

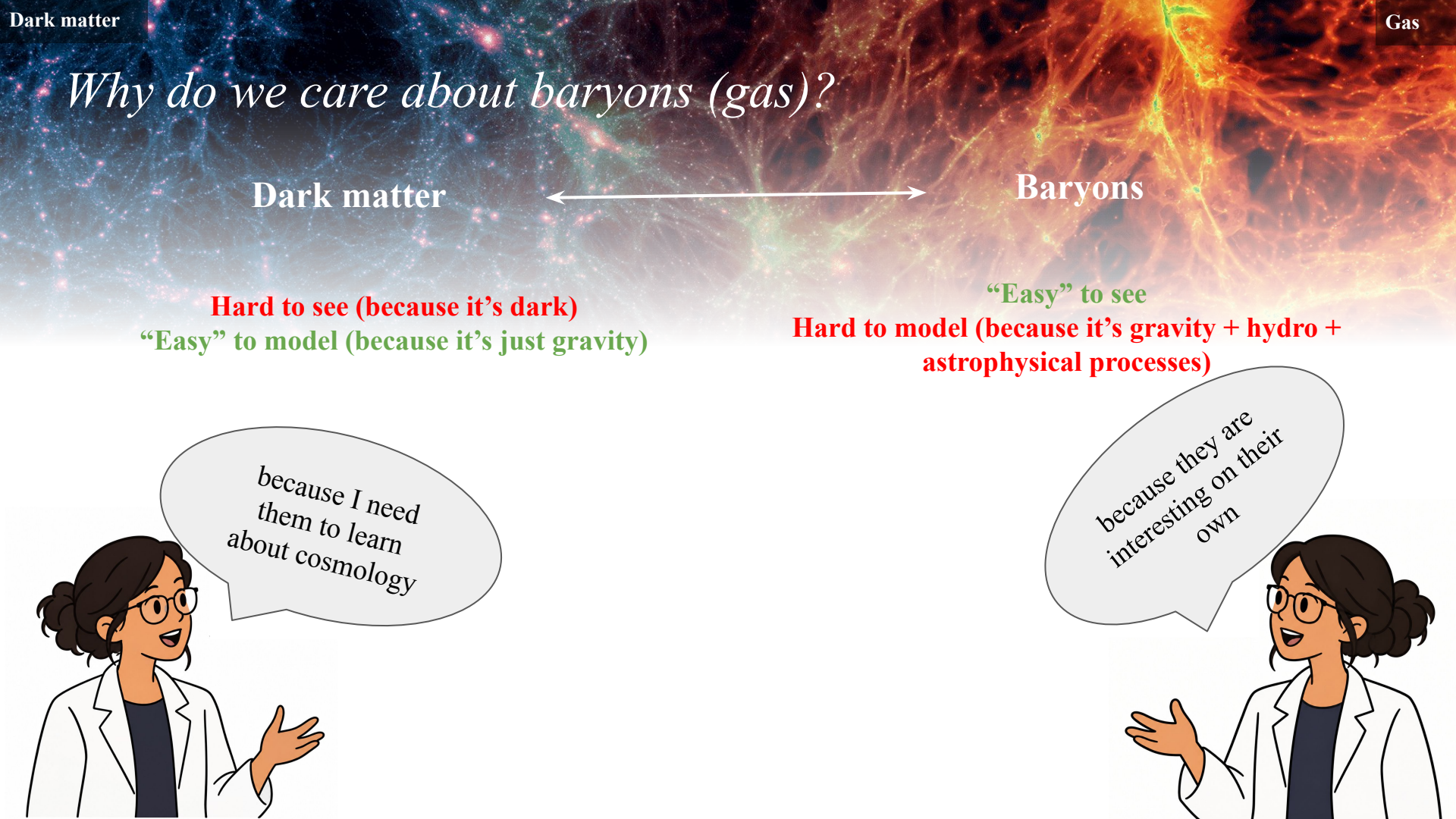
A visualization of the cosmic web, showing a complex network of filaments and clusters of galaxies. The filaments are colored in shades of blue, green, and yellow, while the clusters are more densely packed and appear in warmer colors like orange and red. The background is dark, emphasizing the glowing structures.

Probing baryonic feedback with kinetic SZ: *velocity reconstruction, non-linear velocities and satellite galaxies*

Lurdes Ondaro Mallea
Research Associate at
University of Cambridge

*based on **Ondaro-Mallea**+2025 (arxiv:2412.09526);
+2026a (arxiv:2607.23339);
+2026b (next few weeks in arxiv!)*

UC Berkeley, September 29th 2026



Why do we care about baryons (gas)?

Dark matter

Baryons

Hard to see (because it's dark)

“Easy” to model (because it's just gravity)

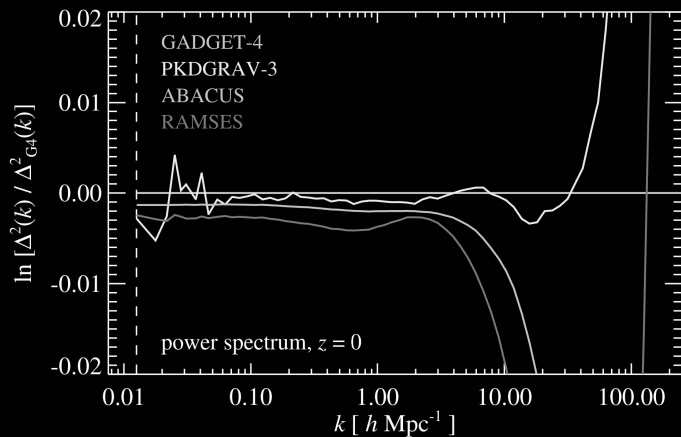
“Easy” to see

Hard to model (because it's gravity + hydro + astrophysical processes)



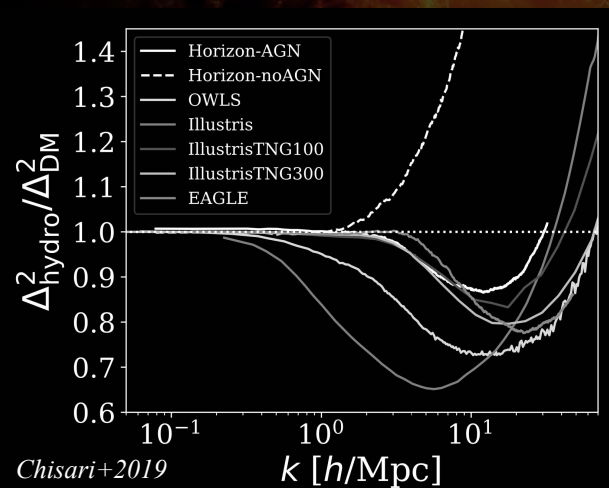
Weak lensing: “seeing” dark matter & baryons

Gravity-only: 1% accuracy at $k=10\text{Mpc}/h$



$$\propto P_m(k)$$

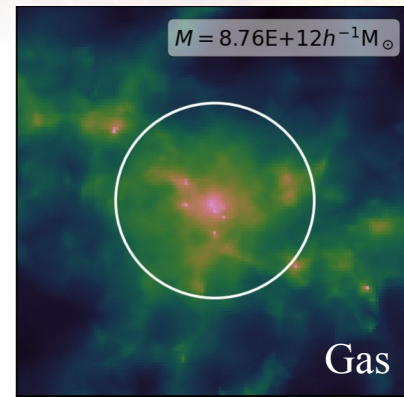
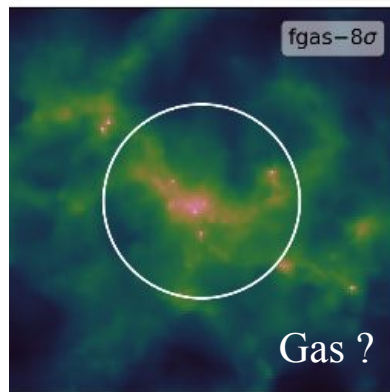
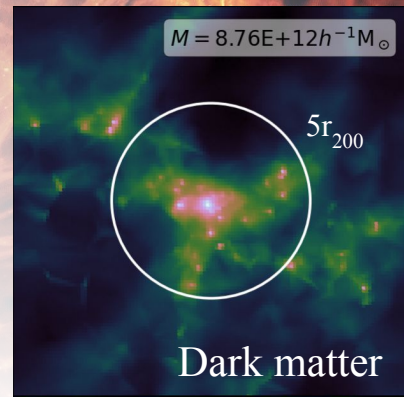
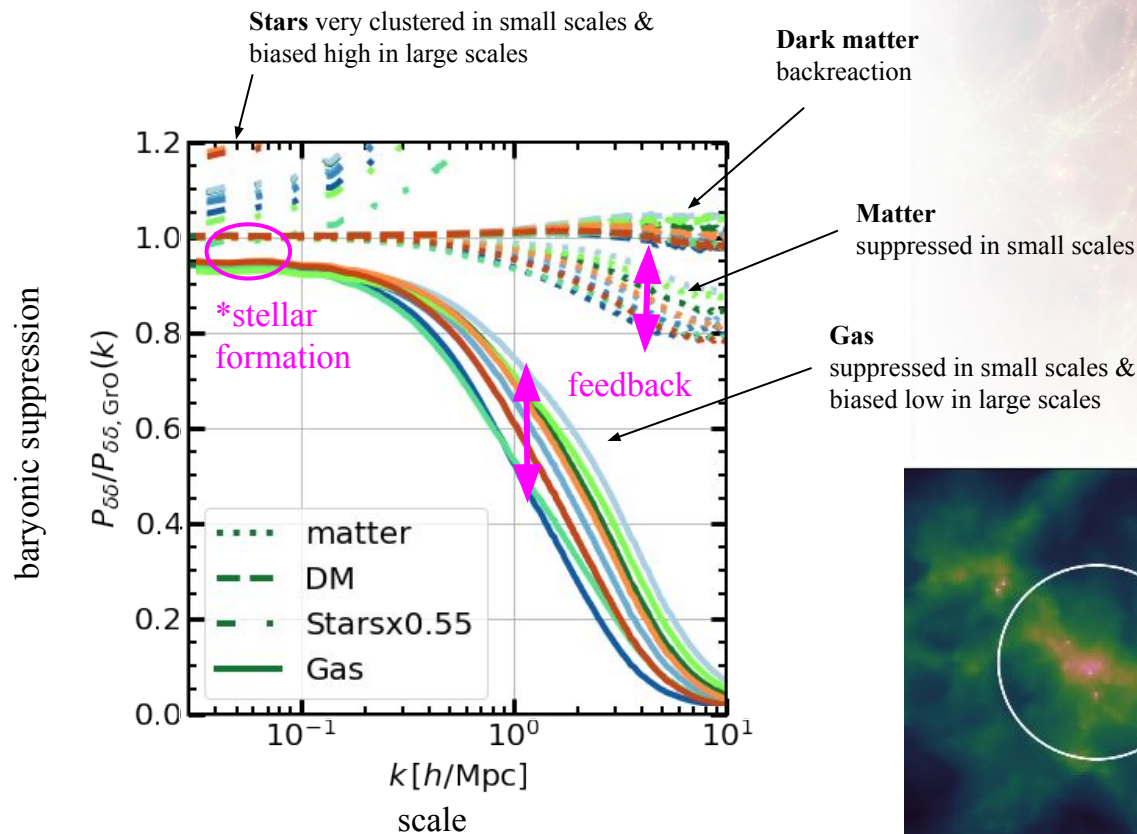
Including baryons: 30% at k of few



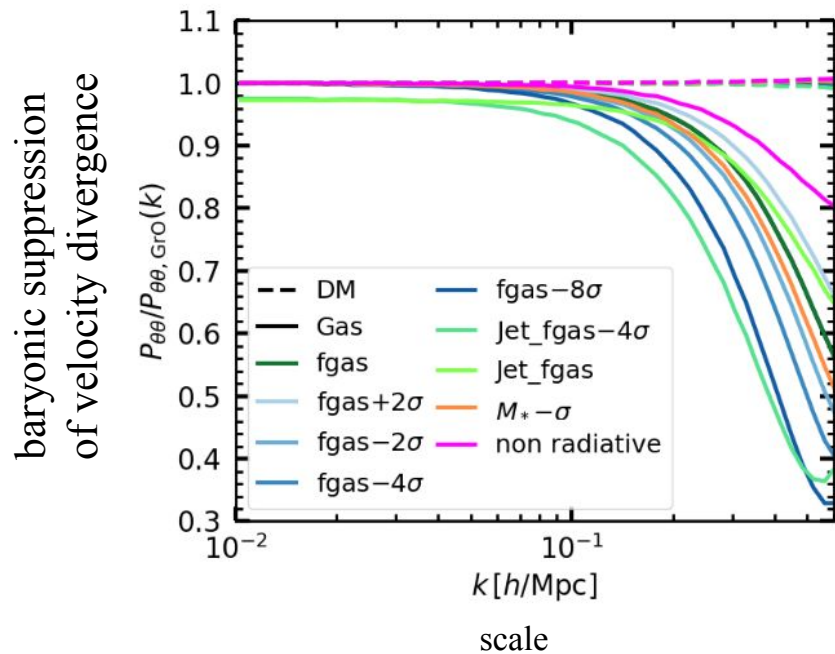
Chisari+2019

Springel+2020

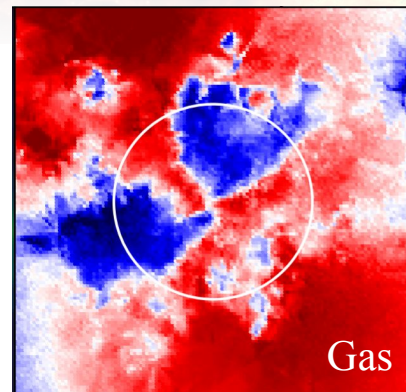
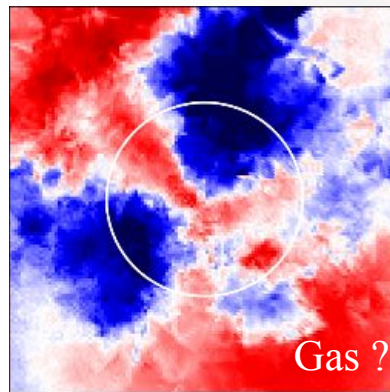
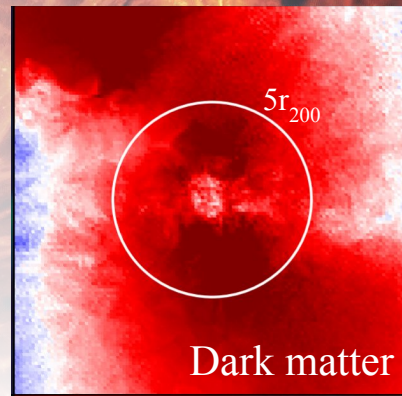
Modelling baryons: density field



Modelling baryons: velocity field



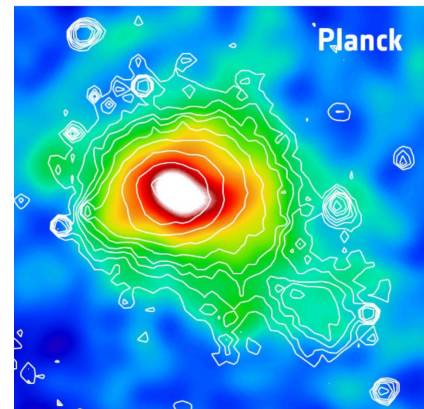
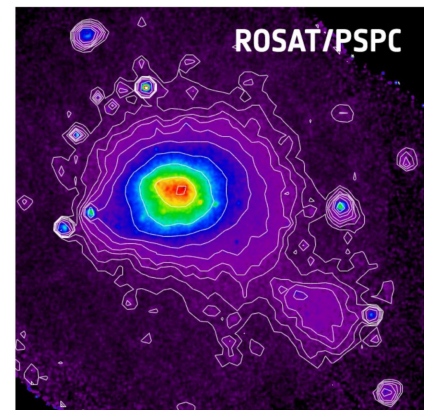
Radial
velocity
inflowing
outflowing



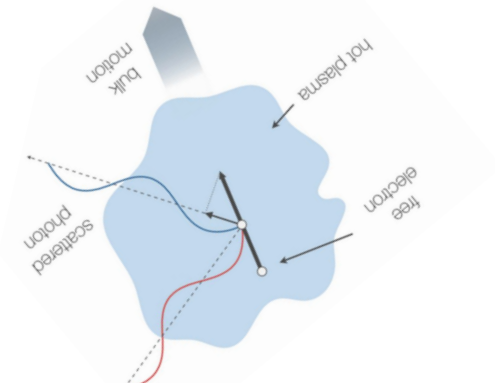
Baryons are hard to model, “easy” to see

- **X-rays:**
pro: highest S/N
cons: traces hot, dense gas; point-sources
- **thermal SZ:**
pro: high S/N
cons: traces diffuse hot gas; hard to disentangle (CIB)
- **kinetic SZ:**
pro: traces diffuse gas; clean measurement
cons: low S/N

Coma cluster



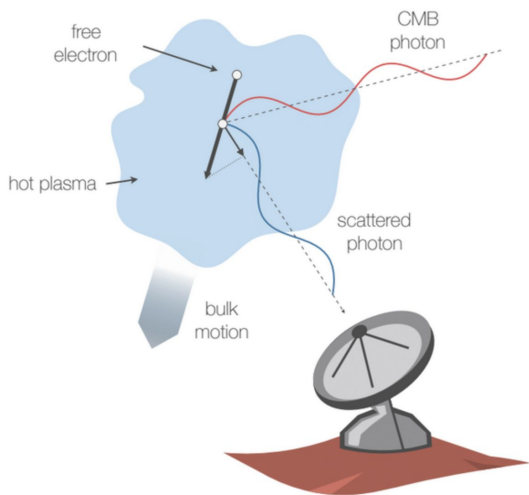
Where's the gas: stacking kinetic SZ



$$\frac{\Delta \mathcal{T}_{\text{kSZ}}}{T_{\text{CMB}}}(r_p) \propto \int \rho(\chi, r_p) v(\chi, r_p) d\chi,$$

gas density x line-of-sight velocity

*(when IGM is fully ionized)

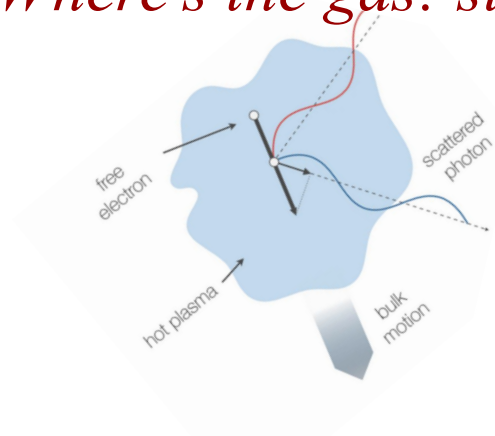


astrophysics
(small scales)

cosmology
(large scales)

$$T_{\text{kSZ}}(r_p) \propto \left\langle \frac{\Delta \mathcal{T}_{\text{kSZ}}}{T_{\text{CMB}}}(r_p) \right\rangle = 0,$$

Where's the gas: stacking kinetic SZ



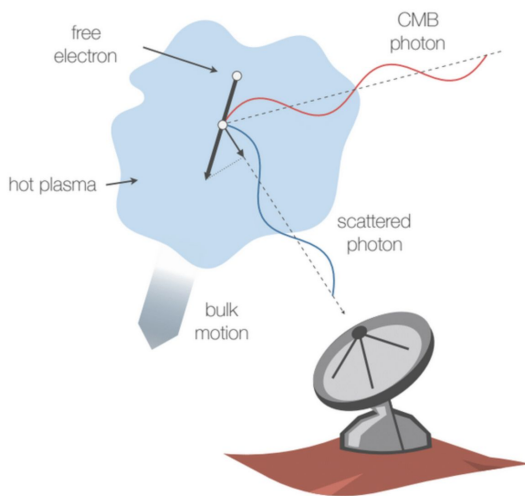
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astrophysics
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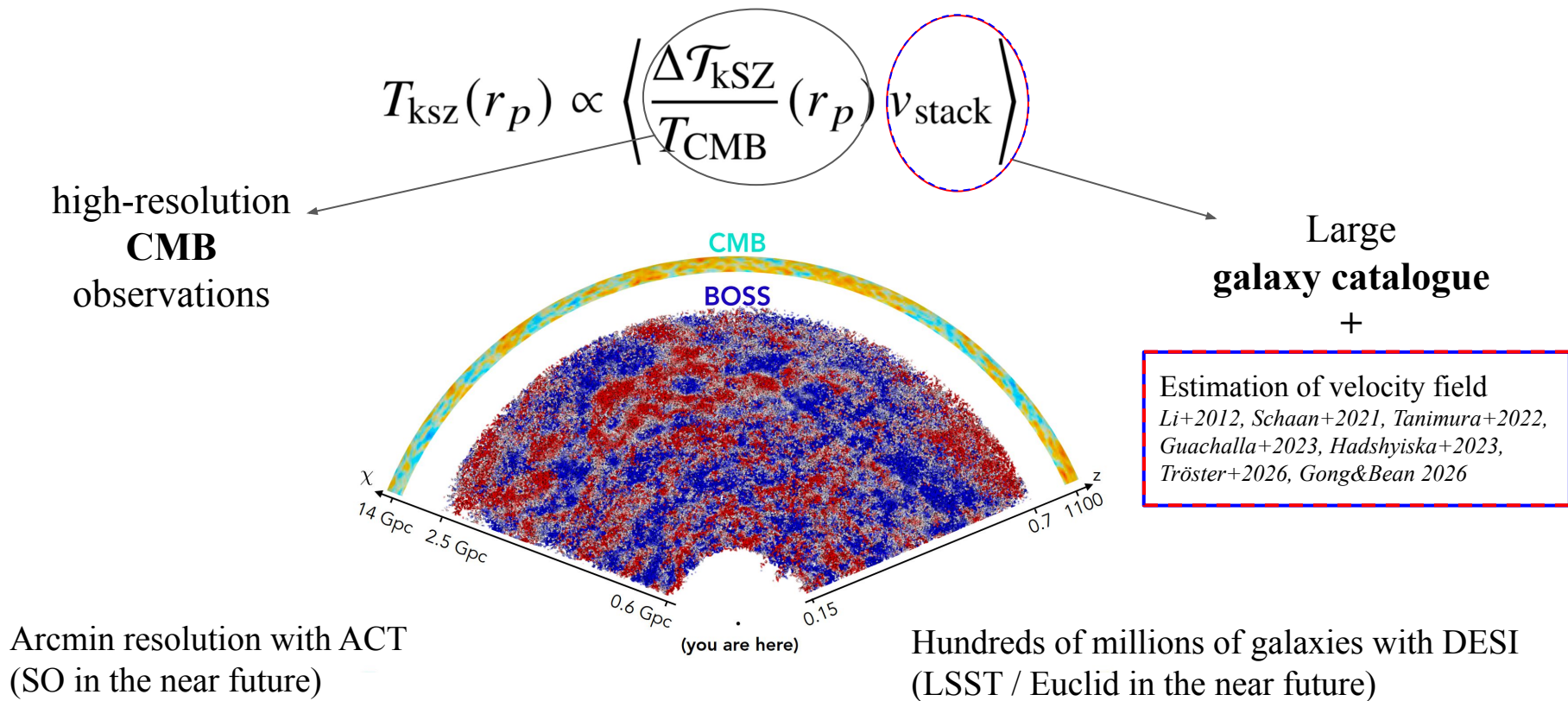
cosmology
(large scales)



$$T_{\text{kSZ}}(r_p) \propto \left\langle \frac{\Delta \mathcal{T}_{\text{kSZ}}}{T_{\text{CMB}}}(r_p) v_{\text{stack}} \right\rangle \neq 0,$$

*only signals that correlate with the velocity direction survive

Where's the gas: stacking kinetic SZ

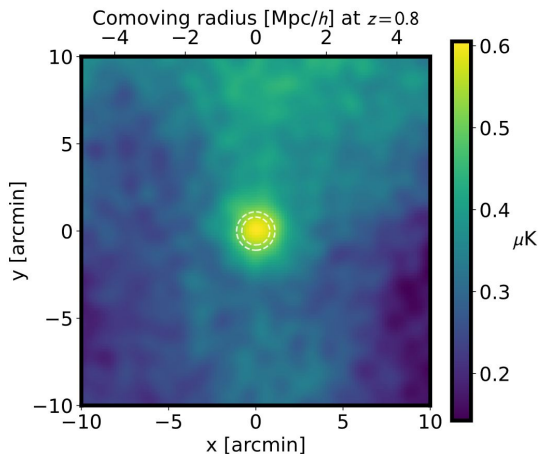


Where's the gas: stacking kinetic SZ on galaxy samples

$\sim 20\sigma$ measurements

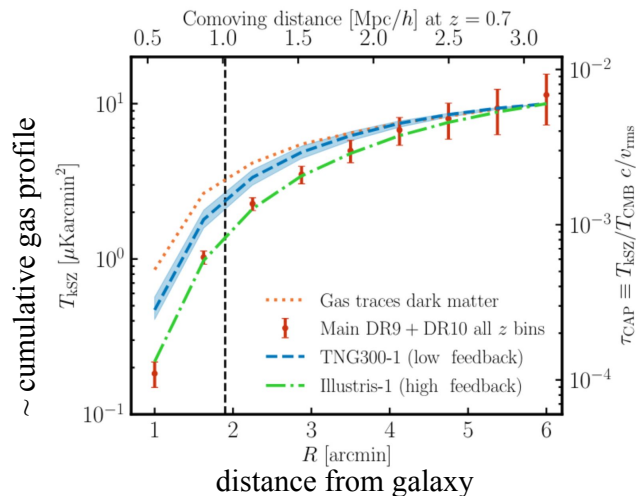
DESI LRGs x ACT

(but also BGS, ELG)



interpretation

extended gas distribution and *strong* baryonic feedback



Qu+2026

(see also Schaan+2021; Hadzhiyska+2024; Ried-Guachalla+2025; Hadzhiyska+2026)

Hadzhiyska+2024

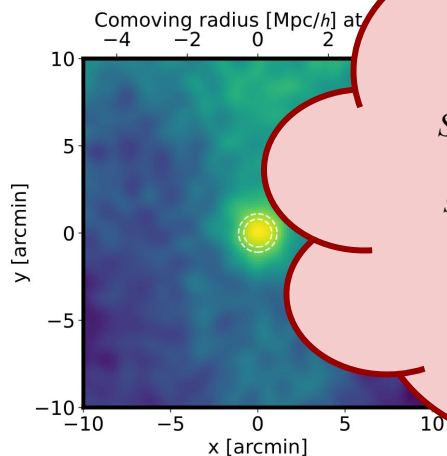
(see also Amodeo+2021; Bigwood+2024; McCarthy+2025; Kovac+2025; Siegel+2025; Siegel+2026)

Where's the gas: stacking kinetic SZ on galaxy samples

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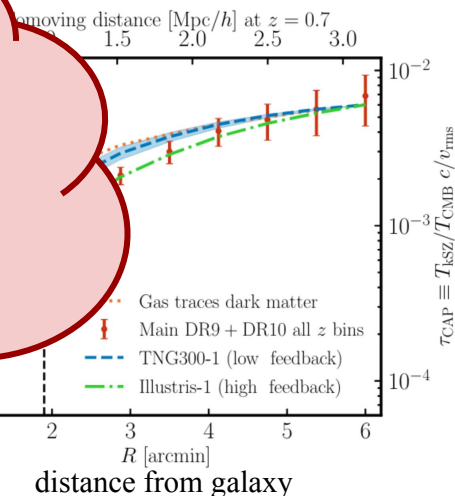
Is this an interpretation issue? / Are theoretical models complex enough?

Systematic tests on realistic DESI-like galaxy samples (LRG, BGS, ELG), including self-consistently baryonic effects, non-linear velocities, velocity reconstruction using FLAMINGO simulations

Ondaro-Mallea+2026a,b

interpretation

Interpreting the distribution and *strong* baryonic feedback



Qu+2026

(see also Schaan+2021; Hadzhiyska+2024; Ried-Guachalla+2025; Hadzhiyska+2026)

Hadzhiyska+2024

(see also Amodeo+2021; Bigwood+2024; McCarthy+2025; Kovac+2025; Siegel+2025; Siegel+2026)

Stacked kSZ: from measurement to interpretation

$$\frac{\Delta\mathcal{T}_{\text{kSZ}}}{T_{\text{CMB}}}(r_p) \propto \int \rho(\chi, r_p) v(\chi, r_p) d\chi,$$

* assuming all gas is ionized

$$T_{\text{kSZ}}(r_p) \propto \left\langle \frac{\Delta\mathcal{T}_{\text{kSZ}}}{T_{\text{CMB}}}(r_p) v_{\text{stack}} \right\rangle$$

Do we need to model...

- Baryonic effects on gas velocities?
- Decorrelation of gas velocities ($v(\chi, r_p) \neq v_h$)?
- Velocity reconstruction?
- The inclusion of satellites in the sample?

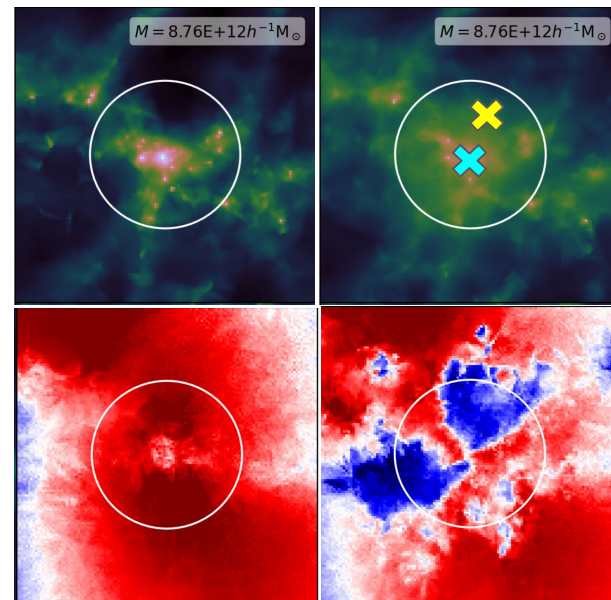
we are after this

Density

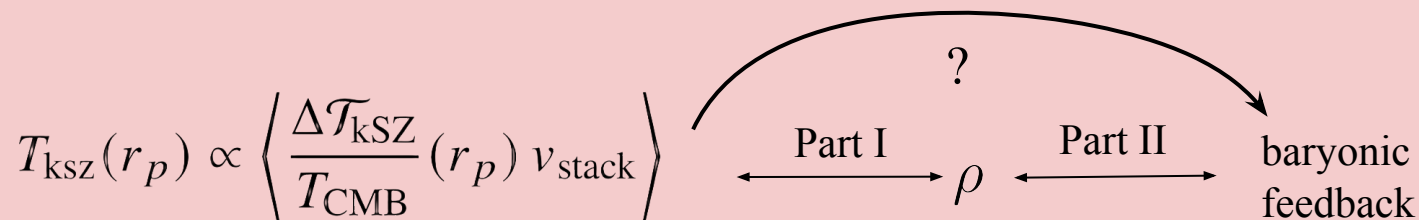
Radial
velocity
inflowing
outflowing

Dark matter

Gas



Stacked kSZ: from measurement to interpretation



- Part I: non-linear velocities & velocity reconstruction (based on *Ondaro-Mallea+2026a*)
- Part II: satellites in the sample (based on *Ondaro-Mallea+2026b in prep*)

Sample selection

DESI-like samples: LRGs ($z = 0.7, M = 10^{13.2} h^{-1} M_{\odot}$)
BGS ($z = 0.25, M = 10^{13.24} h^{-1} M_{\odot}$)
ELG ($z = 1.1, M = 10^{12.4} h^{-1} M_{\odot}$)



Schaye+2023

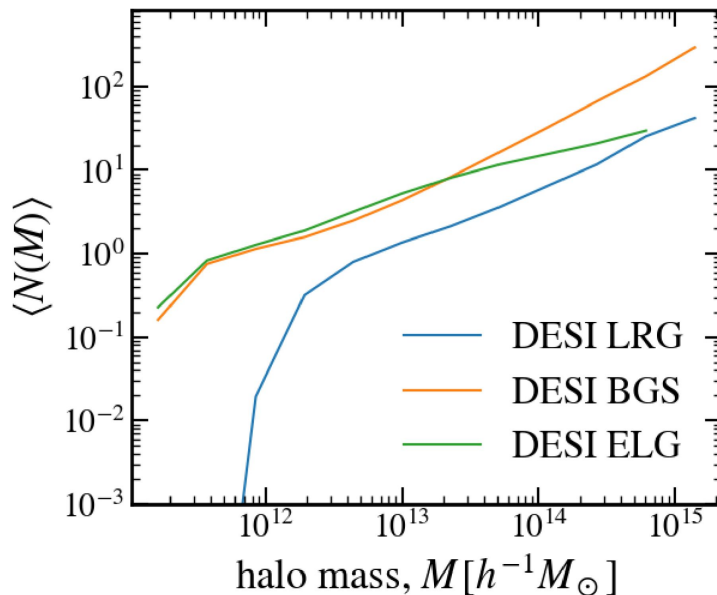
+ rank order by stellar mass,
select top N galaxies
so that the sample has
measured mean halo mass
with CMB lensing

Hadzhiyska+2025

FLAMINGO sims

- several feedback variations
- at the redshift of each sample

HOD of galaxy samples



Stacked kSZ: decomposition

$$\begin{aligned}
 T_{\text{ksz}}(r_p) &= \frac{1}{r v_{\text{rms}}^{\text{stack}}} \left\langle \left[\int \rho(\chi, r_p) v(\chi, r_p) d\chi \right] v_{\text{stack}} \right\rangle = \\
 &\quad \text{mean density x velocity rms} \quad \text{density and (halo) velocity correlation} \quad \text{(gas) velocity decorrelation} \\
 &= \langle \tau(r_p) \rangle v_{\text{rms}}^h + \frac{1}{r v_{\text{rms}}^{\text{stack}}} \left[\text{Cov}(\tau(r_p), v_h v_{\text{stack}}) + \text{Cov}(p'(r_p), v_{\text{stack}}) \right].
 \end{aligned}$$

*have to calibrate cross-correlation coefficient of real and

reconstructed velocities (*amplitude*)

Ried-Guachalla+2023; Hadhziyska+2023

Linear theory for velocity:

Velocity constant in the scales where density varies a lot

Non-linearities in velocity:

Correlations of small-scale density and velocities with stacking velocity

$$v(\chi, r_p) = v_h + v'(\chi, r_p),$$

Non-linear terms as a function of stacking velocity

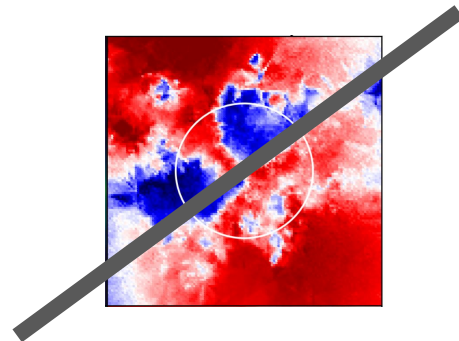
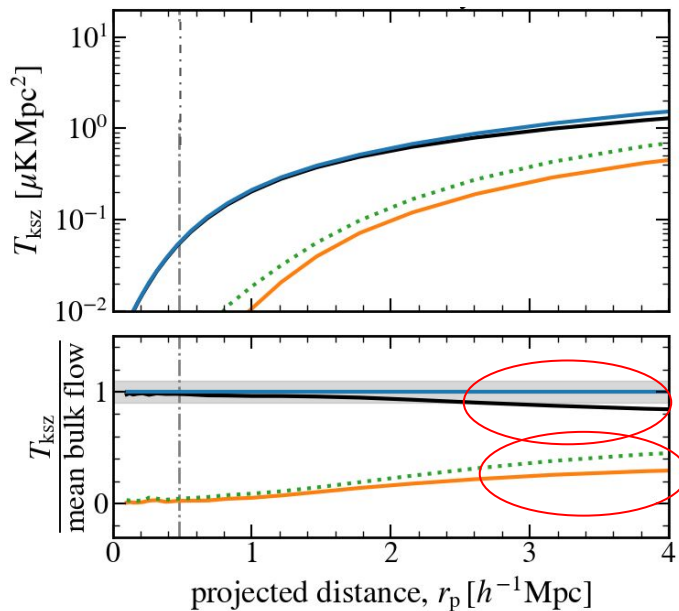
— estimator
 — mean bulk flow $\propto \langle \tau \rangle$
 — density-bulk flow correlation
 — velocity decorrelation
⋯ negative ($\times -1$)

Option 1

Perfect knowledge of halo velocities

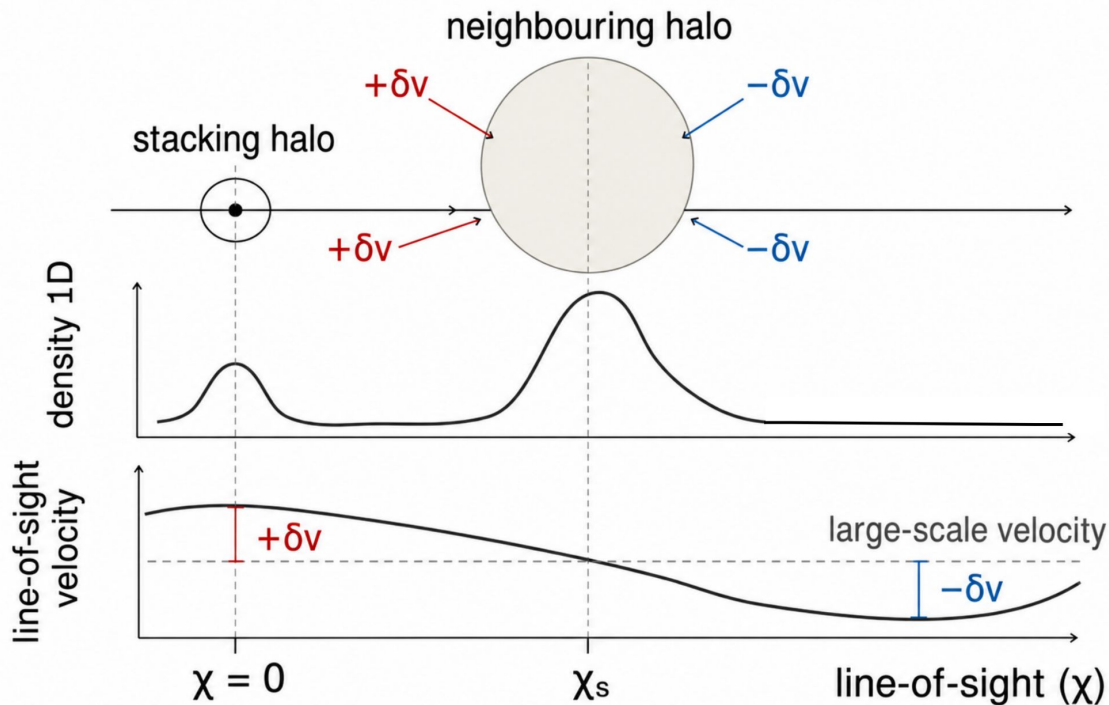
net non-linear terms $\sim 10\text{-}20\%$ suppression

*largely independent of baryonic effects
 $\rightarrow$ gravitational process



integrate along $l_{\text{os}} \rightarrow 0$

Physical origin of non-linear terms

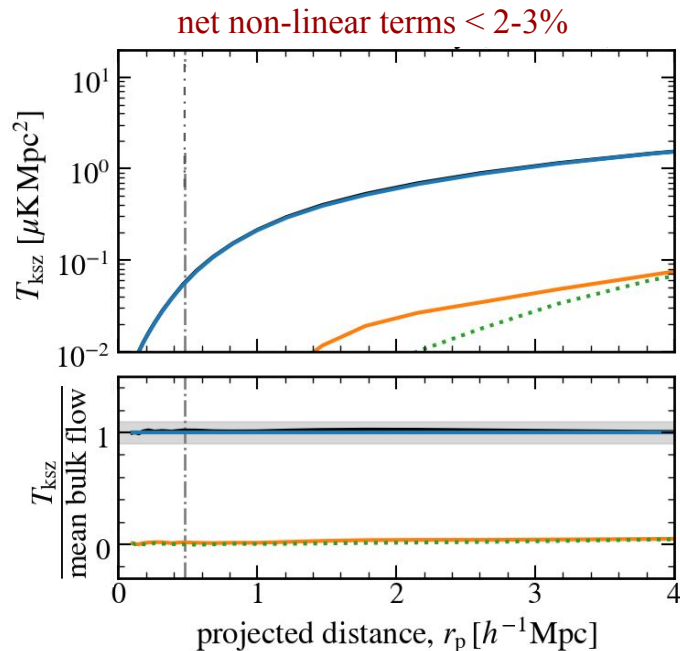


1. Velocity of the stacking halo is larger if it lives in high density environments
(density-bulk flow correlation)
2. The l.o.s. velocities decorrelate faster in high density environments
(velocity decorrelation)

Non-linear terms as a function of stacking velocity

— estimator
 — mean bulk flow $\propto \langle \tau \rangle$
 — density-bulk flow correlation
 — velocity decorrelation
⋯ negative ($\times -1$)

Option 2
 Reconstructed velocities
 (continuity equation
 w/o redshift-space distortions)



Physical interpretation:
 Non-linear effects in gas density and velocities
 $\times$
 linear estimation of velocities
 $= 0$

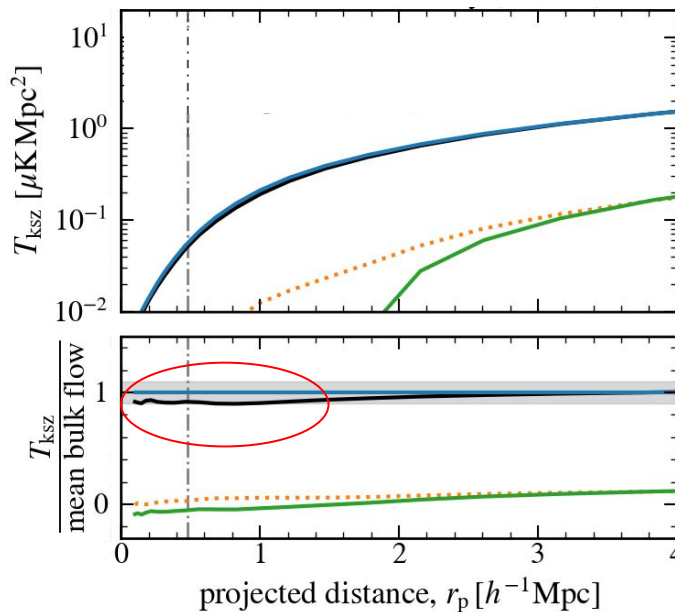
Non-linear terms as a function of stacking velocity

— estimator — mean bulk flow $\propto \langle \tau \rangle$ — density-bulk flow correlation — velocity decorrelation

..... negative ($\times -1$)

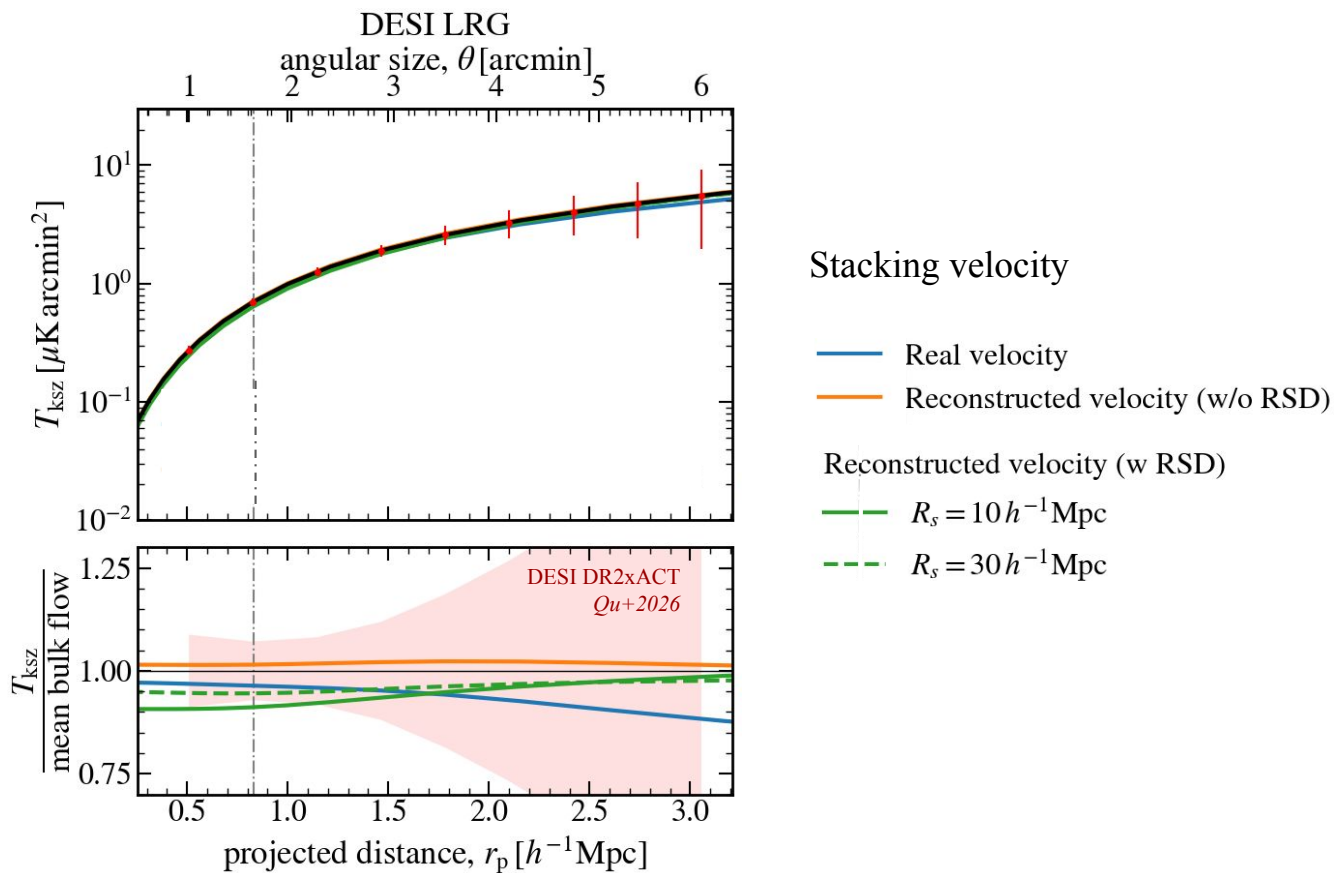
Option 3
Reconstructed velocities
(continuity equation
w redshift-space distortions)

net non-linear terms $\sim 10\%$ suppression on small-scales

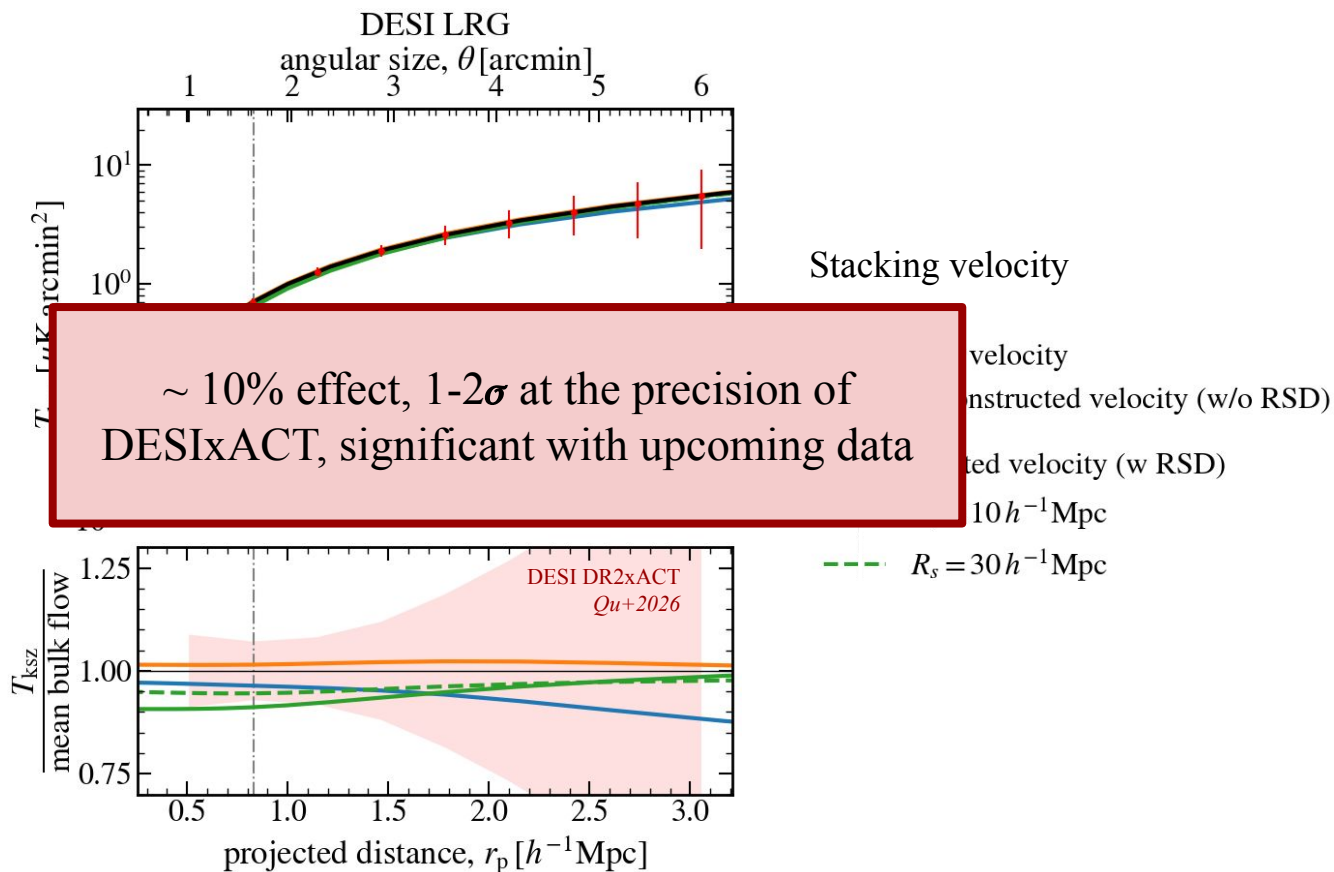


Physical interpretation:
FoG-induced errors on the velocity reconstruction
 $\times$
non-linearities in the gas field
 $\neq 0$

Non-linear terms vs statistical uncertainty



Non-linear terms vs statistical uncertainty

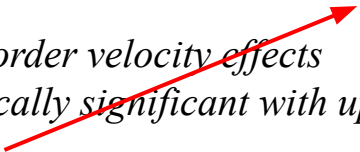


Stacked kSZ: optical depth

$$T_{\text{kSZ}} \propto \left\langle \frac{\Delta \mathcal{T}_{\text{kSZ}}}{T_{\text{CMB}}} v_{\text{stack}} \right\rangle \propto \langle \tau \rangle \quad + \quad \text{higher-order velocity effects}$$

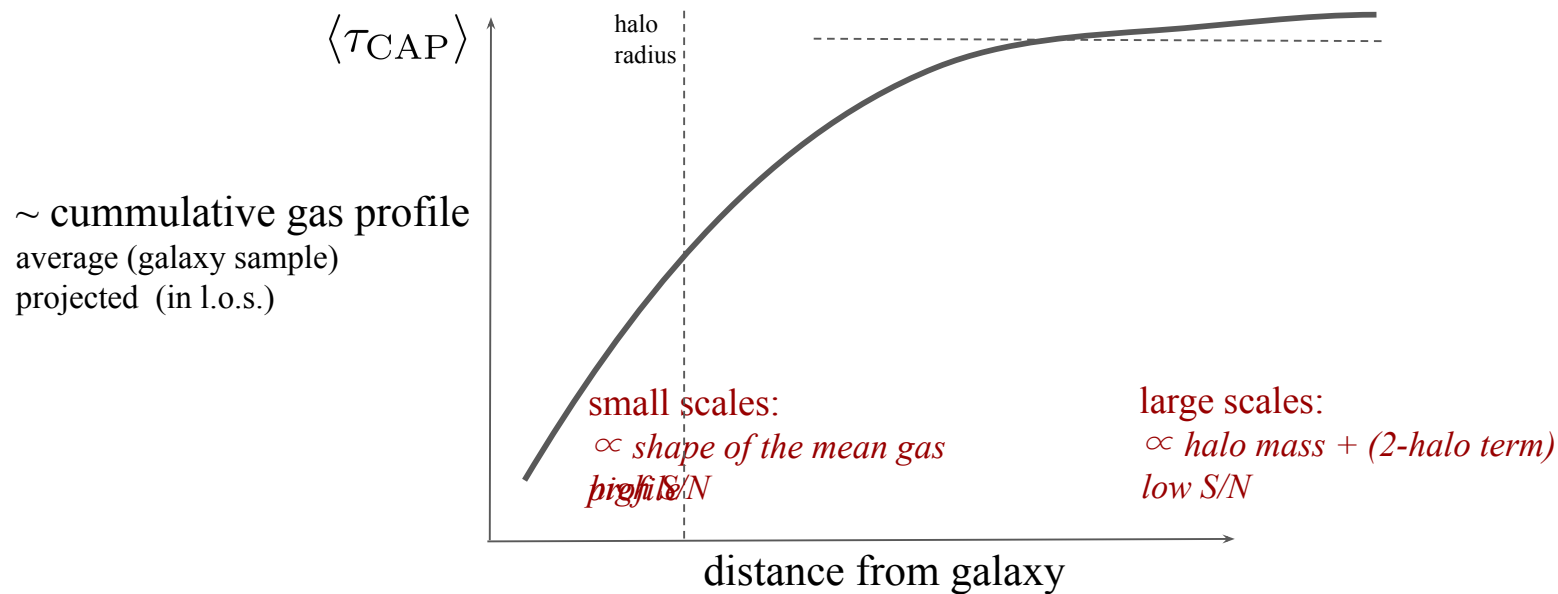
(for now)

(statistically significant with upcoming data)



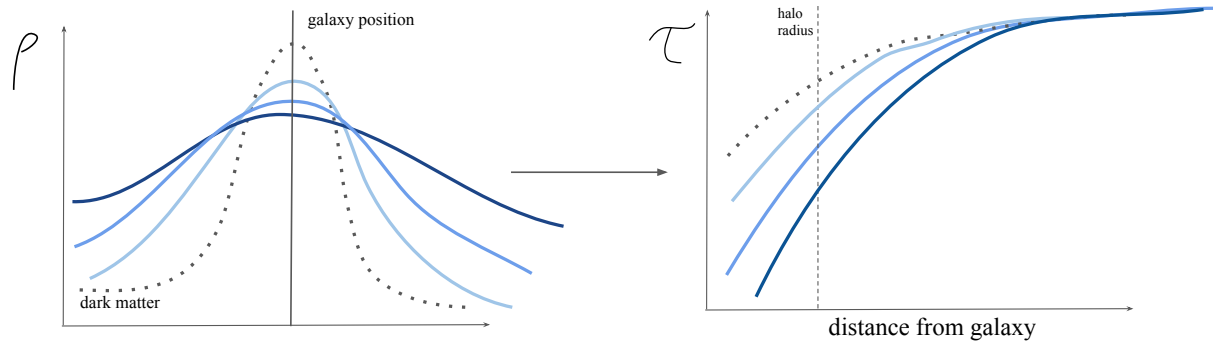
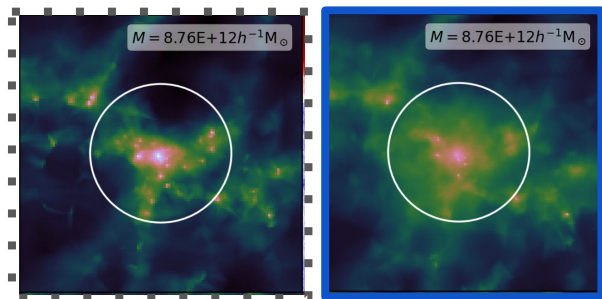
Stacked kSZ : optical depth

$$T_{\text{kSZ}} \propto \left\langle \frac{\Delta \mathcal{T}_{\text{kSZ}}}{T_{\text{CMB}}} v_{\text{stack}} \right\rangle \propto \langle \tau \rangle \propto \text{average optical depth (ionized gas density) around a galaxy sample (centrals + satellites)}$$

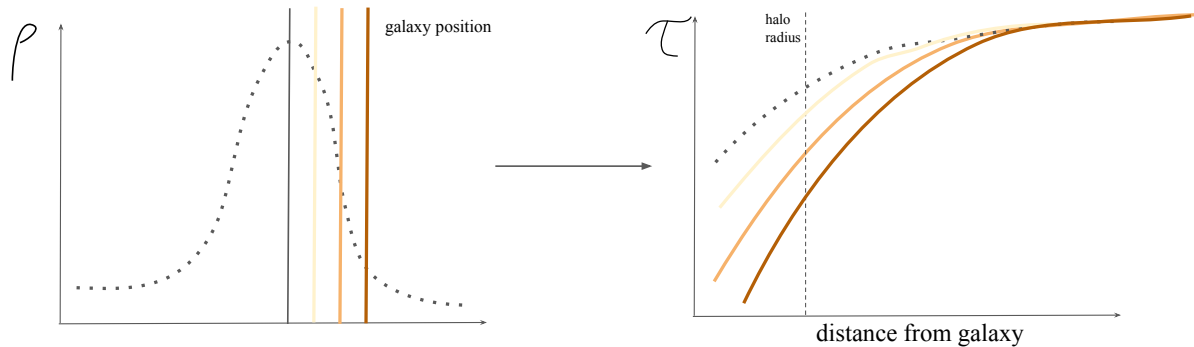
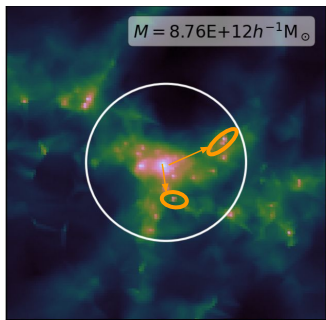


Shape of the small-scale optical depth (at fixed halo mass)

Baryonic feedback:



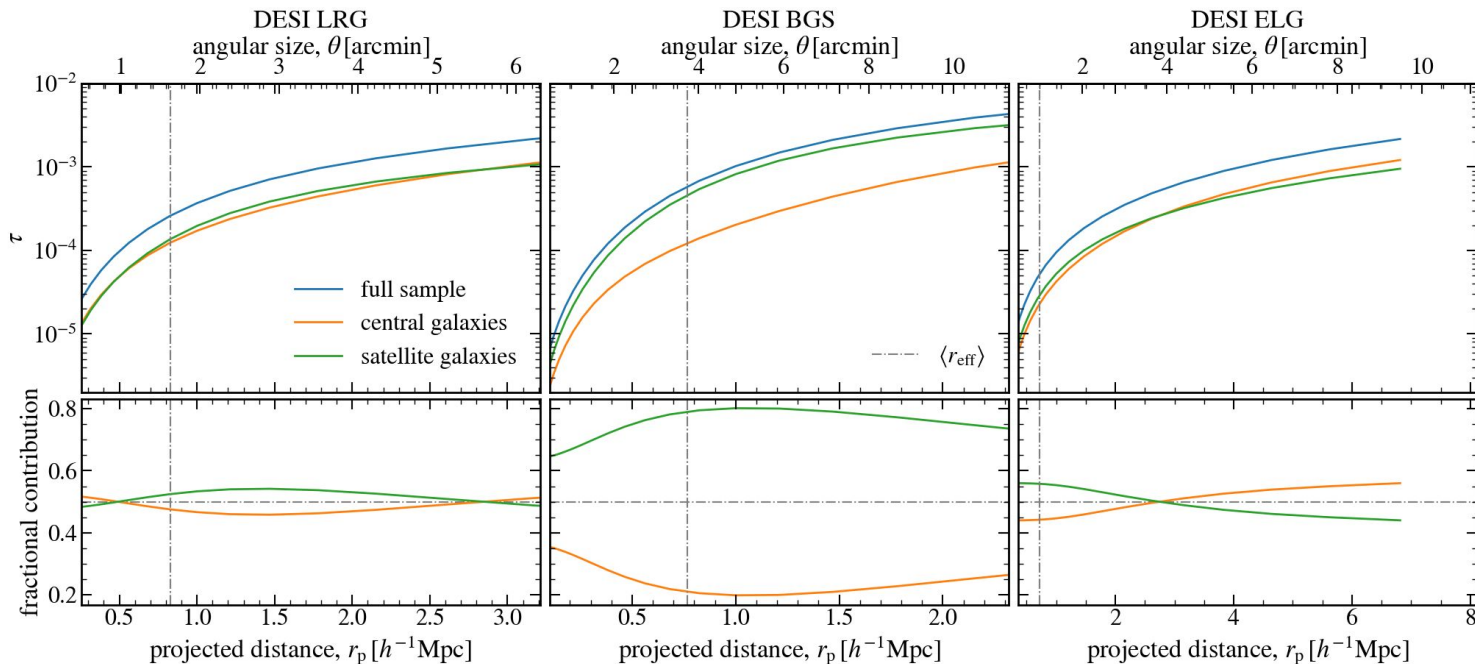
Satellite miscentering:



Are satellites relevant?

$$kSZ \propto \tau \propto M$$

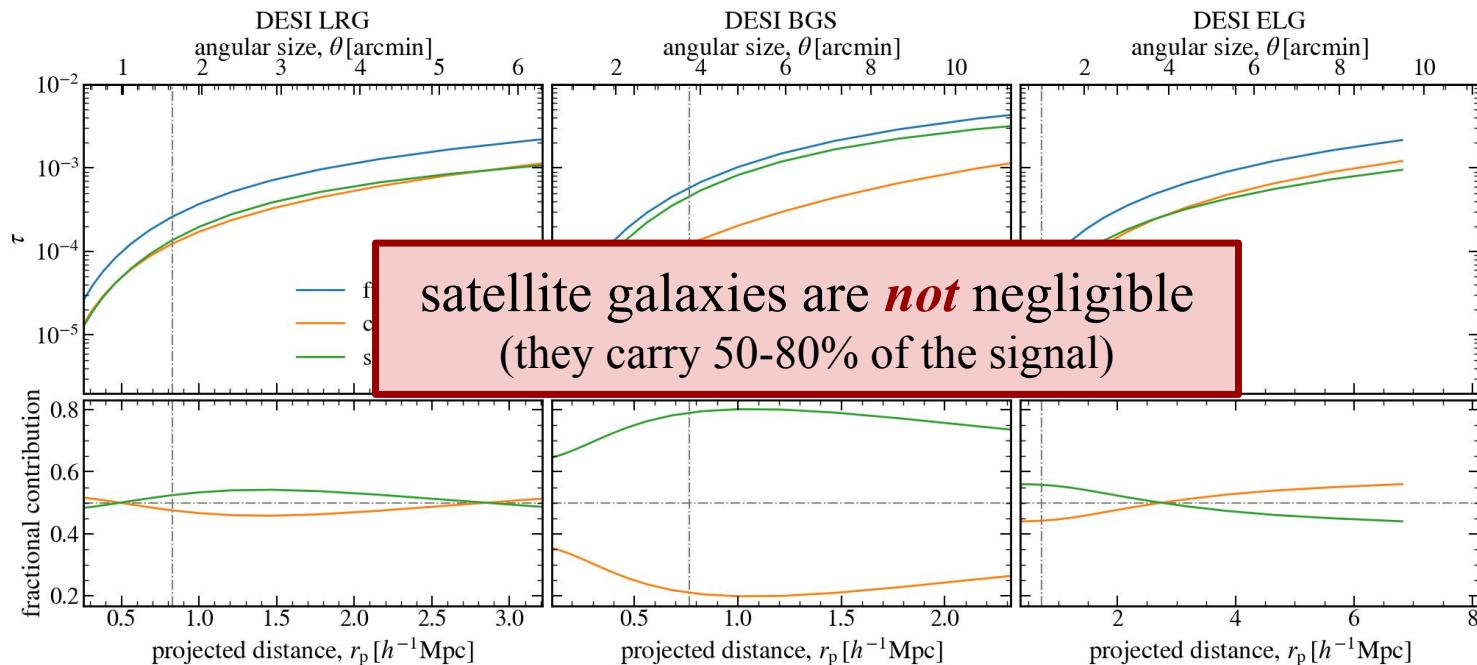
Sample	f_{sat}	$\langle M_{\text{sat}} \rangle / \langle M_{\text{cen}} \rangle$
DESI LRG	0.24	6.32
DESI BGS	0.32	31.66
DESI ELG	0.30	7.65



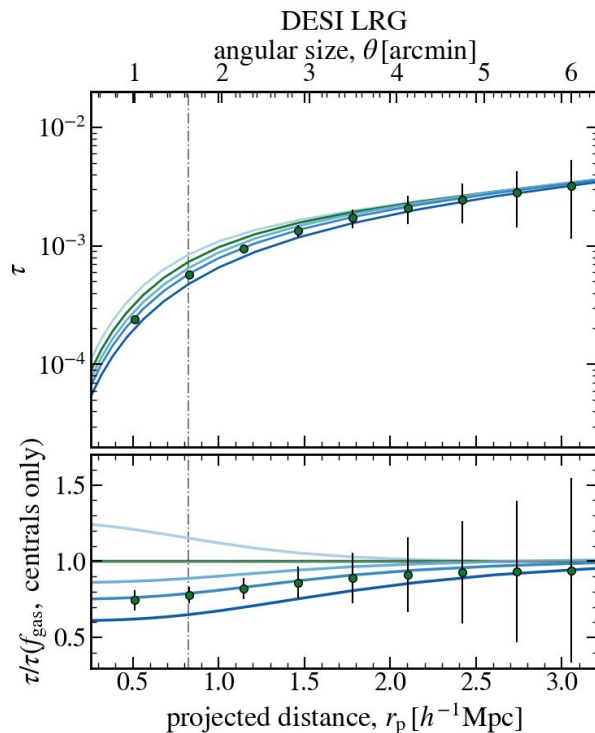
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Degeneracy satellites & baryonic feedback



centrals only:

$f_{\text{gas}} + 2\sigma$

f_{gas}

$f_{\text{gas}} - 2\sigma$

$f_{\text{gas}} - 4\sigma$

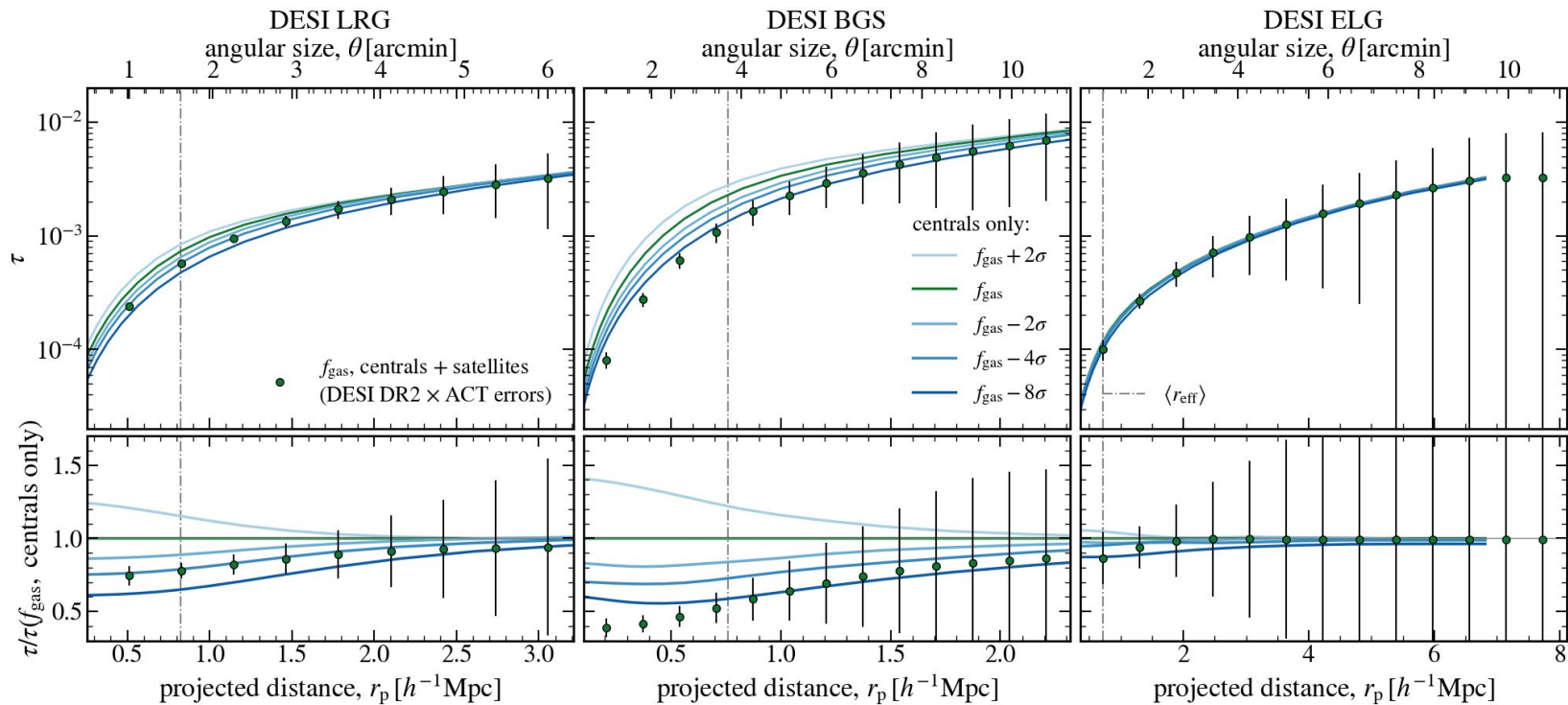
$f_{\text{gas}} - 8\sigma$

$\sim 40\%$ suppression at the virial radius
(fiducial to strongest feedback in FLAMINGO)

$f_{\text{gas}}, \text{centrals} + \text{satellites}$
(DESI DR2 $\times$ ACT errors)

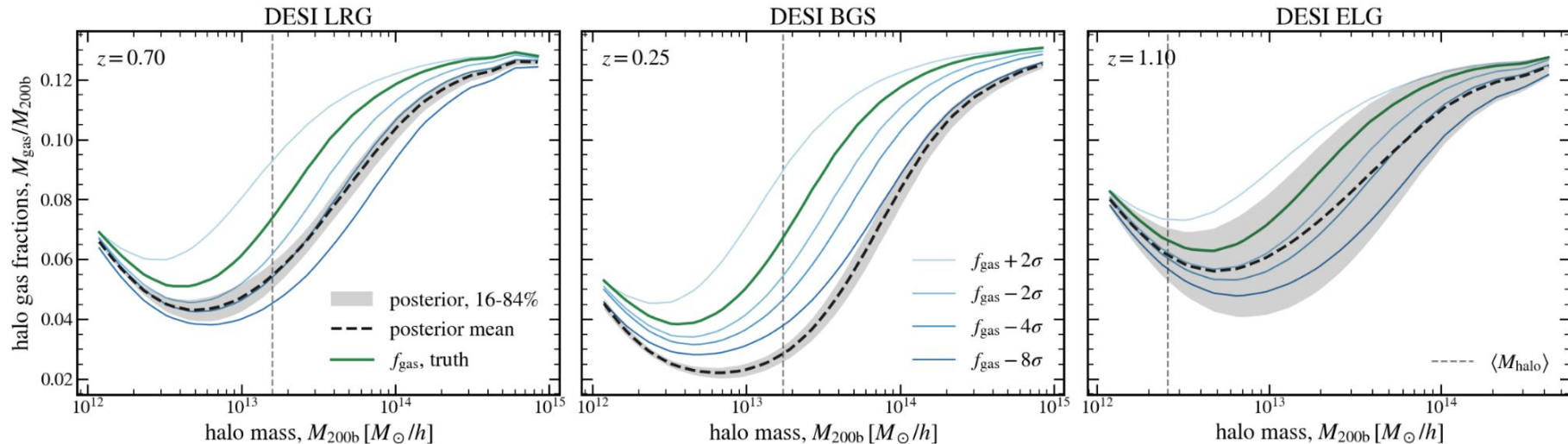
$\sim 30\%$ suppression at the virial radius
(including satellites in the sample vs centrals-only)

Degeneracy satellites & baryonic feedback



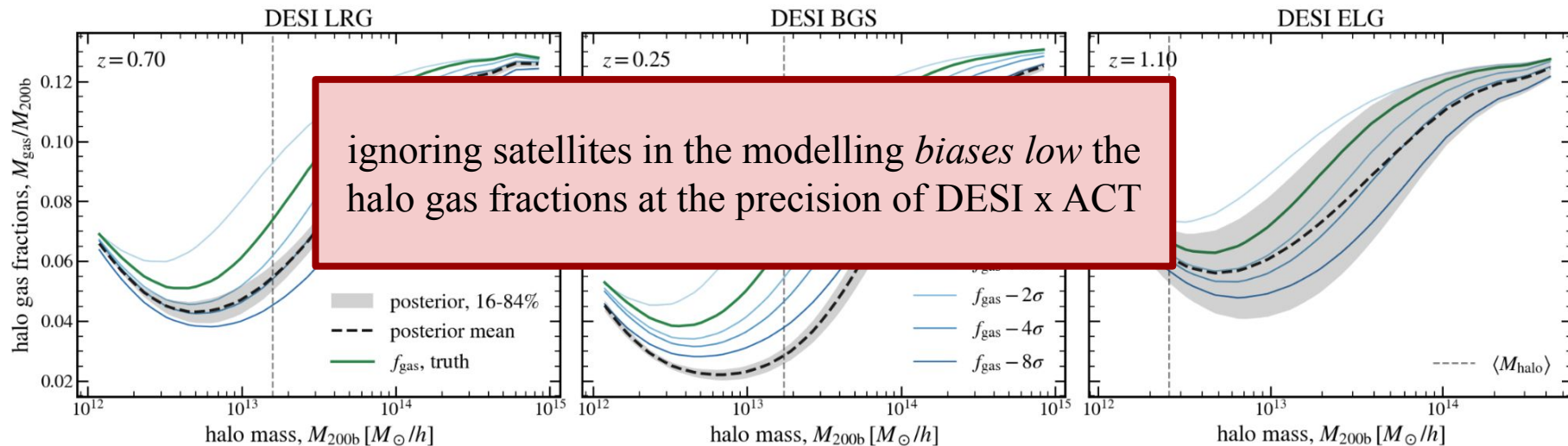
Toy analysis

- *model*: GP trained on mock kSZ on *central-only* sample at varying feedback ($f_{\text{gas}}(M) \rightarrow T_{\text{kSZ}}(\theta)$);
- *data*: mock kSZ on *central+satellite* sample with fiducial feedback
- fit data with DESI x ACT observational covariance, infer halo gas fractions



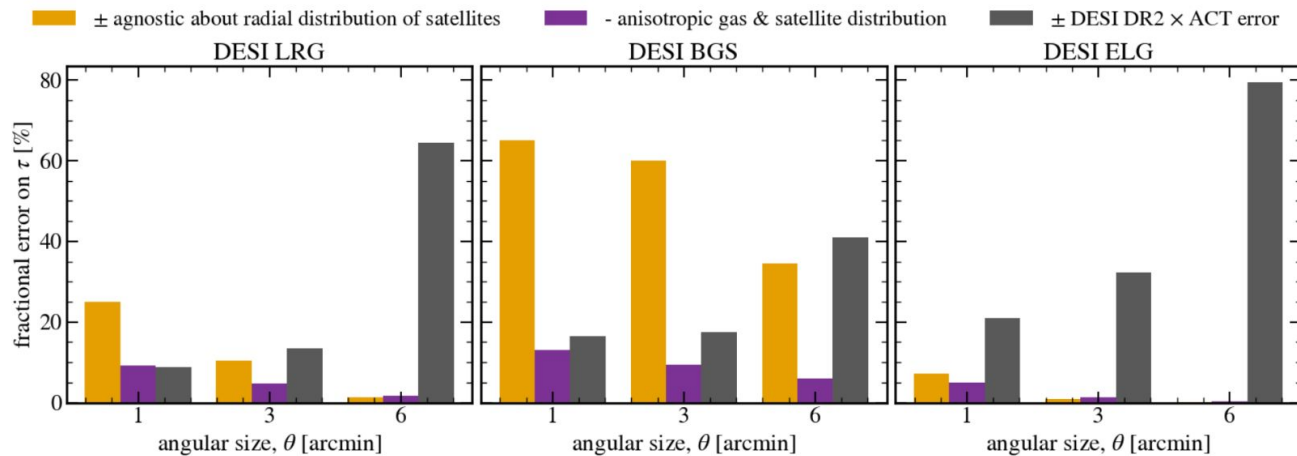
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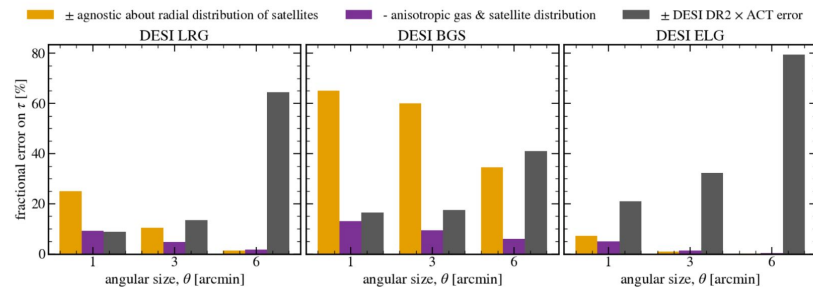
Satellites matter... what should we do?

1) Be agnostic about satellites: marginalize



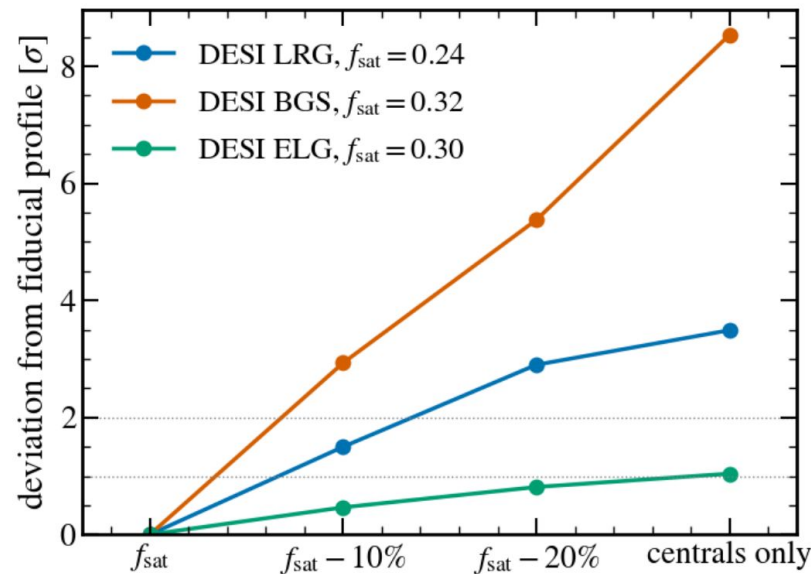
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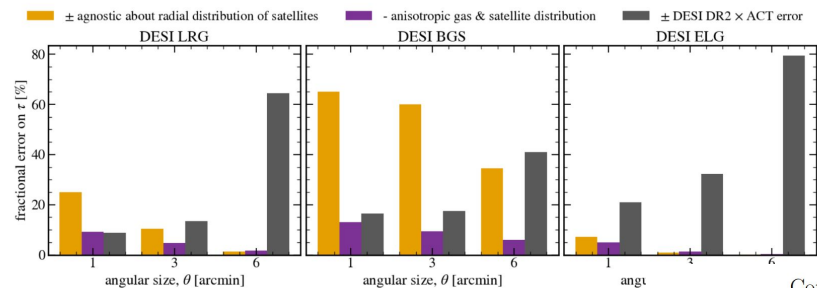
2) Constrain satellite population with external datasets

(lensing, clustering)



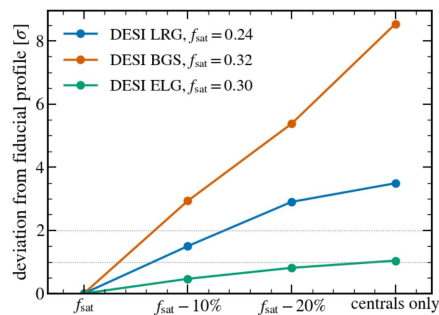
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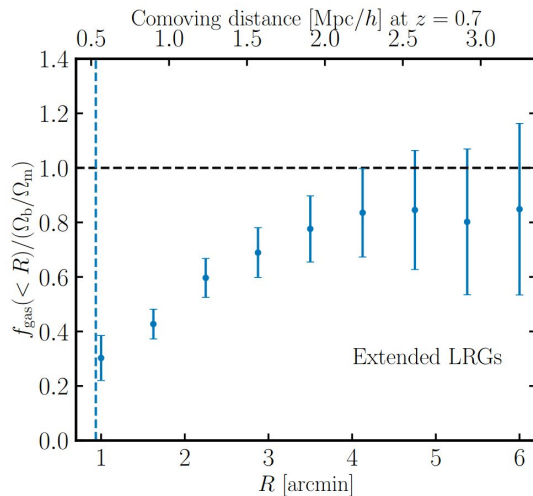
(lensing, clustering)



3) Observations that are more robust:

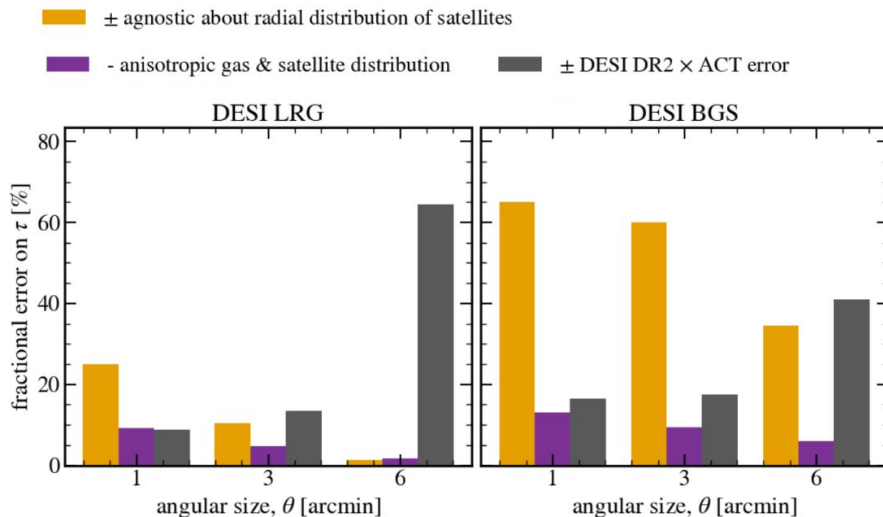
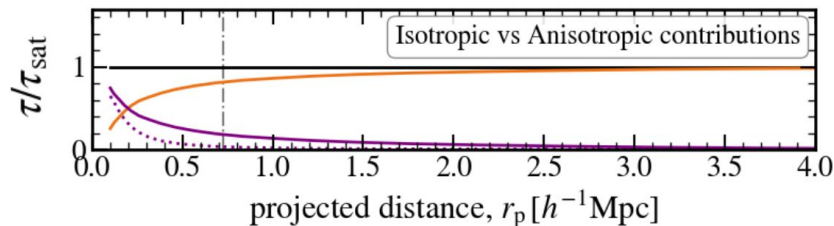
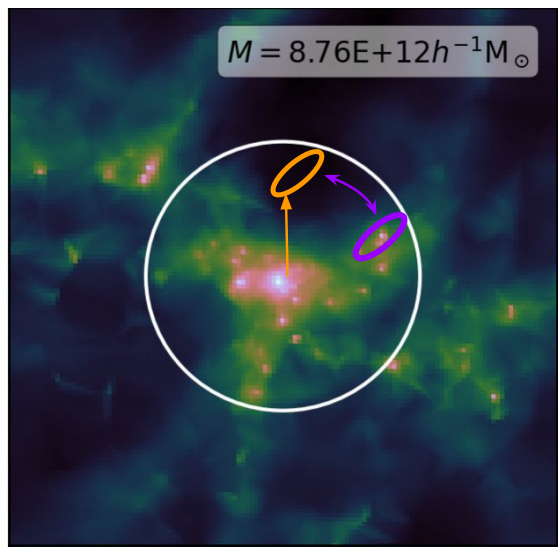
kSZ-to-lensing ratio

Hadzhiyska+2025, Liu+2026



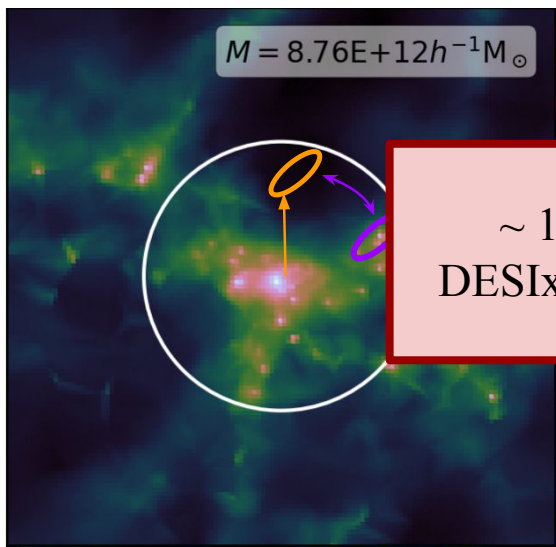
Higher order effects: gas & satellite anisotropy

satellites trace the anisotropy of matter
(and gas) around the halo

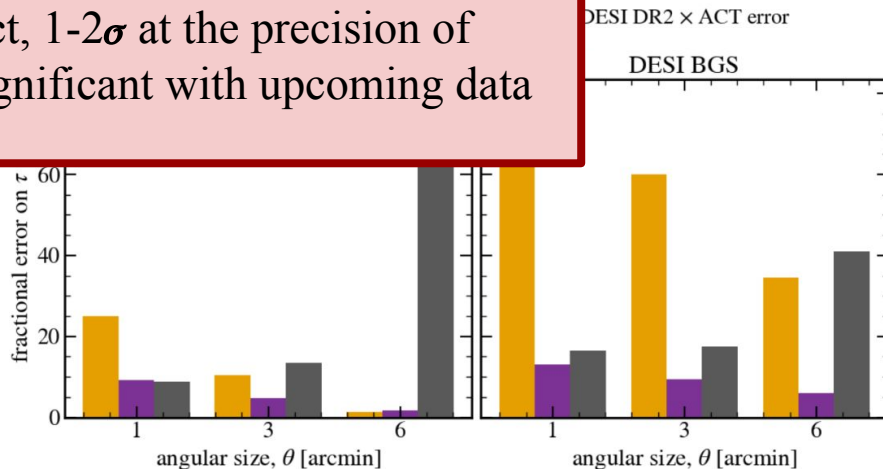
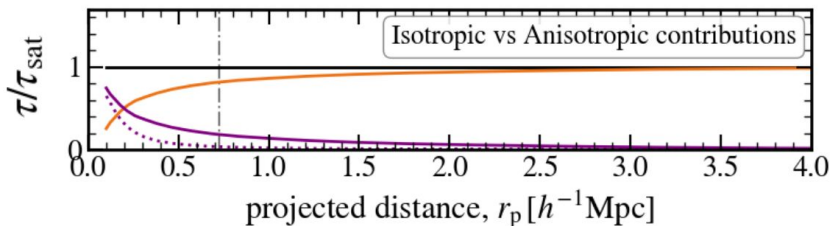


Higher order effects: gas & satellite anisotropy

satellites trace the anisotropy of matter
(and gas) around the halo



$\sim 10\%$ effect, $1-2\sigma$ at the precision of
DESIxACT, significant with upcoming data



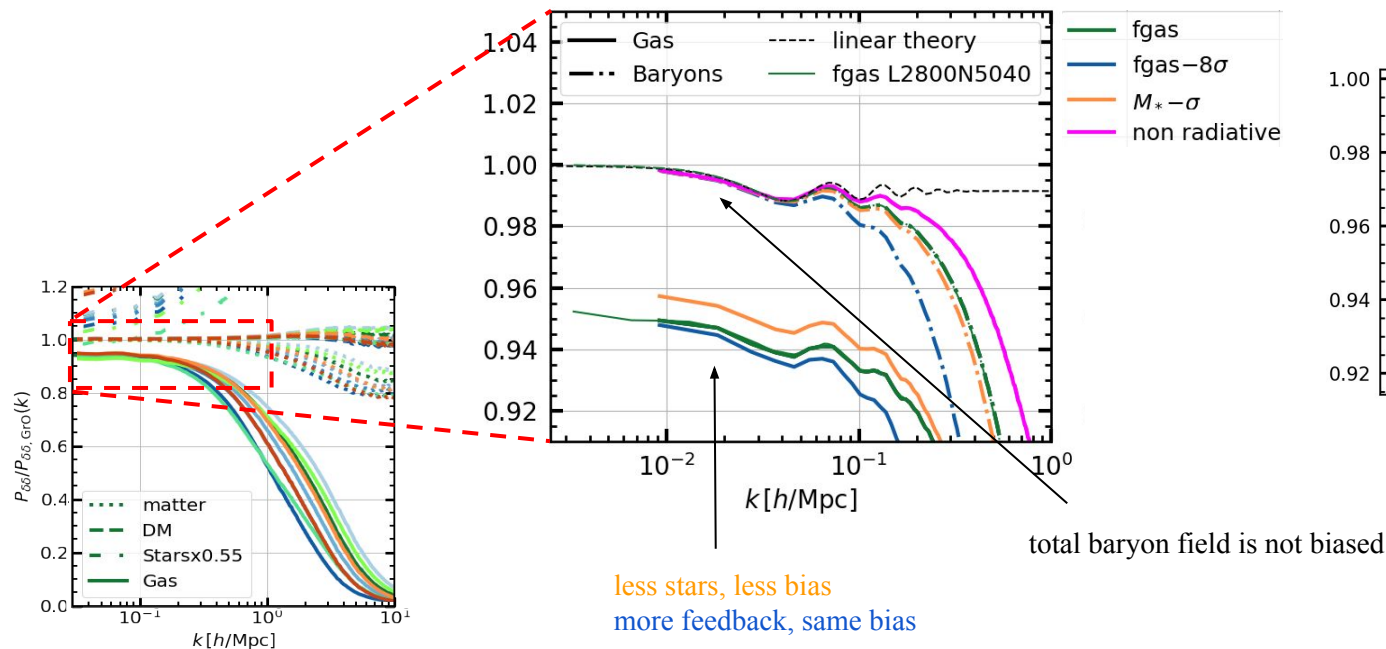
Interpreting stacked kinetic SZ

The stacked kSZ signal is very sensitive to the gas distribution around galaxies and great probe of baryonic feedback, but there are other effects that have to be taken account in the *interpretation*:

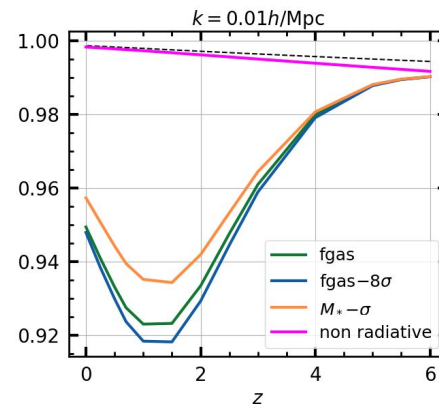
Physical origin	Effect on the measured profile	Amplitude	Relevance	Modelling requirement
Satellite miscentering within the host halo can be confused with strong feedback!!	Suppression on small scales	up to $\approx 50\%$ at the virial radius	at current precision (DESI DR2 $\times$ ACT)	both analytical or simulation based
Anisotropic gas and satellite distributions around the halo	Contribution on small scales	$\approx 10\%$	in future measurements (LSST / Euclid $\times$ SO)	simulation based
Coupling of gas velocity non-linearities to reconstructed velocities	Suppression on small scales	$\approx 10 - 20\%$	in future measurements (LSST / Euclid $\times$ SO)	simulation based

Back-up slides

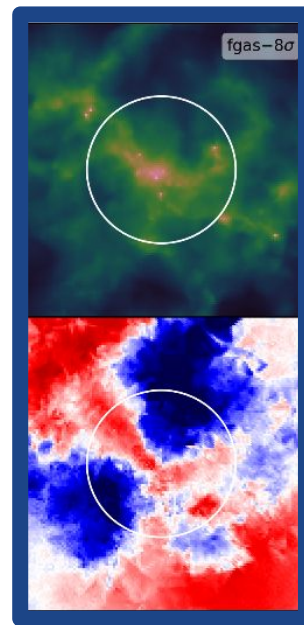
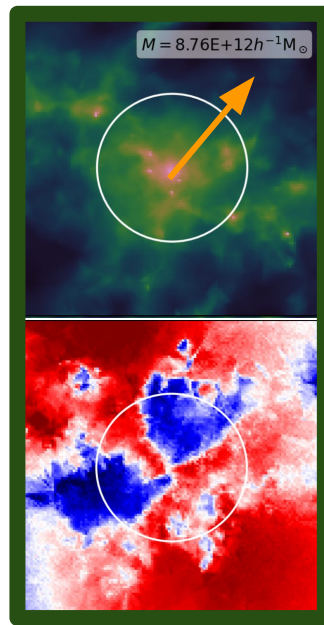
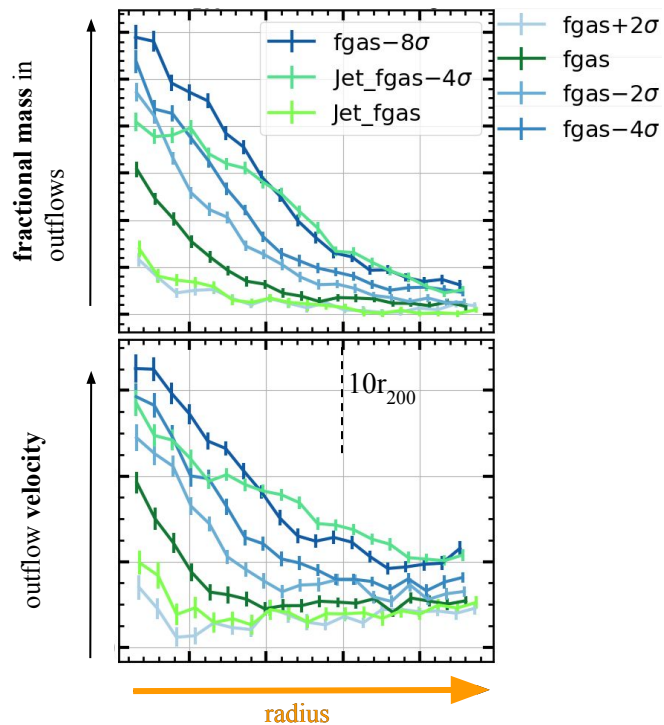
Large-scale gas bias



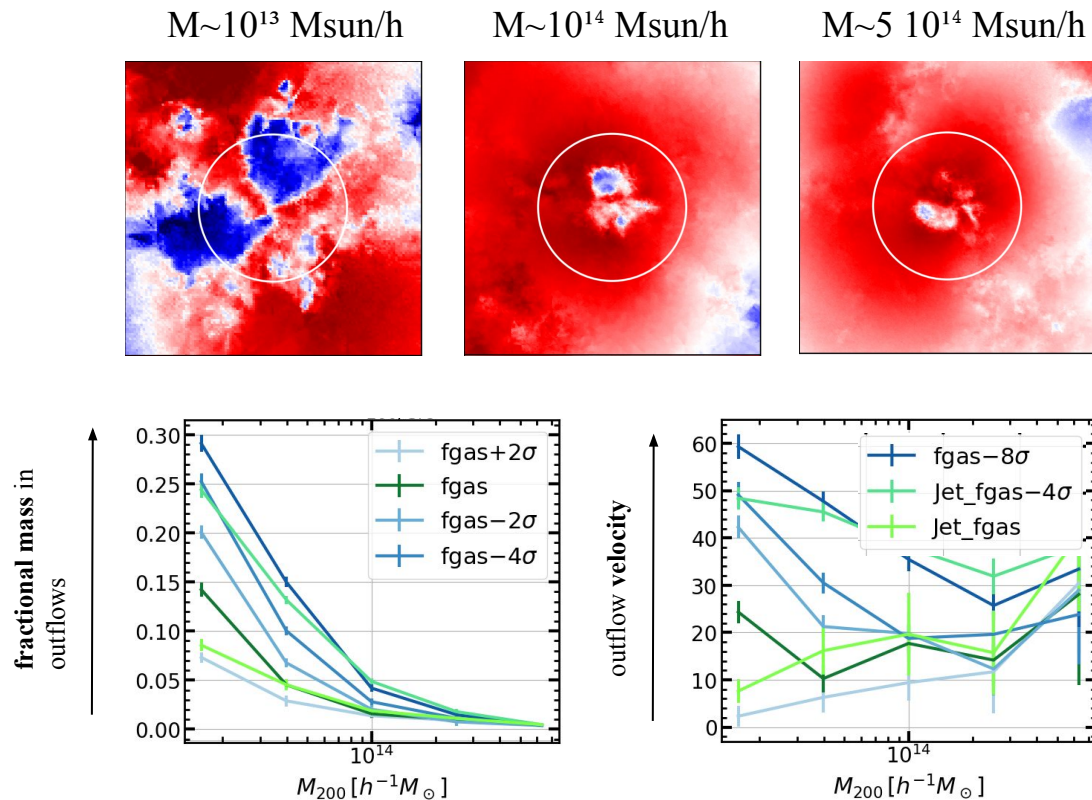
redshift evolution of gas bias



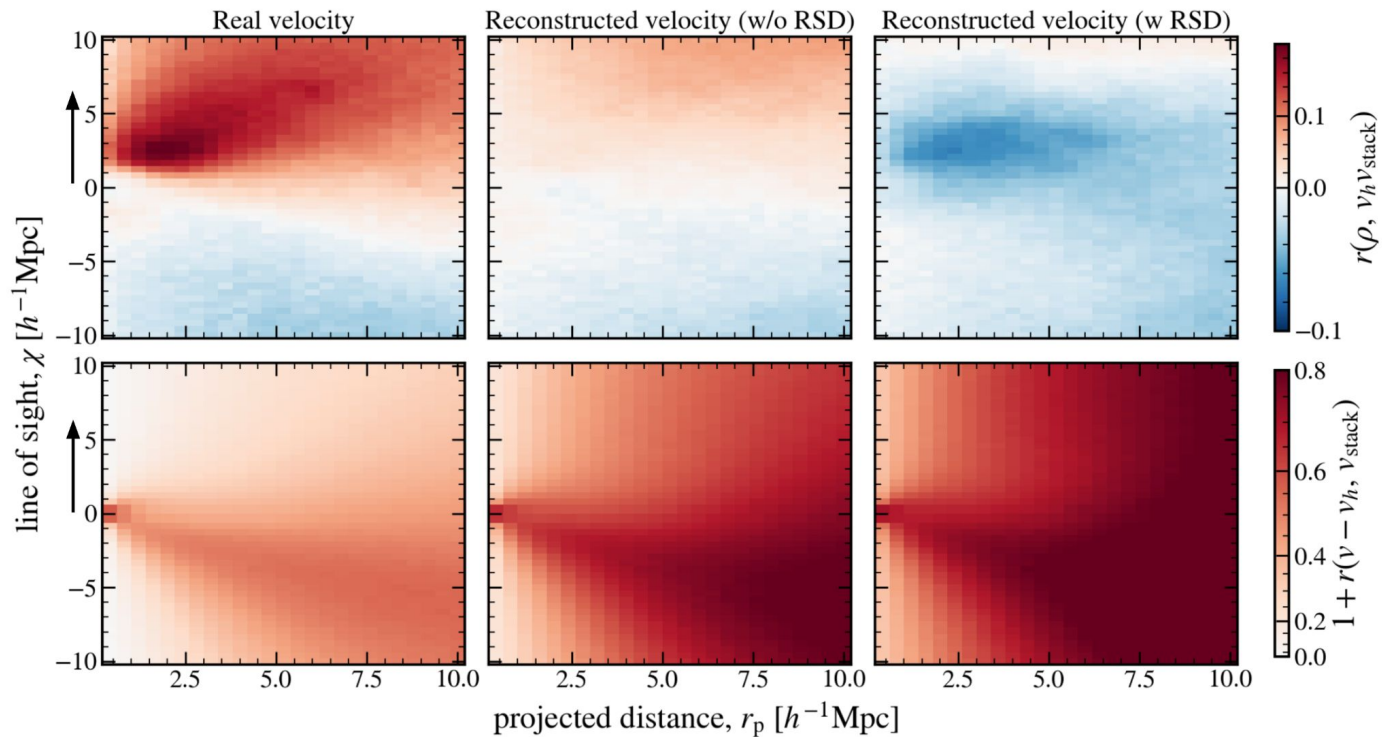
DM – Gas mapping: outflows



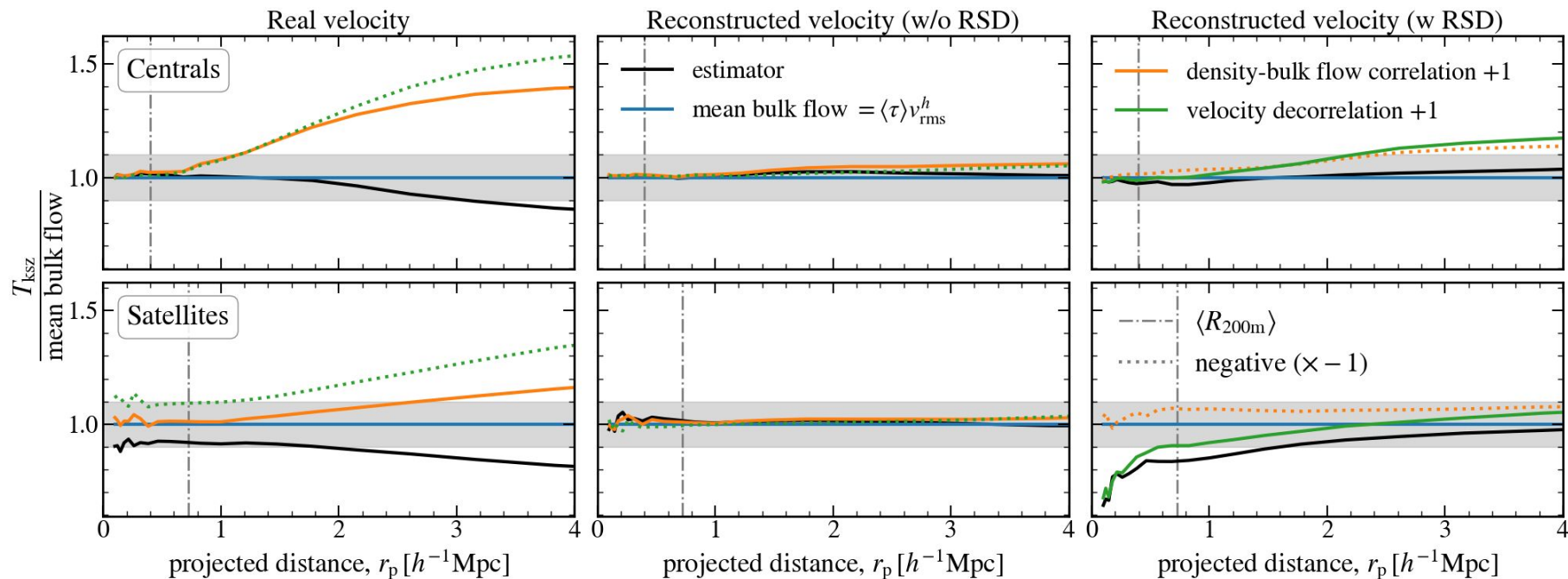
DM – Gas mapping: outflows



Physical origin of non-linear terms



Non-linear terms: centrals vs satellites



Non-linear terms with reconstructed velocities w RSD

Dependence on smoothing scale

