

COSMOLOGICAL PROBE COMBINATION FOR CURRENT & FUTURE SURVEYS

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Paco Villaescusa-Navarro - Princeton/CCA

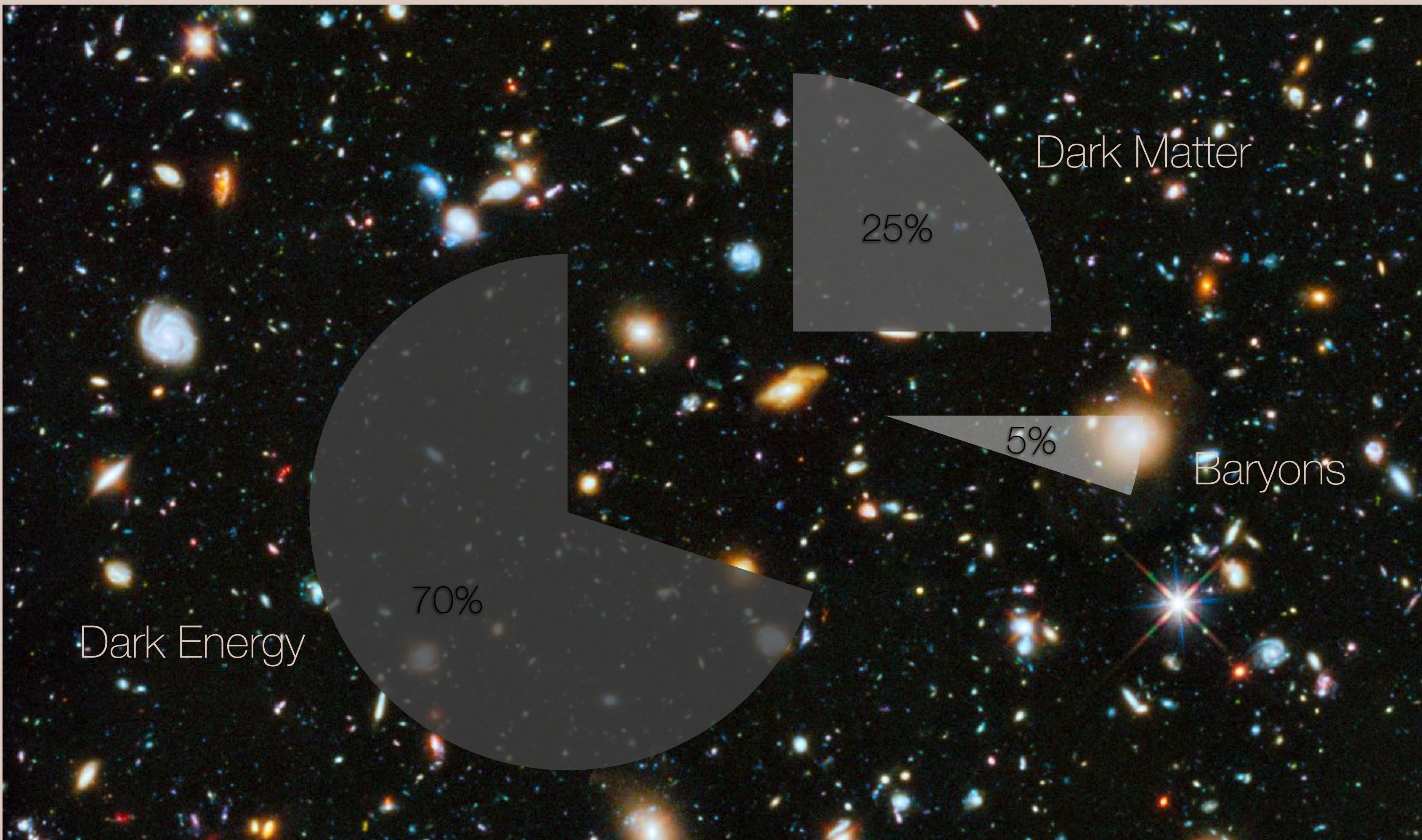
+ LSST-DESC LSS working group, Alexandre Refregier, Adam Amara

THE PILLARS OF THE Λ CDM COSMOLOGICAL MODEL

Λ + DM + GR + INFLATION



OUR DARK UNIVERSE



“I say, there is no darkness but ignorance.”
— William Shakespeare, Twelfth night (IV.II)

COSMOLOGICAL PROBES

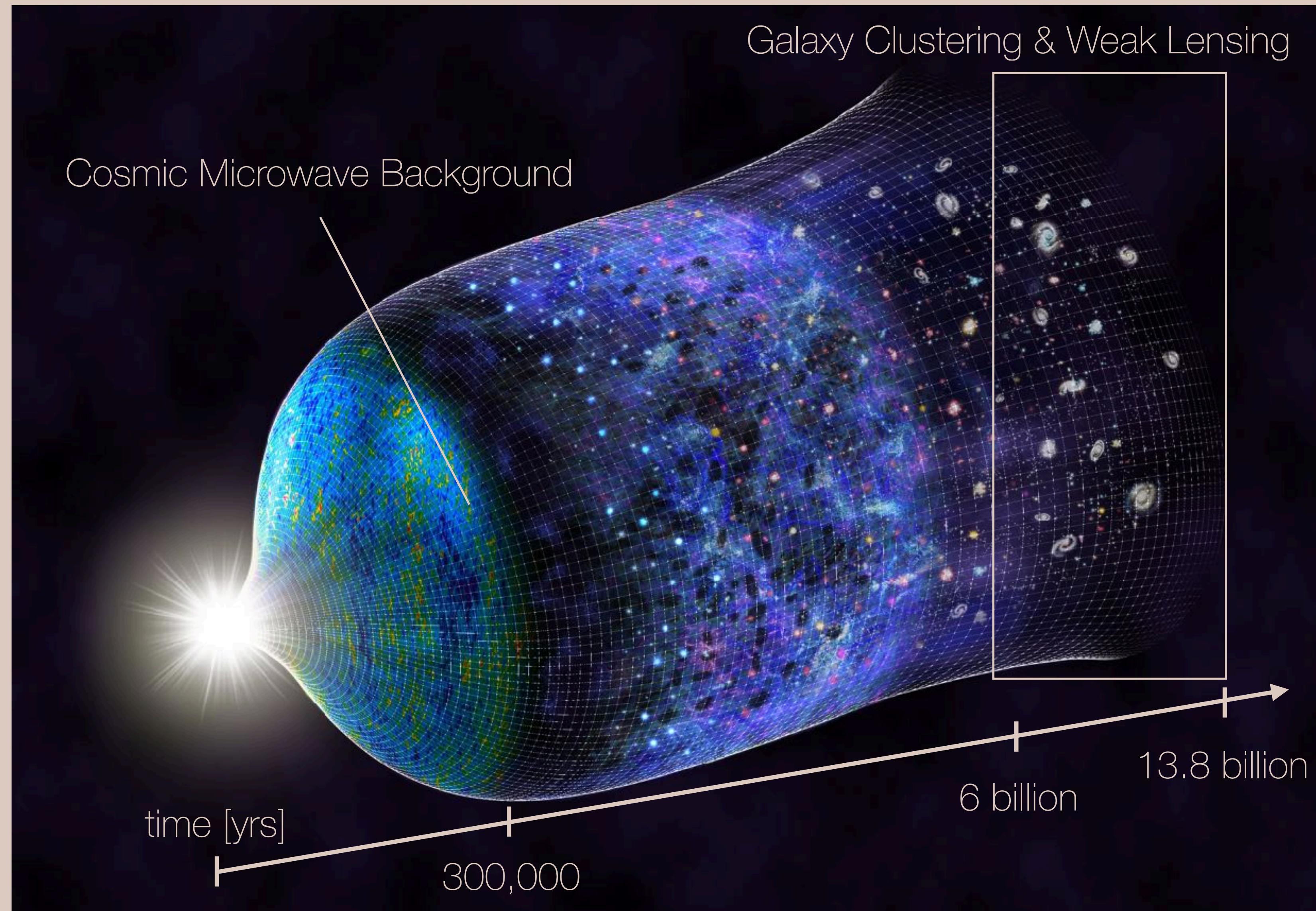
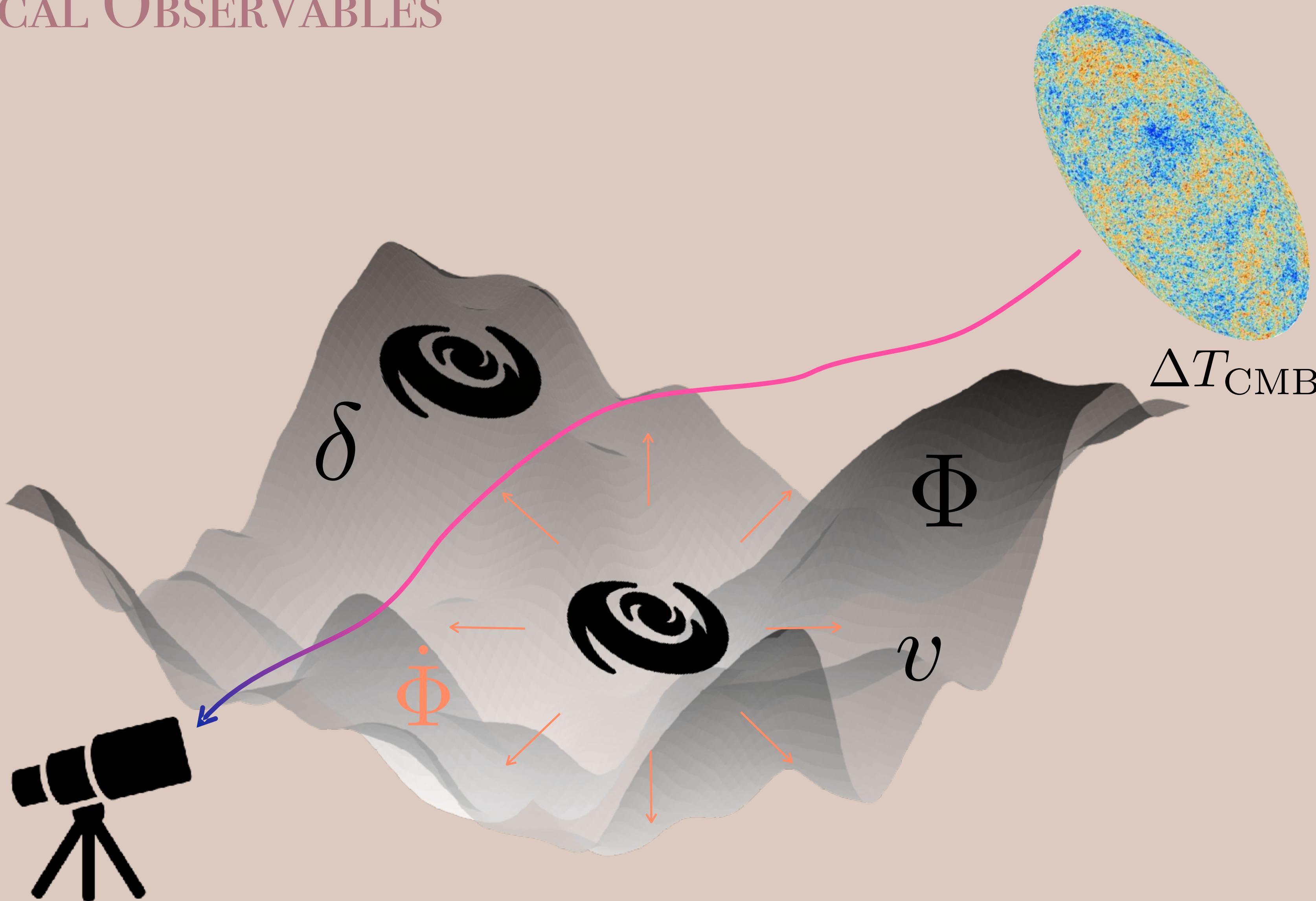


Image: Nicolle R. Fuller, National Science Foundation

COSMOLOGICAL OBSERVABLES



Images: Planck, Science, icons made by Freepik from www.flaticon.com

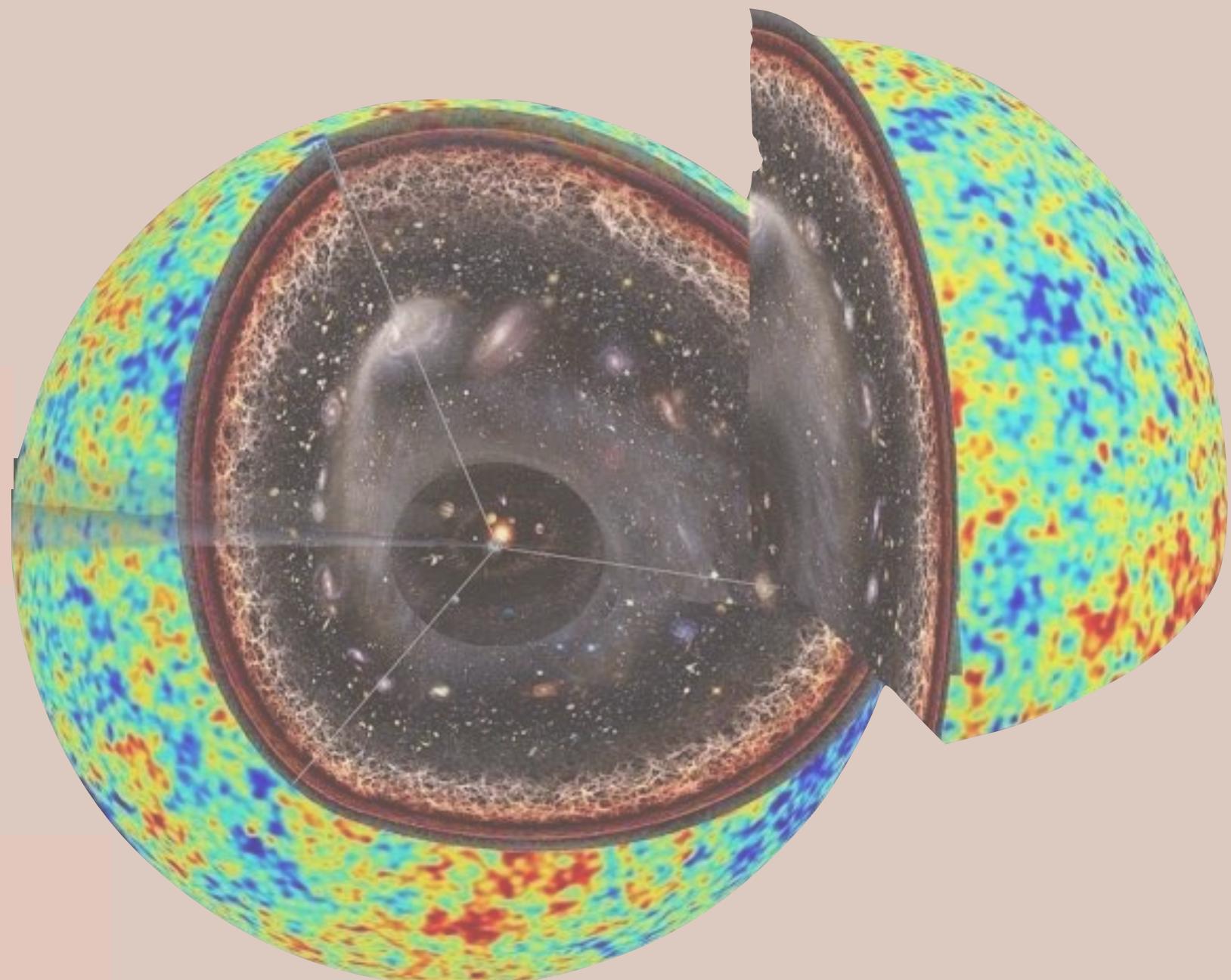
THE POTENTIAL OF JOINT ANALYSES

Robust constraints on Λ CDM & extensions due to complementarity

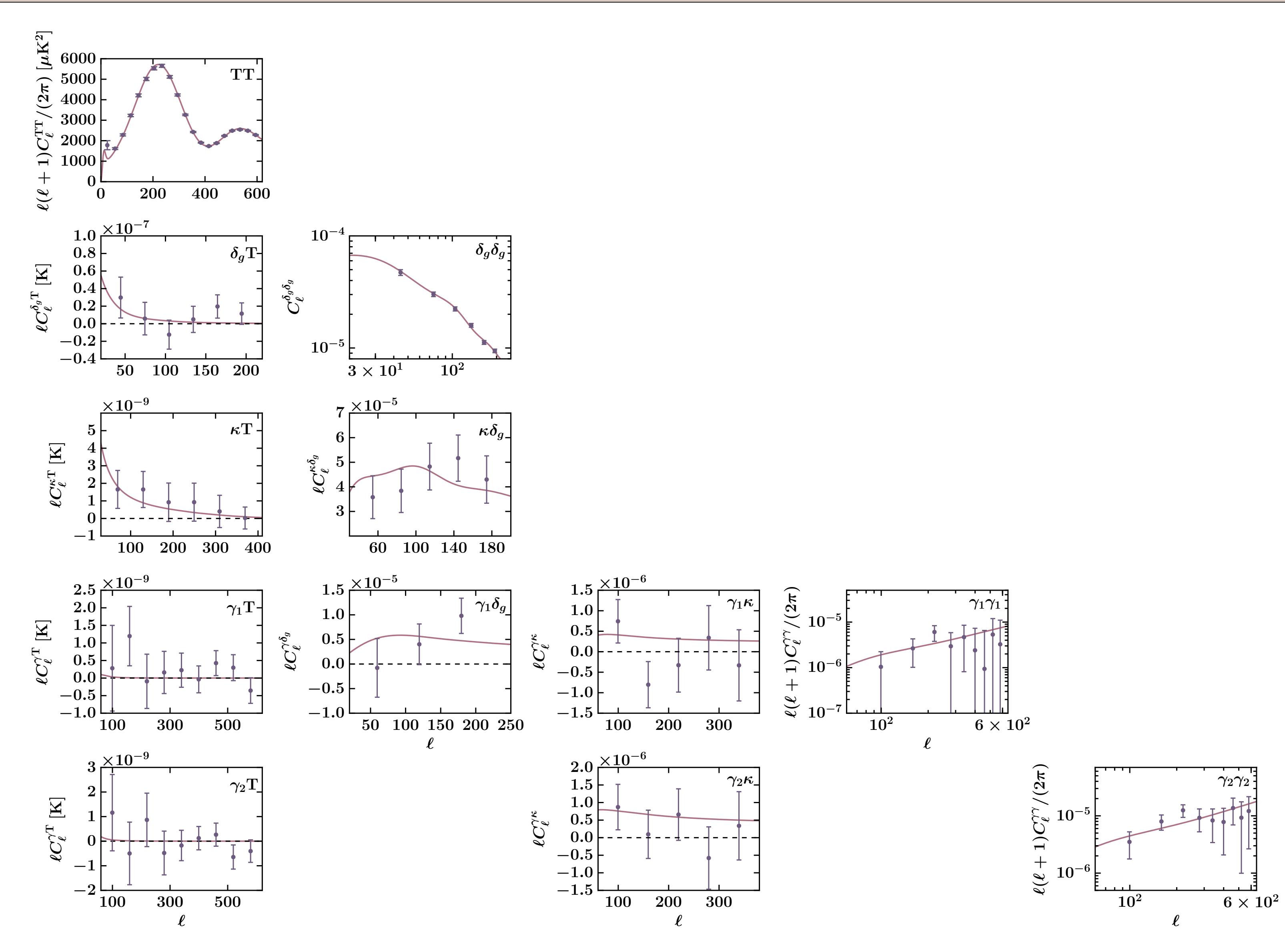
Consistency tests of cosmological model

Constraints on astrophysical systematics, e.g. baryon feedback

Systematics calibration & identification



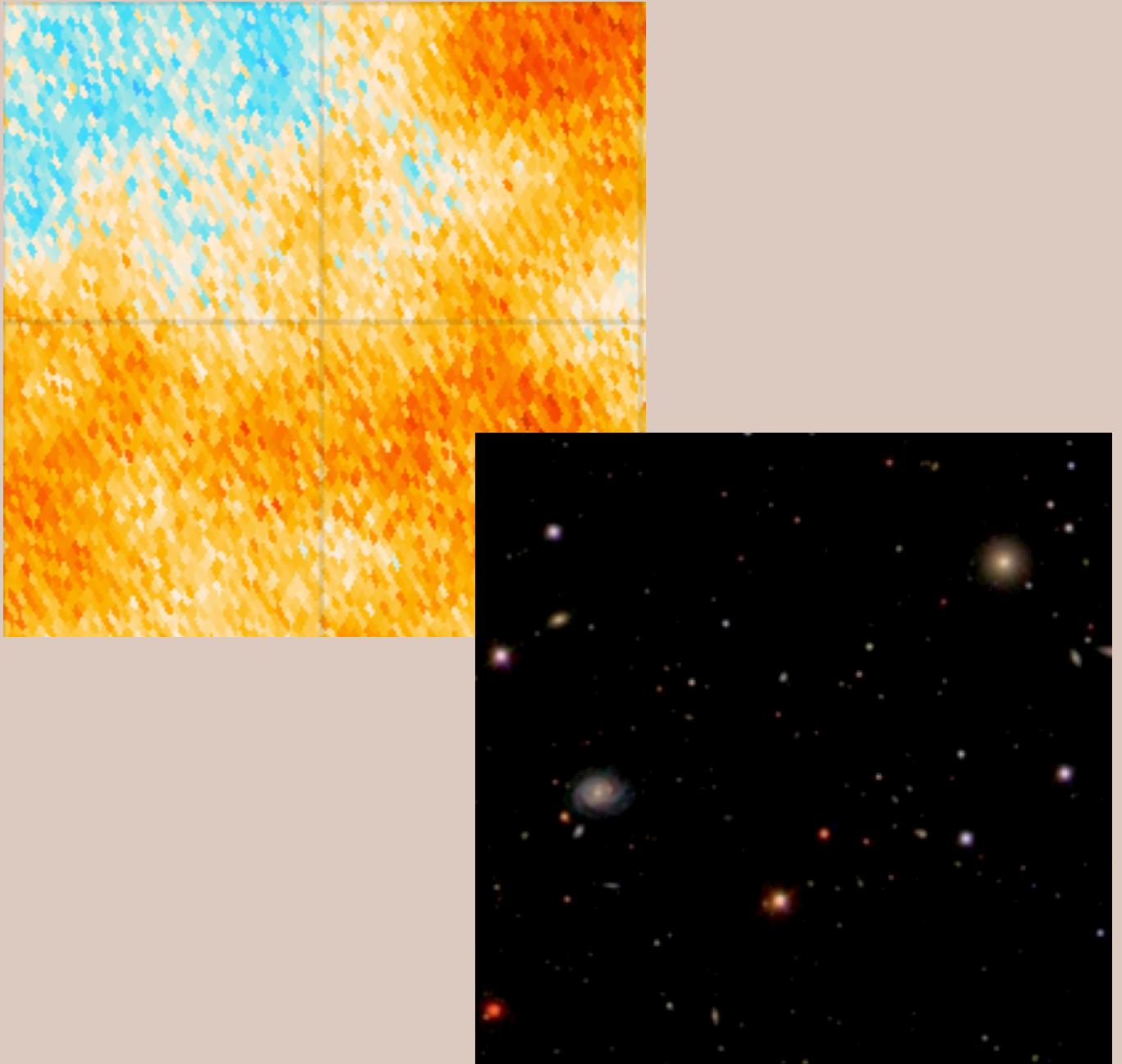
POWER SPECTRA



Nicola et al., 2017

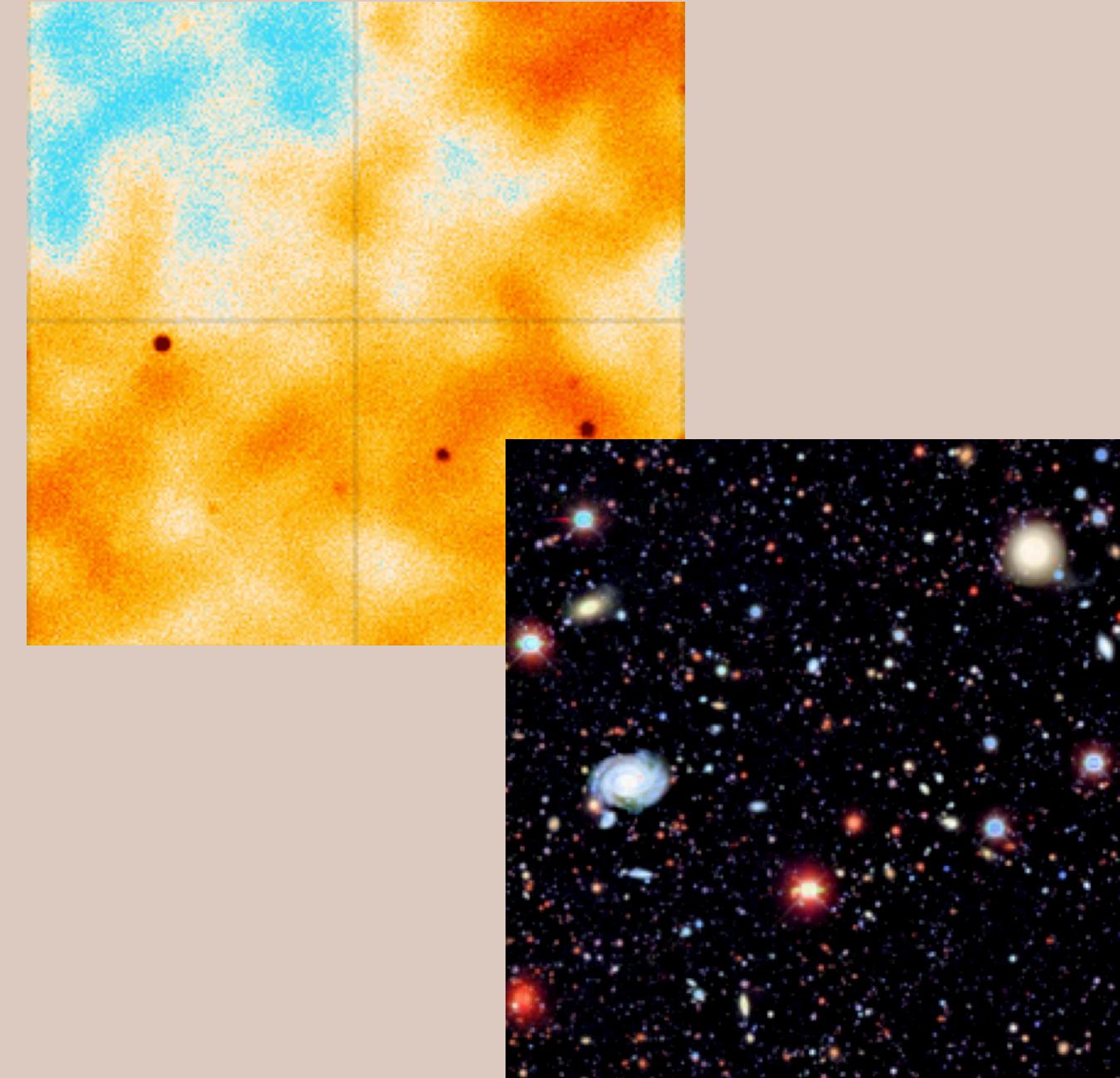
A NEW ERA FOR OBSERVATIONAL COSMOLOGY

PAST



e.g. SDSS, Planck

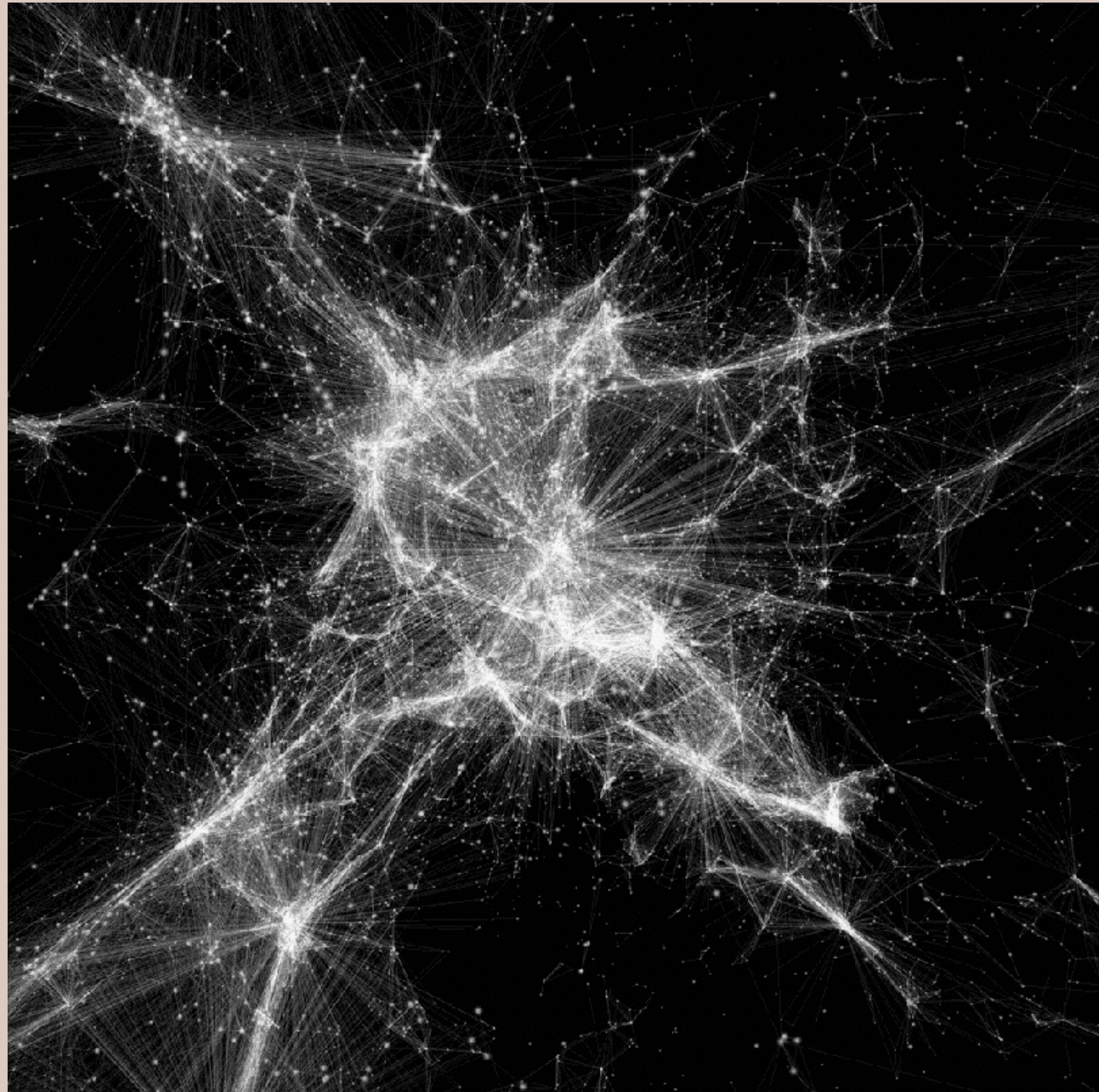
PRESENT & FUTURE



e.g. HSC, LSST/Rubin,
ACT/SPT, CMB S4

Images: ACT, Ivezic et al., 2008

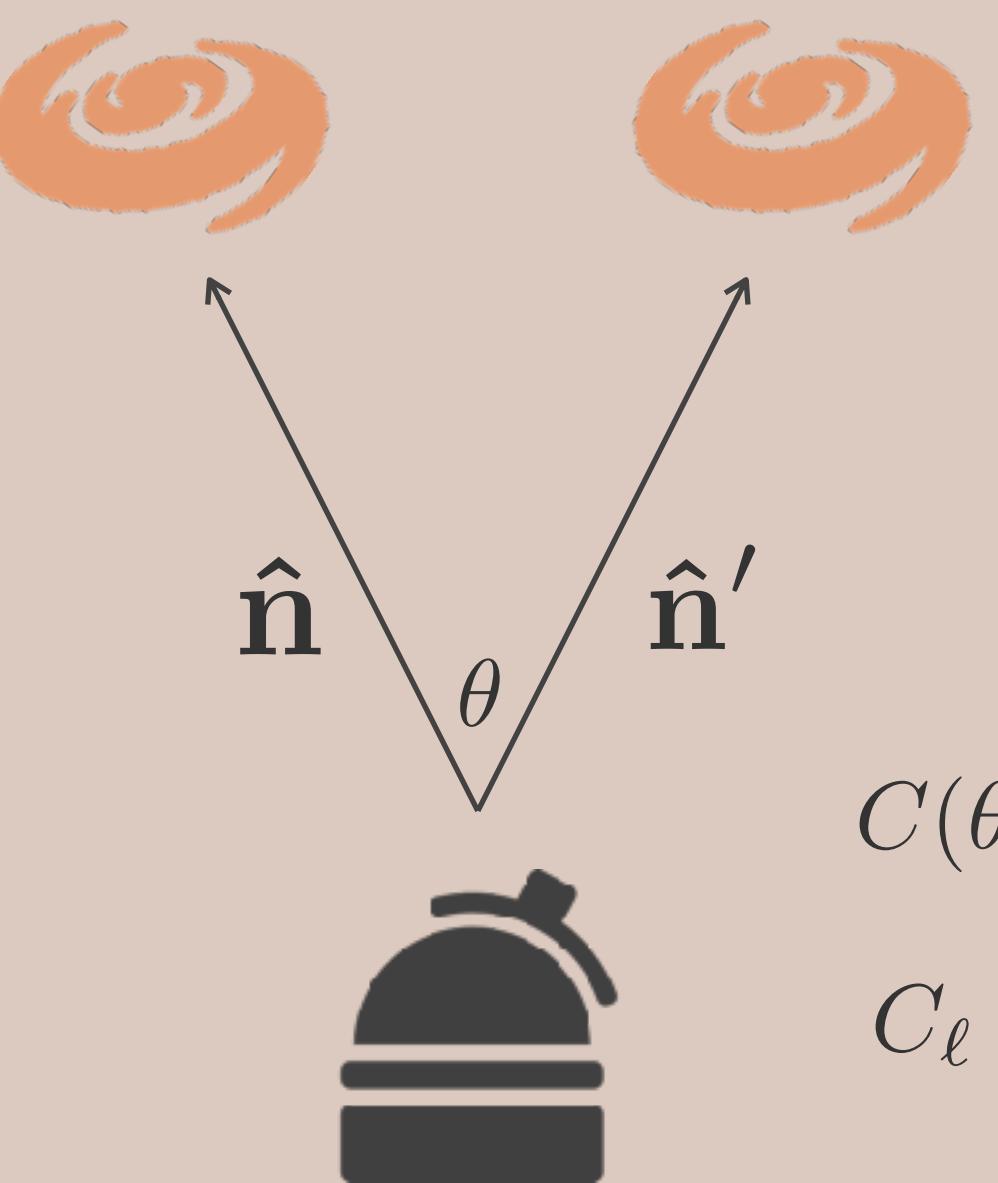
OUR NON-LINEAR UNIVERSE



Additional information contained in:
Cosmological fields at small spacial scales
Non-Gaussian features

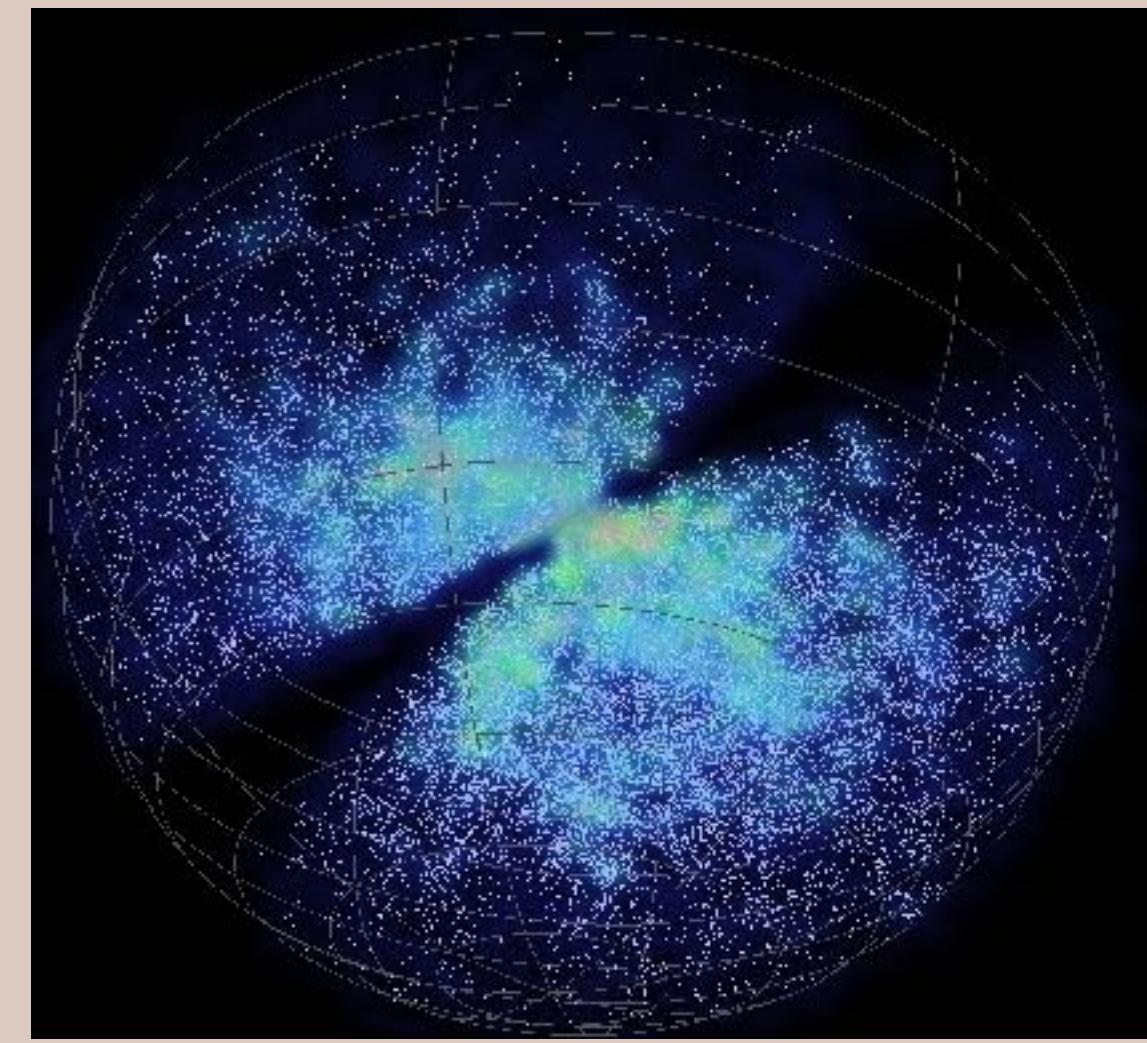
Image: Illustris Collaboration / Illustris Simulation

GALAXY CLUSTERING



$$C(\theta) = \langle \delta(\hat{\mathbf{n}}) \delta(\hat{\mathbf{n}}') \rangle$$

$$C_\ell = \langle \delta_{\ell m} \delta_{\ell m} \rangle$$



Images: 6dF, Science News

HSC PHOTOMETRIC CLUSTERING WITHIN LSST DESC

Apply/test LSST pipeline on LSST-like data set

Test viability of tomographic Fourier space analysis for photometric clustering

Try to maximize sample size, i.e. go beyond e.g. LRGs, redMaGiC

Include small-scale information



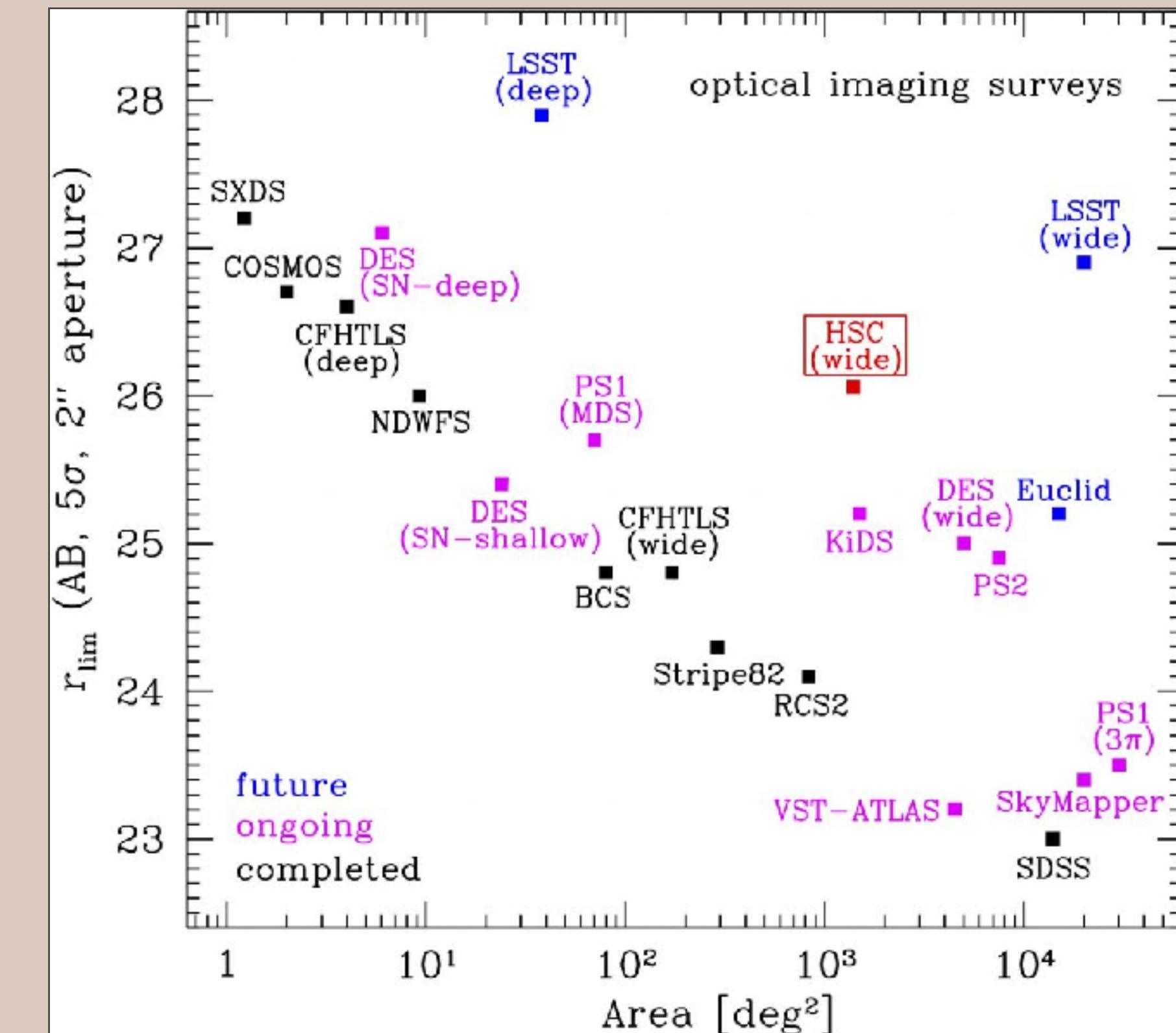
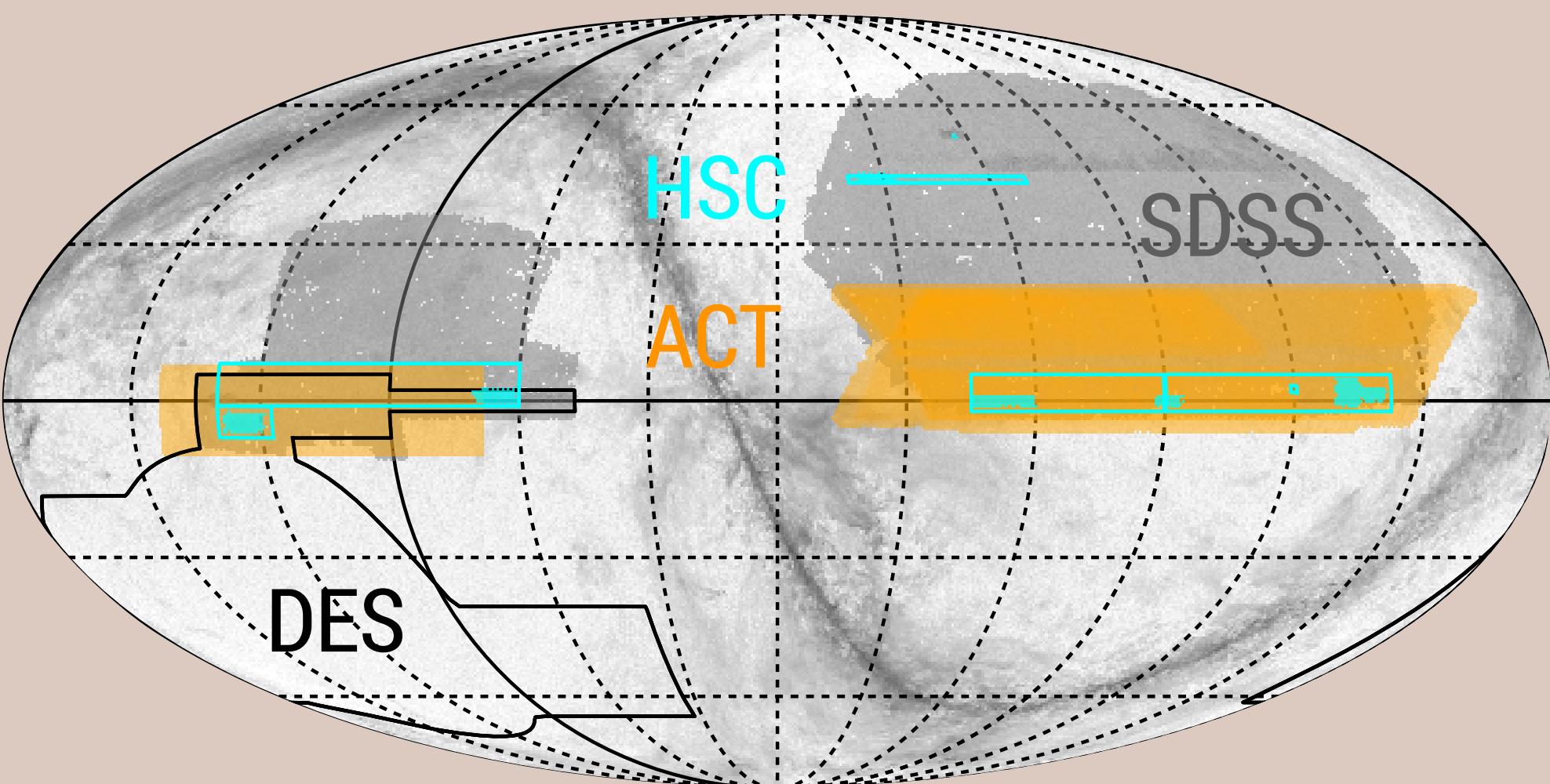
THE HYPER SUPRIME CAM SURVEY (HSC) AS A PRECURSOR FOR LSST

HSC area: 1000 sq. deg.

Deep ($r_{\text{lim}} \sim 26$), good seeing

Precursor to LSST

Most analyses focused on 150 sq. deg. (DR1)



Survey table: HSC SSP, footprint: E. Medezinski

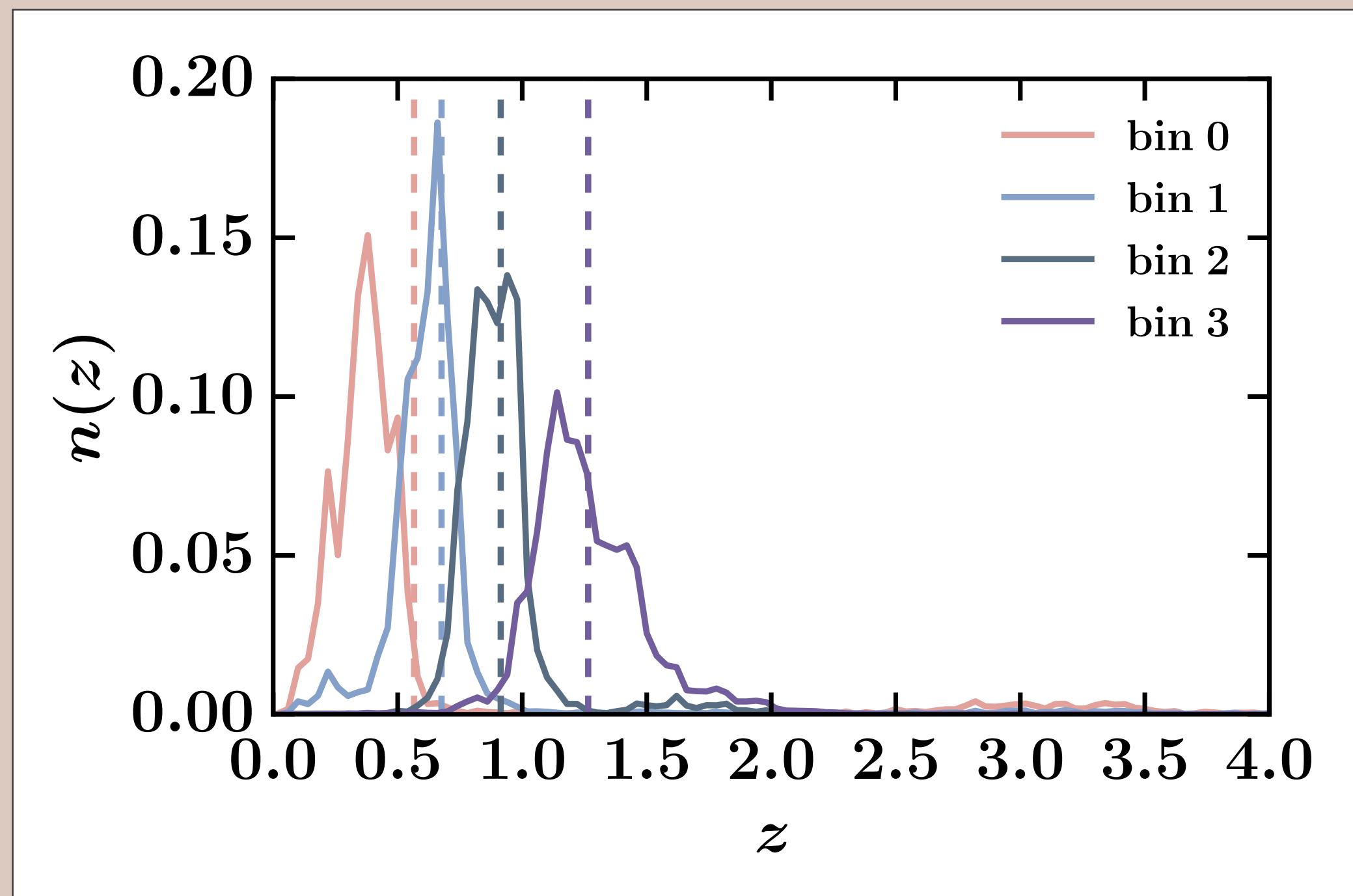
SAMPLE SELECTION

HSC DR1 data

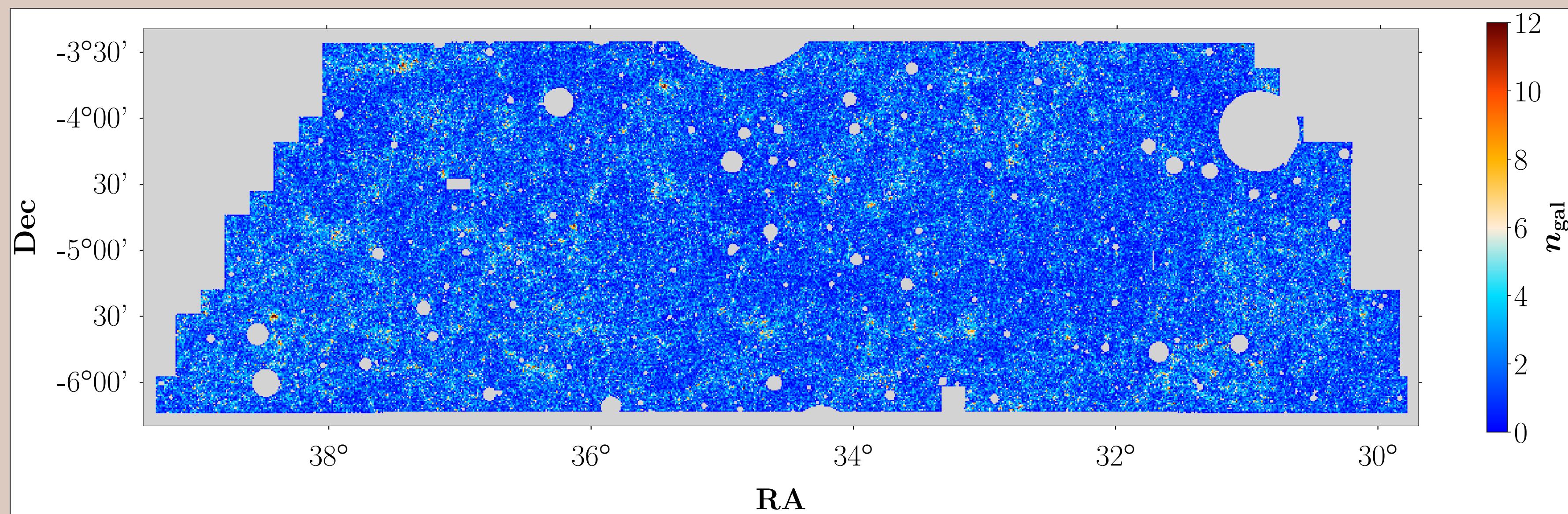
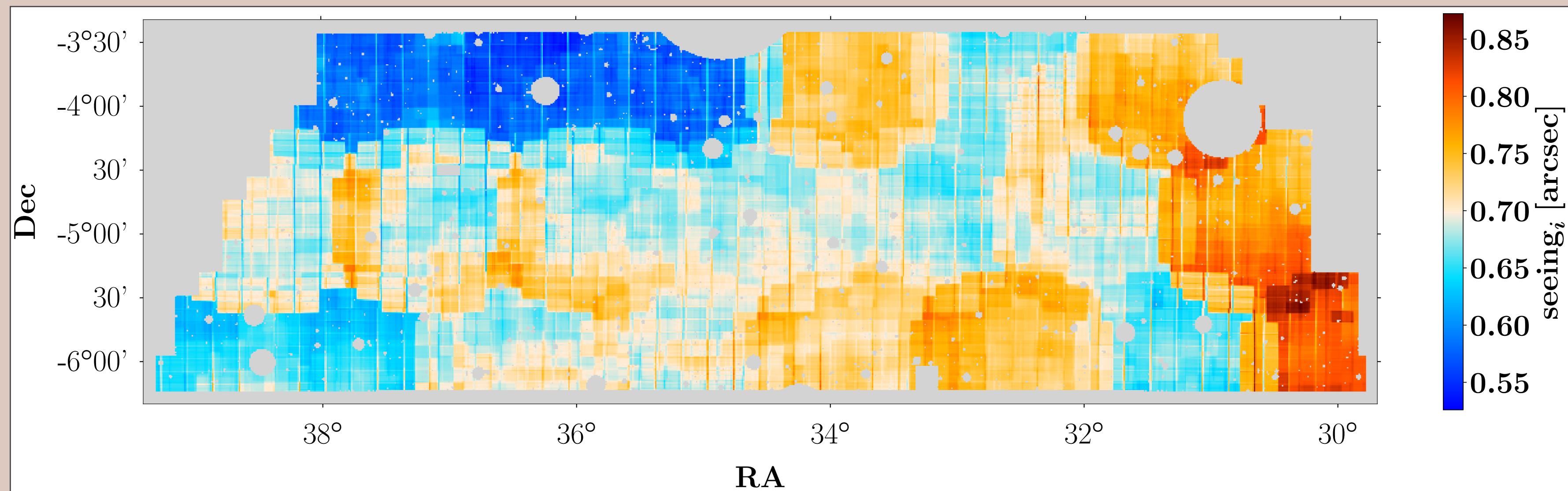
Galaxies with $\text{mag}_i < 24.5$

4 redshift bins: 0.15-0.50, 0.50-0.75,
0.75-1.00, 1.00-1.50

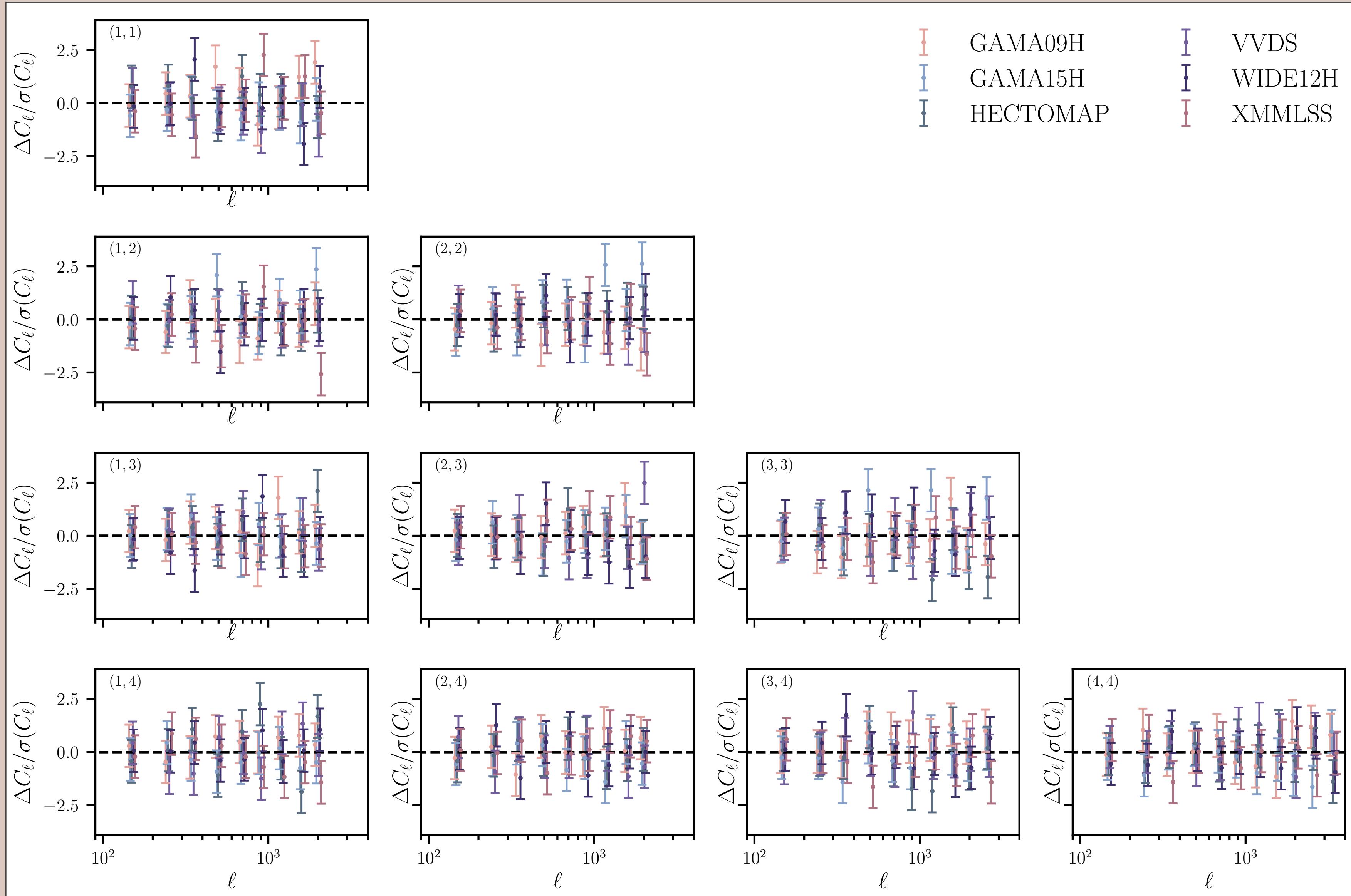
Photo-z: COSMOS reweighting



SYSTEMATICS & SIGNAL MAPS



POWER SPECTRUM CONSISTENCY TESTS

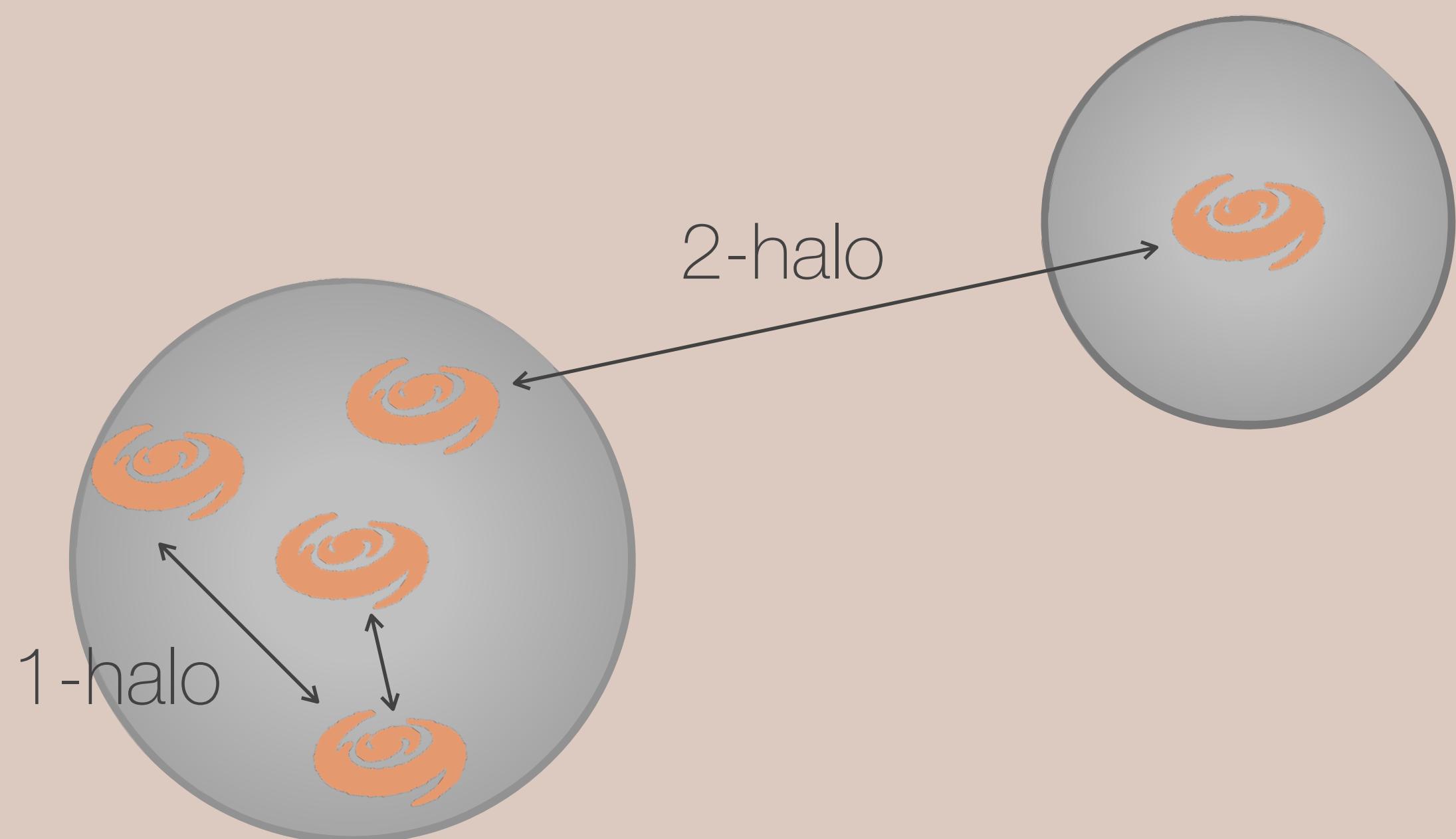


THEORETICAL MODELING

Small-scale clustering ($k_{\max} \sim 1 \text{ Mpc}^{-1}$)

Halo model (e.g. Seljak 2000, Peacock et al., 2000, Ma et al., 2000)

Halo occupation distribution (e.g. Berlind & Weinberg, 2002, Zheng et al., 2005)



$$P_{gg}(z, k) = P_{gg,1h}(z, k) + P_{gg,2h}(z, k)$$

$$P_{gg,1h}(k) = \frac{1}{\bar{n}_g^2} \int dM \frac{dn}{dM} \bar{N}_c \left[\bar{N}_s^2 u_s^2(k) + 2\bar{N}_s u_s^2(k) \right]$$

$$P_{gg,2h}(k) = \left(\frac{1}{\bar{n}_g} \int dM \frac{dn}{dM} b_h(M) \bar{N}_c [1 + \bar{N}_s u_s(k)] \right)^2 P_{\text{lin}}(k)$$

HOD MODELING DETAILS

Redshift-dependent 6-parameter HOD model

$$\bar{N}_g(M) = \bar{N}_c(M)(f_c + \bar{N}_s(M))$$

centrals: $\bar{N}_c(M) = \frac{1}{2} \left[1 + \text{erf} \left(\frac{\log M - \log M_{\min}(z)}{\sigma_{\ln M}} \right) \right]$

satellites: $\bar{N}_s(M) = \Theta(M - M_0(z)) \left(\frac{M - M_0(z)}{M_1(z)} \right)^\alpha$

where

$$\log M_i(z) = \mu_i + \mu_{i,p} \left(\frac{1}{1+z} - \frac{1}{1+z_p} \right), \quad i \in [\min, 0, 1]$$

Fiducial model

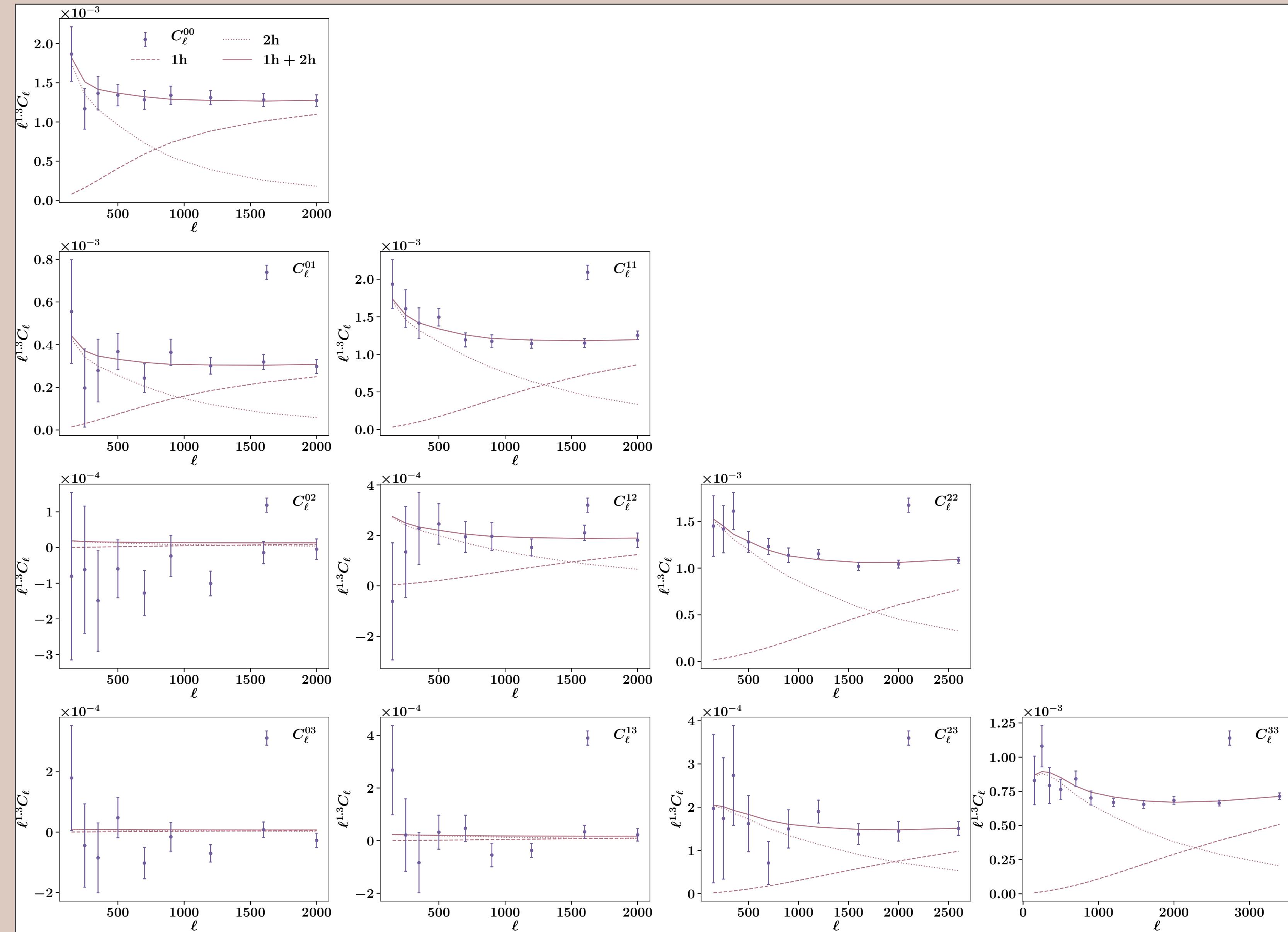
Redshift-dependent 3(+3)-parameter HOD: $M_{\min}(z)$ $M_0(z)$ $M_1(z)$

Remaining HOD parameters fixed to $f_c = 1$ $\alpha = 1$ $\sigma_{\ln M} = 0.4$

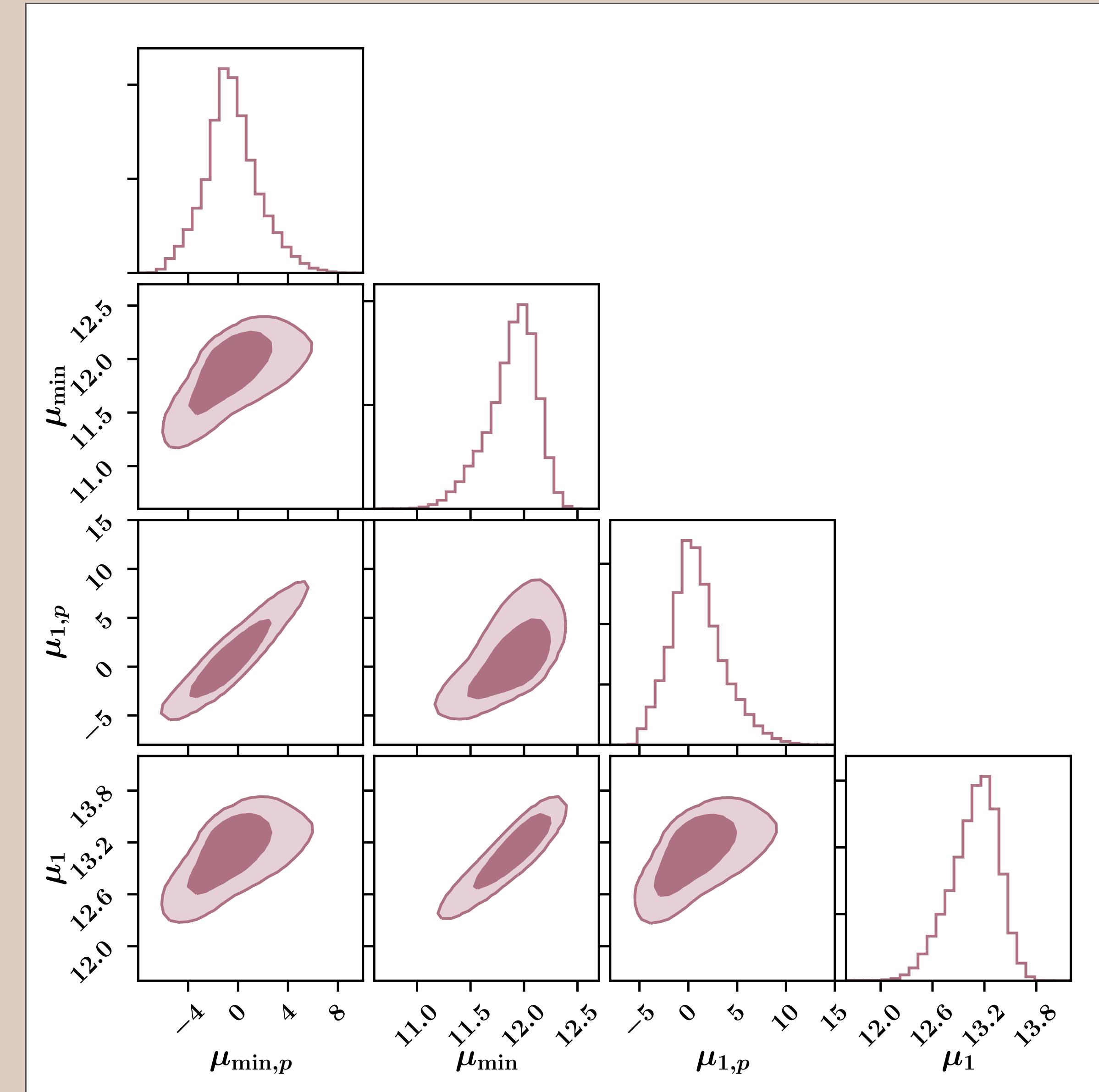
Cosmological parameters fixed to Planck 2018

Photo-z uncertainties: $p(z)$ shift Δz_i & width $z_{w,i}$

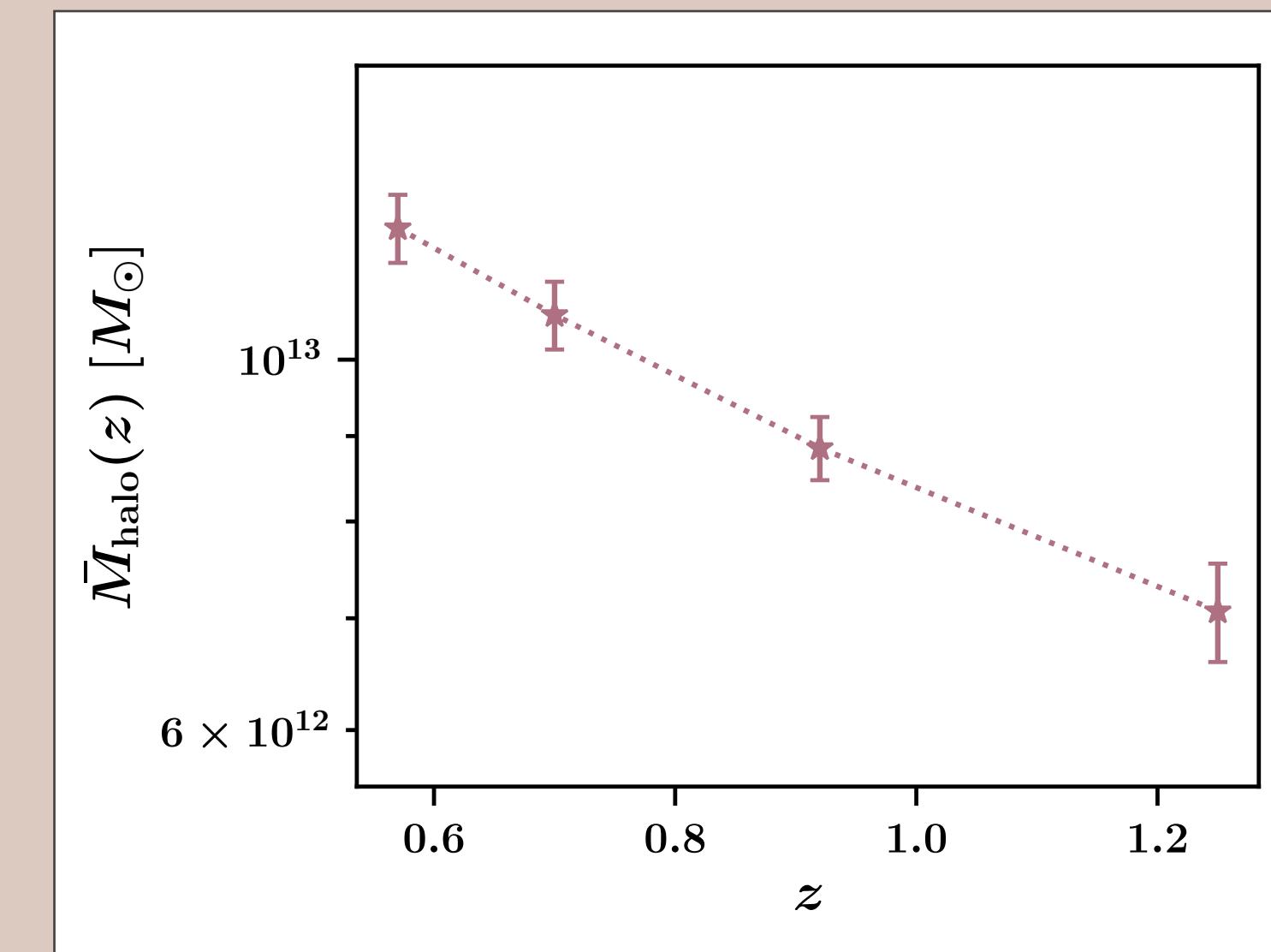
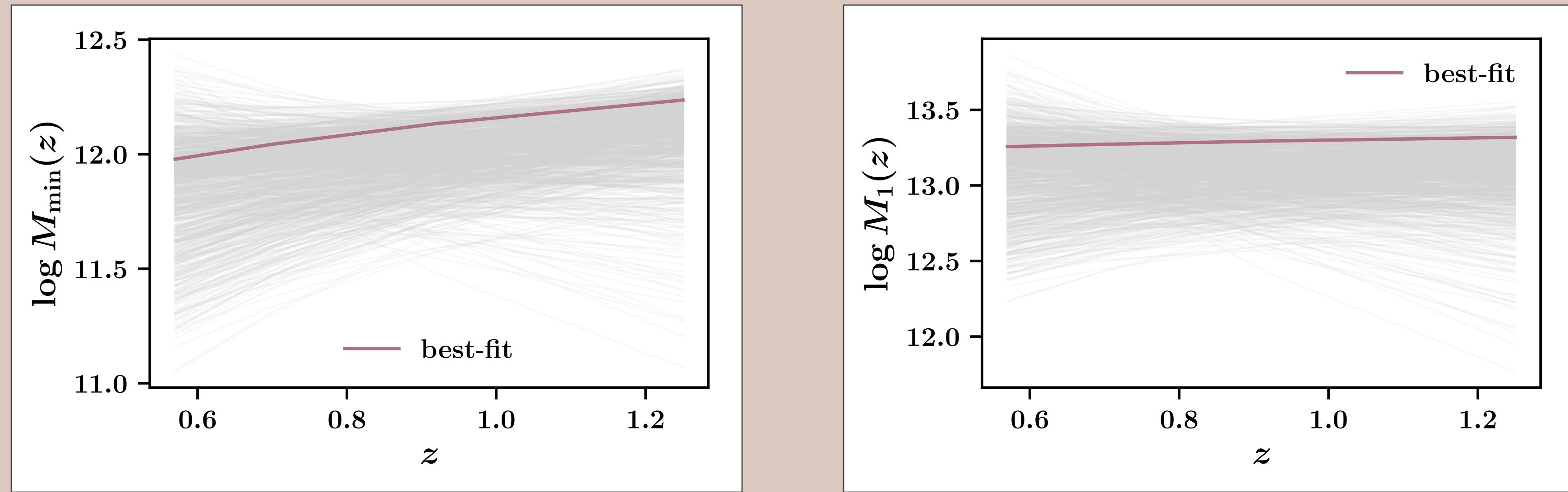
POWER SPECTRA



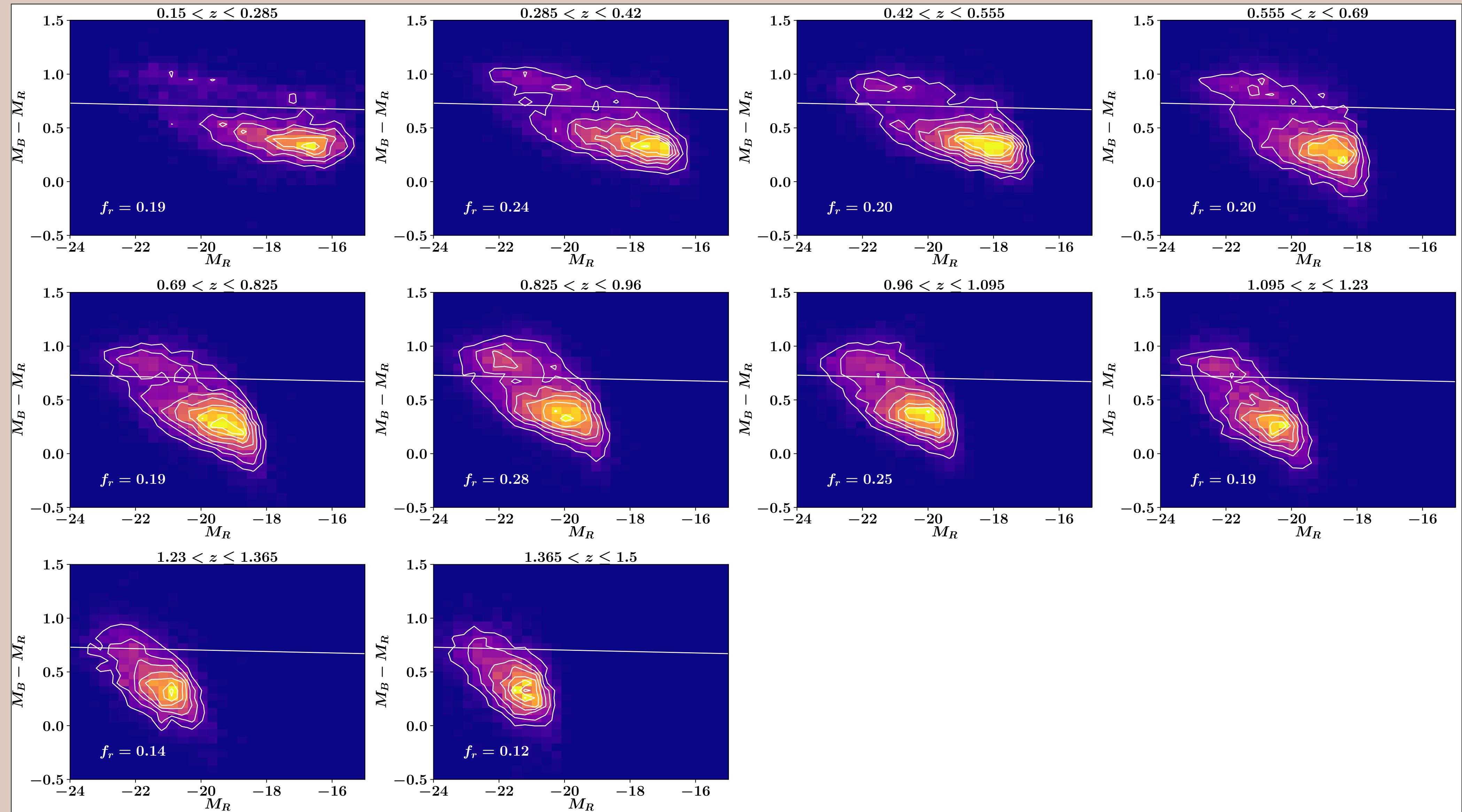
HOD CONSTRAINTS



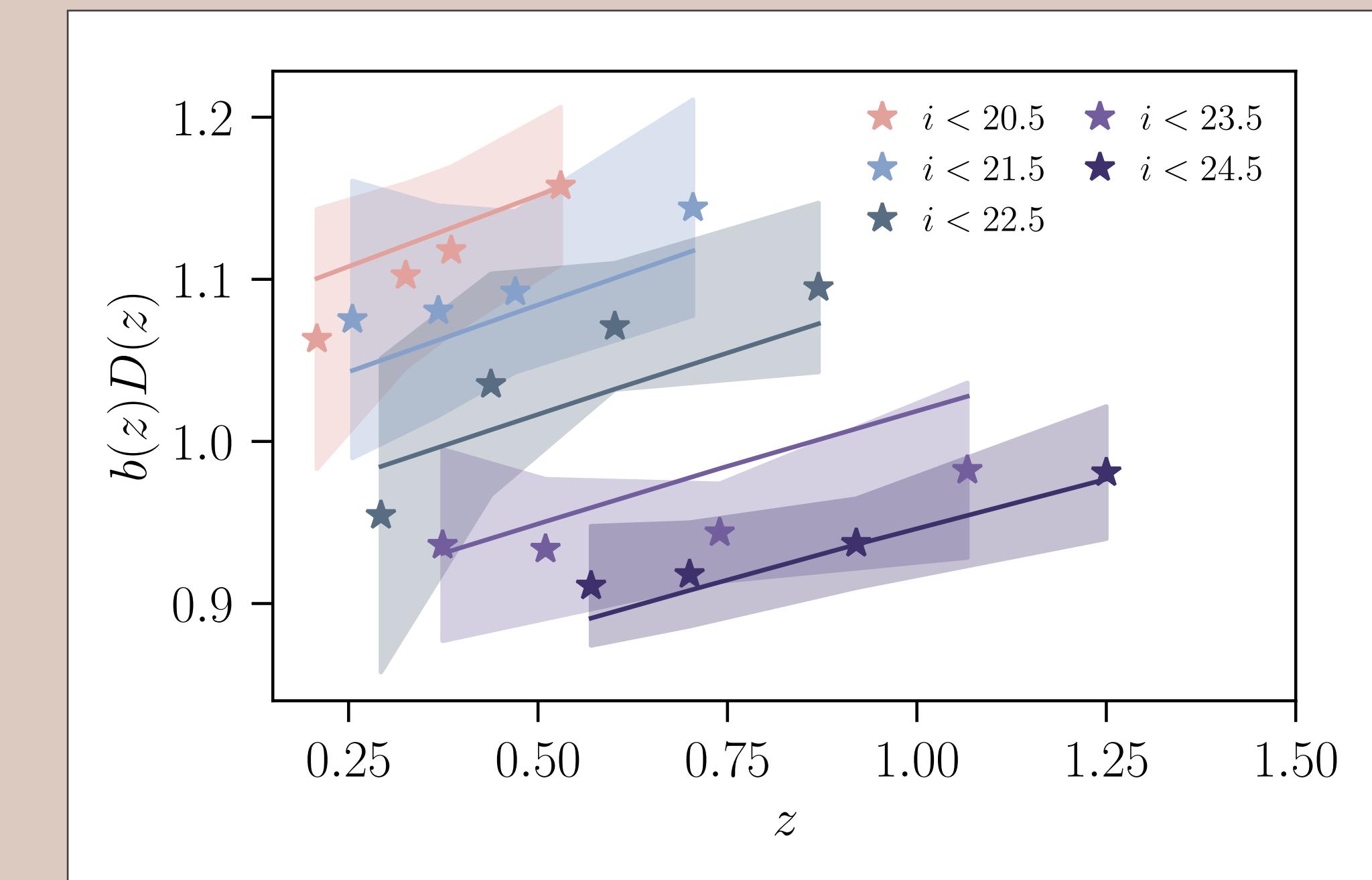
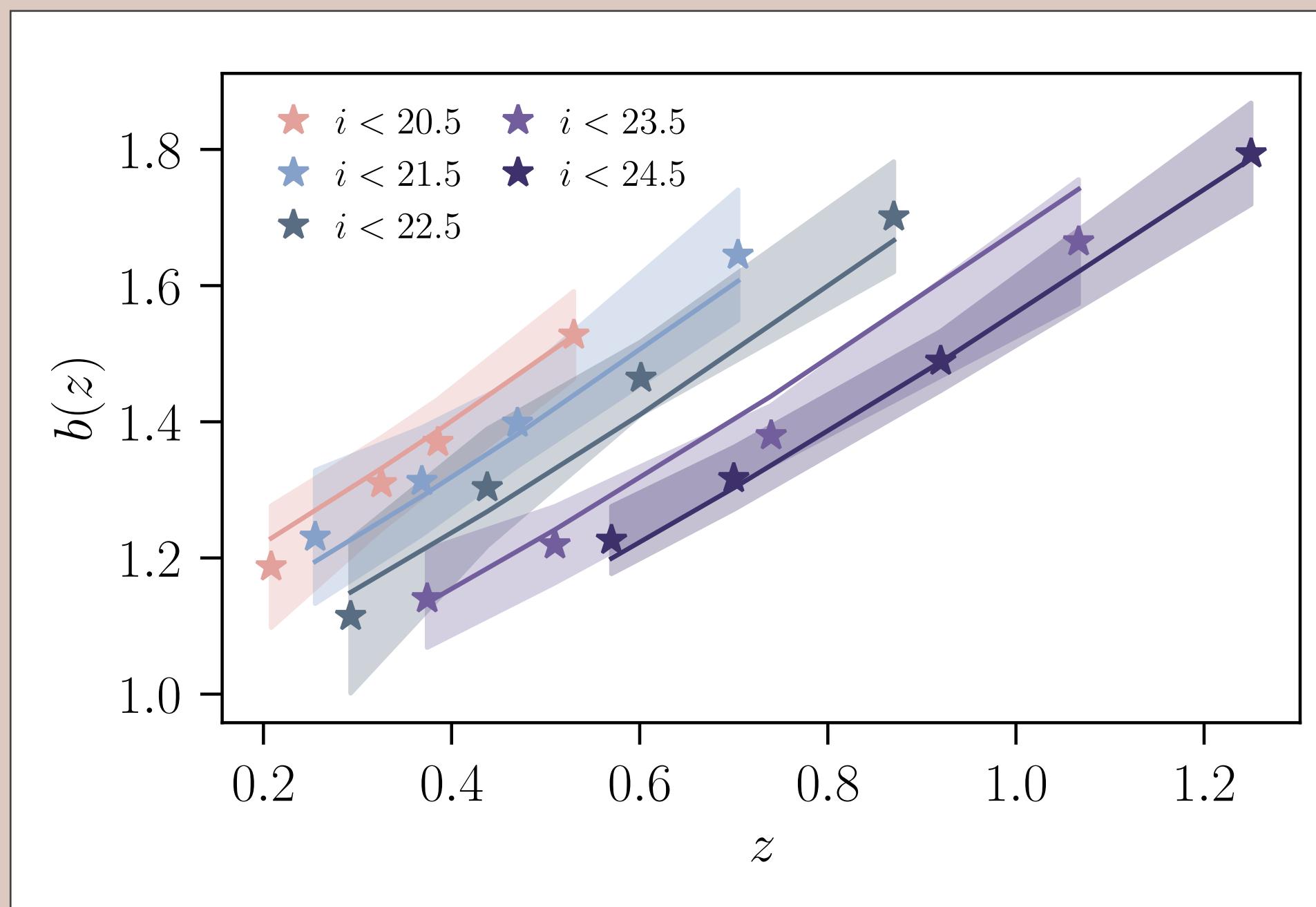
HOD REDSHIFT EVOLUTION



PROPERTIES OF GALAXY SAMPLE



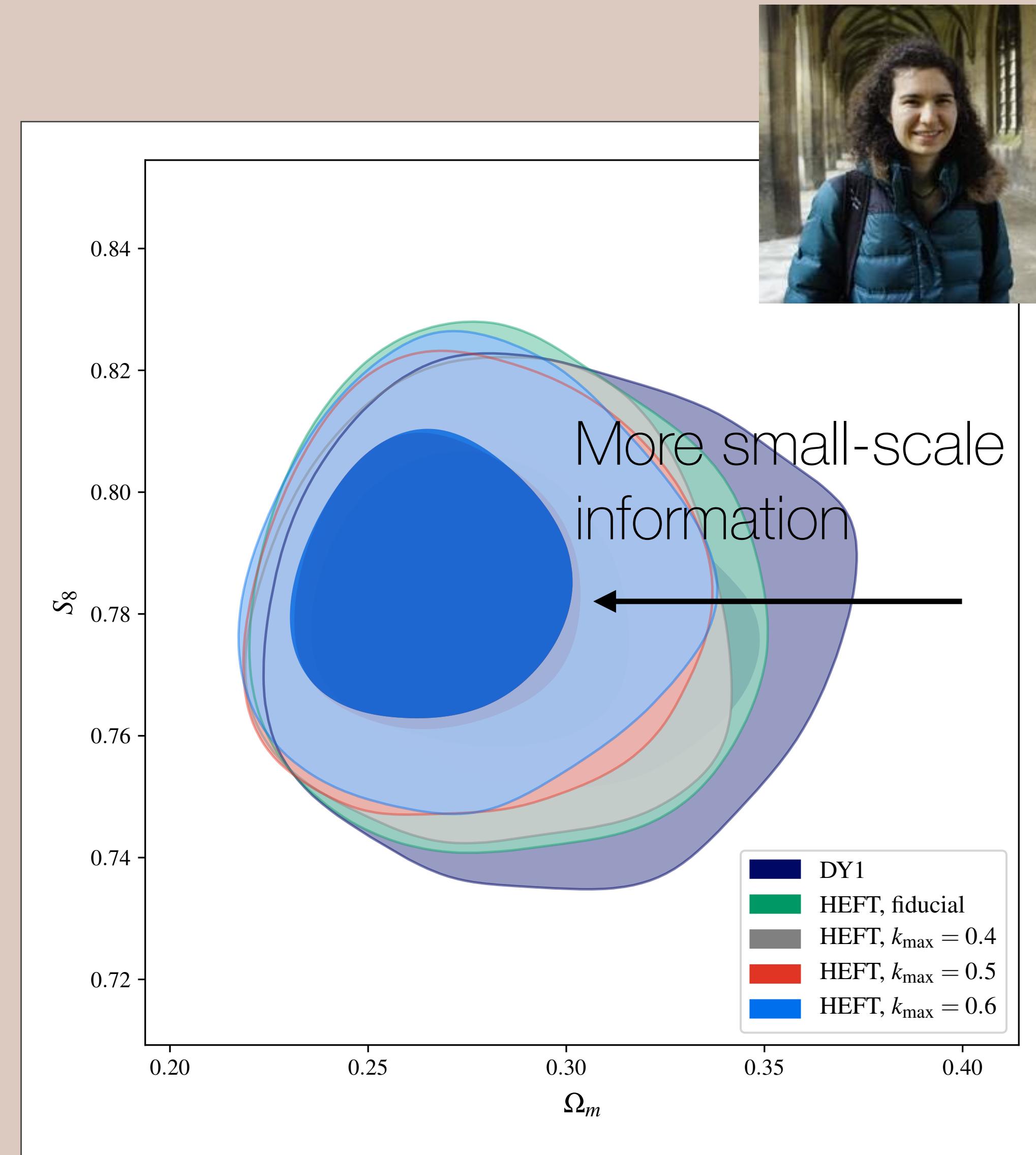
GALAXY BIAS FOR MAGNITUDE-LIMITED SAMPLES



$$b(z, m_{\text{lim}}) = \bar{b}(m_{\text{lim}}) D(z)^\alpha$$

Nicola et al., 2020

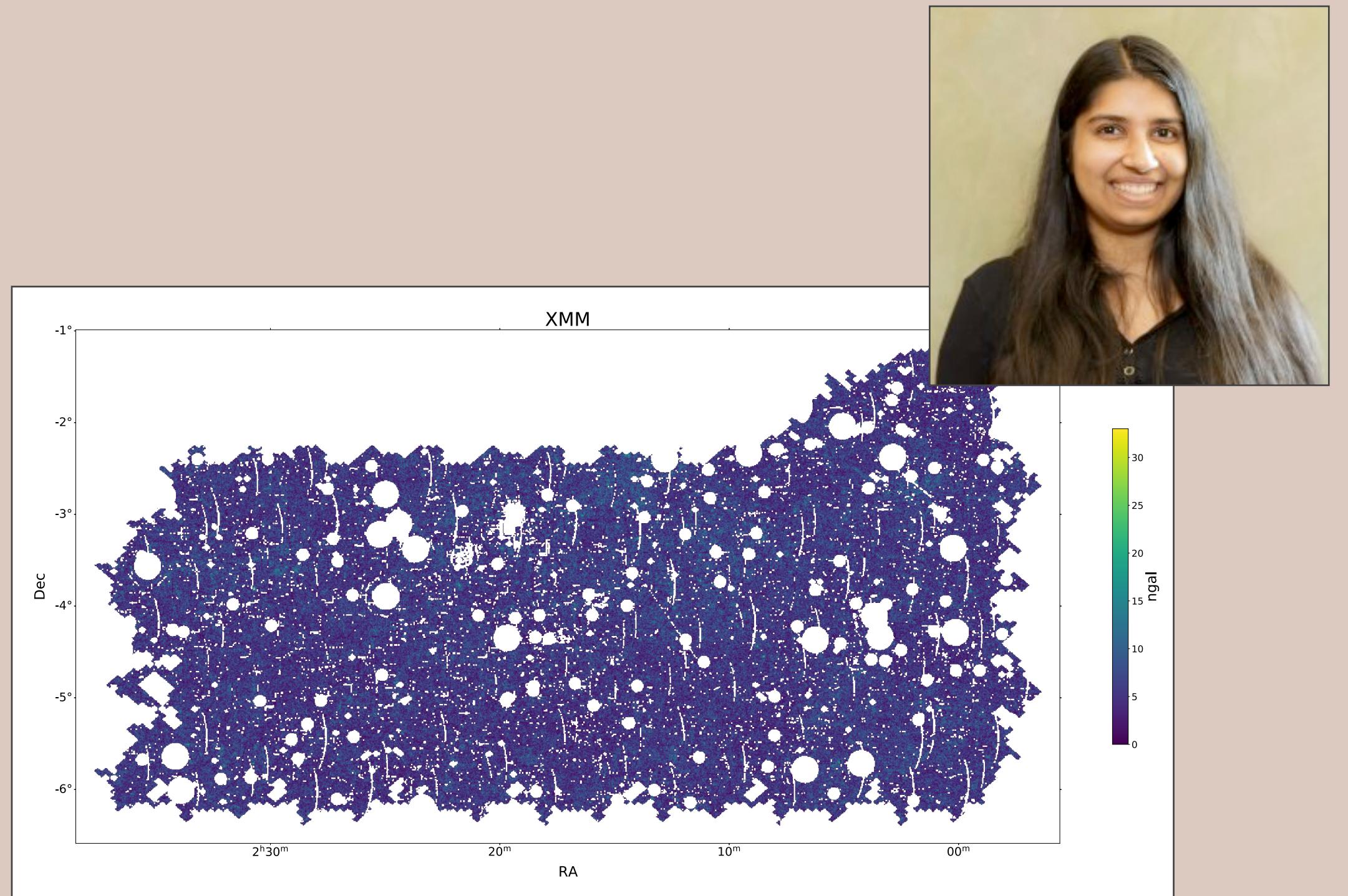
SMALL-SCALE POWER SPECTRUM



Hadzhiyska et al., 2021

SMALL-SCALE POWER SPECTRUM - ONGOING WORK

GALAXY CLUSTERING WITH HSC DR3

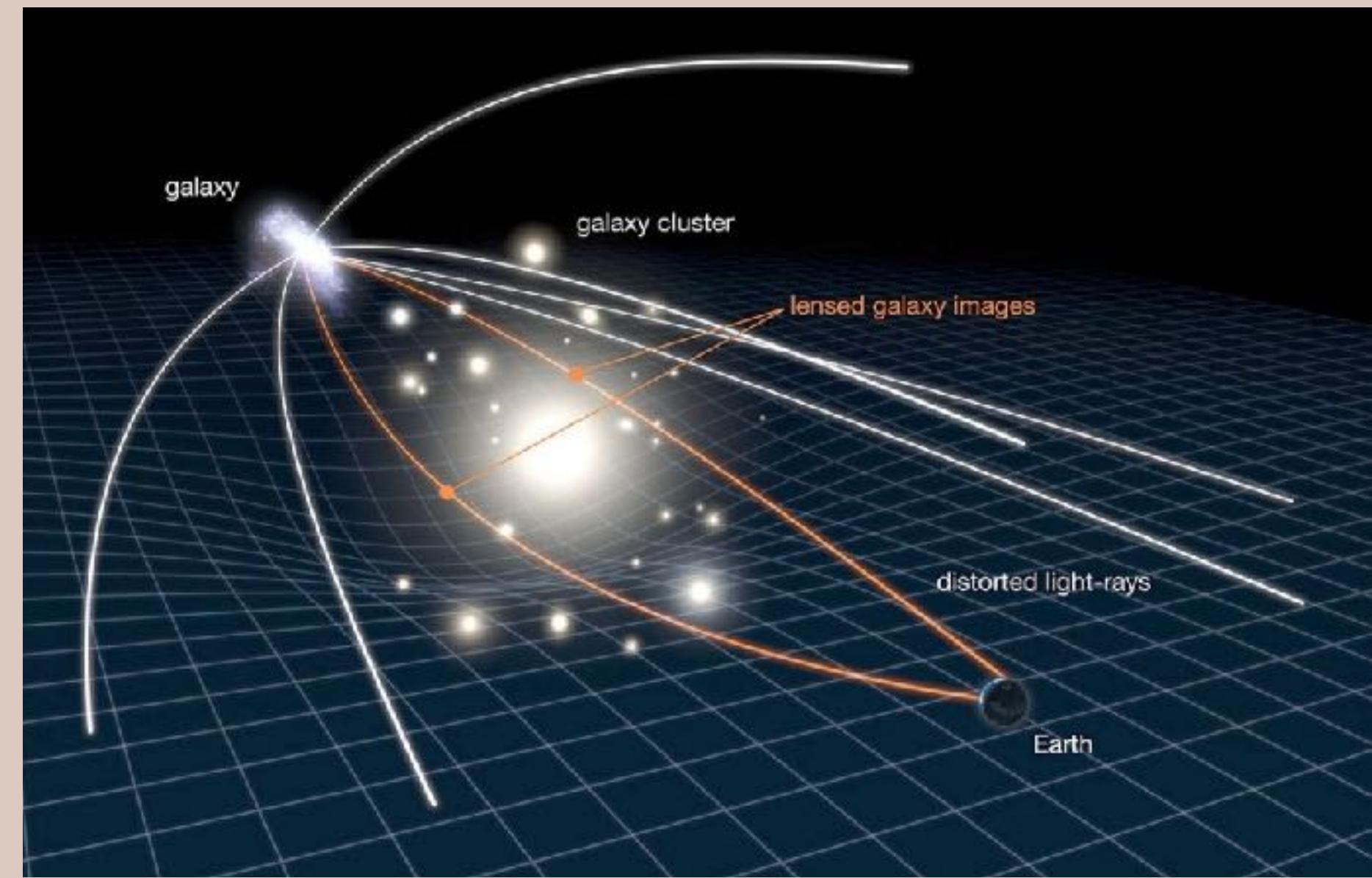


Dalal et al., *in prep.*

LSST DESC BIAS CHALLENGE

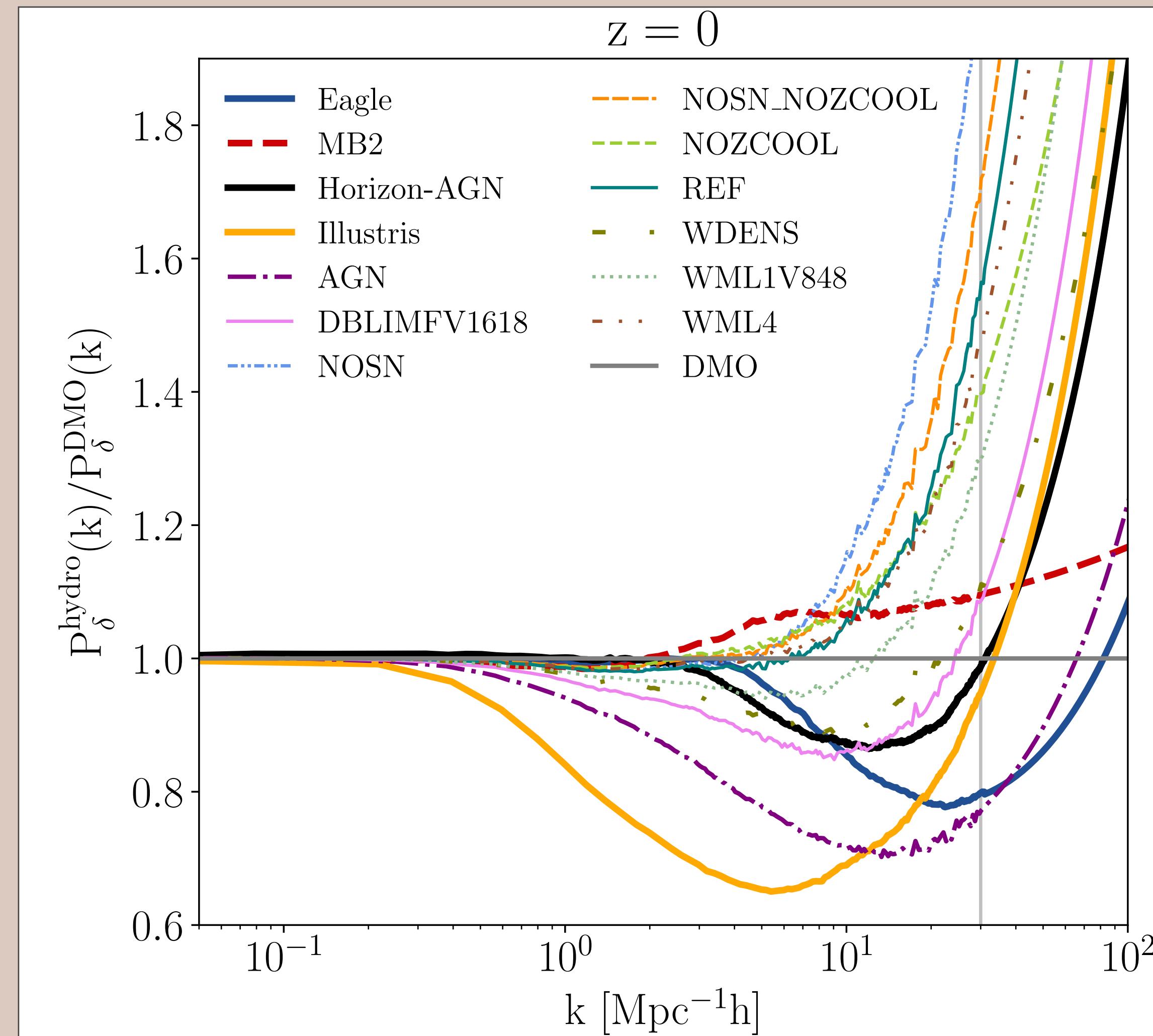


WEAK GRAVITATIONAL LENSING



Images: NASA/ESA, radioGREAT, NASA/STScI

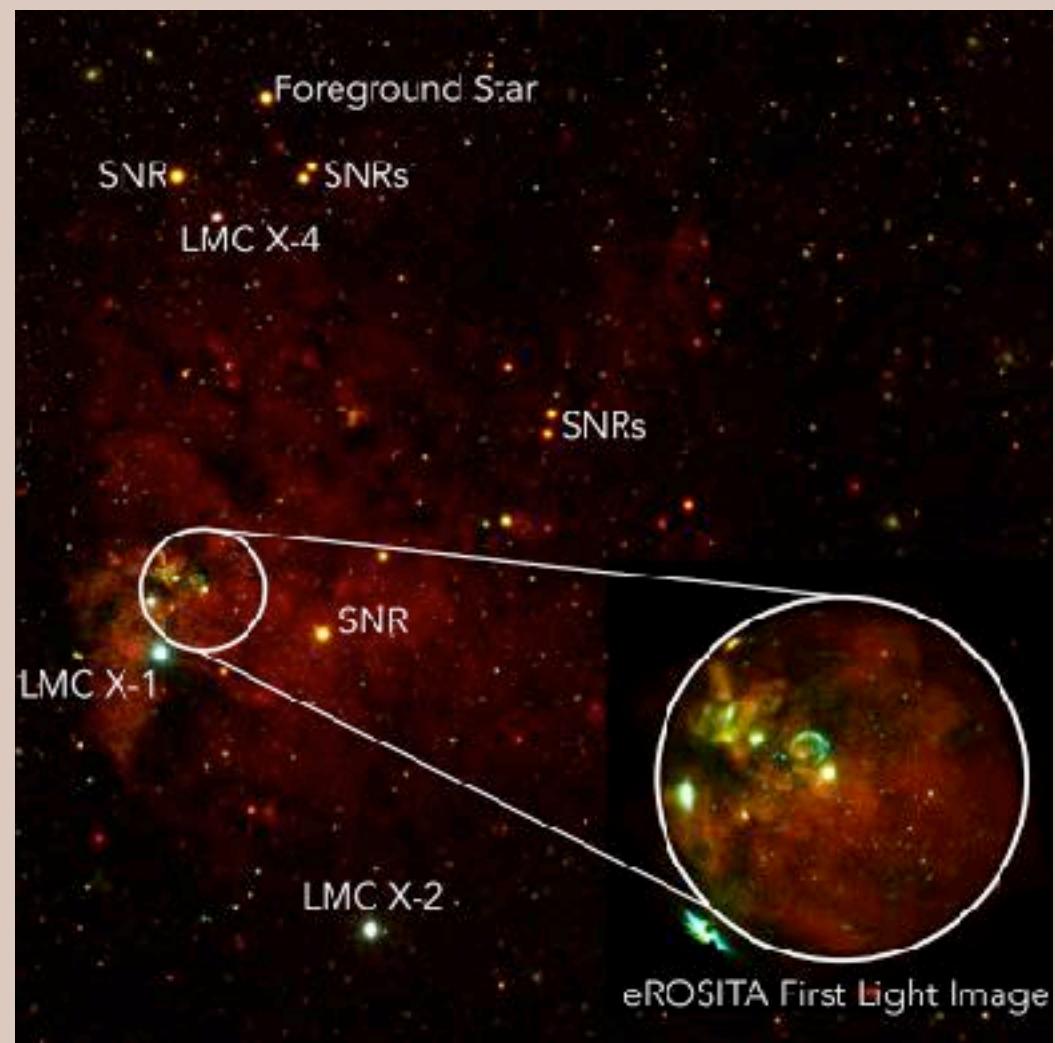
ACCESSING SMALL-SCALE INFORMATION WITH WEAK LENSING



Images: S. Skillman, Y-Y. Mao, KIPAC/SLAC National Accelerator Laboratory, Huang et al., 2019

CONSTRAINING COSMOLOGY & BARYON PHYSICS FROM 2PT-FUNCTIONS

X-RAY



TSZ



FRBs

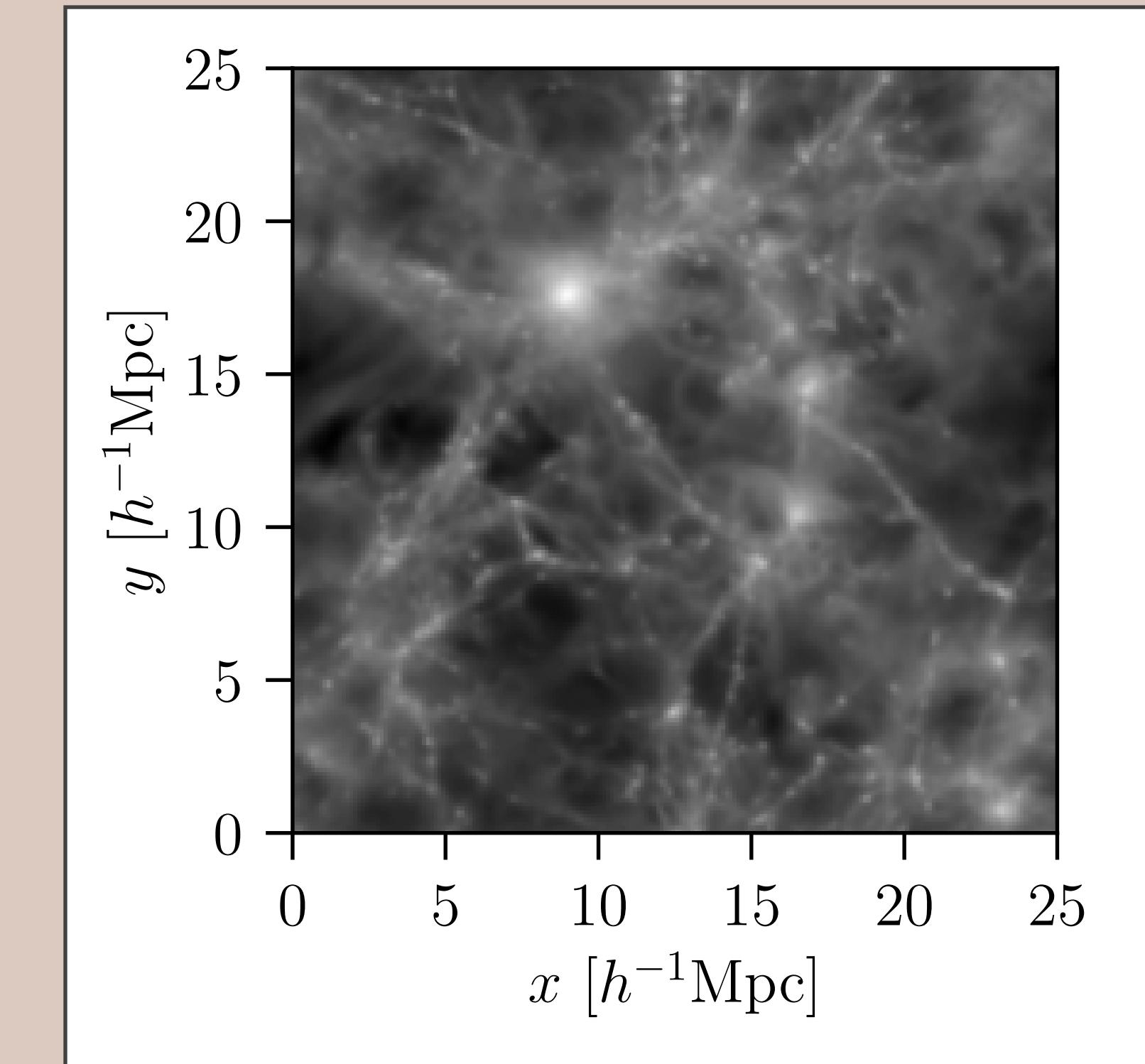
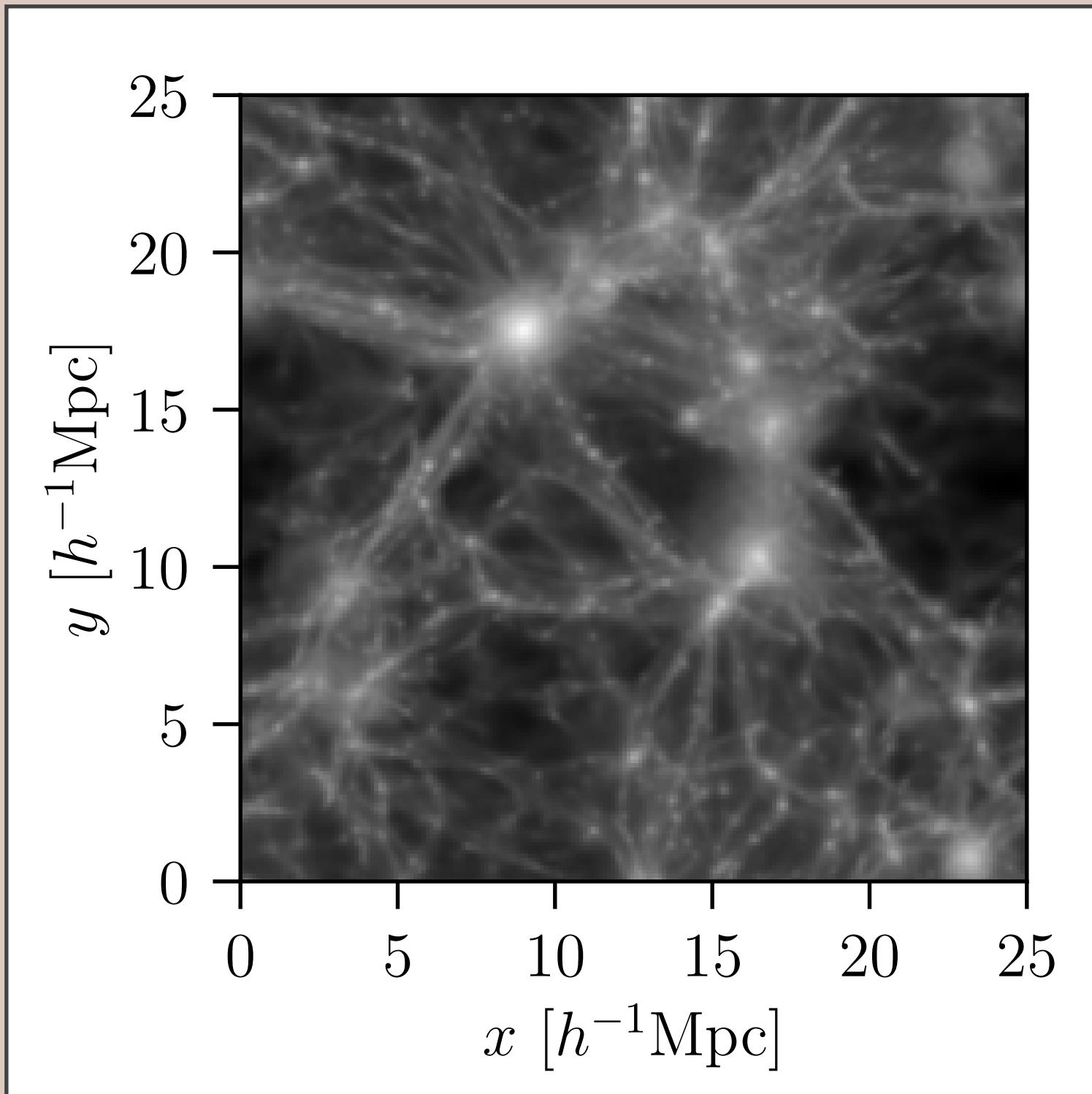


Images: eROSITA, Madhavacheril et al., 2020,
Danielle Futselaar/artsouce.nl

SIMULATIONS

CAMELS

ILLUSTRIS TNG

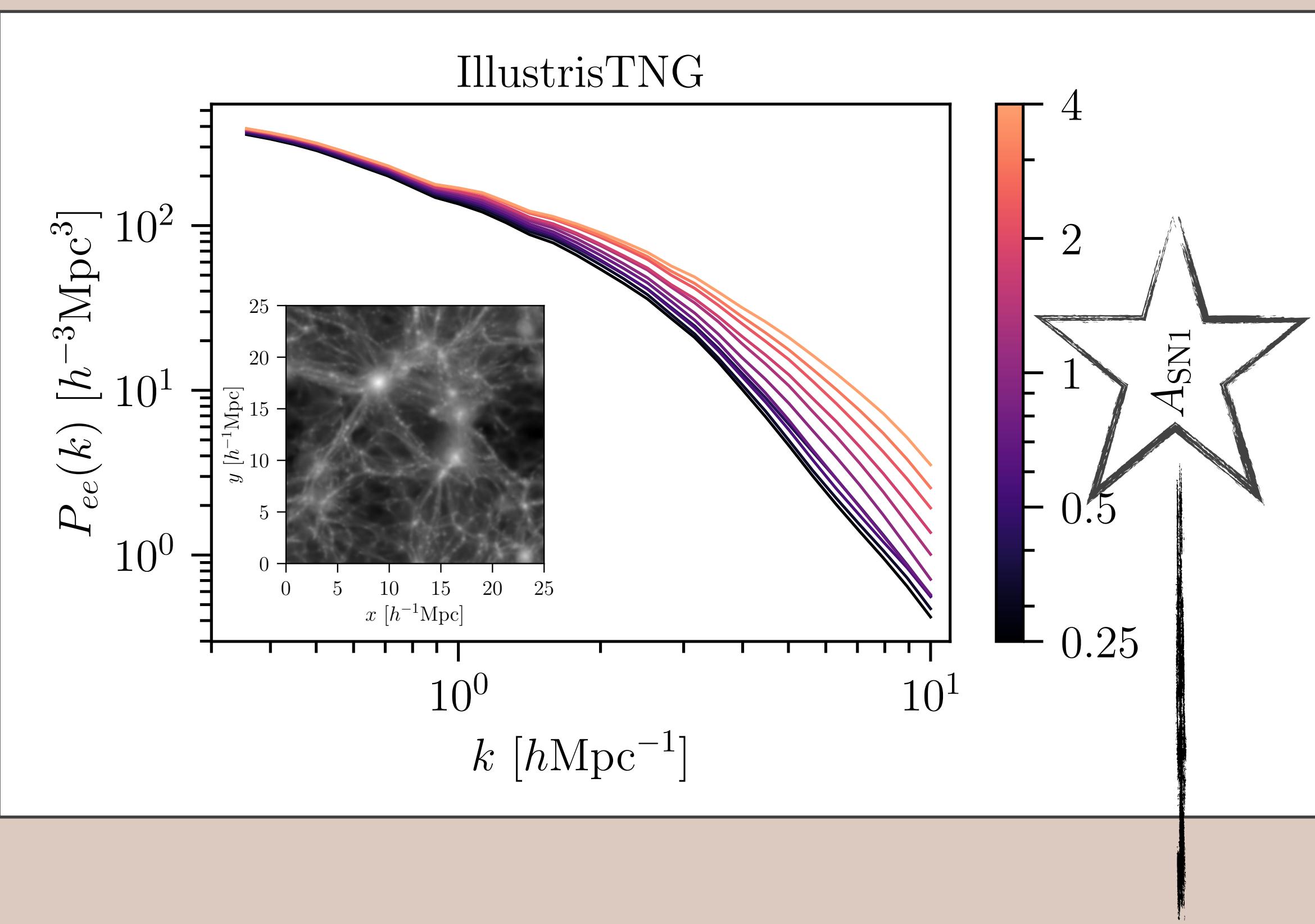


CAMELS: 2000+ simulations of $V = (25 \text{ } h^{-1} \text{ Mpc})^3$, run for IllustrisTNG/SIMBA

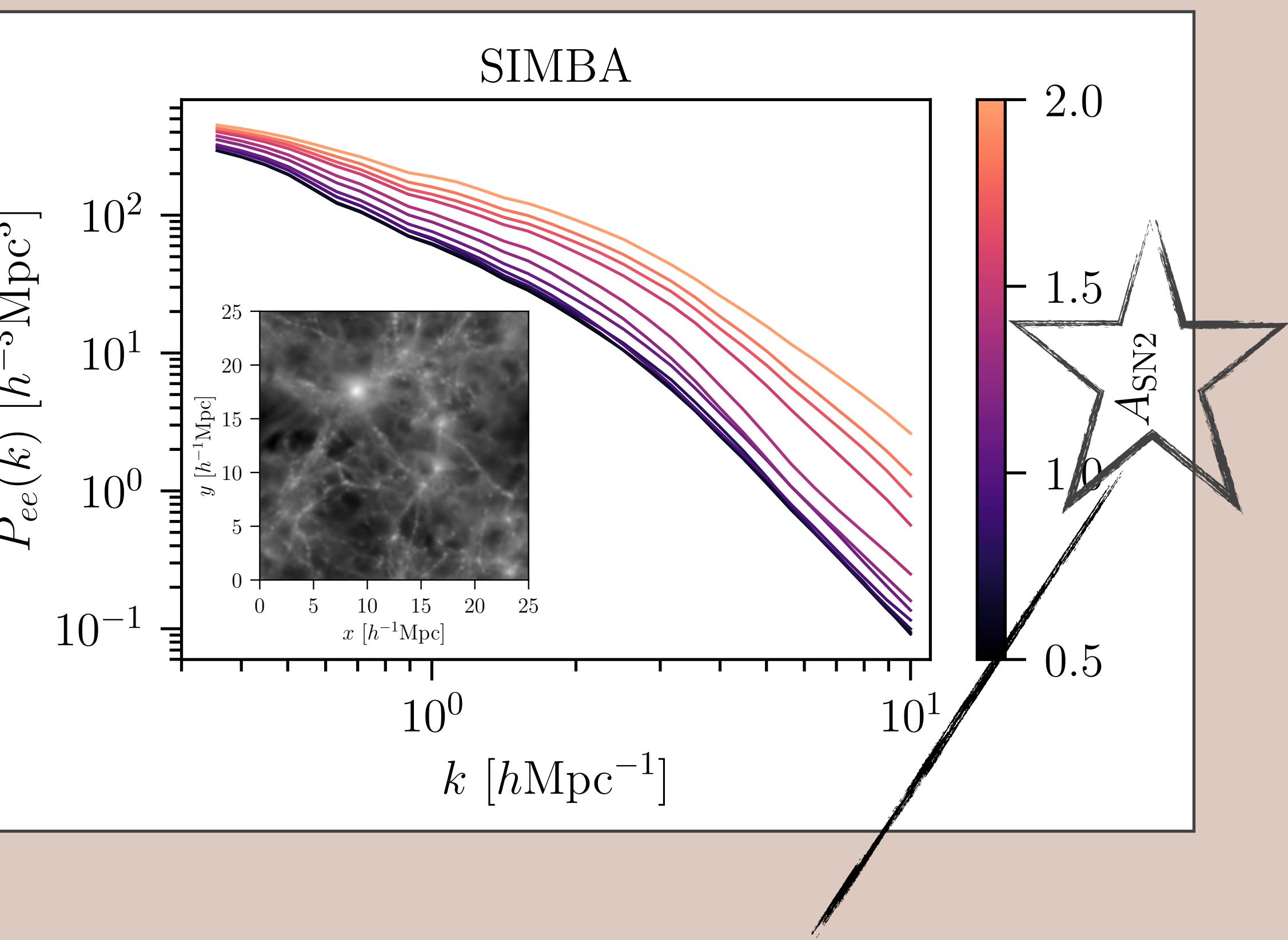
Nelson et al., 2019, Davé et al., 2019, Villaescusa-Navarro et al., 2021

DATA

ILLUSTRIS TNG



SIMBA



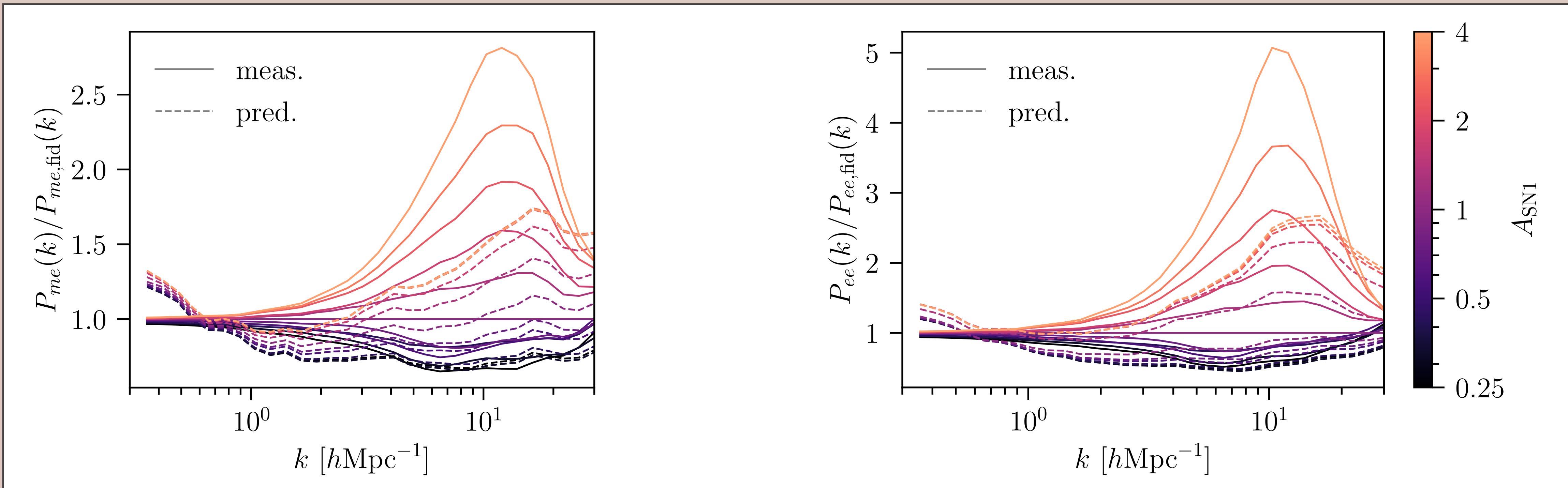
SNe feedback energy

SNe feedback wind speed

Weinberger et al., 2017, Pillepich et al., 2018, Davé et al., 2019

BARYON FRACTION AS PREDICTOR OF FEEDBACK

$$\bar{f}_{\text{bar}} = \frac{1}{N_h} \sum_i^{N_h} \frac{M_{\text{bar},h,i}}{M_{\text{tot},h,i}}, \quad 10^{12} < M_{\text{tot},h,i} < 10^{13} h^{-1} M_\odot$$

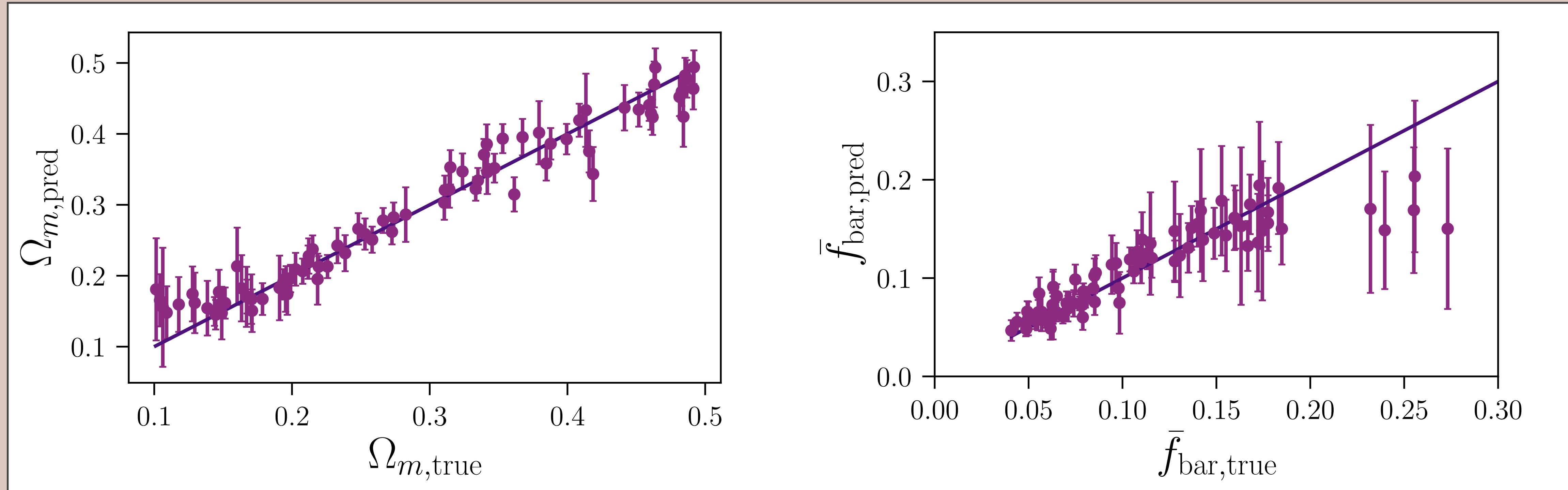


Averaged relative accuracy: $\langle \delta P/P \rangle \sim 25\%$

van Daalen et al., 2020

FORECASTING CONSTRAINTS

FORECASTED ERRORS FROM ILLUSTRIS TNG

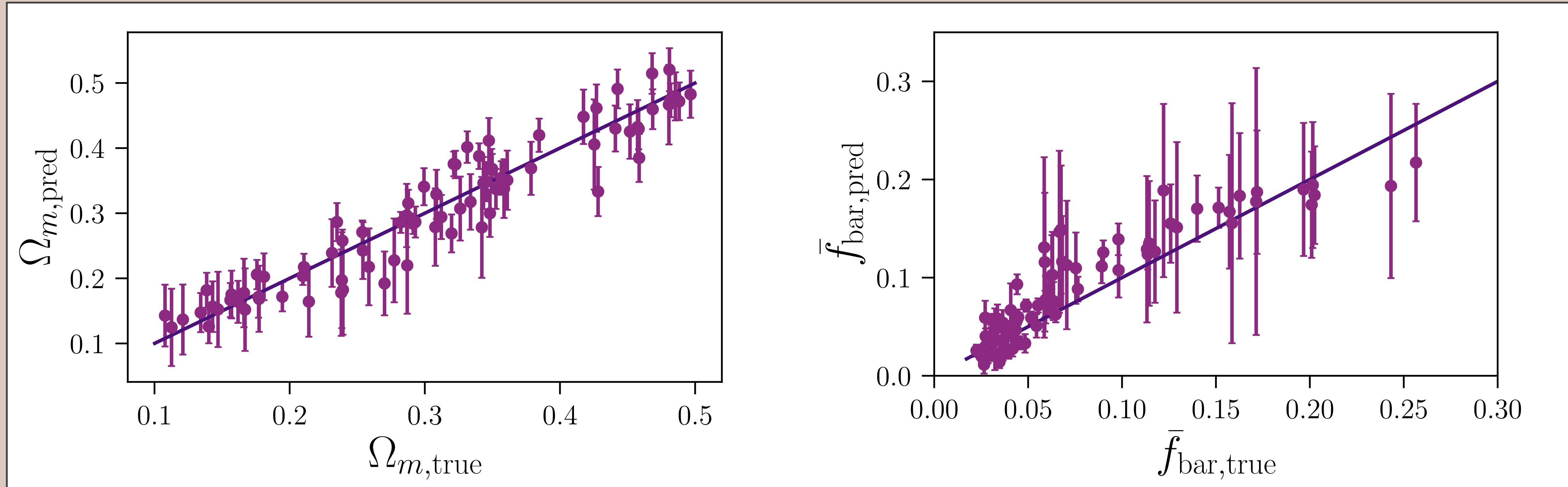


Forecasts for $P_{ee}(k)$, $z = 0$, $k_{\max} = 10 h \text{ Mpc}^{-1}$

Nicola et al., 2022

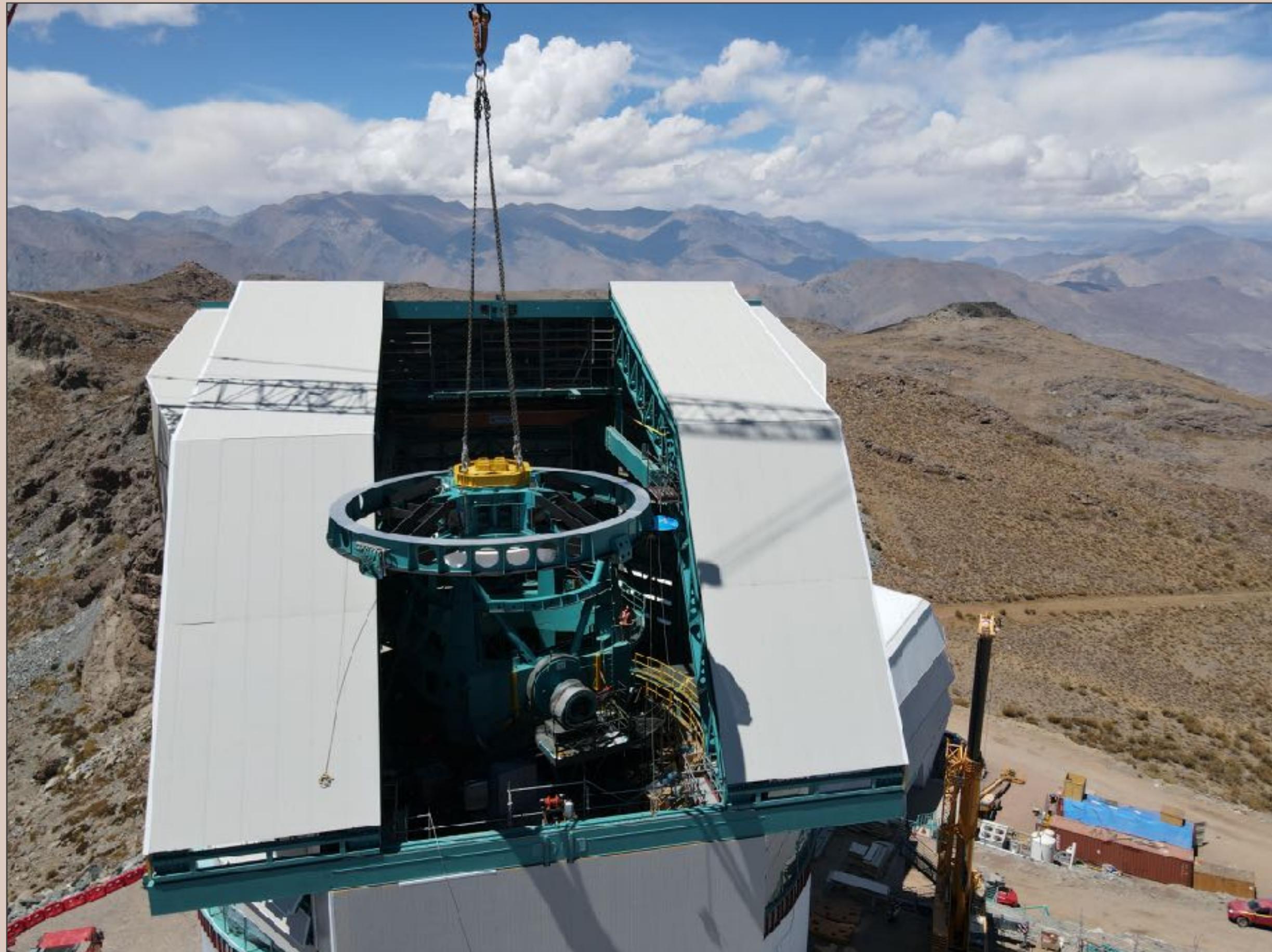
ROBUSTNESS OF CONSTRAINTS TO SUBGRID PHYSICS

SYSTEMATIC UNCERTAINTIES FROM TESTING ON SIMBA



Bias on recovered values not significant relative to error bars

RUBIN/LSST



Cerro Pachón, March 2nd 2021



10 year optical survey of 20'000 sq. deg.
First data expected in 2023
Deep, will image $\sim 10^9$ s of galaxies
Main observables: weak lensing & clustering

MOVING BEYOND TRADITIONAL METHODS

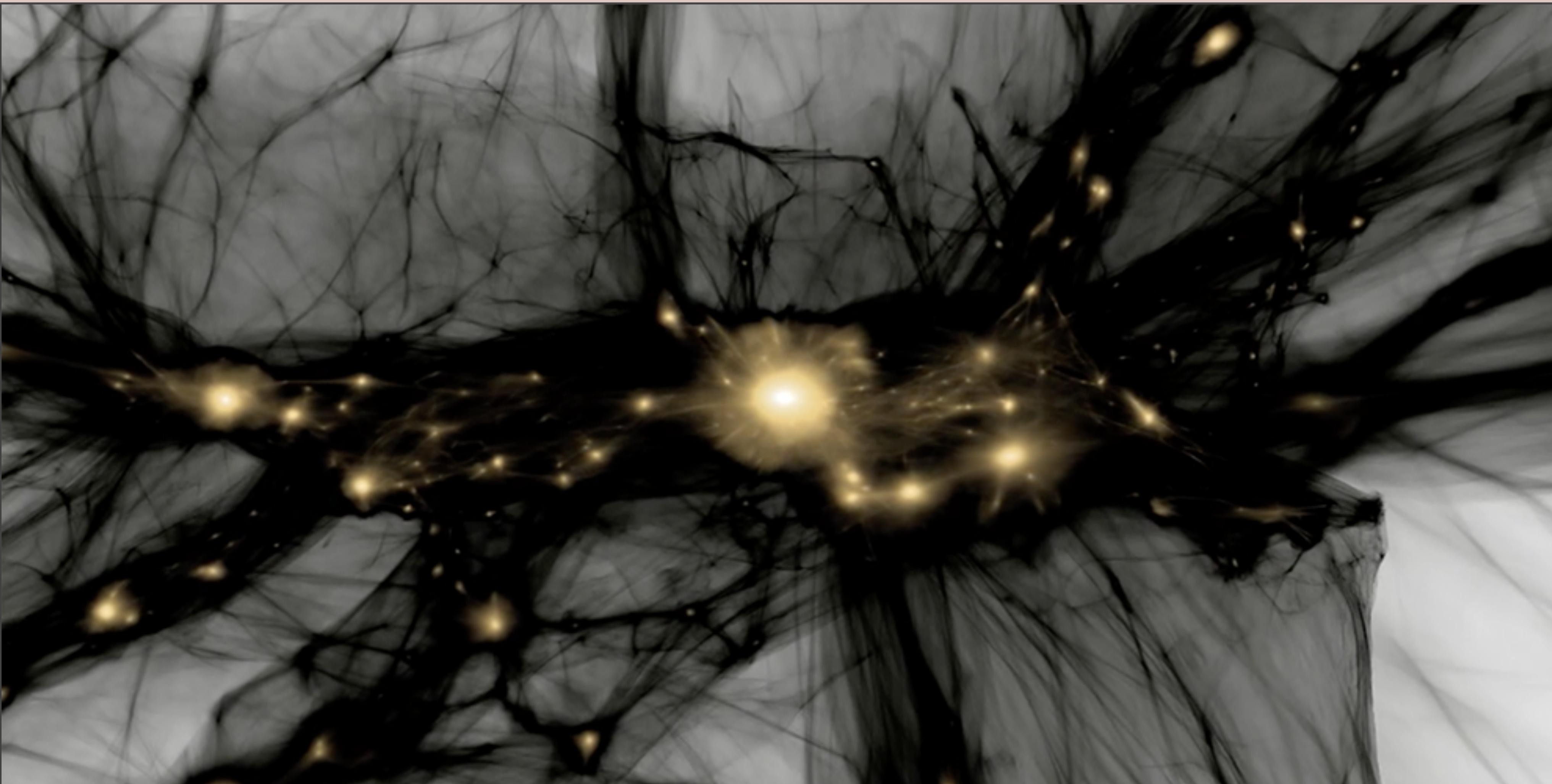
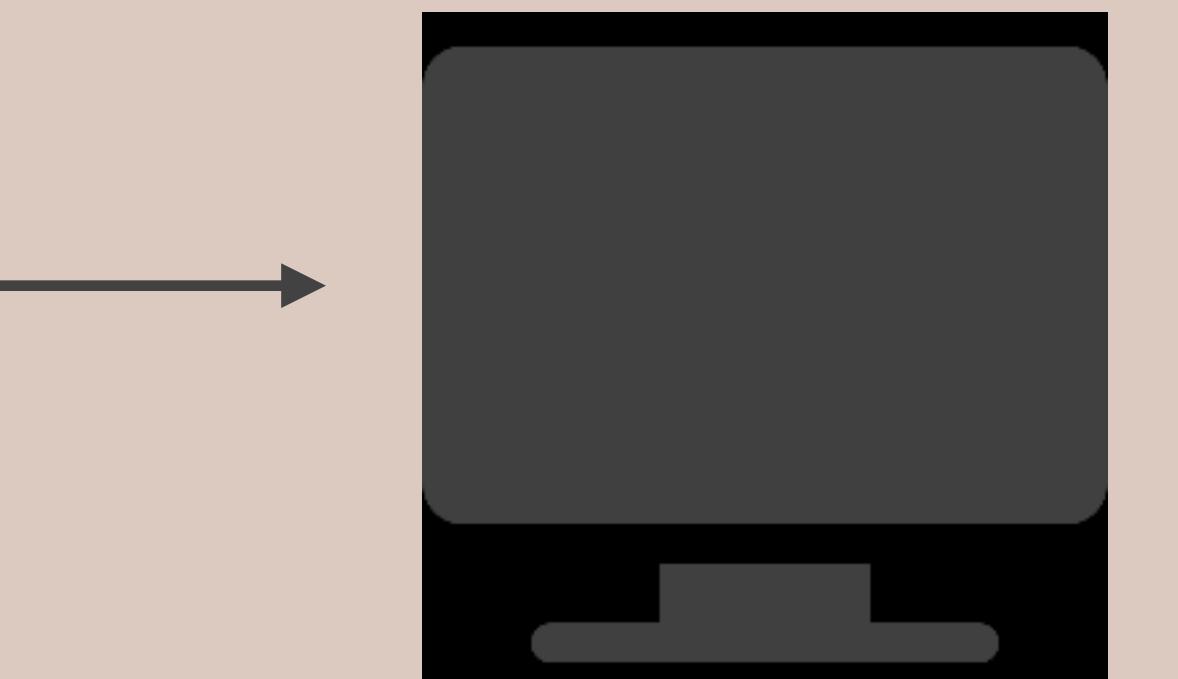


Image: S. Skillman, Y-Y. Mao, KIPAC/SLAC National Accelerator Laboratory

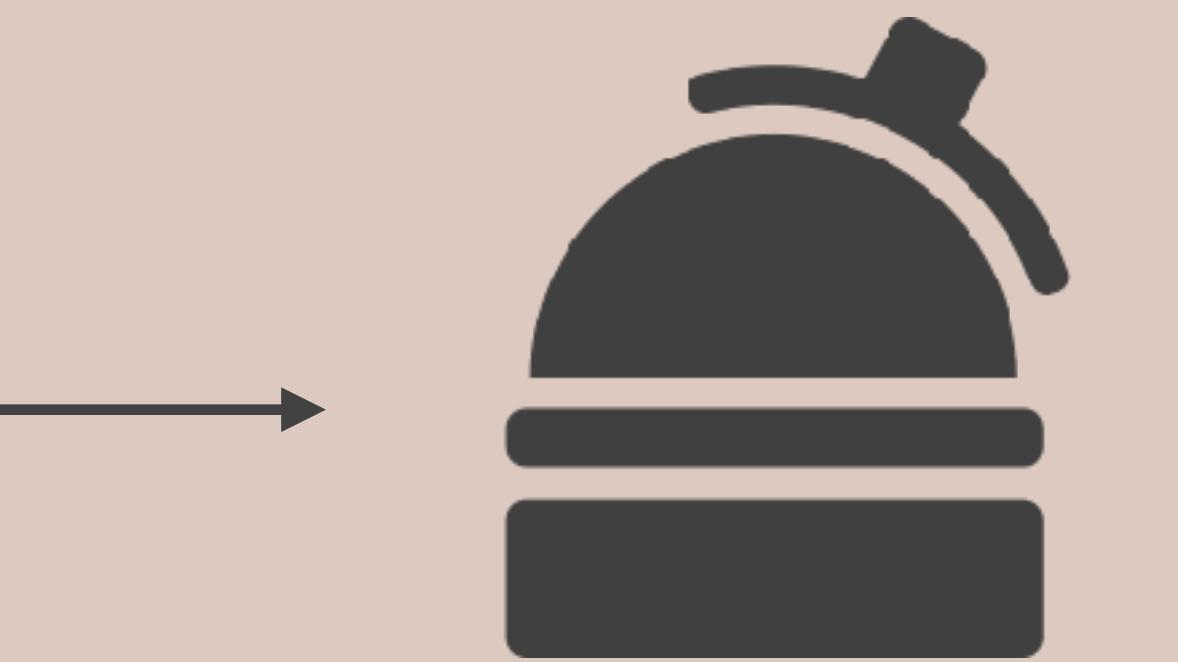
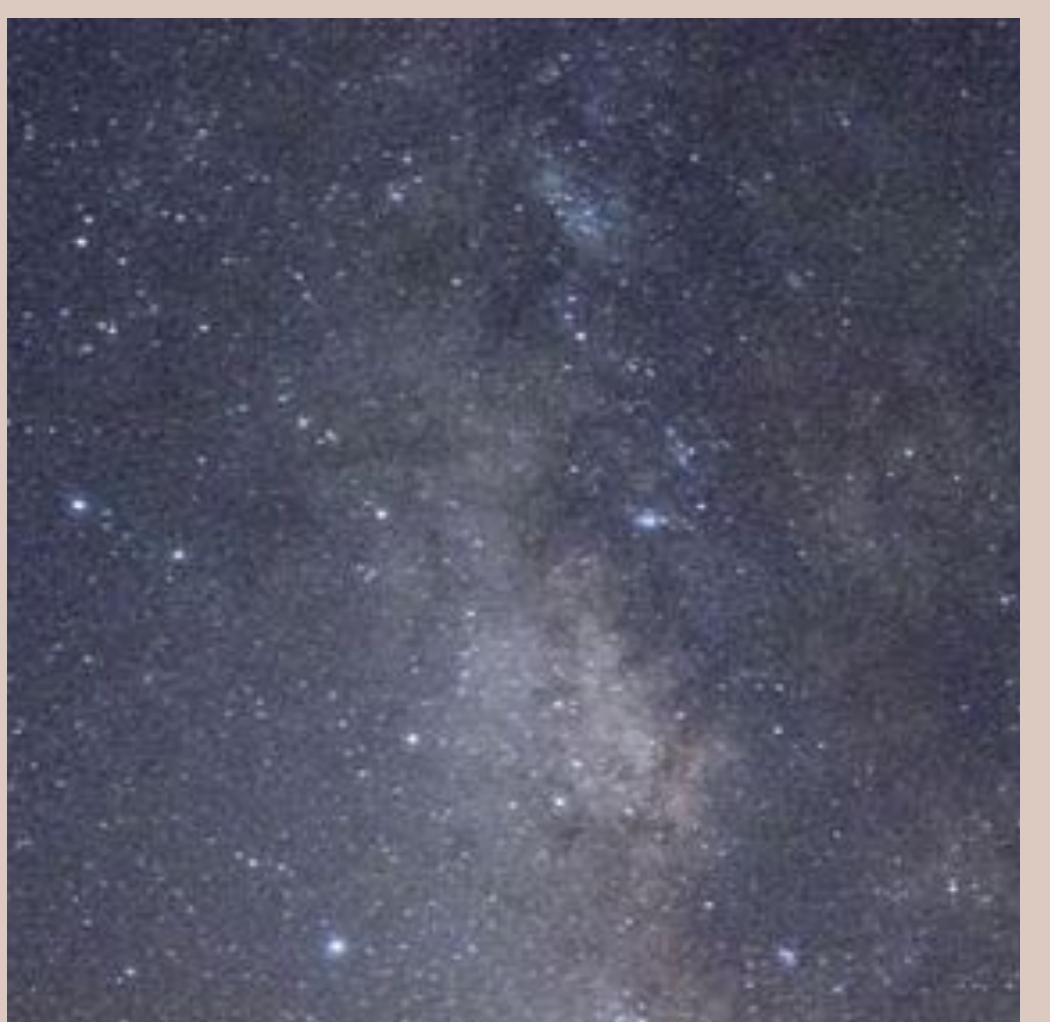
SIMULATION-BASED INFERENCE

0	-0.688112459158571250	-0.59574424463865	-0.46563891459485534
1	-0.1647915212045744	-0.1875765563666334	-0.25435596167105957
2	-0.13550491502776187	-0.17024431361355550	-0.033718467049267418
3	-0.816266875142649410	-0.922174214327891622	-1.87666870829129855
4	-0.3868686100686394	-0.85071589169523001	-1.7443027595610986
5	-0.1725792152000000	-0.15311088617947550	-0.4274111516156979
6	-0.1872677921583782203	-0.15311088617947550	-0.4274111516156979
7	-0.86489182687638824	-0.883478856186071945	-0.8725482741631598
8	-0.8298828953256755	-0.932134645597369934	-3.62447624633897993
9	-0.173432808744484585	-0.181300324148692694	-1.885253221194155
10	-0.825293859314459665	-0.841114555897429544	-2.6461818784754593
11	-0.1619366757876493	-0.16134227762268392	-0.253280367606576844
12	-0.16261298174	-0.14717386430384390	-0.35257676999531107
13	-0.62619801950000014	-0.693466113176874665	-0.1518051525251905476
14	-0.7976578132076614	-0.170232377151536294	-0.176323877151536294
15	-0.808933026933241784	-0.871036808708857943	-0.877555682326618672
16	-0.89981699598883063	-0.819593975518332644	-0.83561724182928428
17	-0.888811638257818066	-0.89411593984756513	-0.116507363674148469
18	-0.8215587866978743	-0.820561162175622761	-0.833745253854859515
19	-1.136329593199381	-0.155836293125366685	-0.170003463828397325
20	-0.821426628285817623	-0.81981115025863316176	-0.930833867978891437
21	-0.8225088123939804825	-0.837214256042534744	-0.9355510206463791487
22	-0.607859180515765946	-0.69495619500433605	-0.11571426216130997
23	-0.14584510520291110	-0.13495850301547603	-0.1270773151050953321
24	-0.08111184566101107	-0.04246000001006064497	-0.05100610737559296905
25	-0.8020333721965510867	-0.830886315867099127	-0.856813245697868590
26	-0.87816672295769734	-0.829844825854456267	-0.841654546118267686
27	-0.85648482278265811	-0.8528937724385573	-0.83351538352387278
28	-0.866341338792565436	-0.8873587571652721565	-0.9328452594778832
29	-0.7555393843783754	-0.169242521058676826	-0.173315472887885716
30	-0.89560007722031675	-0.892356458040153527	-0.07626364698669134
31	-0.8229691381575176	-0.817257991592727031	-0.99911733033899501
32	-0.102844111752555666	-0.112633100156734647	-0.12161116647787216
33	-0.13654677215390703	-0.1309050301474003205	-0.09465113848839741
34	-0.099098425899853415	-0.088846570351648132	-0.03688137793660888
35	-0.6758986983858992	-0.891461598773204	-0.11568038444345442
36	-0.88252611655929177	-0.89932645925563673	-0.95285485622288046
37	-0.126692687247393	-0.11562851120654866	-0.18410964976369179
38	-0.16418323588288582	-0.113833958212555781	-0.14241766527947225
39	-0.12293242221485195	-0.16041485715453923	-0.07407176217518037
40	-0.9230419560229621603	-0.9377436971943324	-0.95184125670872035
41	-0.10675537637176175	-0.0502966101146427854	-0.051840515006559812736
42	-0.1604487823312016	-0.15843281131804204	-0.1477313770585822
43	-0.8556688293675436	-0.821898742143738554	-0.936611657367828685
44	-0.227391638498667915	-0.824415241416884743	-0.93735105576569619
45	-0.7352533986519388	-0.18995937184455894	-0.15483073661778195



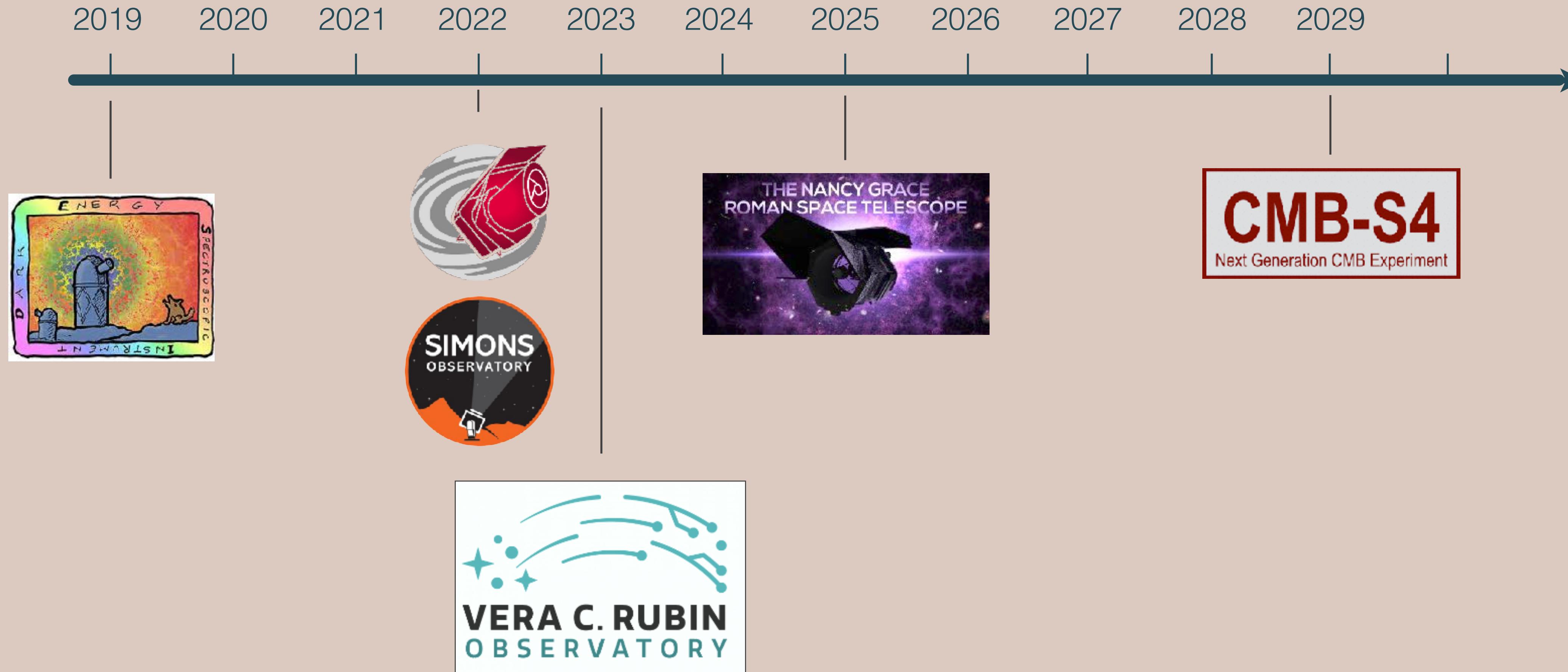
Akhmetzhanova et al., in prep.

$$p(D_* \mid \theta)$$



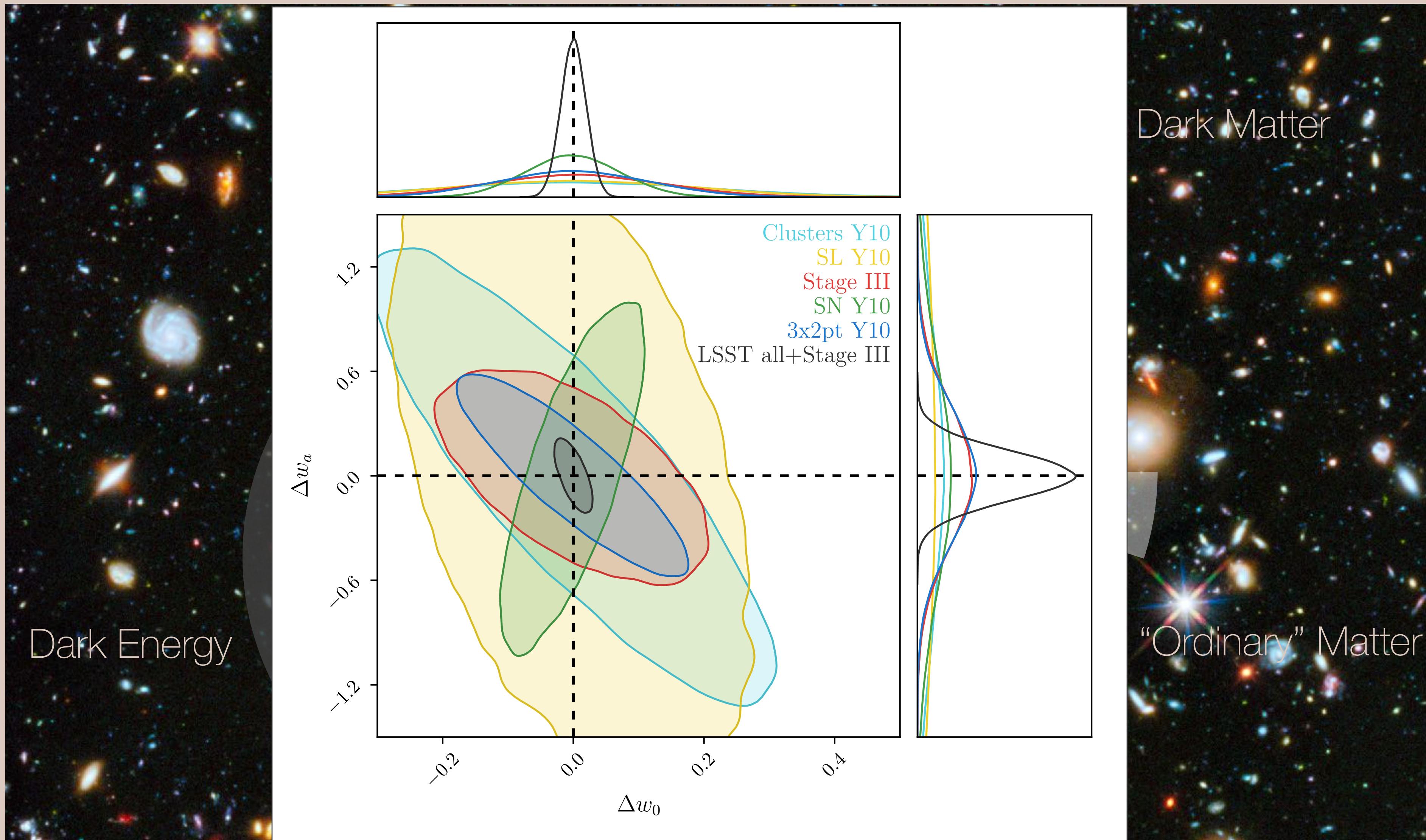
Alsing et al., 2019, Tejero-Cantero et al., 2020

THE COSMOLOGICAL DATA REVOLUTION



Images: DESI, Euclid, SO, Rubin/LSST, Roman, CMB S4

TESTING PILLARS OF Λ CDM WITH FUTURE SURVEYS



LSST DESC SRD, 2018

SUMMARY

Combined probe analyses essential to constrain cosmology

- Break parameter degeneracies

- Robust test of cosmological model

- Identification, understanding and calibration of systematics

Future surveys will deliver high-precision data

- Significant information in small-scales, non-Gaussian features

- Limited by systematics

Two approaches

- Extend traditional analysis methods

- Develop novel analysis methods based on joint forward-modeling and simulation-based inference

Thank you!