Integrated Cosmological Probe Combination

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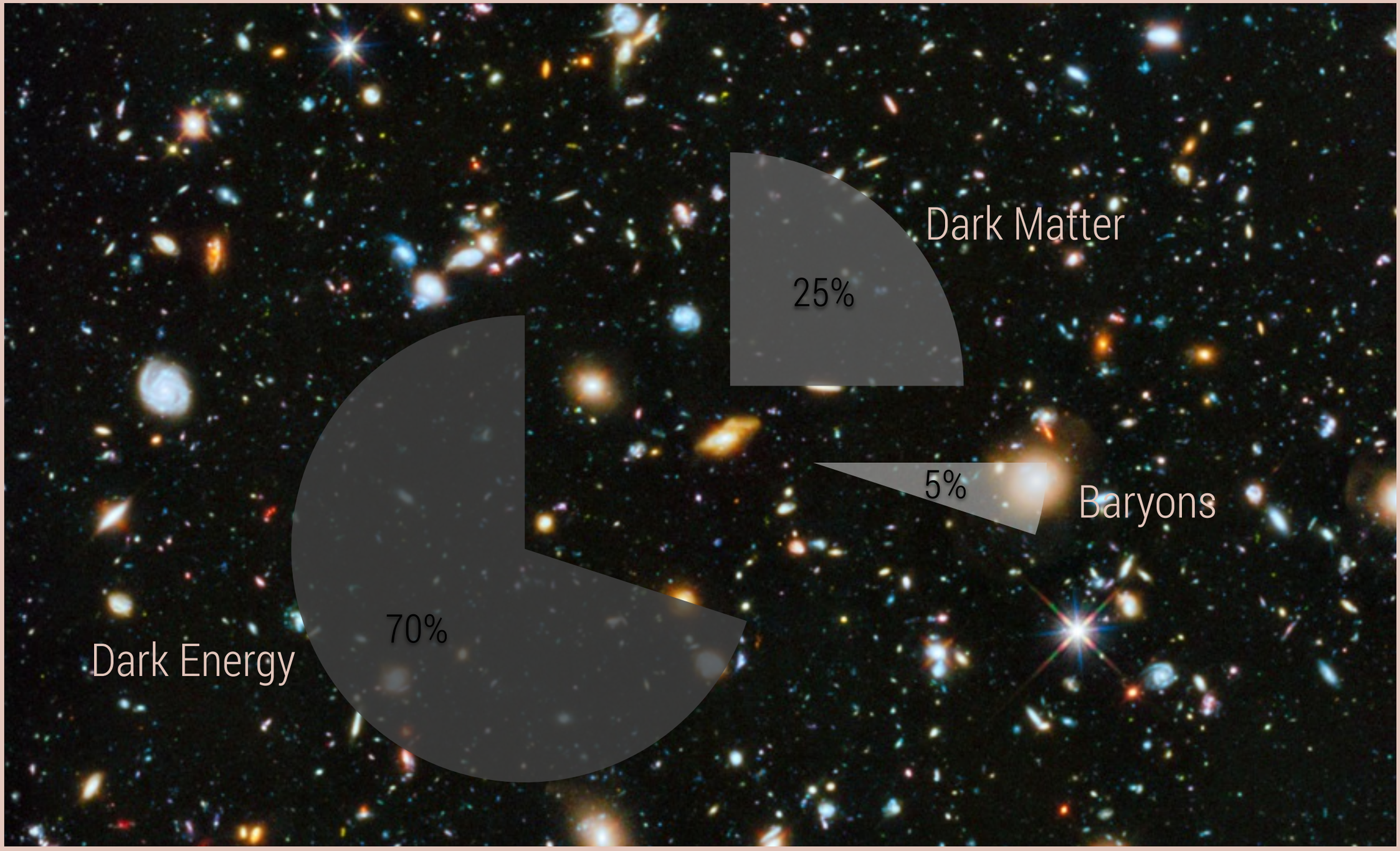
+ Alexandre Refregier, Adam Amara, LSST-DESC LSS group

Our Mysterious Universe



"I say, there is no darkness but ignorance."

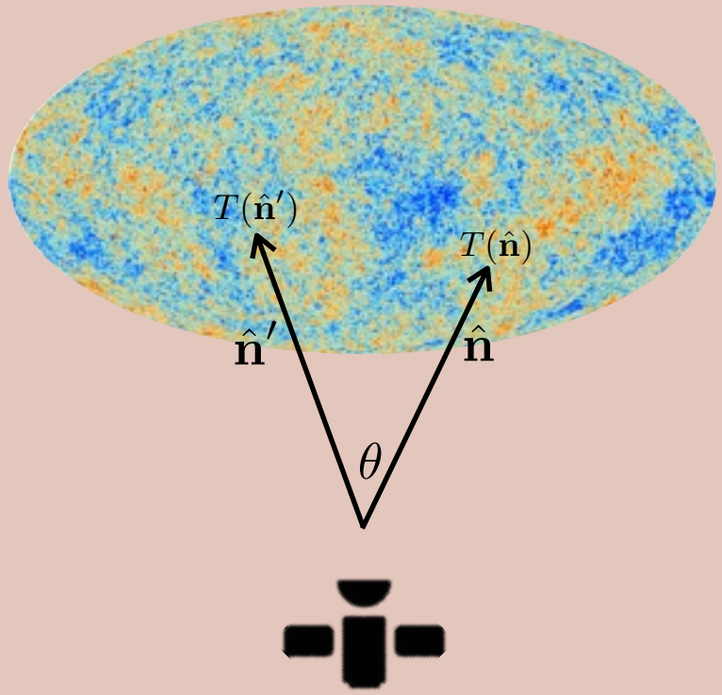
— William Shakespeare, Twelfth night (IV.II)

Our Universe: the Cosmological Lab

Photo by Dr. Hideaki Fujiwara - Subaru Telescope, NAOJ

Cosmological Probes

Cosmic Microwave Background

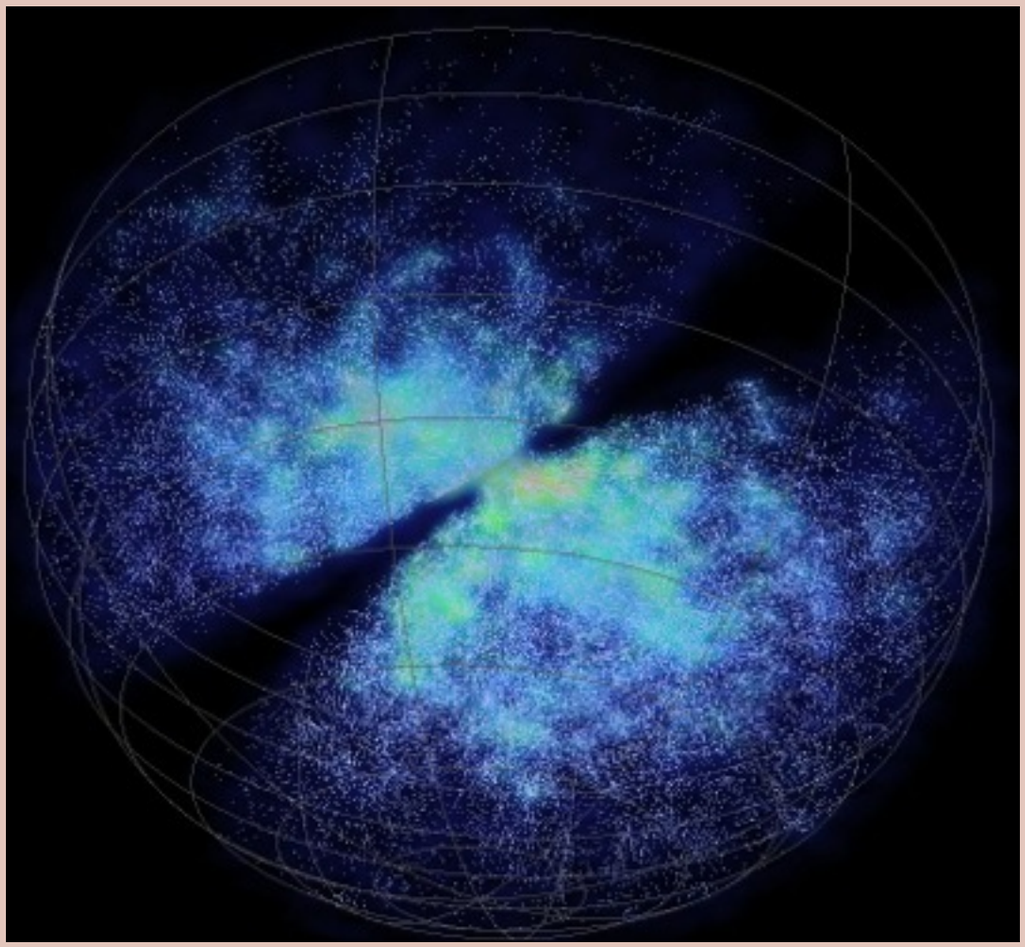


$$C(\theta) = \langle \frac{\Delta T(\hat{\mathbf{n}})}{\bar{T}} \frac{\Delta T(\hat{\mathbf{n}}')}{\bar{T}} \rangle \qquad C_\ell = \langle a_{\ell m} a_{\ell m} \rangle$$

Images: Planck,
Planck (Damien P. George)

Cosmological Probes

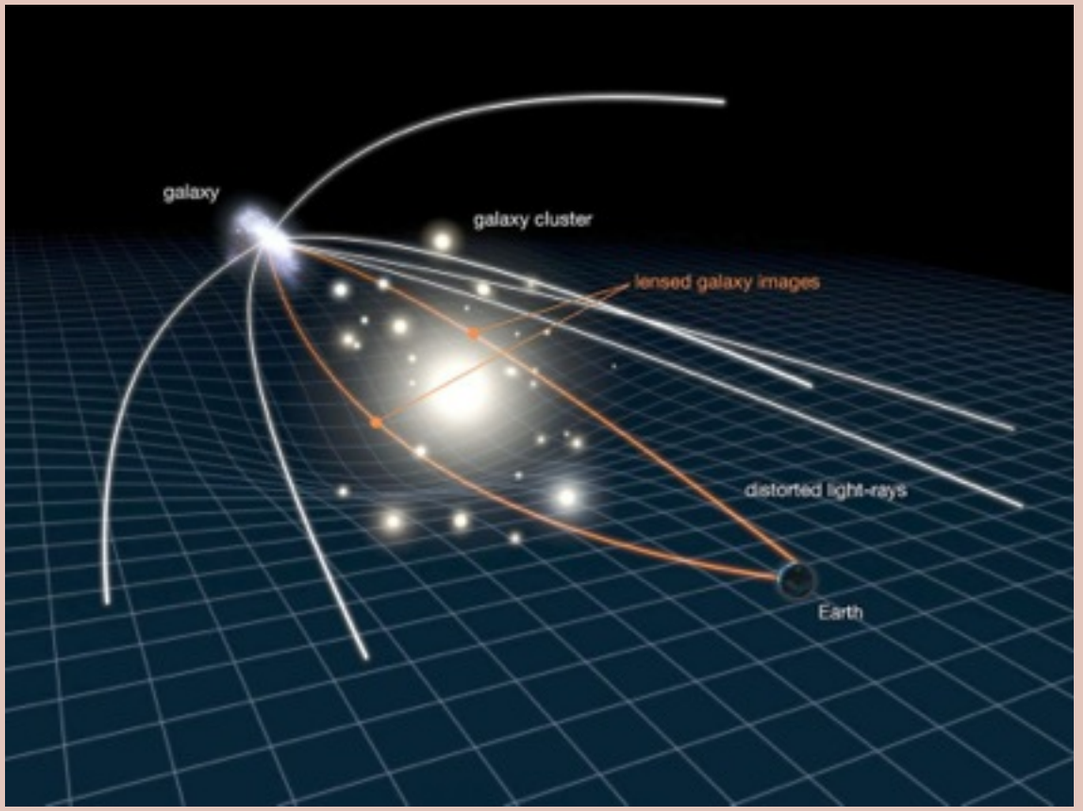
Galaxy clustering



Images: 6dF, Science News

Cosmological Probes

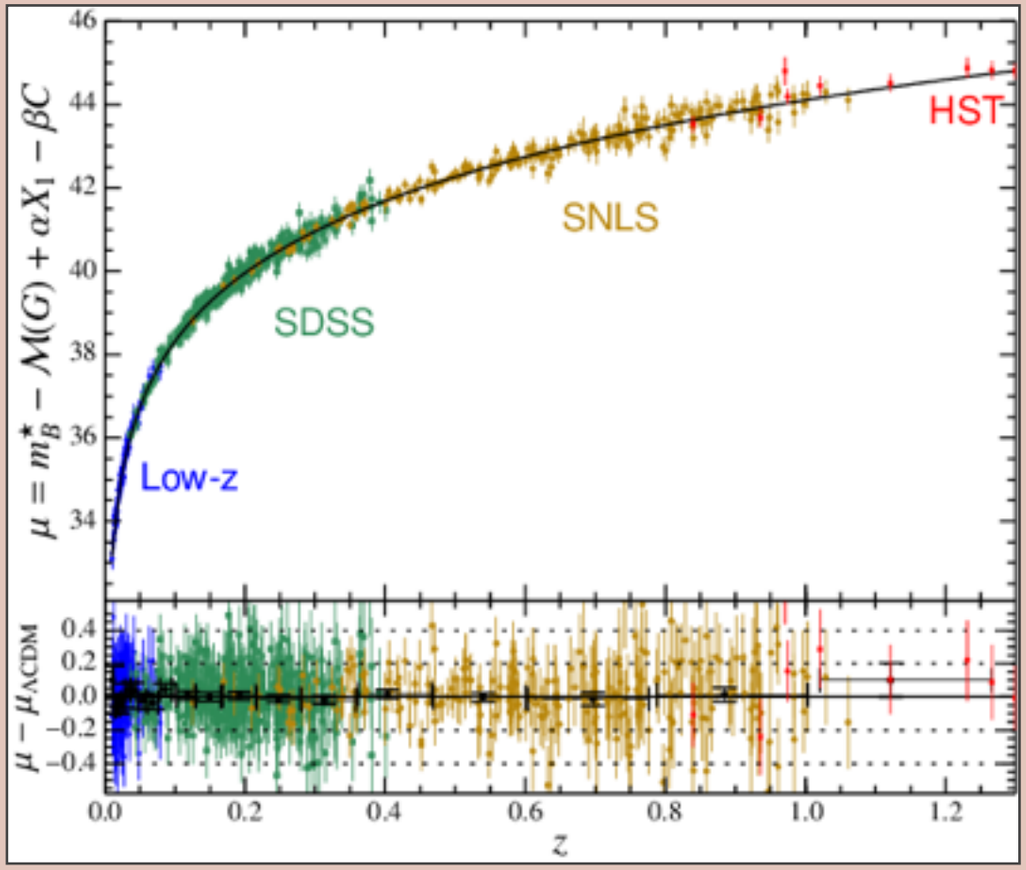
Weak gravitational lensing



Images: NASA/ESA, radioGREAT

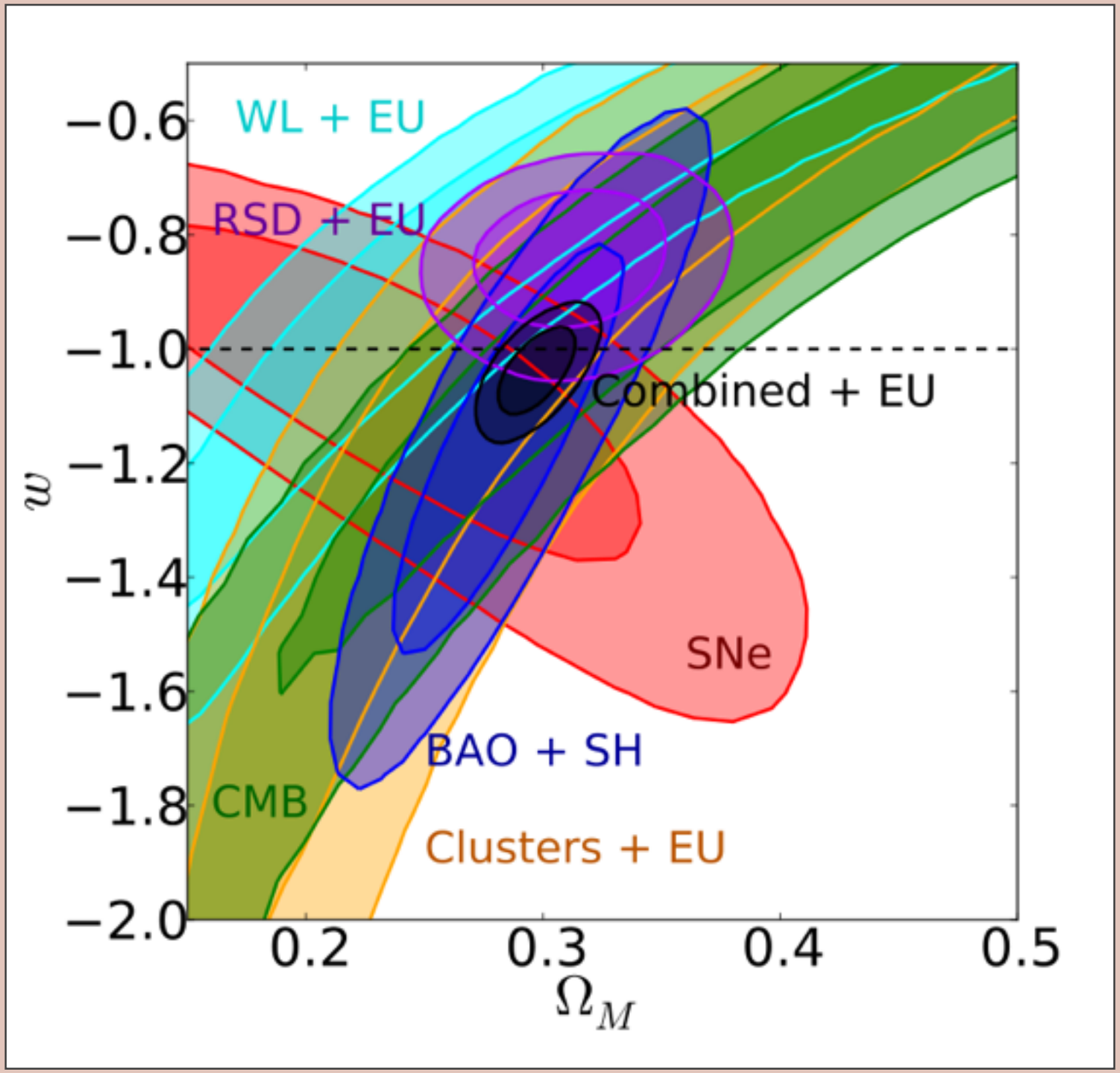
Cosmological Probes

Supernovae



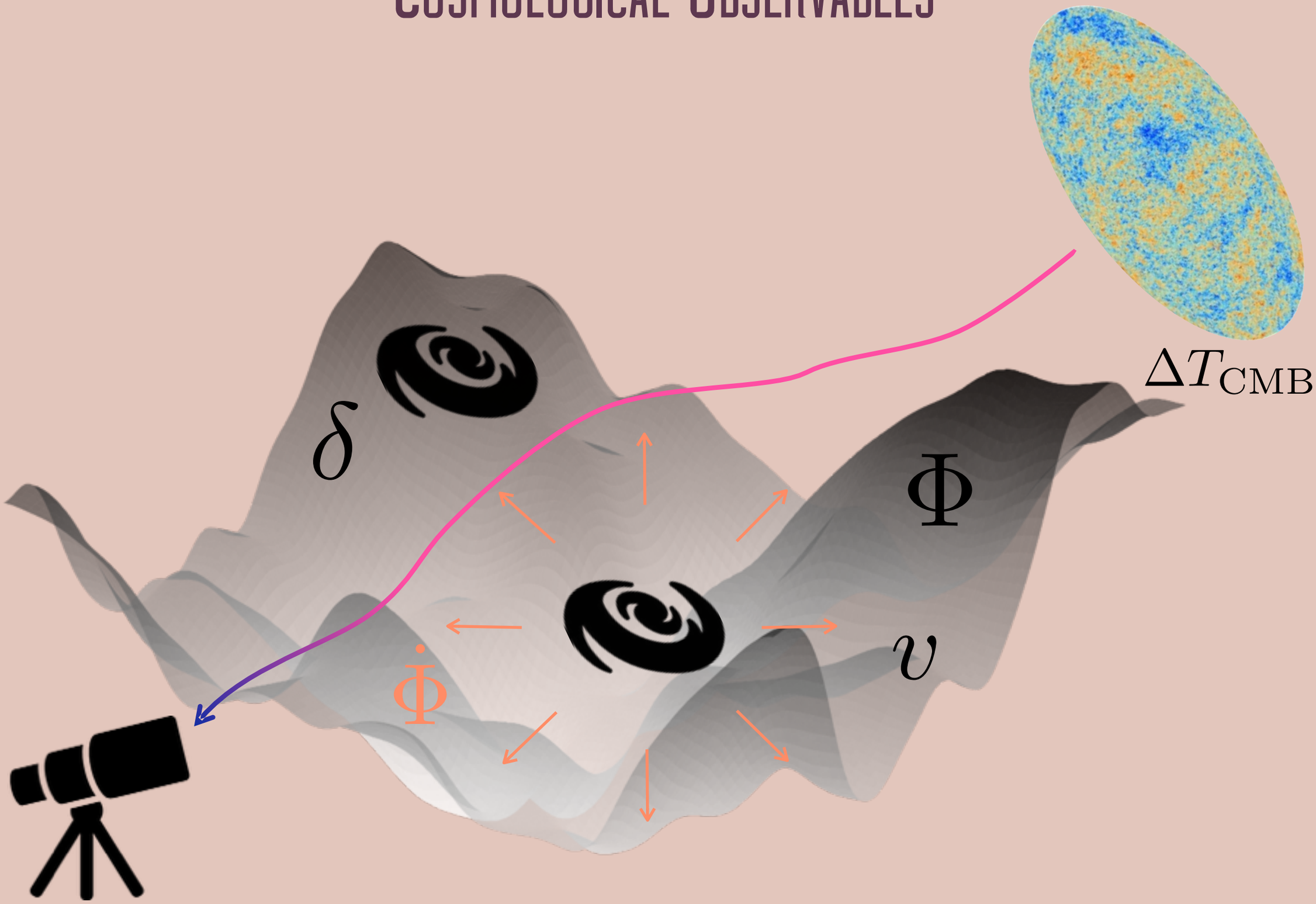
Images: HST, JLA

Joint Analyses I



Ruiz et al., 2015

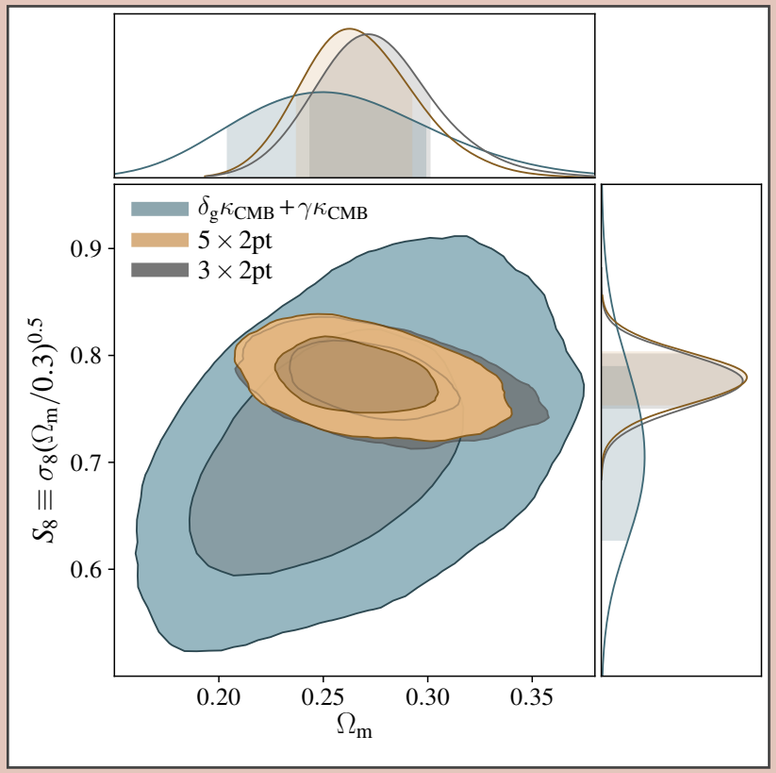
Cosmological Observables



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

Joint Analyses II

DES Y1 & SPT



Abbott et al., 2018

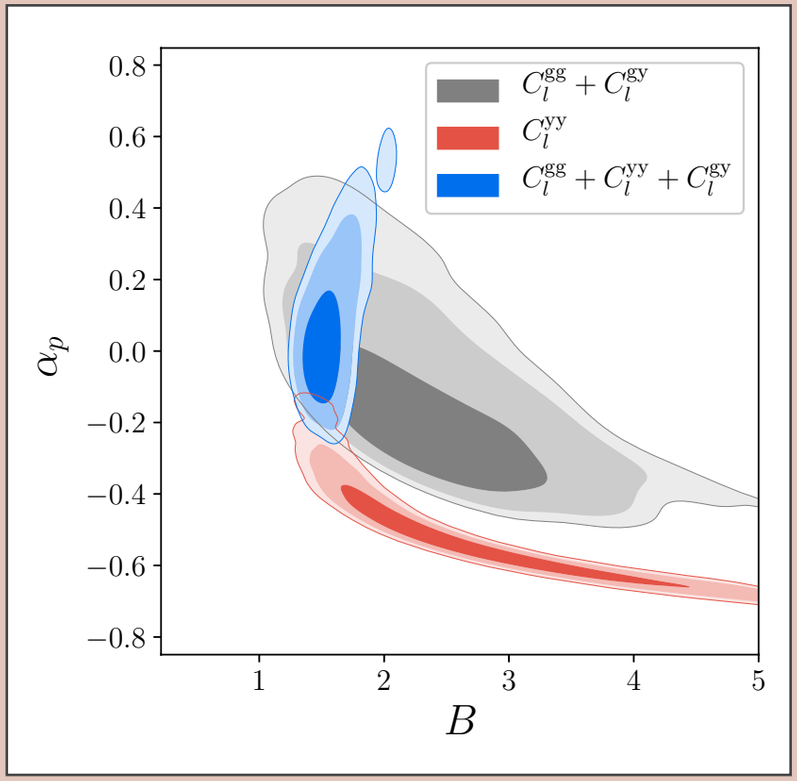
Combination of:

DES Y1 weak lensing

DES Y1 galaxy clustering

SPT CMB lensing

Planck & 2MASS



Makiya et al., 2018

Combination of:

Planck tSZ

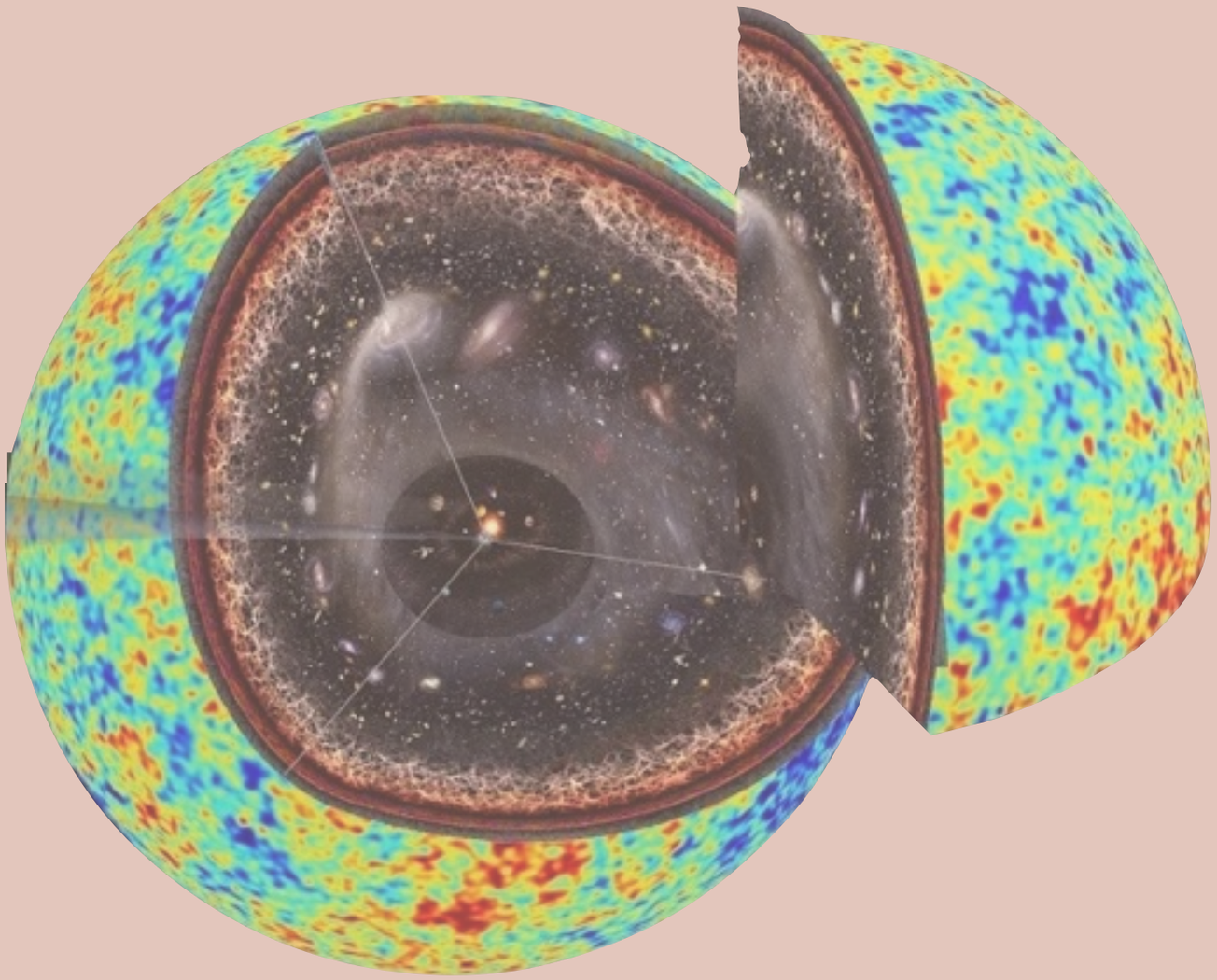
2MASS galaxy clustering

Potential of Integrated Analyses

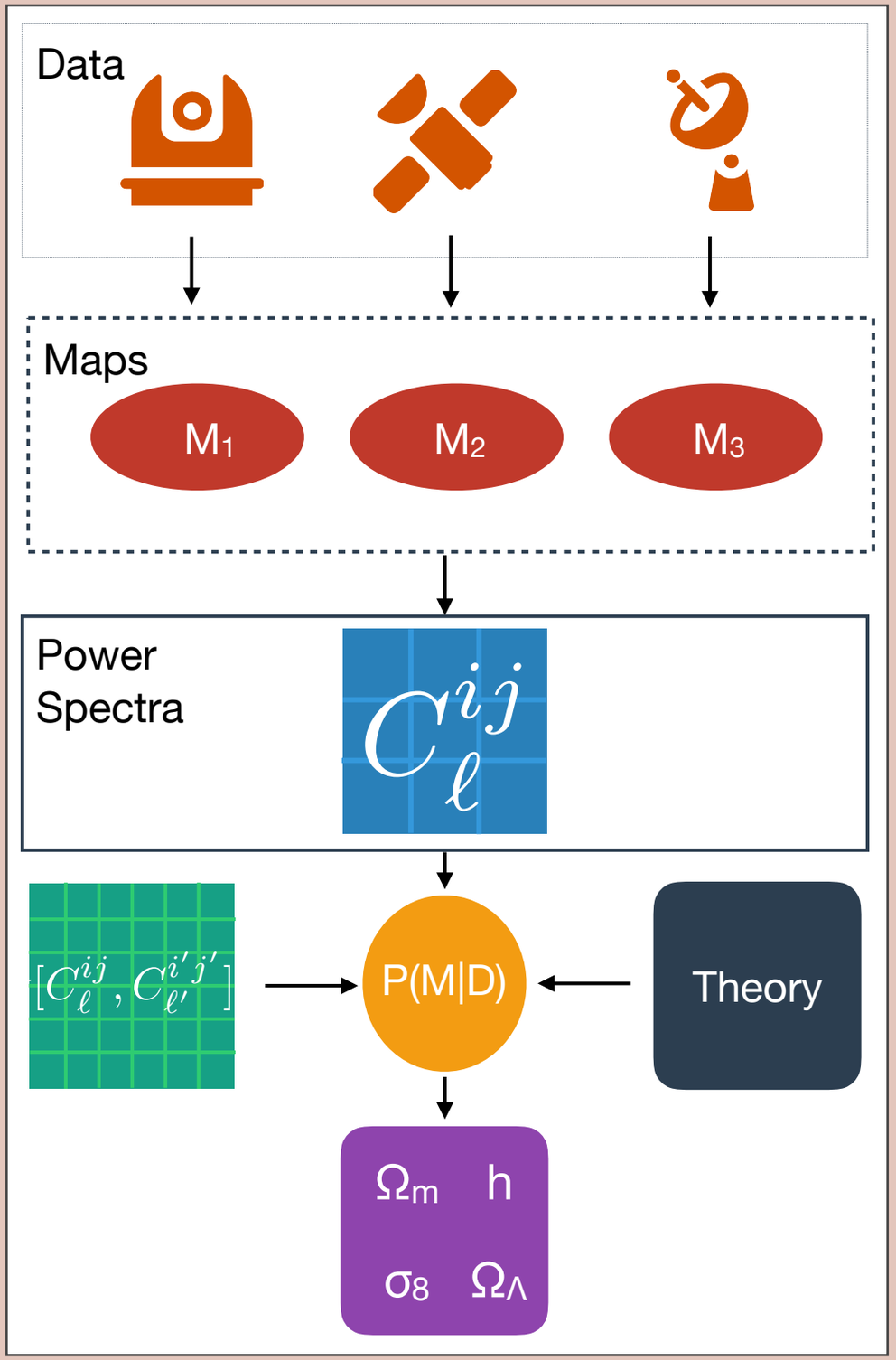
Tighter constraints due to complementary information

Robust tests of cosmological model by comparing consistency of different tracers

Cross-correlations: systematics identification

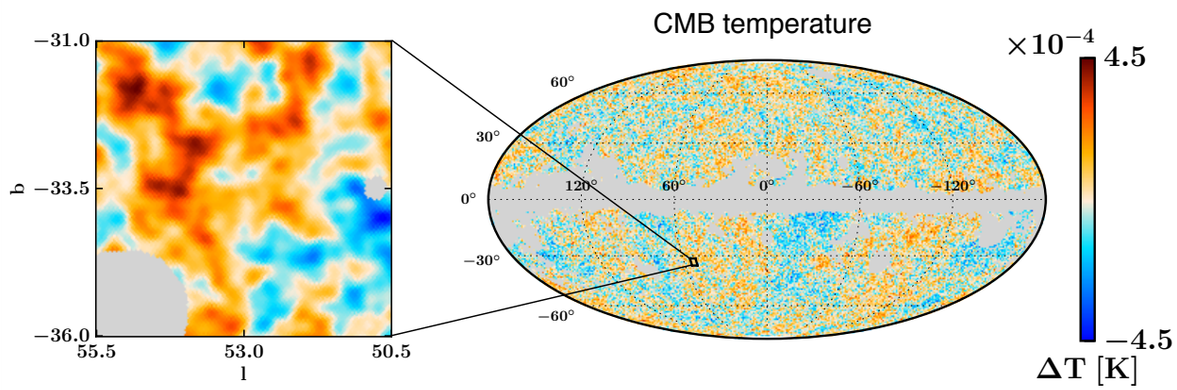


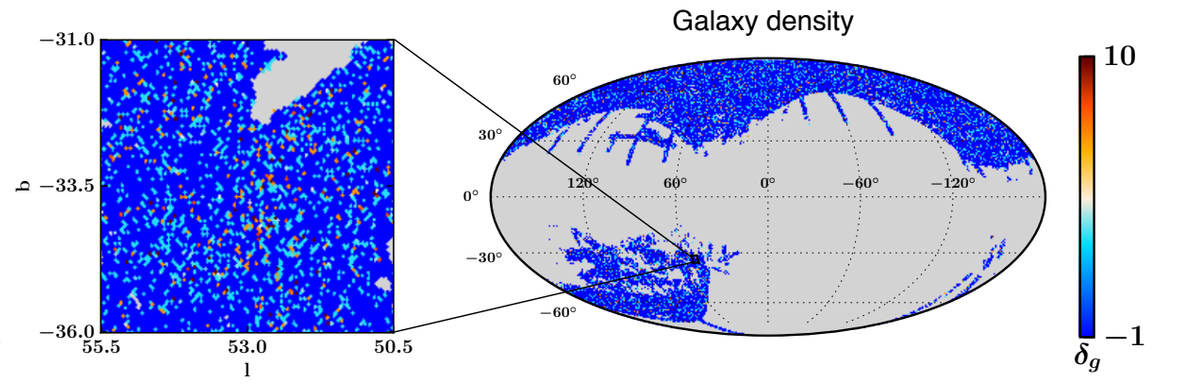
Framework

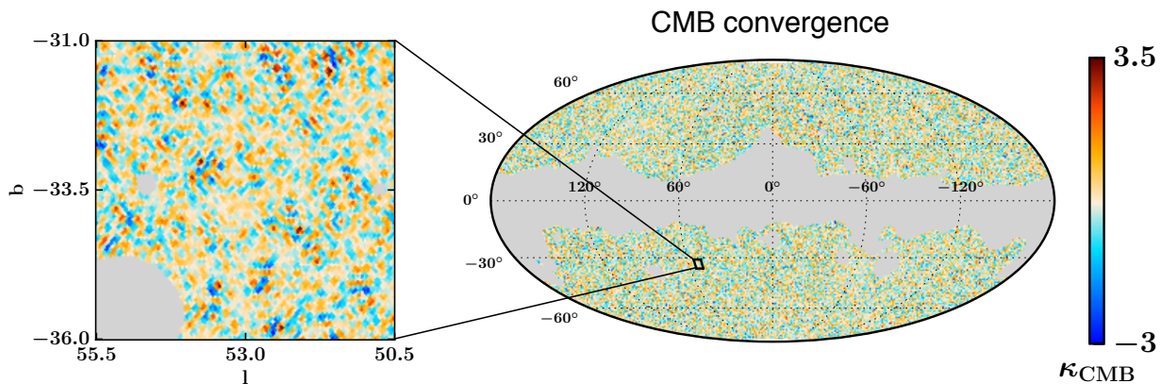


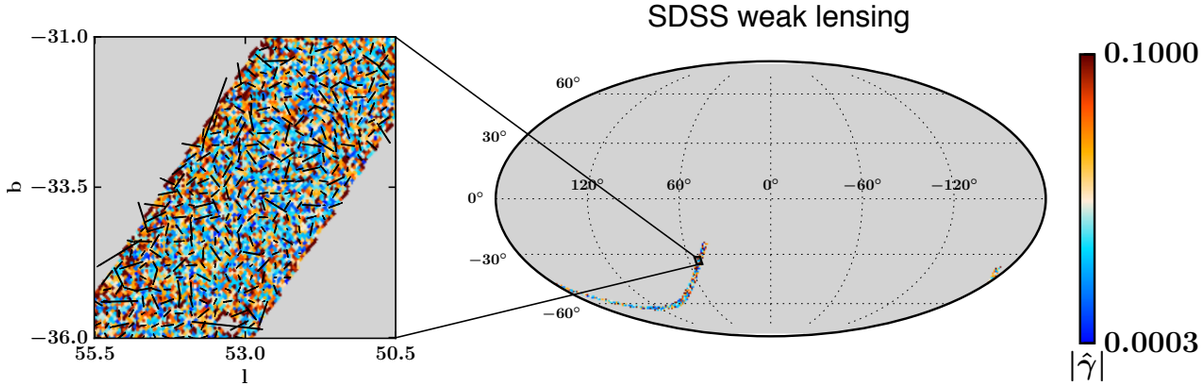
Nicola et al., 2016, 2017a

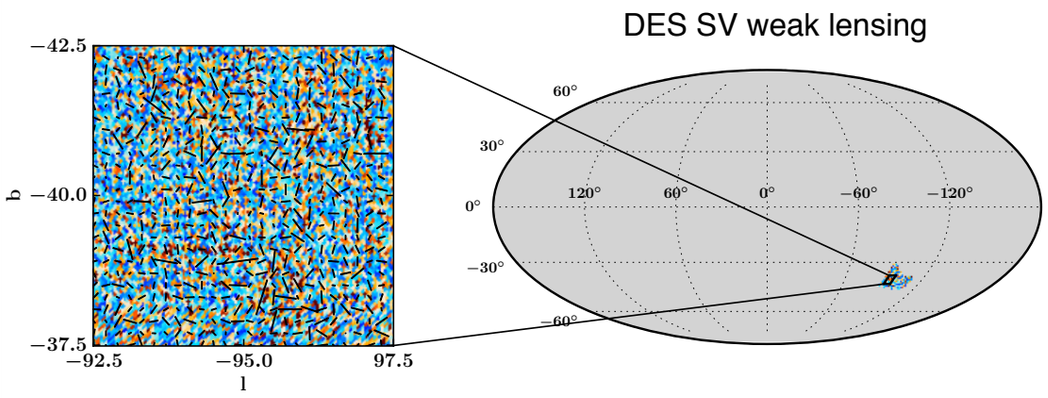
Maps & Background Probes

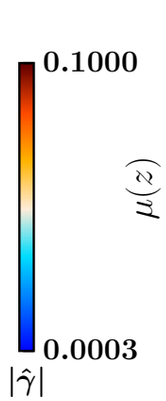


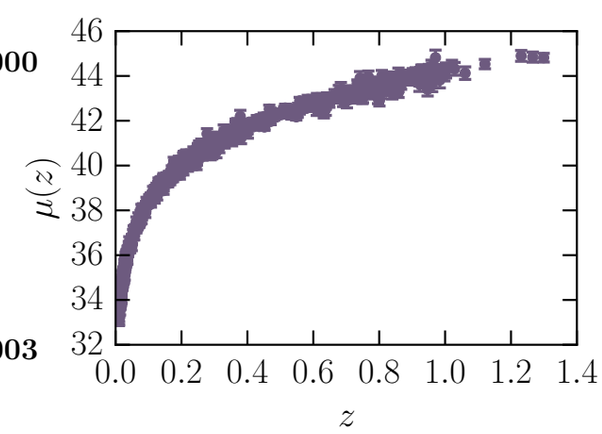


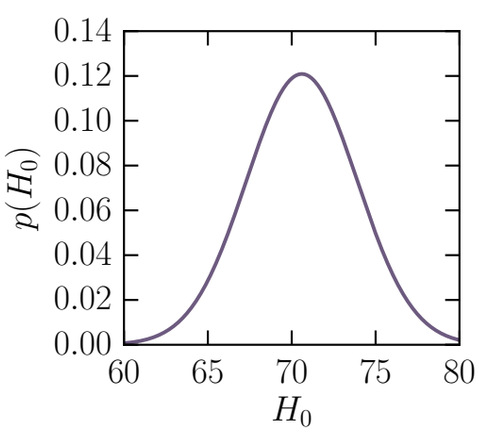






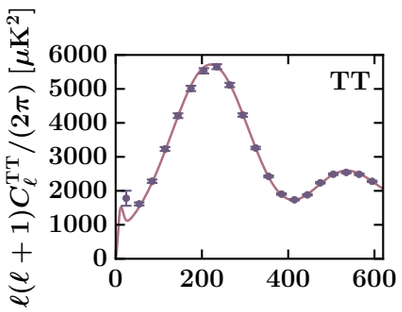


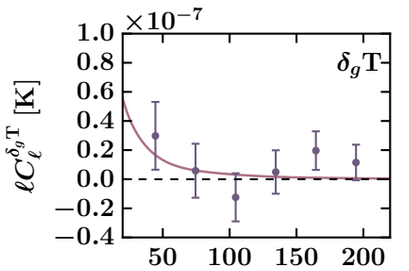


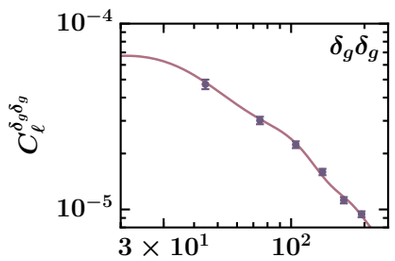


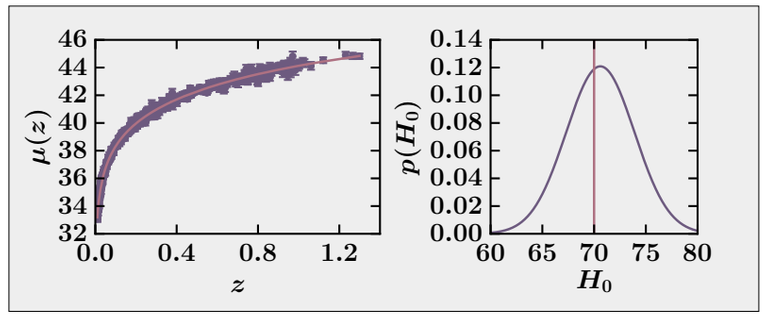
Nicola et al., 2016, 2017a

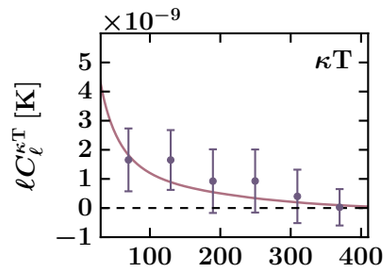
Power Spectra & Background Probes

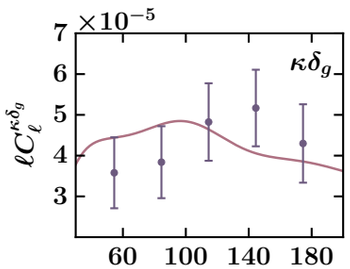


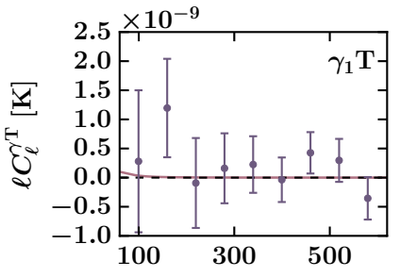


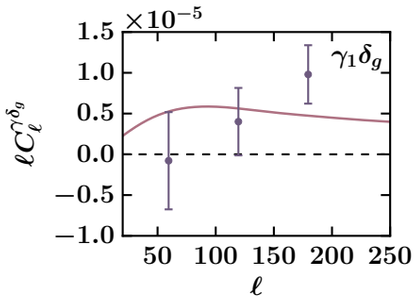


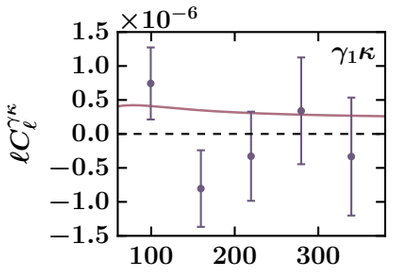


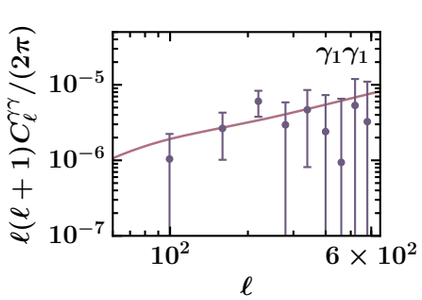


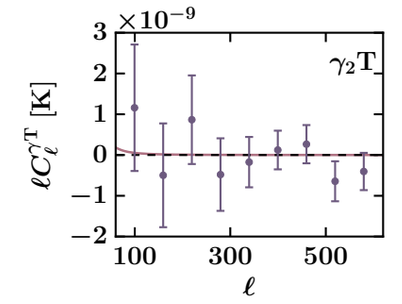


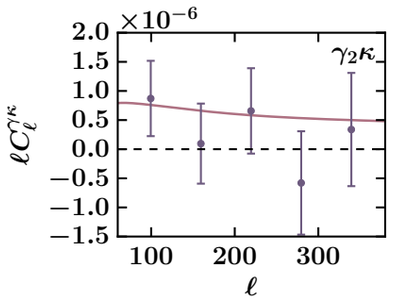


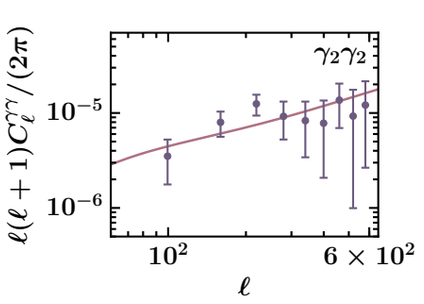










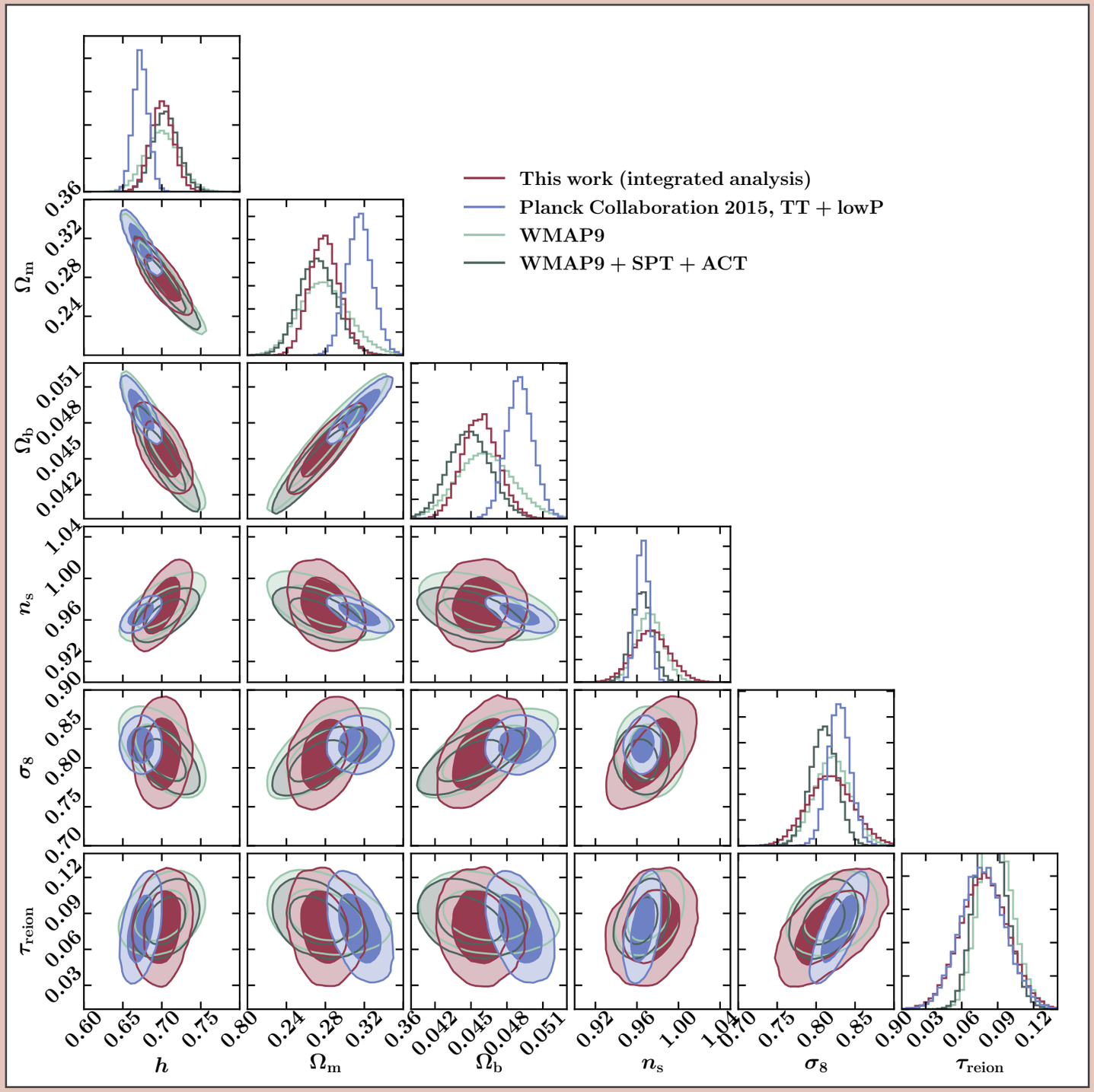


Model Parameters

Parameter	
h	ΛCDM
$\Omega_{\rm m}$	
$\Omega_{\rm b}$	
$n_{\rm s}$	
σ_8	
$\tau_{\rm reion}$	
b	nuisance parameters
$m_*^{\rm SDSS}$	
$m_*^{\rm DES}$	
$m_{\kappa_{\rm CMB}}$	
α	
β	
$M_{\rm B}^1$	
ΔM	

Nicola et al., 2017a

Cosmological Parameter Constraints



Nicola et al., 2017a

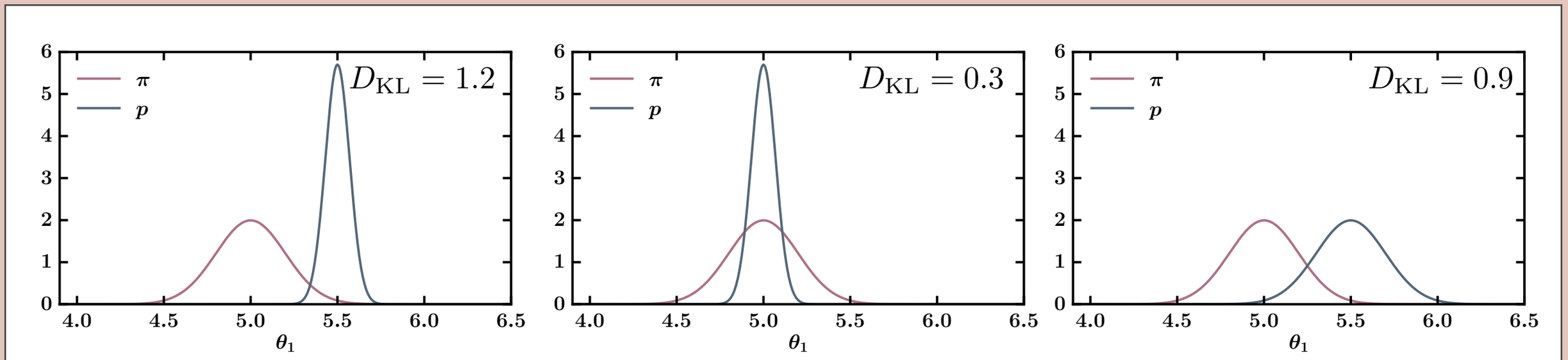
The Relative Entropy (aka KL Divergence)

Measure for difference between

$\pi(\boldsymbol{\theta})$: prior

$p(\boldsymbol{\theta})$: posterior

$$D_{\mathrm{KL}}(p||\pi) = \int \mathrm{d}\boldsymbol{\theta}\; p(\boldsymbol{\theta}) \log \frac{p(\boldsymbol{\theta})}{\pi(\boldsymbol{\theta})}$$



Kullback & Leibler, 1951

Data Set Consistency

$$D_{\mathrm{KL}}(p||\pi) = \int \mathrm{d}\boldsymbol{\theta}\; p(\boldsymbol{\theta}) \log \frac{p(\boldsymbol{\theta})}{\pi(\boldsymbol{\theta})}$$ observed

$$S = D_{\mathrm{KL}}(p||\pi) - \langle D_{\mathrm{KL}} \rangle$$ Surprise = observed - expected

Kullback & Leibler, 1951
Seehars et al., 2014, 2016

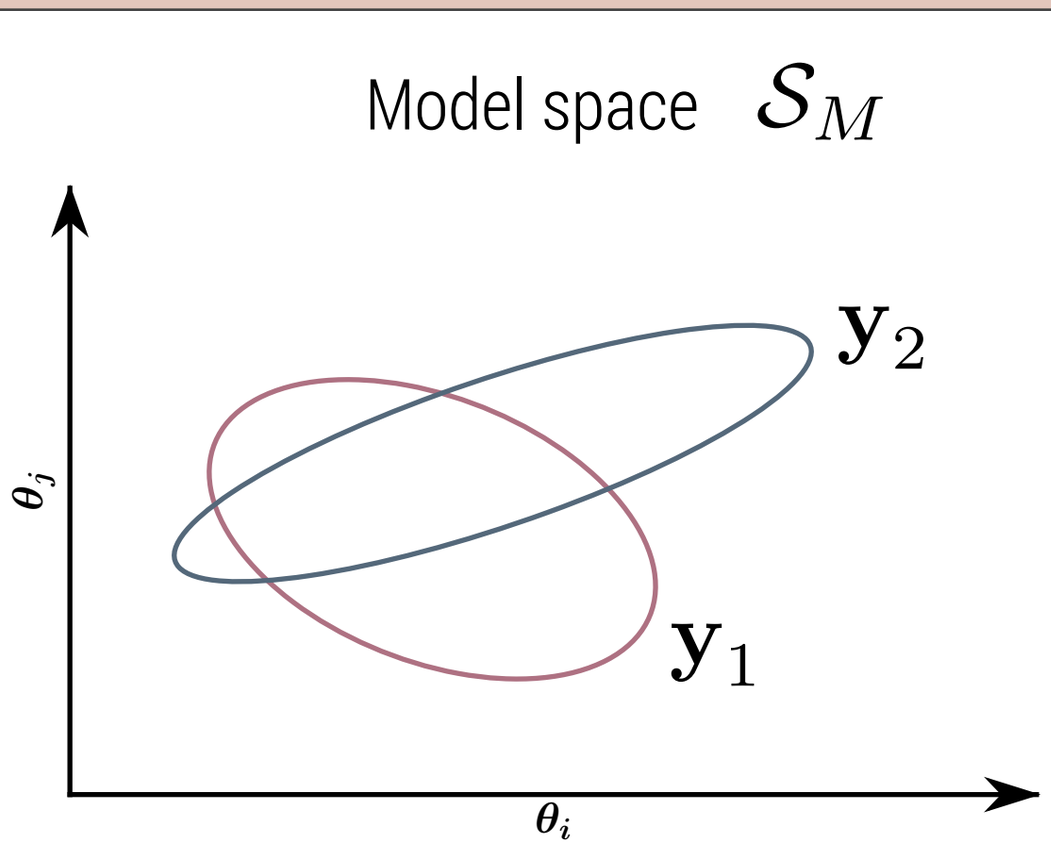
Two Types of Consistency Tests

Data set consistency

Comparison of $\mathbf{y}_1$, $\mathbf{y}_2$

Comparison in model space

Surprise: *Seehars et al., 2014*

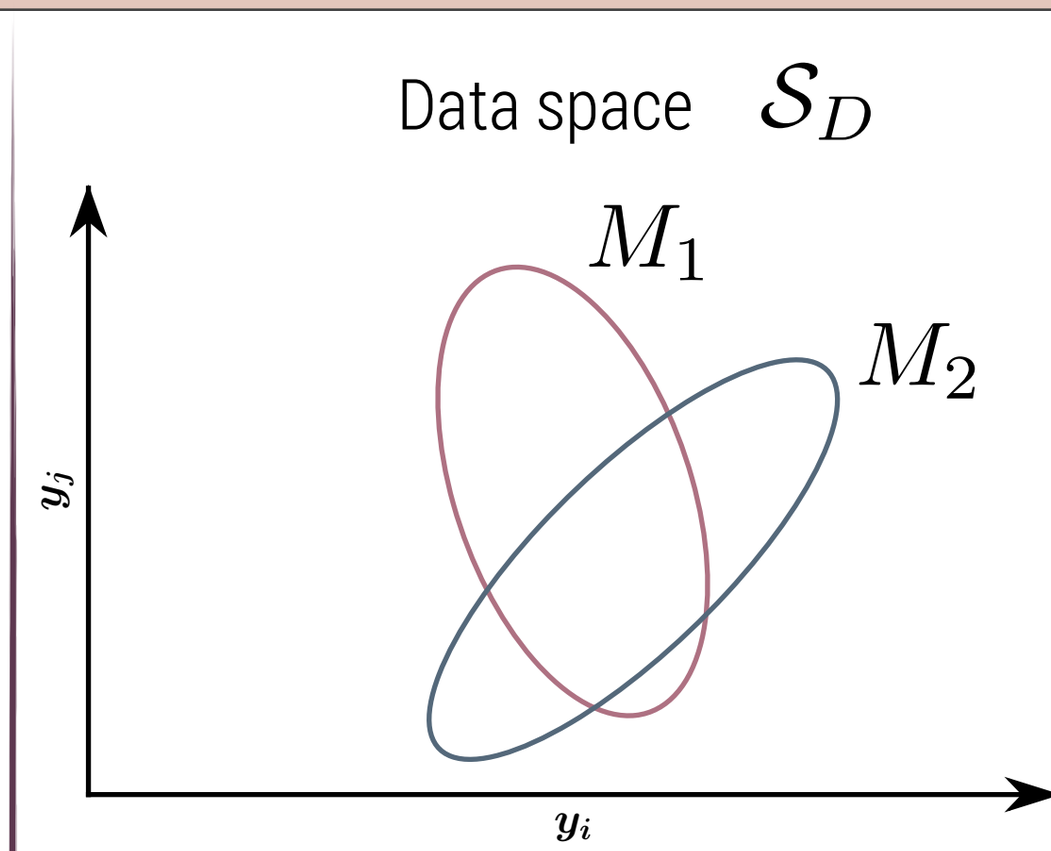


Model testing/Rejection

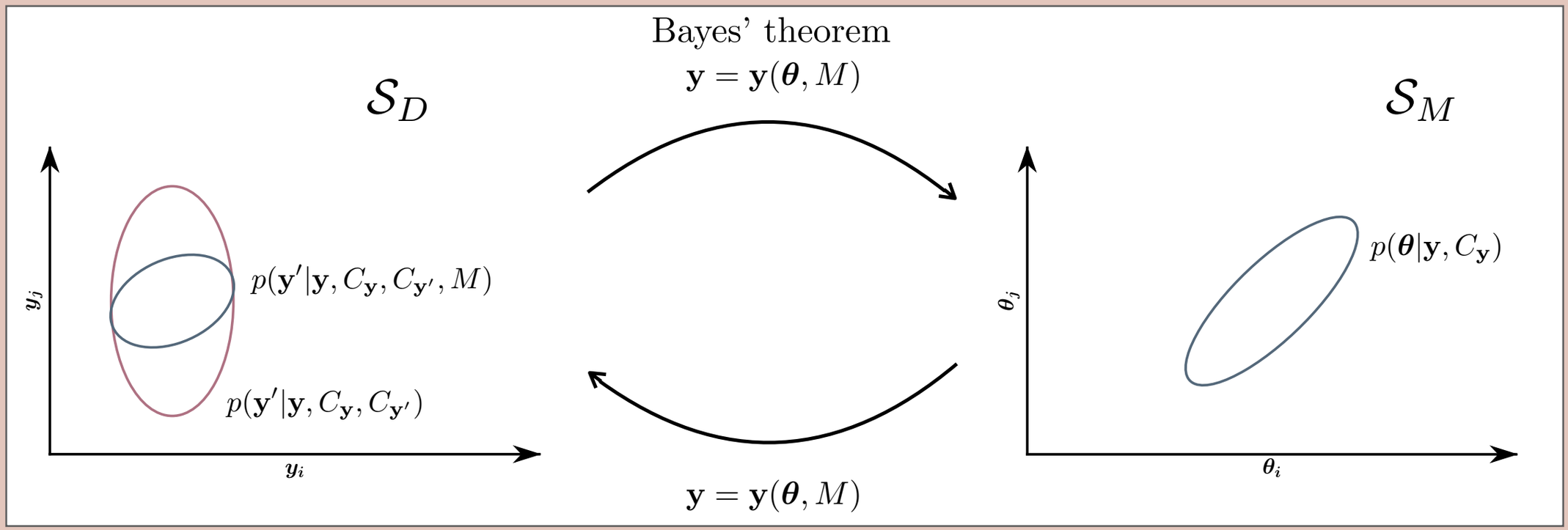
Comparison of $\mathbf{M}_1$, $\mathbf{M}_2$

Comparison in data space

Nicola et al., 2019



Model Rejection

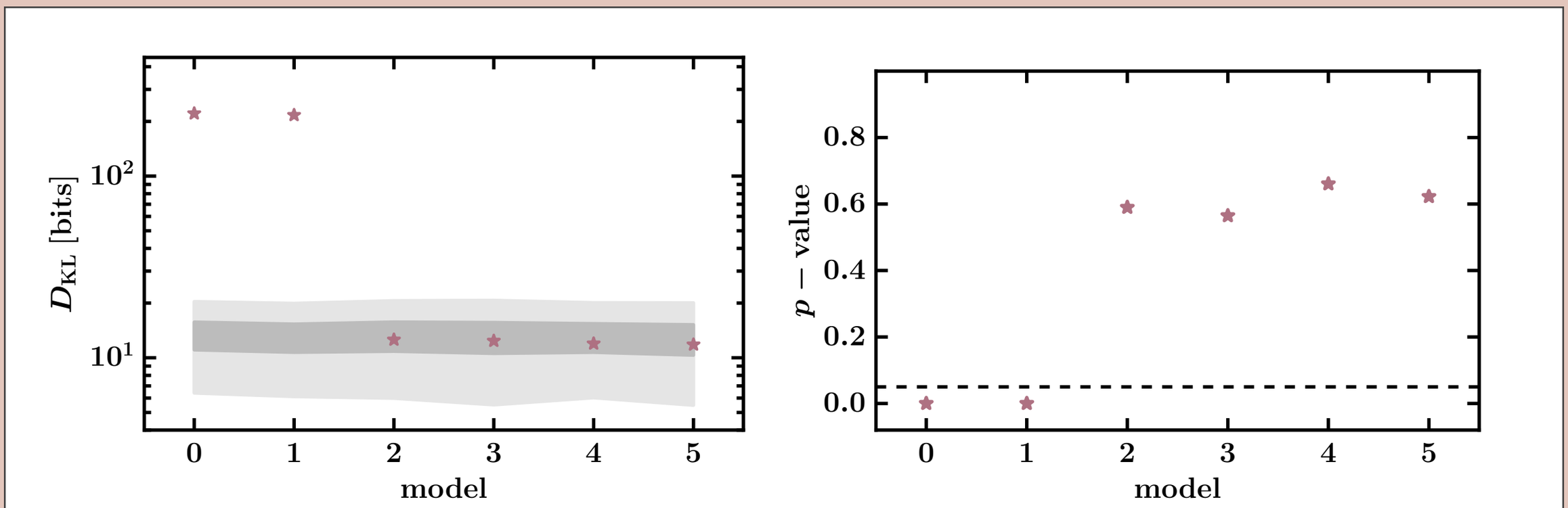


Algorithm based on combination of posterior predictive distribution and relative entropy

Compare observed information gain from model to expectation

Nicola et al., 2019

Model Rejection with Relative Entropy



Tested models:

0:	CDM	1:	curved CDM
2:	ΛCDM	3:	curved ΛCDM
4:	w_0CDM	5:	w_0w_aCDM

Planck Collaboration, 2015
Betoule et al., 2014
Nicola et al., 2019

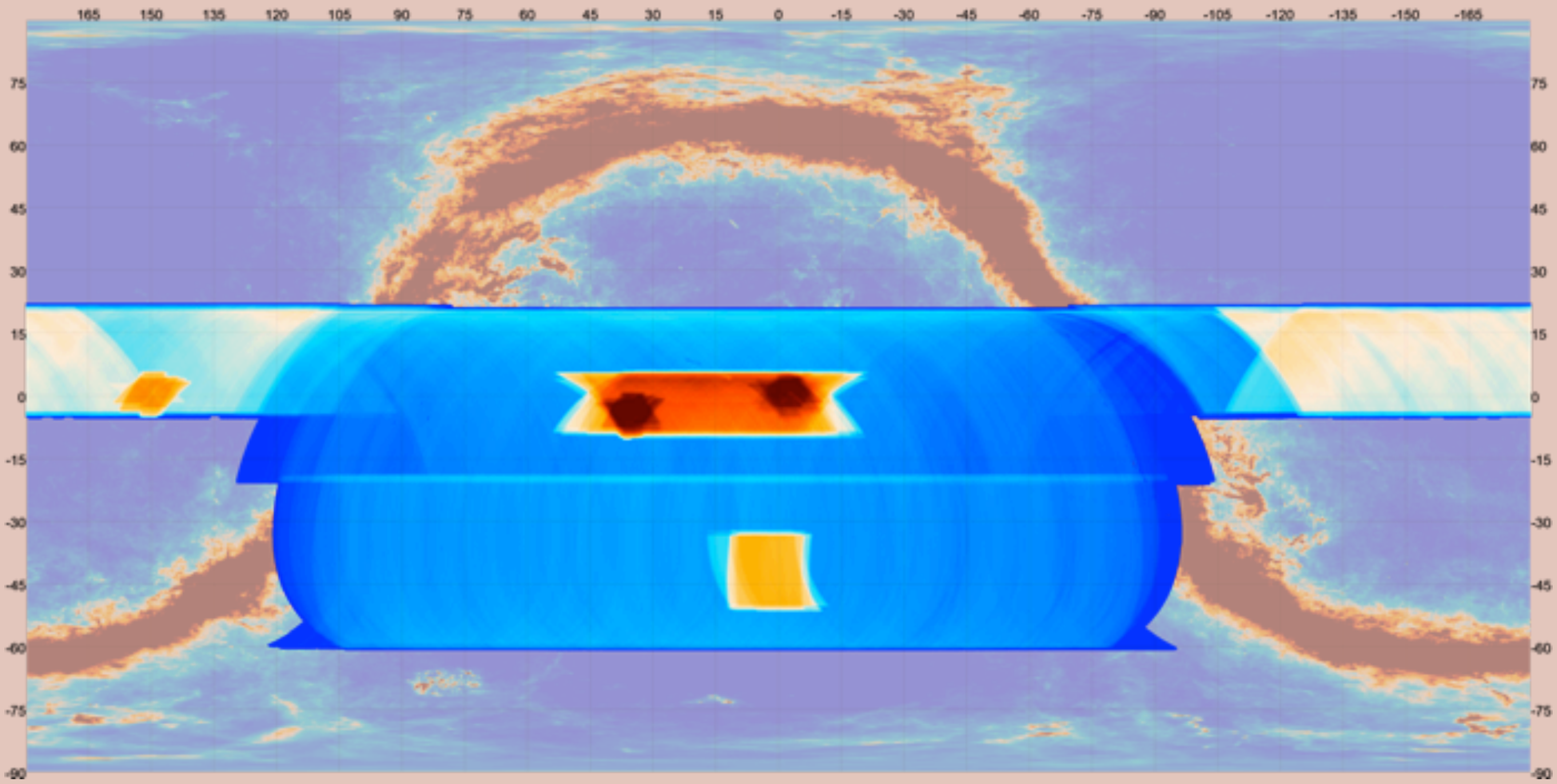
Atacama Cosmology Telescope (ACT)

ACT: 6-year survey, covering 20’000 sq. deg.

s13-s15/s16 data to be released soon

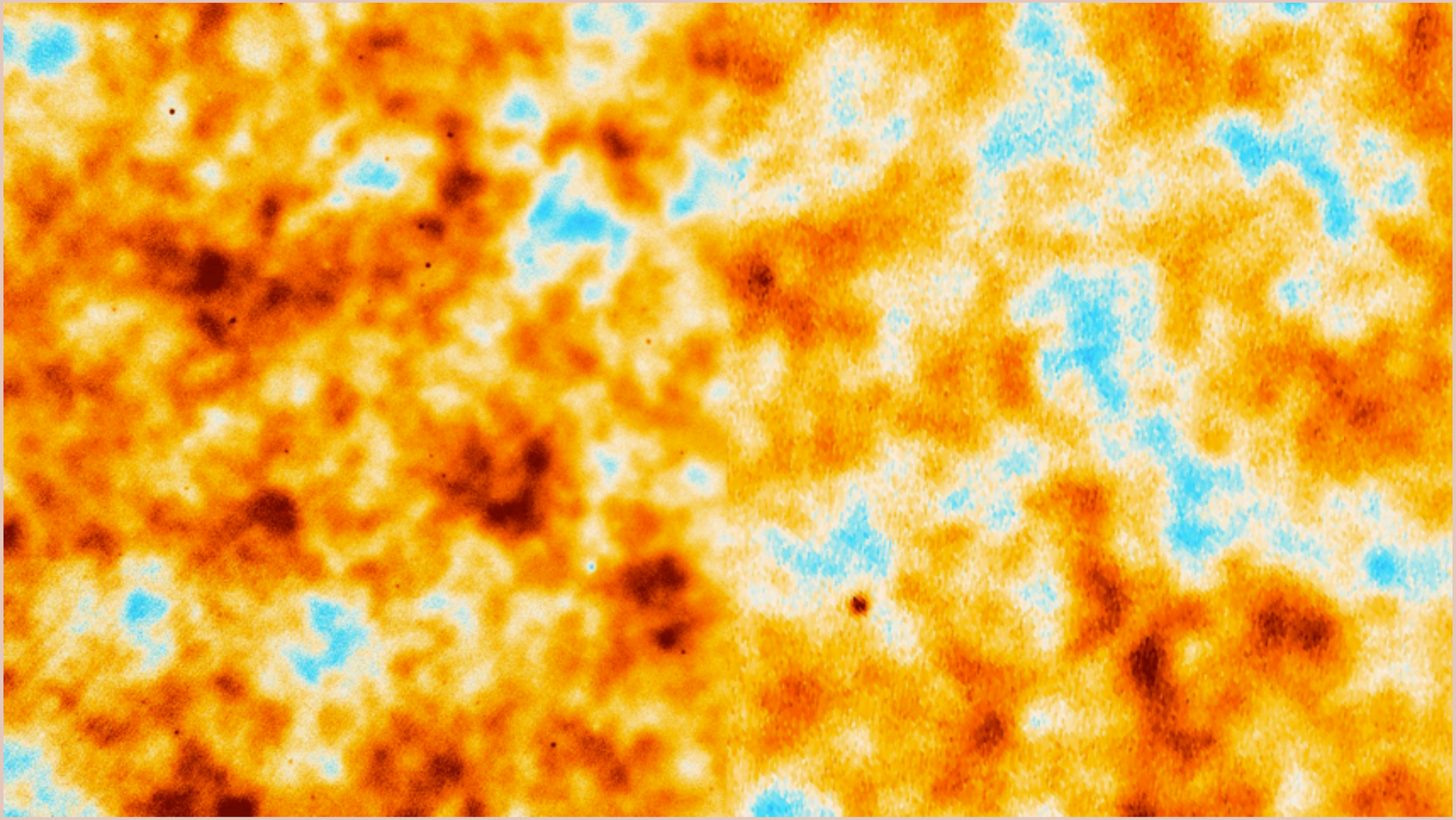
Current data: ~ 3000 sq. deg. at 90 & 150 GHz

Results on temperature, polarization and CMB lensing soon



Map: S. Næss & S. Aiola

Atacama Cosmology Telescope (ACT)



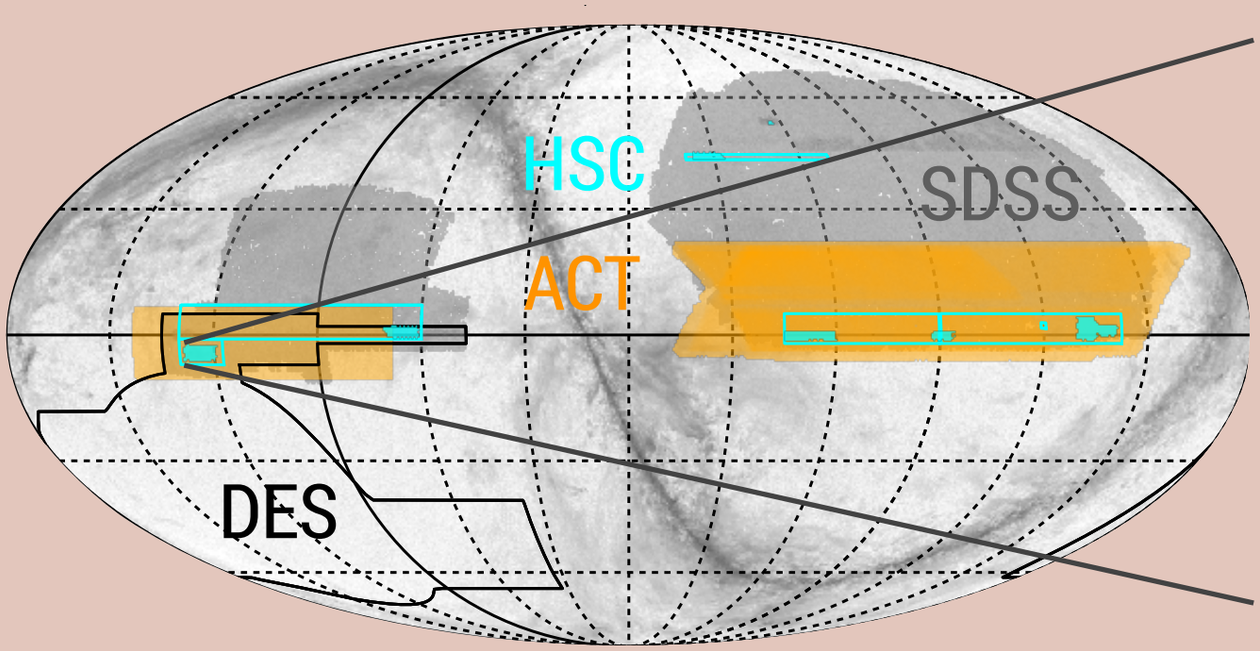
Movie: Sigurd K. Næss

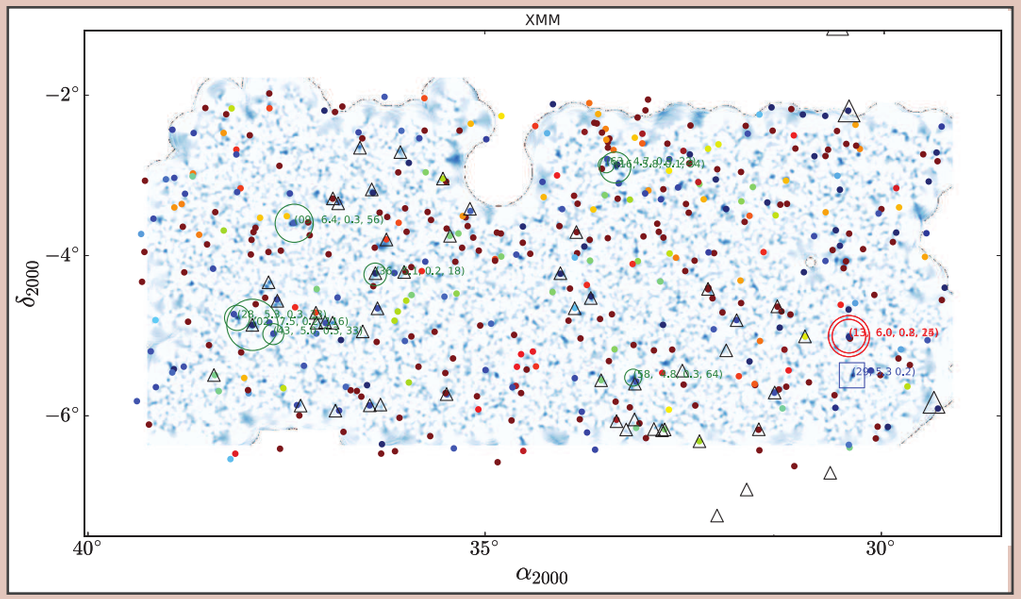
Hyper Suprime Cam (HSC) Survey

HSC: 5-year survey, covering 1400 sq. deg.

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

Deep, very good seeing

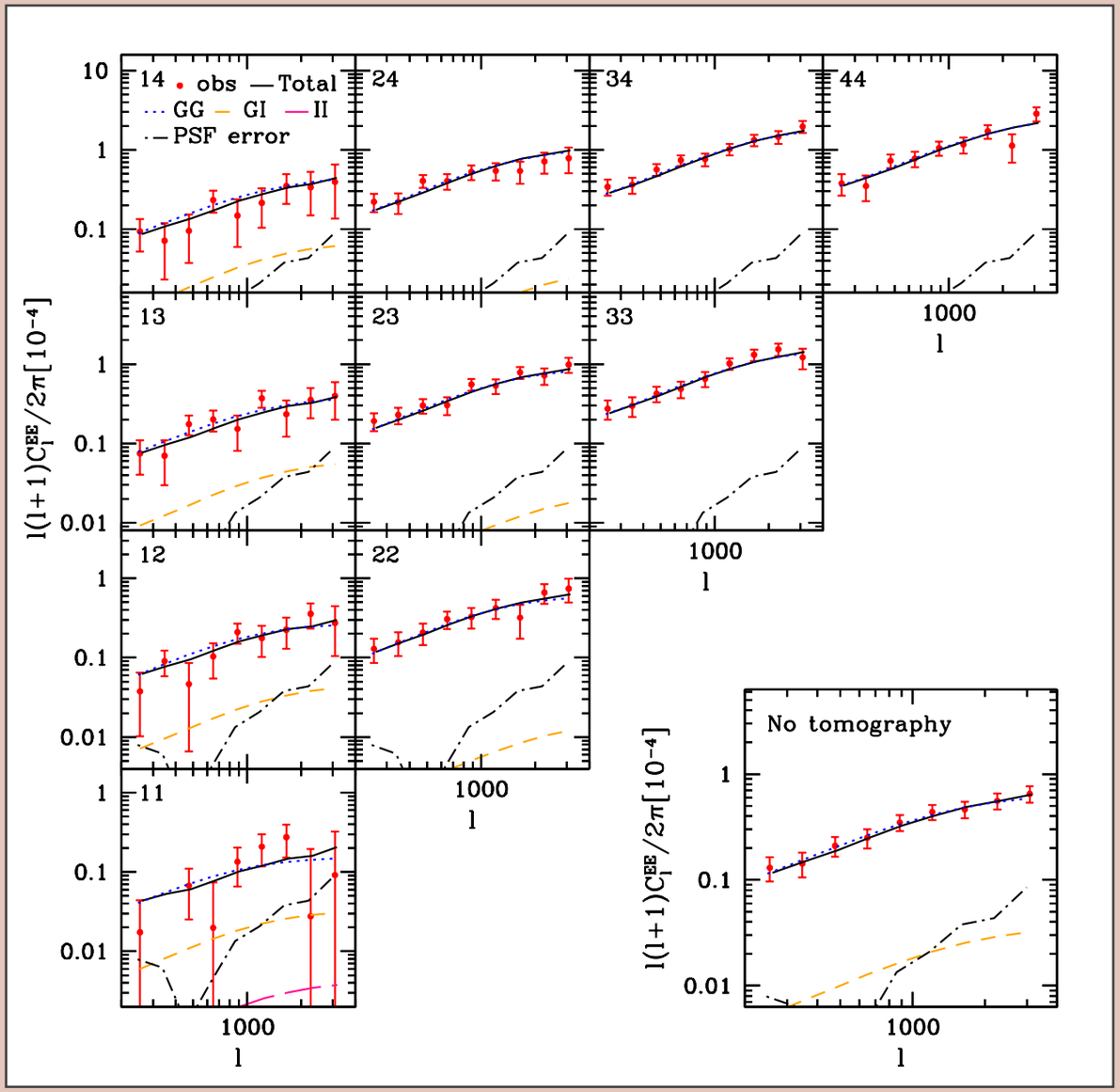


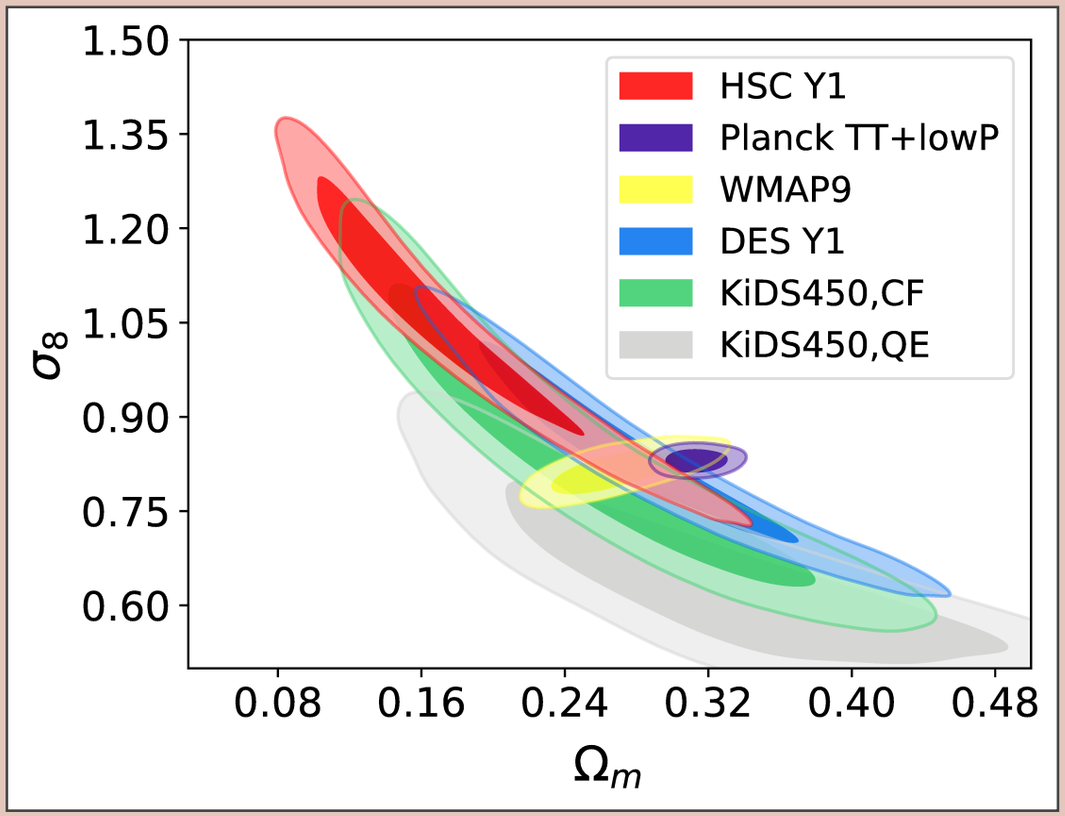


Miyazaki et al., 2018

Footprint: E. Medezinski

HSC Cosmic Shear





Hikage et al., 2019

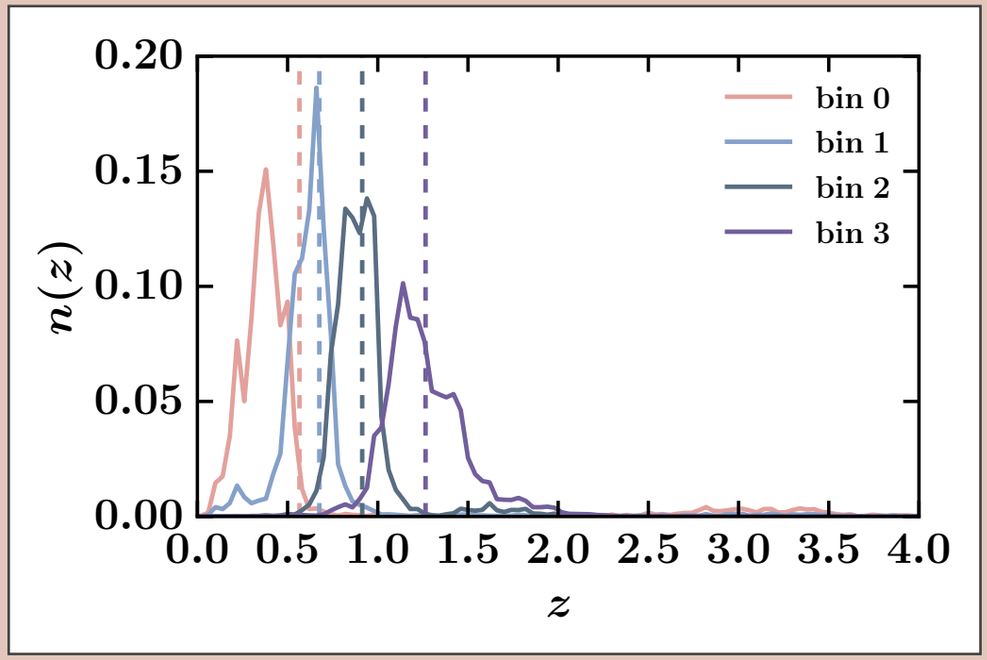
HSC Clustering

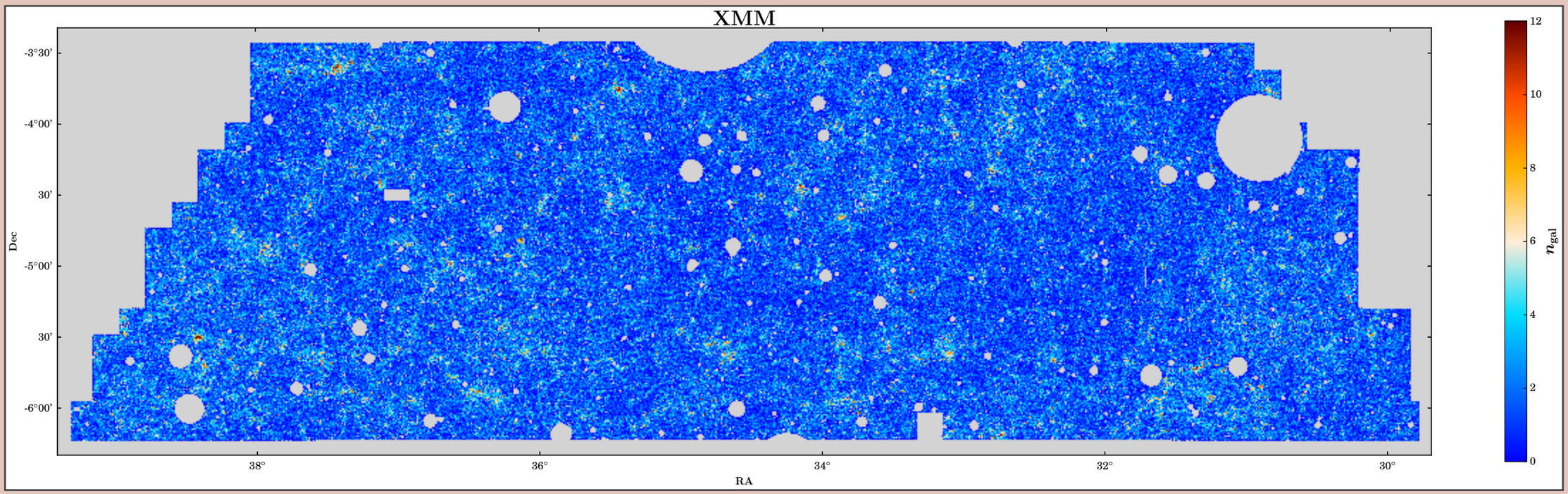
Preliminary!

HSC DR1 data

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

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

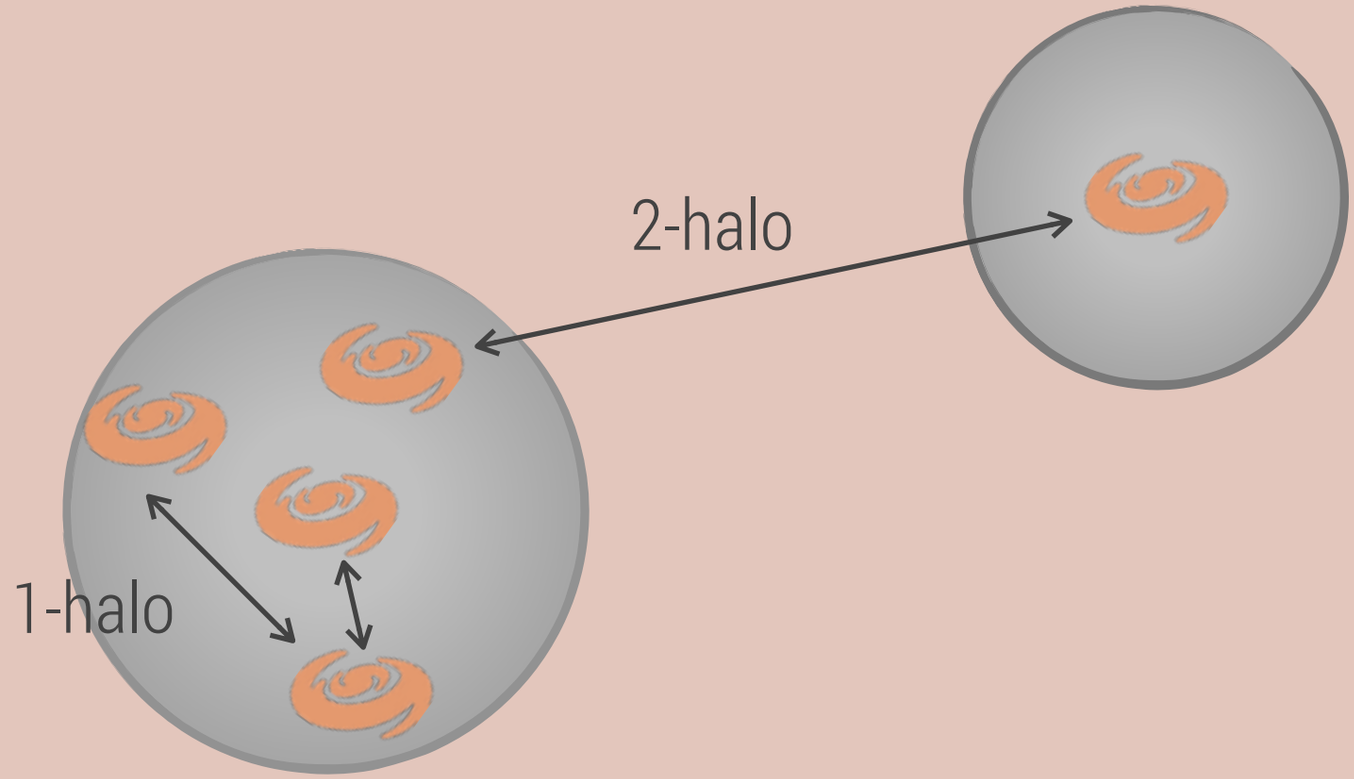




LSST DESC et al., in prep.

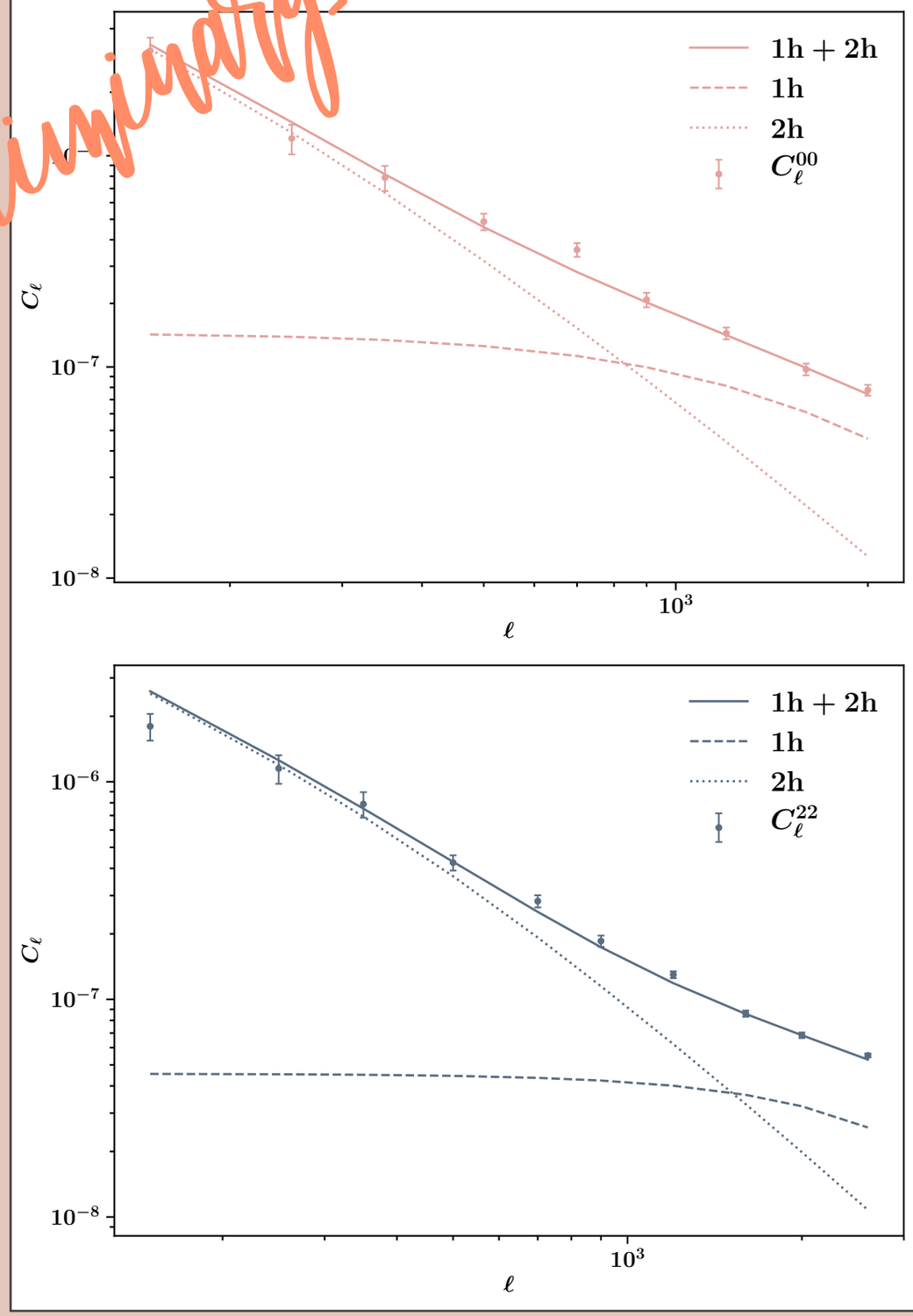
Theoretical Modeling

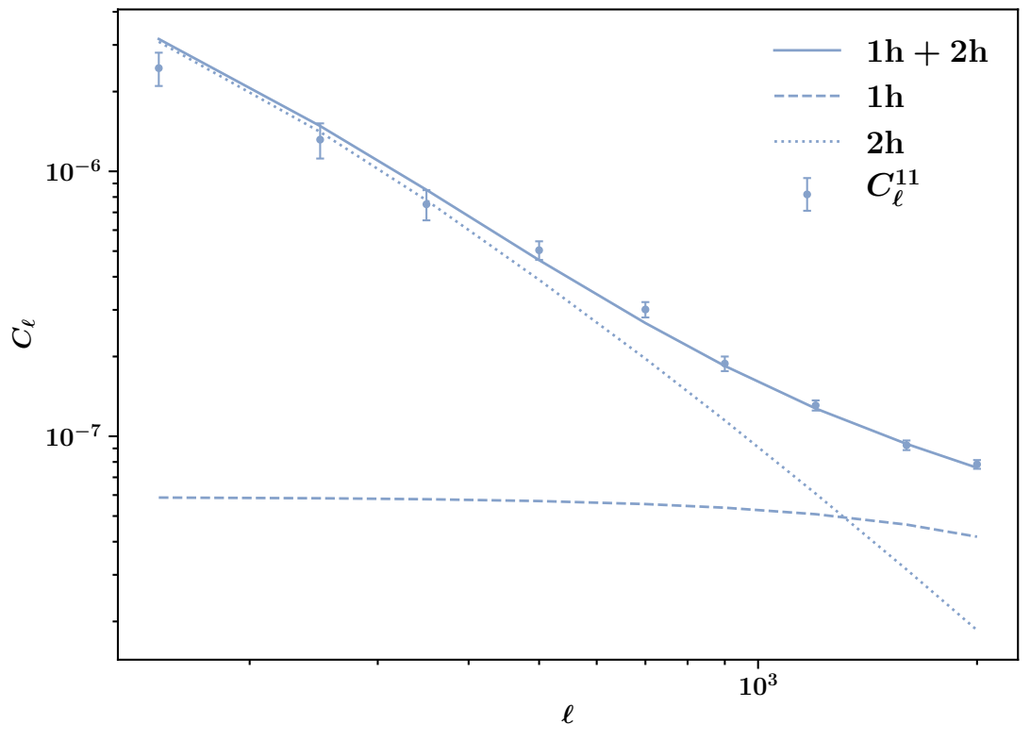
Small-scale clustering ($k_{max} \sim 1$ Mpc^{-1})
Halo model (e.g. *Seljak 2000*, *Peacock et al., 2000*, *Ma et al., 2000*)
Halo occupation distribution (e.g. *Berlind & Weinberg, 2002*)

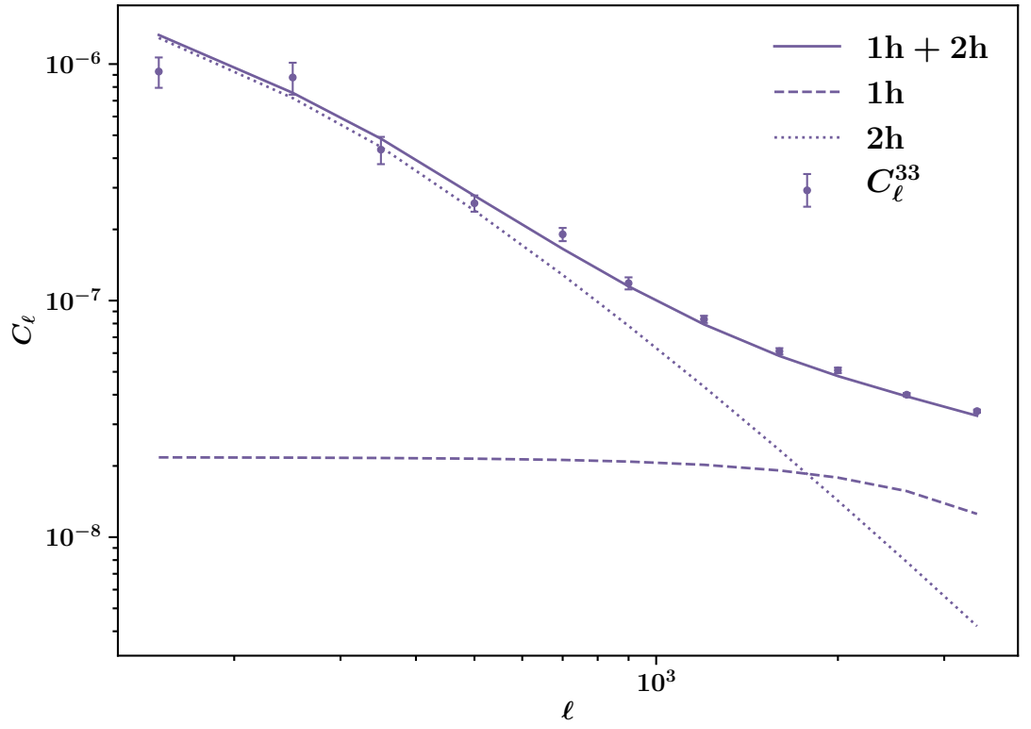


HSC Clustering

Preliminary!







LSST DESC et al., in prep.

Joint Analysis HSC-ACT

Combination of HSC weak lensing and clustering with ACT CMB lensing

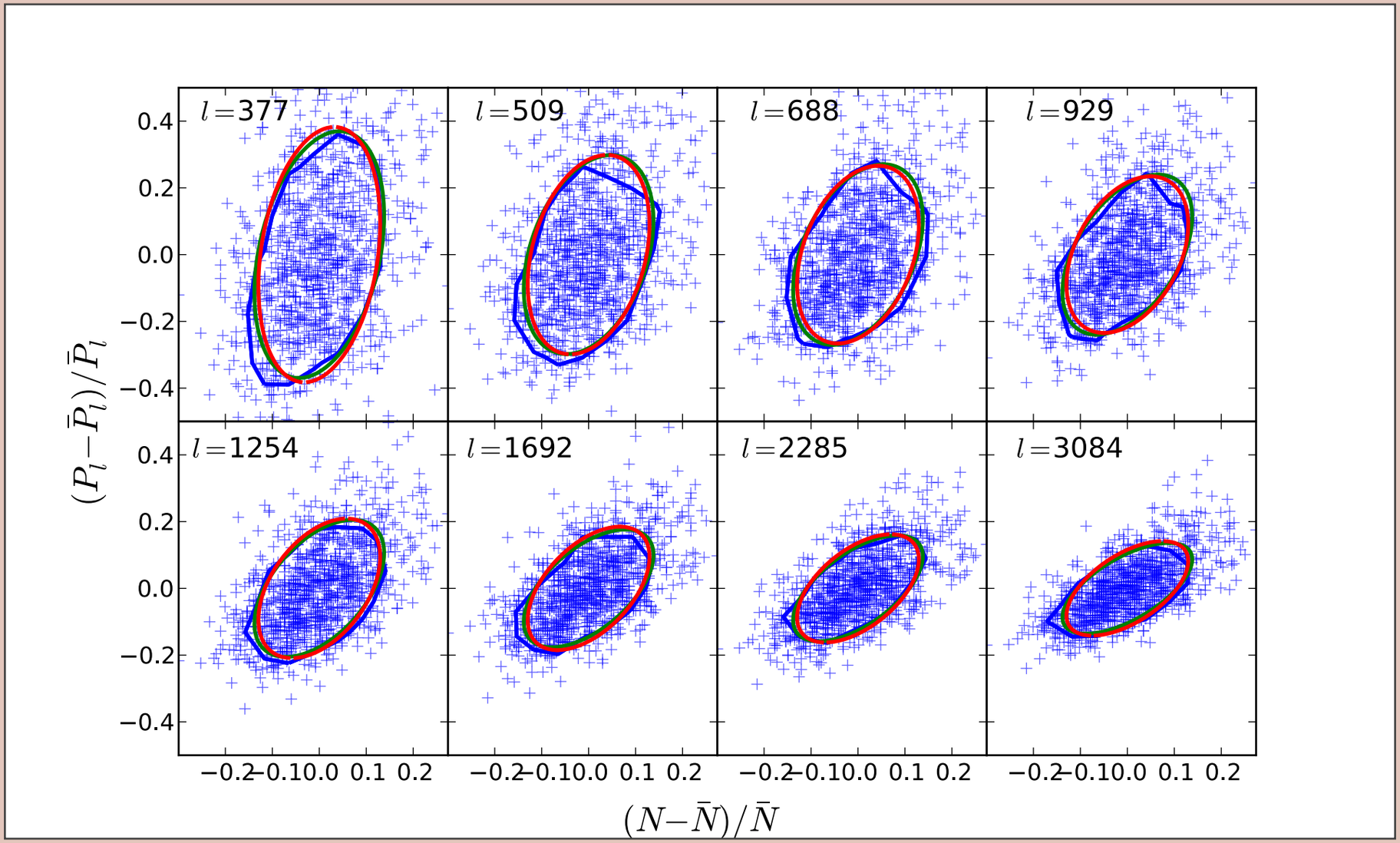
Investigation of impact of photometric redshift uncertainties

Internal HSC consistency check

External systematics calibration

Nicola et al., in prep.

Galaxy Cluster Cosmology & Mass Calibration



Schaan et al., 2014

Summary

Integrated cosmological probe combination
- Break parameter degeneracies
- Robust test of cosmological model
- Identification, understanding and calibration of systematics

Implementation with CMB temperature, CMB lensing, galaxy clustering, weak lensing from SDSS and DES SV and background probes

Quantification of possible tensions with external data using relative entropy

Proposed model selection framework based on relative entropy and posterior predictive distribution

First results on HSC galaxy clustering

Application of framework to combination of HSC & ACT

Joint probes with galaxy clusters

Messi vielmol!

(for reference: Thank you in swiss german)