Stress-Testing LCDM with Large-Scale Structure

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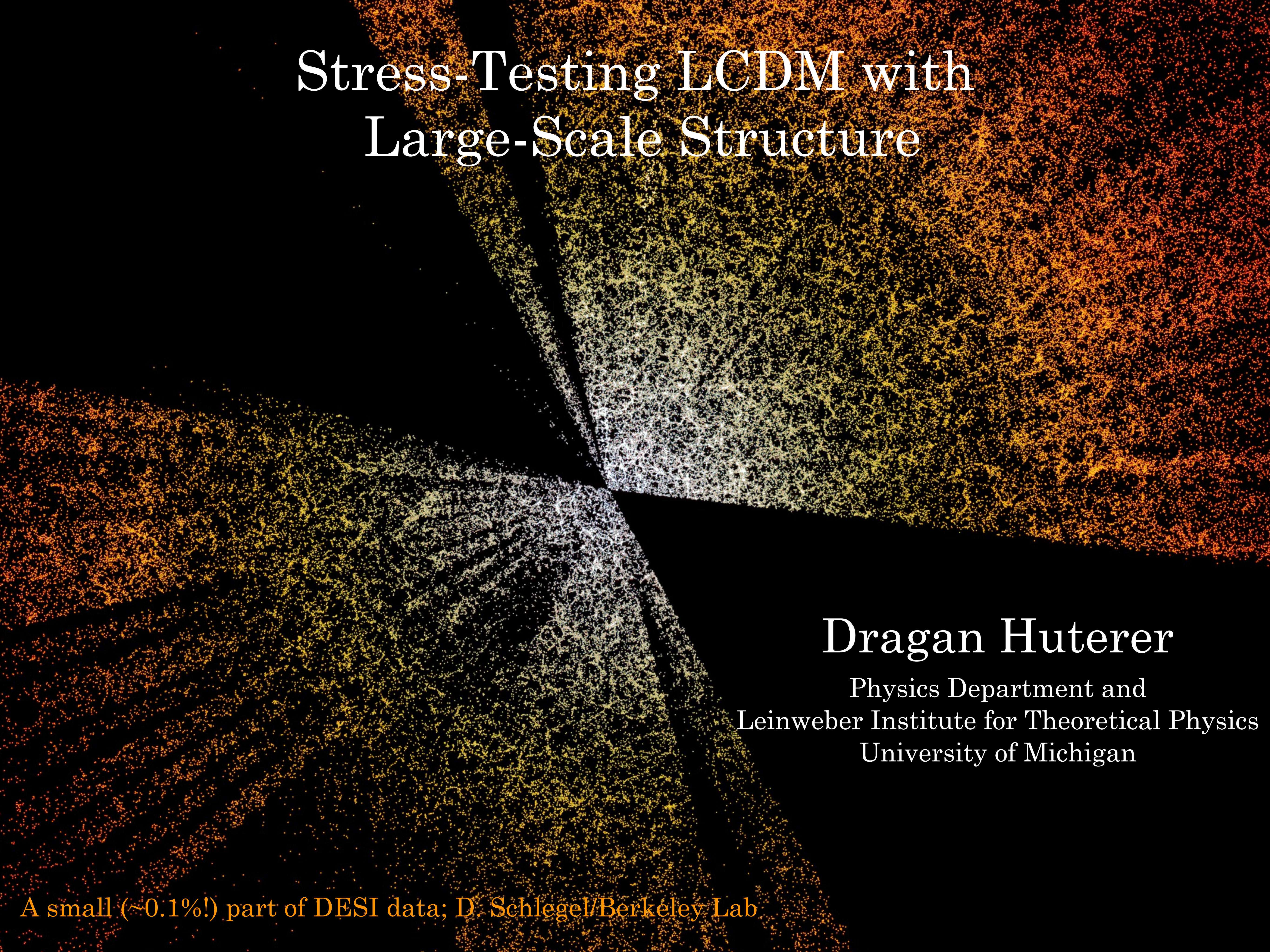
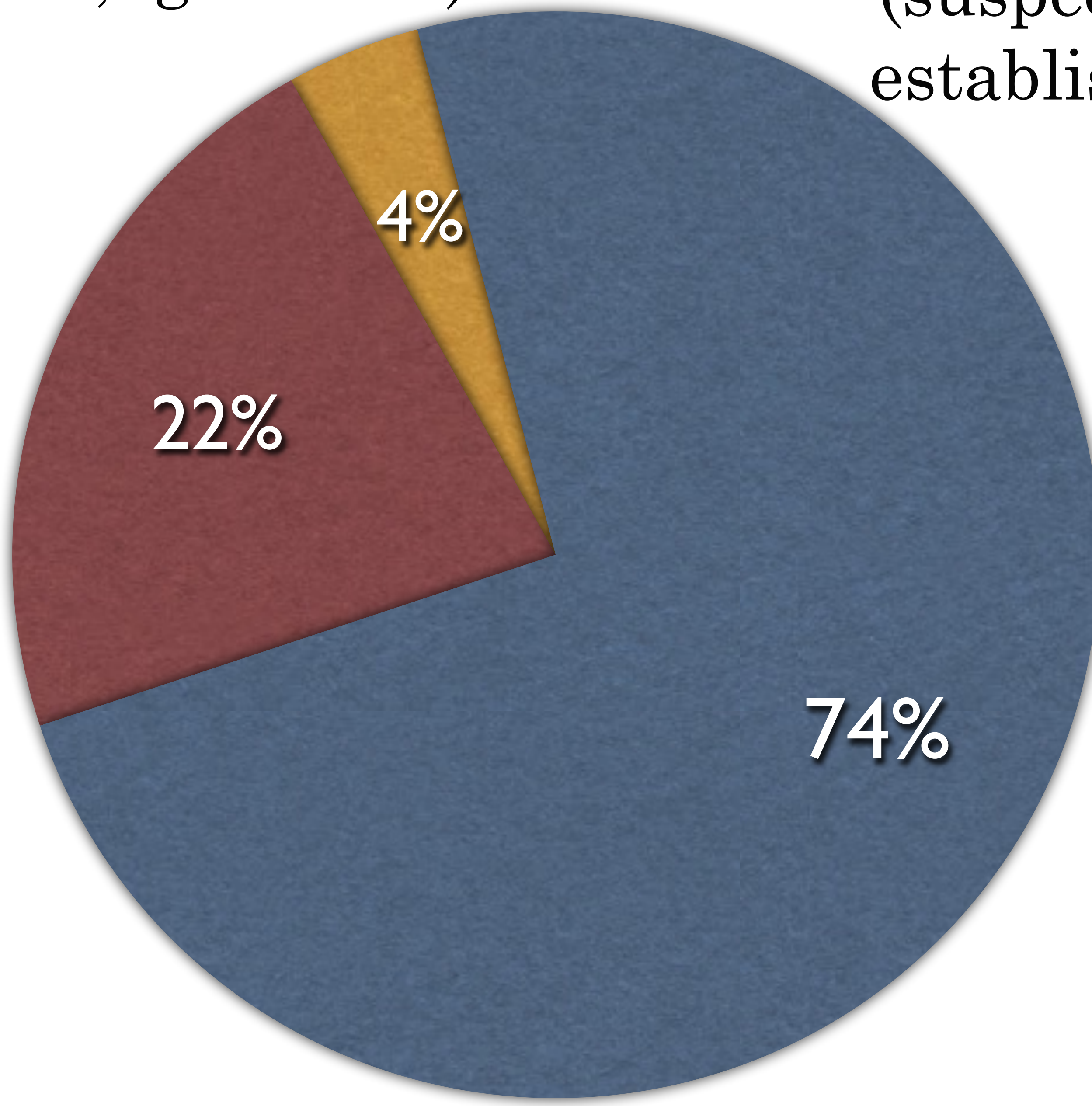


A small (~0.1%!) part of DESI data; D. Schlegel/Berkeley Lab

Makeup of universe today

Baryonic Matter
(stars 0.4%, gas 3.6%)

Dark Energy
(suspected since 1980s
established since 1998)

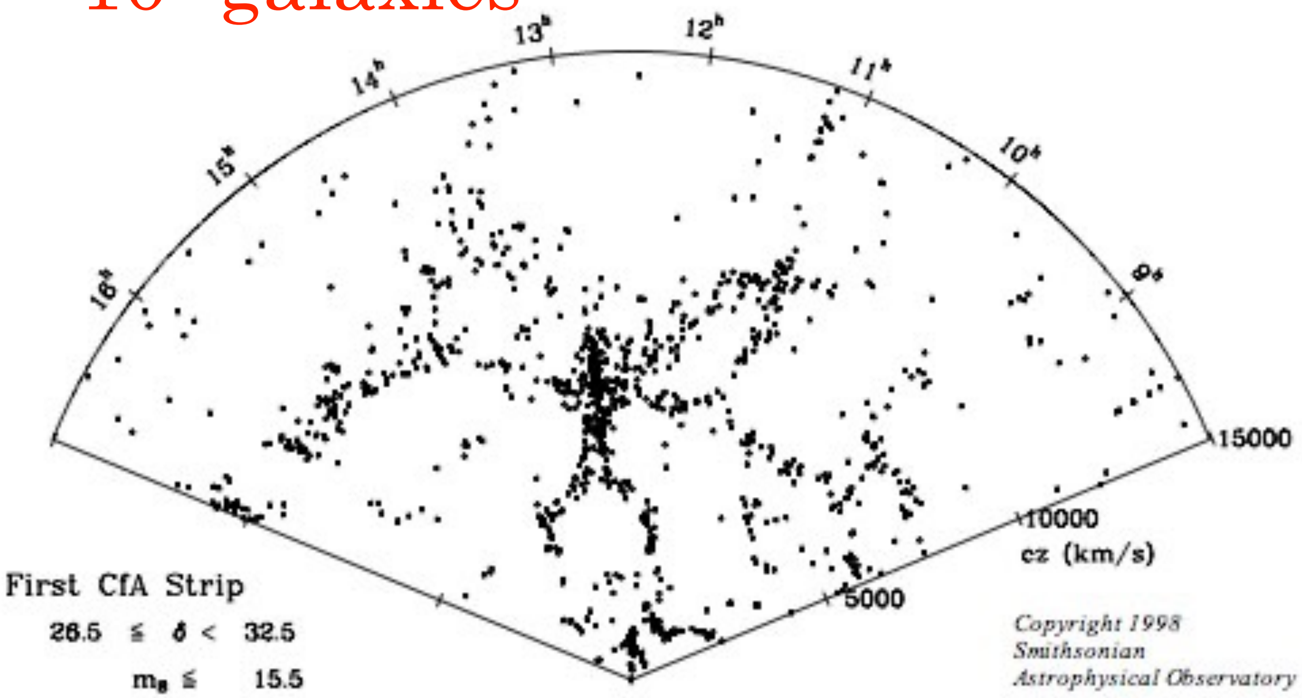


Dark Matter
(suspected since 1930s
established since 1970s)

Also:
radiation (0.01%)

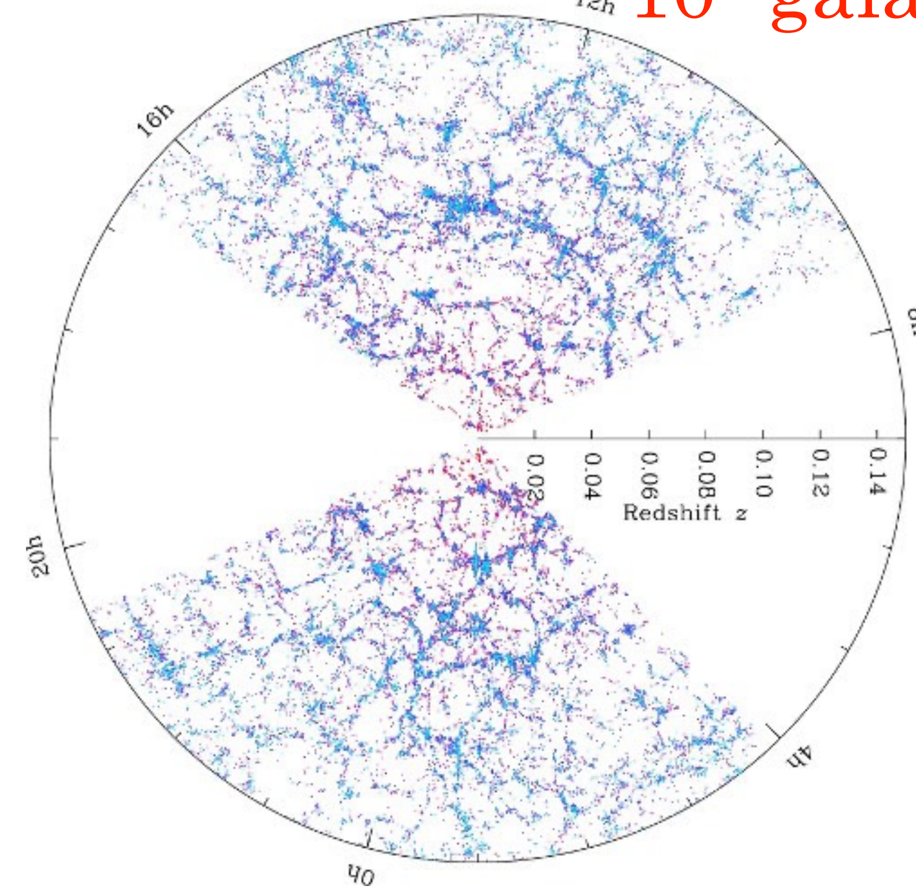
How do we describe the large-scale structure and constrain cosmological model?

~10^4 galaxies

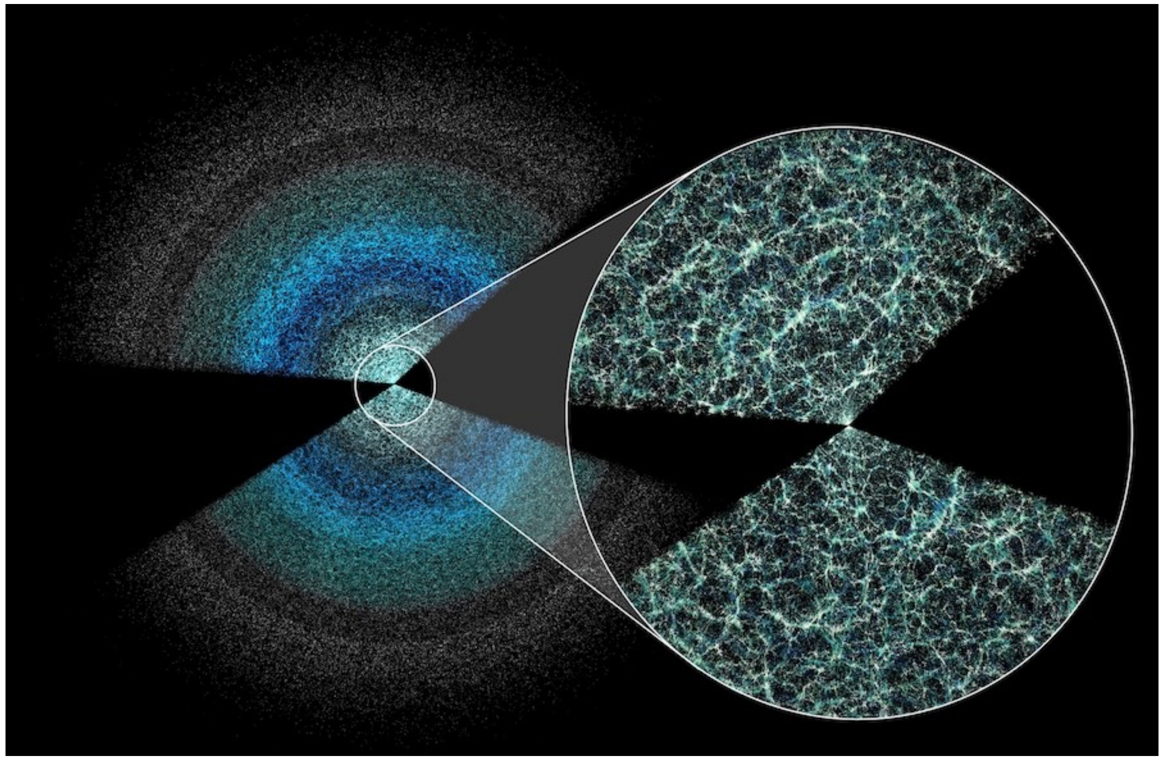


Harvard-Cfa survey;
de Lapparent, Geller & Huchra (1986)

~10^6 galaxies



SDSS/BOSS survey
SDSS/BOSS collaboration



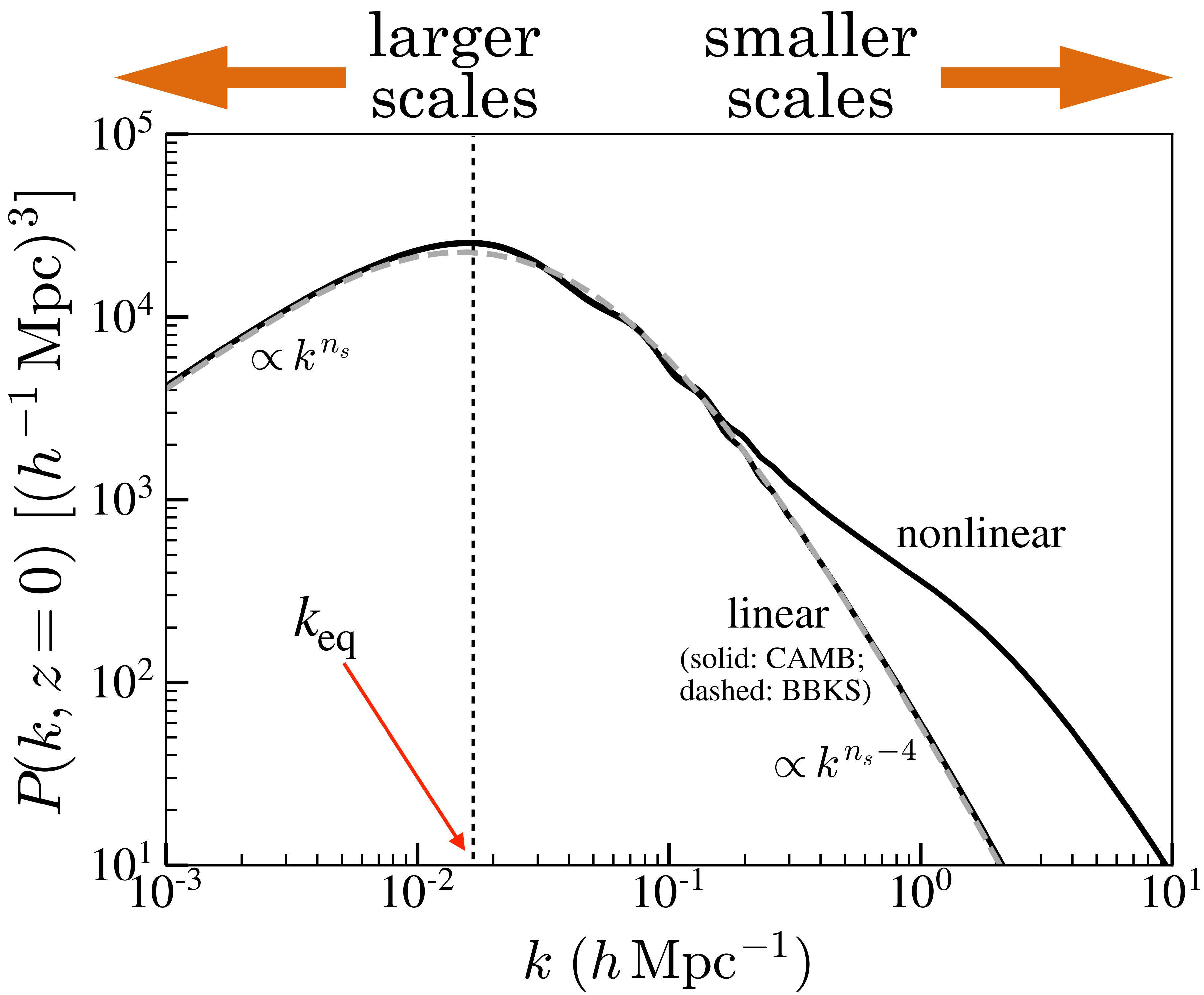
~0.5×10^8 galaxies

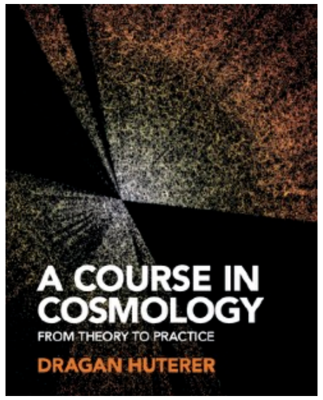
Claire Lamman and DESI collaboration

Ongoing or upcoming DE experiments:

- **Ground photometric:**
  - Kilo-Degree Survey (KiDS)
  - Dark Energy Survey (DES) $\Longrightarrow$ final results on webinar on 22nd Jan
  - Hyper Supreme Cam (HSC)
  - LSST on Vera Rubin Telescope
- **Ground spectroscopic:**
  - Prime Focus Spectrograph (PFS)
  - $\boxed{\text{Dark Energy Spectroscopic Instrument (DESI)}}$
- **Space:**
  - Euclid
  - Roman Space Telescope

Galaxy power spectrum





Matter power spectrum contains (almost!) all information at large scales in cosmology

Linear galaxy power spectrum $\Delta_g^2(k)$

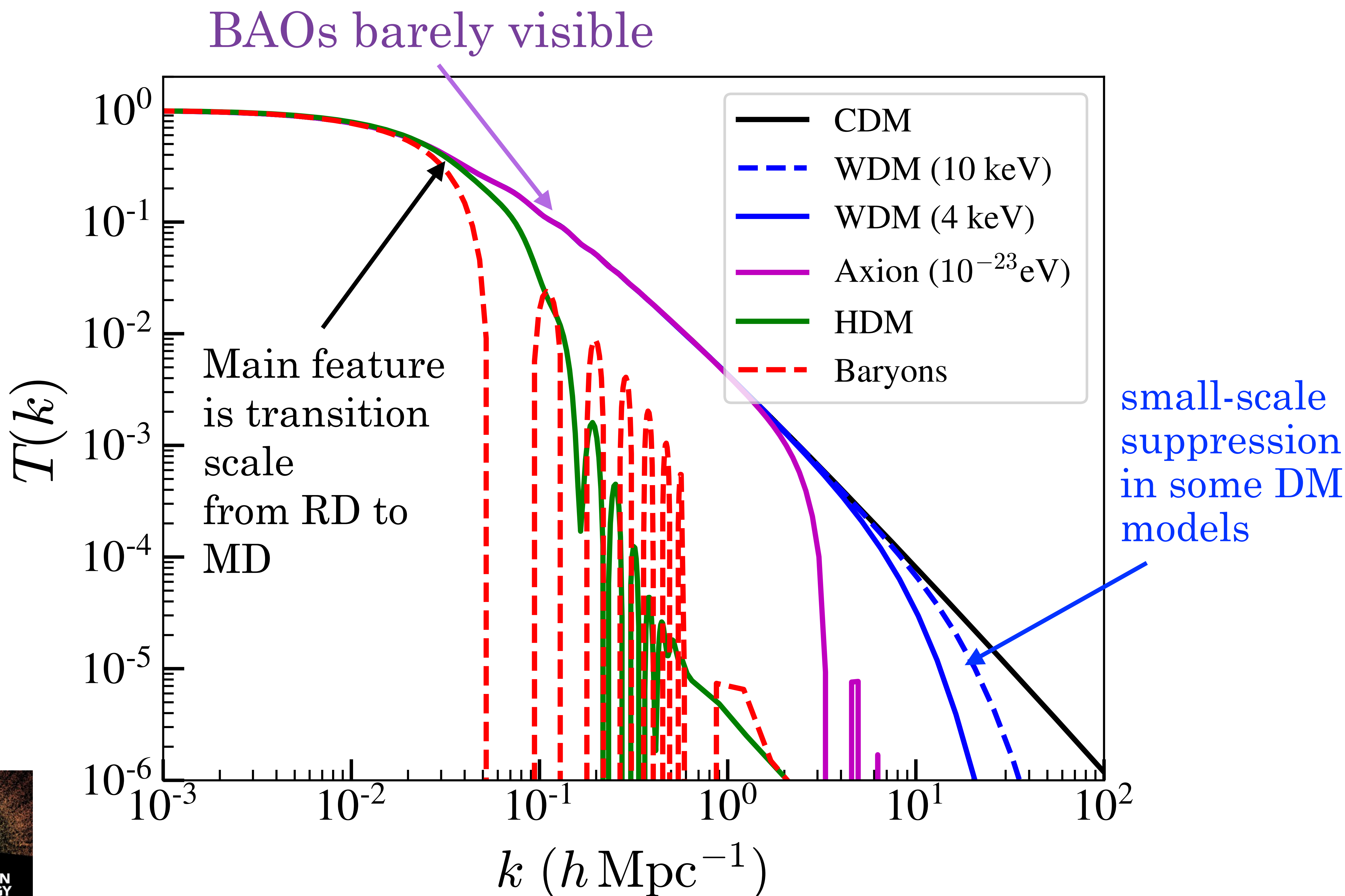
$$\Delta_g^2(k,a) \equiv \frac{k^3 P_g(k)}{2\pi^2}$$

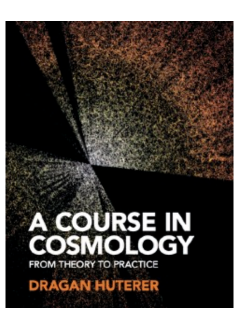
$$= b^2(k,a) A_s \frac{4}{25} \frac{1}{\Omega_M^2} \left(\frac{k}{k_{\rm piv}}\right)^{n_s-1} \left(\frac{k}{H_0}\right)^4 [ag(a)]^2 T^2(k)$$

Principal sensitivity to cosmo parameters comes from:

- growth function $D(a) = ag(a)/g(1)$ (D is linear growth, g is growth suppression, i.e. value relative to EdS)
- transfer function T(k)
- (for non-Gaussianity only): galaxy bias b
- [Also anisotropic power spectrum, not shown above, RSD will be discussed in a bit]

Transfer function

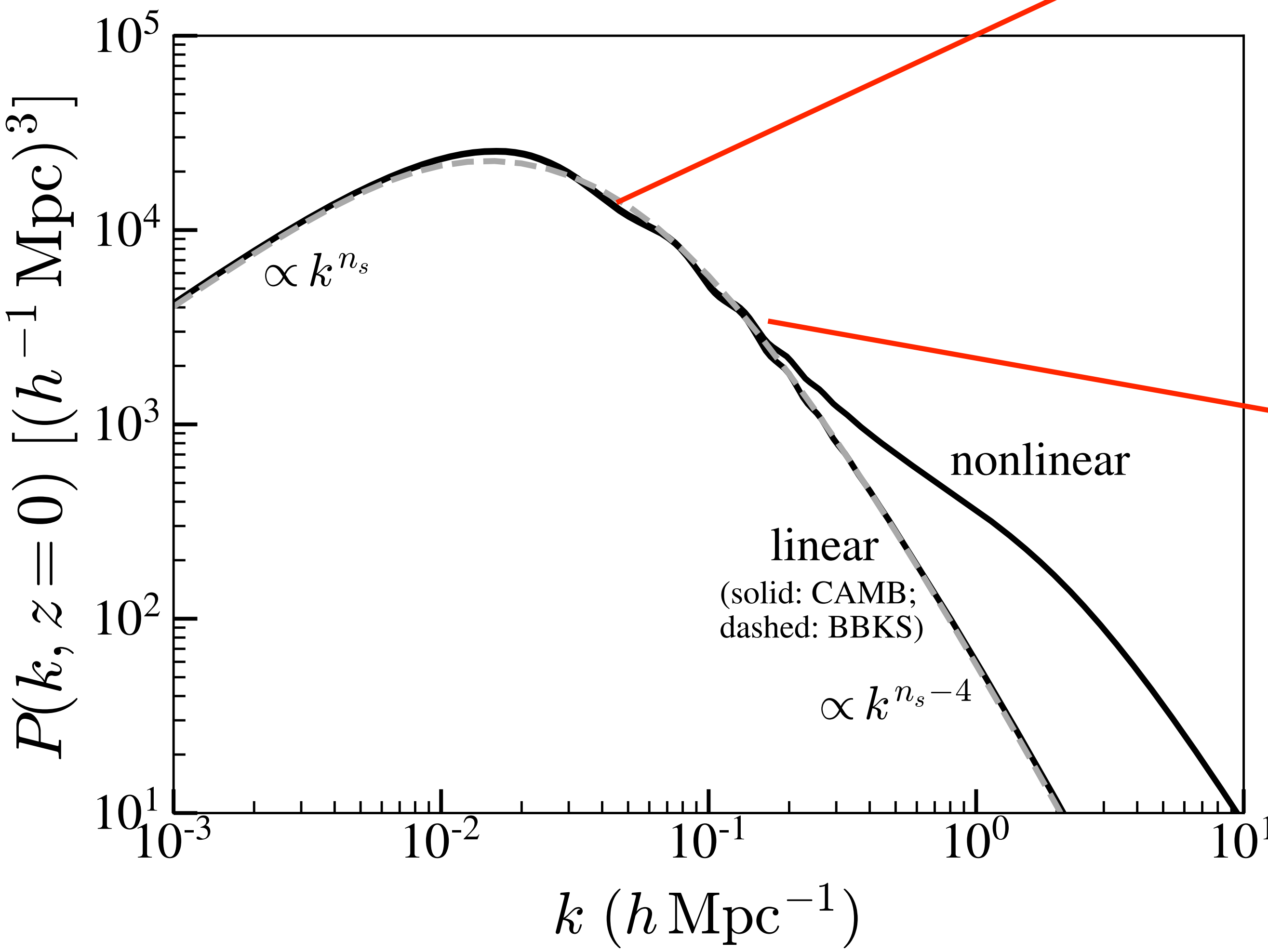


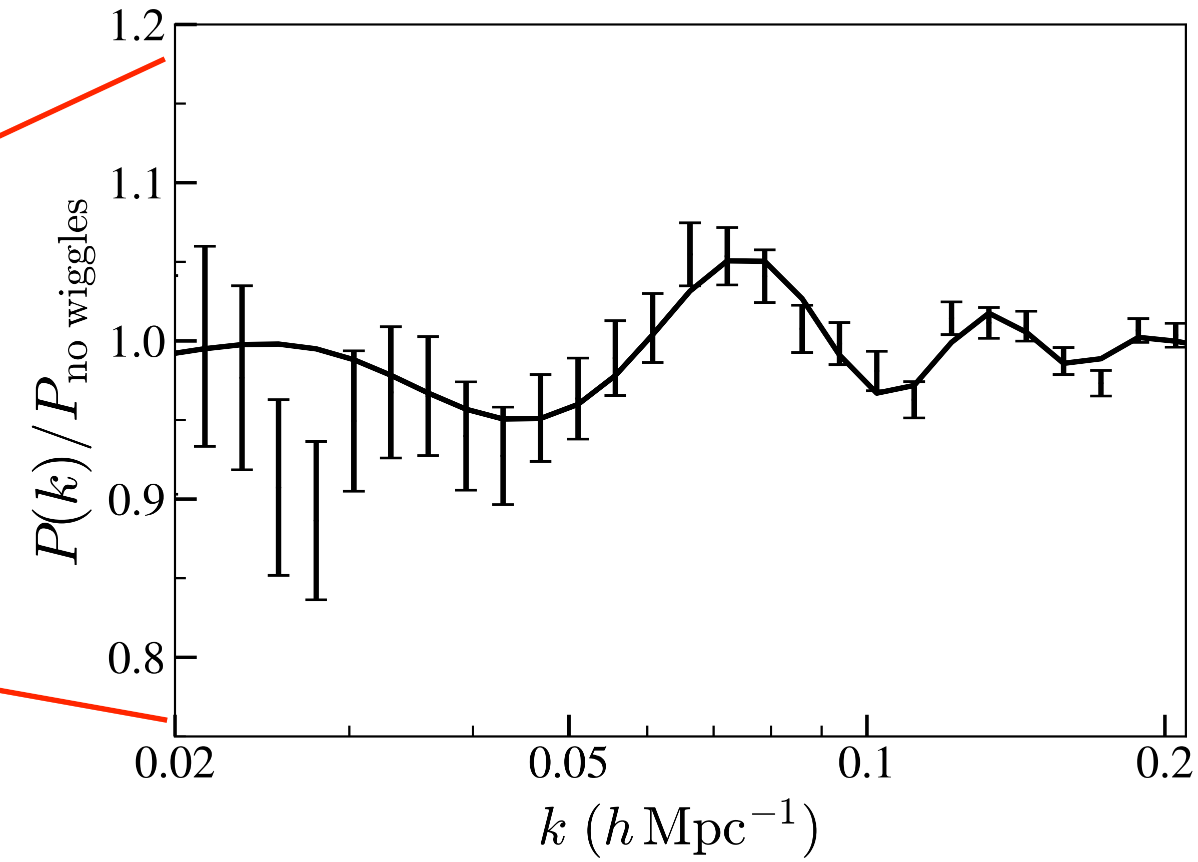


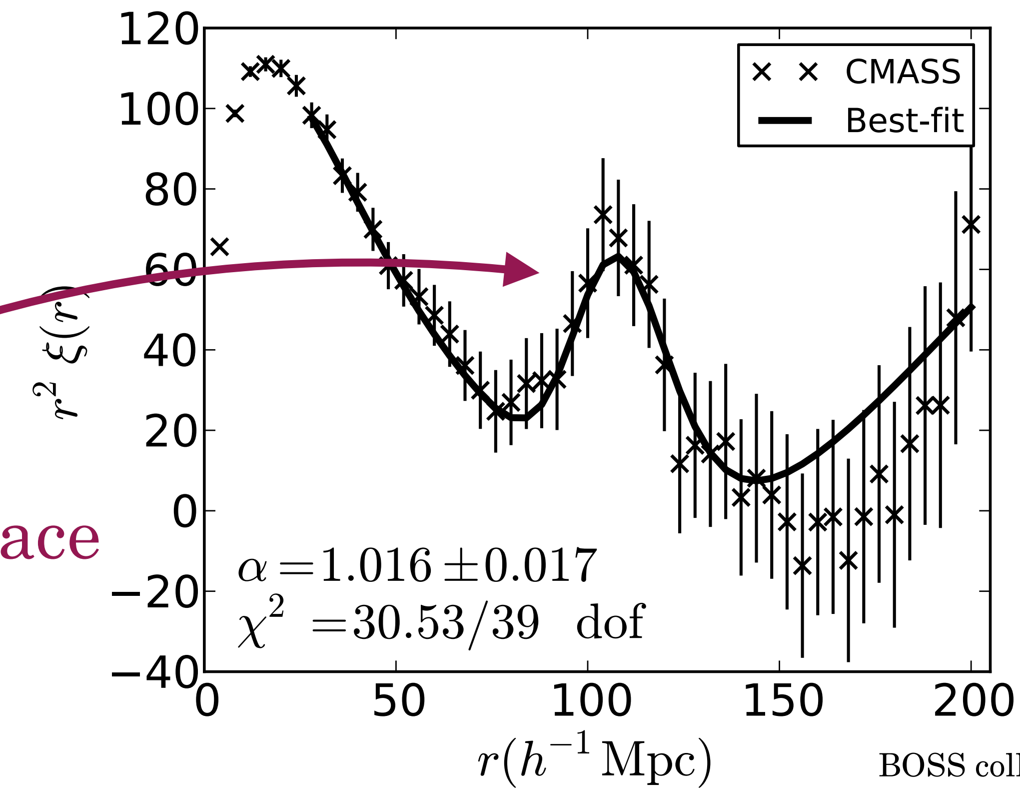
Baryon Acoustic Oscillations (BAO)

First discussed in: Sunyaev & Zeldovich, 1972

Multiple wiggles in Fourier space
(power spectrum)







…or one wiggle in configuration space
(2-point correlation function)

BOSS collaboration

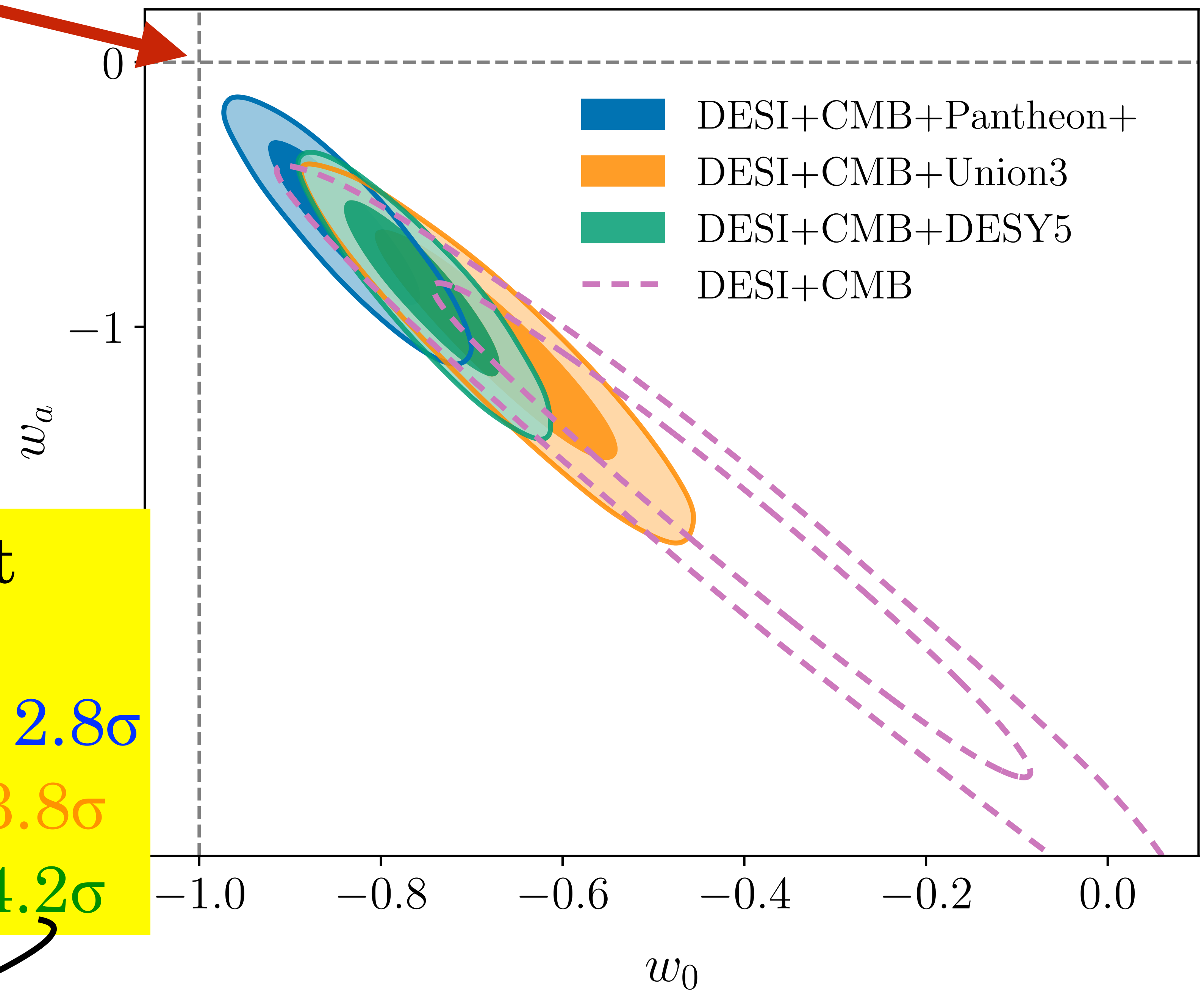
Dark energy - (w_0, w_a)

$$w(a) = w_0 + w_a(1 - a)$$

a is scale factor
a=0: Big Bang
a=1: today

ΛCDM
(standard model)

DESI shows preference for $w_0 > -1$, $w_a < 0$

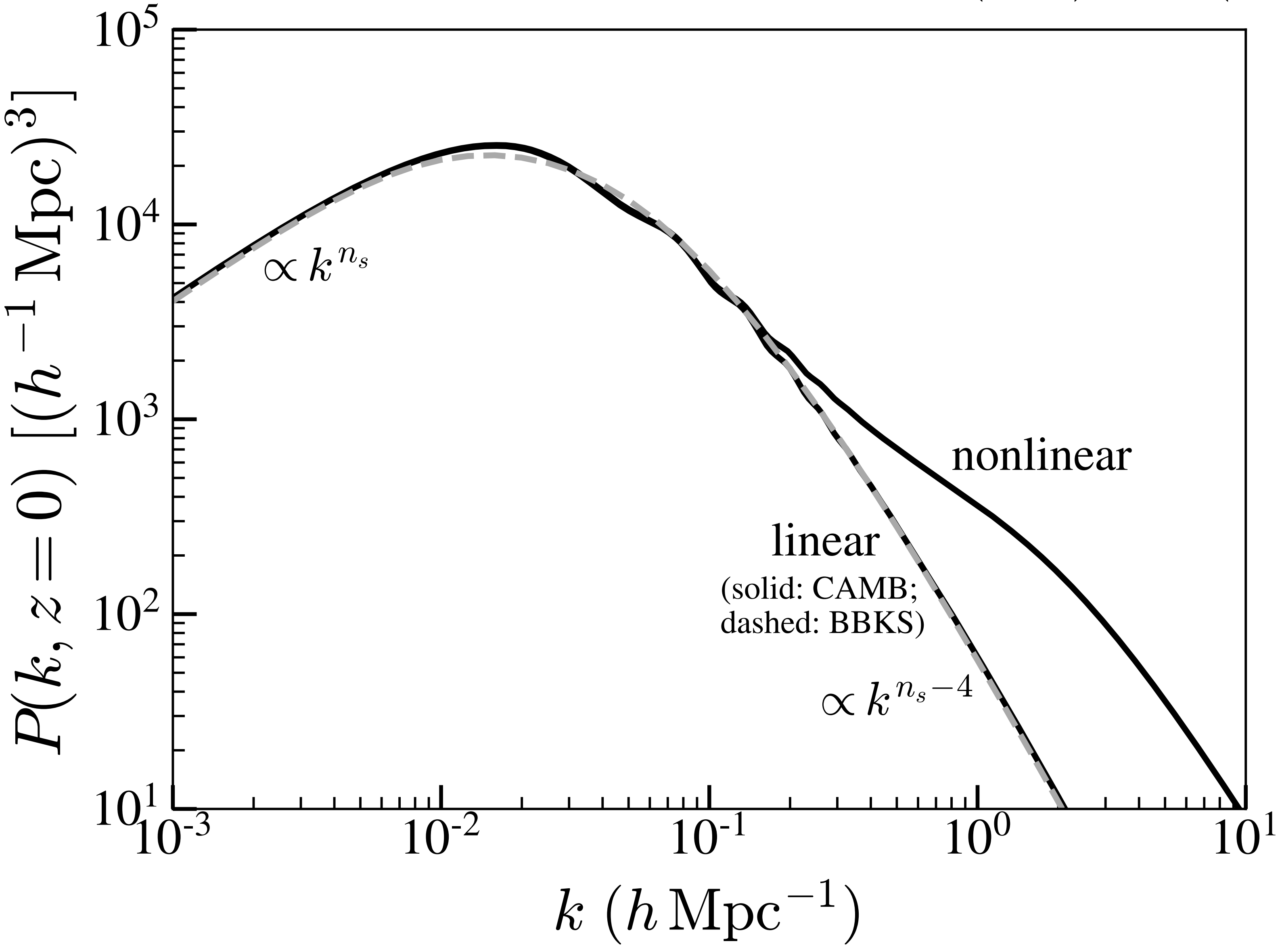


Significance against LCDM:
DESI+CMB+Pantheon: 2.8σ
DESI+CMB+Union3: 3.8σ
DESI+CMB+DESY5: 4.2σ

becomes 3.2σ with update DES SNIa “Dovekie” analysis (Popovic et al, arXiv:2511.07517)

What about the growth function?

$$\Delta^2(k,z) = b^2(k,a)\,A_s\,\frac{4}{25}\frac{1}{\Omega_M^2}\left(\frac{k}{k_{\rm piv}}\right)^{n_s-1}\left(\frac{k}{H_0}\right)^4 [ag(a)]^2\,T^2(k)$$



[no good
"publicity photo"
for full-shape analysis]

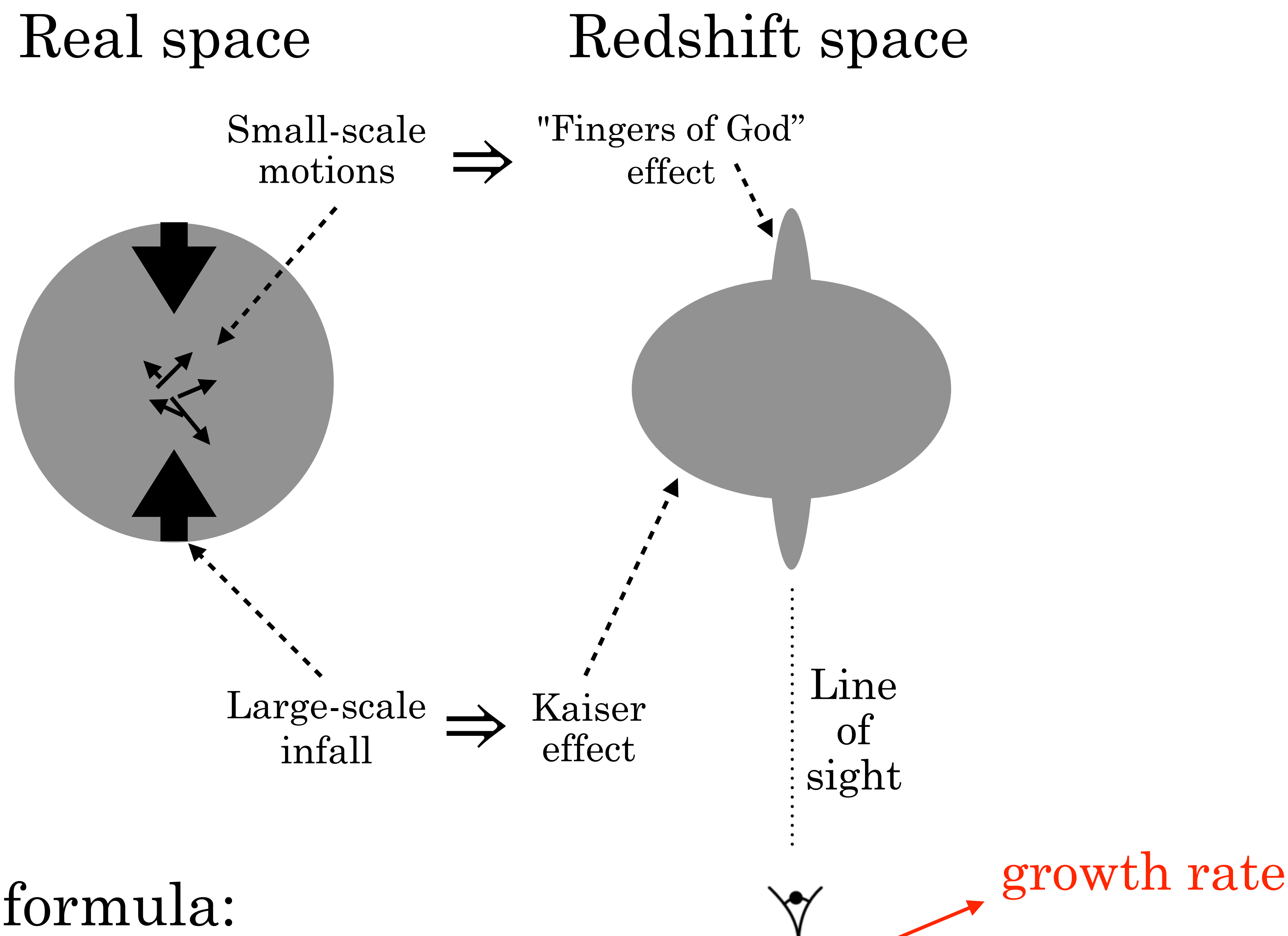
Power spectrum is actually not separable in k and a (except on very linear scales)

⇒ need a more sophisticated modeling of P(k, z) in redshift and k bins

⇒ a **"full-shape"** modeling approach (includes EFT or HOD for small scales)

⇒ constrains geometry and growth but doesn't cleanly separate them

Redshift-space distortions



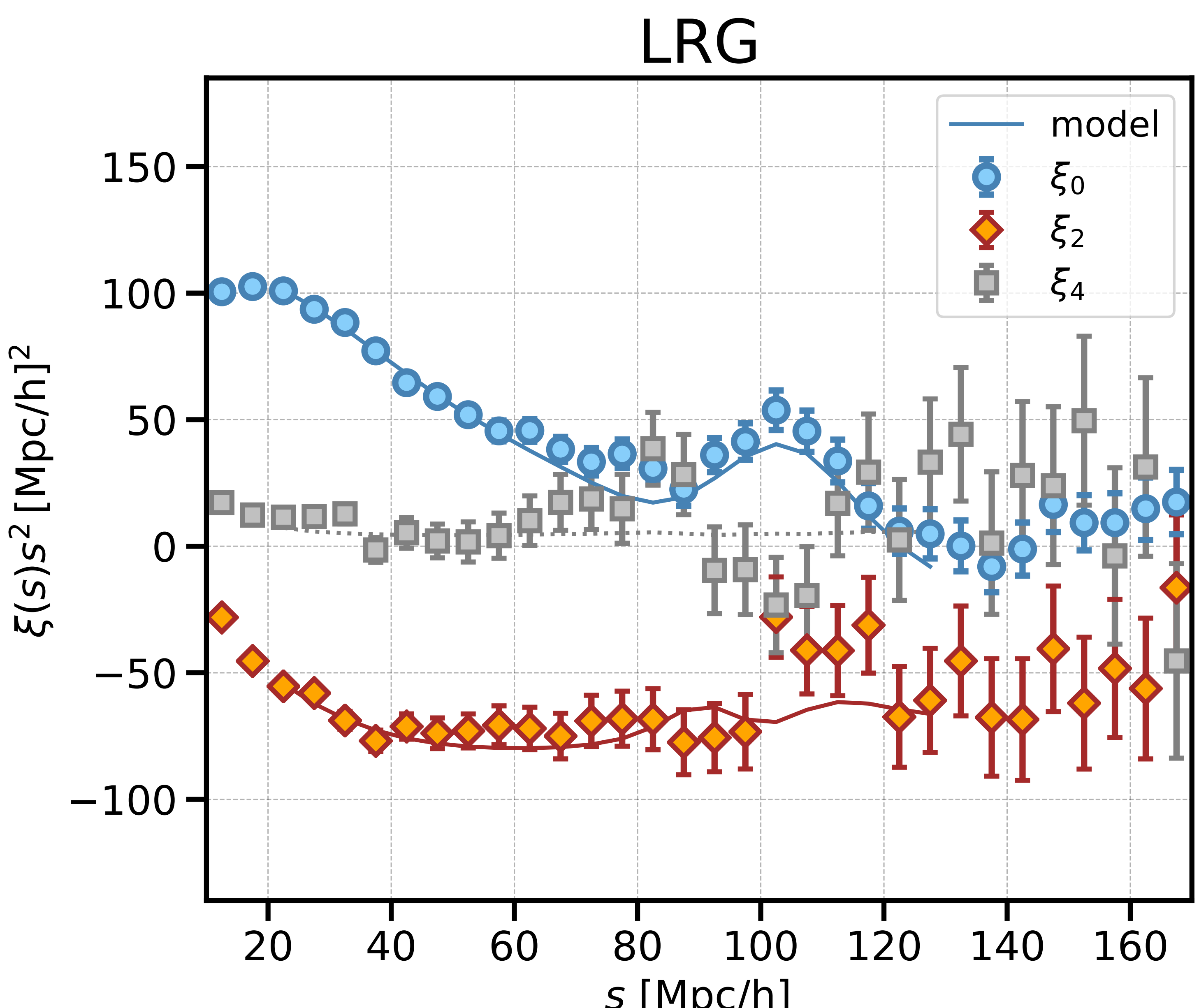
Kaiser (1987) formula:

$$\boxed{P(\mathbf{k})^{(s)} = b^2\left[1+\beta\mu^2\right]^2 P(k)} \quad \text{where} \quad \beta \equiv \frac{f}{b};\ \mu \equiv \hat{\mathbf{k}}\cdot\hat{r}_z = k_z/k$$

Redshift Space Distortions

Kaiser RSD formula (roughly ok at large scales):

$$P(\mathbf{k})^{(s)} = b^2 \left[1 + \beta\mu^2\right]^2 P(k)$$



Bautista et al. (2020)
(plot by Jiamin Hou, MPE)

μ^0, μ^2, μ^4 terms become the monopole (l=0), quadrupole (l=2) and hexadecapole (l=4), respectively

In addition to the power spectrum (BAO and RSD), let me mention very briefly these probes/combinations:

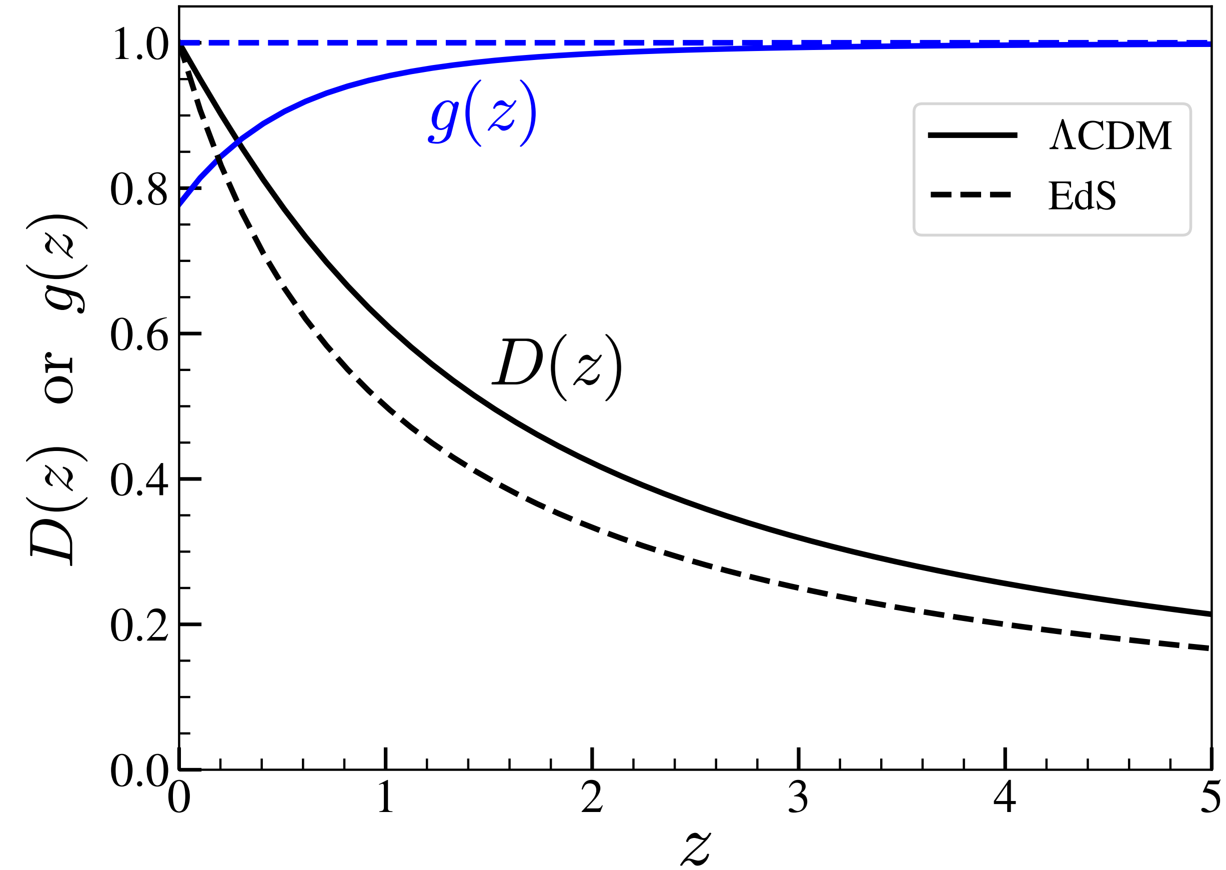
1. Peculiar velocities
2. Bispectrum (of galaxy distribution)
3. Gravitational lensing and 3x2 cosmology

Peculiar velocities

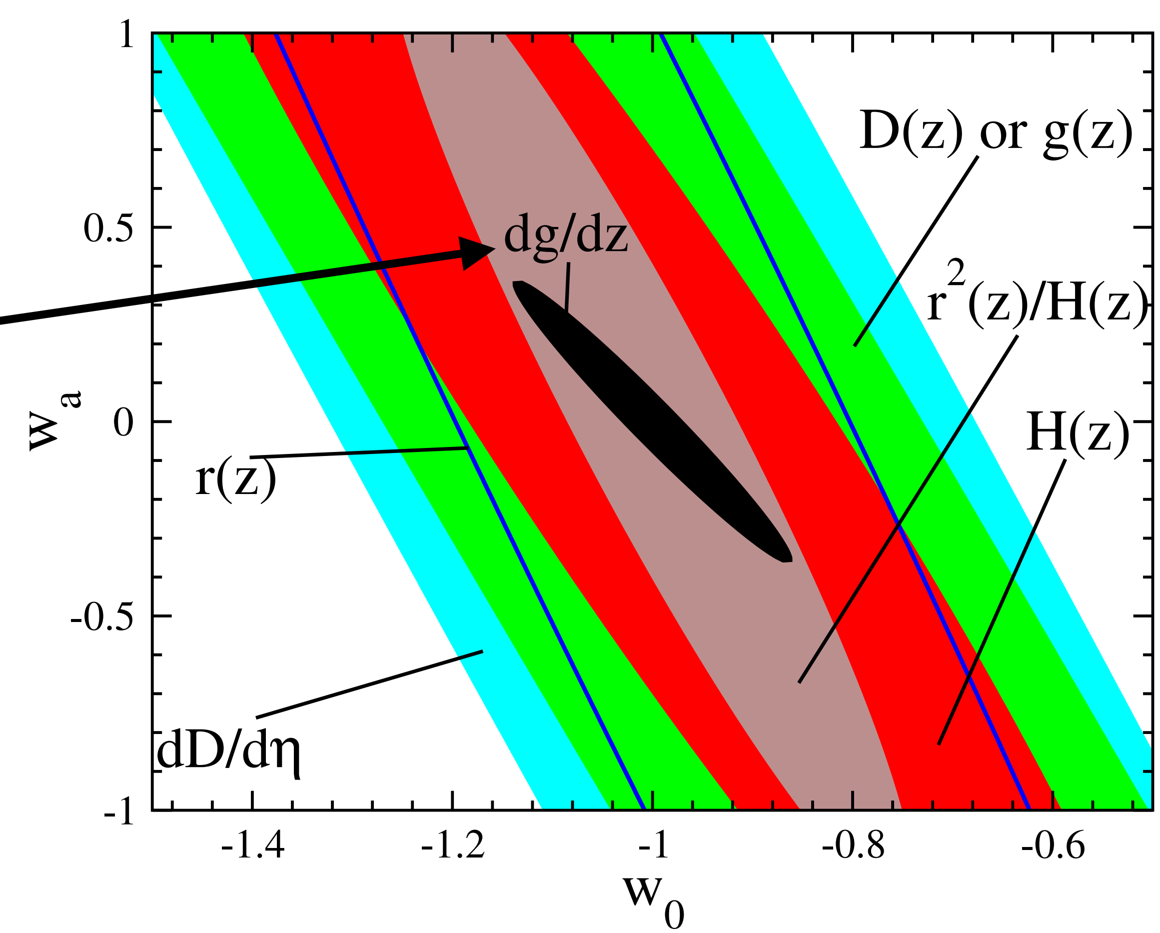
Consider a galaxy at redshift z; then $cz_{\rm obs} \approx cz + v_{\rm pec}$

- Imagine now that you measure redshifts and distances $r(z) \simeq cz/H_0$.
- The former gets you $z_{\rm obs}$, them latter gives you z
- [Getting distances is the hard part; use Fundamental Plane or Tully-Fisher relation]
- Hence you get a (noisy) measurement of $v_{\rm pec}$
- Correlating these $v_{\rm pec}$, get a measurement of the velocity power spectrum, since $\nabla \cdot \mathbf{v} = aHf\delta$ (in linear theory), it follows that $\langle vv \rangle \propto f^2 P(k) \propto f^2\sigma_8^2$
- …and hence pecvel are sensitive to $f\sigma_8 \equiv f(z)\sigma_8(z)$

Why pecvel are very sensitive to DE and MG

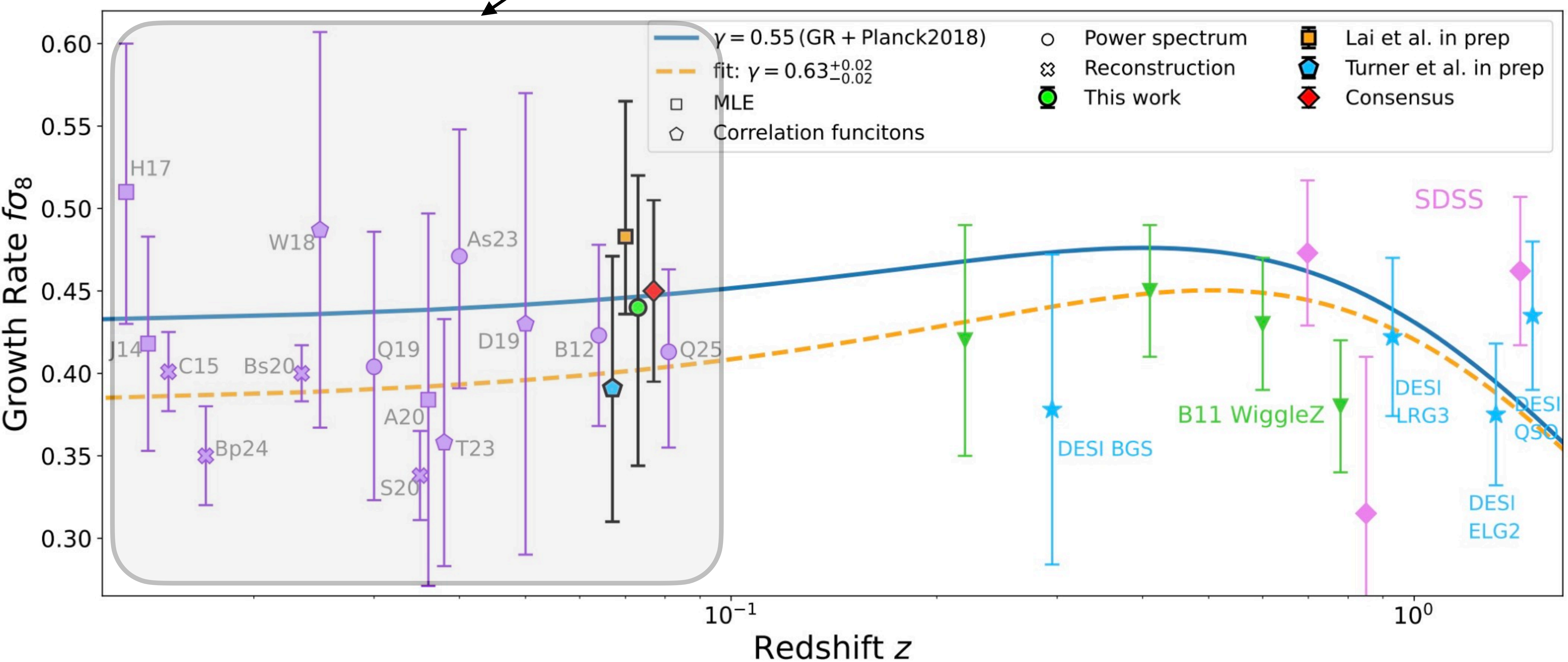


Probes that measure growth rate $f(a) \equiv \dfrac{d\ln D}{d\ln a}$ are particularly valuable (*peculiar velocities and RSD!*)



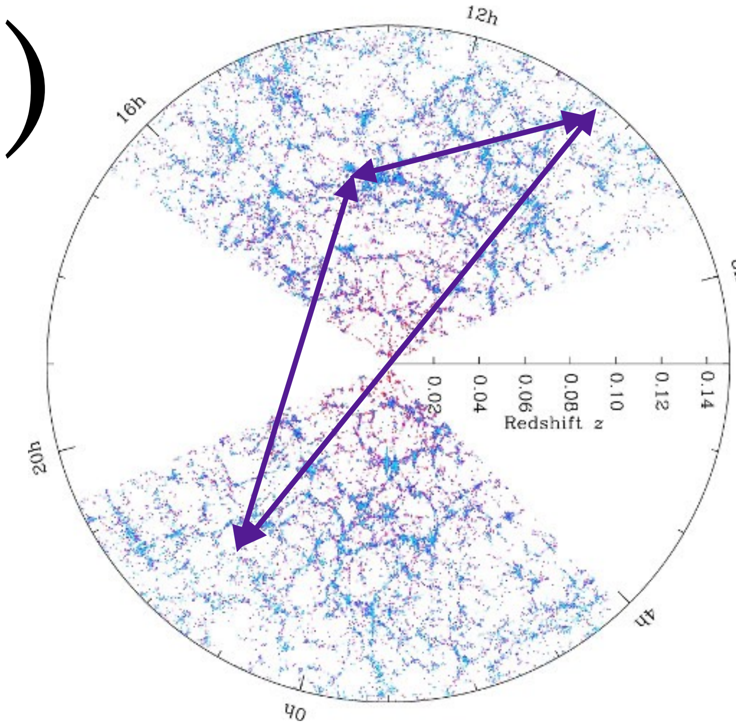
Cooray, Huterer & Baumann (2004)

1. Peculiar velocities



F. Qin et al (DESI collaboration), arXiv:2512.03231

2. Bispectrum (of galaxies)



Fourier space:

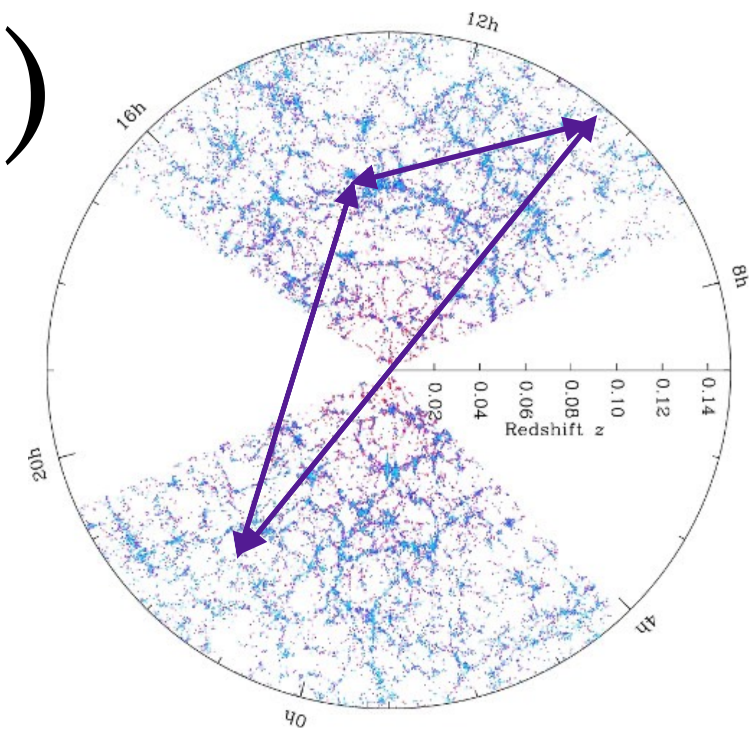
$$\langle \delta_{\vec{k}_1}\, \delta_{\vec{k}_2}\, \delta_{\vec{k}_3} \rangle = (2\pi)^3\, \delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\, B(\vec{k}_1, \vec{k}_2, \vec{k}_3)$$

Harmonic space:

$$\langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle \equiv B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3}$$

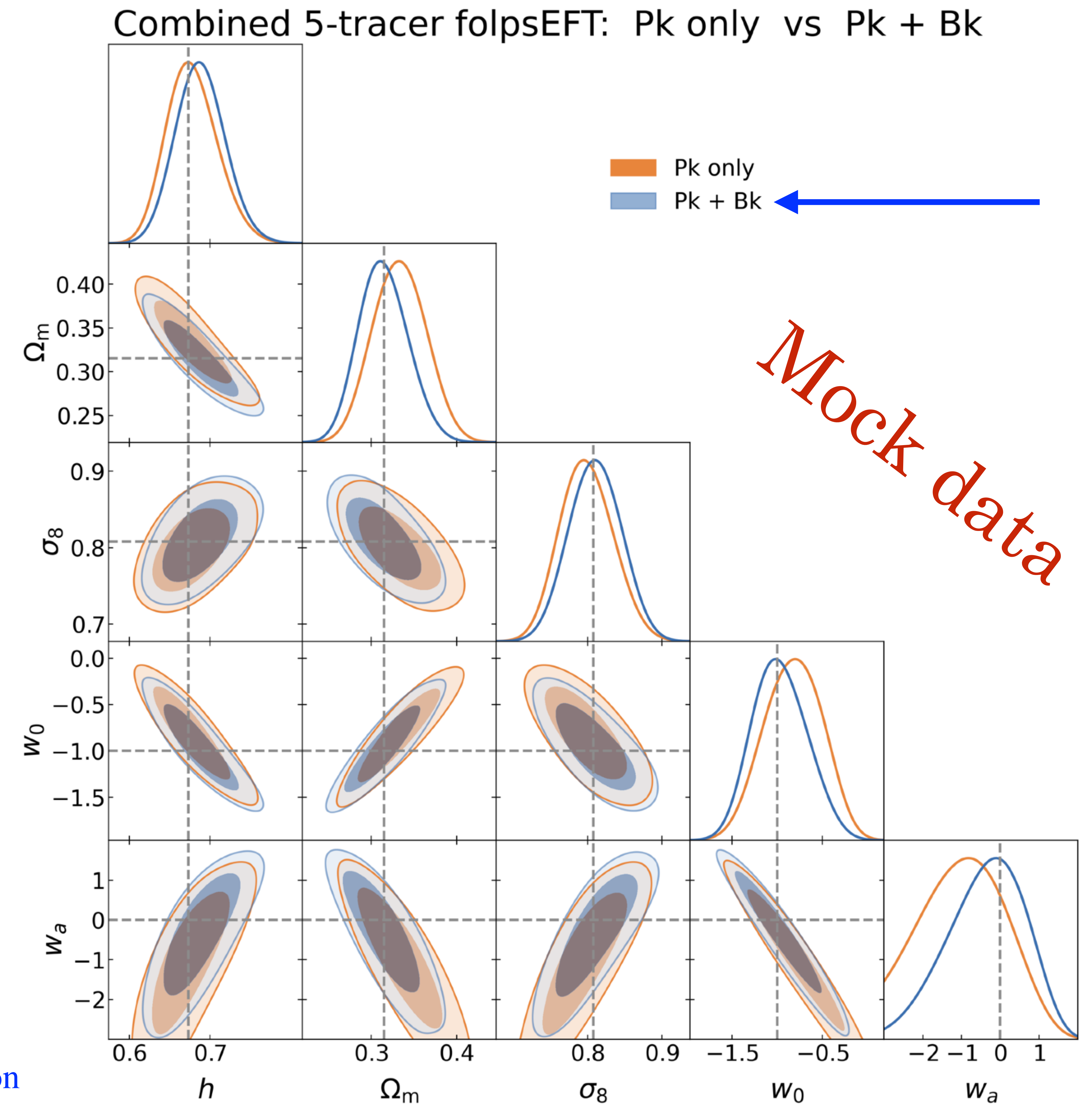
So depends on six numbers (describing a triangle in 3D space); the angle-averaged version, $B(k_1, k_2, k_3)$ or B_{ℓ_1,ℓ_2,ℓ_3}, still depends on three numbers (recall P(k) depends on just k)

2. Bispectrum (of galaxies)



In principle a major source of cosmological information at quasi-linear and nonlinear scales!
But:

- Years of promises (the “bispectrum winter”), but recent progress
- Challenging to measure (lots of triangles)
- Challenging to theoretically predict, both B and its Cov matrix
- Challenging to control systematics in (!)
- Proportional to galaxy bias cubed — both a problem and a feature
- DESI in process of making major advances in measurements of, and constraints from, the bispectrum



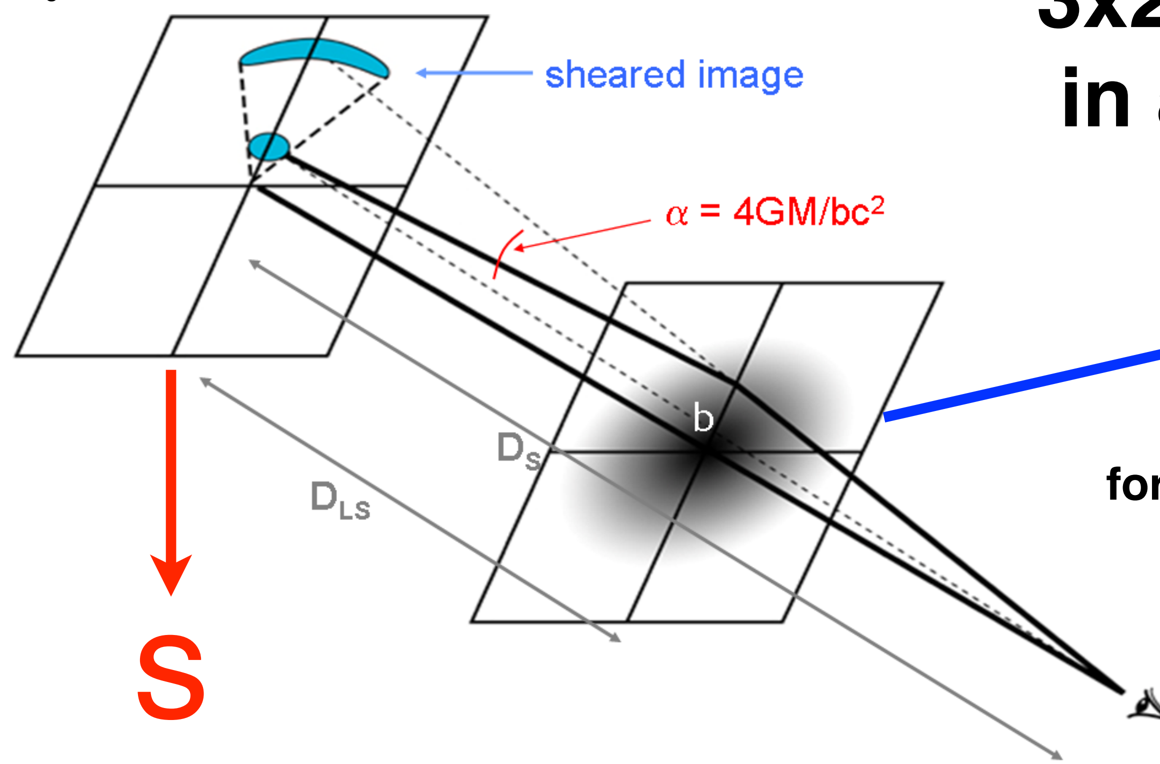
Prakhar Bansal
and
DESI collaboration

3. Gravitational lensing and 3x2 cosmology

Can correlate:

1. galaxy position with galaxy position (galaxy clustering)
2. galaxy shape with galaxy shape (weak lensing)
3. galaxy position with galaxy shape (galaxy-galaxy lensing)

image: LSST science book



3x2 analysis in a picture

g

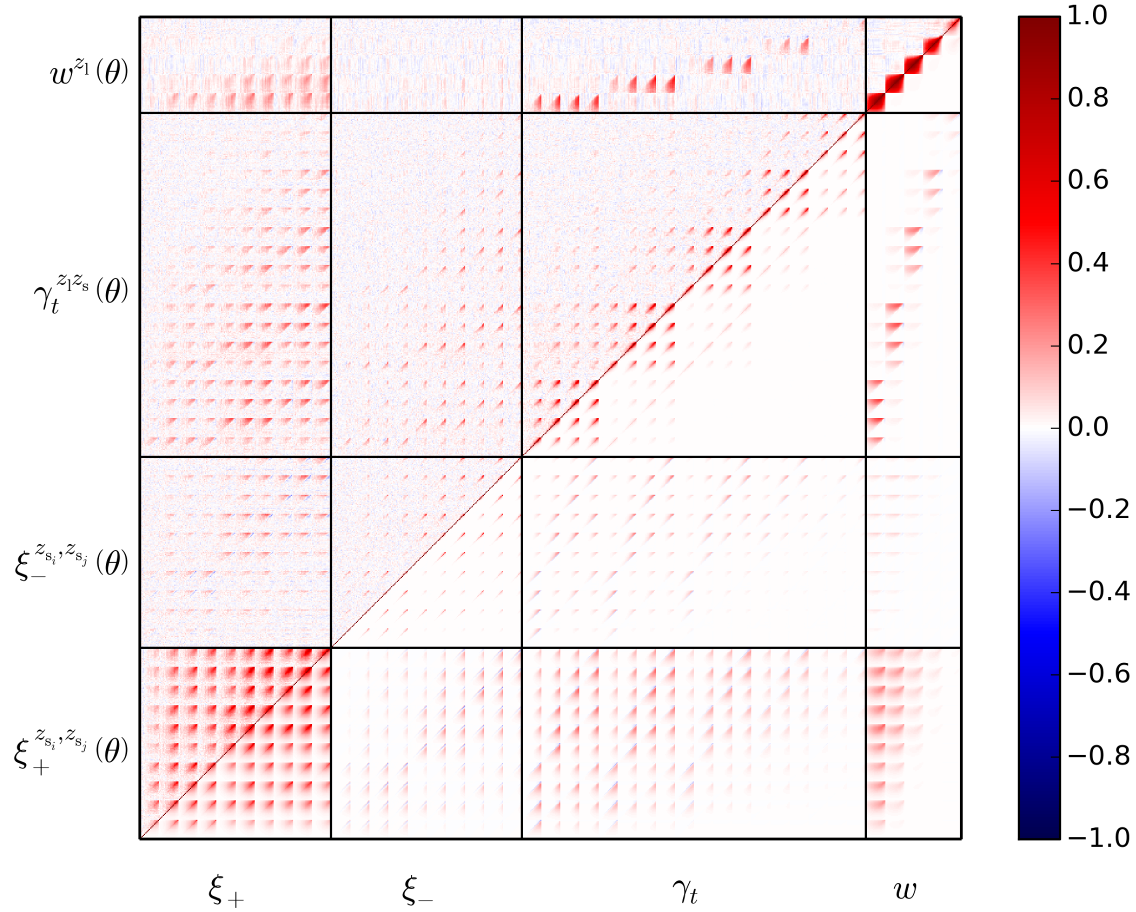
(**positions** of **foreground** galaxies; 5 redshift bins)

s

(**shear** of **background** galaxies; 5 redshift bins)

"3x2 (point-function)" clustering measurements: $\begin{bmatrix} gg & gs \\ gs & ss \end{bmatrix}$

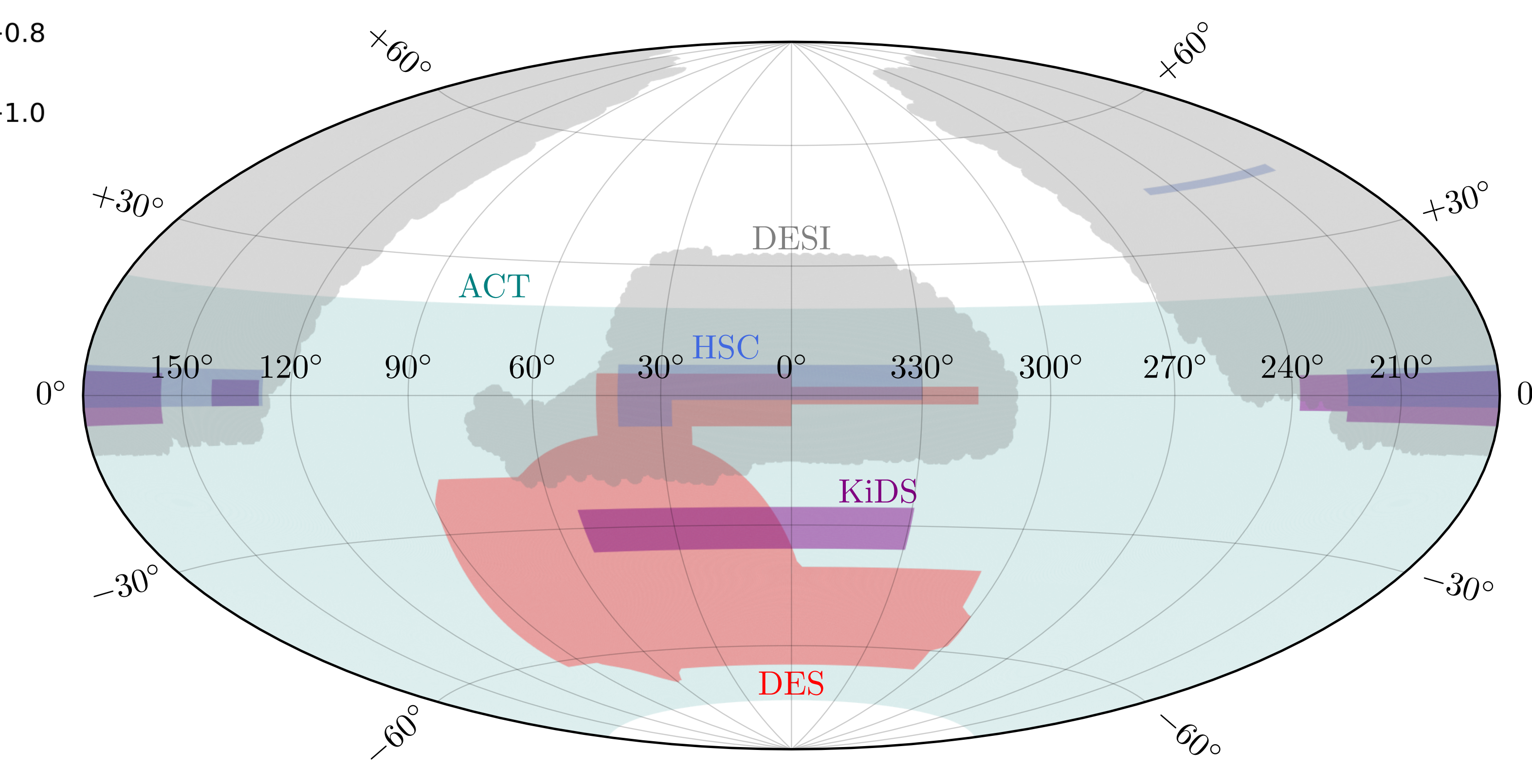
Gravitational lensing and 3x2 cosmology



Krause, Eifler et al (2017) [3x2 Cov for DES]

Covariance is non-trivial to calculate.

… but effort in progress to combine DESI with DES, KiDS, HSC (and I am sure Euclid, Roman and DESC in other efforts)

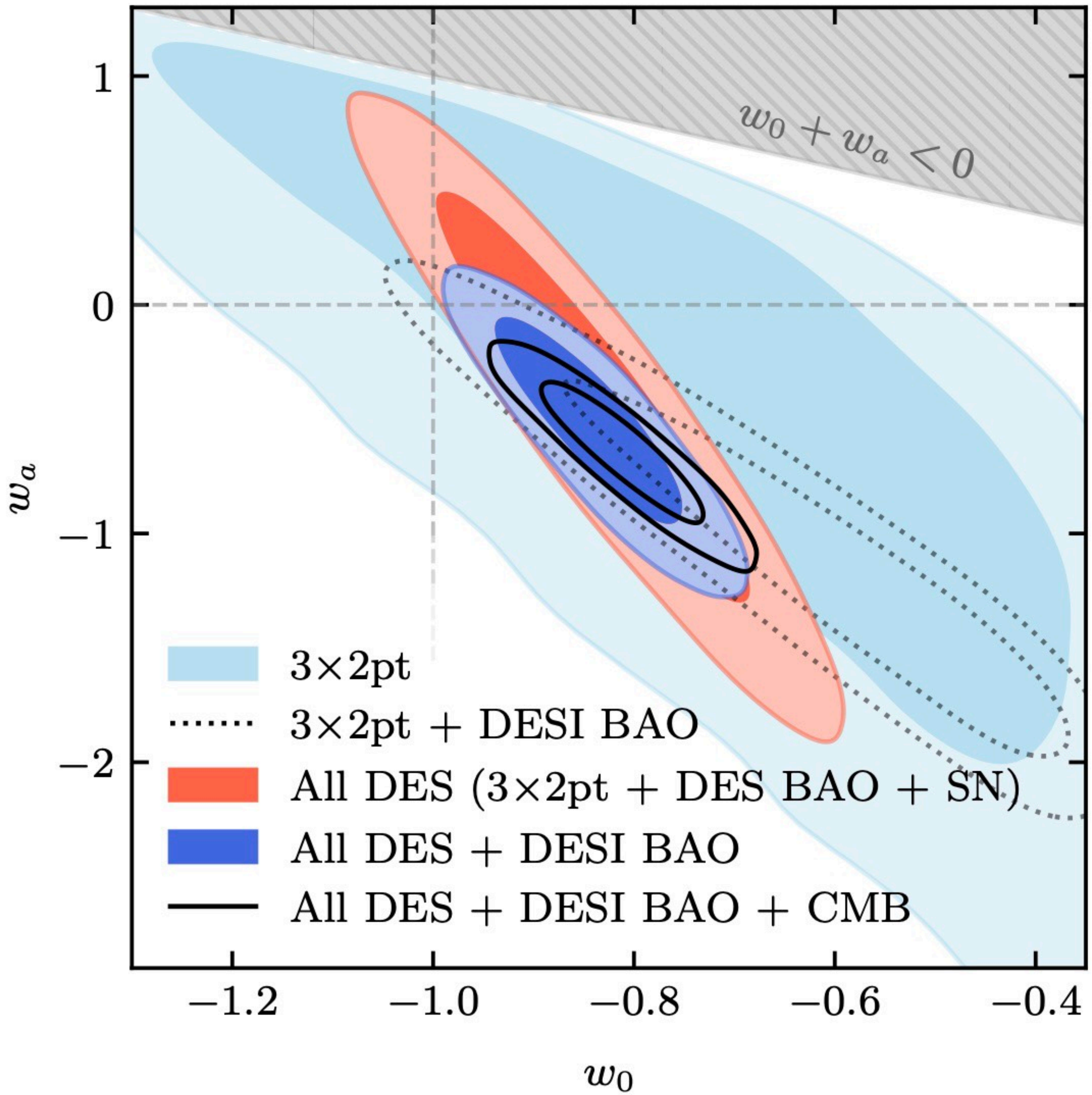


J. Lange for DESI C3 WG

Also important: LSS×CMB cross-correlations (“6x2” etc)!

Constraints on DE from 3x2 in DES

(and 3x2+BAO+SN, all DES)



Abbott et al (DES collaboration),
"Constraints on dynamical DE from Multiple Probes in the full DES", arXiv:2506:27221

Beyond cosmological parameters:
testing LCDM (and "testing gravity")

Options include

- non-parametric methods
- comparing at level of observations (eg. compare D_L and D_A)
- <u>geometry-growth split</u>

Comparing geometry and growth
("geometry-growth split")

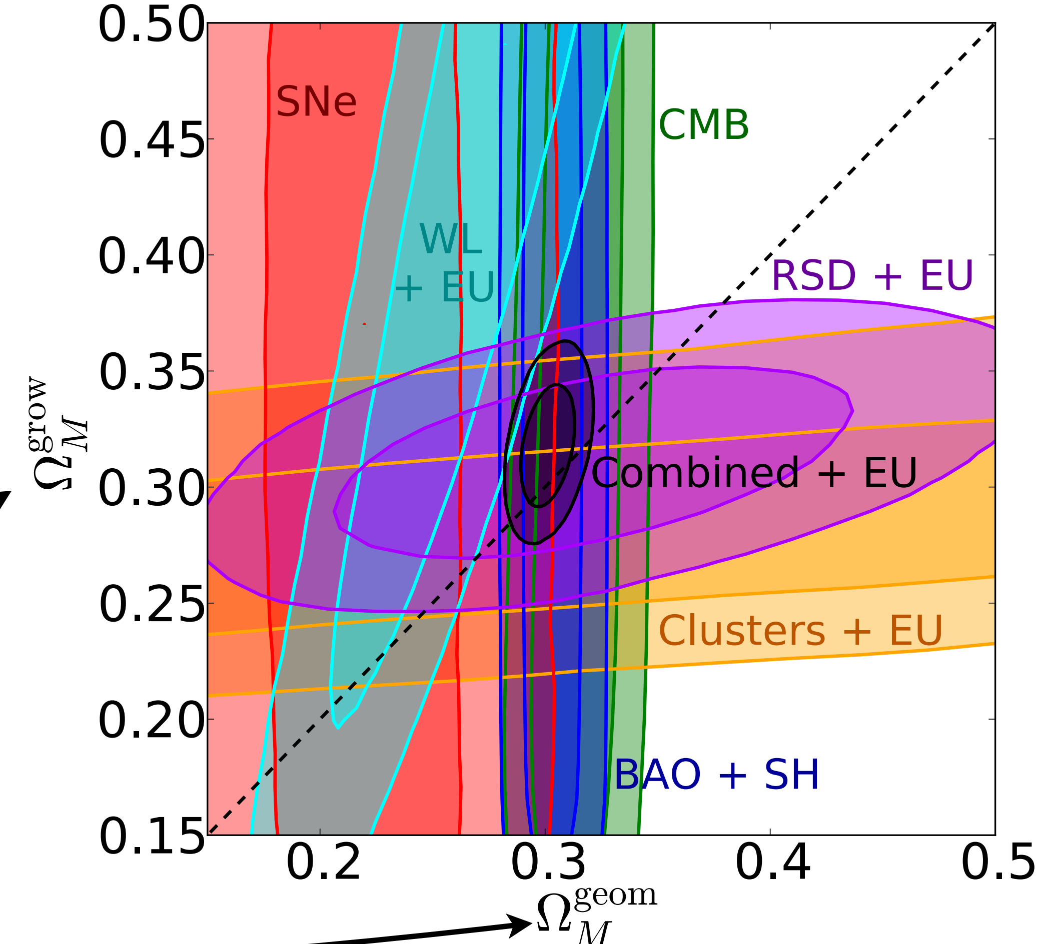
proposed by Zhang, Hui, & Stebbins (2005);
reviewed in Huterer (2023)

One approach: Double the standard DE parameter space

Instead of Ω_M and w, have:

$\Omega_M^{\rm geom}$, $w^{\rm geom}$ $\Omega_M^{\rm grow}$, $w^{\rm grow}$

[In addition to other, usual parameters]

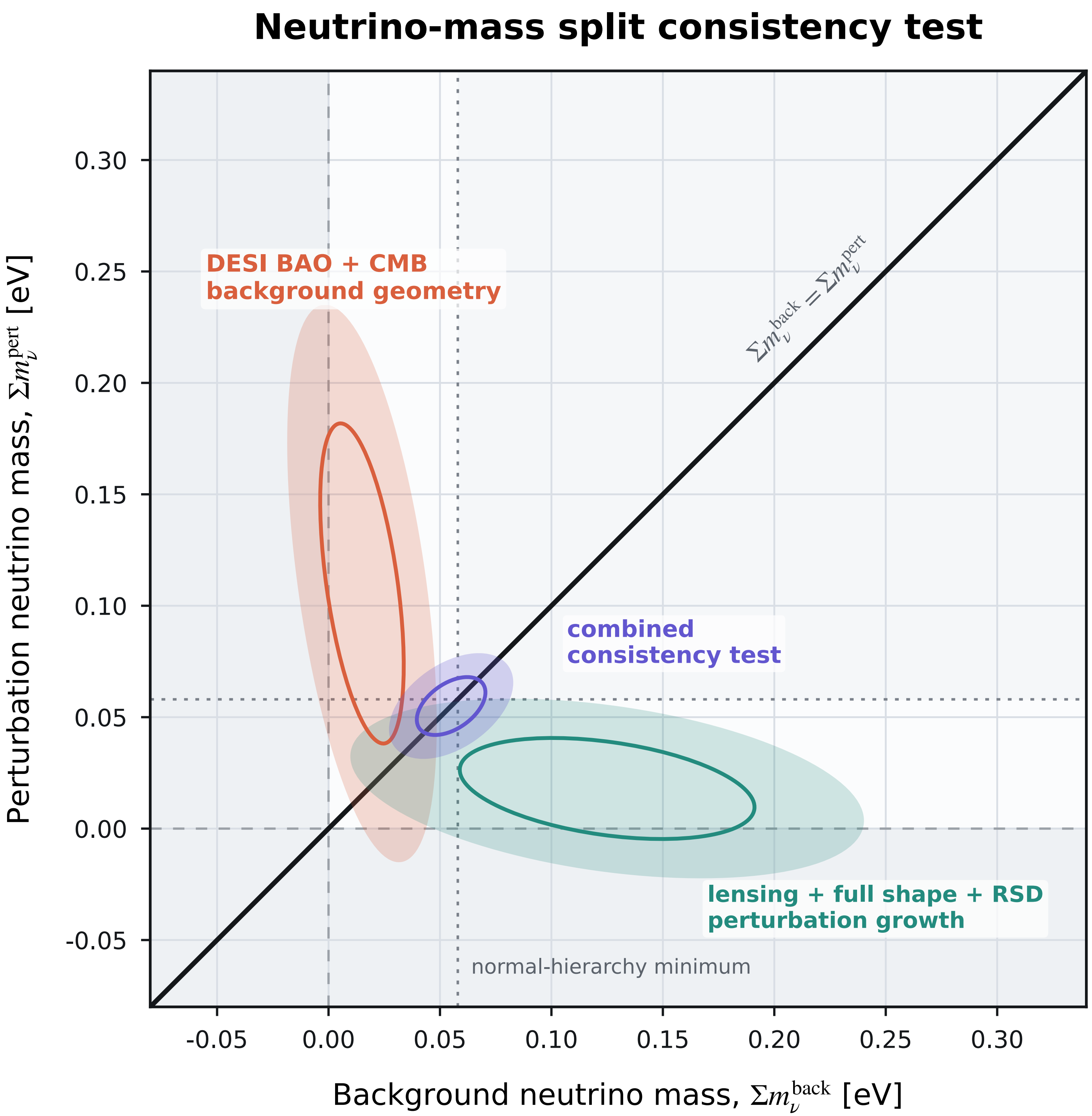


Ruiz & Huterer (2015)

Cosmological Probe	Geometry	Growth
SN Ia	$H_0 D_L(z)$	—
BAO	$\{D_M(z); D_H(z)\}$	$r_d(z_d)$
CMB	$j_\ell[k\chi(z)]$	$S_T(k,z)$
Weak lensing	$\frac{d\chi(z)}{d(z)} g_i(z) g_j(z)$	$\Omega_m^2 P_\delta\left(\frac{\ell}{\chi}, z\right)$
RSD	—	$f(z)\sigma_8(z)$

Andrade et al (2021)

Geometry-growth split



- Advantages:
- motivated by physical considerations (e.g. MG)
- particularly effective with a wealth of cosmo probes (lensing, SNIa, CMB, BAO, pecvel,…)
- geom ≠ growth indicates a tension under ***any*** implementation of geom-growth split

DESI DR2 (+CMB+…) forecast by U. Andrade

A simpler alternative to full geometry-growth split:

growth index γ

(Peebles ~1980, Linder 2005)

$$f(a) \equiv \frac{d\ln D}{d\ln a} \simeq \Omega_m(a)^\gamma$$

then the linear growth is

$$D(a) = \exp\int_1^a d\ln a'\,\Omega_m^\gamma(a')$$

fits DE models in GR,
to very high accuracy (0.1%)

$$\gamma \simeq 0.55$$

(really $\gamma \simeq 0.55[1+0.02w(z=1)]$)

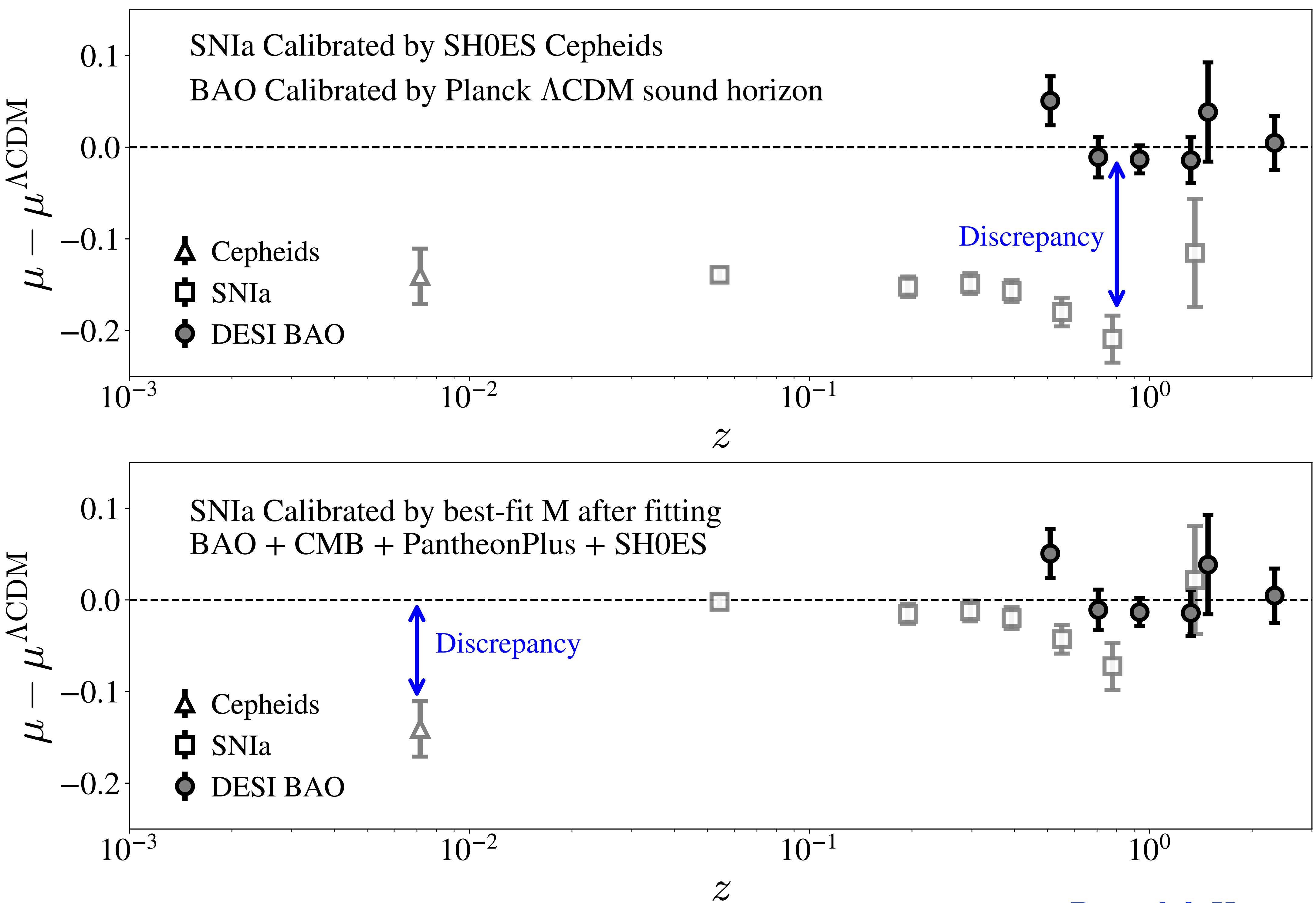
- Pros: γ is easy to implement
- Cons: not “physical”
- Pros: very robust - if $\gamma \neq 0.55$ then *something* is wrong

Some hints for a higher-than-standard γ (~0.65)

[Nguyen Huterer &Wen 2023, Calabrese et al (ACT collab) 2024, Giare et al 2025, Qin et al (DESI collab)]

Bonus feature:
Two facts about the Hubble tension

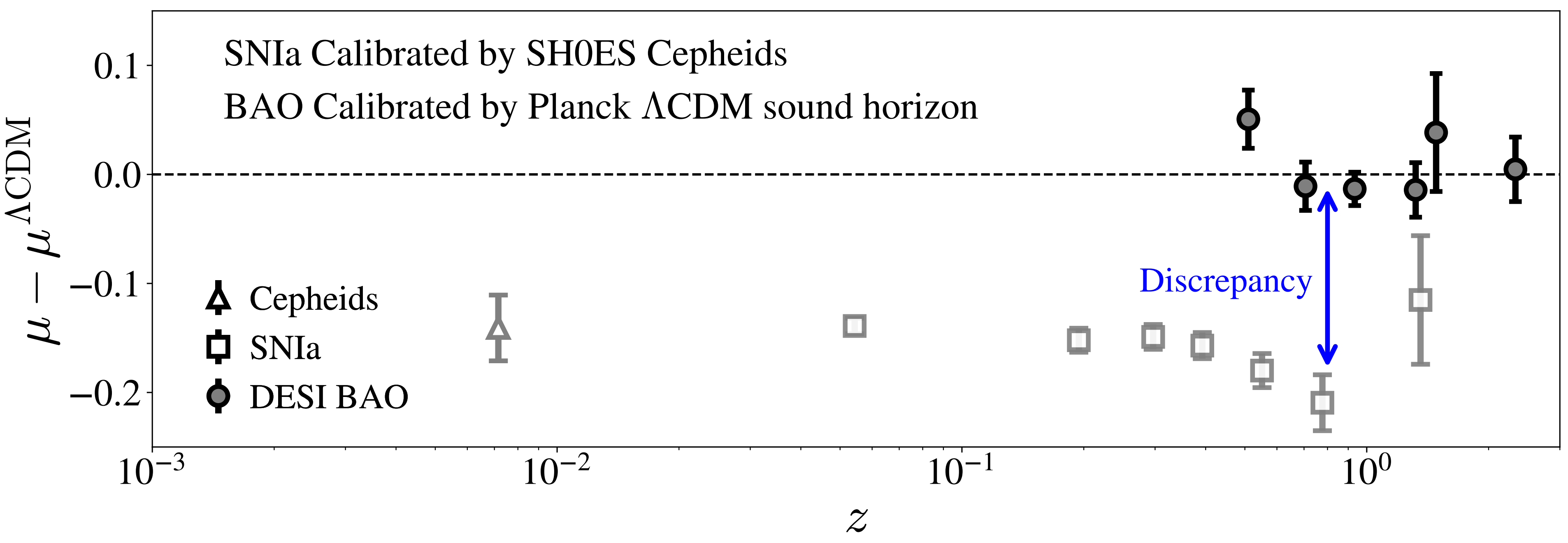
1. Late-time solutions to Hubble tension don't work!



Bansal & Huterer, arXiv:2602.06293

See also Efstathiou (2025), Poulin et al (2025), Dainotti et al (2021)…

1. Late-time solutions to Hubble tension don't work



- SNIa data can move up and down by a constant, but tension always persists
- A solution that changes H(z) doesn't work since it would introduce a "slope" to SNIa
- A successful solution would have to make M time-dependent (*extremely* contrived; we show a "physical" example)

Bansal & Huterer, arXiv:2602.06293

2. Local H0 depends (somewhat) on cosmological model!

$$m - M = 5 \log \left(\frac{1}{H_0} \int \frac{dz}{E(z)} \right)$$

Recall that, under LCDM,
H0 = 73.50 ± 0.81 (Casertano et al)

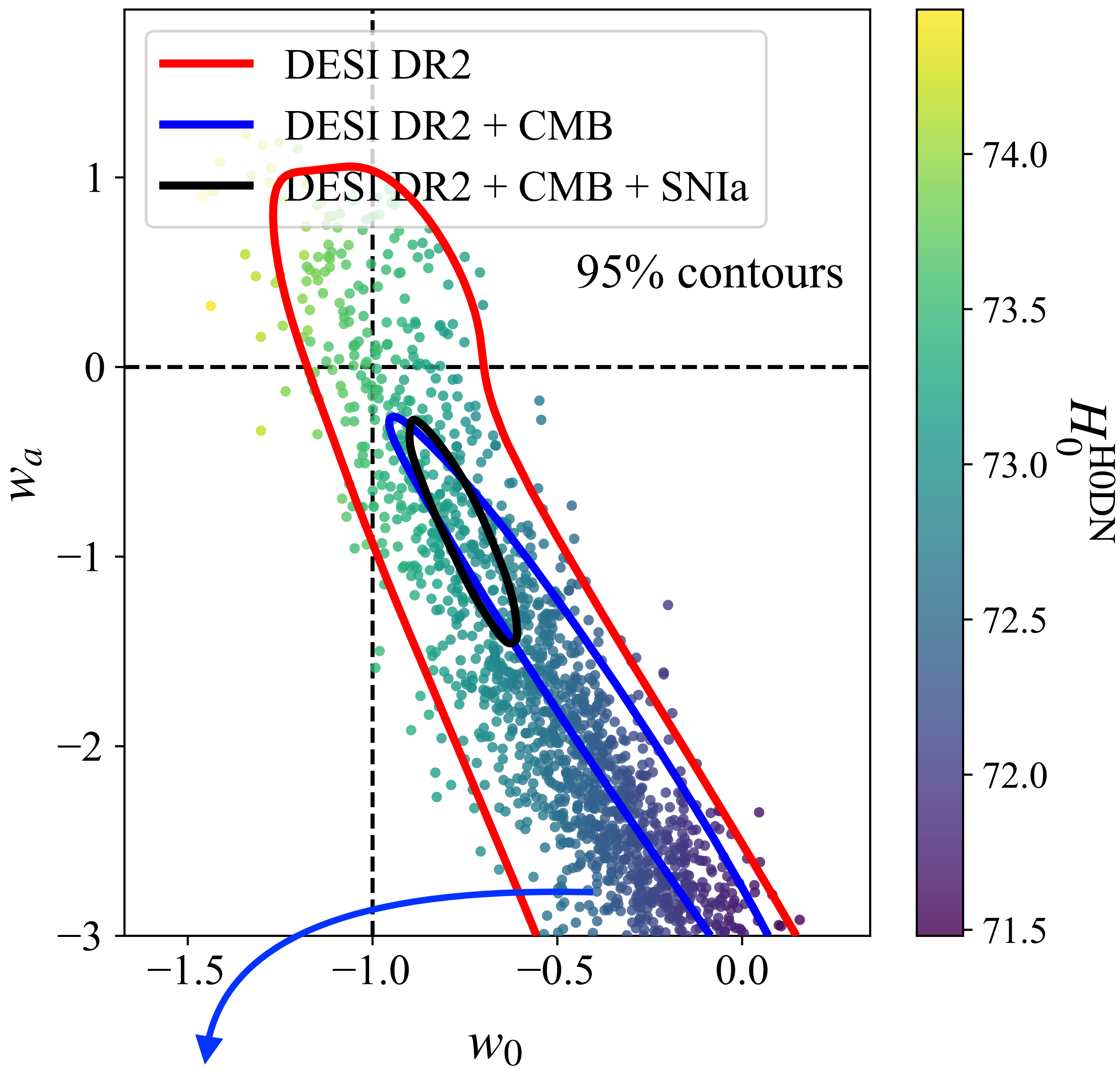
$$H_0^{\mathrm{DN/DESI+CMB+SNIa}} = 73.03 \pm 0.81 \pm 0.11$$

$$H_0^{\mathrm{DN/DESI+CMB}} = 72.44 \pm 0.81 \pm 0.38$$

$$H_0^{\mathrm{DN/DESI}} = 72.64 \pm 0.81 \pm 0.54$$

Mean goes down

Extra var due to cosmo model uncertainty



H0DN values (running code from Casertano et al 2026)

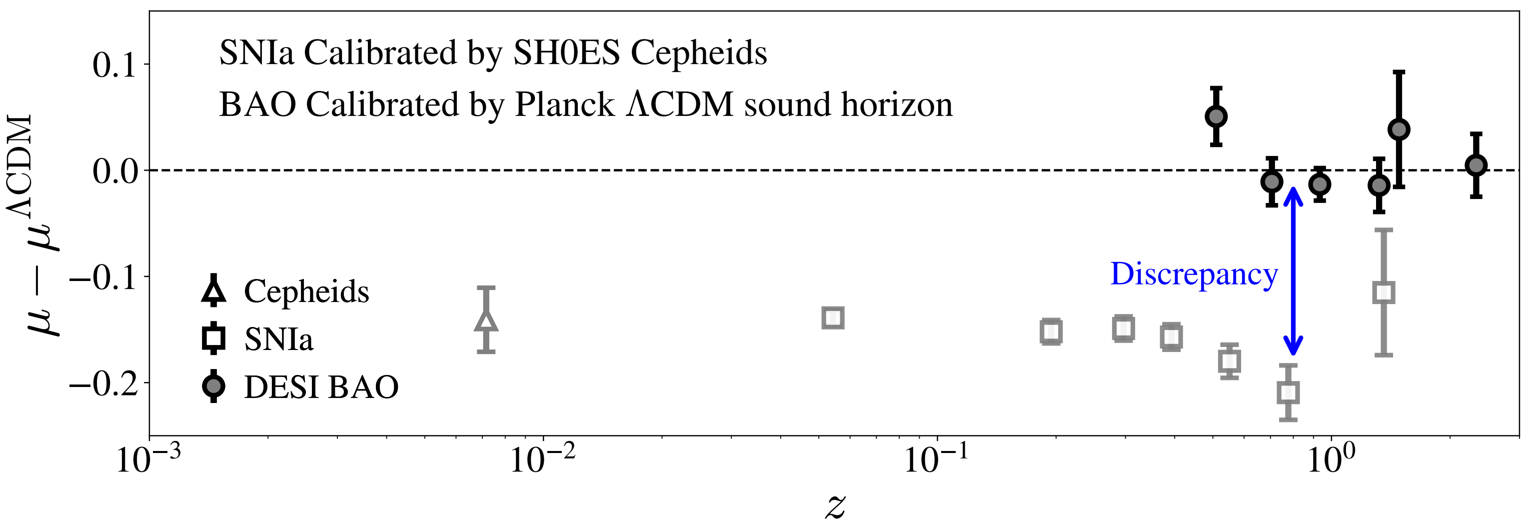
Turner & Huterer, arXiv:2606.05358

Conclusions I

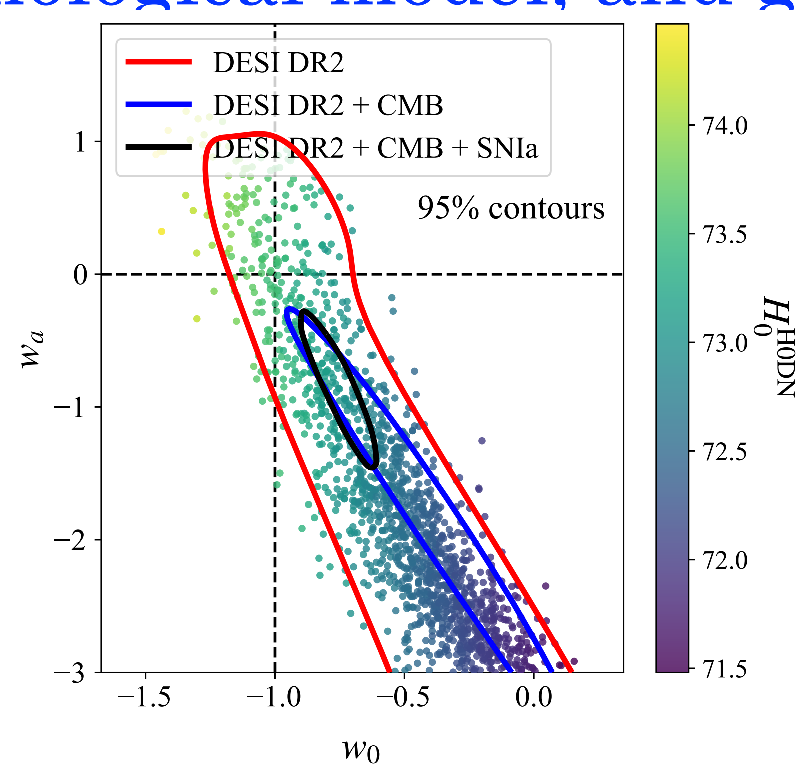
- LSS is sensitive to cosmology via
  - BAO and RSD
  - “full shape” power spectrum (includes growth)
  - peculiar velocities
  - bispectrum
  - combination with weak lensing (“3x2”)
- Parametric direct comparison of geometry to growth is a powerful way to test the standard model (LCDM or wCDM, e.g.)
- Hints for DDE are exciting, but to claim <u>evidence</u> for departure from the standard LCDM model should require a **very high bar**
- It will be exciting to see what forthcoming data show:
  - DESI DR2 full shape (later this year; see Sam Brieden talk)
  - DESI Pk + Bk (same)
  - DESI DR3, then Run 1b, Run 2 (more DESI! - talk to Lado S.)
  - ZTF, SO, cross-correlations, Euclid? Spherex?

Conclusions II

- Hubble tension cannot be solved with late-time physics

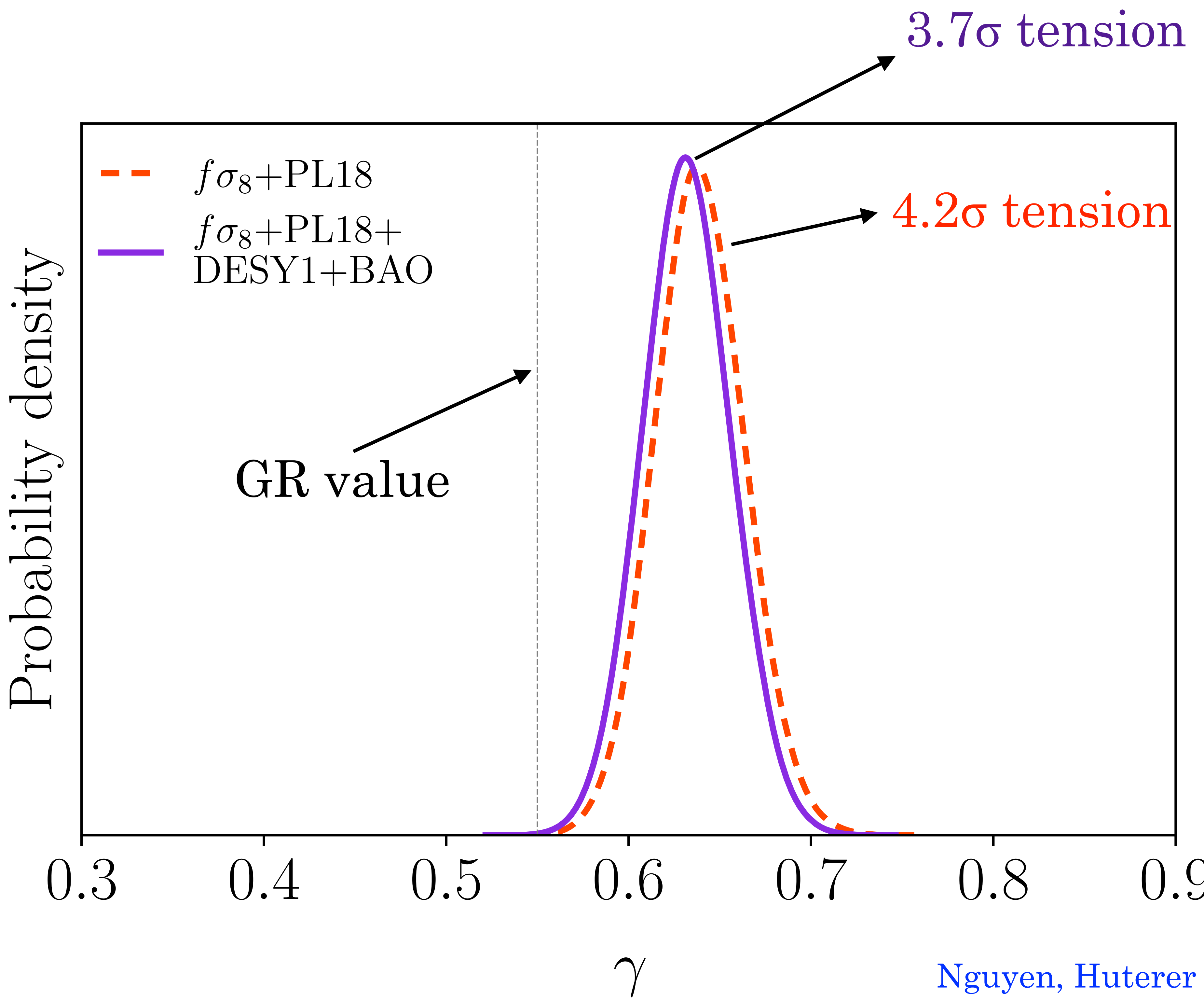


- Local H0 (from e.g. Distance Network) somewhat depends on cosmological model, and goes down (by up to ~1 km/s/Mpc) with DDE



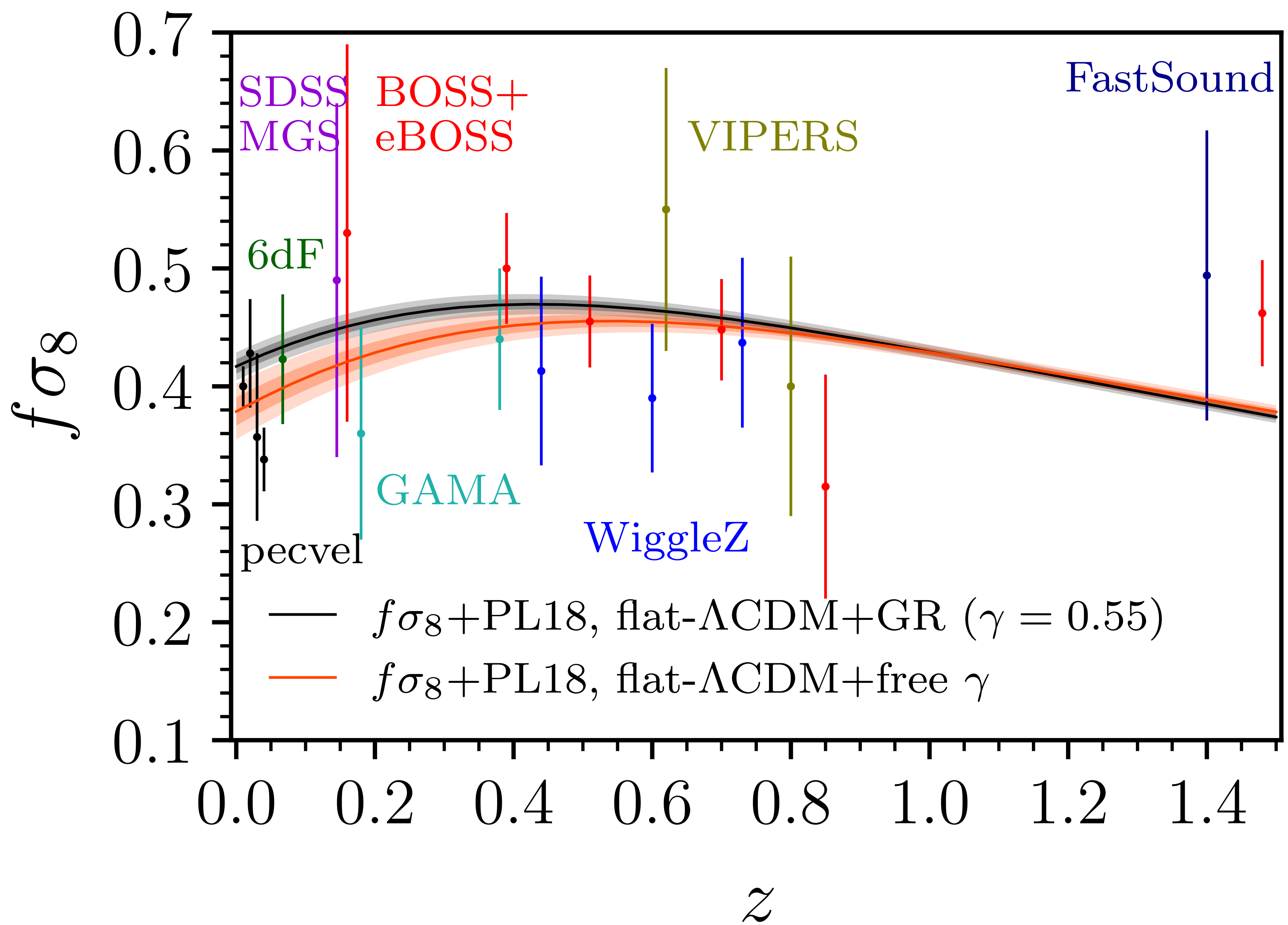
Extra slides

Basic result:



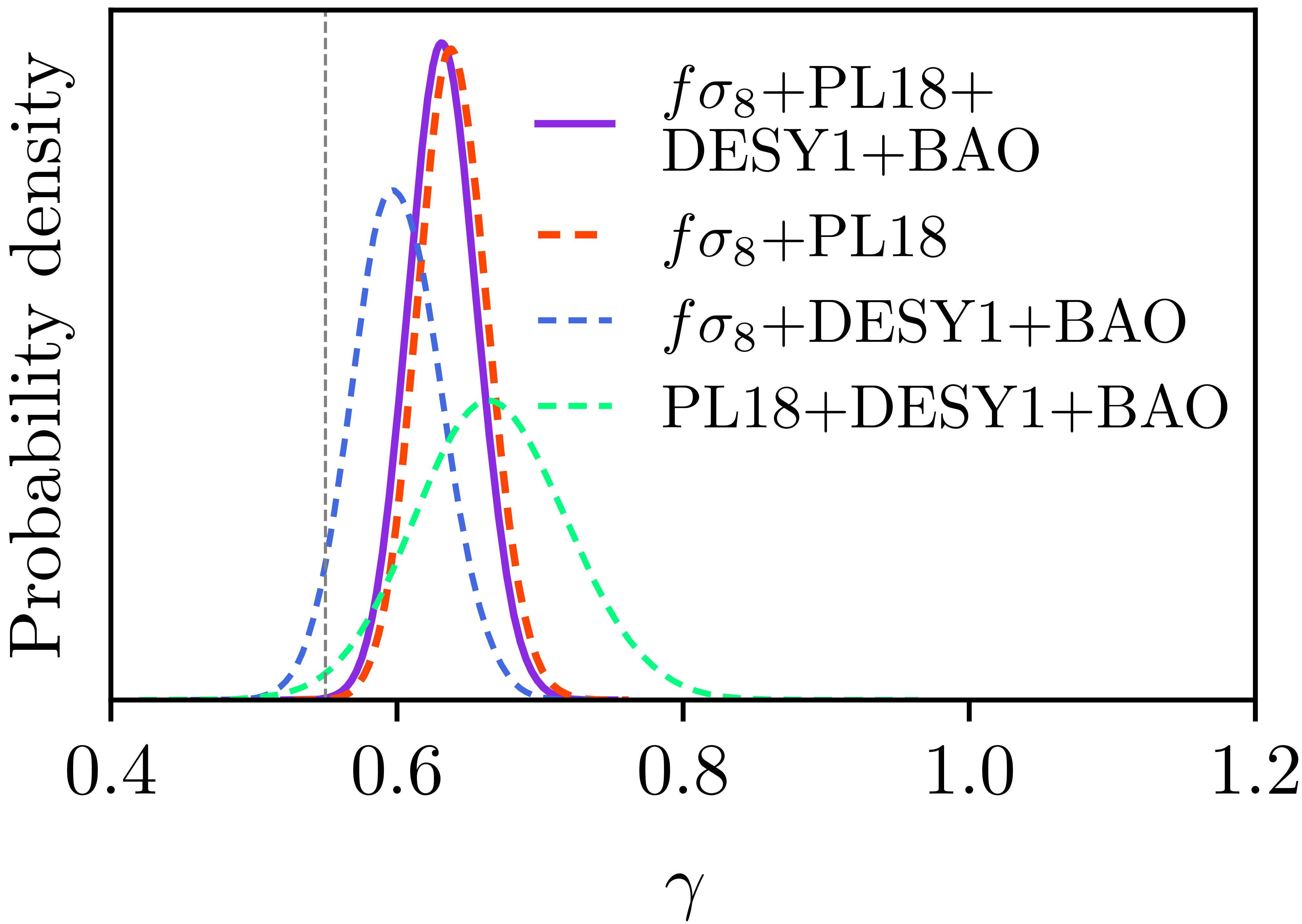
Nguyen, Huterer & Wen (2023)

Data	γ	S_8	H_0 [$\mathrm{kms^{-1}Mpc^{-1}}$]	$\lvert\log_{10}\mathrm{BF}_{10}\rvert$	$\Delta\chi^2 \equiv \chi^2_\gamma - \chi^2_{\gamma=0.55}$
PL18	$\mathbf{0.668^{+0.068}_{-0.067}}$	$0.807^{+0.019}_{-0.019}$	$68.1^{+0.7}_{-0.7}$	0.4	-2.8
PL18+$f\sigma_8$	$\mathbf{0.639^{+0.024}_{-0.025}}$	$0.814^{+0.011}_{-0.011}$	$67.9^{+0.5}_{-0.5}$	1.7	-13.6
PL18+$f\sigma_8$+DESY1+BAO	$\mathbf{0.633^{+0.025}_{-0.024}}$	$0.802^{+0.008}_{-0.008}$	$68.4^{+0.4}_{-0.4}$	1.2	-13.2
PL18+$f\sigma_8$+DESY1+BAO (flat ΛCDM+GR)	**0.55**	$0.803^{+0.008}_{-0.008}$	$68.5^{+0.4}_{-0.4}$	-	0



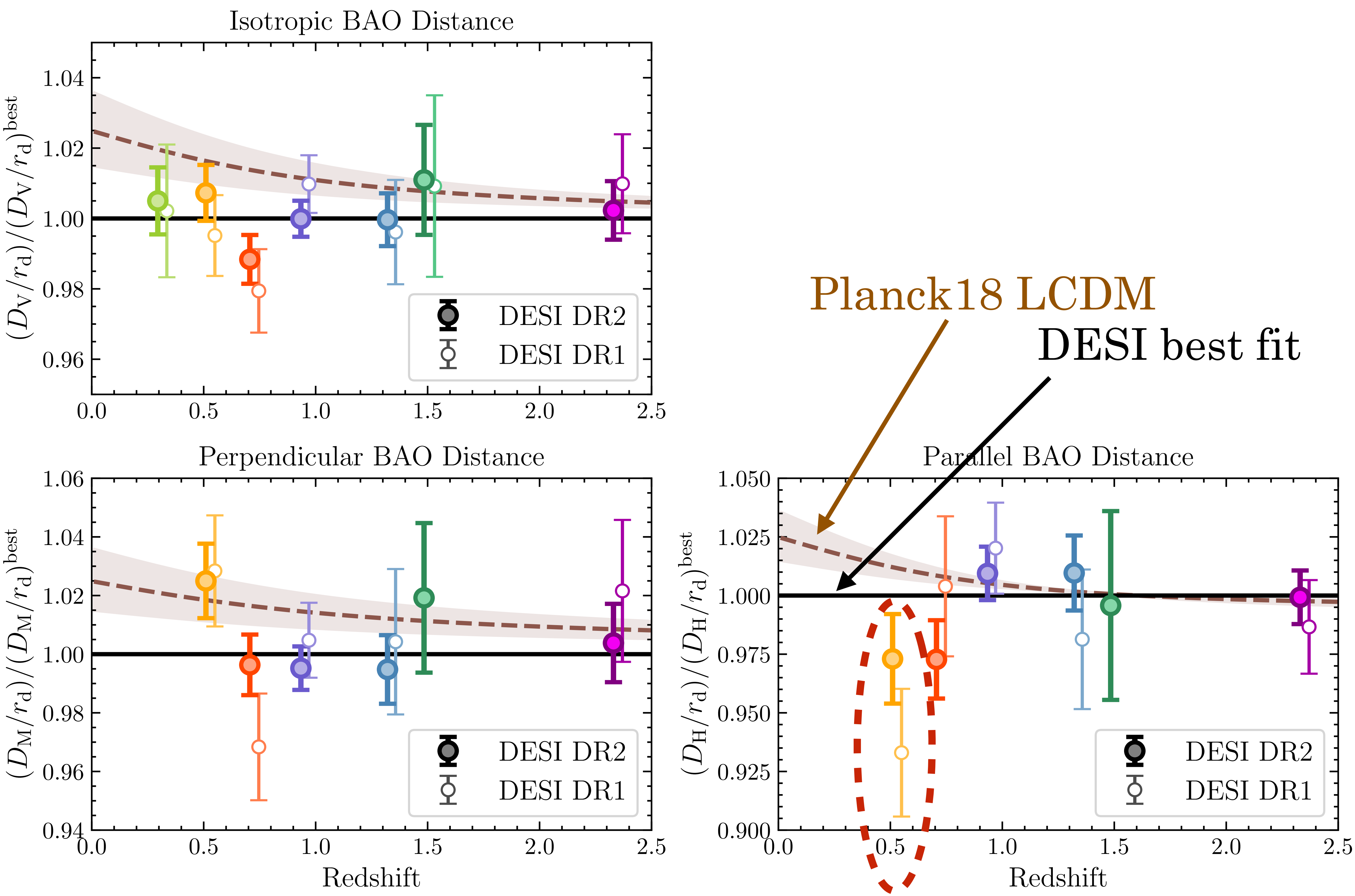
Nguyen, Huterer & Wen (2023)

More details



Nguyen, Huterer & Wen (2023)

DR2 Distance Measurements



Why preference for w0wa (from DR2 key paper)