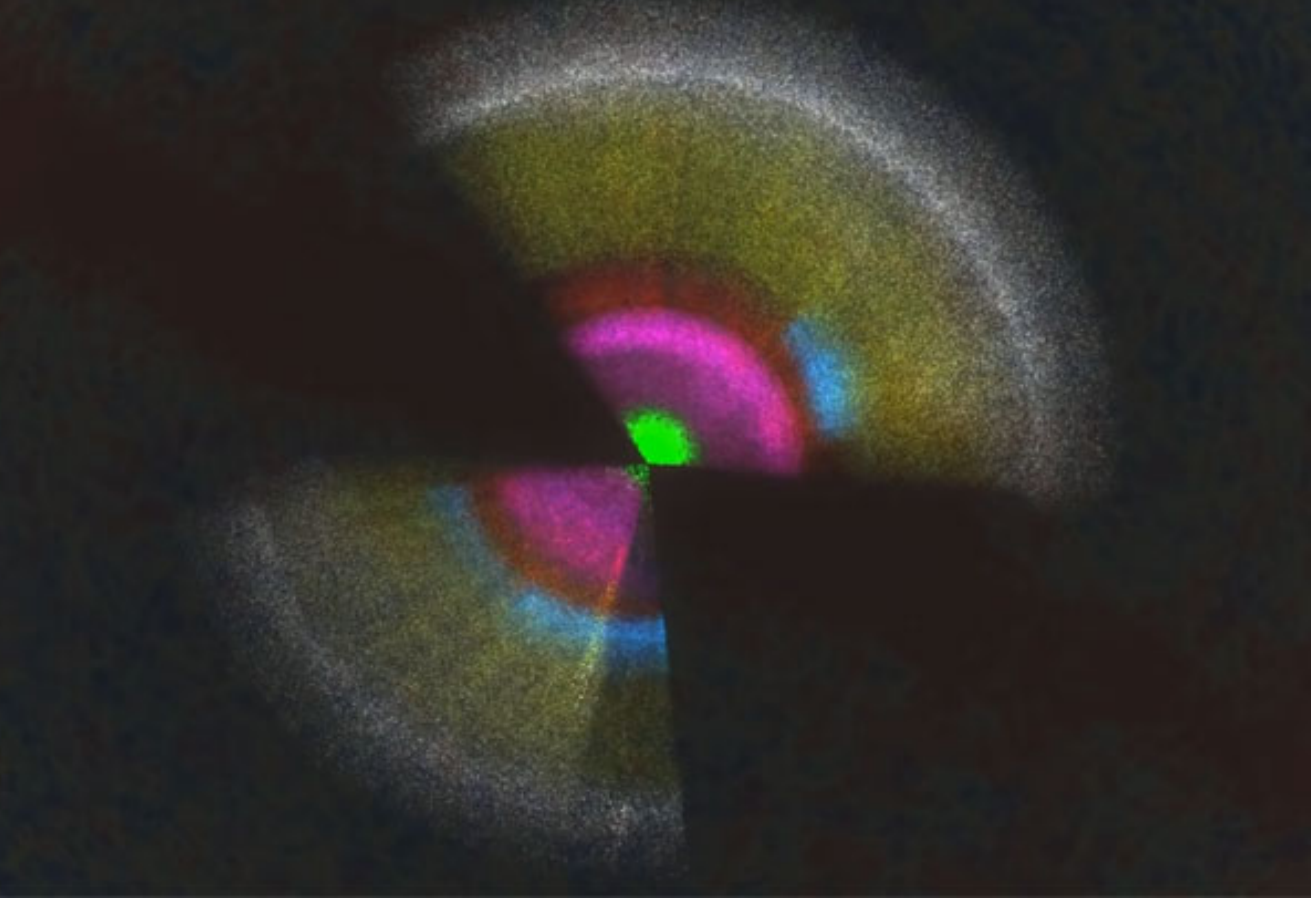

Cosmology from galaxy redshift surveys: current results and future techniques

LIneA, an e-Astronomy laboratory Webinar,
14th October 2021

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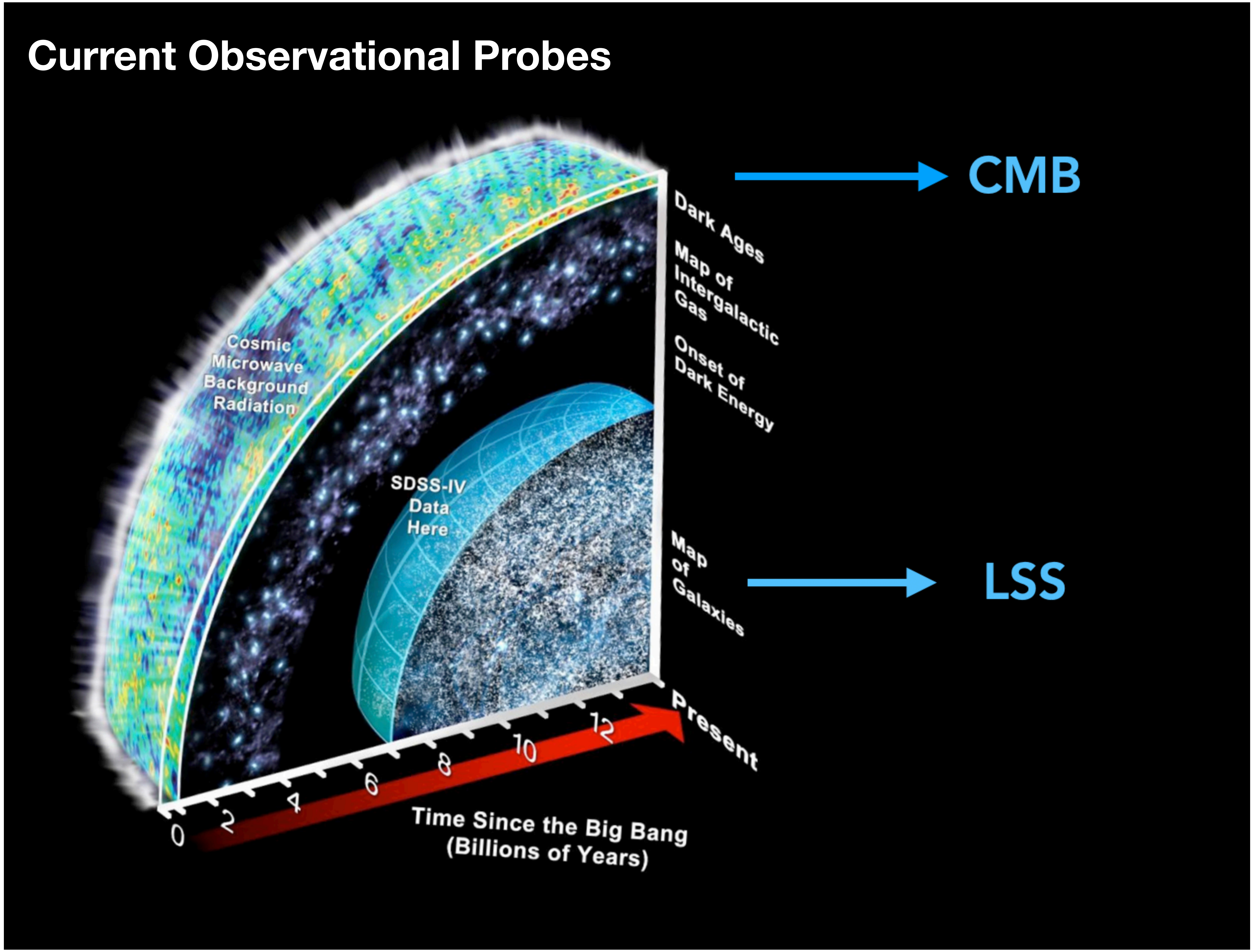
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science
eBOSS
SDSS
"la Caixa" Foundation
erc European Research Council
ICCUB
Institut de Ciències del Cosmos UNIVERSITAT DE BARCELONA



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

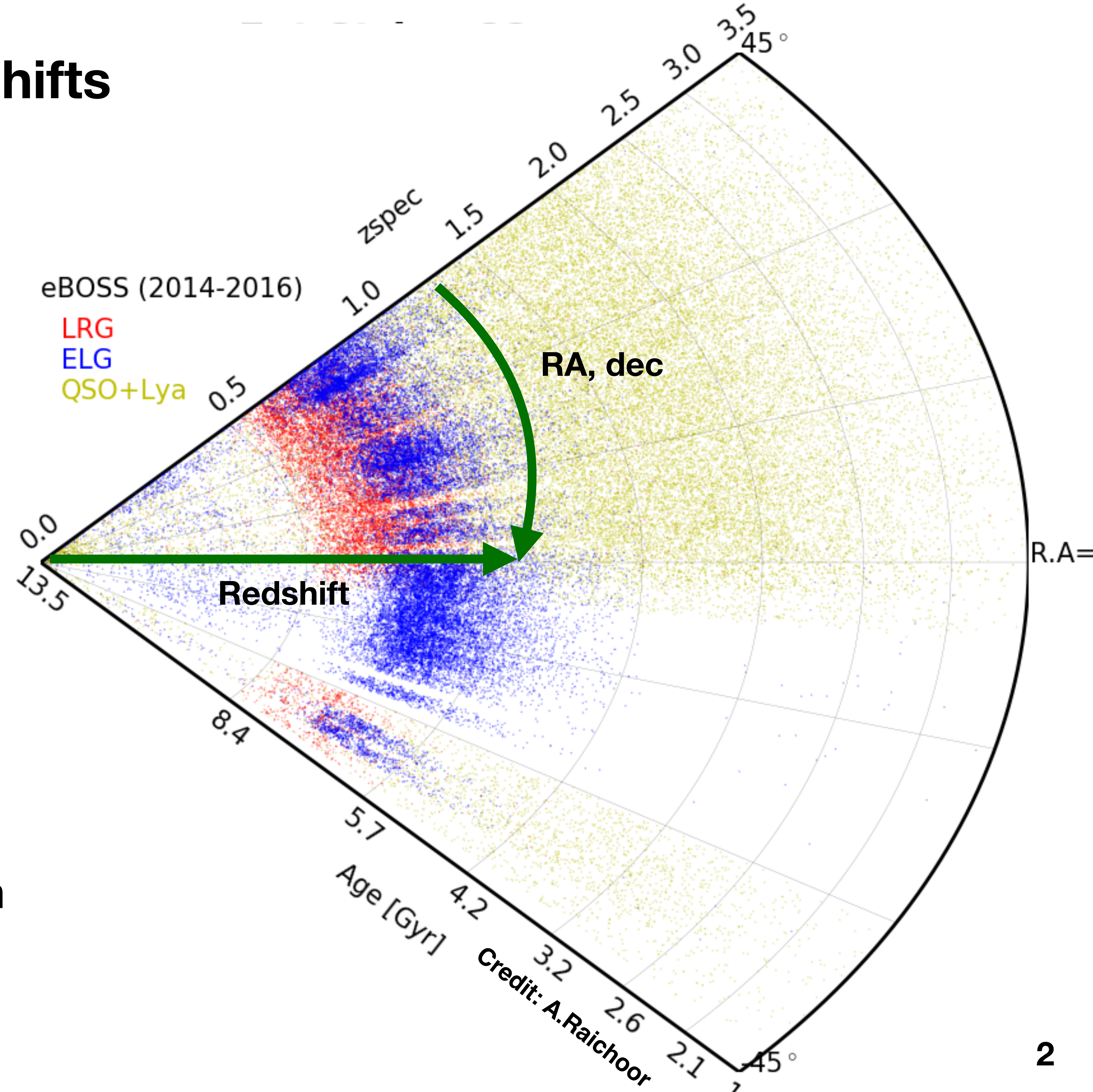
Spectroscopic surveys: **angles** and **redshifts**

- 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**

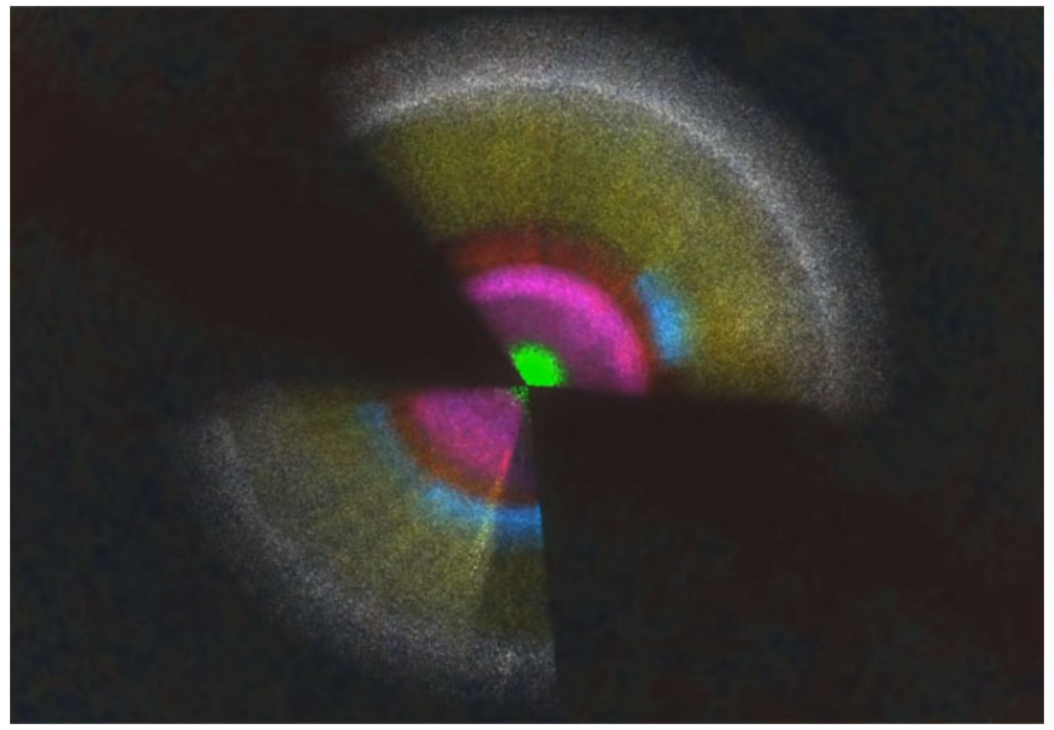
$$r(z) = \int_0^z \frac{c\,dz'}{H(z', \Omega)}$$

- Produce a 3D map we use to extract information



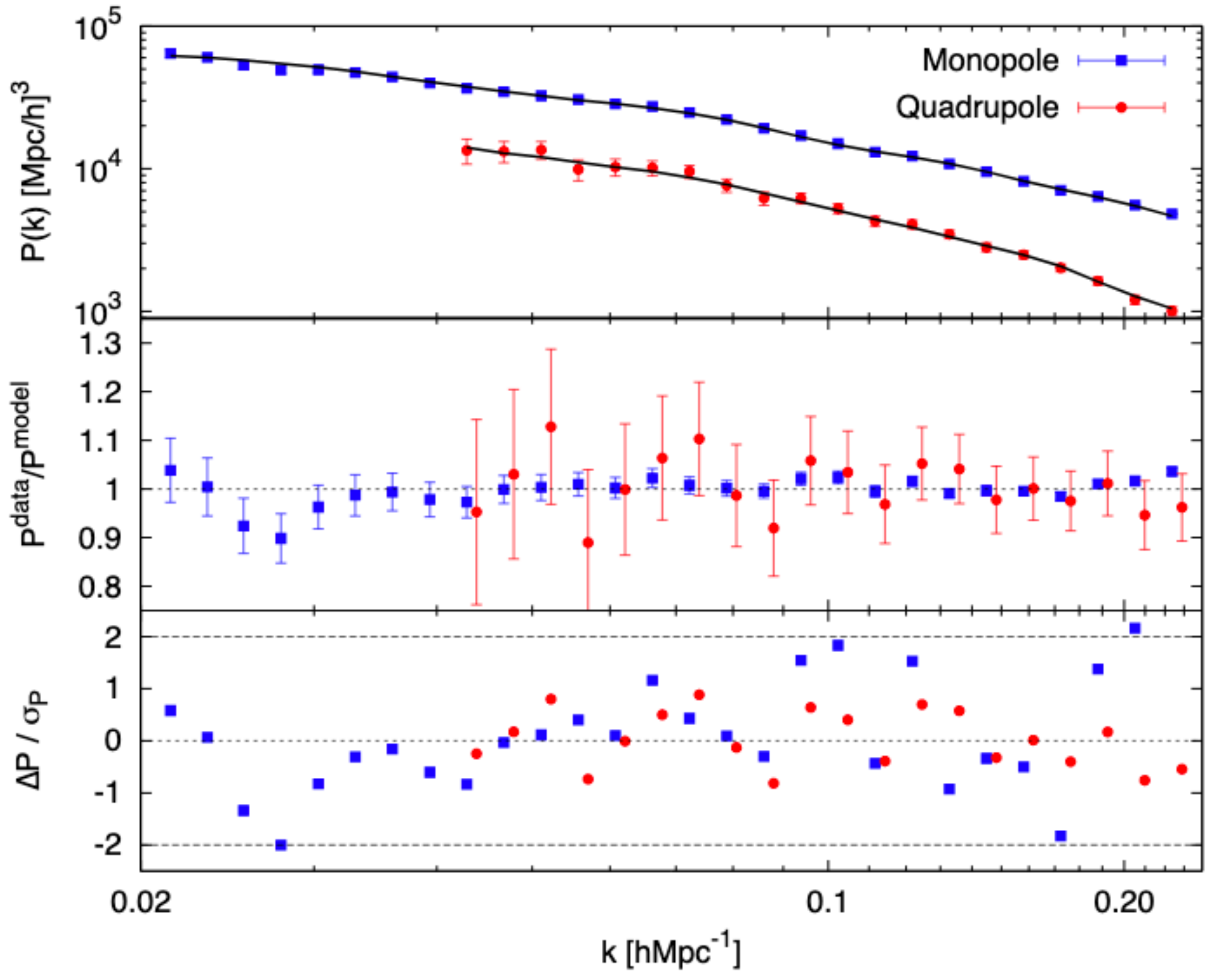
Spectroscopic surveys: **information content**

- **LSS Galaxy Maps**



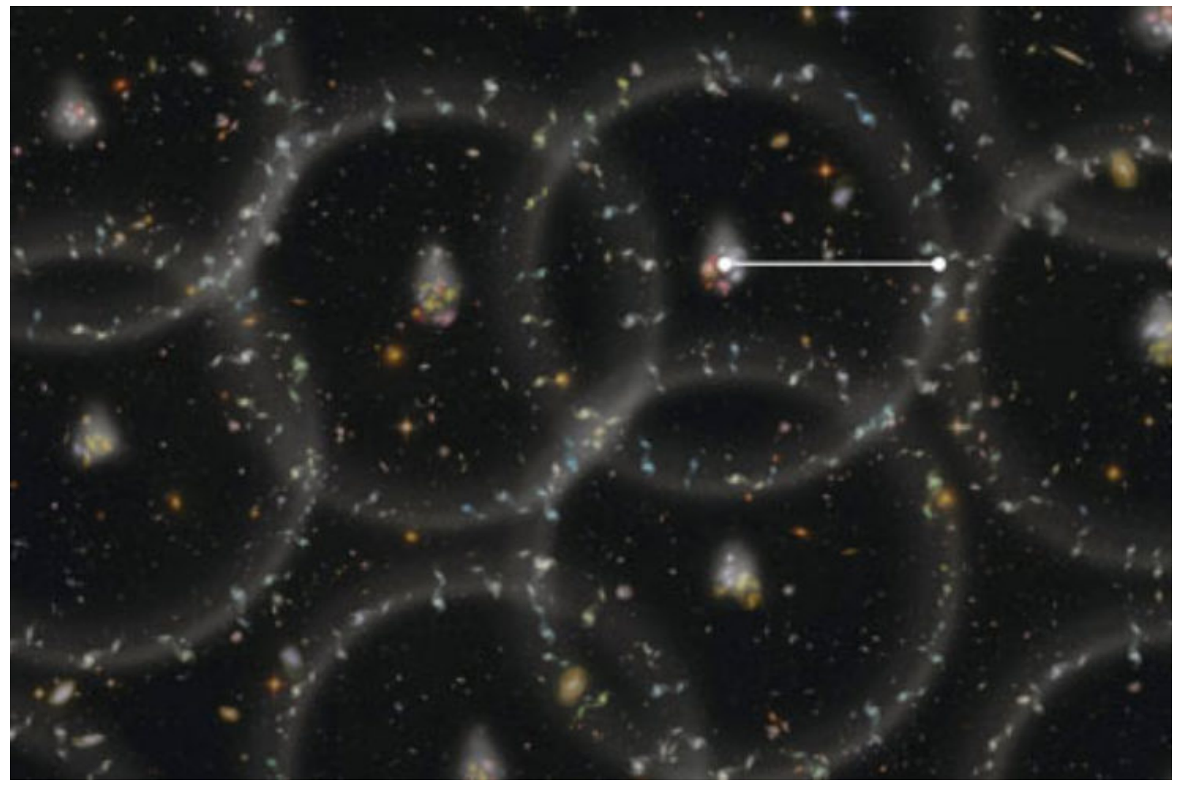
a) Compression

- **Summary Statistics**



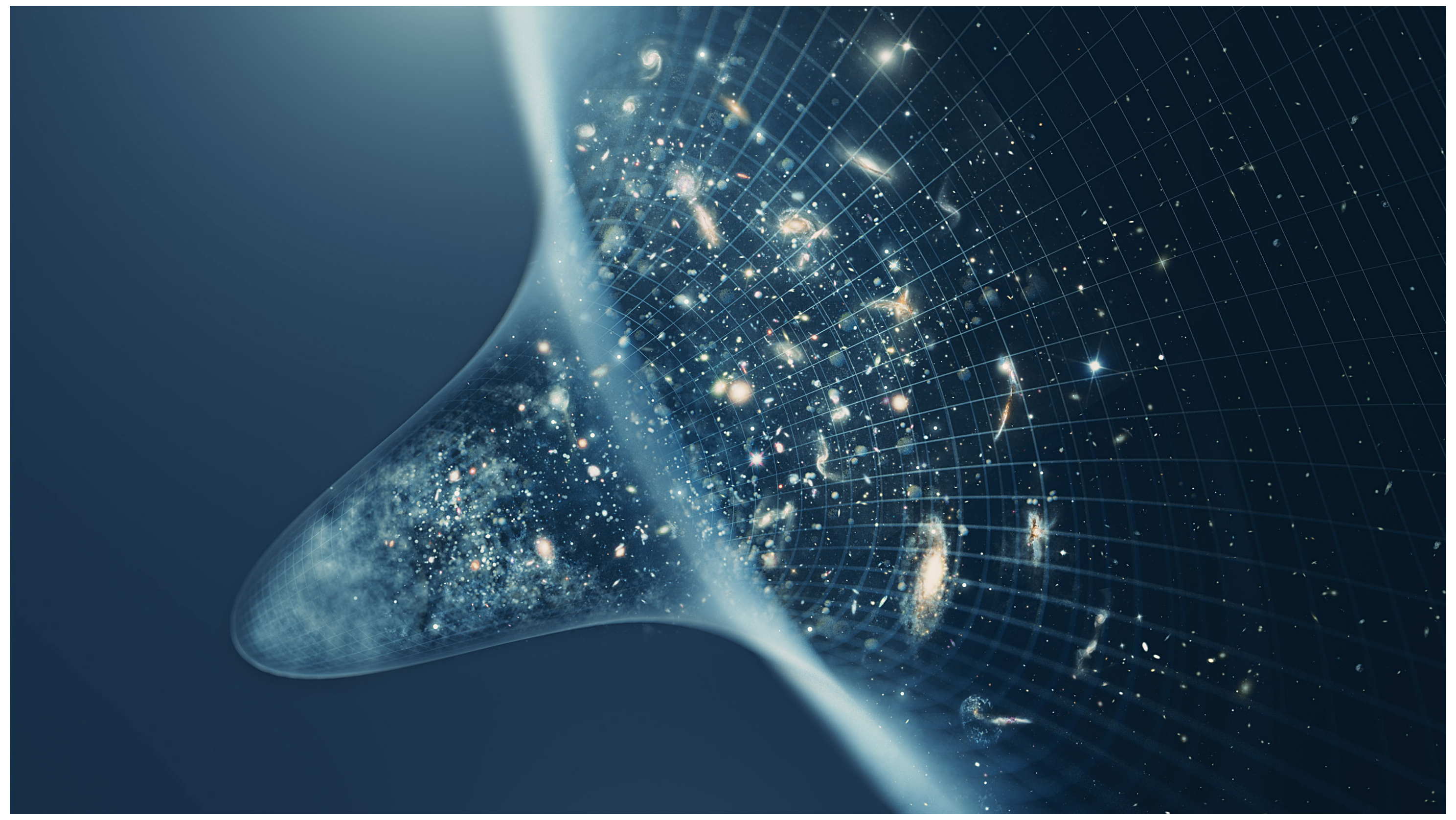
b) Identification of robust features

- **Features (BAO, RSD)**



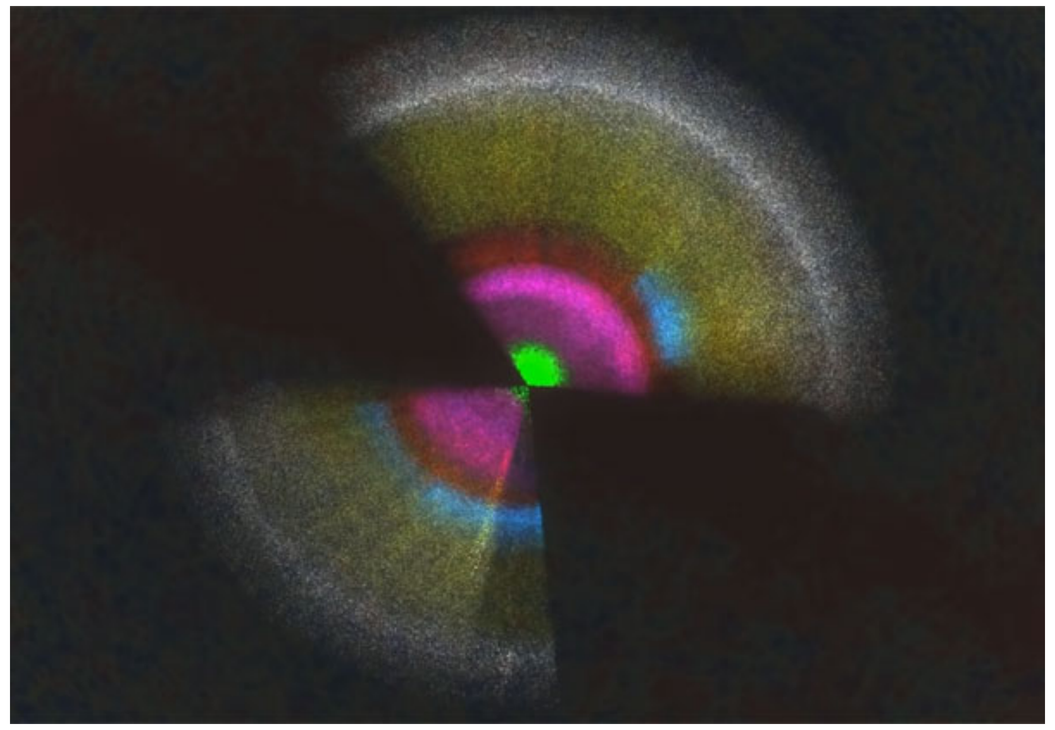
c) Interpretation

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



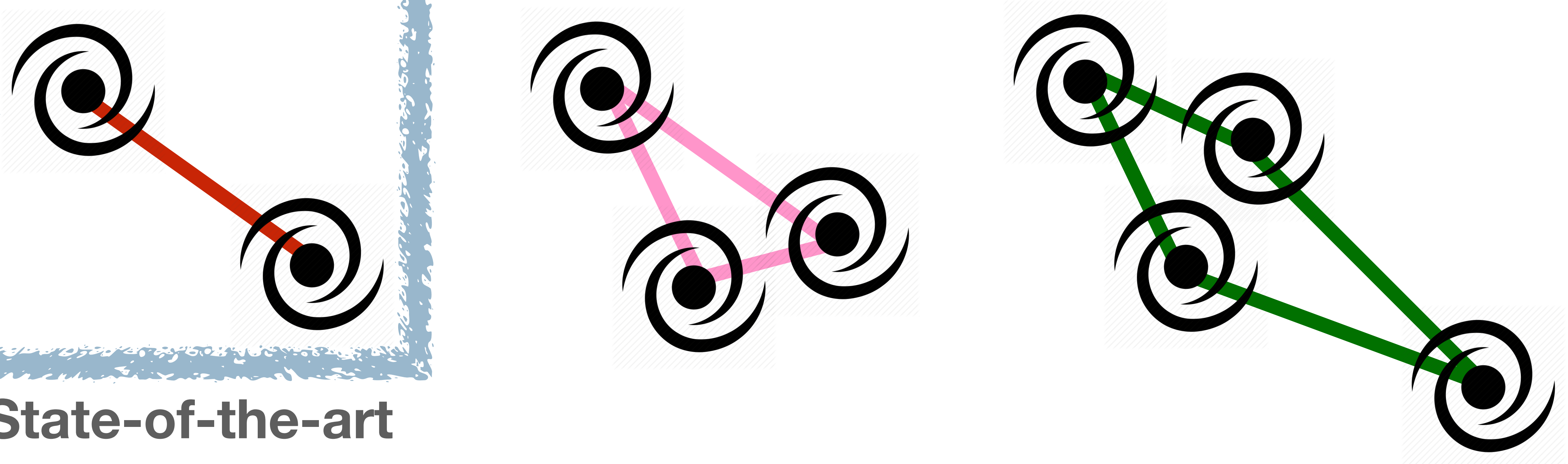
a) Compression: Summary statistics

- **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**

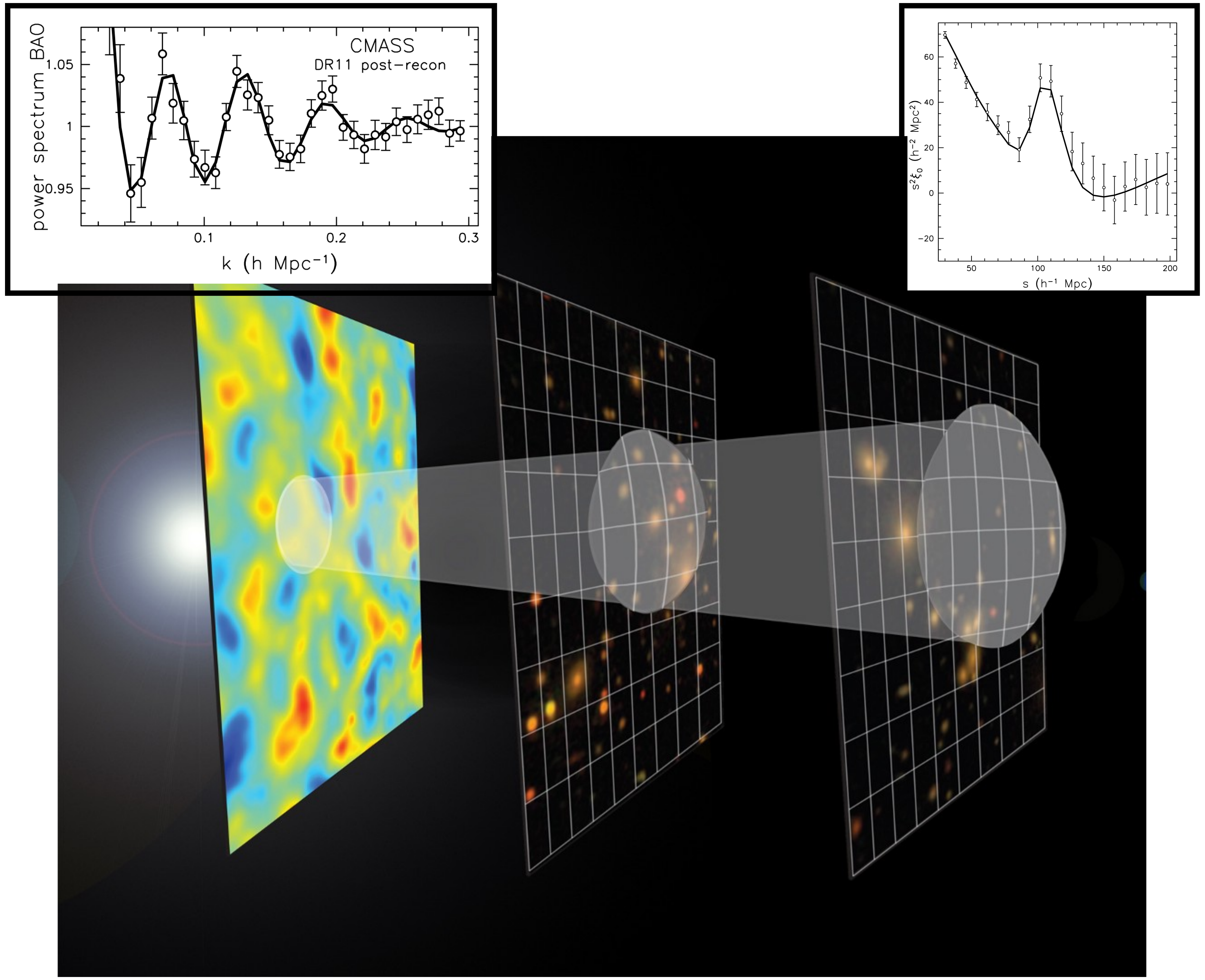
1. For Gaussian fields (like CMB) P(k) contains all relevant information

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

****for BOSS bispectrum measurements see GM et al. 2016***

b) Robust features: BAO as standard ruler

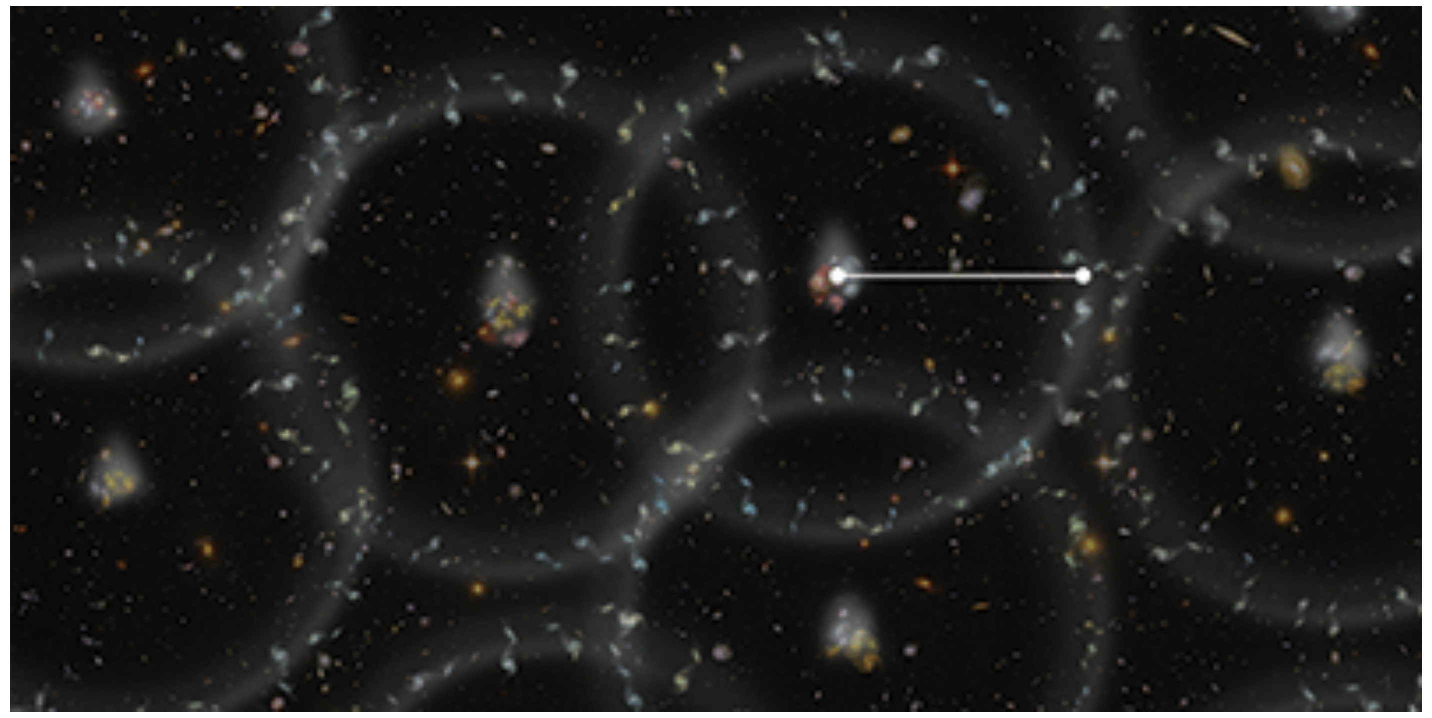
Sound waves travelling in early-time plasma until decoupling → **Imprinted in CMB photons & baryonic and DM distribution**



- 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_{drag}
    - uncalibrated BAO measures Ω_m

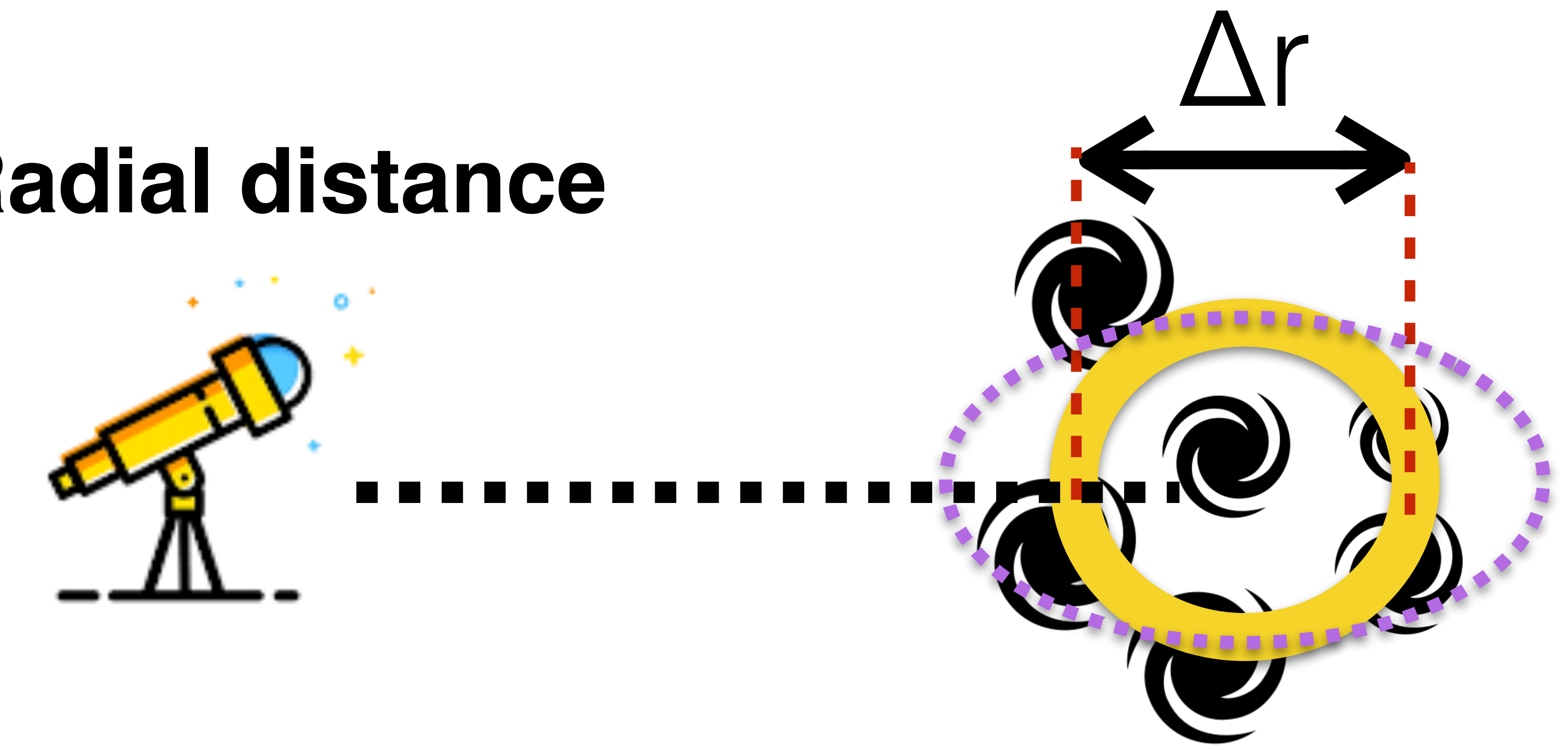
b) Robust features: BAO & AP



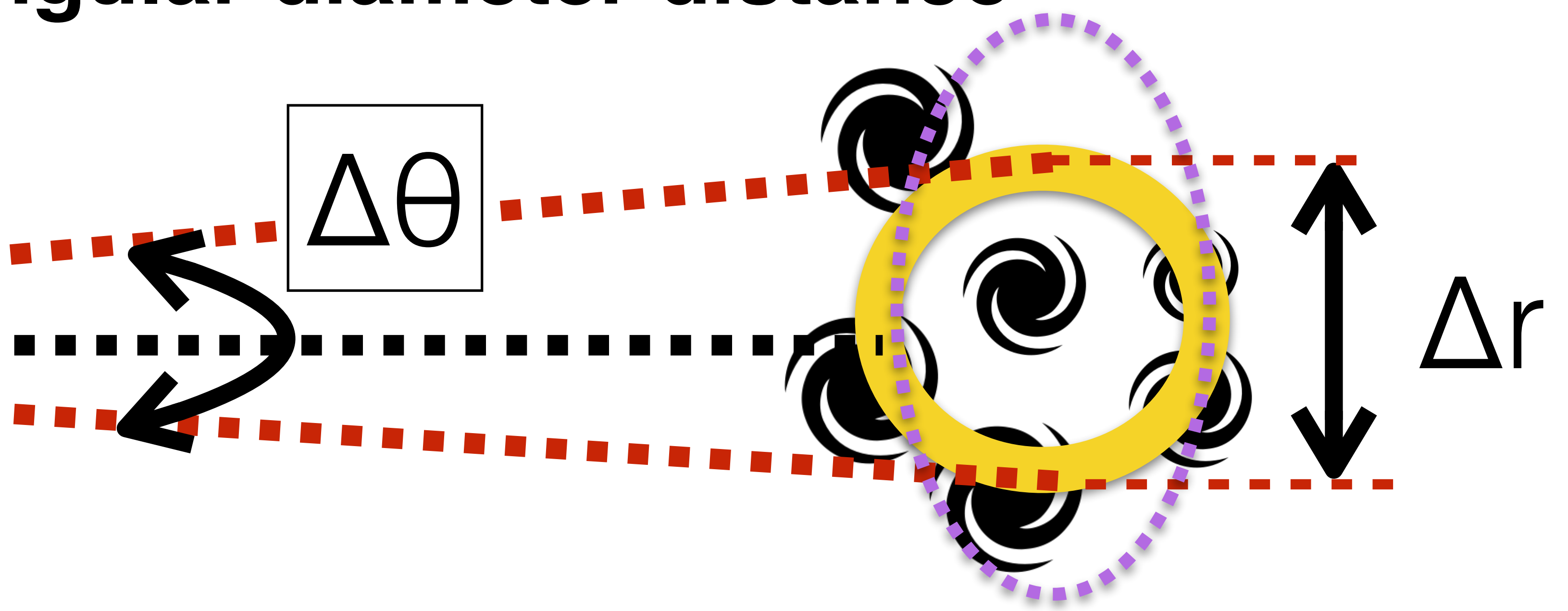
- Universe assumed **isotropic** and **homogeneous**

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

Radial distance



Angular diameter distance



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

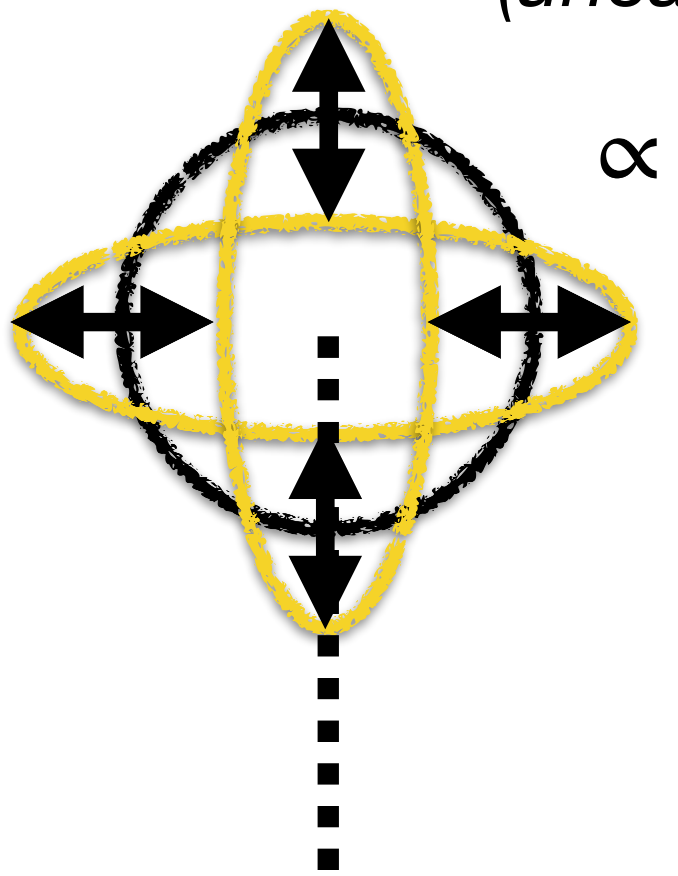
$$\Delta r_{\perp}(\theta_1,\theta_2;z,\Omega_m)=\Delta\theta\int_0^{z}\frac{c\,dz'}{H(z',\Omega_m)}\sim D_M(z)$$

BAO provides a reference-structure for the AP effect

b) Robust features: horizon scale r_{drag}

BAO-warping (AP)

(uncalibrated BAO)

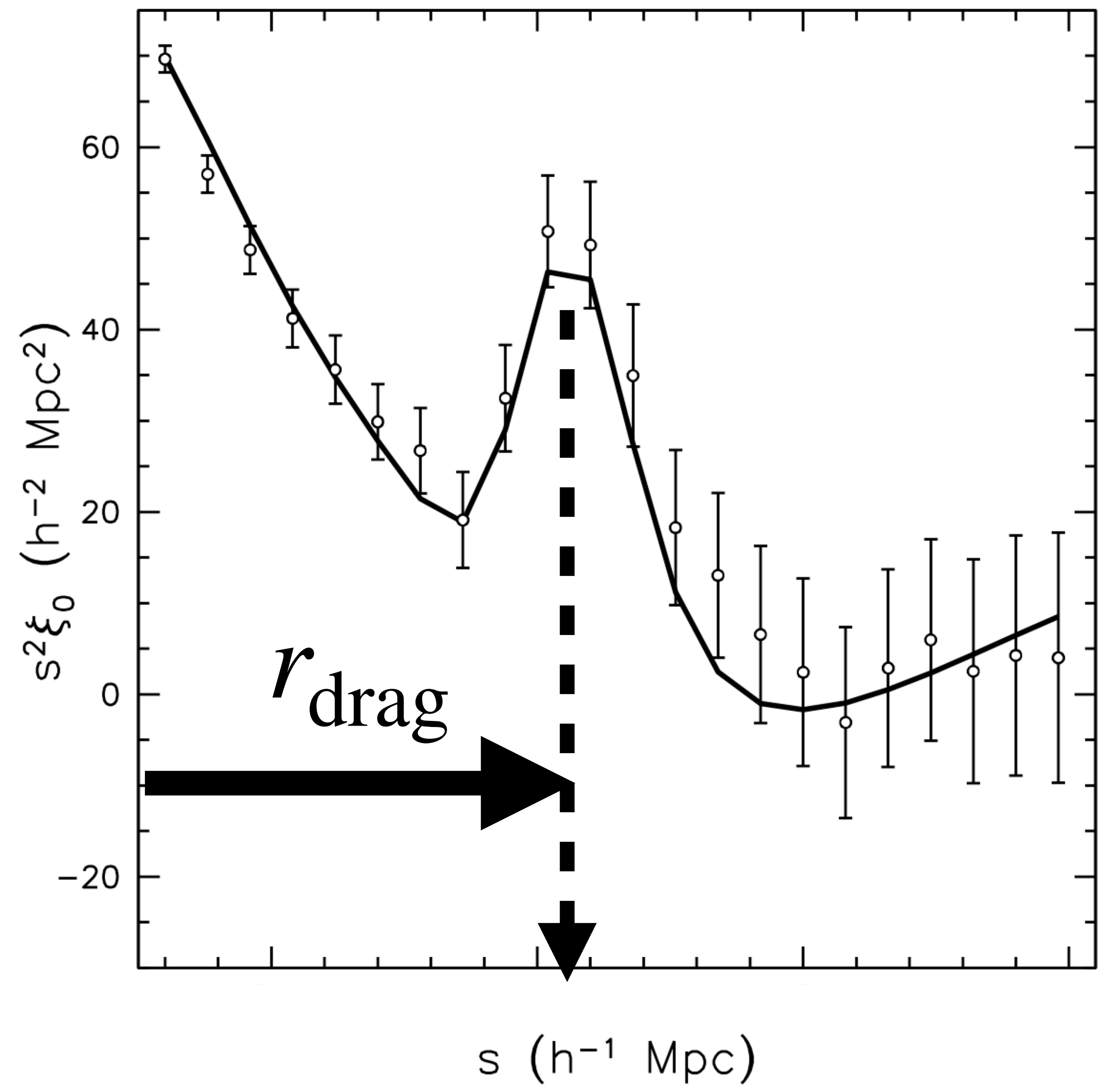


$\propto D_M(z)/D_H(z)$

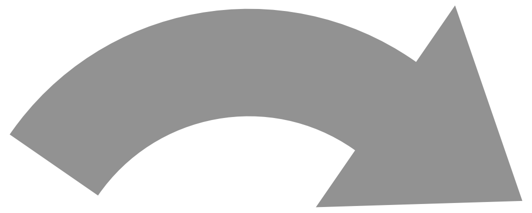
$\downarrow$

Ω_m

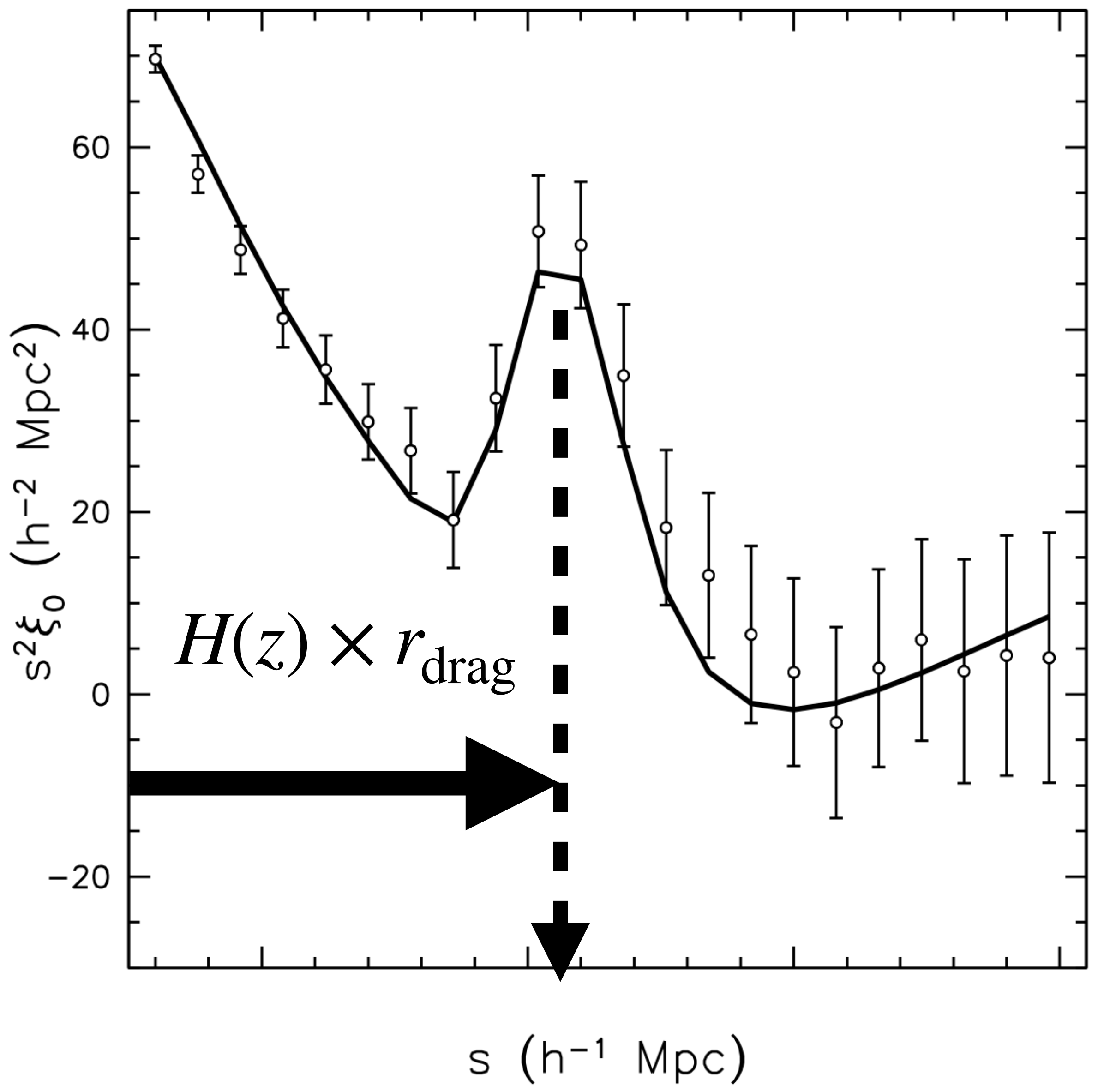
At recombination time



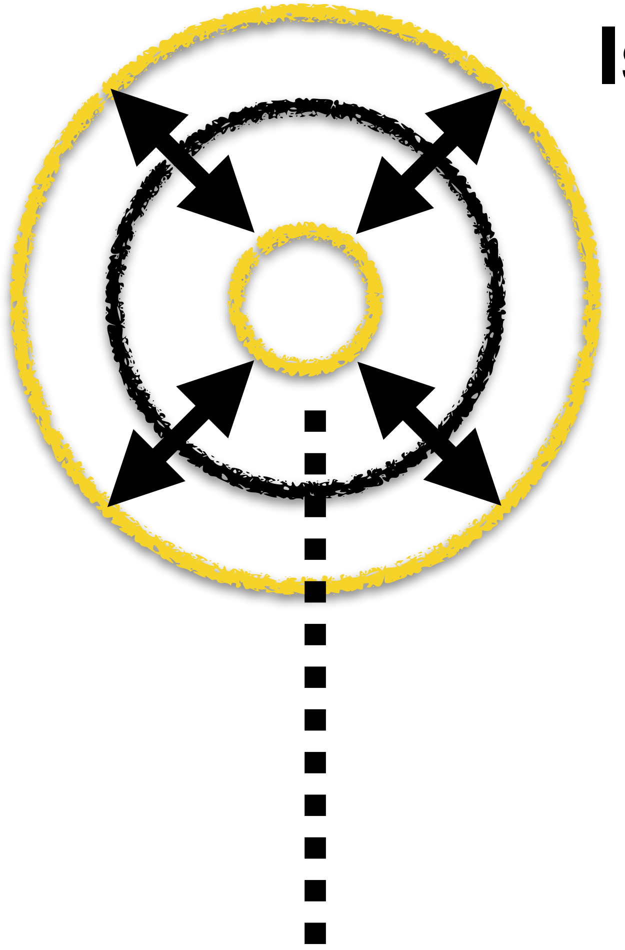
Expansion



Galaxy surveys (late-time)



Isotropic dilation



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

$\downarrow$

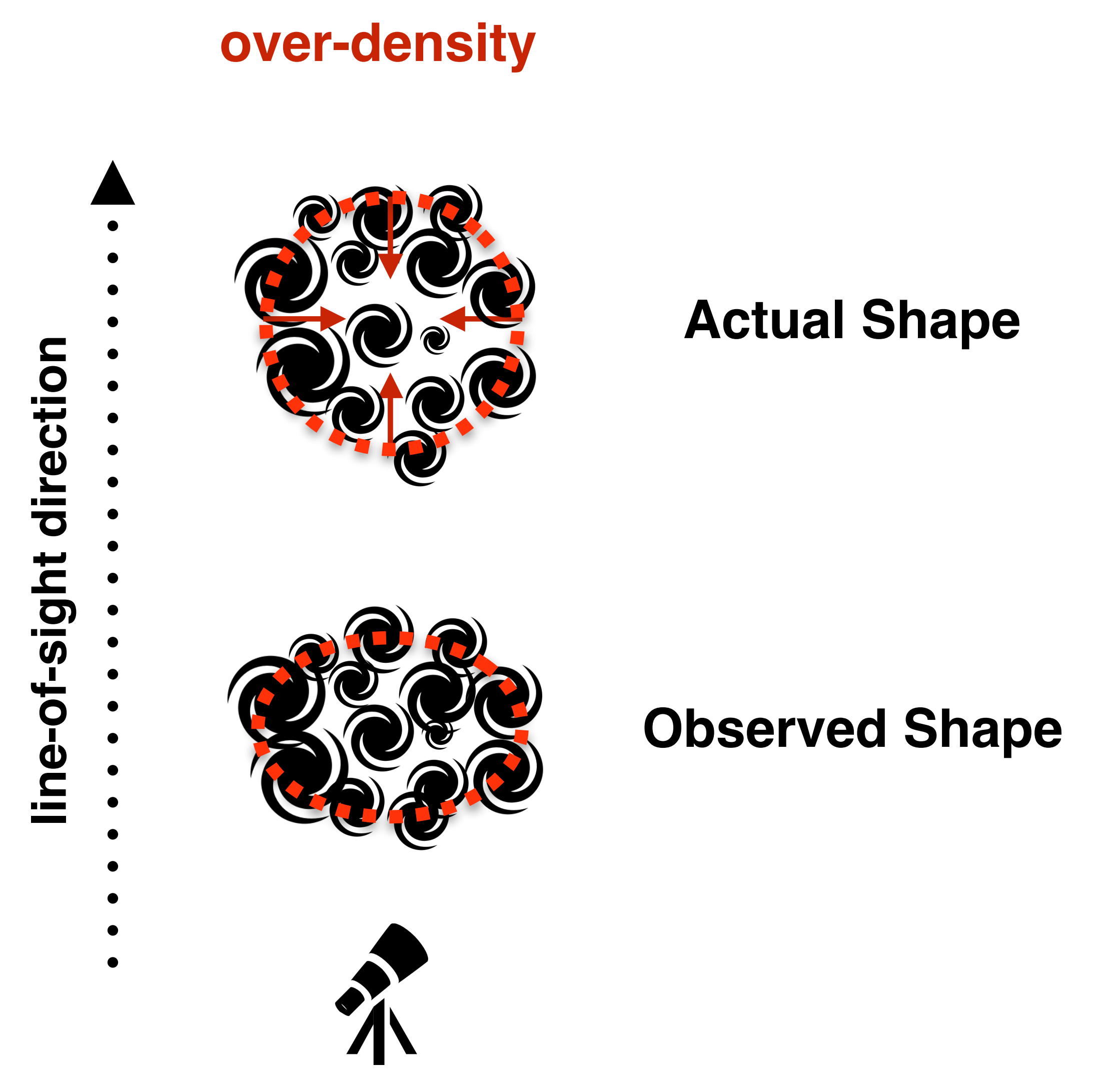
$H_0 \times r_{\rm drag}$

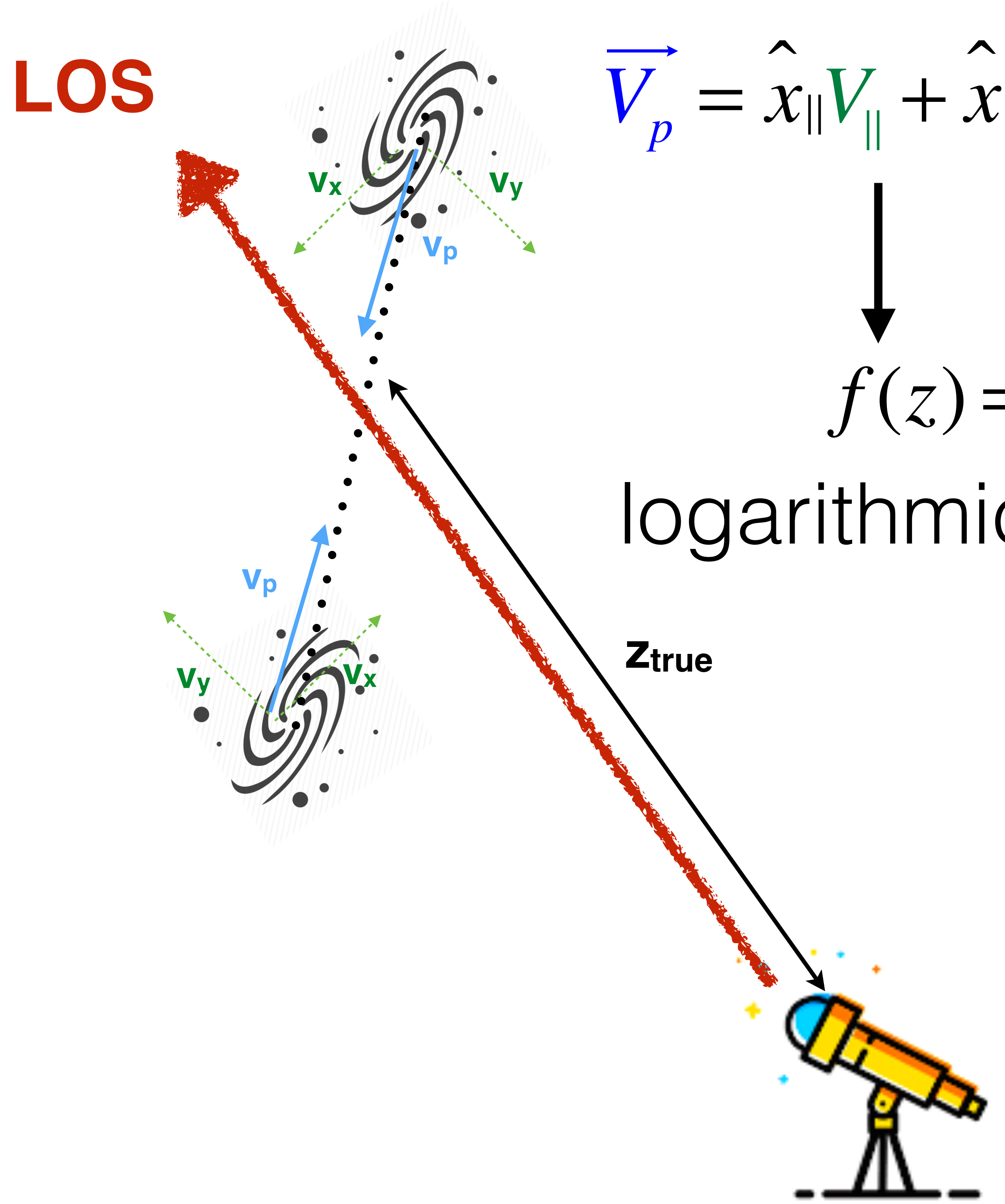
Under LCDM interpretation BAO in late-universe: $H_0 \times r_{\rm drag}$ & Ω_m

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)





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

$$\downarrow$$

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

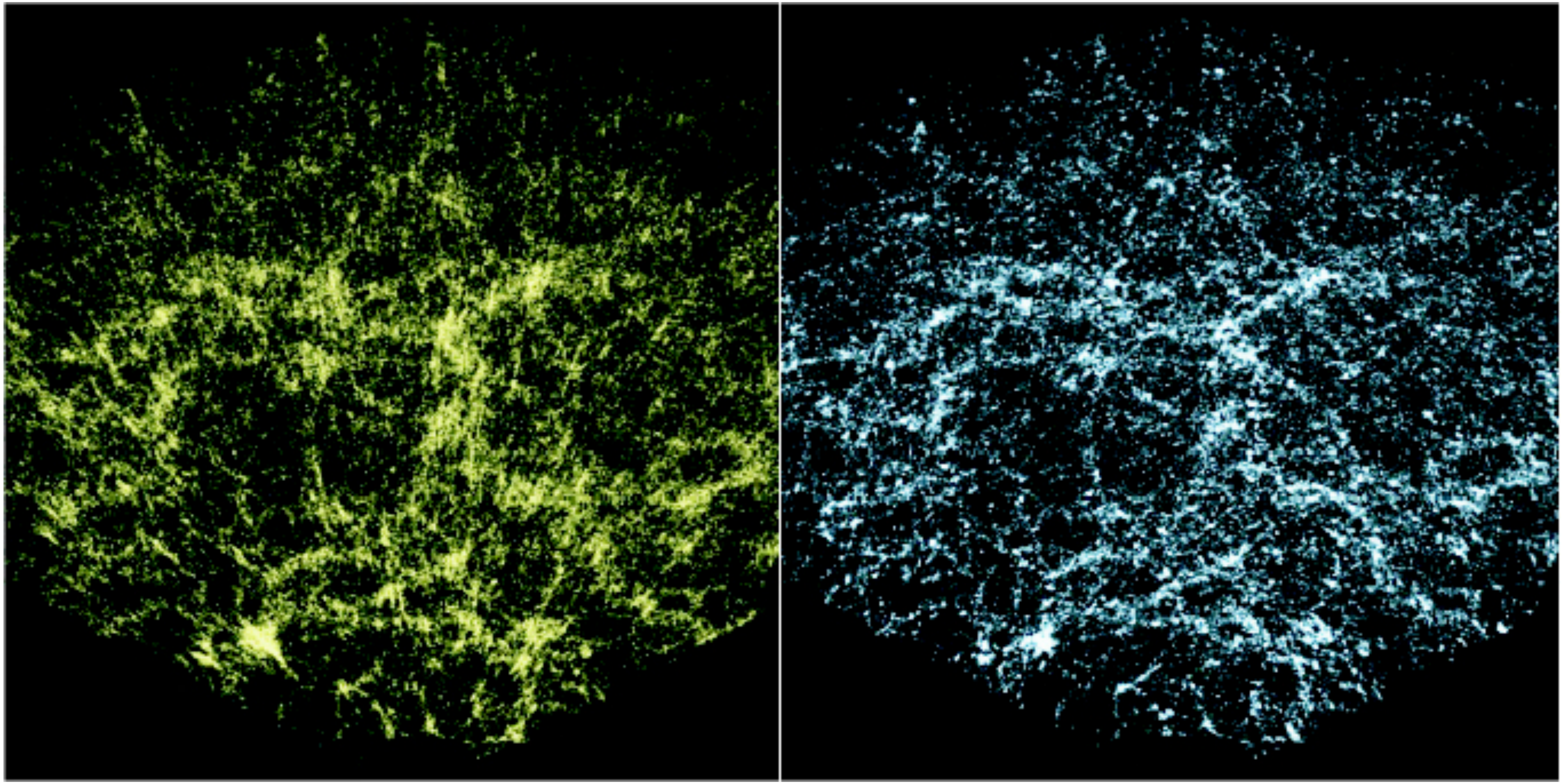
logarithmic growth of structure

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

1. Hubble flow

2. Coherent with growth of structure

Observed ‘redshift' space True ‘real’ space



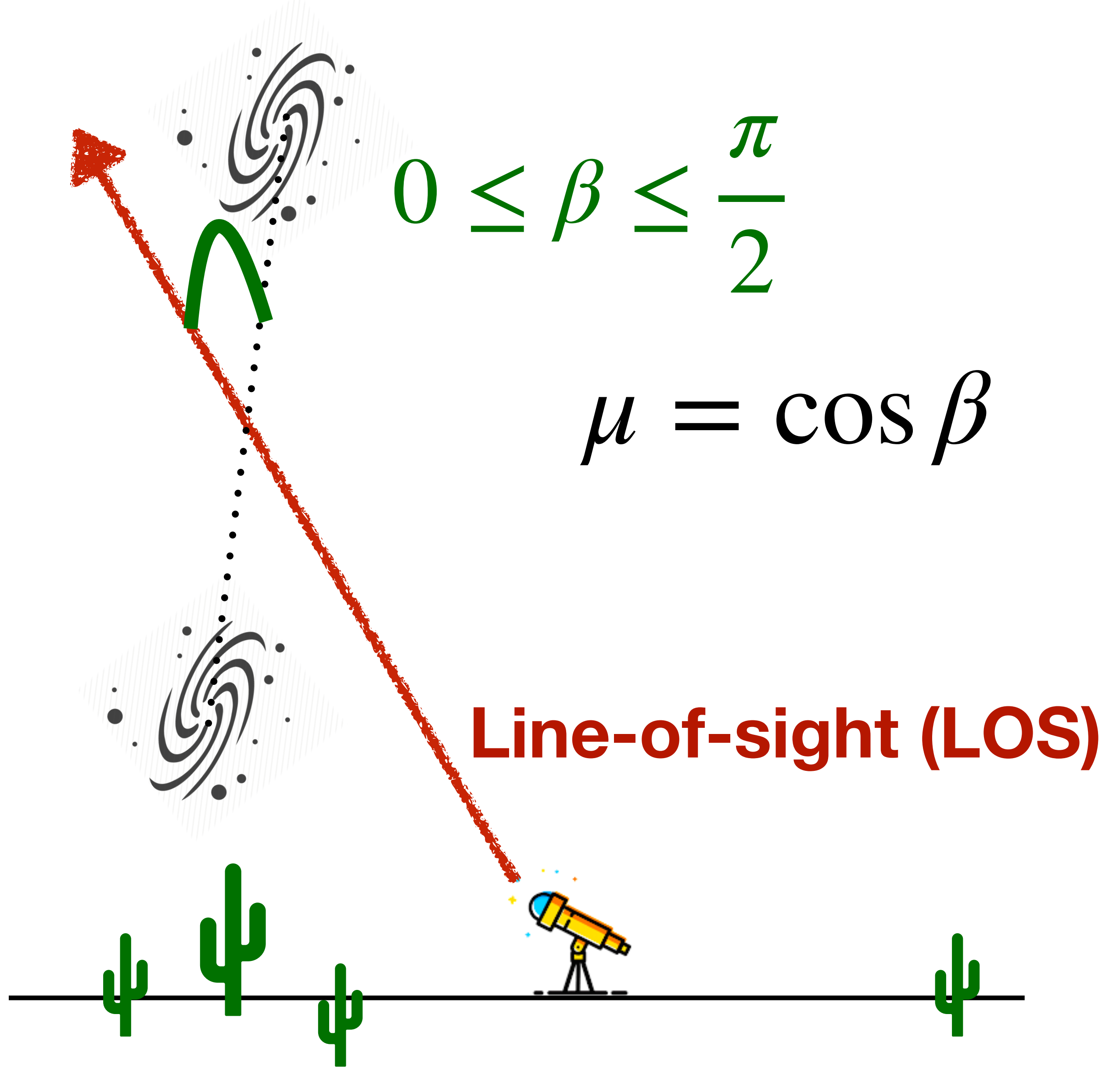
b) Robust features: Kaiser toy model

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



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

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

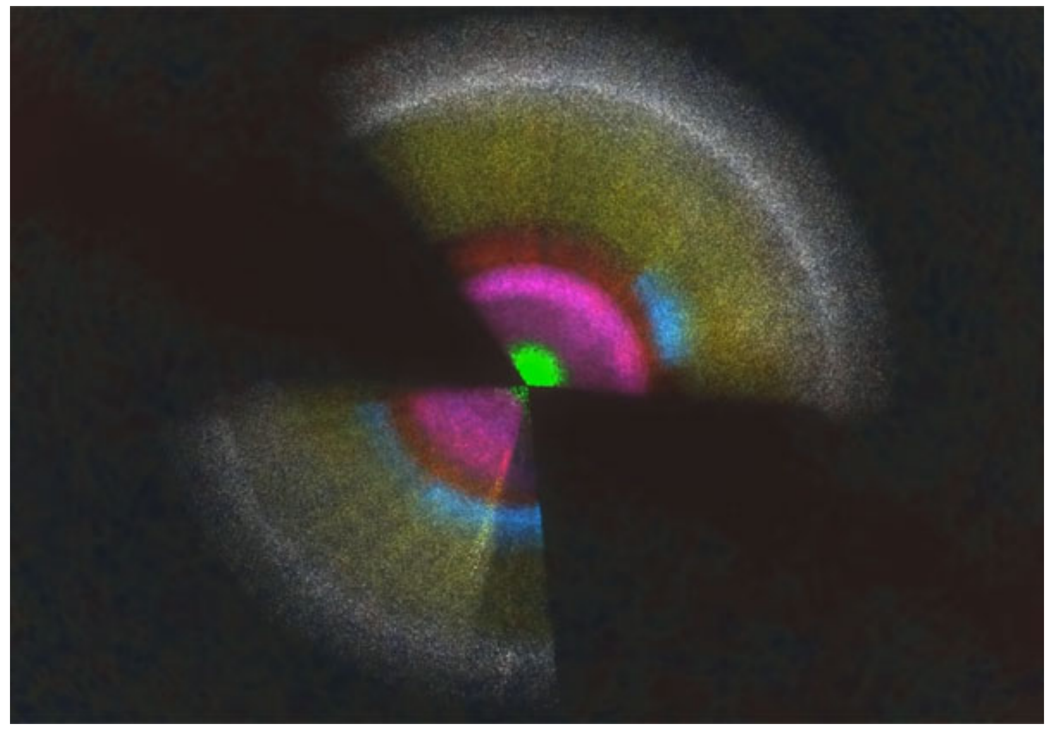
$$P^{(4)}(k,z) = \left(\frac{8}{35} f(z)^2 \right) P_m(k,z)$$

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

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

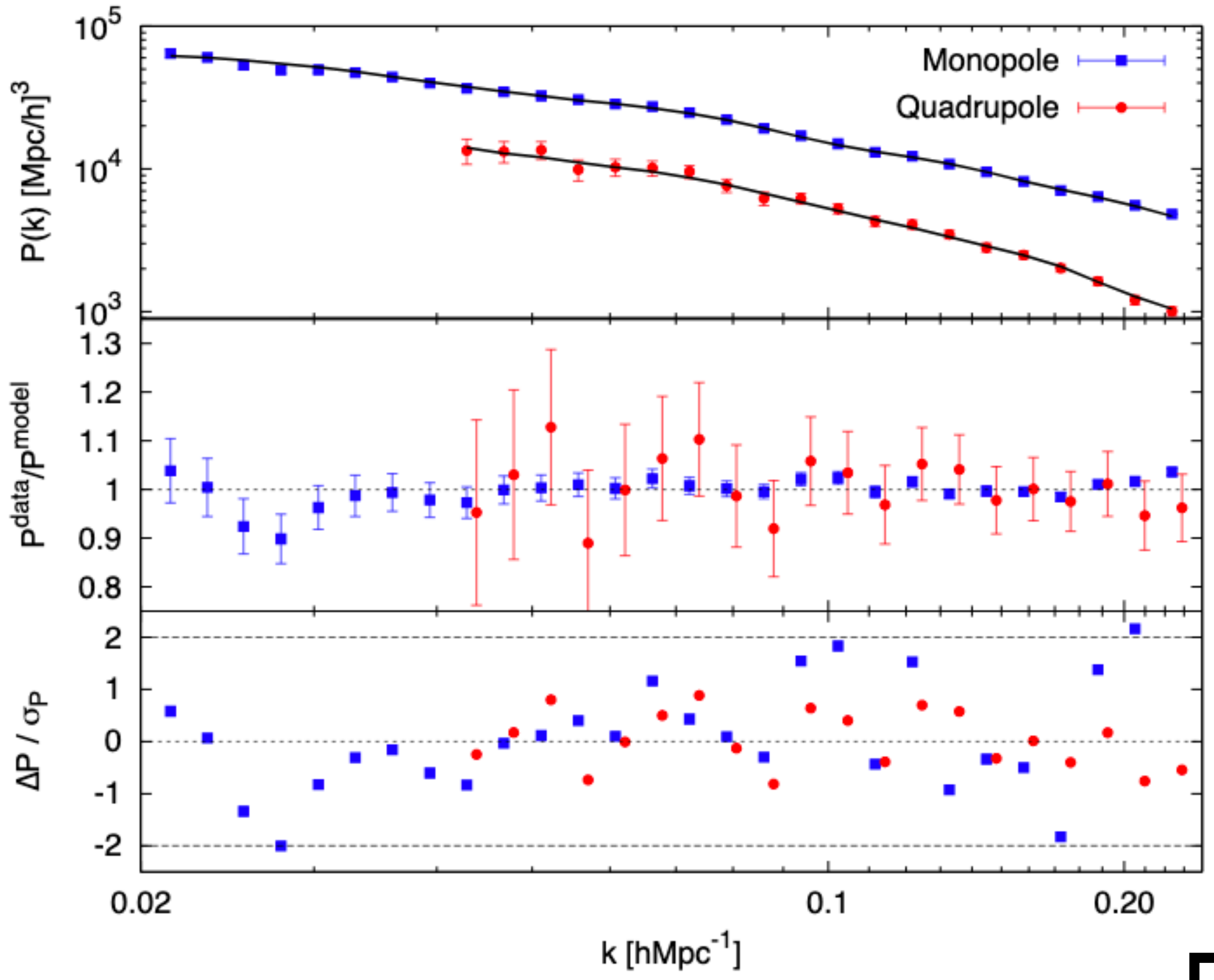
Spectroscopic surveys: **information content**

- **LSS Galaxy Maps**



a) Compression

- **Summary Statistics**



b) Identification of robust features

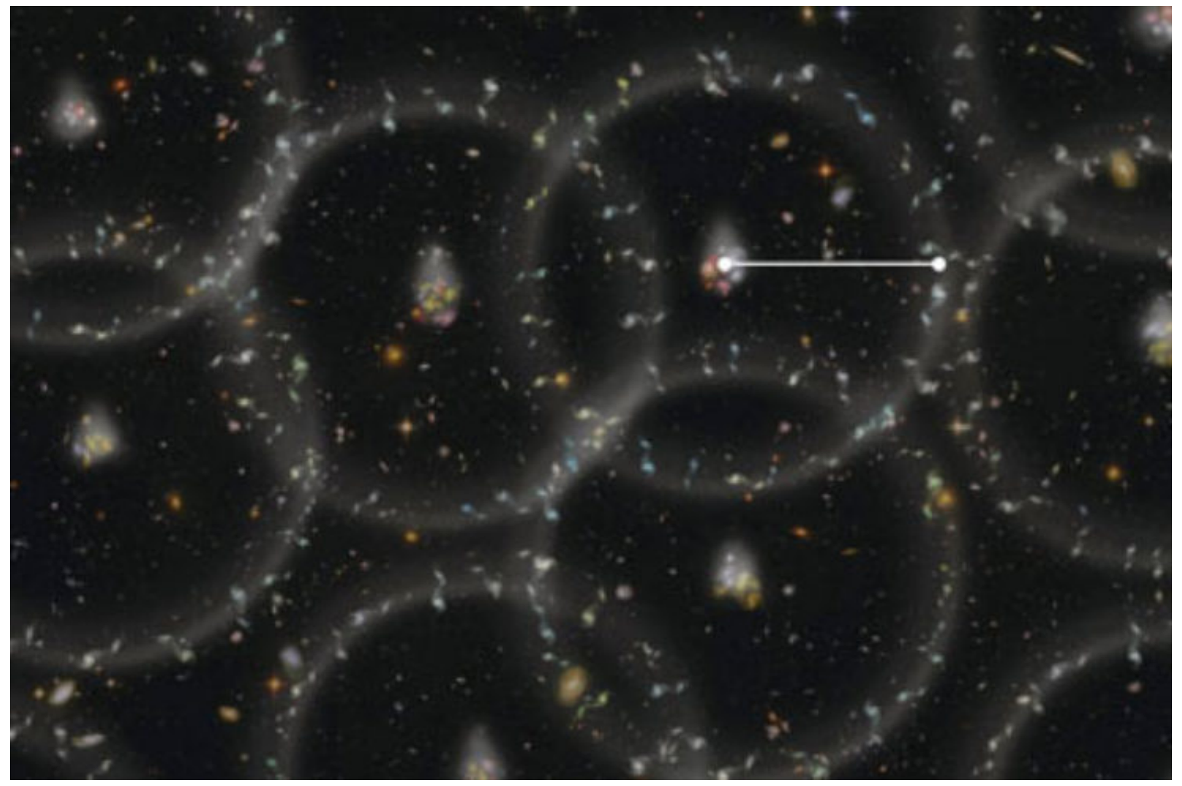
Compressed set of parameters

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

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

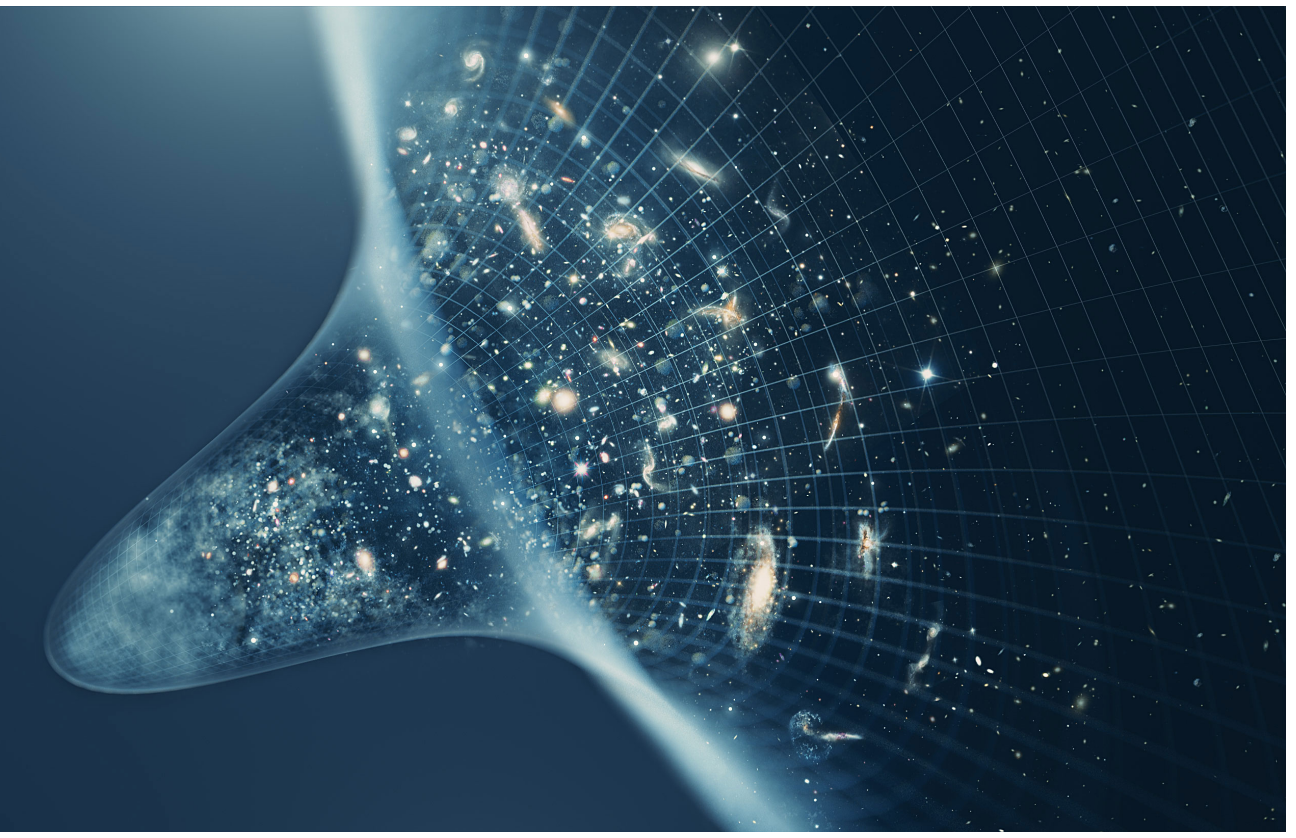
$$f\sigma_8(z, \mathbf{\Omega}) = \Omega_m(z, \mathbf{\Omega})^\gamma \sigma_8(z)$$

- **Features (BAO, RSD)**

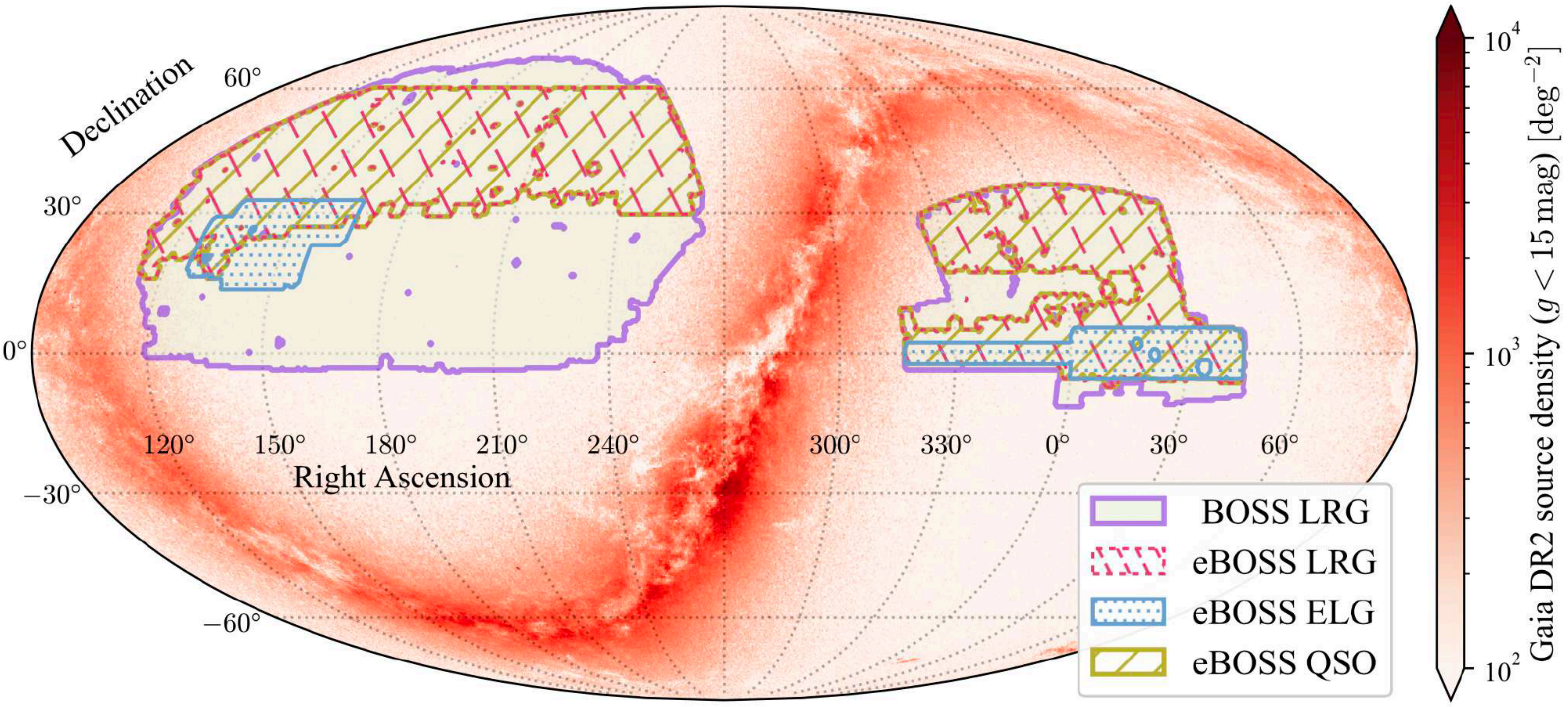


c) Interpretation

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



BOSS & eBOSS



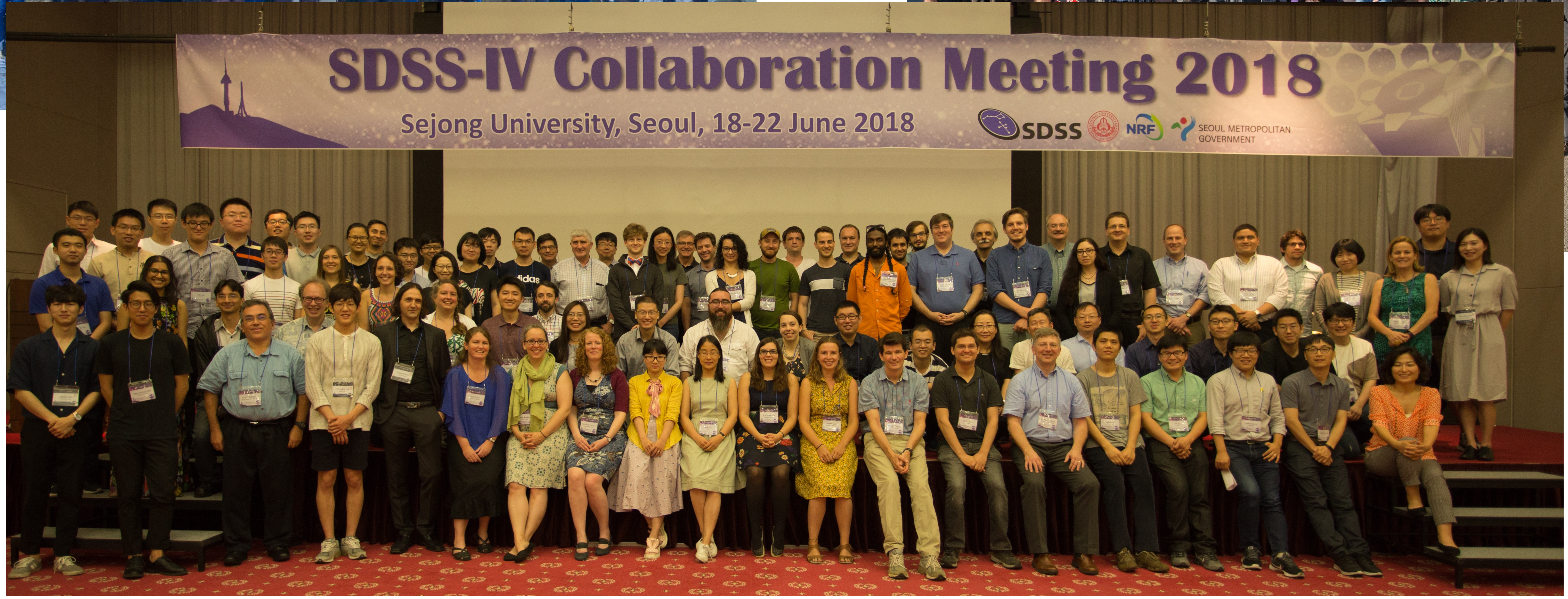
Credit: C. Zhao et al. 2020

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

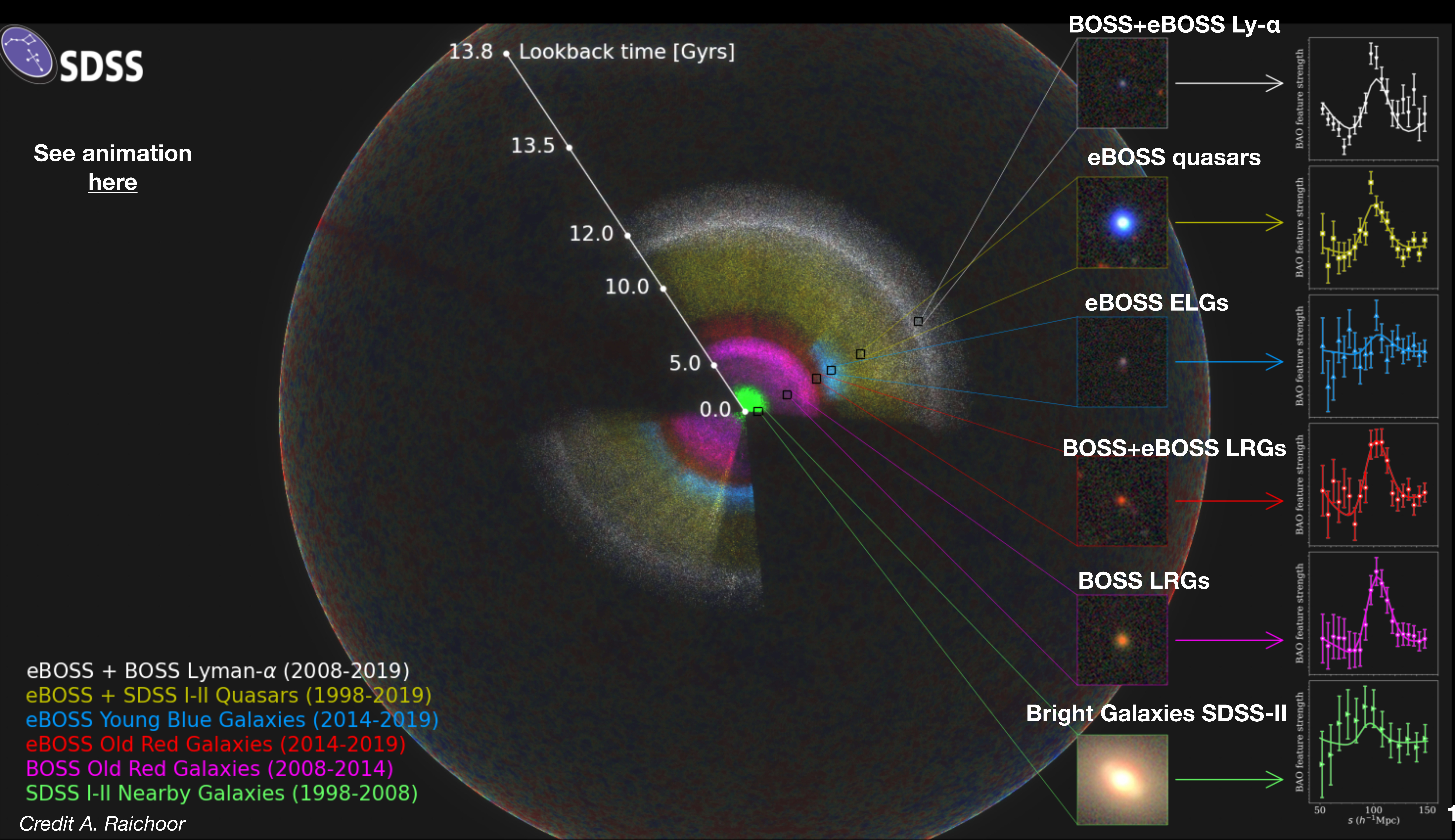
BOSS & eBOSS

eBOSS meeting 2018, München

BOSS meeting 2013, Berkeley



SDSS-IV meeting 2018, Seoul


SDSS
See animation here
13.8
Lookback time [Gyrs]
13.5
12.0
10.0
5.0
0.0
BOSS+eBOSS Ly-α
eBOSS quasars
eBOSS ELGs
BOSS+eBOSS LRGs
BOSS LRGs
Bright Galaxies SDSS-II
BAO feature strength
50
100
150
$s\ (h^{-1}\mathrm{Mpc})$
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

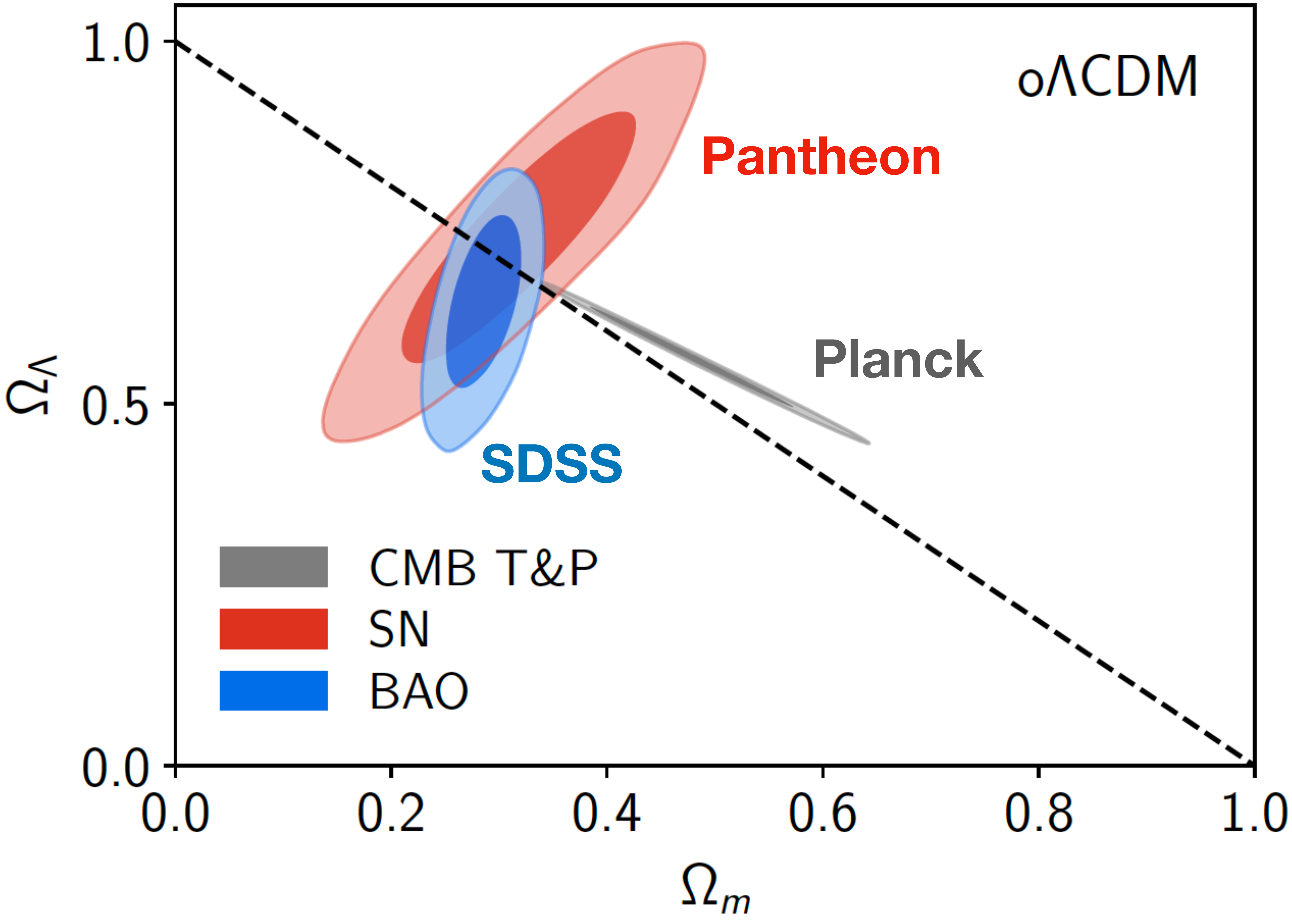
- Cosmology interpretation: eBOSS collaboration et al.
- Catalogues: Ross et al. (LRG & QSO), Raichoor et al. (ELG)
- LRG BAO & RSD: Bautista et al. (Config.), **GM et al**. (Fourier)
- ELG BAO & RSD: Tamone et al. (Config.), de Mattia et al. (Fourier)
- QSO BAO & RSD: Hou et al. (Config.), Neveux et 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

- 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

(eBOSS Collaboration, 2020)



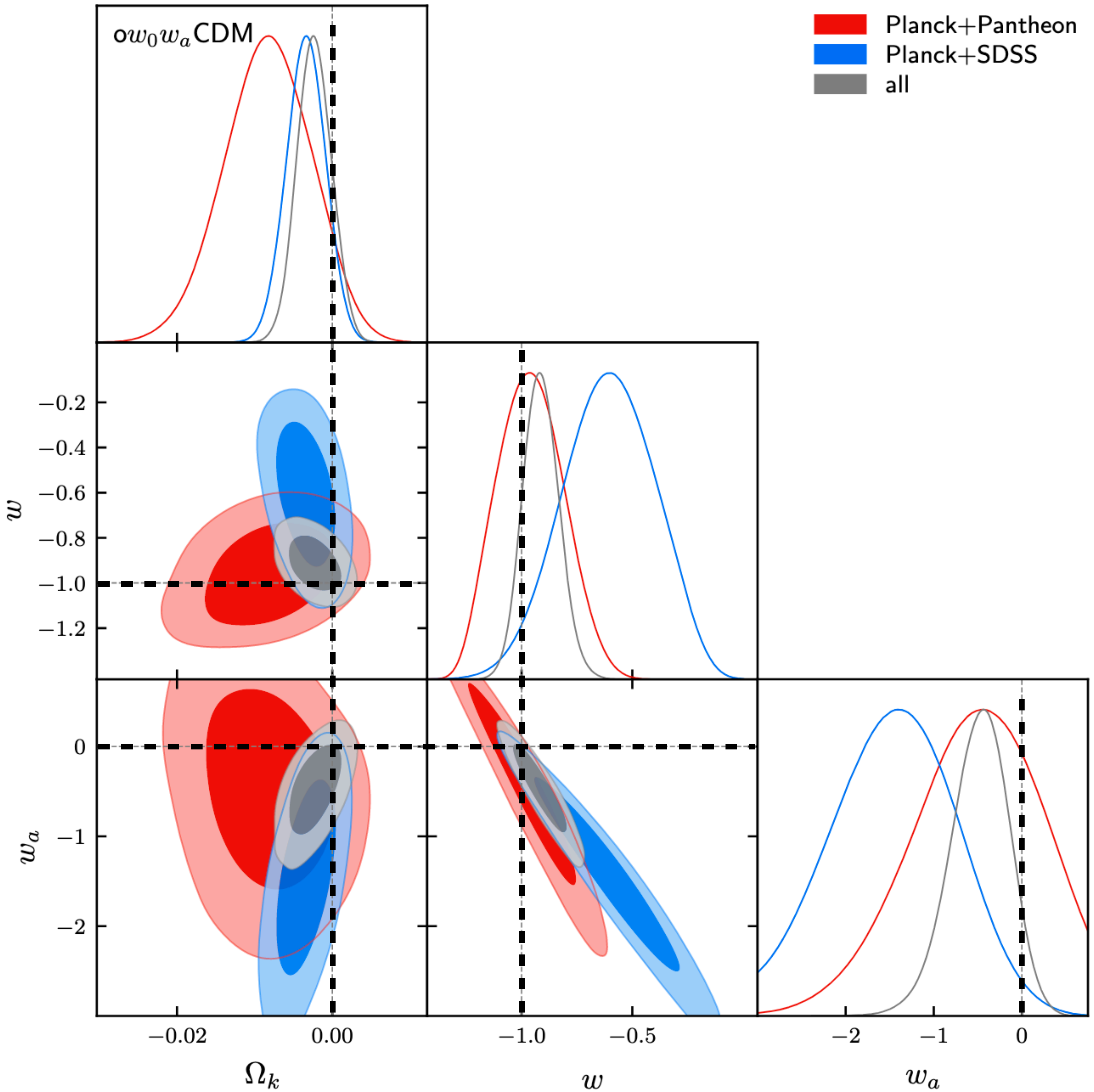
c) Interpretation: ω-ω_a-Ω_k

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

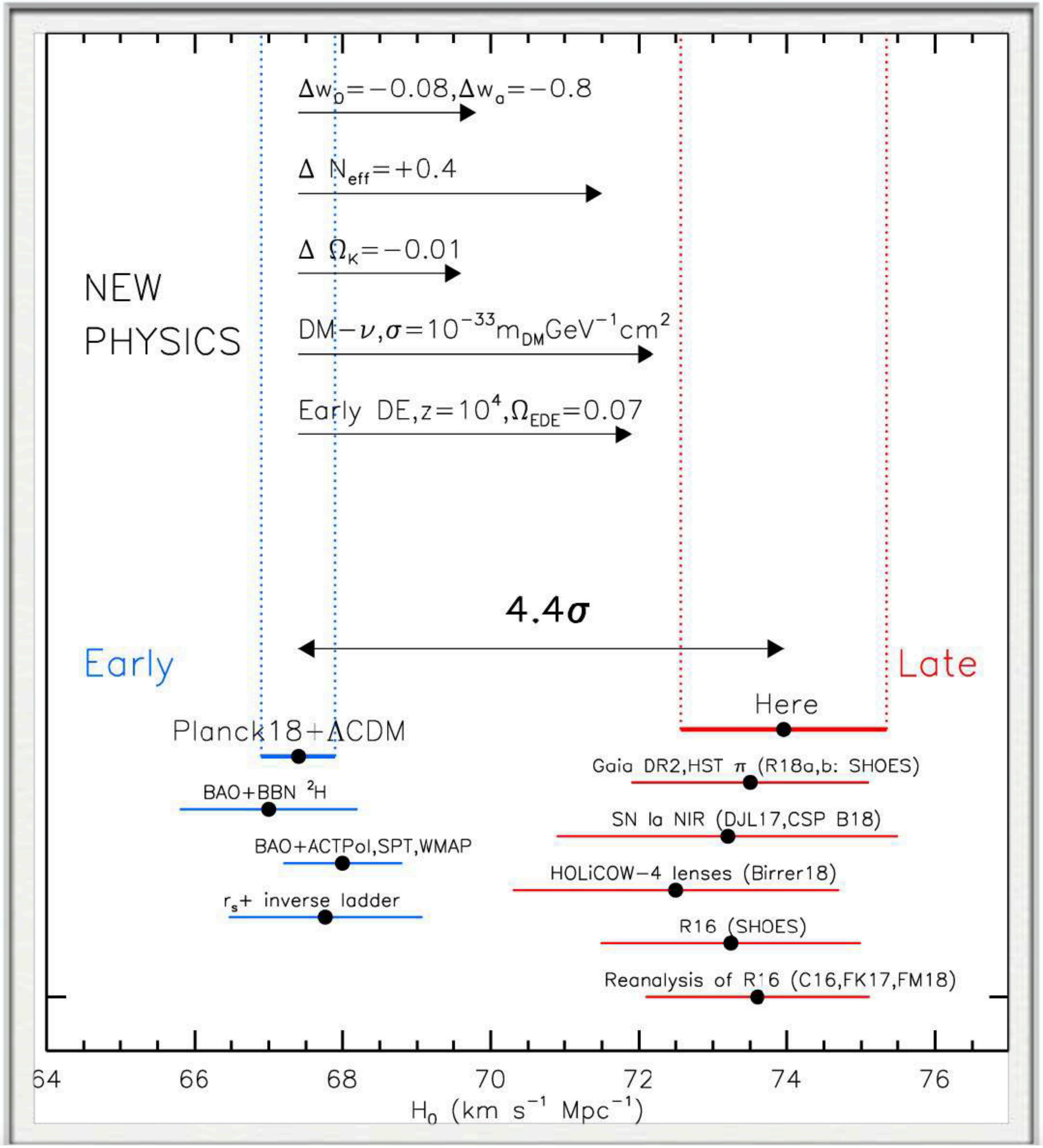
time evolving

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

constant

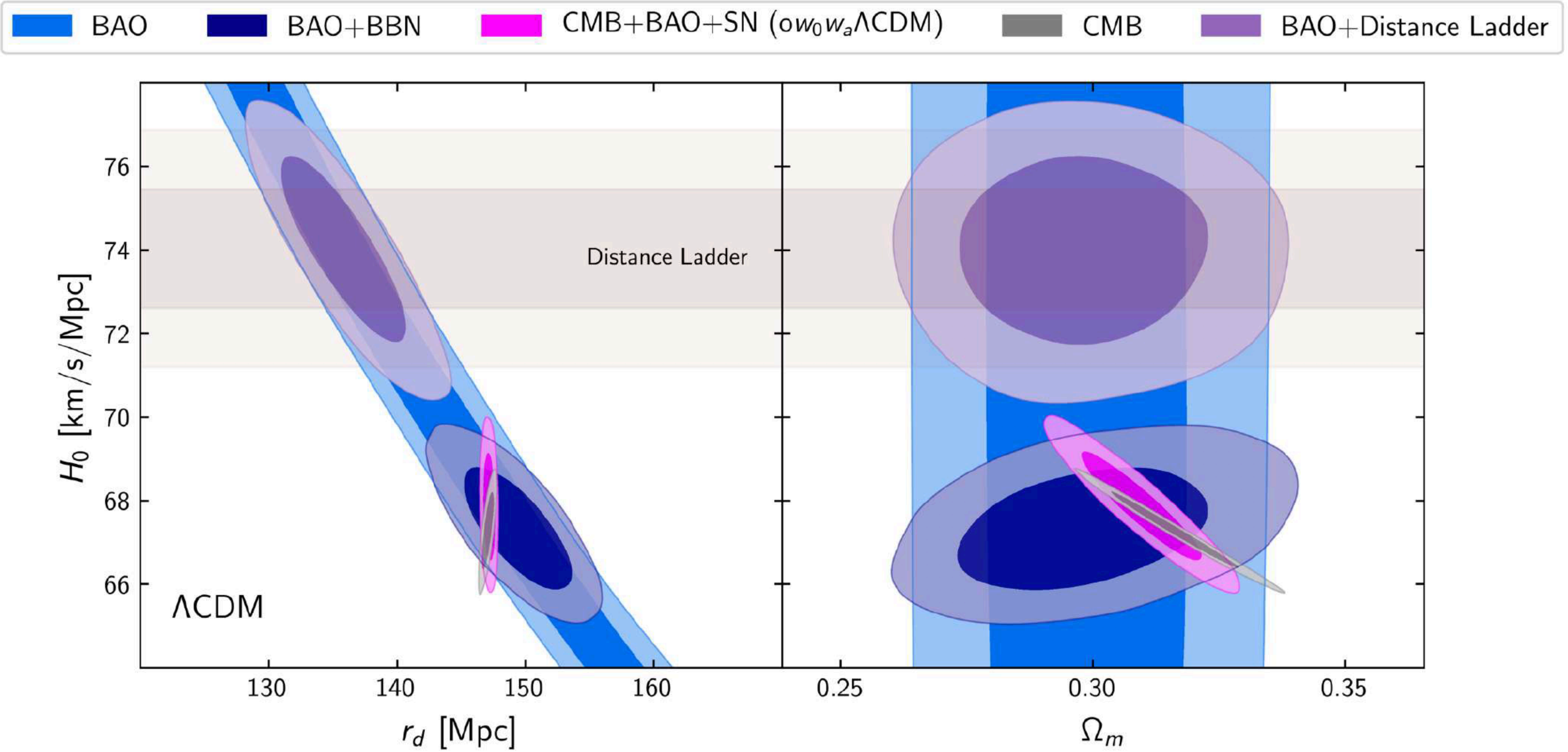


c) Interpretation: H_0



Riess et al. 2019

(inverse distance lader)



Credit: Eva-Maria Müller & SDSS

BAO only measures $D_H(z)/r_{\rm drag}$ $D_M(z)/r_{\rm drag}$

$$r_{\rm drag} = \int_{z_{\rm drag}}^{\infty} dz \, \frac{c_s(z)}{H(z)}$$

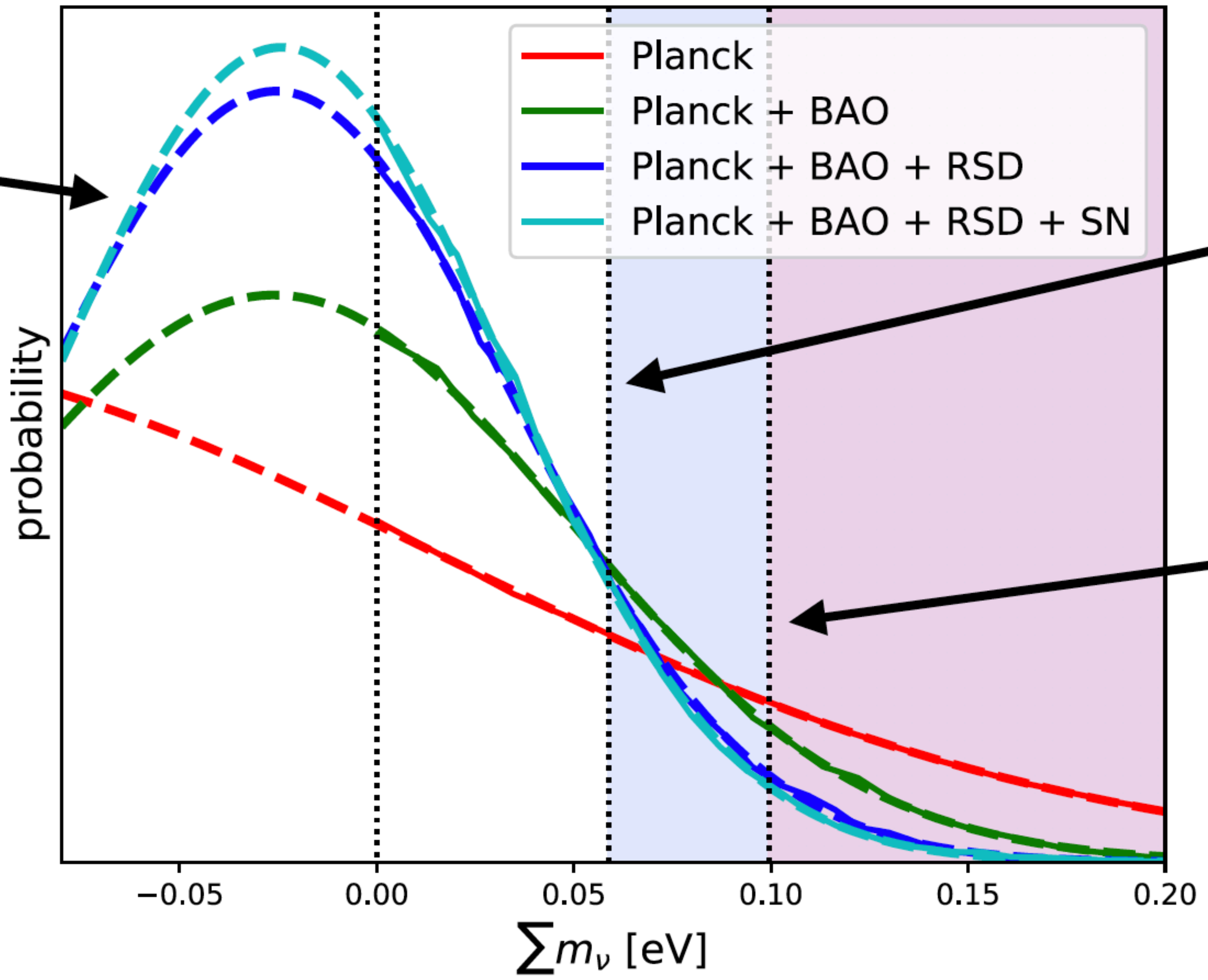
(need info on $h^2\Omega_b$)

c) Interpretation: Neutrinos

Gaussian fits

Cosmology sensitive to the sum of neutrino masses

- Slight preference for Normal Hierarchy



Normal Hierarchy

$\Sigma m_\nu > 60$ meV

Inverted Hierarchy

$\Sigma m_\nu > 100$ meV

Note

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

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

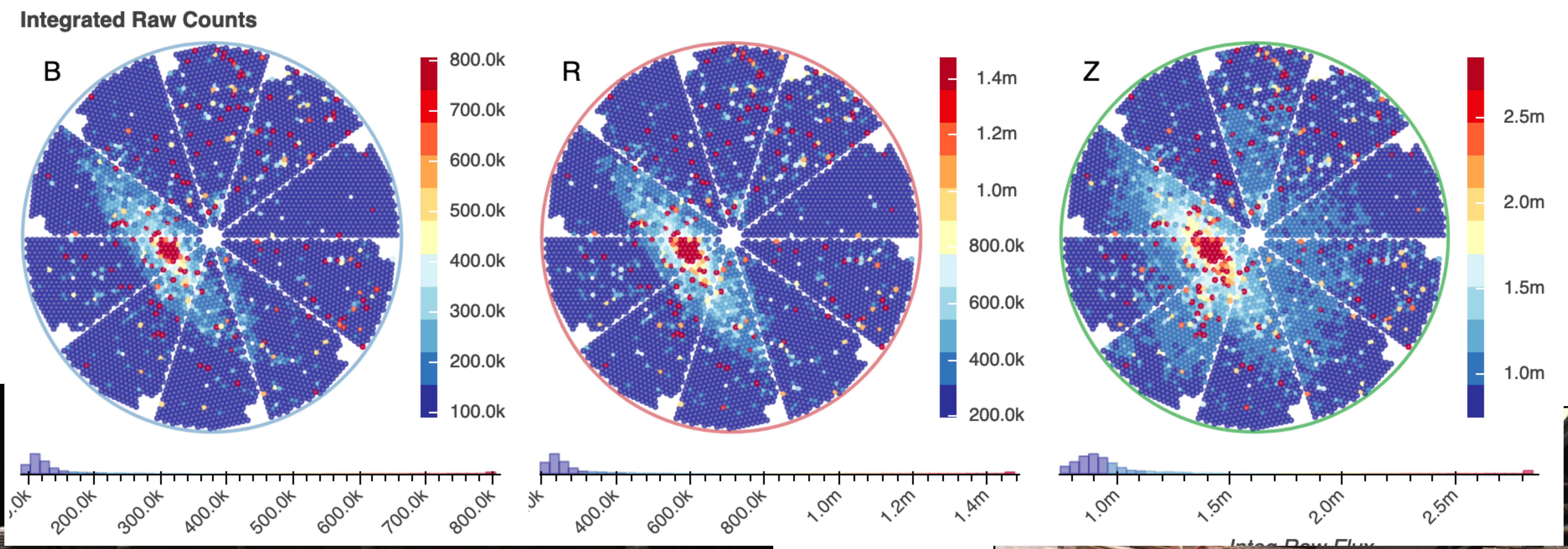
Dark Energy Spectroscopic Instrument: 2021 - 2026

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

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

Spectroscopy **0<z<3.5, 5k fibers**

- Data collection has just started!
- BAO, RSD, fnl, neutrinos, …
- First results expected by the end of 2022 with 1/5 of total volume (~3k deg^2) !


Integrated Raw Counts
B
800.0k
700.0k
600.0k
500.0k
400.0k
300.0k
200.0k
100.0k
200.0k
300.0k
400.0k
500.0k
600.0k
700.0k
800.0k
R
1.4m
1.2m
1.0m
800.0k
600.0k
400.0k
200.0k
400.0k
600.0k
800.0k
1.0m
1.2m
1.4m
Z
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2.0m
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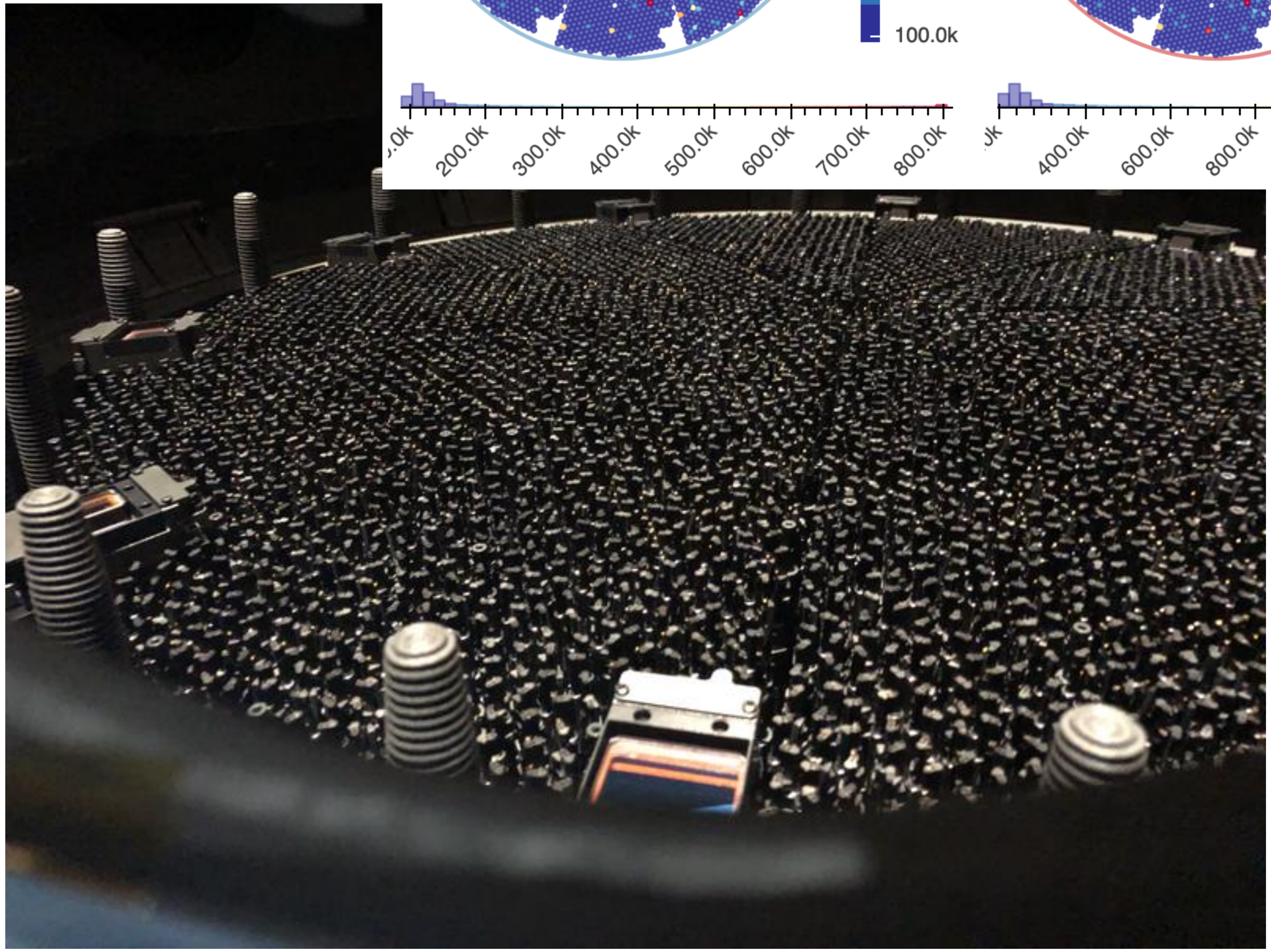
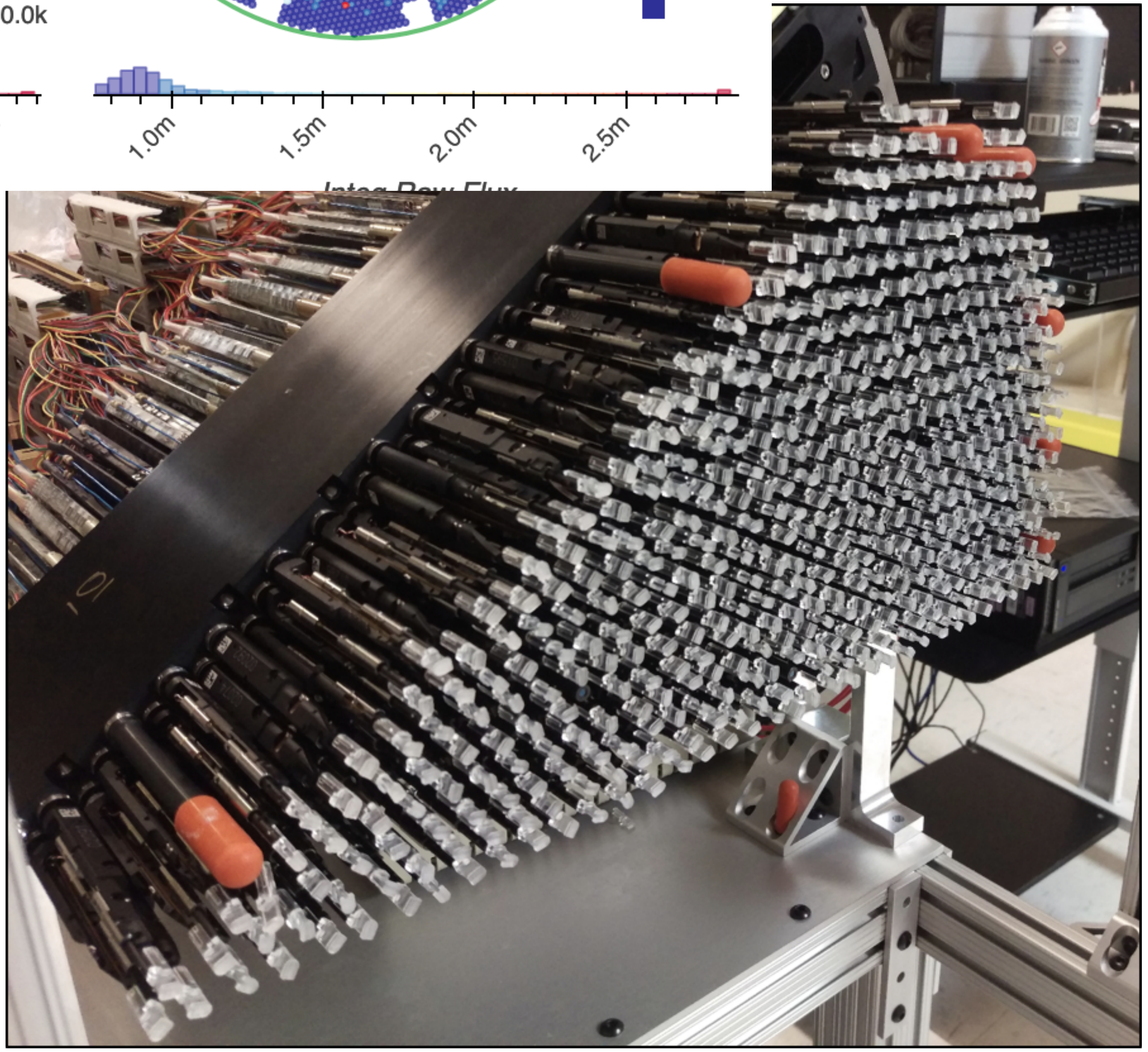
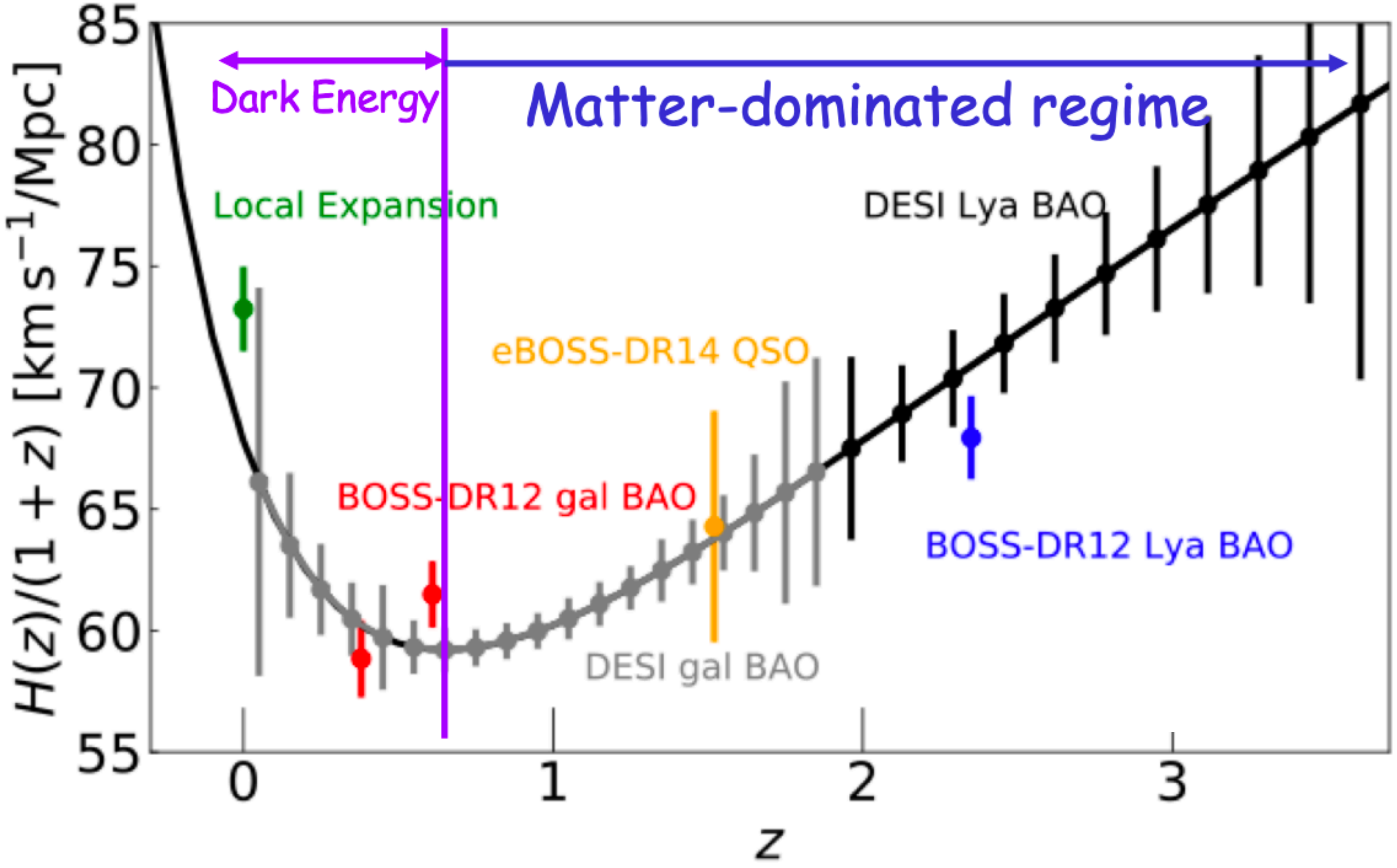
1.5m
2.0m
2.5m



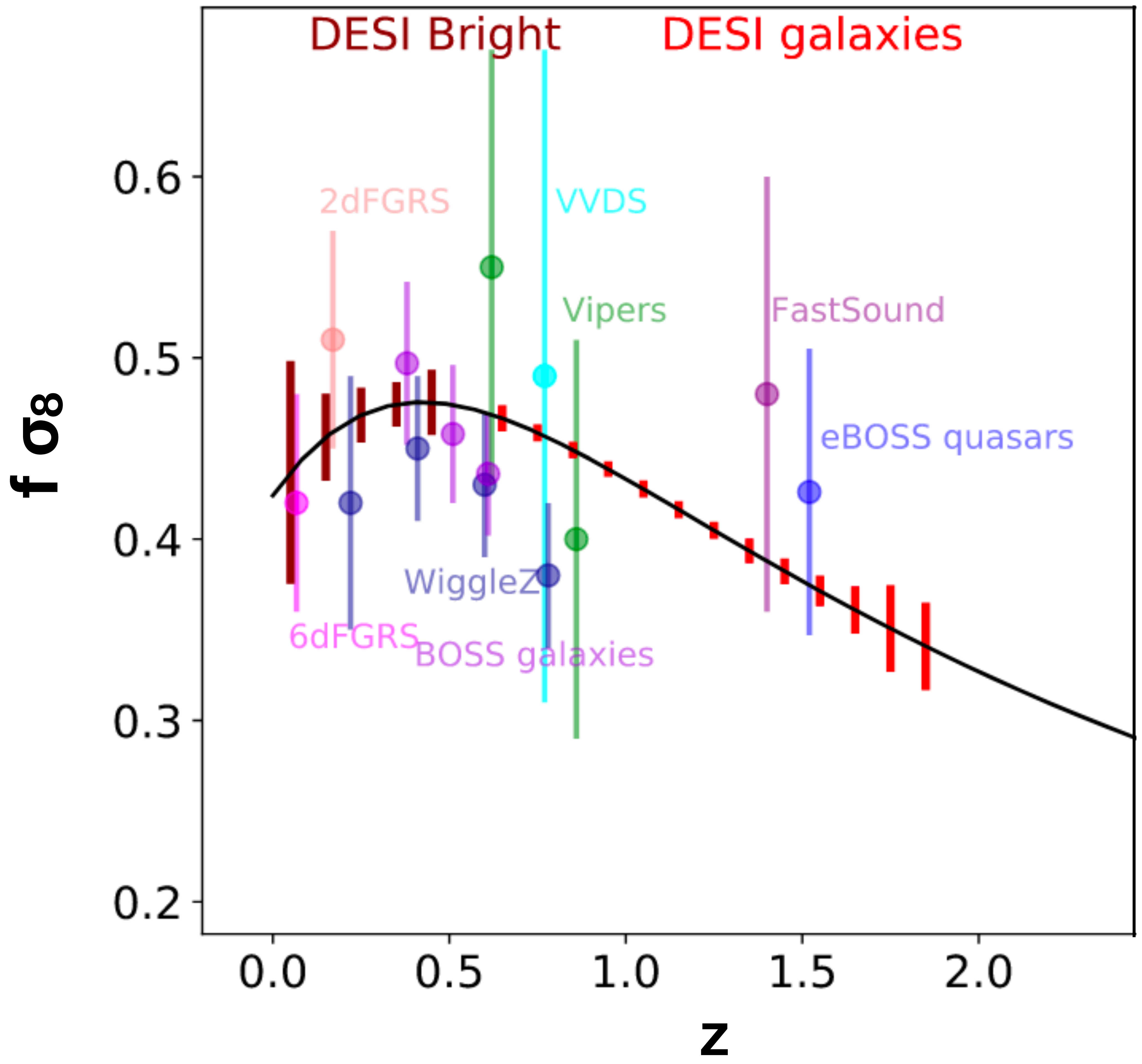


DESI Forescast

Background expansion



Growth of structure



Why should we go blind?

- Avoid confirmation bias

What do we want to blind?

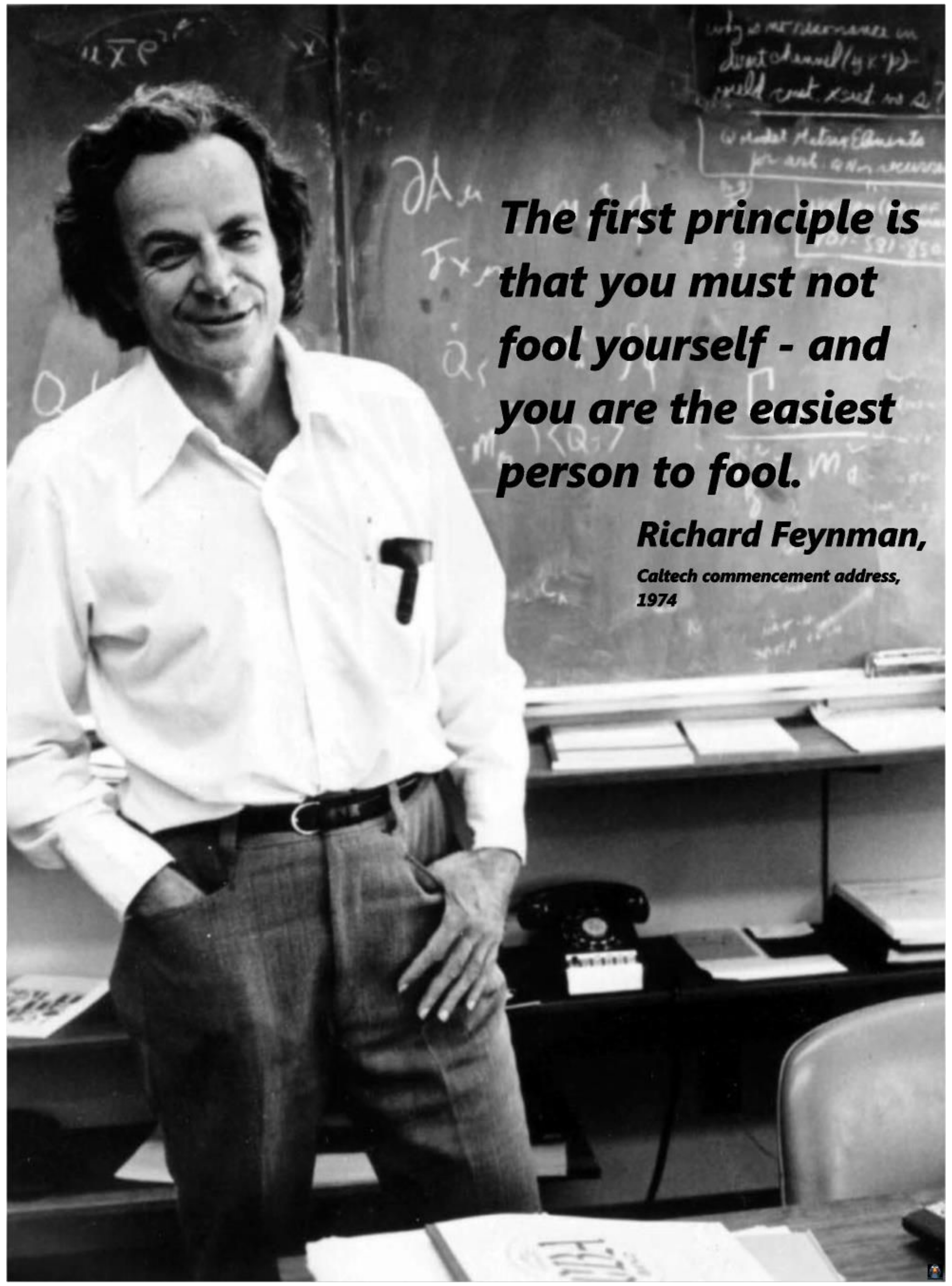
- We blind the redshifts, not angular positions. Blind for cosmology not for systematics

BAO blinding

- Aim to blind the AP geometrical distortions along the LOS

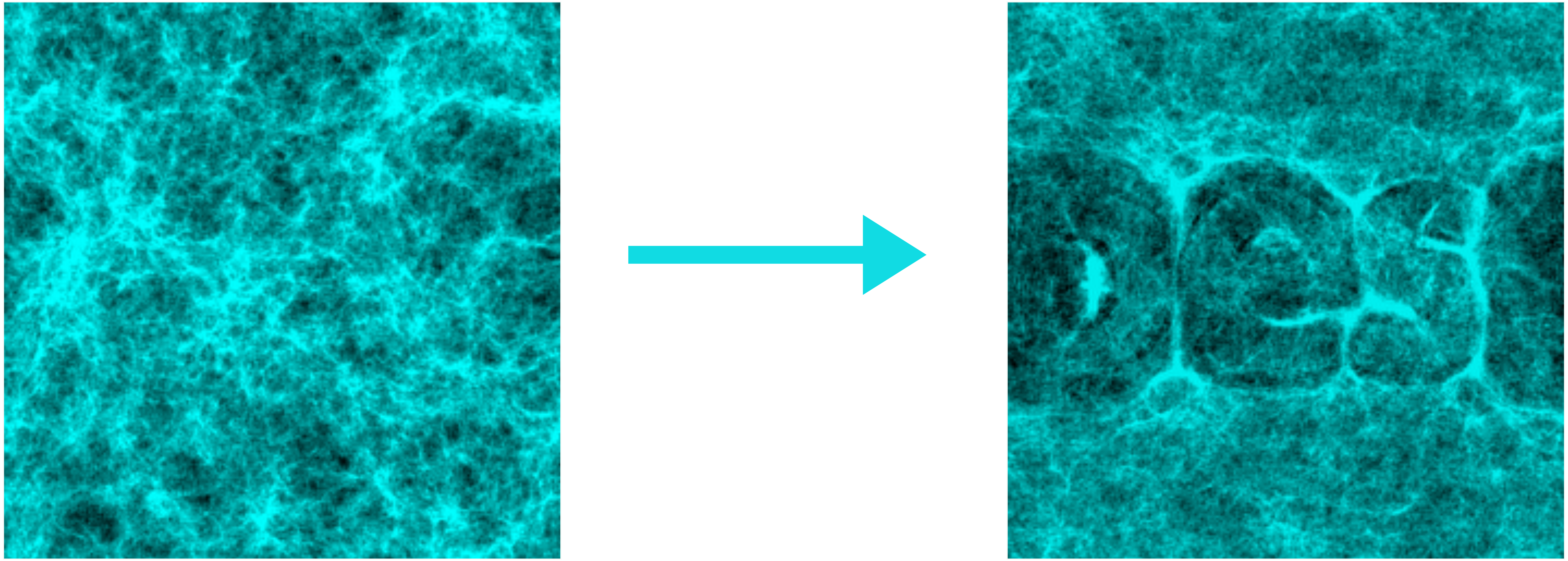
RSD blinding

- Aim to blind the the growth factor, f (along LOS)



Blinding Strategy

Proposal for blinding: catalogue level



- Pros: consistently blind for all statistics at once (eg. P(k) and ξ(r)).
- Cons: more complex process than just blind on summary statistics

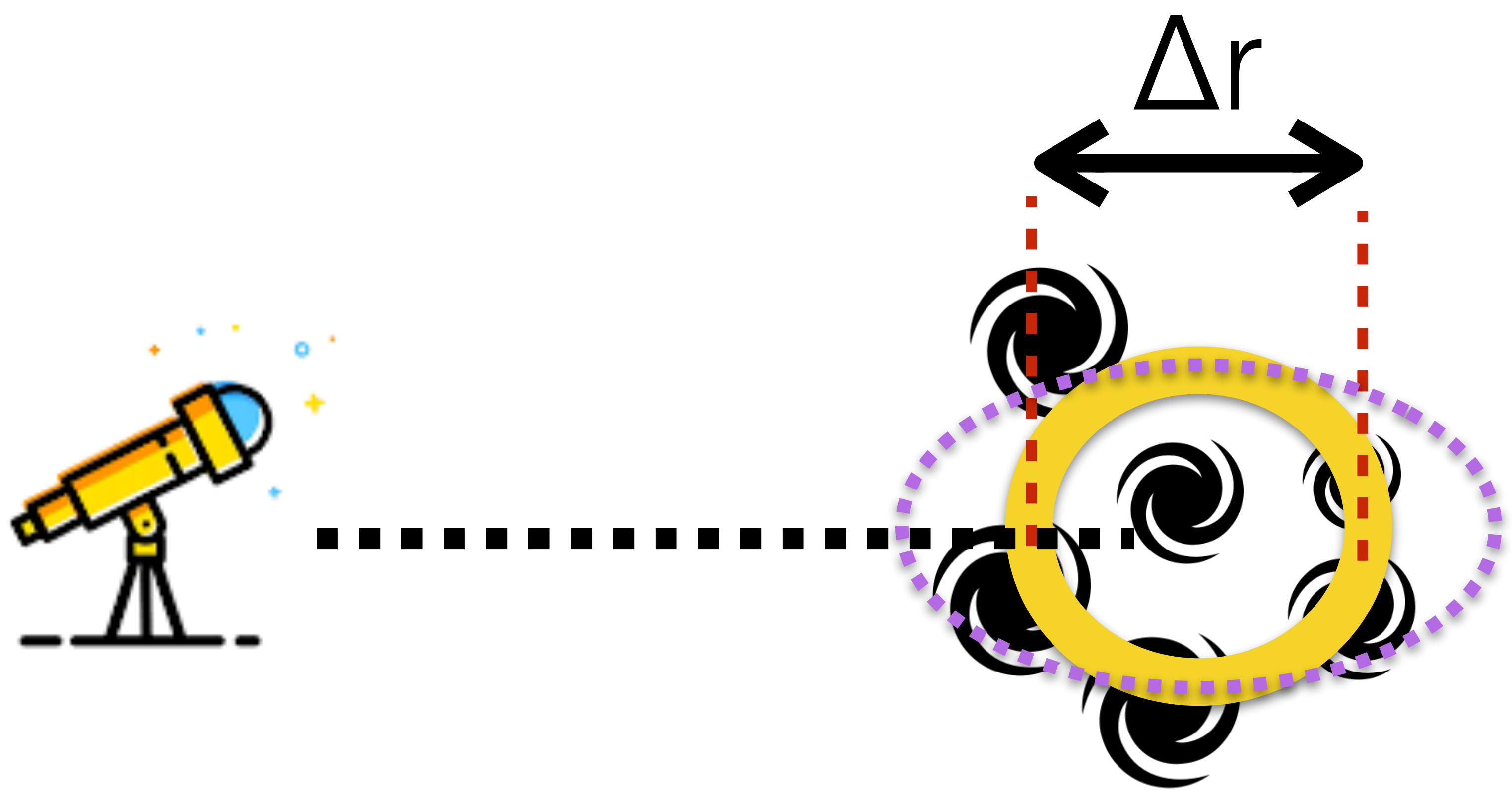
Ref: Brieden, GM, Verde, Bernal 2020, arXiv: 2006.10857

Blinding Strategy

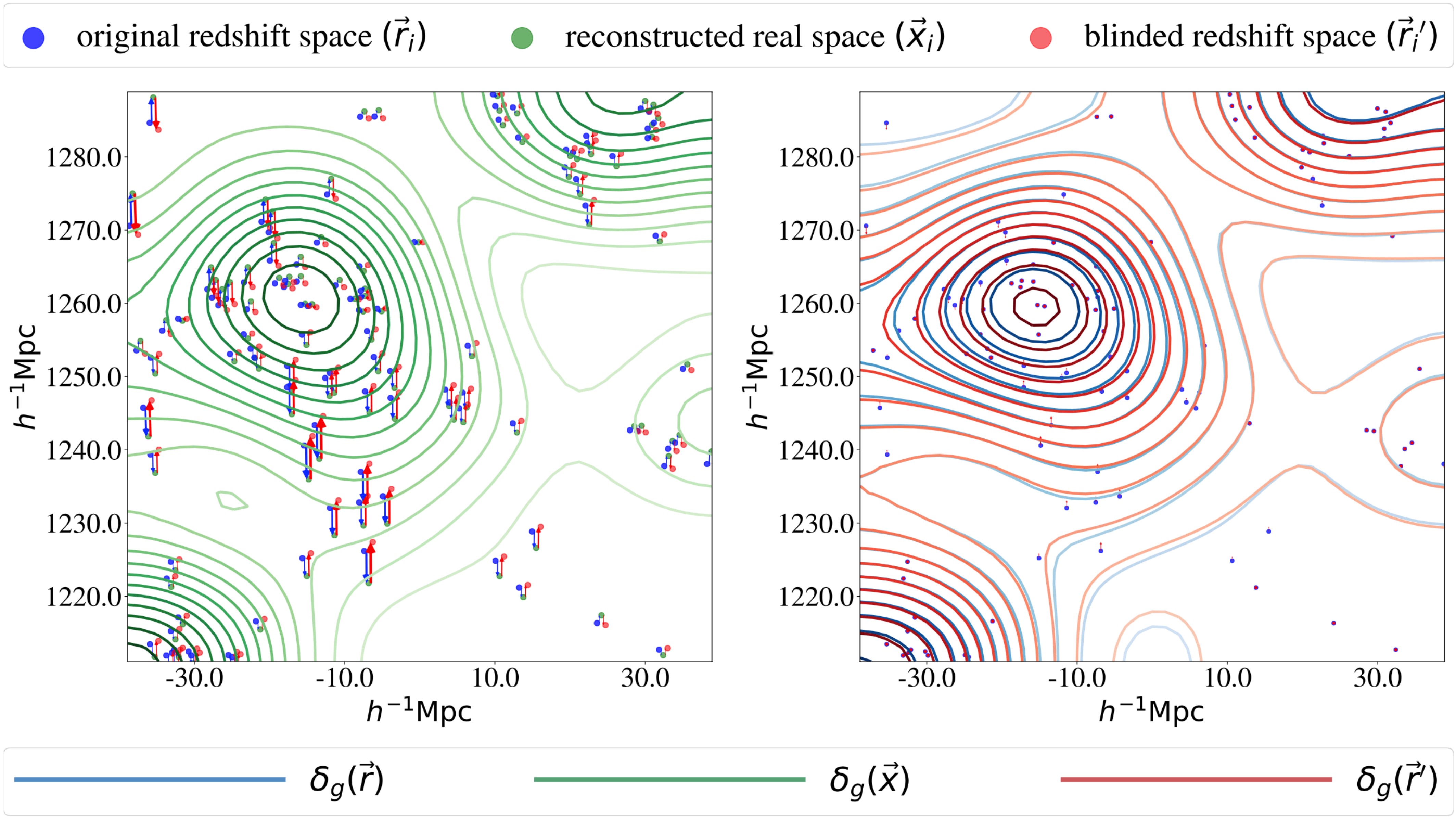
Blind along the line-of-sight

- Avoid modifying angular positions (imaging clustering is not blind anyway)
- Blind for BAO & RSD signal at the catalogue level through two redshift shifts,

1. geometrical AP-like shift



2. density-dependent RSD-like shift (requires reconstruction)



Blinding Strategy

Blinding the background (BAO)

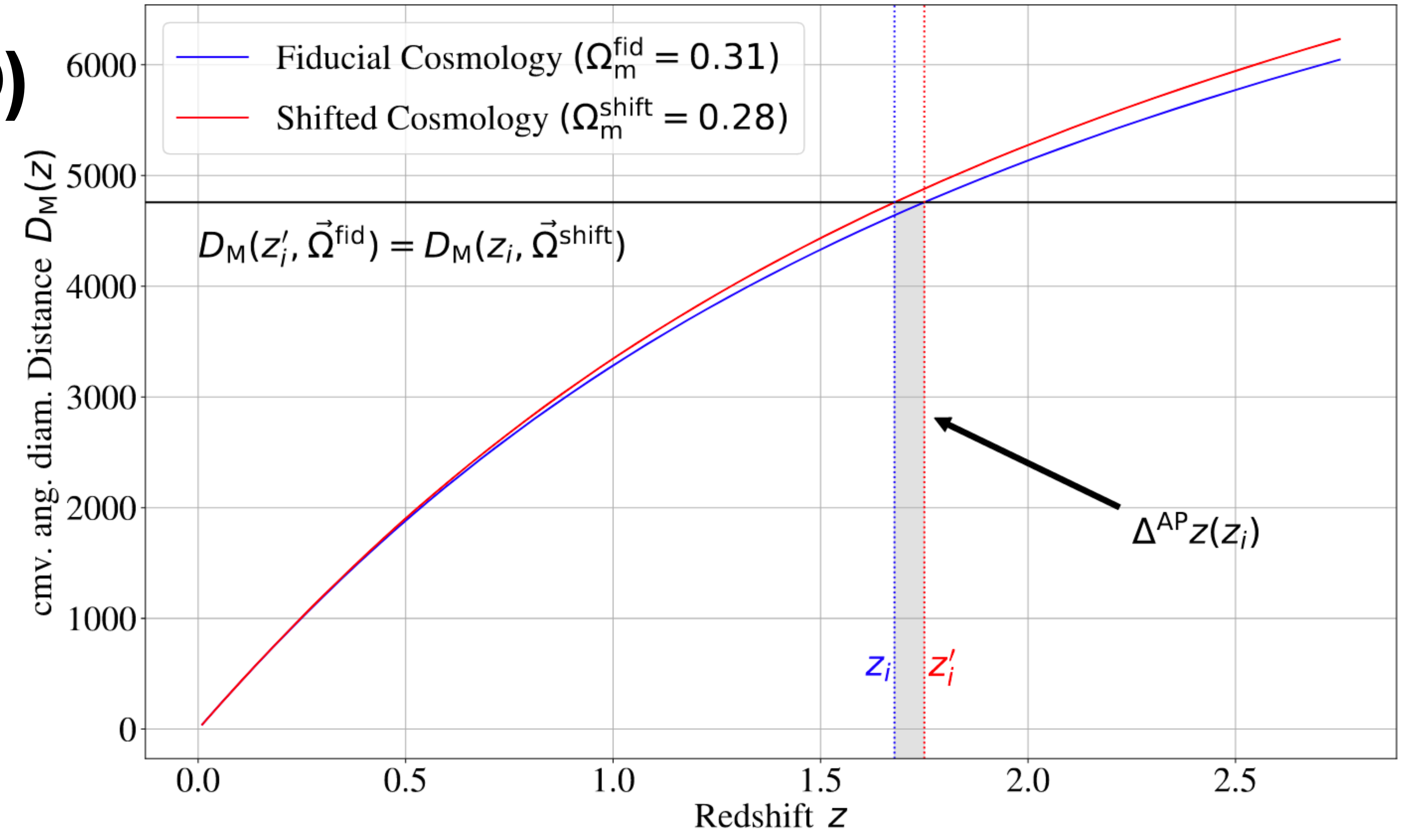
$\Omega^{\rm fid} = \{\Omega_m, h, \ldots\}$ Arbitrary fiducial cosmology

$$\Omega^{\rm shift} = \Omega^{\rm fid} + \Delta\Omega$$

$$z_i \xrightarrow{\Omega^{\rm fid}} D_{M,i} \xrightarrow{\Omega^{\rm shift}} z_i' \xrightarrow{\Omega^{\rm fid}} D_{M,i}'$$

(blinded distances or blinded redshifts)

$$z_i' = z_i + \Delta z$$



Fiducial

$$\alpha_{\parallel,\perp} = \frac{D_x r_d^{\rm fid}}{D_x^{\rm fid} r_d};$$

Blinded

$$\alpha_{\parallel,\perp}' = \frac{D_x r_d^{\rm fid}}{D_x^{\rm shift} r_d};$$

$\longrightarrow$

$$\alpha_{\parallel,\perp} = \alpha_{\parallel,\perp}' \frac{D_x^{shift}}{D_x^{\rm fid}}$$

Correction after unblinding before re-analysing

Blinding Strategy

Blinding the perturbations (RSD)

- Use reconstruction to imprint a new logarithmic growth rate along the LOS

Smooth the density field to solve for Ψ

$$\nabla \cdot \Psi + \frac{f}{b}\nabla \cdot (\Psi \cdot \hat{r})\hat{r} = -\frac{\delta_g}{b};$$

Shift galaxies back by the total displacement field ψ, only using Δf=f-f'

$$r \longrightarrow r' + (f - f')(\Psi \cdot \hat{r})\hat{r};$$

- This effectively imprint a new growth factor f' at large scales.
- Scales below smoothing scale unmodified

where

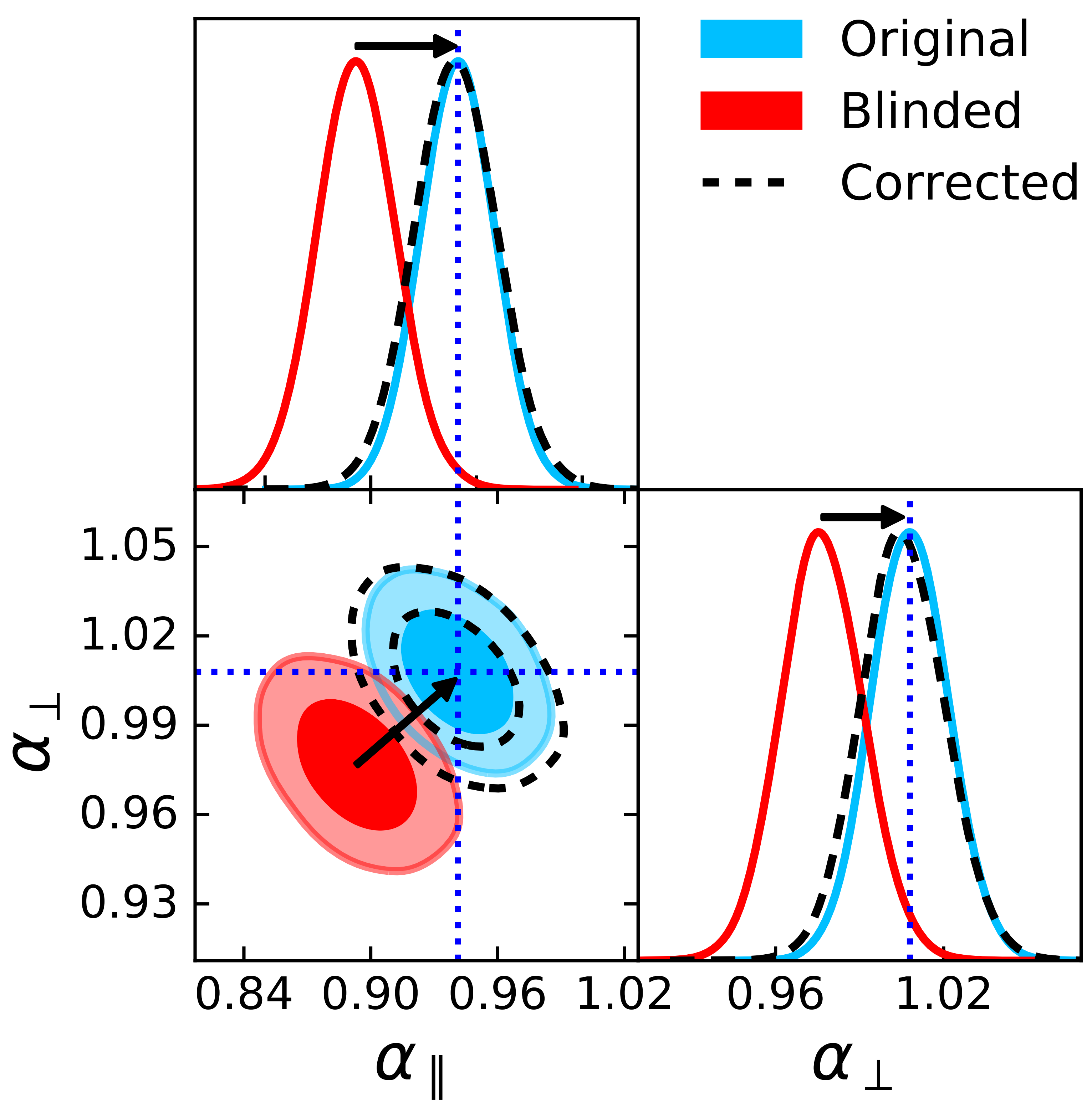
$$f(z) = \Omega(z)^{\gamma^{GR}};$$

$$f'(z) = \Omega(z)^{\gamma'};$$

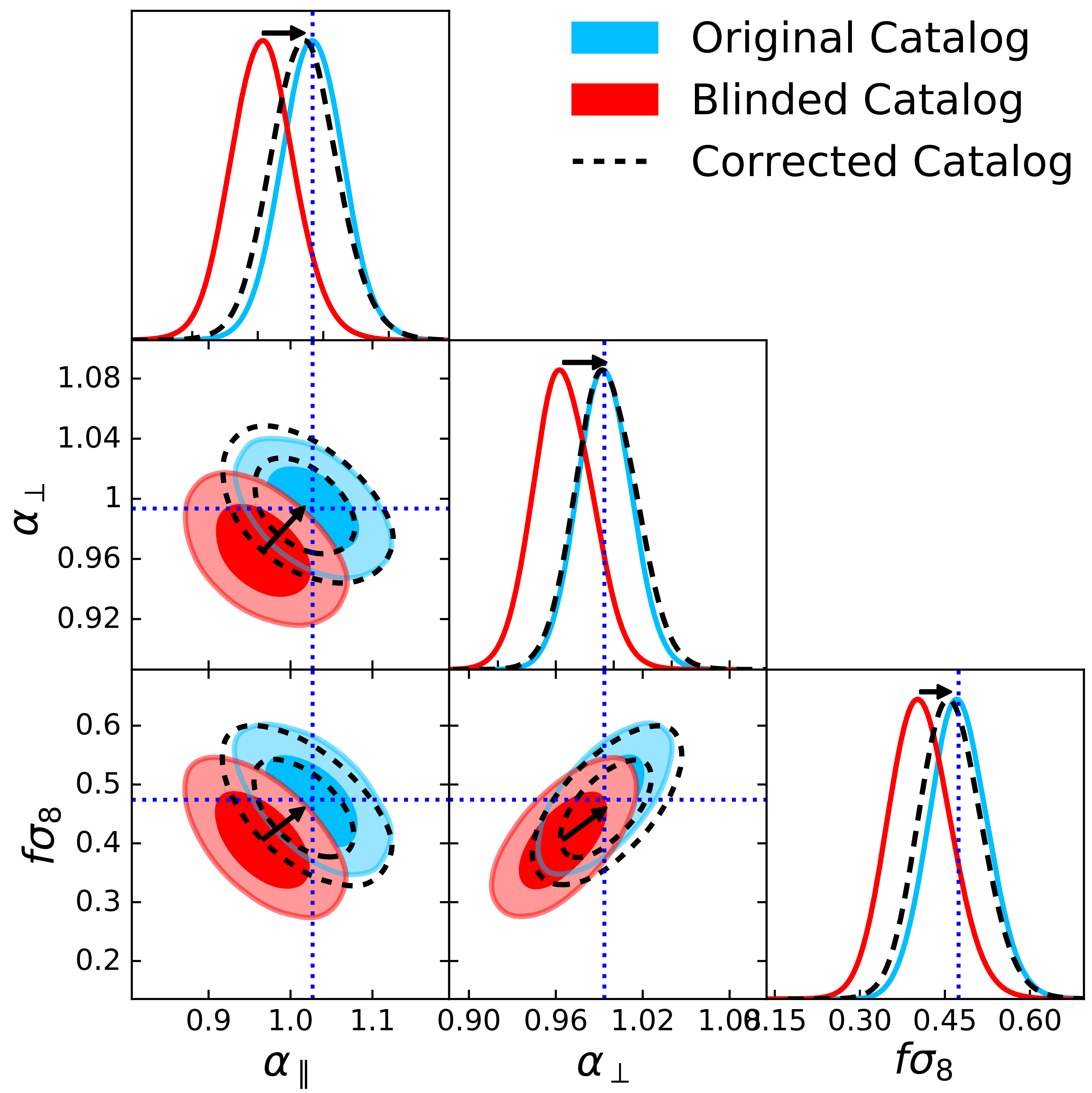
Blinding Tests

Proof of concept with BOSS CMASS & LOWZ data

BAO post-recon



Full Shape



Ref: Brieden, GM, Verde, Bernal 2020, arXiv: 2006.10857

ShapeFit: beyond BAO and RSD

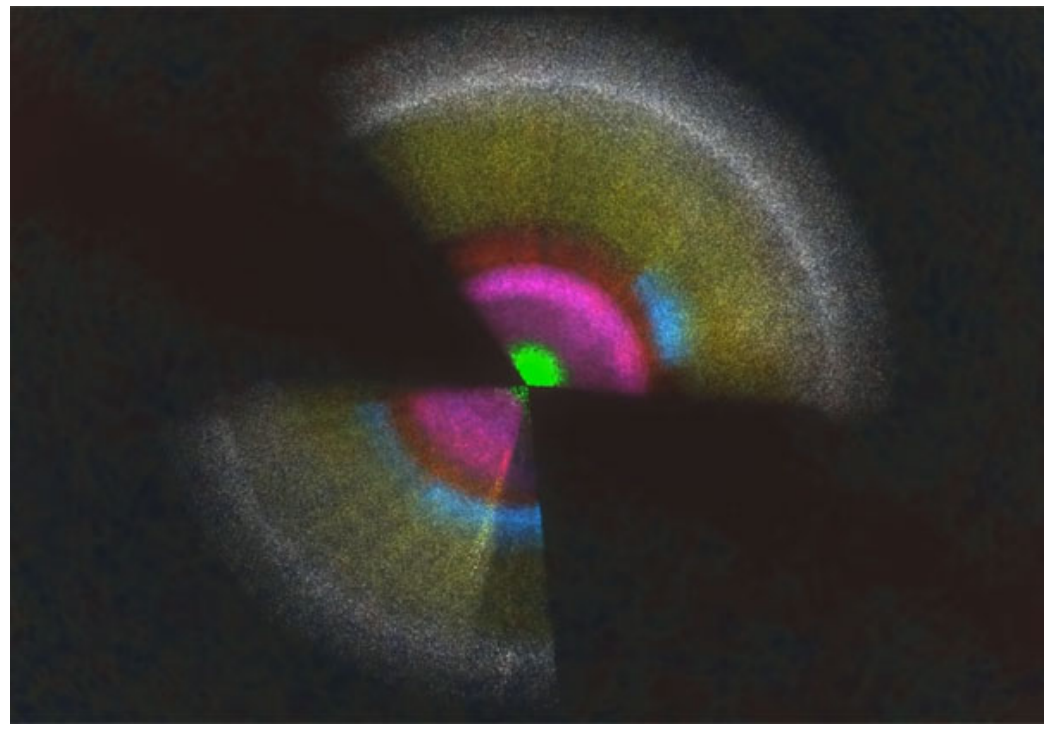
Standard analysis: Uses a fixed template and modify it according to physical quantities: BAO (parallel and perpendicular) and RSD signal, and constrain: $D_H(z)/r_{drag}$, $D_M(z)/r_{drag}$, $f\sigma_8(z)$. Then later these can be used to constrains the parameters of any specific model: $\Omega_x h^2$, h, A_s, etc

Full Modellig (à la Planck): Boltzman code + non-linear correction to generate a P(k) signal and directly constrains the parameters of the model: $\Omega_x h^2$, h, A_s, etc

- **How much information is lost when compressing?**
- **Where does this (extra) information come from?**
- **Is this information robust under systematics?**
- **Which is the effect of fixing the template in the classical analysis?**

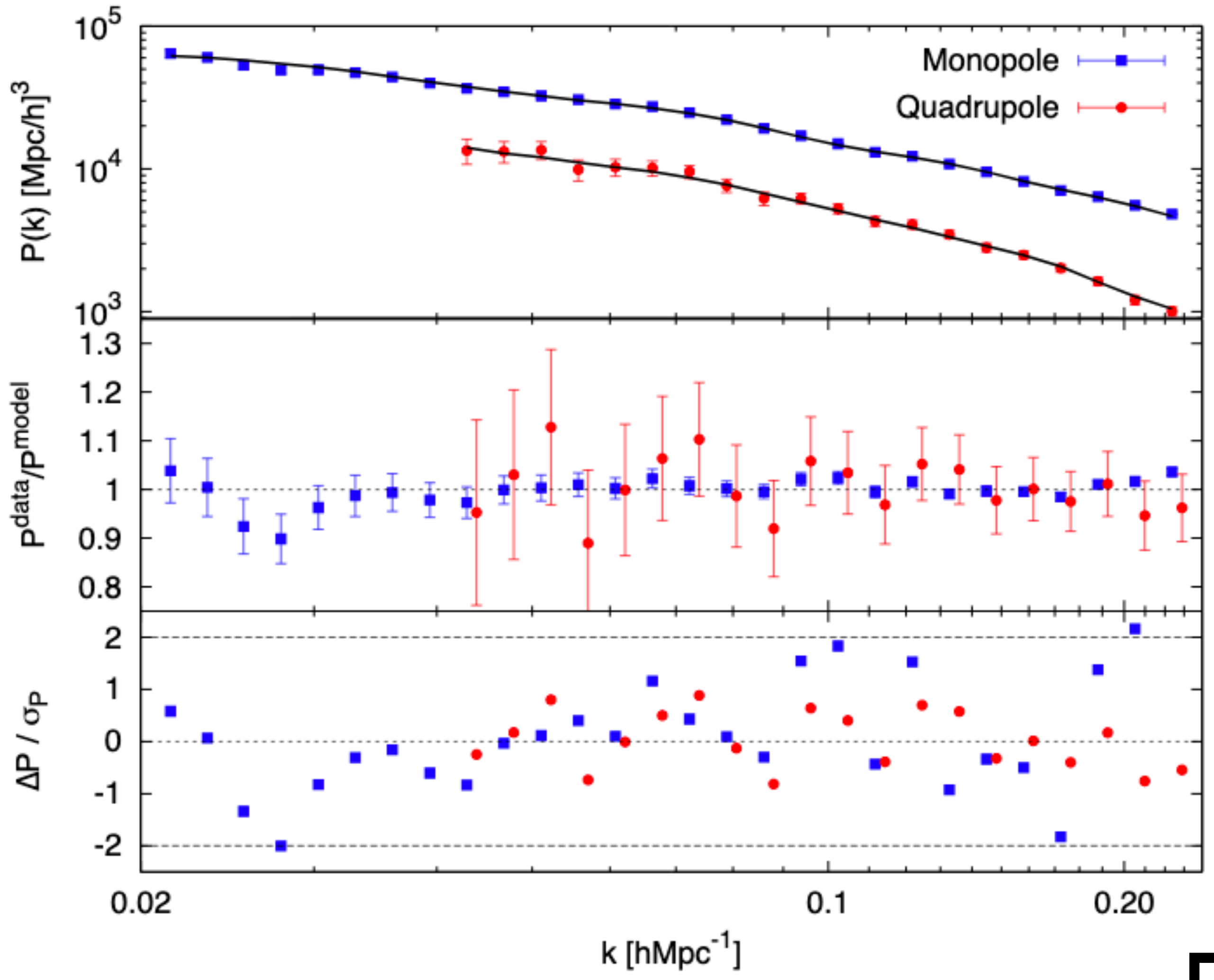
ShapeFit: beyond BAO and RSD

- **LSS Galaxy Maps**



a) Compression

- **Summary Statistics**



b) Identification of robust features

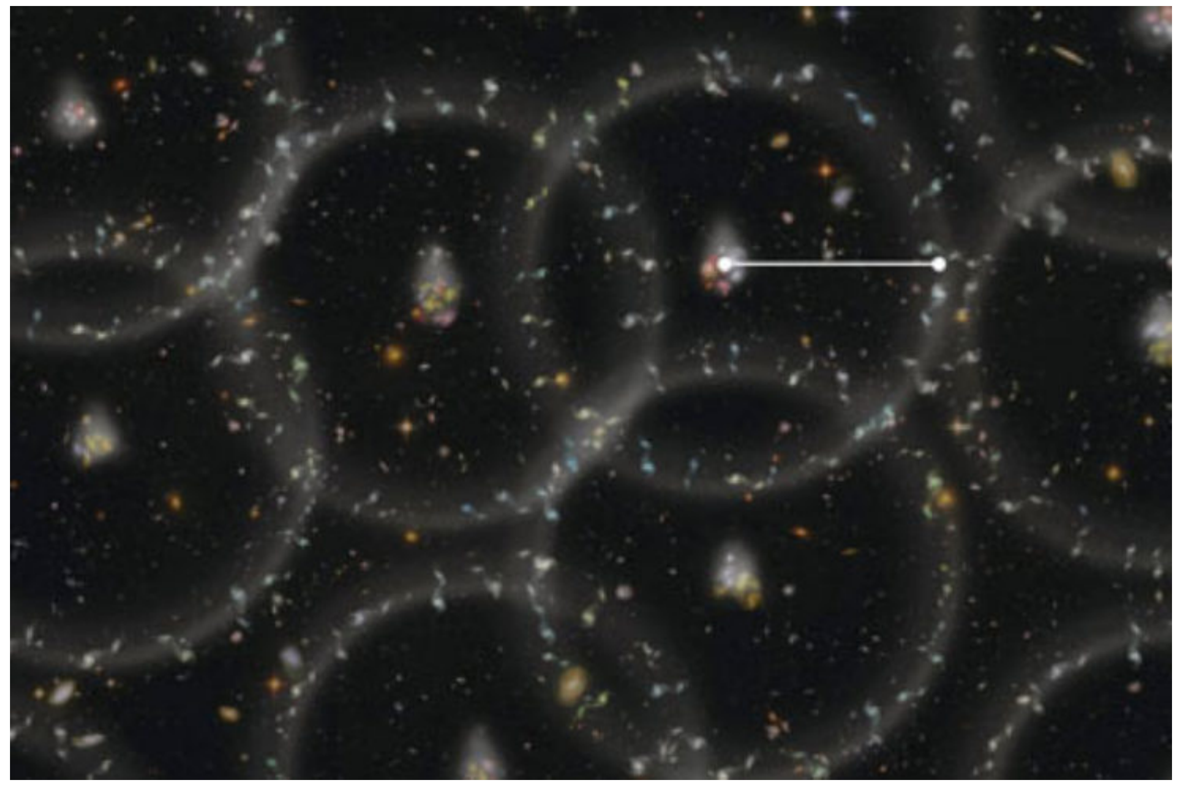
Compressed set of parameters

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

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

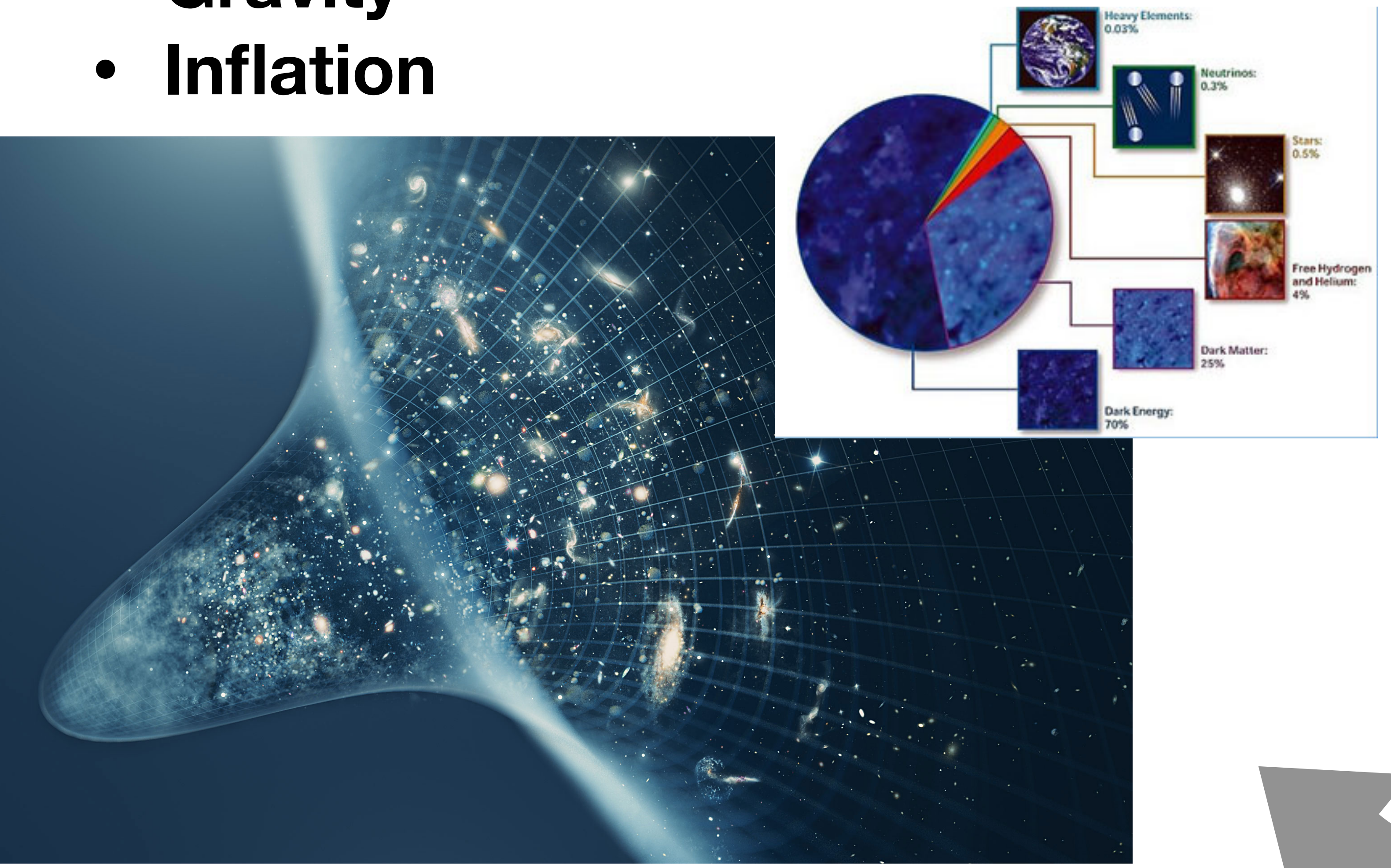
$$f\sigma_8(z,\mathbf{\Omega}) = \Omega_m(z,\mathbf{\Omega})^\gamma \sigma_8(z)$$

- **Features (BAO, RSD)**



c) Interpretation

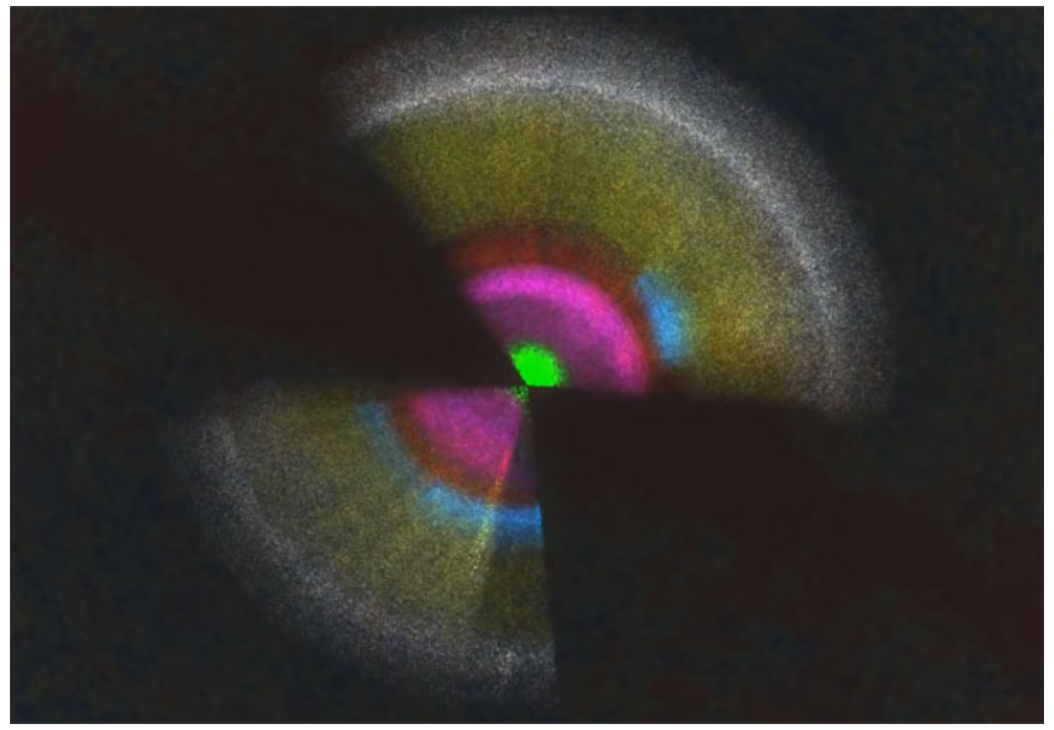
- **Cosmological parameters**
- **Gravity**
- **Inflation**



$\{\Omega_b h^2, \Omega_m h^2, h, A_s, n_s, \ldots\}$

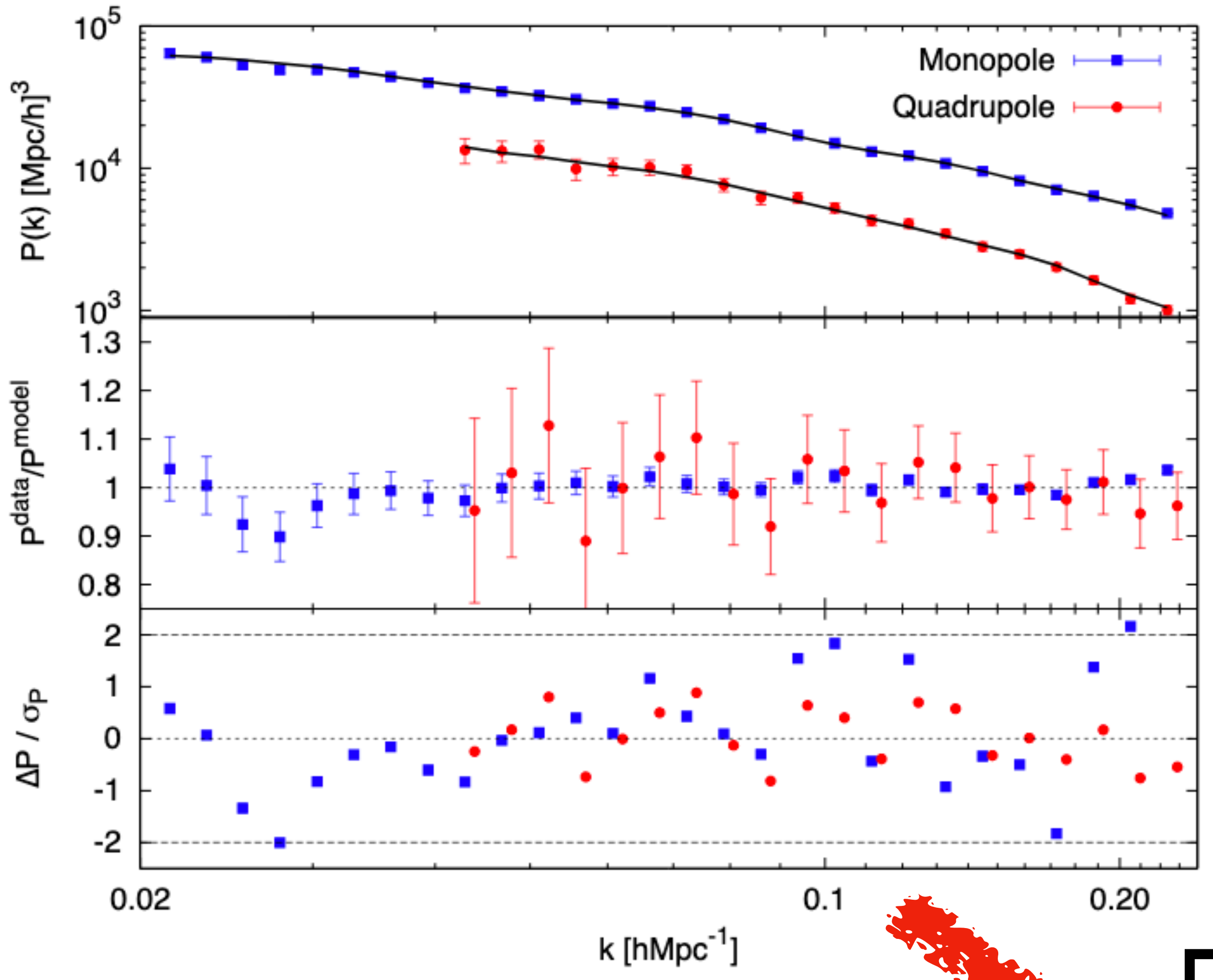
ShapeFit: beyond BAO and RSD

- **LSS Galaxy Maps**



a) Compression

- **Summary Statistics**



b) Identification of robust features

Compressed set of parameters

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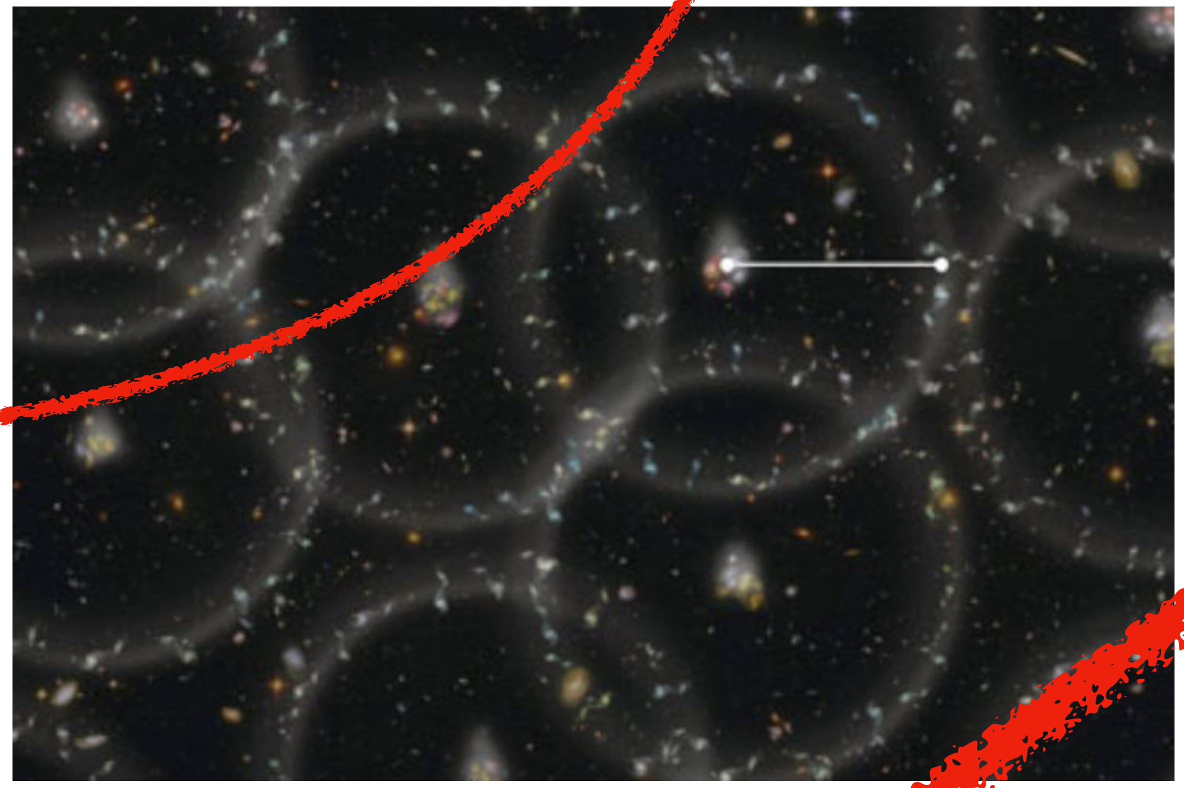
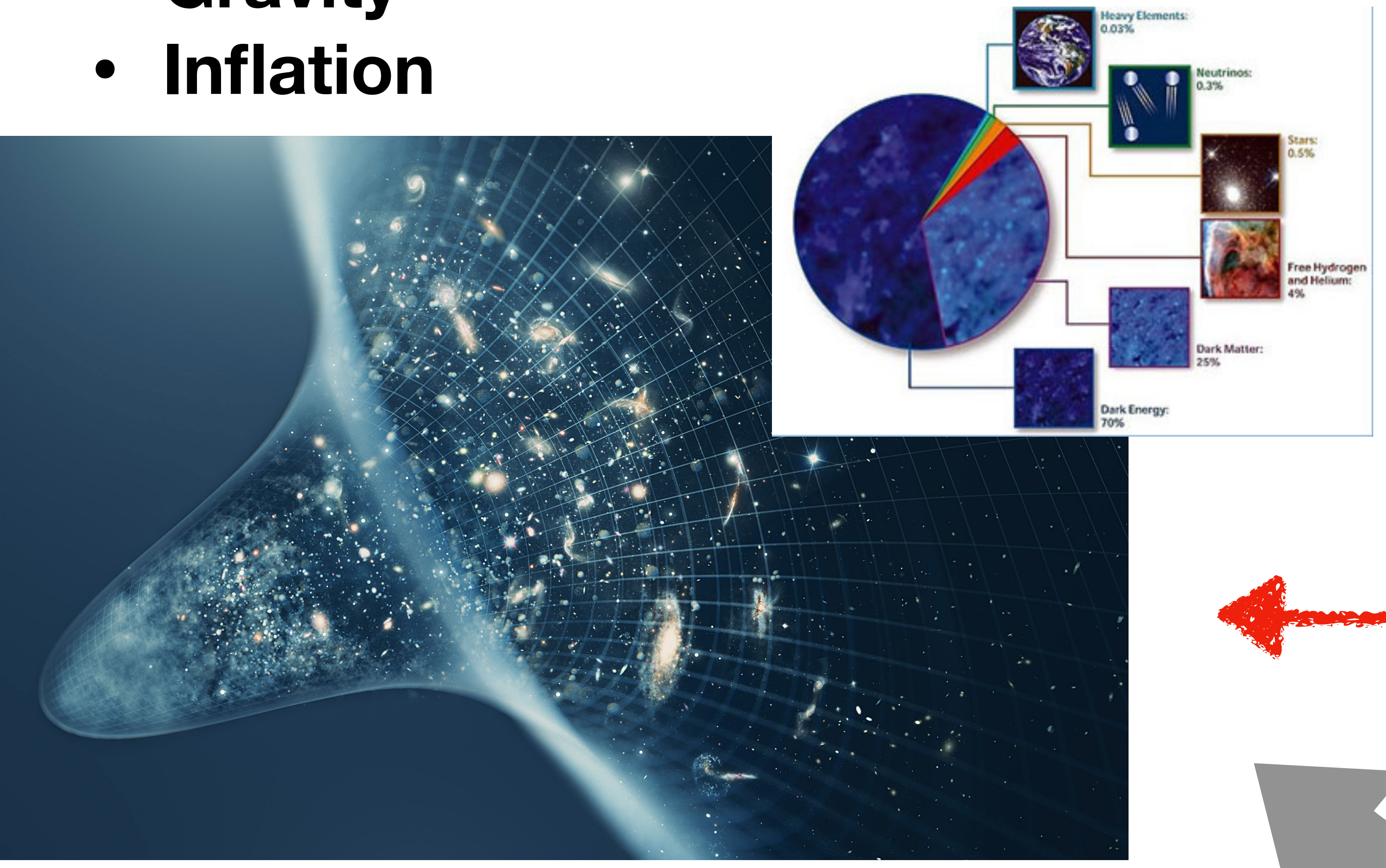
- **Features (BAO, RSD)**



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



$\{\Omega_b h^2, \Omega_m h^2, h, A_s, n_s, \ldots\}$

c) Interpretation

General Picture

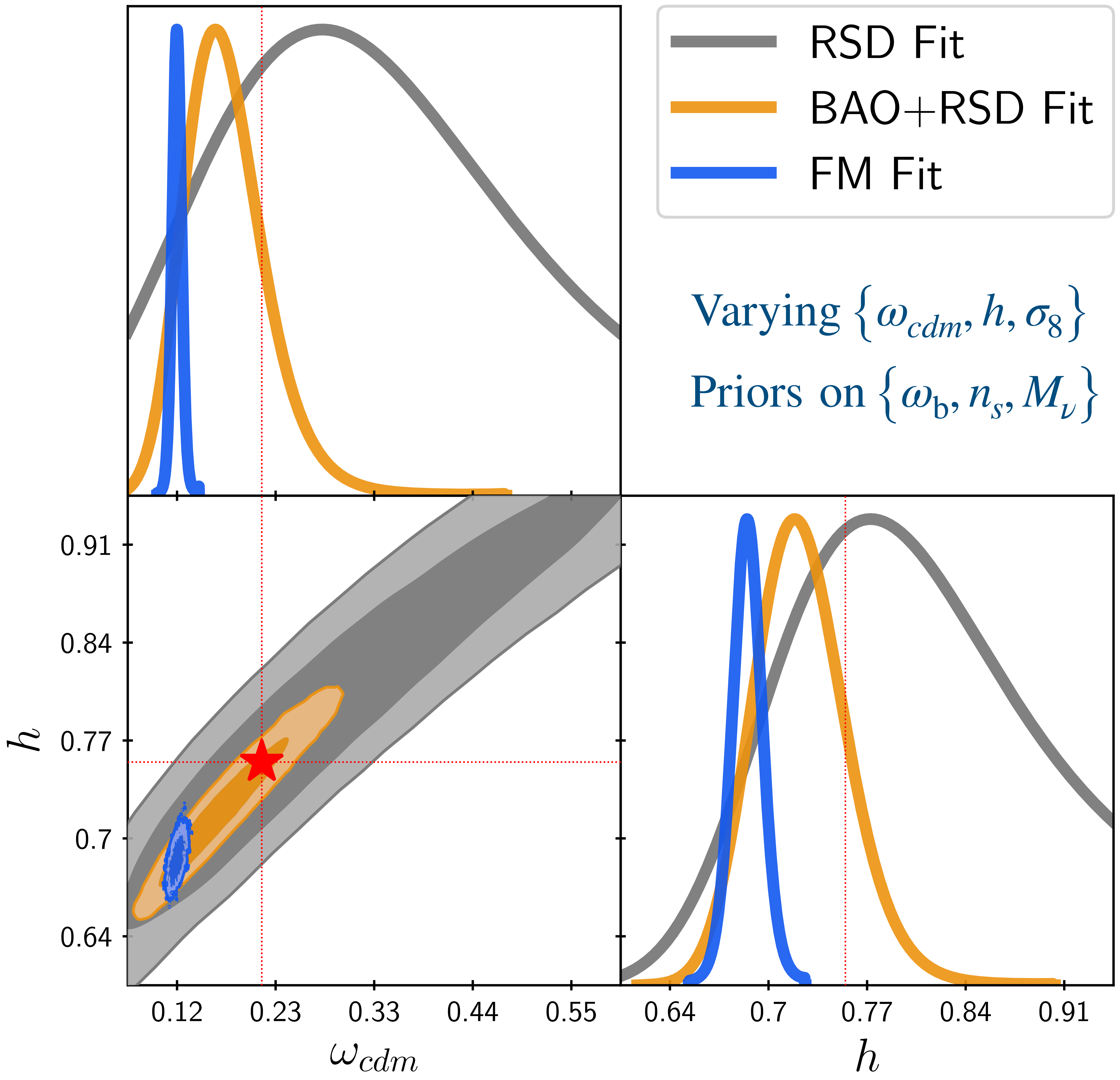
"Standard RSD"	**"Full Modelling"**
"Model-independent"	"Model-dependent"
"Fixed template"	"Varying template"
"Late-time physics"	"Early-time physics"
"Parameter compression"	"No compression"
$\left\{\alpha_{\parallel}, \alpha_{\perp}, f\sigma_8, \ldots\right\}$	$\{\omega_{\rm b}, \omega_{cdm}, h, \sigma_8, n_s, M_\nu, \ldots\}$
"Observation"	**"Theory"**

Quick Comparison

- Grey: Standard RSD
- Orange: Standard RSD + reconstructed BAO
- Blue: Full modelling (FM)

FM Fit gets much tighter constrains on cosmological parameters

Application to BOSS DR12:



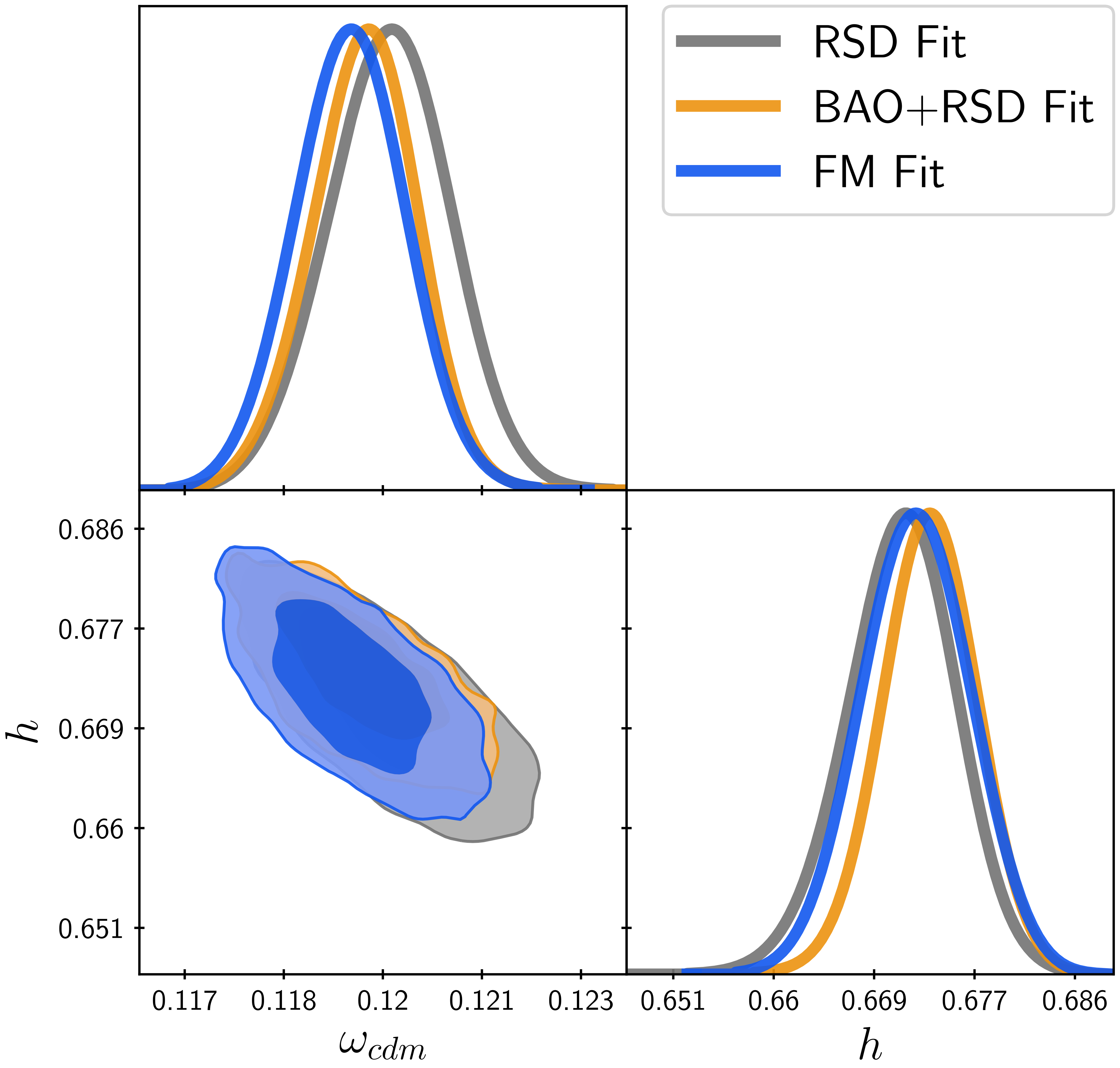
Varying $\{\omega_{cdm}, h, \sigma_8\}$

Priors on $\{\omega_b, n_s, M_\nu\}$

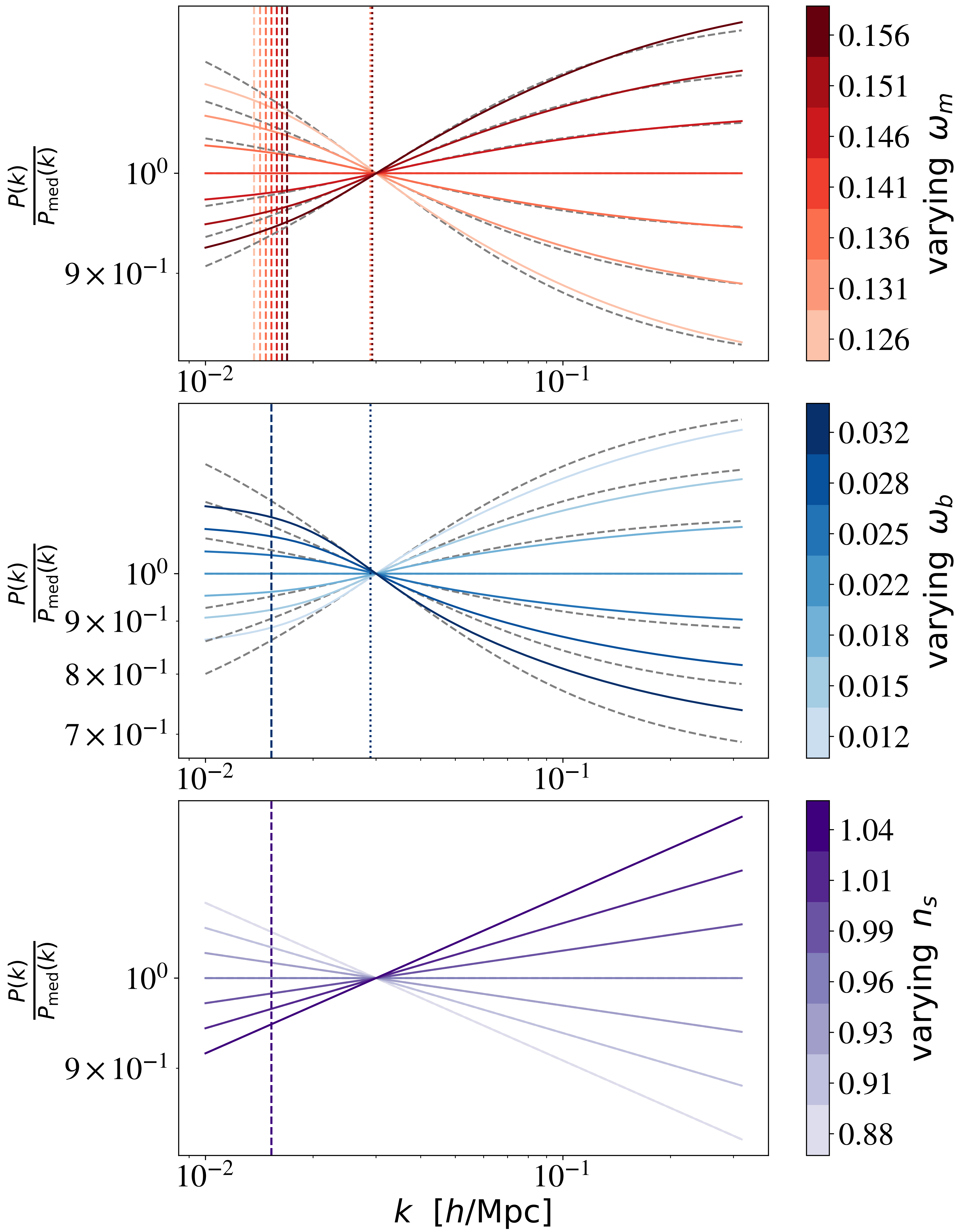
Quick Comparison

- Grey: Standard RSD
- Orange: Standard RSD + reconstructed BAO
- Blue: Full modelling (FM)

Application to BOSS DR12 + Planck:



FM Fit gets much tighter constrains on cosmological parameters



Modelling transfer function dependence

Take EH98 shape function, and fit sigmoid to it:

$$\frac{P^{\rm true}(k)}{P^{\rm fid}(k)} = \exp\left\{\frac{m_1}{a}\tanh\left[a\ln\left(\frac{k}{k_p}\right) + m_2\ln\left(\frac{k}{k_p}\right)\right]\right\}$$

$$a = 0.6; \qquad k_p = \pi/r_d^{\rm ref}$$

$m_1[\Omega_m h]$ ⟶ **Extra free parameter** $m_1 \equiv m$

$m_2[n_s]$ ⟶ **Fix to fiducial**

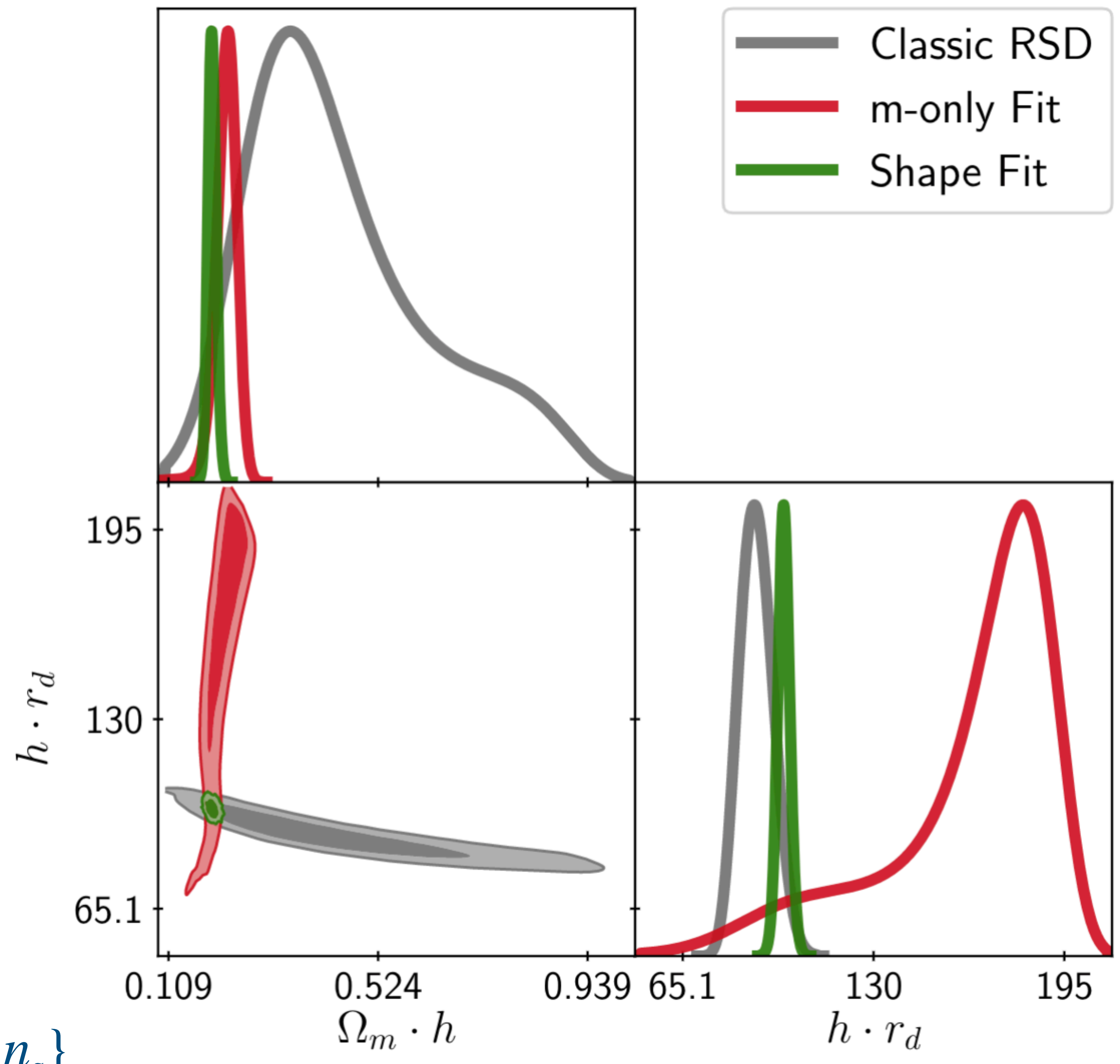
Ref: Brieden, GM, Verde 2021, arXiv: 2106.07641

Main message, in one slide:

	Compressed Variables		LCDM Variables
Standard BAO analysis	$D_H(z)/r_{\rm drag}$, $D_M(z)/r_{\rm drag}$	→	Ω_m, $h \times r_{\rm drag}$
+			
Standard RSD analysis	$f \times \sigma_8$	→	A_s
+			
ShapeFit analysis	m	→	$\Omega_m h$

$\{\Omega_m h, A_s\} + \{\Omega_b, n_s\}$

$\{D_M(z)/r_{\rm drag}, D_H(z)/r_{\rm drag}, f\sigma_8(z), m(z)\}$



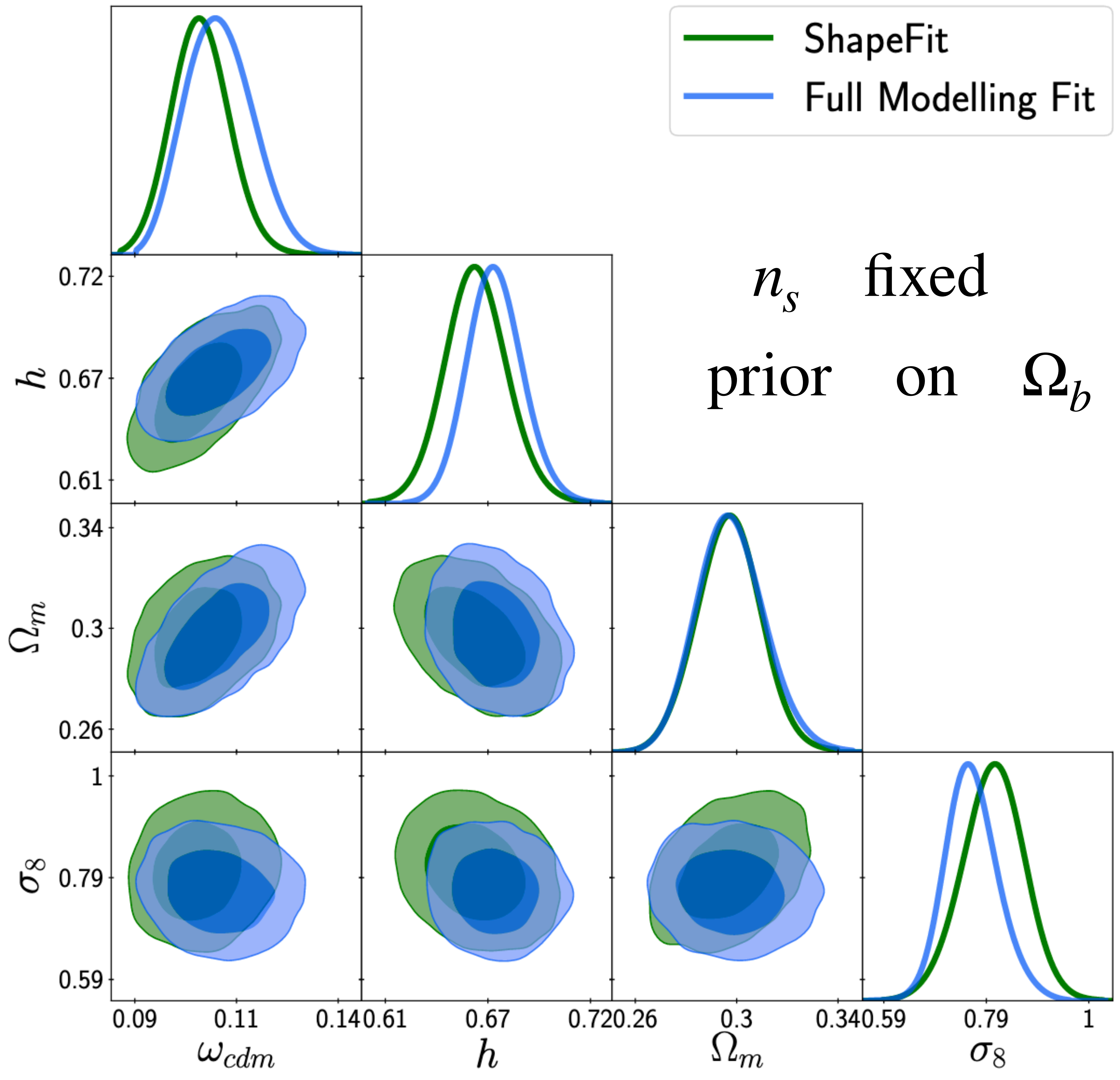
Ref: Brieden, GM, Verde 2021, arXiv: 2106.11931

Main message, in one slide:

	Compressed Variables		LCDM Variables
Standard BAO analysis	$D_H(z)/r_{\rm drag}$ $D_M(z)/r_{\rm drag}$	$\longrightarrow$	Ω_m $h \times r_{\rm drag}$
+			
Standard RSD analysis	$f \times \sigma_8$	$\longrightarrow$	A_s
+			
ShapeFit analysis	m	$\longrightarrow$	$\Omega_m h$

$$\{D_M(z)/r_{\rm drag}, D_H(z)/r_{\rm drag}, f\sigma_8(z), m(z)\}$$

$$\{\Omega_m h, A_s\} + \{\Omega_b, n_s\}$$



Ref: Brieden, GM, Verde 2021, arXiv: 2106.11931

Summary

- BOSS+eBOSS is the 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 and detection of DE using BAO-only

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DESI has just started observing. Stay tuned for 2022!

- DESI analyses will be blind to BAO/RSD. Results more robust
- Extra physics beyond BAO/RSD (transfer function) may be used to extract extra cosmology information (ShapeFit methodology).