Jumping to Conclusions: Unbiased Cosmological Parameter Estimation from Emission Line Surveys with Interlopers

Henry S. Grasshorn Gebhardt
with Donghui Jeong

Institute for Gravitation and the Cosmos
Department of Astronomy and Astrophysics
The Pennsylvania State University

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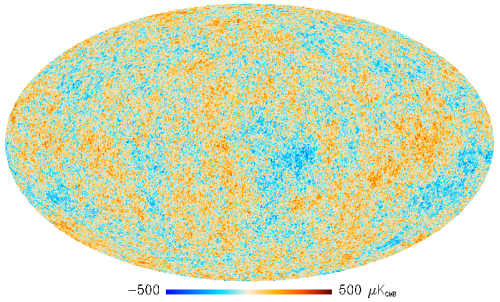
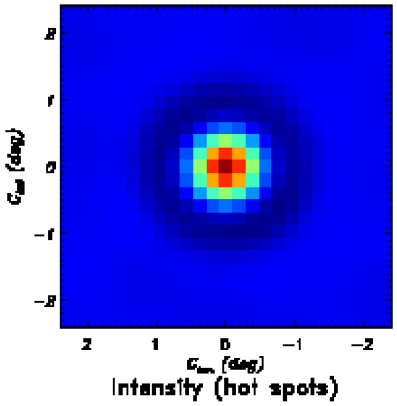
Outline

- Motivation
- Interlopers in Emission Line Surveys: HETDEX and *WFIRST*
- Spherical harmonic space
  - Projecting non-linearities, FoG
  - HETDEX and *Euclid* in spherical harmonic space
- Conclusion

Some things never change: BAO scale is frozen-in since recombination

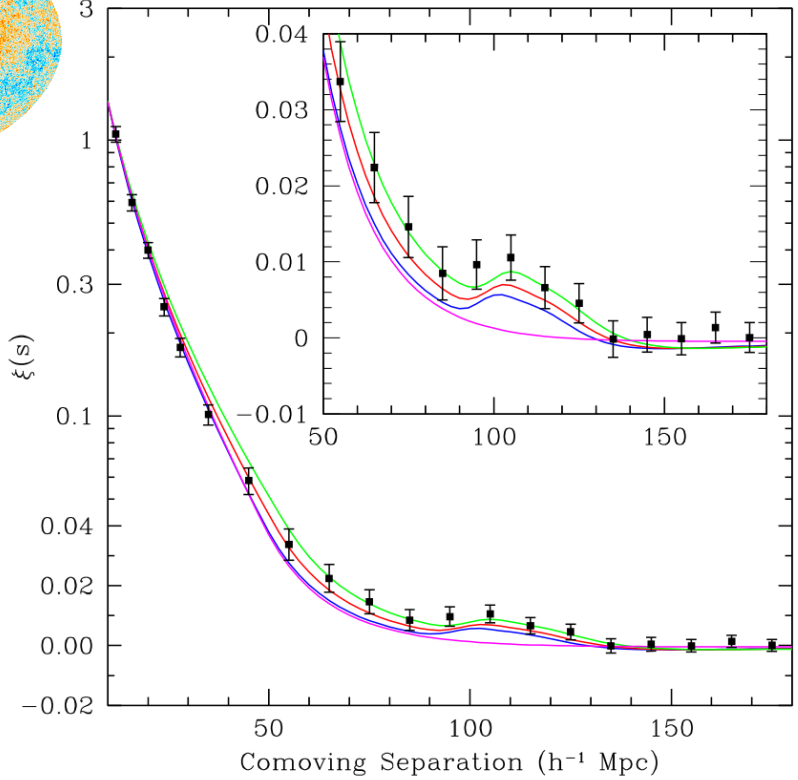


z ~ 1000

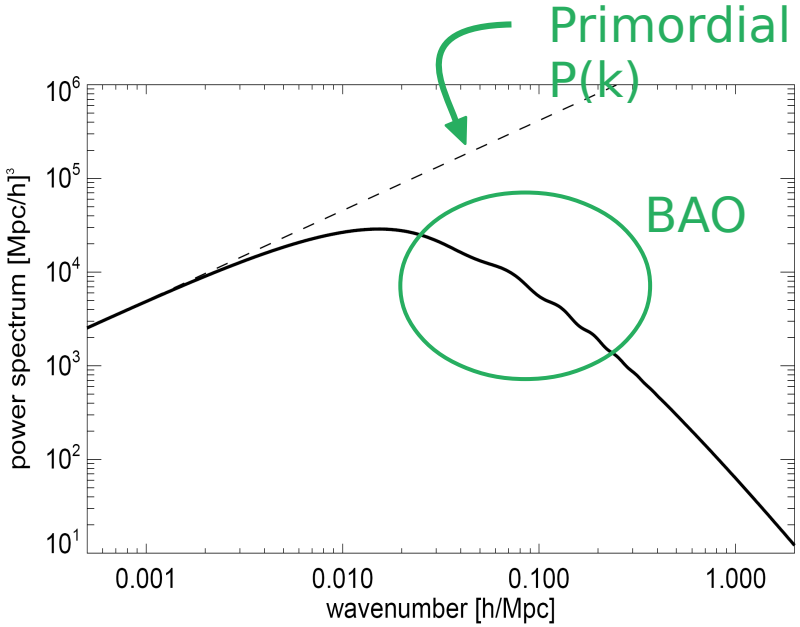


Planck 2014

BAO: baryon acoustic oscillations



Eisenstein et al 2005 z ~ 0



Power spectrum = FourierTransform[Configuration-space correlation function]

Using a Standard Ruler

- d_{BAO} given by CMB
- Can measure angular diameter distance $d_A(z)$ and Hubble parameter H(z):

$$d_{\rm BAO} = d_A(z)\,\Delta\theta = \frac{\Delta z}{H(z)}$$

- Both depend on dark energy:

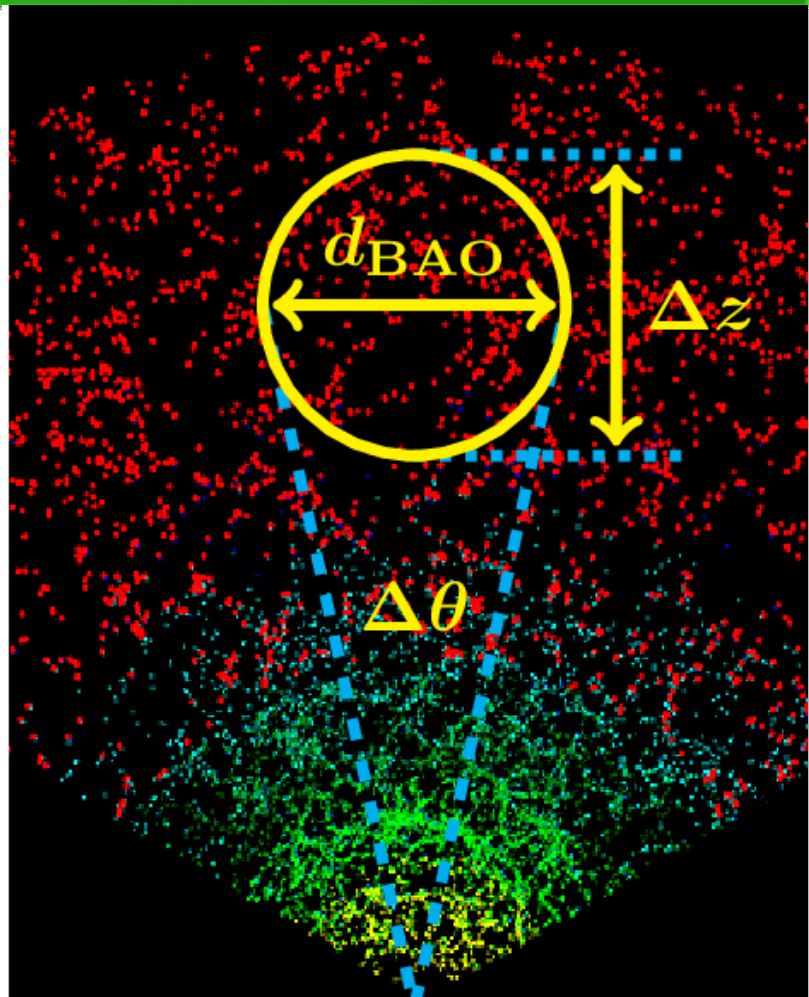
Baryons + Cold Dark Matter

Curvature

Dark Energy

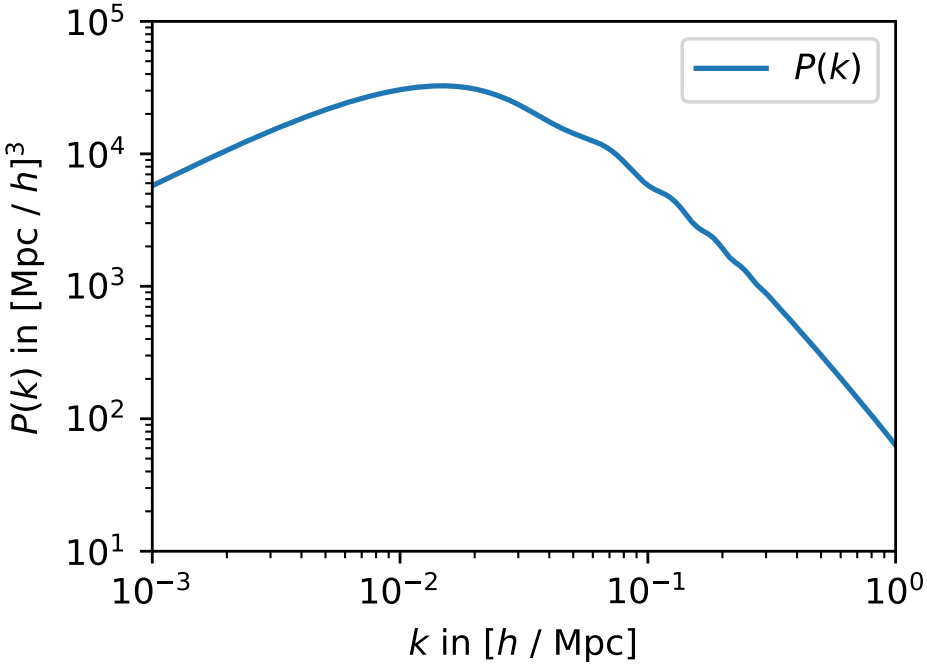
$$H^2(z) = H_0^2\left[\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{\rm DE}(1+z)^{3(1+w)}\right]$$

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



The power spectrum contains lots of cosmological information!

- Baryon acoustic oscillations (BAO)
  → Distances!
- Alcock-Paczynski test
  → Distances!
- Growth of structure
  → Test modified gravity
- Non-Gaussianity
- Neutrinos



Interlopers in HETDEX

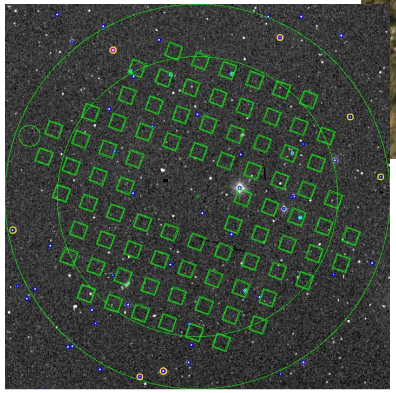
- **Introduction**
  - **HETDEX: Instrument and Survey**
  - **Interlopers in HETDEX: Biased distance measurement!**
- Fixing interloper bias
  - Method: Joint fitting
  - Results: No interloper bias
- More future applications: *WFIRST*
- Caveats: Danger, danger!
- Spherical Harmonic Space

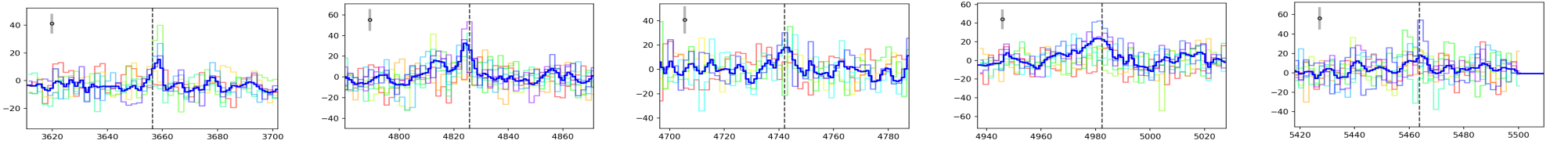
Grasshorn Gebhardt, Jeong, *et al.* 2019

HETDEX

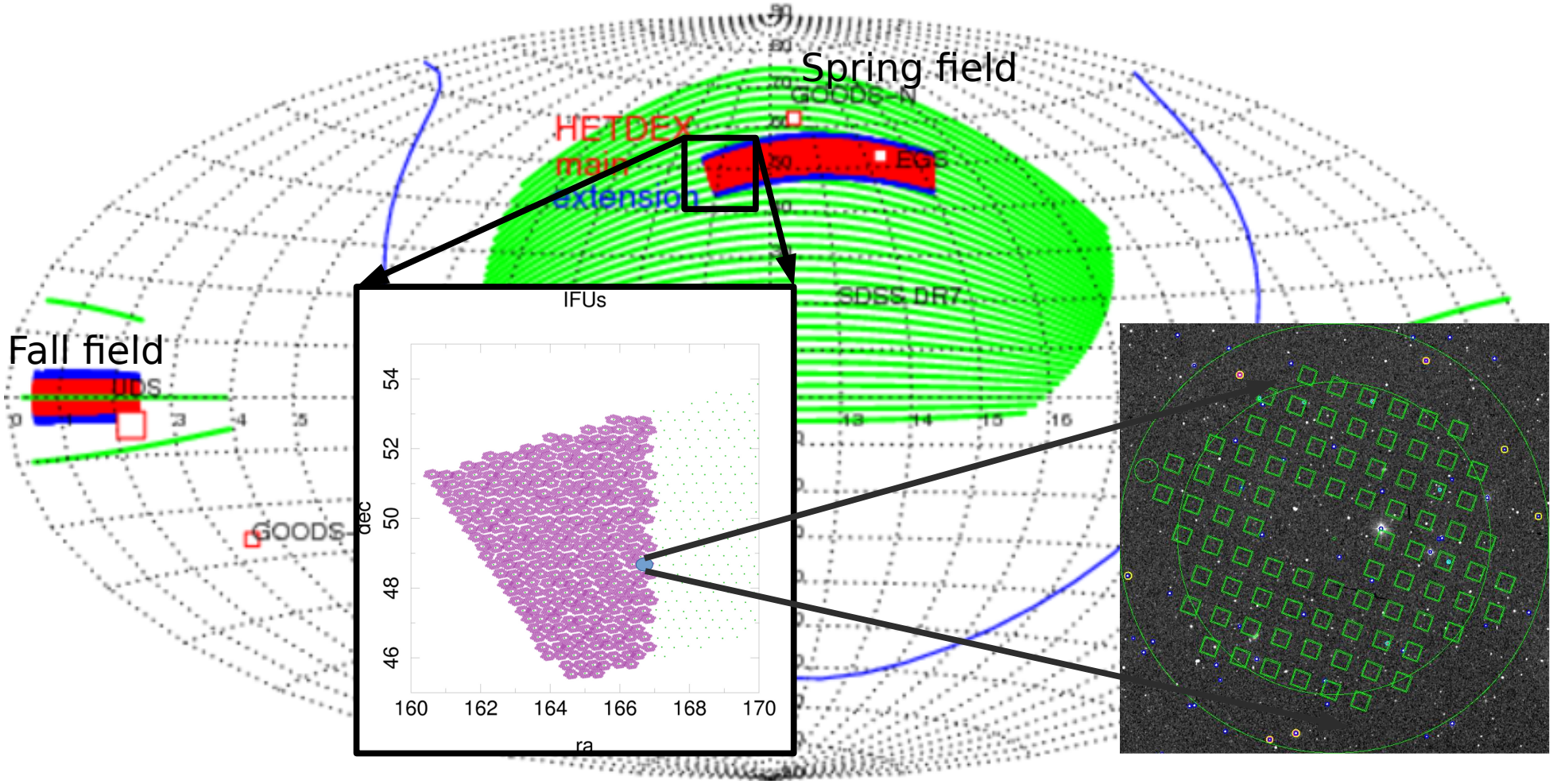
Hobby-Eberly Telescope Dark Energy eXperiment

- 78 IFUs → 35,000 spectra per exposure
  → *blind* spectroscopic survey
- R ~ 700, 3500Å < λ < 5500Å
- f_{sky} = 1% over 3 years
- ~0.8×10⁶ Ly-α emitters (LAE)
  1.9 < z < 3.5
- ~1.6×10⁶ [O II] 3727 emitters
  z < 0.5

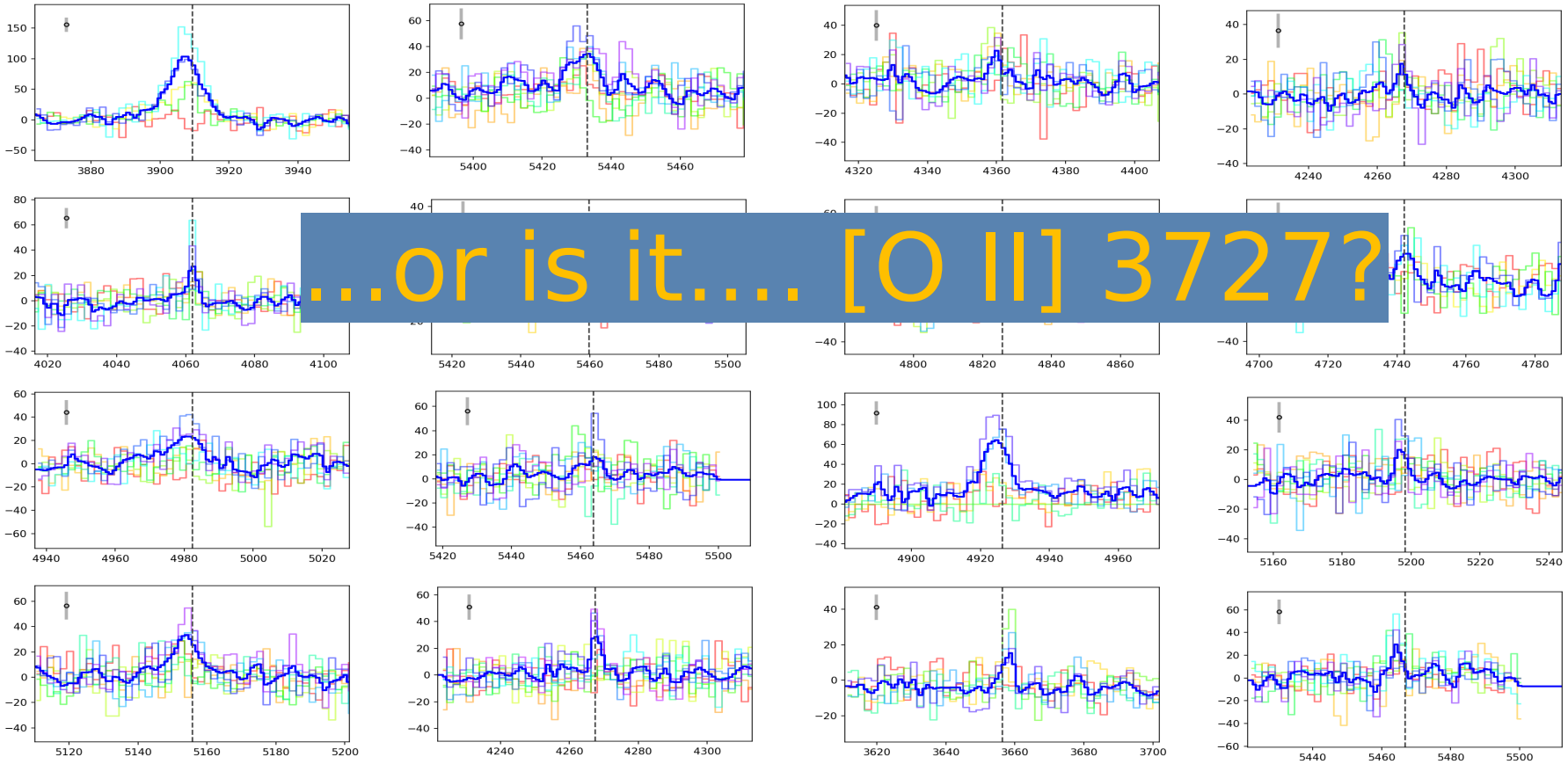




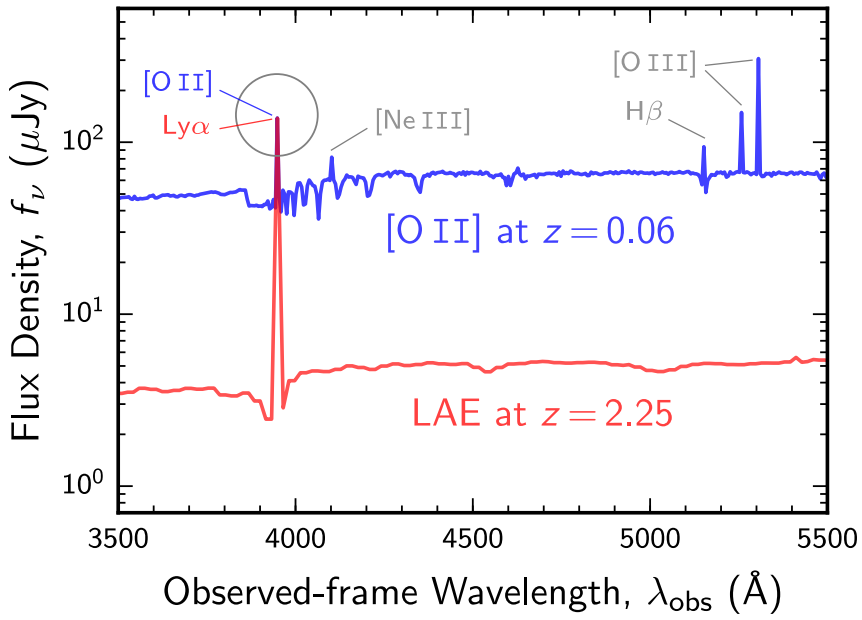
Survey footprint



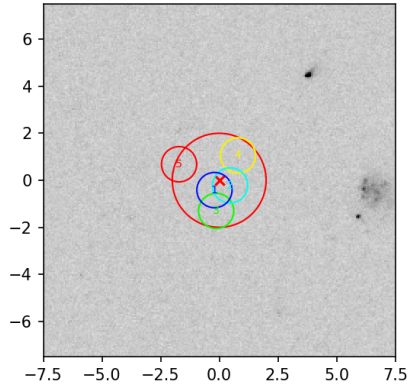
HETDEX finds Ly-α!



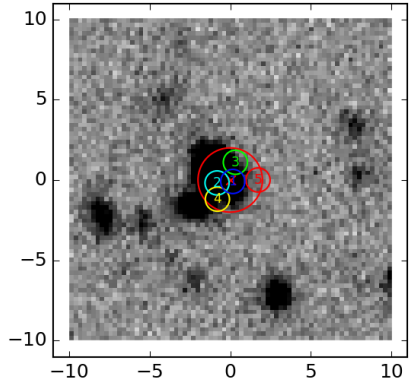
LAE and OIIE identification



LAE?
EW > 20 Å



[O II]?
EW < 20 Å



$$\lambda_{\rm obs} = (1+z_\alpha)\,\lambda_\alpha = (1+z_{[\rm O\ II]})\,\lambda_{[\rm O\ II]}$$

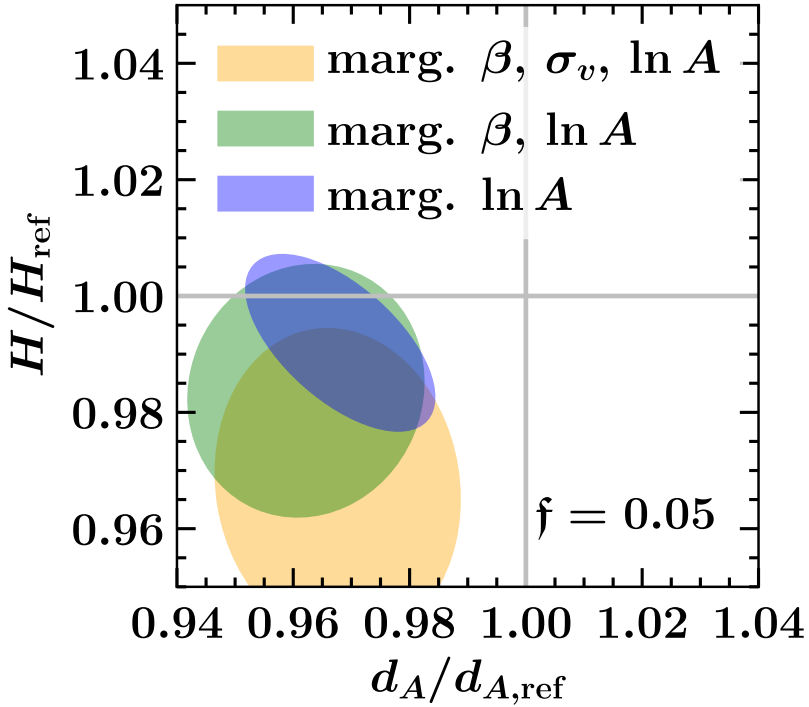
Leung+ 2017

$$EW = \frac{F_{\rm line}}{f_{\rm continuum}}$$

Contamination introduces *Interloper Bias*

LAE sample

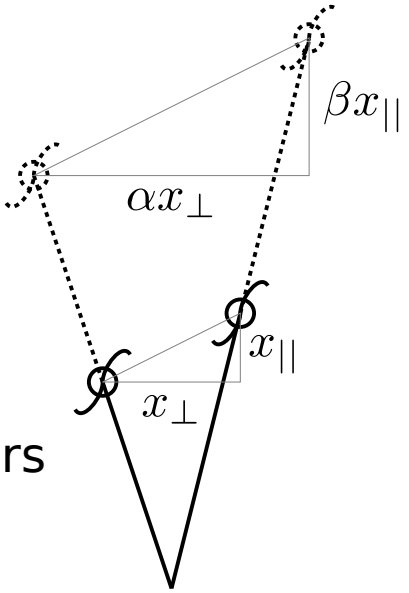
$$\mathfrak{f} = \frac{N^{\text{misidentified}}_{[\text{O II}]}}{N^{\text{total}}_{\text{LAE}}}$$



Interlopers bias the cosmological measurements! :(

How do interlopers affect
the power spectrum?

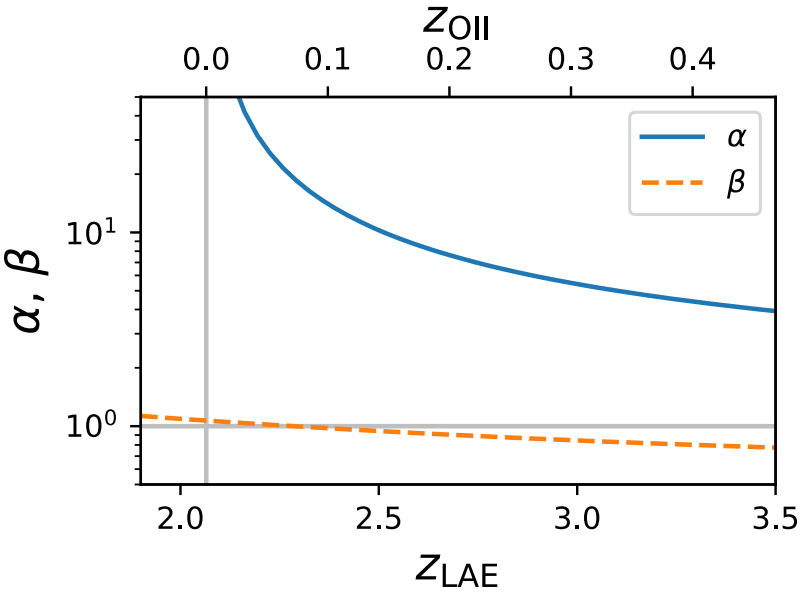
Interlopers project small scales to large scales, small volume to large volume



$$\alpha = \frac{d_A(z_{\rm LAE})}{d_A(z_{\rm [O\ II]})}$$

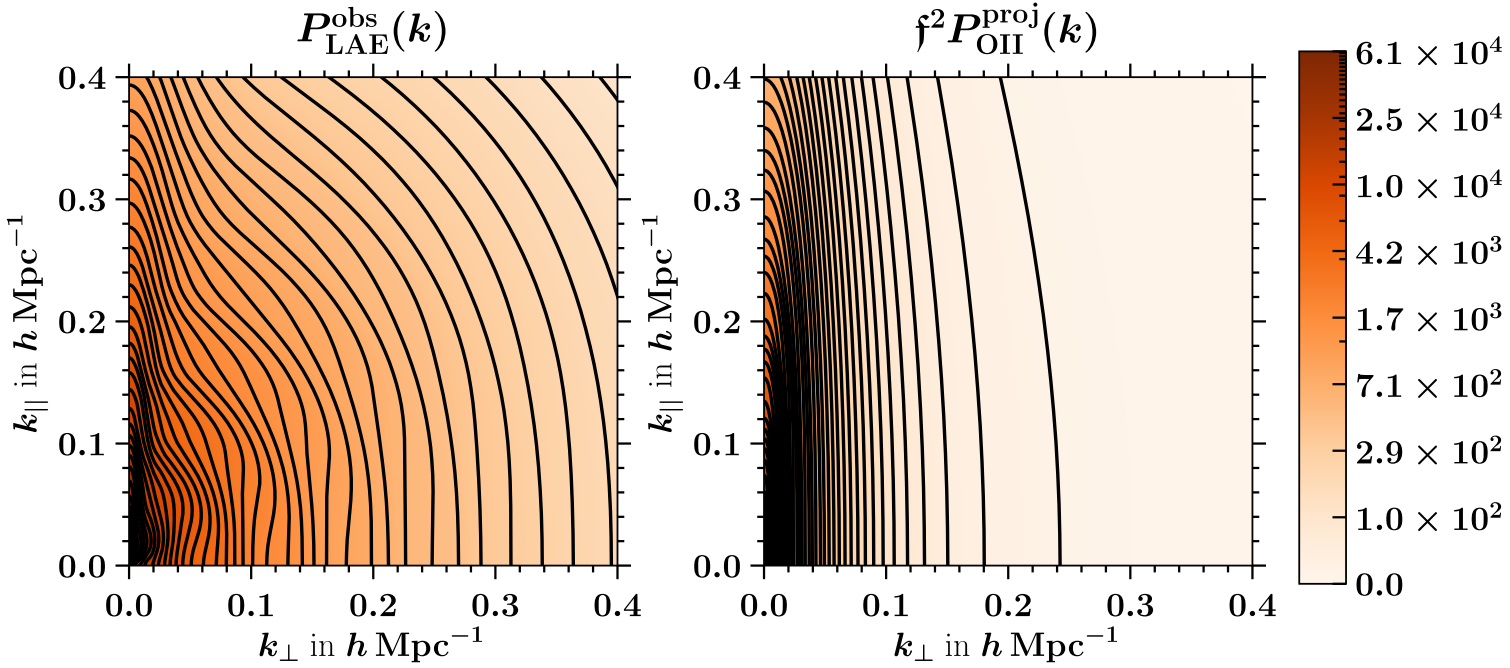
$$\beta = \frac{\lambda_{\rm [O\ II]}}{\lambda_{\rm LAE}} \frac{H(z_{\rm [O\ II]})}{H(z_{\rm LAE})}$$

- Small volume gets projected to large volume $V \propto \alpha^2 \beta$
- Small scales get projected to large scales $\alpha \sim 7$
- Observed anisotropy $\alpha \neq \beta$



Effect on Power Spectrum

$$P^{\mathrm{obs}}_{\mathrm{LAE}}(\boldsymbol{k}) = (1-\mathfrak{f})^2 P_{\mathrm{LAE}}(\boldsymbol{k}) + \mathfrak{f}^2 P^{\mathrm{proj}}_{\mathrm{OII}}(\boldsymbol{k})$$



$$\mathfrak{f} = \mathfrak{g} = 0.1$$

All power spectra are projected into the LAE volume.

Talk Outline

- Introduction
  - Cosmology with HETDEX
  - Interlopers in HETDEX: Biased distance measurement!
- **Fixing interloper bias**
  - **Method: Joint fitting**
  - **Results: No interloper bias**
- More future applications: WFIRST
- Caveats: Danger, danger!
- Spherical Harmonic Space

Joint fitting!

LAE sample

$$f = \frac{N^{\text{misidentified}}_{[\text{O II}]}}{N^{\text{total}}_{\text{LAE}}} \sim 1\,\%$$

Joint fitting!

LAE sample

[O II]-emitter sample

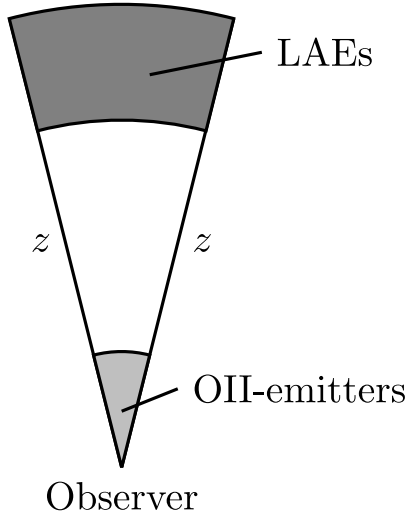
$$\mathfrak{f} = \frac{N^{\text{misidentified}}_{[\text{O II}]}}{N^{\text{total}}_{\text{LAE}}} \sim 1\,\%$$

$$\mathfrak{g} = \frac{N^{\text{misidentified}}_{\text{LAE}}}{N^{\text{total}}_{[\text{O II}]}} \sim 0-10\,\%$$

Cross-correlation vanishes in the absence of interlopers

The cross-correlation between LAEs and [O II]-emitters should be zero due to their large physical separation.

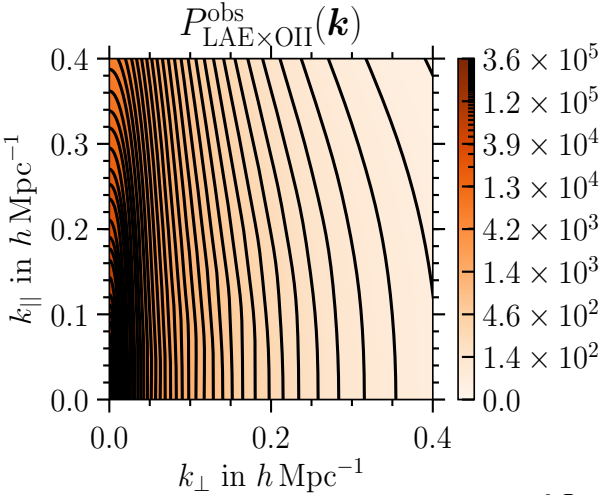
If it isn't zero, then there are interlopers.



Without interlopers:

$$\mathbf{P}_{\mathrm{LAE}\times\mathrm{OII}}(\mathbf{k}) \approx \mathbf{0}$$

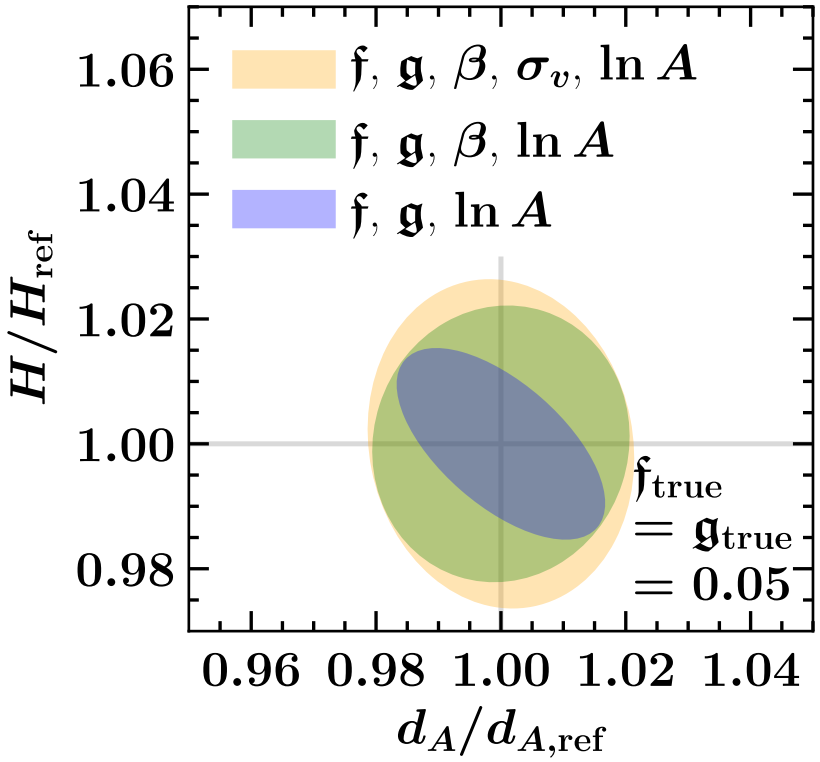
With interlopers (10%):



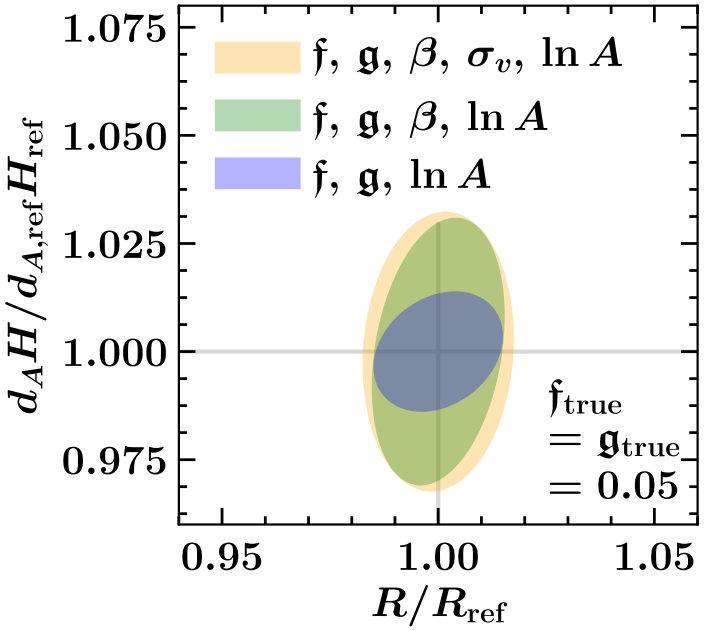
Joint fitting: No more interloper bias!

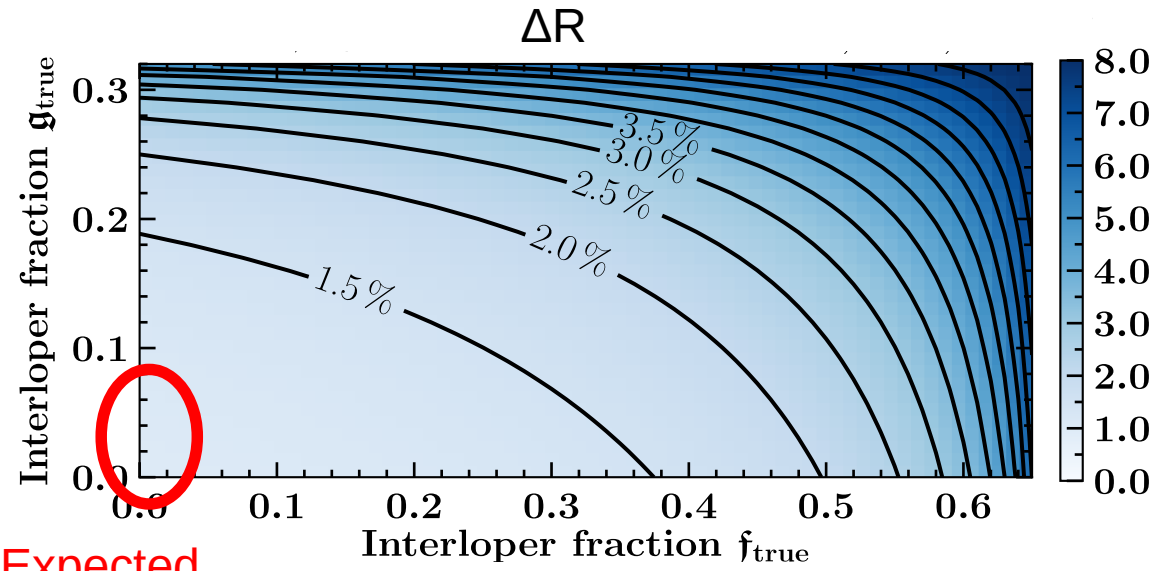
LAEs:

[O II]-emitters:



Joint fitting: R and $d_A H$





Expected
for HETDEX
ΔR ~ 1%

$R = (d_A^2/H)^{\frac{1}{3}}$ (from BAO)

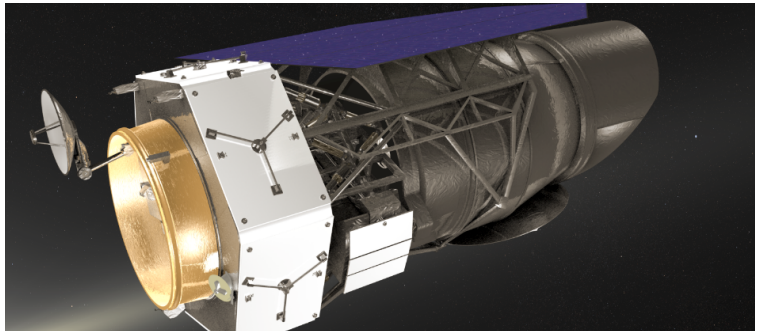
Beyond HETDEX: *WFIRST*

- f_{sky} ~ 5%
- Hα at 1.0 < z < 1.88 (~1.6×10^7 objects)
- [O III] λ5007 at 1.7 < z < 2.77 (~1.4×10^6)

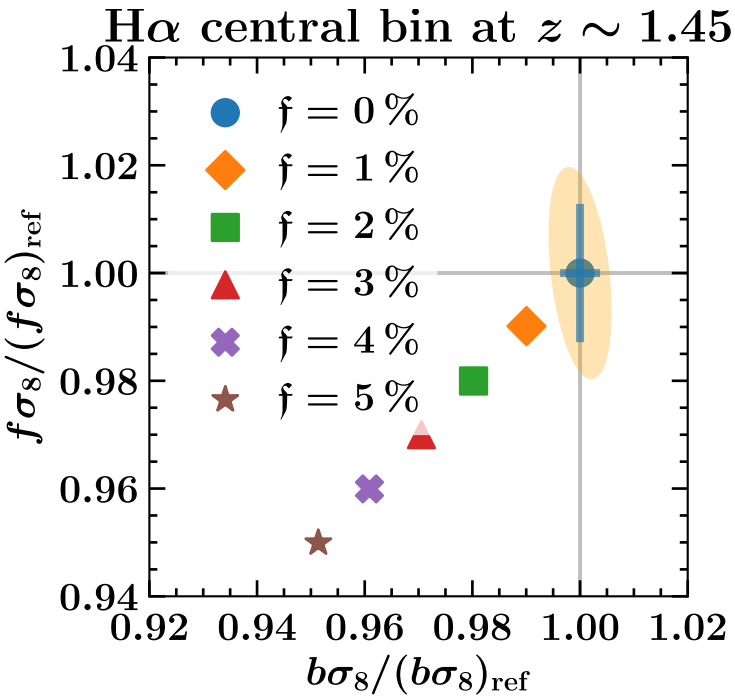
→ Interlopers overlap in redshift!

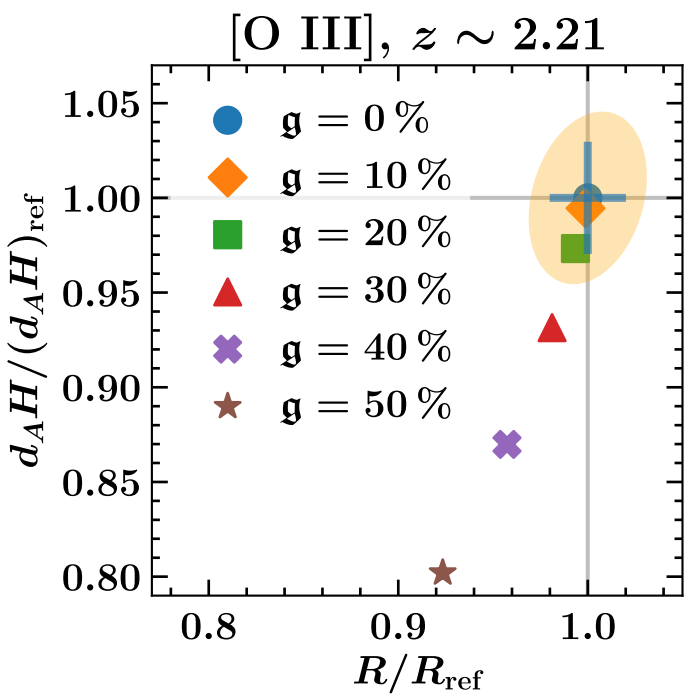
→ Split into three regions:

- z<1.2: Absence of second line identifies Hα
- 1.2<z<1.7: Fit for interloper fractions
- 1.7<z: Presence of both lines identifies redshift

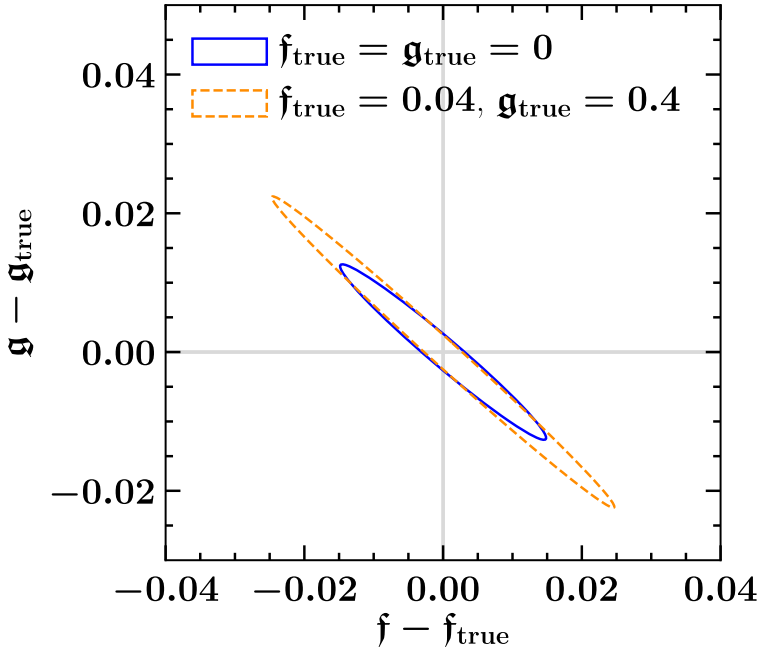


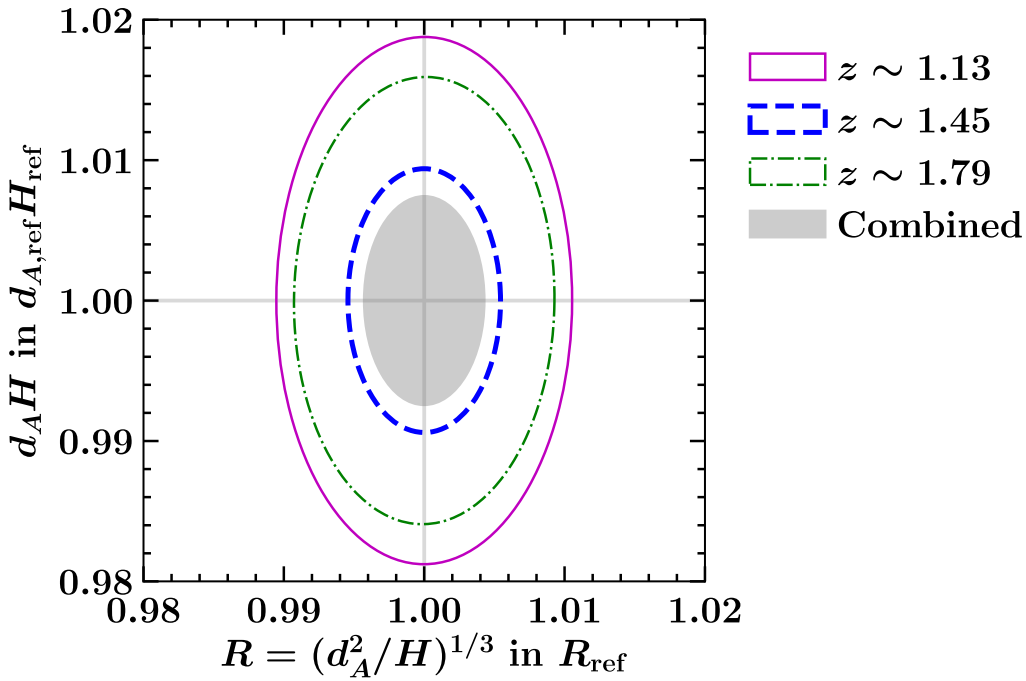
WFIRST: Interloper Bias





WFIRST: Joint fitting removes interloper bias





Combined: ΔR~0.3%, agrees with WFIRST paper (Spergel *et al.* 2015)

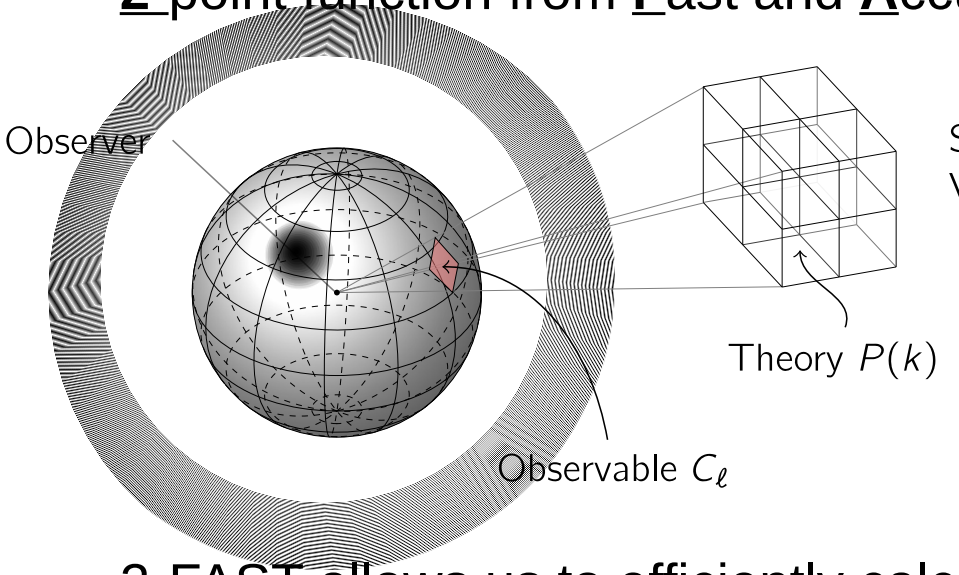
Caveats: Danger, danger!

- **Limited to small-area surveys (flat-sky approximation)**
- **“Odd” cross-correlation**: Awkward projection of OIIEs into LAE volume to get the angular cross-correlation.
- **No lensing**: Light from LAEs must pass through matter distribution associated with the OIIEs. → Intrinsic cross-correlation is actually non-zero!
- **No redshift evolution** (e.g. Volume effects, growth of structure, evolution of luminosity function)

→ Going to spherical harmonic space will solve all of these!

2-FAST algorithm: projecting the 2-point function into spherical harmonic space

2-point function from **F**ast and **A**ccurate **S**pherical Bessel **T**ransform



$$C_\ell(r, r') \simeq \frac{2}{\pi} \int_0^\infty \mathrm{d}k\, k^2\, P(k)\, j_\ell(kr)\, j_\ell(kr')$$

2-FAST allows us to efficiently calculate spherical harmonic projection with linear Kaiser effect.

… but may also be useful for perturbation theory!

Grasshorn Gebhardt & Jeong 2018

More Spherical Harmonic Problems to Solve: Projecting non-linear terms

- Non-linear terms in P(k) → Integral diverges!

  → Fingers of God (FoG): Bang!

  → Non-linear Kaiser: Bang!

$$C_\ell(r,r') \simeq \frac{2}{\pi}\int_0^\infty \mathrm{d}k\, k^2\, P(k)\, j_\ell(kr)\, j_\ell(kr')$$

- Solution:

  → FoG result in convolution of $C_\ell(r,r')$ with Gaussian or exponential

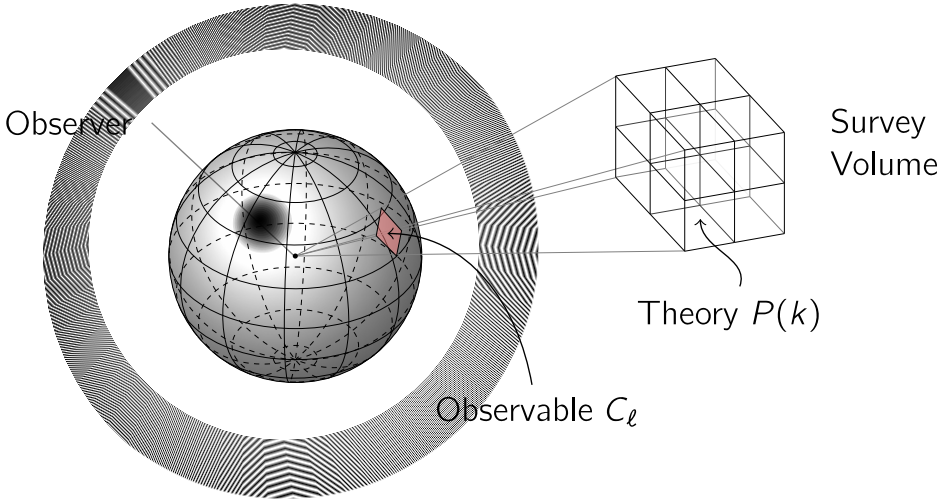
  → Non-linear Kaiser can be calculated as derivatives on the window function.

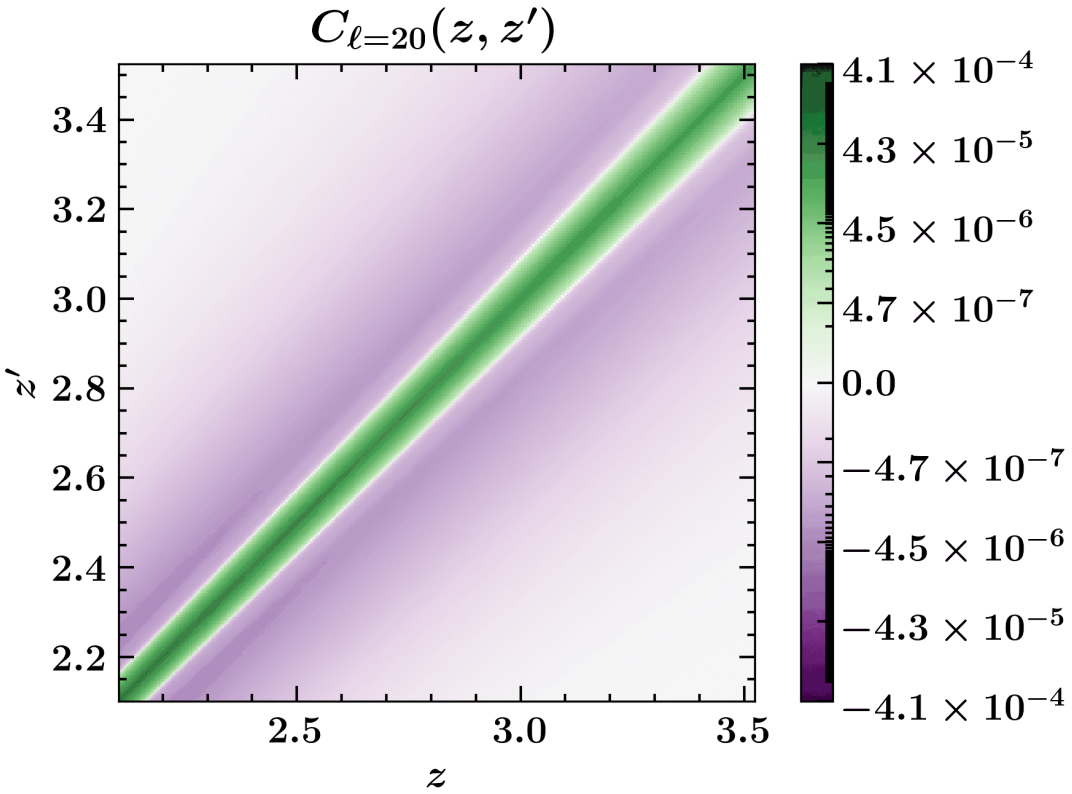
$$\delta_g(\vec{k}) = (b + f\mu^2)\tilde{A}_{\mathrm{FoG}}(k\mu)\,\delta_m(\vec{k})$$

Calculating $C_\ell(z,z')$

- Projection:

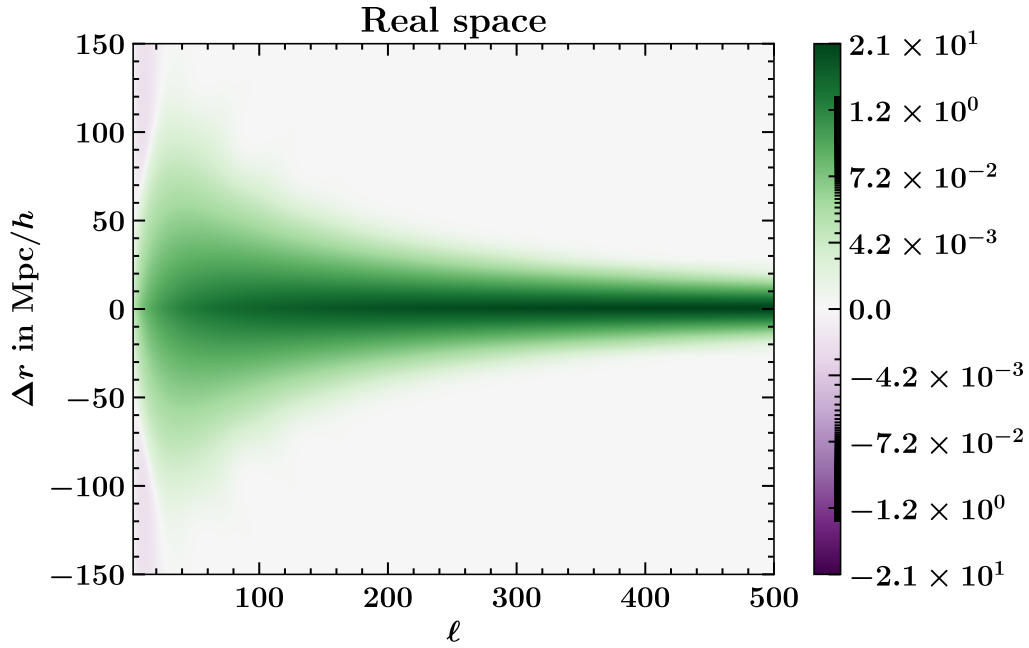
  $P(k_\perp, k_\parallel) \rightarrow C_\ell(z,z')$





Spherical harmonic Space: $C_\ell(r_{mid},\Delta r)$

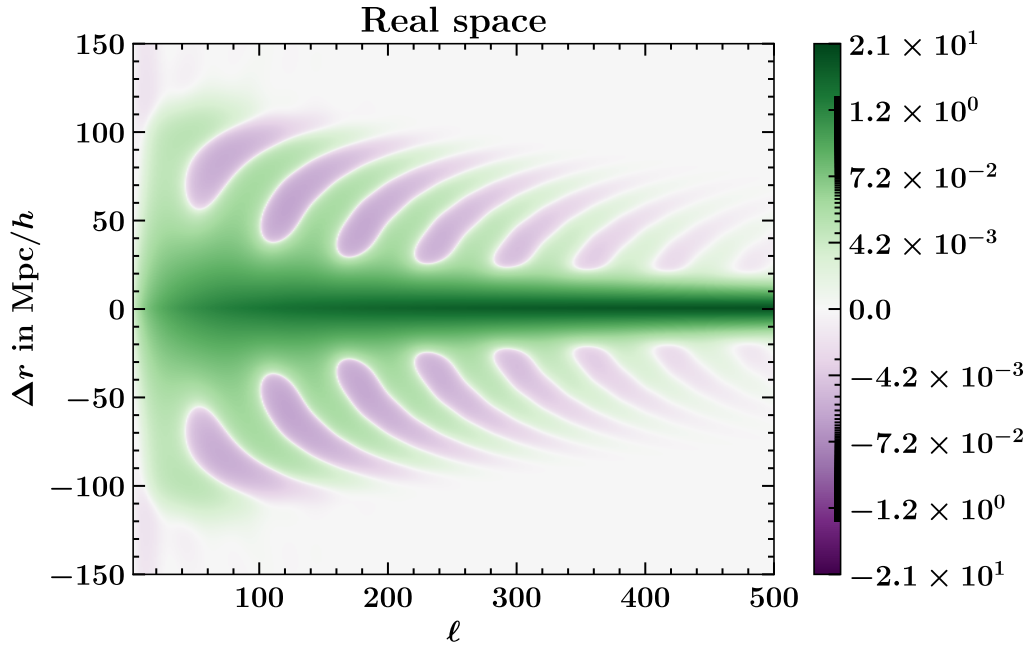
- Real space



$k_\perp r \sim \ell + 0.5$

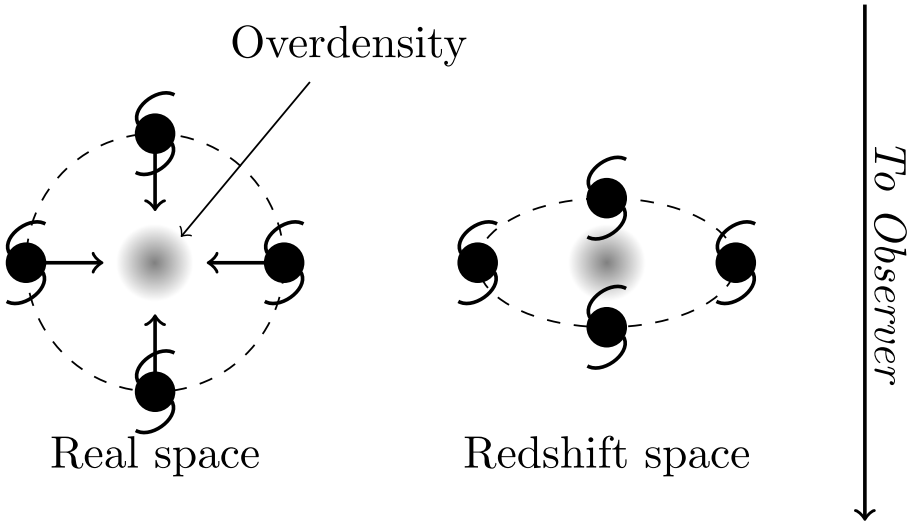
$C_\ell(r_{mid},\Delta r)$

- Real space
  + BAO



$k_\perp r \sim \ell + 0.5$

The Kaiser Effect



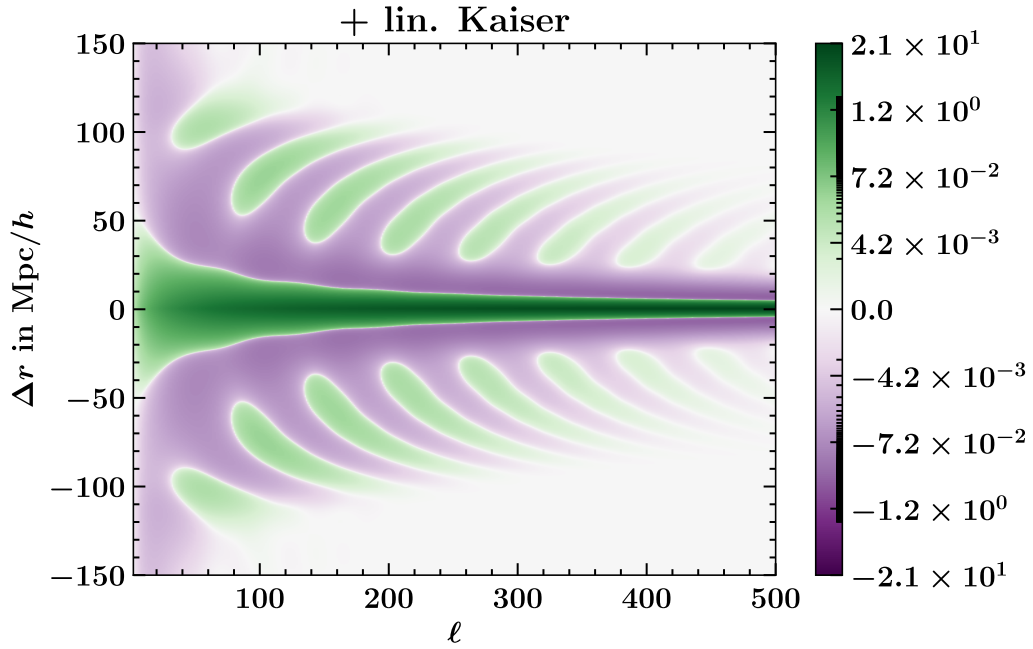
- Galaxies tend to move towards overdensities.
- ➔ Increased clustering along the line of sight direction.

$C_\ell(r_{mid},\Delta r)$

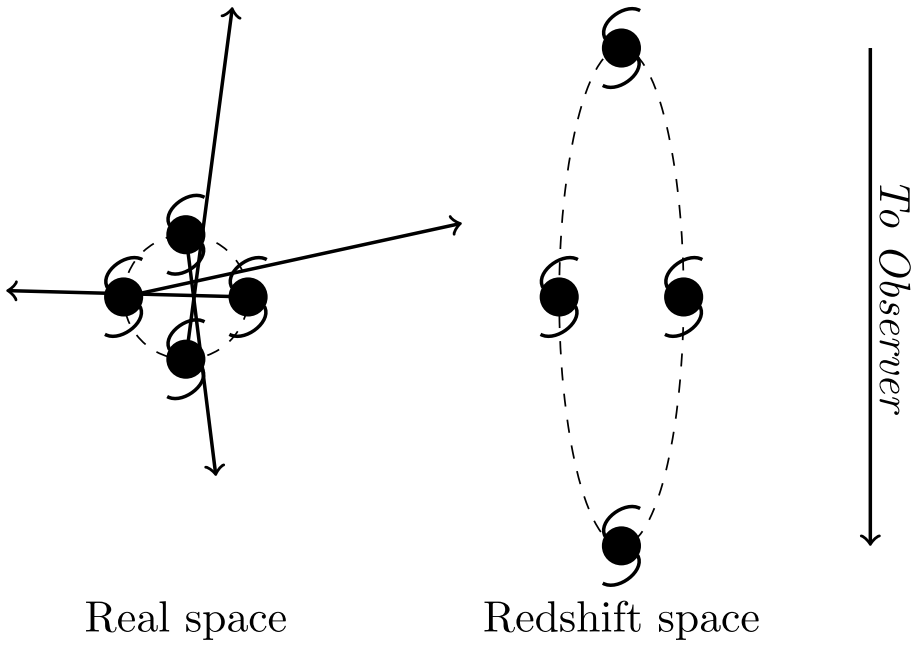
- Real space

  + BAO

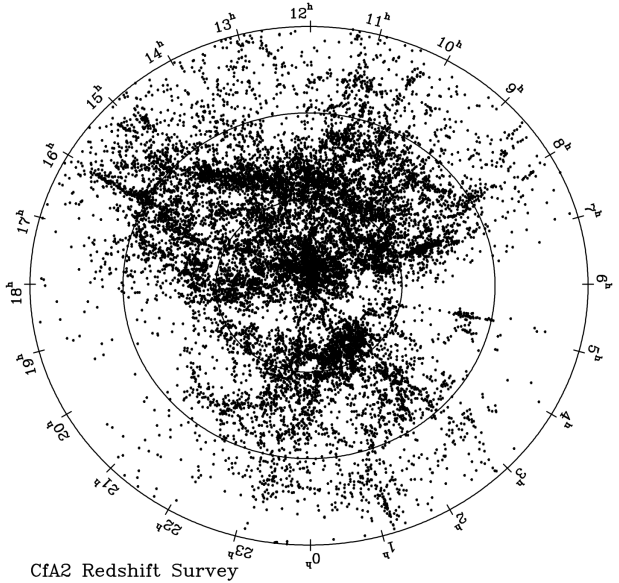
  + Linear Kaiser: coherent inflow into galaxy clusters



Fingers of God



- Stochastic motions of galaxies
- ➔ Suppression of clustering in line of sight direction.



$C_\ell(r_{mid},\Delta r)$

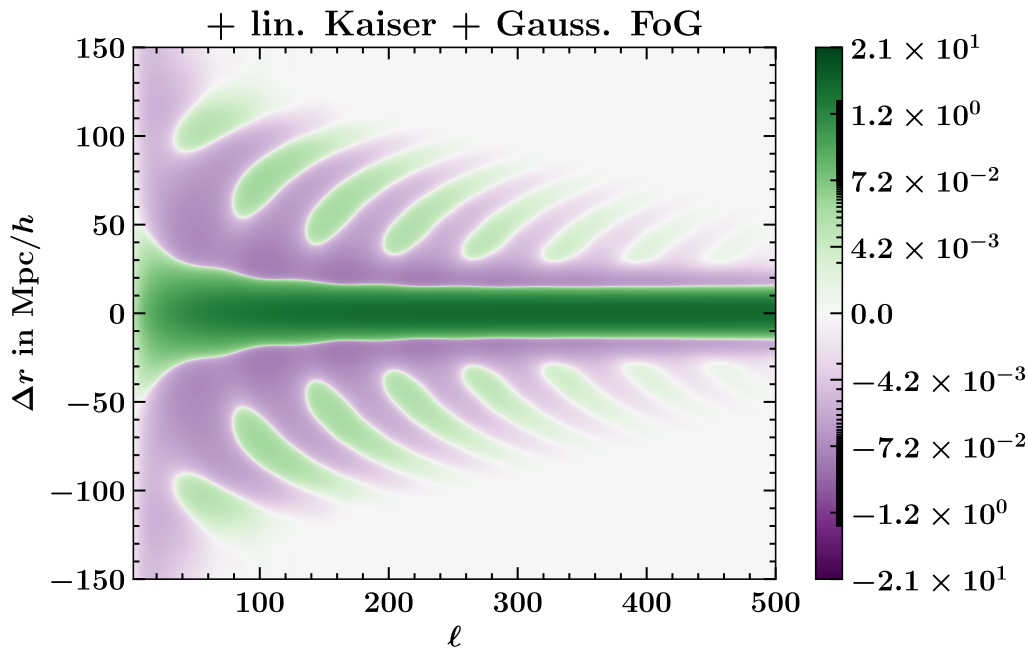
- Real space

  + BAO

  + Linear Kaiser: coherent inflow into galaxy clusters

  + Fingers of God (FoG) blur our vision!

- ➔ Redshift space



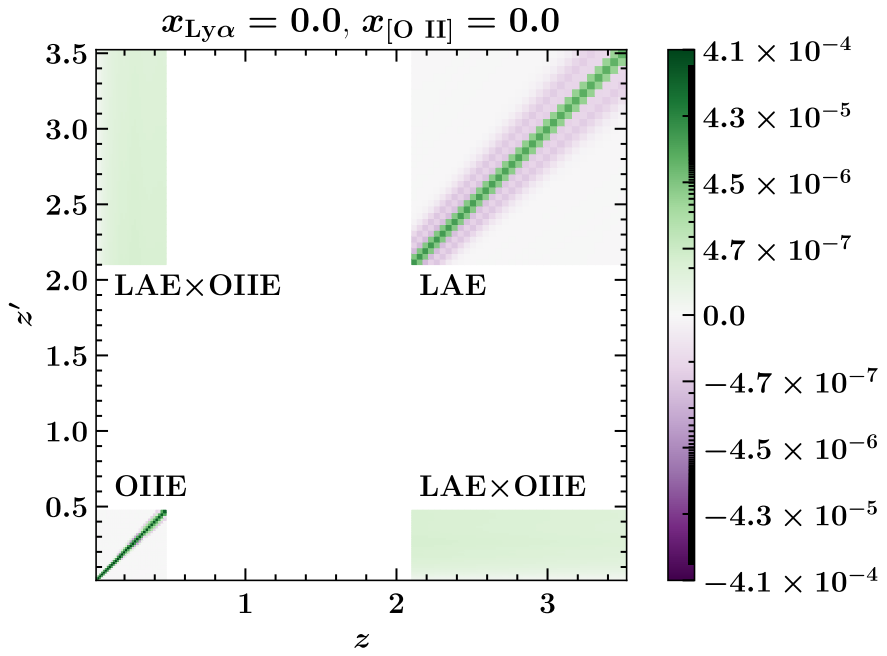
Putting it all together: Fisher forecasts in spherical harmonic space

- ✔ Can do wide-angle analysis
- ✔ Now includes Kaiser and FoG
- ✔ Lensing is included
- ✔ Redshift evolution is included

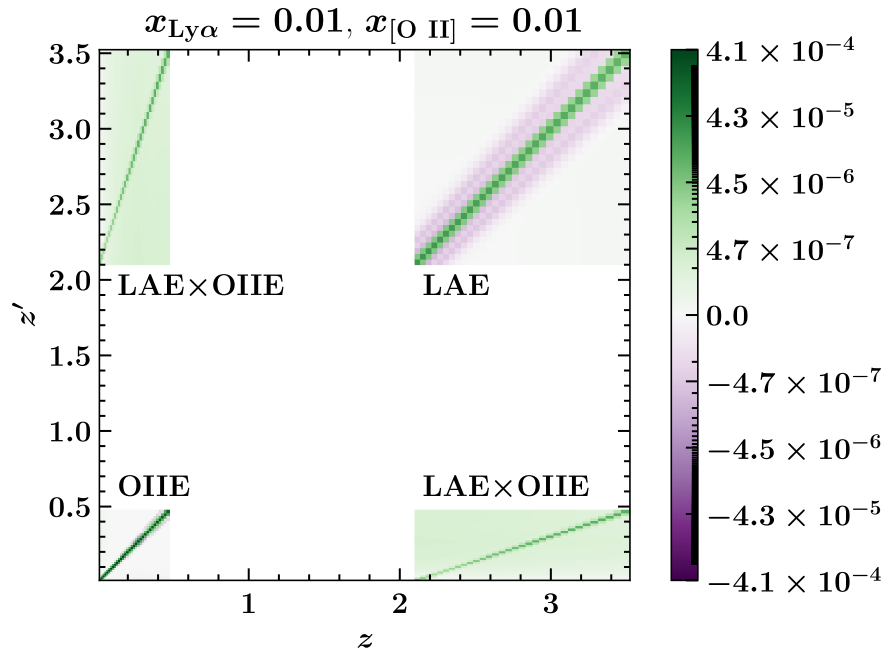
Where are the interlopers in spherical harmonic space?

Interlopers in C_ℓ space

Without interlopers



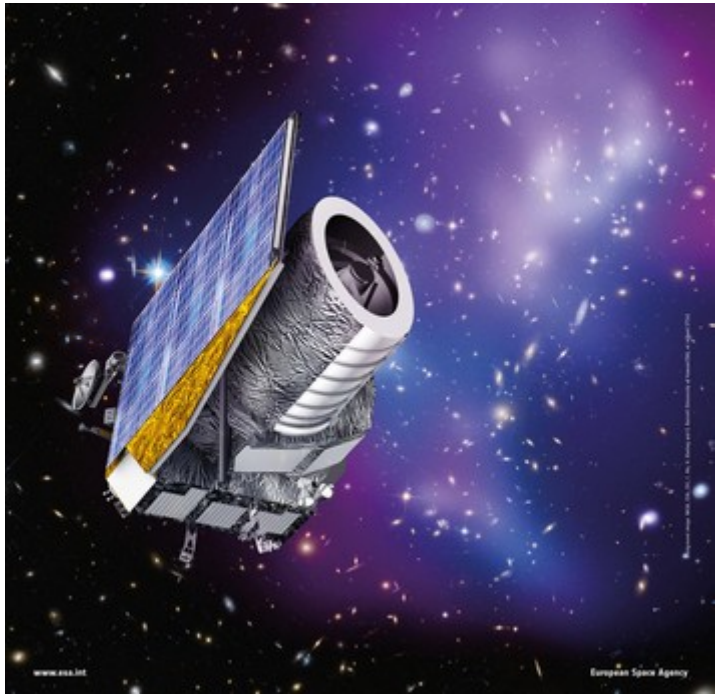
With interlopers



→ Diagonal of cross-correlation is most significantly affected.

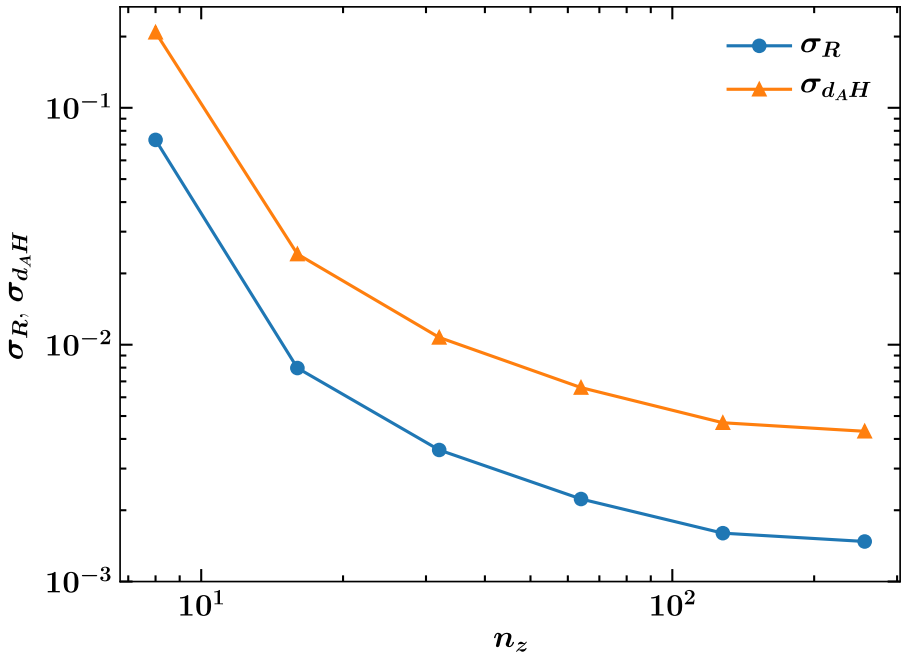
Euclid

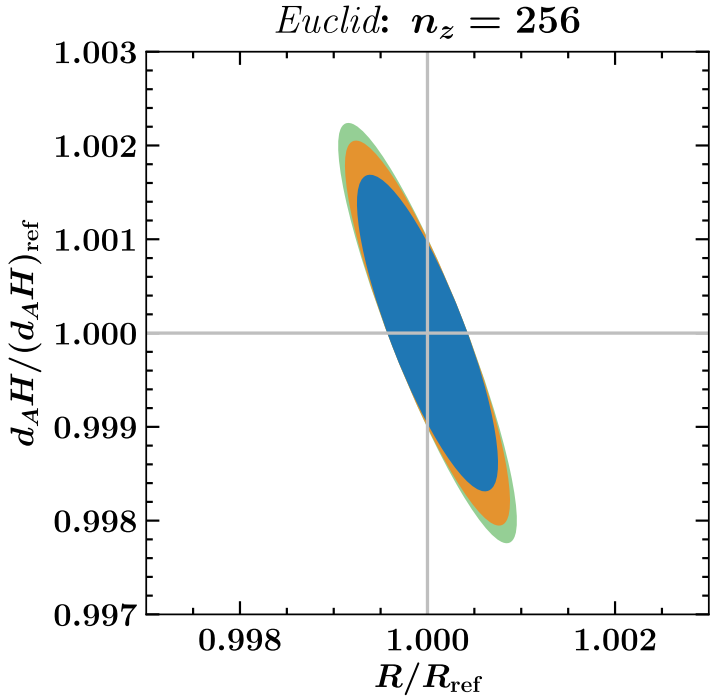
- Covers 36 % of the sky
- Near Infrared Spectrometer and Photometer (NISP), R~380, 1.25μm < λ < 1.85μm
- Hα 6563, 0.9 < z < 1.82
- [O III] 5007, 1.5 < z < 2.7
- Launch planned for 2022



www.euclid-ec.org

Euclid wide-angle forecast results





$\Delta\chi \sim 2\pi / k_{max} \sim 30$ Mpc/h

z ~ 2.7

Conclusion and Future Outlook

- Joint fitting removes interloper bias
- Spherical harmonic projection is 2-FAST now.
- Fingers-of-God and non-linear Kaiser can be done in spherical harmonic space
- Fisher forecasts for HETDEX, *WFIRST*, and *Euclid* including lensing, redshift evolution, wide-angle effects.
- Future:
  - Exploit interlopers for cosmology
  - Use multiple tracers