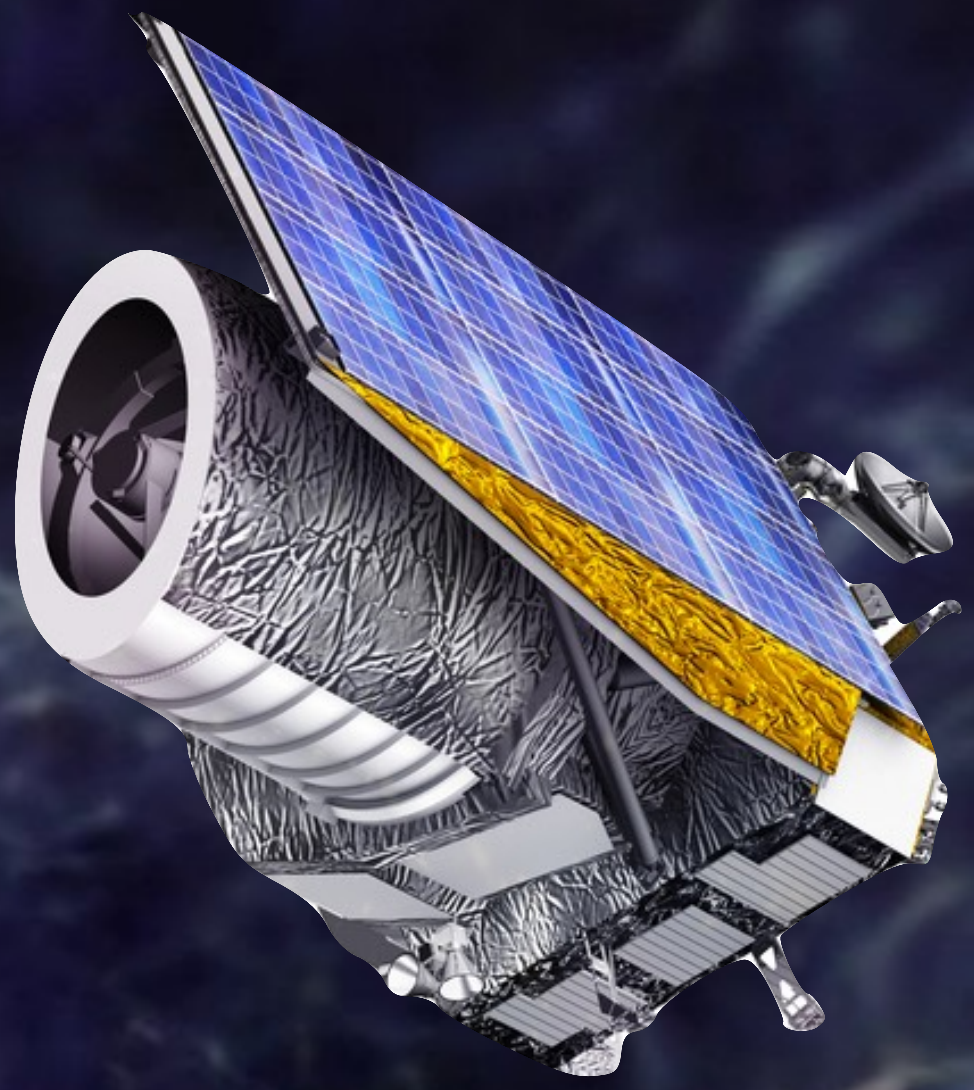


The Euclid Spectroscopic Sample

a unique opportunity to test General Relativity

Elena Sarpa

HI Density

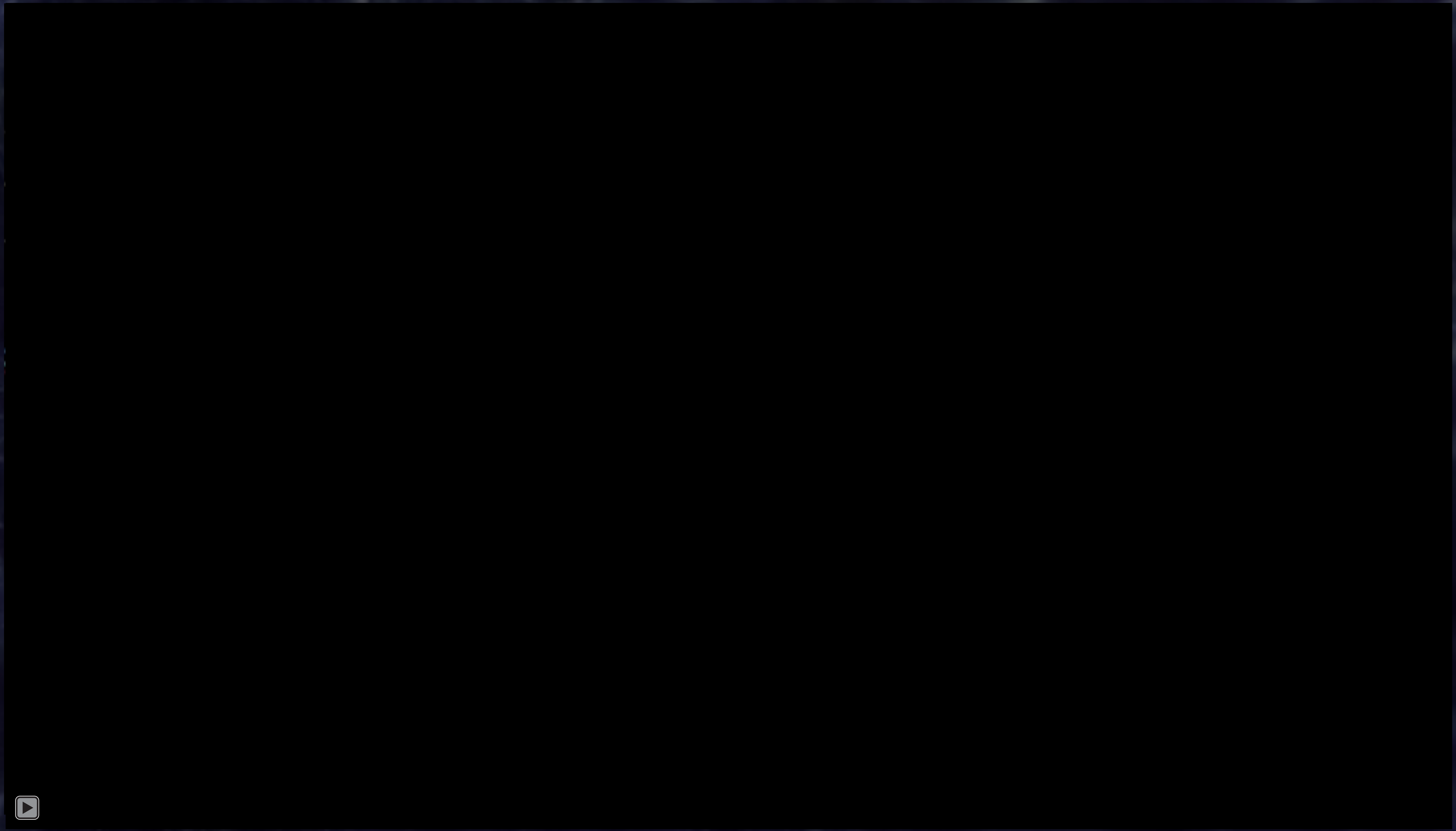
Credits: M. Norman & H. Xu, B. O'Shea, M. J. WiseKyungjin Ahn, Chosun U.

A journey that just began

Launched the 1st Jul 2023

The widest galaxy survey to date

1st data released in 2025



GET READY !

HI Density

THE DARK UNIVERSE

- **Dark Matter (DM)**

  * Infer the DM distribution and abundance from light deflection

  * Trace the growth of structures as a function of time

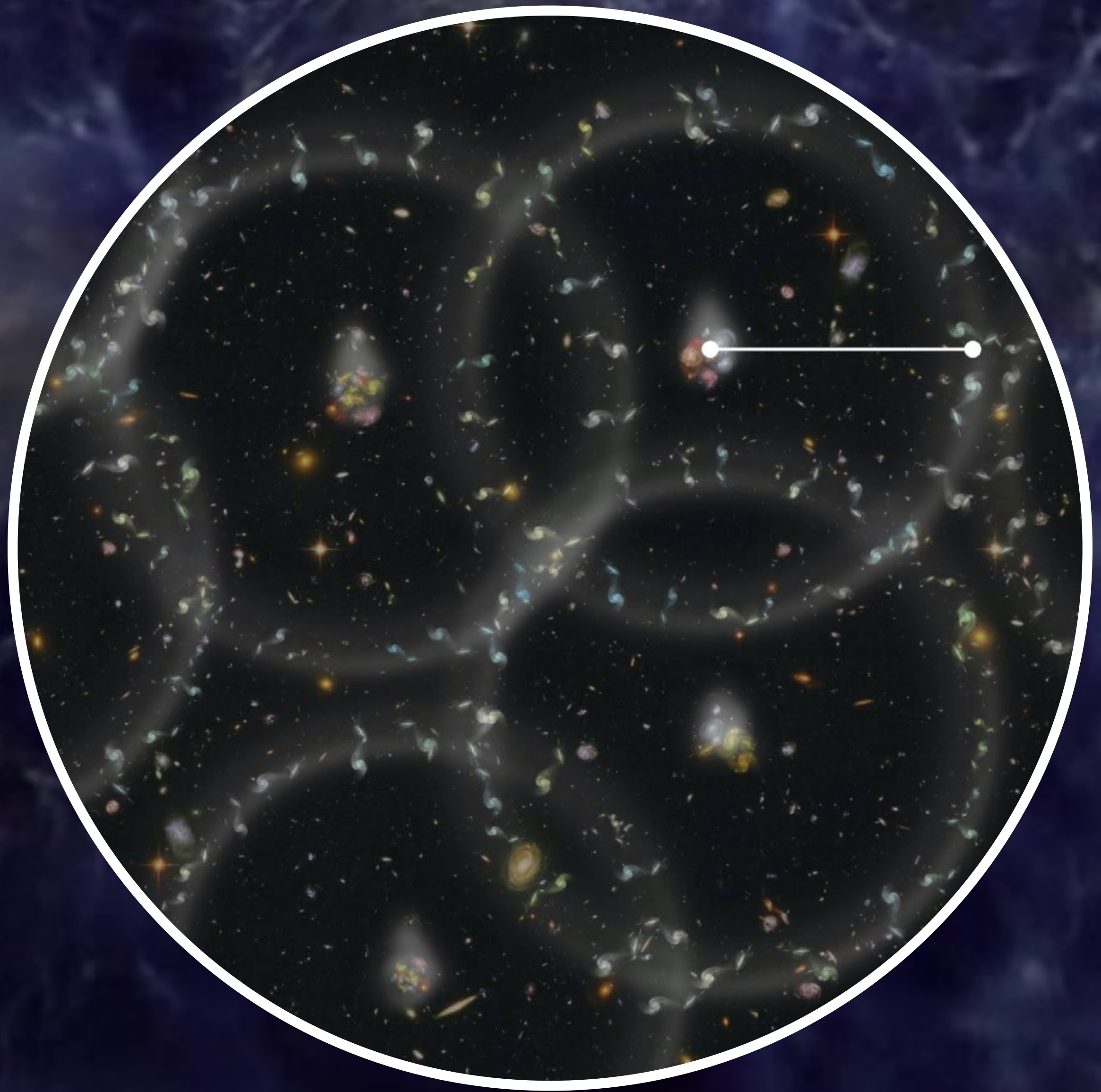
- **Dark Energy (DE)**

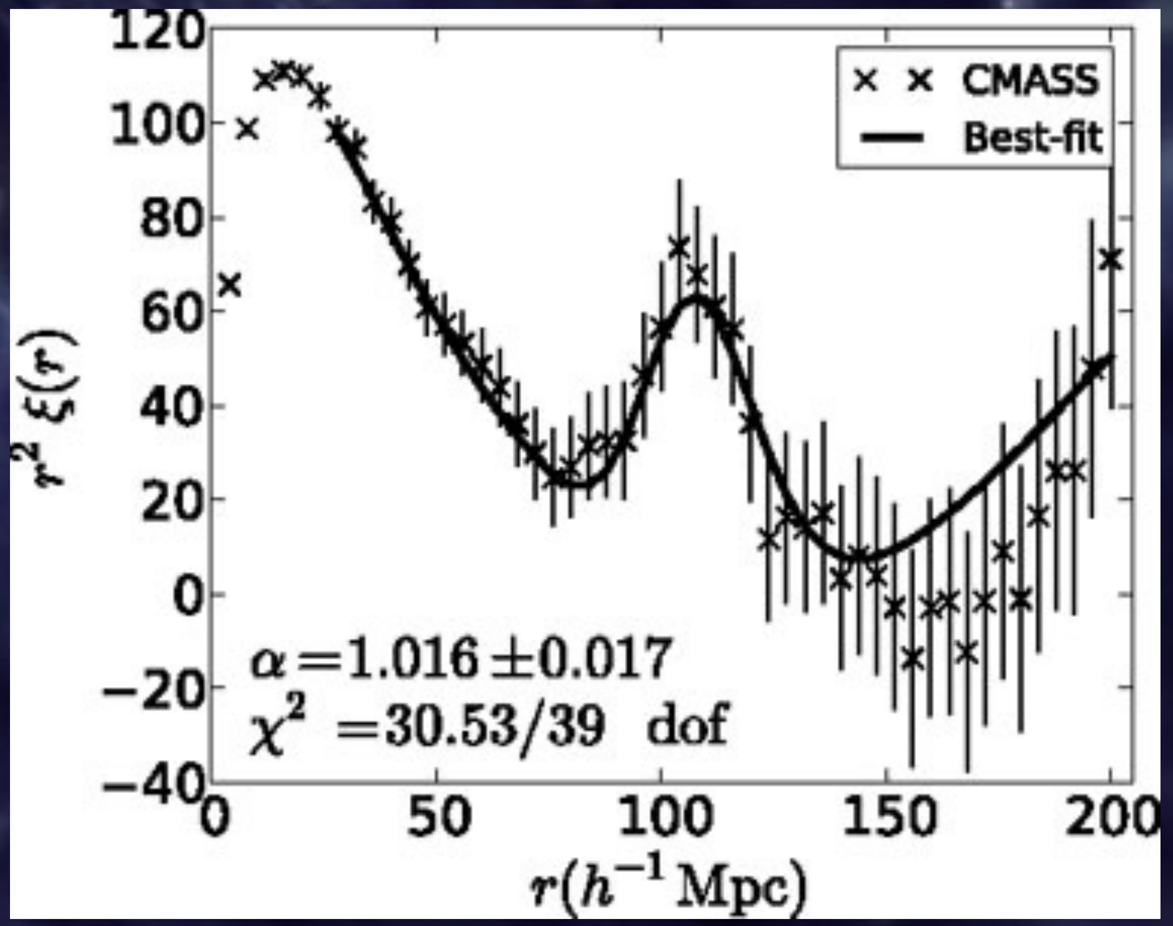
  * Constrain the expansion history of the Universe and growth of structures from the observed 3D distribution of galaxies

  * Study the properties of the source of expansion (e.g. DE equation of state)

WEAK GRAVITATIONAL LENSING

GALAXY CLUSTERING





SDSS-BOSS DR9 (Anderson et al. 2012)

THE WIDE SURVEY

Euclid preparation: I. The Euclid Wide Survey
[Scaramella et al. 2021, arXiv:2108.01201]

- **The instruments**

  * VISible instrument (VIS):
    imaging in the visible light,
    used for weak lensing

  * Near infrared Spectrometer and Photometer (NISP):
    galaxies angular positions and spectra,
    used for galaxy clustering studies

- **Survey specifics**

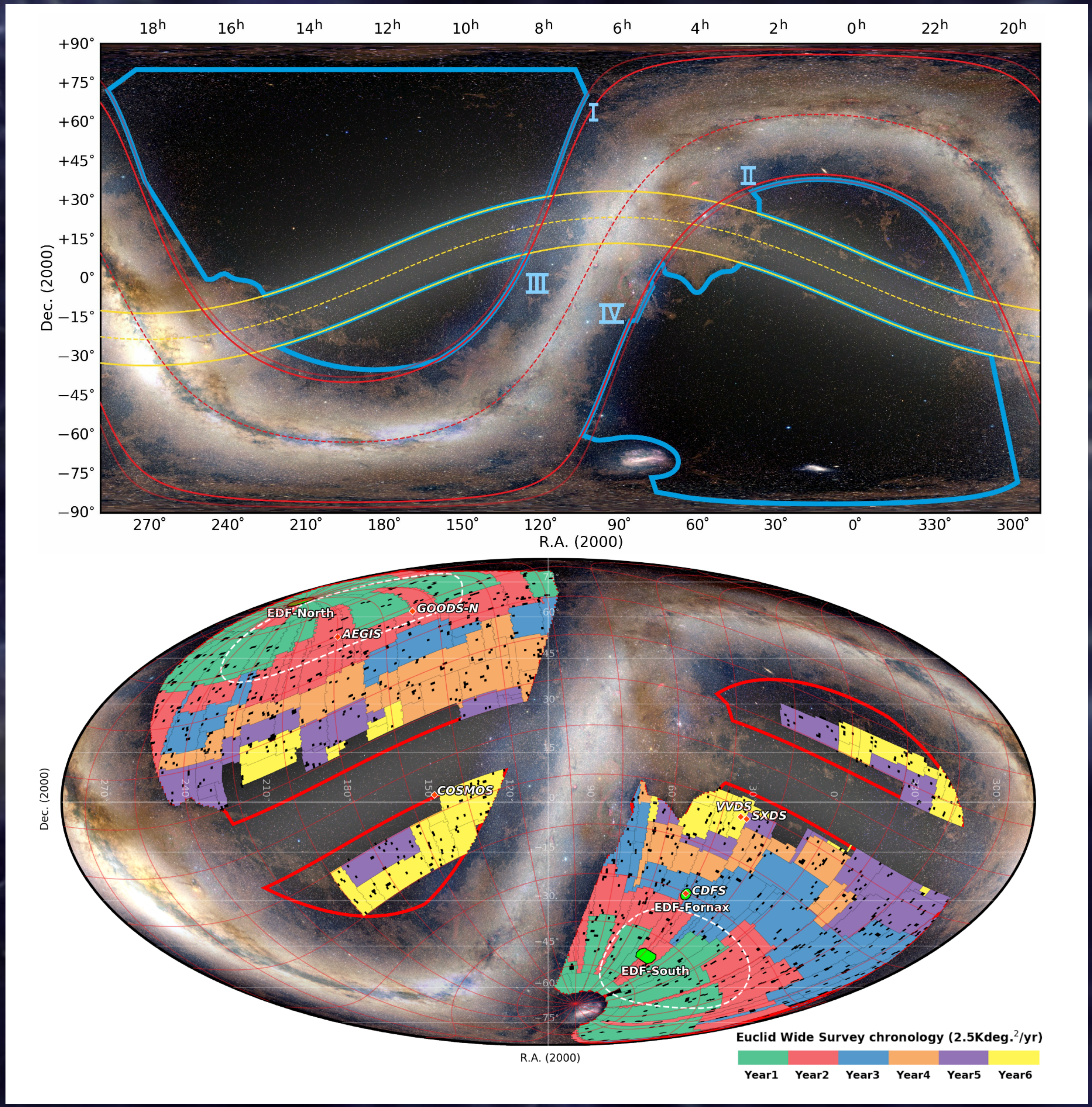
  * Area: 15000 deg^2, 1/3 full sky
  * Redshift range: $z \in [0.9, 1.8]$,
    (look-back time $\in [7.4, 10.3]\ Gyr$)

  * Objects: 1.5 billions of photometric galaxies,
    30 millions of spectra

- **Public data release**

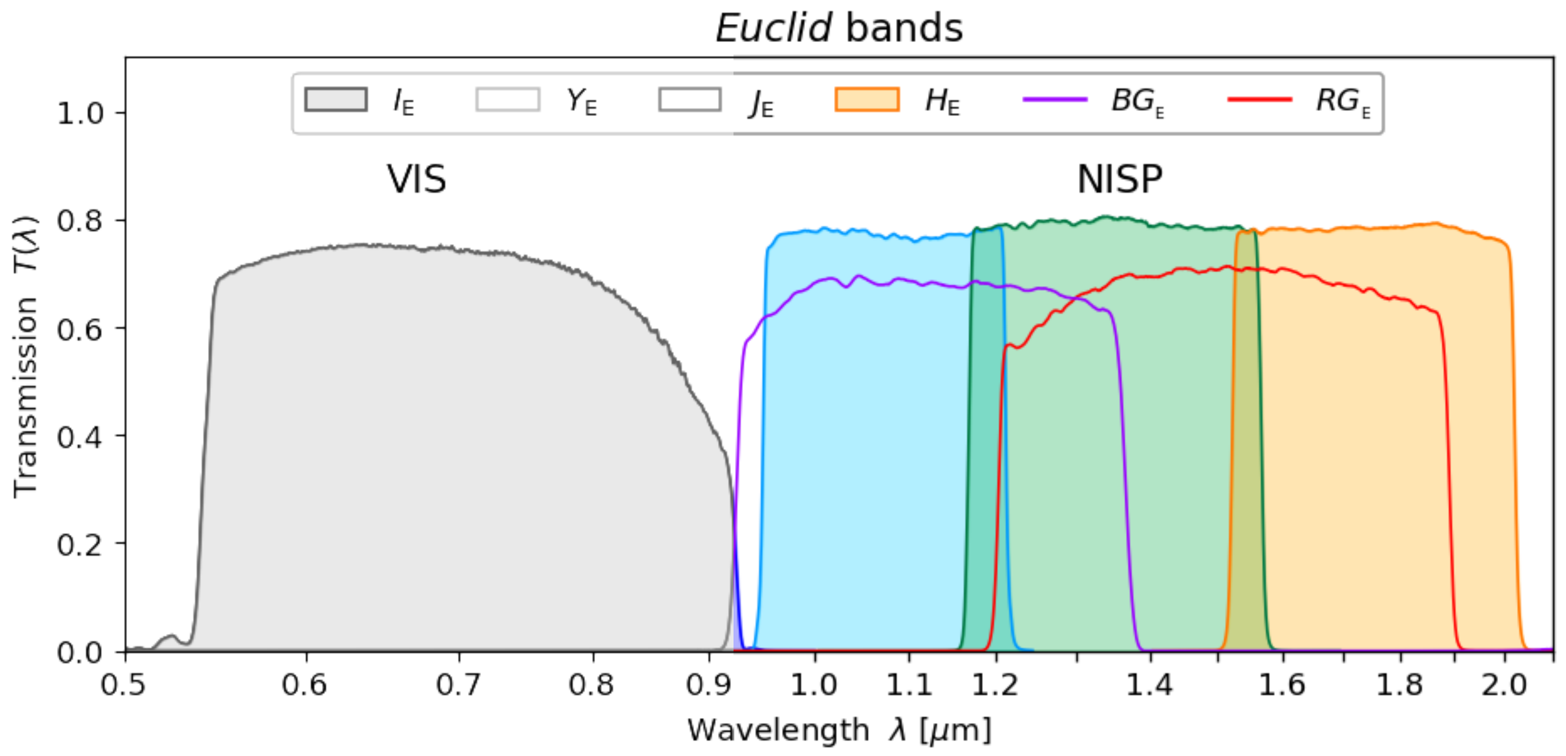
  * DR1: mid 2025 (1/6 of the survey)
  * DR2: mid 2027 (1/2 of the survey)
  * DR3: mid 2031 (full survey)

SURVEY FOOTPRINT

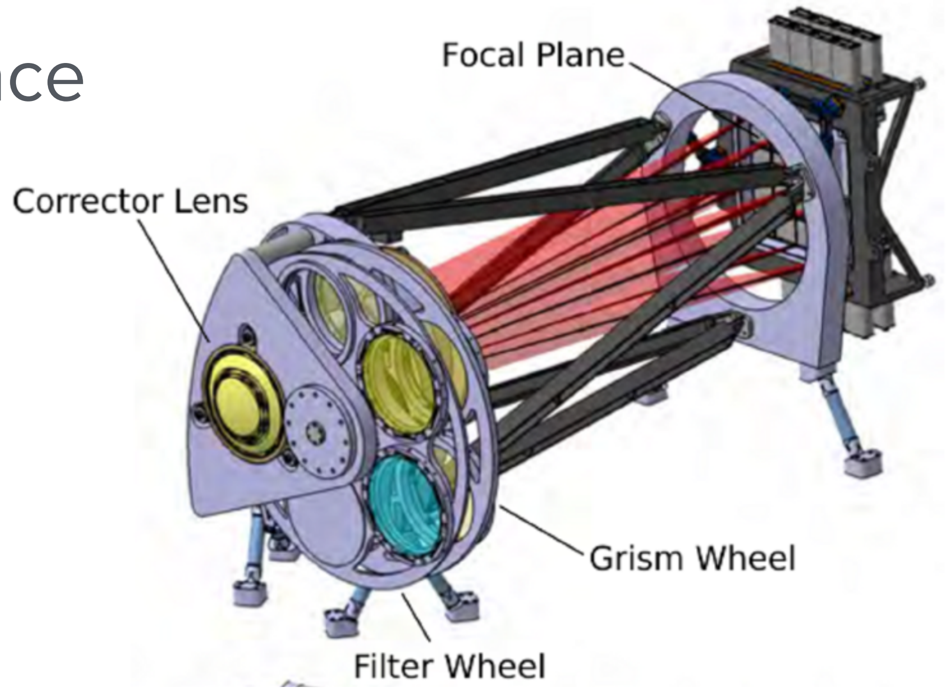


THE SPECTROSCOPIC SURVEY

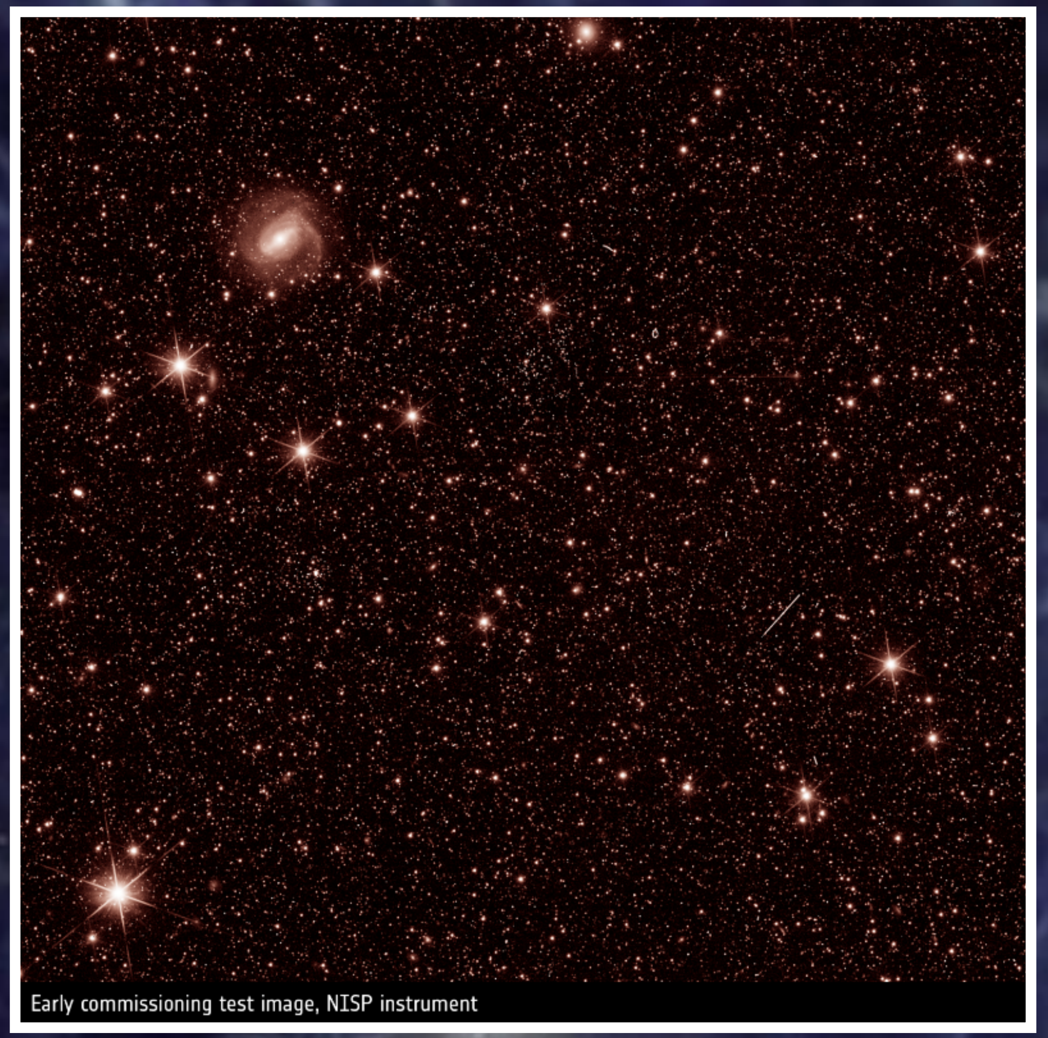
- **Imaging**
  * Direct images in 3 bandpasses

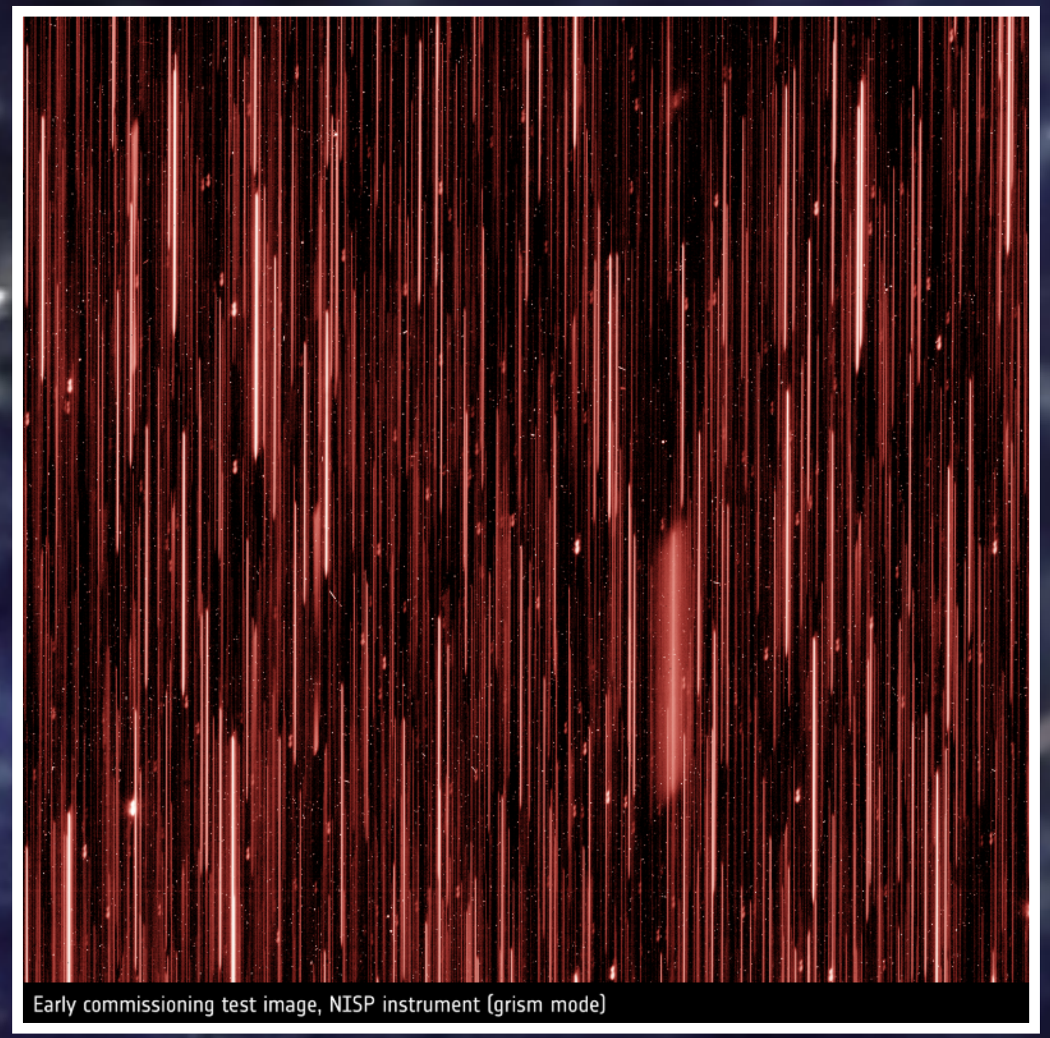


- **Spectra**
  * Grism (slitless):
    projects spectra of every source along one axis
  * Individual spectra identified trough rotation (0°,180° + telescope rotations)
- **Fun fact:** no fibers in space

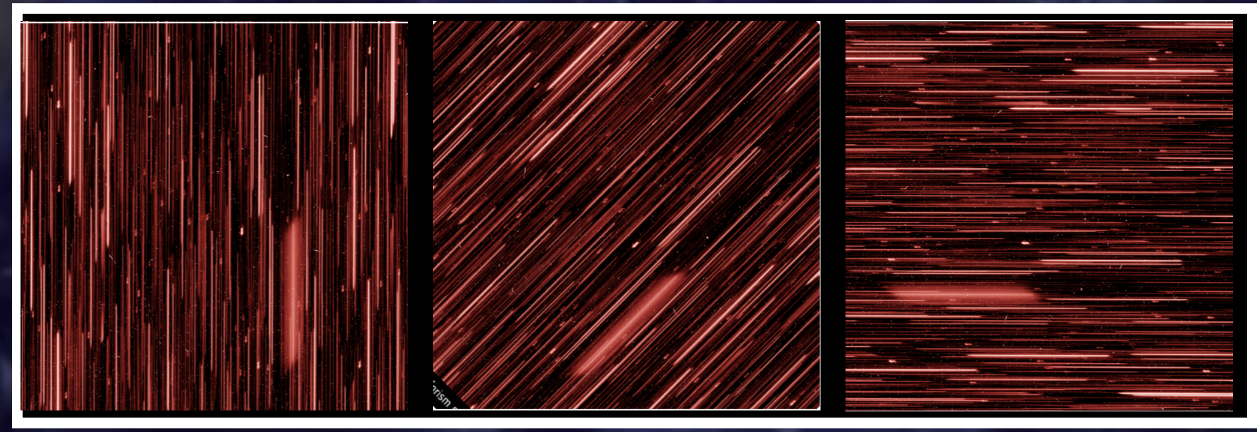


EUCLID FIRST LIGHT (Jul 28th 2023)

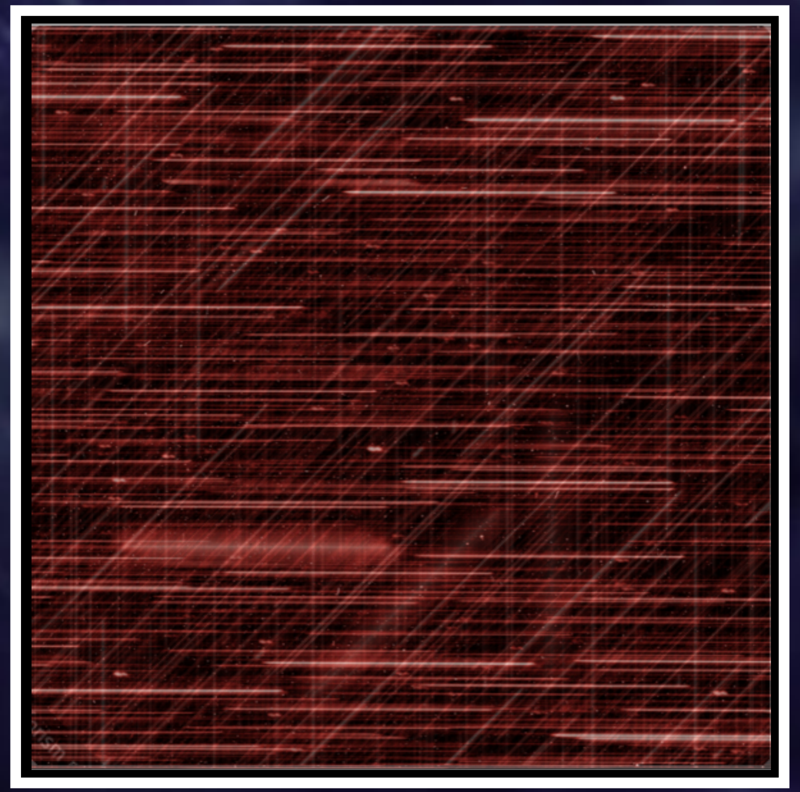




Multiple angles



spectra superposition

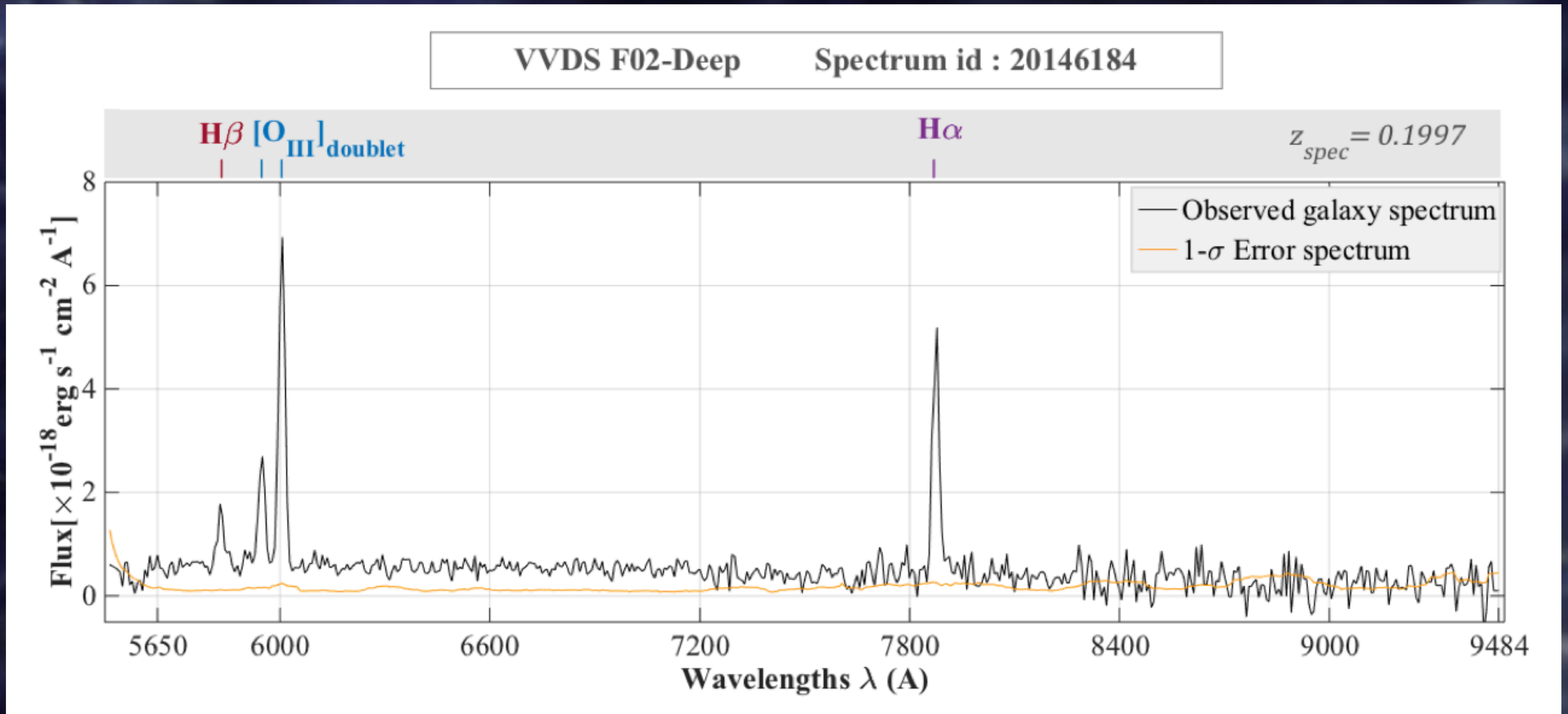


REDSHIFT DETERMINATION

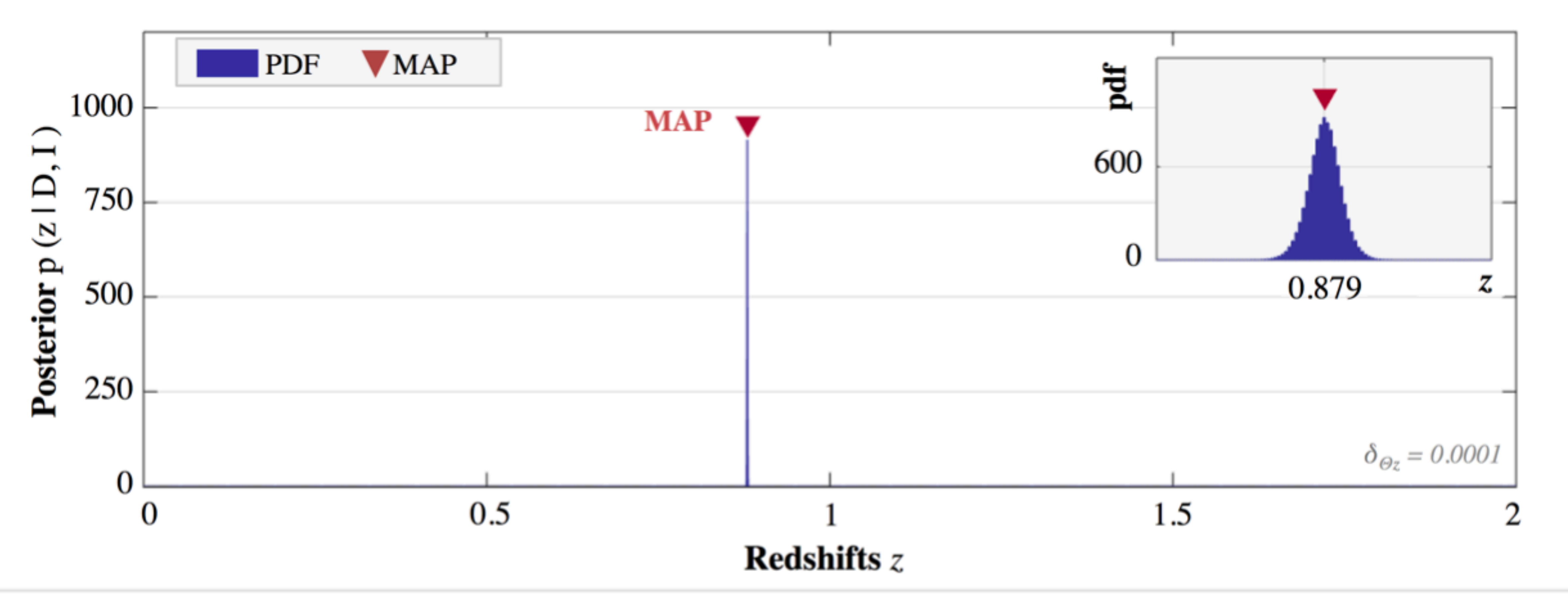
- **Cosmological redshift**
  * The source spectral light gets progressively “stretched” (redshifted) by the Universe’s expansion in its journey from the galaxy to Euclid
  * A proxy of distance and time of emission
  * With angular position, gives the 3D map of the galaxy distribution

- **Redshift extraction**
  * Identify emission/absorption lines
  * Estimate the redshift by comparison with fiducial templates

SOURCE SPECTRA



REDSHIFT POSTERIOR

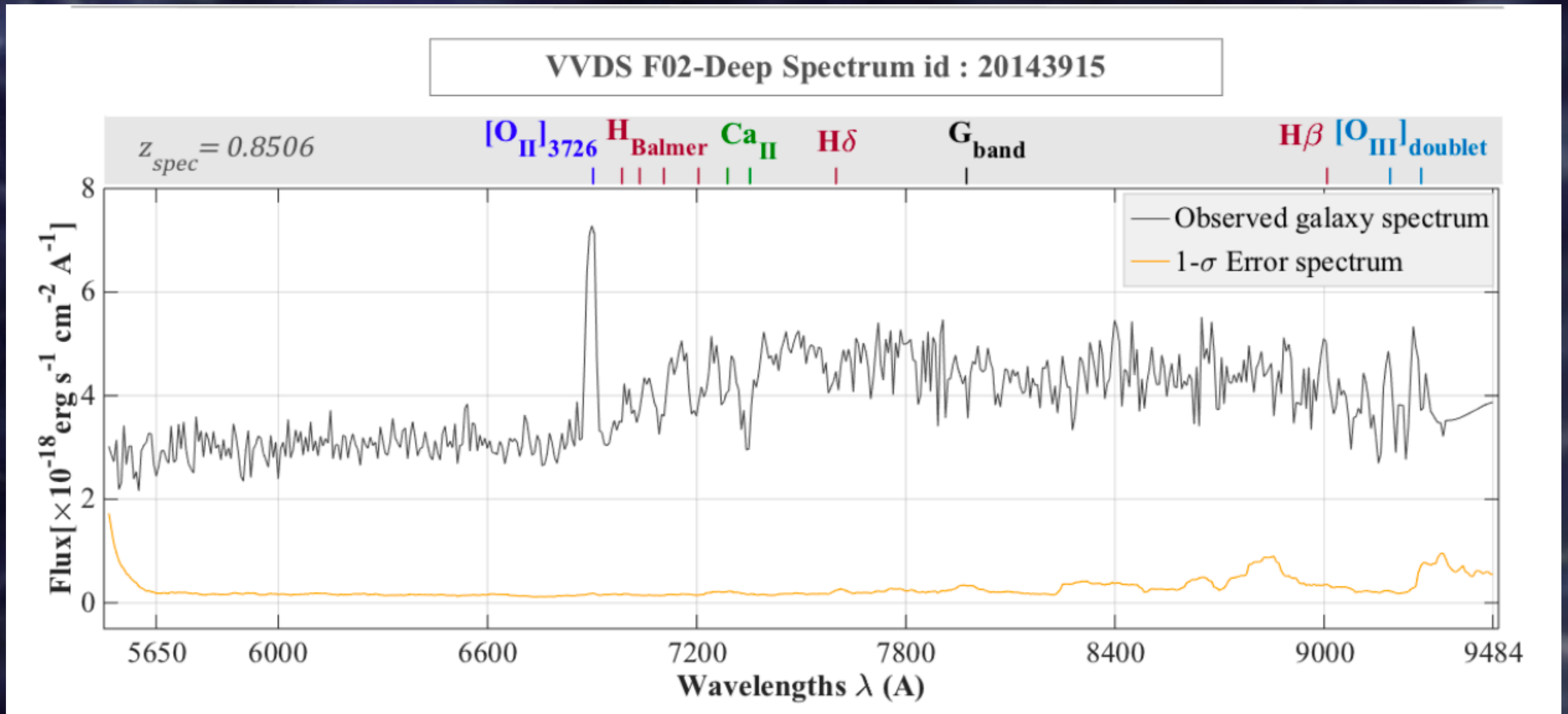


Credits: Jamal et al. 2017

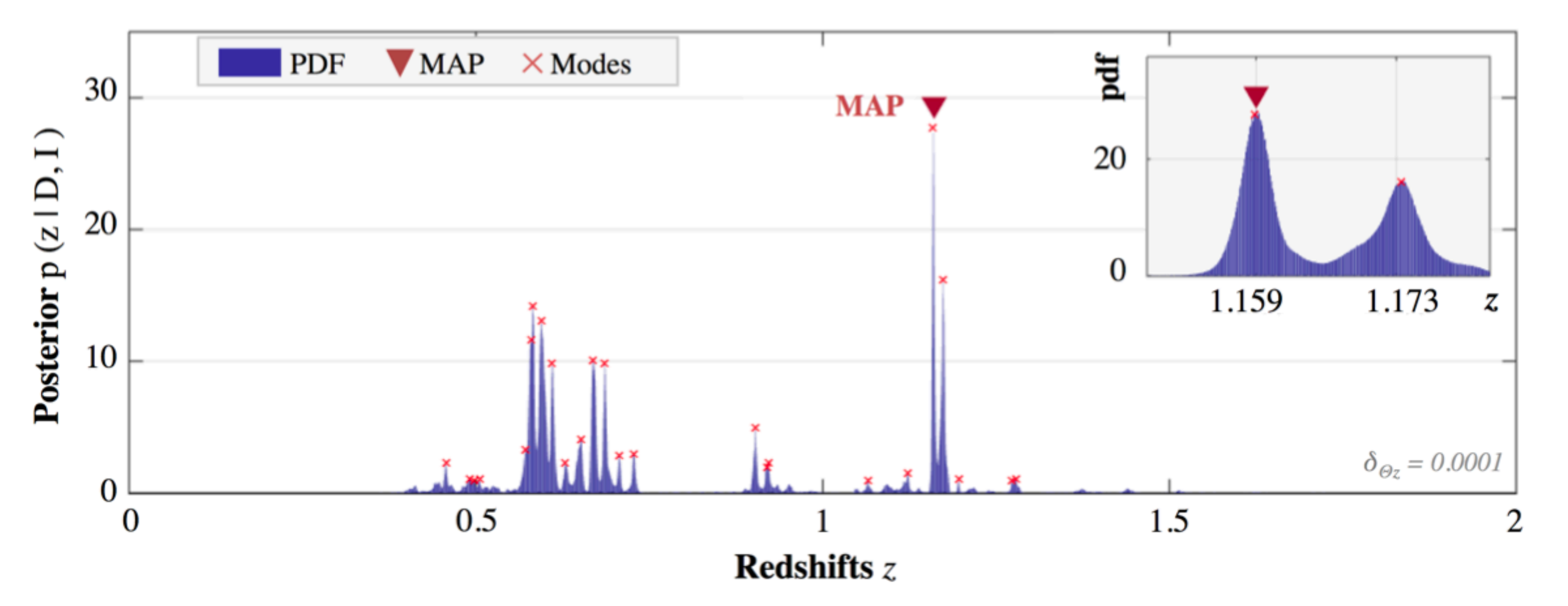
RELIABILITY

- **Problematic spectra**
  - * Low signal-to-noise ratio
  - * Single emission line
- **Redshift posterior**
  - * Multimodal
  - * Highly disperse
- **Reliability flag**
  - * likelihood of the redshift to be well determined

SOURCE SPECTRA



REDSHIFT POSTERIOR



Credits: Jamal et al. 2017

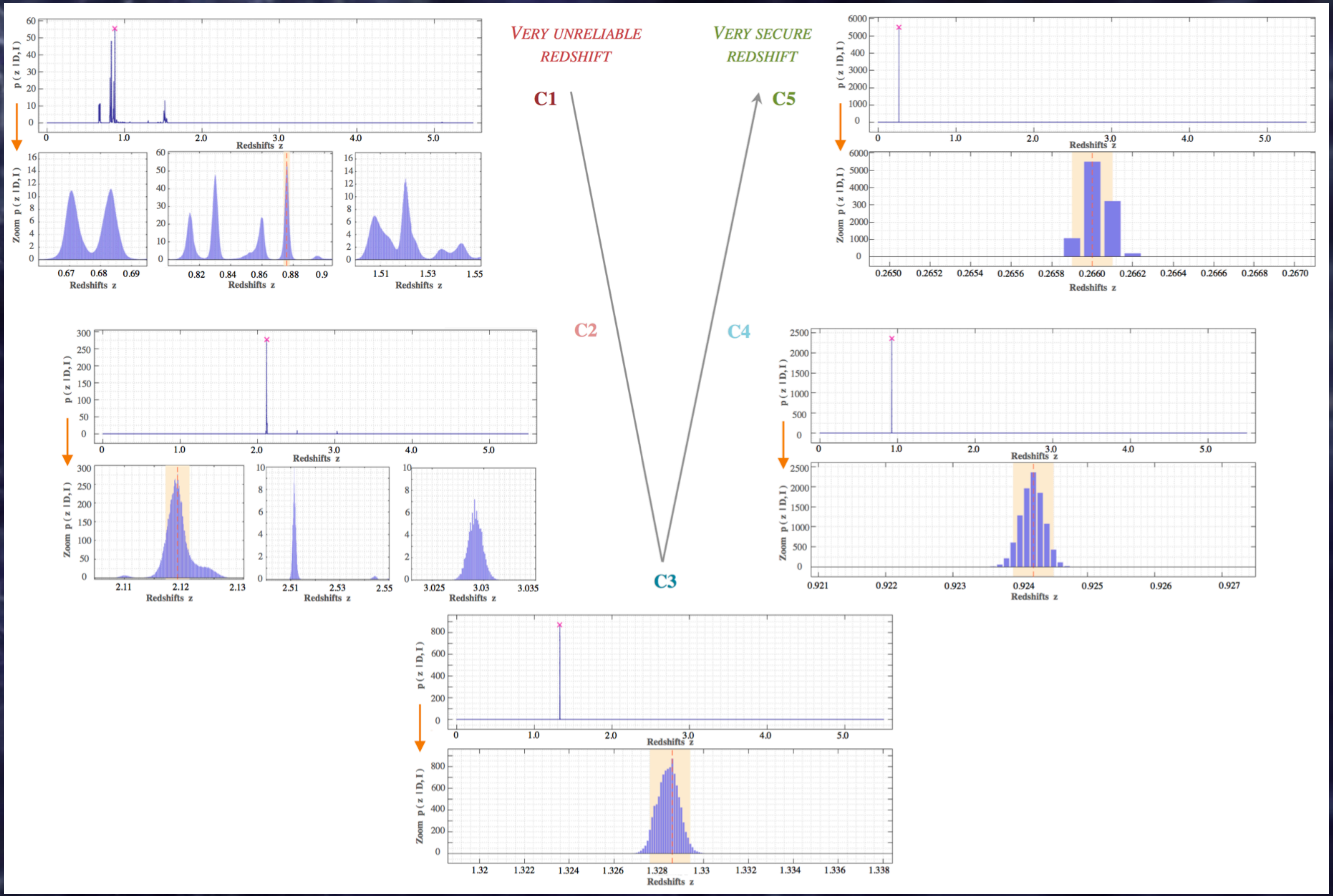
AMAZED: EUCLID SOFTWARE

Jamal et al 2017

- **Machine learning redshift classification,** based on bayesian inference
- **Reliability classes**
  * C1: highly dispersed PDFs with multiple equiprobable modes
  * C2: less dispersedPDFs, with few modes and low probabilities
  * C3: low σ, intermediate probabilities
  * C4: unimodal PDFs with low dispersion, higher probabilities
  * C5: strong unimodal PDFs with extremely low dispersion,
- **Results on Euclid mocks**

Set	Fraction of spectra with $\varepsilon_z \leq 10^{-3}$				
	"C1"	"C2"	"C3"	"C4"	"C5"
S1	1/3	59/61	313/313	835/835	1957/1957
S2	260/383	1221/1275	550/555	662/662	294/294

CLASSIFICATION

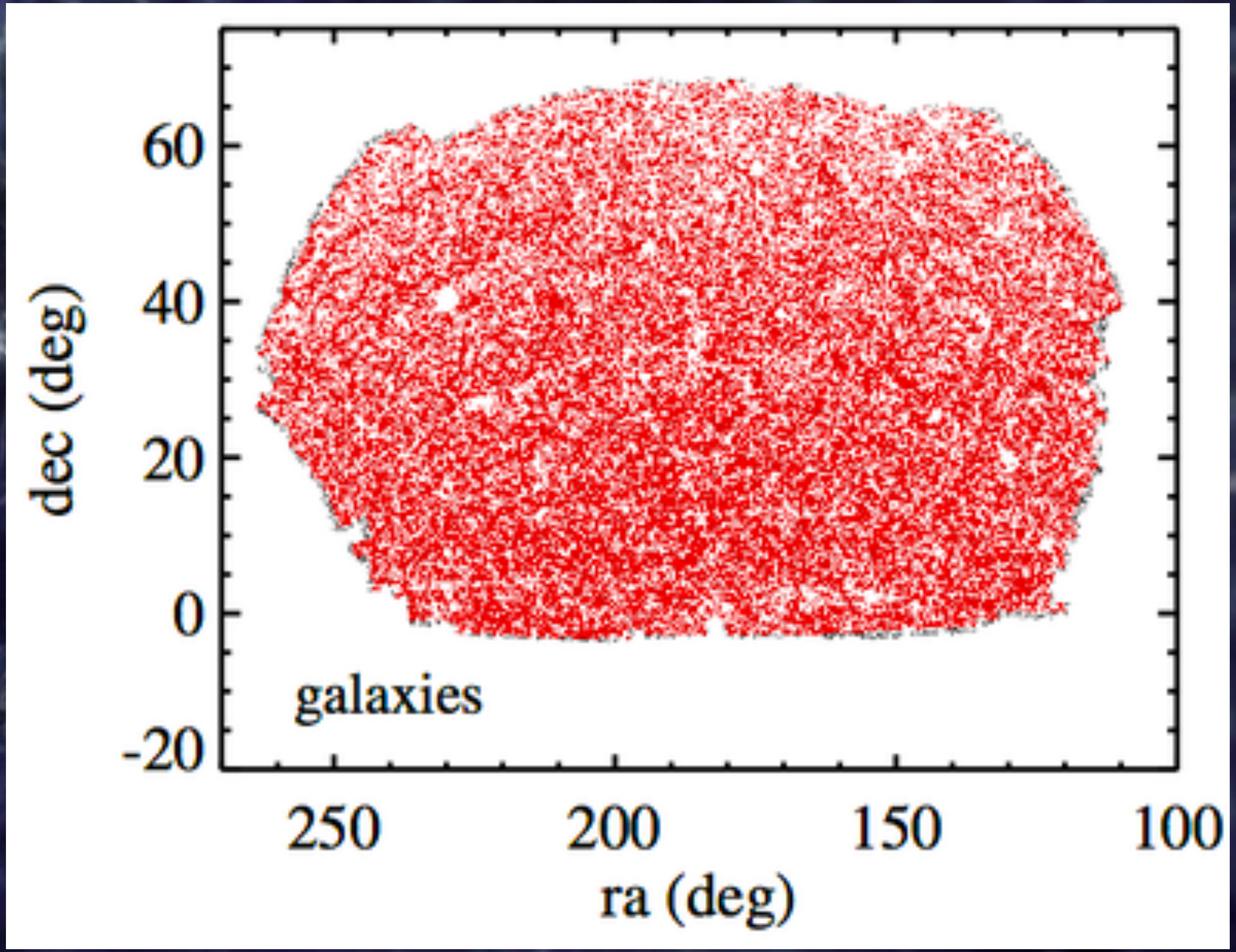


Credits: Jamal et al. 2017

CATALOGUE INFORMATIONS

- **Angular position: RA, DEC**
- **Redshift**
- **Statistical weight** (e.g. seeing, …)
- **Local density** (for Power-spectrum)
- **Reliability flag**
- **Galaxy type: central or satellite**
- **Magnitude in different bans**

GALAXY DISTRIBUTION



Credits: SDSS-DR12, Song et al 2016

Use it wisely! Know your instrument, know your data

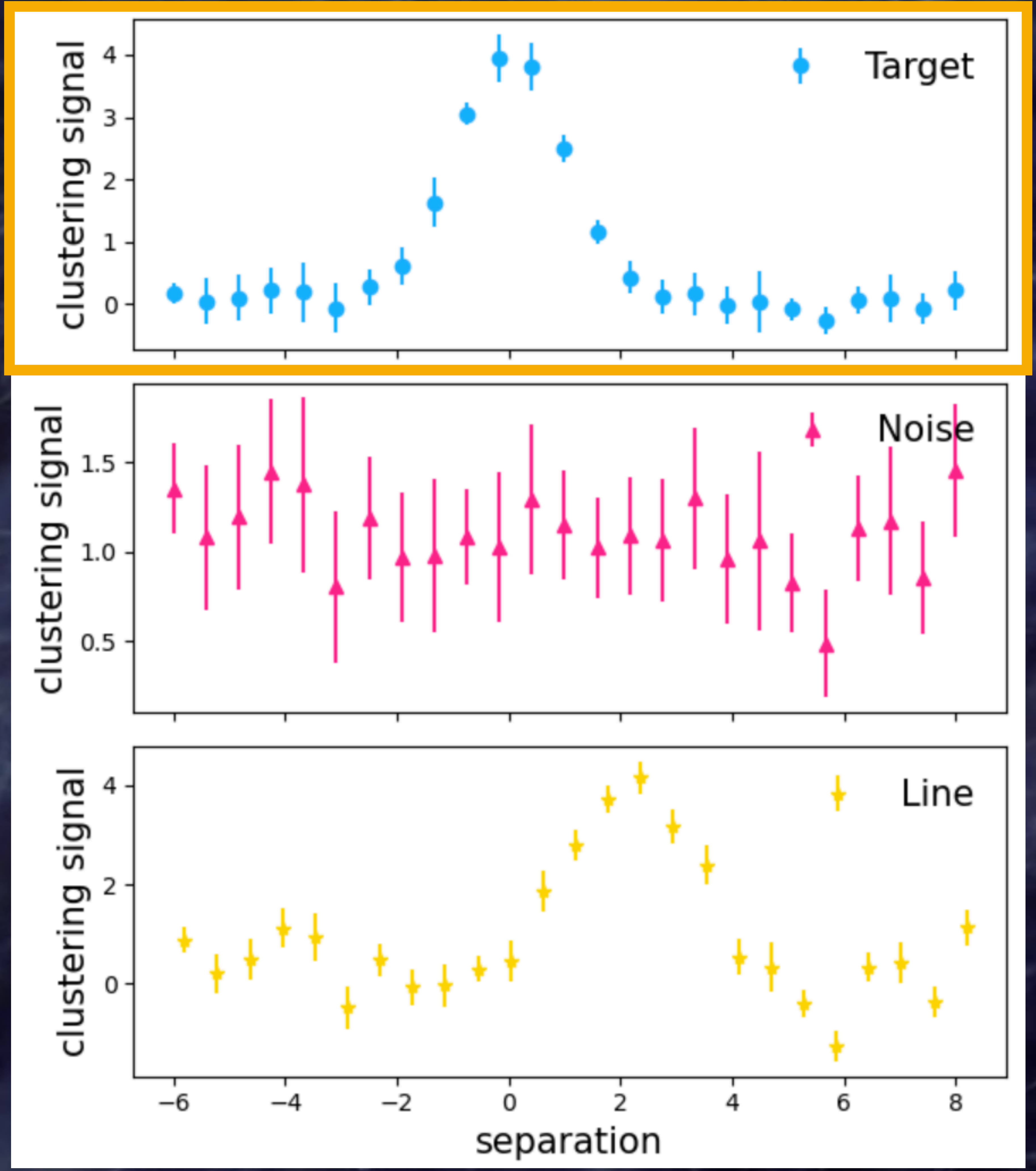
HI Density

CHOOSE YOUR CATALOGUE

MAIN CONTAMINANTS: INTERLOPERS

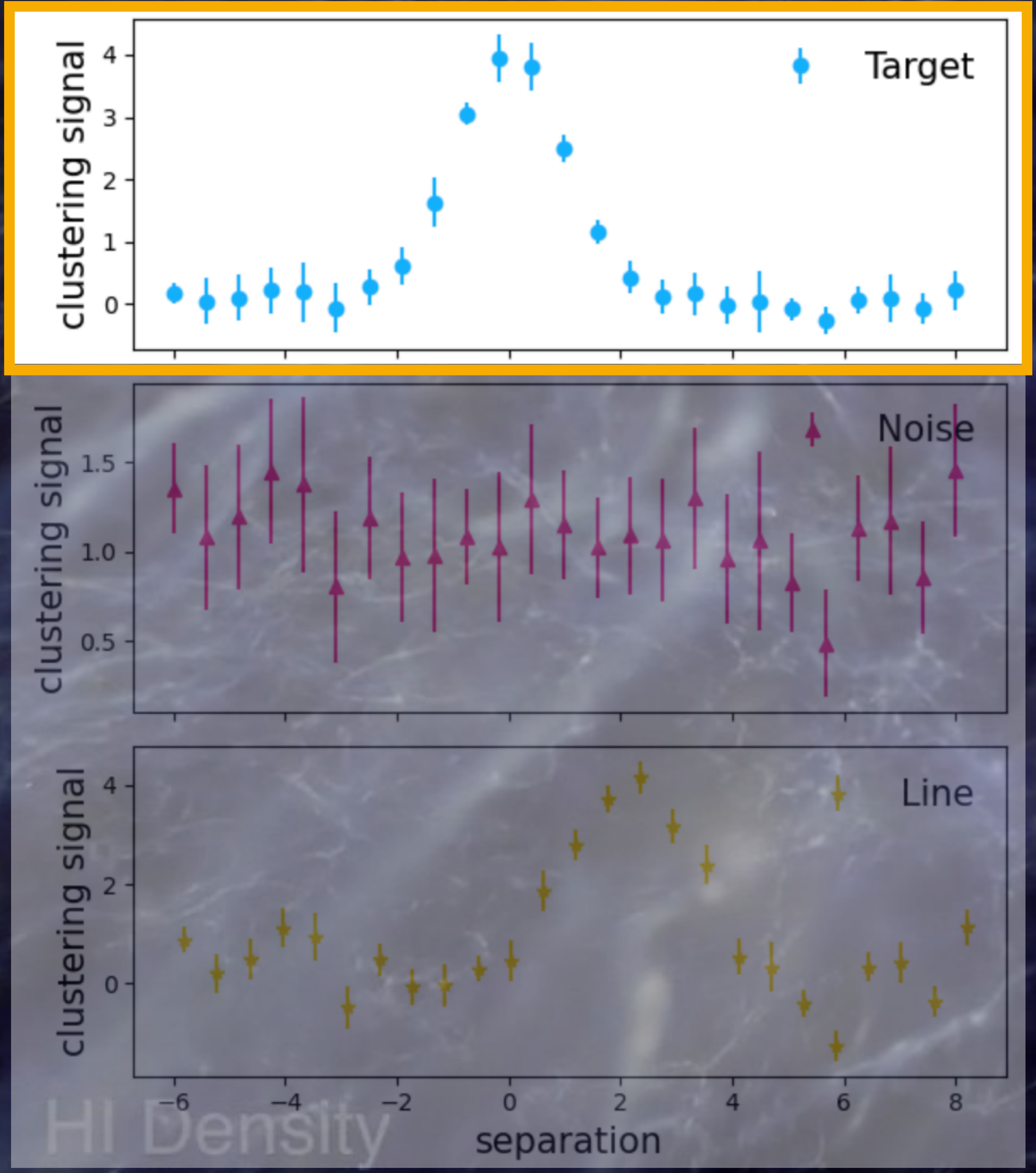
PURE

COMPLETE

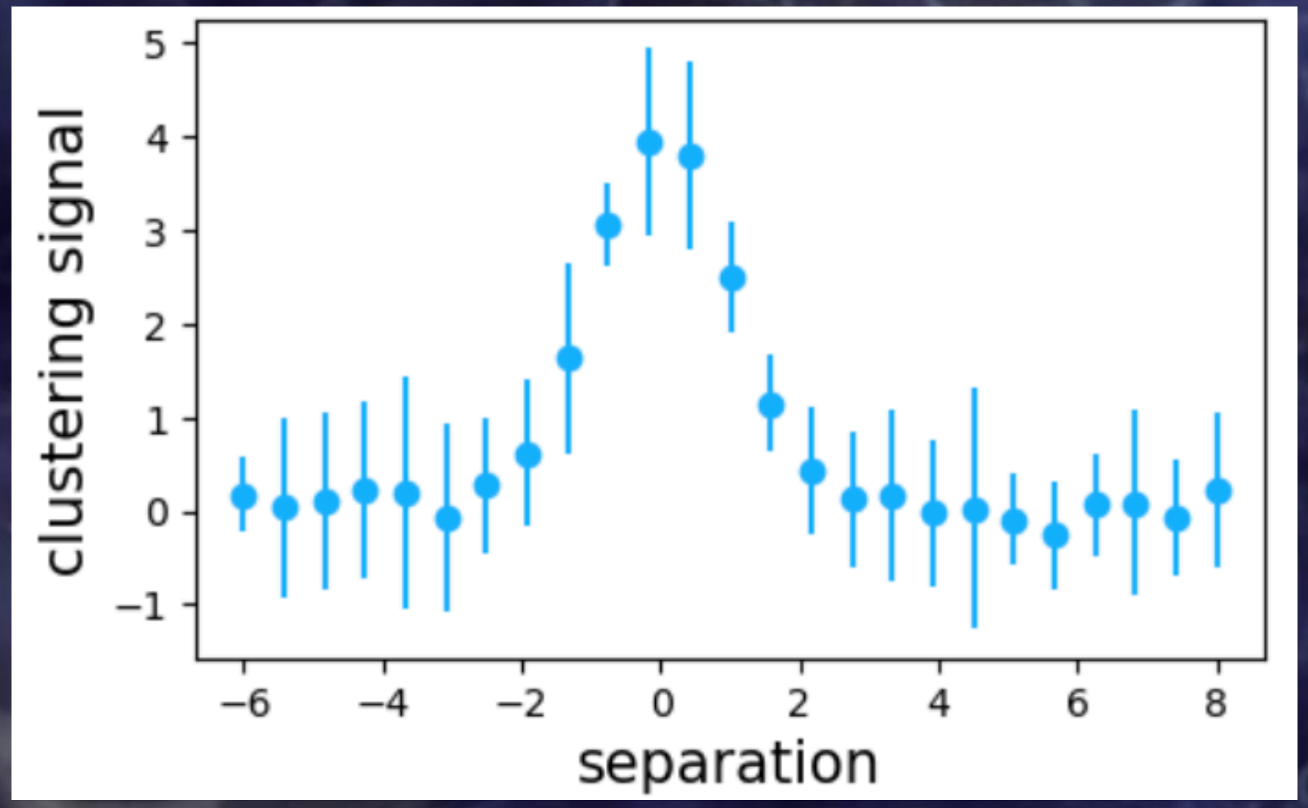


CHOOSE YOUR CATALOGUE

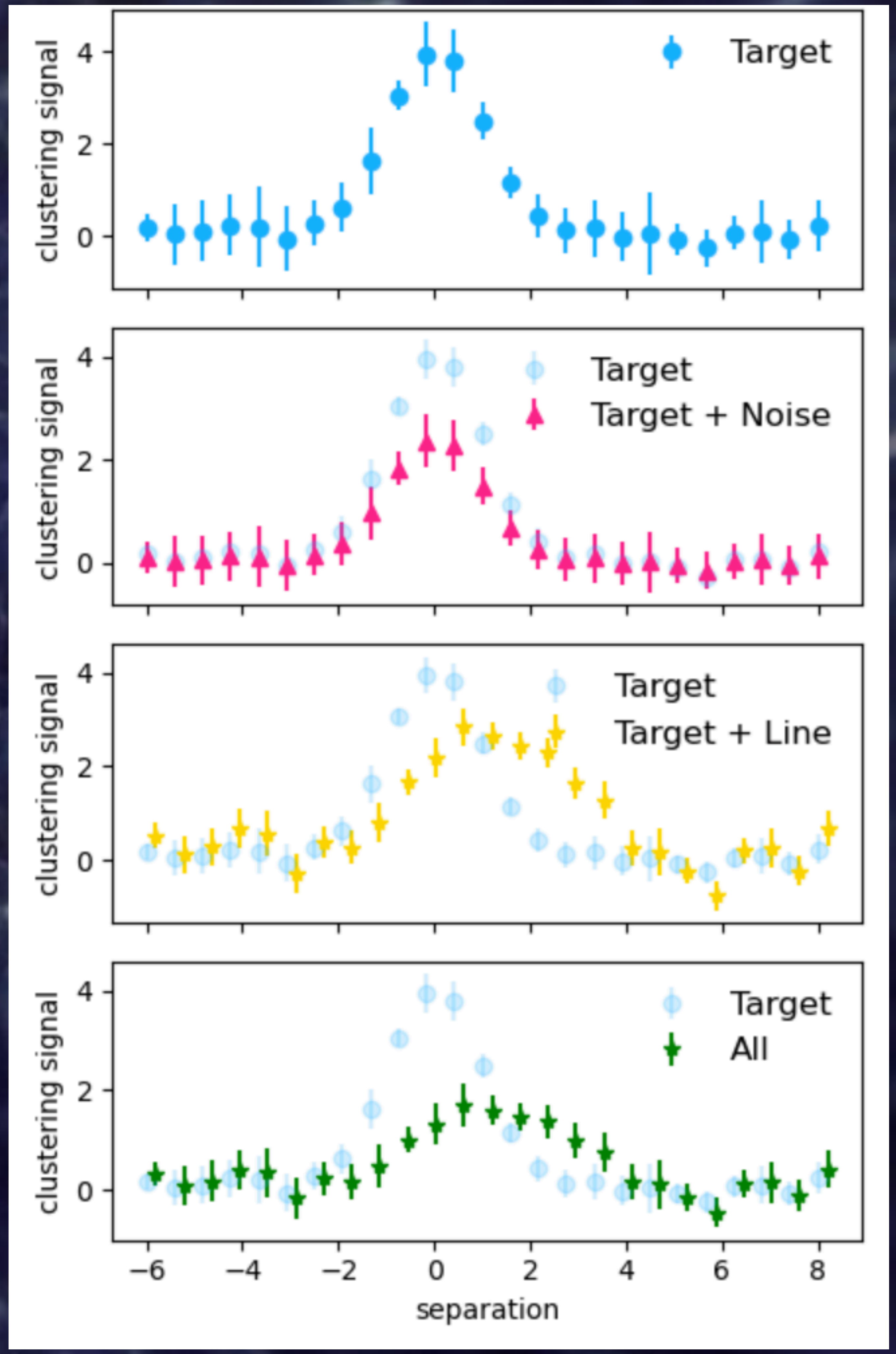
MAIN CONTAMINANTS: INTERLOPERS



PURE



COMPLETE



What are we searching for?

Redshift, distances, and standard spheres

Observe, translate, and compare

COSMOLOGICAL DISTANCES

- **Goal:**
  Find the imprint of the Universe expansion in the galaxy distribution

- **From Redshift, $z_{\rm obs}$, to distances, χ**
  * $\chi(z_{\rm obs}) = \int_0^{z_{\rm obs}} \frac{c dz}{H(z)}$
  * $H(z)$ traces the expansion of the Universe as a function of time

- **Assuming a cosmology**
  * separation along the line-of-sight

  $$s_\parallel^{\rm true} = s_\parallel^{\rm fiducial} \frac{H^{\rm fiducial}(z)}{H^{\rm true}(z)}$$

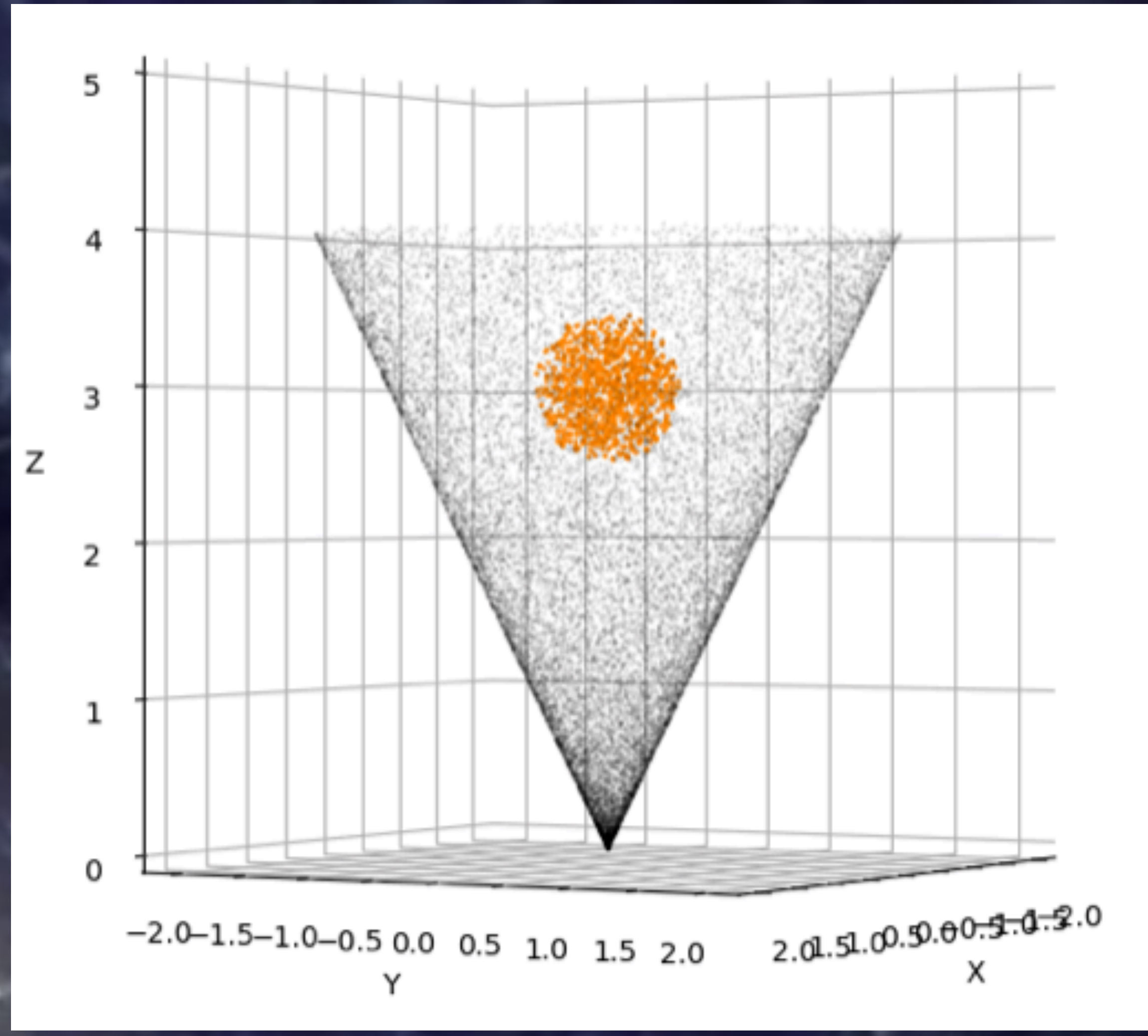
  * separation transfers to the line-of-sight

  $$s_\perp^{\rm true} = s_\perp^{\rm fiducial} \frac{D_{\rm A}^{\rm true}(z)}{D_{\rm A}^{\rm fiducial}(z)}$$

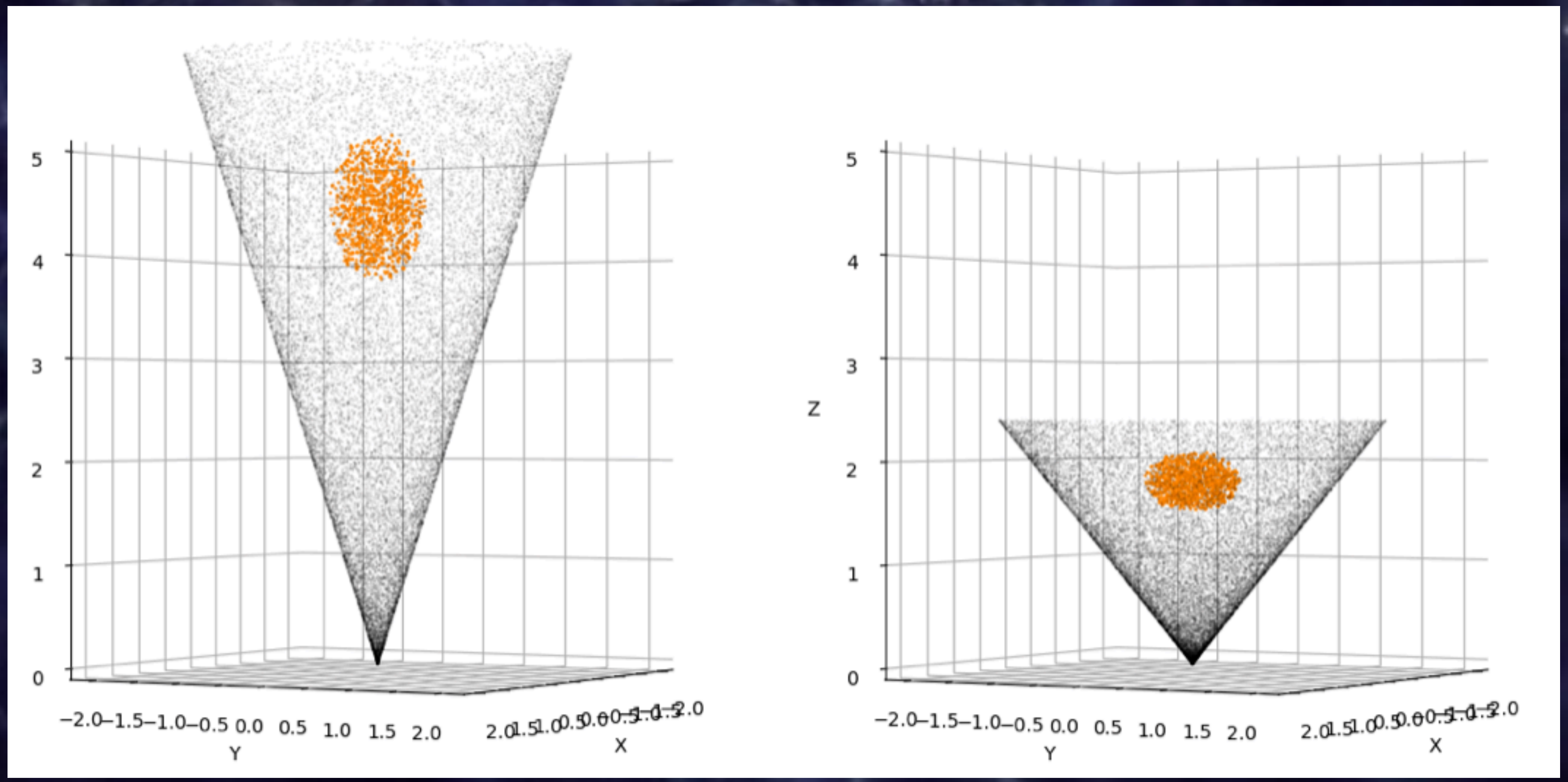
- **Find the true cosmology**
  * Observe features of known size and symmetry (e.g. spherical)
  * Measure their observed shape and size
  * Model the distortions to constrain true cosmology

OBSERVING A SPHERE

$H^{\rm fiducial} = H^{\rm true}$



$H^{\rm fiducial} < H^{\rm true}$ $\qquad$ $H^{\rm fiducial} > H^{\rm true}$



BARYON ACOUSTIC OSCILLATIONS

- **BAO as a standard ruler**
  * Ripples in the galaxy distribution formed in the primordial Universe
  * **Peaks/isotropic rings** in the 2-point clustering statistics of galaxies, ξ
  * **True size well known** from Cosmic Microwave Background Measurements (Planck)
- **Observed distortions**
  * **Fiducial cosmology different from true one**
  * Peculiar motion of galaxies: redshift-space distortions

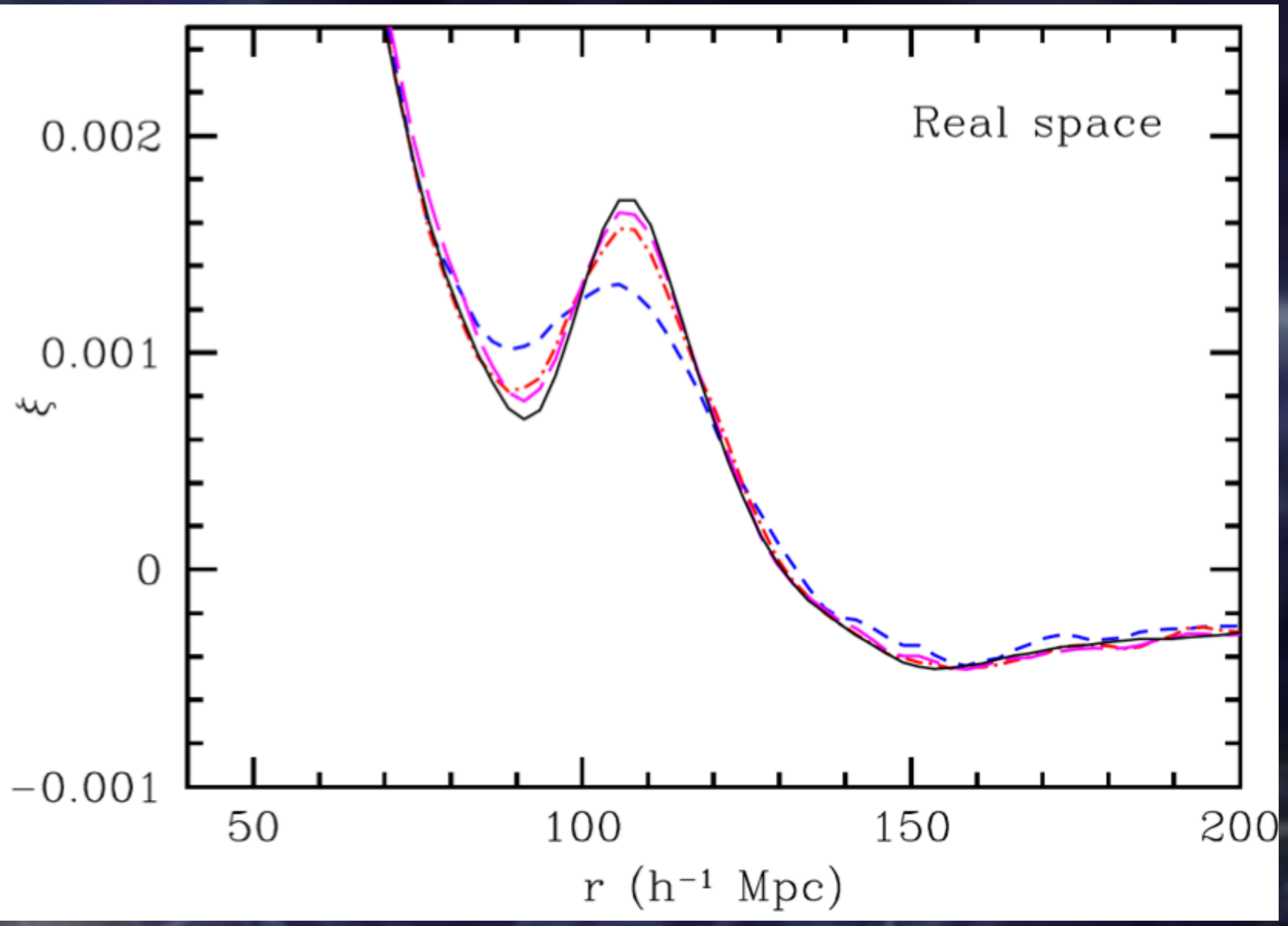
$$z_{\text{obs}} = (z_{\text{cosmo}} + 1)(z_{\text{pec}} + 1),$$

$z_{\text{pec}} = v/c$: Doppler shift

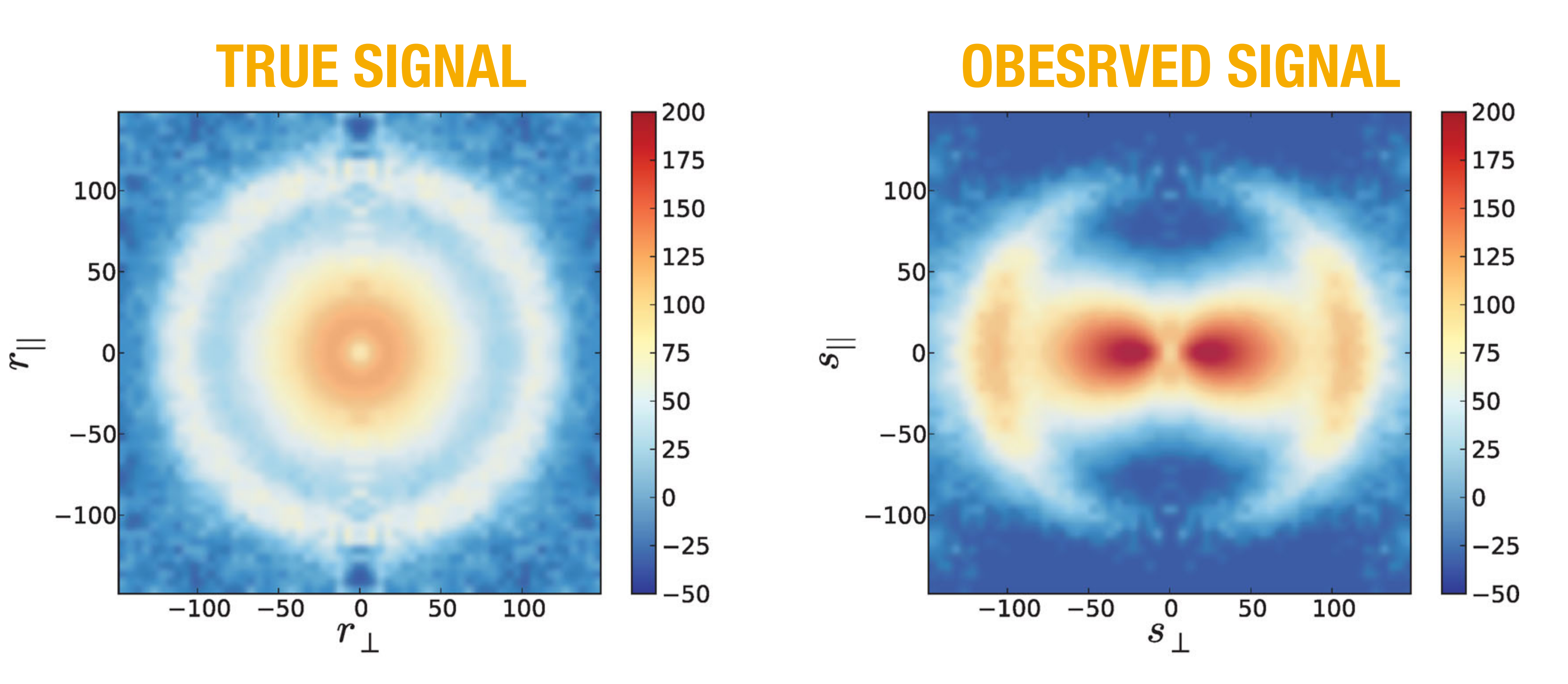
- **Growth of structures, f**
  * Regulates the velocity response of a galaxy to an underling over-density, δ

$$v(x) \sim f\delta(x)$$

2PCF



Credits: Eisenstein et al 2017b



Credits: Padmanabhan et al 2012

BAO DETECTION

- **Required data**

  * Galaxy catalogue:
  RA, DEC, redshift, weights, (reliability)

  * Random catalogue, unclustered distribution:
  RA, DEC, redshift, weights, (reliability)
    - same footprint of galaxy catalogue
    - same redshift range of galaxy catalogue
    - same selection function (and reliability cut)
    - higher number density (usually 50x)

- **2PCF estimator**, Landy-Szalay (1993)

$$\xi(r,\mu) = \frac{DD(r,\mu) + RR(r,\mu) - 2DR(r,\mu)}{RR(r,\mu)}$$

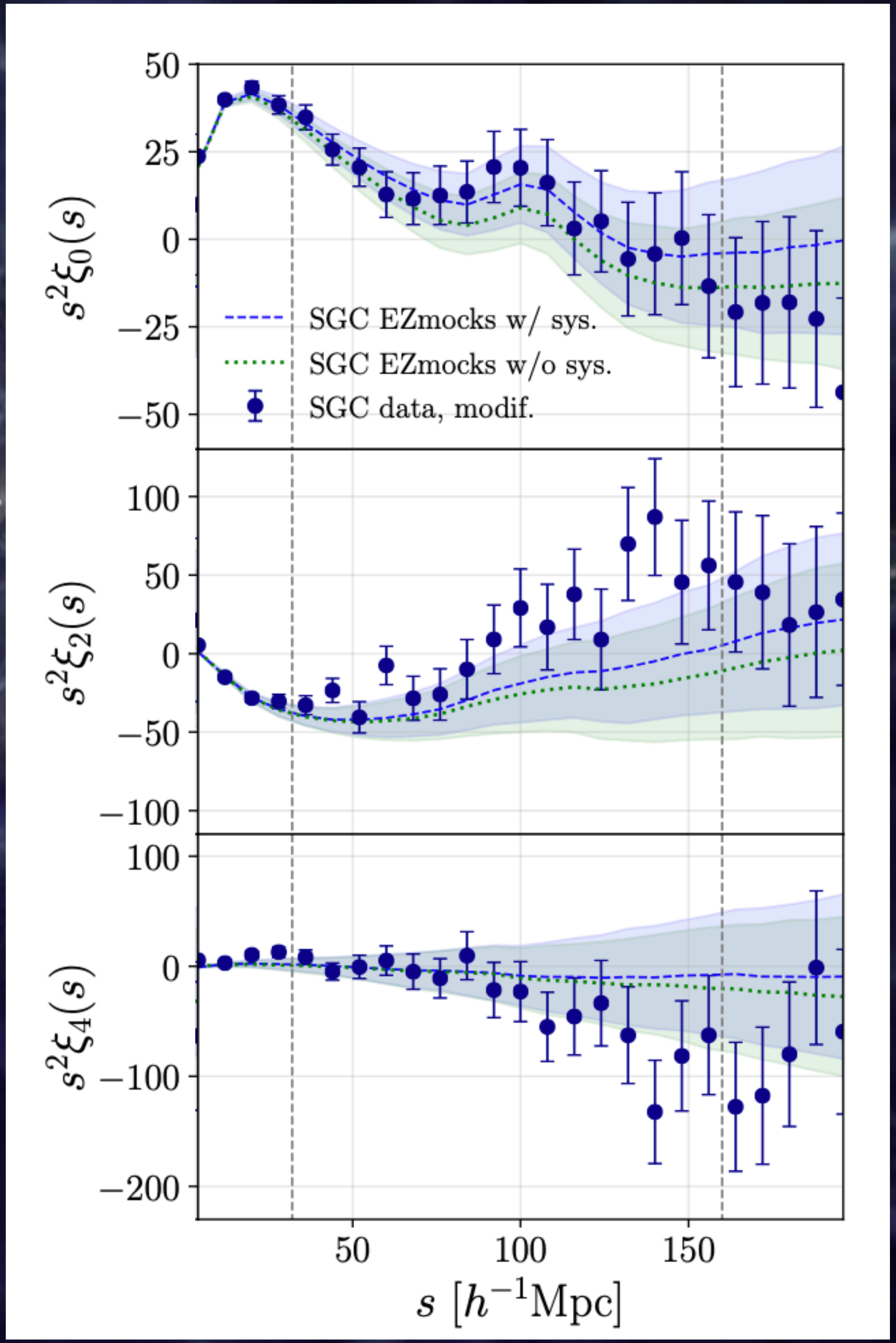
$DD(r,\mu)$: data-data counts
$RR(r,\mu)$: random-random counts
$DR(r,\mu)$: data-random counts

Ready to use code (DESI):
2PCF: https://github.com/cosmodesi/pycorr
P(k): https://github.com/cosmodesi/pypower

- **2PCF multipoles** (isolate isotropies)

$$\xi_l(r) = \frac{2l+1}{2}\int_{-1}^{1} \xi(r,\mu)P_l(\mu)d\mu$$

eBOSS ELG 2PCF MULTIPOLES

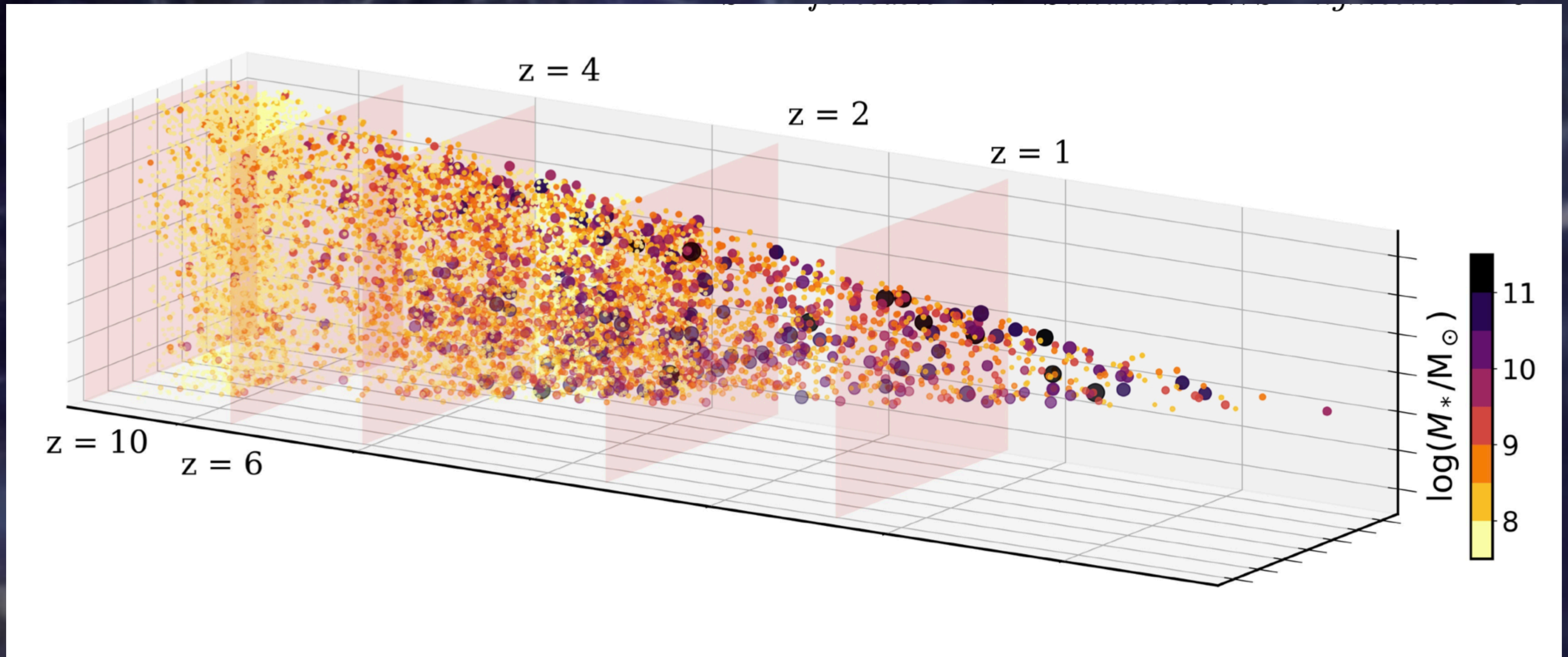


Credits: Tamone et al 2020

REDSHIFT BINS

- **Redshift as a proxy of time**
  * Galaxies observed at different redshifts belong to different epochs
  * The clustering amplitude, expansion of the Universe, and growth of structures vary with time (redshift)
- **Redshift slices:**
  a compromised between statistics and clustering evolution
  * One mean "epoch" for all galaxies in the bin
  * Deepness: > 4x BAO scale
- **Keep in mind**
  * Correlation between clustering signal in different bins
  * The measured clustering is a weighted time average

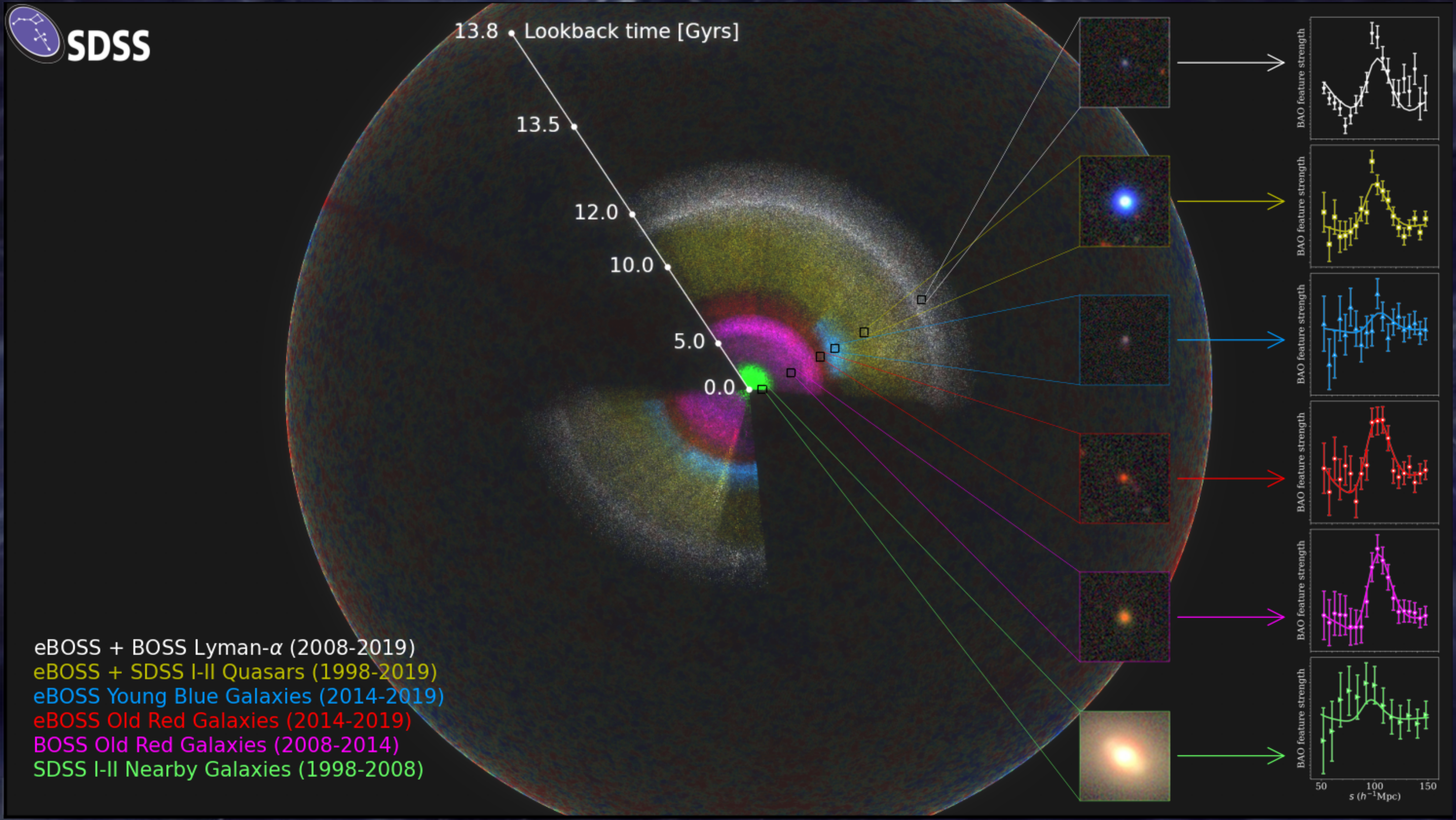
LIGHTOCONE



Credits: simulated lightcone of the COSMOS field, Aaron Yung et al 2022

CONSTRAINING COSMOLOGICAL PARAMETERS: A TEST FOR GENERAL RELATIVITY

MODELLING BAO AT DIFFERENT REDSHIFTS



Credits: Raichoor , Ross, and the SDSS Collaboration

MODELLING BAO SIGNAL

- **Construct 2PCF template with fiducial cosmology**
  $\xi^{\text{fiducial}}(r, \mu), \quad \xi_l^{\text{fiducial}}(r)$
- **Introduce distortions**
  $\xi^{\text{observed}}(r, \mu, \alpha_\parallel, \alpha_\perp, f), \quad \xi_l^{\text{observed}}(r, \alpha_\parallel, \alpha_\perp, f)$

$$\alpha_\parallel = \frac{H^{\text{fiducial}} r_d^{\text{true}}}{H^{\text{true}} r_d^{\text{fiducial}}}$$

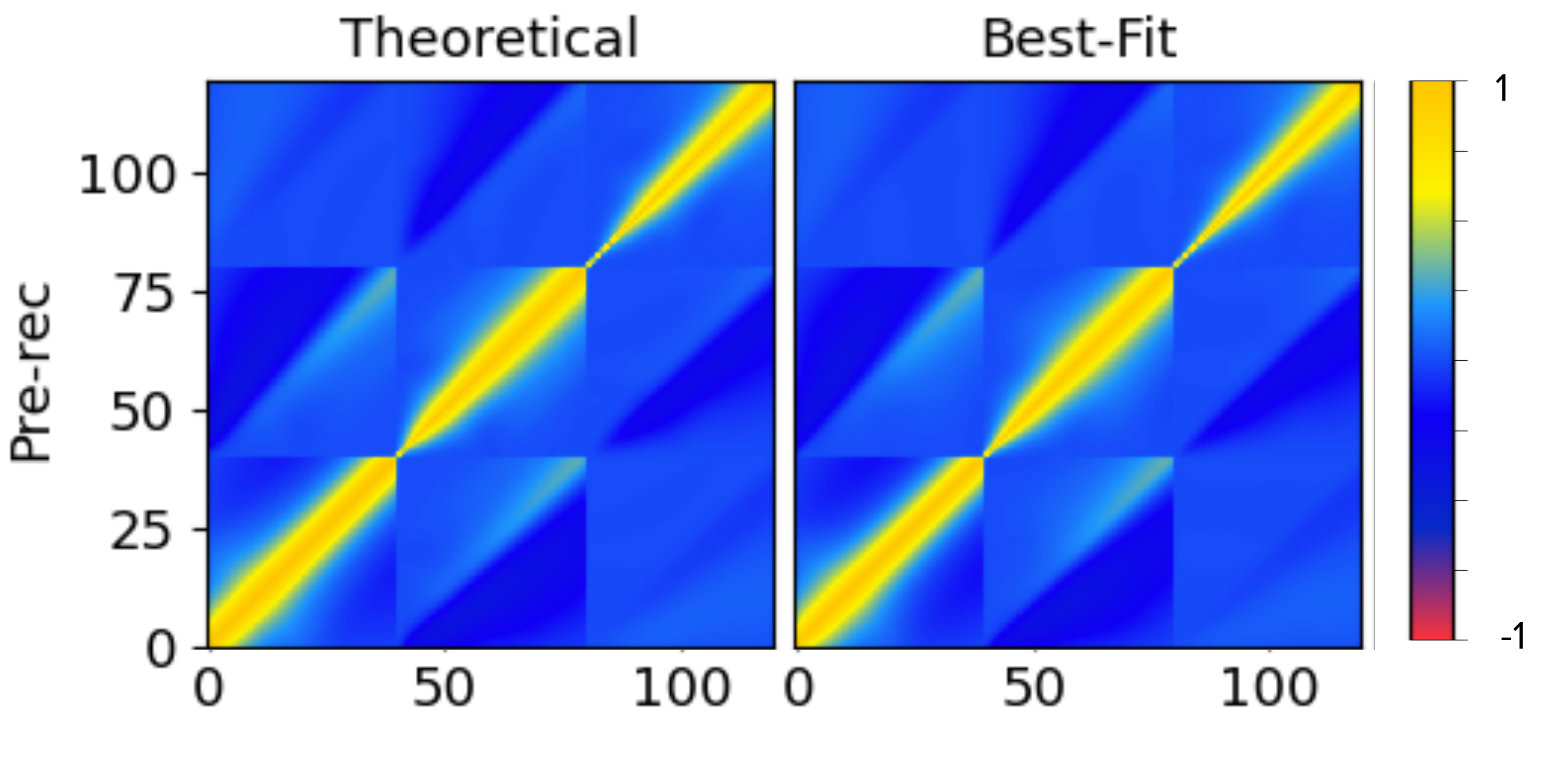
$$\alpha_\perp = \frac{D_A^{\text{true}} r_d^{\text{true}}}{D_A^{\text{fiducial}} r_d^{\text{fiducial}}}$$

- **Construct covariance matrix**
  * Mocks: covariance of several synthetic realisations
  * Analytical: Gaussian covariance constructed from the fiducial template
  * Semi-Analytical: fiducial template + polynomials fitted to match the data

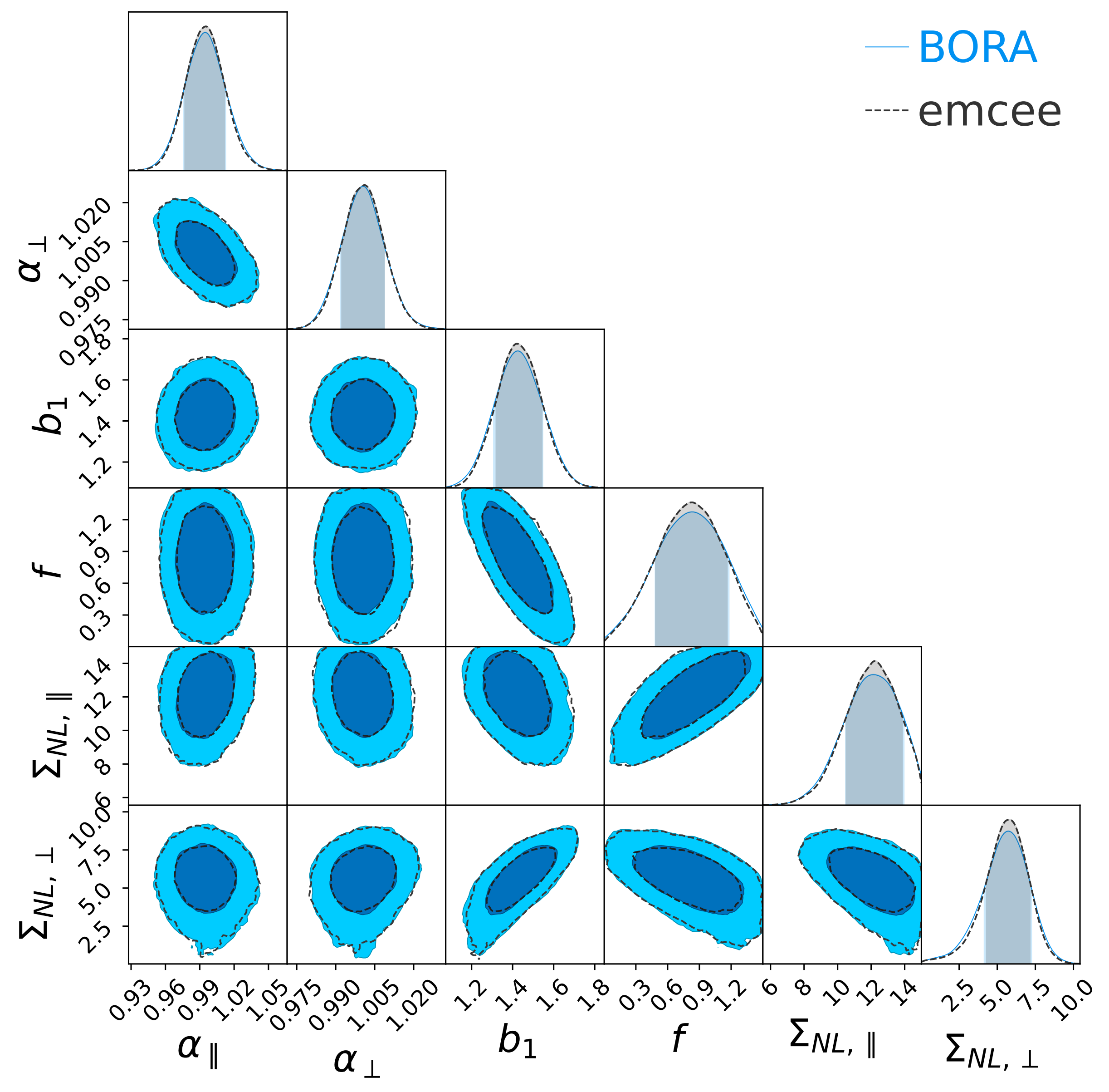
  Ready ti use code (Euclid)
  BeXiCov (Sarpa et al in prep):
  https://github.com/esarpa/BeXiCov

- **Model the clustering signal in each redshift bin**
  * $\alpha_\parallel(z), \alpha_\perp(z), f$

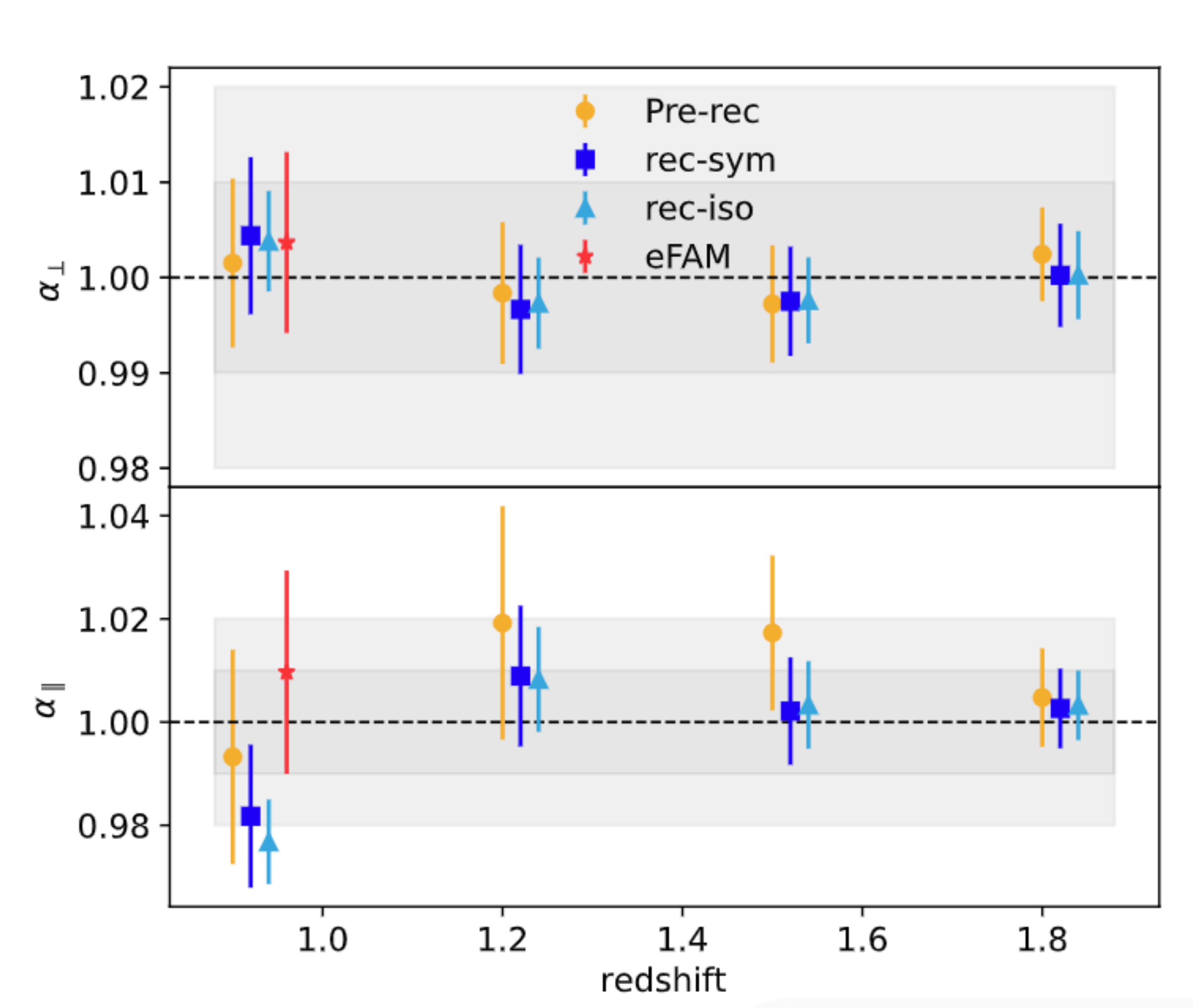
CORRELATION MATRIX



LIKELIHOOD PROFILES



RESULTS



TEST GENERAL RELATIVITY

- **Dark energy (DA)**
  - * Source of Universe accelerated expansion
  - * "Exotic" fluid with negative pressure
  - * In GR: energy density, ρ_Λ, constant in time (ΛCDM)

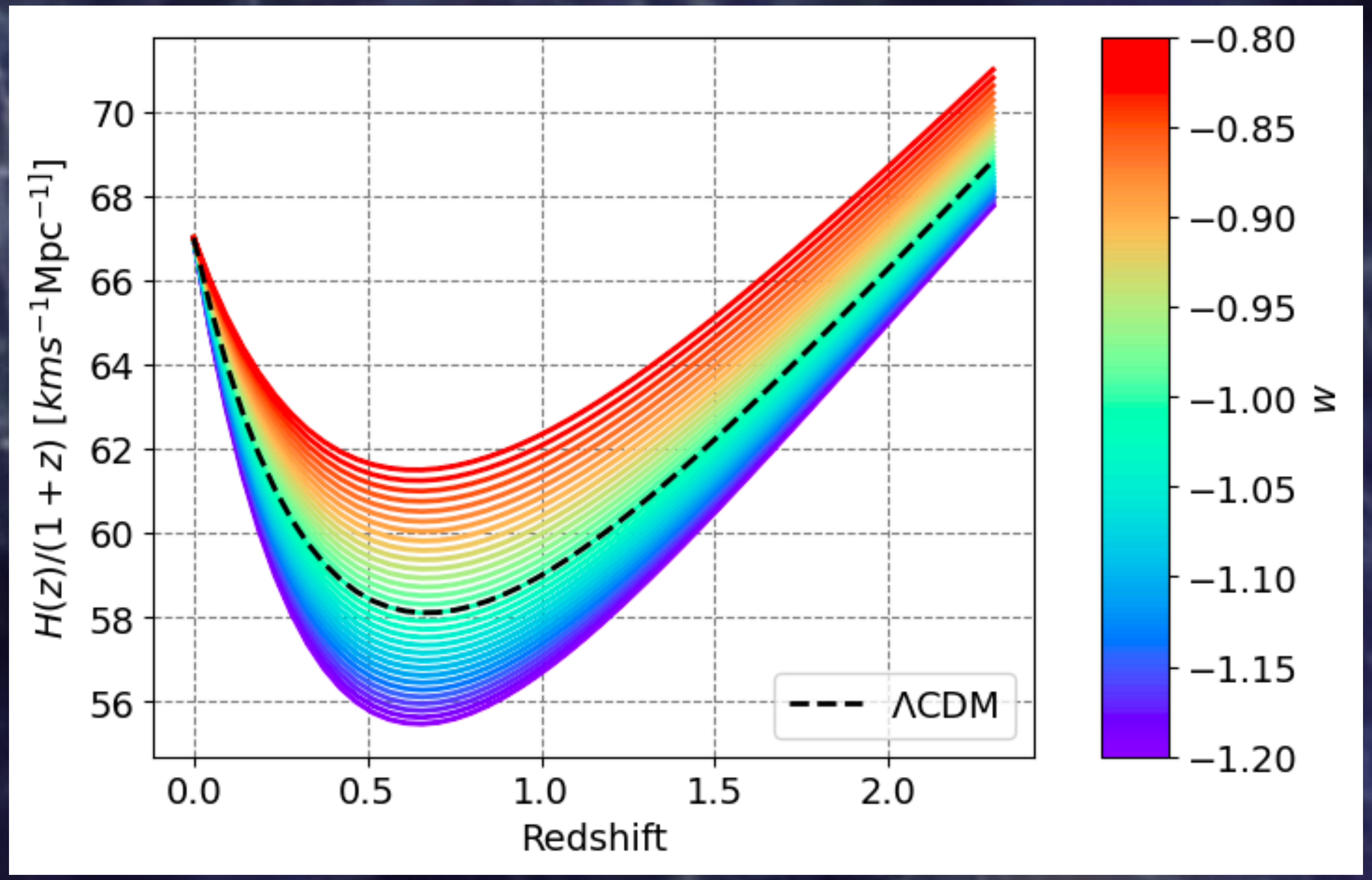
- **Is ΛCDM correct?:**

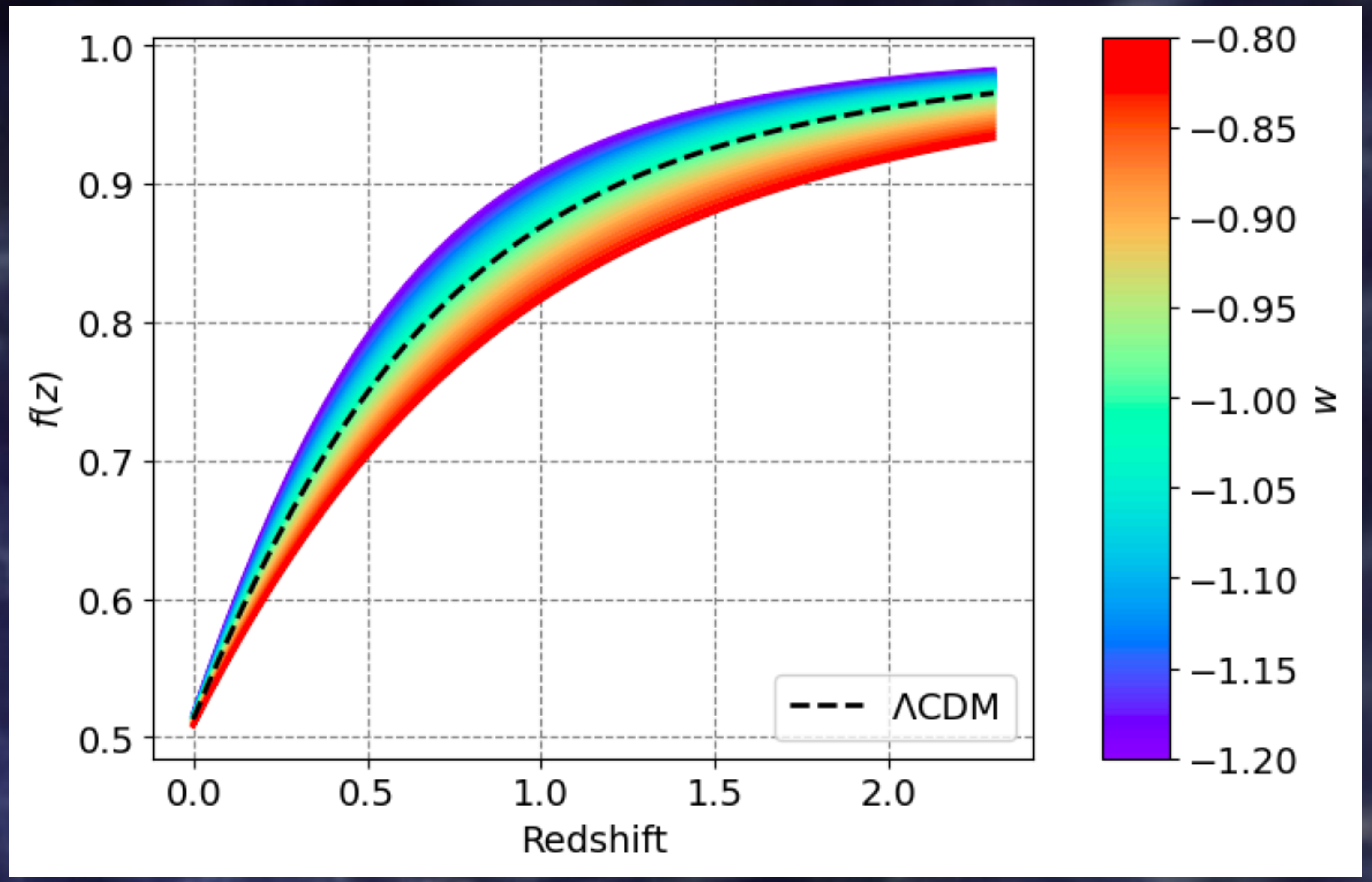
$$\rho_{\rm DE}(z) = \rho_{\rm DE,0}(1+z)^{3(1+w_0+w_a)}\exp\left[-3w_a\frac{z}{1+z}\right]$$

  - * $\Lambda CDM: w_0 = -1; w_a = 0$

- **Testing ΛCDM**
  - * impact of w_0, w_a on $H(z), f(z)$
  - * need to probe a wide redshift range

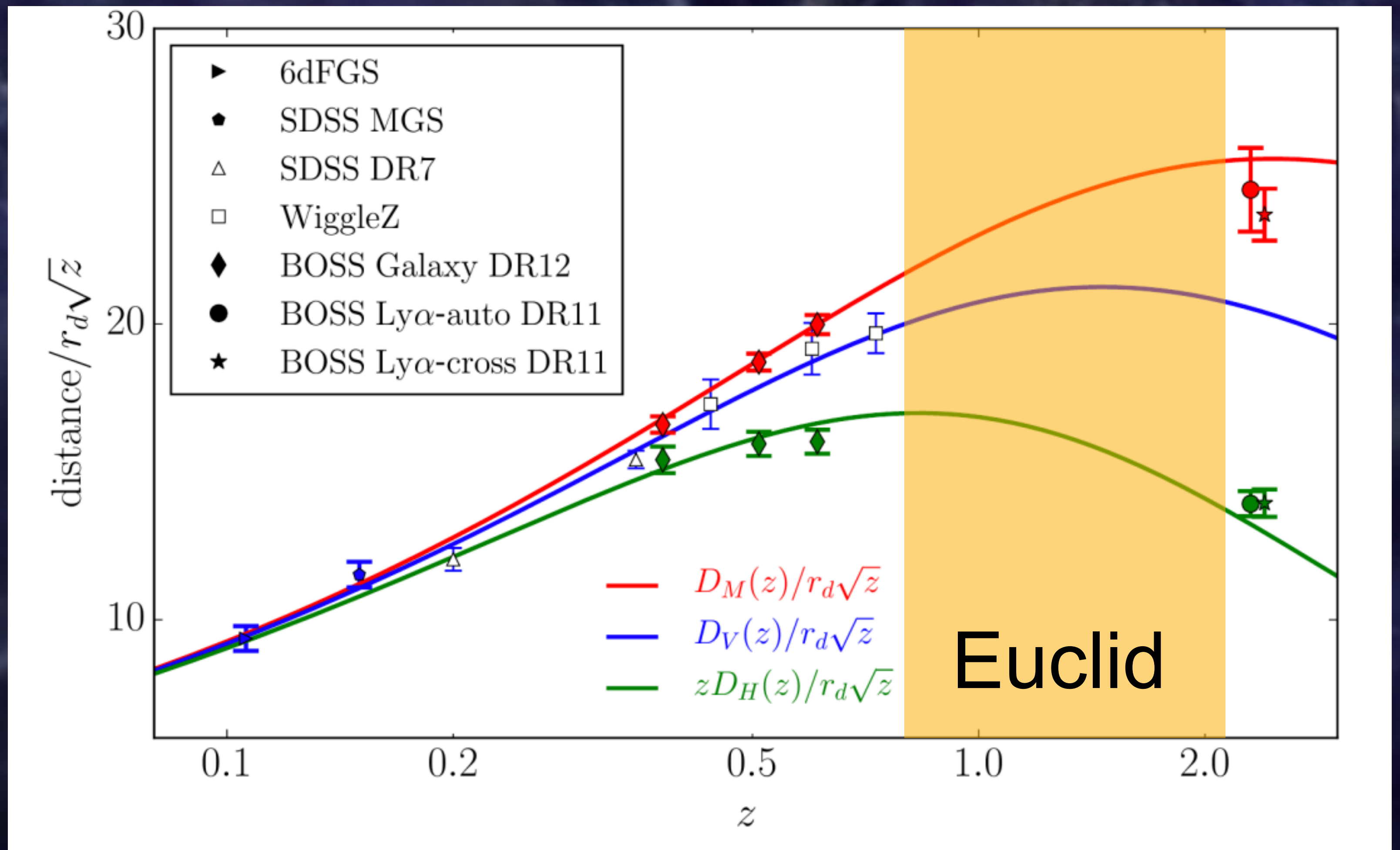
VARYING THE DA MODEL



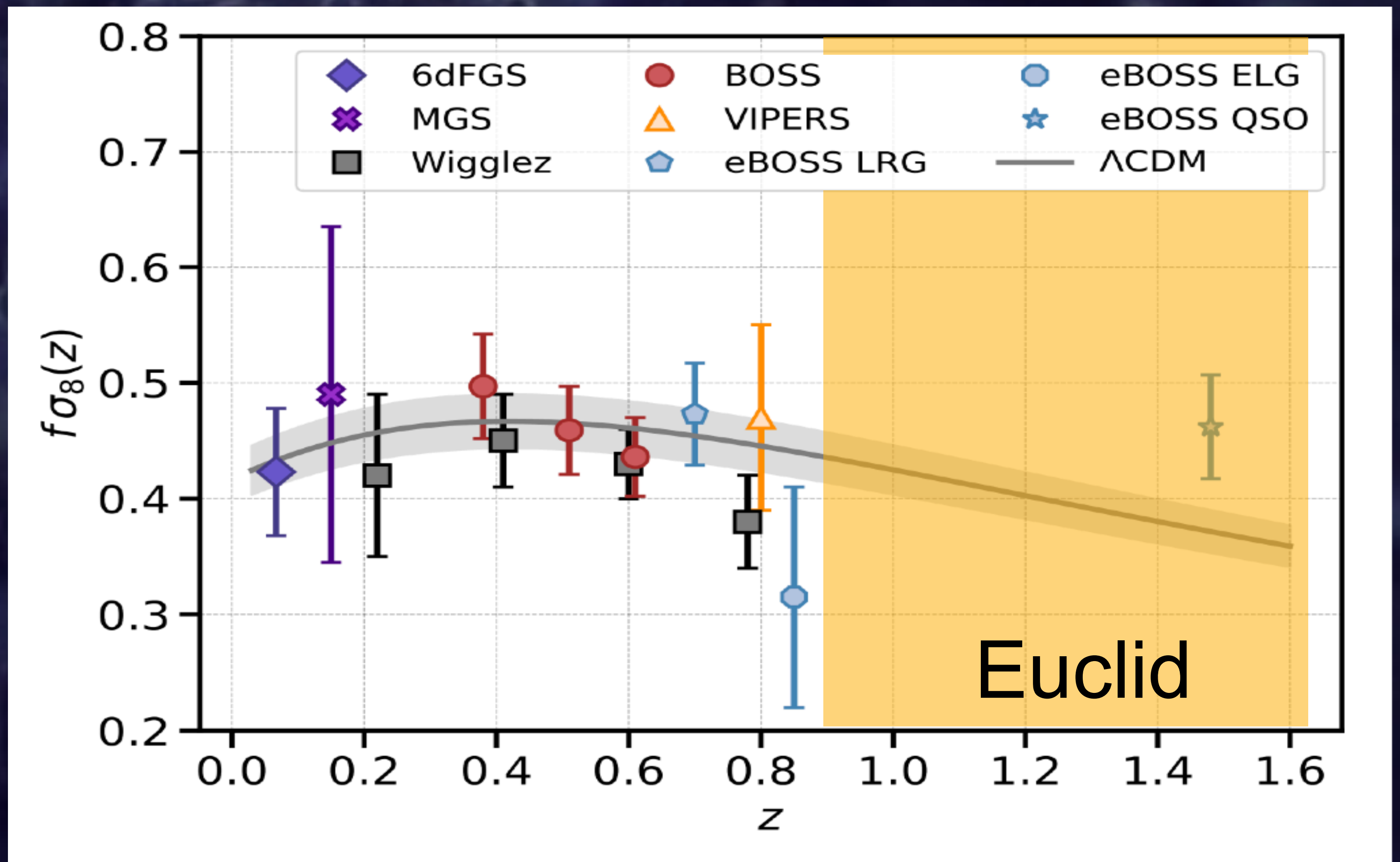


Credits: Veropalumbo

STATE-OF-THE-ART



Credits: Alam et al. 2016



Credits: Hou et al. 2023

TRY YOURSELF: TD-CLUSTERING EXERCISES BY A. DE MATTIA

https://github.com/adematti/TD_clustering

Repo for exercises given at the Euclid summer school

Everything (including installation of packages and data) should be included in the notebooks.

Y1: Hands on eBOSS LRG (plus BOSS CMASS) sample

- Inspecting catalogues: statistical weights to correct observational systematics
- Measure the clustering: 2PCF and Power-spectrum multipoles

Y2: Cosmological constraints with BAO

See cosmo_bao.ipynb

- Build the fiducial isotropic BAO Power-spectrum template
- Construct and sample the likelihood (MCMC) to constrain cosmological distortions
- Constrain cosmological parameters from distortion measurements

SUMMARY & OPEN QUESTIONS (PROPAGATE YOUR CHOICE)

EUCLID GOAL:

TEST GENERAL RELATIVITY, THE NATURE OF DARK ENERGY

- Data: 3D galaxy positions via imaging and spectroscopic survey
- Measurements: clustering signal at different epochs
- Cosmological constraints: $\{H(z), f(z)\}_z$
- Test General relativity: $w_0, w_a, \Omega_m, \Omega_b, \Omega_\Lambda$

- Spectra reliability: accounting for interlopers contamination
- Correlation between measurements, “internal” evolution, optimal choice of redshift slices
- How to:
  * Two steps extraction
    $\{H(z), f(z)\}_z \rightarrow w_0, w_a, \Omega_m, \Omega_b, \Omega_\Lambda$
  * Joint fit: from clustering signal to
    $w_0, w_a, \Omega_m, \Omega_b, \Omega_\Lambda$

HI Density