Studying dark-energy with the large-scale structures of our Universe

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How the structures of the Universe can inform us about dark energy?

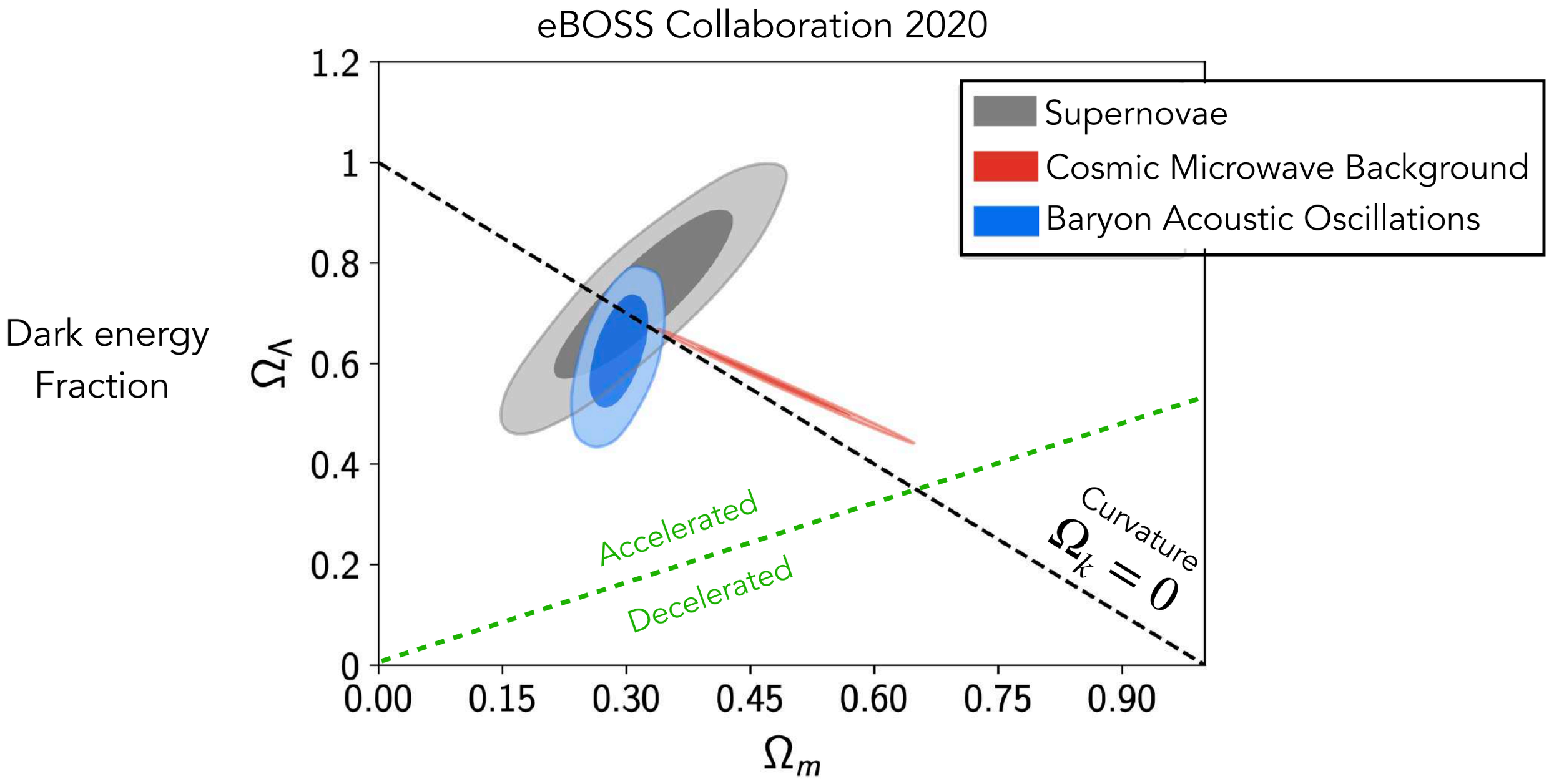
Observing structures with eBOSS

Analysis of the red galaxy sample from eBOSS

Future surveys

Cosmology with type-Ia supernovae

Acceleration of the expansion of the Universe



Dark and baryonic matter fraction

Independent probes confirm acceleration

Acceleration of the expansion of the Universe

General Relativity
+
Λ : cosmological constant
or
Λ, w_0, w_a: dark energy

or

Modifications or alternatives
to
General Relativity

How to distinguish between these two ?

Large-scale structures of the Universe

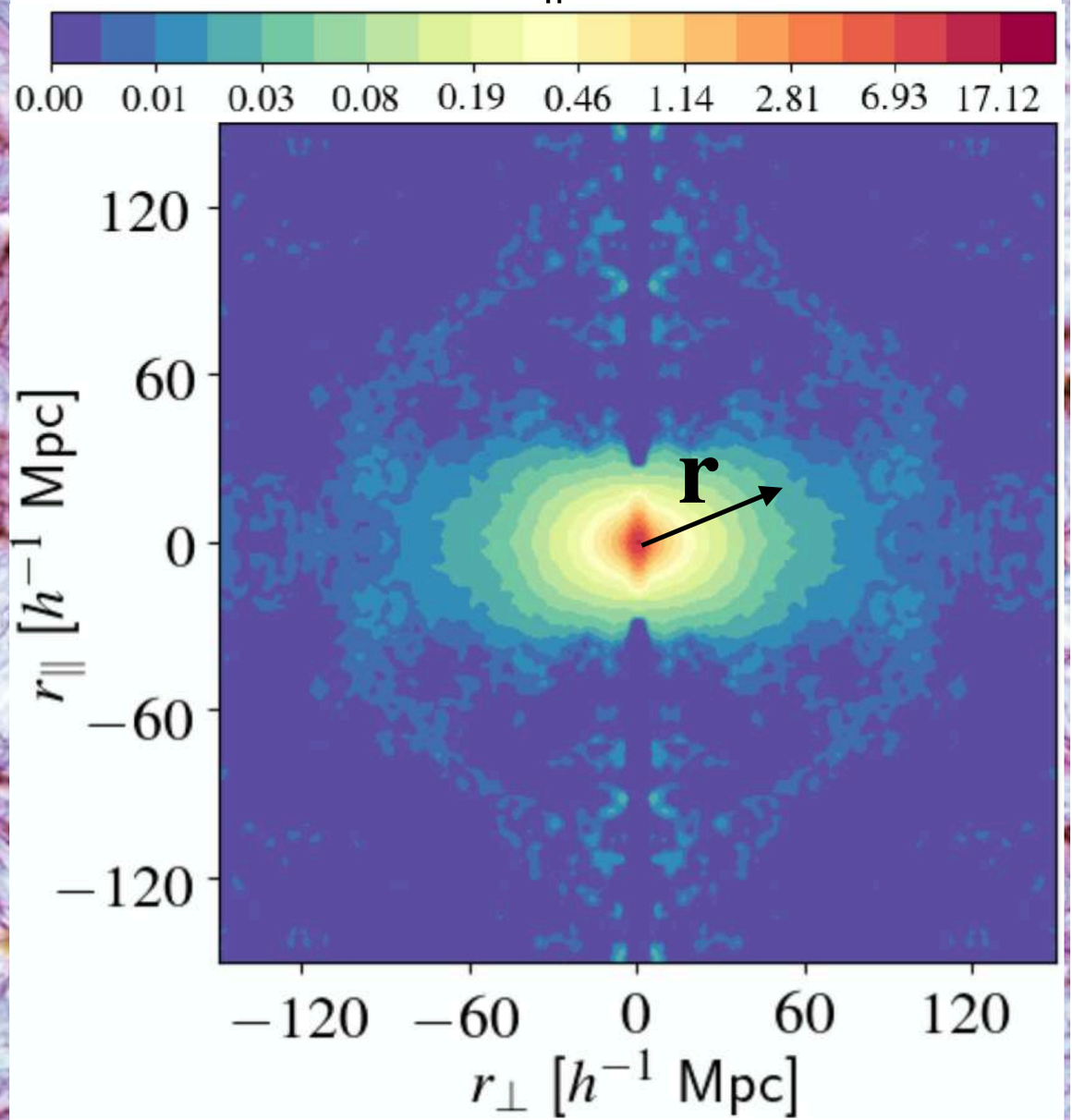
Simulation Illustris TNG

Gravity

Expansion

Mean "density" profile

$\xi(r_{\parallel}, r_{\perp})$



Bautista et al. 2020

Cosmological probes in the large-scale structures

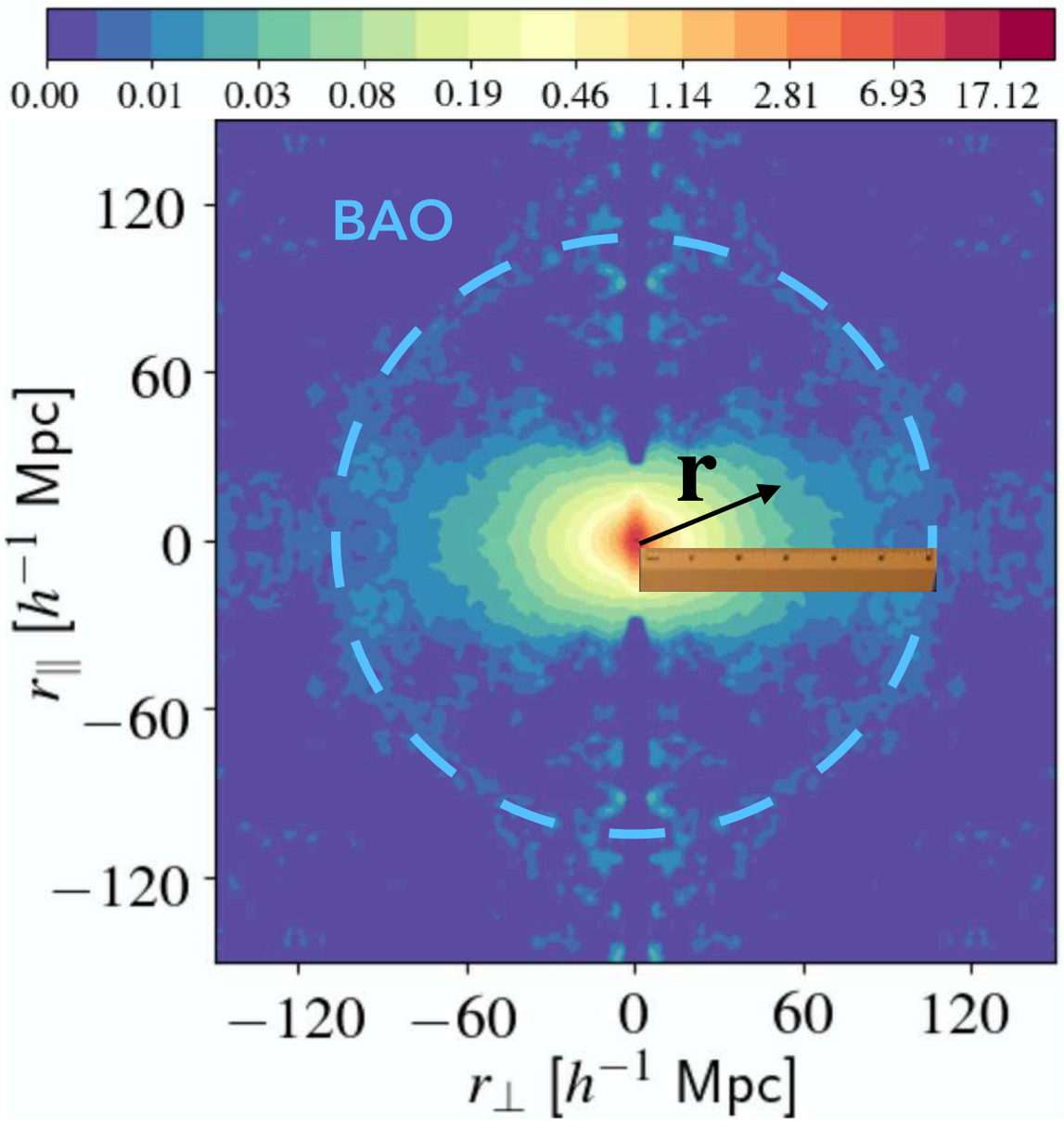
BAO - Baryon Acoustic Oscillations

Expansion rate H(z)

General Relativity
+
Λ, w_0, w_a: dark energy

Mean "density" profile

$\xi(r_\parallel, r_\perp)$



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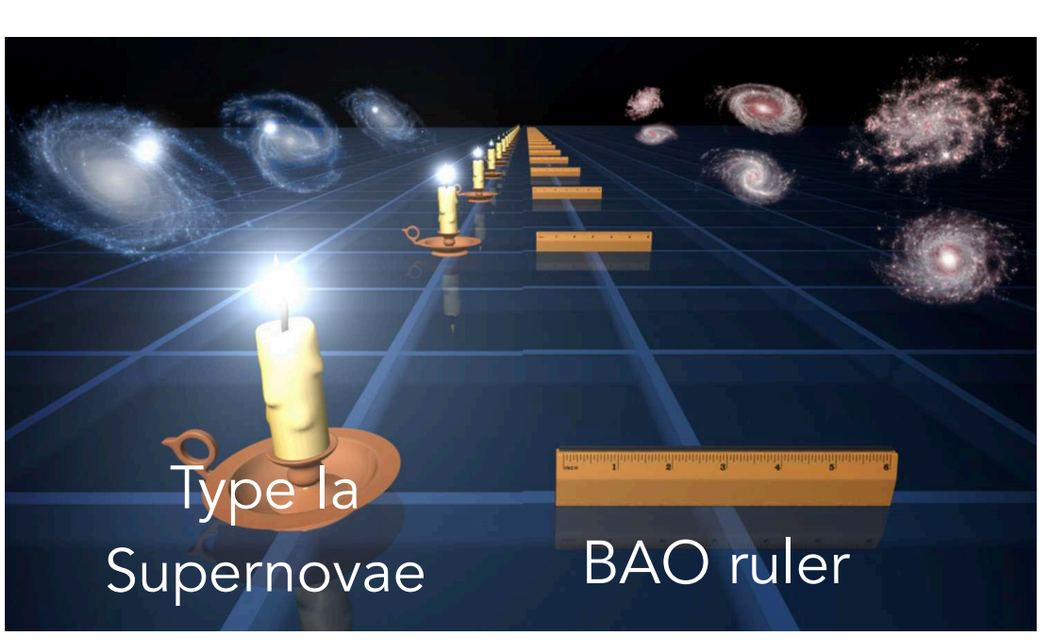
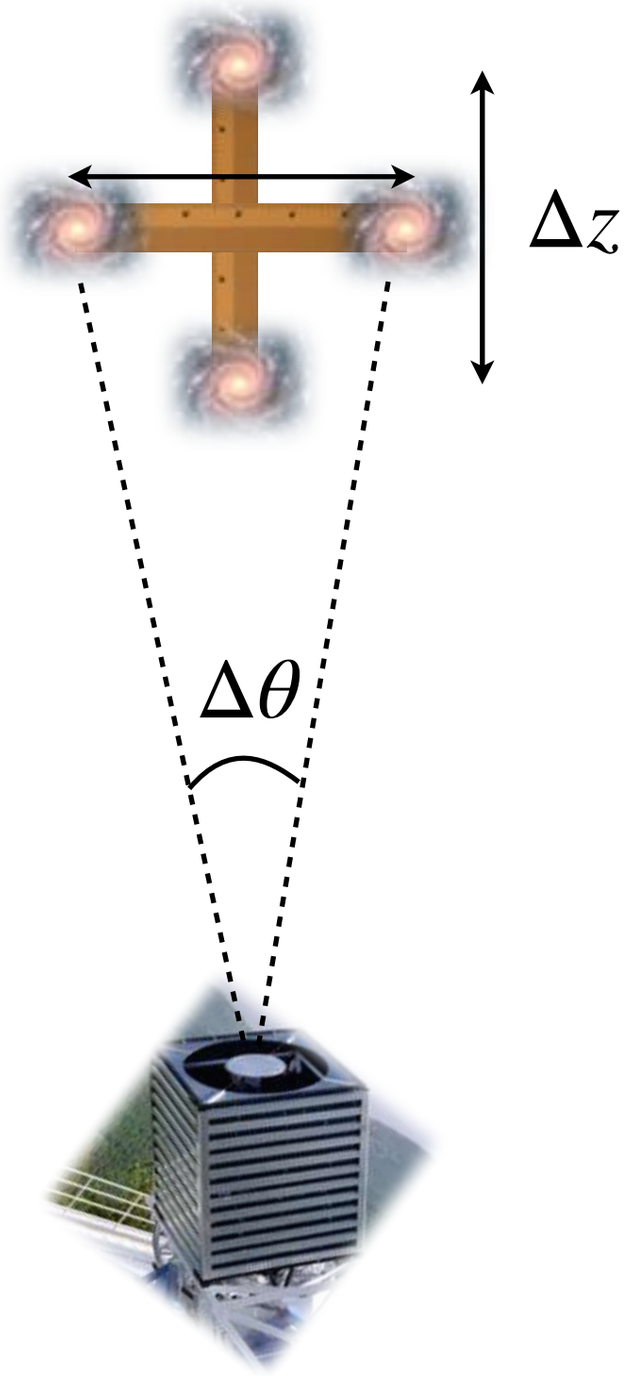


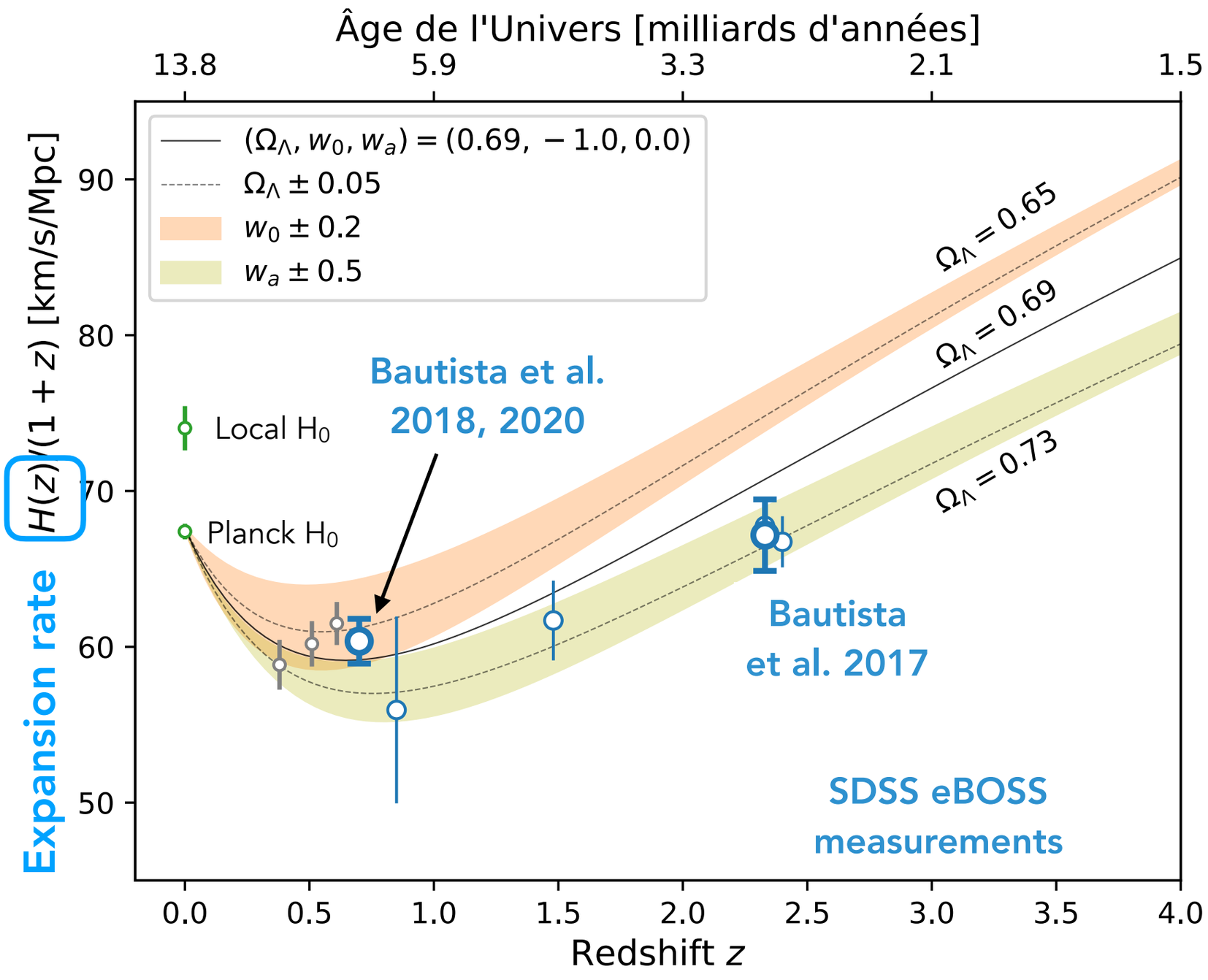
$$\Delta z = \frac{r_{\mathrm{BAO}}}{c}\,H(z)$$

$$\Delta\theta = \frac{r_{\mathrm{BAO}}}{c\int \frac{\mathrm{d}z}{H(z)}}$$



Cosmological probes in the large-scale structures

BAO - Baryon Acoustic Oscillations



Cosmological probes in the large-scale structures

BAO - Baryon Acoustic Oscillations

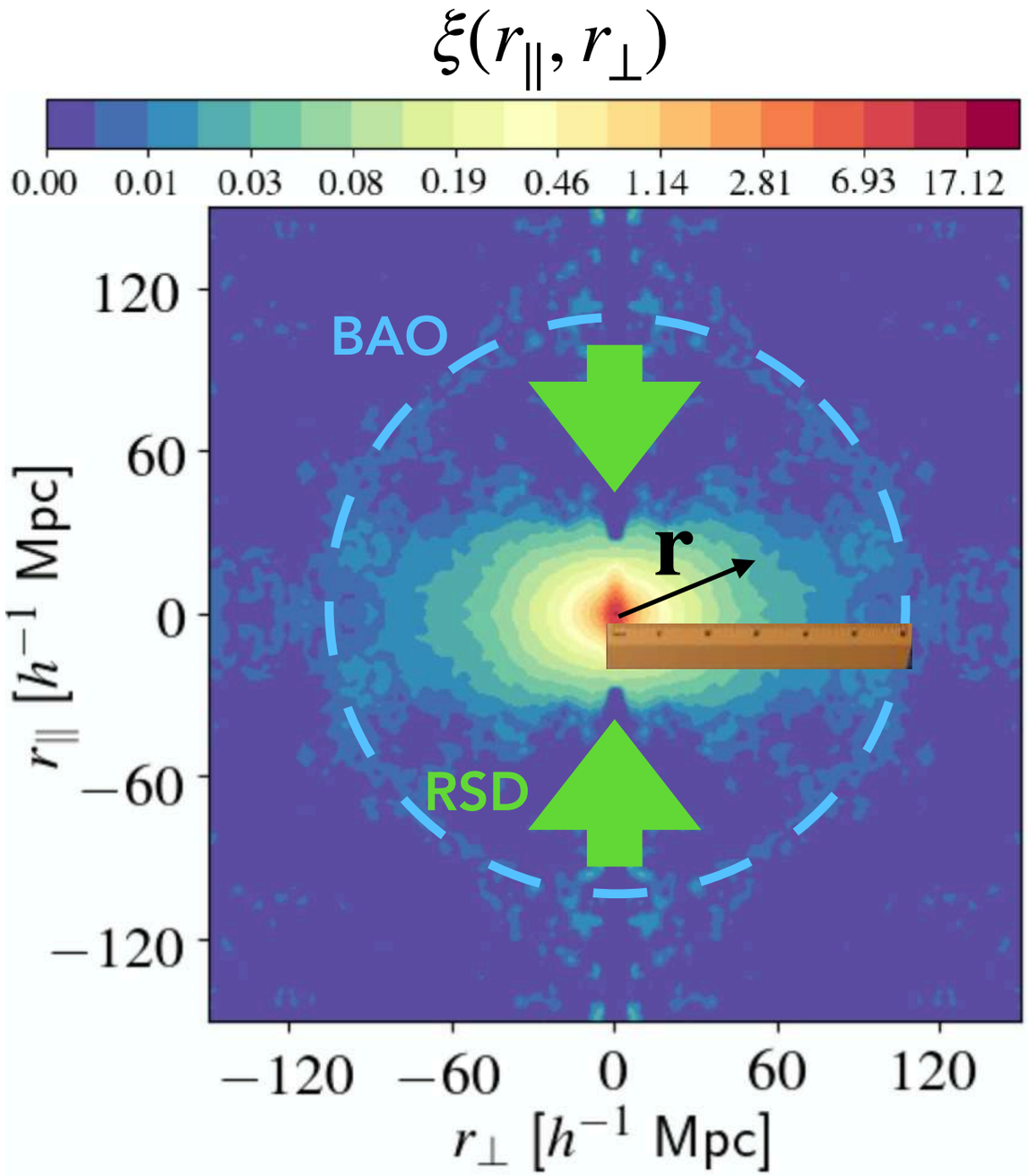
Expansion rate H(z)

General Relativity
+
Λ, w_0, w_a: dark energy

RSD - Redshift-space distortions

Growth rate of structures f(z)

Modifications or
alternatives to
General Relativity



Bautista et al. 2020

Cosmological probes in the large-scale structures

RSD - Redshift-space distortions

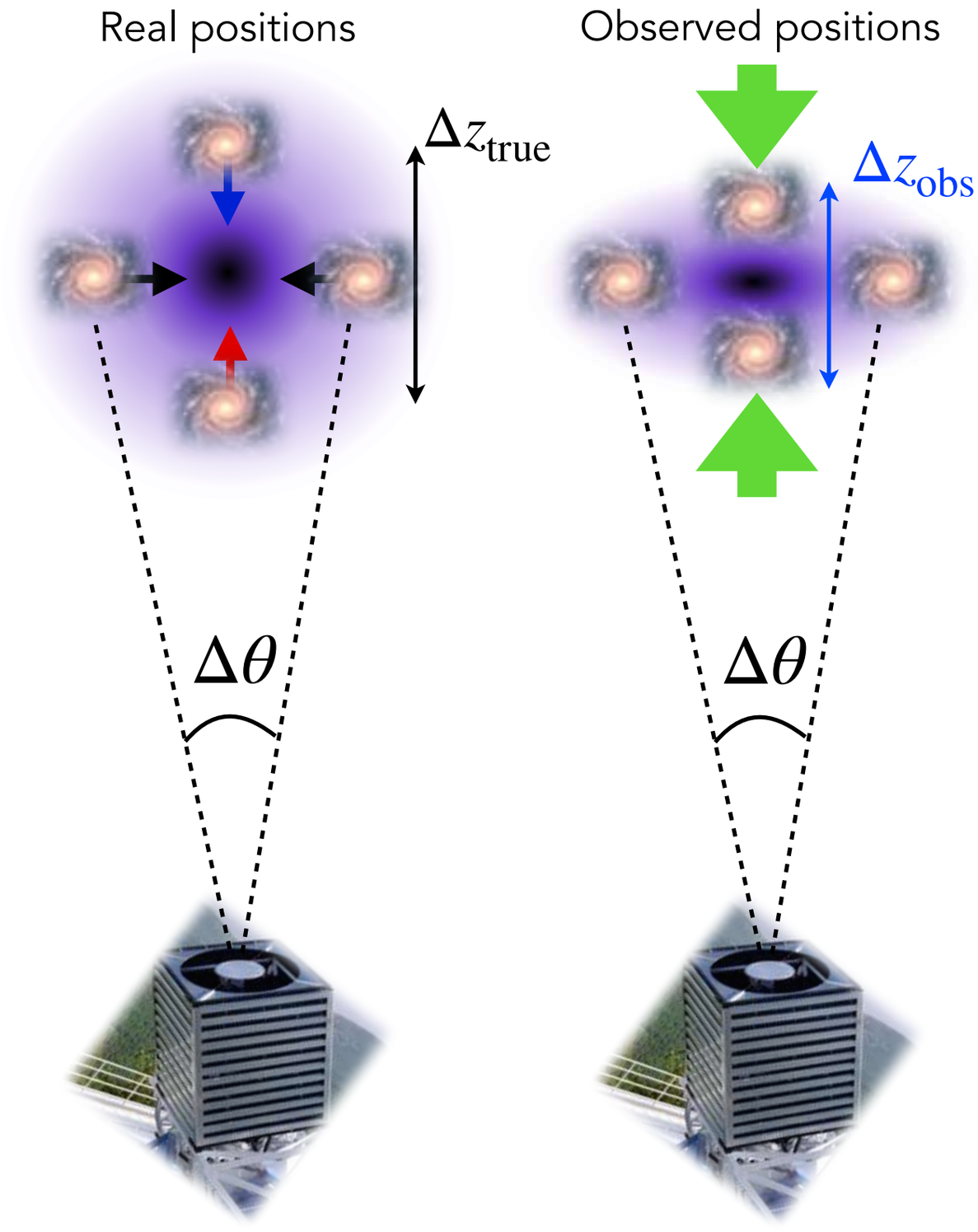
Velocities "flatten"
the structures radially

Growth rate of structures
in general relativity

$$f(z) \sim \left[\Omega_m(z)\right]^{\gamma=0.55}$$

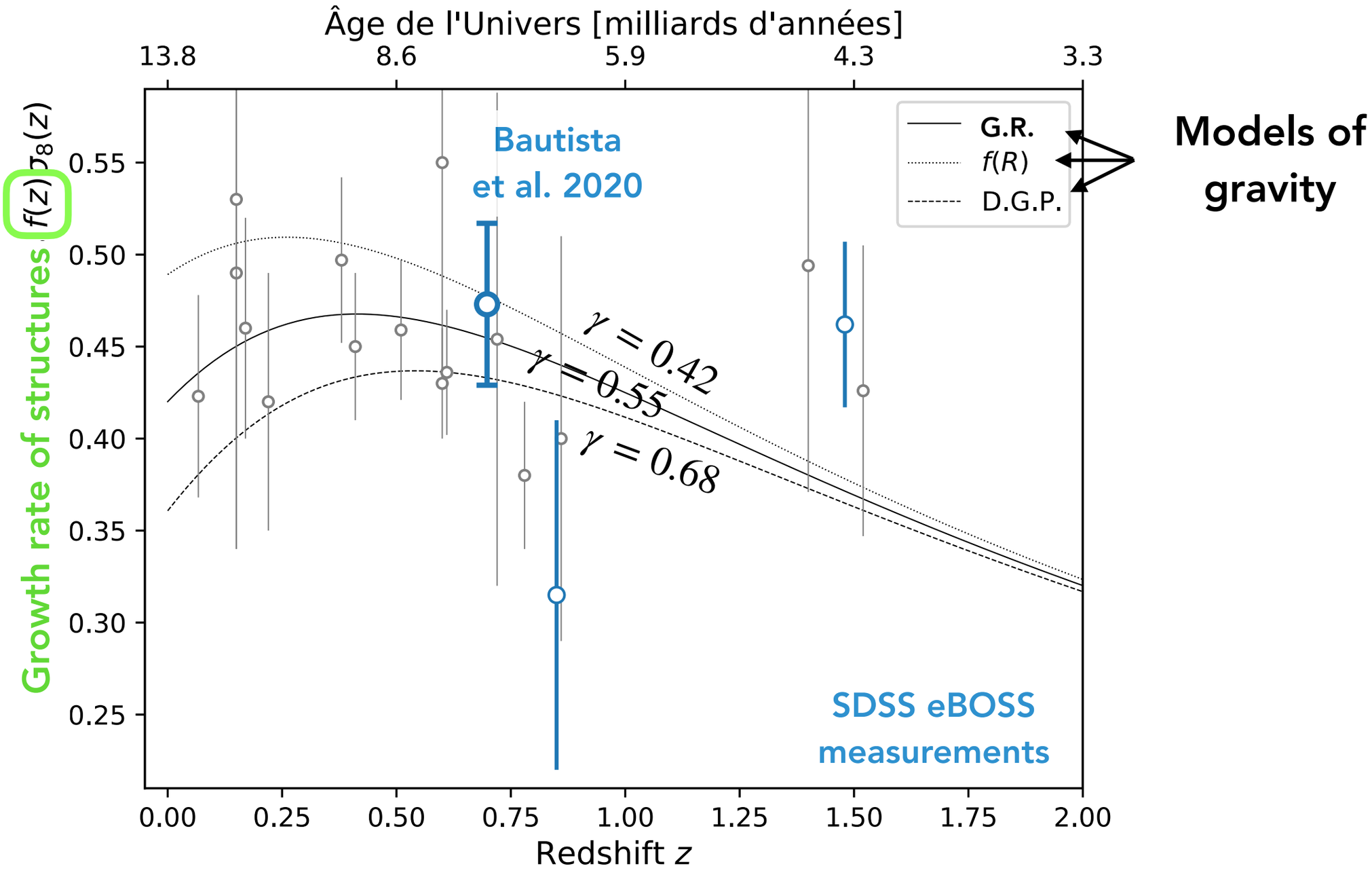
Else: $\gamma \neq 0.55$

Modifications or
alternatives to
General Relativity



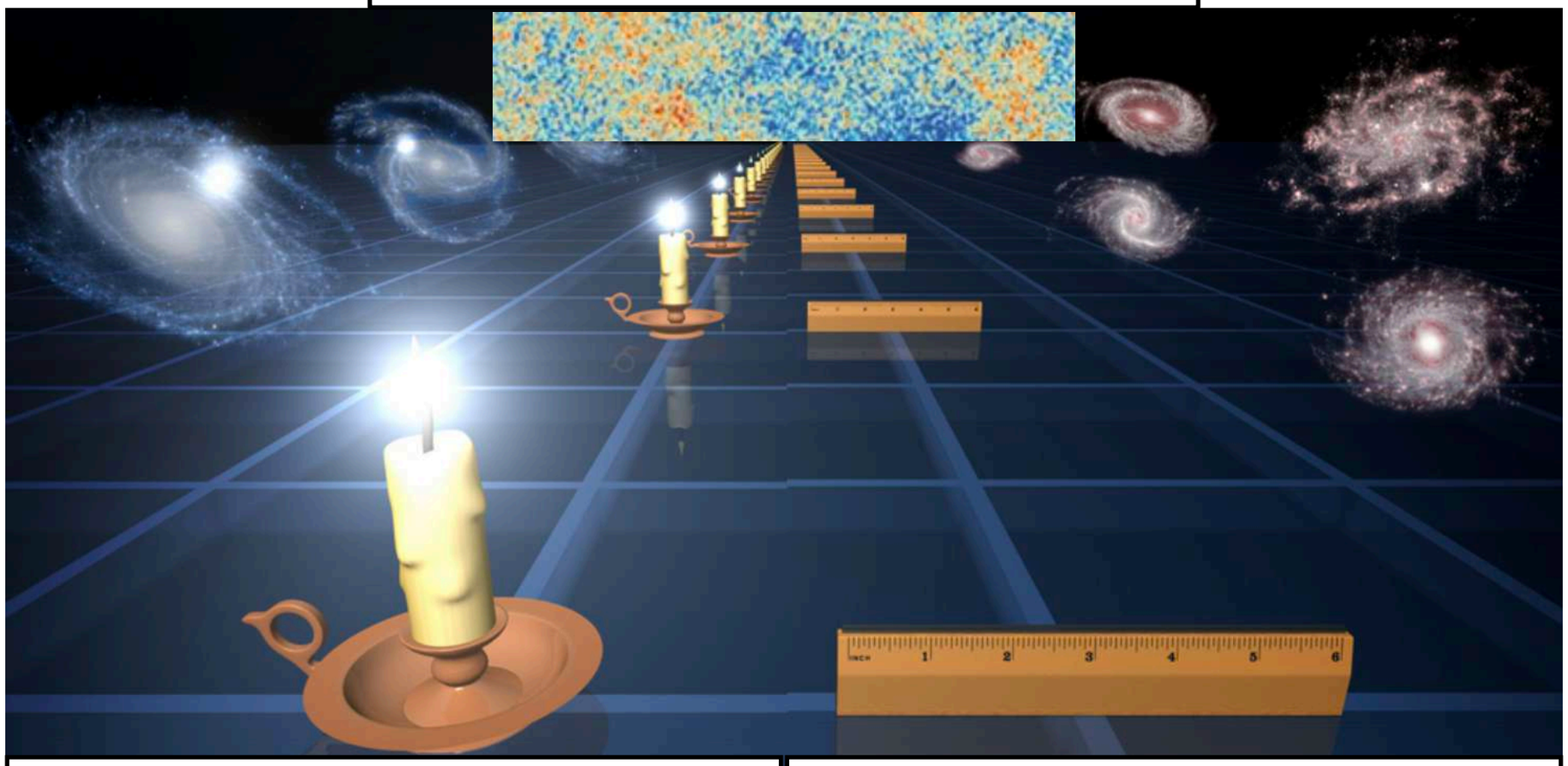
Cosmological probes in the large-scale structures

RSD - Redshift-space distortions



Expansion rate H(z)

Cosmic microwave background (CMB)
z ~ 1100 or t ~ 380 000 years

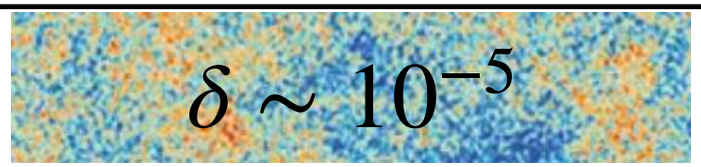


Type-Ia Supernovae (SNIa) as standard candles 0 < z < 1.5 5 Gy < t < 13.8 Gy	Baryon Acoustic Oscillations (BAO) as standard ruler 0.1 < z < 2.5 3 Gy < t < 13 Gy

$$F = \frac{L_{\text{candle}}}{4\pi D_L^2(z)} \qquad \Delta\theta = \frac{r_{\text{ruler}}}{D_M(z)} \qquad \Delta z = \frac{r_{\text{ruler}}}{D_H(z)}$$

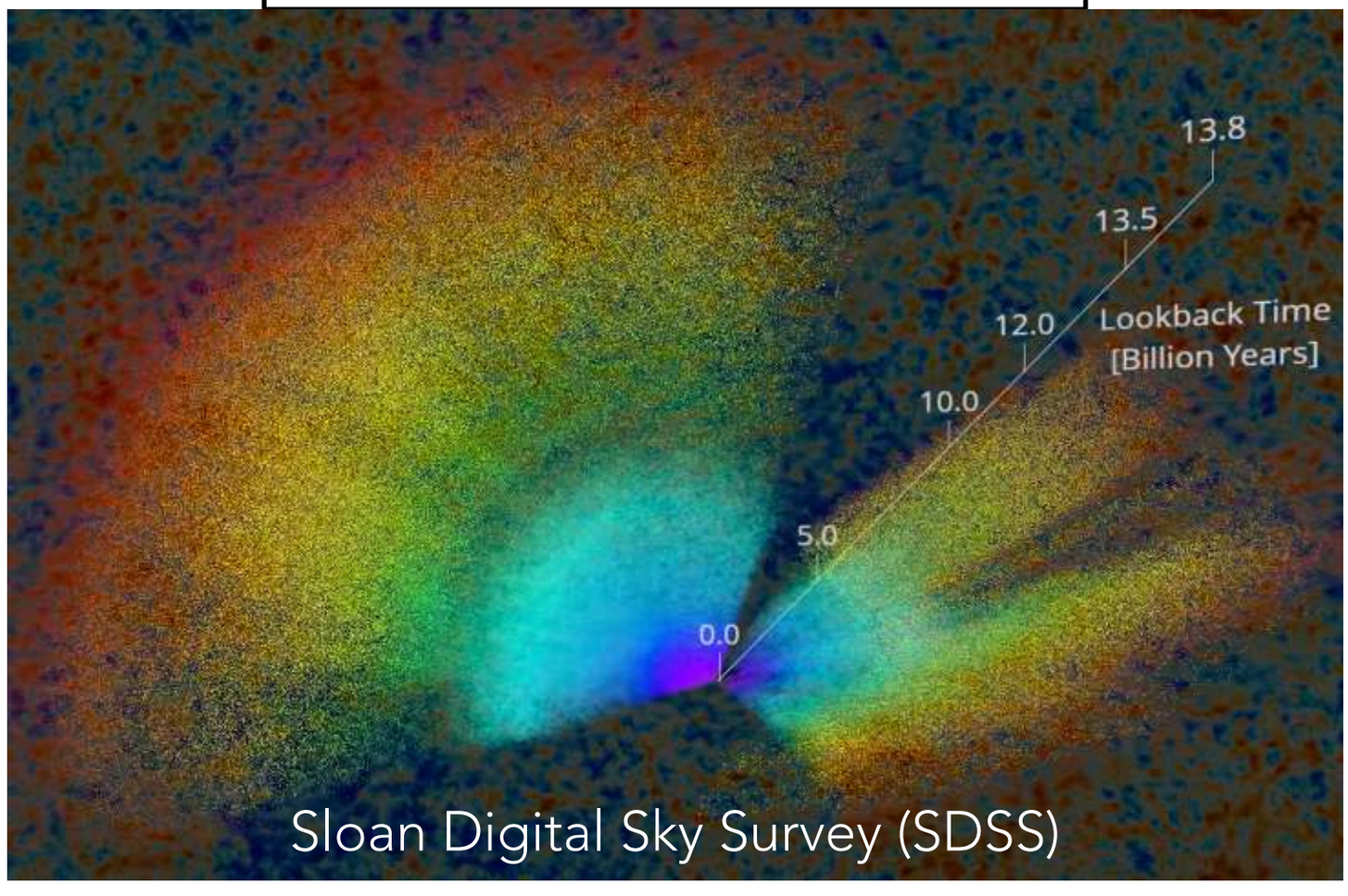
Growth rate of structures f(z)

Cosmic microwave background (CMB)
z ~ 1100 or t ~ 380 000 years



Gravitational lensing
0 < z < 1
6 Gy < z < 13.8 Gy

RSD of
galaxies, quasars, clusters, voids



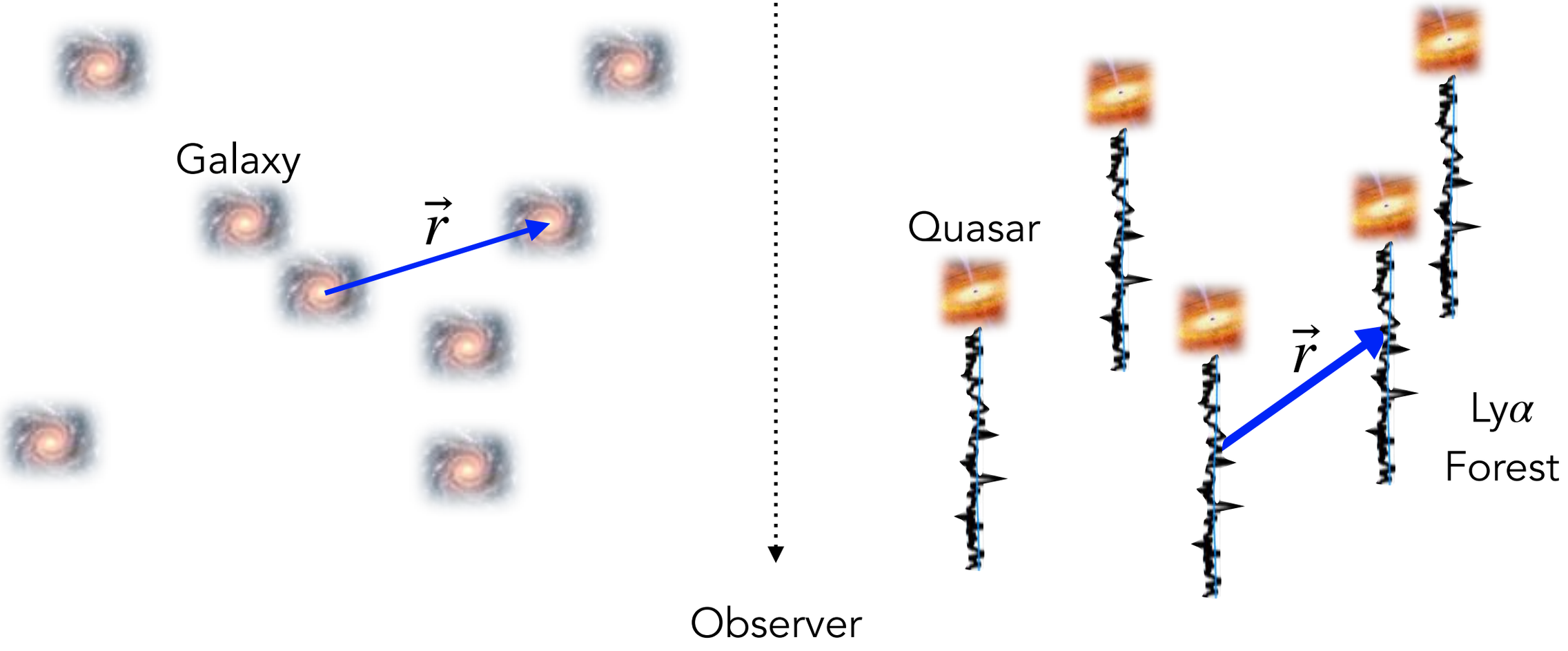
Observing the structures

Galaxies

- low redshift, z < 2
- trace high density regions
- traditional method

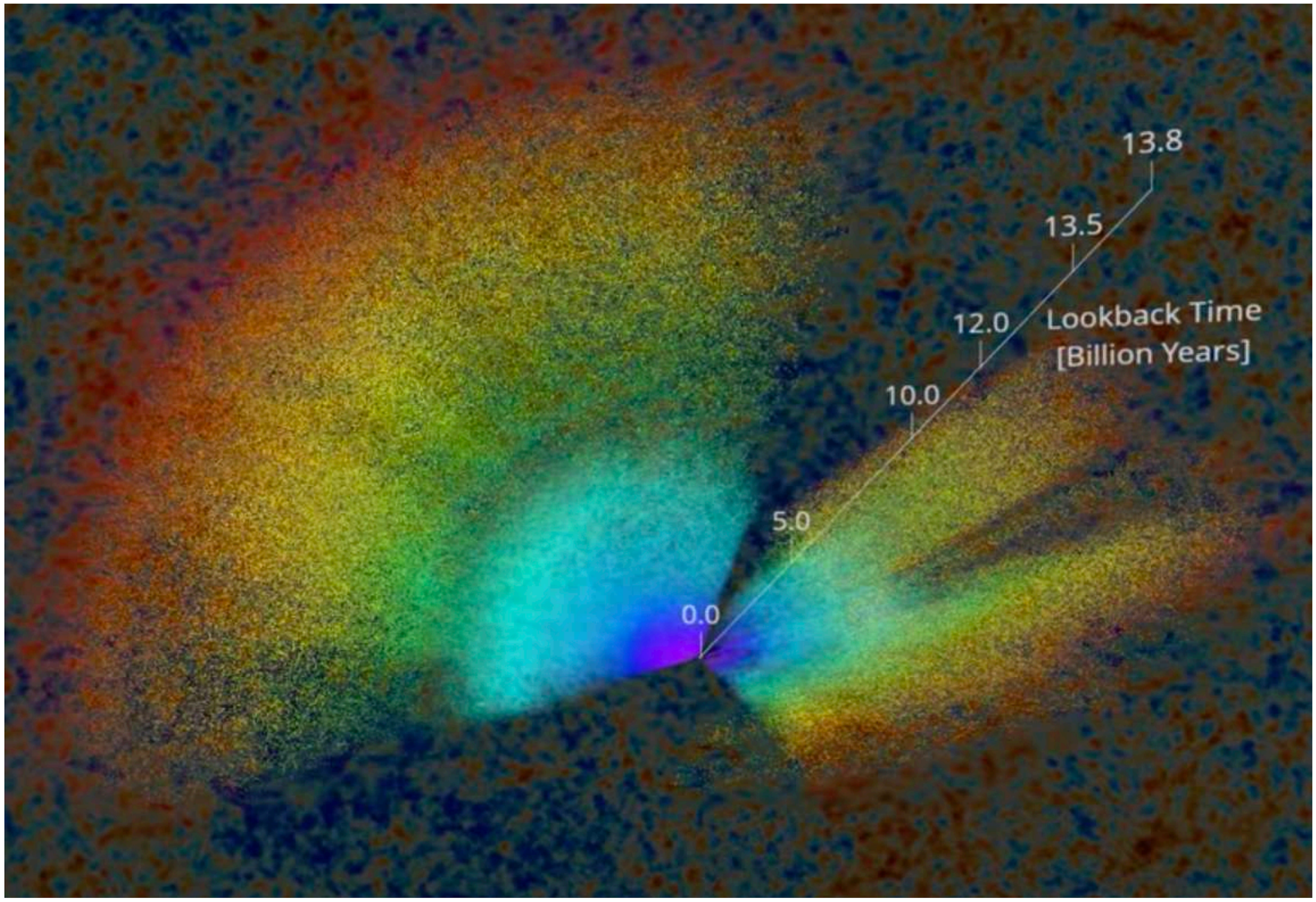
Lyman-α forests

- unique* access to high redshift, z > 2
- trace low density in the line-of-sight
- recent method



eBOSS

and the state-of-the-art map of the Universe's structures



20 years of redshift surveys with SDSS

https://www.youtube.com/watch?v=KJJXbcf8kxA (by EPFL.ch)

eBOSS

extended Baryon Oscillation Spectroscopic Survey

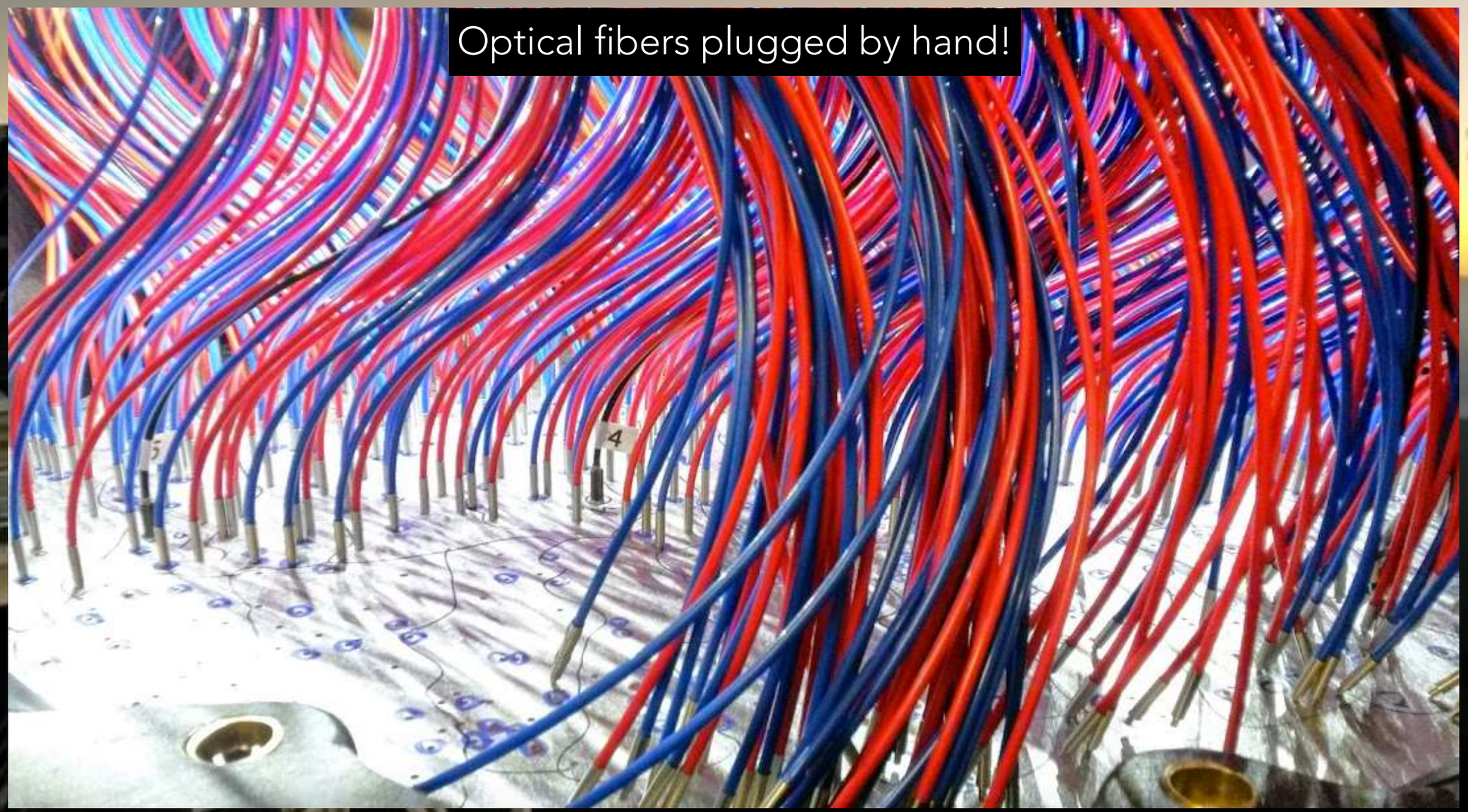
Dawson et al. 2016

2.5-meter
mirror

Sloan Digital Sky Survey Telescope
Apache Point Observatory, New Mexico, USA

eBOSS

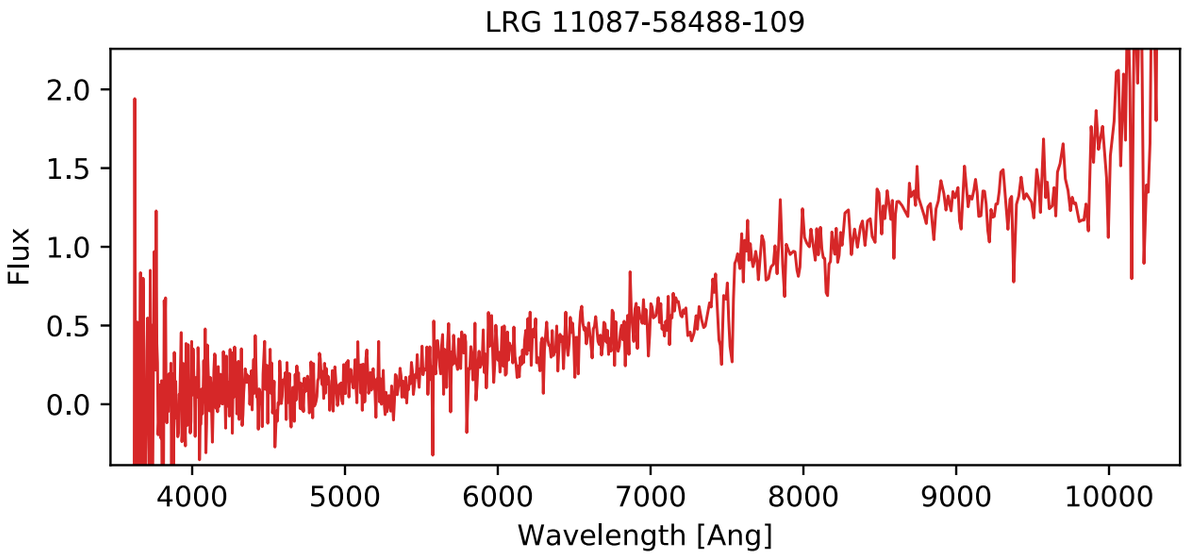
extended Baryon Oscillation Spectroscopic Survey



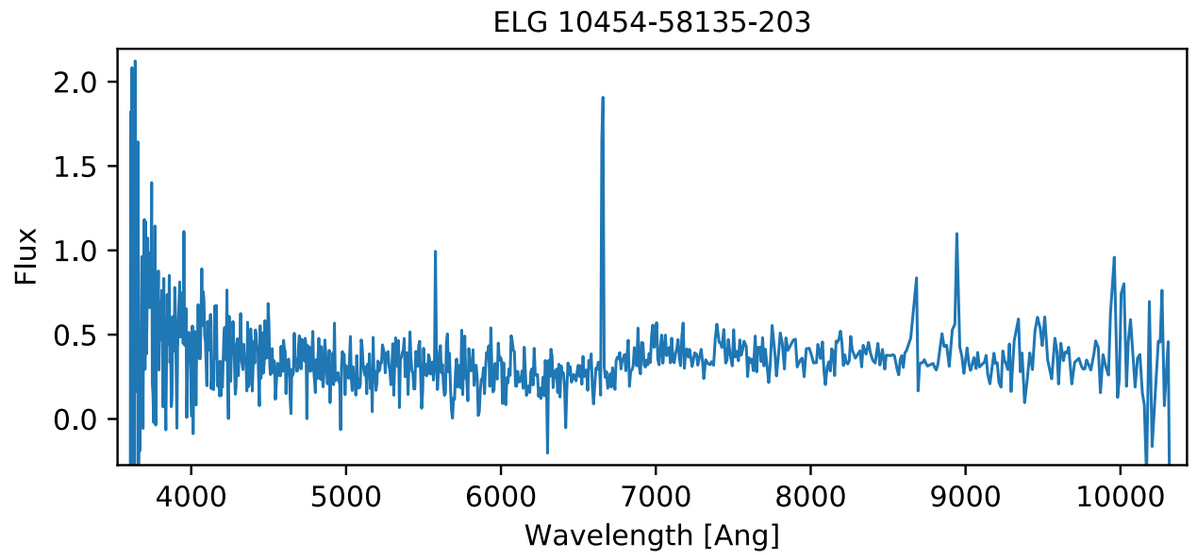
1-meter focal plane

eBOSS Spectra

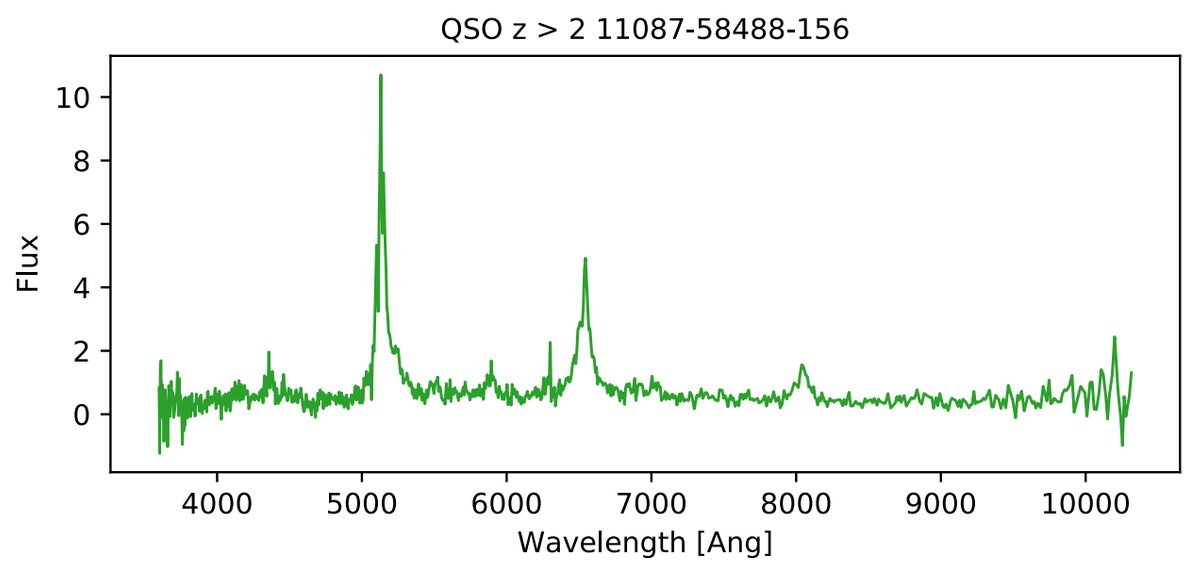
Luminous Red Galaxies (0.6 < z < 1.0)



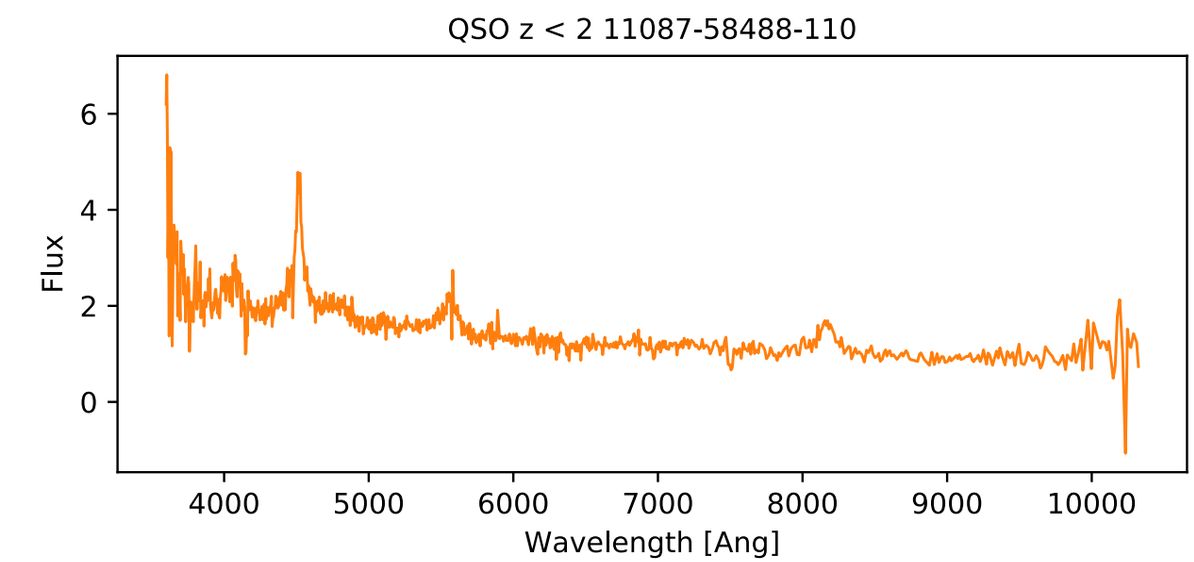
Emission Line Galaxies (0.7 < z < 1.1)



Quasars (z > 2) for Lyman-alpha forest



Quasars for clustering (0.8 < z < 2.2)



Redshifts obtained with PCA templates, neural networks
and some visual inspection (for QSOs)

Extracting cosmological overdensities

Ross, **Bautista**, Tojeiro et al. 2020

Galaxy overdensity: $$\delta_g(\vec{x}) = \frac{n_g(\vec{x})}{\bar{n}_g} - 1$$

Random catalog

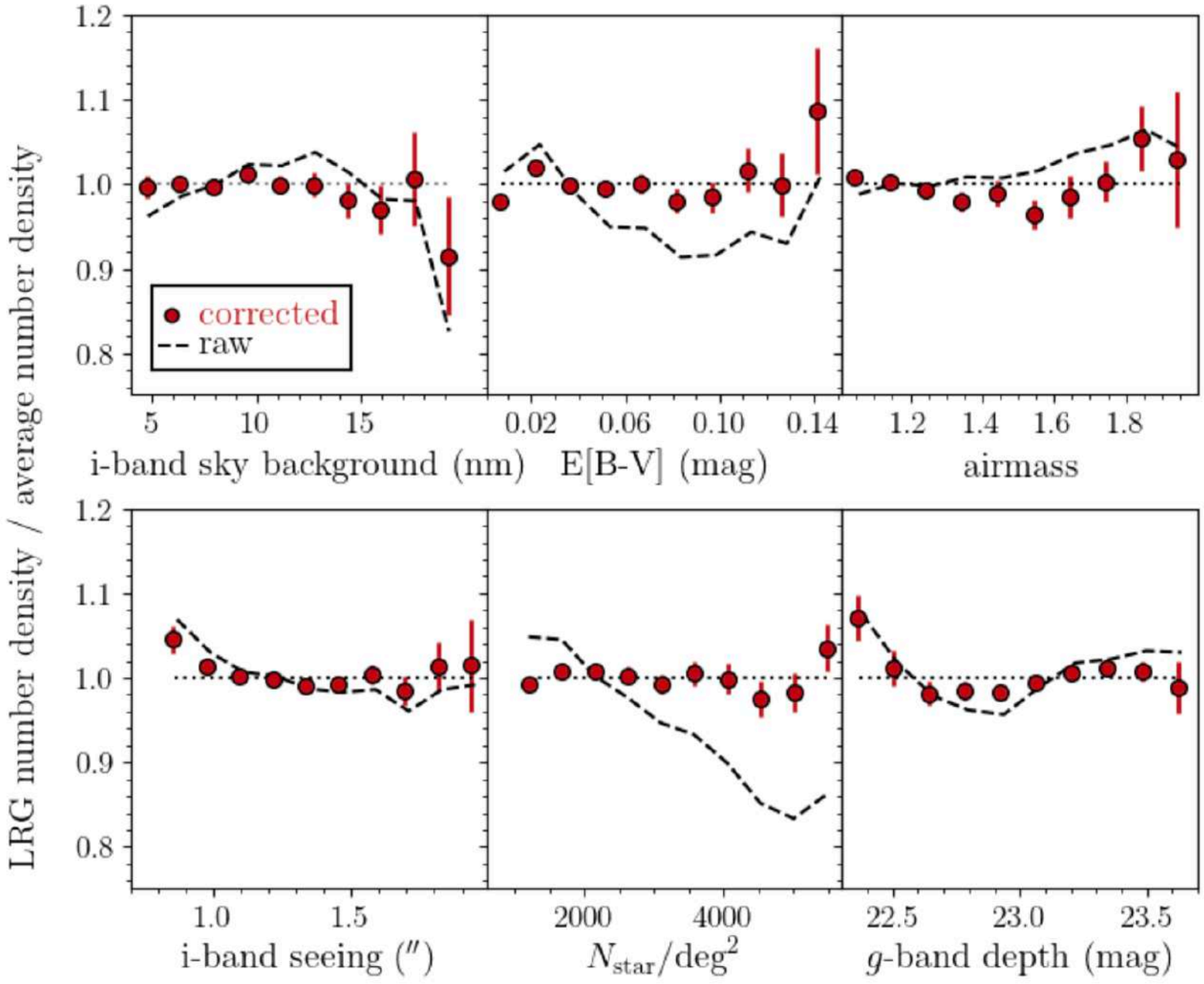
Features or systematics to take into account:

Survey footprint	Observational completeness	Fake overdensities caused by photometry
"Collisions" of fibers	Reconstruction of linear density field for BAO	Spectra without confident redshift measurement

1000 simulated surveys used to test methods, covariance, systematic errors
(Zhao, Chuang, **Bautista**, et al. 2020)

Extracting cosmological overdensities

Ross, **Bautista**, Tojeiro et al. 2020

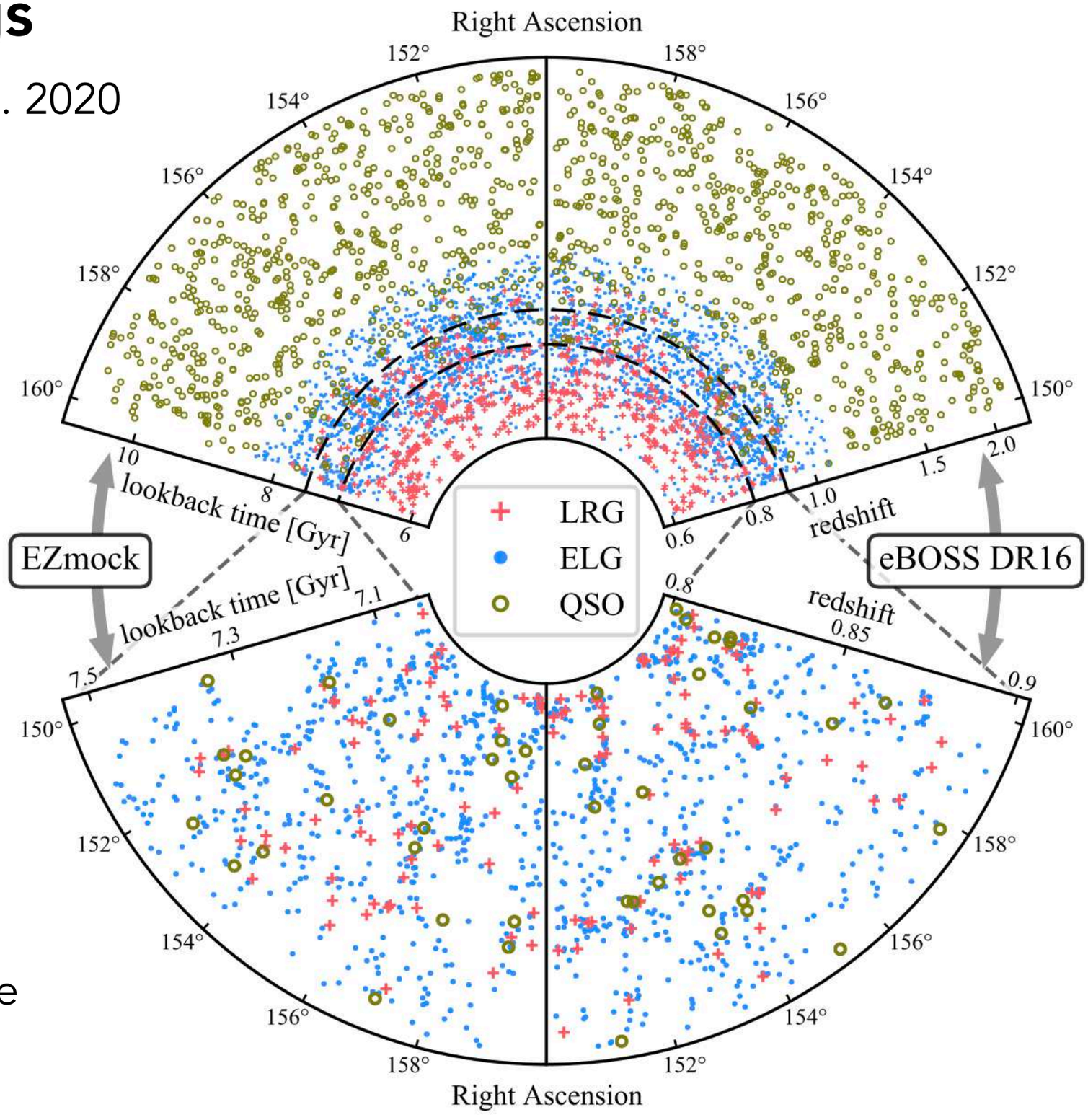


Fake overdensities
caused by photometry

EZmock catalogs

Zhao, Chuang, **Bautista**, et al. 2020

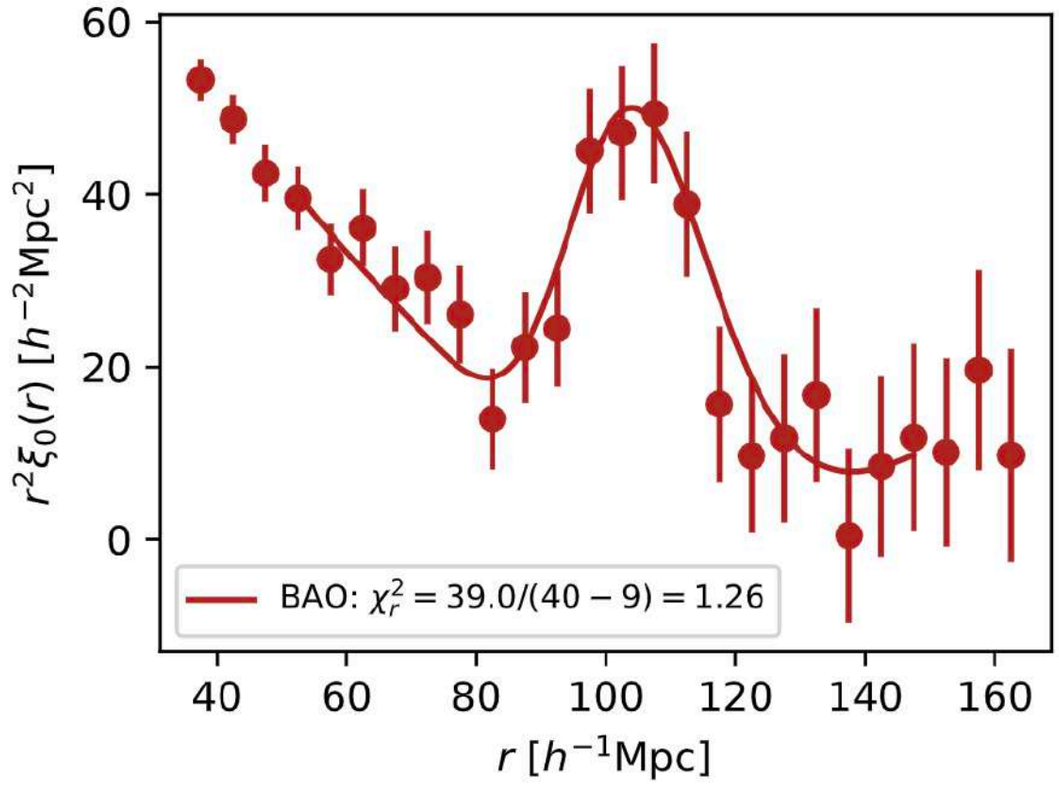
- Zel'dovich approximations to rapidly construct density field
- 1000 realizations of the survey
- includes redshift evolution
- includes observational effects
- includes cross-correlations between tracers
- used to test our methods, estimate systematic errors and compute covariance matrices

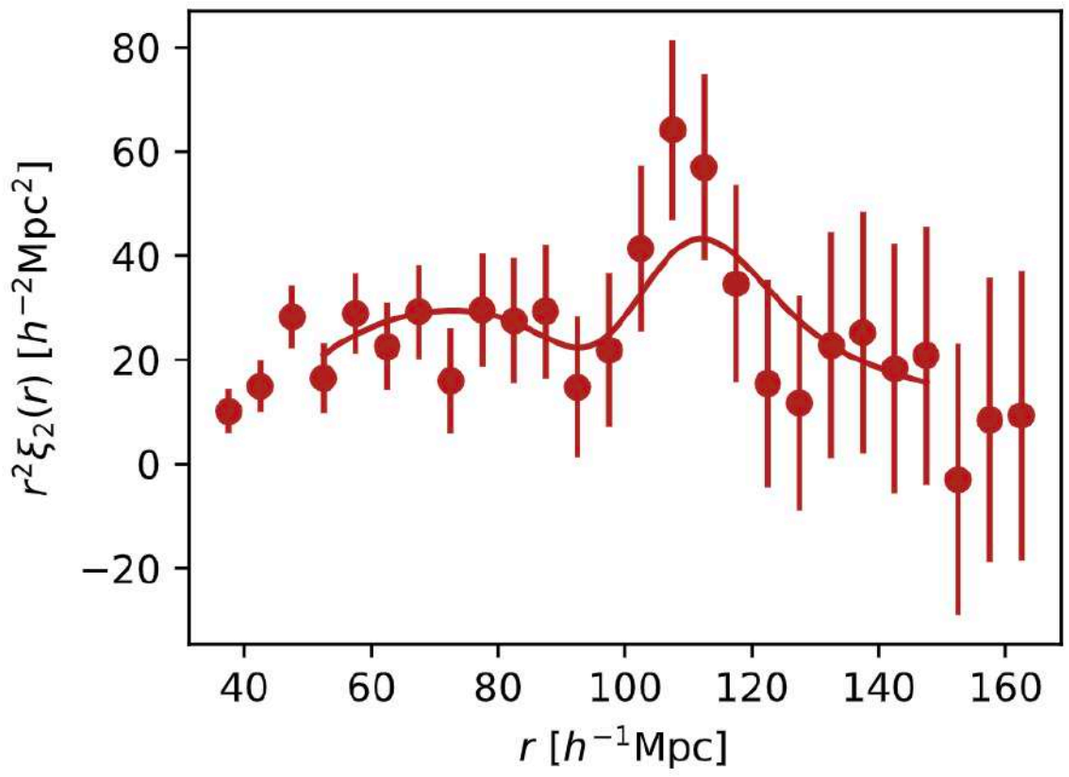


BAO analysis

eBOSS LRG sample

Post-reconstruction multipoles





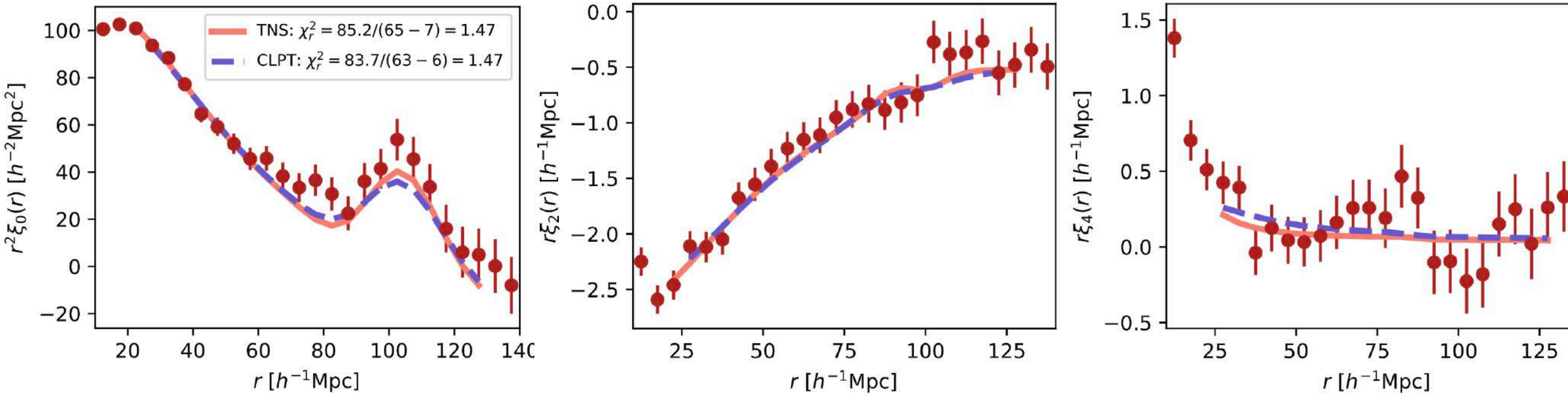
Estimate D_M/r_d and D_H/r_d from BAO peak position (and nothing else)

Model from Bautista et al. 2018

RSD analysis

eBOSS LRG sample

Pre-reconstruction multipoles



Growth rate of structures

Estimate D_M/r_d, D_H/r_d and $f\sigma_8$ from the full-shape of the correlation function

Two models:

TNS (Taruya et al. 2010) with non-linear bias

CLPT (Carlson et al. 2013) with Gaussian streaming (Reid & White 2011)

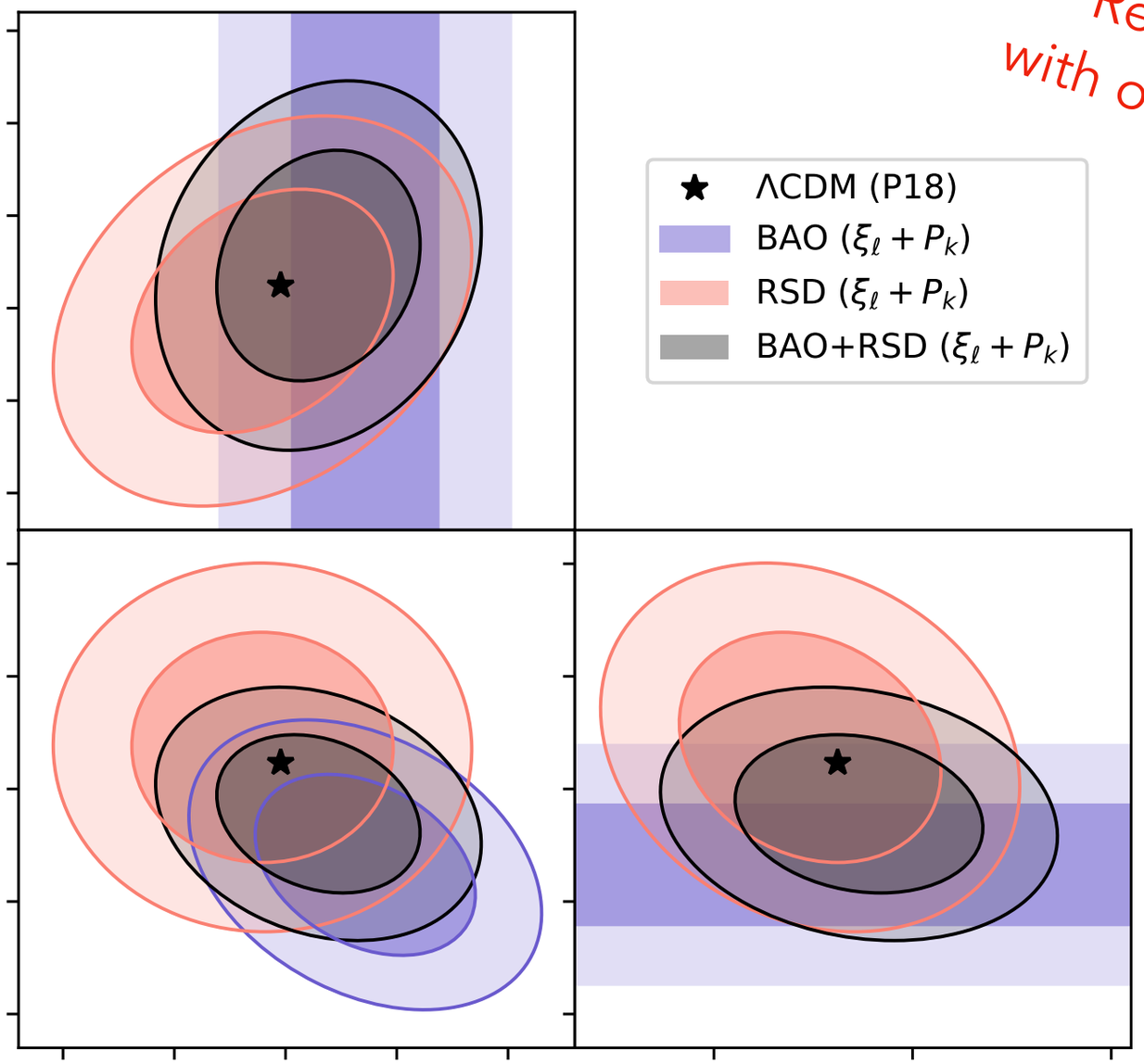
Final results from the LRG sample at z = 0.7

BAO + RSD $\xi_\ell + P_\ell$

Results don't change with order of combination!

Growth rate of structures $f\sigma_8$

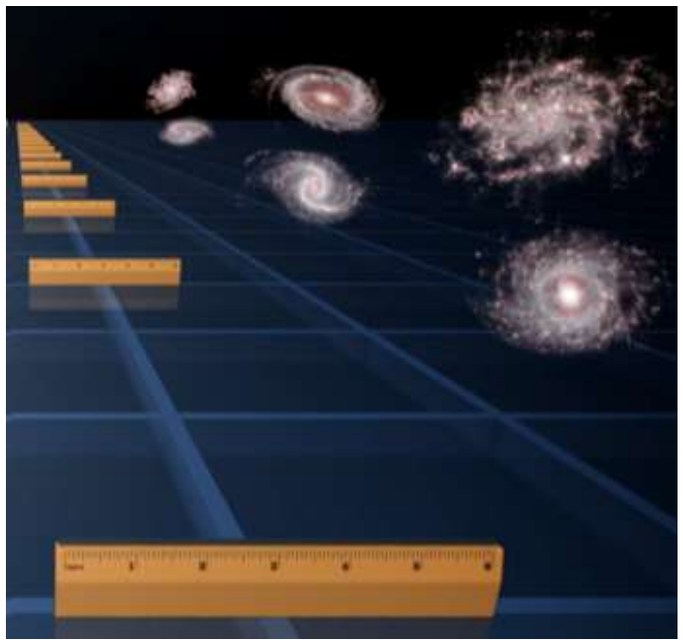
Radial BAO scale $D_H(z)/r_{\rm drag}$

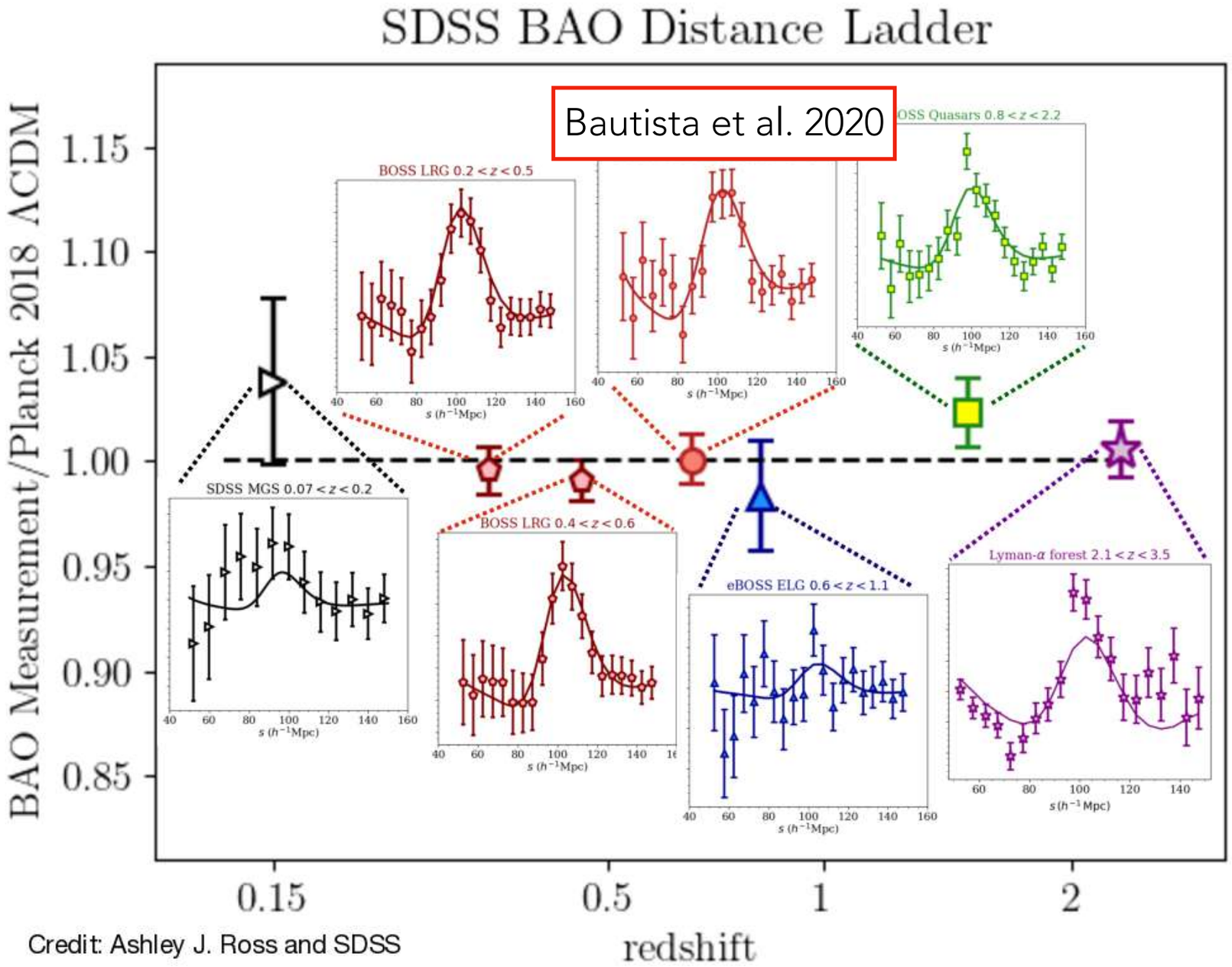


Transverse BAO scale $D_M(z)/r_{\rm drag}$

Growth rate of structures $f\sigma_8$

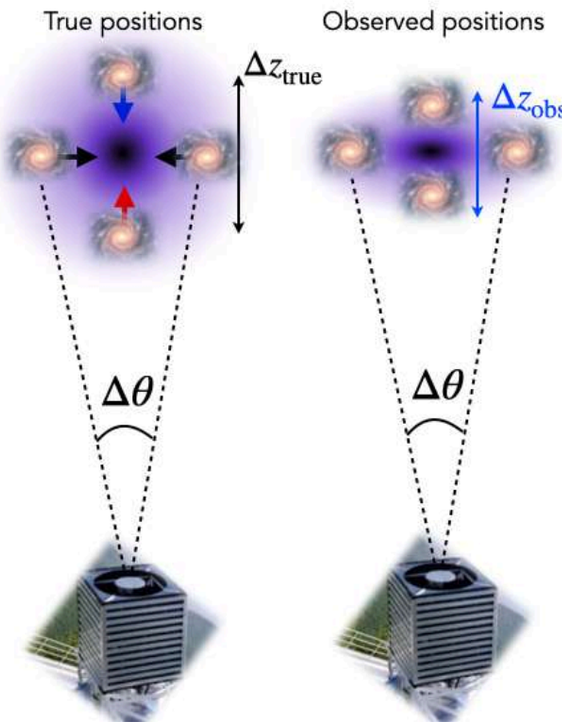
Expansion-rate
with Baryon Acoustic Oscillations (BAO)

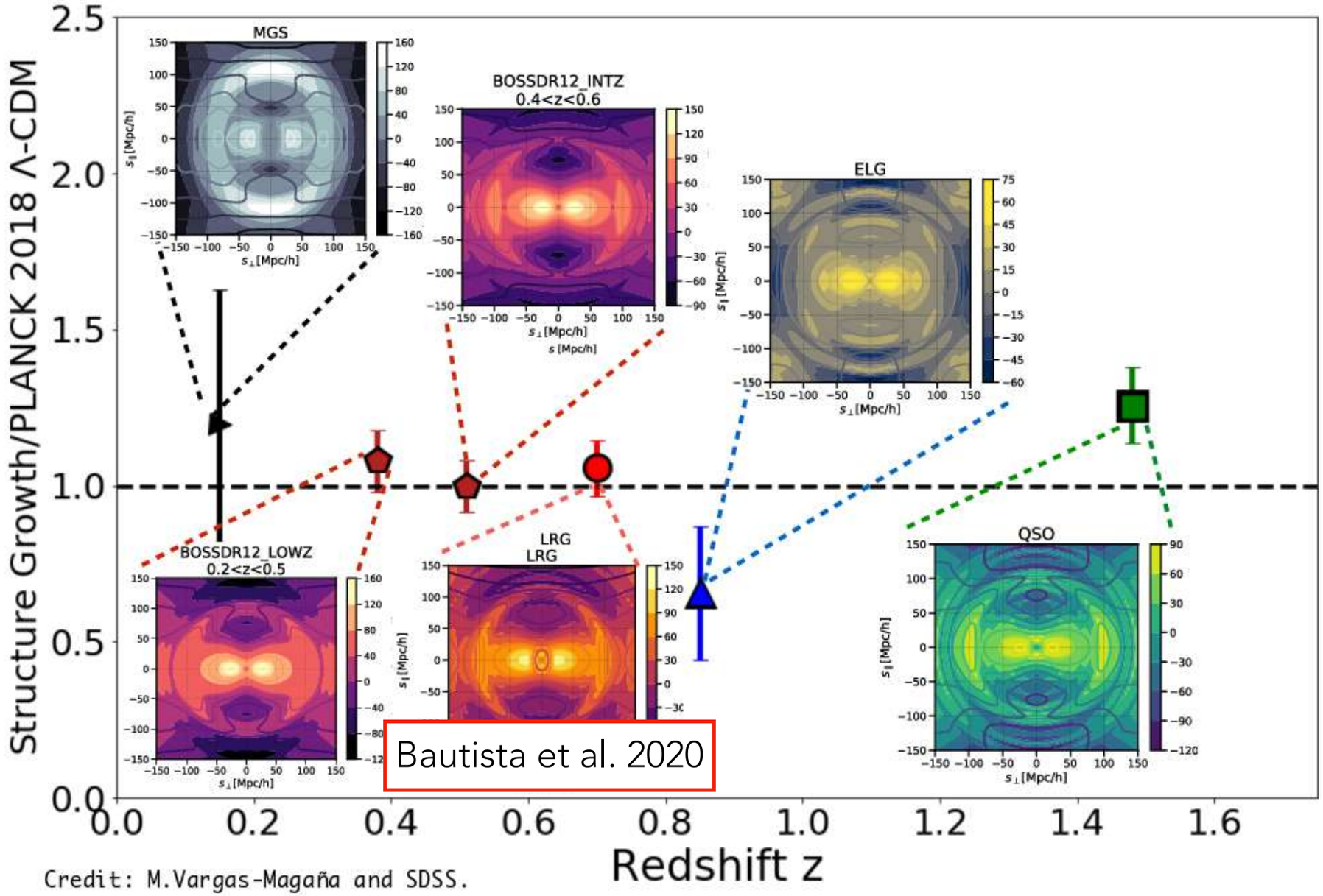




Credit: Ashley J. Ross and SDSS

Growth-rate of structures with redshift-space distortions (RSD)



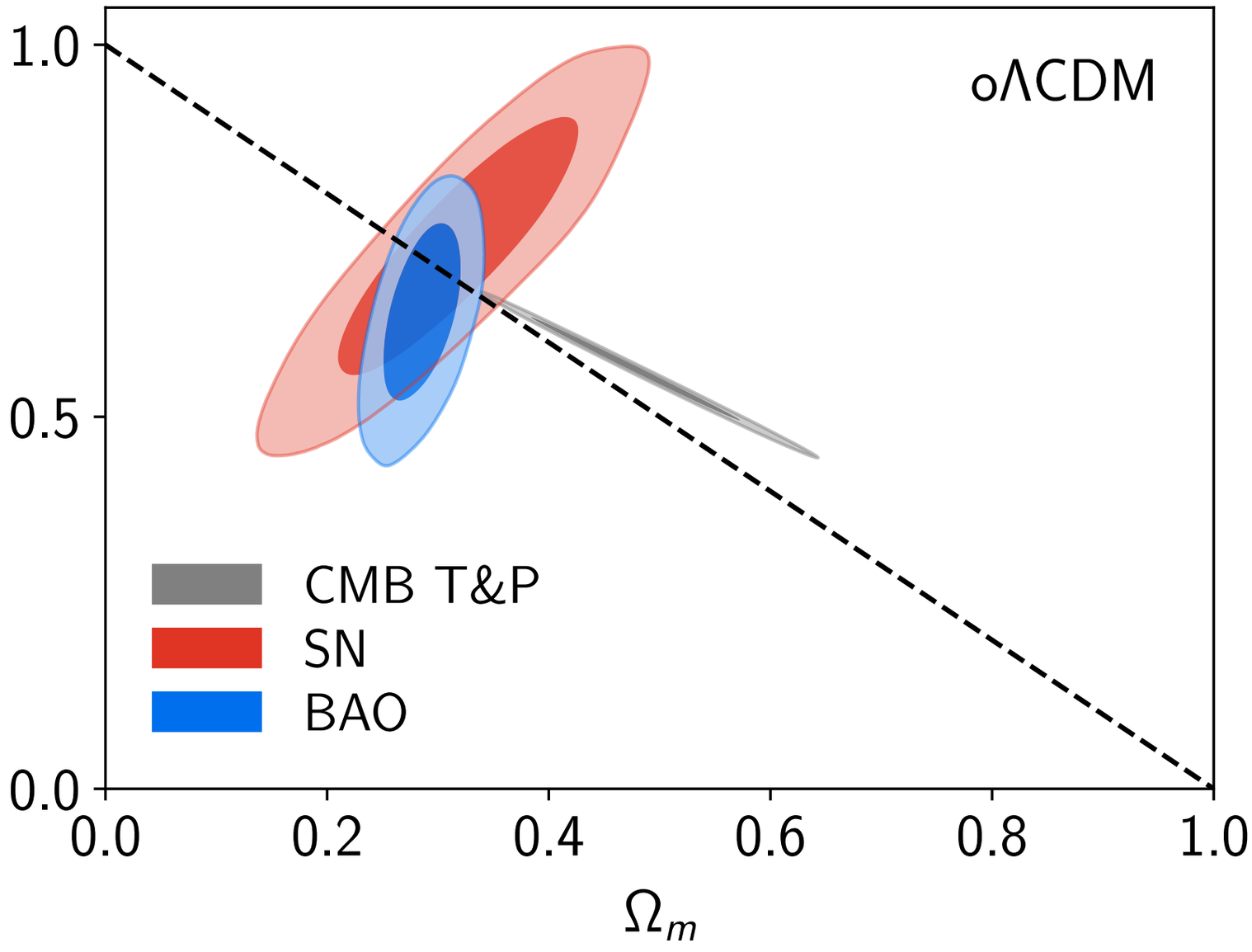


Also using cosmic-voids: Aubert, Cousinou, Escoffier, et al. 2020

Cosmological implications

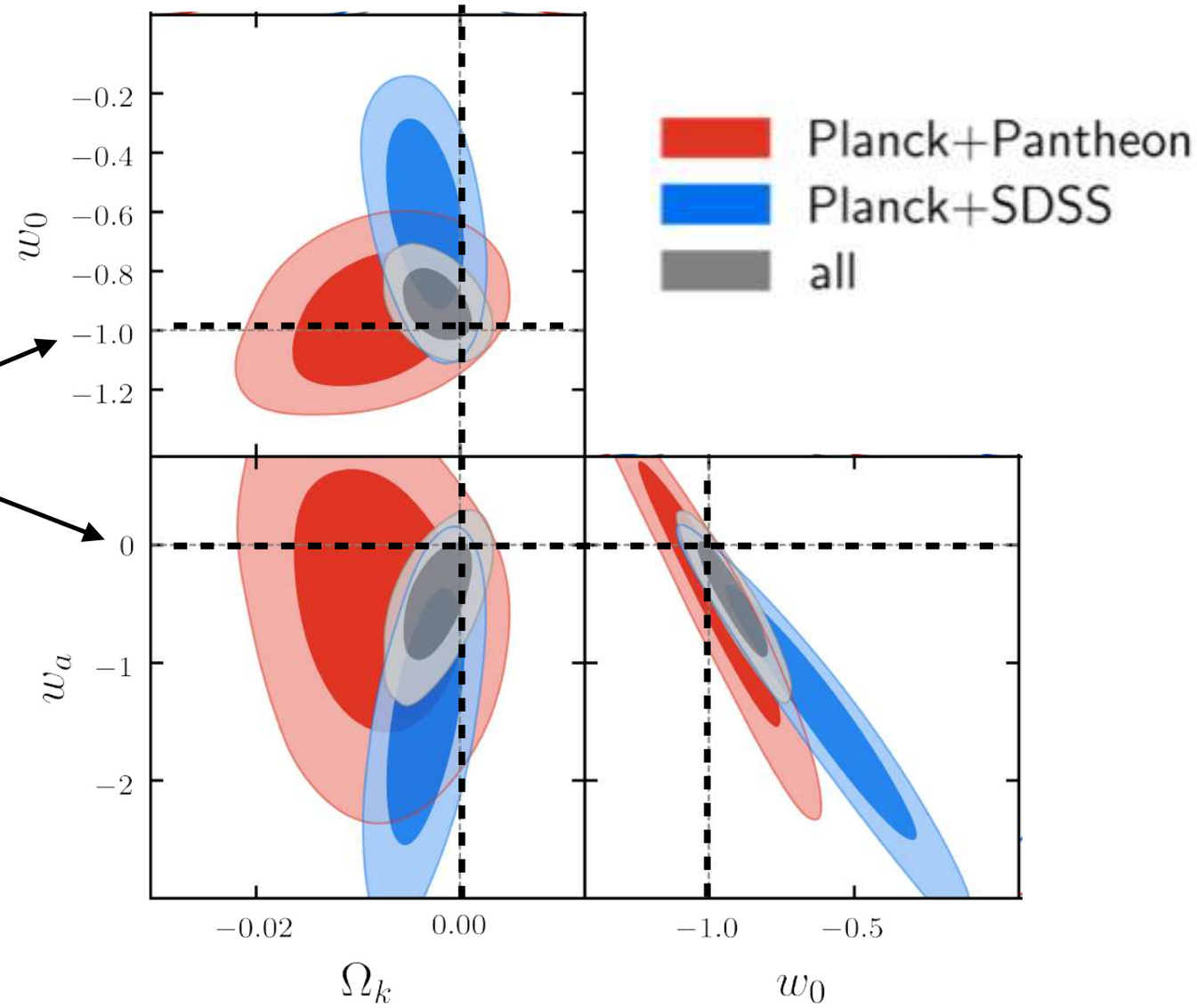
(eBOSS Collaboration, 2020)

Cosmological constant



Cosmological implications

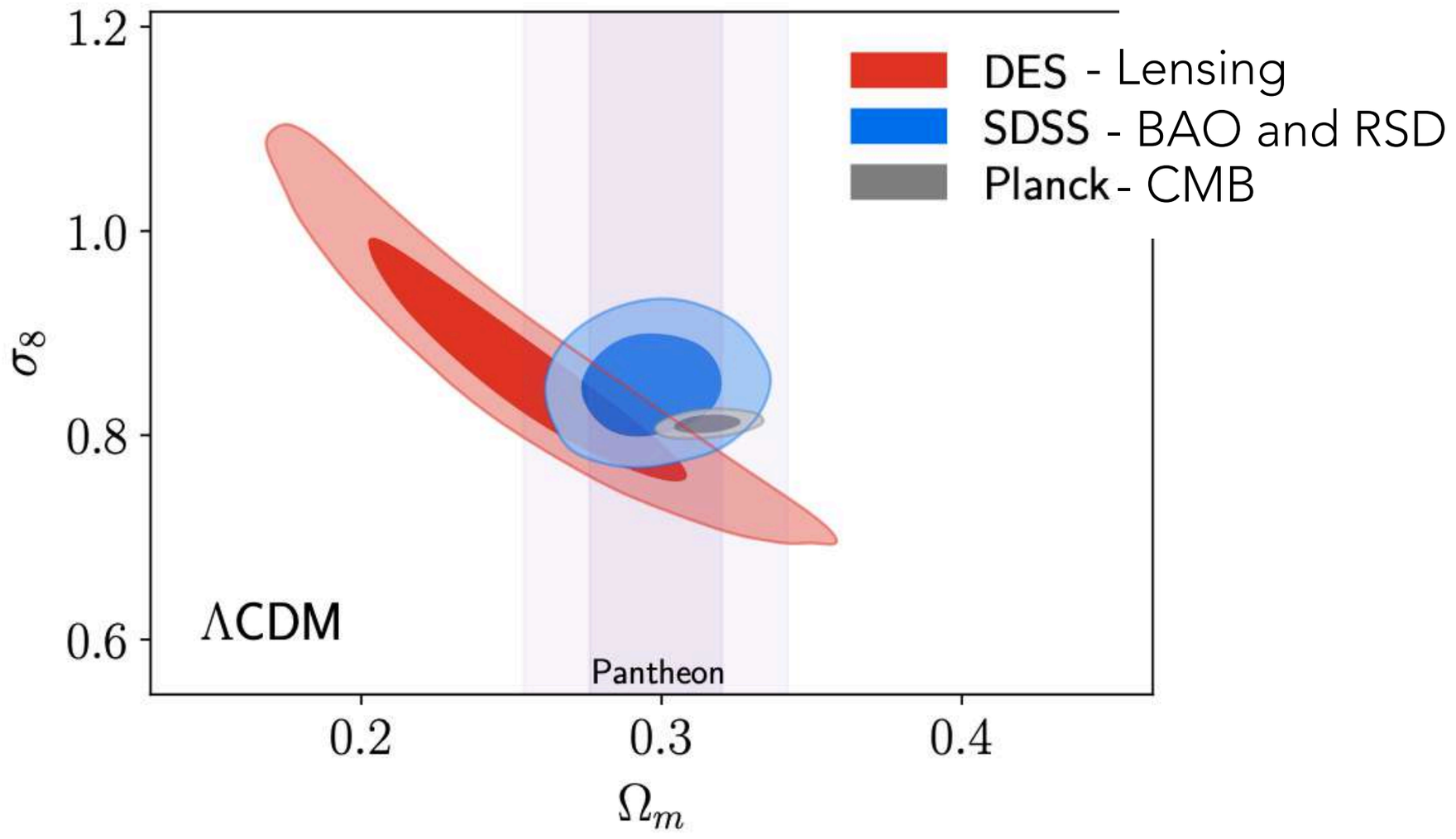
Cosmological constant



(eBOSS Collaboration, 2020)

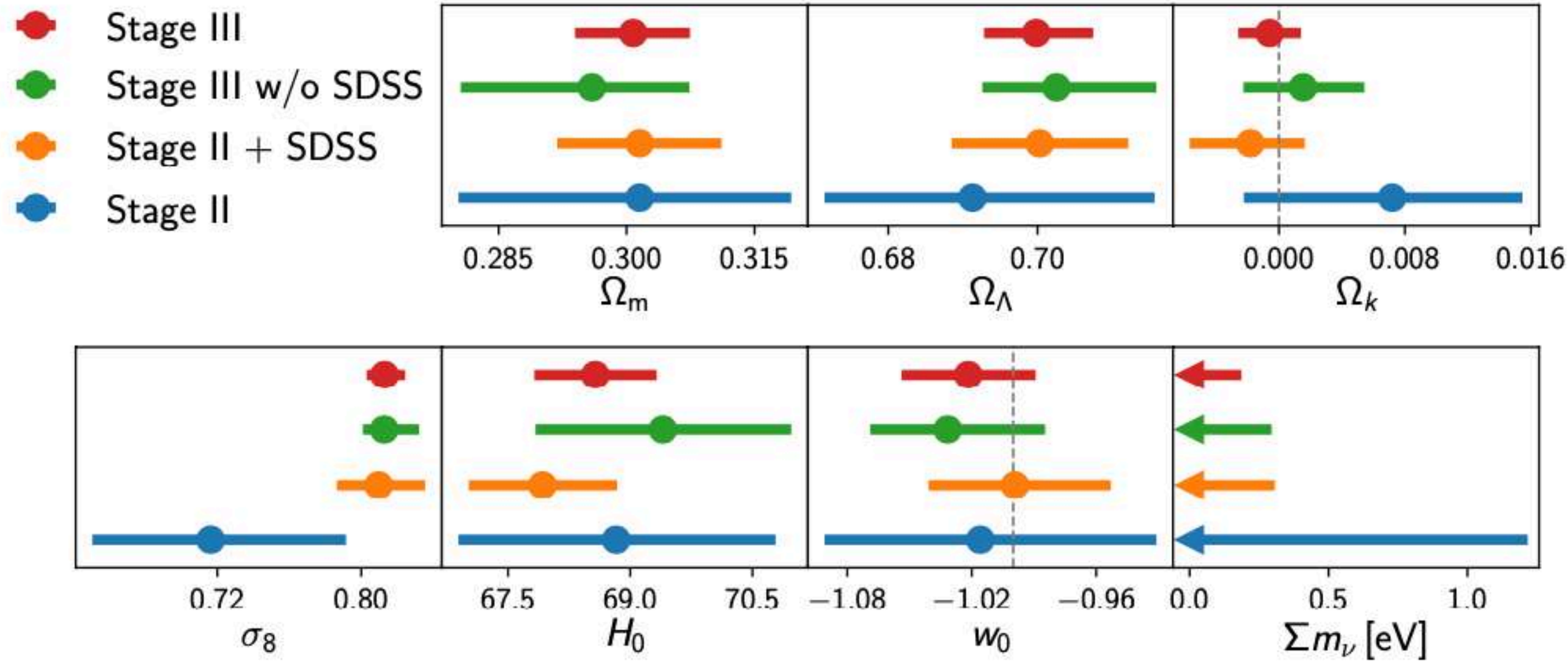
Cosmological implications

Variance of δ
(with 8 Mpc/h smoothing)



(eBOSS Collaboration, 2020)

Cosmological implications



(eBOSS Collaboration, 2020)

Stage III: SDSS final, Planck CMB, Pantheon SN Ia, and DES 3x2pt
Stage II: SDSS DR7, WMAP CMB, JLA SN Ia

Future

and making high-resolution maps

Next-generation surveys of the structures

Telescope with 4m mirror
5000 spectra at a time
~ 20 million galaxies
2021-2026

DARK ENERGY SPECTROSCOPIC INSTRUMENT

Satellite with 2m mirror
~30 million galaxies
2022 - 2028

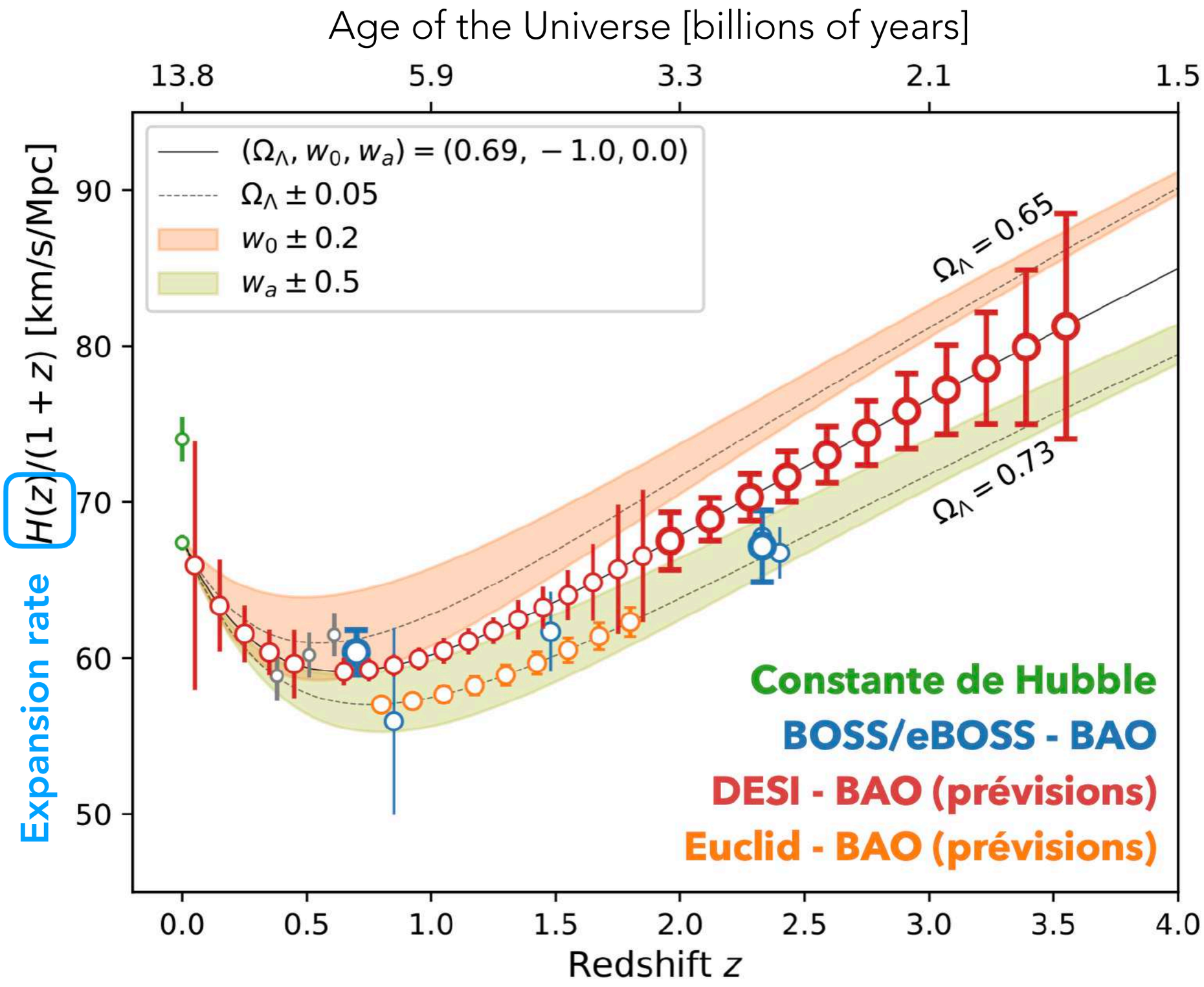
euclid

Telescope with 8.4m mirror
Largest camera in the world
~ 300k supernovae
2023 - 2033

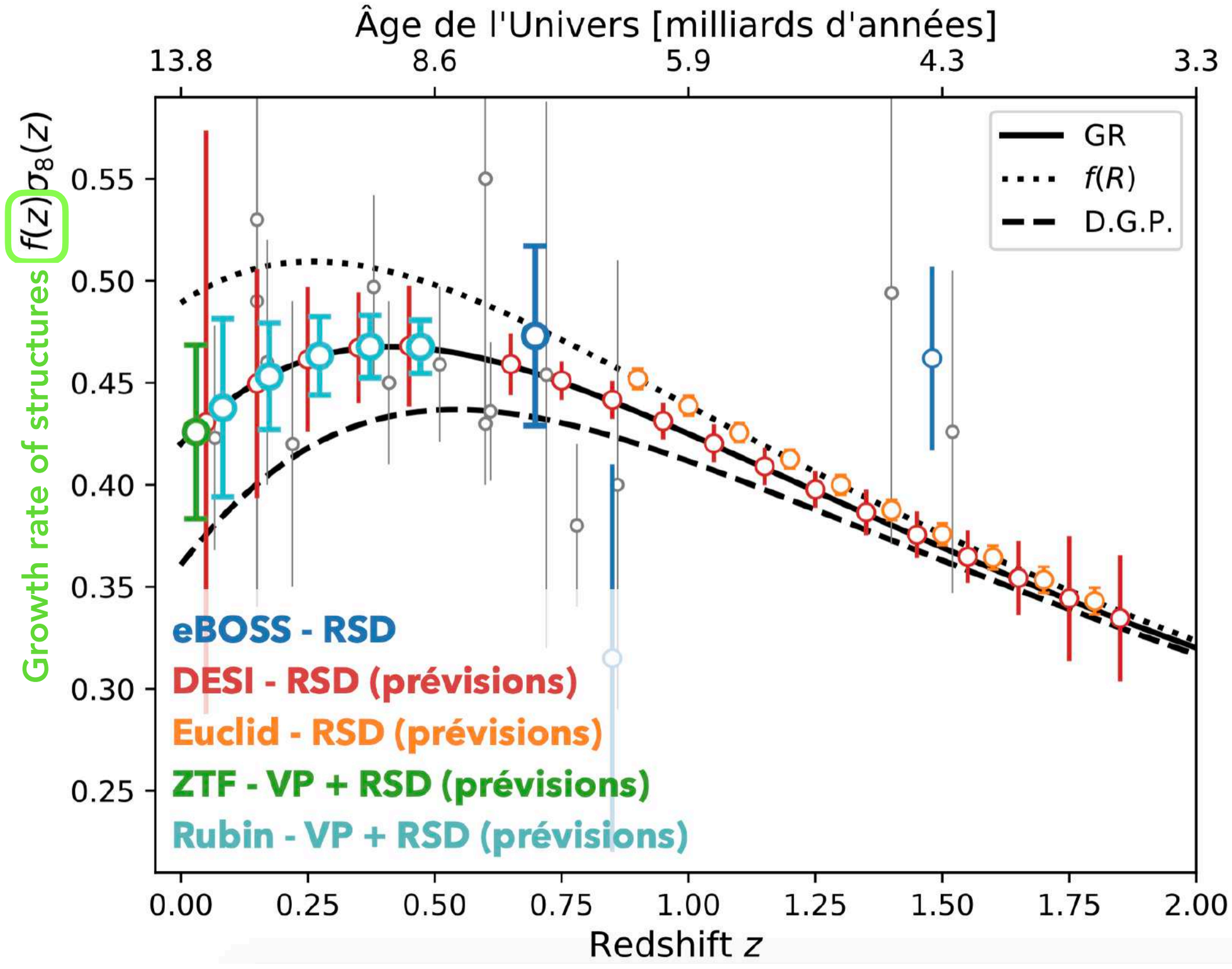
Rubin Observatory

Key participation of CPPM in these projects

Expansion-rate

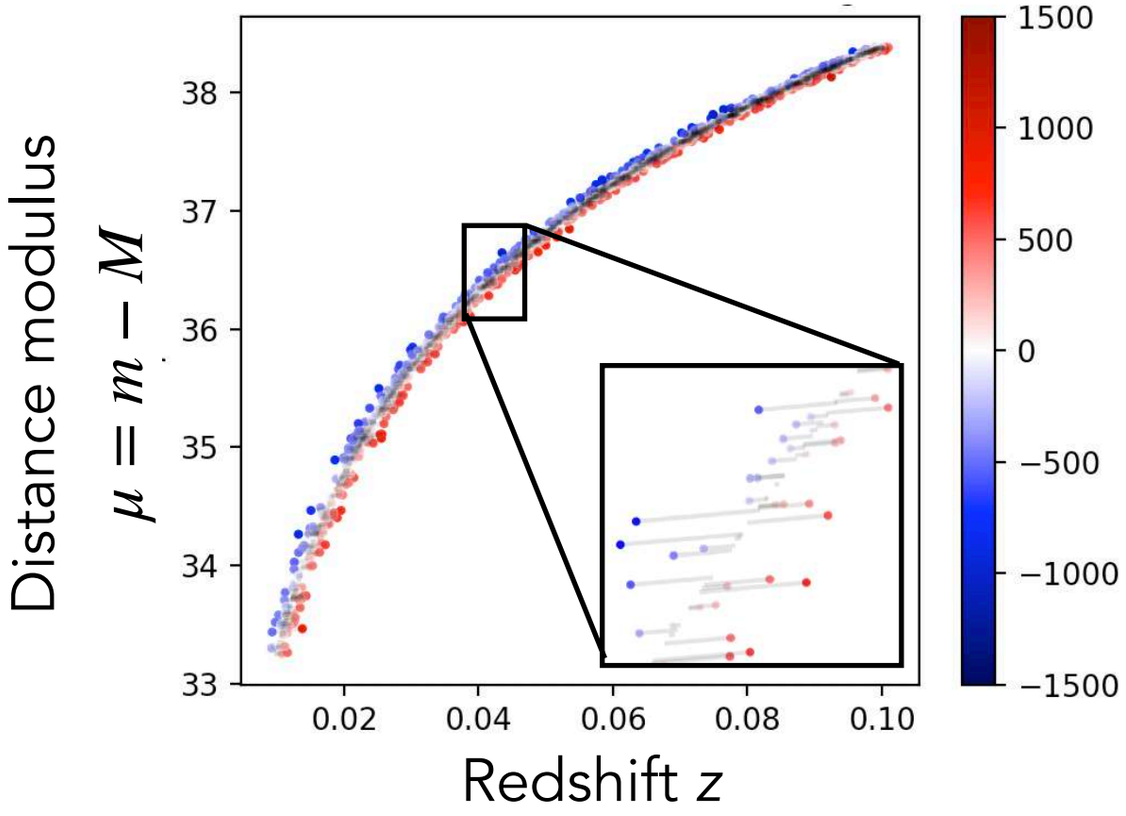


Growth-rate

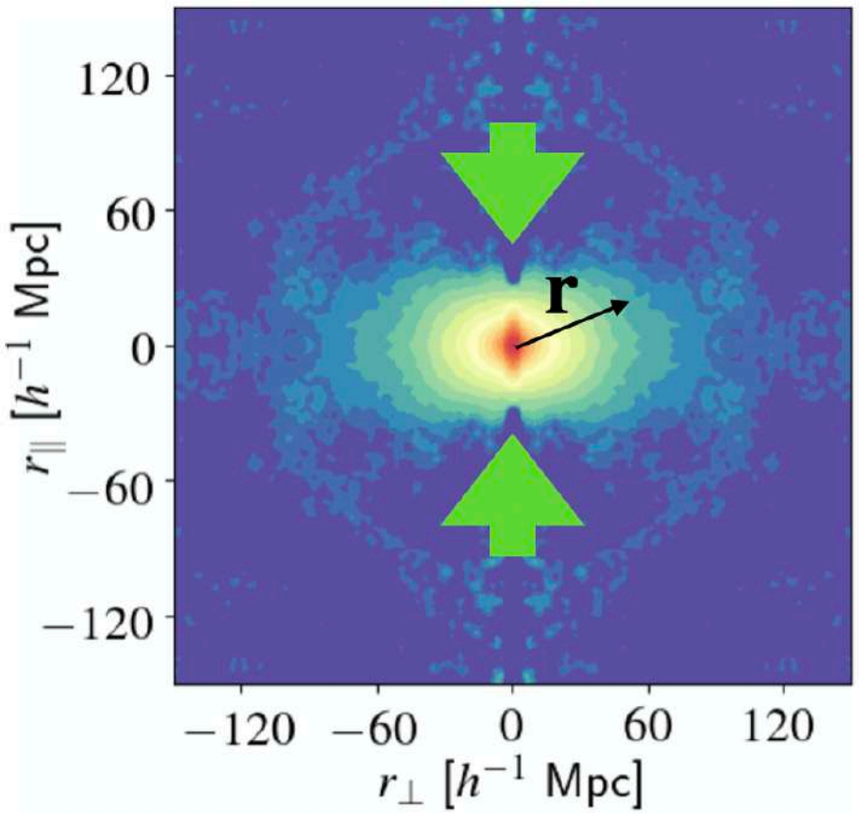

Âge de l'Univers [milliards d'années]
13.8
8.6
5.9
4.3
3.3
Growth rate of structures $f(z)\sigma_8(z)$
0.55
0.50
0.45
0.40
0.35
0.30
0.25
GR
$f(R)$
D.G.P.
eBOSS - RSD
DESI - RSD (prévisions)
Euclid - RSD (prévisions)
ZTF - VP + RSD (prévisions)
Rubin - VP + RSD (prévisions)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Redshift z

Testing GR with type-Ia supernovae peculiar velocities

Peculiar velocities measured from SNIa



RSD of low redshift galaxies



Photometric surveys

ZTF

Rubin-LSST

Spectroscopic surveys

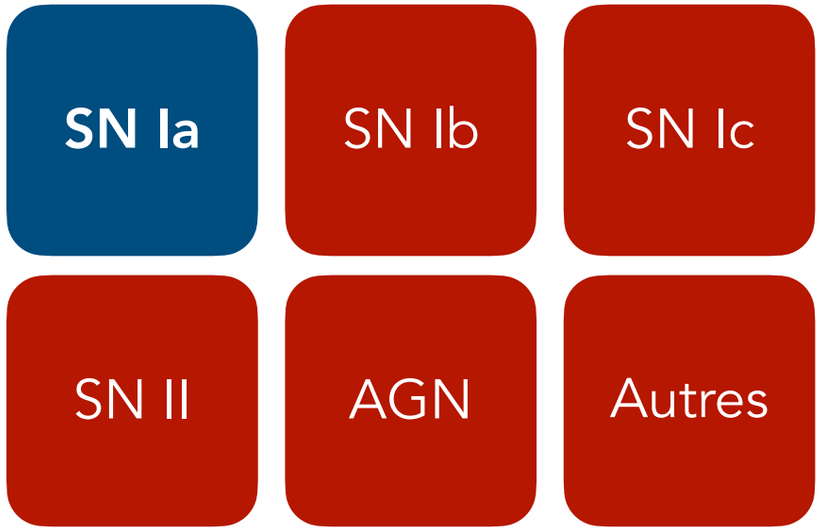
DESI

4MOST

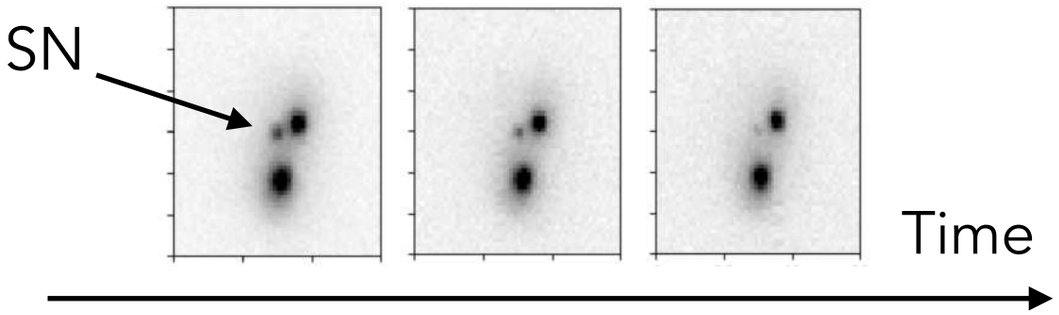
This new type of measurement will be competitive for the first time (with SNIa)

Cosmology with type Ia supernovae

Photometric classification of supernovae with *deep learning*

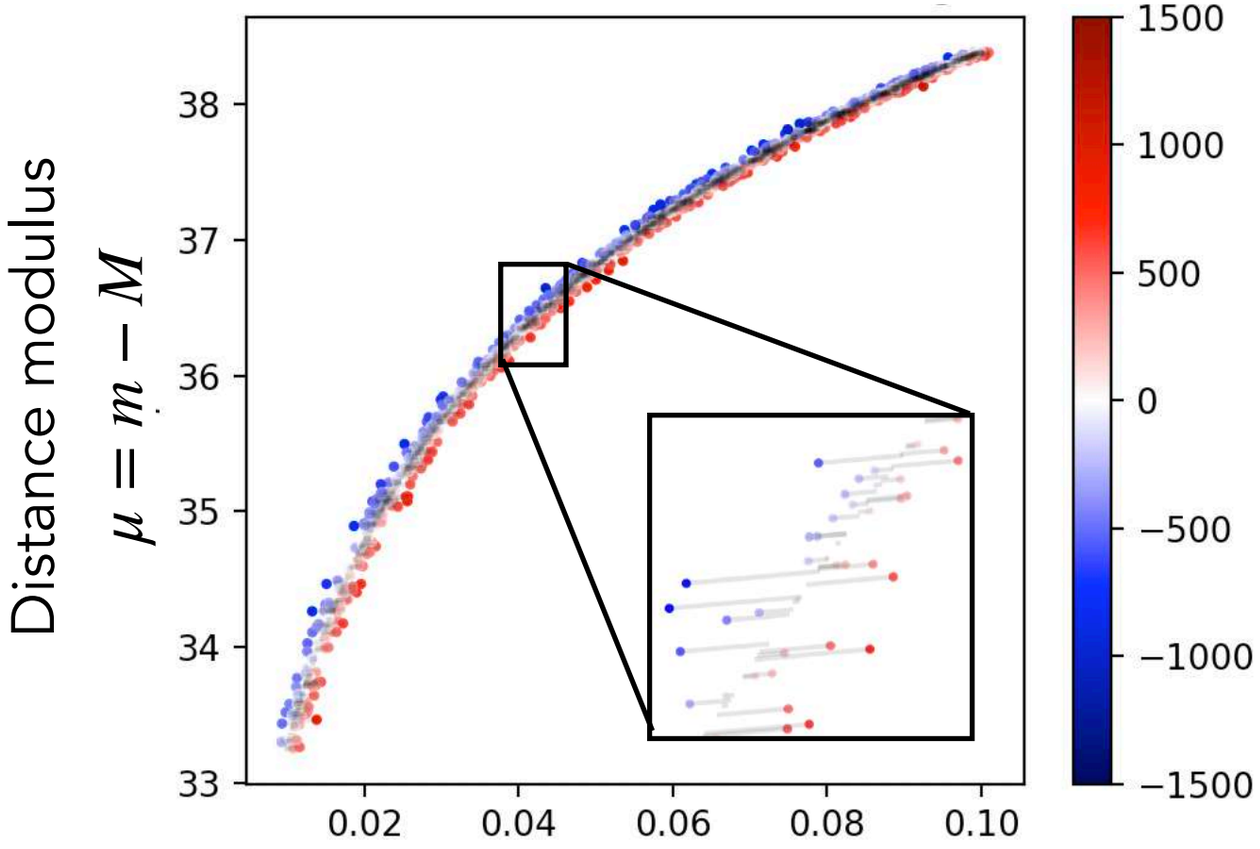


Use images as input for learning



Collaboration with LIRMM et TETIS

Peculiar velocities from SNIa



Project in collaboration with:
Bastien Carreres, doctorant, CPPM
Mariam Sabalbal, master 2, AMU
Nattapon Preedasak, master 1, AMU

Préparation à l'analyse cosmologique de la prochaine génération

Conclusion

What is dark energy? We don't know yet

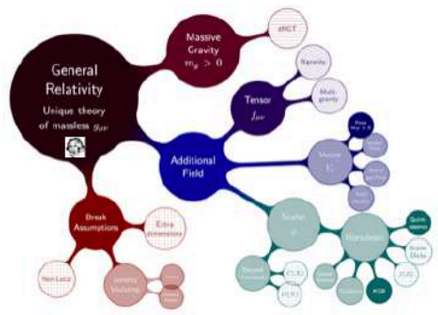
$\Omega_\Lambda[a(t)]^{-3(1+w_0+w_a)}e^{3w_a[1-a(t)]}$

dark energy
(quintessence, phantom force)

70%

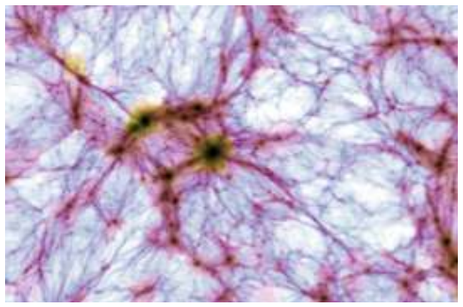
Empirical dark-energy?

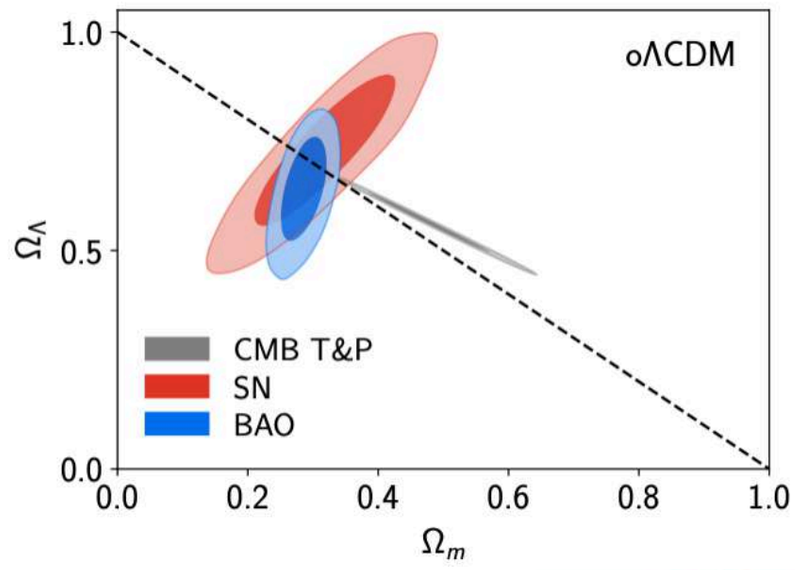
or



Alternative to GR?

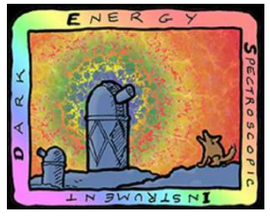
Statistics of the structures of our Universe can inform us





SDSS produced the state-of-the-art map of the structures measuring expansion-rates and growth-rates

Future is promising with next-gen surveys



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Ongoing project to test GR with SNIa peculiar velocities