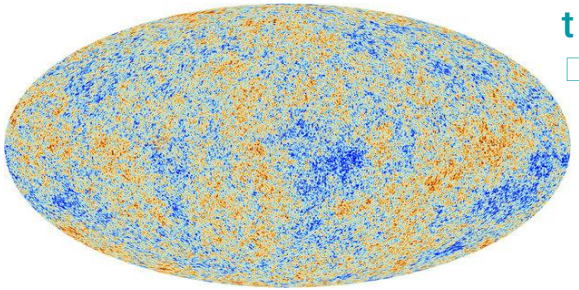
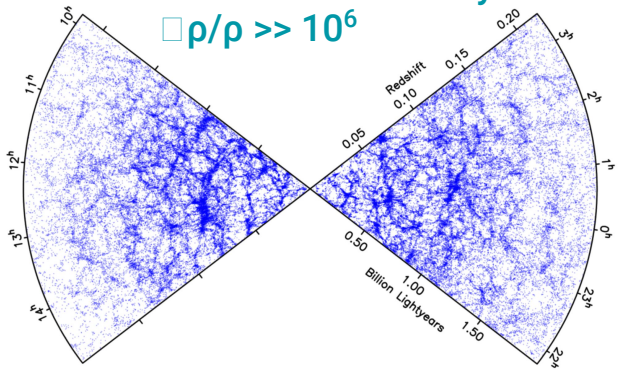

SWIFT
&
FLAMINGO
Matthieu Schaller
Lorentz Institute & Leiden Observatory
Gas Density
Temperature
Dark Matter
Shocks
Metallicity

Cosmological simulations for theory



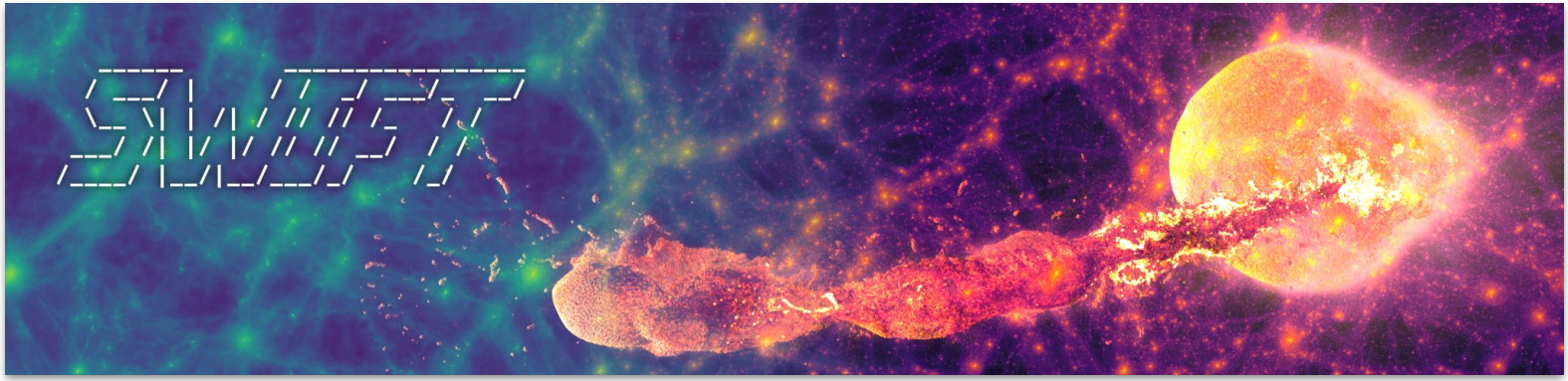
t = 380’000 years
□ρ/ρ ≈ 10^{-5}

t = 13’800’000’000 years
□ρ/ρ >> 10^{6}



?

ΛCDM?
Dark energy?
Modified gravity?
MOND?
Warm dark matter?
Self-interacting dark matter?
Axion dark matter?
Massive neutrinos?
Variable speed of light?
Non-standard inflation?
...



SWIFT: A modern highly-parallel gravity and smoothed particle hydrodynamics solver for astrophysical and cosmological applications

Matthieu Schaller [1,2★], Josh Borrow [3,4], Peter W. Draper [4], Mladen Ivkovic [5,6,7], Stuart McAlpine [8,9], Bert Vandenbroucke [2,10], Yannick Bahé [4,2,5], Evgenii Chaikin [2], Aidan B. G. Chalk [11], Tsang Keung Chan [12,4], Camila Correa [13], Marcel van Daalen [2], Willem Elbers [4], Pedro Gonnet [14], Loïc Hausammann [5,15], John Helly [4], Filip Huško [4], Jacob A. Kegerreis [16,4], Folkert S. J. Nobels [2], Sylvia Ploeckinger [1,17], Yves Revaz [5], William J. Roper [18], Sergio Ruiz-Bonilla [4], Thomas D. Sandnes [4], Yolan Uyttenhove [10], James S. Willis [19], and Zhen Xiang [1,20]

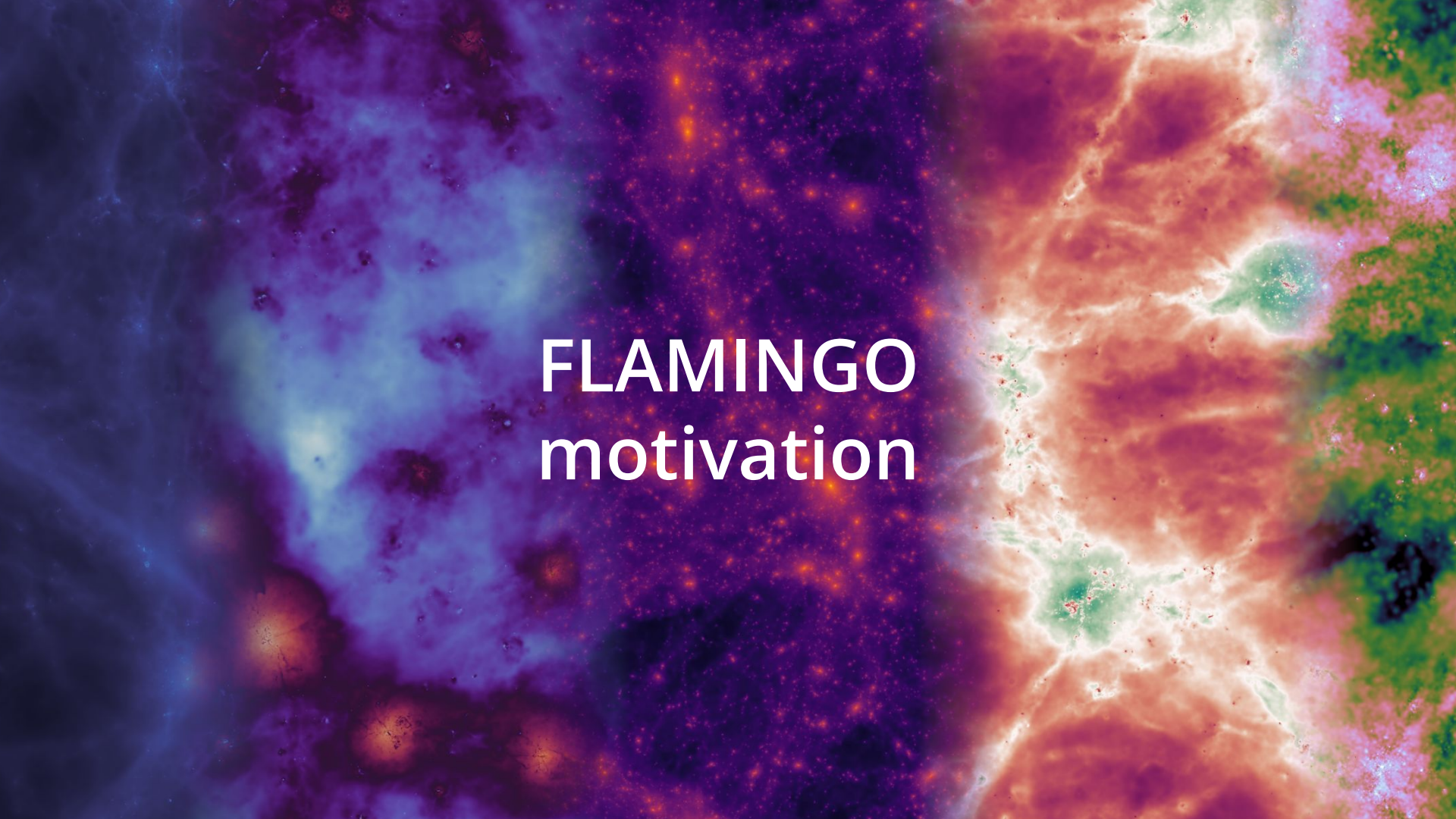
arXiv:2305.13380

www.swiftsim.com

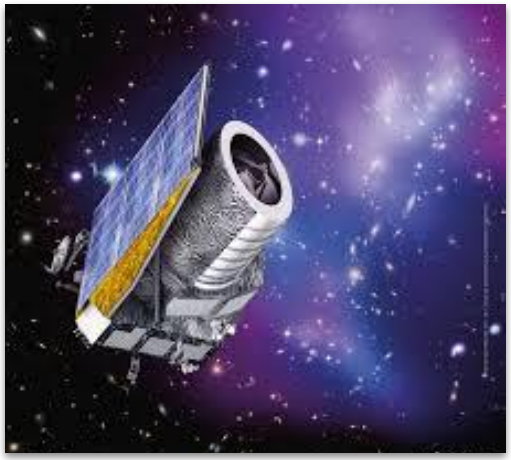
Features

- Short-range gravity using FMM.
- Long-range (periodic) gravity via PM.
- Multiple flavours of SPH & other hydro.
- Default SPH model designed for cosmological applications. (Borrow+21)
- Coupled to VELOCIraptor 6DFOF structure finder. (Elahi+19)
- On-the-fly lightcones and power spectra.
- All open source. Very scalable.

- Particle-based neutrinos using “delta-f” method. (Elbers+21)
- **SIDM implementation. (Correa+21)**
- Moment-based RT on top of SPH. (Chan+21)
- EAGLE-like subgrid model.
- GEAR subgrid model. (Revaz 2019)
- AGN jet model. (Husko & Lacey 22)
- >150 test problems and examples.


FLAMINGO
motivation

Euclid: Measuring the late-time Universe



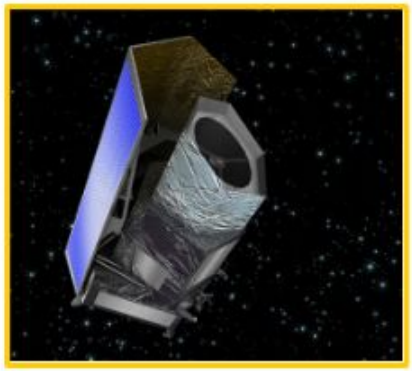
Euclid satellite mission statement:

“Constrain the nature of dark matter by measuring halo sub-structures”

“Achieve 1% accuracy on the key dark energy model parameters”

“Constrain the sum of neutrino masses and structure of the mass hierarchy”

Surveys in a nutshell



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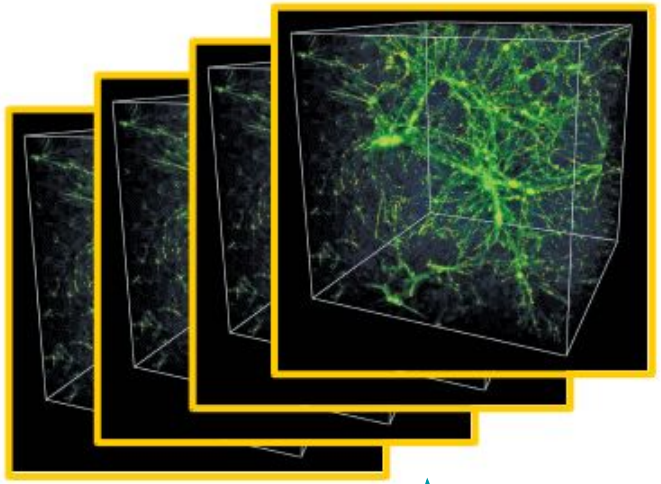

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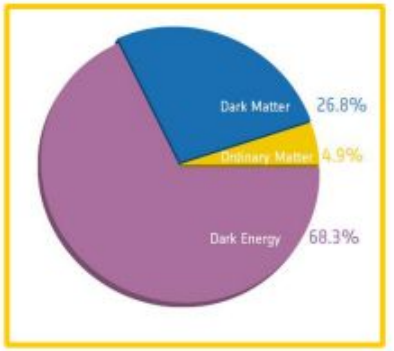
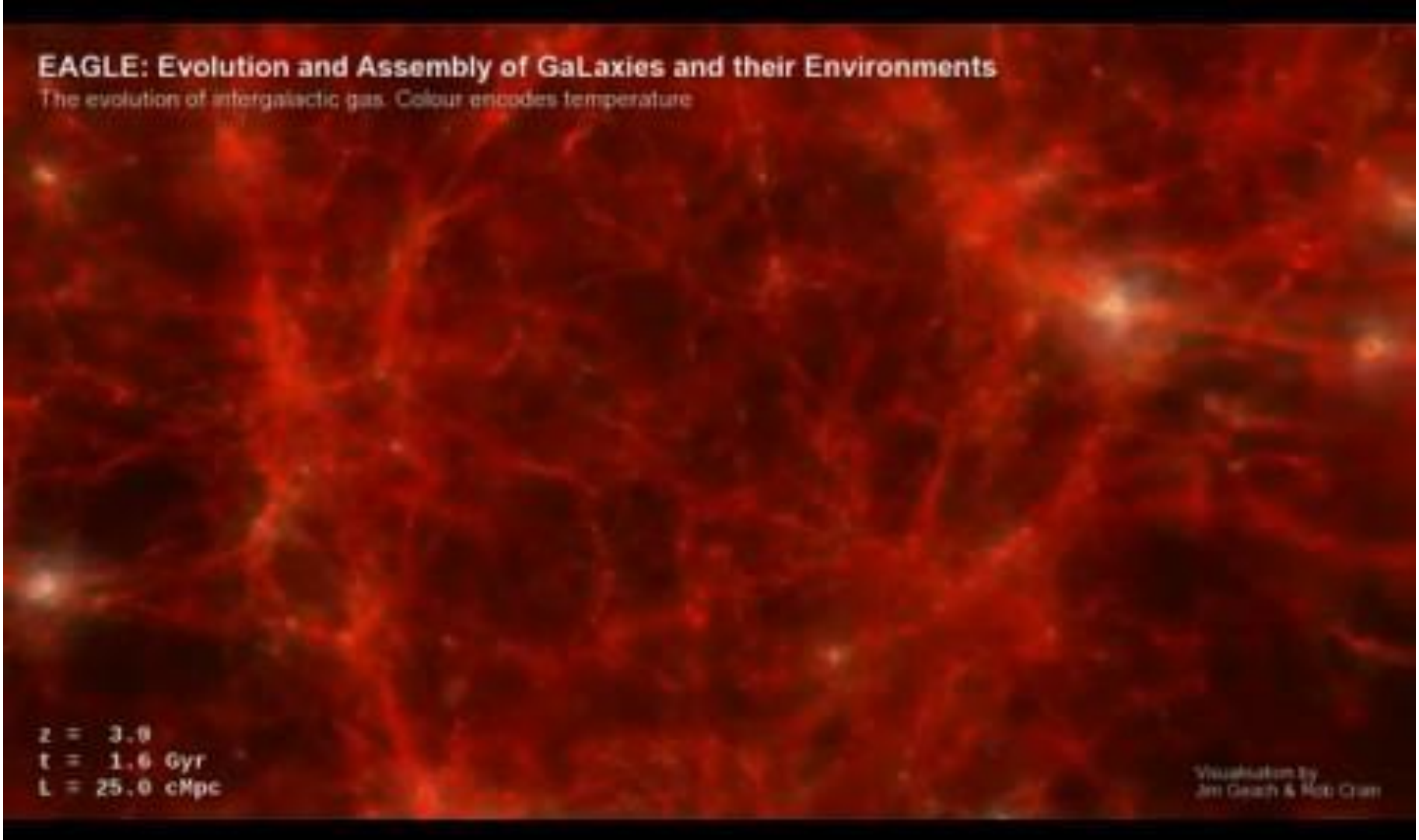
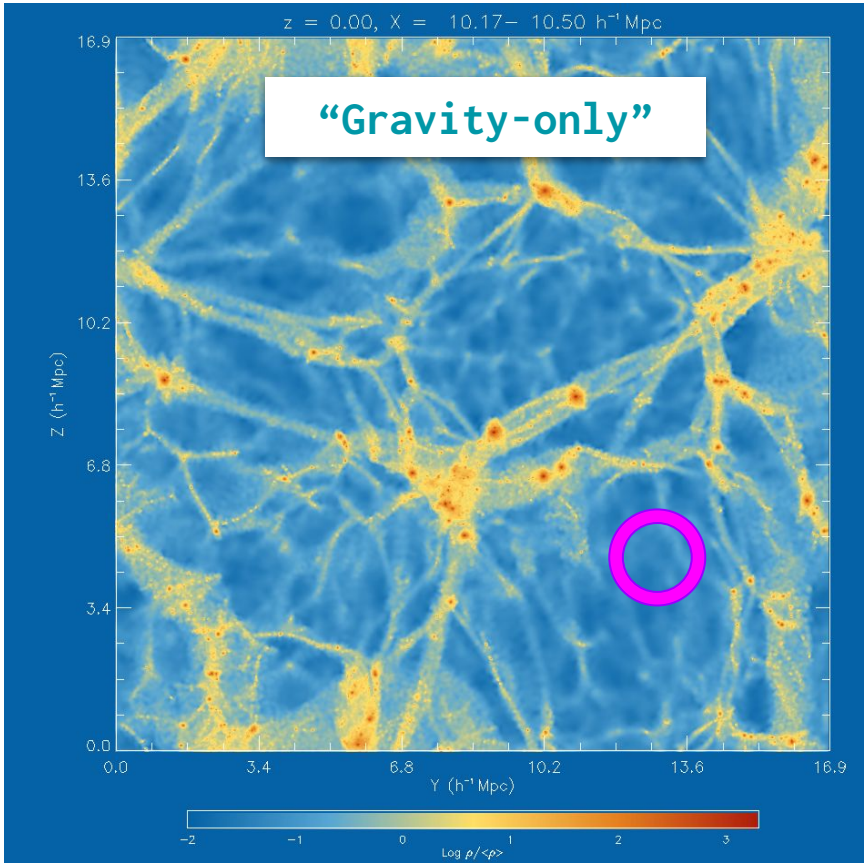
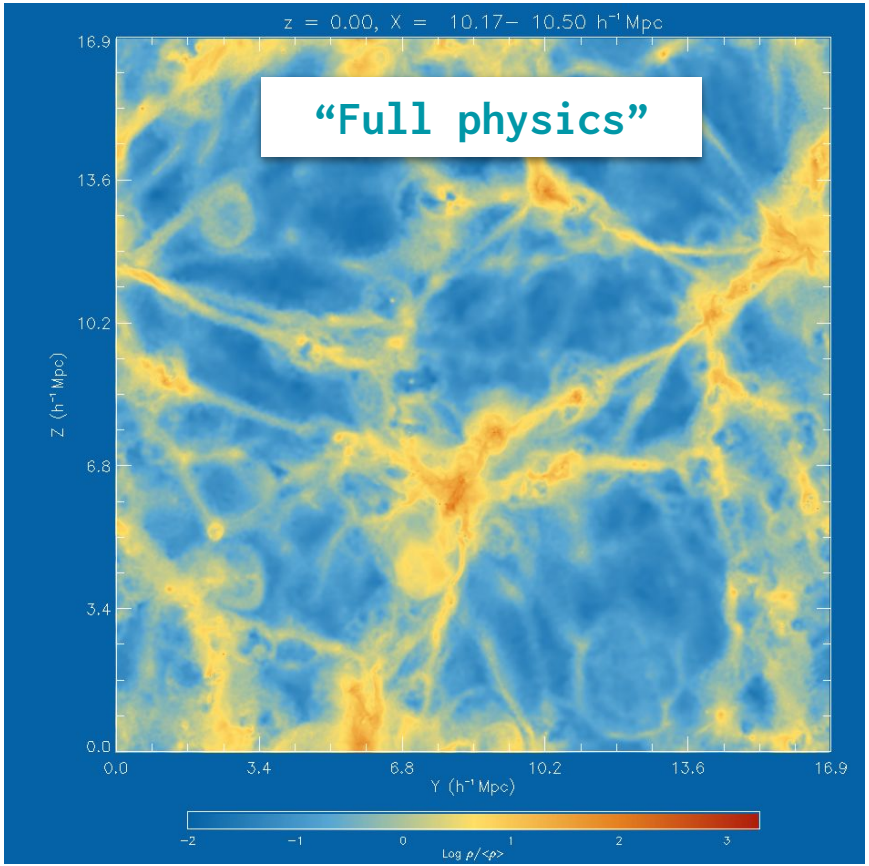


Perturbation theory, Semi-analytic, Simulations, Emulators, …

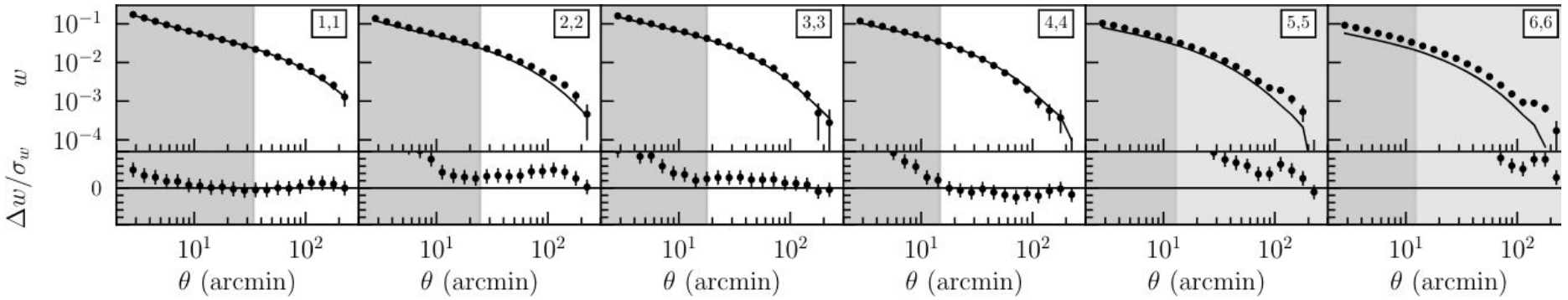

EAGLE: Evolution and Assembly of GaLaxies and their Environments
The evolution of intergalactic gas. Colour encodes temperature
z = 3.0
t = 1.6 Gyr
L = 25.0 cMpc
Visualisation by
Jim Geach & Rob Crain

Baryon effects on the matter field





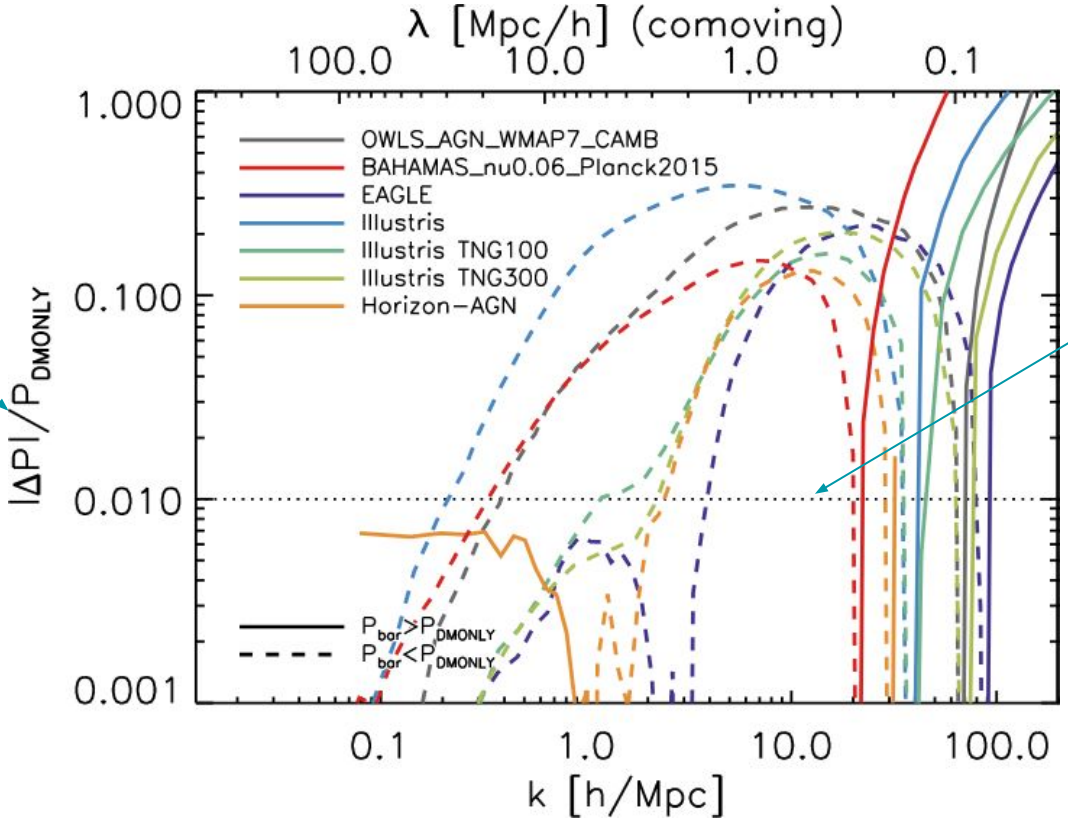
The DES solution?



DES collab. 2021

Effect on total matter power-spectrum

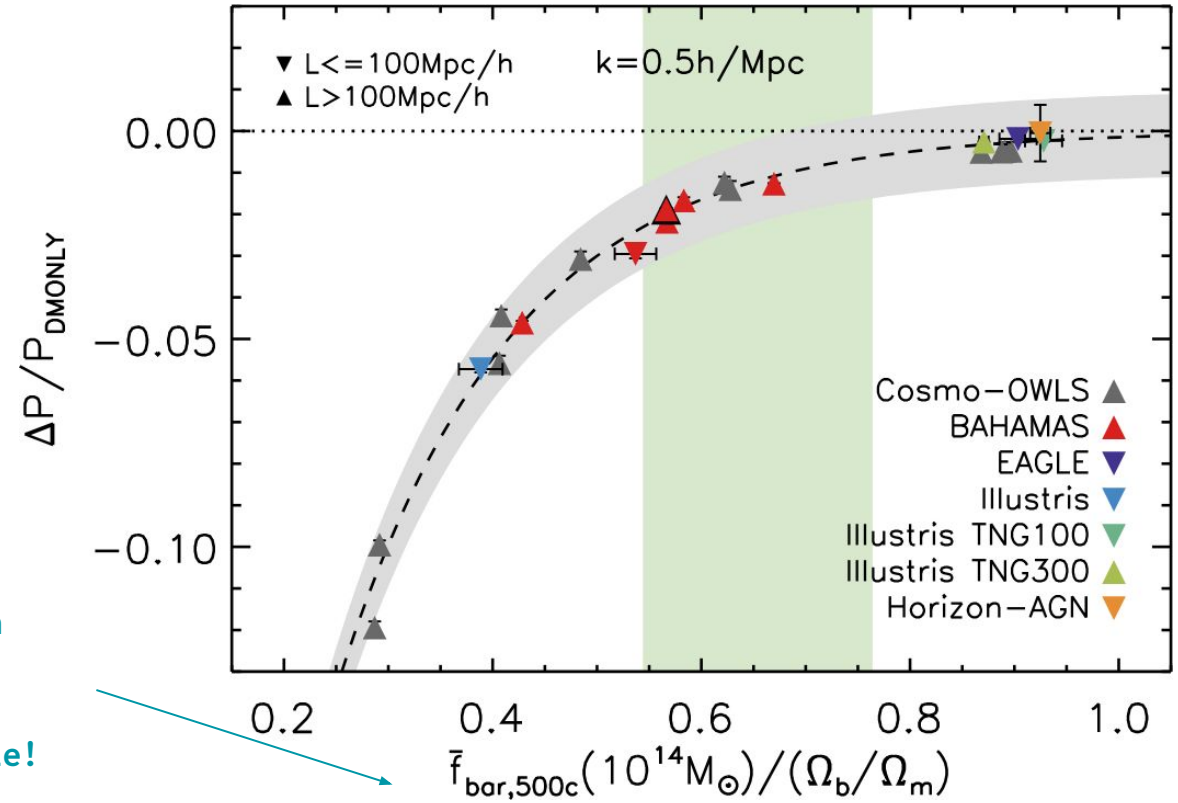
Deviation from DMO (aka. gravity-only) simulations



1% difference

van Daalen+20

Relevant data?



Baryon fraction in groups/clusters

Actually observable!

van Daalen+20

The Plan

1. Measure $f_{\mathrm{bar}}\,(R_{500})$ in groups.

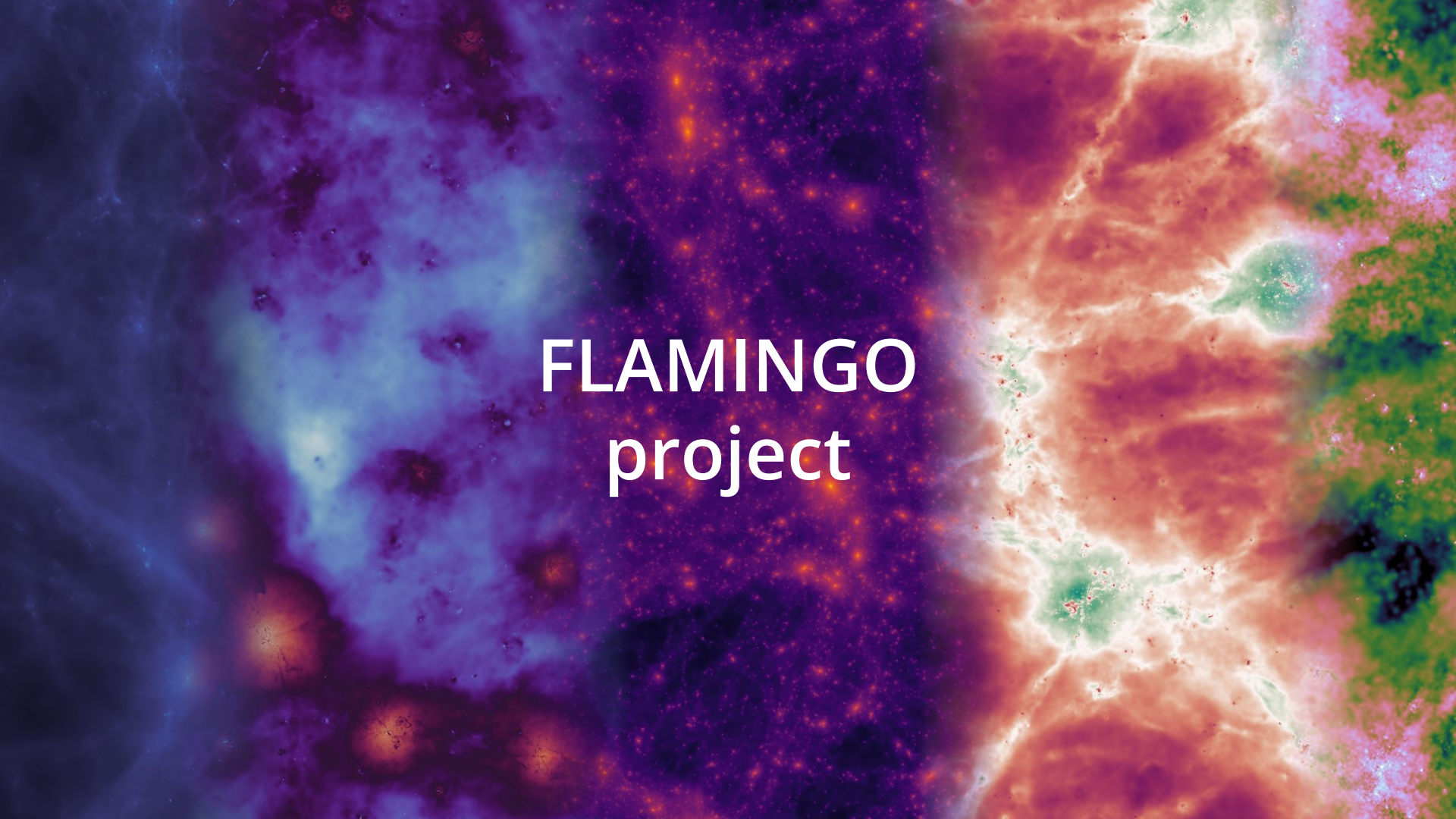
eRosita very timely here!

2. Design a network of subgrid models that matches this.

3. Run **large simulations** varying cosmology.

4. Build an emulator for cosmology inference.

5. Infer cosmological parameters from the data using the emulator.


FLAMINGO
project

FLAMINGO: **F**ull-hydro **L**arge-scale structure simulations with **A**ll-sky **M**apping for the **I**nterpretation of **N**ext **G**eneration **O**bservations

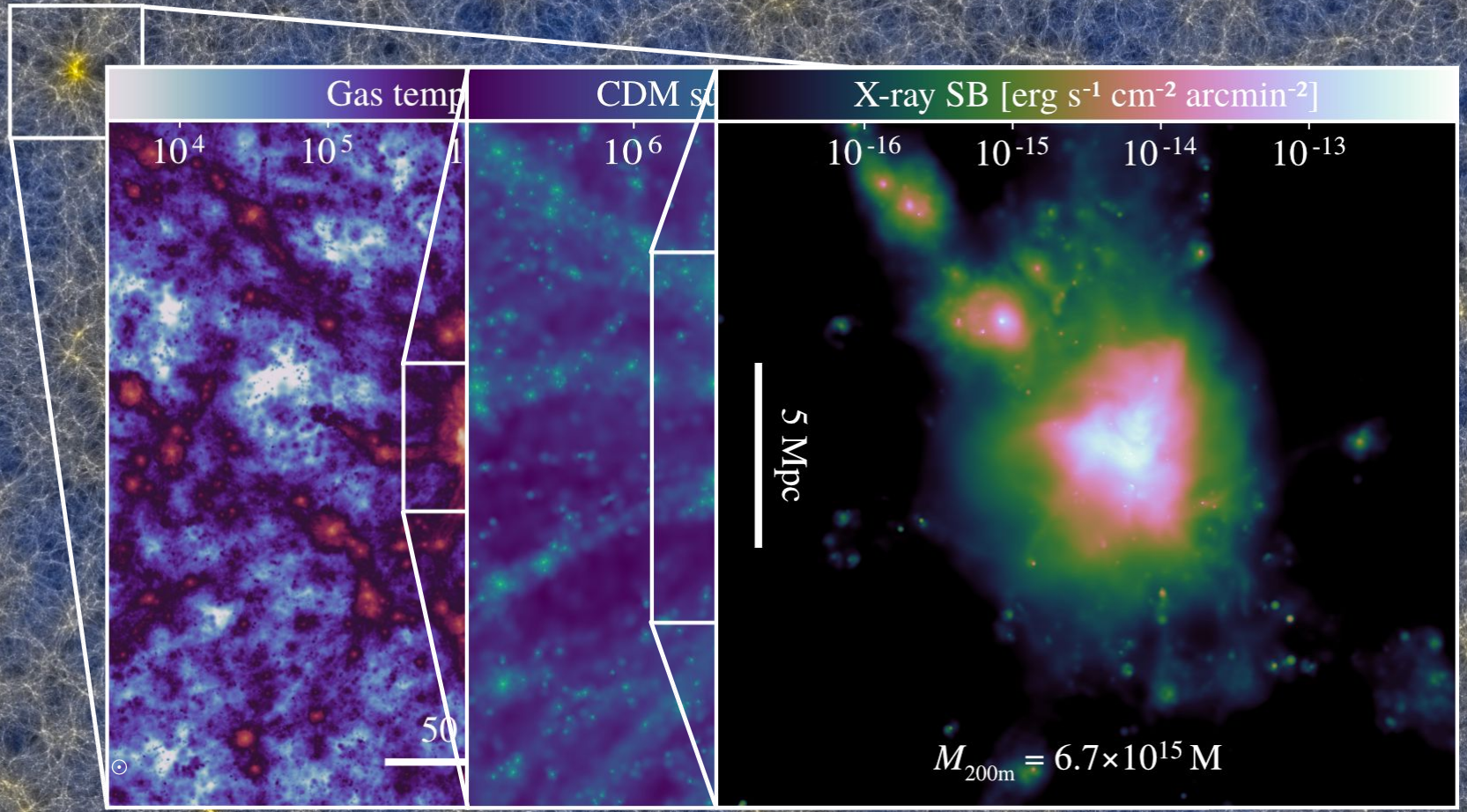
Successor to the BAHAMAS project

Designed to be a "*virtual twin*" to late-time cosmology probes (Euclid, SZ, eROSITA, …)

Leiden, Liverpool & Durham collaboration

Braspenning, Elbers, Frenk, Helly, Kugel, Kwan, McCarthy, Salcido, Schaller, Schaye, van Daalen, Vandenbroucke

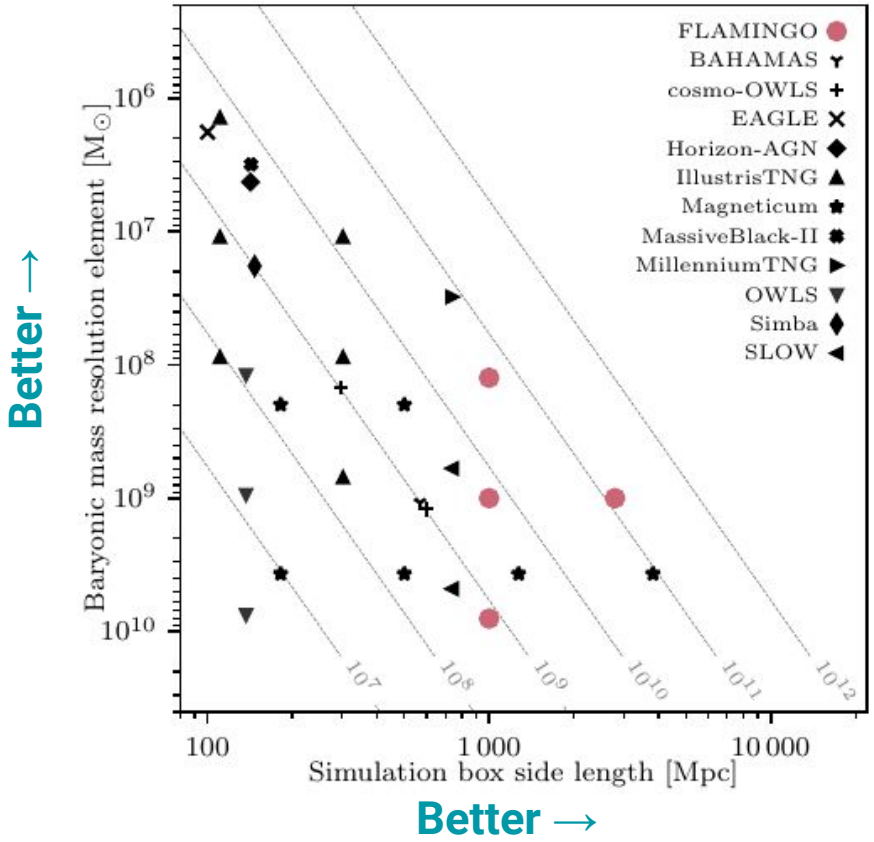
arXiv:2306.04024


Gas temp
CDM s
X-ray SB [erg s-1 cm-2 arcmin-2]
10 4
10 5
10 6
10 -16
10 -15
10 -14
10 -13
1 Gpc
5 Mpc
50
M200m = 6.7×10 15 M

FLAMINGO basics

- Series of boxes and resolution from **1 Gpc** to **5.6 Gpc** and **10^8 to 10^{10} $M_\odot$ resolution**.
- SWIFT solver with PM+4th order FMM, SPHENIX SPH, particle-based neutrinos, and ML-calibrated subgrid models.
- **Flagship run: 2.8 Gpc with 5040^3 gas, 5040^3 DM, and 2800^3 ν particles.**
- Cosmological parameters are "DES 3x2pt + all external" (flat, Ω_m=0.306, Ω_b=0.0486, h=0.681, Σm_ν=0.06 eV, σ_8=0.804, n_s=0.967)

FLAMINGO runs



Key ingredients

Core components:

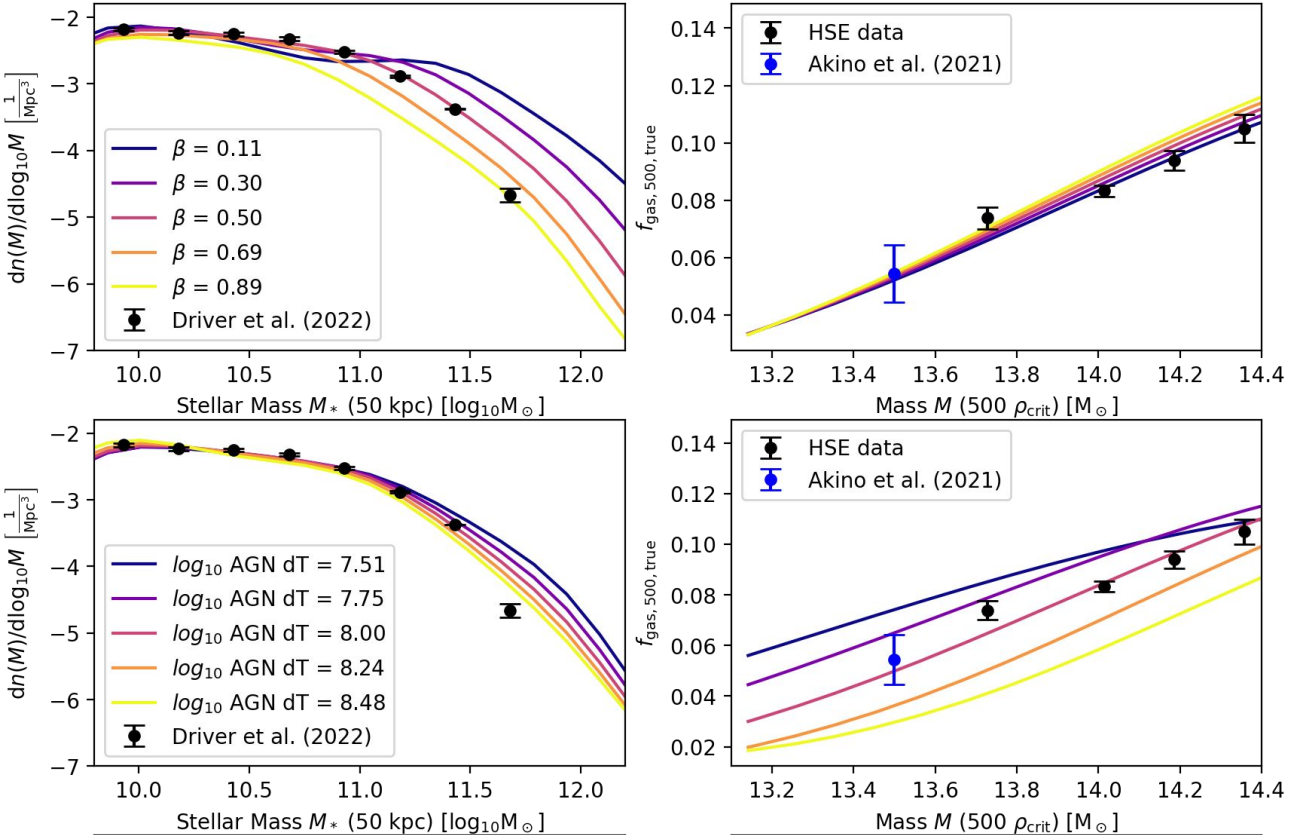
- **SWIFT** cosmo hydro solver
- **SPHENIX SPH** (Borrow+22)
- Massive neutrinos (Elbers+21)
- Multi-fluid ICs - monofonIC code (Hahn+21)
- Many full-sky light-cones

Subgid physics:

- Radiative cooling (Ploeckinger+20)
- Star formation (Schaye+08)
- Enrichment (Wiersma+09)
- SF feedback (Chaikin+22)
- AGN feedback (Booth+09, Bahe+22)

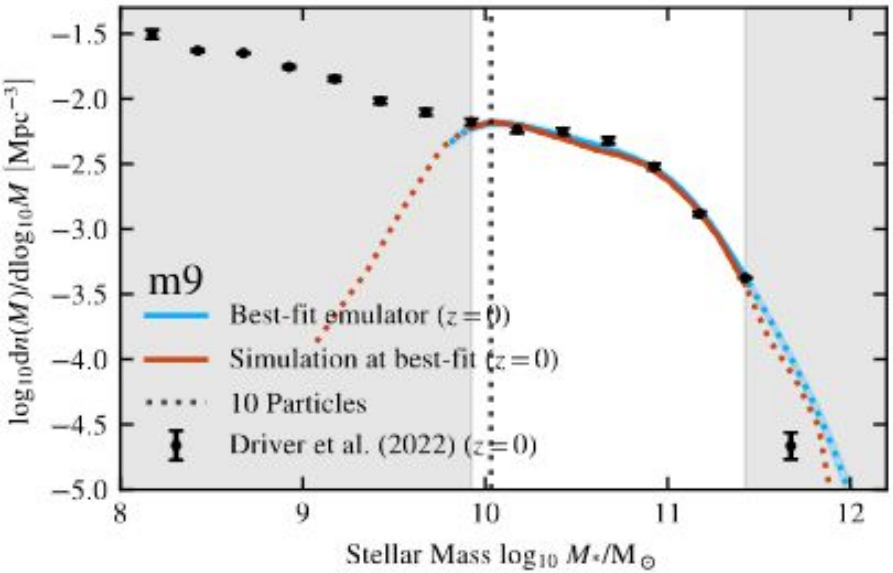
→ Calibration via Gaussian process emulator

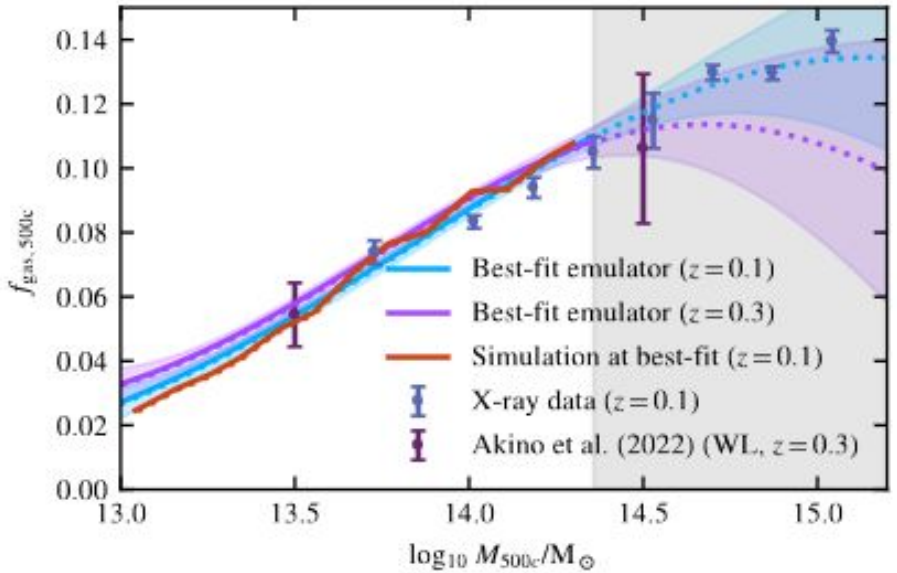
Calibration of the model



Kugel+23

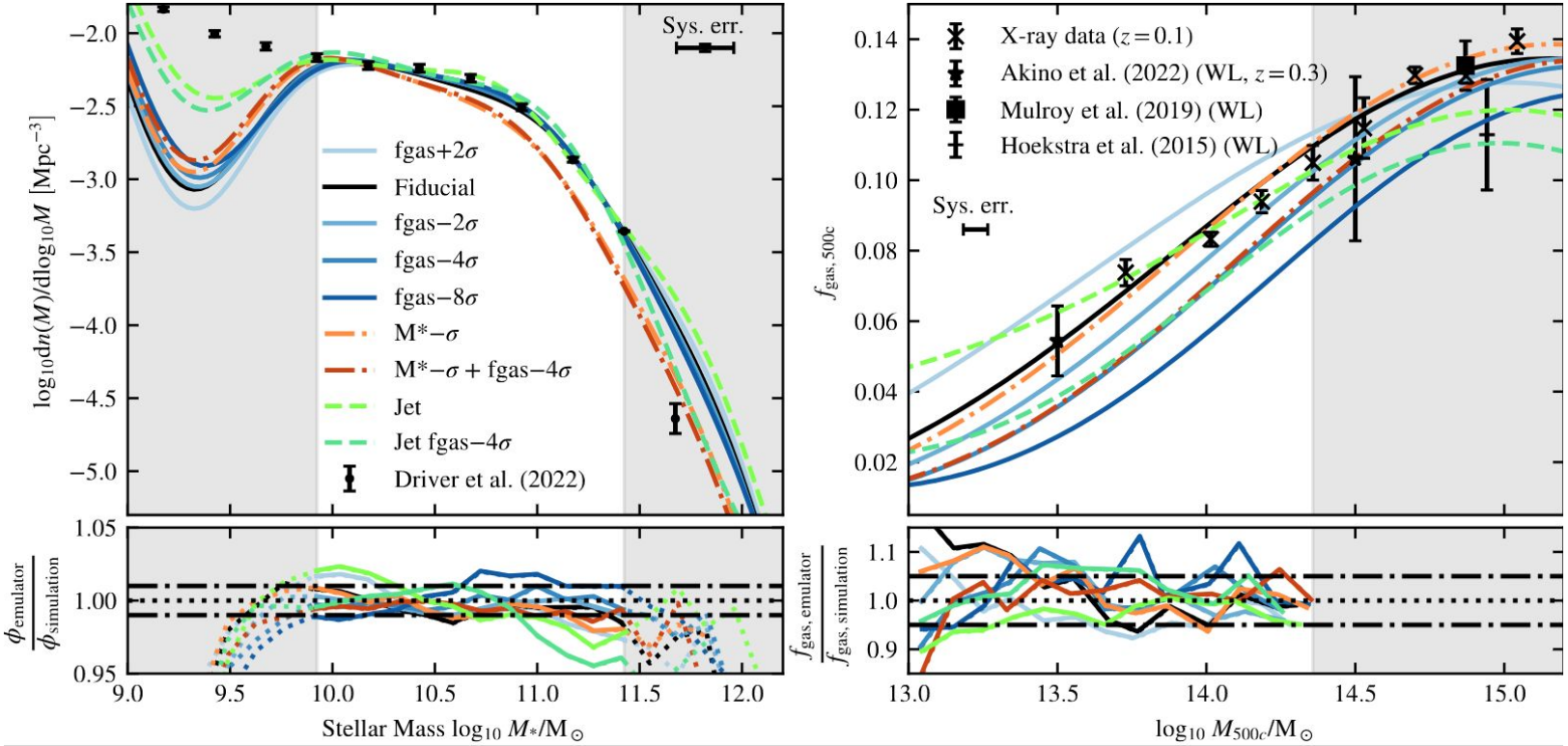
Calibration of the model



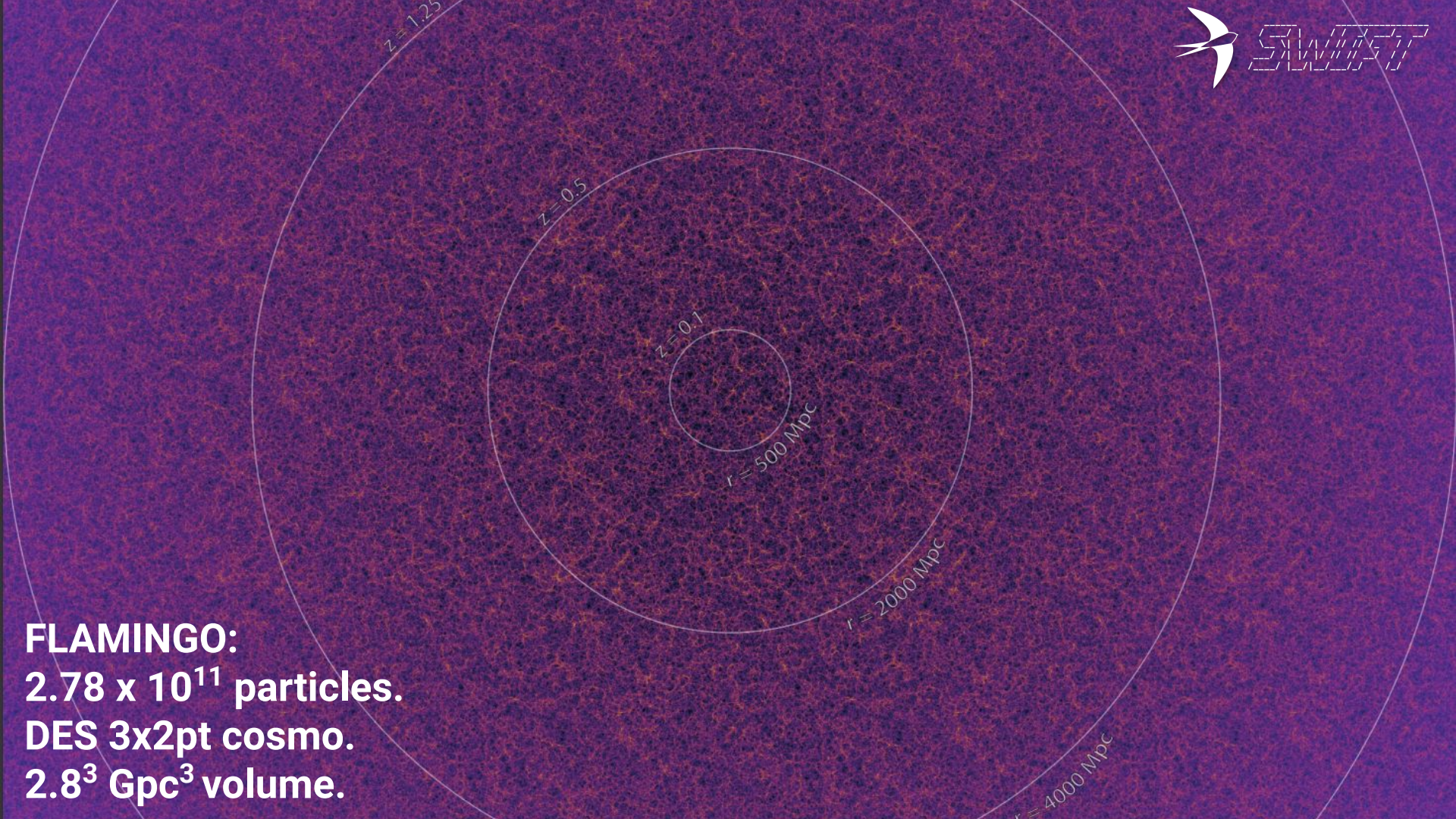


Kugel+23

Model variations

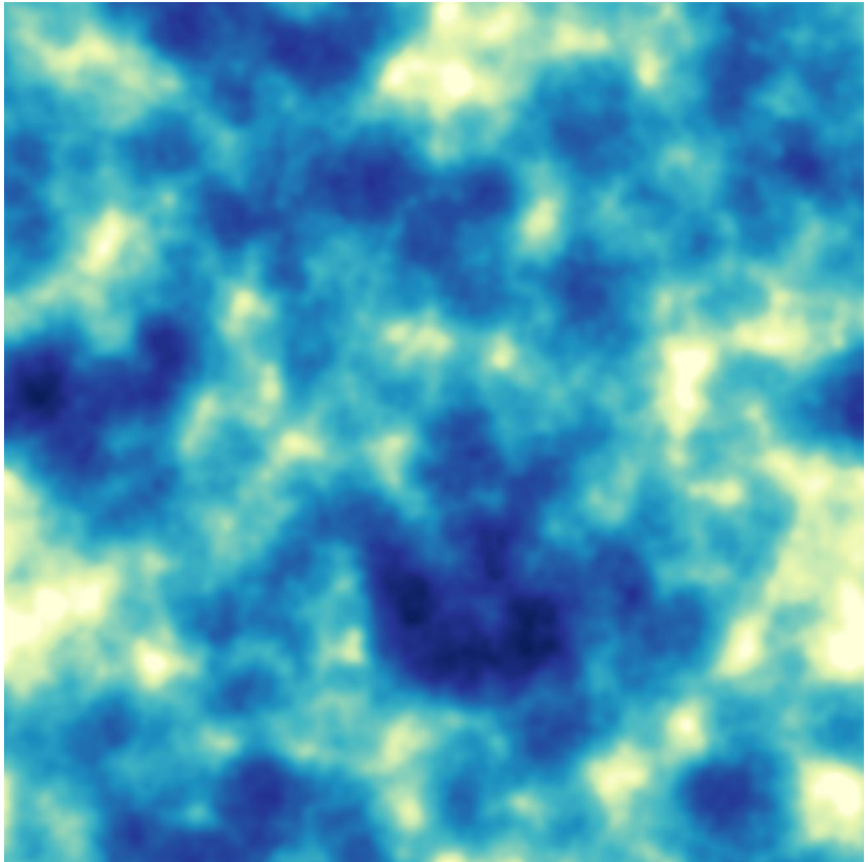


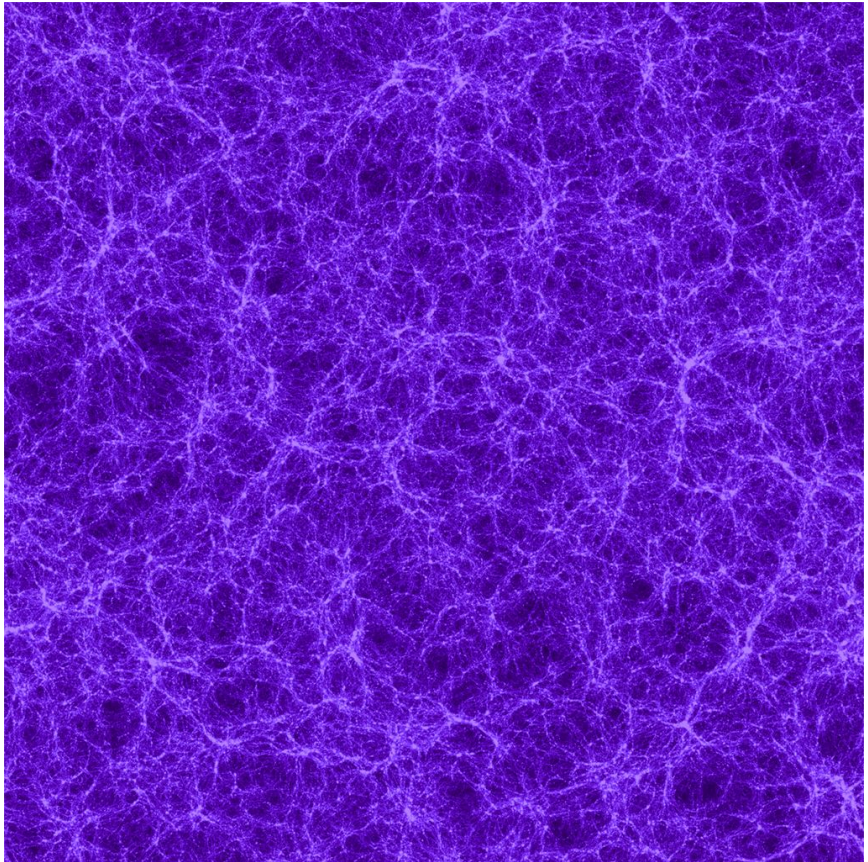
Kugel+23



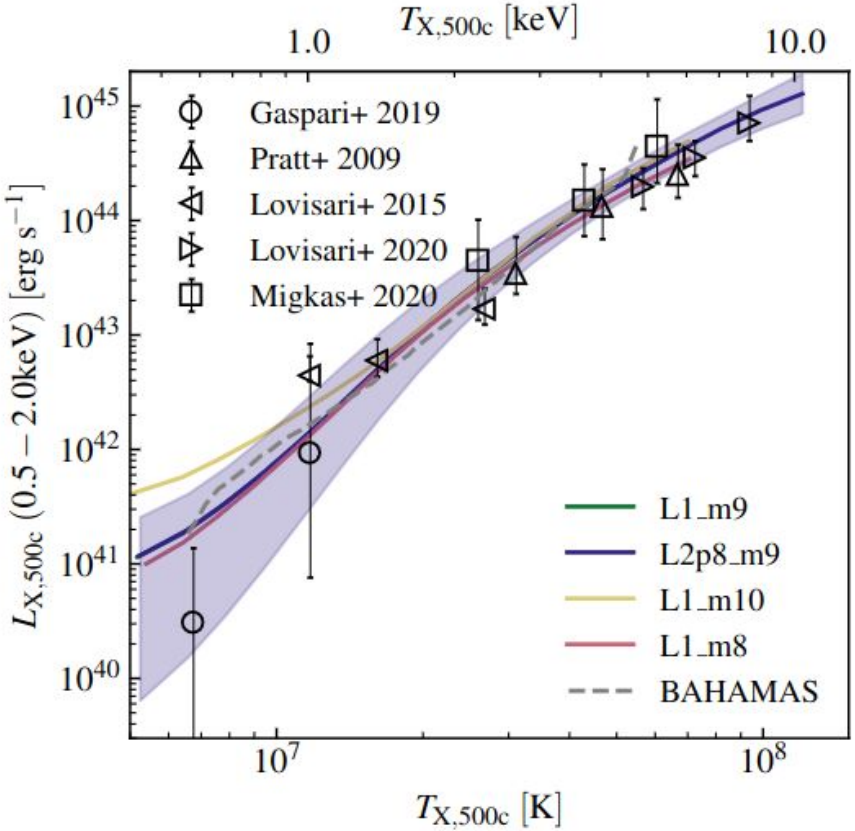
FLAMINGO:
2.78 x 10^{11} particles.
DES 3x2pt cosmo.
2.8^3 Gpc^3 volume.

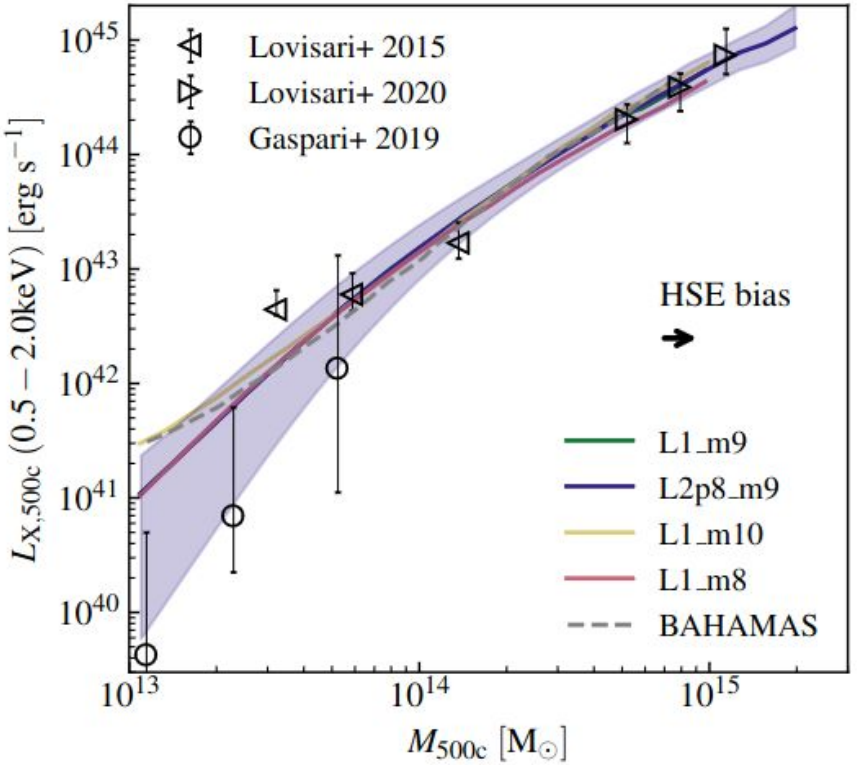
Neutrino clustering



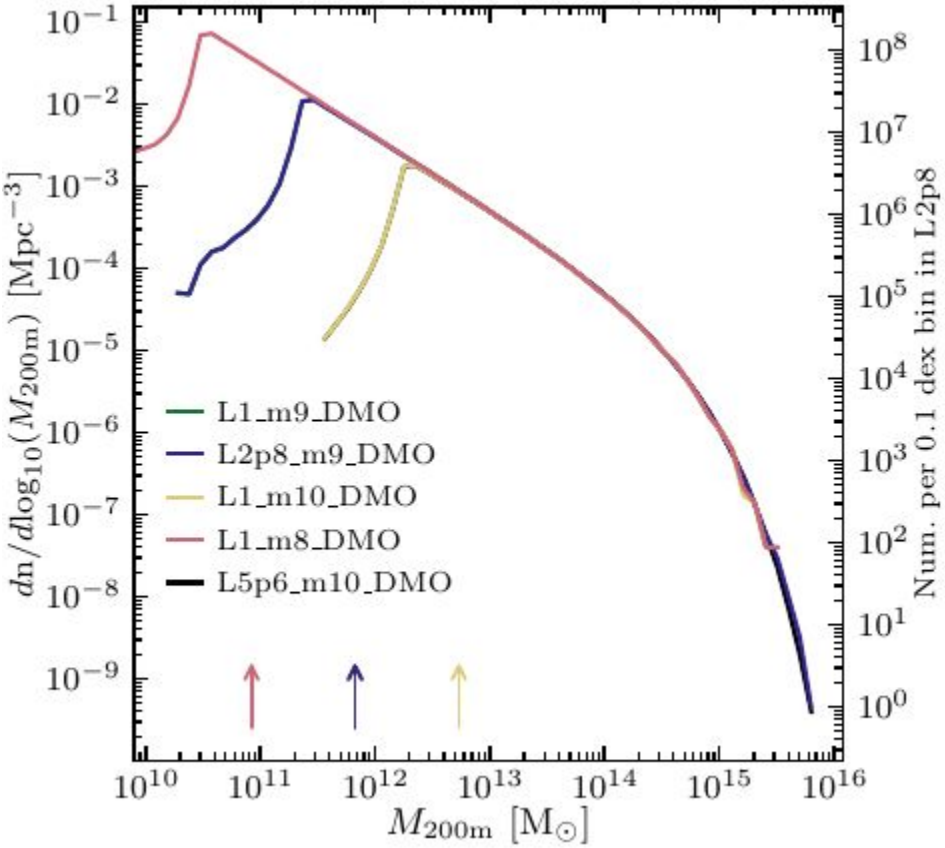


Cluster gas properties

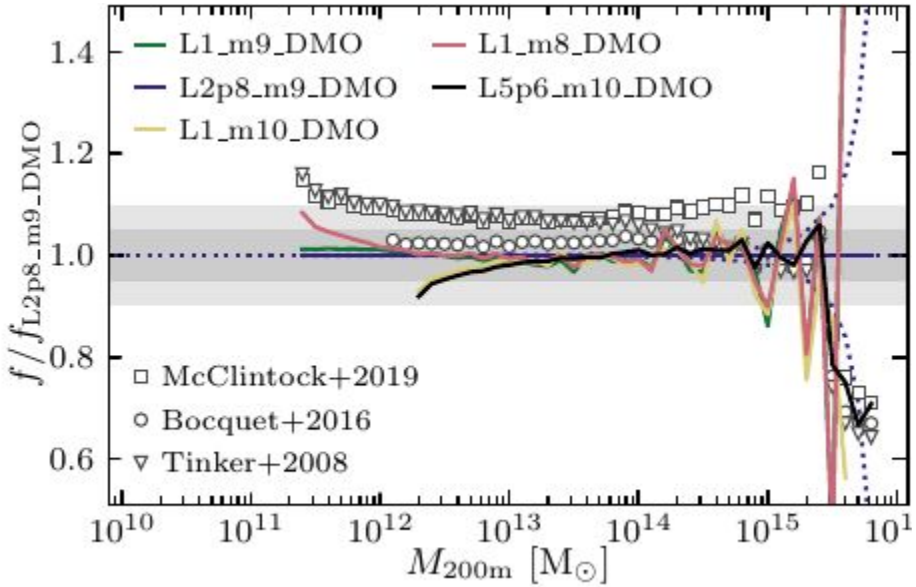


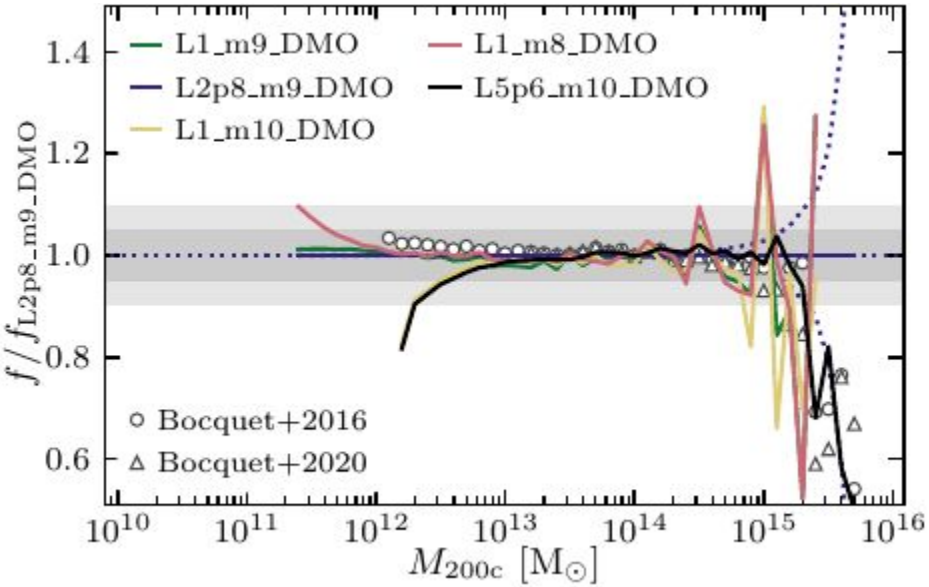


Halo mass function

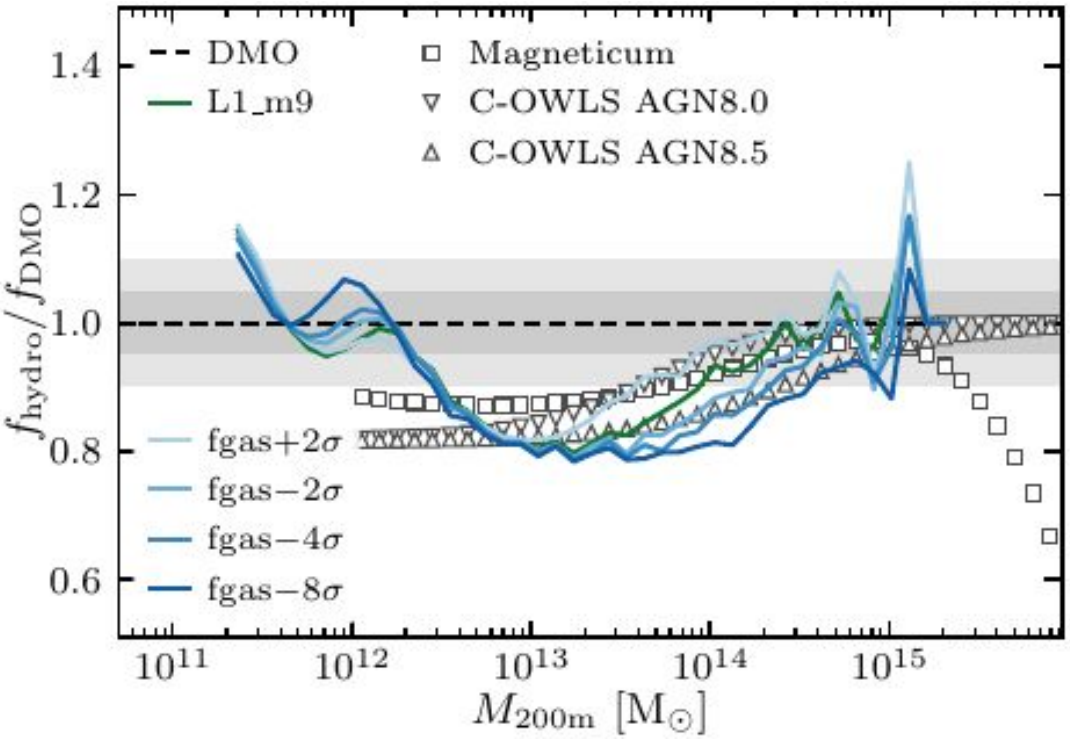


Halo mass function comparison

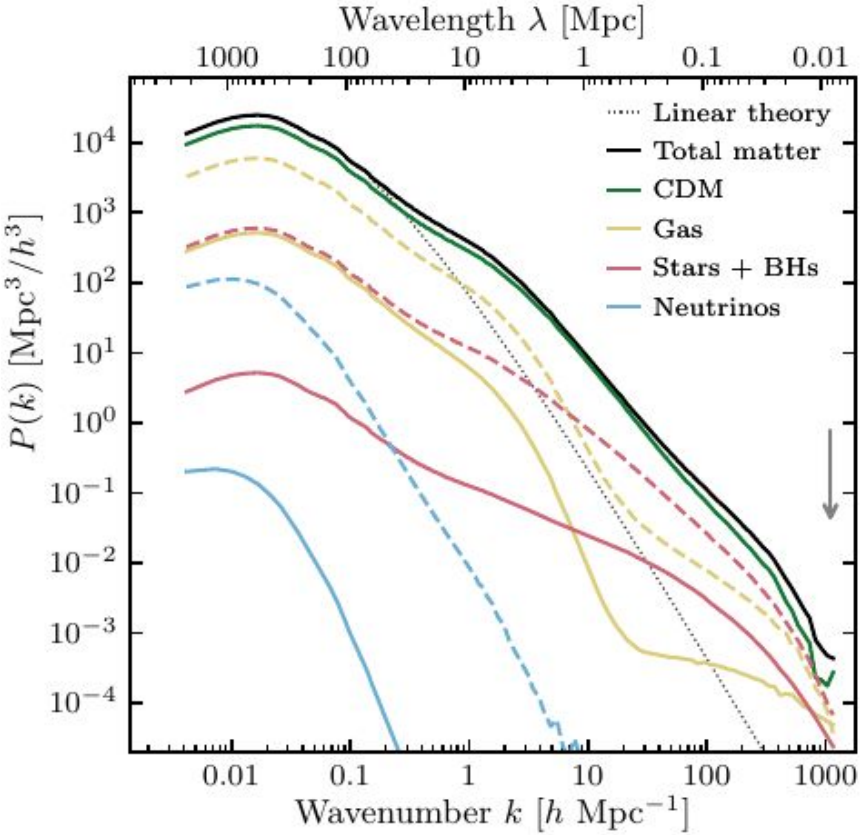




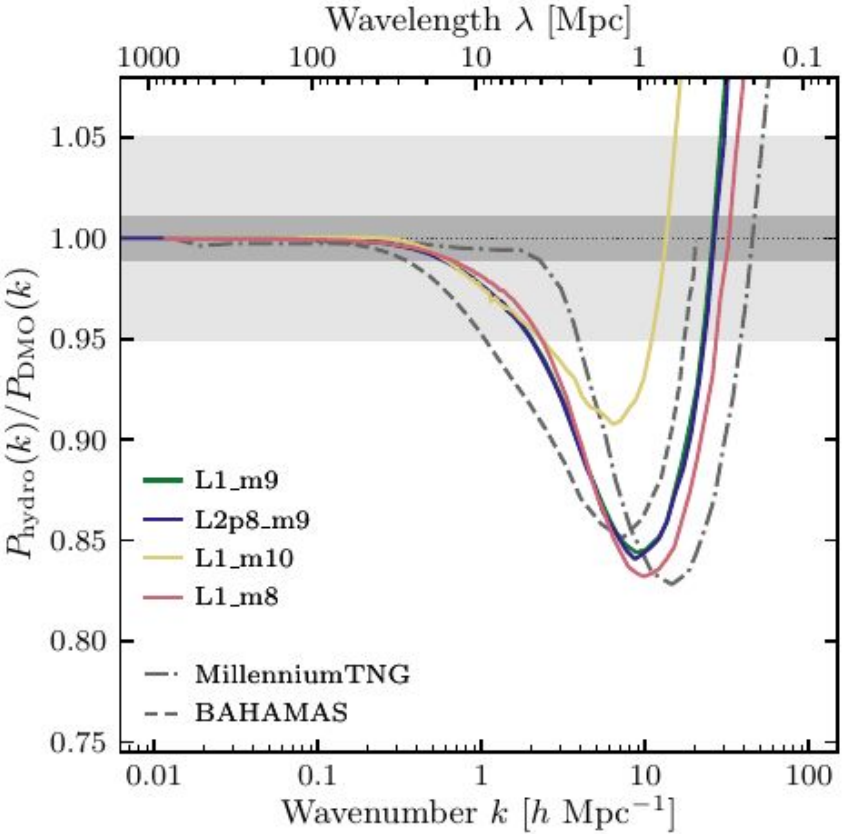
Halo mass function with baryons



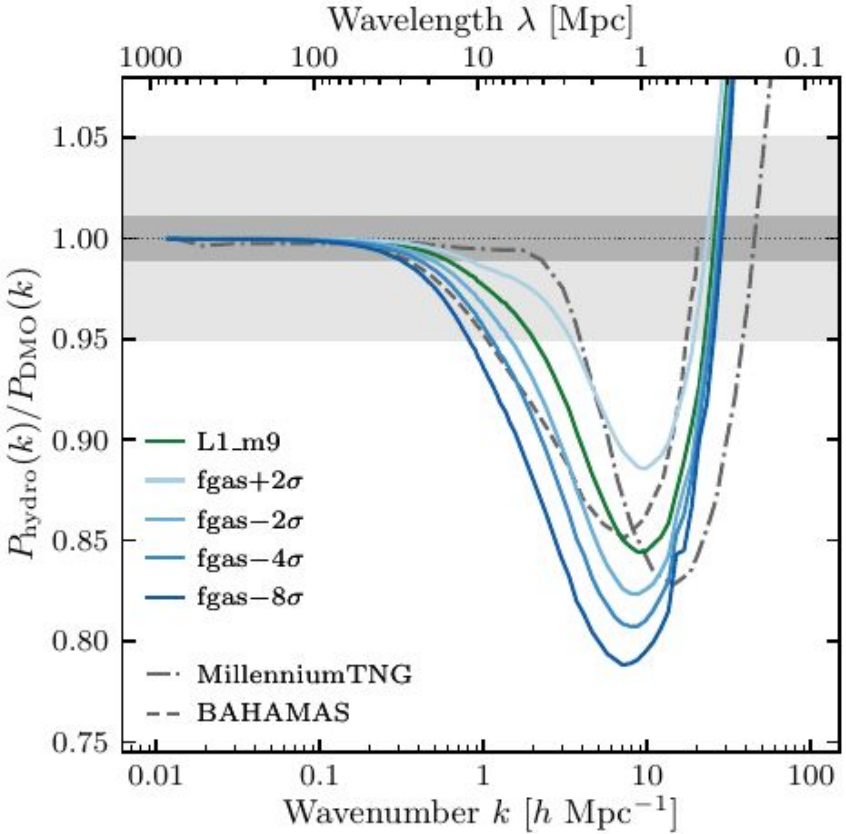
Total matter power spectrum



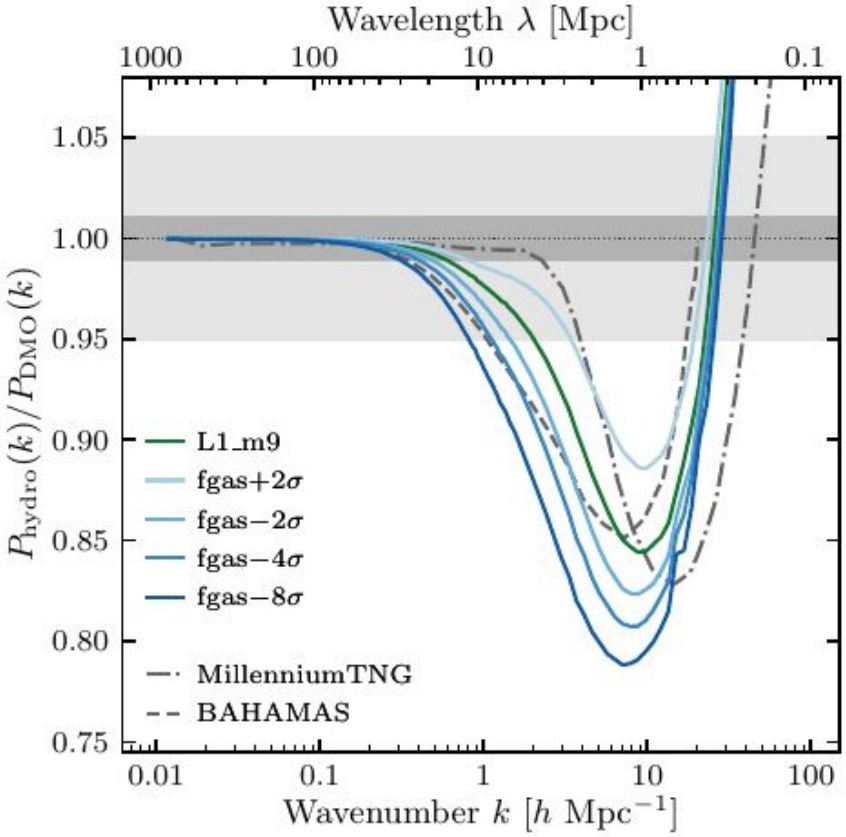
Baryon effect on matter PS

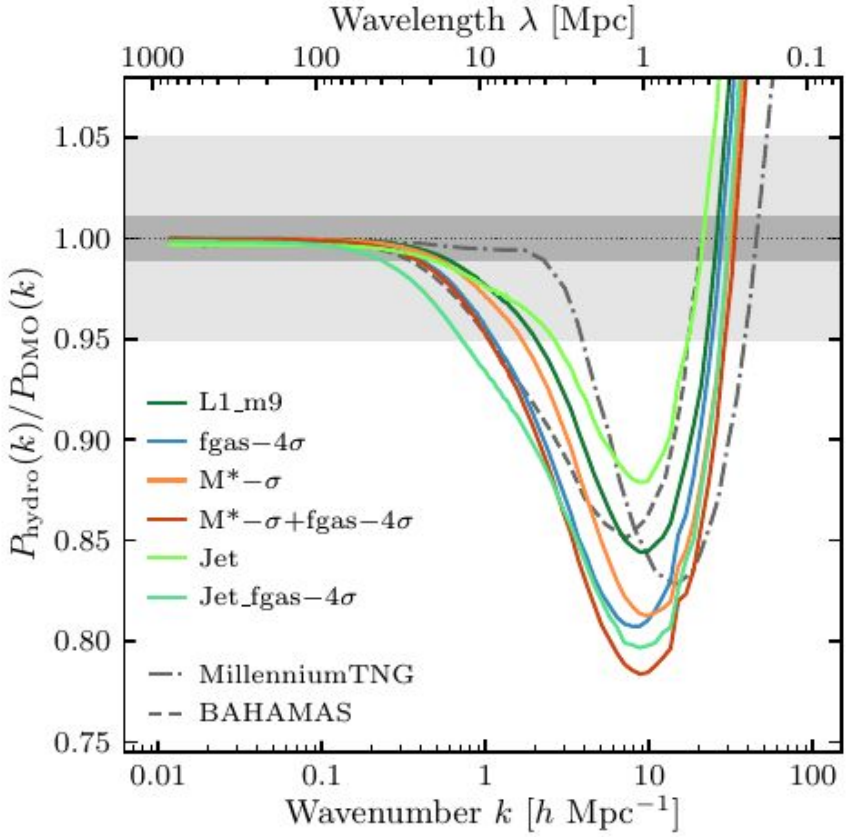


Baryon effect on matter PS

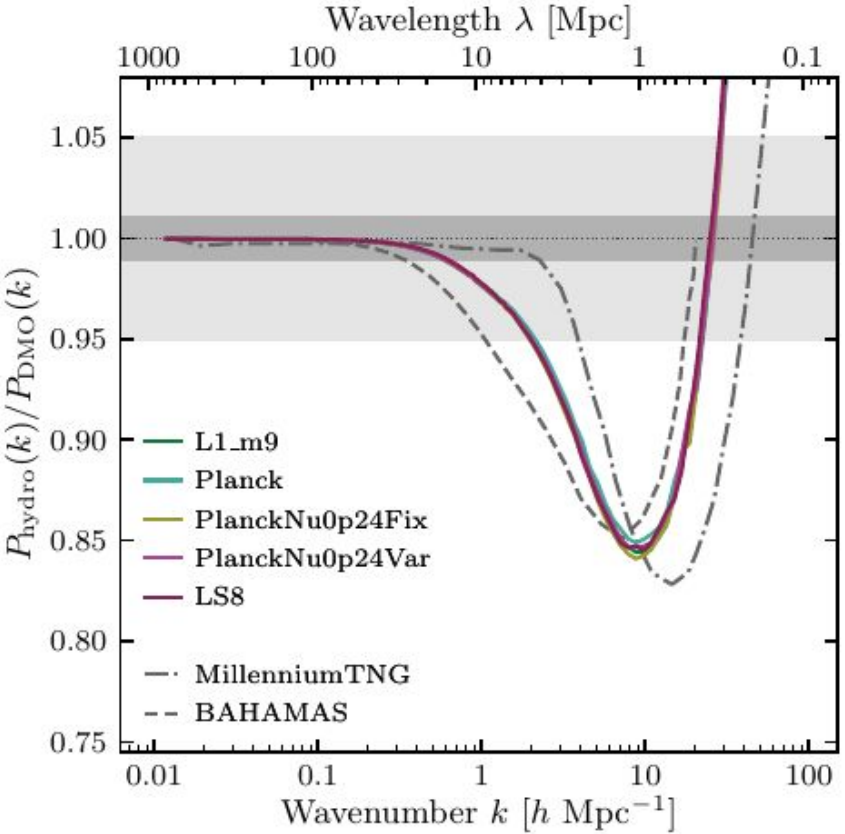


Baryon effect on matter PS

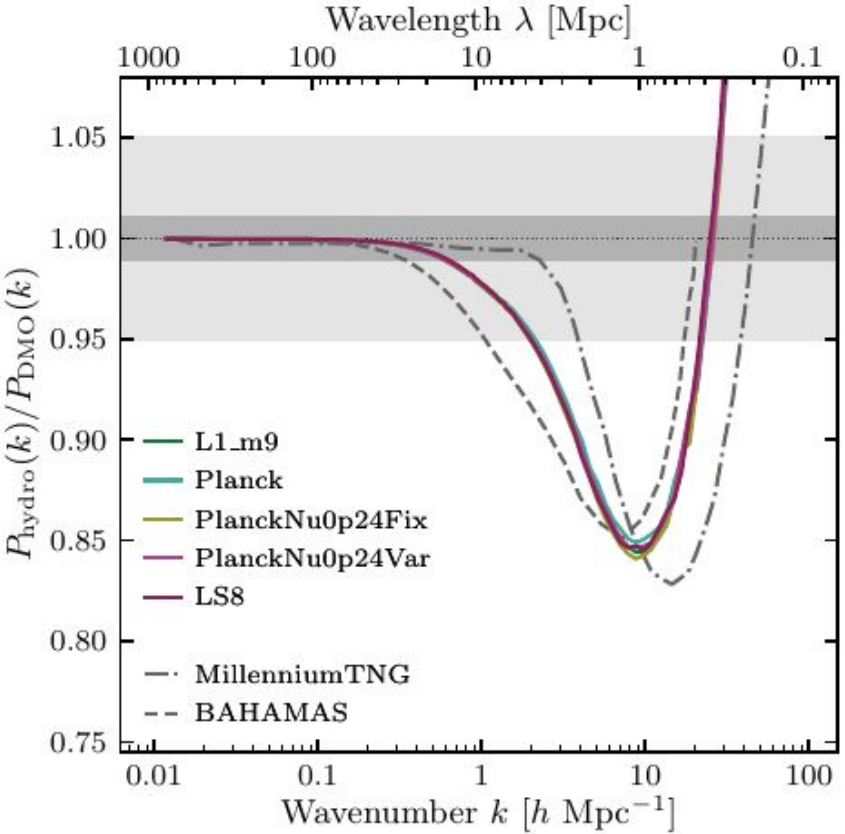




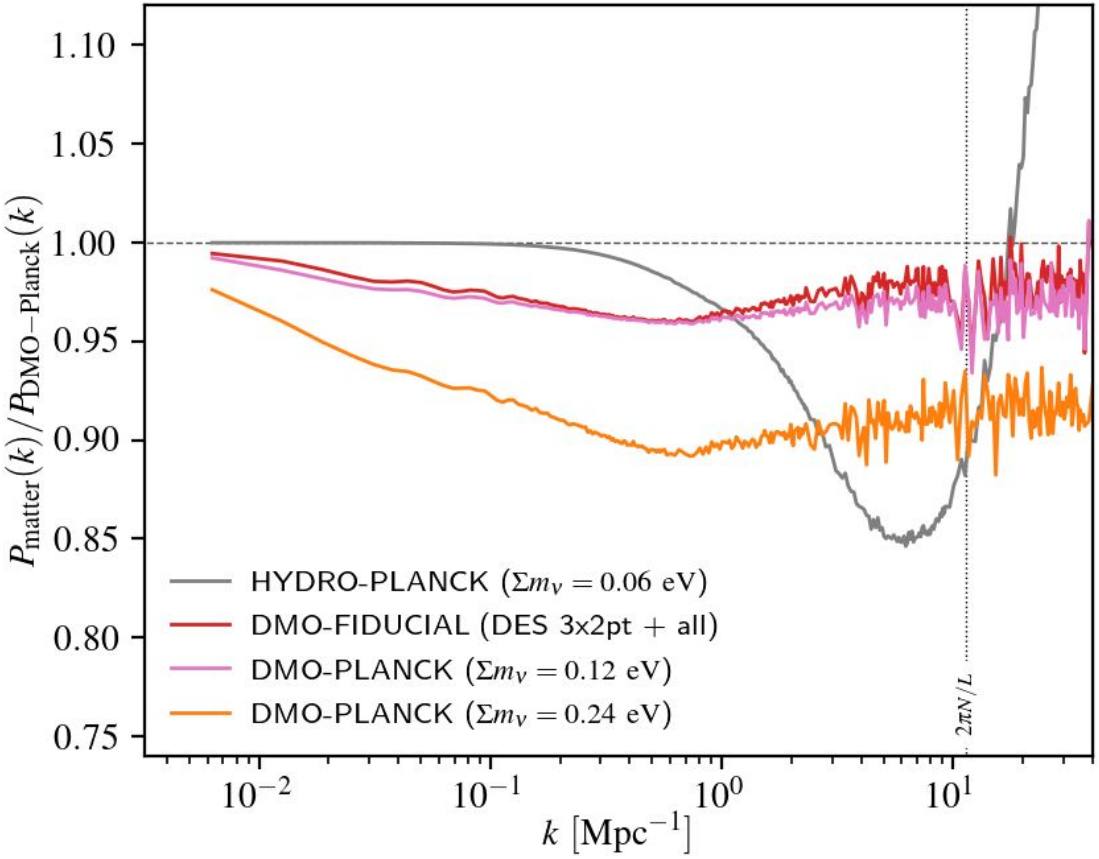
Baryon effect on matter PS



Baryon effect on matter PS



Baryon suppression vs. nu's



FLAMINGO - 2nd phase: Bracket the real Universe

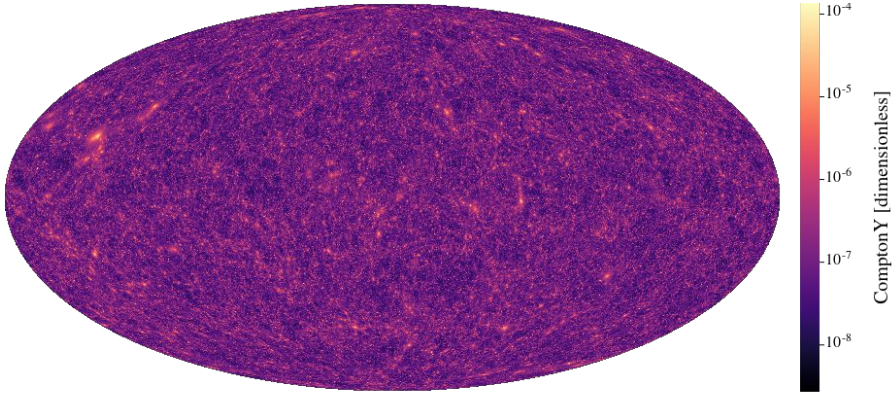
Cosmology variations Latin hypercube:

- $0.2 < \Omega_m < 0.4$
- $0.14 < \Omega_b/\Omega_m < 0.17$
- $0.6 < h < 0.8$
- $0.94 < n_s < 1.0$

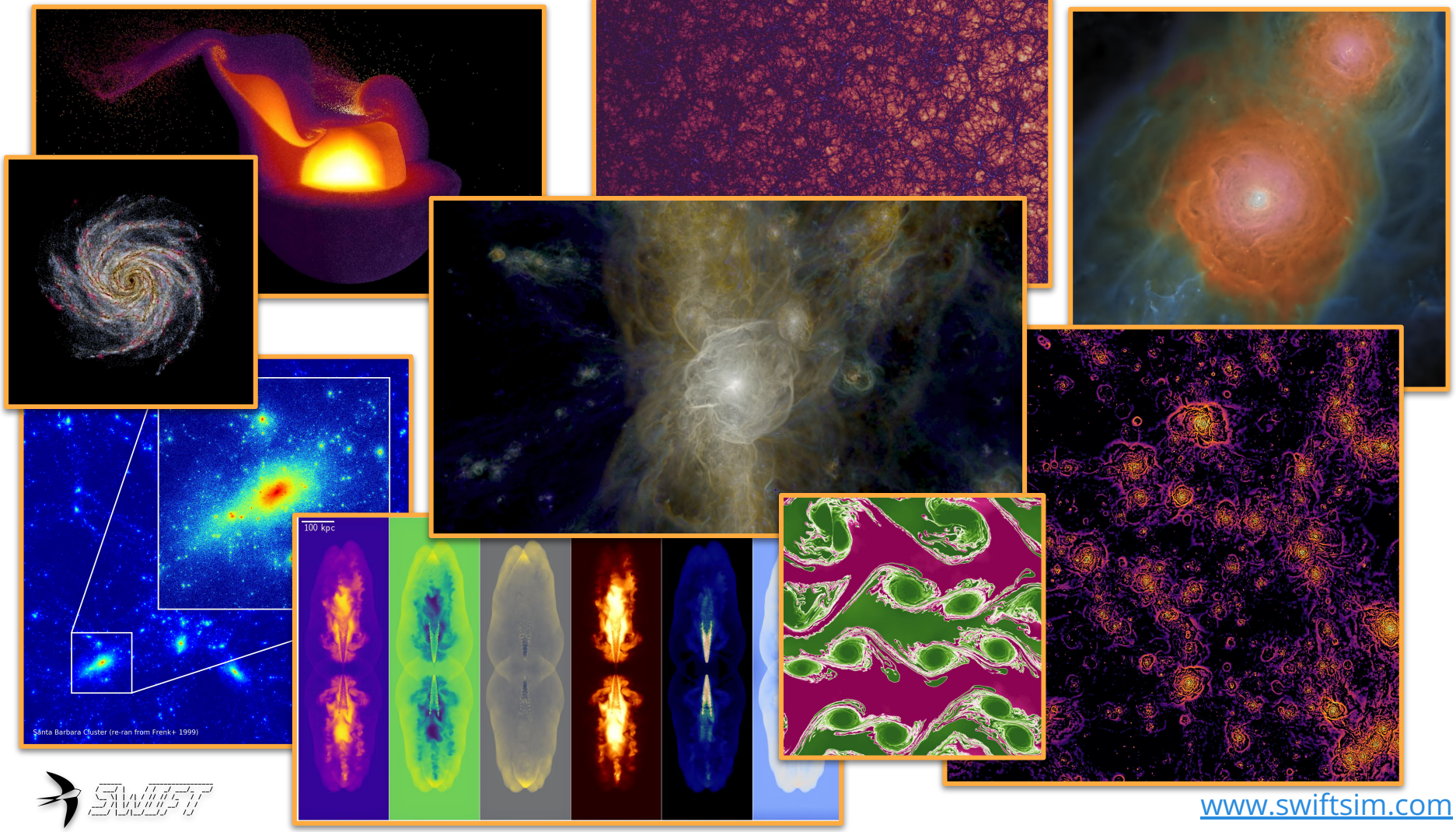
+ SIDM

- $-1.3 < w_0 < -0.7$
- $\sim -0.7 < w_a < 0.7$
- $0 < \Omega_\nu h^2 < 0.005$
- "Feedback intensity"

For each, produce all-sky maps matching different probes:



Also X-ray, SZ, weak-lensing, CMB lensing, correlation functions, RSD, ...



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