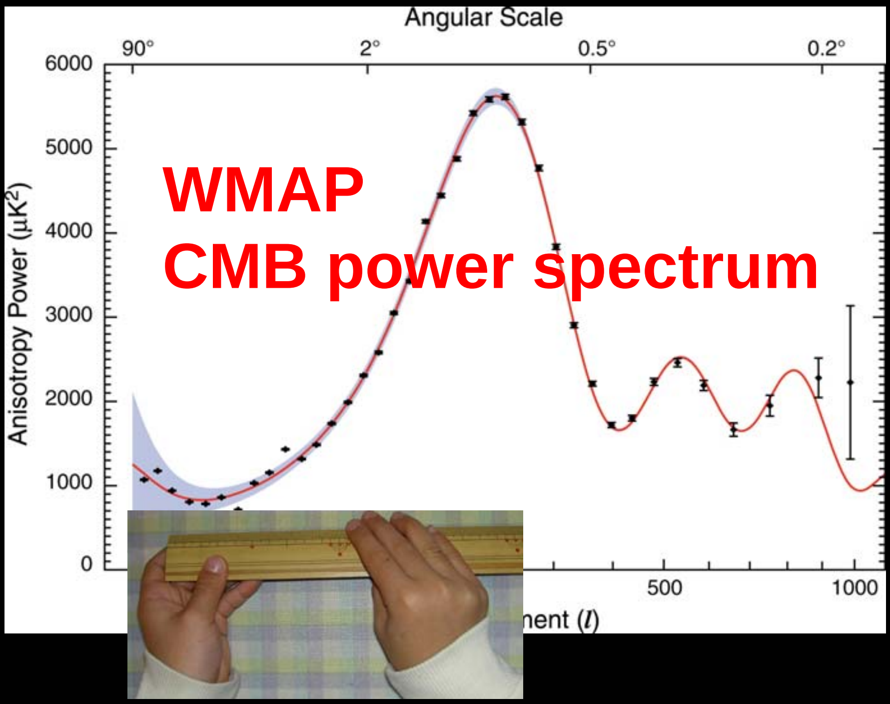
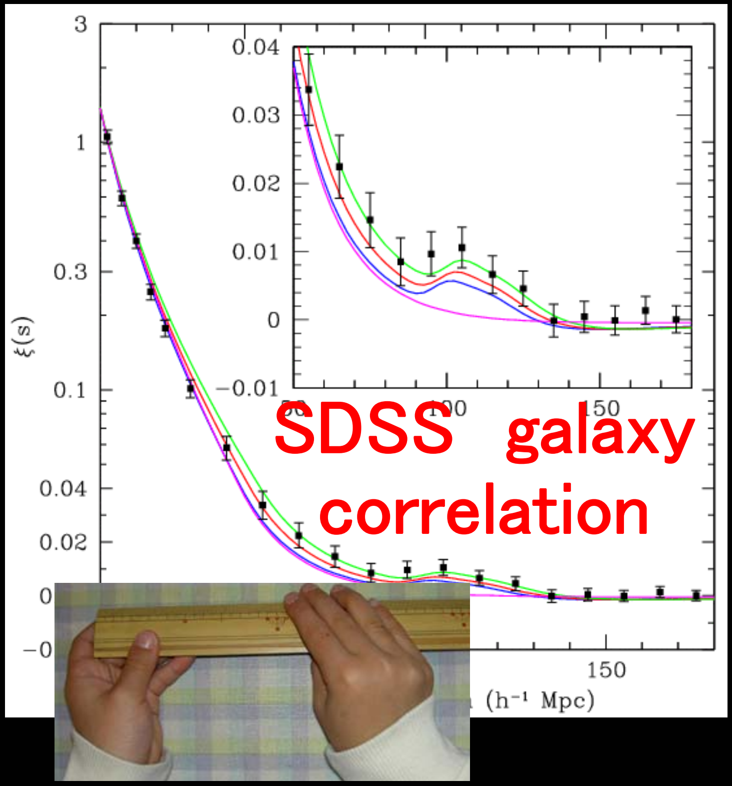
Exploring dark energy in the universe through baryon acoustic oscillation





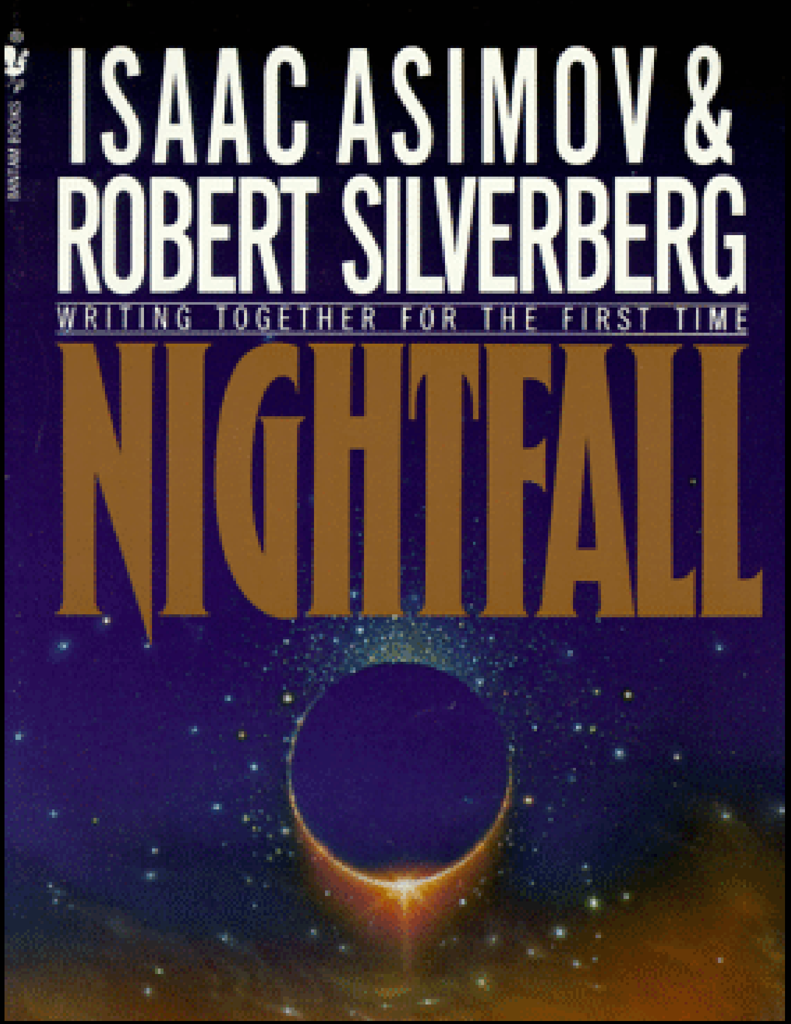
Yasushi Suto *Department of Physics, University of Tokyo*

KEK Annual Theory Meeting on Particle Physics Phenomenology (KEKPH07): March 3, 2007

Without dark nights, one could have never imagined ...


what really dominates
our world

a planet with six Suns

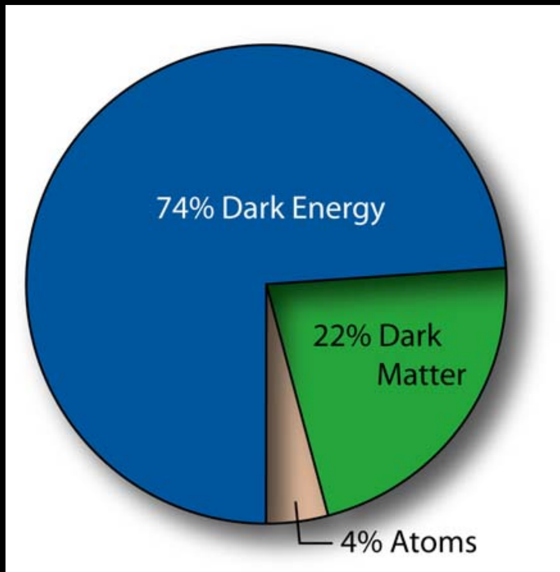


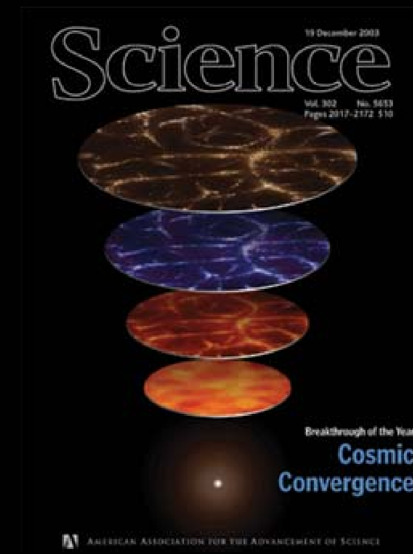
- no “night” except the total eclipse due to another planet every 2050 years
- People realized the true world for the first time through the darkness full of “stars”

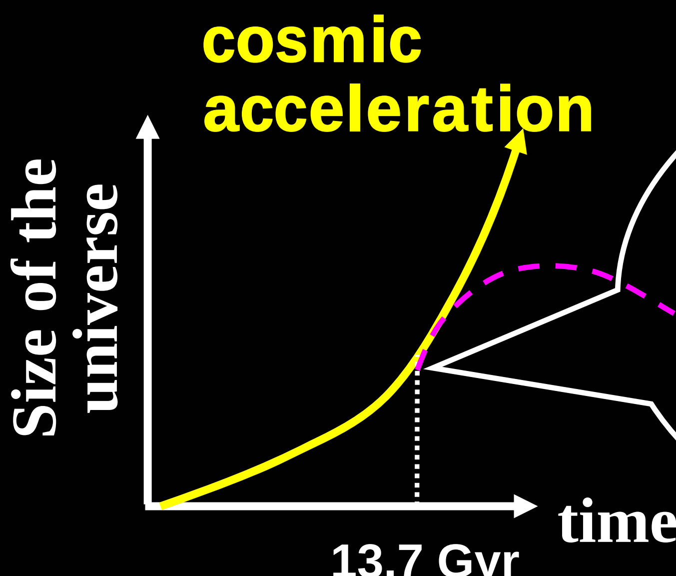
Darkness is the key to understanding our world better

- Beyond the edge of our current horizon (= “darkness”, “dark night”)
- philosophy, astronomy, and therefore physics started from thinking in the dark
- Should still apply now
  - Another element: dark matter, dark energy
  - Another Earth: extrasolar planet
  - Another world: Multiverse
  - Another life: extra-terrestrial intelligence

Dark energy in the universe







Universal repulsion?
Cosmological constant?
Dark energy?
Modified gravity?

From cosmological constant to dark energy

- 1916: general relativity
- 1917: Einstein's static universe
- After 1980's: vacuum energy density

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \boxed{+\Lambda} g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Cosmological constant
(geometrical quantity)

Dark energy
(matter field)

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G \left(T_{\mu\nu} \boxed{-\frac{\Lambda}{8\pi G}} g_{\mu\nu} \right)$$

- Natural value: the Planck units

$$\Lambda = \frac{c^5}{\hbar G} \approx 5.2 \times 10^{93}\,\mathrm{g/cm^3} \quad \Leftrightarrow \quad \Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2} \approx 10^{121}$$

- Observed value: $\Omega_\Lambda \approx 0.7$

The worst discrepancy
in the history of physics !

Dark energy and the equation of state of the universe

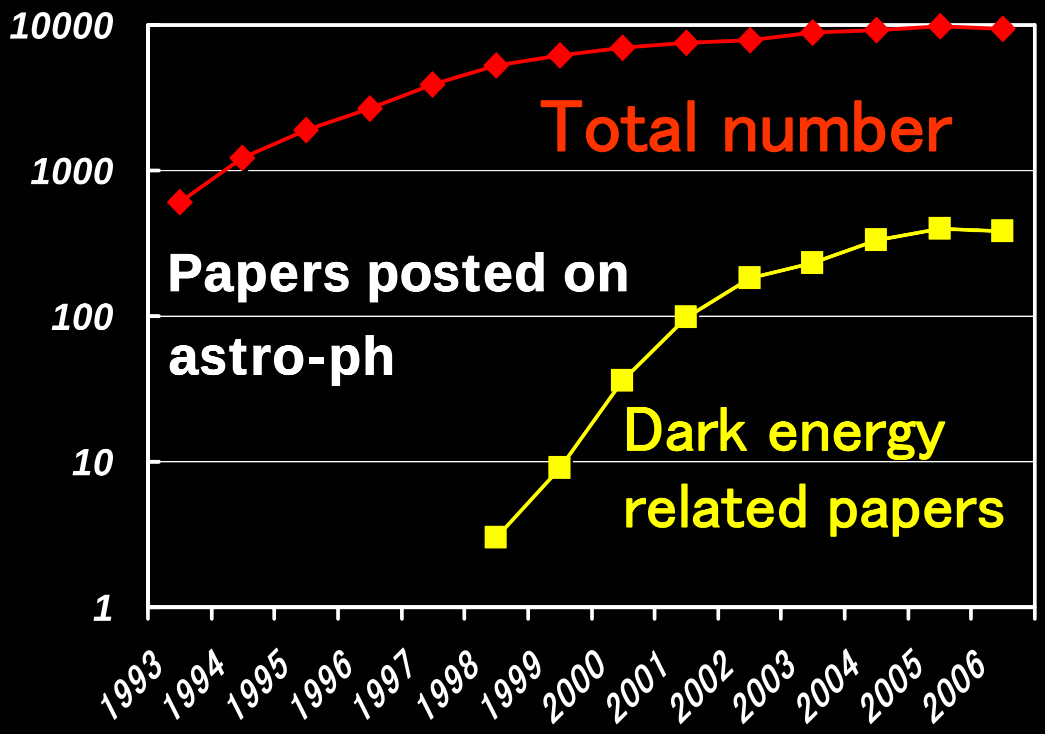
- **Parameterized equation of state**
  - (pressure) = **w** x (density)
    - w=0: dark matter,
    - w=1/3: radiation
    - **w=-1: cosmological constant**
  - Poisson eq. in GR :

    $\Delta \phi = 4\pi G(\rho + 3p) = 4\pi G\rho(1+3w)$

    $w < -1/3 \Rightarrow$ repulsion force
  - Negative pressure: dark energy
  - More generally w may be time-dependent

Why important ?

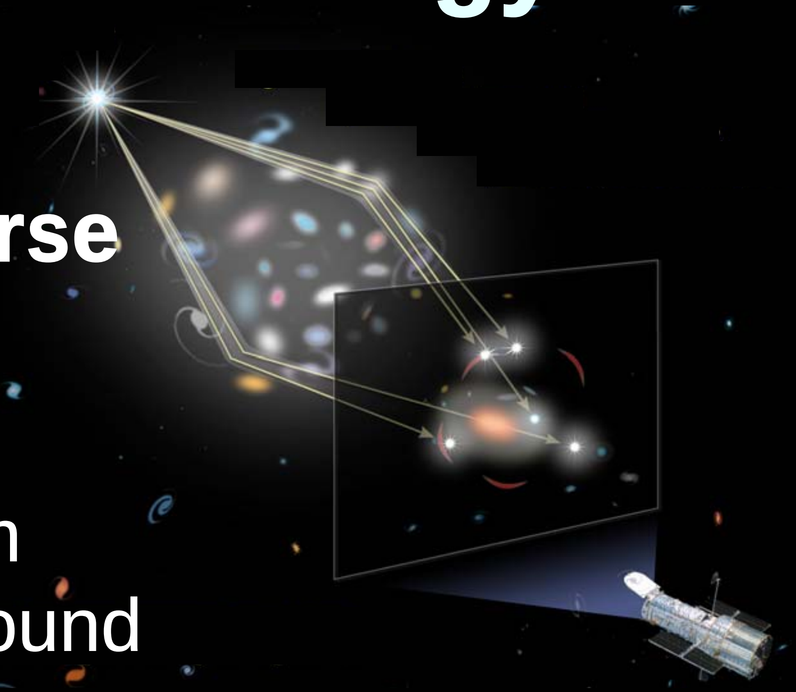
- **New physics**
  - **major but unknown component of the universe ?**
  - **Breakdown of general relativity at cosmological scales？**
- **Astronomy is the key**

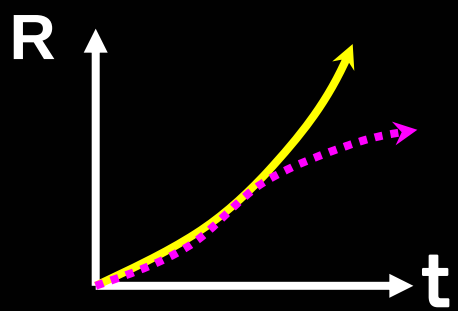


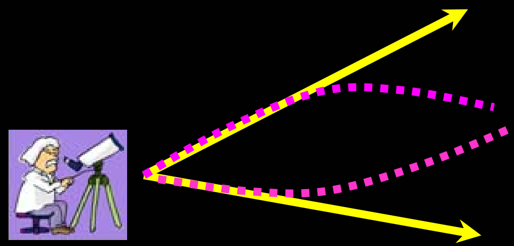
- **Steven Weinberg**
  "Right now, not only for cosmology but for elementary particle theory this is the bone in the throat"
- **Edward Witten**
  "Would be number one on my list of things to figure out"
- **Frank Wilczek**
  "Maybe the most fundamentally ysterious thing in basic science"

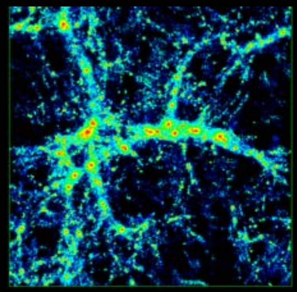
Signatures of dark energy

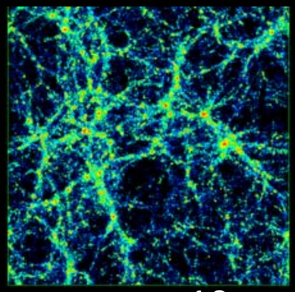
- **cosmic acceleration**
- **geometry of the universe**
- **evolution of structure**
- **Probes**
  - Supernova Hubble diagram
  - Cosmic Microwave Background
  - Gravitational lensing
  - ***Baryon Acoustic Oscillation***





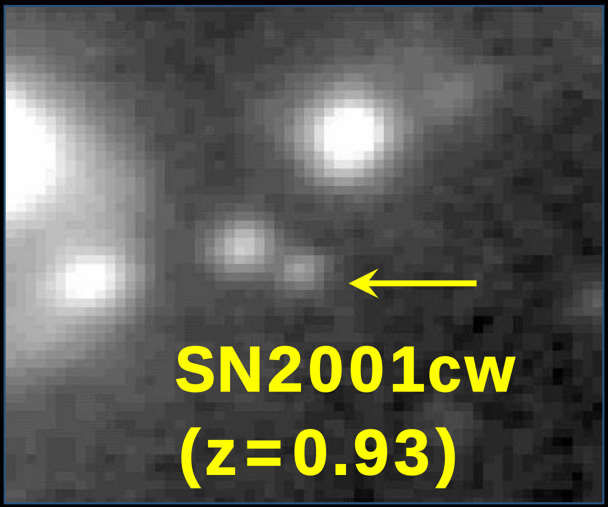






Standard candle: Type Ia Supernova

observed flux: F



absolute luminosity: L

Distance: D

$$D = \sqrt{\frac{L}{4\pi F}}$$

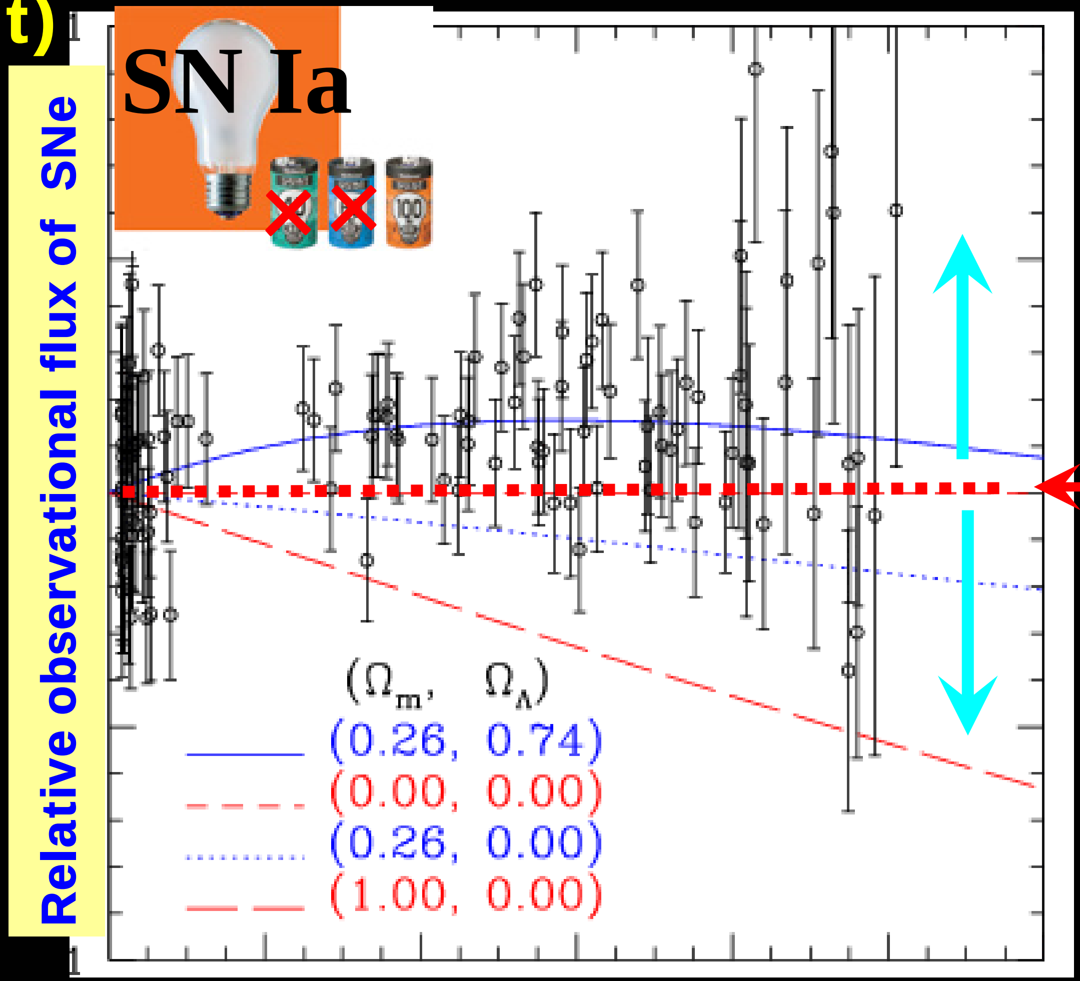
observational estimate

dark energy parameter can be read off from the comparison between the model and the observation

Accelerating universe from SN Ia data

SN Legacy Survey (Astier et al. 2006)

Dimmer
(more distant)



acceleration

normalized by empty universe prediction

deceleration

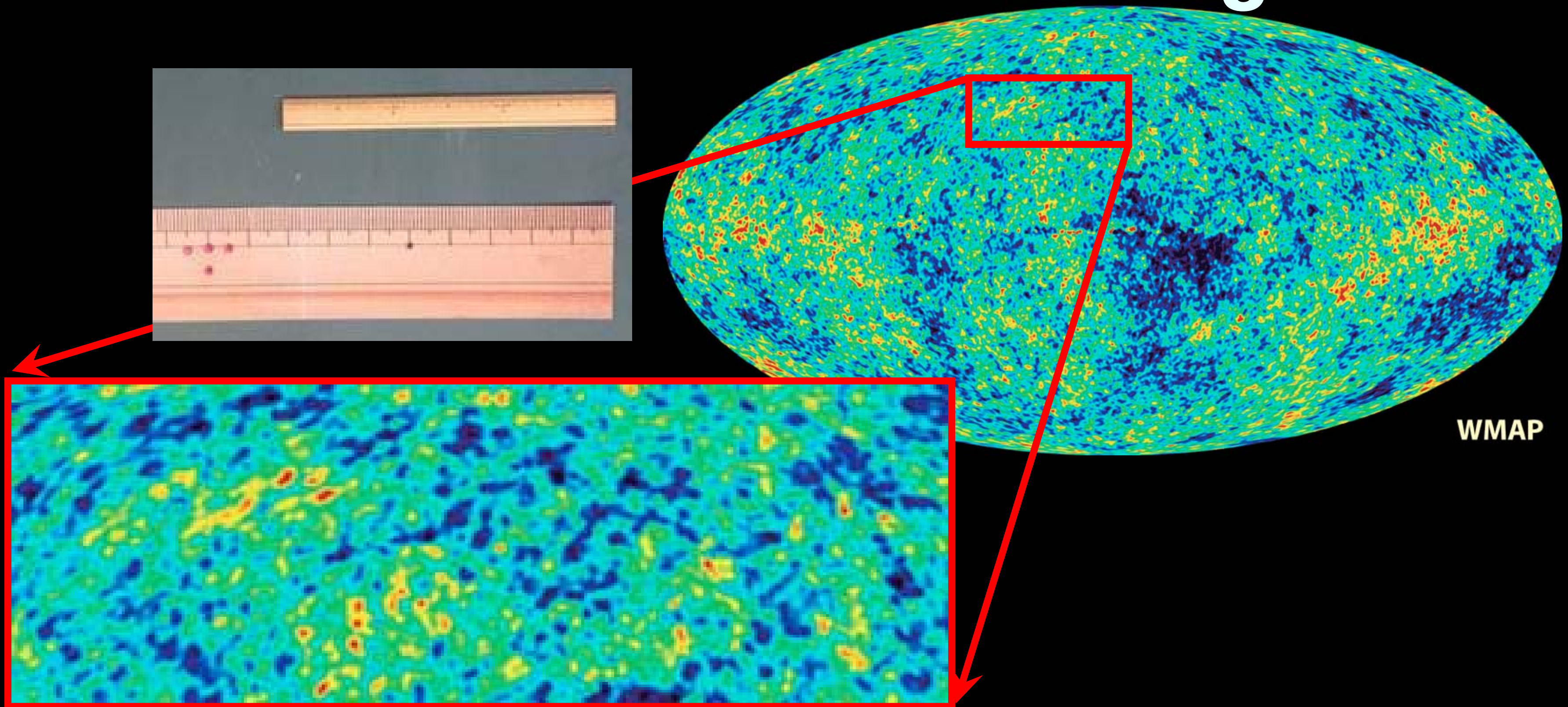
Brighter
(closer)

present

time

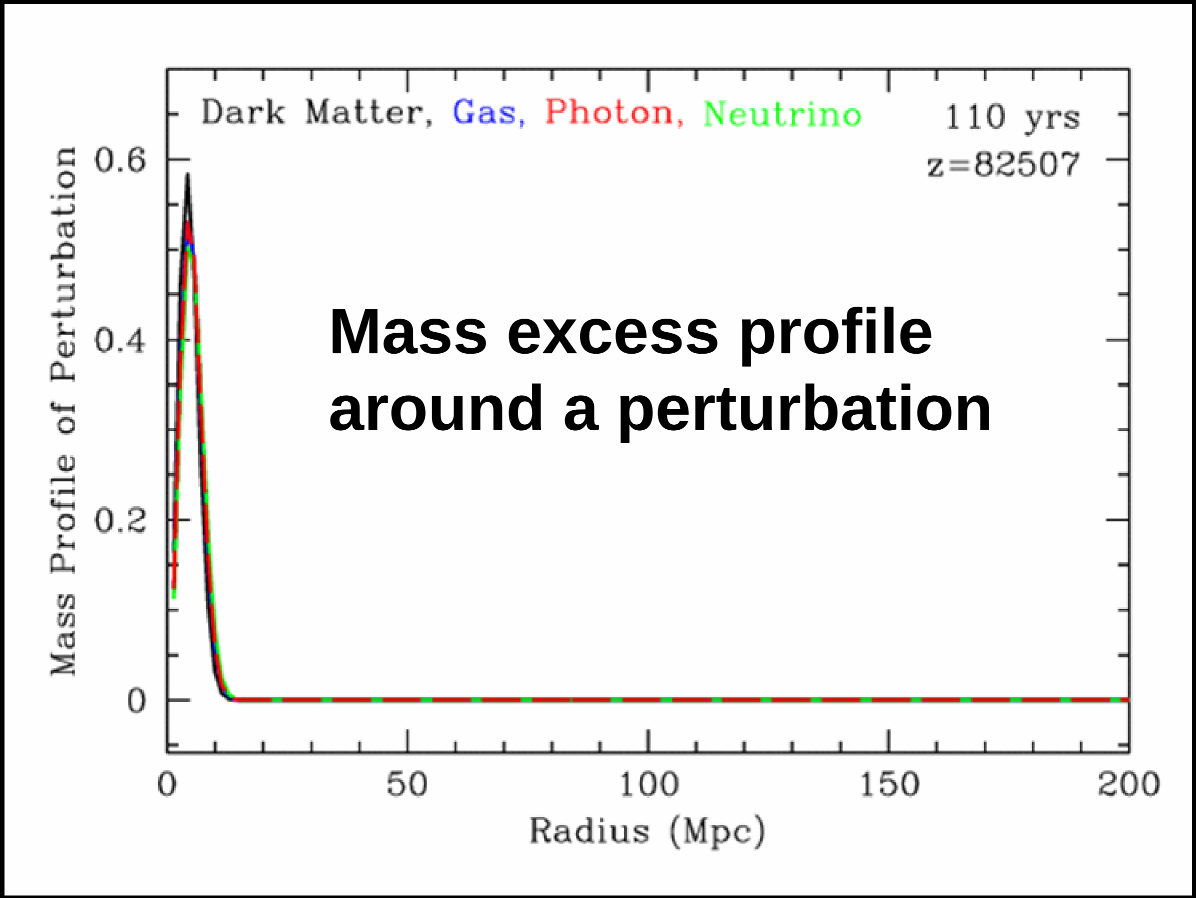
past

Standard ruler: baryon-photon acoustic oscillation length



- Sound horizon length at recombination (=c_s × 0.37Myr)
  - $r_s = 147\ (\Omega_m h^2 / 0.13)^{-0.25}\ (\Omega_b h^2 / 0.024)^{-0.08}$ Mpc
- Estimate the distance to the CMB last-scattering surface using the above as a standard ruler

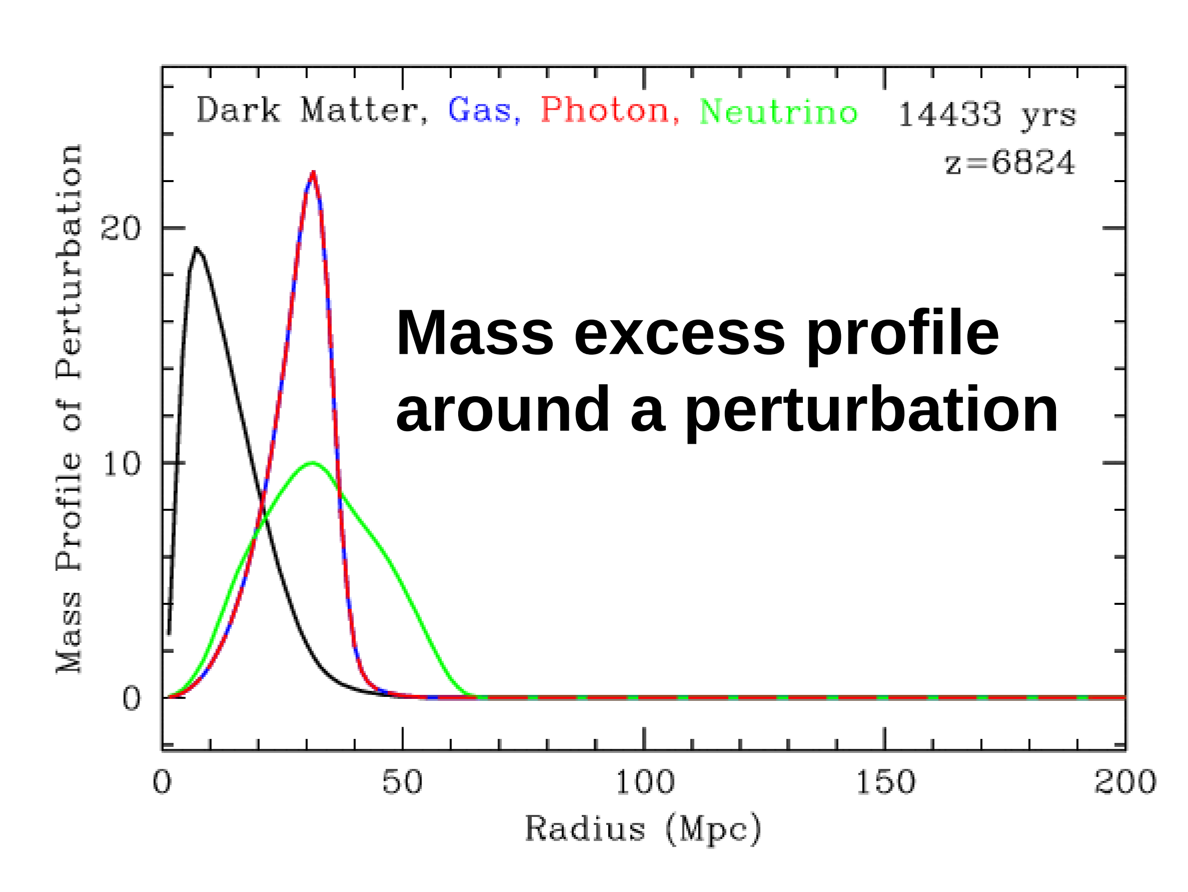
Acoustic oscillation illustrated (1)



- in the early universe, the major components of the universe, i.e., dark matter, baryons, photons, neutrinos, behave as a strongly-coupled single fluid

http://cmb.as.arizona.edu/~eisenste/acousticpeak/acoustic_physics.html

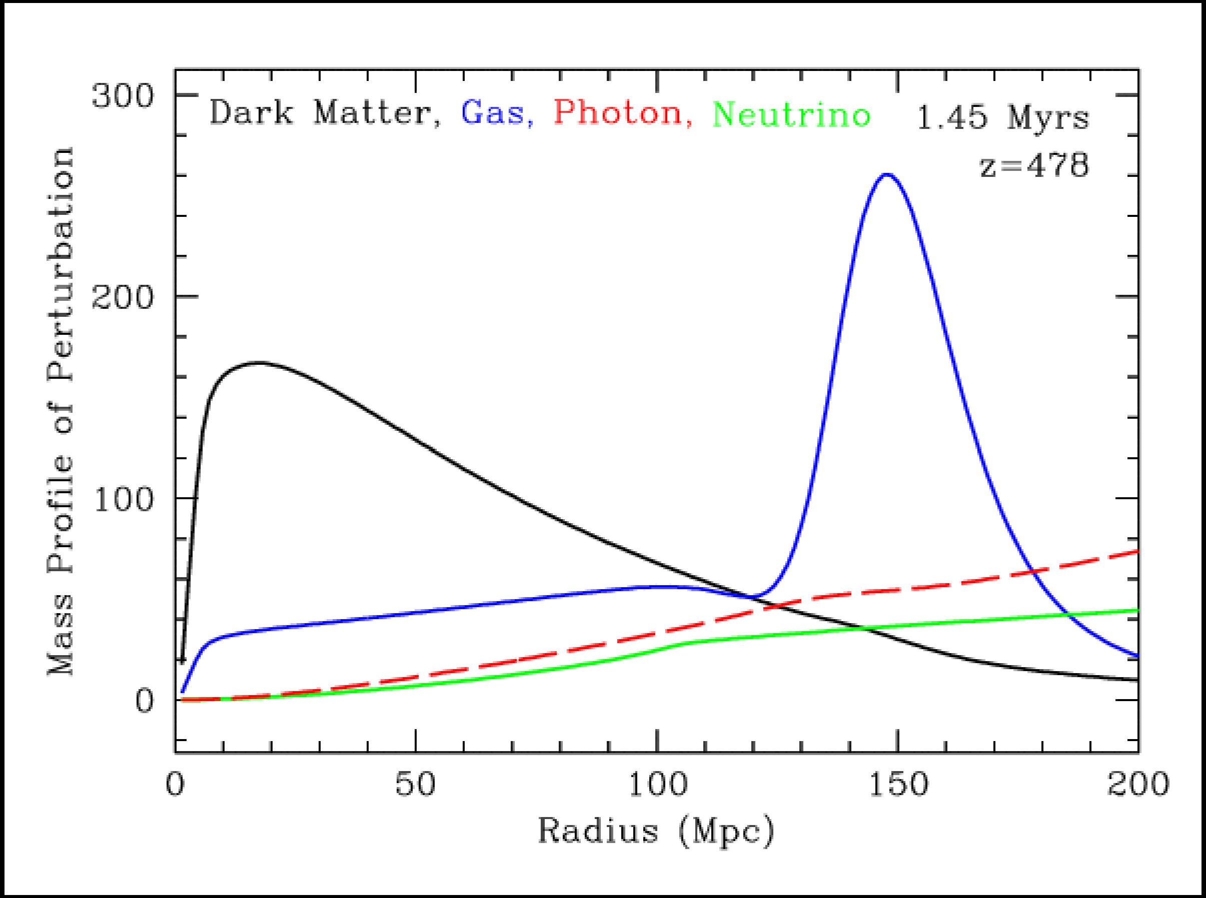
Acoustic oscillation illustrated (2)



- neutrinos decouple earlier and start free-streaming
- dark matter stays around the center due to its self-gravity
- baryons and photons behave as a single fluid. The central concentration induces pressure and generates an outward acoustic spherical wave

http://cmb.as.arizona.edu/~eisenste/acousticpeak/acoustic_physics.html

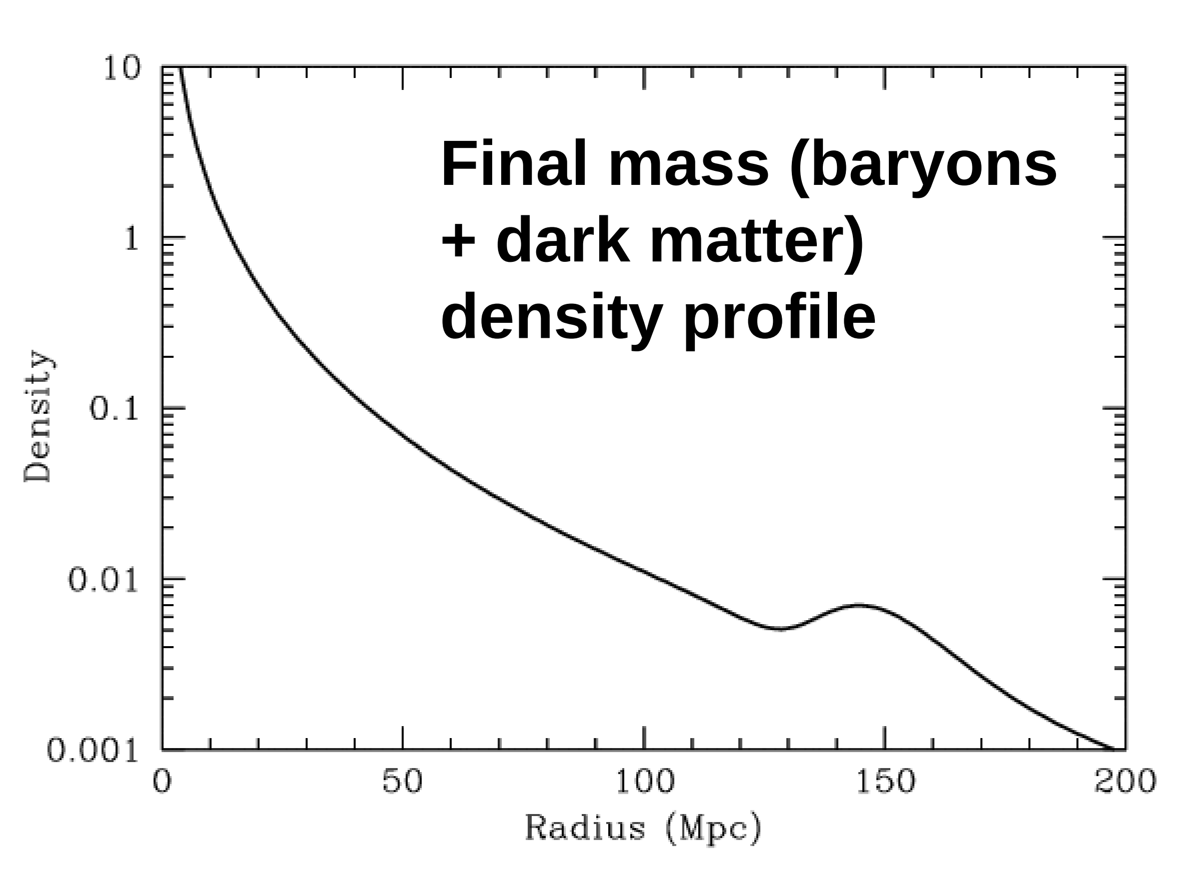
Acoustic oscillation illustrated (3)



- After recombination (z=1000, t=0.37Myr) , baryons and photons decouple. photons start free-streaming while baryons keep the acoustic features

http://cmb.as.arizona.edu/~eisenste/acousticpeak/acoustic_physics.html

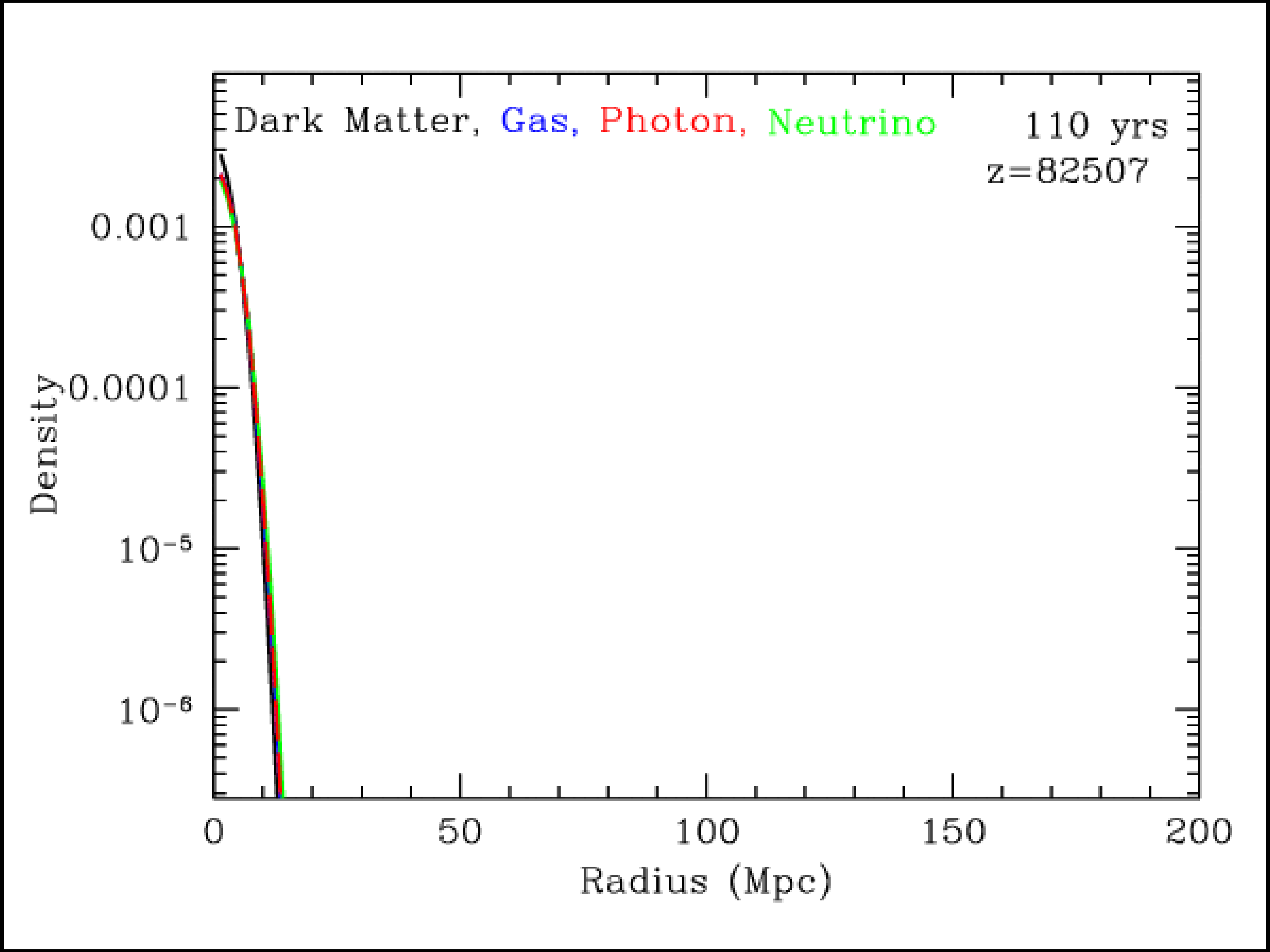
Acoustic oscillation illustrated (4)



- after decoupled from photons, baryons fall into the gravitational potential due to dark matter
- dark matter acquires the baryon acoustic feature via their gravitational evolution

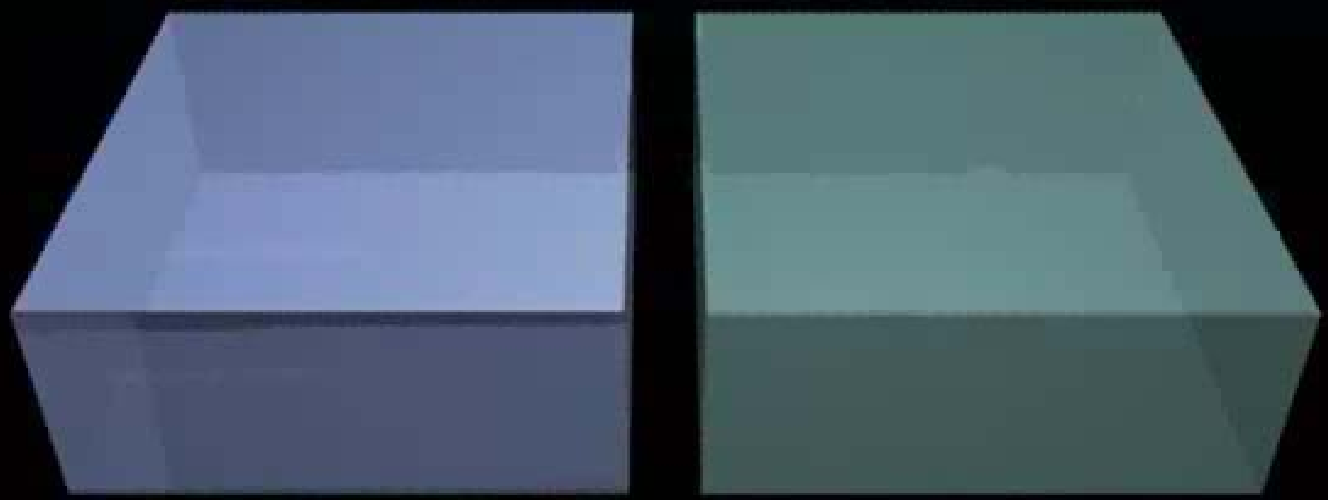
http://cmb.as.arizona.edu/~eisenste/acousticpeak/acoustic_physics.html

Evolution of density profile around a peak



http://cmb.as.arizona.edu/~eisenste/acousticpeak/acoustic_physics.html

CMB acoustic oscillation

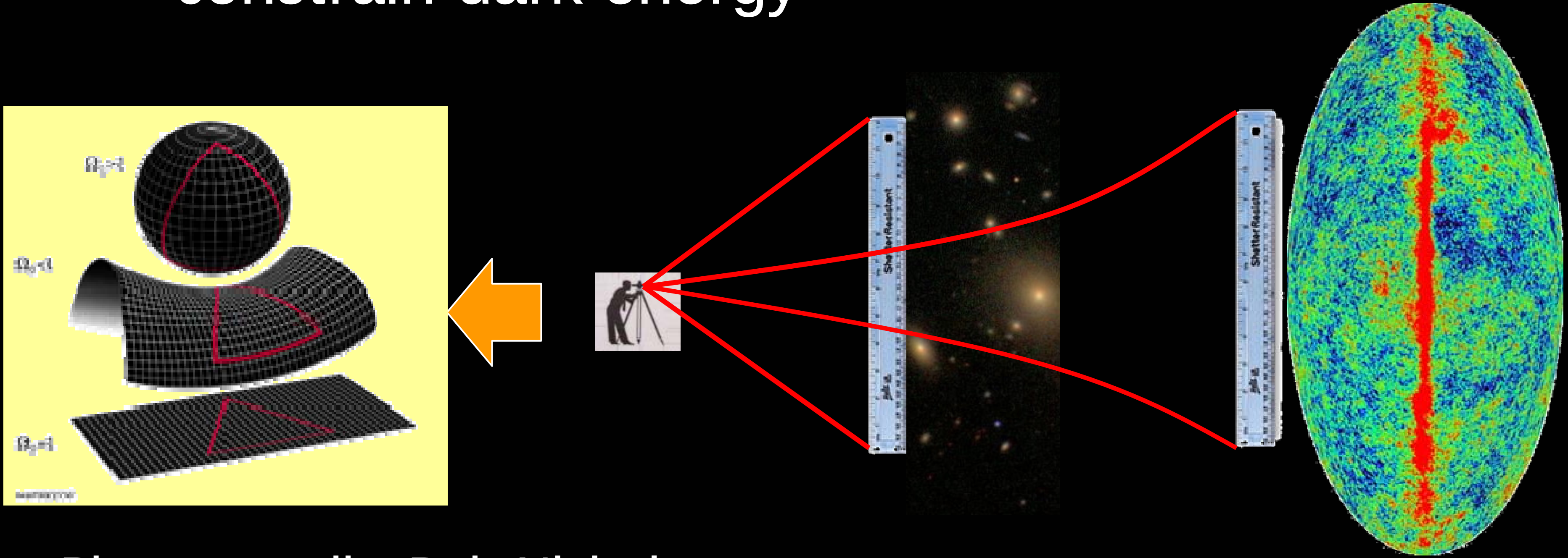


NASA / WMAP Science Team

BAO as a standard ruler

$$r_s = 147(0.13/\Omega_m h^2)^{0.25}(0.024/\Omega_b h^2)^{0.08}\ \mathrm{Mpc}$$

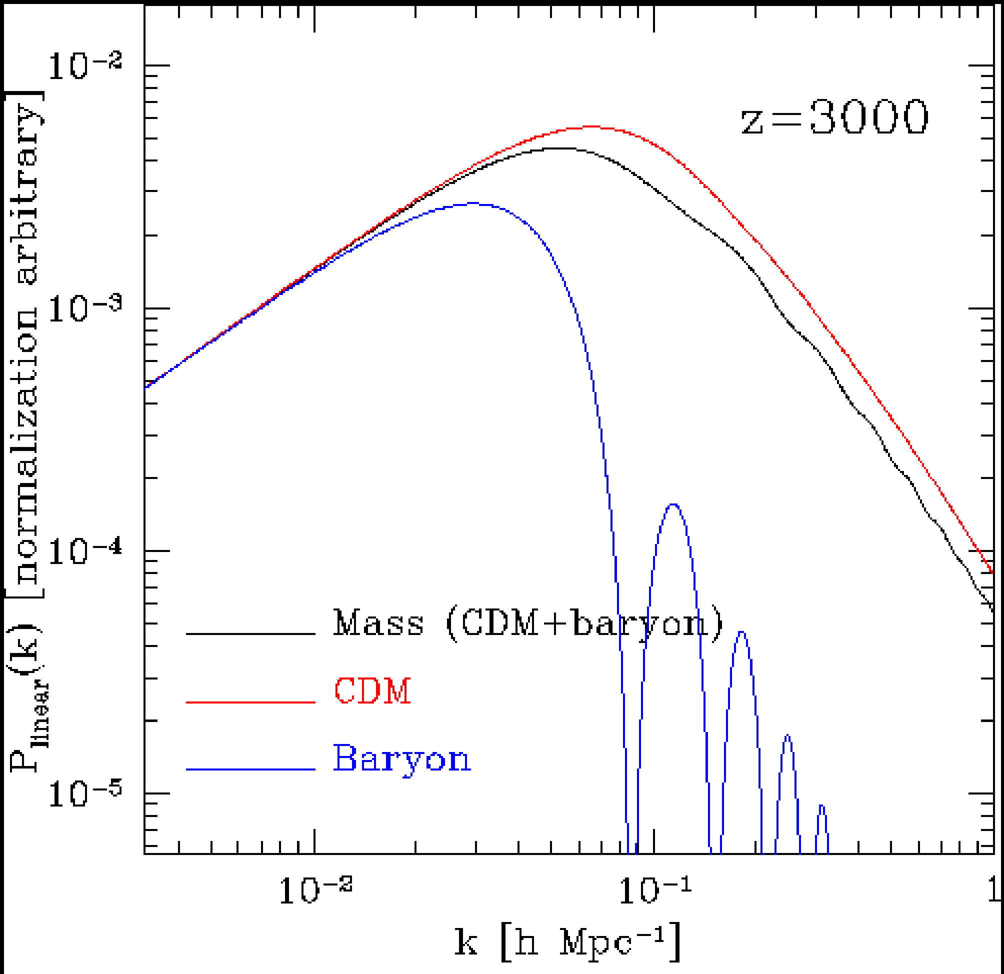
- Distant measurement at different epochs
- Promising methodology to observationally constrain dark energy

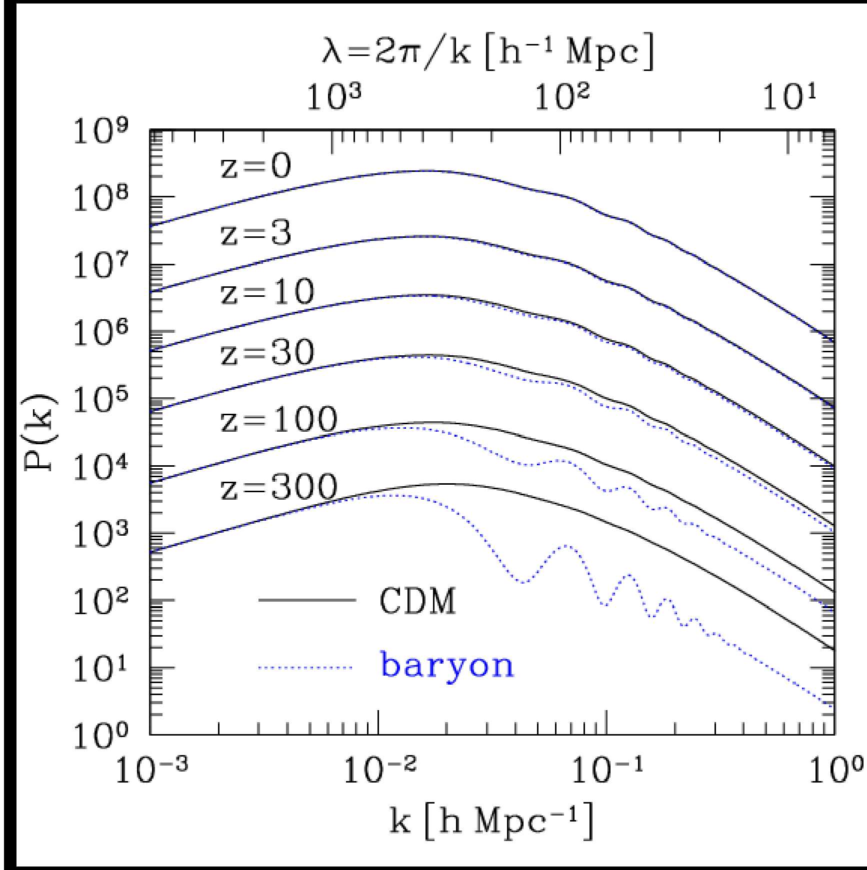


Picture credit: Bob Nichol

Acoustic scales and geometry of the universe

Power spectrum of mass density fluctuations with baryon acoustic oscillation effect

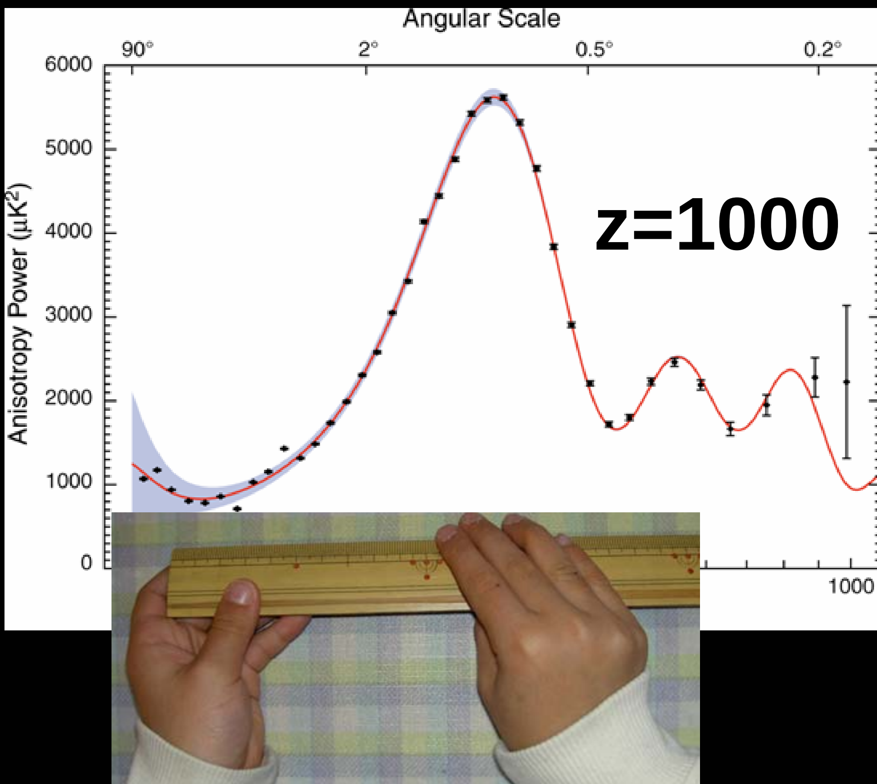


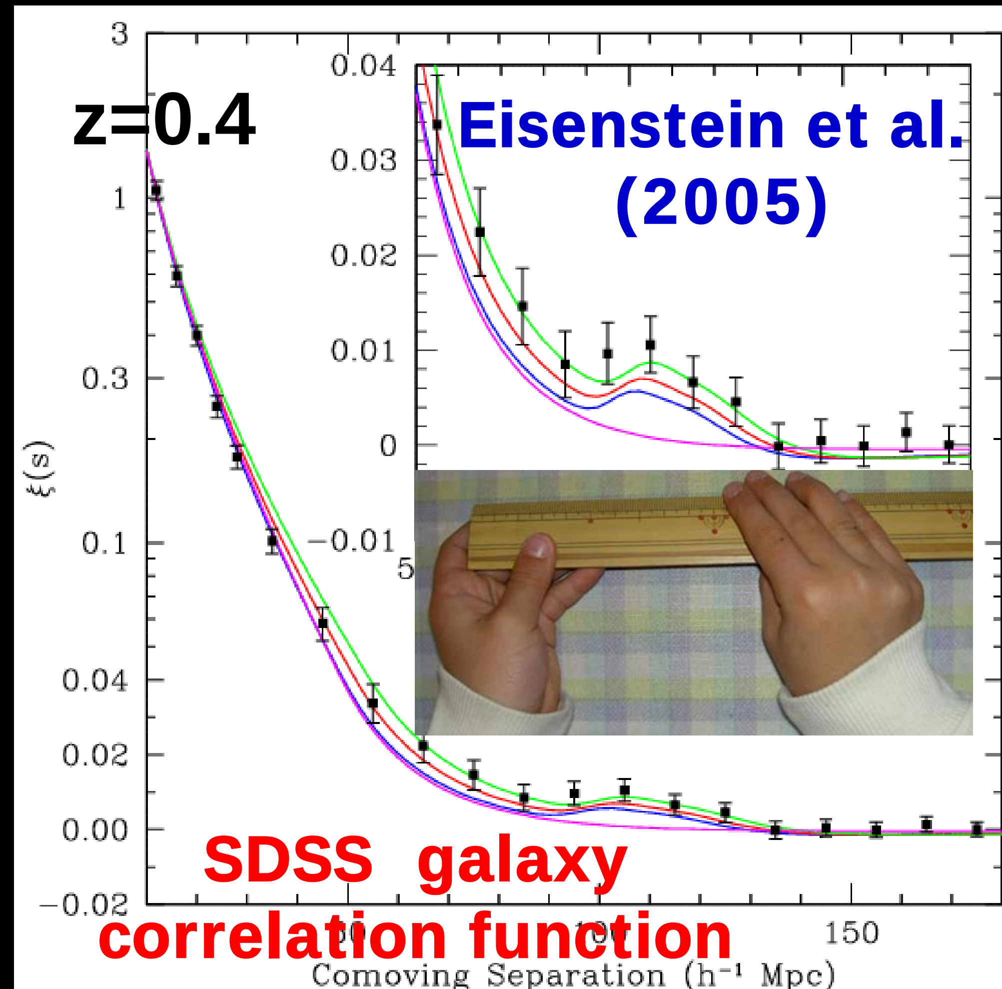


(A.Taruya, T. Nishimichi)

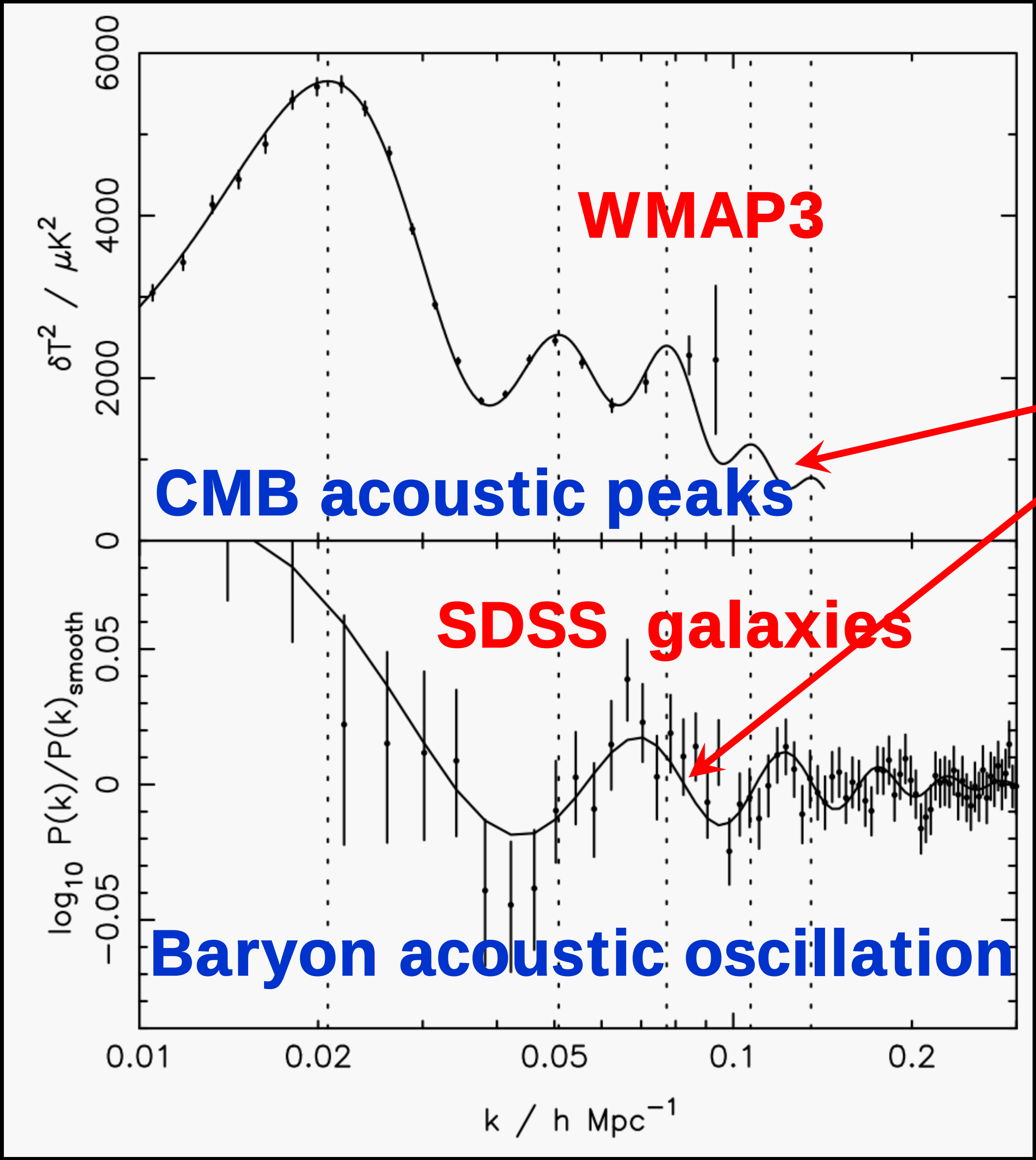
Acoustic oscillations detected

CMB photons
WMAP 3yr
(Spergel et al. 2007)





$$r_s = 147(0.13/\Omega_m h^2)^{0.25}(0.024/\Omega_b h^2)^{0.08}\ \mathrm{Mpc}$$

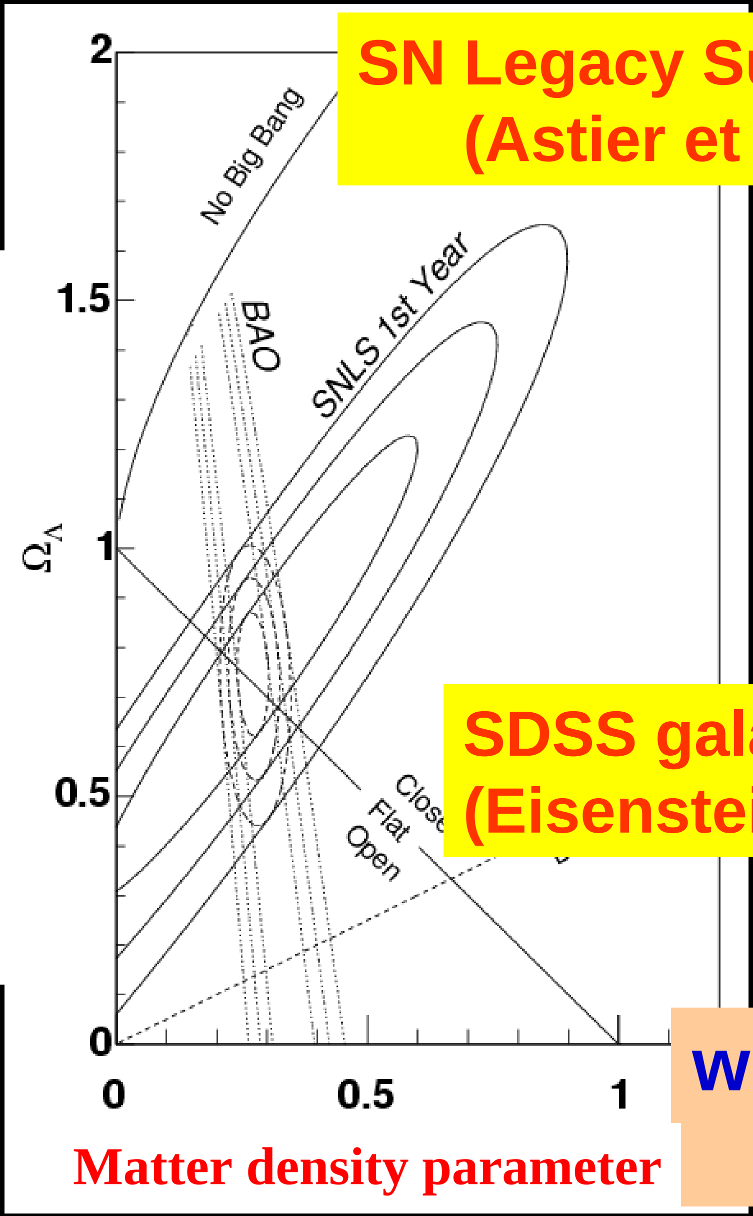


$\Omega_m = 0.24$ best-fit WMAP model

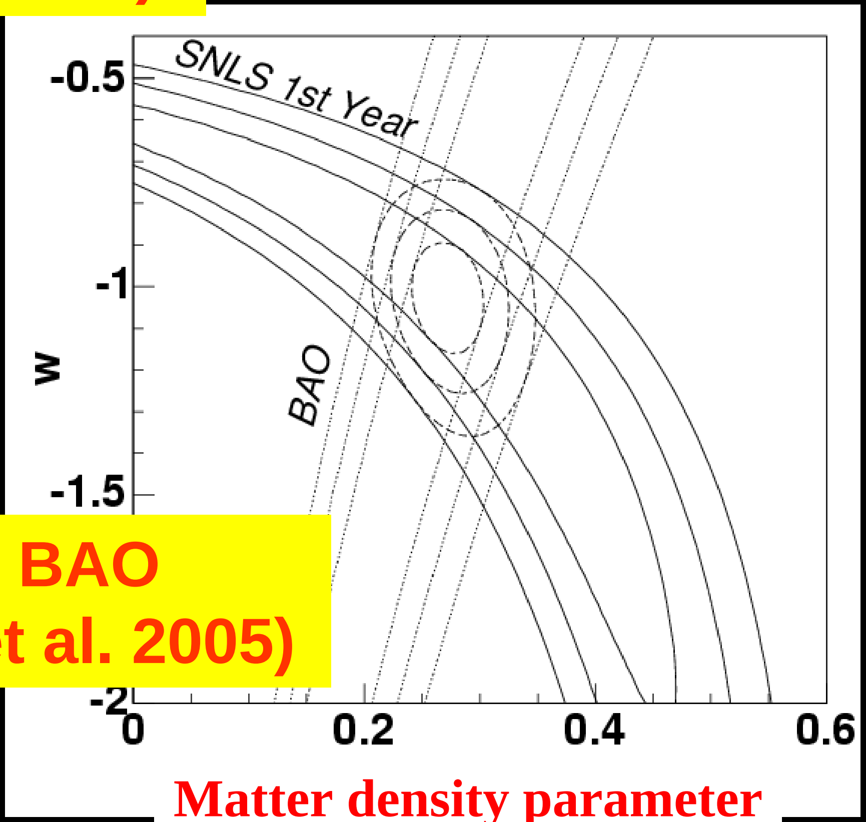
Percival et al. (2007)

Combined constraints from SN and BAO

SN Legacy Survey
(Astier et al. 2006)



SDSS galaxy BAO
(Eisenstein et al. 2005)

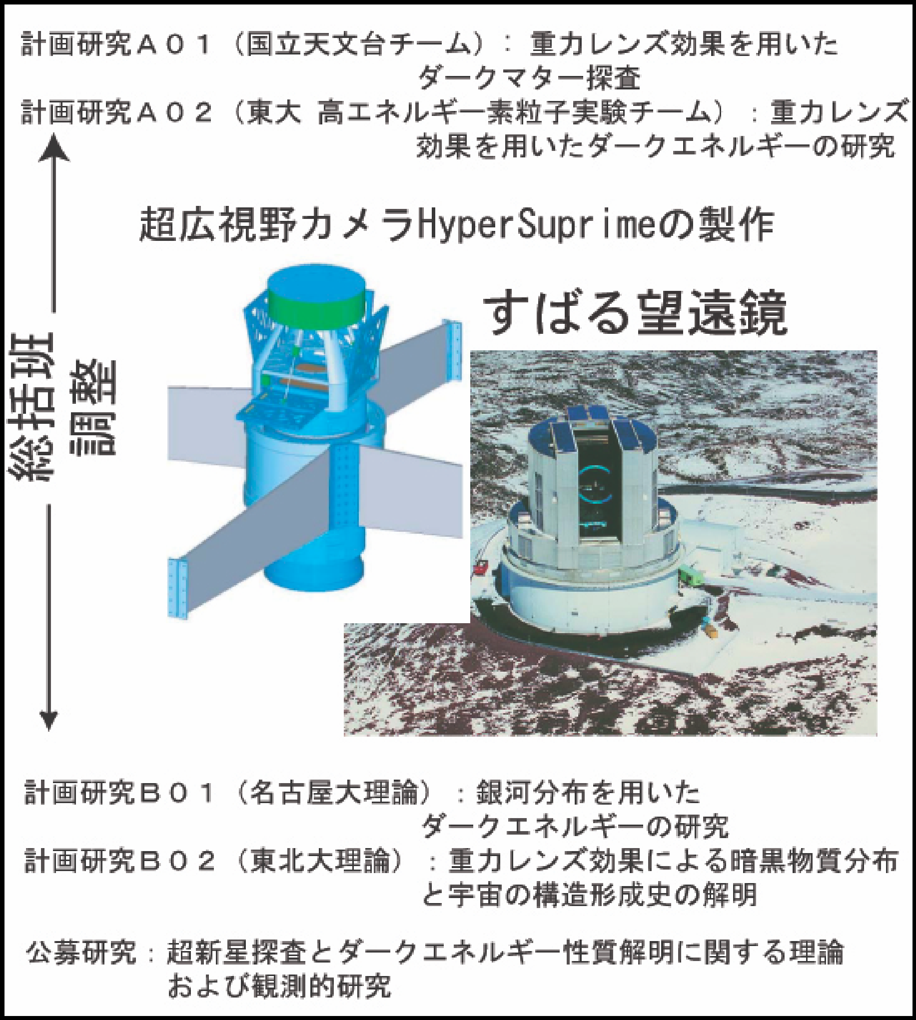


w=－1.023±0.090（systematic）
±0.054（statistical）

future dark energy survey projects

- DES: Dark Energy Survey (Fermi Lab+, 2011-?)
  - Imaging galaxy survey
  - 5000 deg^2@Chile 4m telescope
- HSC: Hyper Suprime-Cam (Subaru+Princeton, 2011-)
  - Imaging galaxy survey 1.5deg FOV
  - 2000 deg^2@Subaru 8m telescope
- LSST: Large Synoptic Survey Telescope (SLAC+, 2014-?)
  - Imaging galaxy survey
  - 20000 deg^2@Chile 8.4m dedicated telescope
- WFMOS: Wide Field Multi-Objects Spectrograph (Subaru+Gemini+???, 2015-???)
  - Spectroscopic galaxy survey 1.5deg FOV
  - 4000 fibers, 20000 galaxy redshifts a night

Hyper Suprime-Cam project



- **Ministry of Education, Special Priority Area Grant-in-Aid: 2006-2011 "Study of Dark Energy from Wide-Field Deep Survey of the Universe"**
- Constraining dark energy via gravitational lensing survey
  - PI: Hiroshi Karoji (NAOJ)
  - CCD: Satoshi Miyazaki (NAOJ)
  - DAQ: Hiroaki Aihara (U.Tokyo)
  - Theory groups at NAOJ, Univ. of Tokyo, Nagoya Univ. Tohoku Univ.
- Princeton Univ. will join officially

WFMOS proposal: Subaru+Gemini spectroscopic survey

- Observational constraints on dark energy
- Accurate measurement of the baryon acoustic scales in galaxy distribution
- 4000 multi-fiber spectrograph on 1.5deg FOV cameta at Subaru prime focus
  - 0.5<z<1.3: emission line galaxies
    - 2×10^6 gals/2000 deg^2 ⇒ 1400 pointings（900hours）
  - 2.3<z<3.3: Lyman-break galaxies
    - 6×10^5 gals/300 deg^2 ⇒ 200 pointings（800hours）
- Determine H(z) and D(z) within 1% precision
- Determine w within 3% precision and dw/dz within 25% precision

modified gravity vs. cosmological constant: from SDSS to WFMOS

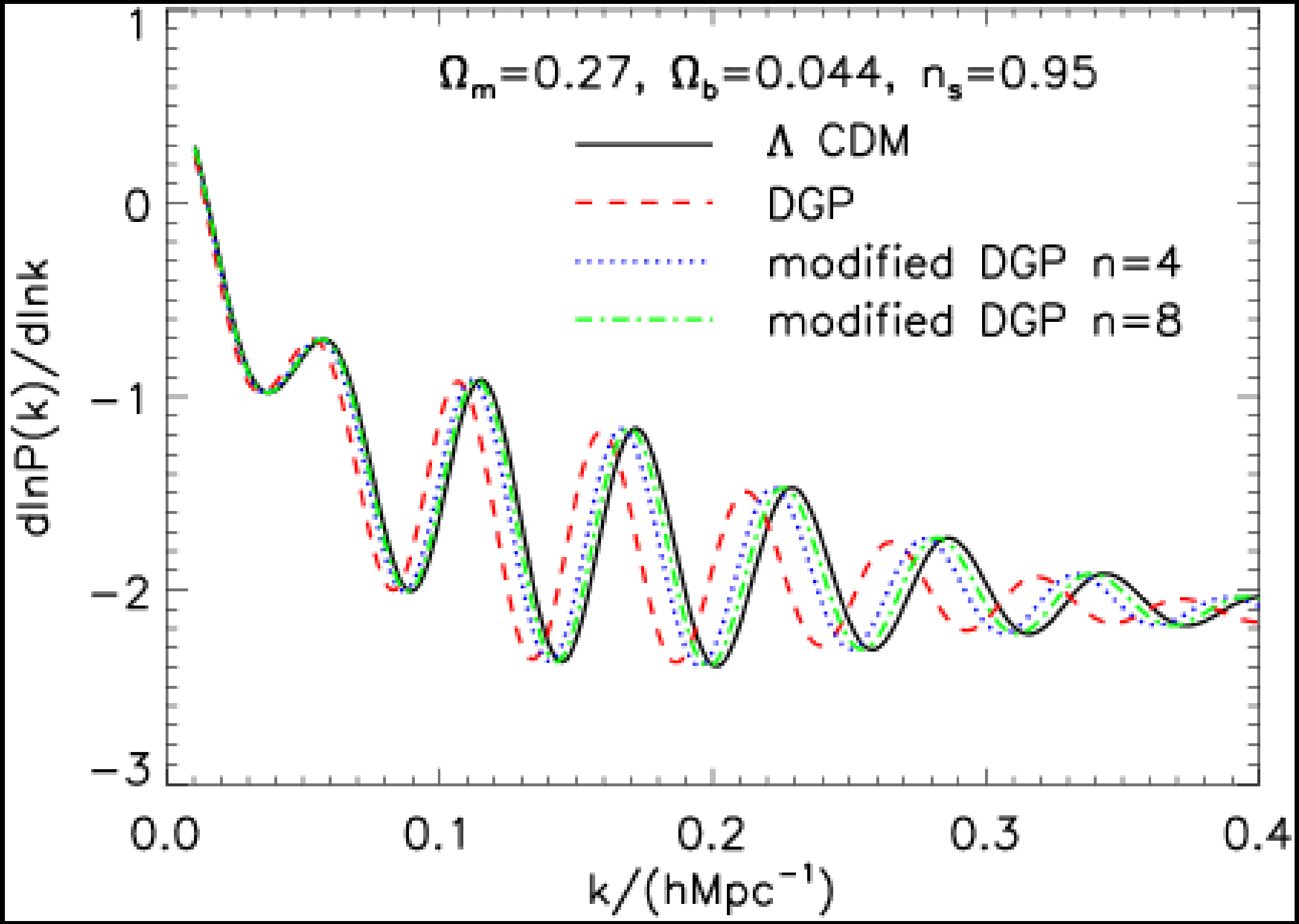
Yamamoto, Bassett, Nichol, Suto & Yahata
PRD 74(2006)063525, astro-ph/0605278

- modified Friedmann equation (spatially flat)

$$H^2 - \frac{H^{2/n}}{r_c^{2-2/n}} = \frac{8\pi G}{3}\rho$$

  - n=2: DGP model, n=∞ : cosmological constant
- r_c: key parameter $\sim 1/H_0$
  - $r<r_c$: 4D space-time, $r>r_c$: 5D space-time
  - if spatially flat $(H_0 r_c)^{2/n-2} = 1-\Omega_m$

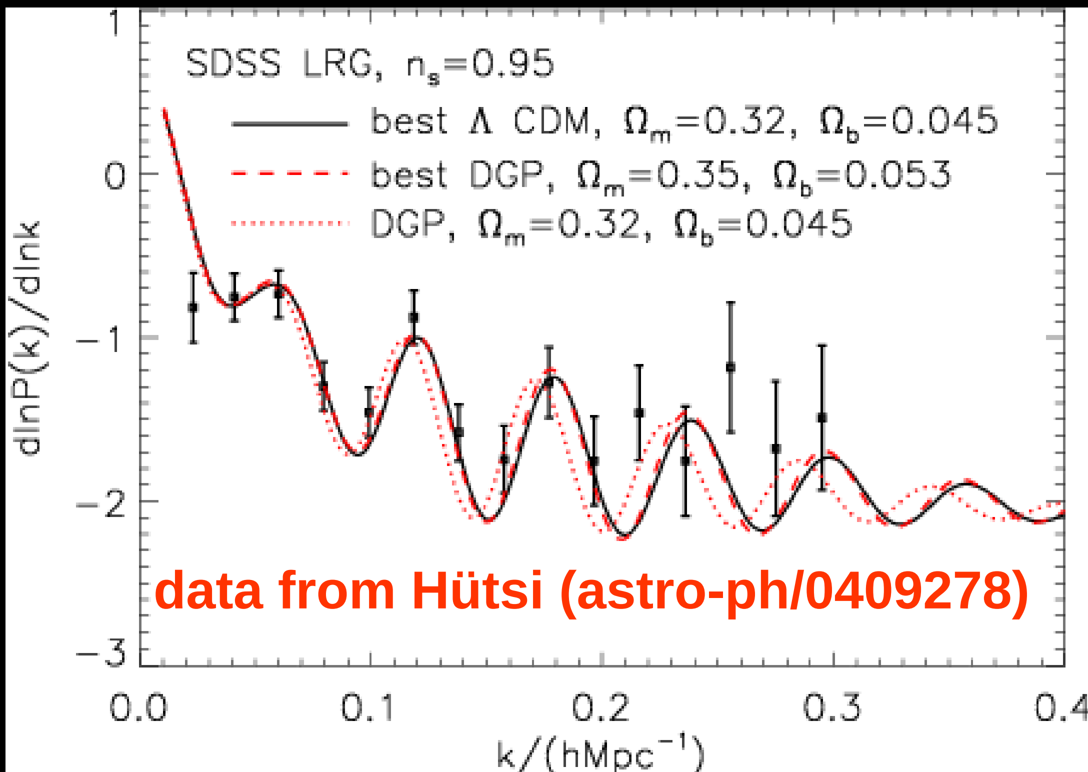
Predicted shifts of BAO peaks

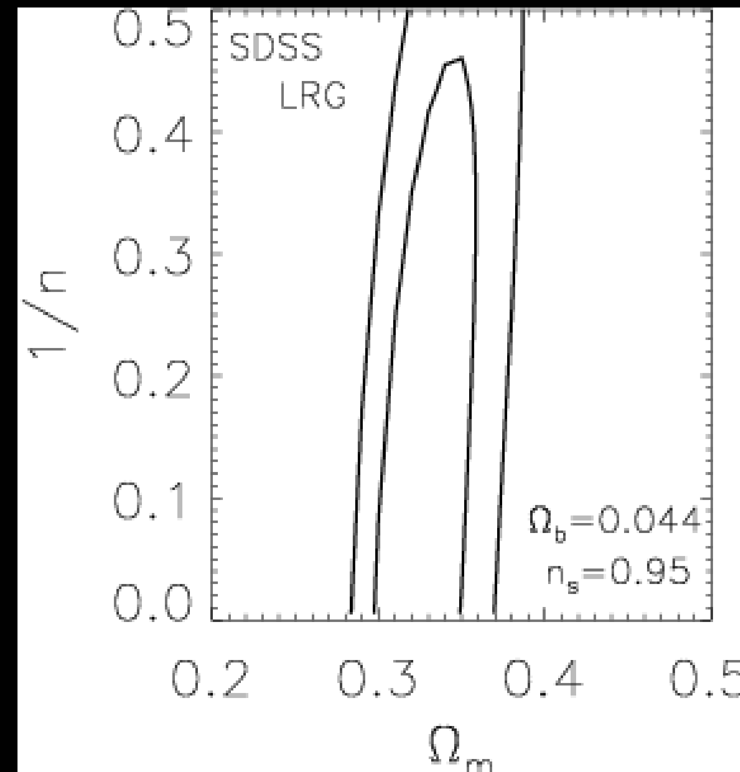


purely linear theory, observation in ΛCDM assumed

Yamamoto et al. (2006)

Current constraints from the SDSS LRG sample

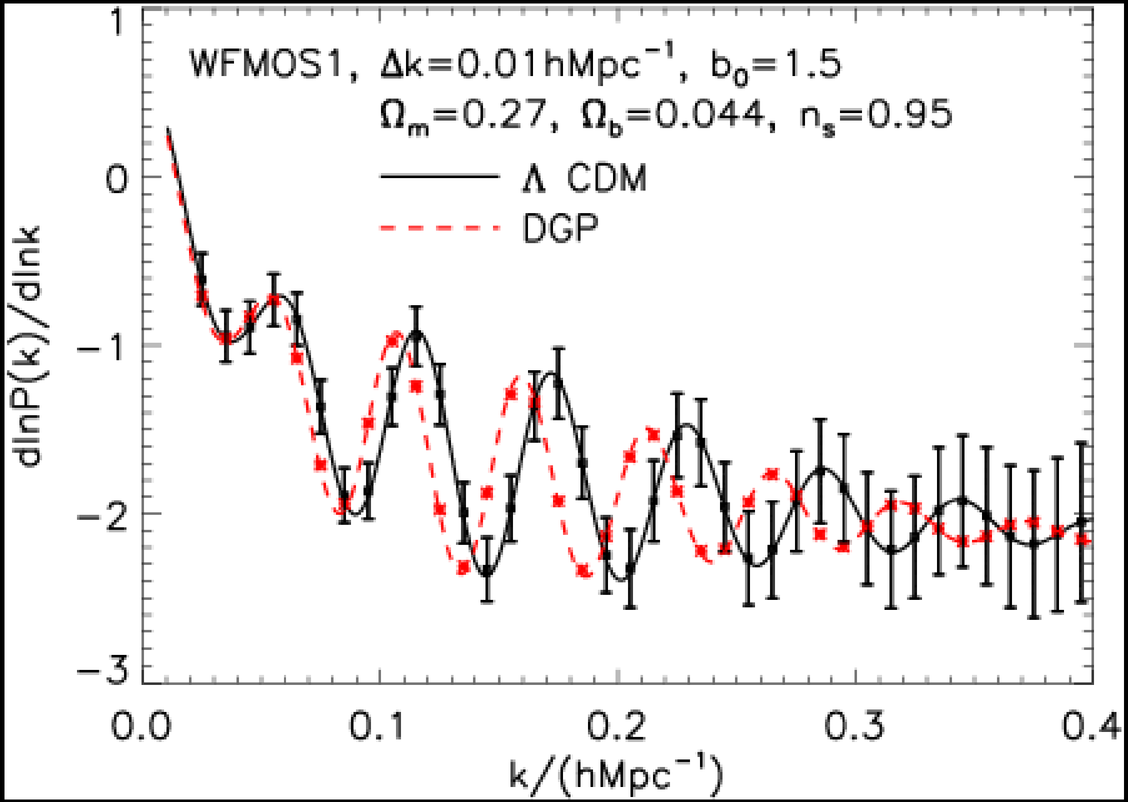


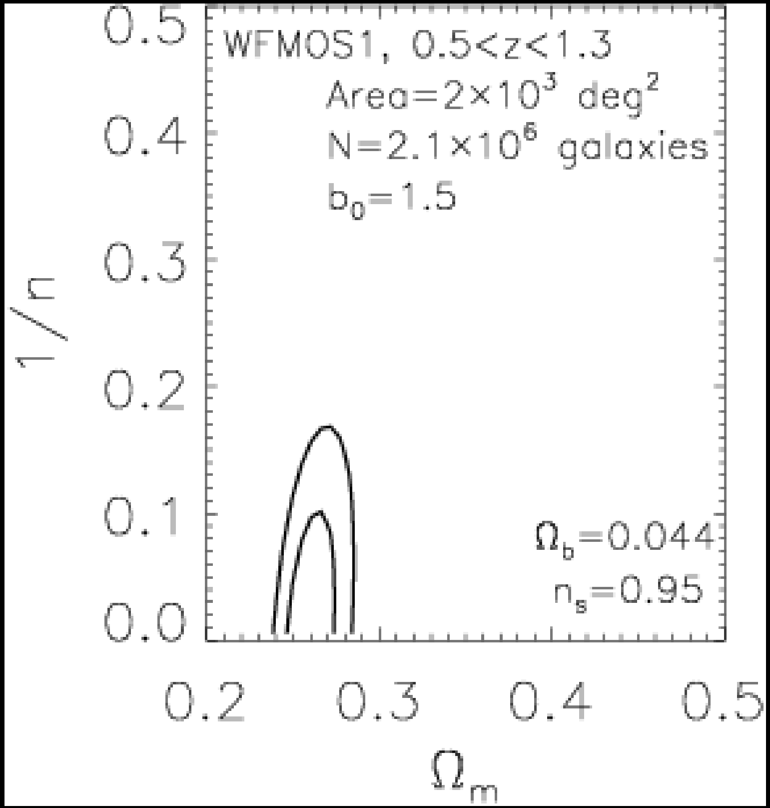


fit to linear theory for k<0.2hMpc^{-1}
observation in ΛCDM assumed

Yamamoto et al. (2006)

Expected constraints from future WFMOS z=1 sample





Yamamoto et al. (2006)

International Research Network for Dark Energy (JSPS, core-to-core program 2007-2008)

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Dept. of Astrophys. Sci.
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Univ. of Tokyo
Res. Center for the Early Universe
coordinator
Yasushi Suto

Caltech
Dept. of Astron.
coordinator
Richard Ellis

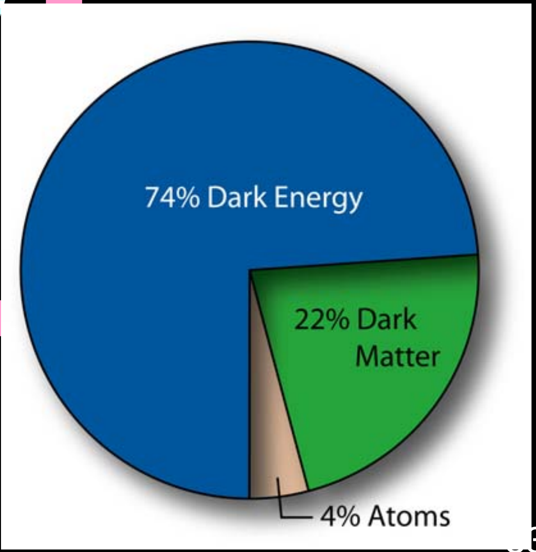
CMB
Gravitational lens
Baryon oscillation

Tohoku Univ.
NAOJ
Hiroshima Univ.
Kyoto Univ.
Nagoya Univ.

Supernova
Weak lens mapping

Edingburgh U.
Royal Obs.
coordinator
John Peacock

Theoretical model
Baryon oscillation
Weak lens mapping



We now realize an amazing fact that our world beyond this blue sky is dominated by dark energy

Let us thank our Earth for wonderful dark nights