Primordial Cosmology through Large-scale Structure of the Universe

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Observations and Theoretical Challenges in Primordial Cosmology,
KITP, April 26, 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?

Cosmology: Next Decade?

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TABLE I Summary of Science Frontiers Panels' Findings

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	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*

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*

Motivating running index...

- $n_s<1$ **discovered**. Now what?

$$n_s - 1 = M_{\rm pl}^2\left[-3\left(\frac{V'}{V}\right)^2 + 2\left(\frac{V''}{V}\right)\right] \sim O(1/N) \sim O(1/50)$$

For "large-field" potentials, $r \sim \left(\frac{V'}{V}\right)^2 \sim O(1/N) \sim \left(\frac{V''}{V}\right)$

For "plateau-like" potentials, $r \sim \left(\frac{V'}{V}\right)^2 \sim O(1/N^2) \ll \left(\frac{V''}{V}\right)$

Motivating running index...

- $n_s<1$ **discovered**. Now what?

$$dn_s/d\ln k = 2M_{\rm pl}^4\left[4\left(\frac{V'}{V}\right)^2\left(\frac{V''}{V}\right) - 3\left(\frac{V'}{V}\right)^4 - \left(\frac{V'V'''}{V^2}\right)\right]$$

For "large-field" potentials, $dn_s/d\ln k \sim O(1/N^2)$ [detectable, with some effort]

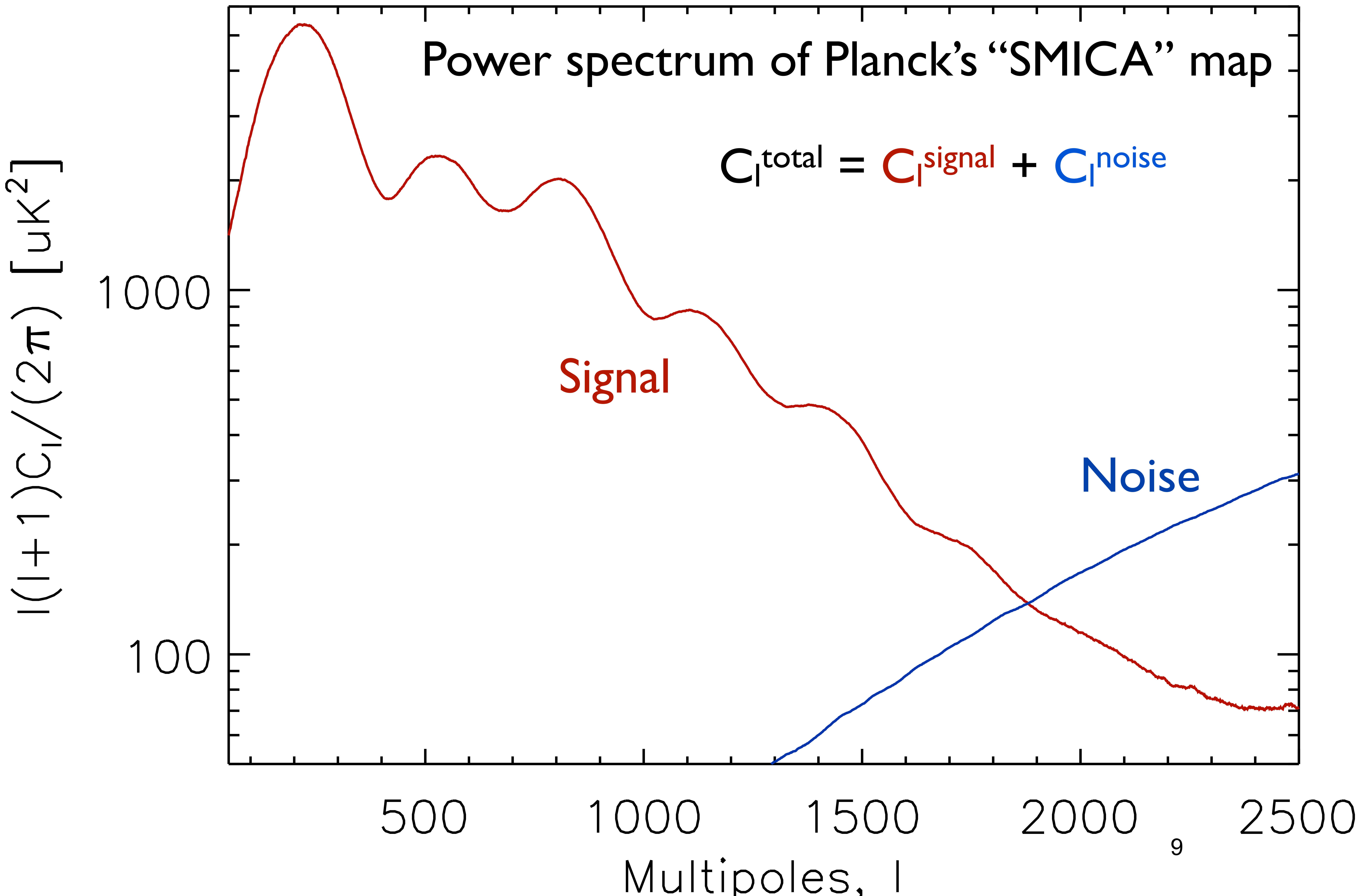
For "plateau-like" potentials, $dn_s/d\ln k \sim$ MAX[$O(1/N^3)$, $O(1/N*V'''/V)$] [undetectable, unless V'''/V is O(1/N)]

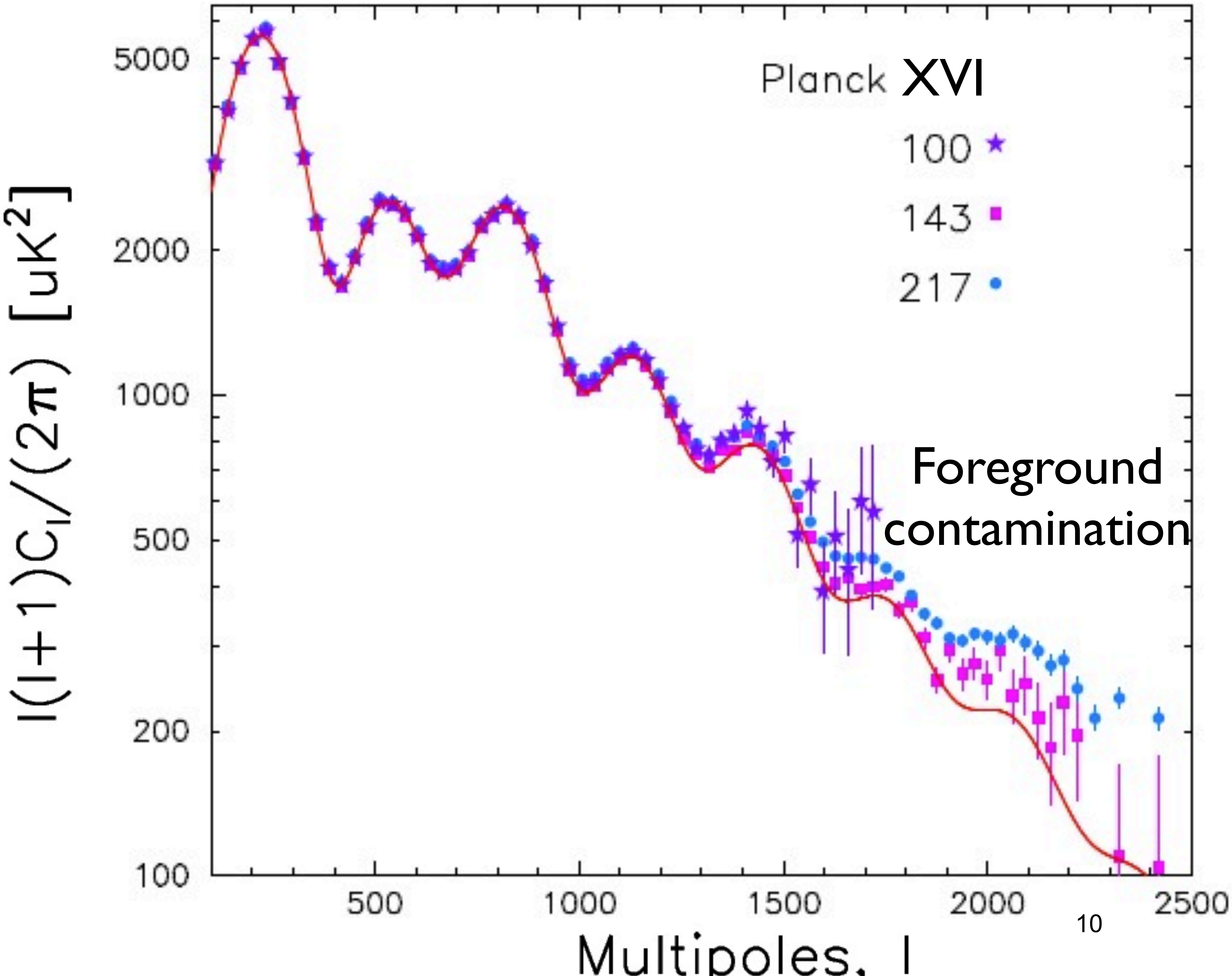
Why large-scale structure?

- Two-dimensional field: CMB, gravitational lensing, etc
  - $T(n)=\sum a_{lm} Y_{lm}(n)$
  - The number of modes grows as ~ $(l_{max})^2$
- Three-dimensional density field: galaxies with measured redshifts, Lyman-alpha forest, 21-cm forest, etc
  - $n_{galaxy}(\mathbf{x})=n\sum[1+\delta(\mathbf{k})]e^{i\mathbf{k}\cdot\mathbf{x}}$
  - The number of modes grows as ~ $(k_{max})^3$

What determines l_{max}?

- Instrumental noise
- Resolution ("beam")
- Foreground contamination


Power spectrum of Planck's "SMICA" map
$C_l^{total} = C_l^{signal} + C_l^{noise}$
Signal
Noise
1000
100
500
1000
1500
2000
2500
Multipoles, l
l(l+1)Cl/(2π) [uK²]



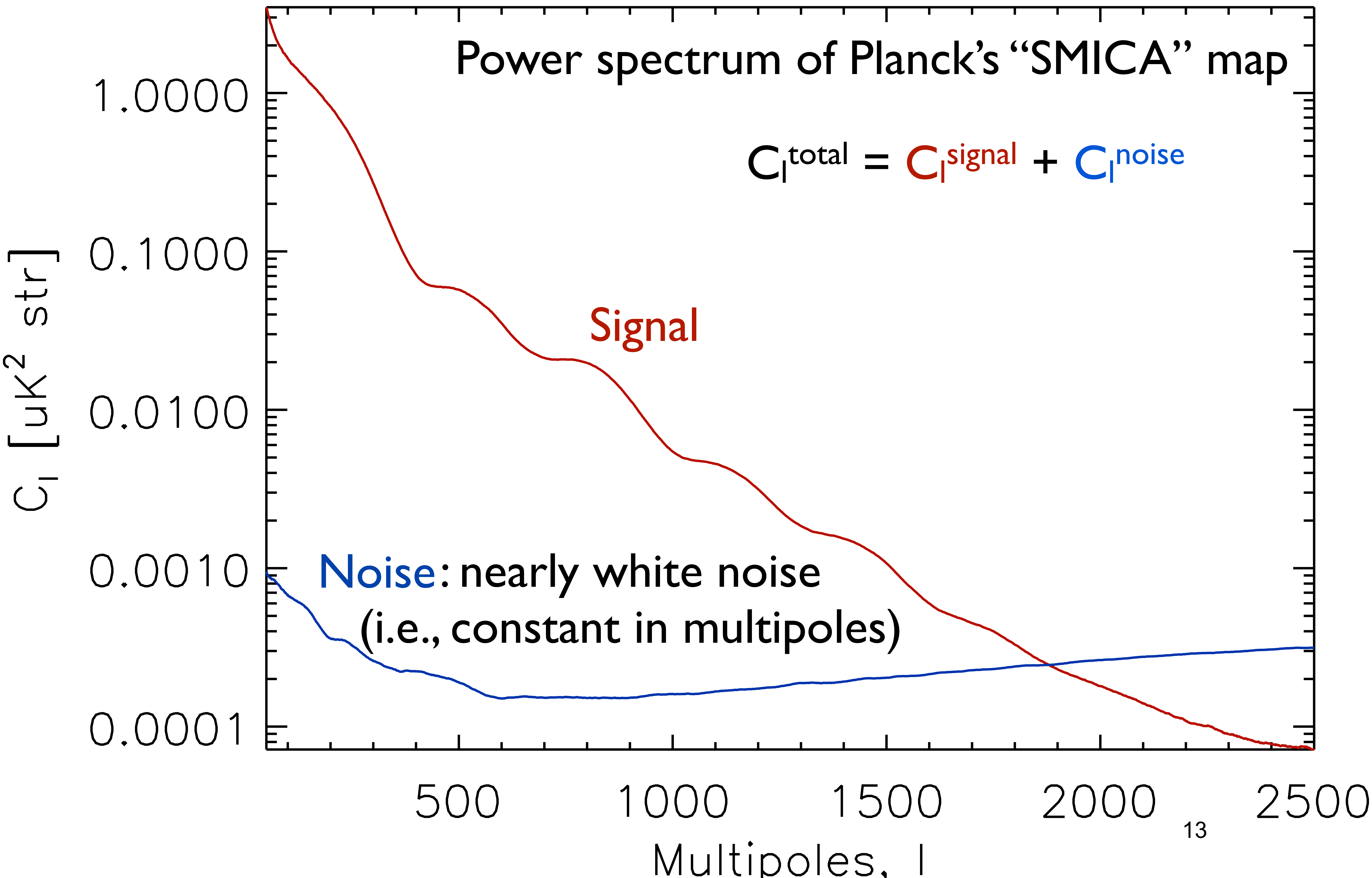
Planck XVI
100
143
217
Foreground contamination
5000
2000
1000
500
200
100
500
1000
1500
2000
2500
l(l+1)C_l/(2π) [uK²]
Multipoles, l

$l(l+1)C_l/(2\pi)$

- Why plotting $l(l+1)C_l/(2\pi)$?
  - Because it becomes a constant for a scale-invariant spectrum at low multipoles if only the primordial fluctuation is at work (just Sachs-Wolfe; no ISW; no acoustic oscillation)
  - Because it gives a good estimate of the temperature variance per logarithmic multipole interval
  - $\langle T^2 \rangle = (1/4\pi)\sum(2l+1)C_l = \sum l^{-1}[\mathbf{l(l+0.5)C_l/(2\pi)}]$

C_l

- Let's plot C_l [in units of μK^2 **steradian**]
  - A good exercise before we look at the power spectrum of matter/galaxy distribution that is commonly used by the large-scale structure community.

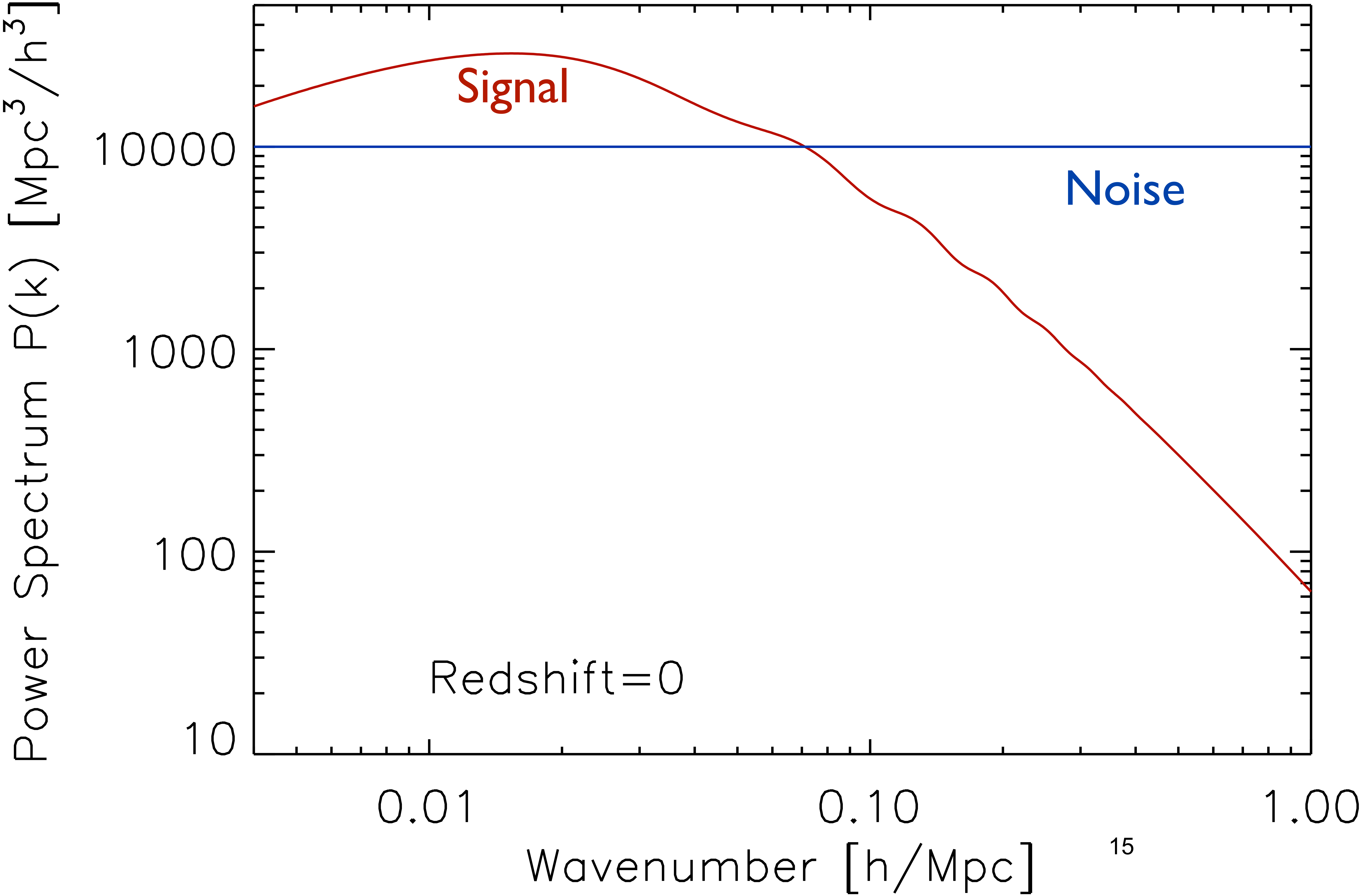


Power spectrum of Planck's "SMICA" map
$C_l^{total} = C_l^{signal} + C_l^{noise}$
Signal
Noise: nearly white noise
(i.e., constant in multipoles)
1.0000
0.1000
0.0100
0.0010
0.0001
C_l [uK^2 str]
500
1000
1500
2000
2500
Multipoles, l

Multipoles to wavenumbers

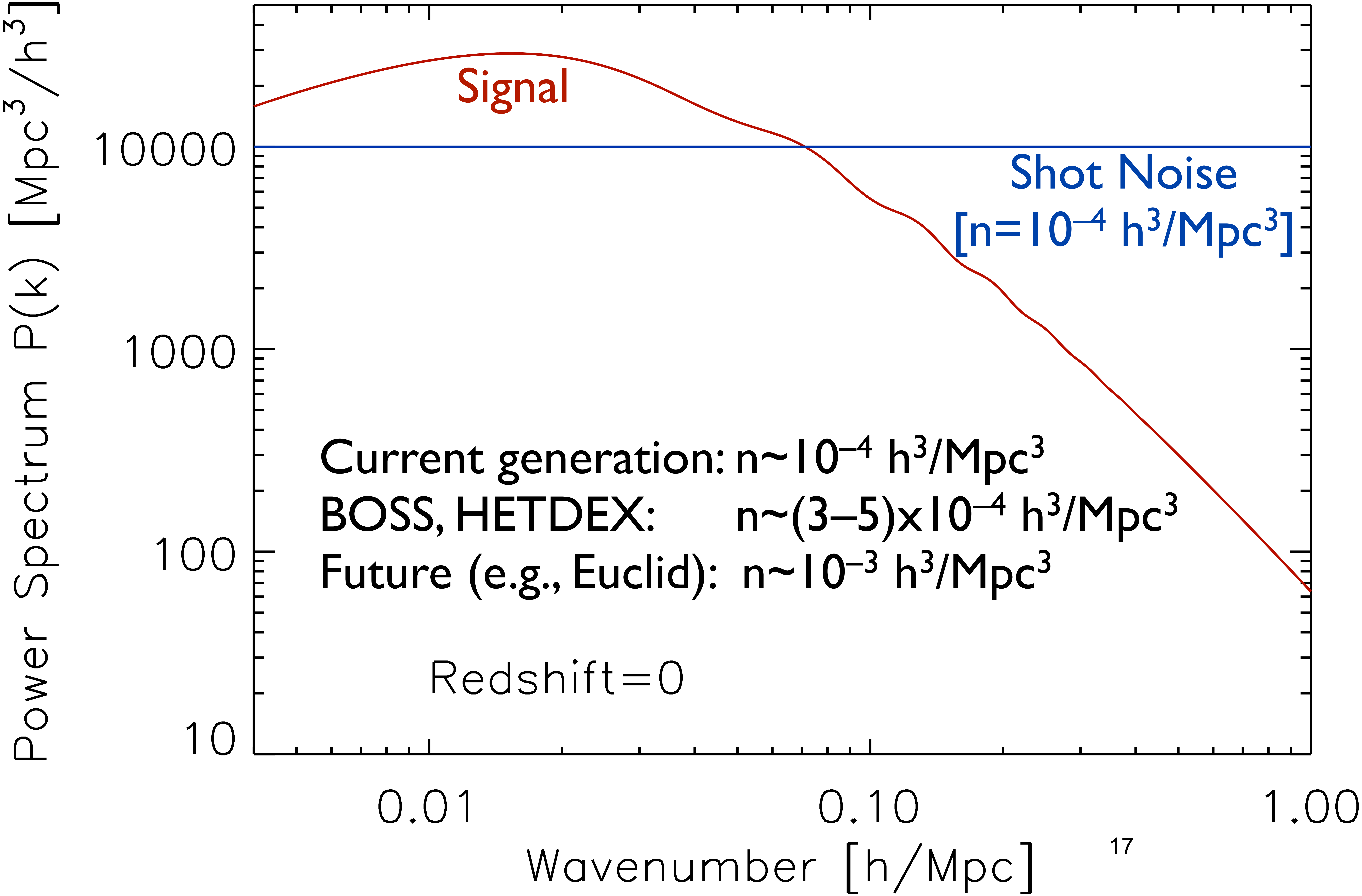
- k = [multipoles]/[angular diameter distance to z=1090]
- k = [multipoles]/(14,000 Mpc)
  - l=2: k~0.00014/Mpc ~ 0.0002 h/Mpc [h~0.7]
  - l=1000: k~0.071/Mpc ~ 0.10 h/Mpc
  - l=2500: k~0.18/Mpc ~ 0.26 h/Mpc

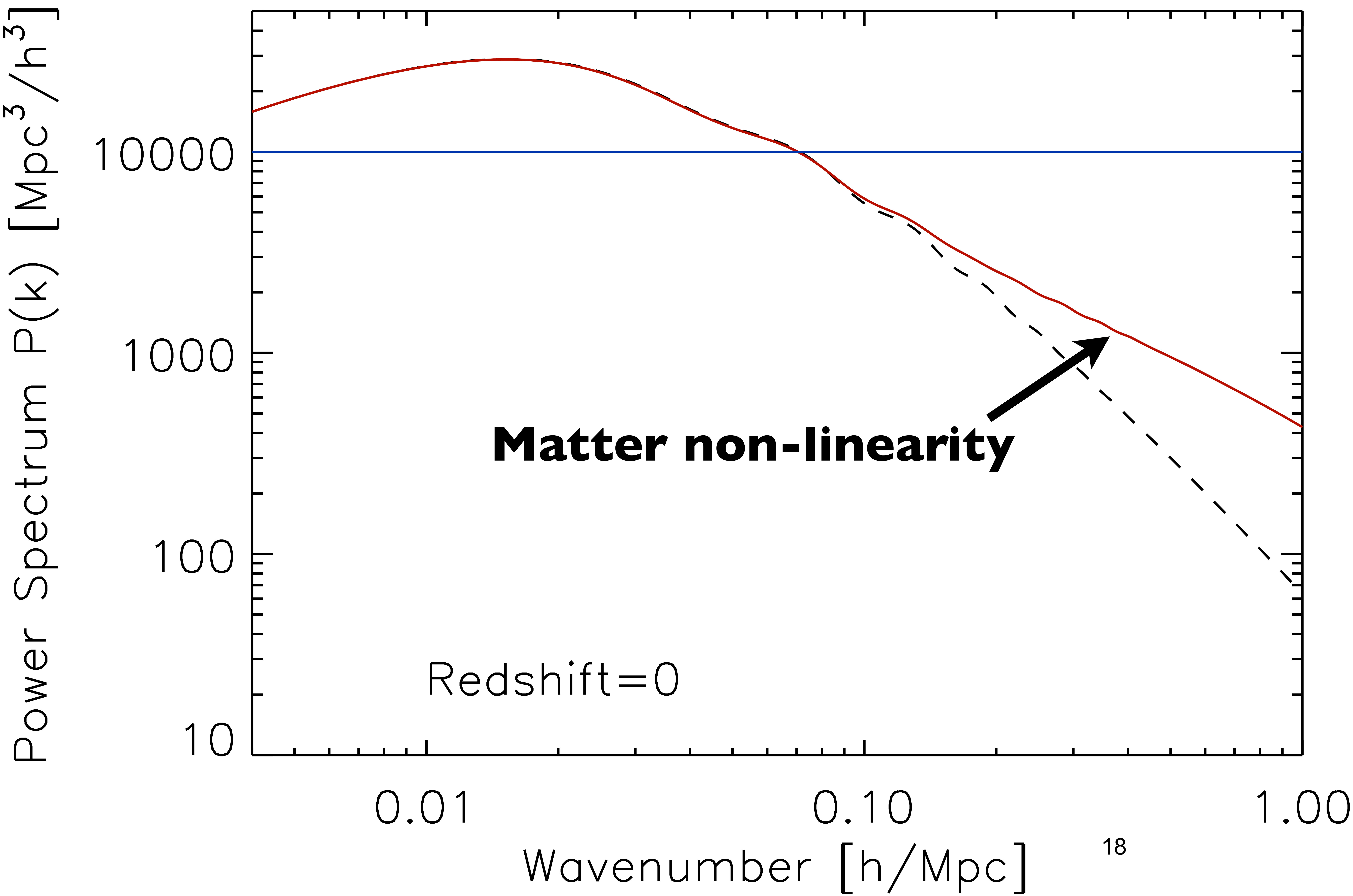
Planck data probe fluctuations in $2\times10^{-4} < k < 0.26$ h/Mpc


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

What determines k_{max}?

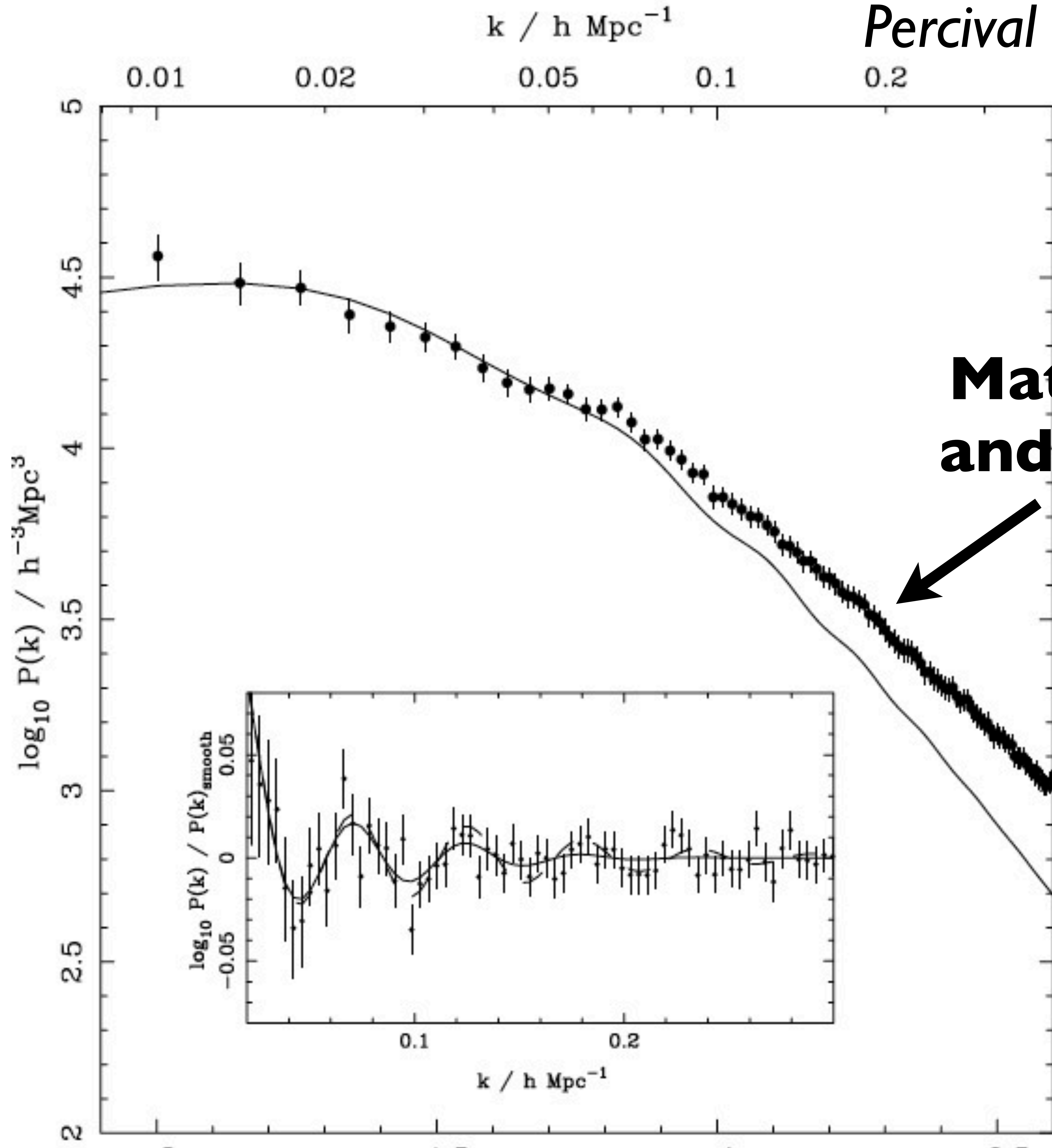
- Shot noise = 1/[the number density of galaxies]
- Non-linearities
  - Dark matter non-linearity [gravity]
  - Redshift space distortion non-linearity [gravity/astro]
  - Astrophysical non-linearities [astro]


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]

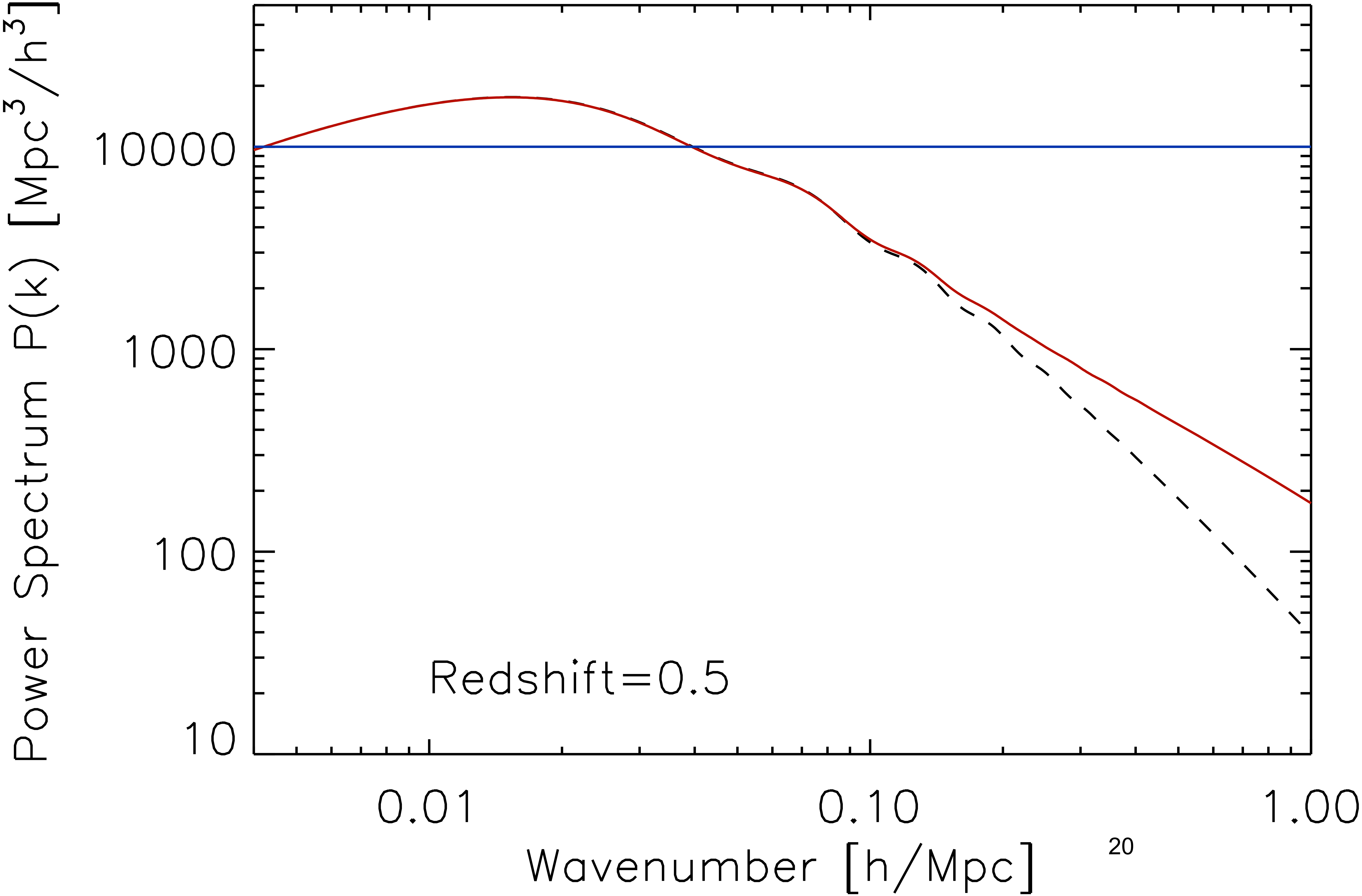


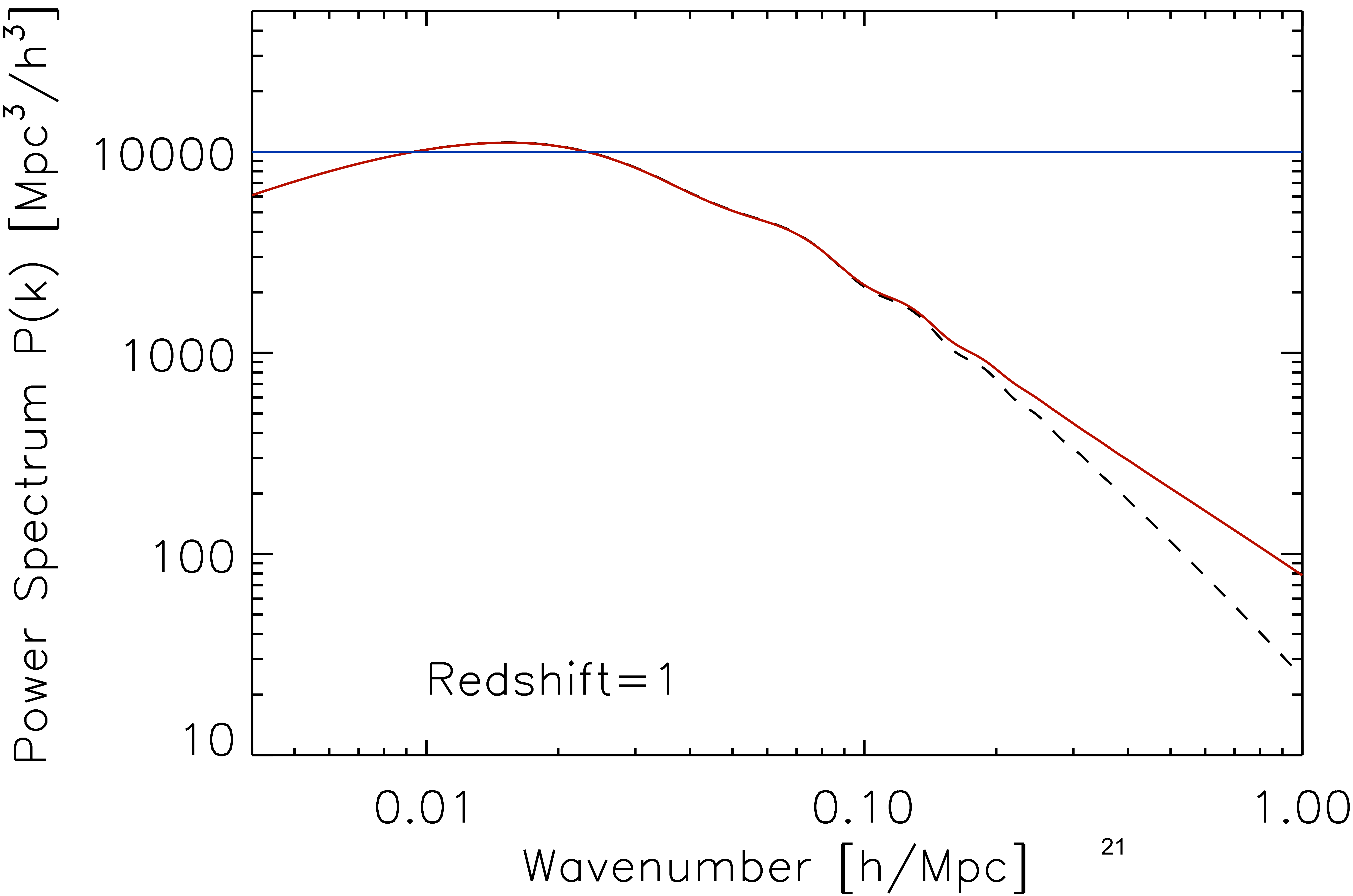
Power Spectrum P(k) [Mpc³/h³]
10000
1000
100
10
Matter non-linearity
Redshift=0
0.01
0.10
1.00
Wavenumber [h/Mpc]

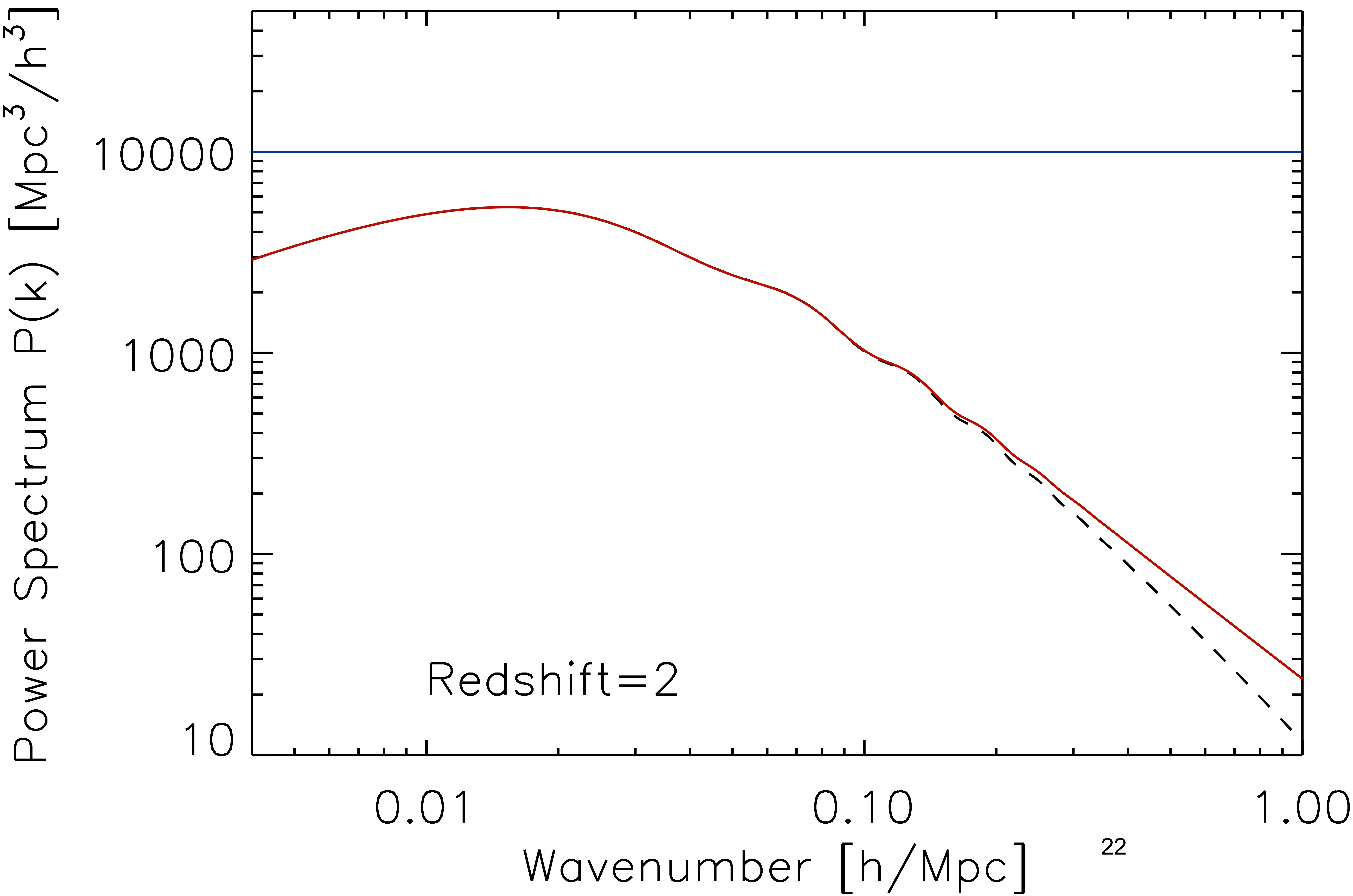
Percival et al. (2007) SDSS DR5



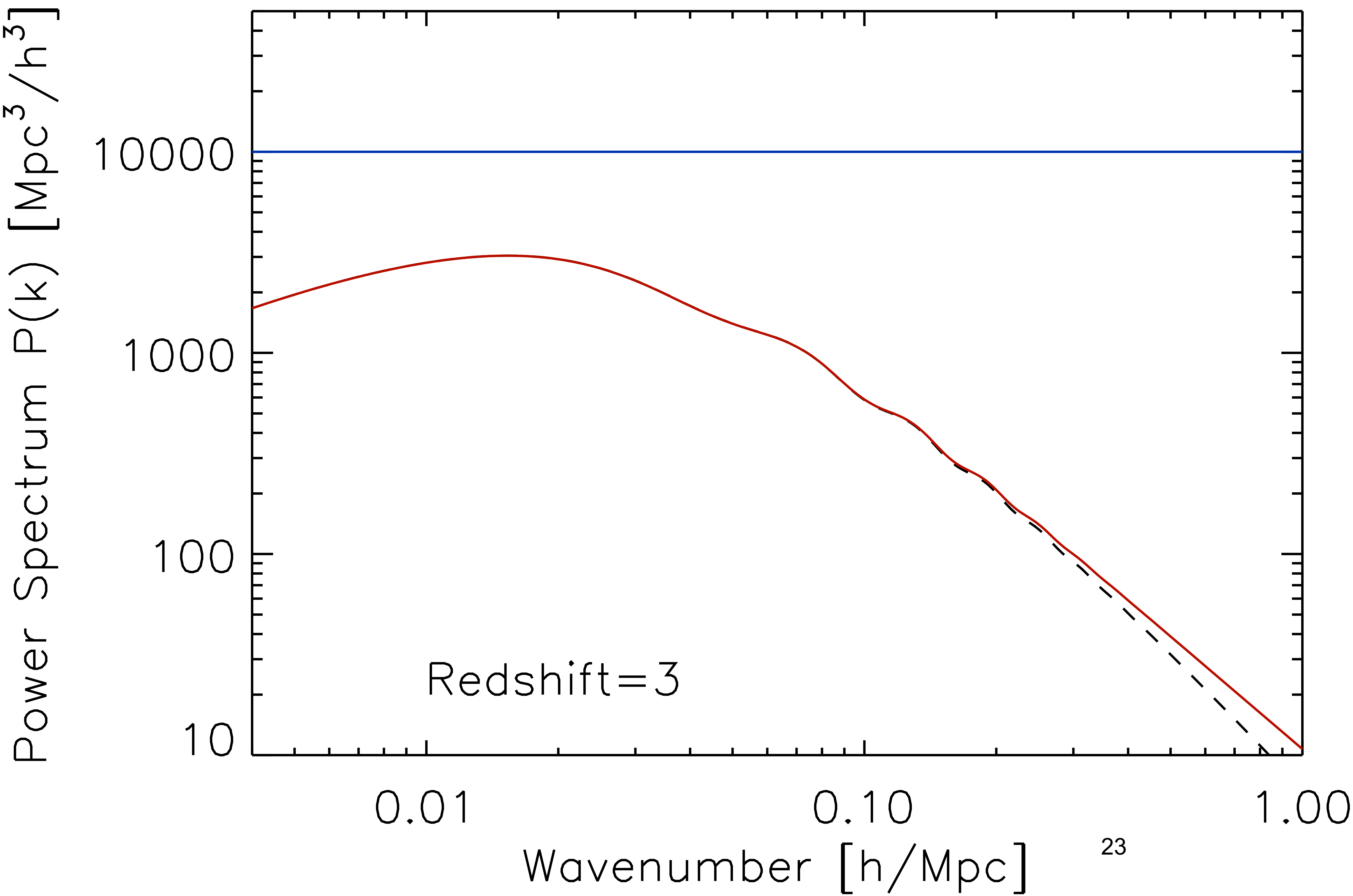
Matter non-linearity and galaxy formation


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

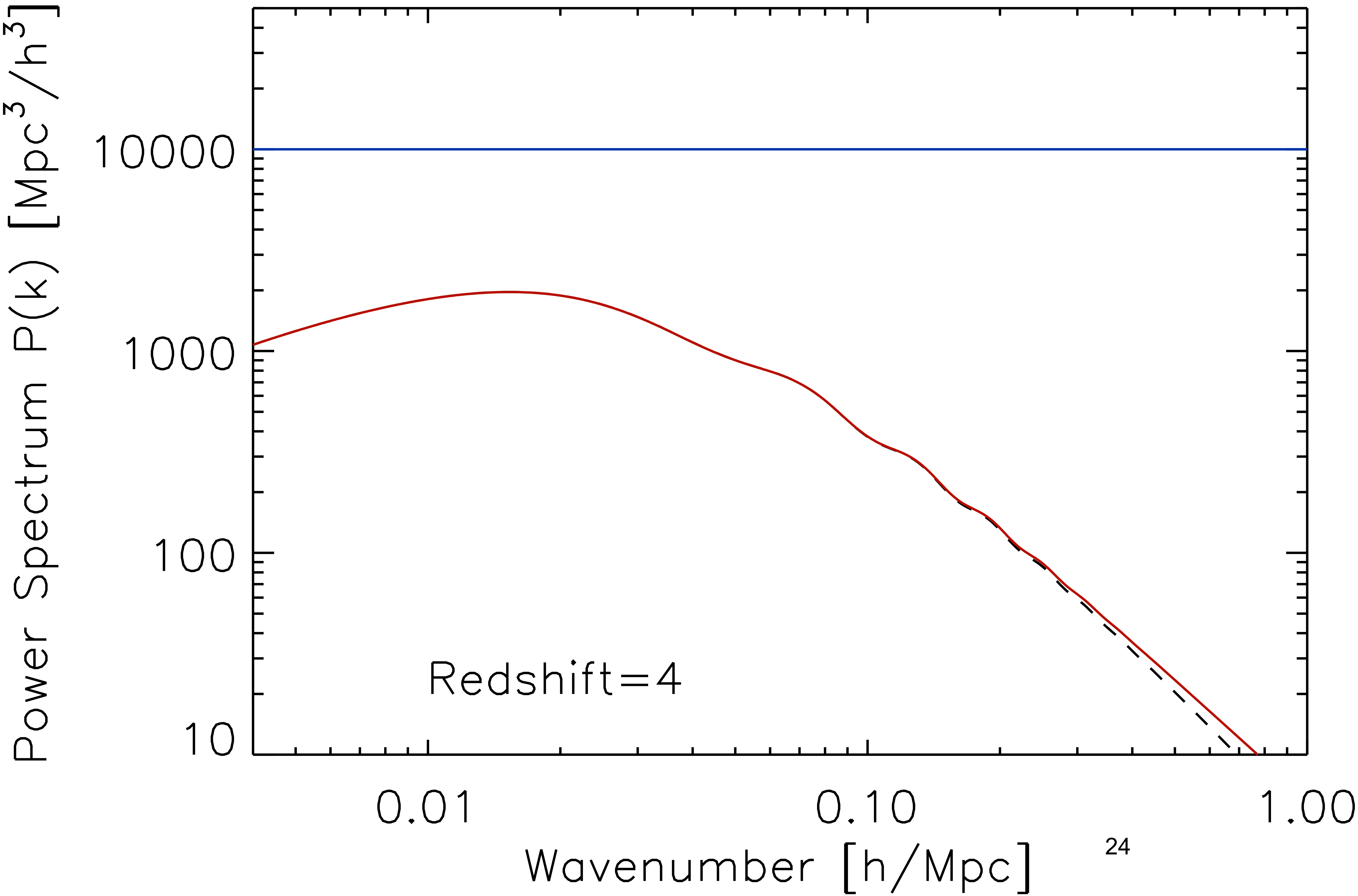

Power Spectrum P(k) [Mpc^3/h^3]
10000
1000
100
10
Redshift=1
0.01
0.10
1.00
Wavenumber [h/Mpc]



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



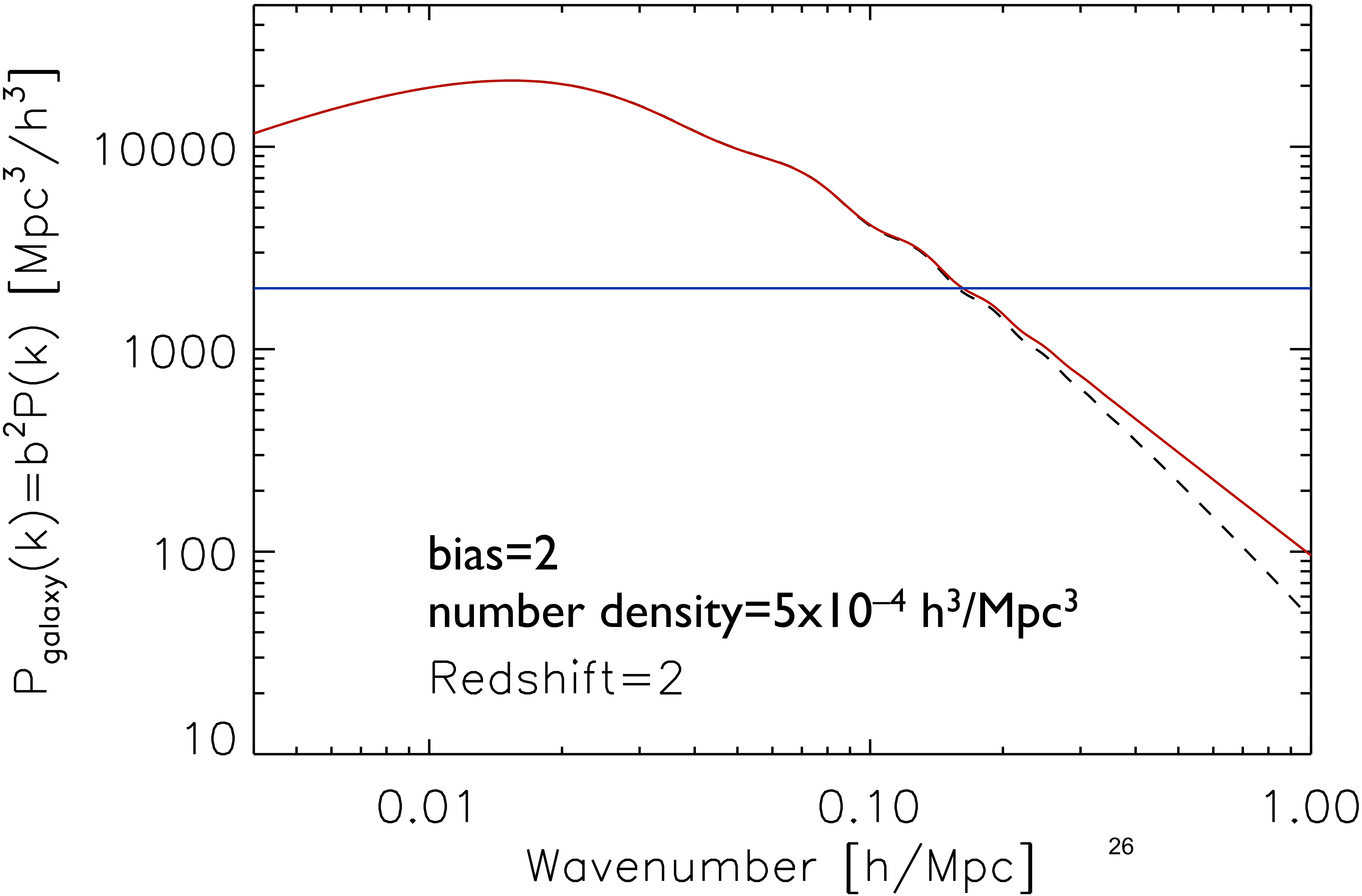
Power Spectrum P(k) [Mpc^3/h^3]
10000
1000
100
10
Redshift=3
0.01
0.10
1.00
Wavenumber [h/Mpc]



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



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

Having thought a lot about high-z galaxy surveys

- Since 2004, we have been thinking a lot about a potential of high-z galaxy surveys exactly within the context of "inflation," "dark energy," and "neutrino mass."
- Inflation: non-Gaussianity, and...... running index!
- This was the time when SDSS was reaching up to z~0.35. We were thinking about z>2, ..., all the way up to 6.

PHYSICAL REVIEW D **73**, 083520 (2006)

Cosmology with high-redshift galaxy survey: Neutrino mass and inflation

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(Received 14 December 2005; revised manuscript received 7 March 2006; published 18 April 2006)

High-z galaxy redshift surveys open up exciting possibilities for precision determinations of neutrino masses and inflationary models. The high-z surveys are more useful for cosmology than low-z ones owing to much weaker nonlinearities in matter clustering, redshift-space distortion, and galaxy bias, which allows us to use the galaxy power spectrum down to the smaller spatial scales that are inaccessible by low-z surveys. We can then utilize the two-dimensional information of the linear power spectrum in angular and redshift space to measure the scale-dependent suppression of matter clustering due to neutrino free-streaming as well as the shape of the primordial power spectrum. To illustrate capabilities of high-z surveys for constraining neutrino masses and the primordial power spectrum, we compare three future redshift surveys covering 300 square degrees at $0.5 < z < 2$, $2 < z < 4$, and $3.5 < z < 6.5$. We find that, combined with the cosmic microwave background data expected from the Planck satellite, these surveys allow precision determination of the total neutrino mass with the projected errors of $\sigma(m_{\nu,\mathrm{tot}}) = 0.059$, 0.043, and 0.025 eV, respectively, thus yielding a positive *detection* of the neutrino mass rather than an upper limit, as $\sigma(m_{\nu,\mathrm{tot}})$ is smaller than the lower limits to the neutrino masses implied from the neutrino oscillation experiments, by up to a factor of 4 for the highest redshift survey. The accuracies of constraining the tilt and running index of the primordial power spectrum, $\sigma(n_s) = (3.8, 3.7, 3.0) \times 10^{-3}$ and $\sigma(\alpha_s) = (5.9, 5.7, 2.4) \times 10^{-3}$ at $k_0 = 0.05\ \mathrm{Mpc}^{-1}$, respectively, are smaller than the current uncertainties by more than an order of magnitude, which will allow us to discriminate between candidate inflationary models. In particular, the error on α_s from the future highest redshift survey is not very far away from the prediction of a class of simple inflationary models driven by a massive scalar field with self-coupling, $\alpha_s = -(0.8\text{–}1.2) \times 10^{-3}$.

Measuring a scale-dependence of $n_s(k)$

- As far as the value of n_s is concerned, CMB is probably enough.
- However, if we want to measure the scale-dependence of n_s, we need the small-scale data.
  - This is where the large-scale structure data become quite powerful
  - Schematically:
    - $dn_s/d\ln k = [n_s(\mathrm{CMB}) - n_s(\mathrm{LSS})]/(\ln k_{\mathrm{CMB}} - \ln k_{\mathrm{LSS}})$

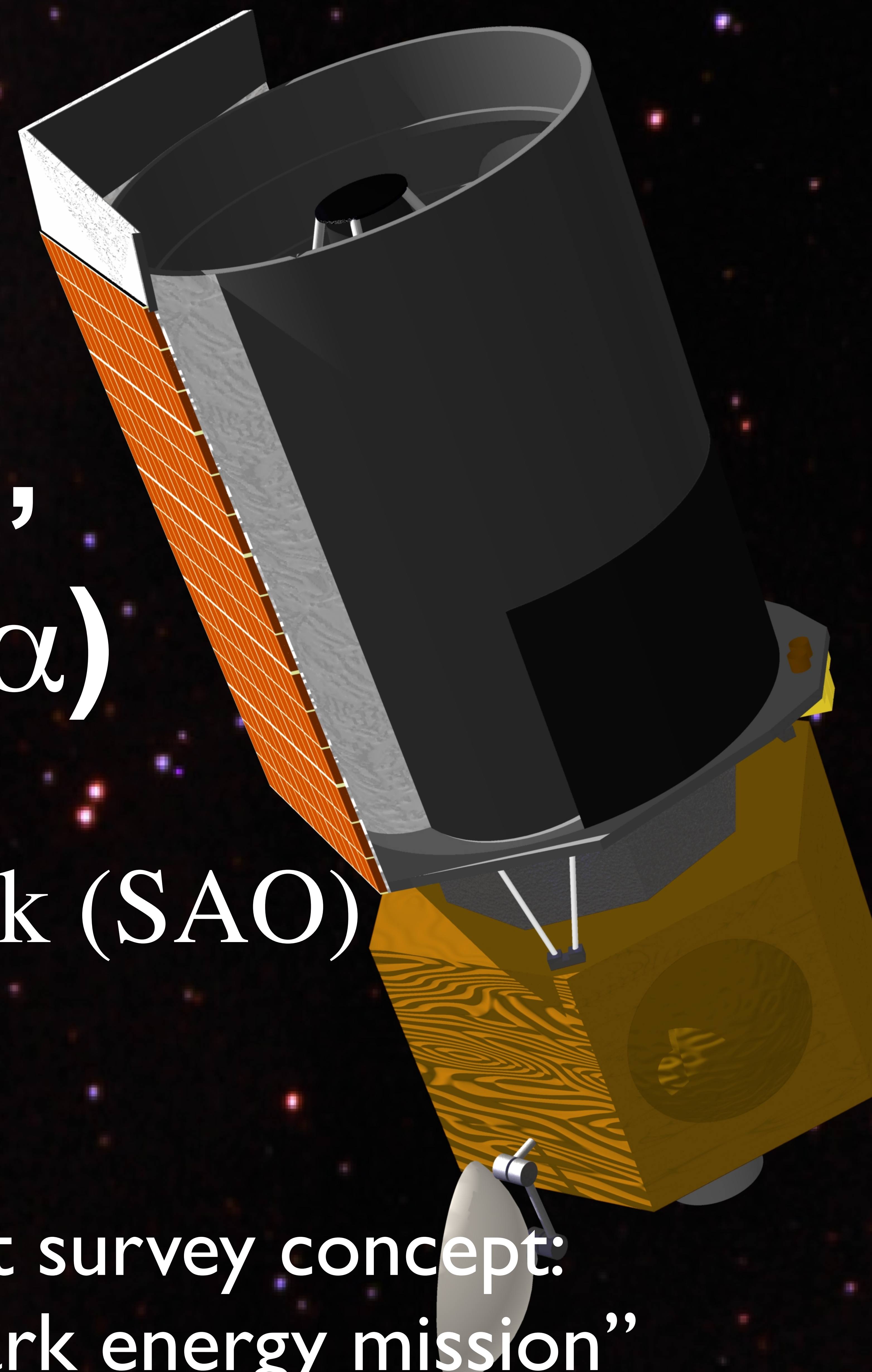
Expected uncertainties

Survey	$f_\nu(m_{\nu,\mathrm{tot}}$ eV)	n_s	$dn_s/d\ln k$
Planck alone	$\cdots$	0.0062	0.0067 -> 0.009 Planck XXII
G1 +Planck	0.0045(0.059)	0.0038	0.0059
G2 +Planck	0.0033(0.043)	0.0037	0.0057
SG +Planck	0.0019(0.025)	0.0030	0.0024

Survey	z_{center}	k_{max} ($h\mathrm{Mpc}^{-1}$)	Ω_{survey} (deg^2)	V_s (h^{-3} Gpc^3)	$\bar{n}_g$ ($10^{-3}h^3$ Mpc^{-3})	Bias	$P_g\bar{n}_g$ (k_{max})
G1 ($0.5 < z < 2$)	0.75	0.14	300	0.33	0.5	1.22	4.83
	1.25	0.19	300	0.53	0.5	1.47	2.49
	1.75	0.25	300	0.64	0.5	1.75	1.38
G2 ($2 < z < 4$)	2.25	0.32	300	0.68	0.5	2.03	0.80
	2.75	0.41	300	0.69	0.5	2.32	0.46
	3.25	0.52	300	0.67	0.5	2.62	0.27
	3.75	0.64	300	0.64	0.5	2.92	0.16
SG ($3.5 < z < 6.5$)	4	0.71	300	1.26	5	4	2.19
	5	1.01	300	1.13	5	5	1.04
	6	1.50	300	1.02	5	5.5	0.35

CIP

COSMIC INFLATION PROBE



λ=2.5-5μm,

z=3-6.5 (Hα)

PI: Gary Melnick (SAO)

Slitless grism redshift survey concept:
now absorbed by a "dark energy mission"

PHYSICAL REVIEW D **76,** 083004 (2007)

Bispectrum of galaxies from high-redshift galaxy surveys: Primordial non-Gaussianity and nonlinear galaxy bias

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(Received 21 May 2007; published 17 October 2007)

The greatest challenge in the interpretation of galaxy clustering data from any surveys is galaxy bias. Using a simple Fisher matrix analysis, we show that the bispectrum provides an excellent determination of linear and nonlinear bias parameters of intermediate and high-z galaxies, when all measurable triangle configurations down to mildly nonlinear scales, where perturbation theory is still valid, are included. The bispectrum is also a powerful probe of primordial non-Gaussianity. The planned galaxy surveys at $z \gtrsim 2$ should yield constraints on non-Gaussian parameters, $f_{NL}^{\rm loc.}$ and $f_{NL}^{\rm eq.}$, that are comparable to, or even better than, those from cosmic microwave background experiments. We study how these constraints improve with volume and redshift range, as well as the number density of galaxies. Finally, we show that a halo occupation distribution may be used to improve these constraints further by lifting degeneracies between gravity, bias, and primordial non-Gaussianity.

A lot have happened since 2007

	V	n_g	z	$k_{\max}$	b_1	b_2
SDSS	0.3	30		0.09	1.19	−0.10
LRG	0.72	1	0.35	0.11	2.14	0.96
APO-LSS	3.8	4	0.35	0.11	1.69	0.21
WFMOS1	1.6	5	0.7	0.14	1.87	0.45
	2.4	5	1.1	0.18	2.16	1.00
ADEPT	45	1	1.25	0.20	2.97	3.44
	55	1	1.75	0.26	3.44	5.43
WFMOS2	0.5	5	2.55	0.38	3.27	4.64
	0.5	5	3.05	0.48	3.64	6.39
HETDEX	0.68	5	2.25	0.34	3.05	3.70
	0.69	5	2.75	0.42	3.42	5.32
	0.67	5	3.25	0.53	3.79	7.16
	0.64	5	3.75	0.65	4.14	9.20
					...	...
CIP	1.26	50	4	0.71	3.16	4.12
	1.13	50	5	1.03	3.72	6.76
	1.02	50	6	1.46	4.26	9.90
					...	...

A lot have happened since 2007

BOSS

PFS (>2018)

WFIRST; EUCLID (>2020)

reincarnation

reincarnation

dead

starting!

reincarnation

	V	n_g	z	$k_{\max}$	b_1	b_2
SDSS	0.3	30		0.09	1.19	−0.10
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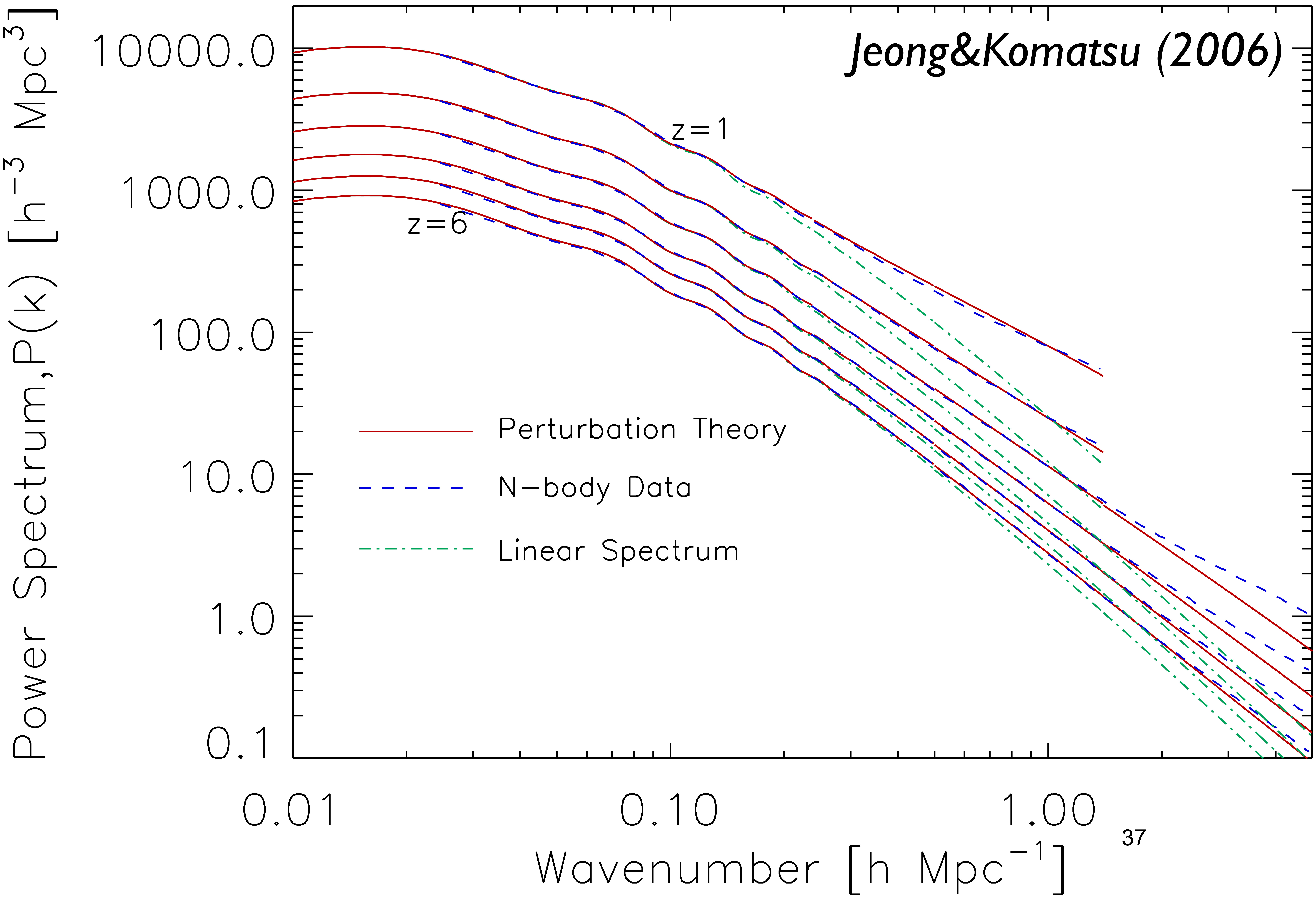
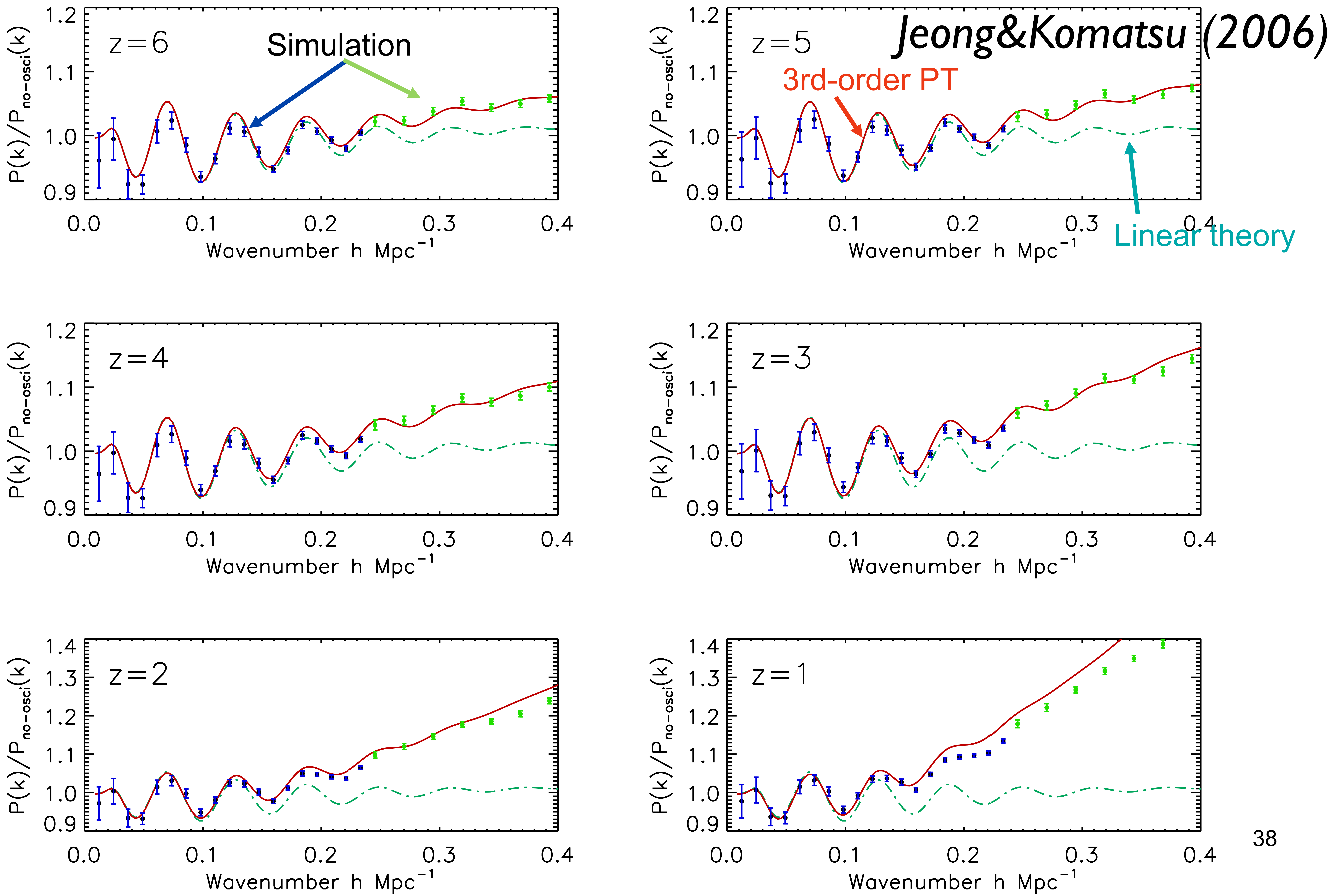
	0.67	5	3.25	0.53	3.79	7.16
	0.64	5	3.75	0.65	4.14	9.20
					...	...
CIP	1.26	50	4	0.71	3.16	4.12
	1.13	50	5	1.03	3.72	6.76
	1.02	50	6	1.46	4.26	9.90
					...	...

	V [Gpc^3/h^3]	n_g [10^{-4} h^3/Mpc^3]	z	k_{max}	b_1	b_2	Δb_1	Δb_2	$\Delta f_{NL}^{eq.}$
ADEPT	45	1	1.25	0.20	2.97	3.44	0.031	0.111	73
	55	1	1.75	0.26	3.44	5.43	0.025	0.112	53
	combined						...	...	43
WFMOS2	0.5	5	2.55	0.38	3.27	4.64	0.094	0.406	256
	0.5	5	3.05	0.48	3.64	6.39	0.087	0.439	215
	combined							...	164
HETDEX	0.68	5	2.25	0.34	3.05	3.70	0.083	0.326	244
	0.69	5	2.75	0.42	3.42	5.32	0.077	0.357	202
	0.67	5	3.25	0.53	3.79	7.16	0.076	0.401	177
	0.64	5	3.75	0.65	4.14	9.20	0.079	0.469	163
	combined				...	...	...	...	95
CIP	1.26	50	4	0.71	3.16	4.12	0.016	0.066	51
	1.13	50	5	1.03	3.72	6.76	0.015	0.079	40
	1.02	50	6	1.46	4.26	9.90	0.016	0.102	36
	combined				...	...	...	...	24

So, it seems:

- Indeed, the large-scale structure is quite powerful, especially when it goes to high redshifts ($z>2$), where k_{max} can be made (much) bigger than k_{max} at $z<<1$.
  - Running index of $dn/d\ln k \sim 10^{-3}$ is challenging, but doable. $f_{NL}^{equil} \sim$ a few tens also doable.
  - [Detection of the neutrino mass may be just around the corner]
- Perturbation theory approach promising at $z>2$
  - Jeong&Komatsu (2006) [DM]; (2009) [galaxy bias]
- Redshift space distortion non-linearity -> more later


Jeong&Komatsu (2006)
z=1
z=6
Perturbation Theory
N-body Data
Linear Spectrum
Power Spectrum, P(k) [h^{-3} Mpc^3]
Wavenumber [h Mpc^{-1}]
10000.0
1000.0
100.0
10.0
1.0
0.1
0.01
0.10
1.00


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
0.0
0.1
0.2
0.3
0.4
0.9
1.0
1.1
1.2
1.3
1.4

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Max-Planck-Institut für Astrophysik

UNIVERSITY OF OXFORD

Hobby-Eberly Telescope Dark Energy Experiment (HETDEX)

What is HETDEX?

- Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) is:
  - 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 galaxy survey at high z $[1.9<z<3.5]$
    - The previous big surveys were all done at $z<1$
    - High-z surveys barely reached $\sim 10^{-2} Gpc^3$

Who are we?

- About ~50 people at Univ. of Texas; McDonald Observatory; LMU; AIP; MPA; MPE; Penn State; Gottingen; Texas A&M; and Oxford
  - Principal Investigator: Gary J. Hill (Univ. of Texas)
  - Project Scientist: Karl Gebhardt (Univ. of Texas)

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  - Principal Investigator: Gary J. Hill (Univ. of Texas)
  - Project Scientist: Karl Gebhardt (Univ. of Texas)
- Enormous contributions from young postdocs and students! Cosmological analyses led by:

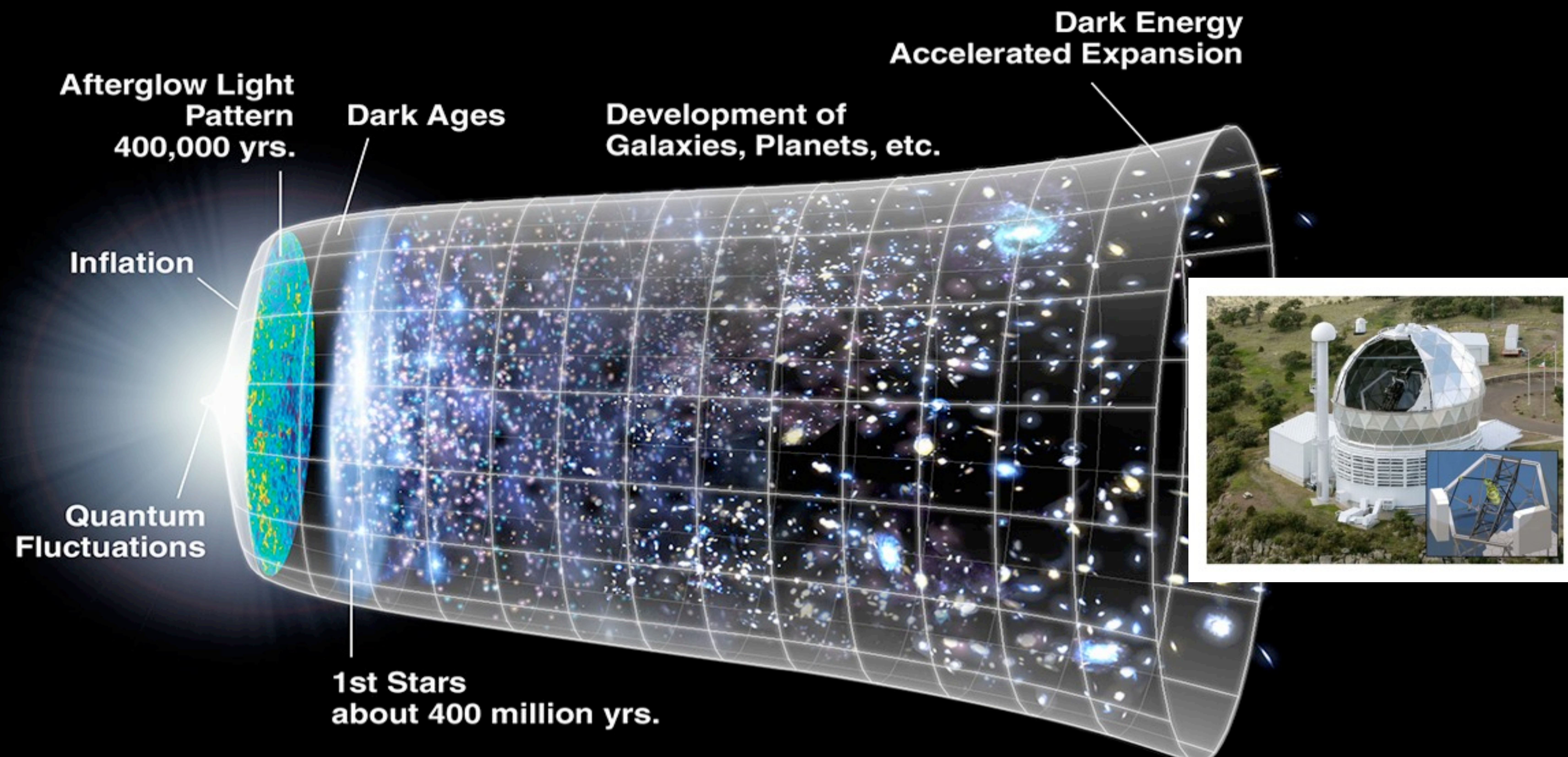
Donghui Jeong (JHU)

Chi-Ting Chiang (MPA)

Proud 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)



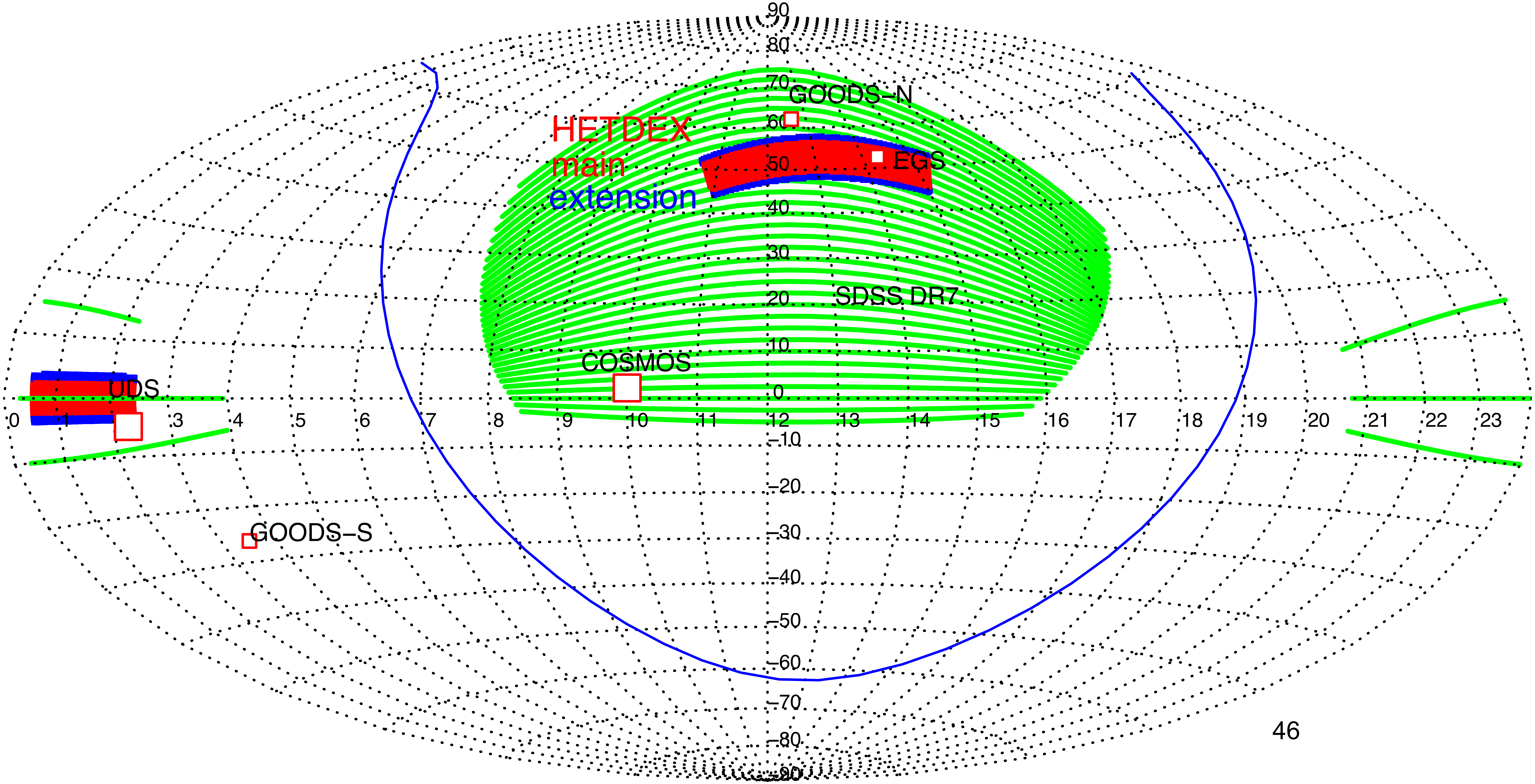
Use 10-m HET to map the universe using 0.8M Lyman-alpha emitting galaxies in z=1.9–3.5

Team

Many, MANY, spectra

- HETDEX will use the new integral field unit spectrographs called "VIRUS" (Hill et al.)
  - We will build and put 75–96 units (depending on the funding available) on a focal plane
- Each unit has two spectrographs
- Each spectrograph has 224 fibers
- Therefore, **VIRUS will have 33K to 43K fibers on a single focal place** (Texas size!)

HETDEX Foot-print (in RA-DEC coordinates)



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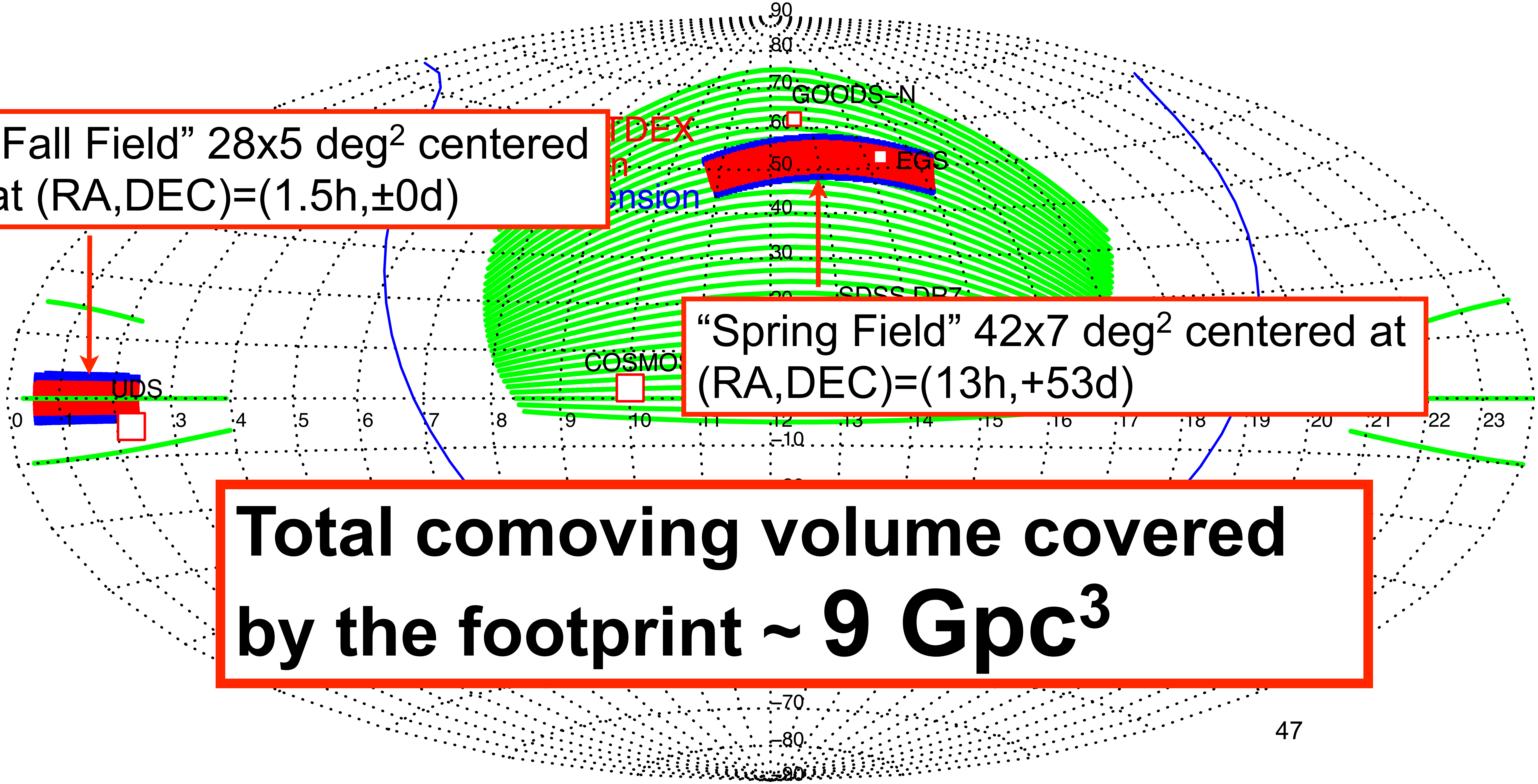
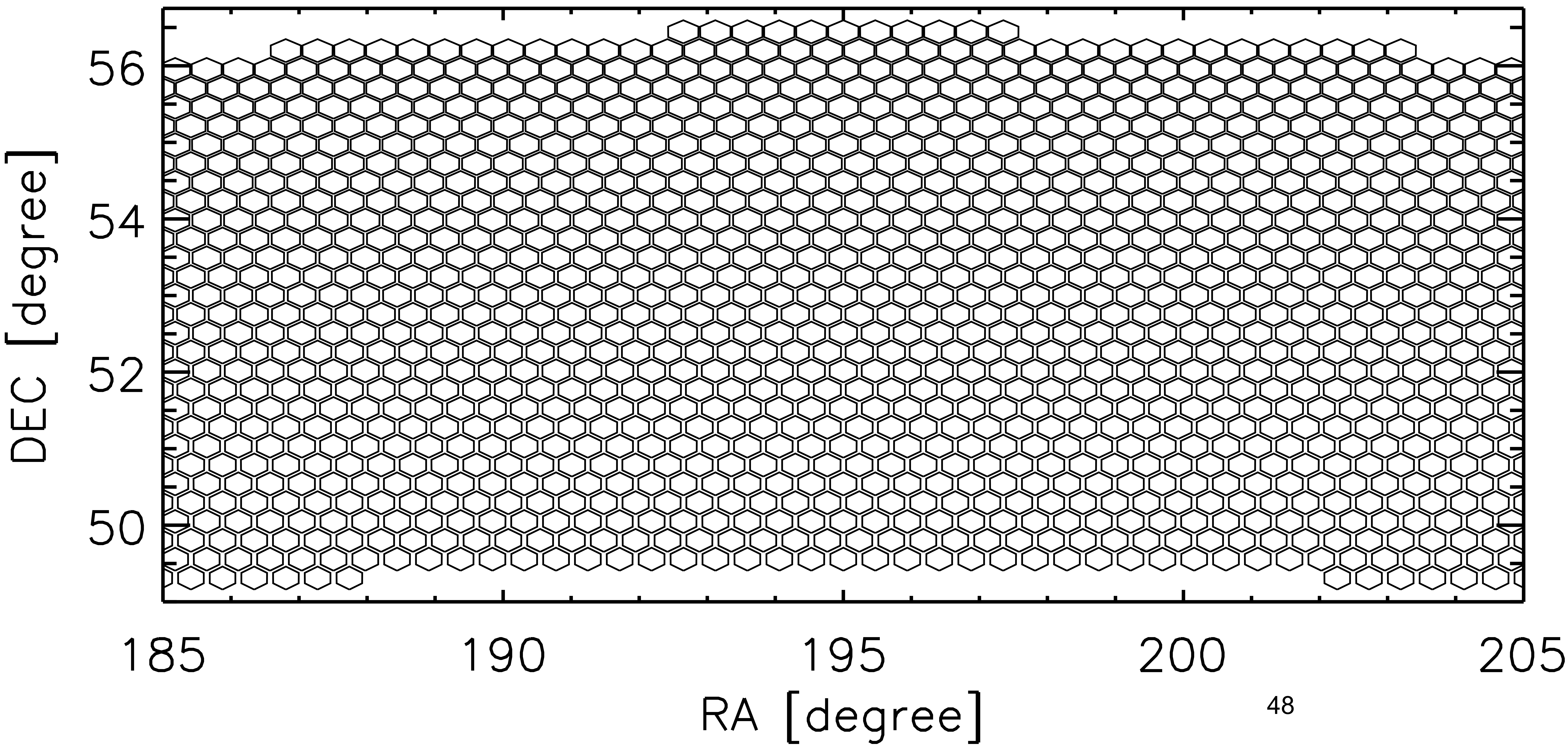


"Fall Field" 28x5 deg^2 centered at (RA,DEC)=(1.5h,±0d)

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

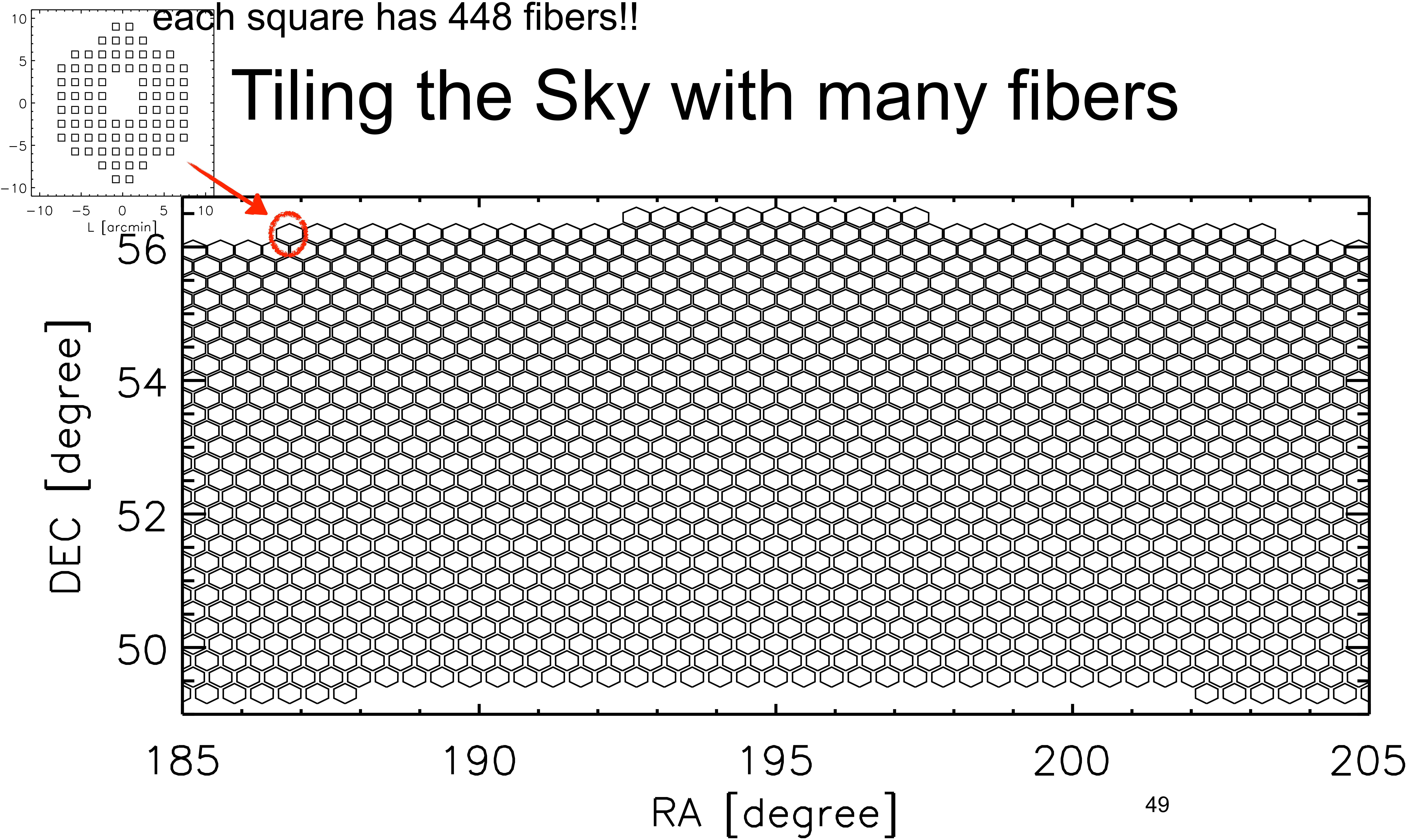
Total comoving volume covered by the footprint ~ 9 Gpc^3

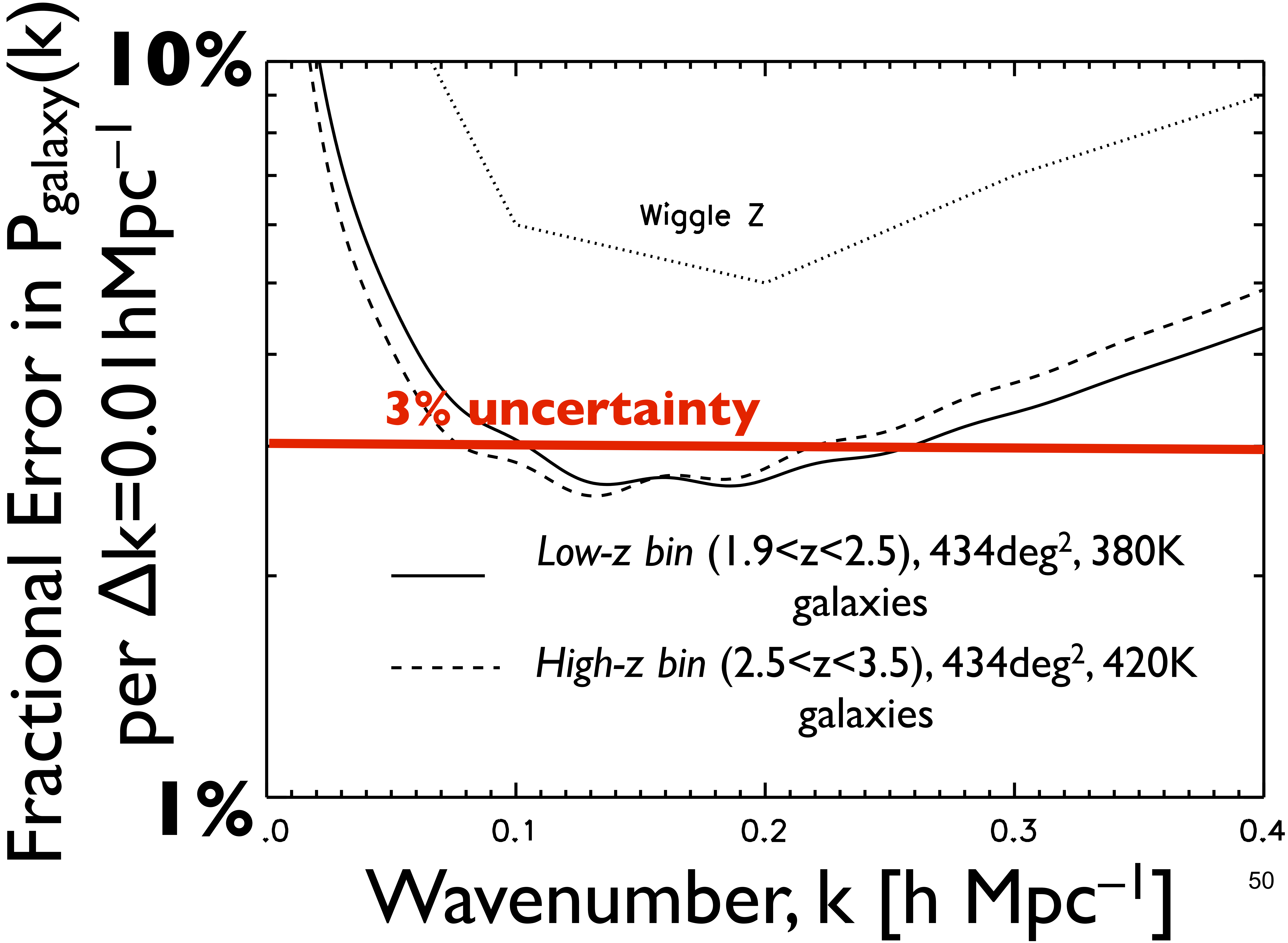
Tiling the Sky with many fibers



Tiling the Sky with many fibers

each square has 448 fibers!!





Fractional Error in $P_{galaxy}(k)$ per $\Delta k = 0.01\,h\,Mpc^{-1}$
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}]

What do we detect?

- λ=350–550nm with the resolving power of R=800 would give us:
  - ~0.8M Lyman-alpha emitting galaxies at $1.9<z<3.5$
  - ~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 **first 2 hours** of the HETDEX survey

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 BAO and the full shape and anisotropy
  - 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

- The name, “Sub-prime science,” was coined by Casey Papovich at Texas A&M Univ.
  - 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

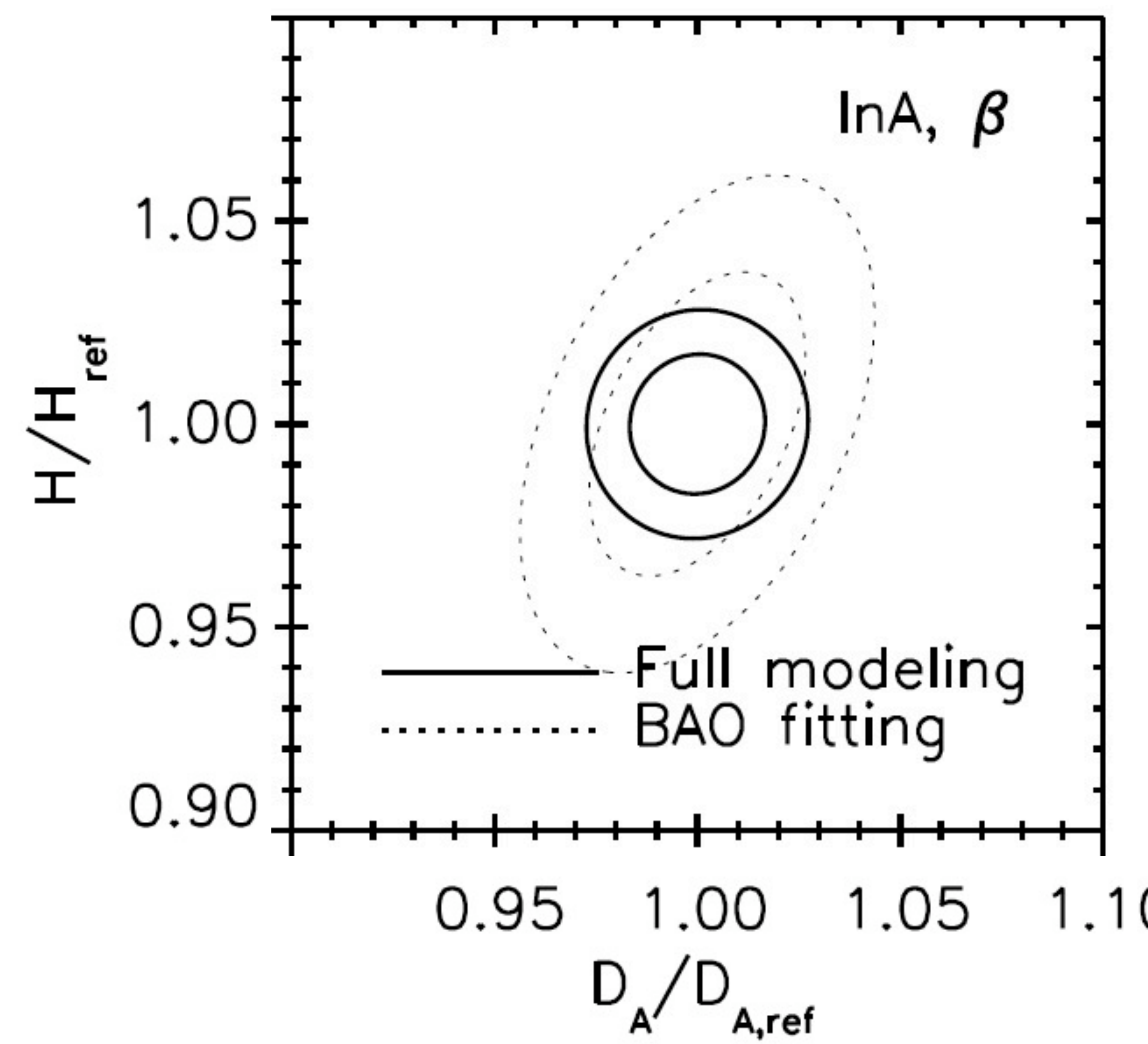
Beyond BAO

- 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)

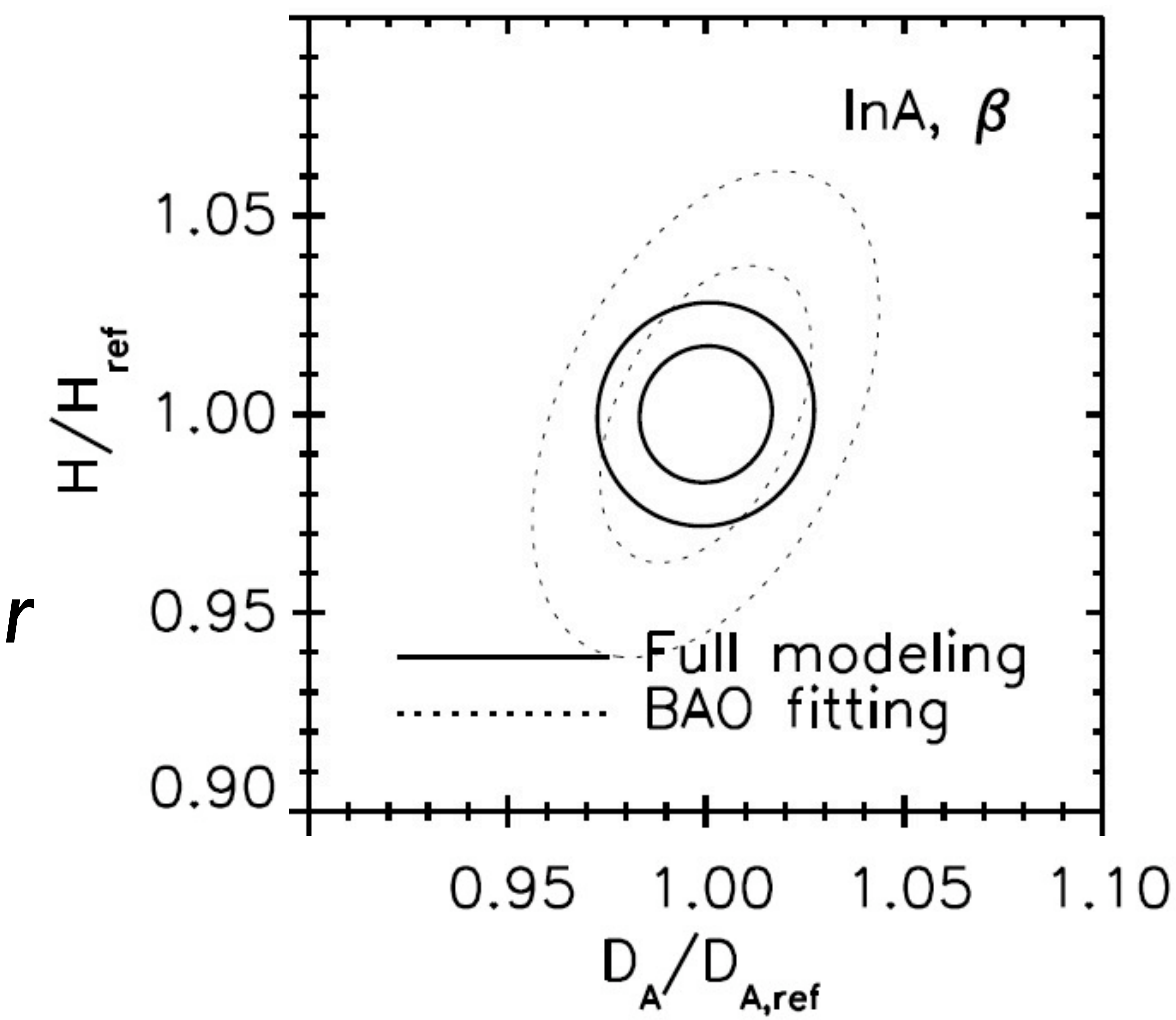
BAO vs Full Modeling

- 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.*



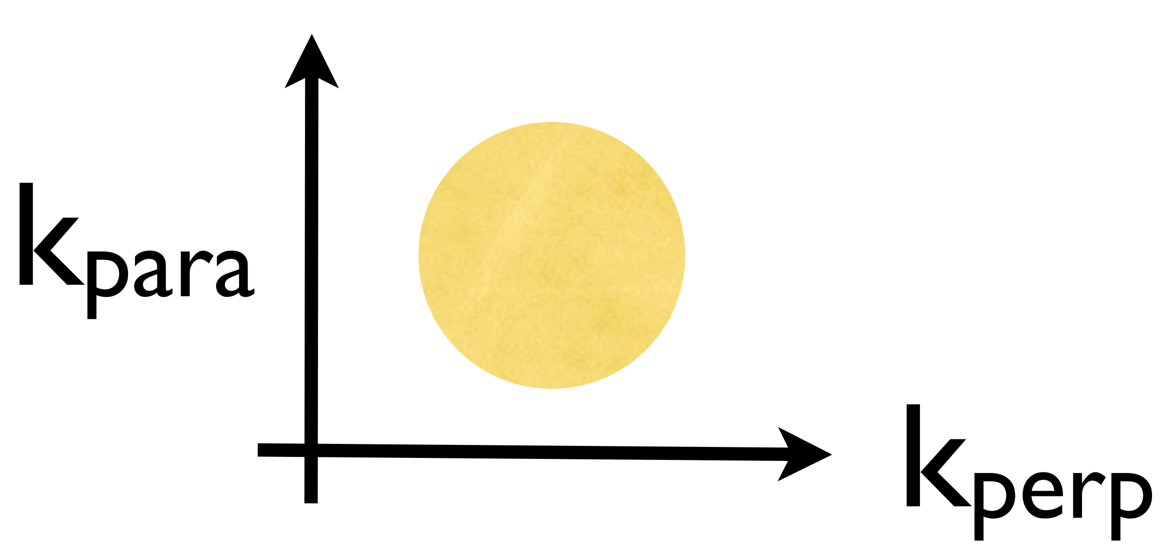
The AP Test: How That Works

- 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.

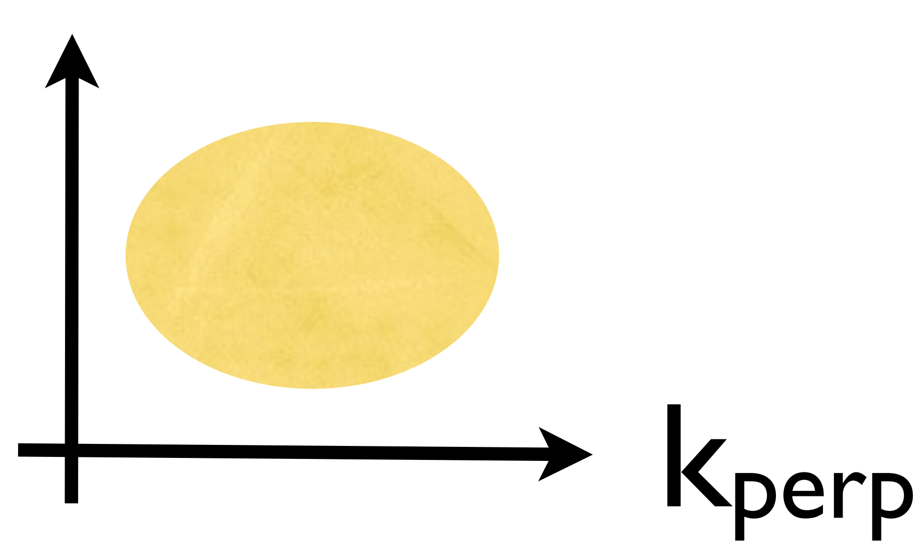
The AP Test: How That Works

- **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**$/(c\Delta z)$

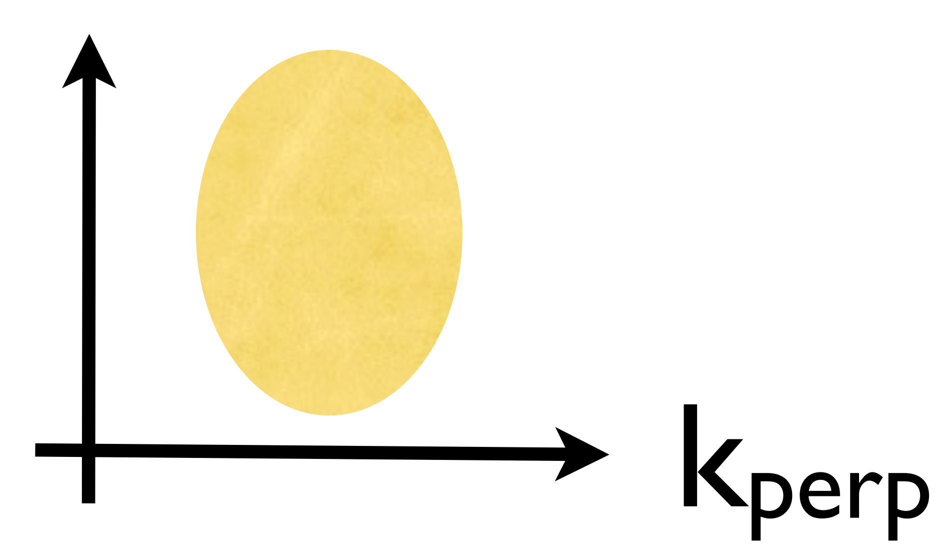
If D_A and H are correct:



If D_A is wrong:



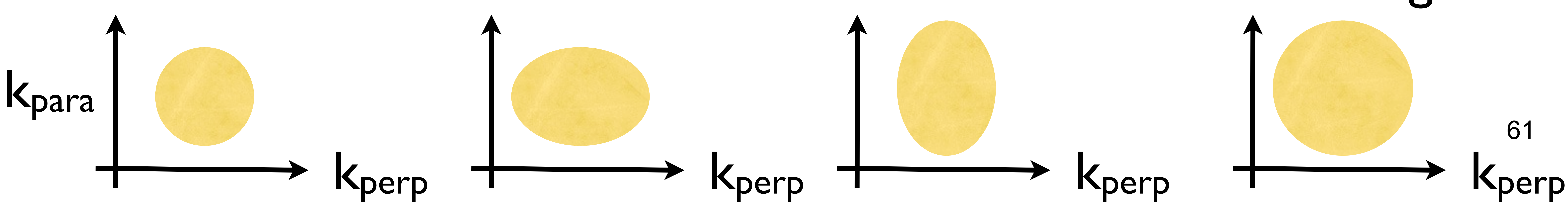
If H is wrong:



The AP Test: How That Works

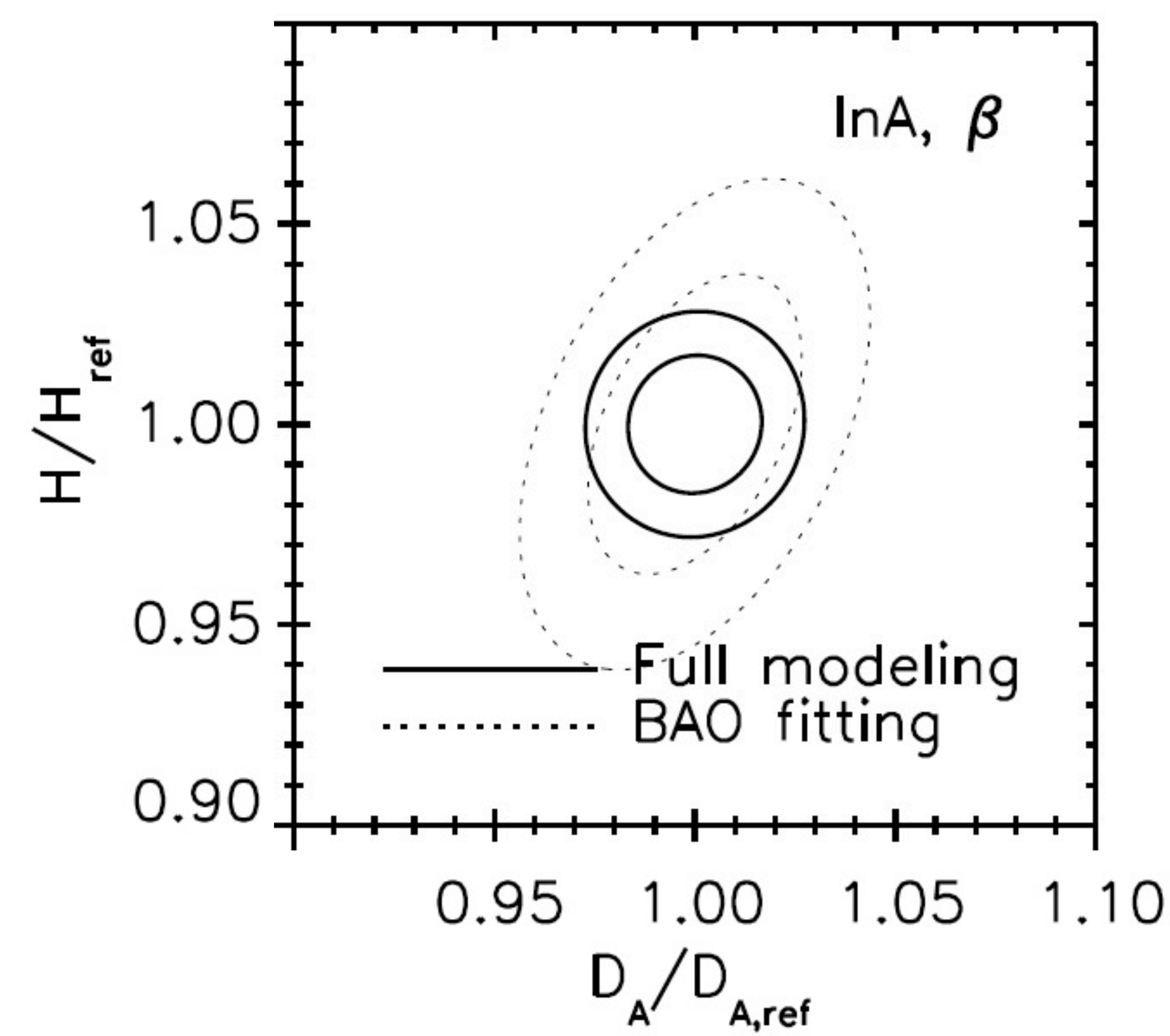
- **D_A**: (RA,Dec) to the transverse separation, r_{perp}, to the transverse wavenumber
  - $k_{perp} = (2\pi)/r_{perp} = (2\pi)$[Angle on the sky]$/$**$D_A$**
- **H**: redshifts to the parallel separation, r_{para}, to the parallel wavenumber
  - $k_{para} = (2\pi)/r_{para} = (2\pi)$**$H$**$/(c\Delta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

If D_A and H are correct: | If D_A is wrong: | If H is wrong: | If D_A and H are wrong:

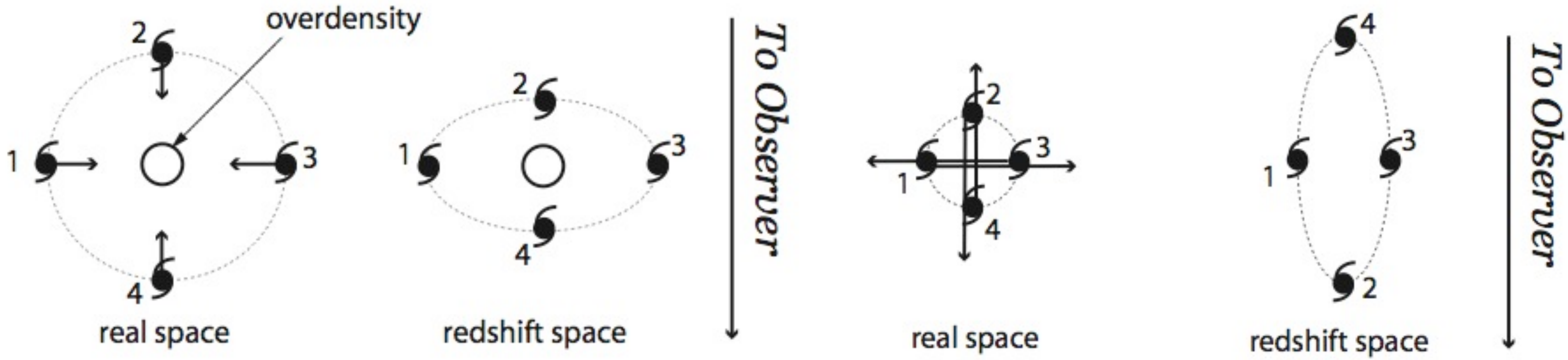


$D_A H$ from the AP test

- 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.

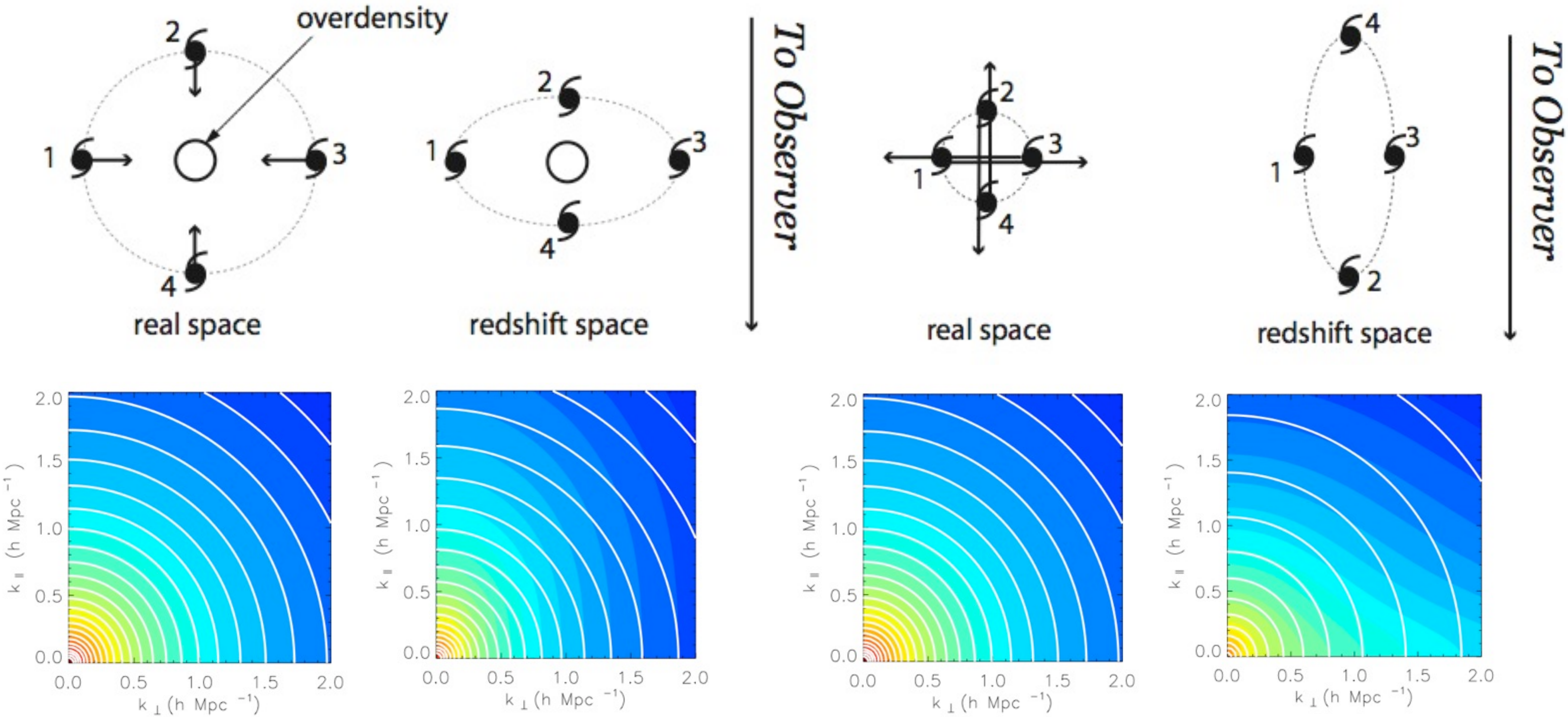


Redshift Space Distortion



- (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

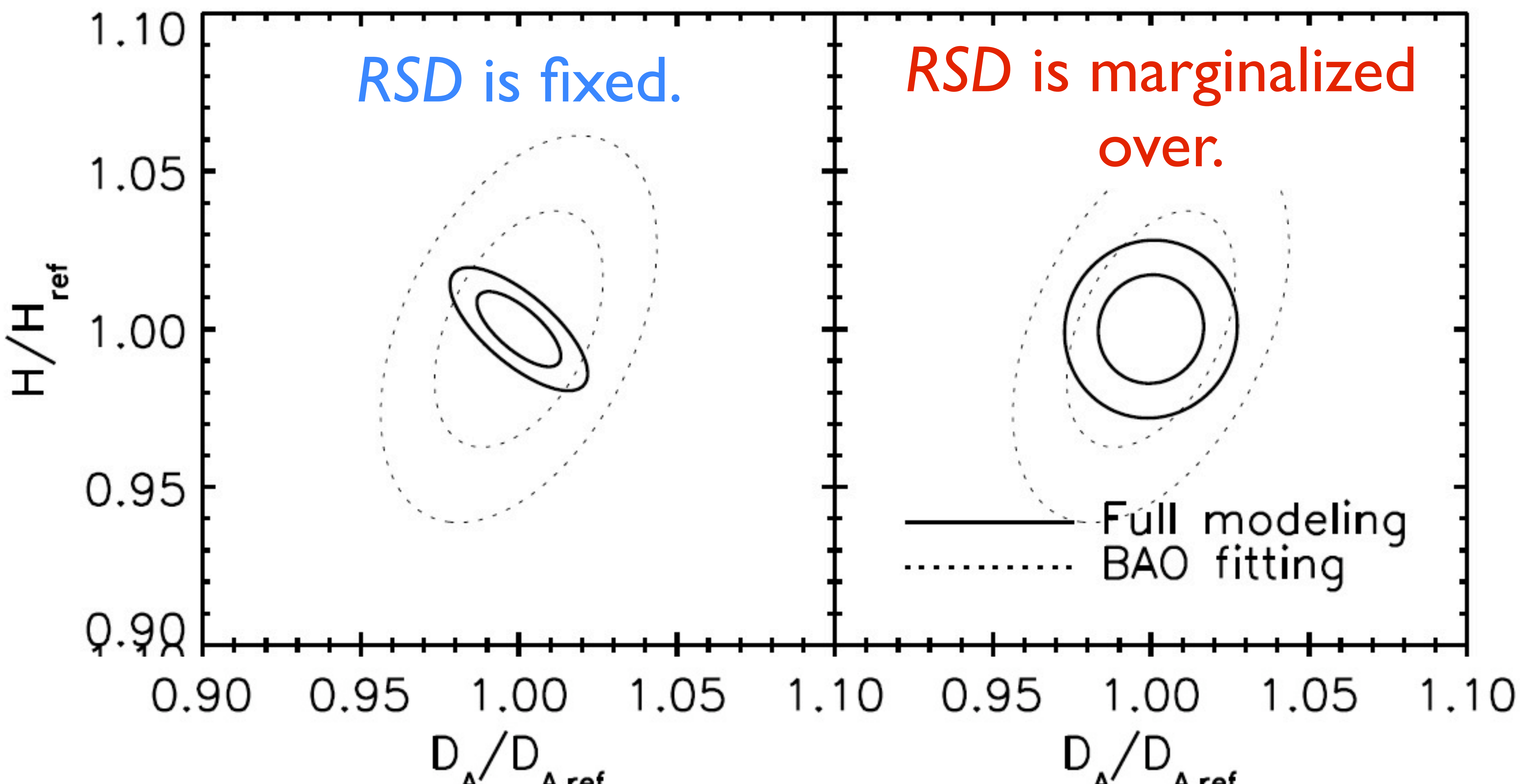
Non-linear

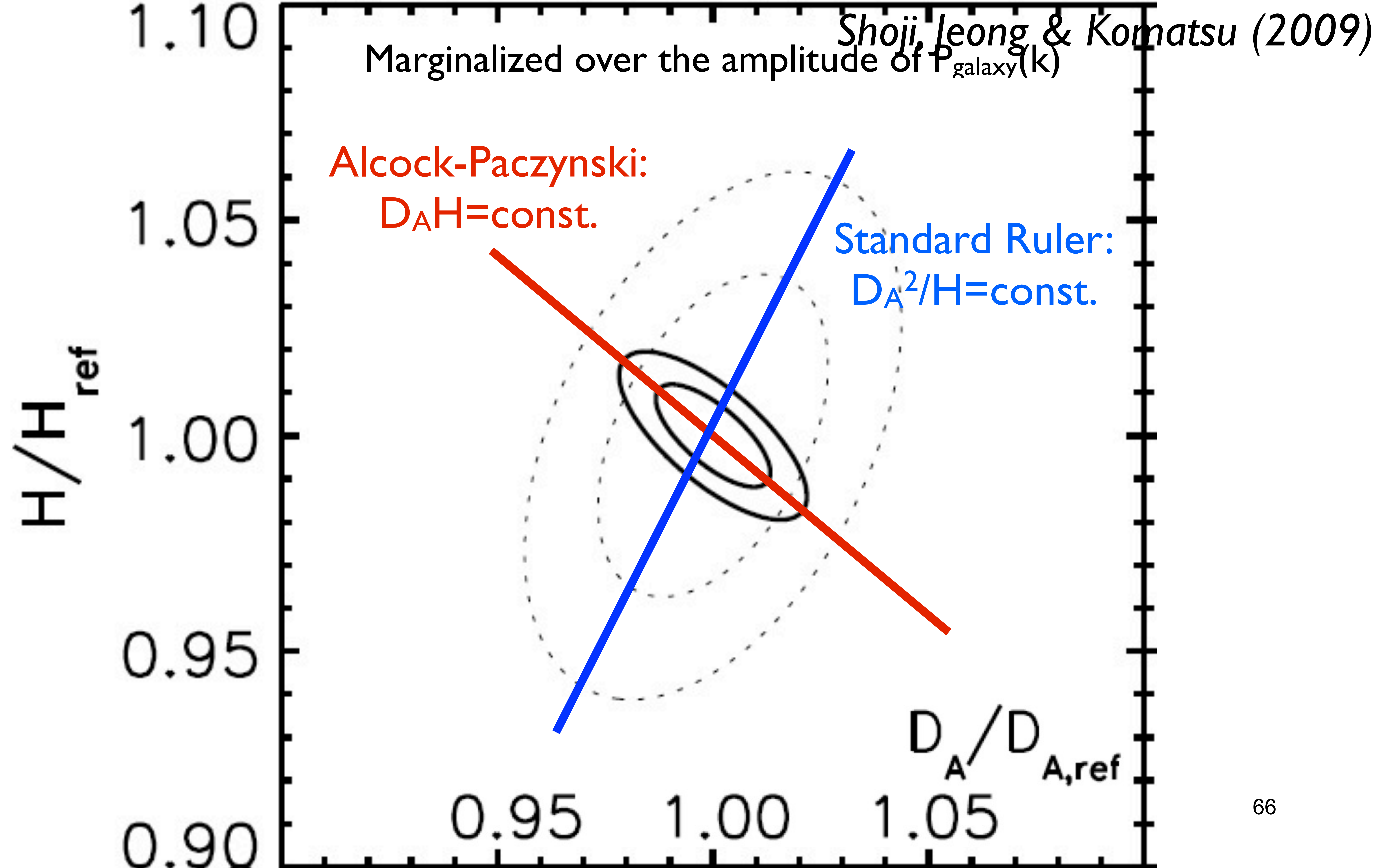
Shoji, Jeong & Komatsu (2009)

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!

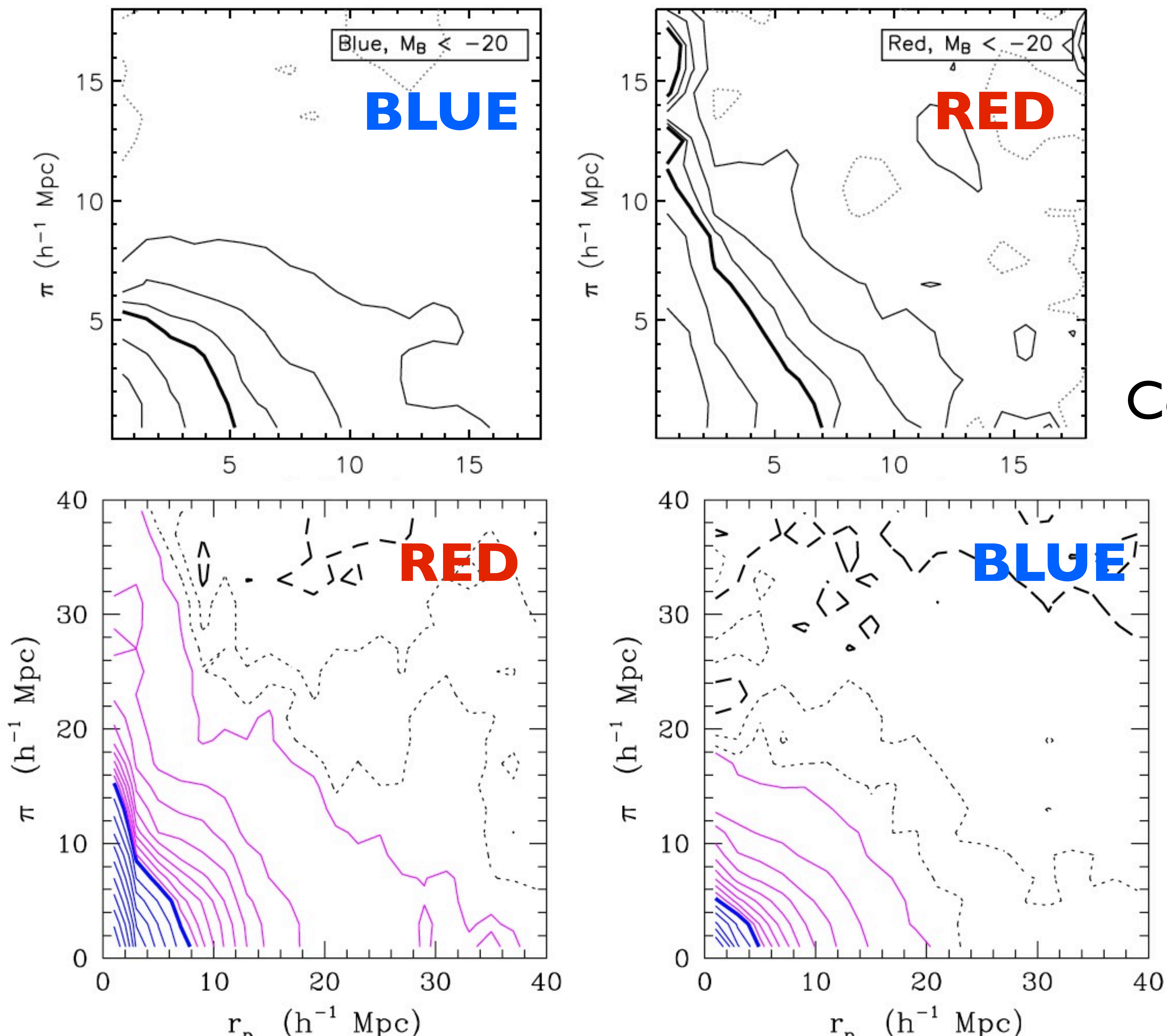



Shoji, Jeong & Komatsu (2009)
Marginalized over the amplitude of $P_{galaxy}(k)$
Alcock-Paczynski:
D_AH=const.
Standard Ruler:
D_A^2/H=const.
H/H_{ref}
$D_A/D_{A,ref}$
1.10
1.05
1.00
0.95
0.90
0.95
1.00
1.05

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

I am hopeful (=optimistic)

- Blue galaxies are typically star-forming, emission-line galaxies.
- Lyman-alpha galaxies that we are going to observe with HETDEX are exactly those populations.
  - Perhaps we will not see much FoG?
  - We will probably figure this out within a few months of the survey. Fingers crossed.

Summary

- Three (out of four) questions:
  - What is the physics of inflation?
    - P(k) shape (esp, dn/dlnk) and non-Gaussianity
  - What is the nature of dark energy?
    - $D_A(z)$, $H(z)$, growth of structure
  - What is the mass of neutrinos?
    - P(k) shape
- **HETDEX is a powerful approach for addressing all of these questions**