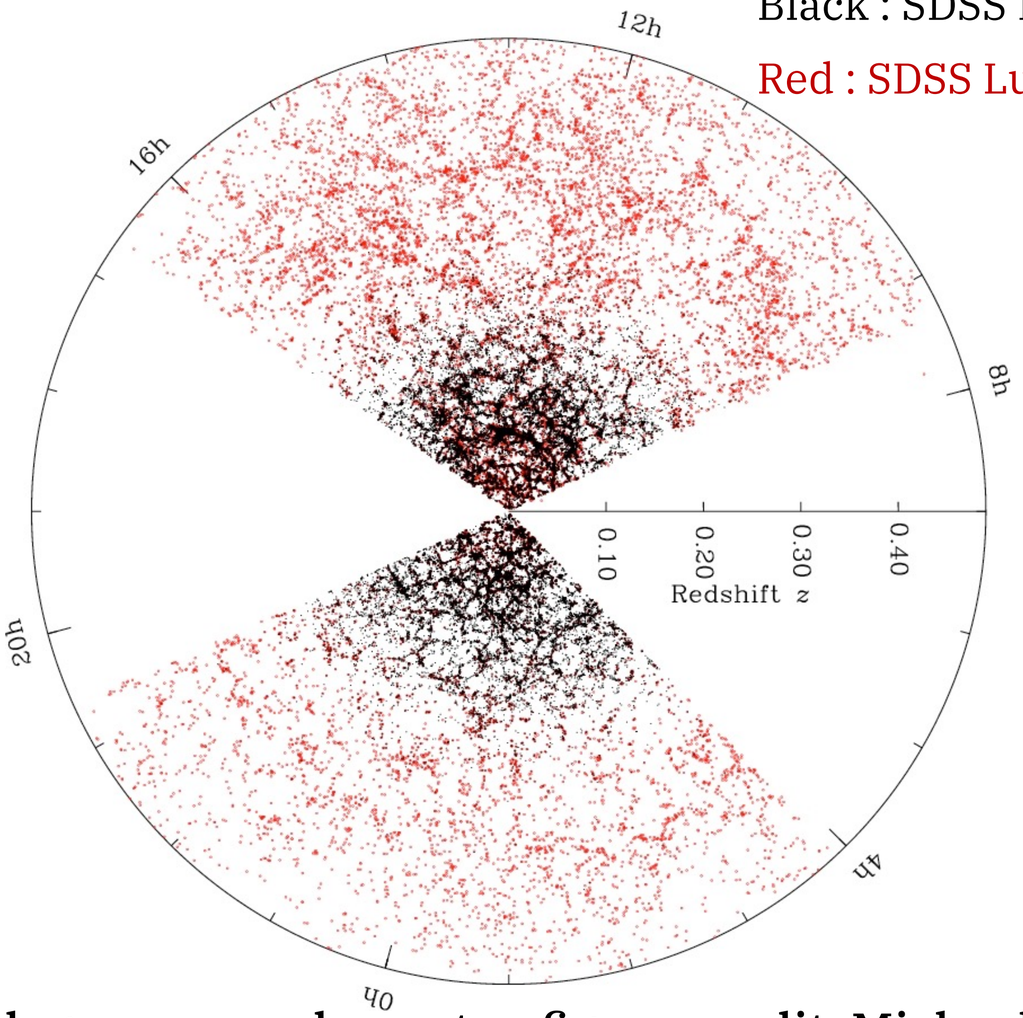
The Interplay between Space- and Ground-Based BAO Studies

Donghui Jeong

Department of Astronomy and Astrophysics
The Pennsylvania State University

14 January 2021, Cosmic Structure SIG @ AAS

LSS and galaxy distribution



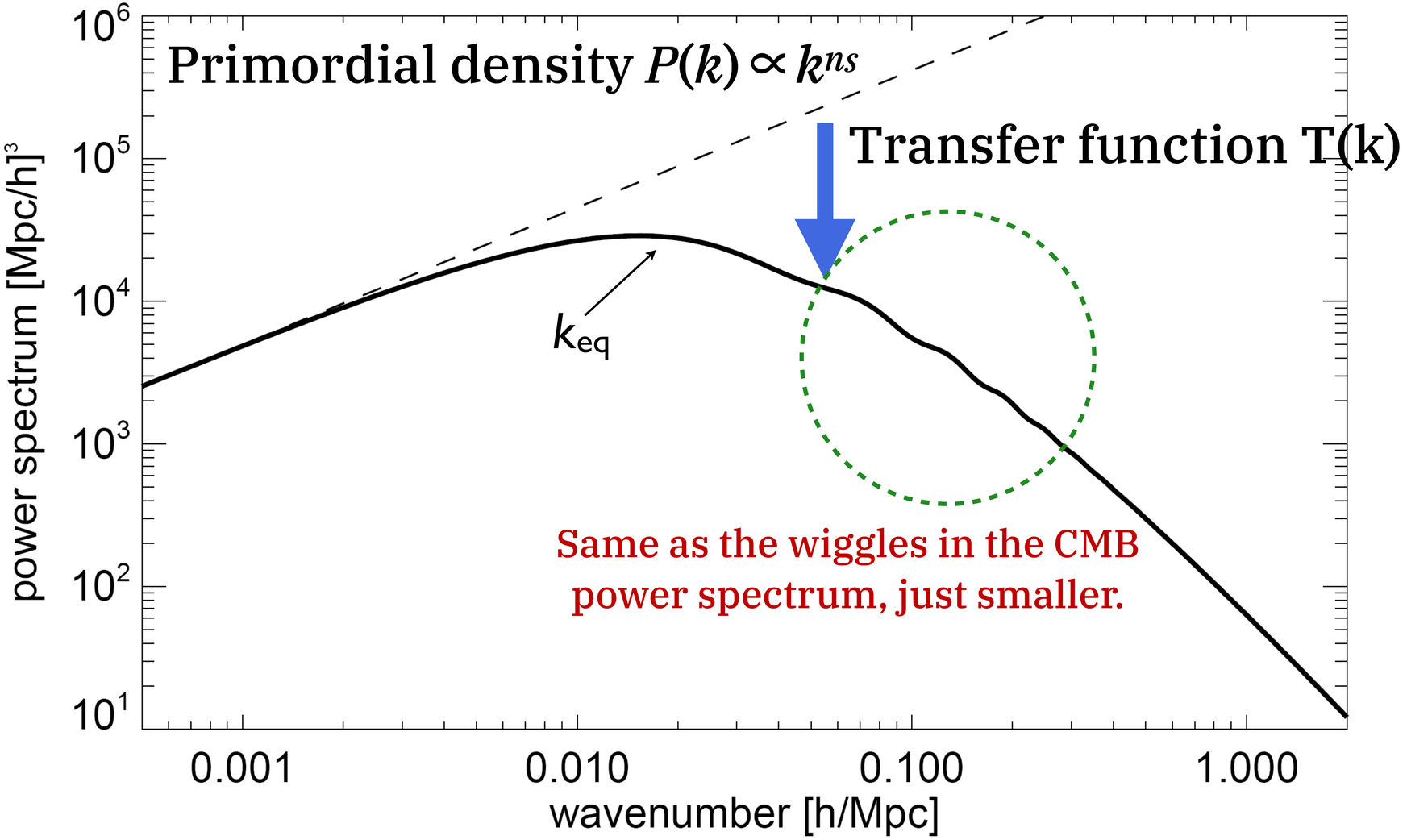
Black : SDSS Main Galaxy Samples

Red : SDSS Luminous Red Galaxies)

- Because of the large-scale structure of the Universe, galaxies are ***not randomly*** distributed.
- Q: How do we quantify/analyze deviation from the random
  A: **correlation functions** and **Fourier analysis**.

3degree around equator. figure credit: Michael Blanton

Baryon Acoustic Oscillation



Dark energy from BAO

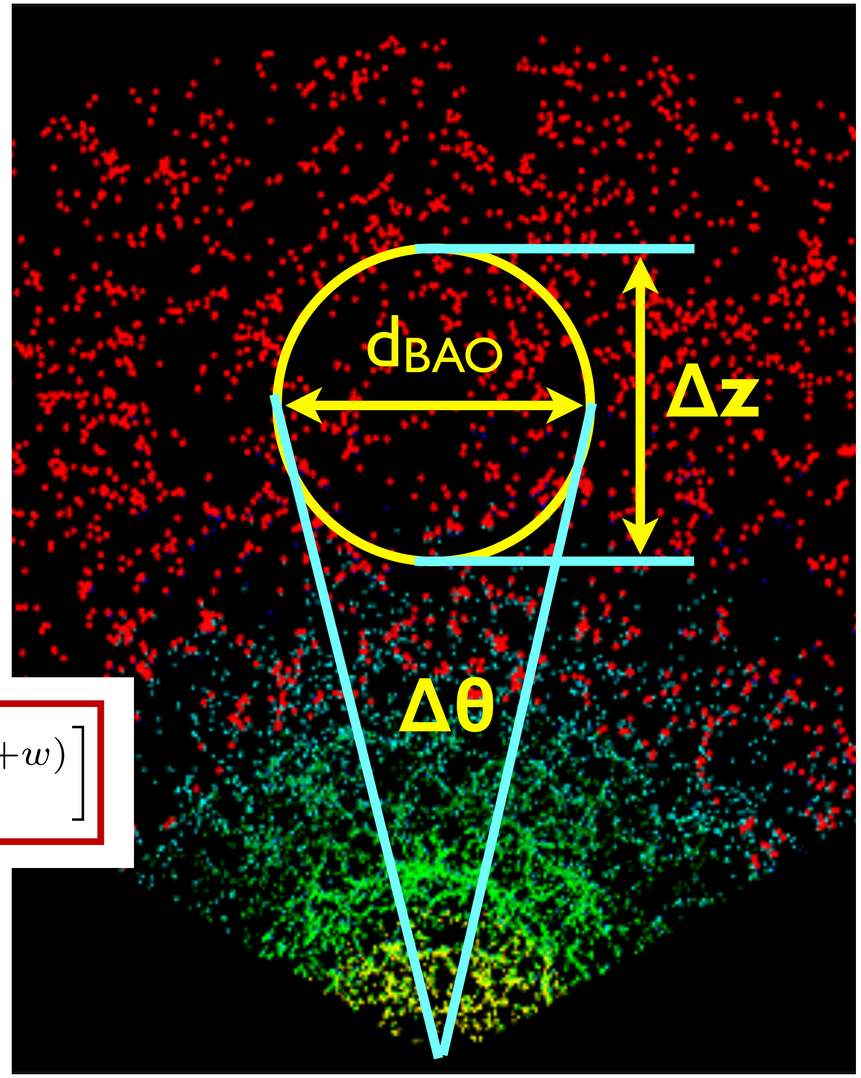
- The BAO length scale d_{BAO} is given by CMB.
- We can measure the angular diameter distance, $d_A(z)$ and Hubble parameter, H(z):

$$d_{\rm BAO} = d_A(z)\Delta\theta = c\Delta z/H(z)$$

- $d_A(z)$, $H(z)$ depend on dark energy!

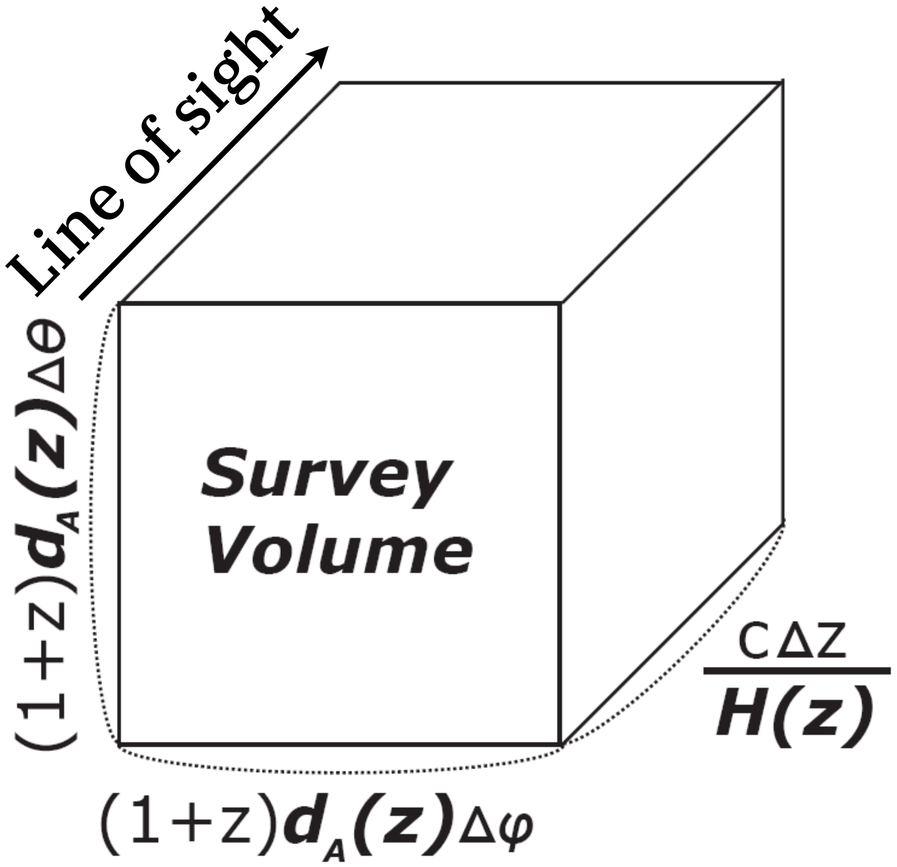
$$H^2(z) = H_0^2\left[\Omega_m(1+z)^3 + \Omega_K(1+z)^2 + \Omega_{\rm DE}(1+z)^{3(1+w)}\right]$$

$$d_A(z) = \frac{\chi(z)}{1+z}\left[1 - \frac{k}{6}\frac{\chi^2(z)}{R^2}\right] \quad \chi(z) = c\int\frac{dz}{H(z)}$$



Beyond the BAO, full-shape of P(*k*)

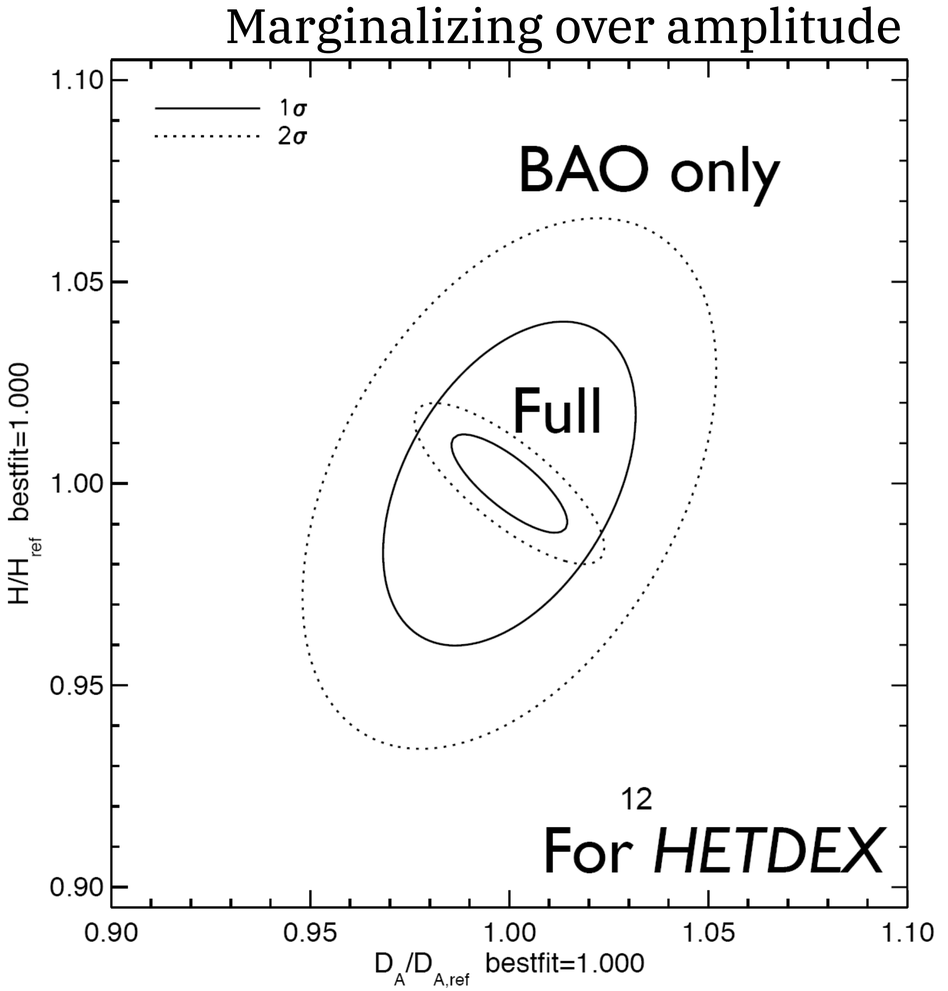
- In galaxy surveys, we chart galaxies by (R.A., Dec., redshift)
- Observed power spectrum using a reference cosmology is rescaled and shifted (in log scale) relative to the true power spectrum!



$$k_{\mathrm{ref}\perp} \equiv \frac{D_A}{D_{A,\mathrm{ref}}} k_\perp \qquad k_{\mathrm{ref}\parallel} \equiv \frac{H_{\mathrm{ref}}}{H} k_\parallel$$

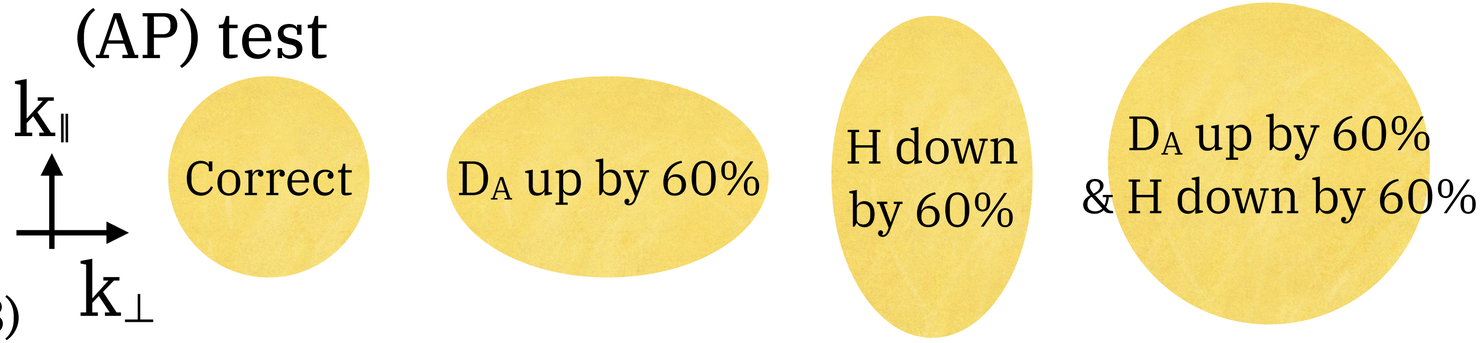
$$P_{\mathrm{obs}}(k_{\mathrm{ref}\perp}, k_{\mathrm{ref}\parallel}) = \left(\frac{D_{A,\mathrm{ref}}}{D_A}\right)^2 \left(\frac{H}{H_{\mathrm{ref}}}\right) P_s^g(k_\perp, k_\parallel)$$

Improvement from full-shape $P(k)$

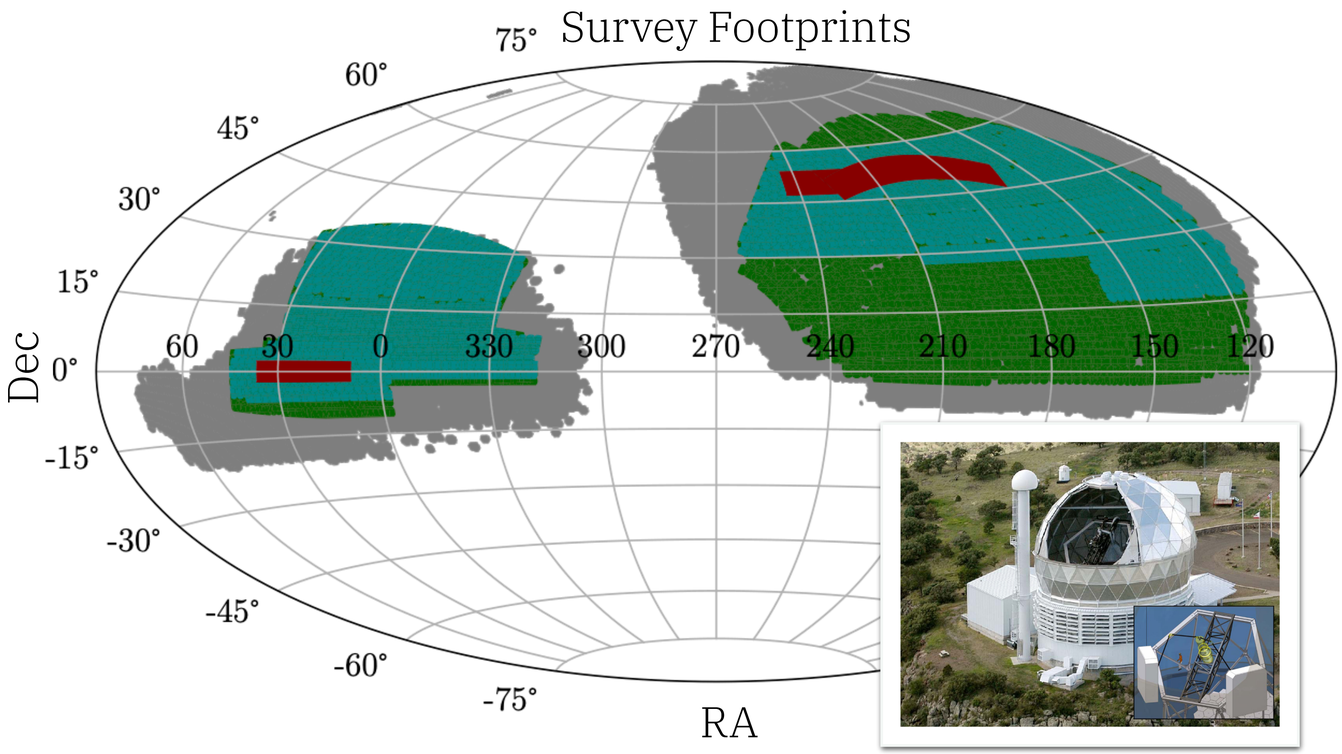


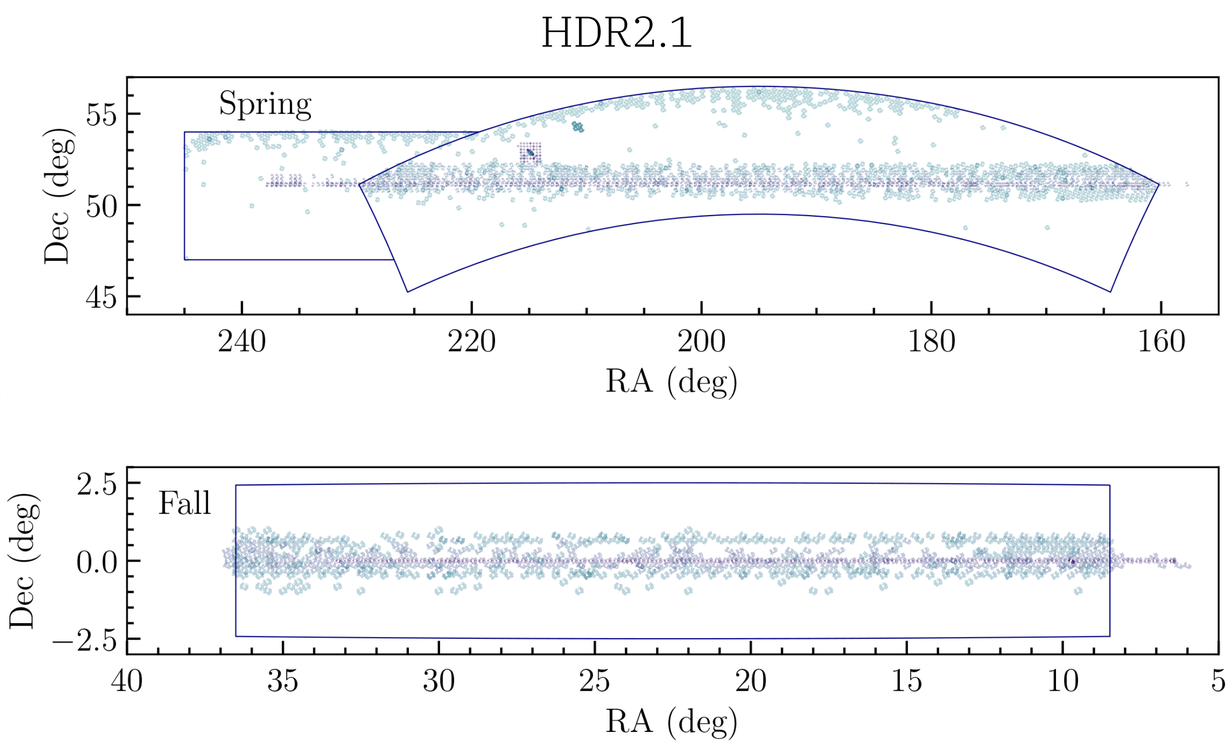
Shoji, Jeong & Komatsu (2008)

- The contour using the full shape inclines differently because of the Alcock-Paczynski (AP) test which is sensitive to ***$d_A H$***.
- Using *full power spectrum* will improve upon the determination of both d_A and H by a factor of two, and the area of ellipse by about a factor of four!



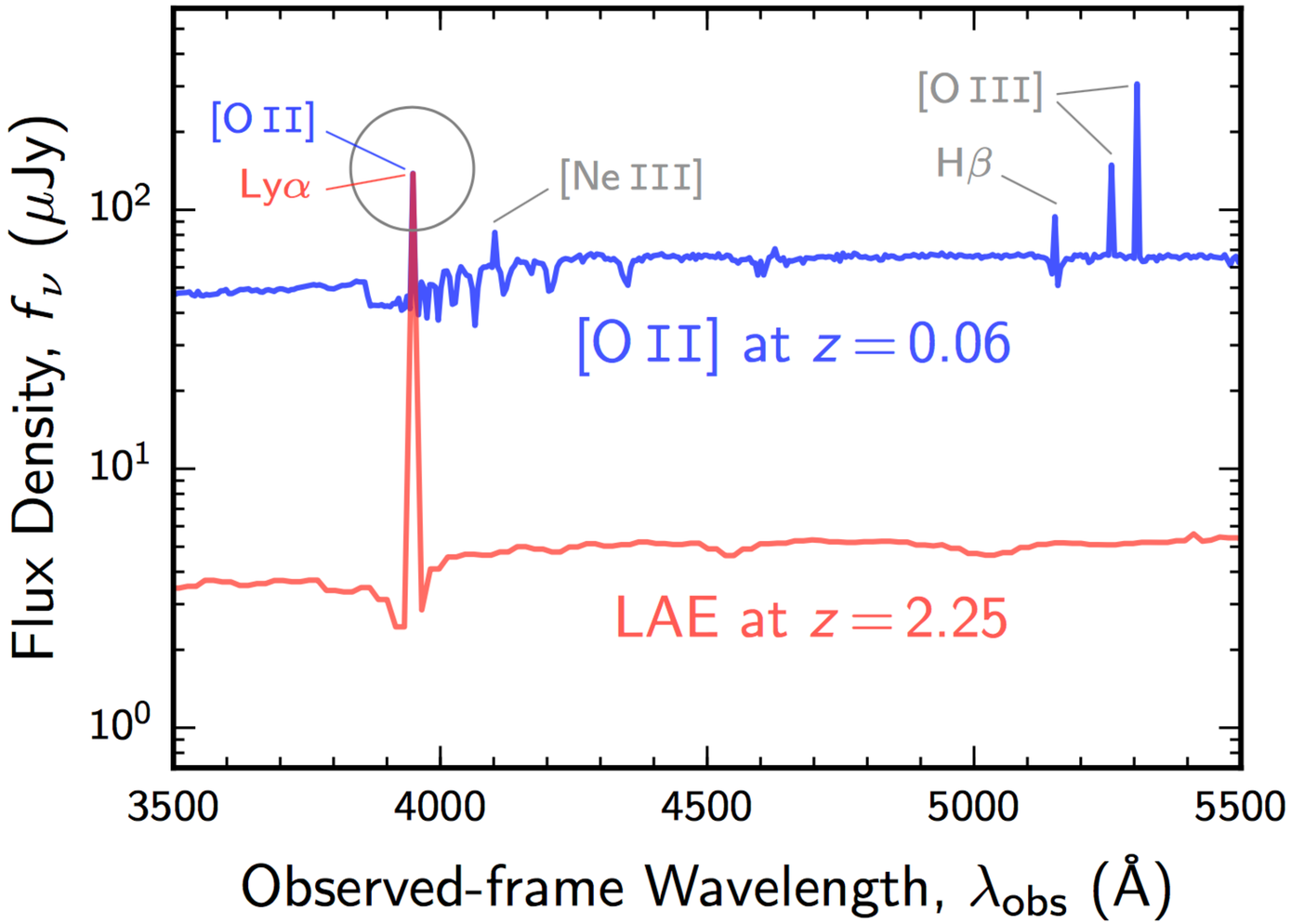
The HETDEX survey





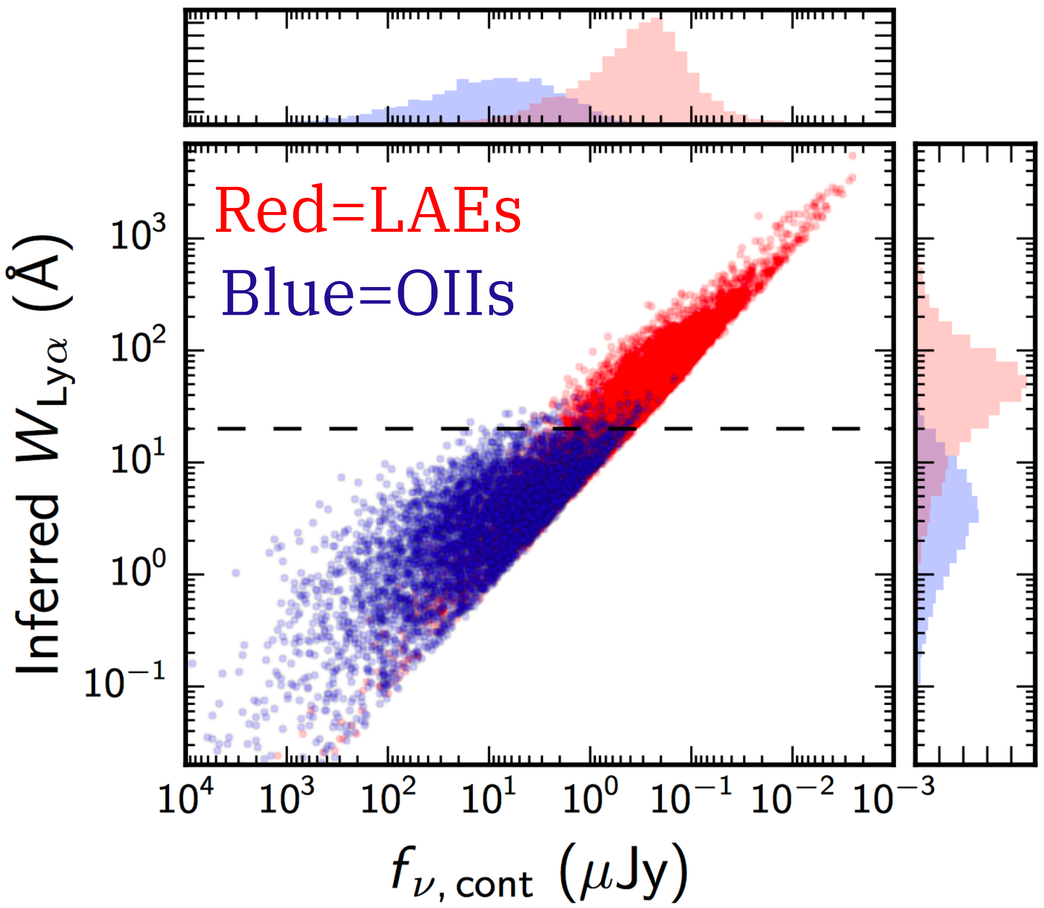
Hobby-Eberly Telescope Dark Energy Experiment is using 10m HET to map the universe using 1.2M Lyman-alpha emitting galaxies (LAEs) in z=1.9–3.5 (540 □°), 10 Gpc³.

LAE vs. [OII] λ3727



- Because [OII] λ3727 is a fairly *isolated* line.
- [OII] λ3727 from low-redshift galaxies can be confused as LAEs.
- Key to distinguish them:
  - Equivalence width
  - Continuum flux

The separation is not perfect!



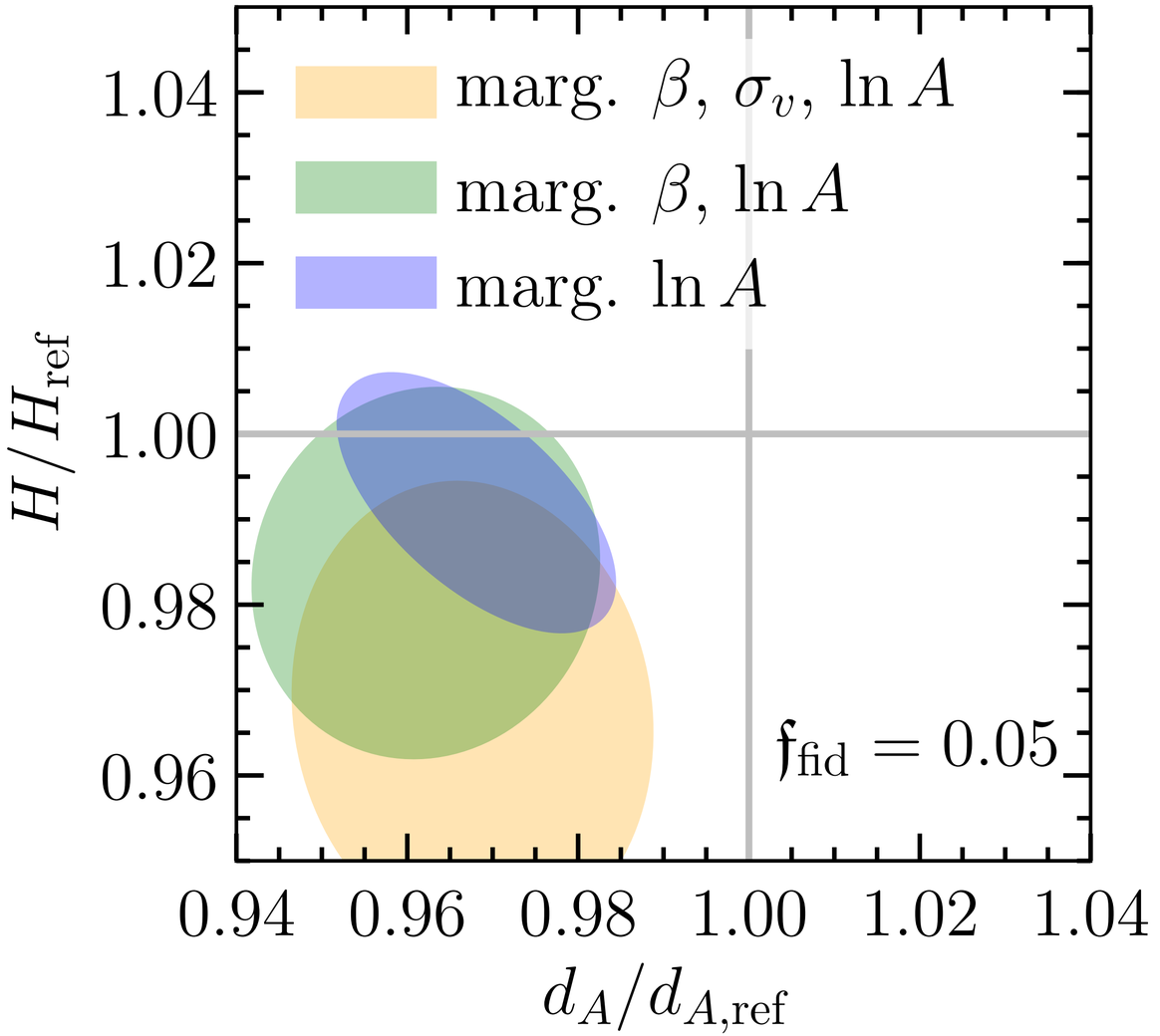
Leung+ 2016

- Can reduce the OIIE interloper fraction to 0.5%, at the expense of loosing 6% of LAEs.
- 6% of LAEs = 60,000 LAEs!
- What happens if we ignore the interlopers?
- ***Interloper bias!***

Grasshorn Gebhardt et al. (2019): HETDEX, RomanST
Addison et al. (2019): Euclid

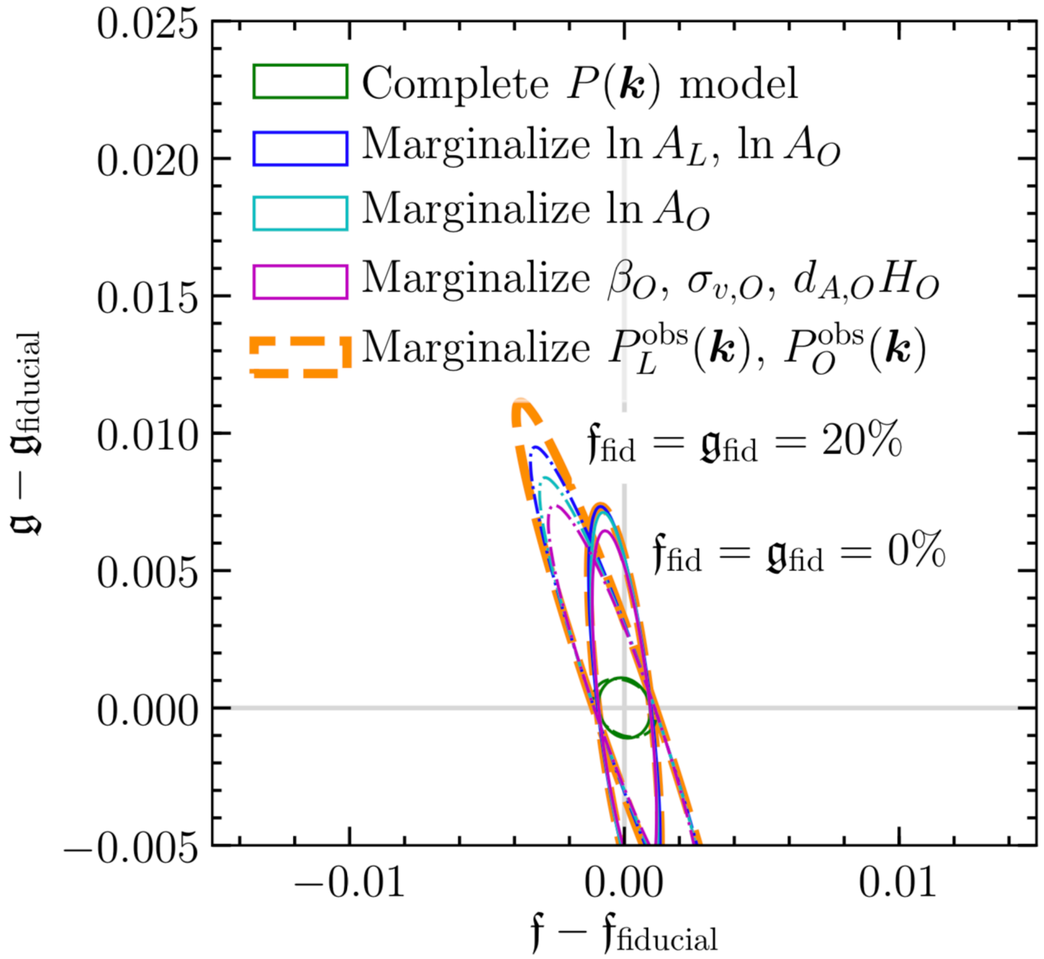
Interloper bias

$$\mathfrak{f} = \frac{N_{\mathrm{OII}}^{\mathrm{interloper}}}{N_{\mathrm{LAE}}^{\mathrm{total}}}$$



Grasshorn Gebhardt et al. (2019)

f and g from cross spectrum

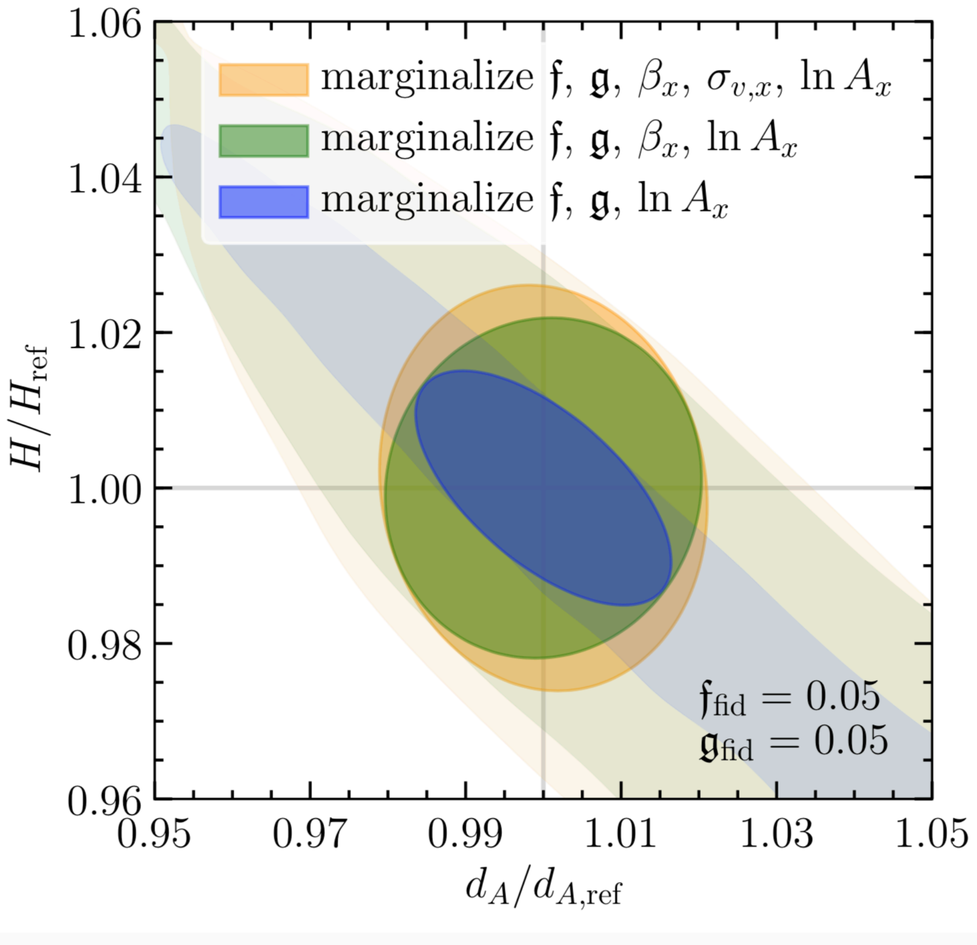


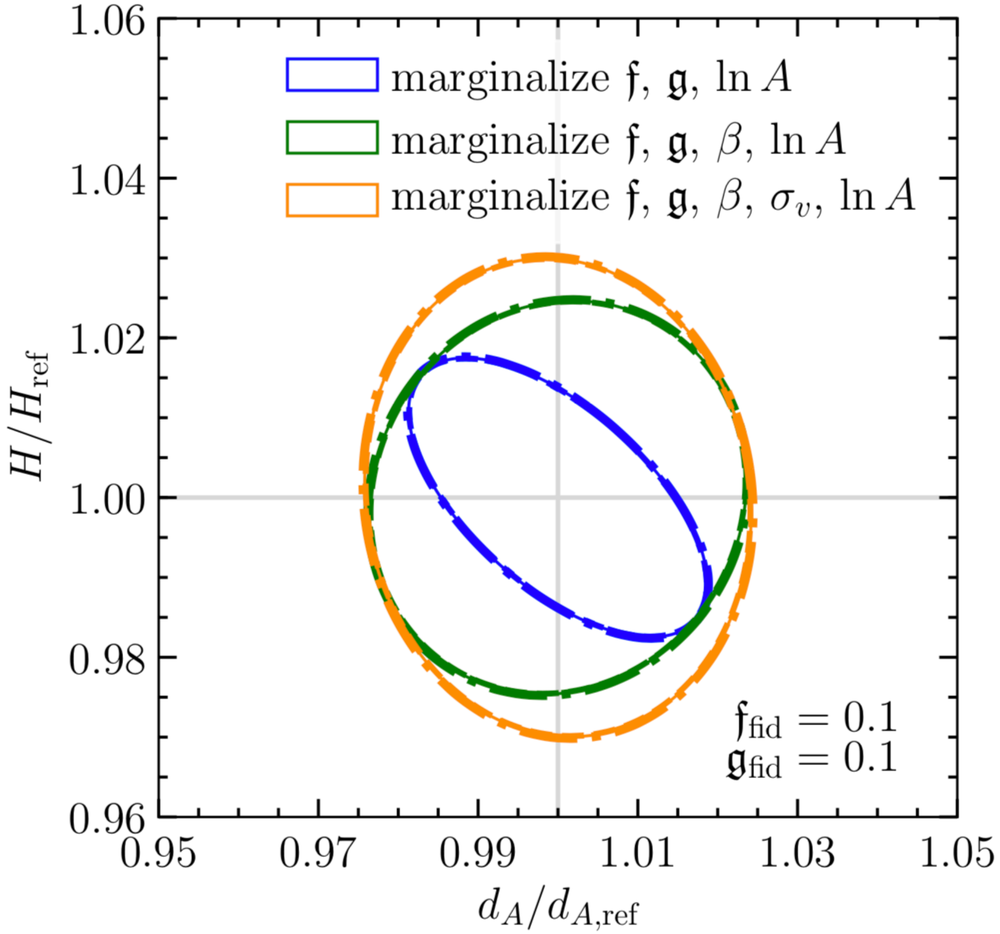
Ideal case

Worst case

Grasshorn Gebhardt et al. (2019)

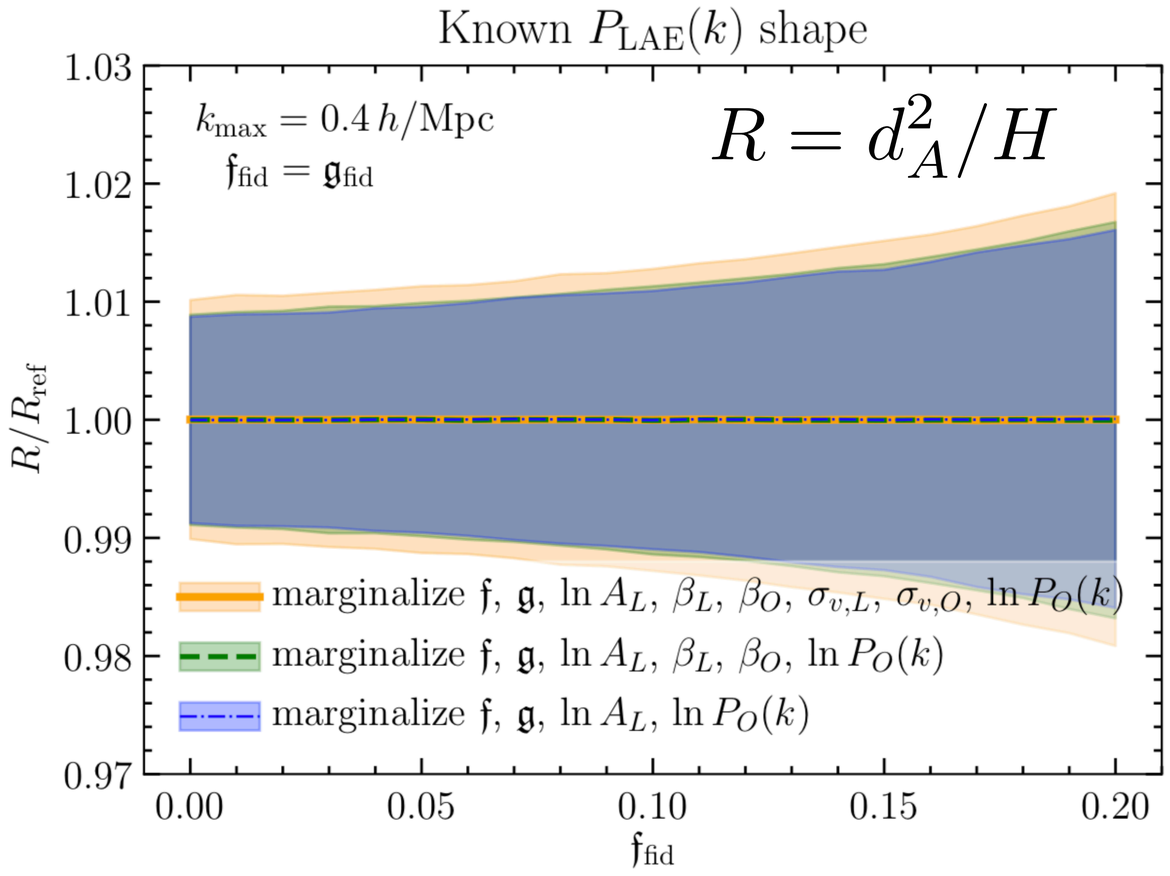
Joint-analysis removes the bias!

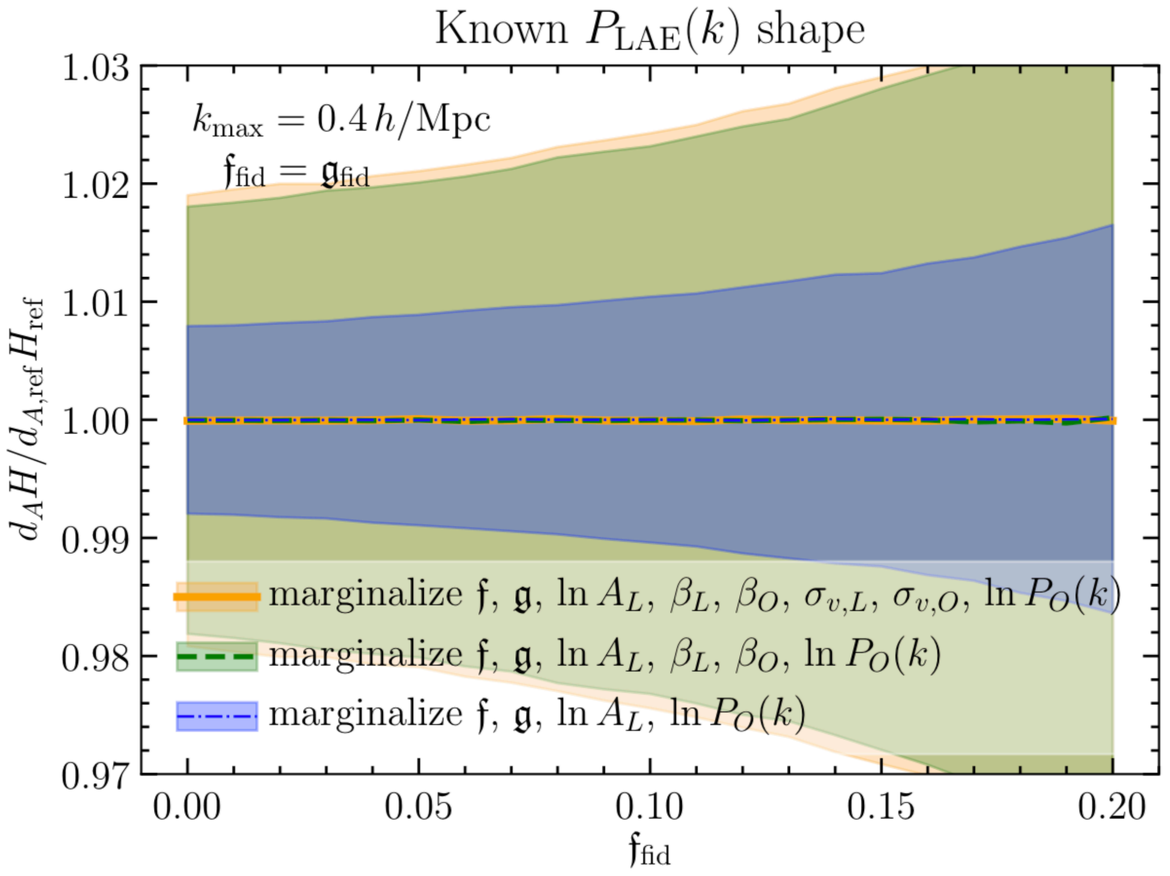




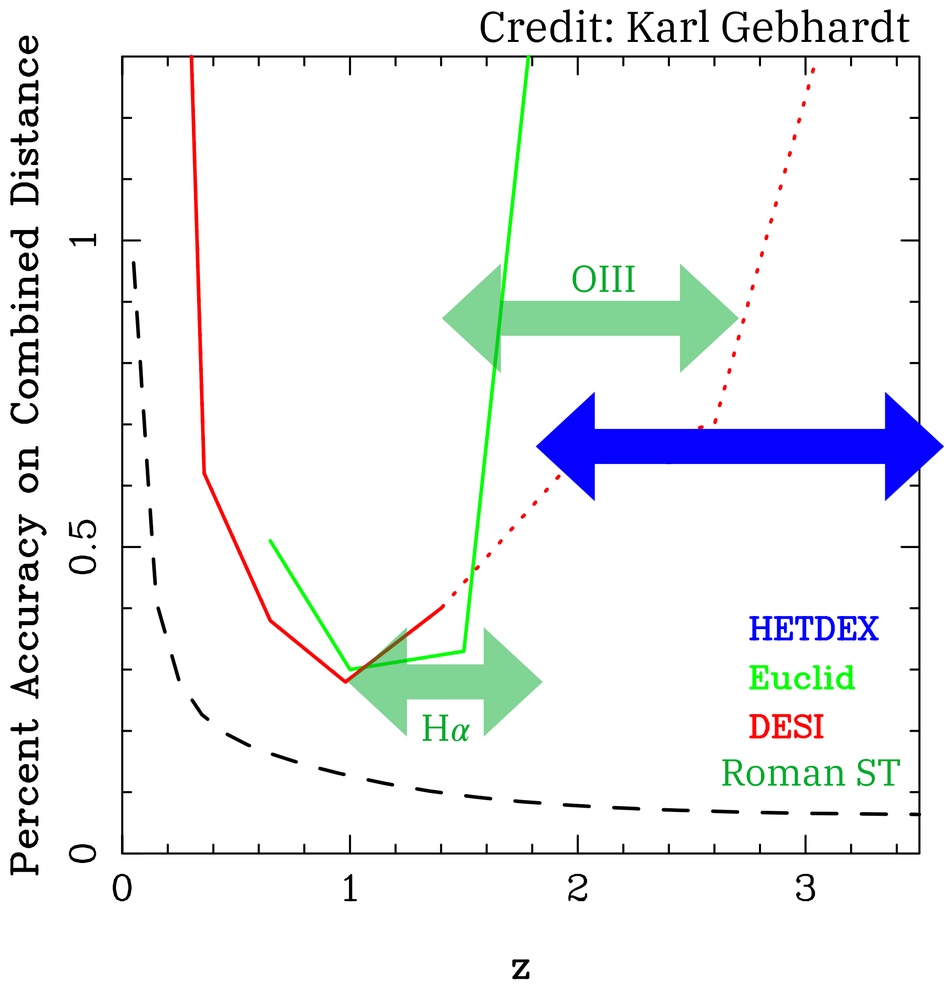
Grasshorn Gebhardt et al. (2019)

Of course, we pay (a little) price





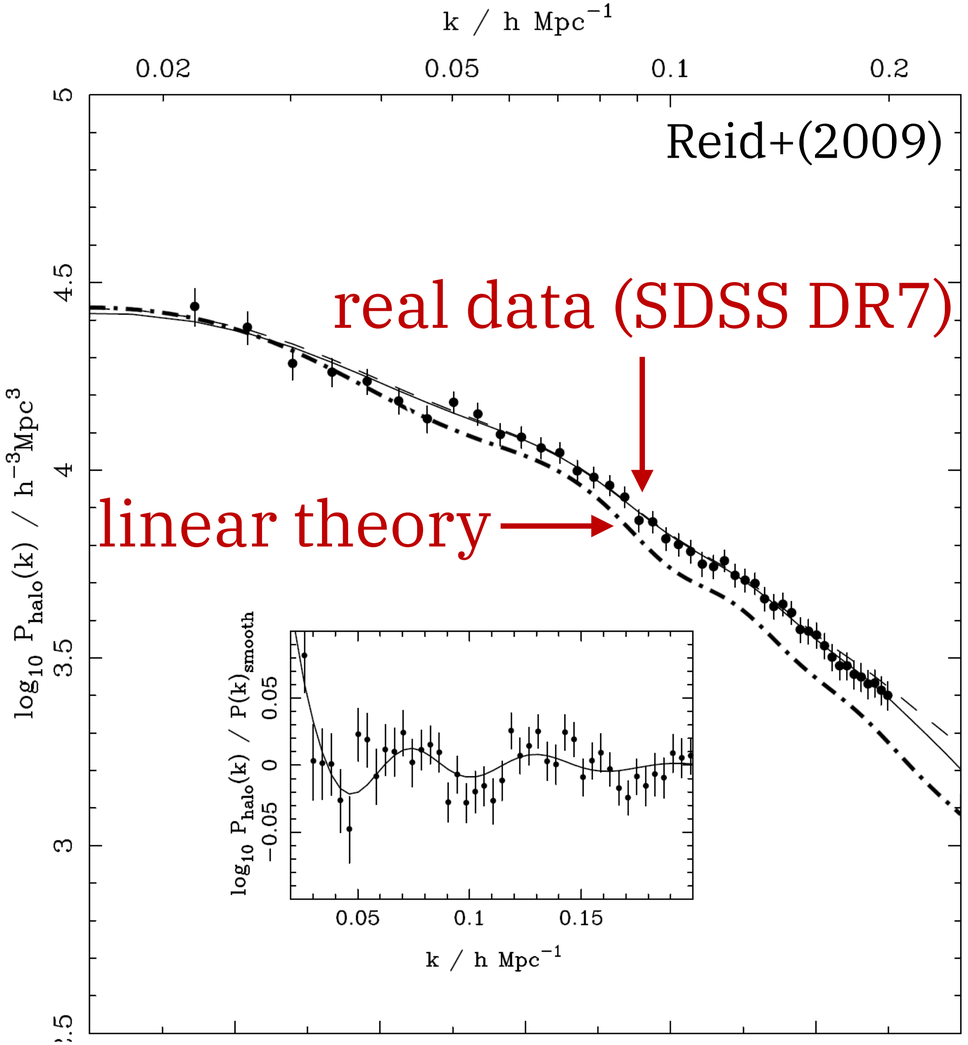
Projected dark energy constraints



- Complementary in redshift range!
- High-z surveys will be good for
  - Time evolution of dark energy
  - Dynamical test of dark energy
  - Curvature of the Universe
- Synergy for blind surveys: line-identification (cross-matching; cross correlation; photometric information)

Backup slides

The challenge



- Three sources of non-linearities:
  - non-linear clustering of matter
  - non-linear bias
  - non-linear redshift space distortion
- BAO is popular b/c it is not very sensitive to nonlinearities
- To exploit the information in the galaxy power spectrum, we need to model the non-linearities!

Vishiniac 1983; Fry 1984; Goroff+ 1986; Suto & Sasaki 1991; Makino+ 1992;
Jain & Bertschinger 1994; Scoccimarro & Frieman 1996

The tool: Standard Perturbation Theory

- Completely ***analytic perturbative solution*** of the matter and density field satisfying following equation:

$$\dot{\delta} + \nabla \cdot [(1+\delta)\boldsymbol{v}] = 0$$

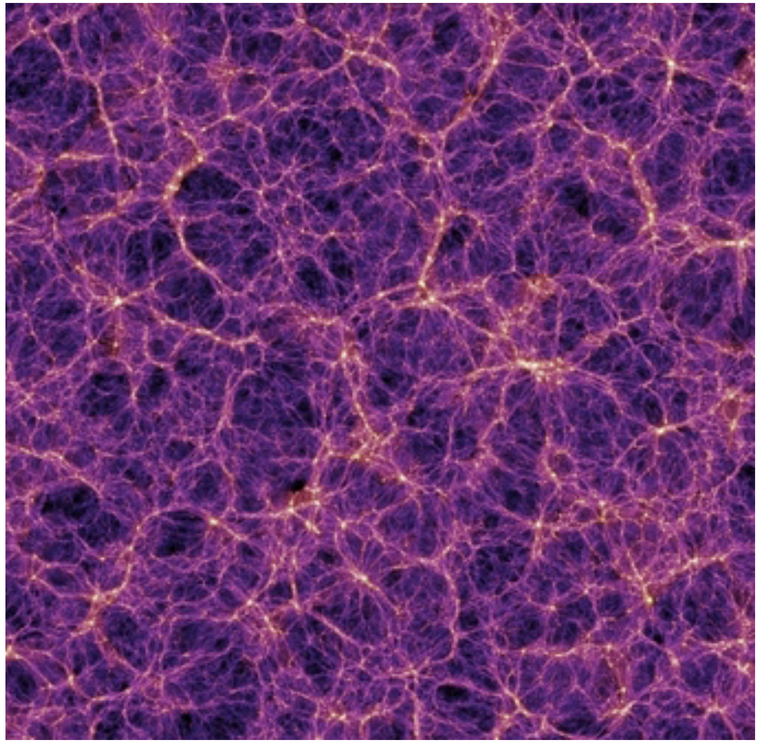
$$\dot{\boldsymbol{v}} + (\boldsymbol{v} \cdot \nabla)\,\boldsymbol{v} = -\frac{\dot{a}}{a}\boldsymbol{v} - \nabla\phi$$

$$\nabla^2\phi = 4\pi G a^2 \bar{\rho}\delta$$

- The perturbation variable = linear density contrast: $\delta_{\rm L}(k)$.

What is galaxy bias?

What we can predict from perturbation theory



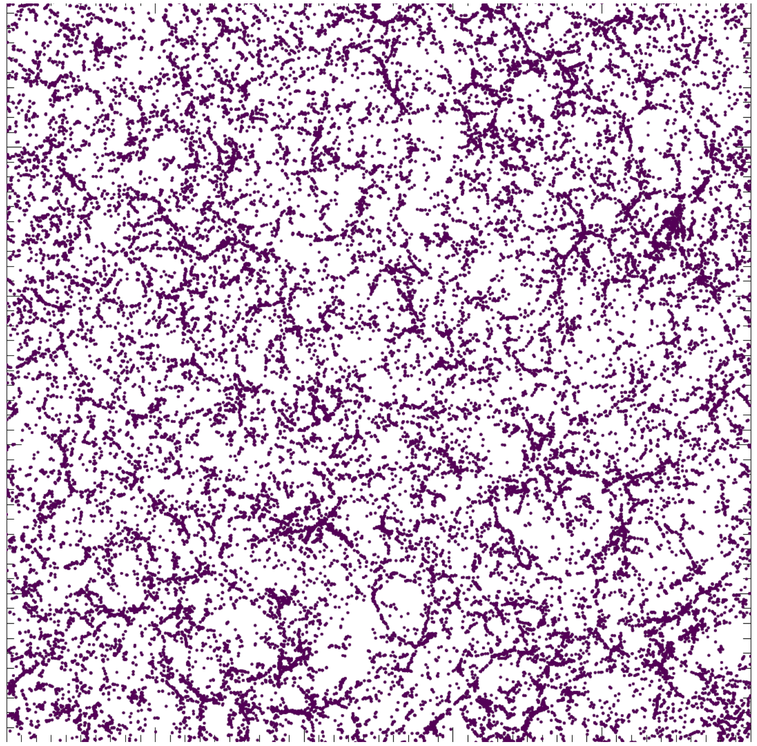
matter density: δ_m

Springel+ 2005

$$\delta_g(\boldsymbol{x}) = \mathcal{F}\left[\delta_m(\boldsymbol{x})\right]$$

- Halo formation
- Halo merger
- Gas cooling
- Fragmentation
- Star formation
- Feedback
- Accretion
- ...

What we observe from galaxy surveys



galaxy density: δ_g

De Lucia+ 2007

Desjacques, Jeong & Schmidt (2018)

All PNonLinearOrder terms

- We have introduced tons of new parameters to 3rd order, but luckily ***not all parameters contribute*** to the nonlinear galaxy power spectrum, as some of them are ***renormalized***:

$$\delta_{g,s}\Big|_{P^{\rm NLO}} = \sum_{O\in\mathfrak{O}_{\rm tot}} b_O O + \epsilon + \epsilon_\delta\delta + \epsilon_\eta\eta + b_\eta\left[\beta_{\nabla^2\boldsymbol{v}}\nabla^2\eta + \beta_{\partial^2_\parallel\boldsymbol{v}}\partial^2_\parallel\eta + \varepsilon_\eta\right] - u_\parallel\partial_\parallel\left[b_1\delta + b_\eta\eta + b_{\Pi^{[2]}_\parallel}\Pi^{[2]}_\parallel\right]$$

$$\mathfrak{O}_{\rm tot} = \mathfrak{O}_1 \cup \mathfrak{O}_{\rm hd} \cup \mathfrak{O}_2 \cup \mathfrak{O}_3$$

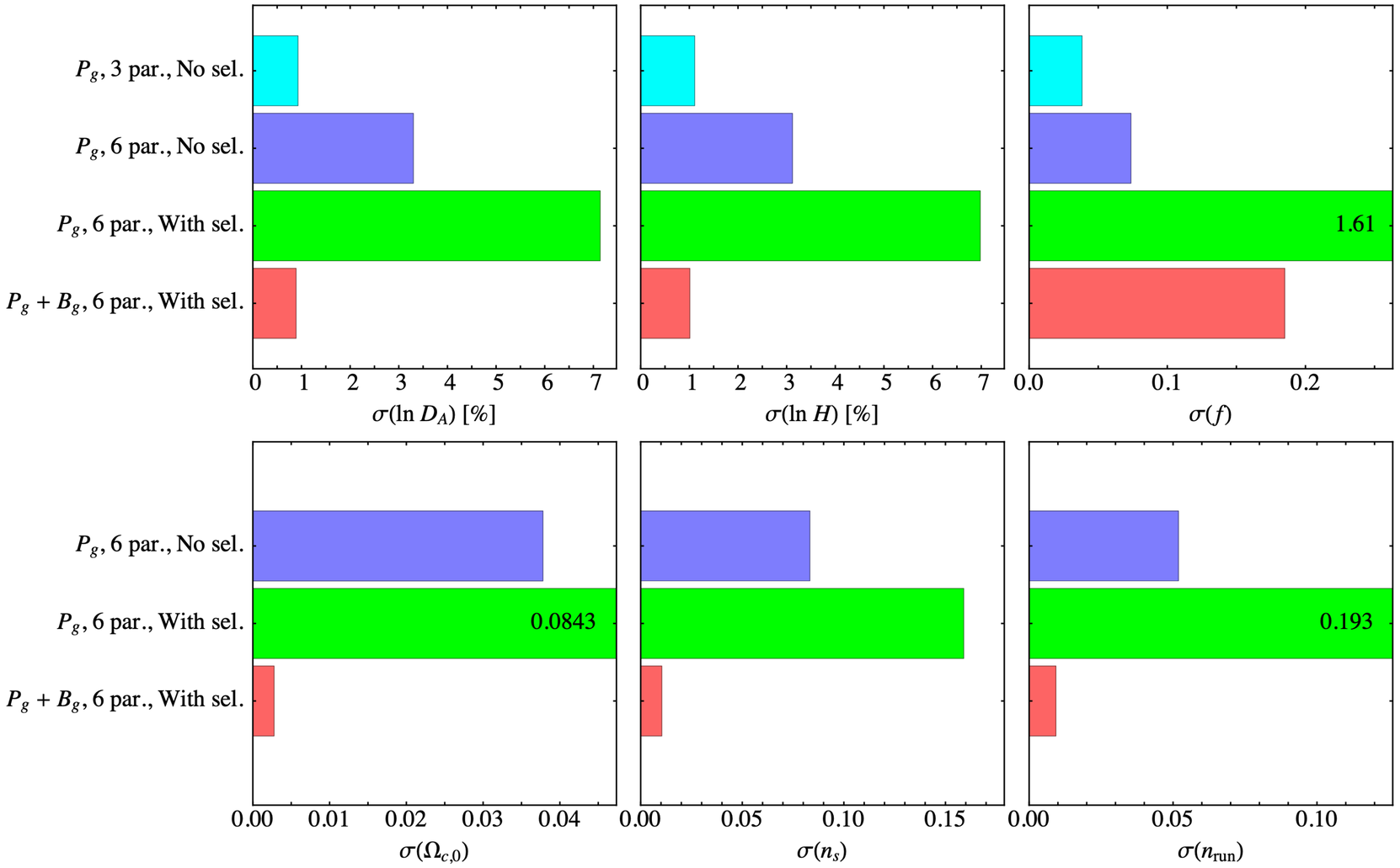
$$\mathfrak{O}_1 = \left\{\delta\,,\ \eta\right\};\quad \mathfrak{O}_{\rm hd} = \left\{\nabla^2\delta\right\}$$

$$\mathfrak{O}_2 = \left\{\delta^2\,,\ K^2\,,\ \delta\eta\,,\ \eta^2\,,\ (KK)_\parallel\,,\ \Pi^{[2]}_\parallel\right\}$$

$$\mathfrak{O}_3 = \left\{O_{\rm td}\,,\ \delta\Pi^{[2]}_\parallel\,,\ \eta\Pi^{[2]}_\parallel\,,\ (\Pi^{[2]}K)_\parallel\,,\ \Pi^{[3]}_\parallel\ \right\}$$

Agarwal, Desjacques, Jeong & Schmidt (2021)

Cosmology with 22 (!!) parameters



- More nuisance parameters (selection bias) increase the uncertainties.
- Bispectrum measures the selection bias parameters.
- $f = \Omega_{\rm m}^{0.55}$ can be an important test of GR!