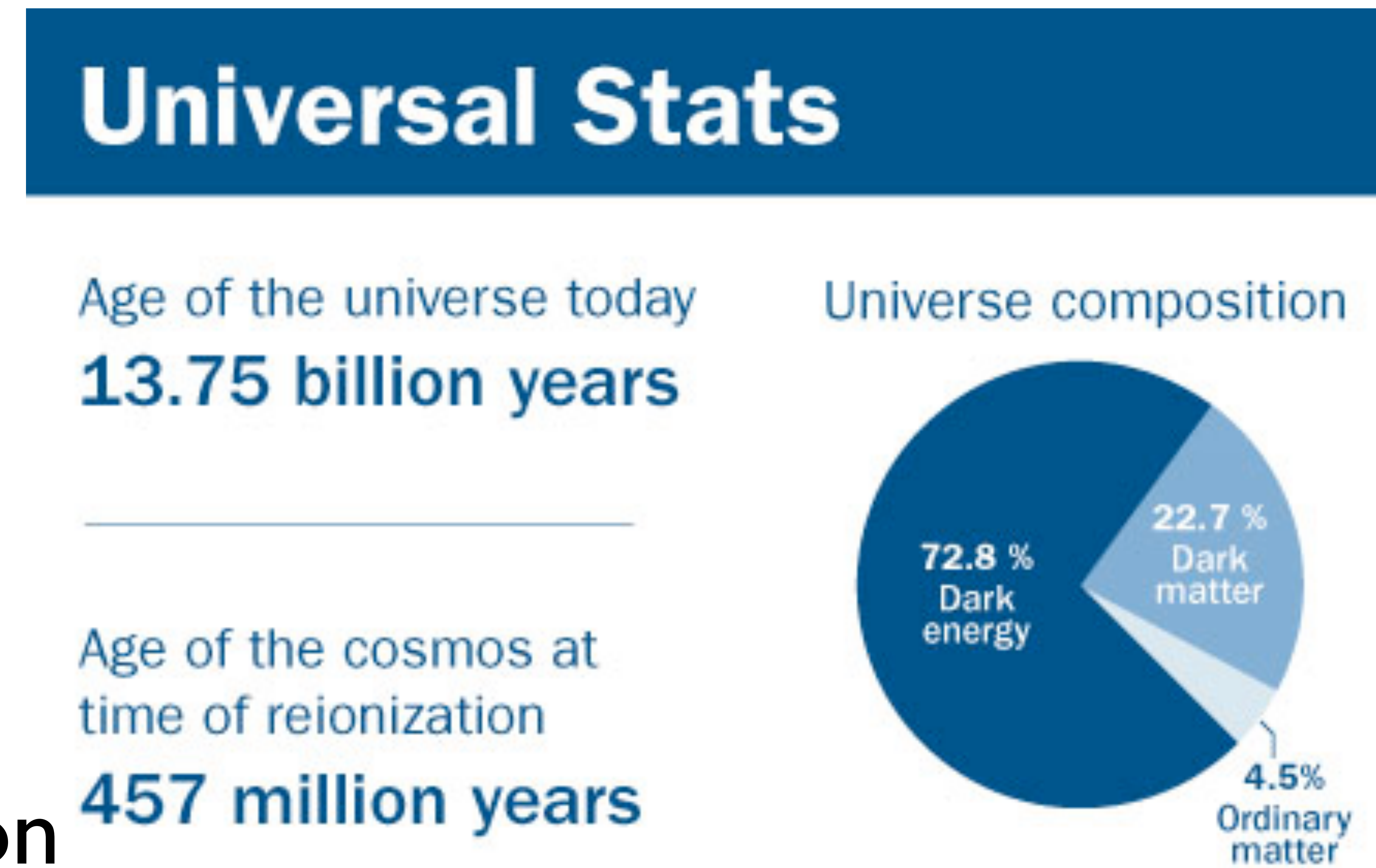
Cosmology with Large-scale Structure of the Universe

Eiichiro Komatsu (Texas Cosmology Center, UT Austin)

Korean Young Cosmologists Workshop, June 27, 2011

Cosmology Update: WMAP 7-year+

- **Standard Model**
  - H&He = 4.58% (±0.16%)
  - Dark Matter = 22.9% (±1.5%)
  - Dark Energy = 72.5% (±1.6%)
  - H_0=70.2±1.4 km/s/Mpc
  - Age of the Universe = 13.76 billion years (±0.11 billion years)



"ScienceNews" article on the WMAP 7-year results

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?

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

TABLE I Summary of Science Frontiers Panels' Findings

Panel		Science Questions	
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*

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*

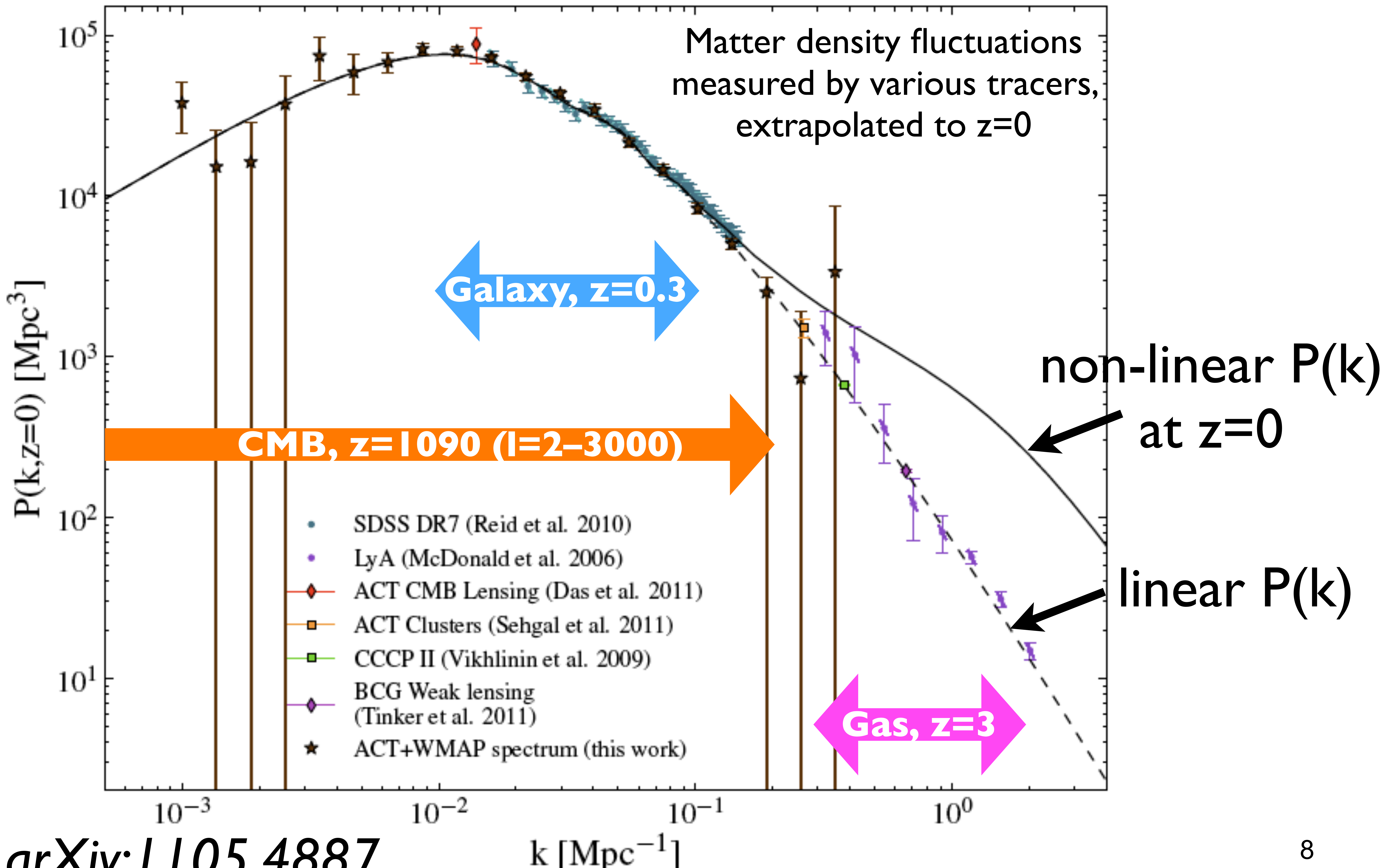
What to measure?

- **Inflation**
  - Shape of the initial power spectrum (n_s; $dn_s/d\ln k$; etc)
  - Non-Gaussianity (3pt f_{NL}^{local}; 4pt τ_{NL}^{local}; etc)
- **Dark Energy**
  - Angular diameter distances over a wide redshift range
  - Hubble expansion rates over a wide redshift range
  - Growth of linear density fluctuations over a wide redshift range
  - Shape of the matter power spectrum (modified grav)

What to measure?

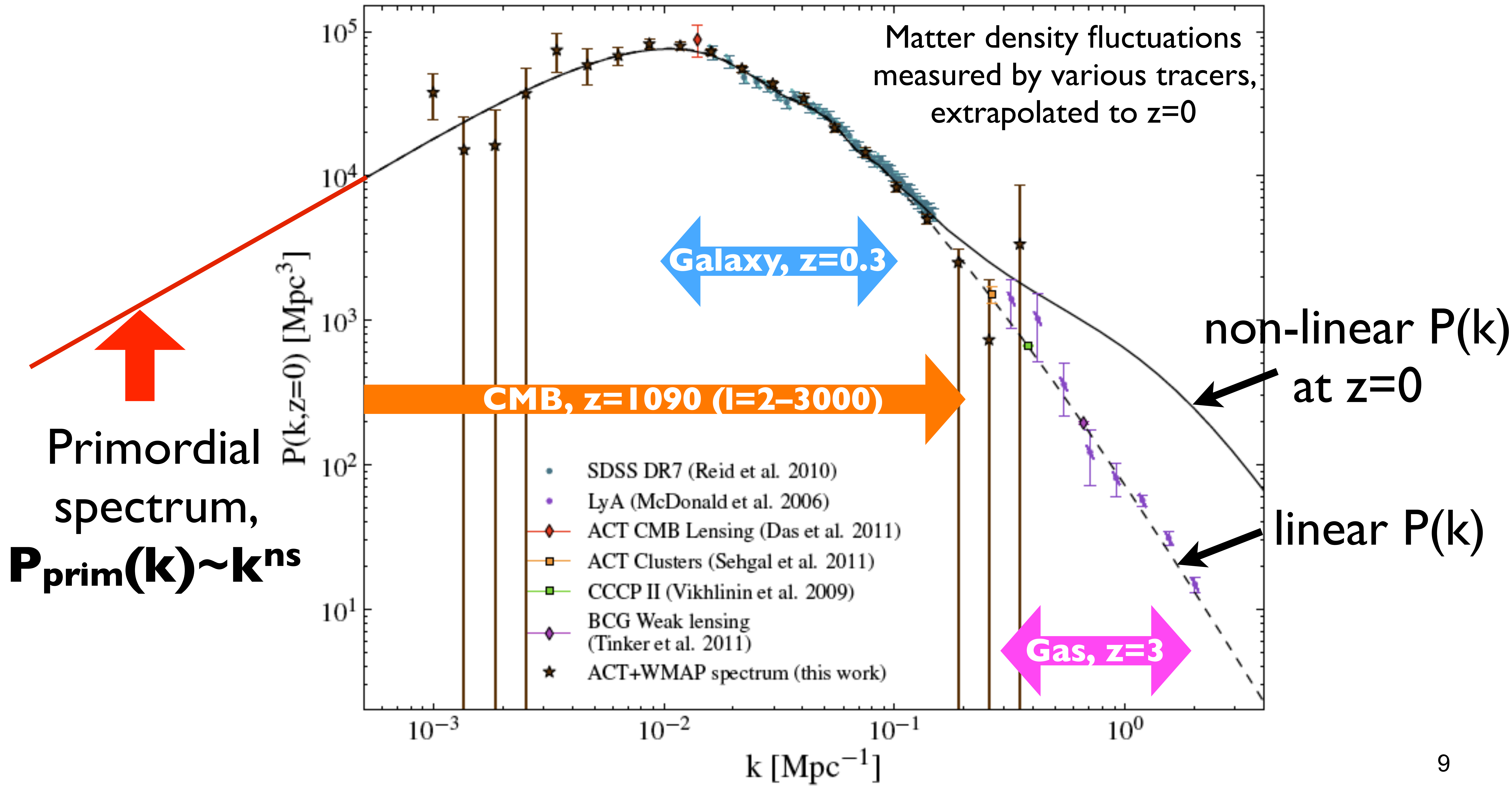
- **Neutrino Mass**
  - Shape of the matter power spectrum
- **Dark Matter**
  - Shape of the matter power spectrum (warm/hot DM)
  - Large-scale structure traced by γ-ray photons

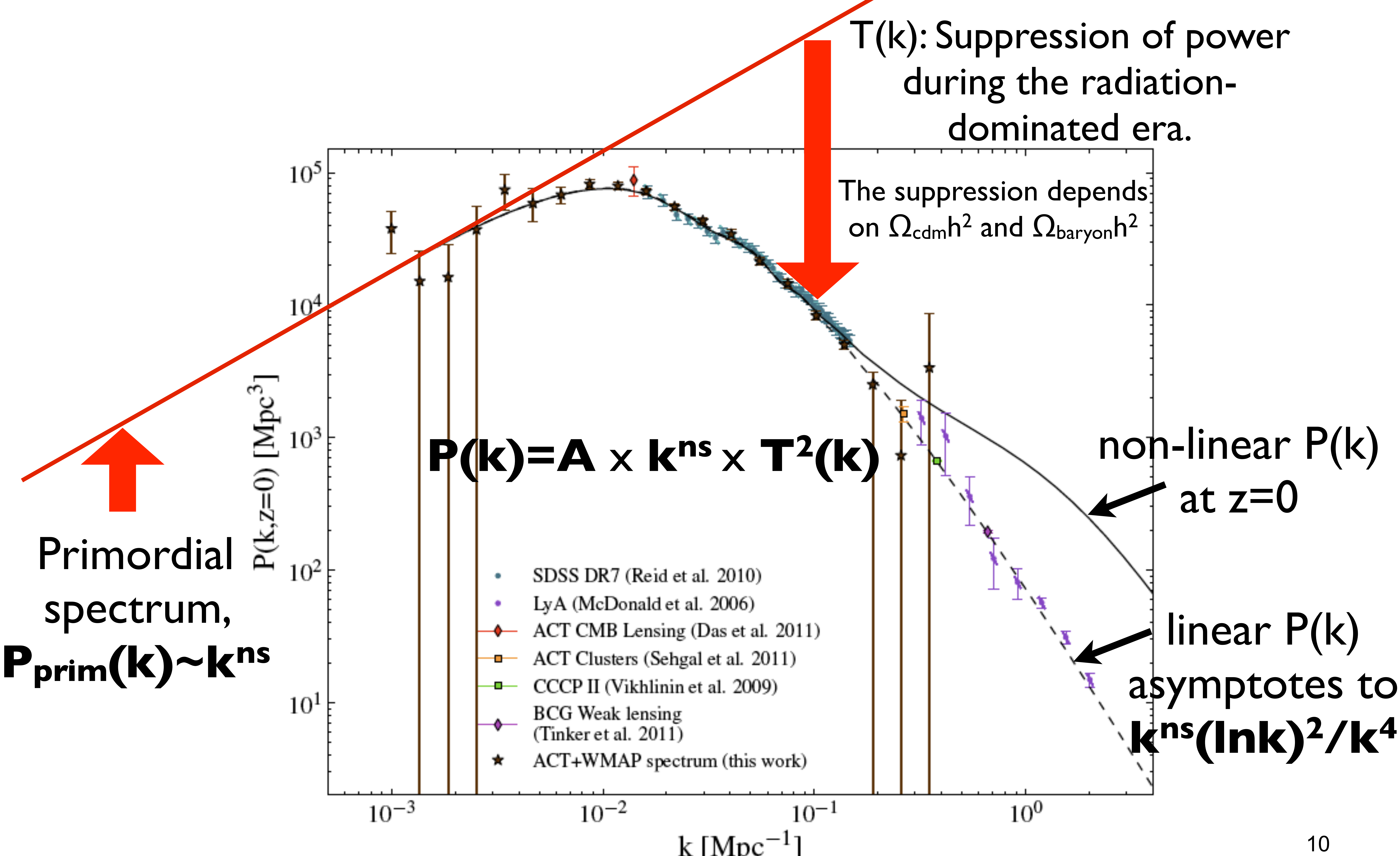
Shape of the Power Spectrum, P(k)



Hlozek et al., arXiv:1105.4887

Shape of the Power Spectrum, P(k)




T(k): Suppression of power during the radiation-dominated era.
The suppression depends on $\Omega_{cdm}h^2$ and $\Omega_{baryon}h^2$
$P(k)=A \times k^{ns} \times T^2(k)$
non-linear P(k) at z=0
linear P(k) asymptotes to $k^{ns}(\ln k)^2/k^4$
Primordial spectrum, $P_{prim}(k) \sim k^{ns}$
P(k,z=0) [Mpc^3]
k [Mpc^{-1}]
SDSS DR7 (Reid et al. 2010)
LyA (McDonald et al. 2006)
ACT CMB Lensing (Das et al. 2011)
ACT Clusters (Sehgal et al. 2011)
CCCP II (Vikhlinin et al. 2009)
BCG Weak lensing (Tinker et al. 2011)
ACT+WMAP spectrum (this work)

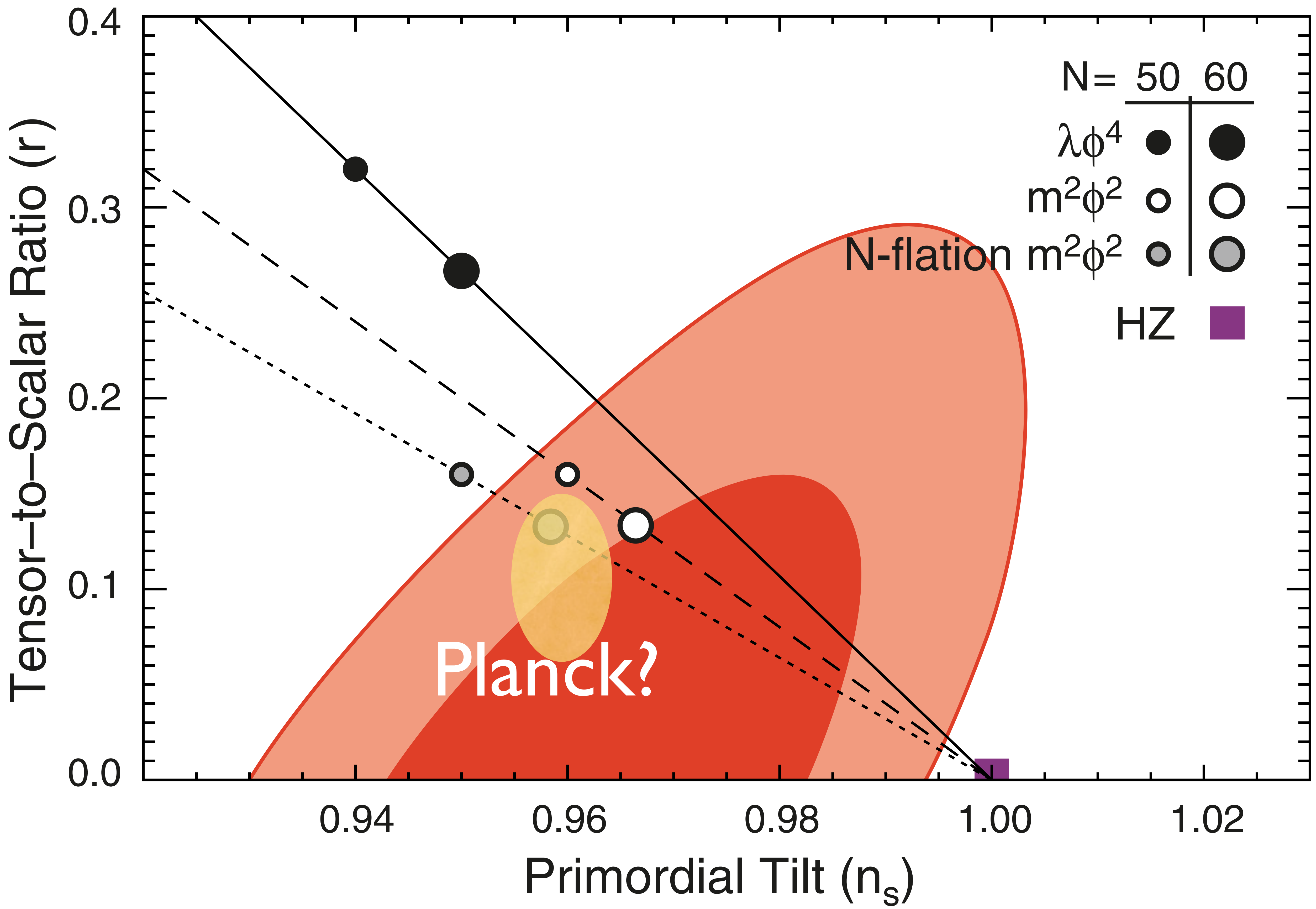
Current Limit on n_s

- Limit on the tilt of the power spectrum:
  - **n_s=0.968±0.012** (68%CL; Komatsu et al. 2011)
  - Precision is dominated by the WMAP 7-year data

- Planck's CMB data are expected to improve the error bar by a factor of ~4.

Probing Inflation (2-point Function)

r = (gravitational waves)^2 / (gravitational potential)^2

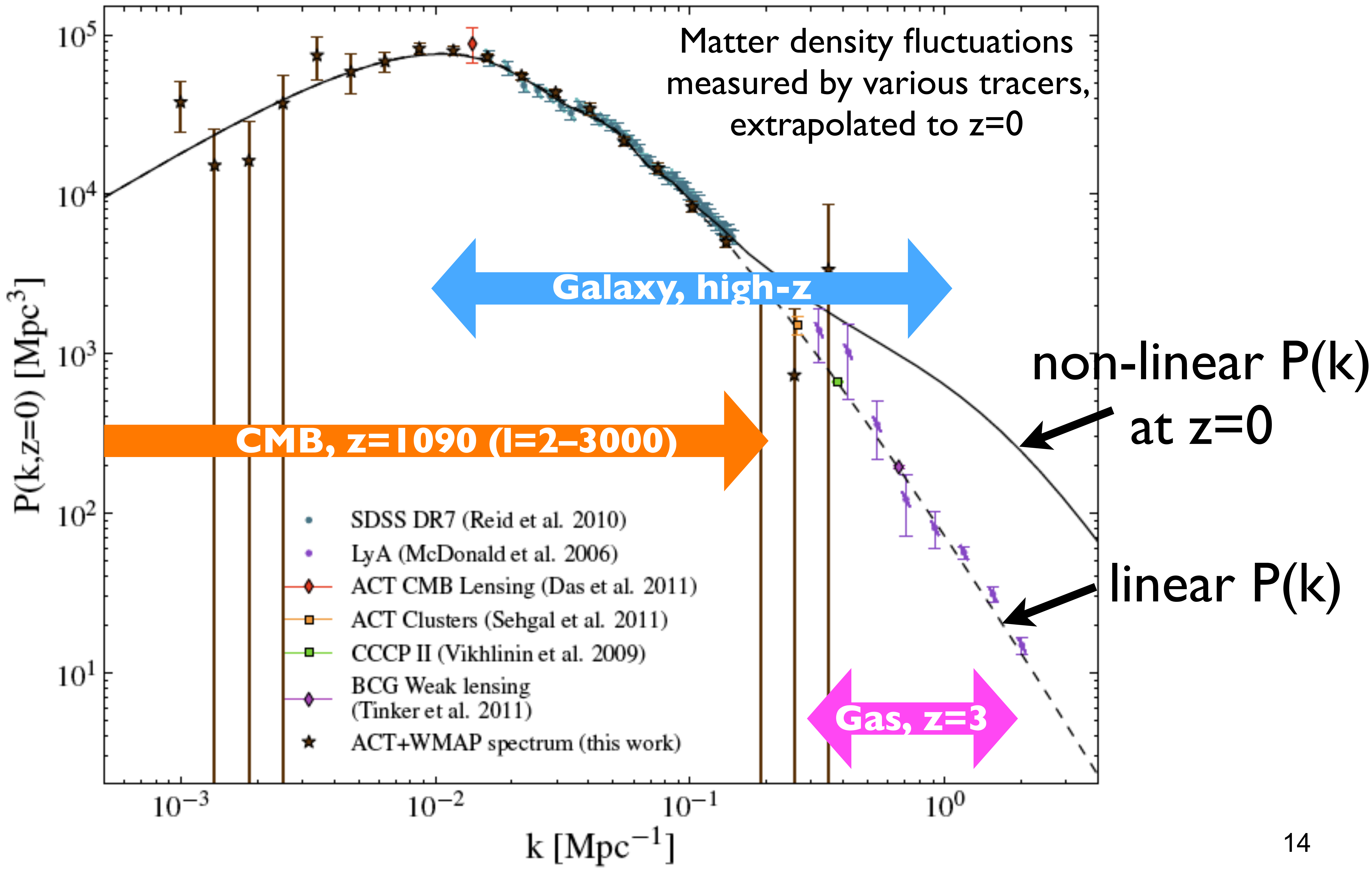


- Joint constraint on the primordial tilt, n_s, and the tensor-to-scalar ratio, r.
  - Not so different from the 5-year limit.
  - $r < 0.24$ (95%CL)
- Limit on the tilt of the power spectrum: $n_s = 0.968 \pm 0.012$ (68%CL)

Role of the Large-scale Structure of the Universe

- However, CMB data can't go much beyond $k=0.2\ Mpc^{-1}$ ($l=3000$).
    - Large-scale structure data are required to go to smaller scales.

Shape of the Power Spectrum, P(k)



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

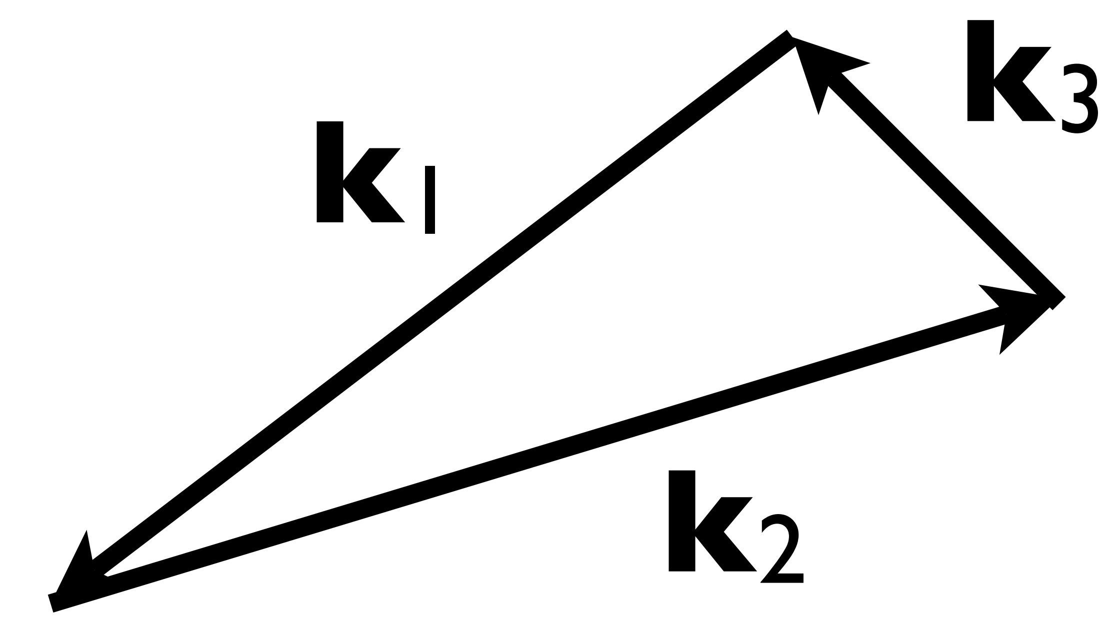
- As far as the value of n_s is concerned, CMB is probably enough.
- However, if we want to measure the scale-dependence of n_s, i.e., deviation of $P_{prim}(k)$ from a pure power-law, then we need the small-scale data.
  - This is where the large-scale structure data become quite powerful (Takada, Komatsu & Futamase 2006)
- Schematically:
  - $dn_s/d\ln k = [n_s(CMB) - n_s(LSS)]/(\ln k_{CMB} - \ln k_{LSS})$

Probing Inflation (3-point Function)

Can We Rule Out Inflation?

- Inflation models predict that primordial fluctuations are very close to Gaussian.
  - In fact, ALL SINGLE-FIELD models predict a particular form of **3-point function** to have the amplitude of f_{NL}^{local}=0.02.
  - Detection of f_{NL}>1 would rule out ALL single-field models!

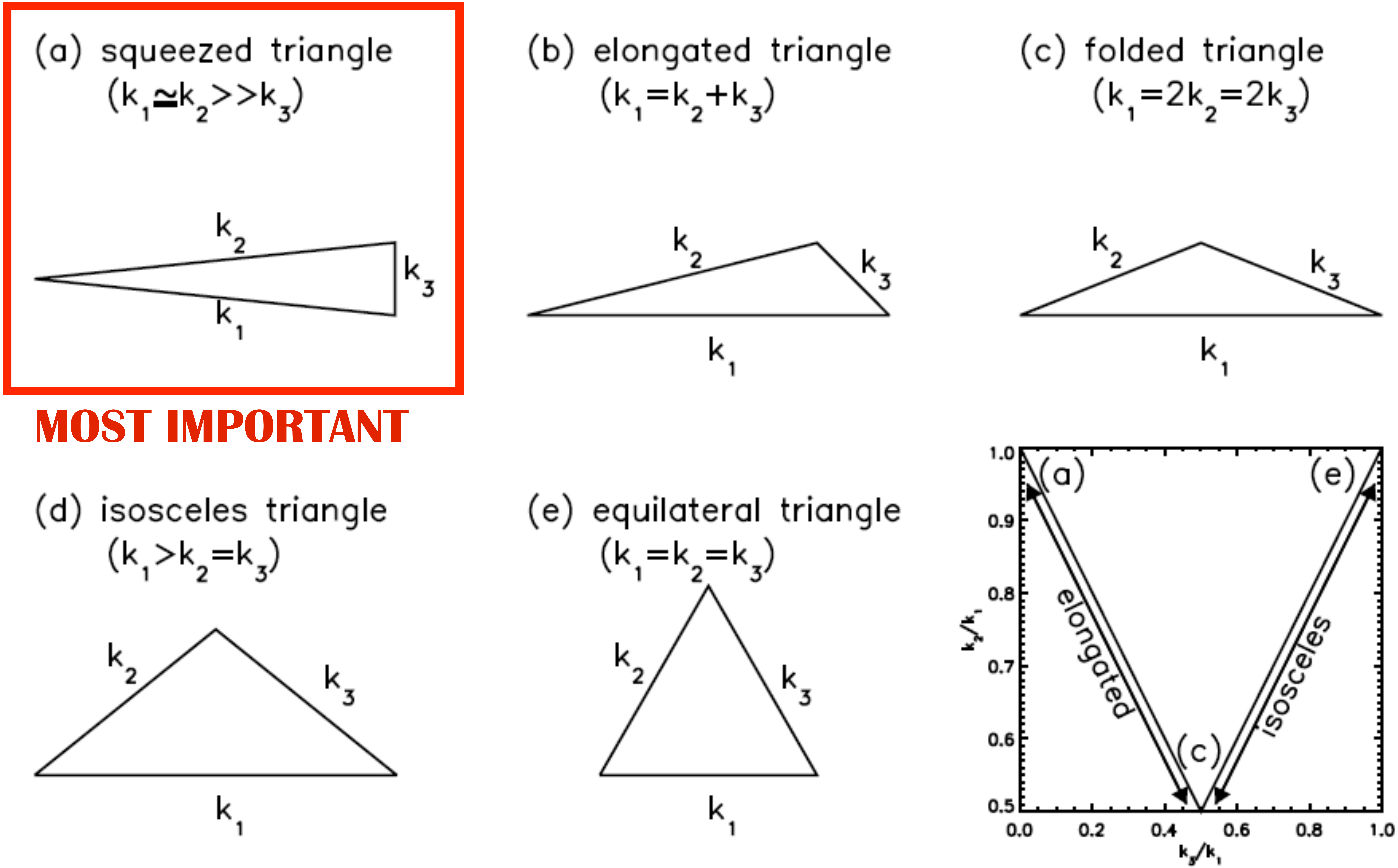
Bispectrum



- Three-point function!
- $B_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$
  $= \langle \zeta_{\mathbf{k}1}\zeta_{\mathbf{k}2}\zeta_{\mathbf{k}3} \rangle$ = (amplitude) x $(2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)F(k_1,k_2,k_3)$

  model-dependent function

Primordial fluctuation


(a) squeezed triangle
(k1≃k2>>k3)
MOST IMPORTANT
(b) elongated triangle
(k1=k2+k3)
(c) folded triangle
(k1=2k2=2k3)
(d) isosceles triangle
(k1>k2=k3)
(e) equilateral triangle
(k1=k2=k3)
k1
k2
k3
elongated
isosceles
k2/k1
k3/k1
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.2
0.4
0.6
0.8
1.0

Maldacena (2003); Seery & Lidsey (2005); Creminelli & Zaldarriaga (2004)

Single-field Theorem (Consistency Relation)

- For **ANY** single-field models*, the bispectrum in the squeezed limit is given by
  - $B_\zeta(\mathbf{k}_1 \sim \mathbf{k}_2 << \mathbf{k}_3) \approx (1-n_s) \times (2\pi)^3 \delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3) \times P_\zeta(k_1) P_\zeta(k_3)$
  - Therefore, all single-field models predict $f_{NL} \approx (5/12)(1-n_s)$.
  - With the current limit $n_s=0.968$, f_{NL} is predicted to be 0.01.

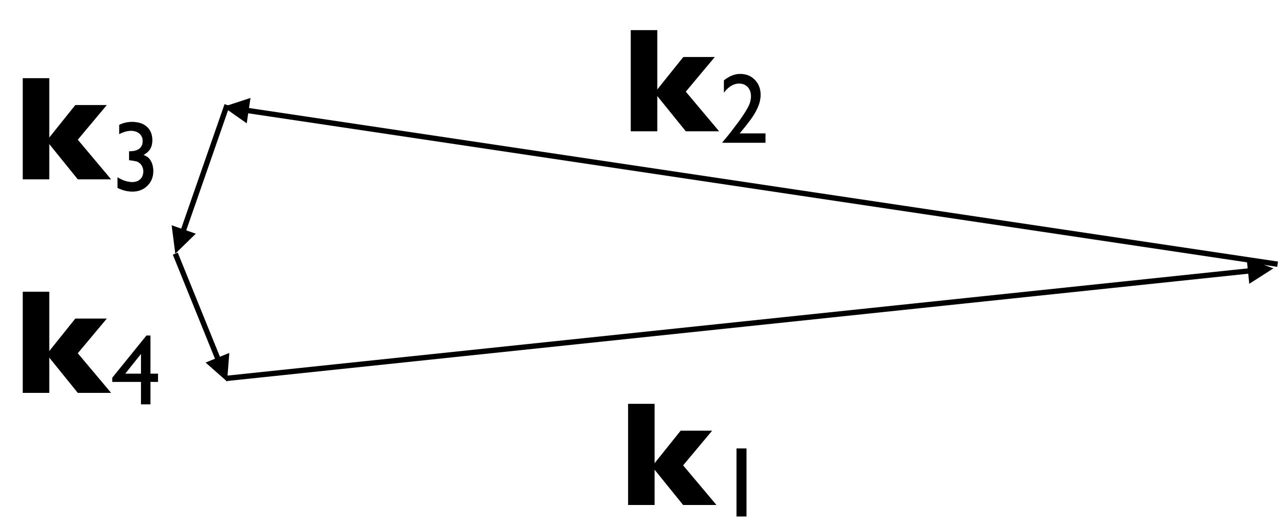
* for which the single field is solely responsible for driving inflation and generating observed fluctuations.

Probing Inflation (3-point Function)

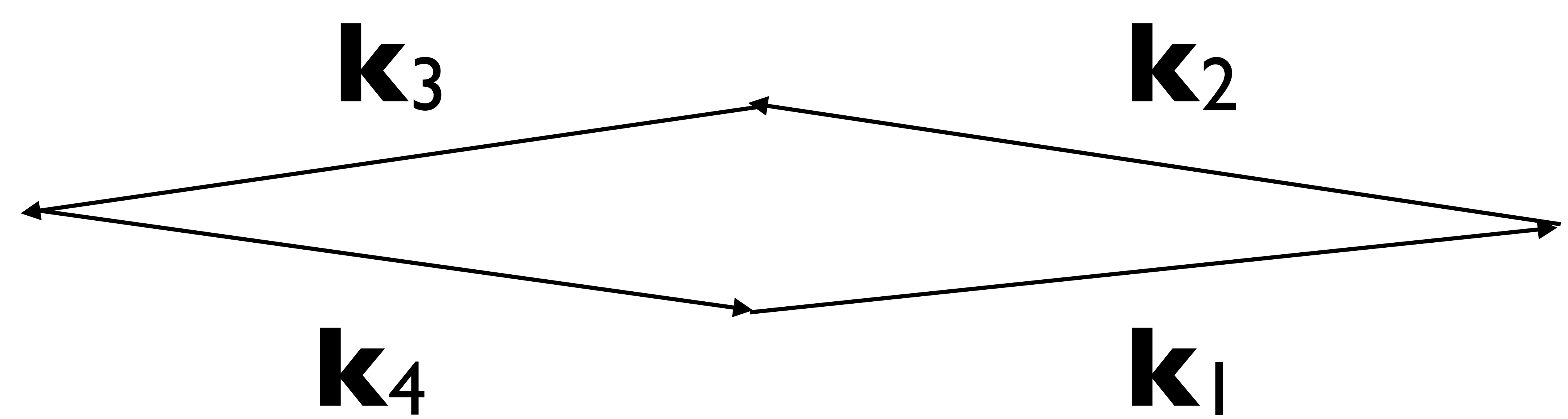
- No detection of 3-point functions of primordial curvature perturbations. The 95% CL limit is:
  - $-10 < f_{NL}^{local} < 74$
- The 68% CL limit: $f_{NL}^{local} = 32 \pm 21$
  - The WMAP data are consistent with the prediction of **simple single-field inflation** models: $1-n_s \approx r \approx f_{NL}$
- The Planck's expected 68% CL uncertainty: $\Delta f_{NL}^{local} = 5$

Trispectrum

- $T_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4)=(2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3+\mathbf{k}_4)\ \{g_{NL}[(54/25)P_\zeta(k_1)P_\zeta(k_2)P_\zeta(k_3)+\mathrm{cyc.}]+\tau_{NL}[P_\zeta(k_1)P_\zeta(k_2)(P_\zeta(|\mathbf{k}_1+\mathbf{k}_3|)+P_\zeta(|\mathbf{k}_1+\mathbf{k}_4|))+\mathrm{cyc.}]\}$

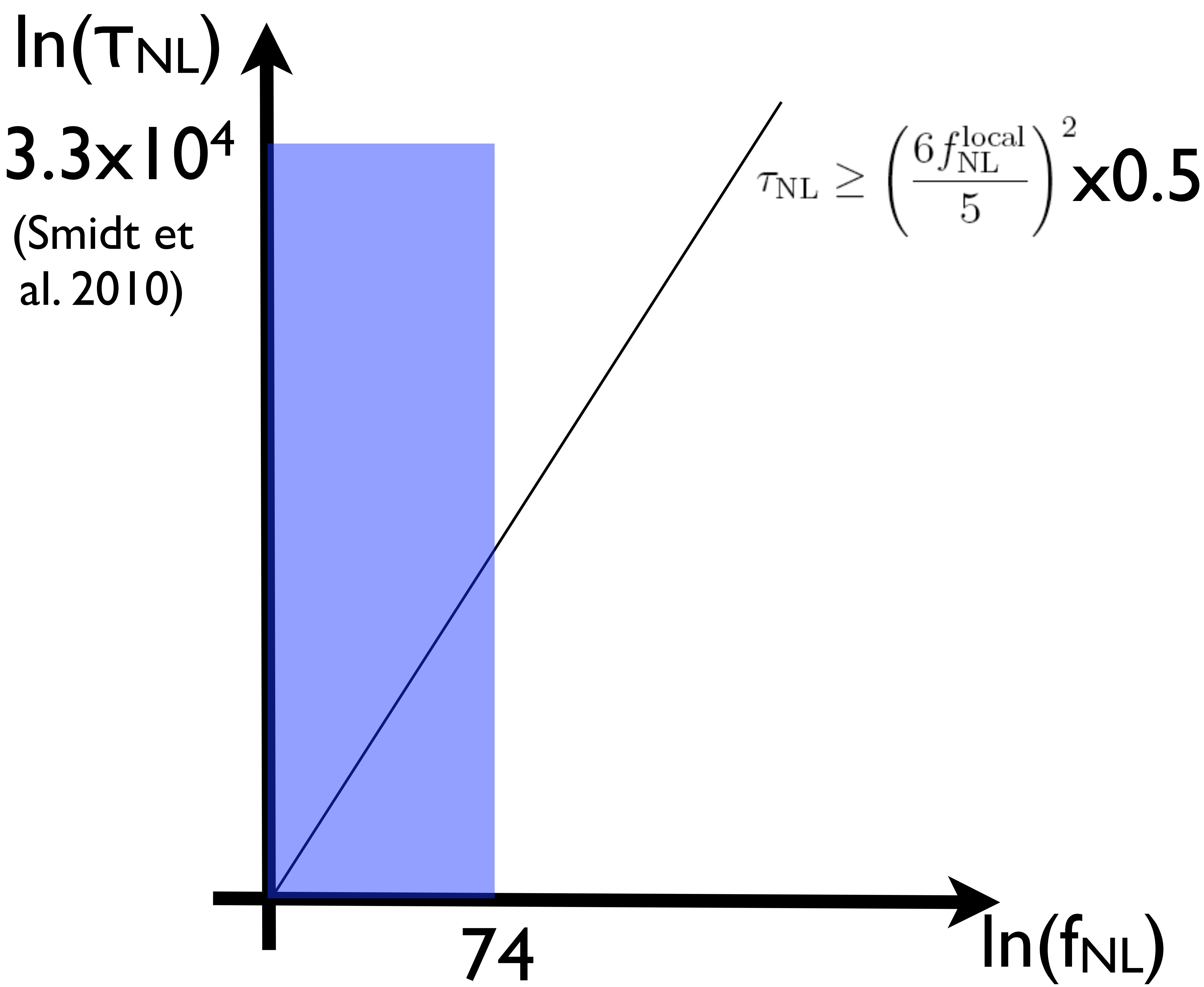


g_{NL}



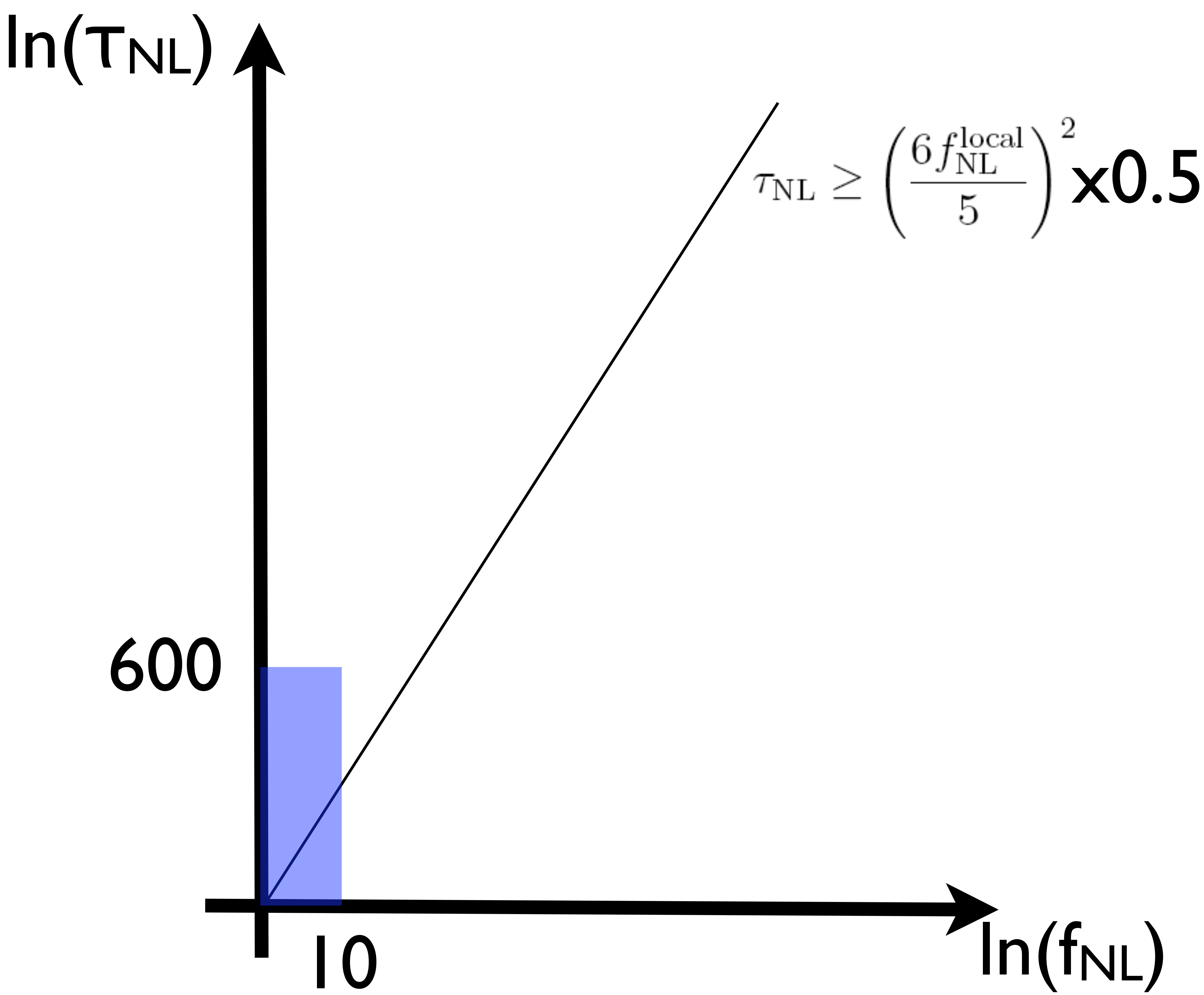
τ_{NL}

τ_{NL}^{local}–f_{NL}^{local} Diagram



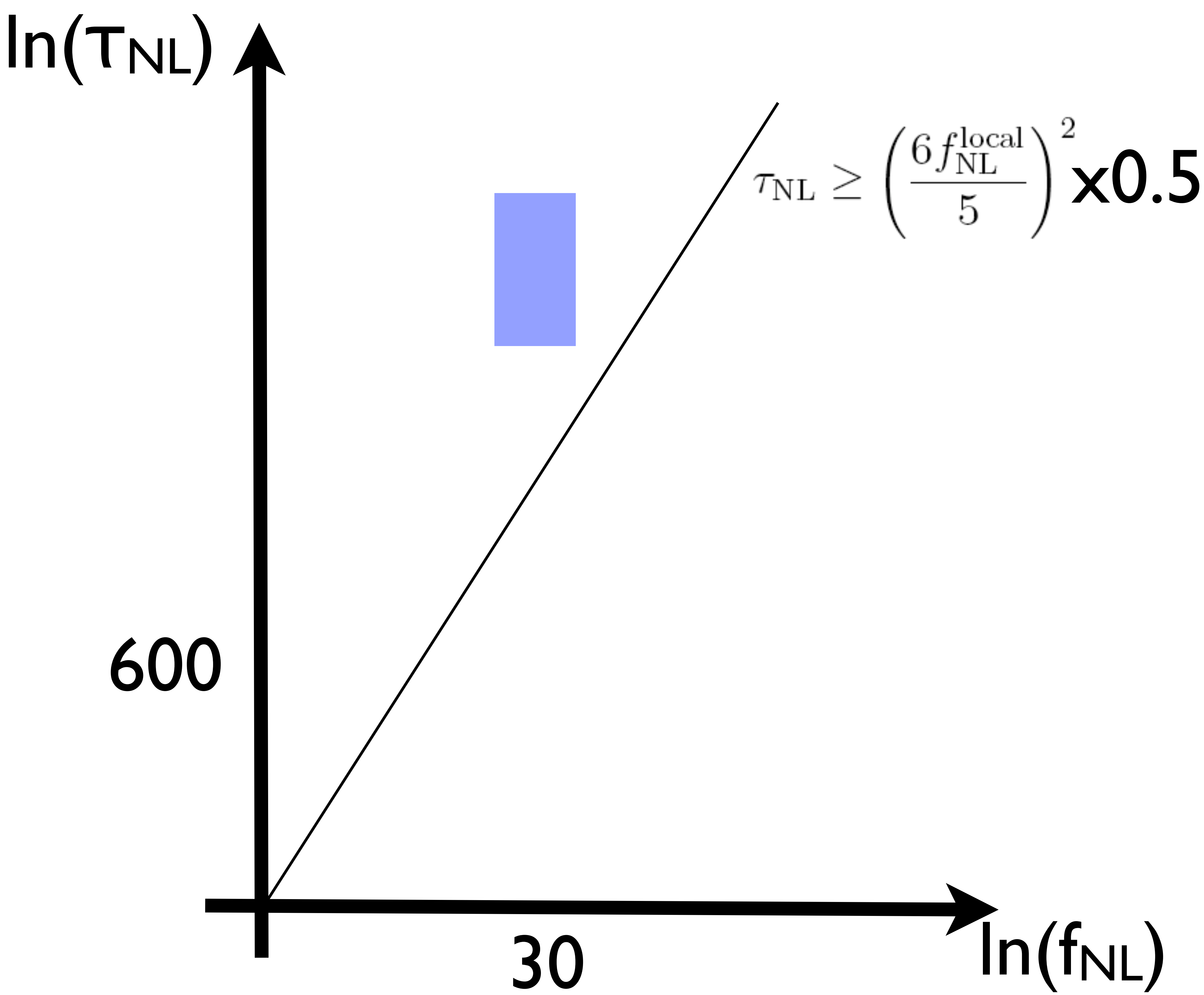
- The current limits from WMAP 7-year are consistent with single-field or multi-field models.
- So, let's play around with the future.

Case A: Single-field Happiness



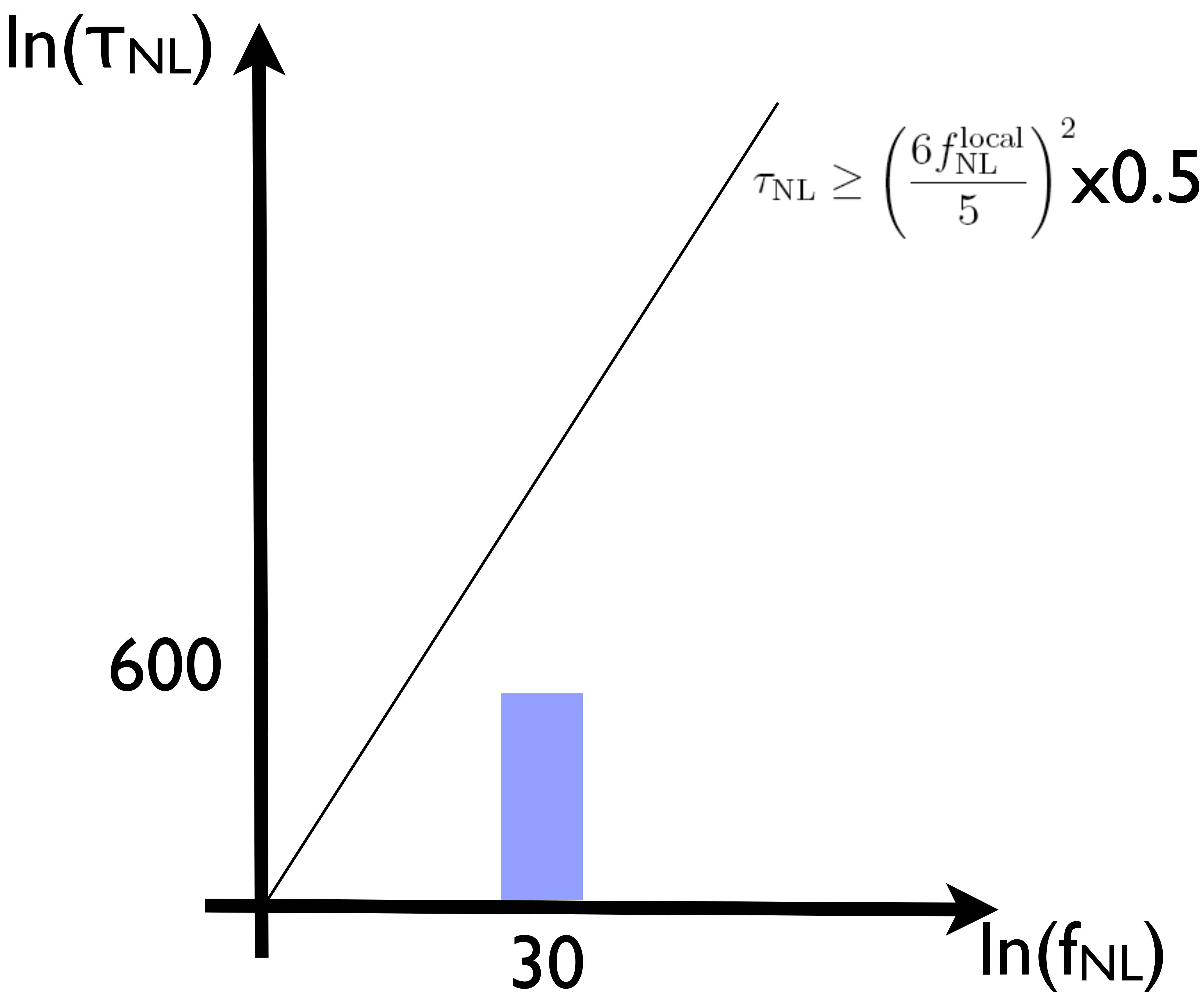
- No detection of anything after Planck. Single-field survived the test (for the moment: the future galaxy surveys can improve the limits by a factor of ten).

Case B: Multi-field Happiness



- f_{NL} is detected. Single-field is dead.
- But, τ_{NL} is also detected, in accordance with multi-field models: $\tau_{NL}>0.5\,(6f_{NL}/5)^2$ [Sugiyama, Komatsu & Futamase (2011)]

Case C: Madness



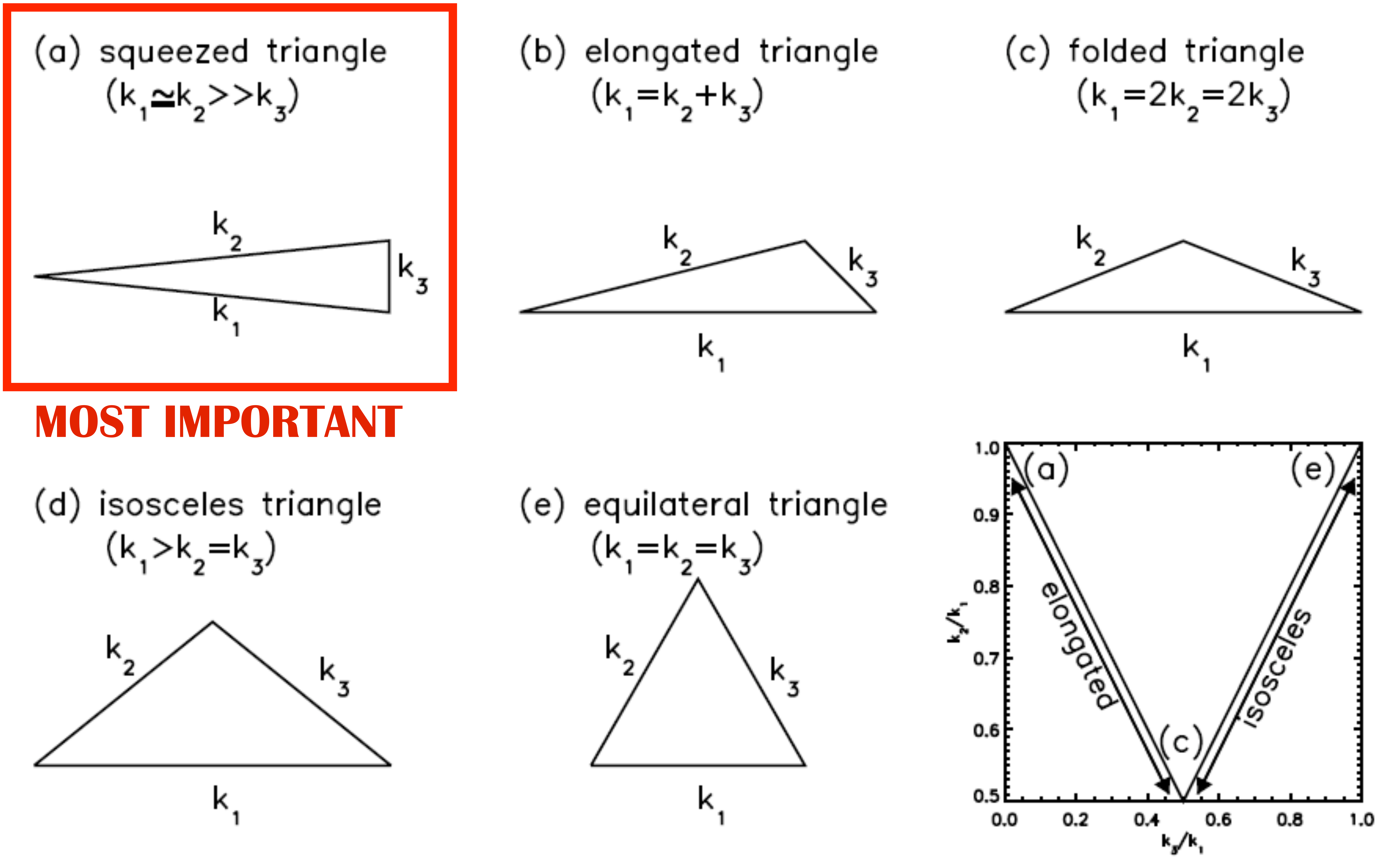
- f_{NL} is detected. Single-field is dead.
- But, τ_{NL} is **not** detected, inconsistent with the multi-field bound.
- (With the caveat that this bound may not be completely general) BOTH the single-field and multi-field are gone.

Beyond CMB: Large-scale Structure!

- In principle, the large-scale structure of the universe offers a lot more statistical power, because we can get 3D information. (CMB is 2D, so the number of Fourier modes is limited.)

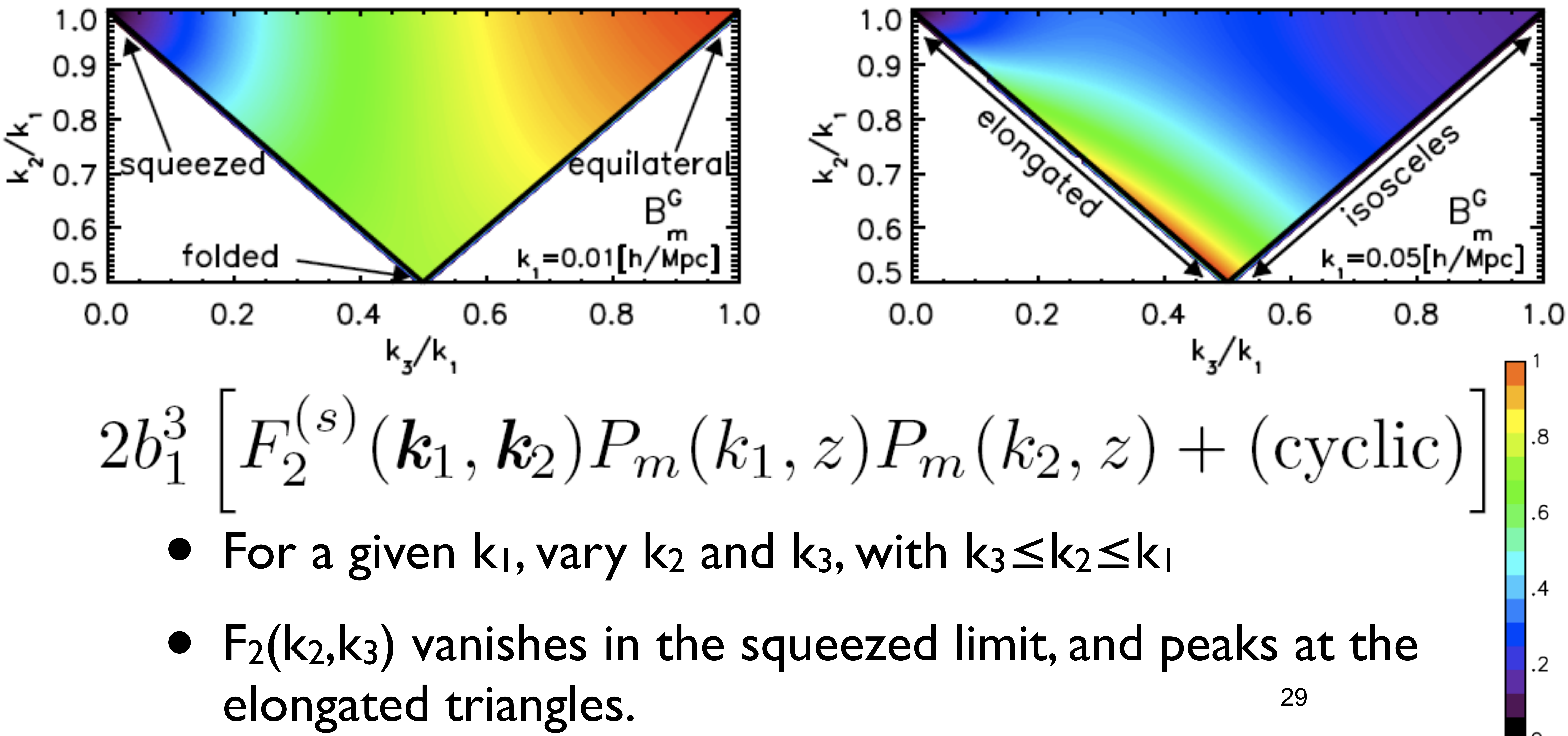
Beyond CMB: Large-scale Structure?

- Statistics is great, but the large-scale structure is non-linear, so perhaps it is less clean?
  - Not necessarily.



(a) squeezed triangle
(k1≃k2>>k3)
k2
k3
k1
MOST IMPORTANT
(b) elongated triangle
(k1=k2+k3)
k2
k3
k1
(c) folded triangle
(k1=2k2=2k3)
k2
k3
k1
(d) isosceles triangle
(k1>k2=k3)
k2
k3
k1
(e) equilateral triangle
(k1=k2=k3)
k2
k3
k1
(a)
(e)
(c)
elongated
isosceles
k2/k1
k3/k1
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.2
0.4
0.6
0.8
1.0

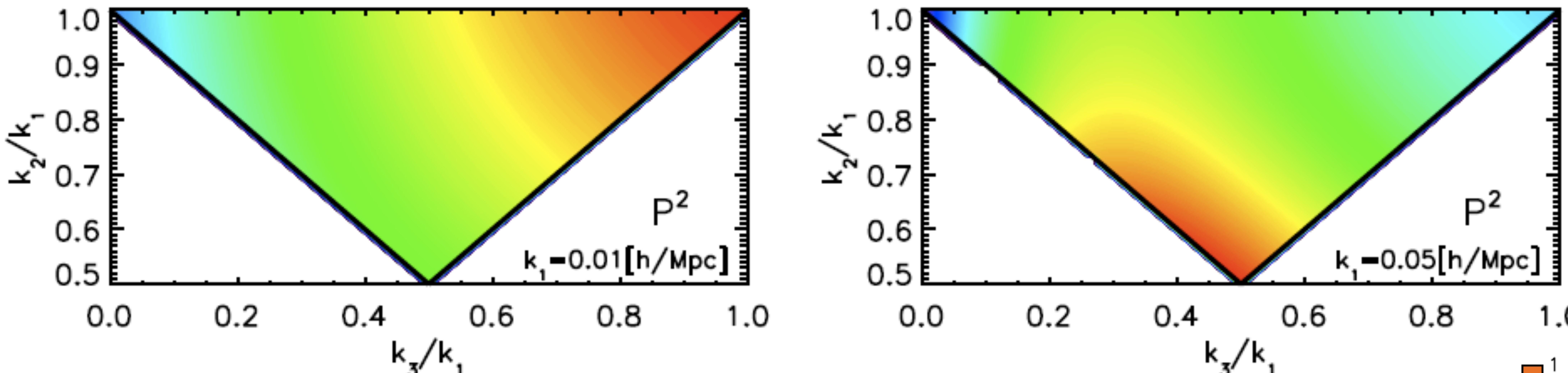
Non-linear Gravity

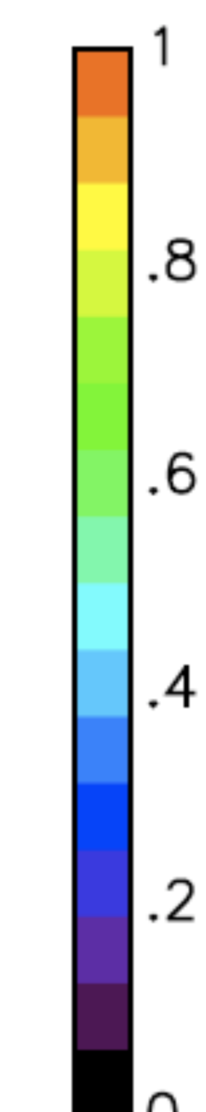


$$2b_1^3\left[F_2^{(s)}(\boldsymbol{k}_1,\boldsymbol{k}_2)P_m(k_1,z)P_m(k_2,z)+(\text{cyclic})\right]$$

- For a given k_1, vary k_2 and k_3, with $k_3 \le k_2 \le k_1$
- $F_2(k_2,k_3)$ vanishes in the squeezed limit, and peaks at the elongated triangles.

Non-linear Galaxy Bias

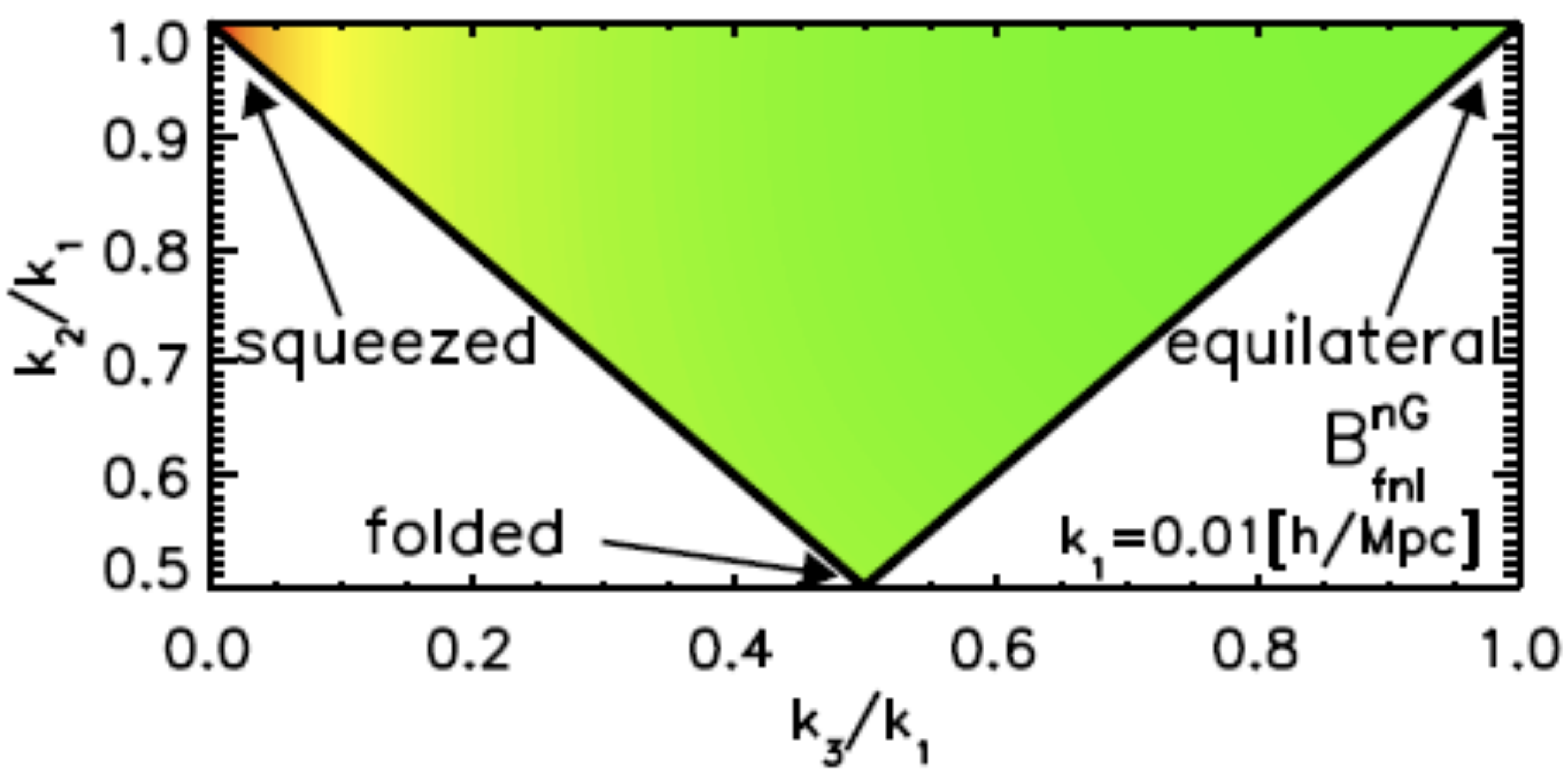


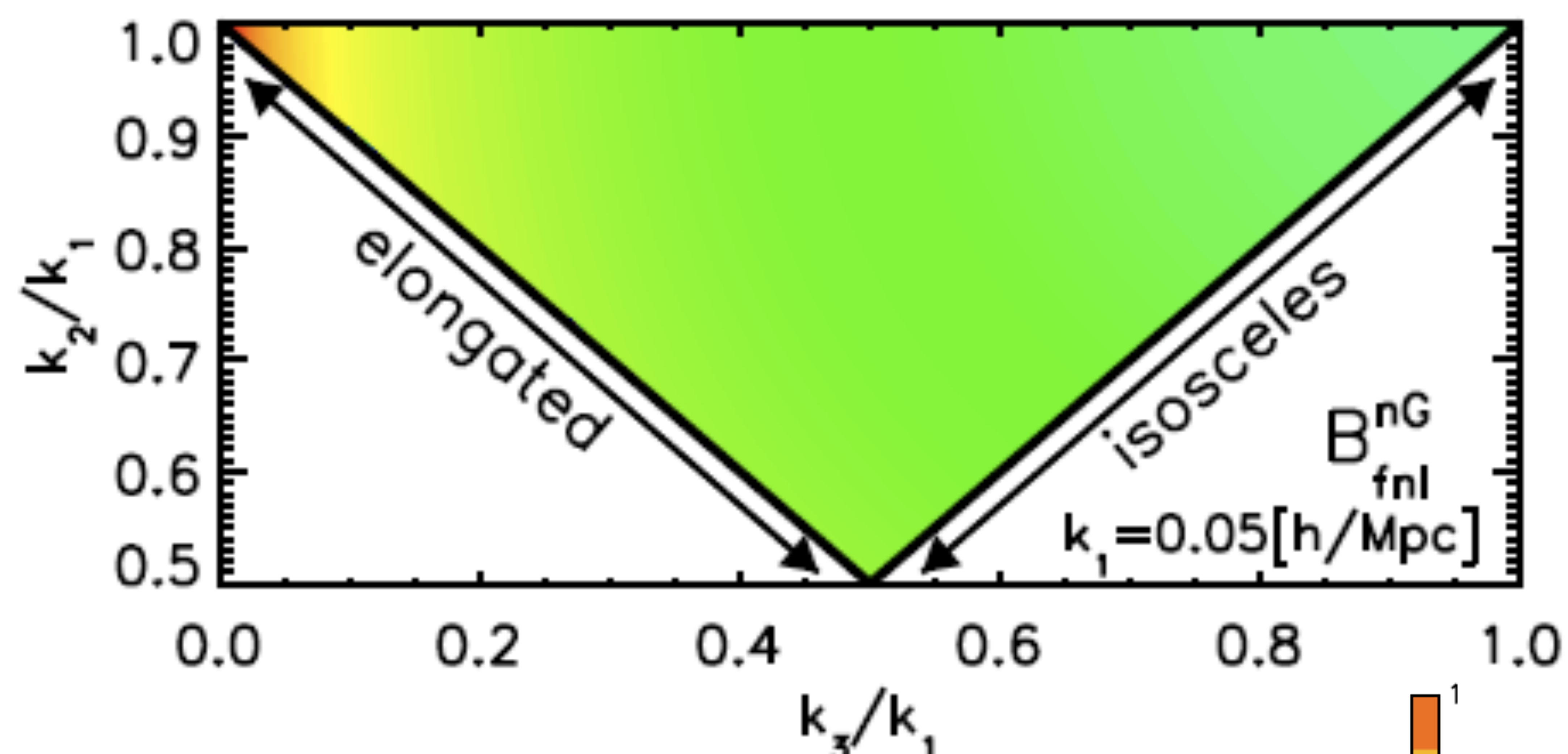


$$b_1^2 b_2 \left[P_m(k_1, z) P_m(k_2, z) + (\text{cyclic})\right]$$

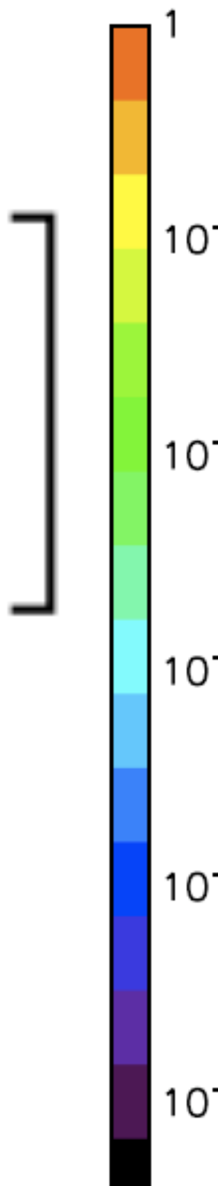
- There is no F_2: less suppression at the squeezed, and less enhancement along the elongated triangles.
- Still peaks at the equilateral or elongated forms.

Primordial Non-Gaussianity





$$3b_1^3 f_{\rm NL}\Omega_m H_0^2 \left[\frac{P_m(k_1,z)}{k_1^2T(k_1)}\frac{P_m(k_2,z)}{k_2^2T(k_2)}\frac{k_3^2T(k_3)}{D(z)} + ({\rm cyclic})\right]$$



- This gives the peaks at the squeezed configurations, clearly distinguishable from other non-linear/ astrophysical effects.

Bispectrum is powerful

- $f_{NL}^{local} \sim O(1)$ is quite possible with the bispectrum method. (See Donghui Jeong's talk)
- This needs to be demonstrated by the real data! (e.g., SDSS-LRG)

Need For Dark "Energy"

- First of all, DE does not even need to be an 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.
- Measurements of the (3) **growth of structure** break degeneracy. (The best data right now is the X-ray clusters.)

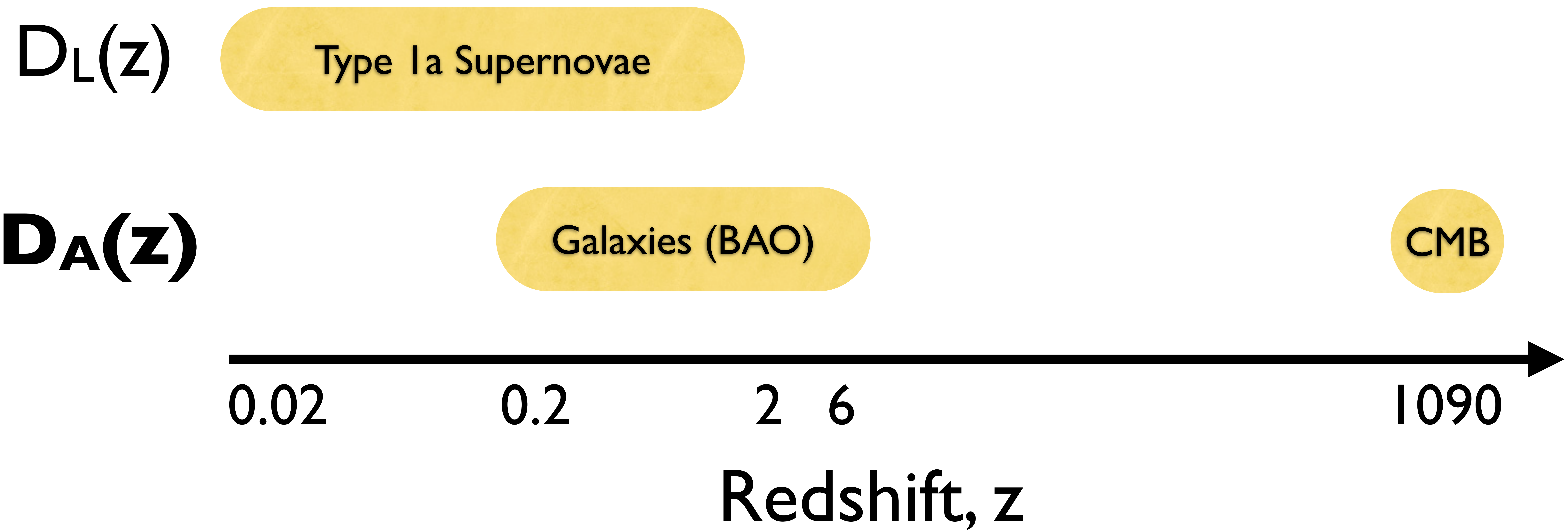
H(z): Current Knowledge

- $H^2(z) = H^2(0)[\Omega_r(1+z)^4+\Omega_m(1+z)^3+\Omega_k(1+z)^2+\Omega_{de}(1+z)^{3(1+w)}]$
  - (expansion rate) $H(0) = 70.2 \pm 1.4$ km/s/Mpc
  - (radiation) $\Omega_r = (8.4\pm0.3)\times10^{-5}$
  - (matter) $\Omega_m = 0.275\pm0.016$
  - (curvature) $\Omega_k < 0.008$ (95%CL)
  - (dark energy) $\Omega_{de} = 0.725\pm0.015$
  - (DE equation of state) $w = -1.00\pm0.06$

H(z) to Distances

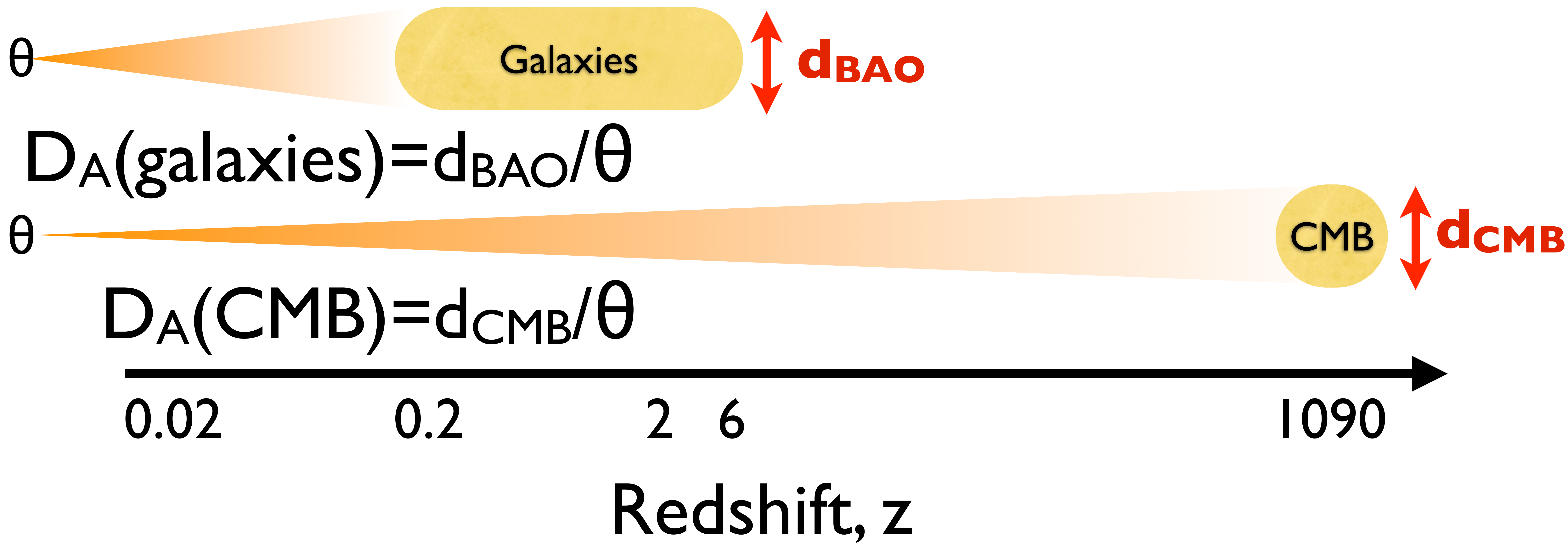
- Comoving Distance
  - $\chi(z) = c\int^z[dz'/H(z')]$
- Luminosity Distance
  - $D_L(z) = (1+z)\chi(z)[1-(k/6)\chi^2(z)/R^2+...]$
  - R=(curvature radius of the universe); k=(sign of curvature)
  - WMAP 7-year limit: $R>2\chi(\infty)$; justify the Taylor expansion
- Angular Diameter Distance
  - $D_A(z) = [\chi(z)/(1+z)][1-(k/6)\chi^2(z)/R^2+...]$

$$D_A(z) = (1+z)^{-2} D_L(z)$$



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

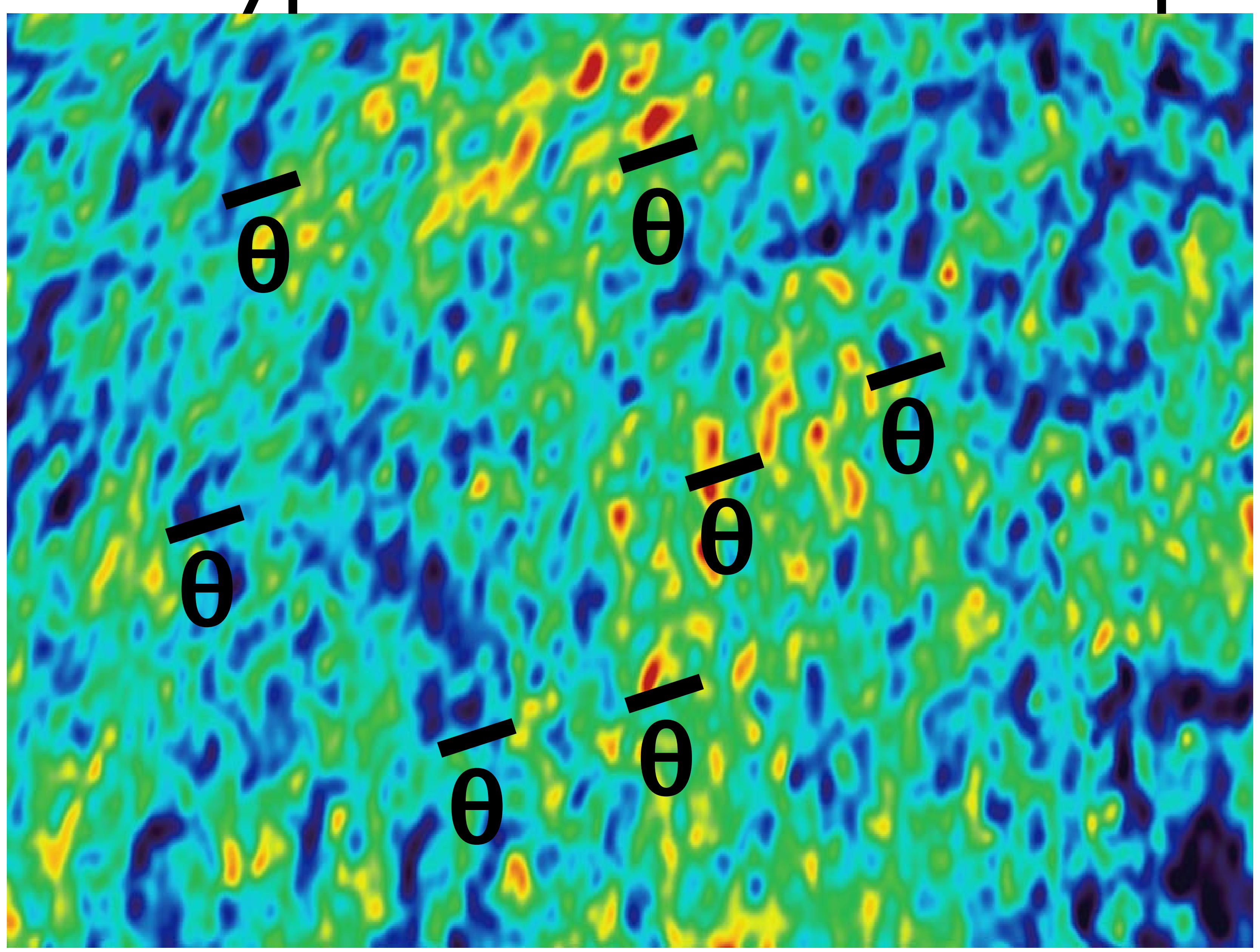
How Do We Measure $D_A(z)$?

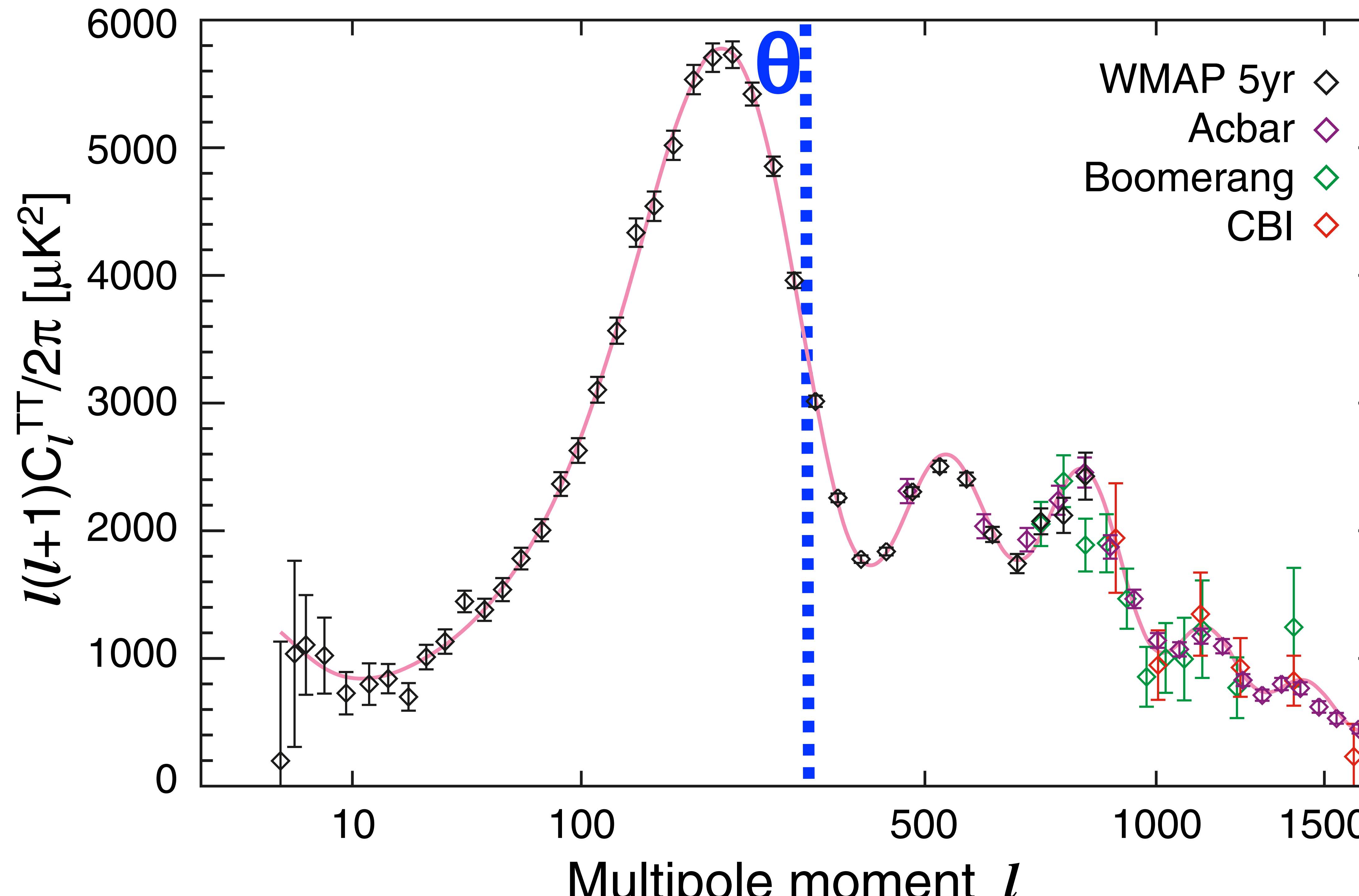


- If we know the intrinsic physical sizes, d, we can measure D_A. What determines d?

CMB as a Standard Ruler

θ~the typical size of hot/cold spots

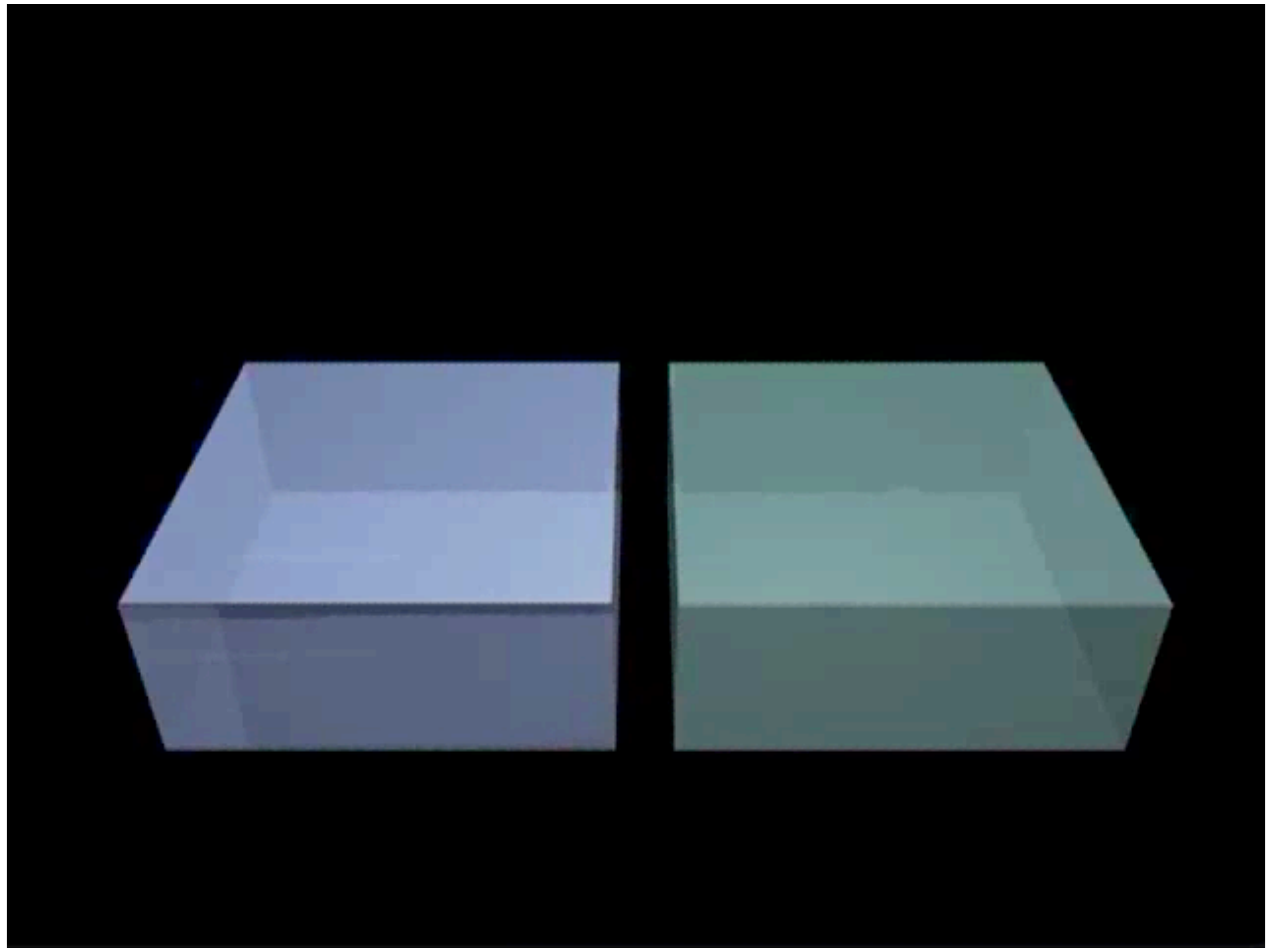


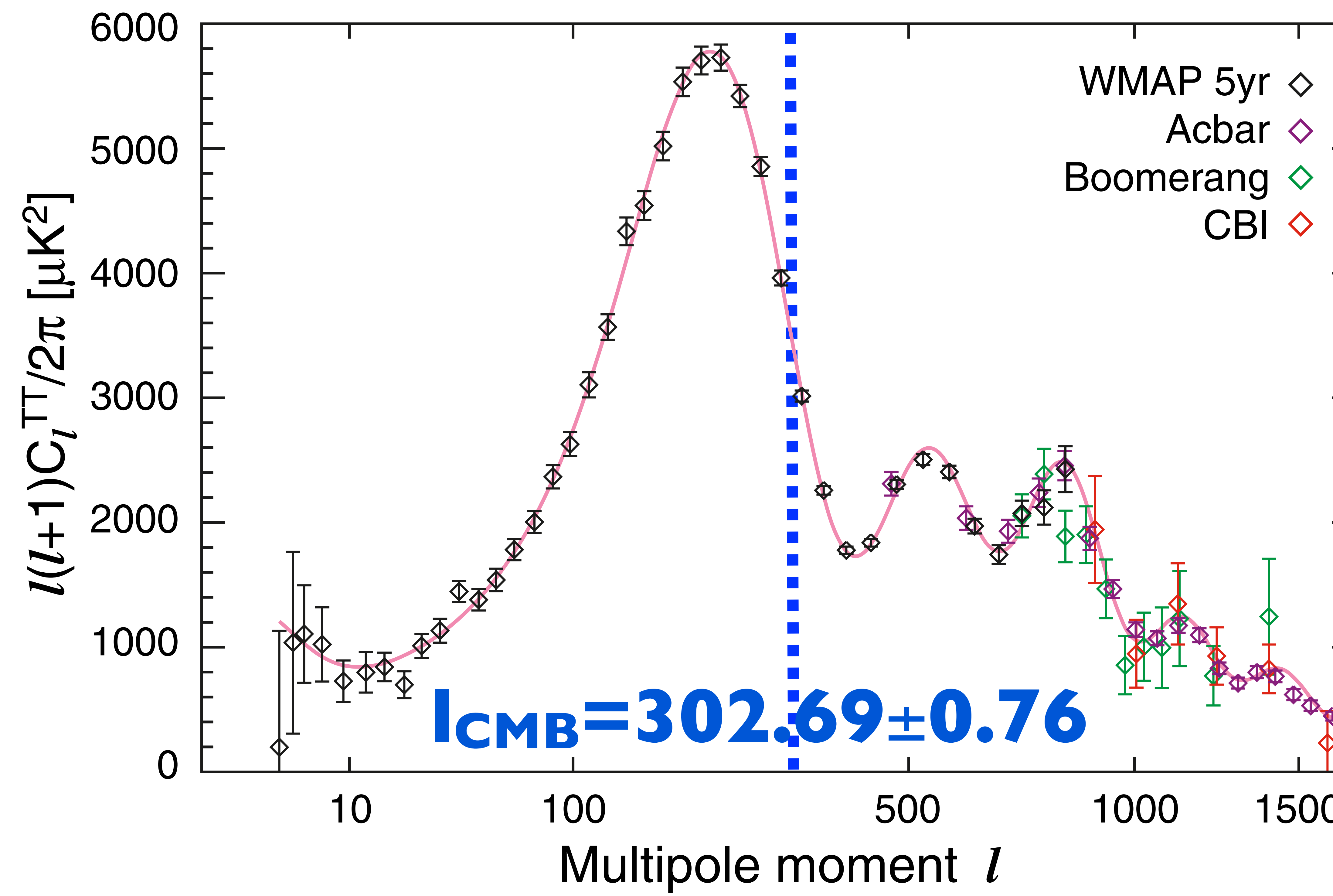


- The existence of typical spot size in image space yields oscillations in harmonic (Fourier) space. What determines the physical size of typical spots, **d_{CMB}**?

Sound Horizon

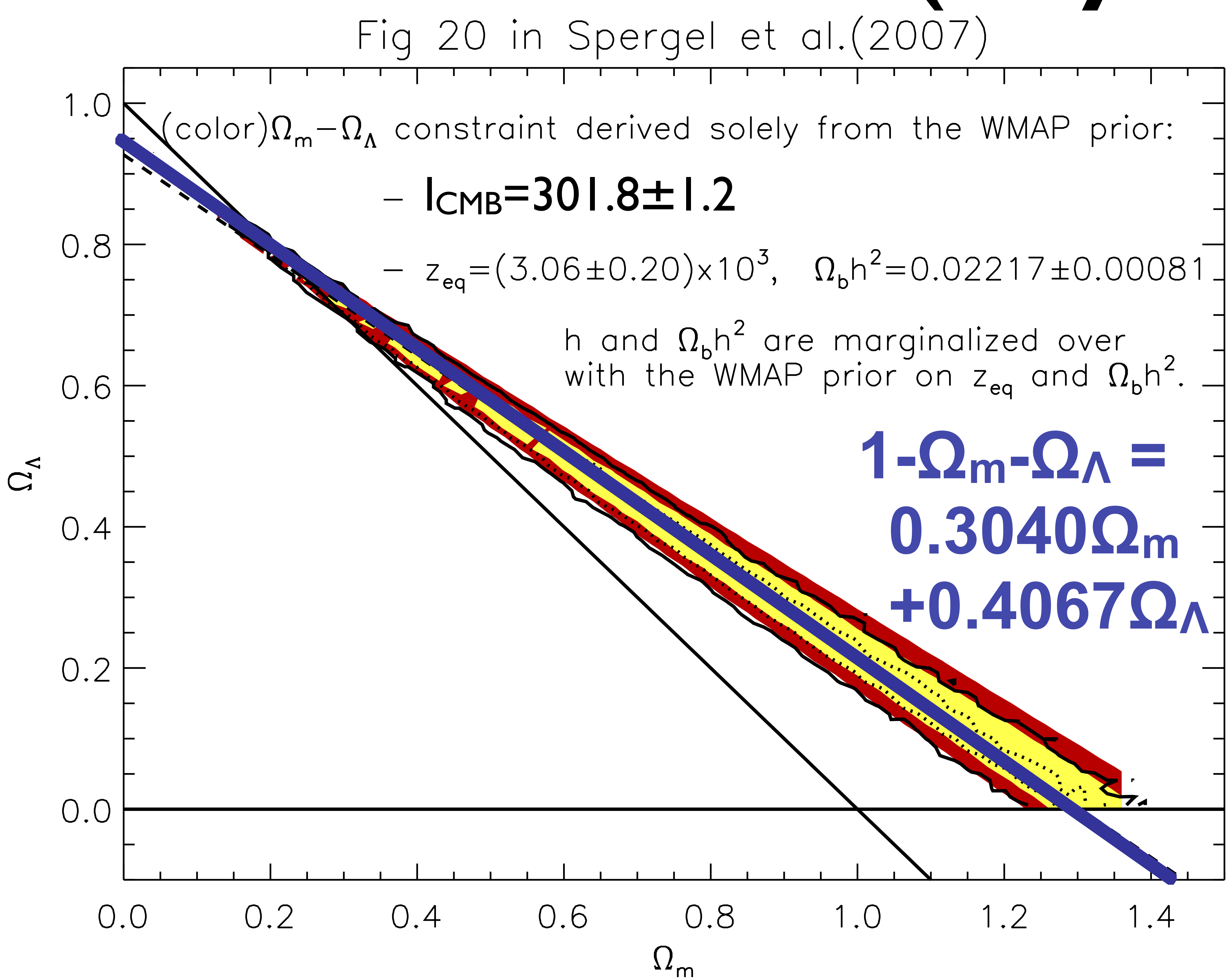
- The typical spot size, **d_{CMB}**, is determined by the **physical distance traveled by the sound wave** from the Big Bang to the decoupling of photons at z_{CMB}~1090 (t_{CMB}~380,000 years).
- The causal horizon (<u>photon</u> horizon) at t_{CMB} is given by
  - $d_H(t_{CMB})$ = a(t_{CMB})*Integrate[**c**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



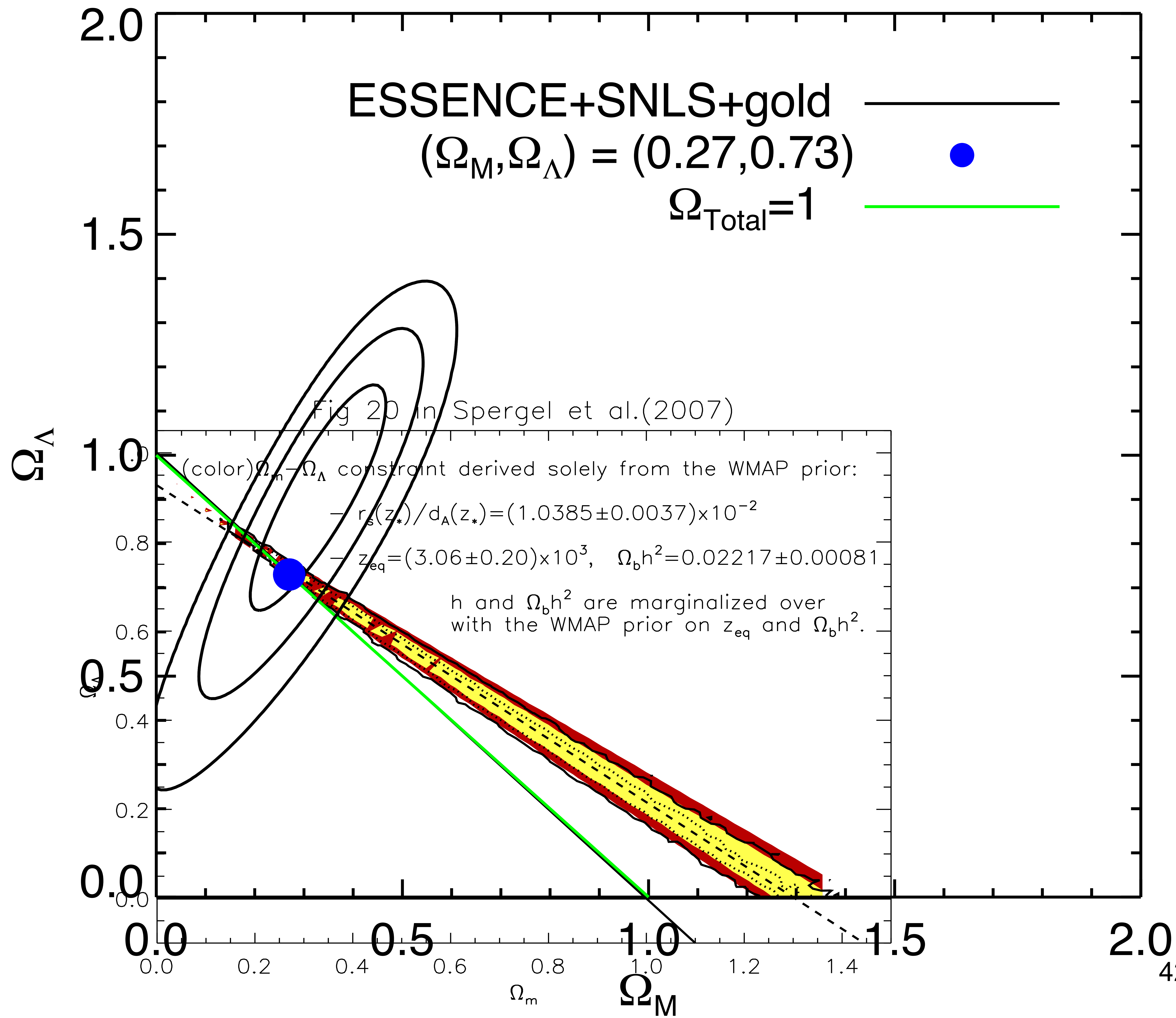


- The WMAP 7-year values:
  - $l_{CMB} = \pi/\theta = \pi D_A(z_{CMB})/d_s(z_{CMB}) = 302.69 \pm 0.76$
  - CMB data constrain the ratio, $\mathbf{D_A(z_{CMB})/d_s(z_{CMB})}$.
  - $r_s(z_{CMB})=(1+z_{CMB})d_s(z_{CMB})=146.6 \pm 1.6$ Mpc (comoving)

What $D_A(z_{CMB})/d_s(z_{CMB})$ Gives You (3-year example)



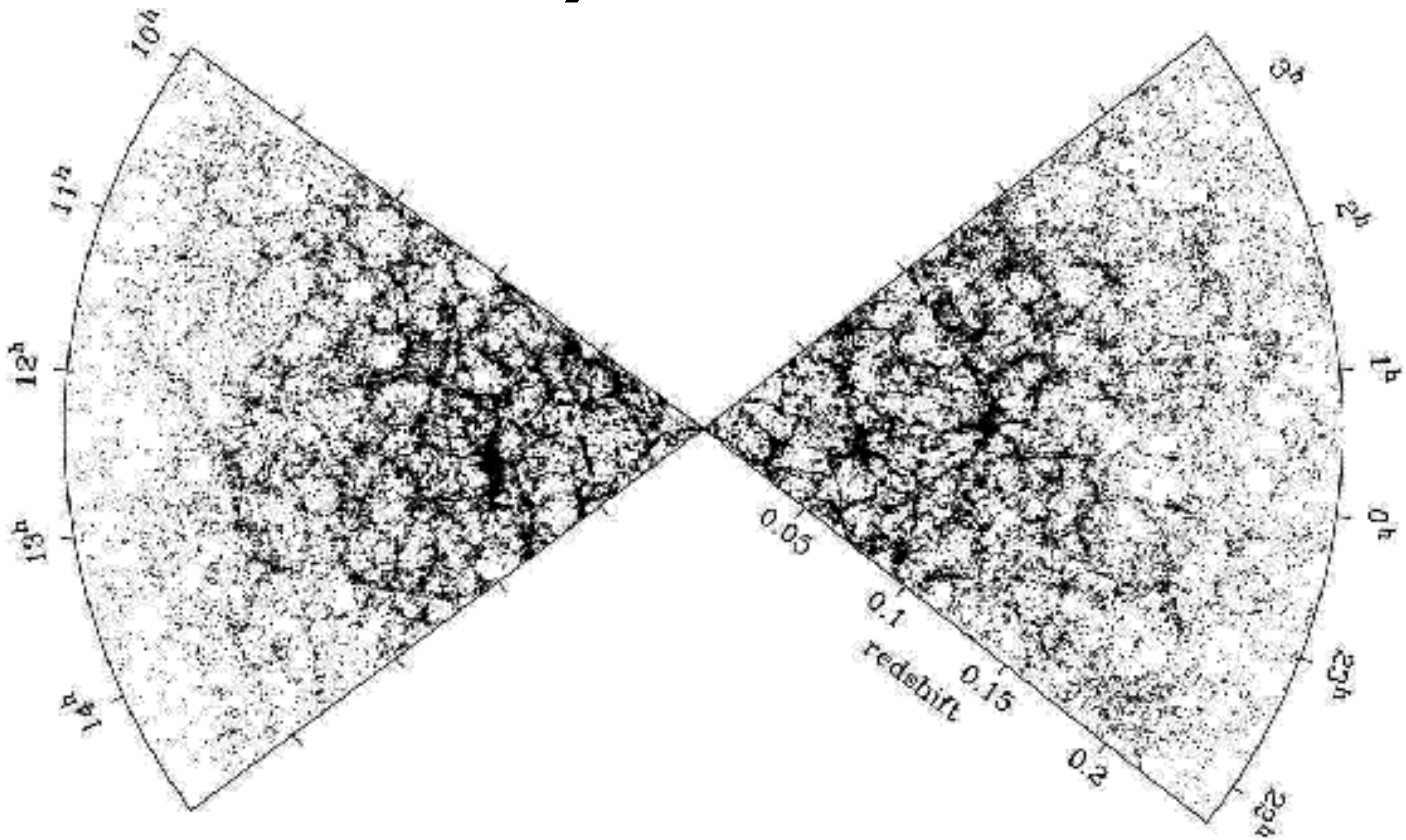
- Color: constraint from $l_{CMB}=\pi D_A(z_{CMB})/d_s(z_{CMB})$ with z_{EQ} & $\Omega_b h^2$.
- Black contours: Markov Chain from WMAP 3yr (Spergel et al. 2007)



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

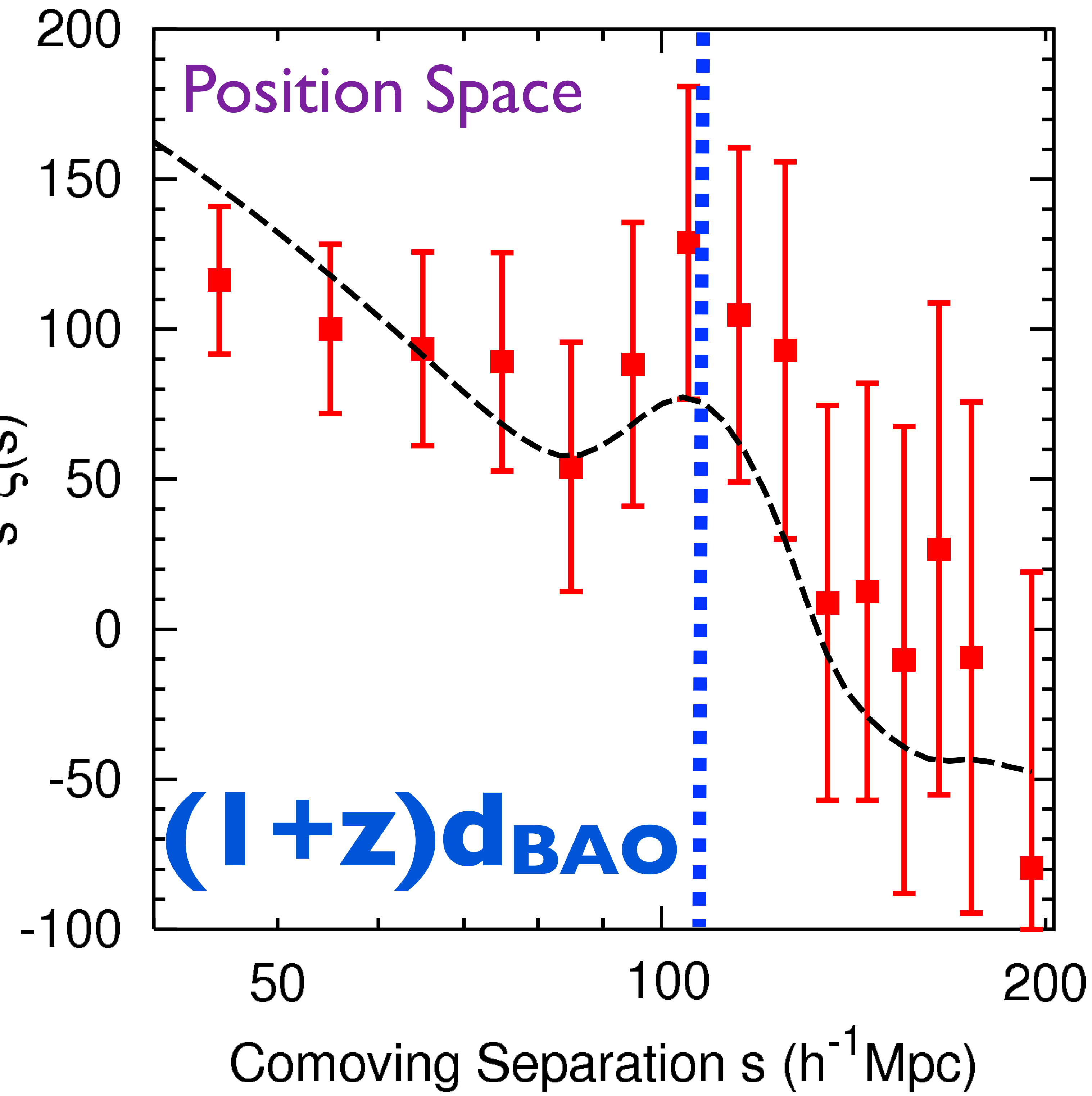
2dFGRS

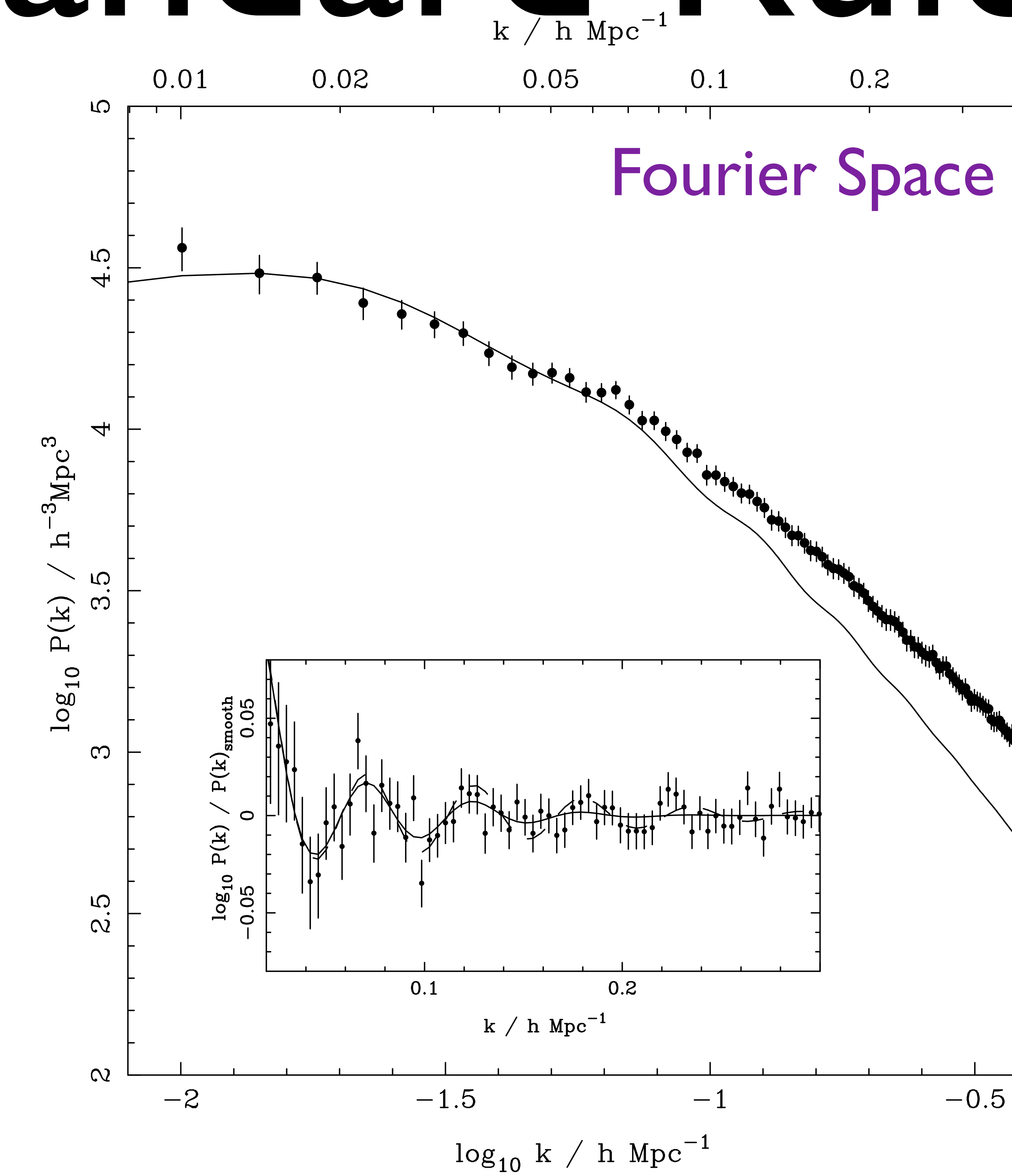


- The same acoustic oscillations should be hidden in this galaxy distribution...

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.

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}=1020.5±1.6 (c.f., z_{CMB}=1091±1).
- 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, $d_{BAO}>d_{CMB}$)

Komatsu et al. (2009)

Standard Rulers in CMB & Matter

	Quantity	Eq.	5-year WMAP
CMB	z_*	(66)	1090.51 ± 0.95
CMB	$r_s(z_*)$	(6)	146.8 ± 1.8 Mpc
Matter	z_d	(3)	1020.5 ± 1.6
Matter	$r_s(z_d)$	(6)	153.3 ± 2.0 Mpc

- For flat LCDM, but very similar results for w≠−1 and curvature≠0!

Not Just $D_A(z)$...

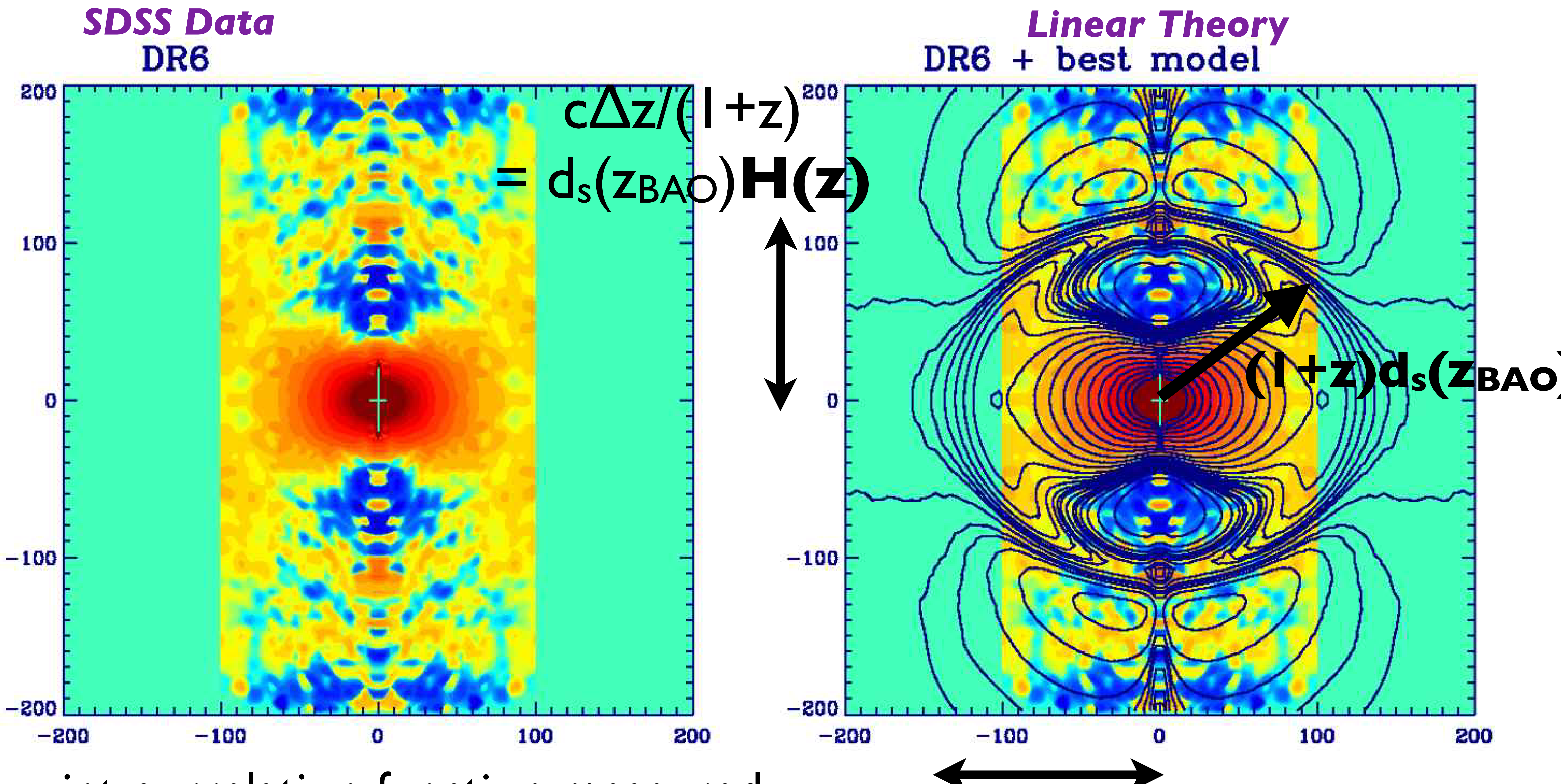
- A really nice thing about BAO at a given redshift is that it can be used to measure not only $D_A(z)$, but also the expansion rate, H(z), directly, at **that** redshift.
  - BAO perpendicular to l.o.s

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

  - BAO parallel to l.o.s

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

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

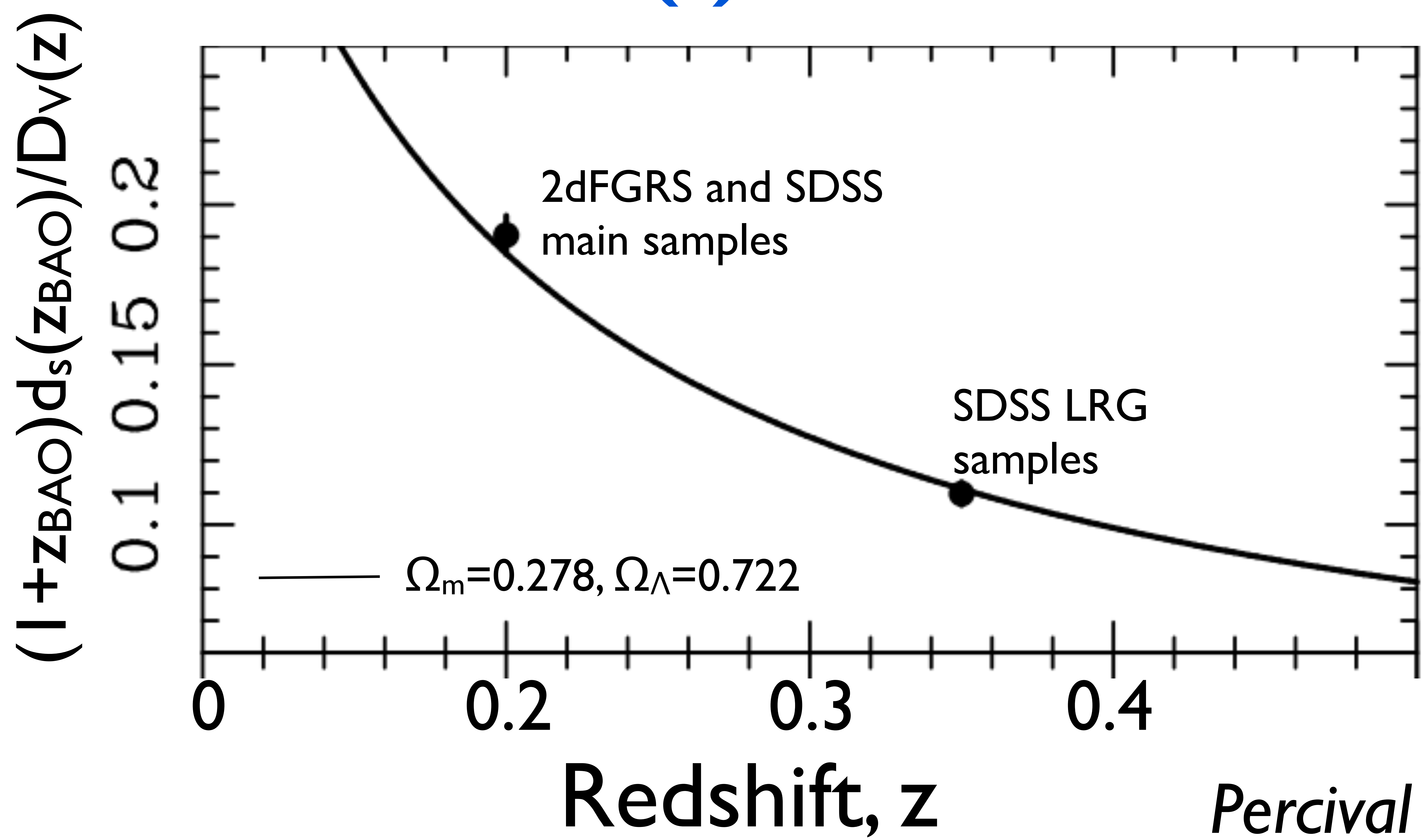


$\theta = d_s(z_{BAO})/\mathbf{D_A(z)}$

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

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

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.

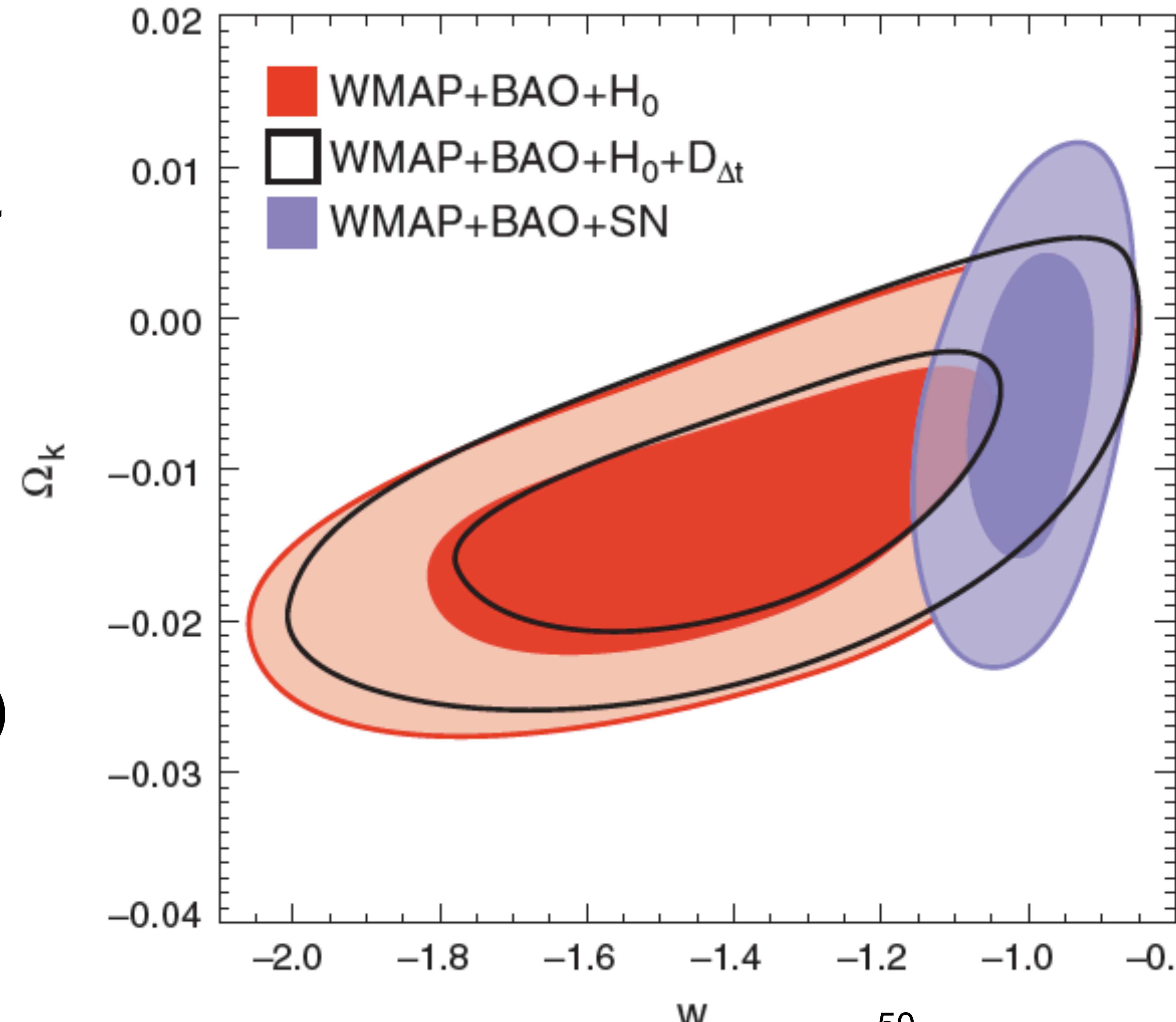


Percival et al. (2010)

Komatsu et al. (2011)

WMAP7+BAO+...

- At the moment, BAO is great for fixing curvature, but not good for fixing w
- We still need supernovae for fixing w, but this would change as more BAO data (especially at higher redshifts) become available.

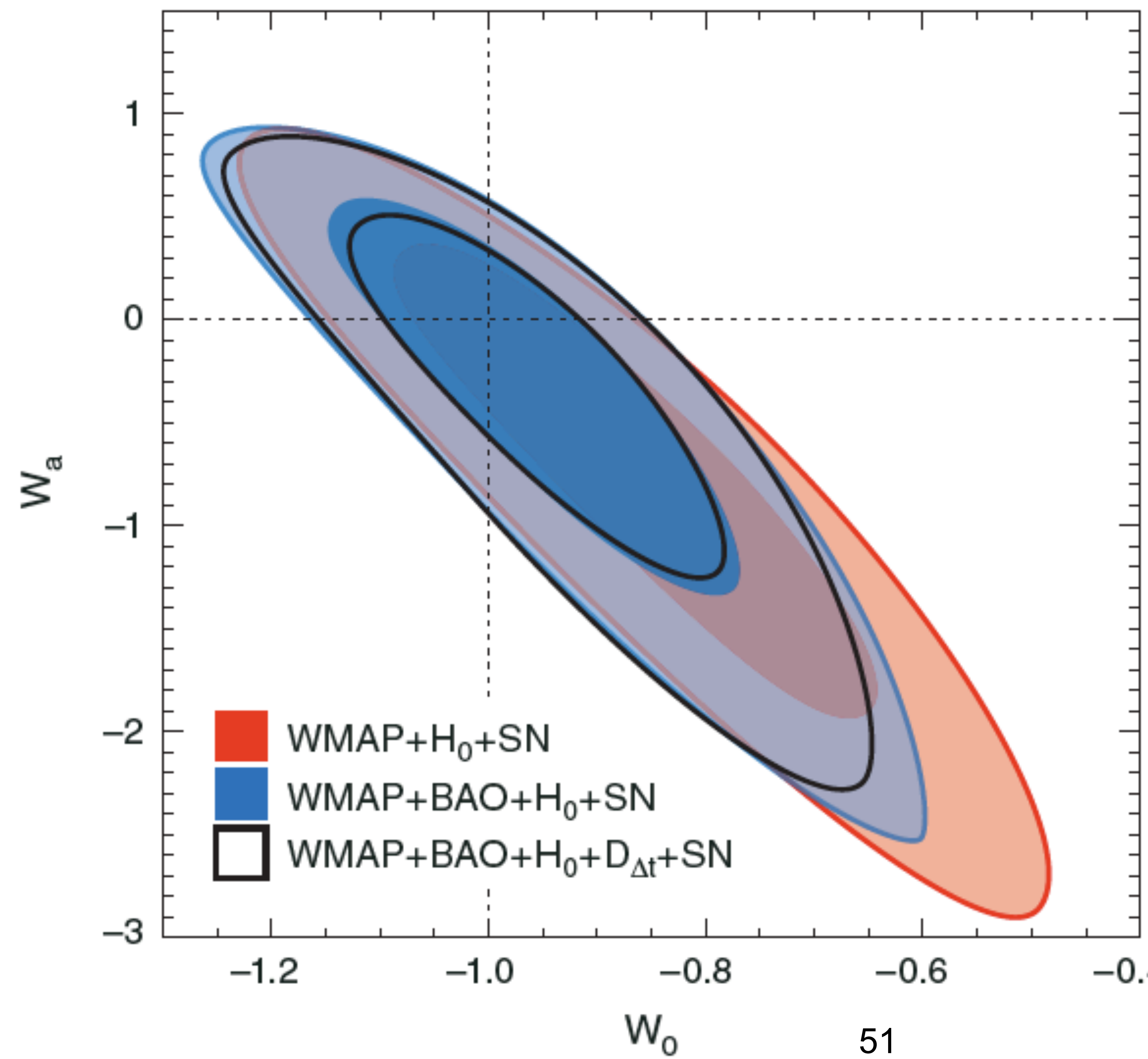


Komatsu et al. (2011)

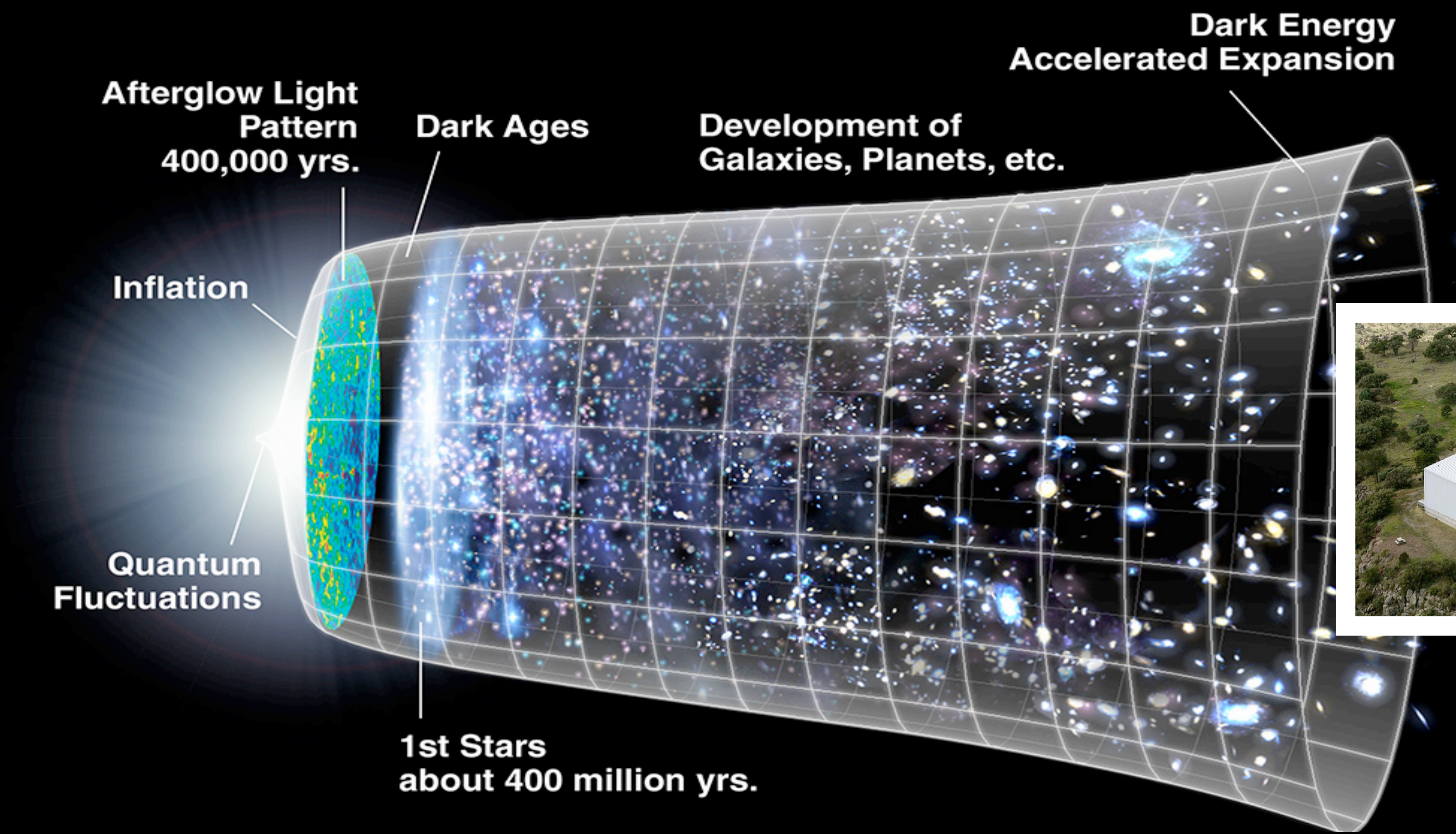
$w(z)=w_0+w_a*z/(1+z)$

- Cosmological constant, $w_0=-1$ and $w_a=0$, are perfectly consistent with data.

- Of course we all want this to change at some point...

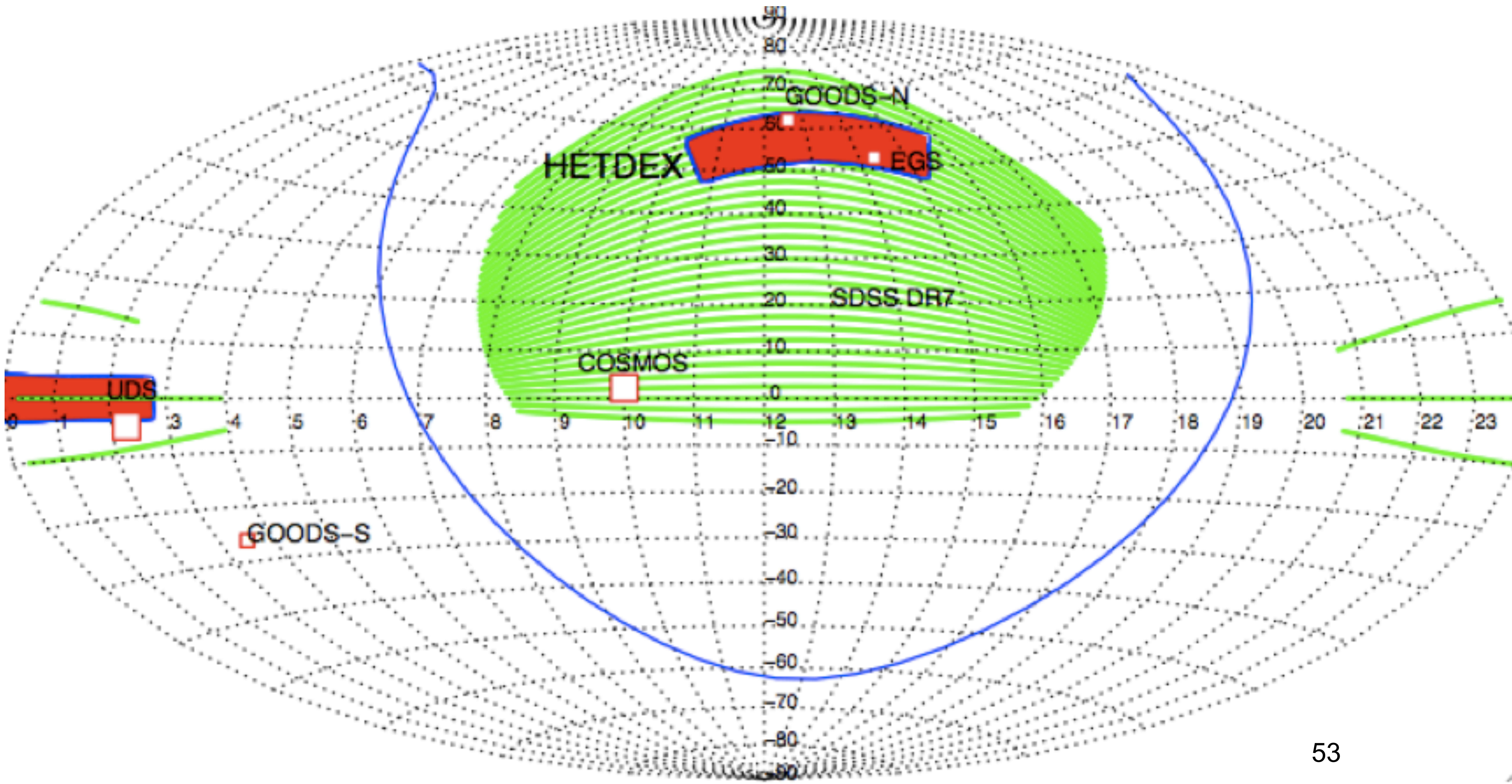


Hobby-Eberly Telescope Dark Energy Experiment (HETDEX)

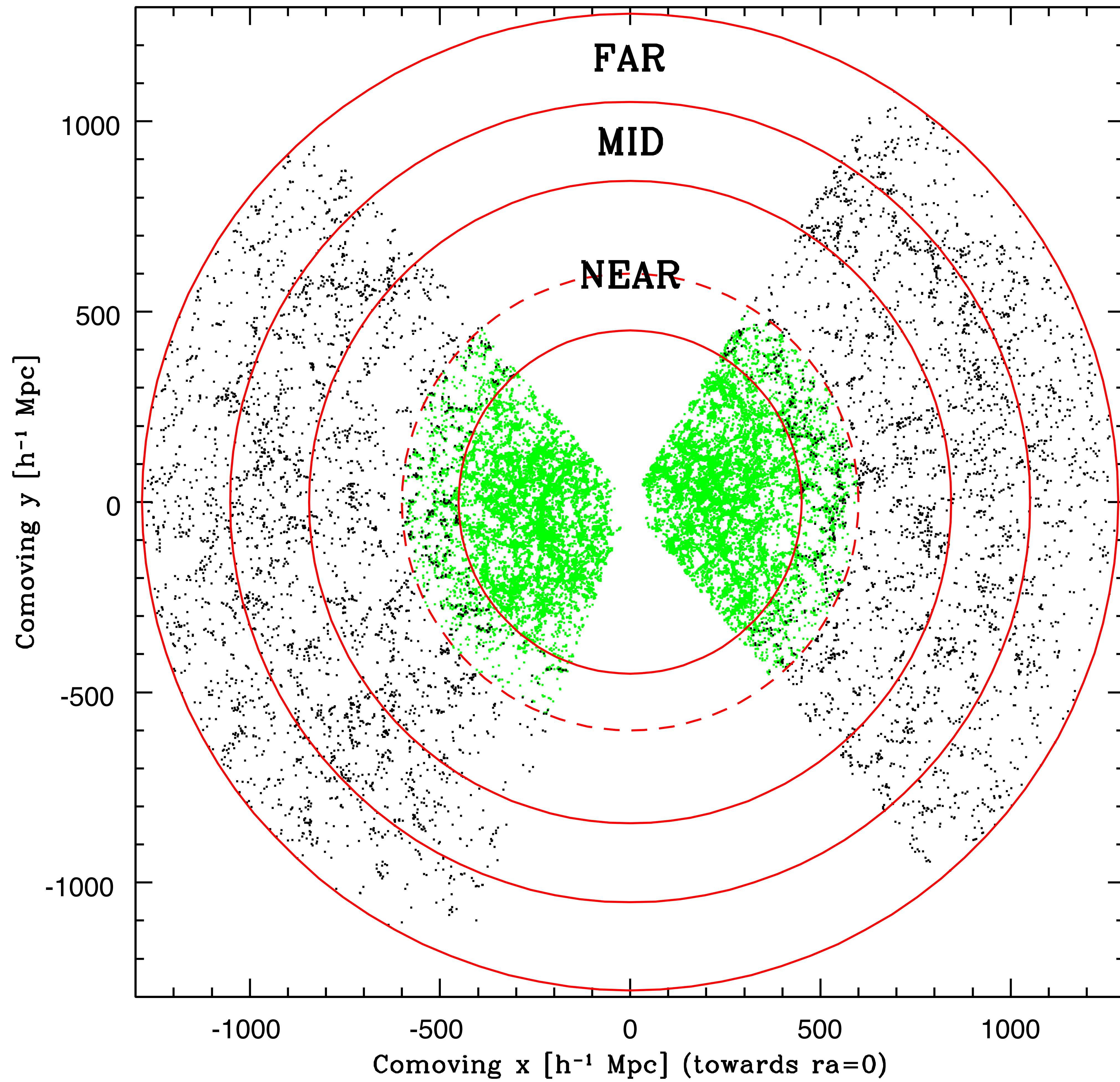


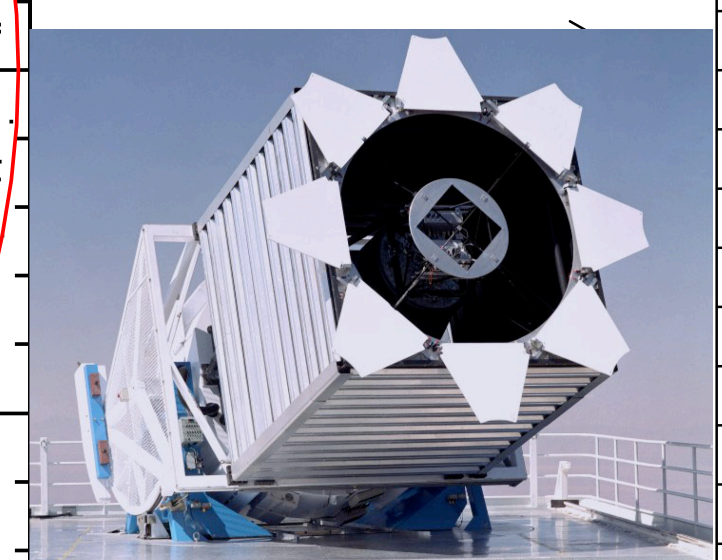
Use 9.2-m HET to map the universe using 0.8M Lyman-alpha emitting galaxies in z=1.9–3.5

HETDEX Foot-print (in RA-DEC coordinates)

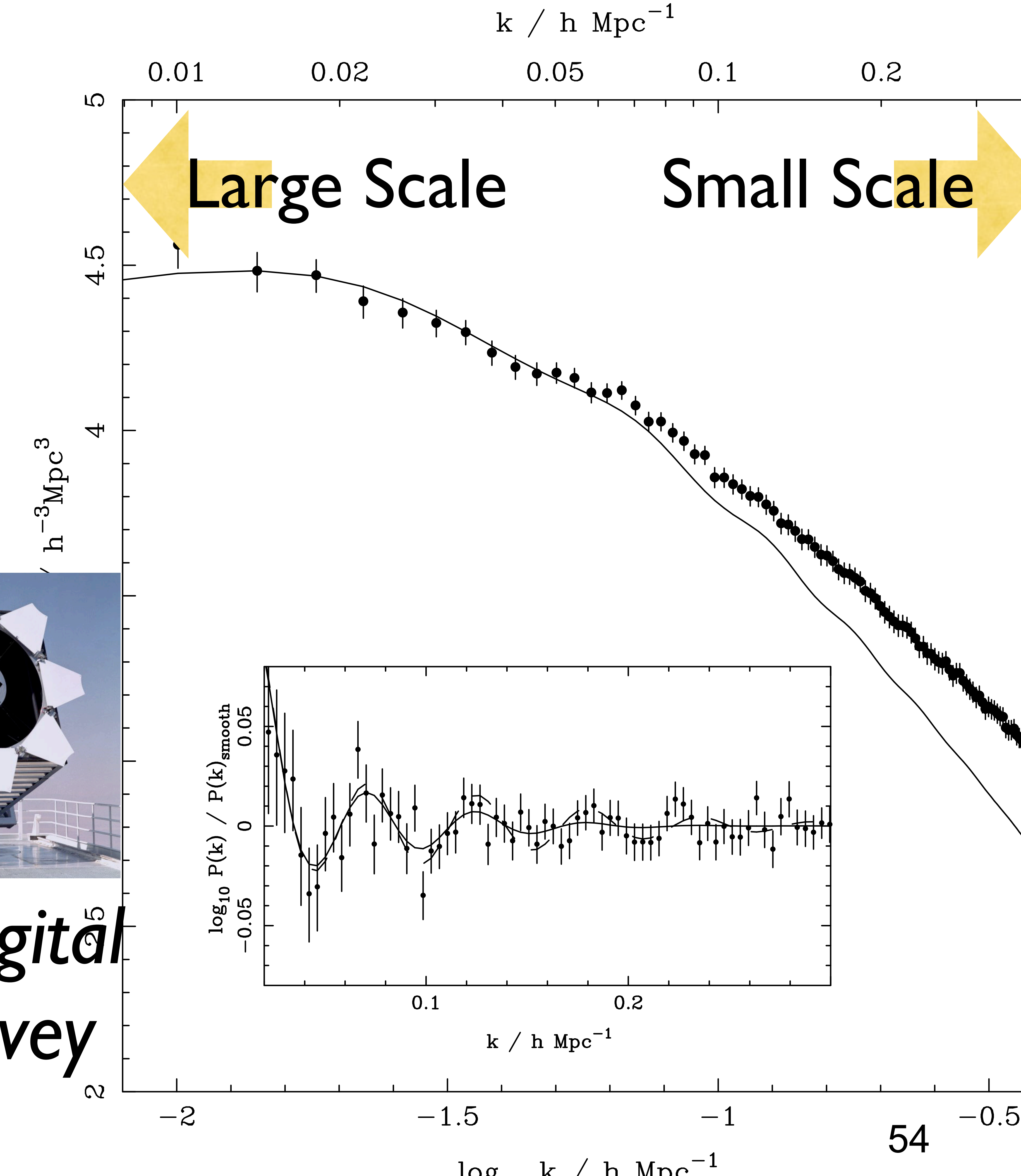


HETDEX: Sound Waves in the Distribution of Galaxies

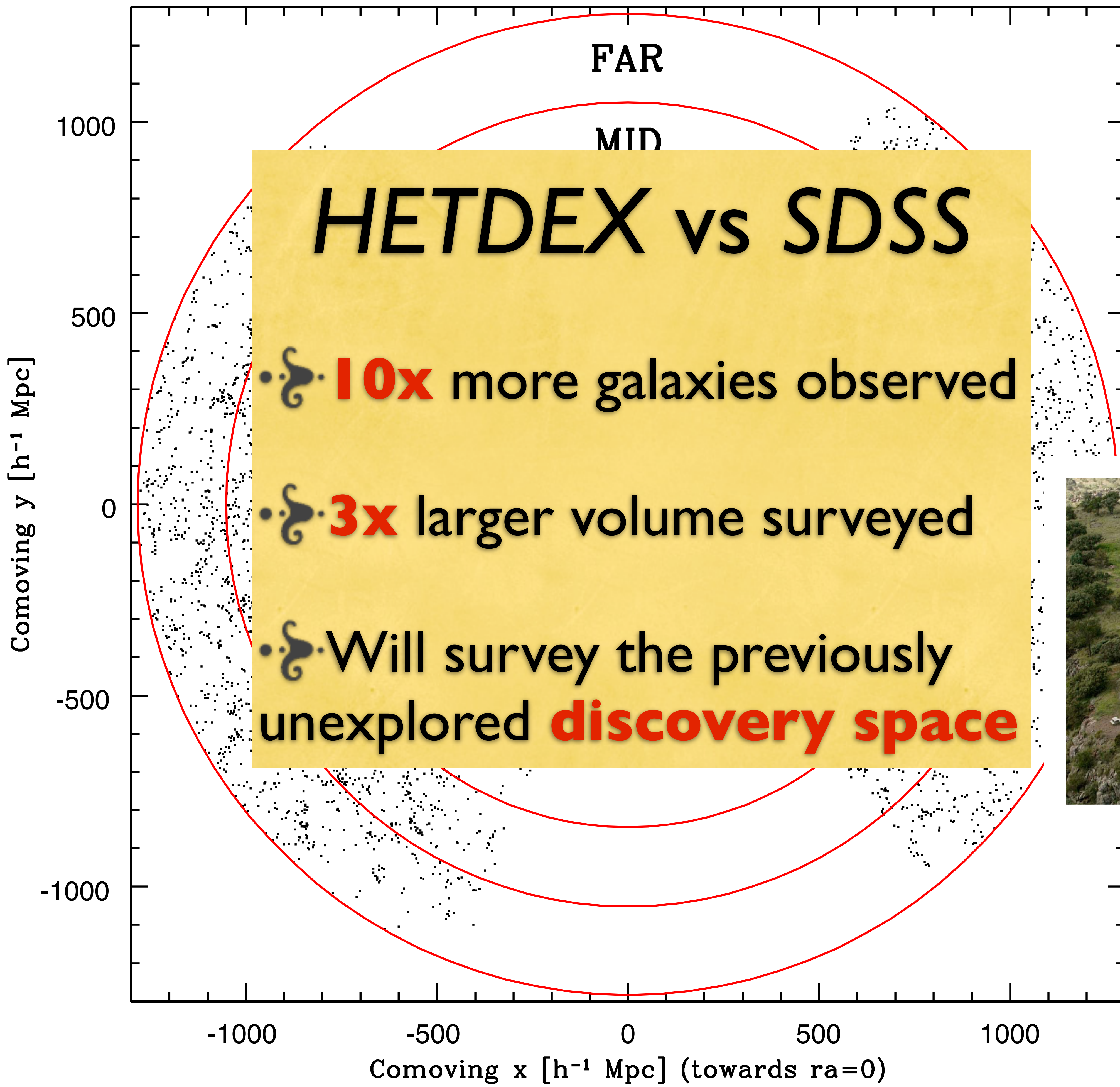




Sloan Digital Sky Survey



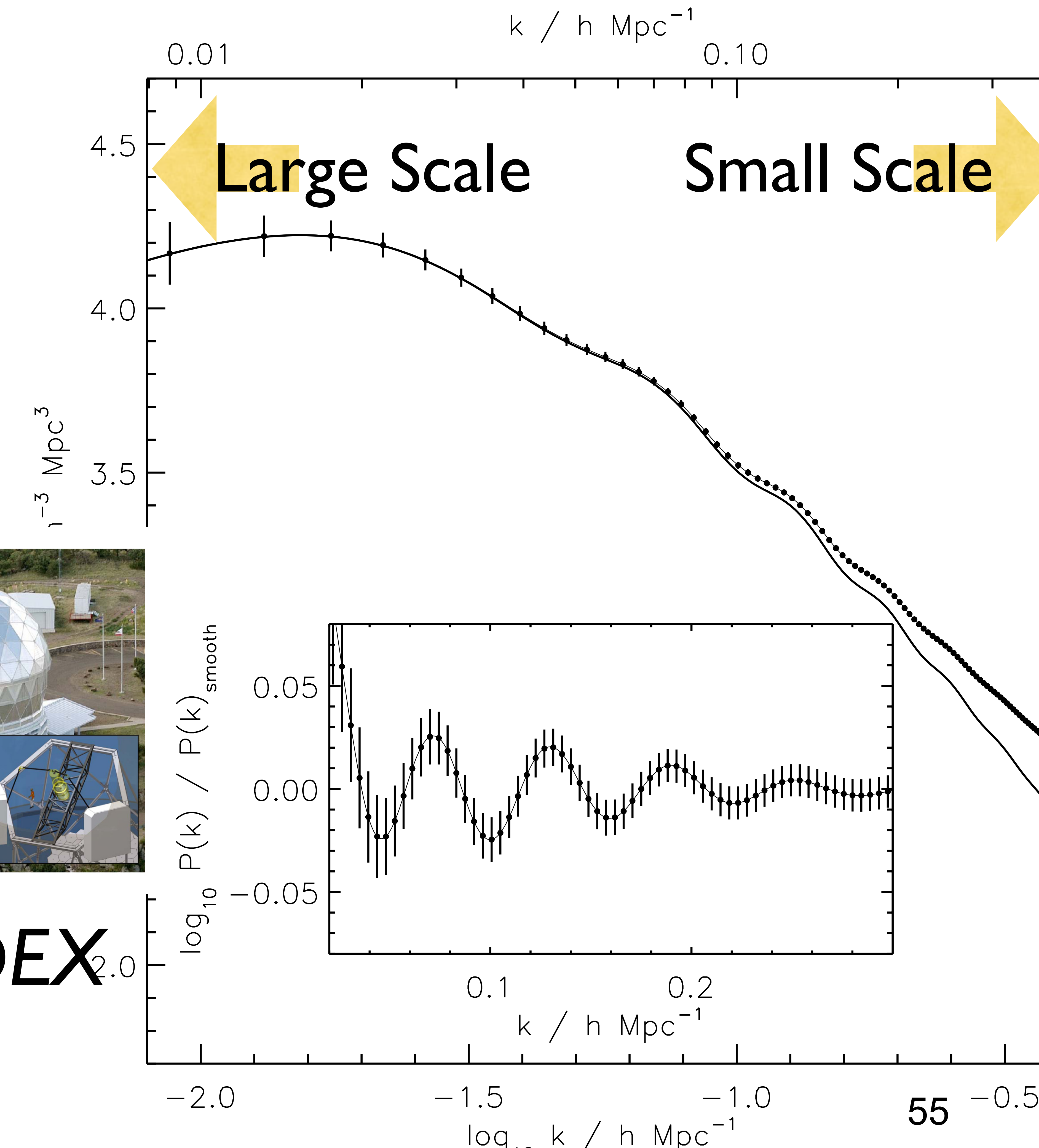
HETDEX: Sound Waves in the Distribution of Galaxies



HETDEX vs SDSS

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

HETDEX



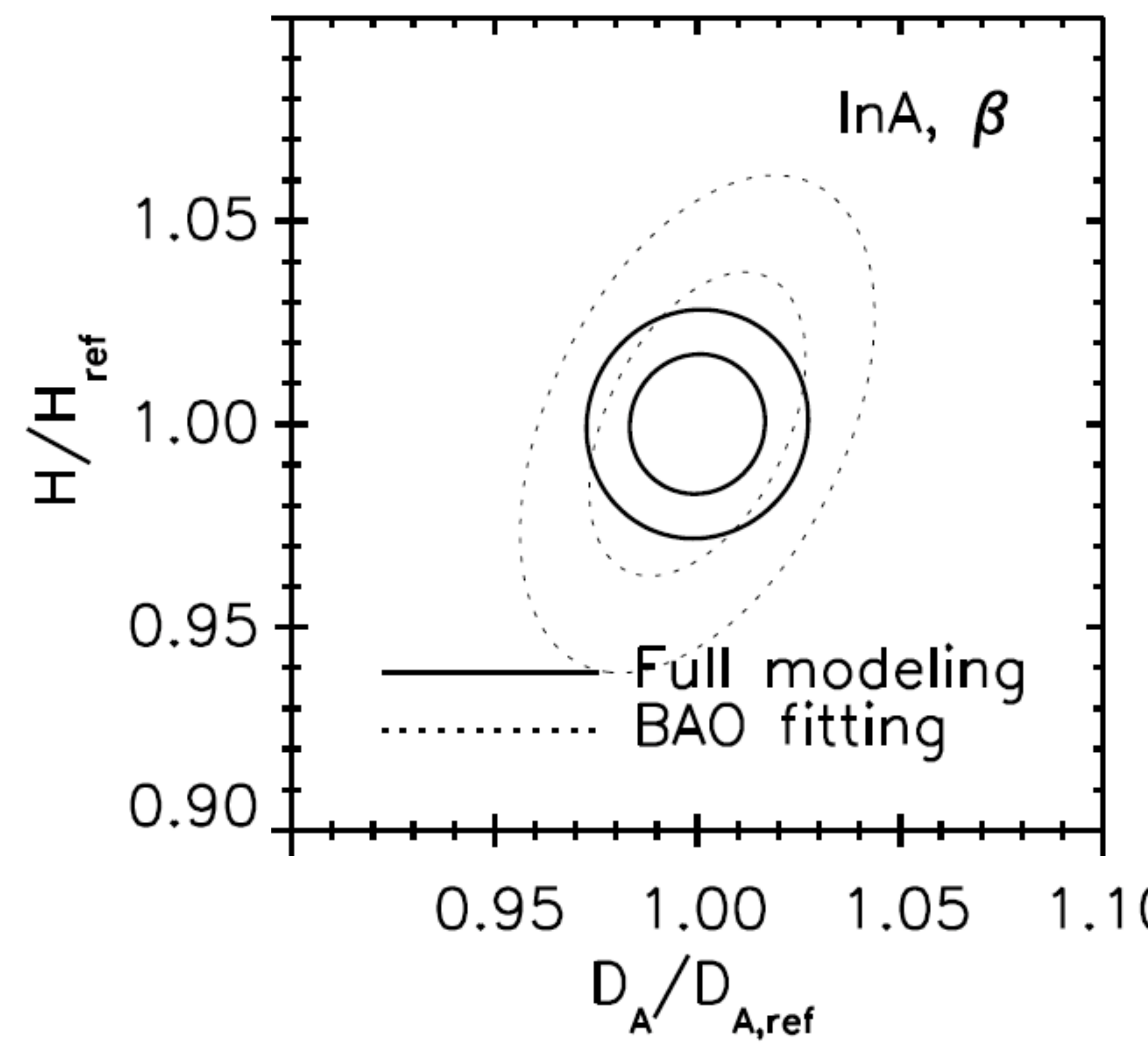
Beyond BAO

- 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)

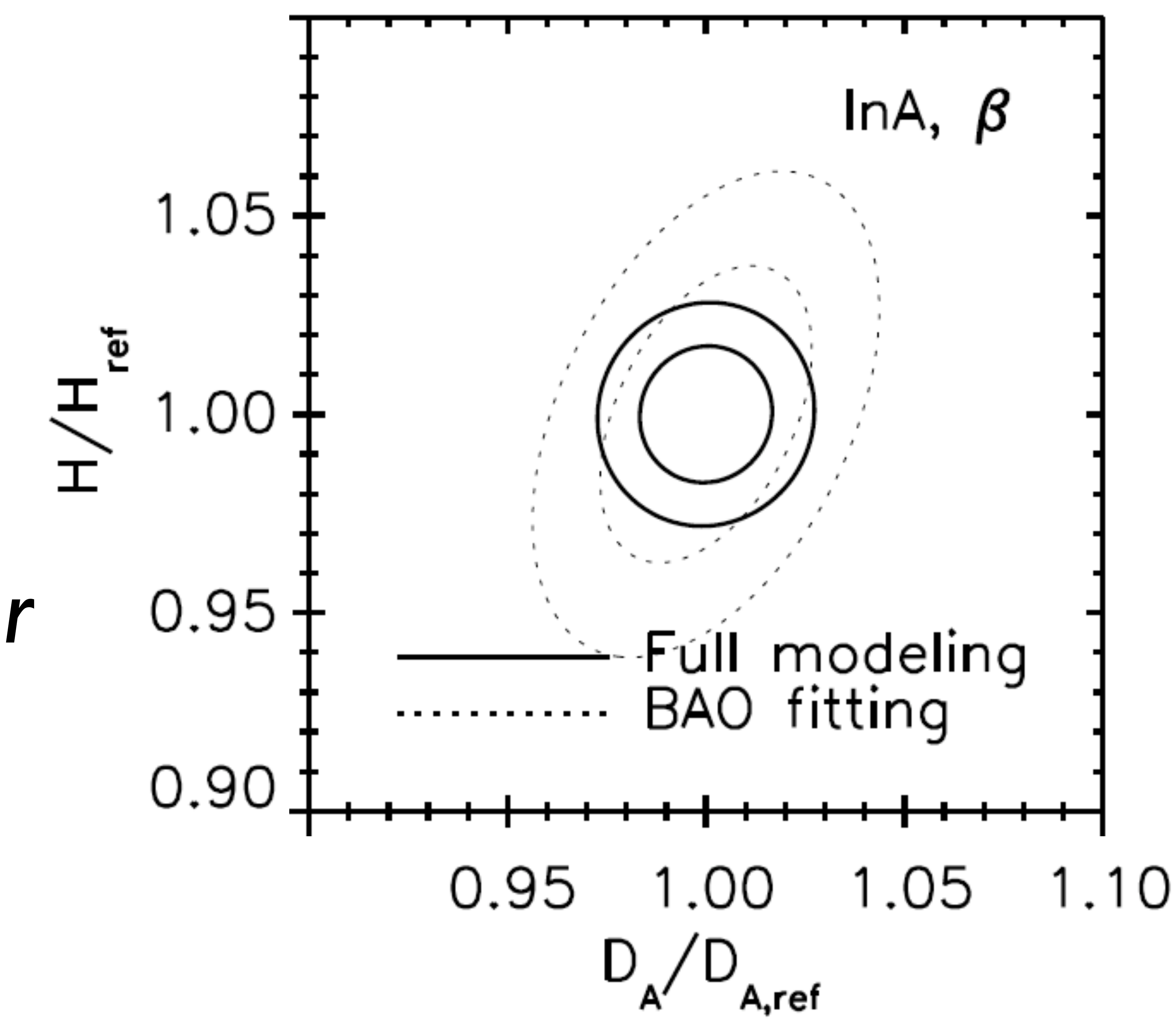
BAO vs Full Modeling

- 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.*



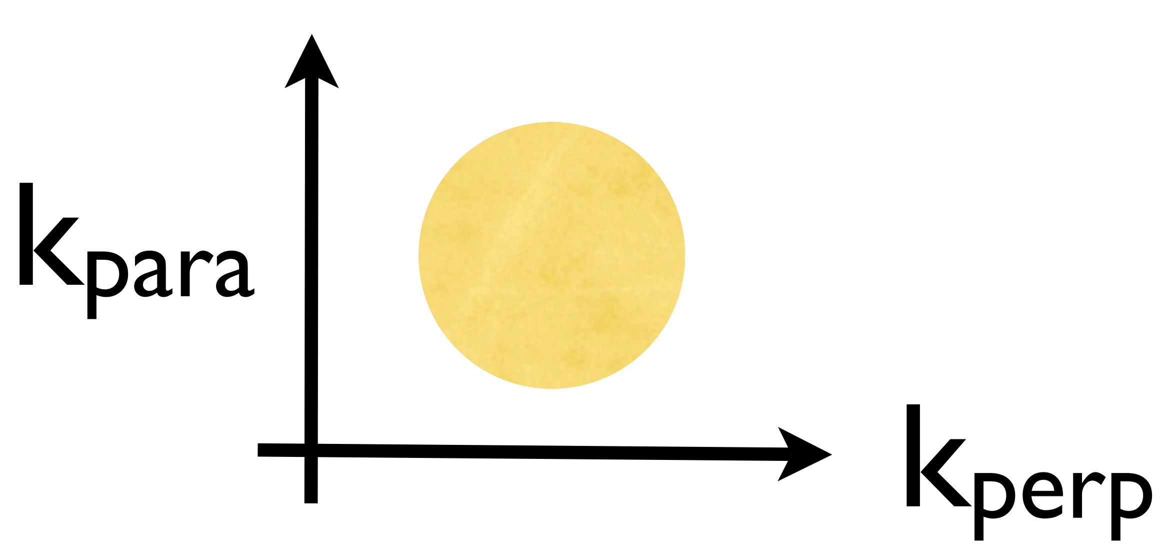
The AP Test: How That Works

- 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.

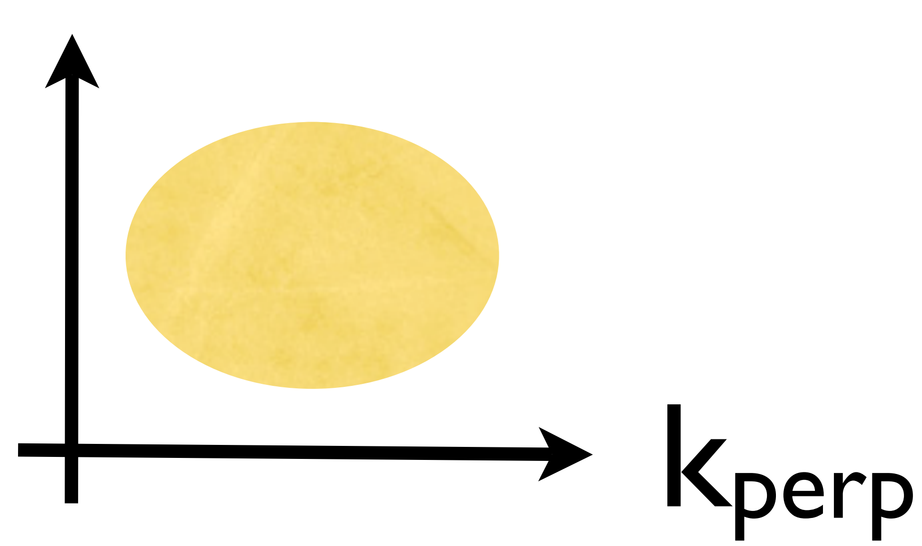
The AP Test: How That Works

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

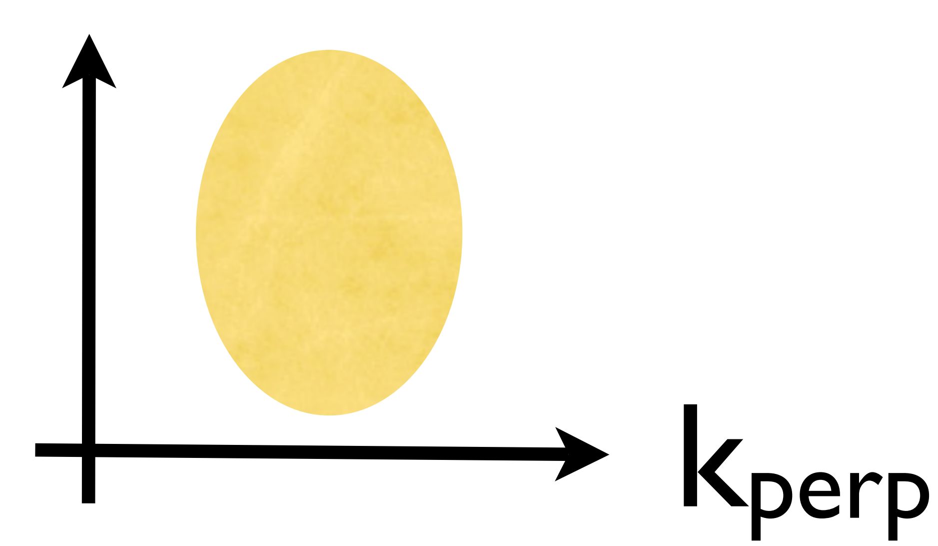
If D_A and H are correct:



If D_A is wrong:



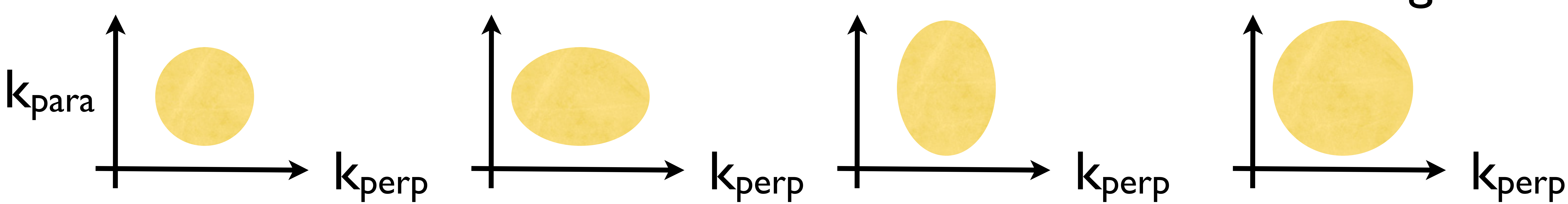
If H is wrong:



The AP Test: How That Works

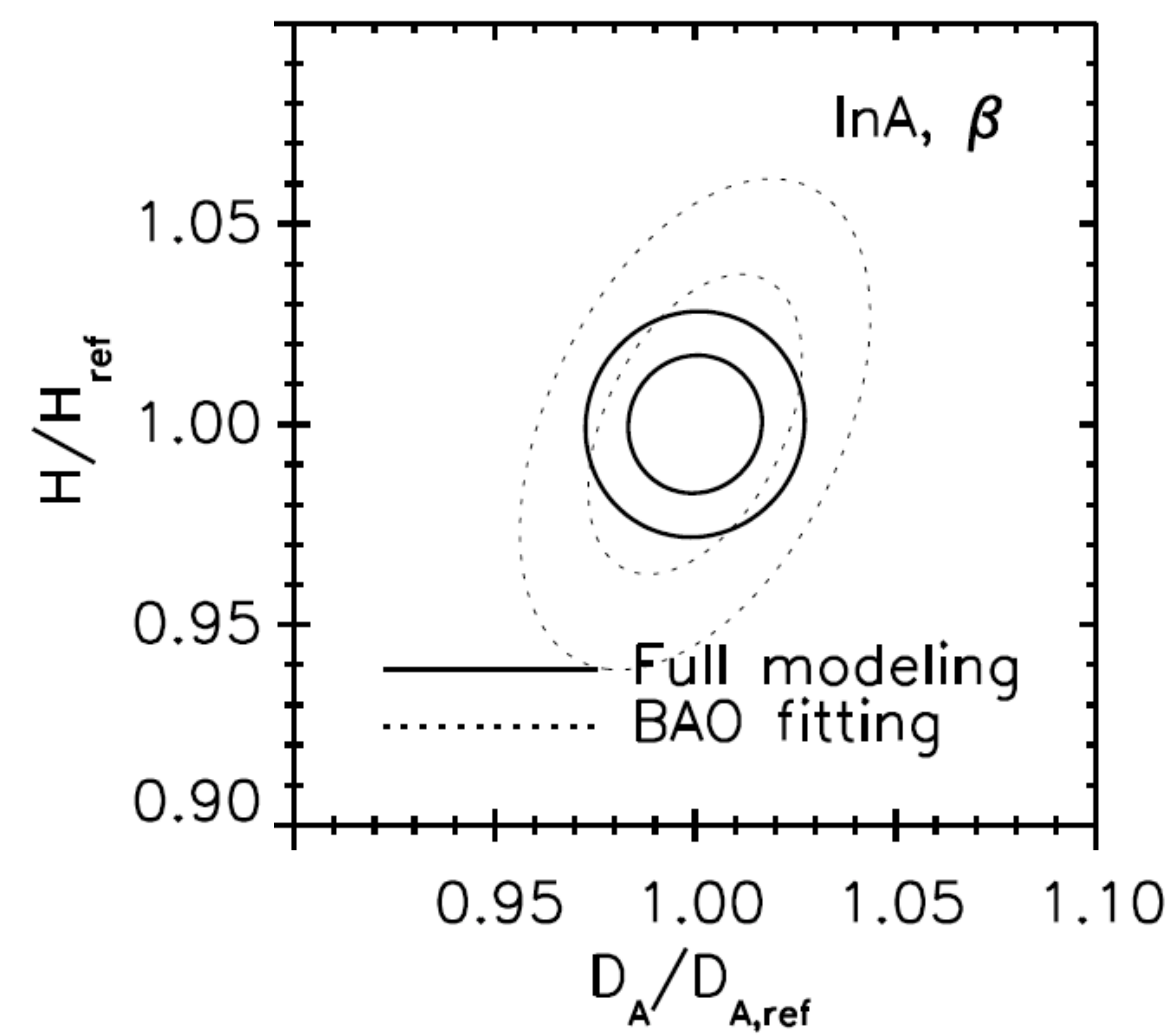
- **D_A**: (RA,Dec) to the transverse separation, r_{perp}, to the transverse wavenumber
  - $k_{perp} = (2\pi)/r_{perp} = (2\pi)[\text{Angle on the sky}]/\mathbf{D_A}$
- **H**: redshifts to the parallel separation, r_{para}, to the parallel wavenumber
  - $k_{para} = (2\pi)/r_{para} = (2\pi)\mathbf{H}/(c\Delta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

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



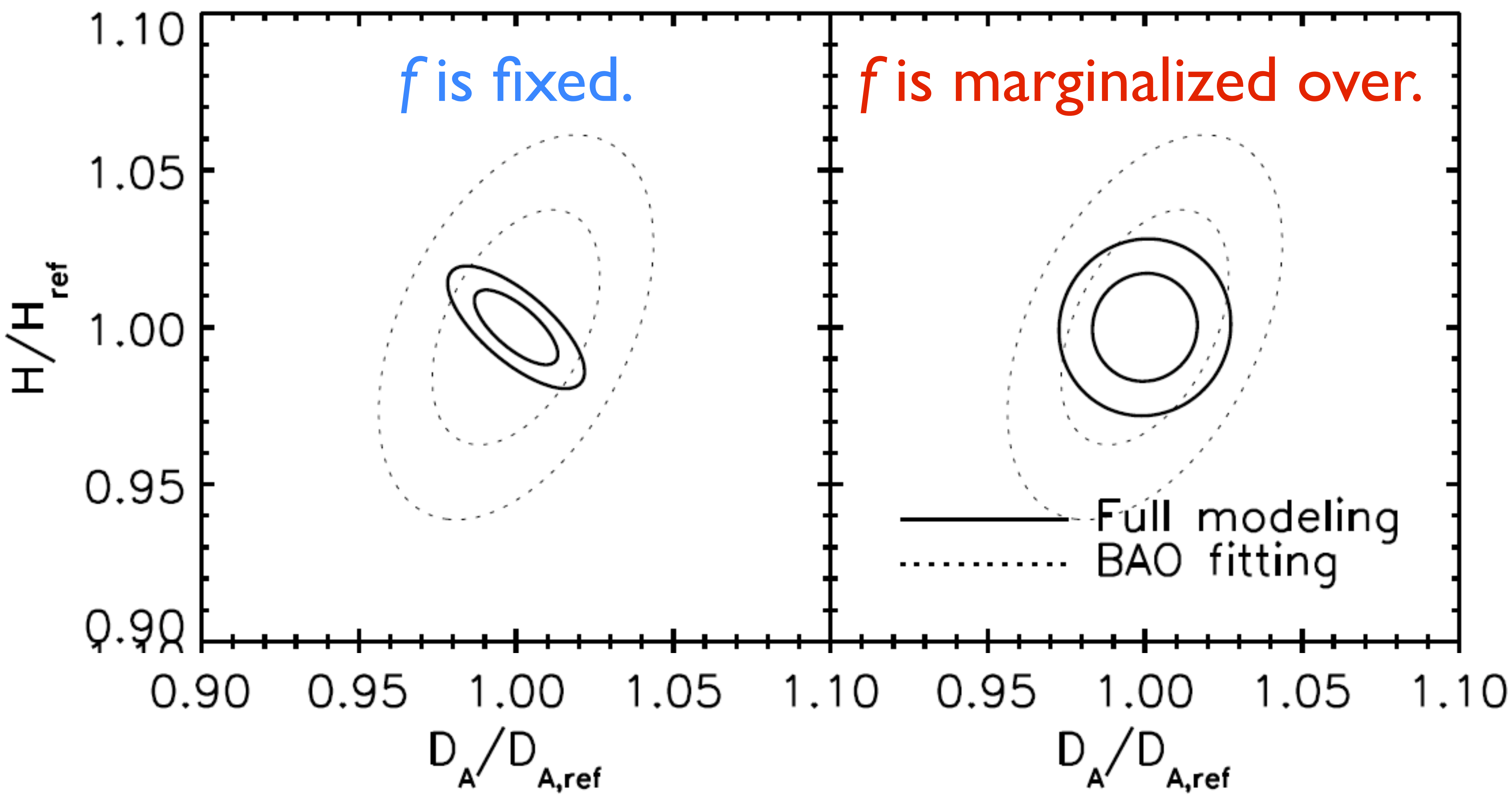
$D_A H$ from the AP test

- 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

- 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!



WMAP Amplitude Prior

- WMAP measures the amplitude of curvature perturbations at z~1090. Let's call that R_k. The relation to the density fluctuation is

$$\delta_{m,\mathbf{k}}(z) = \frac{2k^3}{5H_0^2\Omega_m}\mathcal{R}_{\mathbf{k}}T(k)D(k,z)$$

- Variance of R_k has been constrained as:

$$\Delta^2_{\mathcal{R}}(k_{WMAP}) = (2.208 \pm 0.078) \times 10^{-9} (68\% \text{ CL})$$

where k_{WMAP}=0.027 Mpc^{-1}

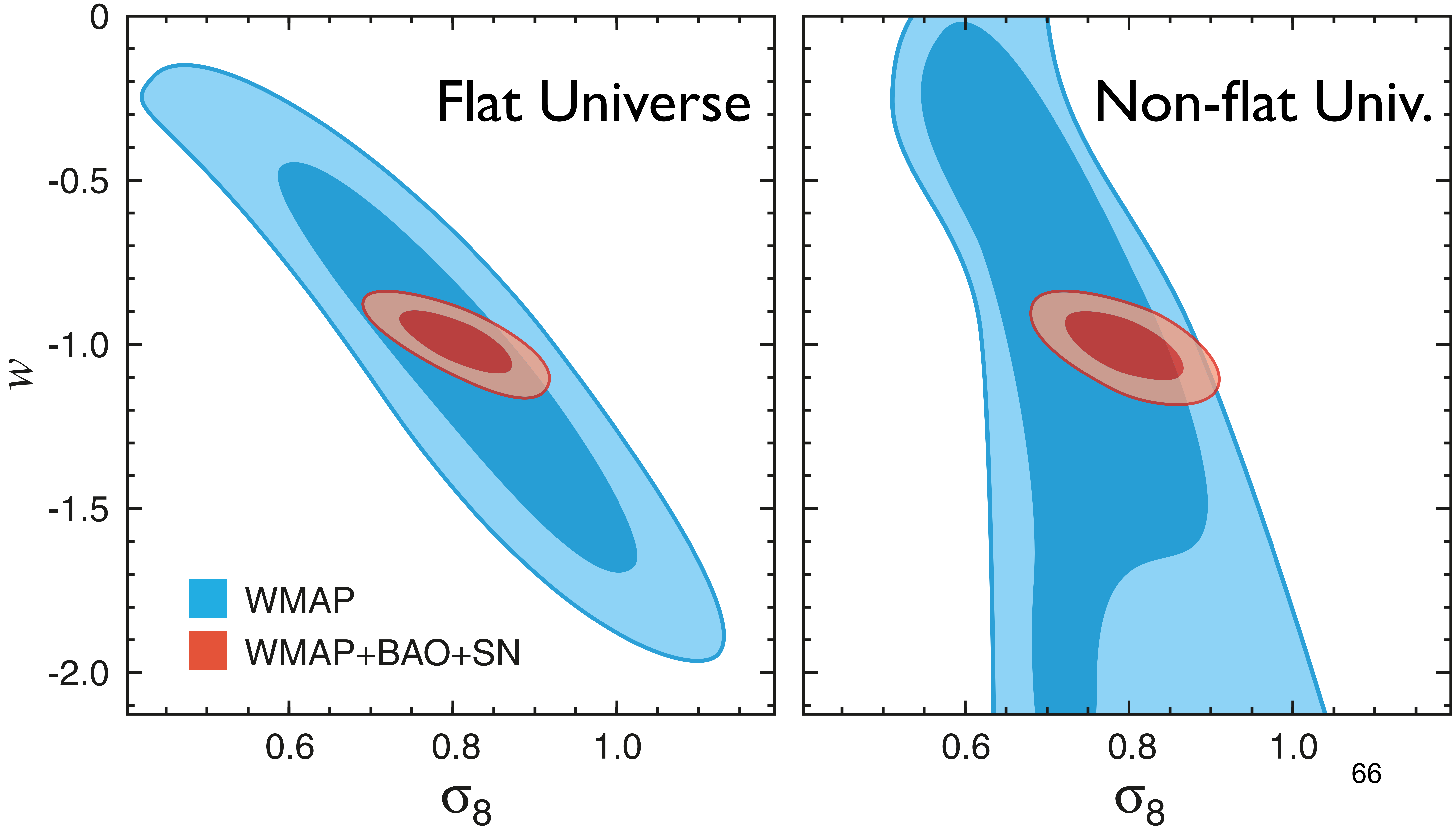
Then Solve This Diff. Equation...

Ignoring the mass of neutrinos and modifications to gravity, one can obtain the growth rate by solving the following differential equation (Wang & Steinhardt 1998; Linder & Jenkins 2003): **g(z)=(1+z)D(z)**

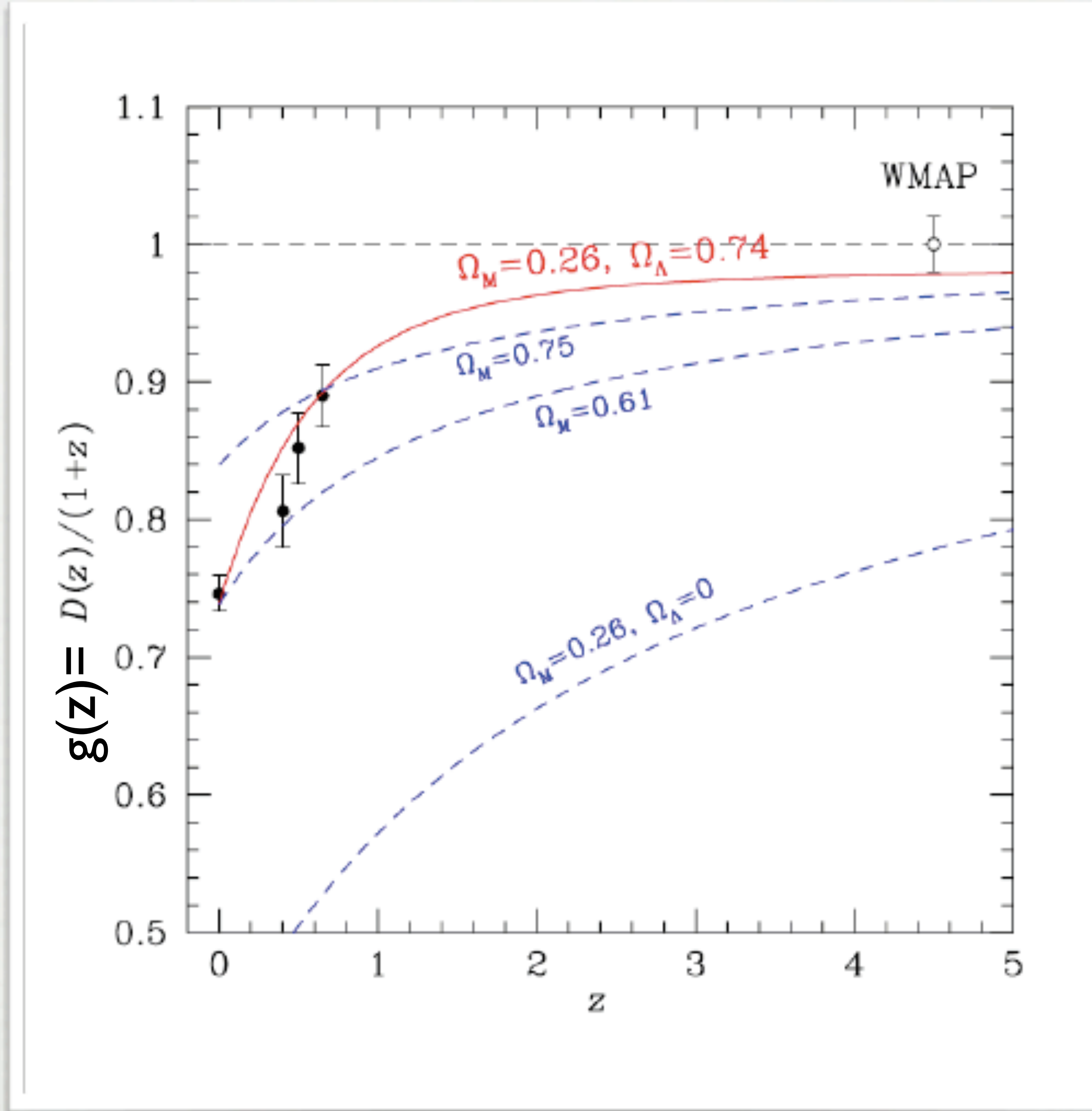
$$\frac{d^2 g}{d \ln a^2} + \left[\frac{5}{2} + \frac{1}{2}\left(\Omega_k(a) - 3\boldsymbol{W}(a)\Omega_{de}(a)\right)\right]\frac{dg}{d\ln a}$$

$$+ \left[2\Omega_k(a) + \frac{3}{2}(1 - \boldsymbol{W}(a))\Omega_{de}(a)\right] g(a) = 0, \qquad (76)$$

Degeneracy Between Amplitude at z=0 (σ_8) and w



DETECTION OF Λ BY GROWTH HISTORY

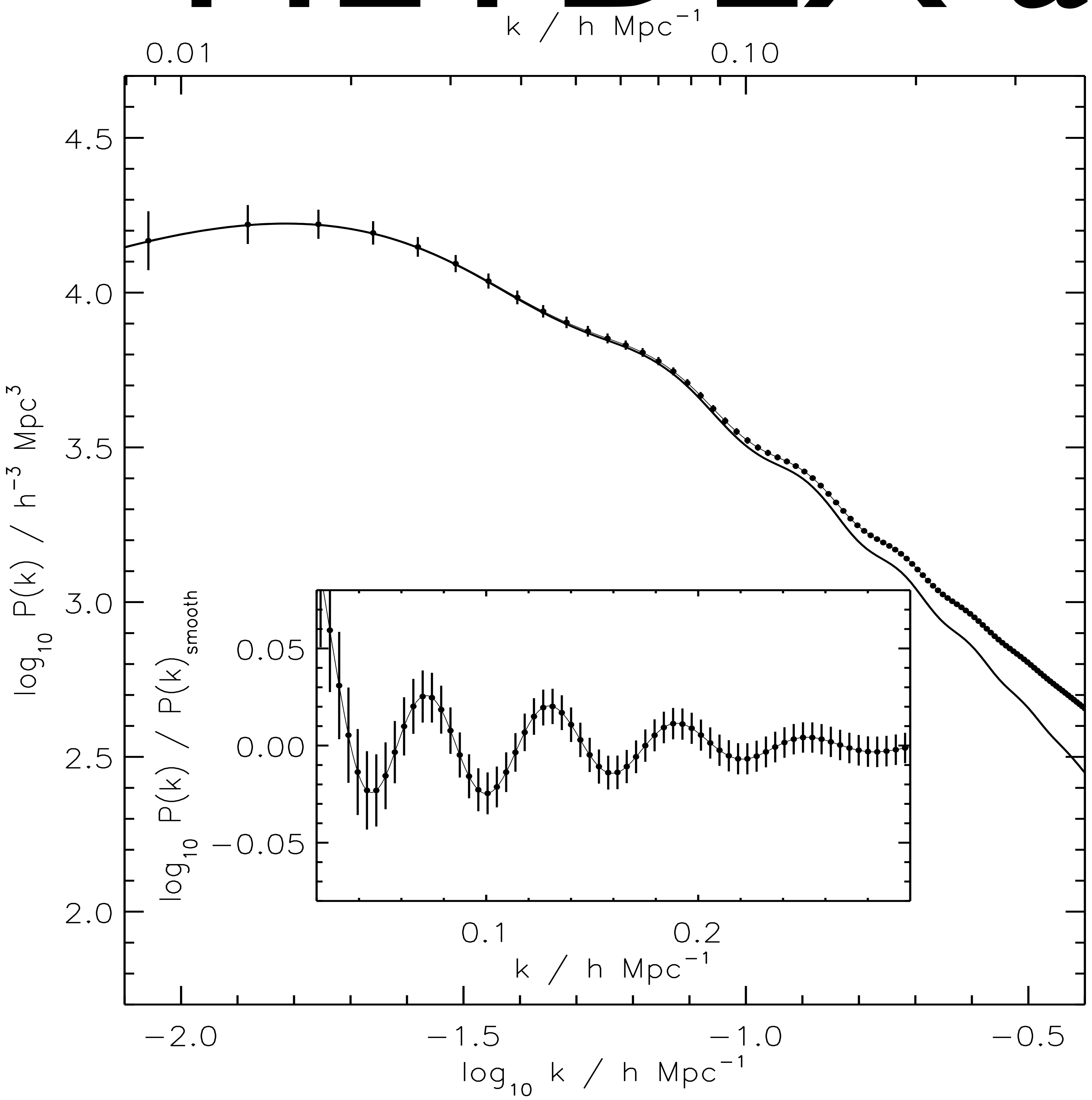


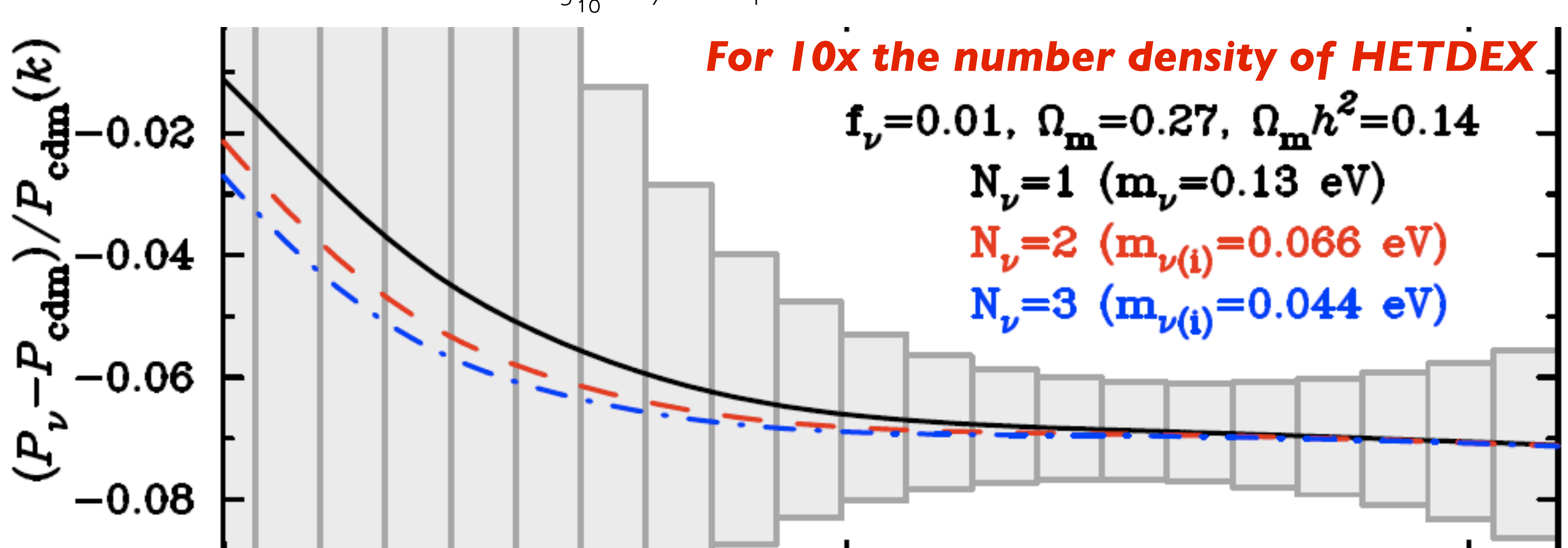
Alexey Vikhlinin, from a slide presented at the IPMU Dark Energy Conference in Japan, June 2009

$\Lambda > 0$ at ~3.5σ from perturbations growth only

at ~5σ from growth + geometry

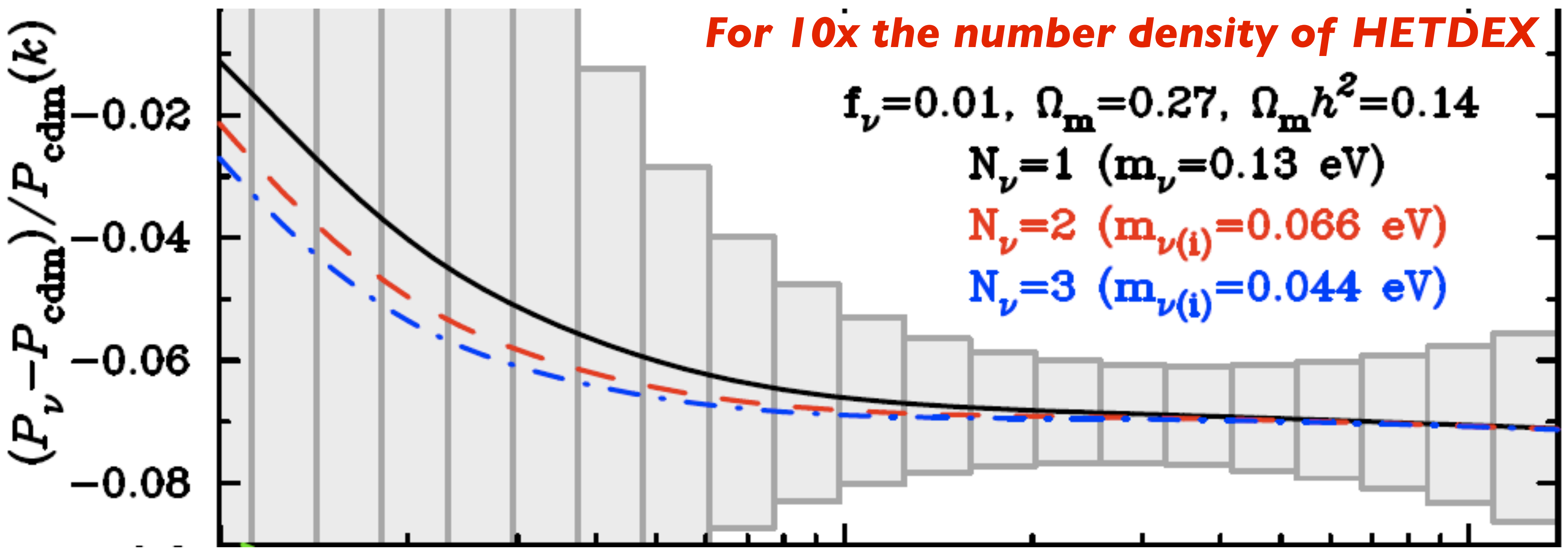
HETDEX and Neutrino Mass





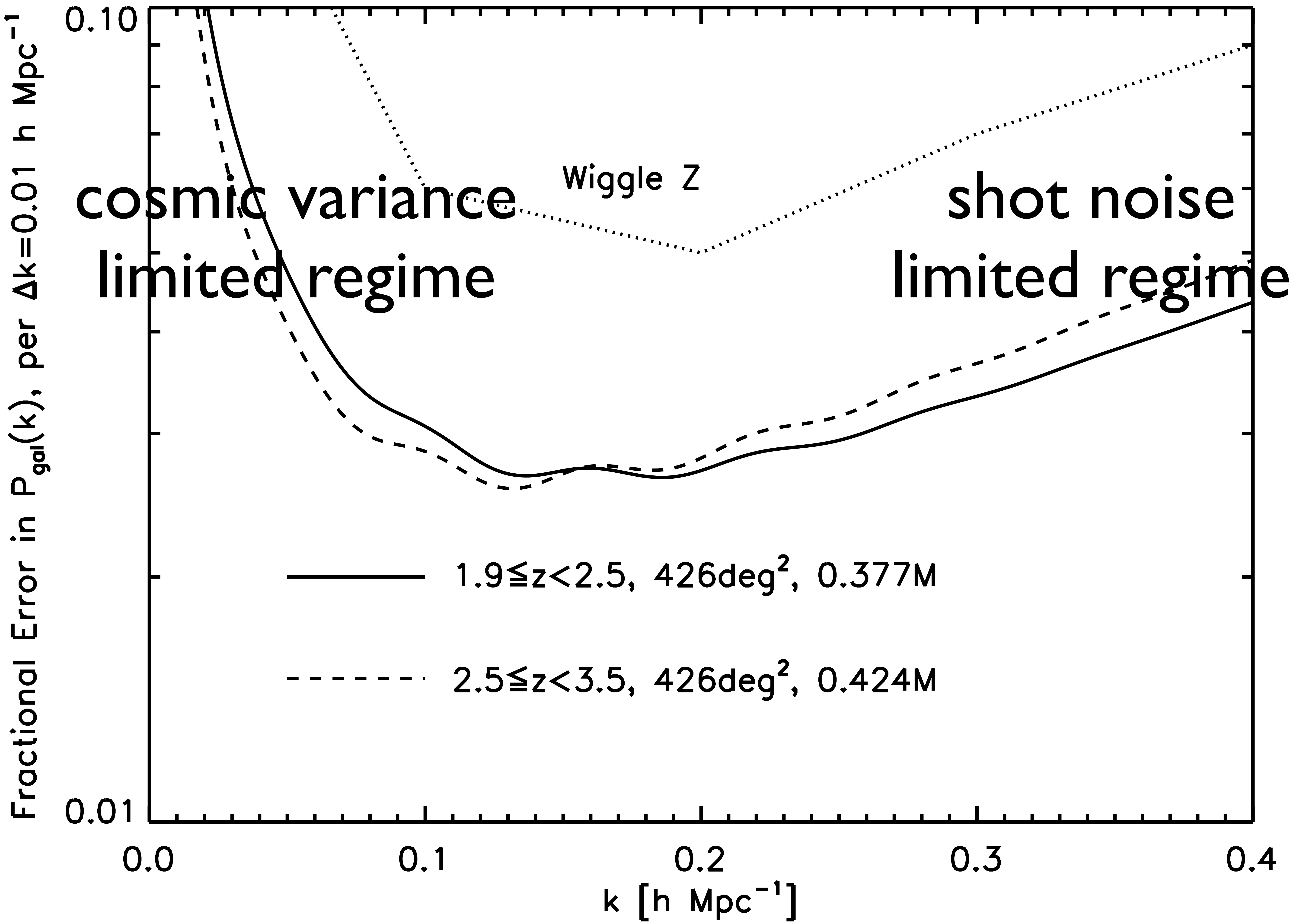
- Neutrinos suppress the matter power spectrum on small scales ($k>0.1\ h\ \mathrm{Mpc}^{-1}$).
- A useful number to remember:
  - For $\sum m_\nu=0.1$ eV, the power spectrum at $k>0.1\ h\ \mathrm{Mpc}^{-1}$ is suppressed by **~7%**.
  - We can measure this easily!

Neutrino Mass and P(k)



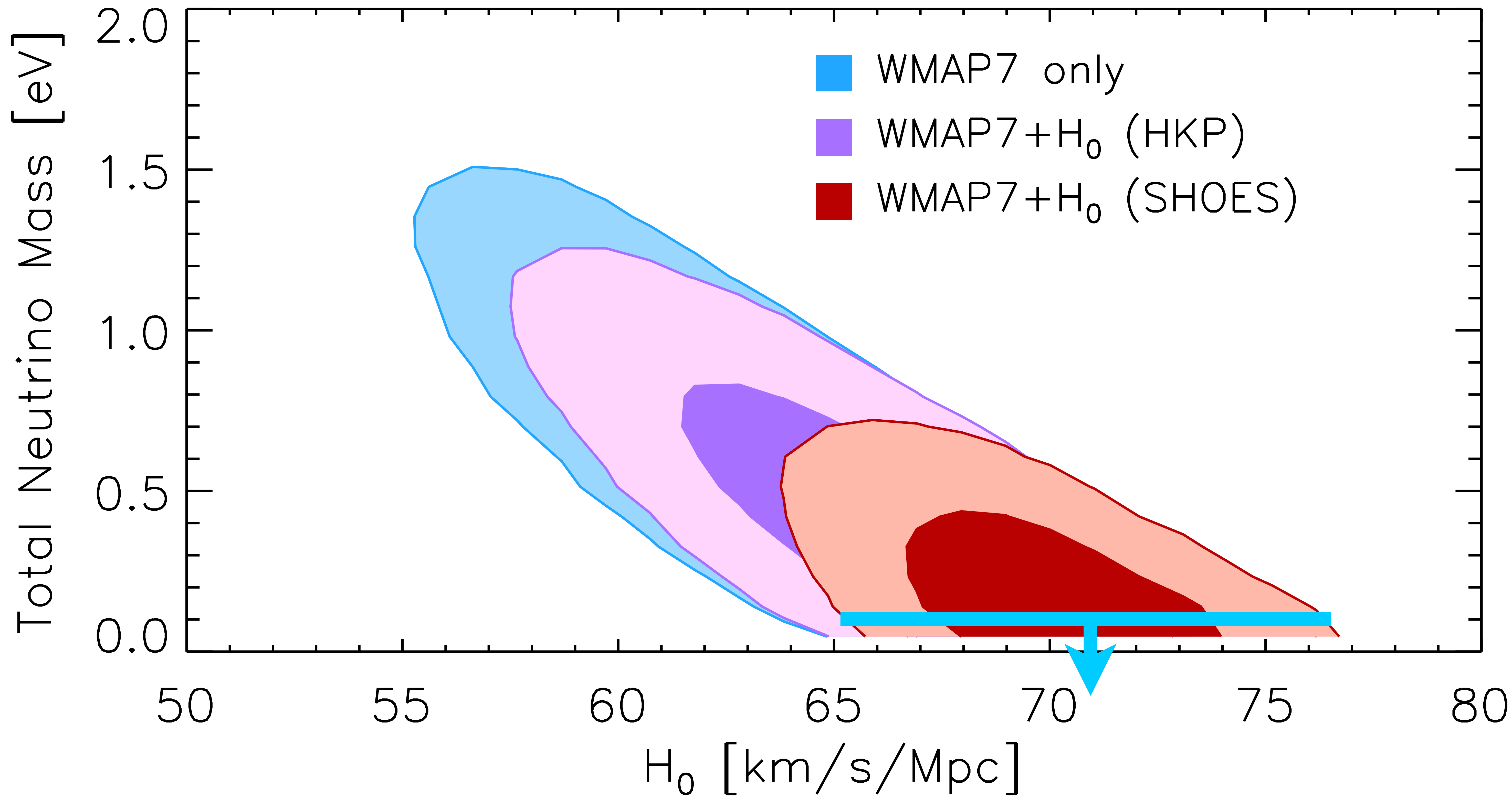
- Total neutrino mass: coming from the small scale
  - $\Delta P/P \sim -8\Omega_\nu/\Omega_m = -[8/(\Omega_m h^2)]\sum m_\nu/($
- Where the suppression begins depends on individual masses!
- $$k_{\mathrm{fs},i}(z) \equiv \sqrt{\frac{3}{2}} \frac{H(z)}{(1+z)\sigma_{v,i}(z)} \simeq \frac{0.677}{(1+z)^{1/2}} \left(\frac{m_{\nu,i}}{1\ \mathrm{eV}}\right) \Omega_{\mathrm{m}}^{1/2} h\ \mathrm{Mpc}^{-1}$$

Expectation for HETDEX



- CV limited: error goes as 1/sqrt(volume)
- SN limited: error goes as 1/(number density)/sqrt(volume)

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
- CMB and large-scale structure observations can lead to major breakthroughs in any of the above questions.