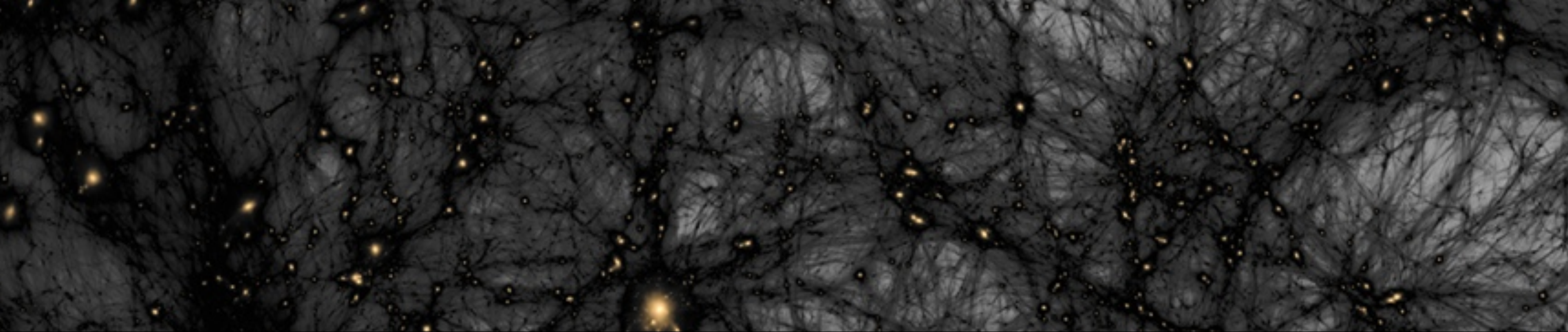


Combined probes of dark energy

Alkistis Pourtsidou

University of Edinburgh

UK Research and Innovation

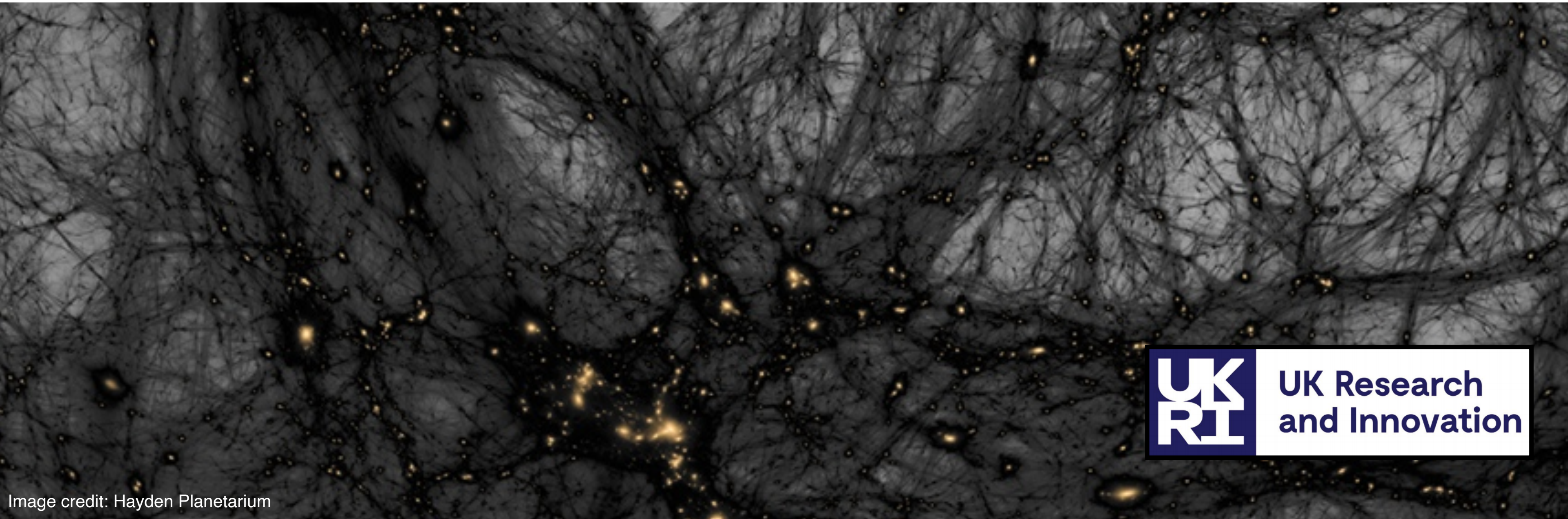
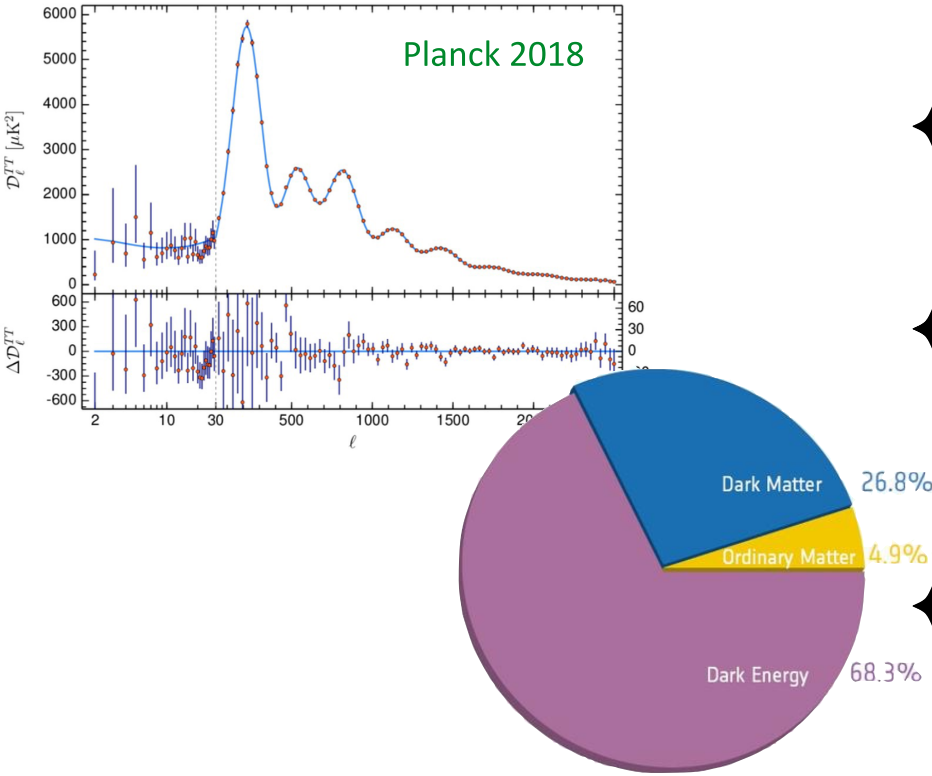
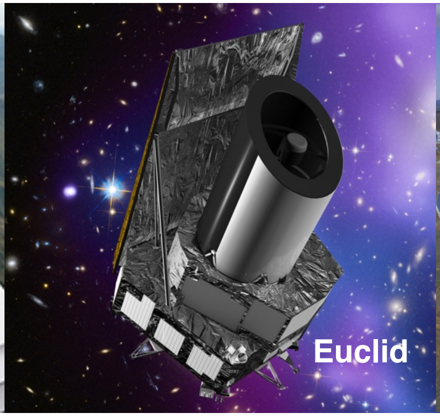


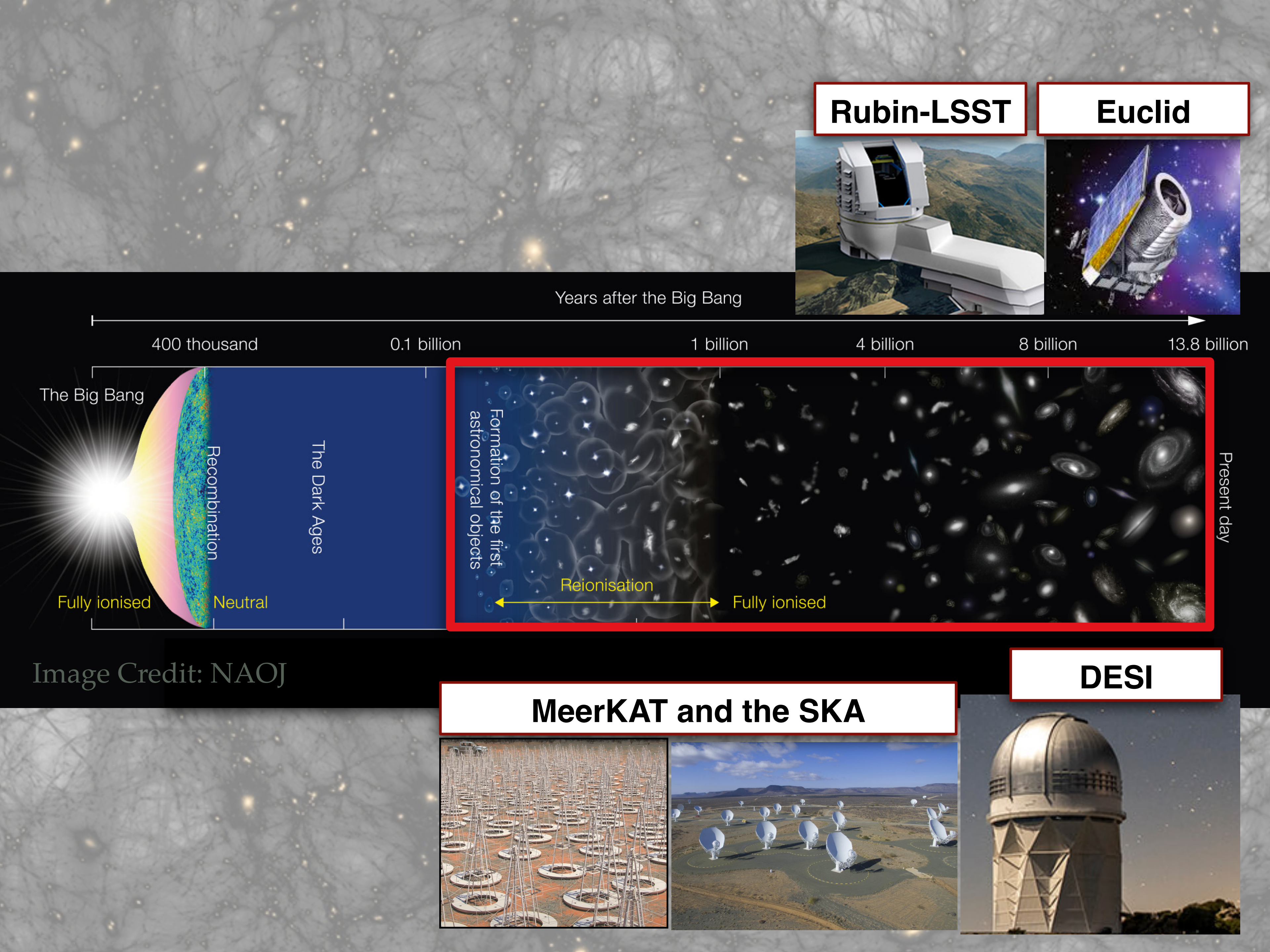
Image credit: Hayden Planetarium

New Frontiers in Observational Cosmology



- 95% of our Universe is dark matter and dark energy
- Use large sky surveys, multiple wavelengths, and multiple probes
- Large scale structure surveys: **DESI, Euclid, Rubin-LSST, SKA**





Rubin-LSST
Euclid
Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Ages
Formation of the first astronomical objects
Reionisation
Fully ionised
Neutral
Fully ionised
Present day
Image Credit: NAOJ
MeerKAT and the SKA
DESI

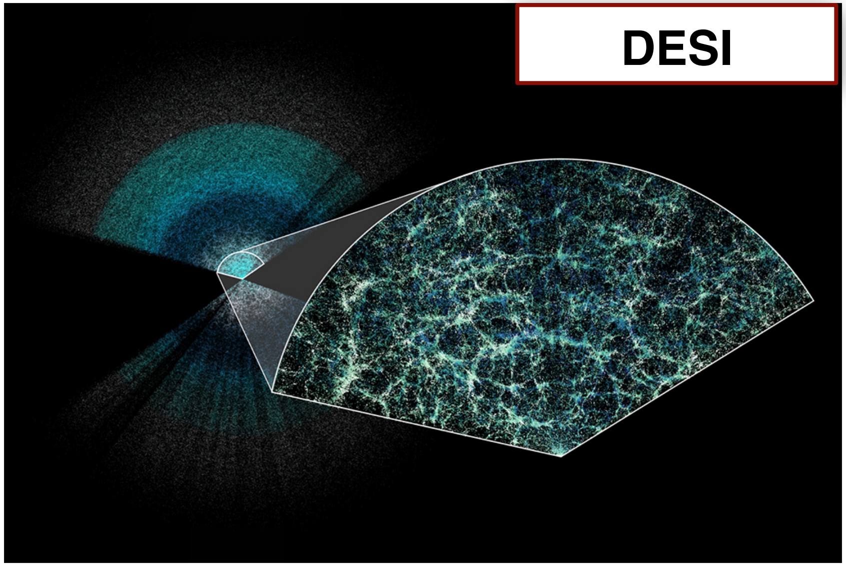
LSS summary statistics

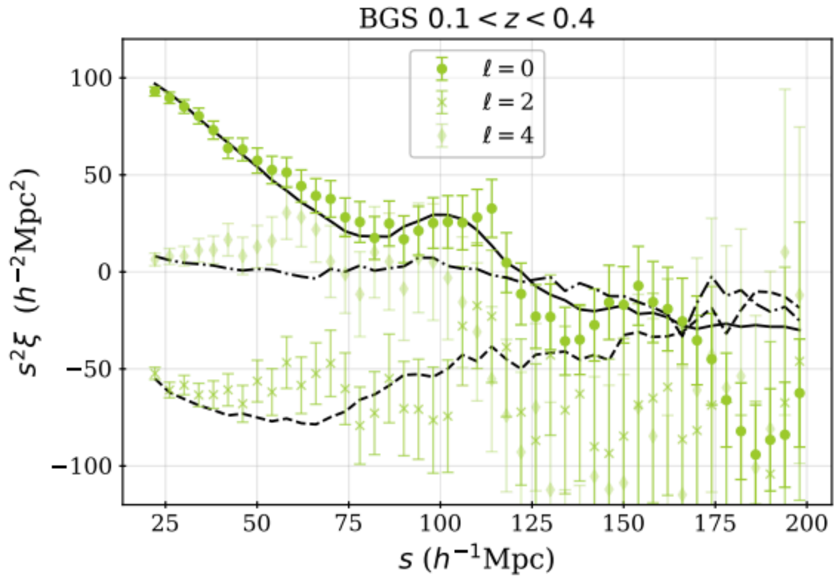
The correlation function is simply the real-space 2-pt statistic of the field

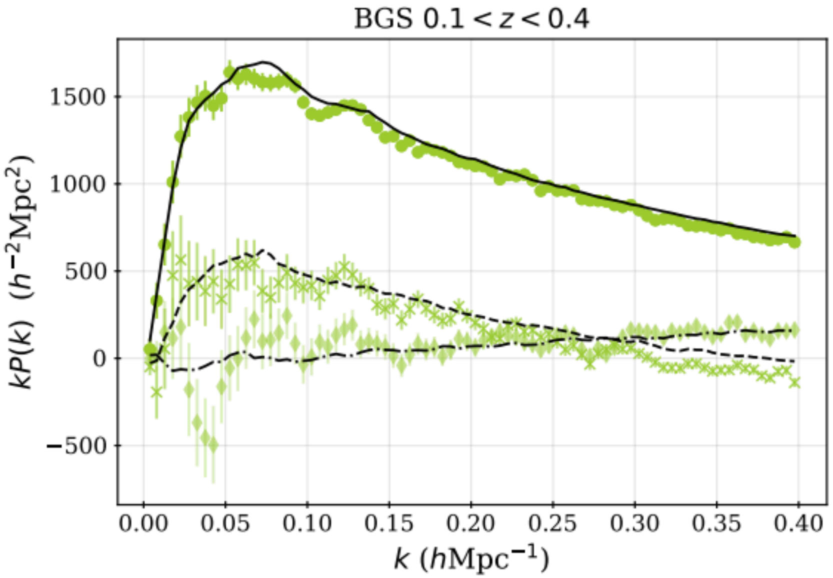
$$\xi(r) = \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r})\rangle$$

Its Fourier analogue, the power spectrum is defined by

$$P(k) = \langle \delta(\mathbf{k})\delta(\mathbf{k})\rangle$$



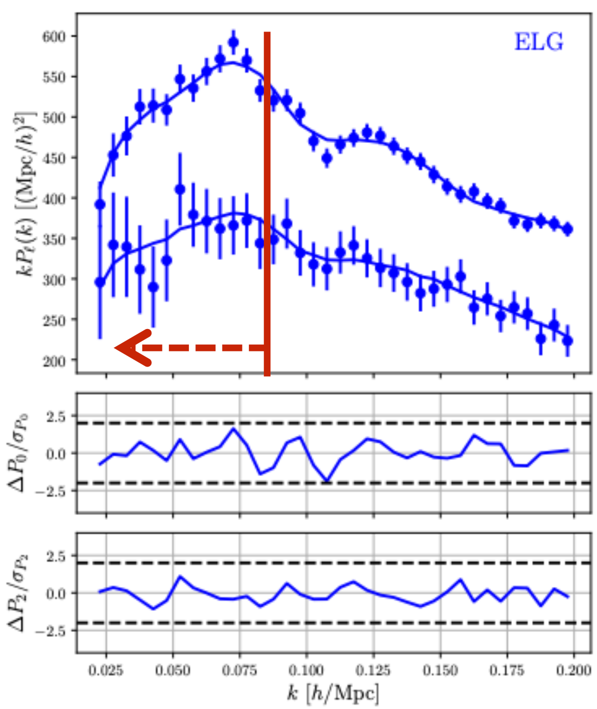




DESI 2024 VI: 2404.03002

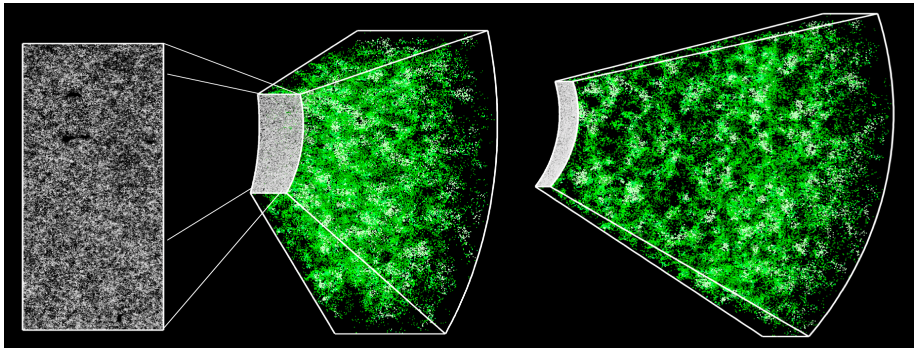
State-of-the-art optical galaxy surveys

Galaxies trace the underlying dark matter distribution – statistical sampling, more volume and more galaxies, better precision on both large and small scales!



DESI 2024 V

- **Spectroscopic:** Very precise redshifts [BOSS/DESI/Euclid]

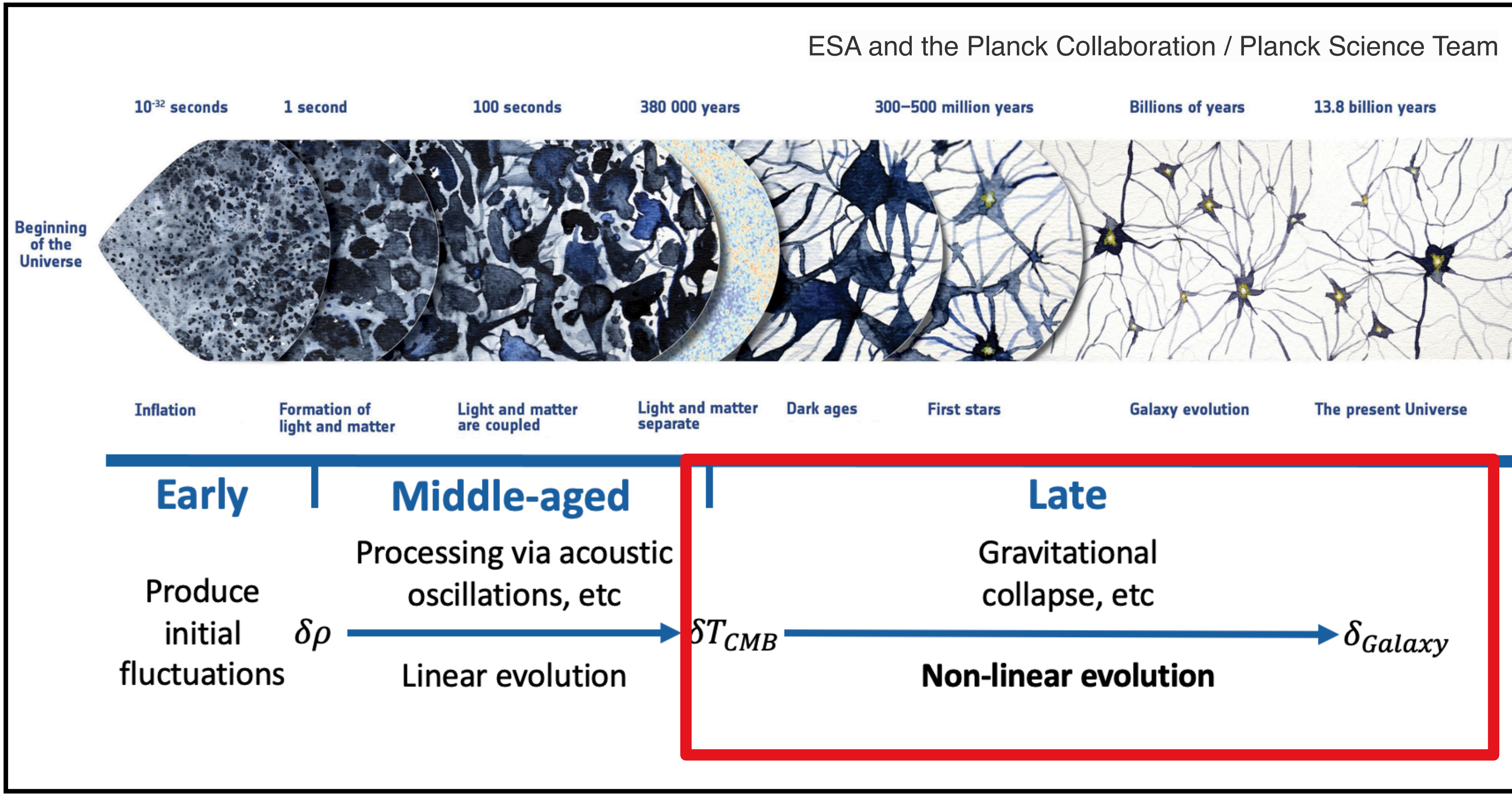


BOSS

LSST

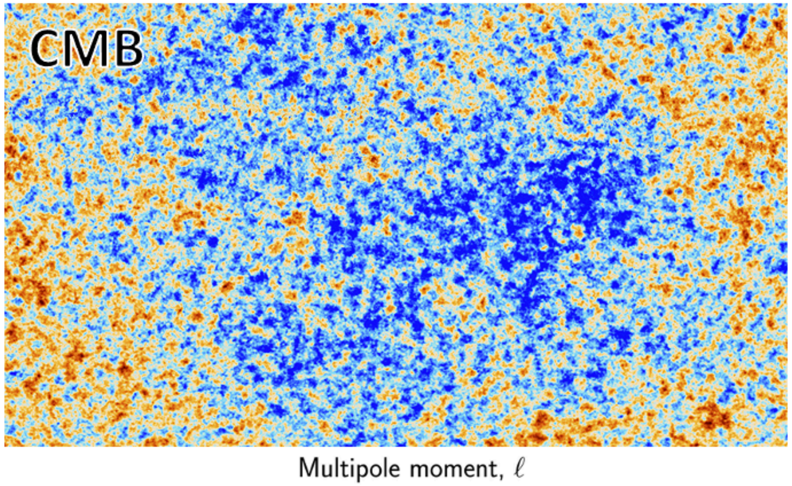
- **Photometric:** Large sky, many galaxies, uncertain redshifts [KiDS/DES/Rubin-LSST]

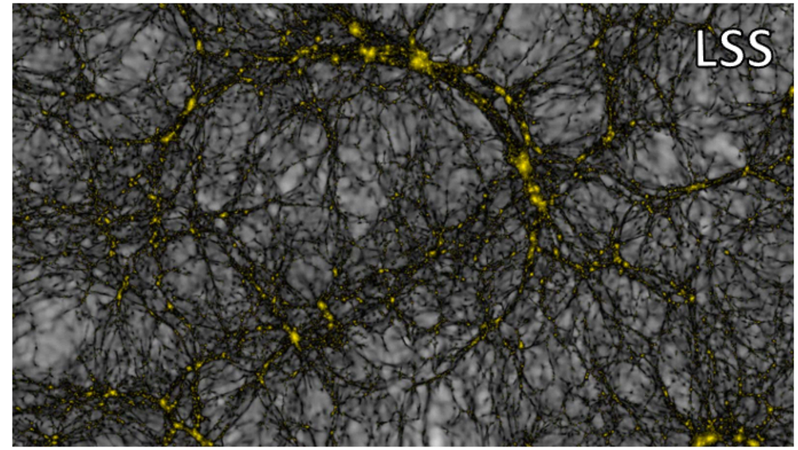
The history of the Universe

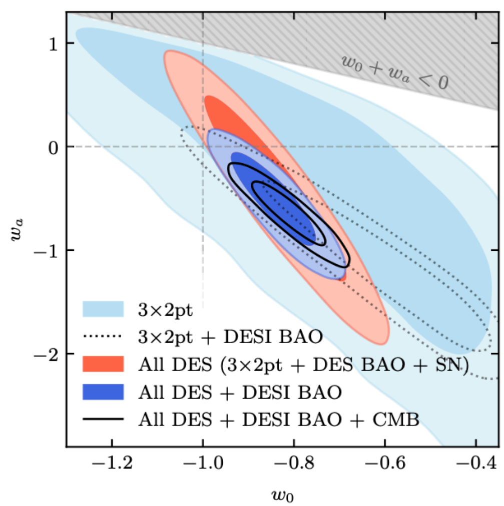


Late time physics dominated by small scale (nonlinear) effects!

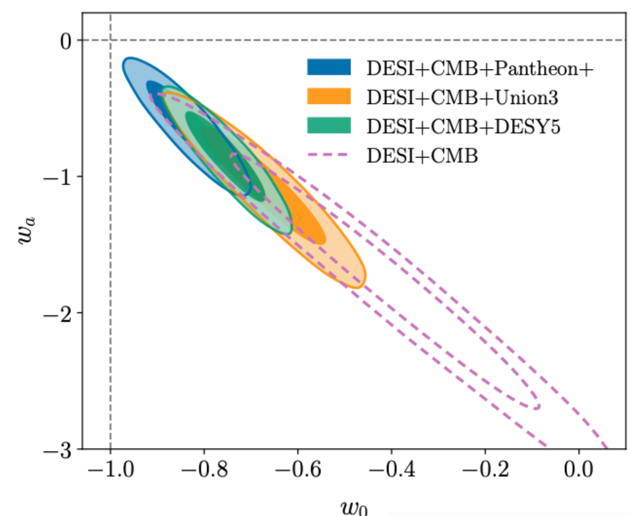
Combined cosmological probes







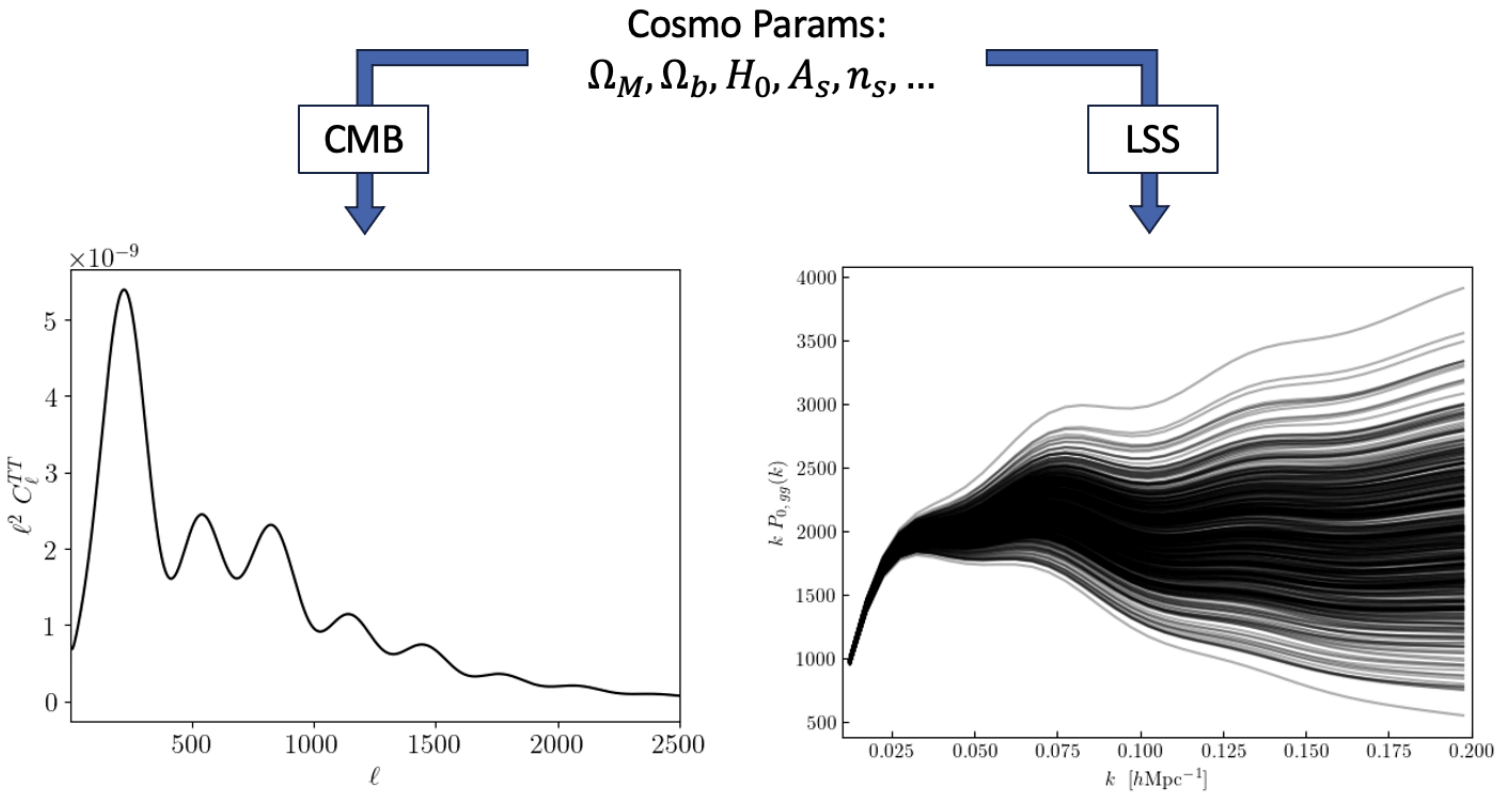
DES collaboration



DESI collaboration

LCDM fits the data well, but there are some “troubles”: e.g. the Hubble and S_8 tensions, and of course the DESI results for evolving dark energy!

Working with nonlinear scales is challenging!



LSS predictions depend strongly on unknown nuisance parameters

The importance of nonlinear modelling for LSS surveys

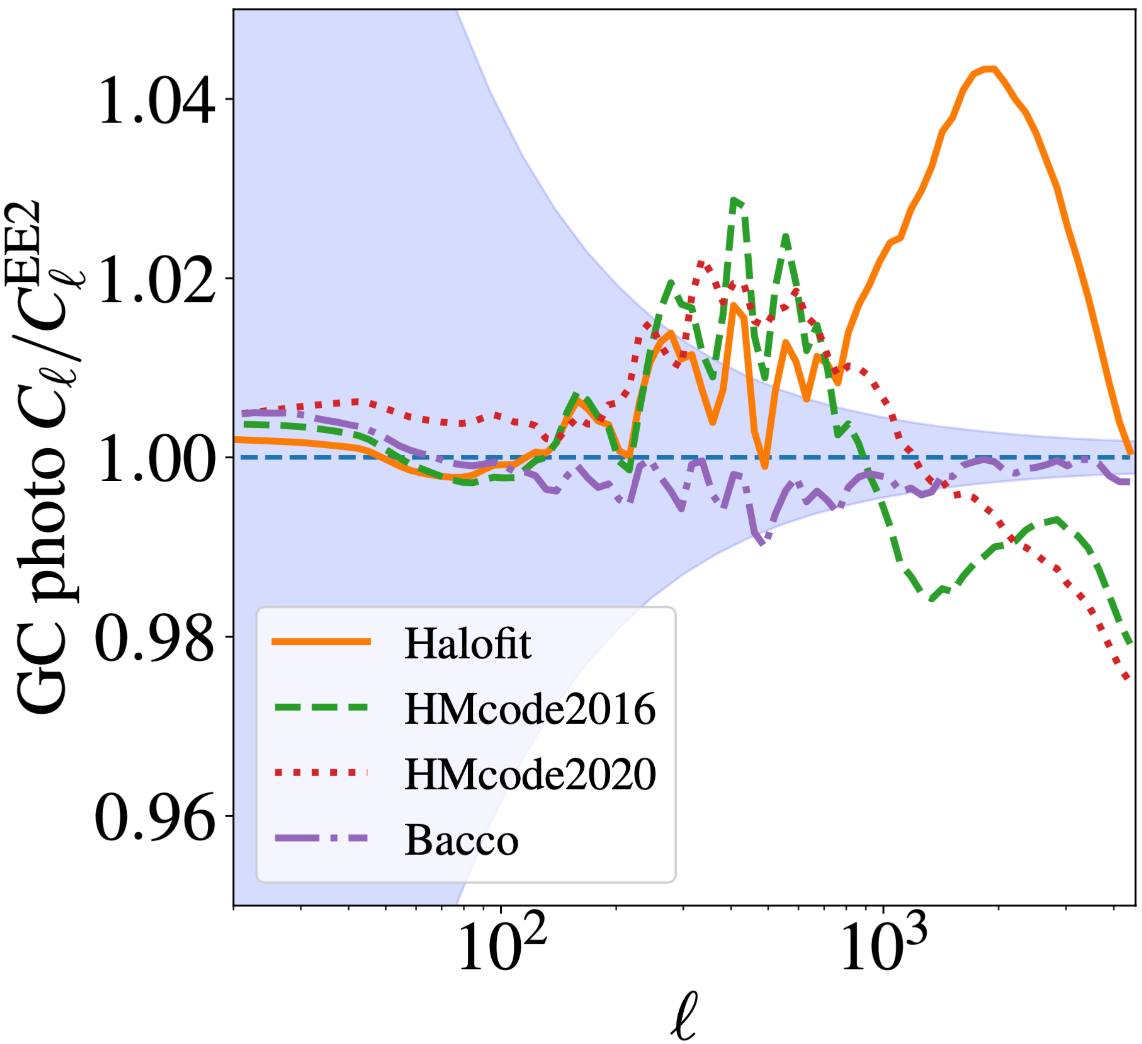
Main LSS Probes: Spectroscopic and photometric galaxy clustering (GC), weak lensing (WL), and their joint analysis

Example: w0wa forecasts for Euclid

w_0, w_a FoM		Flat	Non-flat
Linear setting			
GC_s		40	19
Pessimistic setting			
GC_s		14	10
WL		23	5
GC_s+WL		99	40
GC_{ph}+WL		64	14
GC_s+WL+GC_{ph}		123	49
WL+GC_{ph}+$XC^{(GC_{ph},WL)}$		367	59
GC_s+WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	**Combined probes very powerful**	377	128
Optimistic setting			
GC_s		55	19
WL		44	12
GC_s+WL		157	87
GC_{ph}+WL		235	129
GC_s+WL+GC_{ph}		398	218
WL+GC_{ph}+$XC^{(GC_{ph},WL)}$		1033	326
GC_s+WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	**Nonlinear scales —> high S/N**	1257	500

***Euclid* preparation: VII. Forecast validation for *Euclid* cosmological probes**

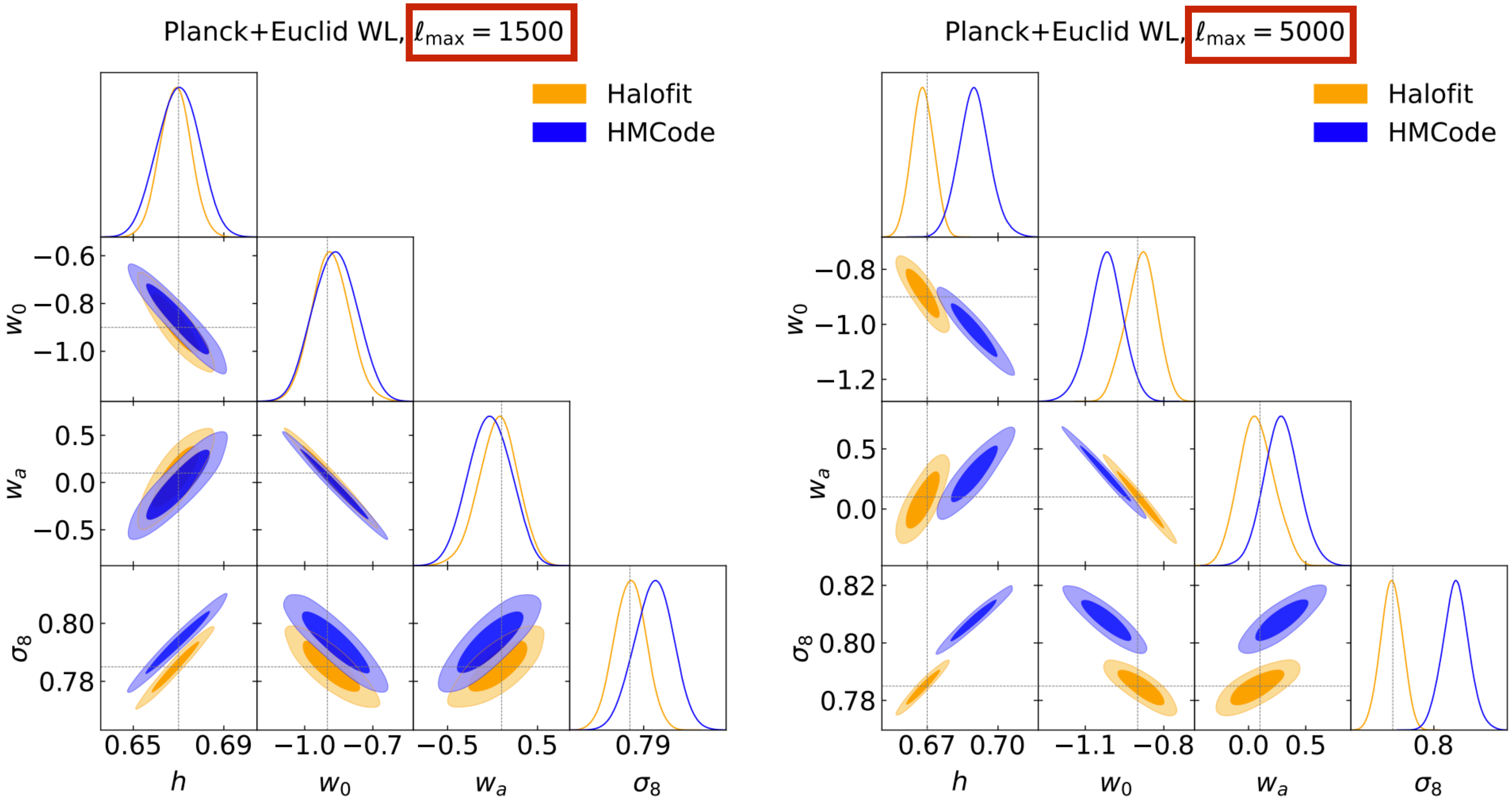
Shrinking error bars: precision vs accuracy crucial



Plot by Pedro Carrilho, Euclid Overview paper

Weak Lensing example — precision vs accuracy

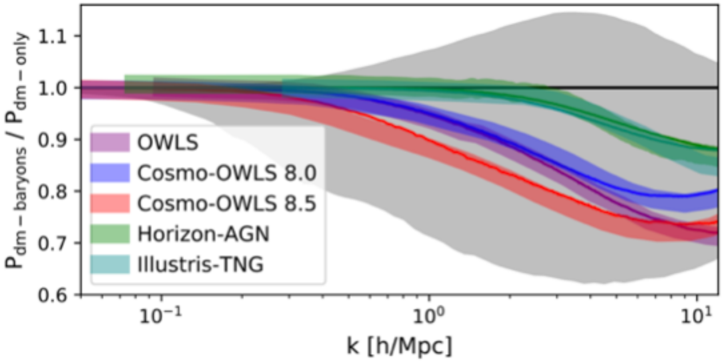
No place for theoretical systematics to hide!

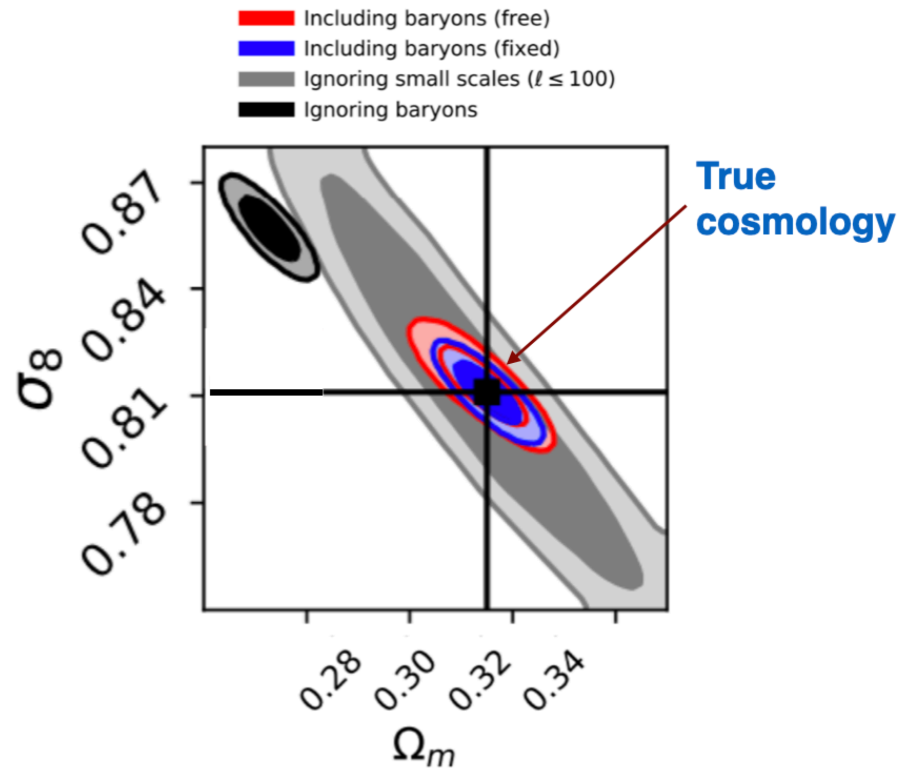


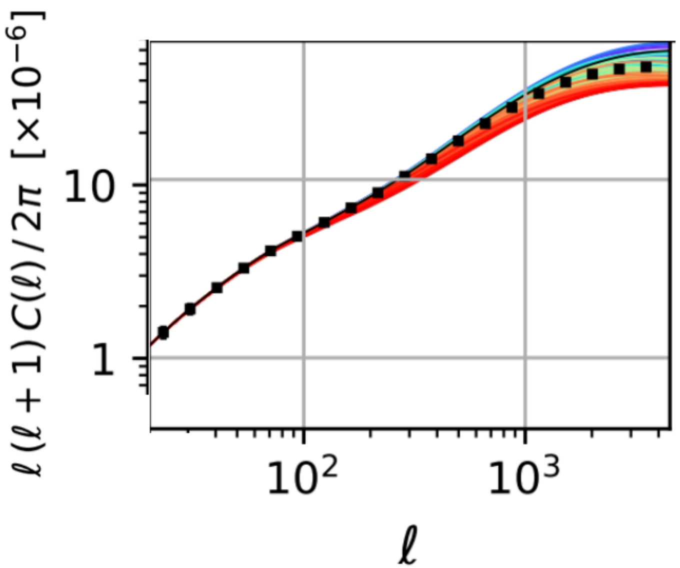
Euclid: impact of nonlinear prescriptions on cosmological parameter estimation from weak lensing cosmic shear*

* M. Martinelli et al. 2021

Baryonic feedback uncertainties … “linear” scales affected too!







Forecasts by A. Schneider et al (2020)

*** can also affect S_8 tension (see e.g. Amon & Efstathiou 2022)**

Methods and tools for Stage-IV analyses

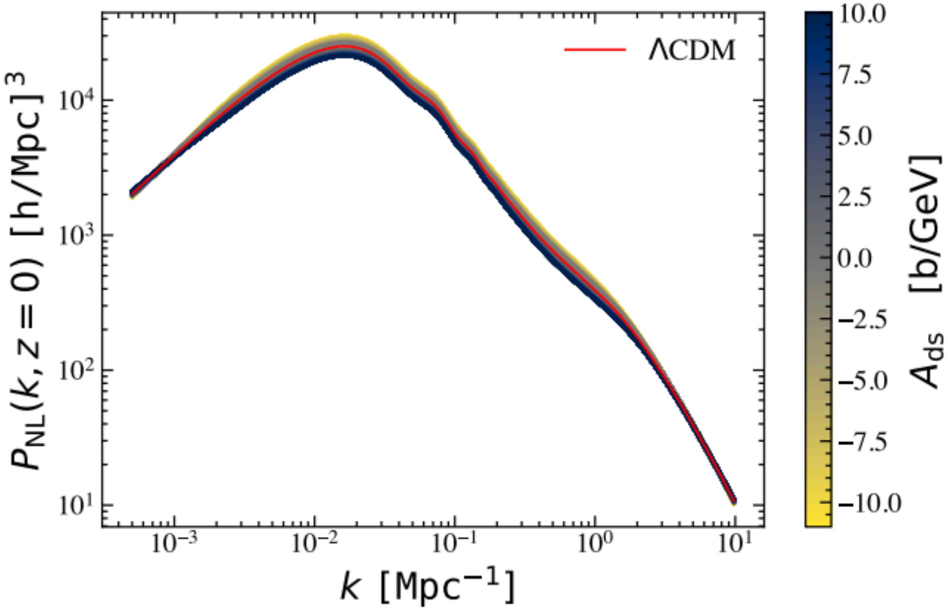
- Perturbation theory [e.g. EFTofLSS, Ivanov et al (and many more)].
- State-of-the-art matter and galaxy power spectrum emulators built on N-body simulations [e.g. bacco, Euclid Emulator 2] Angulo et al., Knabenhams et al.
- **Limitations of emulators:** restricted prior ranges / model space
- State-of-the-art baryonic emulators [e.g. bacco, BCEmu] Angulo et al., Schneider and Giri
- **A few open questions:** How many varying baryonic parameters are optimal? Can we figure out the z-dependence? Intrinsic alignments have similar issues …
- **What about beyond LCDM/wCDM?**
  - possibilities include N-body sims, approximate sims, halo model reaction / ReACT [Cataneo et al., Bose et al.]
  - and baryons added on top à la LCDM (how good is this?)

Stress-testing with current data: a case study for Dark Scattering

- Dark Scattering is an interacting dark matter - dark energy model
- Feature: pure momentum exchange, interaction only affects the perturbations
- Nonlinear modelling with perturbation theory and ReACT: validated on simulations

$$\boxed{\theta_{\mathrm{DM}}' + (\mathcal{H} + \boldsymbol{A\,a\,\rho_{DE}})\theta_{\mathrm{DM}} + \nabla^2\phi = 0}$$

$$A \equiv (1+w)\frac{\sigma_D}{m_{\mathrm{DM}}}$$



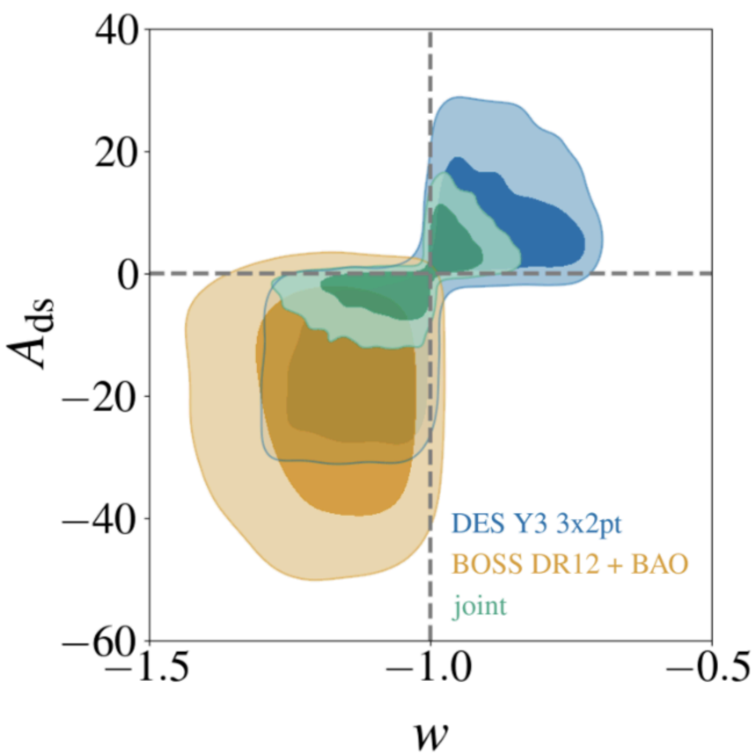
* Simpson et al, Pourtsidou et al, Baldi et al, Bose et al, Carrilho et al, Carrion et al

It's worth it! Joint probes analysis is very powerful

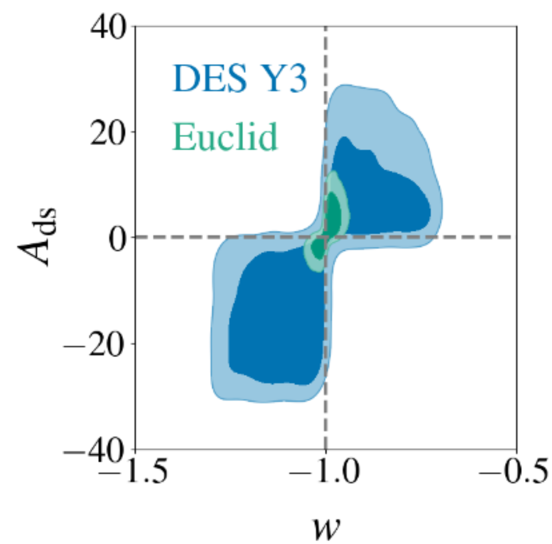
Interacting dark energy constraints from the full-shape analyses of BOSS DR12 and DES Year 3 measurements

M. Tsedrik[1,2,*], S. Lee[3], K. Markovic[3], P. Carrilho[1], A. Pourtsidou[1,2], C. Moretti[4,5,6], B. Bose[1,2], E. Huff[3], A. Robertson[7], P. L. Taylor[8,9,10], J. Zuntz[1]

Current data



The future



* see e.g. Giarè et al 2024, Pourtsidou 2025 for recent Planck + DESI constraints on IDE models

A NEW OBSERVATIONAL WINDOW: 21CM LINE

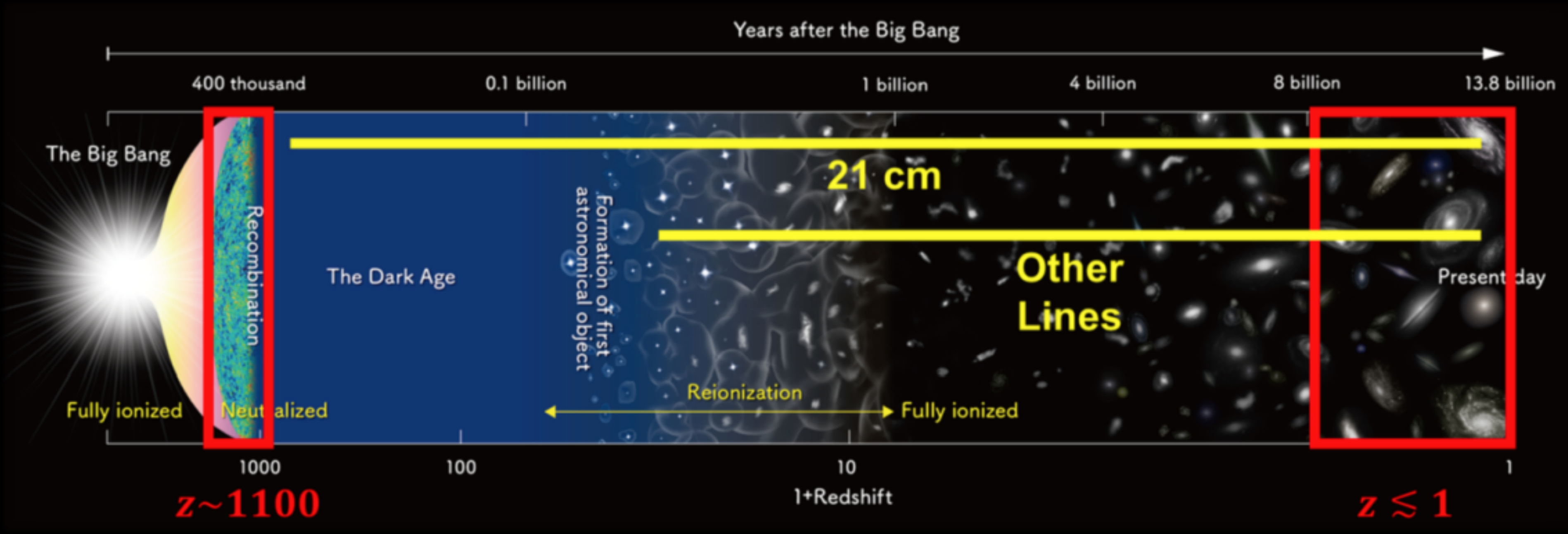
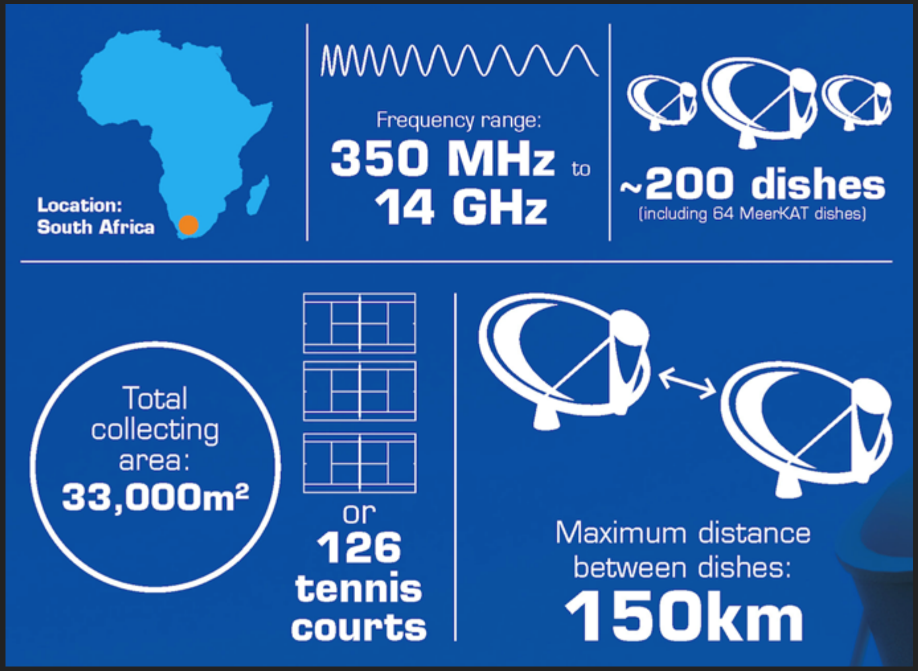


Image Credit: NAOJ [Kovetz et al. 2017]

SKA OBSERVATORY - UNDER CONSTRUCTION

SKA - MID (South Africa)



- Redshift range: $0 < z < 3$
- Late Universe, can complement optical surveys

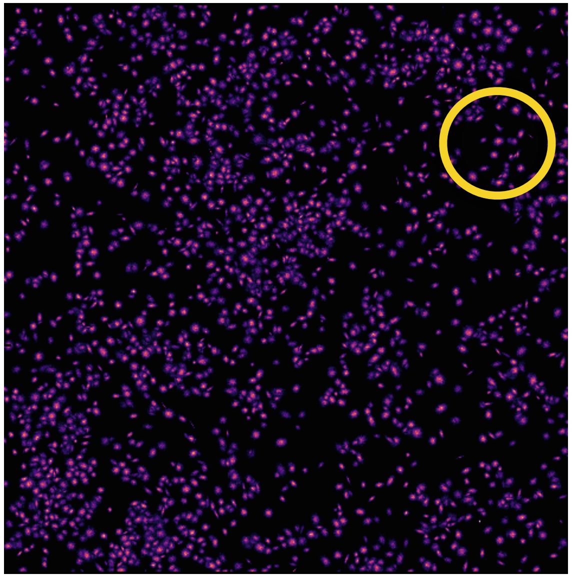
MEERKAT (SKA'S PATHFINDER) - OPERATIONAL !

- 64 dishes, will become part of SKA-MID
- $0.2 < z < 0.58$ (L-band)
- $0.4 < z < 1.45$ (UHF-band)

HI Intensity Mapping

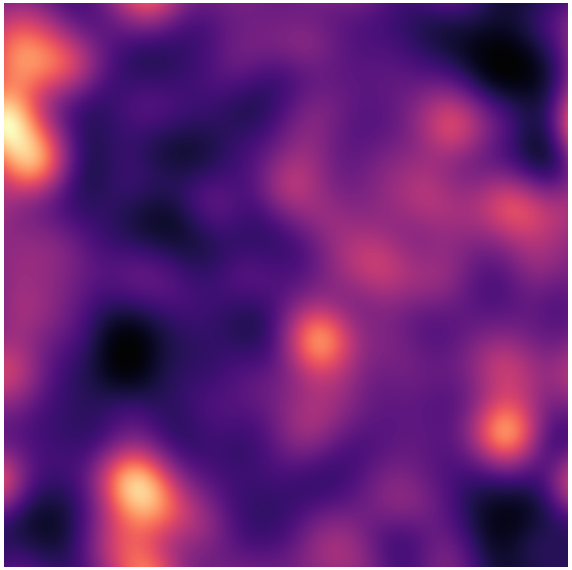
[Chang et al 2008, Peterson et al 2009, Seo et al 2010, …]

Galaxies



the telescope beam

Intensity map

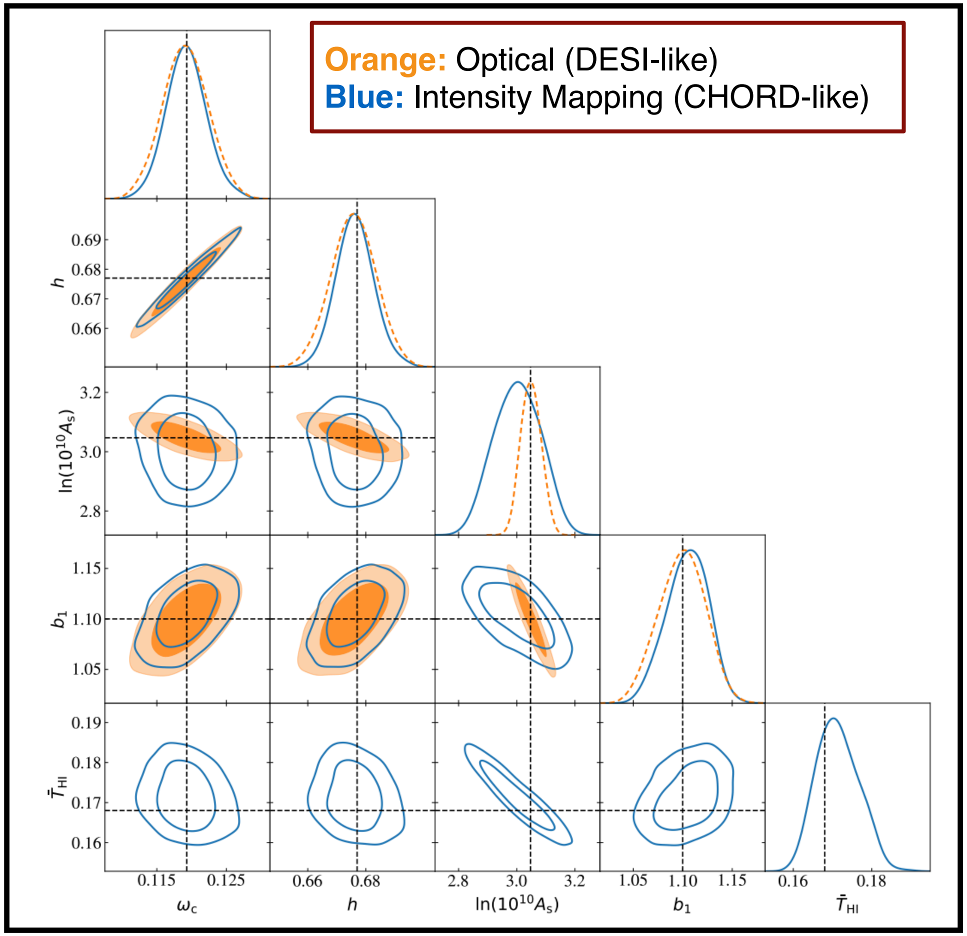


- Need redshifts: very expensive
- In radio: 21cm line – SKA1 not sensitive enough to be competitive

- Intensity mapping is very fast & uses all the photons
- High redshift resolution, low angular resolution

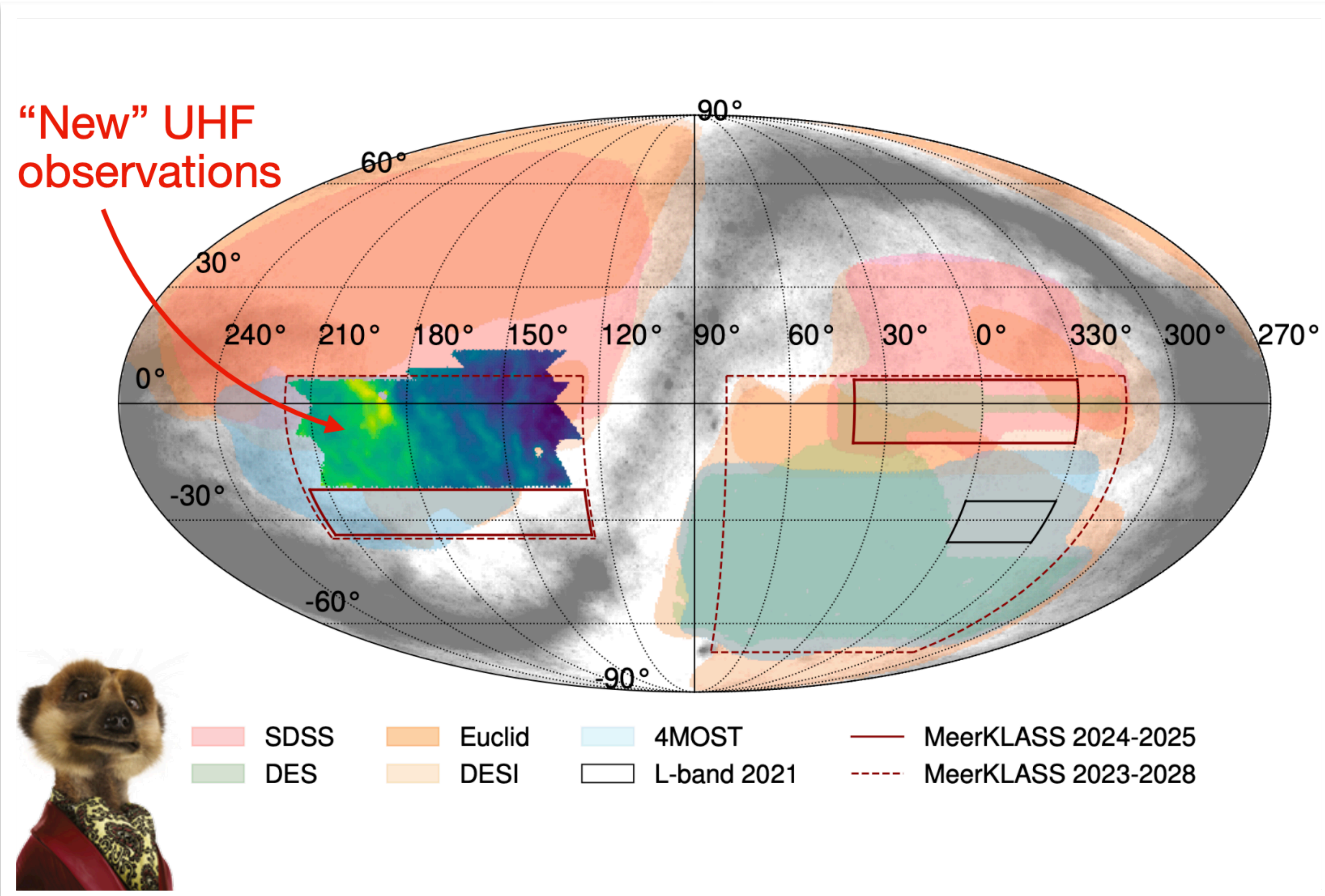
Opportunities for Radio Cosmology

- Can be **competitive with optical galaxy surveys, and can go to high redshift where optical are shot-noise limited**
- Major observational challenges (calibration, foregrounds …) should be addressed



Pourtsidou 2023

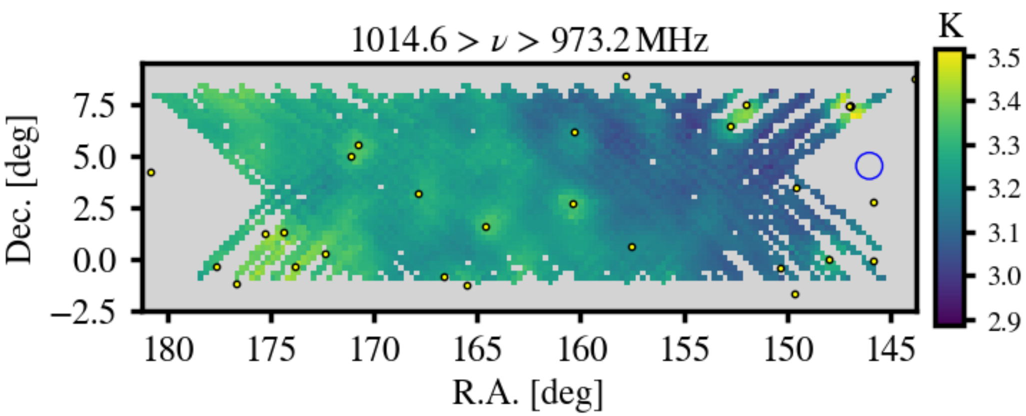
The MeerKLASS survey

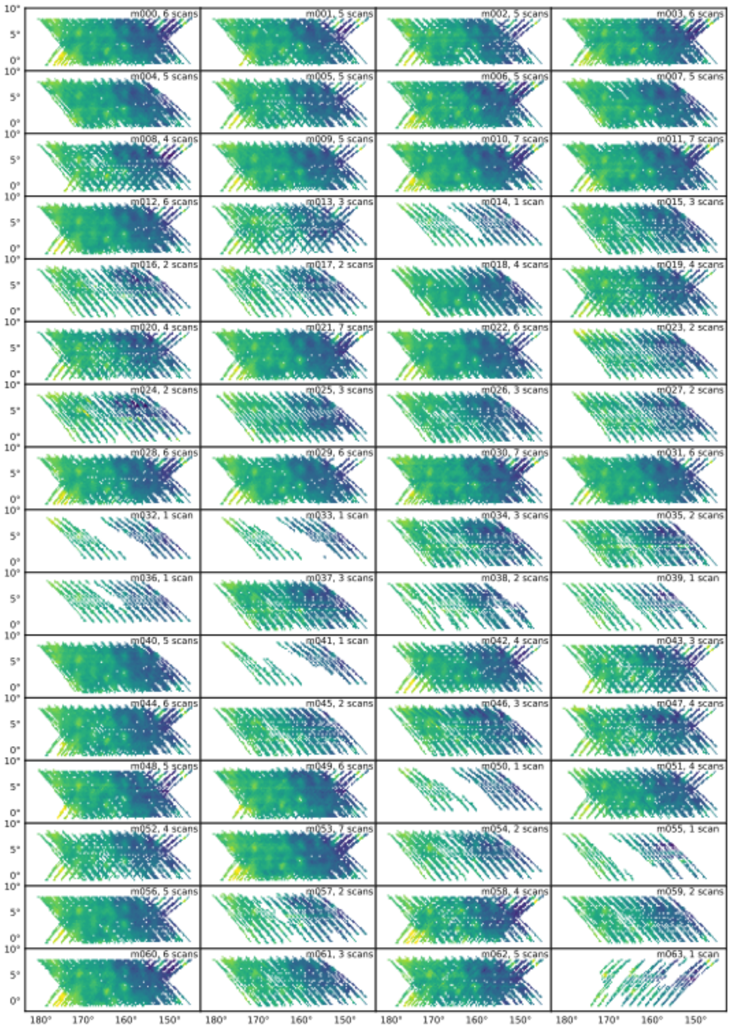


Meerkat data analysis

Pilot survey data:

- 10.5 hours of data from six nights of observations
- Overlapping with the WiggleZ11hr field (~200 deg^2)
- We use data in range 973-1015 MHz ($0.40 < z < 0.46$)



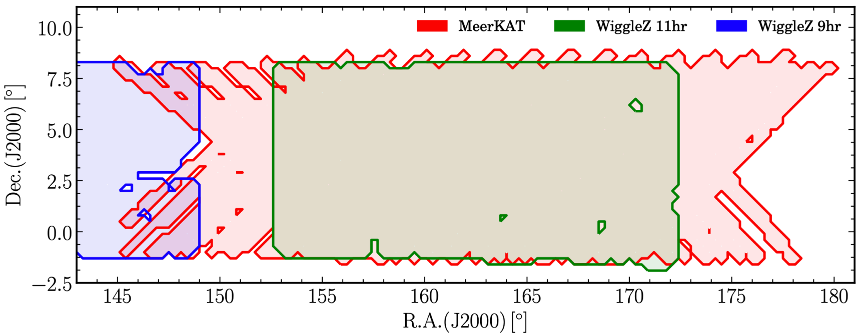


- Loss of data due to RFI
- Foreground removal
- Unknown systematics

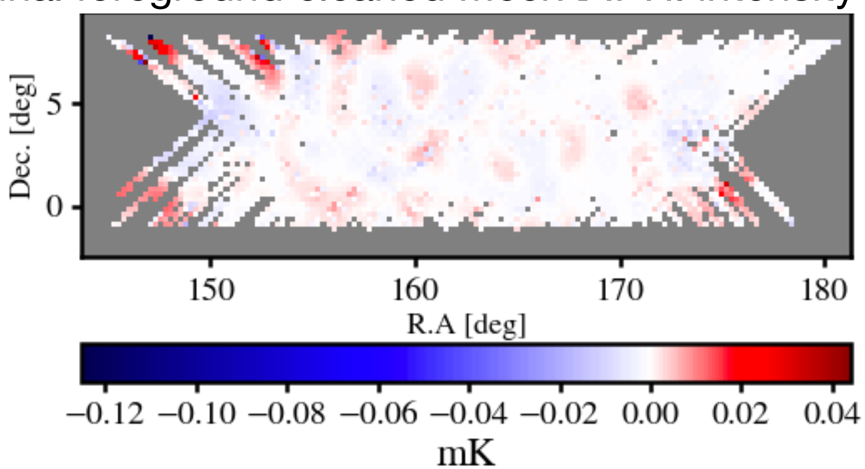
J.Wang et al. 2021 [arXiv:2011.13789]

Cross-correlations with optical surveys

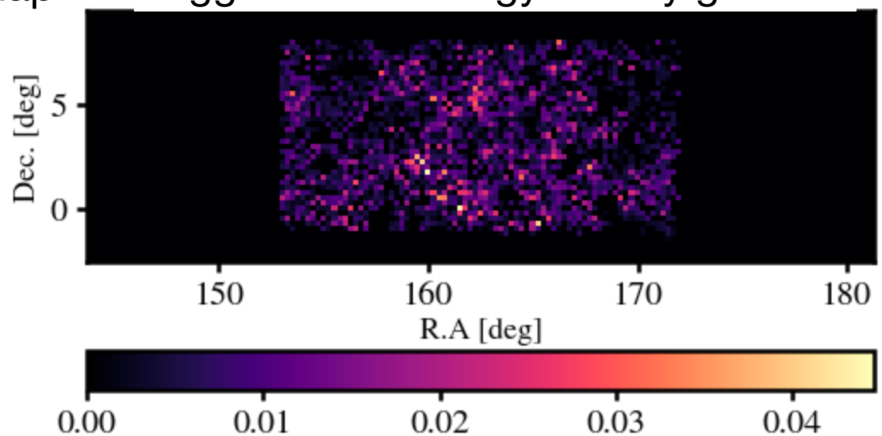
MeerKAT pilot observations conducted in WiggleZ 11hr field



Final foreground cleaned MeerKAT HI intensity map

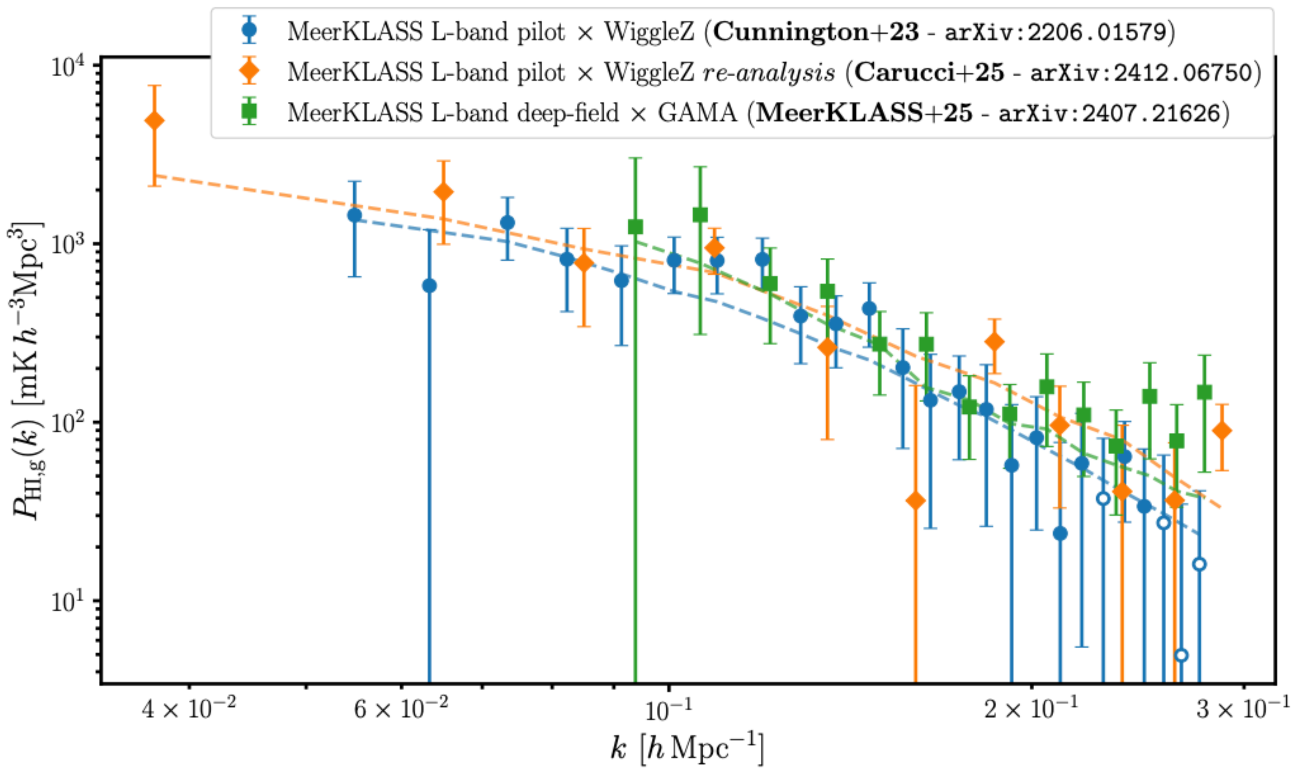


WiggleZ Dark Energy Survey galaxies



Cunnington,Li+22 [arXiv:2206.01579]

Cross-correlation detections so far



MeerKLASS L-band deep-field intensity maps: entering the HI dominated regime

MeerKLASS Collaboration*: Matilde Barberi-Squarotti[1,2,3,4], José L. Bernal[5], Philip Bull[6,7], Stefano Camera[1,8,9,7], Isabella P. Carucci[10,11], Zhaoting Chen[12], Steven Cunnington[6]†, Brandon N. Engelbrecht[7], José Fonseca[7,13,14], Keith Grainge[6], Melis O. Irfan[15,7], Yichao Li[16,7], Aishrila Mazumder[6], Sourabh Paul[6], Alkistis Pourtsidou[12,17,7], Mario G. Santos[7,18], Marta Spinelli[19,7], Jingying Wang[20,7]‡, Amadeus Witzemann[7,6], Laura Wolz[6]

Single-dish HI Intensity Mapping with the SKAO: Precursor Progress with MeerKAT's Large Area Synoptic Survey (MeerKLASS)

Steven Cunnington,[1,2] Jingying Wang,[3,4] Mario G. Santos,[4,5] Matilde Barberi-Squarotti,[6,7,8,9] Philip Bull,[2,4] Stefano Camera,[9,10,11,4] Isabella P. Carucci,[12,13] Zhaoting Chen,[14] Brandon Engelbrecht,[4] José Fonseca,[4,15,16] Karin Fornazier,[4] Keith Grainge,[2] Wenkai Hu,[4] Melis O. Irfan,[17,4] Yichao Li,[18,4] Alkistis Pourtsidou,[14,4] Marta Spinelli,[19,4] Amadeus Witzemann[4,2] and Laura Wolz[2]

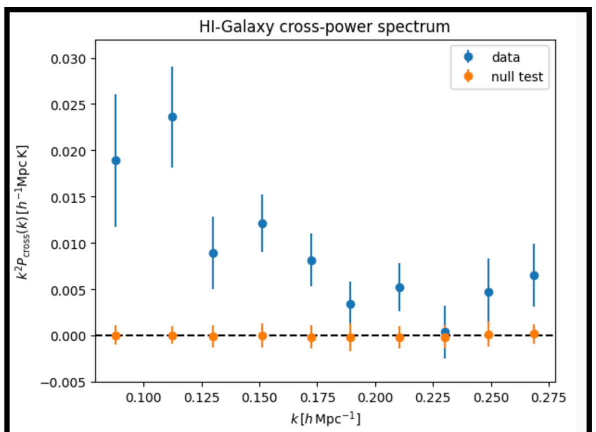
Recent highlight

https://meer21cm.readthedocs.io/en/latest/

MEER21CM: AN ANALYSIS PIPELINE AND COMPREHENSIVE TOOLKIT FOR HI INTENSITY MAPPING

Zhaoting Chen [1], Steven Cunnington [2], Daniel Tassie [2], Alkistis Pourtsidou [1,3], Laura Wolz [4], Gabriele Autieri [5], Matilde Barberi-Squarotti [6,7,8,9], José Luis Bernal [10], Phil Bull [4,11], Stefano Camera [9,12,13,11], Isabella P. Carucci [14,15], Brandon Engelbrecht [11], José Fonseca [16,17,11], Karin Fornazier [11], Keith Grainge [4], Jiakang Han [9], Wenkai Hu [18,11], Melis O. Irfan [19], Piyanat Kittiwisit [11], Yichao Li [20], Sefa Pamuk [10], Mario G. Santos [11,21], Marta Spinelli [22,11], Jingying Wang [23,11], Amadeus Witzemann [11,4], Boyan Zhao [18]
(MeerKLASS Collaboration)

https://meer21cm.readthedocs.io/en/latest/cookbook/2021_Lband_gama_cross.html



Thank you!