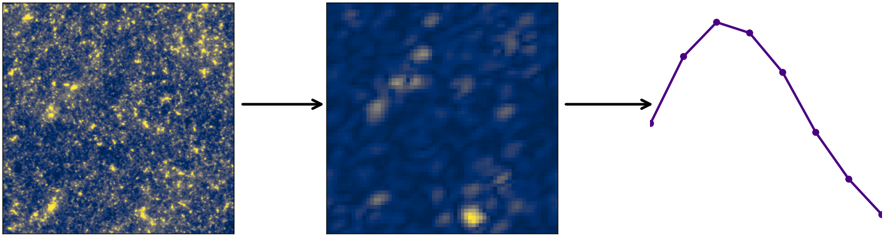
Scattering transforms for weak lensing cosmological inference



Mariia Marinichenko
Leiden University, the Netherlands

Non-Gaussian Universe ▪ June 17, 2026

Key questions

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   - captures non-Gaussian information
   - easy to compute and interpretable

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ST is a fast route from WL maps to comprehensible inference

Why the power spectrum is not enough

The power spectrum tells us **how much fluctuation power** we have at each angular scale

$$P_\kappa(\ell) = \langle |\kappa_\ell|^2 \rangle.$$

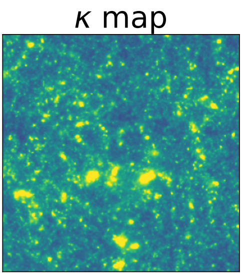
But it does not keep the Fourier phases, which carry information about **where structures are** and **how they are arranged**

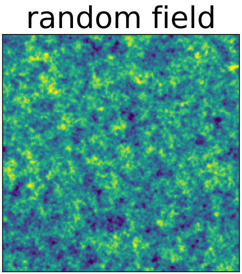
So, we lose part of the information about:

- halos, filaments and voids
- clustering of structures of different sizes
- nonlinear effects from baryons or dark sector physics

Part of this missing information can be recovered with **higher order statistics**

Why the scattering transform?





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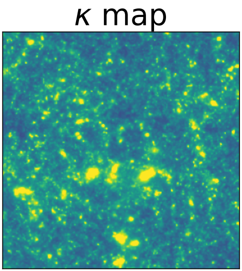

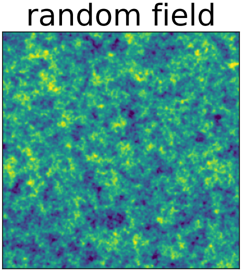

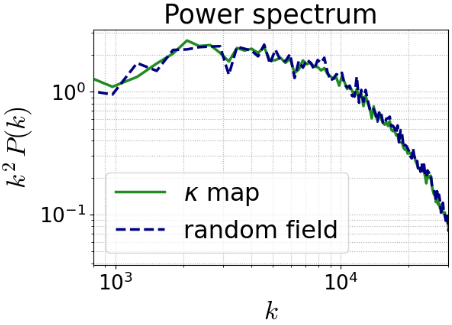

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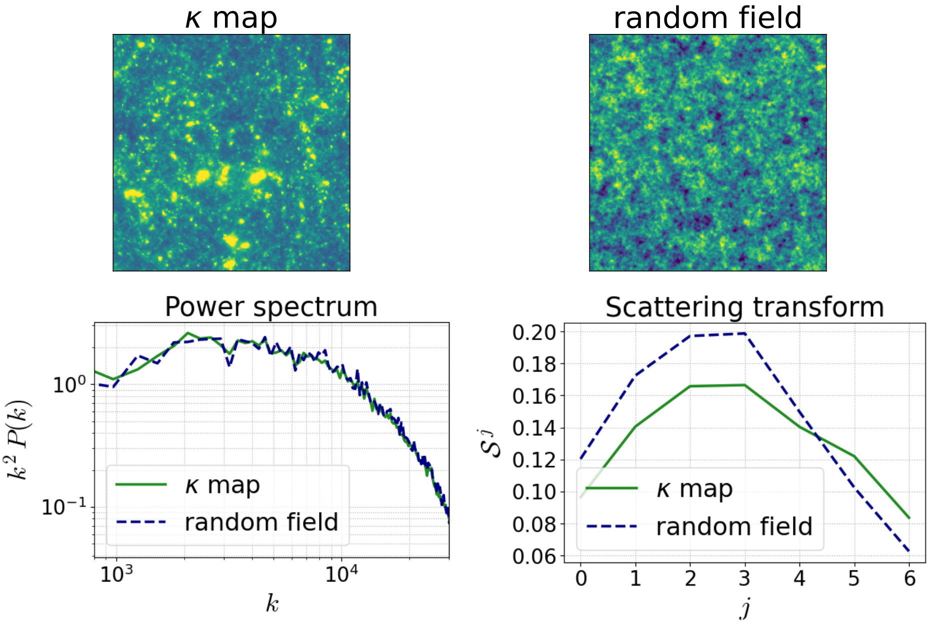
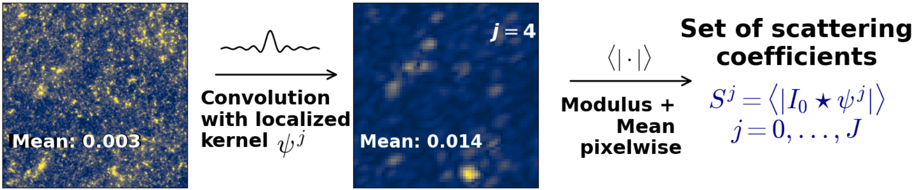


Scattering Transform



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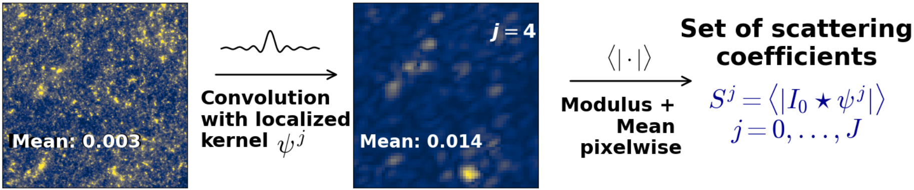

Scattering transform = wavelet convolution + modulus + mean

$$\mathcal{S}^j = \langle| I_0 \star \psi^j |\rangle$$

for a range of dyadic scales $j = 0, ..., J$

filter size = 2^j, $\quad j \sim \theta \sim \frac{1}{\ell} \sim \frac{1}{k}$

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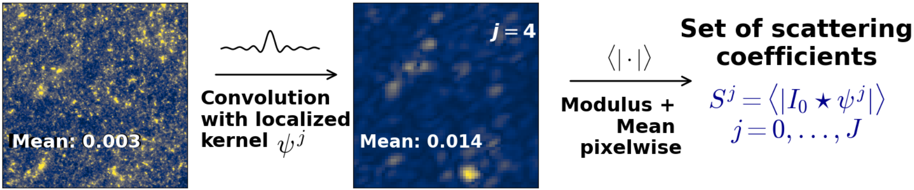

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Advantages

- **Interpretable** (strength of fluctuations)
- **Efficient** (compact set of estimators)
- **Robust** (stable to noise)

What information does ST add?

First order: structures at each scale

$$S_1(j) = \langle |I_0 \star \psi_j| \rangle$$

- measures how much structure appears at some (angular) scale j
- similar idea to the power spectrum, but based on wavelets

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Second order: clustering across scales

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- captures how small structures are grouped into larger ones
- describes the hierarchy of clustering patterns

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ST describes map morphology ordered by scale

Why ST can improve cosmological constraints

Fisher forecast

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ST can break power spectrum degeneracies using clustering information and redshift evolution

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What ST adds

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- compact data vector
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ST adds map morphology in a handy way

What we want to measure

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Sensitivity

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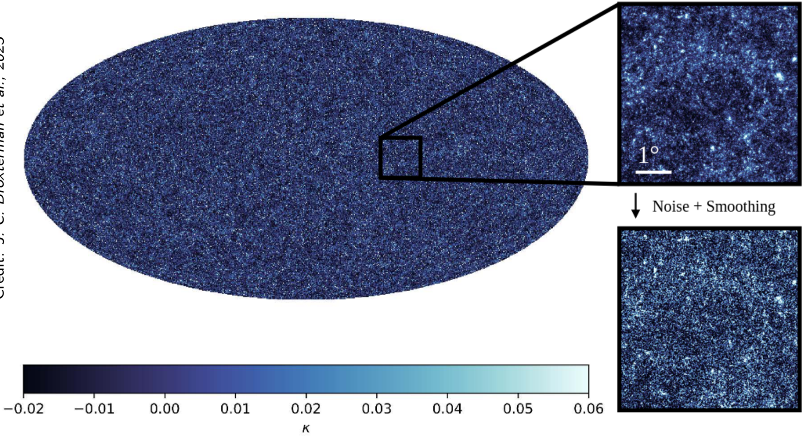
Debiasing

- model baryonic feedback bias with a transfer function
- add Euclid-like galaxy shape noise
- apply filters (Gaussian and Wiener)

FLAMINGO convergence maps

The transfer functions are derived from **Euclid-like WL mocks** from the **FLAMINGO** simulations

Credit: *J. C. Broxterman et al., 2023*



Full-sky weak lensing convergence map

Emulating scattering coefficients

Simulation set

- 100 FLAMINGO hypercube simulations
- 13 varied cosmological parameters (10 independent), including

$$\Omega_m,\ \sigma_8,\ w_0,\ w_a,\ M_\nu,\ \Gamma_{\rm dcdm},\ \dots$$

- matched initial phases for paired runs (with and without decaying DM)

Data vector

- κ maps in 5 tomographic bins
- HEALPix $N_{\rm side} = 8192$
- $3.6 \times 3.6\ {\rm deg}^2$ non-overlapping patches
- 1st ST coefficients for each patch
- Euclid-like Gaussian galaxy shape noise:
- $n_{\rm gal} = 30\,{\rm arcmin}^{-2}$, $\sigma_e = 0.26$

ST for cosmology variations

5 cosmology variations
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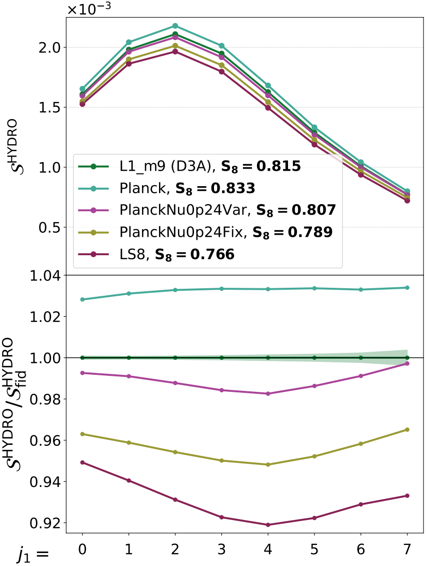
Same feedback, different cosmologies



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Result

Scattering coefficients are highly sensitive to $\mathbf{S_8}$

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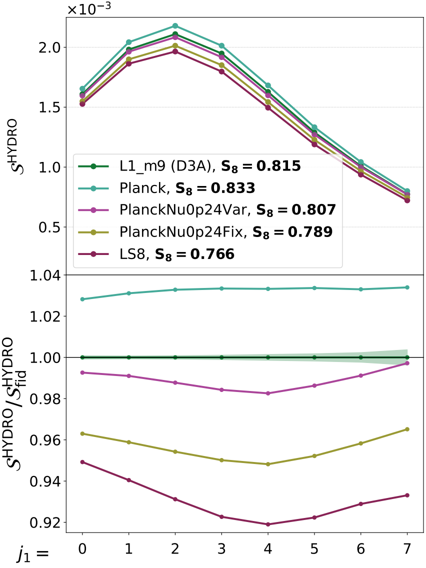

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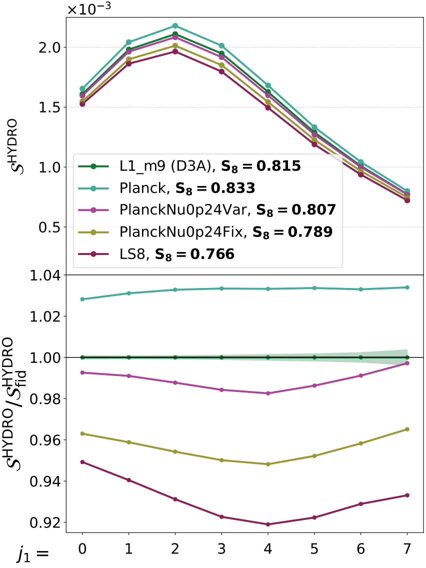

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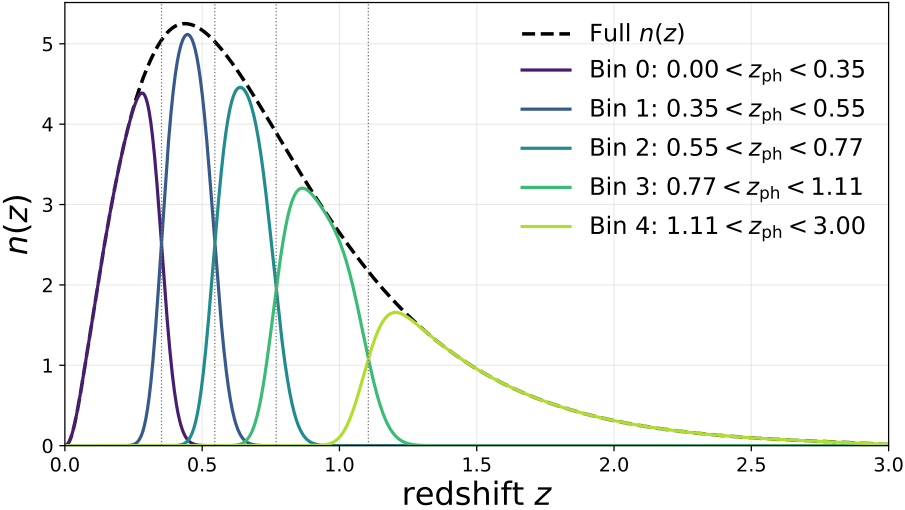
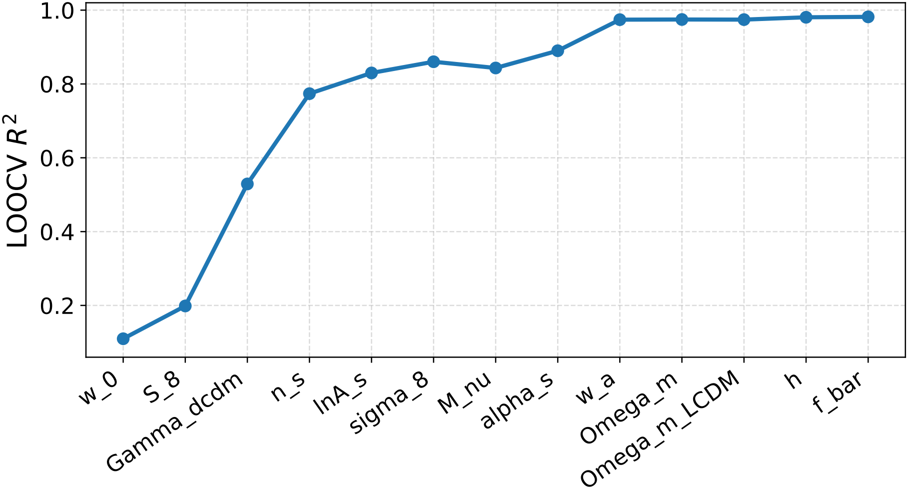
Tomographic bins

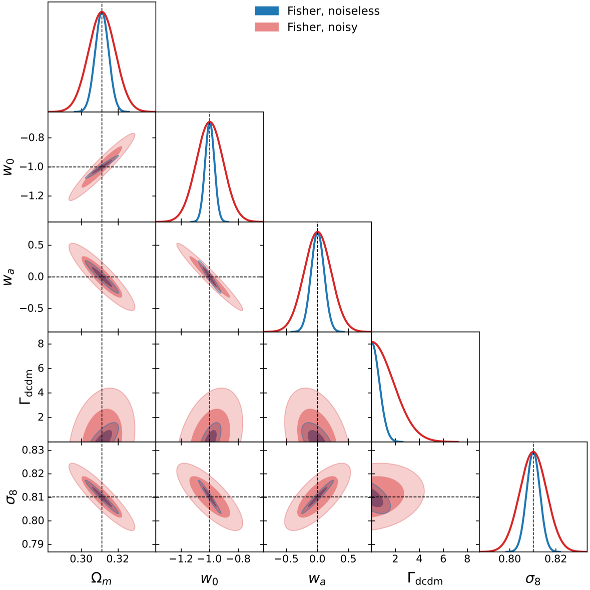


Which parameters matter for the emulator?

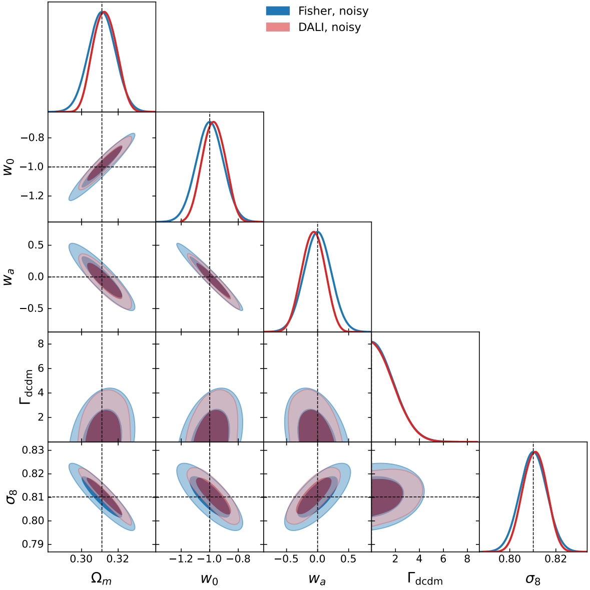


The greedy search selects the physical parameters that ST is sensitive to

ST forecast: noise



DALI improvement of the forecast



Baryonic effects on the weak lensing scattering transform

The effect of baryonic feedback on WL convergence can be quantified through a transfer function, which we extract from **FLAMINGO** simulations.

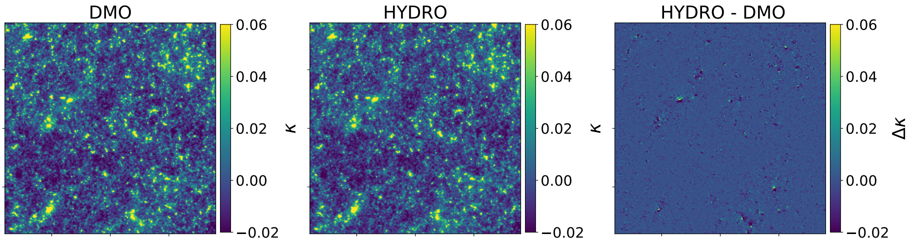


Figure: Convergence, i.e. κ, patches from FLAMINGO

Why weak lensing cares about baryons?

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Baryonic effects in WL **scattering transform** can be separated from cosmology through a **transfer function**

How the baryon model enters inference

Cosmological parameter inference

Observed κ maps $\Rightarrow$ ST data vector $\Rightarrow$ likelihood $\Rightarrow$ $\Omega_{\rm m}$, σ_8, w_0, $\Gamma_{\rm dcdm}$, ...

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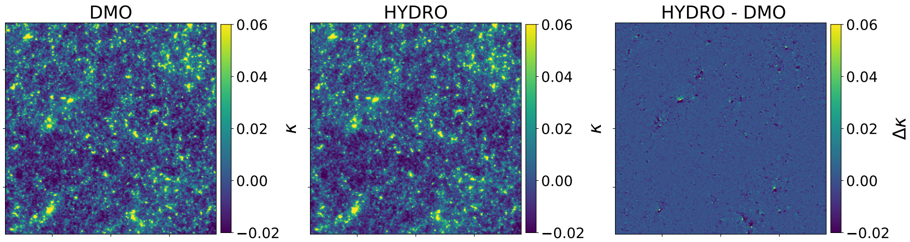
Algorithm: emulate cosmology, multiply by baryonic response, and infer parameters.

Transfer function



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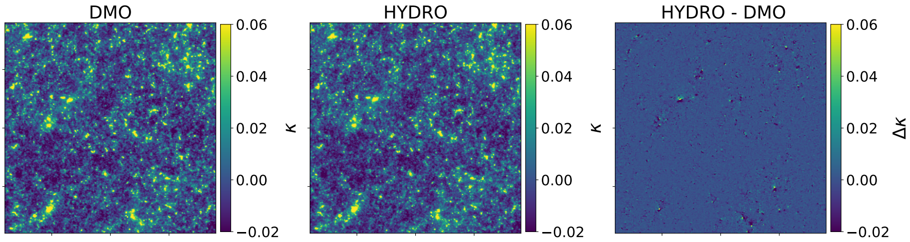
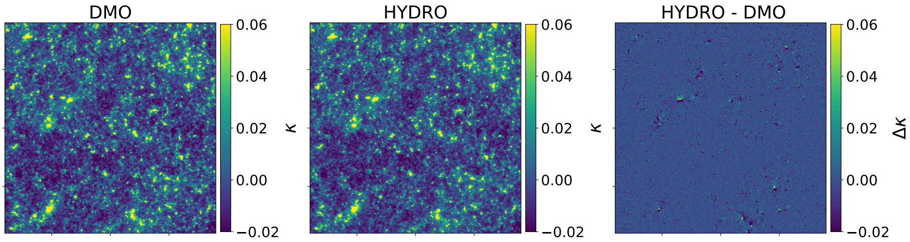


The baryonic suppression (or boost) factor for the total matter $P(k)$:

$$B = \frac{P^{\mathrm{HYDRO}}(k)}{P^{\mathrm{DMO}}(k)}$$

Transfer function



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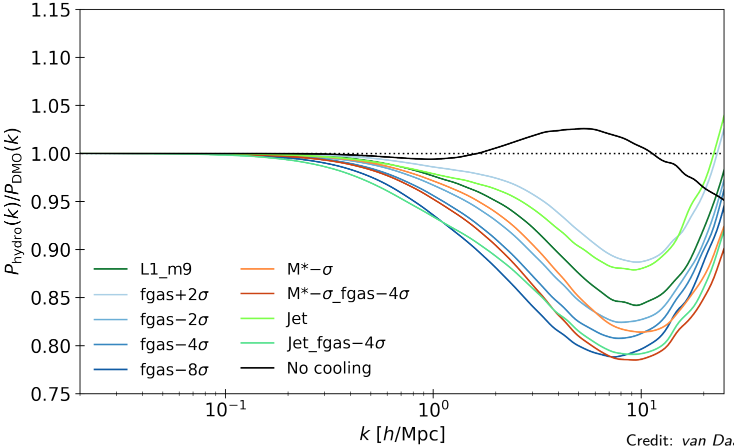
Similarly, we introduce **the baryonic transfer function for the scattering coefficients**:

$$\mathcal{T} = \frac{\mathcal{S}^{\mathrm{HYDRO}}}{\mathcal{S}^{\mathrm{DMO}}}$$

Baryonic feedback in FLAMINGO

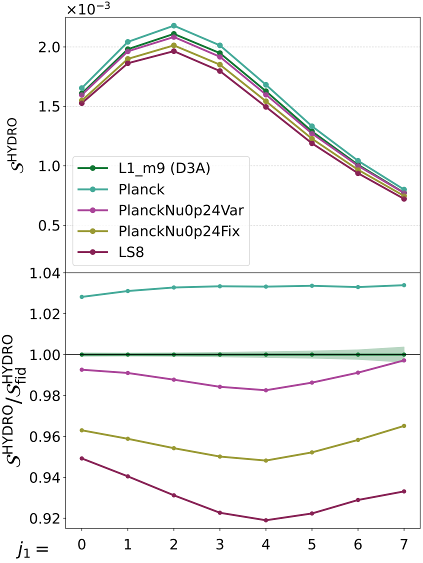
Calibrated to cluster gas fraction, fgas, and stellar mass function, $\mathrm{M}^\star$ at $z \approx 0$



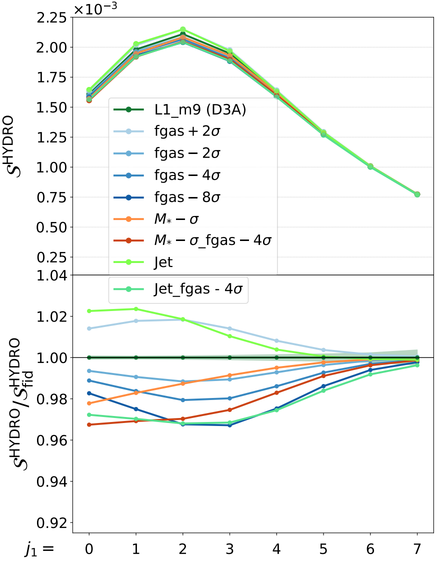
Credit: *van Daalen et al. (2025)*

Impact of baryons in ST

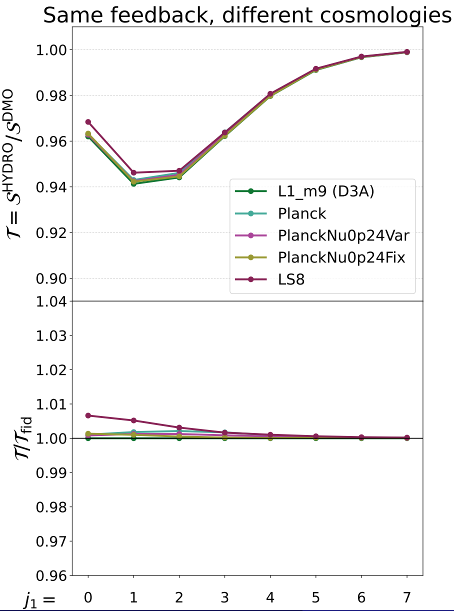
Same feedback, different cosmologies



D3A cosmology, different feedbacks



ST transfer function $\mathcal{T} = \mathcal{S}^{HYDRO}/\mathcal{S}^{DMO}$



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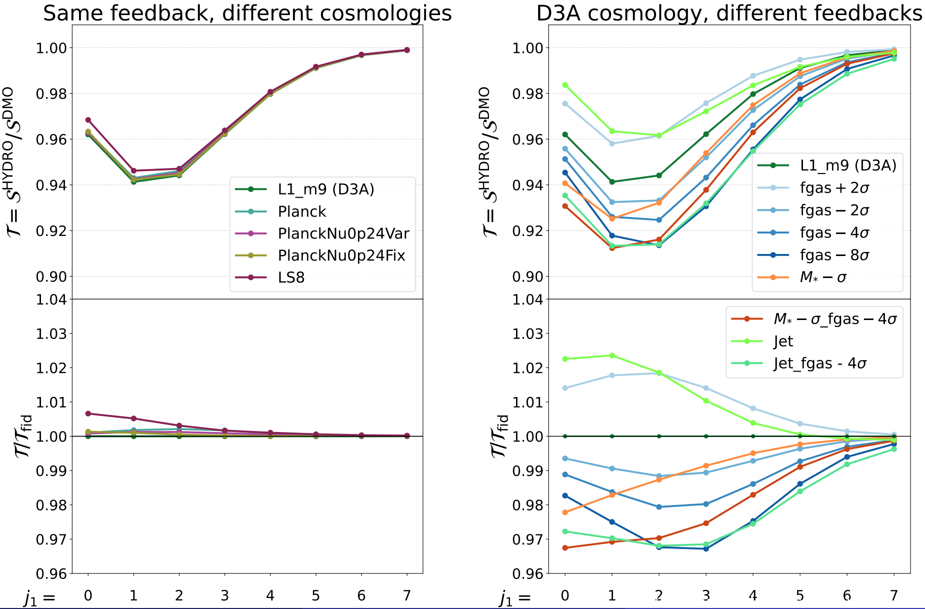
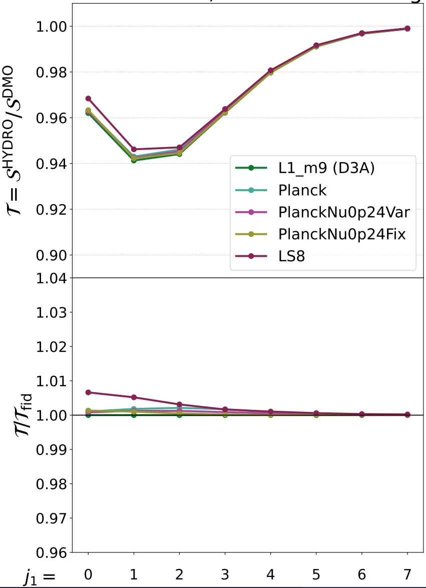


Noise and smoothing

Same feedback, different cosmologies



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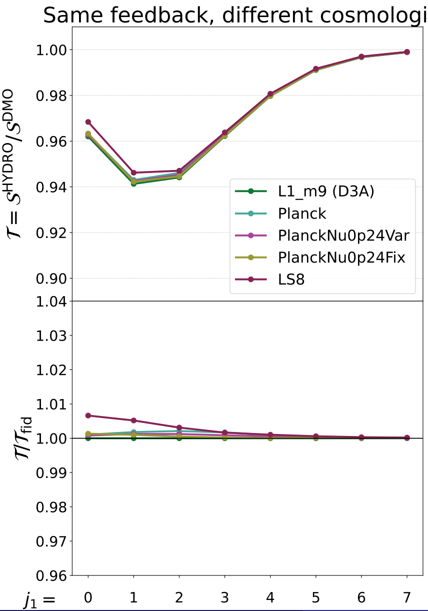
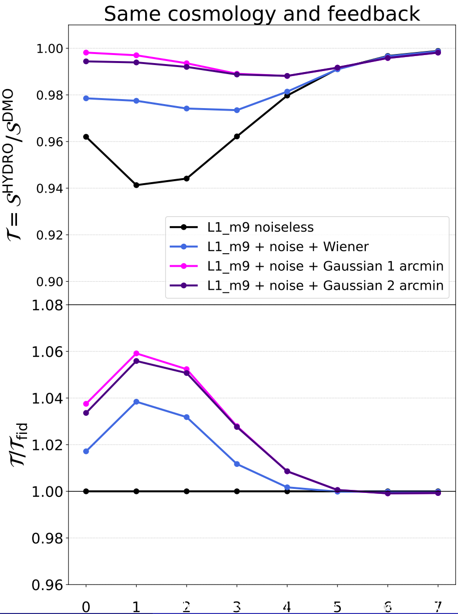
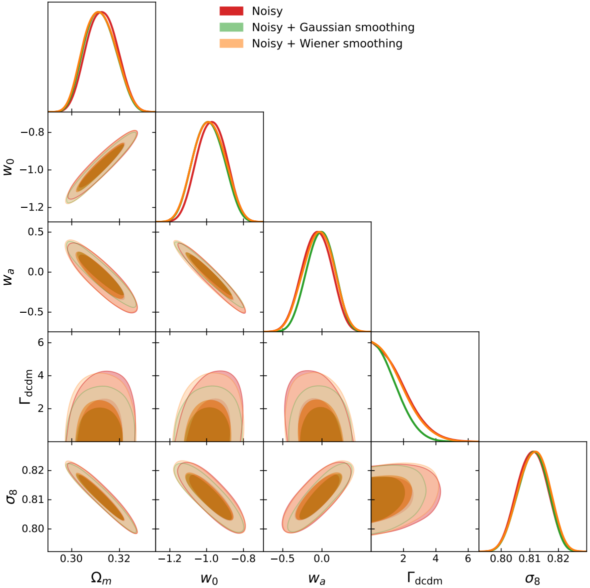
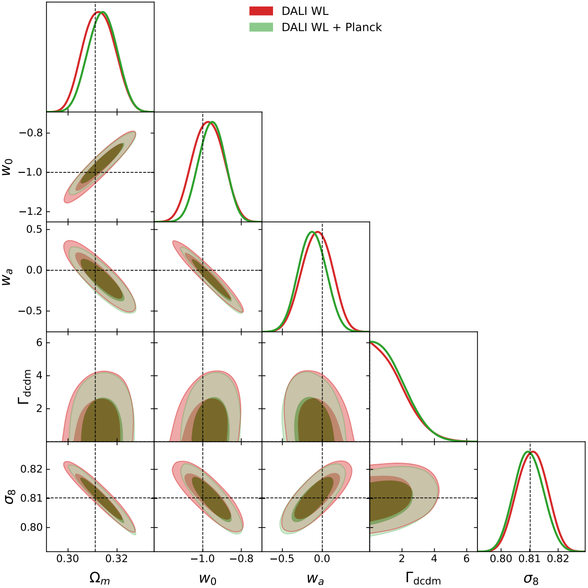




DCDM forecast: smoothing choices



DCDM constraints from ST + Planck

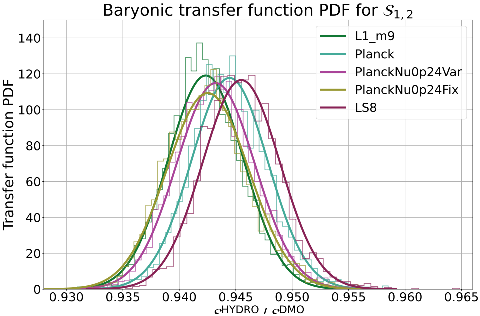


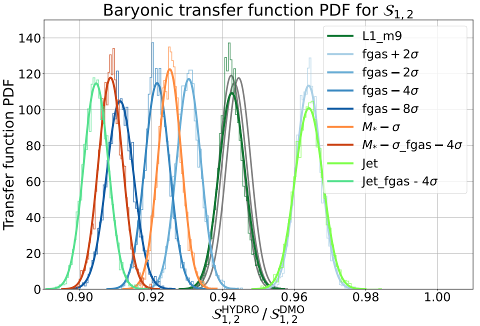
Take-home messages

- Scattering coefficients add **non-Gaussian information** beyond the power spectrum
- ST is **compact, stable and interpretable**
- ST alone provides tight constraints on cosmological parameters such as Γ_{dcdm}, Ω_{m}, σ_8, w_0, w_a
- Baryonic feedback can be modelled in a handy way by transfer function $\mathcal{T}$, but requires smart denoising techniques (e.g., Wiener filtering)

Thank you!

Backup slides


Baryonic transfer function PDF for $\mathcal{S}_{1,2}$
Transfer function PDF
$\mathcal{S}^{\mathrm{HYDRO}}_{1,2} / \mathcal{S}^{\mathrm{DMO}}_{1,2}$
0.930 0.935 0.940 0.945 0.950 0.955 0.960 0.965
0 20 40 60 80 100 120 140
L1_m9
Planck
PlanckNu0p24Var
PlanckNu0p24Fix
LS8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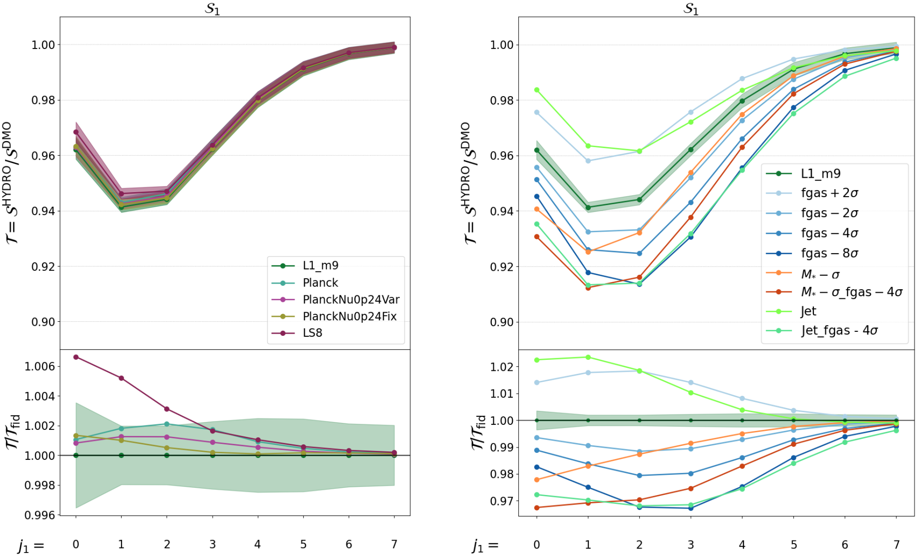
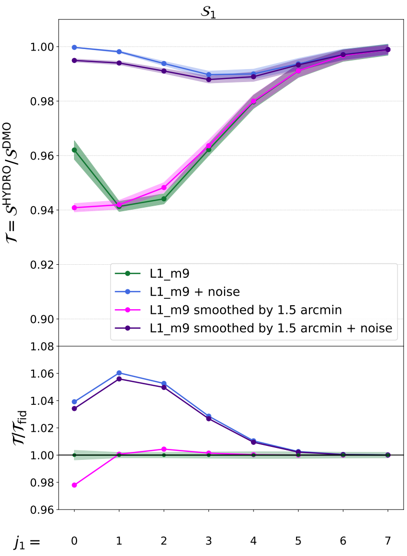
0 20 40 60 80 100 120 140
L1_m9
fgas $+ 2\sigma$
fgas $- 2\sigma$
fgas $- 4\sigma$
fgas $- 8\sigma$
$M_* - \sigma$
$M_* - \sigma$_fgas $- 4\sigma$
Jet
Jet_fgas - 4σ

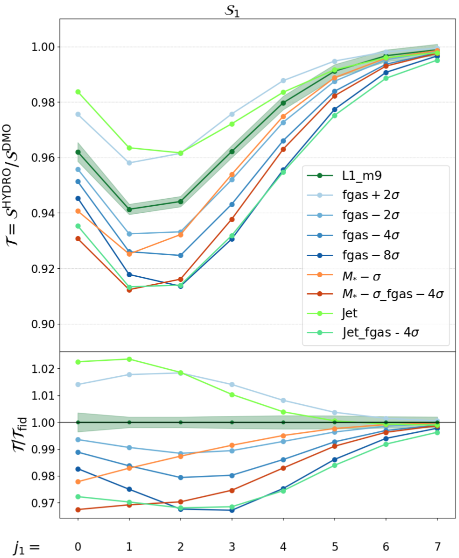
With std

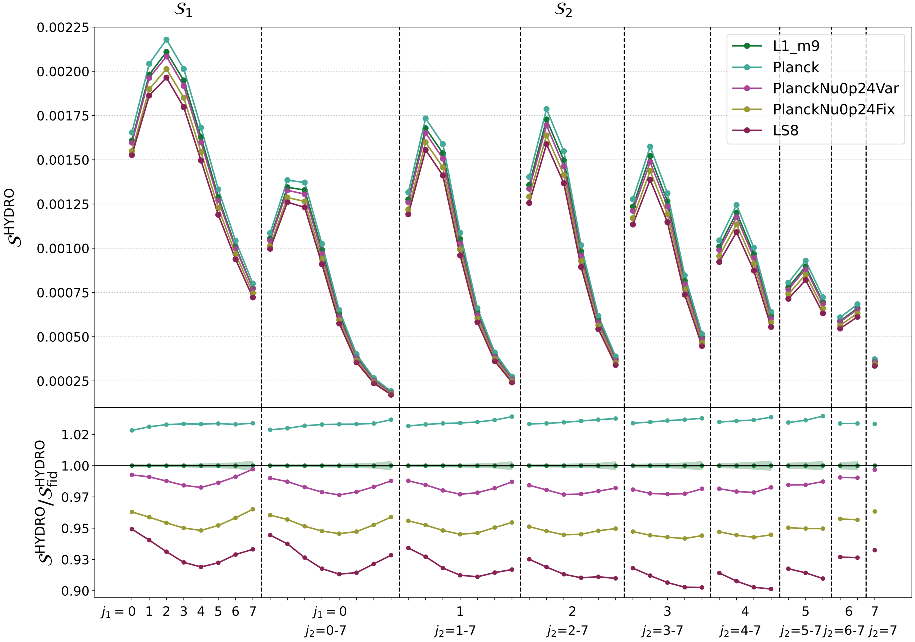


$\mathcal{S}_1$
$\mathcal{T} = S^{\rm HYDRO}/S^{\rm DMO}$
$\mathcal{T}/\mathcal{T}_{\rm fid}$
L1_m9
Planck
PlanckNu0p24Var
PlanckNu0p24Fix
LS8
$\mathcal{S}_1$
L1_m9
fgas + 2σ
fgas − 2σ
fgas − 4σ
fgas − 8σ
$M_* - \sigma$
$M_* - \sigma$_fgas − 4σ
Jet
Jet_fgas - 4σ
$j_1 =$
0 1 2 3 4 5 6 7

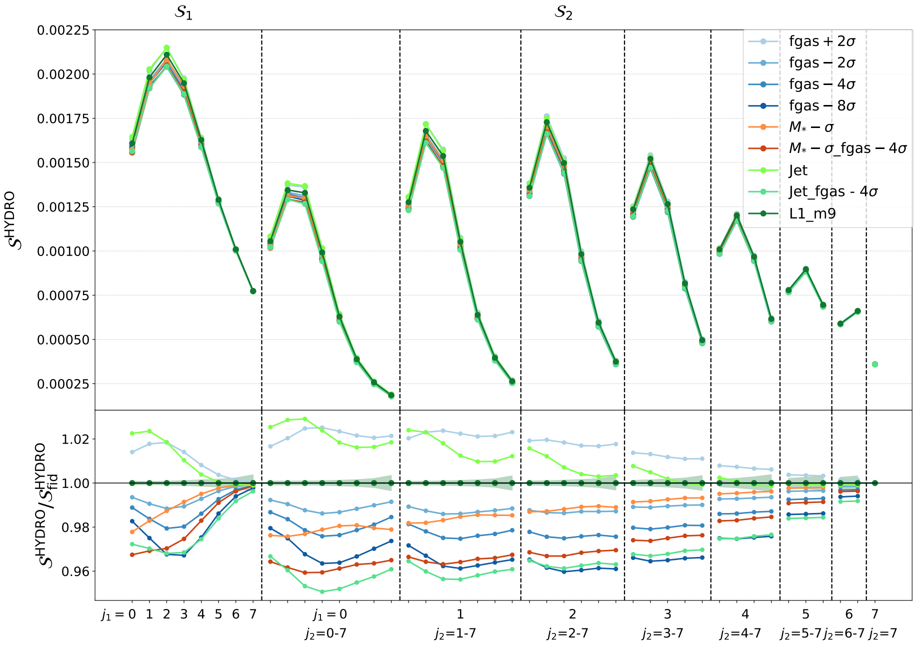
With std

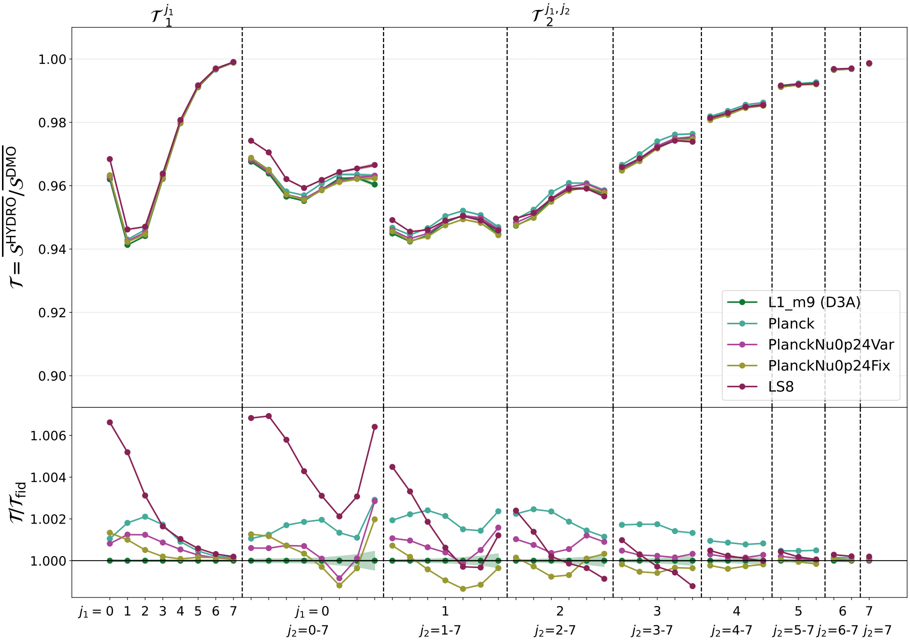

$\mathcal{S}_1$
$\mathcal{T} = \mathcal{S}^{\mathrm{HYDRO}}/\mathcal{S}^{\mathrm{DMO}}$
L1_m9
L1_m9 + noise
L1_m9 smoothed by 1.5 arcmin
L1_m9 smoothed by 1.5 arcmin + noise
$\mathcal{T}/\mathcal{T}_{\mathrm{fid}}$
$j_1 =$ 0 1 2 3 4 5 6 7

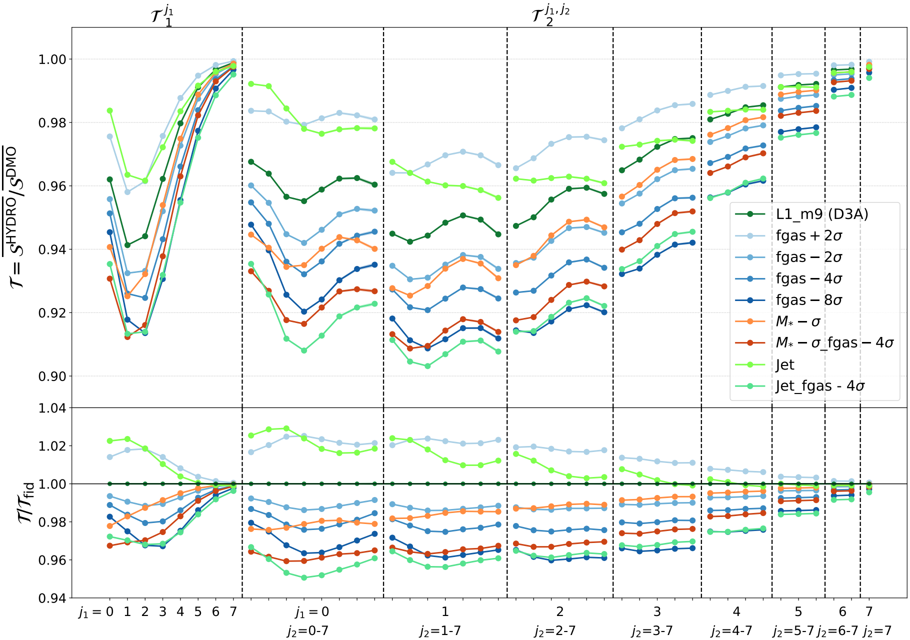

$\mathcal{S}_1$
$\mathcal{T} = \mathcal{S}^{\mathrm{HYDRO}}/\mathcal{S}^{\mathrm{DMO}}$
L1_m9
fgas + 2σ
fgas − 2σ
fgas − 4σ
fgas − 8σ
$M_* - \sigma$
$M_* - \sigma$_fgas − 4σ
Jet
Jet_fgas - 4σ
$\mathcal{T}/\mathcal{T}_{\mathrm{fid}}$
$j_1 =$ 0 1 2 3 4 5 6 7



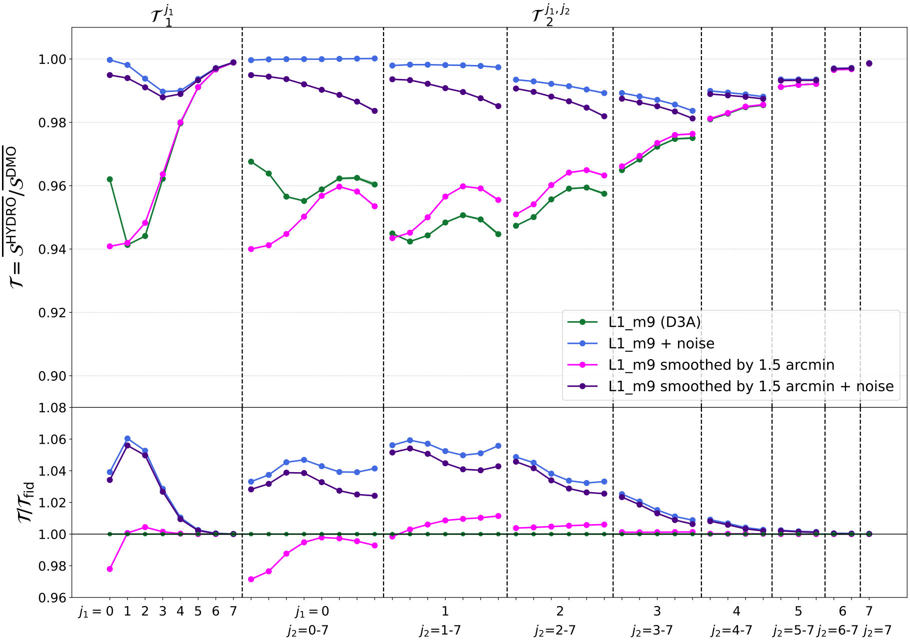
$\mathcal{S}_1$
$\mathcal{S}_2$
L1_m9
Planck
PlanckNu0p24Var
PlanckNu0p24Fix
LS8
$\mathcal{S}^{\rm HYDRO}$
$\mathcal{S}^{\rm HYDRO}/\mathcal{S}^{\rm HYDRO}_{\rm fid}$
0.00225
0.00200
0.00175
0.00150
0.00125
0.00100
0.00075
0.00050
0.00025
1.02
1.00
0.97
0.95
0.93
0.90
$j_1 = 0$ 1 2 3 4 5 6 7
$j_1 = 0$
j_2=0-7
1
j_2=1-7
2
j_2=2-7
3
j_2=3-7
4
j_2=4-7
5
j_2=5-7
6
j_2=6-7
7
j_2=7


$\mathcal{S}_1$
$\mathcal{S}_2$
$\mathcal{S}^{\mathrm{HYDRO}}$
$\mathcal{S}^{\mathrm{HYDRO}}/\mathcal{S}^{\mathrm{HYDRO}}_{\mathrm{fid}}$
fgas + 2σ
fgas − 2σ
fgas − 4σ
fgas − 8σ
$M_* - \sigma$
$M_* - \sigma$_fgas − 4σ
Jet
Jet_fgas - 4σ
L1_m9
$j_1 = 0$ 1 2 3 4 5 6 7
$j_1 = 0$ j_2=0-7
1 j_2=1-7
2 j_2=2-7
3 j_2=3-7
4 j_2=4-7
5 j_2=5-7
6 j_2=6-7
7 j_2=7

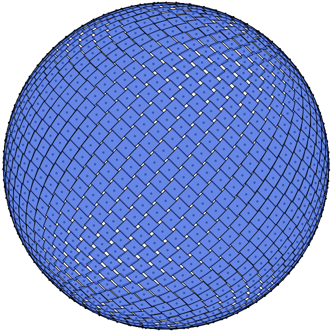

$\mathcal{T}_1^{j_1}$
$\mathcal{T}_2^{j_1,j_2}$
$\mathcal{T} = \overline{S^{\mathrm{HYDRO}}} / \overline{S^{\mathrm{DMO}}}$
$\mathcal{T}/\mathcal{T}_{\mathrm{fid}}$
L1_m9 (D3A)
Planck
PlanckNu0p24Var
PlanckNu0p24Fix
LS8
1.00
0.98
0.96
0.94
0.92
0.90
1.006
1.004
1.002
1.000
$j_1 = 0$ 1 2 3 4 5 6 7
$j_1 = 0$
j_2=0-7
1
j_2=1-7
2
j_2=2-7
3
j_2=3-7
4
j_2=4-7
5
j_2=5-7
6
j_2=6-7
7
j_2=7

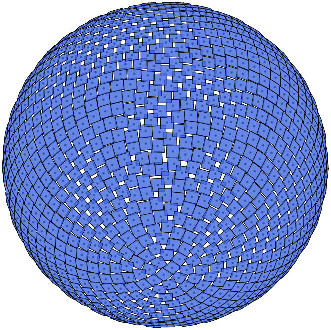


$\mathcal{T}_1^{j_1}$
$\mathcal{T}_2^{j_1,j_2}$
$\mathcal{T} = \overline{S^{\mathrm{HYDRO}}}/\overline{S^{\mathrm{DMO}}}$
$\mathcal{T}/\mathcal{T}_{\mathrm{fid}}$
L1_m9 (D3A)
fgas + 2σ
fgas − 2σ
fgas − 4σ
fgas − 8σ
$M_* - \sigma$
$M_* - \sigma$_fgas − 4σ
Jet
Jet_fgas - 4σ
$j_1 = 0$ 1 2 3 4 5 6 7
$j_1 = 0$ 1 2 3 4 5 6 7
j_2=0-7 j_2=1-7 j_2=2-7 j_2=3-7 j_2=4-7 j_2=5-7 j_2=6-7 j_2=7



$\mathcal{T}_1^{j_1}$
$\mathcal{T}_2^{j_1,j_2}$
$\mathcal{T} = \overline{S^{\mathrm{HYDRO}}} / \overline{S^{\mathrm{DMO}}}$
$\mathcal{T}/\mathcal{T}_{\mathrm{fid}}$
L1_m9 (D3A)
L1_m9 + noise
L1_m9 smoothed by 1.5 arcmin
L1_m9 smoothed by 1.5 arcmin + noise
$j_1 = 0$ 1 2 3 4 5 6 7
$j_1 = 0$ j_2=0-7
1 j_2=1-7
2 j_2=2-7
3 j_2=3-7
4 j_2=4-7
5 j_2=5-7
6 j_2=6-7
7 j_2=7





Scales

Table 2. Scale definitions used throughout the paper, with corresponding diadic scales j, Fourier wavenumbers k, and real-space scales D at $z \approx 1$.

Name	j	k ($h\,\mathrm{Mpc}^{-1}$)	D ($\mathrm{Mpc}\,h^{-1}$)
Smallest	0	3.6	0.3
Small	1 – 2	1.8 - 0.9	0.6 – 1
Intermediate	3 – 5	0.4 – 0.1	2 – 9
Large	6 – 7	0.06 – 0.03	18 – 36