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第２回GCOE若手リトリート
@タナベ名古屋研修センター

Standard cosmological model & dark energy

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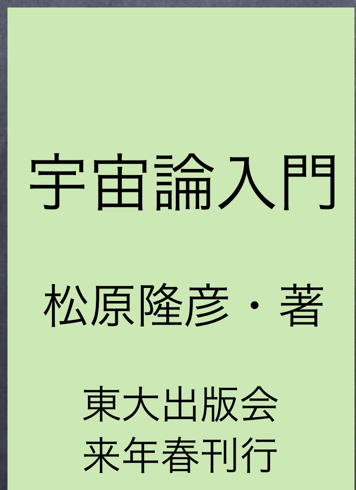
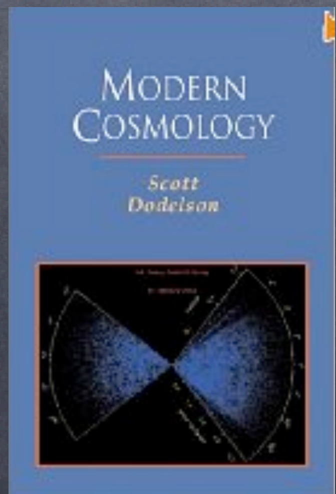
Aim of this talk

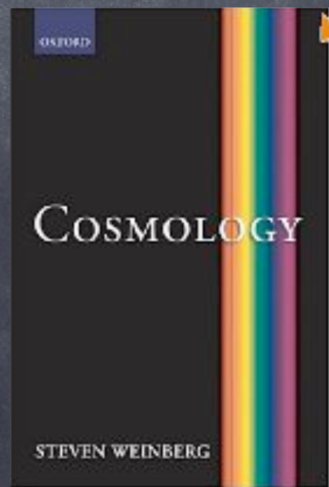
A quick overview of modern cosmology

- brief summary of cosmological physics
- concordant cosmological model: issues & prospects

For further study,







Contents

- Cosmology: fact sheets
- Designing the observed Universe
- Standard cosmological model
- Dark energy
- Future prospects: toward precision cosmology

Cosmology

Ultimate goal of cosmology

Understanding of the nature of the Universe
- Birth and evolution of the Universe
- Matter content of the Universe
- Origin of structure of the Universe
- ⋮

Starting point

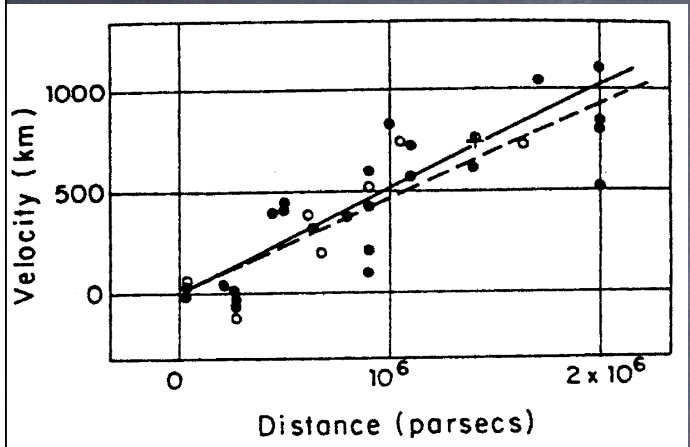
A consistent picture to explain the observed properties of the Universe

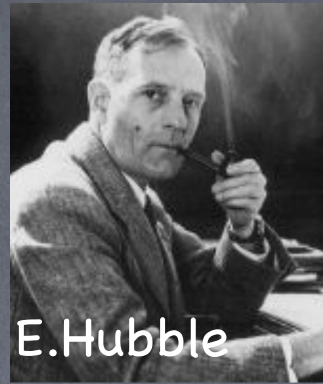
based on theory and cosmological observations

(on theory: minimal)

Fact sheets (1)

Universe is expanding



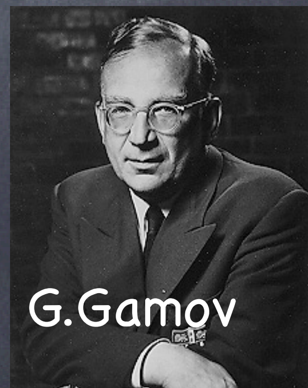


Hubble law $v = Hd$

- v: galaxy recession velocity
- d: distance between galaxy and observer

Universe started with hot plasma (**Big-Bang**):

- Nucleosynthesis → Light-element abundance
  $\mathrm{D},\ {}^3\mathrm{He},\ {}^4\mathrm{He},\ {}^7\mathrm{Li}$
- Photon decoupling from thermal bath
  → Cosmic Microwave Background (CMB)

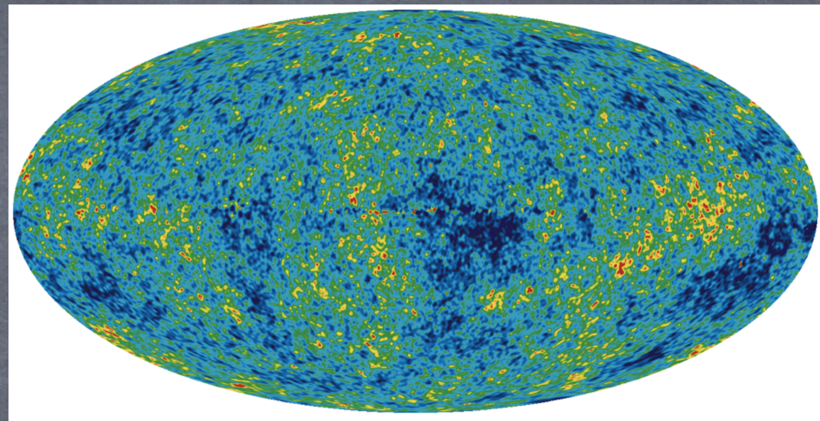


Fact sheets (2)

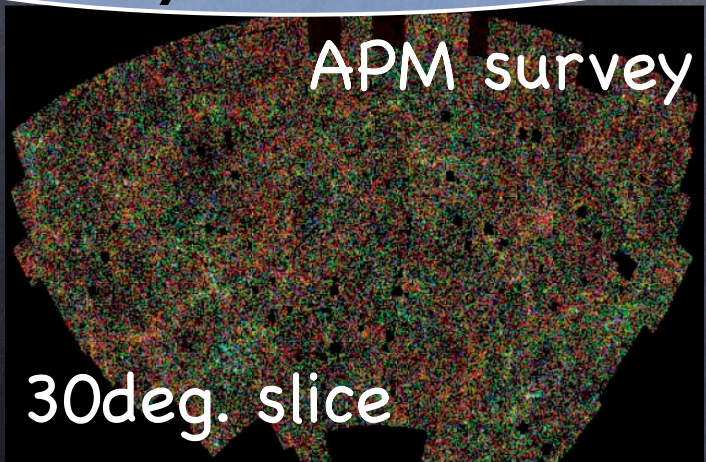
Universe is basically homogeneous,
but there exists (small) inhomogeneities

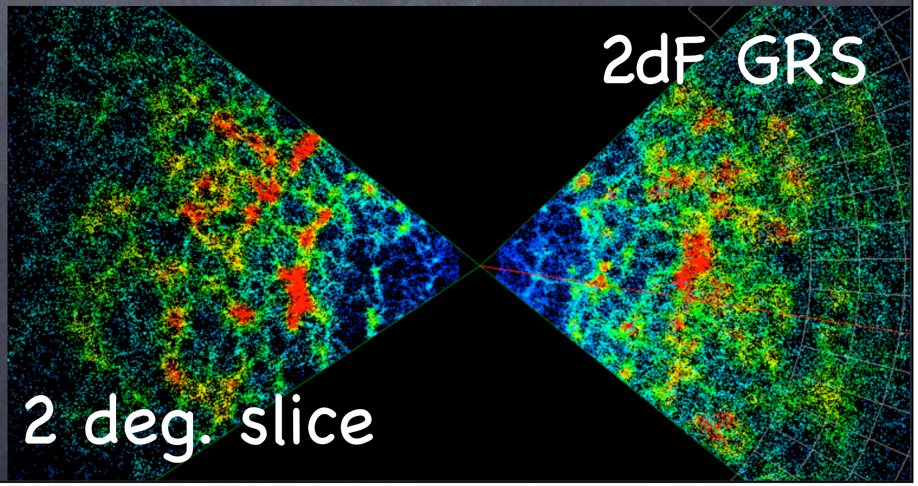
CMB

contrast $\times 10^4$



Galaxy distribution



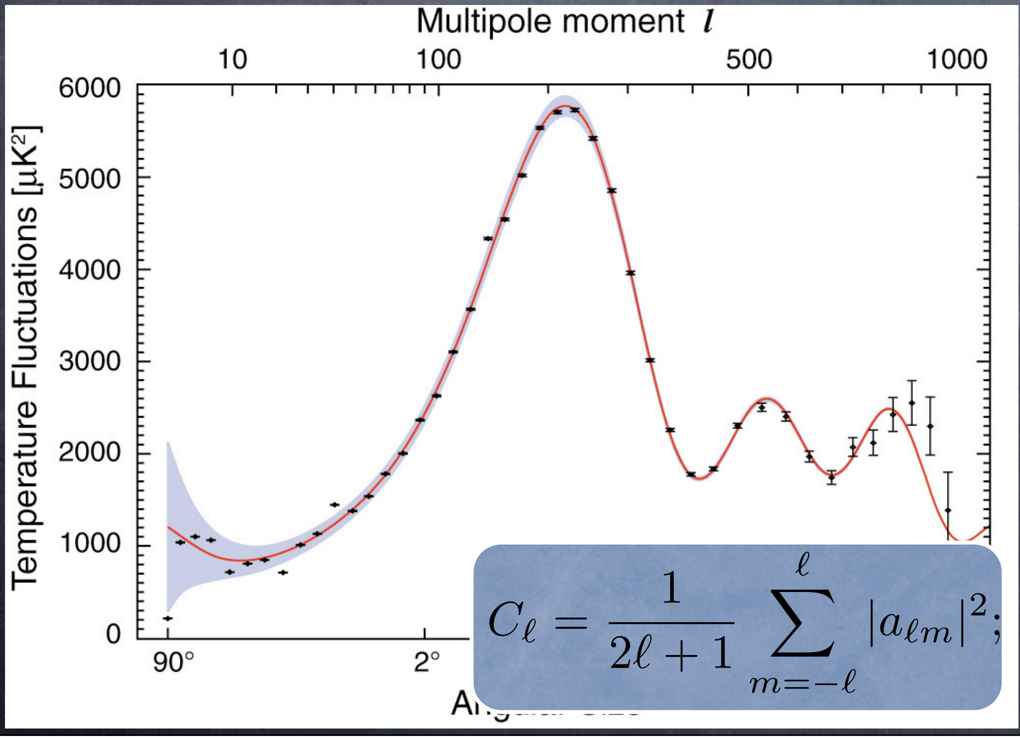


Fact sheets (3)

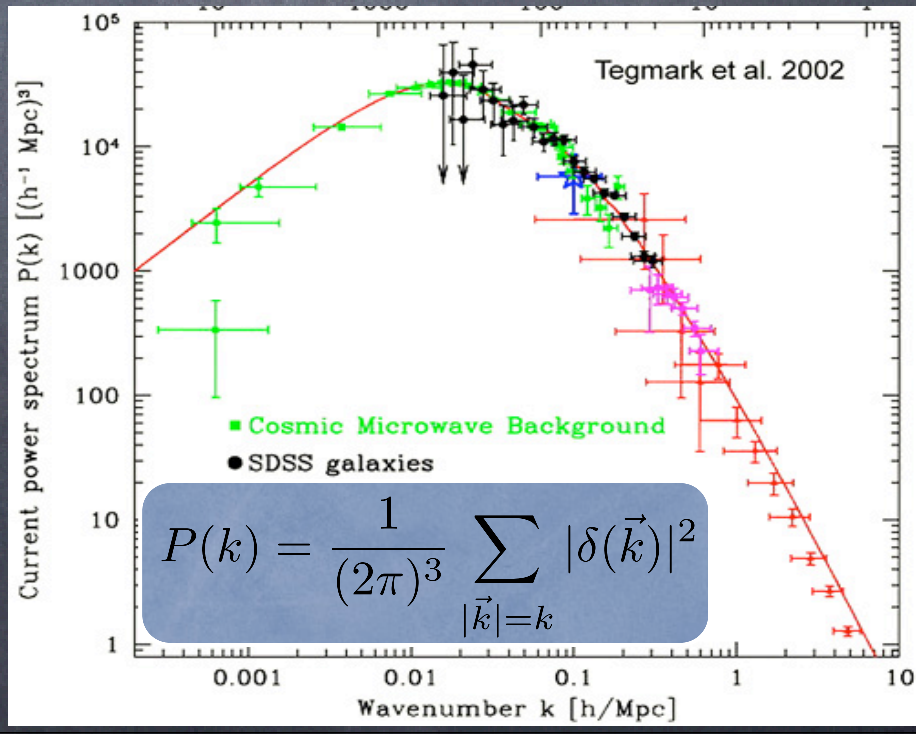
Observed inhomogeneities are apparently random, but have statistically regular nature

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

galaxies $$\frac{n_{\rm gal}(\vec{x})}{\overline{n}_{\rm gal}} - 1 = \int d^3\vec{x}\, \delta(\vec{k})\, e^{i\vec{k}\cdot\vec{x}}$$



$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2;$$



$$P(k) = \frac{1}{(2\pi)^3}\sum_{|\vec{k}|=k} |\delta(\vec{k})|^2$$

Designing the observed Universe

Basic ingredients

- Dynamics of cosmic expansion

  thermal history of the Universe (hot Big-Bang)

- Structure formation

  large-scale structure (LSS) in CMB & galaxy distribution

To understand these, we need both
microphysics and macro-physics

Underlying physics (1)

Standard assumptions

- Dynamics of cosmic expansion:

  general relativity under the cosmological principle
  (homogeneous & isotropic)

- Evolution of inhomogeneities:

  general-relativistic perturbation theory
  coupled with non-equilibrium transport processes

  ↖ microphysics

Key word **Gravity**

Underlying physics (2)

Friedman equation

- basic eq. that describes cosmic expansion
- scale factor 'a' is dynamical variable

(∼size of the Universe)

Einstein eq. with Robertson-Walker metric

$$\rho_{\rm crit} \equiv \frac{3H_0^2}{8\pi G}$$

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{H_0^2 \Omega_K}{a^2}\ ; \quad \rho = \rho_{\rm m} + \rho_{\rm r} + \rho_{\rm DE}$$

$$= \rho_{\rm crit}\left(\frac{\Omega_{\rm m}}{a^3} + \frac{\Omega_{\rm r}}{a^4} + \frac{\Omega_{\rm DE}}{a^{3(w+1)}}\right)$$

H_0 : Hubble parameter at present

※ a=1 implies present time

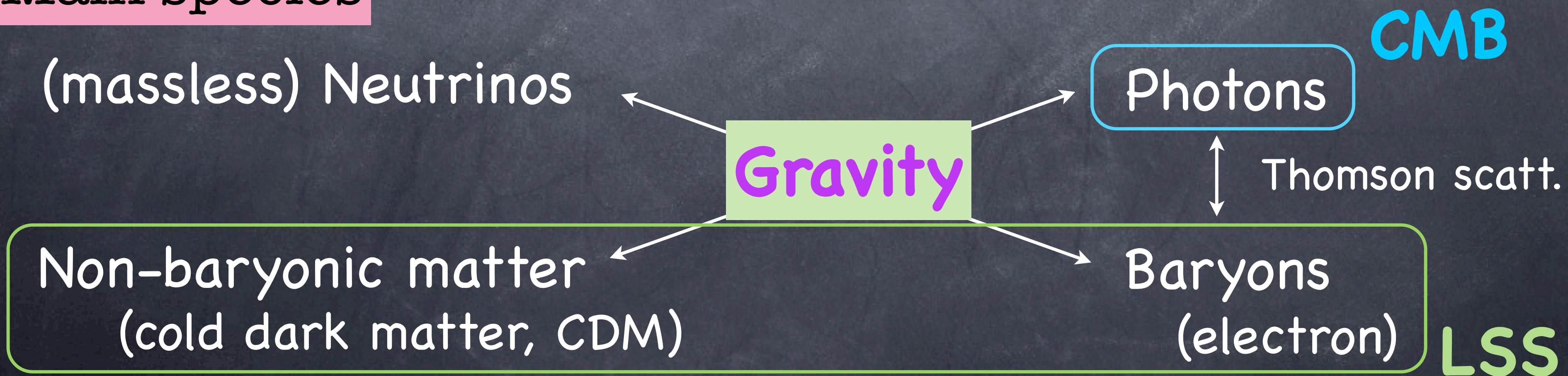
- density parameter of mass $\quad \Omega_{\rm m} = \Omega_{\rm b} + \Omega_{\rm CDM} + \Omega_\nu$
- curvature parameter $\quad \Omega_{\rm K} = \Omega_{\rm m} + \Omega_{\rm r} + \Omega_{\rm DE} - 1 \cong \Omega_{\rm m} + \Omega_{\rm DE} - 1$

Underlying physics (3)

Minimal set of eqs. that account for inhomogeneities (CMB & LSS):

- Cosmological perturbation
  (general-relativistic linear perturbation)
- Relativistic Boltzmann eqs.+ Ionization rate eq.

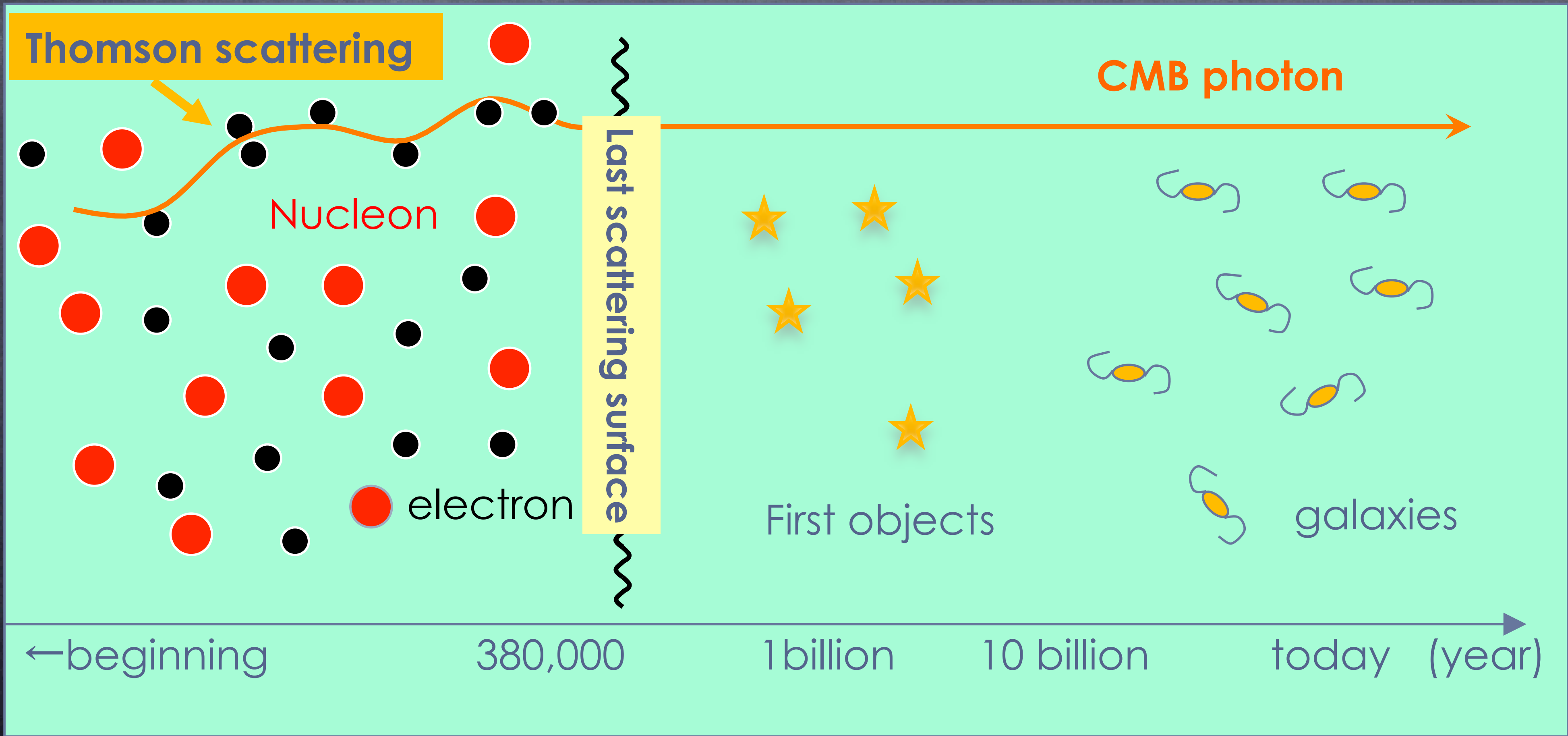
Main species



Basic picture (1)

Microphysics

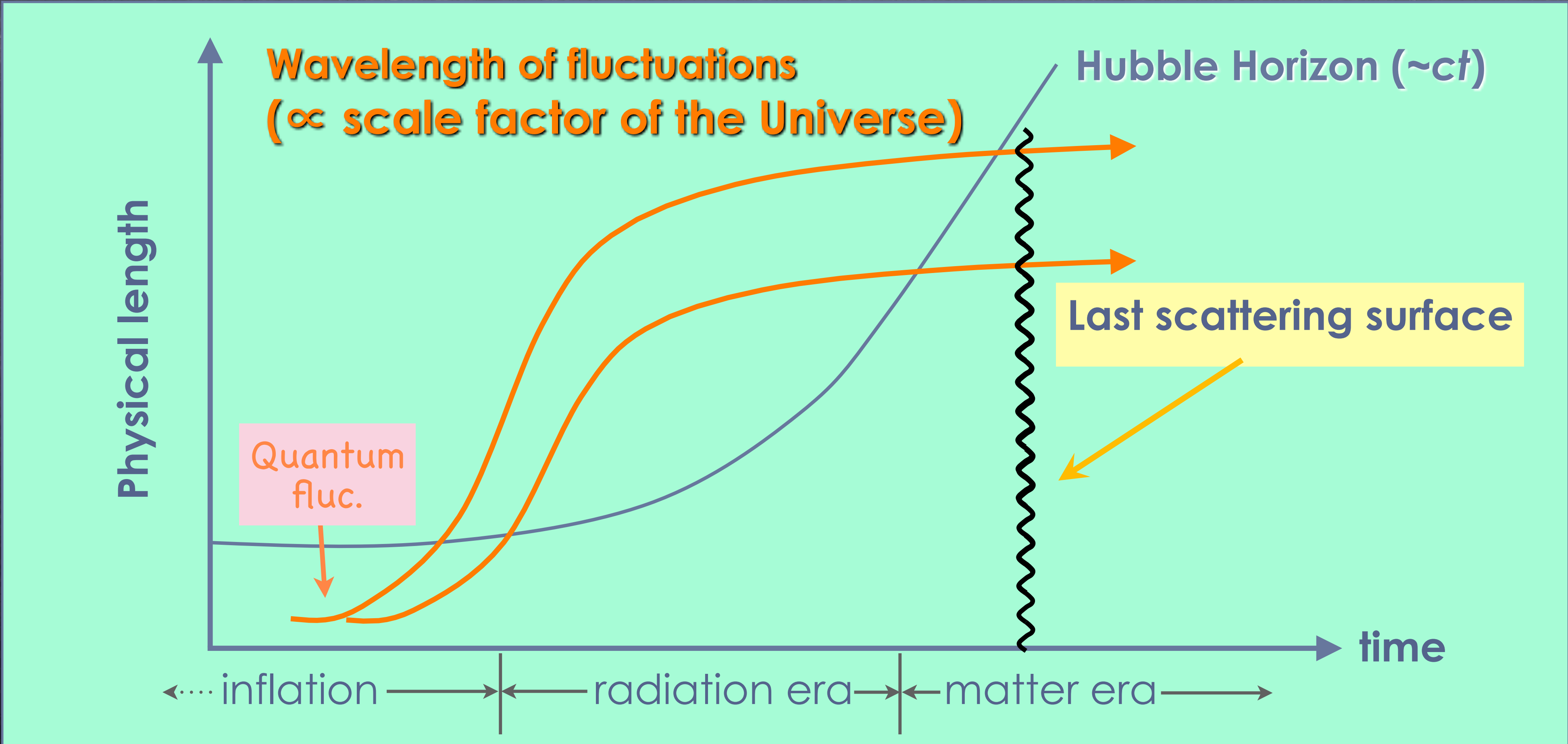
Electromagnetic interaction between the recombination and decoupling time



Basic picture (2)

Macro-physics

Evolution of super-horizon scale fluctuations based on general relativity



Basic equations : summary

Friedman eq.

$$H^2 = H_0^2 \left\{ (1+z)^3 \Omega_{\rm m} + (1+z)^4 \Omega_{\rm r} + (1+z)^{3(1+w)} \Omega_{\rm DE} \right\}$$

Assuming flat universe ($\Omega_{\rm K} = 0$)

Cosmological perturbation coupled with Boltzmann eqs.

$$k^2 \Phi + 3\mathcal{H}\left(\dot{\Phi} - \mathcal{H}\Psi\right) = 4\pi G a^2 \left[\rho\delta + \rho_b \delta_b + 4\rho_r \Theta_0 + 4\rho_\nu \mathcal{N}_0\right]$$

$$k^2 (\Phi + \Psi) = -32\pi G a^2 \left[\rho_r \Theta_2 + \rho_\nu \mathcal{N}_2\right]$$

$$\dot{\Theta} + ik\mu\Theta = -\dot{\Phi} - ik\mu\Psi - \dot{\tau}\left[\Theta_0 - \Theta + \mu v_b - \frac{1}{2}\mathcal{P}_2 \Pi\right]$$

$$\dot{\Theta}_P + ik\mu\Theta_P = -\dot{\tau}\left[-\Theta_P + \frac{1}{2}(1 - \mathcal{P}_2)\Pi\right]$$

$$\dot{\delta}_b - k v_b = -3\dot{\Phi}$$

$$\dot{v}_b + \mathcal{H} v_b = -ik\Psi + \frac{\dot{\tau}}{R}[v_b + 3i\Theta_1]$$

$$\dot{\delta} - kv = -3\dot{\Phi}$$

$$\dot{v} + \mathcal{H} v = -ik\Psi$$

$$\dot{\mathcal{N}} + ik\mu\mathcal{N} = -\dot{\Phi} - ik\mu\Psi$$

$\Phi(k), \ \Psi(k)$:

gravitational potential & curvature perturbation

$\Theta(k, \mu)$:

(photon) temperature fluc.

$\mathcal{N}(k, \mu)$:

neutrino fluc. (massless)

$\delta_b(k), \ v_b(k)$:

baryon density & velocity fluc.

$\delta(k), \ v(k)$:

CDM density & velocity fluc.

Relation with Observables

Solutions of these eqs. can be translated to observables:

LSS

Matter power spectrum

$$P(k) = P_{\rm init}(k) \left| \frac{\delta_{\rm m}(k;\eta_0)}{\delta_{\rm m}(k;\eta_{\rm init})} \right|^2$$

primordial matter spectrum

$$\delta_{\rm m} \equiv \frac{\Omega_{\rm c}}{\Omega_{\rm m}}\delta_{\rm c} + \frac{\Omega_{\rm b}}{\Omega_{\rm m}}\delta_{\rm b} + \frac{\Omega_{\nu}}{\Omega_{\rm m}}\delta_{\nu}$$

CMB

Angular power spectrum of temperature anisotropies

$$C_\ell = \frac{2}{\pi}\int_0^\infty dk\, k^2\, P_{\rm init}(k) \left| \frac{\Theta_\ell(k;\eta_0)}{\delta_{\rm m}(k;\eta_{\rm init})} \right|^2$$

There are several publicly available code to solve these eqs.:

CMBfast, CAMB, CMBEASY, ...

http://lambda.gsfc.nasa.gov/toolbox/

Model parameters

There are a number of model parameters to be specified

- Initial conditions (adiabatic) ················ $P_{\mathrm{init}}(k)$

  A_s scalar amplitude

  n_s scalar spectral index

  α_s scalar running index

  r tensor-to-scalar ratio $= \dfrac{A_t}{A_s}$

  n_t tensor spectral index

  # of parameters further increases if we consider isocurvature fluc.

- Cosmic expansions

  density parameters $\Omega_{\mathrm{c}},\ \Omega_{\mathrm{b}},\ \Omega_{\nu},\ \Omega_{\mathrm{DE}}$

  dark energy E.O.S w

  curvature parameter Ω_{K}

  Hubble parameter $h = H_0/(100\mathrm{km/Mpc})$

- Others

  reionization optical depth τ

  There exist other nuisance parameters such as galaxy bias

Minimal model

- Adiabatic power-law & no tensor contribution

$$\alpha_s = r = n_t = 0$$

- Flat cosmology, massless neutrinos, cosmological const.

$$\Omega_{\rm K} = \Omega_\nu = 0, \;\; w = -1$$

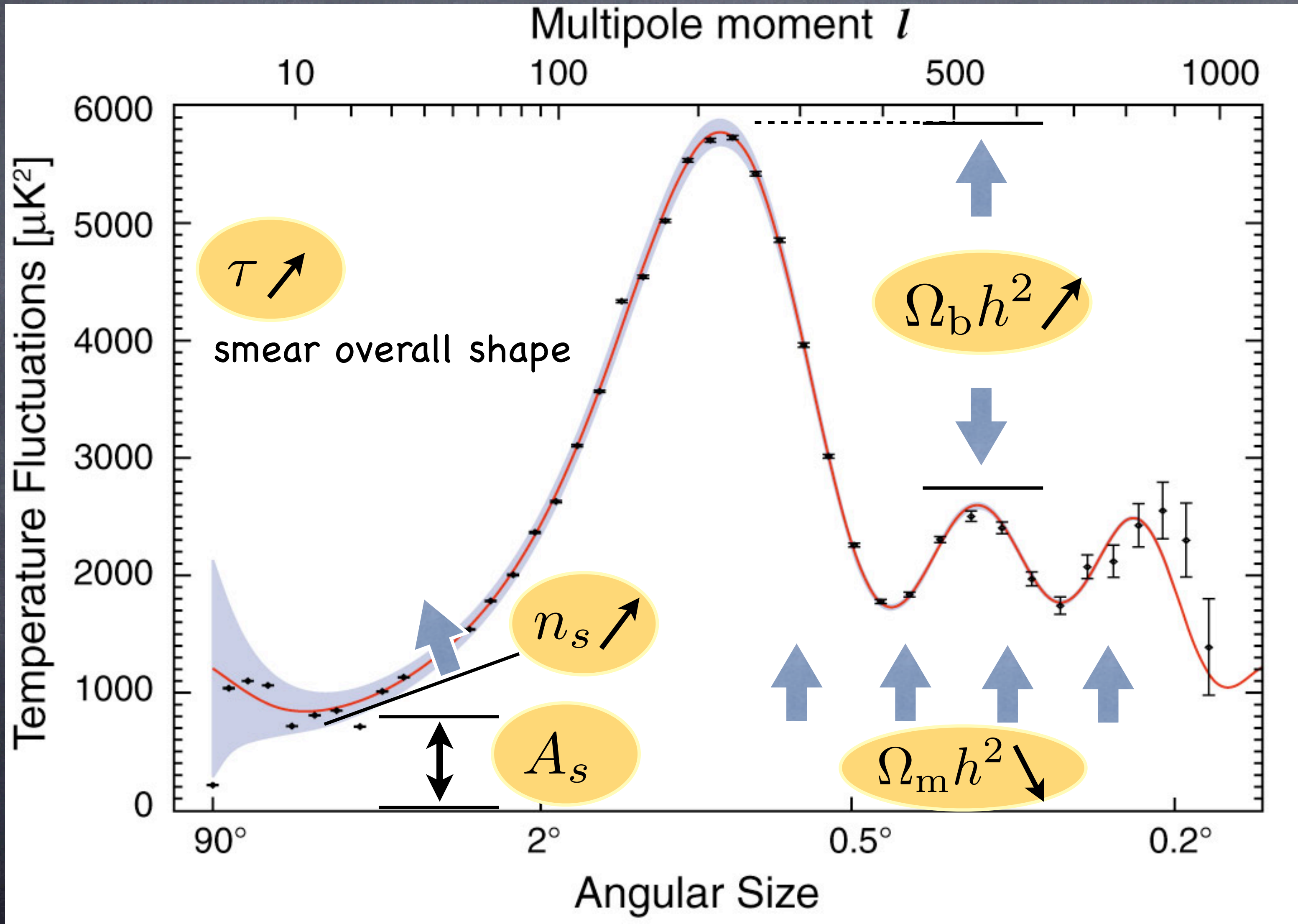
A_s	scalar amplitude
n_s	scalar spectral index
$\Omega_{\rm c}$	density parameter of CDM
$\Omega_{\rm b}$	density parameter of baryon
h	Hubble parameter
τ	reionization optical depth

In total,
6 parameters

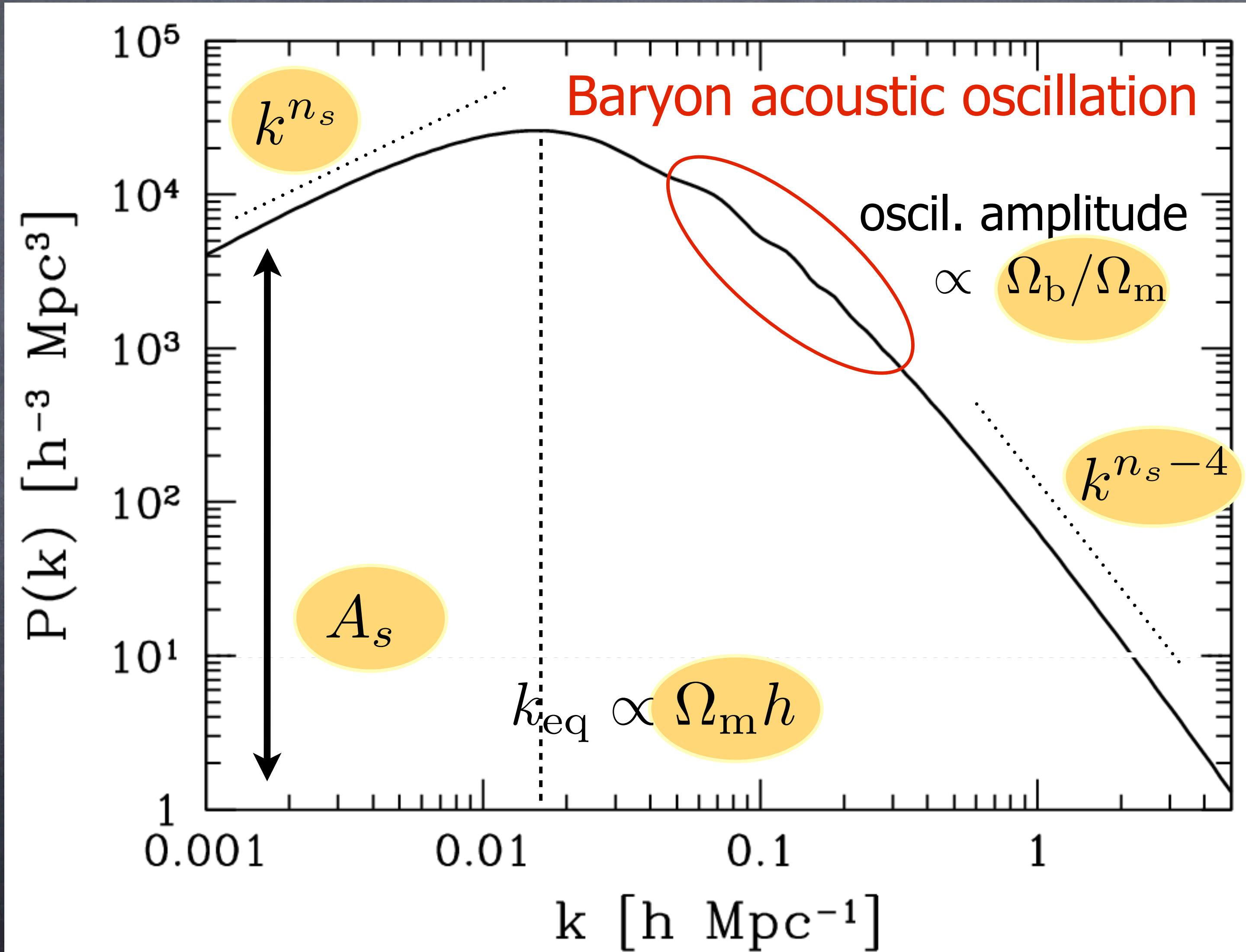
Note-.

$$\Omega_{\rm DE} = 1 - \Omega_{\rm c} - \Omega_{\rm b}$$

Parameter dependence: CMB



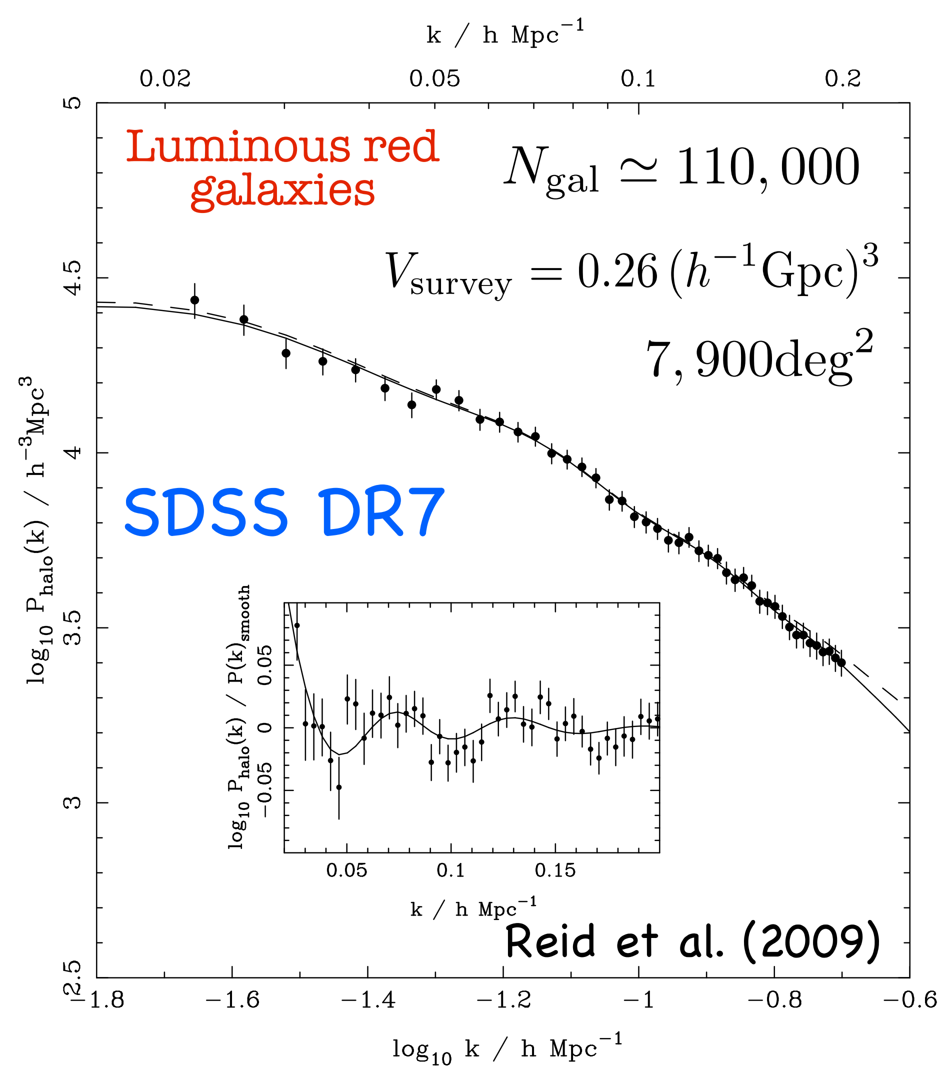
Parameter dependence: LSS

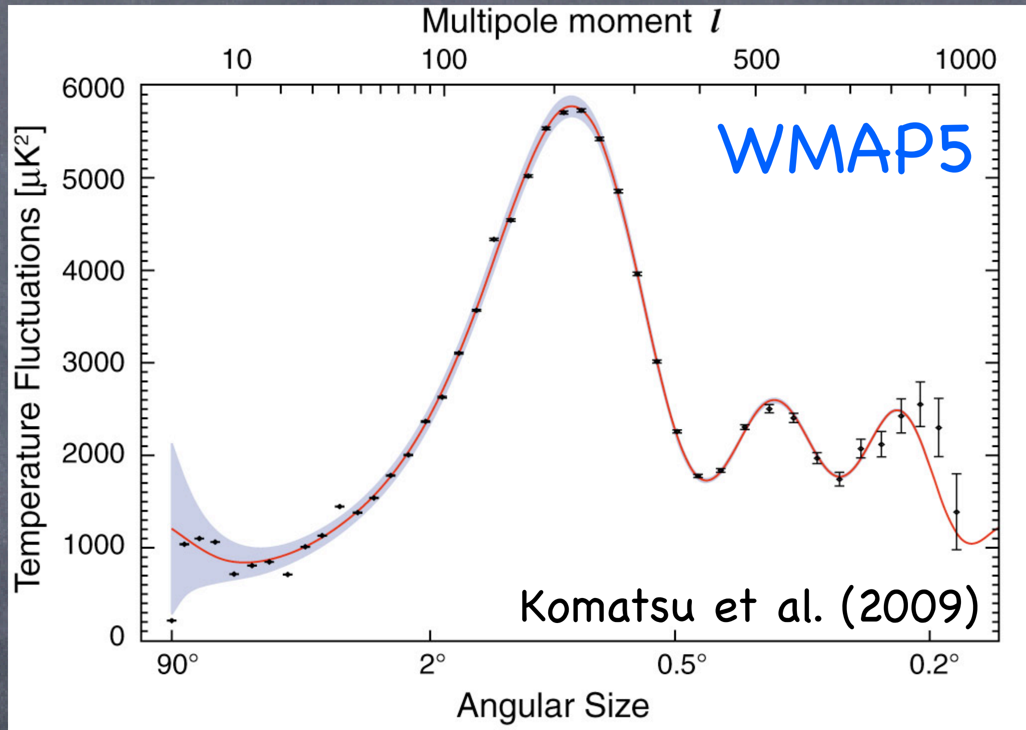


Latest results

Large-scale structure

CMB





In addition, distance-redshift measurement from distant supernova observation is used

Results of parameters

WMAP5 + SDSS DR7

parameter	ΛCDM
Ω_m	0.289 ± 0.019
H_0	69.4 ± 1.6
$D_V(0.35)$	1349 ± 23
$r_s/D_V(0.35)$	0.1125 ± 0.0023
Ω_k	-
w	-
Ω_Λ	0.711 ± 0.019
Age (Gyr)	13.73 ± 0.13
$\Omega_{\rm tot}$	-
$100\Omega_b h^2$	2.272 ± 0.058
$\Omega_c h^2$	$0.1161^{+0.0039}_{-0.0038}$
τ	0.084 ± 0.016
n_s	0.961 ± 0.013
$\ln(10^{10} A_{05})$	$3.080^{+0.036}_{-0.037}$
σ_8	0.824 ± 0.025

Reid et al. (2009) arXiv:0907.1659

c.f. WMAP5 only

Parameter	*WMAP* 5 Year Mean[b]
$100\Omega_b h^2$	2.273 ± 0.062
$\Omega_c h^2$	0.1099 ± 0.0062
Ω_Λ	0.742 ± 0.030
n_s	$0.963^{+0.014}_{-0.015}$
τ	0.087 ± 0.017
$\Delta^2_{\mathcal{R}}(k_0^c)$	$(2.41 \pm 0.11) \times 10^{-9}$

Komatsu et al. (2009)
ApJ.Suppl. 180, 330

$A_s \simeq 2.4 \times 10^{-9}$
$n_s \simeq 0.96$
$\Omega_c \simeq 0.24$
$\Omega_b \simeq 0.047$
$h \simeq 0.69$
$\tau \simeq 0.08$

Note

Extension of parameter set does not significantly change the results

- spectral running
- curvature
- neutrino masses
- tensor contribution
- ...

Minimal 6-parameter model is currently the best standard cosmological model that explains all the observations

From WMAP papers,

Spergel et al. (2003)

8. CONCLUSIONS

Cosmology now has a standard model: a flat universe composed of matter, baryons, and vacuum energy with a nearly scale-invariant spectrum of primordial fluctuations. In this cosmological model, the properties of the universe are characterized by the density of baryons, matter, and the expansion rate:
results, all of the
rated in a single
tion, τ. The pr
characterized by
an adequate fit
polarization data
scale structure da
sistent with the b
tions of D/H in

Spergel et al. (2007)

9. CONCLUSIONS

The standard model of cosmology has survived another rigorous set of tests. The errors on the *WMAP* data at large *l* are now 3 times smaller, and there have been significant improvements in other cosmological measurements. Despite the overwhelming force of the data, the model continues to thrive. This was the basic result of Spergel et al. (2003) and was reinforced by subsequent analyses of the first-year *WMAP* data with the SDSS (Tegmark et al. 2004a) and analy
2dFGRS survey (Sanche
paper were completed, a

Komatsu et al. (2007)

7. CONCLUSION

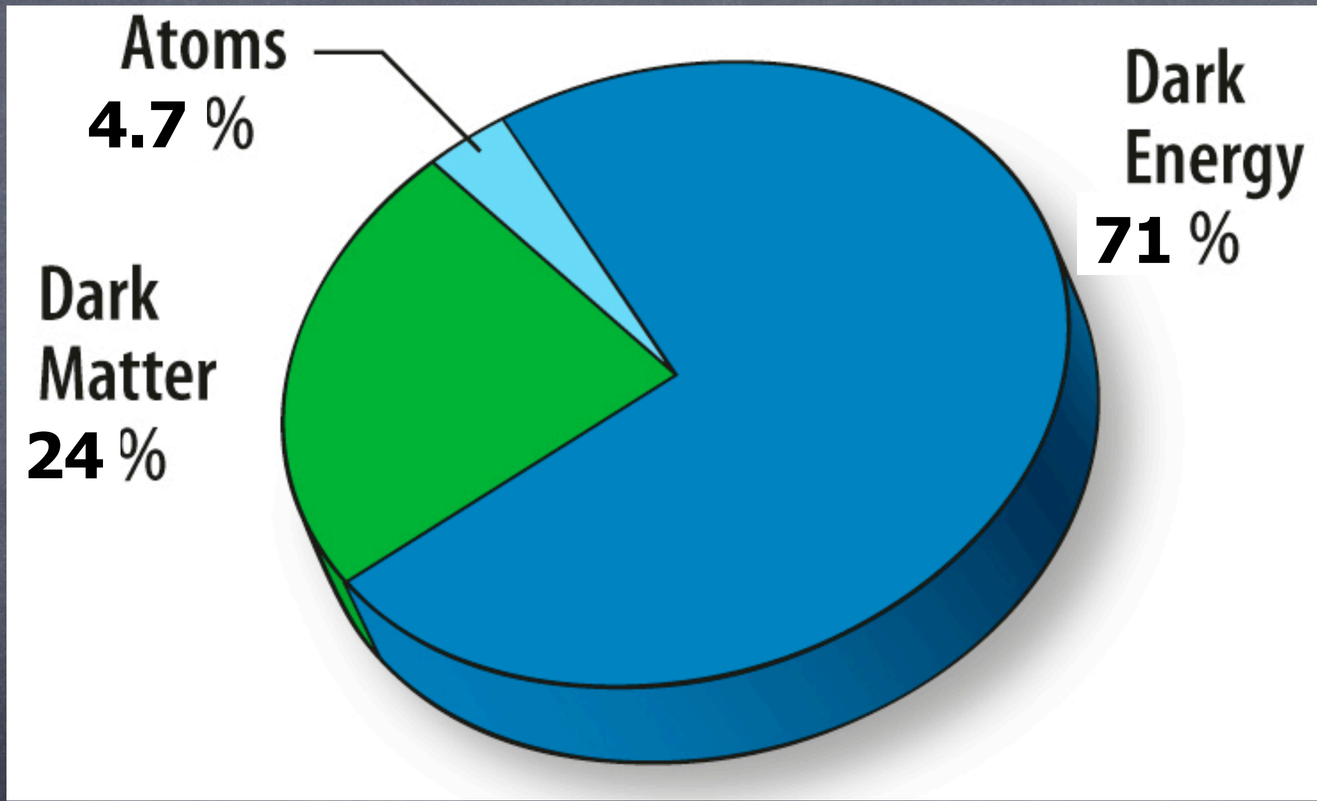
With 5-years of integration, the *WMAP* temperature and polarization data have improved significantly. An improved

. . . . . .

From these studies, we conclude that we have not detected any convincing deviations from the simplest six-parameter ΛCDM model at the level greater than 99% CL. By combining *WMAP* data with the distance information from BAO and SN, we have improved the accuracy of the derived cosmological parameters.

Cosmic pie

Energy composition of the Universe today



The Universe is occupied with unknown components, dark energy and dark matter

Are you really happy about that ?

WMAP papers, again

Cosmology is now in a similar stage in its intellectual development to particle physics three decades ago when particle physicists converged on the current standard model. The standard model of particle physics fits a wide range of data but does not answer many fundamental questions: What is the origin of mass? Why is there more than one family? etc. Similarly, the standard cosmological model has many deep open questions: What is the dark energy? What is the dark matter? What is the physical model behind inflation (or something like inflation)? Over the past three decades, precision tests have confirmed the standard model of particle physics and searched for distinctive signatures of the natural extension of the standard model: supersymmetry. Over the coming years, improving CMB, large-scale structure, lensing, and supernova data will provide ever more rigorous tests of the cosmological standard model and search for new physics beyond the standard model.

Spergel et al. (2003)

Beyond standard model

To do list

Clarifying the nature of dark energy

Constraining early-universe physics

- Adiabaticity of initial condition
- Non-Gaussianity of primordial fluctuations
- Evidence of spectral running
- Detection of non-zero tensor mode

Test of hypothetical assumptions

- General relativity on cosmological scales

Constraining particle physics

- Detection of non-zero neutrino mass

Cosmic acceleration

Sizable amount of dark energy implies that the Universe just started an accelerated expansion

Friedman eq.

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

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

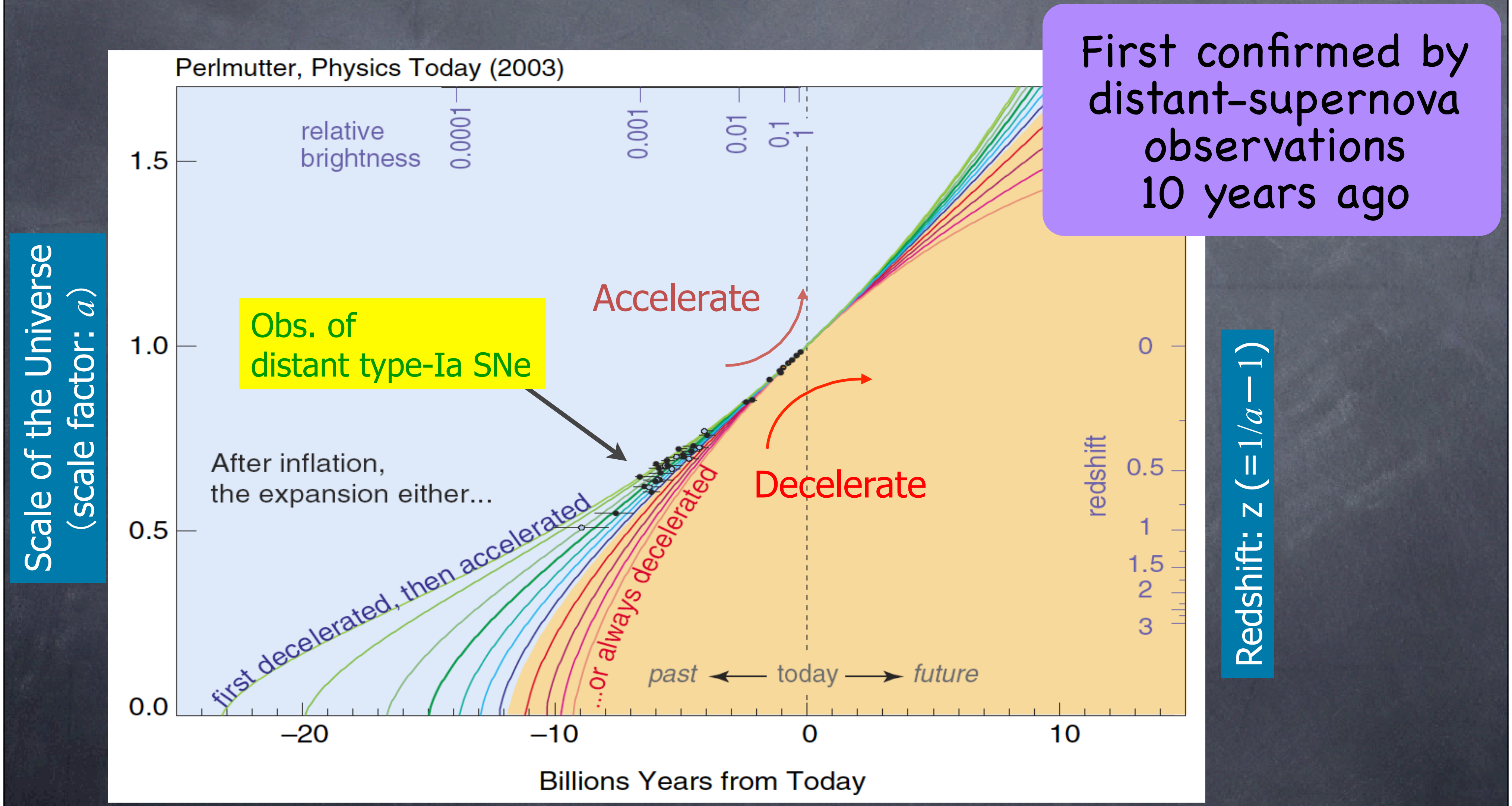
$$P \simeq P_{\rm DE} \approx -\rho_{\rm DE}$$

Since $\rho_{\rm m} > \rho_{\rm DE}$

$$\left.\frac{\ddot{a}}{a}\right|_{\rm today} \approx -\frac{4\pi G}{3}\left(\rho_{\rm m} - 2\rho_{\rm DE}\right)\Big|_{\rm today} > 0$$

Acceleration !

Evidence of cosmic acceleration



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

Nature of dark energy (1)

Cosmological constant

- First invented by Einstein in 1917
- Vacuum energy equivalent to $P_{\rm DE} = -\rho_{\rm DE} = -\dfrac{\Lambda}{8\pi G}$

$$\Lambda \sim 10^{-120} M_{\rm pl}^4$$

Un-naturally small !!

Dynamical scalar field

- Lagrangian density $L = \dfrac{1}{2}\dot{\phi}^2 - V(\phi)$

$\longrightarrow$ effective eq. of state $P_\phi = w(t)\,\rho_\phi\ ;\ w(t) = \dfrac{\dot{\phi}/2 - V(\phi)}{\dot{\phi}/2 + V(\phi)} < -\dfrac{1}{3}$

- Fine-tuning problem, ...

Alternative possibilities

As alternative explanation to cosmic acceleration, we may abandon the standard model assumptions

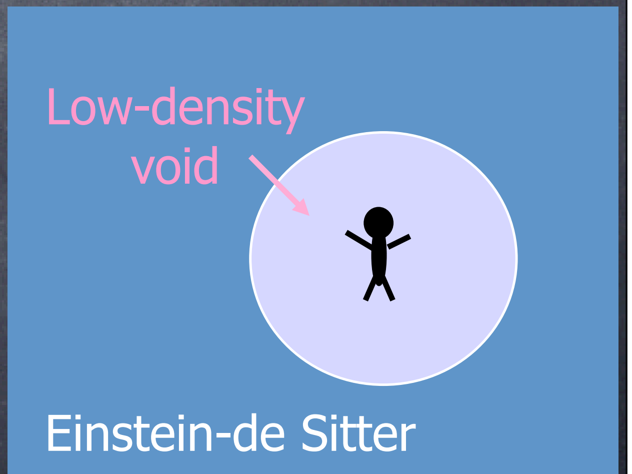
Modification to general relativity

- Hidden gravity sector that modifies Friedman eq.

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

Violation of cosmological principle

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



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 !!

Primary goal

$$\frac{P_{\rm DE}}{\rho_{\rm DE}} = w_0 + (1-a)\,w_a$$

w_0 : ~few %

w_a : ~10 %

- Cosmological constant or not

Executive reports

「Report on the Dark Energy Task Force (DETF)」

Albrecht et al. astro-ph/0609591

We strongly recommend that there be an aggressive program to explore dark energy as fully as possible, …

「Report by the ESA-ESO Working Group on Fundamental Cosmology」

Peacock et al. astro-ph/0610906

..., studies of dark energy and inflation are of the utmost interest to the science community well beyond astrophysics.

Future missions for dark energy

DETF categories

			Improvement factor normalized by stage 2
Stage 1	Current status	WMAP, SCP, 2dF, SDSS-LRG, ...	$\Delta w_0 \sim 5\%$, $\Delta w_a \sim 40\%$ including CMB prior
Stage 2	On-going project	SDSS-II, CFHT-SNLS, CFHTLS, ...	**1**
Stage 3	Near-term project (~2014+)	DES, Pan-STARRS4, **SuMIRe**, BOSS	**~ 3**
Stage 4	Long-term project (~2020+)	LSST, JDEM (space), SKA	**~ 10**

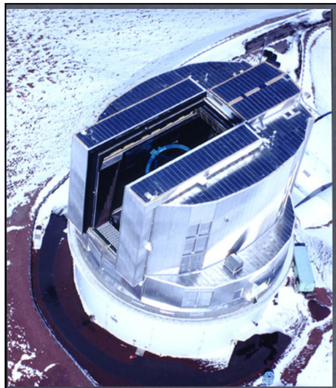
Observational techniques

Precision measurement of { cosmic expansion history / growth of structure }

● (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

Combination of different techniques is quite essential



SuMIRe

Subaru **M**easurement of **I**maging and **Re**dshift

New instruments mounted on Subaru 8.2m telescope:

- Hyper Suprime-Cam (HSC)
  1.5 deg^2 FOV wide-field CCD camera
- Prime Focus Spectrograph (PFS)
  3,000 multi-fiber spectrograph

Imaging survey → Weak lensing measurement
Spectroscopic survey → Baryon acoustic oscillations

The project has been approved by the Council for Science and Technology Policy
(P.I. H. Murayama, IPMU)

Toward precision cosmology

All the signals or features indicating beyond-standard model are basically very weak

Key ingredients:

Precision measurements

- large samples & huge observational volume
- reducing statistical errors and unknown systematics

Precision theoretical calculations

- including various systematic effects ignored currently

Synergy of theory and observation is really demanding

Summary

Cosmology has a minimum standard model that accounts for the observed Universe

- Cosmic expansion
- Thermal history
- Structure formation

But still, our understanding of the Universe is lacking :

- Nature of dark energy / cosmic acceleration
- Origin of inhomogeneities
- Physical model of early universe (inflation)

Next-generation precision cosmology will find an important clue to resolve these issues

Appendix

Baryon acoustic oscillation (BAO)

- Acoustic signature of primeval baryon-photon fluid just before the time of photon decoupling

  $\longrightarrow$ imprinted on galaxy power spectrum

- Characteristic scale of BAO, determined by sound horizon at decoupling time, provides a robust & unique measure.

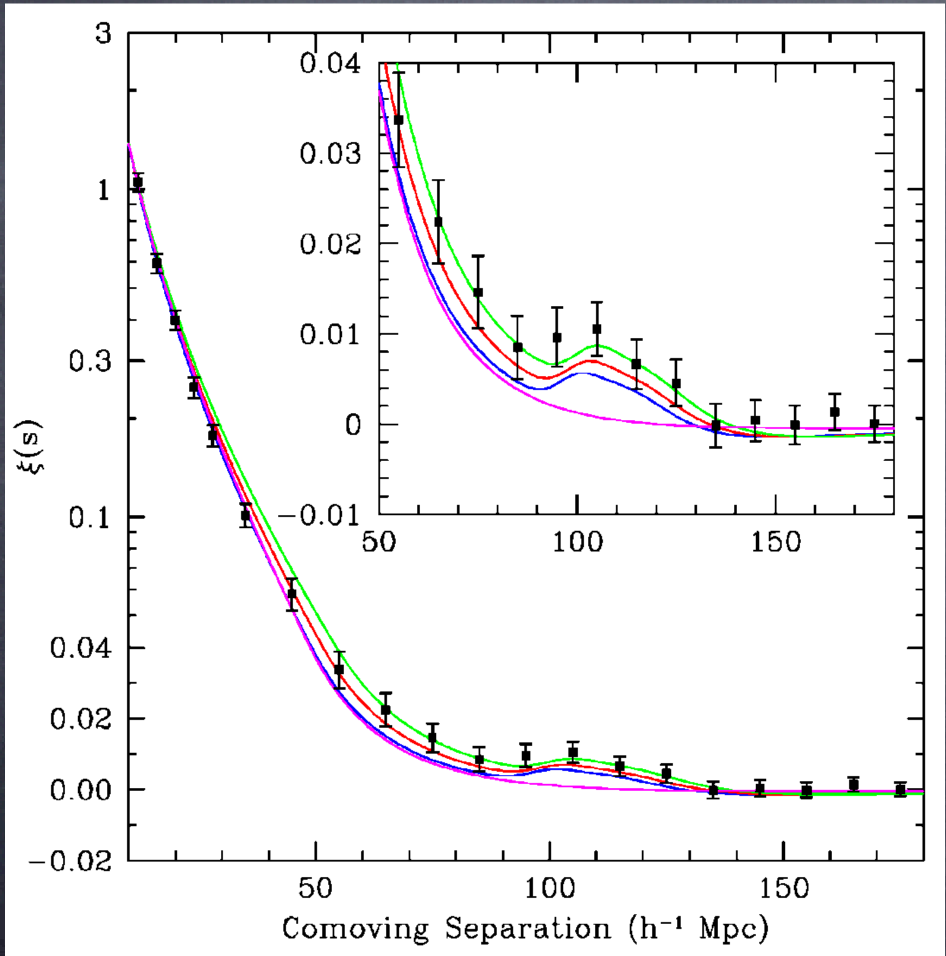
$$r_s \simeq 110 h^{-1}\mathrm{Mpc}$$

$\Rightarrow$ ***Cosmic standard ruler*** to measure the distance-redshift relation for high-z galaxies

Observation of BAO

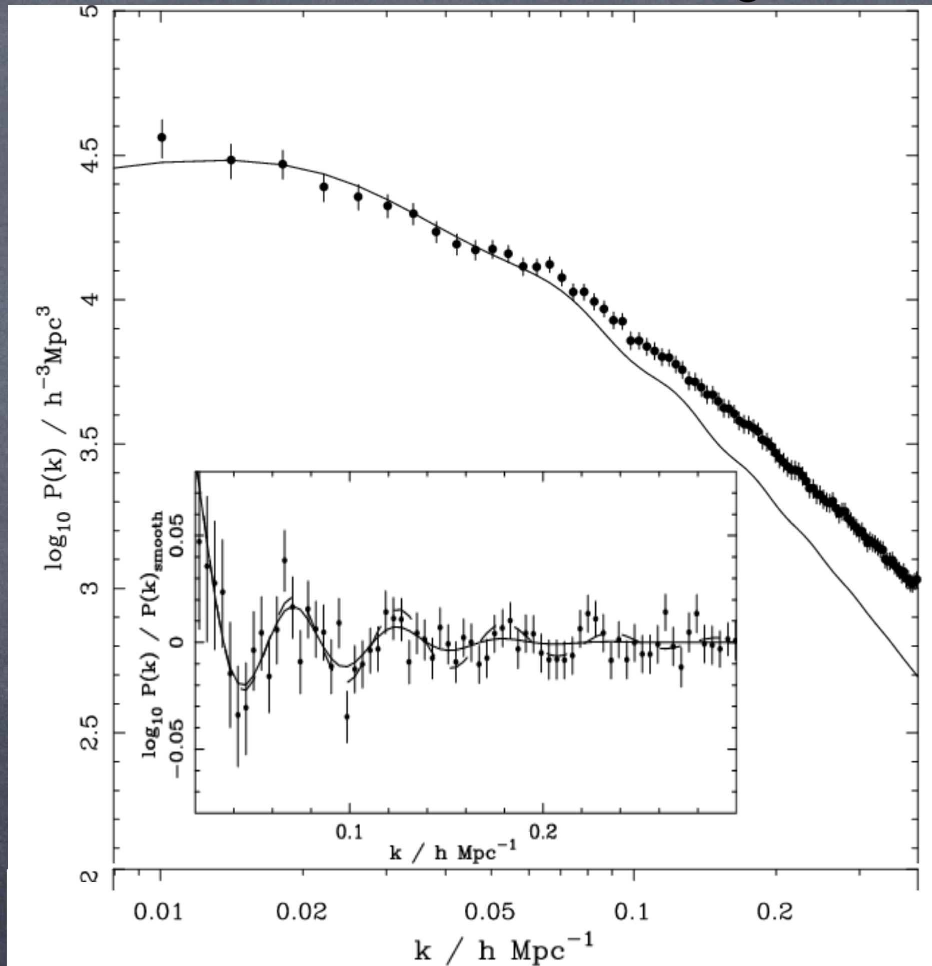
SDSS LRG sample

4.7×10^4 galaxies



Eisenstein et al. (2005)

5.2×10^5 galaxies



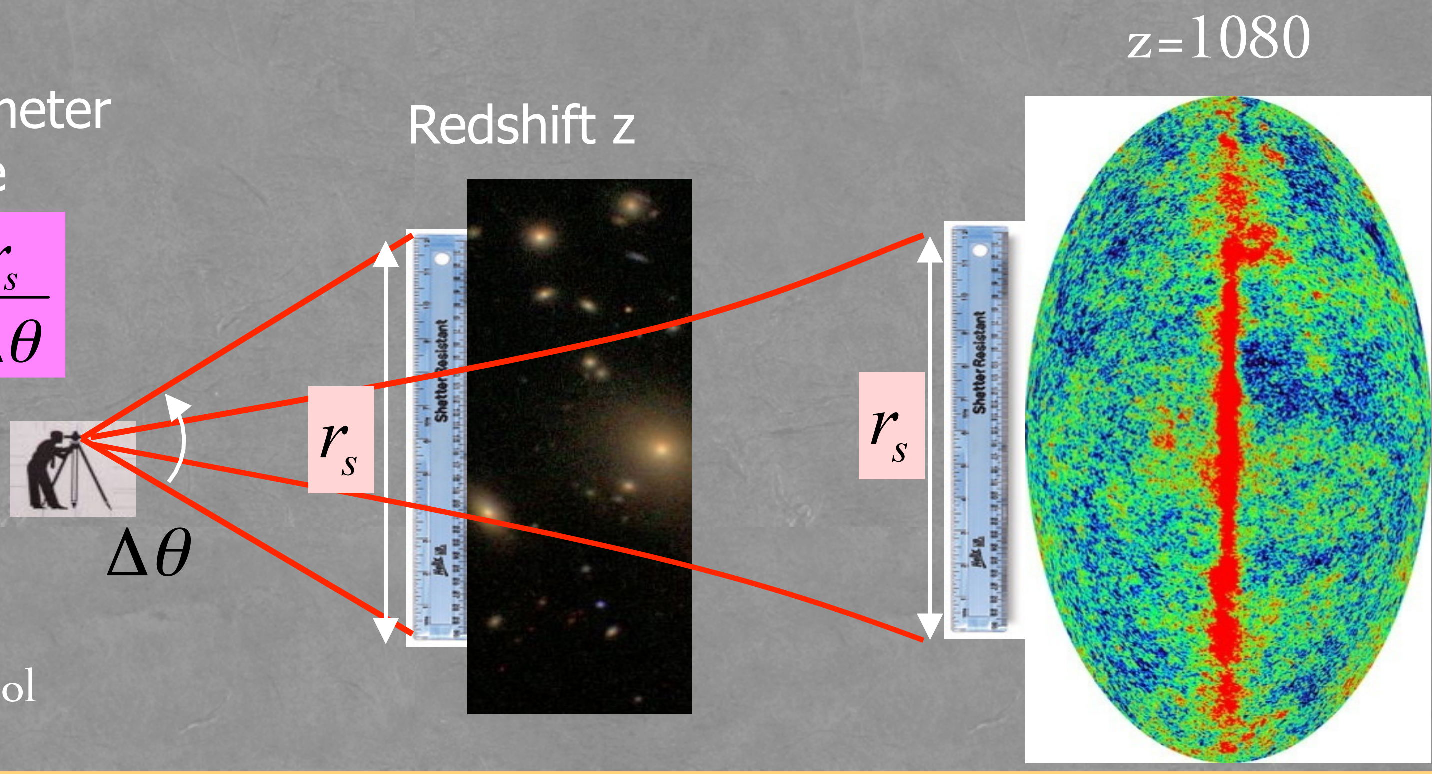
Percival et al. (2007)

BAO as standard ruler

Using BAO scale r_s as standard ruler,
cosmological distance of high-z objects can be measured

Angular diameter distance

$$D_A(z) = \frac{r_s}{\Delta\theta}$$



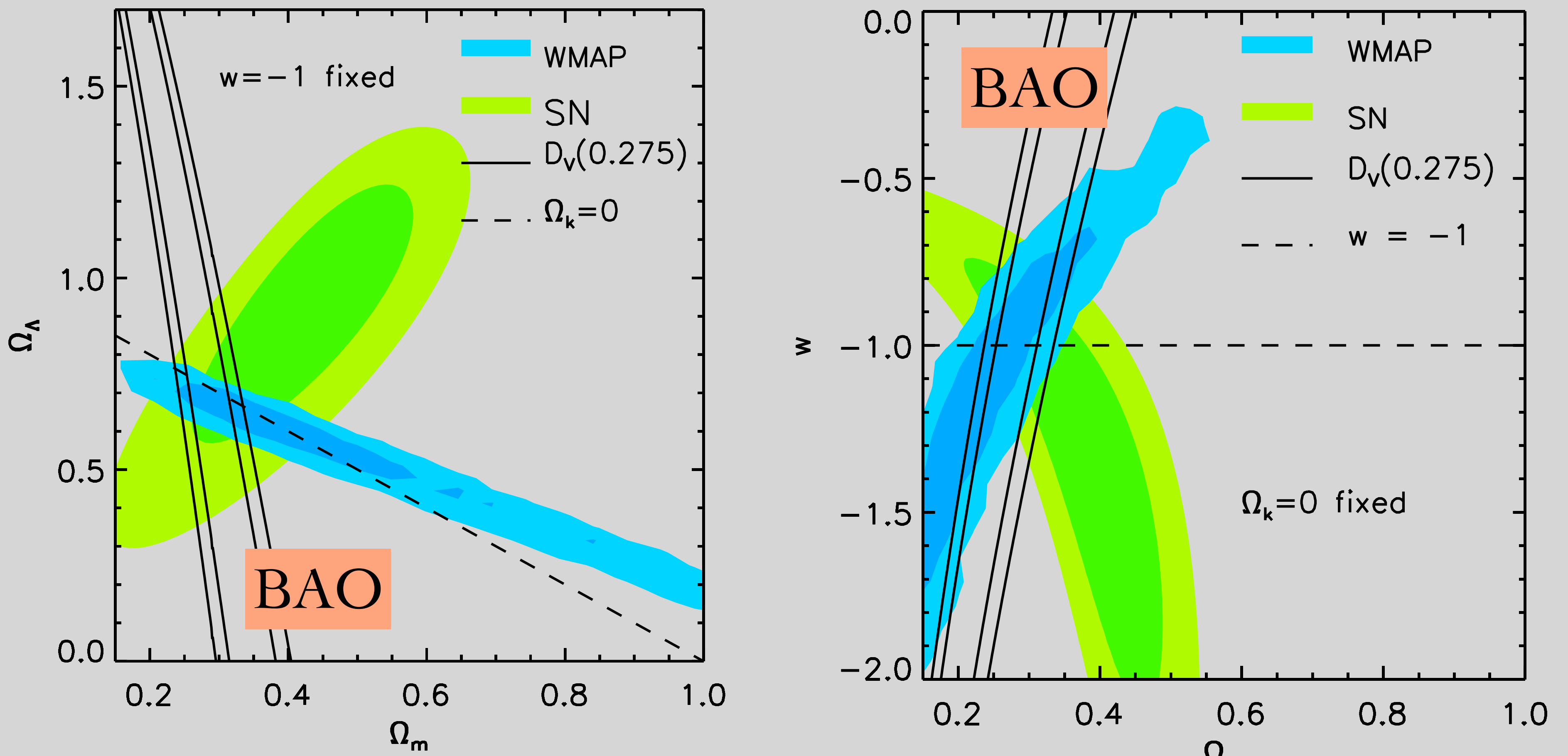
From R.C.Nichol

In addition, Hubble parameter of distant objects, **H(z)**, can be measured through Alcock & Paczynski effect.

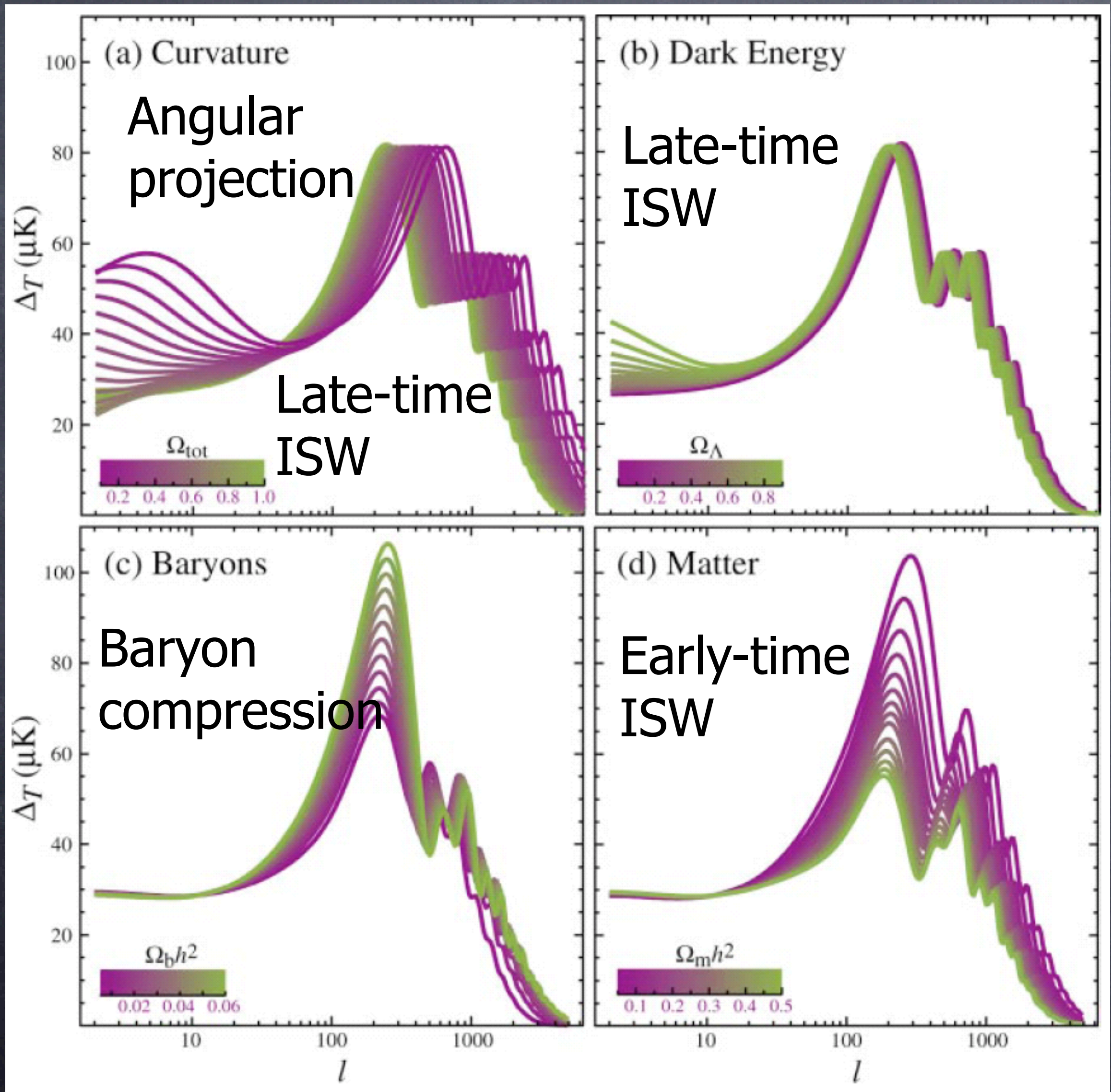
Constraints on dark energy

w = P/ϱ : dark energy equation-of-state parameter

(w=−1: cosmological const.)



Percival et al. (2009)



Fiducial model parameters:

$\Omega_{tot} = 1,\ \Omega_\Lambda = 0.65,\ \Omega_b h^2 = 0.02,$

$\Omega_m h^2 = 0.147,\ n = 1,\ z_{ri} = 0,\ E_i = 0$

Hu & Dodelson (2002)