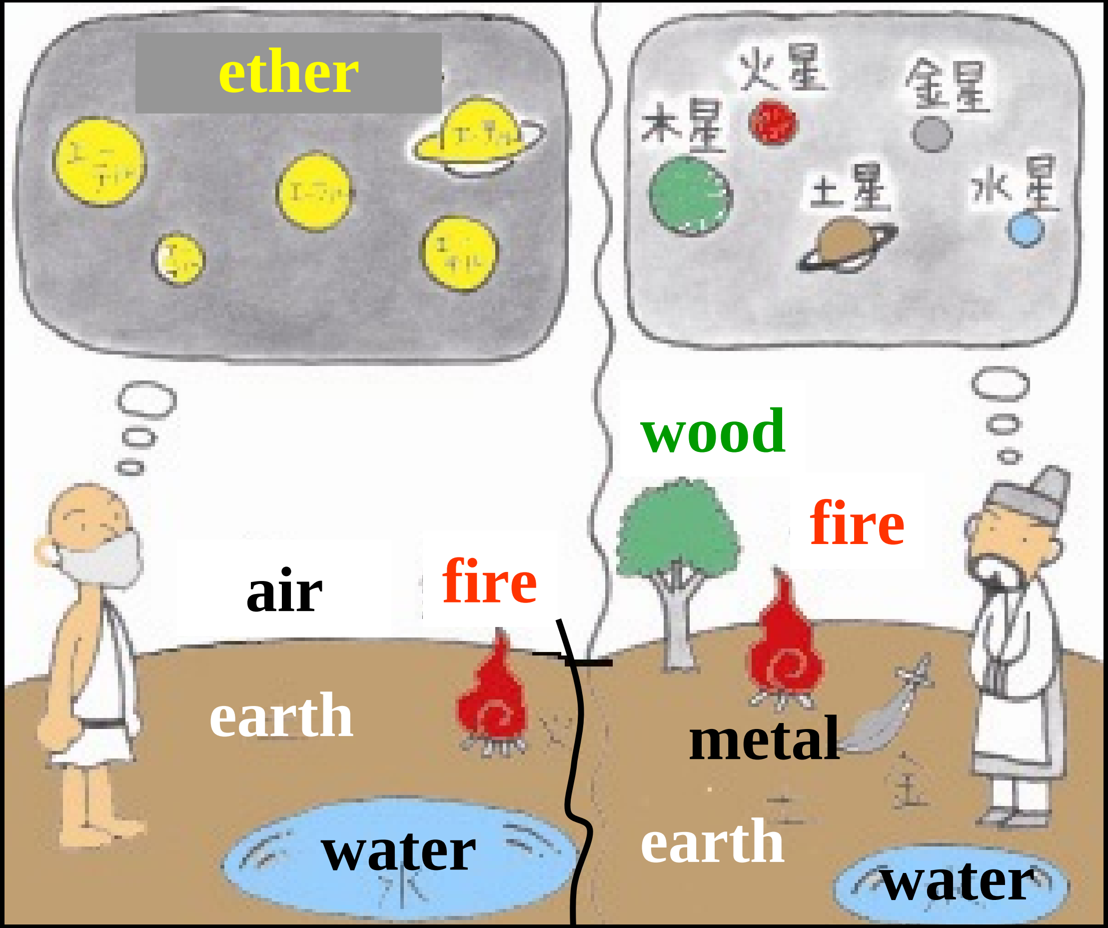
Dark energy in the Universe



	陽	陰
木	きのえ 甲	きのと 乙
火	ひのえ 丙	ひのと 丁
土	つちのえ 戊	つちのと 己
金	かのえ 庚	かのと 辛
水	みずのえ 壬	みずのと 癸

Yasushi Suto *Department of Physics, The University of Tokyo*

Summer School of KEK theory group @ Hakuba
July 30 and 31, 2007

Plan of the talk

Ⅰ importance of darkness

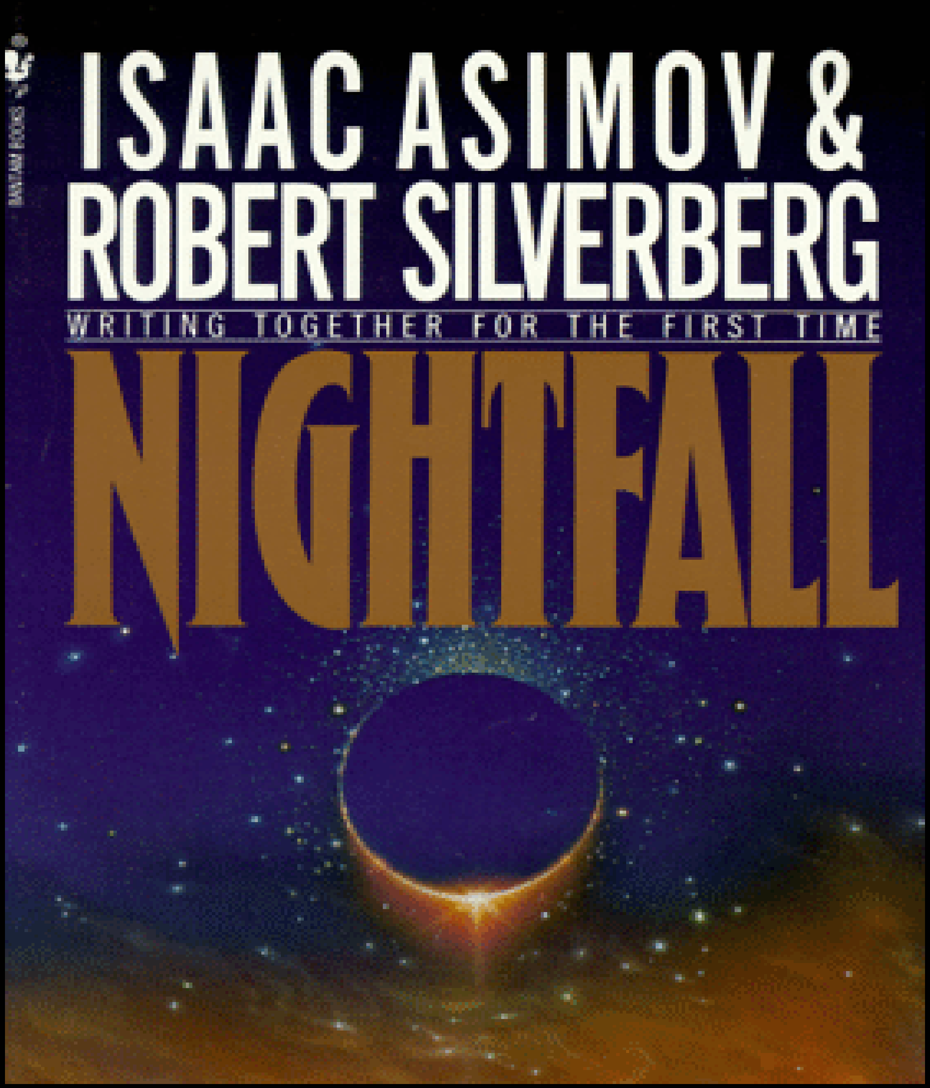
Ⅱ cosmic expansion and dark energy

Ⅲ cosmic acceleration and SN Ⅰa Hubble diagram

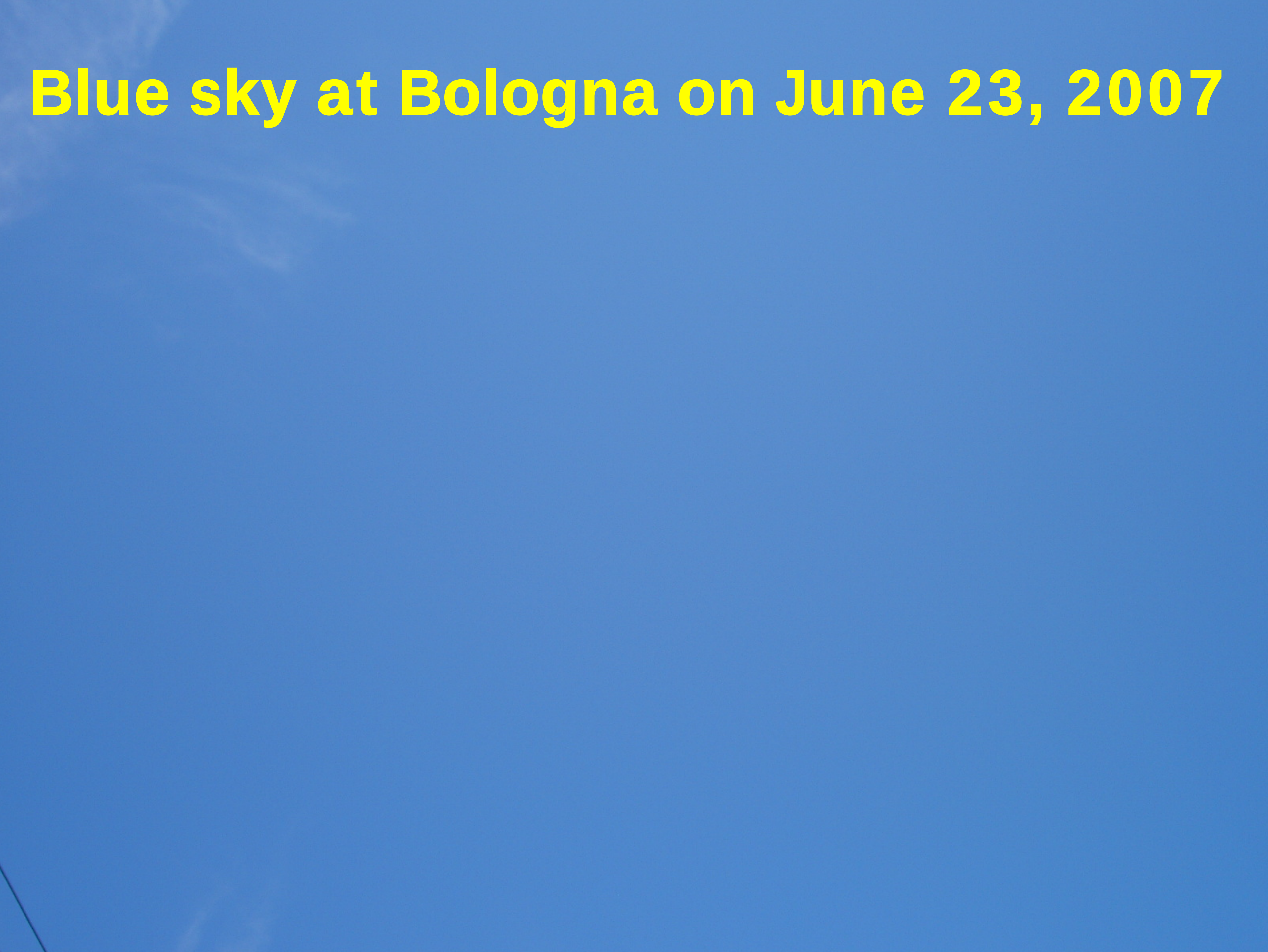
Ⅳ current constraints on dark energy

Ⅴ future dark energy projects

I importance of darkness



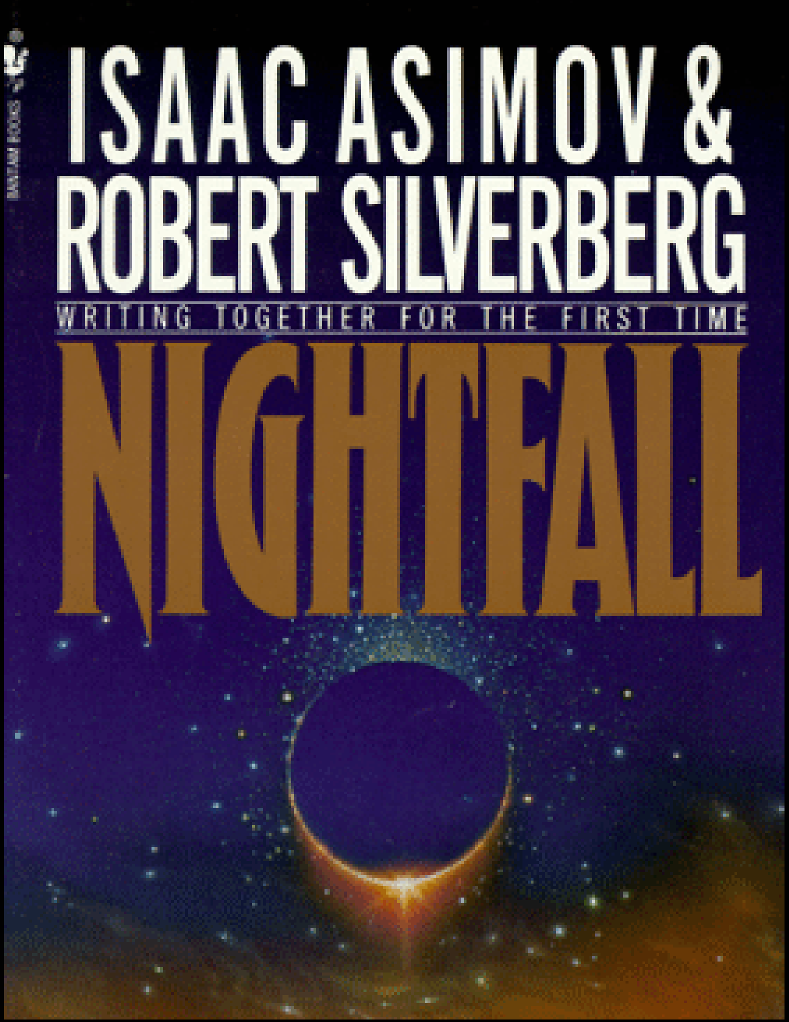
Blue sky at Bologna on June 23, 2007



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

what really dominates our world

a planet with six Suns

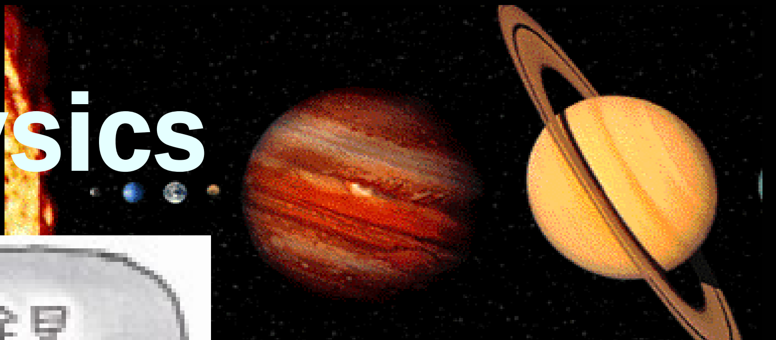


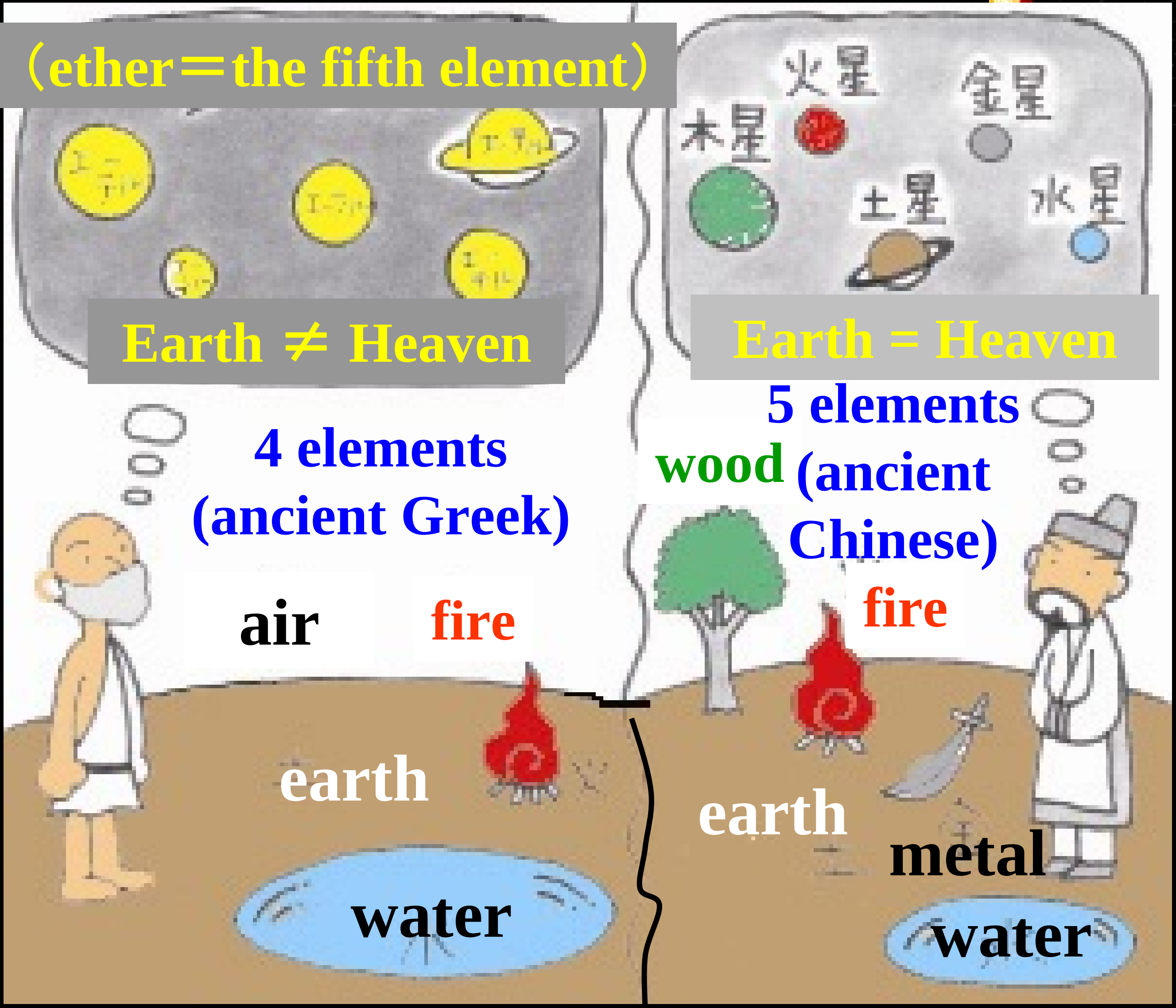
- no “night” except the total eclipse due to another planet every 2050 years
- People realized the true world for the first time through the darkness full of “stars”

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

Ancient particle physics





（ether＝the fifth element）

Earth ≠ Heaven

4 elements
(ancient Greek)

air

fire

earth

water

Earth = Heaven

5 elements

wood

(ancient Chinese)

fire

earth

metal

water

	陽	陰
木	きのえ 甲	きのと 乙
火	ひのえ 丙	ひのと 丁
土	つちのえ 戊	つちのと 己
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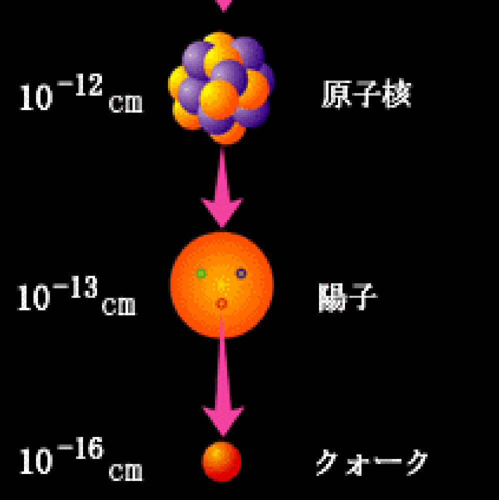


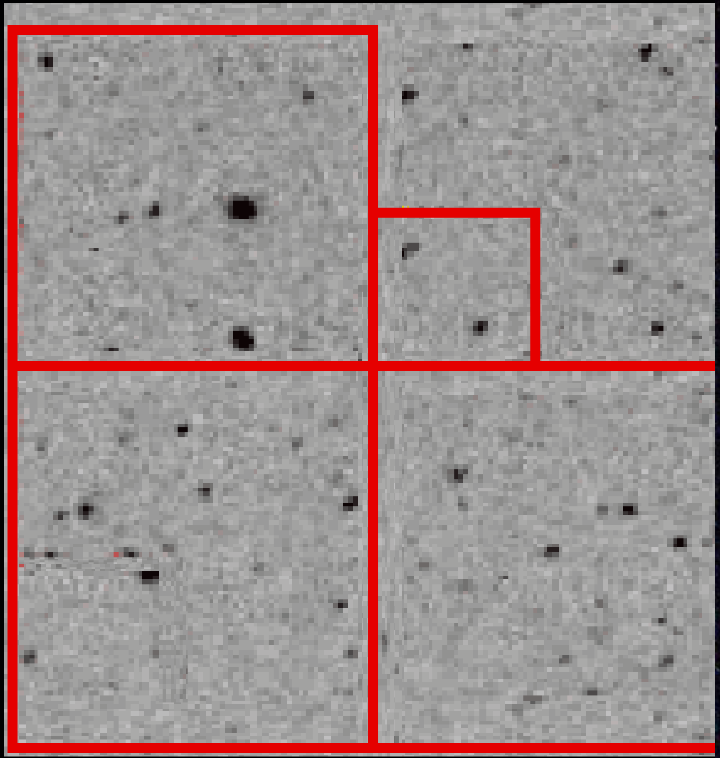
（いずもり よう:須藤靖「ものの大きさ」図1.1より）

SDSS (Sloan Digital Sky Survey)

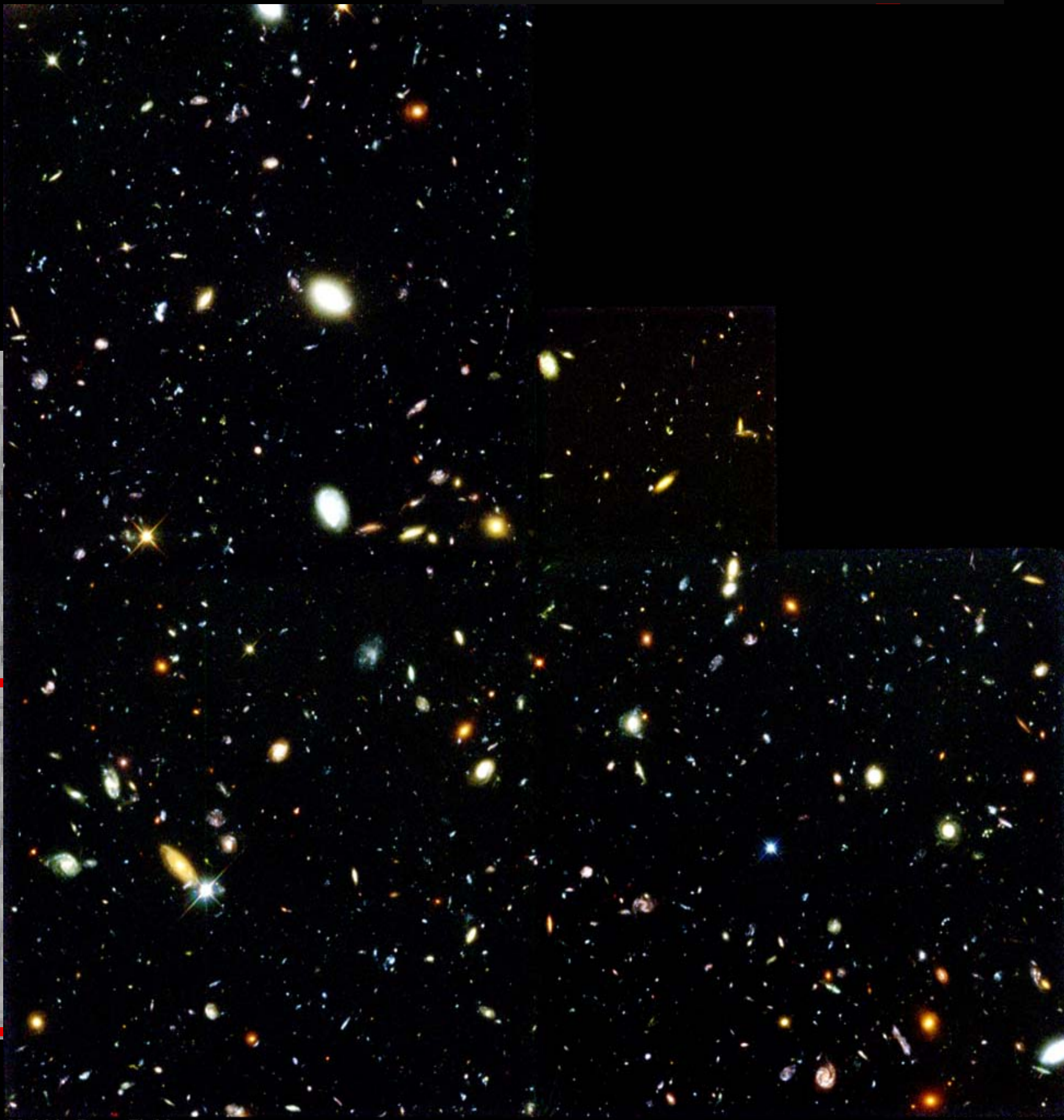
Apache Point Observatory @New Mexico, US

NHK education “Science Zero” broadcast on June 11, 2003

Progress of our eyes to the universe



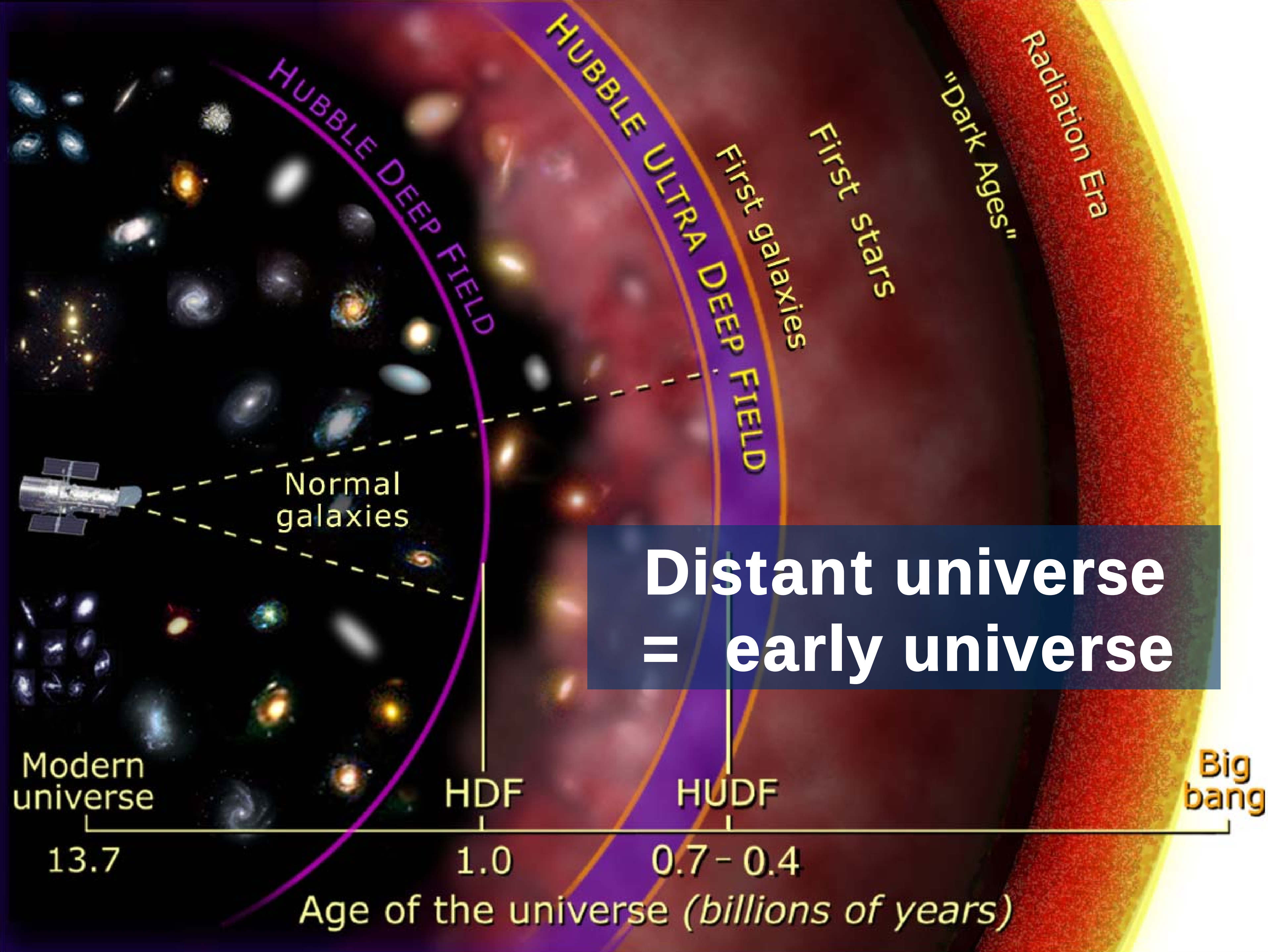
Ground 4m telesope＋CCD
= 100×photographic plate



Hubble Deep Field

ST ScI OPO January 15, 1996 R. Williams and the HDF Team (ST ScI) and NASA

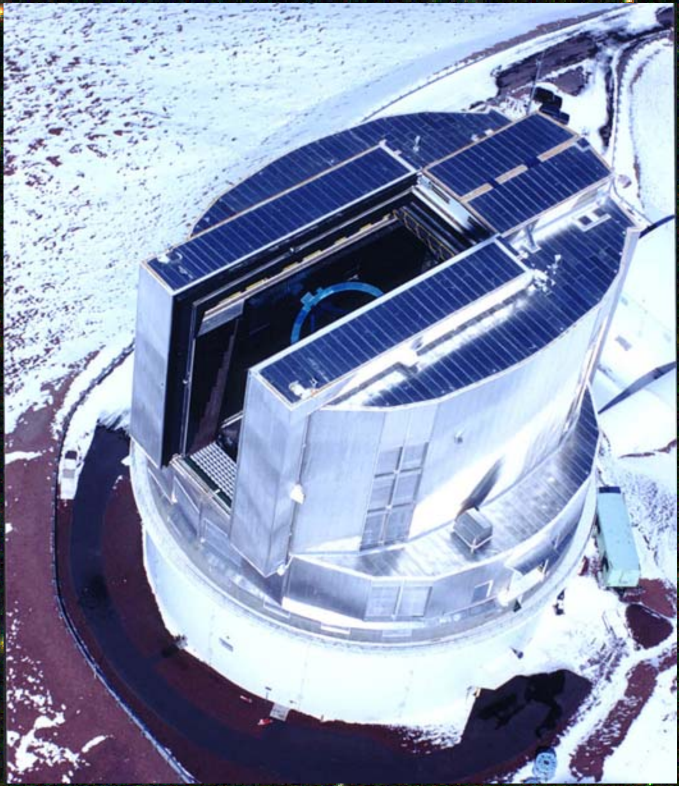
HST(2.4m)＋CCD
=1000×ground telescopes



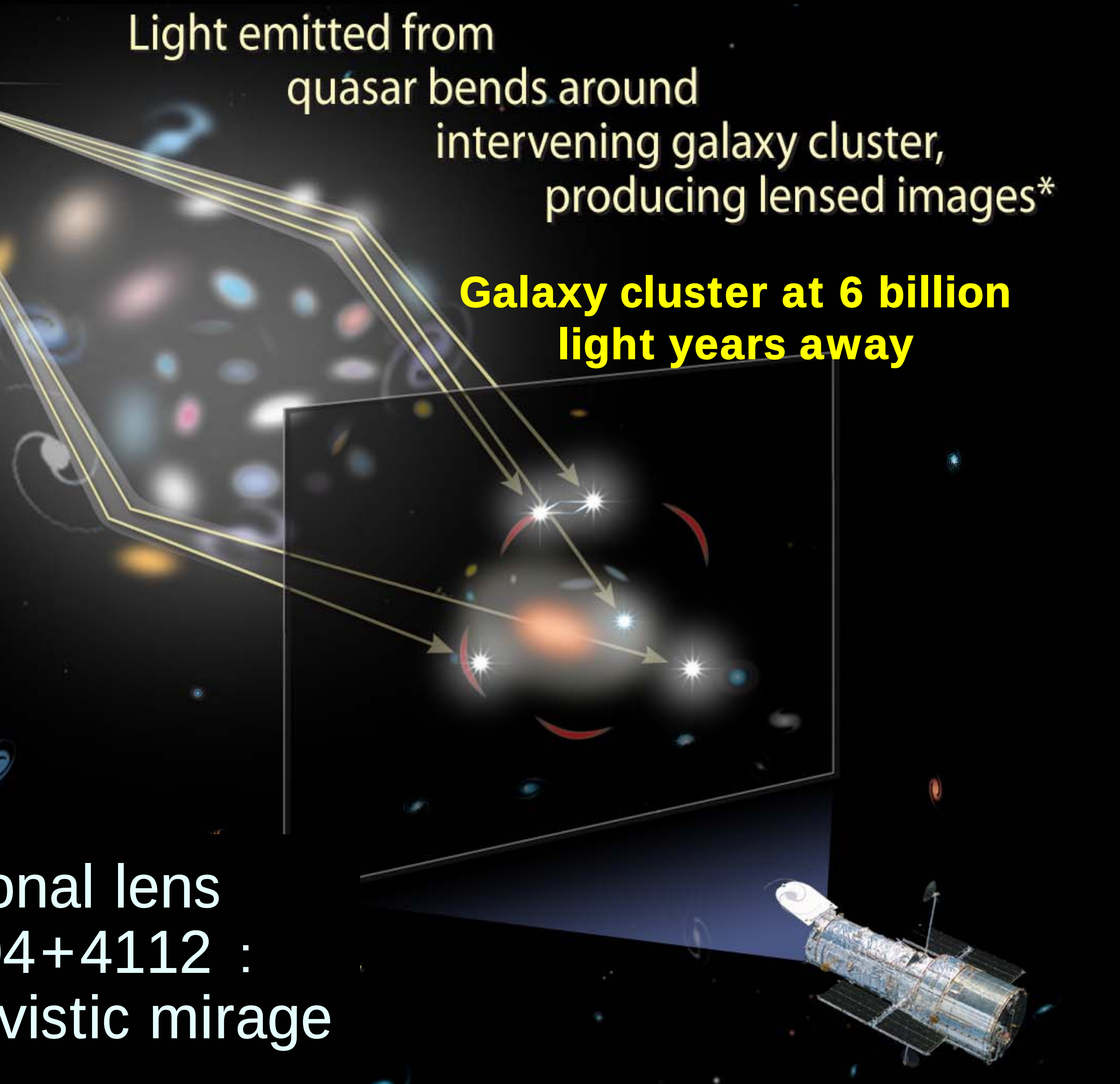
Distant universe
= early universe

Distant universe observed by Subaru telescope

http://www.naoj.org/Gallery/



http://hubblesite.org/newscenter/newsdesk/archive/releases/2006/23/

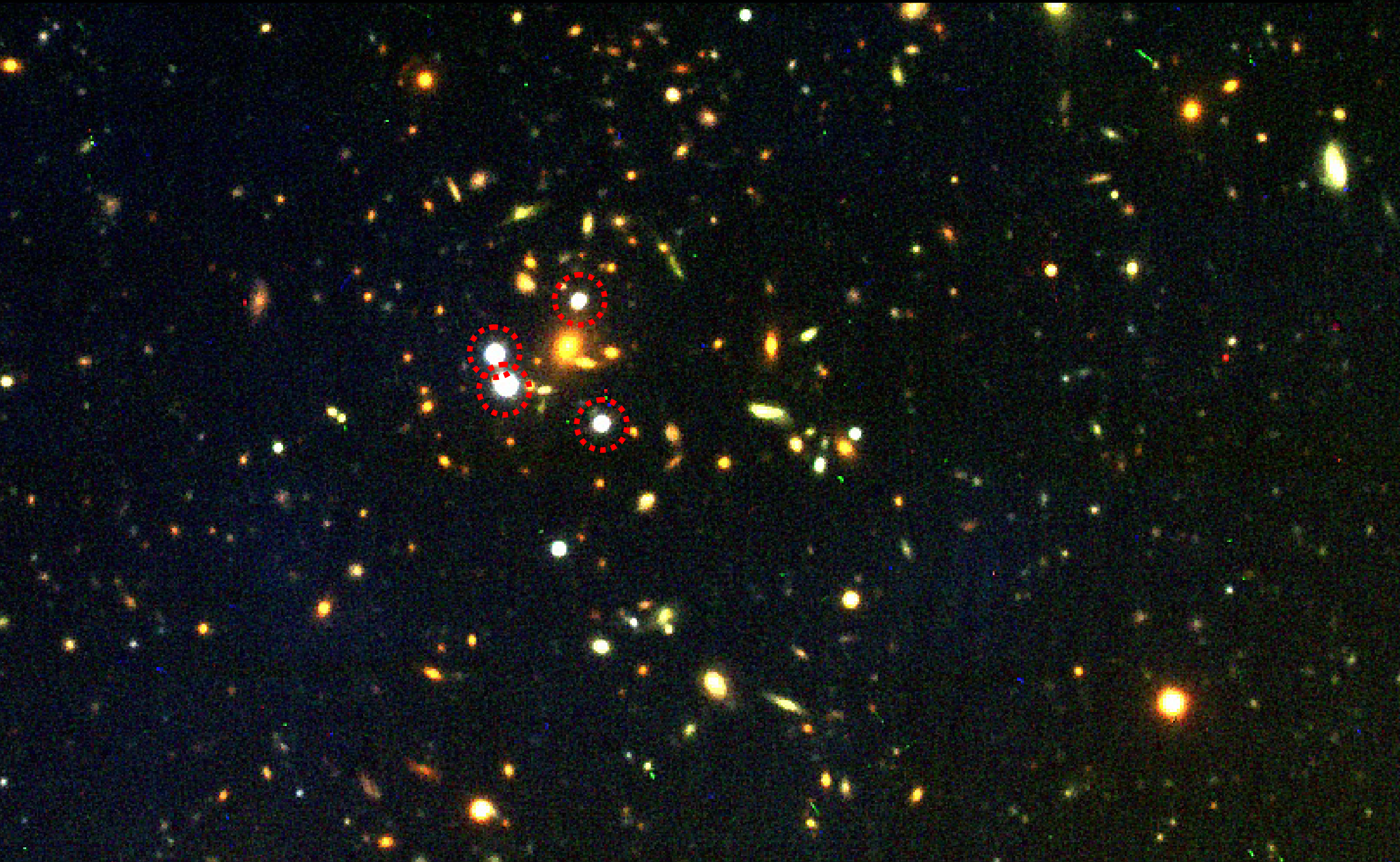


QSO at 10 billion light years away

Galaxy cluster at 6 billion light years away

Gravitational lens SDSS J1004+4112 : general relativistic mirage

Mirage from the universe 10 billion years ago (SDSS J1004+4112)



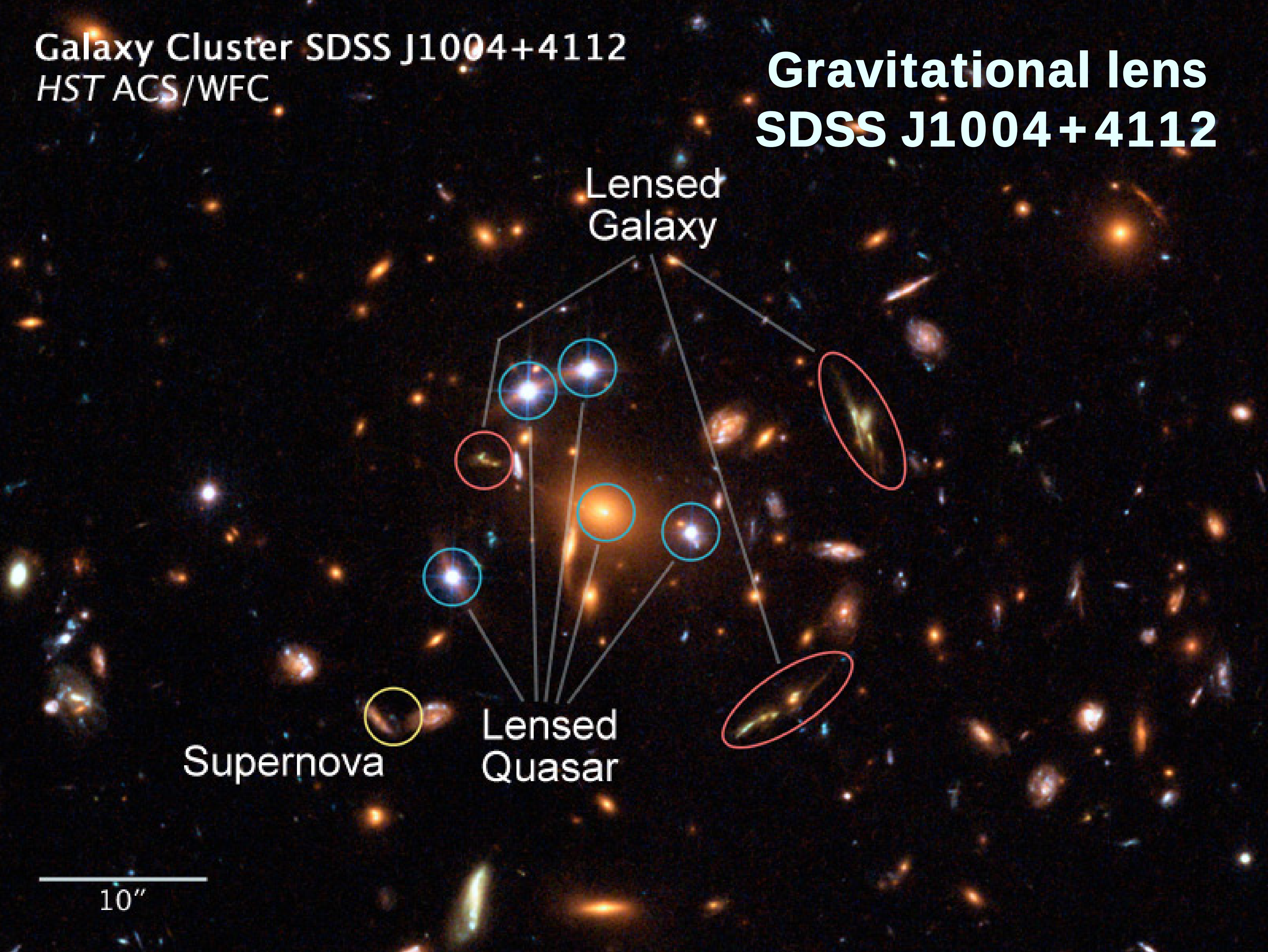
Discovered by N.Inada and M.Oguri at Univ. of Tokyo in 2003
from SDSS images and then confirmed by Subaru and Keck
Inada et al. Nature 426(2003)810

Back to the universe 10 billion years ago

HST photo release on May 23, 2006

http://hubblesite.org/newscenter/newsdesk/archive/releases/2006/23/

Gravitational lens
SDSS J1004+4112



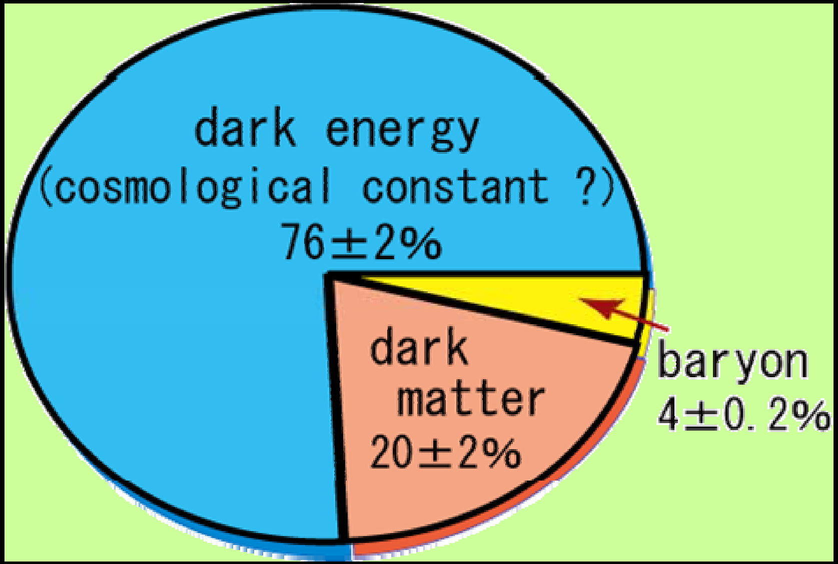
Gravitationally Lensed Quasar in Galaxy Cluster SDSS J1004+4112 *HST* ▪ ACS/WFC

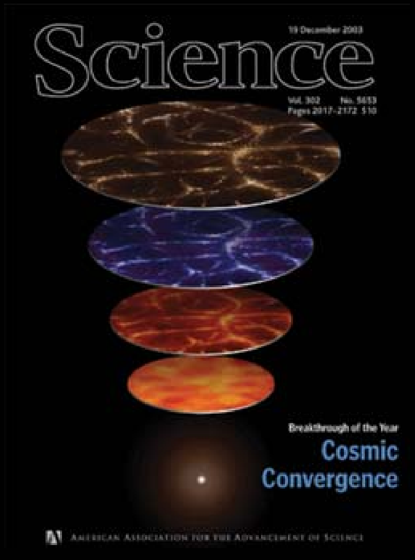
Looking toward the edge of the universe has revealed the presence of dark matter

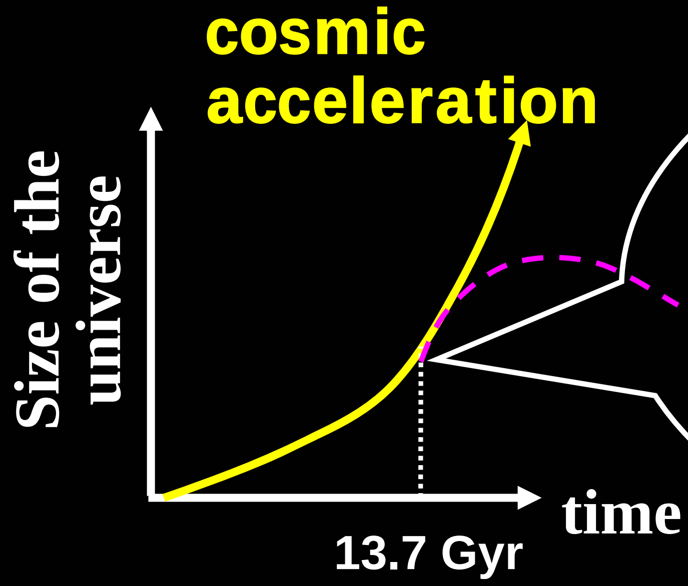
NASA, ESA, K. Sharon (Tel Aviv University) and E. Ofek (Caltech)

STScI-PRC05-23

Dark energy in the universe







Universal repulsion?

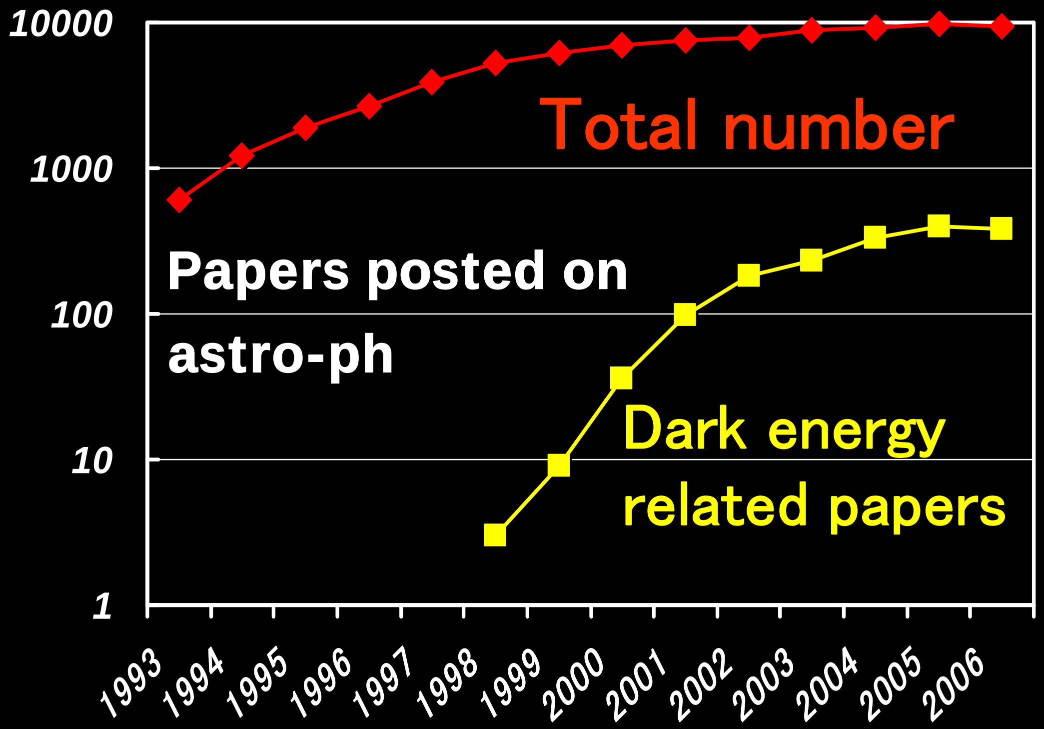
Cosmological constant?

Dark energy?

Modified gravity?

Why important ?

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

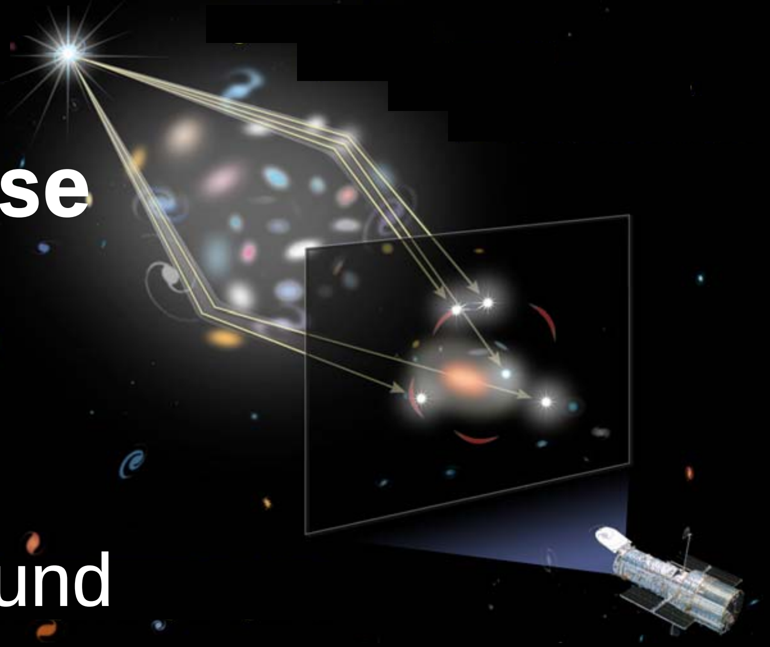


- **Steven Weinberg**
  "Right now, not only for cosmology but for elementary particle theory this is the bone in the throat"
- **Edward Witten**
  "Would be number one on my list of things to figure out"
- **Frank Wilczek**
  "Maybe the most fundamentally ysterious thing in basic science"

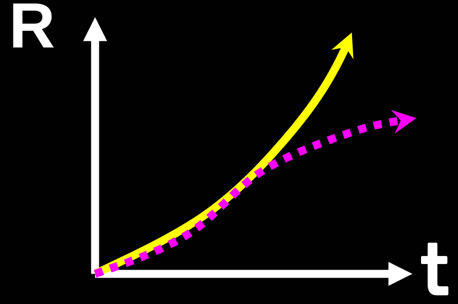
Why observable ?

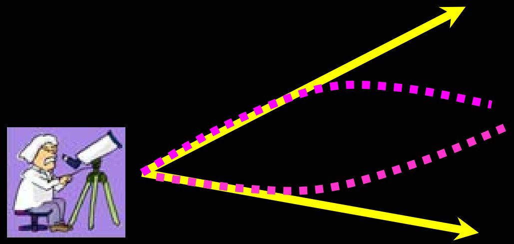
- **Objects are usually identified only through differential observations**
  - Visible matter: contrast between dark and bright regions
  - Dark matter: spatial inhomogeneities dynamically and gravitationally traced by visible stars, galaxies and quasars
- **Dark energy, if exists in a completely homogeneous manner, requires an absolute measurement for detection !?**
  - Time variation (cosmic acceleration, structure growth): differential observation in a time, not spatial, domain

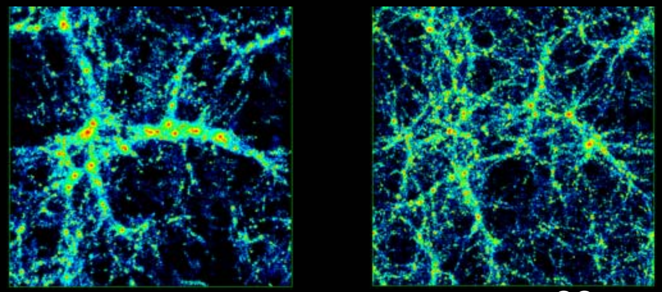
Signatures of dark energy



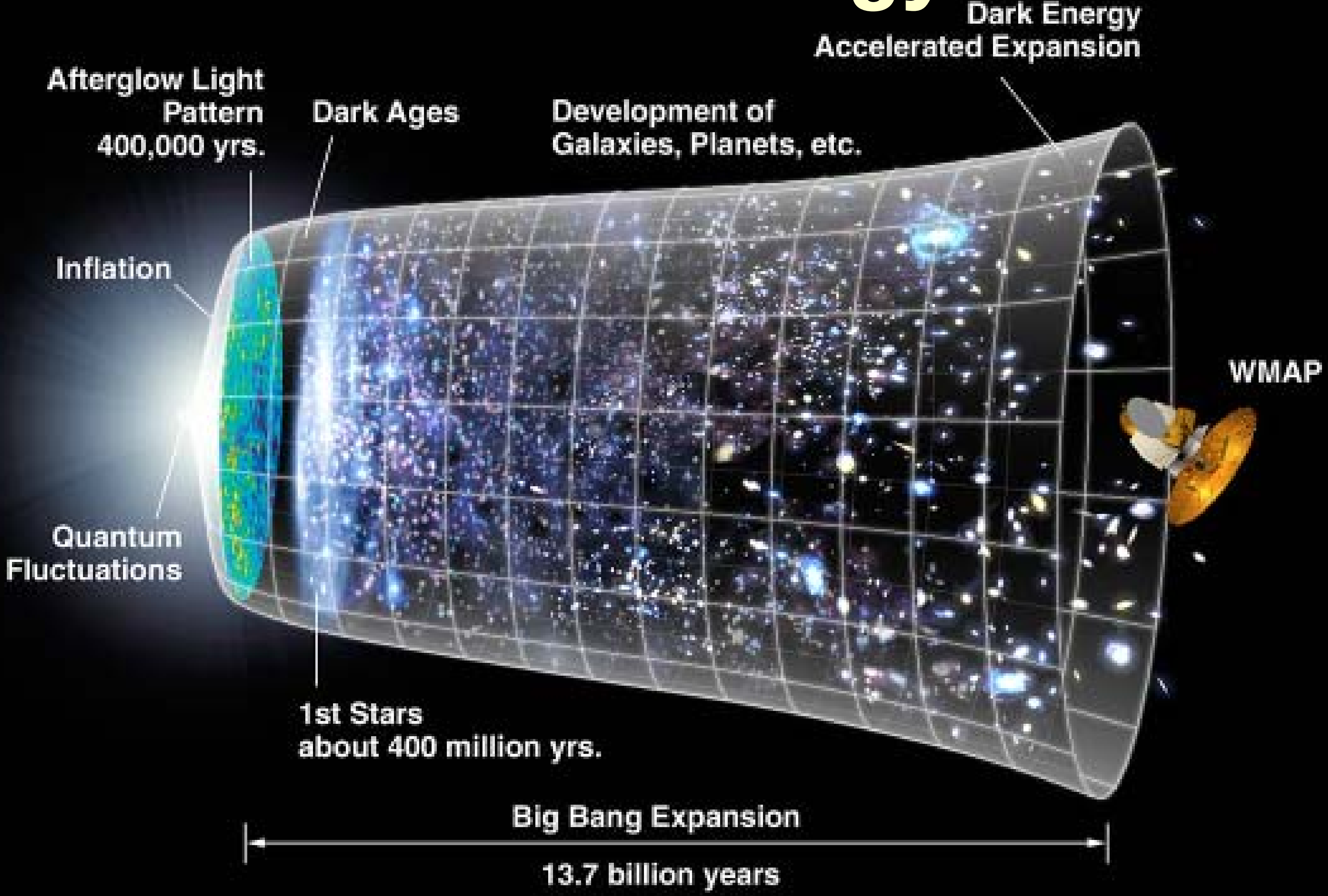
- **cosmic acceleration**
- **geometry of the universe**
- **evolution of structure**
- **Probes**
  - Supernova Hubble diagram
  - Cosmic Microwave Background
  - Gravitational lensing
  - ***Baryon Acoustic Oscillation***







Ⅱ cosmic expansion and dark energy



Expanding the expanding universe

- *Expand* the “radius” of the universe

$$R(t) = R(t_0) + \left.\frac{dR}{dt}\right|_{t_0} (t - t_0) + \frac{1}{2}\left.\frac{d^2R}{dt^2}\right|_{t_0} (t - t_0)^2 + \cdots$$

  - current size:

$$R(t_0)$$ ⇔ no physical meaning: $a(t)=R(t)/R(t_0)$

  - current expansion rate: the Hubble constant

$$H_0 \equiv \left.\frac{dR/dt}{R}\right|_{t_0}$$

⇔ unpredictable: simply due to the initial condition (can be either negative or positive)

  - current acceleration rate: the deceleration parameter

$$q_0 \equiv -\left.\frac{R\, d^2R/dt^2}{(dR/dt)^2}\right|_{t_0}$$

⇔ related to the cosmic energy density via the Einstein eq. (should be positive)

The Friedmann equations

Alexander Friedmann
(1888-1925)

- the Einstein equations:

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

⇒ the Friedmann equations

  - energy conservation equation

$$\left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{K}{a^2(t)} \boxed{+\frac{\Lambda}{3}}$$

  - equation of motion

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3}\left(\rho(t) \boxed{+ 3p(t) - \frac{\Lambda}{4\pi G}}\right)$$

Additional terms from general relativity

Cosmological parameters defined

- energy conservation

$$\left(\frac{\dot{a}(t)}{a(t)}\right)^2 \equiv H^2(t) = \frac{8\pi G}{3}\rho_m(t) + \frac{8\pi G}{3}\rho_r(t) - \frac{K}{a^2(t)} + \frac{\Lambda}{3}$$

$$\Rightarrow \quad 1 = \Omega_m(t) + \Omega_r(t) + \Omega_K(t) + \Omega_\Lambda(t)$$

  - density parameters

$$\Omega_m(t) \equiv \frac{8\pi G\rho_m(t)}{3H^2(t)} \qquad \Omega_\Lambda(t) \equiv \frac{\Lambda}{3H^2(t)}$$

matter and Λ gravitational energies in units of kinetic energy

  - deceleration parameter

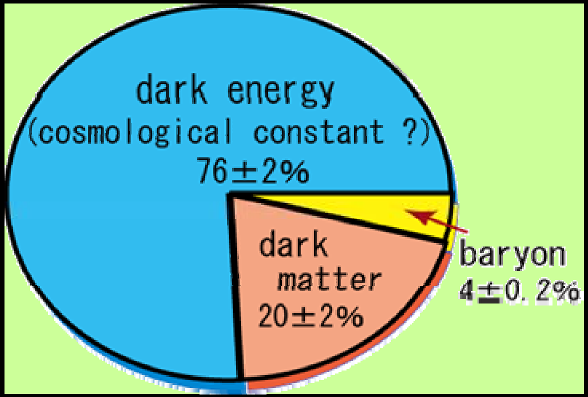
$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3}\left(\rho(t) + 3p(t) - \frac{\Lambda}{4\pi G}\right)$$

$$\Rightarrow \quad q(t) = \frac{\Omega_m(t)}{2} - \Omega_\Lambda(t)$$ **(> positive if $\Lambda = 0$)**

Reasonable guess

- **Simplest universe: $\Omega_m=1, \Omega_K=\Omega_\Lambda=\Omega_r=0$**
  - total energy = 0 (⇔ flat space): $\Omega_K=0$
  - no cosmological constant: $\Omega_\Lambda=0$
  - radiation negligible: $\Omega_r \doteqdot 0$
- Deceleration parameter
  - $q=\Omega_m/2-\Omega_\Lambda=0.5$
  - $q>0$ should be robust as long as $\Omega_\Lambda=0$
  - gravity is always attractive, and thus decelerates the motion. This is why the *deceleration* parameter was introduced.

Observed values



- **fairly complicated**
  - total energy ≒ 0 (⇔ flat space, $\Omega_K \fallingdotseq 0$) seems OK
  - radiation negligible: $\Omega_r \fallingdotseq 0$
  - something like cosmological constant (?) dominates the current universe: $\Omega_\Lambda \fallingdotseq 3/4$
  - $\Omega_m \fallingdotseq 1/4$, more than 80% of the matter is dark ($\Omega_{DM} \fallingdotseq 0.2$, $\Omega_{baryon} \fallingdotseq 0.04$)
- **negative deceleration parameter !**
  - $q = \Omega_m/2 - \Omega_\Lambda \fallingdotseq -0.6 < 0$
  - currently accelerating (repulsive force?)
  - should have defined the acceleration parameter.

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 change with time

w=-1 or not: that is the question

- conventional parameterization (no physics):
  $w(a) = w_0 + w_a(1-a)$ where **$a = 1/(1+z)$**
  - **cosmological constant (w_0=-1 & w_a=0) ???**
  - **w_a=0 or $\neq$0 ???**
  - **w_0=-1 or $\neq$-1 ???**
- physical models desperately needed
  - My colleagues told me that DGP (Dvali-Gabadadze-Porrati) model is approximated by

$$w(a) = -\frac{1}{1+\Omega_m(a)} \quad \text{where} \quad \Omega_m(a) = \frac{\Omega_m}{a^3}\left(\frac{H_0}{H(a)}\right)^2$$

$$\Rightarrow \quad w_0 = -0.78, w_a = 0.32 \quad \text{for} \quad \Omega_m = 0.27$$

although I cannot even pronounce their names…

Time-dependent w model

- if p=w(a)ρ ,

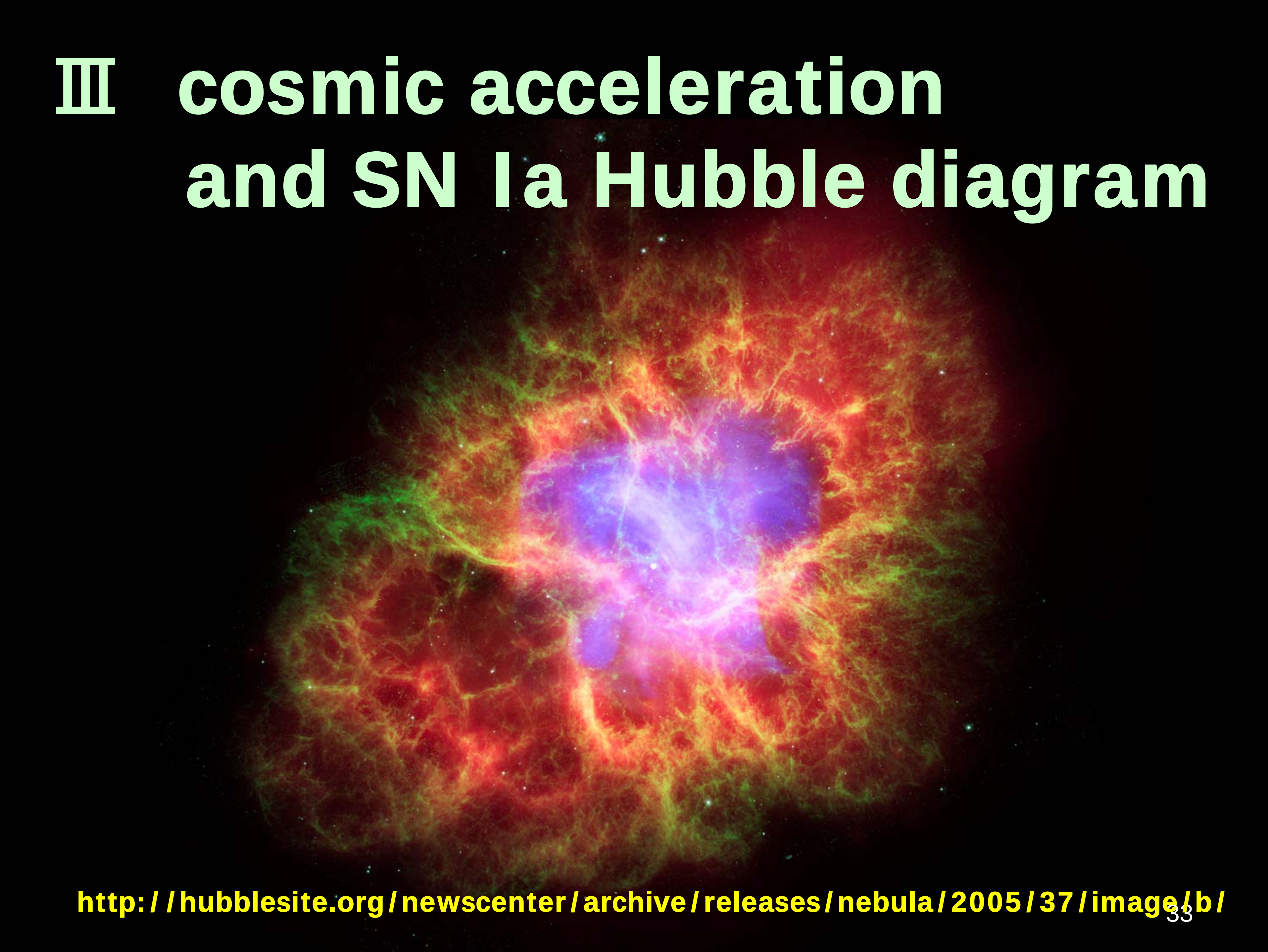
$$\rho(a) = \rho_0 \exp\left[\int_a^1 3[1+w(x)]\frac{dx}{x}\right] \equiv \rho_0 f(a)$$

$$H^2(a) = H_0^2\left[\frac{\Omega_m}{a^3} - \frac{\Omega_K}{a^2} + (1-\Omega_m+\Omega_K) f(a)\right]$$

- for w(a)= w_0+w_a(1-a)

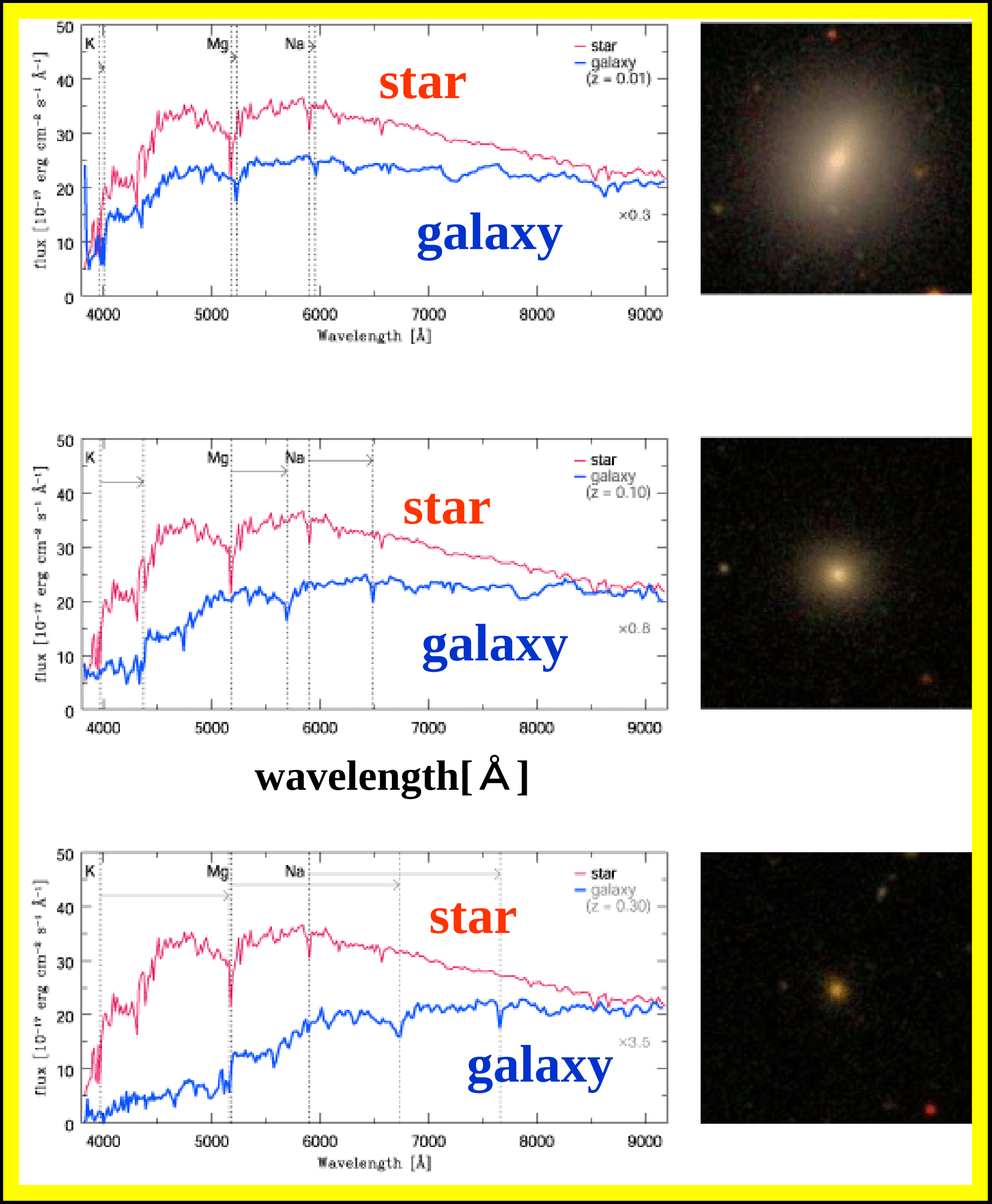
$$f(a) = a^{-3(1+w_0+w_a)} e^{-3w_a(1-a)}$$

Ⅲ cosmic acceleration and SN Ia Hubble diagram



http://hubblesite.org/newscenter/archive/releases/nebula/2005/37/image/b/

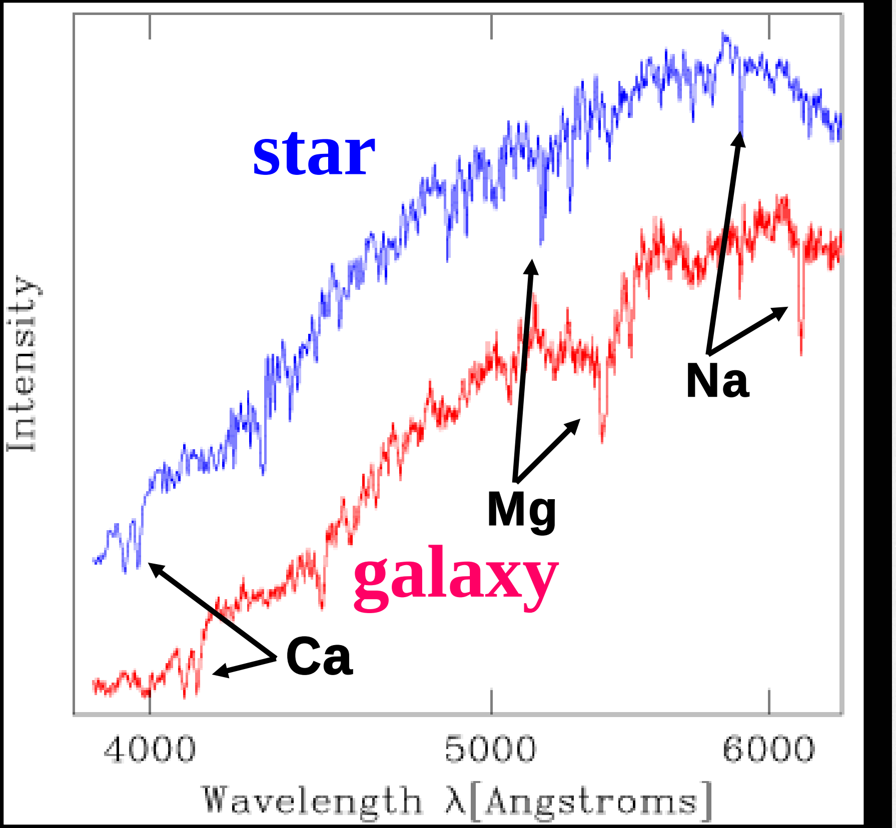
Galaxy spectrum

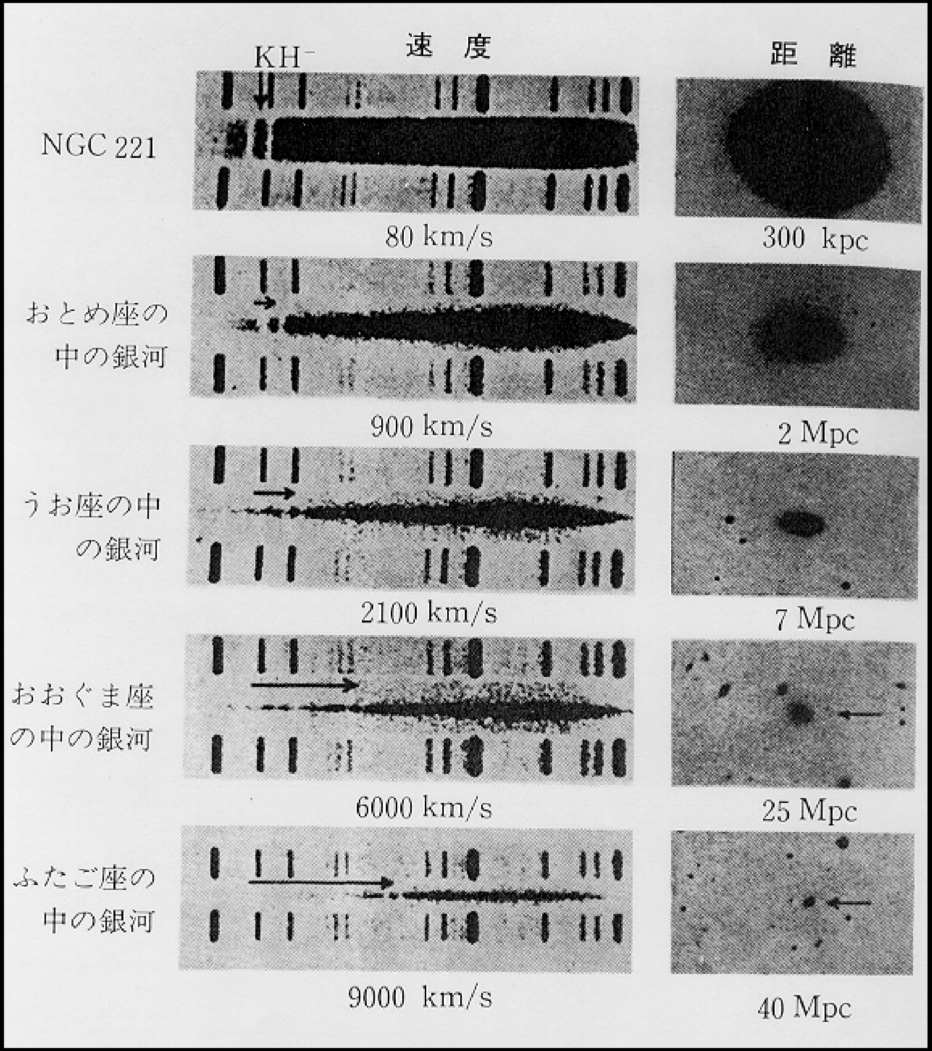


- Galaxy spectrum = Σ(member star spectrum)
- Redshifted due to the cosmic expansion
- Recession velocity is proportional to the distance of the galaxy

(courtesy of K.Yahata)

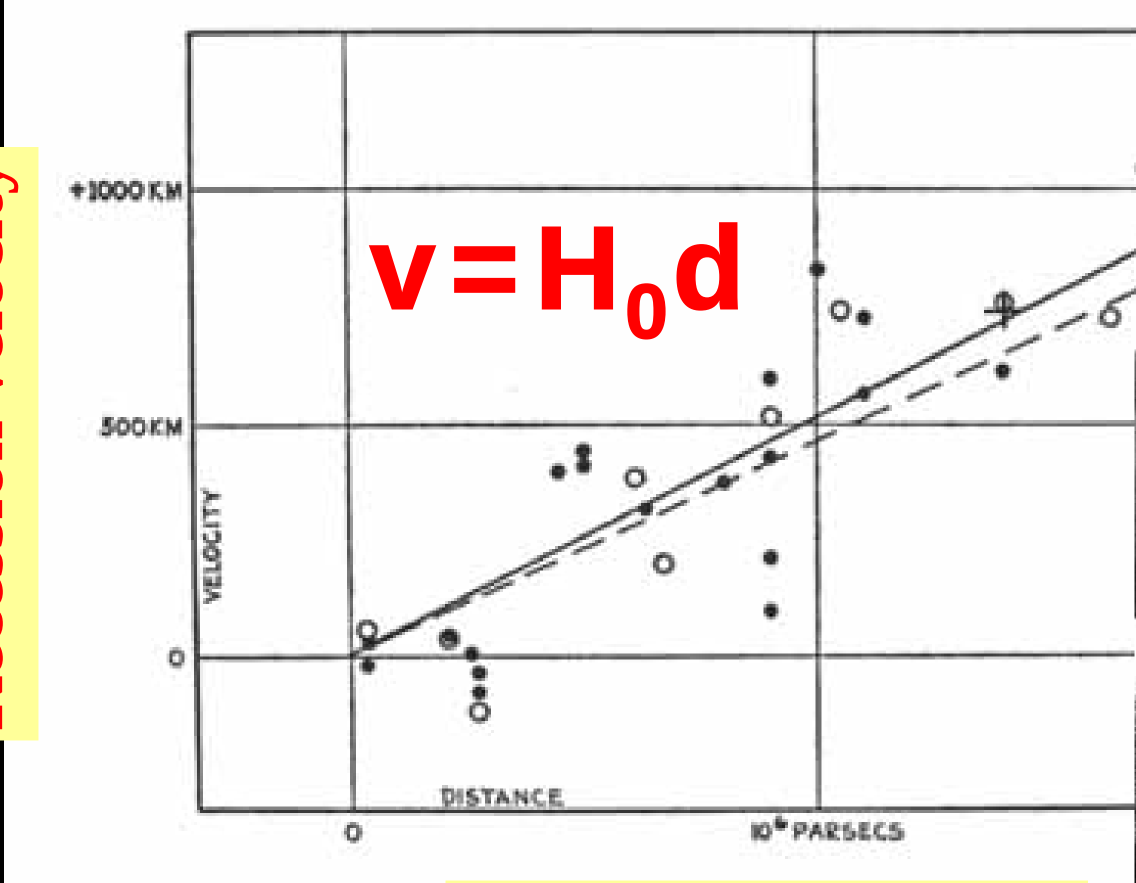
Redshift and recession velocity of galaxies





(E.Hubble; The realm of nebulae)

Hubble's law (1929)



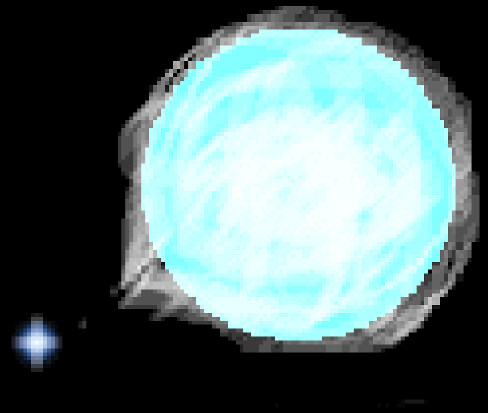
Recession velocity

$v=H_0d$

Estimated distance

H_0=530 instead of 70km/s/Mpc
(due to errors in estimated distance)

Type Ia Supernova



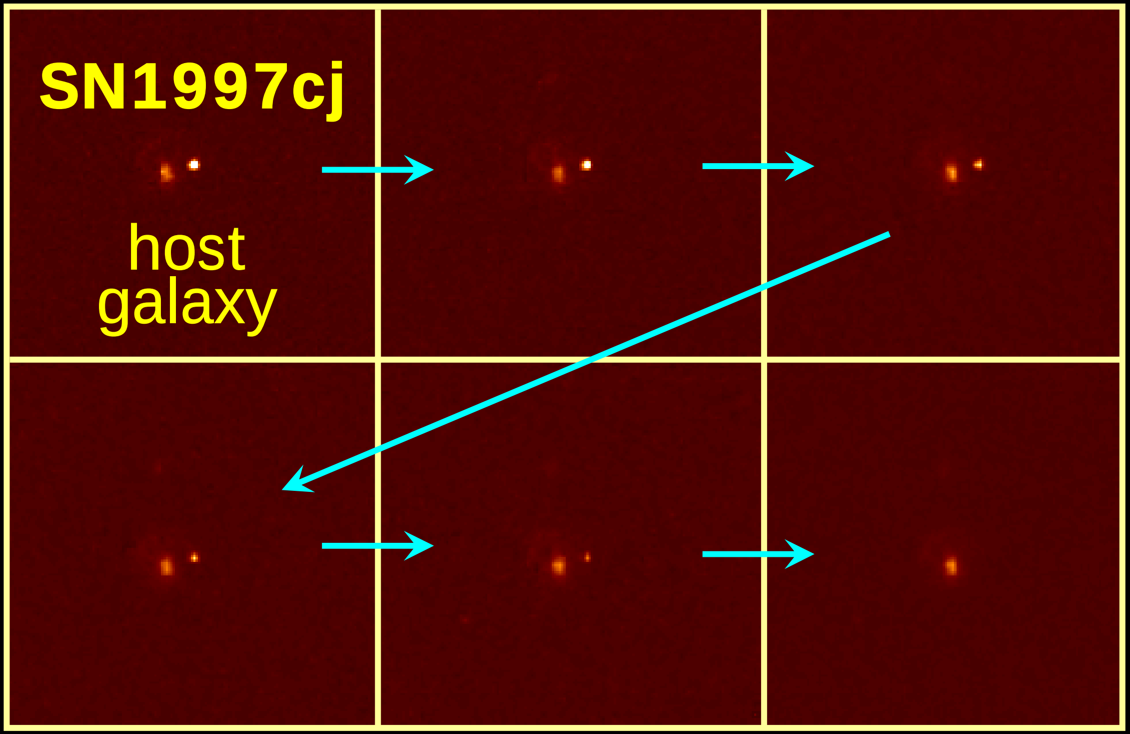
- Progenitor: **white dwarf + red giant**

  a final stage of binary star systems

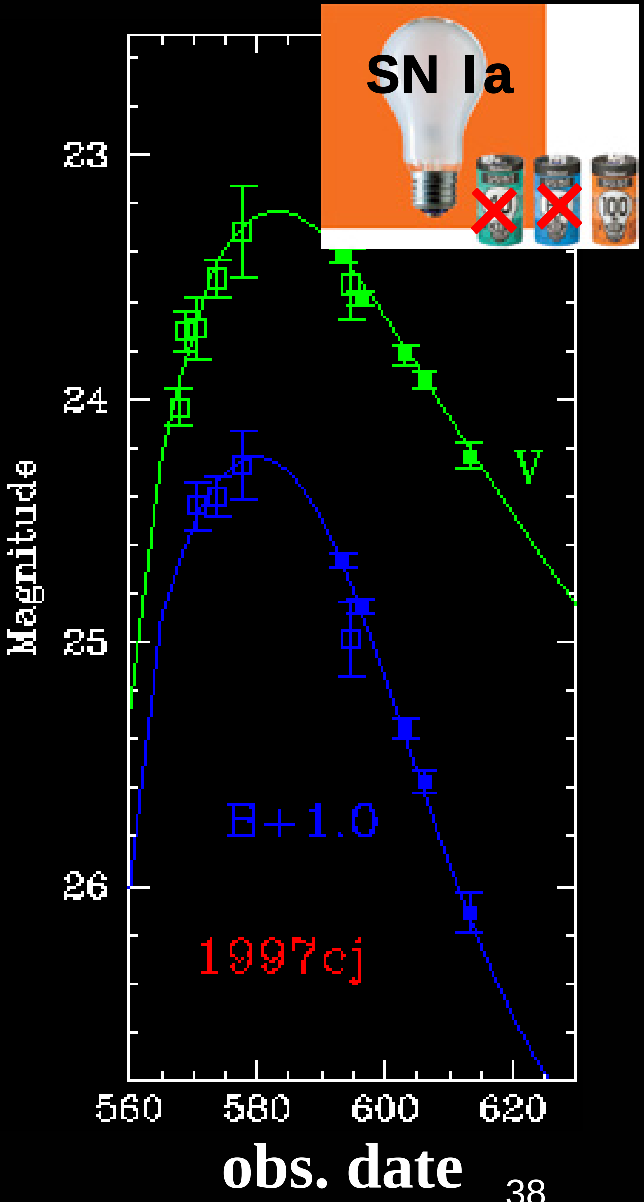
- white dwarf increases its mass via accretion from the red giant
  - Maximum mass of white dwarf (pressure due to the electron degeneracy > gravity)
  - the Chandrasekhar mass ($M_{CH} \fallingdotseq 1.4 M_{sun}$)
  - cannot support gravity and explodes if $M > M_{CH}$

Light-curve of Type Ia Supernova

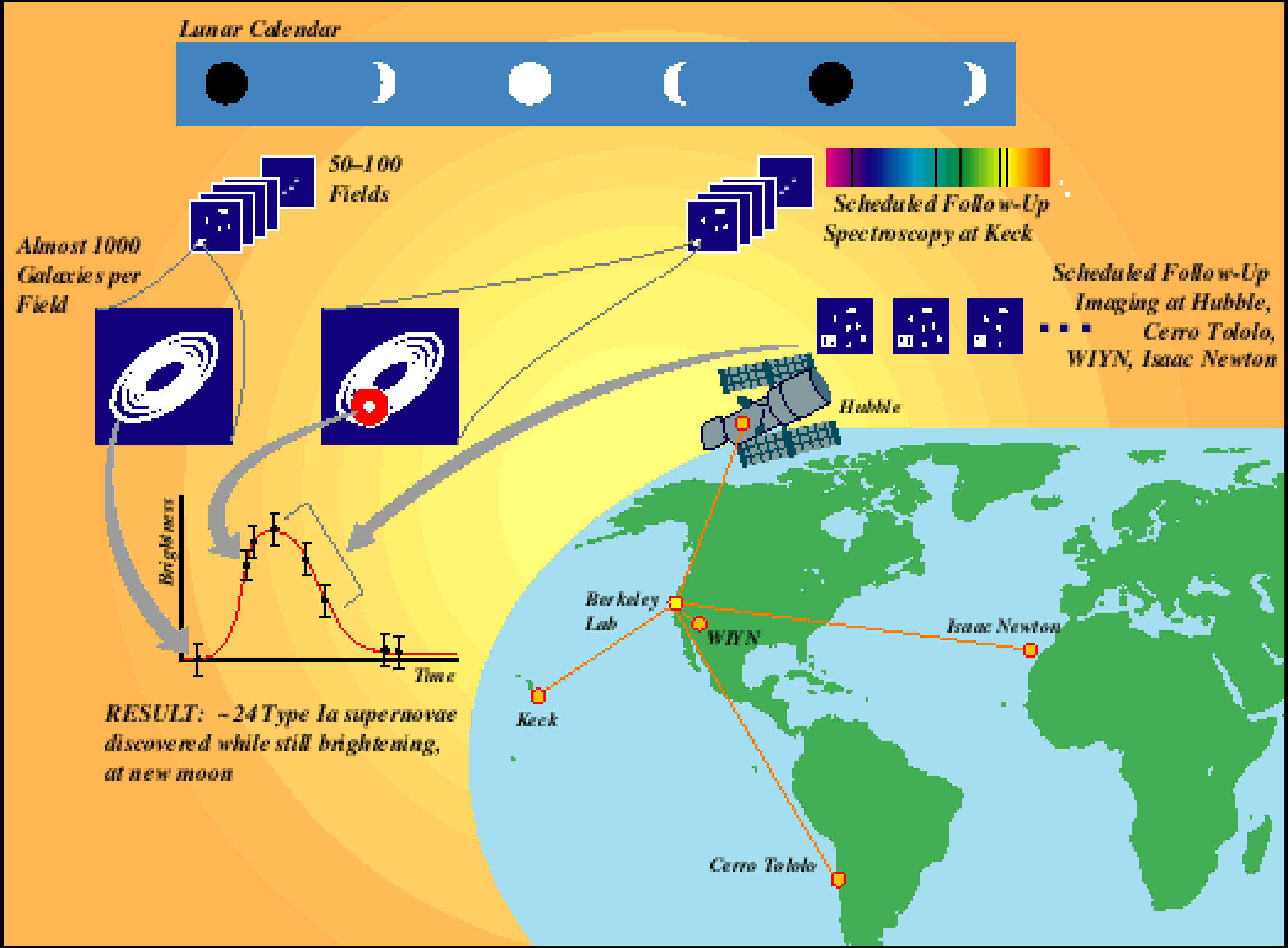
- peak luminosities of all SNe Ia with known distance agree within 10 percent
- discover and monitor SNe Ia for **standard candles** (distance indicator)



Hubble Space Telescope images



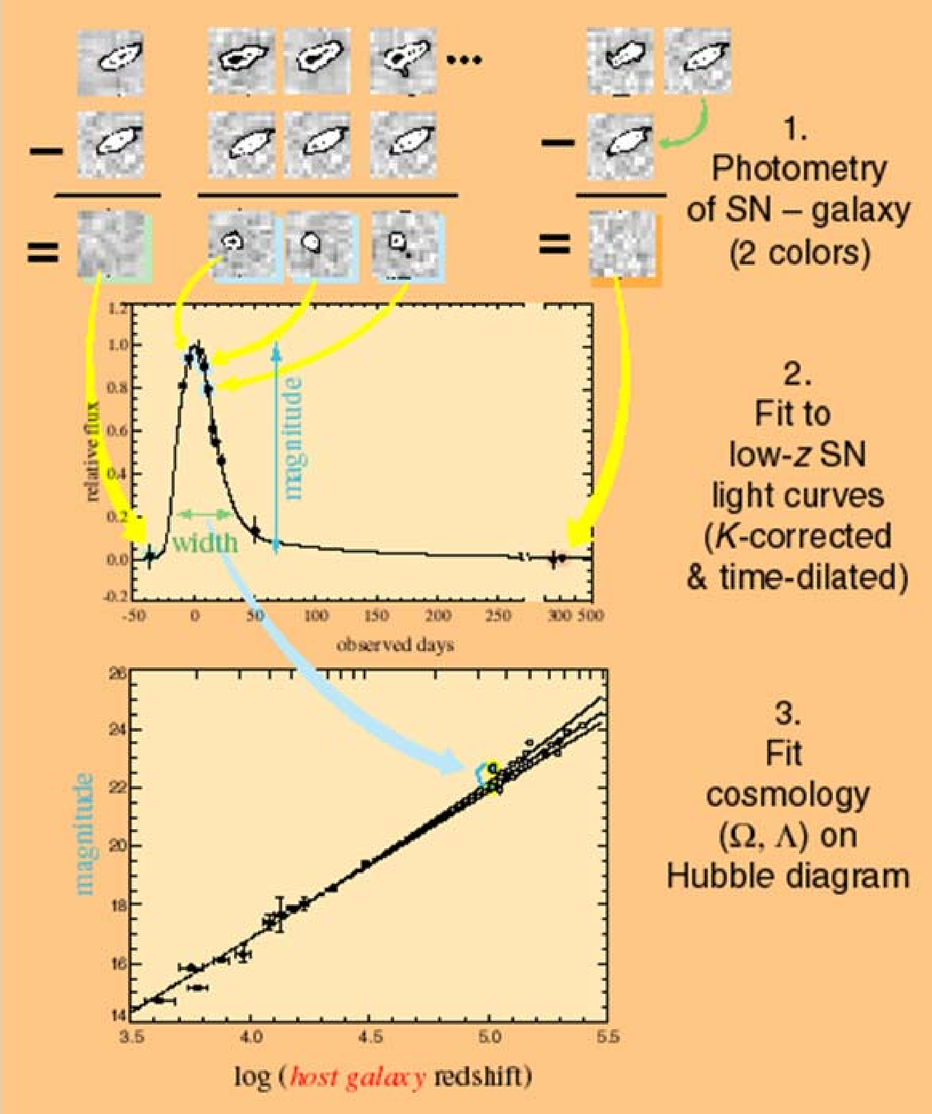
Supernova Cosmology Project: Strategy



RESULT: ~24 Type Ia supernovae discovered while still brightening, at new moon

http://www-supernova.lbl.gov/

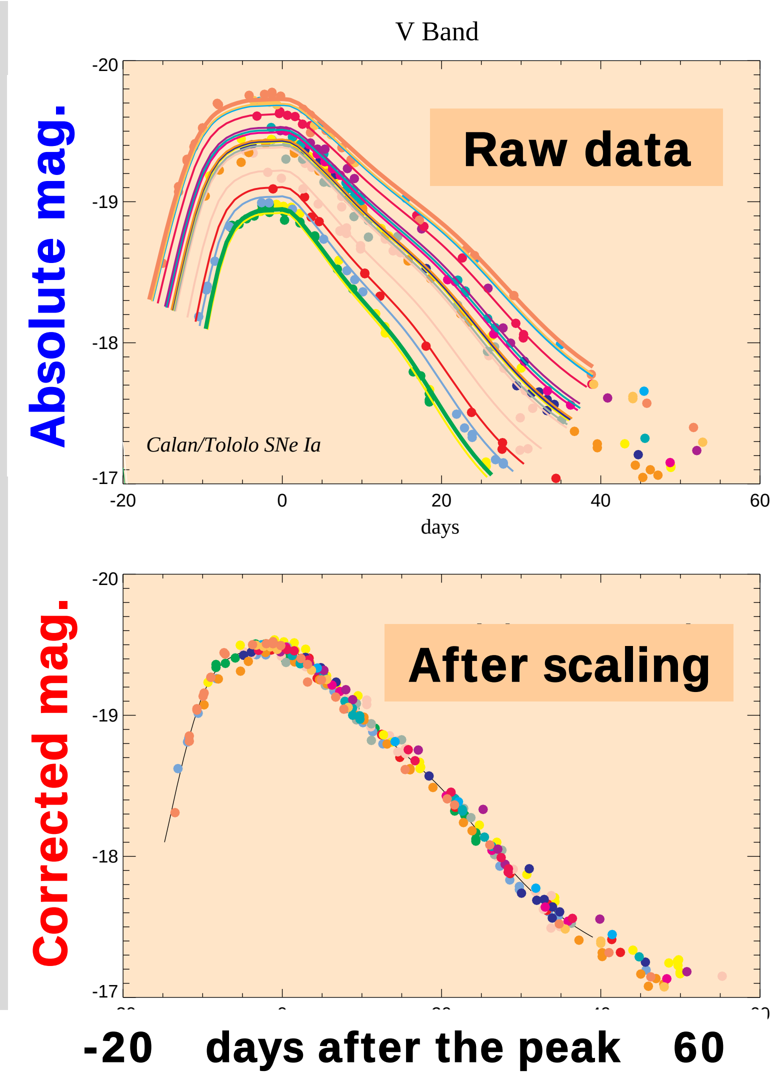
Supernova Cosmology Project: analysis



- **Detection method**
  - deep images of regions on the sky
  - do this again one month later
  - compare two sets of images, looking for new “stars” superimposed on galaxies
- **Spectroscopic follow-up**
  - Several types of supernovae
  - SNe Ia have characteristic spectra

http://www-supernova.lbl.gov/

Multicolor light-curve fitting of SNe Ia

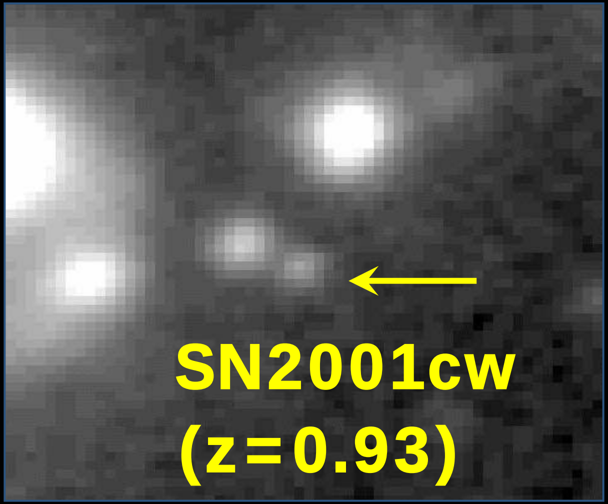


- Brighter SNe Ia ⇒ slower decline of the peak luminosity
- Empirical scaling relation between the peak luminosity and the shape of the light-curve
- More accurate distance estimate after the correction using the empirical scaling

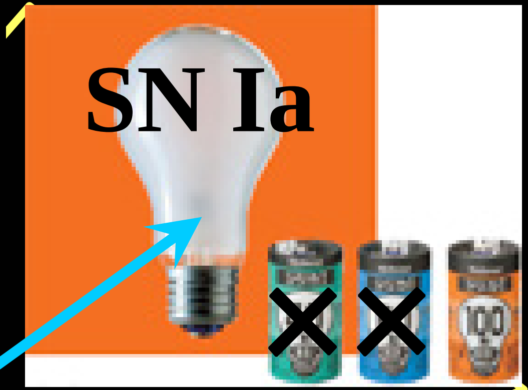
http://www-supernova.lbl.gov/
(Perlmutter 2004, Physics Today, April, p.53)

Standard candle: Type Ia Supernova

observed flux: F



absolute luminosity: L



Distance: D

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

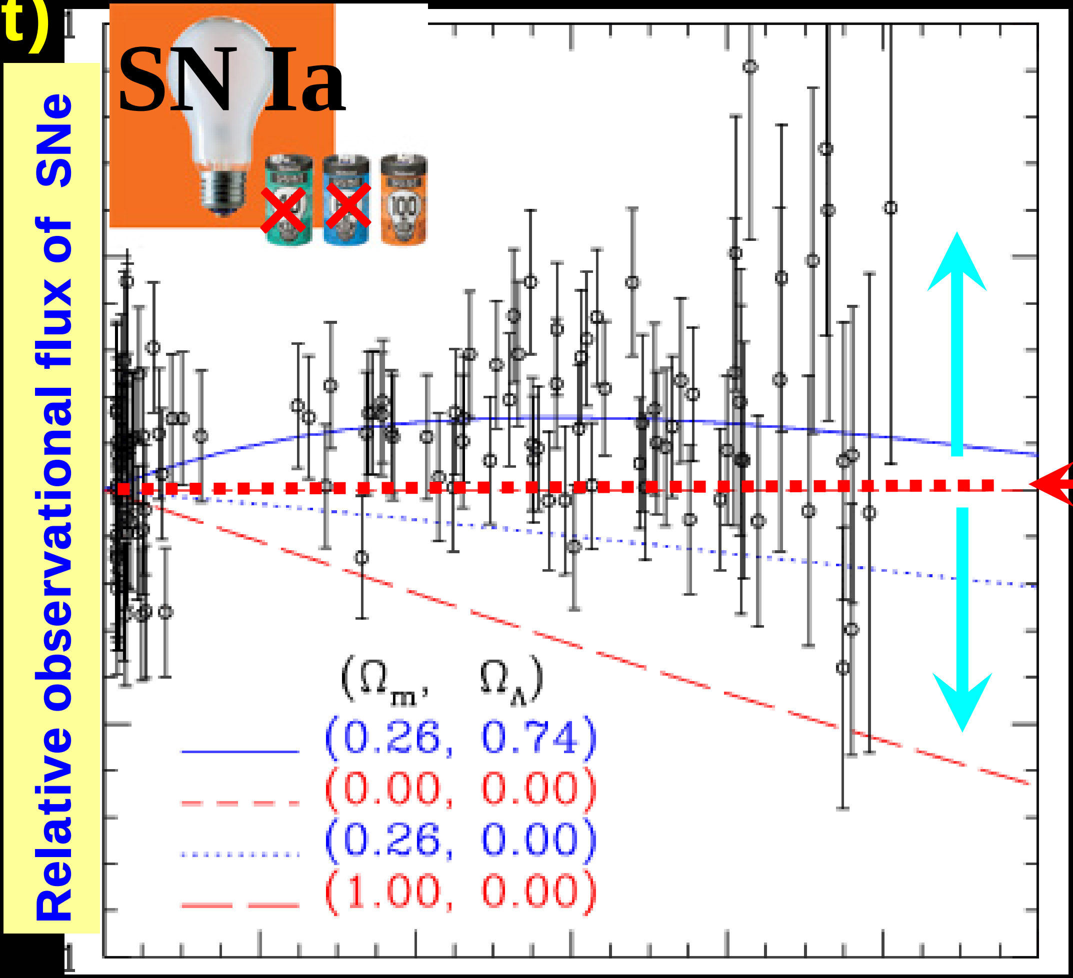
$$D_L = \sqrt{\frac{L}{4\pi F}}$$

observational estimate

Accelerating universe from SN Ia data

SN Legacy Survey (Astier et al. 2006)

Dimmer
(more distant)



acceleration

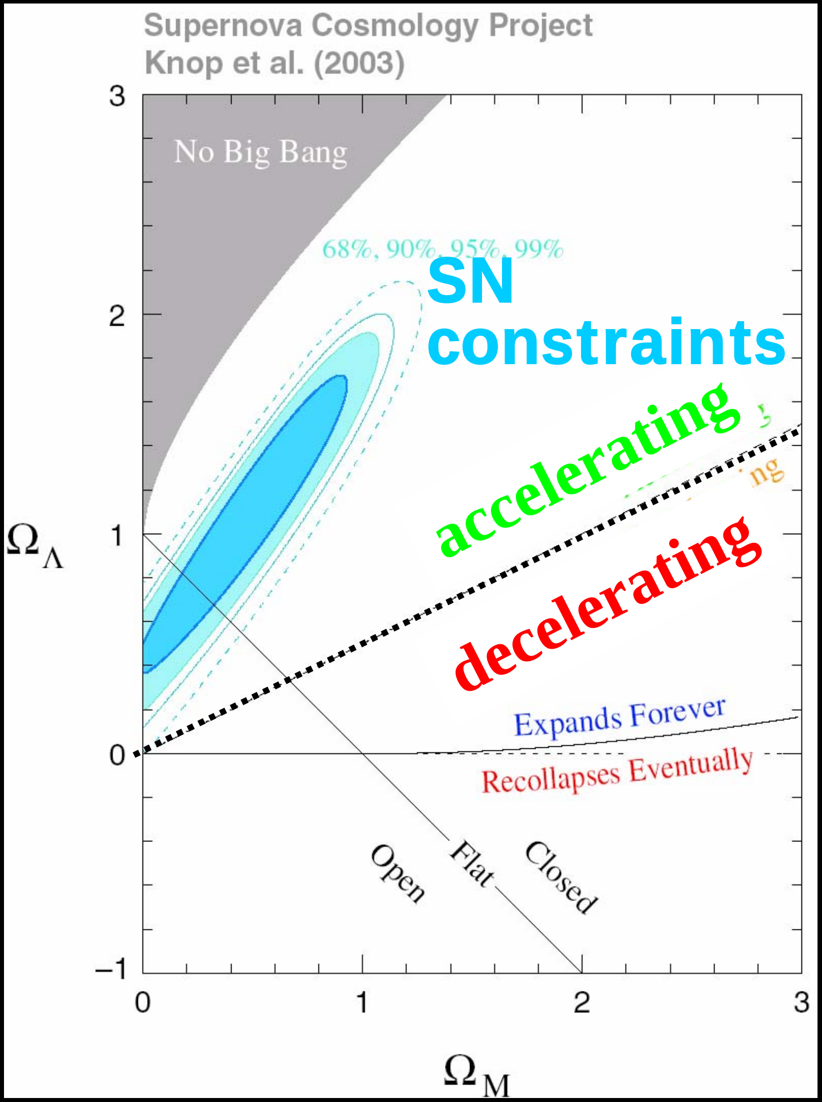
normalized by empty universe prediction

deceleration

Brighter
(closer)

present **time** → **past**

Constraints on Ω_m and Ω_Λ from SN Ia



- acceleration of the universe

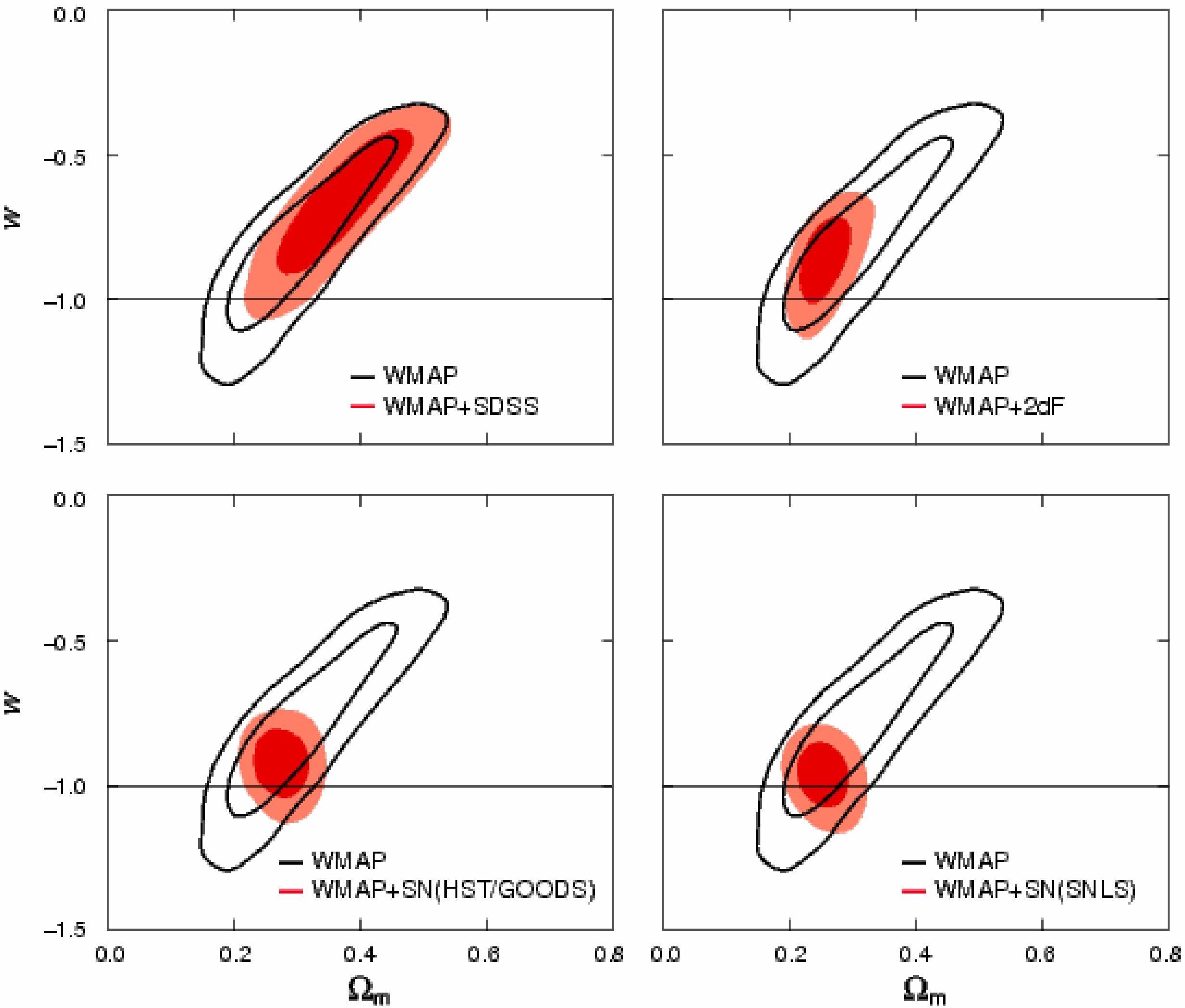
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

- at the present epoch

$$\left.\frac{\ddot{a}}{a}\right|_0 = H_0^2\left(\Omega_\Lambda - \frac{\Omega_m}{2}\right)$$

- **accelerating universe if $\Omega_\Lambda > \Omega_m / 2$**

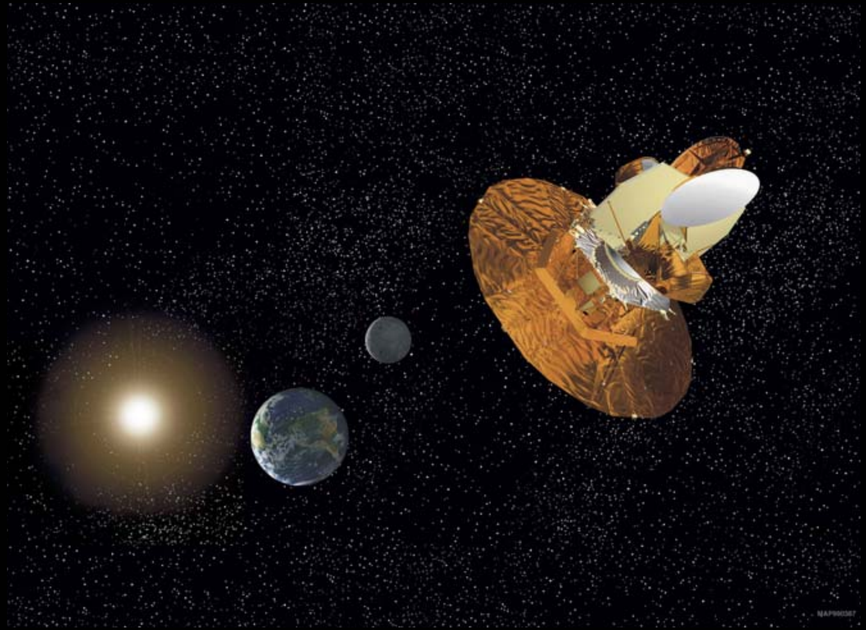
Ⅳ current constraints on dark energy

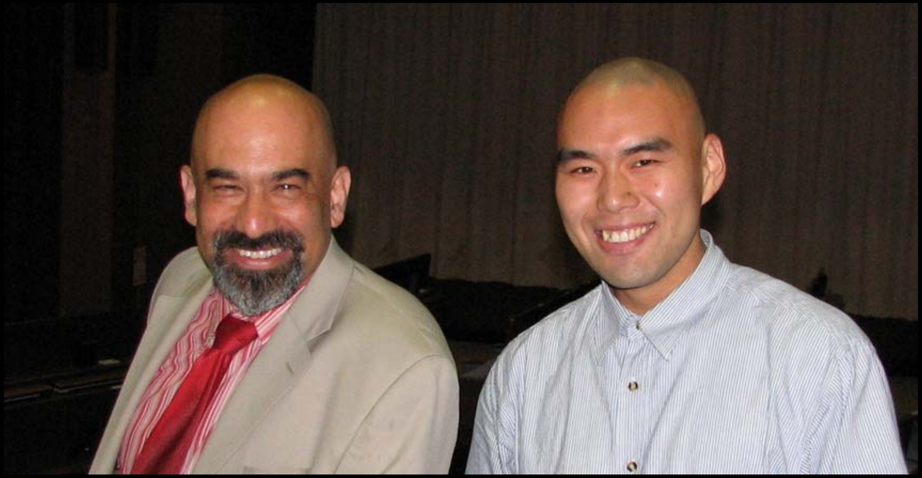


Wilkinson Microwave Anisotropy Probe (WMAP) Three Year Results: Implications for Cosmology

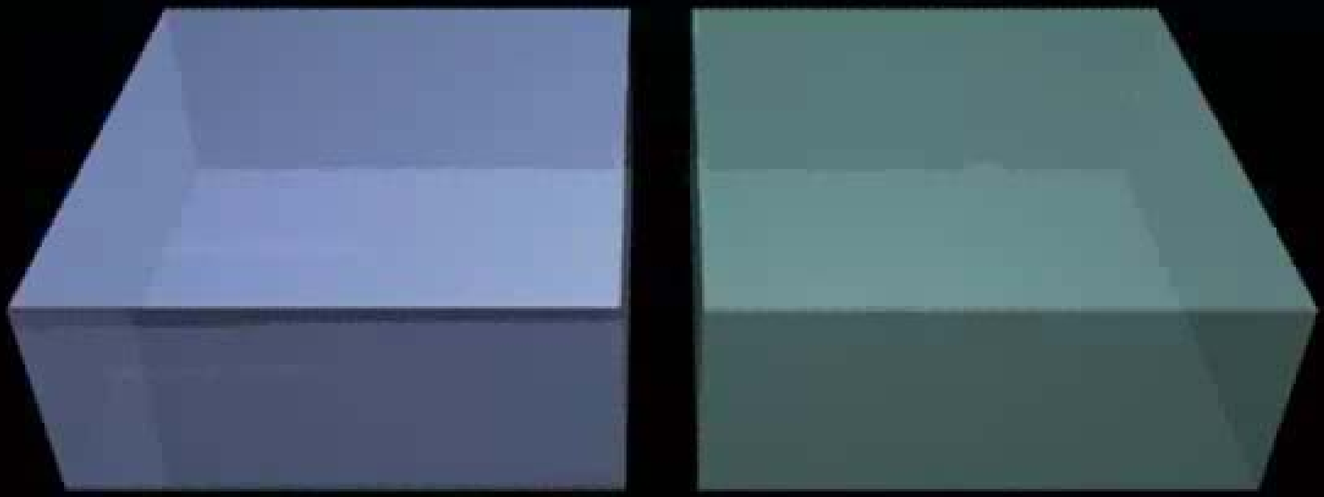
D.N.Spergel et al.

ApJS 170(2007)377





CMB acoustic oscillation



NASA / WMAP Science Team

Photon acoustic oscillation

- Photon fluid behavior inside cosmic horizon
  - Oscillation due to pressure
  - Θ_0: monopole component of $\delta T/T$

$$\frac{d^2\tilde{\Theta}_0(k,\eta)}{d\eta^2}+\frac{1}{a}\frac{da}{d\eta}\left(1-3c_s^2\right)\frac{d\tilde{\Theta}_0(k,\eta)}{d\eta}+k^2c_s^2\tilde{\Theta}_0(k,\eta)\approx 0$$

  - η: conformal time ($dt=ad\eta$)
  - $c_s(\eta)$: sound velocity

- For adiabatic density fluctuations

$$\tilde{\Theta}_0(k,\eta)\approx A(k)\cos[kr_s(\eta)]$$

e.g., Kodama & Sasaki (1987)

Sound horizon scale

- comoving distance that the sound wave propagates before cosmic time t

$$r_s(t) = \int_0^t \frac{c_s(t)}{a(t)} dt \quad (t < t_{dec})$$

where

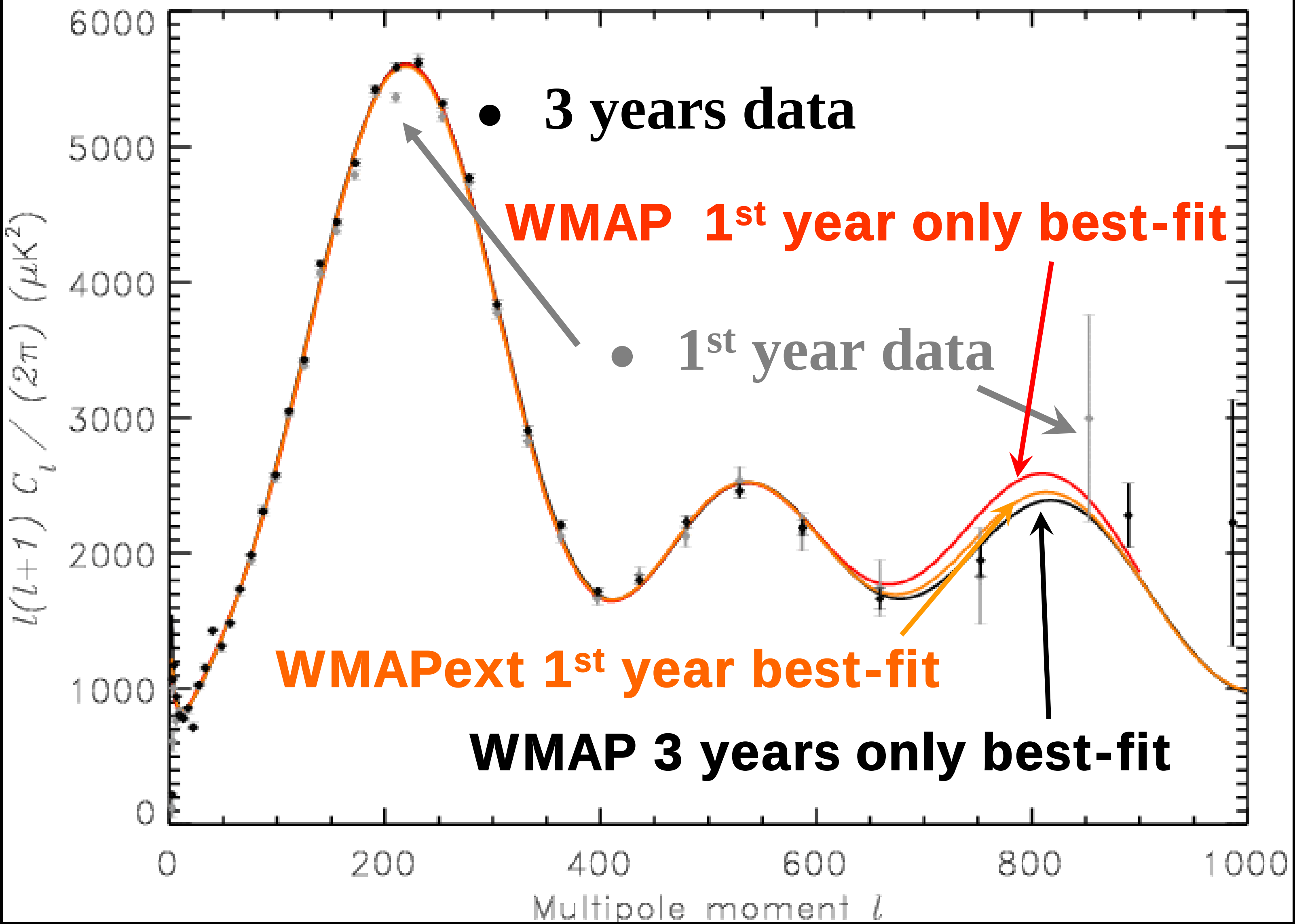
$$c_s^2 = \frac{\partial p}{\partial \rho} = \frac{1}{3}\frac{\partial p_\gamma}{\partial(\rho_\gamma + \rho_b)} = \frac{1}{3(1+R)}, \qquad R \equiv \frac{3\rho_b}{4\rho_\gamma} = \frac{3\Omega_b}{4\Omega_\gamma} a$$

$$\frac{da}{dt} = \frac{H_0}{a}\sqrt{a\Omega_m + \Omega_{rad}}$$

$$\Rightarrow r_s(t_{dec}) = \frac{4\sqrt{\Omega_\gamma}}{3H_0\sqrt{\Omega_b \Omega_m}} \ln\left(\frac{\sqrt{a + \Omega_{rad}/\Omega_m} + \sqrt{a + 4\Omega_{rad}/3\Omega_b}}{\sqrt{\Omega_{rad}/\Omega_m} + \sqrt{4\Omega_{rad}/3\Omega_b}}\right)$$

$$\approx 147(0.13/\Omega_m h^2)^{0.25}(0.024/\Omega_b h^2)^{0.08} \text{ Mpc}$$

Temperature fluctuation angular spectrum



● 3 years data

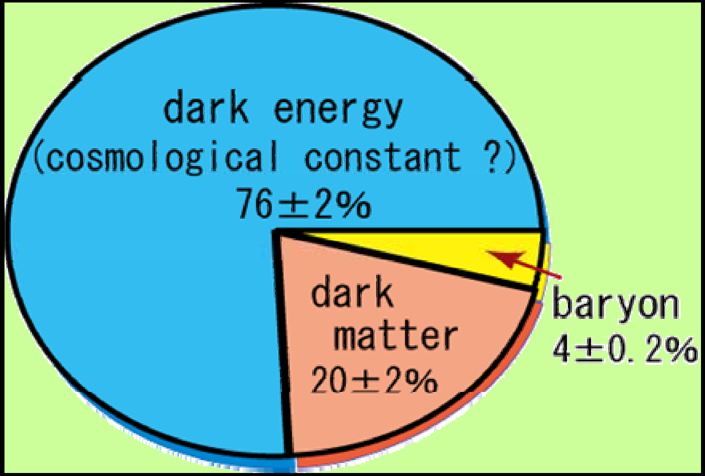
WMAP 1st year only best-fit

● 1st year data

WMAPext 1st year best-fit

WMAP 3 years only best-fit

Weighing the universe



baryon

- ordinary matter makes up merely 4 percent of the entire mass of the universe

dark matter

- galaxies and clusters are surrounded by invisible mass an order-of-magnitude more massive than their visible part
- unknown elementary particles?

dark energy

- universe is dominated by even more exotic component !
- homogeneously fills the universe (unclustered)
- repulsive force (negative pressure; equation of state:$P=-\rho$)
- Einstein’s cosmological constant ?

WMAP 3yrs: cosmological parameters

- + flat power-law ΛCDM

$$\Omega_m h^2 = 0.127^{+0.007}_{-0.013}$$

$$\Omega_b h^2 = 0.0223^{+0.0007}_{-0.0009}$$

$$h = 0.73^{+0.03}_{-0.03}$$

$$n_s = 0.951^{+0.015}_{-0.019}$$

$$\tau = 0.09^{+0.03}_{-0.03}$$

$$\sigma_8 = 0.74^{+0.05}_{-0.06}$$

- +flat+SNLS

$$w = -0.97^{+0.07}_{-0.09}$$

- +SNLS+LSS

$$w = -1.06^{+0.13}_{-0.08}$$

- +w=-1+SNLS

$$\Omega_k = -0.015^{+0.020}_{-0.016}$$

- +others

$$\sum m_\nu < 0.68\mathrm{eV}$$

WMAP: 1st year vs. 3 years

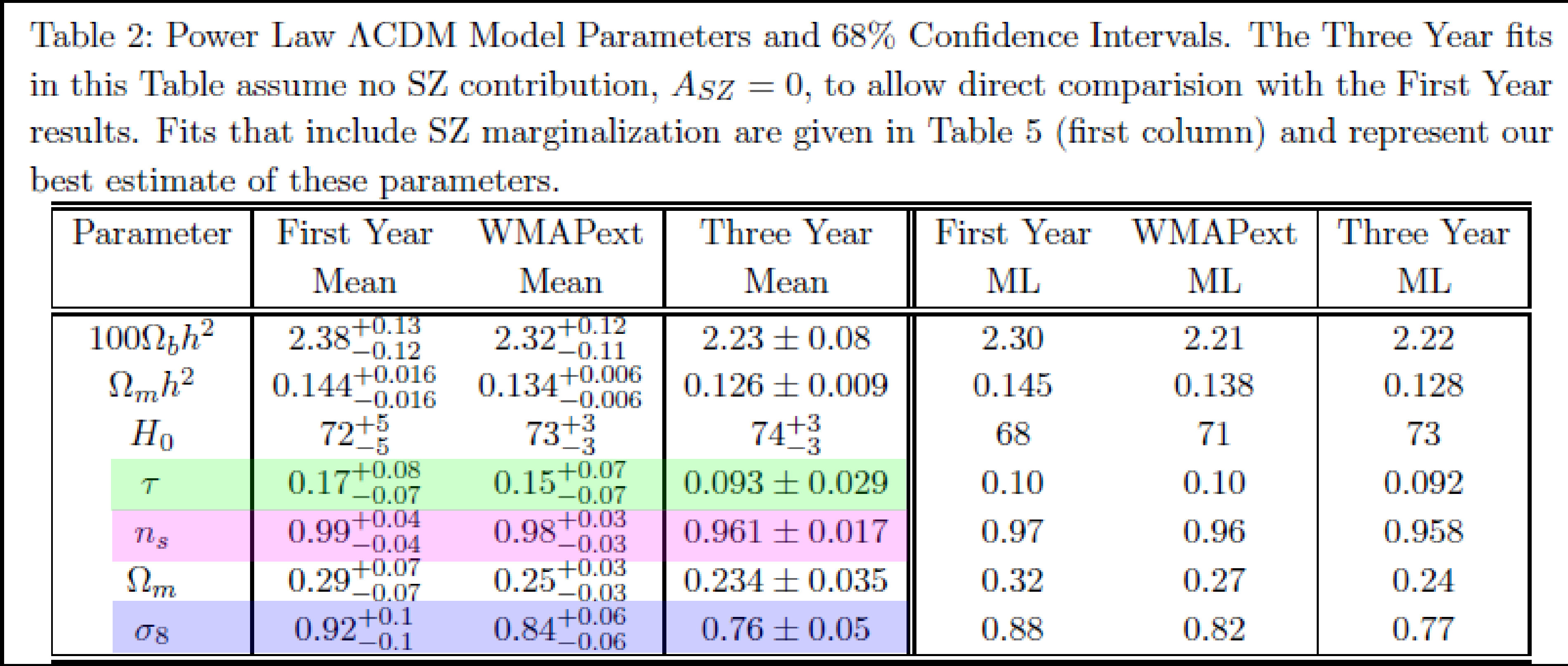
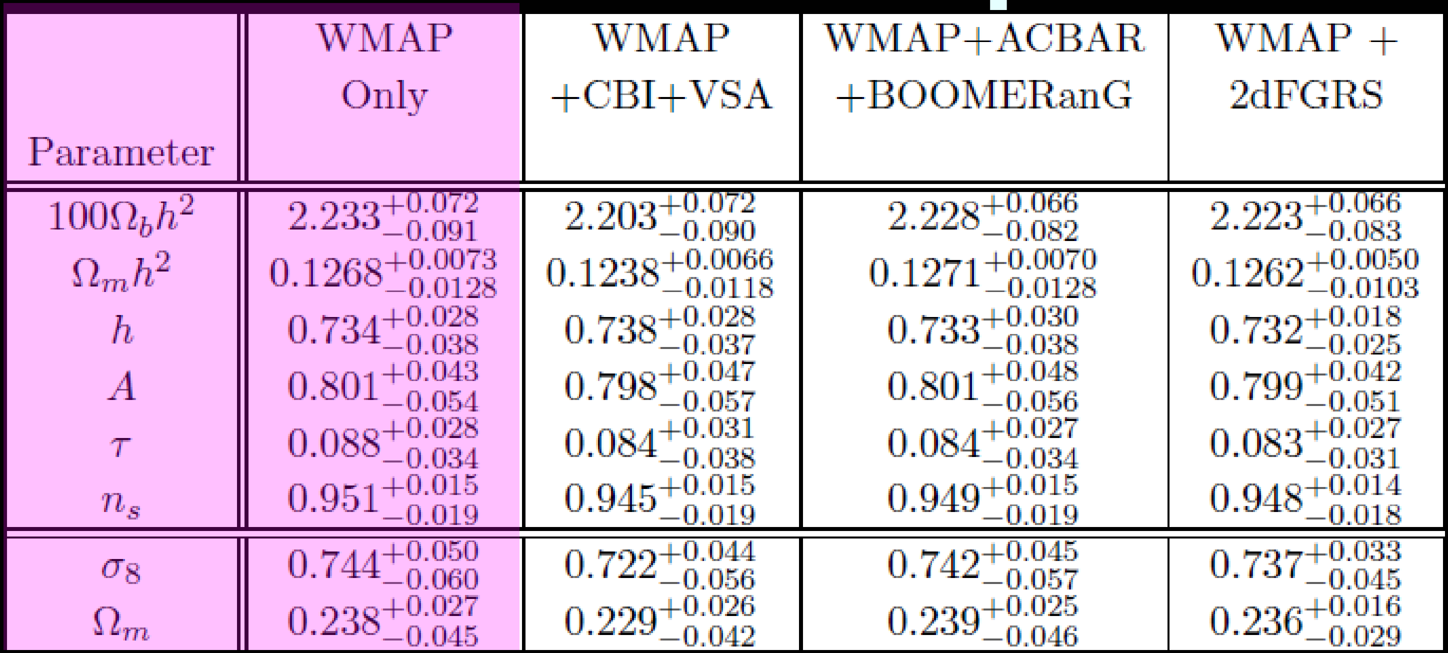


Table 2: Power Law ΛCDM Model Parameters and 68% Confidence Intervals. The Three Year fits in this Table assume no SZ contribution, $A_{SZ} = 0$, to allow direct comparision with the First Year results. Fits that include SZ marginalization are given in Table 5 (first column) and represent our best estimate of these parameters.

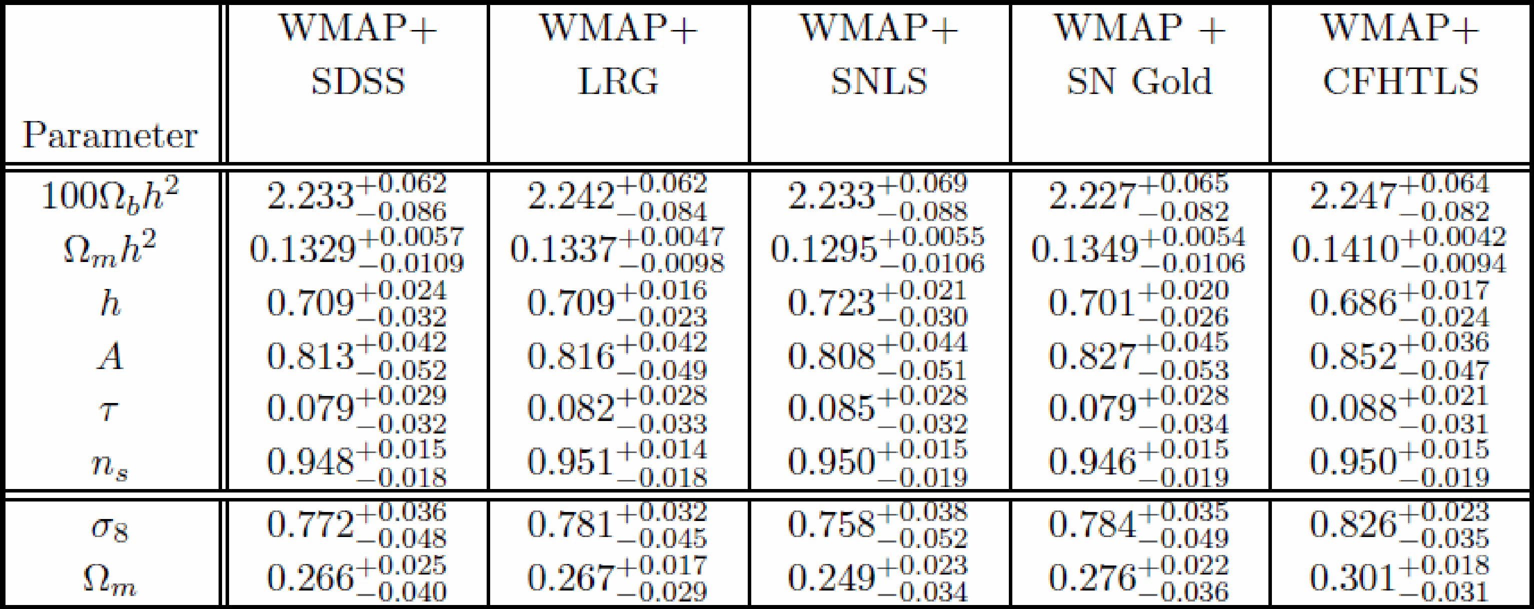
Parameter	First Year Mean	WMAPext Mean	Three Year Mean	First Year ML	WMAPext ML	Three Year ML
$100\Omega_b h^2$	$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08	2.30	2.21	2.22
$\Omega_m h^2$	$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009	0.145	0.138	0.128
H_0	72^{+5}_{-5}	73^{+3}_{-3}	74^{+3}_{-3}	68	71	73
τ	$0.17^{+0.08}_{-0.07}$	$0.15^{+0.07}_{-0.07}$	0.093 ± 0.029	0.10	0.10	0.092
n_s	$0.99^{+0.04}_{-0.04}$	$0.98^{+0.03}_{-0.03}$	0.961 ± 0.017	0.97	0.96	0.958
Ω_m	$0.29^{+0.07}_{-0.07}$	$0.25^{+0.03}_{-0.03}$	0.234 ± 0.035	0.32	0.27	0.24
σ_8	$0.92^{+0.1}_{-0.1}$	$0.84^{+0.06}_{-0.06}$	0.76 ± 0.05	0.88	0.82	0.77

- **a factor of 2 reduction of τ**
- **n_s is consistent with unity**
- **σ_8 and Ω_m become smaller**

WMAP ΛCDM best-fit parameters

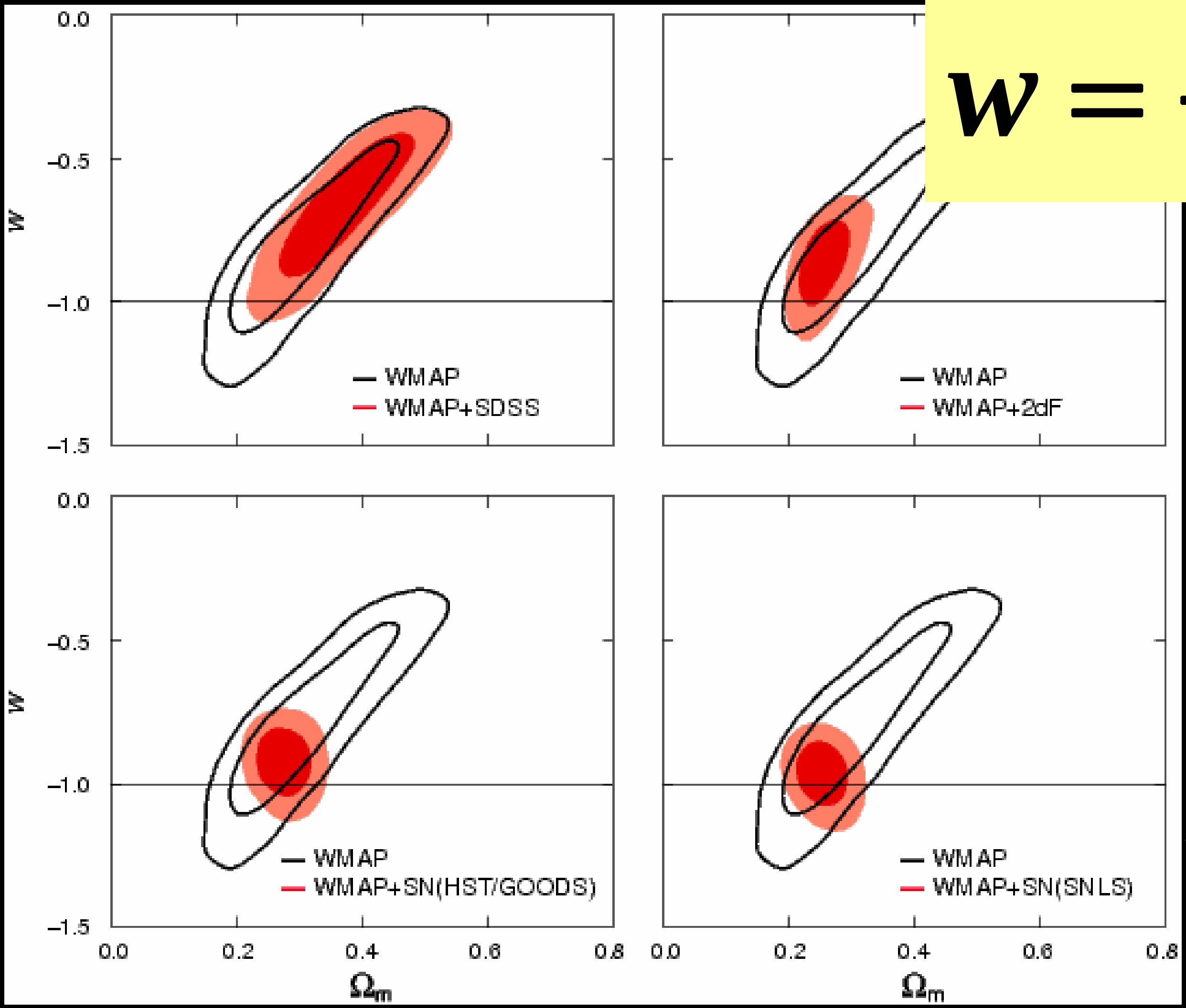


Parameter	WMAP Only	WMAP +CBI+VSA	WMAP+ACBAR +BOOMERanG	WMAP + 2dFGRS
$100\Omega_b h^2$	$2.233^{+0.072}_{-0.091}$	$2.203^{+0.072}_{-0.090}$	$2.228^{+0.066}_{-0.082}$	$2.223^{+0.066}_{-0.083}$
$\Omega_m h^2$	$0.1268^{+0.0073}_{-0.0128}$	$0.1238^{+0.0066}_{-0.0118}$	$0.1271^{+0.0070}_{-0.0128}$	$0.1262^{+0.0050}_{-0.0103}$
h	$0.734^{+0.028}_{-0.038}$	$0.738^{+0.028}_{-0.037}$	$0.733^{+0.030}_{-0.038}$	$0.732^{+0.018}_{-0.025}$
A	$0.801^{+0.043}_{-0.054}$	$0.798^{+0.047}_{-0.057}$	$0.801^{+0.048}_{-0.056}$	$0.799^{+0.042}_{-0.051}$
τ	$0.088^{+0.028}_{-0.034}$	$0.084^{+0.031}_{-0.038}$	$0.084^{+0.027}_{-0.034}$	$0.083^{+0.027}_{-0.031}$
n_s	$0.951^{+0.015}_{-0.019}$	$0.945^{+0.015}_{-0.019}$	$0.949^{+0.015}_{-0.019}$	$0.948^{+0.014}_{-0.018}$
σ_8	$0.744^{+0.050}_{-0.060}$	$0.722^{+0.044}_{-0.056}$	$0.742^{+0.045}_{-0.057}$	$0.737^{+0.033}_{-0.045}$
Ω_m	$0.238^{+0.027}_{-0.045}$	$0.229^{+0.026}_{-0.042}$	$0.239^{+0.025}_{-0.046}$	$0.236^{+0.016}_{-0.029}$



Parameter	WMAP+ SDSS	WMAP+ LRG	WMAP+ SNLS	WMAP + SN Gold	WMAP+ CFHTLS
$100\Omega_b h^2$	$2.233^{+0.062}_{-0.086}$	$2.242^{+0.062}_{-0.084}$	$2.233^{+0.069}_{-0.088}$	$2.227^{+0.065}_{-0.082}$	$2.247^{+0.064}_{-0.082}$
$\Omega_m h^2$	$0.1329^{+0.0057}_{-0.0109}$	$0.1337^{+0.0047}_{-0.0098}$	$0.1295^{+0.0055}_{-0.0106}$	$0.1349^{+0.0054}_{-0.0106}$	$0.1410^{+0.0042}_{-0.0094}$
h	$0.709^{+0.024}_{-0.032}$	$0.709^{+0.016}_{-0.023}$	$0.723^{+0.021}_{-0.030}$	$0.701^{+0.020}_{-0.026}$	$0.686^{+0.017}_{-0.024}$
A	$0.813^{+0.042}_{-0.052}$	$0.816^{+0.042}_{-0.049}$	$0.808^{+0.044}_{-0.051}$	$0.827^{+0.045}_{-0.053}$	$0.852^{+0.036}_{-0.047}$
τ	$0.079^{+0.029}_{-0.032}$	$0.082^{+0.028}_{-0.033}$	$0.085^{+0.028}_{-0.032}$	$0.079^{+0.028}_{-0.034}$	$0.088^{+0.021}_{-0.031}$
n_s	$0.948^{+0.015}_{-0.018}$	$0.951^{+0.014}_{-0.018}$	$0.950^{+0.015}_{-0.019}$	$0.946^{+0.015}_{-0.019}$	$0.950^{+0.015}_{-0.019}$
σ_8	$0.772^{+0.036}_{-0.048}$	$0.781^{+0.032}_{-0.045}$	$0.758^{+0.038}_{-0.052}$	$0.784^{+0.035}_{-0.049}$	$0.826^{+0.023}_{-0.035}$
Ω_m	$0.266^{+0.025}_{-0.040}$	$0.267^{+0.017}_{-0.029}$	$0.249^{+0.023}_{-0.034}$	$0.276^{+0.022}_{-0.036}$	$0.301^{+0.018}_{-0.031}$

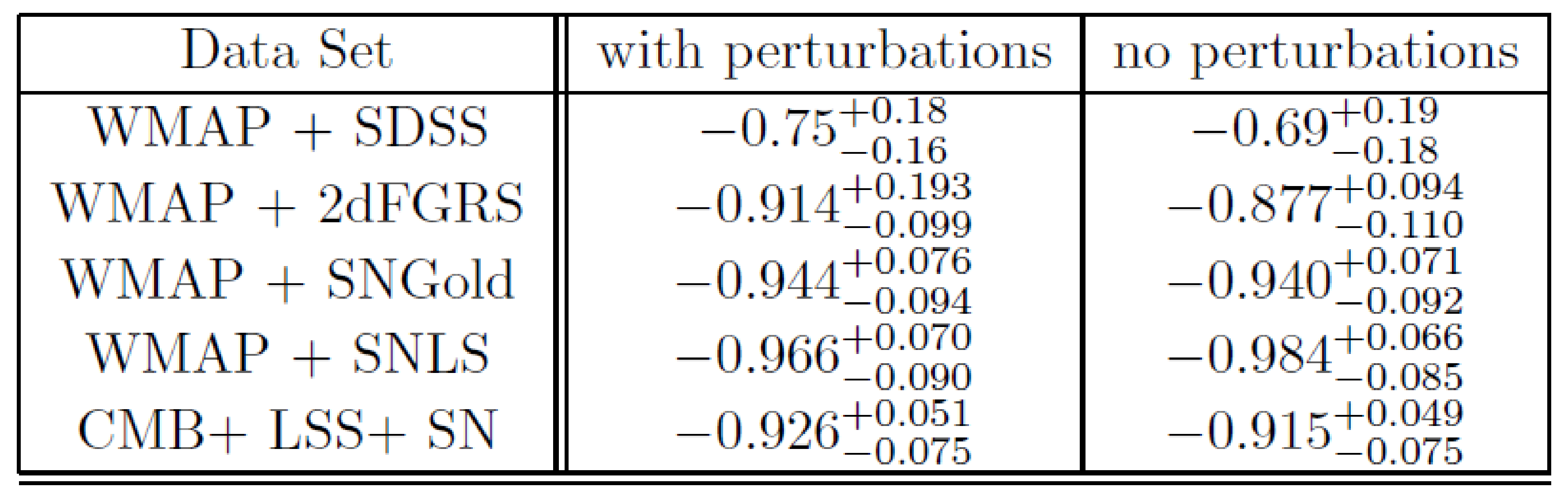
Constraints on w from WMAP3yr + other data



$$w = -0.926^{+0.051}_{-0.075}$$

Spergel et al. (2007

Constraints on w in flat universes



Data Set	with perturbations	no perturbations
WMAP + SDSS	$-0.75^{+0.18}_{-0.16}$	$-0.69^{+0.19}_{-0.18}$
WMAP + 2dFGRS	$-0.914^{+0.193}_{-0.099}$	$-0.877^{+0.094}_{-0.110}$
WMAP + SNGold	$-0.944^{+0.076}_{-0.094}$	$-0.940^{+0.071}_{-0.092}$
WMAP + SNLS	$-0.966^{+0.070}_{-0.090}$	$-0.984^{+0.066}_{-0.085}$
CMB+ LSS+ SN	$-0.926^{+0.051}_{-0.075}$	$-0.915^{+0.049}_{-0.075}$

SN legacy survey 1st year (Astier et al. 2006)

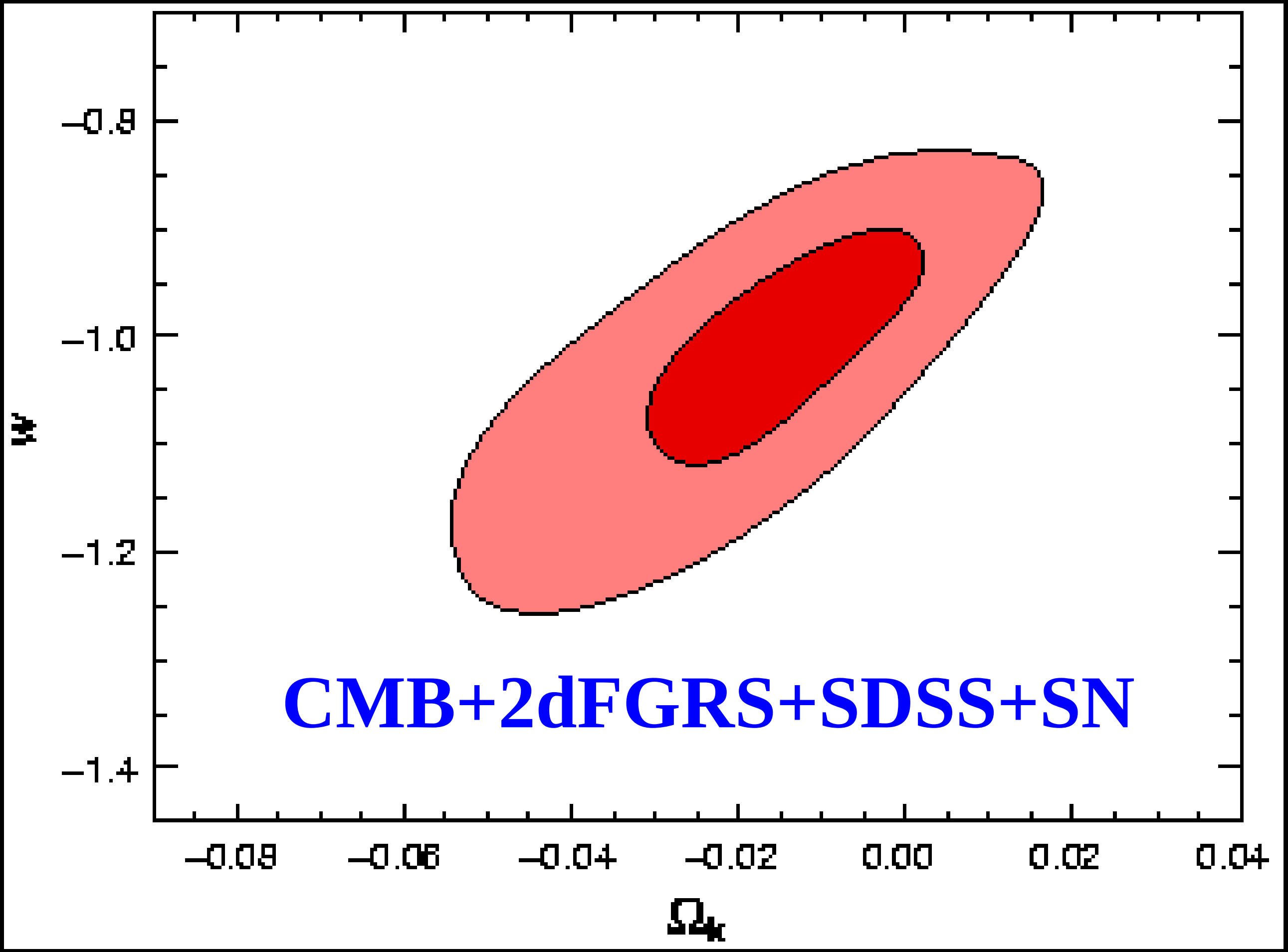
+

SDSS LRG BAO (Eisenstein et al. 2005)

↓

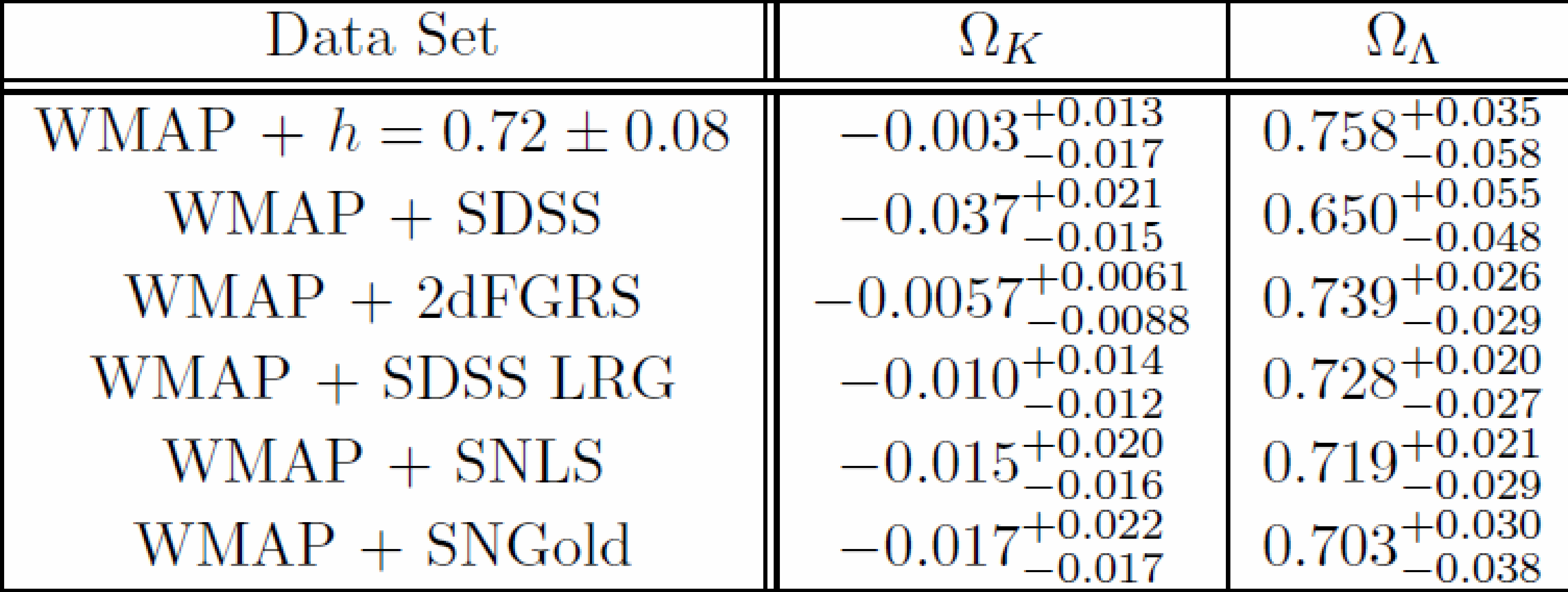
w=－1.023±0.090（sys.）±0.054（stat.）

Constraints on w in non-flat universes



Spergel et al. (2007)

Constraints on the spatial curvature and cosmological constant



Data Set	Ω_K	Ω_Λ
WMAP + $h = 0.72 \pm 0.08$	$-0.003^{+0.013}_{-0.017}$	$0.758^{+0.035}_{-0.058}$
WMAP + SDSS	$-0.037^{+0.021}_{-0.015}$	$0.650^{+0.055}_{-0.048}$
WMAP + 2dFGRS	$-0.0057^{+0.0061}_{-0.0088}$	$0.739^{+0.026}_{-0.029}$
WMAP + SDSS LRG	$-0.010^{+0.014}_{-0.012}$	$0.728^{+0.020}_{-0.027}$
WMAP + SNLS	$-0.015^{+0.020}_{-0.016}$	$0.719^{+0.021}_{-0.029}$
WMAP + SNGold	$-0.017^{+0.022}_{-0.017}$	$0.703^{+0.030}_{-0.038}$

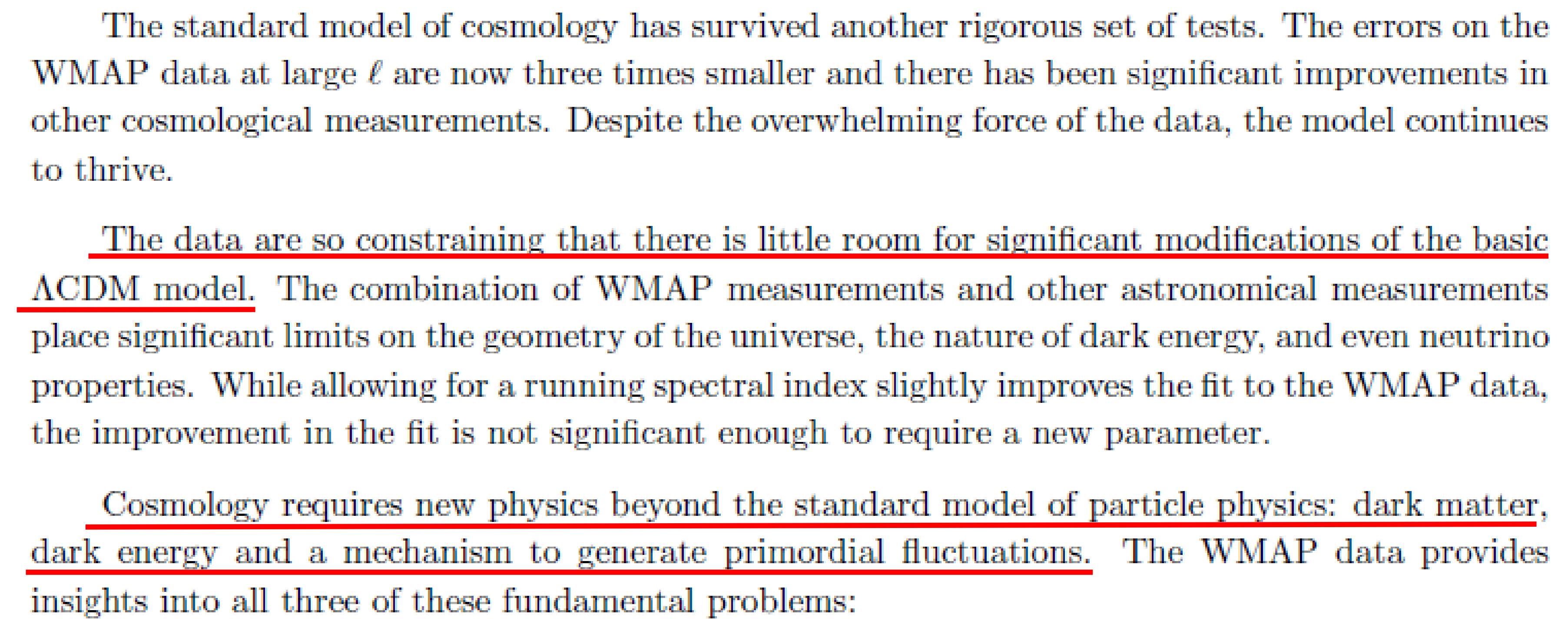
Spergel et al. (2007)

The cosmological standard model: What’s next ?

> 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 even more rigorous tests of the cosmological standard model and search for new physics beyond the standard model.

Spergel et al. ApJS 148 (2003) 175

Cosmology requires new physics beyond the standard model of particle physics



The standard model of cosmology has survived another rigorous set of tests. The errors on the WMAP data at large ℓ are now three times smaller and there has been significant improvements in other cosmological measurements. Despite the overwhelming force of the data, the model continues to thrive.

The data are so constraining that there is little room for significant modifications of the basic ΛCDM model. The combination of WMAP measurements and other astronomical measurements place significant limits on the geometry of the universe, the nature of dark energy, and even neutrino properties. While allowing for a running spectral index slightly improves the fit to the WMAP data, the improvement in the fit is not significant enough to require a new parameter.

Cosmology requires new physics beyond the standard model of particle physics: dark matter, dark energy and a mechanism to generate primordial fluctuations. The WMAP data provides insights into all three of these fundamental problems:

Spergel et al. ApJS 170(2007)377

Baryon acoustic oscillation (BAO)

- Photon acoustic oscillation

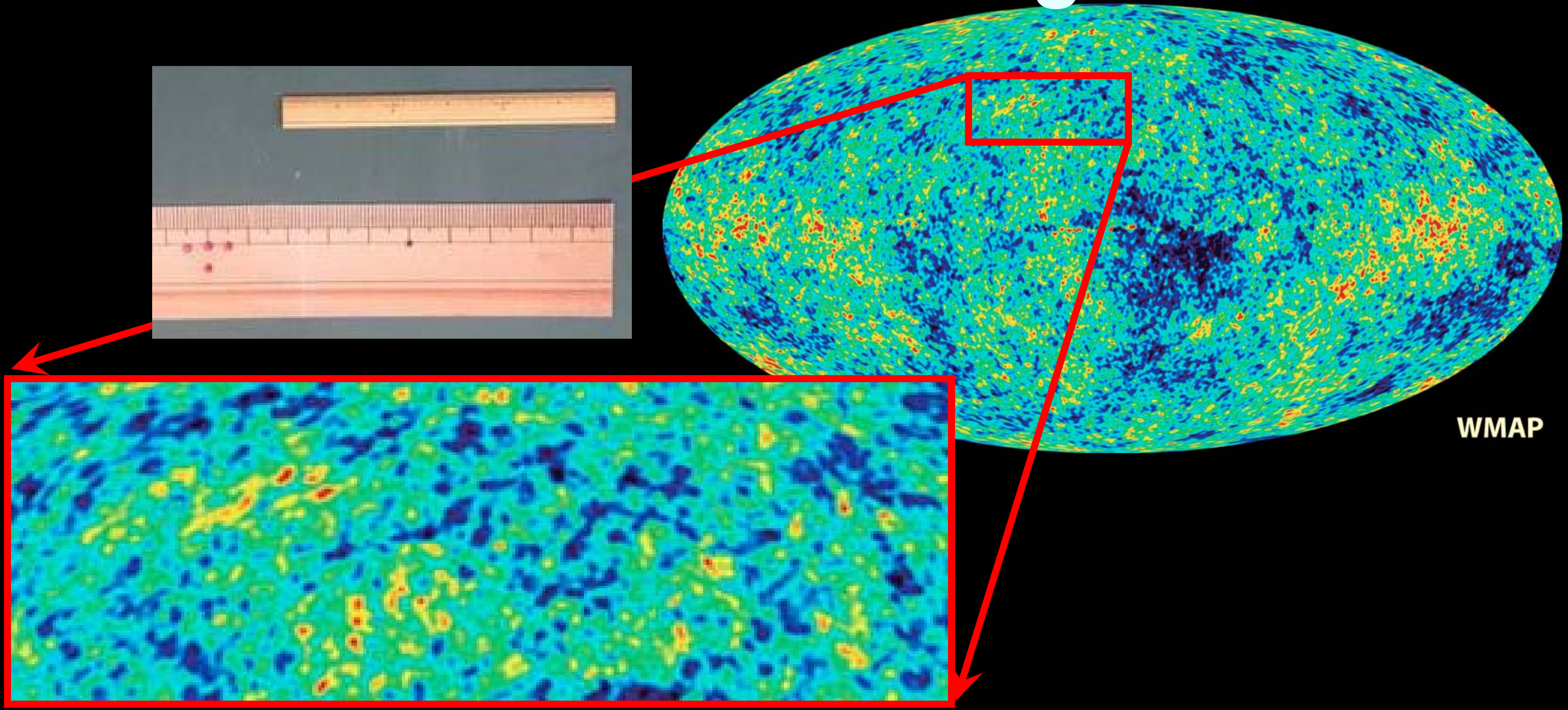
$$\tilde{\Theta}_0(k,\eta) \approx A(k)\cos[kr_s(\eta)]$$

- Coupling between photons and baryons through Thomson scattering leaves an oscillatory feature in baryon density fluctuations at decoupling epoch

$$\tilde{\delta}_{baryon}(k,\eta_{dec}) \approx \underbrace{\tilde{\delta}_{CDM}(k,\eta_{dec})}_{\text{not oscillating}} - \underbrace{\varepsilon(k)\sin[kr_s(\eta_{dec})]}_{\text{oscillatory modulation}}$$

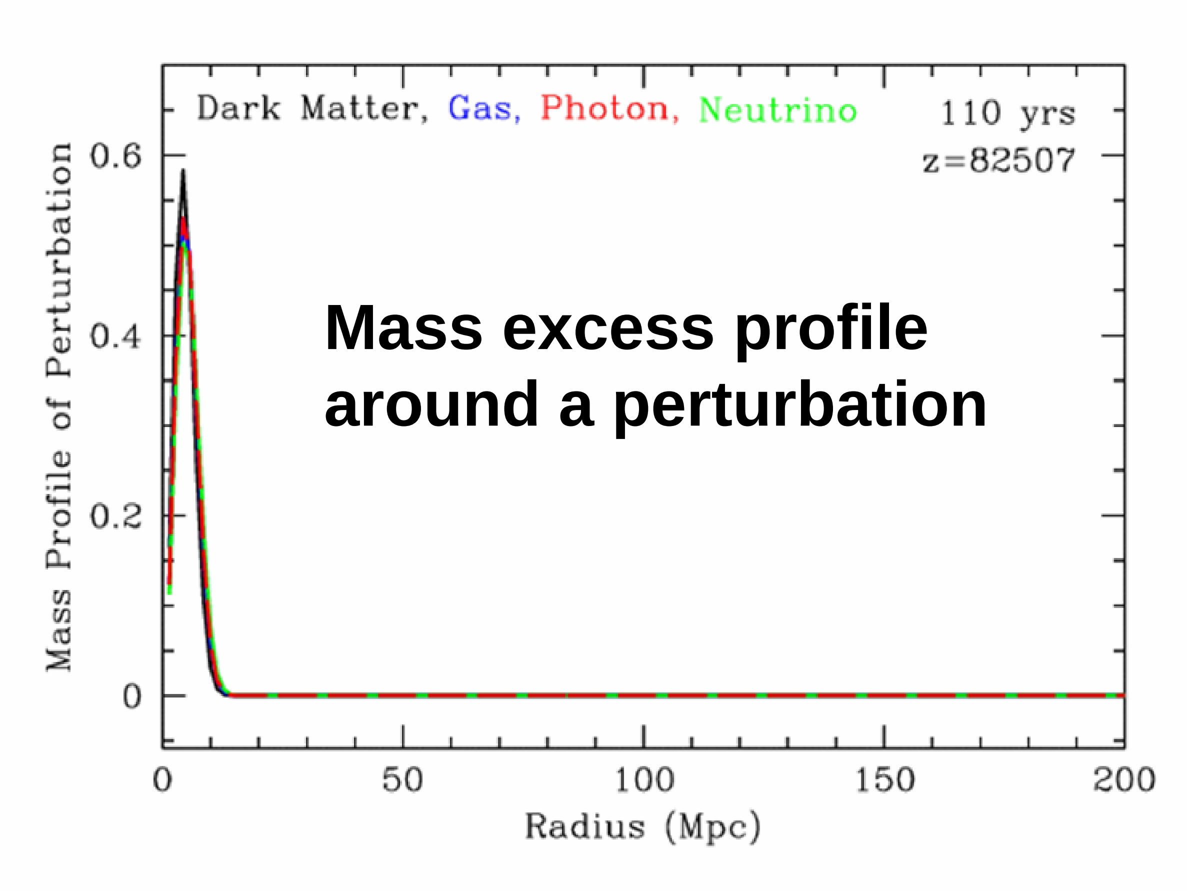
- Eventually gravity transfers the oscillatory feature in the total matter (CDM+baryon) spectrum

Standard ruler: baryon acoustic oscillation length



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

Acoustic oscillation illustrated (1)

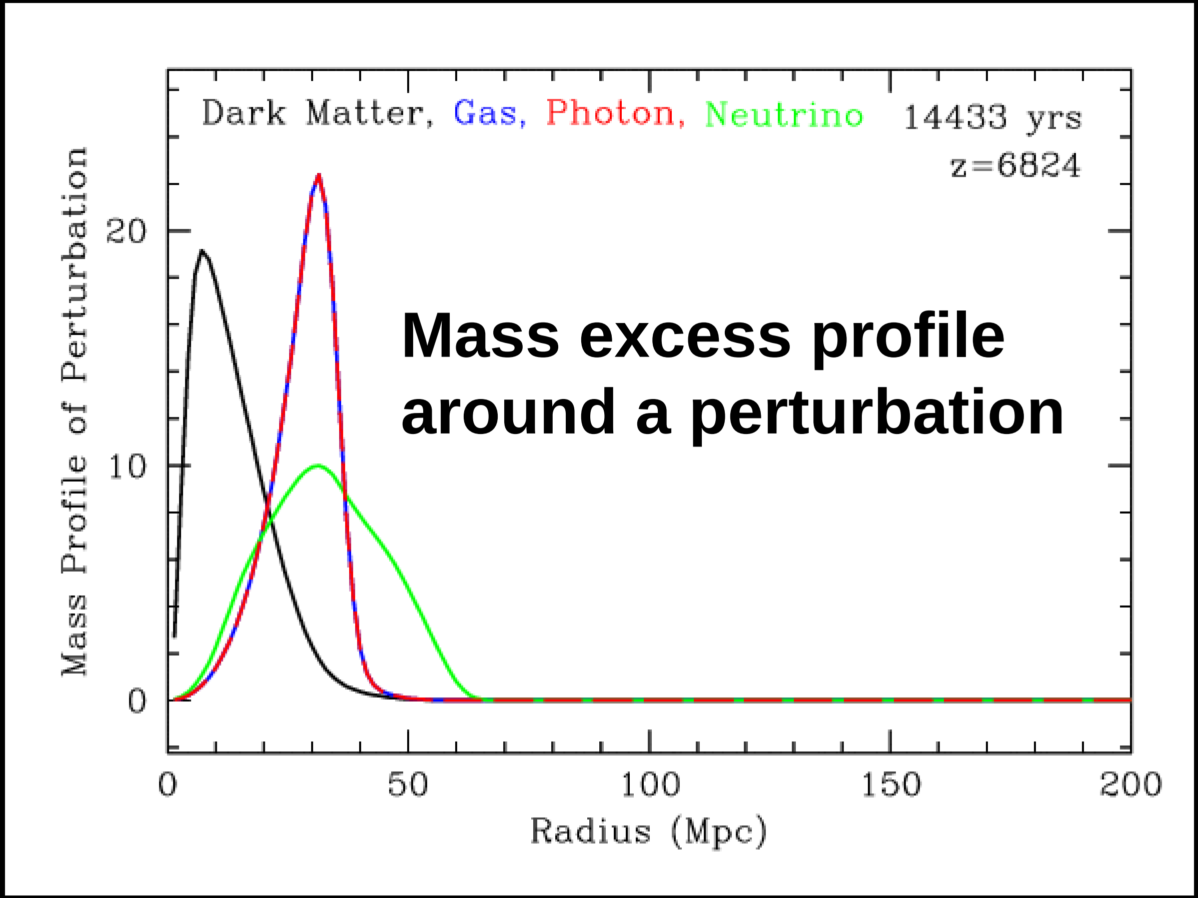


Mass excess profile around a perturbation

- **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)

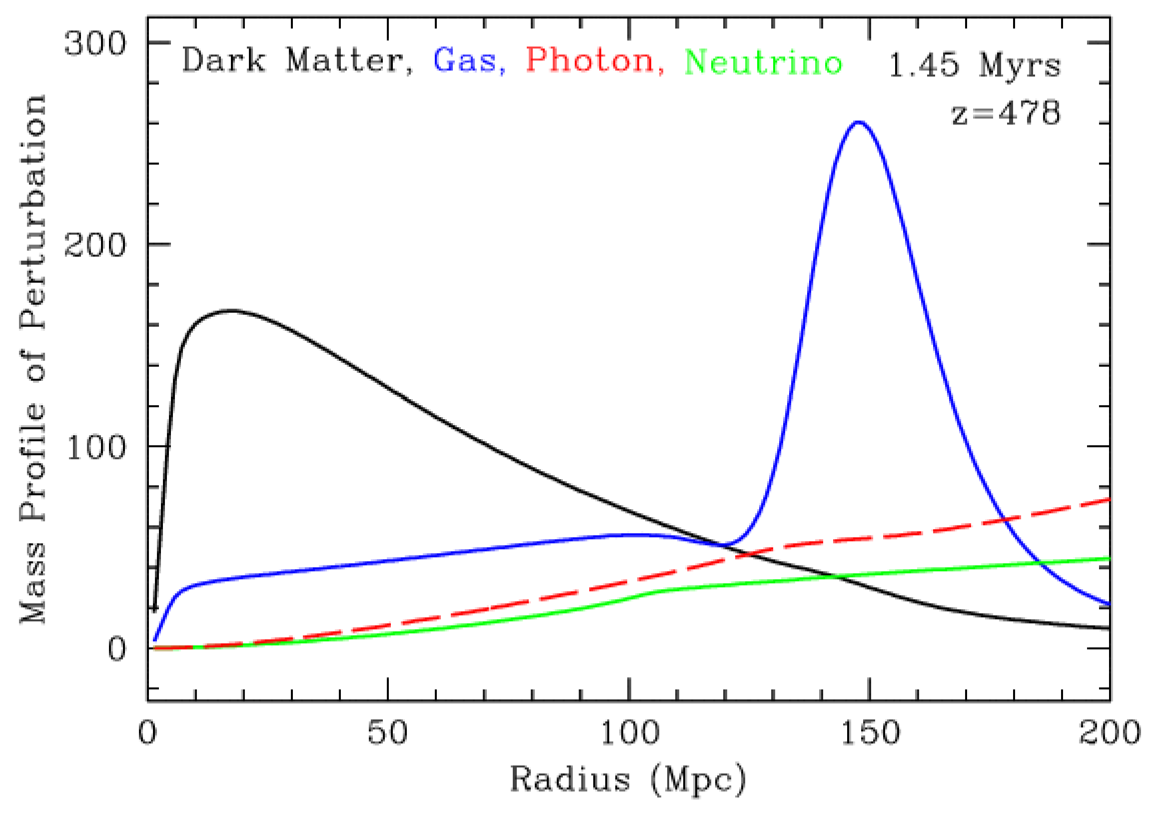


Mass excess profile around a perturbation

- 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

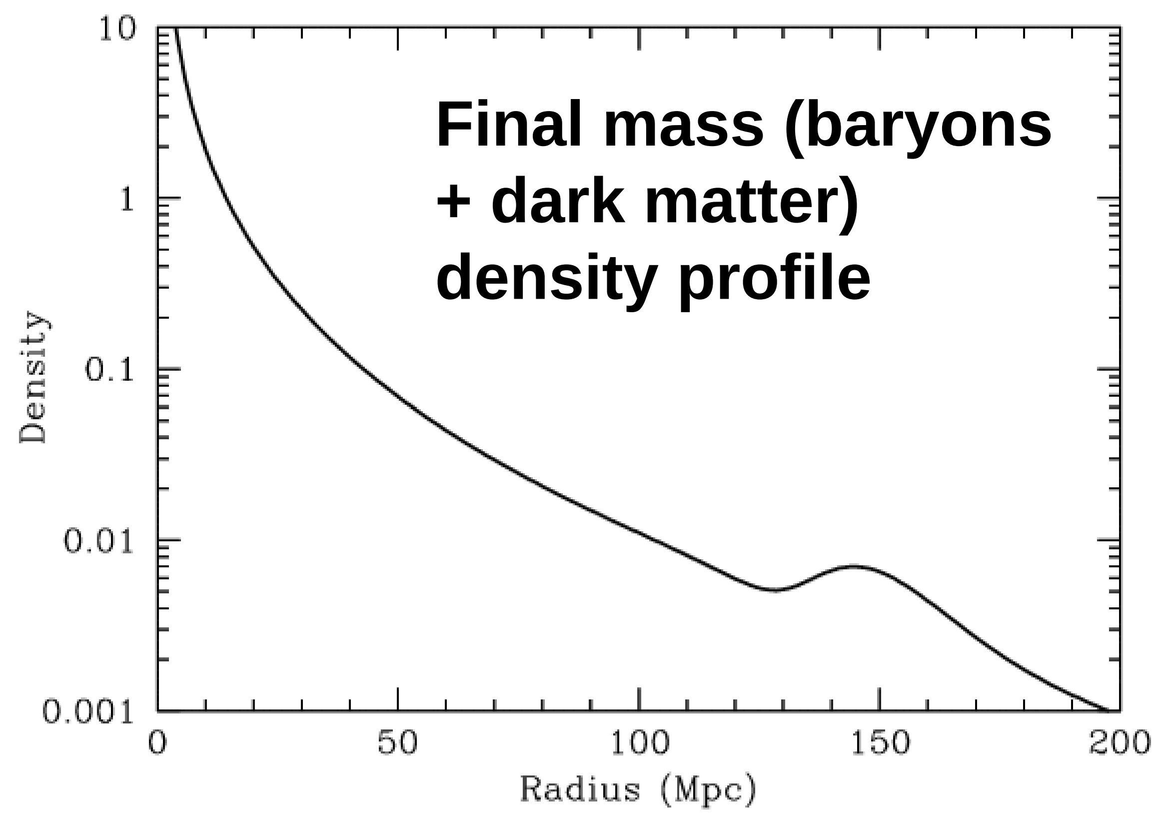
Acoustic oscillation illustrated (3)



- 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

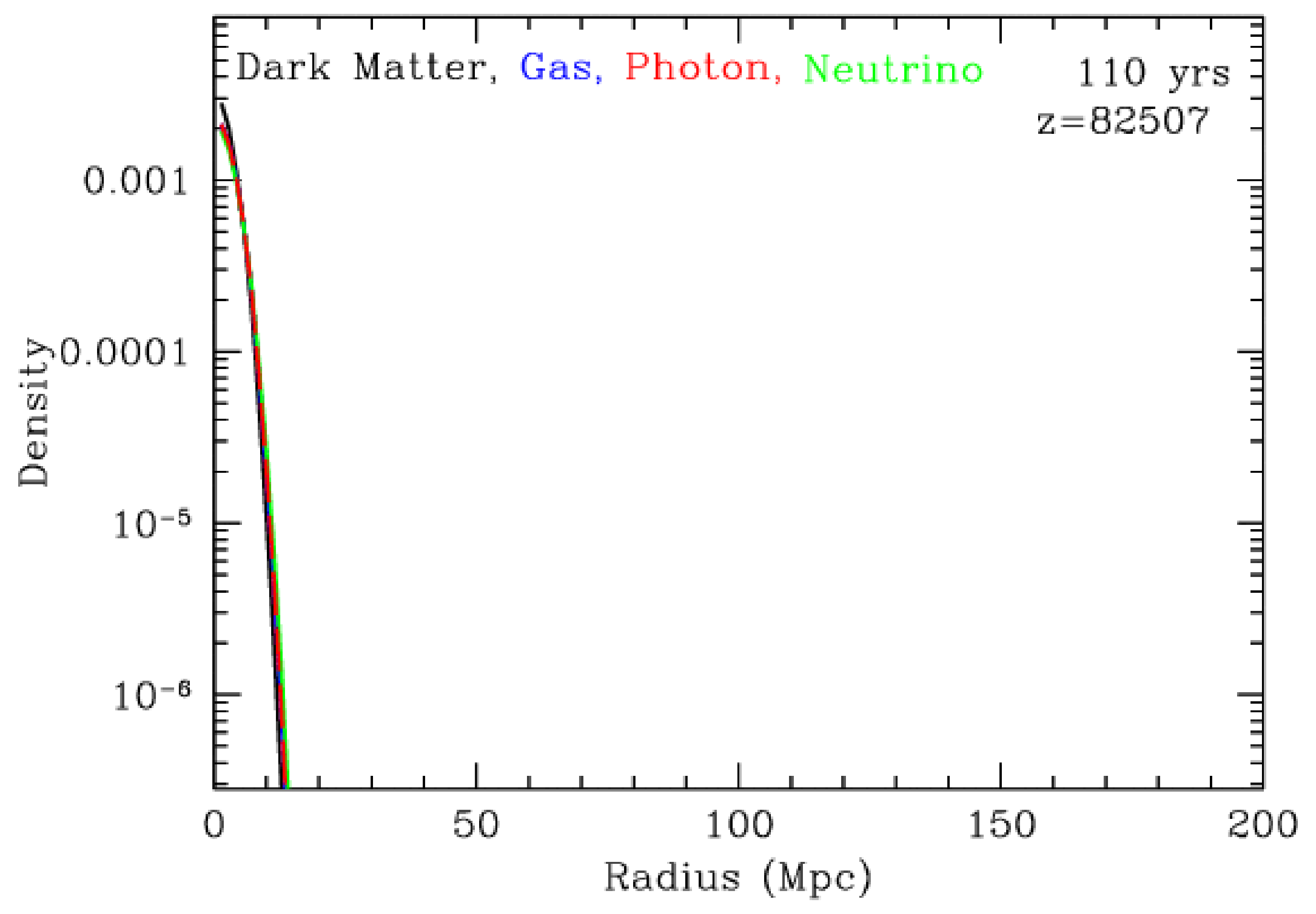
Acoustic oscillation illustrated (4)



- 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

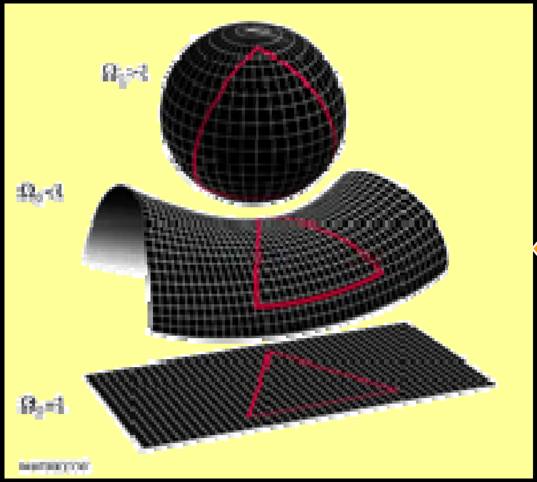


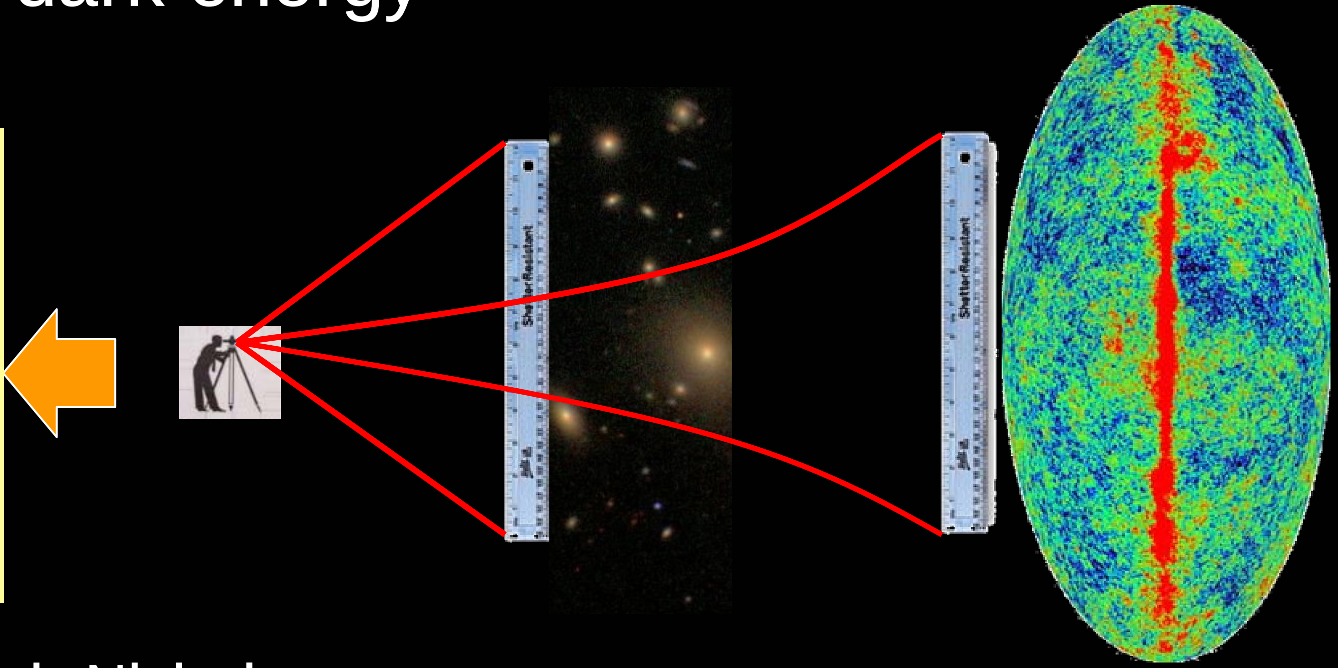
http://cmb.as.arizona.edu/~eisenste/acousticpeak/acoustic_physics.html

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



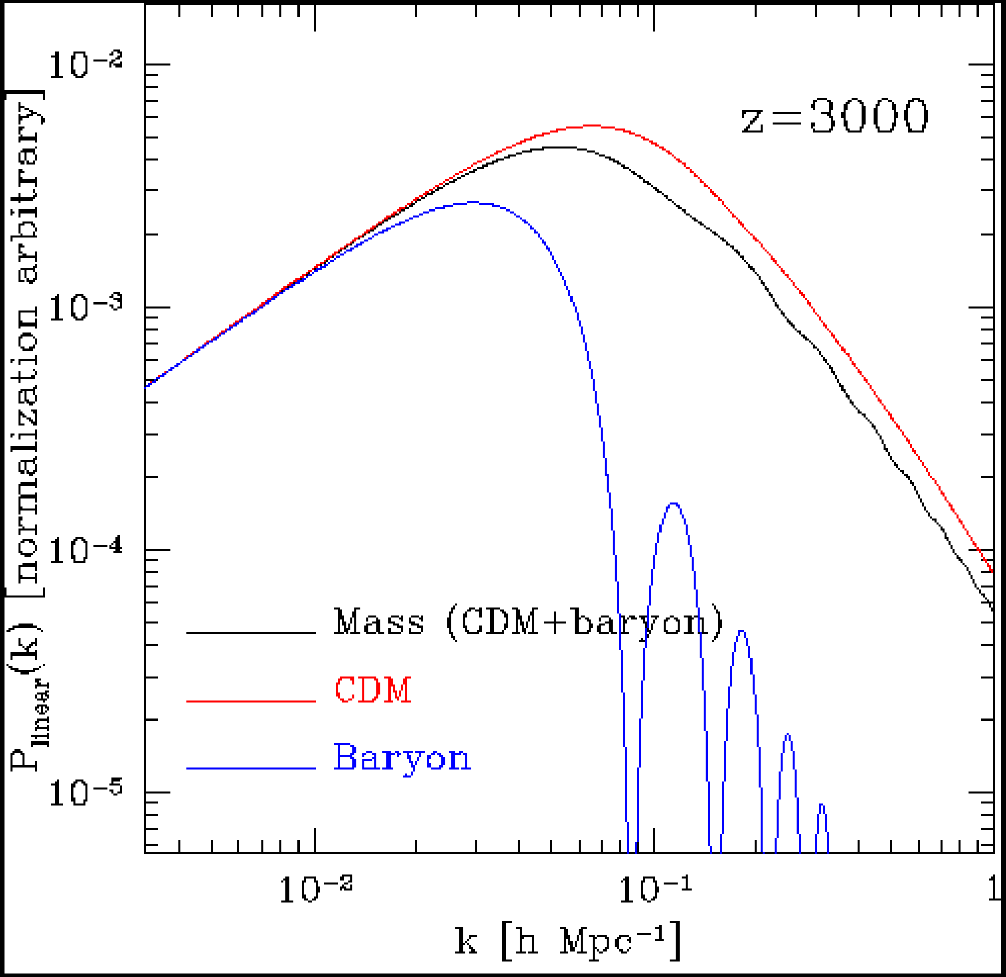


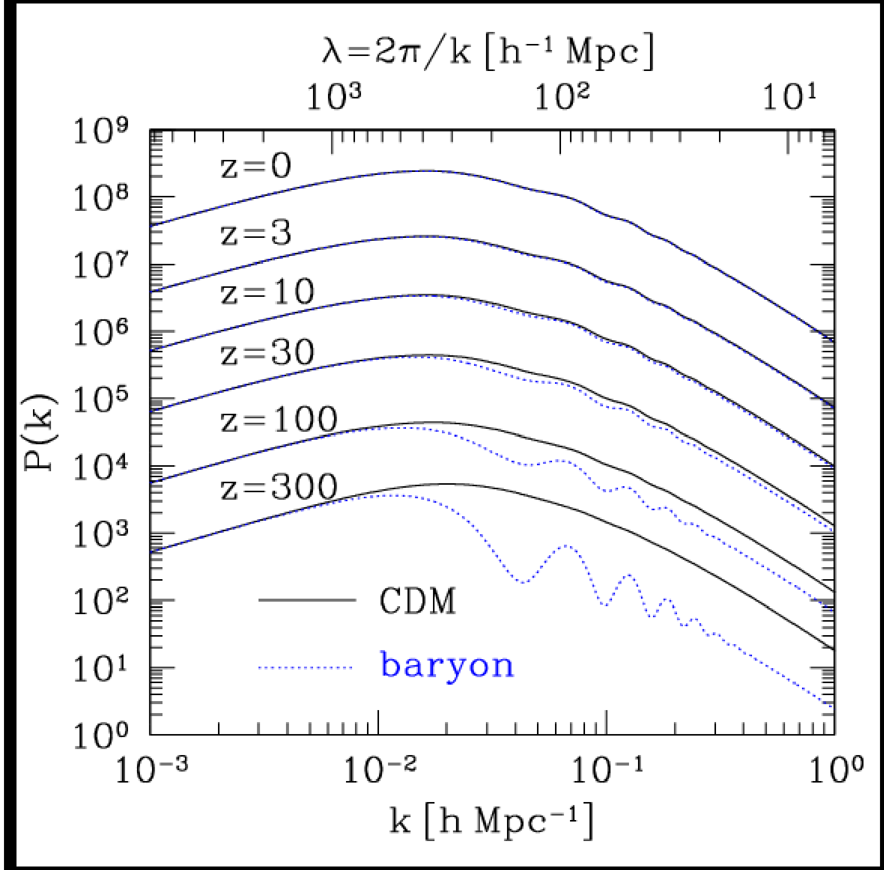
Picture credit: Bob Nichol

Acoustic scales and geometry of the universe

NASA / WMAP Science Team

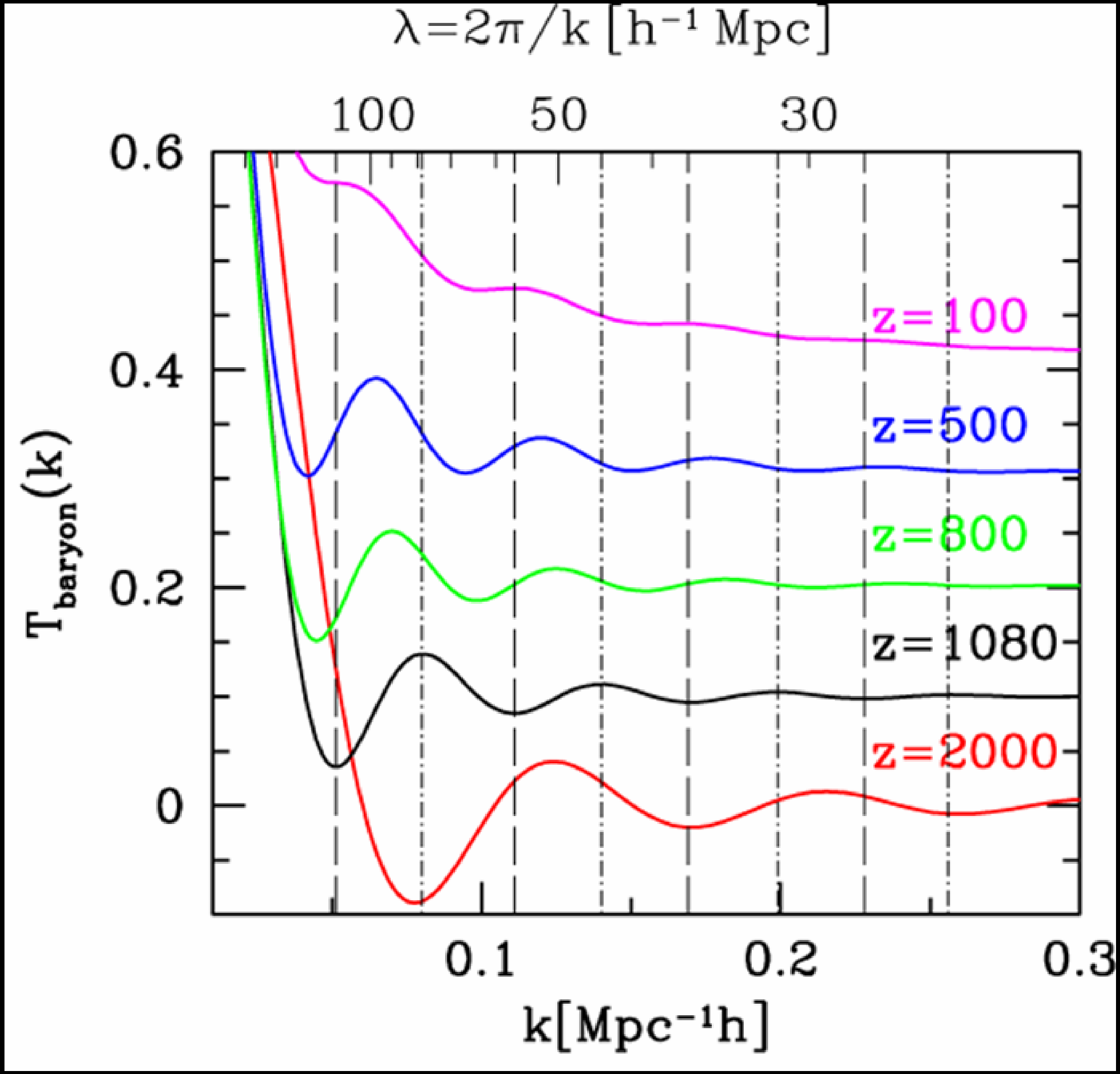
Power spectrum of mass density fluctuations with baryon acoustic oscillation effect





(A.Taruya, T. Nishimichi)

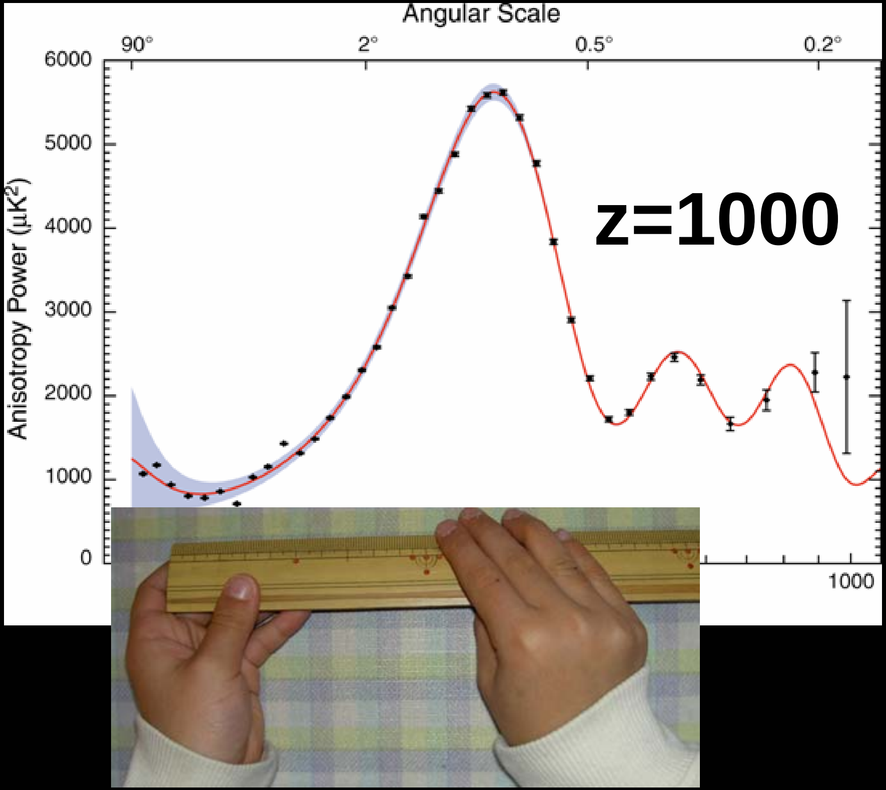
Evolution of baryon acoustic oscillations



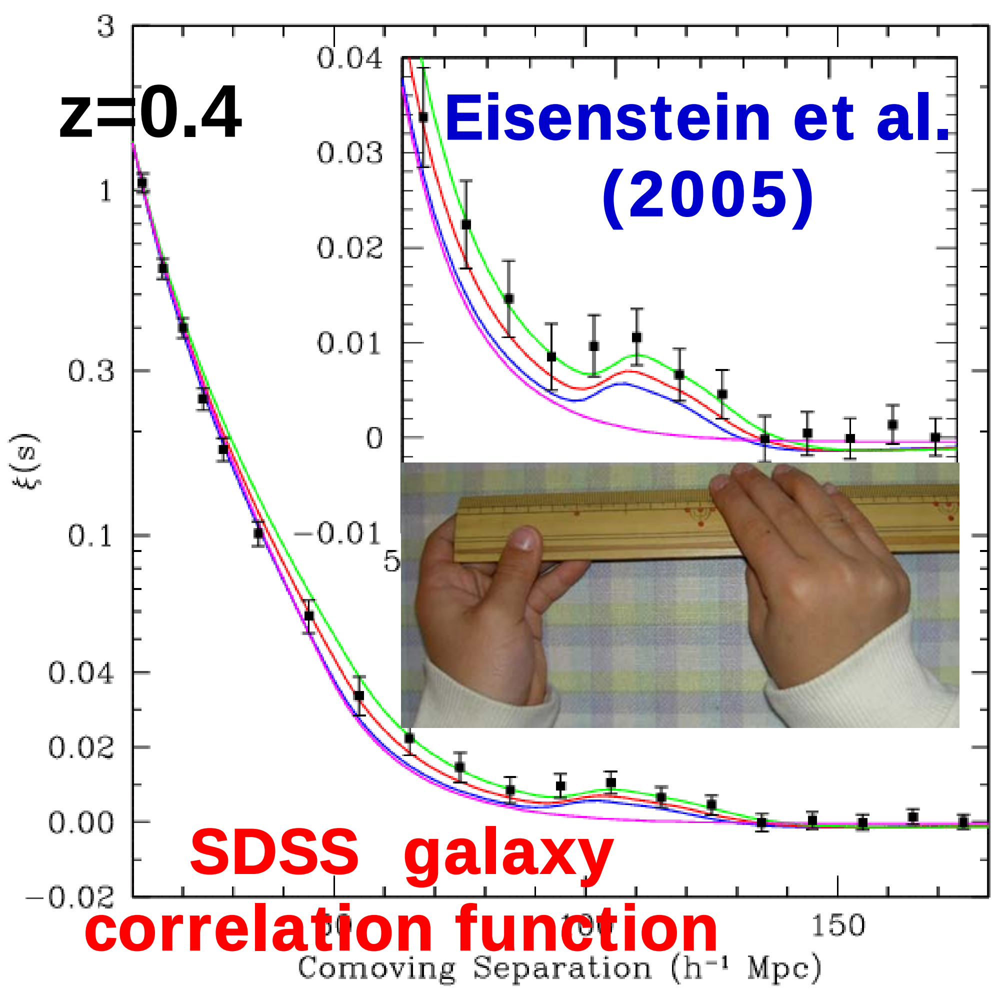
T. Nishimichi

Acoustic oscillations detected

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



z=1000

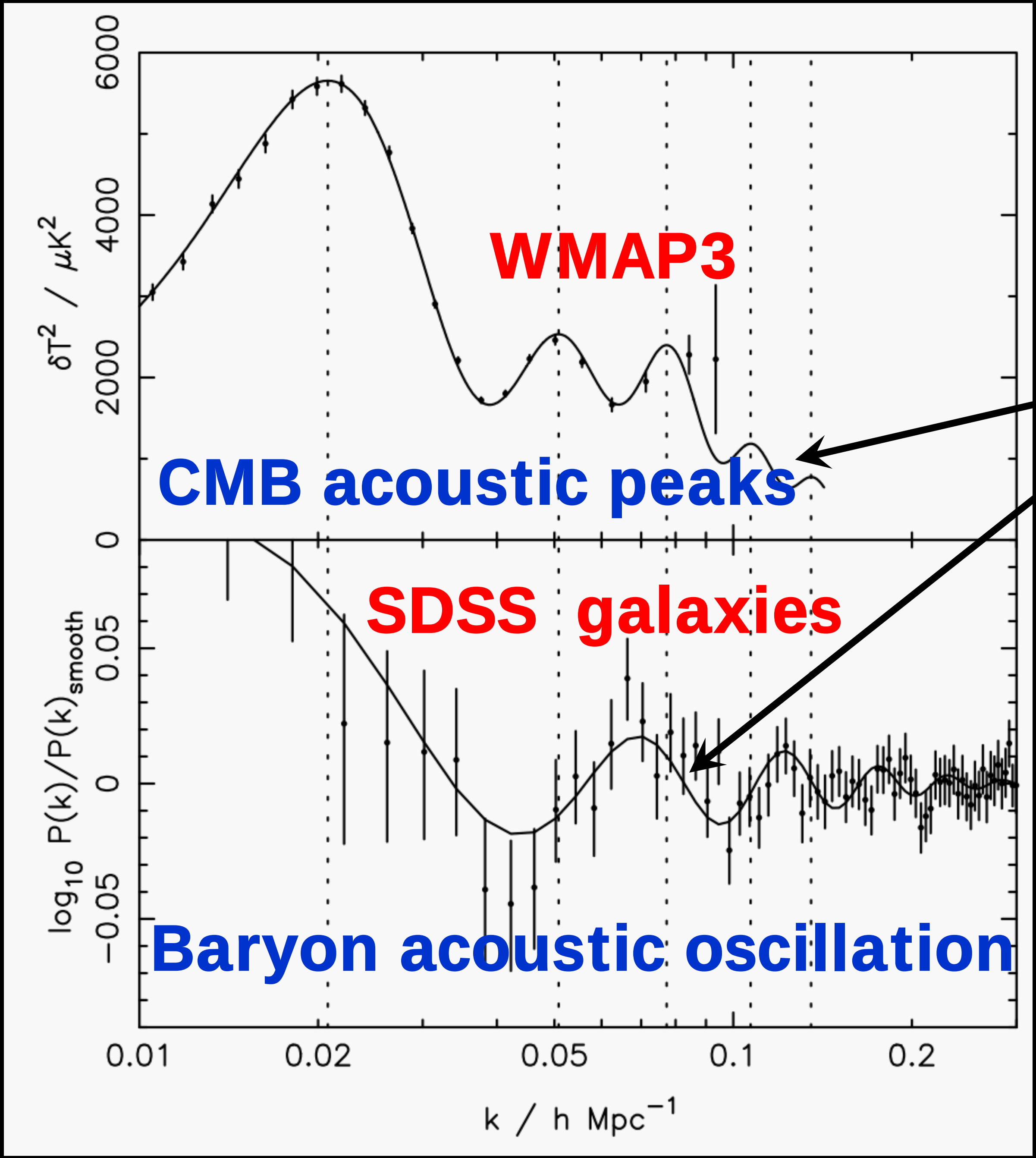


z=0.4

Eisenstein et al. (2005)

SDSS galaxy correlation function

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



WMAP3

CMB acoustic peaks

SDSS galaxies

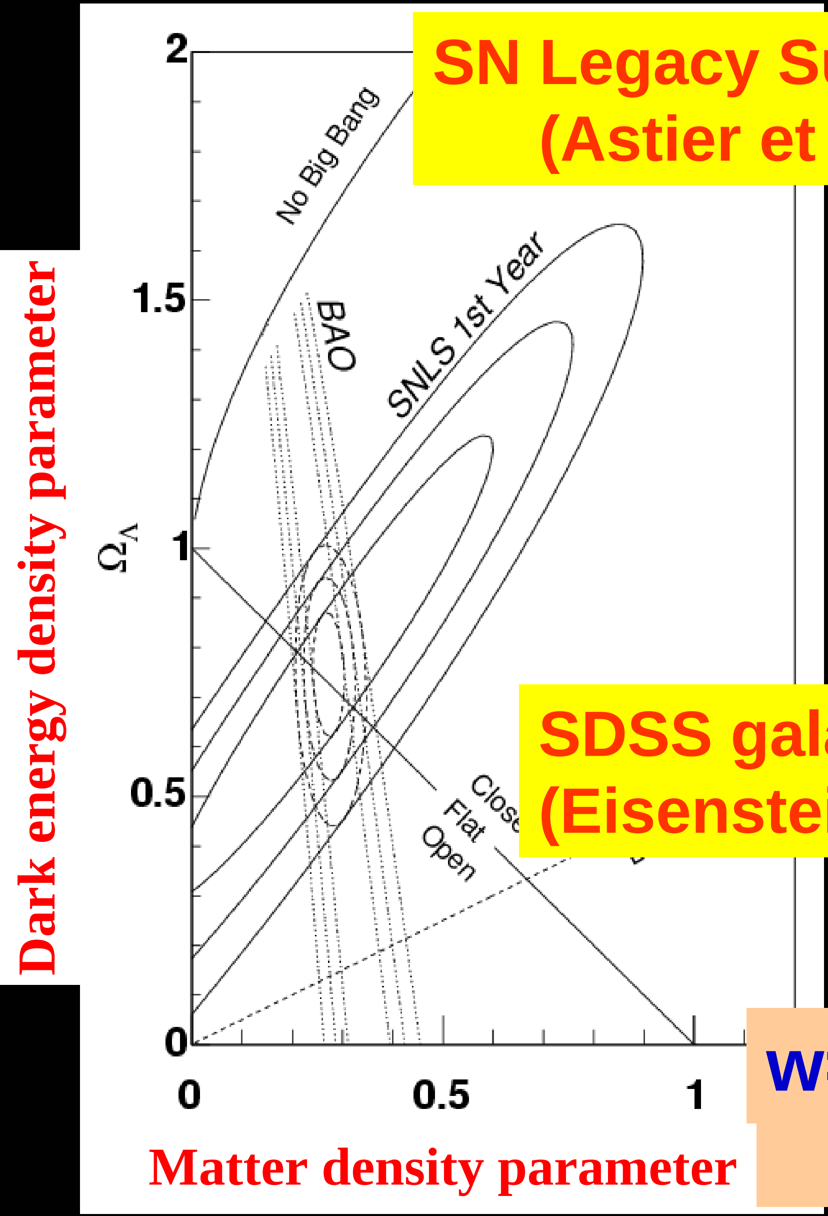
Baryon acoustic oscillation

Ω_m=0.24 best-fit WMAP model

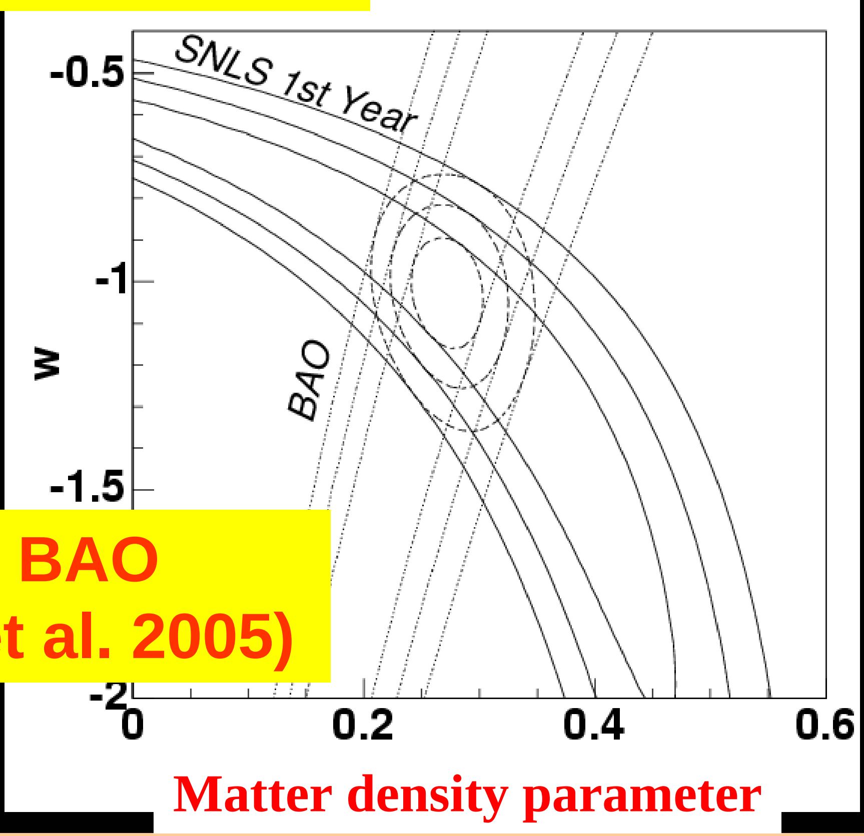
Percival et al. (2007)

Combined constraints from SN and BAO

SN Legacy Survey 1st year (Astier et al. 2006)



SDSS galaxy BAO (Eisenstein et al. 2005)



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

Recent inspirations from brane-world scenario on modified gravity

cosmic acceleration:

induced by dark energy or by extra-dimension ?

matter content or law of physics ?

an example: the DGP model; gravity leaking to extra dimensions

“modified” Friedmann equation

$$H^2 = H_0^2\left[\Omega_k(1+z)^2 + \left(\sqrt{\Omega_M(1+z)^3 + \Omega_{rc}} + \sqrt{\Omega_{rc}}\right)^2\right]$$

$$\Omega_{rc} \equiv \frac{1}{4r_c^2 H_0^2}$$

“modified” Newton Potential

$$V(r) = -\frac{G_{(4)}}{r}\left[1 + \frac{2}{\pi}\left\{-1+\gamma+\ln\left(\frac{r}{r_c}\right)\right\}\left(\frac{r}{r_c}\right) + O(r^2)\right] \;:\; r \ll r_c \sim \frac{1}{H_0}$$

Dvali, Gabadadze & Porrati , PLB 485 (2000) 208
Deffayet, Dvali & Gabadadze, PRD 65 (2002) 044023

modified gravity vs. cosmological constant: from SDSS to WFMOS

Yamamoto, Bassett, Nichol, Suto & Yahata

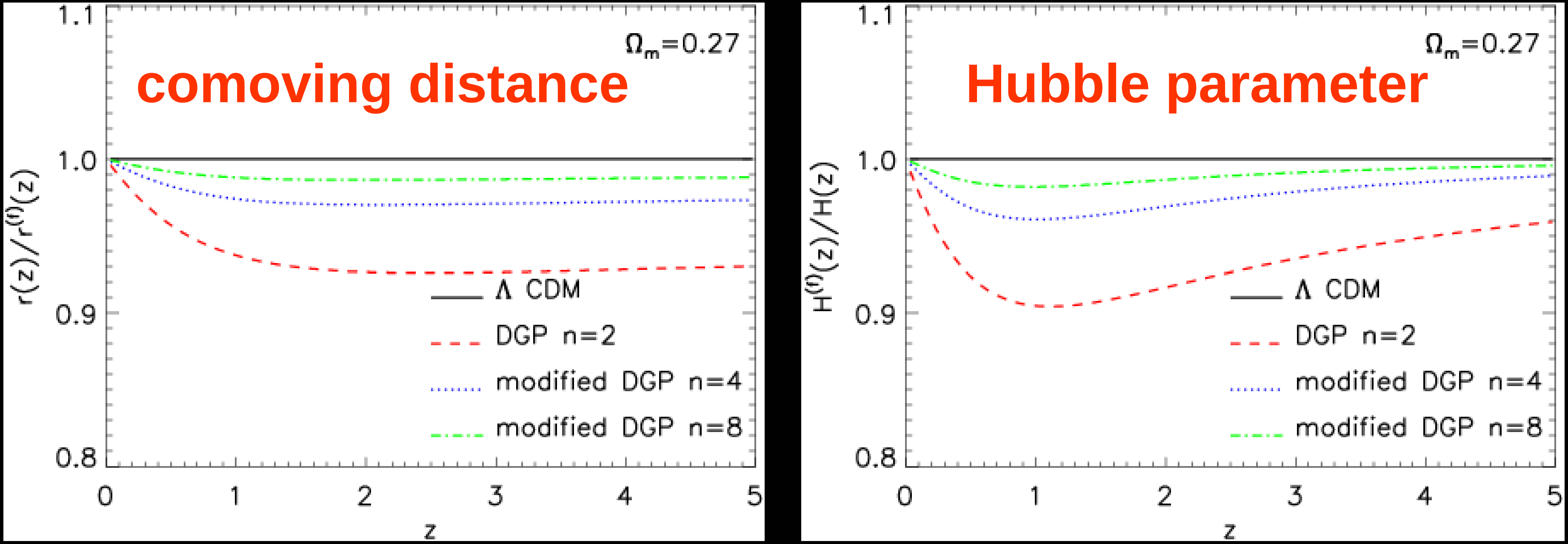
PRD 74(2006)063525

- 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 ∼1/H_0
  - r<r_c: 4D space-time, r>r_c: 5D space-time
  - if spatially flat $(H_0 r_c)^{2/n-2} = 1 - \Omega_m$

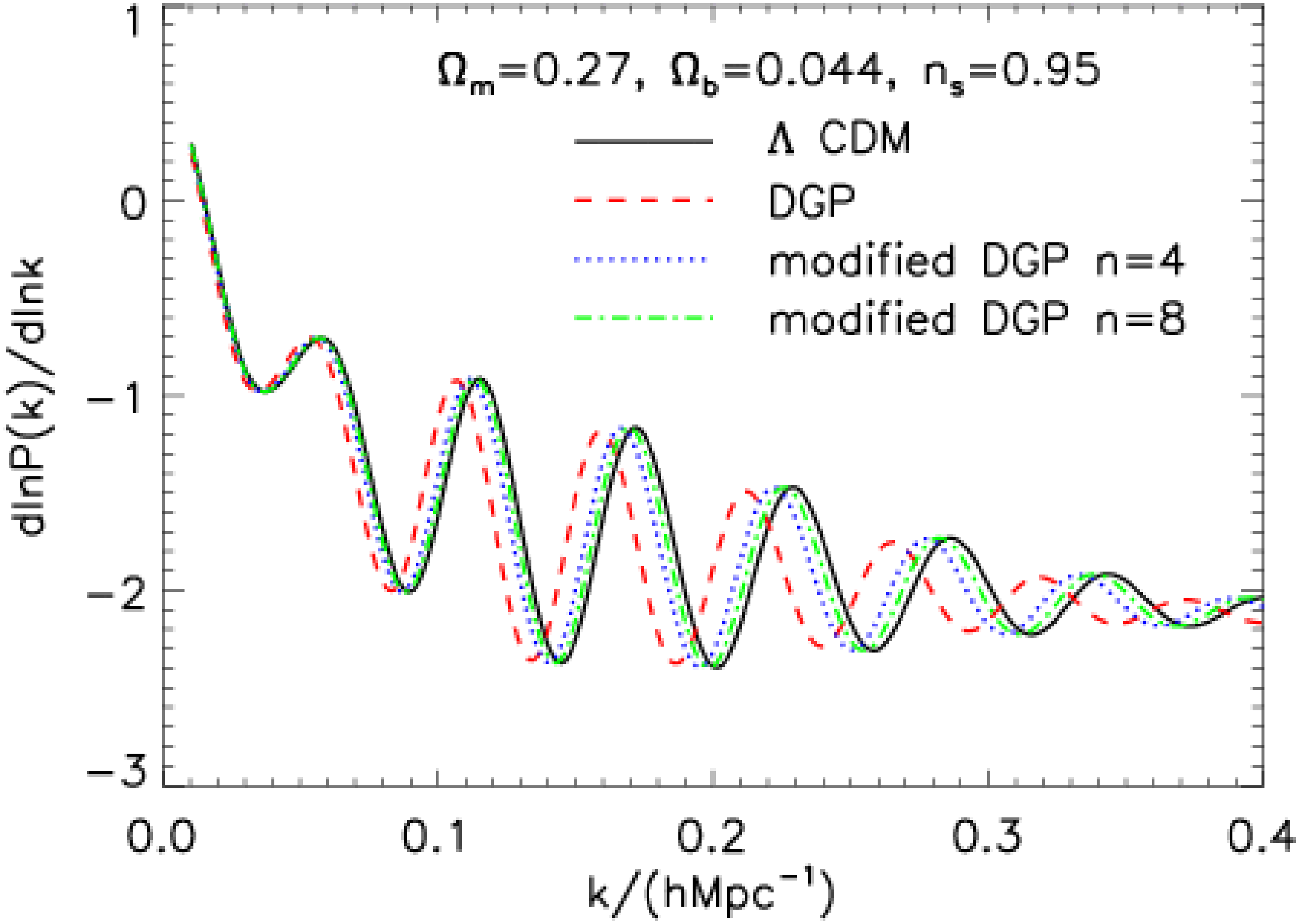
Λ vs. the modified DGP model



ratios relative to the Λ model (spatially flat)

Yamamoto et al. (2006)

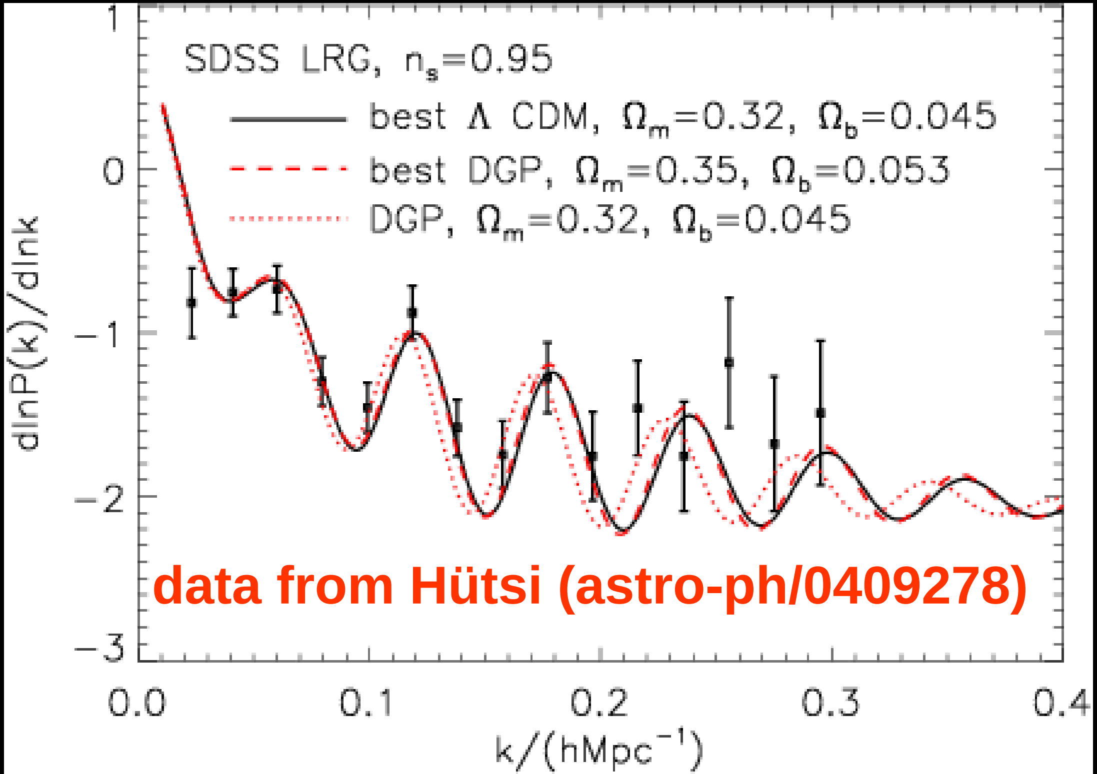
Predicted apparent shifts of BAO peaks



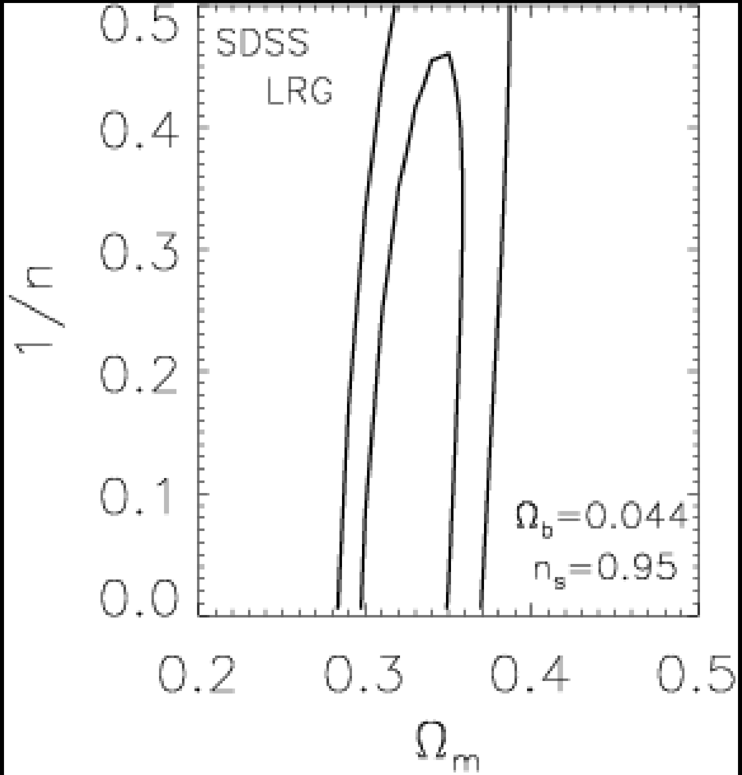
purely linear theory, observation in ΛCDM assumed

Yamamoto et al. (2006)

Current constraints from the SDSS LRG sample



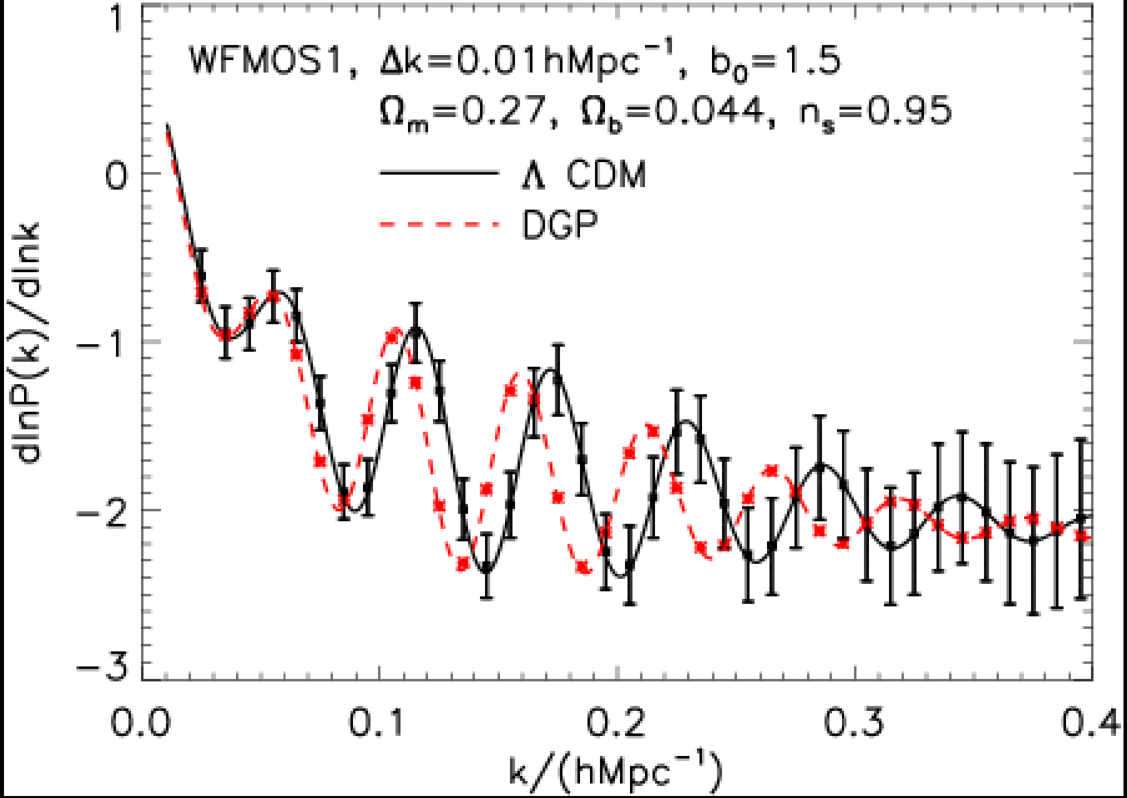
data from Hütsi (astro-ph/0409278)

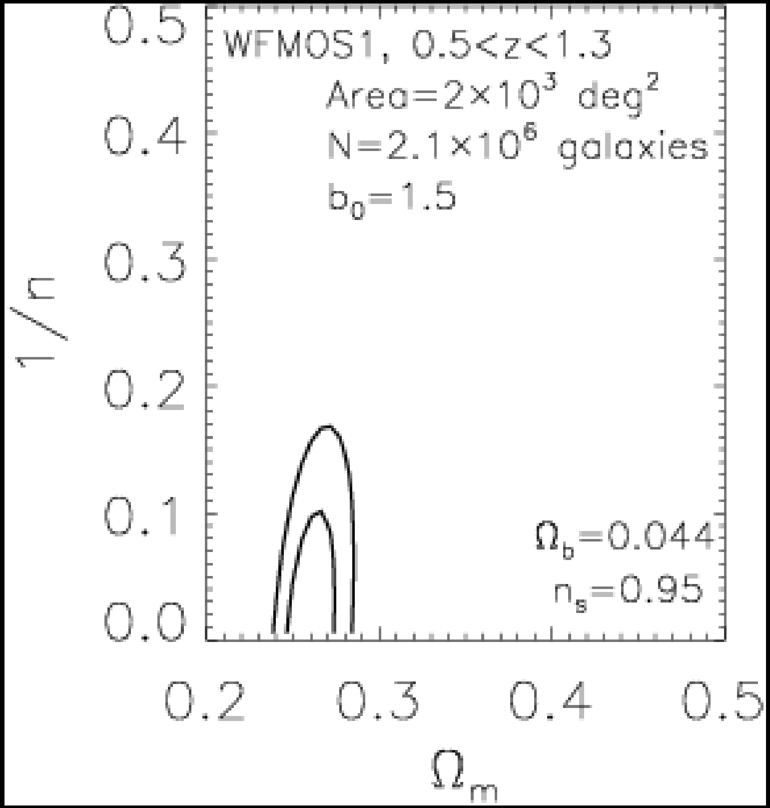


fit to linear theory for $k<0.2h\mathrm{Mpc}^{-1}$
observation in ΛCDM assumed

Yamamoto et al. (2006)

Expected constraints from future WFMOS z=1 sample



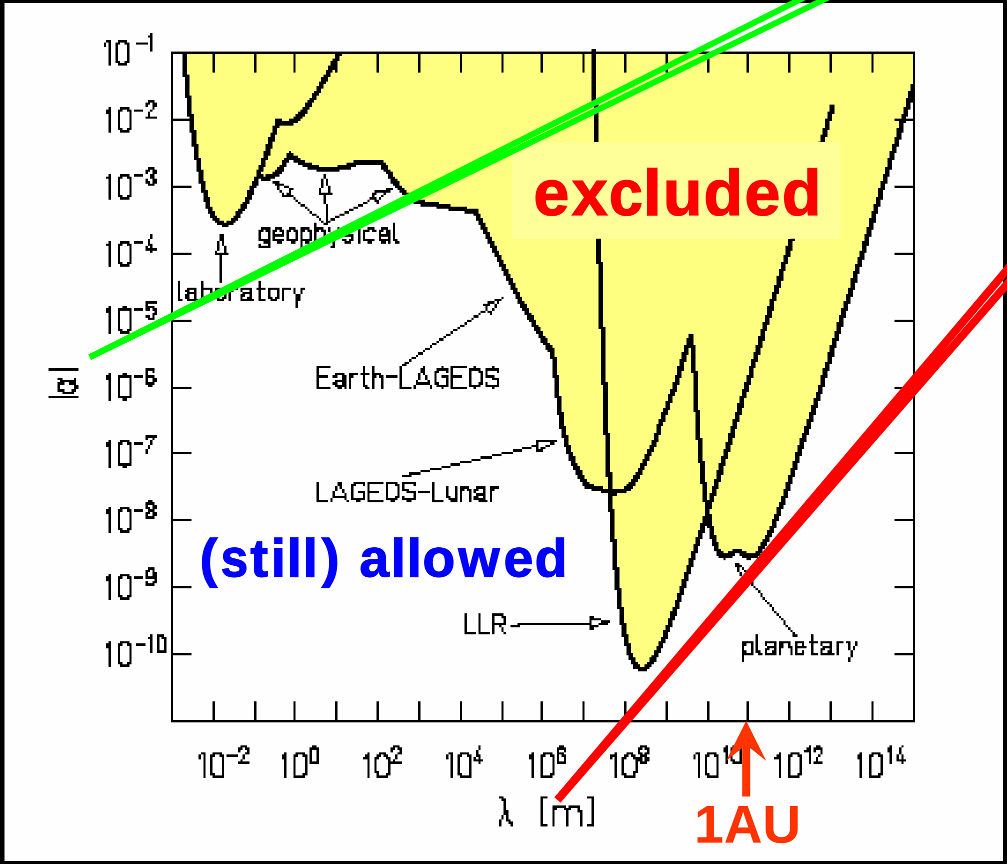


Yamamoto et al. (2006)

Current constraints on deviations from Newton’s law of gravity

Assume the Yukawa-type deviation:

$$V(r) = -G\frac{m_1 m_2}{r}\left\{1 + \alpha \exp\left(-\frac{r}{\lambda}\right)\right\}$$



weak, if any, constraints on cosmological scales so far…

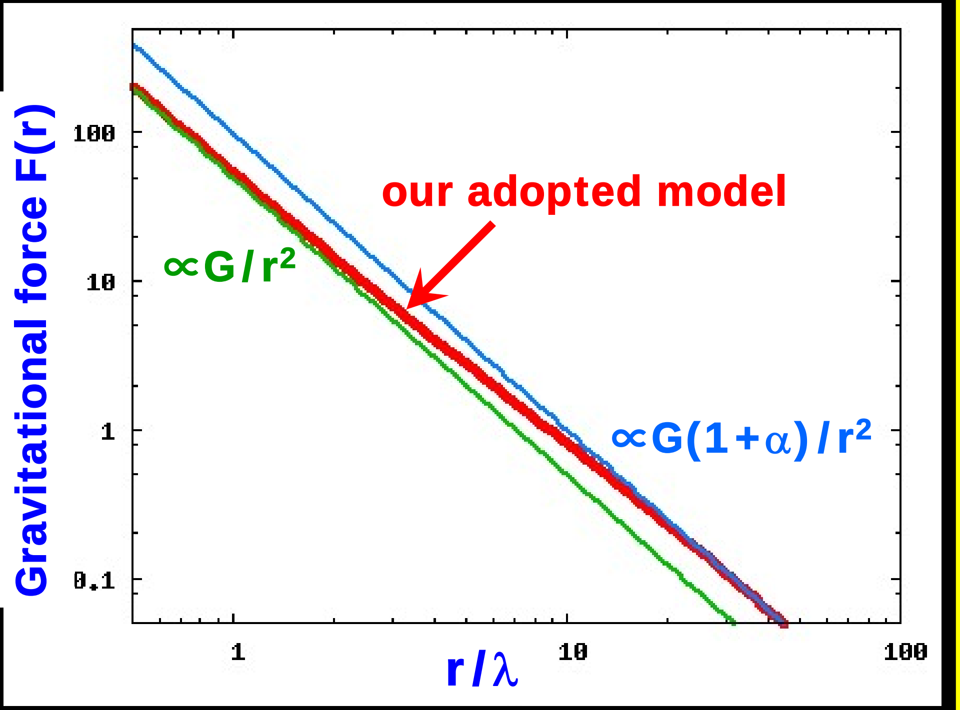
E.G. Adelberger et al. Ann.Rev.Nucl.Part.Sci. 53 (2003) 77

Empirical constraints on deviations from Newton’s law of gravity via SDSS galaxy P(k)

- ad-hoc and empirical approach (Shirata et al. 2005,2006)
  - adopt the standard Friedmann model (i.e, ΛCDM) but with ***an additional Yukawa term*** to gravity
  - adopt the standard interpretation of CMB anisotropy as the initial condition for the primordial fluctuations
  - assume ***scale-independent bias of SDSS galaxies***

Yukawa-type additional gravitational potential

$$V(r) = -G\int d^3r' \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}\left[1+\alpha\left(1-e^{-\frac{|\mathbf{r}-\mathbf{r}'|}{\lambda}}\right)\right]$$



small-scale: Newtonian gravity

$r \ll \lambda$:

$$V(r) \rightarrow -G\int d^3r' \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}$$

large-scale: G ⇒ G(1+α)

$r \gg \lambda$:

$$V(r) \rightarrow -G(1+\alpha)\int d^3r' \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}$$

stronger (weaker) gravity on large scales if $\alpha>0$ ($\alpha<0$), while cosmic expansion is dictated by “correct” G

Method (Shirata et al. 2005)

1) directly solve the linear perturbation equation under the modified Newtonian potential:

$$\ddot{\delta}_{\mathrm{k}} + 2H\dot{\delta}_{\mathrm{k}} - 4\pi G\bar{\rho}\delta_{\mathrm{k}}\left[1+\alpha\frac{(a/k\lambda)^2}{1+(a/k\lambda)^2}\right]=0$$

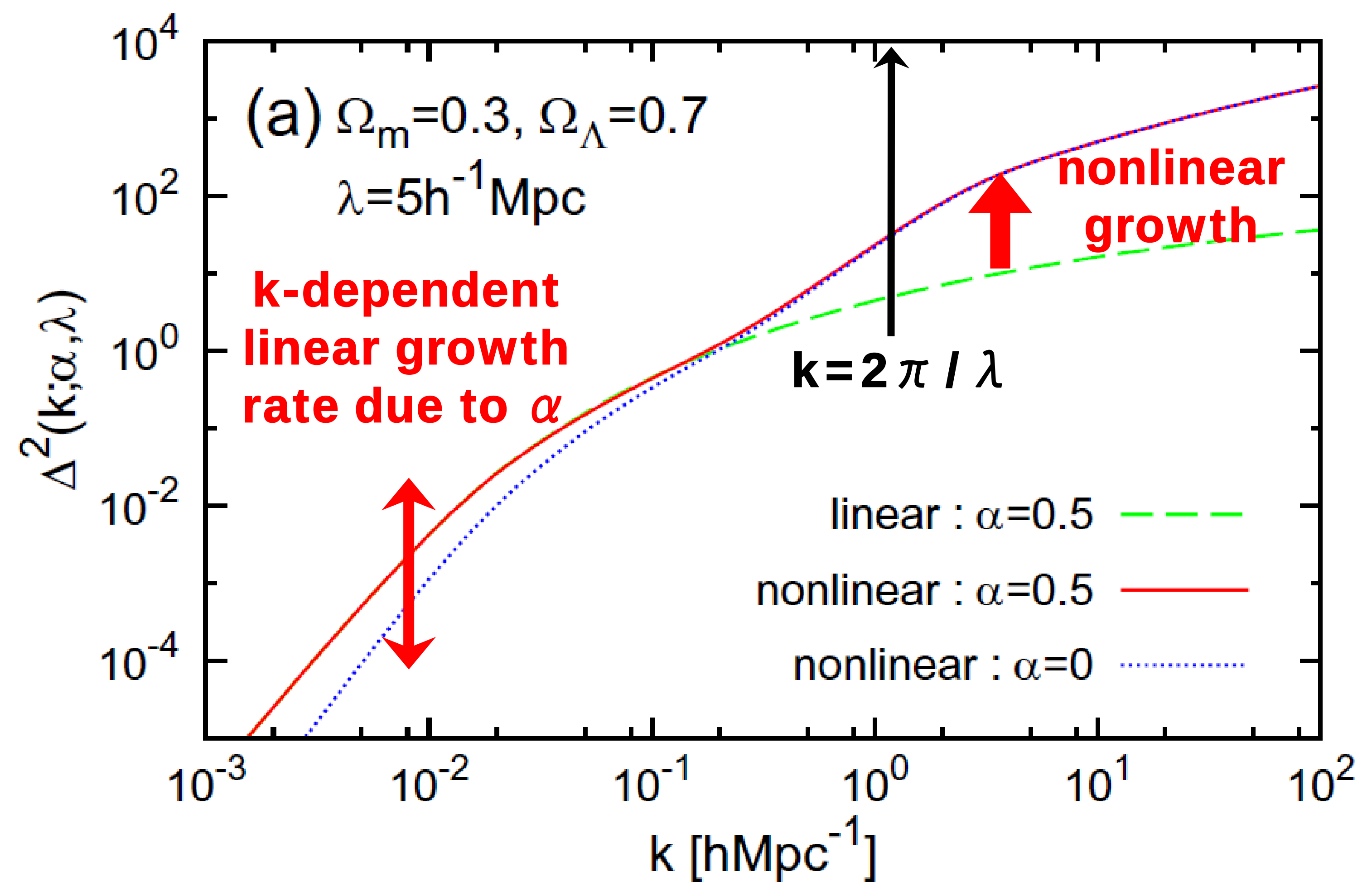
assuming the initial conditions of

$$\delta_{\mathrm{k}}(a_{ini}) = \delta_{\mathrm{k},\Lambda CDM}(a_{ini}), \quad \left.\frac{d\delta_{\mathrm{k}}}{da}\right|_{a=a_{ini}} = \left.\frac{d\delta_{\mathrm{k},\Lambda CDM}}{da}\right|_{a=a_{ini}}$$

2) apply the nonlinear correction using the Peacock-Dodds formula

3) Compare the model predictions with SDSS galaxy P(k) assuming linear bias $(0.01<k[h^{-1}\mathrm{Mpc}]<0.3)$

Nonlinear correction for power spectrum applying the Peacock-Dodds fit



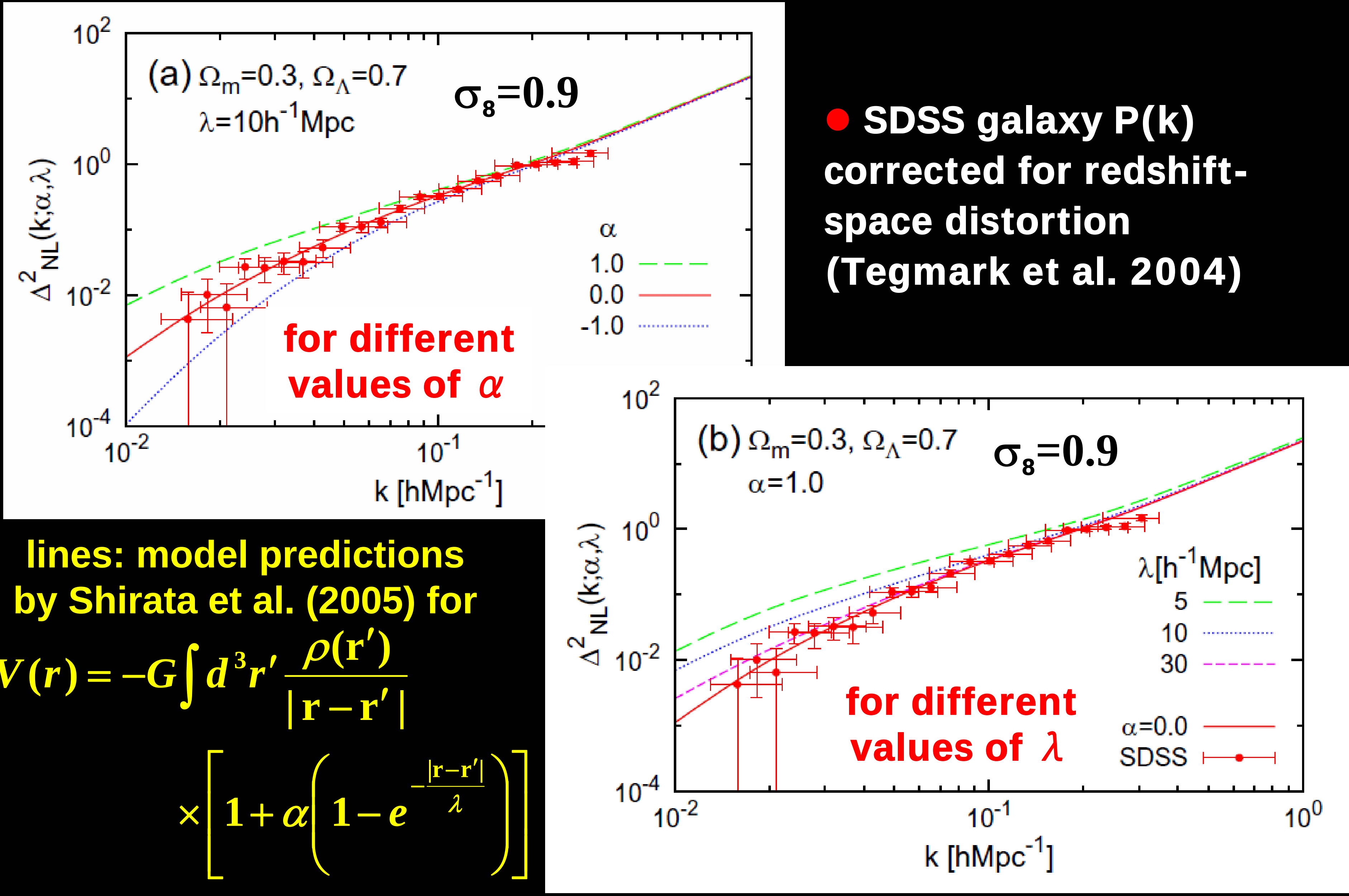
k-dependent linear growth rate due to α

nonlinear growth

$k=2\pi/\lambda$

Shirata, Shiromizu, Yoshida & Suto: Phys.Rev.D 71(2005) 064030

Comparison with SDSS galaxy P(k)



for different values of α

for different values of λ

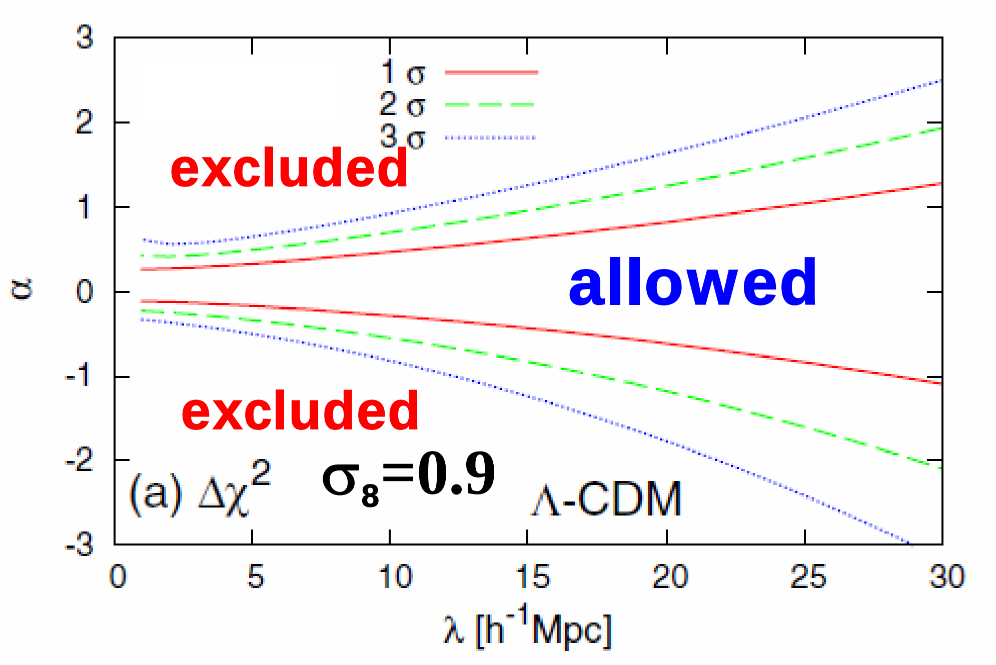
- ● **SDSS galaxy P(k) corrected for redshift-space distortion (Tegmark et al. 2004)**

lines: model predictions by Shirata et al. (2005) for

$$V(r) = -G\int d^3r' \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} \times \left[1+\alpha\left(1-e^{-\frac{|\mathbf{r}-\mathbf{r}'|}{\lambda}}\right)\right]$$

Constraints on model parameters

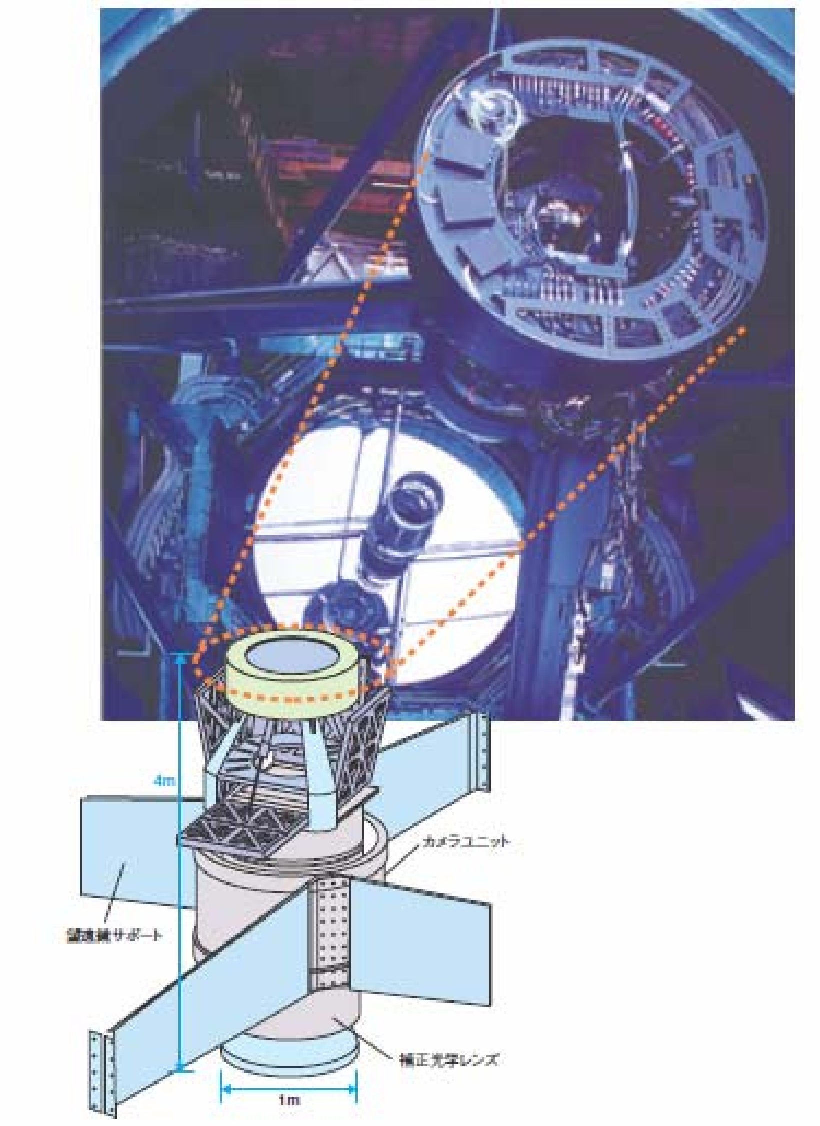
$$V(r) = -G\int d^3r'\,\frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}\left[1+\alpha\left(1-e^{-\frac{|\mathbf{r}-\mathbf{r}'|}{\lambda}}\right)\right]$$



Shirata, Shiromizu, Yoshida & Suto: Phys.Rev.D 71(2005) 064030

- $\lambda = 5h^{-1}$Mpc ⇒ $-0.5 < \alpha < 0.6$ (3σ limits)
- $\lambda = 10h^{-1}$Mpc ⇒ $-0.8 < \alpha < 0.9$ (3σ limits)

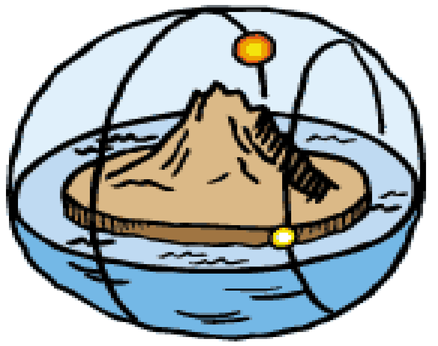
V future dark energy projects



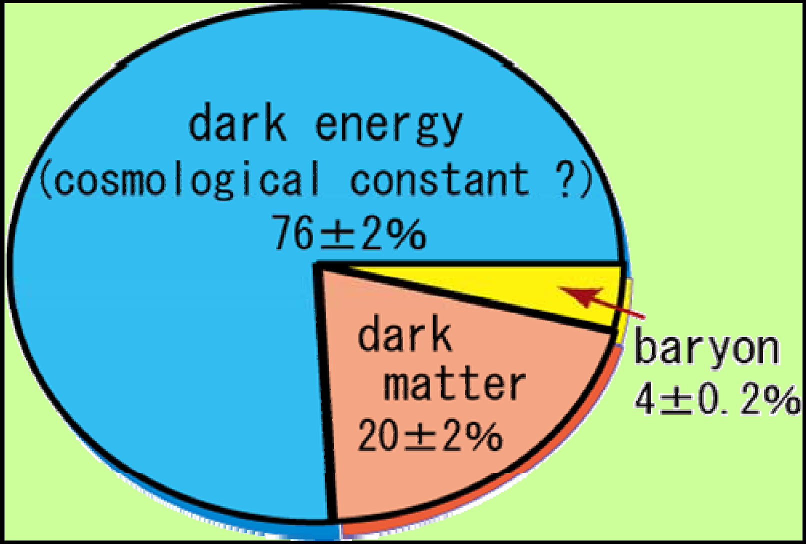
Did we make progress at all ?

Egypt

Chinese



Indian



Why can we conclude that this is a better picture before knowing the nature of dark matter and dark energy ?

Towards understanding of the universe

1. the n-th order parameterized model of the universe
    - Ω_Λ, Ω_m, Ω_b, h, σ_8…
2. improve the precision/accuracy of the numbers
3. understand why
    - (variants of) inflation, superstring, brane…
4. look for something that cannot be described in the n-th order model
    - $w=-1 \Rightarrow w=w_0+w_0(1-a) \Rightarrow w(a) \Rightarrow w(a,r)$
    - linear bias ⇒ nonlinear bias ⇒ non-deterministic bias
    - virialized spherical halo ⇒ triaxial ⇒ shocked+ magnetic+conductive+cosmic ray
5. repeat the above steps 1〜4 until you become tired (or retire) for n=1,2,3,4,5…

Can we understand the dark side of the universe in foreseeable future ?

- **Dark matter**
  - maybe new results from on-going experiments in next 5-10 years, but not from astronomy
- **Dark energy**
  - unlikely to have any breakthroughs from future experiments and/or theories in high energy physics in this century
  - astronomy is the key !
- **Dark baryons**
  - only astronomical observations can make a scientific new contribution since high-energy physicists already know baryons too well !

Dark matter

- high-energy experiments in near future are very promising
- still room for cosmology to help understanding dark matter ?
  - density profile of dark matter halos
  - what is the “true” density profile ? core vs. cusp
  - modeling substructure statistics
  - non-spherical modeling
  - baryonic effect; star formation, feedback,,,

Dark energy

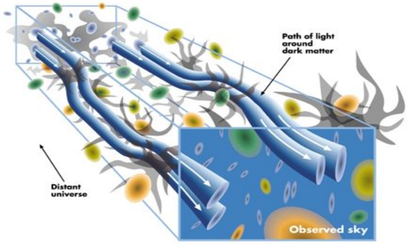
- Meaningful theoretical breakthroughs are unlikely during this century

  ⇒ observational approaches are the keys !
- something really there or just virtual ?
  - right-hand-side in the Einstein equation
  - modified gravity theory
- already (too) many proposals for future observational projects
  - need more accurate modeling
  - need to control systematic effects

Probes of Dark Energy (S.Bridle)

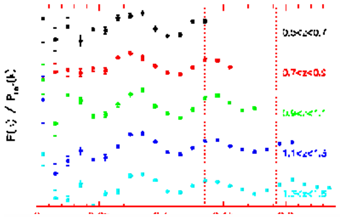
Cosmic Shear

Evolution of dark matter perturbations
Angular diameter distance
Growth rate of structure



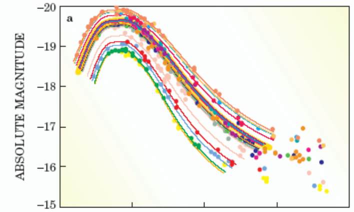
Features in matter P(k)

Standard ruler
Angular diameter distance



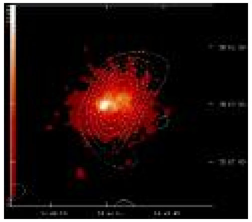
Supernovae

Standard candle
Luminosity distance



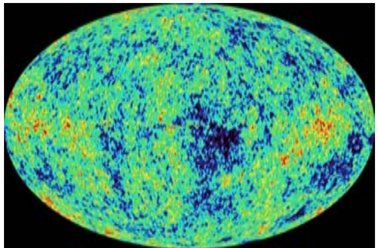
Cluster counts

Evolution of dark matter perturbations
Angular diameter distance
Growth rate of structure

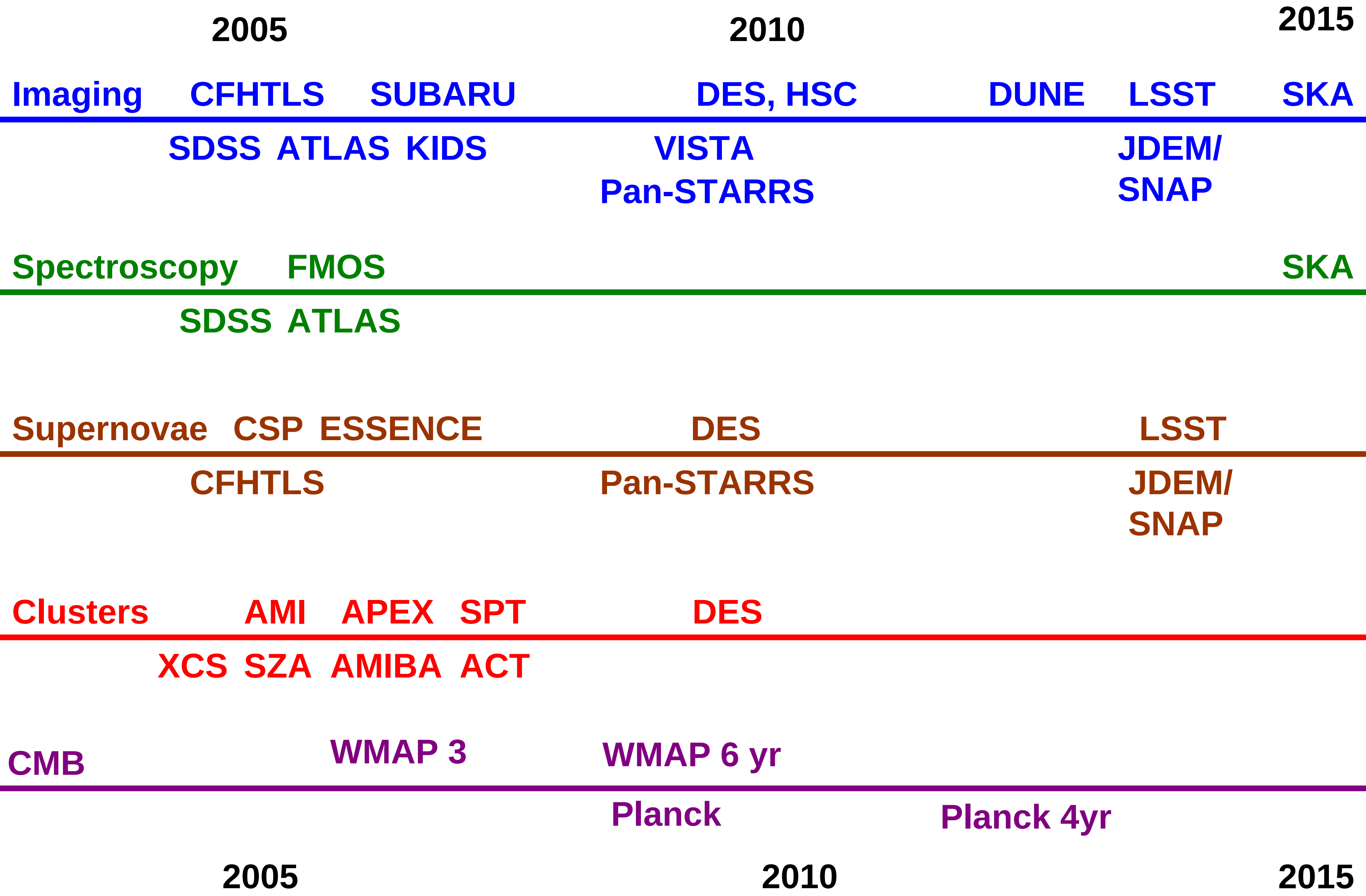


CMB

Snapshot at ~400,000 yr, viewed from z=0
Angular diameter distance to z~1000
Growth rate of structure (from ISW)



Surveys to measure Dark Energy (S.Bridle)



2005 2010 2015

Imaging CFHTLS SUBARU DES, HSC DUNE LSST SKA

SDSS ATLAS KIDS VISTA JDEM/

Pan-STARRS SNAP

Spectroscopy FMOS SKA

SDSS ATLAS

Supernovae CSP ESSENCE DES LSST

CFHTLS Pan-STARRS JDEM/

SNAP

Clusters AMI APEX SPT DES

XCS SZA AMIBA ACT

WMAP 3 WMAP 6 yr

CMB

Planck Planck 4yr

2005 2010 2015

Probing Dark Energy (J.Frieman)

Probe dark energy through the expansion history:

$$H^2(z) = H^2_0 \; [\Omega_M (1+z)^3 + \Omega_{DE} (1+z)^{3(1+w)}] \quad \text{(flat)}$$

matter dark energy (constant *w*)

Geometric tests:

- Comoving distance $r(z) = \int dz/H(z)$
- Standard Candles $d_L(z) = (1+z)\, r(z)$
- Standard Rulers $d_A(z) = (1+z)^{-1}\, r(z)$
- Standard Population (volume) $dV/dzd\Omega = r^2(z)/H(z)$

Structure based-tests:

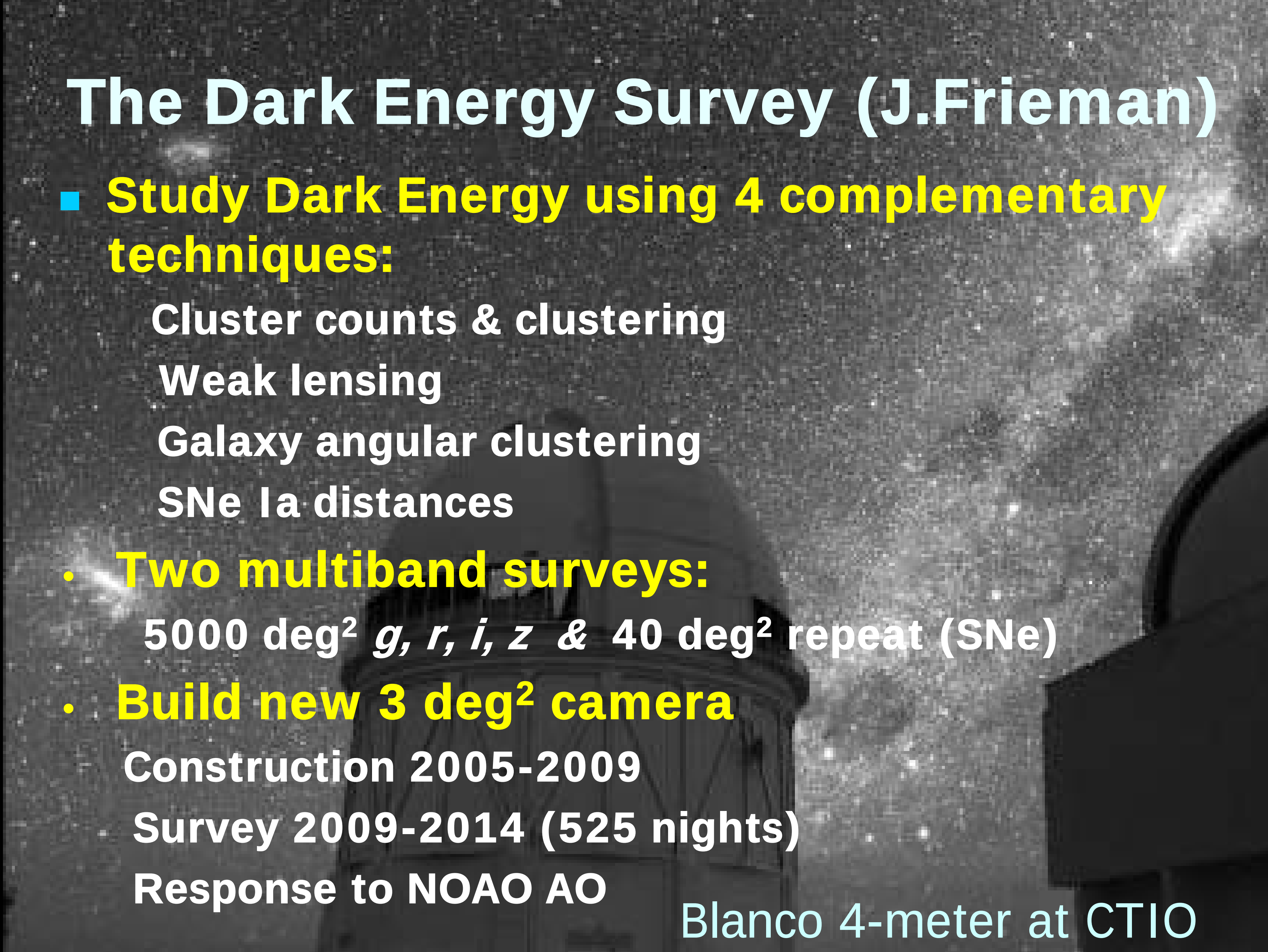
- The rate of growth of structure determined by H(z), by any modifications of gravity on large scales, and by other cosmological parameters

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

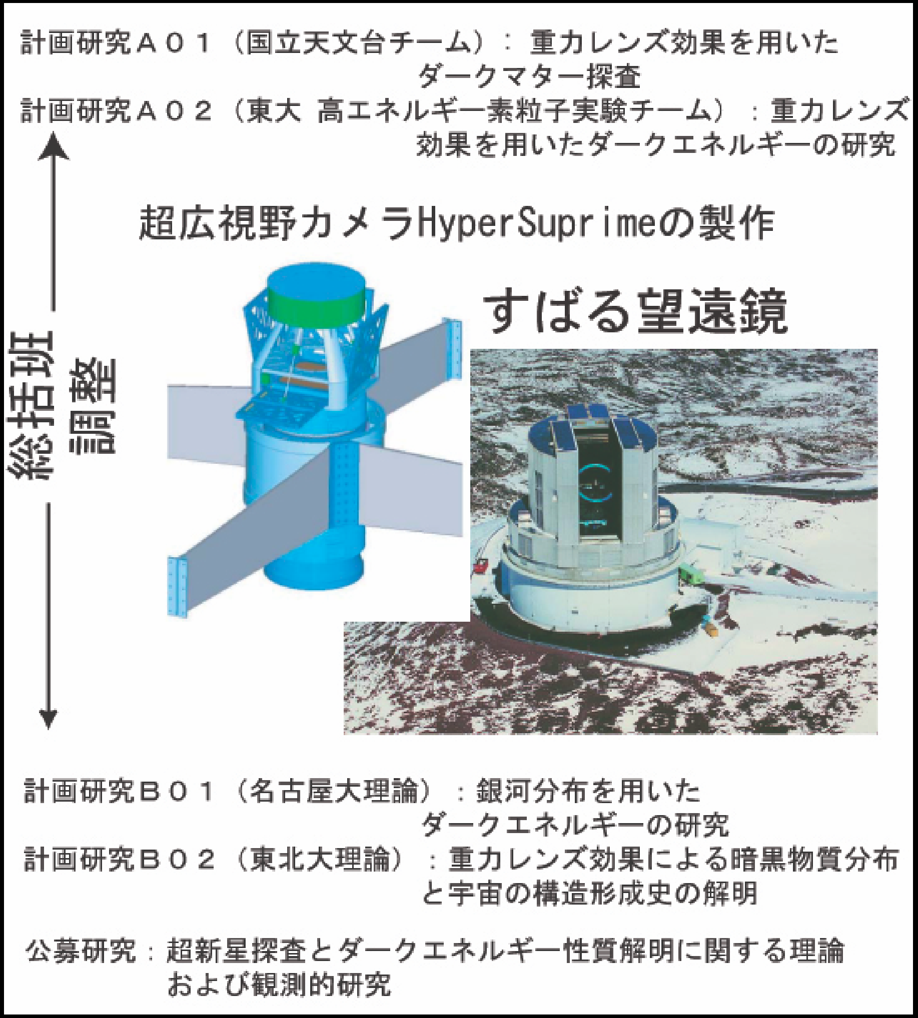
The Dark Energy Survey (J.Frieman)

- **Study Dark Energy using 4 complementary techniques:**
  - Cluster counts & clustering
  - Weak lensing
  - Galaxy angular clustering
  - SNe Ia distances
- **Two multiband surveys:**
  - 5000 deg^2 *g, r, i, z* & 40 deg^2 repeat (SNe)
- **Build new 3 deg^2 camera**
  - Construction 2005-2009
  - Survey 2009-2014 (525 nights)
  - Response to NOAO AO



Blanco 4-meter at CTIO

Hyper Suprime-Cam project



計画研究Ａ０１（国立天文台チーム）：重力レンズ効果を用いた
ダークマター探査

計画研究Ａ０２（東大 高エネルギー素粒子実験チーム）：重力レンズ効果を用いたダークエネルギーの研究

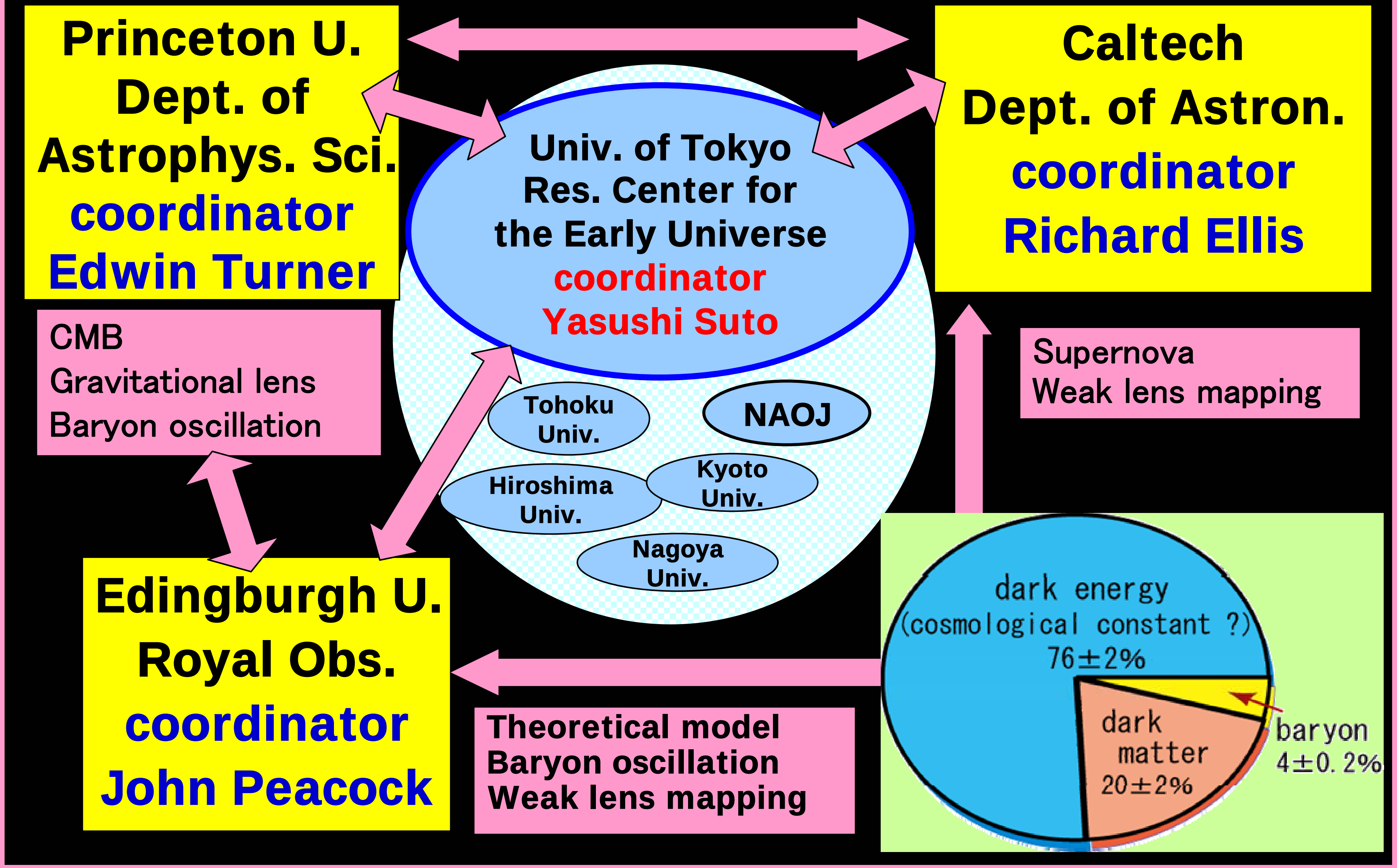
計画研究Ｂ０１（名古屋大理論）：銀河分布を用いた
ダークエネルギーの研究

計画研究Ｂ０２（東北大理論）：重力レンズ効果による暗黒物質分布
と宇宙の構造形成史の解明

公募研究：超新星探査とダークエネルギー性質解明に関する理論
および観測的研究

- **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

International Research Network for Dark Energy
(JSPS, core-to-core program 2007-2009)



Princeton U.
Dept. of Astrophys. Sci.
coordinator
Edwin Turner

CMB
Gravitational lens
Baryon oscillation

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

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

Caltech
Dept. of Astron.
coordinator
Richard Ellis

Supernova
Weak lens mapping

Edingburgh U.
Royal Obs.
coordinator
John Peacock

Theoretical model
Baryon oscillation
Weak lens mapping

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

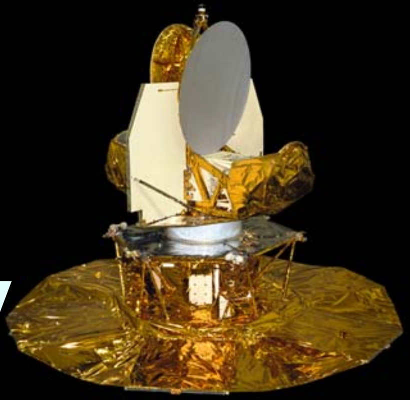
Dark energy research is good or bad for astronomy ?

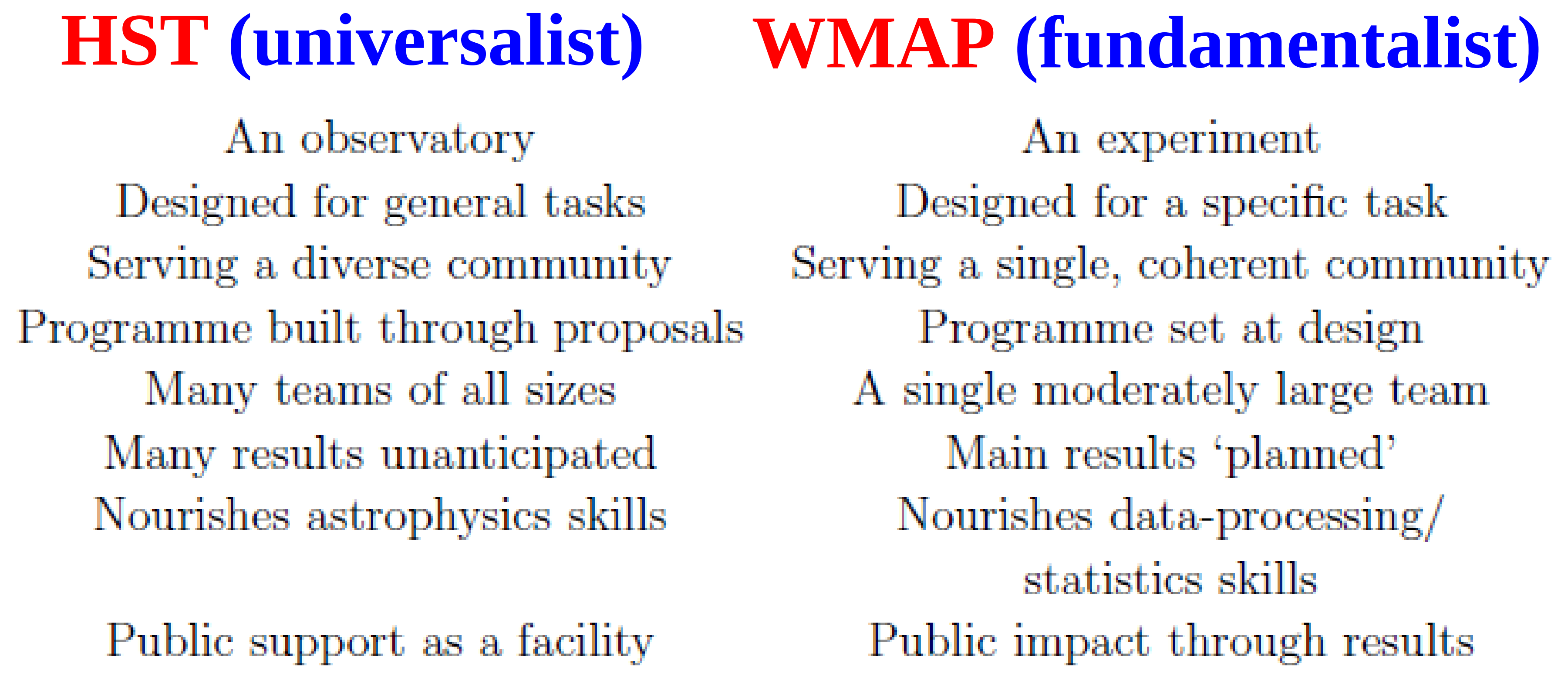
Fundamentalist physics: why dark energy is bad for astronomy

Simon D.M. White, astro-ph/0704.2291

- **Fundamentalist:** high-energy experiments
  - Pursuit of a single truth (LHC, WMAP)
  - Huge international collaborations
- **Universalist:** astronomical observations
  - Multi-purpose (Hubble Space Telescope, SDSS)
  - Relatively small groups
- **Different culture, sense of value, and matter of taste, after all…**

Two very successful but quite different projects in astronomy





HST **(universalist)**	**WMAP** **(fundamentalist)**
An observatory	An experiment
Designed for general tasks	Designed for a specific task
Serving a diverse community	Serving a single, coherent community
Programme built through proposals	Programme set at design
Many teams of all sizes	A single moderately large team
Many results unanticipated	Main results 'planned'
Nourishes astrophysics skills	Nourishes data-processing/ statistics skills
Public support as a facility	Public impact through results

Simon D.M. White: astro-ph/0704.2291

Another successful example: SDSS (Sloan Digital Sky Survey)

- 1345 refereed papers to date
- These papers have been cited over 39,000 times
- 30 of the 200 most cited papers in astronomy since 2000 used SDSS data
- Impact in many areas we didn't anticipate:
  - White dwarfs
  - Brown dwarfs
  - Ultra-low metallicity stars
  - Galaxy-galaxy lensing
  - Supernovae
  - Epoch of reionization

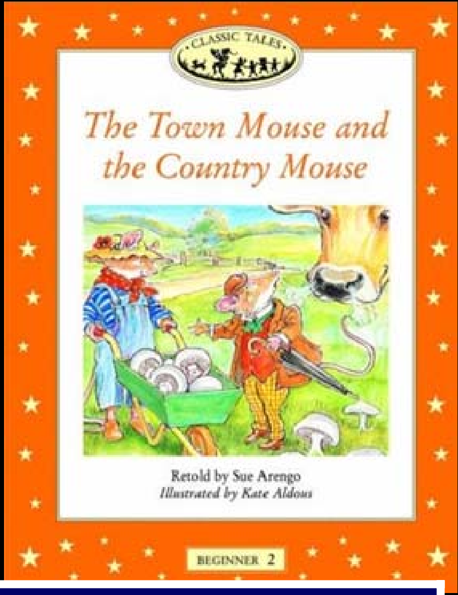
(Dec. 19, 2006@NAOJ, Michael Strauss)

ADS High-Impact Papers 2006

Facility	Number of Citations	Fraction of the Total
SDSS	1843	17.4%
ESO	1365	12.9%
HST	1124	10.6%
WMAP	1121	10.6%
Keck	642	6.0%
Kamiokande	372	3.5%
Chandra	365	3.4%
ACBAR	207	2.0%
NOAO (KPNO/CTIO)	202	1.9%
Las Campanas	176	1.7%

(Dec. 19, 2006@NAOJ, Michael Strauss)

The town mouse and the country mouse (都会のねずみと田舎のねずみ)



Town mouse ?	Country mouse ?
Large Hadron Collider	Subaru telescope
Tristan	Kamiokande
particle theorists	astronomers
dark energy cosmology	extrasolar planet
Subaru (8.2m)	HATnet (11cmx6)

So, what's next ?

- Precision cosmology, not yet ?
  - We have to move on; determine all the cosmological parameters within 0.1% accuracy, for instance.
  - For what ? Really interesting ? Can convince taxpayers ?
- Beyond ***precision*** cosmology ?
  - Stop playing with the *values of parameters*, but try to understand *their meaning*, i.e., matter context in the universe
    - Nature of dark matter and dark energy
    - First objects in the universe
    - initial conditions (physical model of inflation)...
  - Revisit the cosmological observations in a more general framework
    - Equation of state of the universe
    - Validity of the cosmological principle
    - Validity of general relativity on cosmological scales
- Or simply ***beyond cosmology*** itself !
  - Anthropic principle, Extrasolar planet, ...something else