The Hobby-Eberly Telescope Dark Energy Experiment

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)
on behalf of HETDEX collaboration

LSST@Europe: The Path to Science, September 9, 2013

Cosmology: Next Decade?

- Astro2010: Astronomy & Astrophysics Decadal Survey
  - Report from *Cosmology and Fundamental Physics* Panel (Panel Report, Page T-3):

TABLE I Summary of Science Frontiers Panels' Findings

Panel		Science Questions
Cosmology and Fundamental Physics	CFP 1	How Did the Universe Begin?
	CFP 2	Why Is the Universe Accelerating?
	CFP 3	What Is Dark Matter?
	CFP 4	What Are the Properties of Neutrinos?

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	CFP 4	What Are the Properties of N	*Neutrino Mass*

Cosmology: Next Decade?

Large-scale structure of the universe has a potential to give us valuable information on all of these items.

Cosmology and Fundamental Physics	CFP 1	How Did the Universe Begin	*Inflation*
	CFP 2	Why Is the Universe Acceler	*Dark Energy*
	CFP 3	What Is Dark Matter?	*Dark Matter*
	CFP 4	What Are the Properties of N	*Neutrino Mass*

What is HETDEX?

- Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) is a galaxy survey with unique properties.
  - The **first** blind spectroscopic large-scale structure survey
    - We do not pre-select objects; objects are emission-line selected; huge discovery potential
  - The **first** 10 Gpc^3-class survey at high z [$1.9<z<3.5$] with sufficient number density
    - The previous big surveys were all done at $z<1$

Who are we?

- About ~50 people at Univ. of Texas; McDonald Observatory; Penn State; Texas A&M; LMU; AIP; MPE; MPA; Gottingen; and Oxford
  - Principal Investigator: Gary J. Hill (Univ. of Texas)
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- Enormous contributions from young postdocs and students! Cosmological analyses led by:

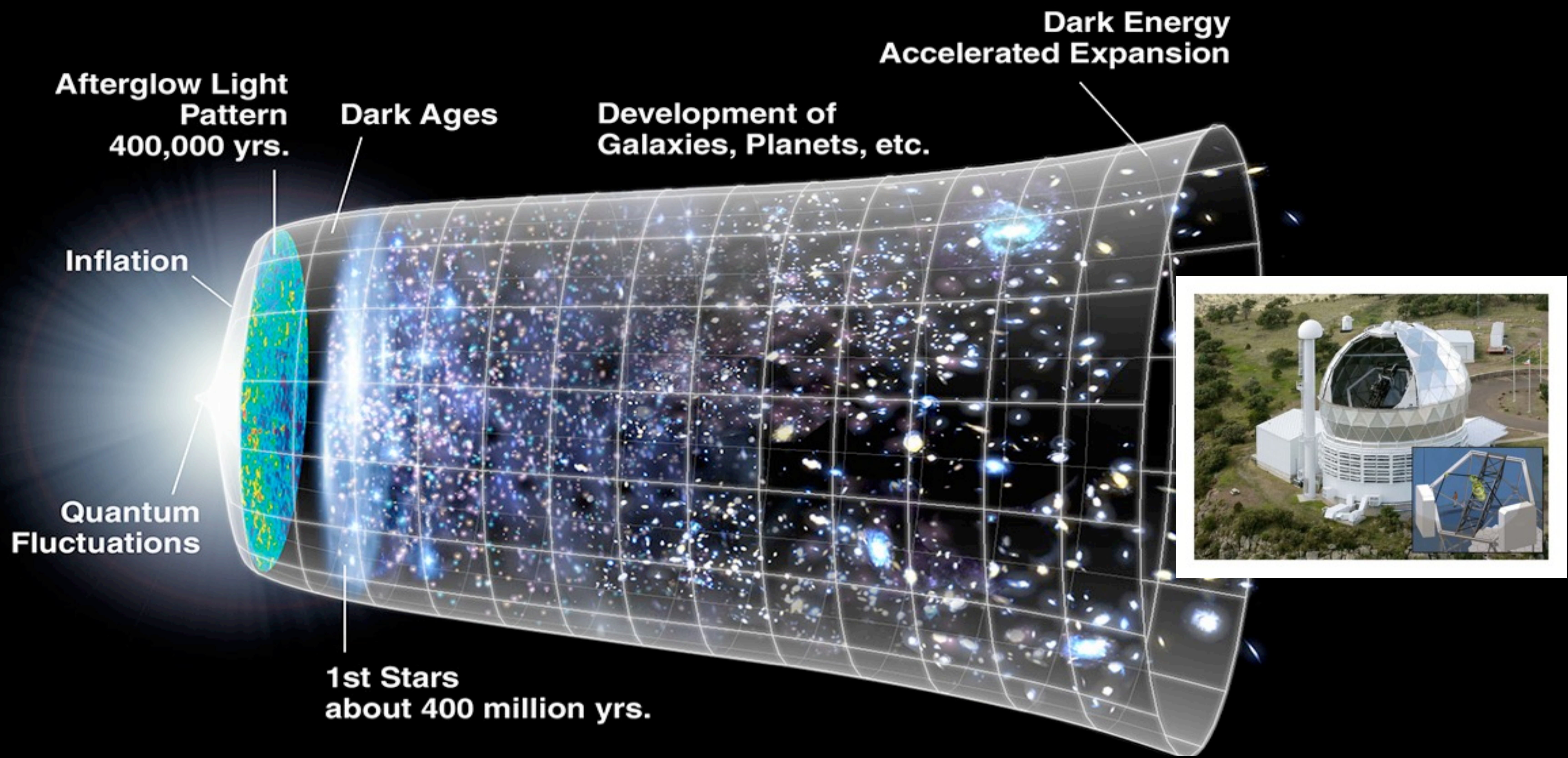
Donghui Jeong (JHU)

Chi-Ting Chiang (MPA)

Glad to be a (former) Texan

- In many ways, HETDEX is a Texas-style experiment:
  - Q. How big is a survey telescope? A. 10m
  - Q. Whose telescope is that? A. Ours
  - Q. How many spectra do you take per one exposure? A. More than 33K spectra – *at once*
  - Q. Are you not wasting lots of fibers? A. Yes we are, but so what? **Besides, this is the only way you can find anything truly new!**

Hobby-Eberly Telescope Dark Energy Experiment (HETDEX)



Use 10-m HET to map the universe using 0.8M Lyman-alpha emitting galaxies in $z=1.9–3.5$

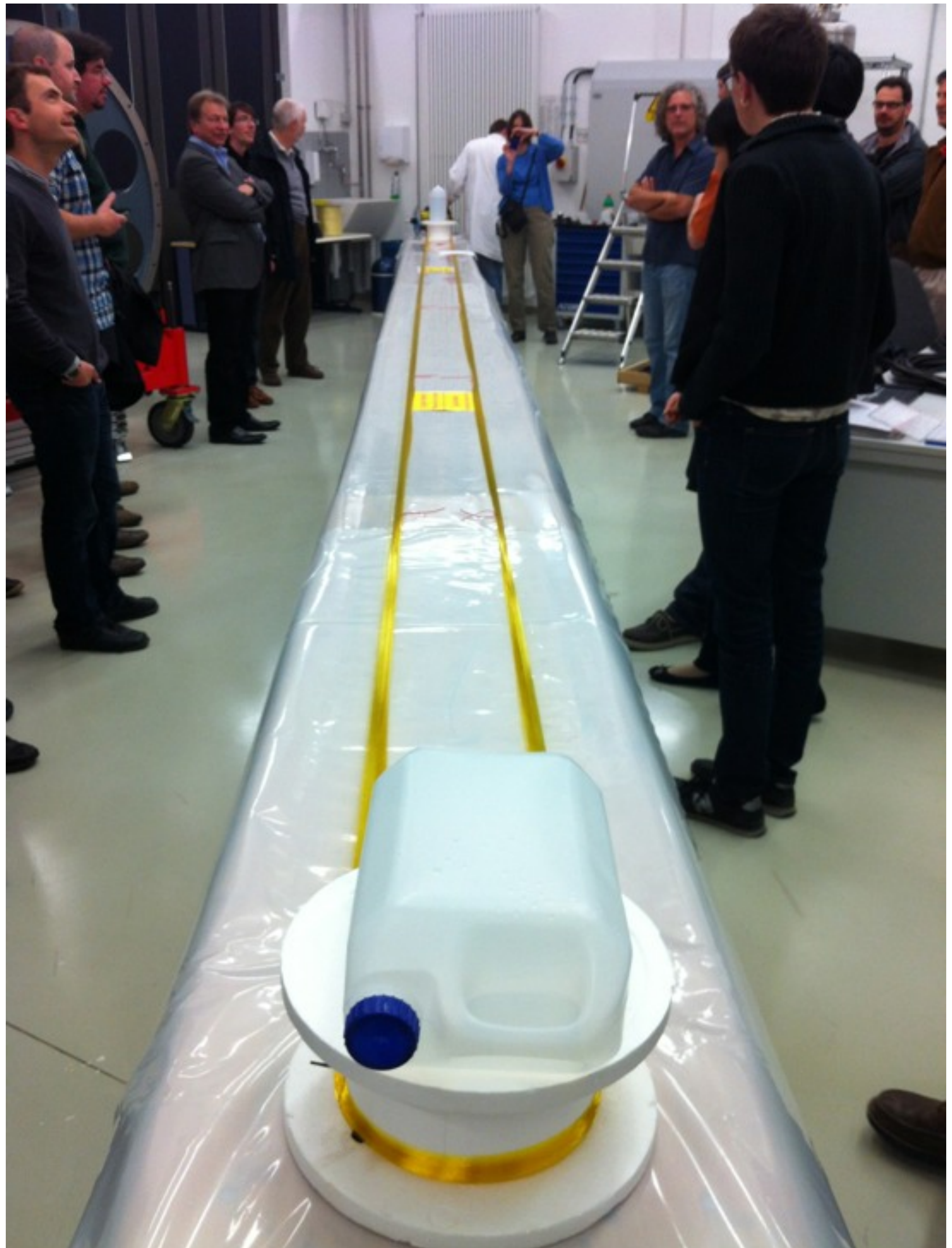
Team

*VIRUS = Visible Integral-field Replicable Unit Spectrograph

Many, MANY, spectra

- HETDEX will use the newly-built integral field unit spectrographs called "VIRUS*" (Hill et al.)
  - We will build and put 75 units on the focal plane
- Each unit has 448 fibers
- Each unit feeds two spectrographs
- Therefore, **VIRUS will have 33K fibers in the sky at once** (Texas size!)

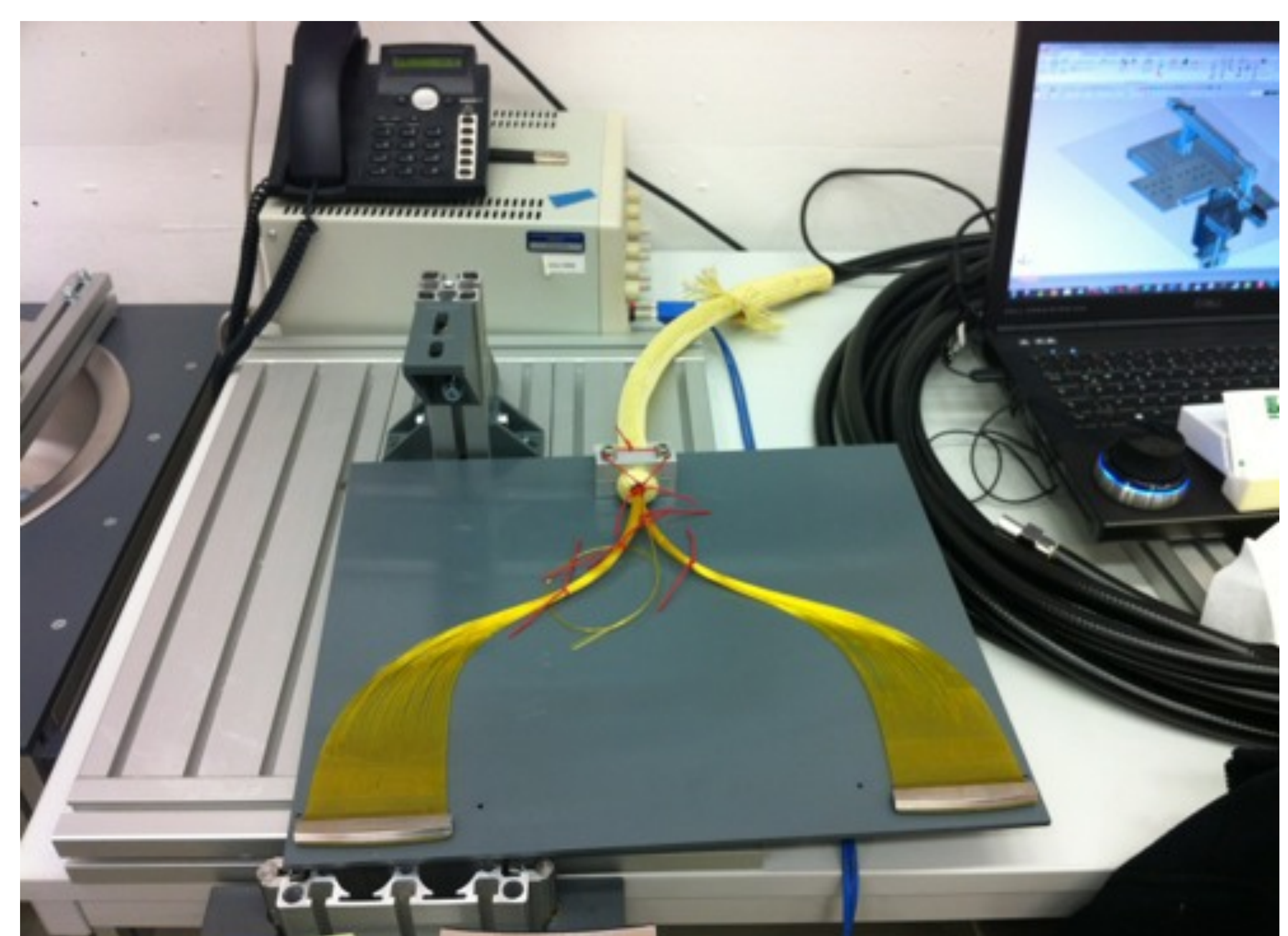
IFUs fabricated at AIP Potsdam



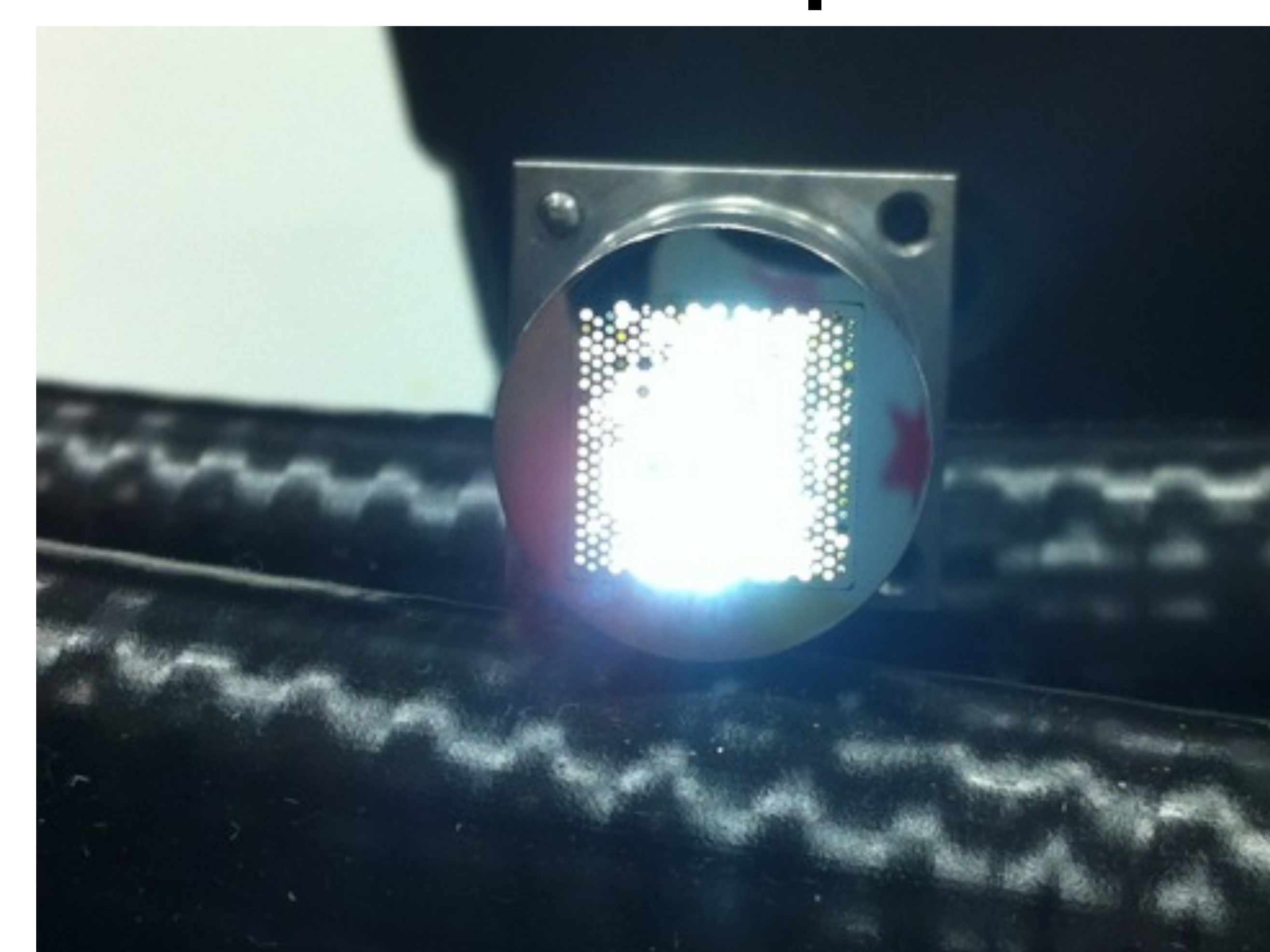
Looong fibers!
(Each fiber sees 1.5”)

Put into cables...

448 fibers per IFU

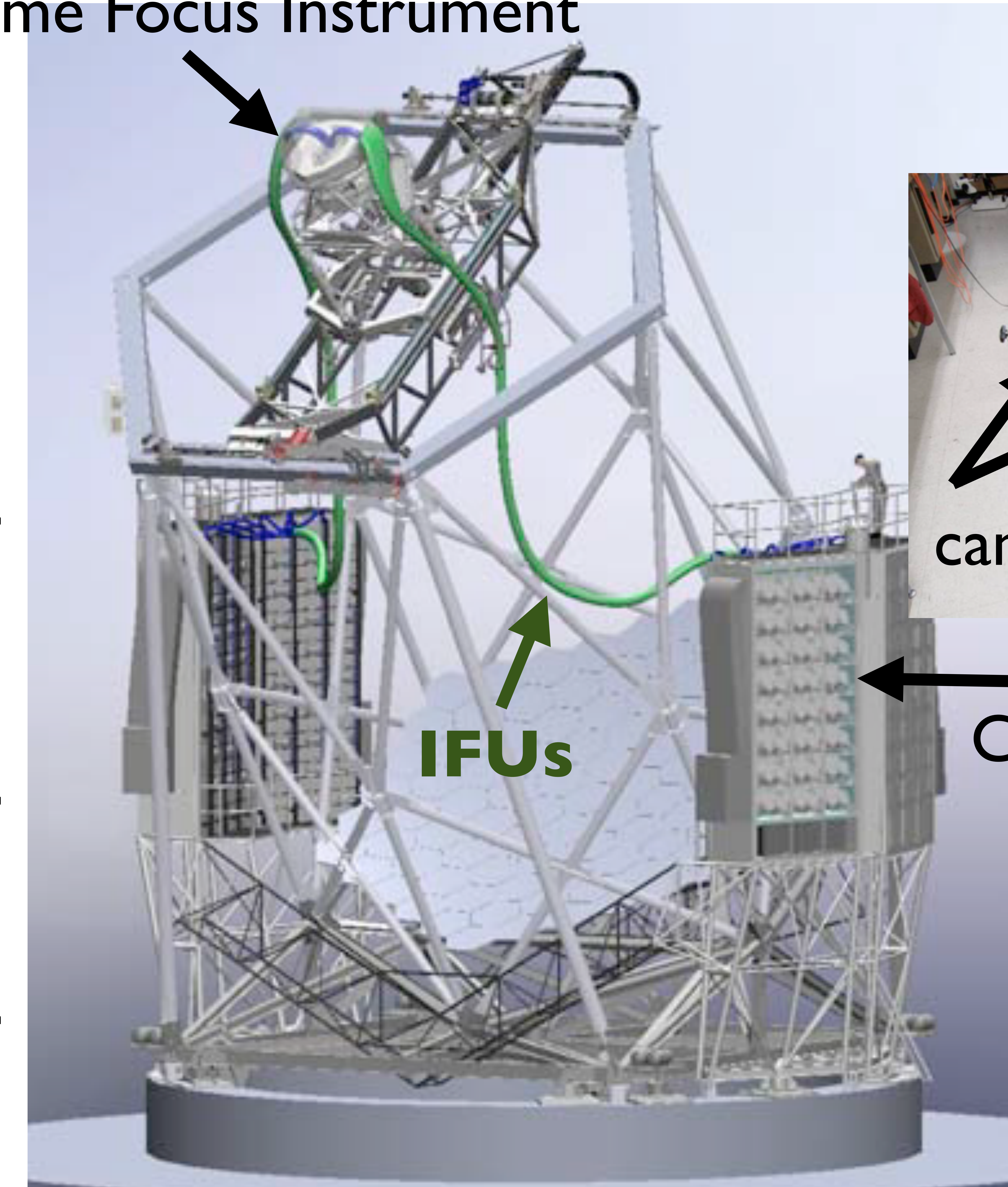


One IFU feeds two spec.

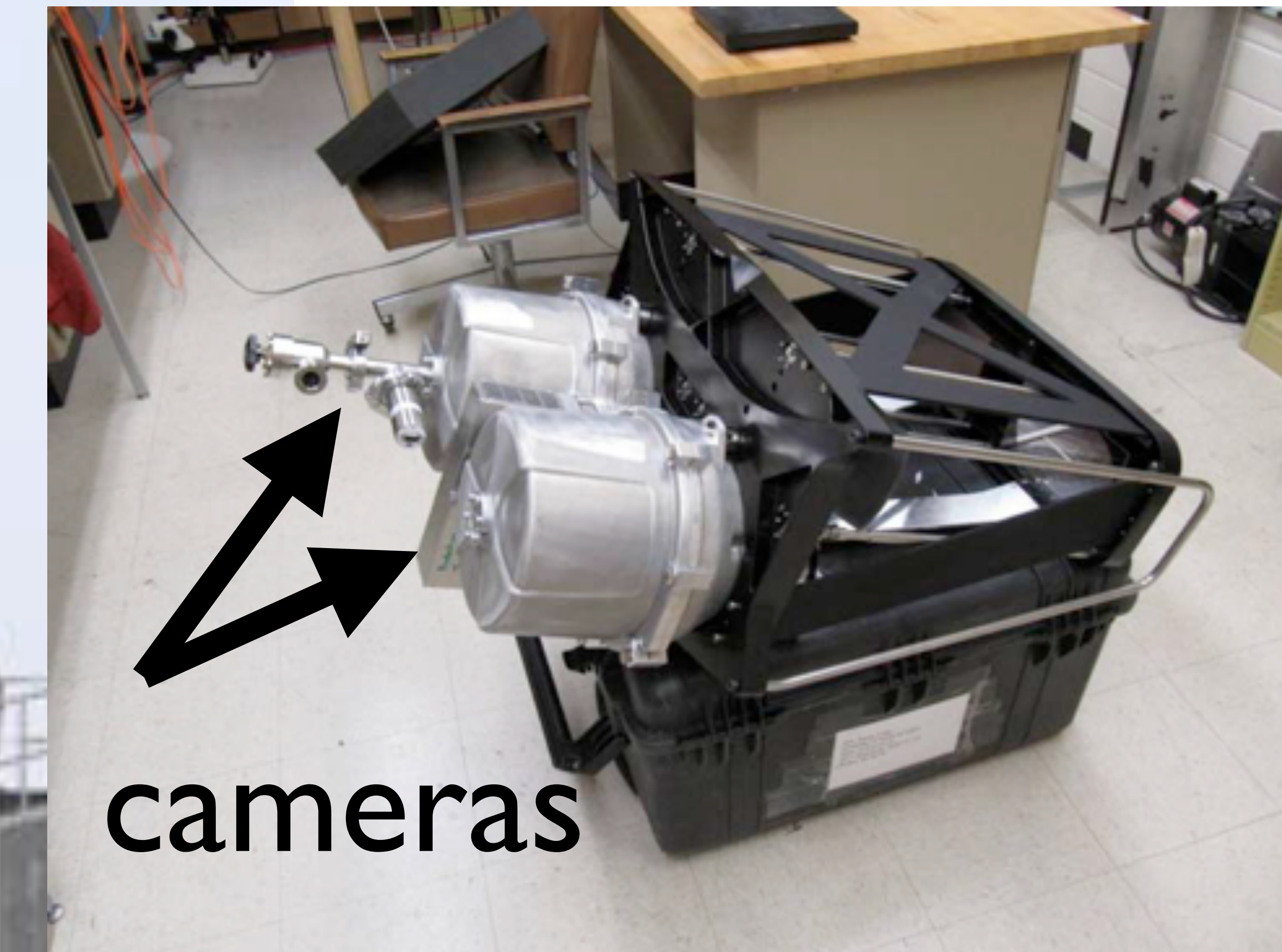


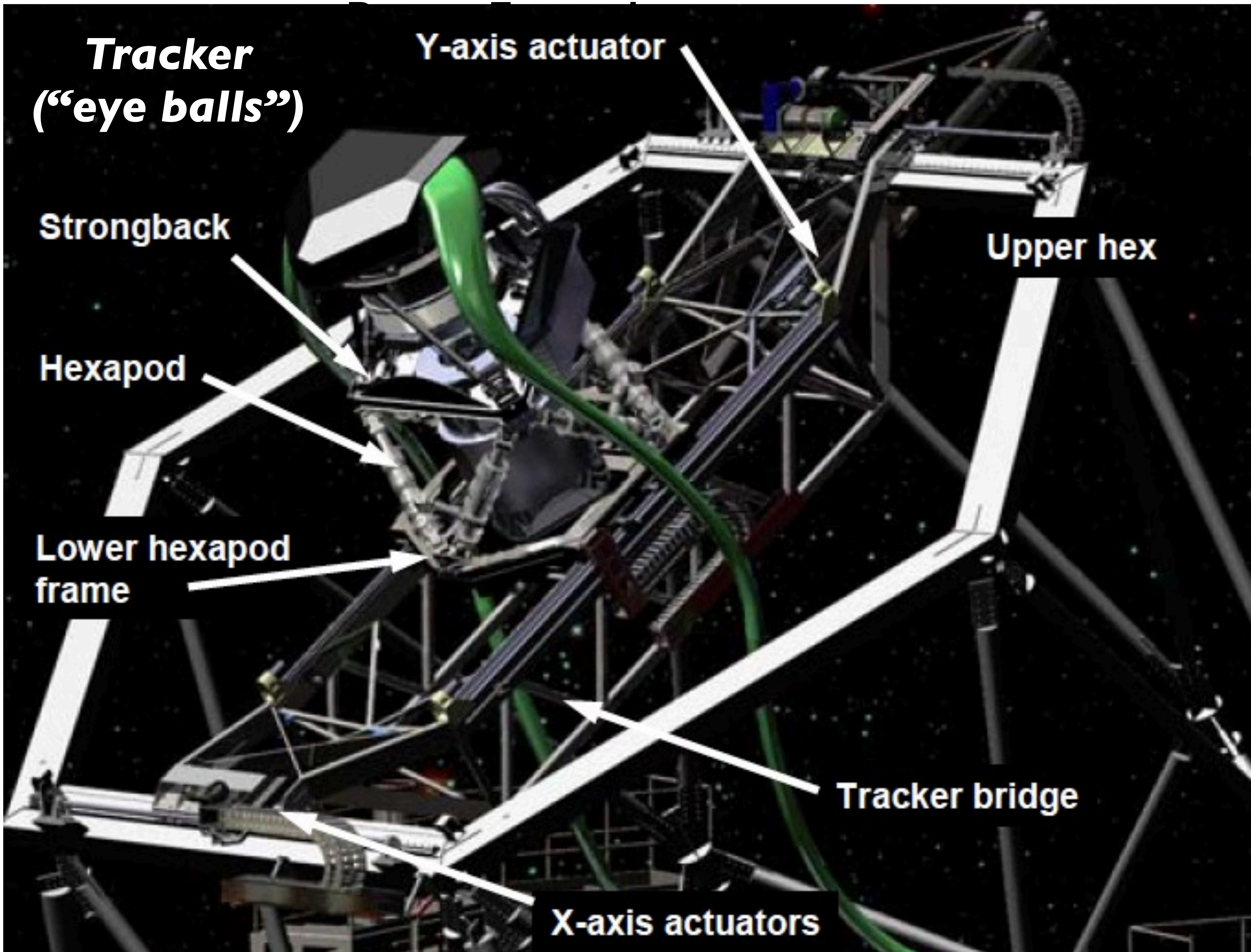
A test IFU being lit

Hobby-Eberly Telescope with VIRUS



One VIRUS Detector Unit

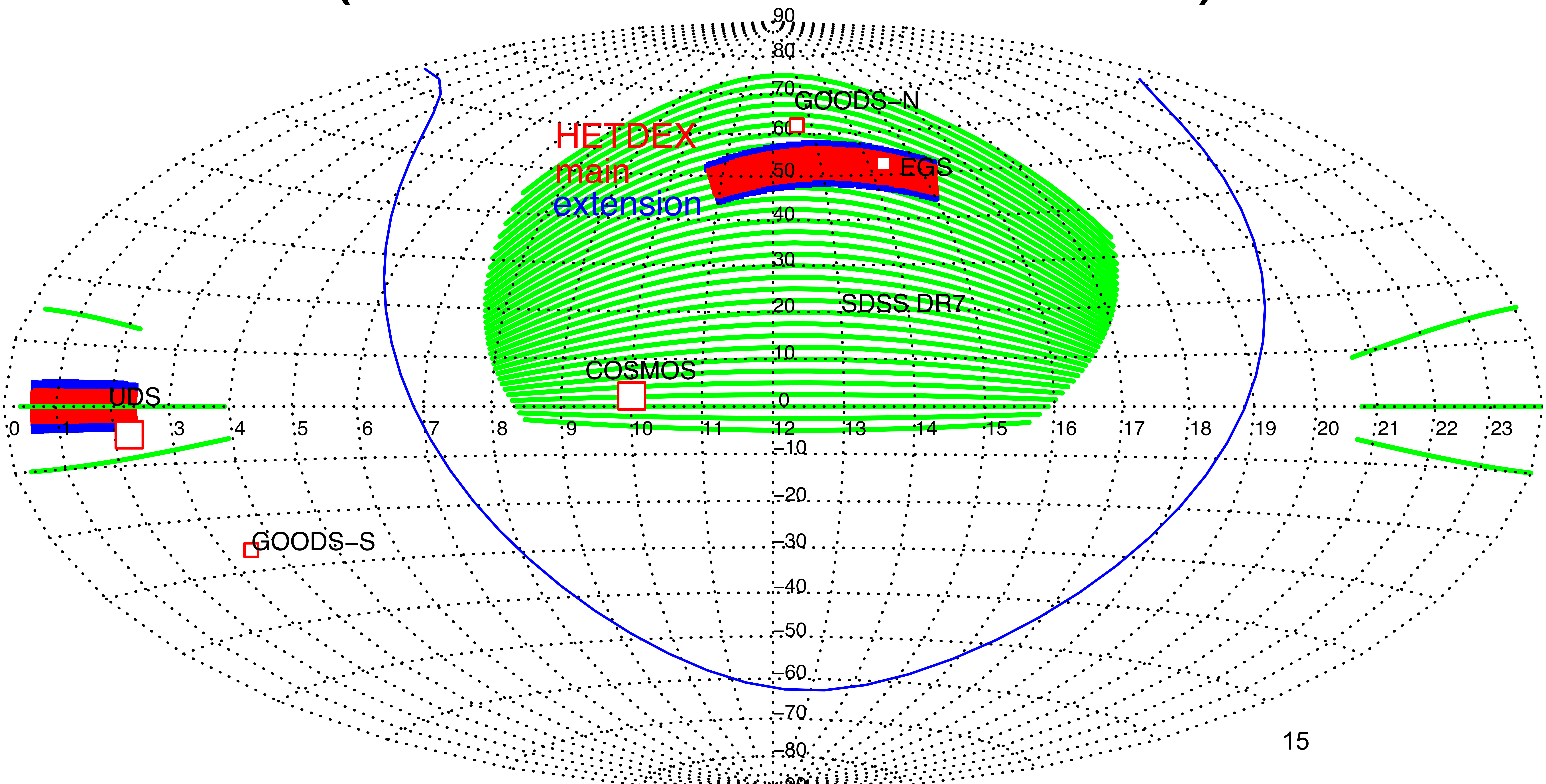




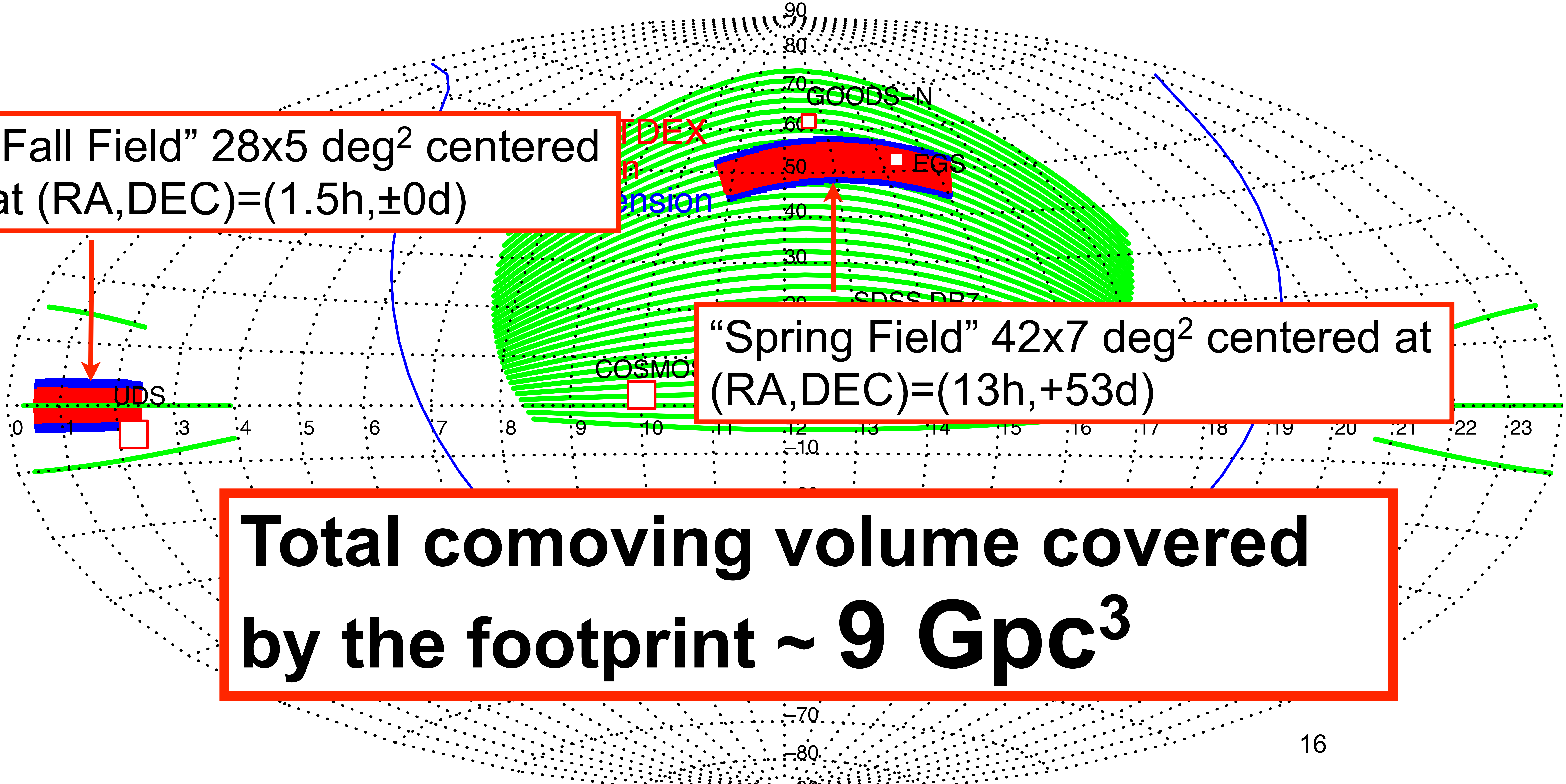
Detectors /
ogenic system

Detectors /
ogenic system

HETDEX Foot-print
(in RA-DEC coordinates)



HETDEX Foot-print
(in RA-DEC coordinates)

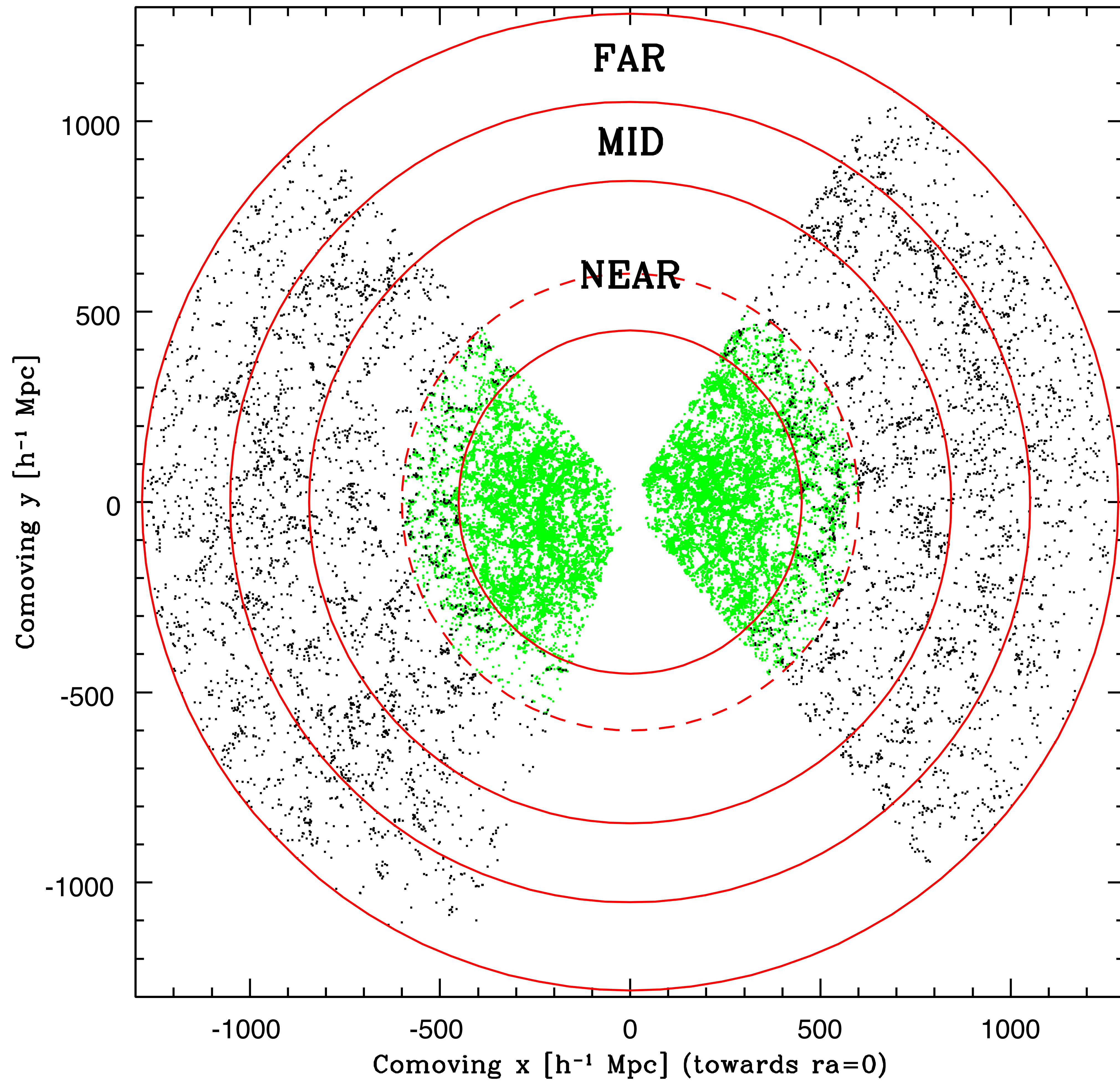


"Fall Field" 28x5 deg^2 centered at (RA,DEC)=(1.5h,±0d)

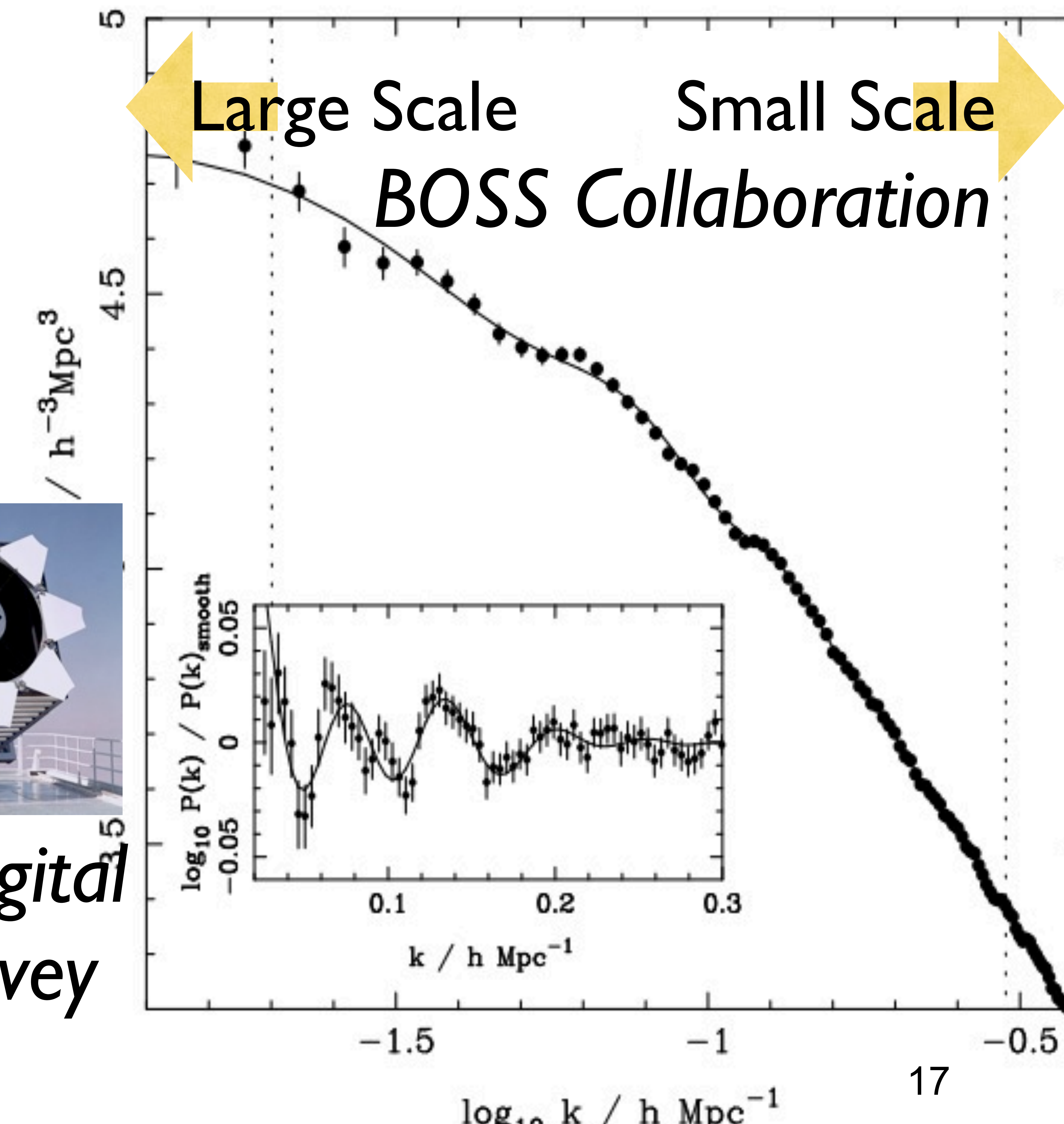
"Spring Field" 42x7 deg^2 centered at (RA,DEC)=(13h,+53d)

Total comoving volume covered by the footprint ~ 9 Gpc^3

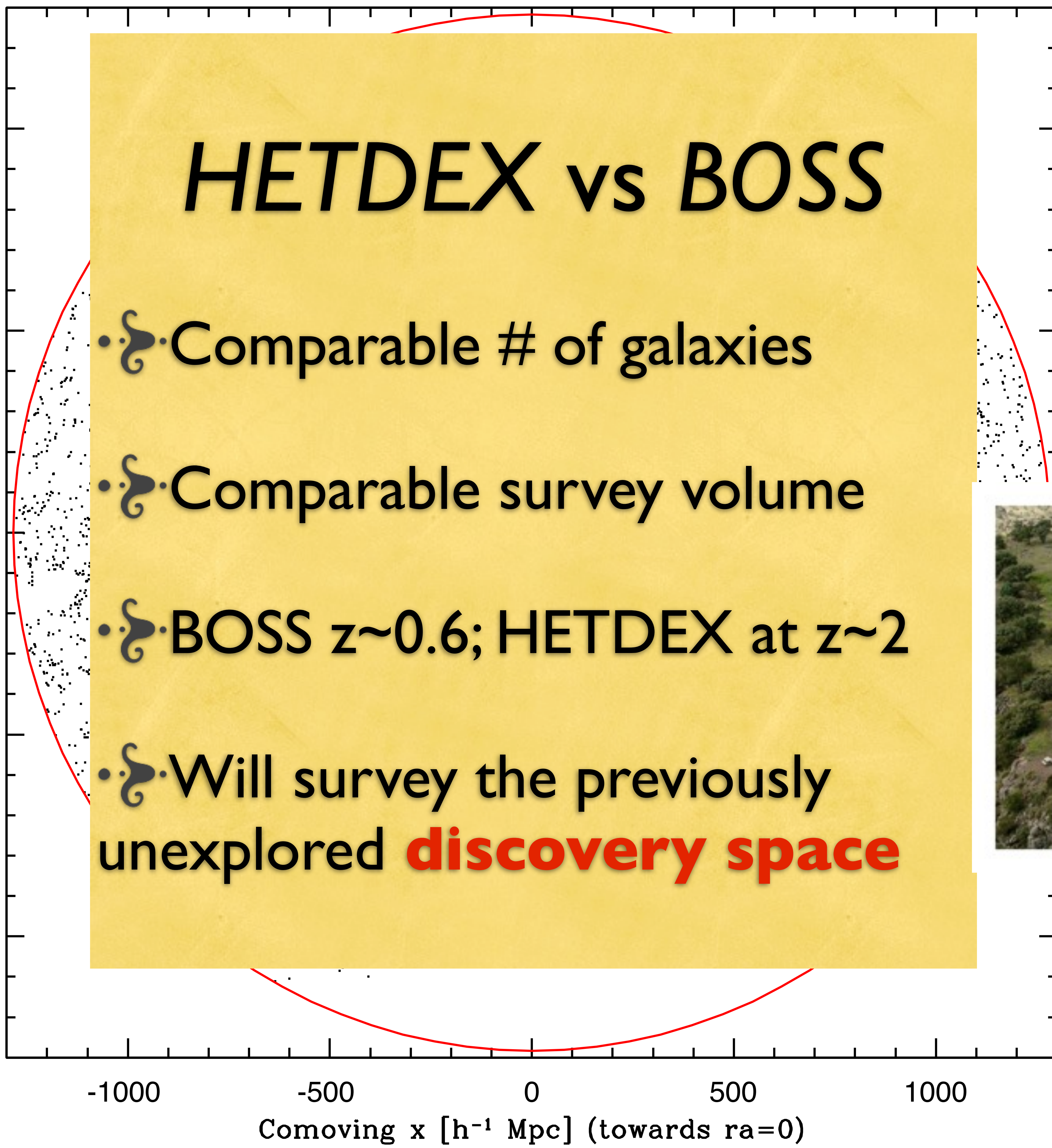
HETDEX: A High-z Galaxy Survey



Sloan Digital Sky Survey



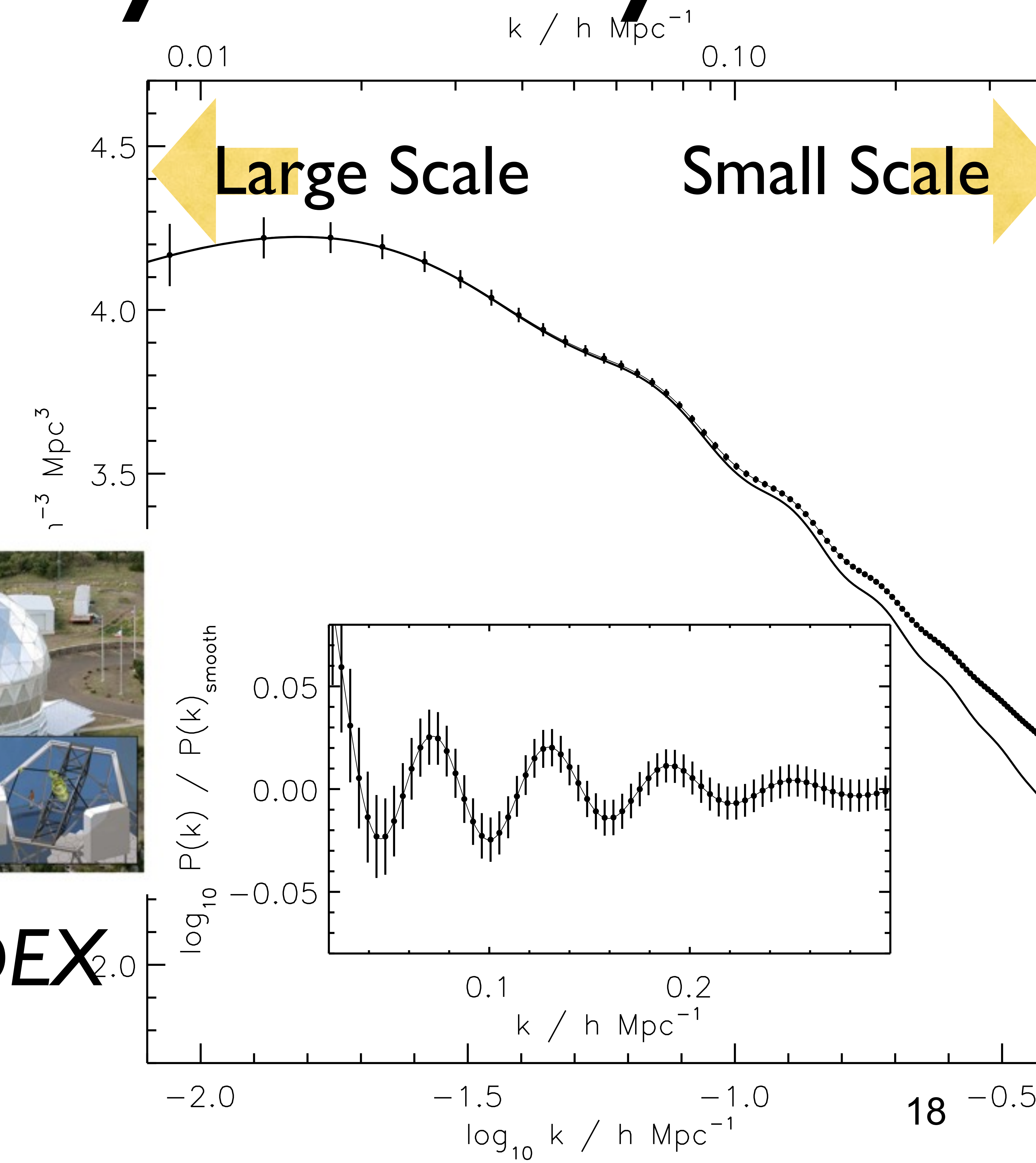
HETDEX:
A High-z Galaxy Survey



HETDEX vs BOSS

- Comparable # of galaxies
- Comparable survey volume
- BOSS z~0.6; HETDEX at z~2
- Will survey the previously unexplored **discovery space**

HETDEX



What do we detect?

- λ=350–550nm with the resolving power of R~700 down to a flux sensitivity of a few x 10^{-17} erg/cm^2/s gives us:
  - ~0.8M Lyman-alpha emitting galaxies at $1.9<z<3.5$
    - 1/10 of them would be AGNs
  - ~2M [OII] emitting galaxies
  - ...and lots of other stuff (like white dwarfs)

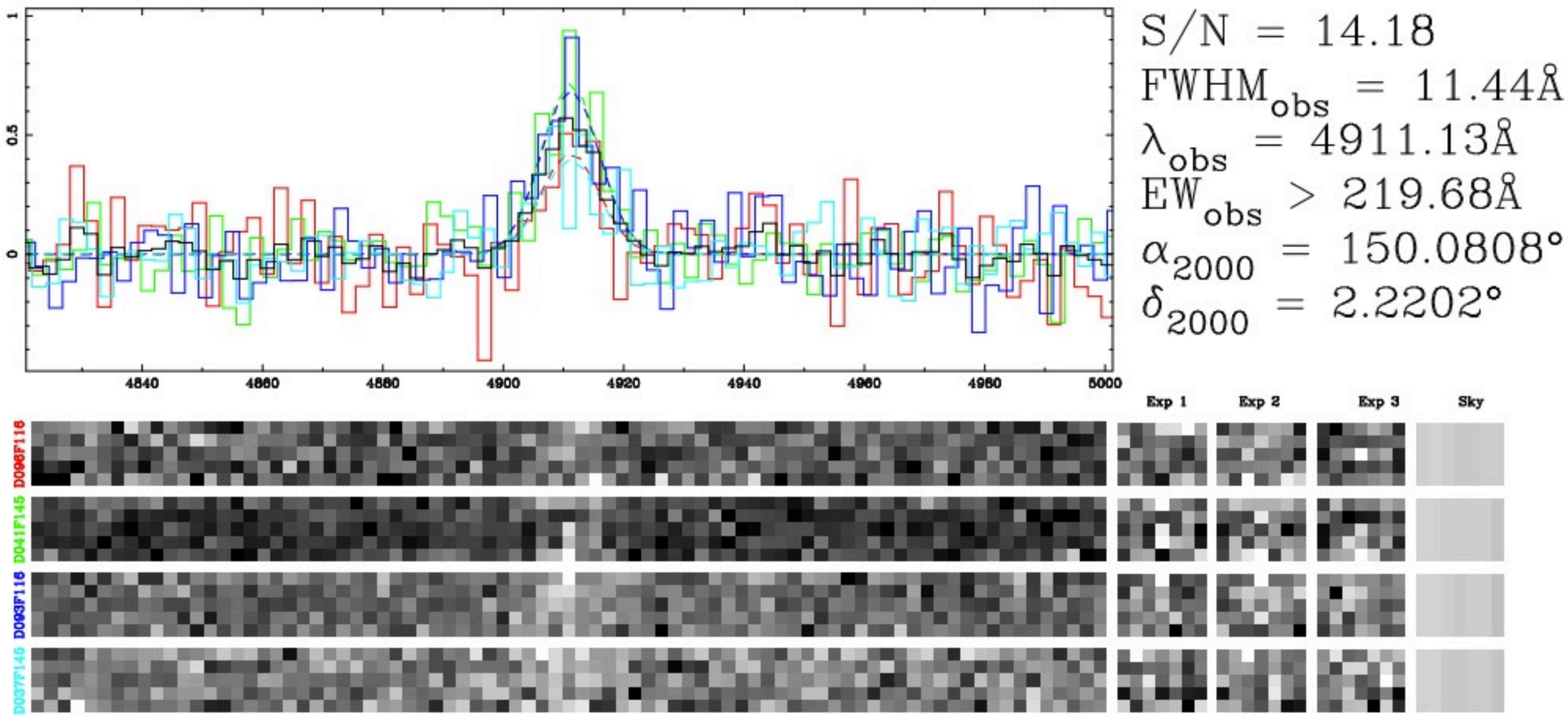
One way to impress you

- So far, about ~1000 Lyman-alpha emitting galaxies have been discovered over the last decade
  - These are interesting objects – relatively low-mass, low-dust, star-forming galaxies
- We will detect that many Lyman-alpha emitting galaxies within the **<u>first 2 hours</u>** of the HETDEX survey

Yes, we do detect LAEs!

HETDEX Pilot Survey

Adams et al. 2011; Blanc et al. 2011



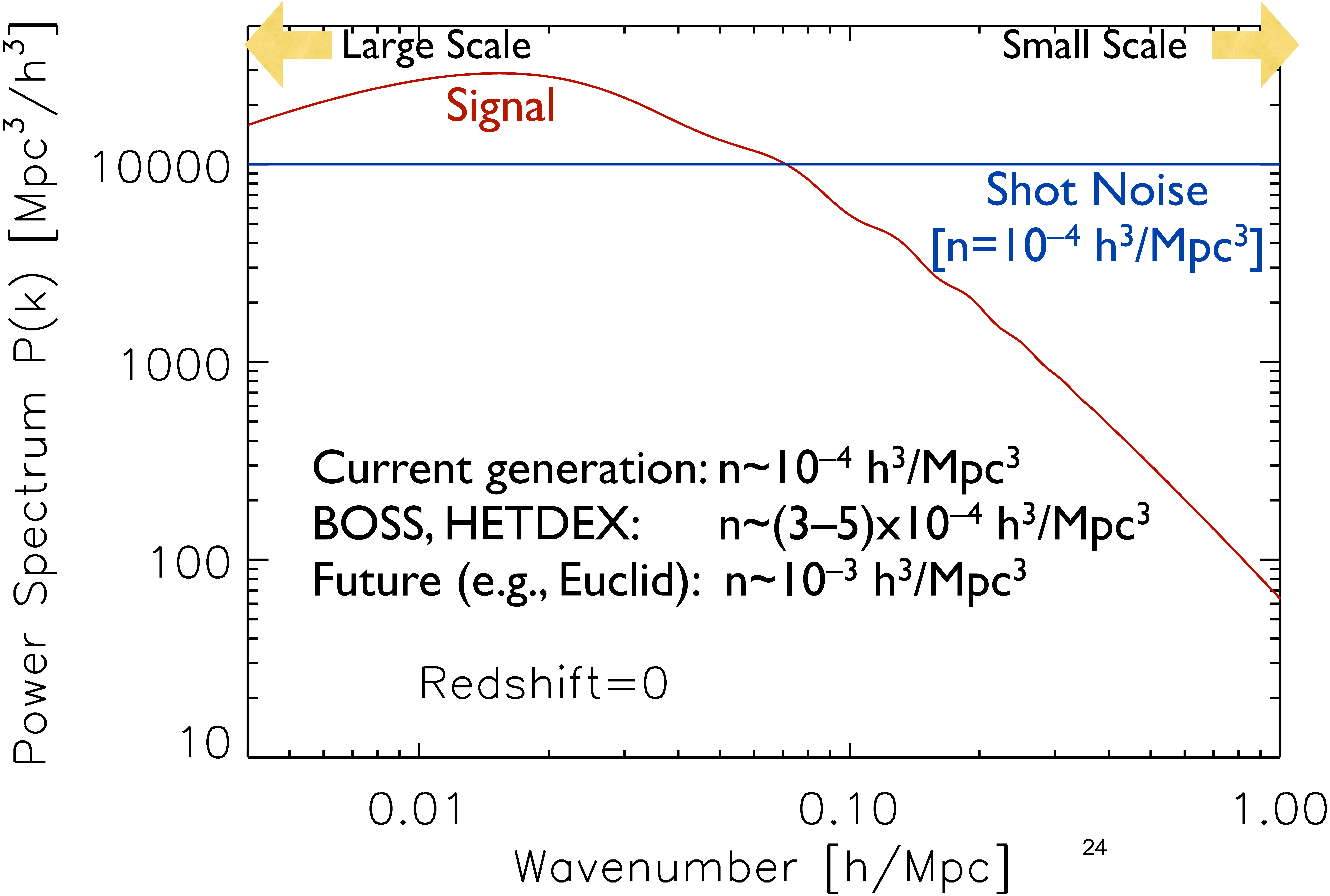
- We have been using ONE spectrograph on the 2.7-m Harlan Smith telescope over 111 nights, detecting **105 LAEs in 1.9<z<3.8 over 169 arcmin^2**.

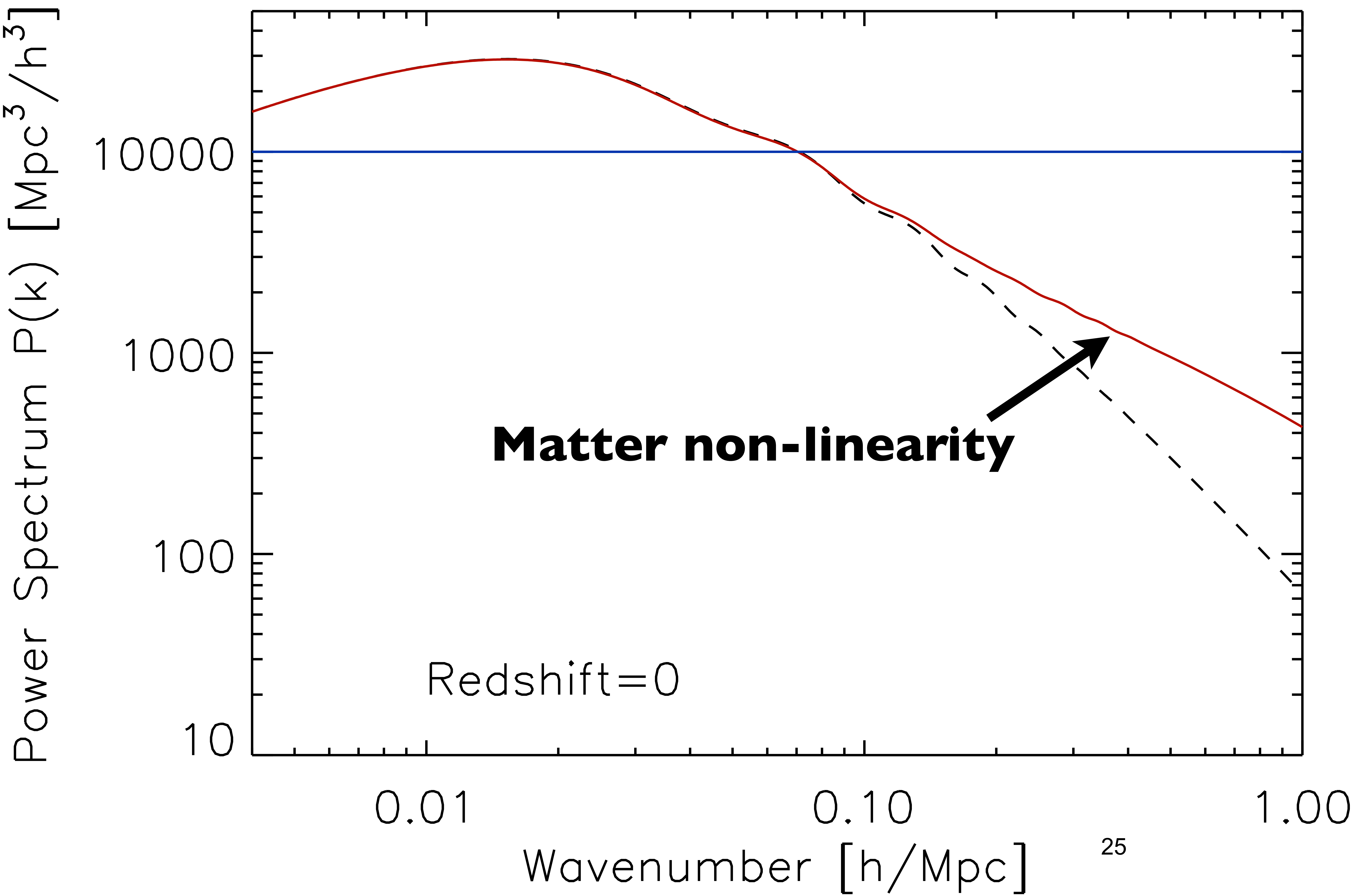
We also detect others

- We have detected 397 emission-line galaxies over 169 arcmin^2 from the HETDEX Pilot Survey on 2.7-m.
- Among these, 105 are LAEs; and the majority of the other objects are [OII] emitters at z<0.56.
- We discriminate between them **using the Equivalent-Width (EW) cut at the rest-frame 20 angstroms** (assuming LAEs).
  - LAEs have larger EWs. With imaging data going down to ~25 mag in g or r, this cut eliminates ~99% of [OII] interlopers. *We can do science with [OII] too!*

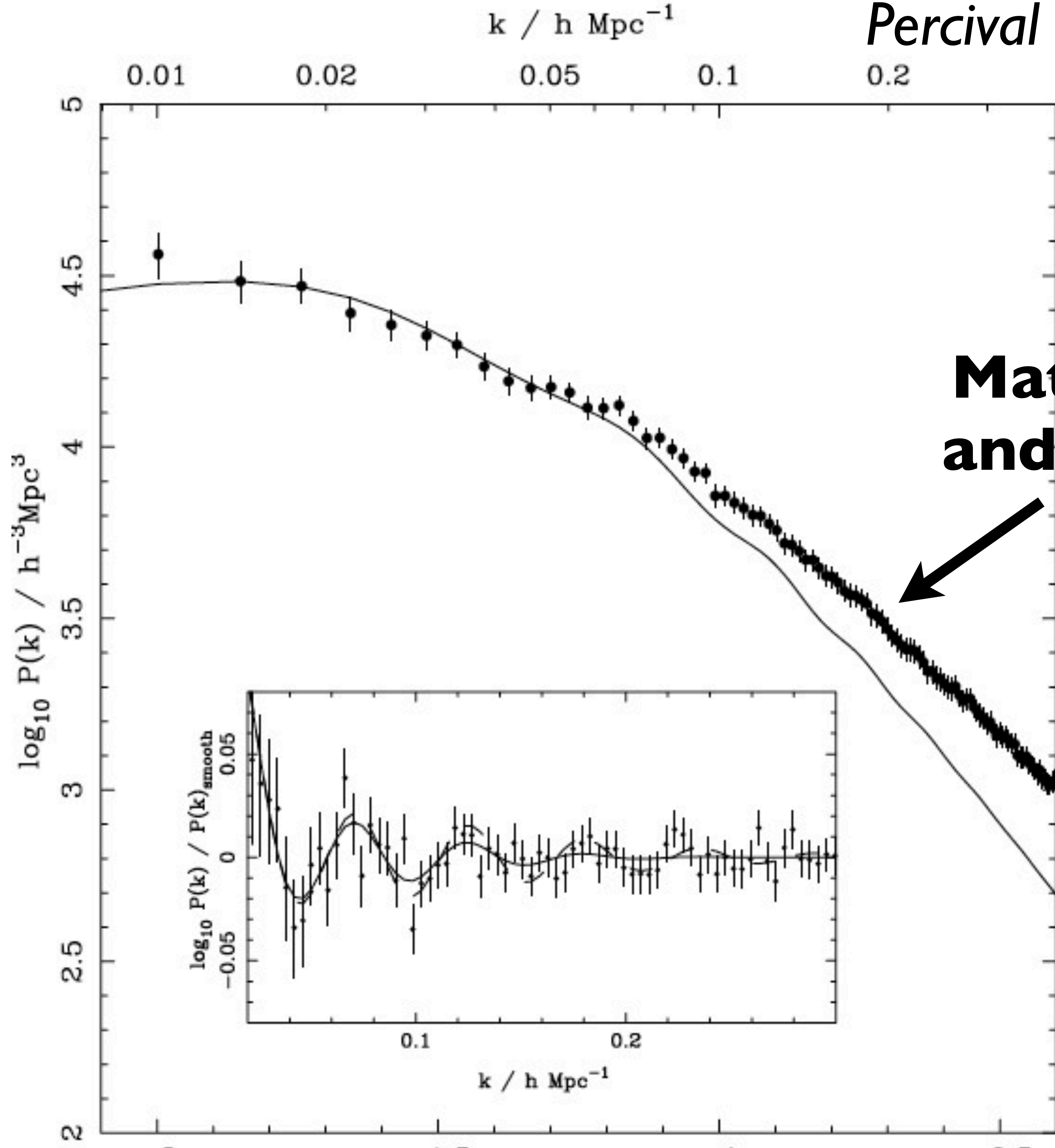
Why higher redshifts?

- Non-linearities preventing us from interpreting the small-scale galaxy clustering. There are 3 non-linearities:
  - Dark matter non-linearity [gravity]
  - Redshift space distortion non-linearity [gravity/astro]
  - Astrophysical non-linearities [astro]
- At least the first two non-linearities are suppressed at higher redshifts, making theorist’s life easier :)

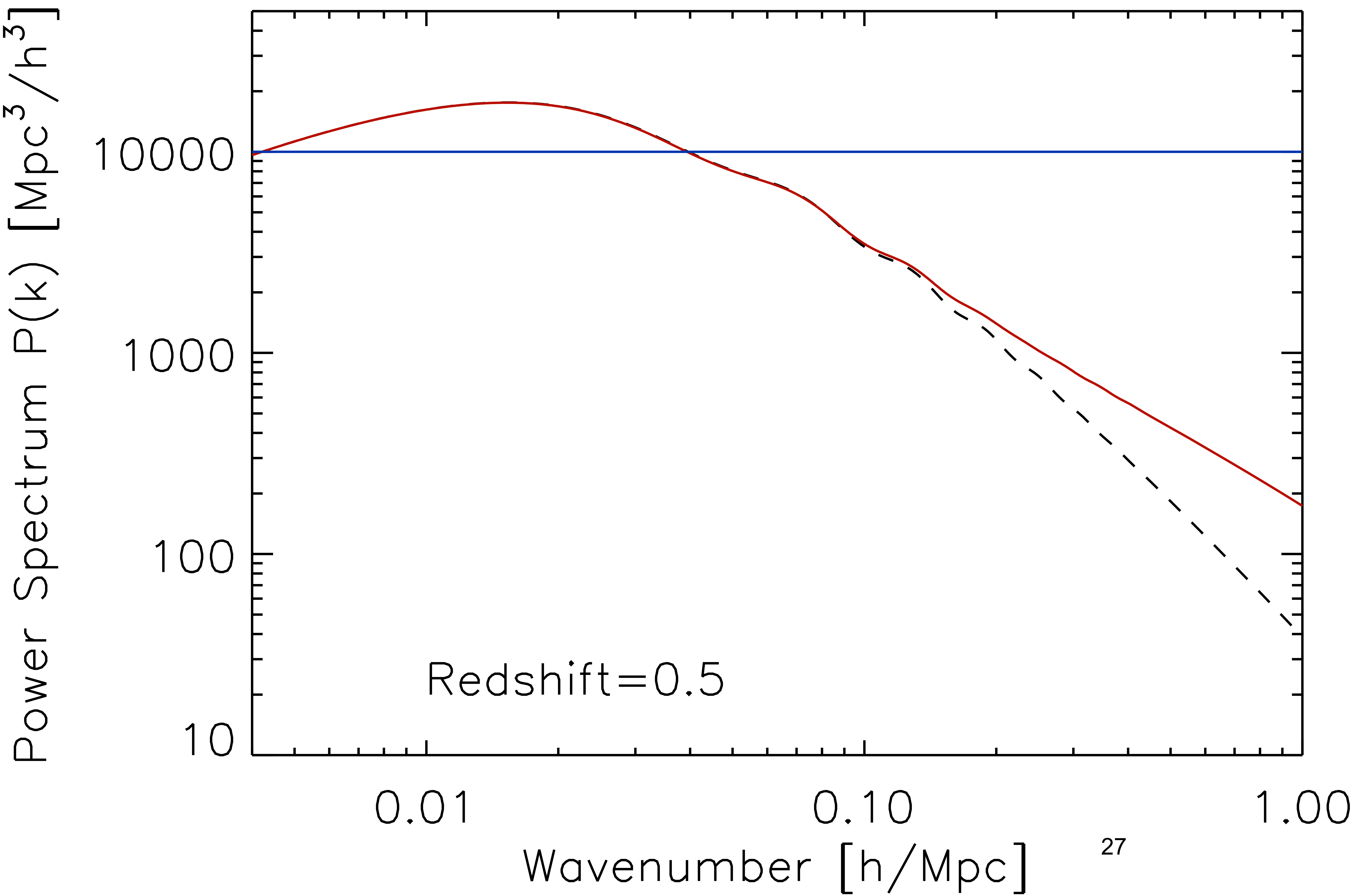

Large Scale
Small Scale
Signal
Shot Noise
[n=10–4 h3/Mpc3]
Current generation: n~10–4 h3/Mpc3
BOSS, HETDEX: n~(3–5)x10–4 h3/Mpc3
Future (e.g., Euclid): n~10–3 h3/Mpc3
Redshift=0
Power Spectrum P(k) [Mpc3/h3]
10000
1000
100
10
0.01
0.10
1.00
Wavenumber [h/Mpc]


Power Spectrum P(k) [Mpc^3/h^3]
10000
1000
100
10
Matter non-linearity
Redshift=0
0.01
0.10
1.00
Wavenumber [h/Mpc]

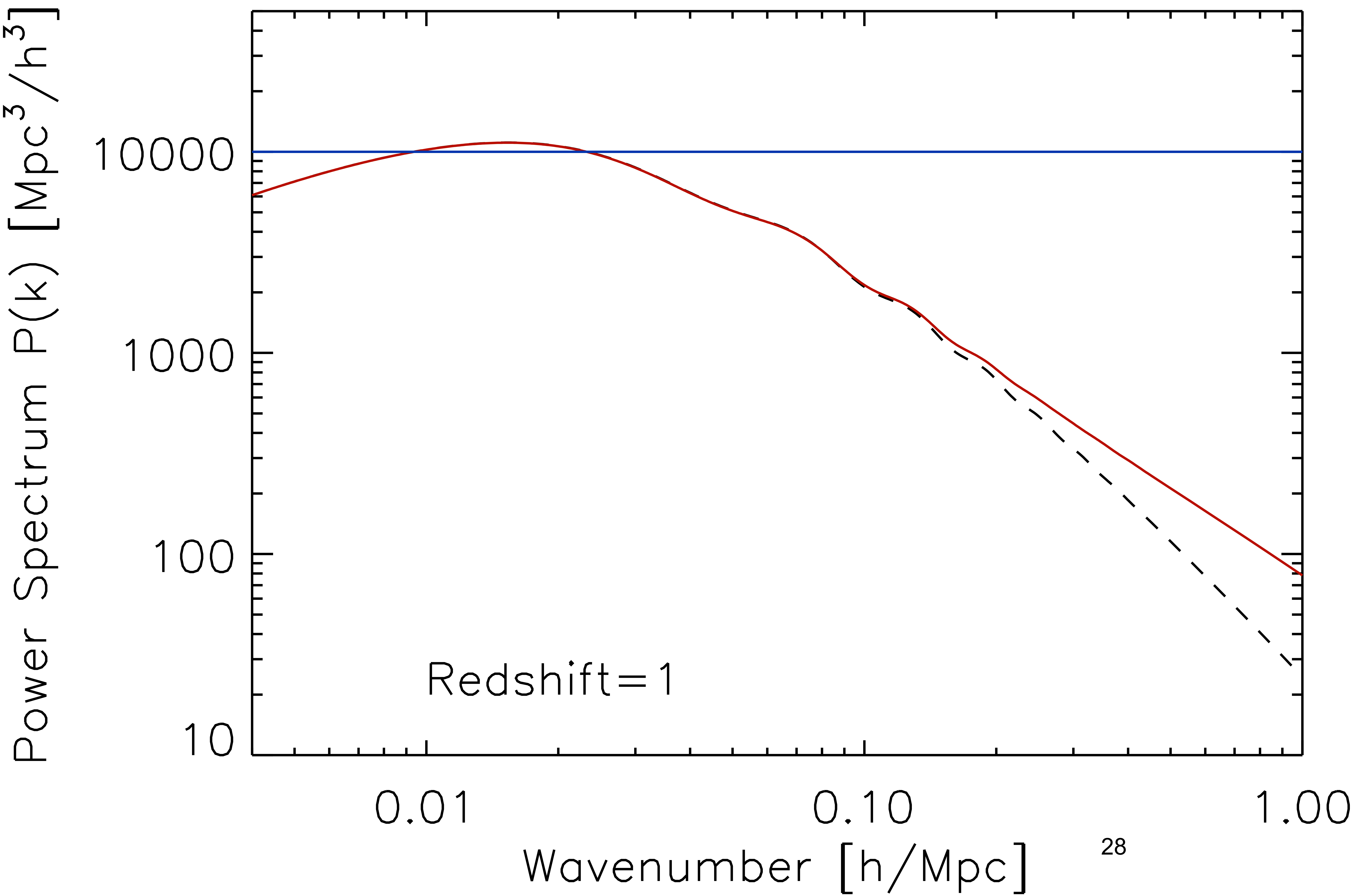
Percival et al. (2007) SDSS DR5

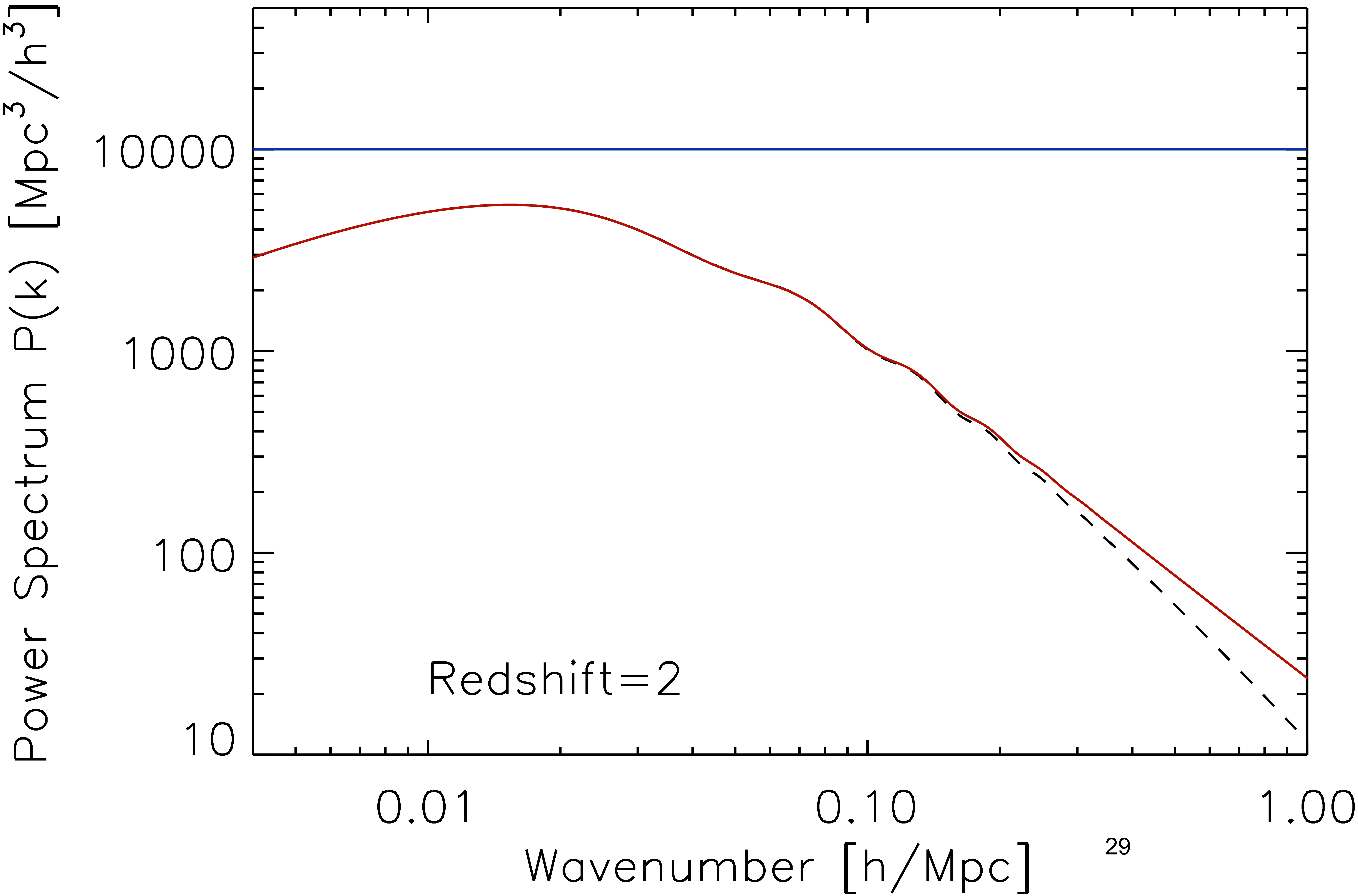


Matter non-linearity and galaxy formation

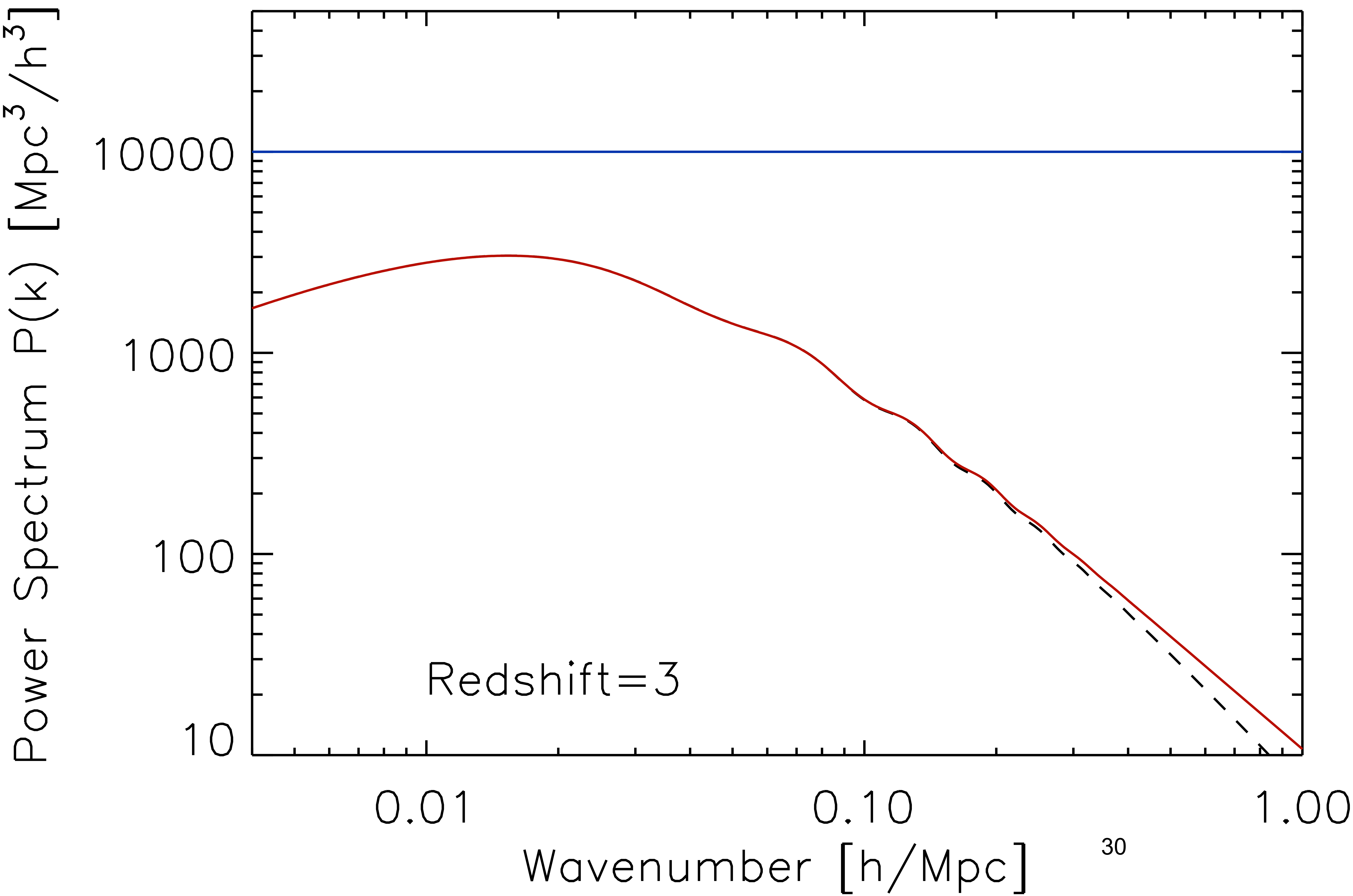


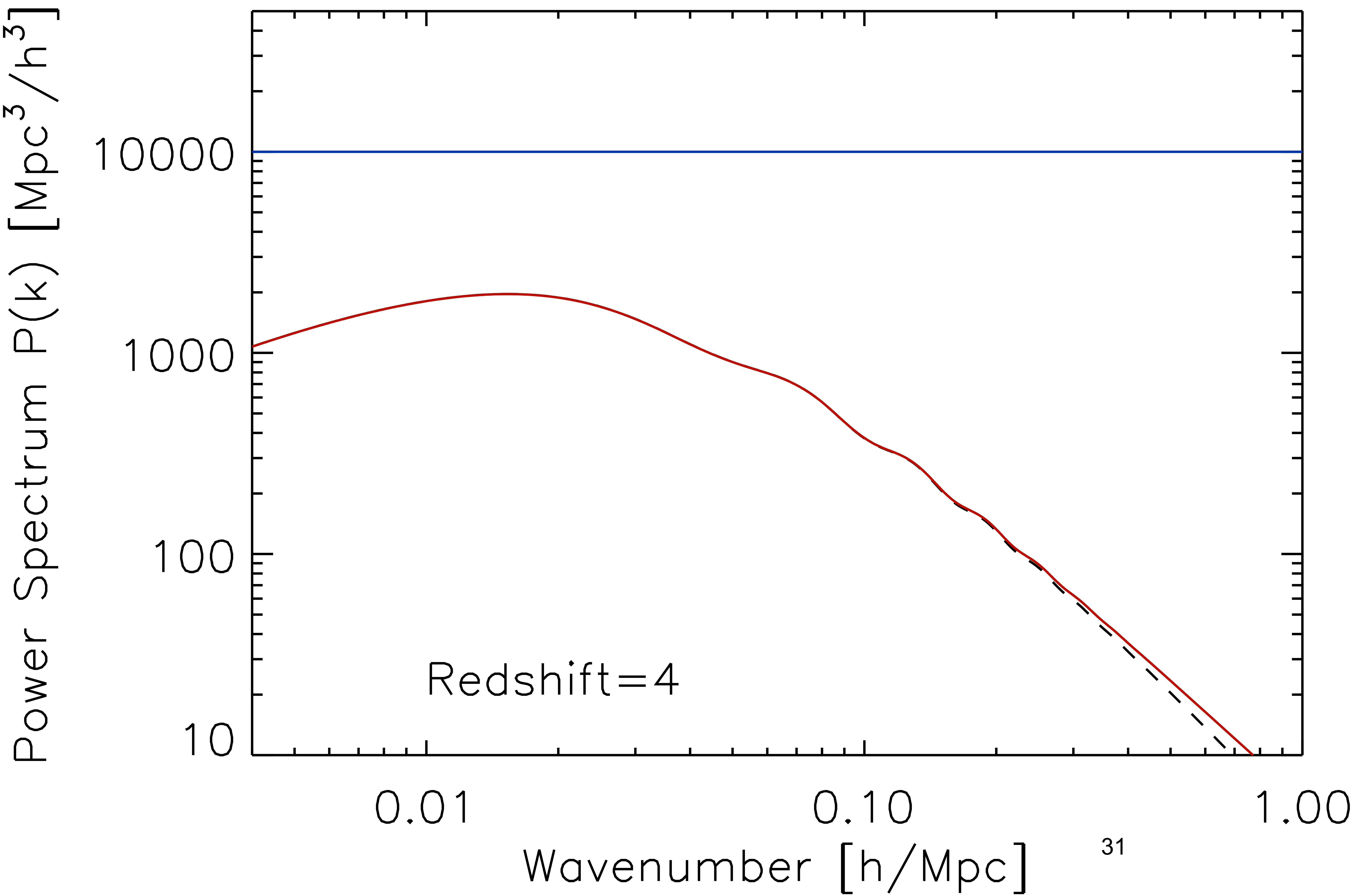
Power Spectrum P(k) [Mpc^3/h^3]
10000
1000
100
10
Redshift=0.5
0.01
0.10
1.00
Wavenumber [h/Mpc]


Power Spectrum P(k) [Mpc^3/h^3]
10000
1000
100
10
Redshift=1
0.01
0.10
1.00
Wavenumber [h/Mpc]



Power Spectrum P(k) [Mpc^3/h^3]
10000
1000
100
10
Redshift=2
0.01
0.10
1.00
Wavenumber [h/Mpc]

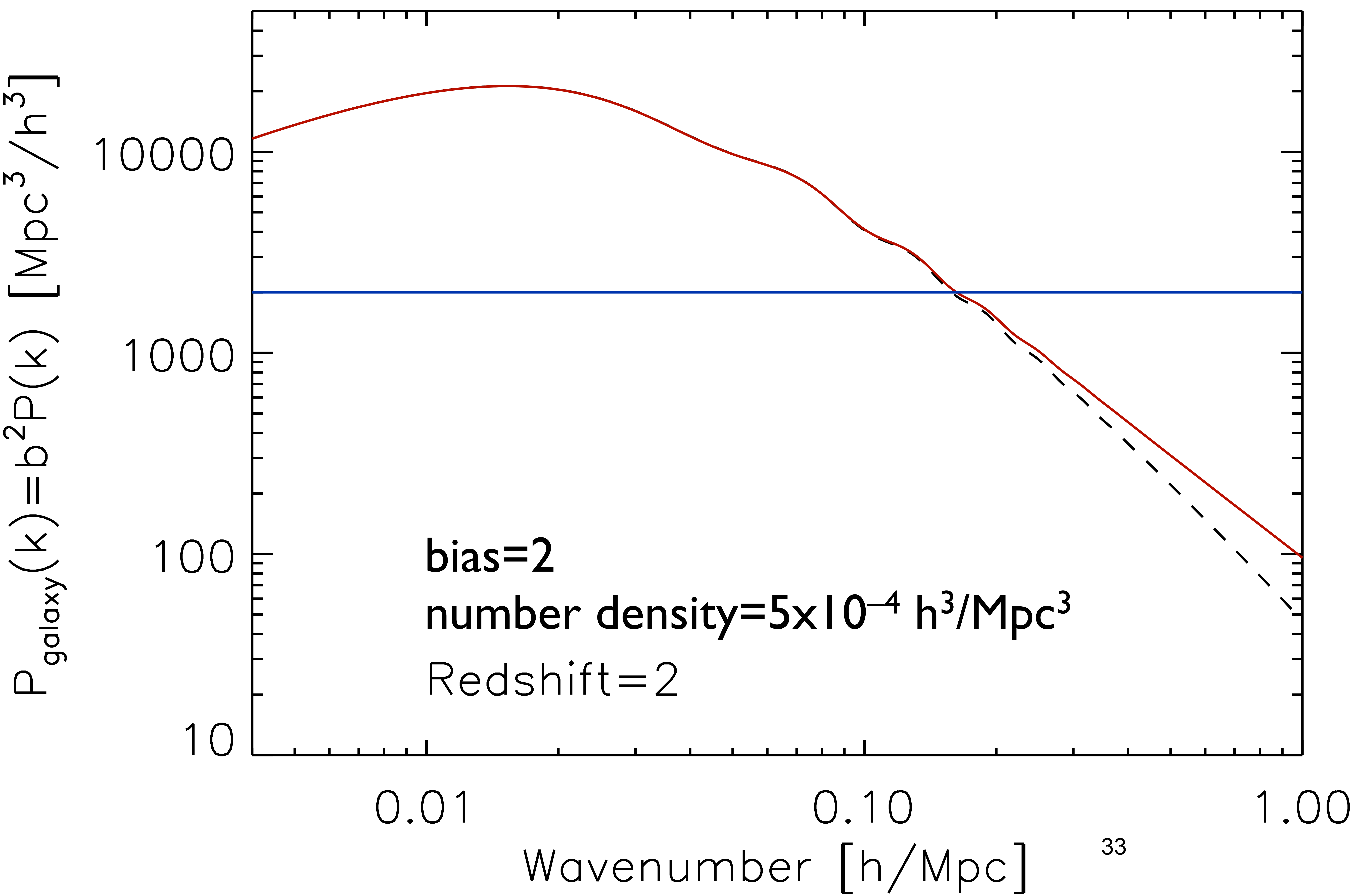

Power Spectrum P(k) [Mpc^3/h^3]
10000
1000
100
10
Redshift=3
0.01
0.10
1.00
Wavenumber [h/Mpc]



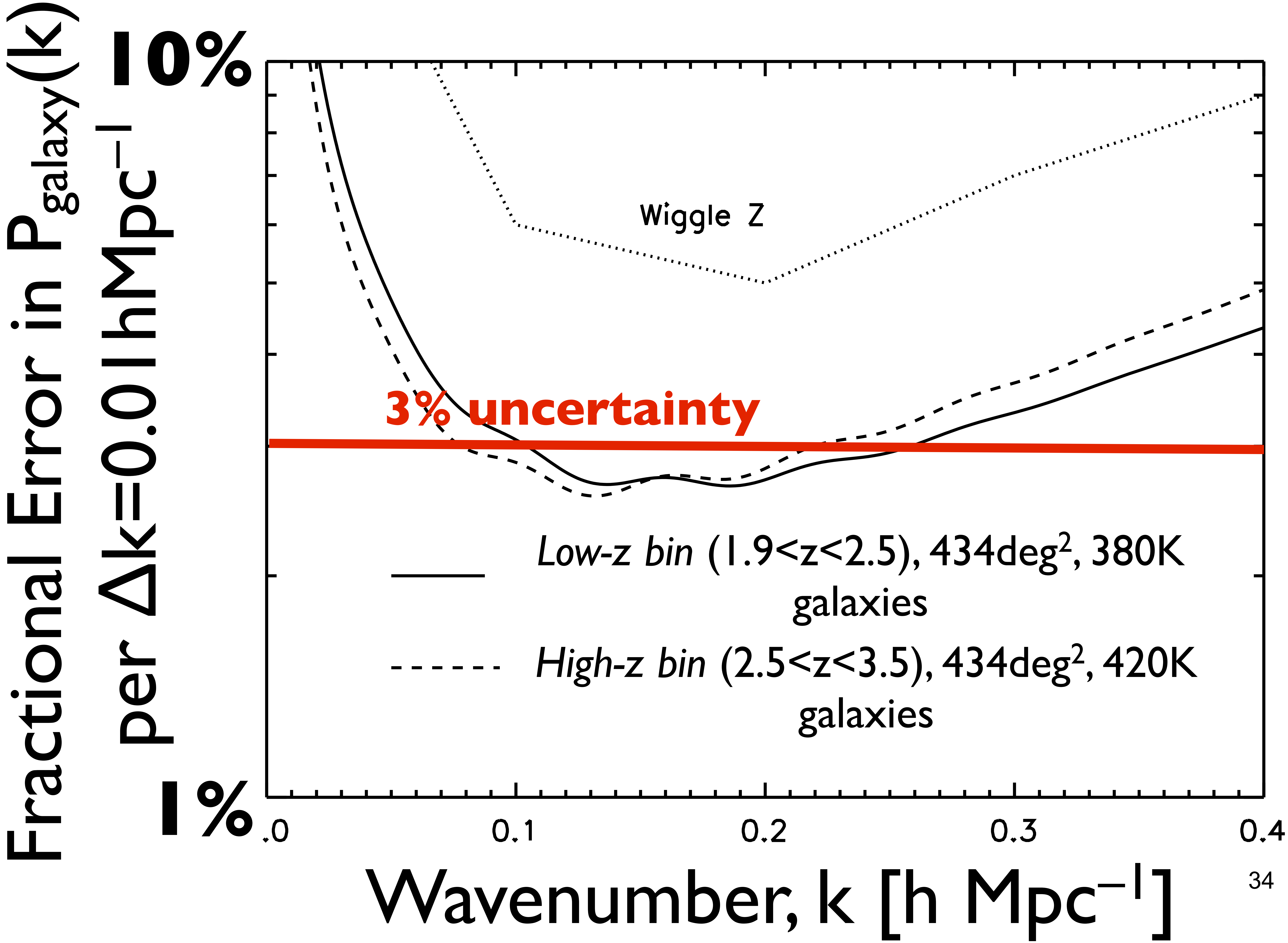
Power Spectrum P(k) [Mpc^3/h^3]
10000
1000
100
10
Redshift=4
0.01
0.10
1.00
Wavenumber [h/Mpc]

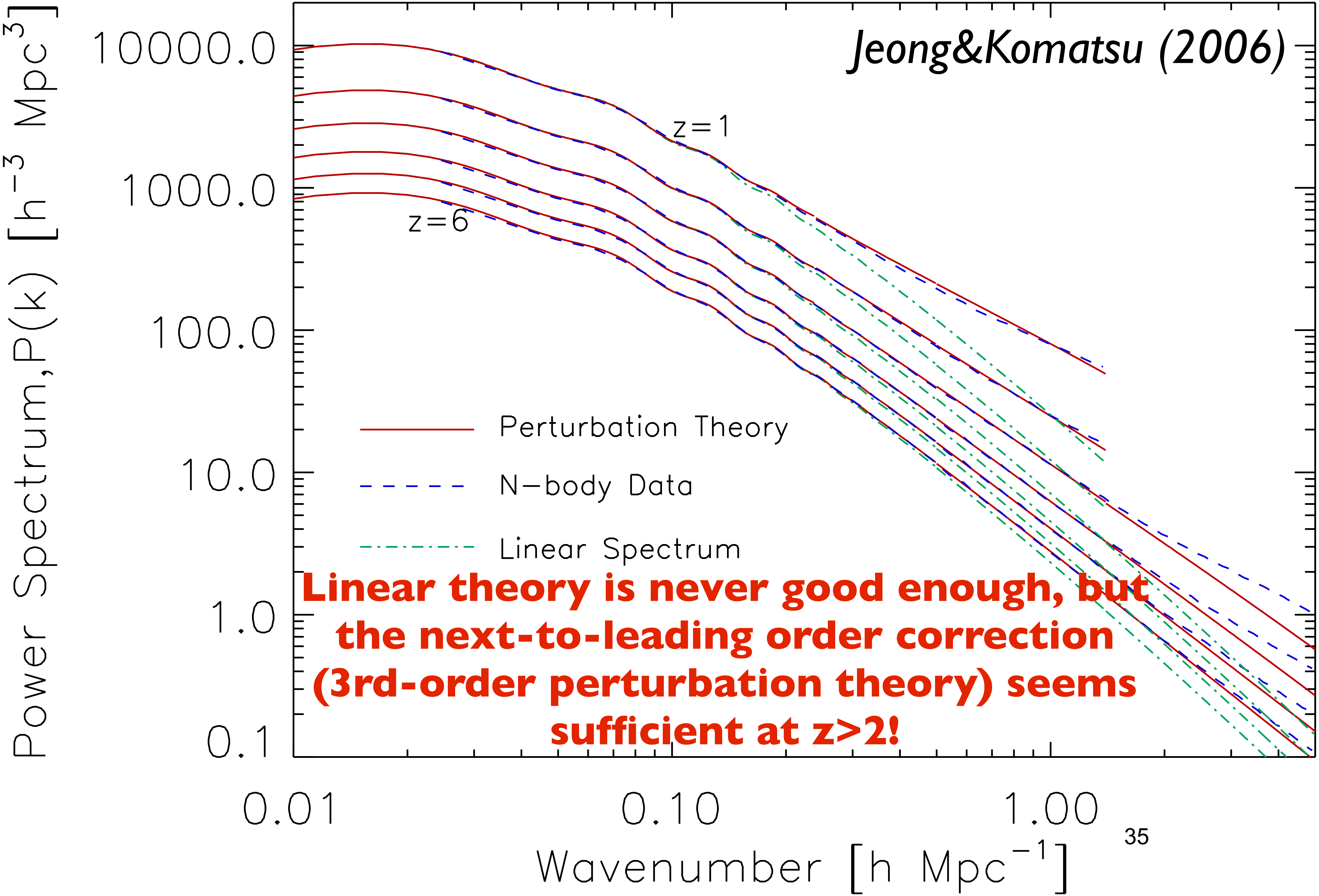
Go to higher redshifts!

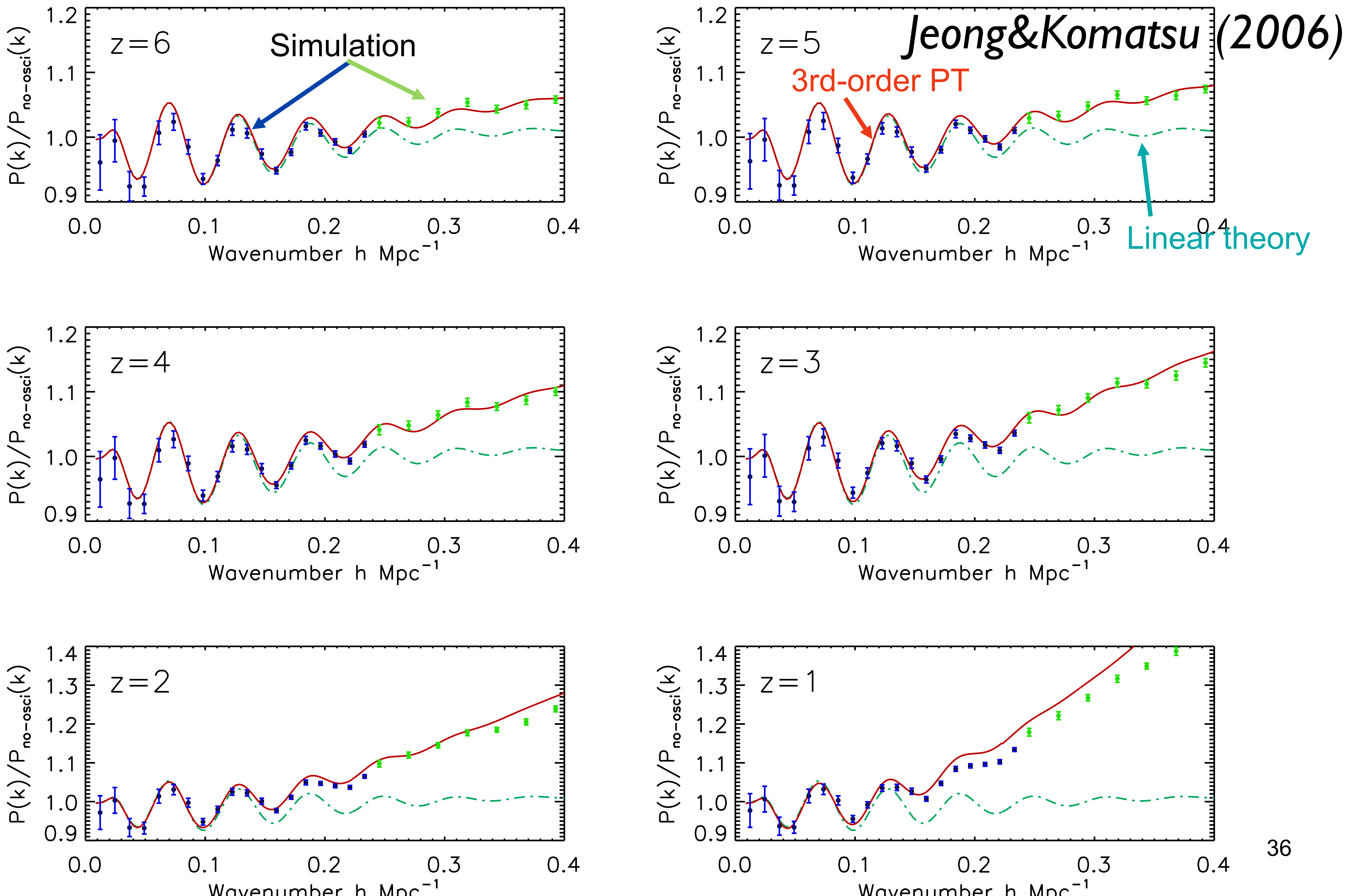
- Non-linearity becomes weaker and weaker as we go to higher redshifts.
- But, for a given number density of galaxies, the signal-to-noise ratio drops at higher redshifts.
- "Galaxy bias" saves you!
  - Galaxies are more strongly clustered than dark matter particles. To the linear approximation, $P_{galaxy}(k)=[bias]^2 P_{dark\ matter}(k)$
  - For example: for HETDEX (z~2), bias~2



bias=2
number density=5x10^{-4} h^3/Mpc^3
Redshift=2
10000
1000
100
10
0.01
0.10
1.00
Wavenumber [h/Mpc]
$P_{galaxy}(k)=b^2P(k)$ [Mpc^3/h^3]


Fractional Error in $P_{galaxy}(k)$ per Δk=0.01hMpc^{-1}
10%
1%
Wiggle Z
3% uncertainty
Low-z bin (1.9<z<2.5), 434deg^2, 380K galaxies
High-z bin (2.5<z<3.5), 434deg^2, 420K galaxies
.0
0.1
0.2
0.3
0.4
Wavenumber, k [h Mpc^{-1}]


Jeong&Komatsu (2006)
z=1
z=6
Perturbation Theory
N-body Data
Linear Spectrum
Linear theory is never good enough, but the next-to-leading order correction (3rd-order perturbation theory) seems sufficient at z>2!
10000.0
1000.0
100.0
10.0
1.0
0.1
0.01
0.10
1.00
Power Spectrum,P(k) [h^-3 Mpc^3]
Wavenumber [h Mpc^-1]


Jeong&Komatsu (2006)
Simulation
3rd-order PT
Linear theory
z=6
z=5
z=4
z=3
z=2
z=1
P(k)/P_no-osci(k)
Wavenumber h Mpc^-1

What can HETDEX do?

- Primary goal: *to detect the influence of dark energy on the expansion rate at z~2 directly*, even if it is a cosmological constant
  - Use both Baryon Acoustic Oscillation and the full shape and anisotropy (more later)
  - ***Supernova cannot reach z>2: a new territory***
- In addition, we can address many other cosmological and astrophysical issues.

Other "Prime" Goals

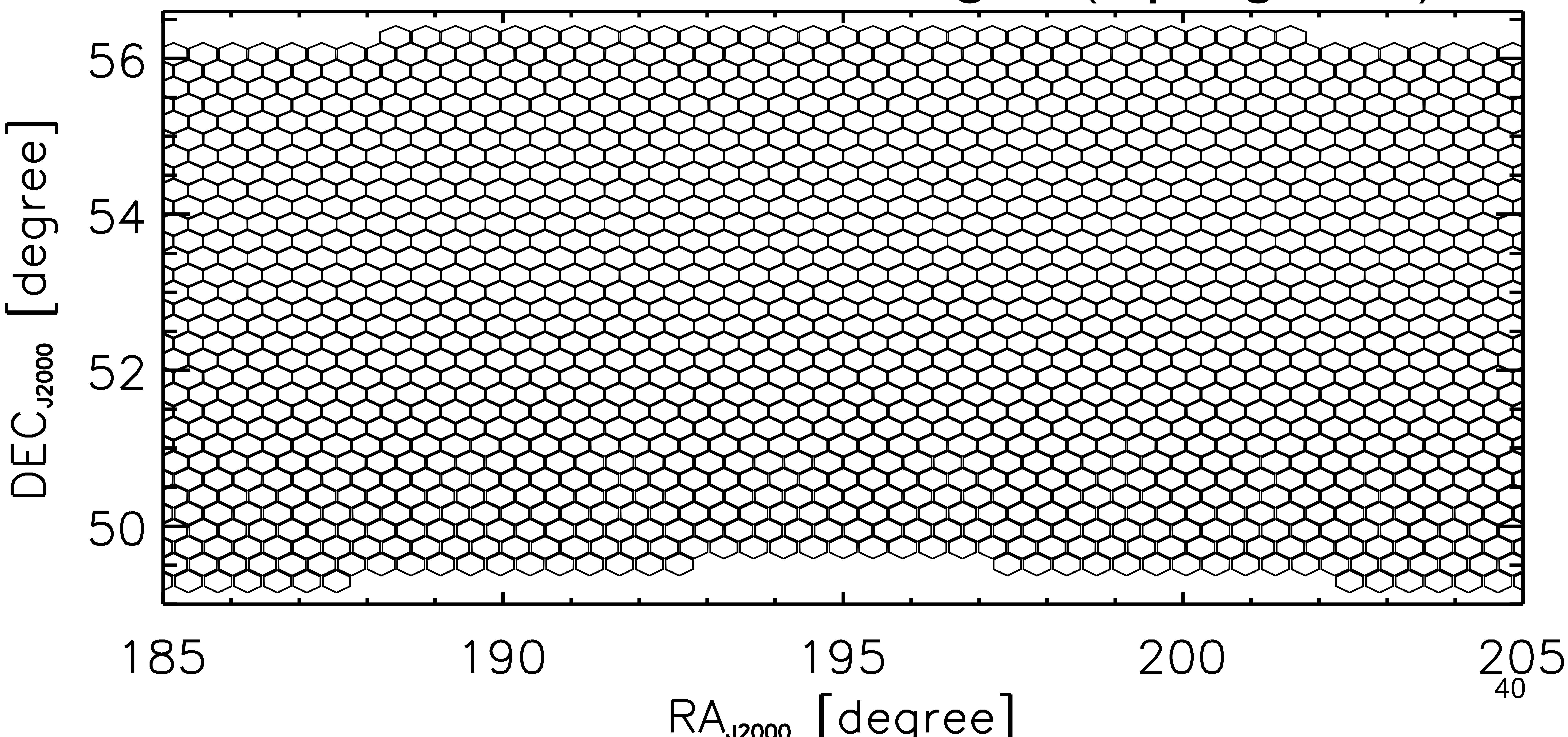
- **Is the observable universe really flat?**
  - We can improve upon the current limit on $\Omega_{curvature}$ by a factor of 10 – to reach $\Omega_{curvature} \sim 10^{-3}$ level.
- **How large is the neutrino mass?**
  - We can detect the neutrino mass if the total mass is greater than about 0.1 eV [current limit: total mass < 0.3eV]
  - The absolute lower limit to the total mass from neutrino experiments is the total mass > 0.05 eV. Not so far away!

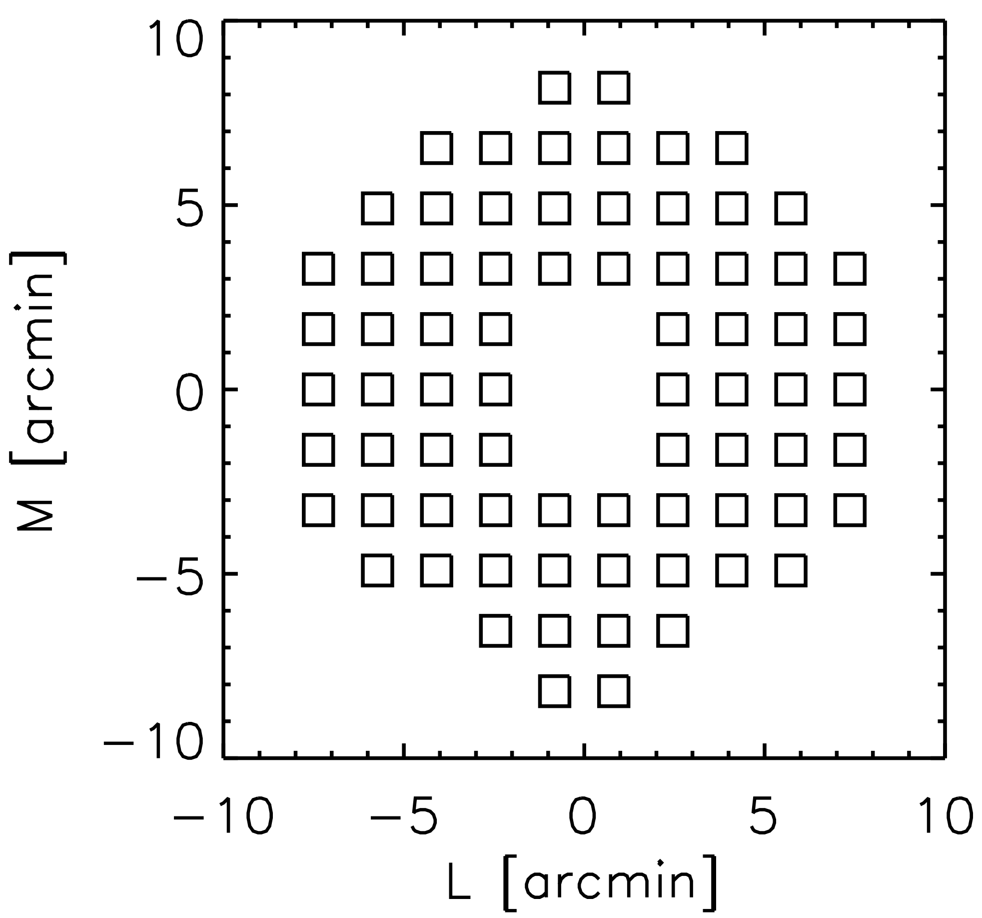
“Sub-prime” Goals

- Being the first blind spectroscopic survey, HETDEX is expected to find unexpected objects.
- Also, we expect to have an unbiased catalog of white dwarfs; metal-poor stars; distant clusters of galaxies; etc

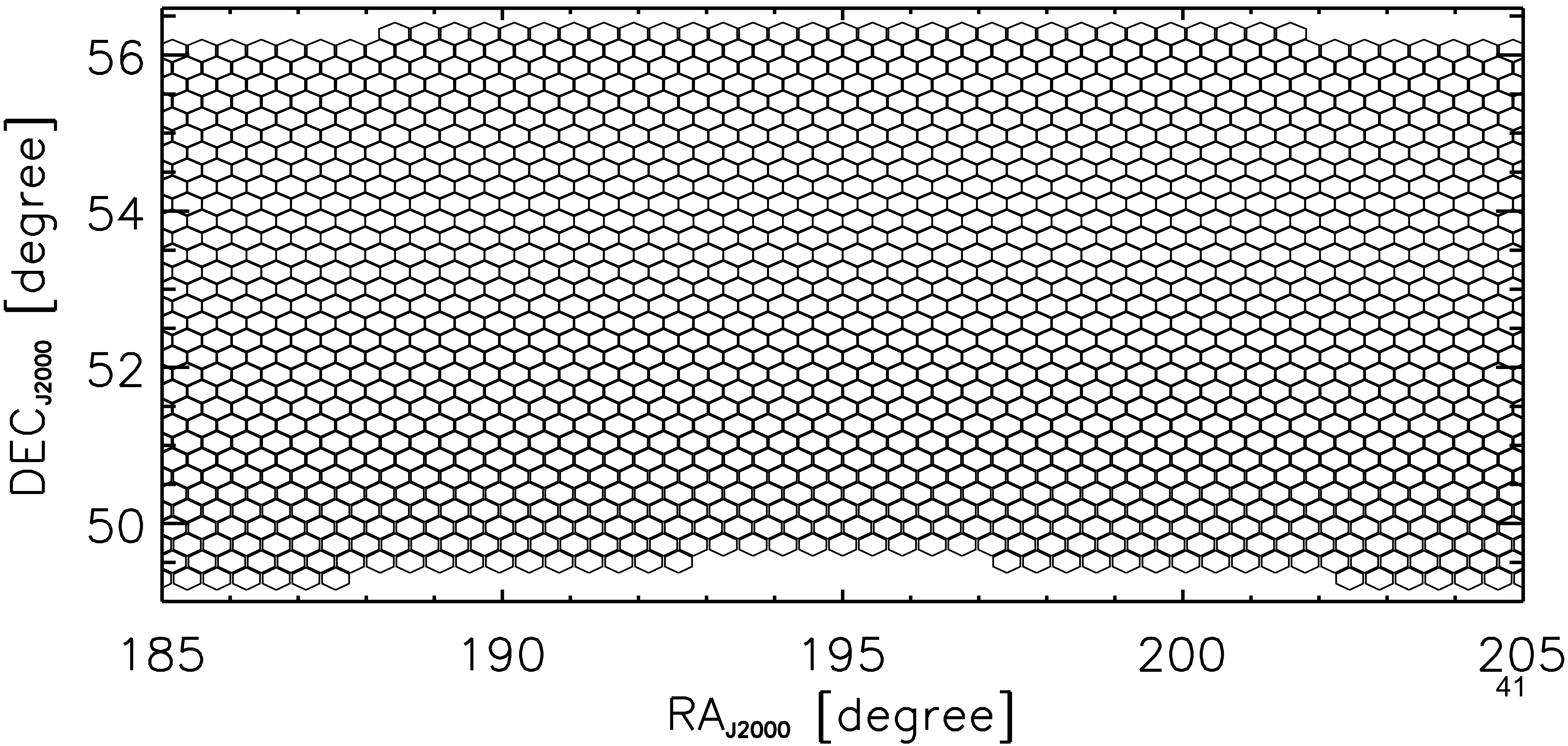
HETDEX Survey Strategy: Tiling the Sky with IFUs

4000 shots in the northern region ("spring field")





- Each "shot" in the sky contains 75 IFUs
  - Spending 20 minutes per shot ~ 200 LAEs
- We do not completely fill the focal plane (if only we had more IFUs...)
- This is the "sparse sampling" method



Sparse Sampling: Basic Idea

- We do not need sample the galaxy distribution at all scales to extract information on large scales.
- Nyquist sampling theorem tells us that we'd need to sample only twice as frequently as the frequency of interest.

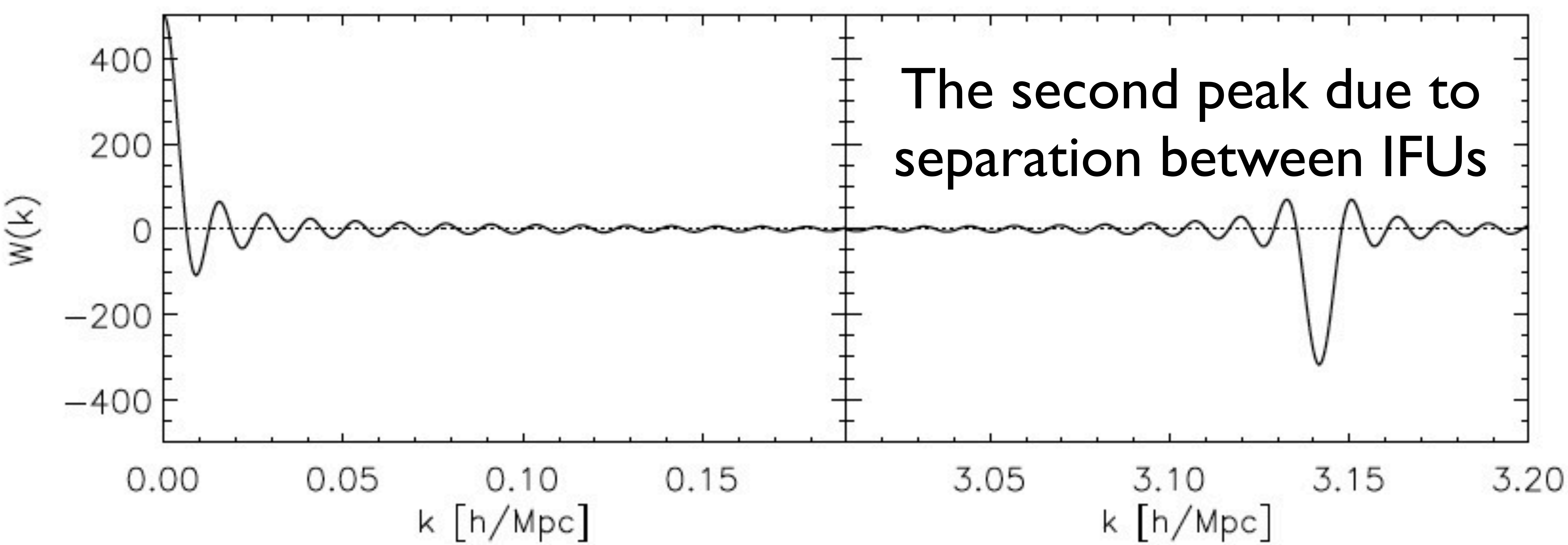
A bit of math

Chiang et al., arXiv:1306.4157

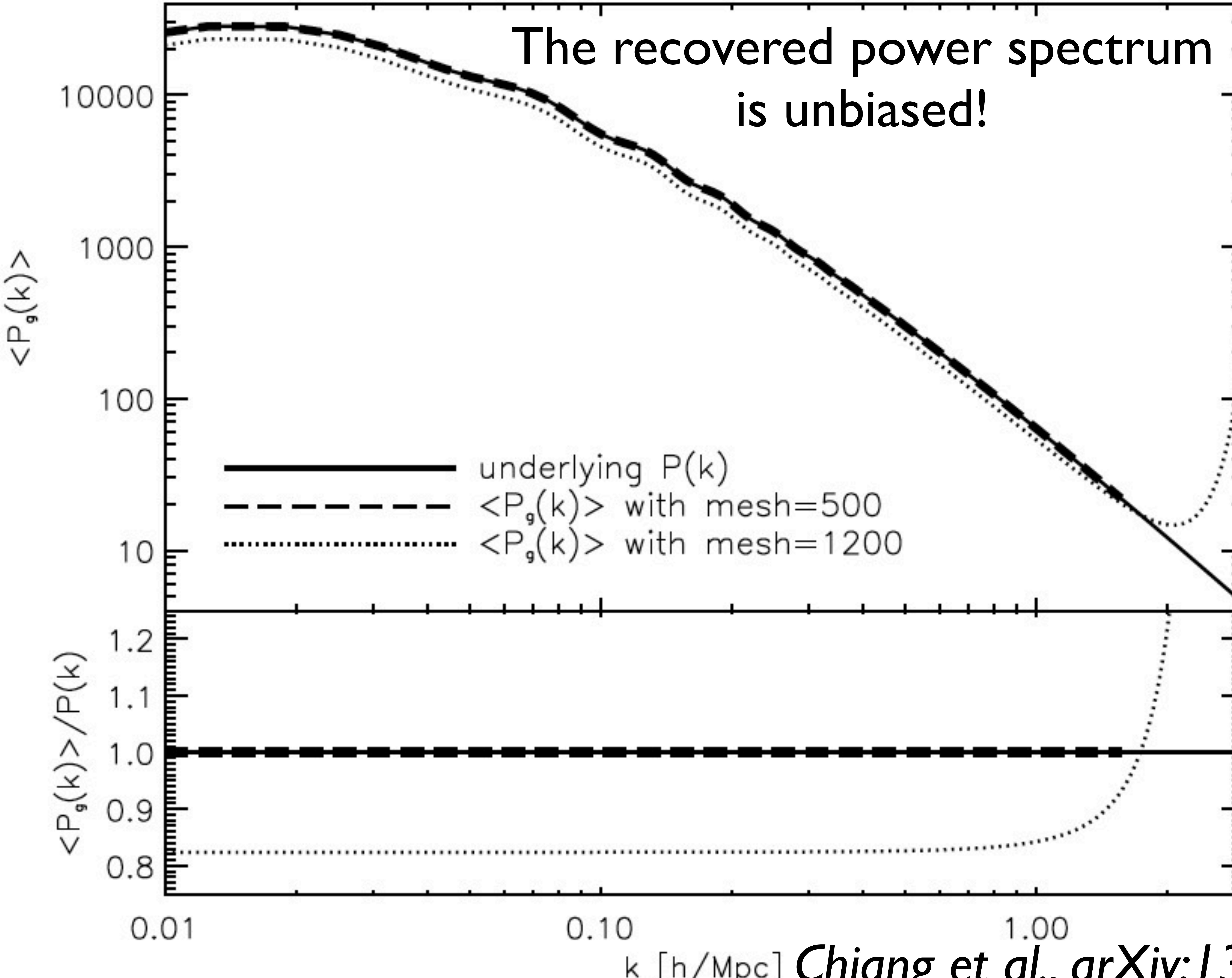
$$n_g(\mathbf{r}) = n(\mathbf{r})W(\mathbf{r})$$

W(r)=1 at the observed locations; 0 otherwise

$$\langle \hat{P}_g(k) \rangle = \frac{1}{W_{\rm sq}} \int \frac{d^3q}{(2\pi)^3} P(\mathbf{q})|W(\mathbf{k}-\mathbf{q})|^2 + P_{\rm shot}$$

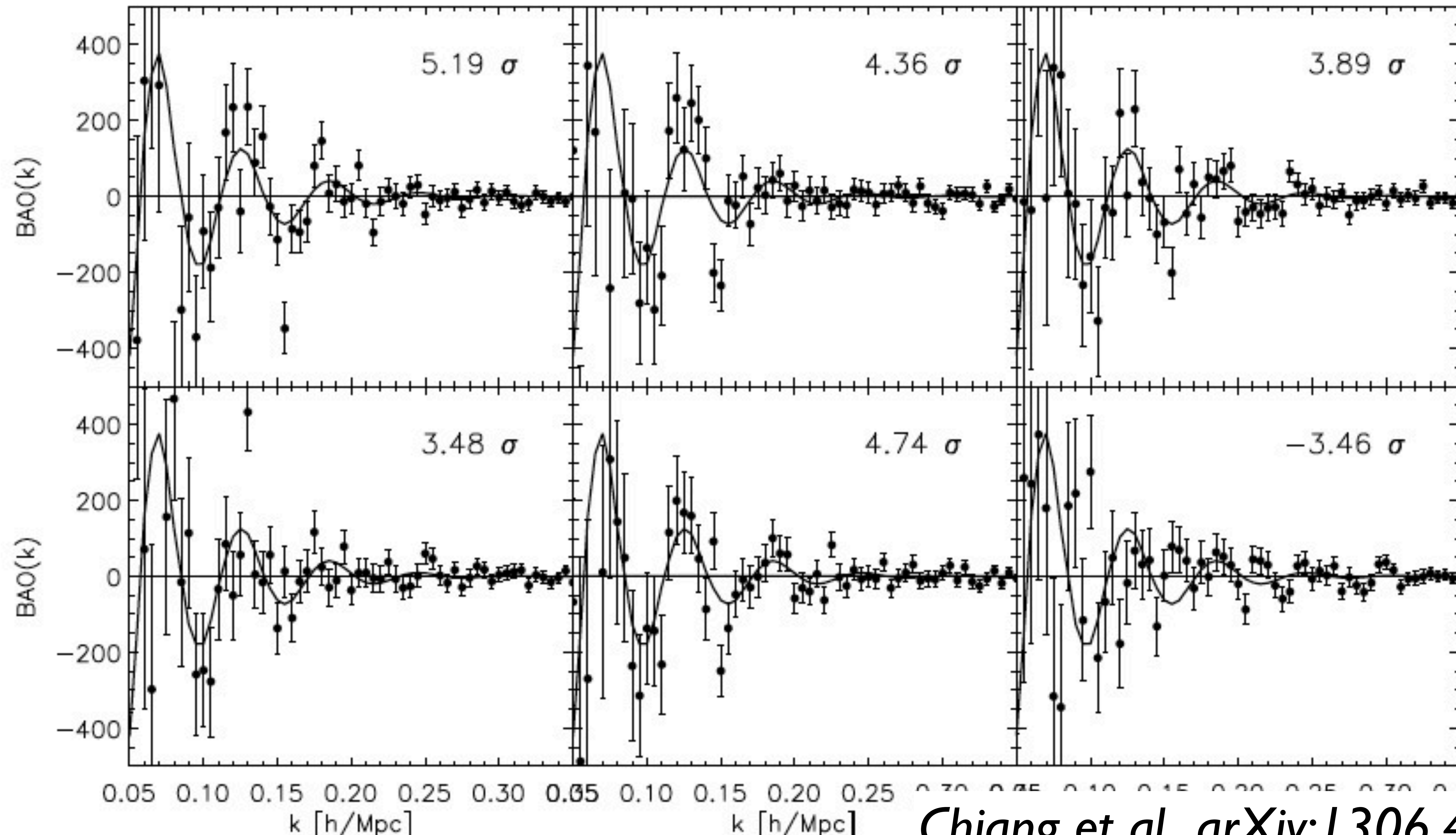


The second peak due to separation between IFUs

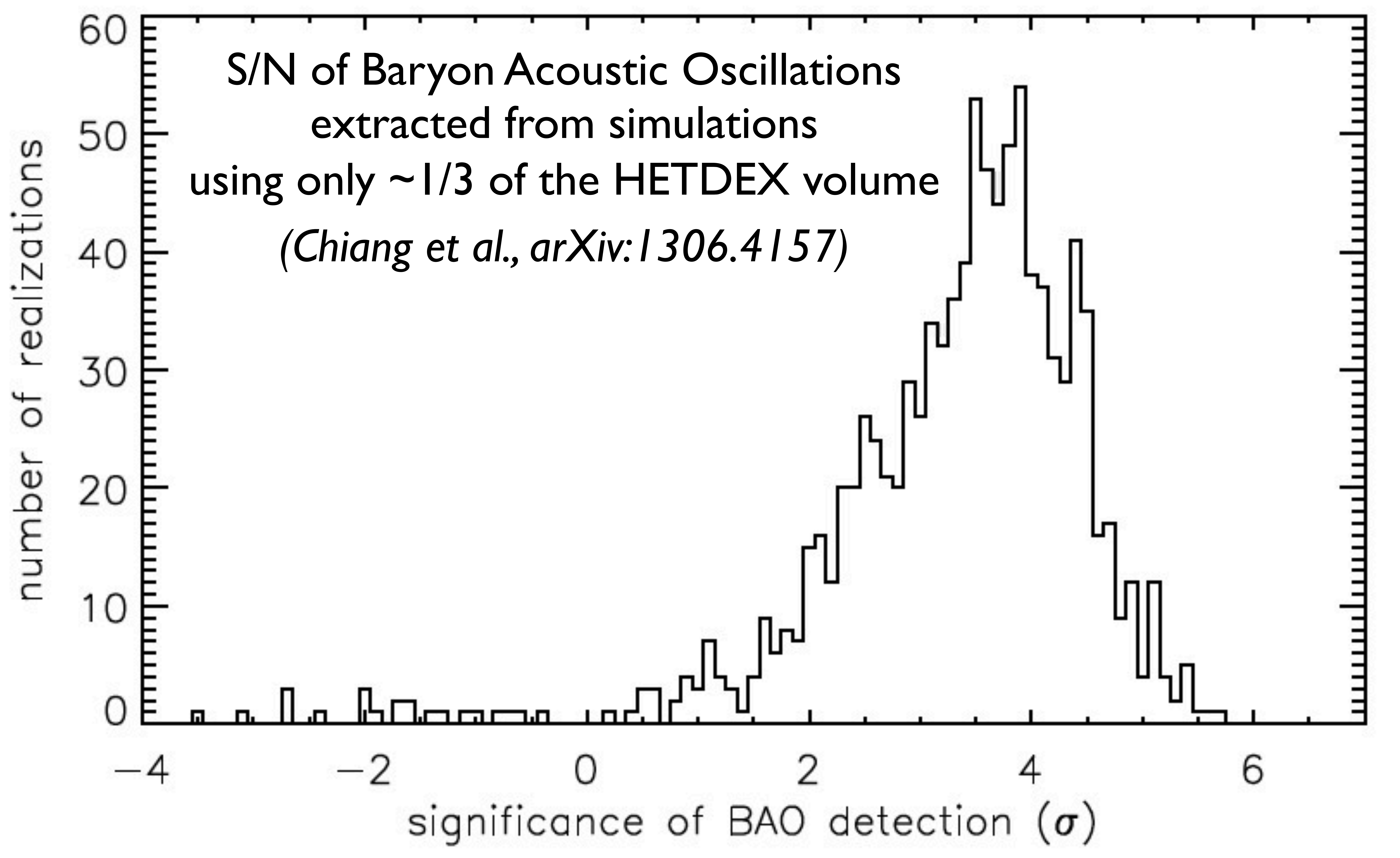


Chiang et al., arXiv:1306.4157

Samples of Baryon Acoustic Oscillations extracted from simulations using only ~1/3 of the HETDEX volume

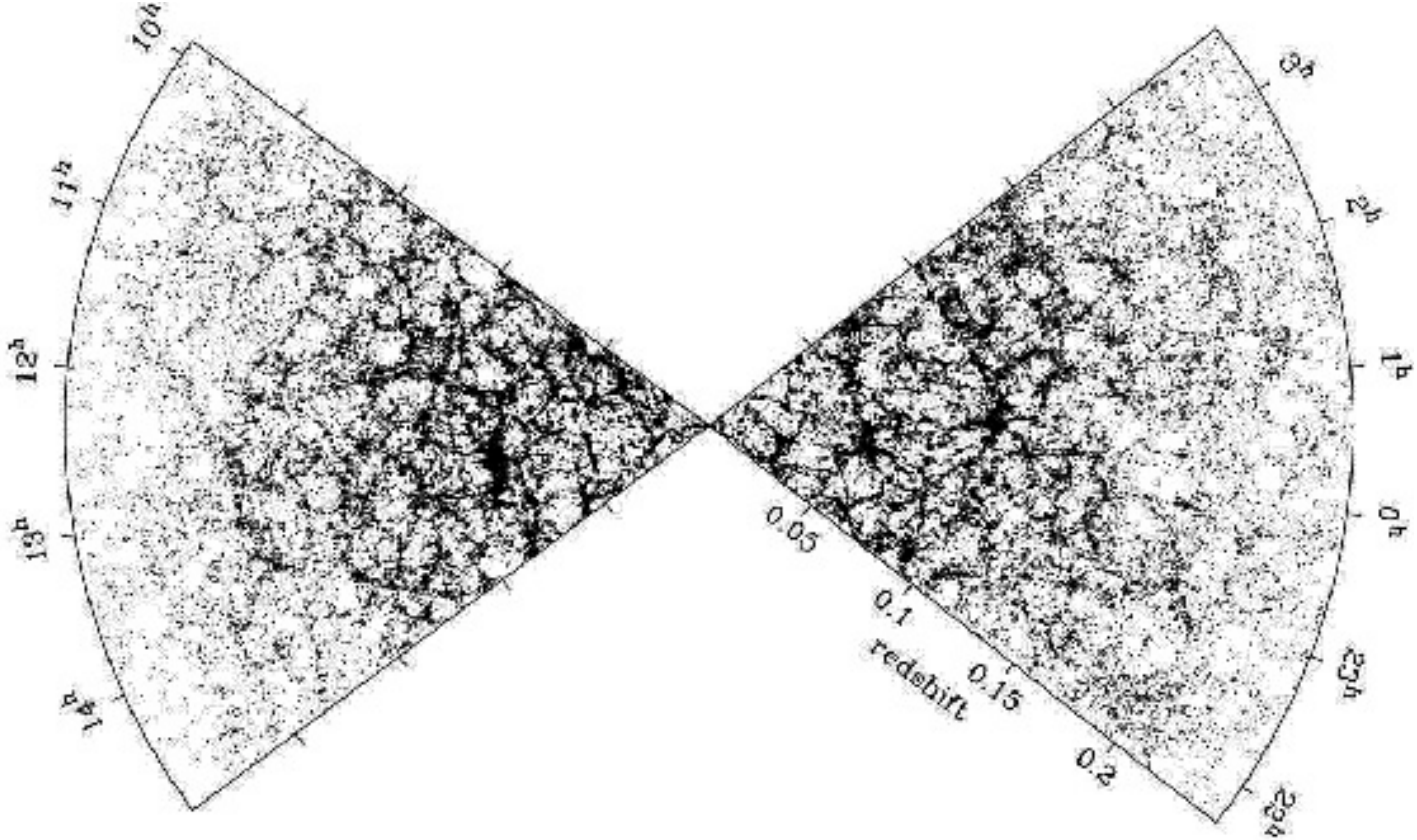


Chiang et al., arXiv:1306.4157


S/N of Baryon Acoustic Oscillations
extracted from simulations
using only ~1/3 of the HETDEX volume
(Chiang et al., arXiv:1306.4157)
number of realizations
significance of BAO detection (σ)
60
50
40
30
20
10
0
−4
−2
0
2
4
6

BAO in Galaxy Distribution

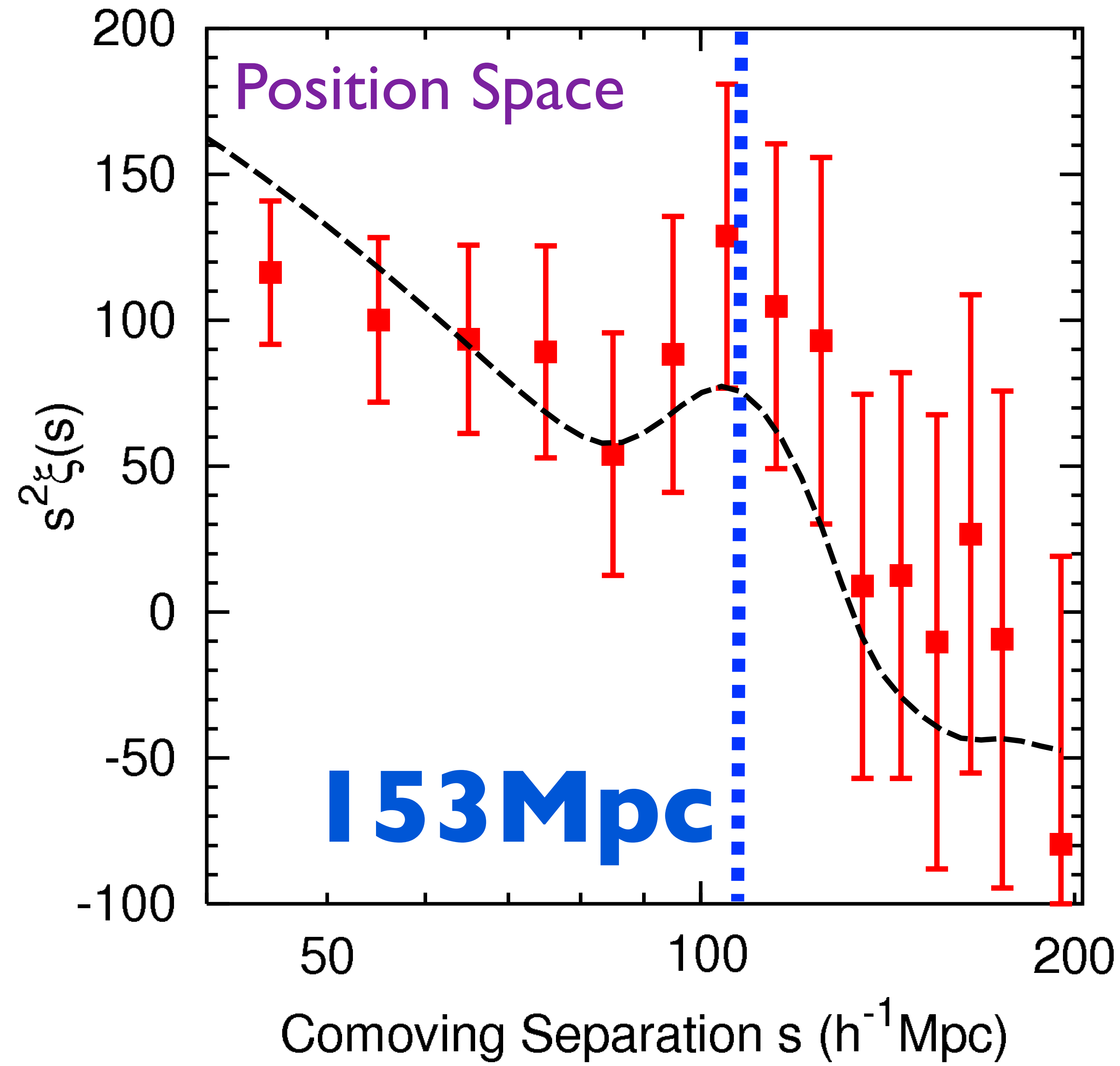
2dFGRS

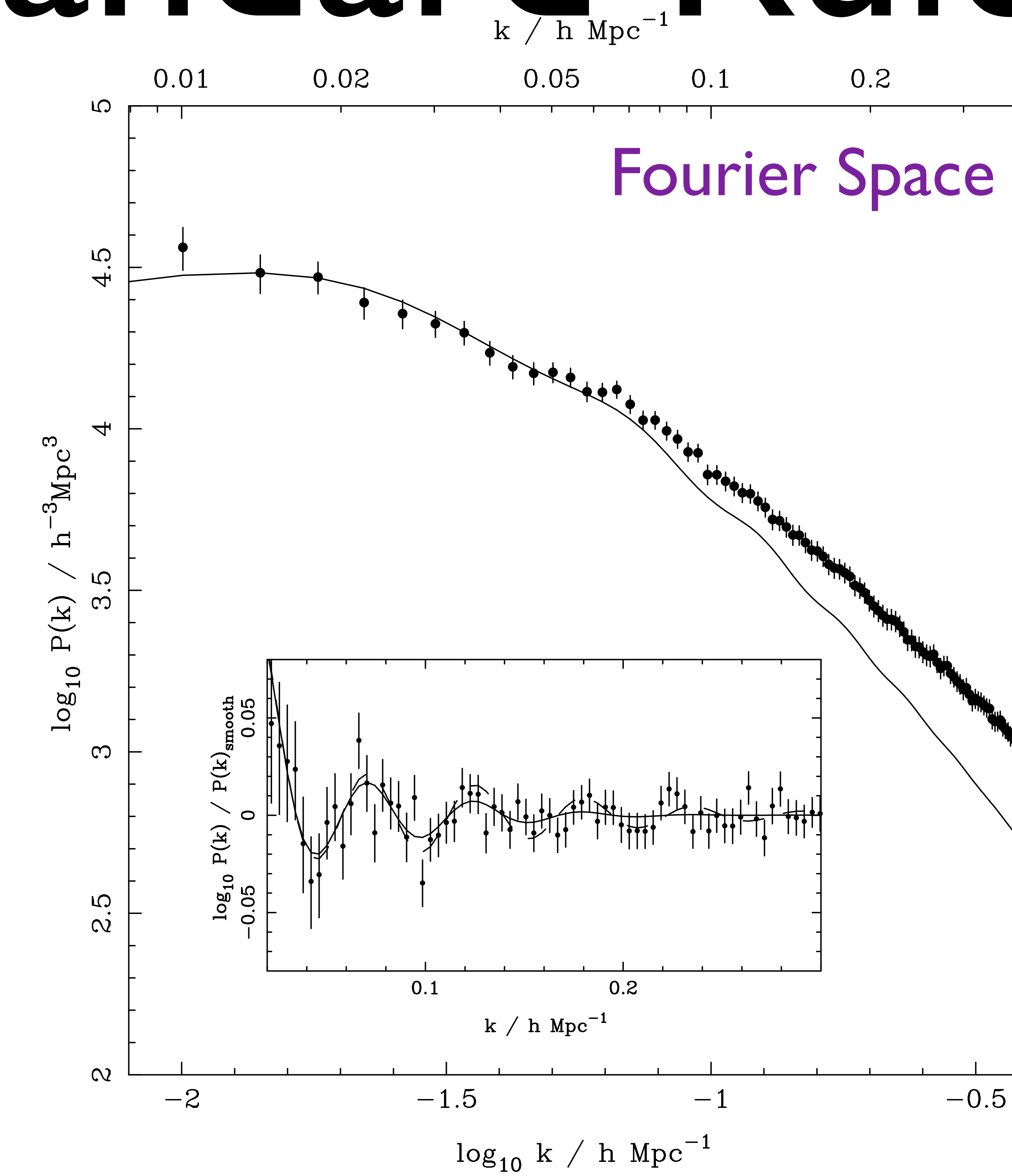


- The acoustic oscillations should be hidden in this galaxy distribution...

BAO as a Standard Ruler

Okumura et al. (2007)





Percival et al. (2006)

- The existence of a localized clustering scale in the 2-point function yields oscillations in Fourier space.

Not Just $D_A(z)$...

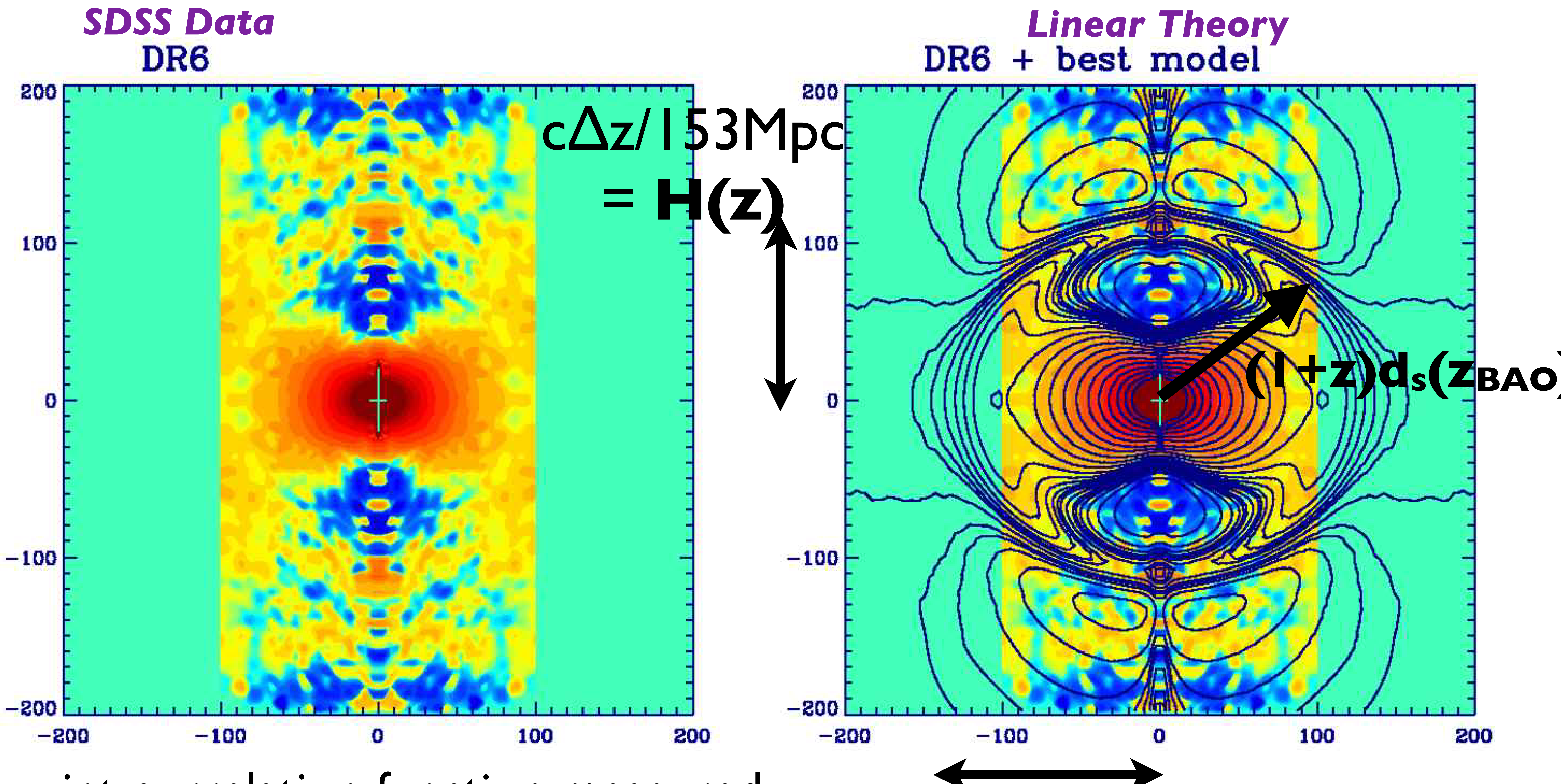
- A really nice thing about BAO at a given redshift is that it can be used to measure not only $D_A(z)$, but also the expansion rate, $H(z)$, directly, at **that** redshift.
  - BAO perpendicular to l.o.s

    $$\Rightarrow D_A(z) = 153\text{Mpc}/[(1+z)\theta]$$

  - BAO parallel to l.o.s

    $$\Rightarrow \mathbf{H(z) = c\Delta z/153Mpc}$$

Transverse=$D_A(z)$; Radial=$H(z)$

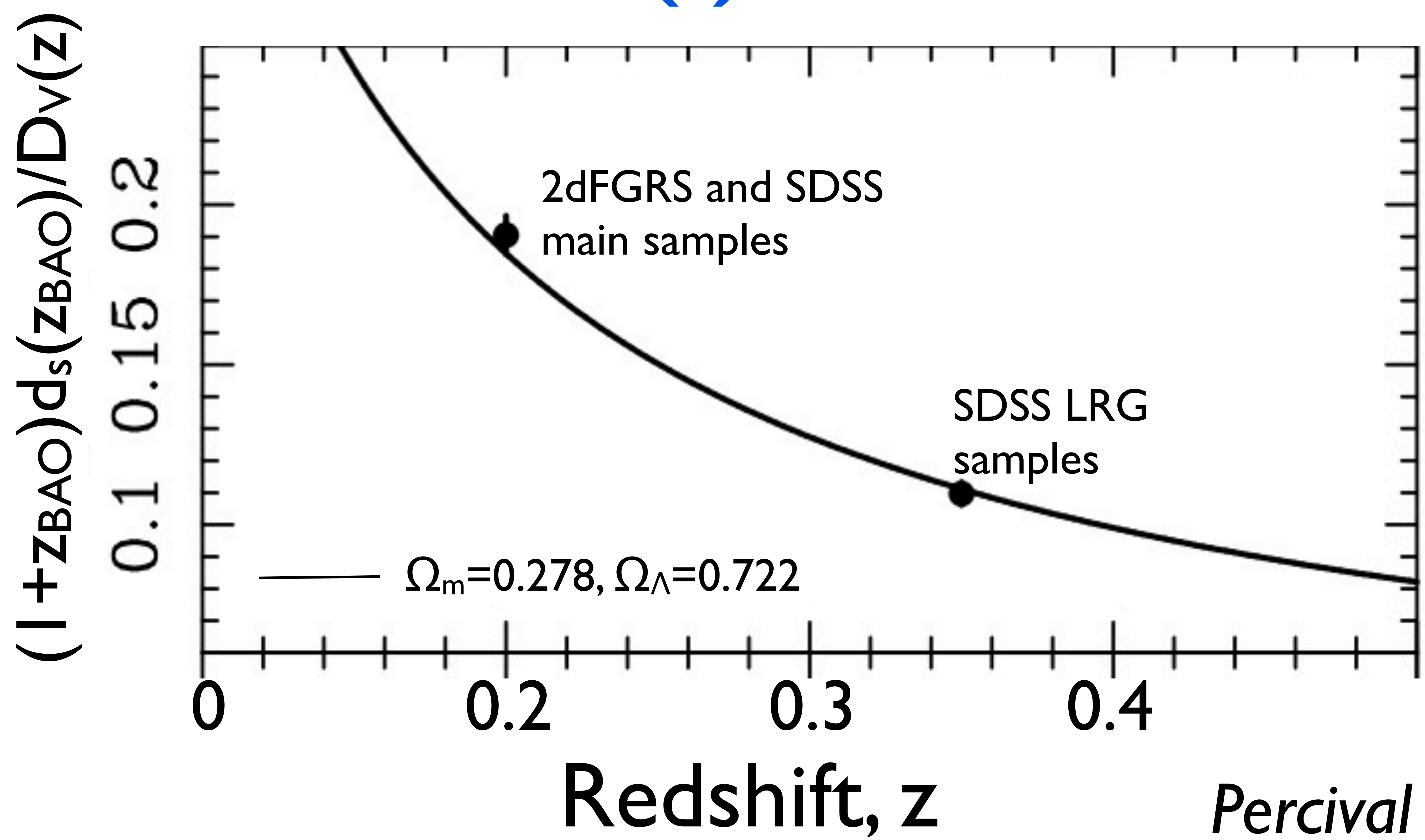


Two-point correlation function measured from the SDSS Luminous Red Galaxies (Gaztanaga, Cabre & Hui 2008)

$\theta = 153\mathrm{Mpc}/[(1+z)\mathbf{D_A(z)}]$

$$D_V(z) = \{(1+z)^2 D_A^2(z)[cz/H(z)]\}^{1/3}$$

Since the current data are not good enough to constrain $D_A(z)$ and $H(z)$ separately, a combination distance, **$D_V(z)$**, has been constrained.



Percival et al. (2010)

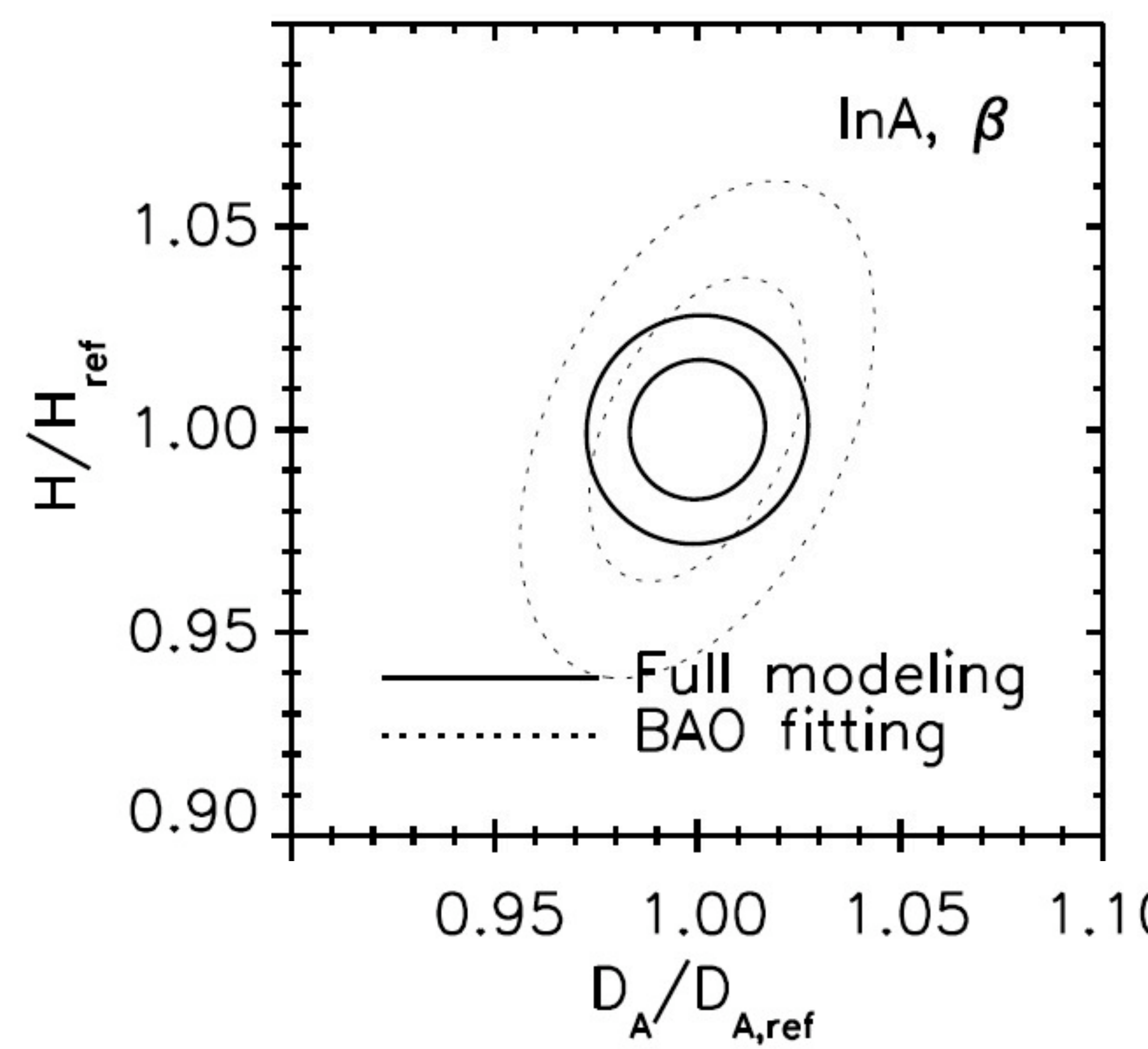
Beyond BAO

- BAOs capture only a **fraction** of the information contained in the galaxy power spectrum!
- The full usage of the 2-dimensional power spectrum leads to a *substantial* improvement in the precision of distance and expansion rate measurements.

Shoji, Jeong & Komatsu (2009)

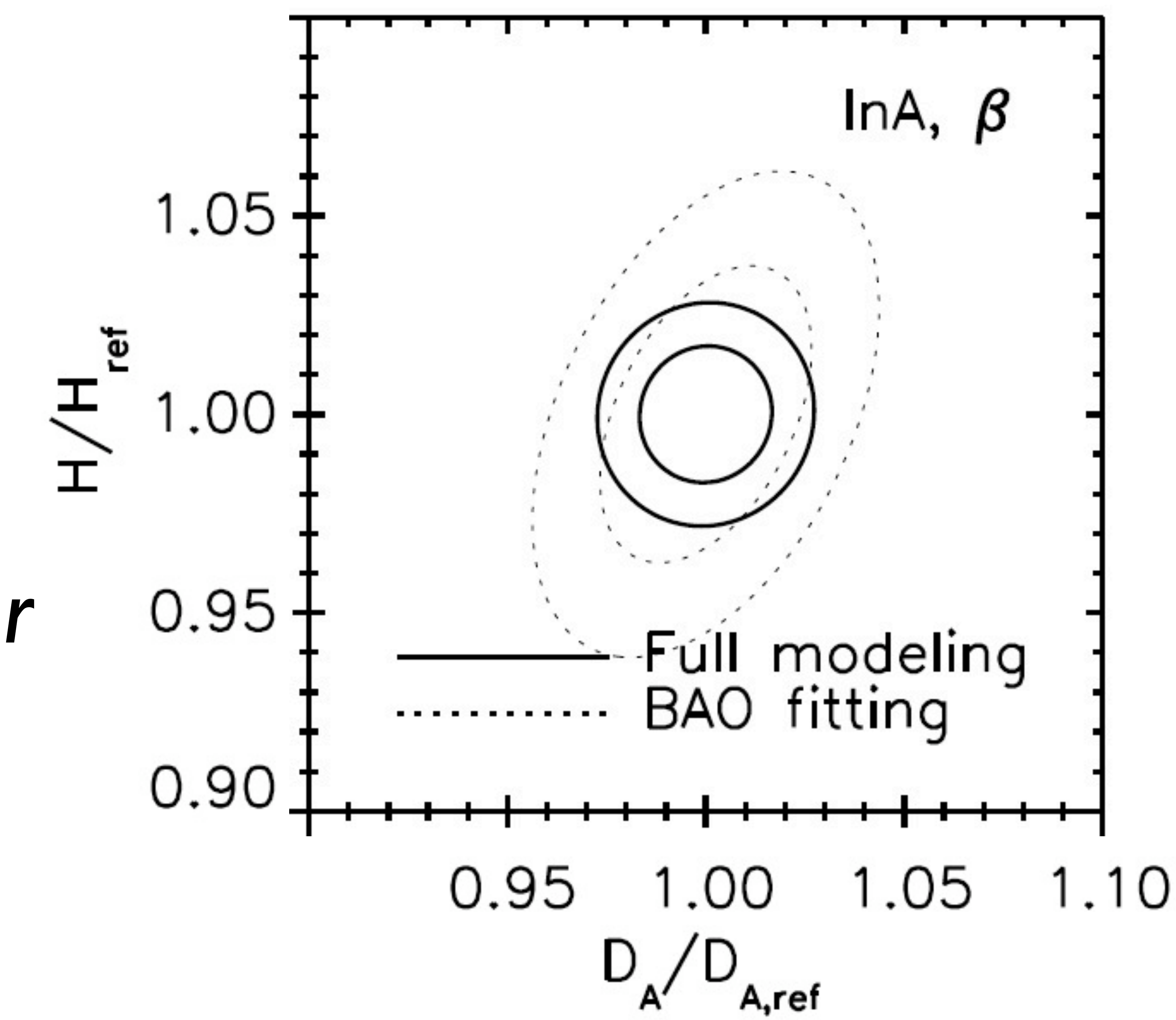
BAO vs Full Modeling

- BAO gives $(D_A^2/H)^{1/3}$
- Full modeling improves upon the determinations of D_A & H by more than a factor of two.
- On the D_A-H plane, the size of the ellipse shrinks by more than a factor of four.



Alcock-Paczynski: The Most Important Thing For HETDEX

- **Where does the improvement come from?**
  - The Alcock-Paczynski test is the key. *This is the most important component for the success of the HETDEX survey.*



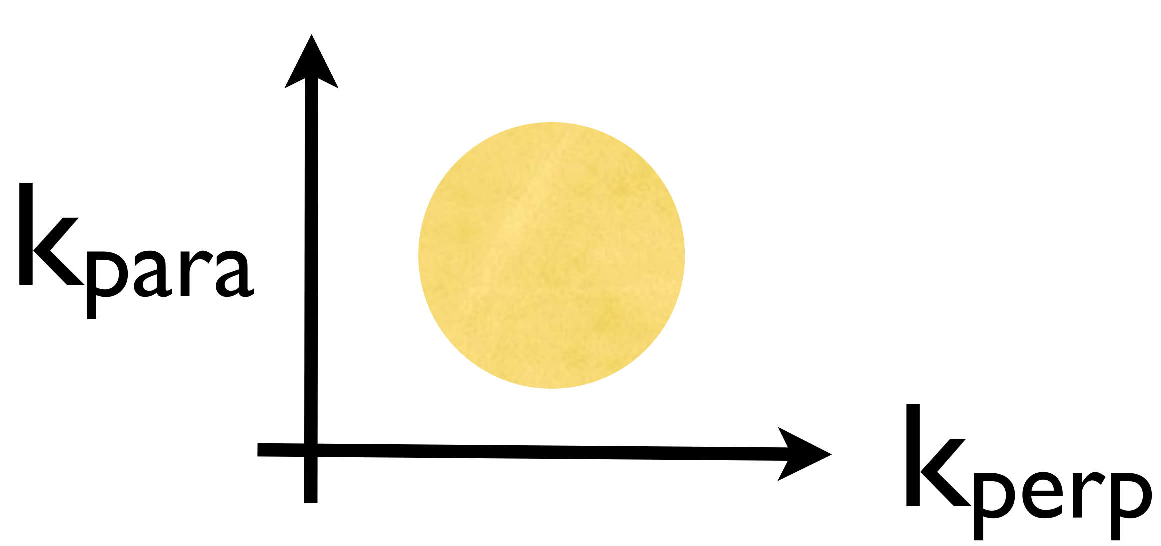
The AP Test: How That Works

- The key idea: (*in the absence of the redshift-space distortion - we will include this for the full analysis; we ignore it here for simplicity*), the distribution of the power should be **isotropic** in Fourier space.

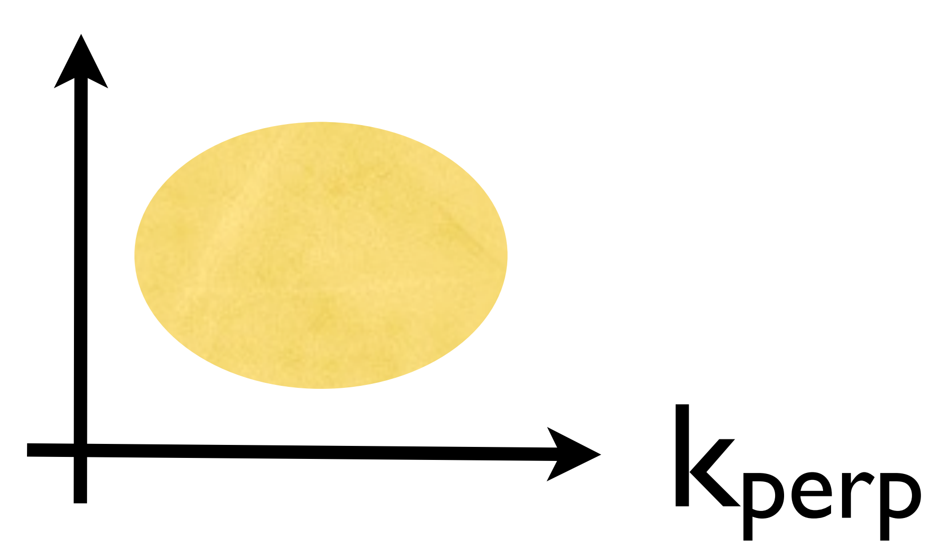
The AP Test: How That Works

- **D_A**: (RA,Dec) to the transverse separation, r_{perp}, to the transverse wavenumber
  - $k_{perp} = (2\pi)/r_{perp} = (2\pi)$[Angle on the sky]/**$D_A$**
- **H**: redshifts to the parallel separation, r_{para}, to the parallel wavenumber
  - $k_{para} = (2\pi)/r_{para} = (2\pi)$**H**$/(c\Delta z)$

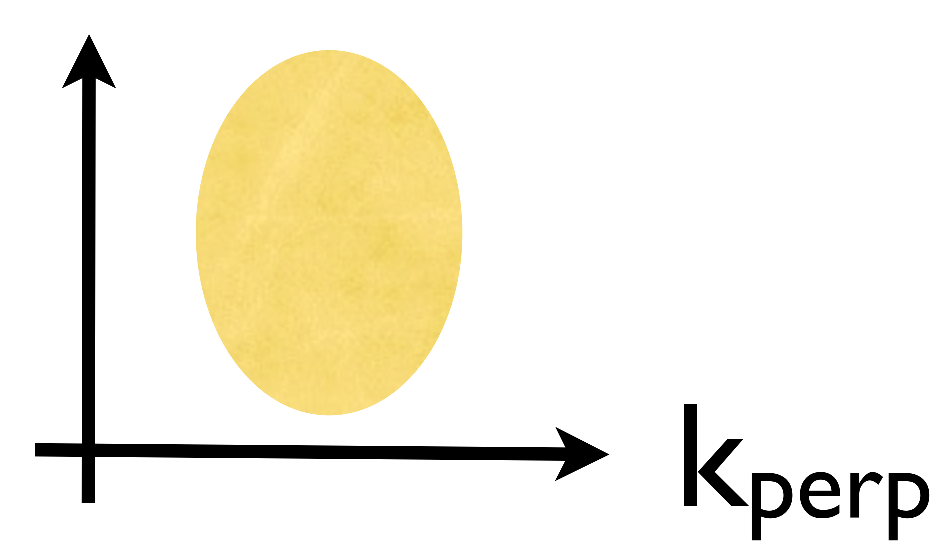
If D_A and H are correct:



If D_A is wrong:



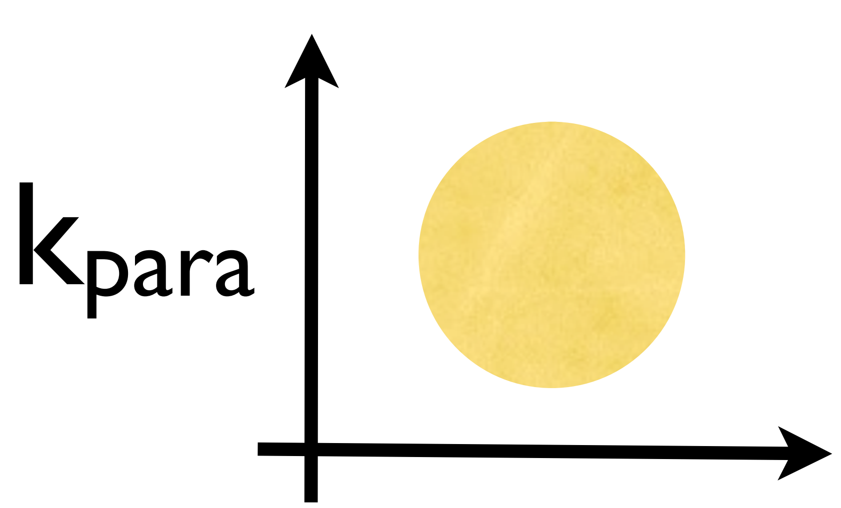
If H is wrong:



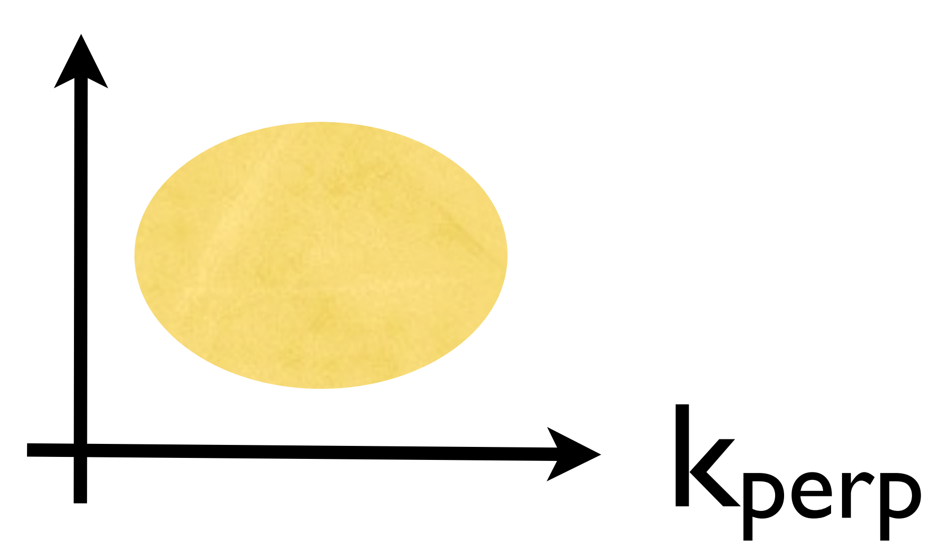
The AP Test: How That Works

- $\mathbf{D_A}$: (RA,Dec) to the transverse separation, r_{perp}, to the transverse wavenumber
  - $k_{perp} = (2\pi)/r_{perp} = (2\pi)$[Angle on the sky]$/\mathbf{D_A}$
- **H**: redshifts to the parallel separation, r_{para}, to the parallel wavenumber
  - $k_{para} = (2\pi)/r_{para} = (2\pi)\mathbf{H}/(c\Delta z)$

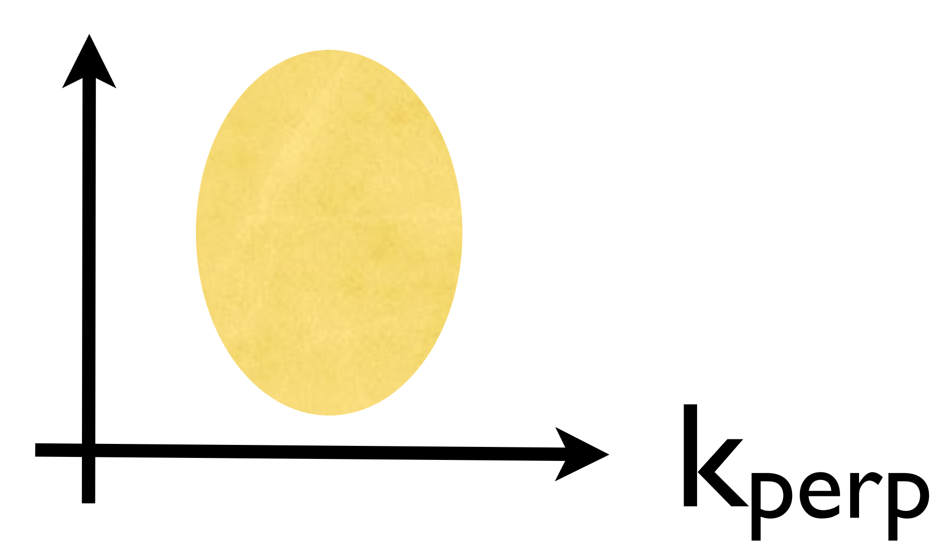
If D_A and H are correct:



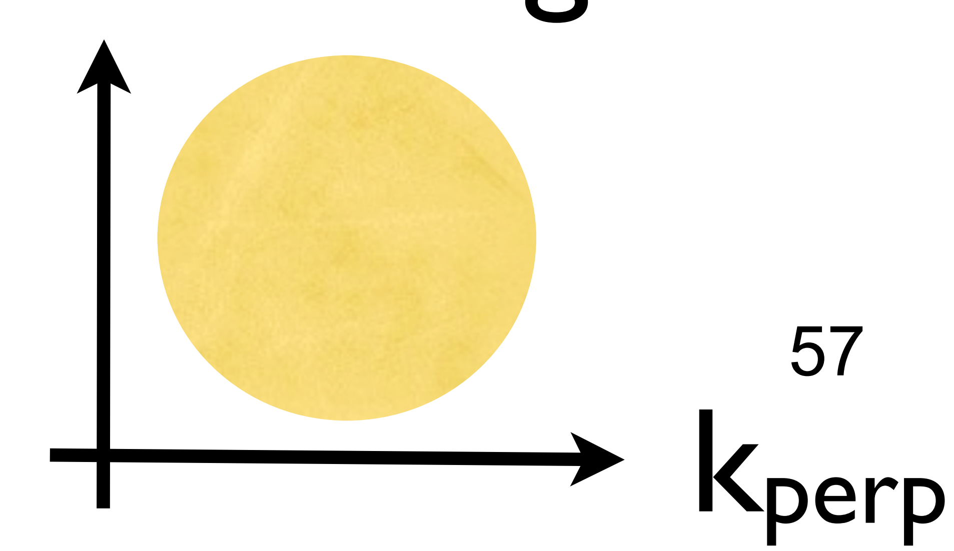
If D_A is wrong:



If H is wrong:

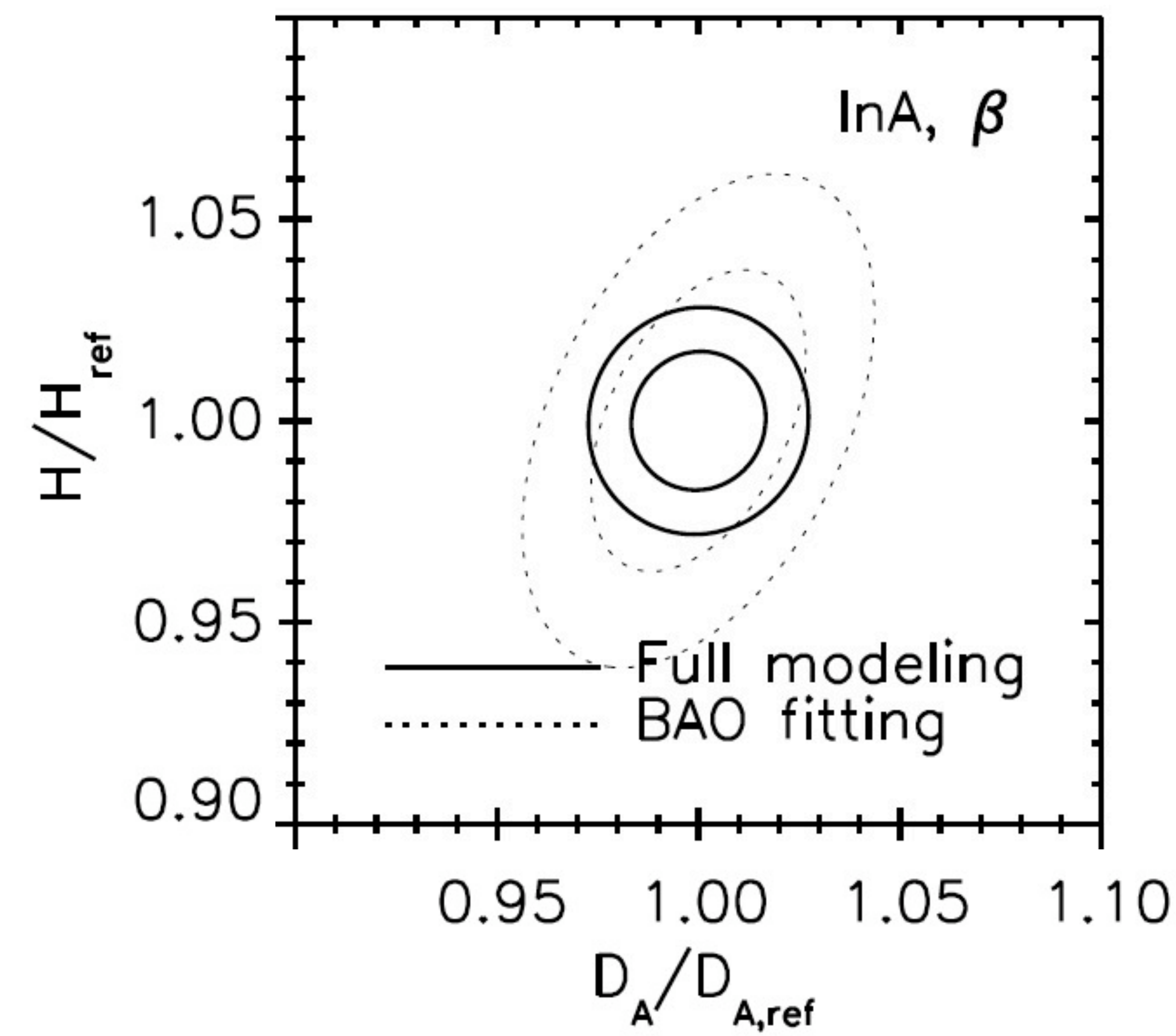


If D_A and H are wrong:

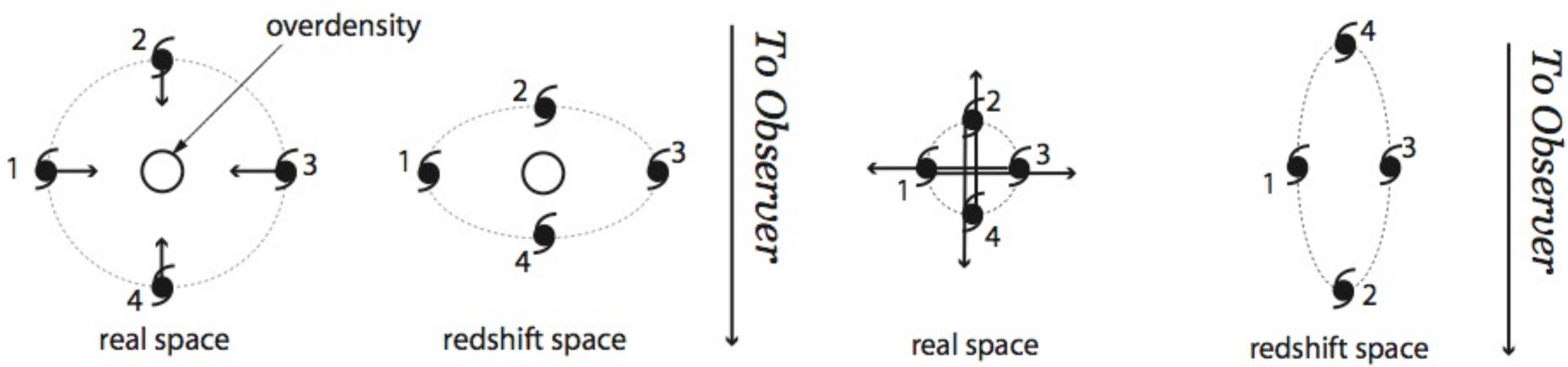


$D_A H$ from the AP test

- So, the AP test can't be used to determine D_A and H separately; however, it gives a measurement of **$D_A H$**.
- Combining this with the BAO information, and marginalizing over the redshift space distortion, we get the solid contours in the figure.

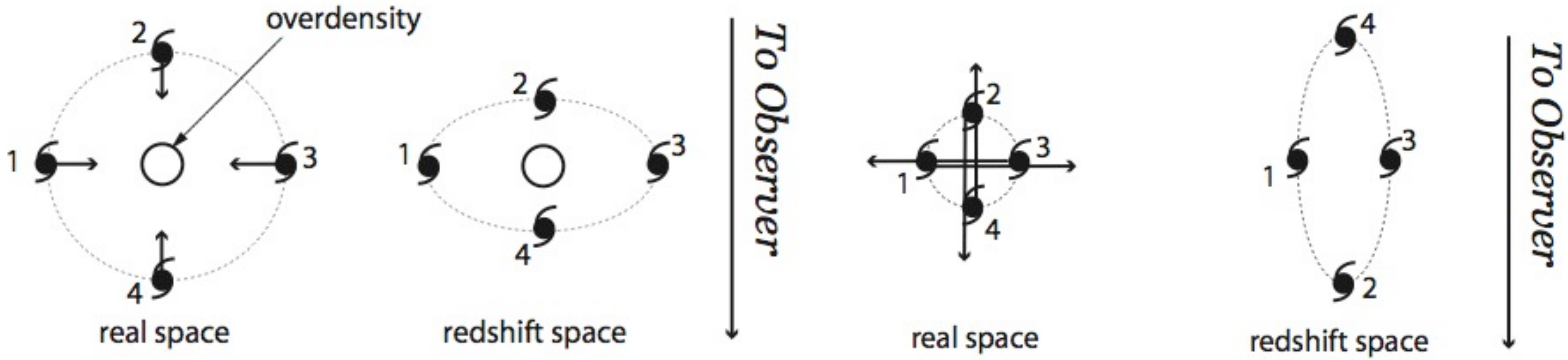


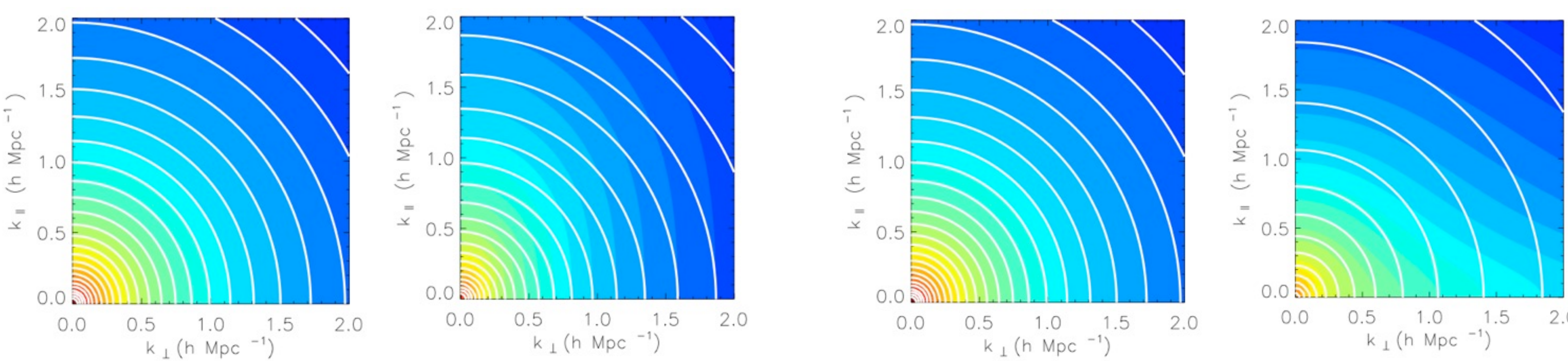
Redshift Space Distortion



- (Left) Coherent flow => clustering **enhanced** along l.o.s
    - "Kaiser" effect
- (Right) Virial motion => clustering **reduced** along l.o.s.
    - "Finger-of-God" effect

Redshift Space Distortion





Linear/Quasi-linear

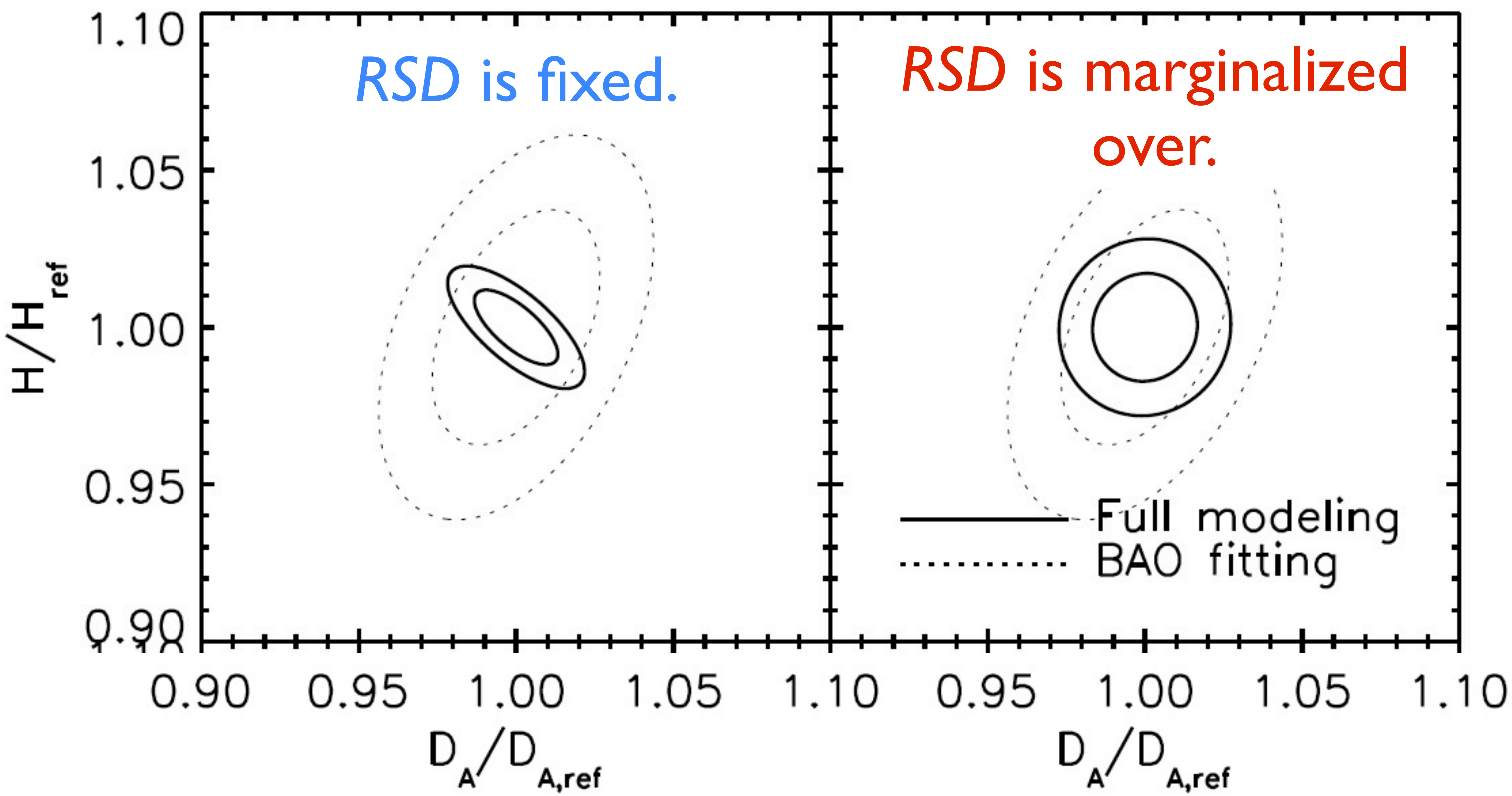
Non-linear

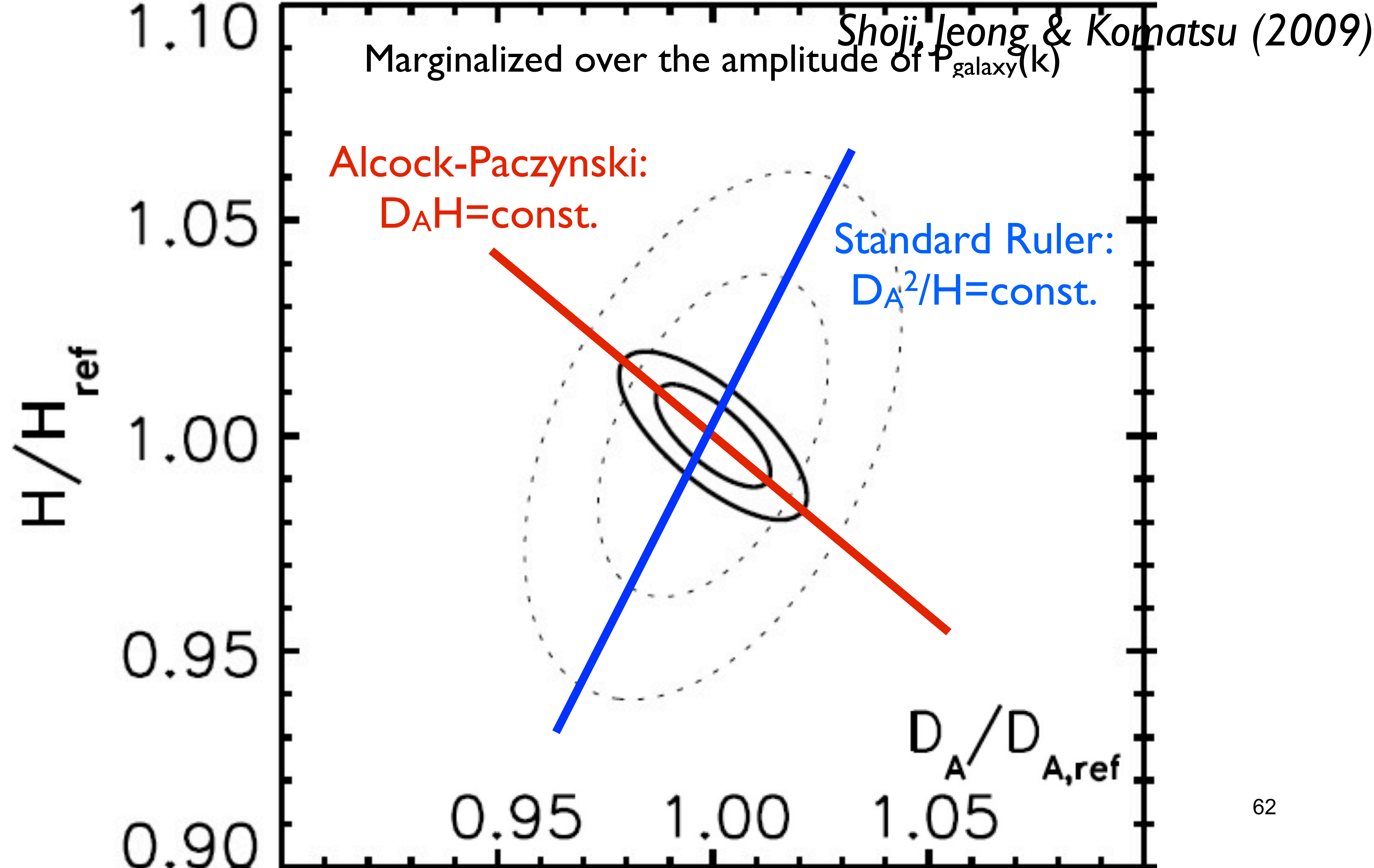
Shoji, Jeong & Komatsu (2009)

Redshift Space Distortion (RSD)

- Both the AP test and the redshift space distortion make the distribution of the power anisotropic. Would it spoil the utility of this method?

  - Some, but not all!



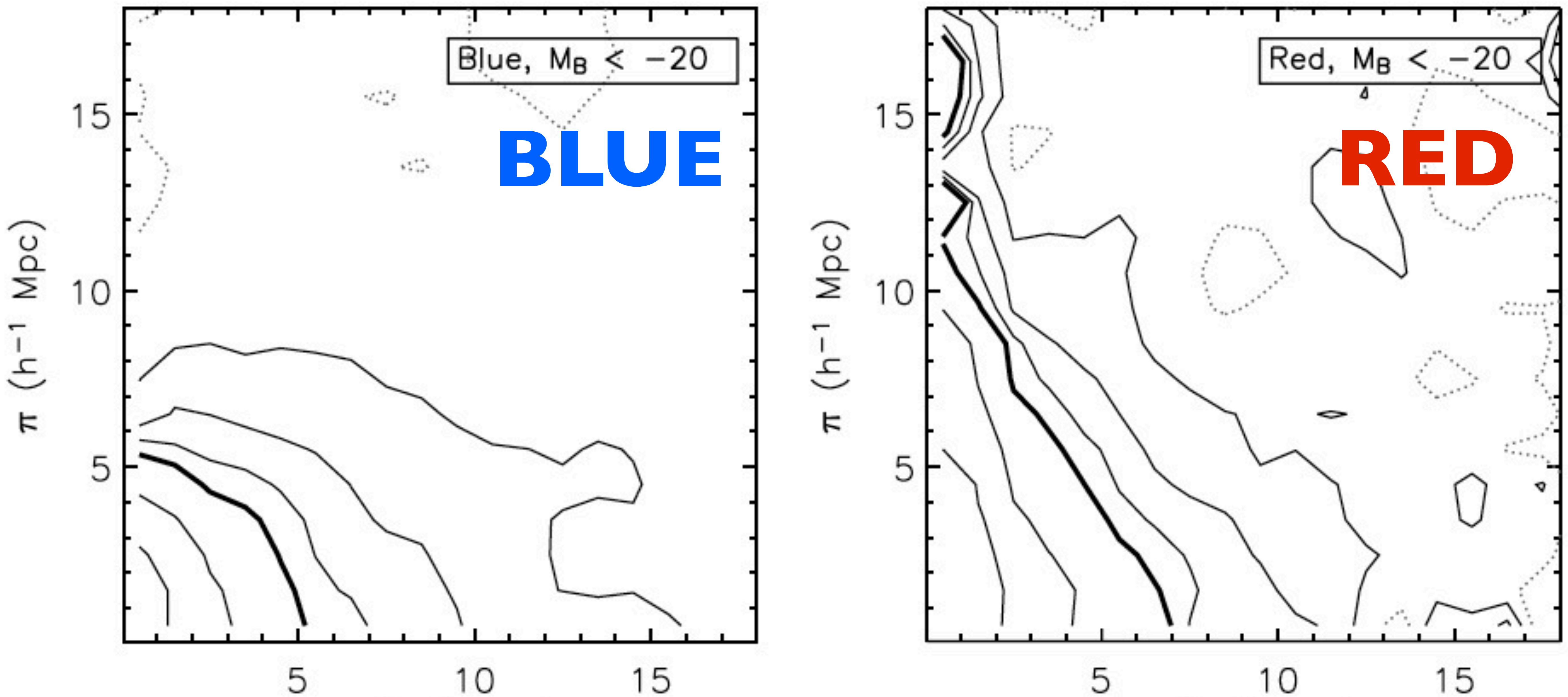


Shoji, Jeong & Komatsu (2009)
Marginalized over the amplitude of $P_{galaxy}(k)$
Alcock-Paczynski:
$D_A H$=const.
Standard Ruler:
D_A^2/H=const.
H/H_{ref}
$D_A/D_{A,ref}$
1.10
1.05
1.00
0.95
0.90
0.95
1.00
1.05

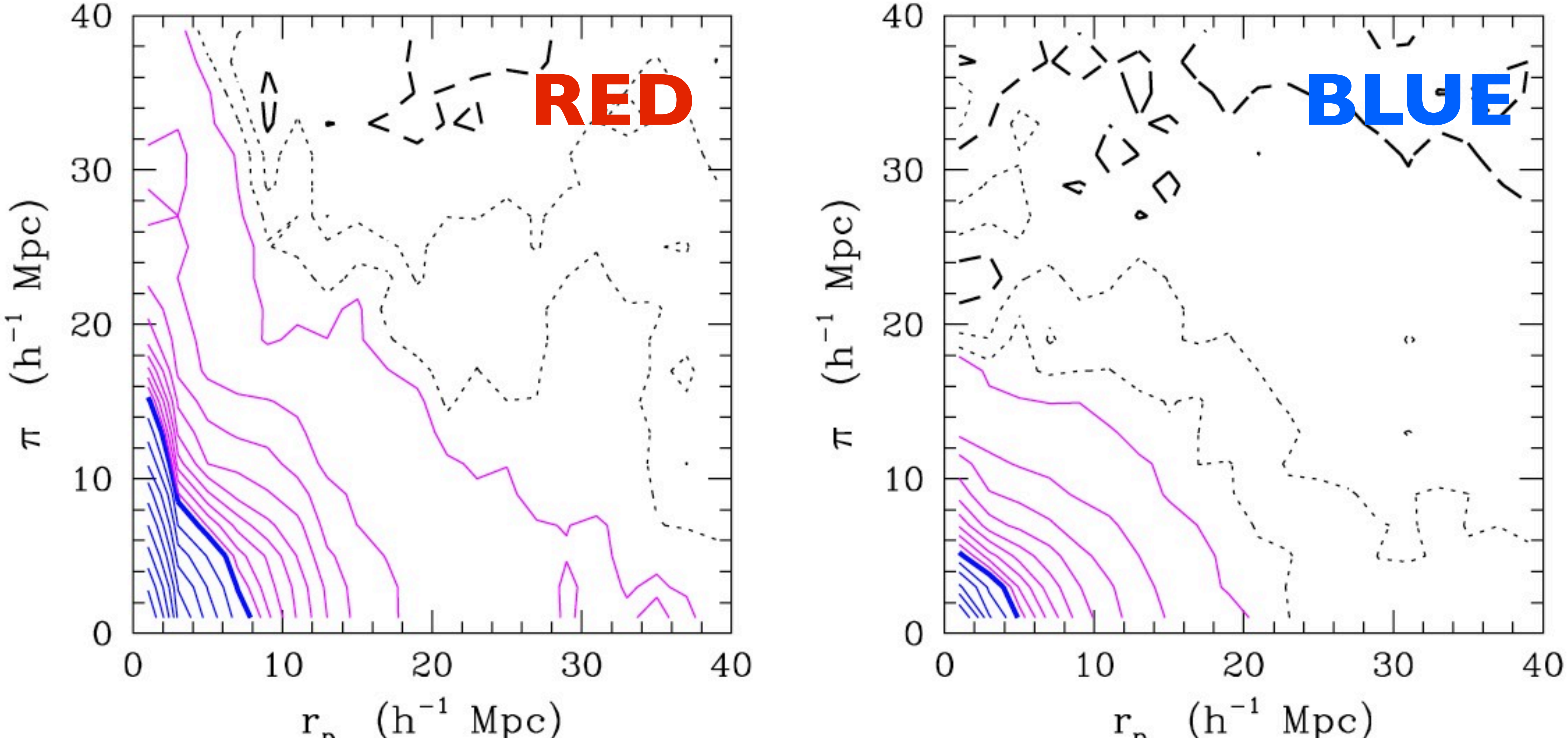
How problematic is FoG?

- It depends on a type of galaxies.
  - Field galaxies not living in bigger halos do not feel FoG.
  - Satellite galaxies living in bigger halos do feel FoG.
- Segregation by galaxy colors has been observed:
  - "Blue" galaxies exhibit substantially less FoG than "red" galaxies, which preferentially live inside bigger halos!

CAUTION:
not in Fourier space



Coil et al. (2008) DEEP2



Zehavi et al. (2011)
SDSS

Summary

- HETDEX will start the main survey next year
- HETDEX is the first **blind** spectroscopic survey with a large (>>1 Gpc^3) volume
- IFU-based surveys seem powerful; we will see soon!
- We expect to detect ~0.8M Lyman-alpha emitting galaxies to map the large-scale structure in an unexplored territory of z=1.9–3.5
- Target: detection of dark energy (even if it is a cosmological constant) at z~2
- We also measure the neutrino mass; curvature; etc