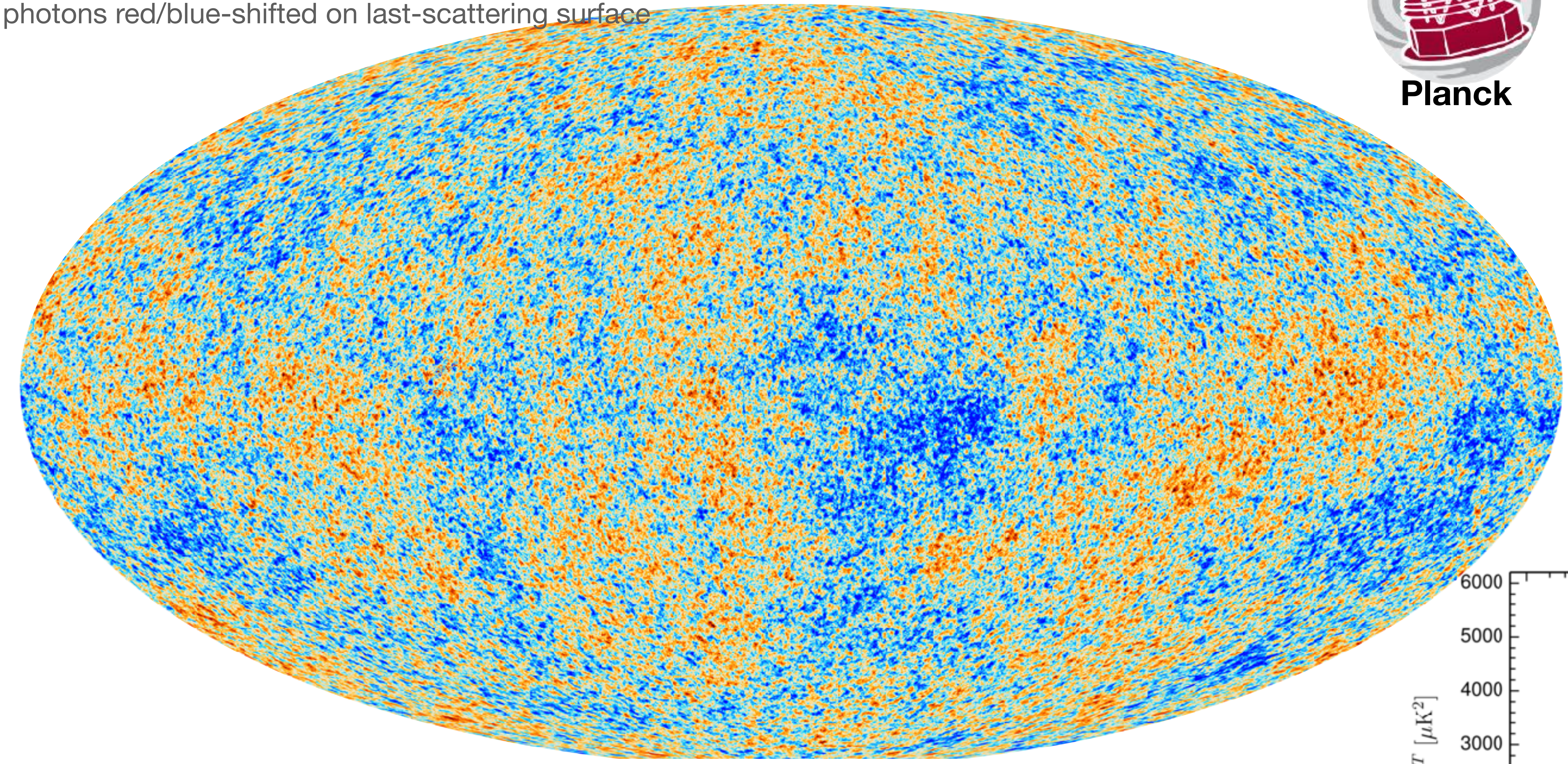
Physics with the large-scale structure of the Universe

Oliver Hahn — Dept. f. Astrophysics & Dept. f. Mathematics, University of Vienna

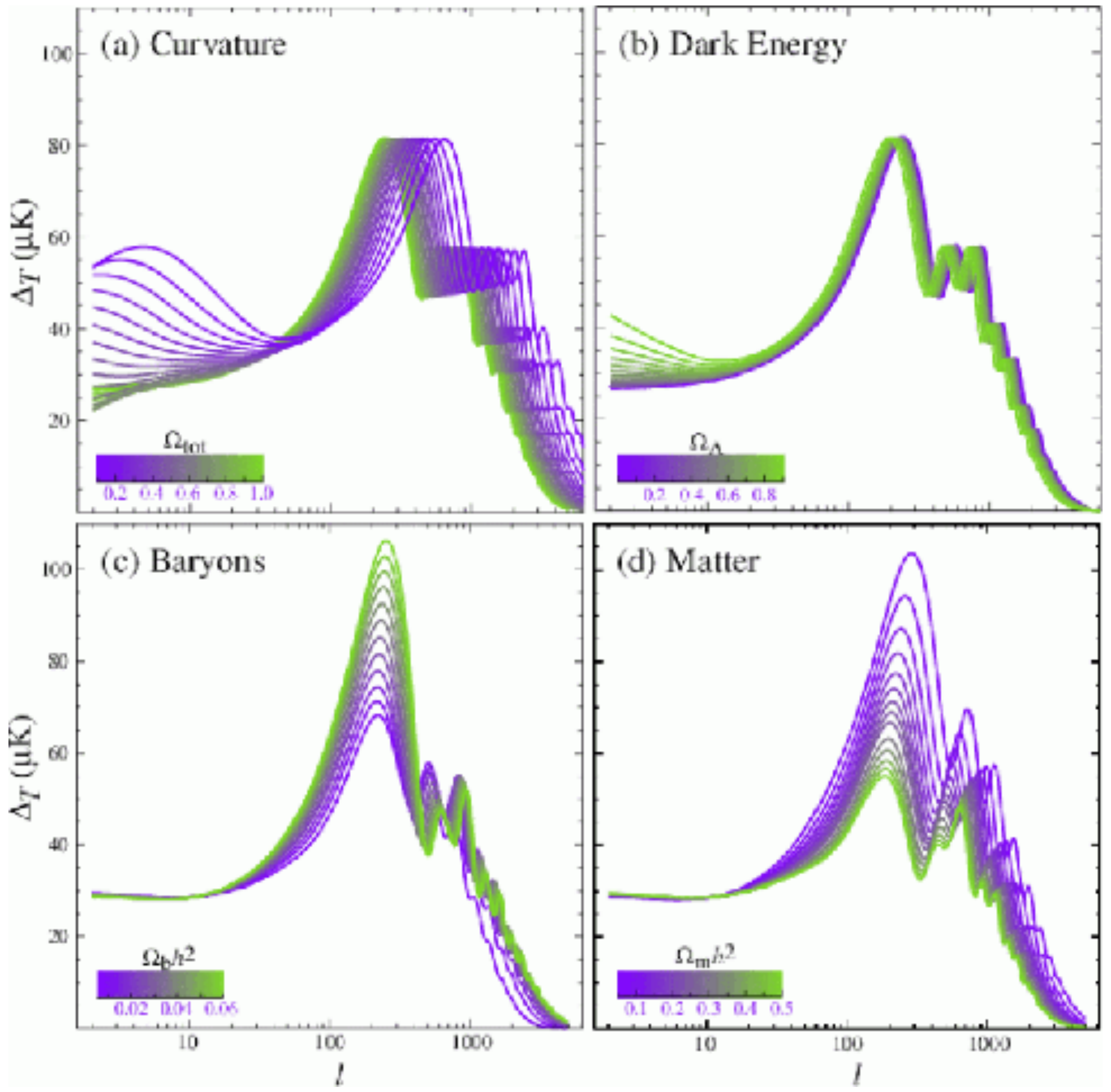
XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP 2023)

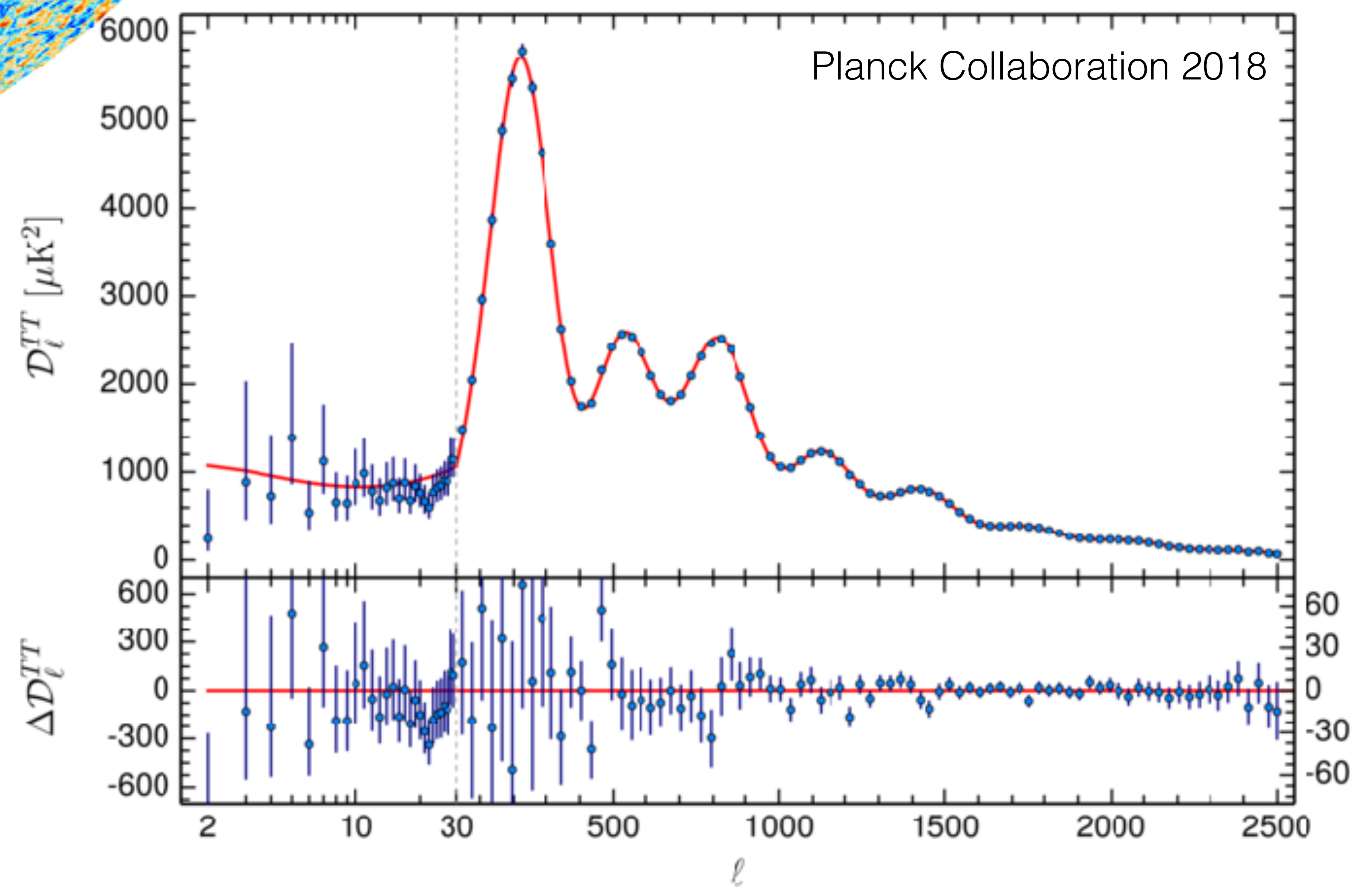
Initial Conditions: the CMB

photons red/blue-shifted on last-scattering surface



Planck



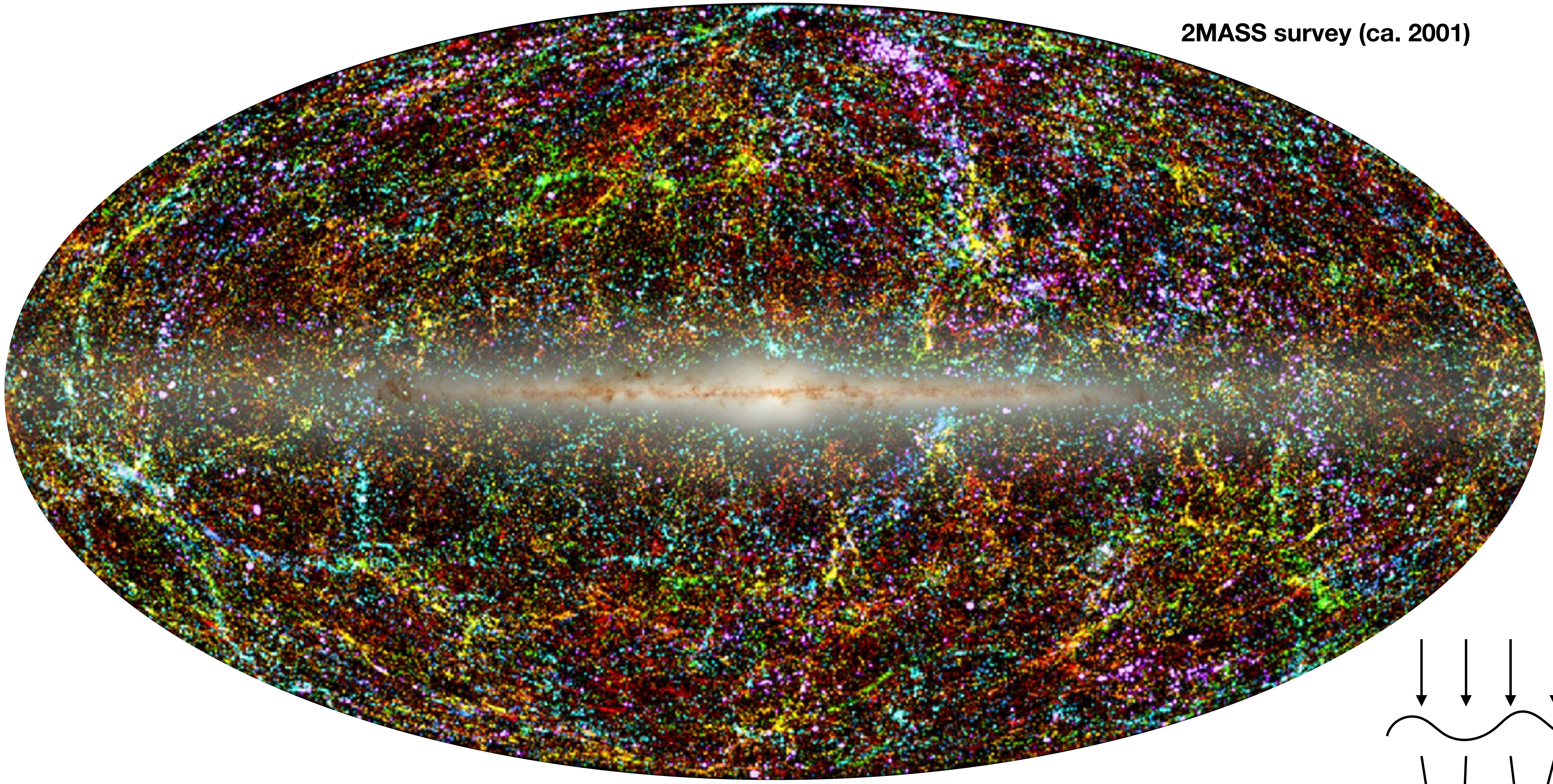


Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10}A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038

+No evidence for primordial non-Gaussianity, no detection of primordial B-modes

$$f_{NL}^{local} = -0.9 \pm 5.1;\ f_{NL}^{equil} = -26 \pm 47; \quad \text{and } f_{NL}^{ortho} = -38 \pm 24 \text{ (68 \% CL, statistical)}$$

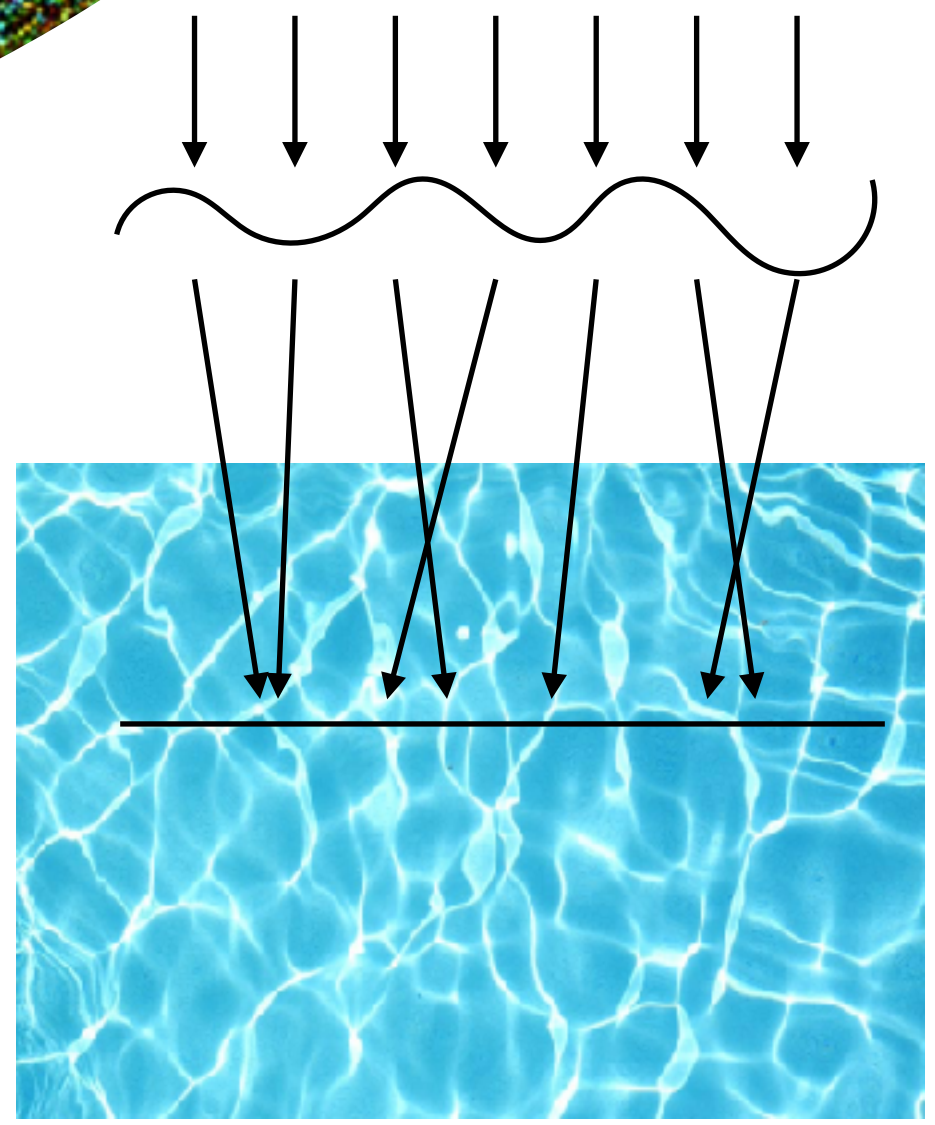
The final state:

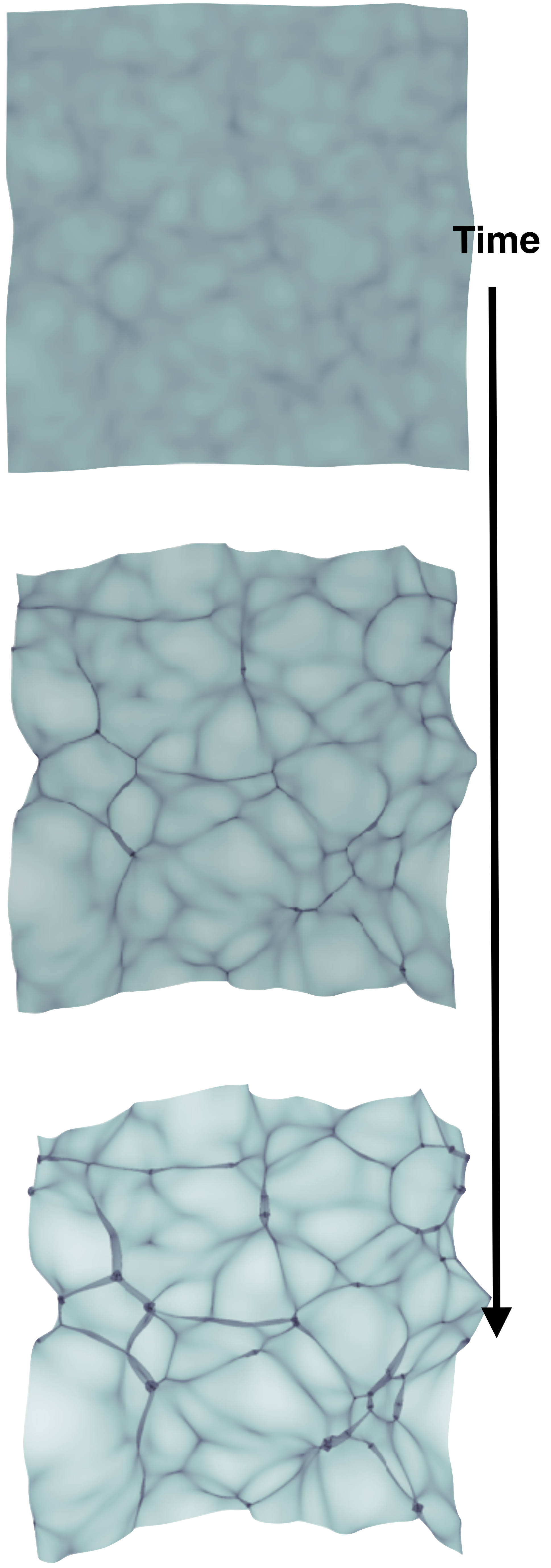

2MASS survey (ca. 2001)

Highly anisotropic ‘**cosmic web**’ (Bond+1996) structure of intergalactic gas and galaxies that developed from **seeds seen in CMB**, **under gravity and astrophysical** processes

probes: expansion history of Universe + growth of structure (gravity) + has many more modes than CMB, but more complicated observables

similar to diffraction at random surface





Physics with the LSS

primordial spectrum from inflation

$P_m(k) \propto k^{n_s}$

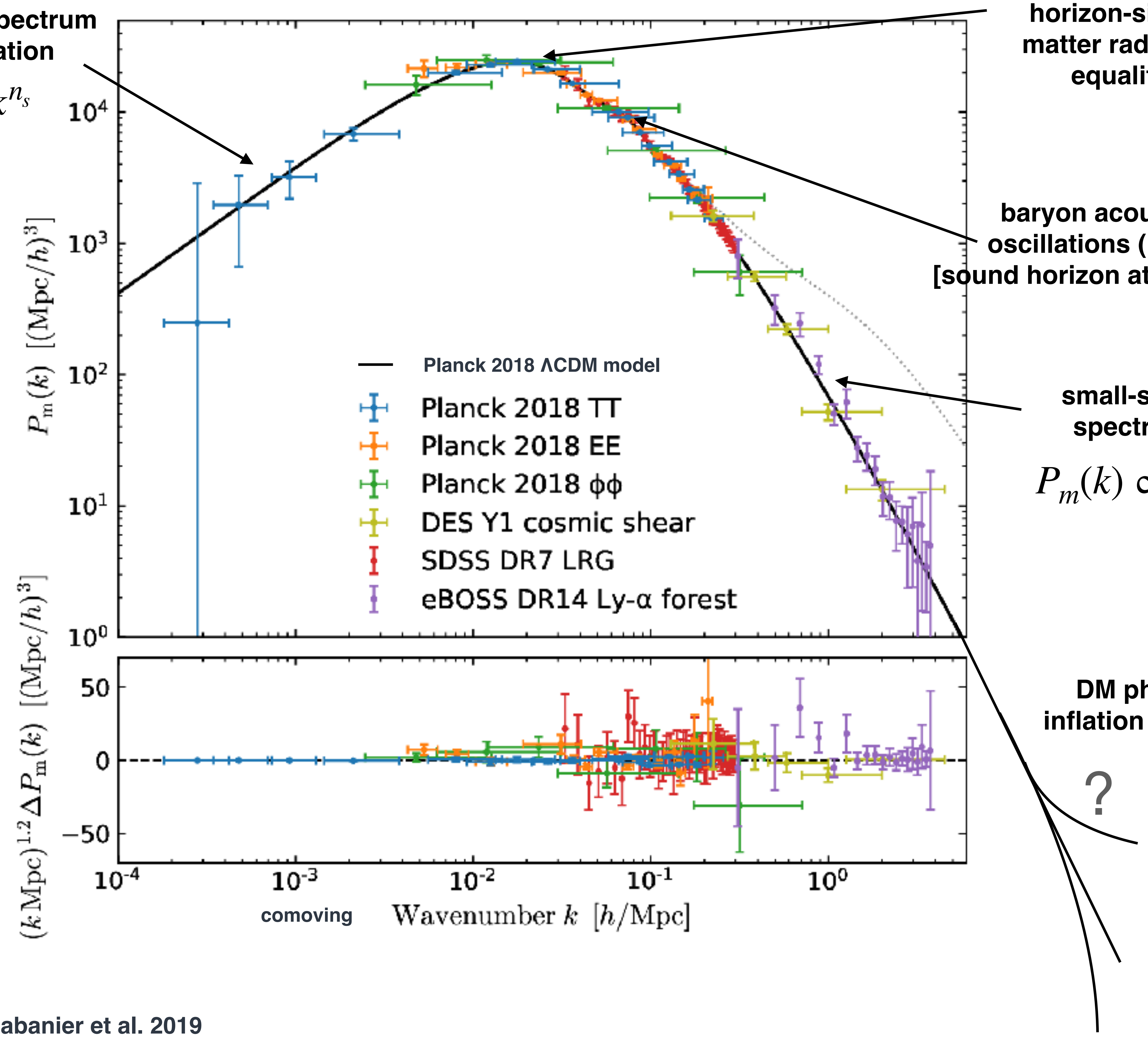
peak set by horizon-size at matter radiation equality

baryon acoustic oscillations (BAO) [sound horizon at recomb.]

small-scale spectrum

$P_m(k) \propto k^{-2}$

DM physics? inflation features?



Chabanier et al. 2019

Key questions:

law of gravity? any deviations from GR?

any hints beyond cosmological constant? w(z)?

initial conditions? what inflation?

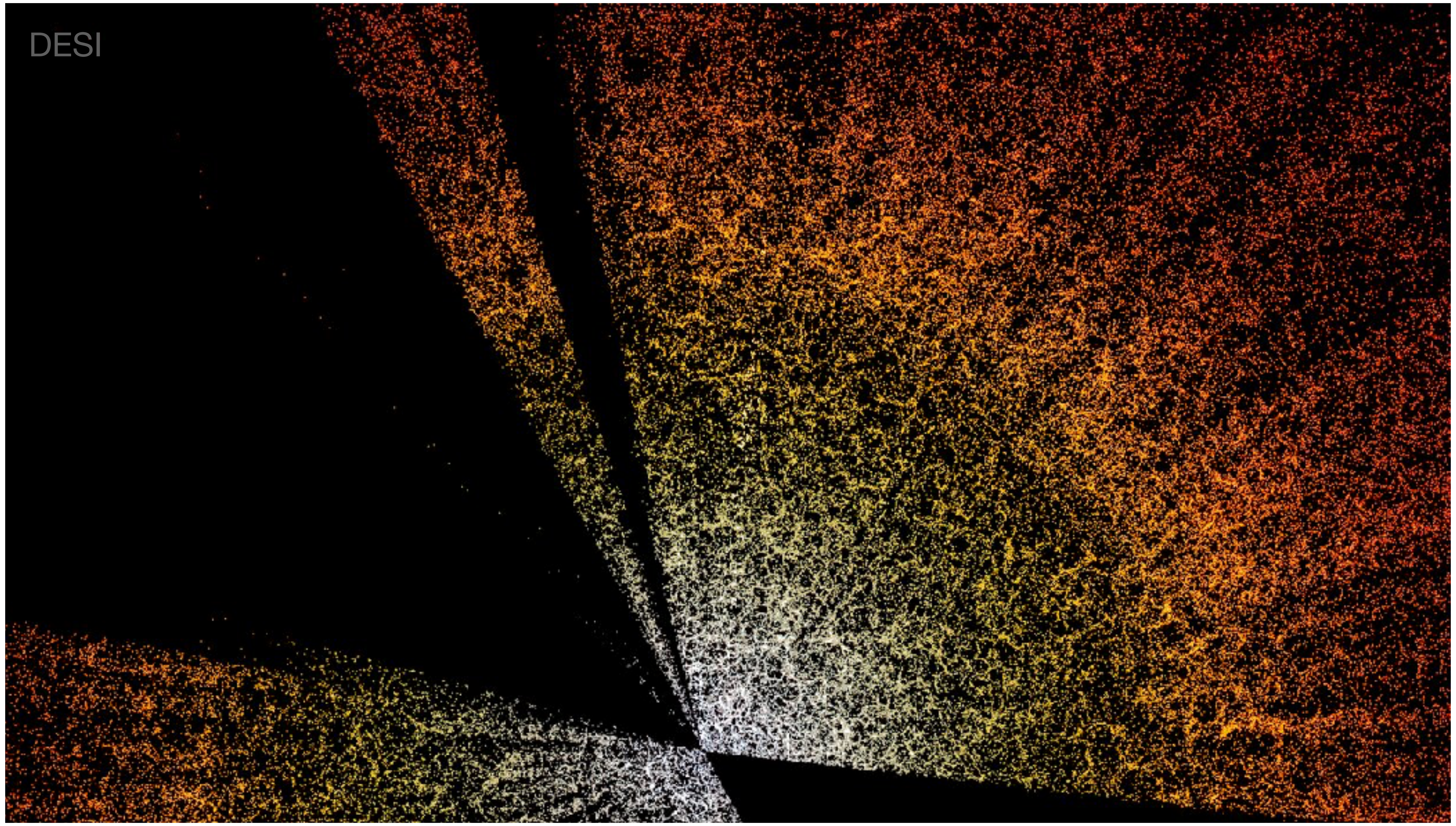
dark matter nature?

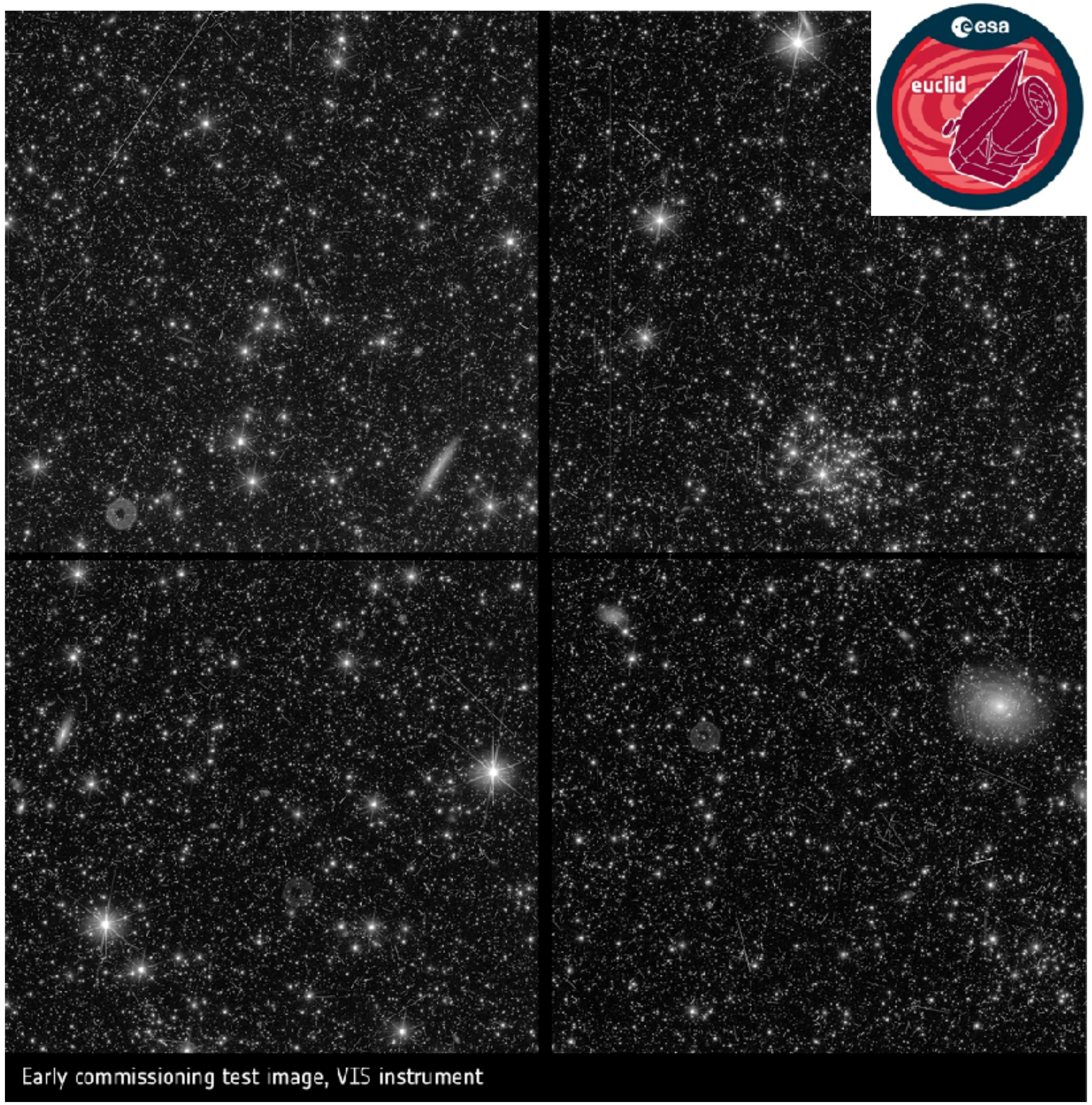
neutrino masses?

do we have see any deviations from LCDM?
(the minimal, not necessarily the favourite model)

Amazing times for LSS

- DESI is underway (2/5 completed)
- Euclid space telescope has seen first light. ->
- ACT is complete
- LSST will see first light 2024
- SPHEREx + Roman 2025+





Early commissioning test image, VIS instrument

Connecting early and late

LCDM-model

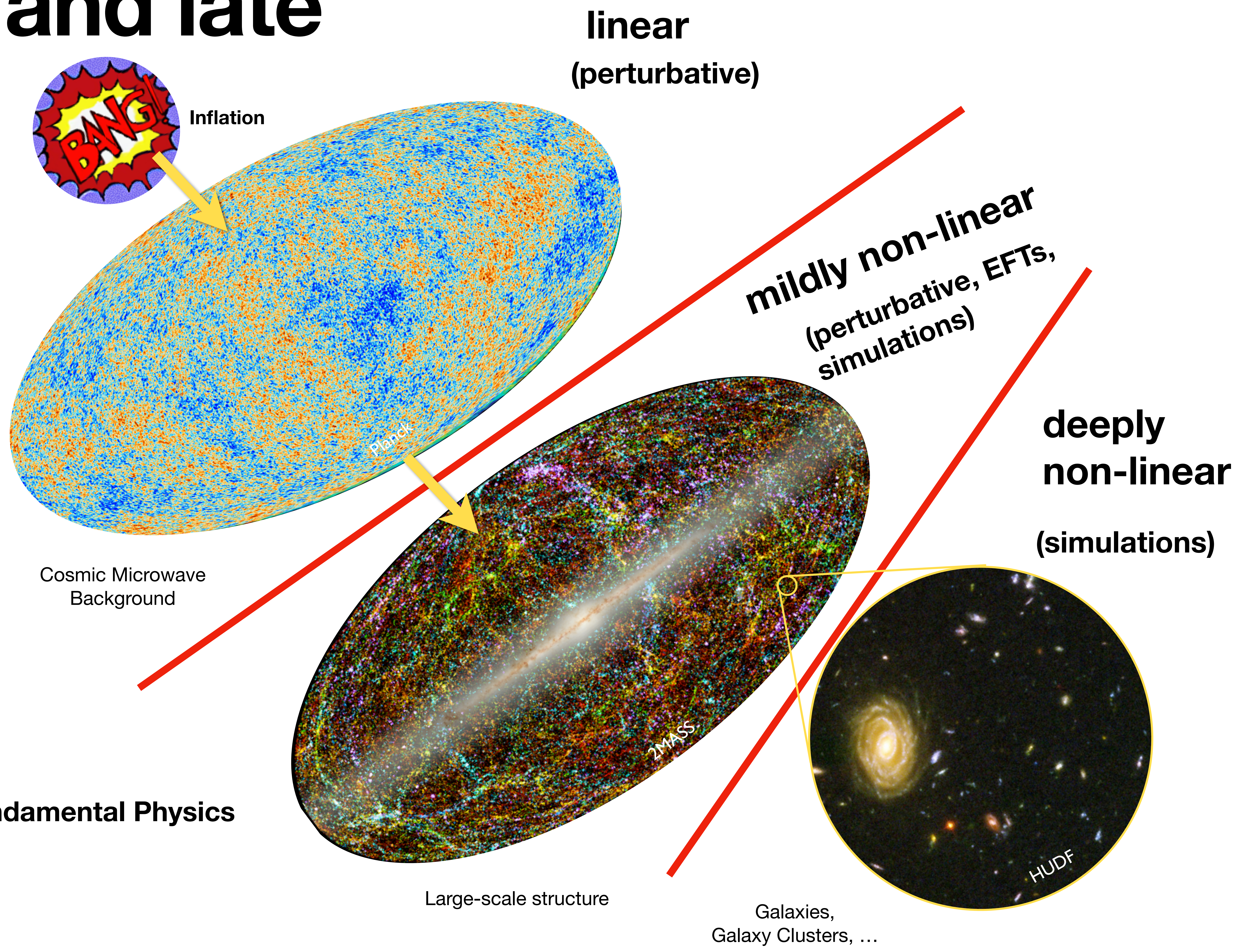
Cosmological parameters

H_0 $\Omega_m, \Omega_\Lambda, \Omega_b,$ σ_8 $n_s, A_s,$ $\sum m_\nu,$ w_0, w_a

Energy content	Primordial/ Inflation	massive Neutrinos	dark energy EOS

General relativity
Inflation
Nature of Dark Matter
Astrophysics

+ initial conditions ((non)-Gaussianity)



Modelling challenge:

predict mapping between physical model and all observables

taking into account uncertainties, and all cross correlations

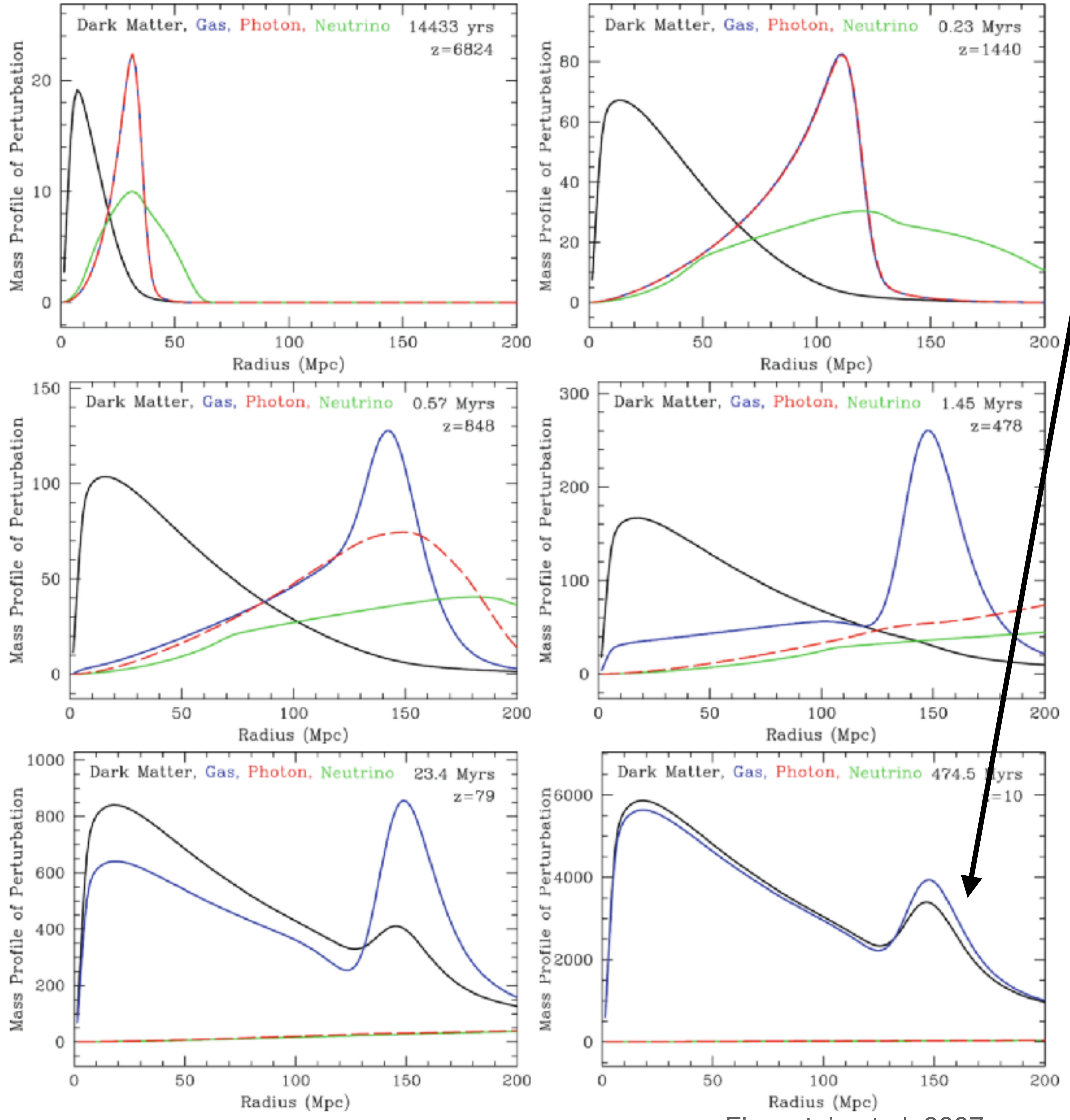
inference limitation is from modelling, not data already with current surveys!

Large-Scale Structure (Late Universe) Probes of Fundamental Physics

Galaxy distribution (clustering, n-point, etc.)
Gravitational Lensing (weak, strong, CMB lensing)
Galaxy Clusters (optical, X-ray, tSZ)
Ly-a, HI mapping

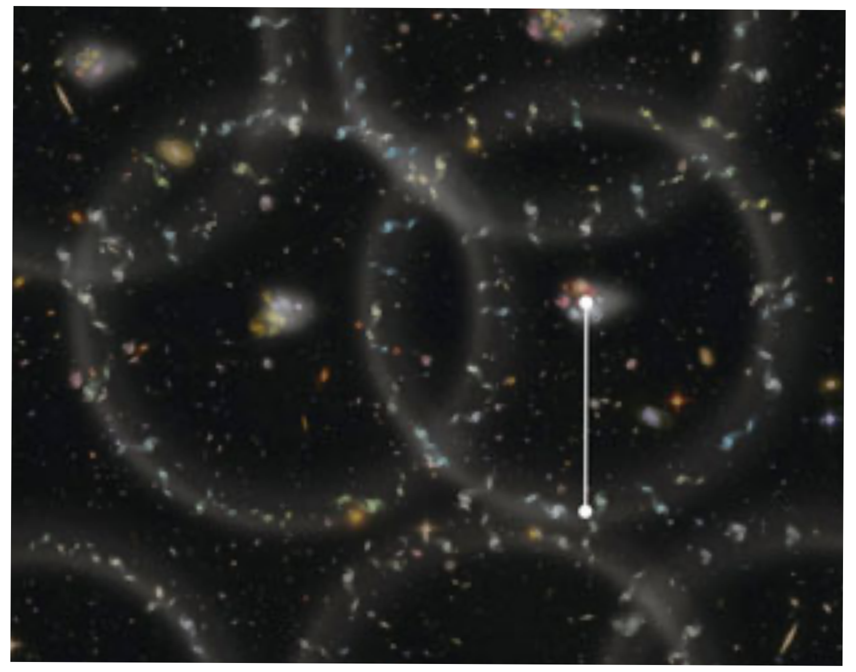
The Baryon Acoustic Oscillation (BAO) standard ruler

Sound horizon is imprinted in matter distribution

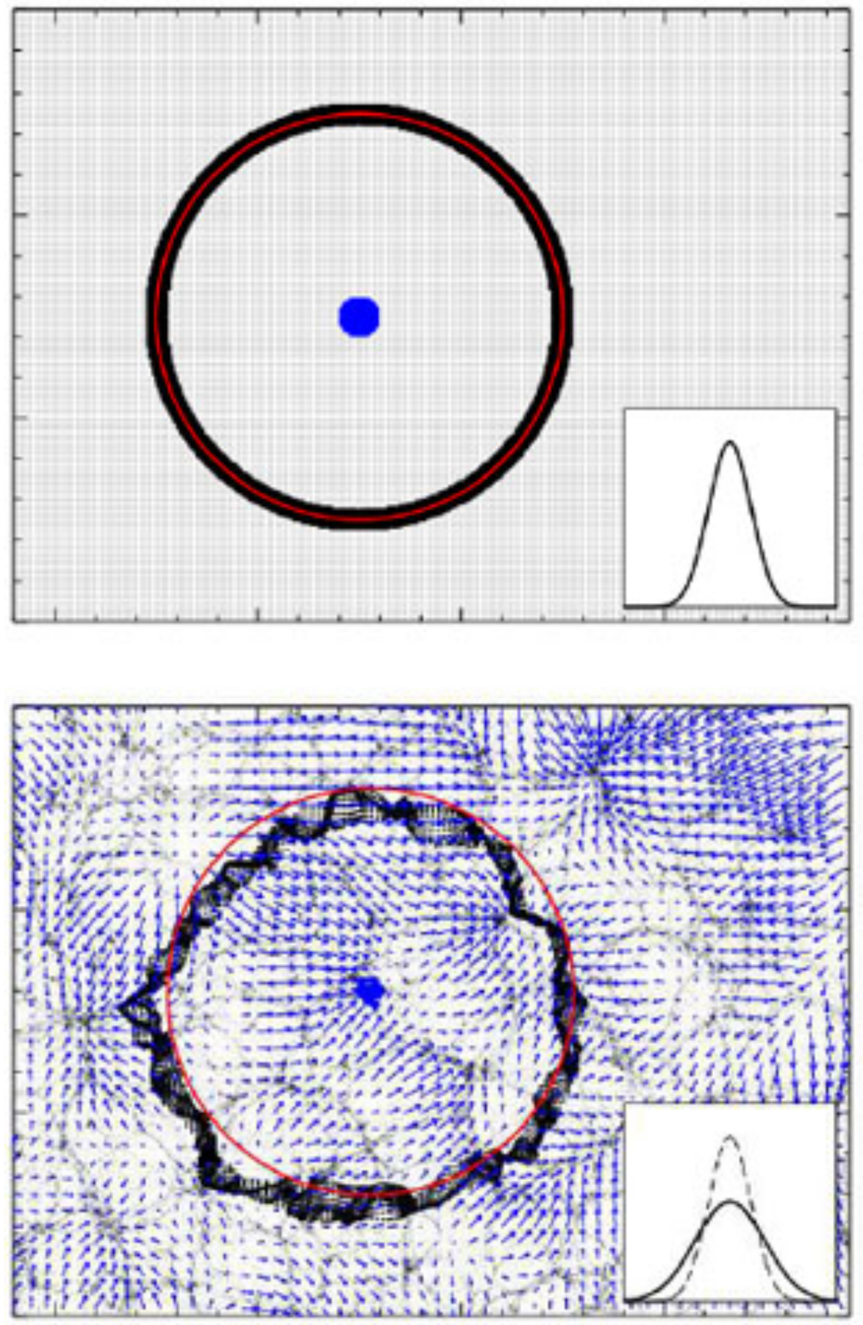


Eisenstein et al. 2007

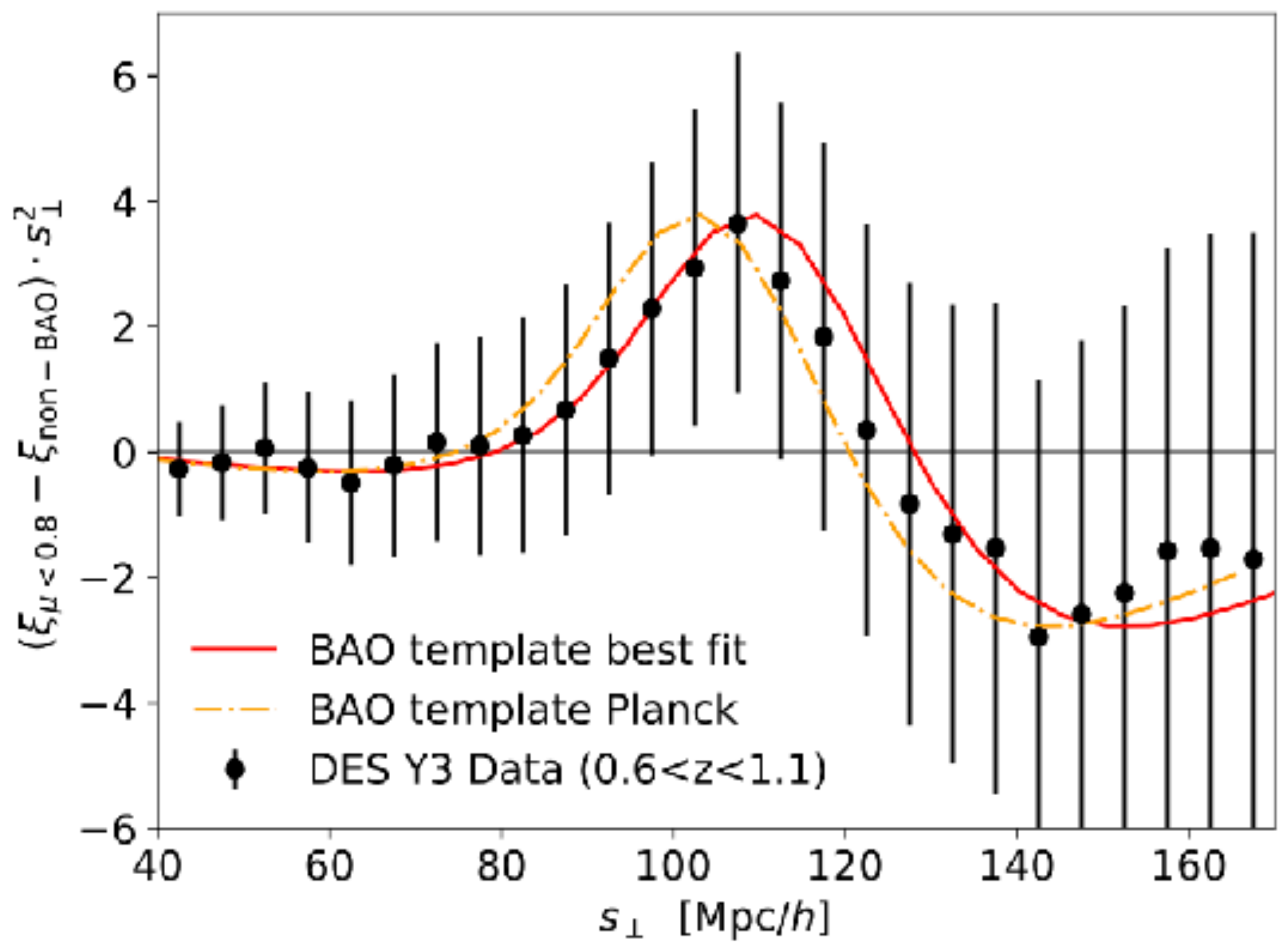
Increase in probability for galaxy pairs (or Ly-a forest)



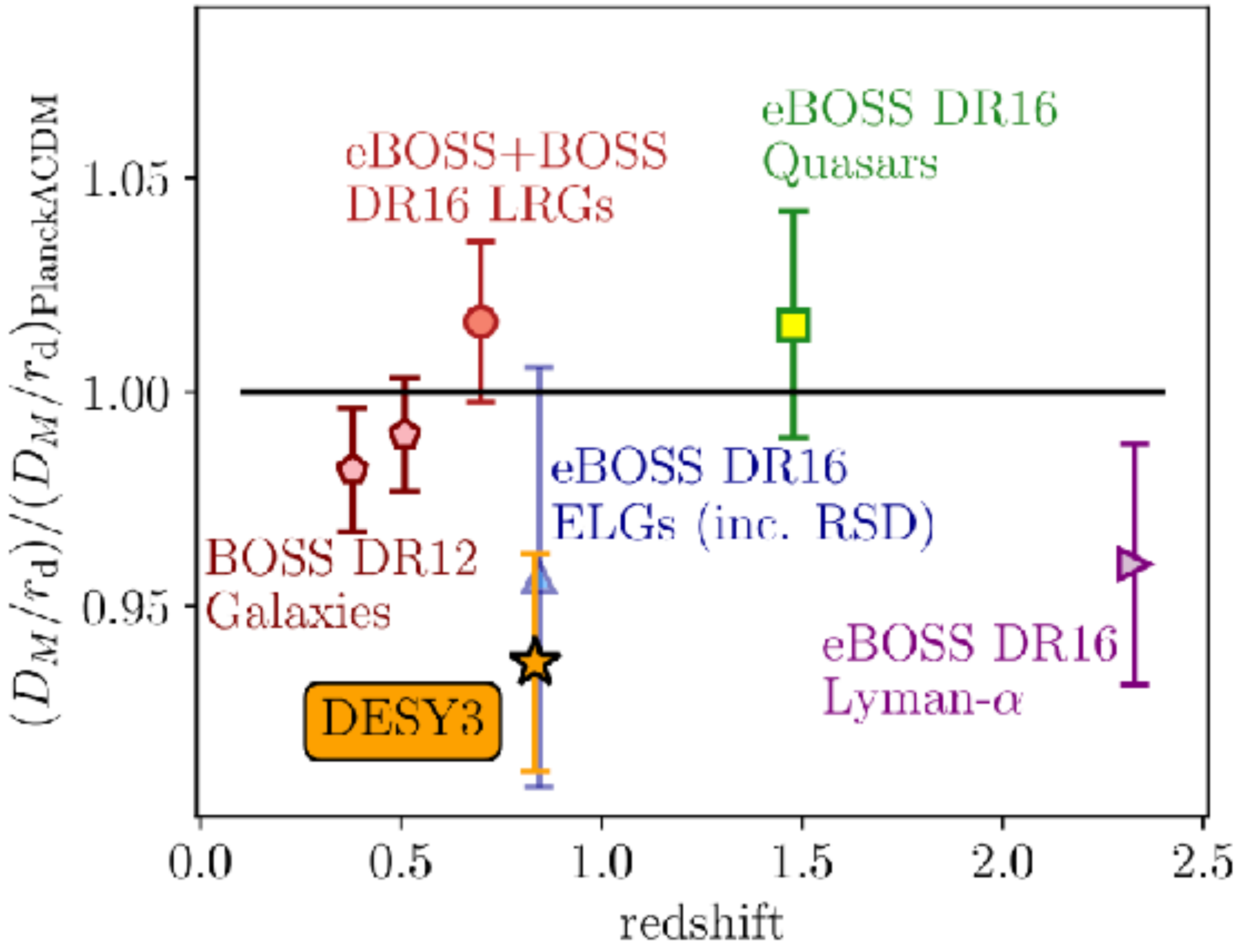
deformation due to non-linear structure formation



DES collaboration 2022



ratio of angular diameter distance from BAO relative to Planck



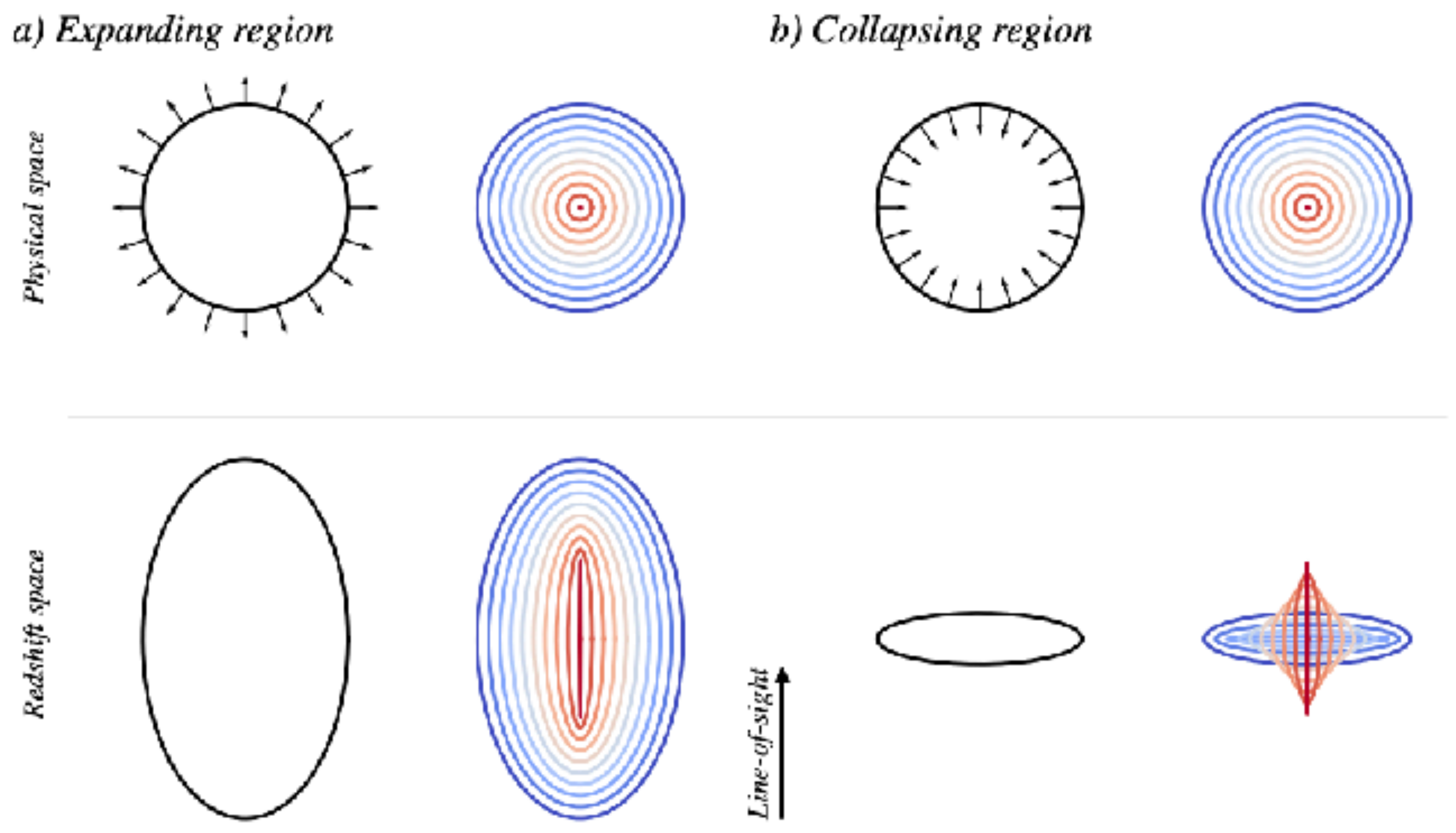
Testing for deviations from GR

e.g. through RSD+clustering

redshift = distance + peculiar motion (+ gravitational redshift+…)

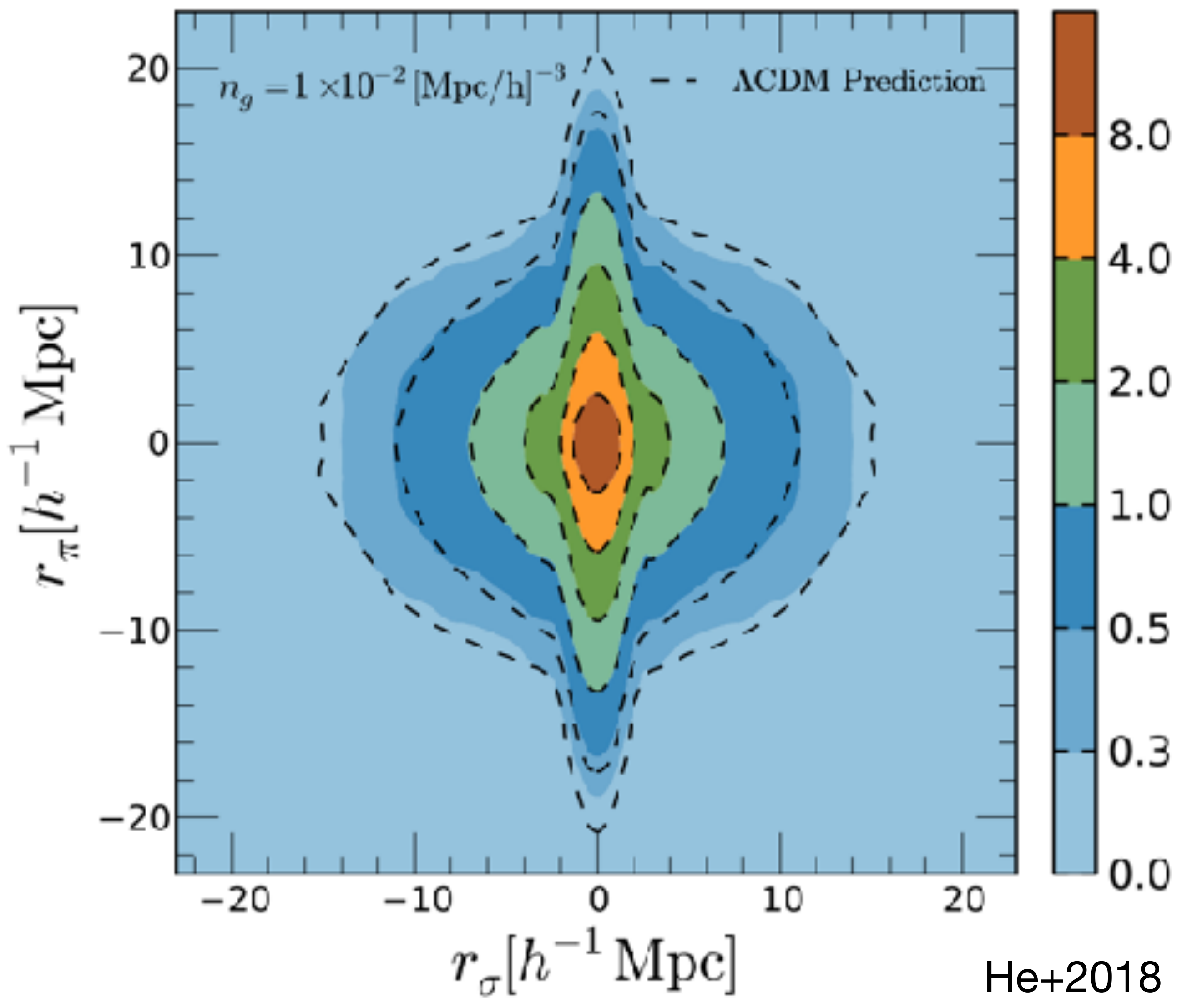
$$c\,z = H_0\,D + v$$

Growth of structure leads to velocities, which lead to line-of-sight deviations from Hubble flow

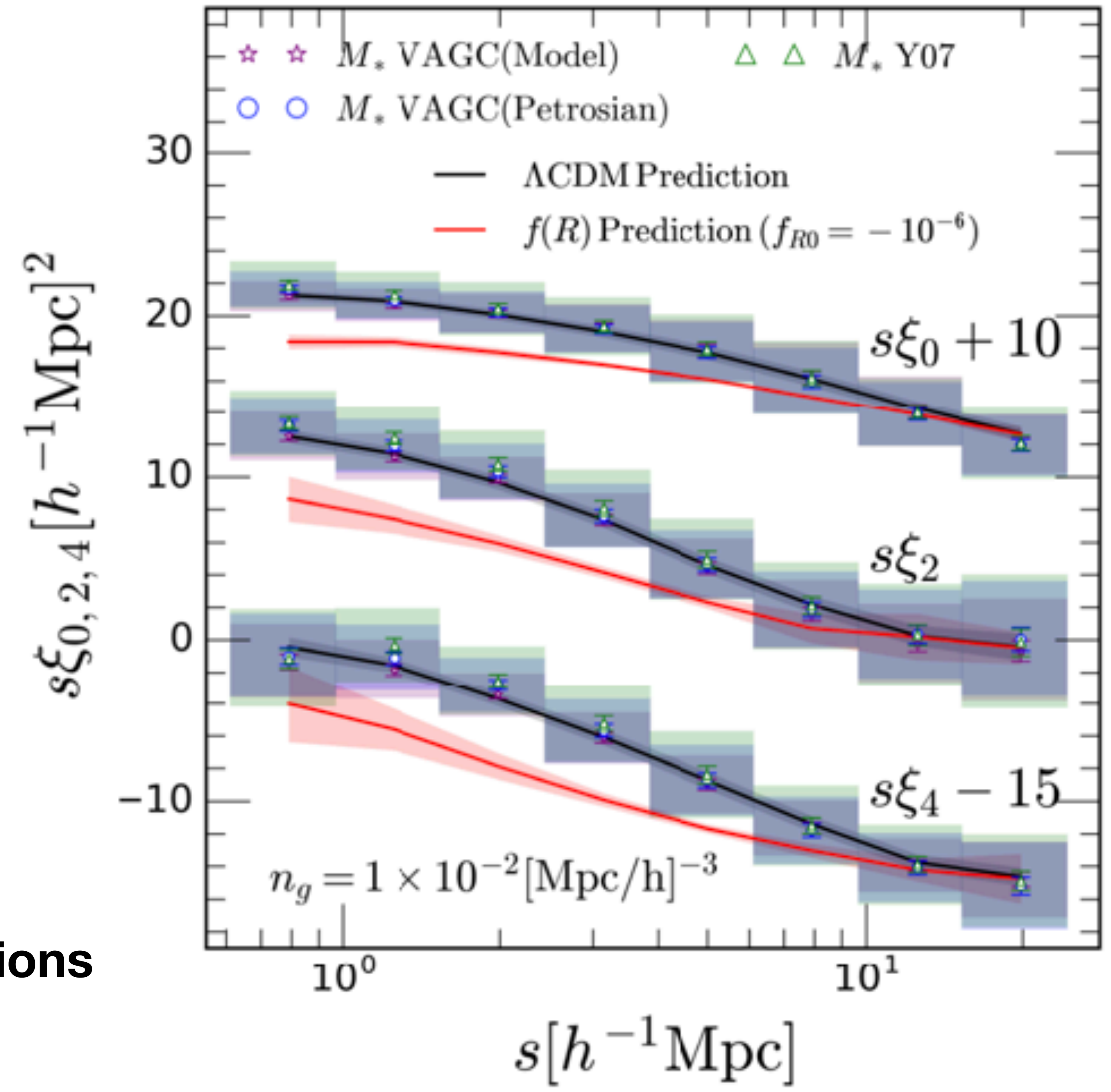


Clustering in redshift space tests density + its time derivative

Forward model simulation + mapping from simulation to observables (e.g. SHAM, bias expansion)

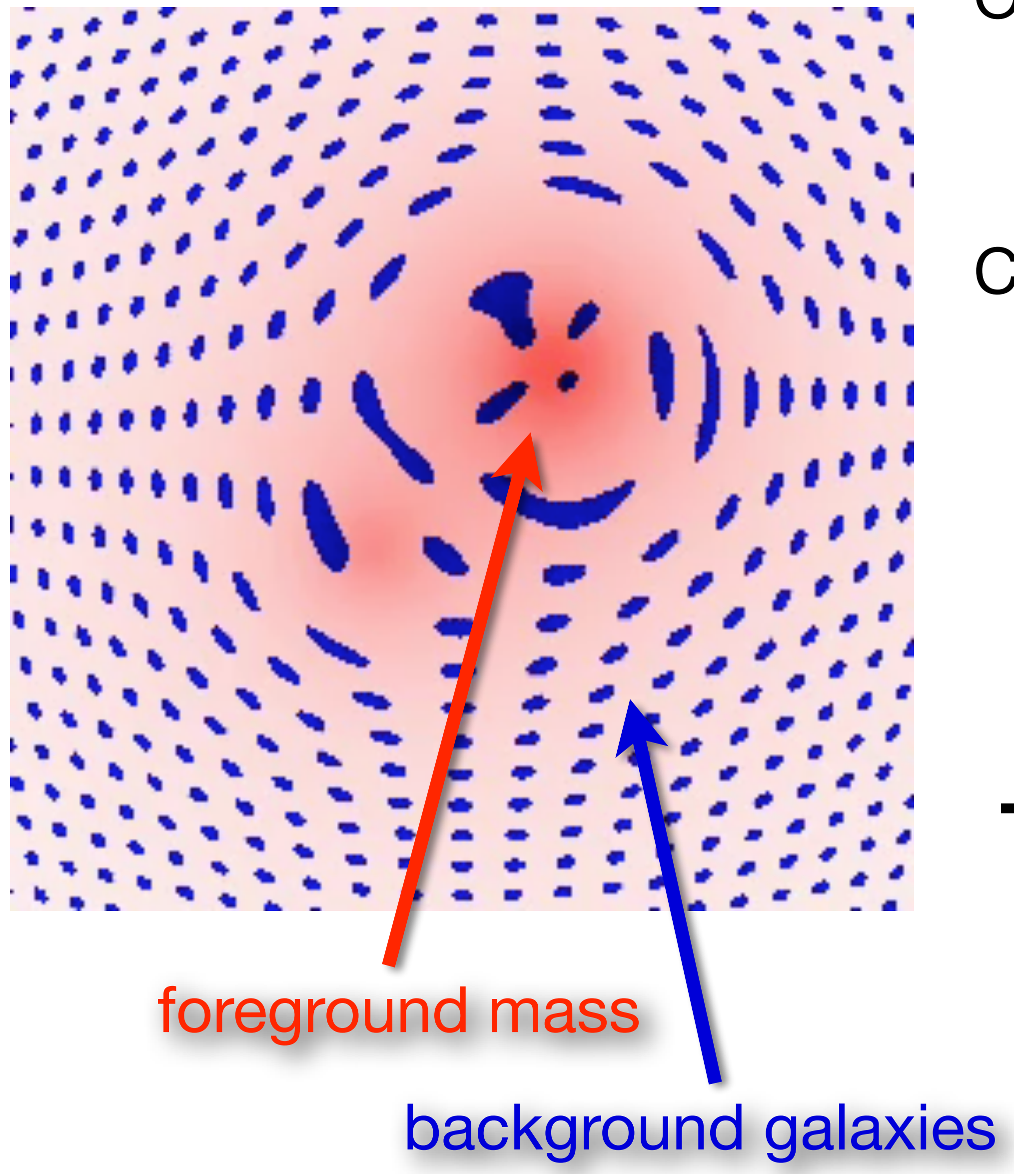


He+2018



He+2018: No evidence for deviations from LCDM within uncertainties

Weak gravitational lensing



Observable is total ellipticity

$$\epsilon_{\rm obs} = \gamma + \epsilon_I$$

Correlation function thus becomes

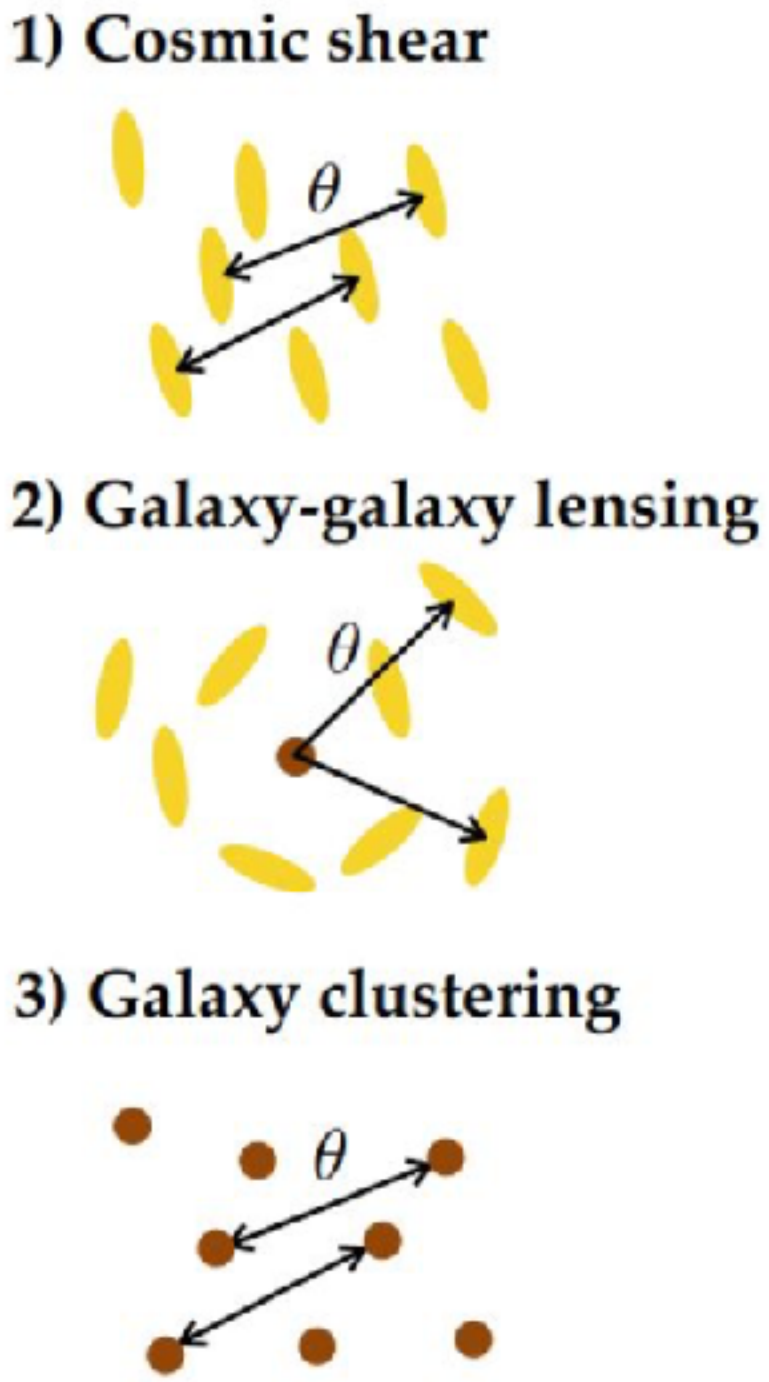
$$\langle \epsilon_{\rm obs} \epsilon'_{\rm obs} \rangle = \langle \gamma\, \gamma' \rangle + \langle \gamma\, \epsilon'_I \rangle + \langle \epsilon_I\, \gamma' \rangle + \langle \epsilon_I\, \epsilon'_I \rangle$$

structure — signal

GI — Intrinsic alignment contamination/signal

II

The 3x2pt analys of shear surveys:

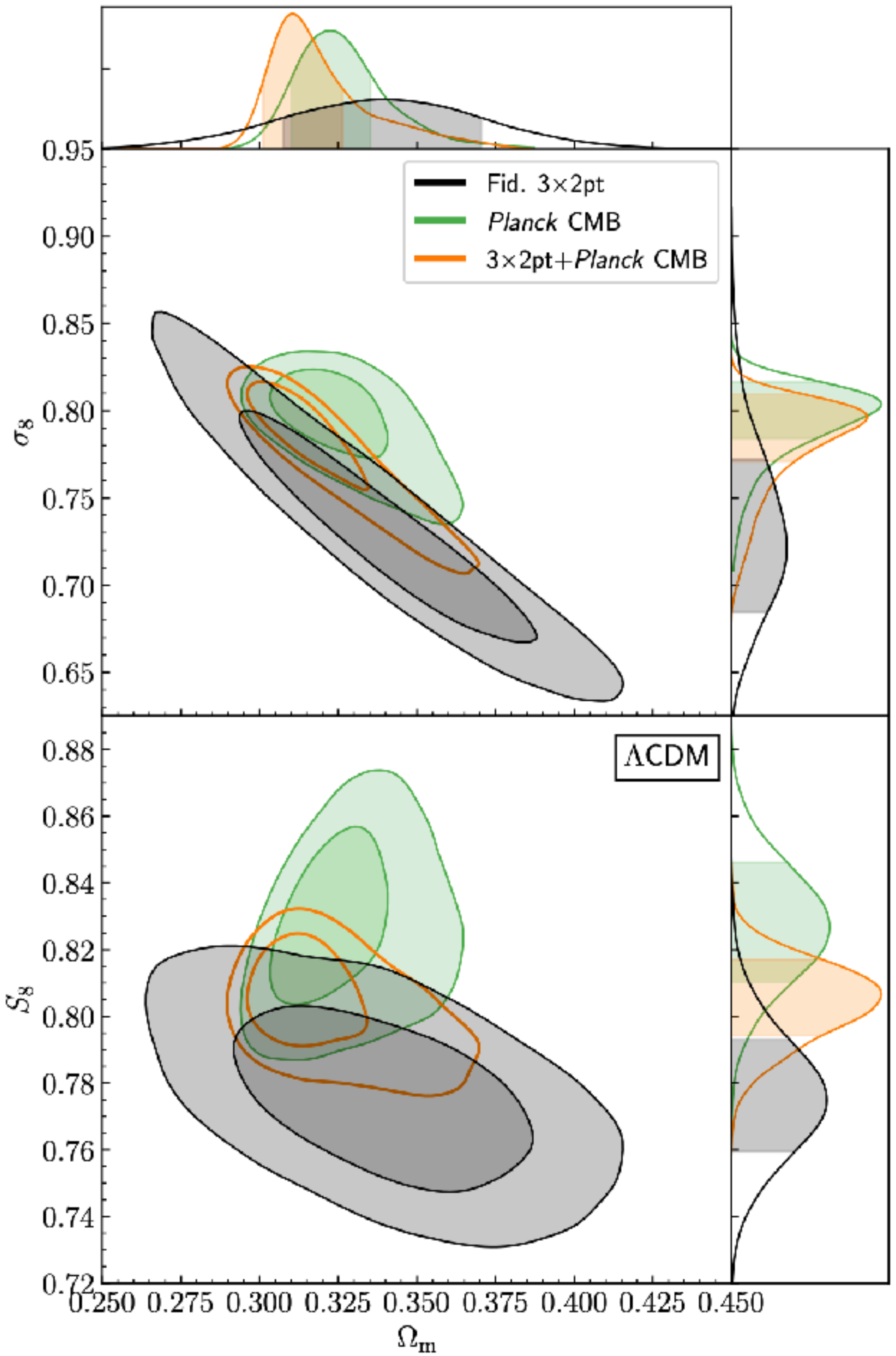


credit: Chihway Chang

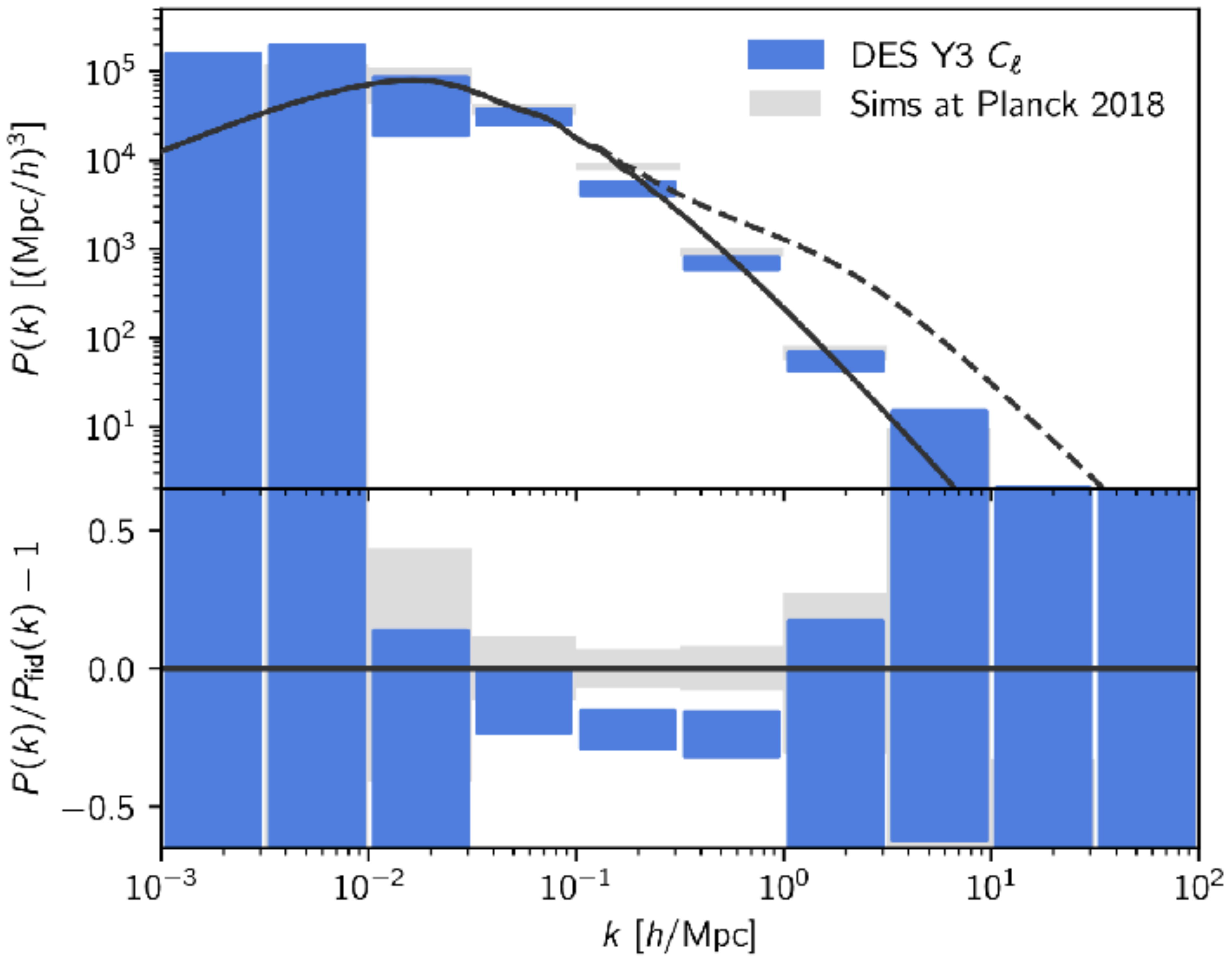
The infamous S8 tension

$$S_8 := \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$$

DES Y3 results (DES collaboration 2022)



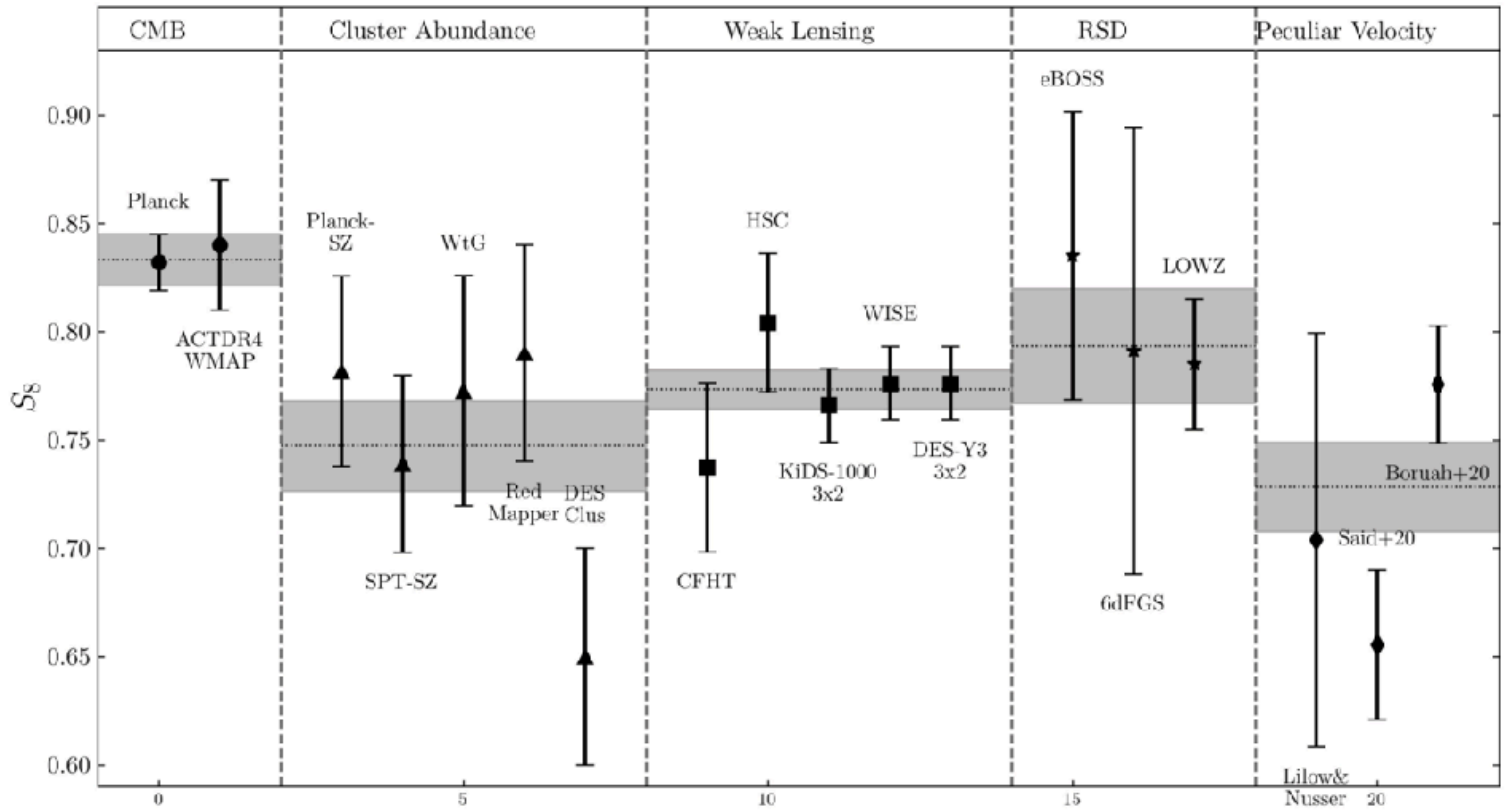
The S8 tension



Doux+2022

Linear power spectrum from DES Y3 relative to Planck linear P(k) at z=0 -> scale-dependent suppression at high significance

->target with new physics (DM-b interaction, DM-DE interactions, modification in growth rate)



updated version from Boruah+2020 by Mike Hudson

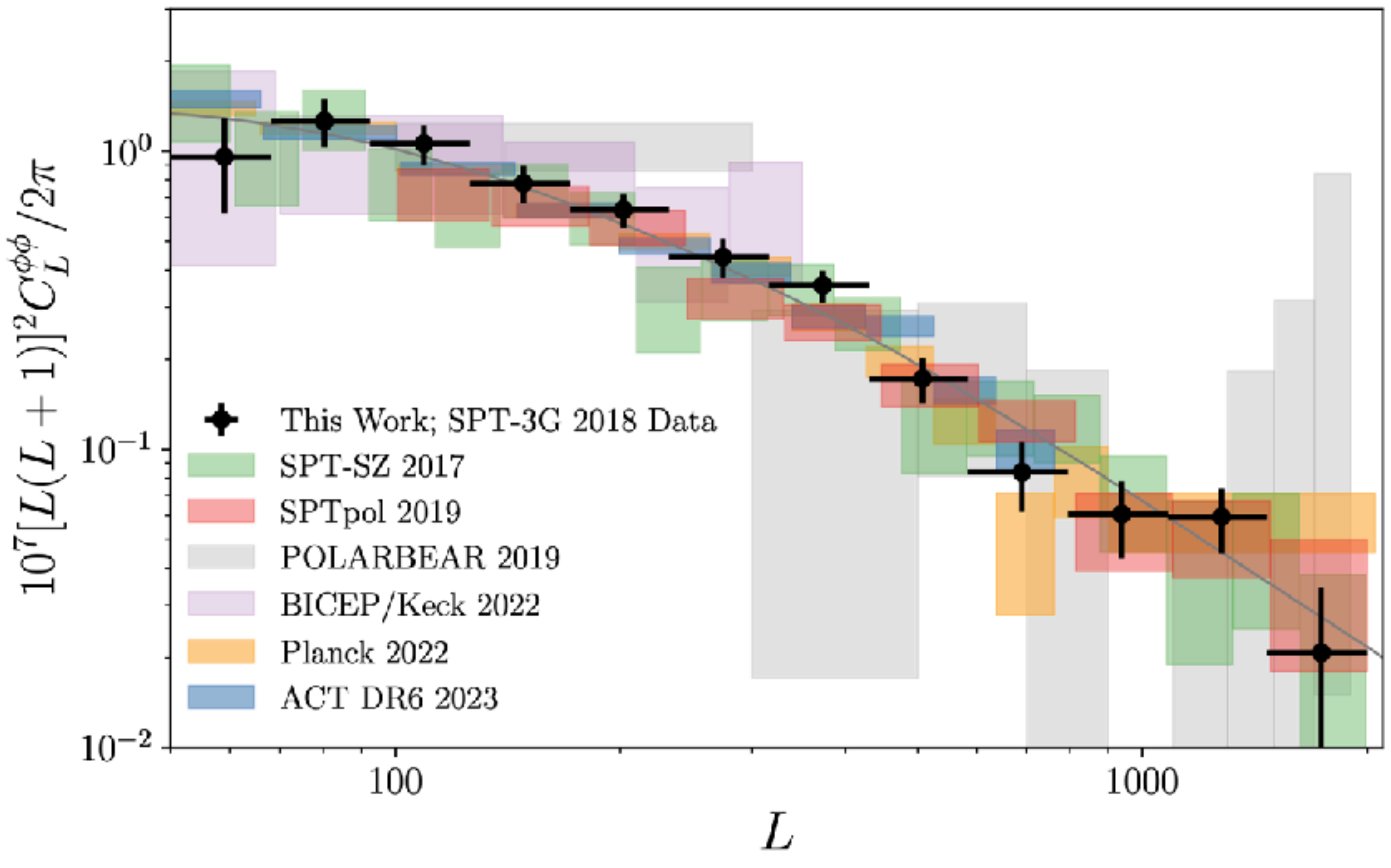
but there are many versions of this plot

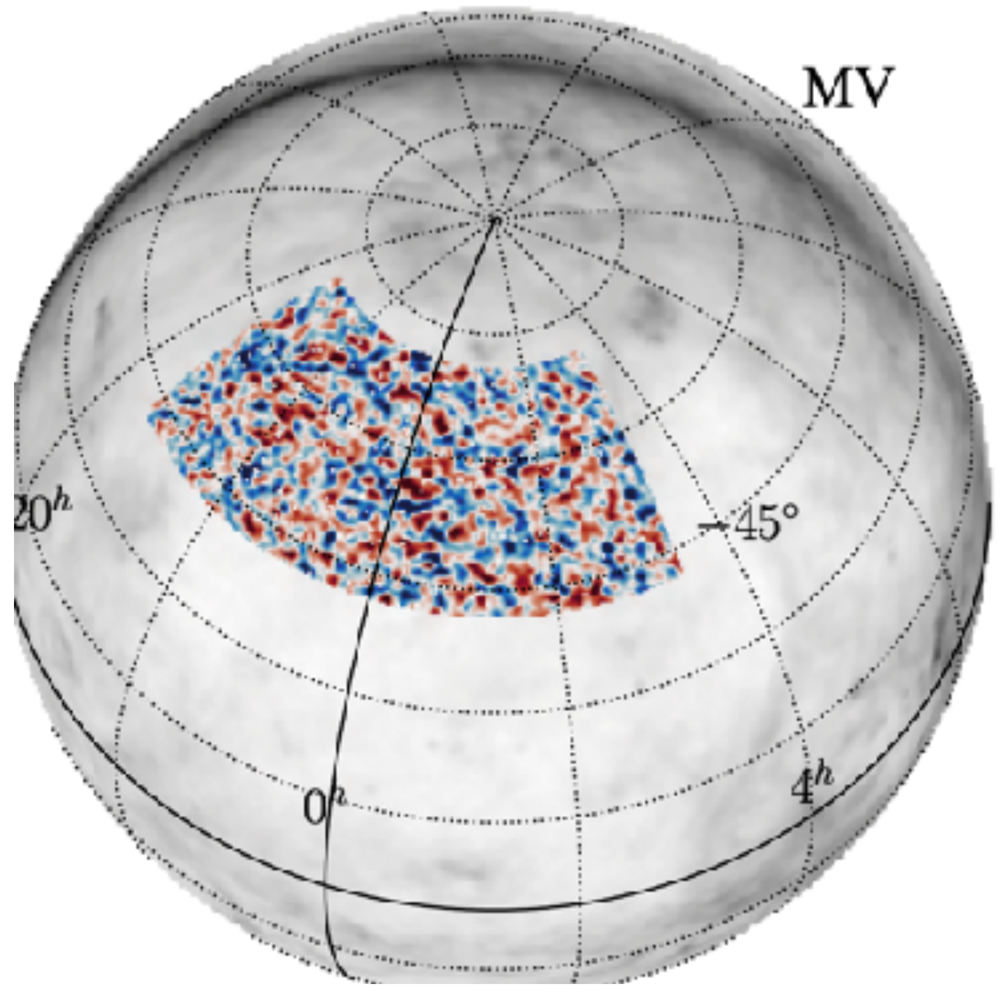
->target with new physics (DM-b interaction, DM-DE interactions, modification in growth rate)

CMB lensing from ACT+SPT

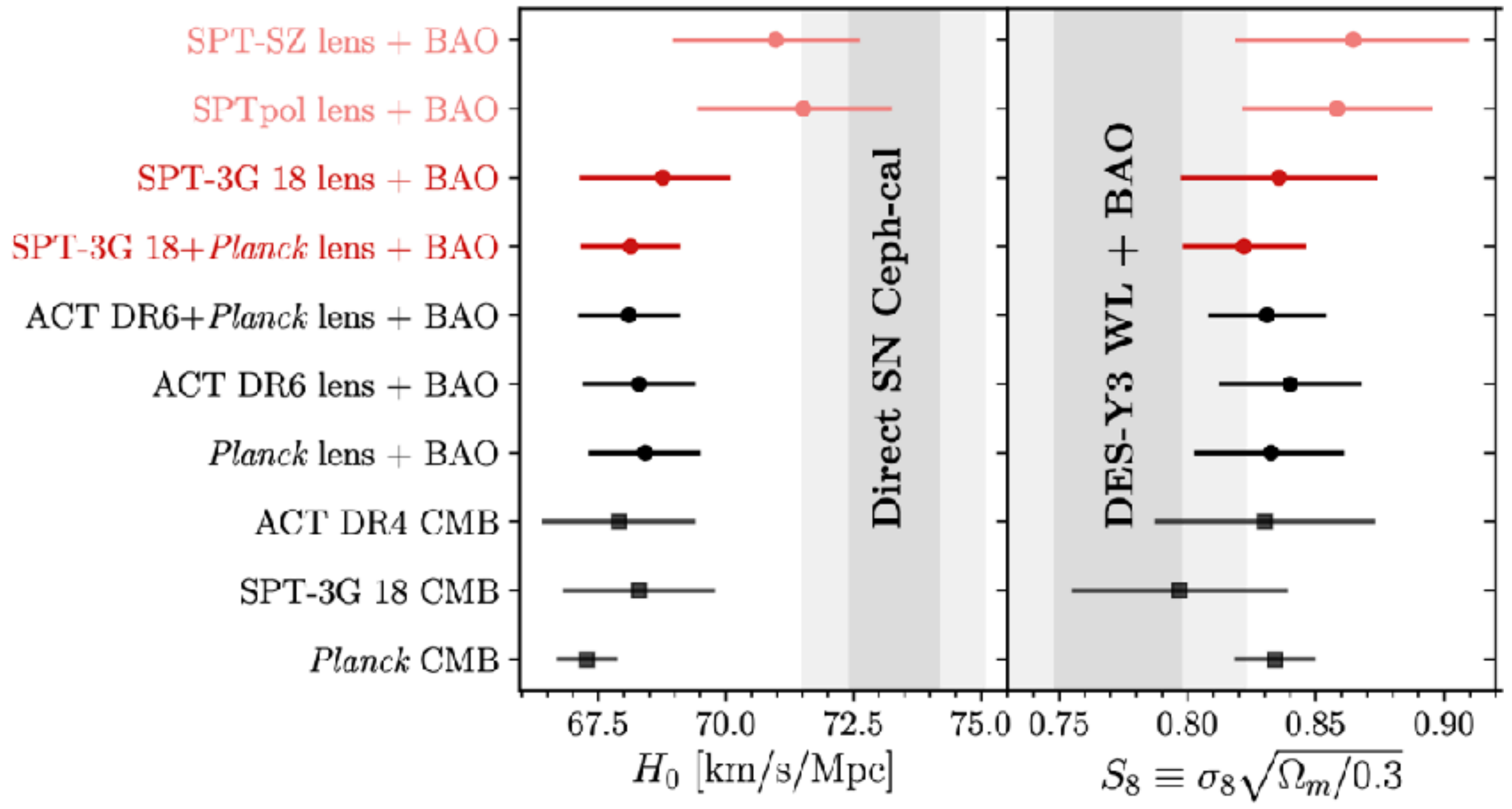
SPT 3G results from last week (Pan et al. 2023)

Lensing power spectrum





Inferred parameters



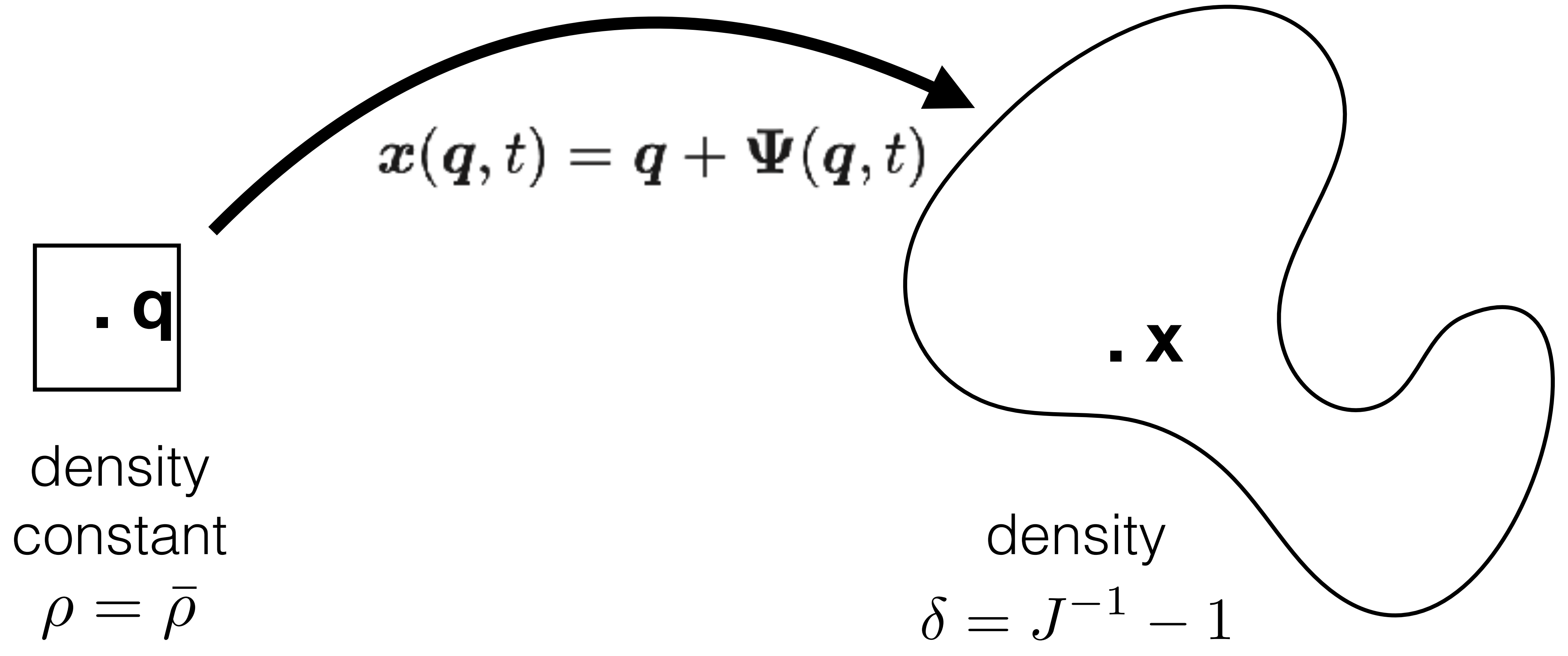
Lensing kernel peaks at z~2

Similar results from ACT, show no tension in S8

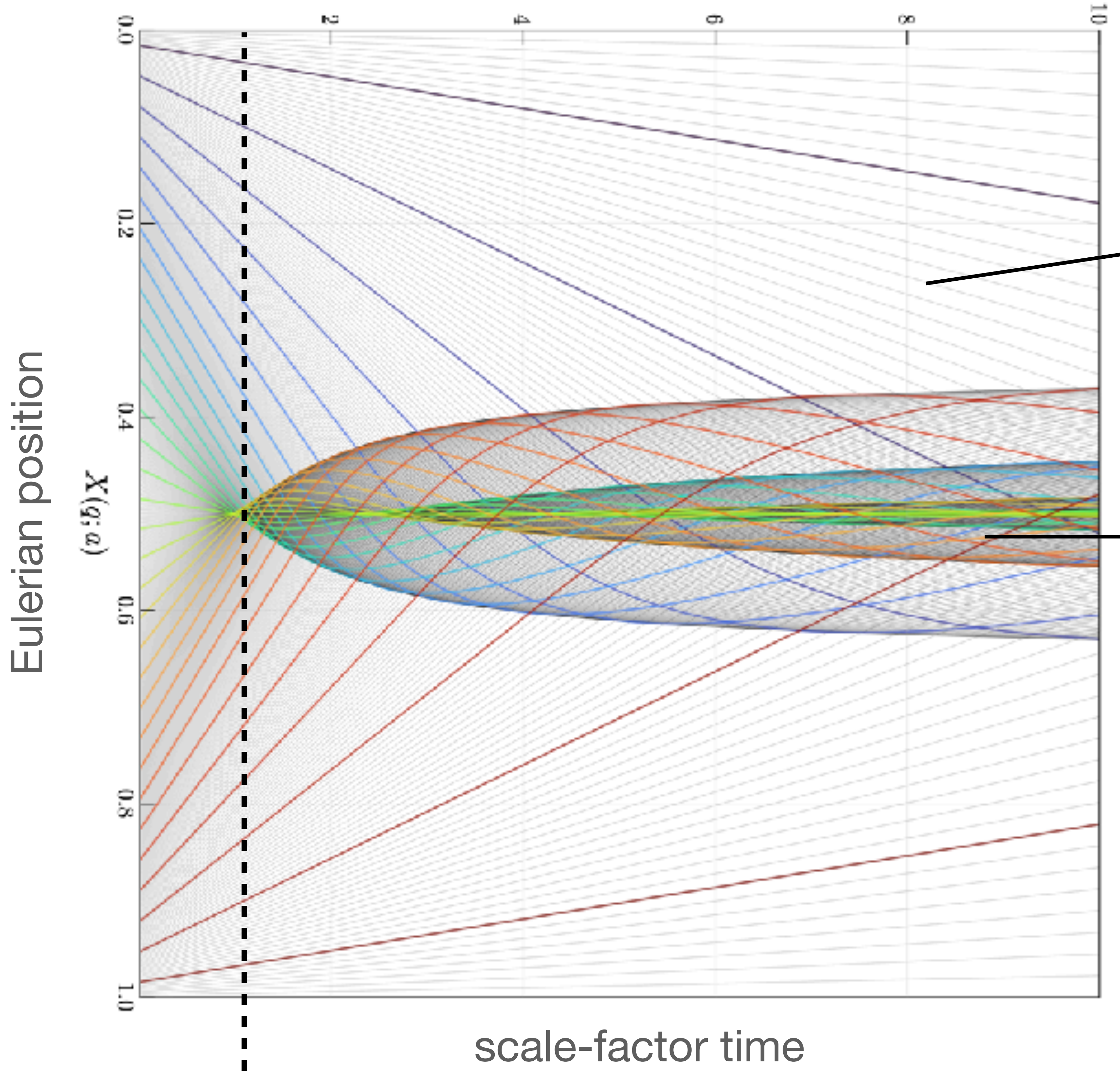
Modelling LSS — Lagrangian perturbation theory

Non-linear evolution of perturbations

Solve Vlasov-Poisson on submanifold characteristics $(\boldsymbol{q}, t) \mapsto (\boldsymbol{x}(\boldsymbol{q}, t), \boldsymbol{p}(\boldsymbol{q}, t))$



density + acceleration singularities



1D singularities: Rampf, Frisch & OH (2021)

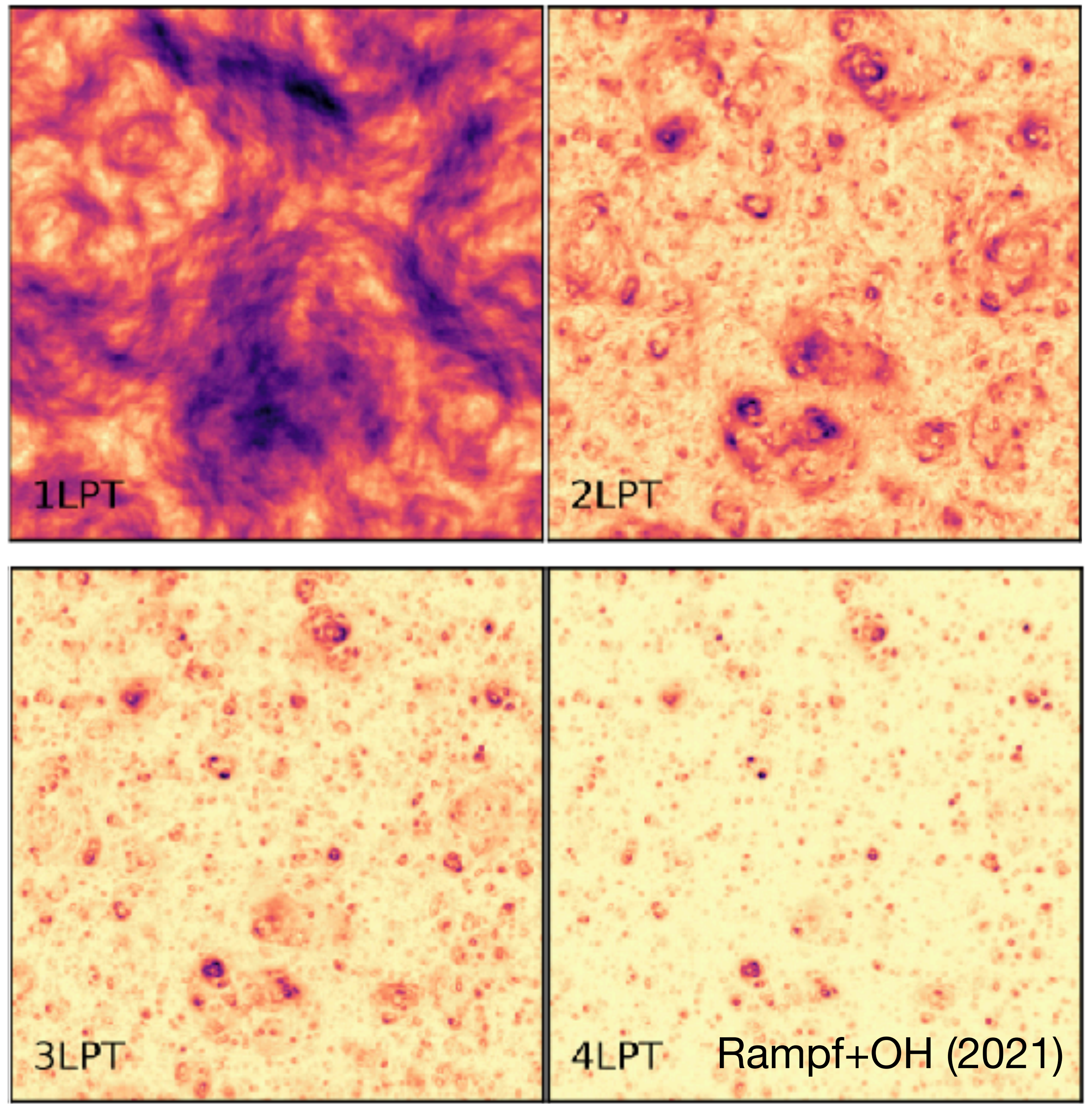
entering the multi-stream region is non-analytic (only finitely many bounded derivatives)

monokinetic, single-valued
(analytic treatment possible)

multikinetic, multi-valued
(simulations, EFTs [by integrating out])

Zeldovich (1970) solution (straight lines) is exact in 1D, beyond: write down PT

$$\boldsymbol{\Psi}(\mathbf{q}, \tau) = \sum_{n=1}^{\infty} D(\tau)^n \, \boldsymbol{\Psi}^{(n)}(\mathbf{q})$$

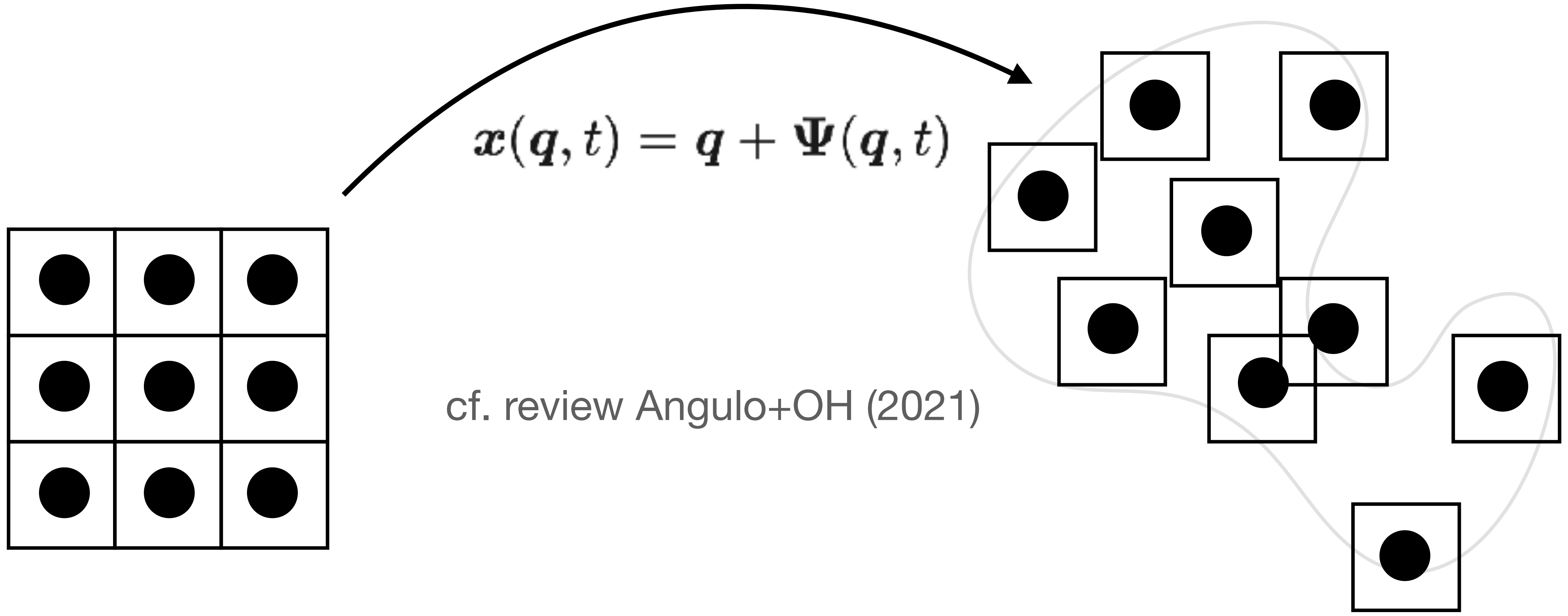


all-order recursion relations now implemented in code

Rampf+OH (2021)
Schmidt (2021)

Modelling LSS: Numerical N-body simulations

simulation maps discrete fluid elements from Lagrangian space to Eulerian space



cf. review Angulo+OH (2021)

the 10^{12} particle frontier:

(from Angulo+OH review)

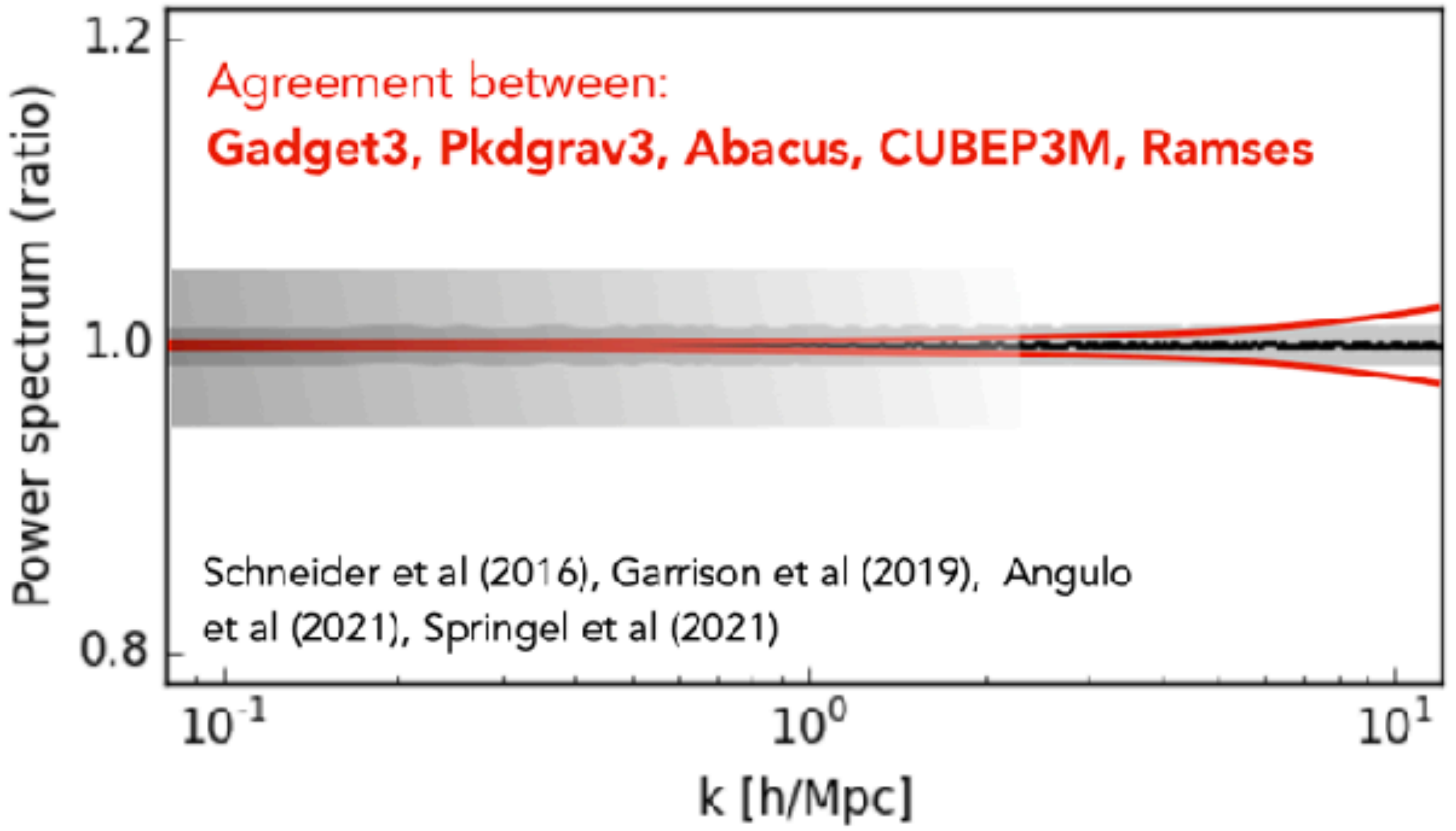
Year	Simulation	Code	Supercomputer	Cores $[10^3]$	N_p $[10^{12}]$	Box $[h^{-1}\mathrm{Gpc}]$	Algorithm	ϵ $[h^{-1}\mathrm{kpc}]$
2014	Dark Sky [916]	2HOT	Titan, USA	20	1.1	8	FMM	36.8
2017	TianNu [469]	CUBEP^{3}M	Tianhe-2, China	331	2.97	1.2	PM-PM-PP	13
2017	Euclid Flagship [201]	PKDGRAV3	PizDaint, Switzerland	4	2.0	3.	Tree-FMM	4.8
2019	Outer Rim [917]	HACC	Mira, USA	524	1.07	3.0	Tree-PM	2.84
2019	Cosmo-π [613]	CUBE	π 2.0, China	20	4.39	3.2	PM-PM	195
2020	Ushuu [918]	GREEM	ATERUI-II, Japan	<40	2.0	2.0	Tree-PM	4.3
2020	Last Journey [919]	HACC	Mira, USA	524	1.24	3.4	Tree-PM	3.14

+ Farpoint (2021)

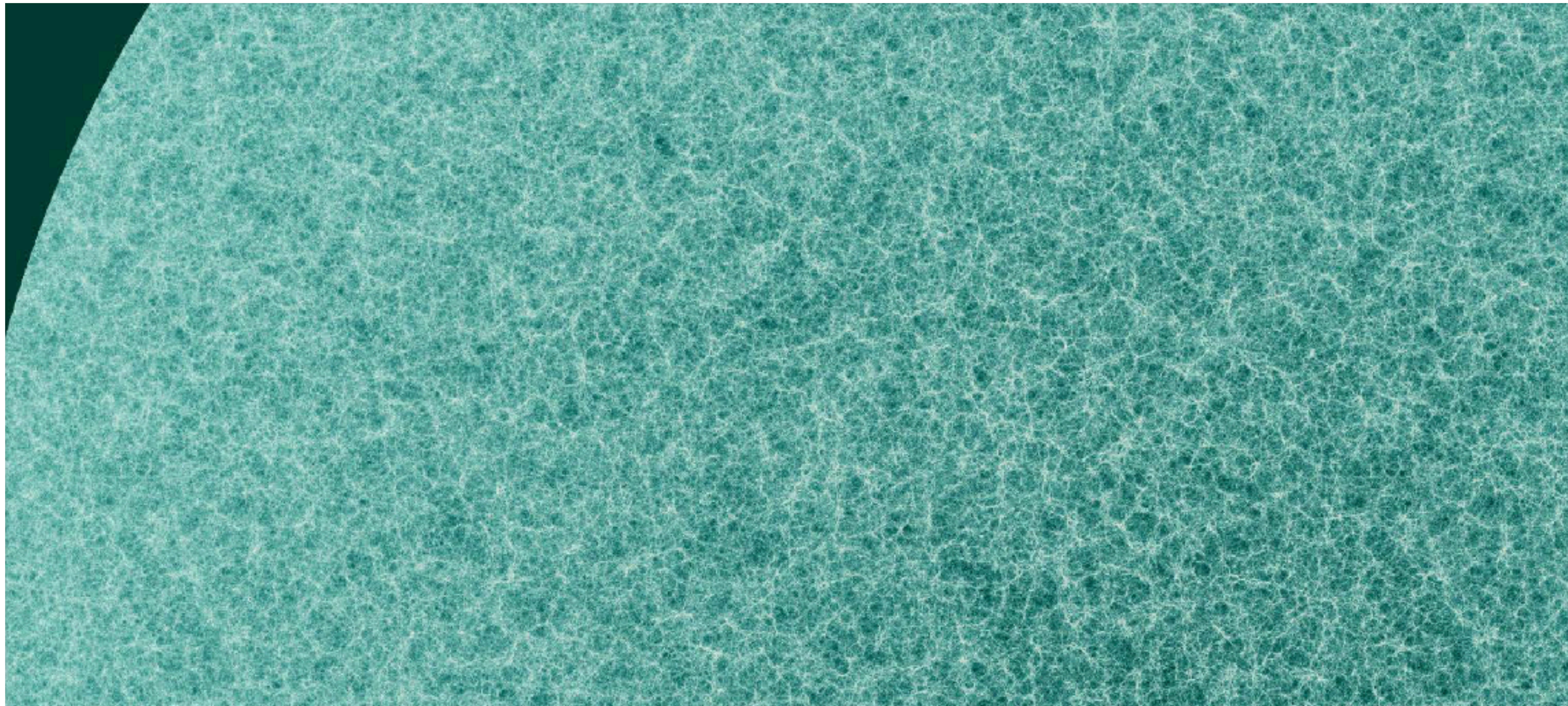
N-body simulations still the main work horse of LSS!

Theory error in non-linear simulations under control (without including astrophysics effects)

Gravity only LCDM predictions for matter distribution in the Universe have essentially no theory error any more



4π Lightcone from the Euclid Flagship simulation (Potter et al. 2017)



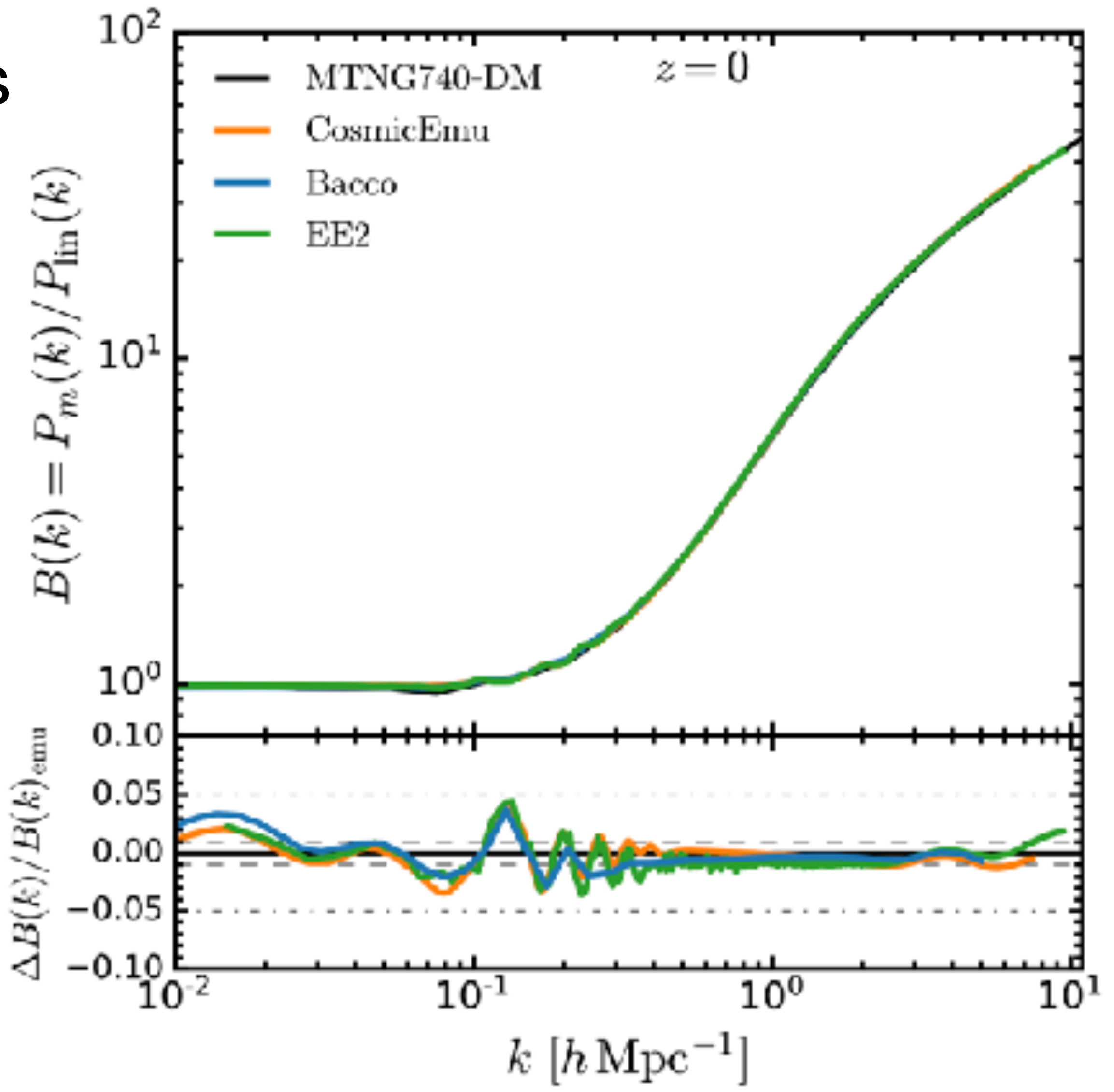
Faster and more accurate modelling

parameter space is increasing faster than computing power

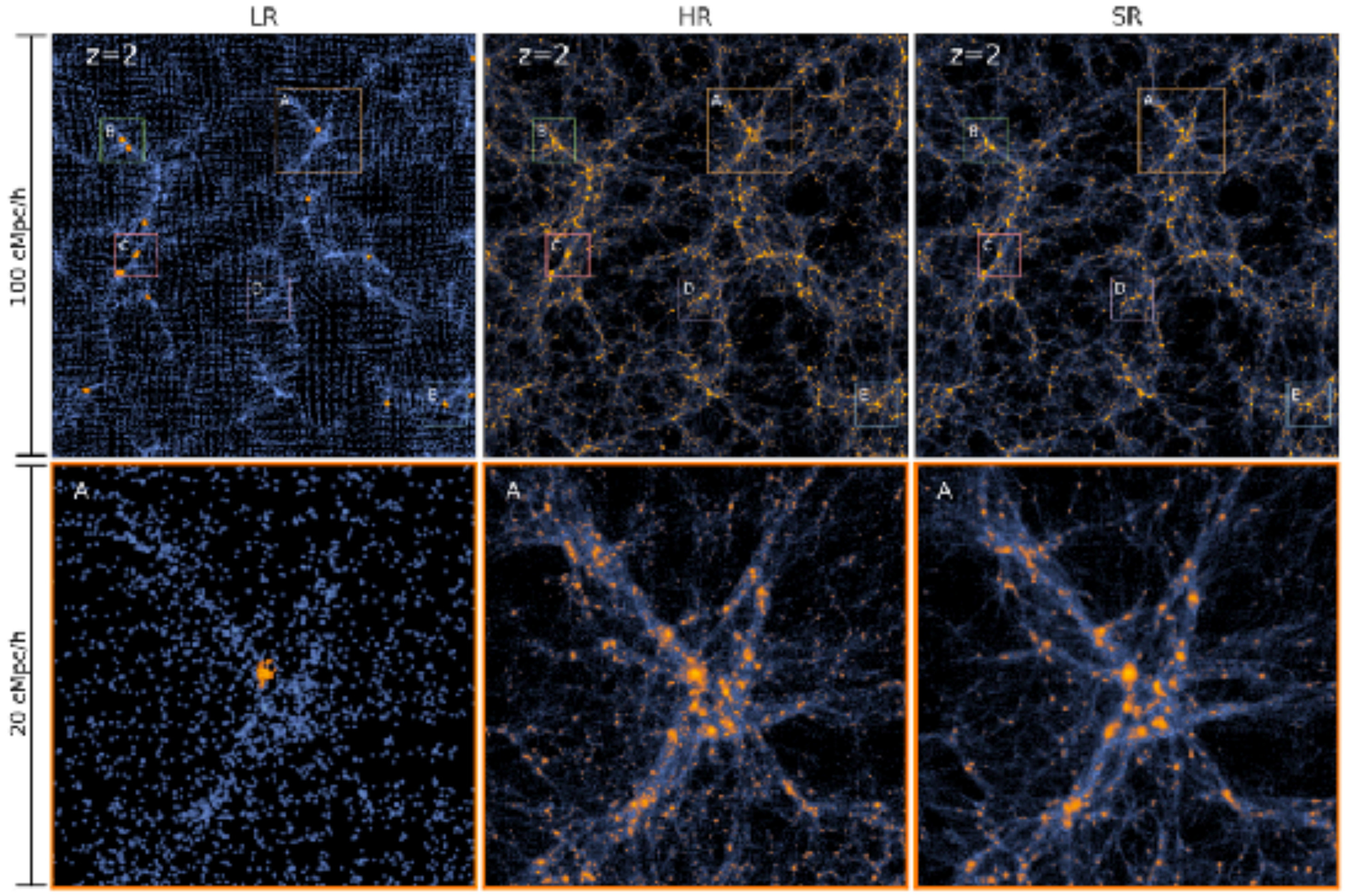
Increasing use of emulators
to interpolate between expensive simulations

CosmicEmu (Moran+2022)
Bacco (Angulo+2021)
EuclidEmulator2 (Knabenhans+2021)

comparison of emulator
against Millennium TNG:
Hernandez-Aguayo+(2023) ->

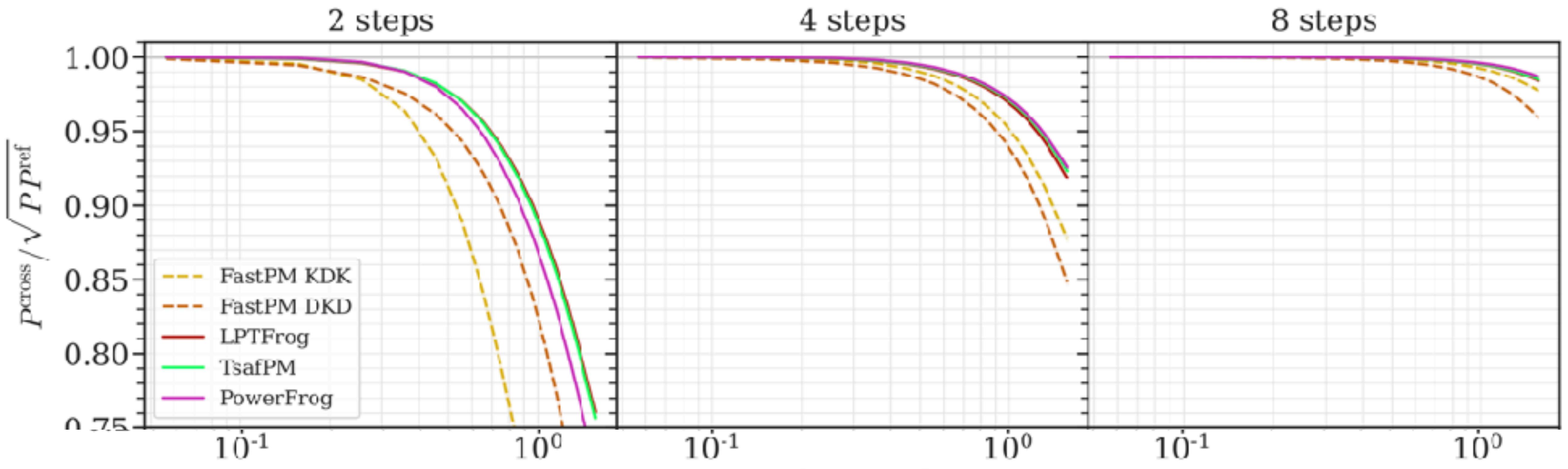


GANs for super-resolution augmentations of low-res simulations,
Ramanah+2020, Ni+2021, Li+2021



Li+ 2021

New perturbation theory informed integrators
merging together perturbation theory and fully-nonlinear simulations



List+OH(2023)

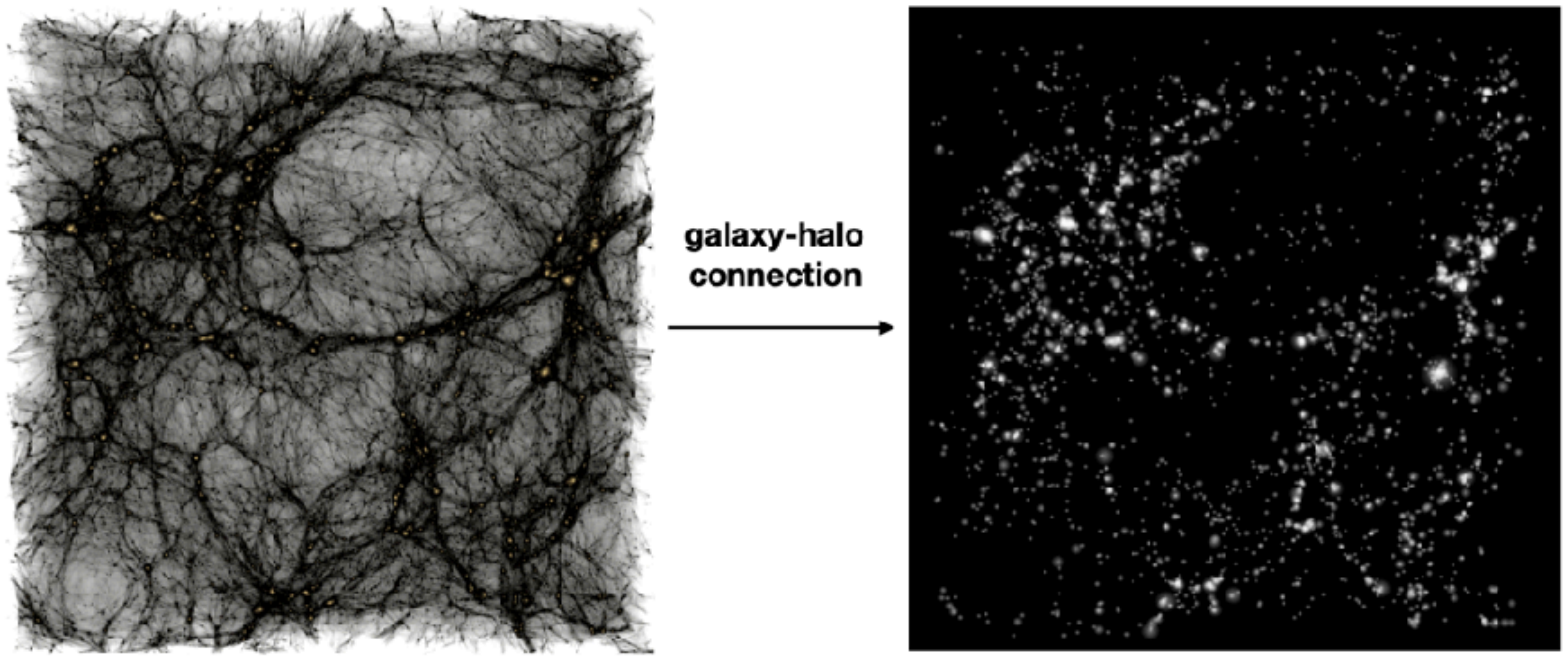
...and many more

(fully differentiable simulations,
better ICs, better control of simulation errors,...)

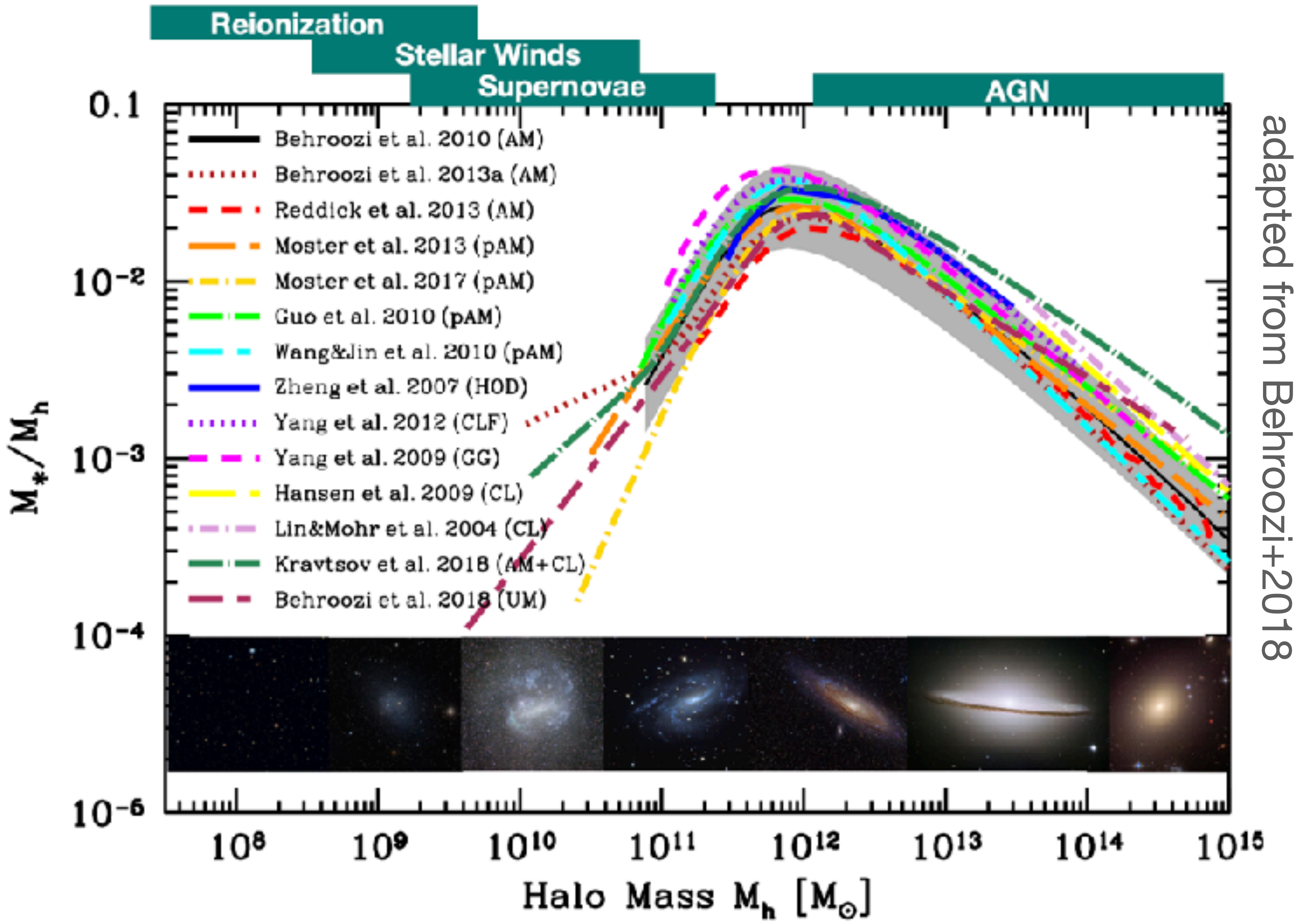
From N-body simulations to observables

-> construct observables on the backward lightcone, there are multiple ways forward, state of the art:

- identify structures in simulation, populate with "galaxies", e.g. **SHAM** (Kravtsov+2004), **HOD** (van den Bosch+2003), …



Review: Wechsler&Tinker 2018



Review: Wechsler&Tinker 2018, adapted from Behroozi+2018

occupation depends non-trivially on current halo properties+assembly history+environment?+…

- more recent approach: **hybrid effective field theory** (**HEFT**, cf. Modi+2020, Pellejero-Ibanez+2022) by causality, every observable can only depend on properties of the Lagrangian field up to some scale -> expand probability to form observables in Lagrangian space ('Lagrangian bias expansion', Matsubara 2008, Desjacques+2018), use simulations to map them forward in time.

  Galaxy density is functional of Lagrangian fields $\delta_{gal}[\delta_m, \partial v_m, \partial\partial\phi, \ldots]$ -> Taylor expand -> advect with simulation

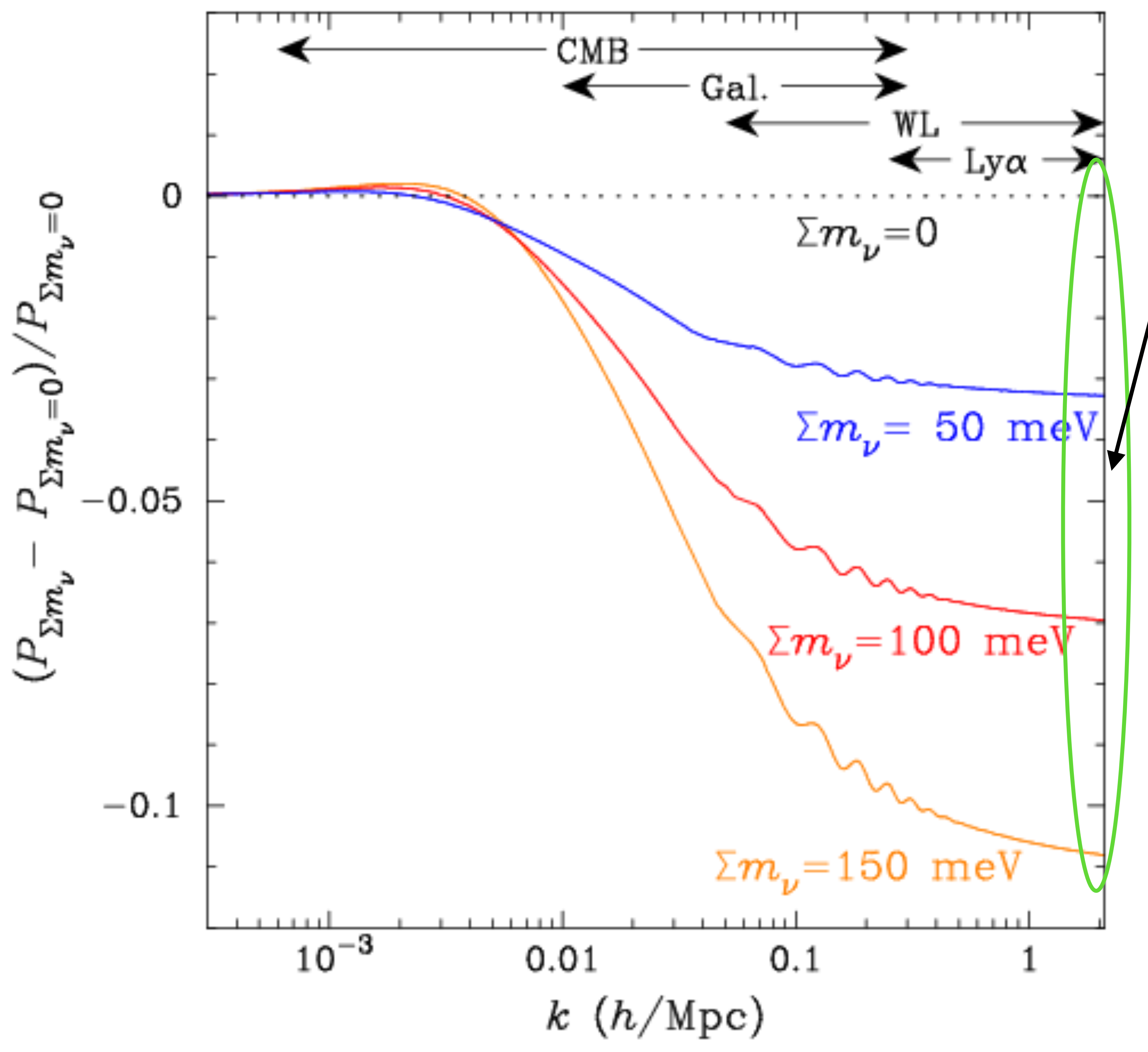
The massive neutrino signature on LSS

constraining neutrino masses with the LSS

Flavour-oscillations imply non-zero mass, but m<1eV

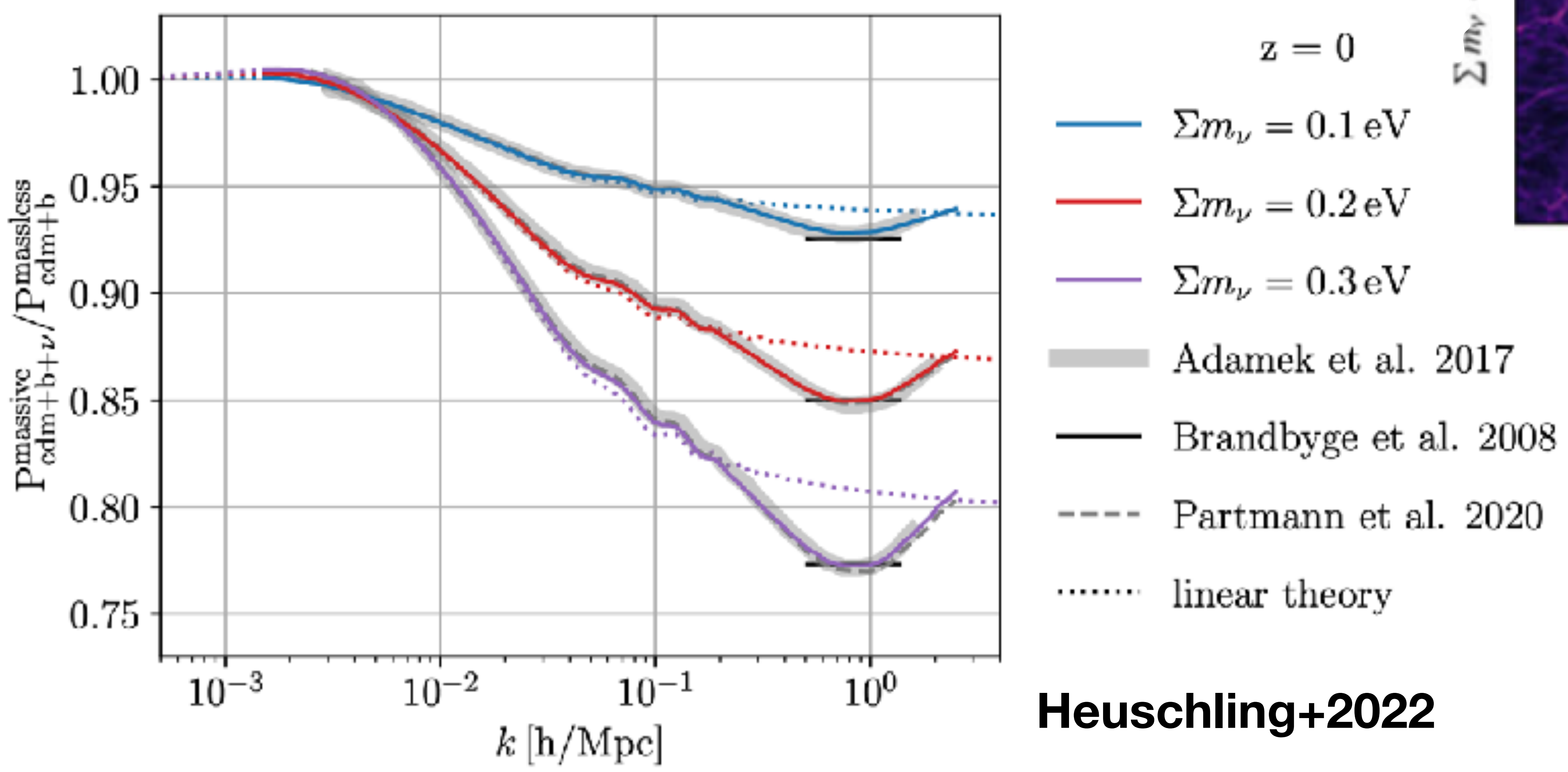
Effect on homogeneous and inhomogeneous cosmology

Abazijan+2015

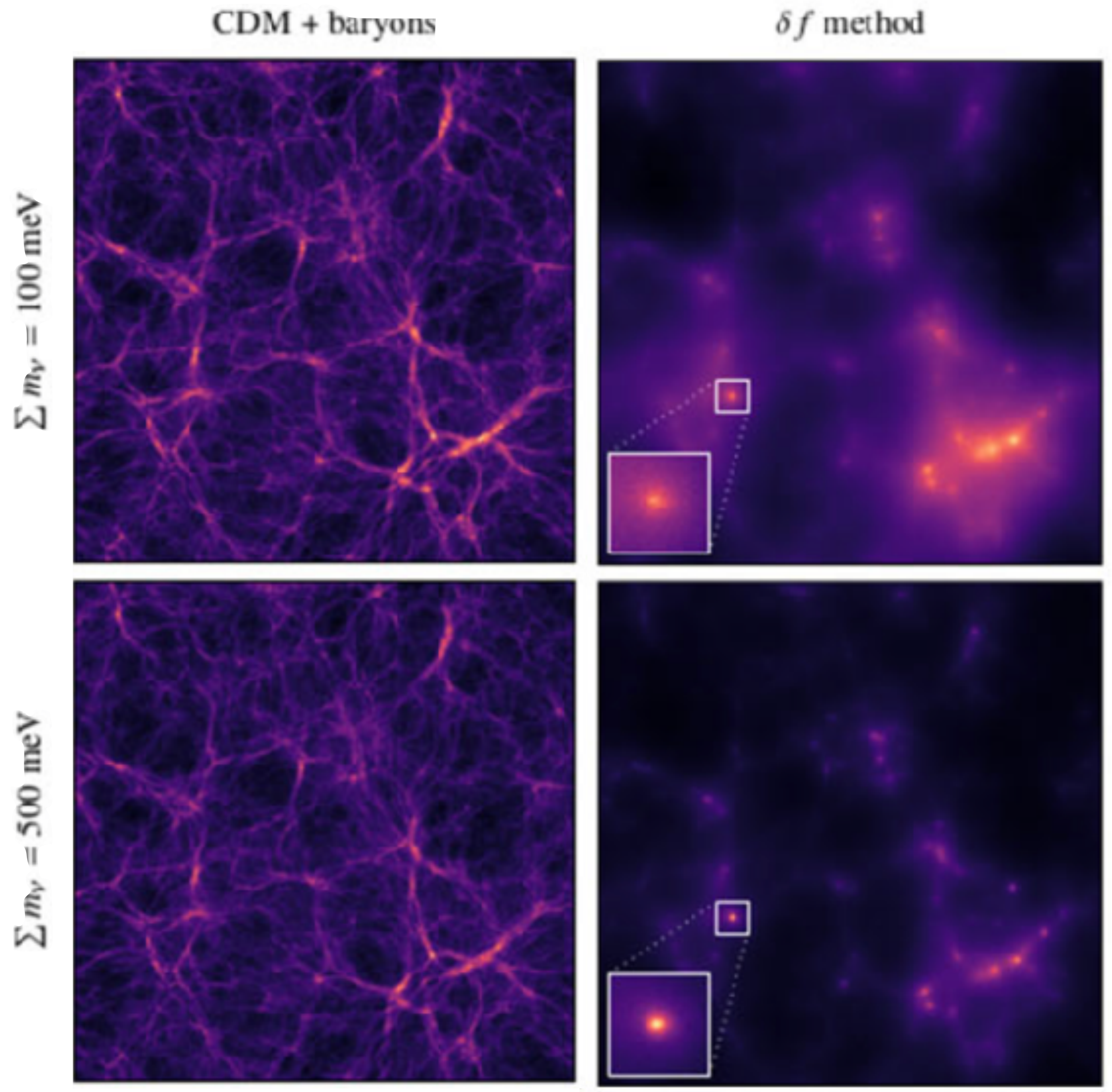


Linear Effect mostly from difference in background evolution:

neutrinos transition from relativistic (dark radiation) to non-relativistic (dark matter) during epoch of structure formation



Heuschling+2022



Elbers+2021

non-linear clustering of neutrinos around galaxy clusters

KATRIN: UL 0.7 eV (Aker+2022)

potential of CMB-S4 + LSST: 0.01-0.04eV (Chen&Dvorkin 2021)

The new generation of large-scale structure simulations

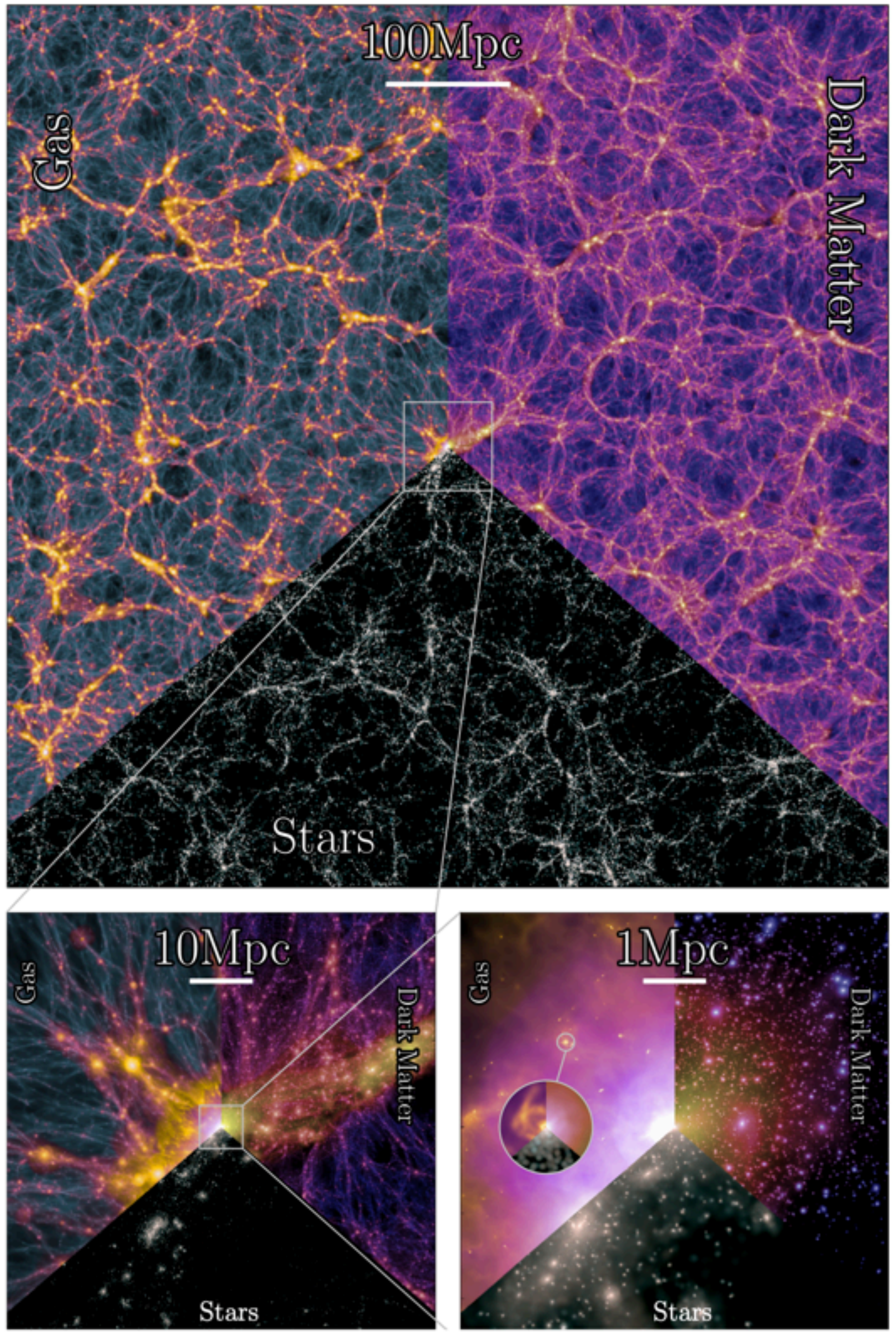
We are just now seeing the first generation of 'cosmological' volume full astrophysics simulations (>500 Mpc)

include treatment of
intergalactic gas,
galaxy formation physics,
SMBH formation,
SNe, etc…

allows joint analysis of all observables, given cosmological model, astrophysical parameters (latter tuned to a few observables)

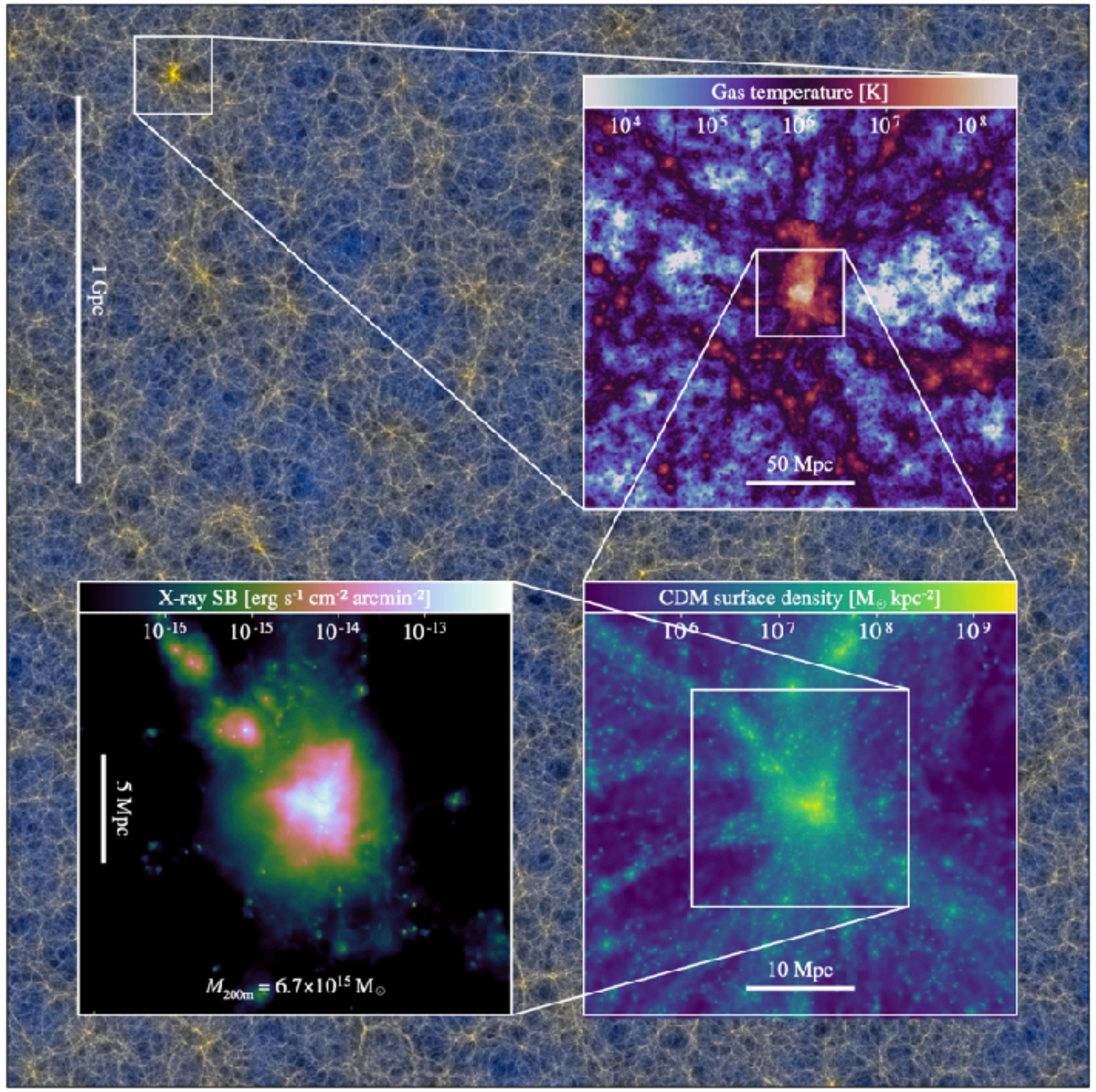
all include now massive neutrinos

Millennium TNG (Pakmor et al. 2023)



MTNG: full astrophysics, volume (740 Mpc)^3
2x 4320^3 particles
mass resolution ~2x10^8 Msun
+ multiple runs with massive neutrinos (0, 0.1, 0.3 eV)

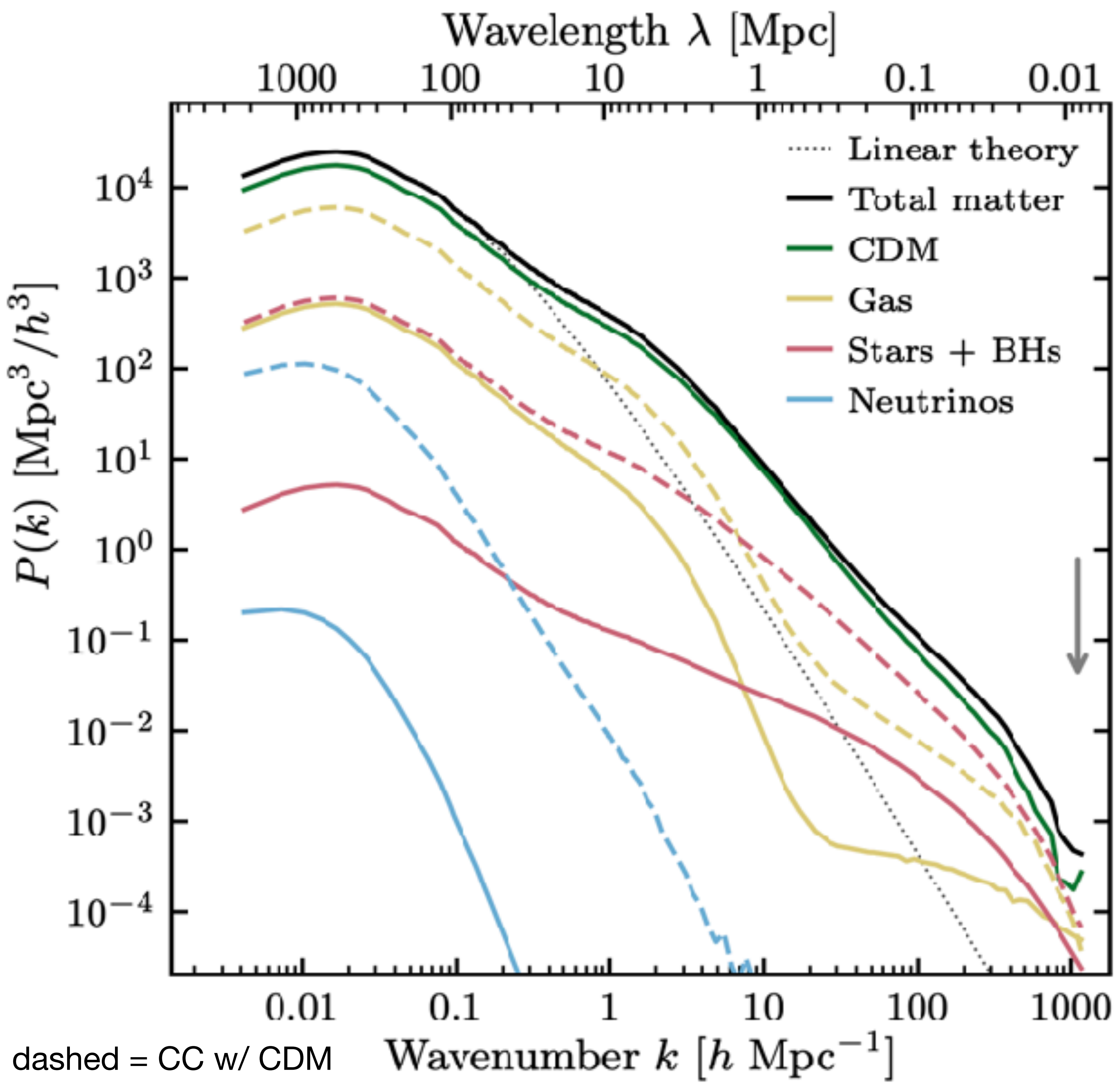
Flamingo (Schaye et al. 2023)



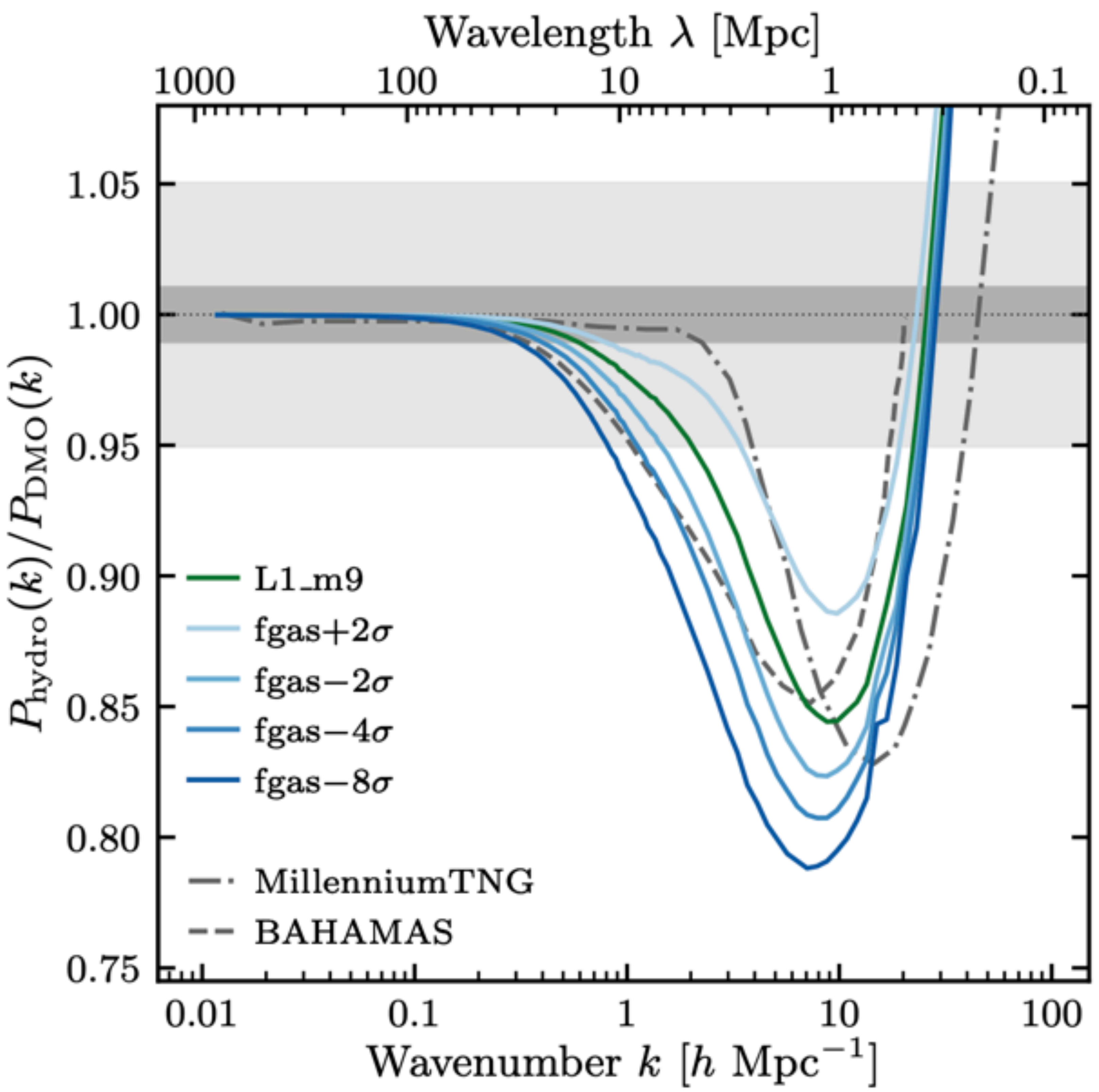
Flamingo: full astrophysics, volume (1 Gpc)^3
best mass resolution ~7x10^8 Msun
2x 3600^3 particles
+ multiple runs with massive neutrinos (0, 0.1, 0.3 eV)
+ multiple runs with astrophysics variations

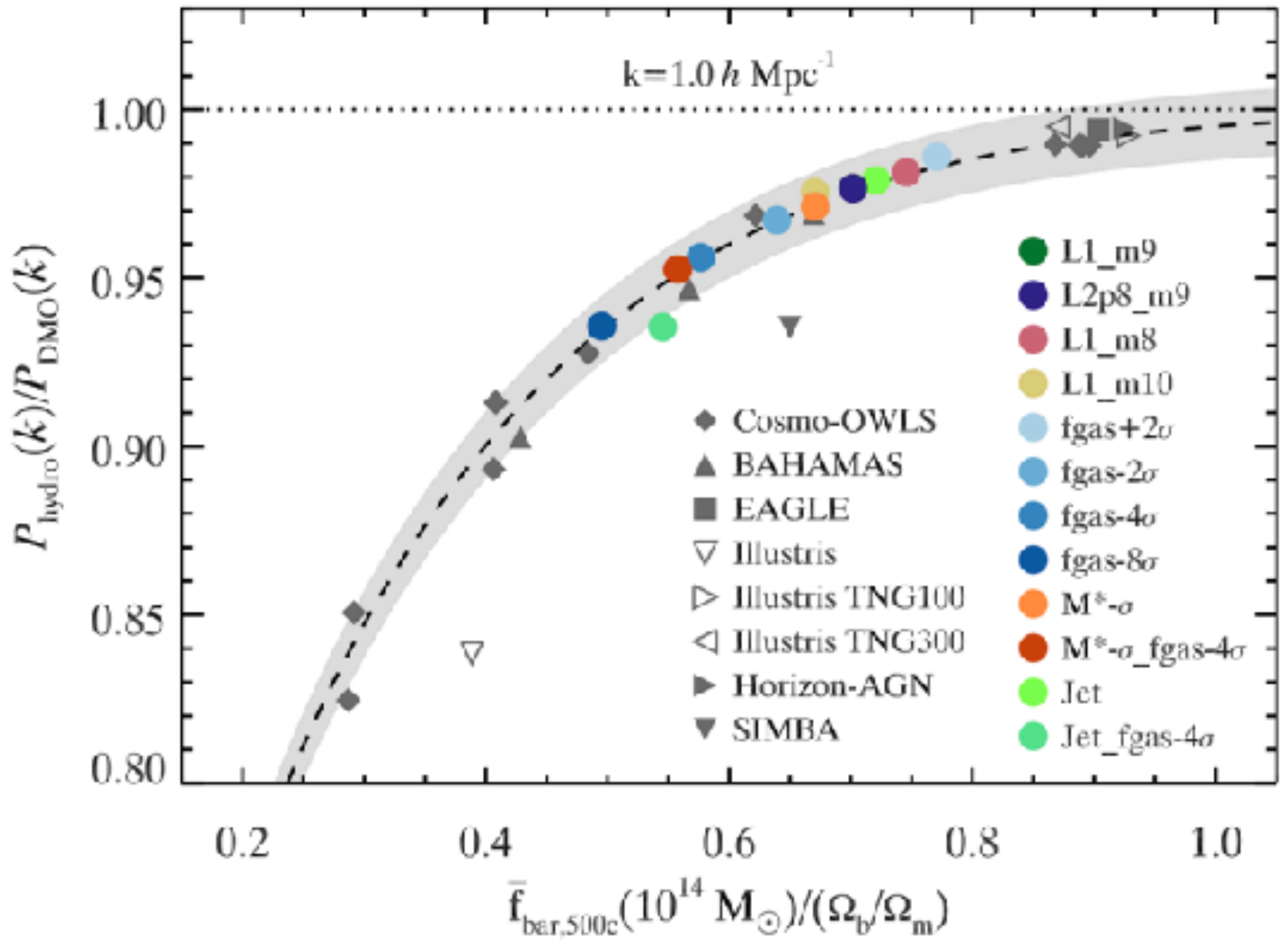
The full astrophysics non-linear power spectrum

FLAMINGO results (Schaye+2023)



dashed = CC w/ CDM





astrophysics affects the total matter power spectrum at the >1 per cent level at k~1

either these scales must be excluded from the analysis, or they need to be modeled

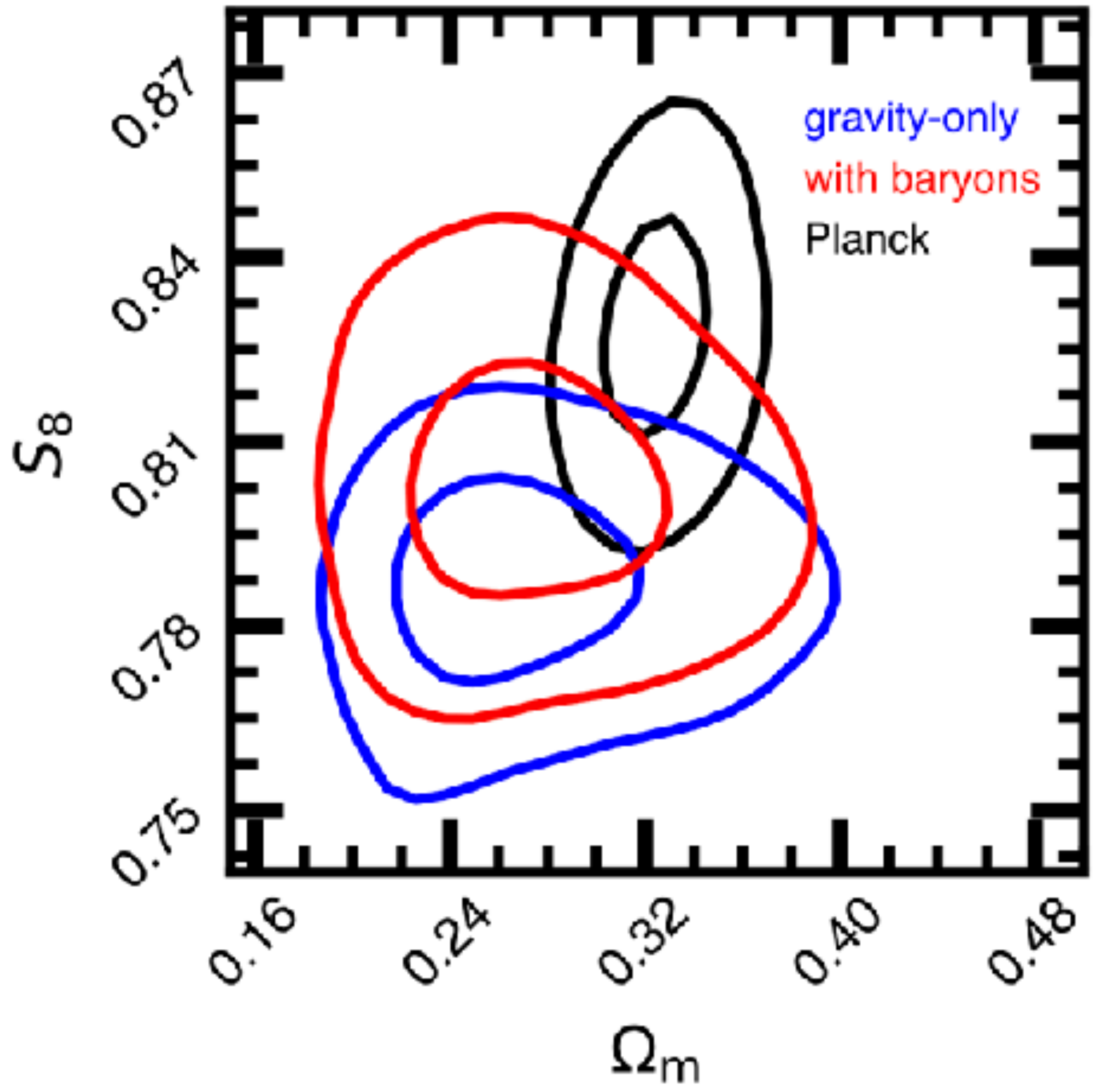
quest for “baryonification models” that can capture this with few parameters,
can be calibrated to baryon fraction in galaxy groups

The impact of astrophysics

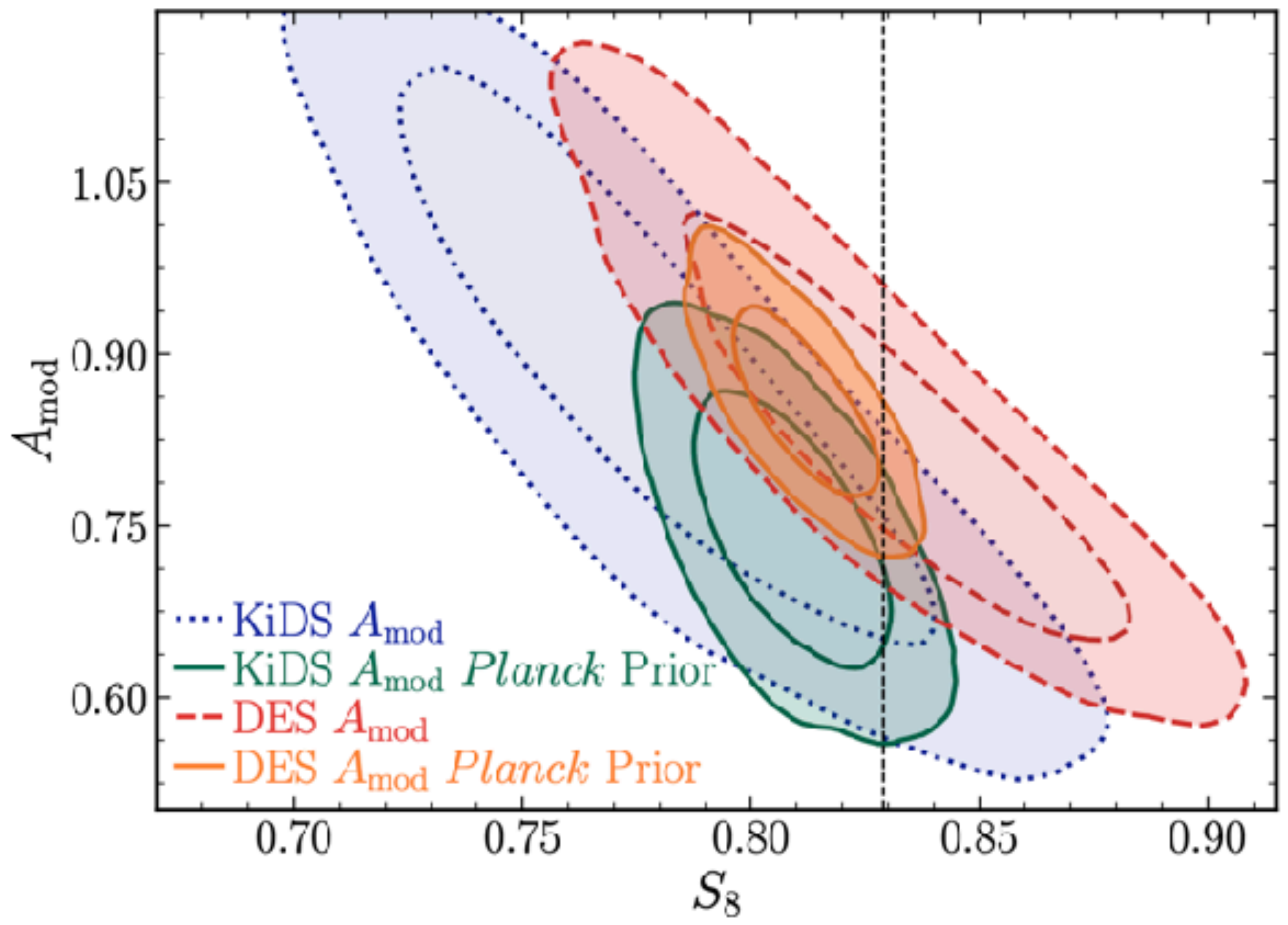
the big uncertainty?

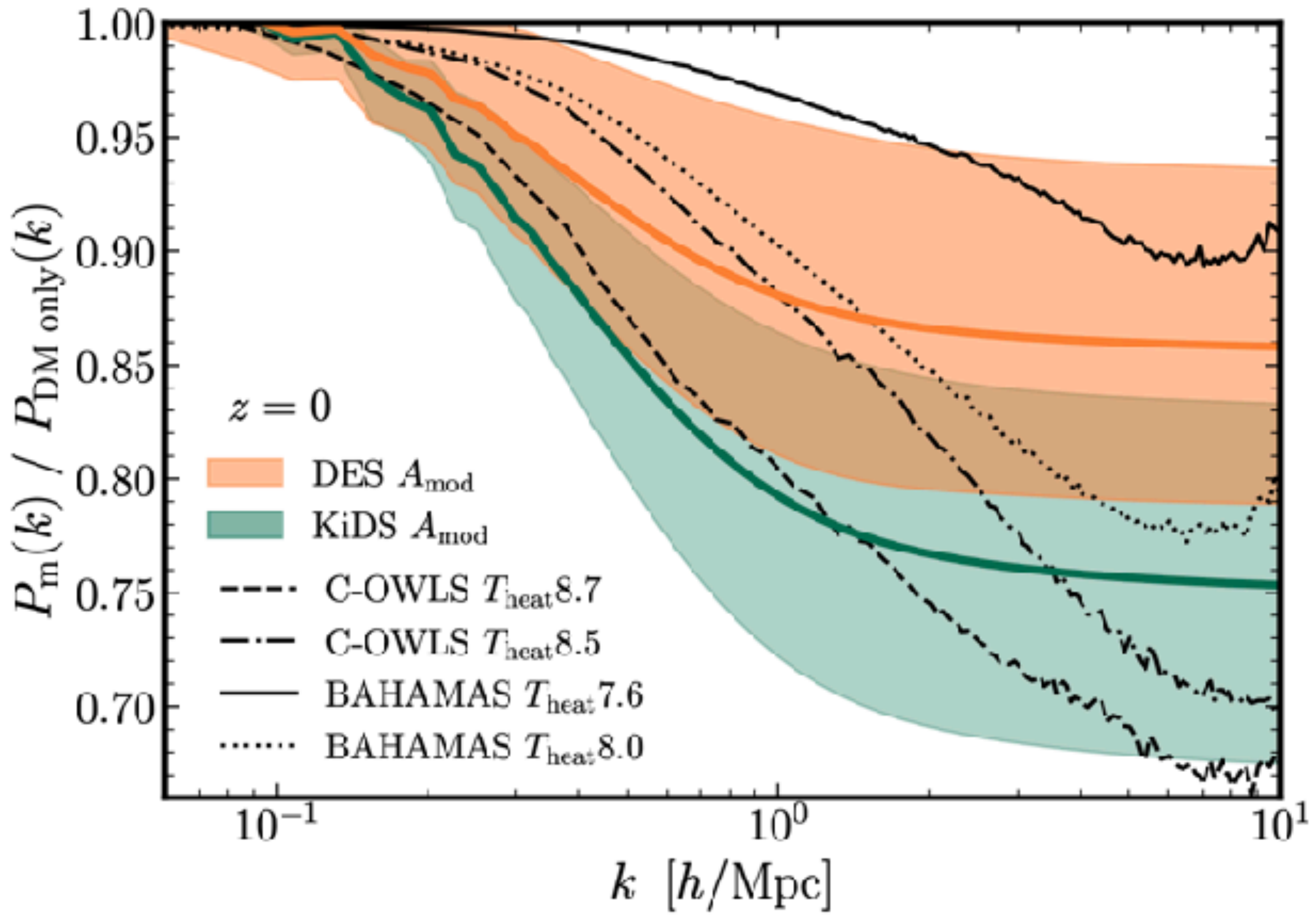
DES re-analysis by BACCO group

Arico+2023



Impact of small-scale power suppression on DES/KiDS constraints on S8 Preston+2023





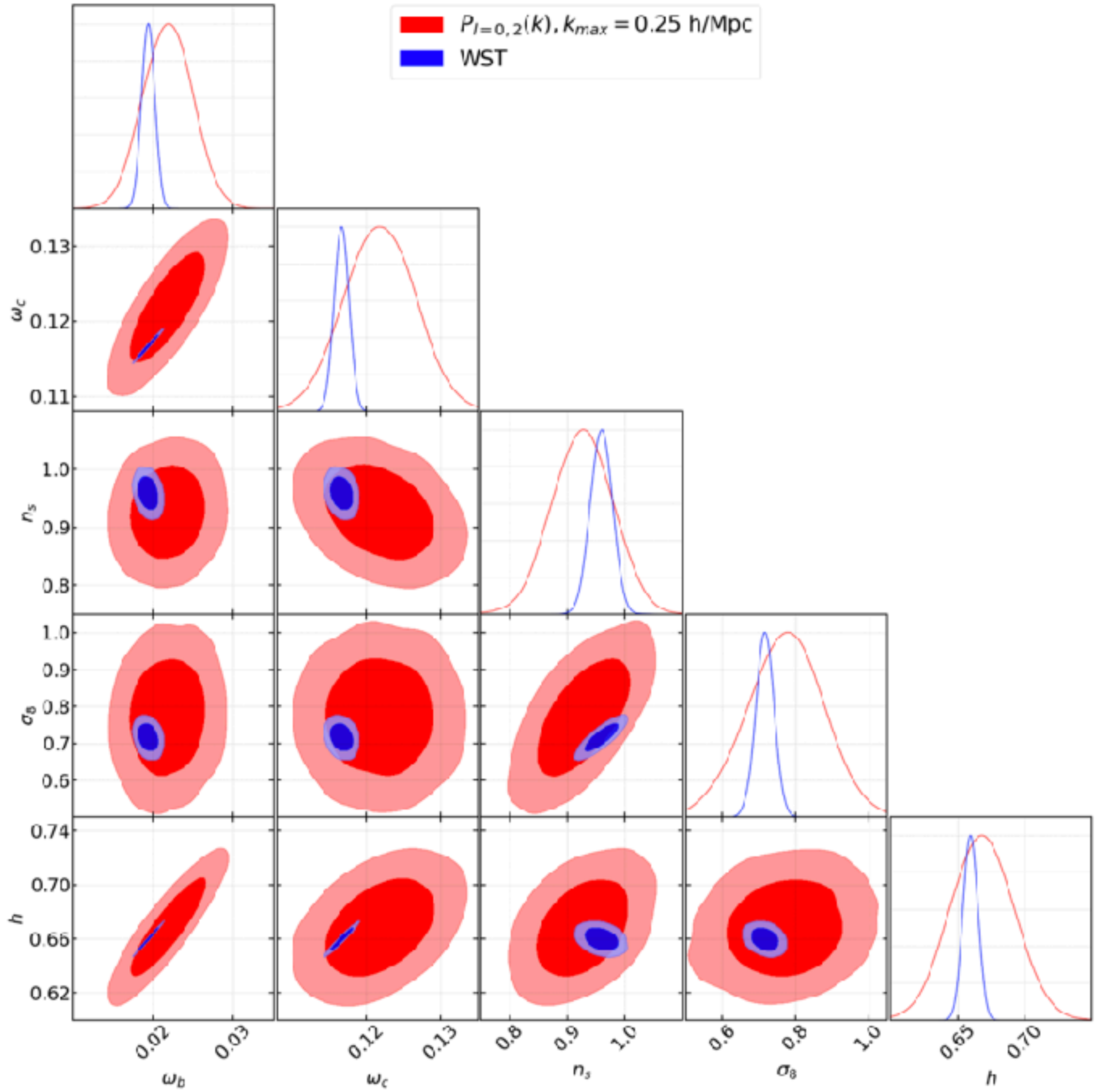
independent observations, especially tSZ/kSZ/X-ray can constrain these models

e.g. Schneider+2022

New statistical tools

Extracting Maximum of Information from given data:
beyond classical n-point approach which is ill-suited to large density fluctuations

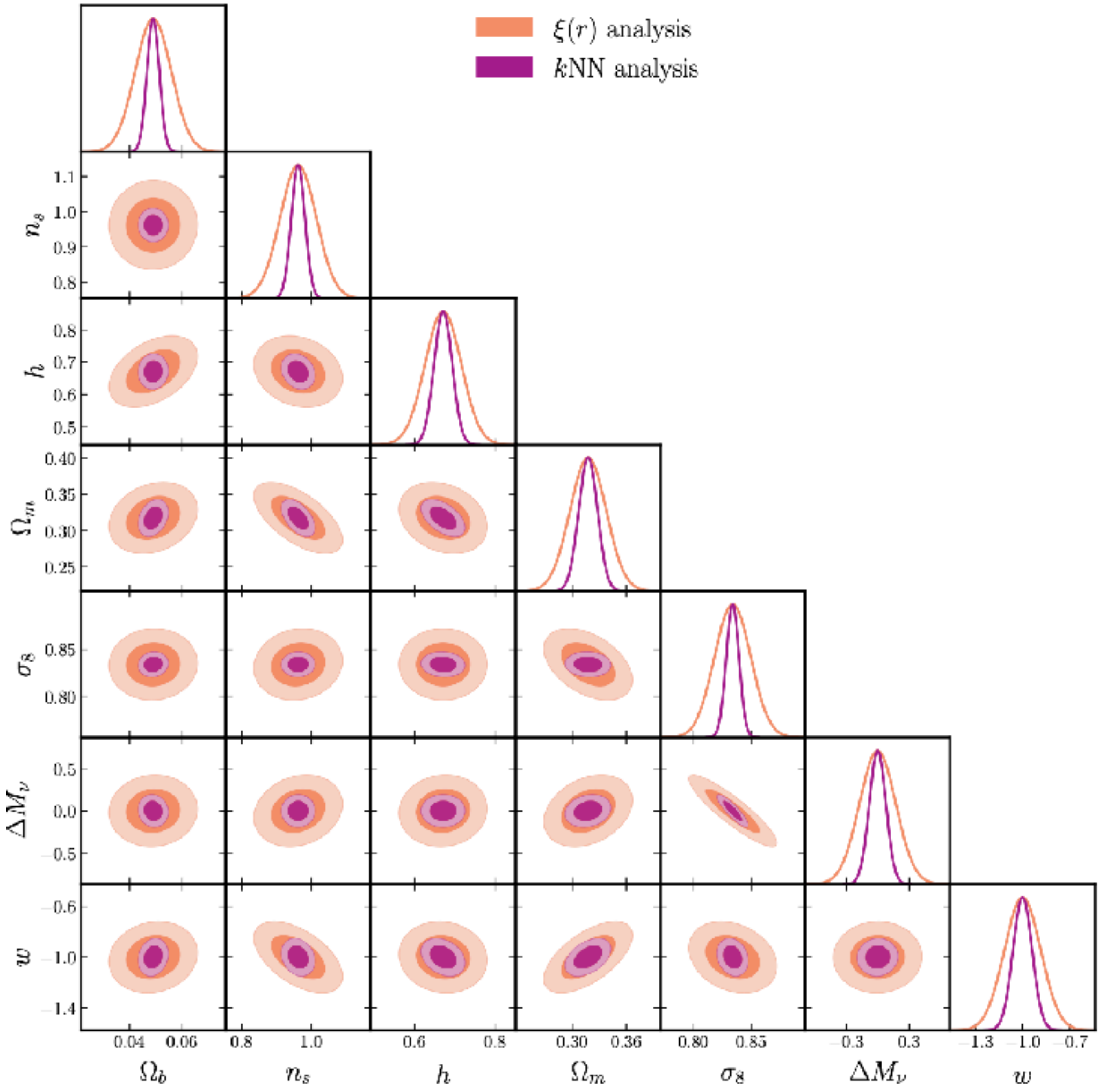
Wavelet Scattering Transform Mallat 2012, Cheng+2020



Valogiannis & Dvorkin (2022)

new statistics show big improvement over 2-point

kNN statistics Banerjee & Abel (2020)



Banerjee & Abel (2020)

Or: avoiding summary statistics altogether -> going “field level”

Summary

- exciting times for LSS cosmology, many surveys coming up (DESI, Euclid, LSST, Roman, Spherex,…)
- probe growth of structure and distribution of matter
- currently interesting S8 tension between CMB and other probes
- LSS still competitive for neutrino masses, all new N-body simulations include treatment of massive neutrinos
- frontier is to be able to push to smaller scales, learn how to deal with astrophysical effects (not necessarily only contaminant)
- next generation of simulations quantify both cosmological models and astrophysics
- precision and statistics is increasing breathtakingly -> modelling has to step up

Image credit: D. Schlegel / DESI / Lawrence Berkeley National Laboratory / M. Zamani, NSF's NOIRLab