Hobby-Eberly Telescope Dark Energy Experiment

Eiichiro Komatsu (Texas Cosmology Center, UT Austin)
on behalf of HETDEX collaboration
Cook's Branch Workshop on Supernovae, April 13, 2012

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*
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	CFP 3	What Is Dark Matter?	*Dark Matter*
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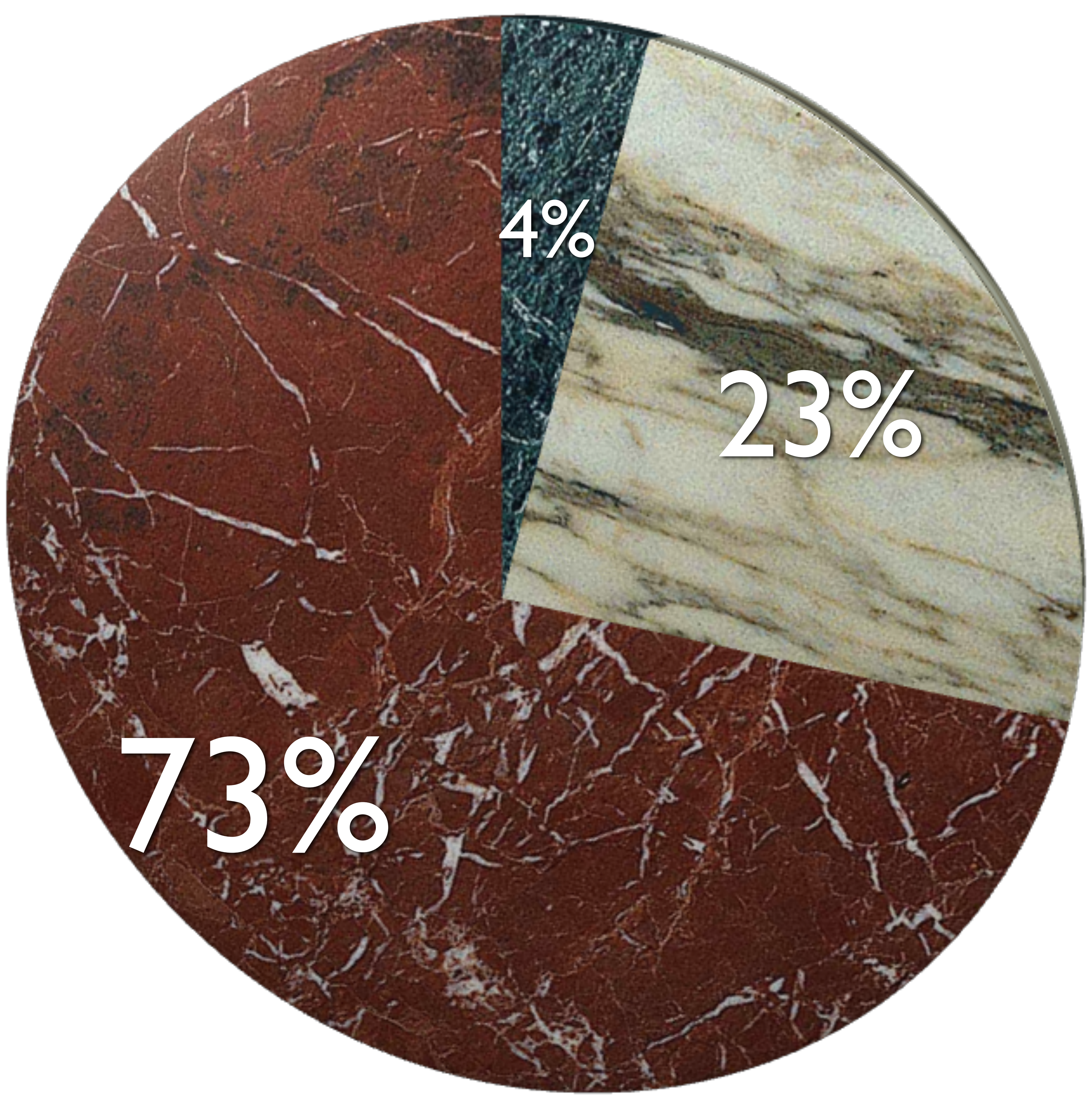
Dark Energy

Energy Content



- What do we need Dark Energy for?

Need For Dark "Energy"

- First of all, DE does not even need to be energy.
- At present, *anything* that can explain the observed

  (1) **Luminosity Distances** (Type Ia supernovae)

  (2) **Angular Diameter Distances** (BAO, CMB)

  simultaneously is qualified for being called "Dark Energy."
- The candidates in the literature include: (a) energy, (b) modified gravity, and (c) extreme inhomogeneity.

Primary Goal of HETDEX

- Using precision determinations of the **angular diameter distance** and the **Hubble expansion rate** at z~2.2, constrain (or find!) time-evolution of Dark Energy.
  - Can we rule out a cosmological constant?

What is HETDEX?

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

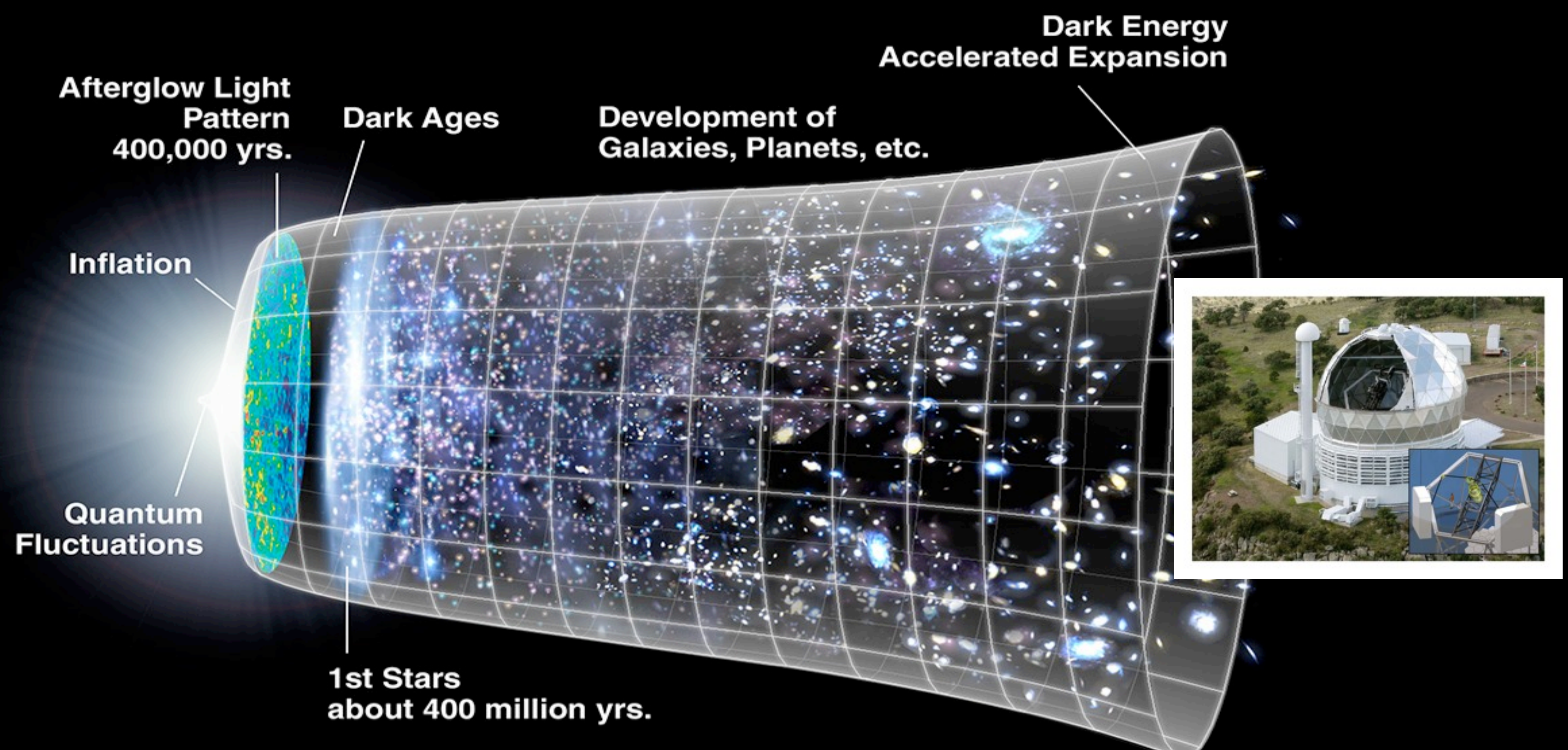
Who are we?

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

Glad to be in Texas

- 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)



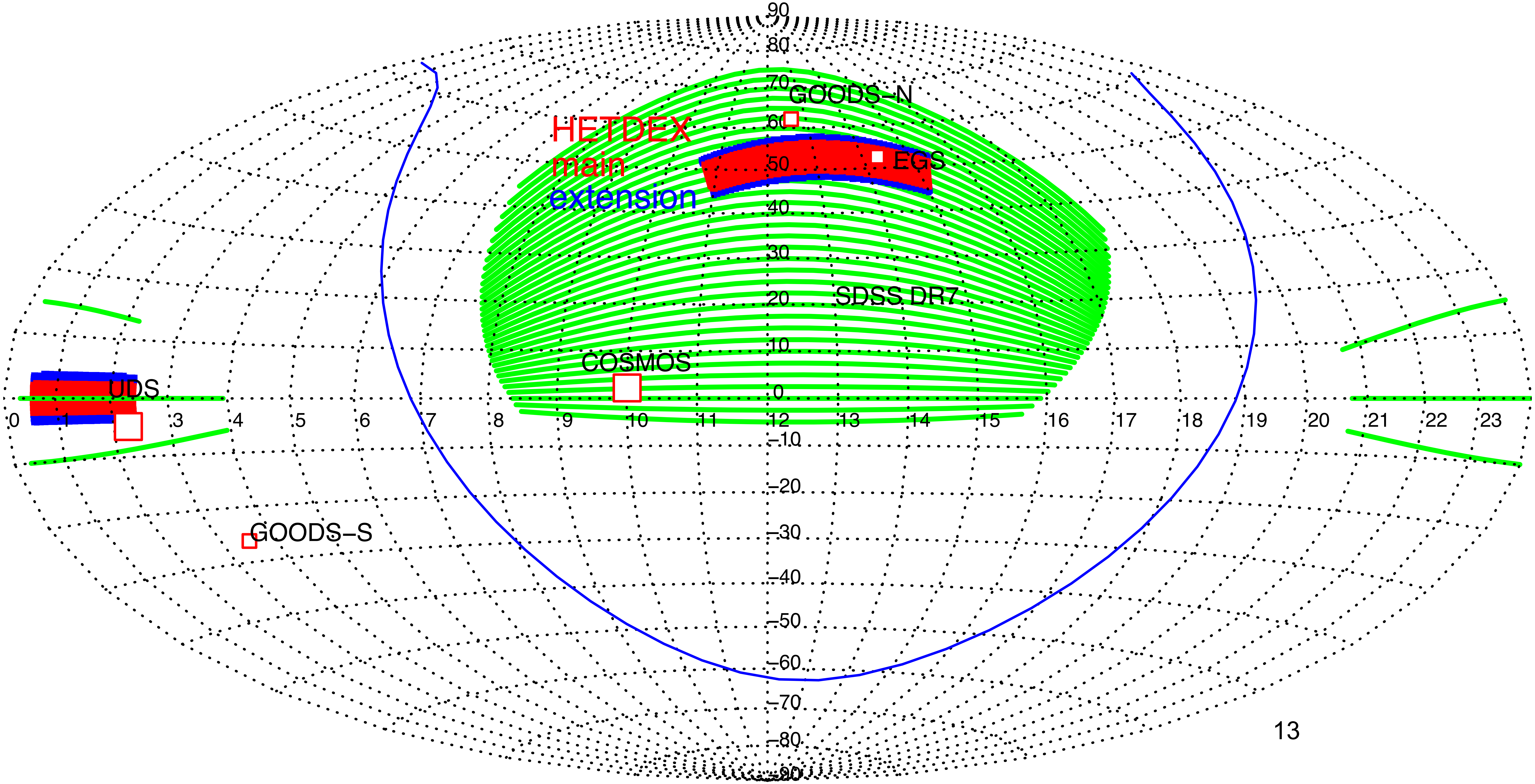
Use 10-m HET to map the universe using 0.8M Lyman-alpha emitting galaxies in z=1.9–3.5

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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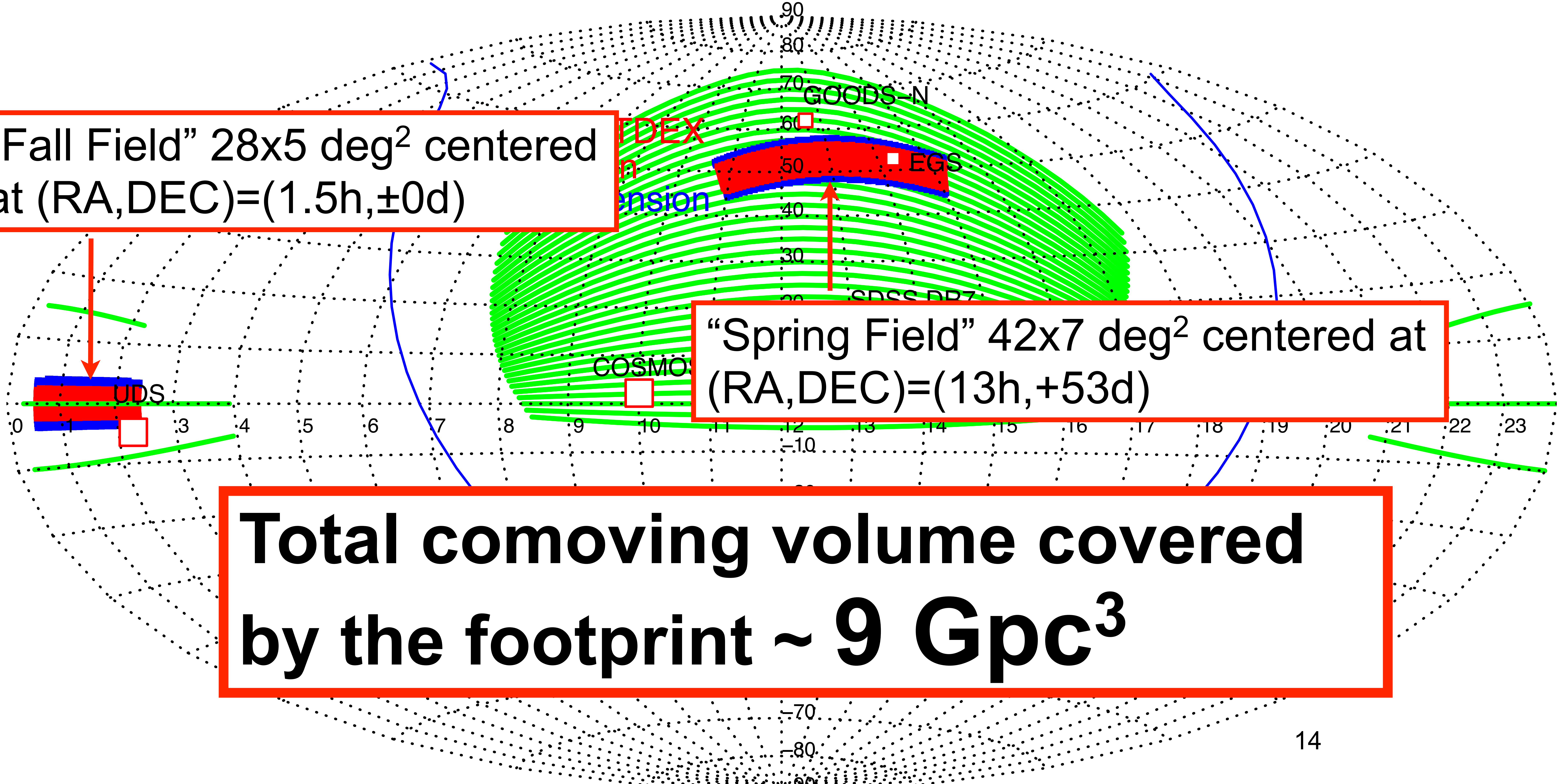
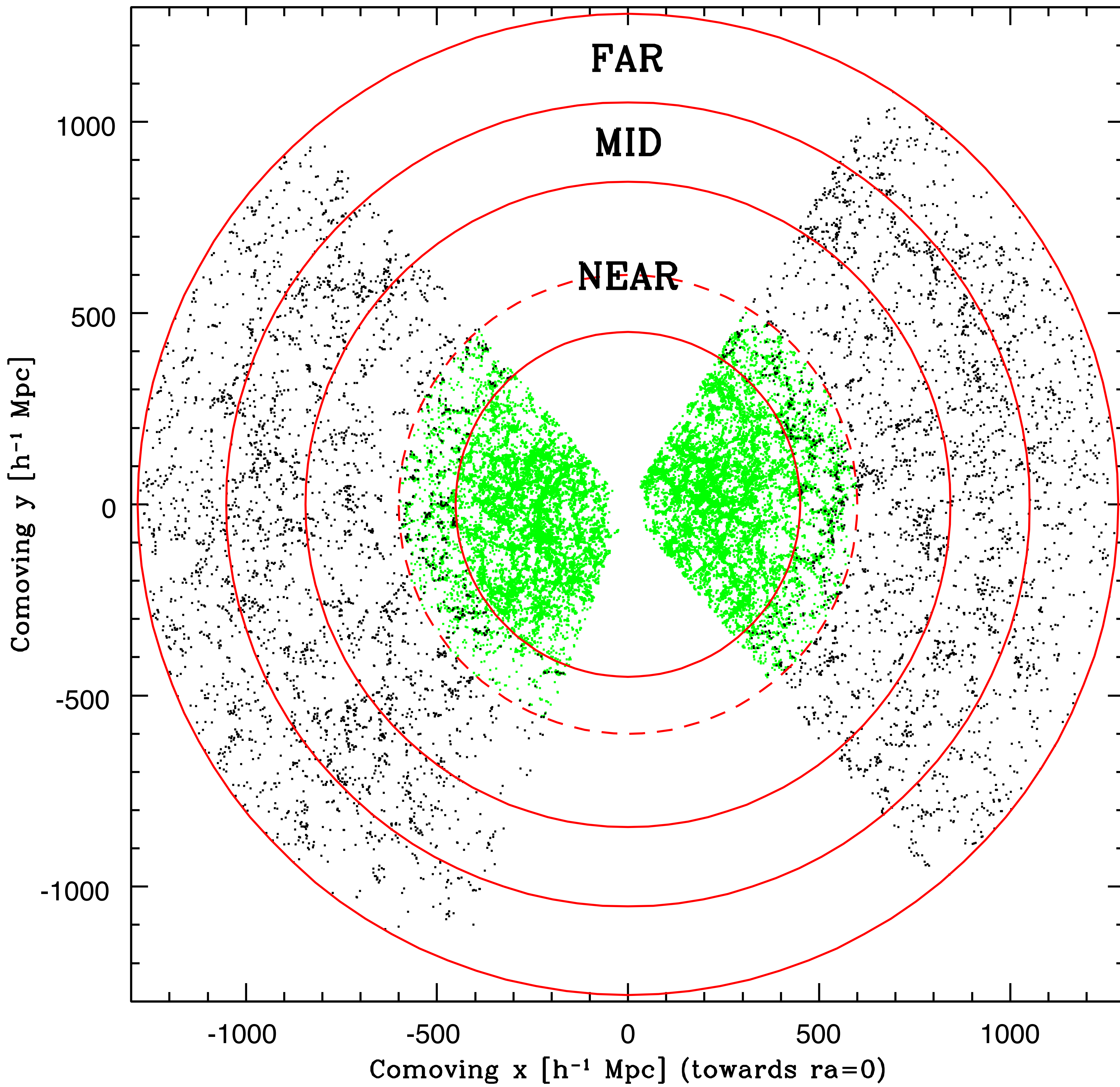


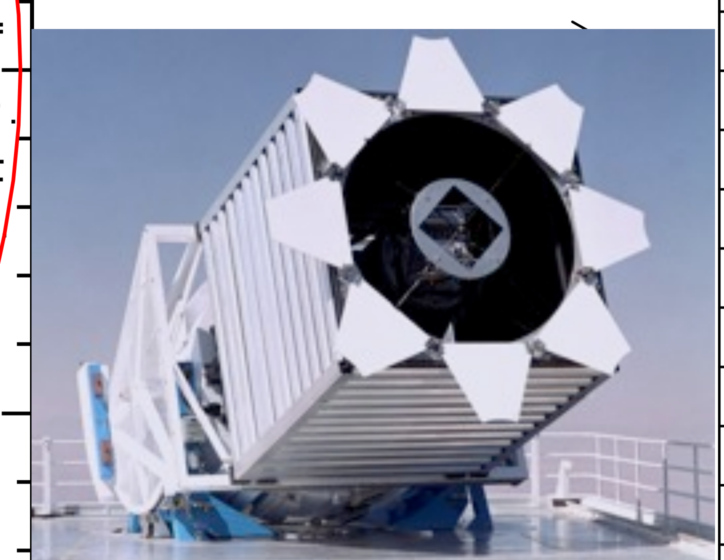
"Fall Field" 28x5 deg^2 centered at (RA,DEC)=(1.5h,±0d)

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

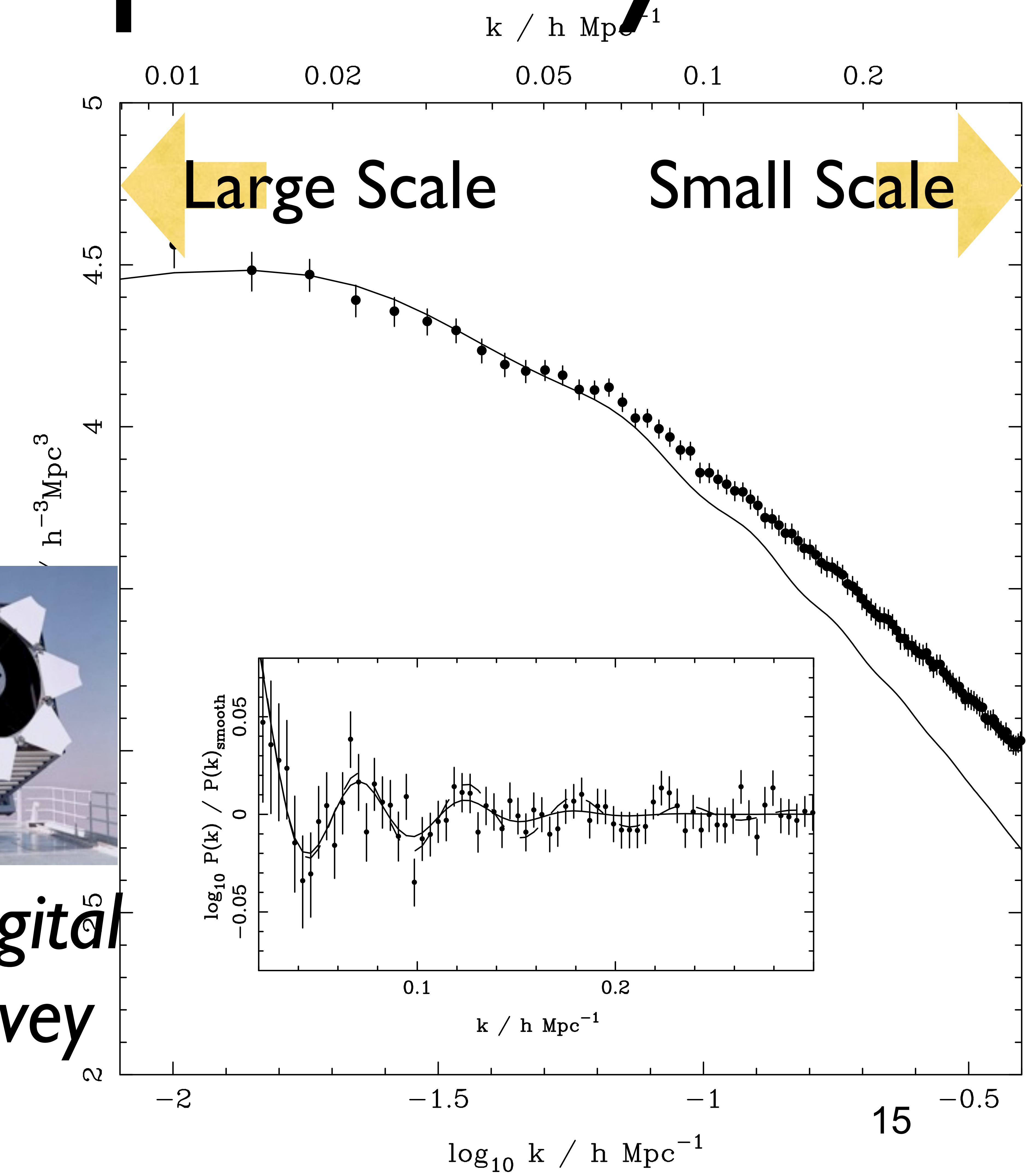
Total comoving volume covered by the footprint ~ 9 Gpc^3

HETDEX:
A Quantum Leap Survey

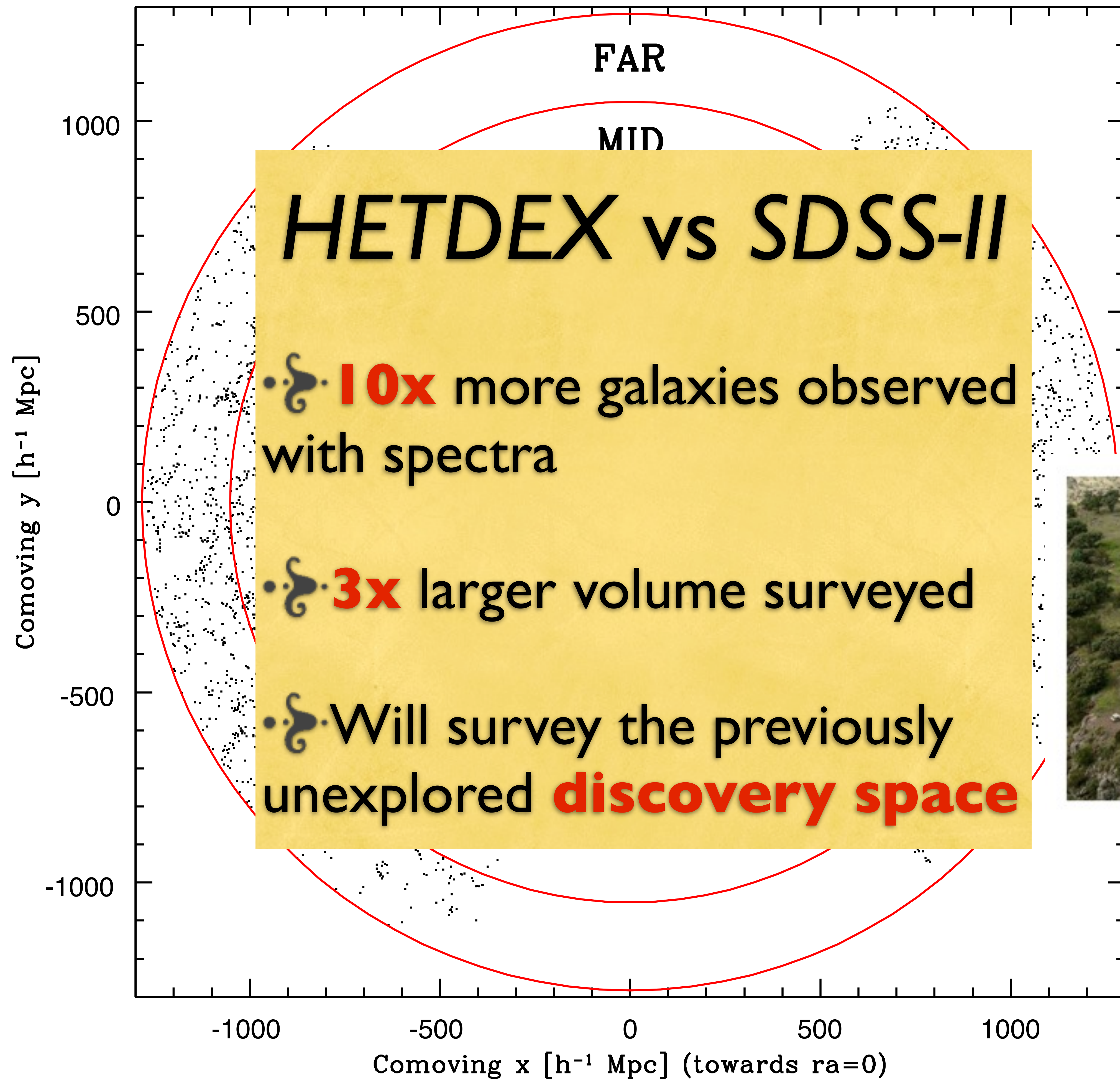




Sloan Digital Sky Survey



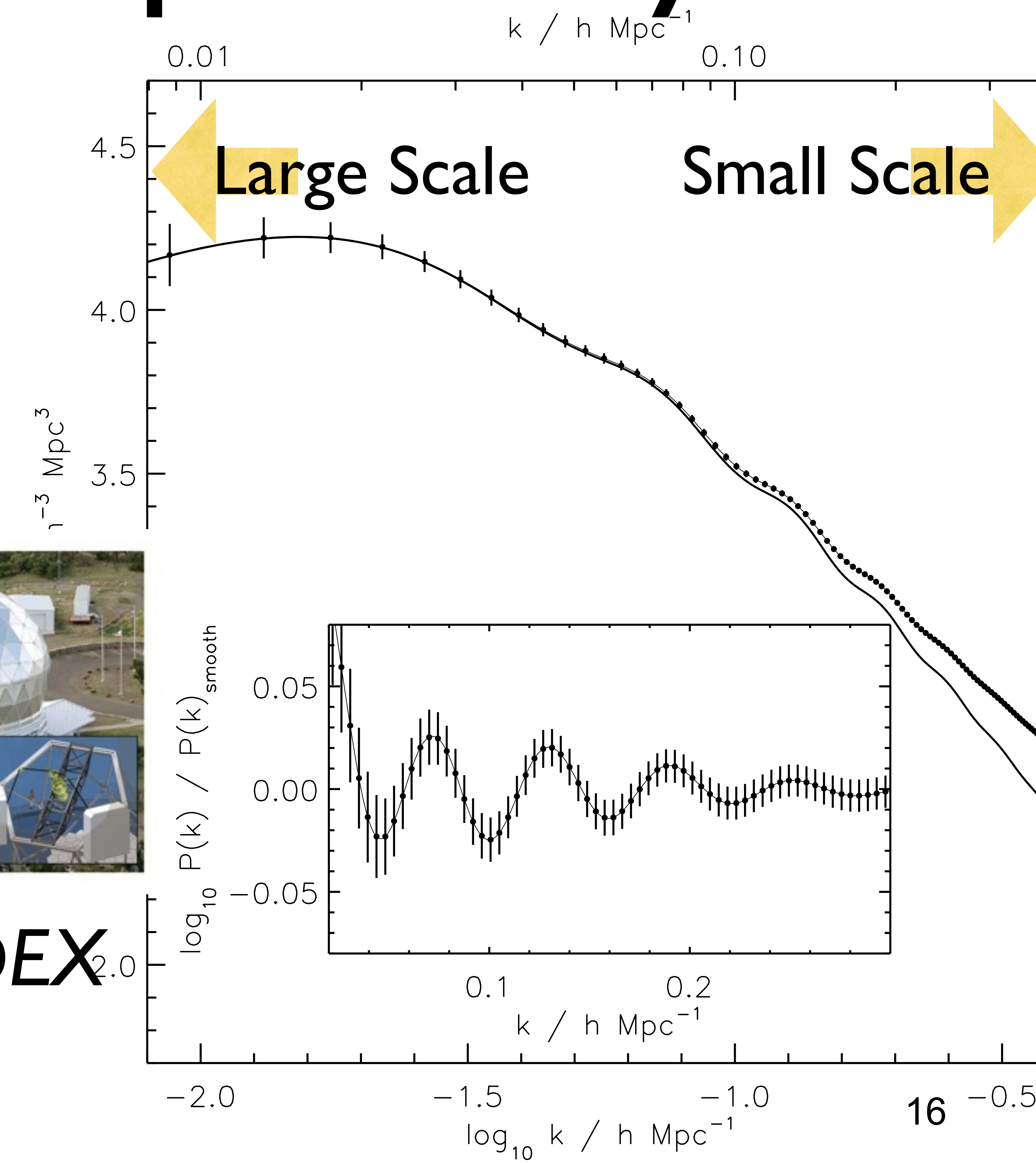
HETDEX: A Quantum Leap Survey

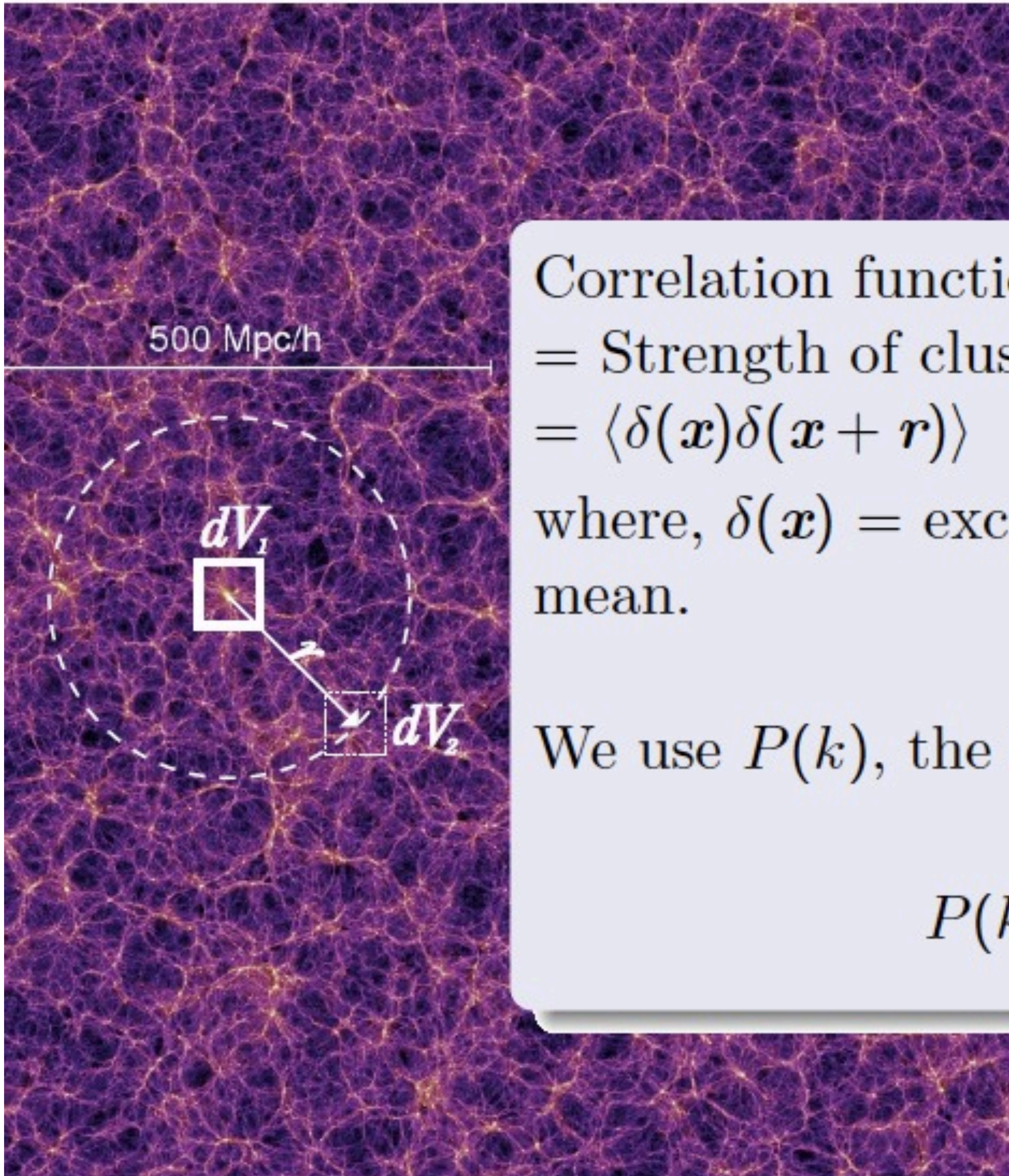


HETDEX vs SDSS-II

- **10x** more galaxies observed with spectra
- **3x** larger volume surveyed
- Will survey the previously unexplored **discovery space**

HETDEX

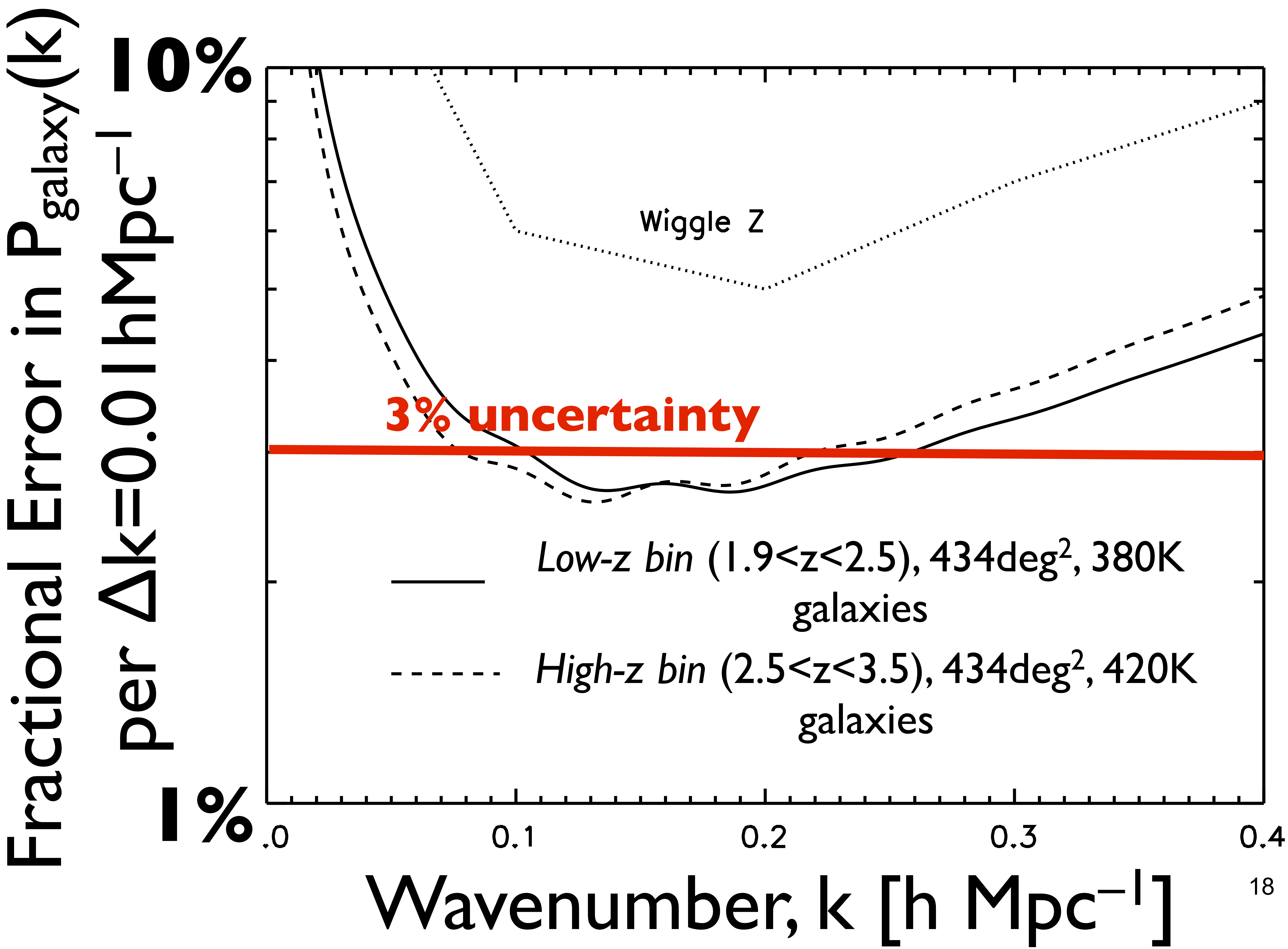




Correlation function $\xi(r)$
$= $ Strength of clustering at a given separation r
$= \langle \delta(\boldsymbol{x})\delta(\boldsymbol{x}+\boldsymbol{r})\rangle$
where, $\delta(\boldsymbol{x}) =$ excess number of galaxies above the mean.

We use $P(k)$, the Fourier transform of $\xi(r)$:

$$P(k) = \int d^3\boldsymbol{r}\,\xi(r)e^{-i\boldsymbol{k}\cdot\boldsymbol{r}}$$


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), 434deg², 380K galaxies
High-z bin (2.5<z<3.5), 434deg², 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 **<u>first 2 hours</u>** 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
  - Supernova cannot do this.
- 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 < 0.5eV]
  - The absolute lower limit to the total mass from neutrino experiments is the total mass > 0.05 eV. Not so far away!

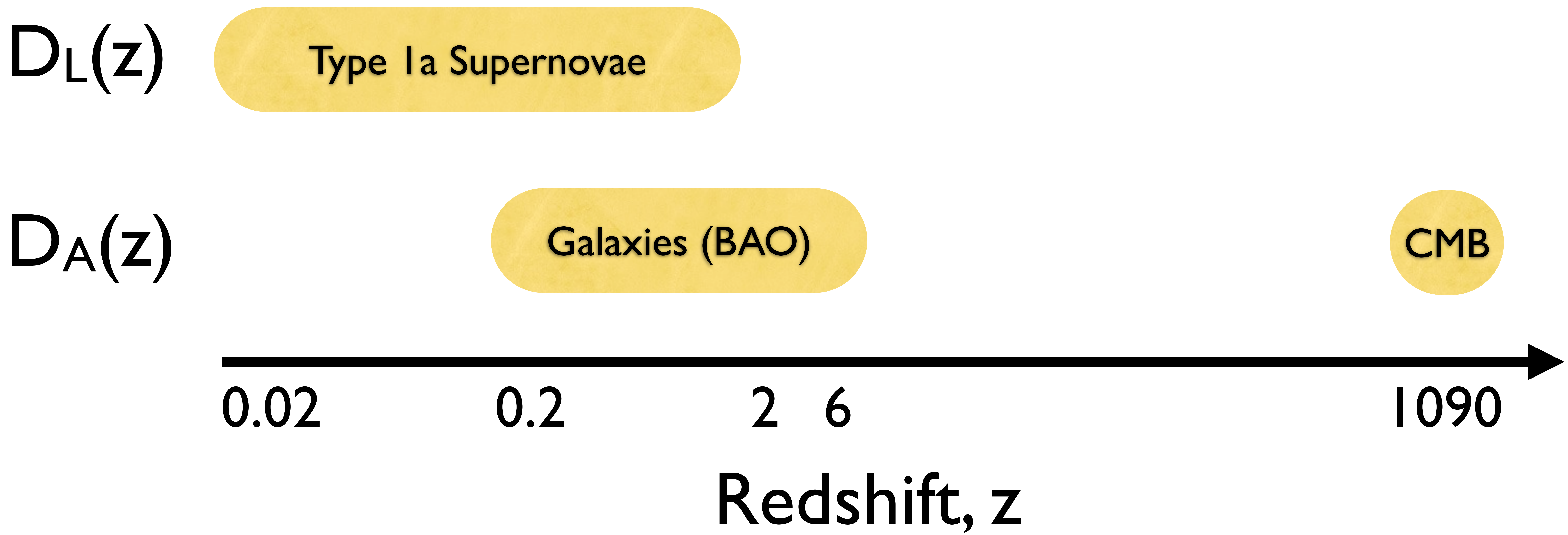
“Sub-prime” Goals

- The name, “Sub-prime science,” was coined by Casey Papovich
  - 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

The Goal

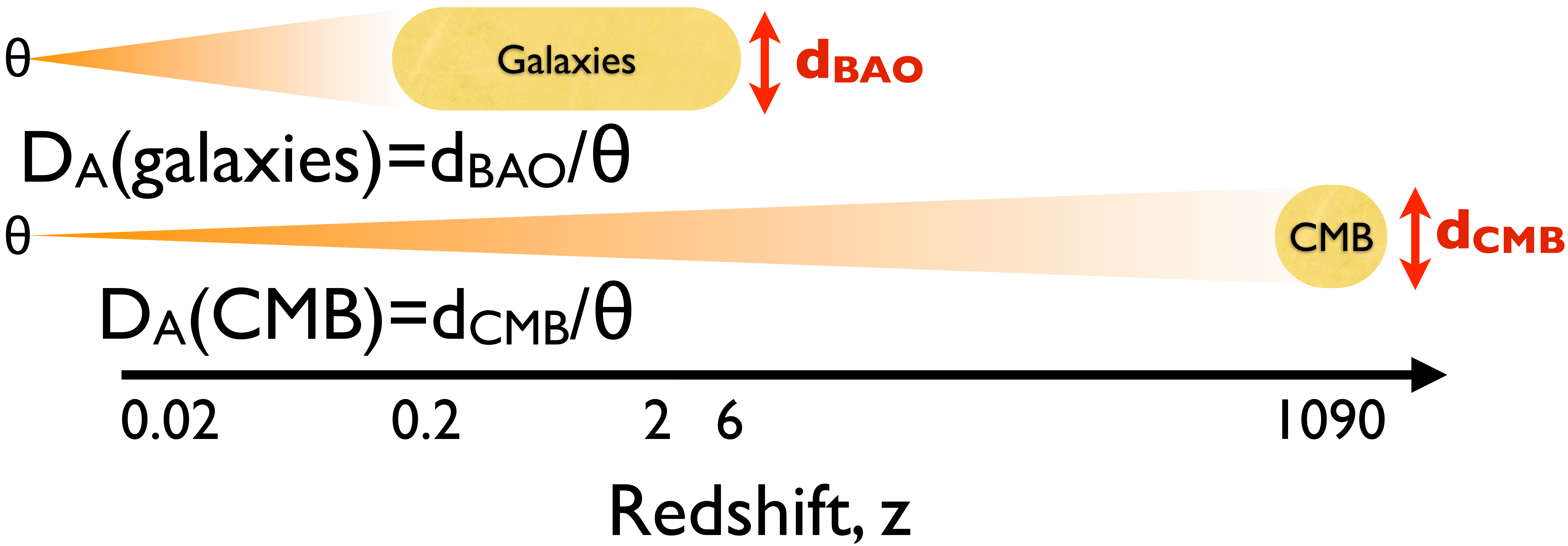
- Measuring the angular diameter distance, $D_A(z)$, and the Hubble expansion rate, $H(z)$.

$$D_L(z) = (1+z)^2 D_A(z)$$



- To measure $D_A(z)$, we need to know the intrinsic size.
- What can we use as the *standard ruler*?

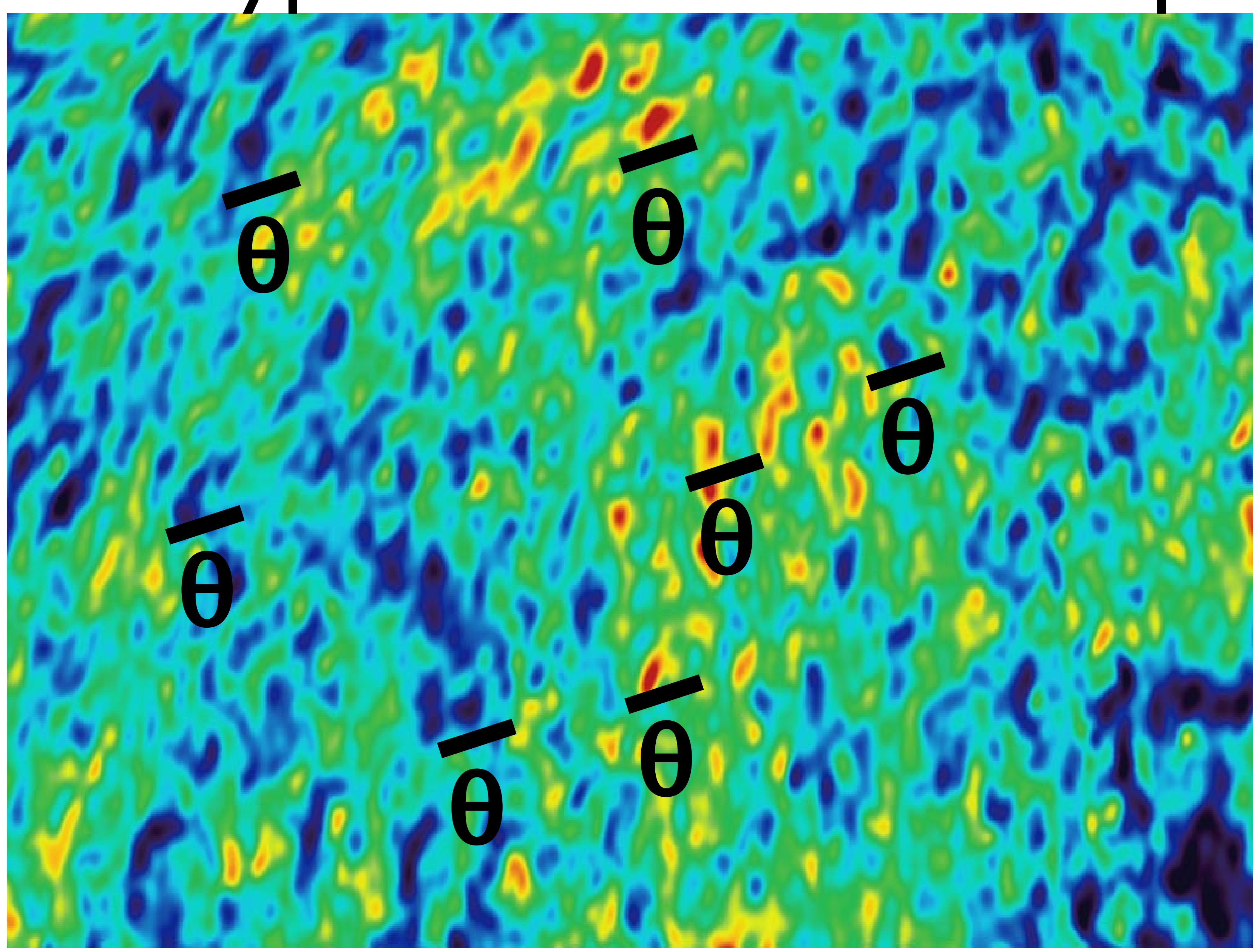
How Do We Measure $D_A(z)$?

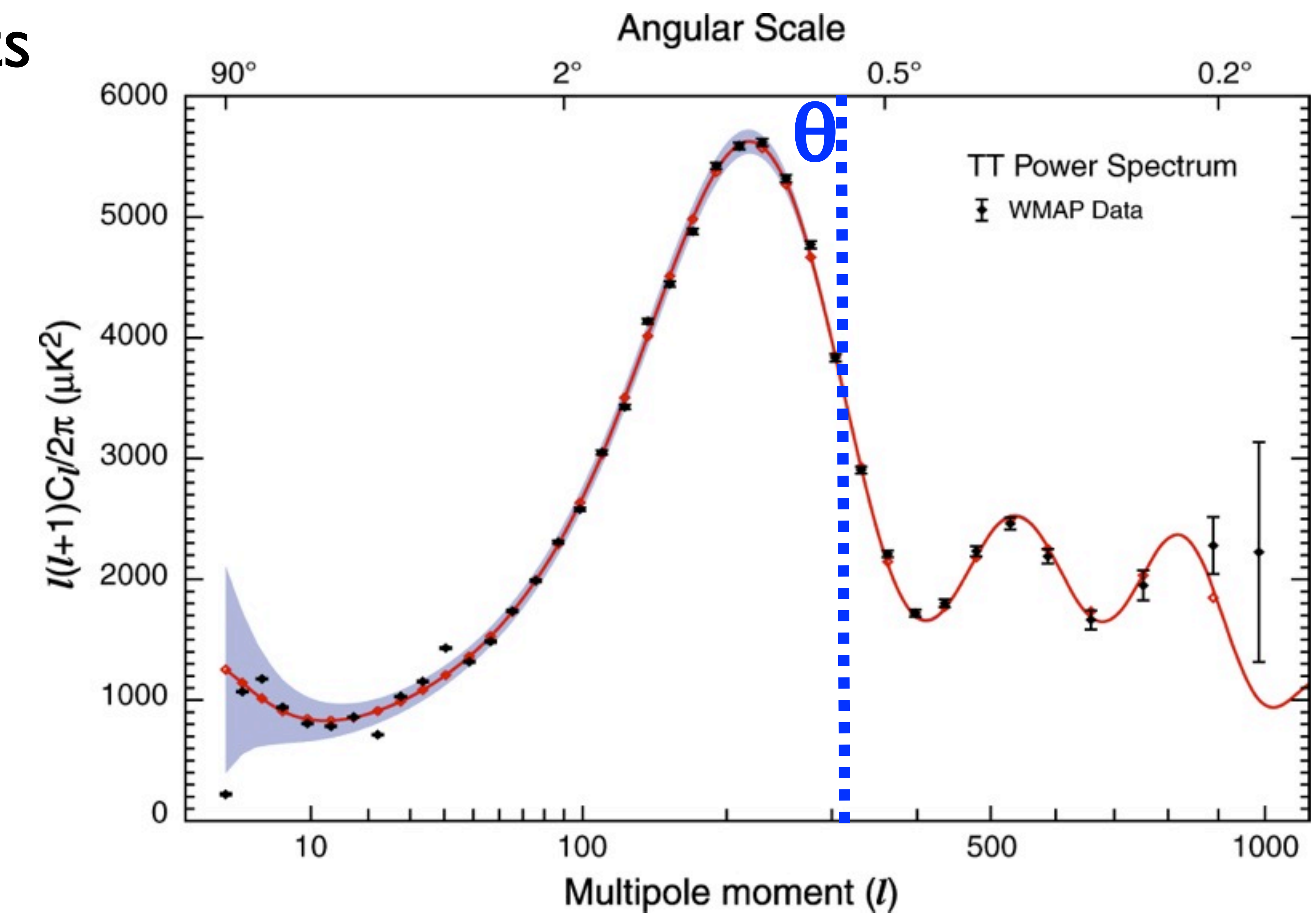


- If we know the intrinsic physical sizes, d, we can measure D_A. What determines d?

CMB as a Standard Ruler

θ~the typical size of hot/cold spots

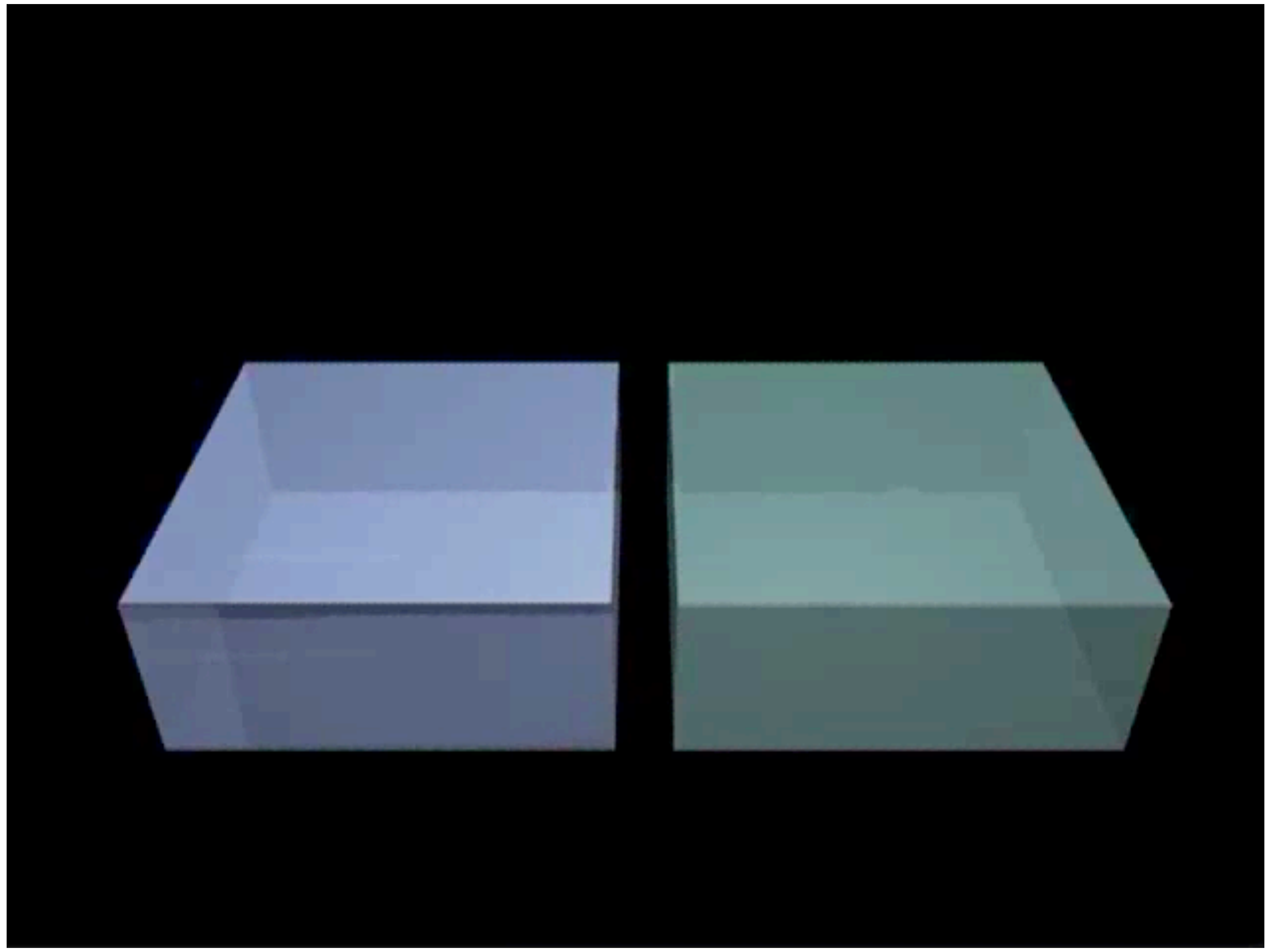


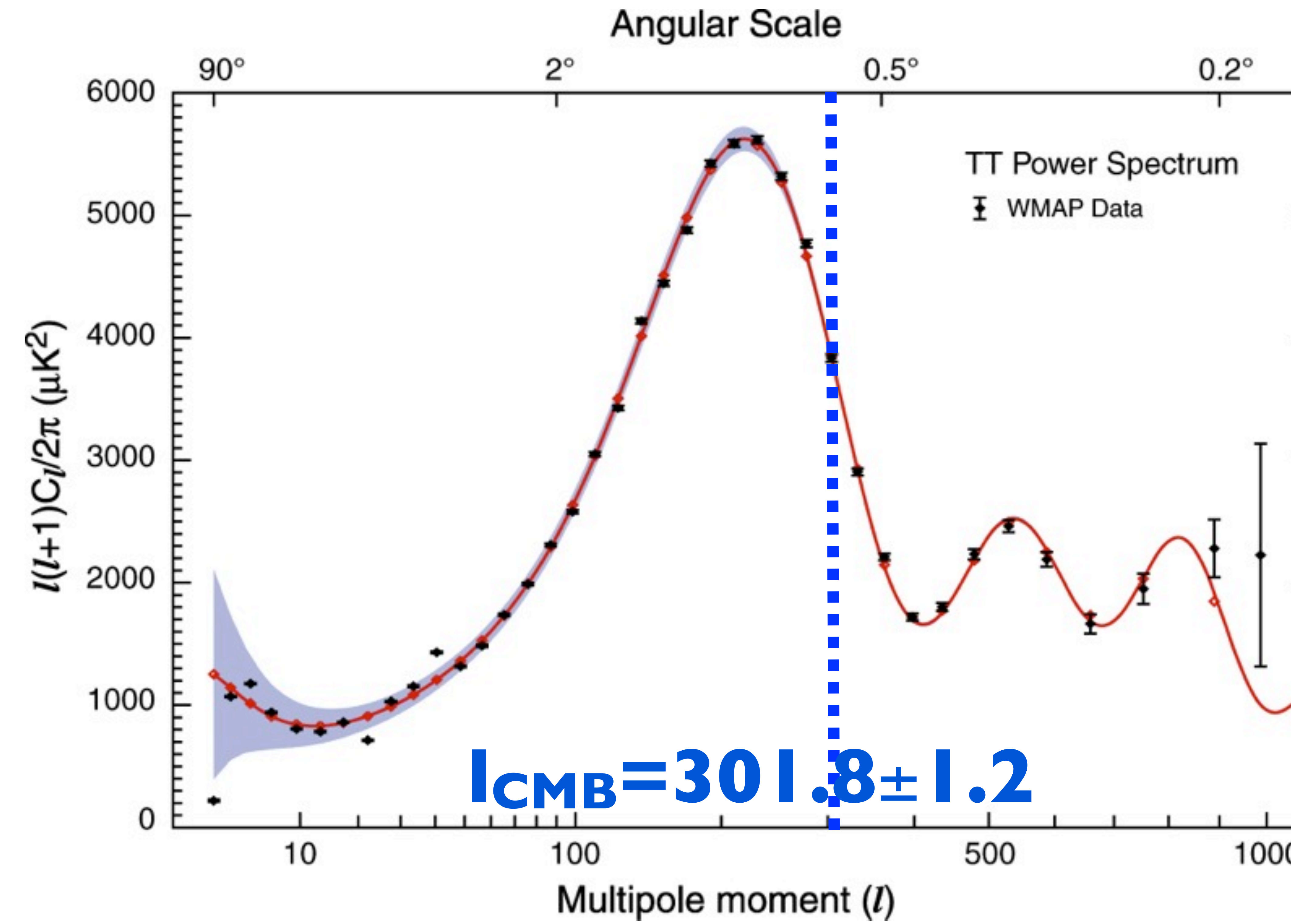


- The existence of typical spot size in image space yields oscillations in harmonic (Fourier) space. What determines the physical size of typical spots, **d_{CMB}**?

Sound Horizon

- The typical spot size, **d_{CMB}**, is determined by the **physical distance traveled by the sound wave** from the Big Bang to the decoupling of photons at z_{CMB}~1090 (t_{CMB}~380,000 years).
- The causal horizon (photon horizon) at t_{CMB} is given by
  - $d_H(t_{CMB})$ = $a(t_{CMB})$*Integrate[**c** dt/a(t), {t,0,t_{CMB}}].
- The **sound** horizon at t_{CMB} is given by
  - $d_s(t_{CMB})$ = $a(t_{CMB})$*Integrate[**c_s(t)** dt/a(t), {t,0,t_{CMB}}], where c_s(t) is the time-dependent **speed of sound of photon-baryon fluid**.



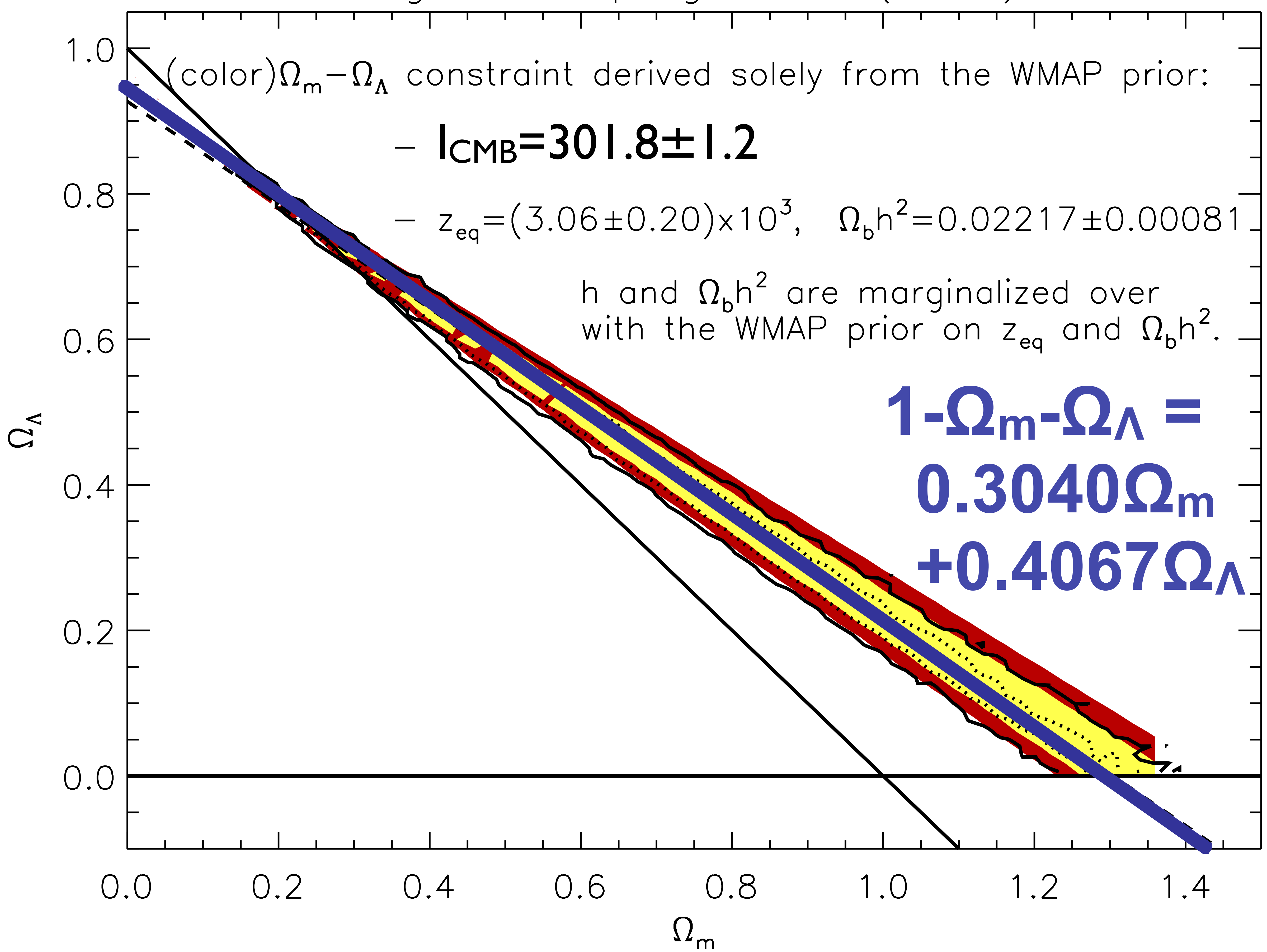


Hinshaw et al. (2007)

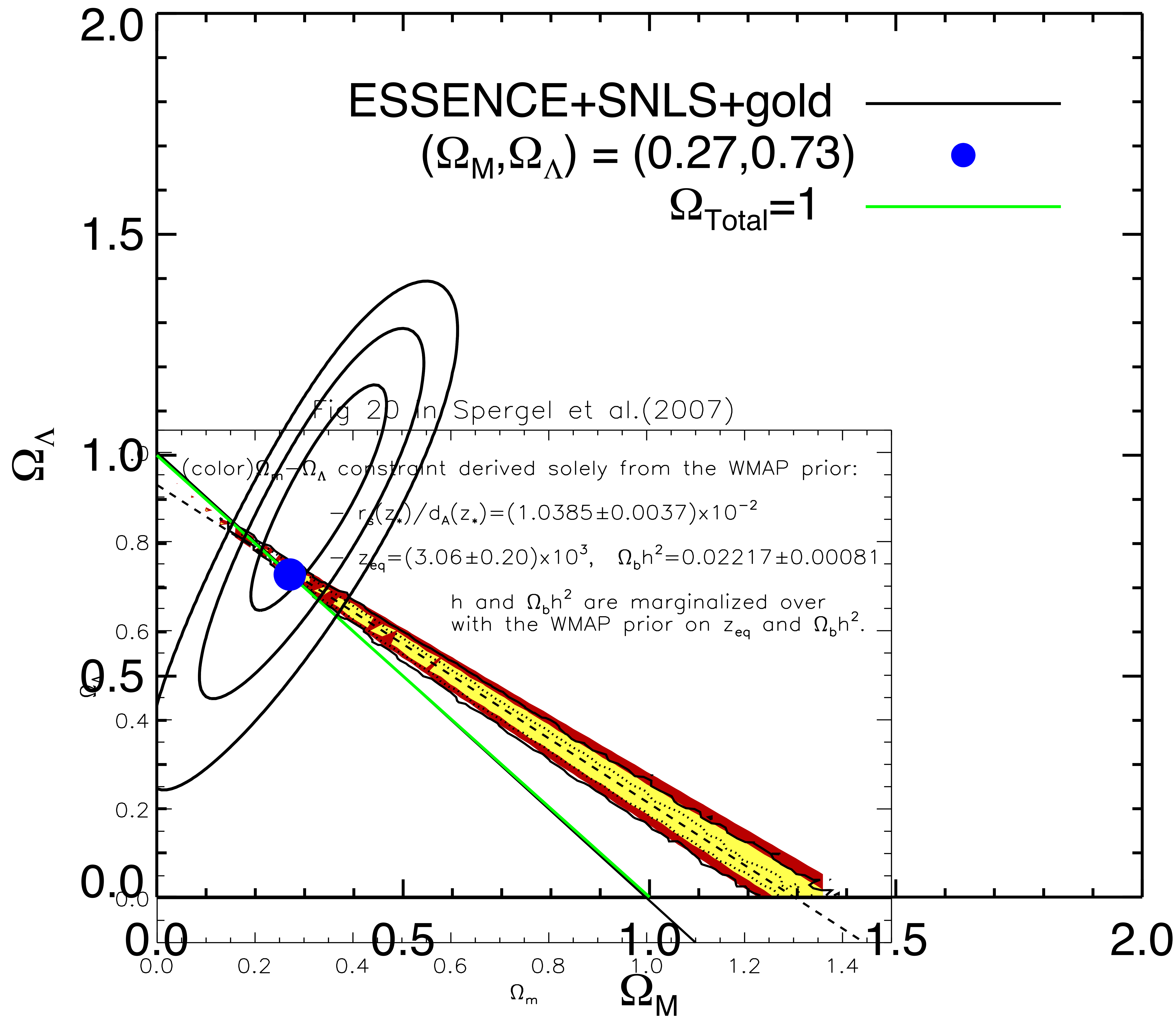
- The WMAP 3-year Number:
  - $l_{CMB} = \pi/\theta = \pi D_A(z_{CMB})/d_s(z_{CMB}) = 301.8 \pm 1.2$
  - CMB data constrain the ratio, $\mathbf{D_A(z_{CMB})/d_s(z_{CMB})}$.

What $D_A(z_{CMB})/d_s(z_{CMB})$ Gives You

Fig 20 in Spergel et al.(2007)

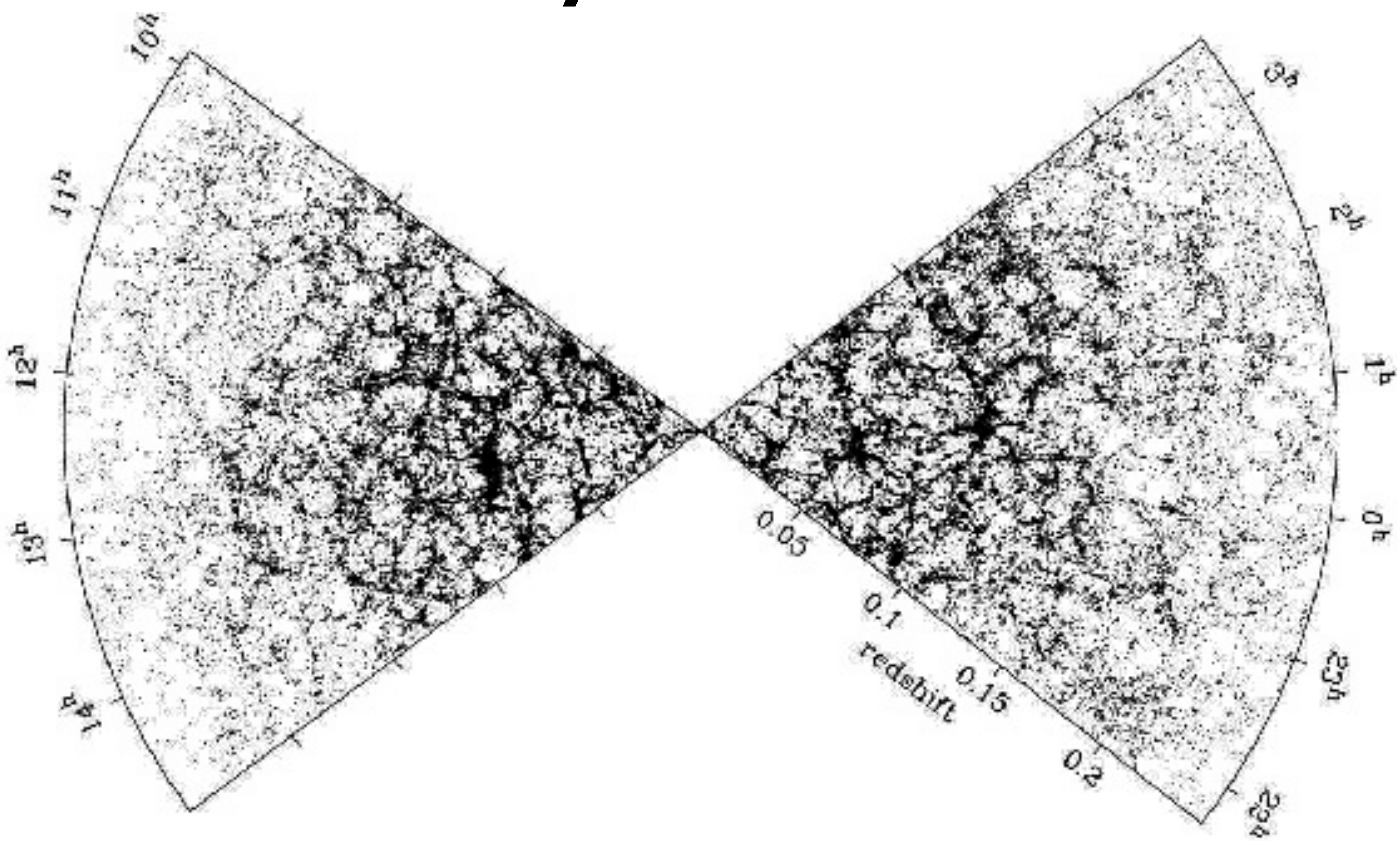


- Color: constraint from $l_{CMB}=\pi D_A(z_{CMB})/d_s(z_{CMB})$ with z_{EQ} & Ω_bh^2.
- Black contours: Markov Chain from WMAP 3yr (Spergel et al. 2007)


ESSENCE+SNLS+gold
$(\Omega_M,\Omega_\Lambda) = (0.27,0.73)$
$\Omega_{Total}=1$
Fig 20 in Spergel et al.(2007)
(color) $\Omega_m-\Omega_\Lambda$ constraint derived solely from the WMAP prior:
— $r_s(z_*)/d_A(z_*)=(1.0385\pm0.0037)\times10^{-2}$
— $z_{eq}=(3.06\pm0.20)\times10^3$, $\Omega_b h^2=0.02217\pm0.00081$
h and $\Omega_b h^2$ are marginalized over
with the WMAP prior on z_{eq} and $\Omega_b h^2$.
Ω_Λ
Ω_M
Ω_m

BAO in Galaxy Distribution

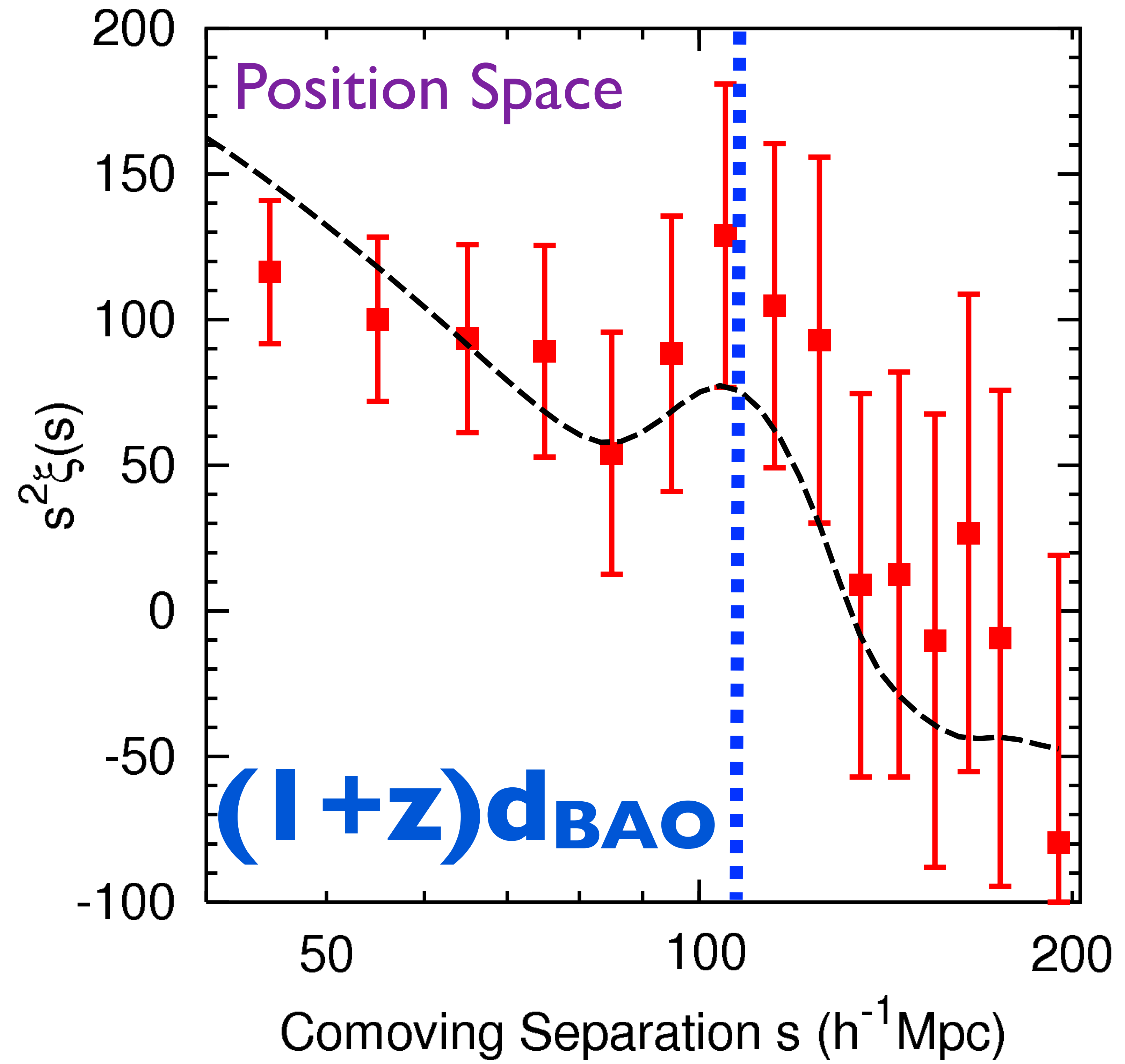
2dFGRS

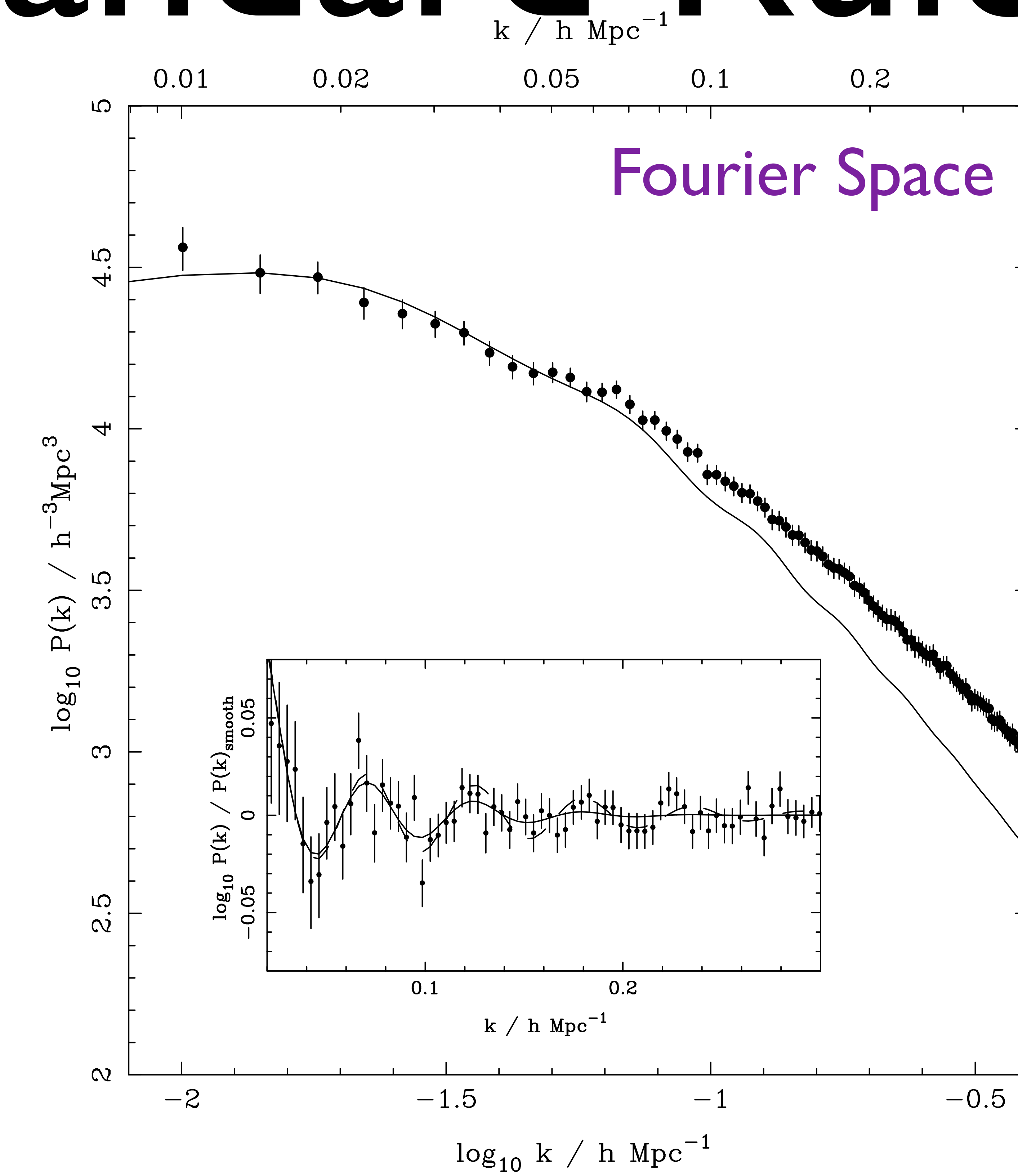


- The acoustic oscillations should be hidden in this galaxy distribution...

BAO as a Standard Ruler

Okumura et al. (2007)

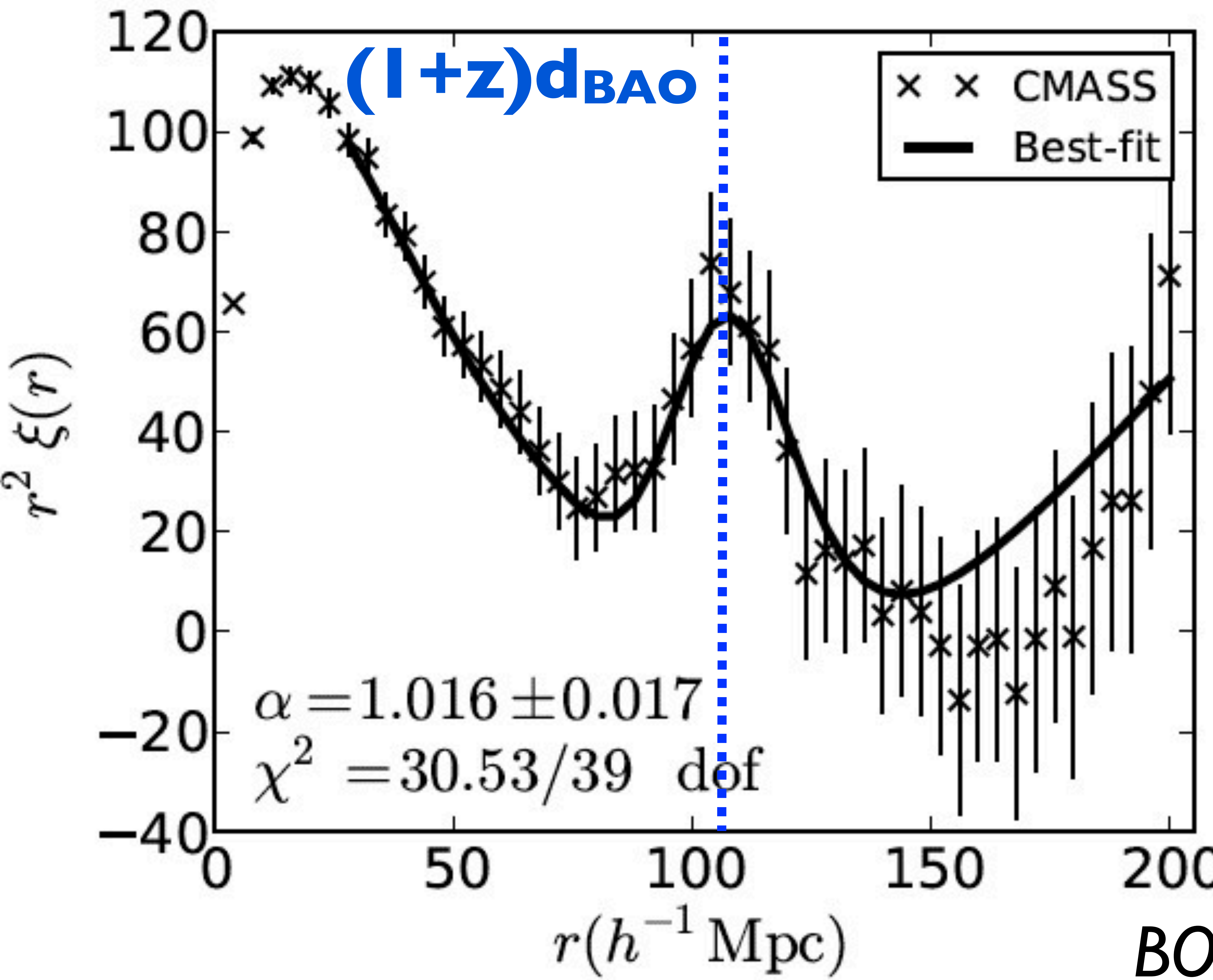




Percival et al. (2006)

- The existence of a localized clustering scale in the 2-point function yields oscillations in Fourier space. What determines the physical size of clustering, d_{BAO}?

Latest Measurement of BAO at z=0.57 (BOSS/SDSS-III)



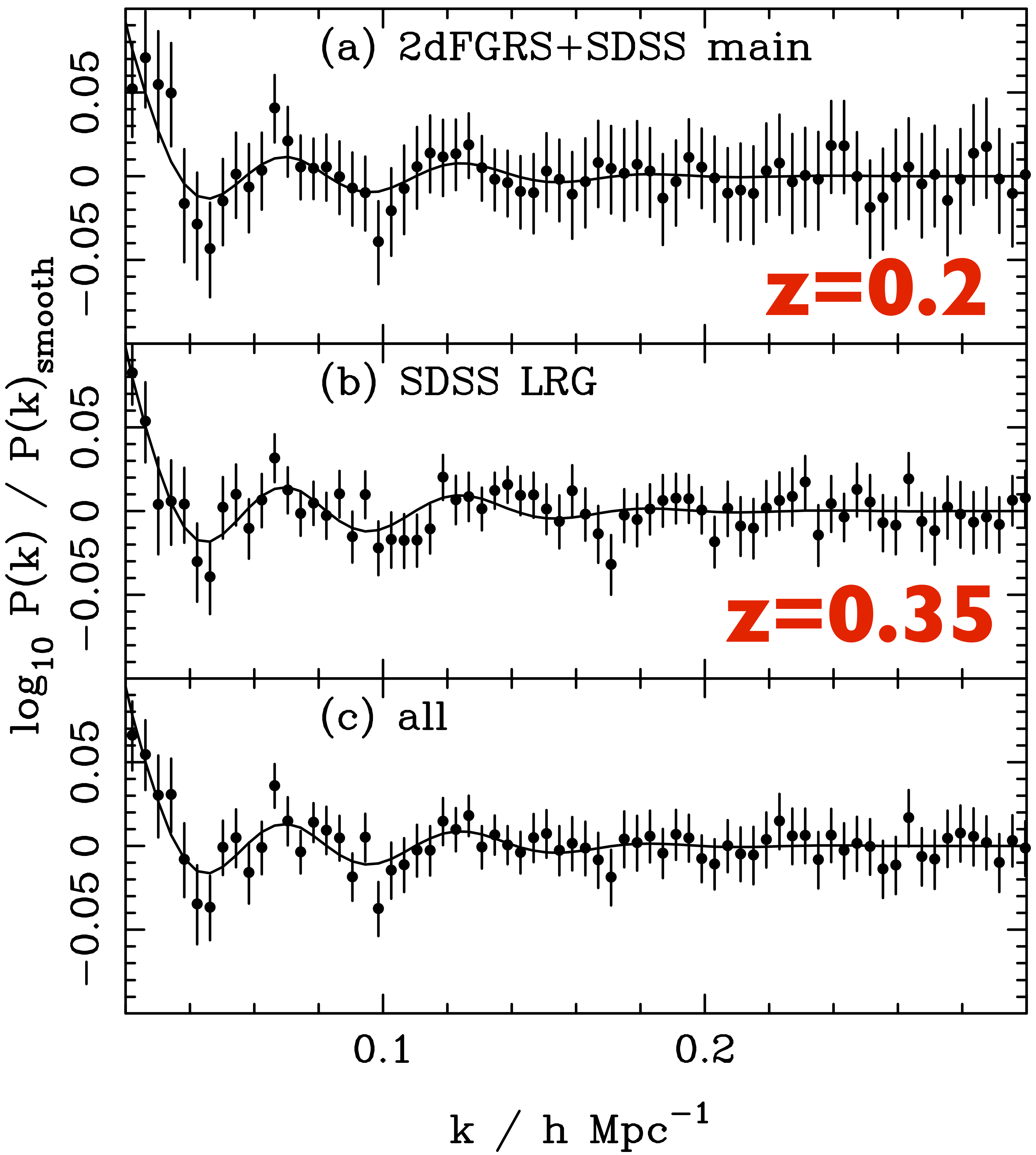
- 5σ detection of the BAO bump!
- 1.7% determination of the distance to z=0.57
- What determines the physical size of clustering, **d_{BAO}**?

BOSS Collaboration, arXiv:1203.6594

Sound Horizon Again

- The clustering scale, **d_{BAO}**, is given by the physical distance traveled by the sound wave from the Big Bang to the **decoupling of baryons** at z_{BAO}~1080 (c.f., z_{CMB}~1090).
- The baryons decoupled slightly later than CMB.
  - By the way, this is not universal in cosmology, but *accidentally* happens to be the case for our Universe.
  - If $3\rho_{baryon}/(4\rho_{photon}) = 0.64(\Omega_b h^2/0.022)(1090/(1+z_{CMB}))$ is greater than unity, $z_{BAO}>z_{CMB}$. Since our Universe happens to have $\Omega_b h^2=0.022$, $z_{BAO}<z_{CMB}$. (ie, $d_{BAO}>d_{CMB}$)

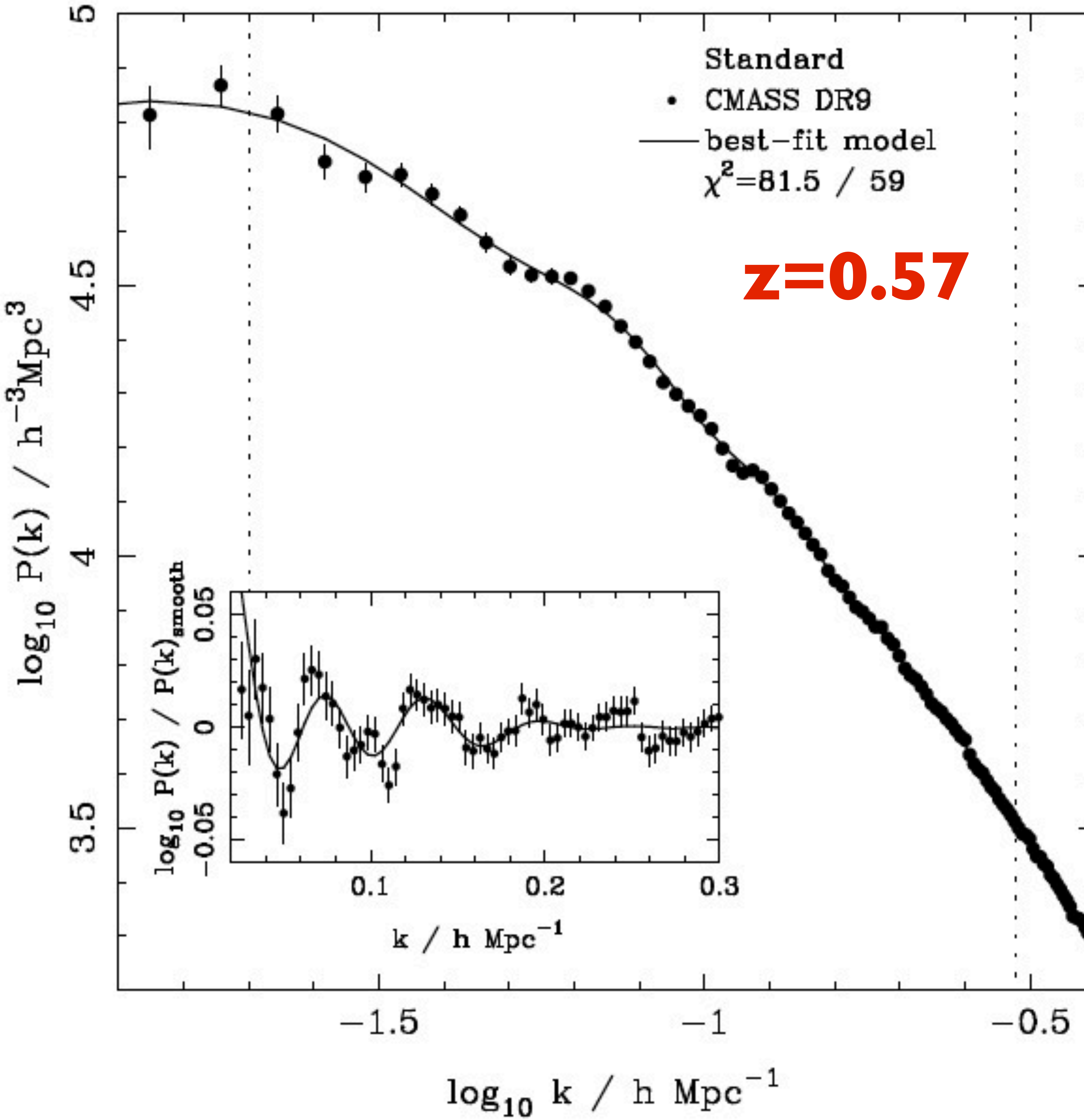
Early BAO Measurements in P(k)



- 2dFGRS and SDSS main samples at z=0.2
- SDSS LRG samples at z=0.35
- These measurements constrain the ratio, **$D_A(z)/d_s(z_{BAO})$**.

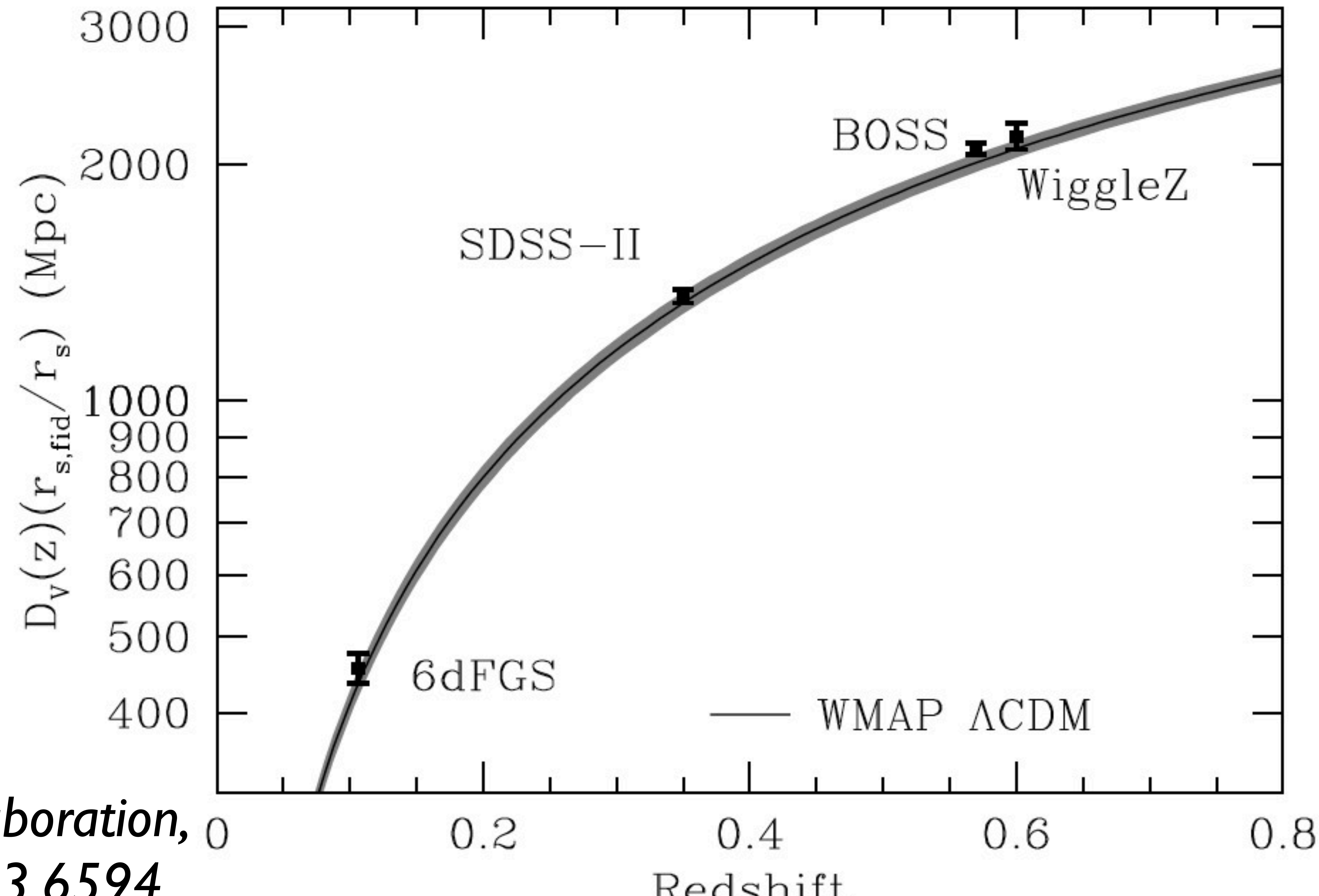
Percival et al. (2007)

Latest BAO Measurement in P(k)



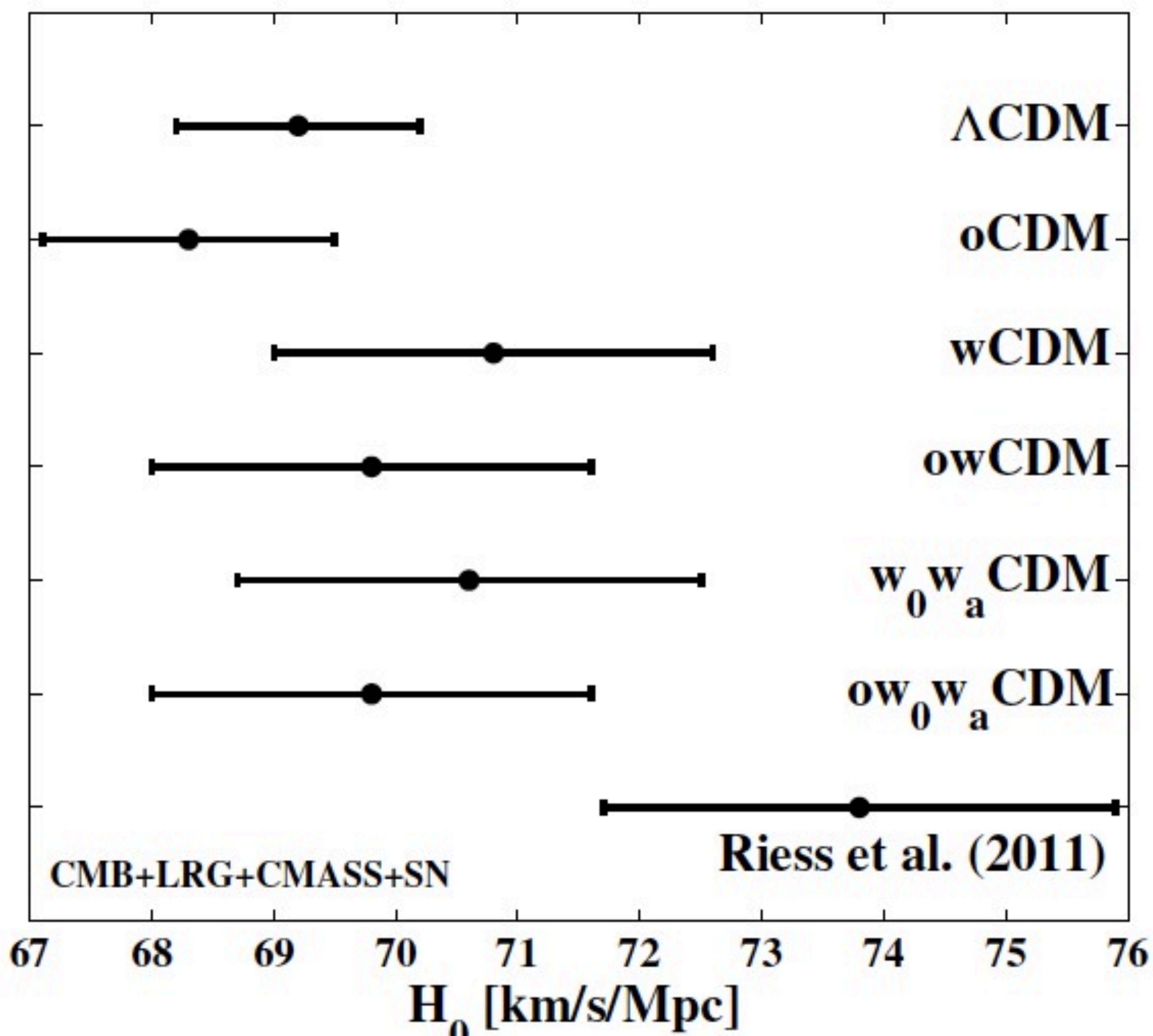
BOSS Collaboration, arXiv:1203.6594

Hubble Diagram from BAO



BOSS Collaboration, arXiv:1203.6594

H_0: "tension"?



- CMB+BAO can give a precise estimate of H_0.
  - There has been a persistent difference between H_0 from CMB +BAO (about 70km/s/Mpc) and the local determination (about 74km/s/Mpc)
- Interesting tension?

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

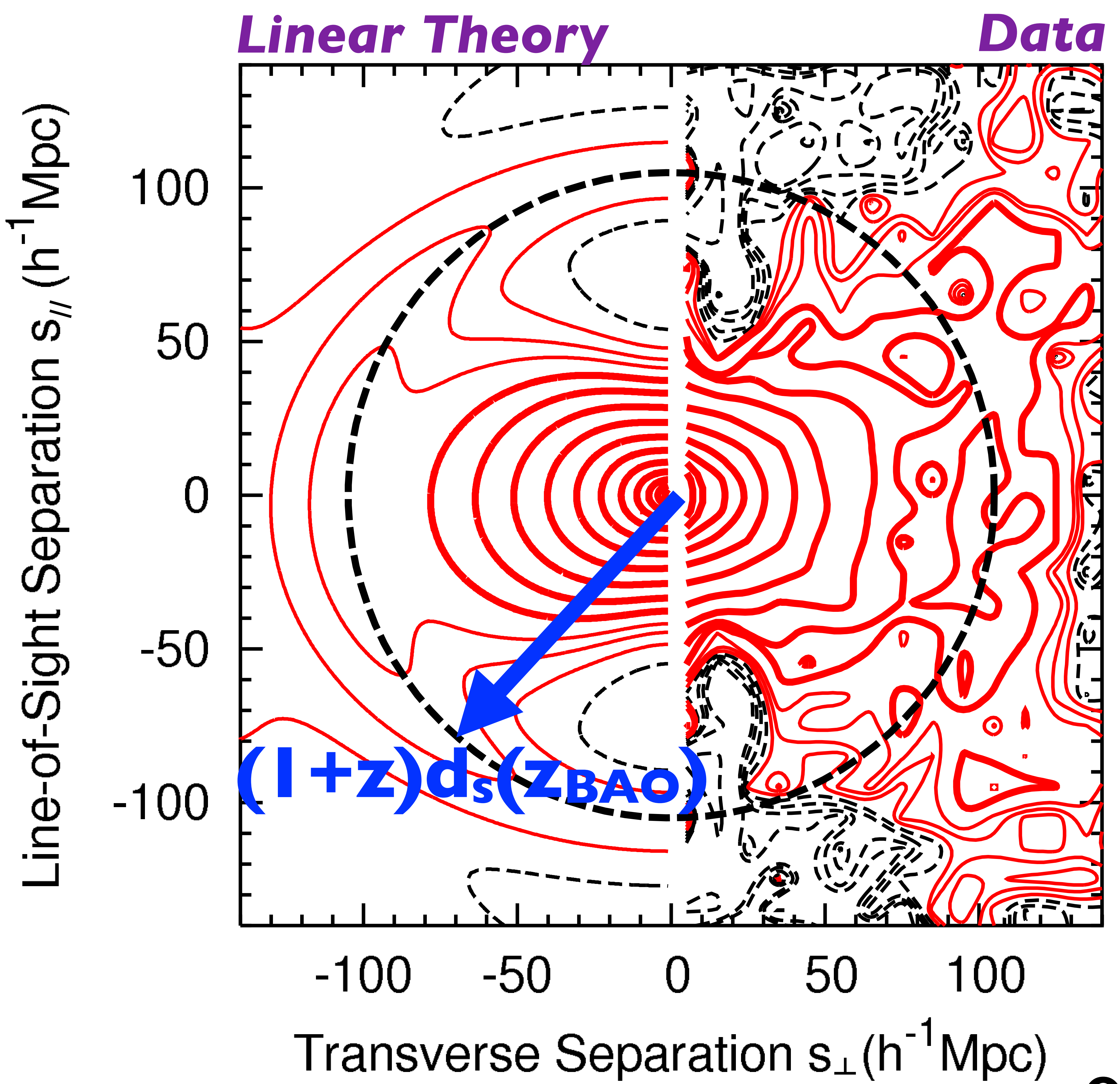
    => $D_A(z) = d_s(z_{BAO})/\theta$

  - BAO parallel to l.o.s

    => $\mathbf{H(z) = c\Delta z/[(1+z)d_s(z_{BAO})]}$

Measuring $D_A(z)$ & $H(z)$

$c\Delta z/(1+z)$
$= d_s(z_{BAO})\mathbf{H(z)}$



2D 2-pt function from the SDSS LRG samples (Okumura et al. 2007)

$\theta = d_s(z_{BAO})/\mathbf{D_A(z)}$

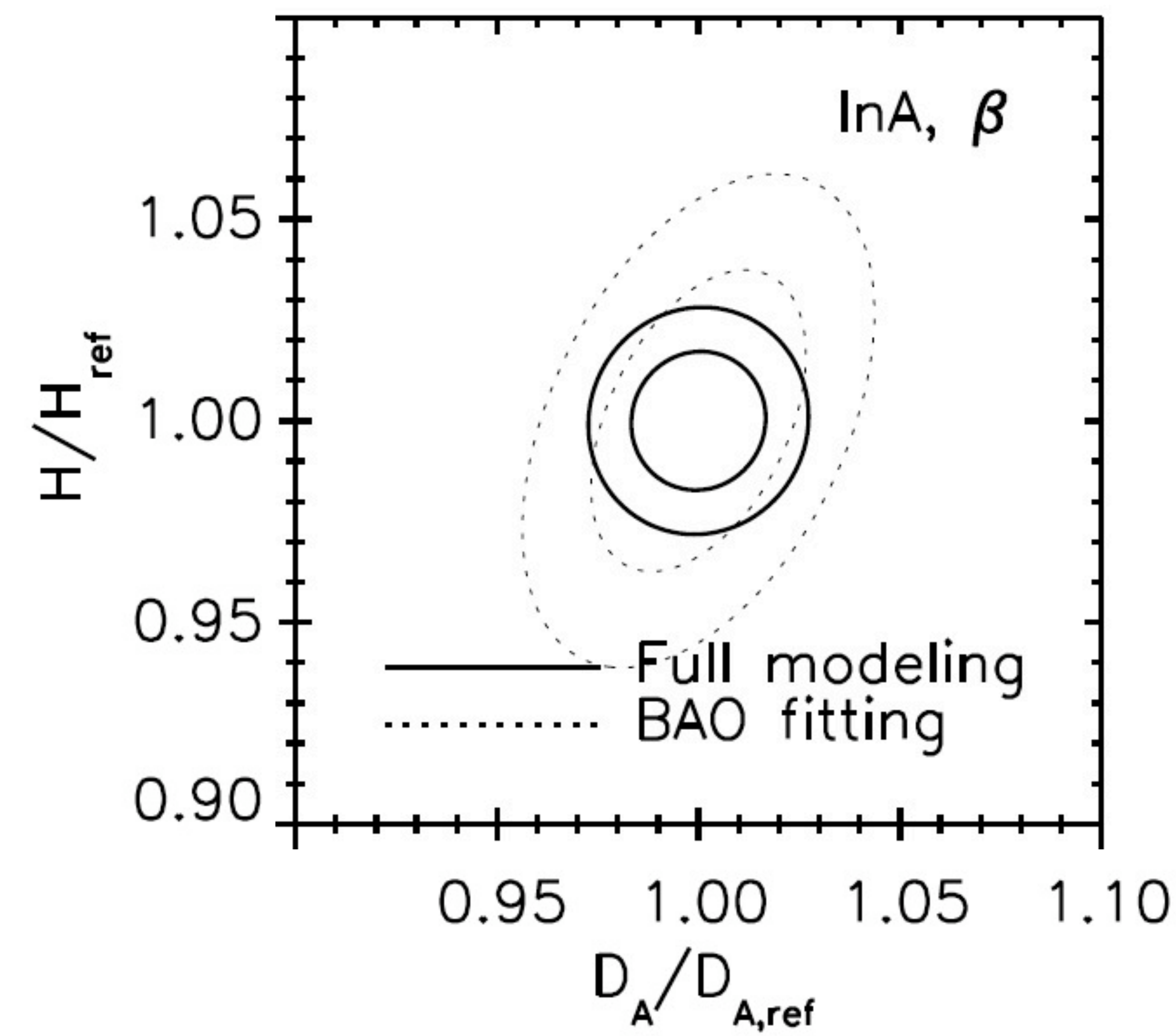
Beyond BAO

- 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 (2008)

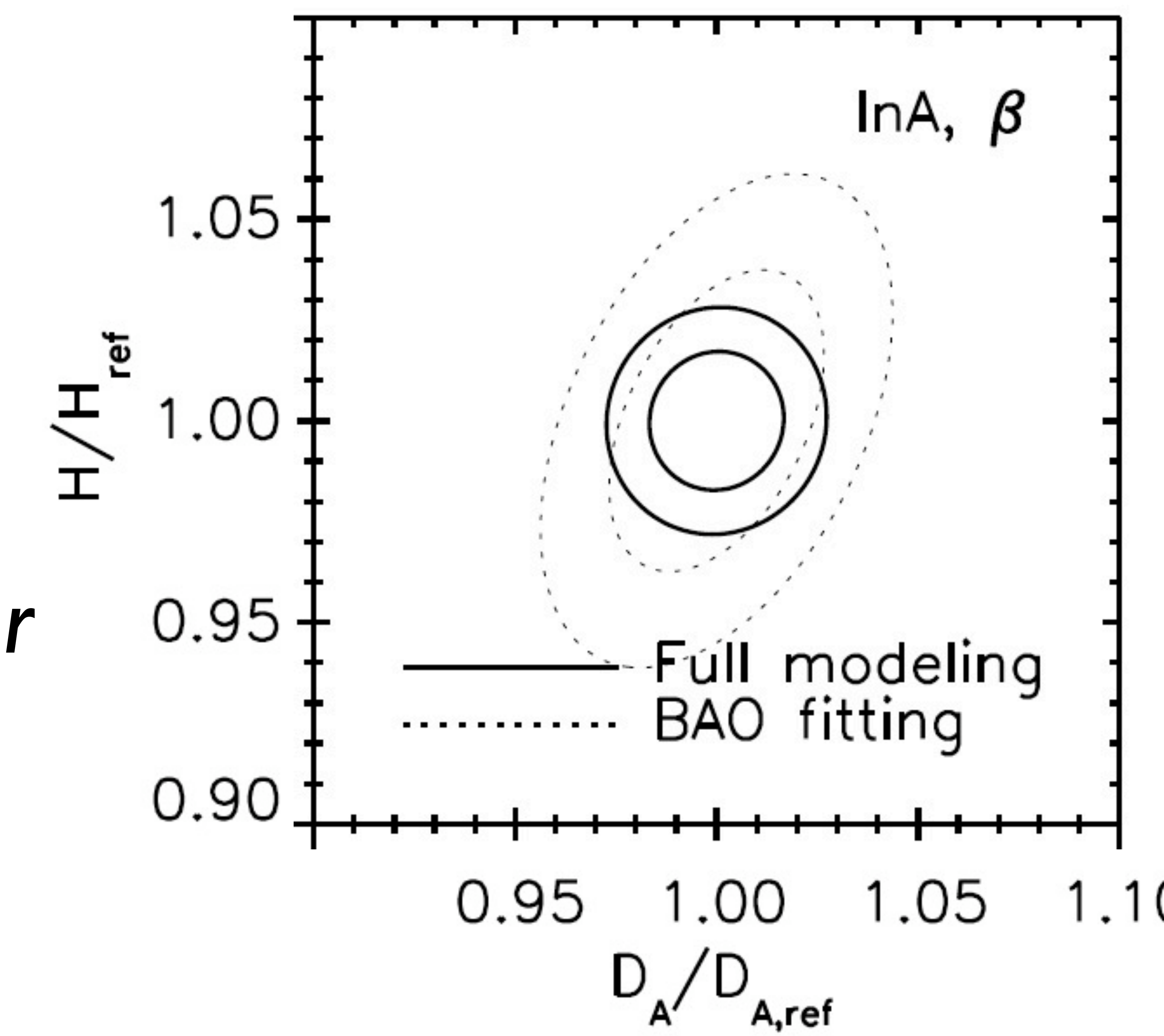
BAO vs Full Modeling

- 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.*



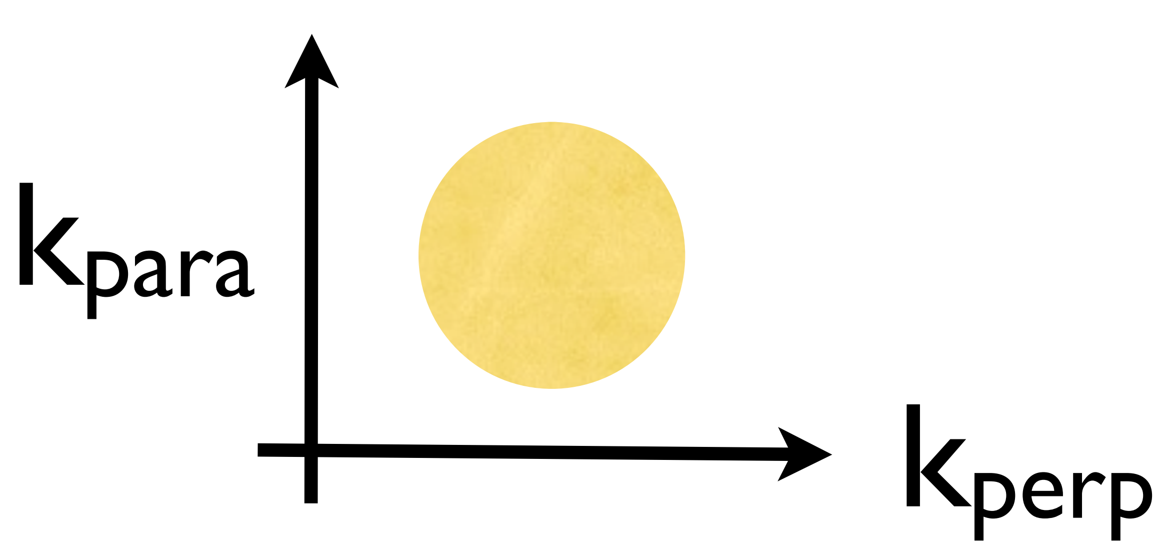
The AP Test: How That Works

- 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.

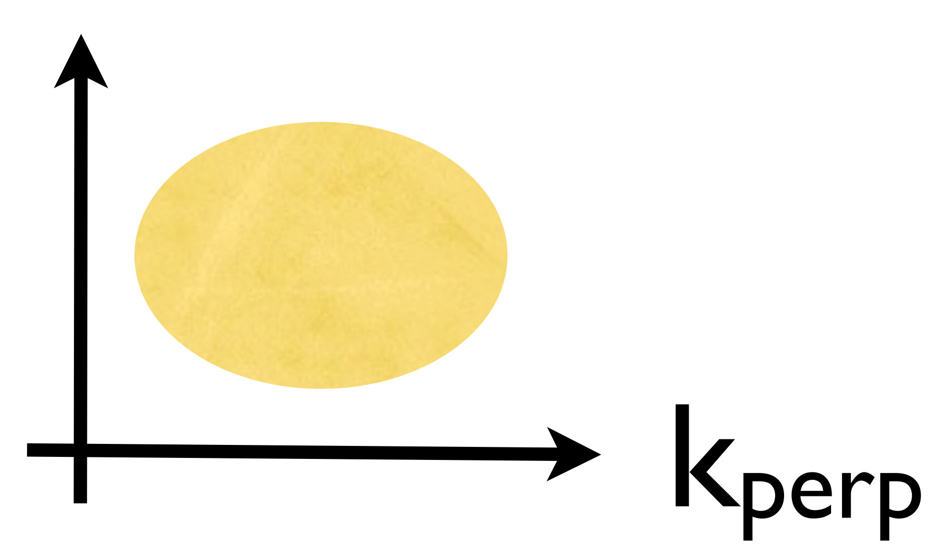
The AP Test: How That Works

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

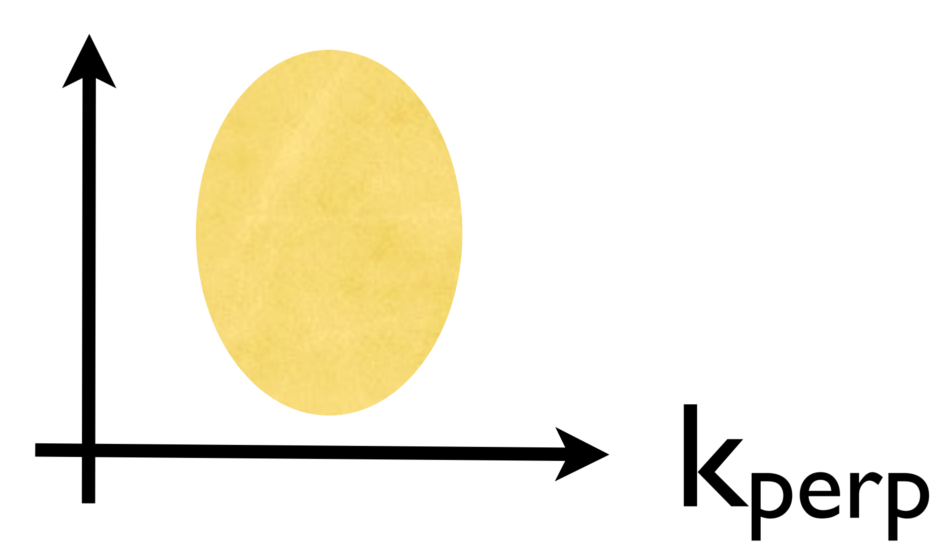
If D_A and H are correct:



If D_A is wrong:



If H is wrong:



The AP Test: How That Works

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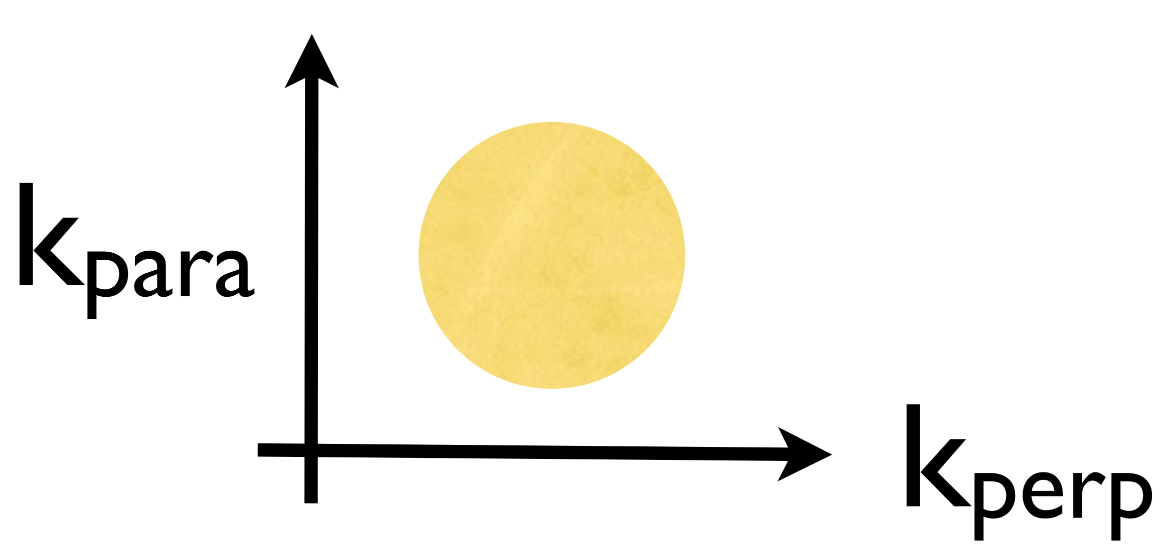
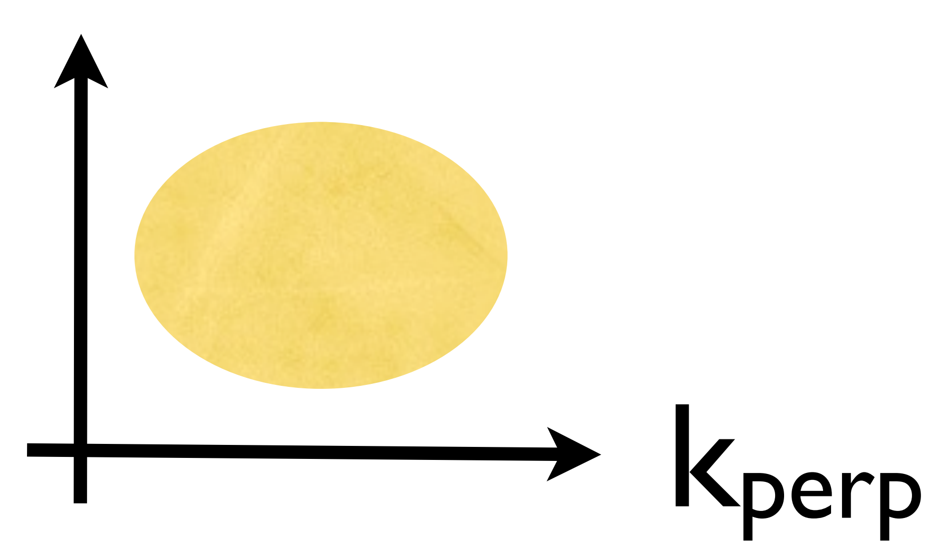


If D_A is wrong:



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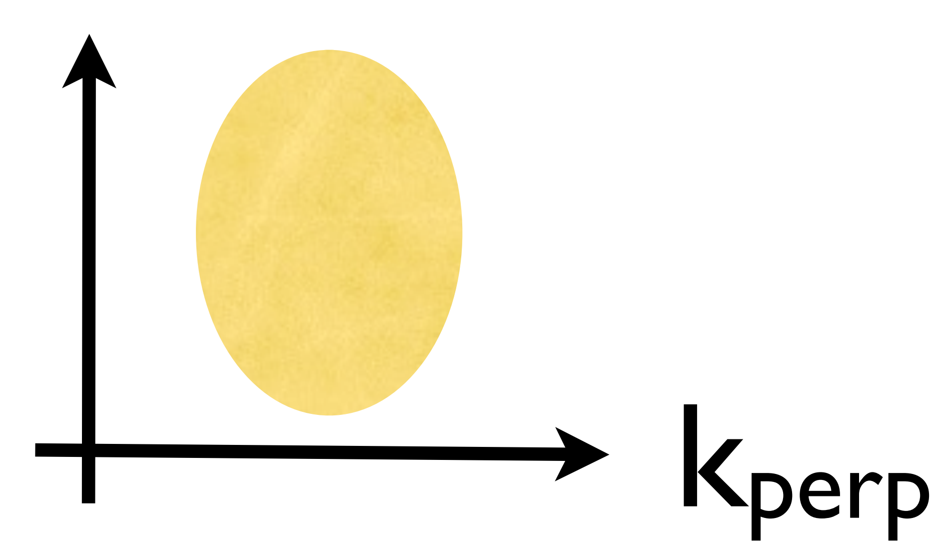
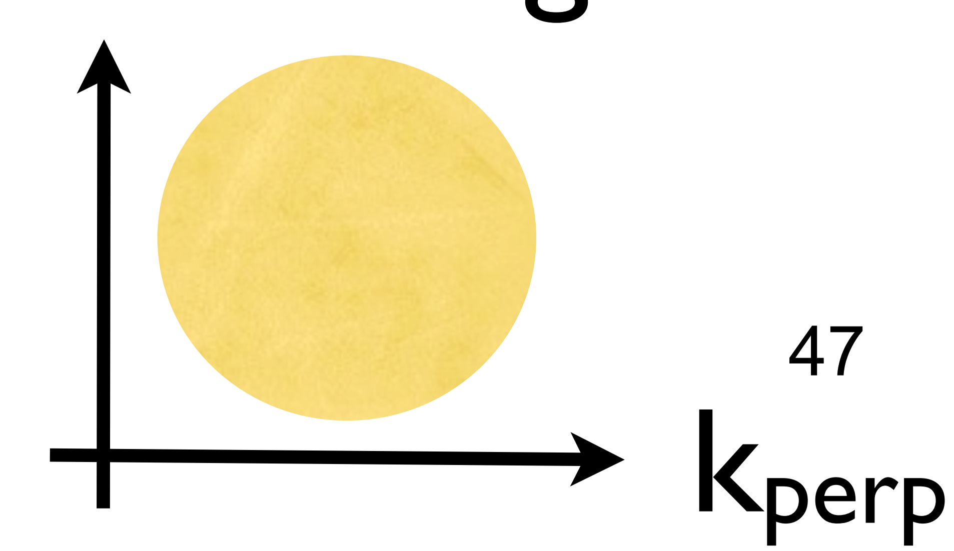
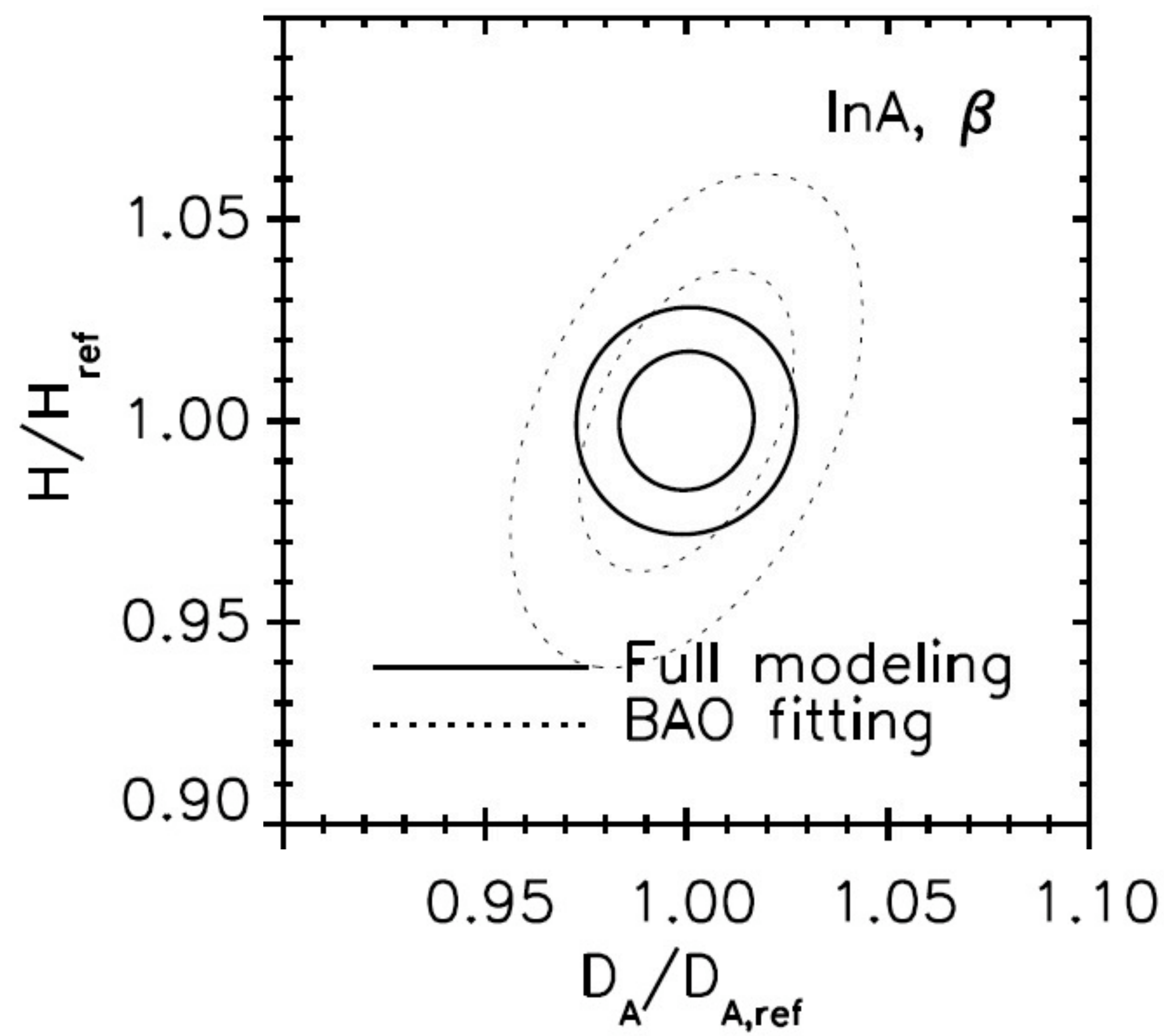


If D_A and H are wrong:



$D_A H$ 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.



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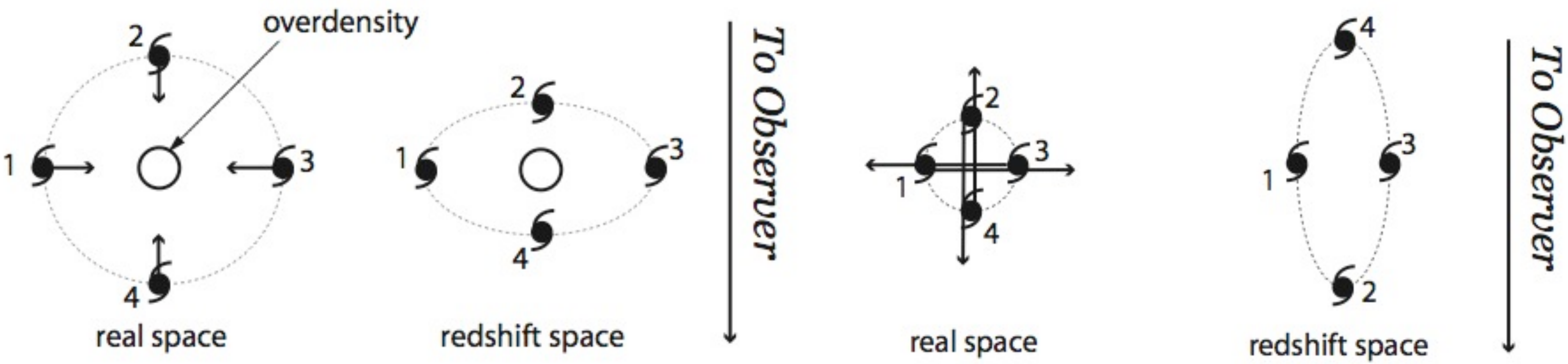
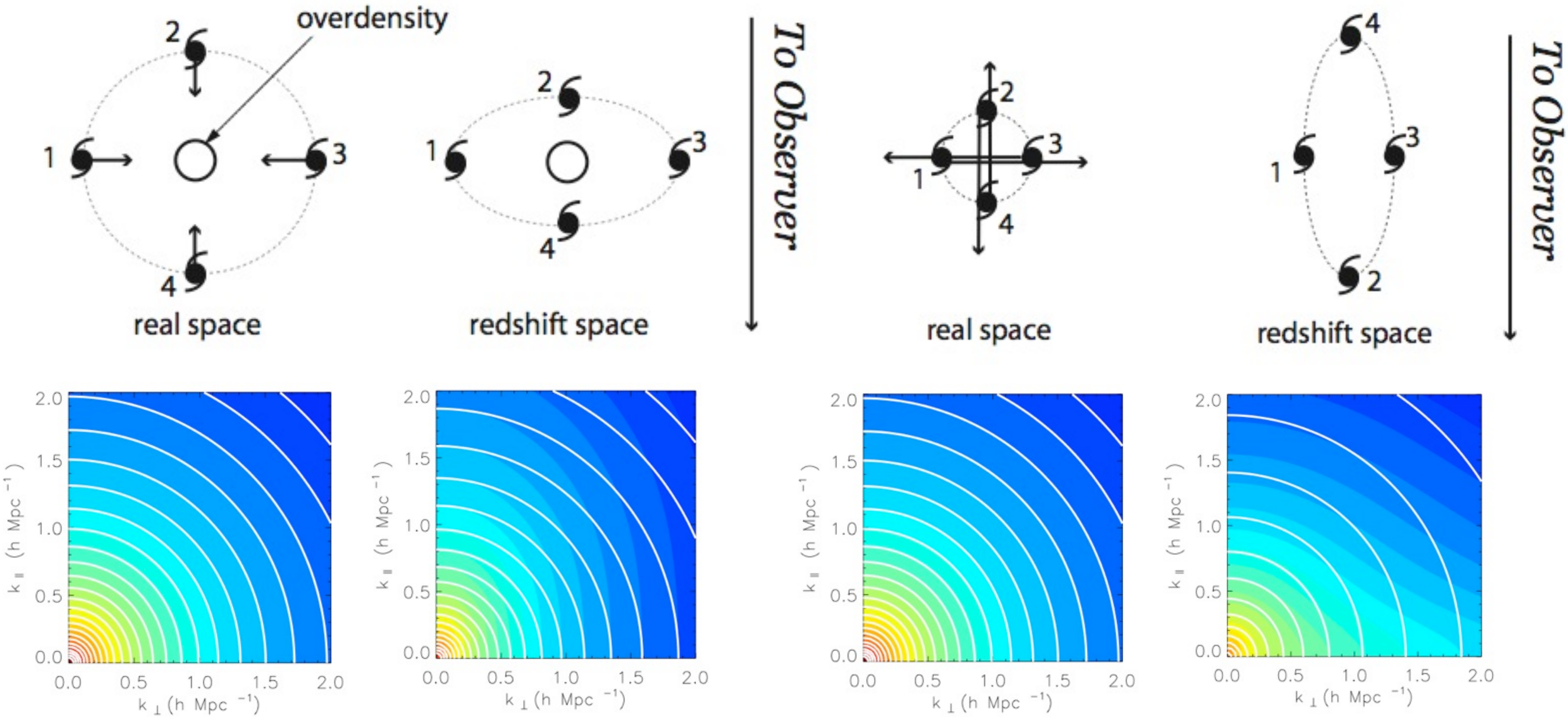
Redshift Space Distortion



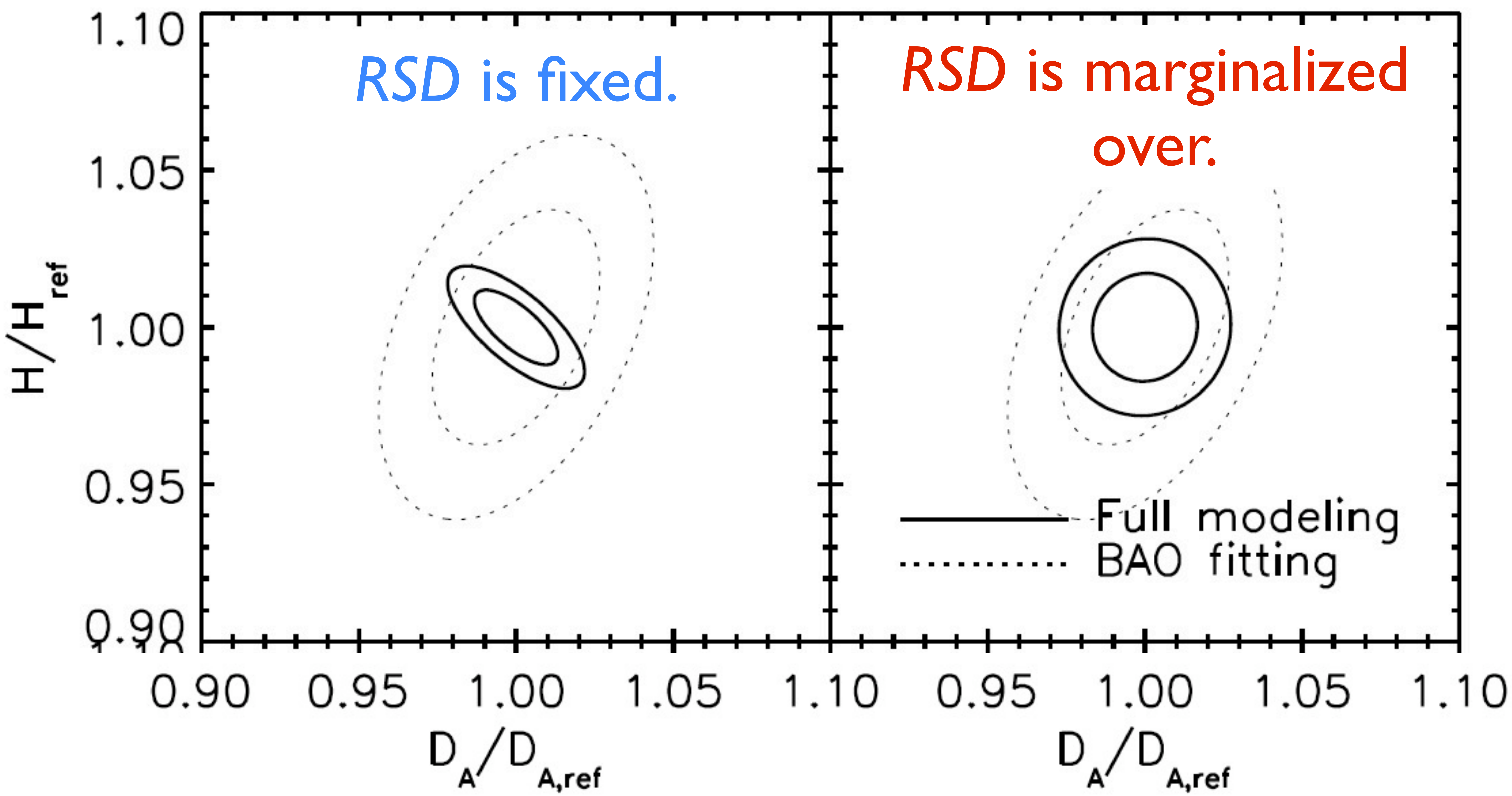
- (Left) Coherent flow => clustering **enhanced** along l.o.s
    - "Kaiser" effect
- (Right) Virial motion => clustering **reduced** along l.o.s.
    - "Finger-of-God" effect

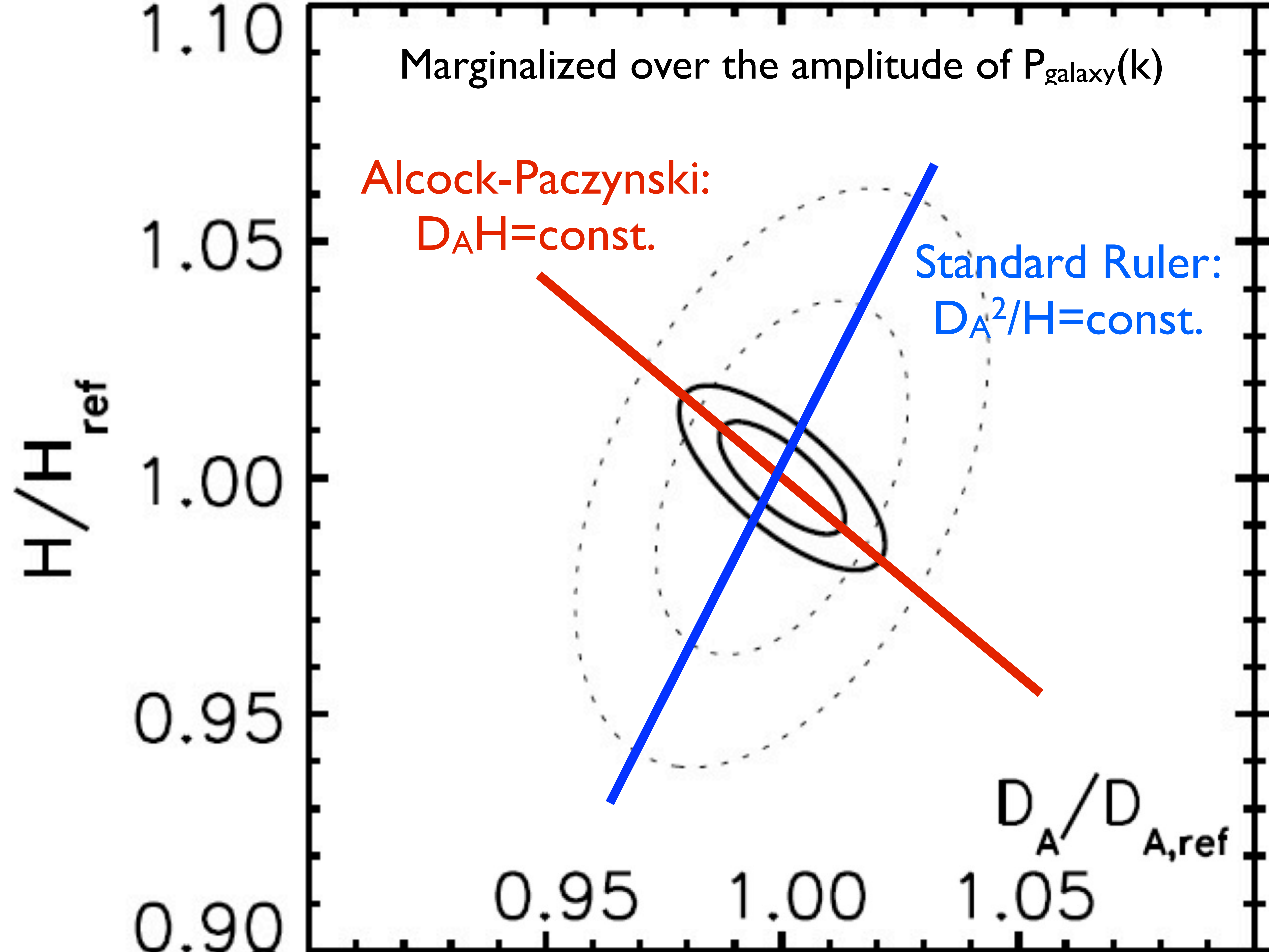
Redshift Space Distortion



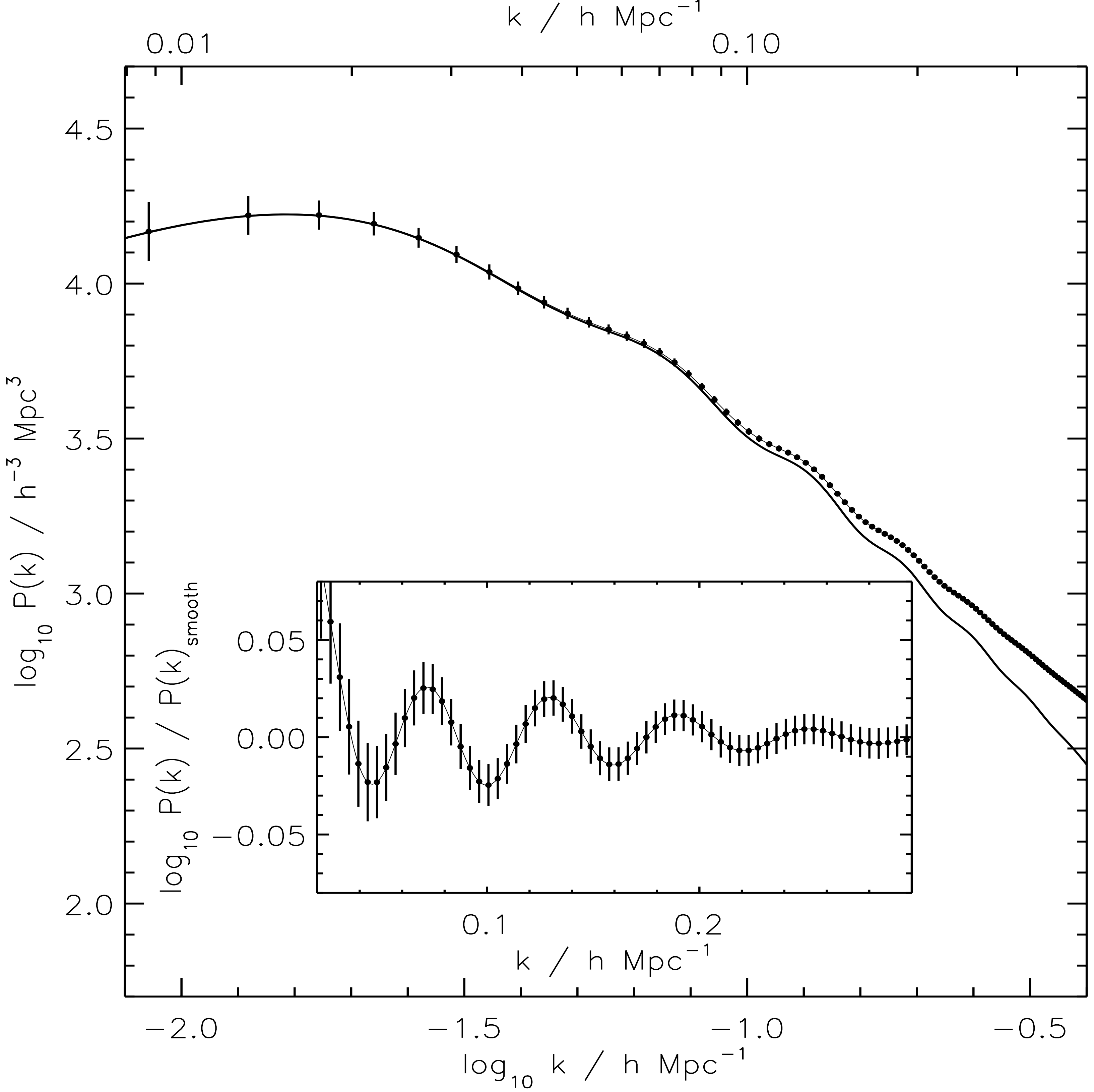
Redshift Space Distortion (RSD)

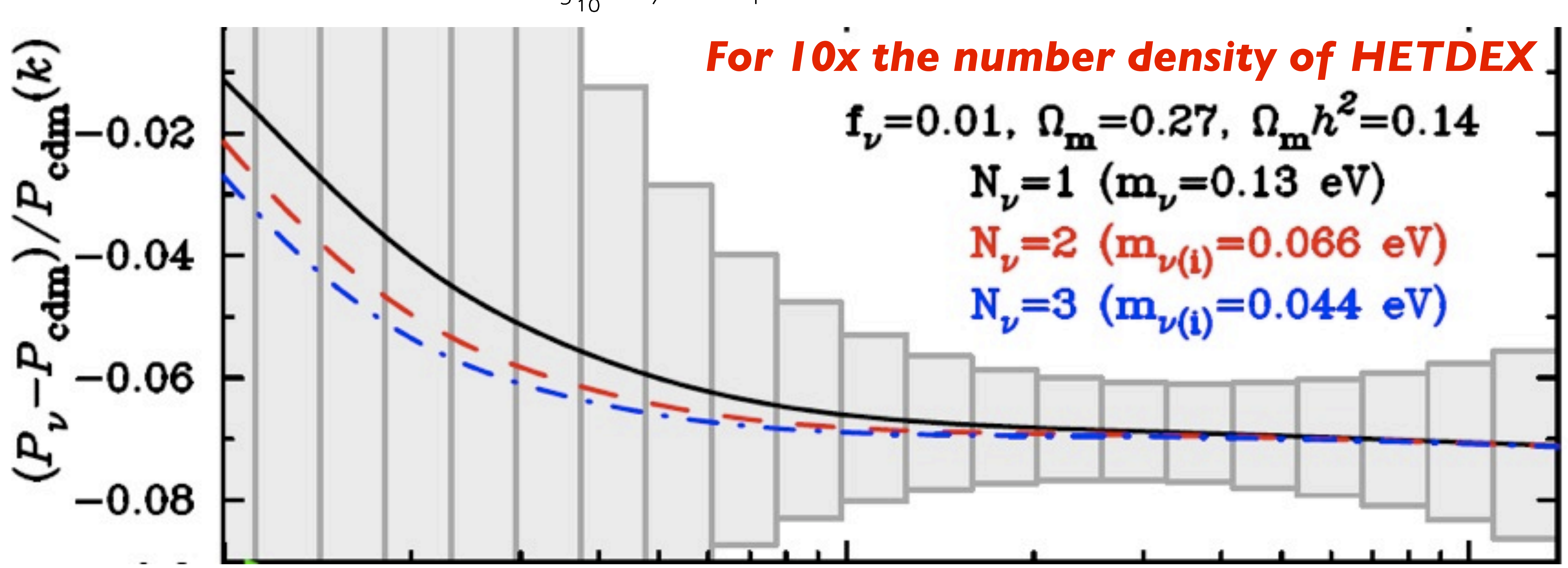
- Both the AP test and the redshift space distortion make the distribution of the power anisotropic. Would it spoil the utility of this method?
  - Some, but not all!




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

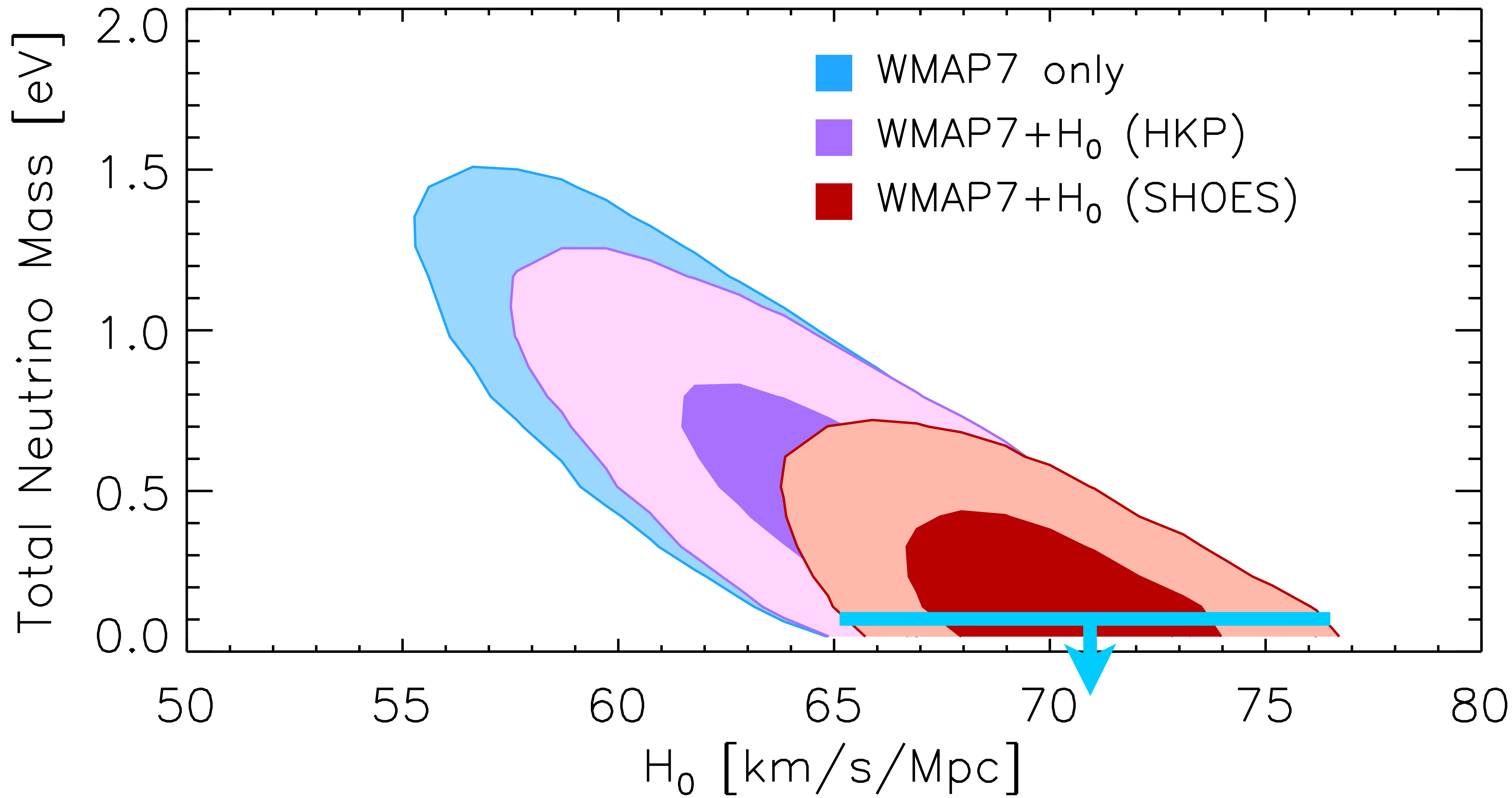
HETDEX and Neutrino Mass





- Neutrinos suppress the matter power spectrum on small scales (k>0.1 h Mpc^{-1}).
- A useful number to remember:
  - For $\sum m_\nu$=0.1 eV, the power spectrum at k>0.1 h Mpc^{-1} is suppressed by **~7%**.
  - We can measure this easily!

Expected HETDEX Limit



- ~6x better than WMAP 7-year+H_0

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**