The cosmic web with warm dark matter, scale-dependant primordial non-Gaussianities and early dark energy

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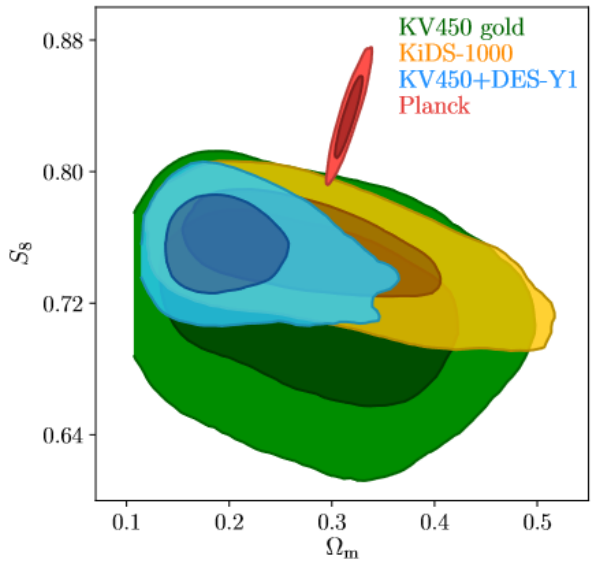
in collaboration with Katarina Kraljic, Clément Stahl and Benoit Famaey

RAMSES SNO days – November 25, 2025

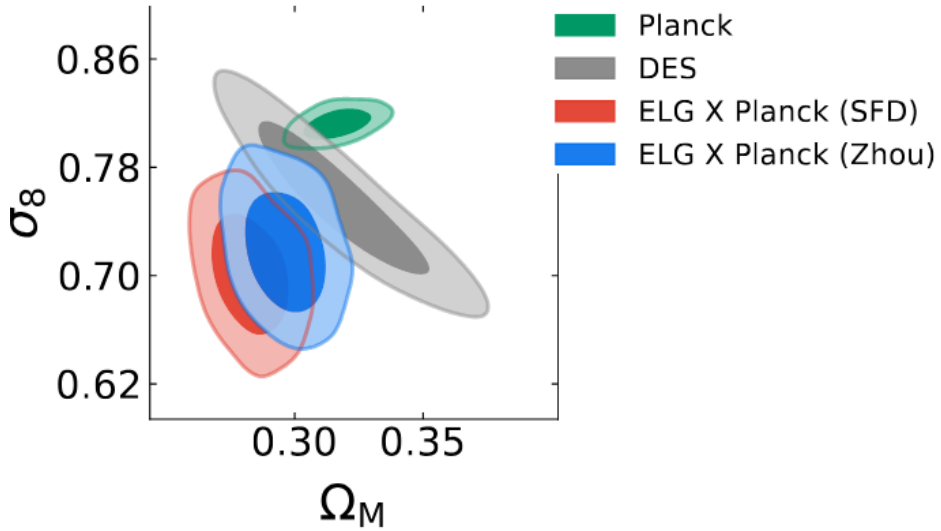
Potential tension on S_8



Asgari et al. 2021

- S_8 : measures clustering of matter on small scales
- Weak lensing measurements in local universe from KiDS and DES originally found a tension of $\sim 3\sigma$ with Planck CMB
- Recent reanalyses from KiDS reduced this tension to $\sim 1\sigma$: finally coherent with Planck

Potential tension on S_8



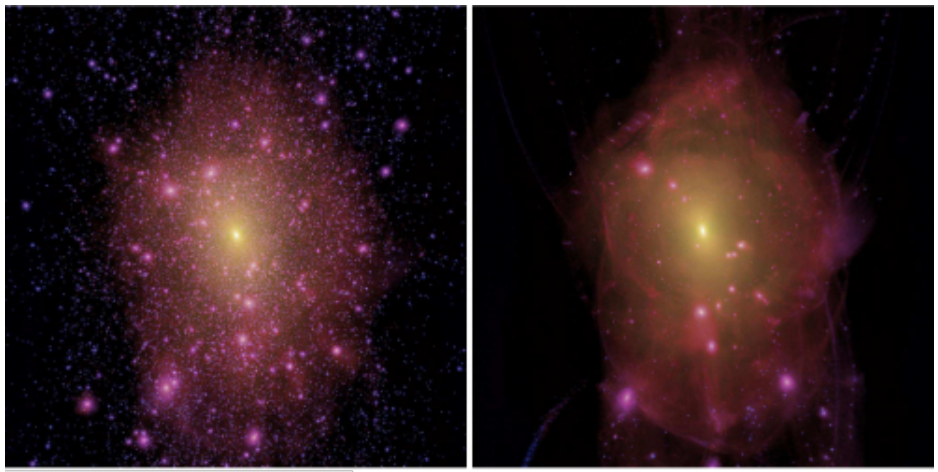
Karim et al. 2025

- S_8 from DESI galaxy clustering in tension of $\sim 3\sigma$, but sensible to systematics (eg. dust)
- The existence or not of a tension on S_8 will be clarified by Euclid, which will measure S_8 with more precision
- If not due to systematics, this tension motivates cosmological models that form less small-scale structures than ΛCDM

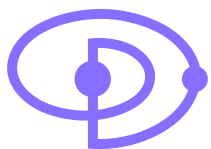
Primordial non-Gaussianities and warm dark matter

Two extensions that suppress structures at small scales :

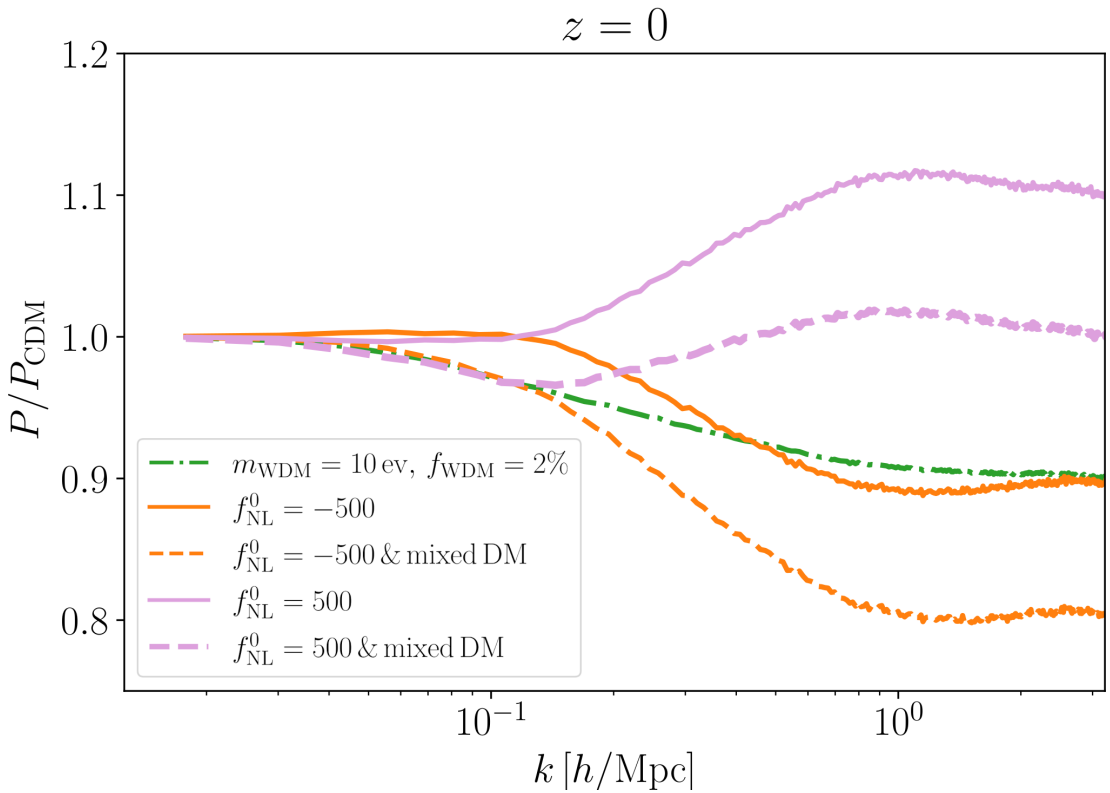
1. Scale-dependant primordial non-Gaussianities (sPNG) : modification of the initial distribution of δ (Stahl et al. 2024)
   - Amplitudes of the PNG $f_{\mathrm{NL}}(\mathbf{k})$: can be positive or negative (favors the apparition of over- or under-densities)
2. Warm dark matter (WDM) : diminution of the mass of the dark matter particles (Bode et al. 2001)
   - The lower the mass of the particles, the more small structures are suppressed



Credits : Angulo, 2021



Degeneracies on the power spectrum

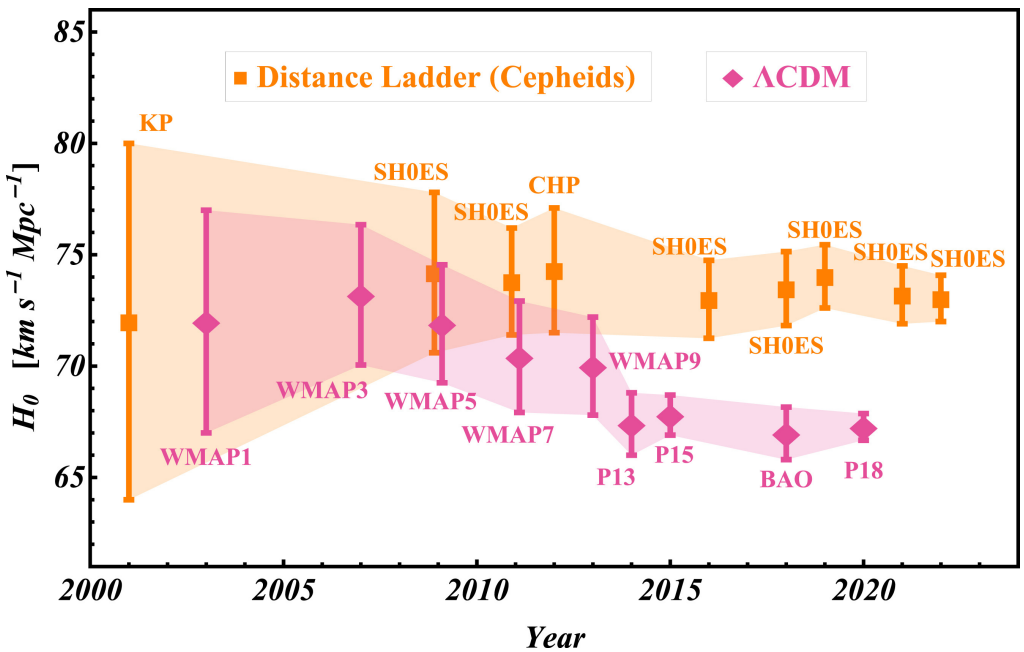


Stahl, Famaey, Ibata, Kraljic and **Castillo** 2025

- Warm dark matter and $f_{\rm NL} < 0$ (and their combination) are able to reduce S_8
- By combining $f_{\rm NL} > 0$ and WDM we can reproduce ΛCDM

The Hubble tension

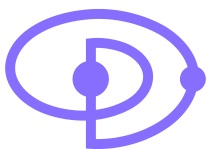
- Tension between measurements by type Ia supernovae in the local universe, and value extrapolated from the CMB
- Can be solved by models that change the expansion history of the universe before the emission of CMB



Perivolaropoulos and Skara, 2022

Early dark energy

- Early dark energy (EDE) : additional dark energy component in the early universe, active at $z \sim 3500$, then dissolves faster than radiation
- Latest data from ACT DR6 + DESI DR2 show a preference for EDE over ΛCDM at 5σ (Poulin et al. 2025)
- However models with EDE increase $P(k)$ at all k : worsens the S_8 tension (Stahl et al. 2025). This is a common problem to all models that solve H_0 by modifying pre-recombination physics
- Even if Euclid confirms that the S_8 measurements are coherent in ΛCDM, **they may still be inconsistent in models that solve the Hubble tension**



Motivations

- Simulations of models that combine EDE with $f_{\rm NL} < 0$ to compensate the increase of S_8
- Problem : **degeneracies** $\rightarrow$ construction of new statistical observables to distinguish all models
- Several observables can be built from the cosmic web : network of peaks $\mathcal{P}$, filaments $\mathcal{F}$, walls $\mathcal{W}$ and voids $\mathcal{V}$

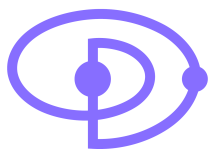
Sousbie 2011

Simulation setup

Simulation of WDM, sPNG, EDE and the following combinations :

1. $f_{\rm NL} = 500$ & WDM : reproduces the ΛCDM power spectrum at $z \leq 3$;
2. $f_{\rm NL} = -500$ & WDM : solves S_8 ;
3. $f_{\rm NL} = -300$ & EDE : solves H_0, leaves S_8 invariant (Stahl 2025) ;
4. $f_{\rm NL} = -1100$ & EDE : solves H_0 and S_8.

- Box of size 500 Mpc/h, 512^3 particles
- Initial conditions with MONOFONIC (Hahn 2020), $N-$body with GADGET–4 (Springel 2010) and RAMSES (Teyssier 2002)
- Density field smoothed on $R_s = 2$ Mpc
- 5 realizations to study cosmic variance



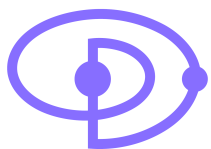
Minkowski functionals

Minkowski functionals : integral of topological quantities on different integration domains indexed by θ

- $v_0(\theta)$: volume occupied by regions of different densities,
- $v_1(\theta)$: area of the boundary of these regions,
- $v_2(\theta)$: mean curvature of the boundary,
- $v_3(\theta)$: Euler characteristic

The integral is performed on

$$C_\theta = \{x \in R^3 | \delta(x) \geq \theta\}.$$



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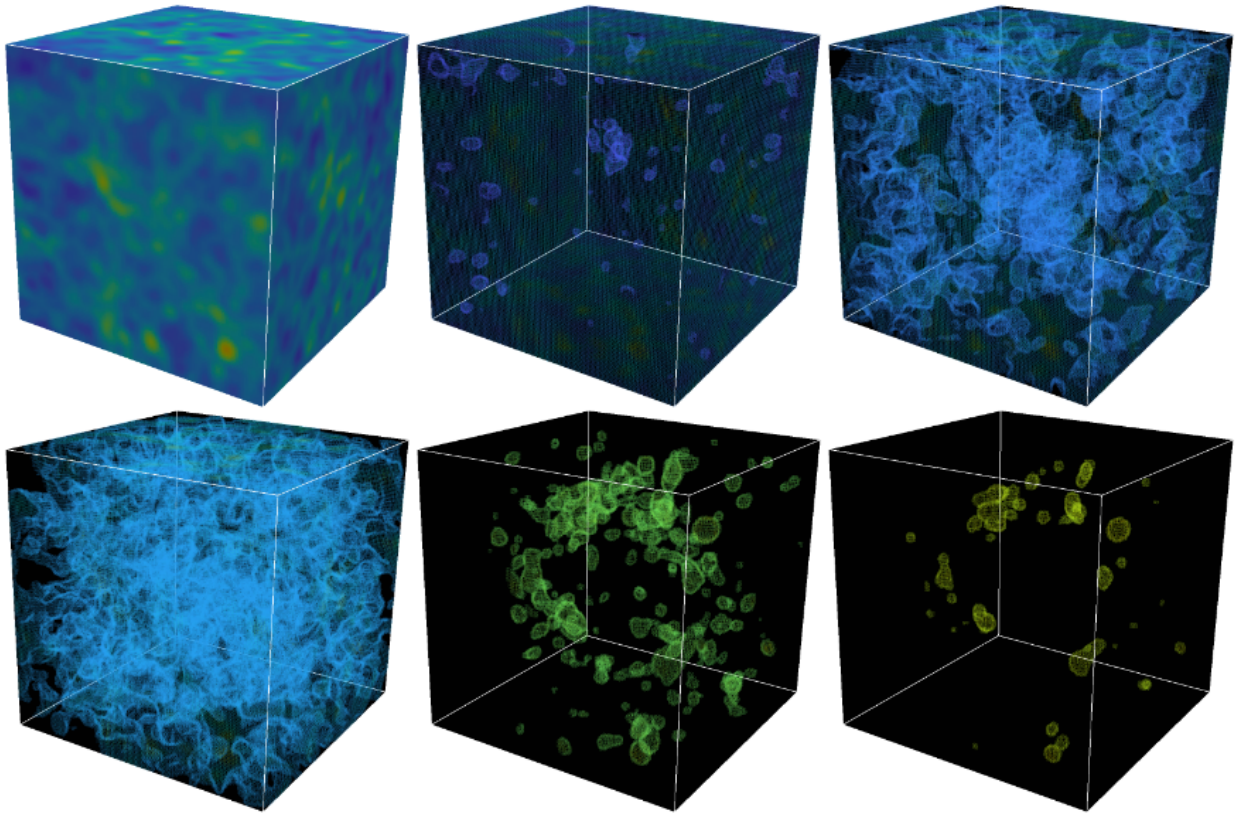
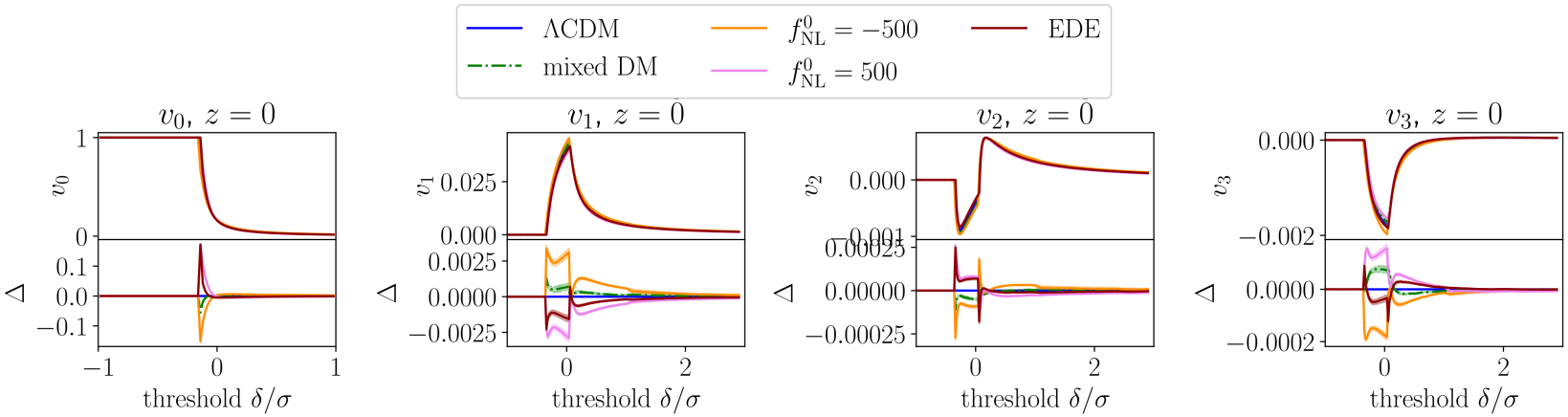


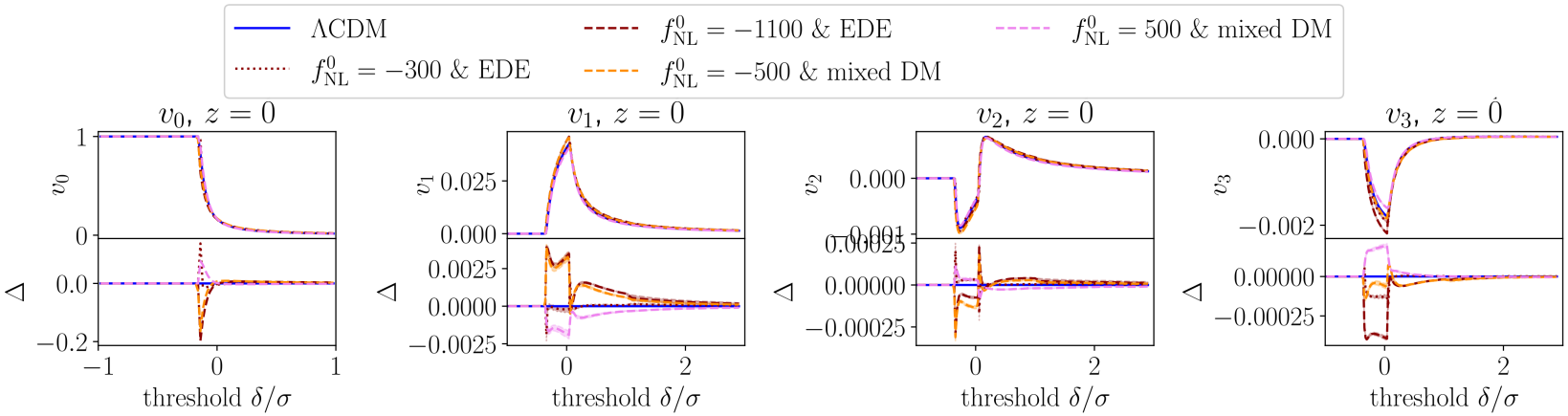
Schimd et al. 2024

Minkowski functionals



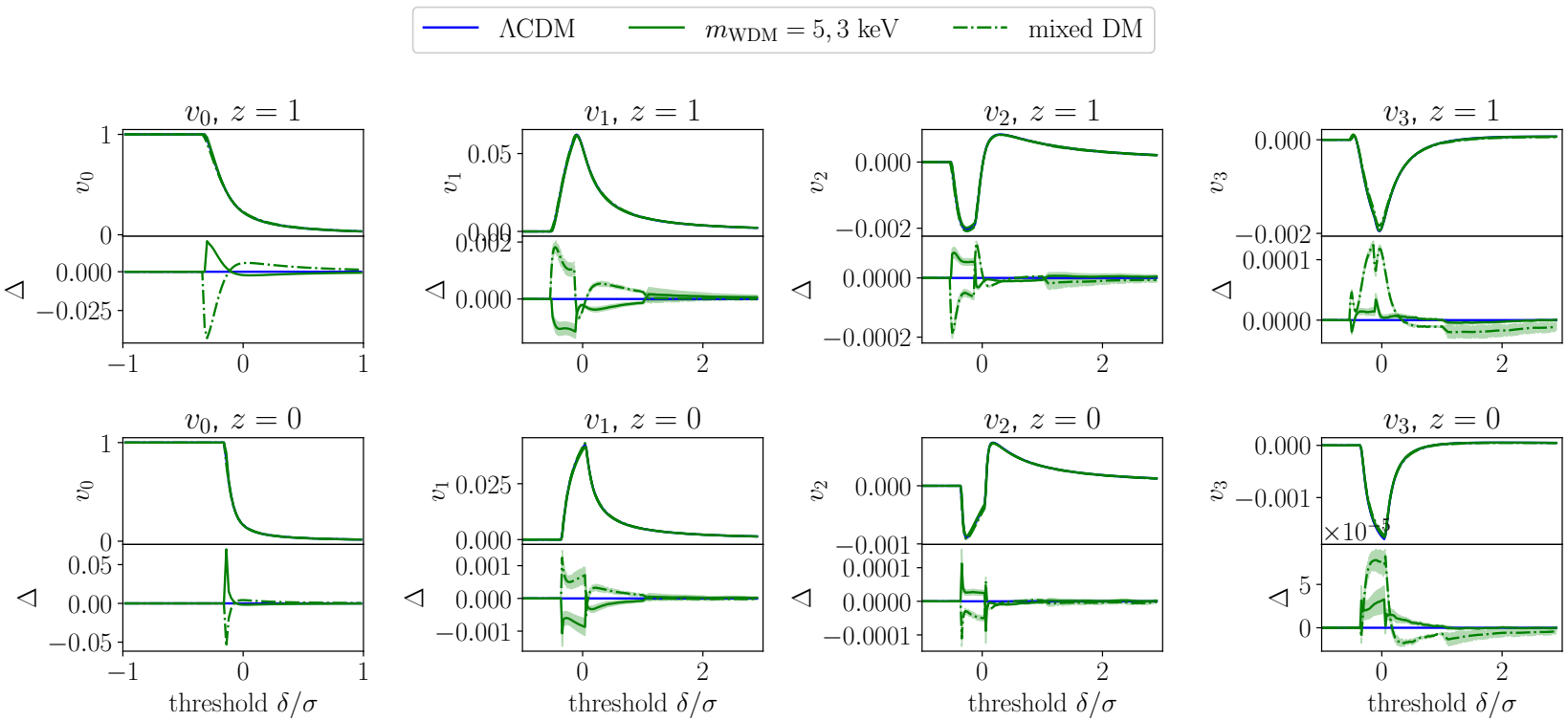
- $f_{\rm NL} < 0$ has a similar effect than WDM on v_0, v_1 and v_2 **but an opposite effect** than WDM on v_3
- The same behavior occurs for $f_{\rm NL} > 0$ and EDE
- Hence, combining two functionals is particularly promizing

Minkowski functionals



- The $f_{\rm NL} > 0$ + WDM model, that reproduces the ΛCDM power spectrum, can be distinguished from ΛCDM with v_3.
- Strong deviations (> 10 %) for at least one v_i for all models
- These deviations happen at $z = 0$ and $\theta \sim 0$: easy to observe

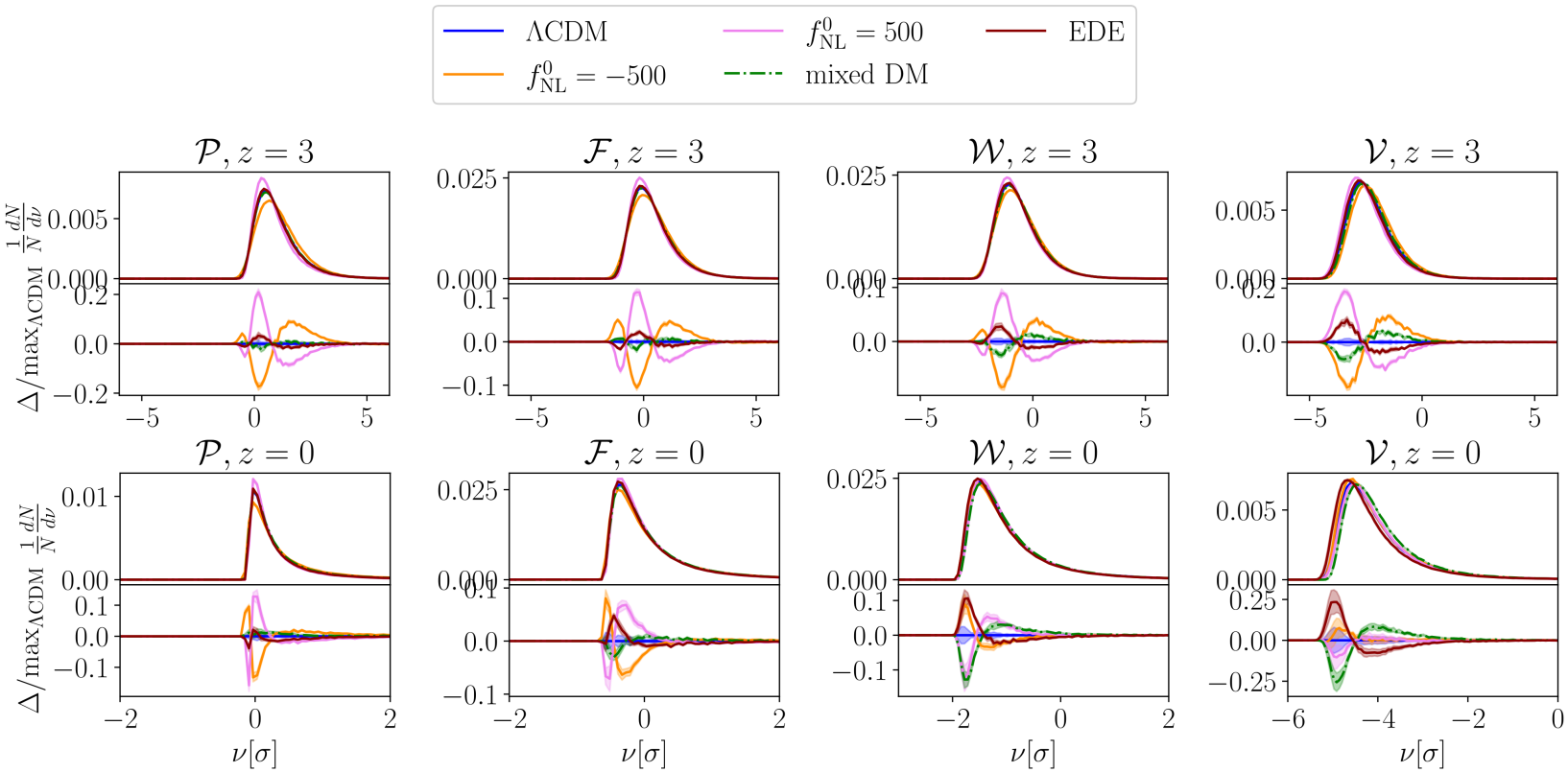
MF of WDM and mixed DM



- Opposite signature of WDM and mixed DM on v_0, v_1 and v_2
- Opens the possibility to constrain WDM mass from a low z measurement, in complement to Ly$-\alpha$ forest observations

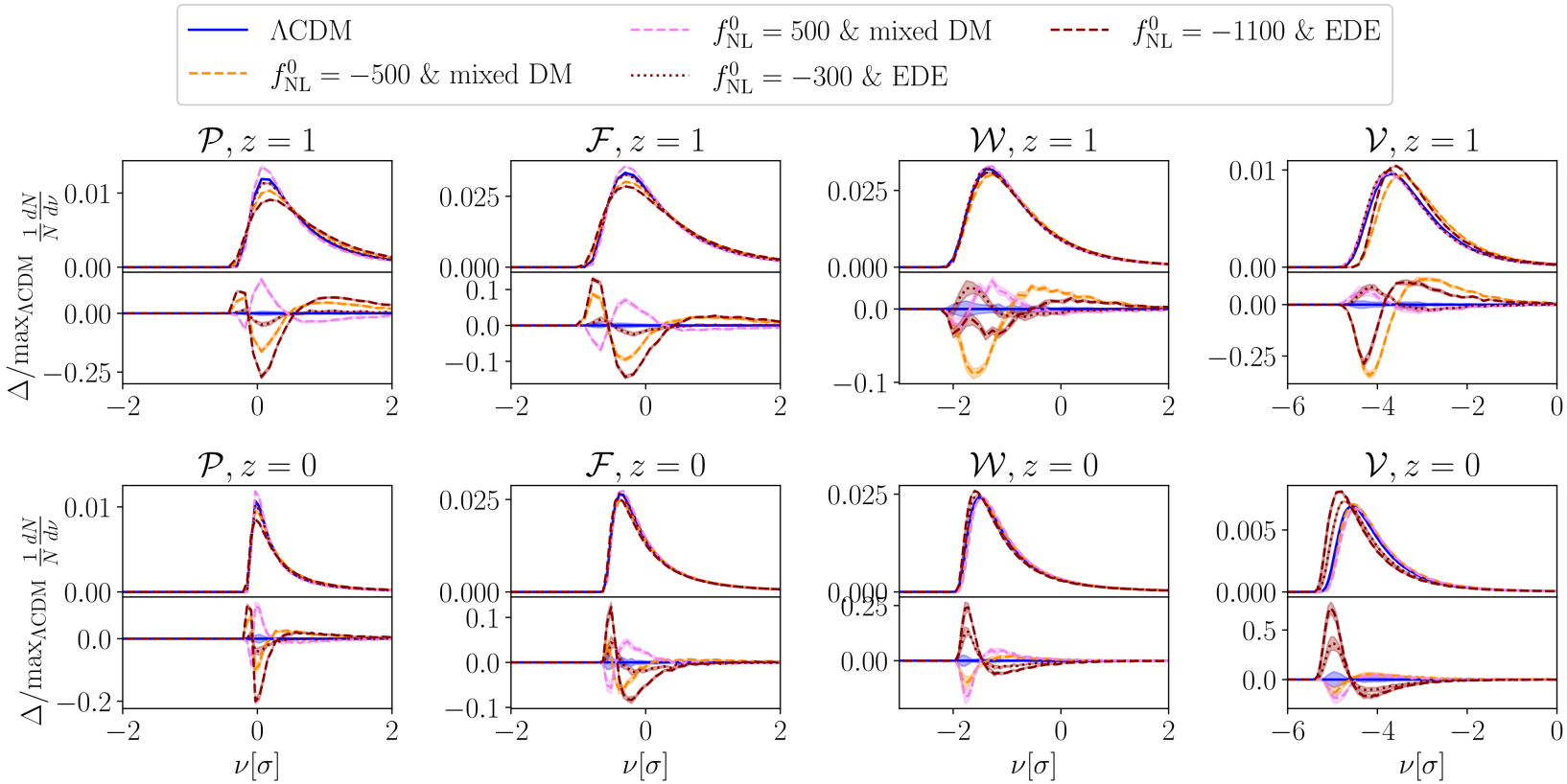
One-point functions of critical points

- Rarity of critical points : $\nu = \delta/\sigma$
- Peaks $\mathcal{P}$, Filaments $\mathcal{F}$, Walls $\mathcal{W}$ and Voids $\mathcal{V}$



- Counter-intuitive effect of PNG on walls and voids, as for v_3

One-point functions of critical points



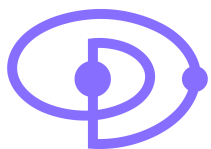
- Deviations on $\mathcal{V}$ of ~ 50 % in both models with PNG + EDE
- $f_{\rm NL} > 0$ + mixed DM has also a non-negliglible impact $(\sim 10\%)$ on $\mathcal{P}, W$ and $\mathcal{V}$

Two-point functions of critical points

- Two-point functions of critical points

$$1 + \zeta_{ij}(r) = \frac{\langle C_i C_j \rangle}{\sqrt{\langle C_i R_j \rangle \langle C_j R_i \rangle}} \sqrt{\frac{N_{R_i} N_{R_j}}{N_{C_i} N_{C_j}}}.$$

- C_i : collection of a particular type of critical points
- R_i : catalogue of uniformly distributed points
- $\langle XY \rangle$: pairs between X and Y with separation r.
- N_X : number of points in the catalog X.



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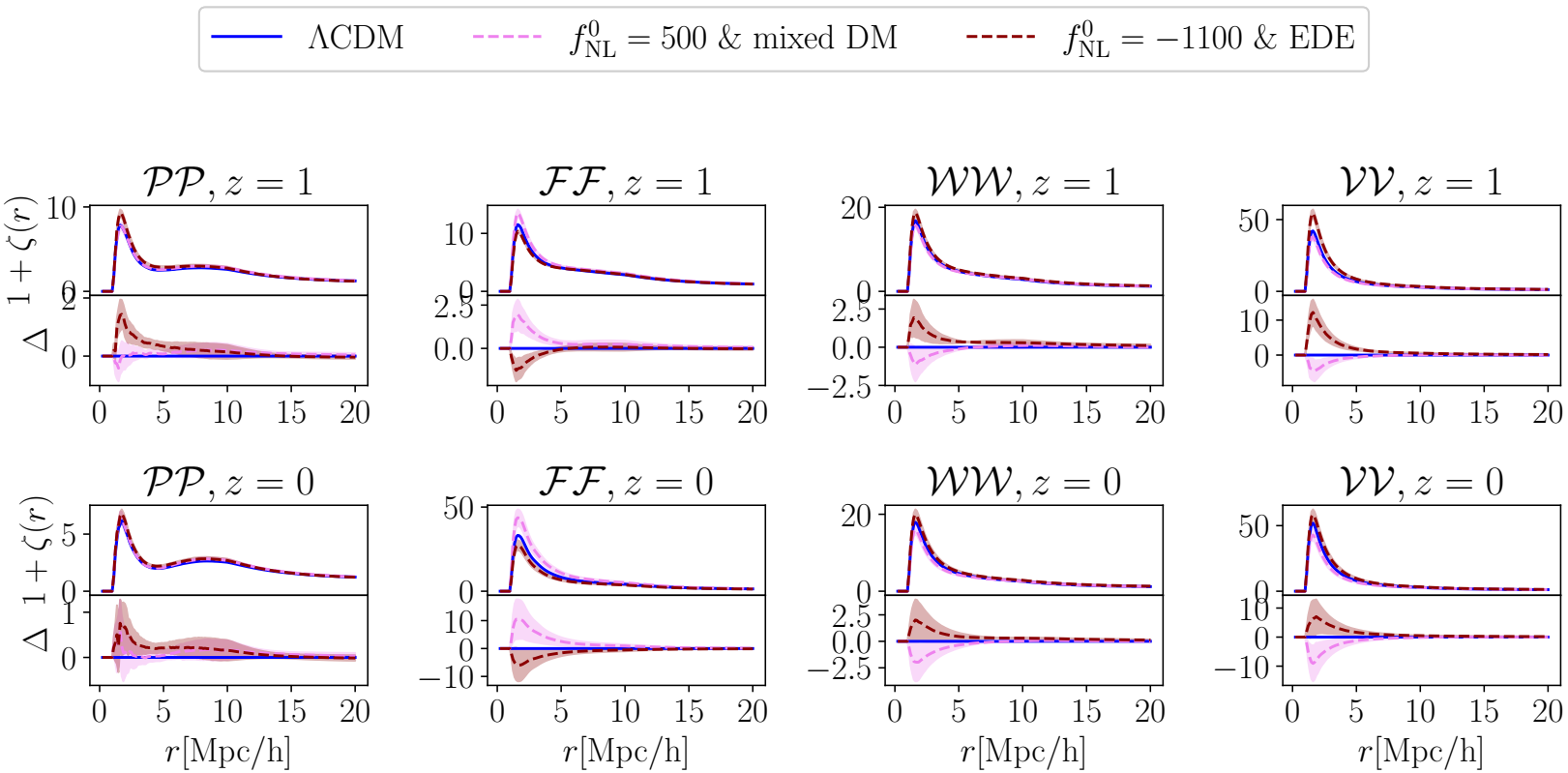
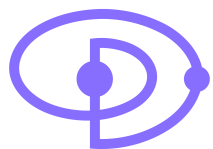


- Very sensitive to cosmic variance : for most models, deviations smaller than 1σ

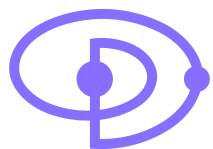
Conclusions

- Current observational tensions could be a sign of new physics beyond ΛCDM
- There is still room for adding several extensions to ΛCDM, that can reproduce some observables while slightly changing others
- Combining several quantities related to the large-scale structure is powerful to break degeneracies between different cosmological models

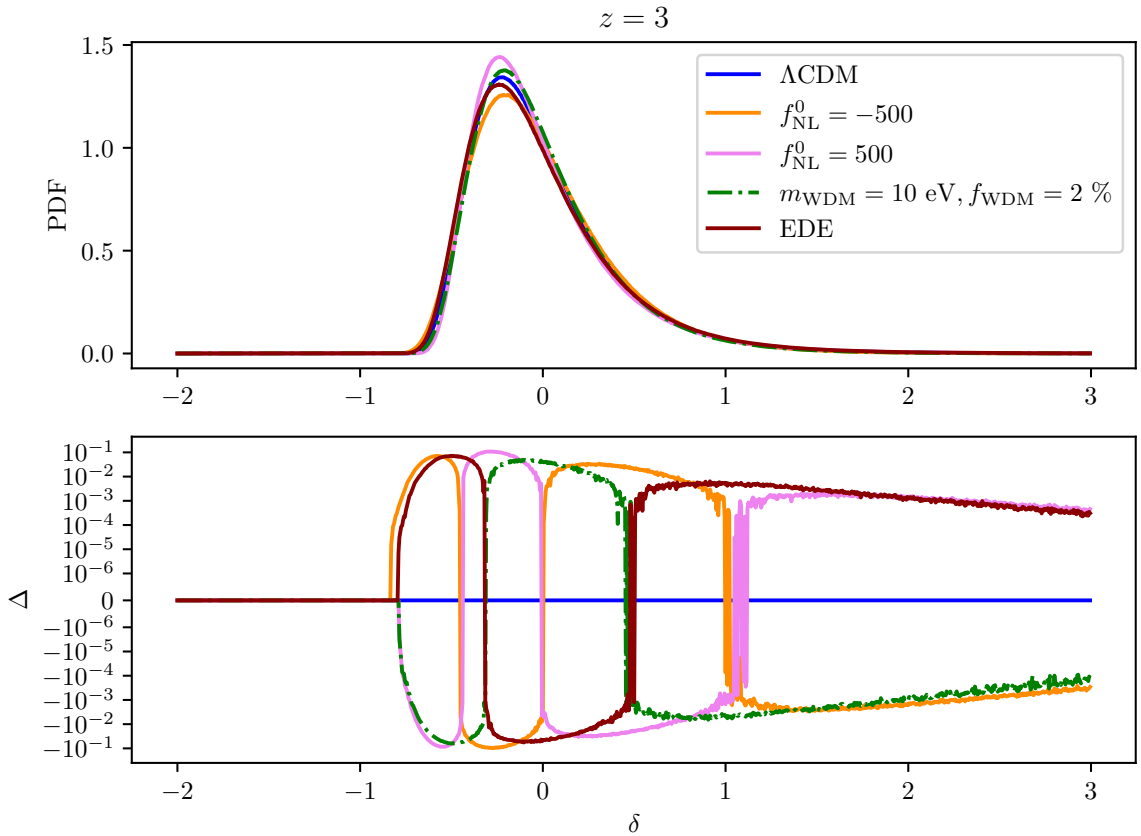


Perspectives during PhD

- Evaluate **relativistic corrections** on these quantities by performing ray-tracing
- Compute these quantities for other models, eg. modified gravity
- Hydrodynamical simulations with RAMSES to compare with observations

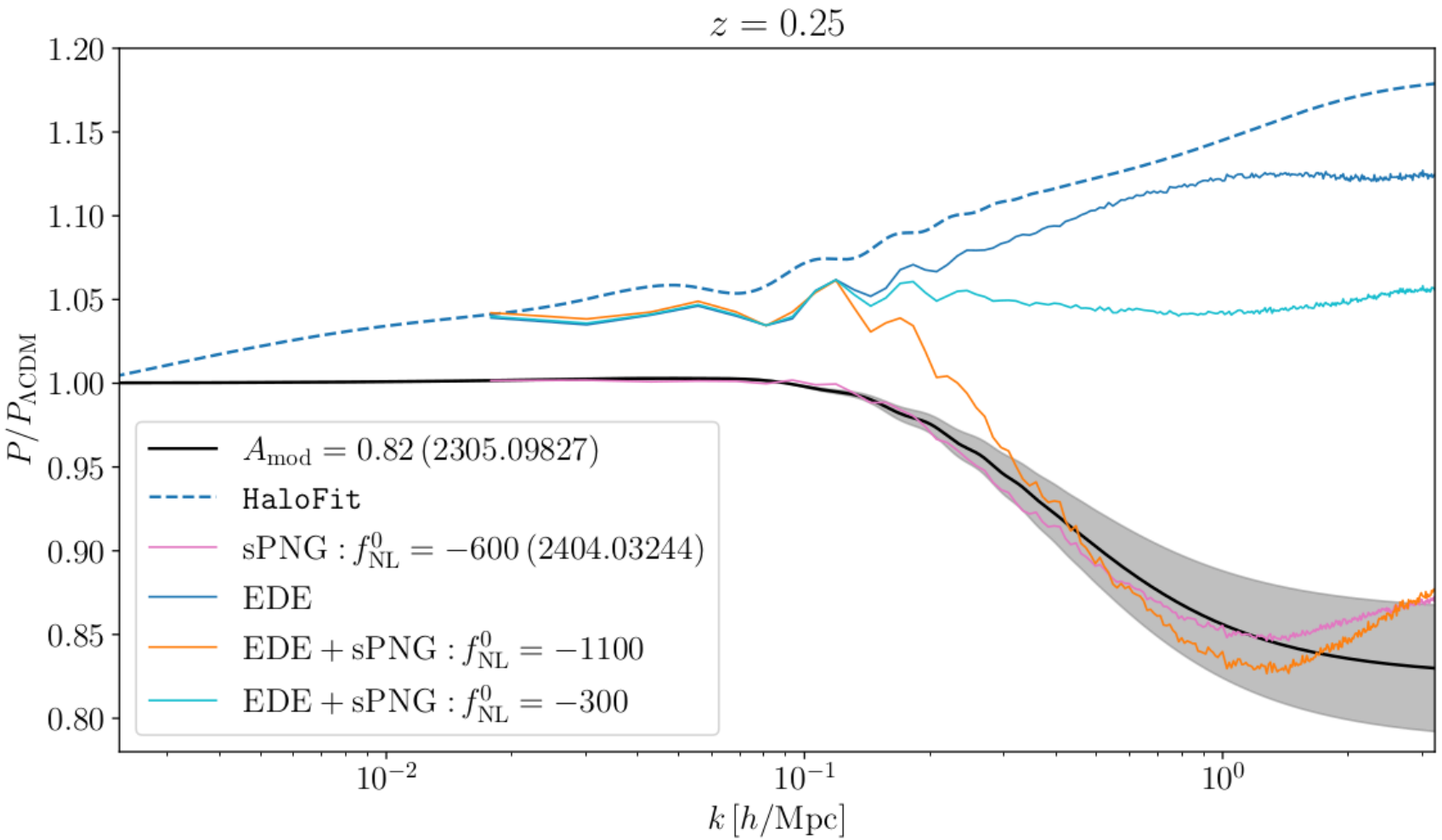


Appendix : Density contrast



- These results can be interpreted with the distribution of the matter density contrast
- Asymptotic behavior ($\delta \gg 1$) intuitive, and the several sign changes occur at different rarities

Appendix : Early dark energy



Stahl et al. 2025