How DESI constrains the early and late Universe

Dragan Huterer
DESI Collaboration Meeting in Hawaii
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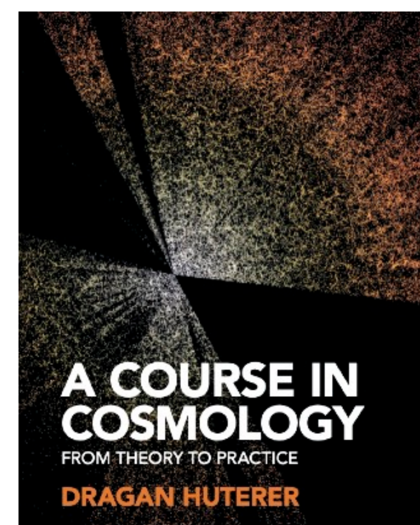
Overview of this lecture

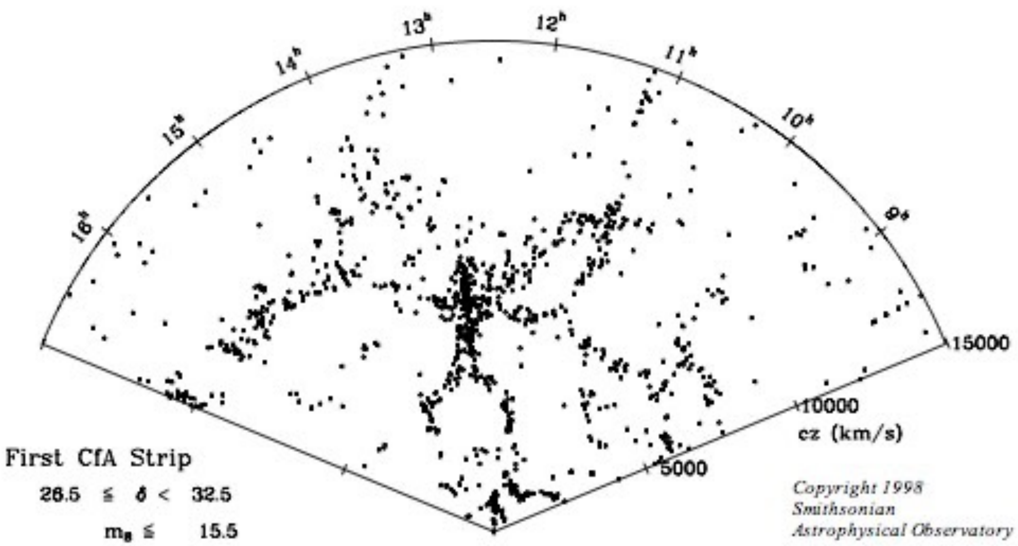
- Aimed at a fairly new cosmologist (but with basic cosmology background!)
- [If you are a practicing cosmologist, you probably know 85-90% or more of what is in these notes]
- Some details might be swept under the rug (or perhaps “wrong”); technical details (and citations) occasionally skipped
- Focus on: 1) dark energy, 2) massive neutrinos, 3) primordial non-Gaussianity
- Based on (and plots from) relevant material in my textbook
- Another relevant reading: D. Weinberg et al, “Observational Probes of DE”, Phys Rept, 2013



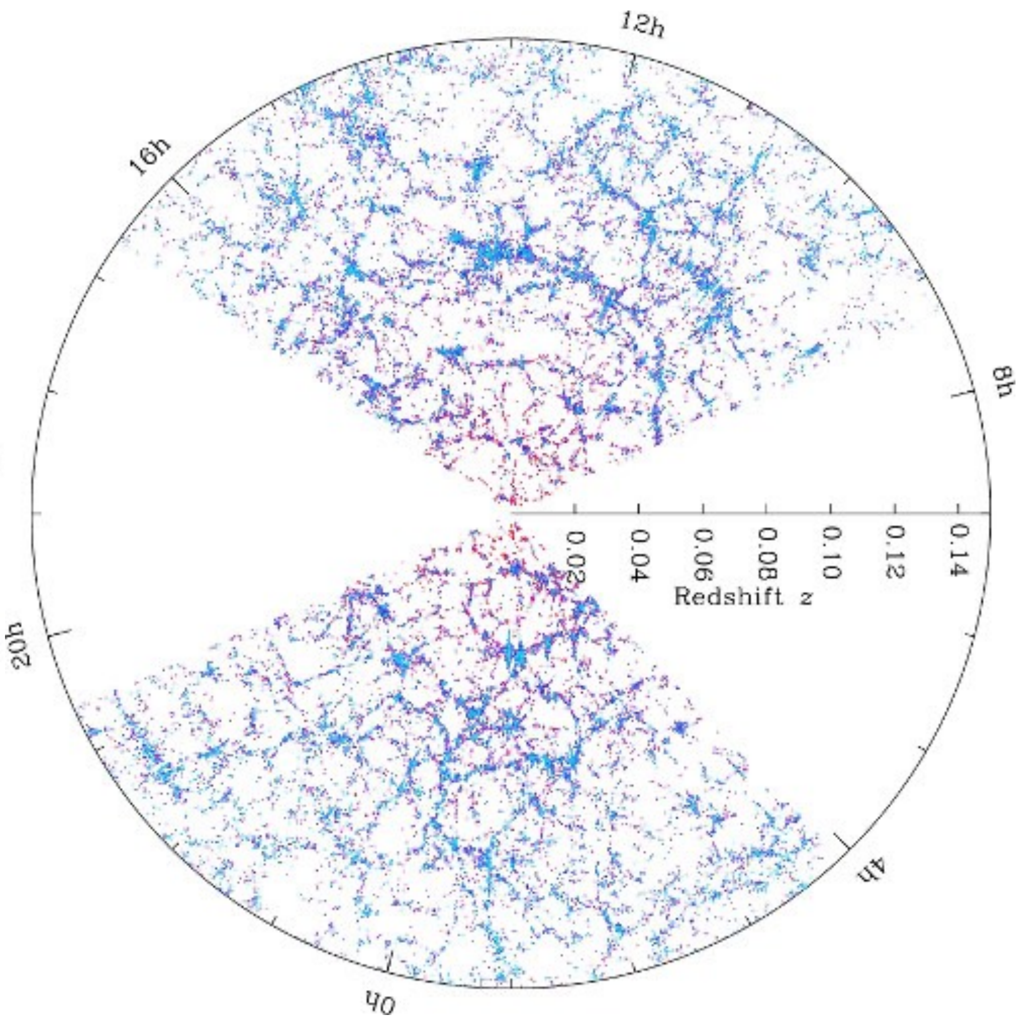
Part I:

What "theorist's observables" that DESI measures are sensitive to DE/m_ν/f_{NL}

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

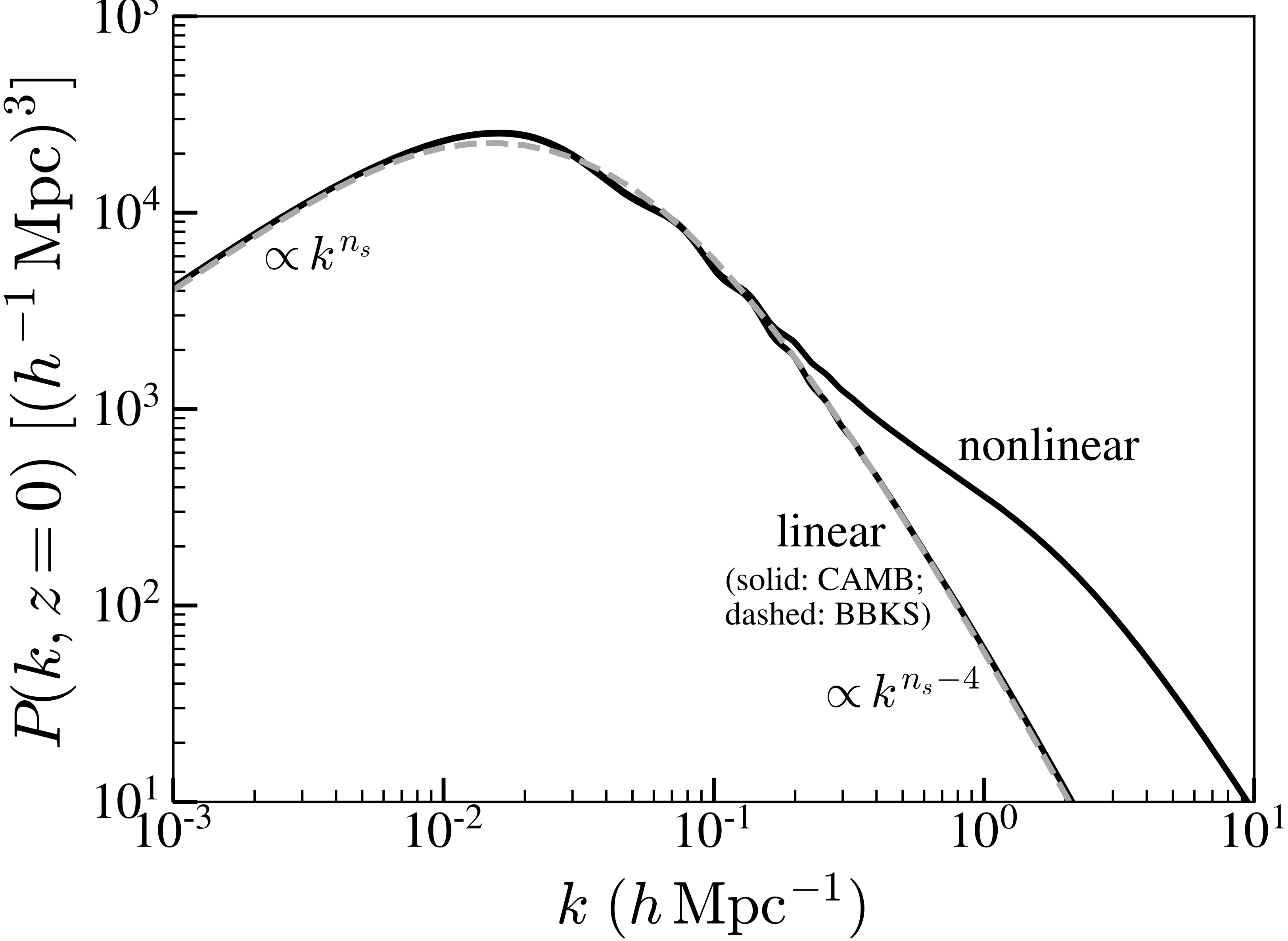


Harvard-Cfa survey;
de Lapparent, Geller & Huchra (1986)



SDSS/BOSS survey
SDSS/BOSS collaboration

The galaxy (≃matter) power spectrum!



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

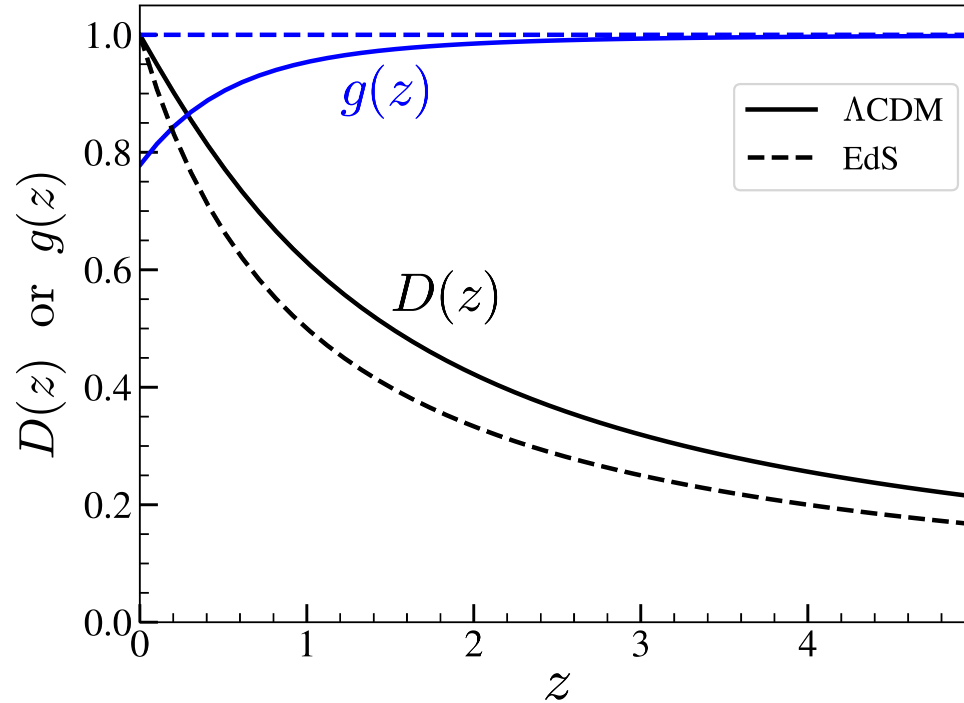
$$\Delta_g^2(k,a) \equiv \frac{k^3 P_g(k)}{2\pi^2}$$

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

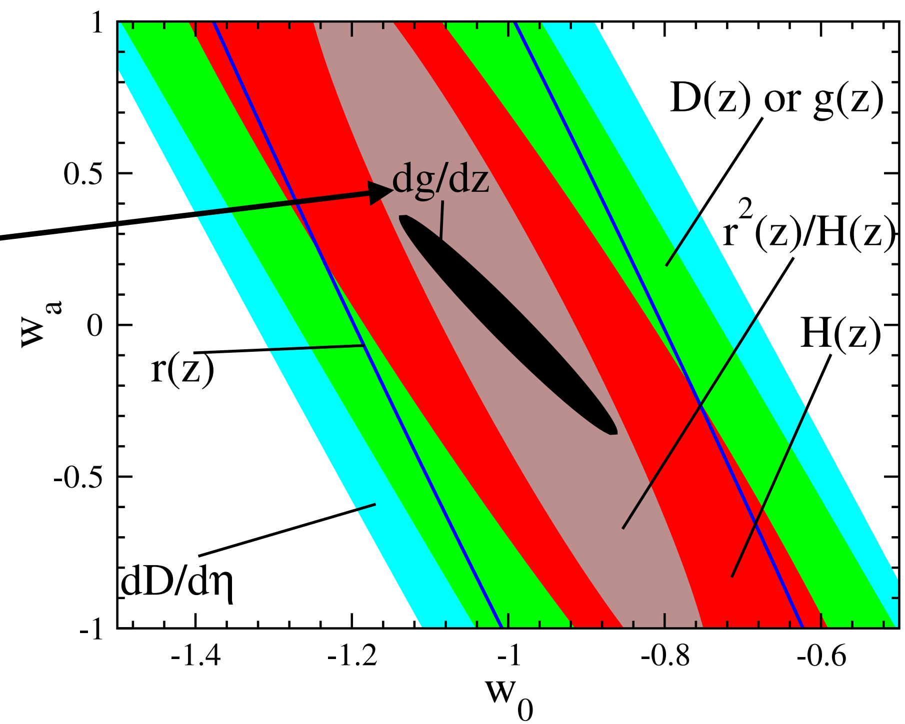
Principal sensitivity to cosmo parameters comes from:

- 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]

Growth function D(z) or g(z)

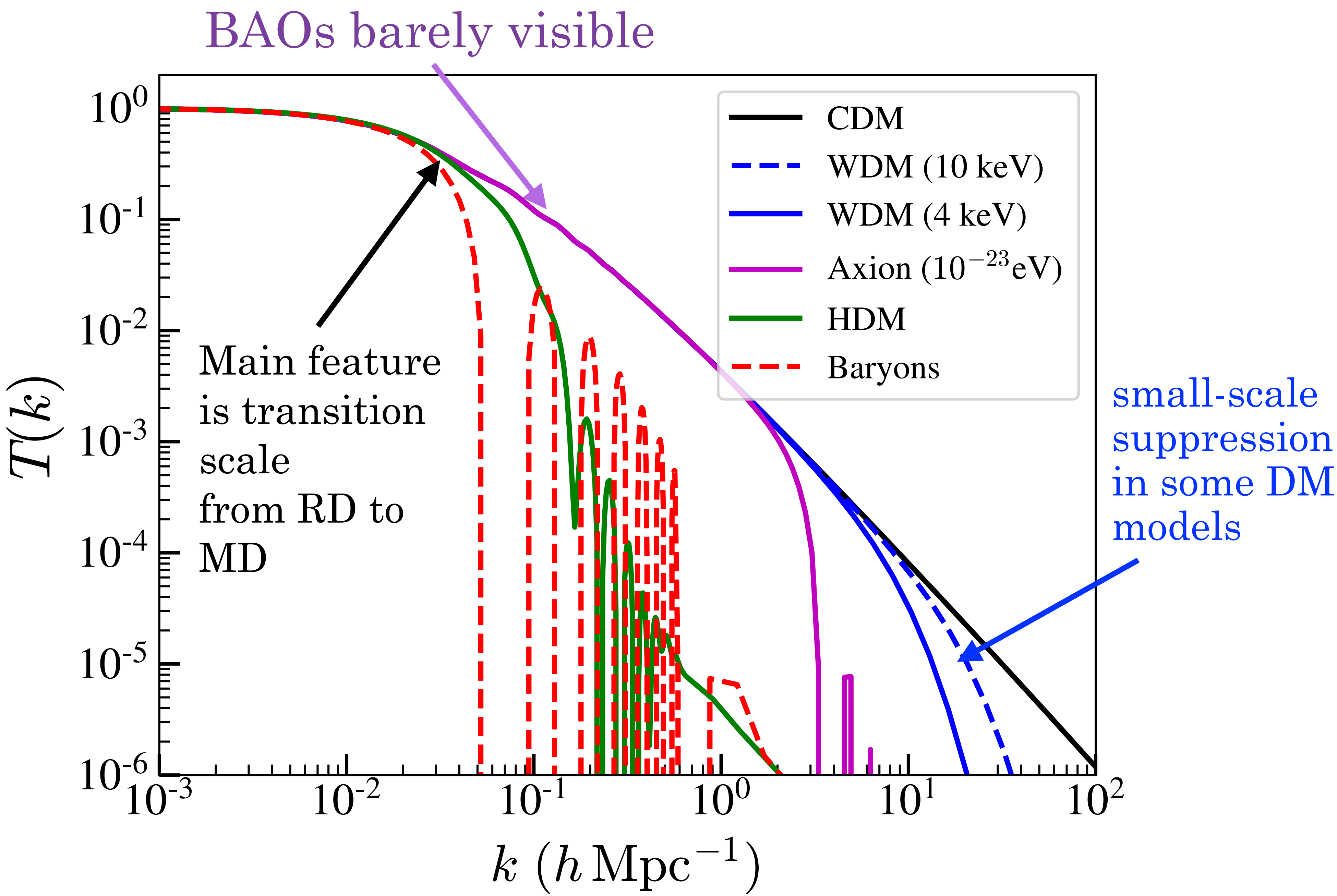


Probes that measure growth rate $f(a) \equiv \frac{d\ln D}{d\ln a}$ are particularly valuable (*why?*)

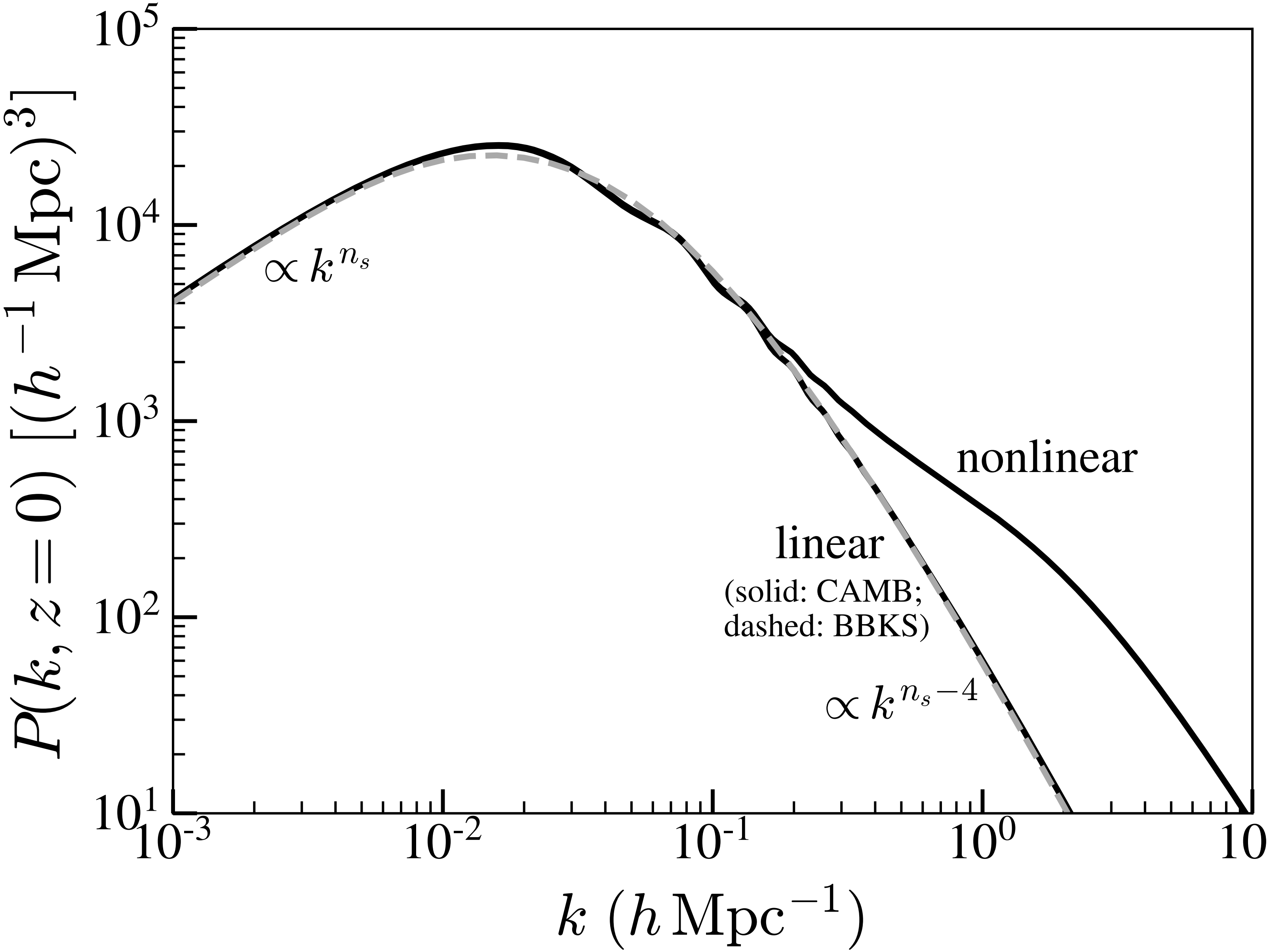


Cooray, Huterer & Baumann (2004)

Transfer function

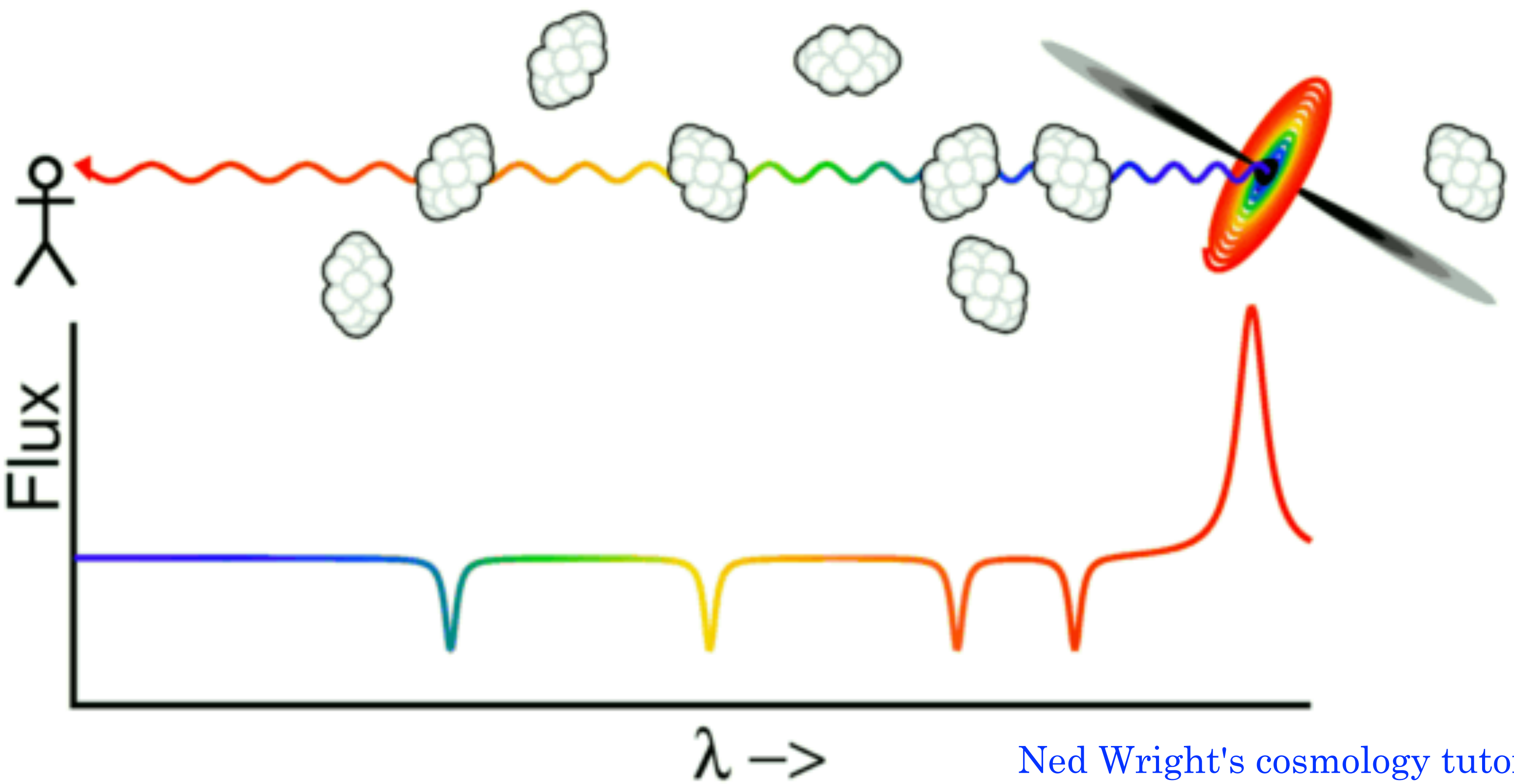


$$\Delta_g^2(k,a) = b^2(k,a)\, A_s \frac{4}{25}\frac{1}{\Omega_M^2}\left(\frac{k}{k_{\rm piv}}\right)^{n_s-1}\left(\frac{k}{H_0}\right)^4 [ag(a)]^2\, T^2(k)$$



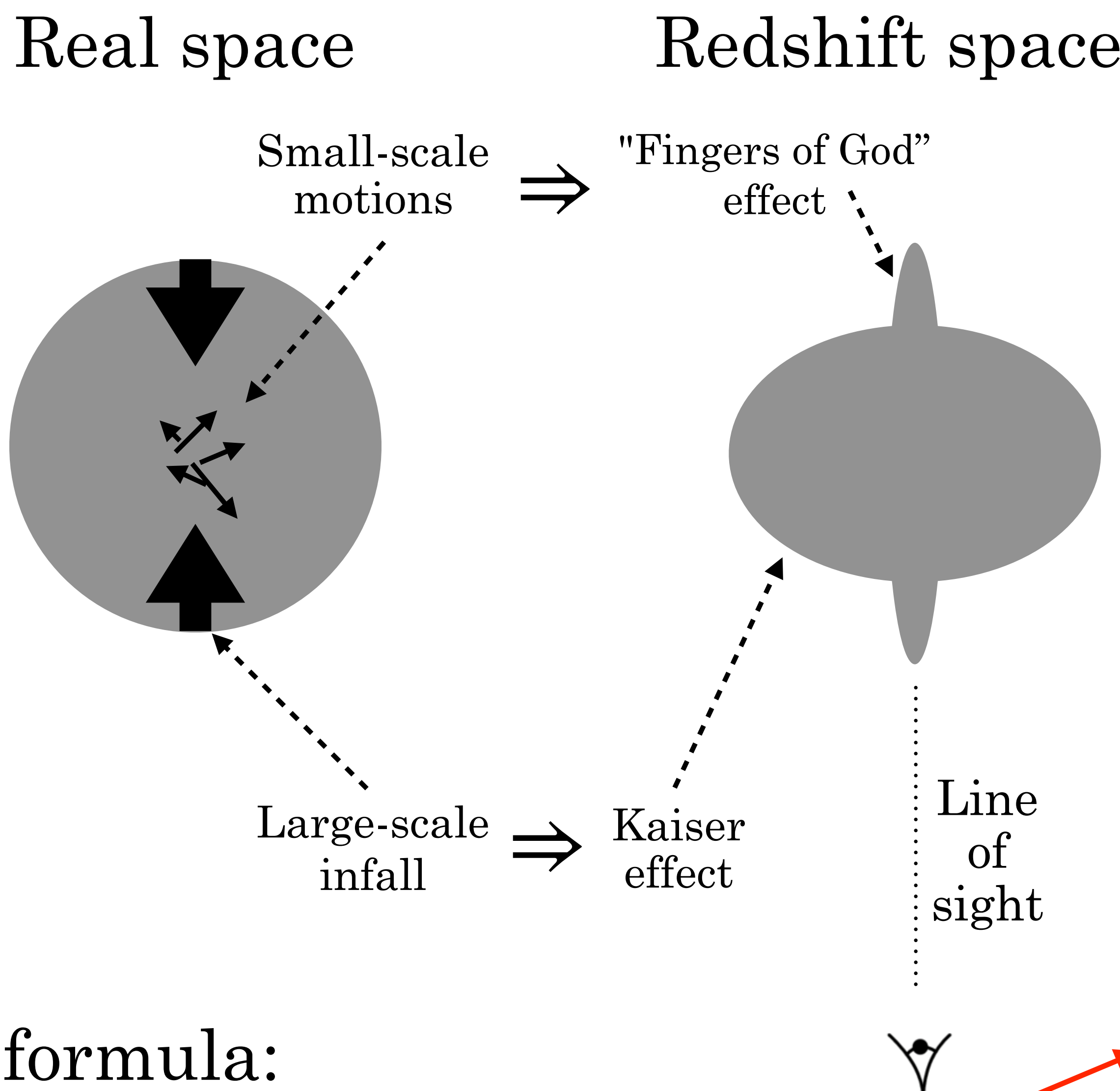
Lyman-alpha forest

Note that Lyman-alpha forest also measures essentially the matter power spectrum — and isolates the BAO in it



Ned Wright's cosmology tutorial

Redshift-space distortions



Kaiser (1987) formula:

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

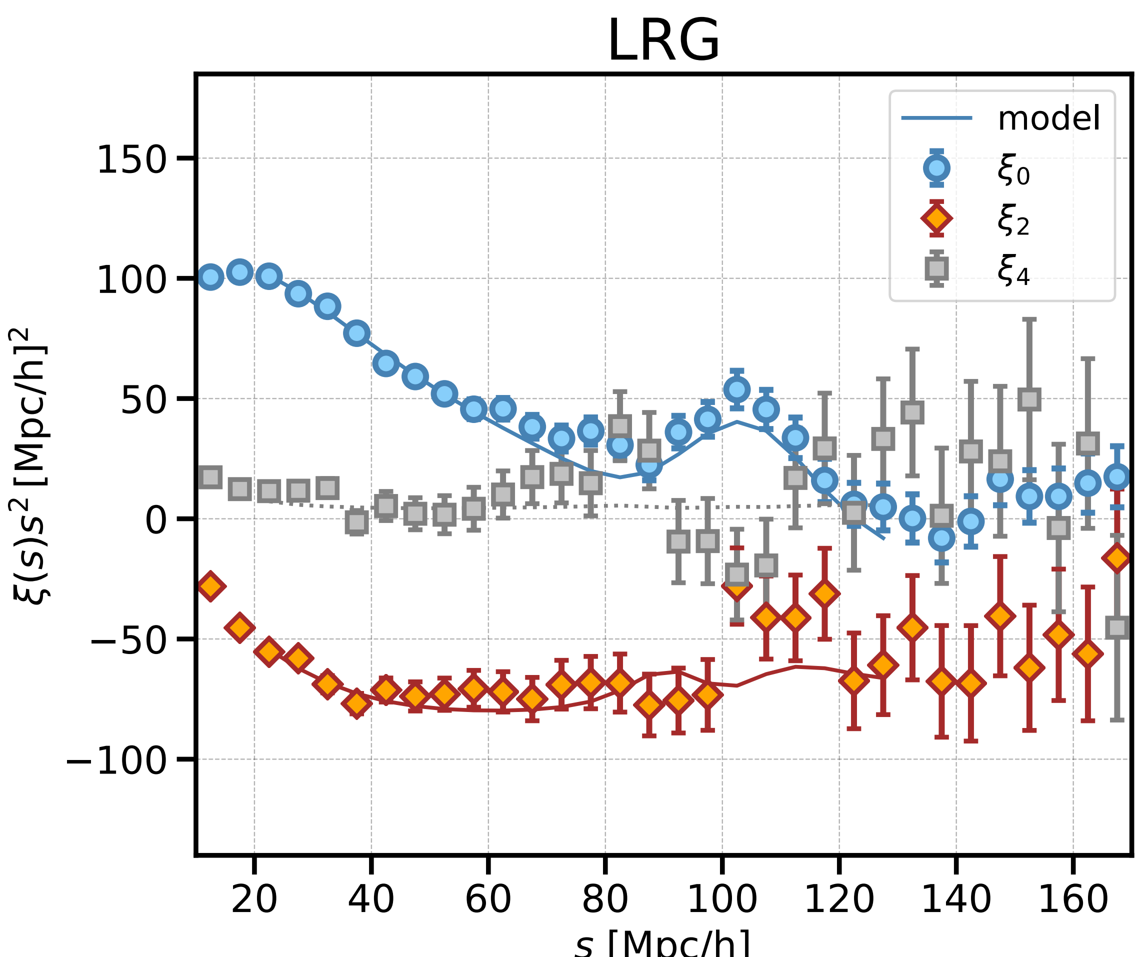
where $\beta \equiv \dfrac{f}{b};\ \mu \equiv \hat{\mathbf{k}} \cdot \hat{r}_z = k_z/k$

growth rate!

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 DESI probes/combinations:

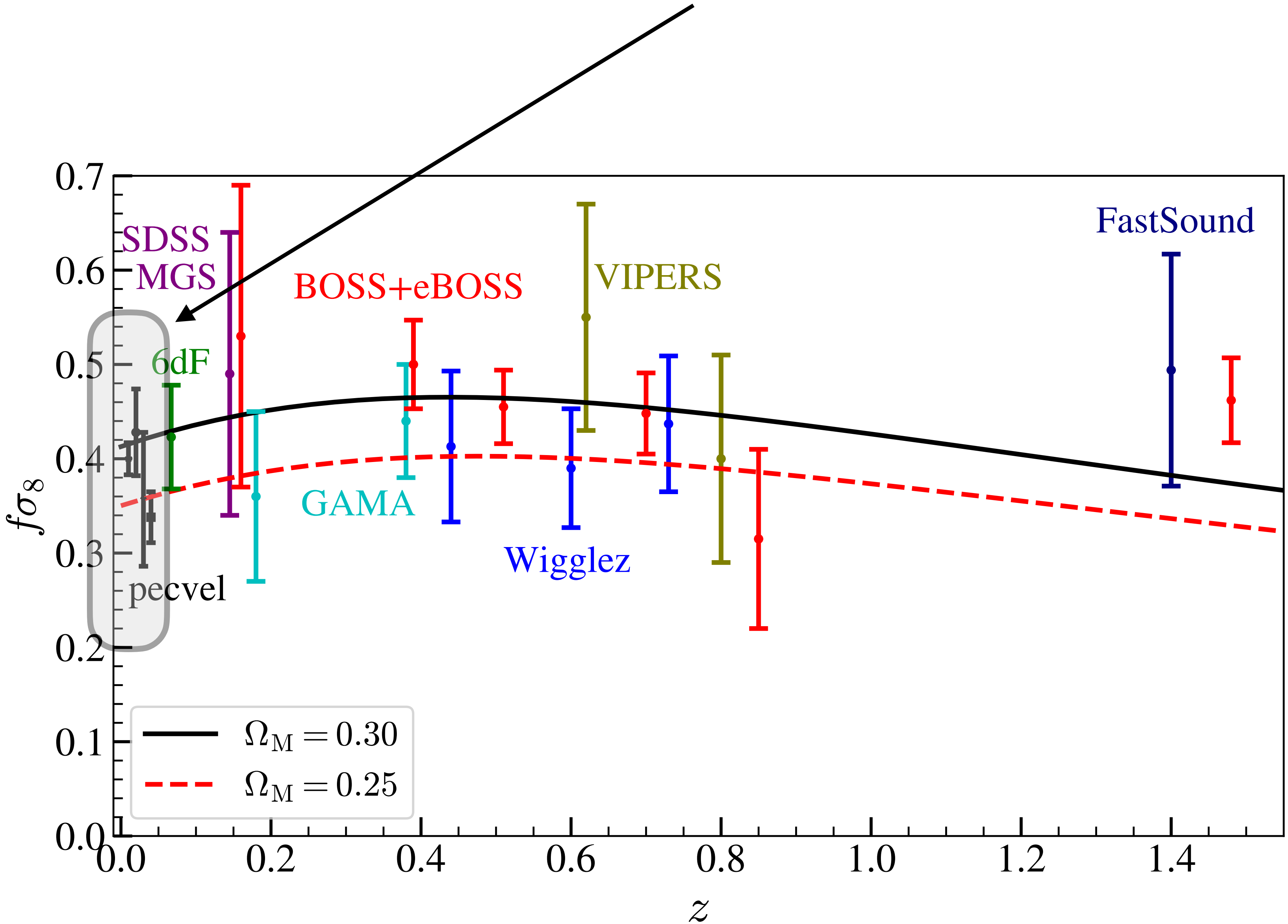
1. Peculiar velocities
2. Bispectrum (of galaxy distribution)
3. Gravitational lensing and 3x2 cosmology

1. Peculiar velocities

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

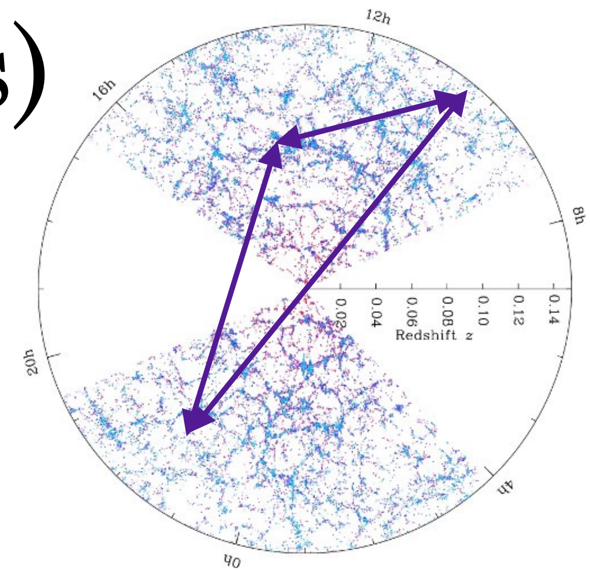
- Imagine now that you measure redshifts and distances $r(z) \simeq cz/H_0$.
- The former gets you $z_{\rm obs}$, them latter gives you z
- [Getting distances is the hard part; use type Ia supernovae or Tully-Fisher relation]
- Hence you get a (noisy) measurement of $v_{\rm pec}$
- Correlating these $v_{\rm pec}$, 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 $f\sigma_8 \equiv f(z)\sigma_8(z)$

1. Peculiar velocities



Huterer, Astron. Astrophys. Rev. (2023)

2. Bispectrum (of galaxies)



Fourier space:

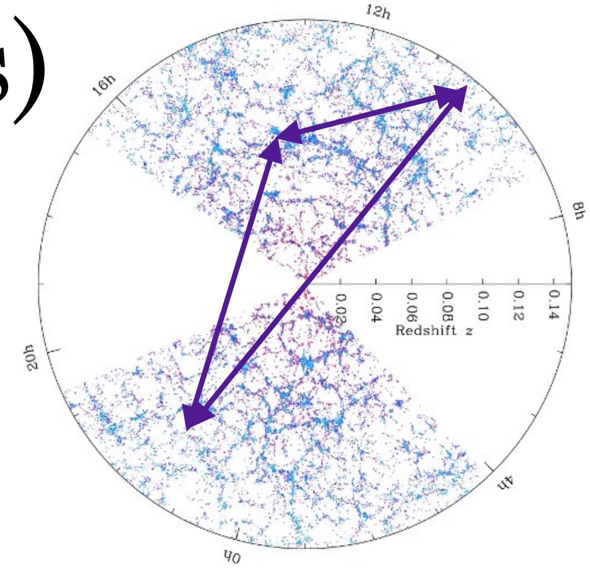
$$\langle \delta_{\vec{k}_1}\, \delta_{\vec{k}_2}\, \delta_{\vec{k}_3} \rangle = (2\pi)^3\, \delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\, B(\vec{k}_1, \vec{k}_2, \vec{k}_3)$$

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:

- 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
- Years of promises (the "bispectrum winter"), but recent progress, and also
- DESI will have likely be making major advances in measurements of, and constraints from, the bispectrum

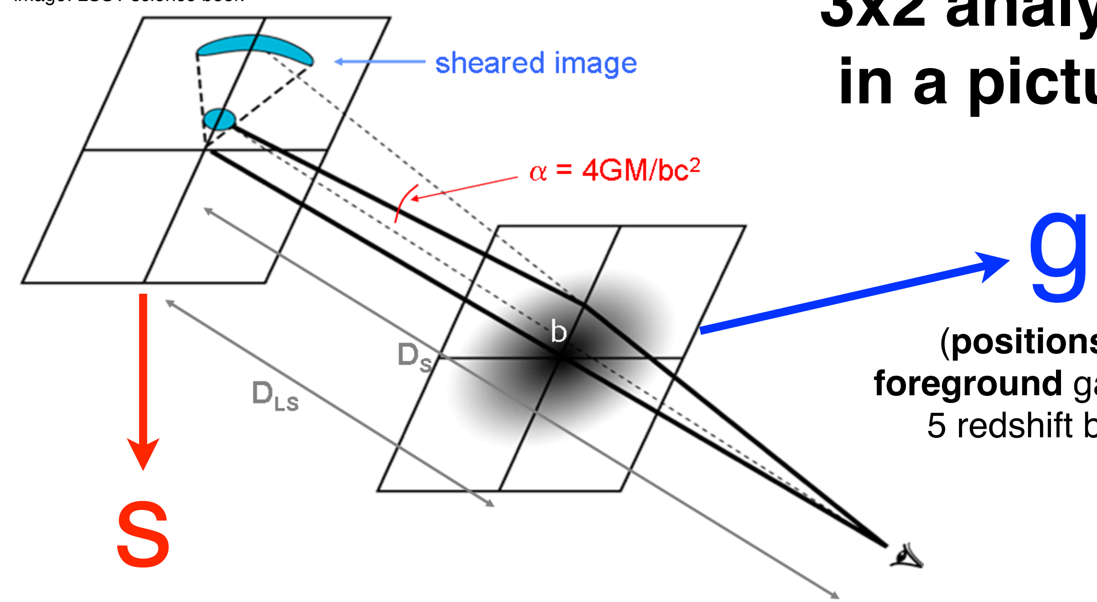
3. Gravitational lensing and 3x2 cosmology

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)

3x2 analysis in a picture

image: LSST science book

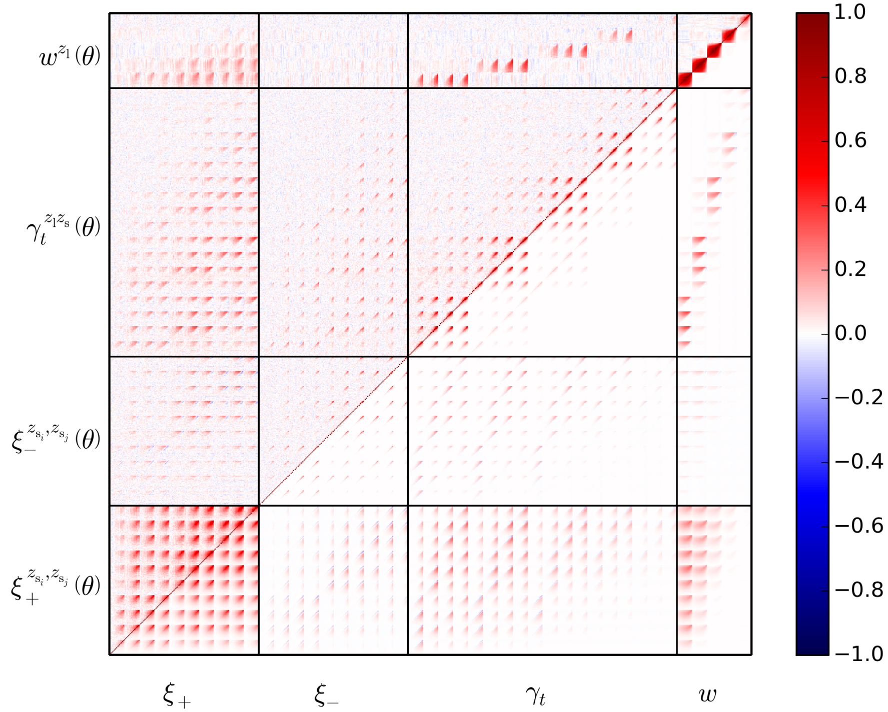


(**positions** of **foreground** galaxies; 5 redshift bins)

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

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

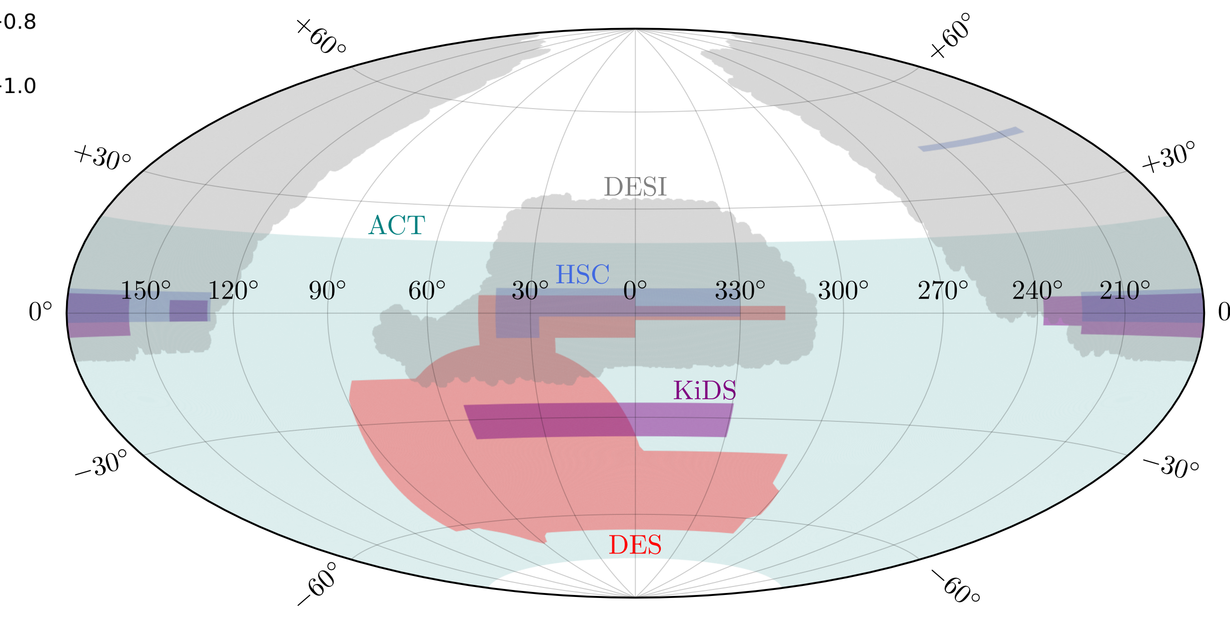
3. Gravitational lensing and 3x2 cosmology



Krause, Eifler et al (2017) [3x3 Cov for DES]

Covariance is non-trivial to calculate…

… but piece of cake for DESI C³ group, which will combine DESI with DES, KiDS, HSC…



J. Lange for DESI C3 WG

Also important: LSS×CMB cross-correlations!

Part II:

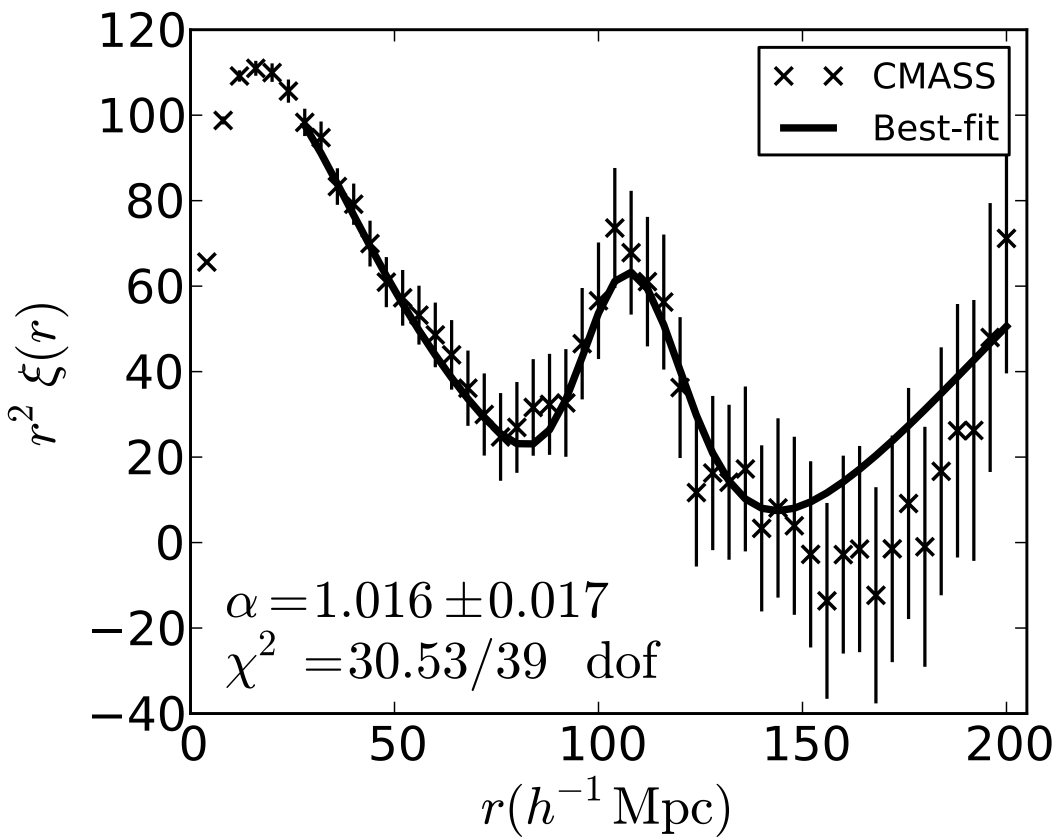
How these observables constrain DE/m_ν/f_{NL}

How DESI Constrains Dark Energy

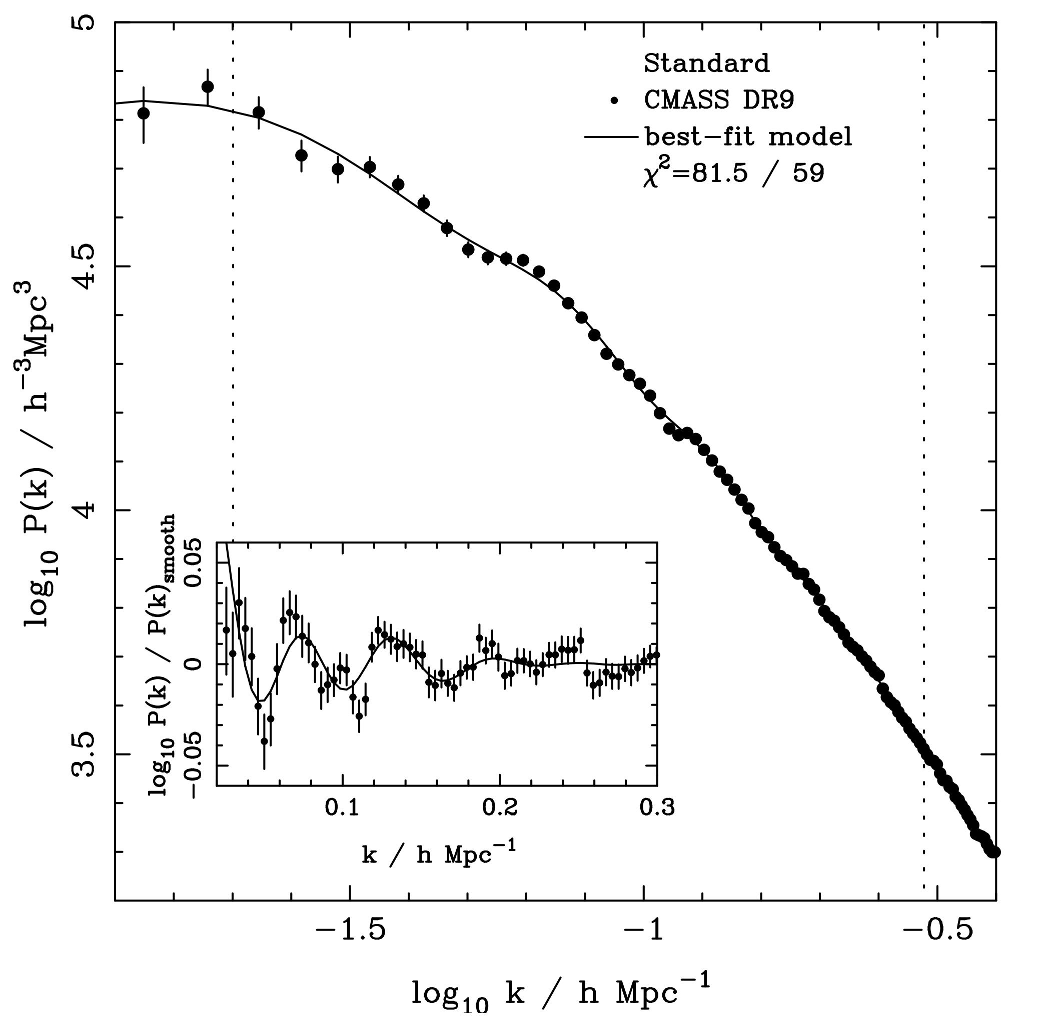
[This is the “most essential” application of DESI data]

Baryon Acoustic Oscillations

In the correlation function

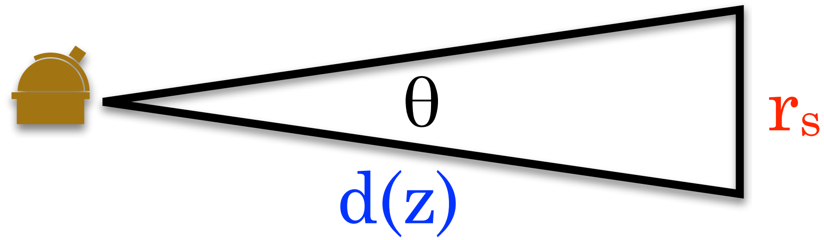


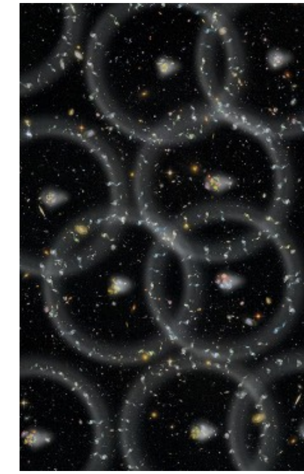
In the power spectrum



Anderson et al (BOSS collaboration), arXiv:1203.6594

Baryon Acoustic Oscillations





- From the BAO: measure d(z)/r_s [relative to some fiducial ratio]. We are measuring the angle of a feature
- Which kind of distance d? Angular diameter distance! [Actually for transverse modes measure $d_A(z)$, for radial modes measure $1/H(z)$, sometimes combine them into $d_V(z) \propto \left(d_A^2(z)/H(z)\right)^{1/3}$
- What feature? The distance at which there is a ~10% extra probability of galaxy pairs (the sound horizon!)

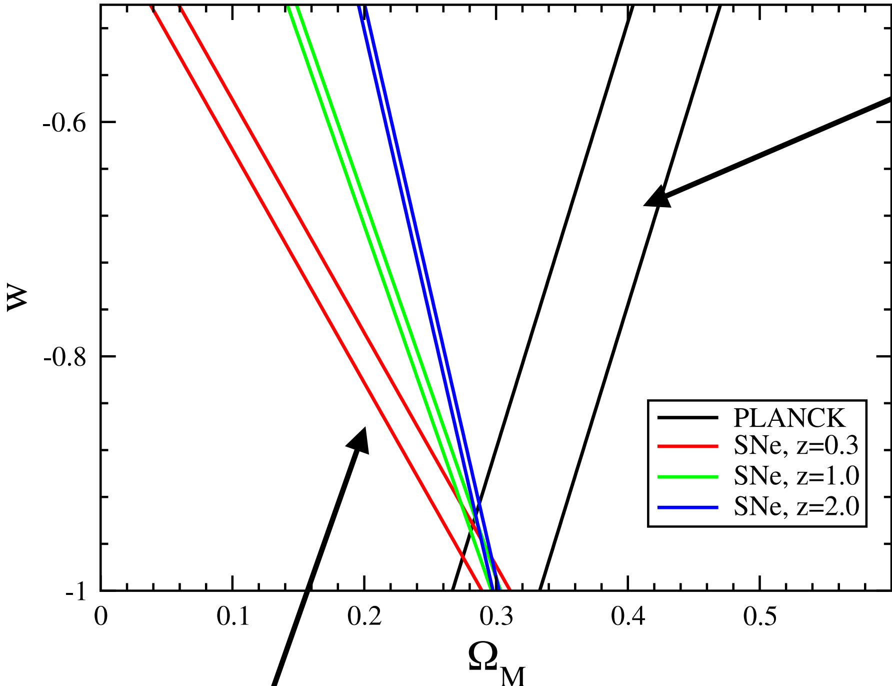
$$r_s = \frac{1}{\sqrt{3}} \int_0^{a_*} \frac{da}{a^2 H(a) \sqrt{1 + \frac{3\Omega_B}{4\Omega_\gamma} a}} \simeq 100\, h^{-1}\mathrm{Mpc}$$

Baryon Acoustic Oscillations

- r_s in BAO context is usually called r_d or r_{drag} - it is the sound horizon evaluated at the end of the baryon *drag epoch* (since there are ~10^9 photons for each baryon, the epoch when photons stop feeling the baryons comes earlier than the drag epoch when the baryons stop feeling the photons)
- r_d is independently measured (by e.g. CMB peak morphology; 147.09 ± 0.26 Mpc from Planck).
- Hence, BAO measures the distance with r_d (or roughly, with $\Omega_M h^2$ - or really, more like $\Omega_M h^3$) fixed

Baryon Acoustic Oscillations

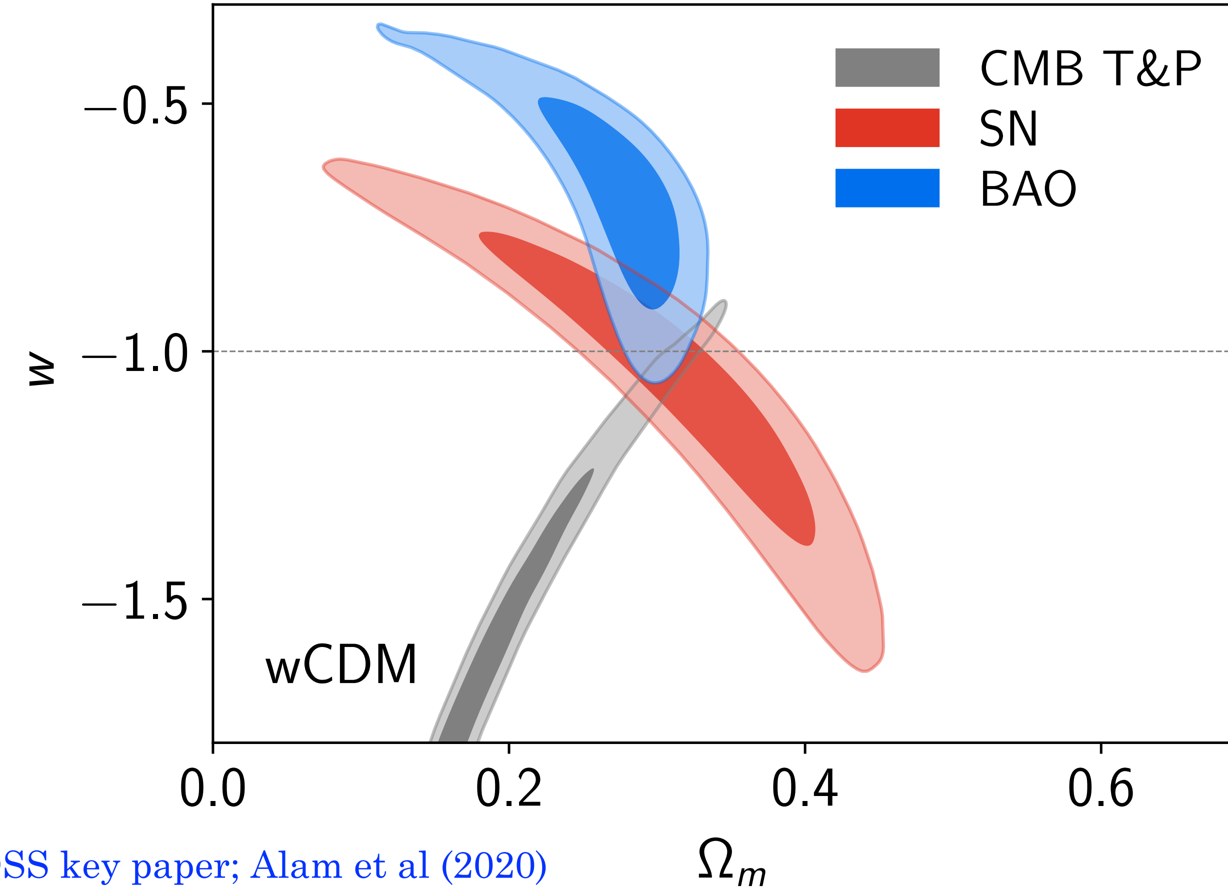
Frieman, Huterer, Linder & Turner (2004)



just distance (SNIa example)

distance with $\Omega_M h^2$ fixed (CMB example);

$$r(z) = \frac{1}{\sqrt{\Omega_M H_0^2}} \int \frac{dz'}{\sqrt{(1+z')^3 + \frac{1-\Omega_M}{\Omega_M}(1+z')^{3(1+w)}}}$$

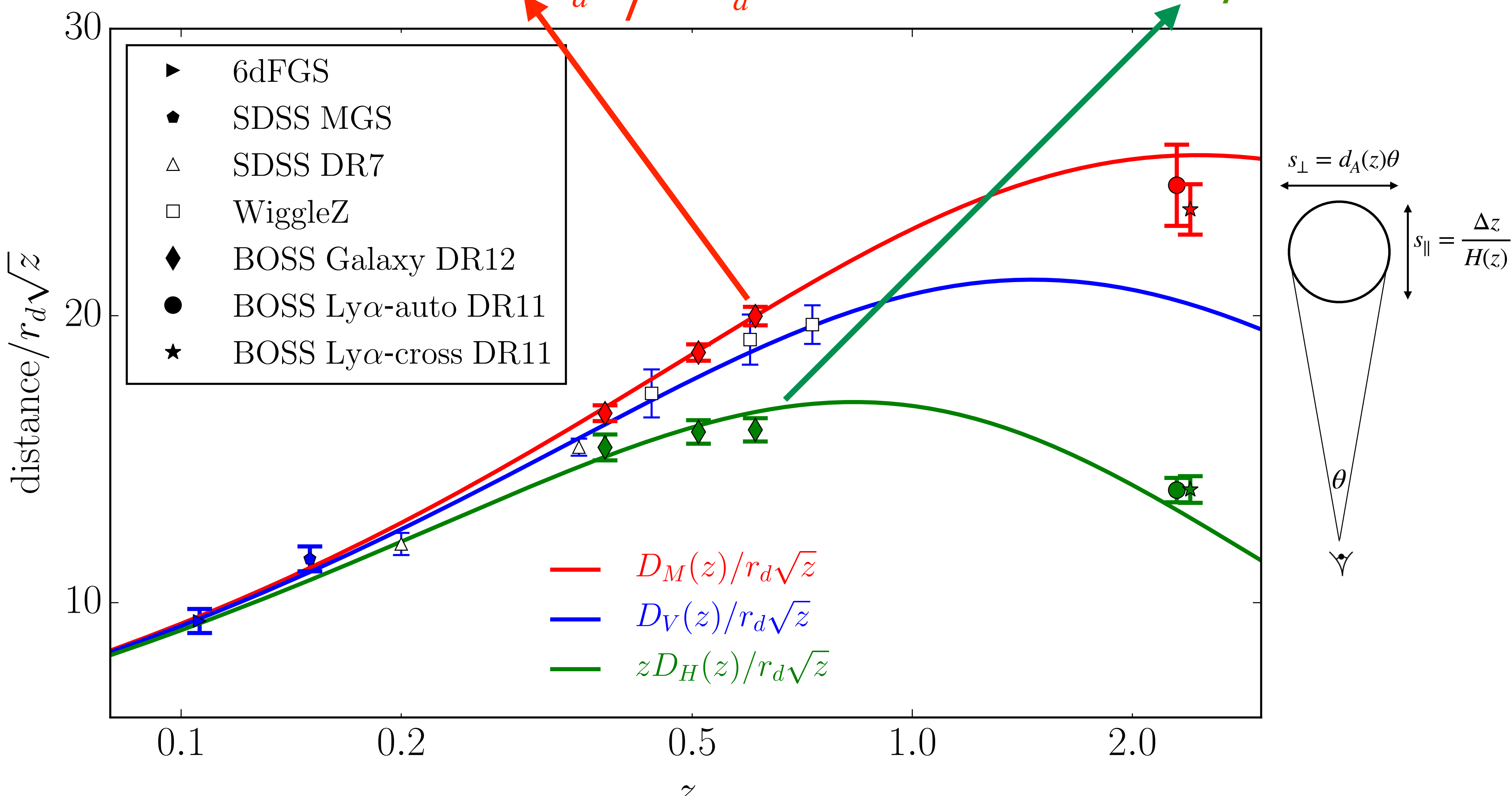


eBOSS key paper; Alam et al (2020)

Baryon Acoustic Oscillations

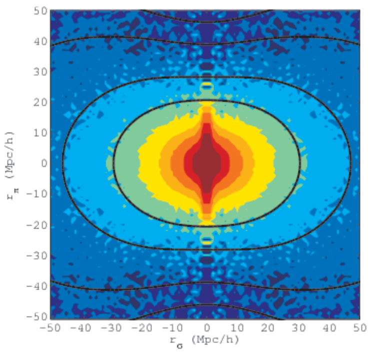
(common notation:)

$$\alpha_\perp(z) \equiv \frac{d_A(z)}{r_d} \Big/ \frac{d_A^{\rm fid}(z)}{r_d^{\rm fid}} \qquad \alpha_\parallel(z) \equiv \frac{H^{-1}(z)}{r_d} \Big/ \frac{(H^{-1})^{\rm fid}(z)}{r_d^{\rm fid}}$$



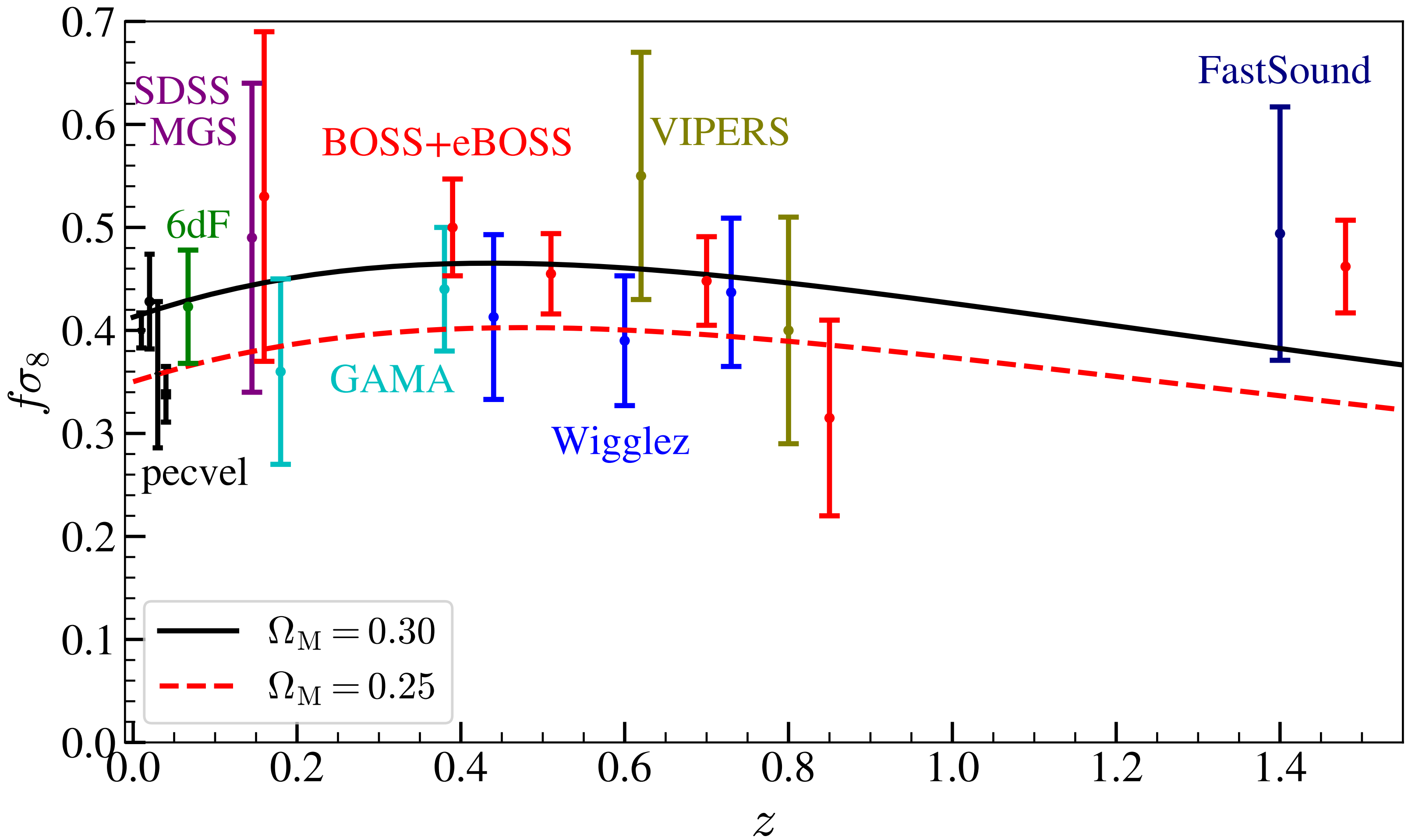
The BOSS Collaboration, Alam et al, 1607.03155

Redshift space distortions



Reid et al (2012)

Remember, in addition to the BAO, the RSD also provide a very helpful signal for dark energy



Huterer, Astron. Astrophys. Rev. (2023)

Summary

Dark energy (in DESI) is measured by:

- BAO feature(s)
- RSD
- broadband P(k) [e.g. turnover position in k]
- peculiar velocities
- bispectrum
- cluster counts, void abundances
- .....

How DESI Constrains Neutrino Masses

Neutrino basics

- Three neutrino flavors (e, mu, tau)
- Definitely massive (neutrino oscillations detected)
- $\Omega_\nu h^2 = \frac{\sum_i m_{\nu,i}}{94\text{eV}}$,
- Cosmology largely sensitive to $\sum m_{\nu,i}$
- Cosmological upper bound: $\sum m_{\nu,i} < 0.15\,\text{eV}$ (or so)

From the oscillation constraints, we conclude:

$$(\Delta m^2)_{sol} \simeq 8\times10^{-5}\ \text{eV}^2$$
$$(\Delta m^2)_{atm} \simeq 3\times10^{-3}\ \text{eV}^2$$

$\sum m_i = 0.06$ eV* (normal)

vs.

$\sum m_i = 0.11$ eV* (inverted)

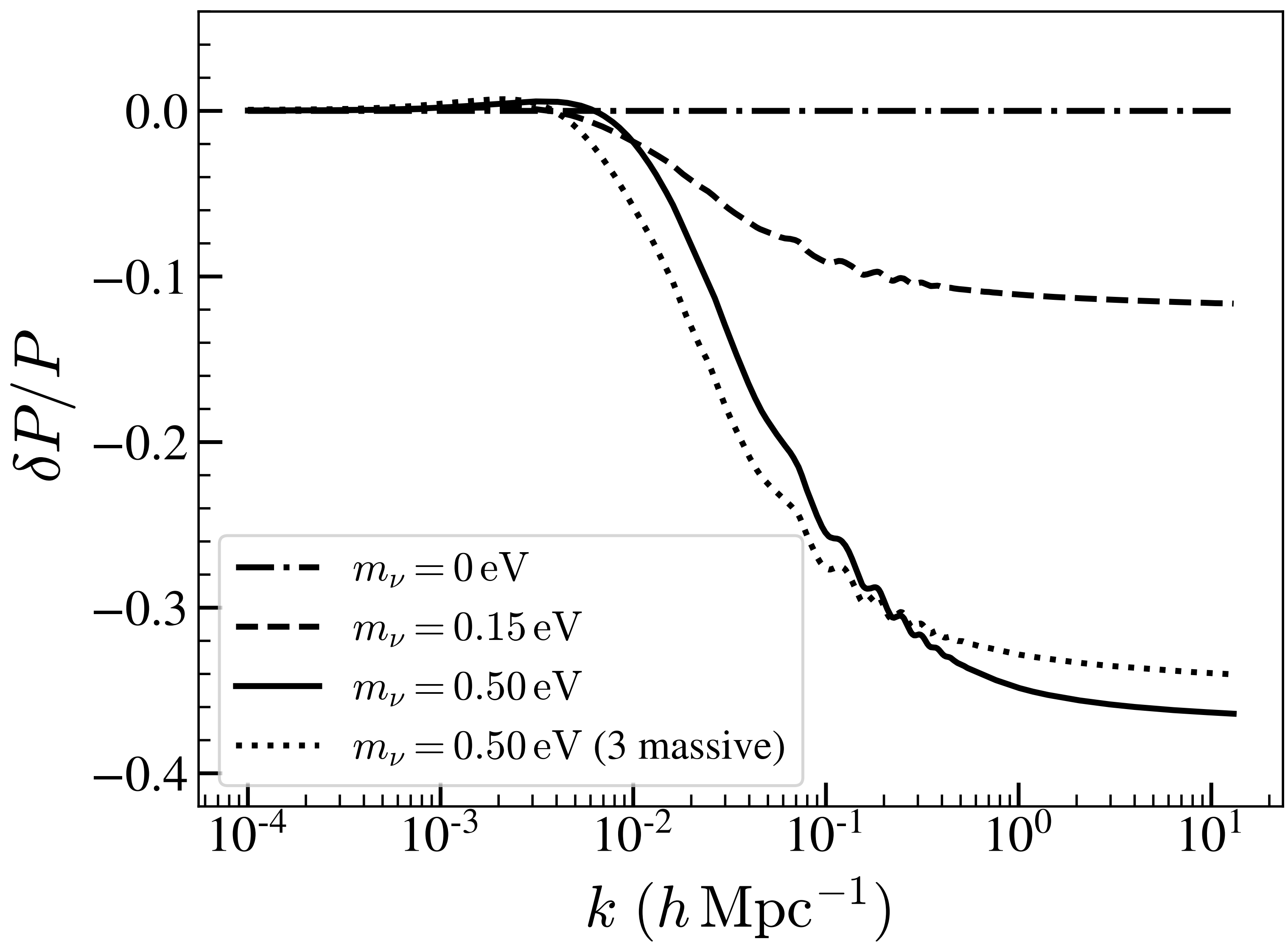
*(assuming m_3=0)

So the goal is to

1. distinguish $\sum m_i$ of 0.06 eV from 0.11 eV
2. distinguish $\sum m_i$ of 0.06 eV from zero eV

Neutrino free-streaming leaves signatures in P(k)

$$\lambda_{\rm FS} \simeq 300 \left(\frac{1\rm eV}{m_\nu}\right) \rm Mpc; \quad k_{\rm FS} \equiv \frac{2\pi}{\lambda_{\rm FS}} \simeq 0.02 \left(\frac{m_\nu}{1\rm eV}\right) \rm Mpc^{-1},$$



$$\frac{\delta P}{P} \simeq -8 f_\nu$$

Neutrino masses: prospects

- Neutrino masses are in principle output of a standard P(k) full-shape analysis (with or without the RSD)
- However, theoretically modeling the impact of neutrinos is famously challenging — need Nbody simulations, tricky to get sufficient precision
- Recent progress (including by DESI members) appears to have largely solved the above challenge
- Specific predictions of the effect of m_ν on observables make these tests highly physics-y. Cosmology tests of m_ν: a great (and correspondingly cheap) complement to particle-physics experiments

How DESI Constrains Primordial non-Gaussianity

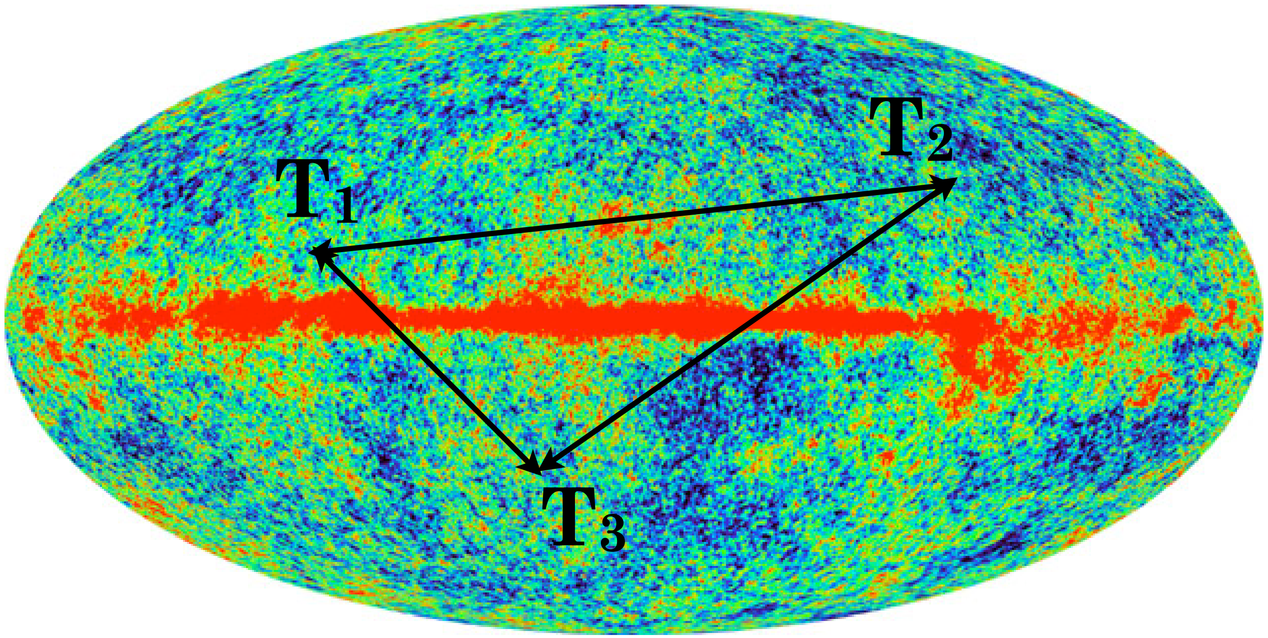
Standard Inflation, with...

1. a single scalar field
2. the canonical kinetic term
3. always slow rolls
4. in Bunch-Davies vacuum
5. in Einstein gravity

produces **unobservable** NG

Therefore, measurement of nonzero NG would point to a **violation** of one of the assumptions above

NG from 3-point correlation function



"Local NG" (squeezed triangles) is defined as

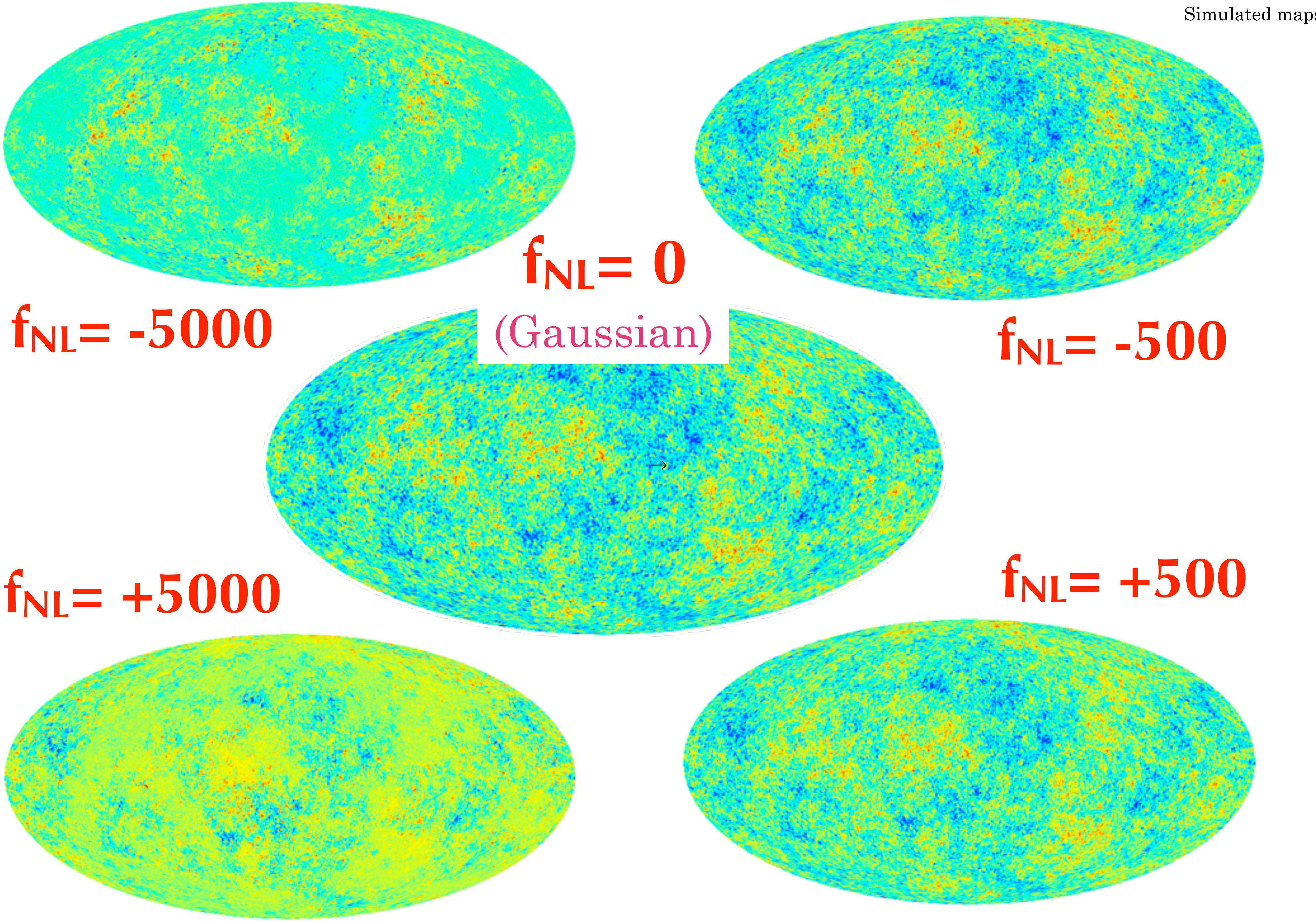
$$\Phi = \Phi_G + f_{\rm NL}\left(\Phi_G^2 - \langle \Phi_G^2 \rangle\right)$$

"Local", "Equilateral", "orthogonal" $f_{\rm NL}$ - refers to triangle shapes

$\Rightarrow$ test number of fields & their interactions

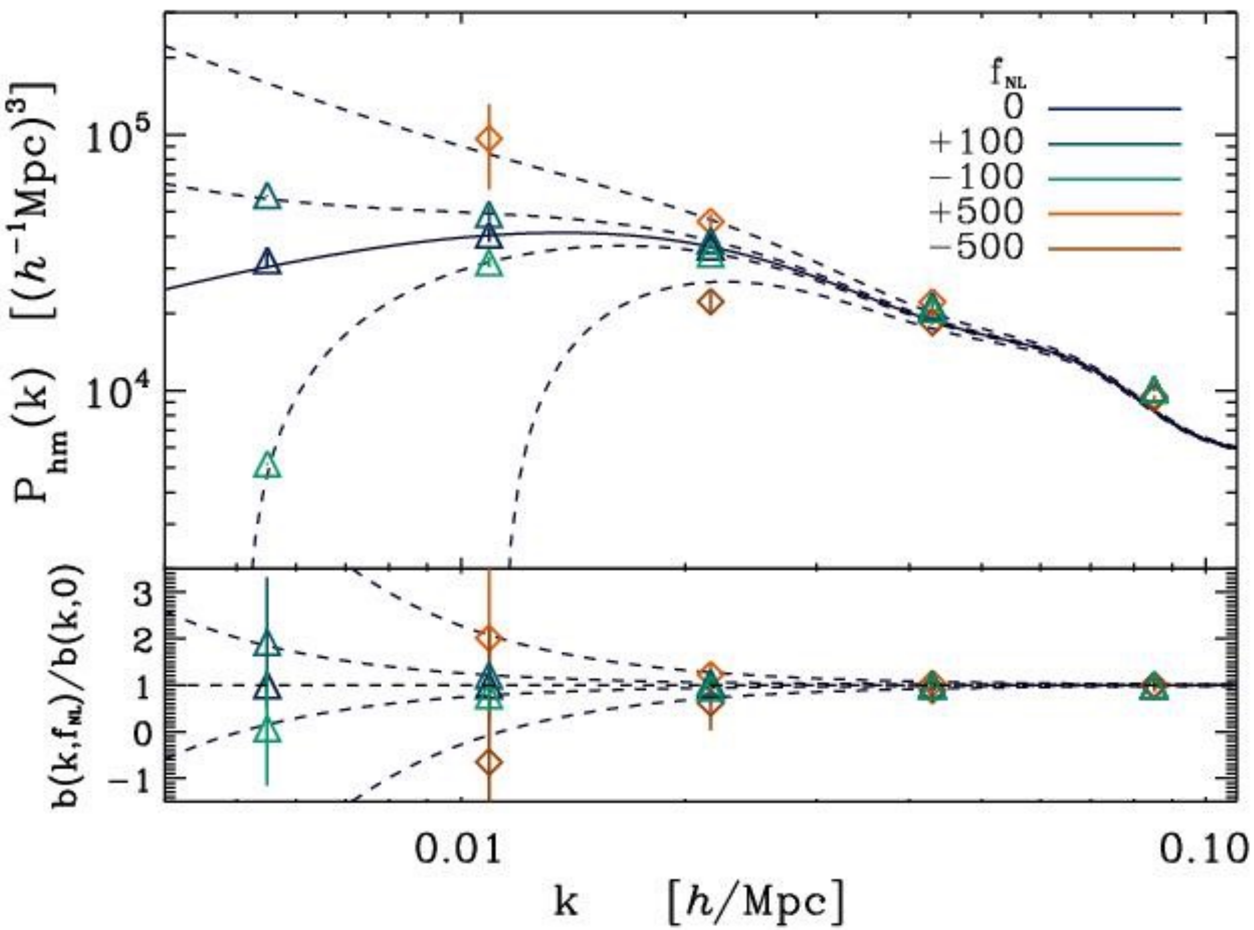
Threshold for new physics: $f_{\rm NL}^{\rm any\ kind} \gtrsim O(1)$

Alvarez et al, arXiv:1412.4671



Planck Temp + Pol: $f_{\mathrm{NL}} = -0.9 \pm 5.1$

Scale dependence of NG halo bias



$$b(k) = b_{\rm G} + f_{\rm NL}\,\frac{\rm const}{k^2}$$

Verified using a variety of theoretical derivations and numerical simulations.

Dalal, Doré, Huterer & Shirokov 2008

$$\Delta b(k) = f_{\rm NL}(b_G - 1)\,\delta_c\,\frac{3\,\Omega_M H_0^2}{T(k)D(a)k^2}$$

Implications:

- Unique $1/k^2$ scaling of bias; no free parameters
- Straightforwardly measured (g-g, g-T,...)
- Distinct from effect of all other cosmo parameters
- Complements CMB measurements (LSS measures f_{NL} at different scales)
- Unfortunately very degenerate with imaging systematics
(see e.g. Rezaie et al (2023) DESI paper on fNL from DESI imaging data)
- Measuring it using DESI to high accuracy will require independently getting an independent handle on the imaging systematics

Summary

DESI measurements of matter power spectrum, esp its BAO and RSD aspects, directly probe dark energy

Broadband matter power spectrum is sensitive to massive neutrinos

While the bispectrum eventually has the most information to constrain primordial non-Gaussianity, most progress in the near term will come through the large-scale ($1/k^2$) effect of f_{NL} on galaxy bias in the power spectrum