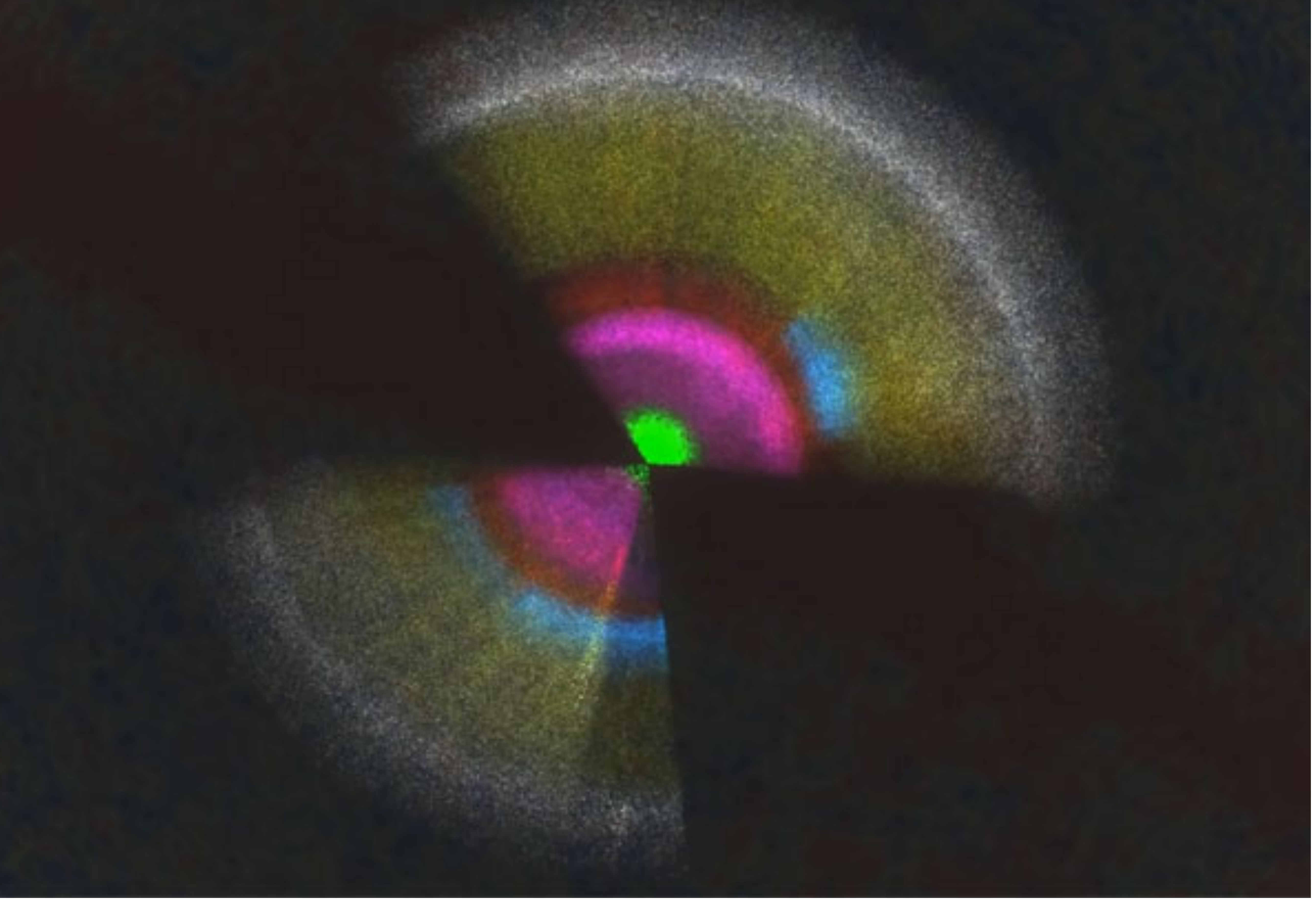
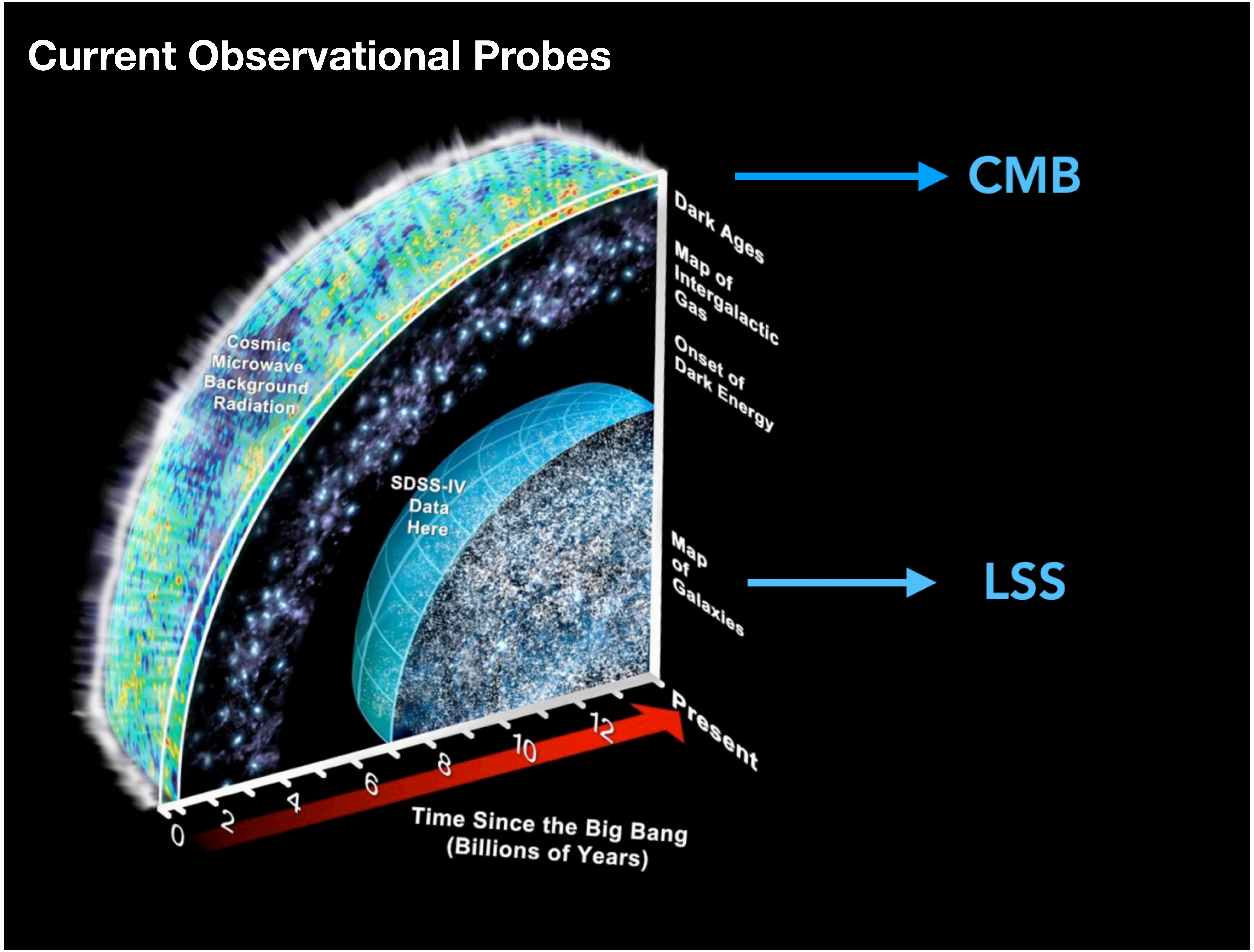


Cosmology from galaxy redshift surveys: current results and future prospects

EuCAPT Symposium, 6th May 2021

Héctor Gil-Marín
Institut de Ciències del Cosmos, Universitat de Barcelona
hectorgil@icc.ub.edu

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science
eBOSS
SDSS
"la Caixa" Foundation
ICCUB
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA



CMB
- Early-time physics
- Quasi-linear physics
- 2D surface
- Primary anisotropies are CV limited

LSS
- Late-time physics (DE - Λ)
- Non-linear physics
- 3D volume
- Galaxy bias
- Peculiar velocities
- Wealth source of information

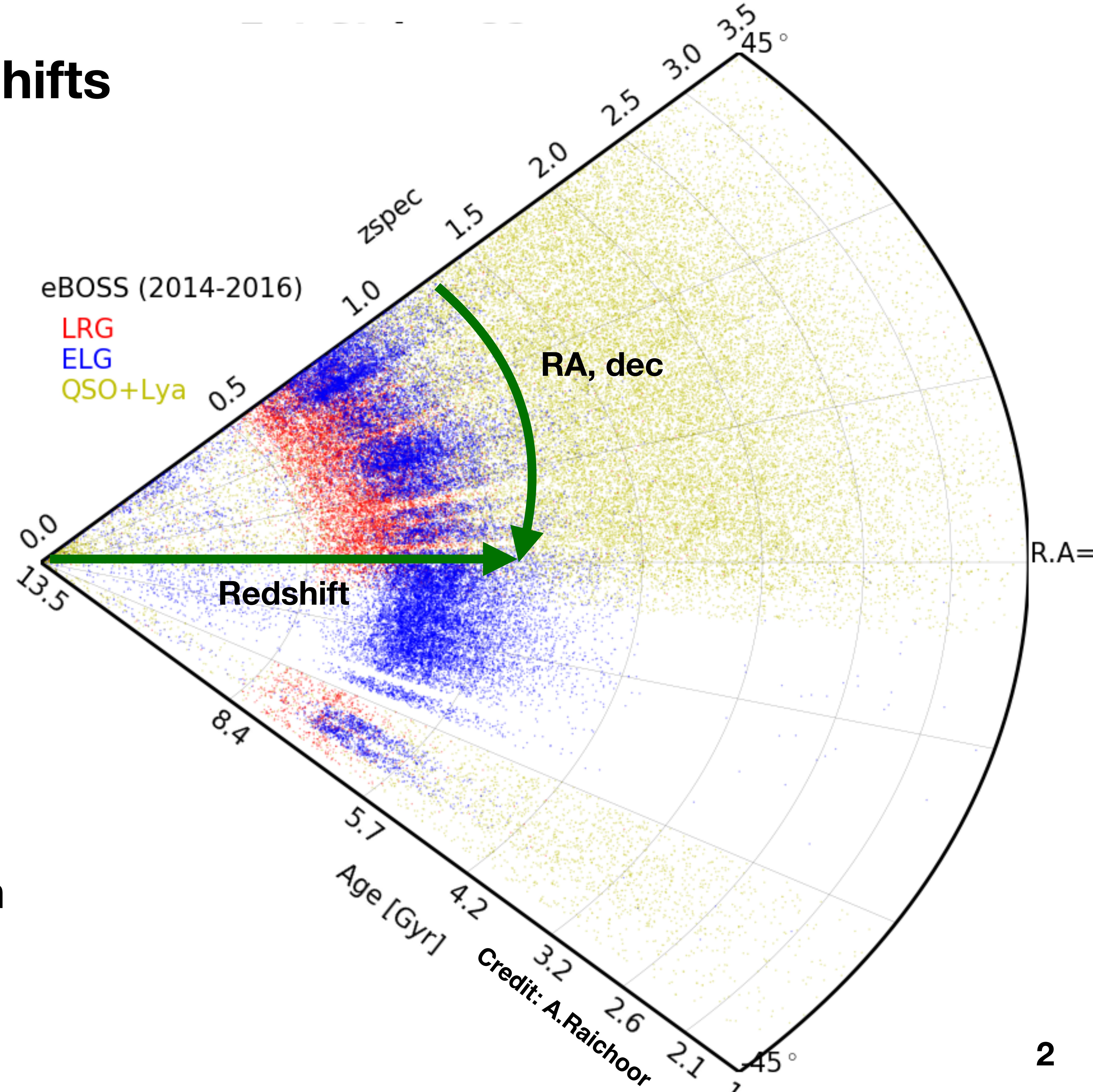
Spectroscopic surveys: **angles** and **redshifts**

- The redshift survey catalogues deliver: angles and redshifts for each galaxy

- Redshifts are converted to comoving distances **assuming a cosmological model** and **assuming velocities are due to Hubble flow**

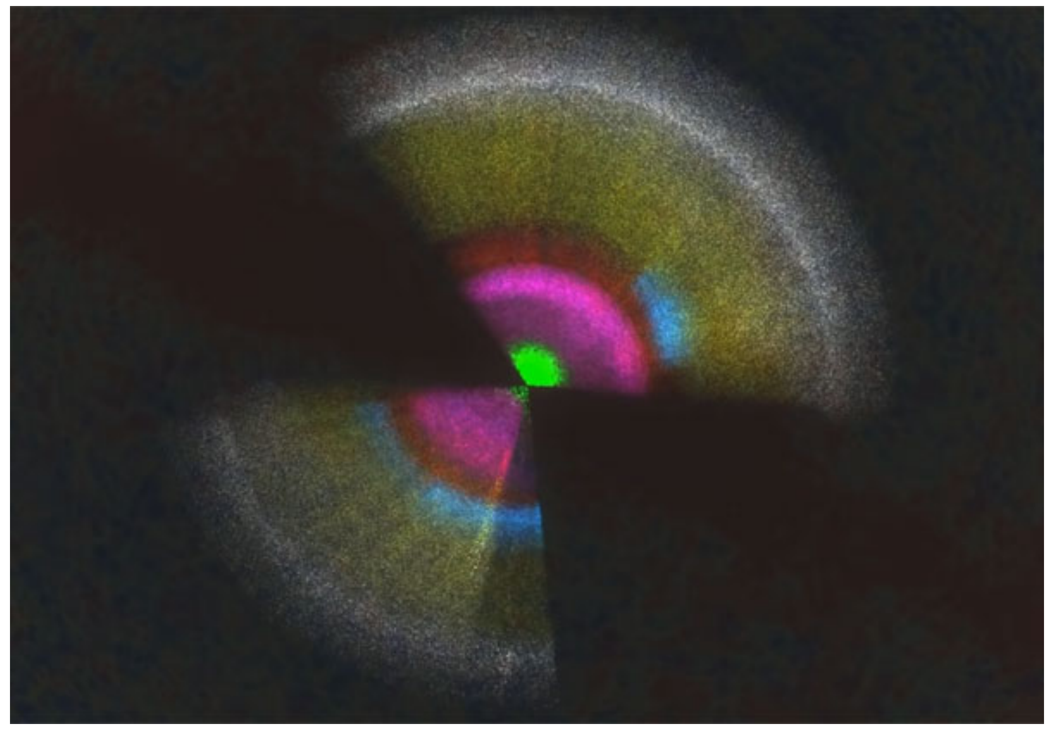
$$r(z) = \int_0^z \frac{c dz'}{H(z', \Omega)}$$

- Produce a 3D map we use to extract information



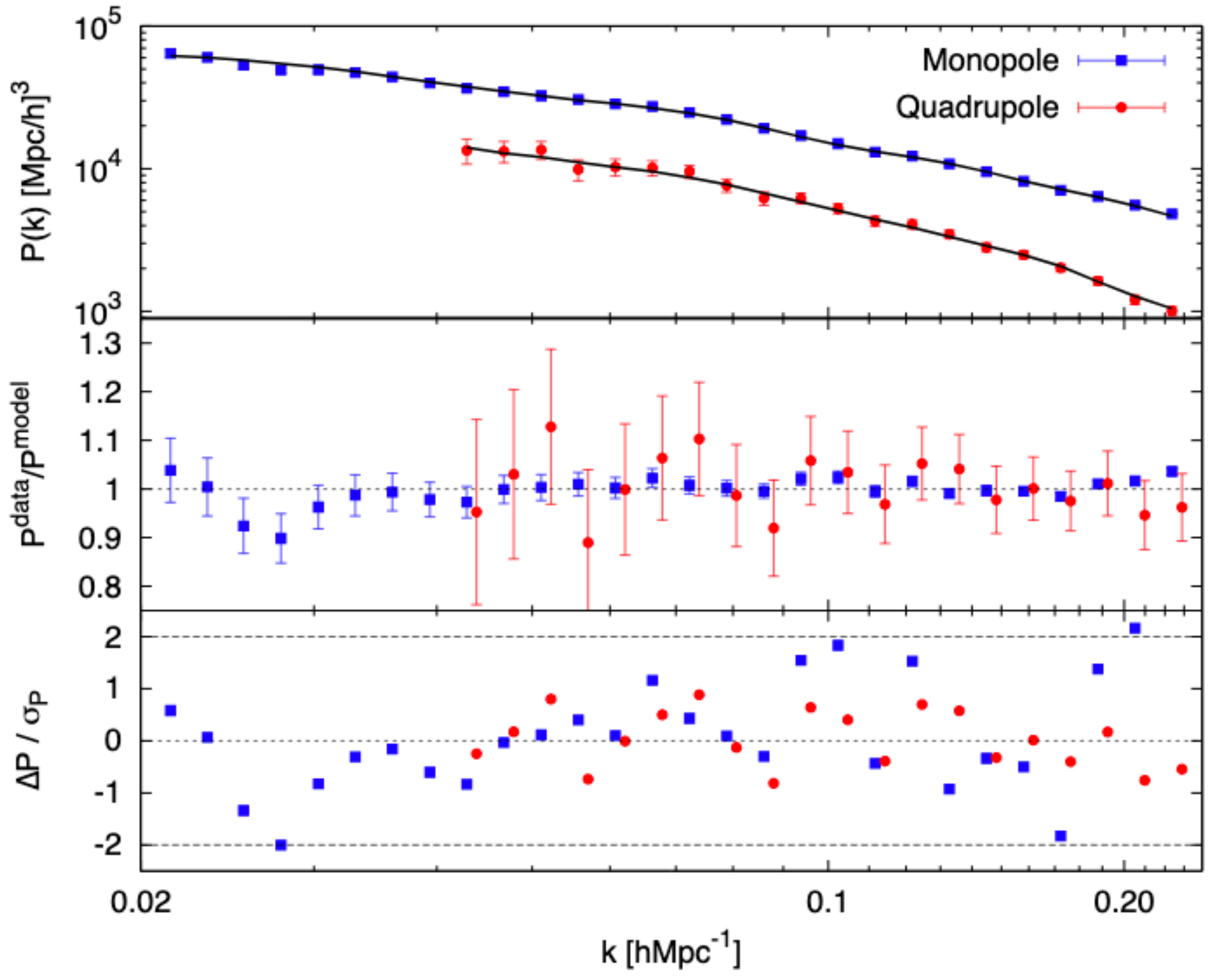
Spectroscopic surveys: **information content**

- **LSS Galaxy Maps**



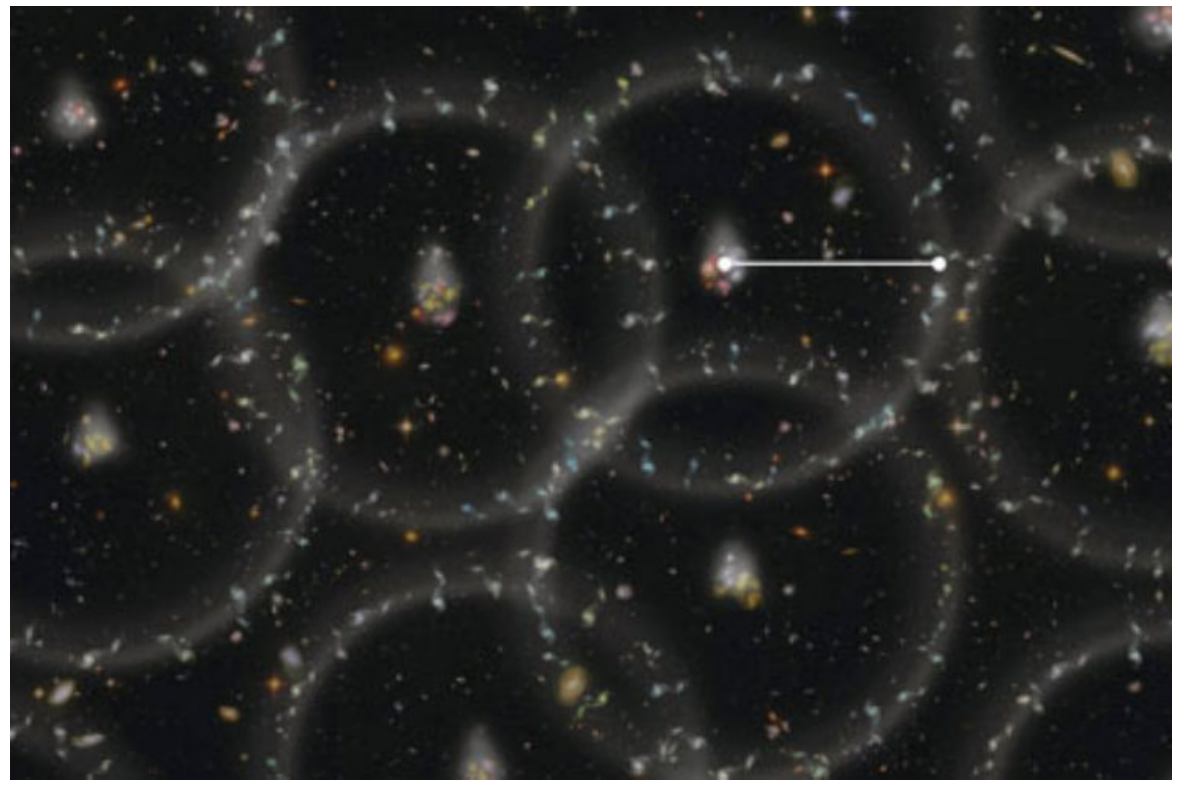
a) Compression

- **Summary Statistics**



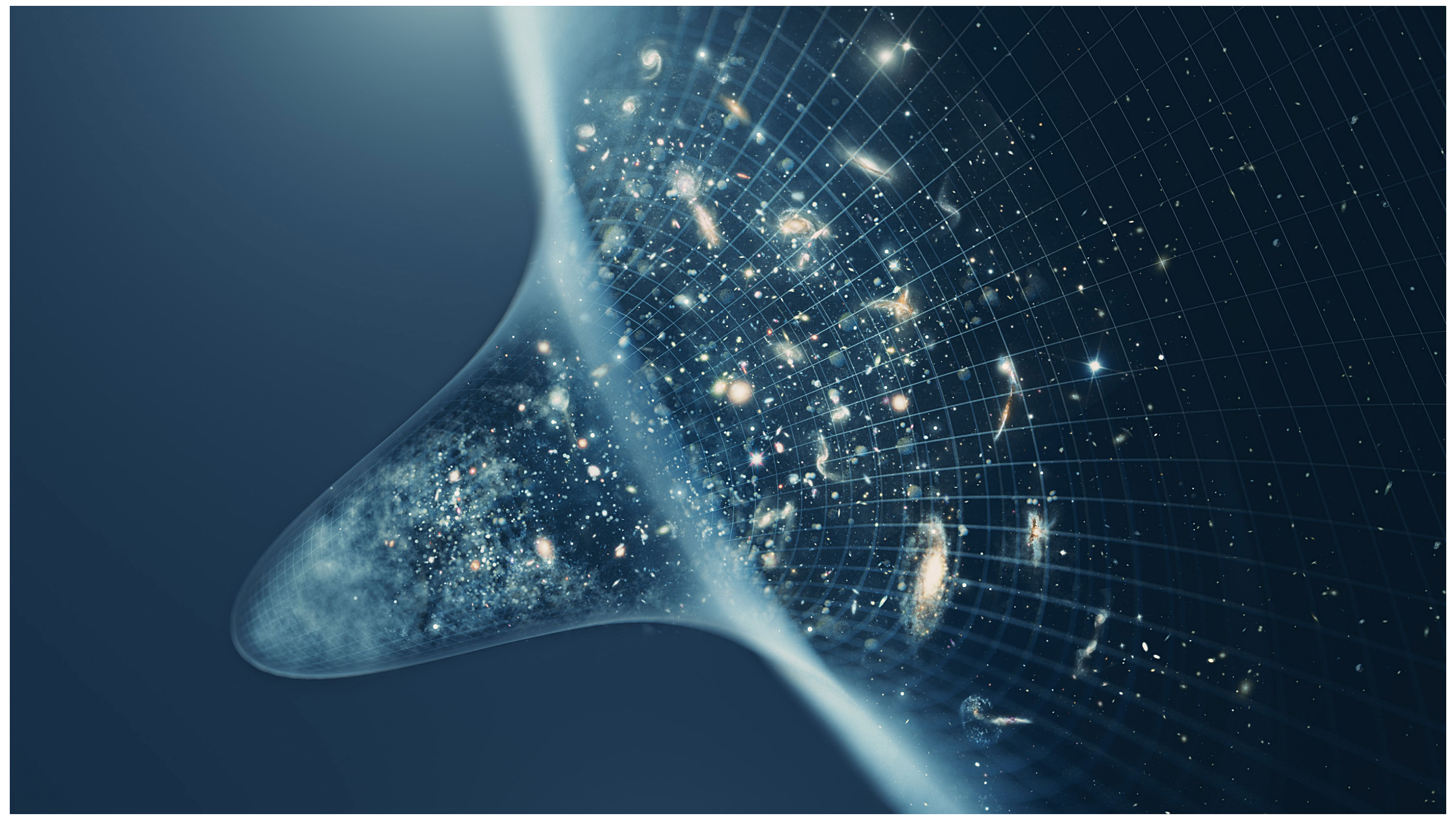
b) Identification of robust features

- **Features (BAO, RSD)**



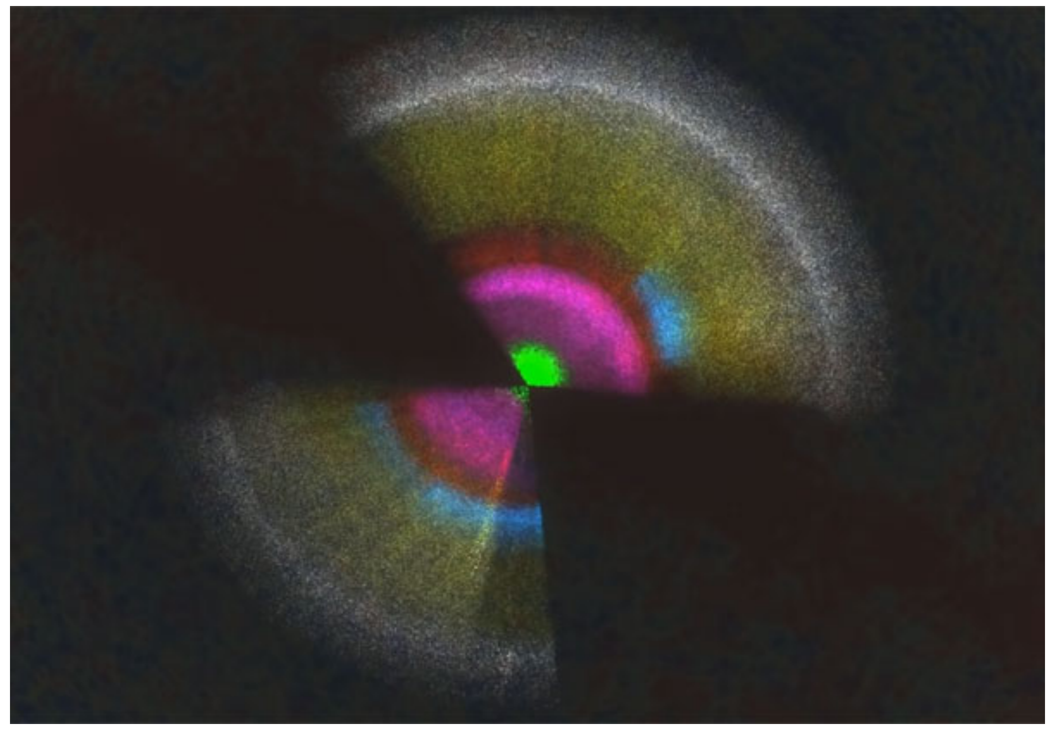
c) Interpretation

- **Cosmological parameters,**
  - ◉ **Dark Energy**
  - ◉ **Gravity**
  - ◉ **Inflation**



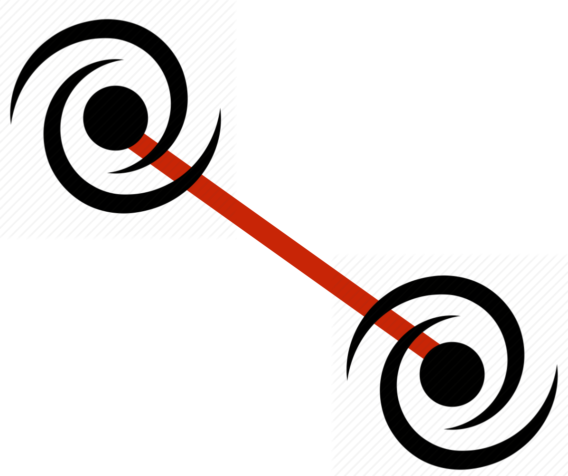
a) Compression: Summary statistics

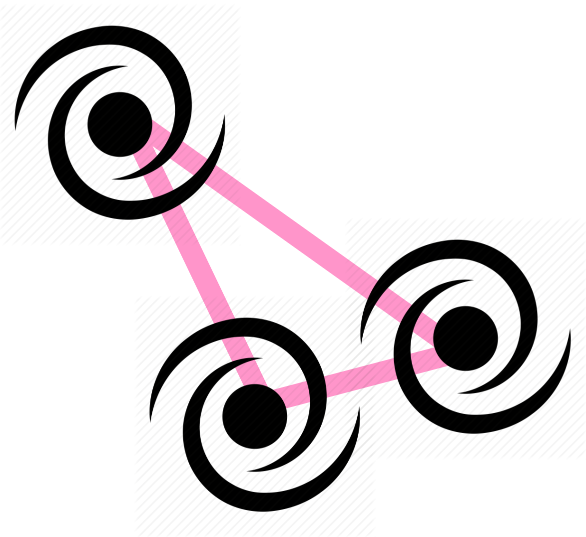
- **Galaxy Maps are non-deterministic**
- **Cosmological information described by n-point correlation functions.**

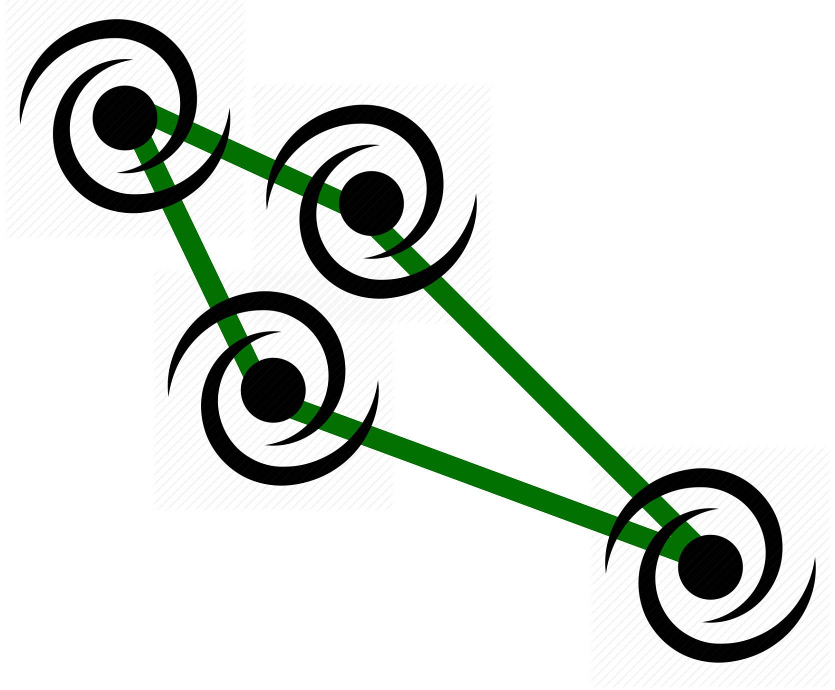


$$\equiv \quad \xi^{(2)}(\mathbf{r}) \oplus \xi^{(3)}(\mathbf{r}_1, \mathbf{r}_2) \oplus \xi^{(4)}(\mathbf{r}_1, \mathbf{r}_2, \ldots)$$

$$P(\mathbf{k}) \oplus B(\mathbf{k}_1, \mathbf{k}_2)^{*} \oplus T(\mathbf{k}_1, \mathbf{k}_2, \ldots)$$







State-of-the-art (this talk)

Higher-order functions

- **Estimator efficiency**
- **Complexity of the model**

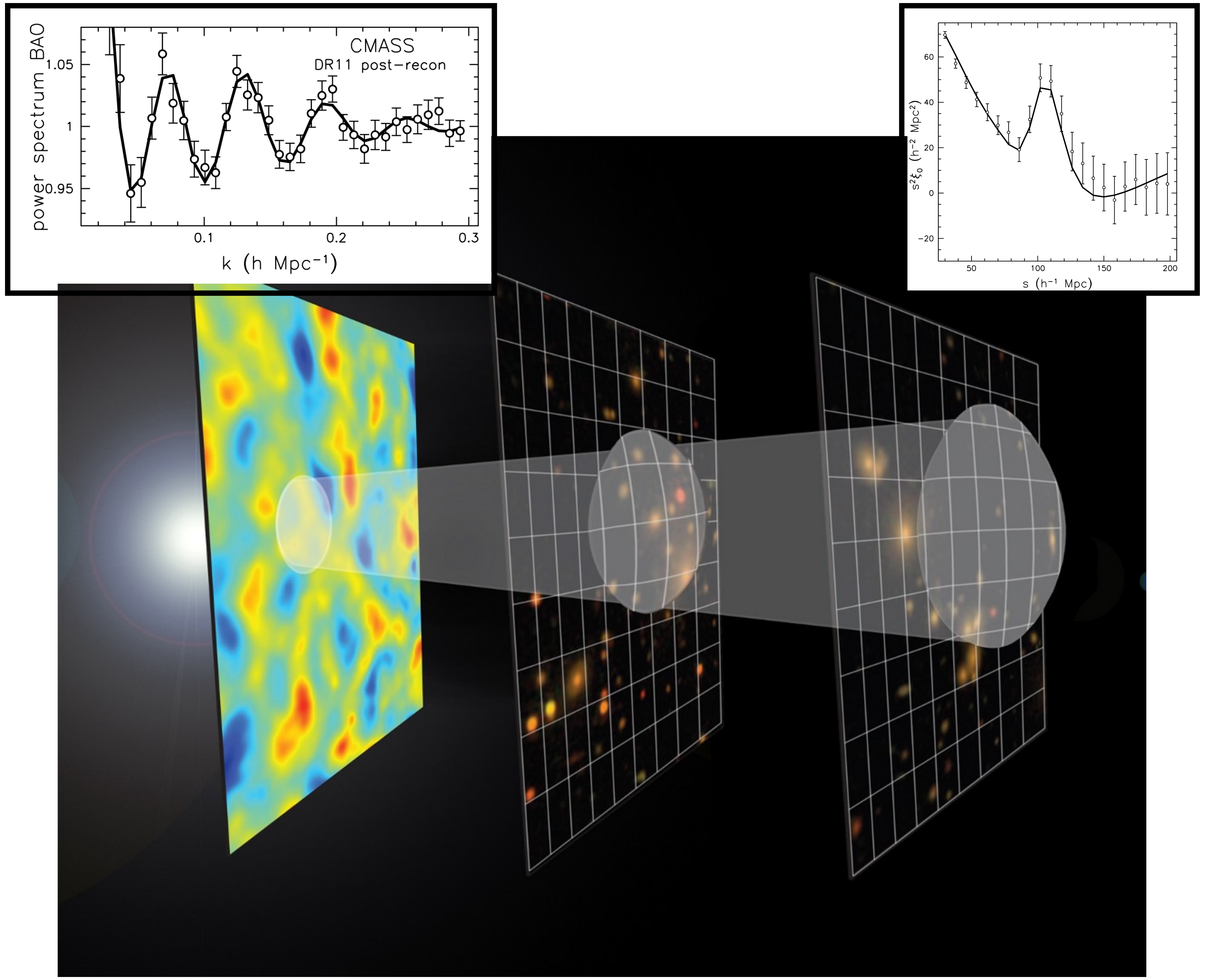
1. For Gaussian fields (like CMB) P(k) contains all relevant information

2. Galaxy field is strongly non-Gaussian due to gravity evolution (mode-coupling)

**for BOSS bispectrum measurements see Gil-Marín 2016*

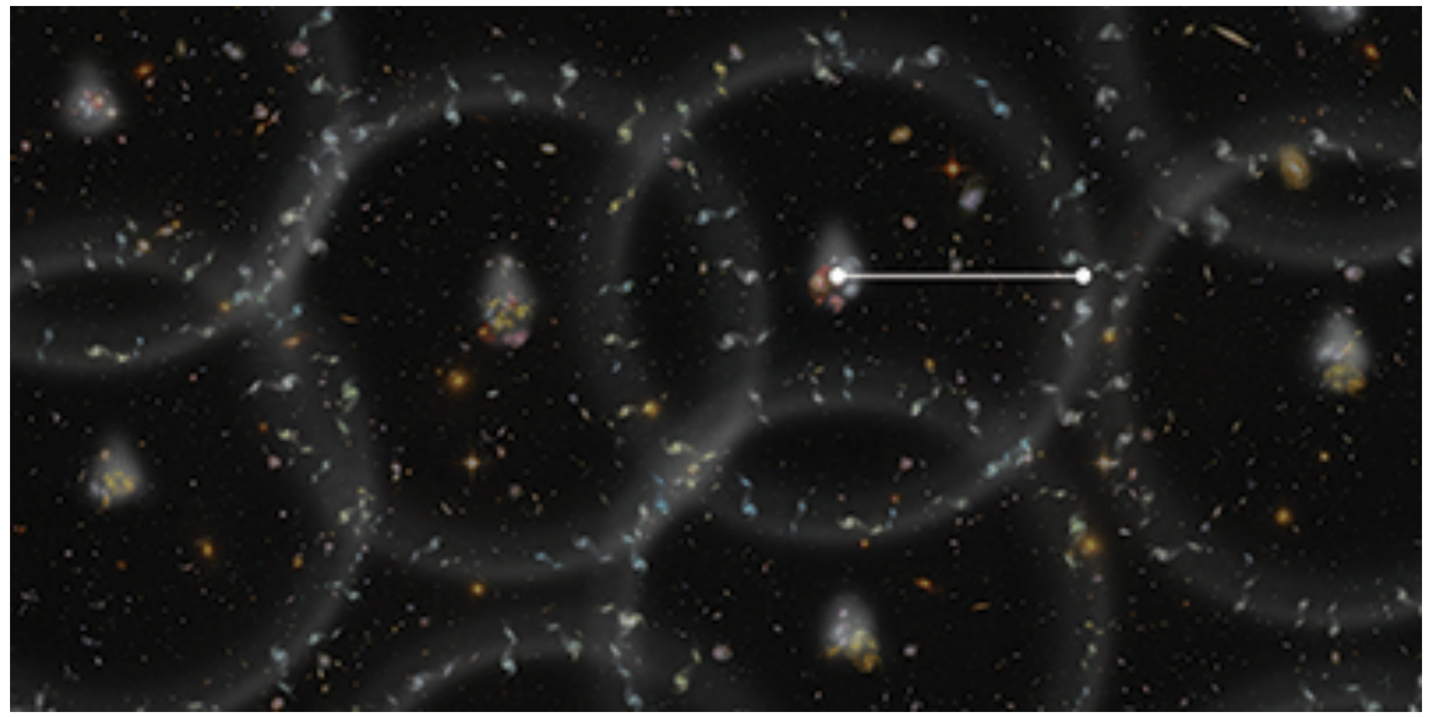
b) Robust features: BAO as standard ruler

Sound waves travelling in early-time plasma until decoupling → **Imprinted in CMB photons & baryonic and DM distribution**



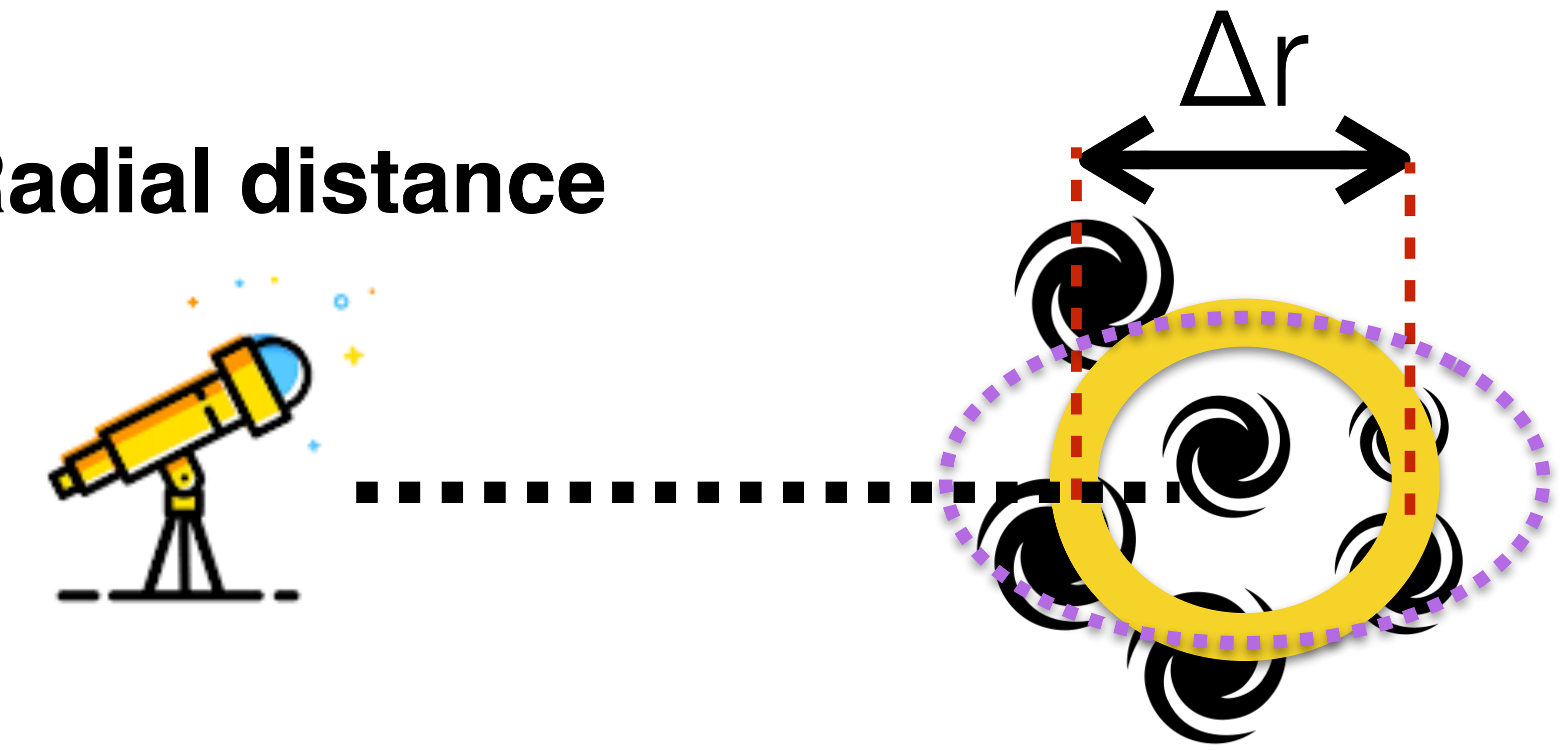
- Cleanest probe to measure expansion in the LSS
- Provides a direct measurement of the **expansion** along and across the line-of-sight given the horizon scale.
    - requires knowledge of the horizon scale at recombination times: r_d
    - uncalibrated BAO measures Ω_m

b) Robust features: BAO & AP

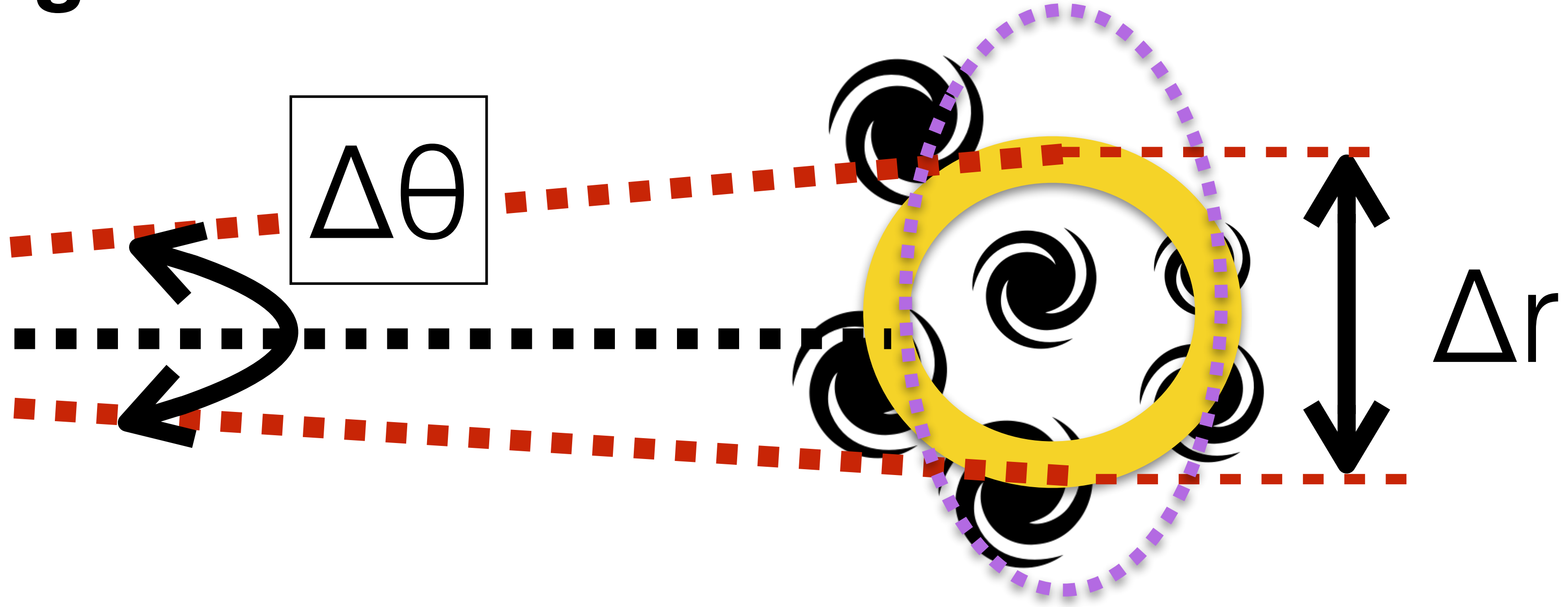


- Universe assumed **isotropic** and **homogeneous**
- **Alcock-Paczynski (AP) effect**: Anisotropy induced by transforming redshifts into coming distances assuming a *reference cosmology* (Alcock & Paczynski 1979)

Radial distance



Angular diameter distance



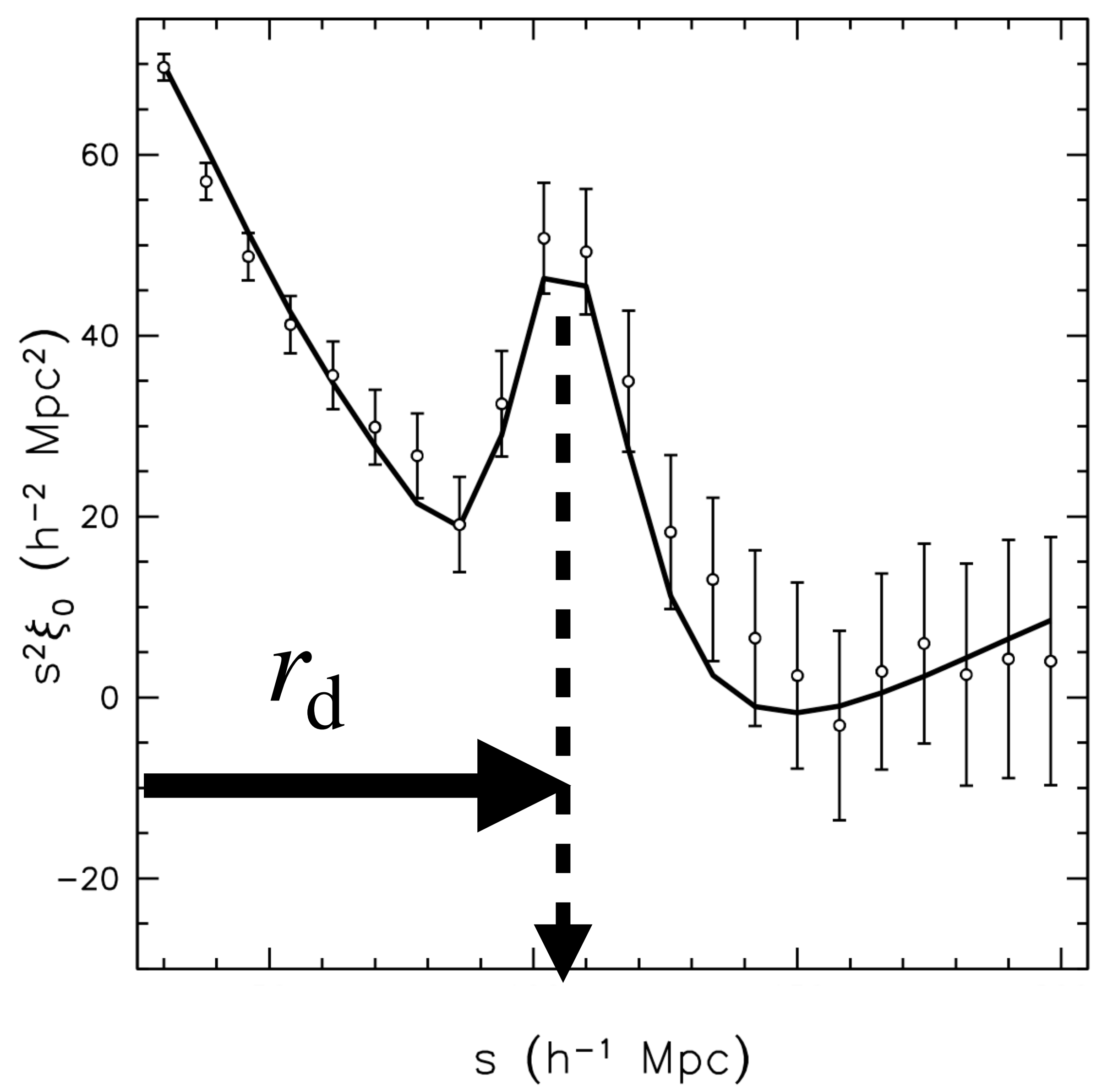
$$\Delta r_{\parallel}(z_1,z_2;\Omega_m)=\int_{z_1}^{z_2}\frac{c\,dz'}{H_0\sqrt{\Omega_m(1+z')^3+1-\Omega_m}}\approx\frac{c\Delta z}{H(\bar{z},\Omega_m)}\sim\frac{c}{H(z)}\equiv D_H(z)$$

$$\Delta r_{\perp}(\theta_1,\theta_2;z,\Omega_m)=\Delta\theta\int_0^z\frac{c\,dz'}{H(z',\Omega_m)}\sim D_M(z)$$

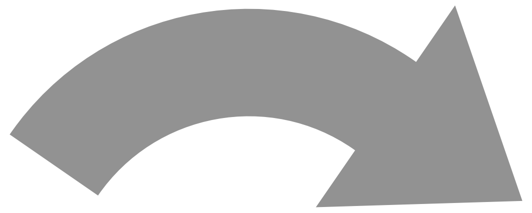
BAO provides a reference-structure for the AP effect

b) Robust features: horizon scale r_{drag}

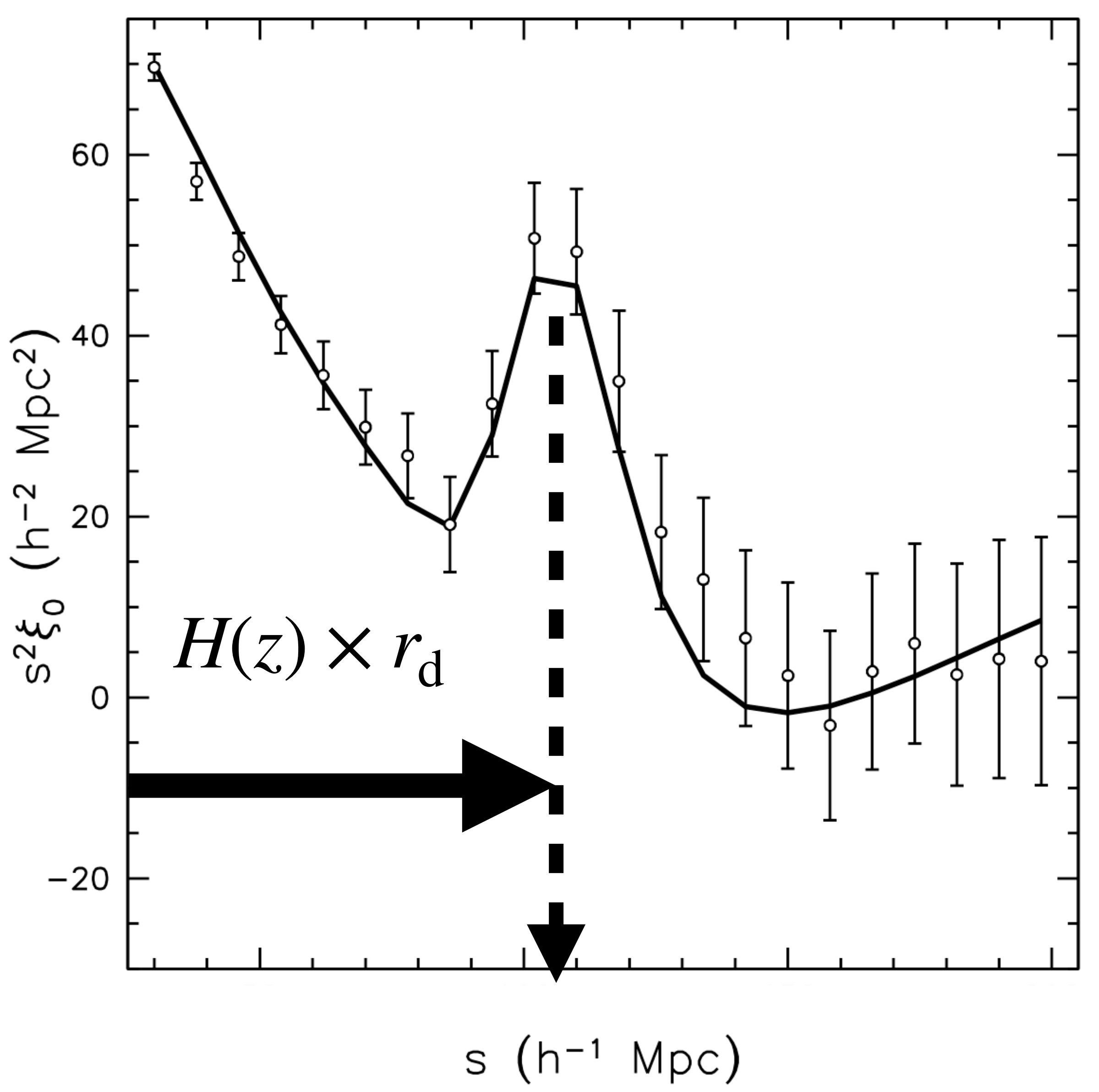
At recombination time



Expansion

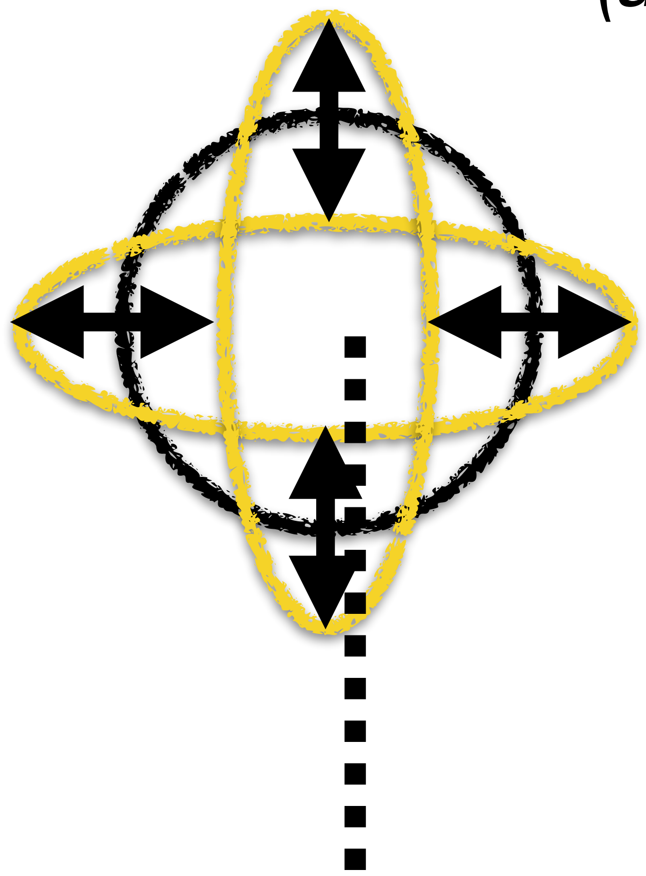


Galaxy surveys (late-time)



BAO-warping (AP)

(uncalibrated BAO)

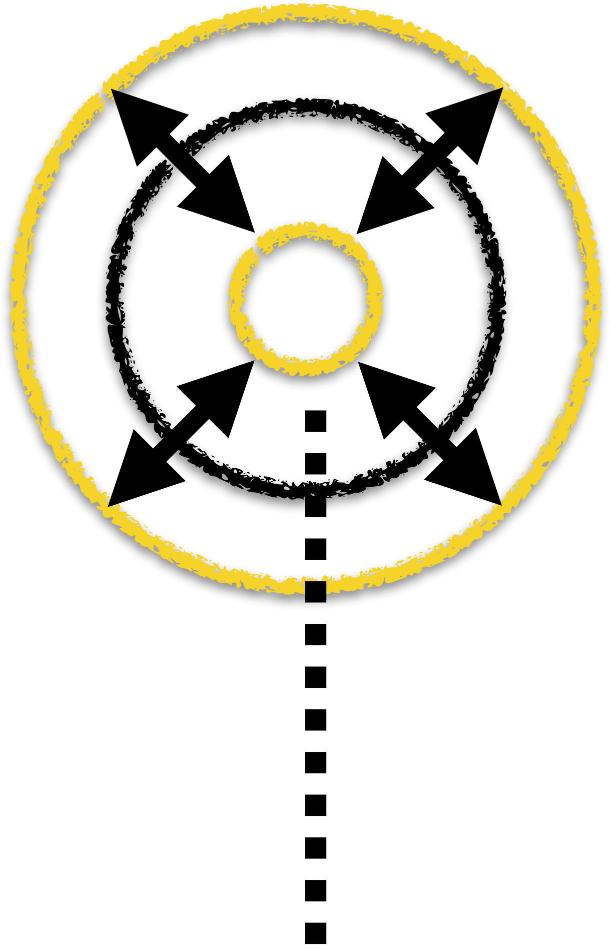


$\propto D_M(z)/D_H(z)$

↓

Ω_m

Isotropic dilation



$\propto [D_M^2(z)D_H(z)]^{1/3}/r_d$

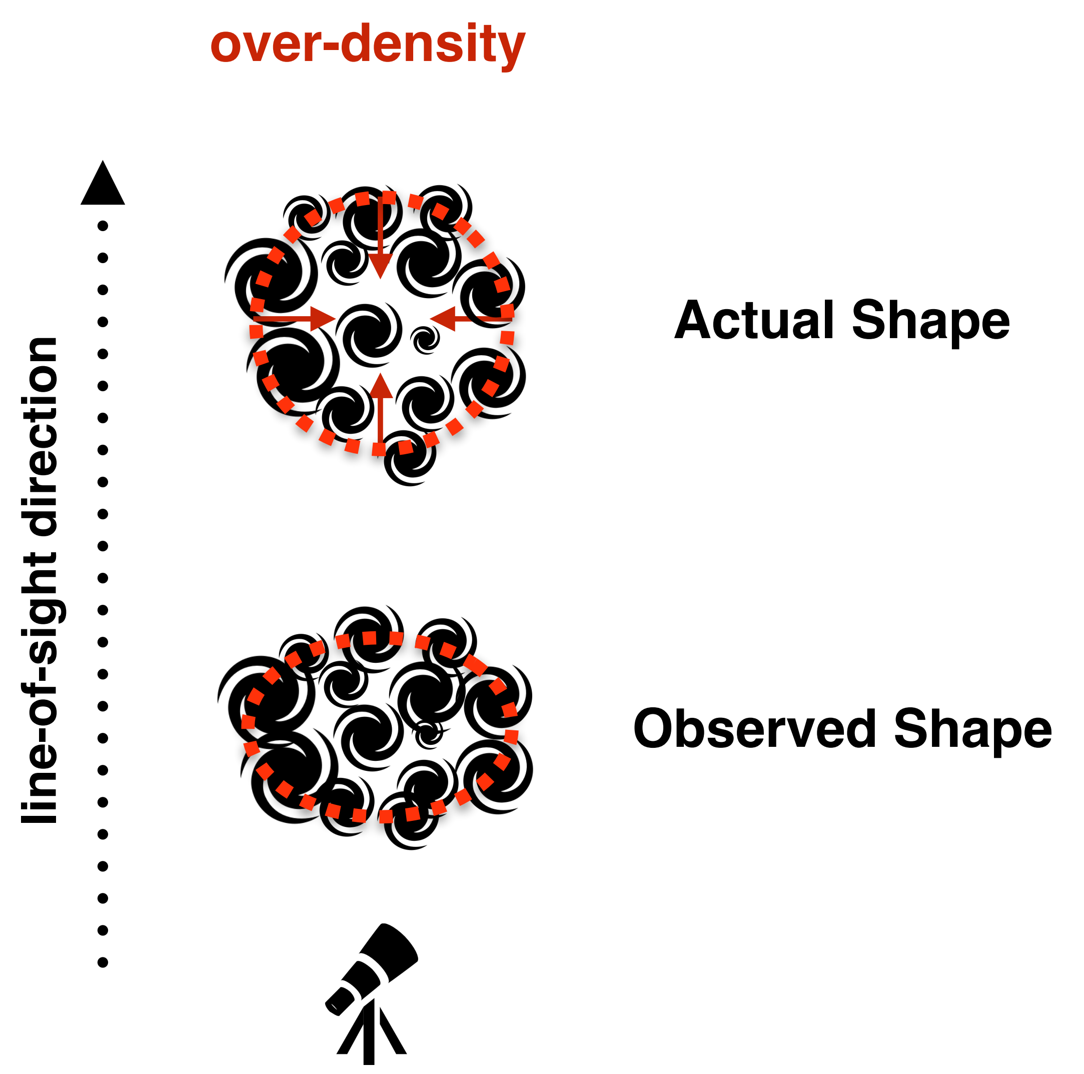
↓

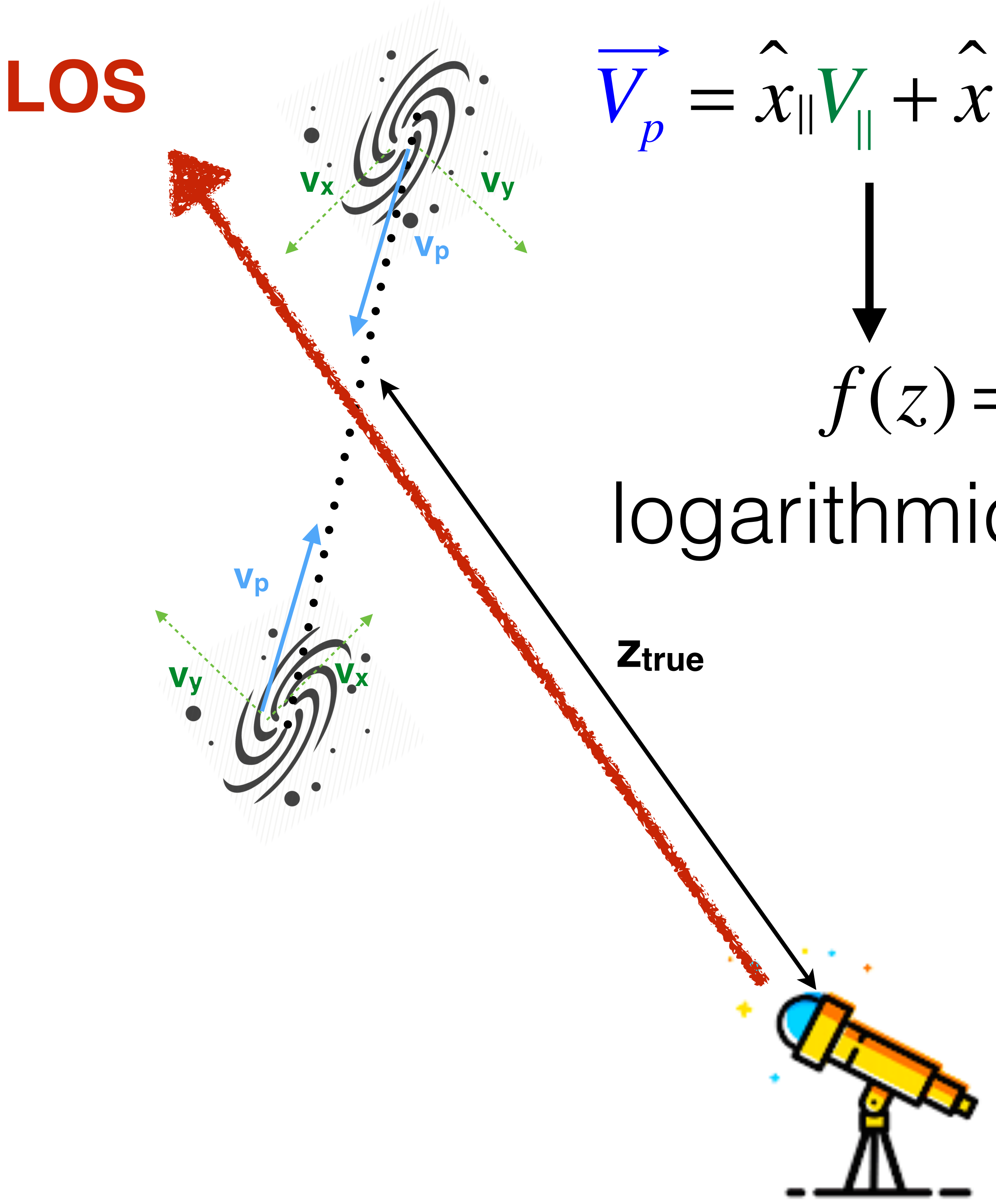
$H_0 \times r_d$

Under LCDM interpretation BAO in late-universe: $H_0 \times r_d$ & Ω_m

b) Robust features: RSD

- Universe assumed **isotropic** and **homogeneous**
- **Redshift Space Distortions (RSD)**: Enhancement / reduction of the clustering along the line-of-sight direction due to peculiar velocities (Kaiser 1987)





$$\vec{V}_p = \hat{x}_{\parallel} V_{\parallel} + \hat{x}_{\perp} V_{\perp}$$

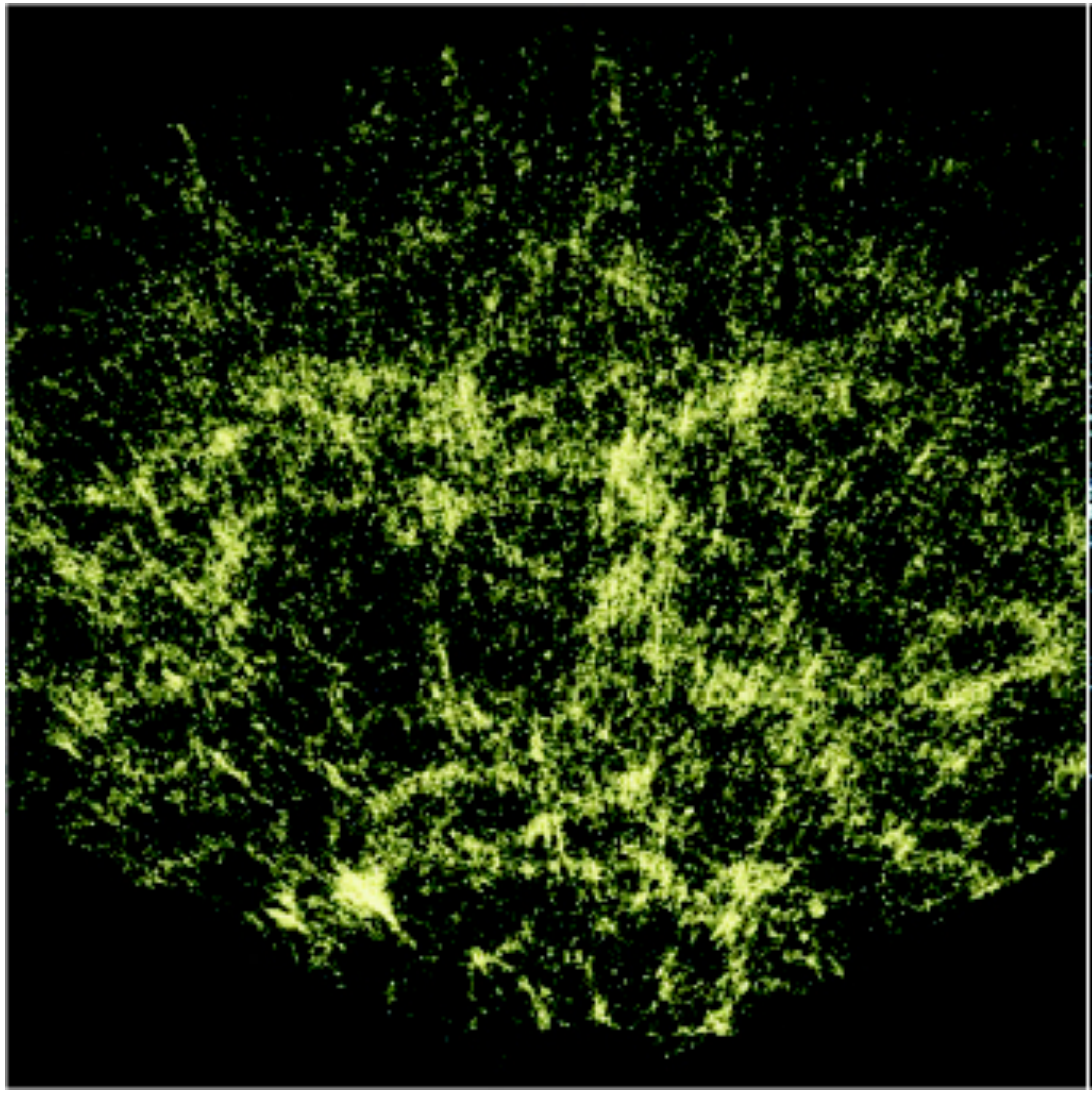
$$f(z) = \Omega_m(z)^{\gamma}$$

logarithmic growth of structure

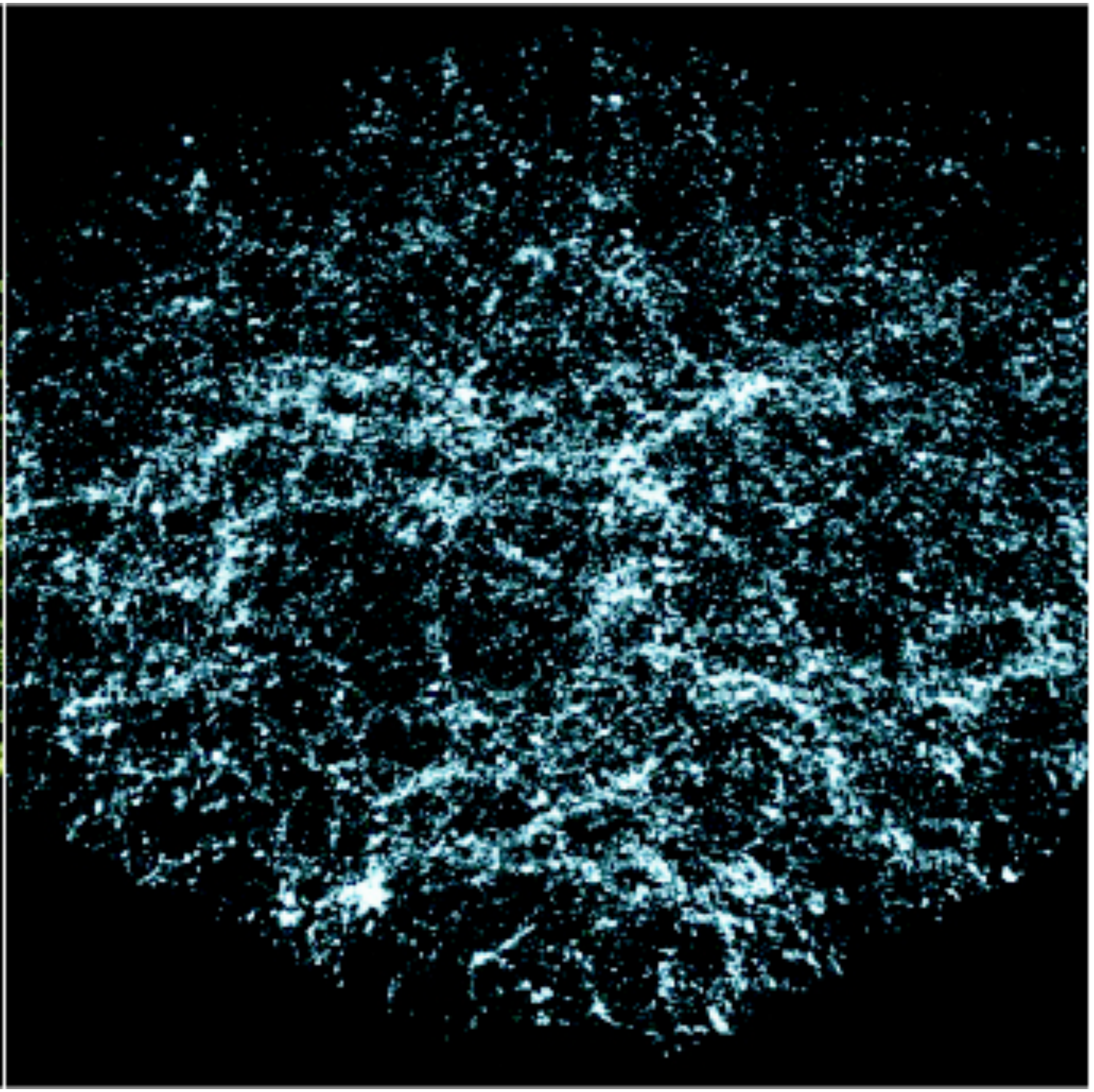
$$z_{obs} = z_{true} \oplus z_{pec} \equiv \left[(1+z_{true}) \times (1+z_{pec}) \right] - 1$$

1. Hubble flow
2. Coherent with growth of structure

Observed ‘redshift' space



True ‘real’ space



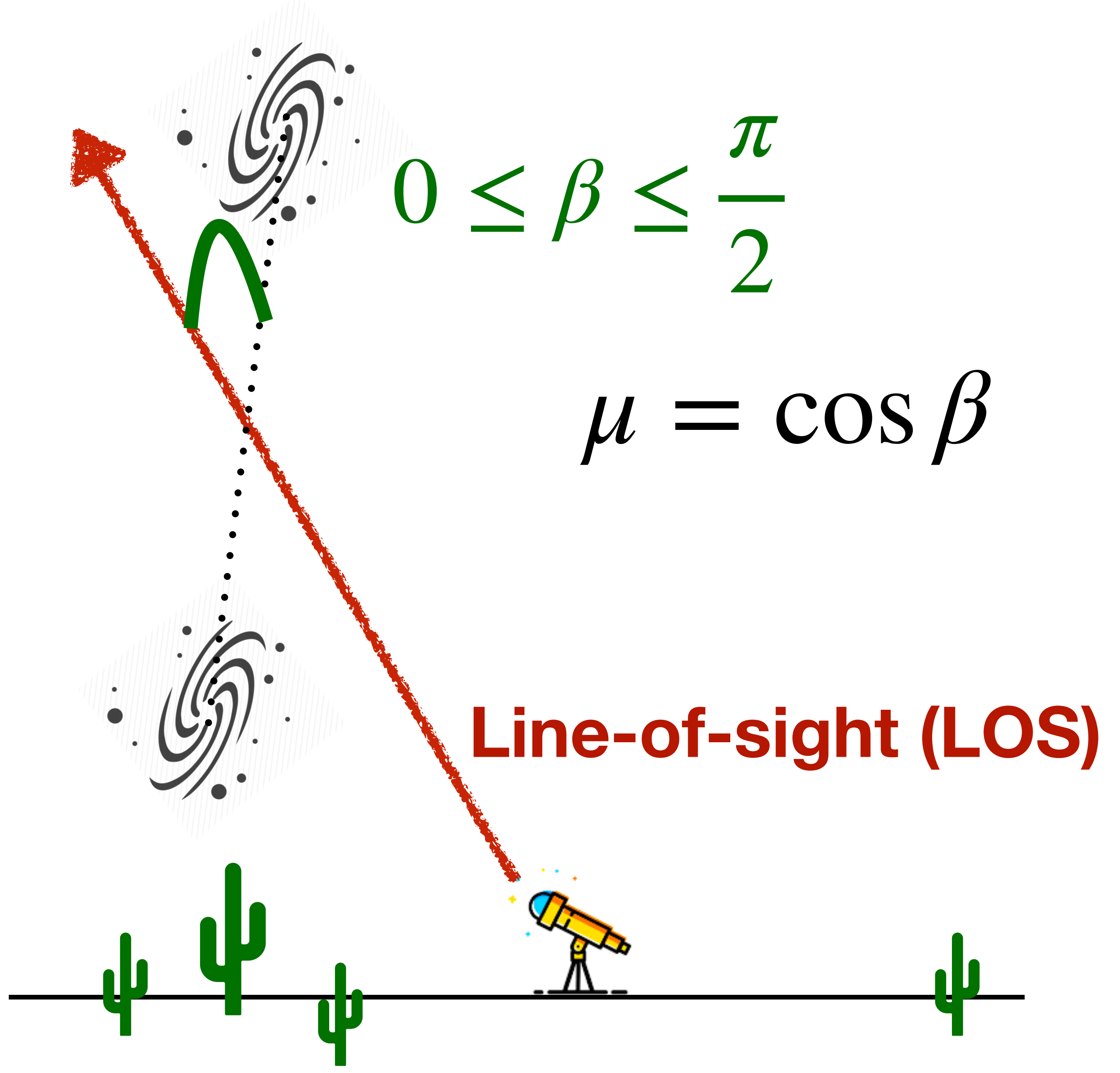
b) Robust features: Kaiser toy model

$$P_g^{(s)}(k,\mu) = \left[b + f\mu^2\right]^2 P_m(k) \longrightarrow$$ Kaiser linear term

$$P^{(s)}(k,\mu) = P^{(0)}(k)L_0(\mu) + P^{(2)}(k)L_2(\mu) + P^{(4)}(k)L_4(\mu)$$

monopole — Isotropic signal

quadrupole, hexadecapole — Anisotropic signal



$$P^{(0)}(k,z) = \left(b(z)^2 + \frac{2}{3}b(z)f(z) + \frac{1}{5}f(z)^2\right)P_m(k,z)$$

$$P^{(2)}(k,z) = \left(\frac{4}{3}b(z)f(z) + \frac{4}{7}f(z)^2\right)P_m(k,z)$$

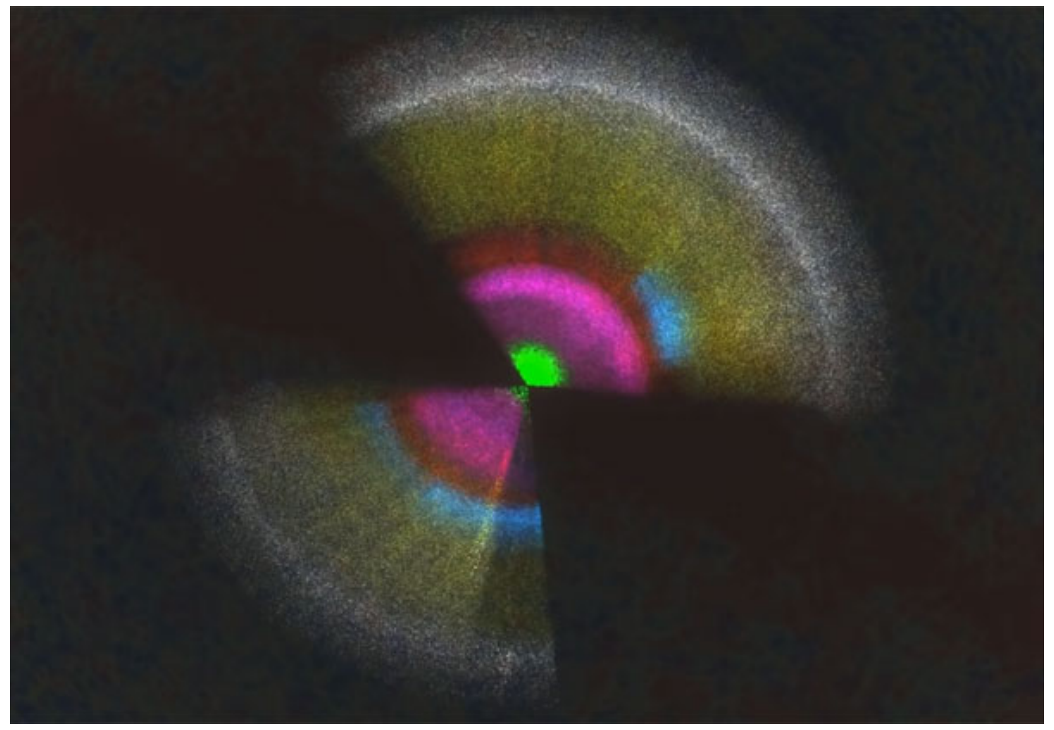
$$P^{(4)}(k,z) = \left(\frac{8}{35}f(z)^2\right)P_m(k,z)$$

$\longrightarrow$ $P_m(k,z) \equiv \sigma_8(z)P_m(k,z=0)$

$f(z)\times\sigma_8(z)$ & $b(z)\times\sigma_8(z)$

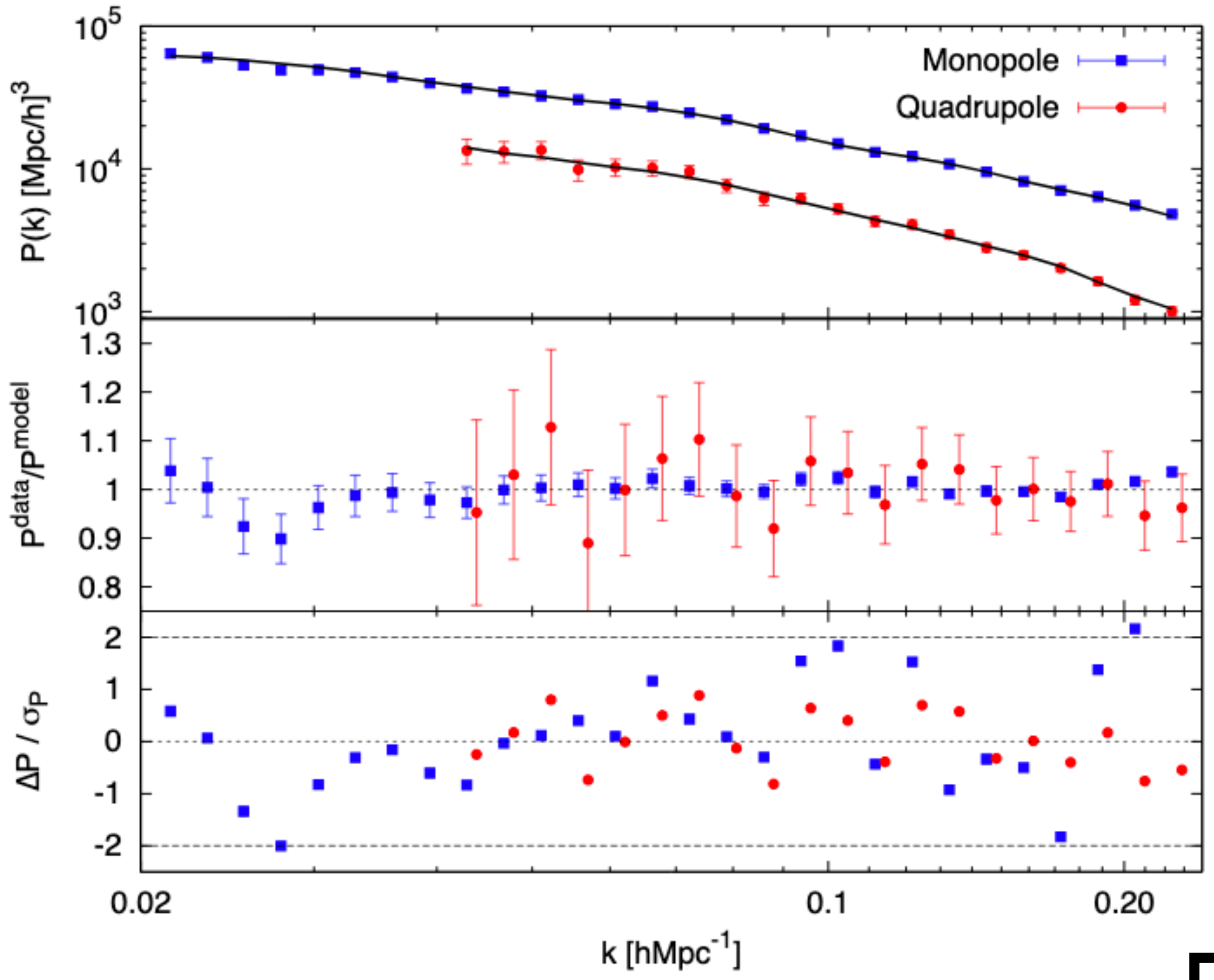
Spectroscopic surveys: **information content**

- **LSS Galaxy Maps**



a) Compression

- **Summary Statistics**



b) Identification of robust features

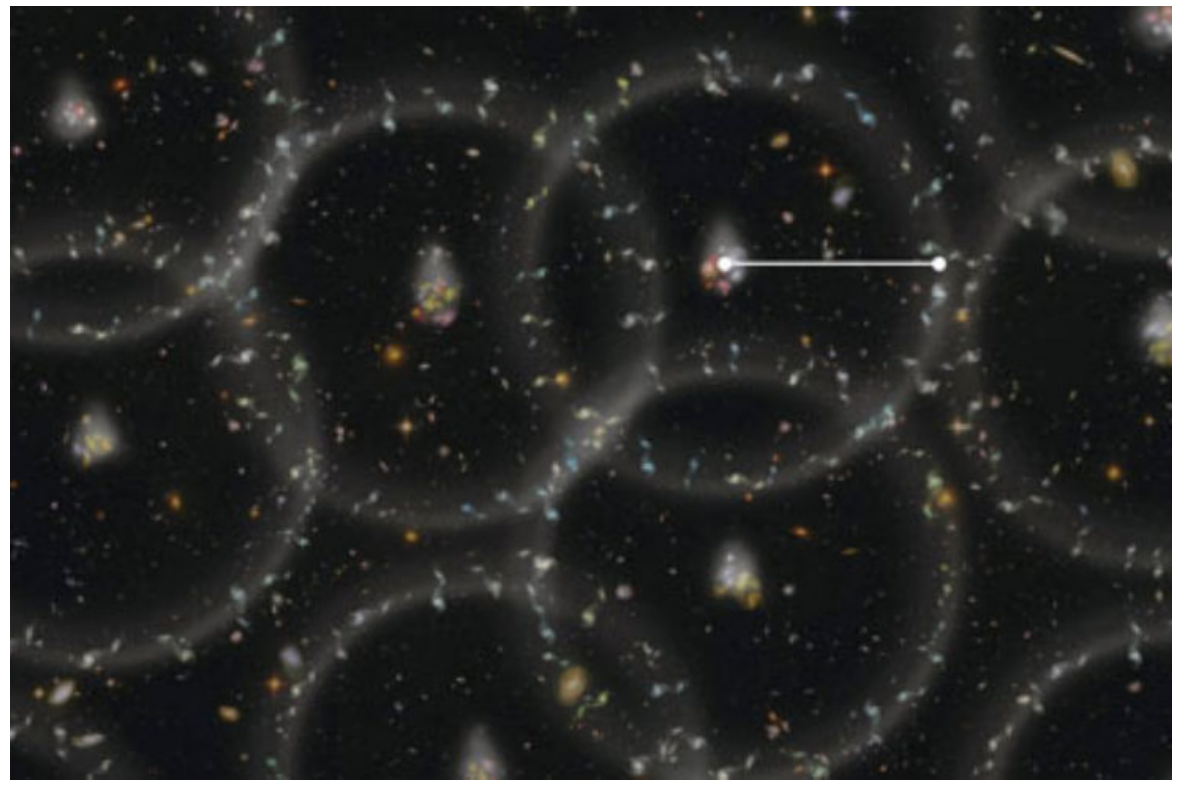
Compressed set of parameters

$$D_H(z, \mathbf{\Omega})/r_{\rm drag} = \frac{c}{H(z, \mathbf{\Omega}) r_{\rm drag}}$$

$$D_M(z, \mathbf{\Omega})/r_{\rm drag} = \int_0^z \frac{c dz'}{H(z', \mathbf{\Omega}) r_{\rm drag}}$$

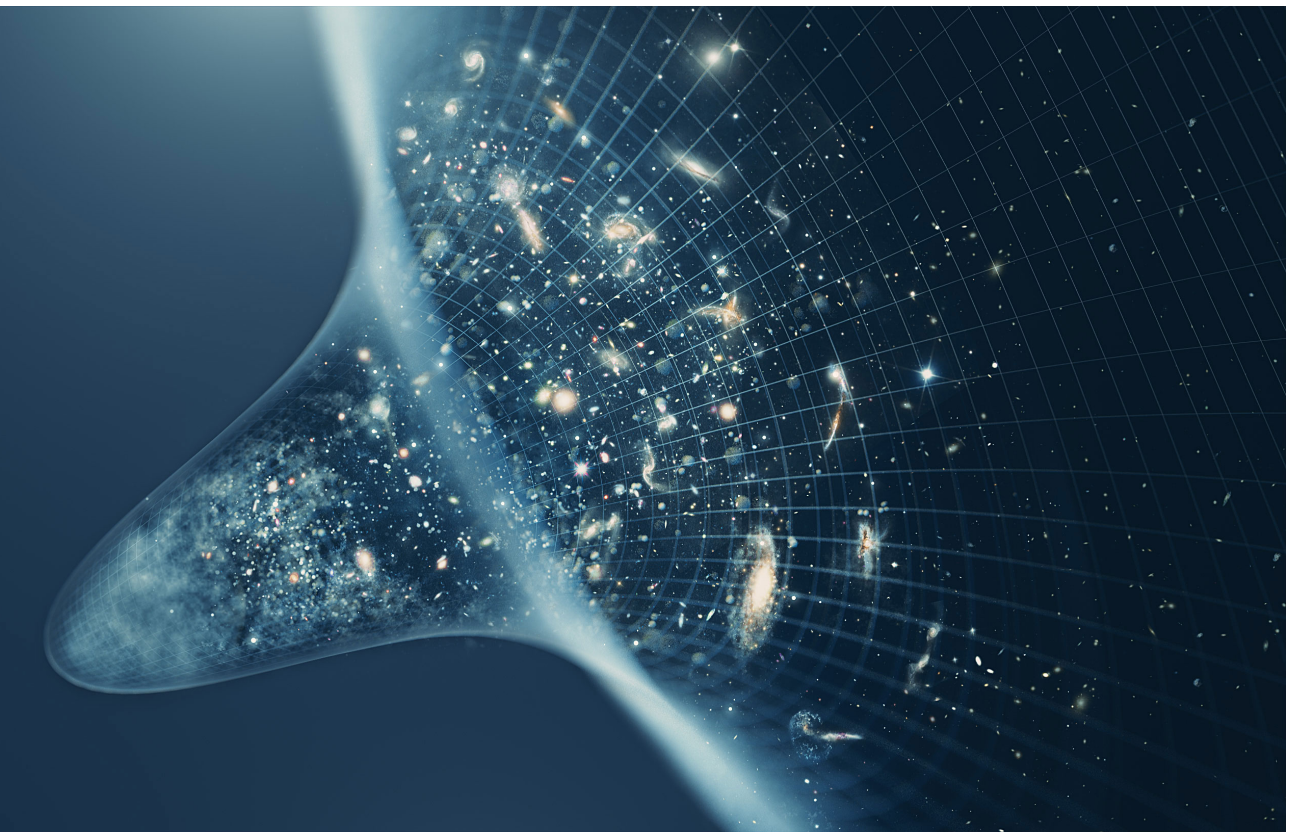
$$f\sigma_8(z, \mathbf{\Omega}) = \Omega_m(z, \mathbf{\Omega})^\gamma \sigma_8(z)$$

- **Features (BAO, RSD)**

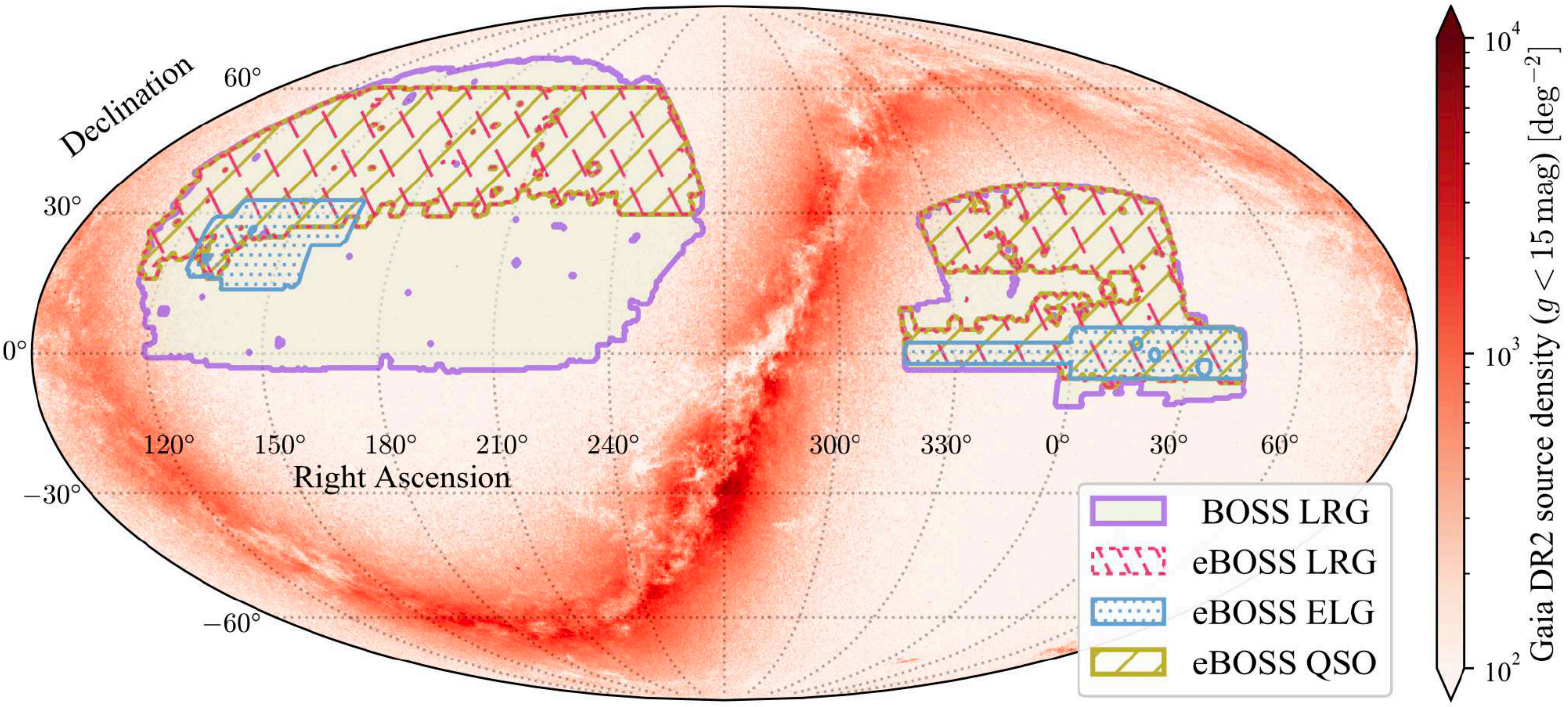


c) Interpretation

- **Cosmological parameters**
- **Gravity**
- **Inflation**



BOSS & eBOSS



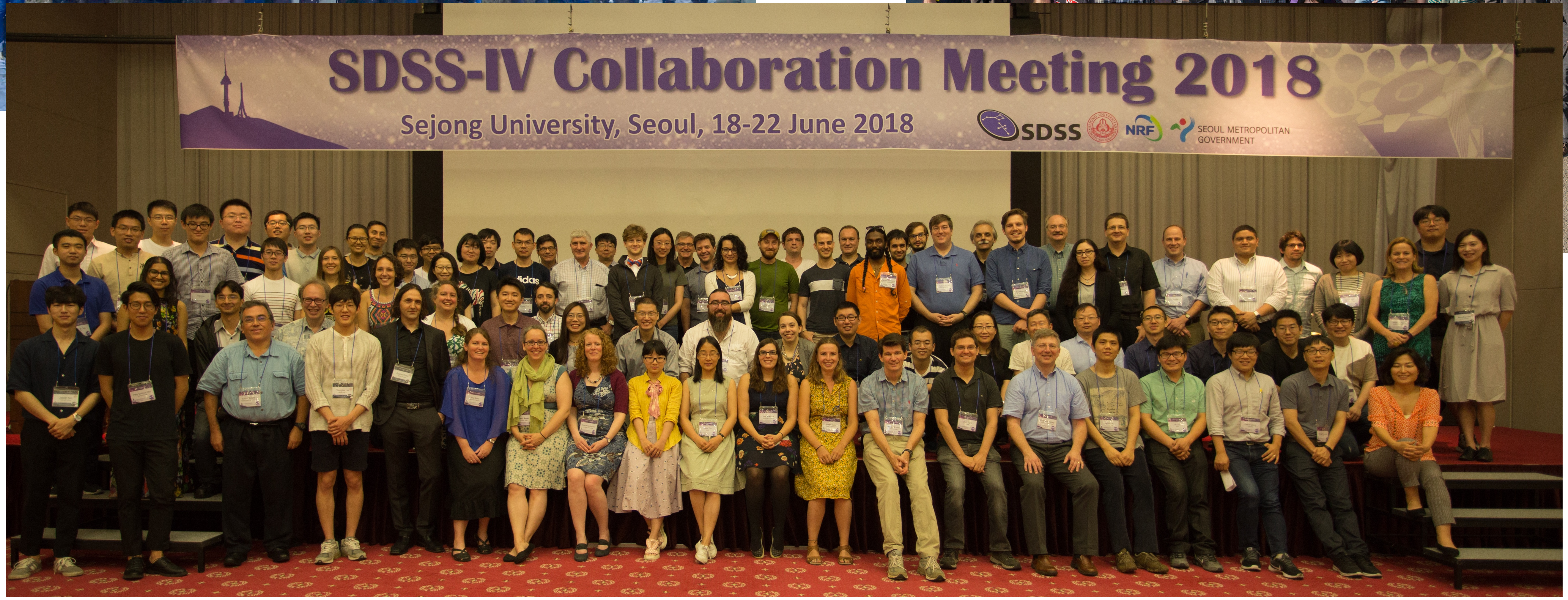
Credit: C. Zhao et al. 2020

Catalogue	Range	Objects
MGS	0.07<z<0.2	63k
LRG	0.2<z<0.5	604k
LRG	0.4<z<0.6	686k
LRG	0.6<z<1.0	377k
ELG	0.6<z<1.1	173k
Quasars	0.8<z<2.2	343k
Ly-α	0.9<z<3.5	551k
Total	0.07<z<3.5	>2M

BOSS & eBOSS

eBOSS meeting 2018, München

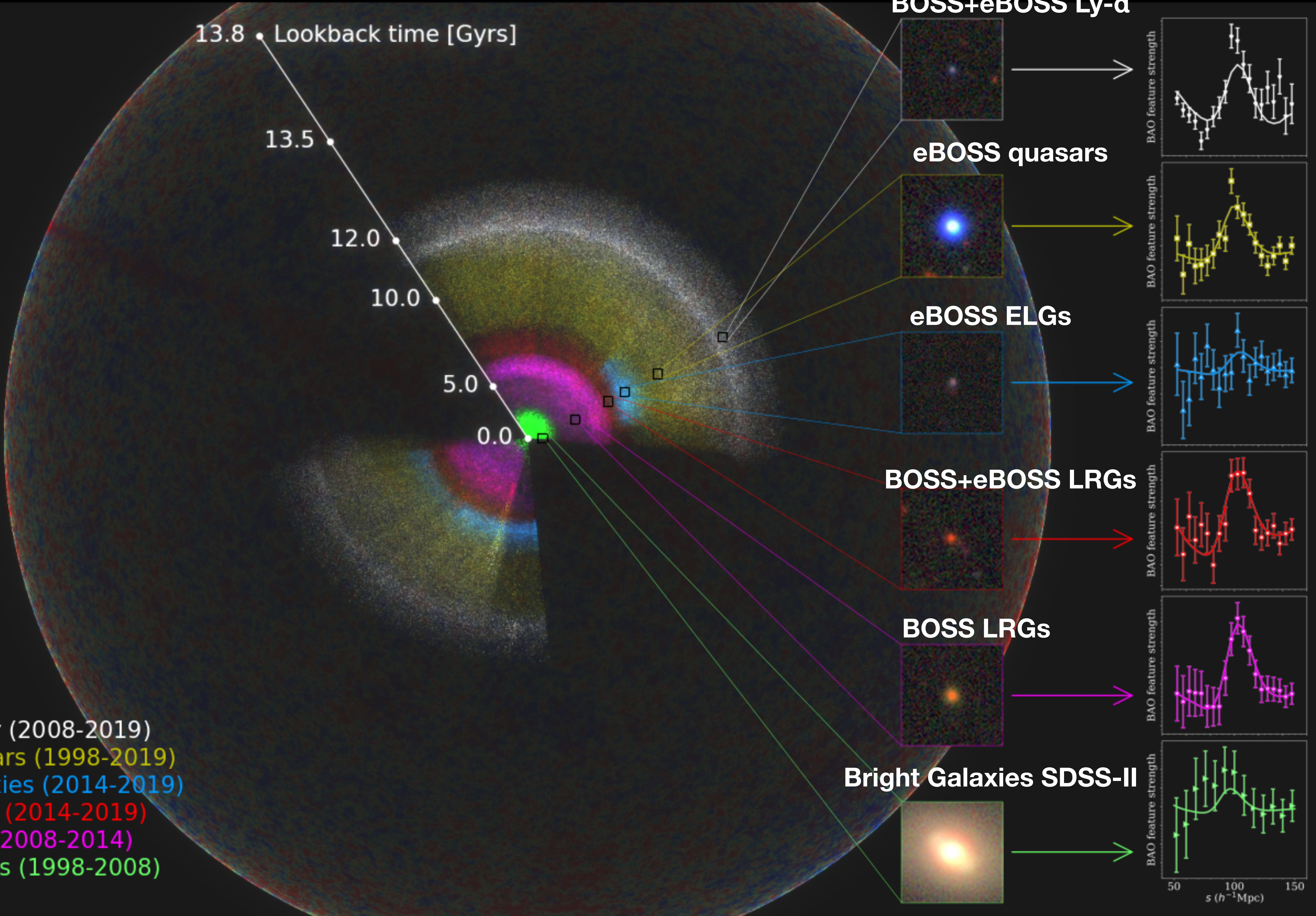
BOSS meeting 2013, Berkeley



SDSS-IV meeting 2018, Seoul

SDSS

See animation [here]



eBOSS + BOSS Lyman-α (2008-2019)
eBOSS + SDSS I-II Quasars (1998-2019)
eBOSS Young Blue Galaxies (2014-2019)
eBOSS Old Red Galaxies (2014-2019)
BOSS Old Red Galaxies (2008-2014)
SDSS I-II Nearby Galaxies (1998-2008)

Credit A. Raichoor

References

20 eBOSS papers submitted

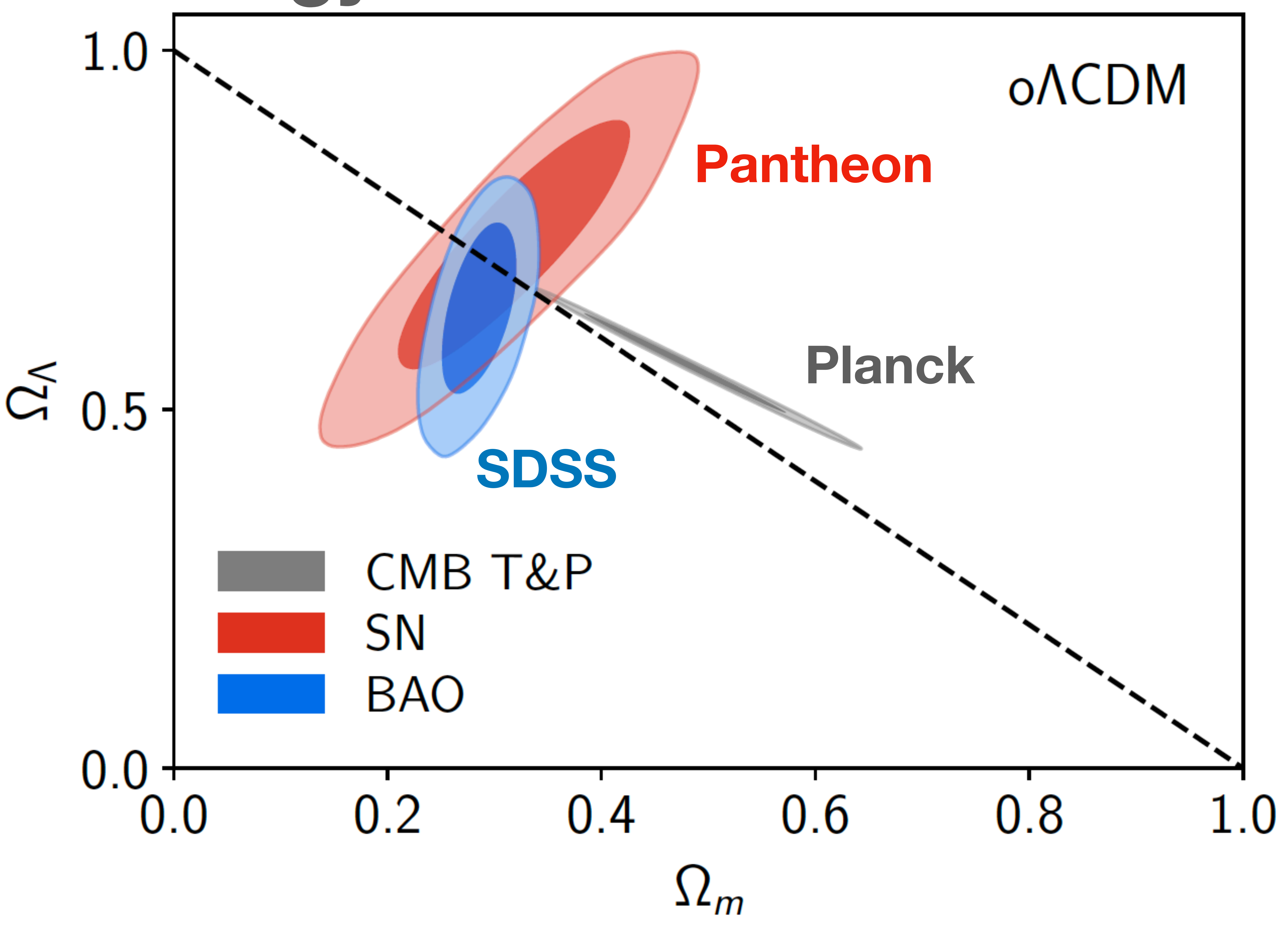
- Cosmology interpretation: eBOSS collaboration et al.
- Catalogues: Ross et al. (LRG & QSO), Raichoor et al. (ELG)
- LRG BAO & RSD: Bautista et al. (Config.), Gil-Marín et al. (Fourier)
- ELG BAO & RSD: Tamone et al. (Config.), de Mattia et al. (Fourier)
- QSO BAO & RSD: Hou et al. (Config.), Neveux et al. (Fourier)
- Ly-α BAO: du Mas des Bourboux et al. (Config.)
- Fast-mocks: Zhao et al. (EZmocks), Sicheng et al. (GLAM-QPM)
- Mock challenges: Rossi et al. (LRG), Smith et al. (QSO), Alam et al. (ELG), Ávila et al. (ELG)
- Other: Zhao et al. (Multi-tracer), Aubert et al. (Voids), Nadathur et al. (Voids), Mohammad et al. (PIP weights)

0.2<z<0.5 **0.4<z<0.6** **0.6<z<1.0** **0.6<z<1.1** **0.8<z<2.2**

c) Interpretation: Dark Energy

(eBOSS Collaboration, 2020)

- 3 independent probes for Λ
- Unfair advantage of BAO: several redshift bins
- BAO tell us about flatness
  - BAO+CMB (Planck or other) tell us Ω_k=0



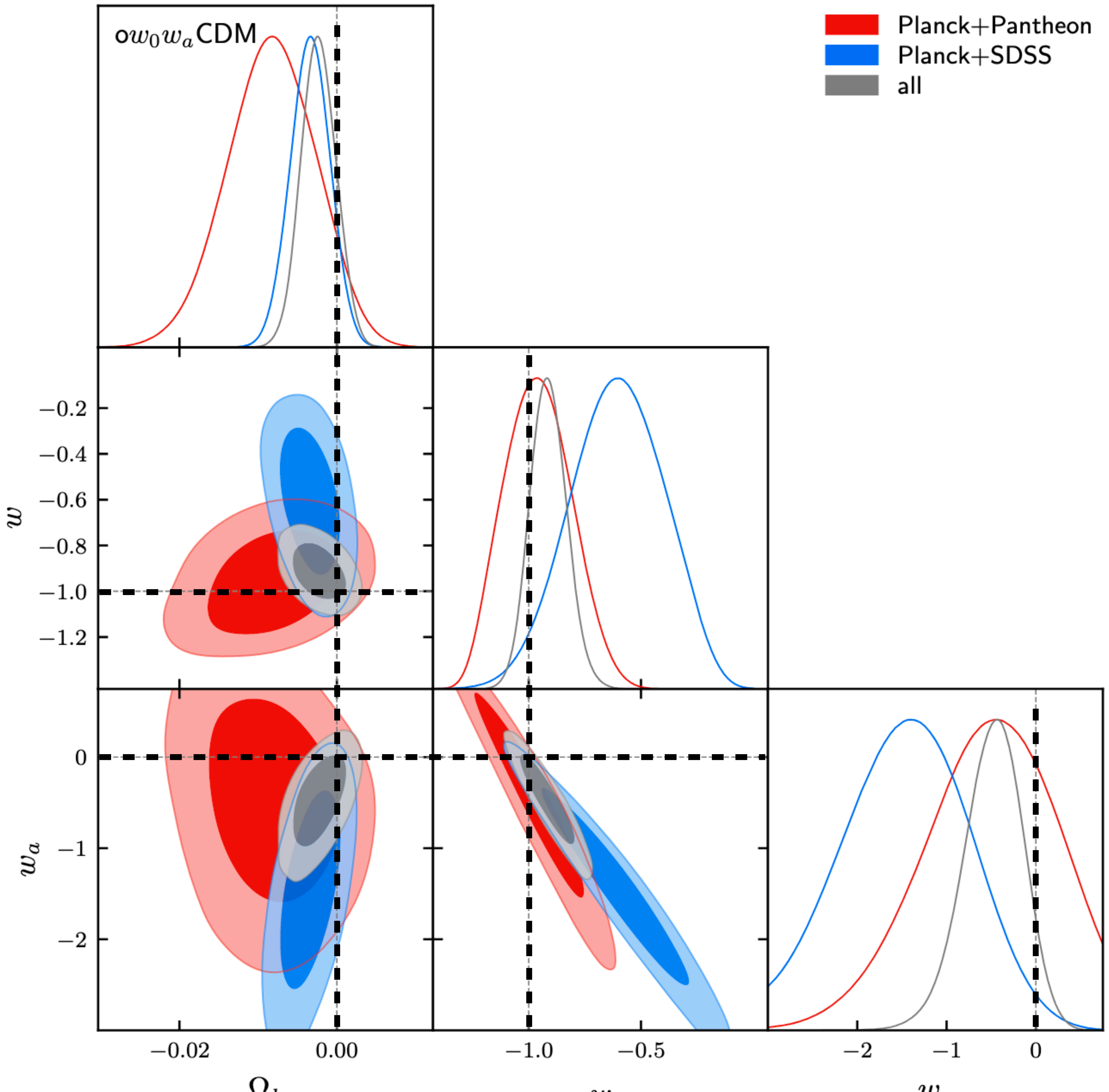
c) Interpretation: ω-ωa-Ωk

- Good agreement with LCDM
- DE consistent with cosmological constant
- Complementarity between BAO/RSD, SN and CMB

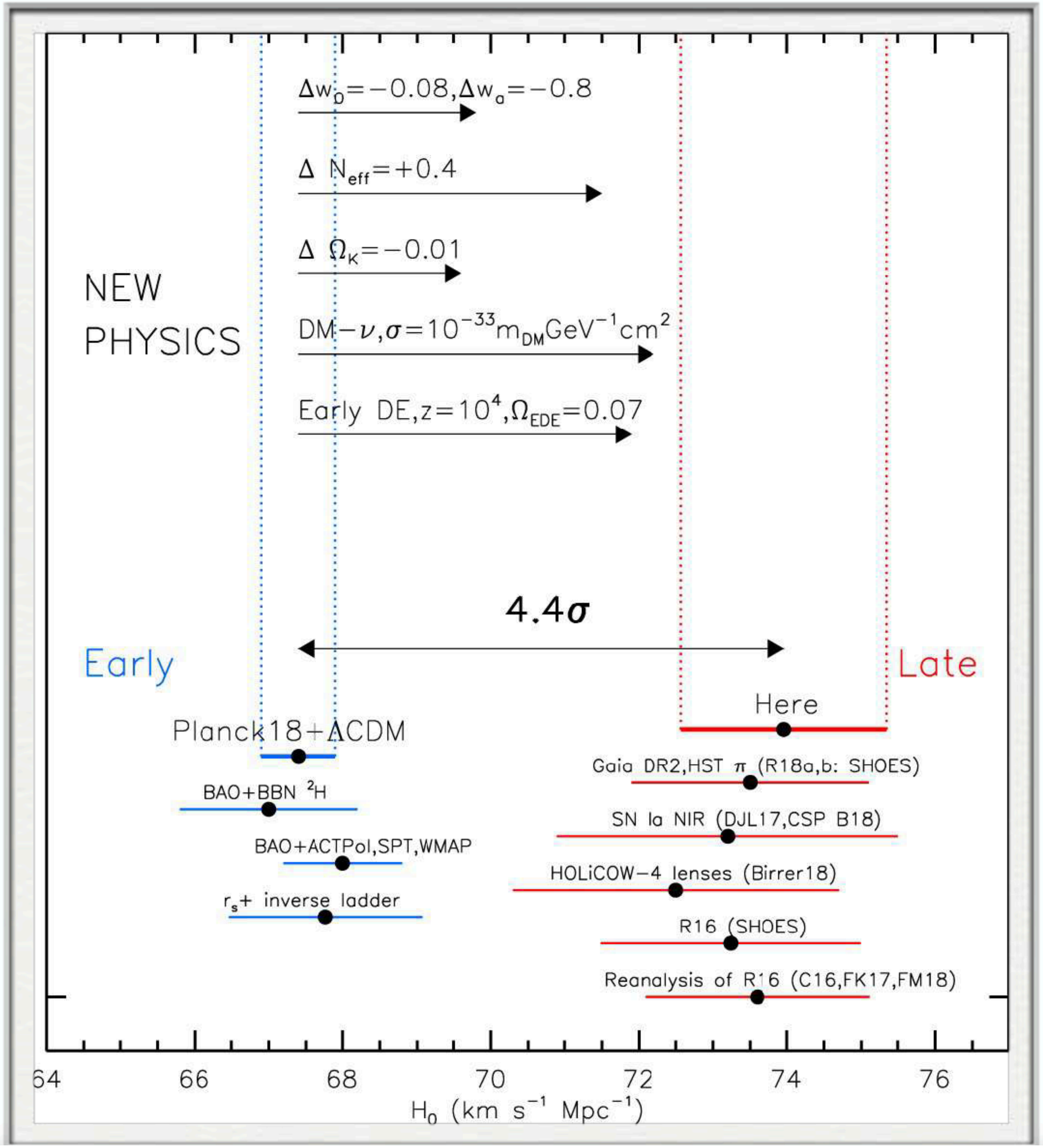
time evolving

$$\omega(a) = \omega_0 + \omega_a(1 - a)$$

constant



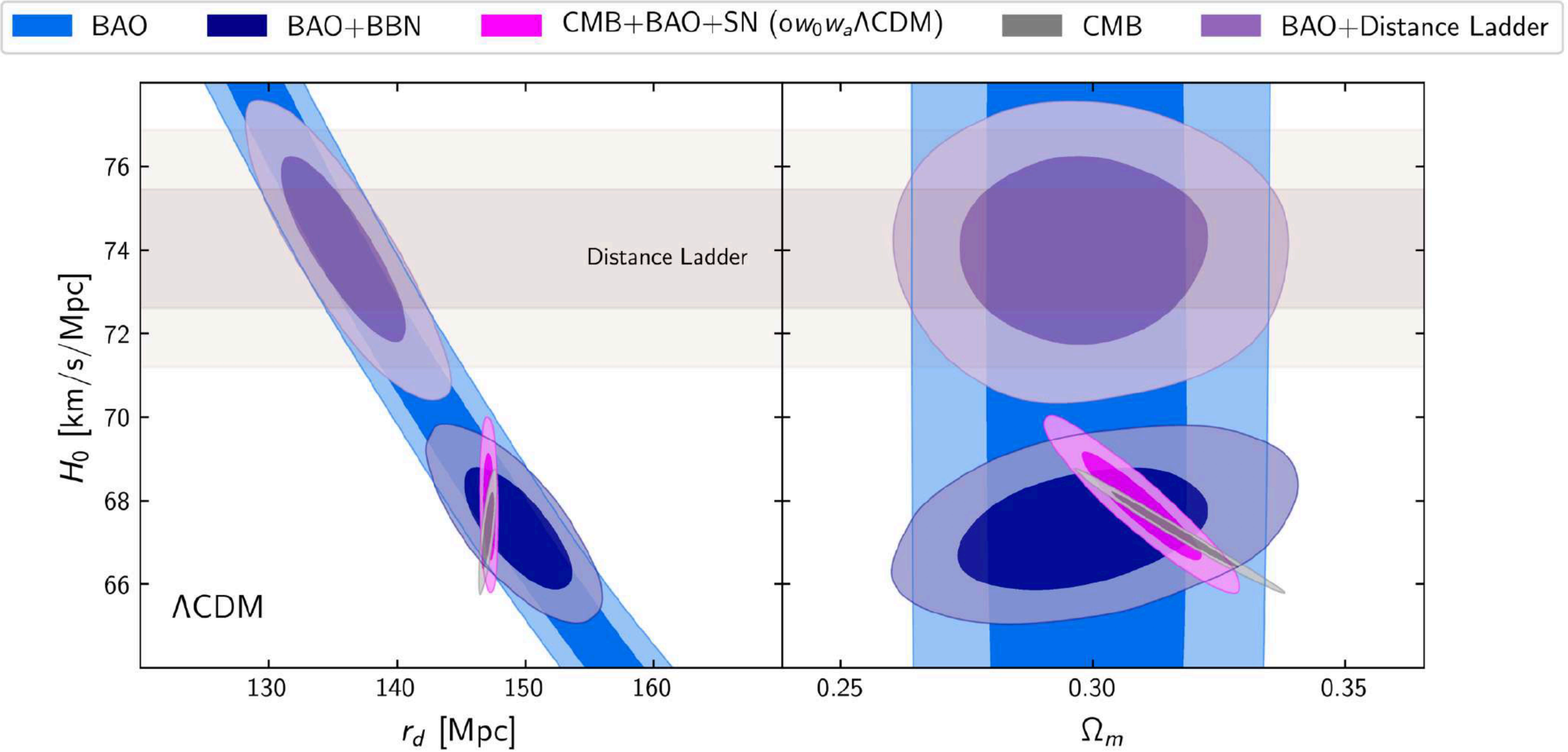
c) Interpretation: H_0



See Vivian's talk

Riess et al. 2019

(inverse distance lader)



Credit: Eva-Maria Müller & SDSS

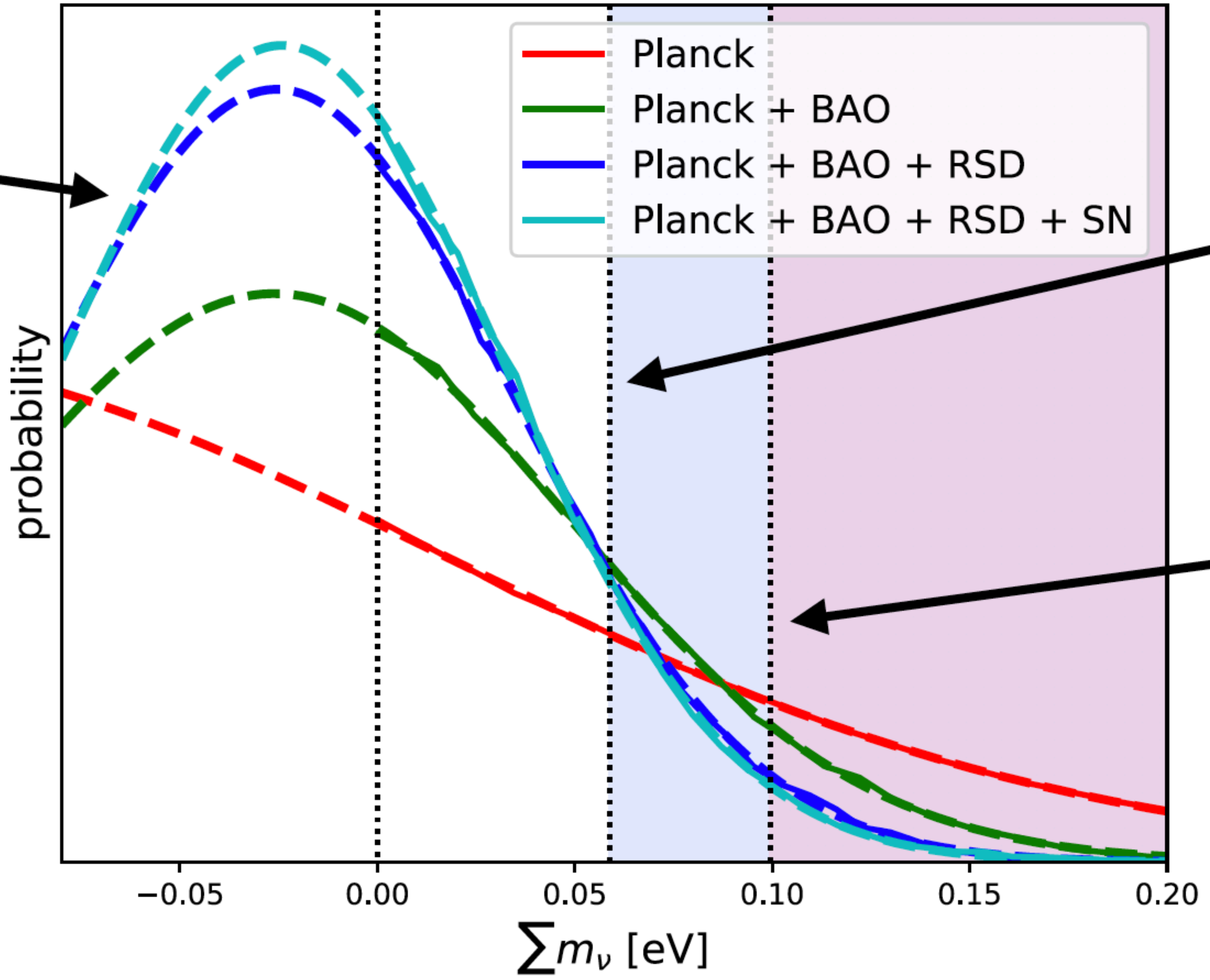
BAO only measures $D_H(z)/r_d$ $D_M(z)/r_d$

$$r_d = \int_{z_d}^{\infty} dz \, \frac{c_s(z)}{H(z)}$$

(need info on $h^2\Omega_b$)

c) Interpretation: Neutrinos

Gaussian fits



Normal Hierarchy

$\Sigma m_\nu > 60$ meV

Inverted Hierarchy

$\Sigma m_\nu > 100$ meV

Cosmology sensitive to the sum of neutrino masses

- Slight preference for Normal Hierarchy

Note

- Solid: posteriors with $\Sigma m_\nu > 0$ prior
- Dashed: Gaussian fits to posteriors

$$\Sigma m_\nu < 0.099 \text{ eV } (95)\%$$

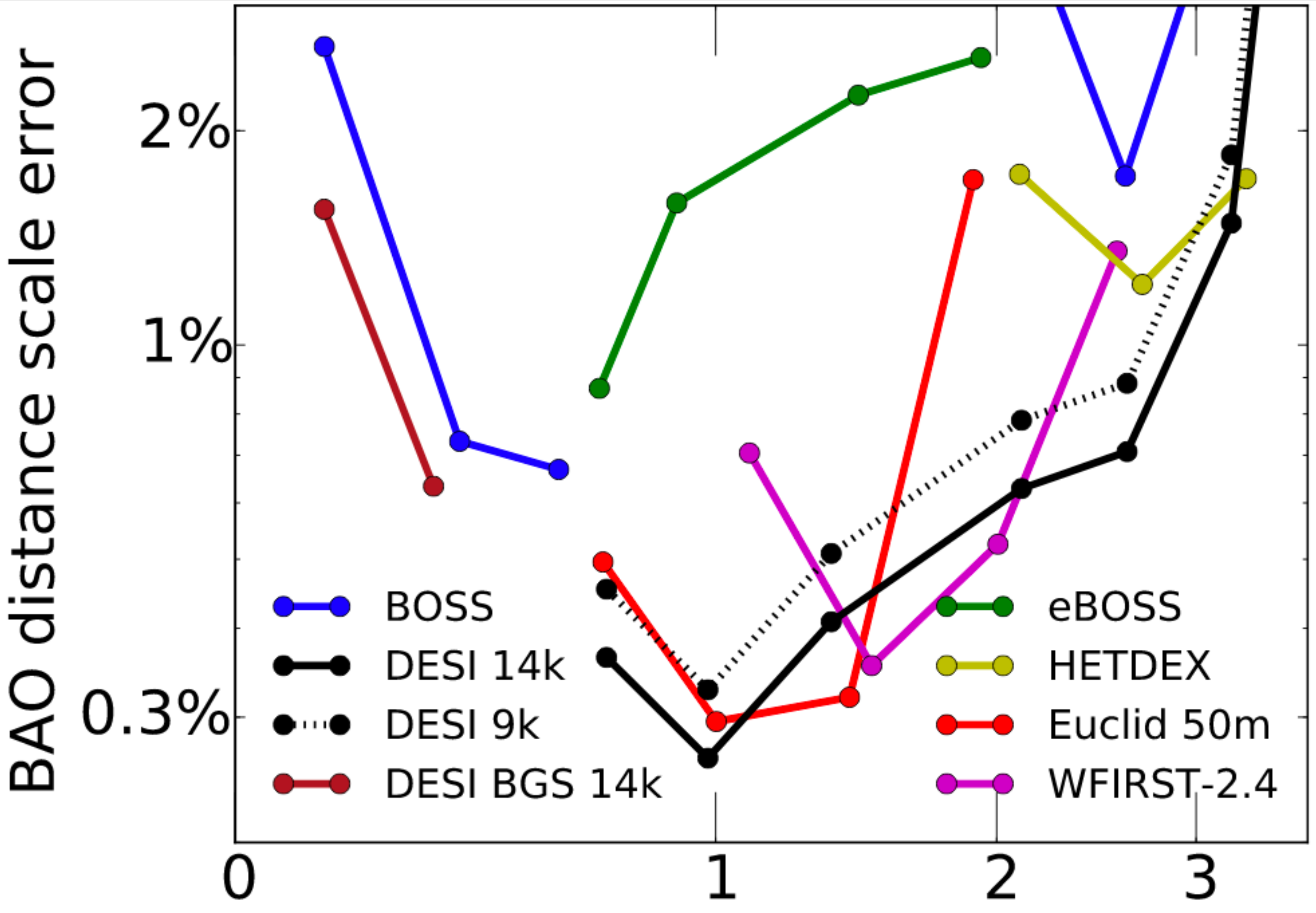
Dark Energy Spectroscopic Instrument: 2021 - 2026

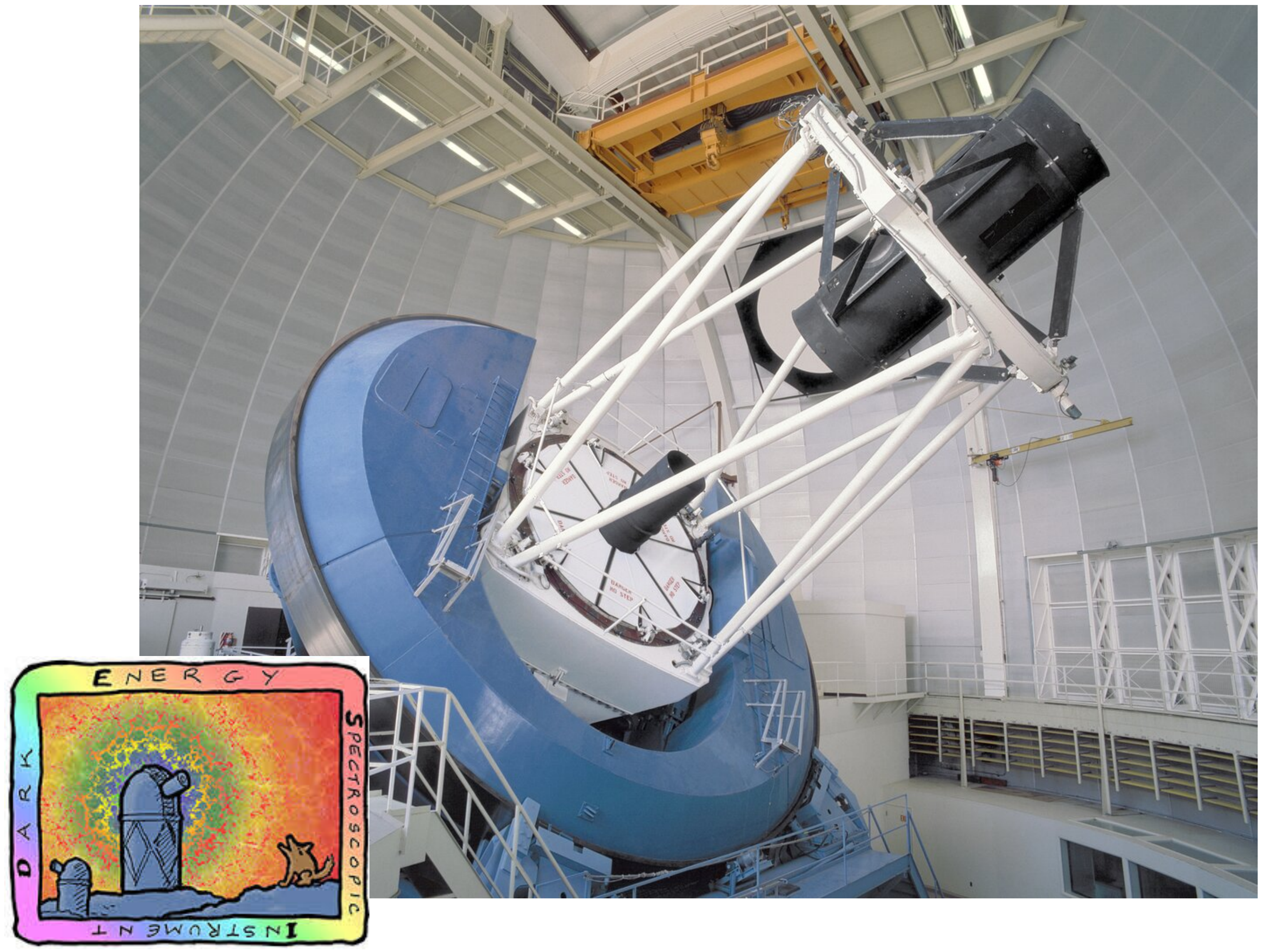
1/3 sky (14k deg^2),

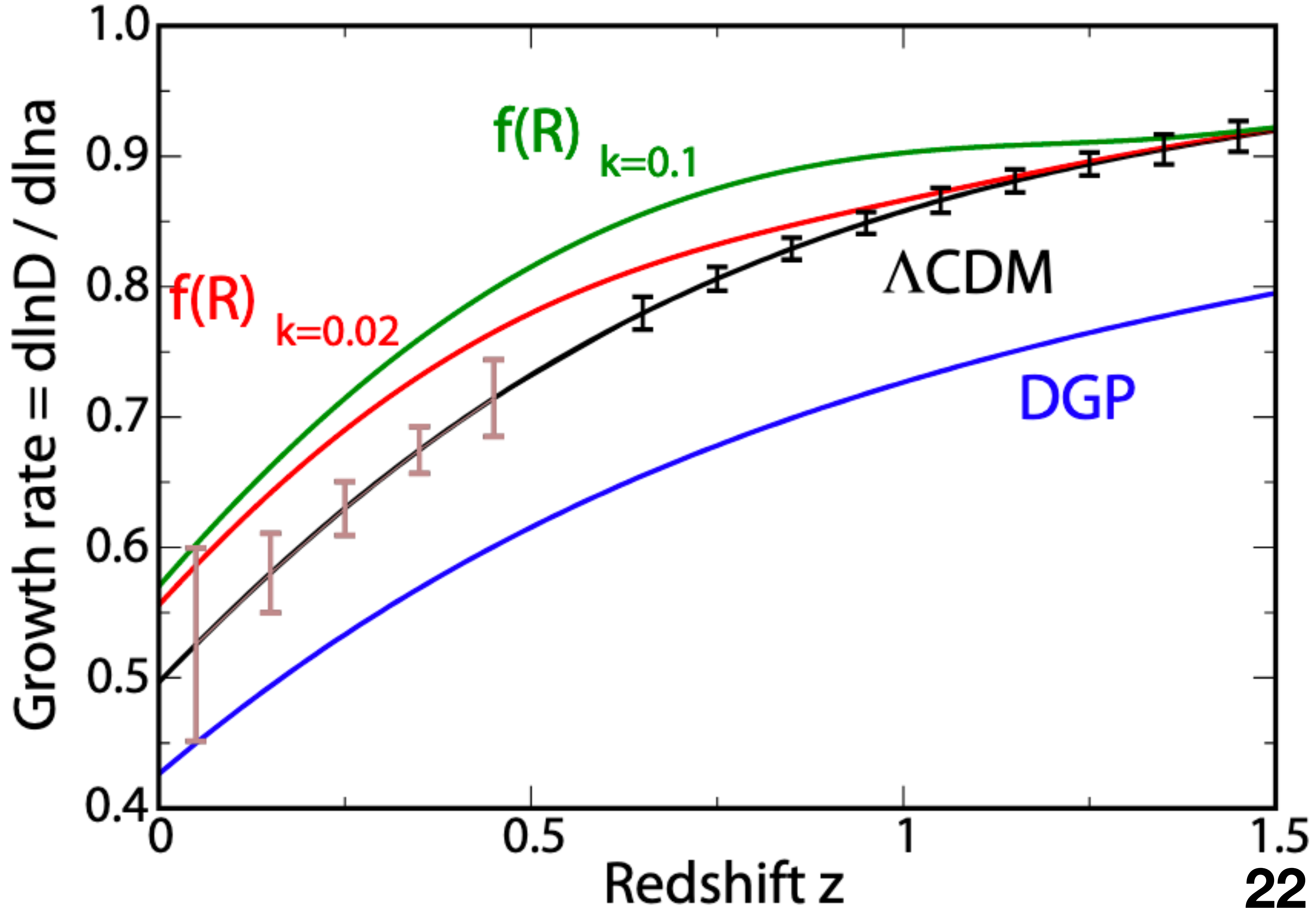
BGS, **LRG**, **ELG**, **QSO**, **Lya**

Spectroscopy **0<z<3.5**

- Data collection has just started!
- First results expected by the end of 2022!







Summary

- Conclusion of Stage-III Dark Energy surveys with spectroscopy
- Over 2M spectra obtained (more spectra than rest of the world combined)
- Sample with the largest redshift range than any other probe
- Percent-level precision on BAO distance scale at each redshift
- Growth measurements to z<1.5

- Agreement with LCDM and Planck results
- Detection of DE using BAO only & flatness
- First stage -IV program (DESI) has just started observing. Stay tuned for 2022!