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理論セミナー
@KEK

Baryon Acoustic Oscillations and Future Galaxy Surveys

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RESCEU=RESearch Center for the Early Universe

Contents

- ★ Current status of our understanding
- ★ Probing cosmic expansion history with BAOs
- ★ Prospects for precision measurement of BAOs

Introduction

(Observational) Cosmology is in revolutionary phase

Observation:

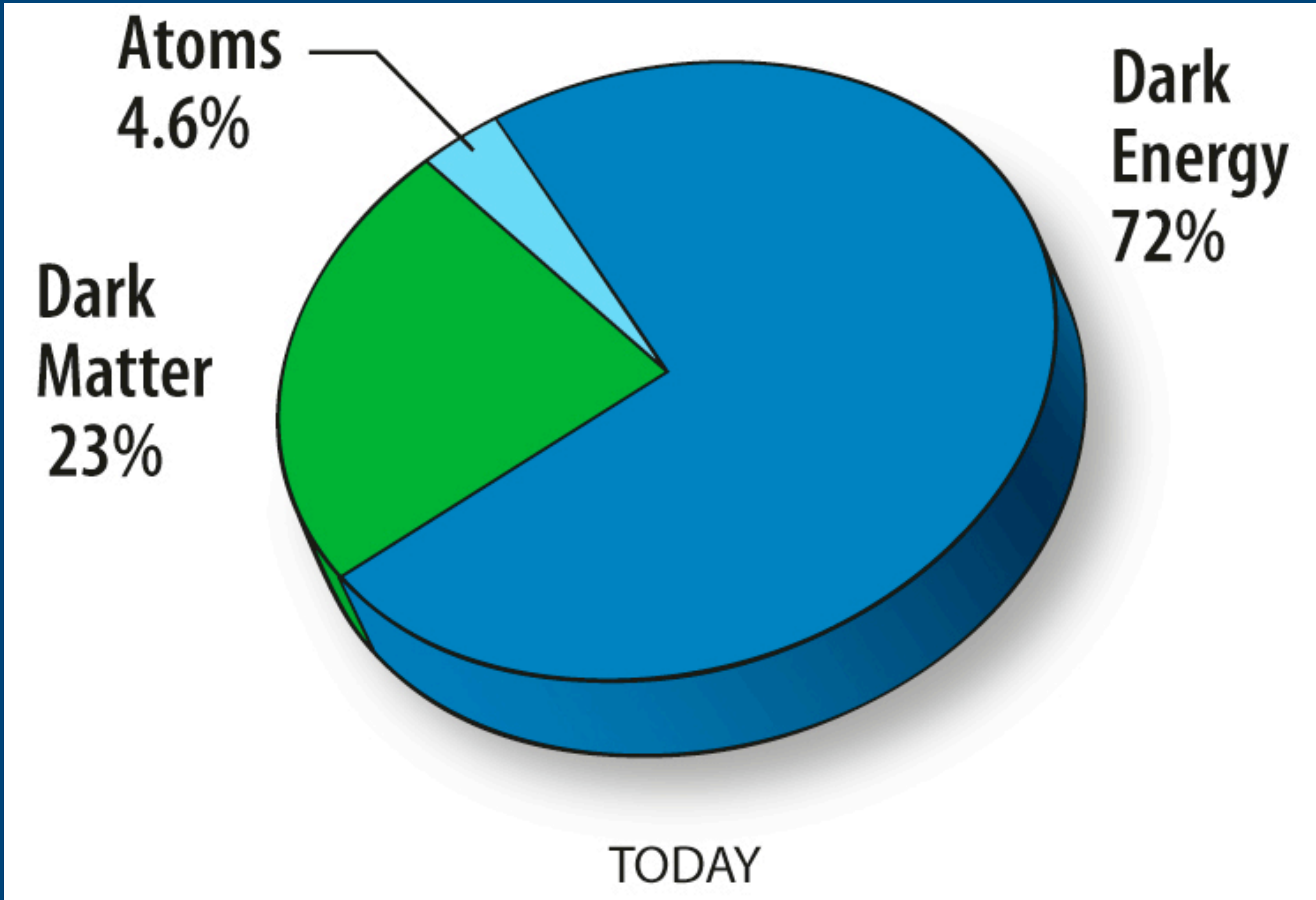
- Cosmic microwave background (CMB)
- Large-scale structure
- Distant type Ia supernovae
- Weak gravitational lensing

Several independent and/or complementary methods enable us to reveal a standard picture of the Universe

⇒ **Geometry of the Universe:** **flat**

Energy contents: → see next

Cosmic Pie



http://map.gsfc.nasa.gov/media/080998/index.html

Standard Model Assumptions

To derive the energy contents of the Universe, we have put the following simple assumptions

Cosmological Principle ·············· homogeneity & isotropy of the Universe

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1 - K r^2} + r^2 d\Omega^2\right] ;$$

Scale factor

- K<0: open
- K=0: flat
- K>0: closed

General Relativity

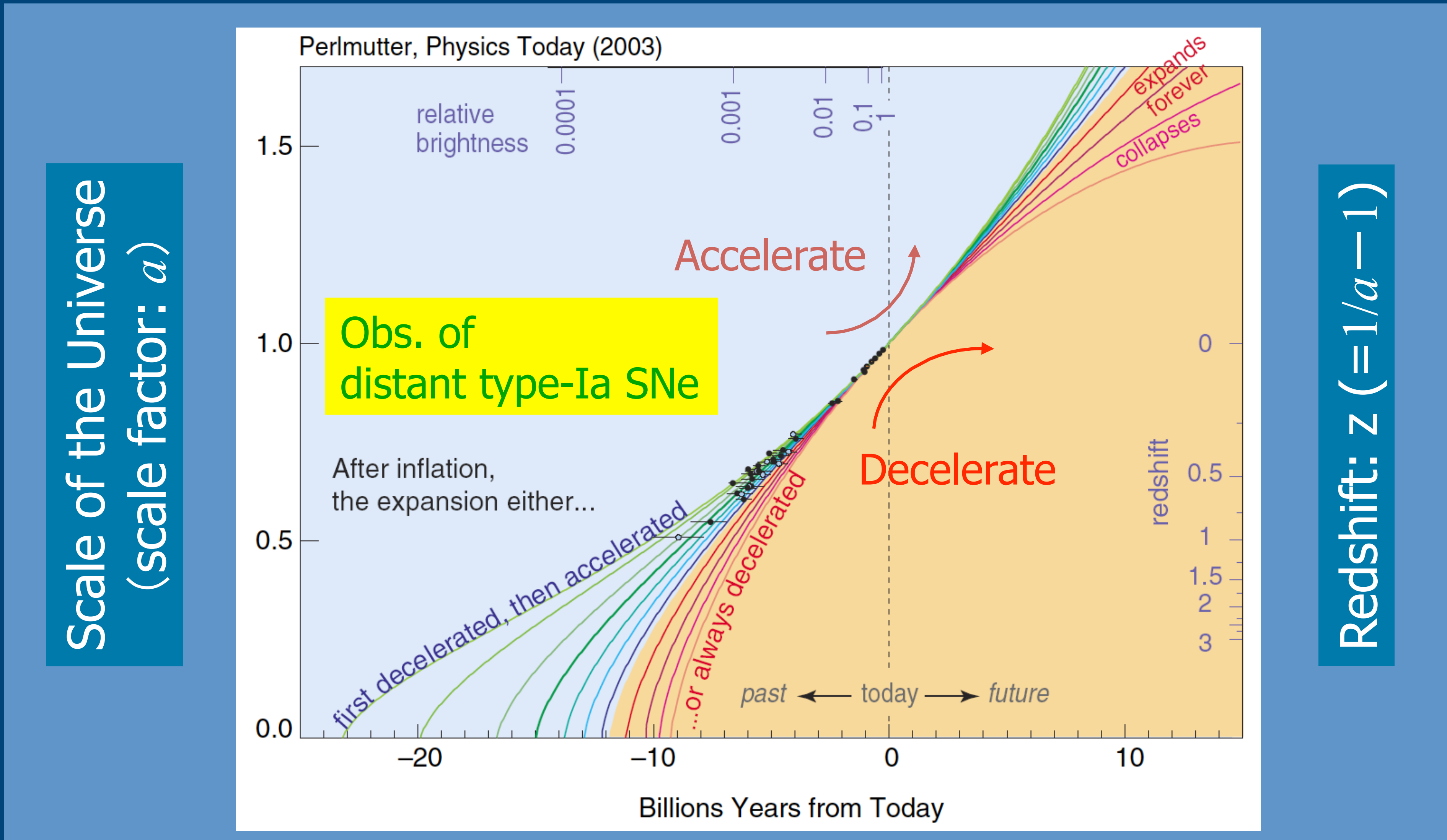
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G T_{\mu\nu} ;$$

$$T_\mu^{\ \nu} = \mathrm{diag}[-\rho, P, P, P]$$

$$\rho = \rho_{\mathrm{m}} + \rho_{\mathrm{DE}}$$

- Matter: $P \cong 0$ (dark matter, baryon(Atoms), neutrinos)
- Dark energy: $P \cong -\rho$

Late-time Cosmic Acceleration



We are living in the second phase of cosmic inflation !?

Cosmic Puzzles (1/2)

What does the presence of mysterious dark energy or the evidence of late-time acceleration really imply ?

Nature of dark energy (DE)

Cosmological constant

un-naturally small !!

- invented by Einstein in 1917
- vacuum energy equivalent to $P = -\rho = -\dfrac{\Lambda}{8\pi G}$; $\Lambda \sim 10^{-120} M_{\rm pl}^4$

Dynamical scalar field

- Quintessence $L_{\rm matter} = \dot{\phi}^2/2 - V(\phi)$
- Effective equation of state $P_\phi = w(t)\,\rho_\phi$; $w(t) \equiv \dfrac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)} < -\dfrac{1}{3}$

Cosmic Puzzles (2/2)

Alternative to DE ………… abandon standard model assumptions

Modification to GR

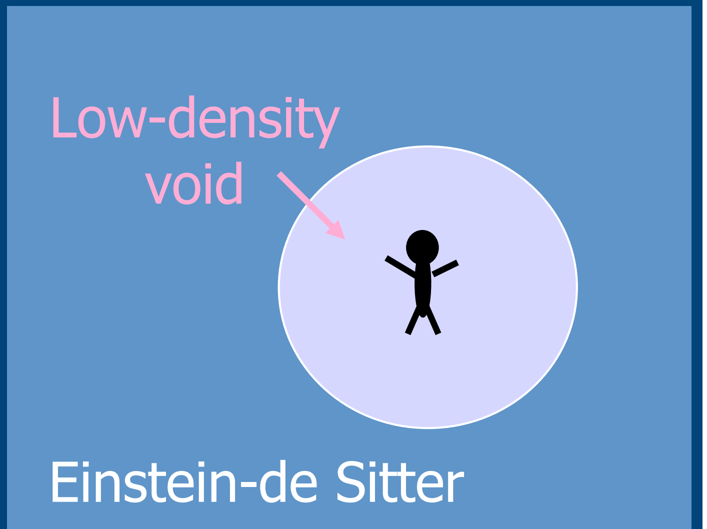
- Hidden gravity sector that modifies Friedman eq.

⇒ Self-accelerating universe (e.g., Dvali-Gabadadze-Poratti model
f(R) model)

Violation of cosmological principle

- We are accidentally living at the center of low-density void
- Late-time acceleration is '*apparently*' observed

(e.g., K. Tomita)



Current Status

- There are currently no natural & consistent explanations

Nevertheless,

- We cannot immediately reject/exclude these possibilities at the level of current precision

Need more observational data !!

Key issues

Precision measurement of
- cosmic expansion history
- growth of structure

~1% level

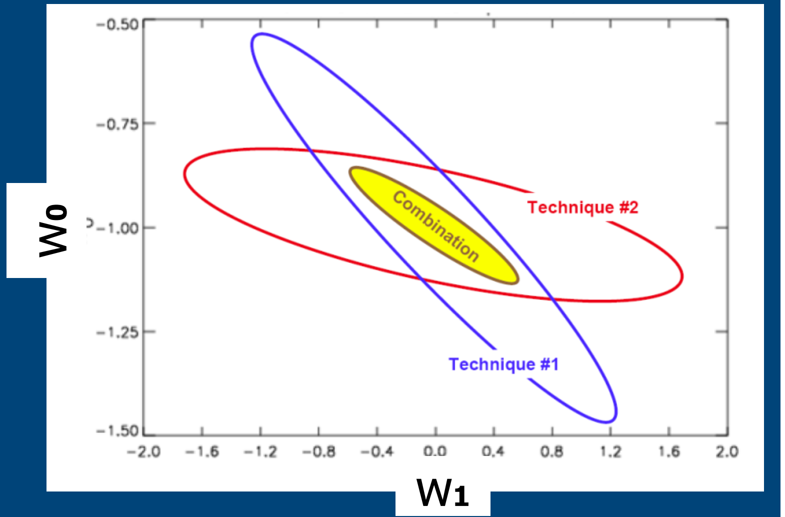
Observational Techniques

● (red) Expansion history
● (blue) Growth of structure

Name	Observation	Main probe		
Type Ia SNe	Light curves of distant supernovae	● (red)	Photo-z	$D_L(z)$
Gravitational lensing	Distortions of each galaxy image	● (blue) ● (red)	Photo-z	$D_A(z)$ $g(z)$
Baryon acoustic oscillation	Spatial patterns of galaxy distribution	● (red)	Spec-z	$D_A(z)$ $H(z)$
Galaxy cluster	Evolution of number density of clusters	● (blue) ● (red)	SZ / WL / X-ray	

Remarks

★ Single technique would not be powerful enough



⇨ Combined analysis with other data set is essential

★ Simultaneous determination of cosmological parameters other than the dark energy properties is also necessary

$$\Omega_{\mathrm{DE}},\ \Omega_{\mathrm{m}},\ \Omega_{\mathrm{b}},\ h,\ \sigma_8,\ \cdots$$

⇨ Use prior information obtained from CMB anisotropy data

$\Omega_{\mathrm{i}} \equiv (8\pi G/3H_0^2)\rho_{\mathrm{i}}$: density parameter

$h \equiv H_0/(100\,\mathrm{km\cdot s^{-1}/Mpc})$: Hubble parameter

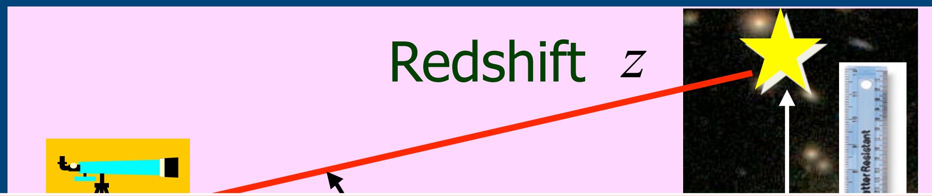
σ_8 : normalization of P(k)

Measuring Expansion History

Distance at cosmological scales
depends on cosmic expansion history

Distance vs. redshift relation

Luminosity distance



Need universal measures to calibrate $D_L(z)$ and $D_A(z)$:

Standard candle for $D_L(z)$ → Light-curves of type Ia supernova

Standard ruler for $D_A(z)$ → Baryon acoustic osicllations (**BAO**s) imprinted on galaxy distributions

Sloan Digital Sky Survey
Data Release 5

Main samples

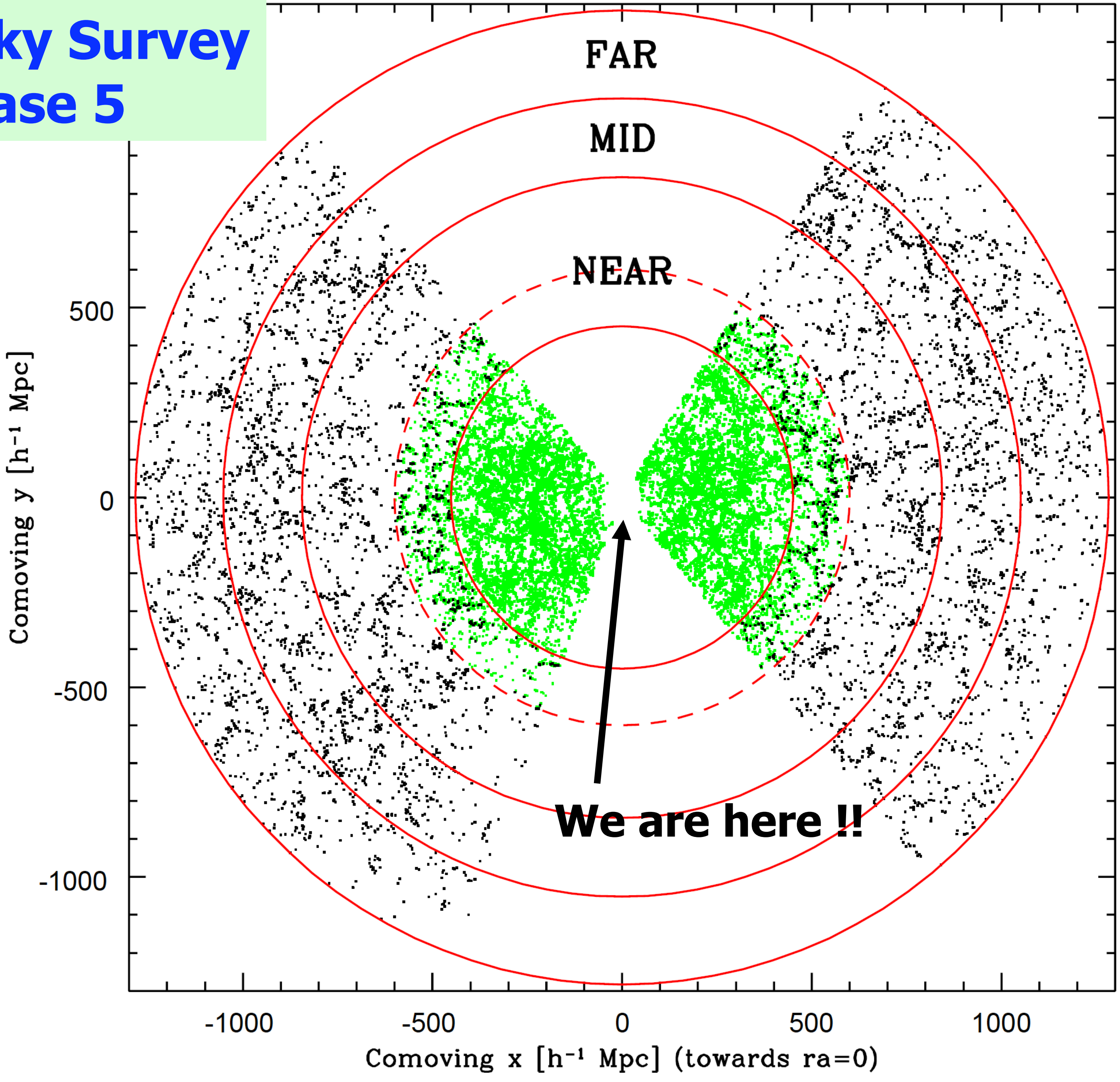
+

Luminous red galaxies

1 Mpc/h

~3,000,000

Light-years



Tegmark et al. (2006)

Characterizing Galaxy Clustering

Statistical characterization of galaxy distributions

Power spectrum

$$P(k) = \frac{1}{(2\pi)^3} \left\langle \left| \delta(\vec{k}) \right|^2 \right\rangle$$

Number density of galaxies

$$\delta(\vec{x}) = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}} = \sum_{\vec{k}} \delta(\vec{k}) e^{i\vec{k}\cdot\vec{x}}$$

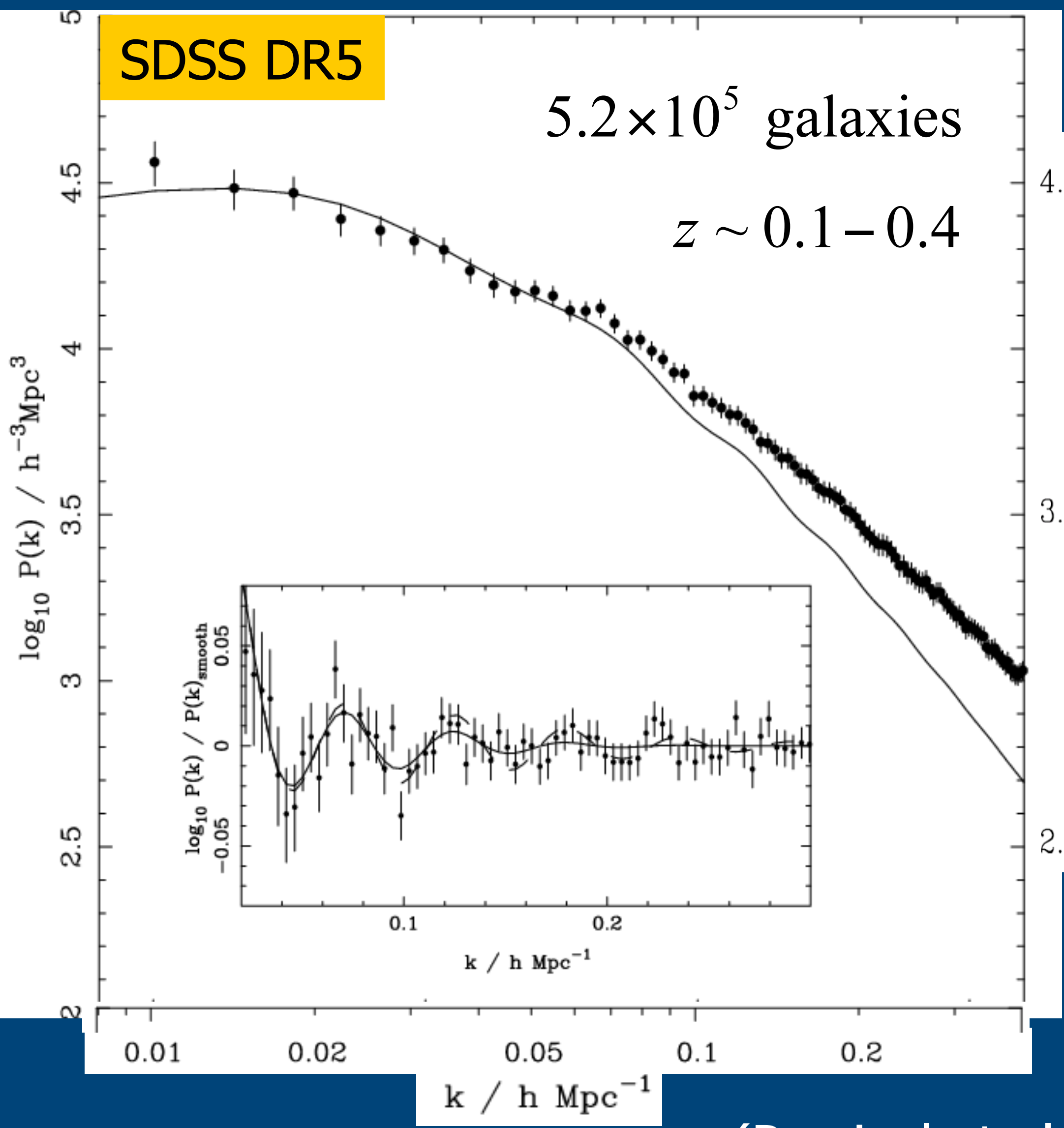
Fourier transform

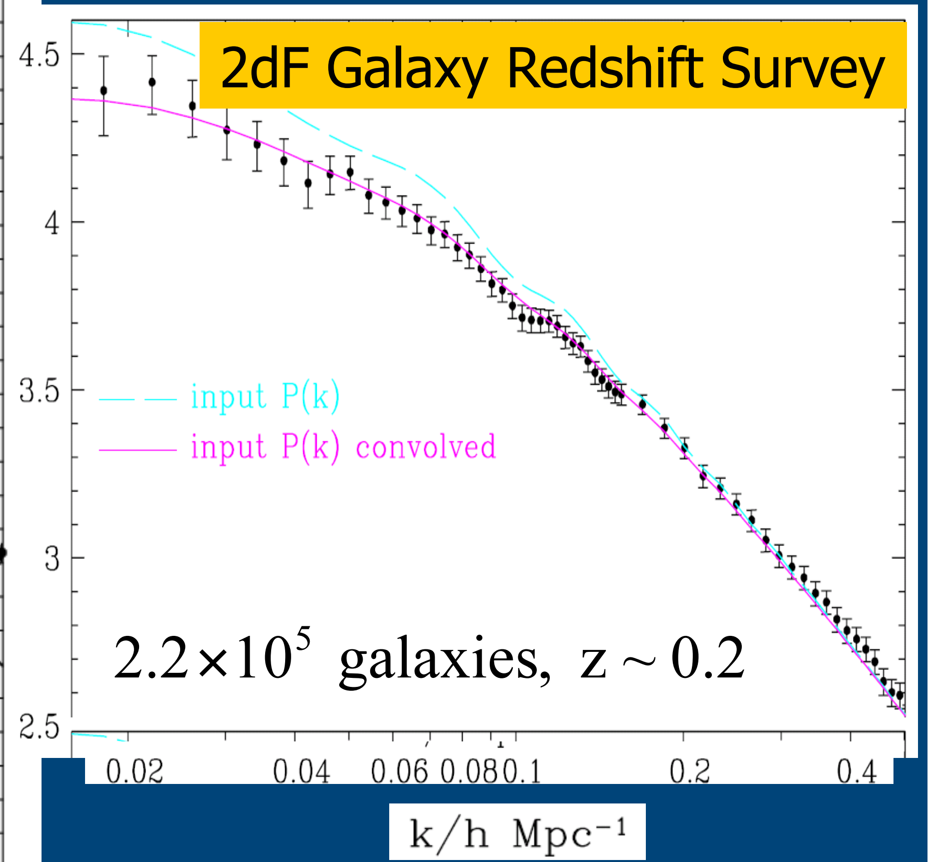
Two-point correlation function

$$dP_2(r) = \bar{n}^2 \left\{ 1 + \xi(r) \right\} dV$$

Excess probability of galaxy pair-count

Power Spectrum



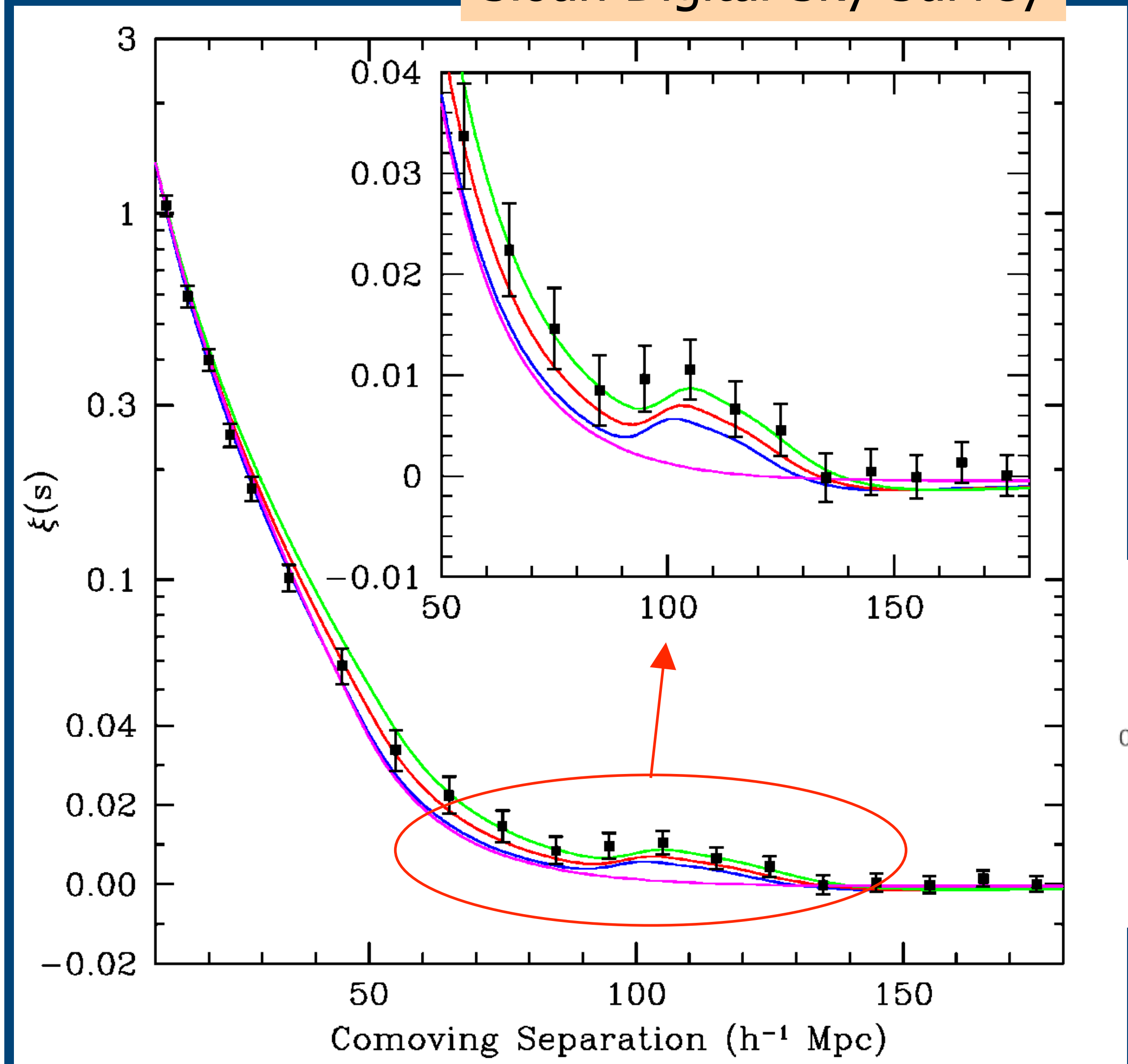


(Cole et al. 2005)

(Percival et al. 2007)

Two-point Correlation Function

Sloan Digital Sky Survey

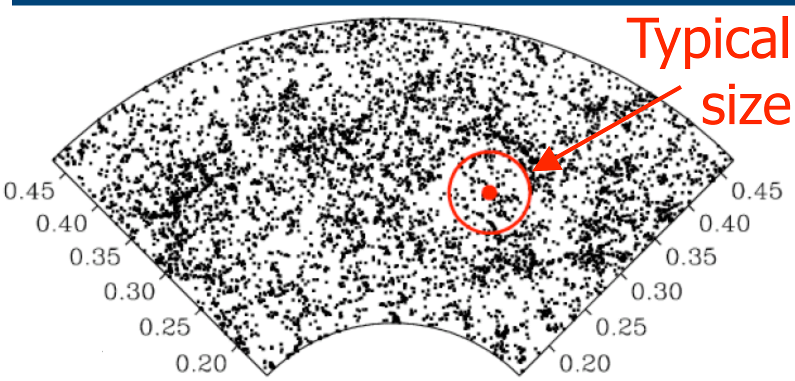


Luminous Red Galaxies

(47,000 samples @z~0.3)

$3800\,\deg^2$)

$$\xi(s) = \int \frac{dk\,k^2}{2\pi^2} P(k) \frac{\sin(ks)}{ks}$$



Eisenstein et al.(2005)

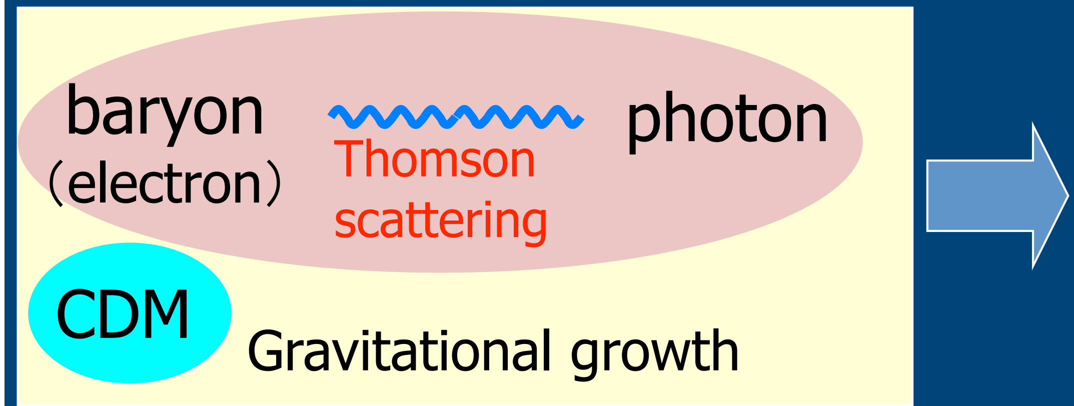
Physics of BAOs ~brief sketch~

~370,000 year after the Big-Bang

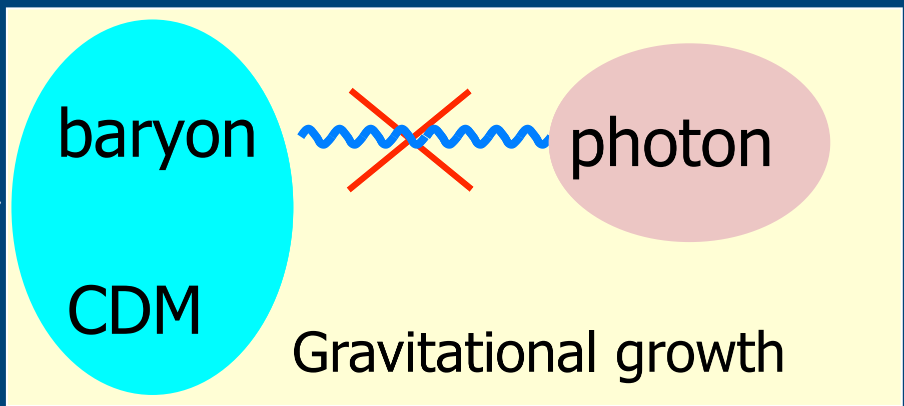
BAO was imprinted around
the time of decoupling of photons from matter

After the decoupling, acoustic patterns of photon and baryon density fields were frozen, and baryon density field has evolved with dark matter under the influence of gravity

Before decoupling,

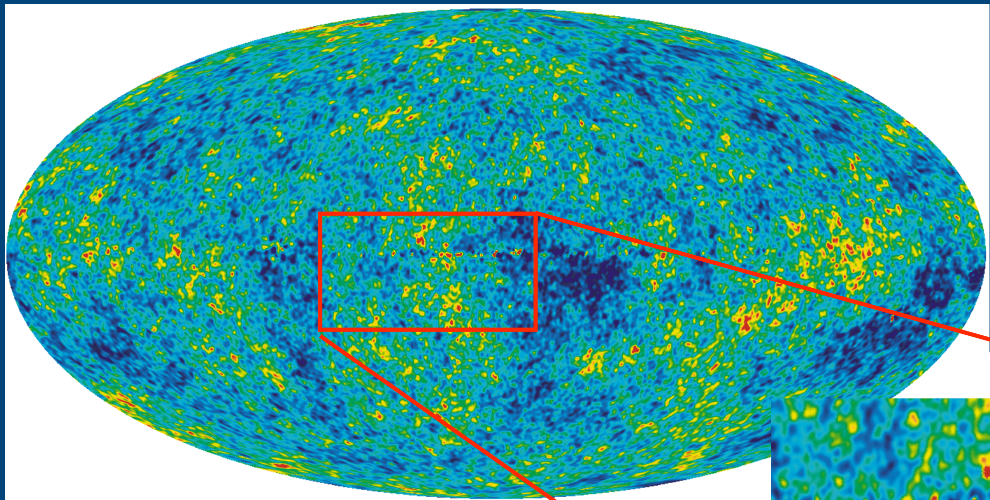


After decoupling,



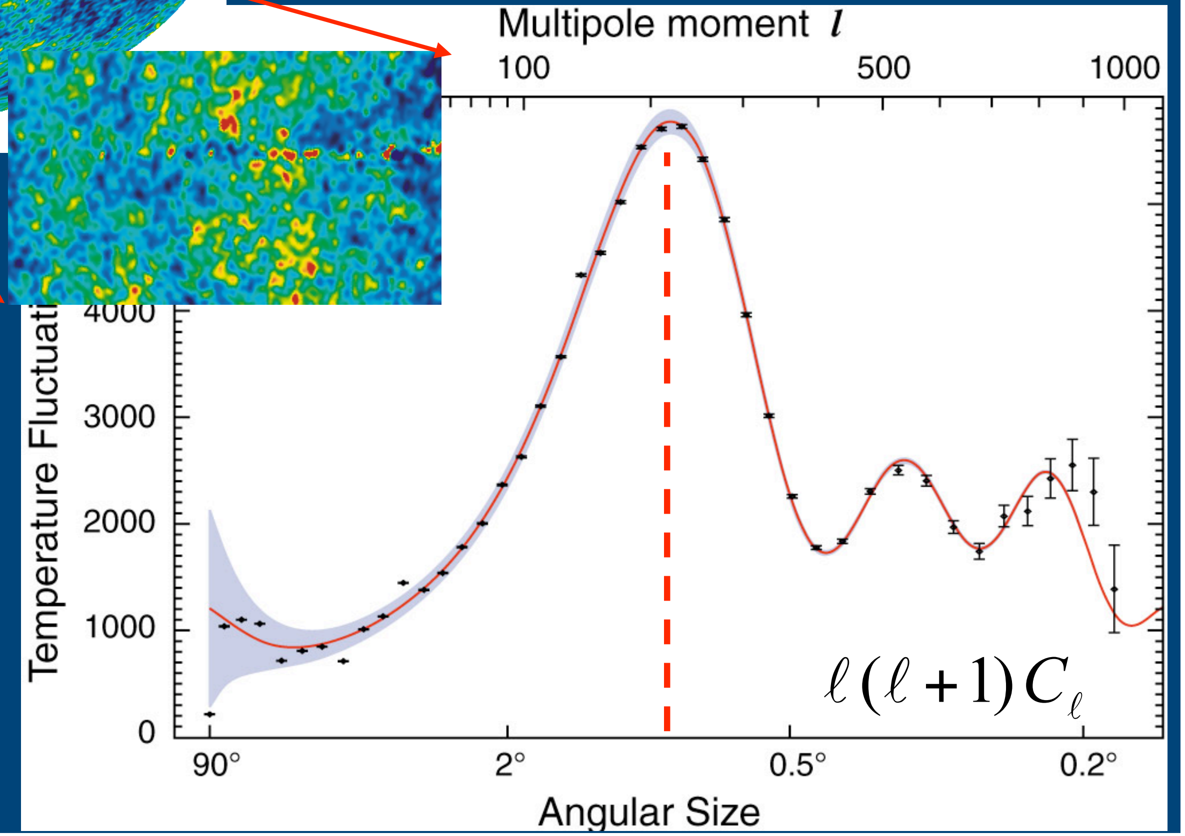
Cosmic Microwave Background

(Counterpart of BAOs)



$$\Delta T(\theta,\varphi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$

$$C_\ell = \left\langle \left| a_{\ell m} \right|^2 \right\rangle$$



5 year WMAP result

Komatsu et al. (2008)

Characteristic Scales of BAOs

Sound horizon scale at the time of decoupling $\left(z_{de} \cong 1089\right)$:

$$r_s(z_{\mathrm{dec}}) \equiv \int_{z_{\mathrm{dec}}}^{\infty} \frac{dz'\, c_s(z')}{H(z')} \approx 147 \ \left(\Omega_{\mathrm{m}} h^2/0.13\right)^{-0.25} \left(\Omega_{\mathrm{b}} h^2/0.023\right)^{-0.08} \mathrm{Mpc}$$

- Physics of BAOs is well-known, unambiguous (c.f. type Ia SNe)
- Insensitive to the presence of dark energy

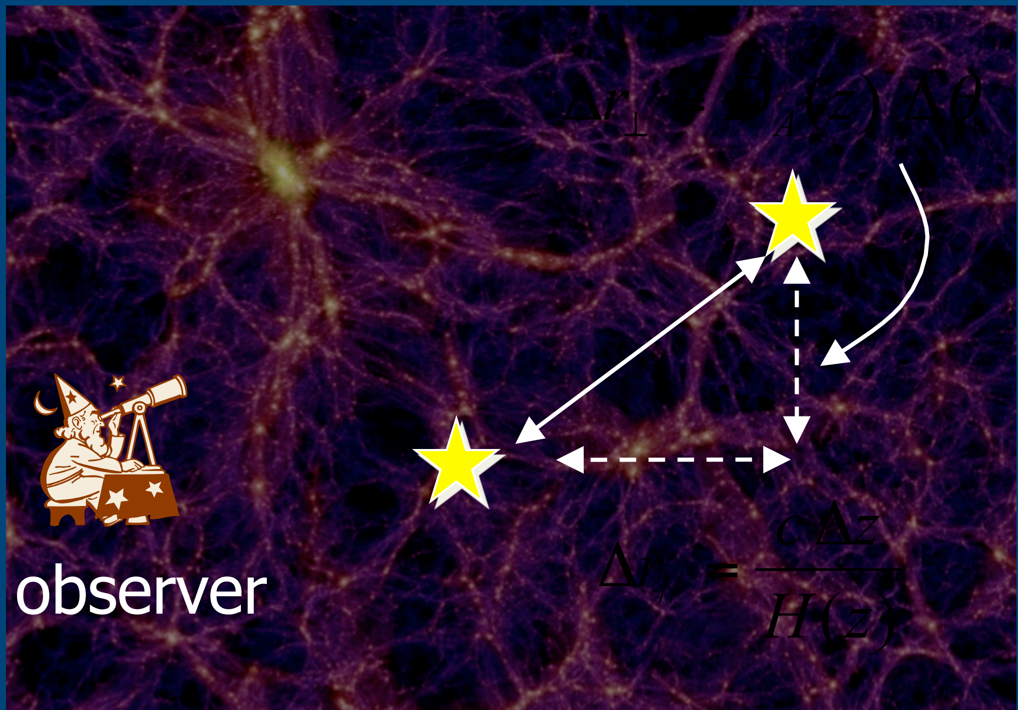
  (Only weakly depends on matter and baryon density parameters)
- There's no significant disturbances that erase acoustic patterns

BAO is a robust standard ruler

Alcock & Paczynski Effect

Differences of distance measurement between parallel and transverse components produce anisotropies in P(k) and x(r)

'apparent'



Angular diameter distance

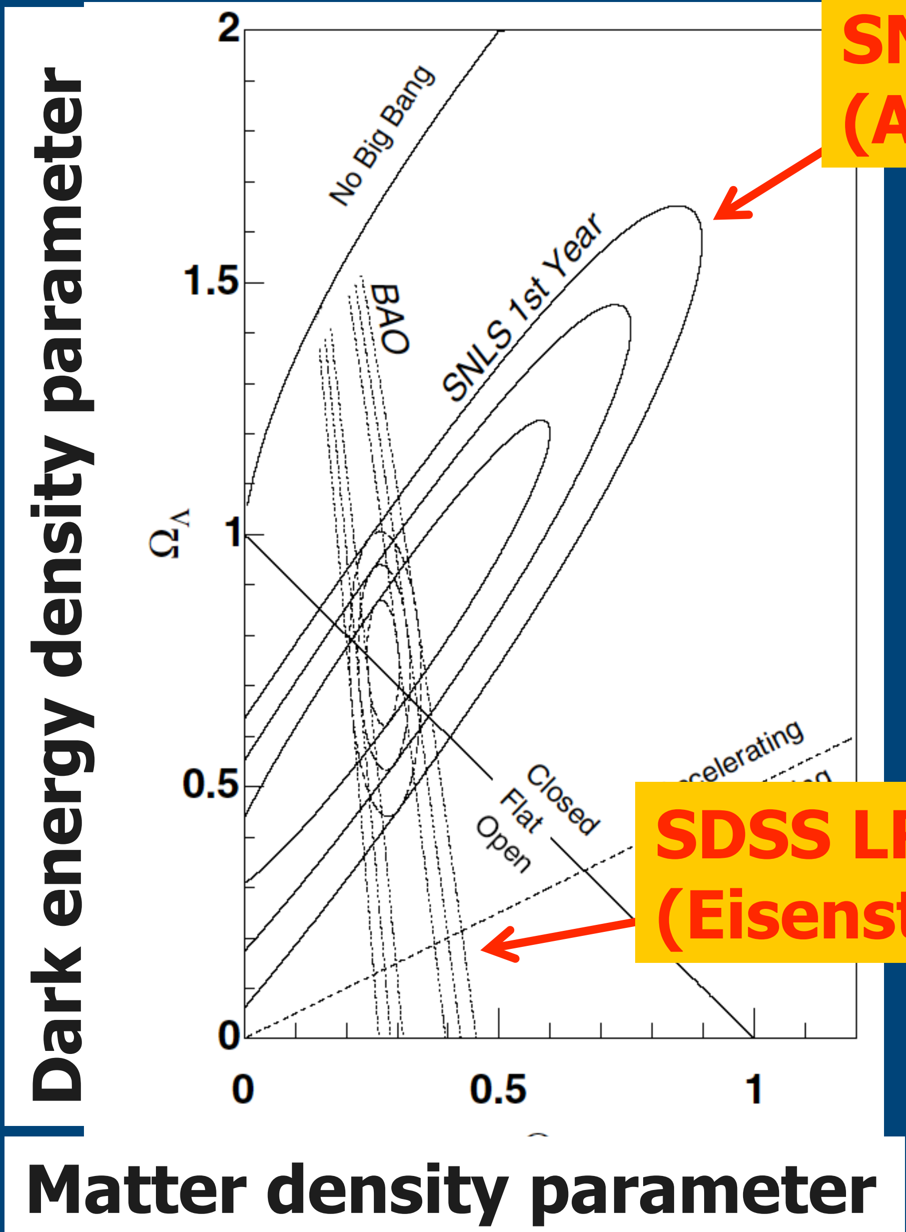
$$D_A(z) = \frac{\sinh\left[\sqrt{-K}\int_0^z dz'/H(z')\right]}{(1+z)\sqrt{-K}}$$

Hubble parameter

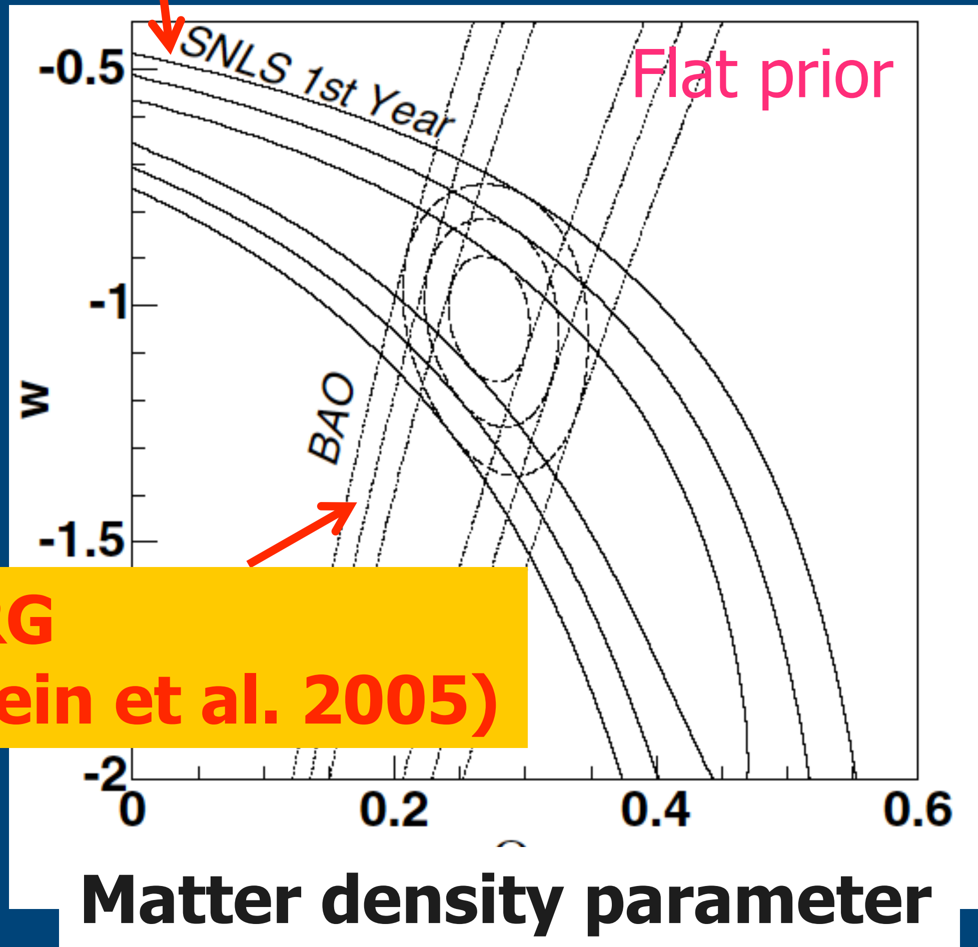
$$H(z) = \frac{\dot{a}}{a}$$

Measuring anisotropic pattern of galaxy clustering simultaneously determines $D_A(z)$ and $H(z)$ → advantage of using BAOs

Combined Constraints (1/2)



SN Legacy Survey
(Astier et al. 2006)



SDSS LRG
(Eisenstein et al. 2005)

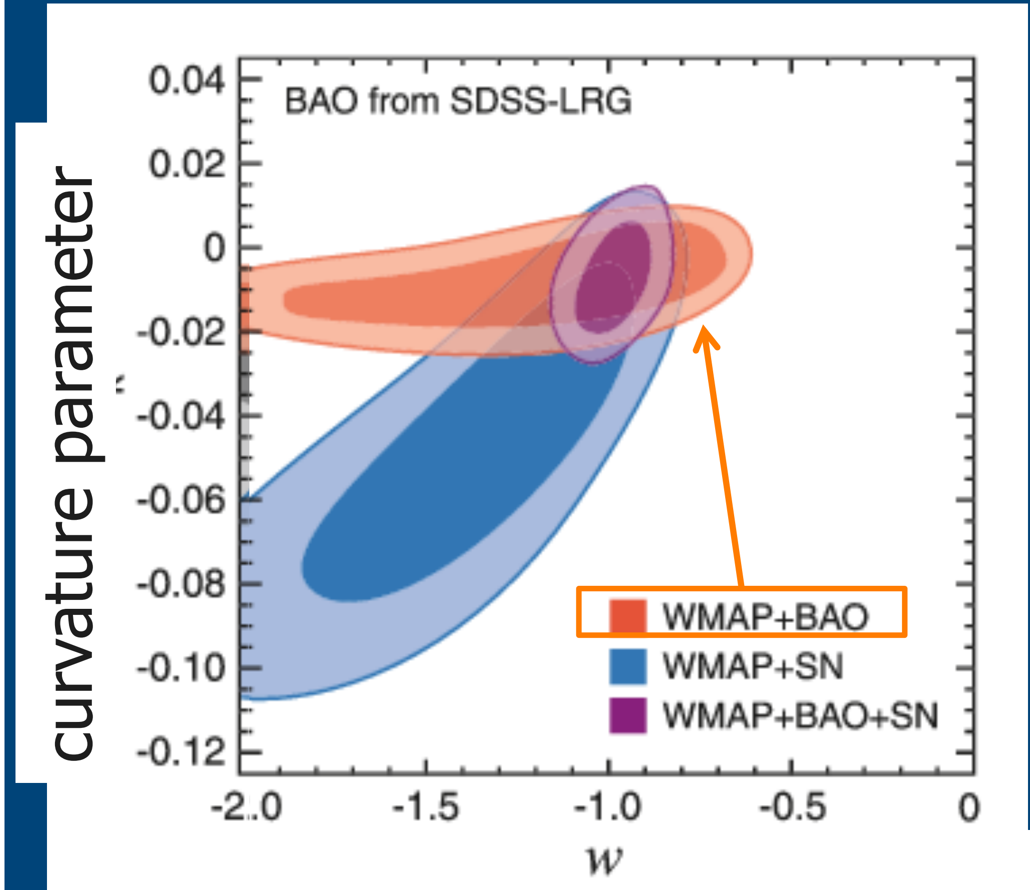
Combined Constraints (2/2)

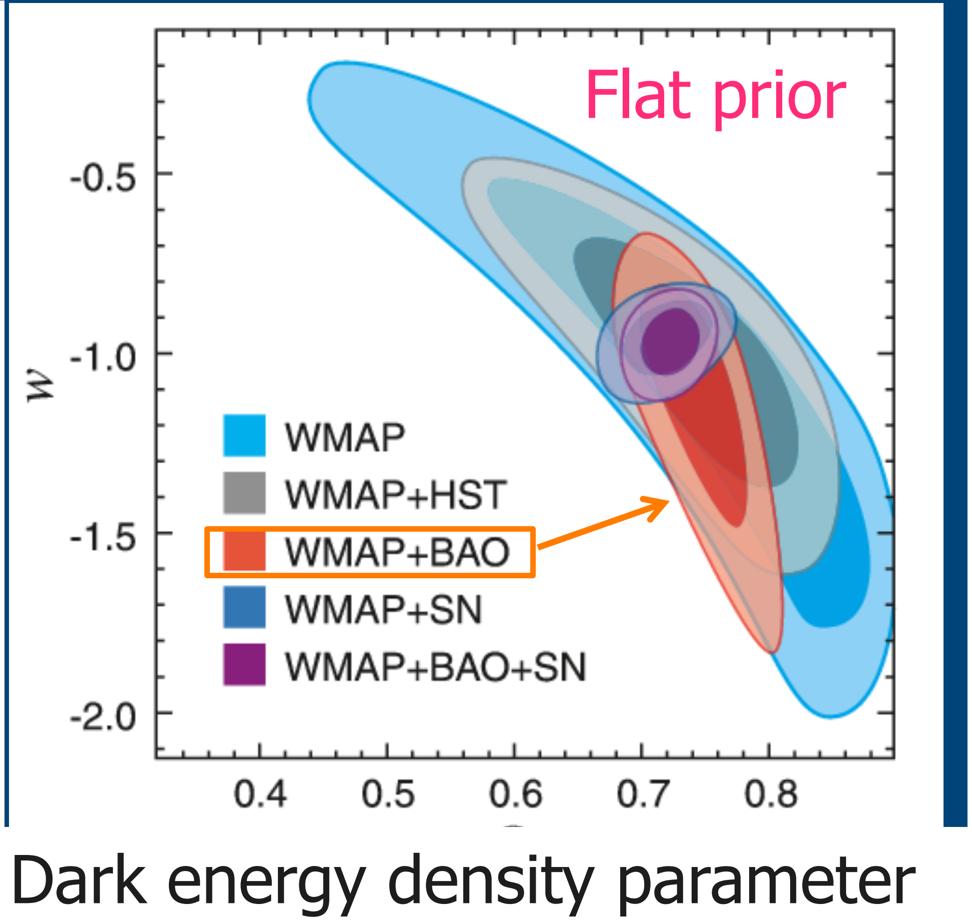
$-1.11 < w < -0.86$ (95% CL)

$-0.0175 < k < 0.0085$ (95% CL).

WMAP5 results

(Komatsu et al. 2008)





Future Galaxy Surveys

Instrumental and/or projects for precision measurement of BAOs

Ground

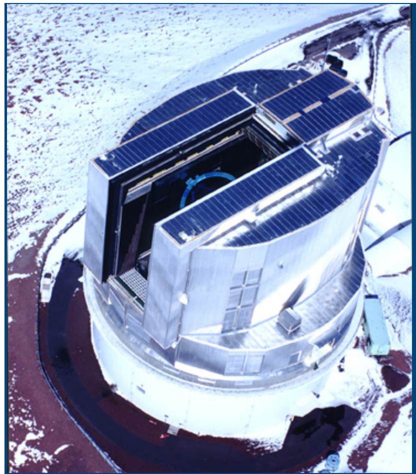
Survey volume	$V_{\rm survey} > 5\ [h^{-3}\ {\rm Gpc}^3]$	
Number of galaxies	$N_{\rm gal} > 2\times 10^6$	
Sky coverage	$\Omega_{\rm survey} > 1{,}000\ [{\rm deg}^{-2}]$	
c.f.	SDSS LRG	$V_{\rm survey} \sim 0.7\ [h^{-3}\ {\rm Gpc}^3]$
	2dF GRS	$V_{\rm survey} \sim 0.1\ [h^{-3}\ {\rm Gpc}^3]$

)

Sp

Advanced Dark Energy Physics Telescope (ADEPT)

SPectroscopic All-Sky Cosmic Explorer (SPACE)



WFMOS

Subaru+Gemini spectroscopic survey
(2012+~)

- Accurate spectroscopic measurement of BAOs
- 4000 multi-fiber spectrograph on 1.5deg FOV camera at Subaru prime focus

0.5<z<1.3: emission line galaxies:
2×10^6 gals/2000 deg^2 (900hours)

2.3<z<3.3: Lyman-break galaxies:
6×10^5 gals/300 deg^2 (800hours)

Determine H(z) & D_A(z) within 1% precision

$\Delta w/w \leq 3\%$

$\Delta(dw/dz)/(dw/dz) \leq 25\%$

Toward precision measurement

Precision measurement of BAOs requires

accurate theoretical models of BAOs

in order to determine the BAO scales

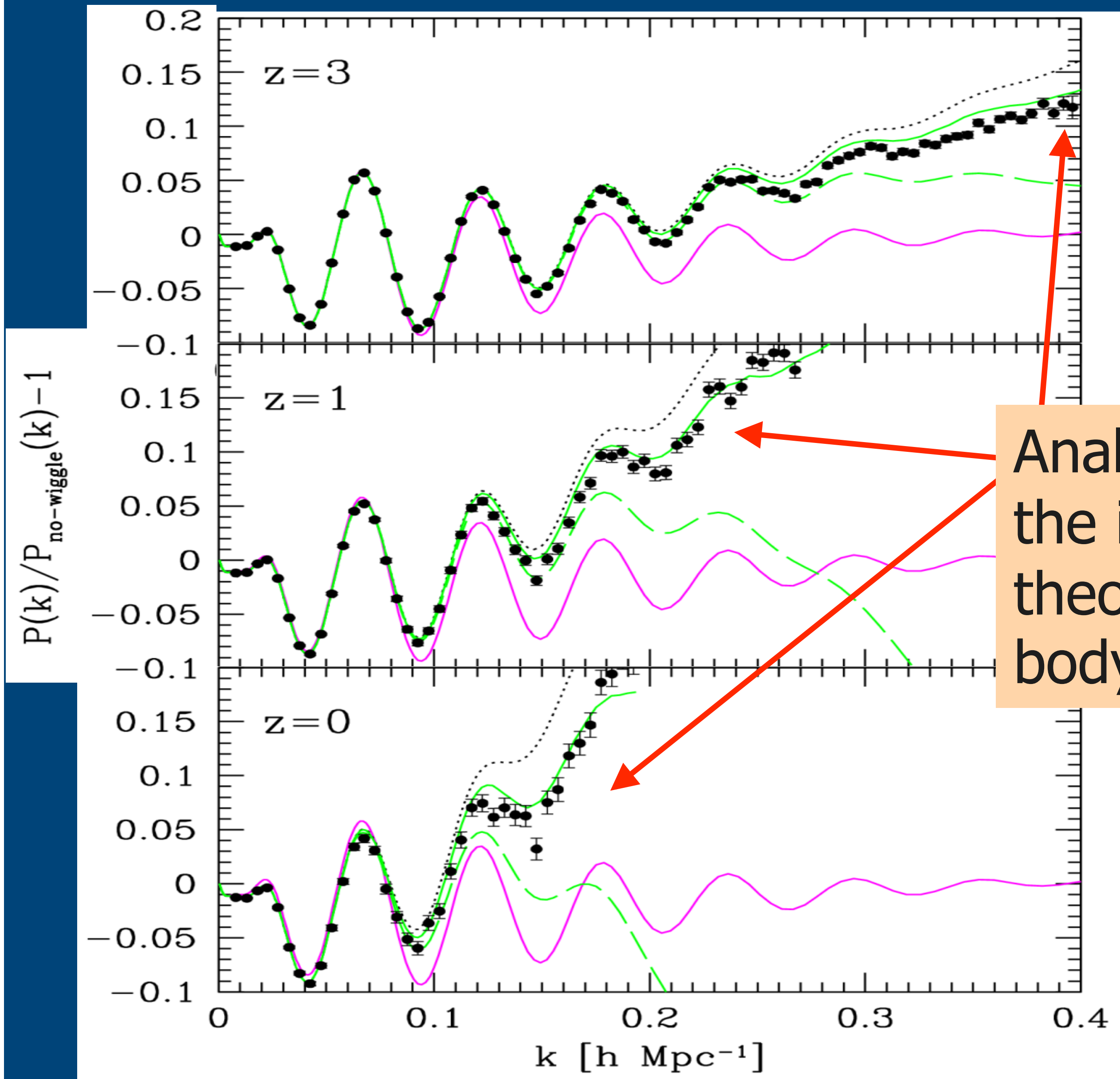
Systematic effects on BAOs:

- Non-linear gravitational evolution
- Redshift-space distortion
- Galaxy Biasing

small, but non-negligible effects at percent level

→ Development of theoretical modeling based on numerical and analytical treatment

Power Spectrum in Real Space



Nishimichi et al.(2008)

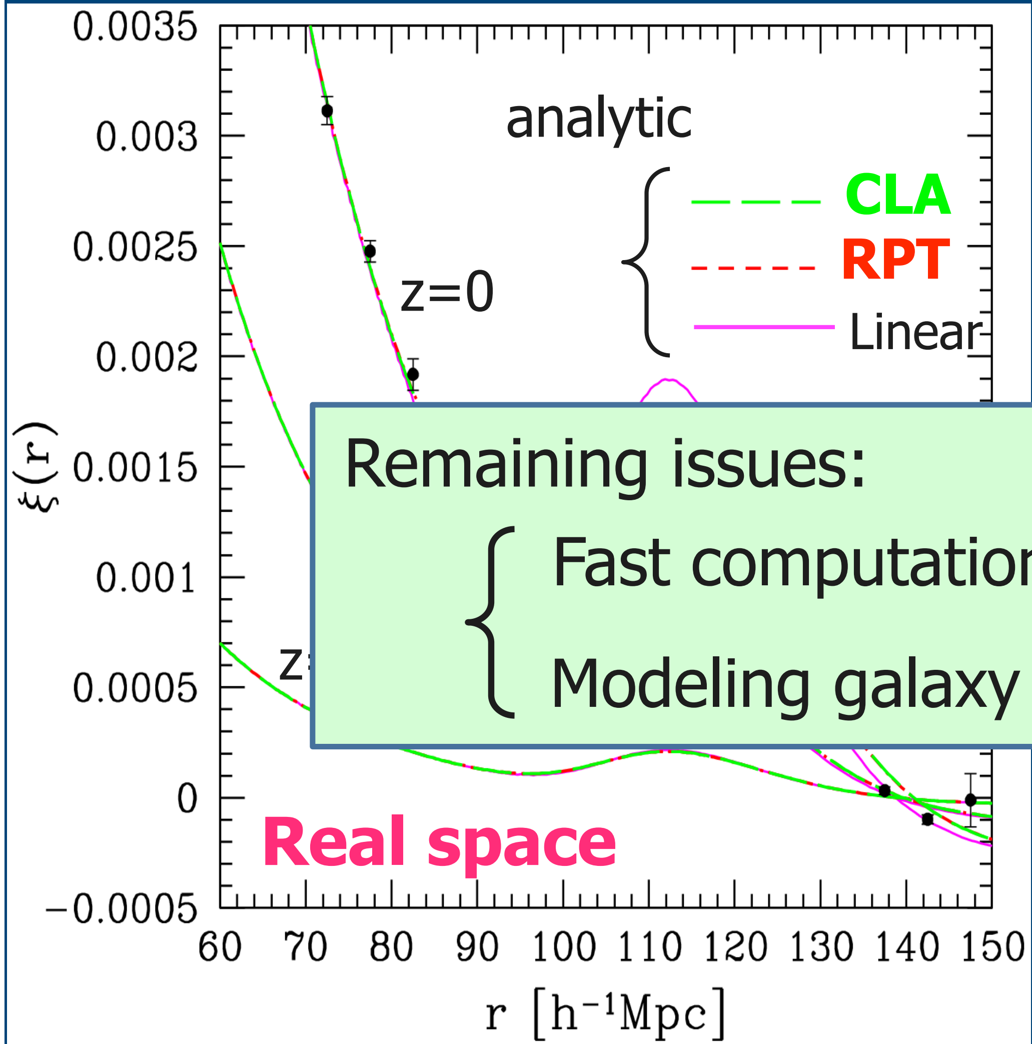
AT & Hiramatsu (2008) in prep.

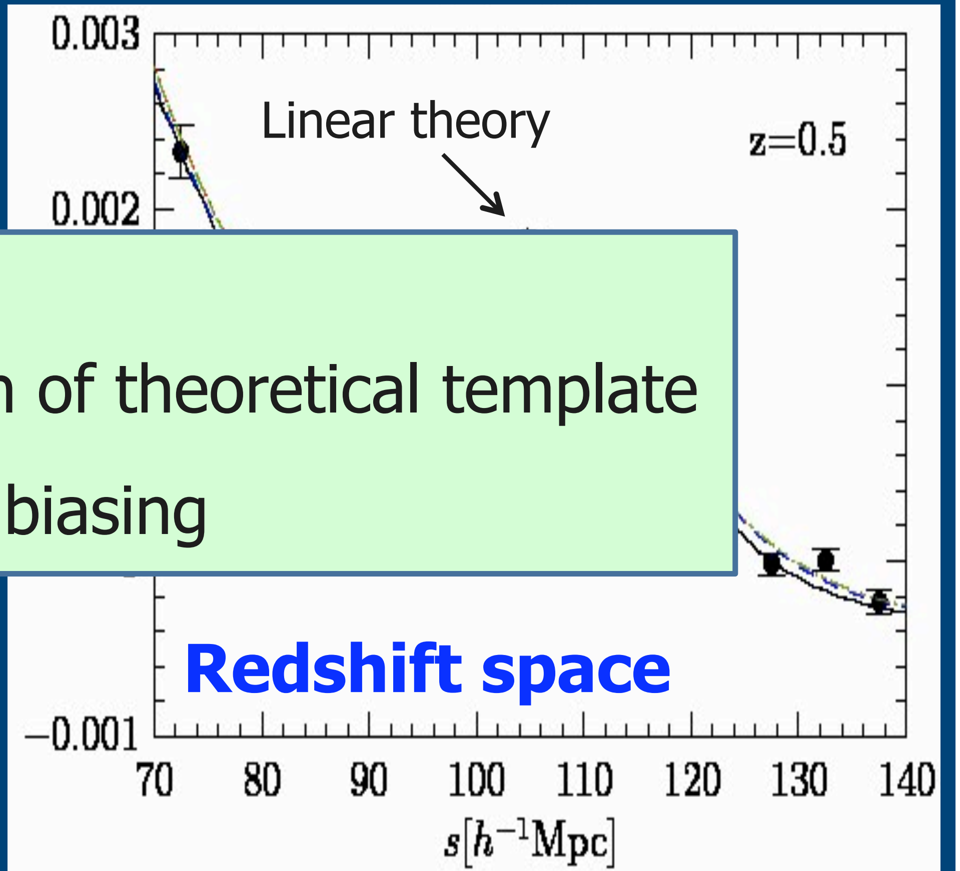
Analytic template based on the improved perturbation theory can reproduce the N-body simulations quite well.

Level of precision now reaches < 1-2%

Two-point correlation

Modeling x(r) in both real & redshift spaces is almost complete.





Remaining issues:

- Fast computation of theoretical template
- Modeling galaxy biasing

Summary

Measurement of BAOs with galaxy redshift surveys opens a new window to probe cosmic expansion history

- Acoustic signature of primeval baryon-photon fluid can be used as cosmic standard ruler

$r_s(z_{\rm dec}) \approx 100\, h^{-1}{\rm Mpc}$

- Measurement of BAOs leads to Simultaneous determination of $D_A(z)$ and $H(z)$

- Future galaxy surveys can reach 1% level precision (remain theoretical issues)

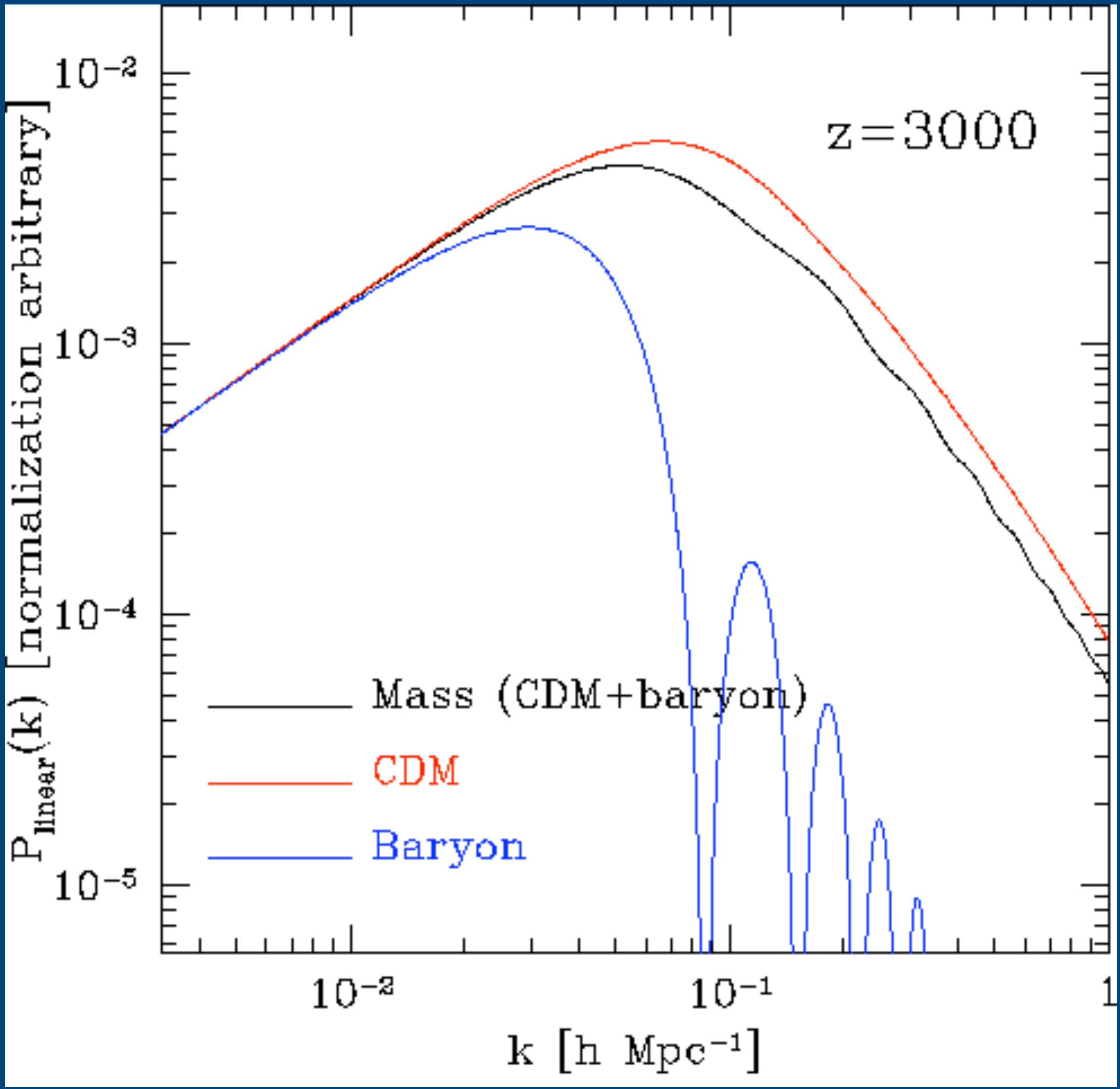
Nature of dark energy (equation-of-state parameter)

Test of standard model assumptions

Many fruitful science can be probed with BAOs

Appendix

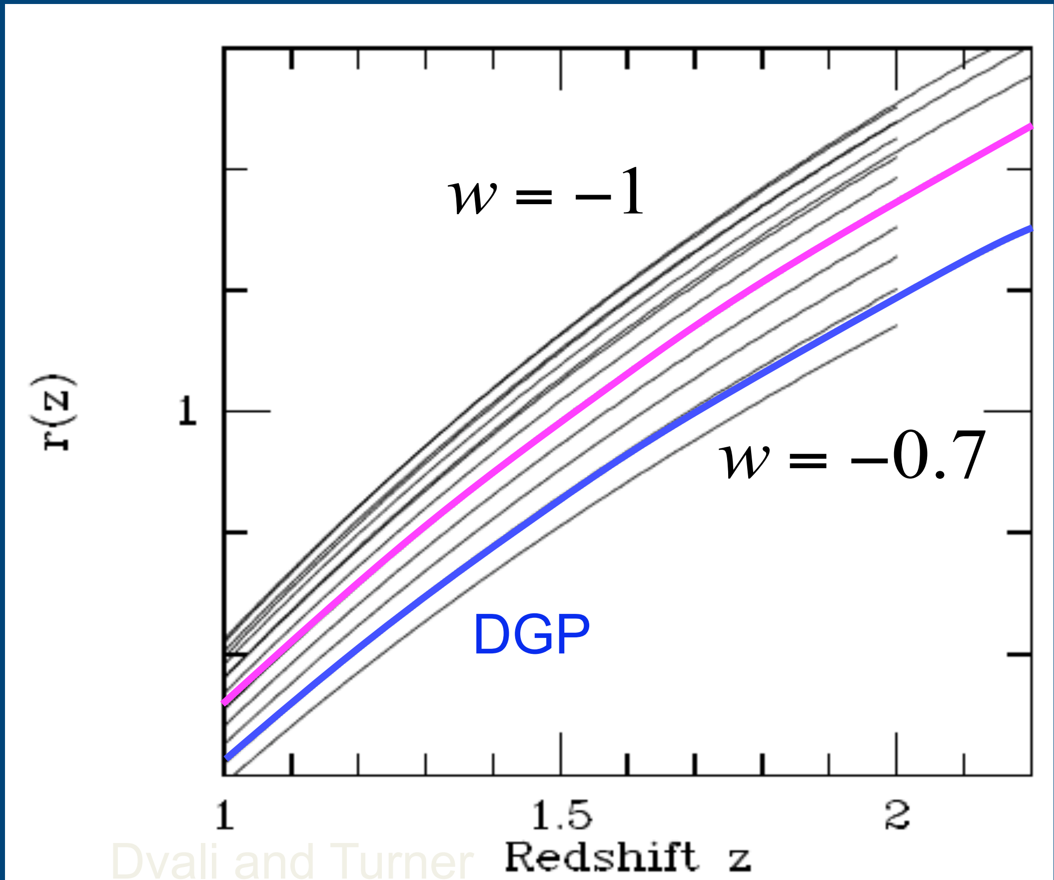
Time evolution of power spectra



CMBFAST

Dark Energy vs. DGP

Can we distinguish between dark energy in GR and DGP ?



$$r(z) = \int_0^z dz\, H(z)^{-1}$$

DGP model is fitted by

$$w(a) = w_0 + w_a (1 - a),$$

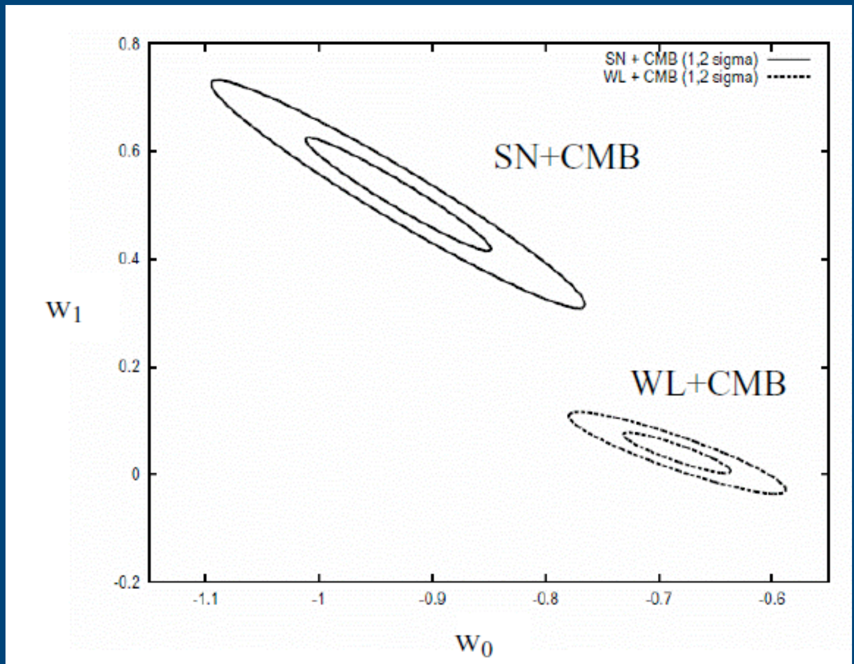
$$w_0 = -0.78,\ w_a = 0.32$$

(Linder)

Experiments

(Ishak,Upadhye and Spergel, astro-ph/0507184)

ASSUME our universe is DGP braneworld, but you do not want to believe this, so fit the data using dark energy model



$$w(z) = w_0 + w_1 z,$$

m(z):
apparent magnitude

R:
CMB shift parameter

G(a):
Growth rate

OR

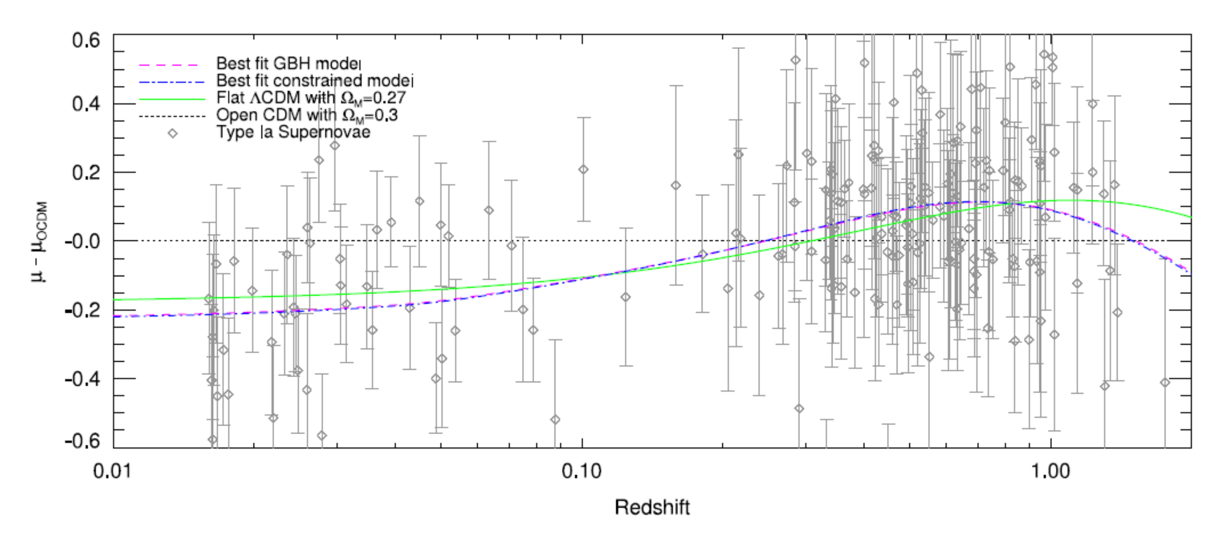
SNe+CMB

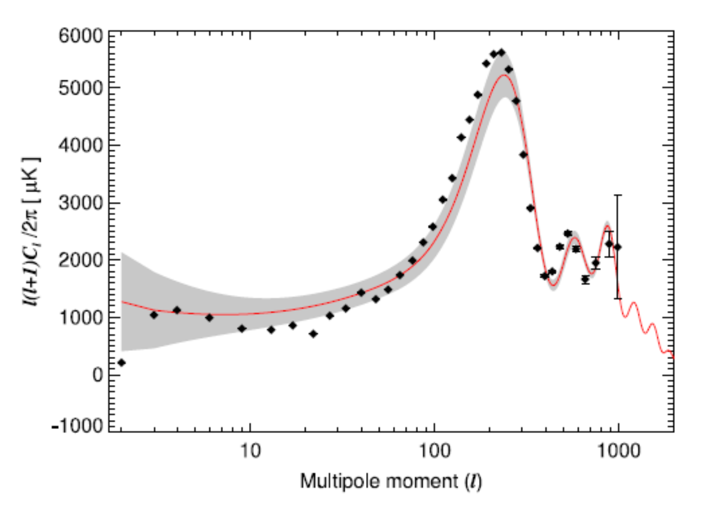
SNe+weak lensing

Inconsistent!

Confronting Local Void with Obs.

Garcia-Bellido & Haugbolle (2008)





All observations can be accommodated within 1-sigma for models with 4 or 5 parameters !

"One cannot exclude the hypothesis that we live within a large local void of an otherwise Einstein-de Sitter model."

Test of Cosmological Principle

Clarkson et al. (2008)

Luminosity distance

$$d_L(z) = \frac{(1+z)}{H_0\sqrt{-\Omega_k}} \sin\left(\sqrt{-\Omega_k}\int_0^z dz' \frac{H_0}{H(z')}\right)$$

$$d_L = (1+z)^2 d_A$$

Angular diameter distance

Curvature parameter

$$\Omega_k = \frac{[H(z)D'(z)]^2 - 1}{[H_0 D(z)]^2}$$

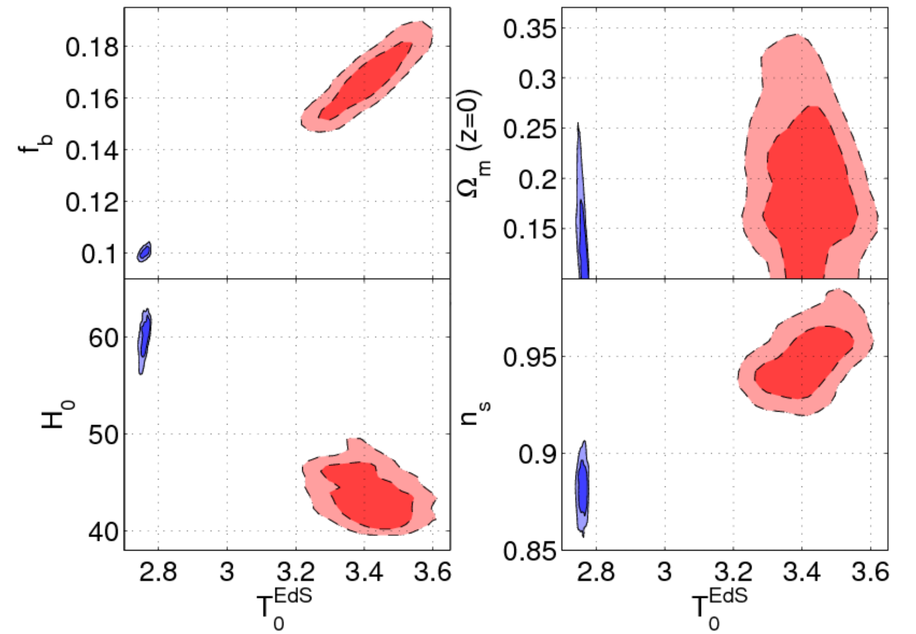
$$D = (1+z)d_A$$

$$\frac{d}{dz}\Omega_k \Rightarrow \mathcal{C}(z) = 1 + H^2(DD'' - D'^2) + HH'DD'$$

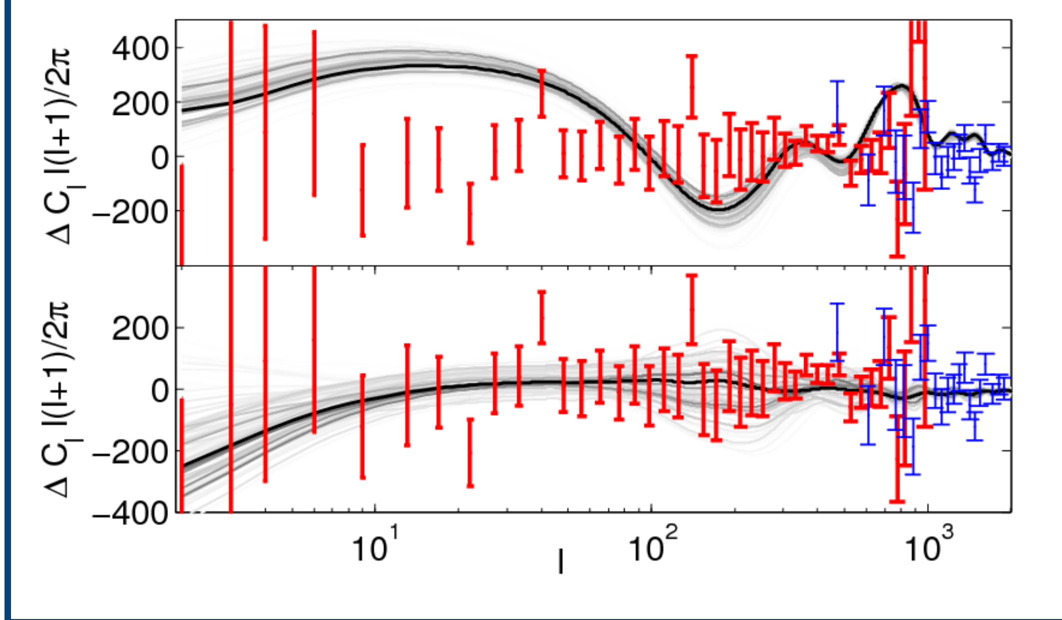
=0 if we use Friedman eq.

$\mathcal{C}(z) \neq 0$ implies violation of cosmological principle

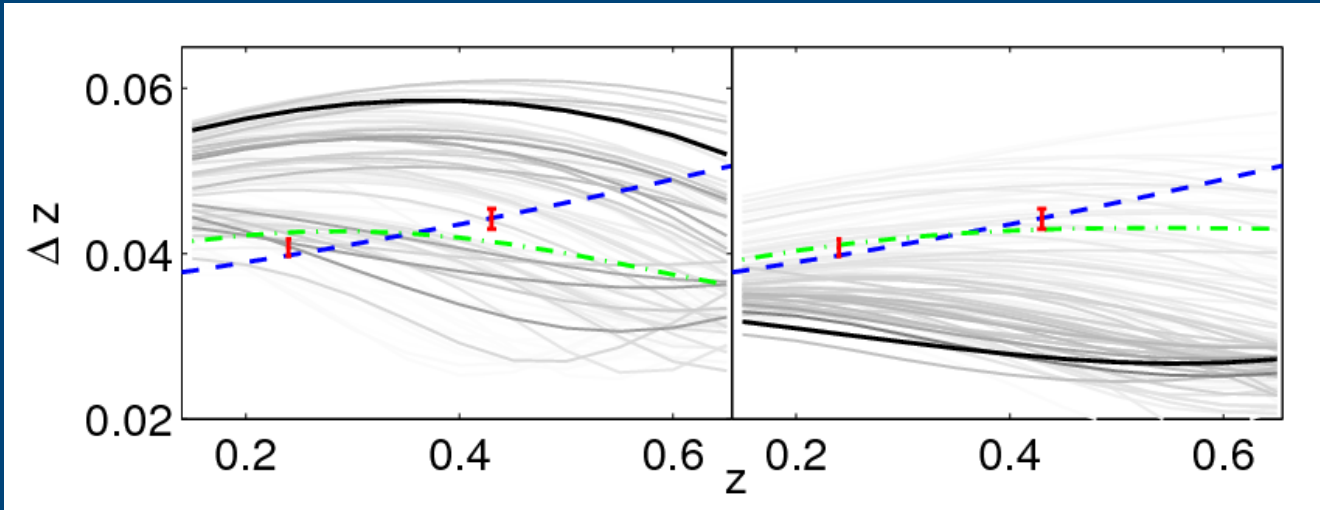
Void



f_b
0.18
0.16
0.14
0.12
0.1
H_0
60
50
40
Ω_m (z=0)
0.35
0.3
0.25
0.2
0.15
n_s
0.95
0.9
0.85
2.8 3 3.2 3.4 3.6
T_0^EdS



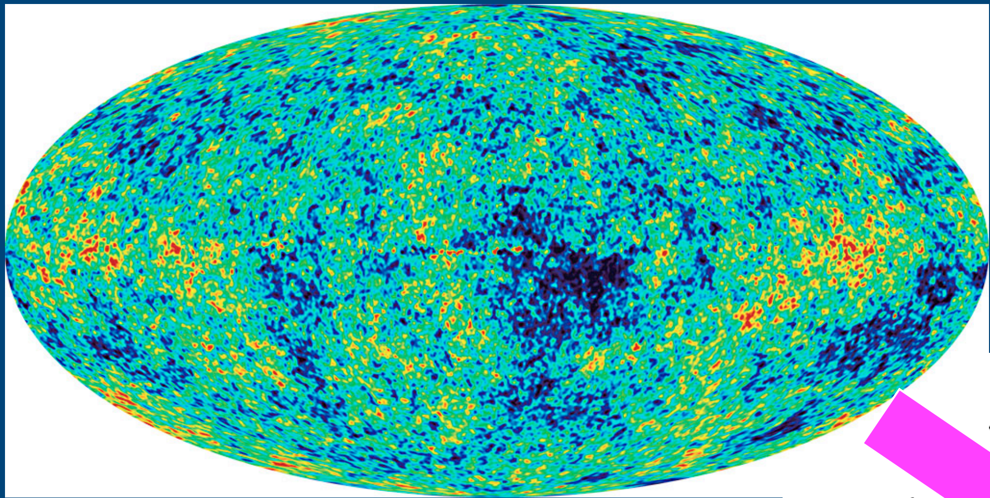
Δ C_l l(l+1)/2π
400
200
0
−200
−400
10^1
10^2
10^3
l



Δ z
0.06
0.04
0.02
0.2 0.4 0.6
z

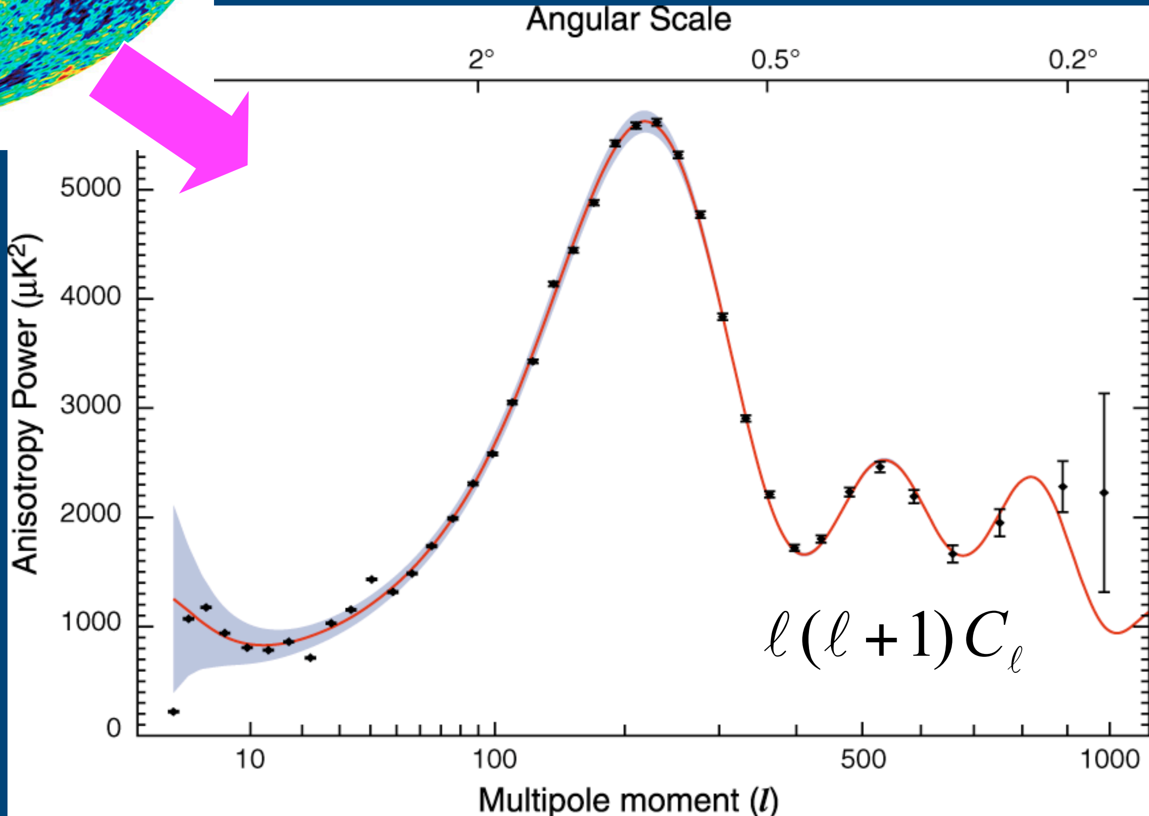
Miscellaneous

Cosmic Microwave Background



$$\Delta T(\theta,\varphi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$

$$C_\ell = \left\langle \left| a_{\ell m} \right|^2 \right\rangle$$

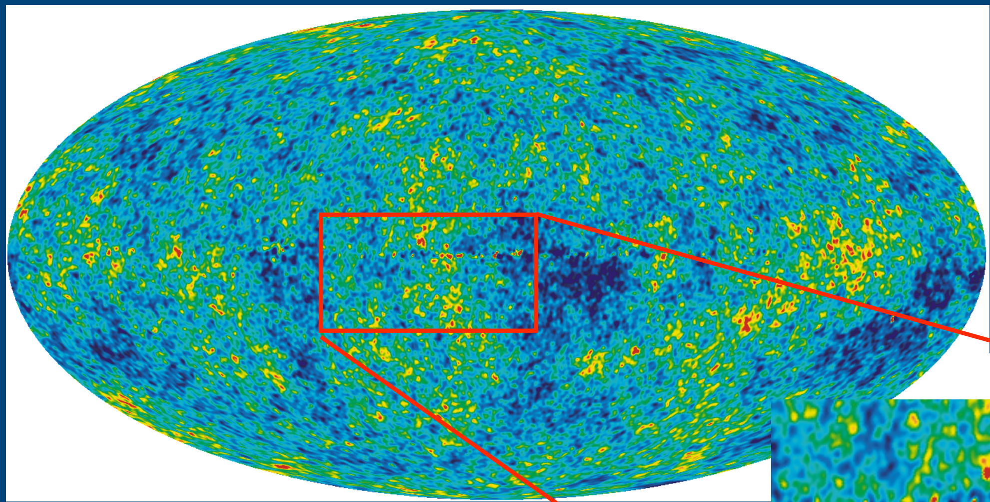


$$\ell(\ell+1)C_\ell$$

3 year WMAP result

Spergel et al. (2007)

Cosmic Microwave Background



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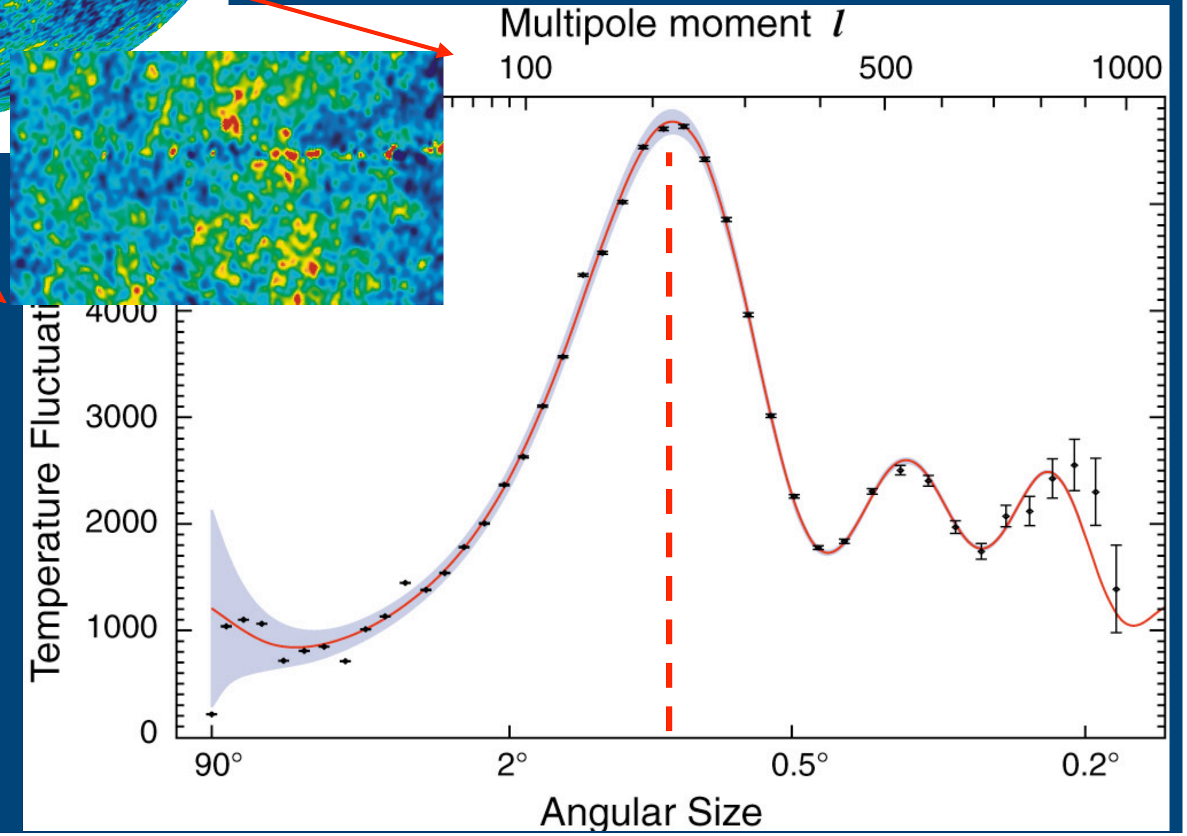

5 year WMAP result

Komatsu et al. (2008)