Cosmology with spectroscopic surveys

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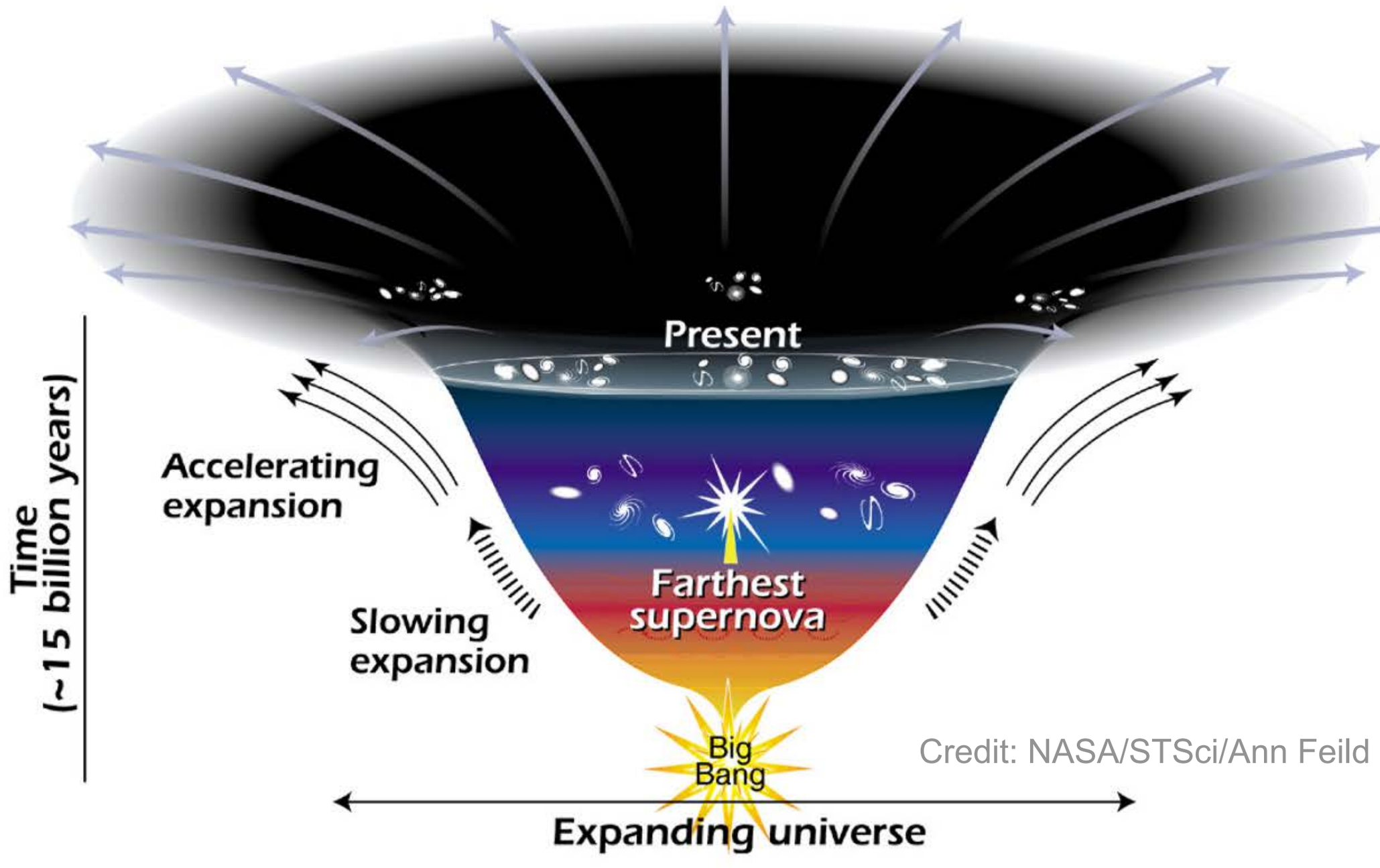
Standard cosmological framework

$$H(a) = H_0^2 \left(\Omega_{\mathrm{r}} a^{-4} + \Omega_{\mathrm{m}} a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda \right)$$



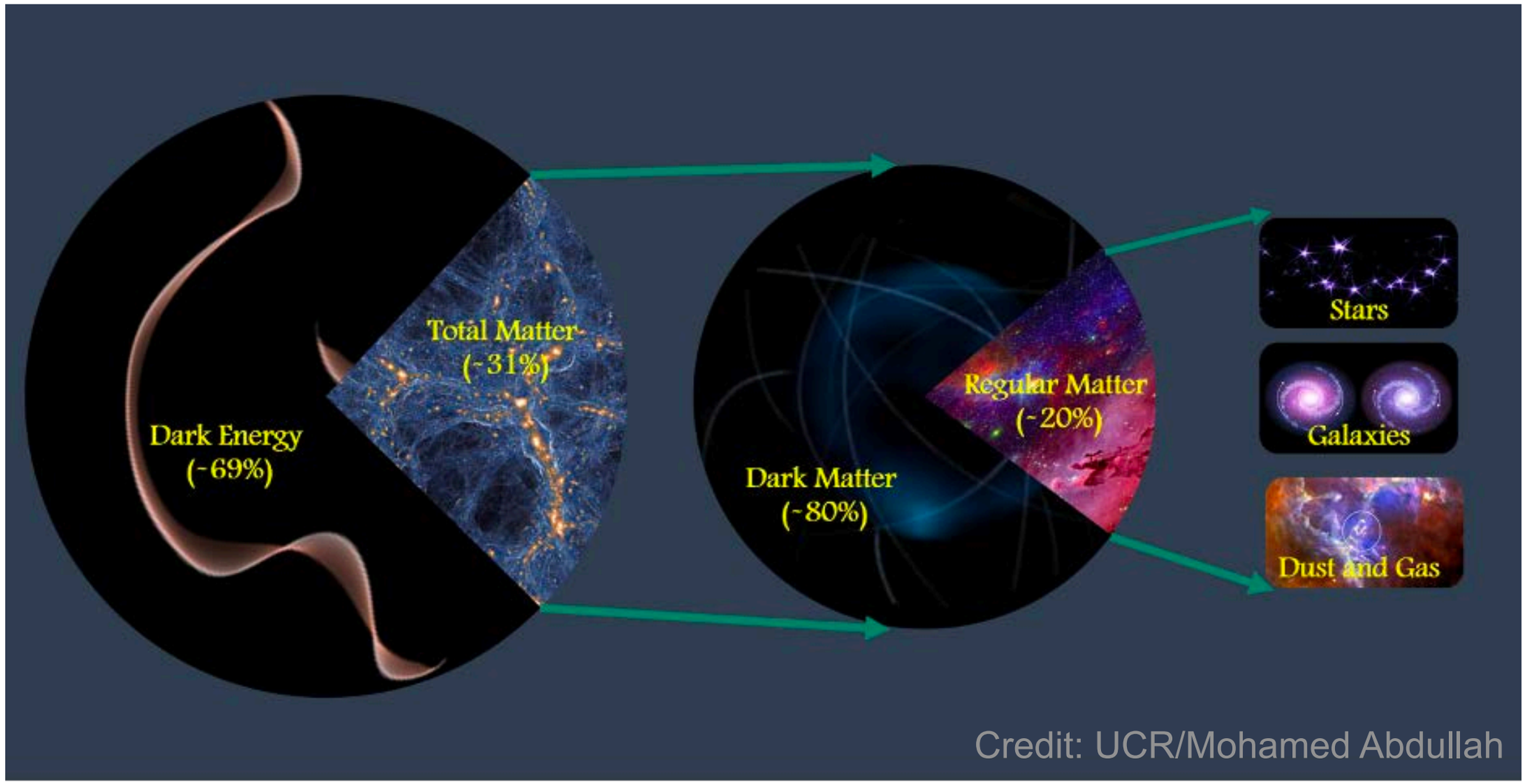
Credit: NASA/STSci/Ann Feild

Standard cosmological framework

$$H(a) = H_0^2 \left(\Omega_{\mathrm{r}} a^{-4} + \Omega_{\mathrm{m}} a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda \right)$$

geometry

components



Dark Universe

Dark Energy (DE)

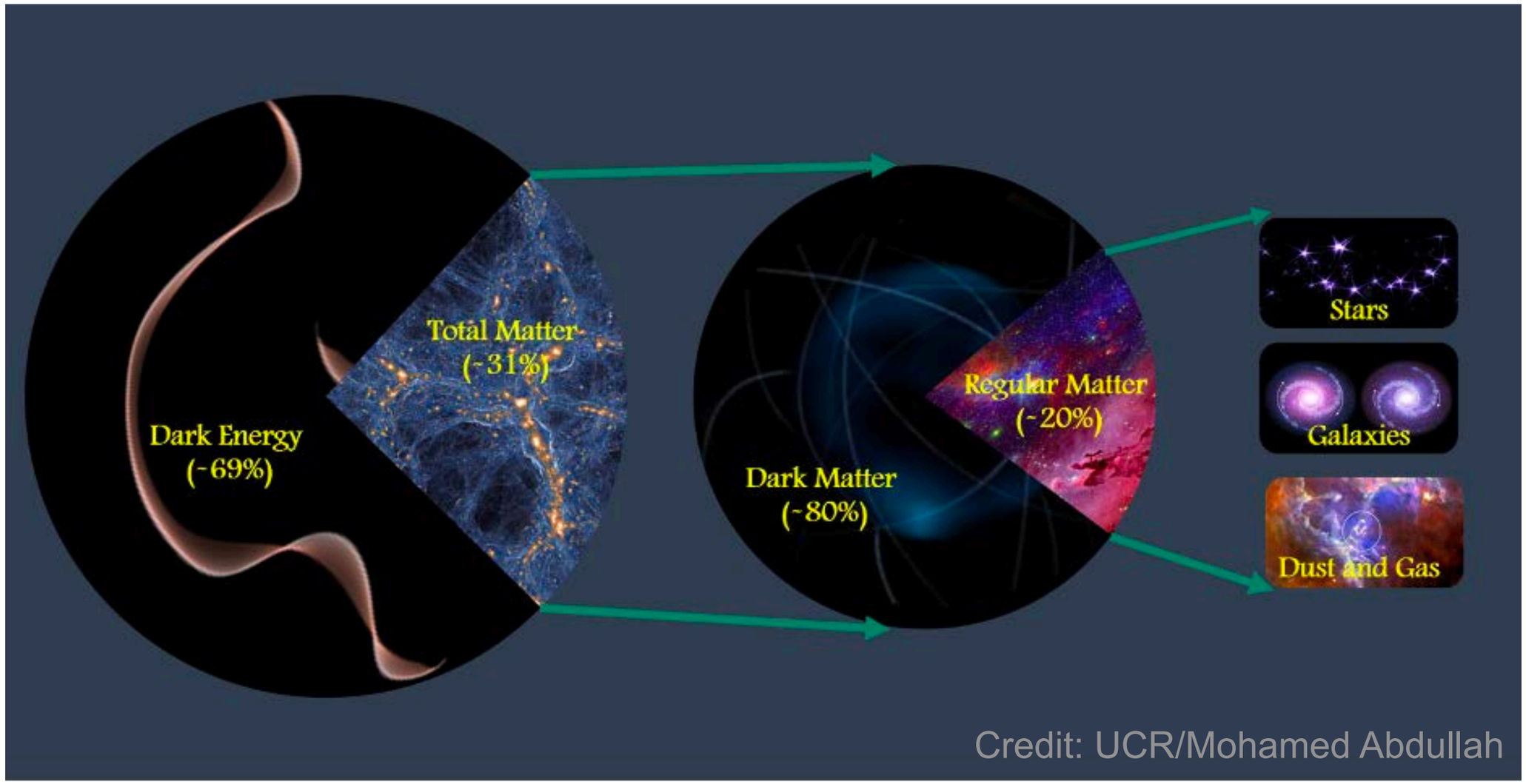
Repulsion

- Smoothly distributed
- Constant energy density
- Accelerating expansion

Dark Matter (DM)

Attraction

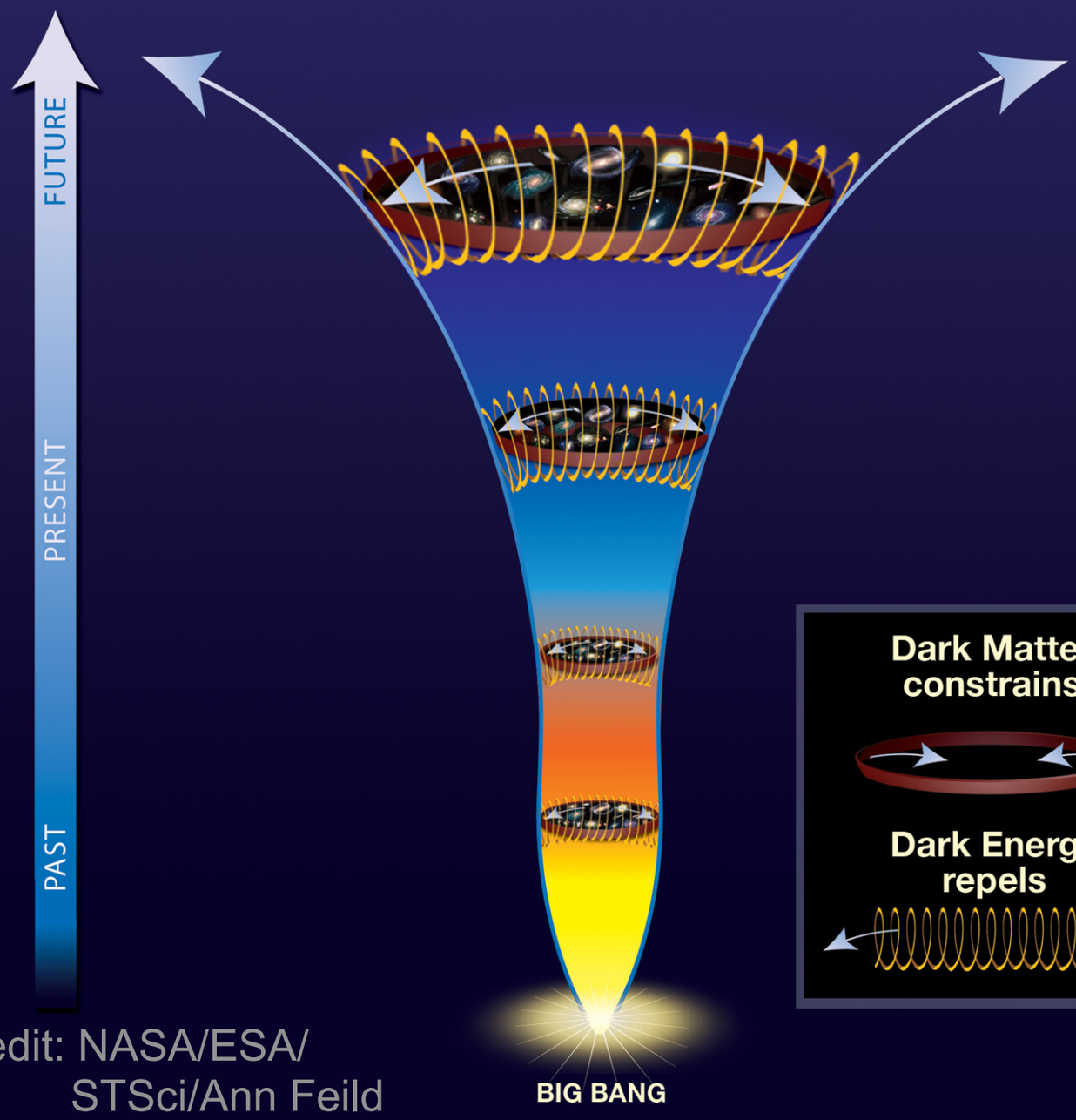
- Weakly interacting
- Mostly cold
- Dominates gravity



Dark Universe

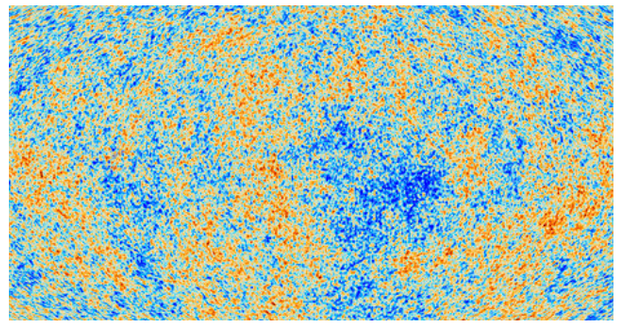
Cosmic tug of war

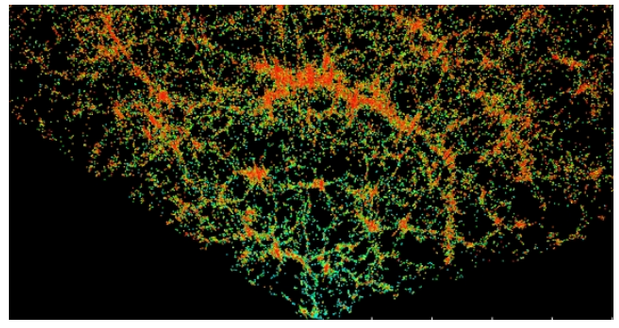
The force of dark energy surpasses
that of dark matter as time progresses.



Credit: NASA/ESA/
STSci/Ann Feild

Inhomogeneity / clustering





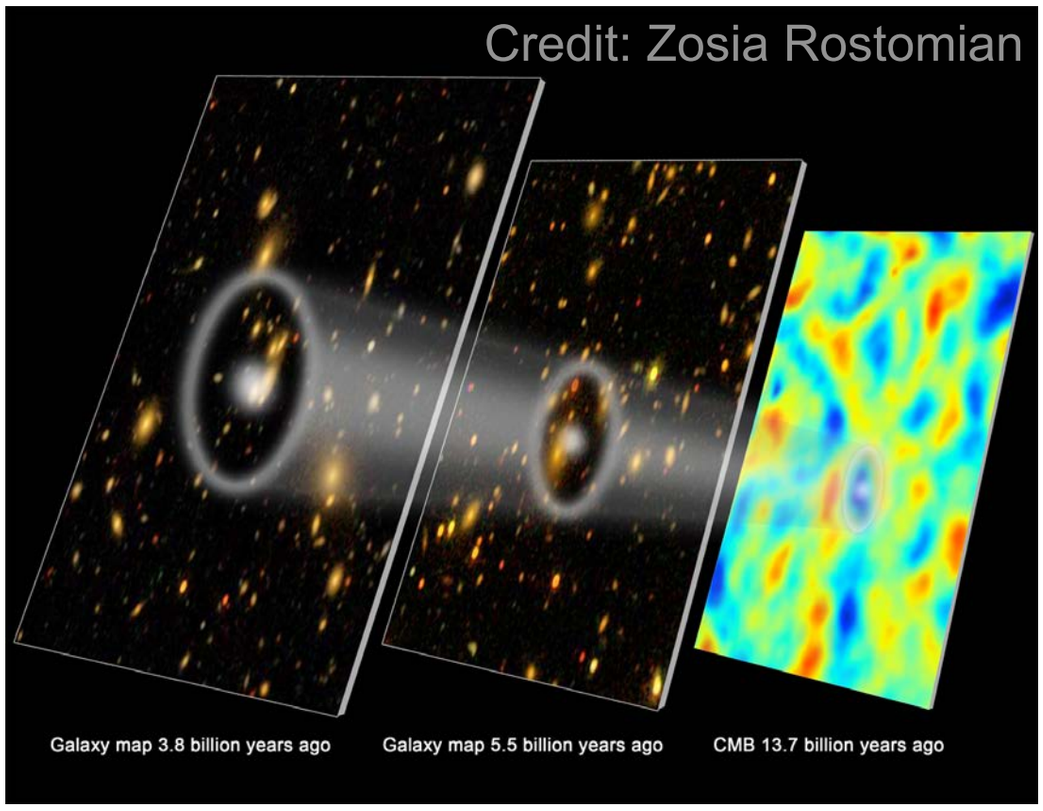
Credit: ESA/Planck, SDSS/BOSS

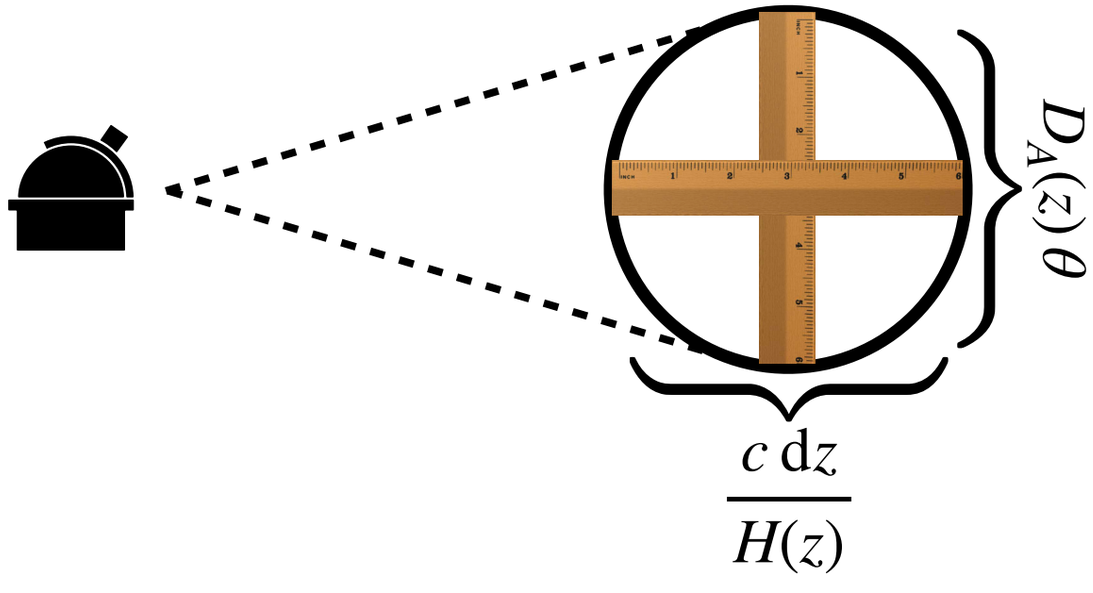
Structure growth

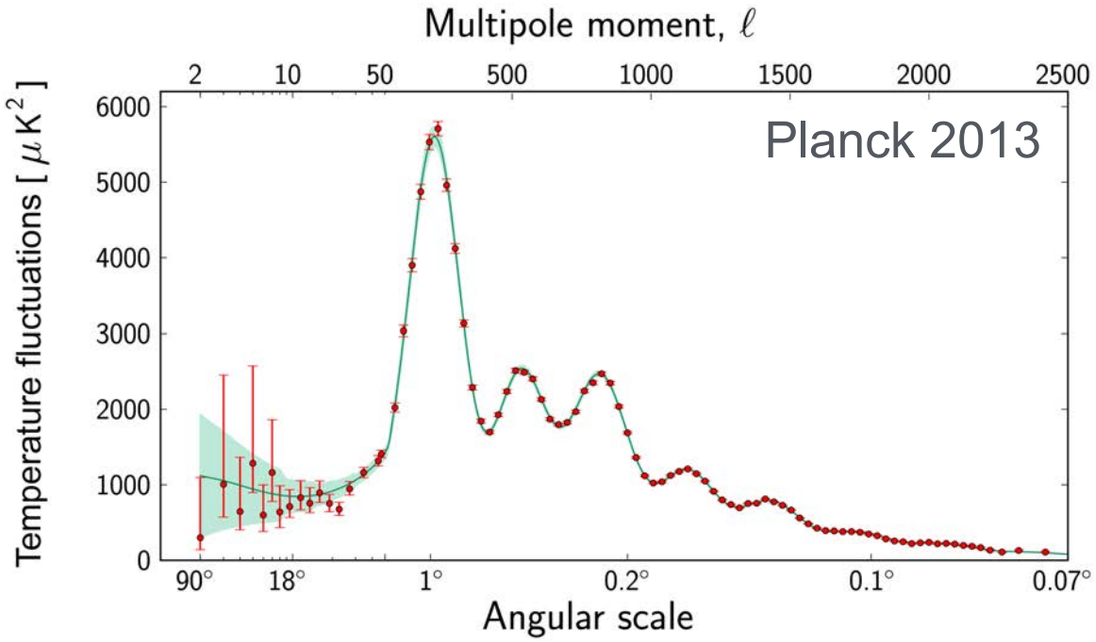
Cosmic expansion

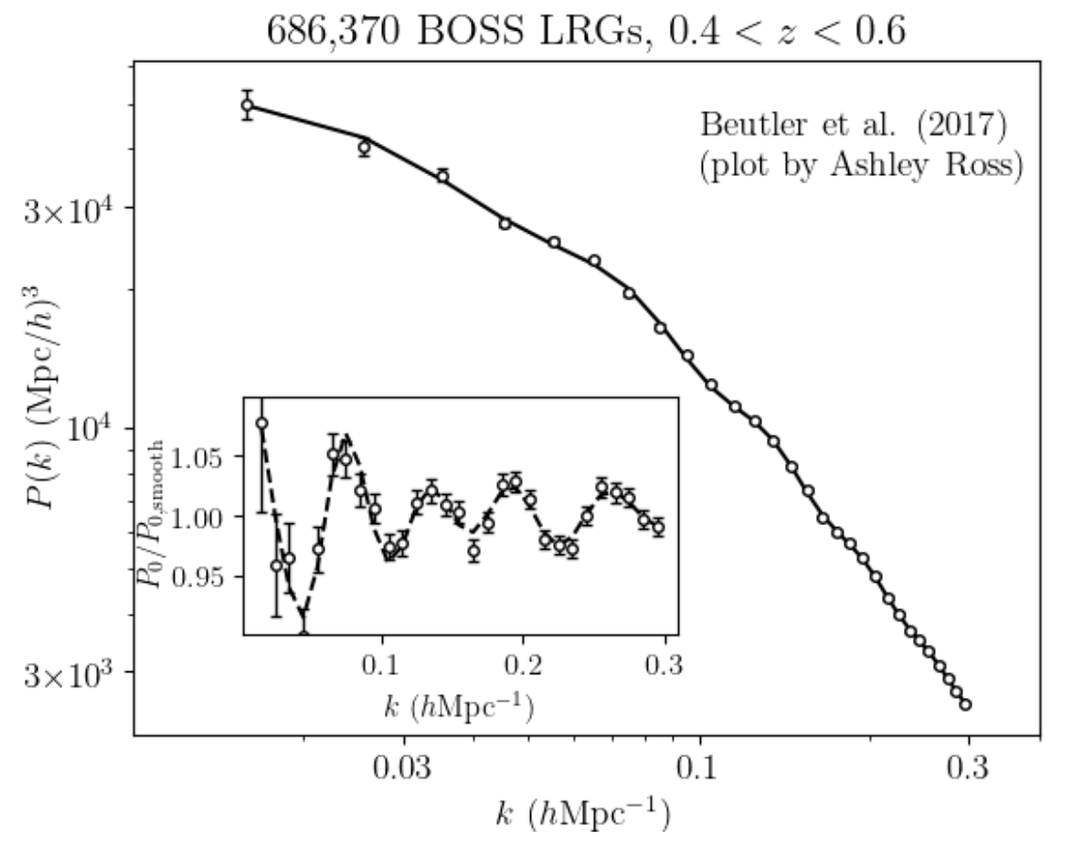
Baryon Acoustic Oscillations

Standard ruler for expansion history



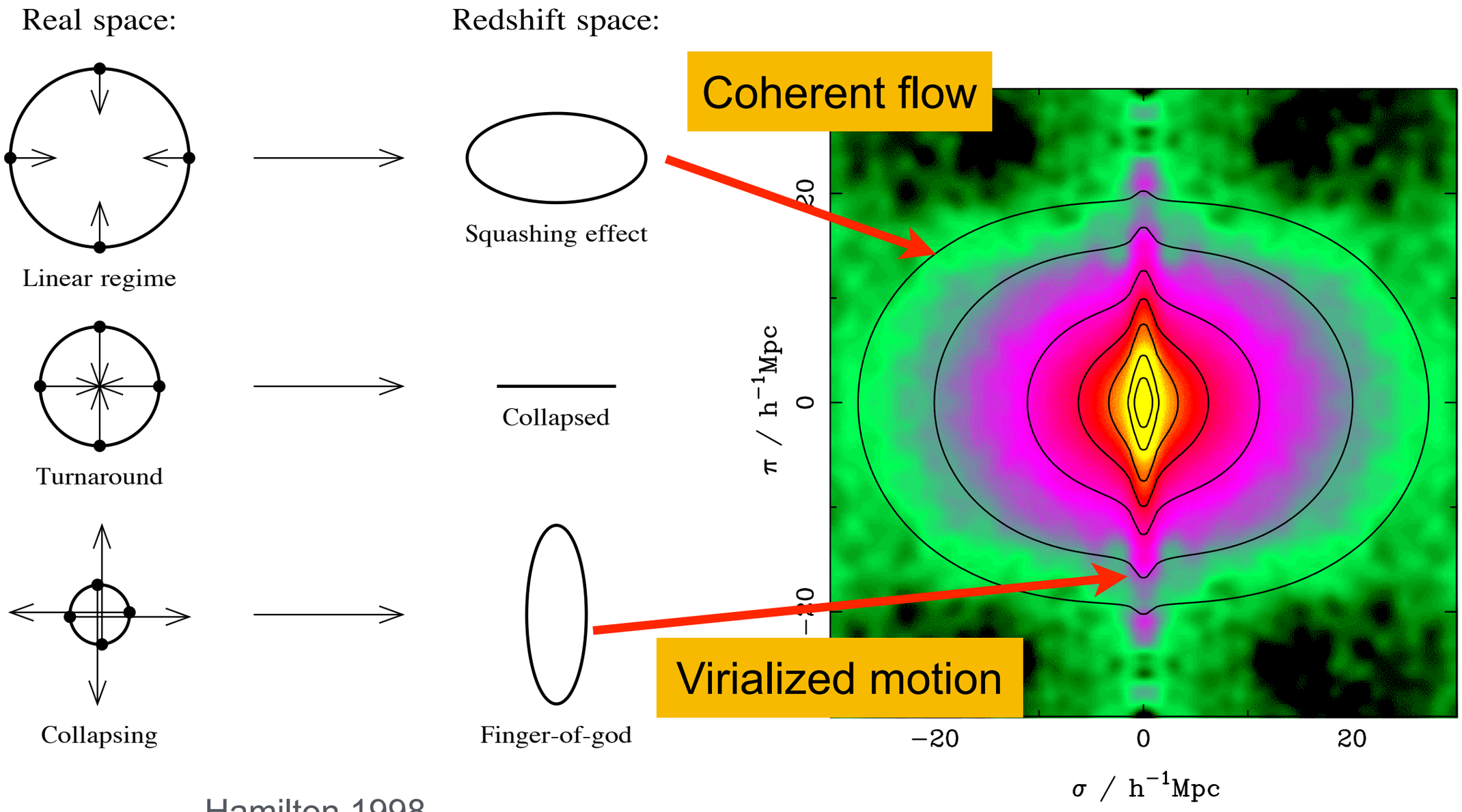






Redshift-Space Distortions

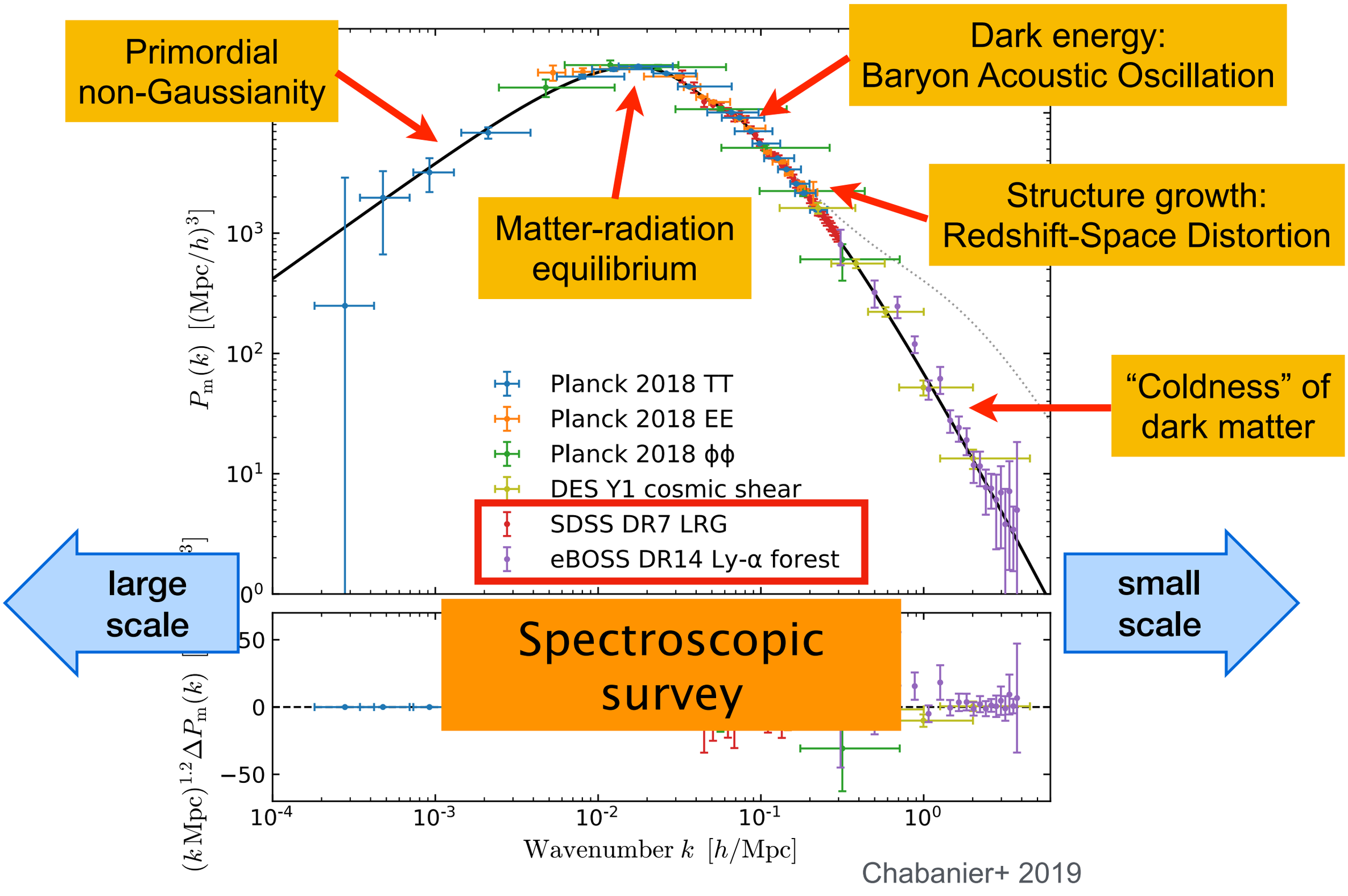
Measurement of structure growth



Hamilton 1998

Peacock+ 2001

Matter power spectrum

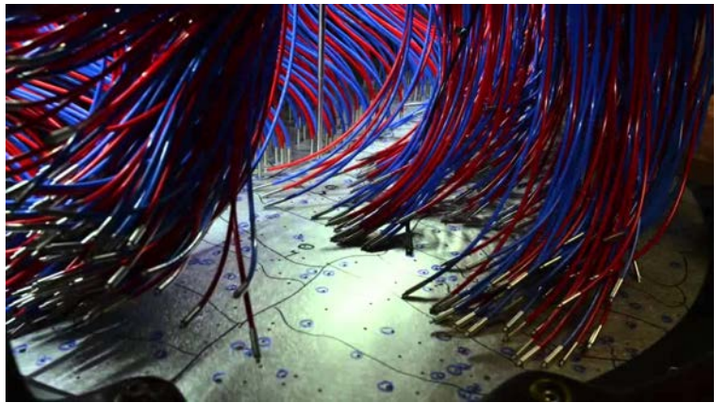


Chabanier+ 2019

Massive spectroscopic surveys

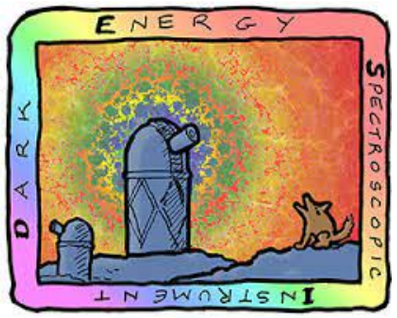
Past

SDSS III

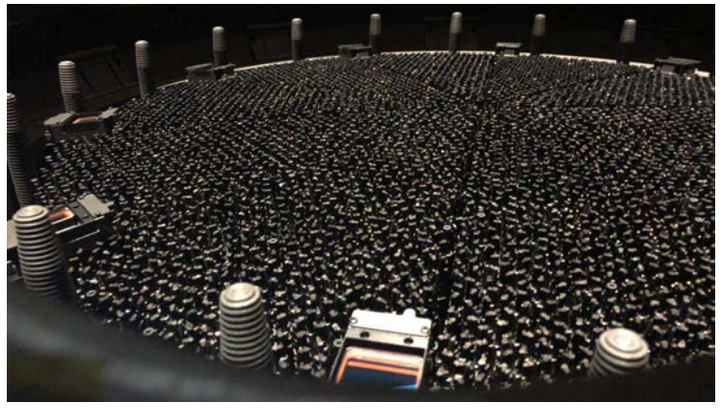


eBOSS

Present



4MOST

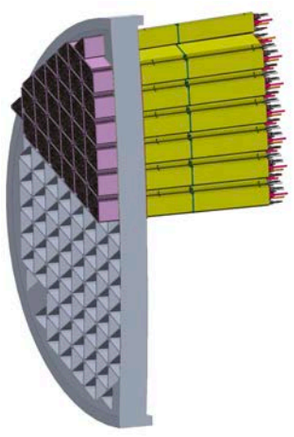


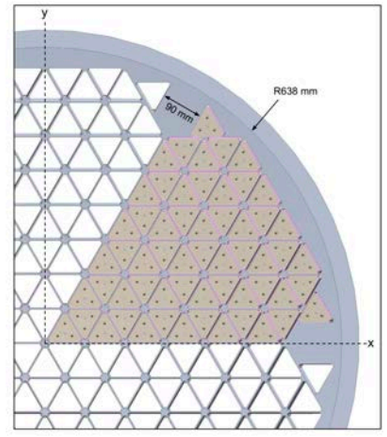
Future

euclid consortium

中国巡天空间望远镜
MULTIPLEXED SURVEY TELESCOPE

and more ...

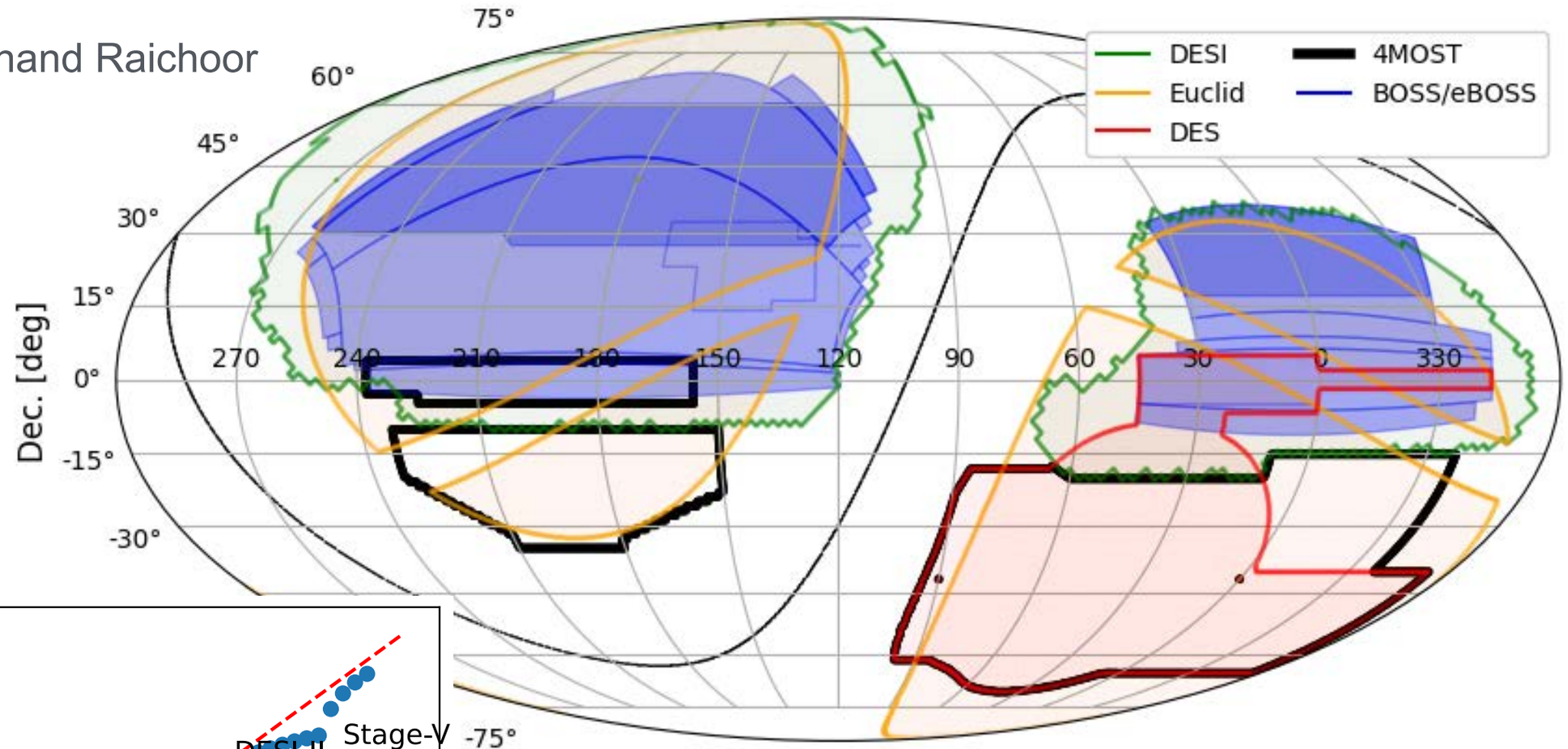


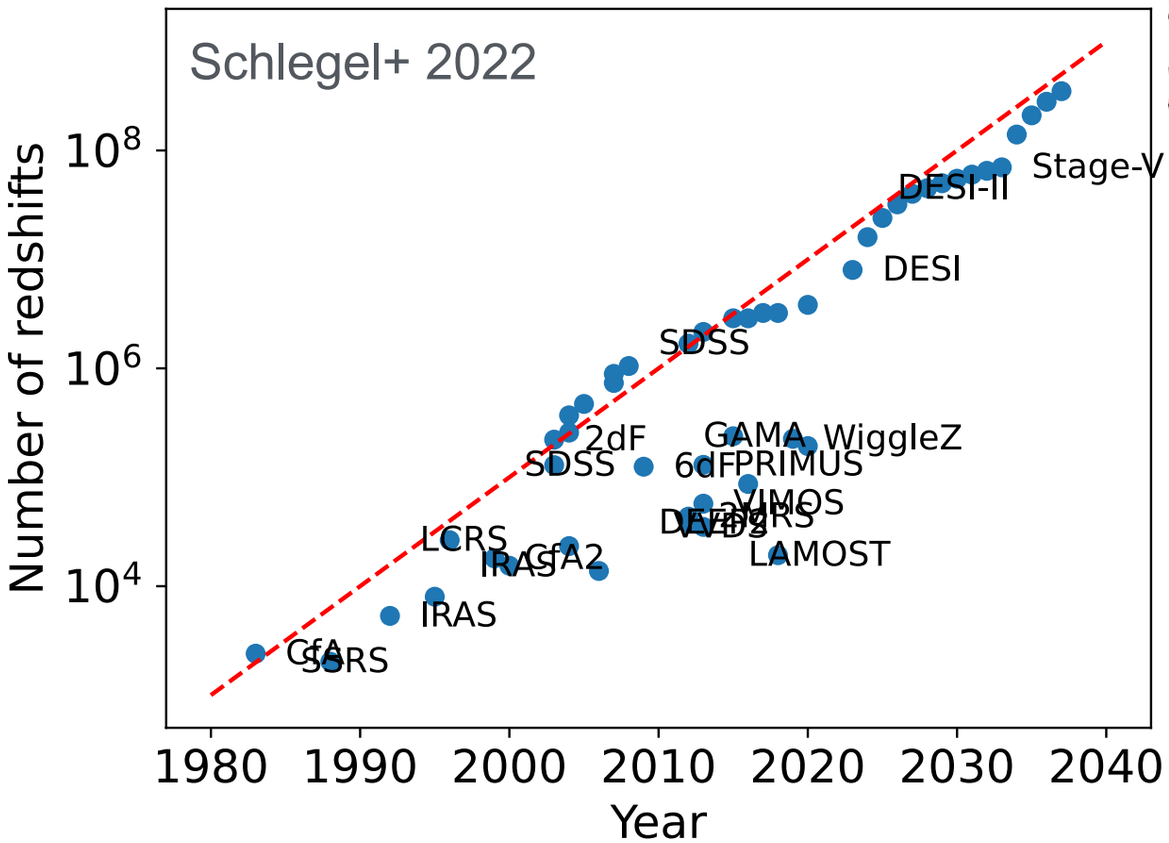


Credit: SDSS, DESI

Massive spectroscopic surveys

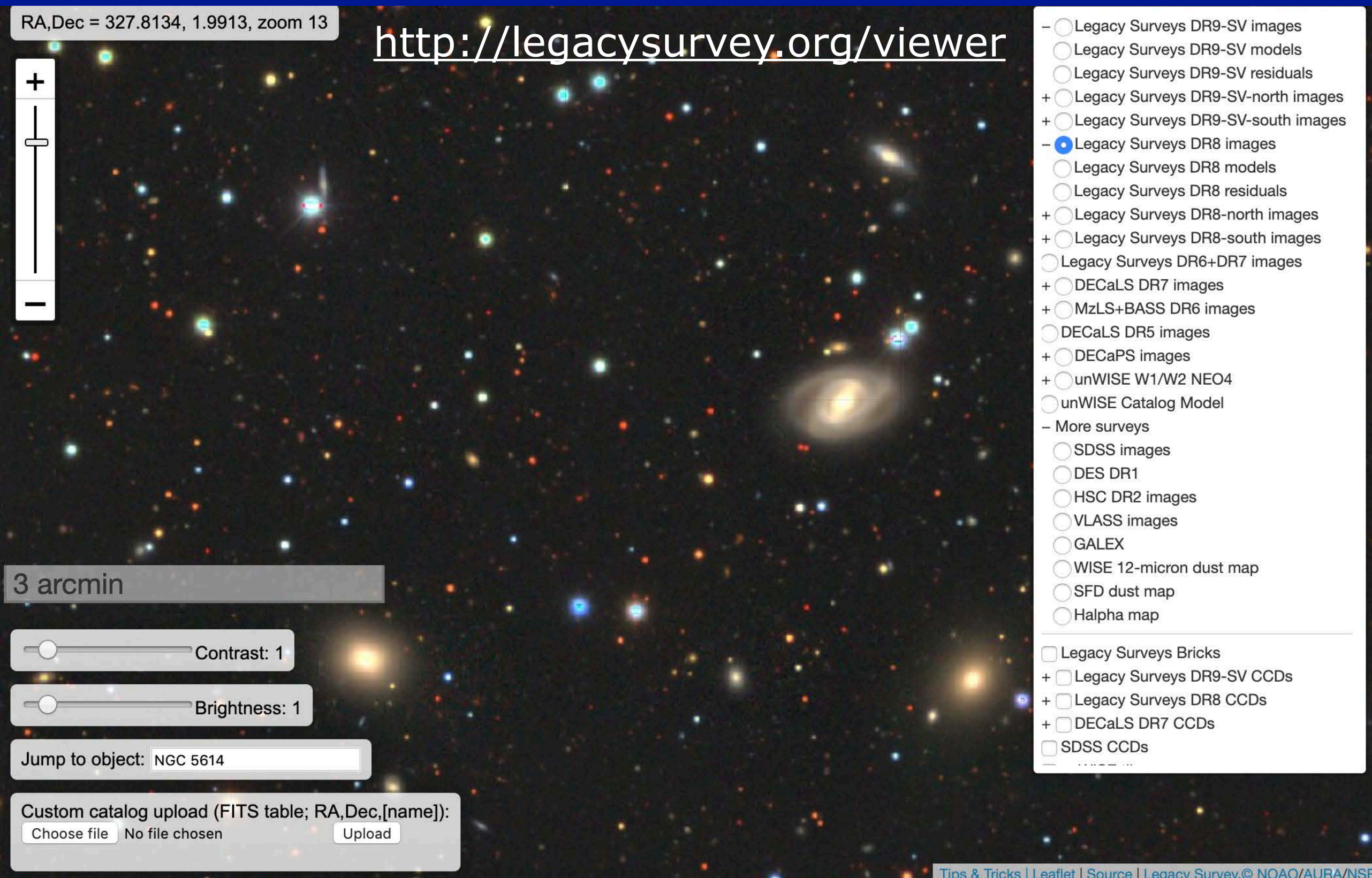
Credit: Anand Raichoor





- BOSS (08–14): 1.5M spectra
- eBOSS (14–19): 1M spectra
- DESI (21–26): 35M spectra
- 4MOST (22-27): 8M spectra
- Euclid (24-29): 50M spectra

Photometric survey

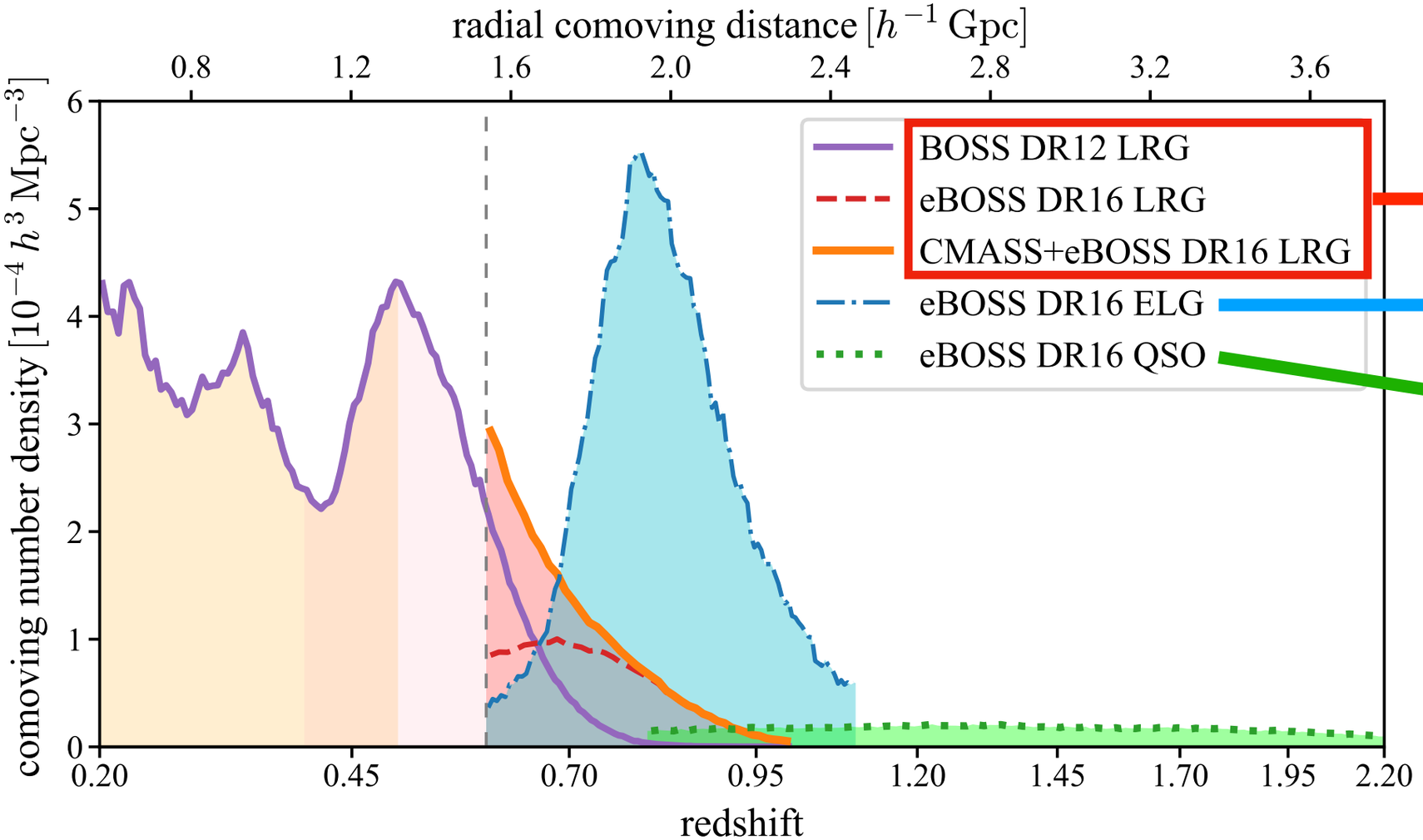


Target selection

- Abundant at desired redshift
- Easily-identified spectral features
  - Strong absorption/emission lines
  - Bright

High redshift (z > 2):

- Lyman-α forest
- Lyman-break galaxies
- Lyman-α emitters



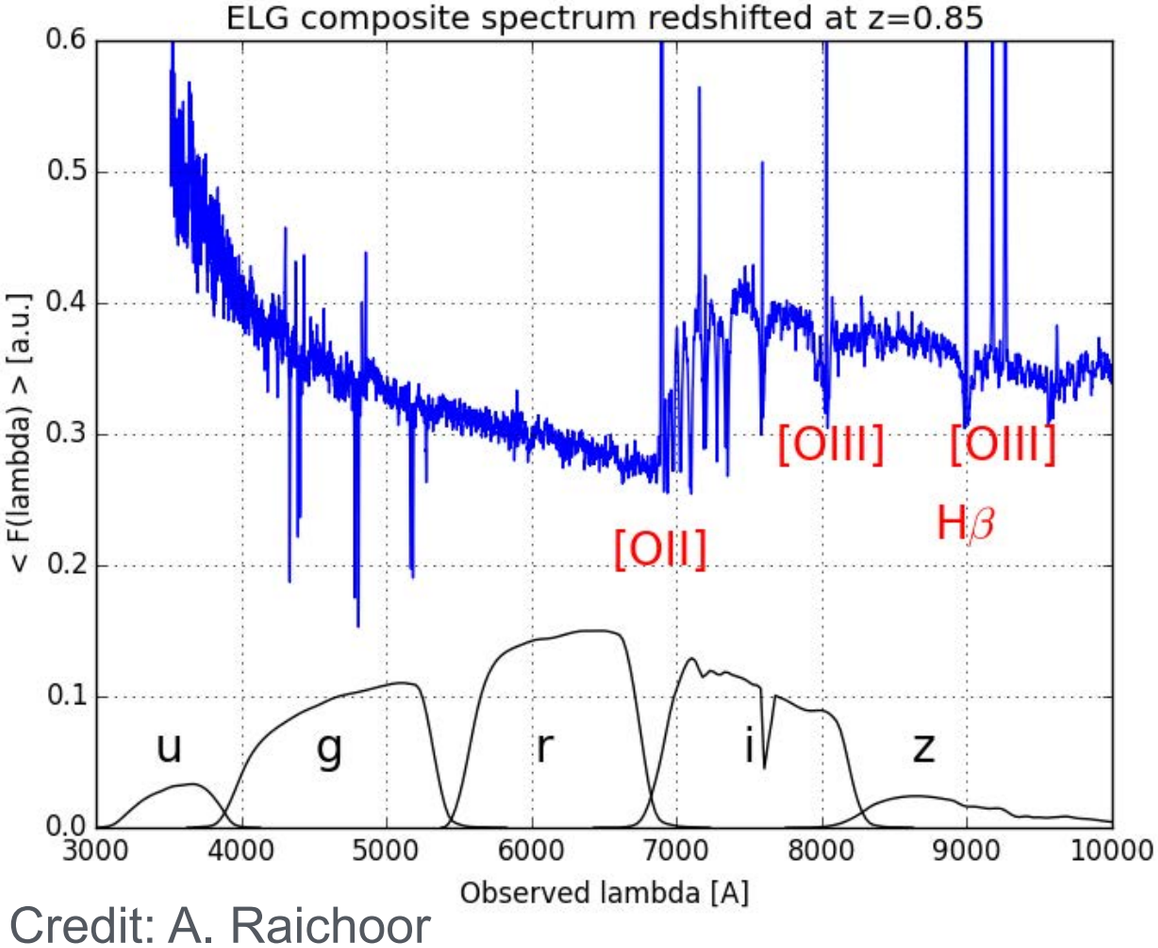
Absorption lines

O_{II} emission line

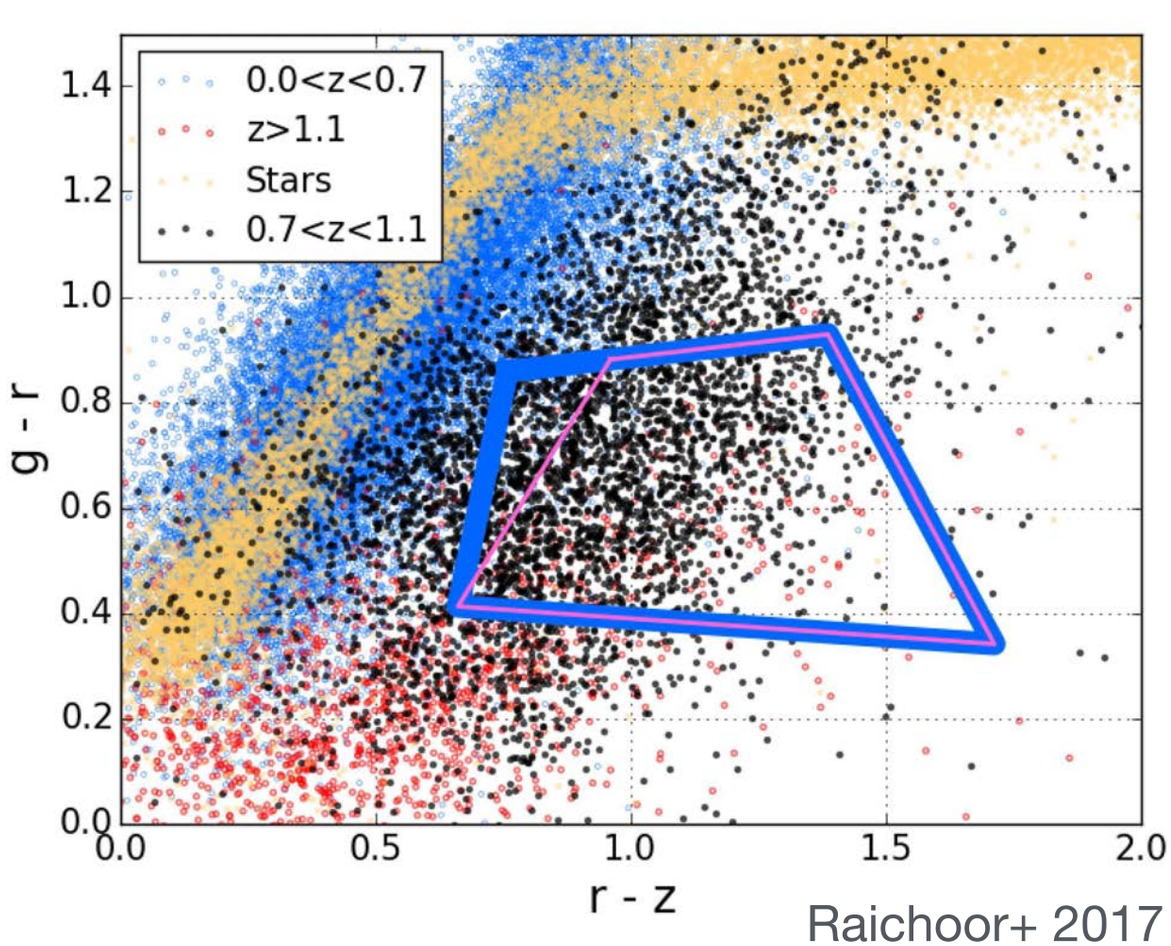
Broad emission lines

Target selection: eBOSS ELG

- Selection criteria
  - Star-forming ➔ « blue » cut in g–r
  - Balmer break ➔ « red » cut in r–z
  - $[O_{II}]$ flux correlates with g-mag ➔ « bright » cut in g-mag
- Target density: ~ 230 deg^{-2}



Credit: A. Raichoor

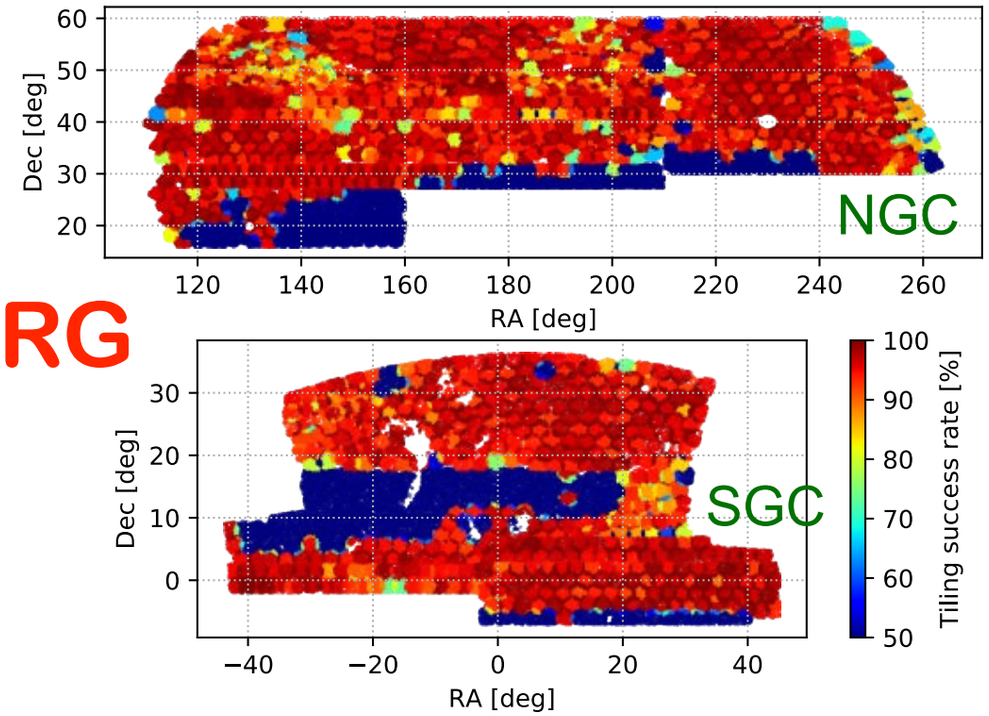


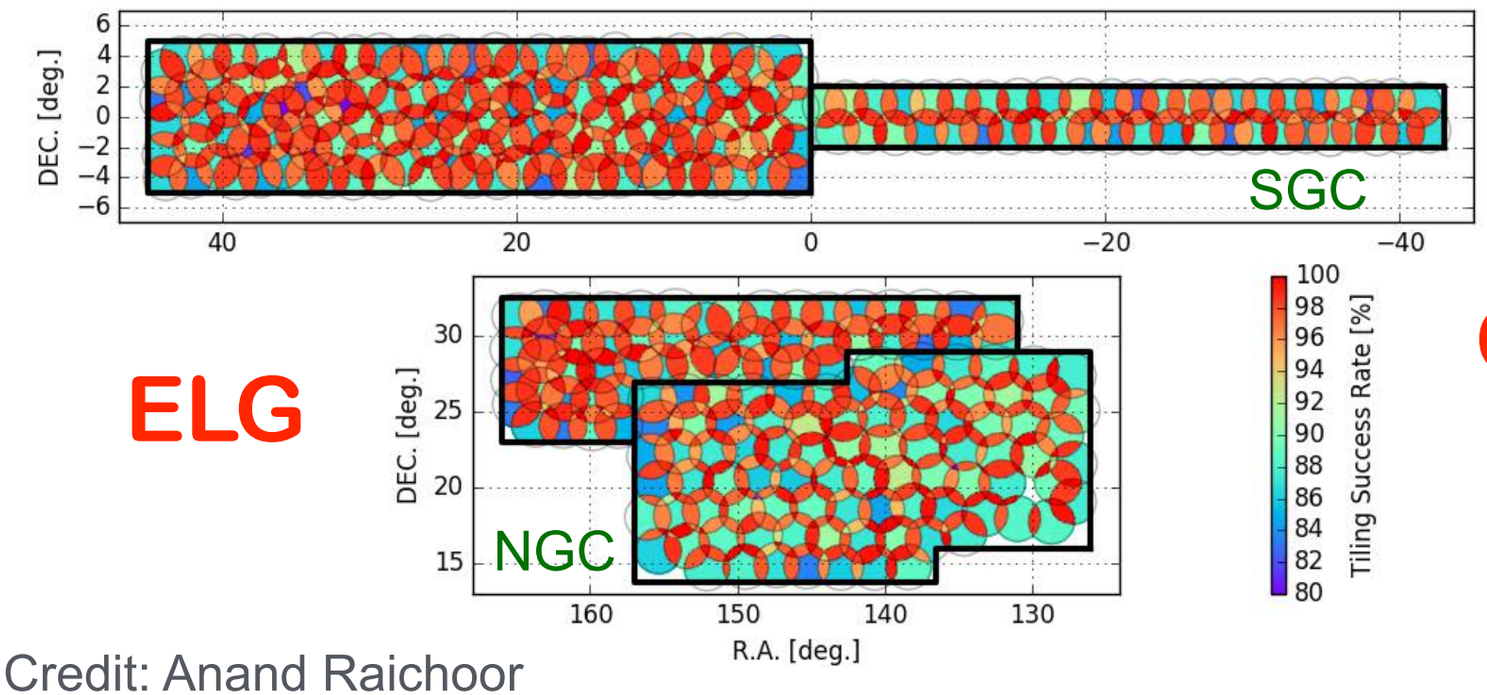
Raichoor+ 2017

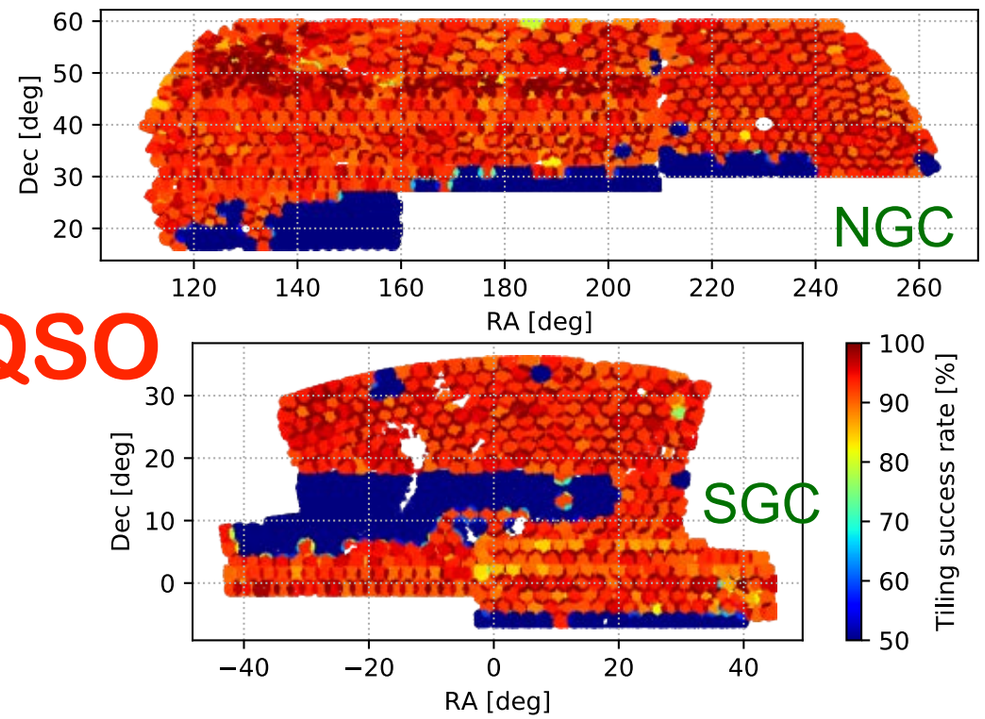
Tiling

Distributing targets to plates (eBOSS)

- LRG (Oct. 2014 — Feb. 2019)
  - 1020 plates, ~ 260 targets per plate
- ELG (Sep. 2016 — Feb. 2018)
  - 305 plates, ~ 820 ELG targets per plate
  - 4 chunks (independent of tiling)
- QSO (Jul. 2014 — Feb. 2019)
  - 1020 plates, ~ 520 QSO targets per plate



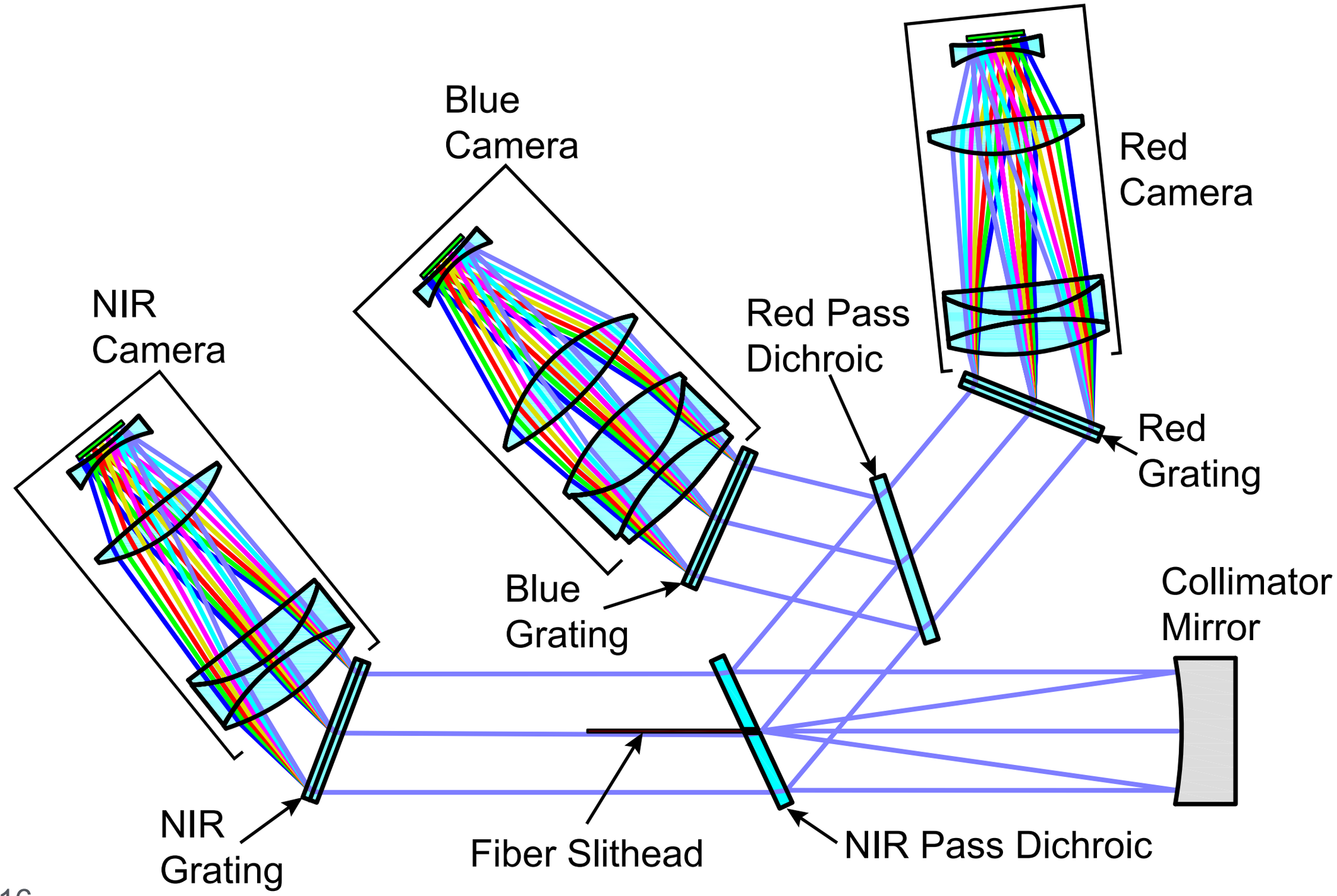




Credit: Anand Raichoor

Spectrograph

DESI spectrograph schematic

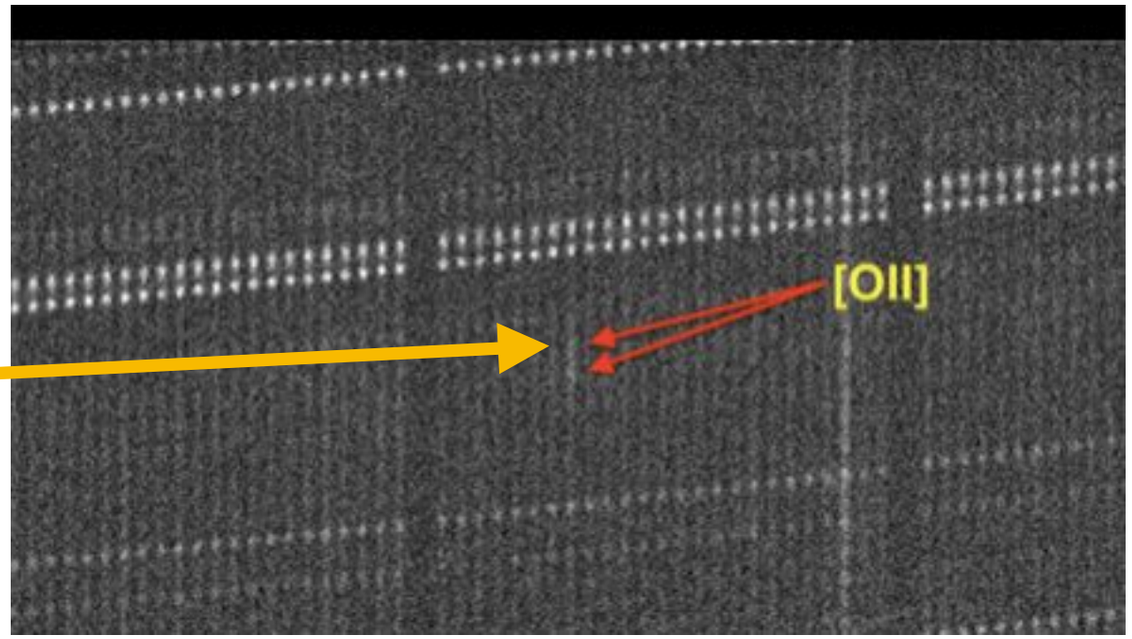


CCD image

Multi-fibre image

Legacy survey image

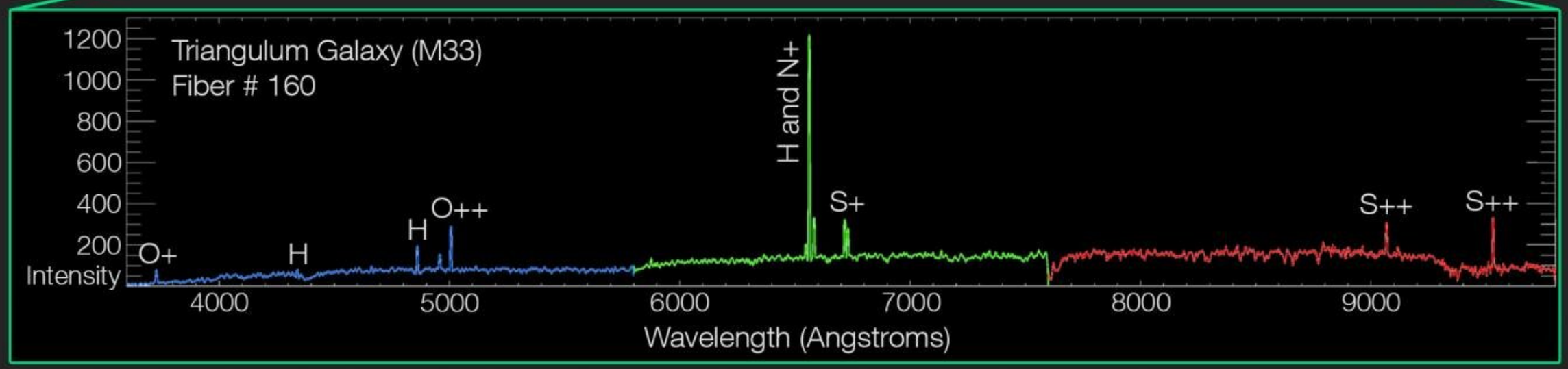
DESI CCD



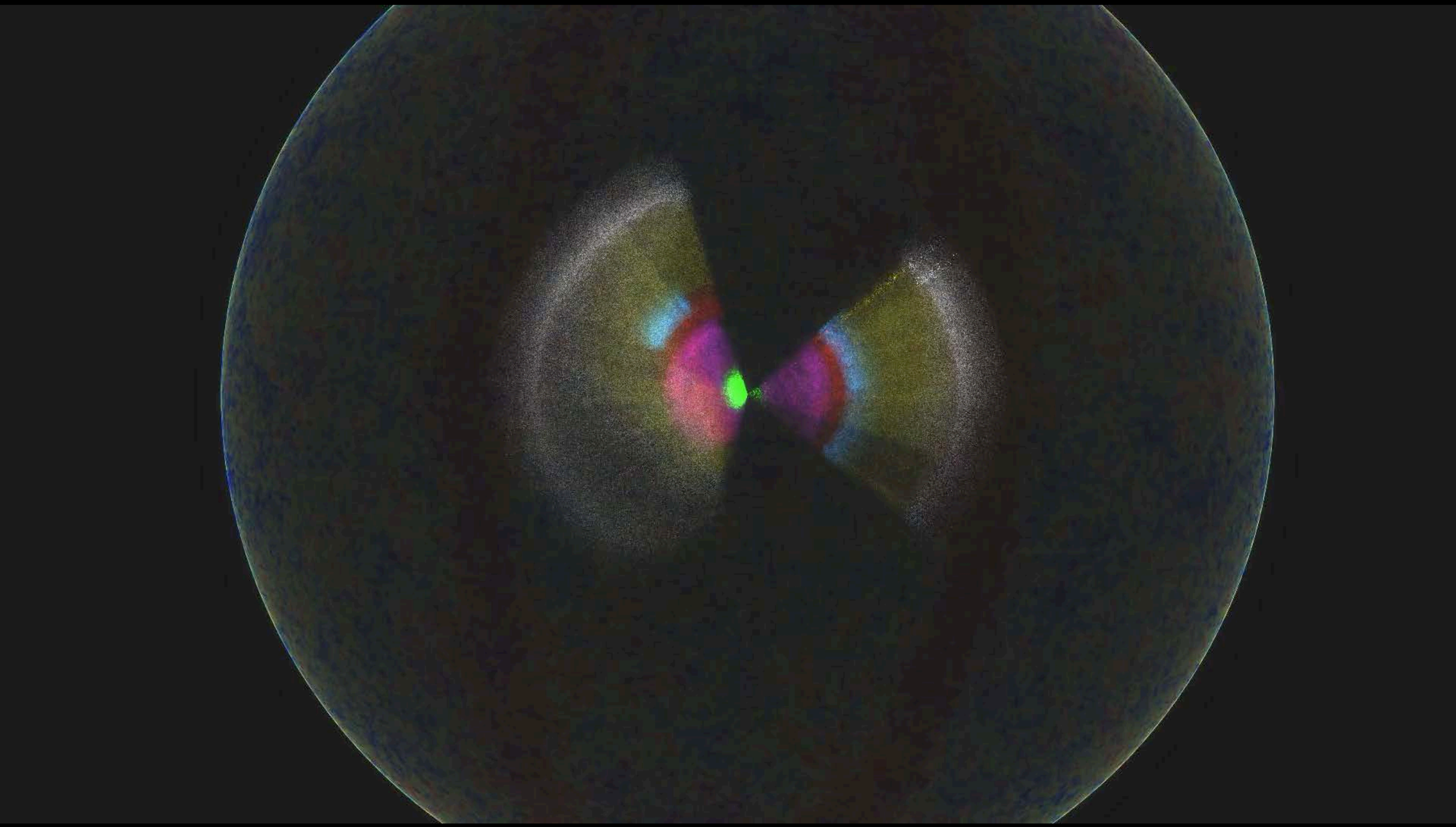
Credit: Paul Martini's slides

- ELG at z=1.619 (976nm, limit ~980nm)
- Sufficient resolution to resolve the doublet for robust redshift

DESI spectrum acquisition



SDSS tracers

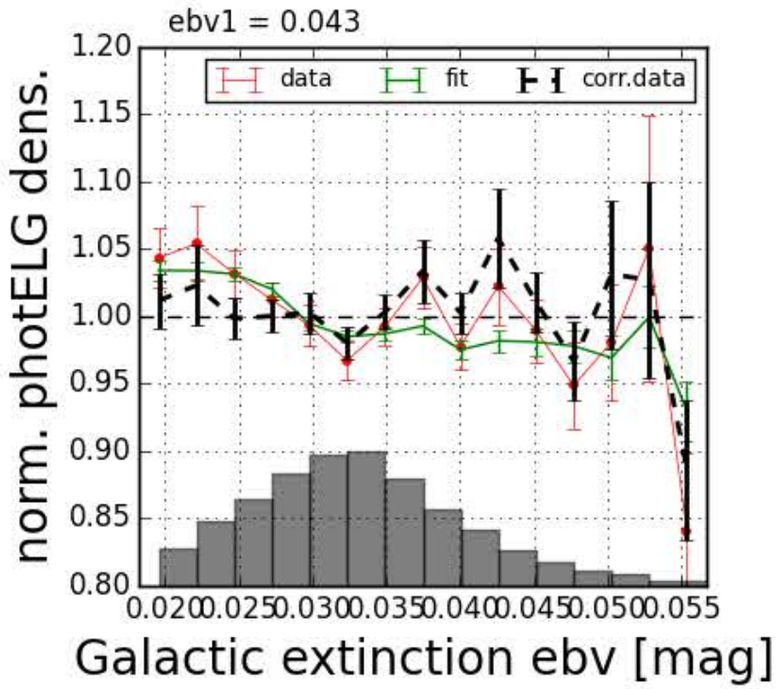


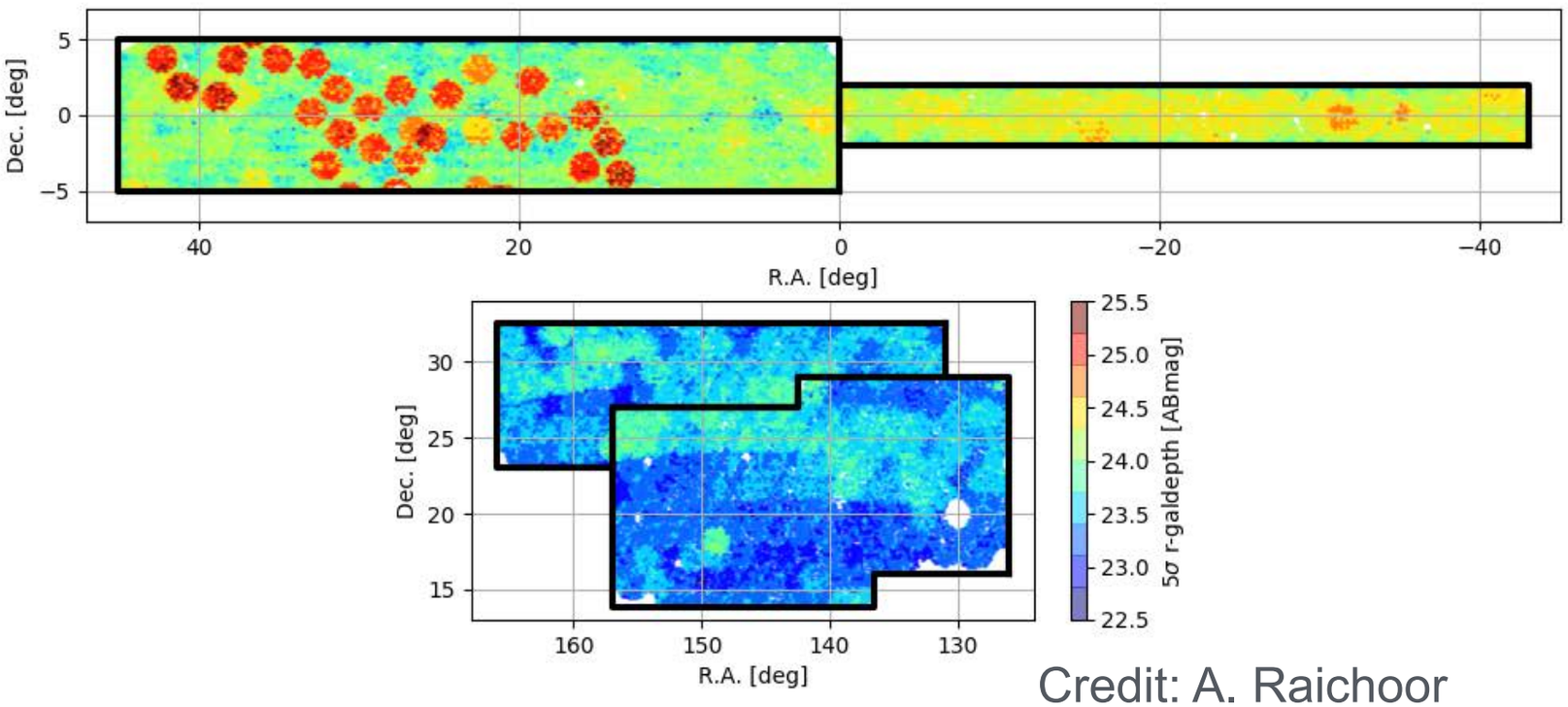
Credit: Anand Raichoor

Systematics

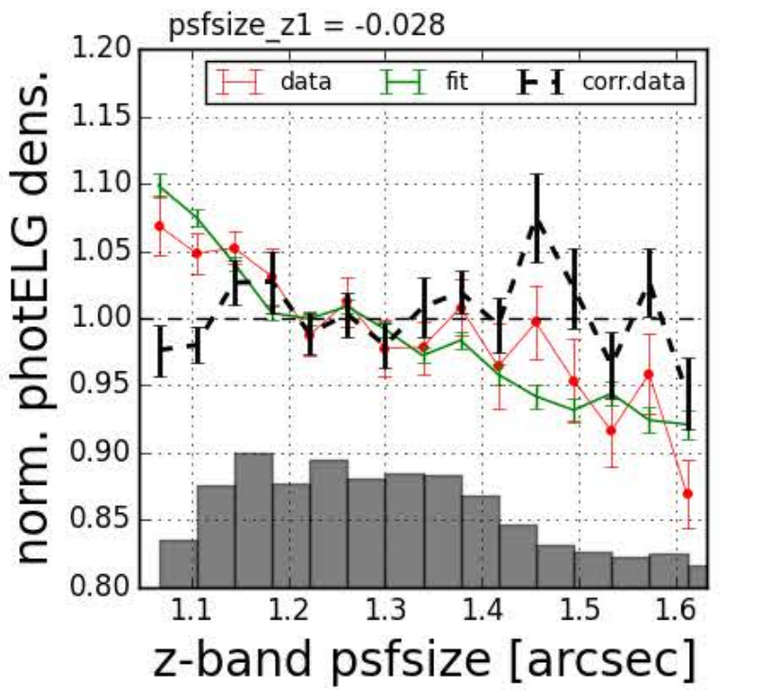
Imaging systematics

- Angular photometric systematics (linear regression)
  - Galaxy extinction
  - Stellar density
  - Depth and seeing
  - Others
- Depth-dependent redshift density (eBOSS ELG)
  - significant imaging depth inhomogeneities





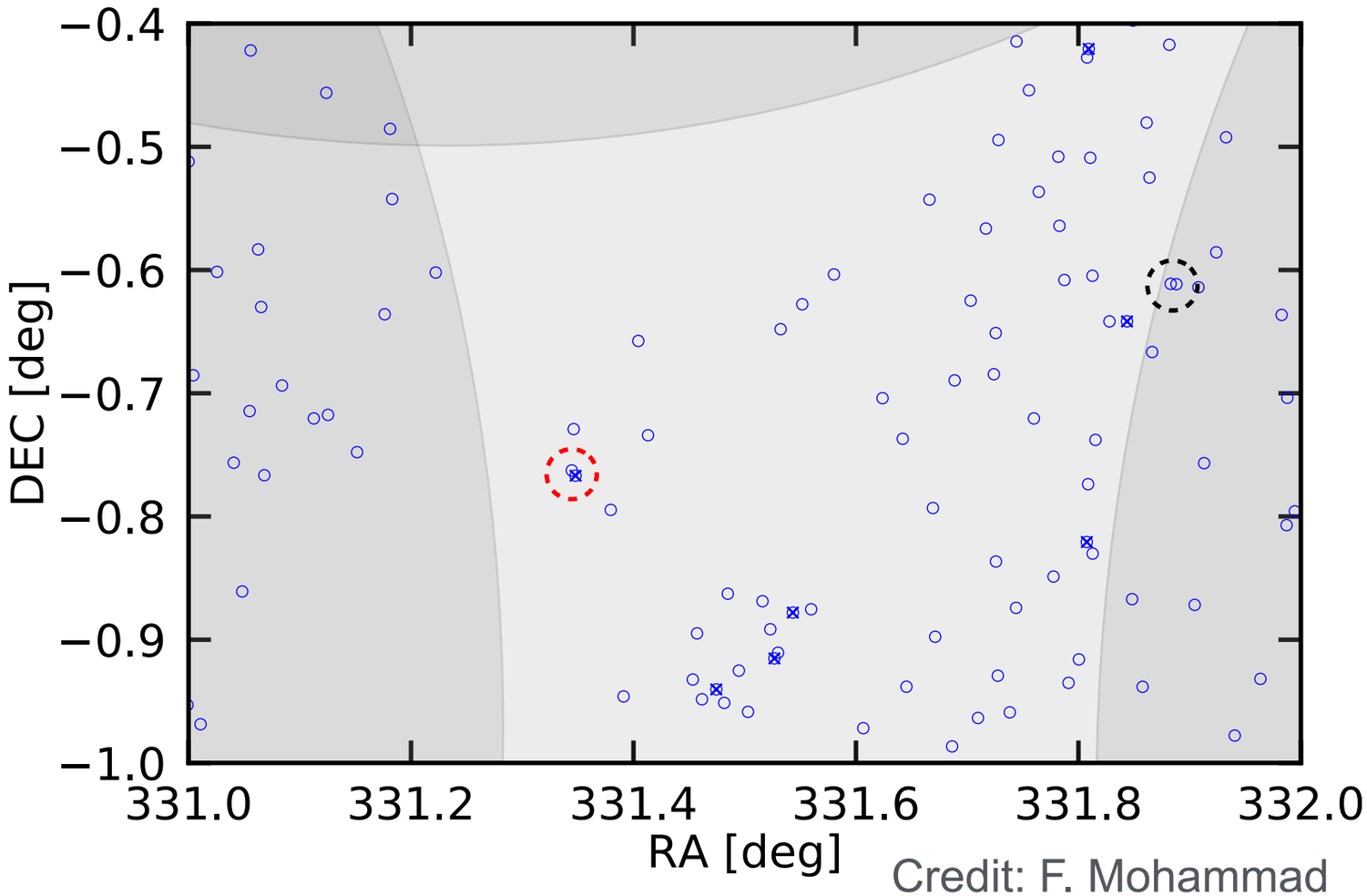
Credit: A. Raichoor



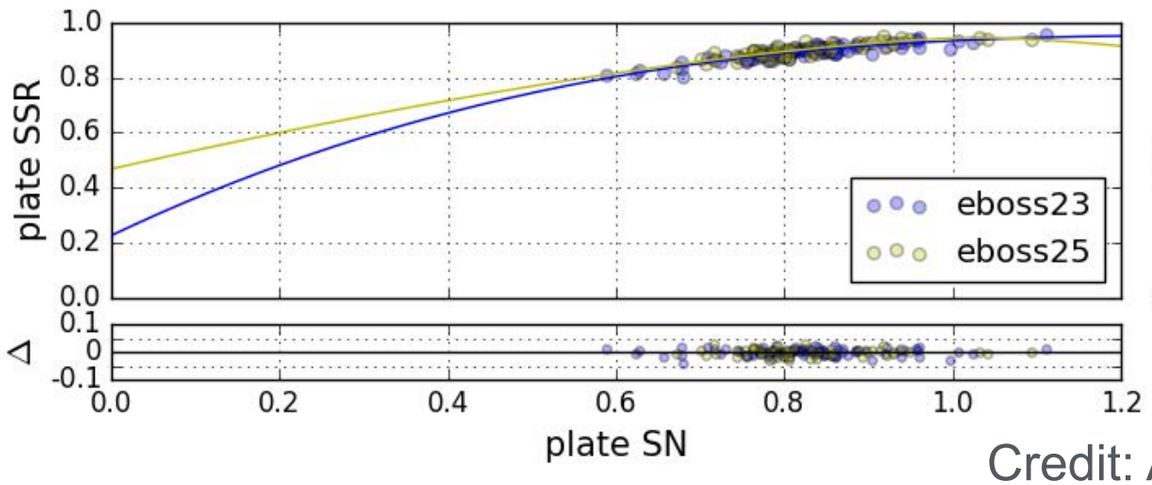
Systematics

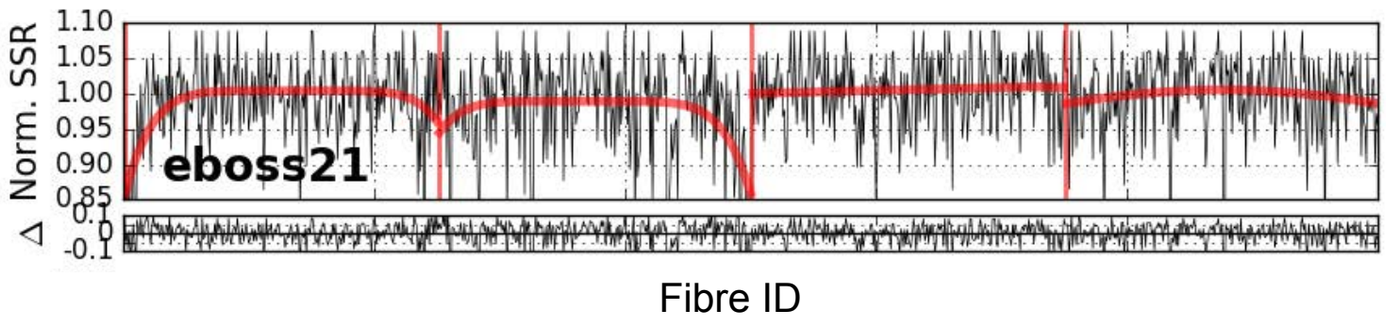
Spectroscopic systematics

- Fibre collision
  - Physical size of fibres
- Redshift failure
  - Position on the focal plane
  - Fibre ID / CCD pixel
  - Observational conditions (signal-to-noise ratio of spectra)
- Redshift error
  - Line confusion



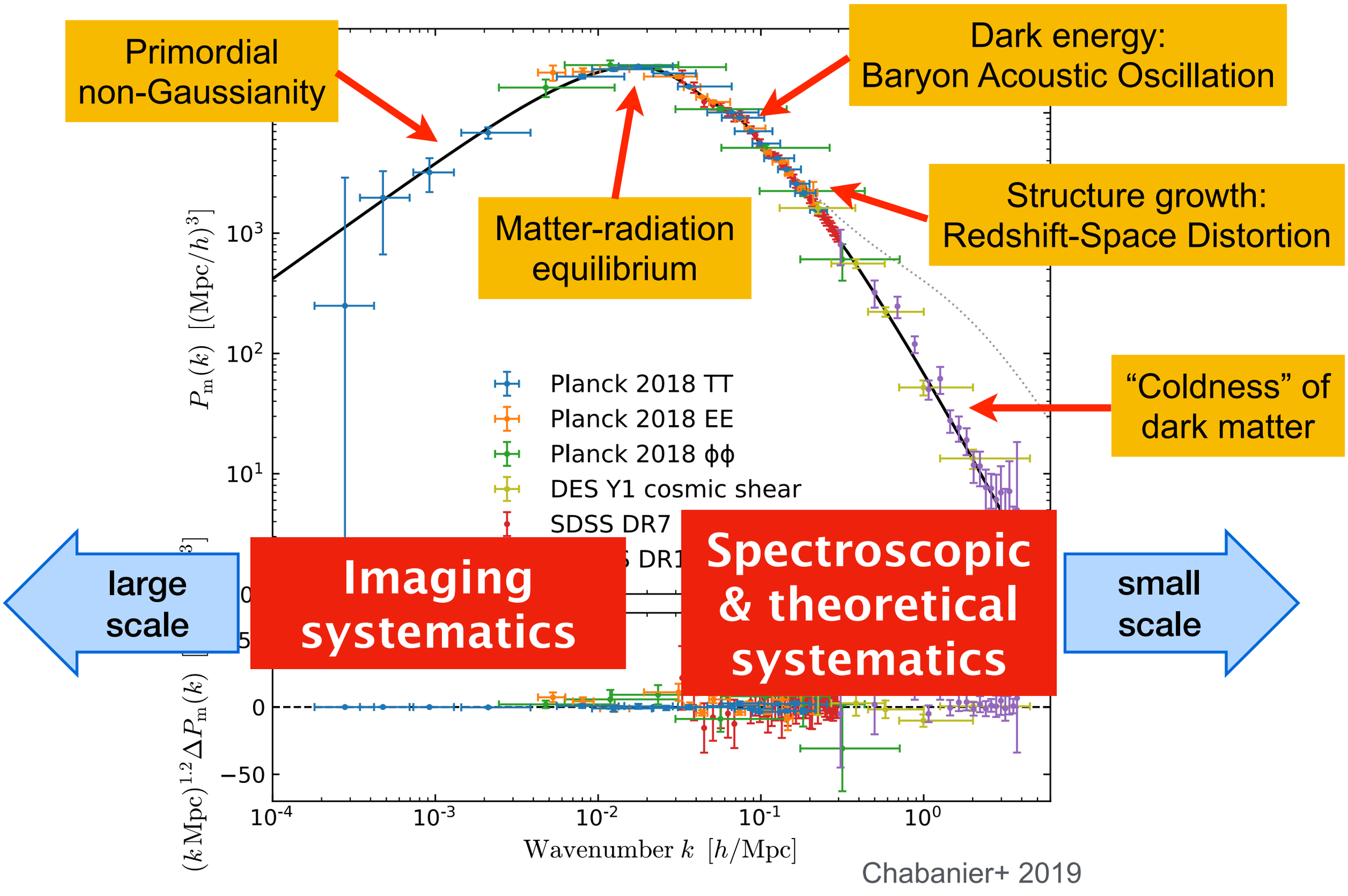
Credit: F. Mohammad





Credit: A. Raichoor

Matter power spectrum

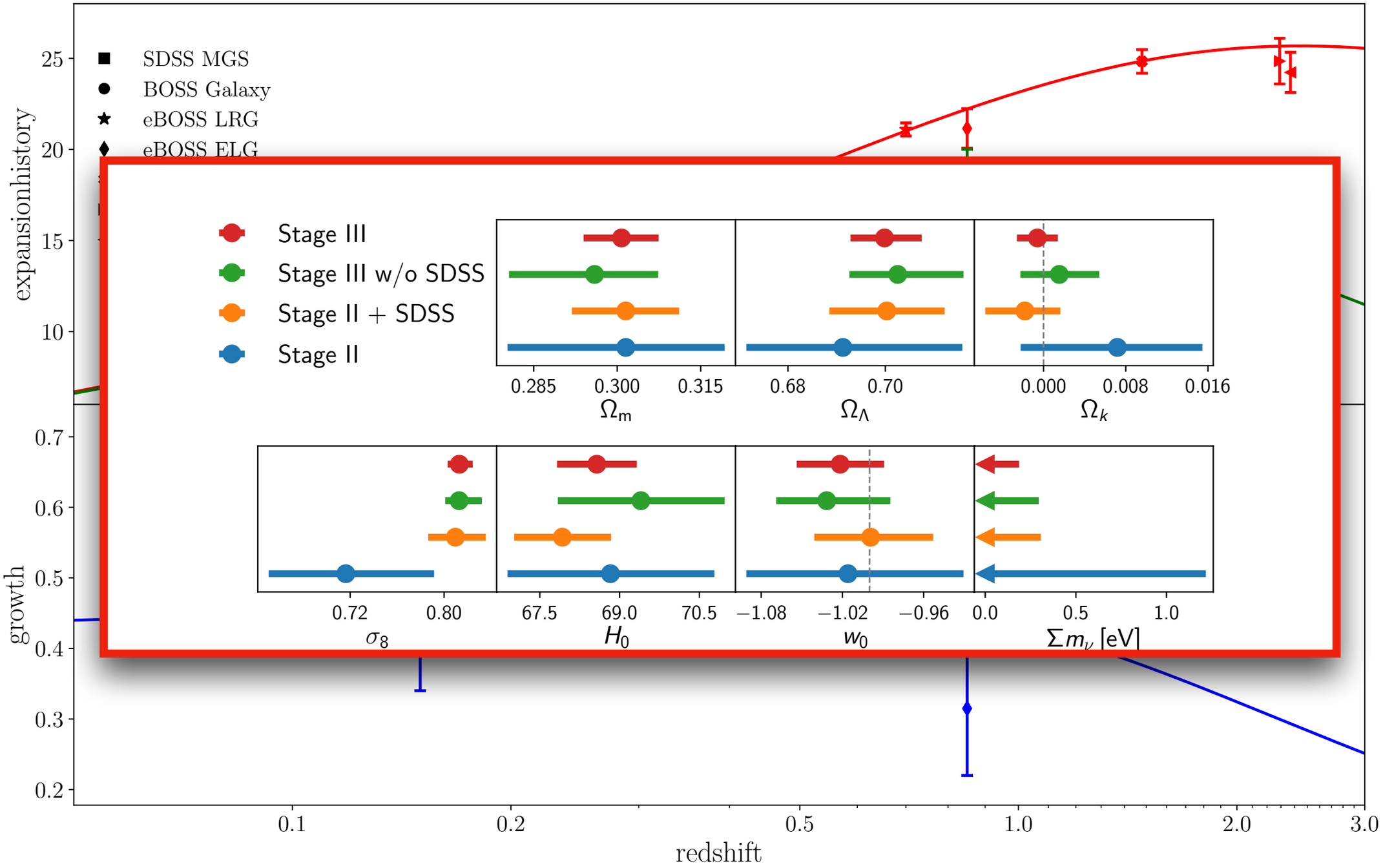


Chabanier+ 2019

SDSS final results

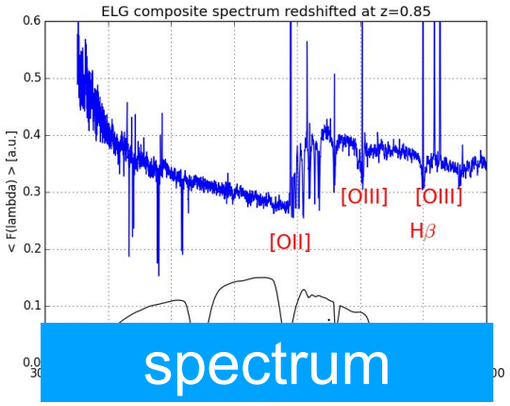
BAO

RSD



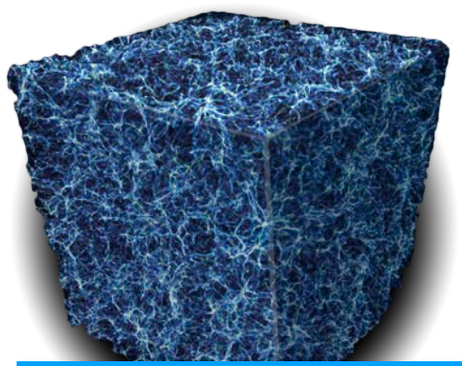
eBOSS 2021

Standard clustering analysis

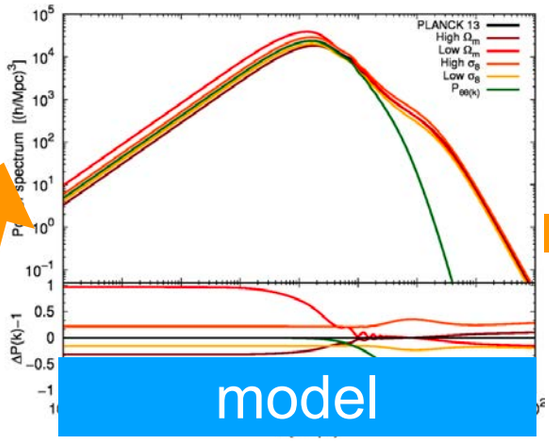


spectrum

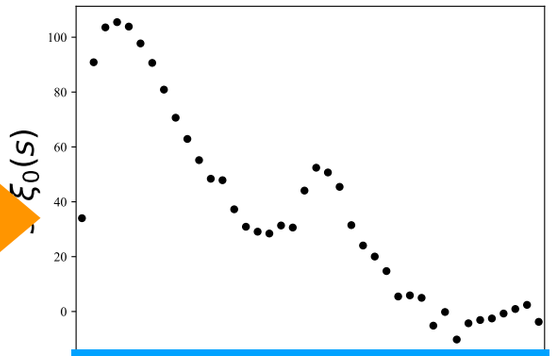
3D map



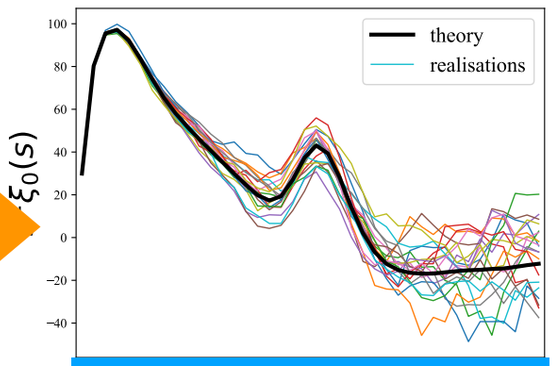
simulations



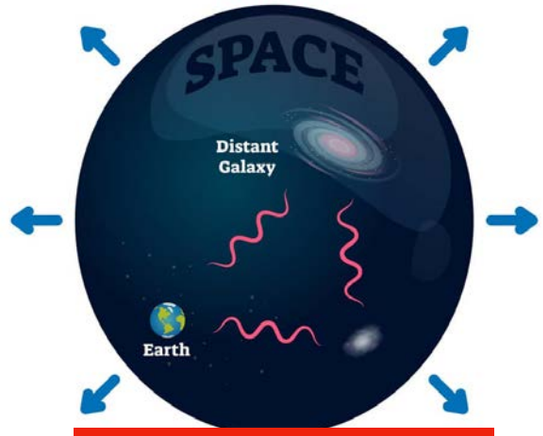
model



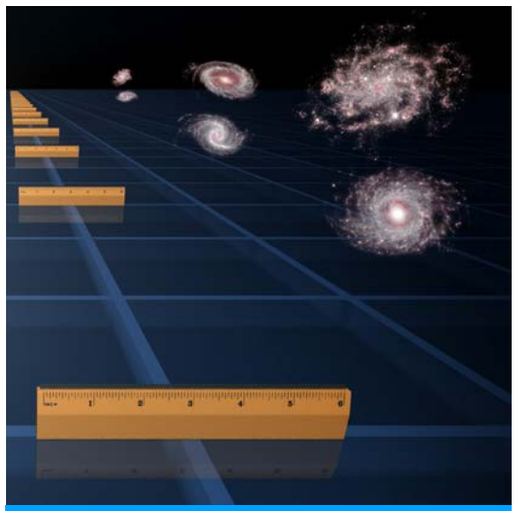
clustering



covariance



cosmology

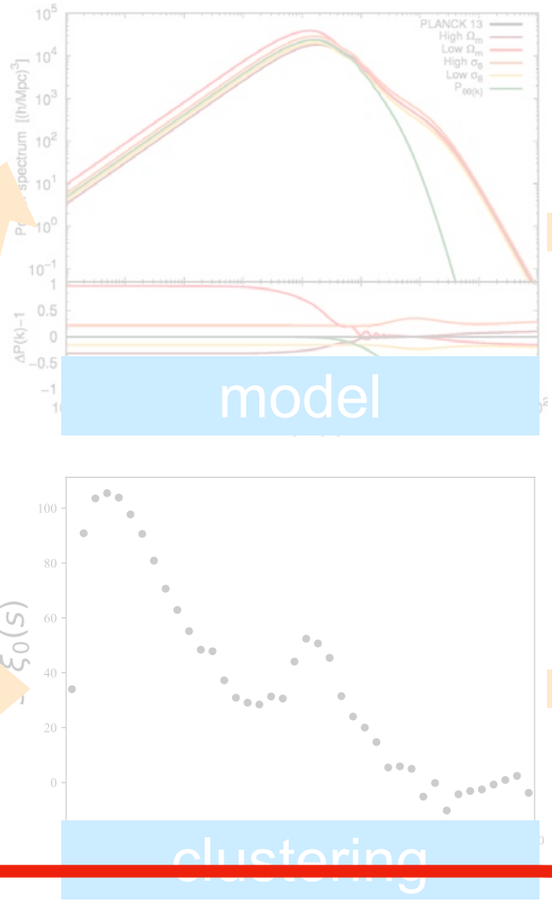


distance
structure growth

Approximate mocks

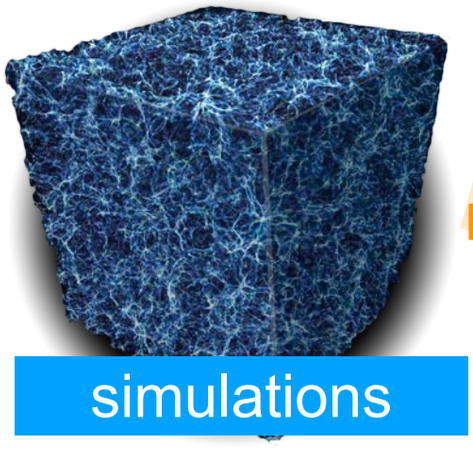
spectrum

3D map

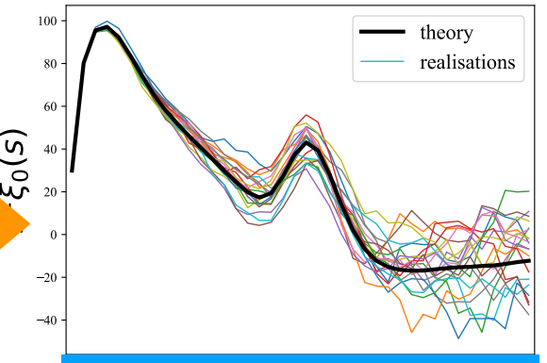


model

clustering



simulations



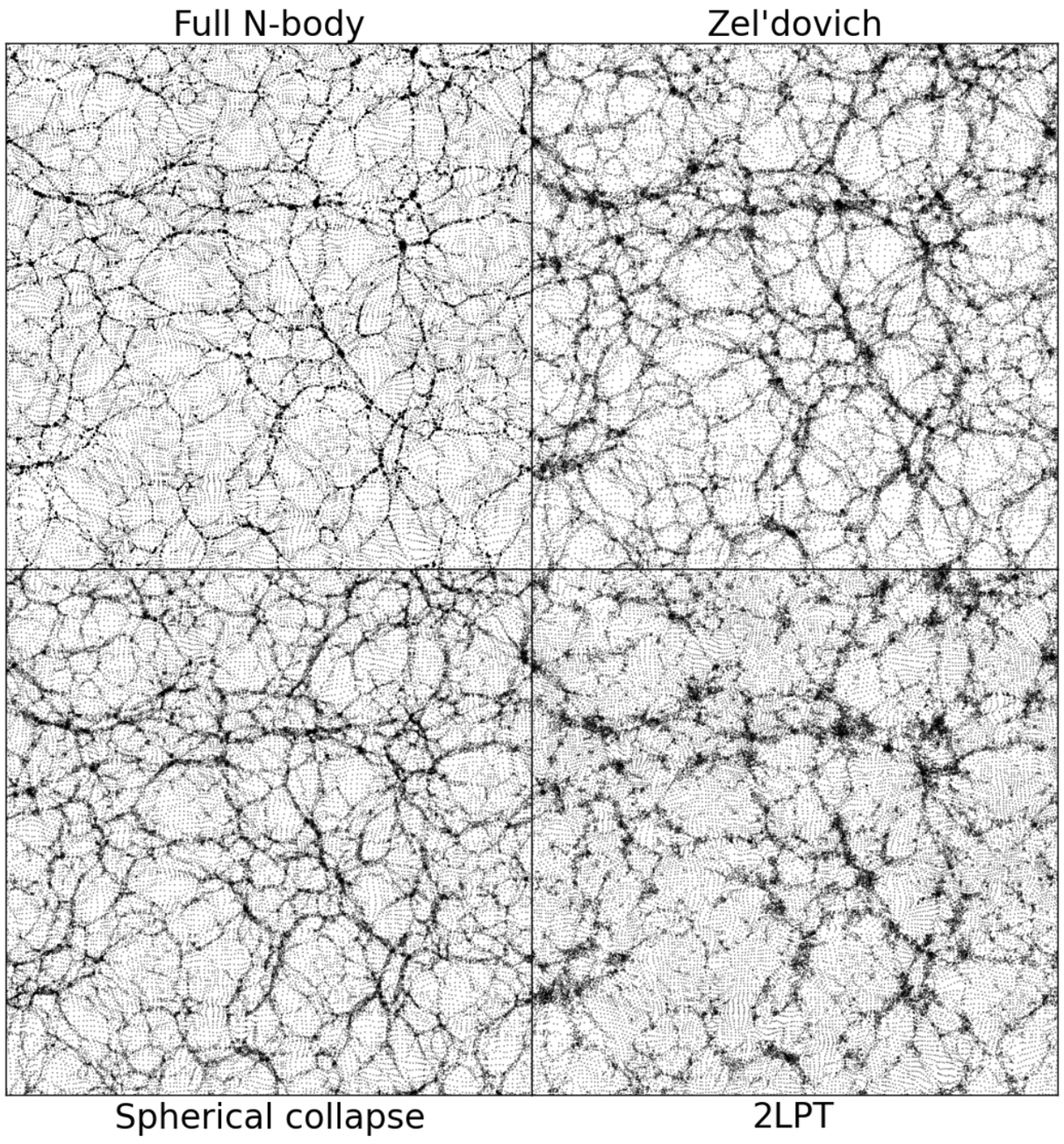
covariance

cosmology

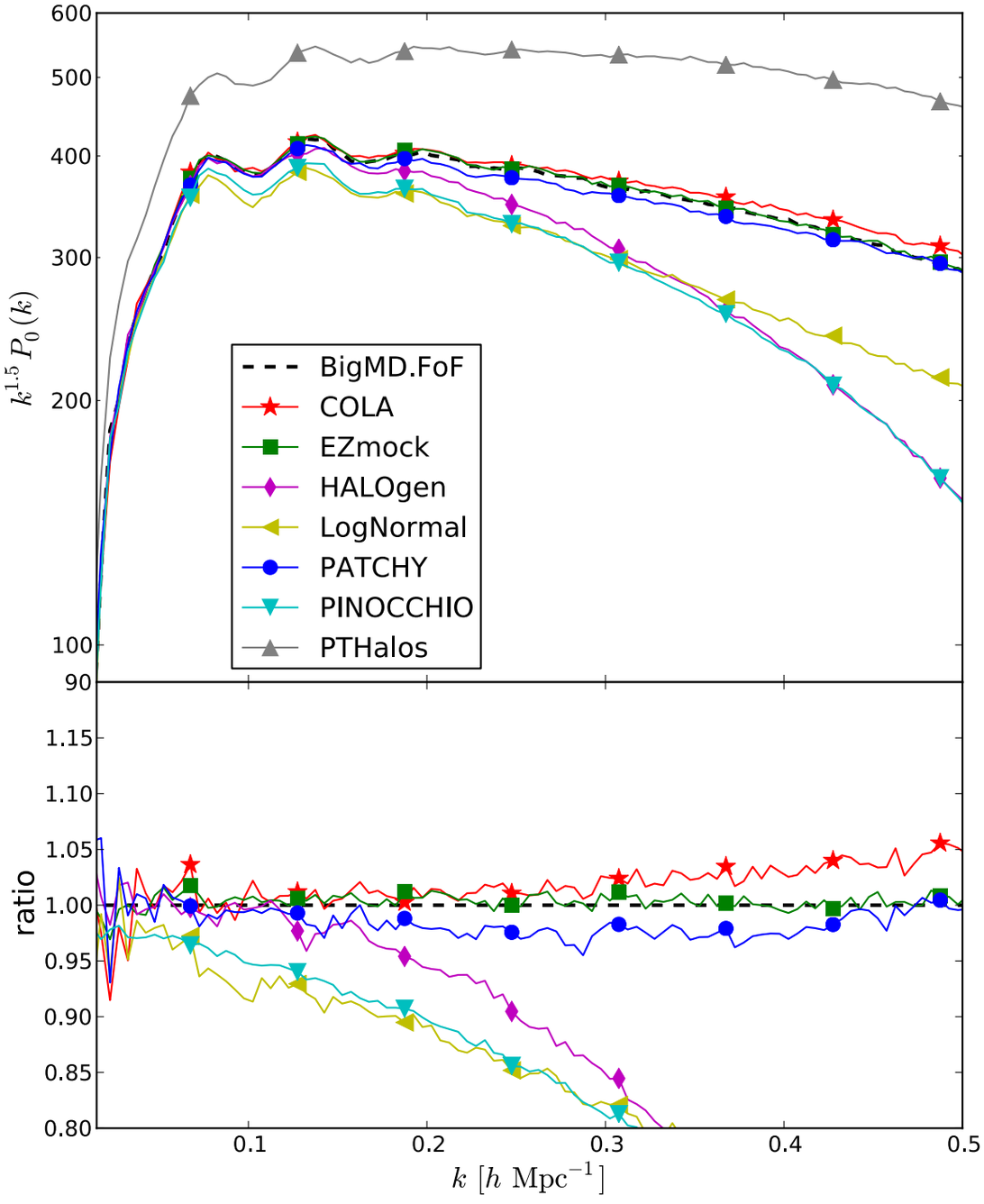
distance
structure growth

Fast mock generation

Perturbation theories / less time steps



Neyrinck+ 2013



Chuang, **CZ**+ 2015

Fast mock: EZmock

Initial condition

Gravity solver

Perturbation Theory:
Zel'dovich approximation

N-body simulation

> 10^6 CPU hours

Dark matter density field

EZmock

~10 CPU hours

Halo finder

Dark matter haloes

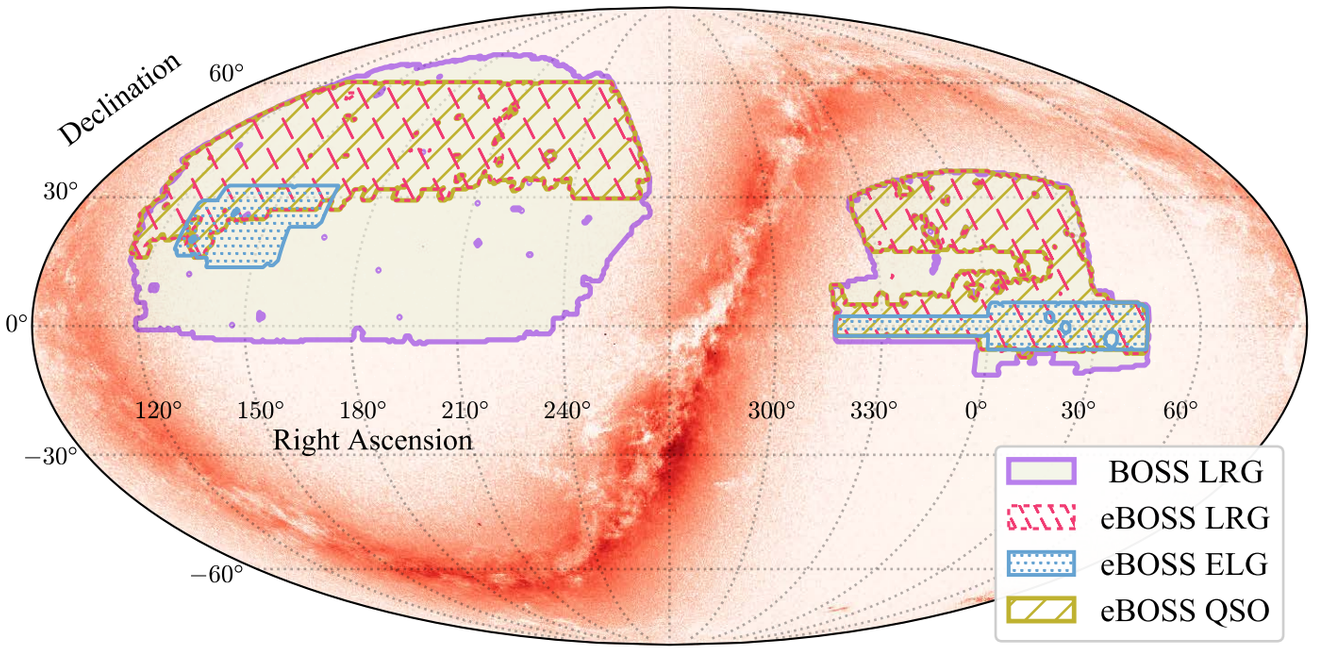
Effective bias model

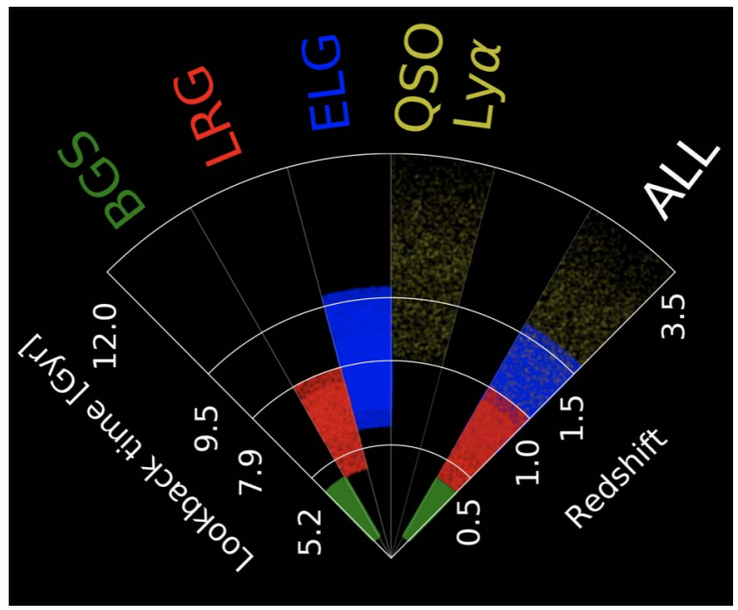
Halo occupation model

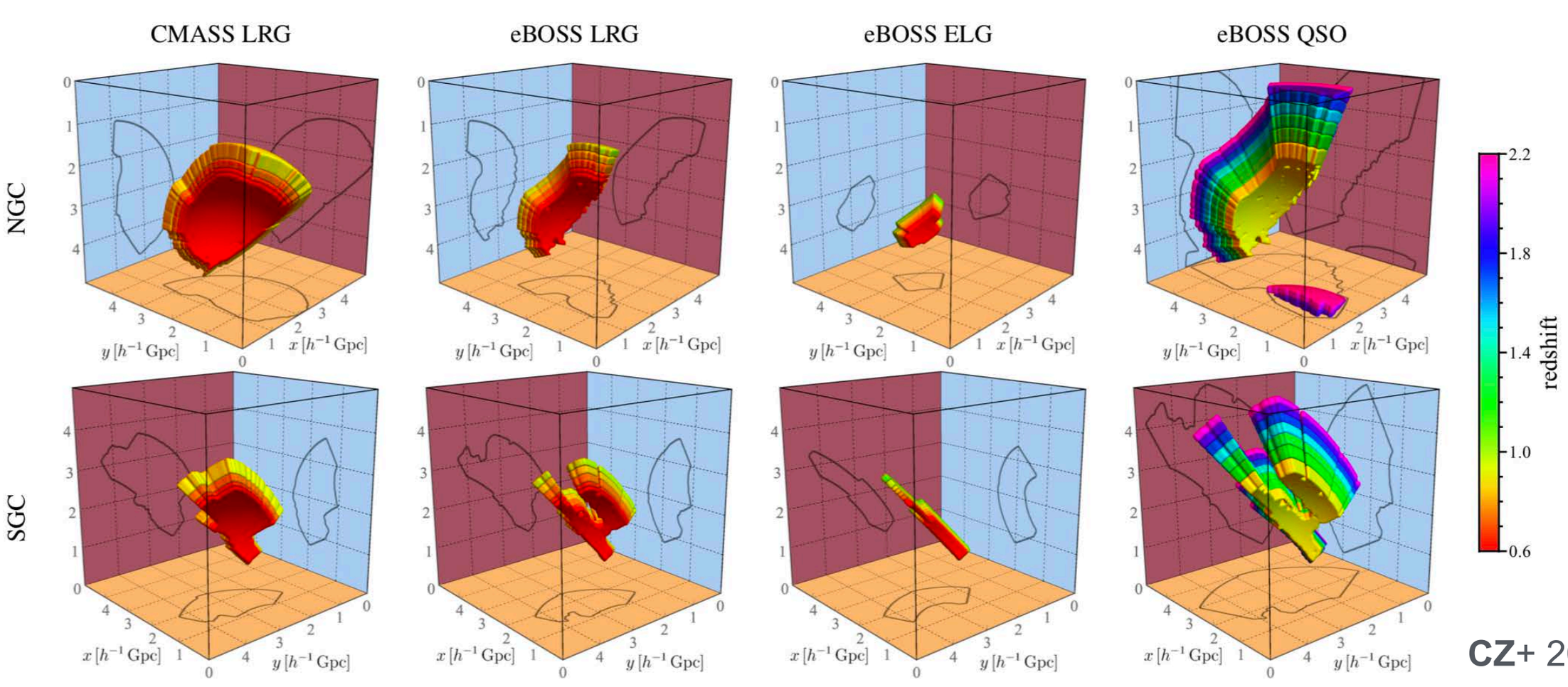
Galaxies

Chuang, …, **CZ**+ 2015

Survey geometry & redshift evolution

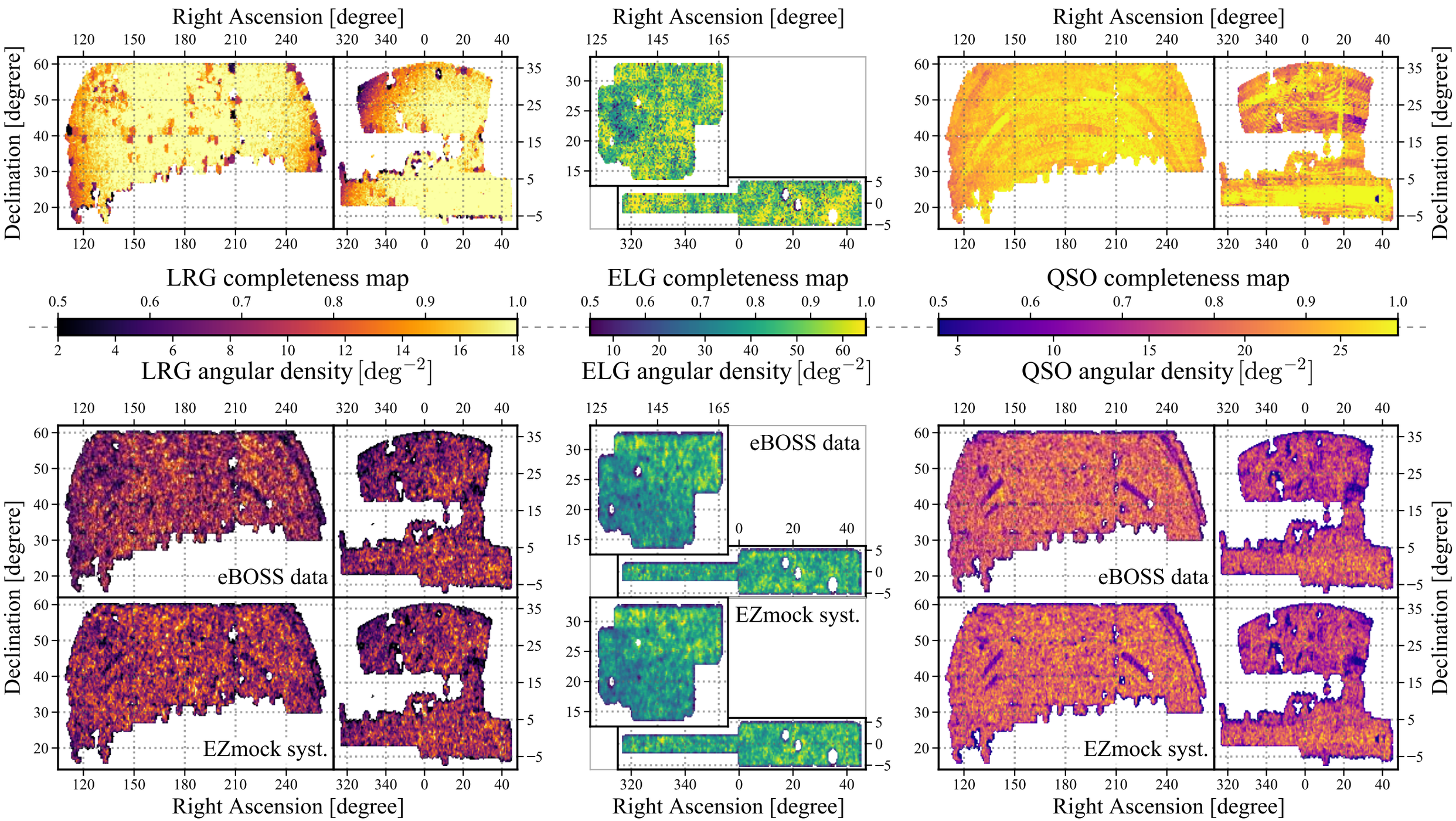






CZ+ 2021

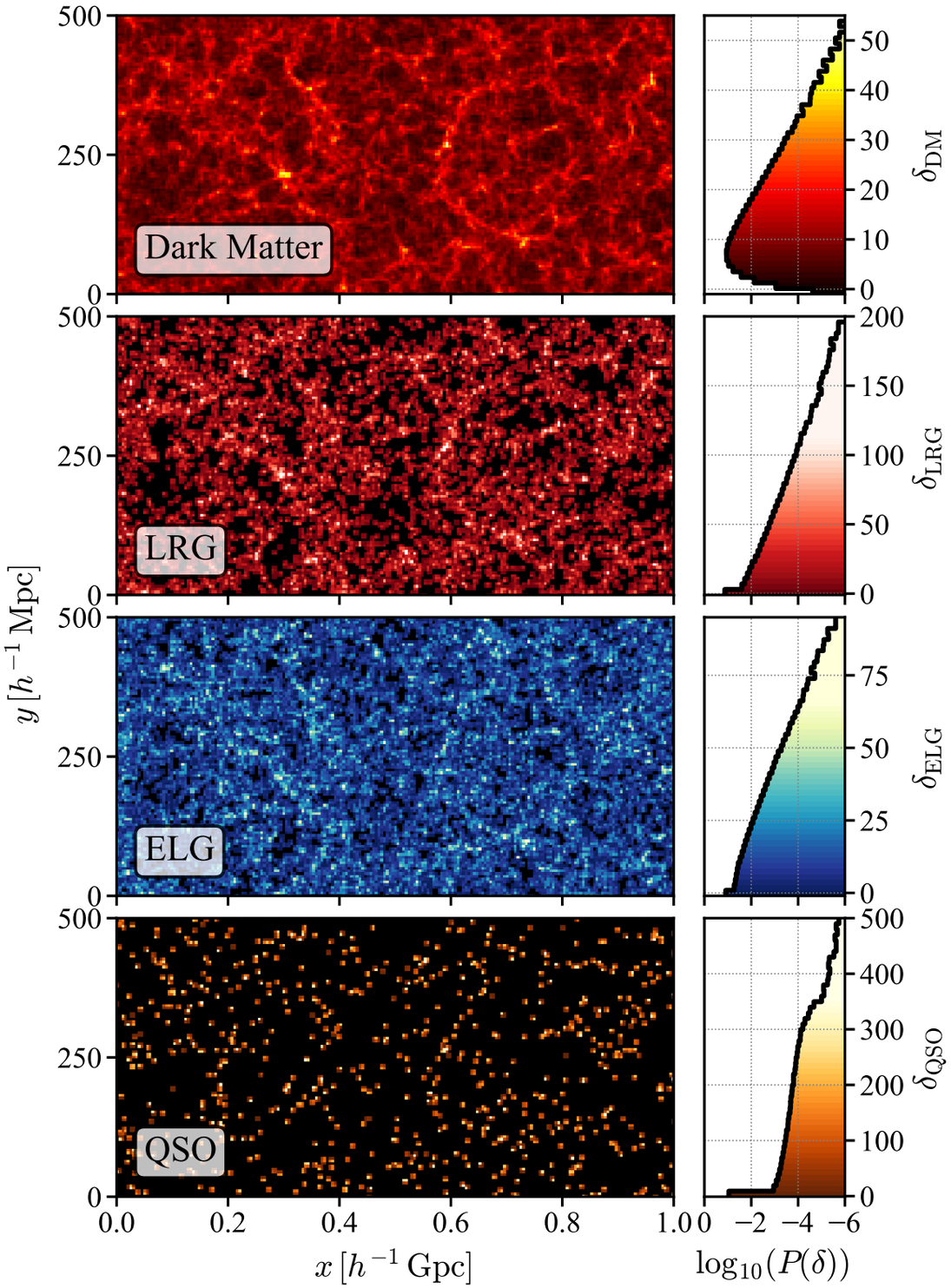
Imaging systematics

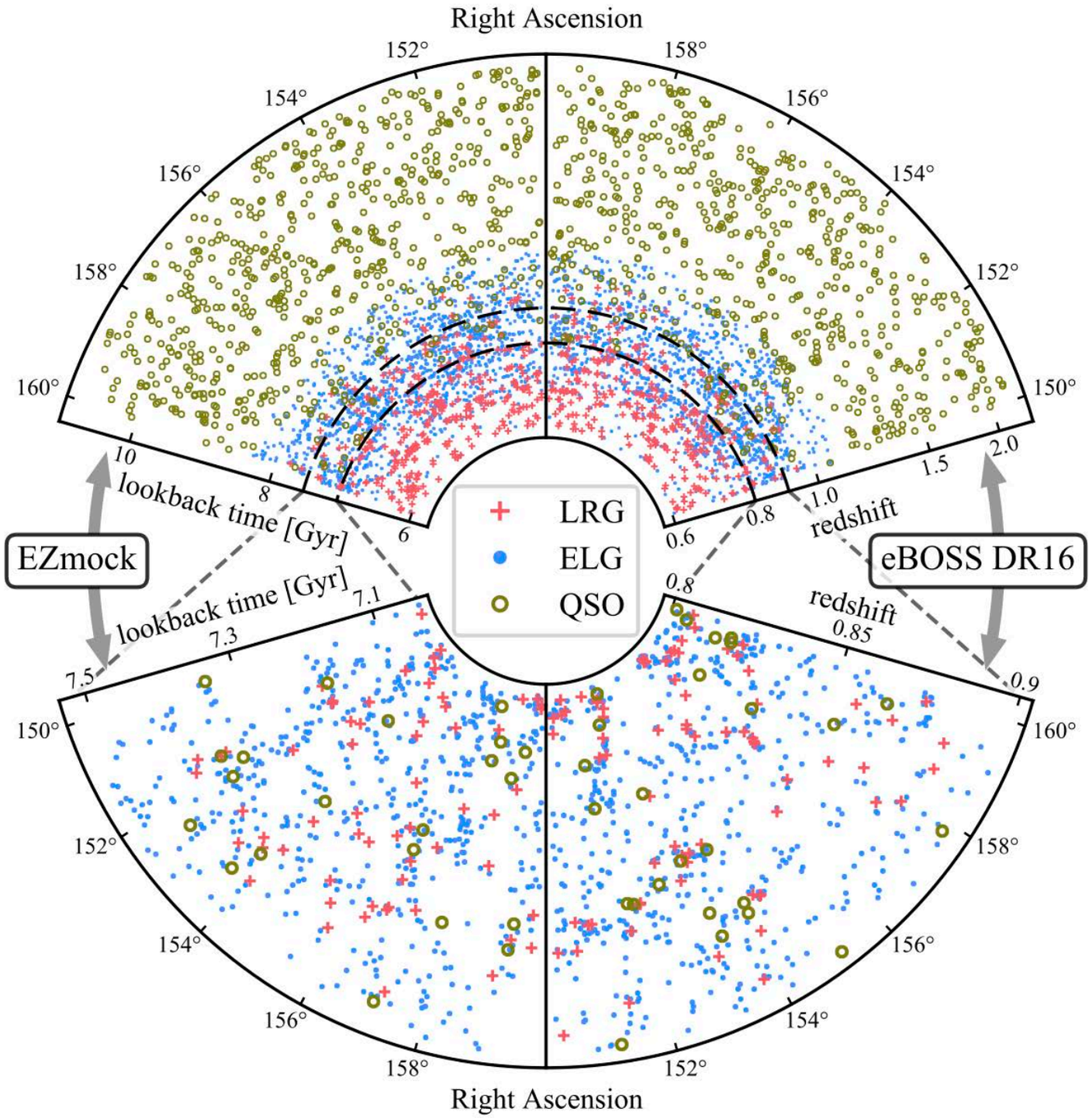


CZ+ 2021

EZmock: density map

eBOSS multi-tracer mocks



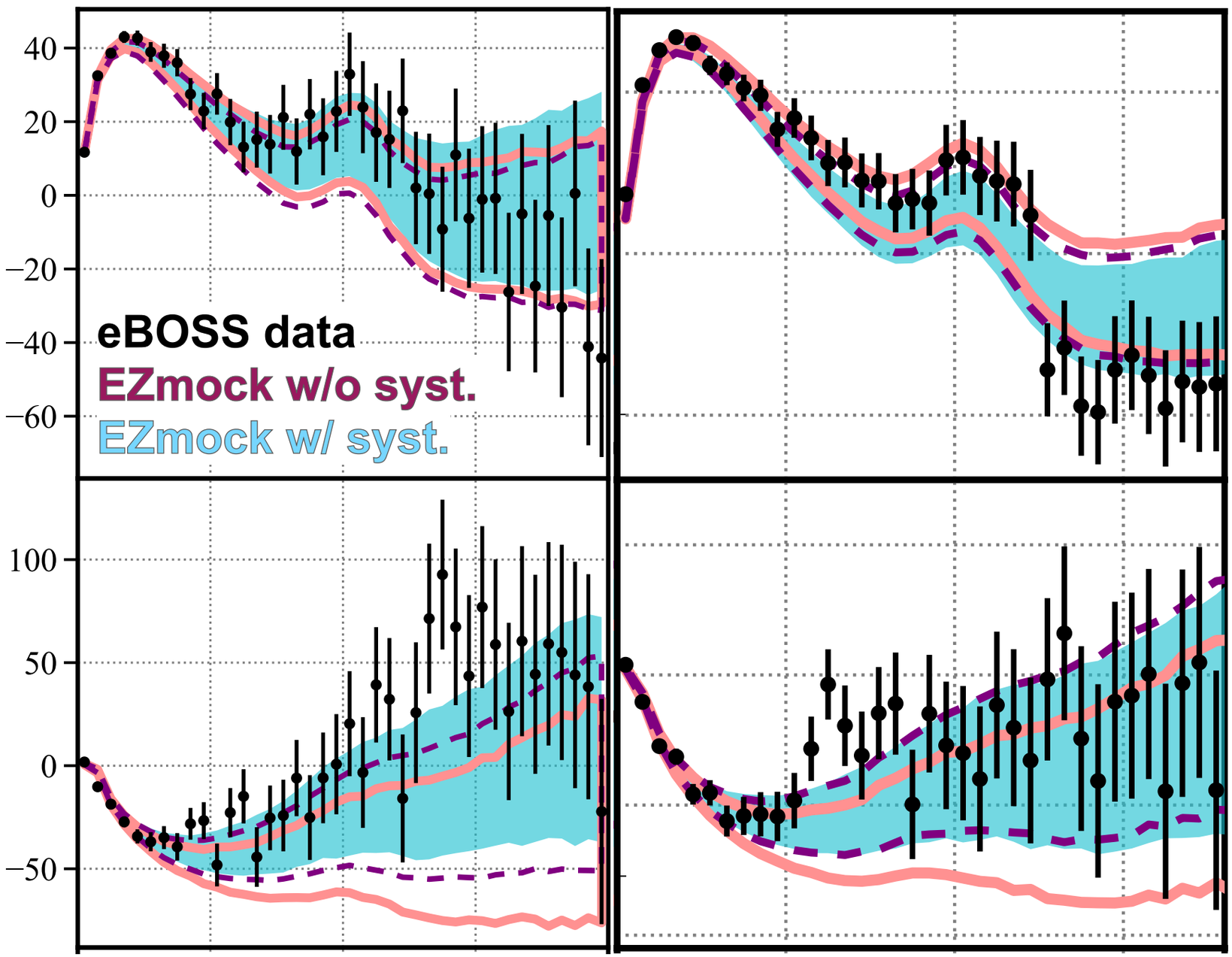


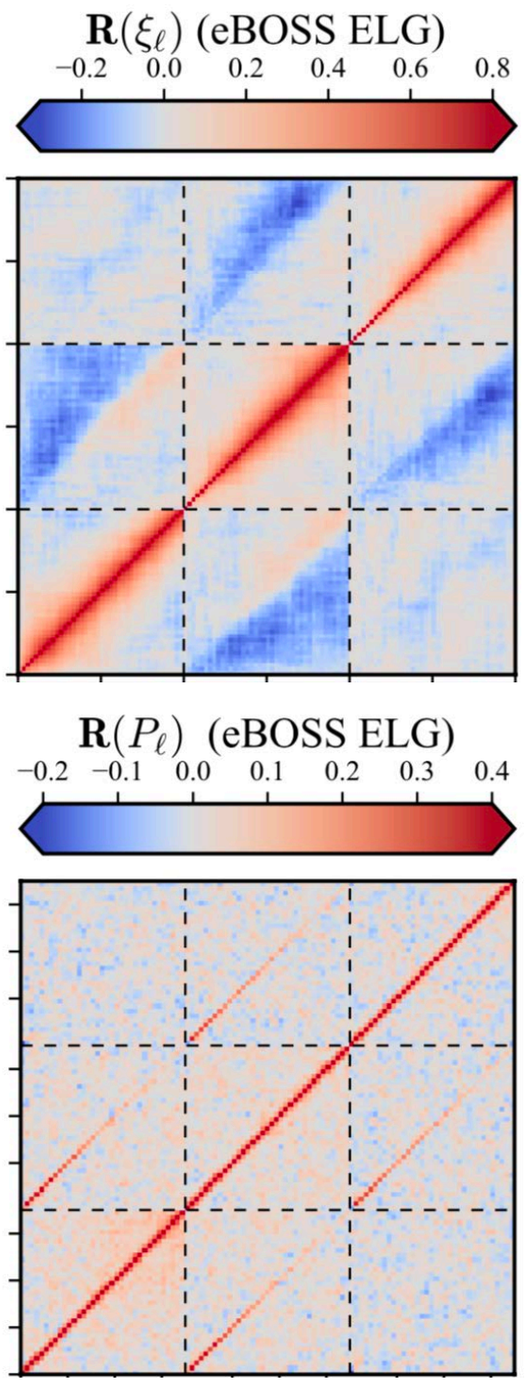
CZ+ 2021

EZmock clustering

ELG auto correlation

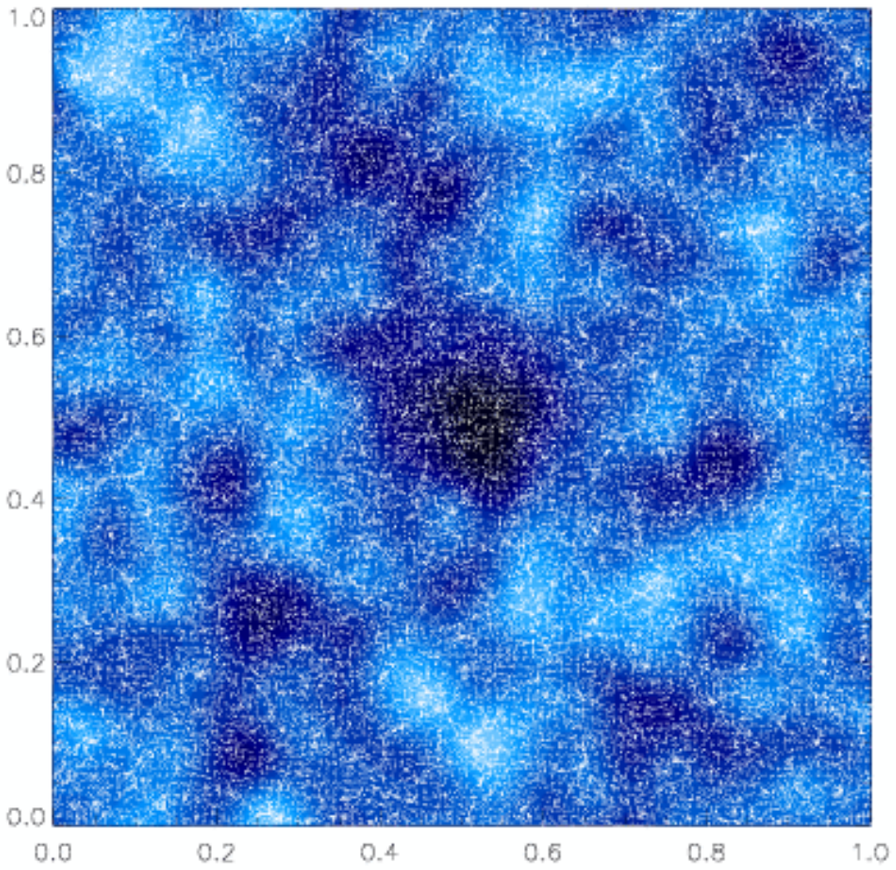
LRG x ELG

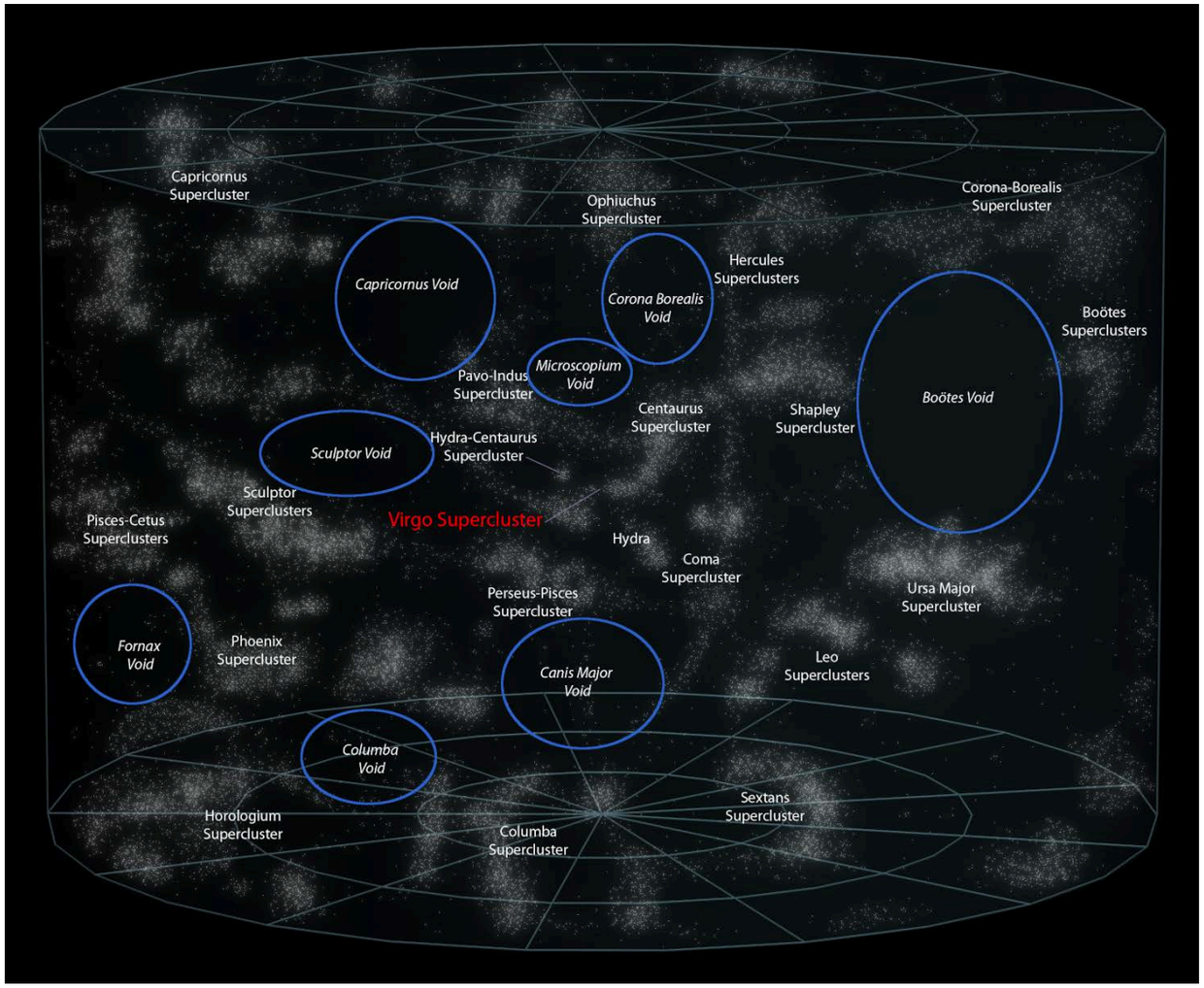




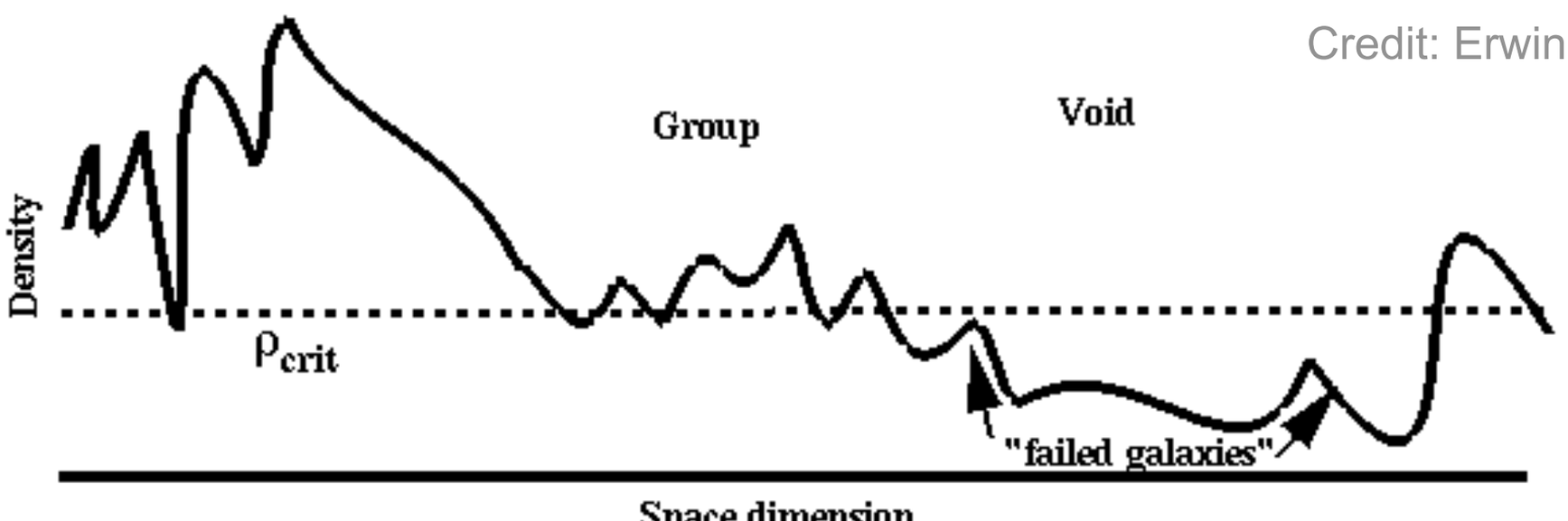
CZ+ 2021

Beyond standard analysis: voids



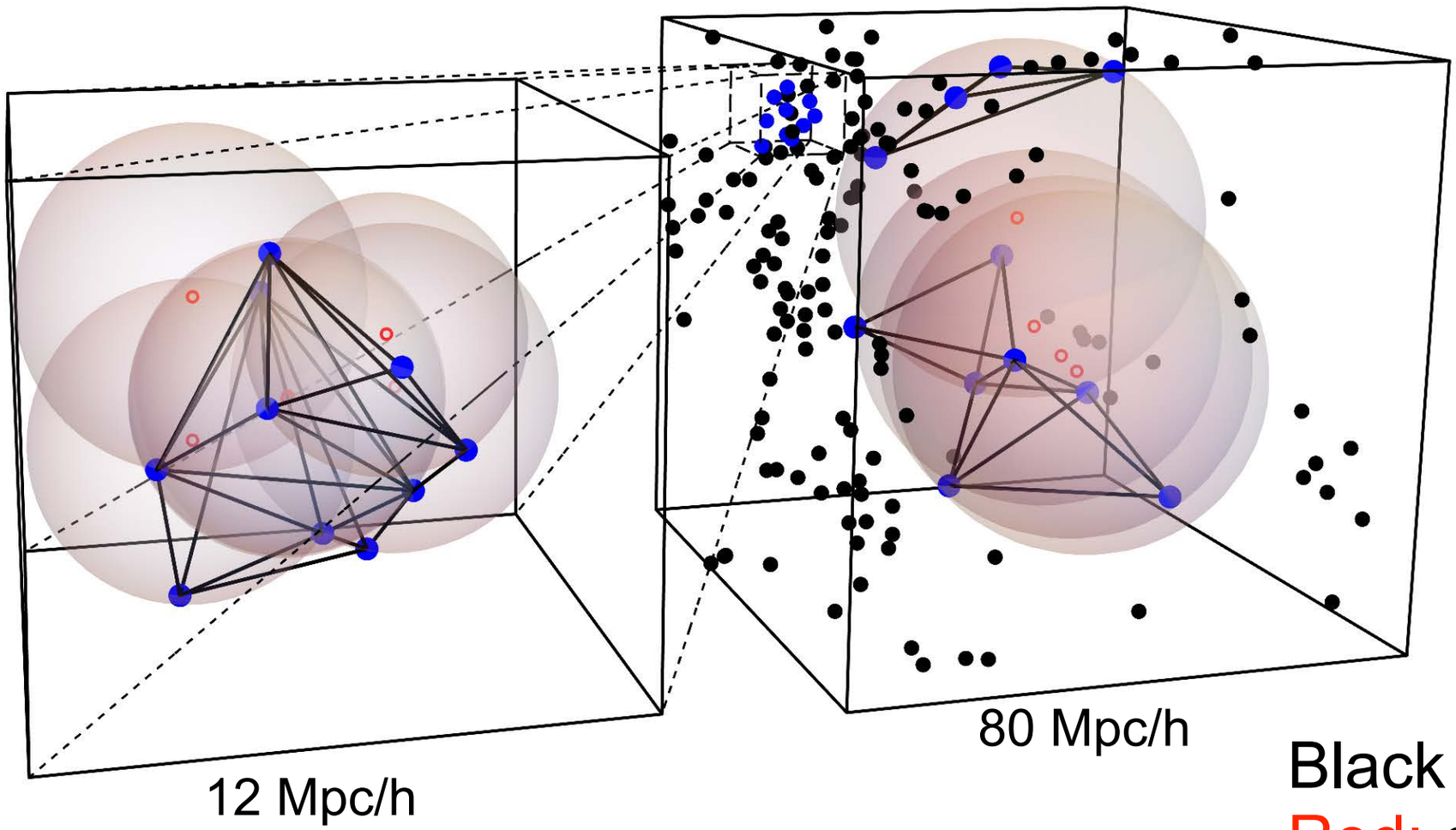


Credit: Erwin Platen, Keel's web



DT “voids”

Visualisation



Black & blue: haloes
Red: centres of “voids”

Cosmology independent

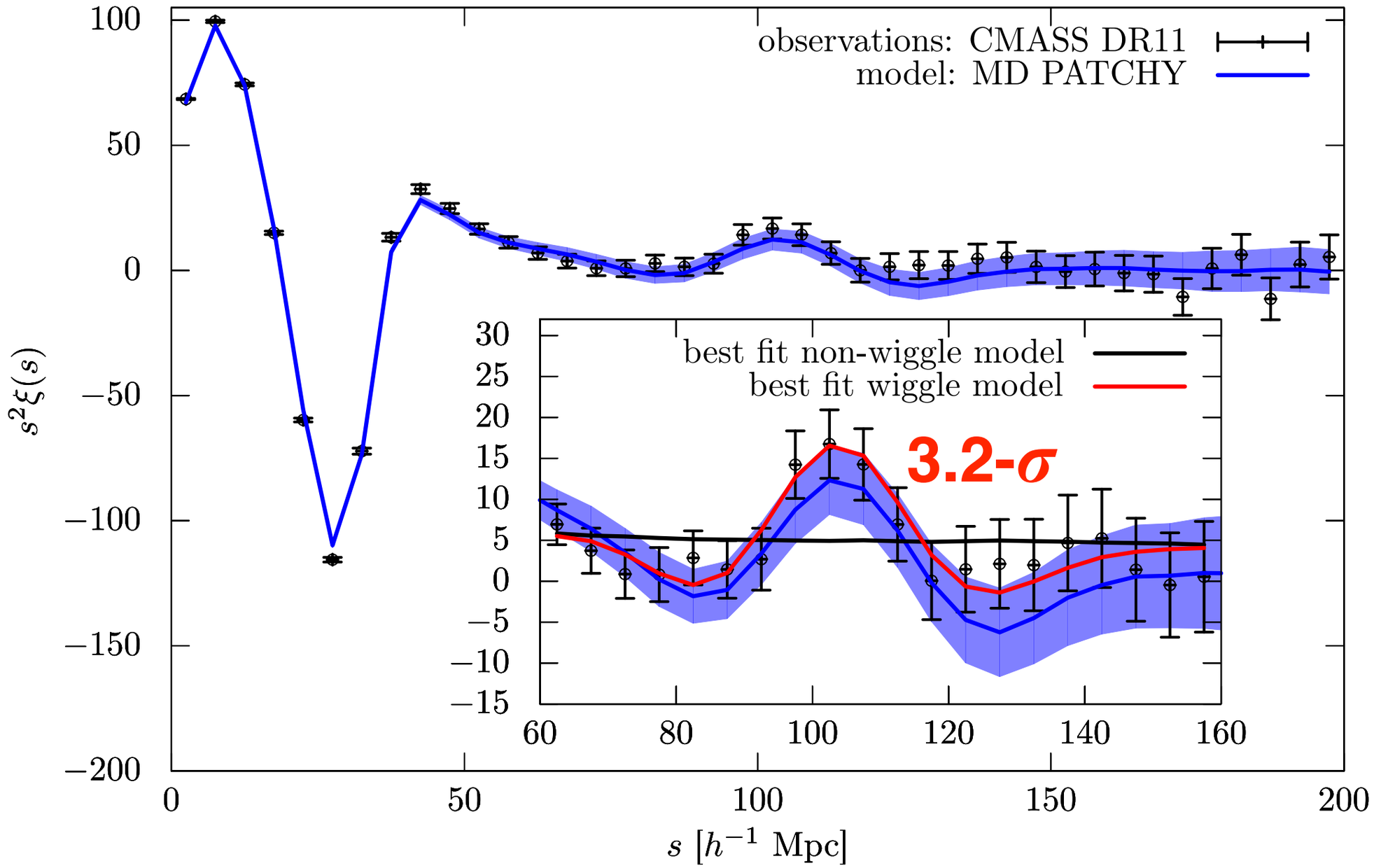
~10 minutes for 5.5 million haloes with one CPU core

Complexity: $N \log(N)$

CZ+ 2016

First void BAO detection

BOSS DR11 data

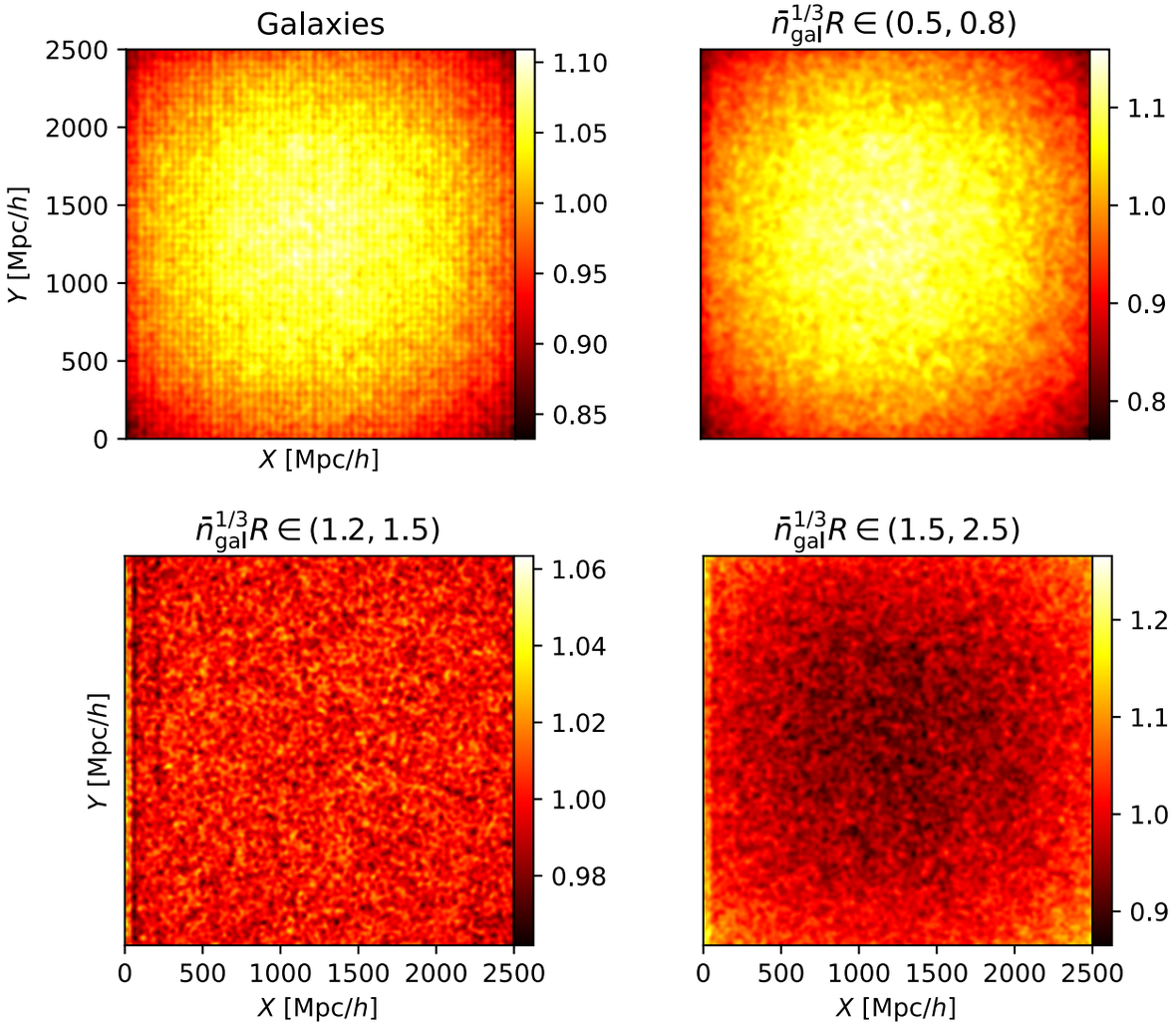


Kitaura, …, **CZ**+ 2016

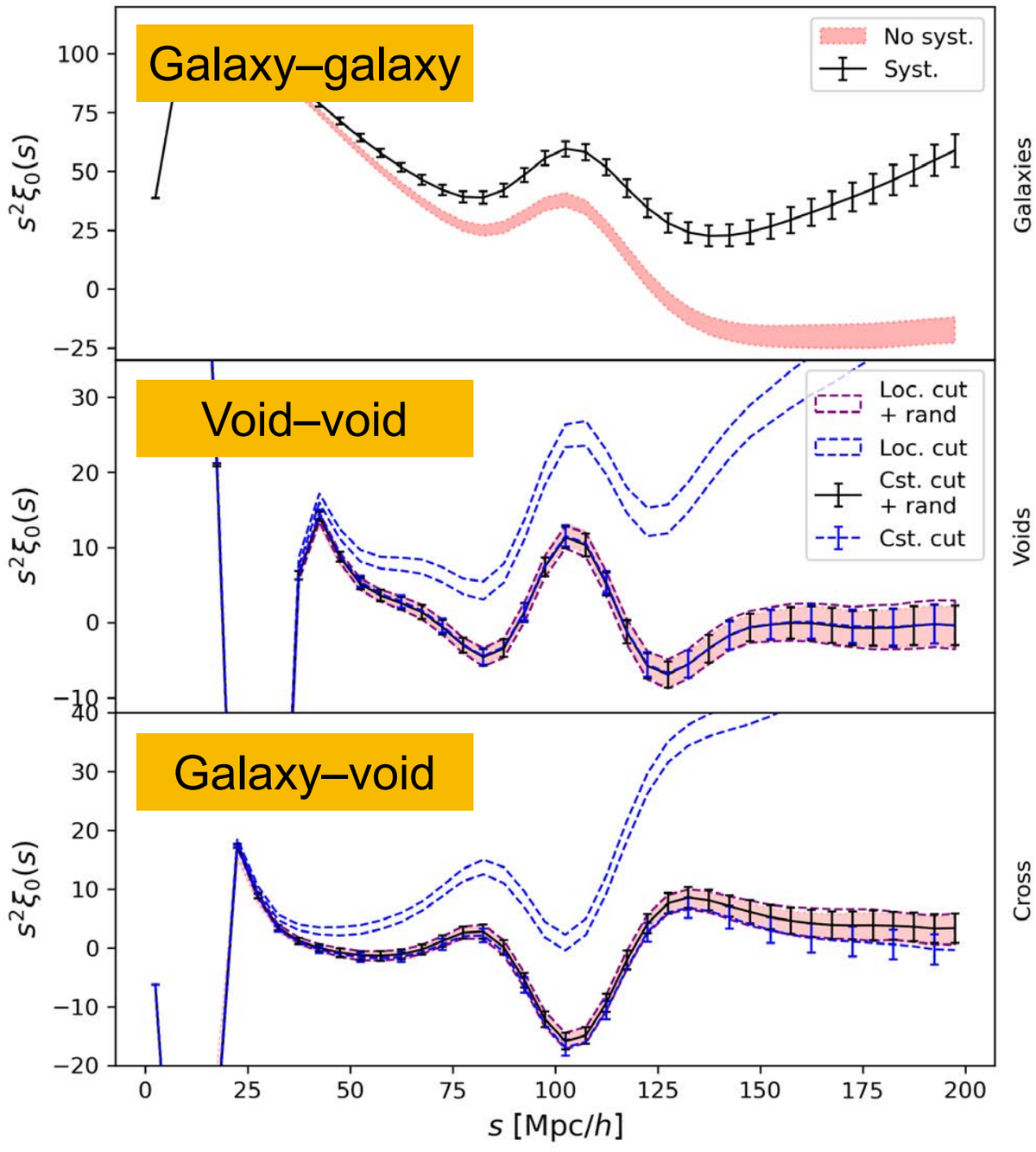
Sensitivity to systematics

Constant radius cut insensitive to moderate systematics

Small DT spheres

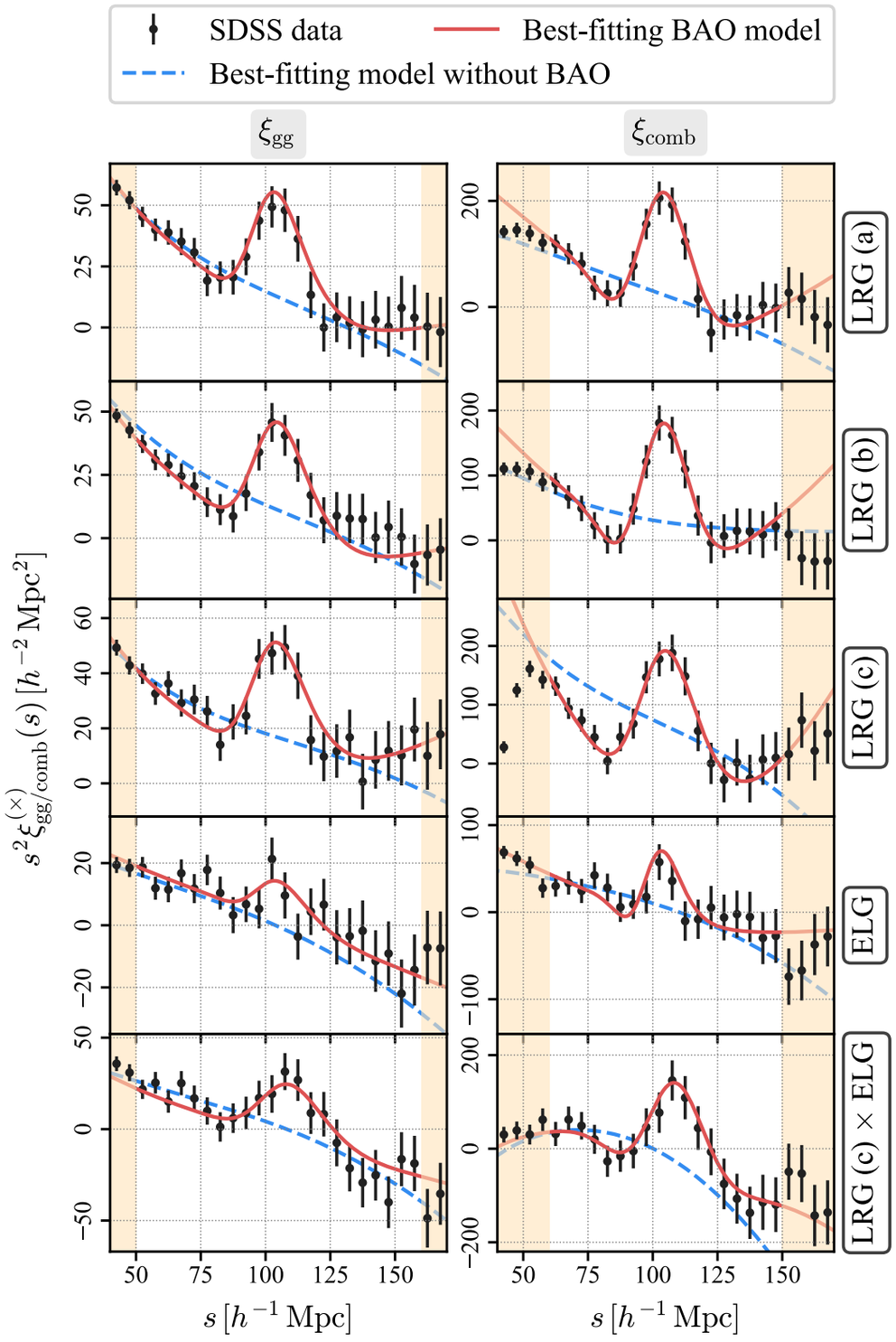


Large DT voids



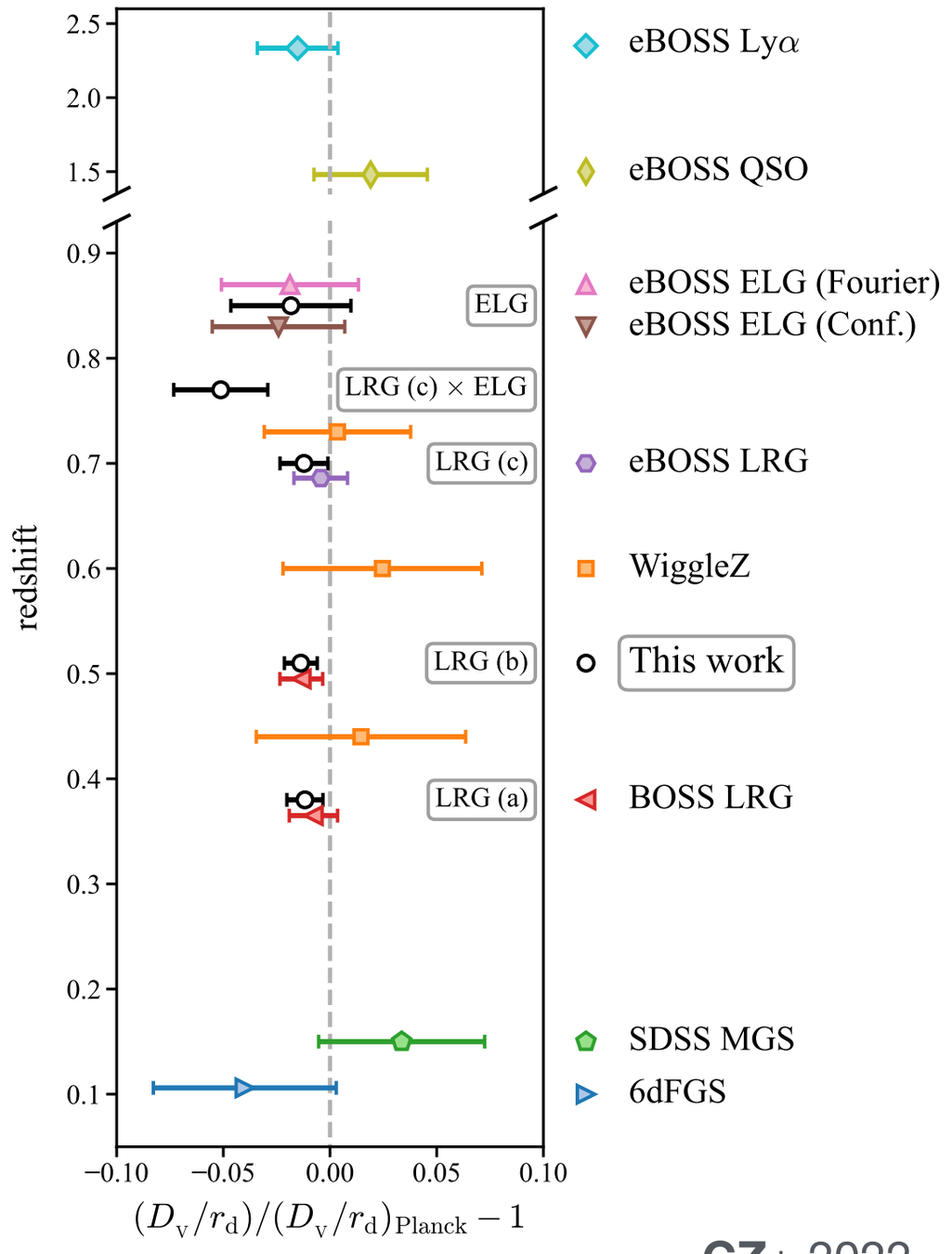
Forero-Sanchez, **CZ**+ 2022

Distance measurements



Galaxy only

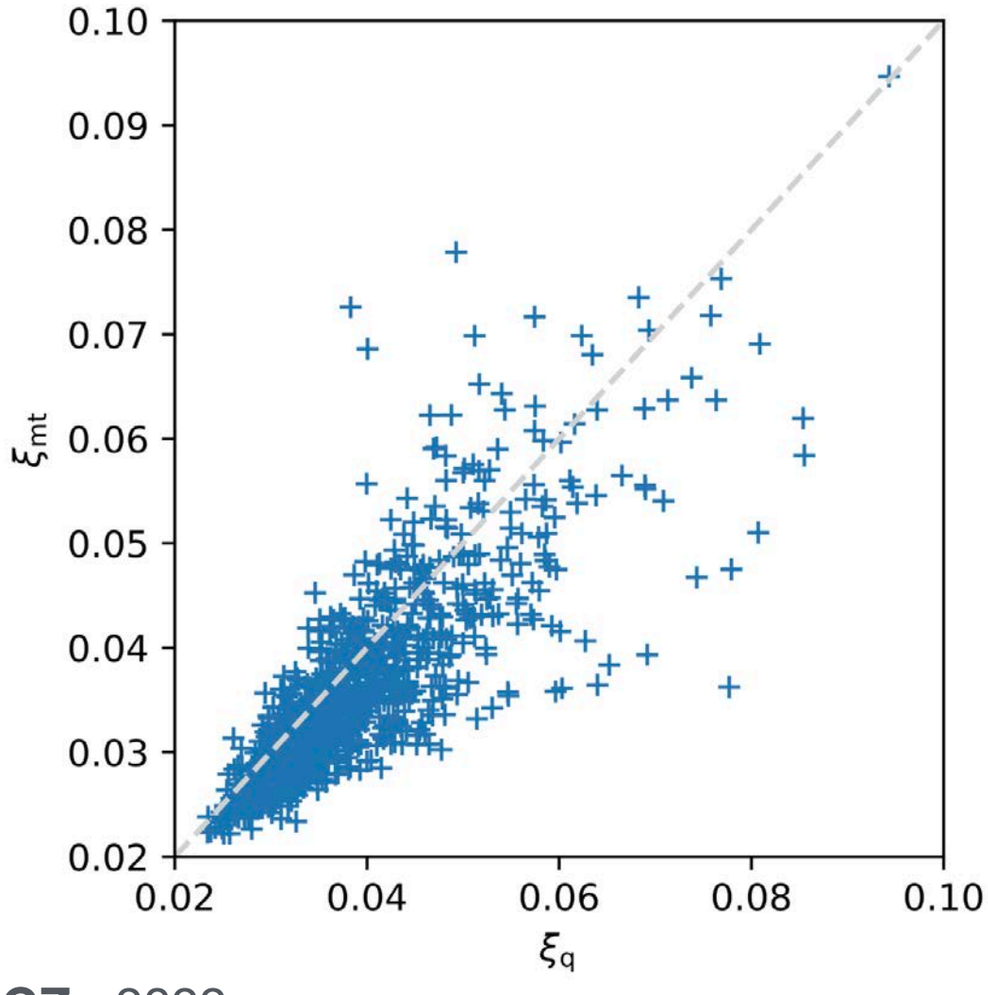
Galaxy + void



CZ+ 2022

Distance measurements

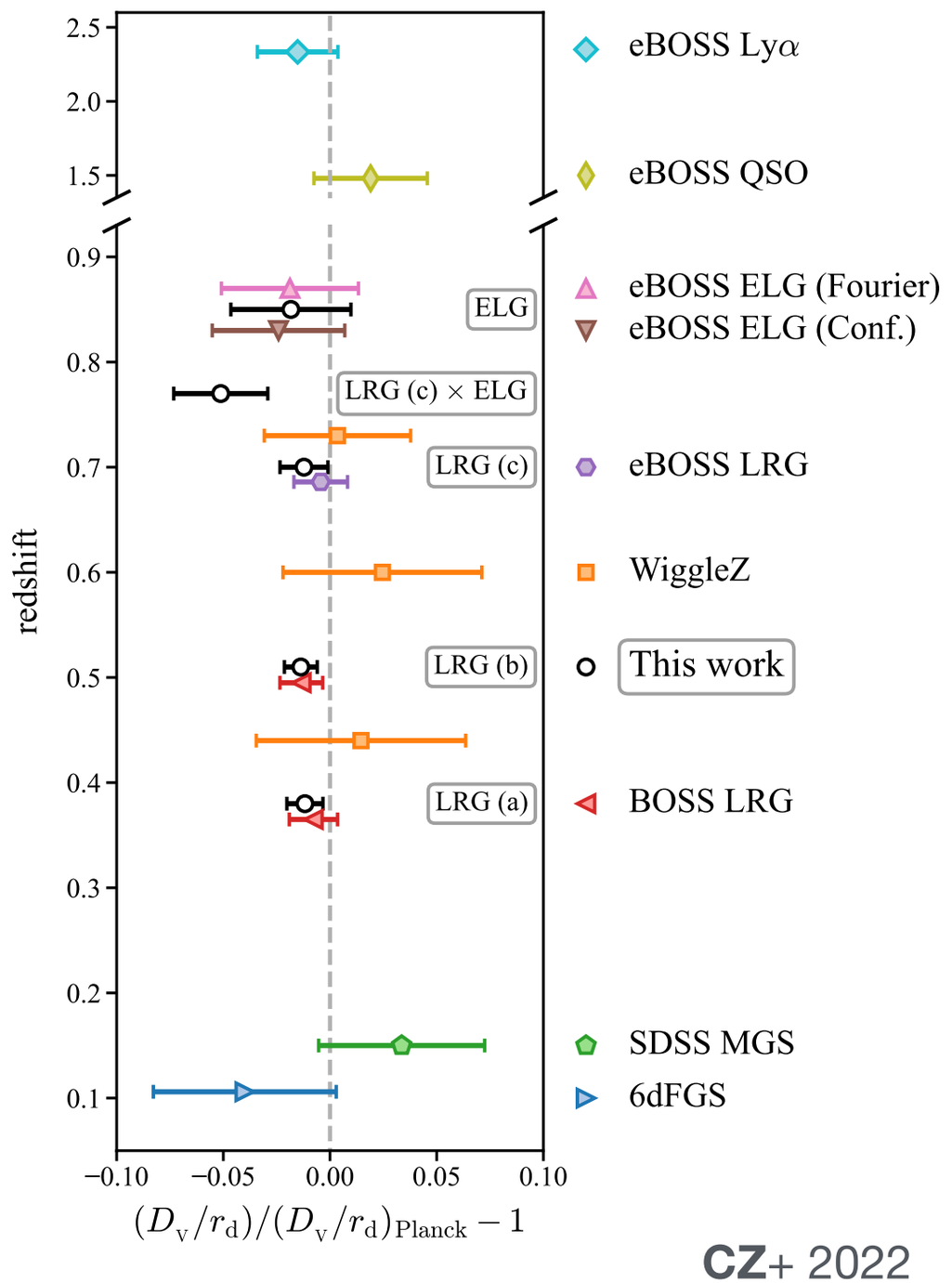
Quasar void: no improvement due to cosmic variance



BAO error: quasar + void

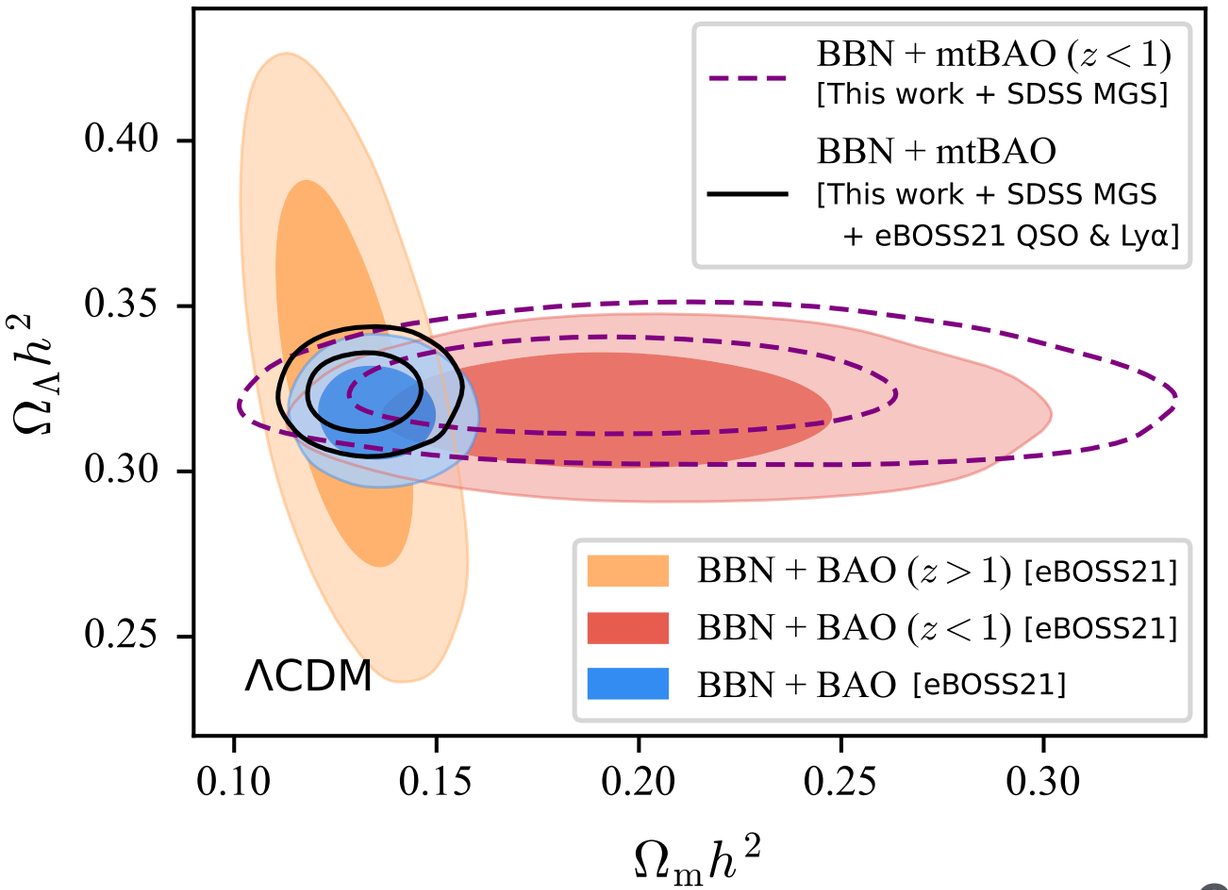
Tamone, **CZ**+ 2022

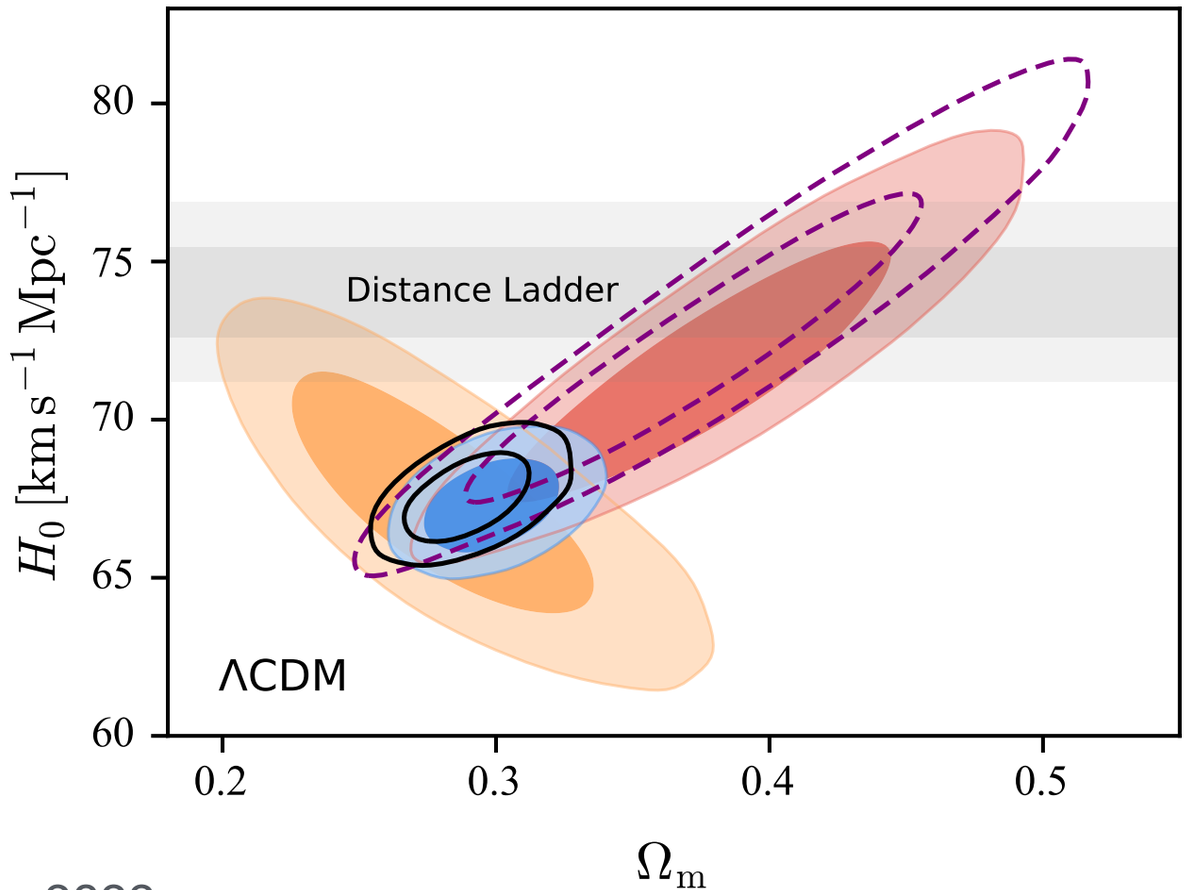
BAO error: quasar only



CZ+ 2022

Cosmology with galaxy+void

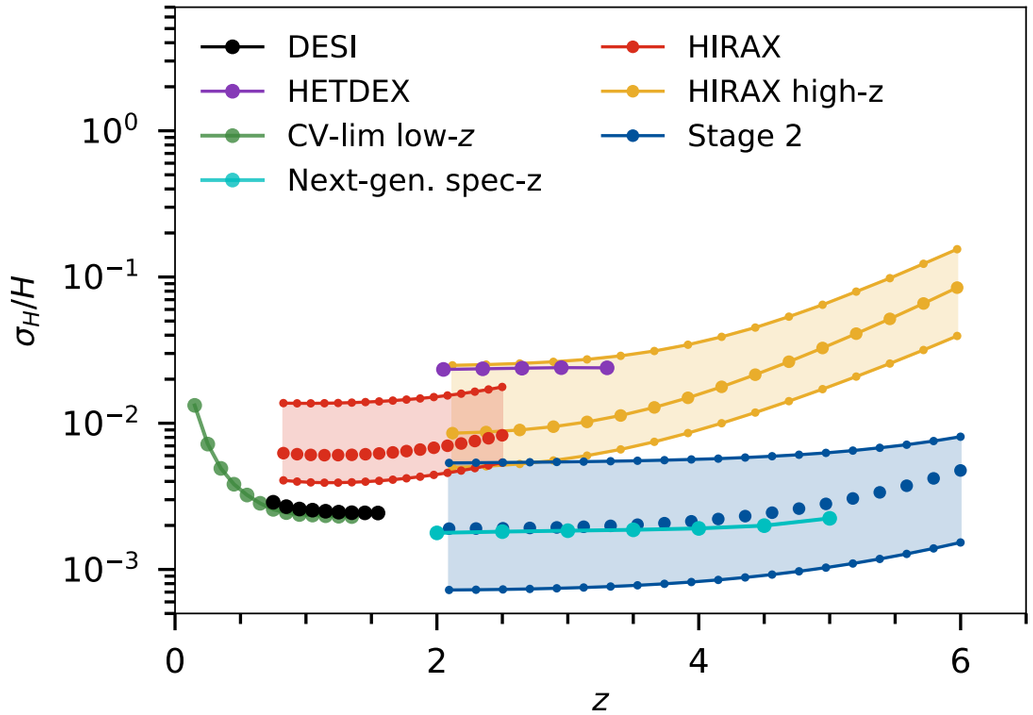


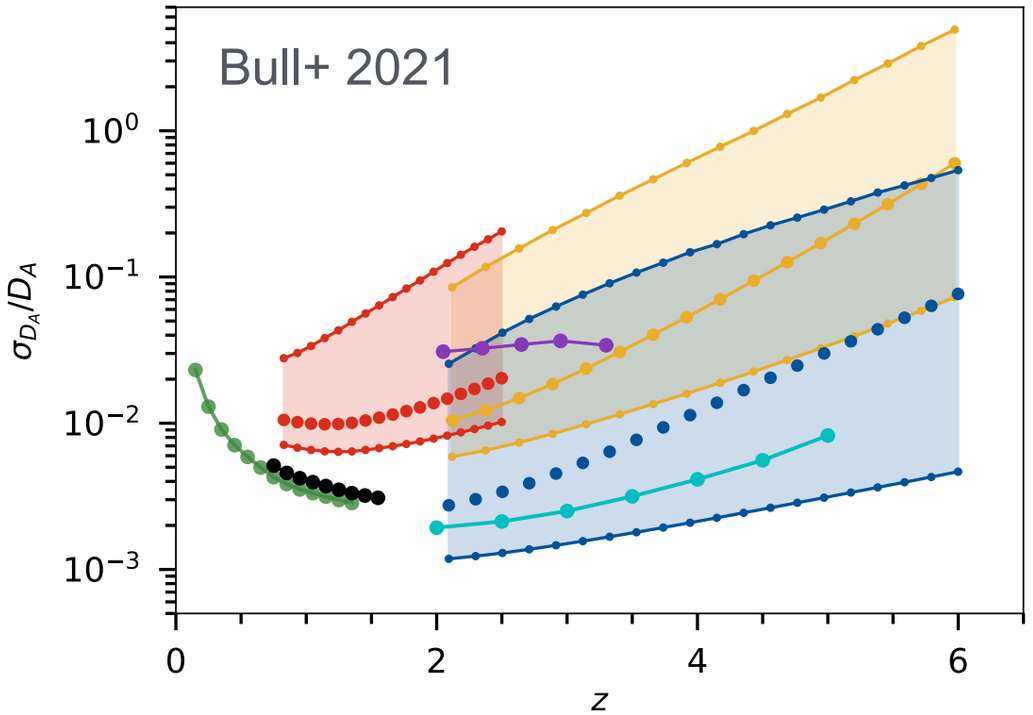


CZ+ 2022

Future work

- Measurements with the state-of-art (DESI) data

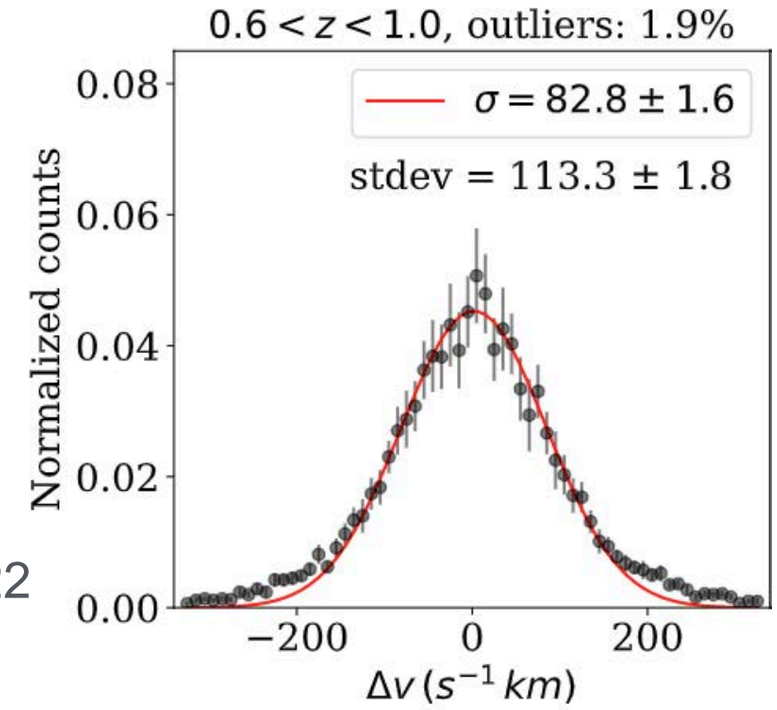




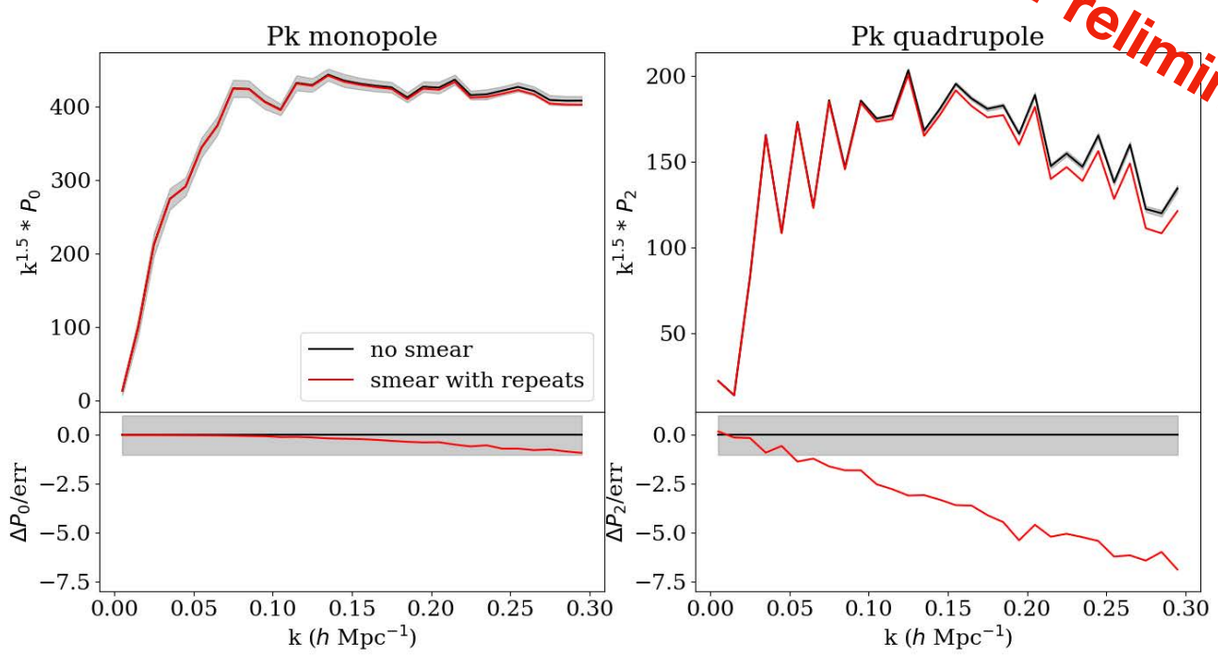
  - Caveat: systematics!
- Multi-probe & multi-tracer constraints
- Beyond standard methods

Future work

- Measurements with the state-of-art (DESI) data



Yu, **CZ**+ 2022

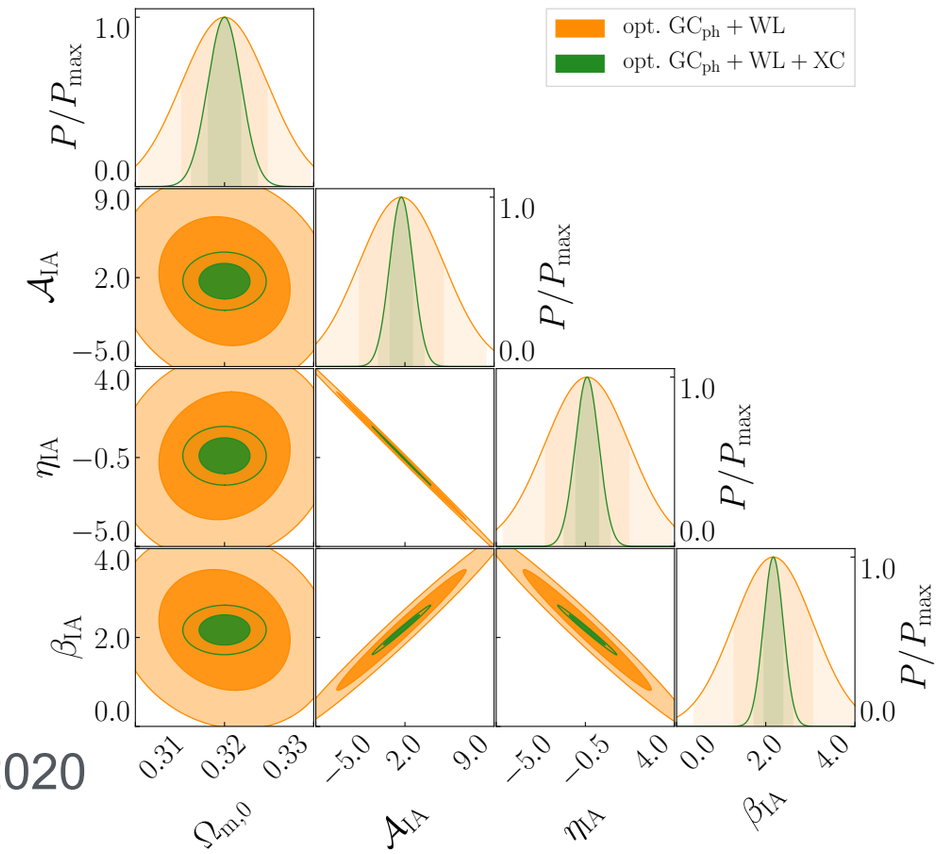


Yu, **CZ**+ in prep.

  - Caveat: systematics!
- Multi-probe & multi-tracer constraints
- Beyond standard methods

Future work

- Measurements with the state-of-art (DESI) data
- Multi-probe & multi-tracer constraints
  - Mitigate systematics
  - Suppress variances

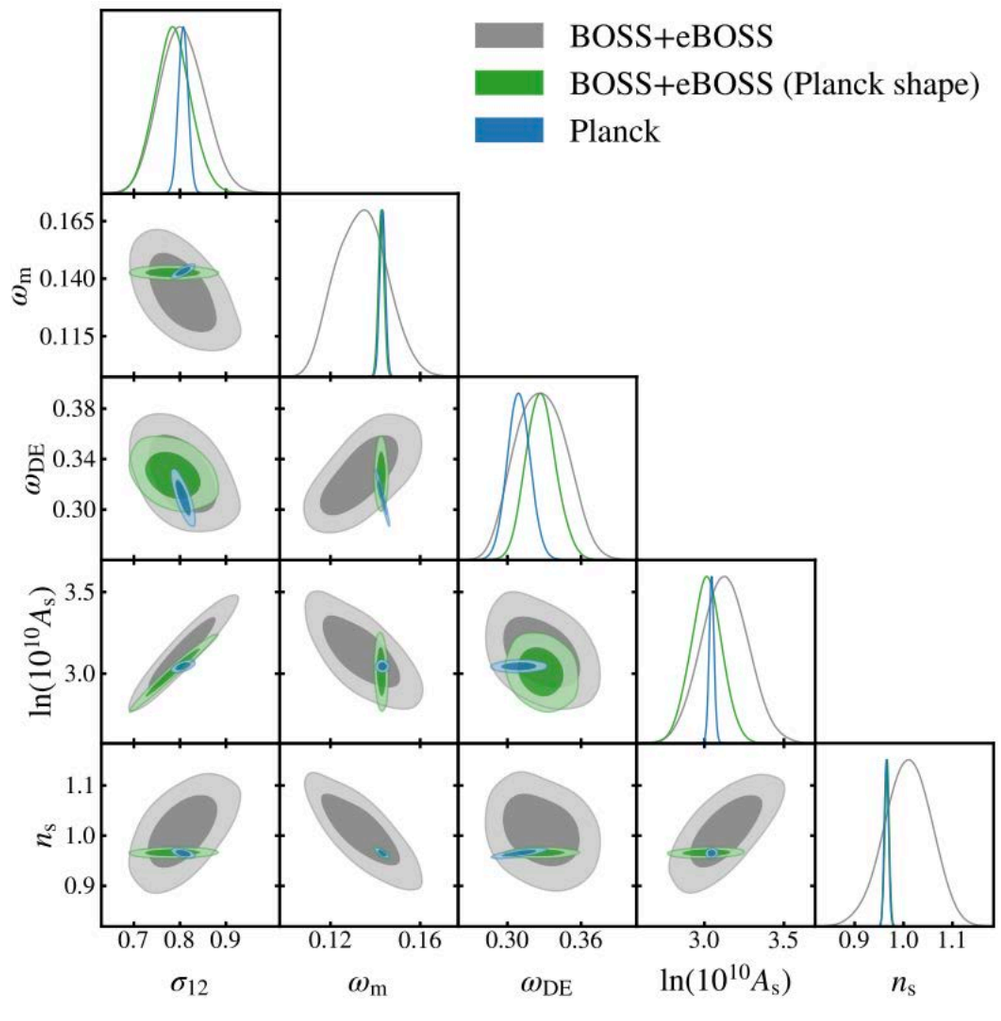


Tutusaus+ 2020

- Beyond standard methods

Future work

- Measurements with the state-of-art (DESI) data
- Multi-probe & multi-tracer constraints
- Beyond standard methods
  - 3-point and higher order
  - Full shape
  - ...



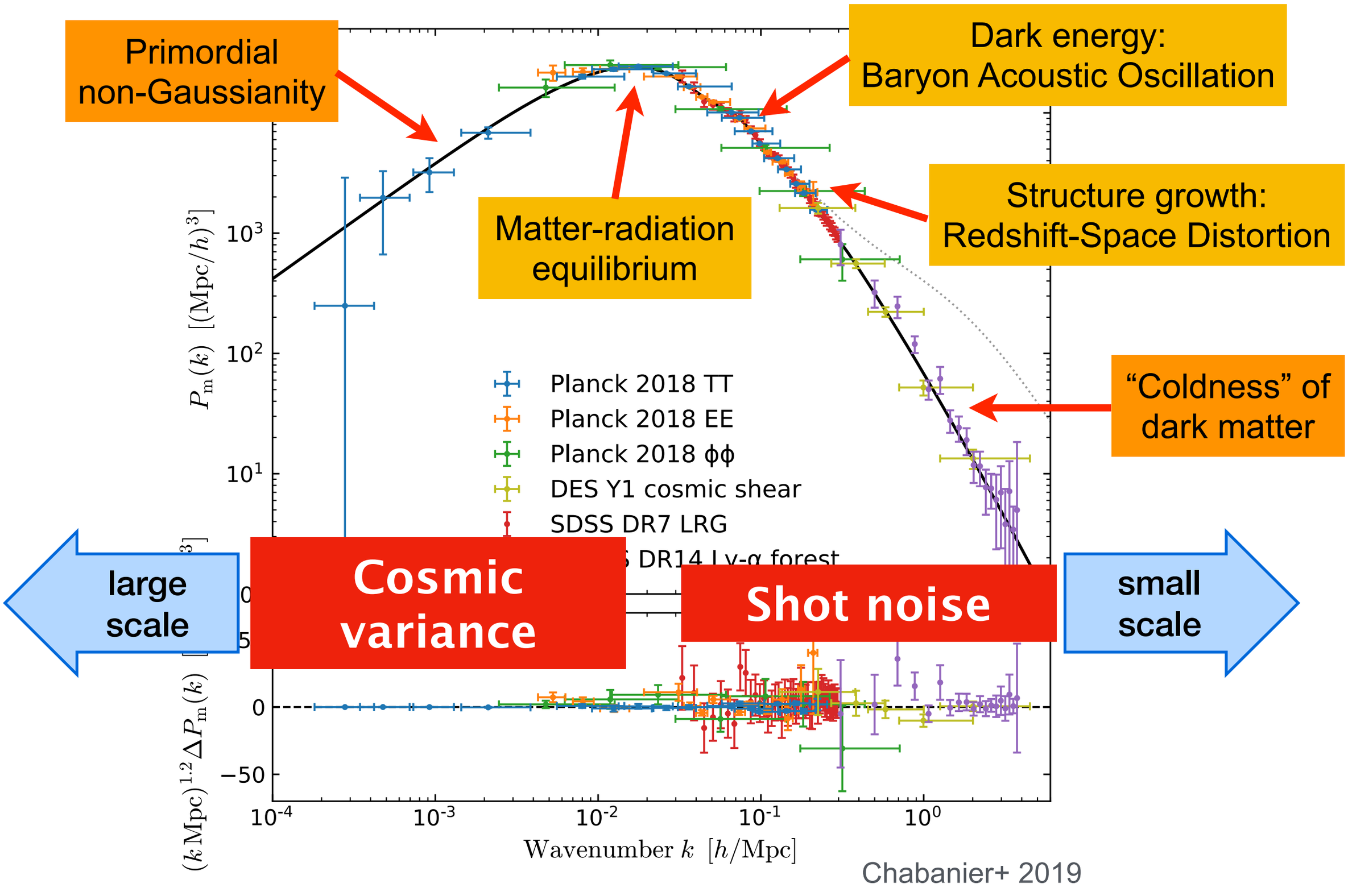
Semenaite, …, **CZ**+ 2022

Future work

- Measurements with the state-of-art (DESI) data
- Multi-probe & multi-tracer constraints
- Beyond standard methods

And NEW survey!

Matter power spectrum



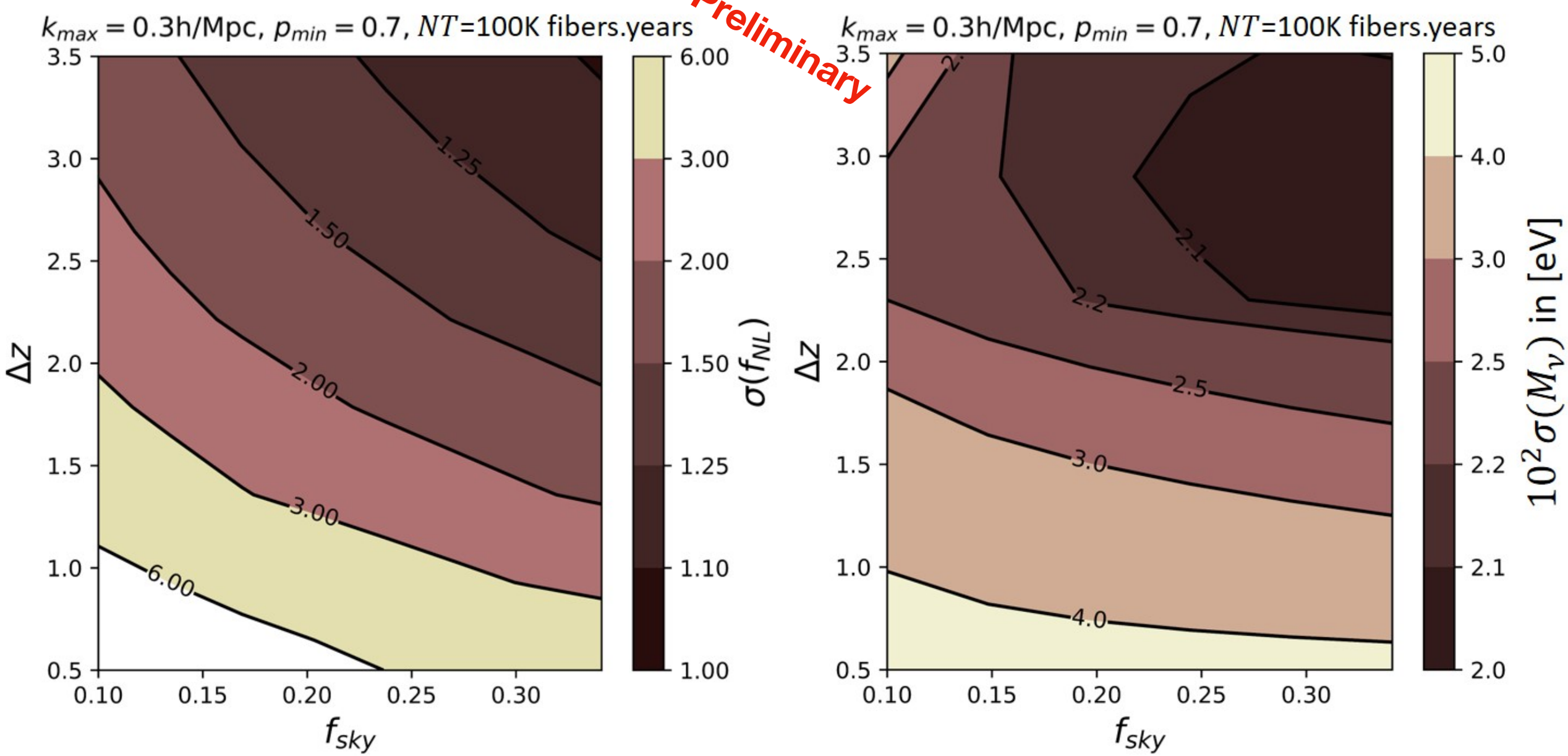
Chabanier+ 2019

Future survey forecast

Primordial non-Gaussianity

Neutrino mass

Preliminary



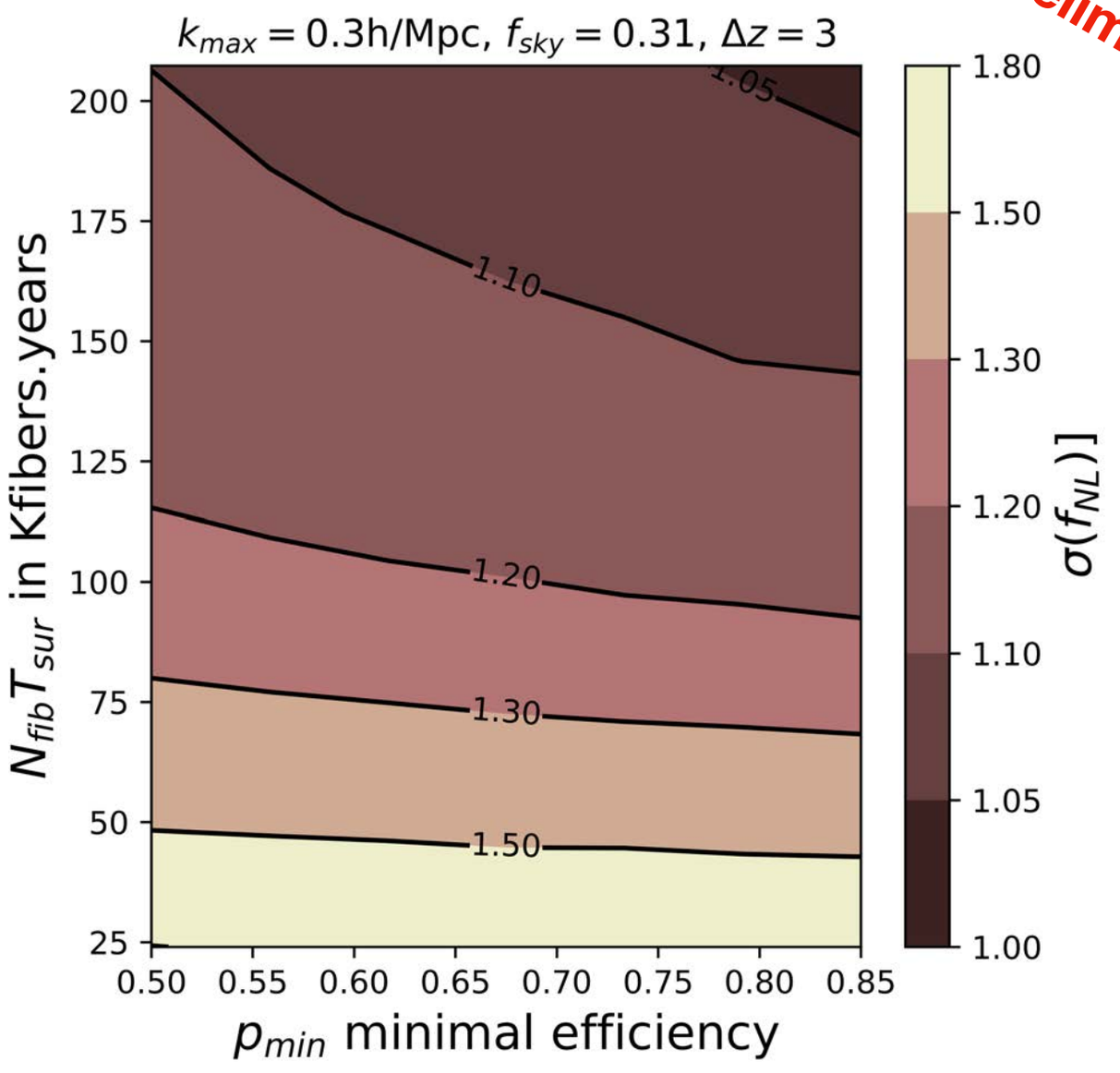
d'Assignies, **CZ**+ in prep.

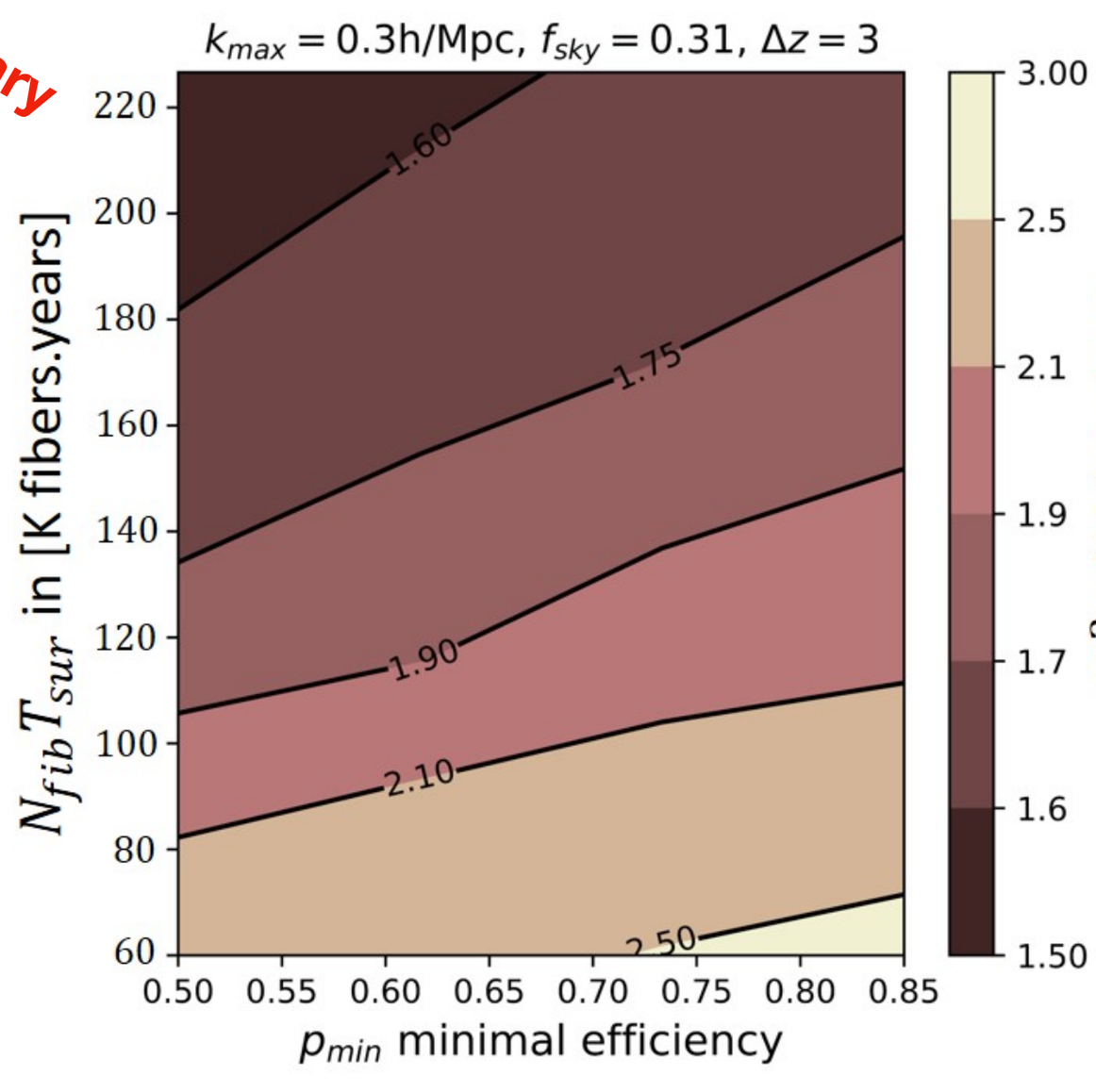
Future survey forecast

Primordial non-Gaussianity

Neutrino mass

Preliminary





d'Assignies, **CZ**+ in prep.

Summary

- Massive spectroscopic surveys are crucial for our understanding of the Universe
  - BAO: cosmic expansion history (dark energy)
  - RSD: structure growth history (gravity)
- EZmock: multi-tracer massive production of fast mocks
- DT void: galaxy + void present better constraint on dark energy
- Systematics may be dominant for non-standard analysis and future data
- Future survey forecasts for different purposes:
  - Primordial non-Gaussianity (quantum gravity?)
  - Nature of dark matter