Constraining baryonic feedback with kinetic Sunyaev-Zeldovich

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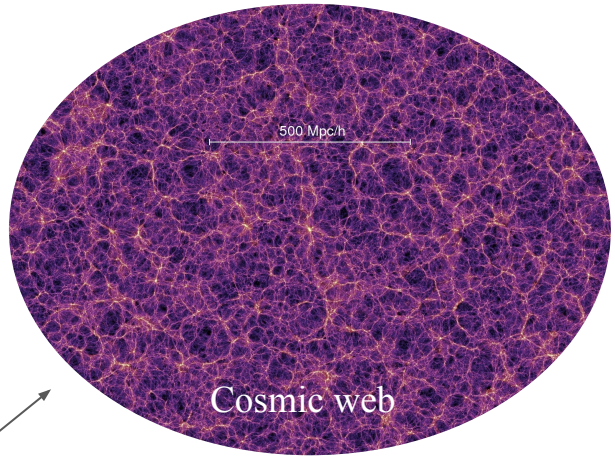
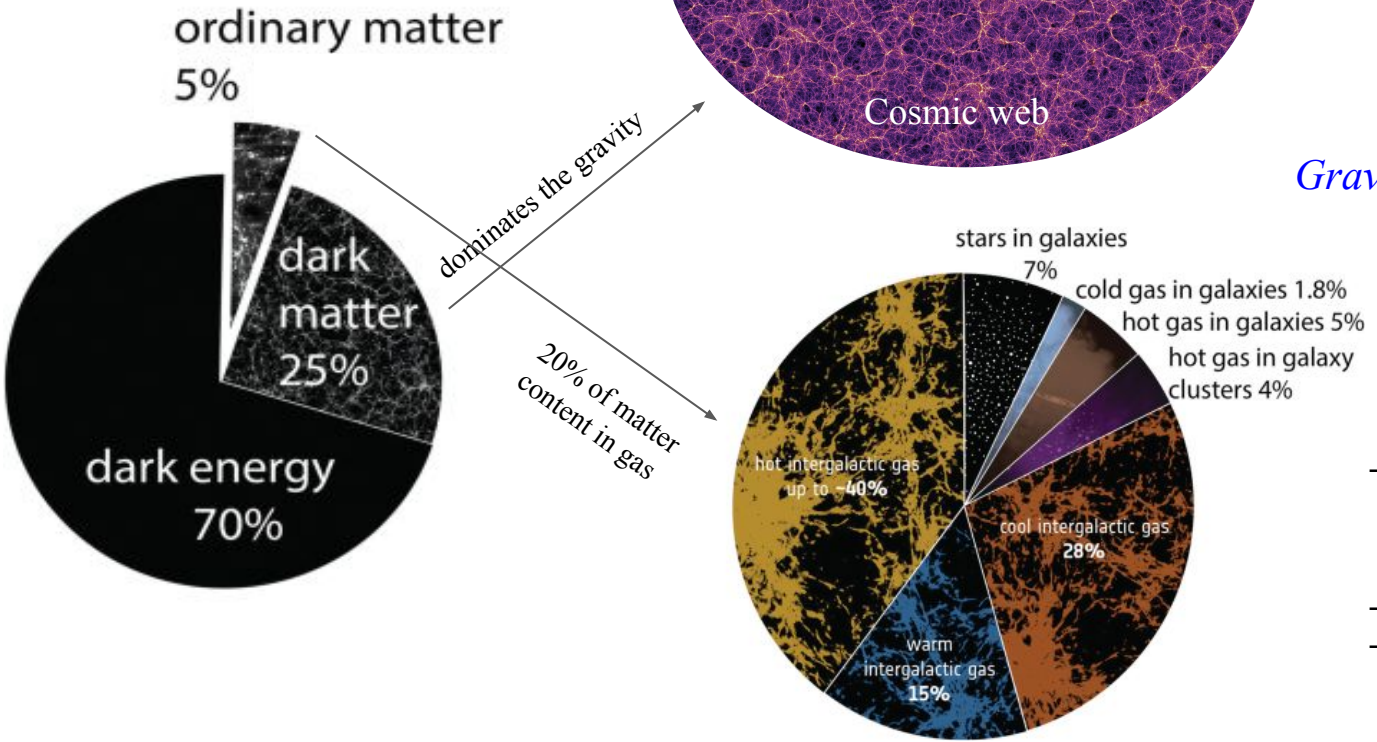
Introduction

Gas for cosmology



- Impact total matter field (weak lensing)
- Gas *is* a cosmological observable



DM ↔ Gas

Gravity ↔ Galaxy formation

- DM colissionless cold fluid
  N-body simulations

- Gas is colissional
- Galaxy formation
  Hydrodynamical simulations

Modeling gas for cosmology

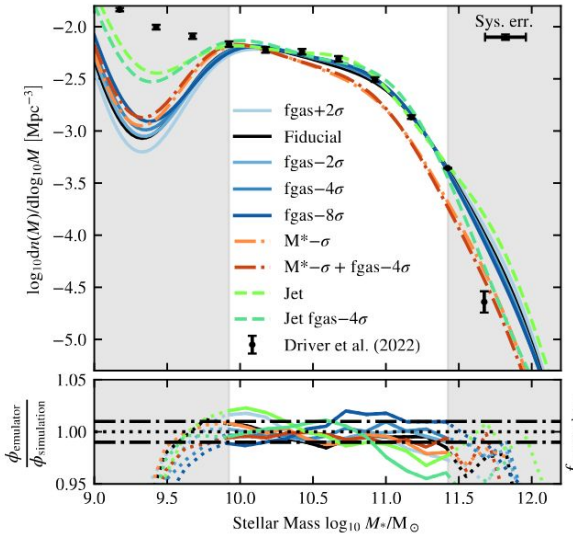
FLAMINGO simulations

- Galaxy formation can not be solved from first principles
- Subgrid prescriptions calibrated to low redshift observables

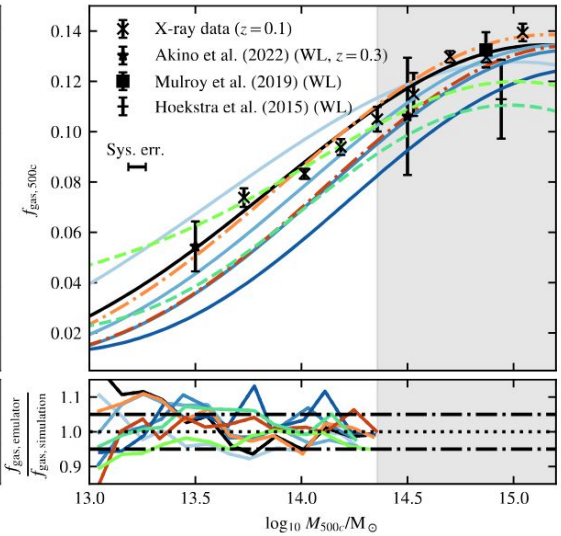
FLAMINGO *Schaye et al. 2023*

- Variations of subgrid parameters to reproduce deviations from the observed relations
- Cosmological boxes (L=1000Mpc)

stellar mass function



gas fractions in clusters

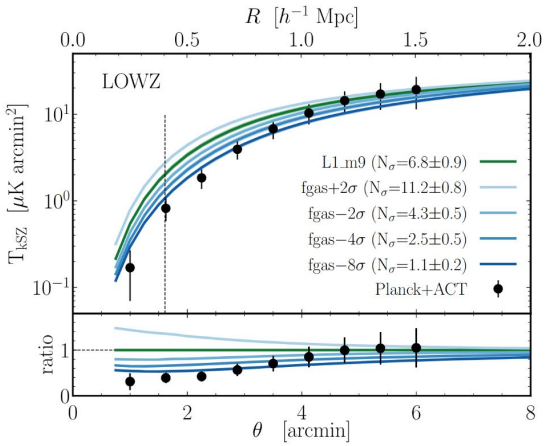


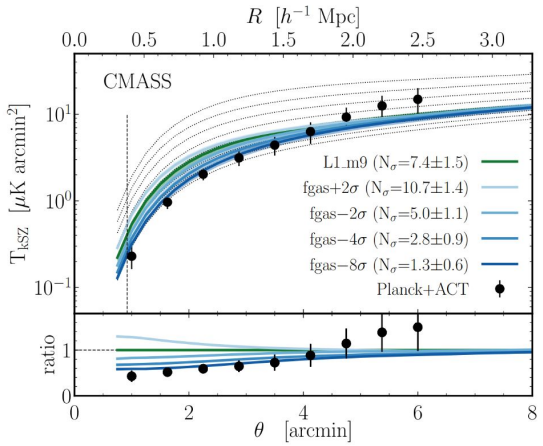
Kugel et al. 2023

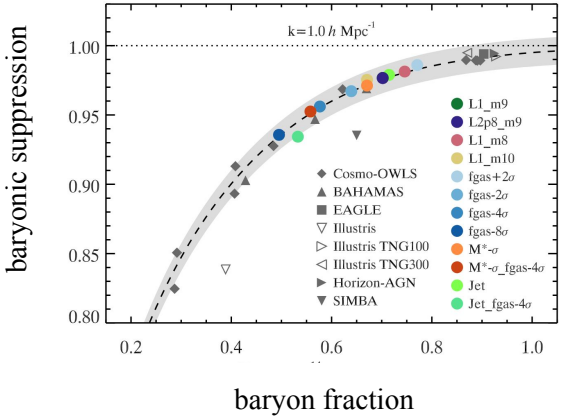
kinetic Sunyaev-Zeldovich effect

FLAMINGO simulations

kSZ seems to suggest stronger feedback than X-rays. What is going on ??







McCarthy et al. 2024

see also *Hadzhiyska et al. 2024*
Bigwood et al. 2024

Schaye et al. 2023

Constraining baryonic feedback with kinetic Sunyaev-Zeldovich

Outline

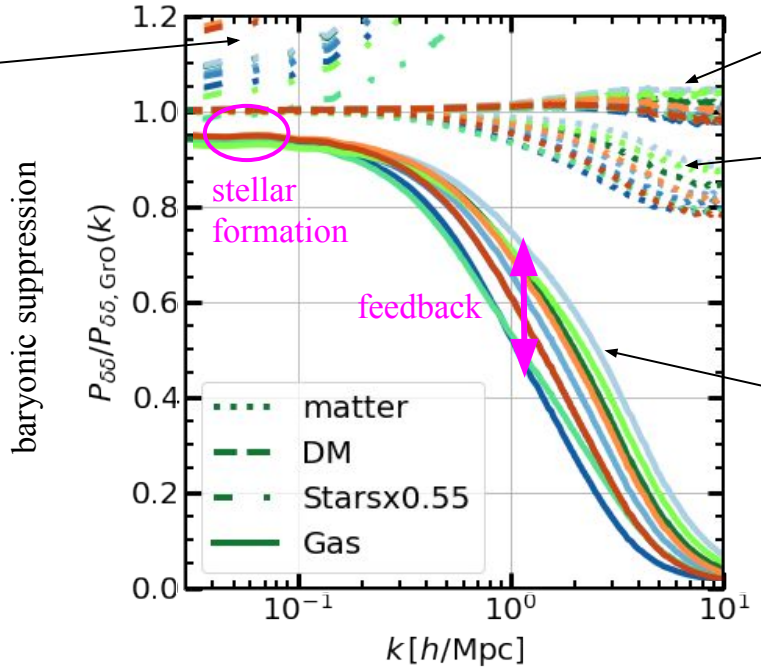
- Take insights from hydrodynamical simulations on how astrophysical processes shape the gas field
- Model stacked-kSZ signal (inspired but not relying on hydrodynamic simulations)
- Bayesian analysis of stacked-kSZ data

Ondaro-Mallea et al. (in prep 2024 a,b)

Density and velocity fields of cosmic gas

Statistics : power spectrum

stars very clustered in small scales & biased high in large scales



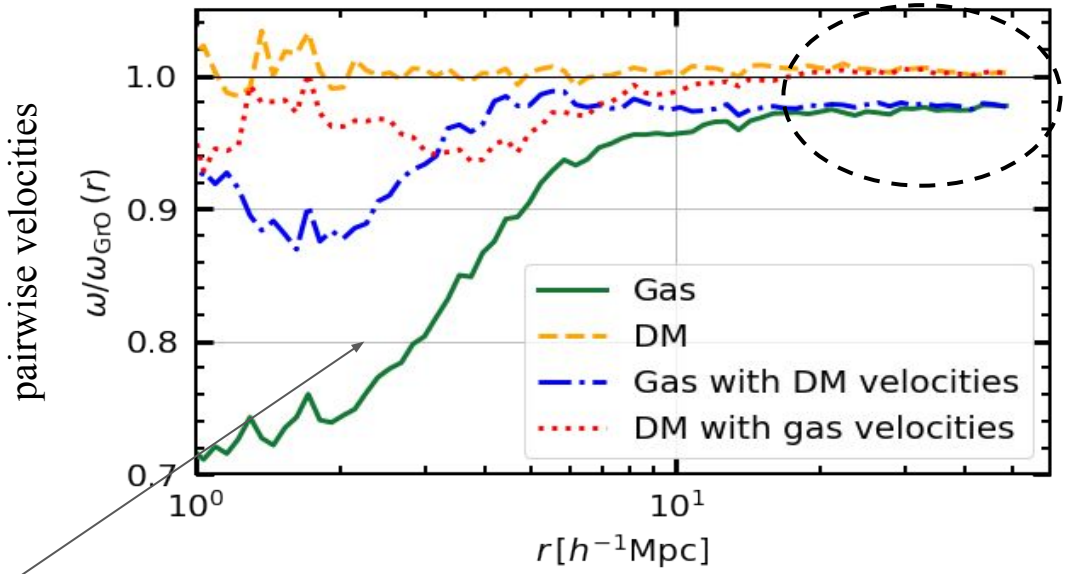
dark matter backreaction

matter clustering suppressed in small scales

gas clustering suppressed in small scales & biased low in large scales

Density and velocity fields of cosmic gas

Statistics : pairwise velocities. Large scale gas bias



at r>10Mpc/h, gas moves slower than dark matter?

see also *Kuruvilla et al. 2020*

gas pairwise velocities suppressed in small scales

biased assuming gas moves as dark matter does

***not* biased** assuming dark moves as gas does

pairwise velocities are a mass-weighted quantity!!

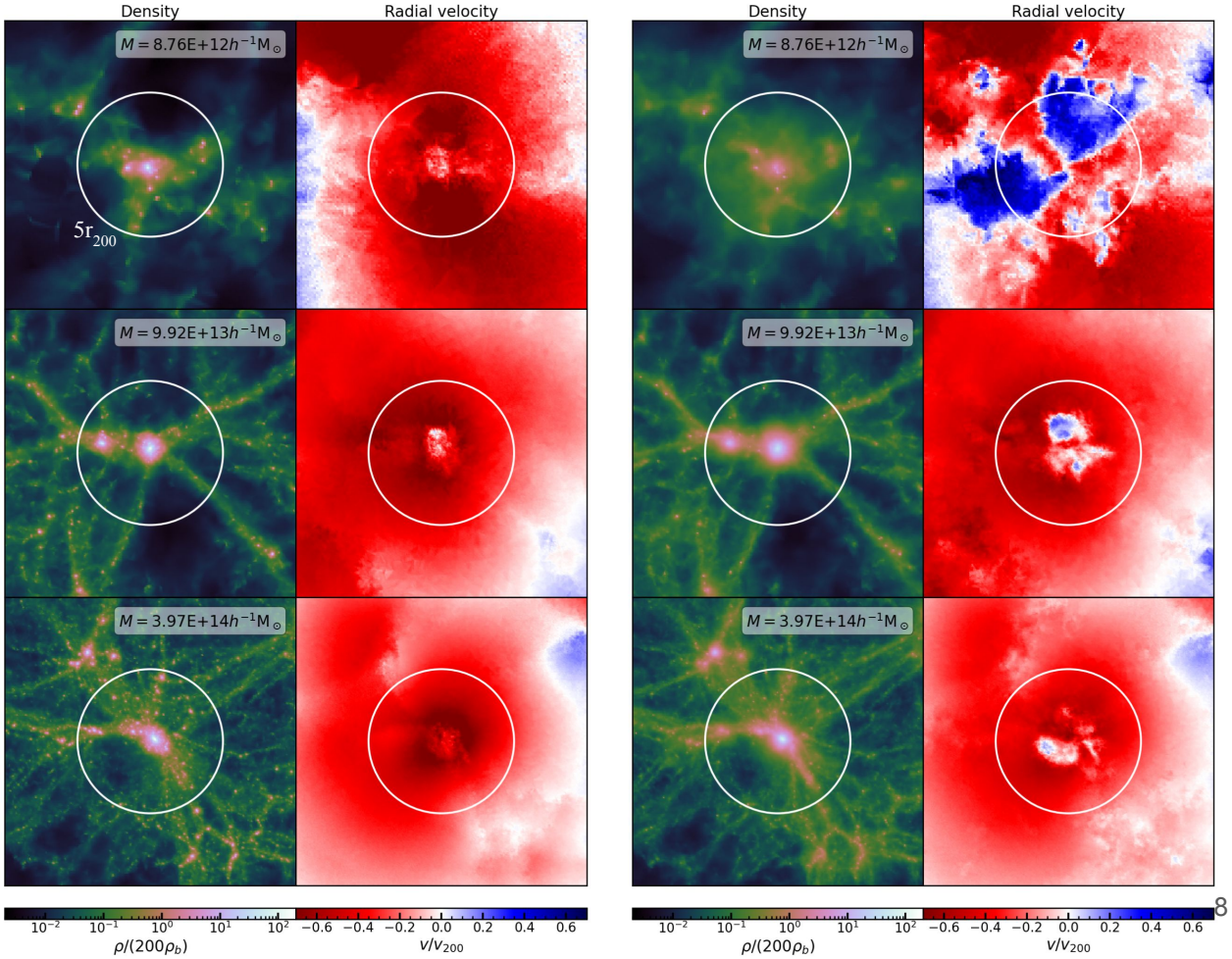
Density and velocity fields of cosmic gas

Gas vs dark matter

- Dark matter:
  - Collisionless
  - Self-similar growth of structure
- Gas:
  - Collisional
  - Feedback (halo mass dependent way)

Feedback impacts group-scale halo outskirts (density+velocity)

[most relevant for weak lensing]

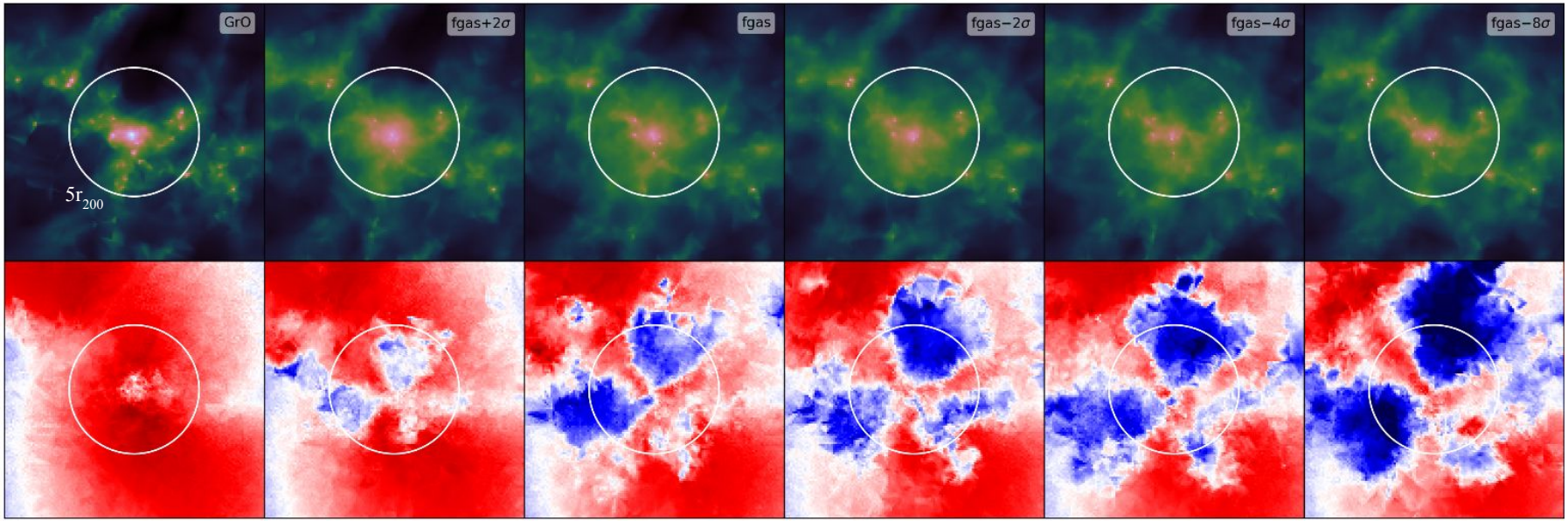


Density and velocity fields of cosmic gas

Gas at increasing feedback strength

Calibrated to X-ray gas fractions in clusters
Kugel et al. 2023

Preferred (and not strong enough) to match kSZ gas fractions in groups
McCarthy et al. 2024



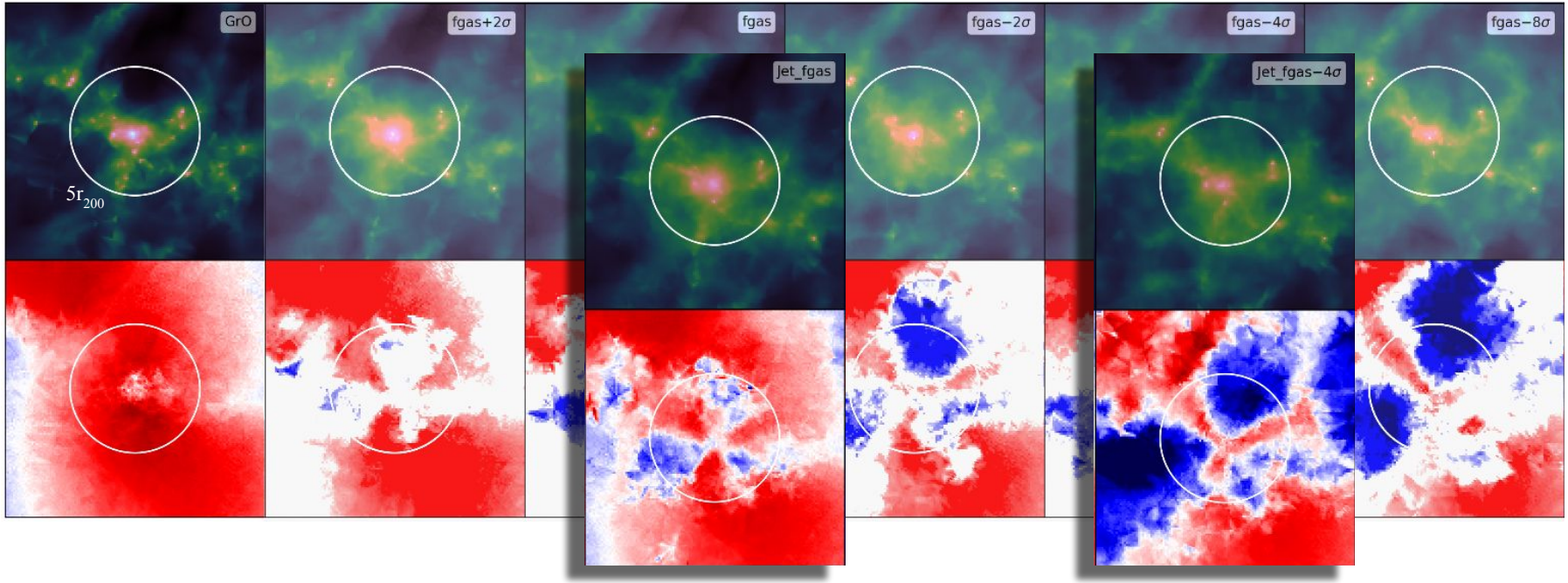
Density and velocity fields of cosmic gas

Gas at increasing feedback strength

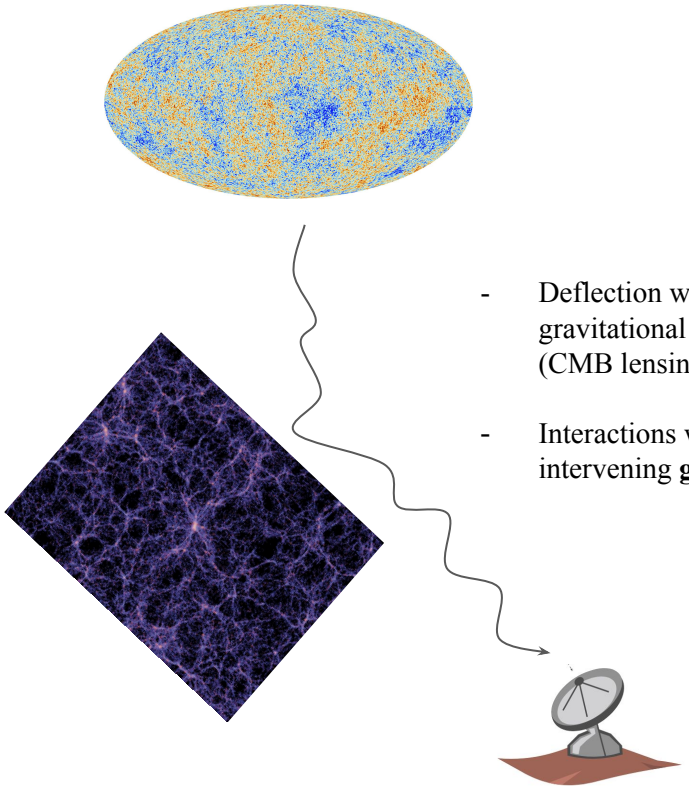
How strong is feedback in the universe?
Does the feedback implementation matter?

Calibrated to X-ray gas fractions in clusters
Kugel et al. 2023

Preferred (and not strong enough) to match kSZ gas fractions in groups
McCarthy et al. 2024



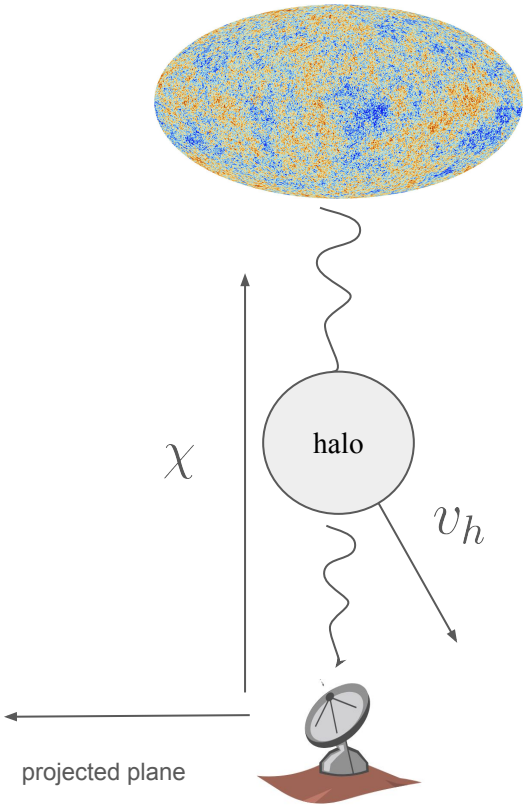
Gas at the halo outskirts:
kinetic Sunyaev-Zeldovich effect



- Deflection with gravitational potentials (CMB lensing, ISW)
- Interactions with the intervening **gas** (SZ)

Gas at the halo outskirts:

kinetic Sunyaev-Zeldovich effect



$$\mathcal{T}_{\rm kSZ}(r_p) \propto \int_{-\infty}^{\infty} \rho(\chi, r_p) v(\chi, r_p) d\chi,$$

$$\mathcal{T}_{\rm kSZ}(r_p) \propto \underbrace{\int_{-\infty}^{\infty} \rho(\chi, r_p) v_h d\chi}_{\mathcal{T}_{\rm bulk}} + \underbrace{\int_{-\infty}^{\infty} \rho(\chi, r_p) v'(\chi, r_p) d\chi}_{\mathcal{T}_{\rm corr}}.$$

assume that velocities correlation length is much longer than that of densities

Velocity-weighted stacked estimator

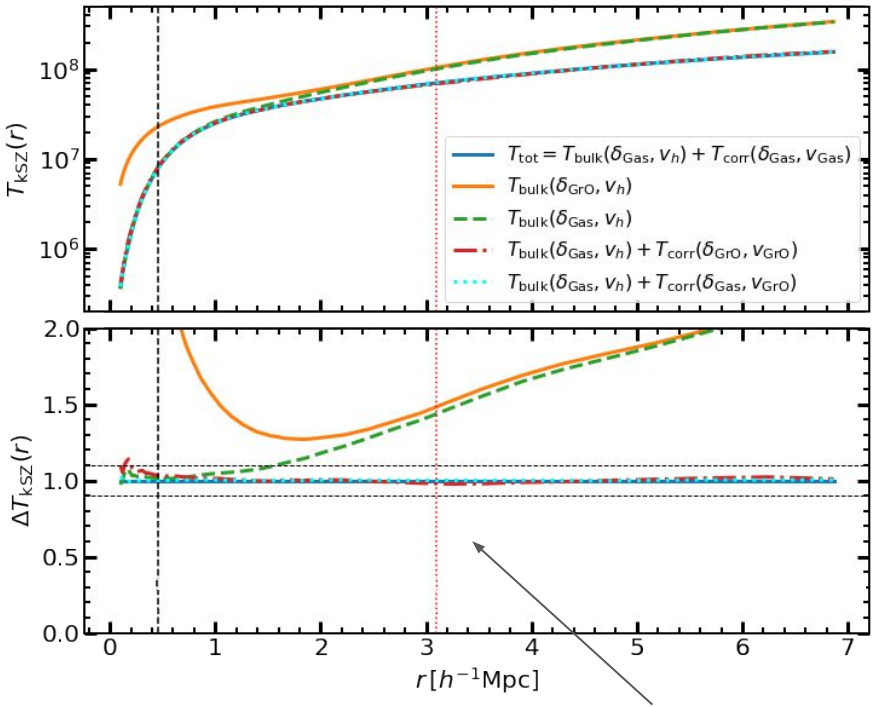
in observations, you need to reconstruct it from your galaxy catalogues

$$T_{\rm kSZ}(r_p) \propto \langle \mathcal{T}_{\rm kSZ}(r_h; r_p) v_h \rangle_h \propto T_{\rm bulk}(r_p) + T_{\rm corr}(r_p)$$

Measures ~ enclosed gas mass profile

Velocity-weighted stacked kSZ signal

What are the modeling requirements?



observations arrive here (Hadshyiska et al. 2024, Schaan et al. 2021)

Measures ~ enclosed gas mass profile

A model of stacked kSZ requires:

- Baryonic effects on the density field
- The decorrelation of velocities (given by gravity-only simulations)
- (*not*) baryonic effects on the velocity field

Baryonification
(on simulations)

Velocity-weighted stacked kSZ signal

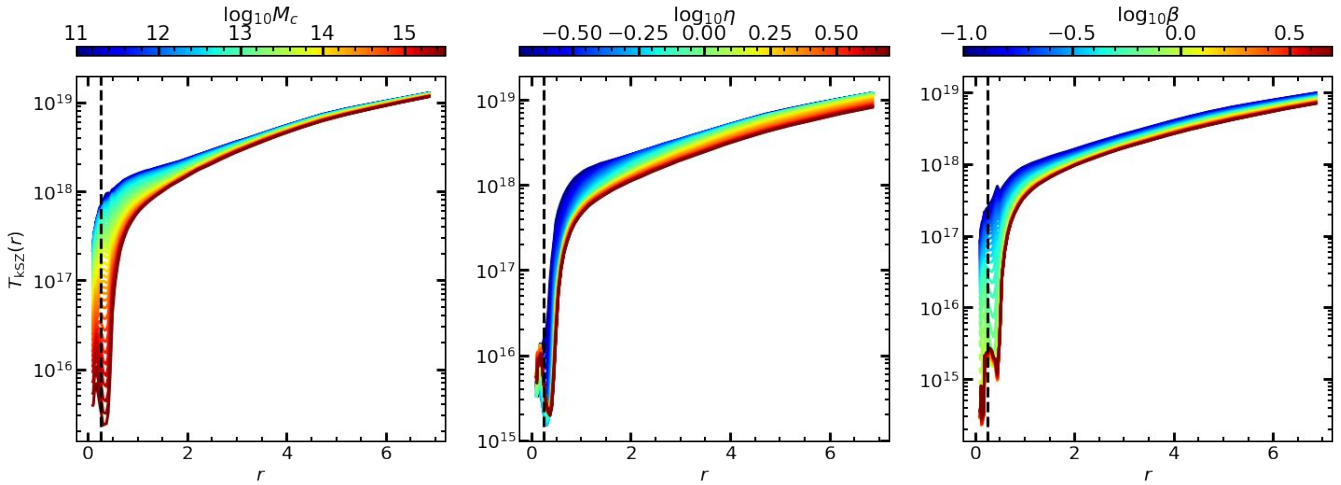
Baryon correction model for kSZ

BCM: Modify outputs of gravity-only simulations to mimic the effects of baryons.

- **Gas**, stars, dark matter
- Parametrize the profile of each component with some free parameters

Schneider&Teissyer 2015, Aricò et al. 2019

Apply it to your N-body simulation & build an emulator



how much gas is ejected

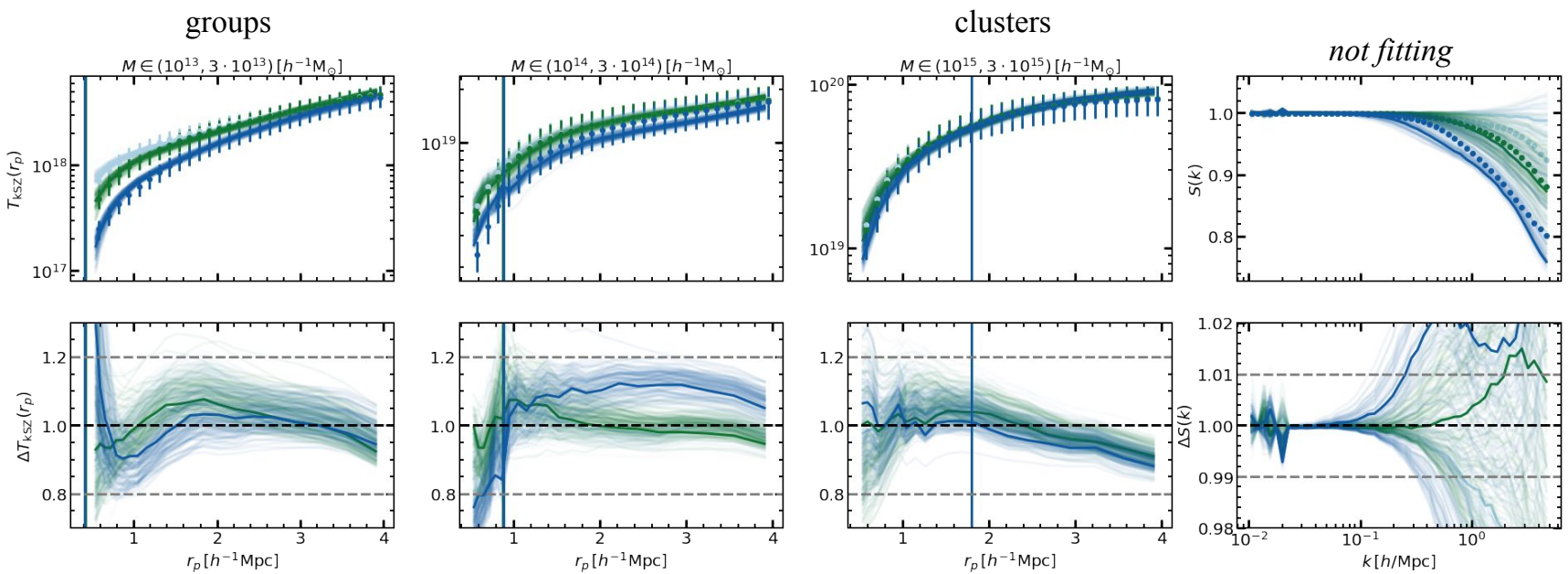
how far gas is ejected

how does it scale with halo mass

Velocity-weighted stacked kSZ signal

Baryon correction model for kSZ

Preliminary

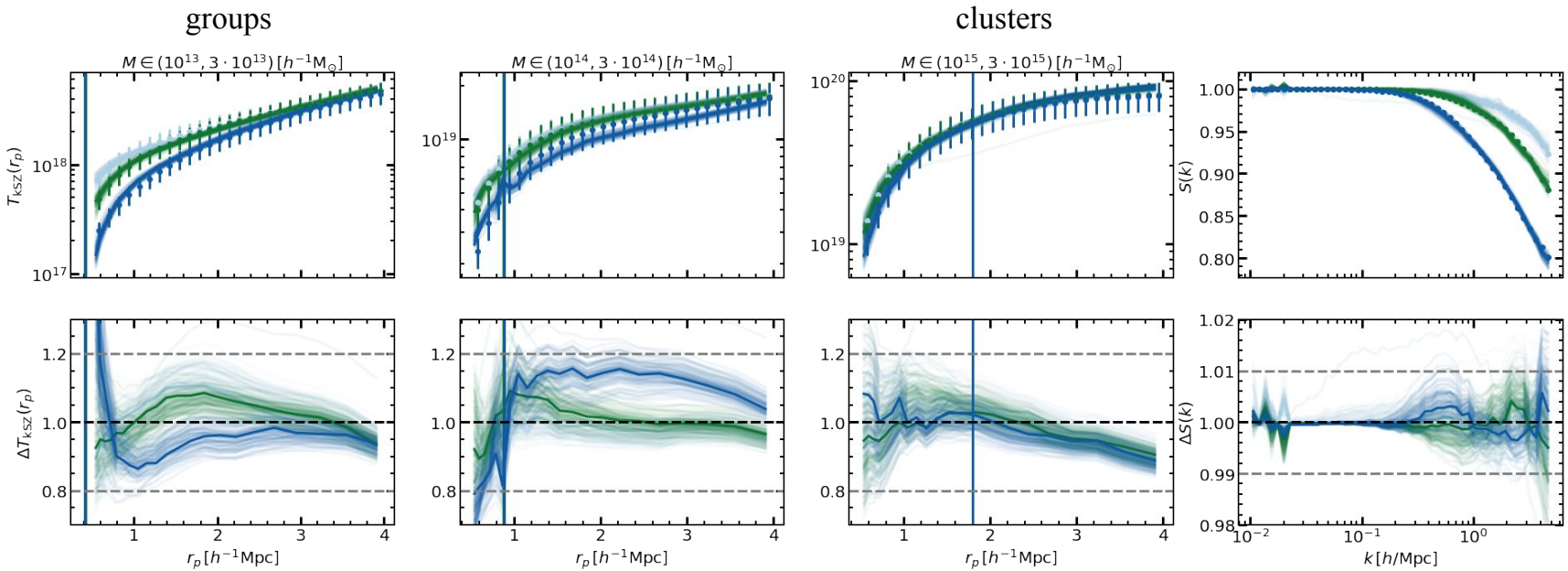


three mass bins kSZ at 20% simultaneously fitting in all flamingo

Velocity-weighted stacked kSZ signal

Baryon correction model for kSZ+ weak lensing

Preliminary

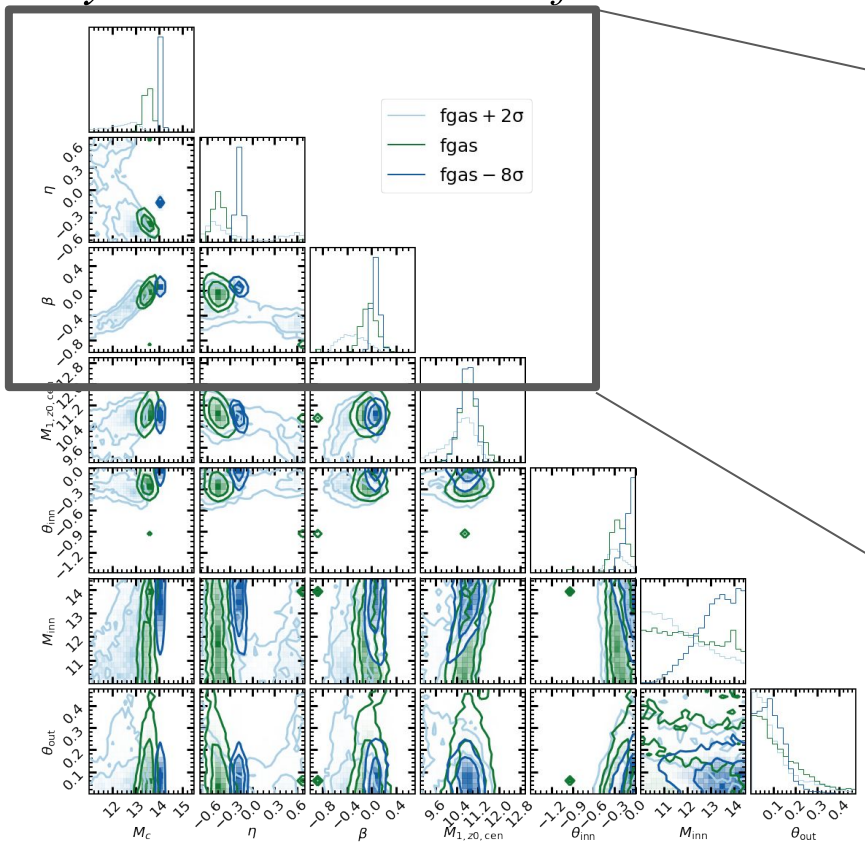


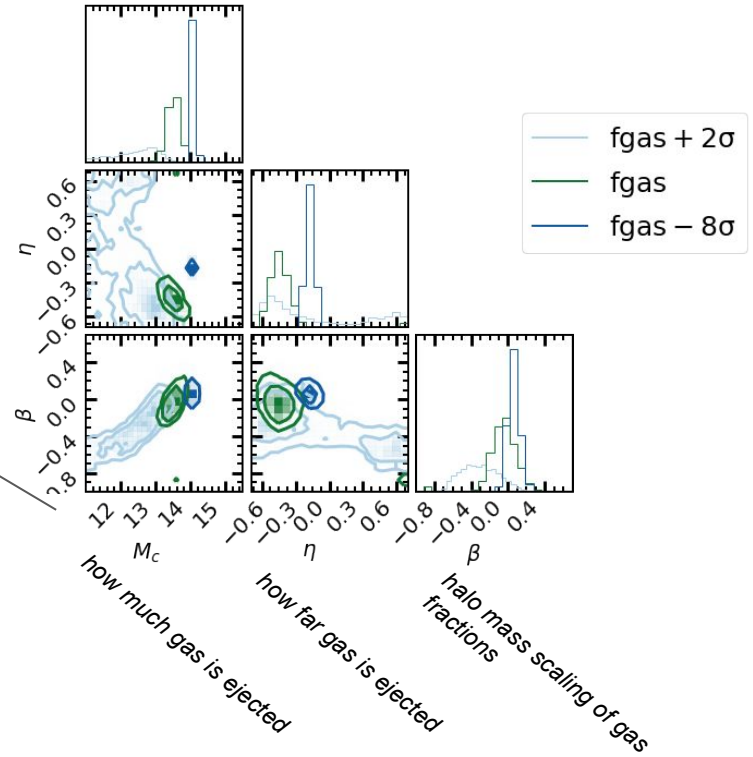
three mass bins kSZ at 20% + power spectrum suppression at 1% simultaneously fitting in all flamingo

Velocity-weighted stacked kSZ signal

Baryon correction model for kSZ+ weak lensing

Preliminary

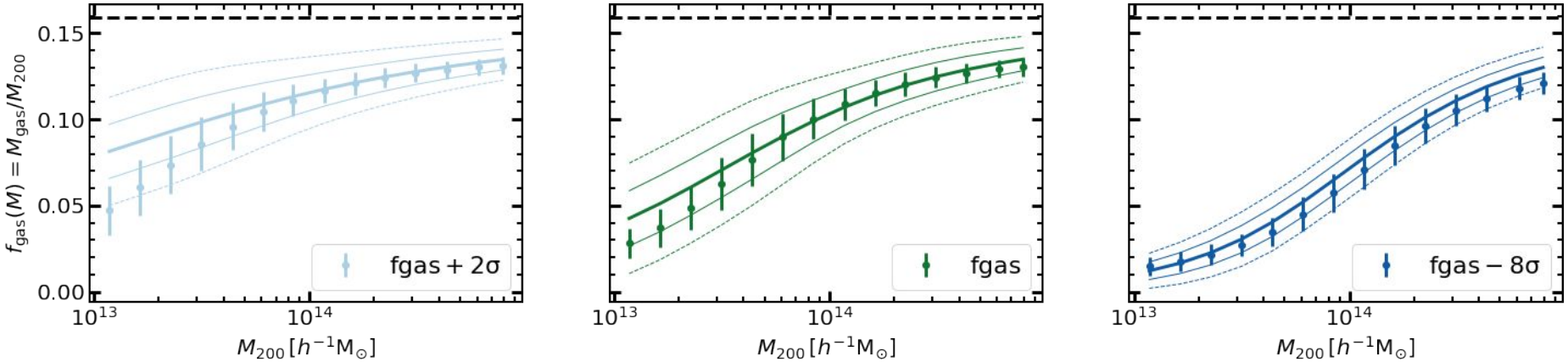




Velocity-weighted stacked kSZ signal

Predictions: gas fractions (kSZ only)

Preliminary

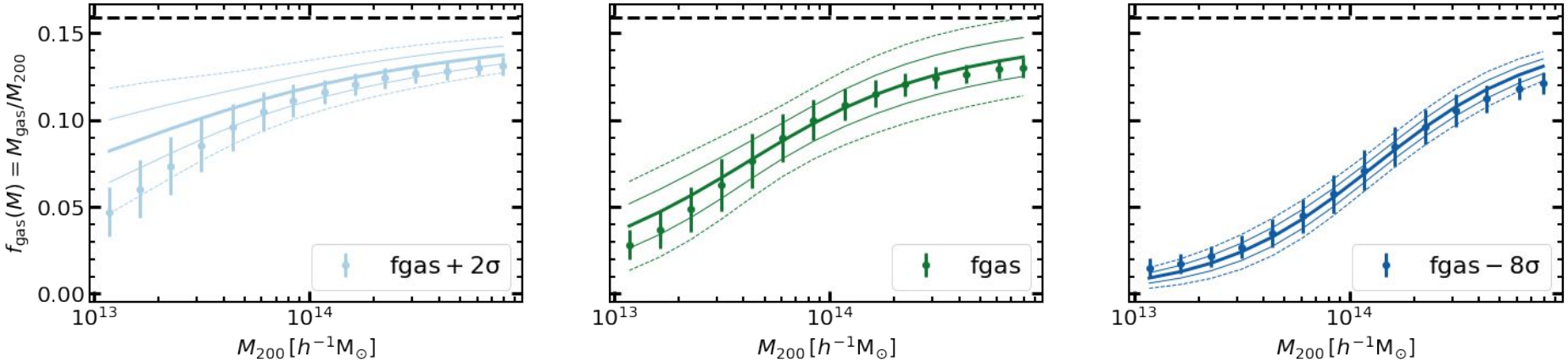


We recover the gas fractions as a function of mass of all flamingo simulations

Velocity-weighted stacked kSZ signal

Predictions: gas fractions (kSZ + weak lensing)

Preliminary



We recover the gas fractions as a function of mass of all flamingo simulations

Conclusions

- Gas – dark matter relation, need to model in a flexible and physically motivated way

- Insights from hydrodynamic simulations on the momentum field of gas:

  - Suppressed gas densities & velocities on small scales — *feedback*
  - Suppressed gas densities on large scales (there is no gas velocity bias) — *stellar formation*

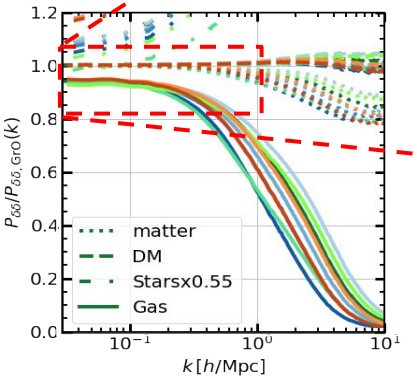
- Feedback is most effective at group scales and can be probed with (stacked) kSZ observations, at the same time informing feedback implementation in hydrodynamic simulations.

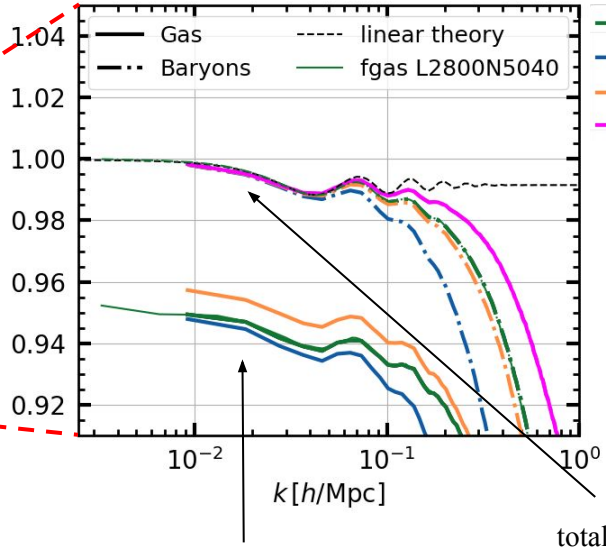
- We have a model that describes kSZ + WL simultaneously… stay tuned for data analysis!

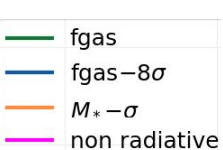
Backup slides

Density and velocity fields of cosmic gas

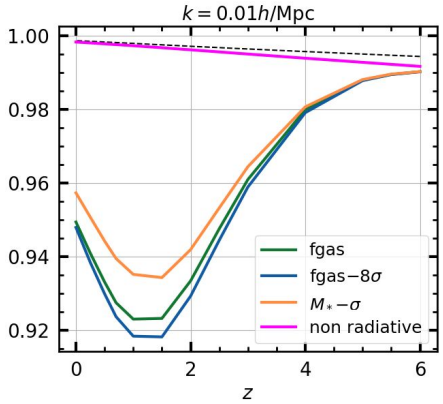
Statistics : power spectrum. Large scale gas bias







redshift evolution of gas bias



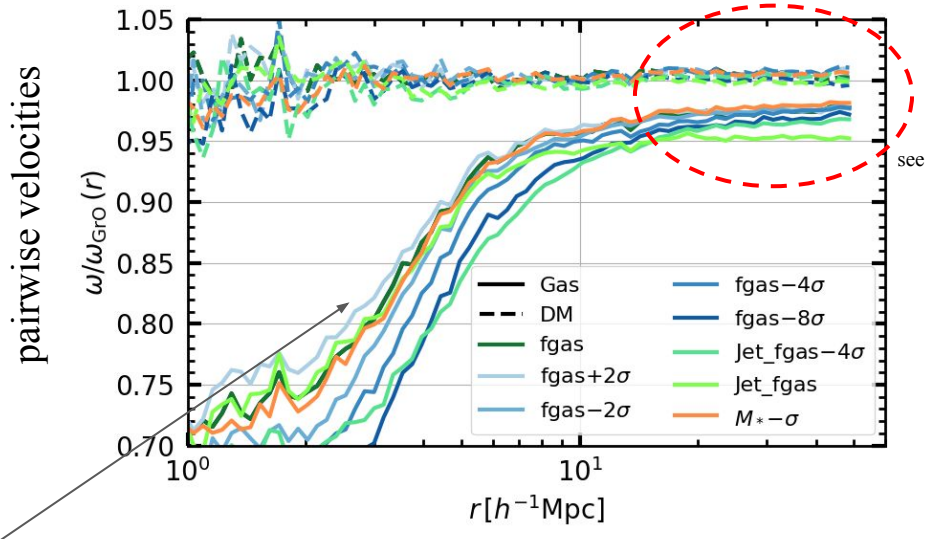
total baryon field is not biased

less stars, less bias

more feedback, same bias

Density and velocity fields of cosmic gas

Statistics : pairwise velocities



at r>10Mpc/h, gas moves slower than dark matter?

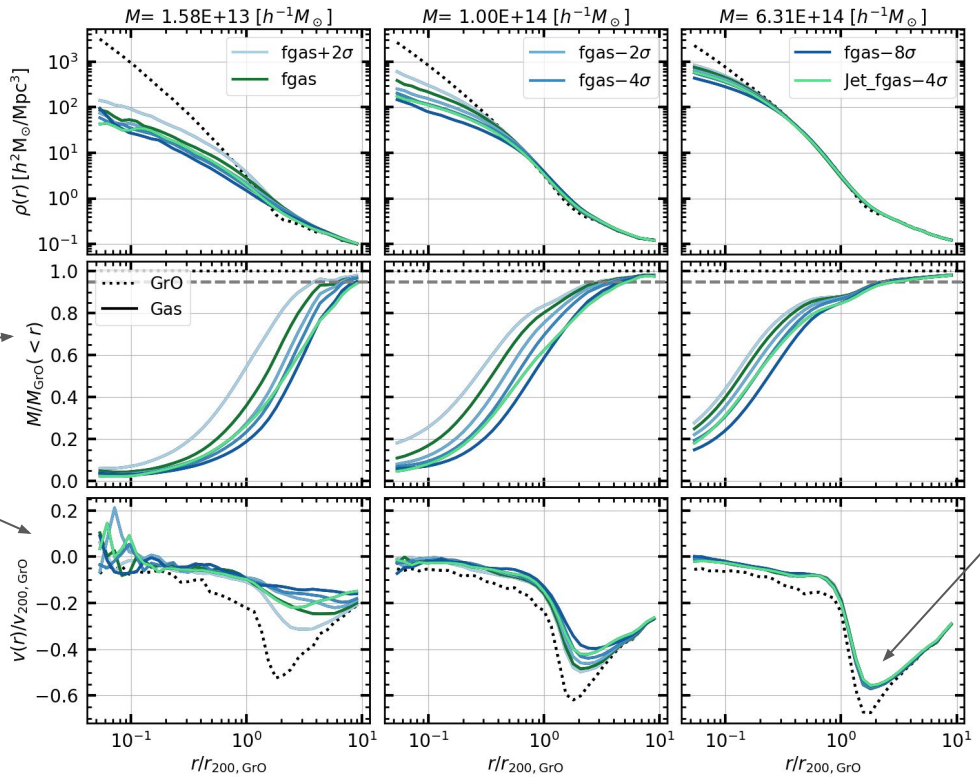
see also Kuruvilla et al. 2020

gas pairwise velocities suppressed in small scales

Density and velocity fields of cosmic gas

Halo profiles

halo mass

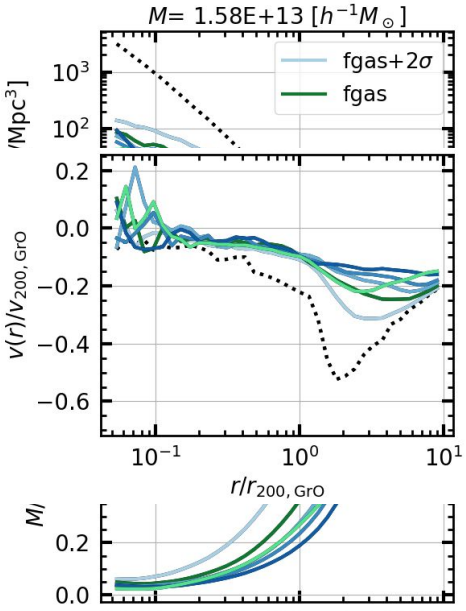


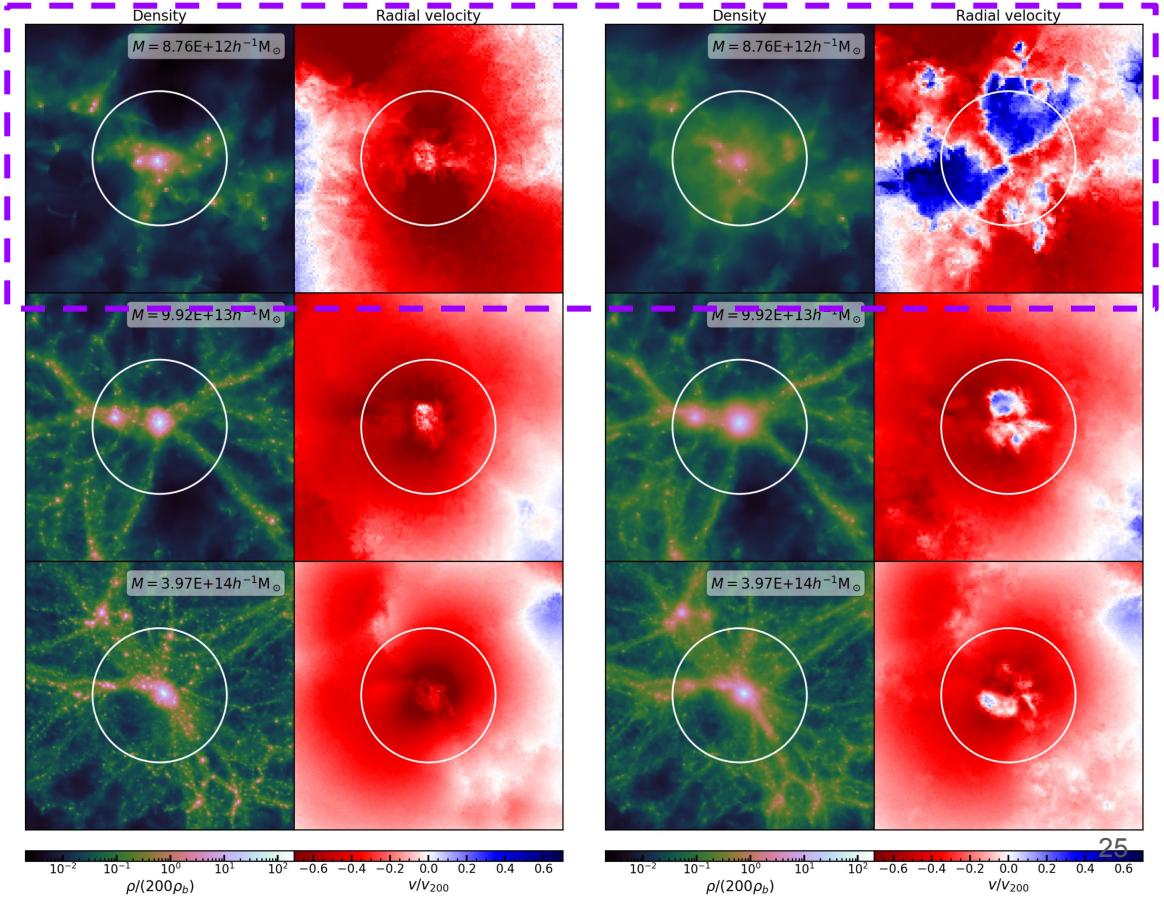
- Gas pushed out of the halo
- Radial velocity profiles depend on feedback
- Why??

- Gas within the halo
- Radial velocities no feedback dependence
- GrO vs gas velocities: Colissionless vs colissional

Density and velocity fields of cosmic gas

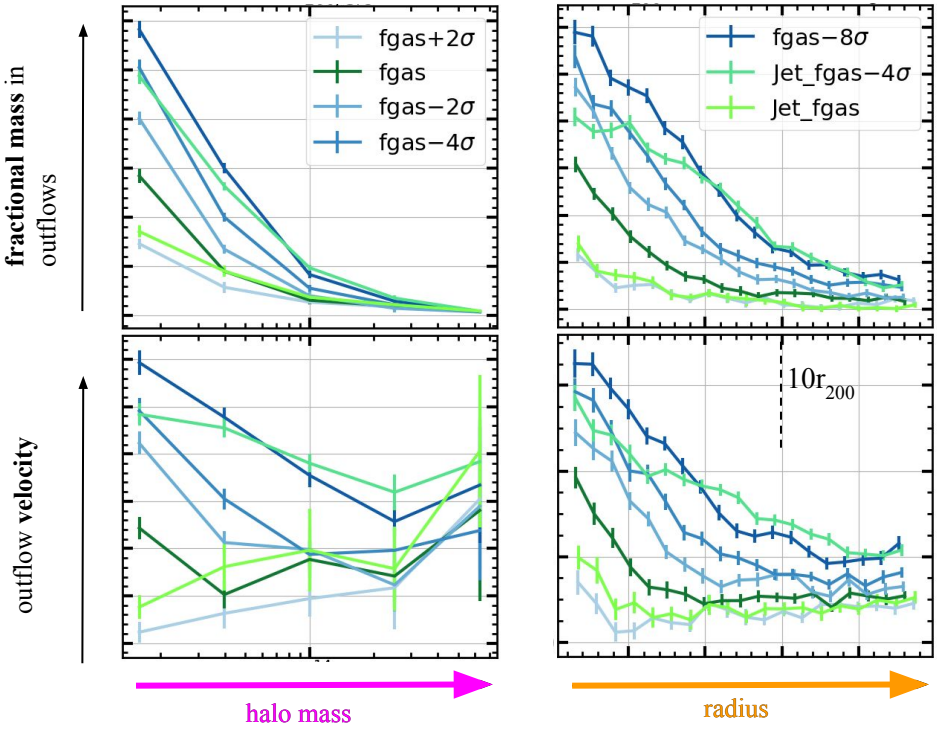
Halo profiles

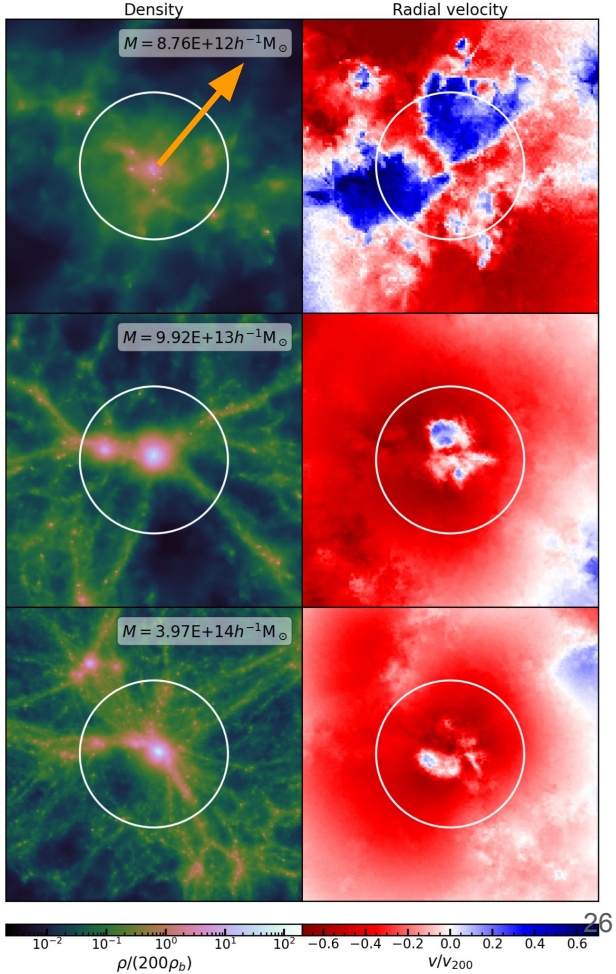




Density and velocity fields of cosmic gas

Outflows





Velocity-weighted stacked kSZ signal

Baryon correction model for kSZ