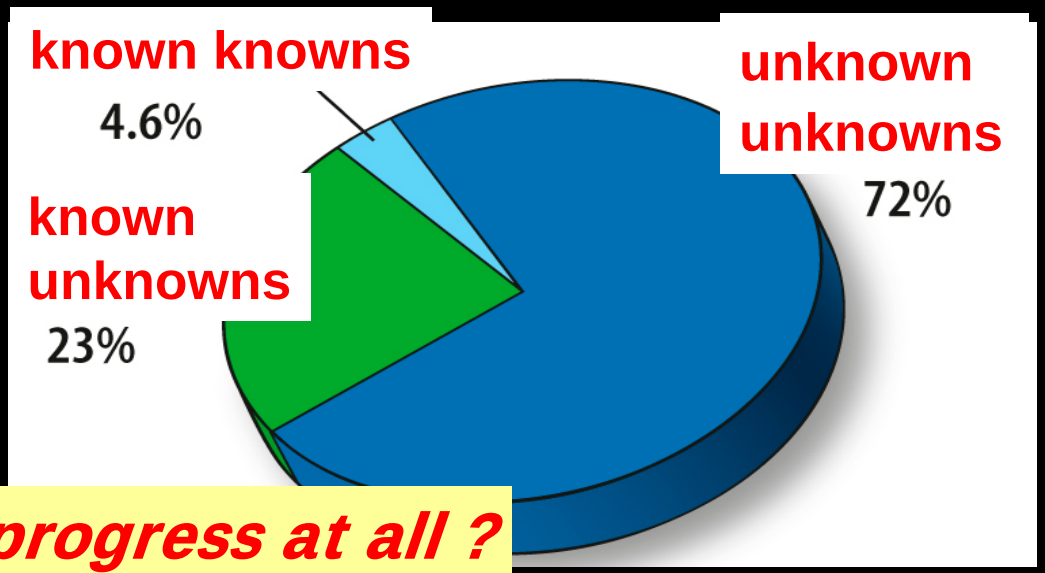
Unknowns and unknown unknowns: *from dark sky to dark matter and dark energy*



Did we make progress at all ?

Yasushi Suto *Dept. of Phys., The University of Tokyo*

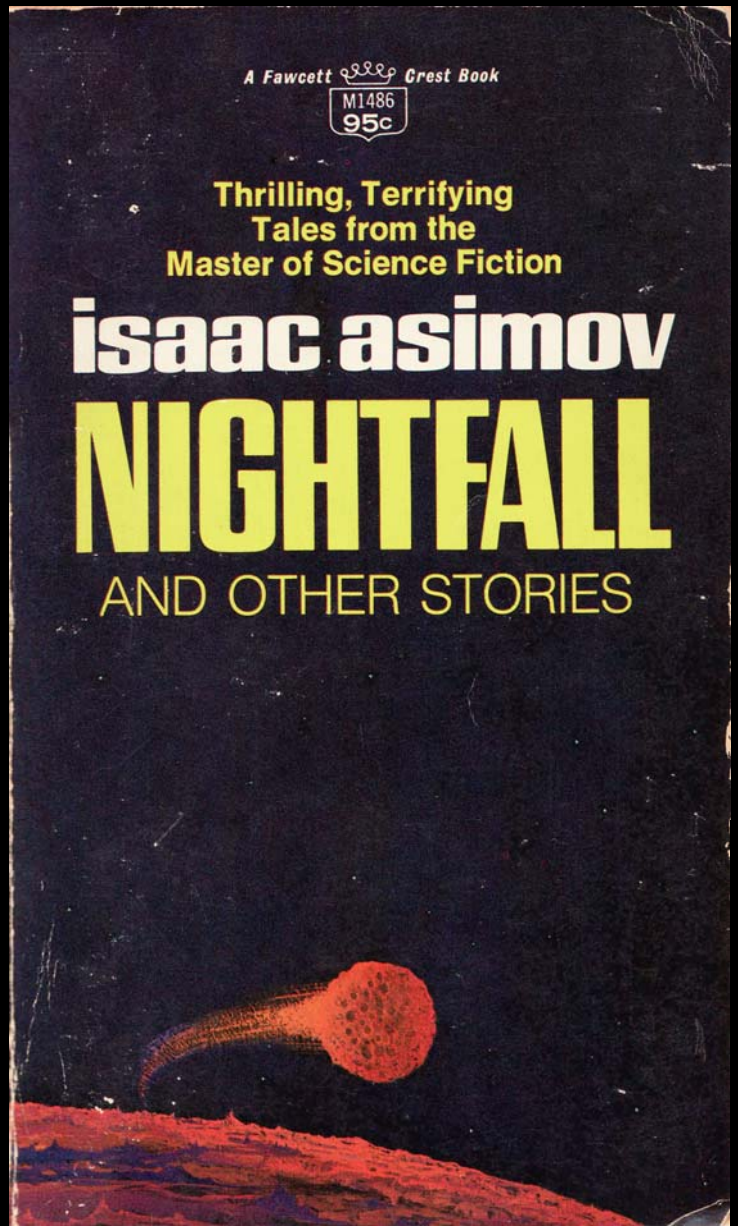
& Global Scholar, Dept. of Astrophys. Sci., Princeton University

SPIE Astronomical Instrumentation "Observational frontiers of astronomy for the new decade", June 28, 2010
@Town and country resort & convention center, San Diego

“Darkness” is key to understanding our “world”

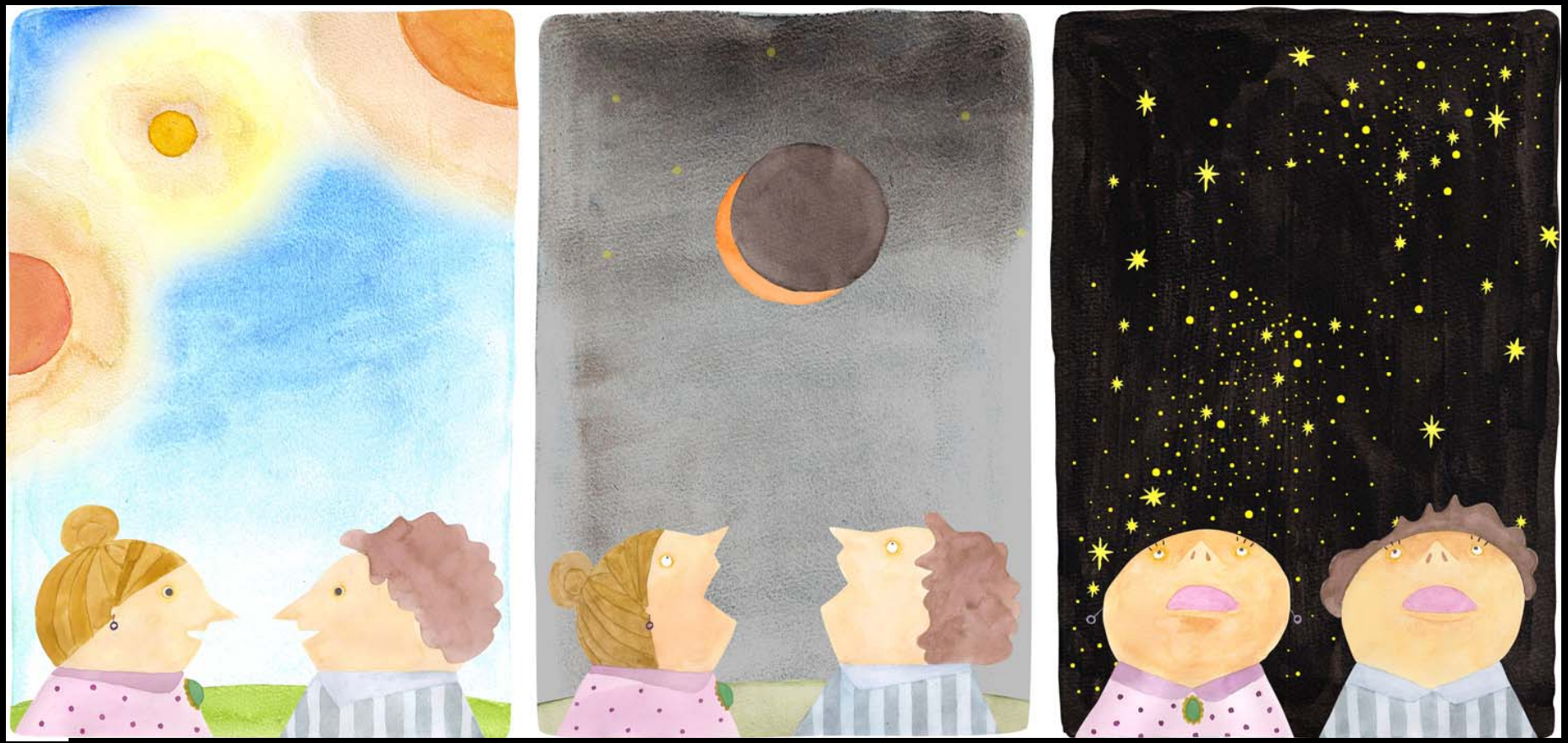
- philosophy, astronomy, and therefore physics started from “thinking in the dark” in the ancient era
- Should still apply now
  - Another element: dark matter, dark energy
  - Another Earth: exoplanet
  - Another life: extra-terrestrial intelligence

Issac Asimov: Nightfall



- "Light !" he screamed. Aton, somewhere, was crying, whimpering horribly like a terribly frightened child. *"Stars -- all the Stars -- we didn't know at all. We didn't know anything."*

Nightfall: We didn’t know anything



(Alisa Haba)

- no “night” except the total eclipse due to another planet every 2049 years on a planet “Lagash”
- People realized the true world for the first time through the darkness full of “stars”

(Yet another) goal of science ?

- To answer the (known) fundamental questions
  - Maybe, yes…
- It is equally, or even more, important *to discover unknown fundamental questions, or to recognize that we didn't understand anything*
- 学問 (Gaku Mon): Japanese/Chinese word
  - No good counterpart in English (academia ? Learning ?)
  - 学 (Gaku) is to learn, and 問 (Mon) is to ask
  - Indeed you can ask questions only after you learn something seriously. Mere learning does not bring any progress without asking something later.


A famous Japanese philosopher
Gundam at Subaru telescope

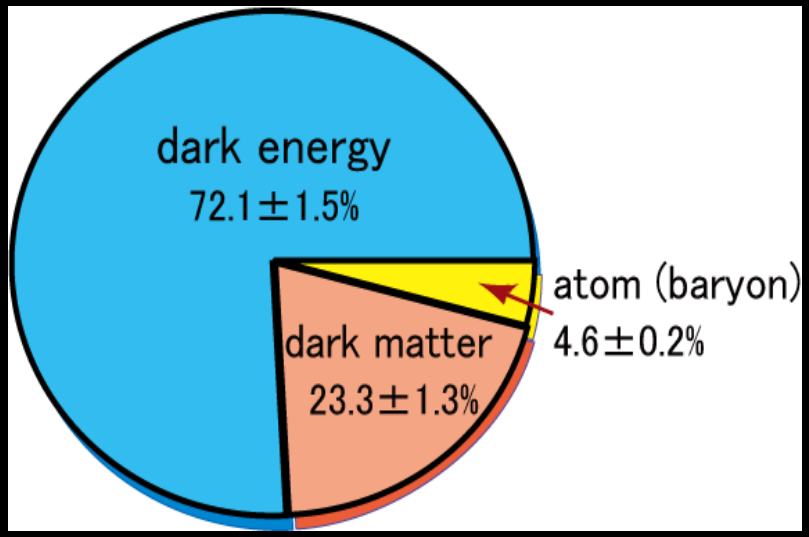
a famous American philosopher and poet: D.H.Rumsfeld

The Unknown

As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know.

—Feb. 12, 2002, Department of Defense news briefing

Composition of the universe



atom (baryons)

- ordinary matter makes up merely 5 percent

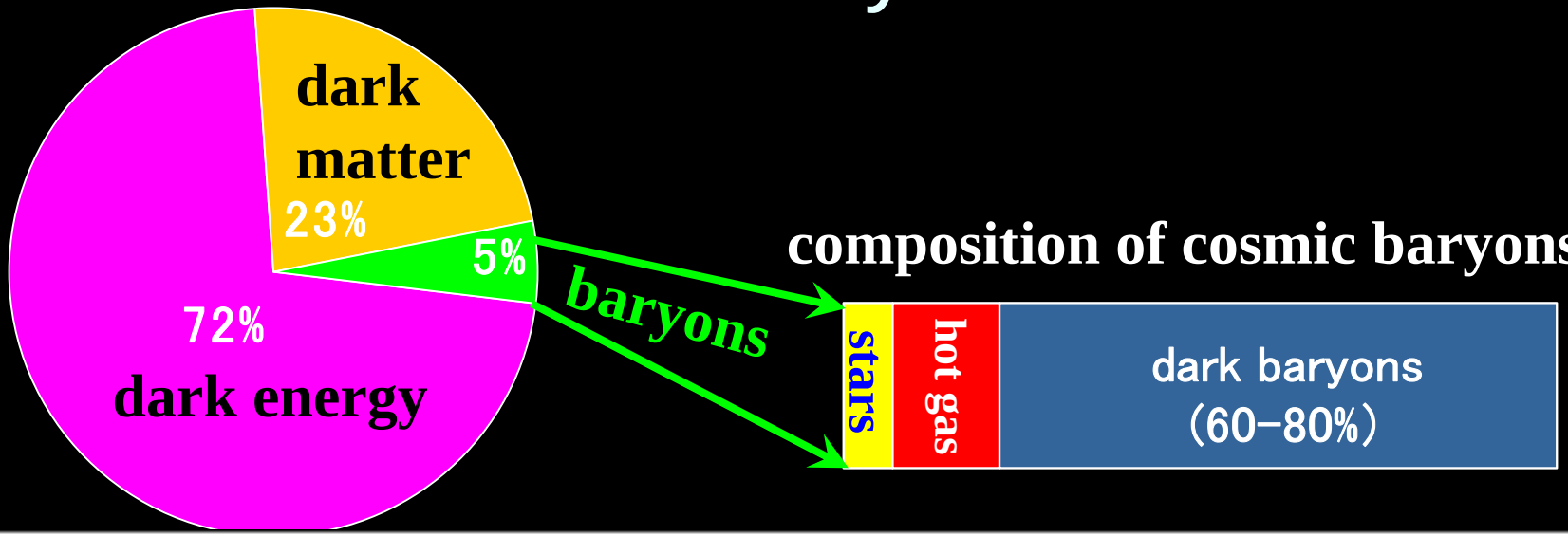
dark matter

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

dark energy

- even more exotic component !
- homogeneously fills the universe (unclustered?)
- repulsive force (negative pressure; $P = -\rho$?)
- Einstein's cosmological constant ?
- or just an illusion ...

Most of the cosmic baryon is “dark” as well

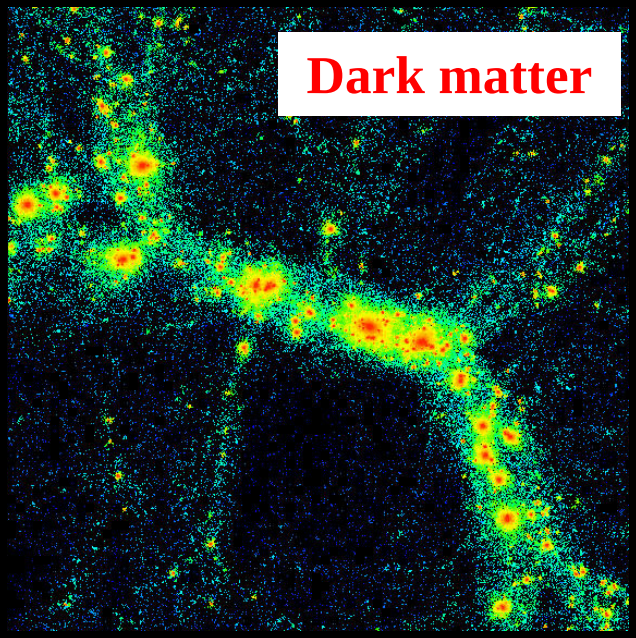


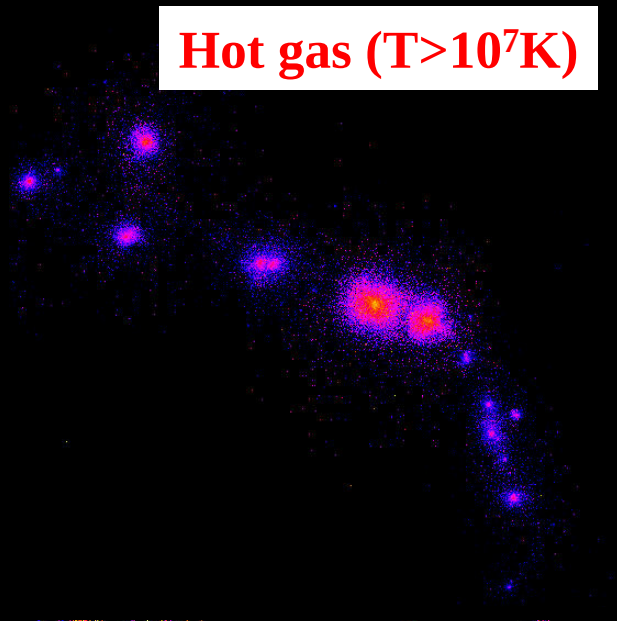
Component	Central	Maximum	Minimum	Grade[a]
Cosmic Baryon Budget: Fukugita, Hogan & Peebles: ApJ 503 (1998) 518				
1. Stars in spheroids	$0.0026\ h_{70}^{-1}$	$0.0043\ h_{70}^{-1}$	$0.0014\ h_{70}^{-1}$	A
2. Stars in disks	$0.00086\ h_{70}^{-1}$	$0.00129\ h_{70}^{-1}$	$0.00051\ h_{70}^{-1}$	A–
3. Stars in irregulars	$0.000069\ h_{70}^{-1}$	$0.000116\ h_{70}^{-1}$	$0.000033\ h_{70}^{-1}$	B
4. Neutral atomic gas	$0.00033\ h_{70}^{-1}$	$0.00041\ h_{70}^{-1}$	$0.00025\ h_{70}^{-1}$	A
5. Molecular gas	$0.00030\ h_{70}^{-1}$	$0.00037\ h_{70}^{-1}$	$0.00023\ h_{70}^{-1}$	A–
6. Plasma in clusters	$0.0026\ h_{70}^{-1.5}$	$0.0044\ h_{70}^{-1.5}$	$0.0014\ h_{70}^{-1.5}$	A
7a. Warm plasma in groups	$0.0056\ h_{70}^{-1.5}$	$0.0115\ h_{70}^{-1.5}$	$0.0029\ h_{70}^{-1.5}$	B
7b. Cool plasma	$0.002\ h_{70}^{-1}$	$0.003\ h_{70}^{-1}$	$0.0007\ h_{70}^{-1}$	C
7′. Plasma in groups	$0.014\ h_{70}^{-1}$	$0.030\ h_{70}^{-1}$	$0.0072\ h_{70}^{-1}$	B
8. Sum (at $h = 70$ and $z \simeq 0$).....	0.021	0.041	0.007	...

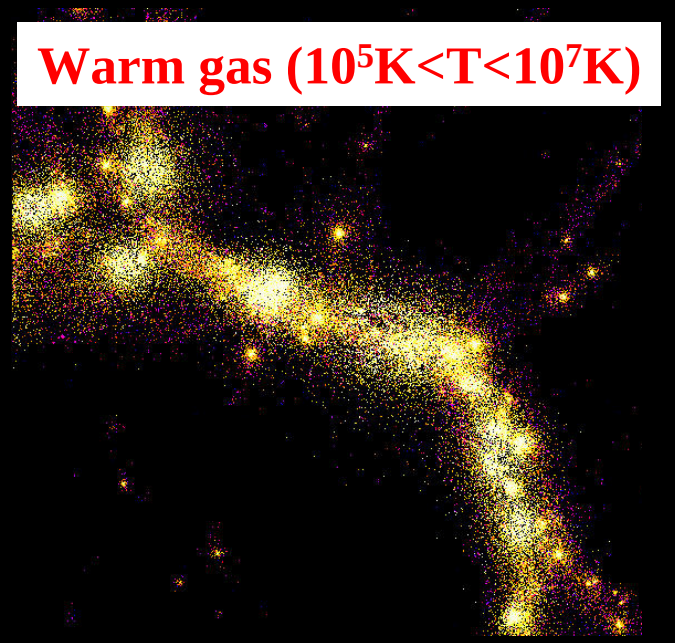
Simulated distribution of matter in the universe

$(30h^{-1}\mathrm{Mpc})^3$ box around a massive cluster at $z=0$

ΛCDM SPH simulation (Yoshikawa, Taruya, Jing & Suto 2001)

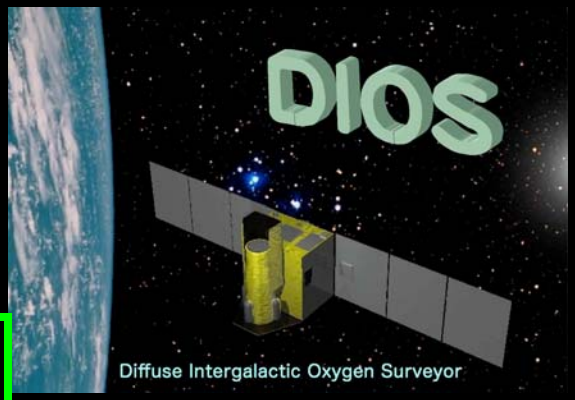






DIOS: Diffuse Intergalactic Oxygen Surveyor

A Japanese proposal of a dedicated X-ray mission for dark baryons (not funded...)

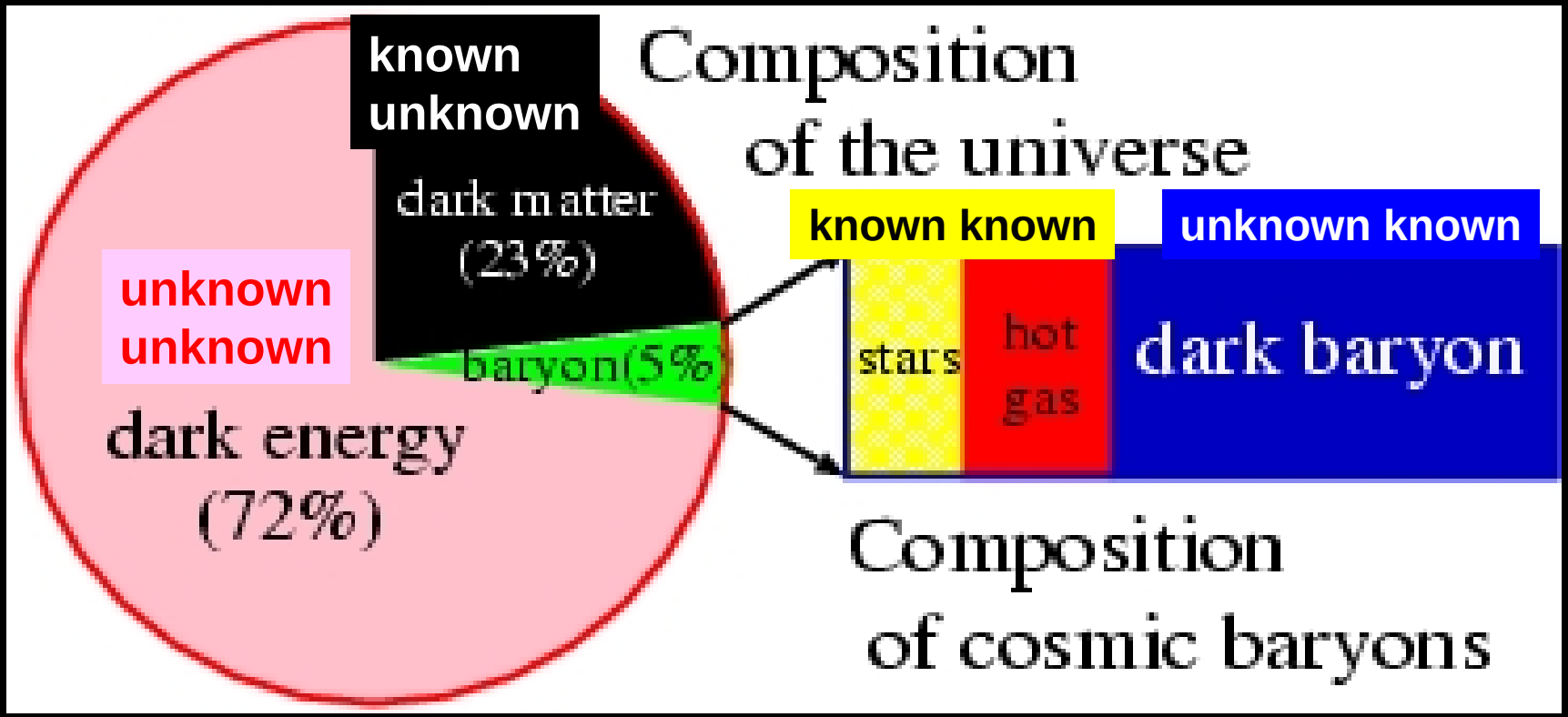


Friday 2 July, 11:20am T.Ohashi (7732-62)

- **PI: Takaya Ohashi** (Tokyo Metropolitan Univ.)
  - + Univ. of Tokyo, JAXA/ISAS, Nagoya Univ., Tokyo Metro. Univ.
- A dedicated small X-ray satellite (< 40M USD)
- Unprecedented energy spectral resolution: **ΔE=2eV in soft X-ray band (0.3-1.5keV)**
- Aim at unambiguous **detection of WHIM via Oxygen emission lines**
- Estimate the dark baryon (WHIM) density contribution to the total cosmic baryon budget

Unknowns and unknown unknowns

- Search for the unknowns in the universe
  - Dark baryons
  - Dark matter
  - Dark energy



Can we unveil the dark sides of the universe soon ?

- **Dark matter**
  - Breakthrough results from on-going accelerators and/or underground experiments in 5-10 years ?
- **Dark baryons**
  - only astronomical observations can make a scientific new contribution
- **Dark energy**
  - unlikely to have any breakthroughs from experiments and/or theories in high energy in this century
  - Astronomy is believed to be the most powerful

Why is dark energy *observable*?

- **Objects are usually identified only through differential measurements**
  - **Visible matter**: contrast between dark and bright regions
  - **Dark matter**: spatial clustering dynamically and gravitationally traced by visible stars, galaxies and quasars
- **Dark energy, if distributed completely homogeneously, can be detected ?**
  - **differential measurements in time domain (cosmic acceleration, structure growth)**

Expanding the expanding universe

- *Expand* the "size" of the universe

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

  - current size:

    $a(t_0)$ ⇔ the value itself has no physical meaning

  - current expansion rate: the Hubble constant

$$H_0 \equiv \left.\frac{da/dt}{a}\right|_{t_0}$$

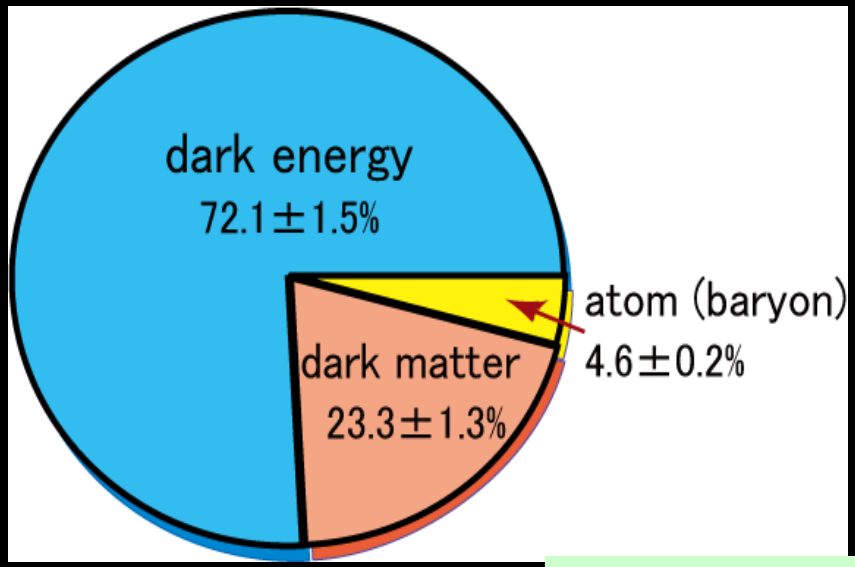
    ⇔ unpredictable: basically determined by the initial condition (can be either negative or positive)

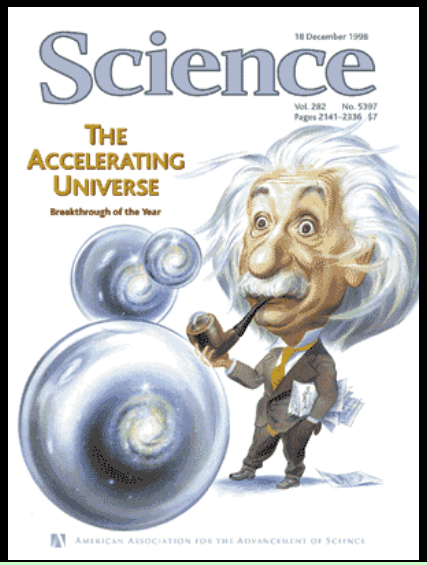
  - current acceleration rate: the deceleration parameter

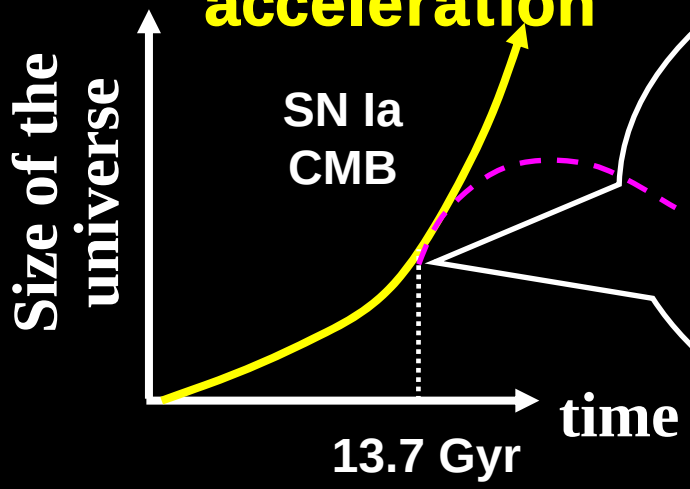
$$q_0 \equiv -\left.\frac{a\, d^2a/dt^2}{(da/dt)^2}\right|_{t_0}$$

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

Cosmic acceleration vs. dark energy







Implies something unknown !

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

Universe should not be accelerated !

- **Newton's inverse square law**

$$\frac{d^2a}{dt^2} = -\frac{GM(<a)}{a^2} = -\frac{G}{a^2}\left(\frac{4\pi}{3}\rho a^3\right) = -\frac{4\pi G}{3}\rho a < 0$$

- **Einstein's general relativity**

$$\frac{d^2a}{dt^2} = -\frac{4\pi G}{3}(\rho + \boxed{3p + \rho_{DE} + 3p_{DE}})a$$

  - Pressure contributes to gravity
  - Negative pressure required for acceleration
    - Cosmological constant: $p_{DE} = -\rho_{DE}$
    - More generally, dark energy: $p_{DE} = w\rho_{DE}$ with $w < -1/3$

- **General relativity is wrong at cosmological scales ? (modified gravity)**

Dark energy and the equation of state of the universe

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

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

w<-1/3 ⇒ repulsion force

w=-1 or not: that is the question

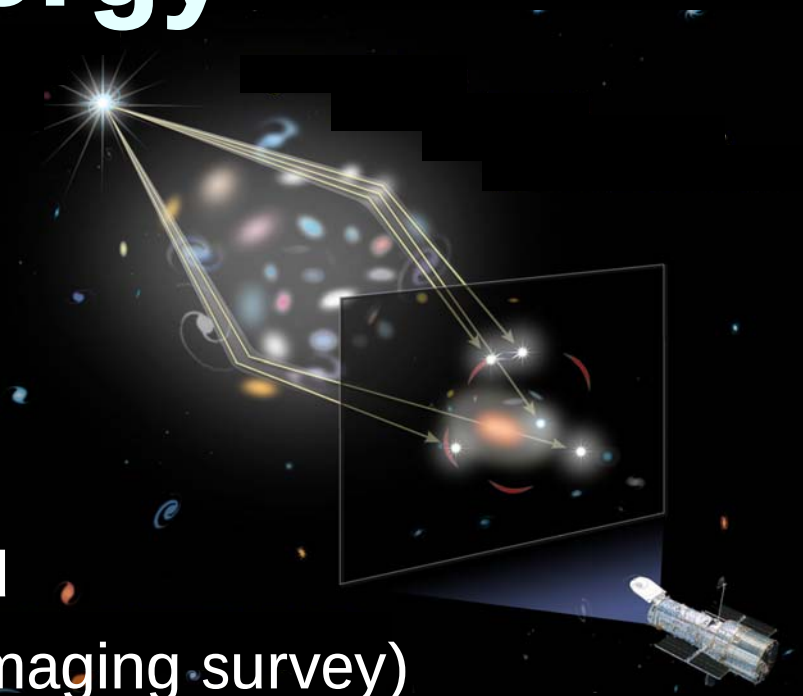
- $p = w\rho$ $(w < -1/3)$
  - Negative pressure: dark energy
  - More generally w may change with time
- conventional but not unique parameterization:

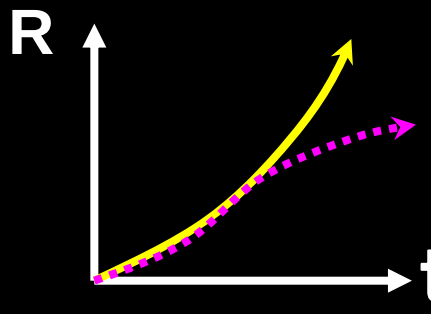
$w(a) = w_0 + w_a(1-a)$ where $a = 1/(1+z)$

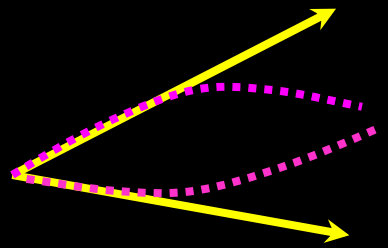
  - $w_0 = -1$ or not ???
  - $w_a = 0$ or not ???
  - $w_0 = -1$ & $w_a = 0$??? (cosmological constant)

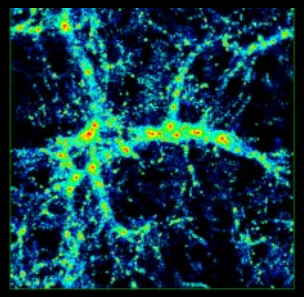
Observational signatures of dark energy

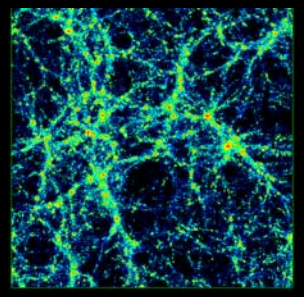
- **cosmic acceleration**
- **geometry of the universe**
- **evolution of structure**
- **4 major probes**
  - Supernova Hubble diagram
  - Cosmic Microwave Background
  - Gravitational lensing (galaxy imaging survey)
  - *Baryon Acoustic Oscillation (galaxy redshift survey)*



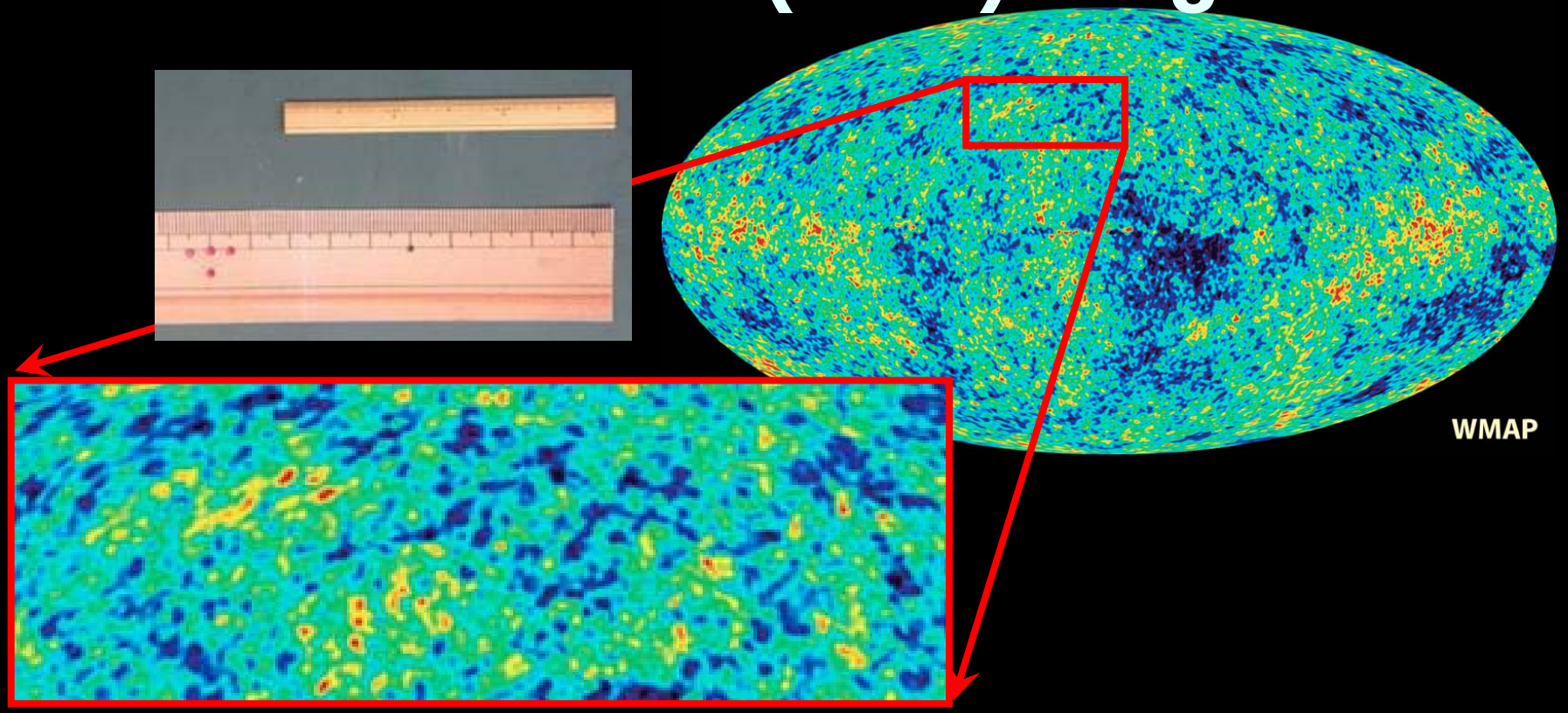








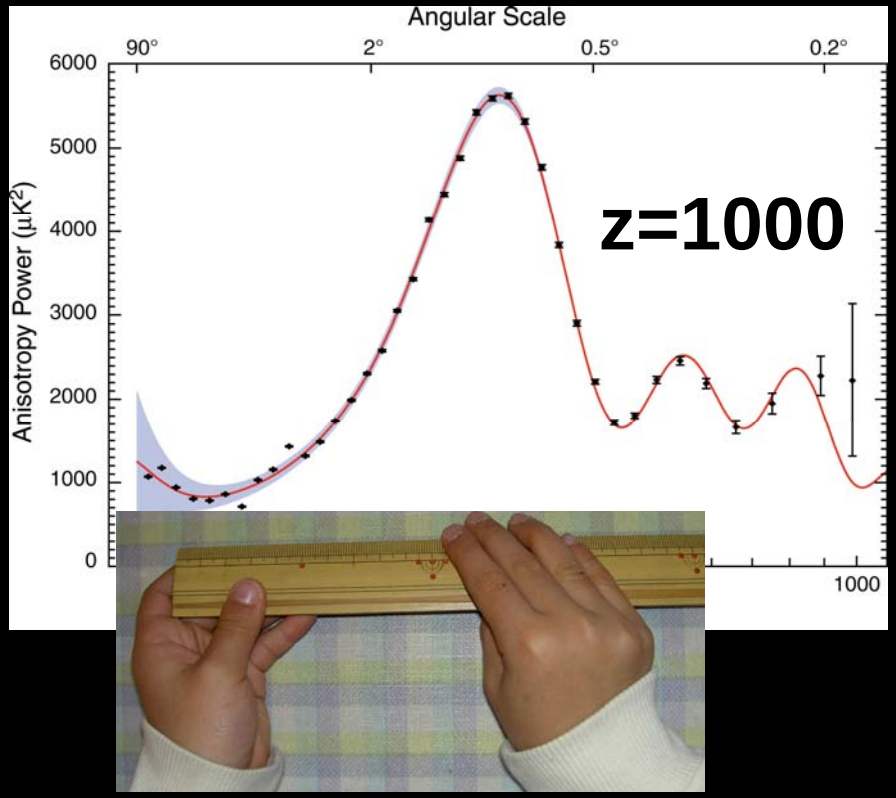
Standard ruler: baryon acoustic oscillation (BAO) length

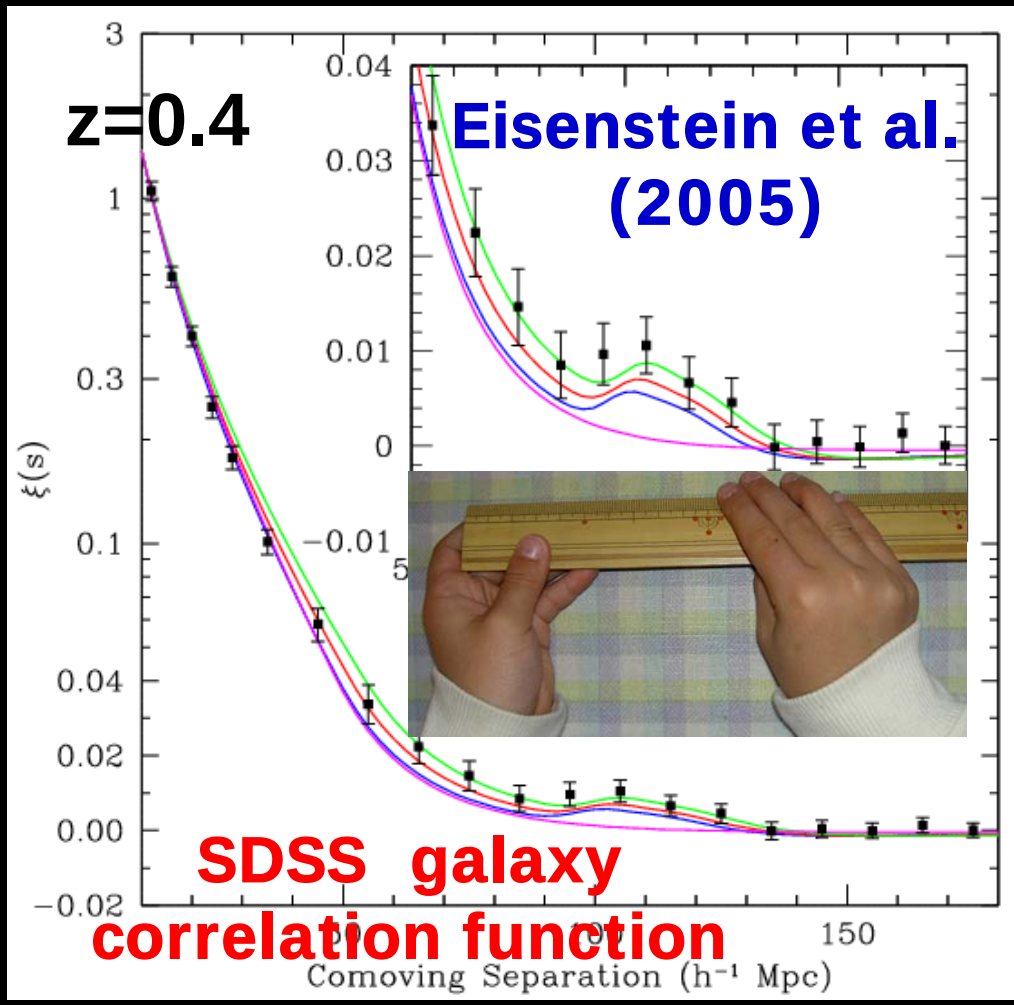


- Sound horizon length at recombination ($\fallingdotseq c_s \times 0.37\mathrm{Myr}$)
  - $r_s = 147\ (\Omega_m\ h^2 / 0.13)^{-0.25}\ (\Omega_b\ h^2 / 0.024)^{-0.08}$ Mpc
- Estimate the distance to the CMB last-scattering surface using the above as a standard ruler

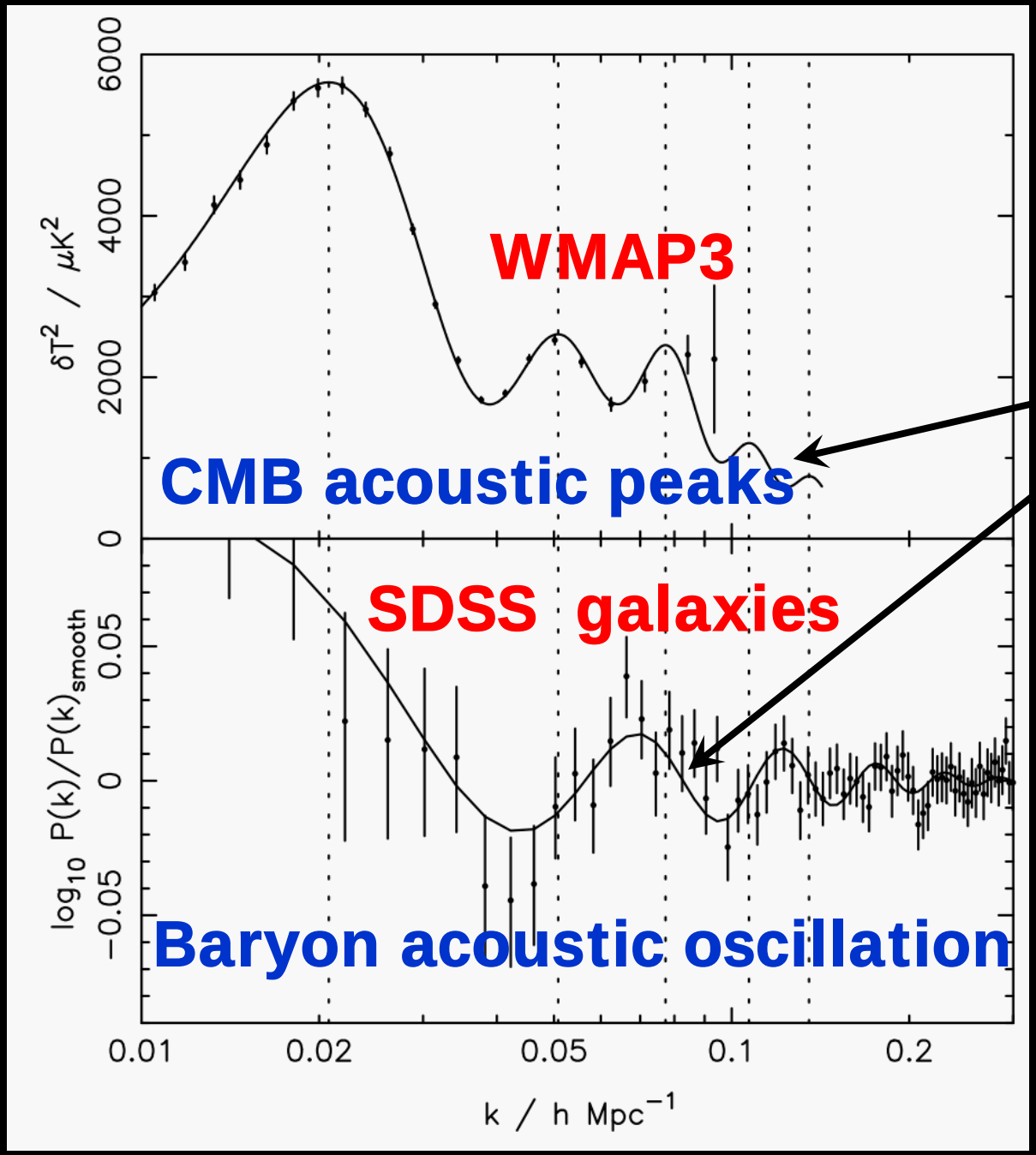
Acoustic oscillations detected

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





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



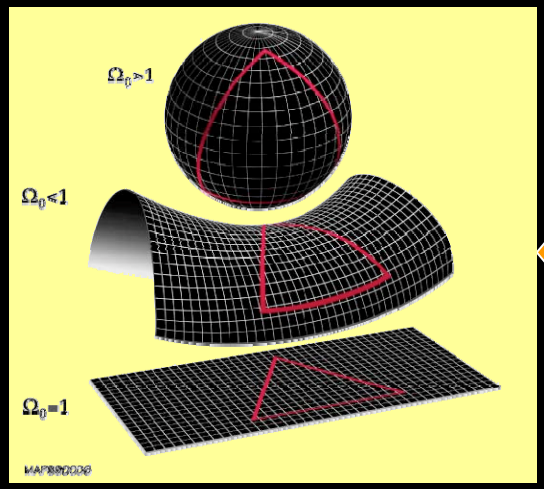
$\Omega_m = 0.24$ best-fit WMAP model

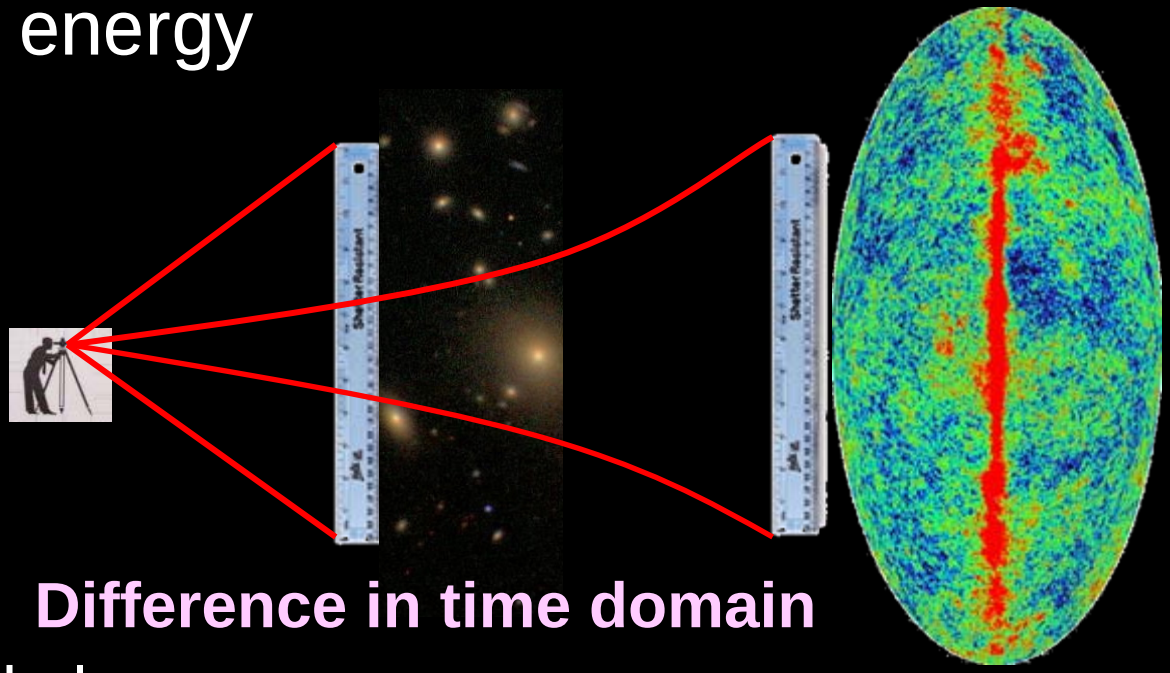
Percival et al. (2007)

Baryon acoustic oscillation (BAO) as a standard ruler

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

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

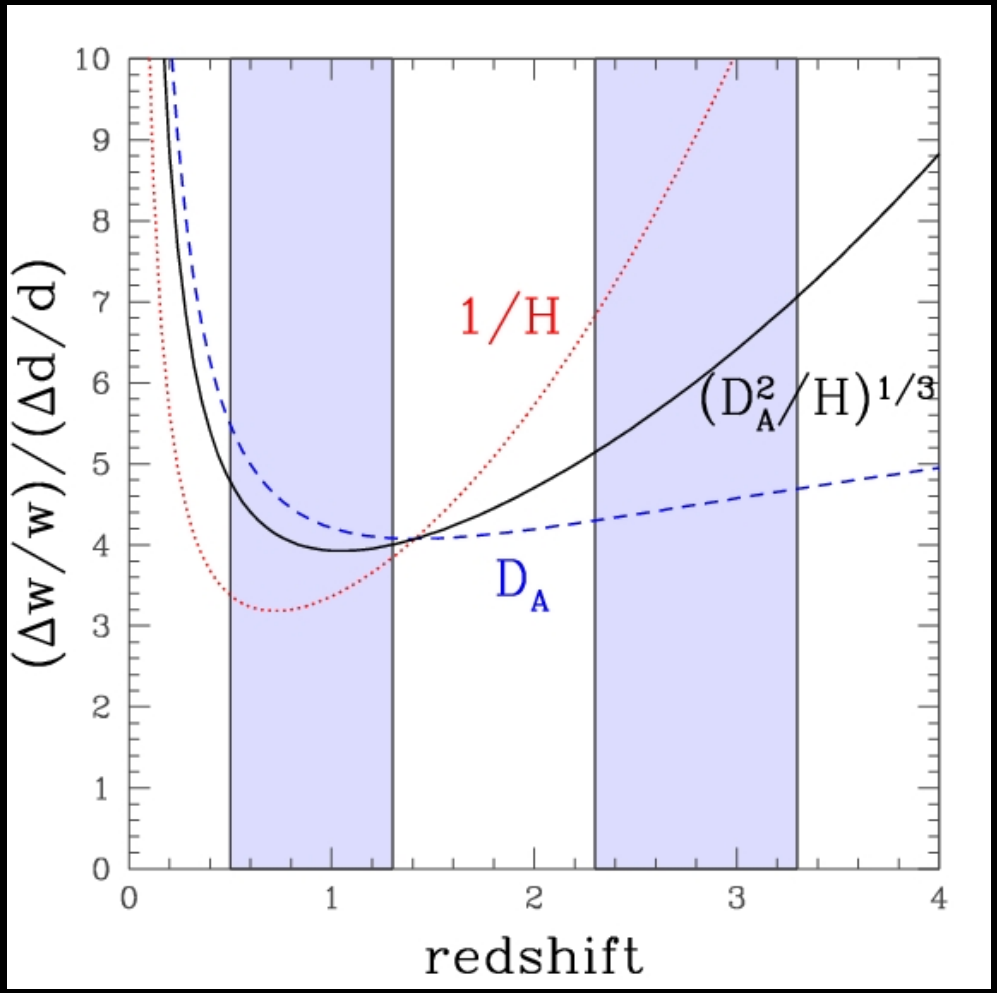




Difference in time domain

Picture credit: Bob Nichol

Required accuracy of the BAO scale measurement to constrain w

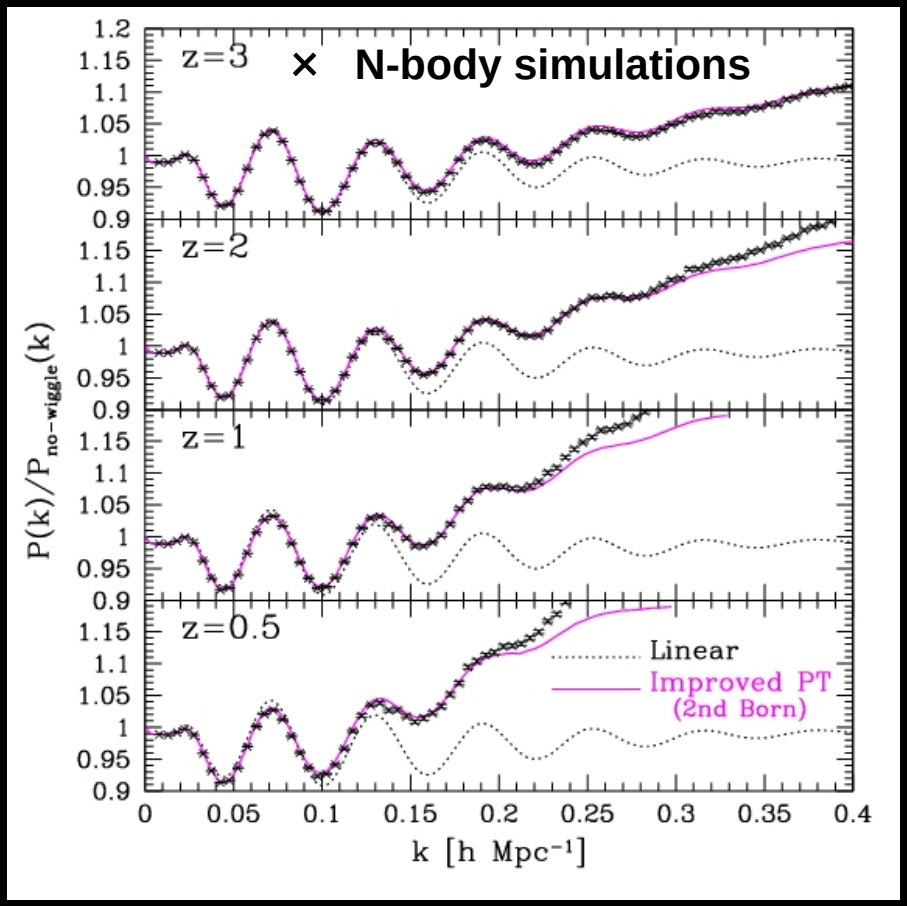


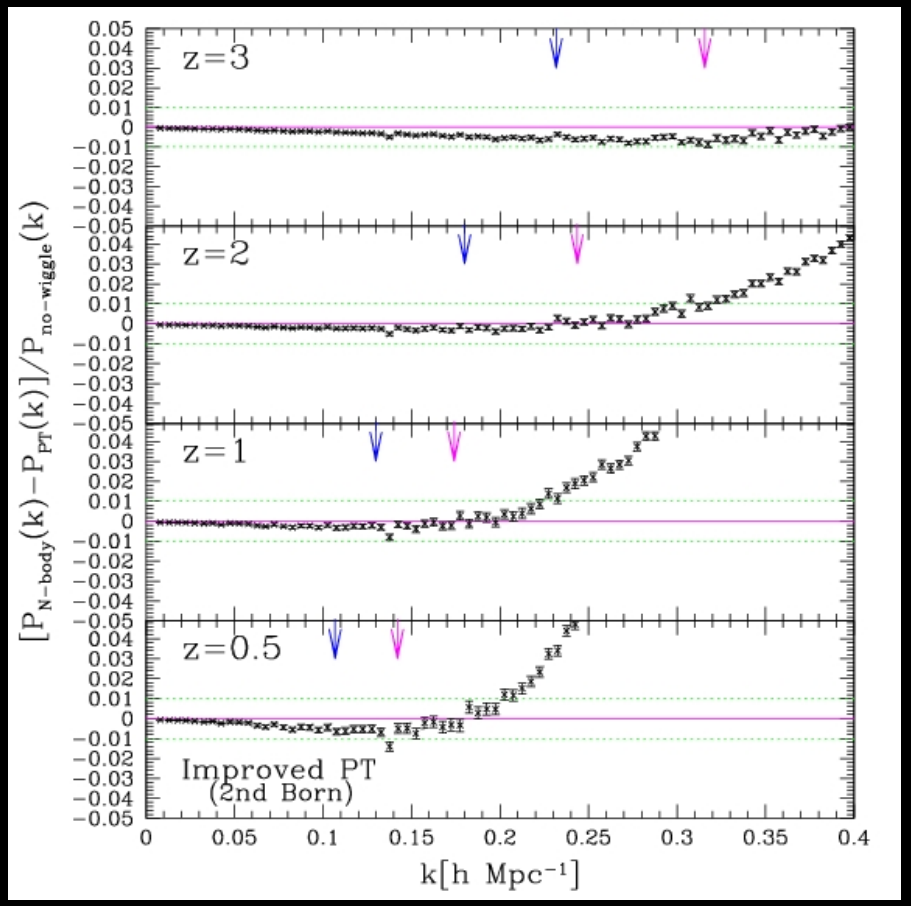
- 3% accuracy of w requires to determine BAO scale at z=1 within <1%

Nishimichi et al. (2007)

Sub-percent level accuracy is demanding even for theoretical template

- Best analytic model of nonlinear gravitational evolution: Taruya et al. (2009)





Future dark energy surveys

- DES: Dark Energy Survey (Fermi Lab+, 2011-?)
  - Imaging galaxy survey
  - 5000 deg^2@Chile 4m telescope
- LSST: Large Synoptic Survey Telescope (SLAC+, 2015-?)
  - Imaging galaxy survey (next talk by Tony Tyson!)
  - 20000 deg^2@Chile 8.4m dedicated telescope
- SuMIRe HSC: Hyper Suprime-Cam (Subaru+, 2012-)
  - Imaging galaxy survey (1.5deg FOV)
  - 1500 deg^2@Subaru 8m telescope
- SuMIRe PFS: Prime Focus Spectrograph (Subaru+???, 2016-???) ex-WFMOS
  - Spectroscopic galaxy survey (1.5deg FOV)
  - 2500 fibers, 10000 galaxy redshifts a night

Galaxy survey project: SuMIRe

***Su*baru *M*easurement of *I*maging and *Re*dshift of the universe**

- PI: Hitoshi Murayama (director of IPMU, U. of Tokyo)
  - Japanese Institutes in charge: IPMU, The University of Tokyo, NAOJ +
- **Imaging survey with HSC** (Hyper-Suprime Cam)
  - Japan + Princeton + ASIAA (Taiwan)
- **Spectroscopic survey with PFS** (Prime Focus Spectrograph)
  - Japan + Various international collaboration scheme is under discussion

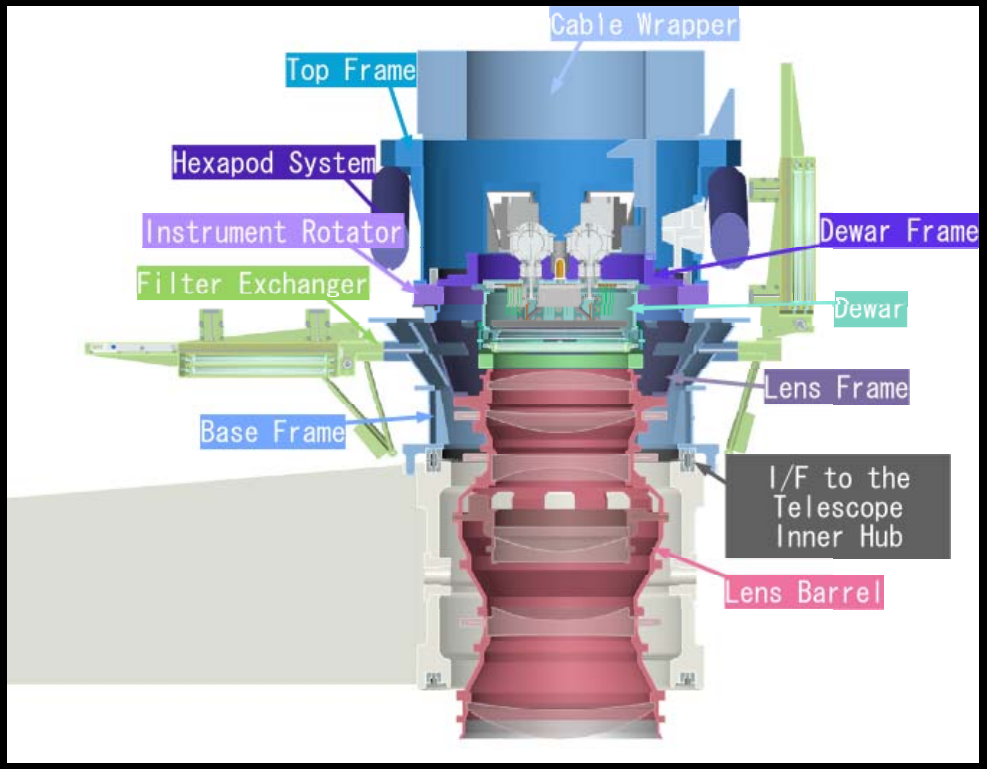
SuMIRe is pronounced as S-me-lé

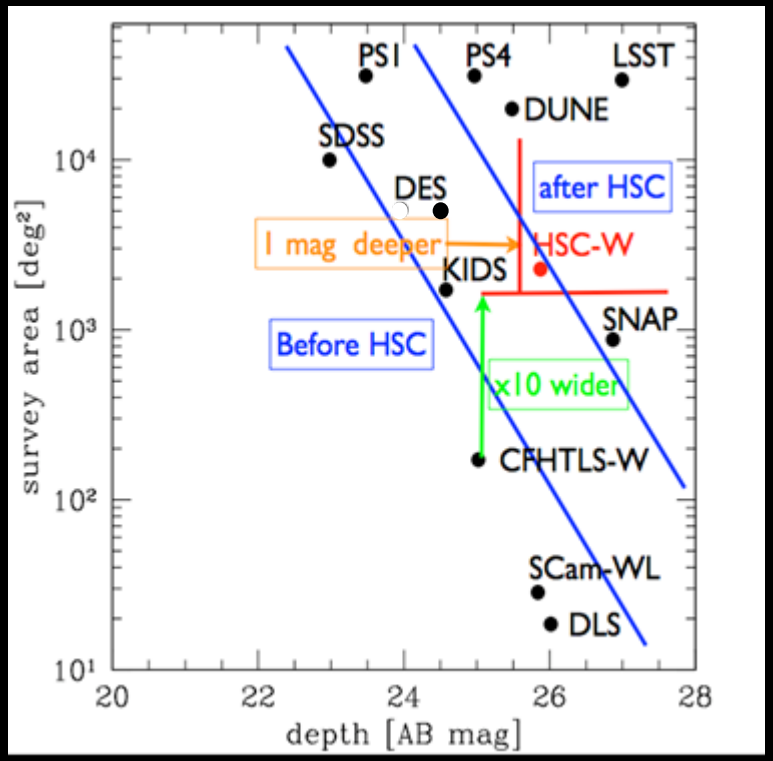
- Don’t pronounce SUMIRE as Smile
  - I = 【i】≠ 【ai】
  - E = 【e】≠ silent
- Don’t care whether R or L
  - “R=L” is the most well-known identity in Japanese

Japanese: Sumire (すみれ)
Chinese: 菫
English: violet (more specifically, Viola mandshurica)

HSC: Hyper-Suprime Cam

- **Japan+Princeton+ASIAA (2012-2016)**
  - Imaging galaxy survey (1.5deg FOV) g,r,i,z,Y
  - 200 nights for 1500 deg^2 wide survey for weak lensing
  - 100 nights for deep surveys of galaxies

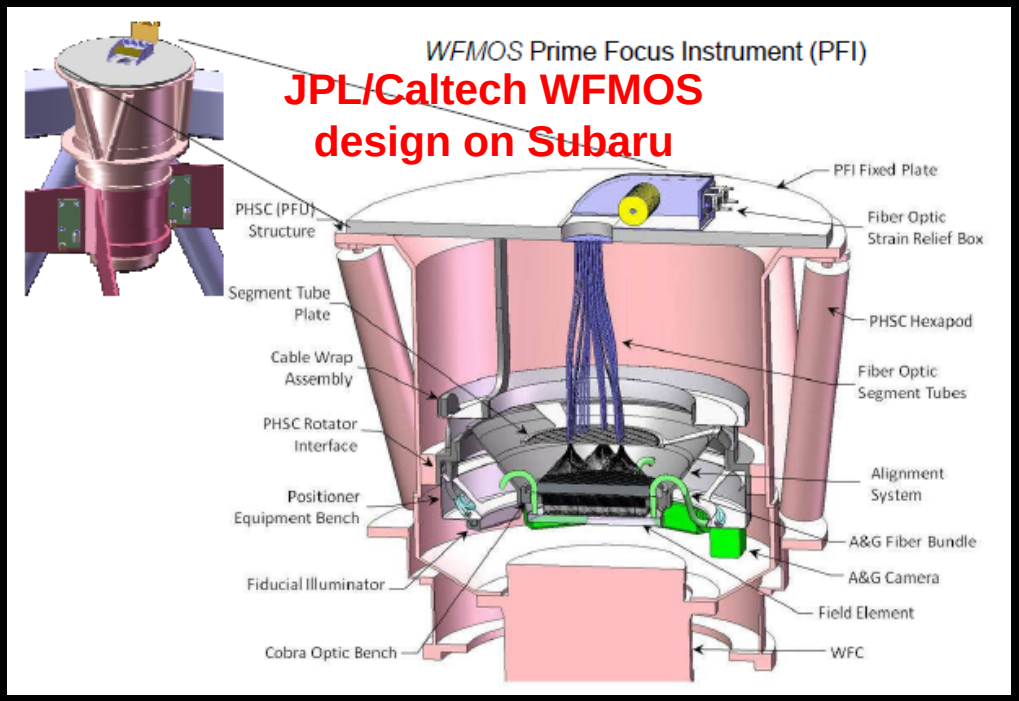




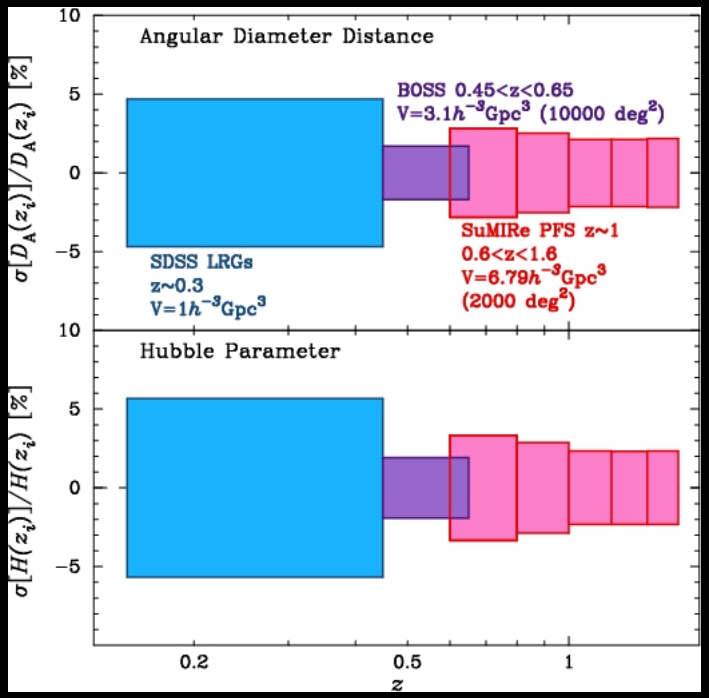
Presented at DENET-Princeton conference (2009) by Satoshi Miyazaki (NAOJ)

PFS: Prime Focus Spectrograph

- **Japan+??? (2016-2020 ???), ex-WFMOS**
  - Spectroscopic galaxy survey (1.3deg FOV)
  - 2500 fibers, 10000 galaxy redshifts a night
  - BAO, galactic evolution, Galactic archaeology



presented at DENET summer school (2009)
by Mike Seiffert (JPL/Caltech)



Courtesy of
Masahiro Takada (IPMU)

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


what dominates our world

S&G emphasized the importance of darkness 45 years ago !

- Dark energy is supposed to be “here and there, everywhere” in the universe
  - Subaru telescope is trying to take pictures of darkness
- A similar philosophical question
  - *Can we record the sound of silence ?*

Hello darkness, my old friend
I’ve come to talk with you again
(The Sound of Silence 1965)

Just before the end of the last century, we thought we knew almost everything...

Seldner, Siebers, Groth, and Peebles, 1977, AJ, 82, 249.

Hopefully soon, we will recognize that we didn't know anything

Hello darkness, my old friend
I've come to talk with you again