BAO:

Where We Are Now, What To Be Done, and Where We Are Going

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The University of Texas at Austin
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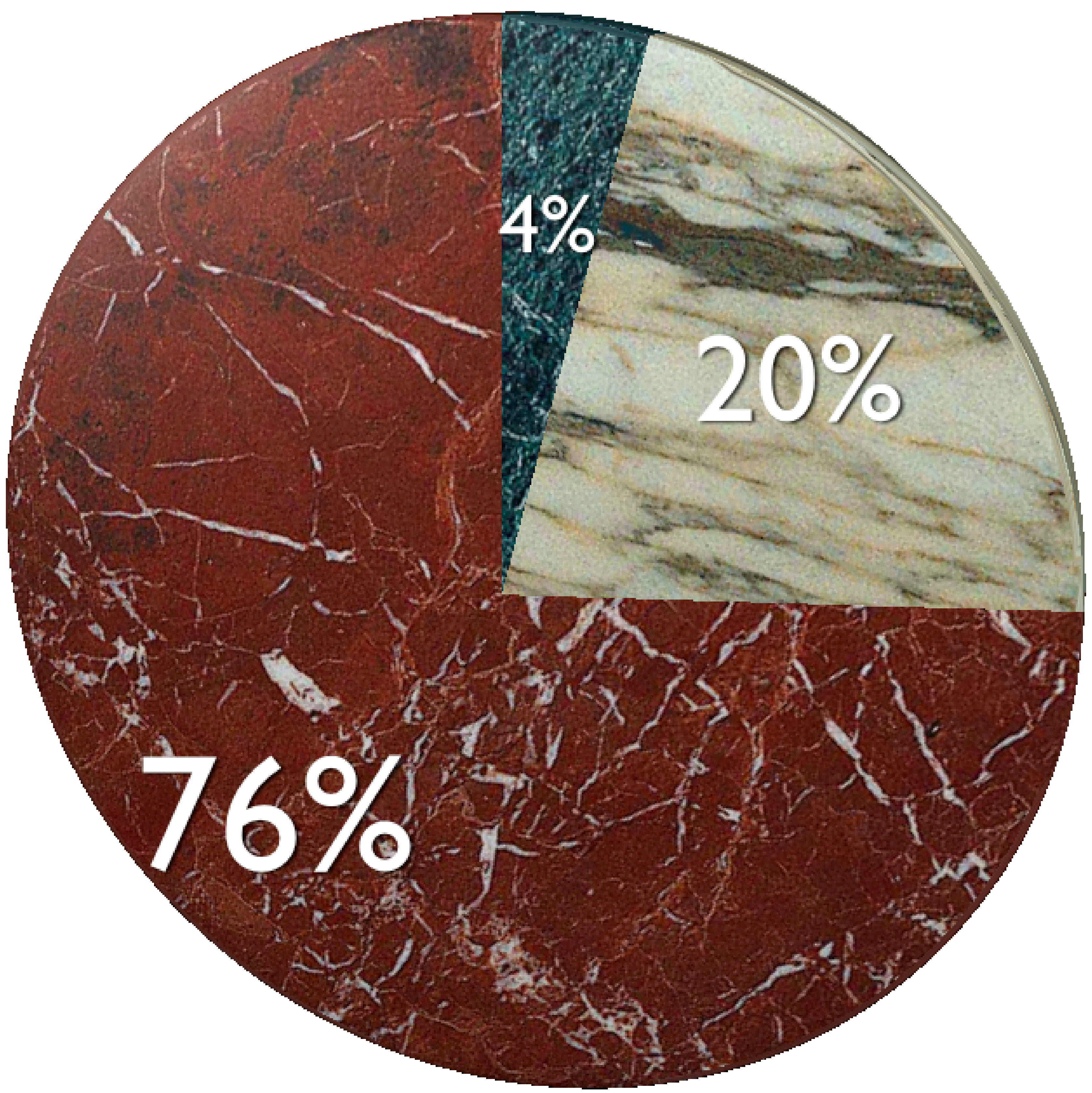
Dark Energy

Energy Content



- Everybody talks about it...
- What exactly do we need Dark Energy for?

Baryon
Dark Matter
Dark Energy

Need For Dark "Energy"

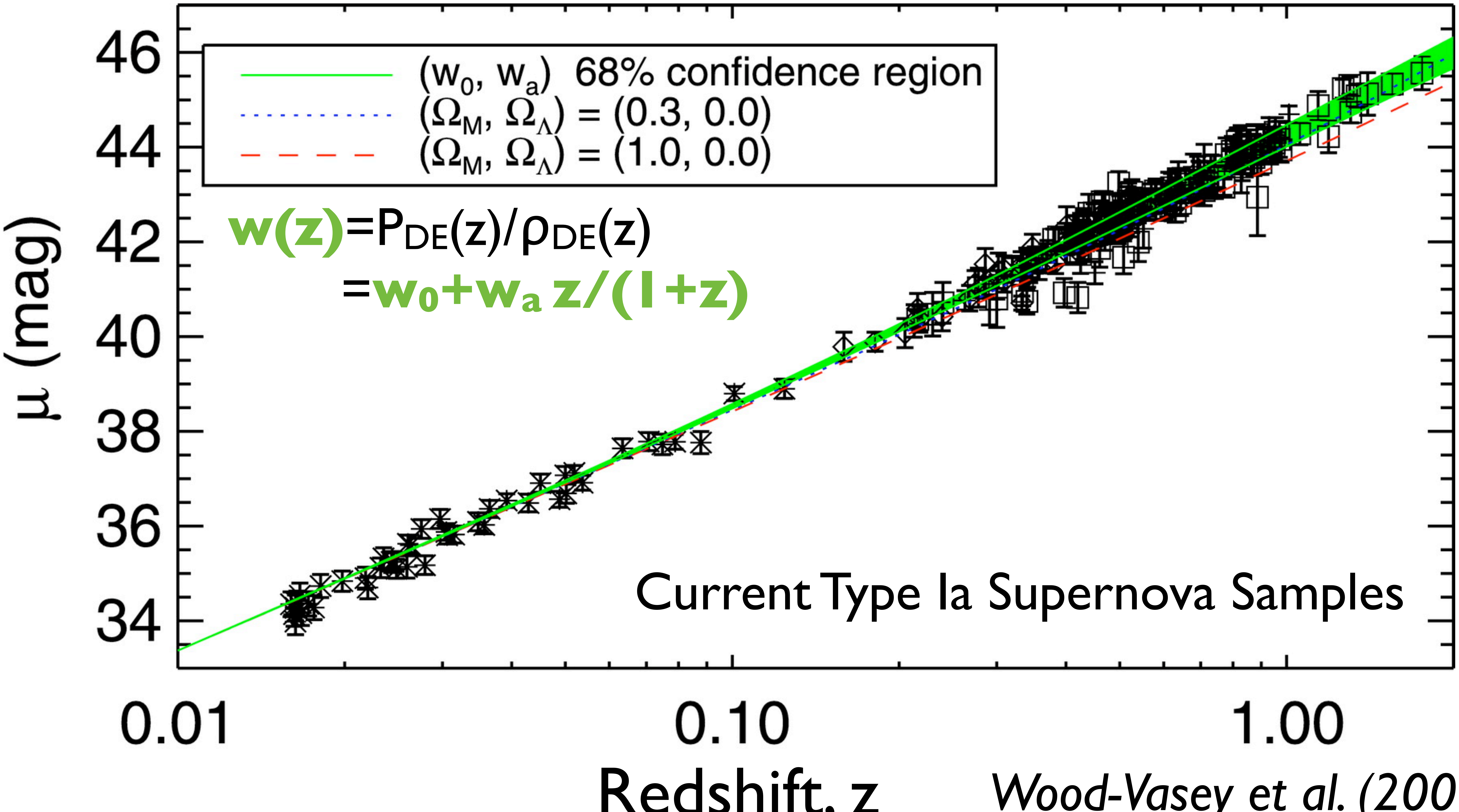
- First of all, DE does not even need to be energy.
- At present, *anything* that can explain the observed

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

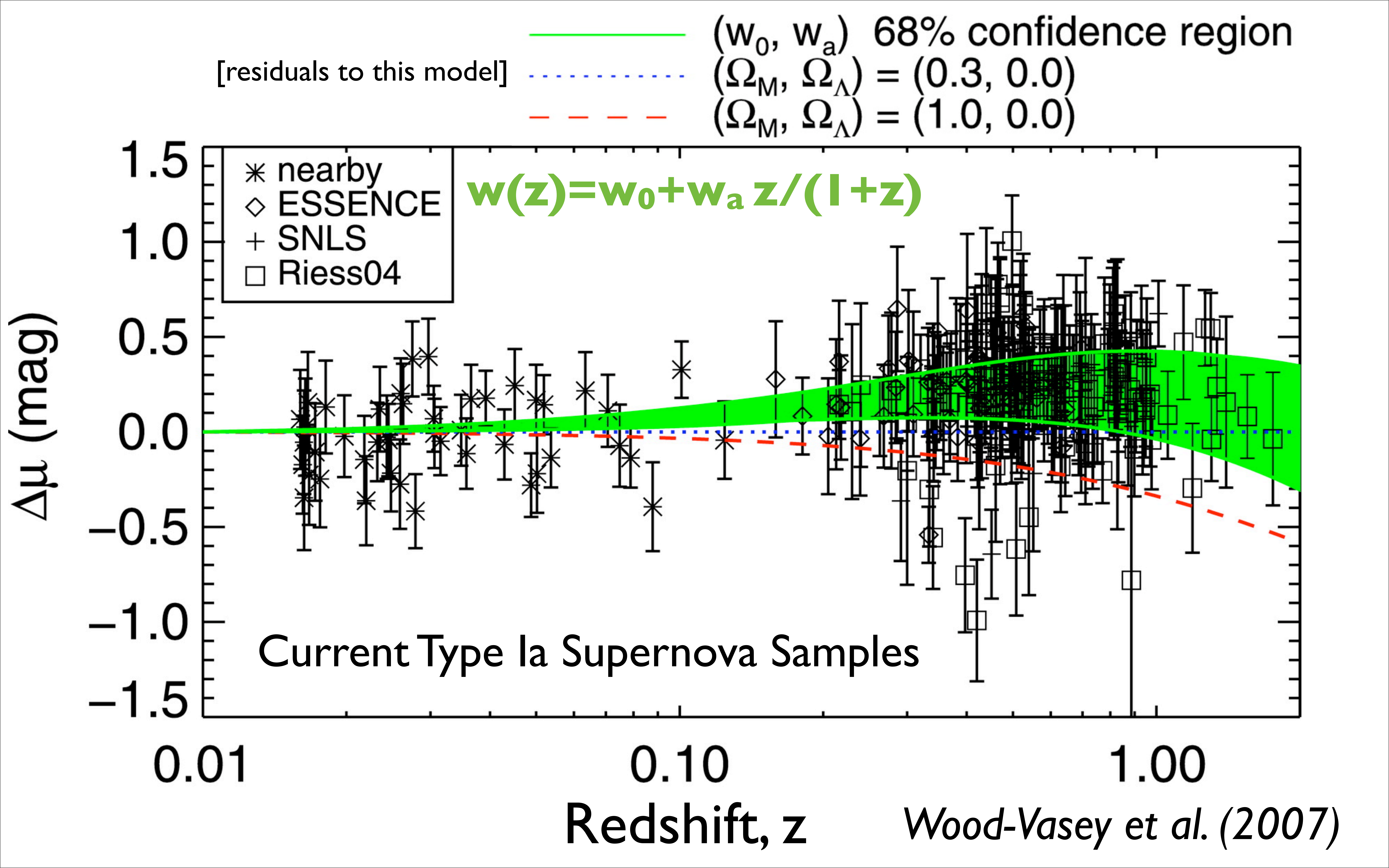
  (2) **Angular Diameter Distances** (BAO, CMB)

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

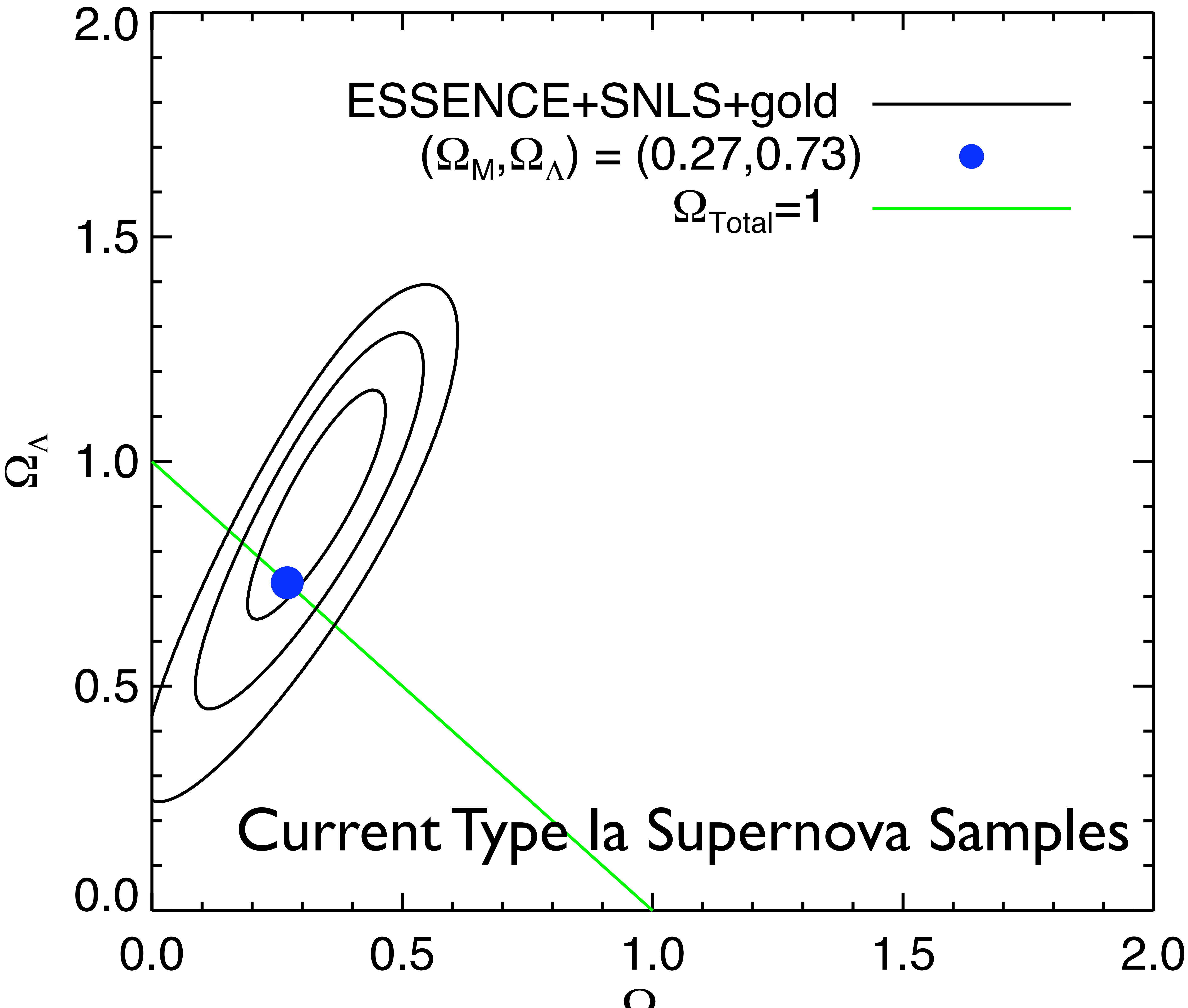
$\mu = 5\mathrm{Log}_{10}[D_L(z)/\mathrm{Mpc}] + 25$



Wood-Vasey et al. (2007)

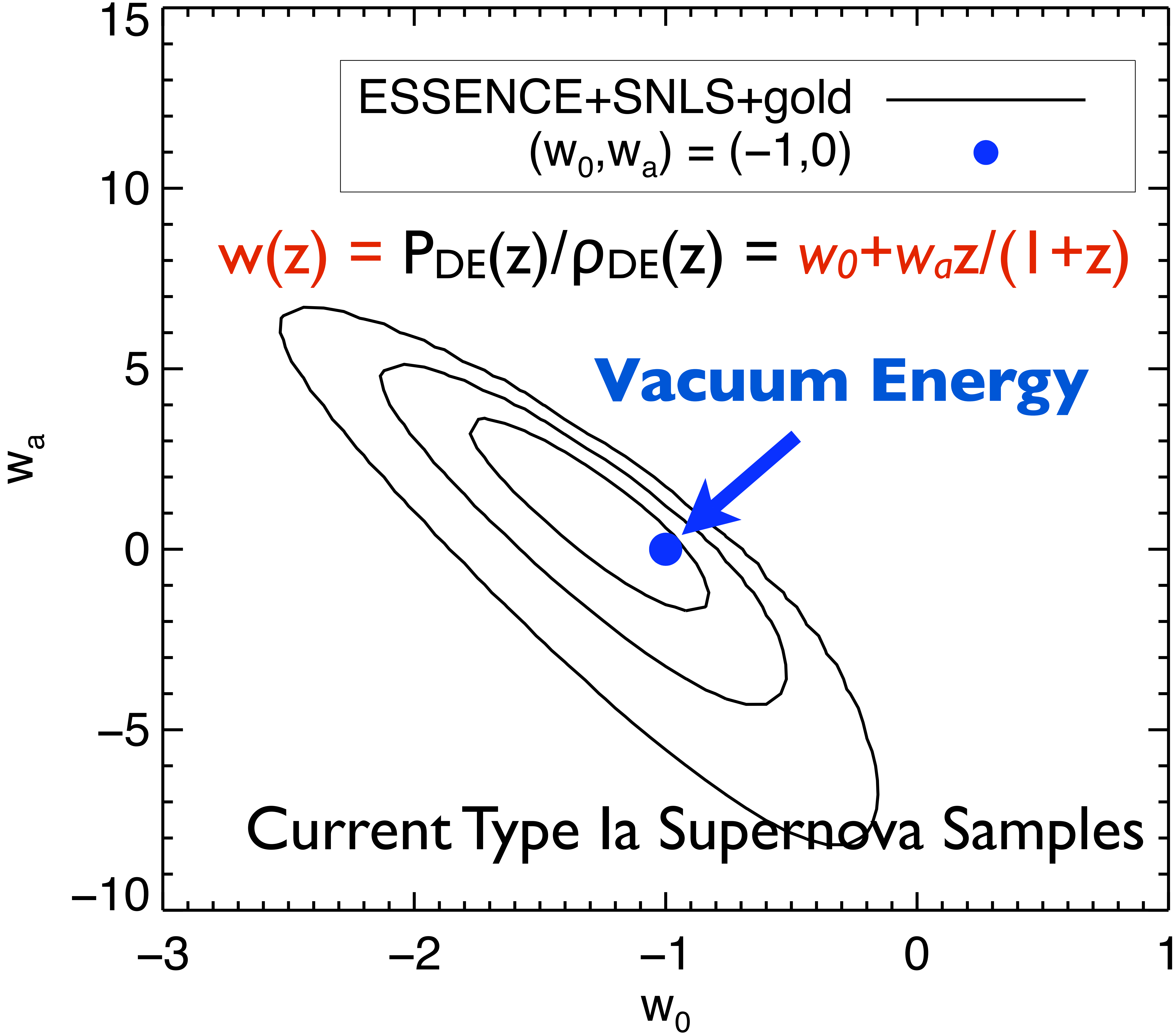


(w_0, w_a) 68% confidence region
[residuals to this model]
$(\Omega_M, \Omega_\Lambda) = (0.3, 0.0)$
$(\Omega_M, \Omega_\Lambda) = (1.0, 0.0)$
nearby
ESSENCE
SNLS
Riess04
$w(z)=w_0+w_a\, z/(1+z)$
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
$\Delta\mu$ (mag)
Current Type Ia Supernova Samples
0.01
0.10
1.00
Redshift, z
Wood-Vasey et al. (2007)



- Within the standard framework of cosmology based on General Relativity...
- There is a clear indication that the matter density alone cannot explain the supernova data.
- Need Dark Energy.

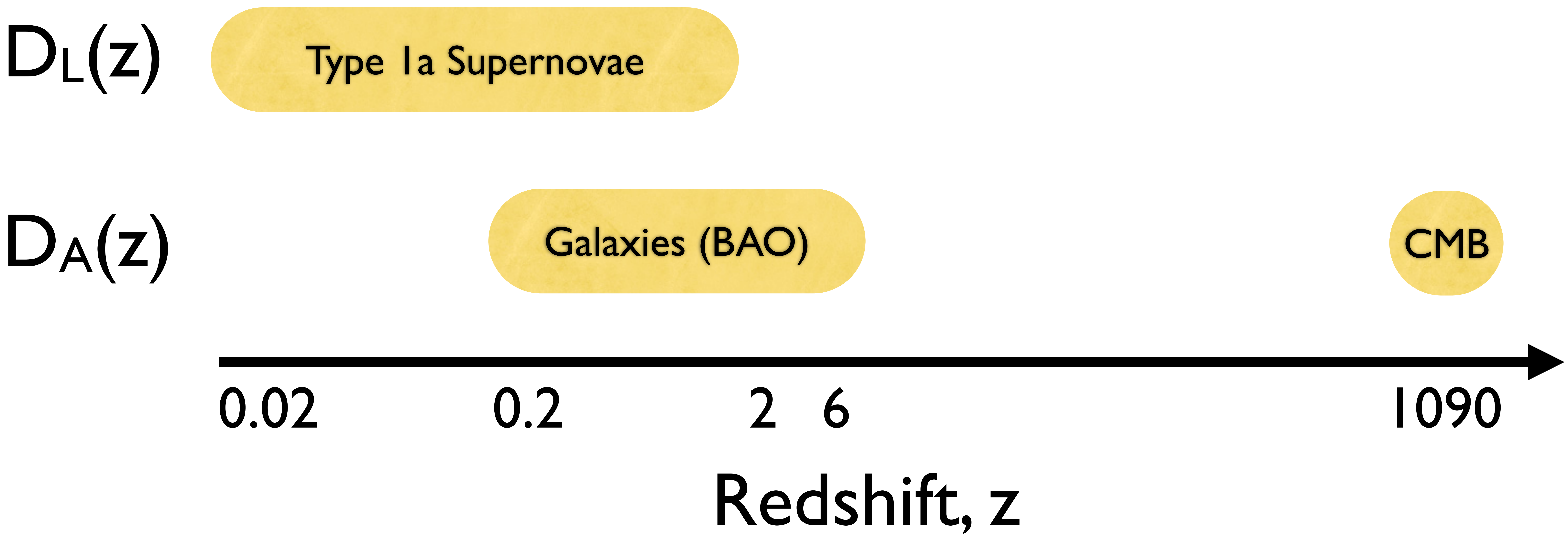
Wood-Vasey et al. (2007)



- Within the standard framework of cosmology based on General Relativity...
- Dark Energy is consistent with "vacuum energy," a.k.a. cosmological constant.
- The uncertainty is still large. Goal: 10x reduction in the uncertainty. [StageIV]

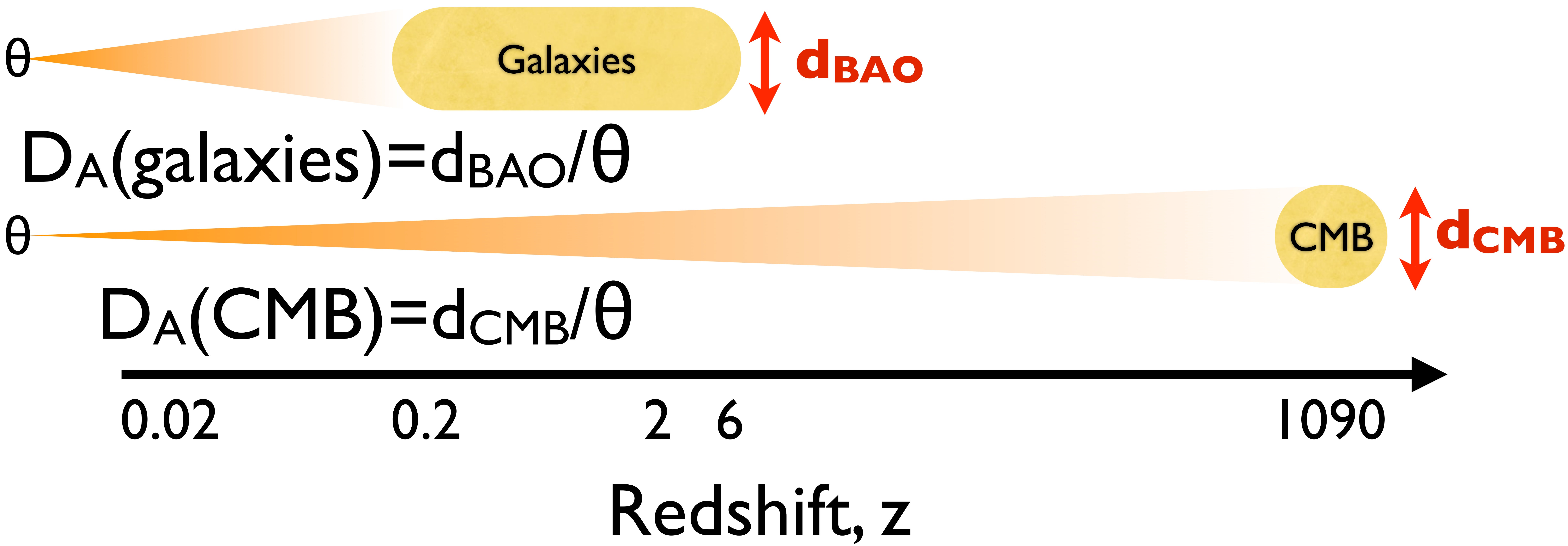
Wood-Vasey et al. (2007)

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



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

How Do We Measure $D_A(z)$?



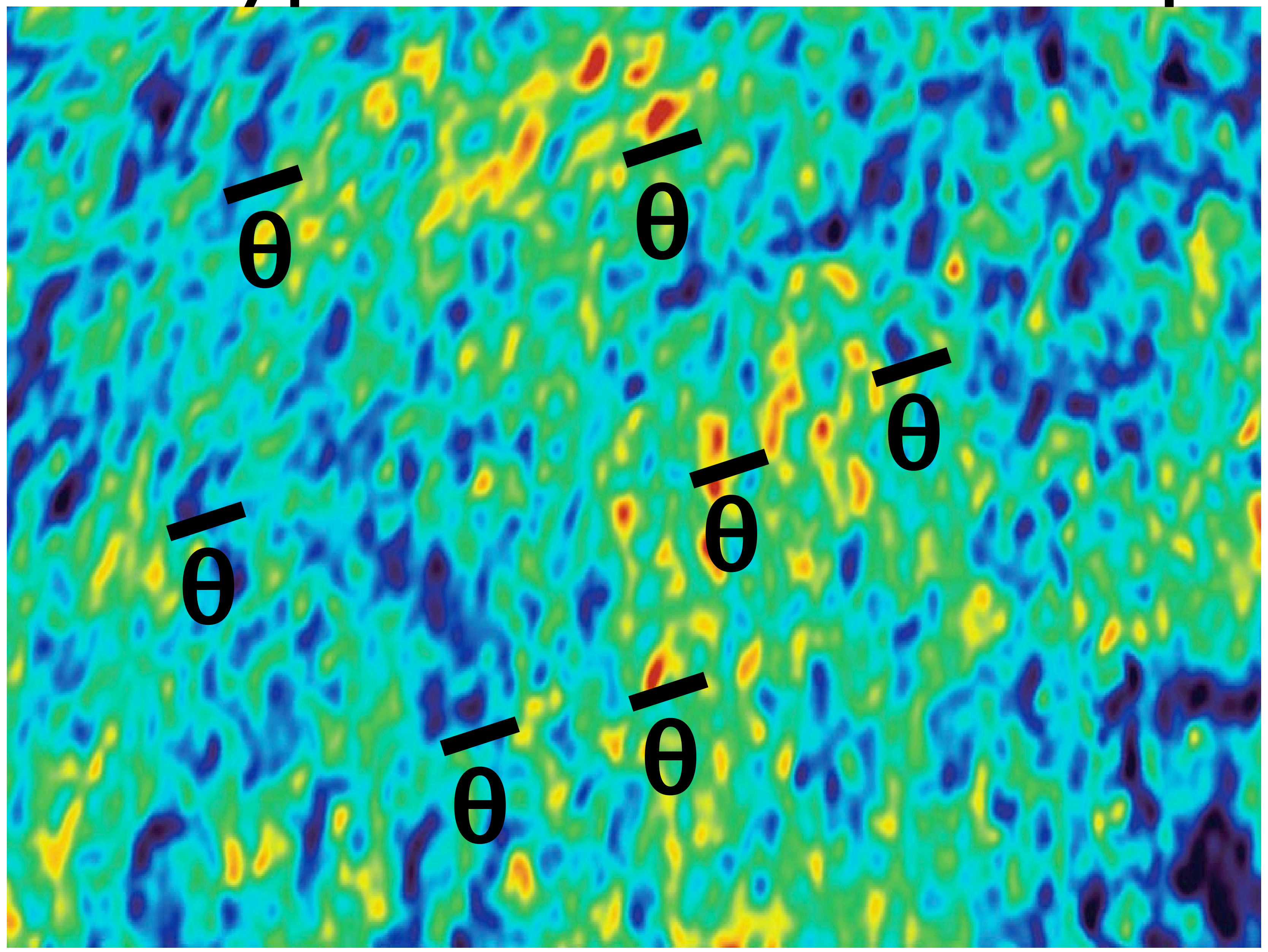
- If we know the intrinsic physical sizes, d, we can measure D_A. What determines d?

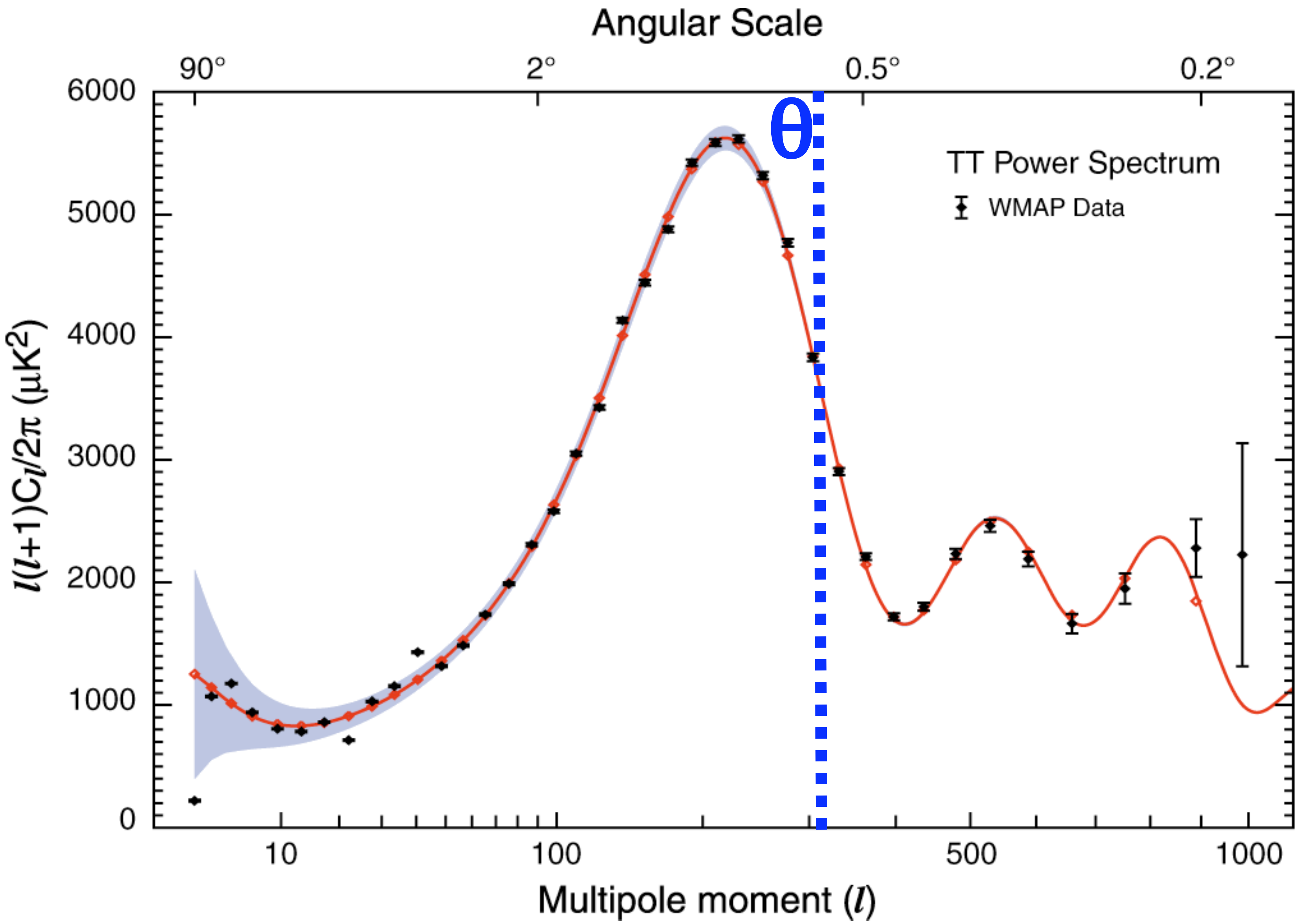
Just To Avoid Confusion...

- When I say $D_L(z)$ and $D_A(z)$, I mean "physical distances." The "comoving distances" are $(1+z)D_L(z)$ and $(1+z)D_A(z)$, respectively.
- When I say d_{CMB} and d_{BAO}, I mean "physical sizes." The "comoving sizes" are $(1+z_{CMB})d_{CMB}$ and $(1+z_{BAO})d_{BAO}$, respectively.
  - Sometimes people use "r" for the comoving sizes.
  - E.g., $r_{CMB} = (1+z_{CMB})d_{CMB}$, and $r_{BAO} = (1+z_{BAO})d_{BAO}$.

CMB as a Standard Ruler

θ~the typical size of hot/cold spots

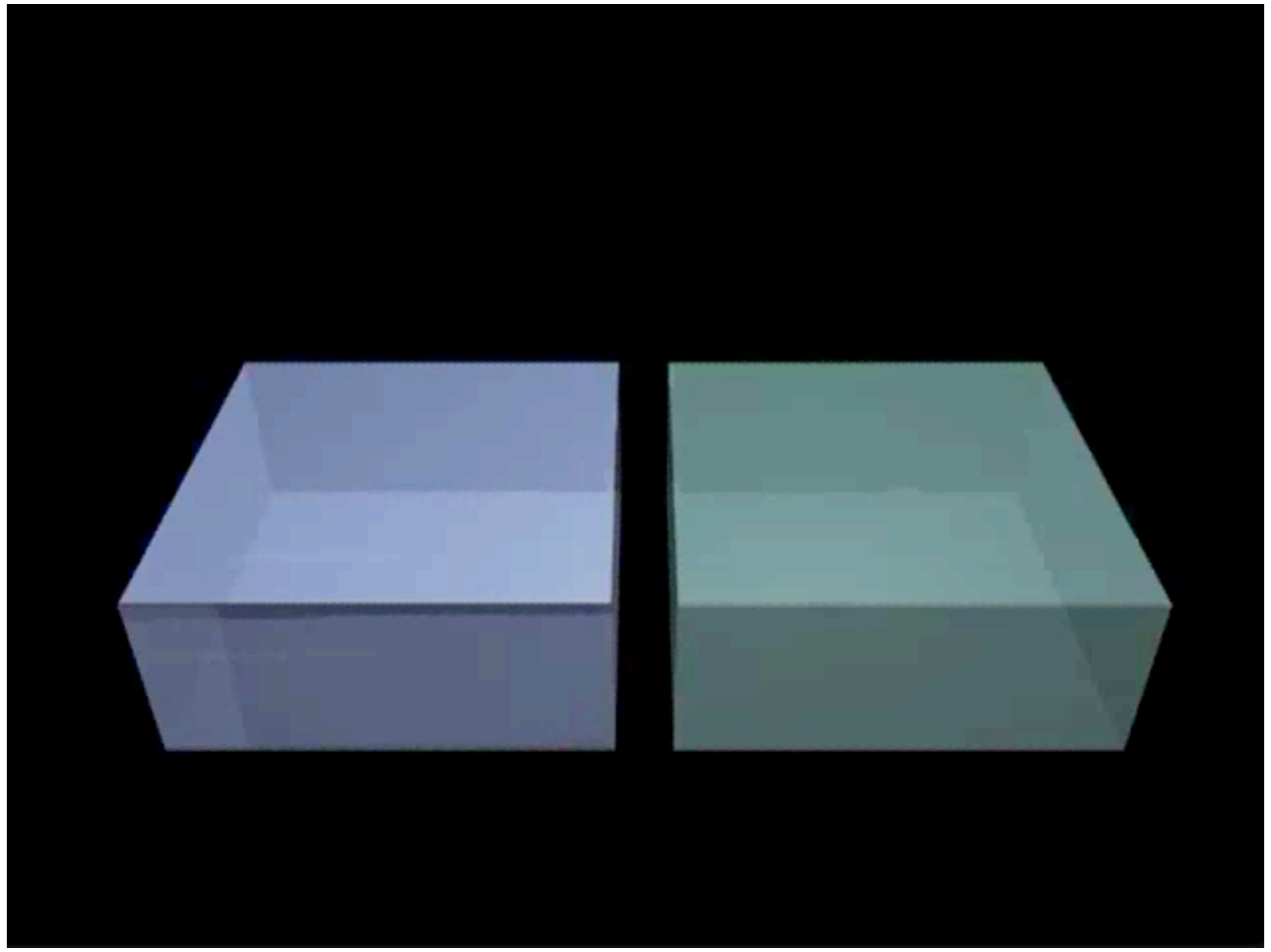


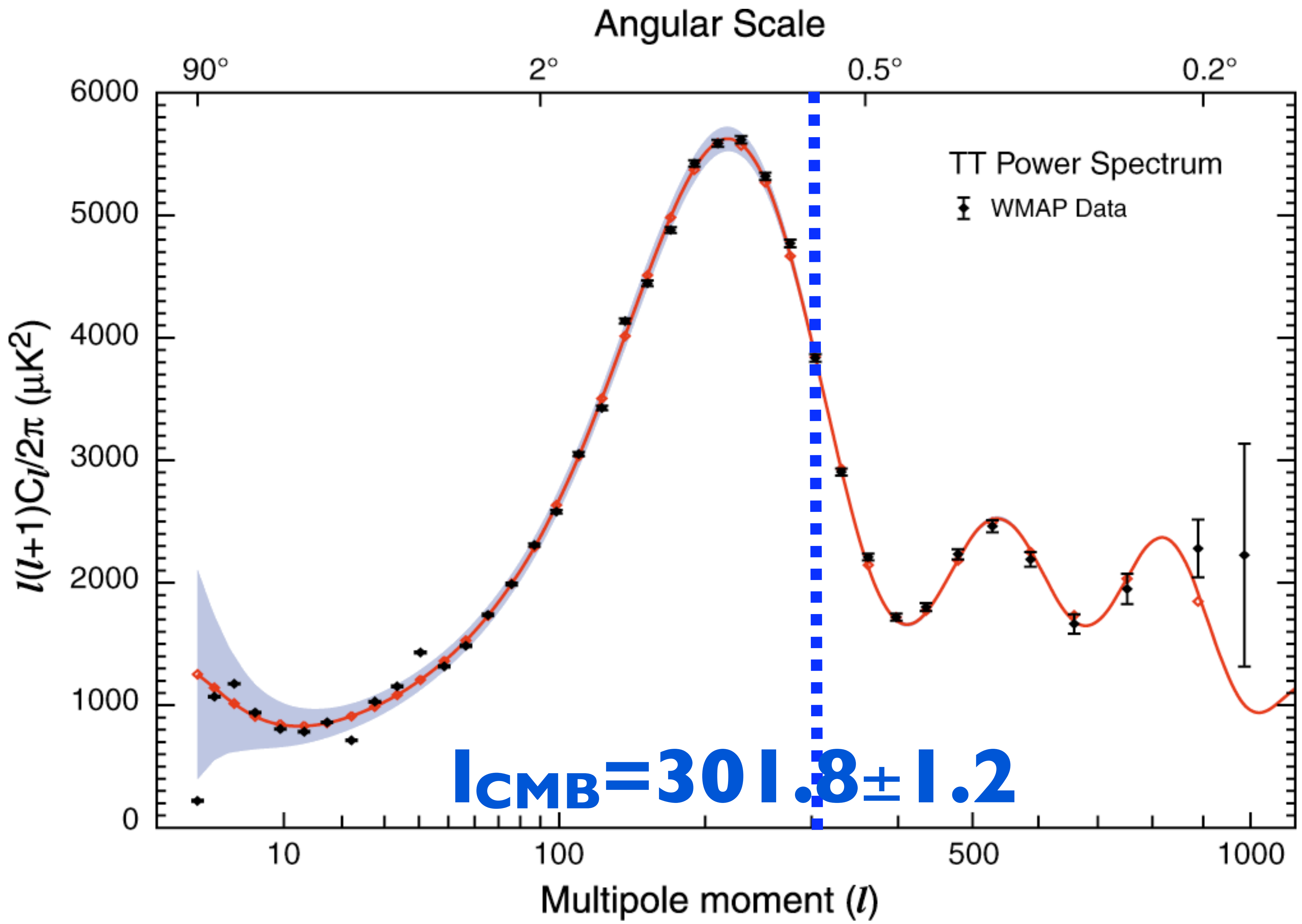


- The existence of typical spot size in image space yields oscillations in harmonic (Fourier) space. What determines the physical size of typical spots, d_{CMB}?

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**.

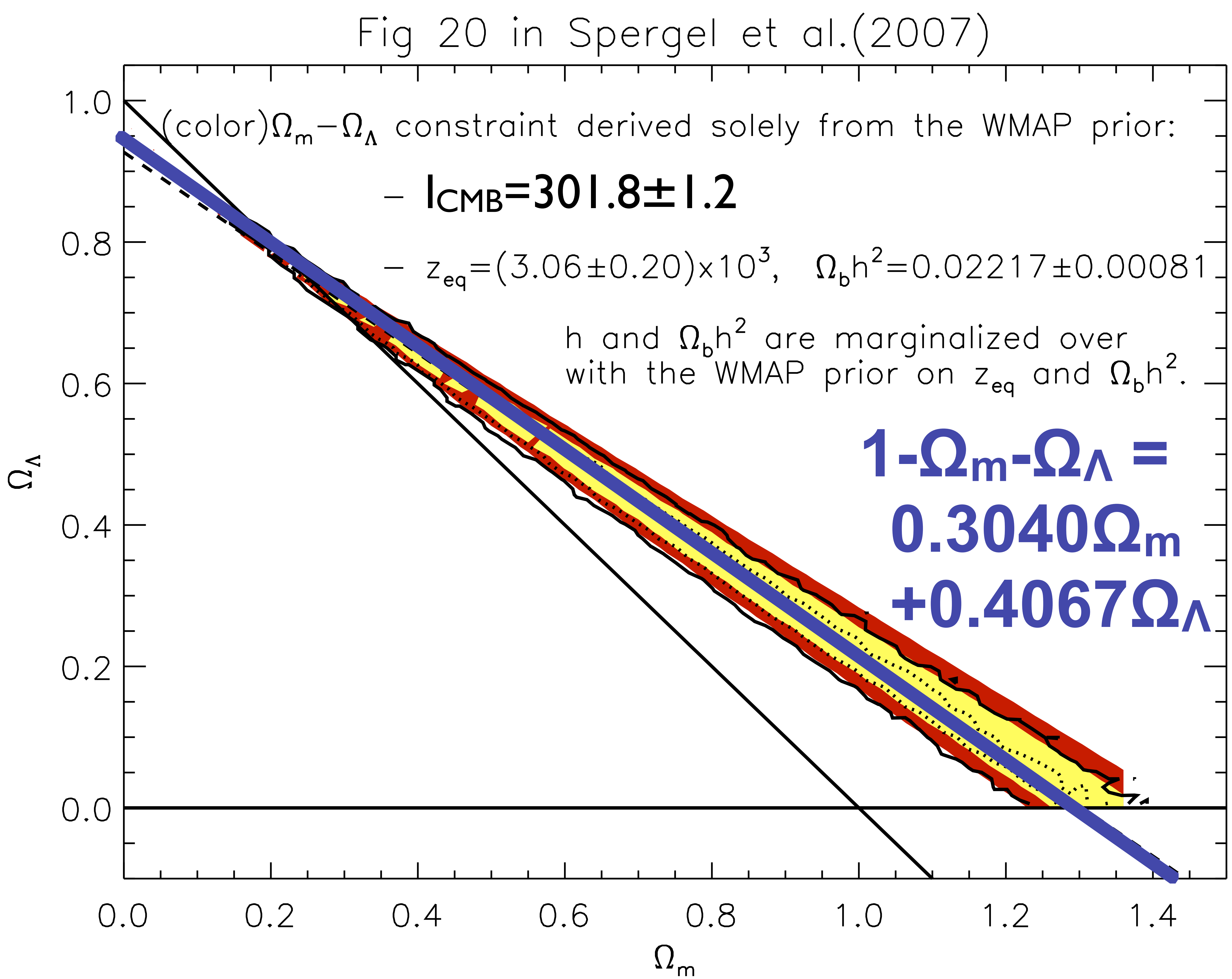




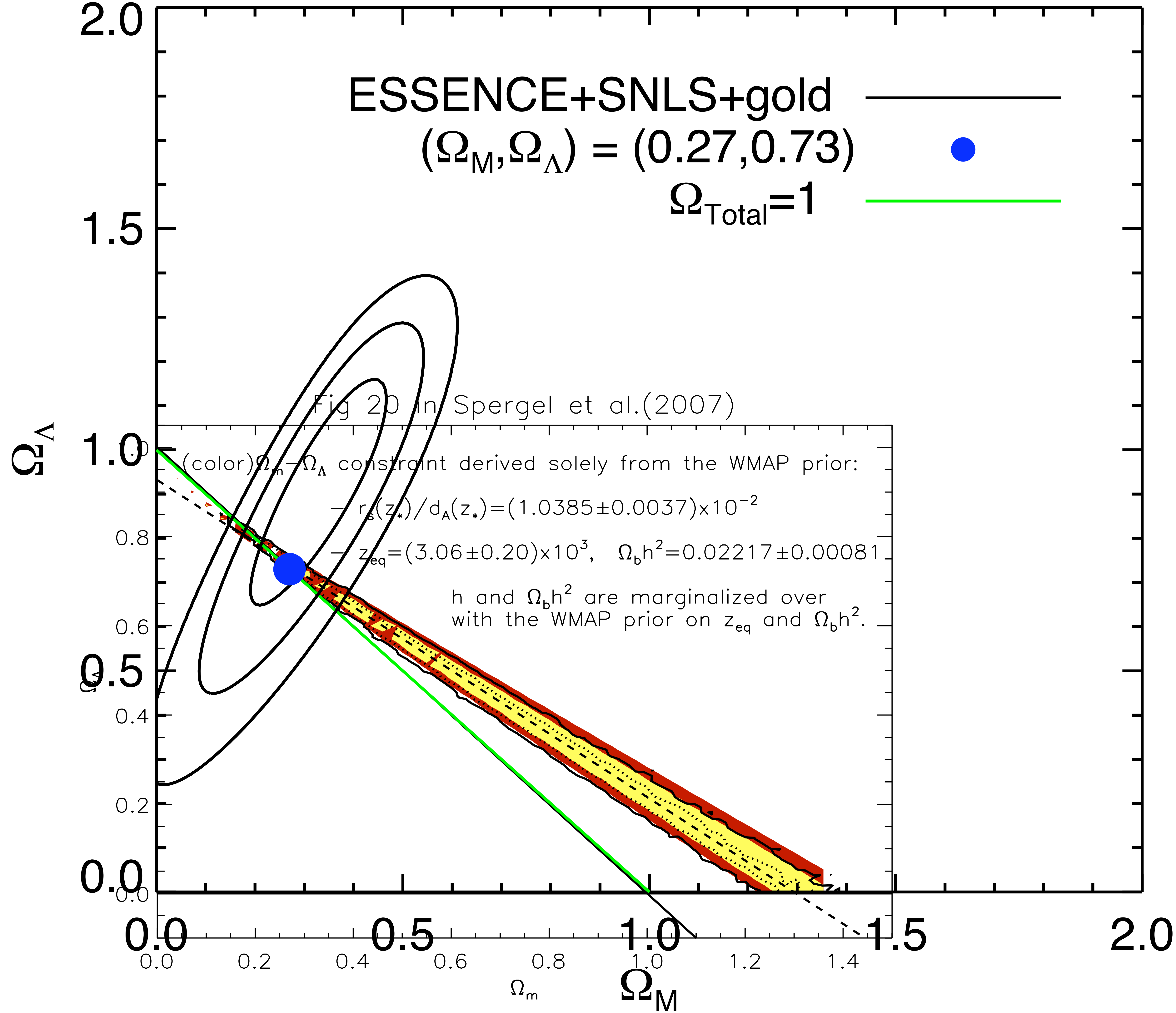
Hinshaw et al. (2007)

- 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



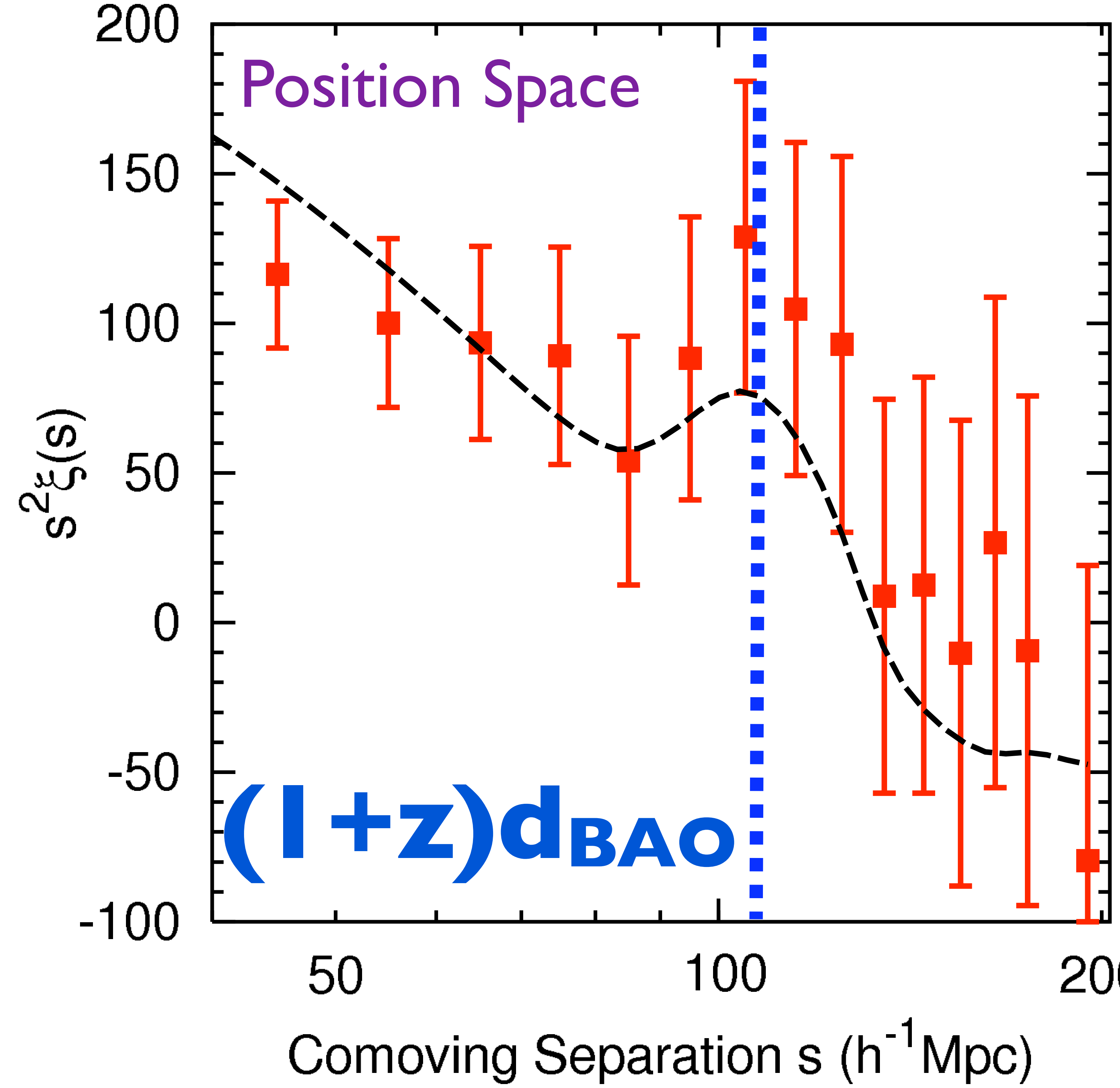
- Color: constraint from $l_{CMB}=\pi D_A(z_{CMB})/d_s(z_{CMB})$ with z_{EQ} & $\Omega_b h^2$.
- Black contours: Markov Chain from WMAP 3yr (Spergel et al. 2007)

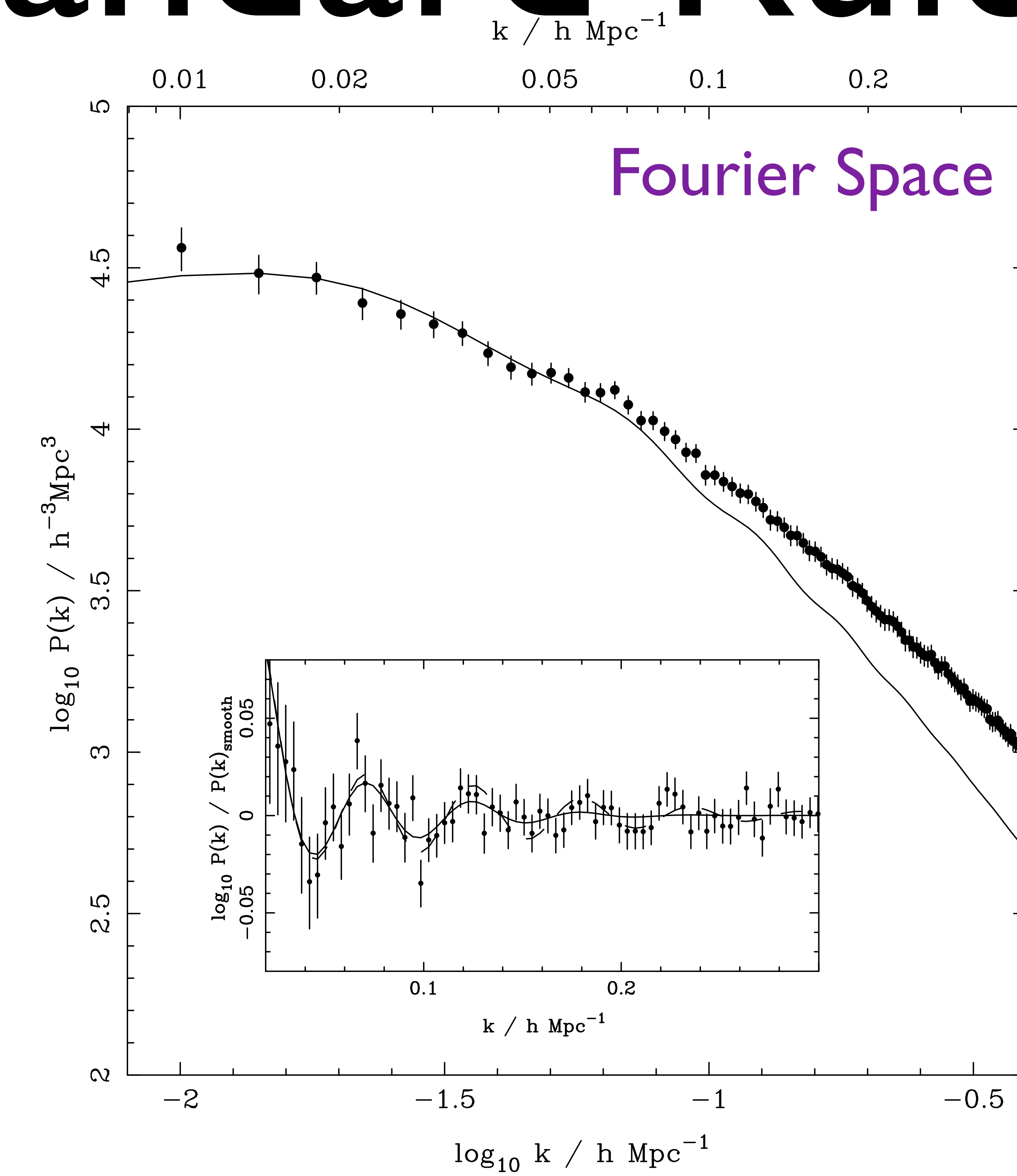


ESSENCE+SNLS+gold
(Ω_M,Ω_Λ) = (0.27,0.73)
Ω_Total=1
Fig 20 in Spergel et al.(2007)
(color)Ω_m−Ω_Λ constraint derived solely from the WMAP prior:
— r_s(z_*)/d_A(z_*)=(1.0385±0.0037)×10^−2
— z_eq=(3.06±0.20)×10^3, Ω_bh^2=0.02217±0.00081
h and Ω_bh^2 are marginalized over
with the WMAP prior on z_eq and Ω_bh^2.
Ω_Λ
Ω_M
Ω_m
0.0
0.5
1.0
1.5
2.0
0.2
0.4
0.6
0.8
1.2
1.4

BAO as a Standard Ruler

Okumura et al. (2007)





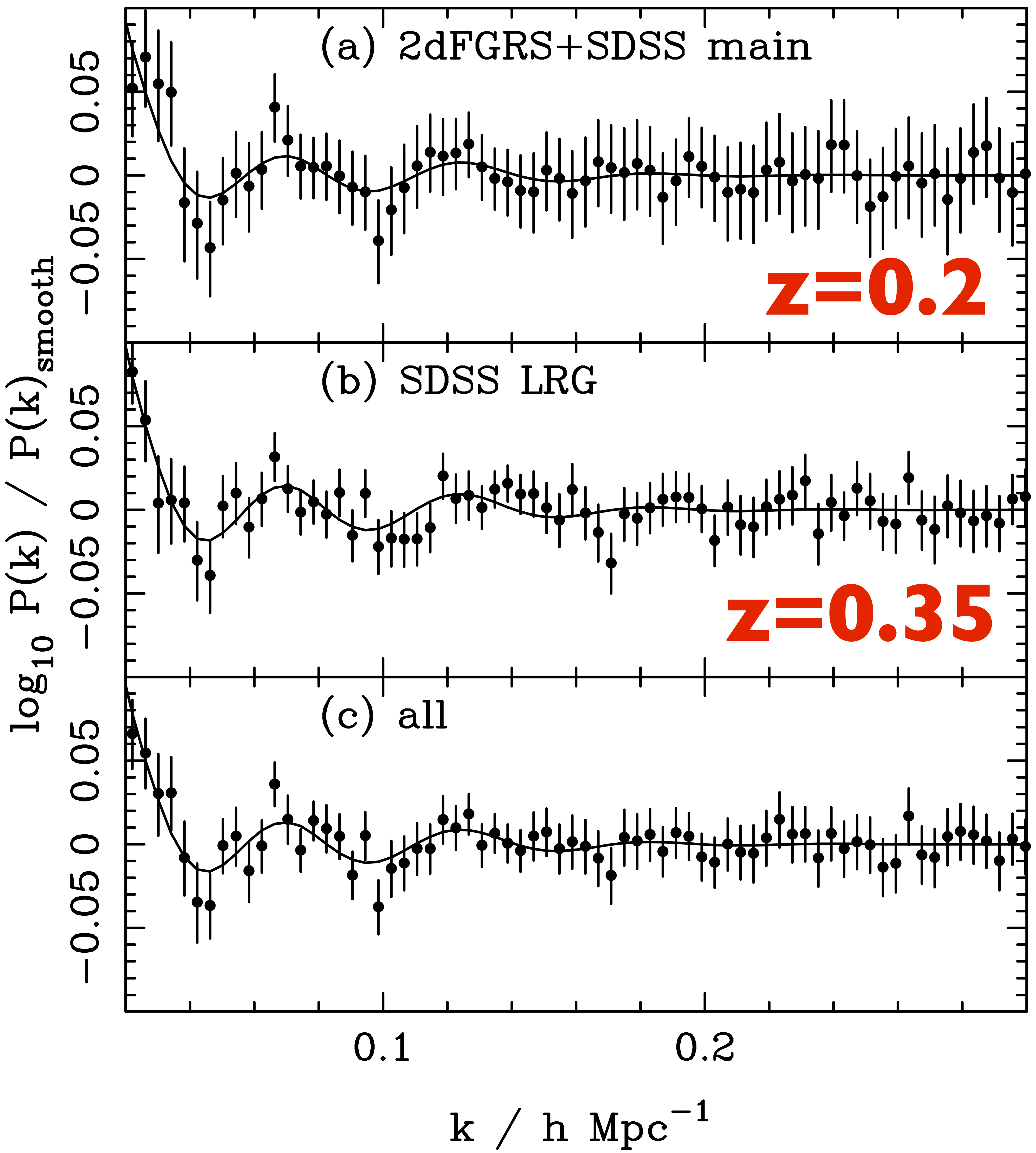
Percival et al. (2006)

- 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}**?

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, $d_{BAO} > d_{CMB}$)

The Latest BAO Measurements



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

Percival et al. (2007)

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

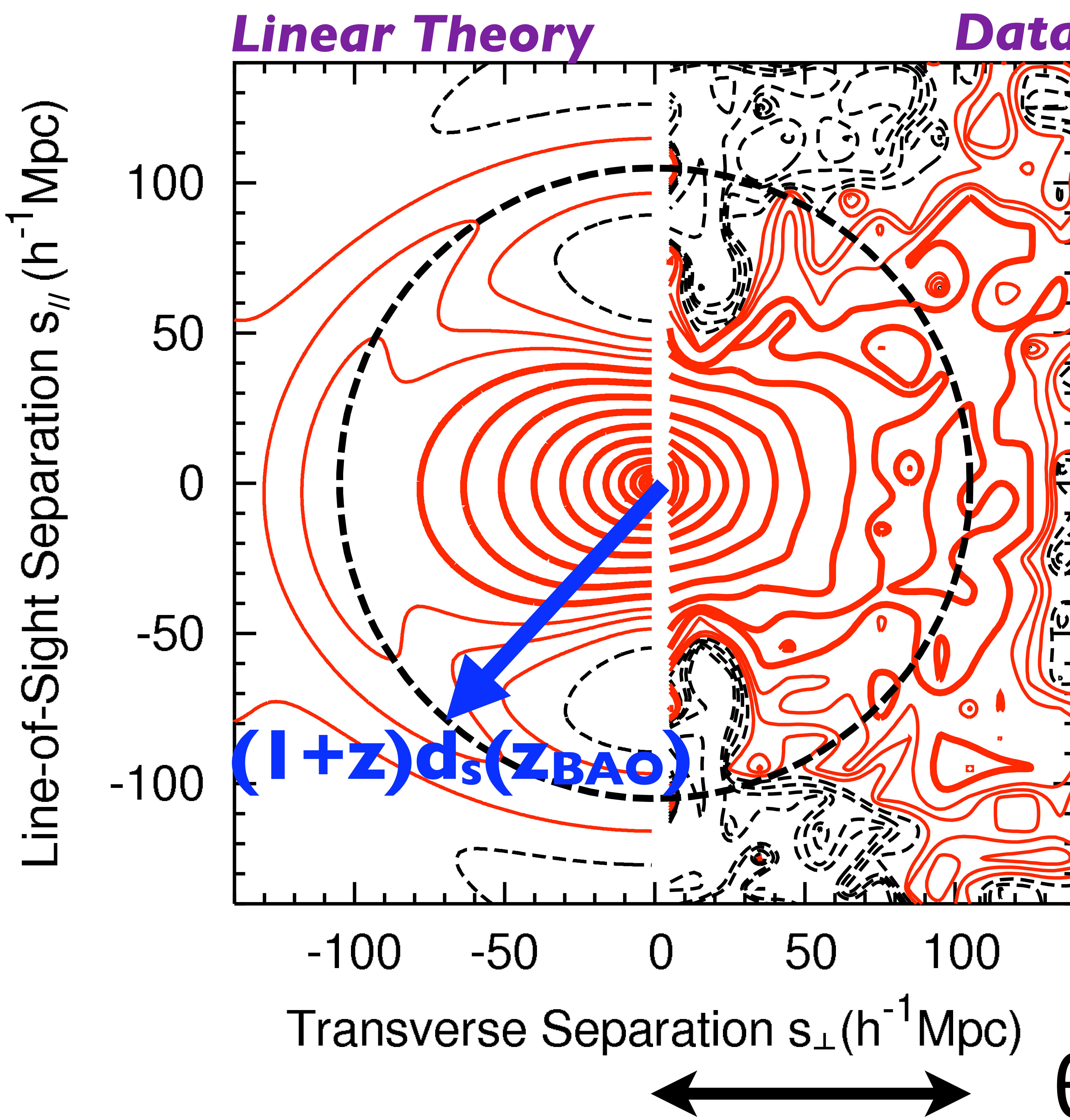
    => $D_A(z) = d_s(z_{BAO})/\theta$

  - BAO parallel to l.o.s

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

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

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

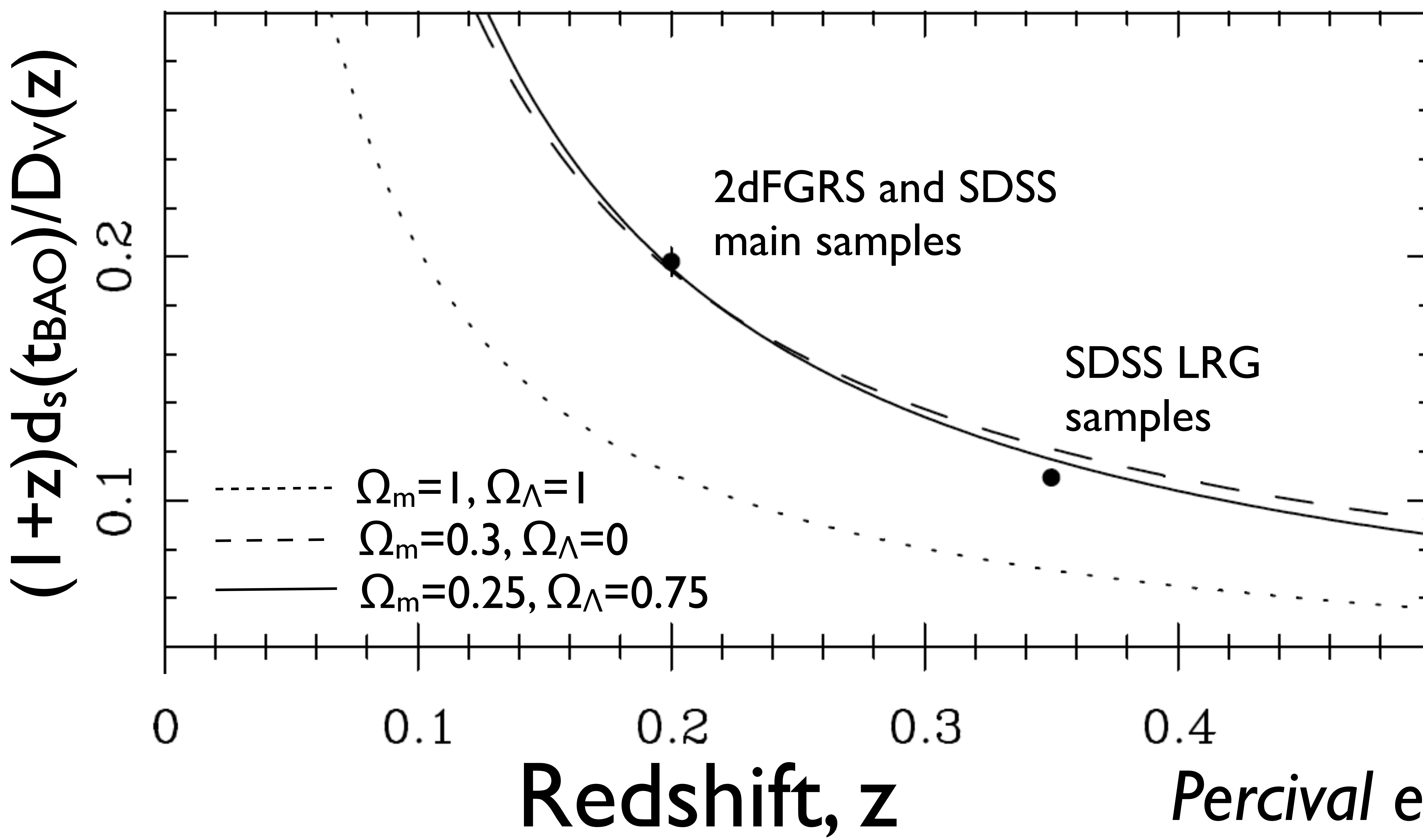


2D 2-pt function from the SDSS LRG samples (Okumura et al. 2007)

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

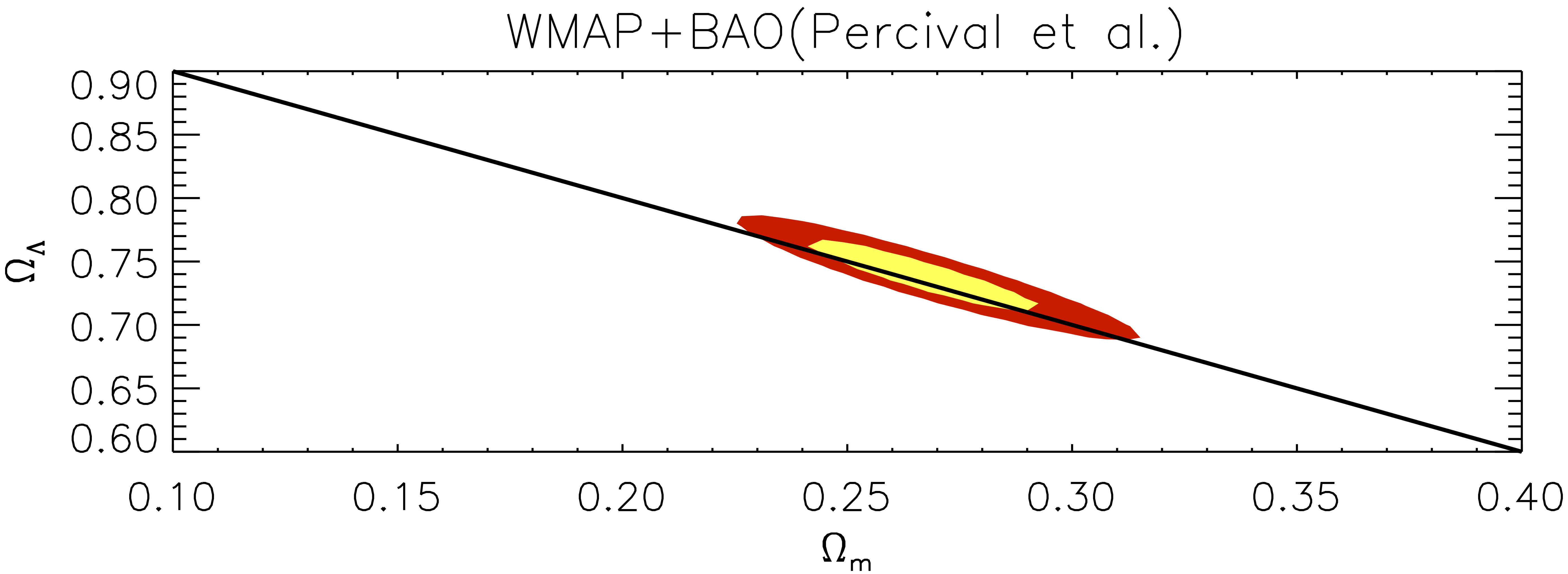
$$D_V(z) = \{(1+z)^2 D_A^2(z)[cz/H(z)]\}^{1/3}$$

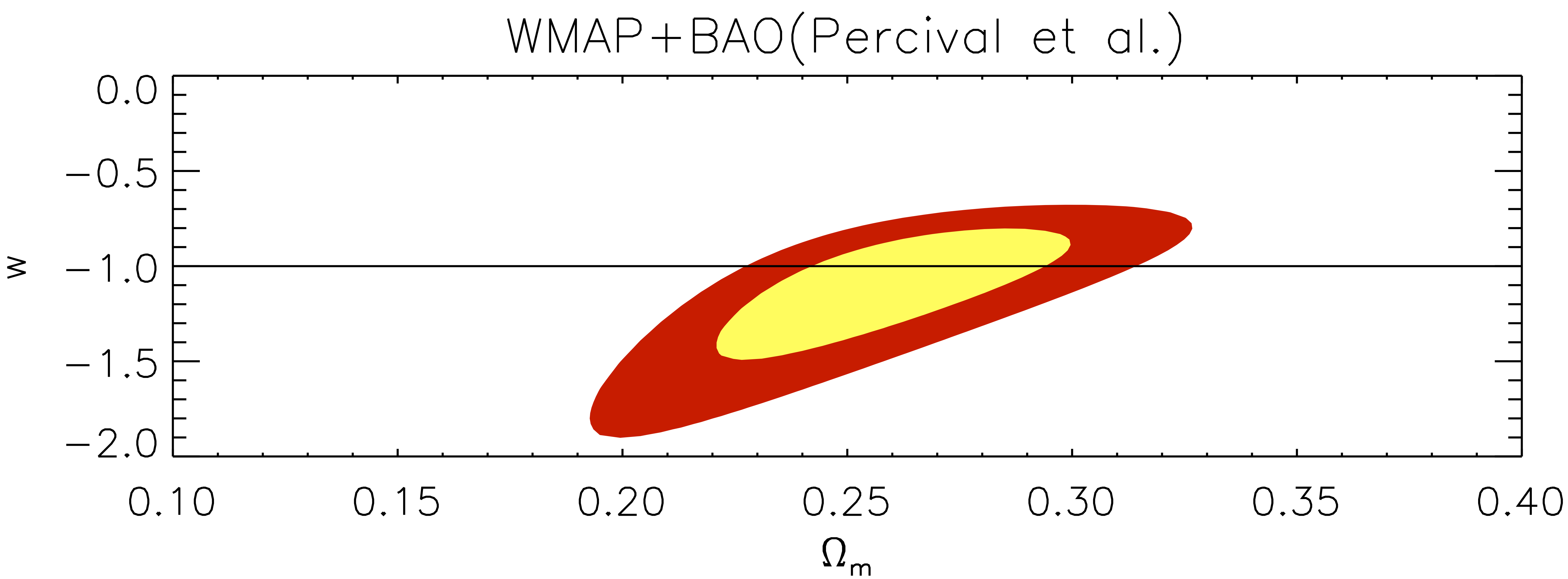
Since the current data are not good enough to constrain $D_A(z)$ and $H(z)$ separately, a combination distance, **$D_V(z)$**, has been constrained.



Percival et al. (2007)

CMB + BAO => Curvature



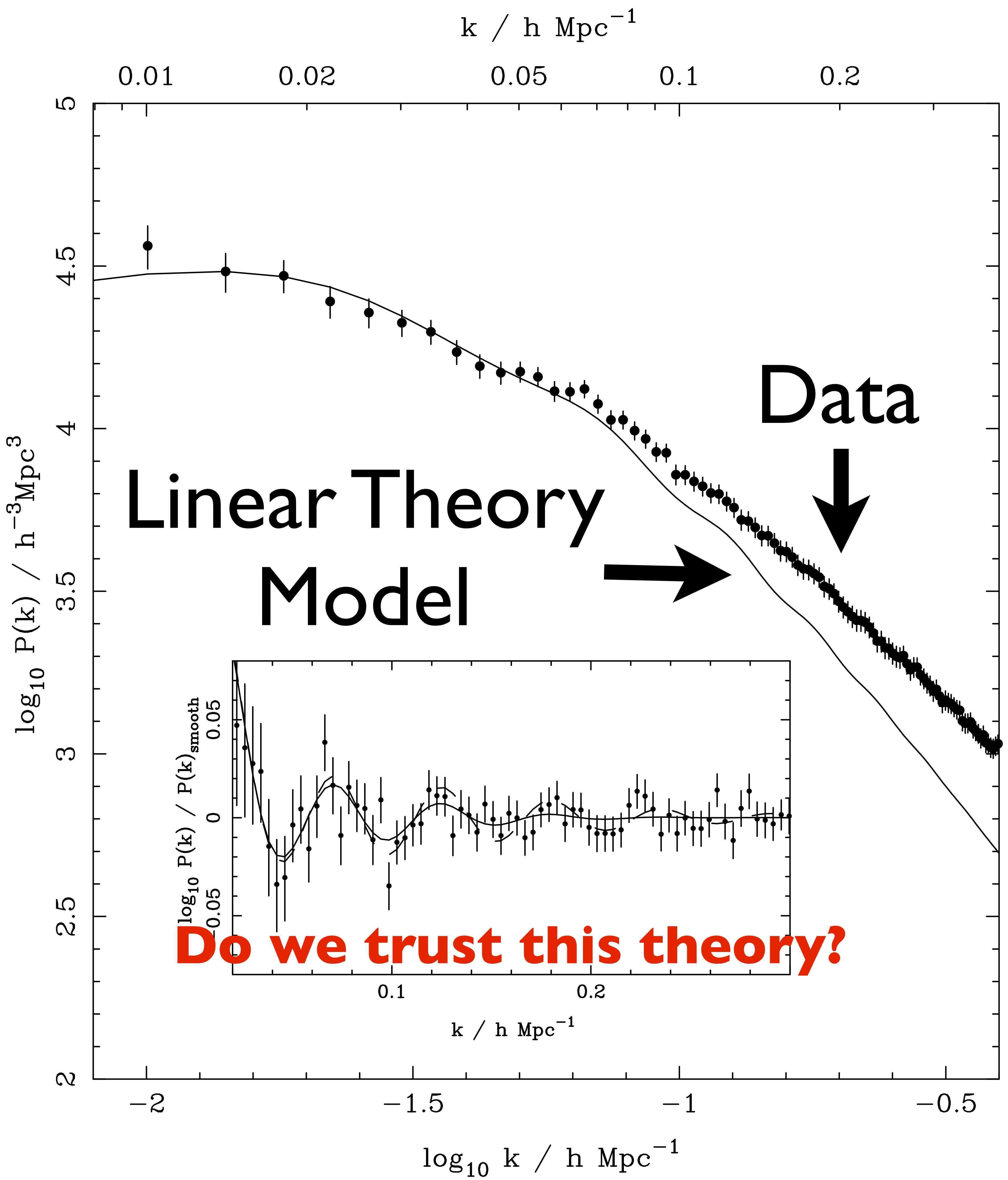


- Both CMB and BAO are **absolute** distance indicators.
- Type Ia supernovae only measure relative distances.
- CMB+BAO is the winner for measuring spatial curvature.

BAO: Current Status

- It's been measured from SDSS main/LRG and 2dFGRS.
- The successful extraction of distances demonstrated. (Eisenstein et al. 2005; Percival et al. 2007)
- CMB and BAO have constrained curvature to 2% level. (Spergel et al. 2007)
- BAO, CMB, and SN1a have been used to constrain various properties of DE successfully. (Many authors)

BAO: Challenges



- Non-linearity, Non-linearity, and Non-linearity!
  1. Non-linear clustering
  2. Non-linear galaxy bias
  3. Non-linear peculiar vel.
- Is our theory ready for the future precision data?

Toward Modeling Non-linearities

- Conventional approaches:
  - Use fitting functions to the numerical simulations
  - Use empirical "halo model" approaches
- Our approach:
  - The linear (1st-order) perturbation theory works beautifully. (Look at WMAP!) Let's go beyond that.
  - **The 3rd-order Perturbation Theory (PT)**

Is 3rd-order PT New?

- No, it's actually quite old. (25+ years)
- A lot of progress made in 1990s (Bernardeau et al. 2002 for a comprehensive review published in Phys. Report)
- However, it has never been applied to the real data, and it was almost forgotten. Why?
  - Non-linearities at z=0, for which the galaxy survey data are available today, are too strong to model by PT at any orders. **PT had been practically useless.**

Why 3rd-order PT Now?

- Now, the situation has changed, dramatically.
- The technology available today is ready to push the galaxy surveys to **higher redshifts**, i.e., z>1.
- Serious needs for such surveys exist: Dark Energy Task Force recommended BAO as the "cleanest" method for constraining the nature of Dark Energy.
- Proposal: **At z>1, non-linearities are much weaker. We should be able to use PT.**

Perturbation Theory "Reloaded"

- My message to those who have worked on the cosmological perturbation theory in the past but left the field thinking that there was no future in that direction...

Come Back Now!

Time Has Come!

Three Equations To Solve

- Focus on the clustering on large scales, where baryonic pressure is completely negligible.
- Ignore the shell-crossing of matter particles, which means that the velocity field is curl-free: rot*V*=0.
- We just have simple Newtonian fluid equations:

$$\dot{\delta} + \nabla \cdot [(1+\delta)\boldsymbol{v}] = 0$$

$$\dot{\boldsymbol{v}} + (\boldsymbol{v} \cdot \nabla)\,\boldsymbol{v} = -\frac{\dot{a}}{a}\boldsymbol{v} - \nabla\phi$$

$$\nabla^2\phi = 4\pi G a^2 \bar{\rho}\delta$$

In Fourier Space

$$
\begin{aligned}
&\dot{\delta}(\boldsymbol{k},\tau)+\theta(\boldsymbol{k},\tau) \\
= \quad & -\int \frac{d^3k_1}{(2\pi)^3}\int d^3k_2\delta_D(\boldsymbol{k}_1+\boldsymbol{k}_2-\boldsymbol{k})\frac{\boldsymbol{k}\cdot\boldsymbol{k}_1}{k_1^2}\delta(\boldsymbol{k}_2,\tau)\theta(\boldsymbol{k}_1,\tau), \\
&\dot{\theta}(\boldsymbol{k},\tau)+\frac{\dot{a}}{a}\theta(\boldsymbol{k},\tau)+\frac{3\dot{a}^2}{2a^2}\Omega_{\rm m}(\tau)\delta(\boldsymbol{k},\tau) \\
= \quad & -\int \frac{d^3k_1}{(2\pi)^3}\int d^3k_2\delta_D(\boldsymbol{k}_1+\boldsymbol{k}_2-\boldsymbol{k})\frac{k^2(\boldsymbol{k}_1\cdot\boldsymbol{k}_2)}{2k_1^2k_2^2}\theta(\boldsymbol{k}_1,\tau)\theta(\boldsymbol{k}_2,\tau)
\end{aligned}
$$

- Here, $\theta=\nabla\cdot\boldsymbol{v}$ is the "velocity divergence."

Taylor Expanding in δ_1

- δ_1 is the linear perturbation.

$$\delta(\boldsymbol{k},\tau)=\sum_{n=1}^{\infty}a^n(\tau)\int\frac{d^3q_1}{(2\pi)^3}\cdots\frac{d^3q_{n-1}}{(2\pi)^3}\int d^3q_n\delta_D(\sum_{i=1}^{n}\boldsymbol{q}_i-\boldsymbol{k})F_n(\boldsymbol{q}_1,\boldsymbol{q}_2,\cdots,\boldsymbol{q}_n)\delta_1(\boldsymbol{q}_1)\cdots\delta_1(\boldsymbol{q}_n),$$

$$\theta(\boldsymbol{k},\tau)=-\sum_{n=1}^{\infty}\dot{a}(\tau)a^{n-1}(\tau)\int\frac{d^3q_1}{(2\pi)^3}\cdots\frac{d^3q_{n-1}}{(2\pi)^3}\int d^3q_n\delta_D(\sum_{i=1}^{n}\boldsymbol{q}_i-\boldsymbol{k})G_n(\boldsymbol{q}_1,\boldsymbol{q}_2,\cdots,\boldsymbol{q}_n)\delta_1(\boldsymbol{q}_1)\cdots\delta_1(\boldsymbol{q}_n)$$

Collect Terms Up To δ_1^3

- $\delta=\delta_1+\delta_2+\delta_3$, where $\delta_2=O(\delta_1^2)$ and $\delta_3=O(\delta_1^3)$.
- The power spectrum, $P(k)=$**$P_L(k)$**$+$**$P_{22}(k)$**$+2$**$P_{13}(k)$**, is given by

$$
\begin{aligned}
&(2\pi)^3 P(k)\delta_D(\boldsymbol{k}+\boldsymbol{k}')\\
&\equiv \langle\delta(\boldsymbol{k},\tau)\delta(\boldsymbol{k}',\tau)\rangle\\
&= \underbrace{\langle\delta_1(\boldsymbol{k},\tau)\delta_1(\boldsymbol{k}',\tau)\rangle}_{P_L} + \langle\delta_2(\boldsymbol{k},\tau)\delta_1(\boldsymbol{k}',\tau)+\delta_1(\boldsymbol{k},\tau)\delta_2(\boldsymbol{k}',\tau)\rangle\\
&\quad + \langle\underbrace{\delta_1(\boldsymbol{k},\tau)\delta_3(\boldsymbol{k}',\tau)}_{P_{13}}+\underbrace{\delta_2(\boldsymbol{k},\tau)\delta_2(\boldsymbol{k}',\tau)}_{P_{22}}+\underbrace{\delta_3(\boldsymbol{k},\tau)\delta_1(\boldsymbol{k}',\tau)}_{P_{13}}\rangle\\
&\quad + \mathcal{O}(\delta_1^6)
\end{aligned}
$$

Odd powers in δ_1 vanish (Gaussianity)

Vishniac (1983); Fry (1984); Goroff et al. (1986); Suto&Sasaki (1991); Makino et al. (1992); Jain&Bertschinger (1994); Scoccimarro&Frieman (1996)

P(k): 3rd-order Solution

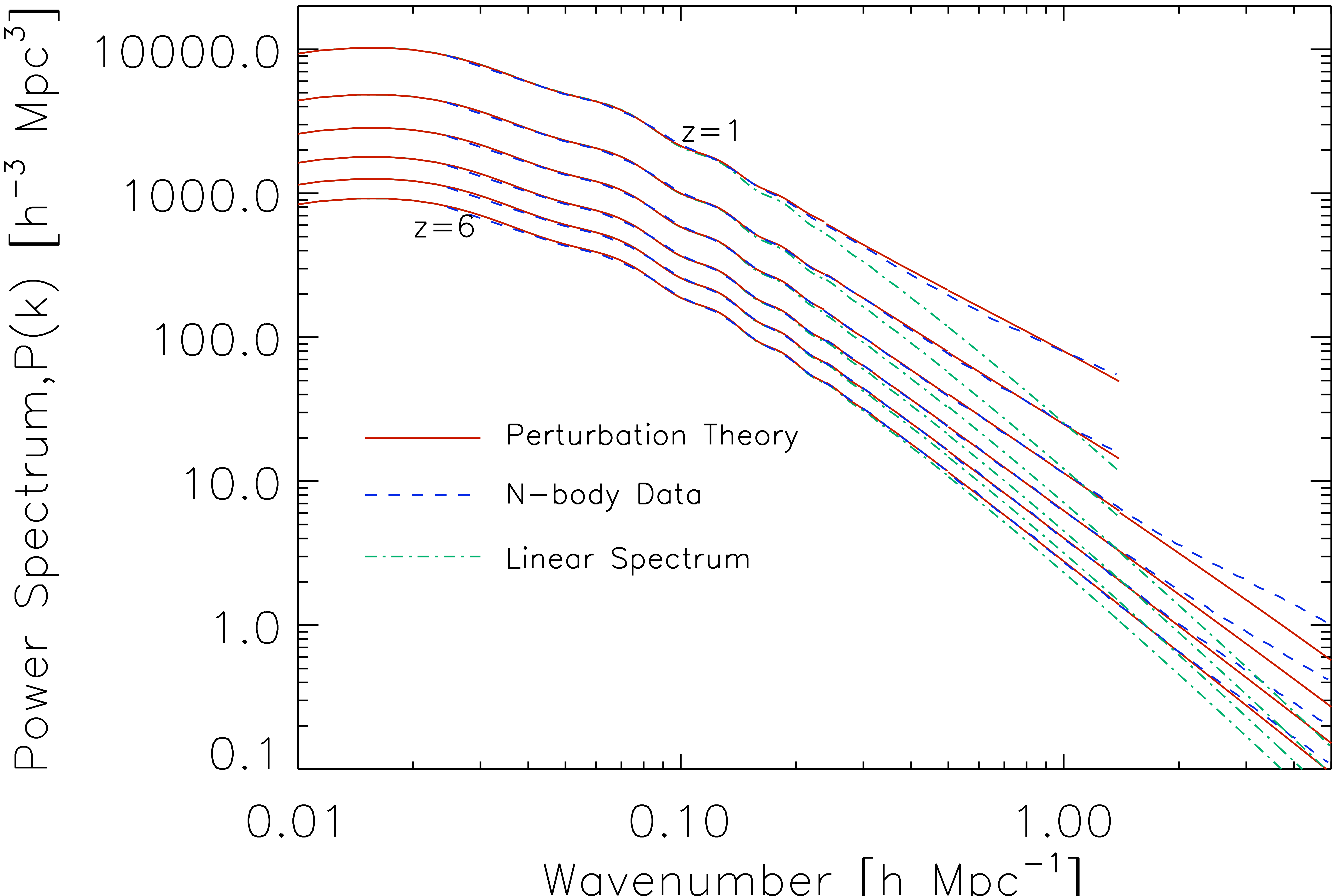
$$P_{22}(k) = 2\int \frac{d^3q}{(2\pi)^3} P_L(q) P_L(|\boldsymbol{k}-\boldsymbol{q}|) \left[F_2^{(s)}(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q})\right]^2$$

$$\begin{aligned} 2P_{13}(k) &= \frac{2\pi k^2}{252} P_L(k) \int_0^\infty \frac{dq}{(2\pi)^3} P_L(q) \\ &\times \left[100\frac{q^2}{k^2} - 158 + 12\frac{k^2}{q^2} - 42\frac{q^4}{k^4}\right. \\ &+ \left.\frac{3}{k^5 q^3}(q^2-k^2)^3(2k^2+7q^2)\ln\left(\frac{k+q}{|k-q|}\right)\right] \end{aligned}$$

- $F_2^{(s)}$ is the known function. (Goroff et al. 1986)

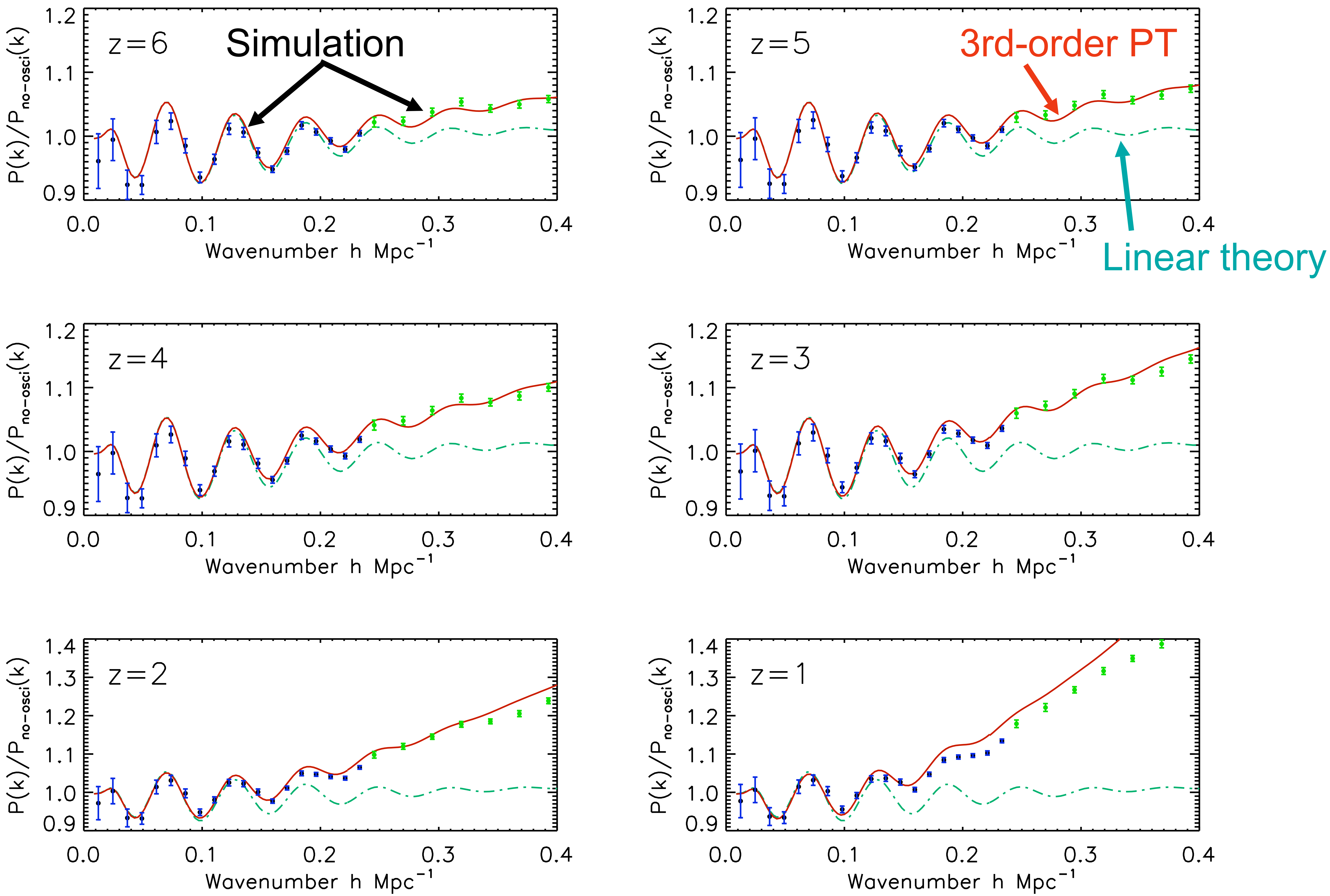
Jeong & Komatsu (2006)

3rd-order PT vs Simulations



Jeong & Komatsu (2006)

Distortions on BAO



A Quote: P. McDonald (2006)

"...this perturbative approach to the galaxy power spectrum (including beyond-linear corrections) has not to my knowledge actually been used to interpret real data. However, between improvements in perturbation theory and the need to interpret increasingly precise observations, the time for this kind of approach may have arrived (*Jeong & Komatsu, 2006*)."

How About Galaxies?

- But, I am sure that you are not impressed yet...
- What we measure is the *galaxy* power spectrum.
  - Who cares about the *matter* power spectrum?
- How can we make it work for galaxies?

Locality Assumption

- Galaxies are biased tracers of the underlying matter distribution. How biased are they?
- Usual "linear bias" model: $P_g(k)=b_l^2 P(k)$, where b_l (linear bias) is a constant multiplicative factor.
- How do we extend this to non-linear cases?
- Assumption: **the galaxy formation process is a local process**, at least on the large scales that we care about.

Gaztanaga & Fry (1993); McDonald (2006)

Taylor Expanding δ_g in δ

$$\delta_g(x) = c_1\delta(x) + c_2\delta^2(x) + c_3\delta^3(x) + O(\delta^4) + \varepsilon(x)$$

where δ is the non-linear matter fluctuations, and ε is the stochastic "noise," which is uncorrelated with matter density fluctuations: $\langle\delta(x)\varepsilon(x)\rangle=0$.

- This is "local," in the sense that they are all evaluated at the same spatial location, x.
- The locality assumption must break down at a certain point. So, we only care about the scales on which the locality is a good approximation.

McDonald (2006)

Galaxy Power Spectrum

$$P_g(k) = N + b_1^2 \left[P(k) + \frac{b_2^2}{2} \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} P(q) \left[P(|\boldsymbol{k} - \boldsymbol{q}|) - P(q) \right] \right.$$
$$\left. + 2b_2 \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} P(q) P(|\boldsymbol{k} - \boldsymbol{q}|) F_2^{(s)}(\boldsymbol{q}, \boldsymbol{k} - \boldsymbol{q}) \right]$$

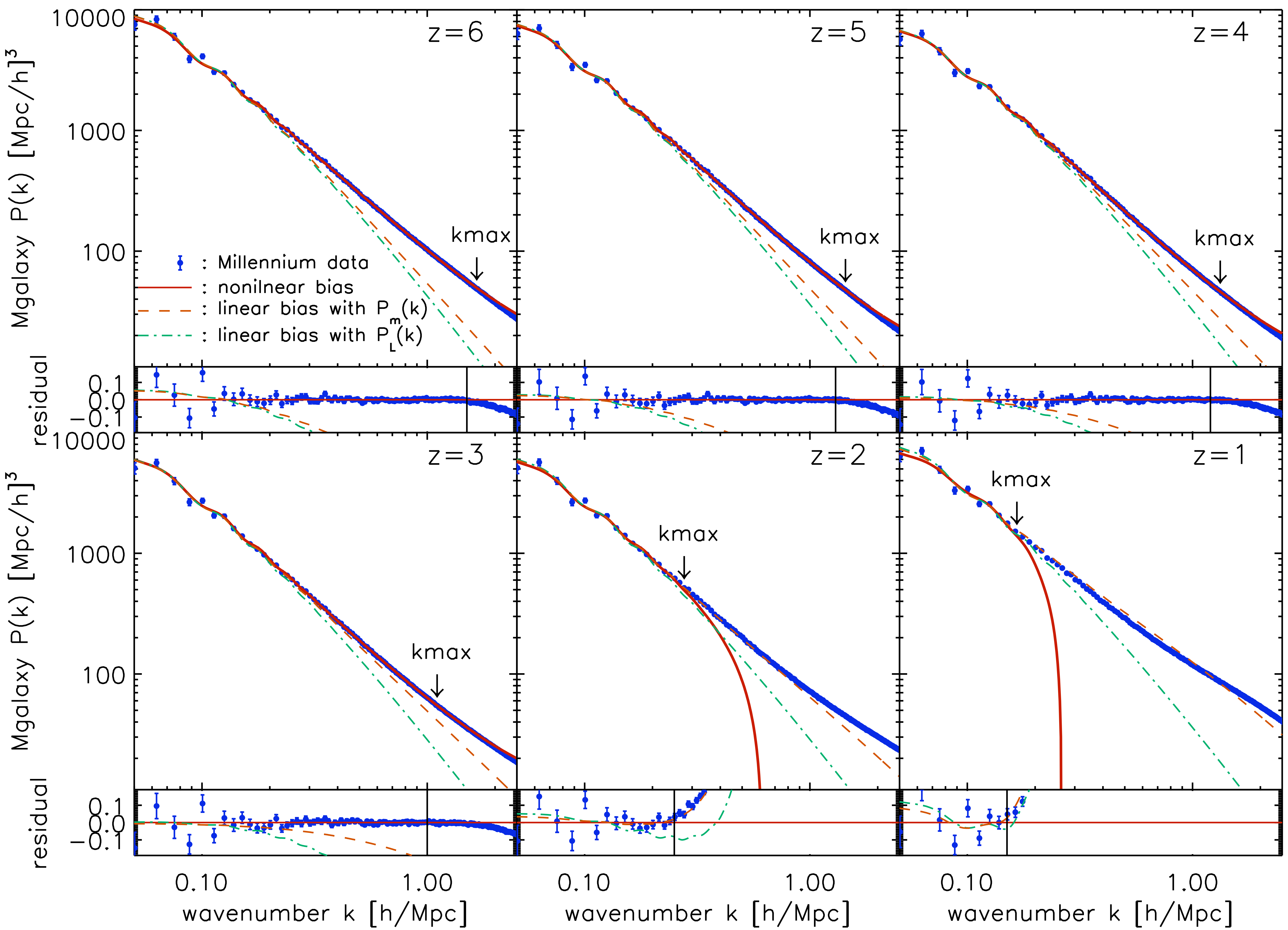
- Bias parameters, b_1, b_2, & N, are related to c_1, c_2, & c_3.
- They capture information about galaxy formation, but we are not interested in that.
- Instead, we will marginalize over b_1, b_2, & N.

Millennium "Galaxy" Simulations

- Now, we want to test the analytical model with cosmological simulations of galaxies.
- However, there aren't any *ab-initio* cosmological simulations of galaxies yet.
- The best available today: the Millennium Simulation (Springel et al. 2005), coupled with the semi-analytical galaxy formation codes.
    - MPA code: De Lucia & Blaizot (2007)
    - Durham code: Croton et al. (2006)

Jeong & Komatsu (2007)

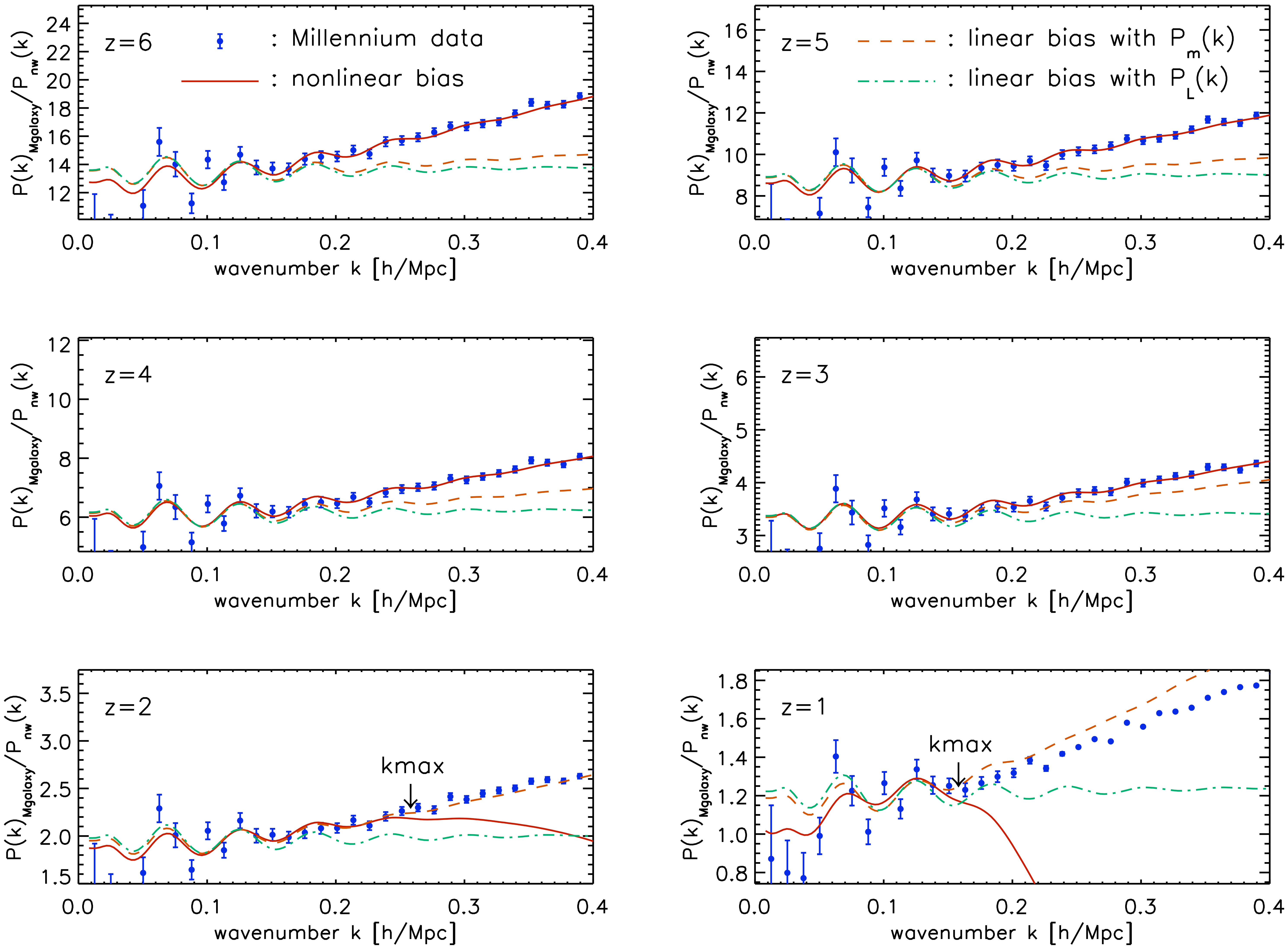
3PT vs MPA Galaxies



- k_{max} is where the 3rd-order PT fails to fit the matter power spectrum.
- This is also where we stop using the data for fitting the bias parameters.
- Non-linear bias model is clearly better at $k<k_{max}$.

Jeong & Komatsu (2007)

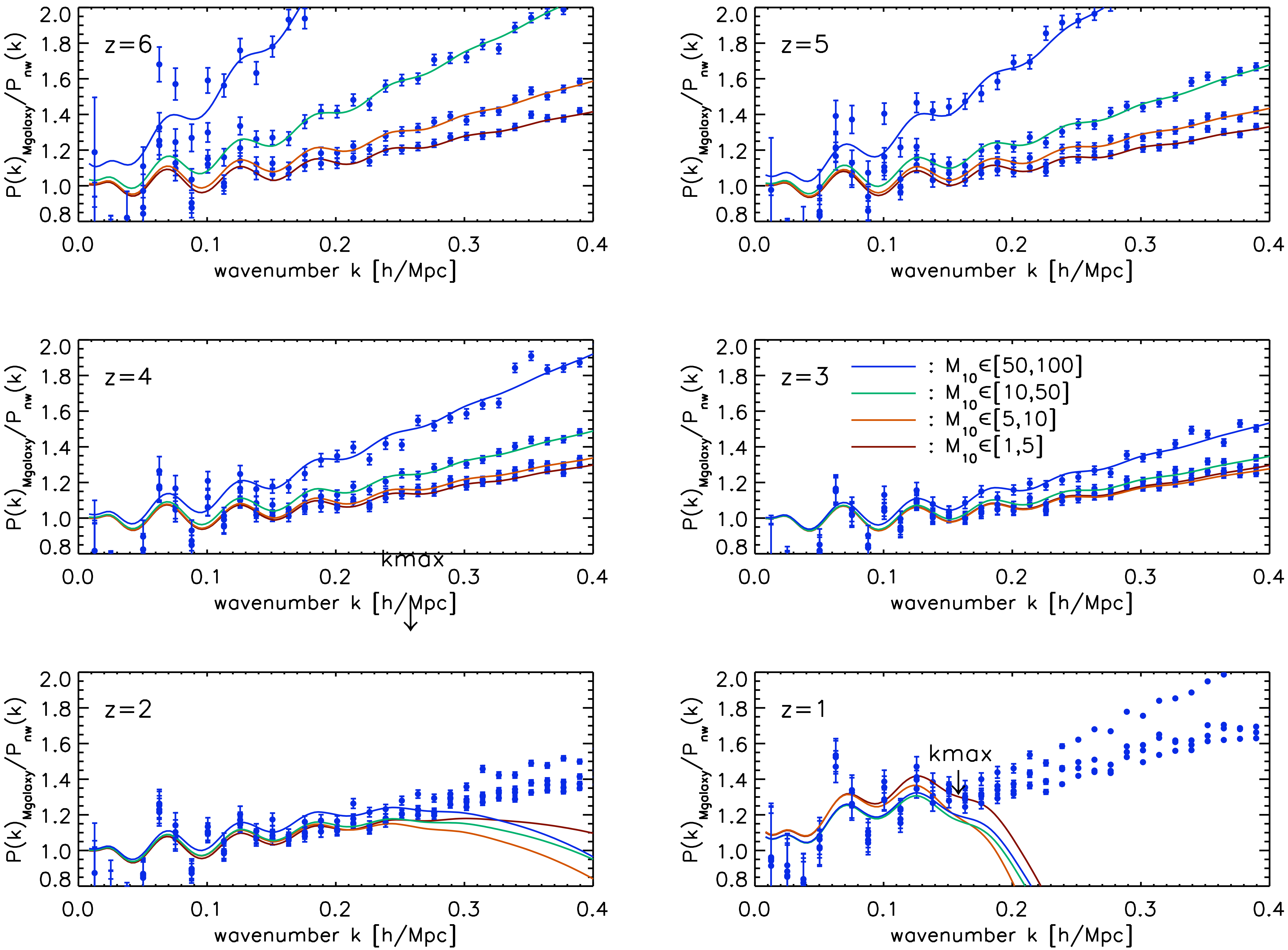
Non-linear Bias on BAO



- It is quite clear that the non-linear bias is important on the BAO scale.
- The Millennium Simulation's box size (500 Mpc)^3 is not very large.
- A large sampling variance on the BAO scale.

Jeong & Komatsu (2007)

Effects of Galaxy Mass



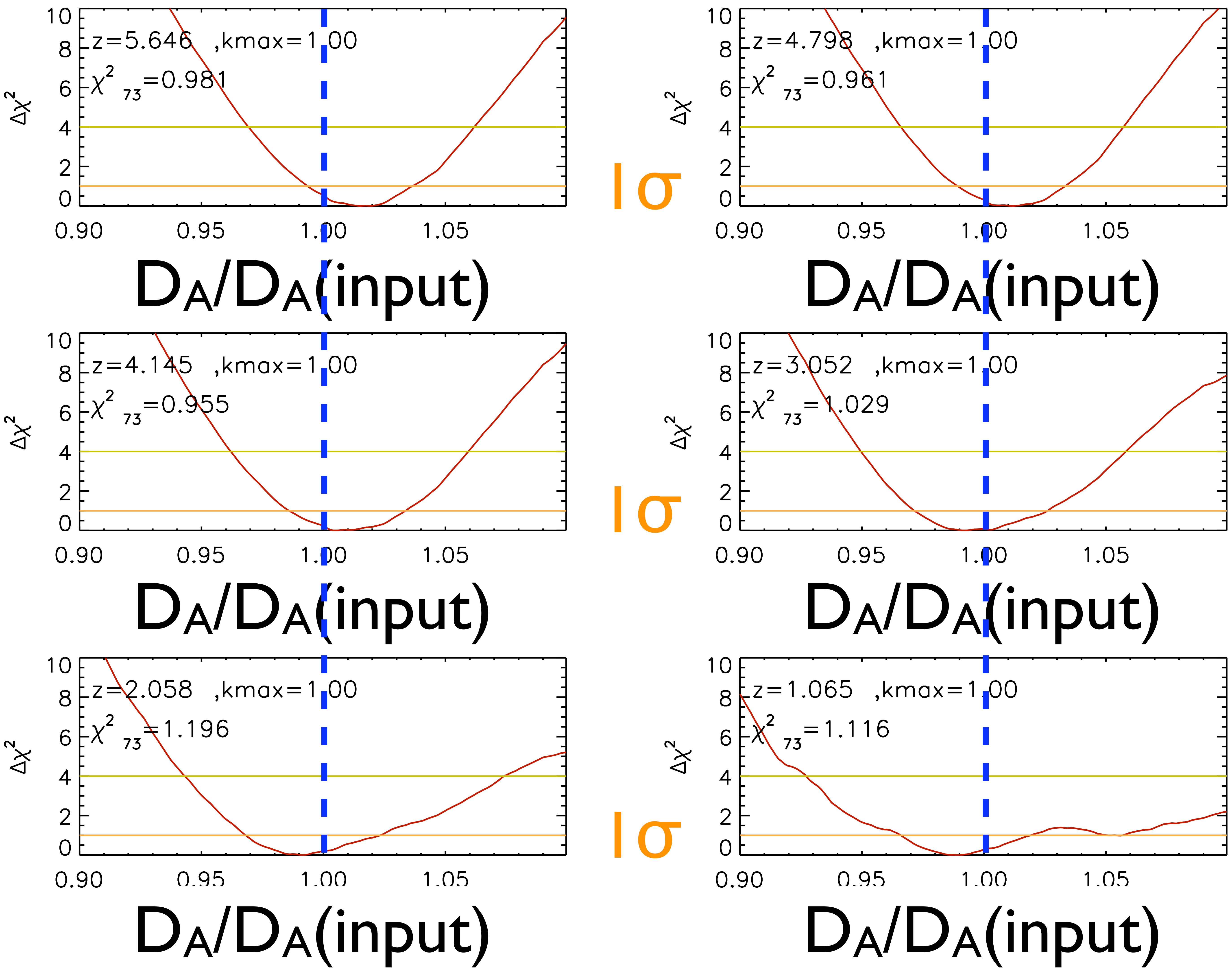
- The effects of galaxy masses: the higher the mass is, the higher and more non-linear the bias becomes.
- The model fits the data regardless of the galaxy masses.
- Higher bias does **not** spoil PT!

"So What?," You Asked...

- I am sure that you are still underwhelmed, thinking "**You have 3 parameters! I can fit anything with 3 parameters!**" You are not alone.
- "*With four parameters I can fit an elephant, and with five I can make him wiggle his trunk.*" - John von Neumann
- Our goal is to answer this question, "**After all this mess, can we recover the correct $D_A(z)$ and $H(z)$ from the galaxy power spectrum?**"

Jeong & Komatsu (2007)

Extracting $D_A(z)$ from $P_g(k)$



- **Conclusion**

  We could extract $D_A(z)$ from the Millennium "Galaxy" Simulation successfully, at z>2.

  (The bias parameters are marginalized over.)

- z=1 is still a challenge.

Where Are We Now?

- Non-linear clustering is under control at z>2.
- Non-linear galaxy bias seems under control, as long as the underlying matter power spectrum is under control.
- Extraction of distances from $P_g(k)$ demonstrated explicitly with the best simulation available today.

What Needs To Be Done?

- Understand non-linear clustering at z=1.
  - Recent new developments, "renormalized PT," by Crocce&Scoccimarro; Matarrese&Pietroni; Velageas; Taruya; Matsubara.
- Run larger galaxy simulations for better statistics.
- Do the same thing for the bispectrum (three-point function), which improves the determinations of bias significantly (Sefusatti & Komatsu 2007). [on-going]

Three-point Function

- The 3pt function (the so-called reduced bispectrum) depends on the bias parameters as

$$Q_g(k_1,k_2,k_3)=(1/\mathbf{b_1})[Q_m(k_1,k_2,k_3)+\mathbf{b_2}]$$

The matter bispectrum, Q_m, is computed from PT.

- This method has been applied to 2dFGRS. (Verde et al. 2002): At z=0.17, b_1=1.04 ± 0.11; b_2=-0.054 ± 0.08

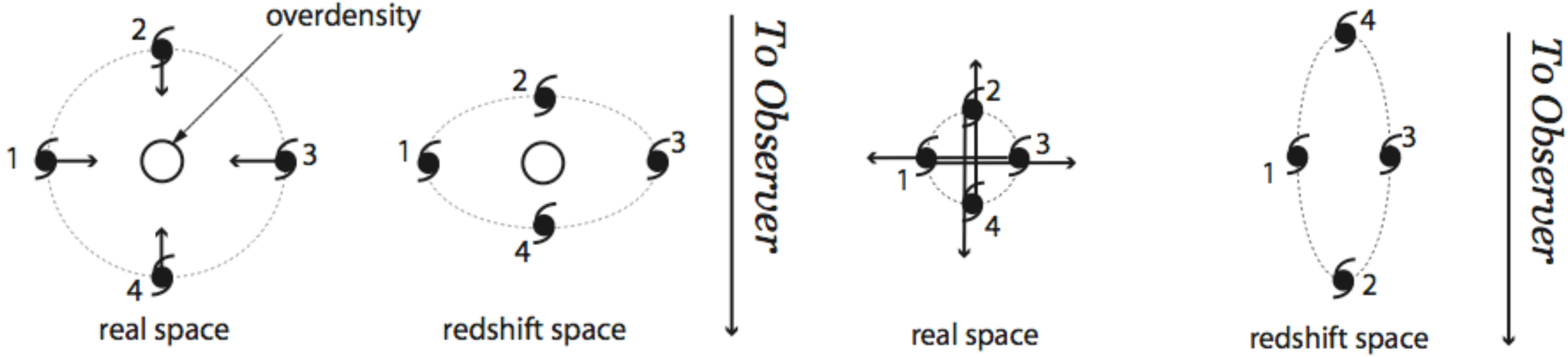
- For high-z surveys, we can improve the accuracy by an order of magnitude. (Sefusatti & Komatsu 2007)

- The bispectrum gives us a very important cross-check of the accuracy of bias parameters extracted from $P_g(k)$.

The Major Challenge

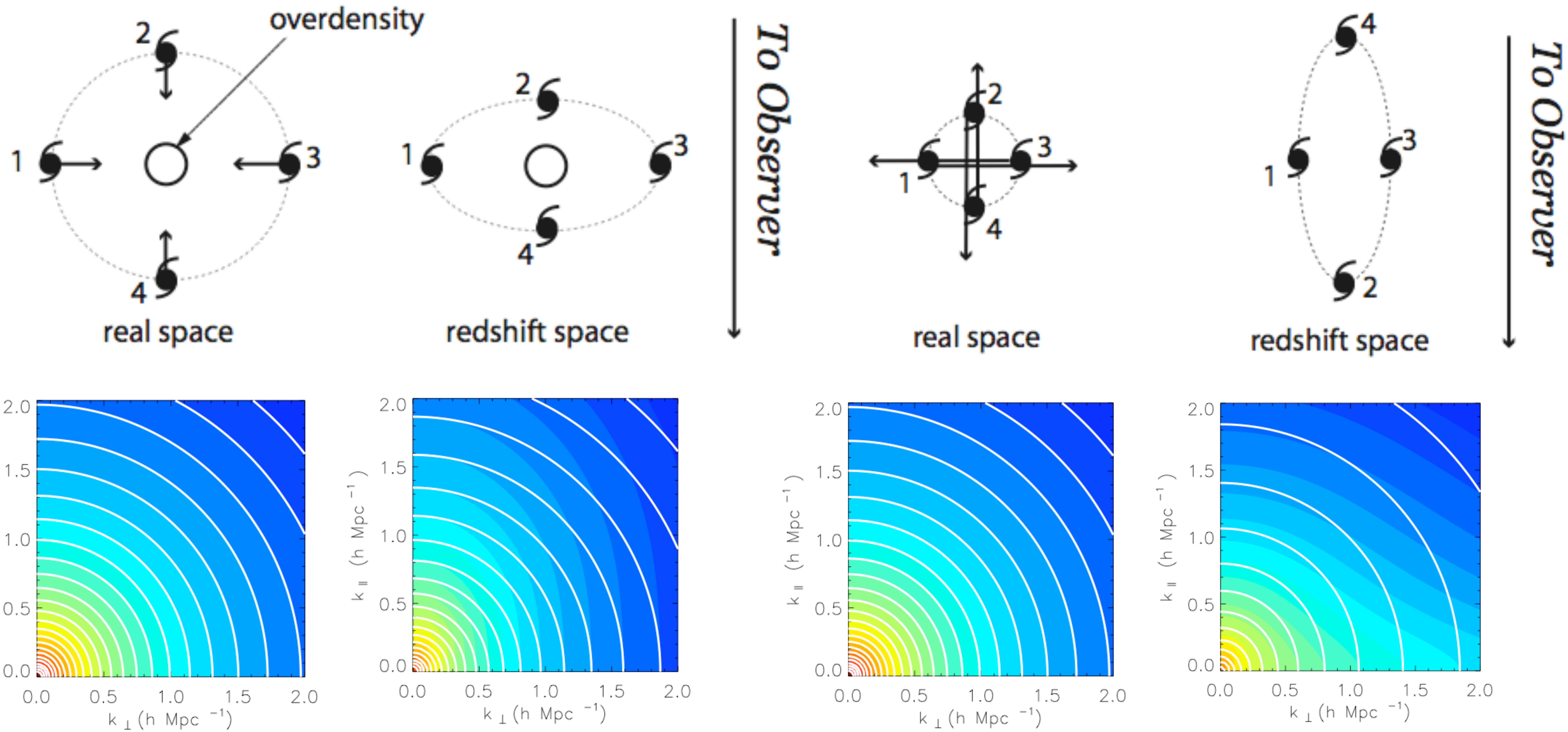
- I do not have much time to talk about this, but the most challenging task is to get the peculiar velocity effect, called "redshift space distortion," under control.
- Understanding this is essential for measuring H(z).
- There is no rigorous PT solution to this problem now, except for some empirical fitting approaches.
- Theoretical breakthrough is required here.

Redshift Space Distortion



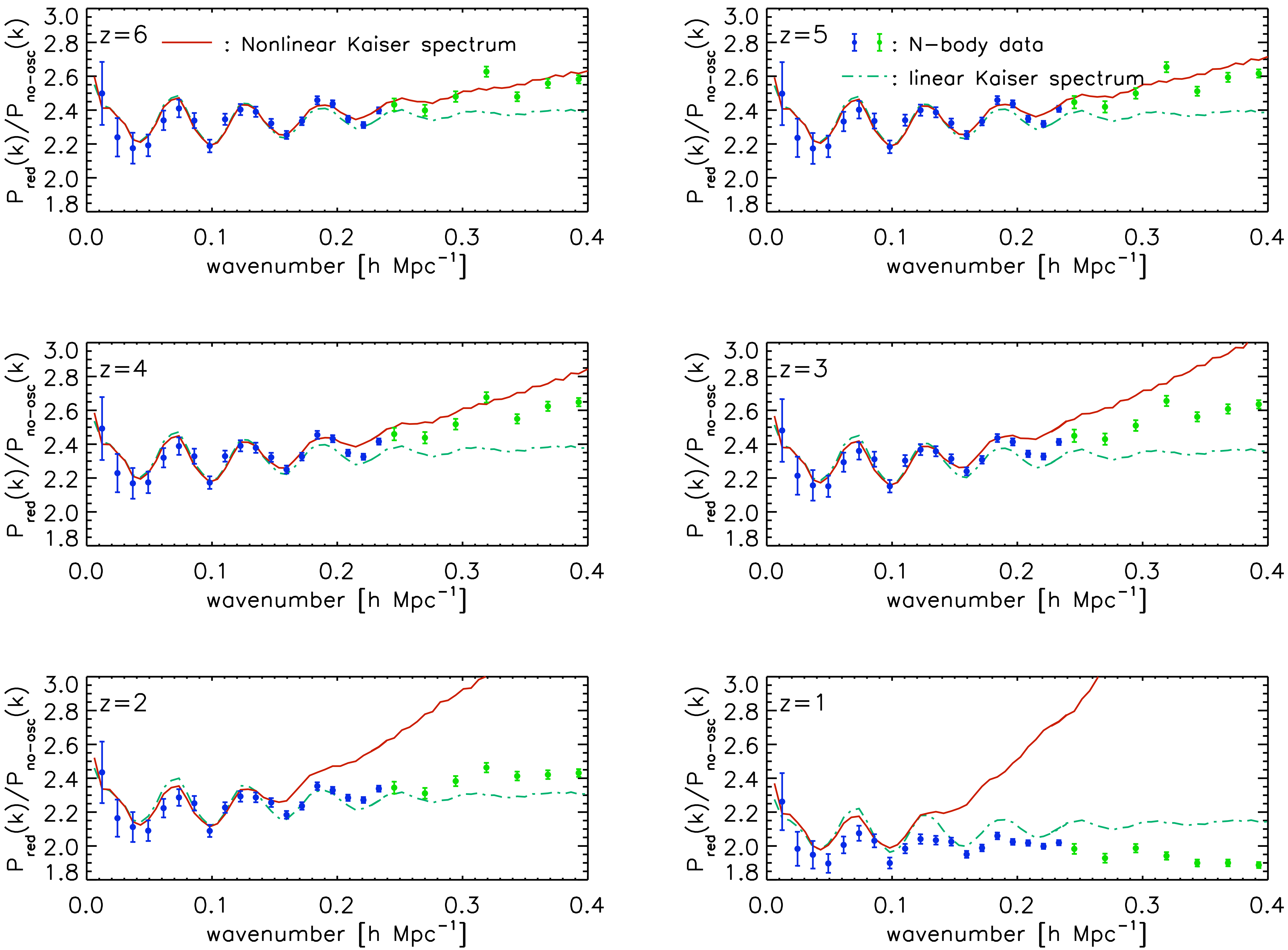
- (Left) Coherent flow => clustering **enhanced** along l.o.s
  - "Kaiser" effect
- (Right) Virial motion => clustering **reduced** along l.o.s.
  - "Finger-of-God" effect

Redshift Space Distortion



Current State of $PT_{\text{redshift space}}$

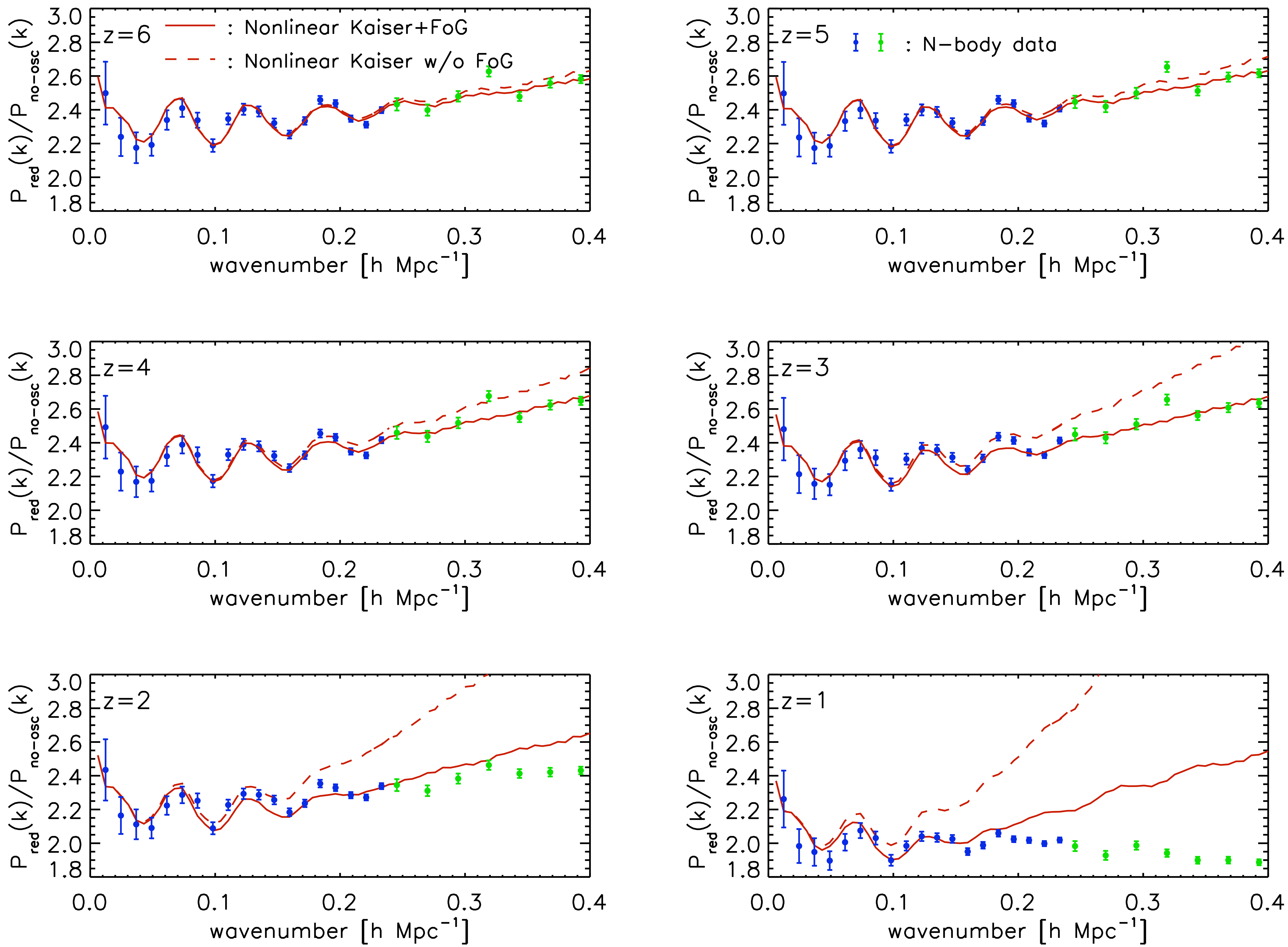
- The non-linear Kaiser effect is modeled by PT well (see z=5&6)
- However, the theory prediction fails badly, even at z=3.
- The theory overestimates the power => the power suppression due to the Finger-of-God.



Current State of PT redshift space

- Here, the Finger-of-God is parameterized by the velocity dispersion, which is treated as an unknown parameter.

- We need a better way to model this without parameters.



Where Are We Going?

- BAO Experiments: Ground-based *spectroscopic* surveys ["low-z" = z<1; "mid-z" = 1<z<2; "high-z" = z>2]
    - Wiggle-Z (Australia): AAT/AAOmega, on-going, low-z
    - FastSound (Japan): Subaru/FMOS, 2008, mid-z (Hα)
    - BOSS (USA): SDSS-III, 2009, low-z (LRG); high-z (LyαF)
    - HETDEX (USA): HET/VIRUS, 2011, high-z (LyαE)
    - WFMOS (Japan+?): >2011, low-z (OII); high-z (LBG)

Where Are We Going?

- BAO Experiments: Space-borne *spectroscopic* surveys
  - SPACE (Europe): >2015, all-sky, z~1 (Hα)
  - ADEPT (USA): >2017, all-sky, z~1 (Hα)
  - CIP (USA): >2017, 140 deg^2, $3<z<6$ (Hα)
- These are Dark Energy Task Force "Stage IV" experiments. (Ie, DE constraints >10x better than now.)

Where Is Japan's Cosmology Going?

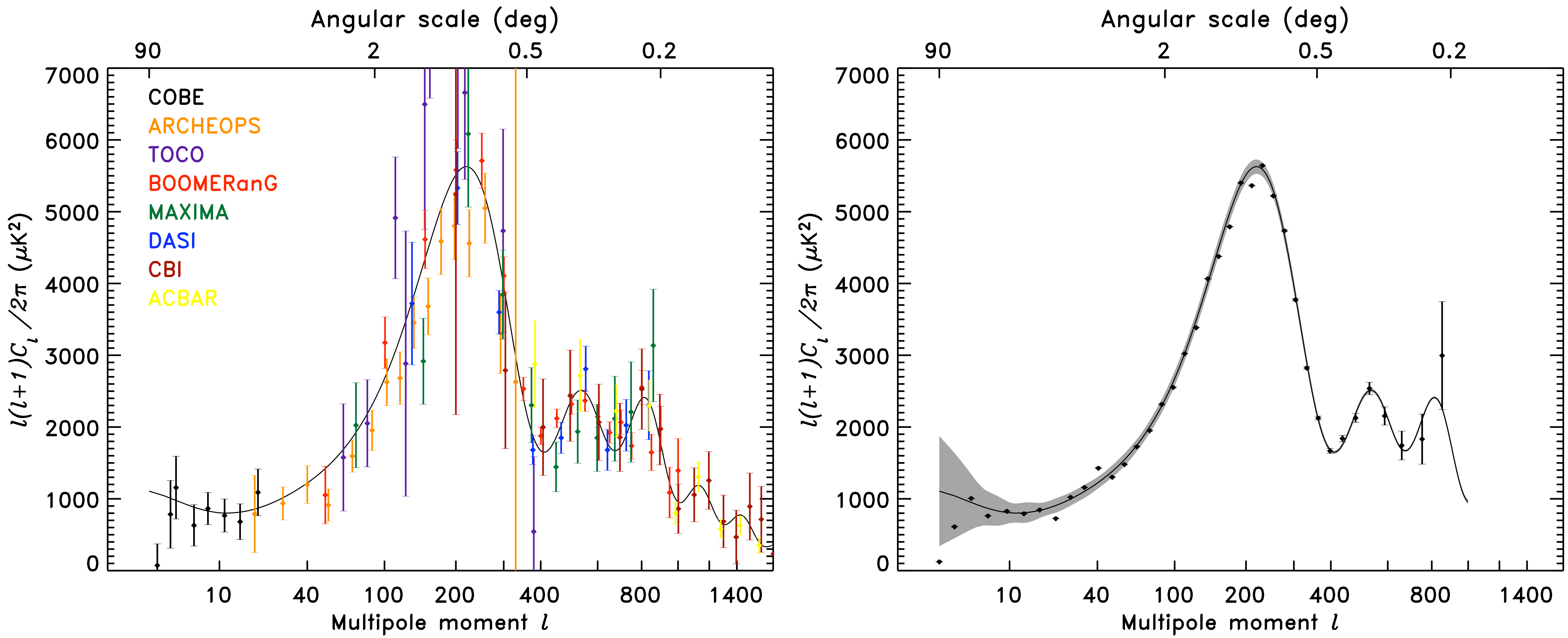
- Japan's cosmology needs experiments. Desperately.
- No experiments, no growth, no glory, no future.
- Can BAO help Japan's cosmology grow stronger?
    - BAO is *definitely* the main stream science.
    - The scientific impact is large.
    - Serious competitions.

Where Is Japan's Cosmology Going?

- The message from the current state of competitions is pretty clear to me: *whoever succeeded in carrying out the Stage IV experiment would win the game*.
- Yes, there will be many ground-based experiments, but...
  - Something to learn from the success of WMAP
- Why should we stop at the ground-based experiments?

Hinshaw et al. (2003)

Pre-WMAP vs Post-WMAP



- A collection of results from the ground-based BAO experiments will look something like the left panel. Don't you want to be the right one?

Japan's Space BAO Mission?

- USA (>2017)
  - JDEM AO, Spring 2008
  - SNAP (SN1a+lensing) vs ADEPT (BAO) vs CIP (BAO) vs ...
- Europe (>2015)
  - Candidate missions for the Cosmic Vision selected
  - DUNE (SN1a+lensing) vs SPACE (BAO) vs ...
- Intense *internal* competitions in USA&EU. Can Japan sneak in while the others are "killing each other?"

Summary

- **Where are we now?**
  - The ability of BAO for constraining DE has been demonstrated by the 2dFGRS and SDSS data.
  - Theory is improving. The PT approach has been shown to be very promising.

Summary

- **What needs to be done?**
  - Understand matter clustering at $z \sim 1$.
    - Important for surveys at $z<2$.
  - Understand the galaxy bispectrum using PT.
    - Important for improving determinations of bias.
  - Understand redshift space distortion. [Challenge!]
    - Important for measuring $H(z)$.

Outlook

- **Where are we going?**
  - Many ground-based BAO experiments are being planned and developed.
  - Why stop at the ground-based experiments?
  - Why not go to space?
  - Can Japan's cosmology compete?
  - Does Japan's cosmology *want* to be competitive?