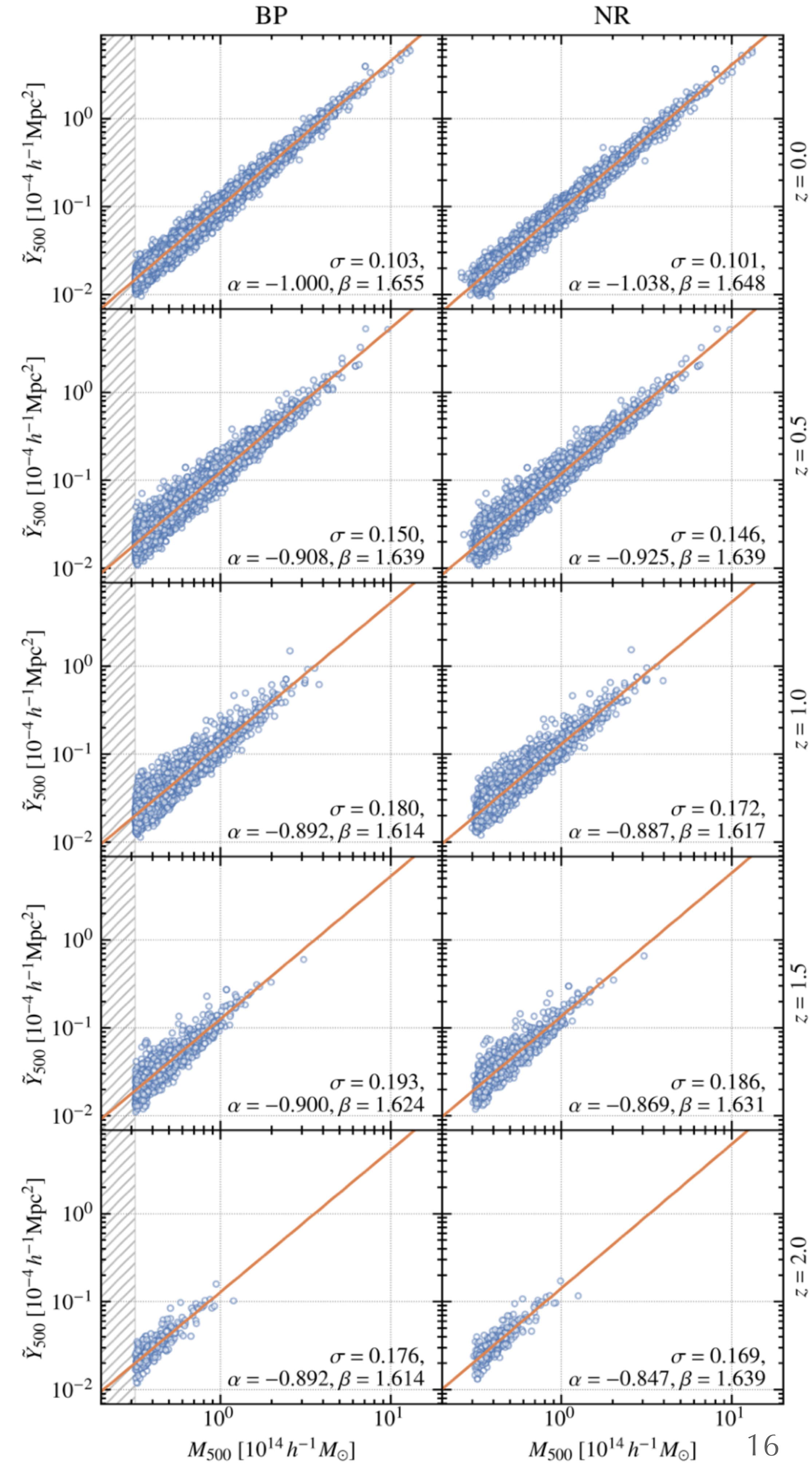


$Y_{500} \,|\, M_{500}$ scaling relation reconstruction

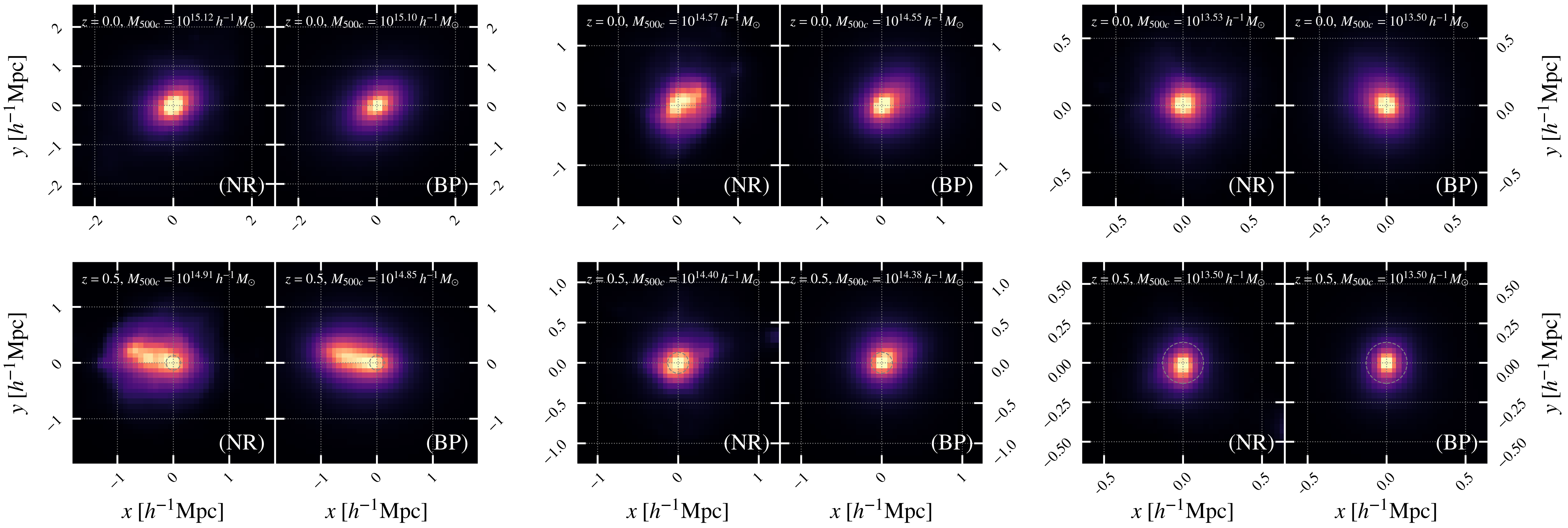
- Y|M: important tool for cluster cosmology
  (See talks by L. Bleem, L. Salvati, L. Perotto, G. Aymerich, A. Moyer, A. Paliwal, …)

$$E^{-2/3}(z)\frac{D_\mathrm{A}^2\, Y_{500}}{10^{-4}\ h^{-1}\mathrm{Mpc}^2} = 10^\alpha \left[\frac{M_{500}}{3\times 10^{14}\ h^{-1}\mathrm{M}_\odot}\right]^\beta + \mathcal{N}(0,\sigma^2)$$

- Compare Y|M from BP (left) vs NR (right):
  - Similar reconstructed parameters
  - Extra scatter due to baryon pasting: $< 5\,\%$ of NR scatter

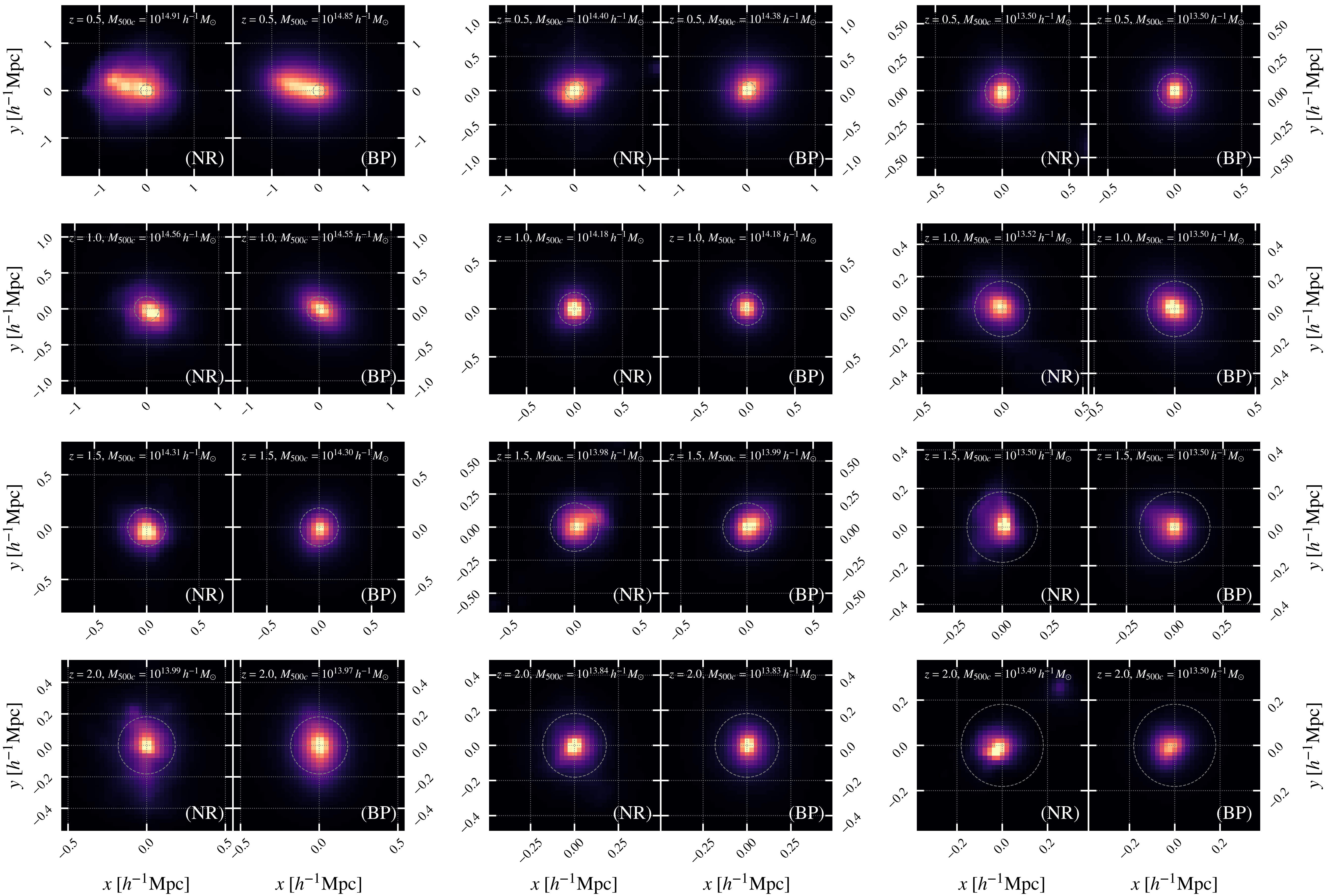


First look at tSZ thumbnails: z=0, z=0.5



- Side-by-side tSZ map of matched halos, in NR (left) & BP (right)
  - → Global shape & tSZ amplitude well reconstructed
- $z > 0$: circle = 1 arcmin (typical resolution of ground-based CMB surveys)

First look at tSZ thumbnails: z>0



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Conclusions

- **Progress towards baryon pasting pipeline for HACC GO simulations**
- Optimized Ostriker+05 model to reproduce hydrodynamic simulation:
  - From direct per-halo comparison on ~40,000 halos, for $z \in [0, 2]$
  - **Redshift trend observed in model parameters**
- **Results: using a gravity-only simulation, up to $z = 2$,**
  - Pressure / density reconstructed with **~few % accuracy, ~20% scatter**
  - $Y_{500} \,|\, M_{500}$ scaling relation well reconstructed, with <5% excess scatter
  - First look at maps: tSZ amplitude / shape reconstructed

What's next?

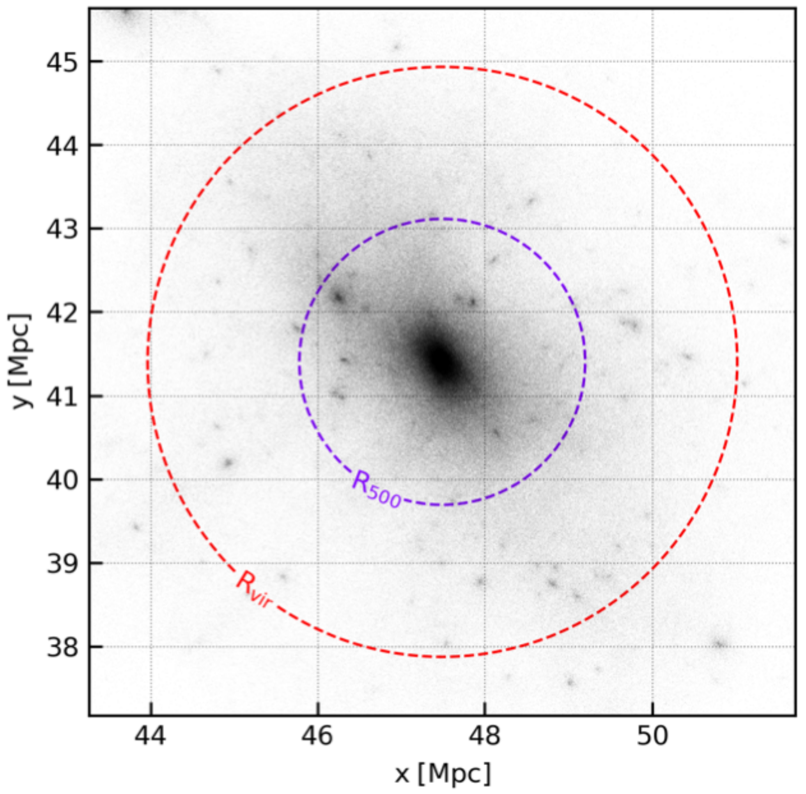
- **Systematic application to HACC gravity-only simulations**
  - OuterRim (DESC cosmoDC2 Universe)
  - Mira-Titan (111 simulations with varying comsology)
  - +all cosmological volumes (Last Journey, Farpoint, ...)

- **Model extension:**
  - This work omits subgrid physics (cooling, star formation, feedback)
  - Absent from the Borg Cube; recently implemented in HACC
    CRK-HACC, Frontiere+23
  - Same analysis to be repeated on newer complete hydro sims
  - Observational data to be used for further validation

Backup

Baryon pasting model

- Model based on Ostriker+05 (see D. Nagai's talk)
- Input data: for one halo, $(M_{\rm vir}, R_{\rm vir})$ + particles
  - Assume polytropic equation of state:
  - $\rho_{\rm g} = \rho_{\rm g,0}\, \theta(\phi)^{\Gamma/(\Gamma-1)}\,;\;\; P_{\rm g} = P_{\rm g,0}\, \theta(\phi)^{1/(\Gamma-1)}$
  - $\theta(\phi)$: fixed from GO grav. potential
  - Γ : gas polytropic index (fixed model parameter)
  - $(\rho_{\rm g,0}, P_{\rm g,0})$: central gas density/pressure, **TBD**



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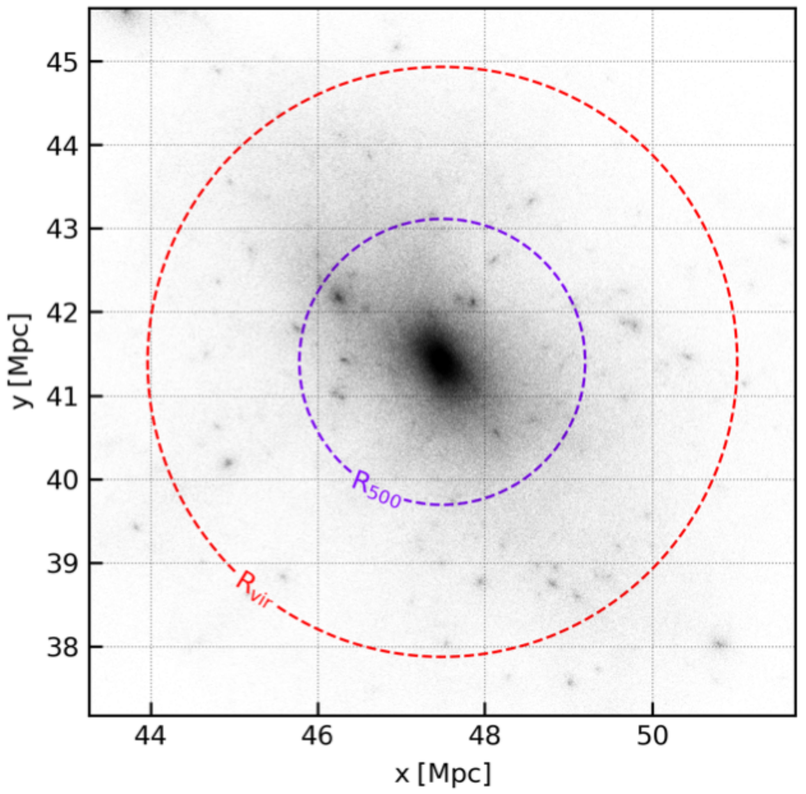

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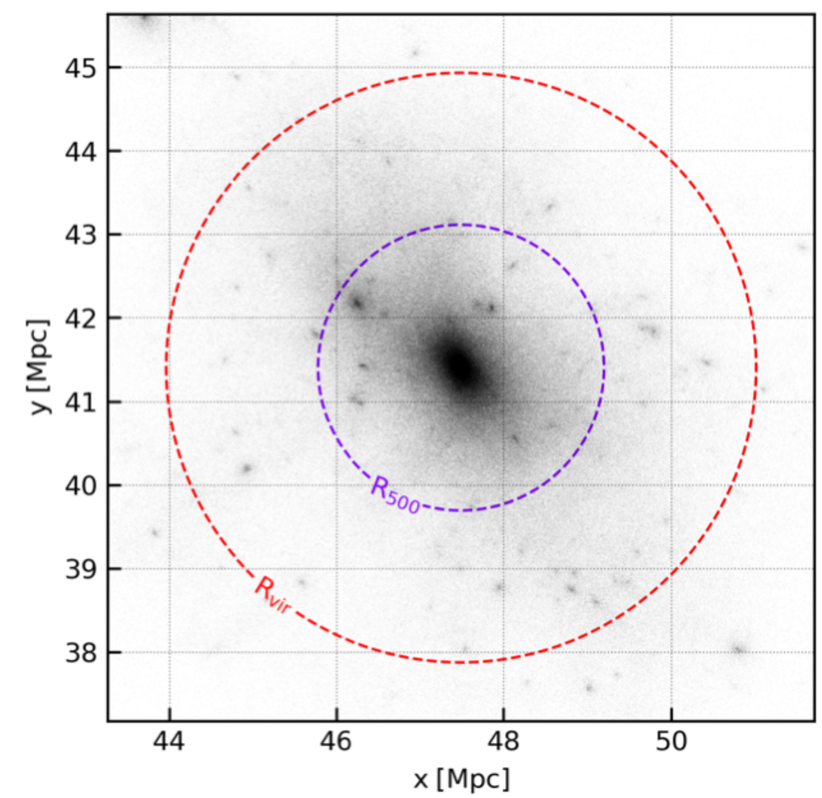
- Finding $(\rho_{\rm g,0}, P_{\rm g,0})$:
  - Assume gas rearrangement



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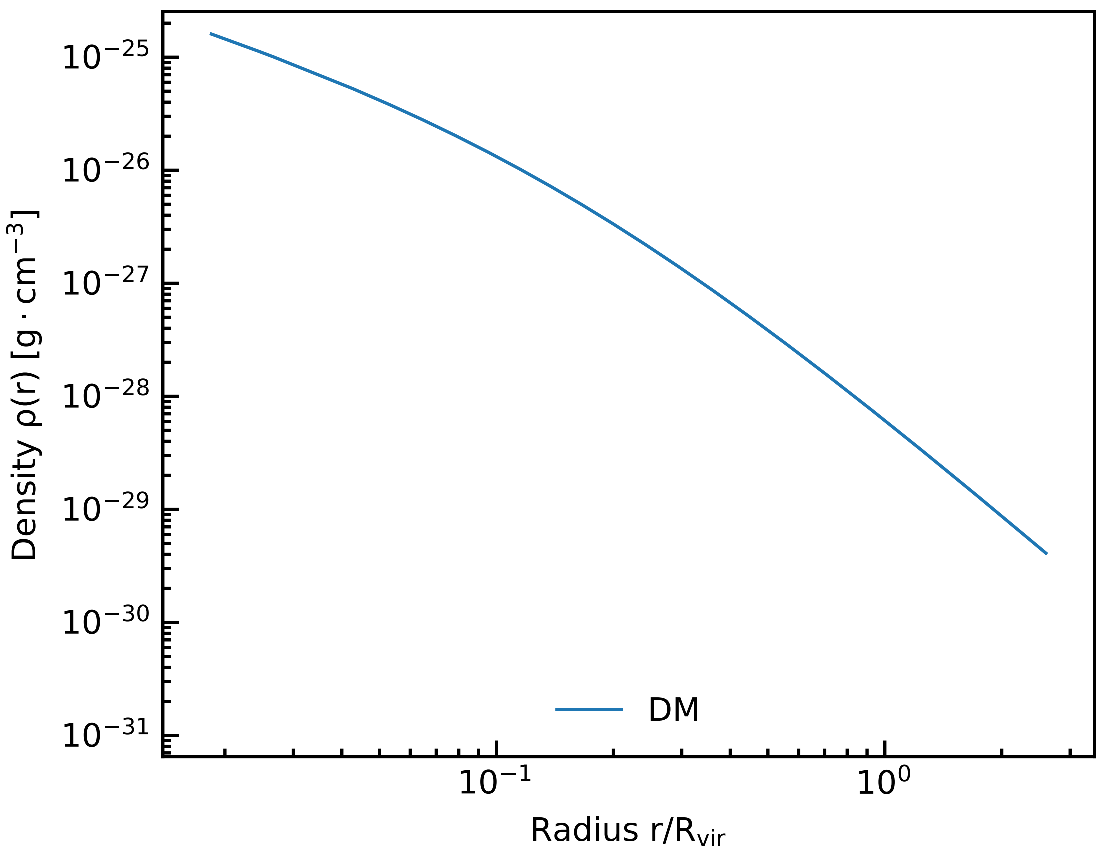

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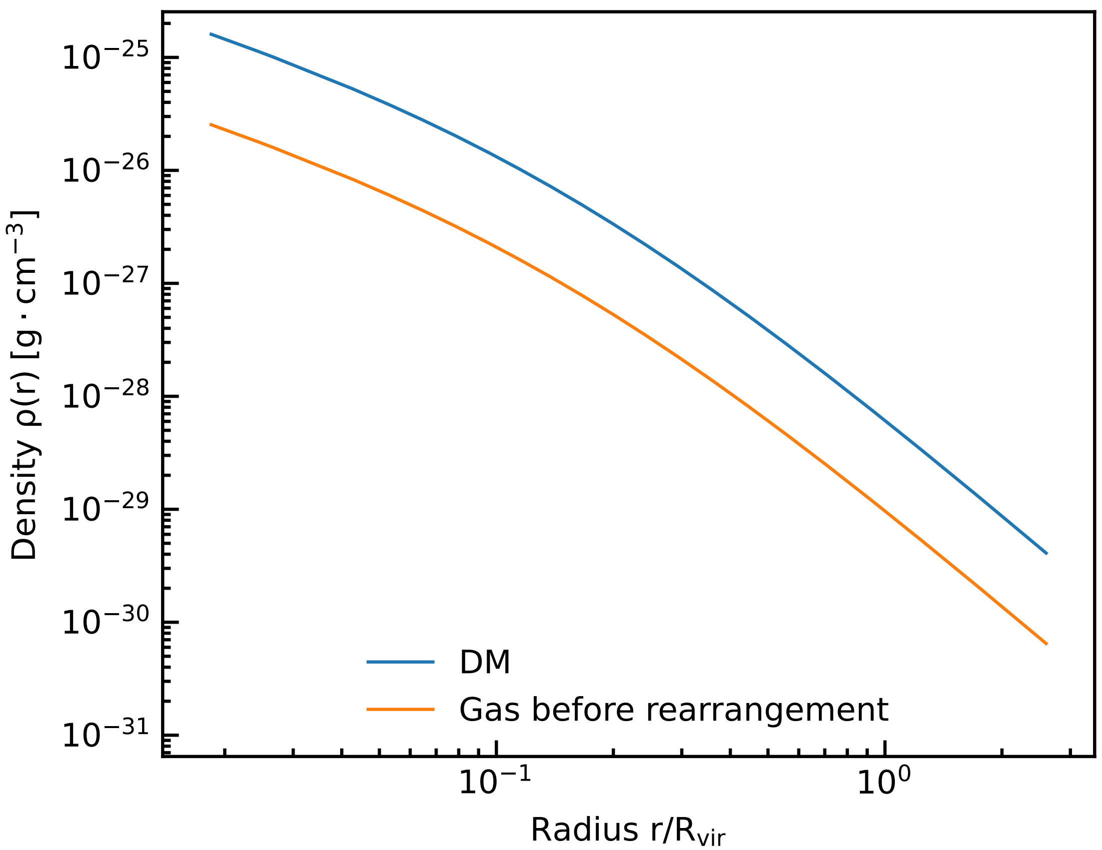

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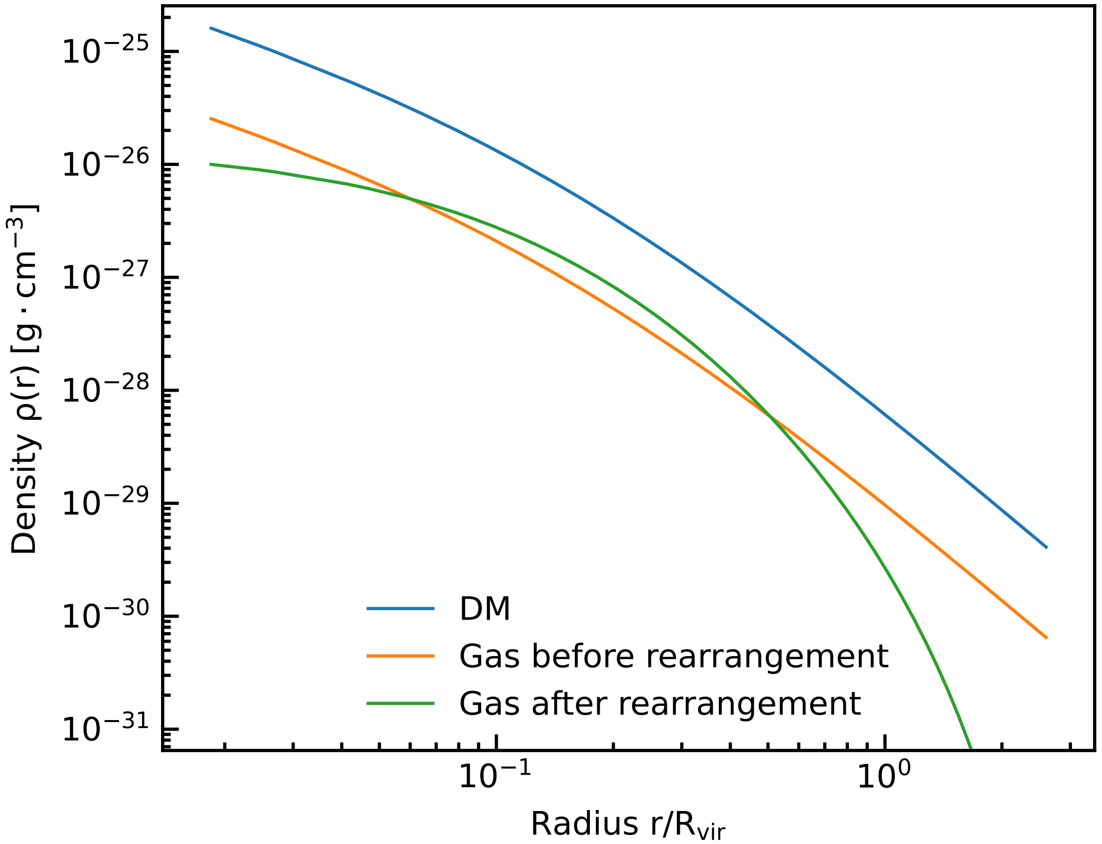

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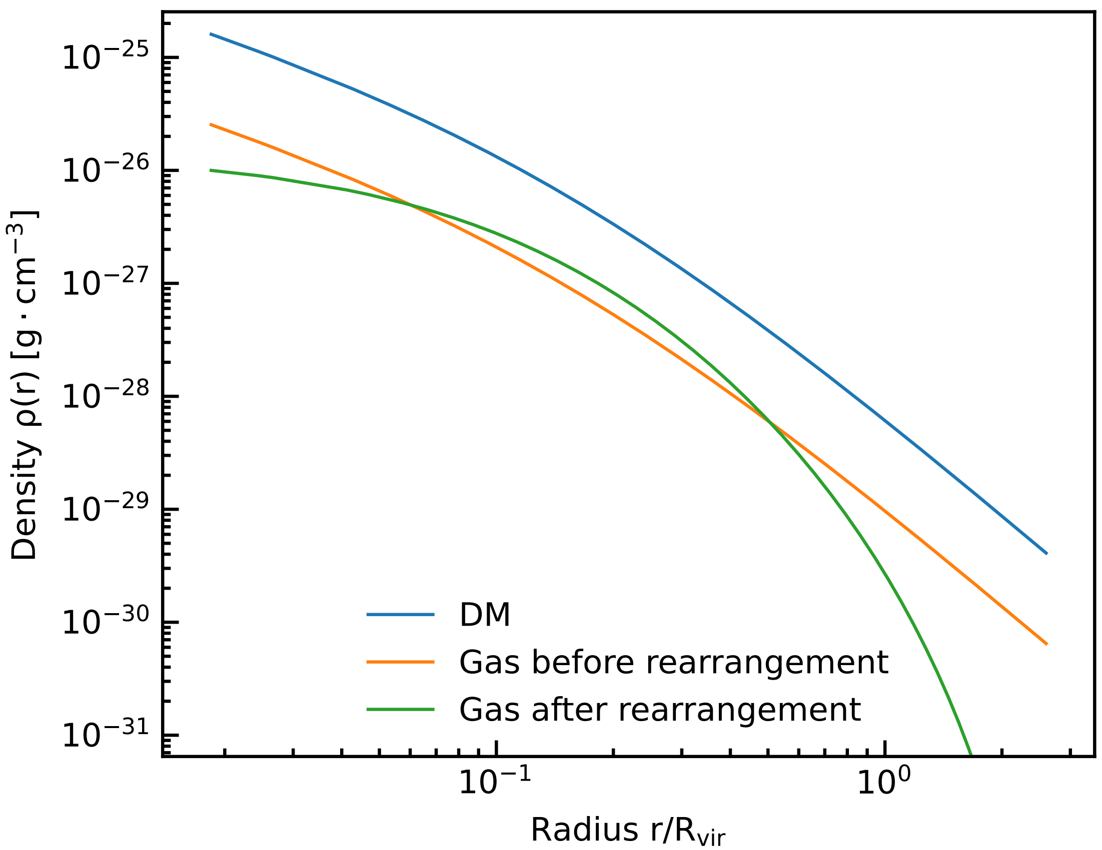
  - Conserving surface pressure / gas energy
  - A fraction $\varepsilon_{\rm DM}$ of CDM energy is transferred to gas (fixed model parameter)



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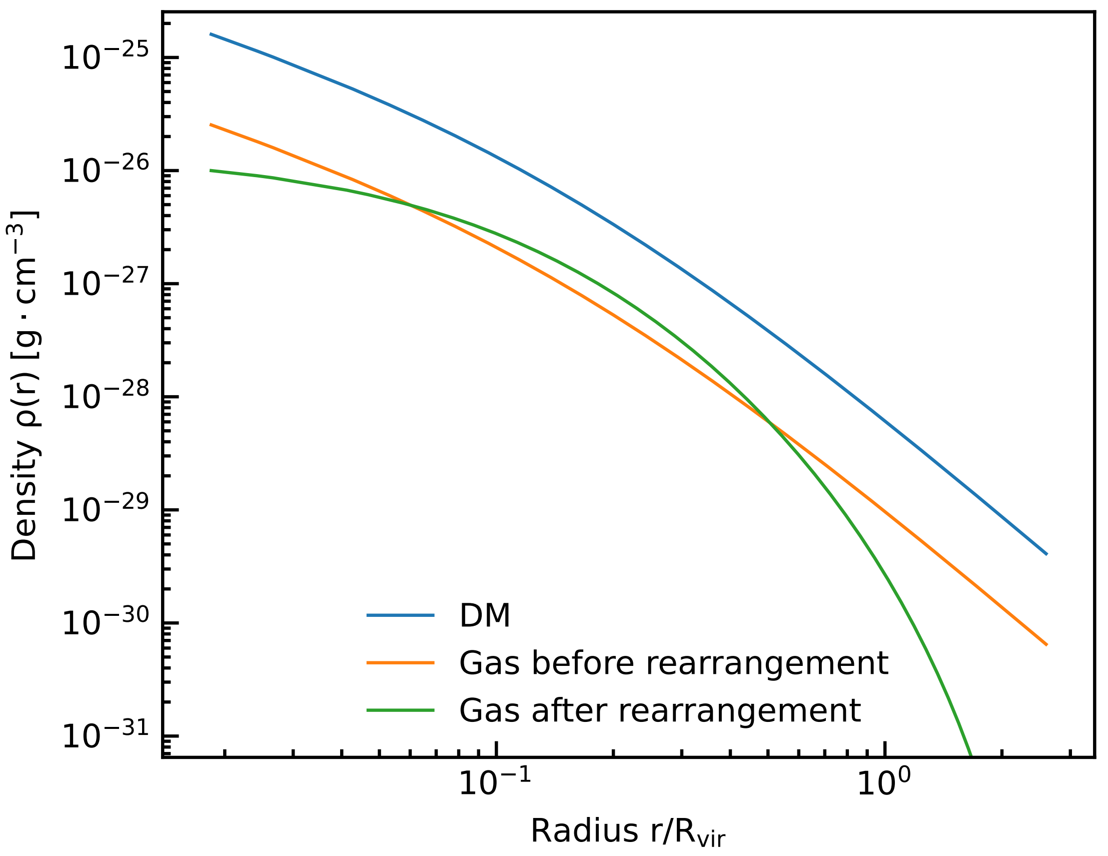

→ **For one halo, gas props fixed by GO particles + 2 model parameters:** $(\Gamma,\, \varepsilon_{\rm DM})$

Scatter in gas properties = scatter in mass?

- Part of the scatter on (ρ, P) is scatter on M_{500c} :
  - Cluster more (less) massive in hydro
    → Has more (less) gas in hydro
  - $M_{500c}^{\rm NR} \,|\, M_{500c}^{\rm GO}$ has scatter → induced scatter in (ρ, P)