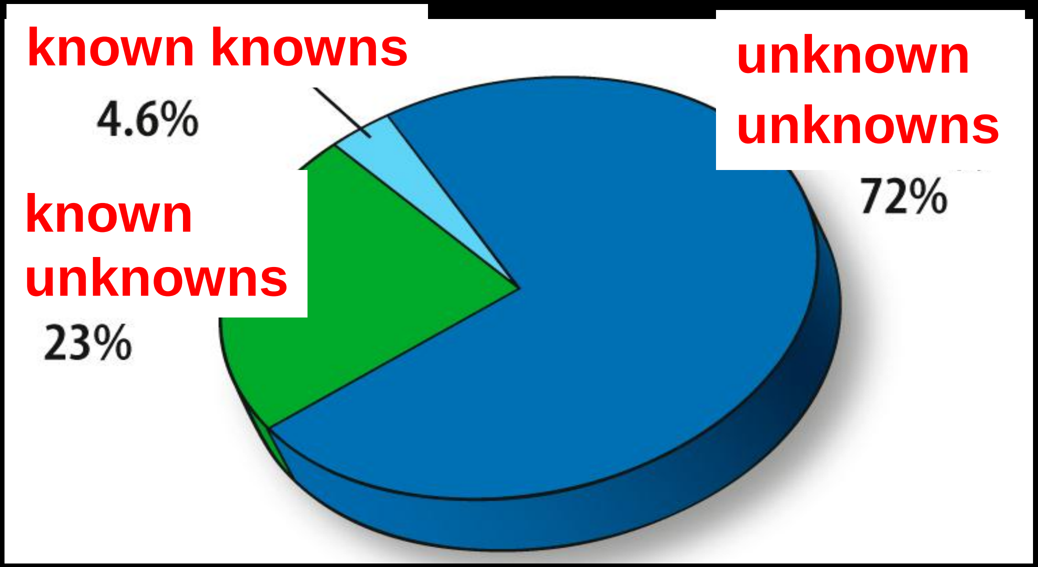
Known unknowns and unknown unknowns: *astronomy vs. physics*



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

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

XVI International Symposium of Multiparticle Dynamics (ISMD) 2011

September 28, 2011

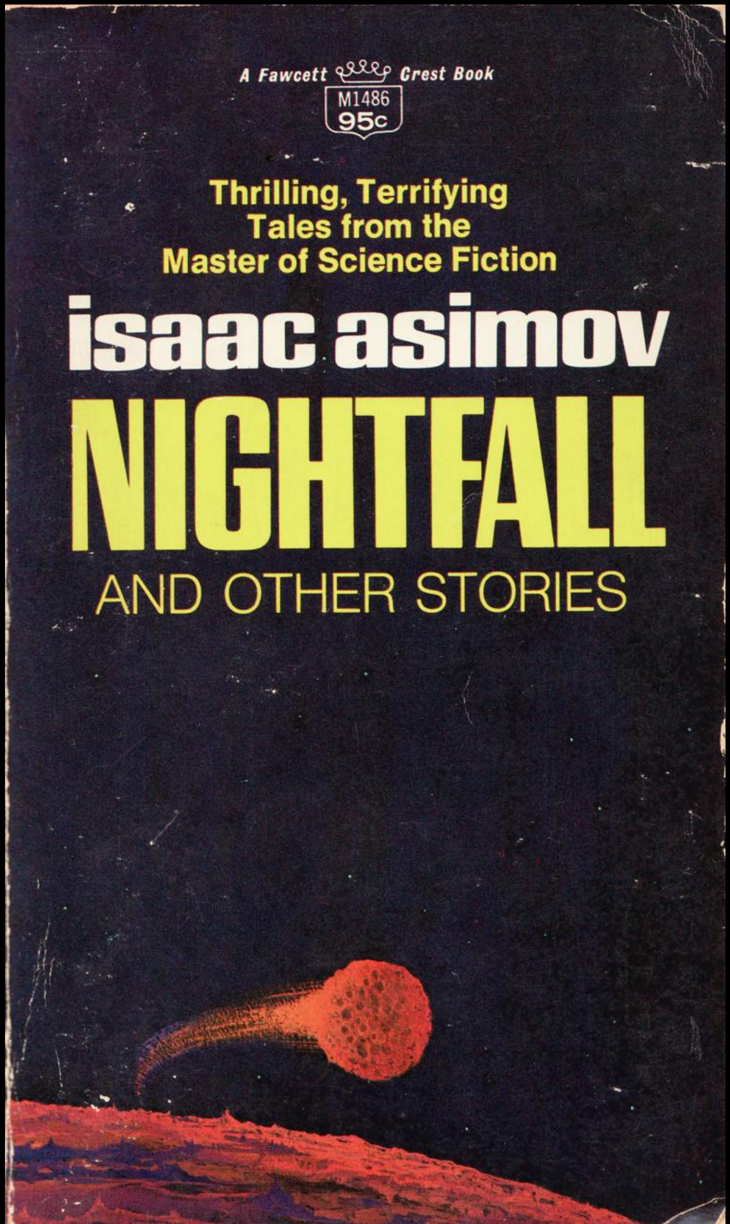
@Miyajima Morinoyado Inn, Hiroshima, Japan

Nightfall: We didn't know anything

(Alisa Haba)

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

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."*


A famous Japanese philosopher
Gundam at Subaru telescope

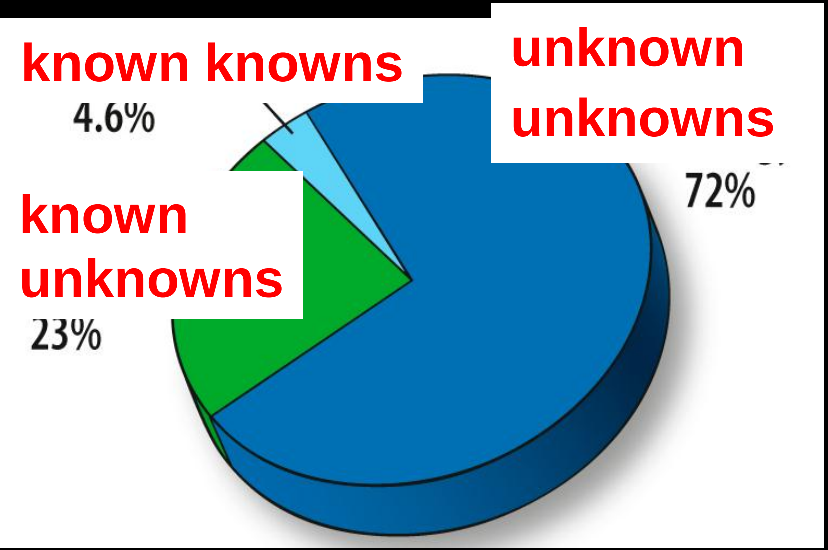
a famous American philosopher and poet: D.H.Rumsfeld

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 un-
knowns,
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 component)
- repulsive force (negative pressure; P=-ρ?)
- Einstein's cosmological constant ?
- or just an illusion …

Dark matter and dark energy: 21^{st} century clouds over the universe?

http://www.physics.gla.ac.uk/Physics3/Kelvin_online/clouds.htm

- Lord Kelvin @ Royal society on April 27, 1900
  - beauty and clearness of theory was overshadowed by two clouds
- Dark matter and dark energy in the 21^{st} century
  - Two dark clouds in astronomy? $\rightarrow$ No !
  - Two probes of new physics? $\rightarrow$ Yes (hopefully)

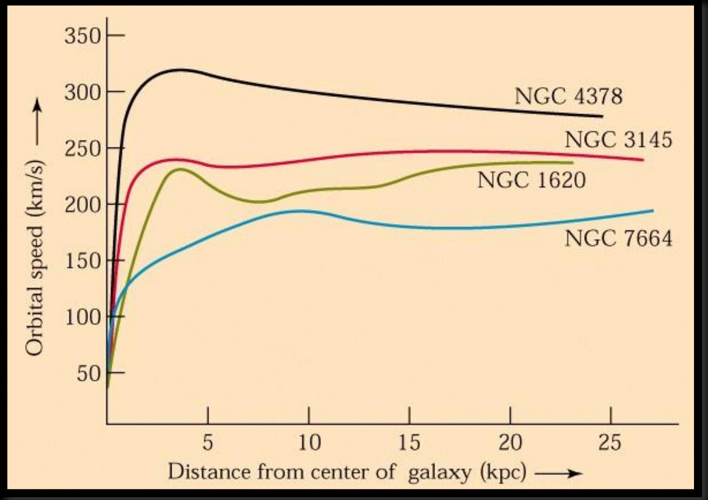
CVs of the two dark clouds

name	dark matter	dark energy
maiden name	missing mass	cosmological constant
year of birth	1933	1917
father	Fritz Zwicky	Albert Einstein
candidates	lightest super-symmetric particle, axion, ALP, WISP	vacuum energy, unknown scalar field, leaks to extra-dimension
weight	23 percent of the universe	72 percent of the universe
character	attractive	repulsive

Dark matter
in the universe

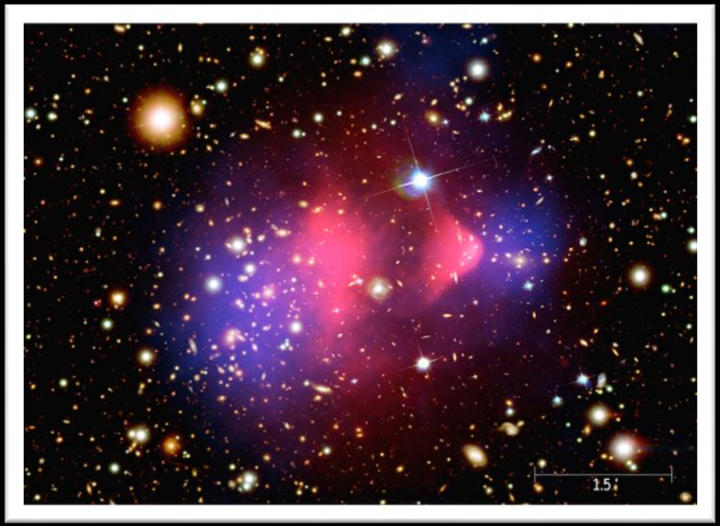
Observational signatures of dark matter

- Flat rotation curves of galaxies

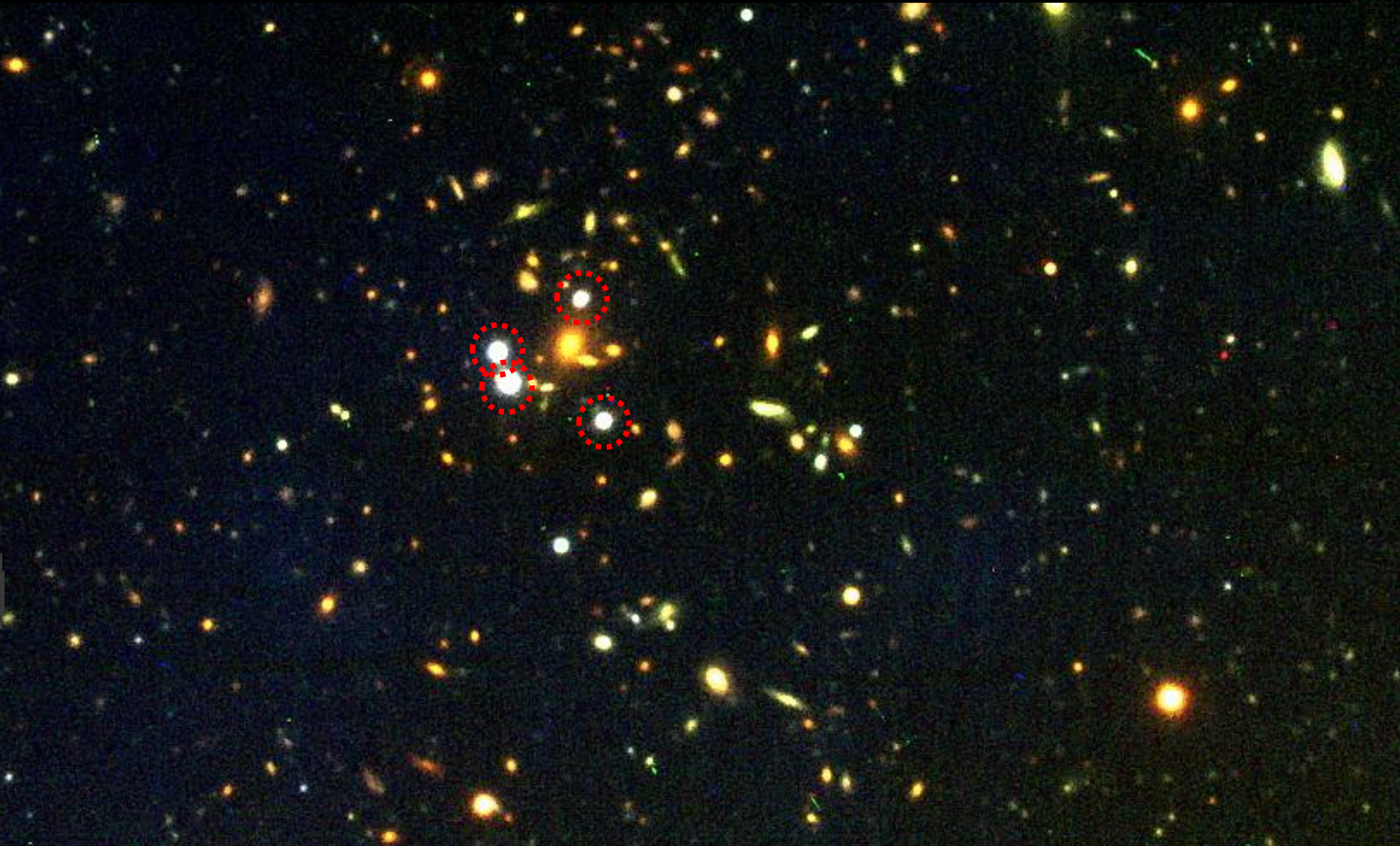


- Multiple images of quasars due to gravitational lensing

- Bullet clusters

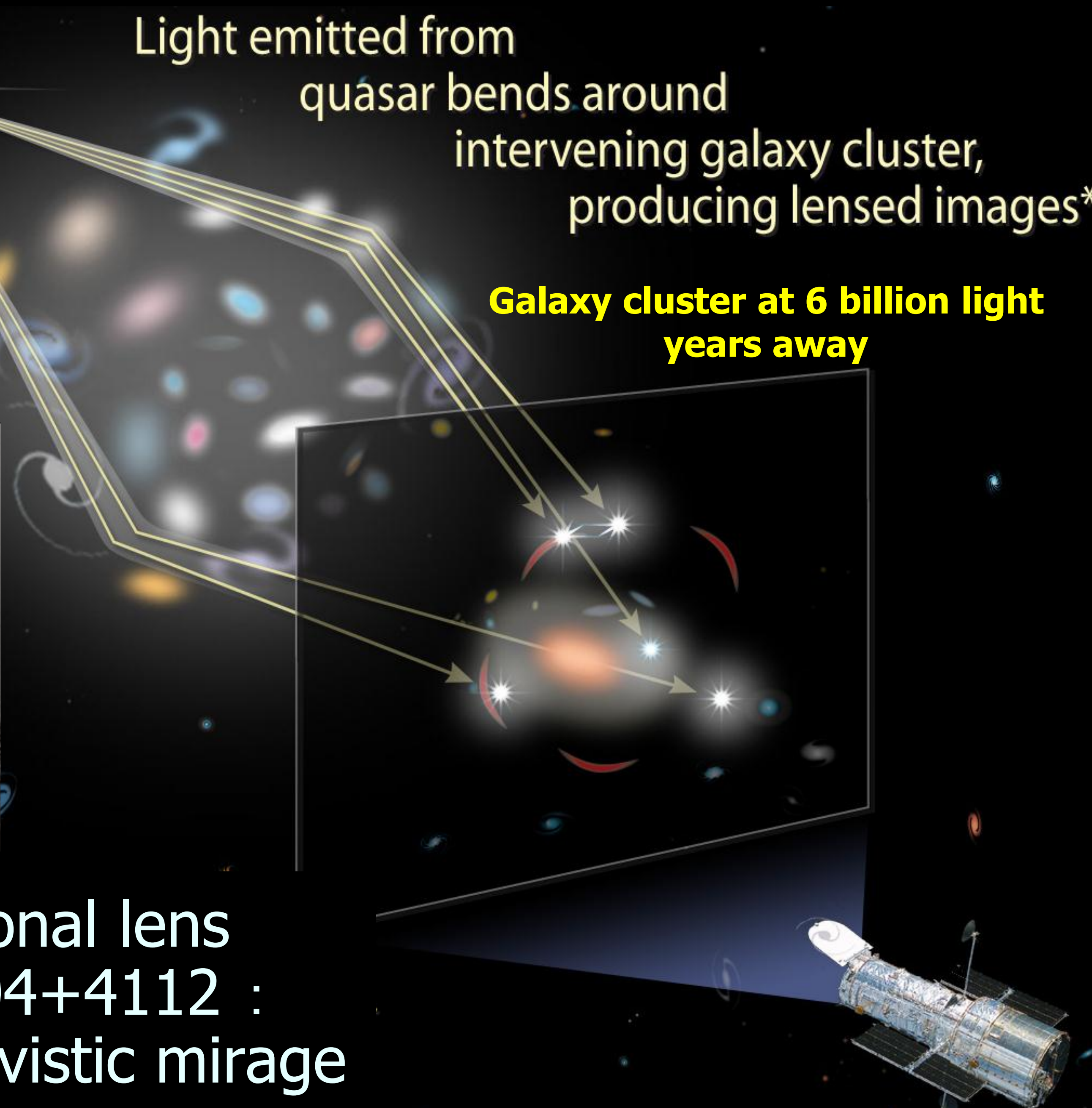


Mirage from the universe 10 billion years ago (SDSS J1004+4112)



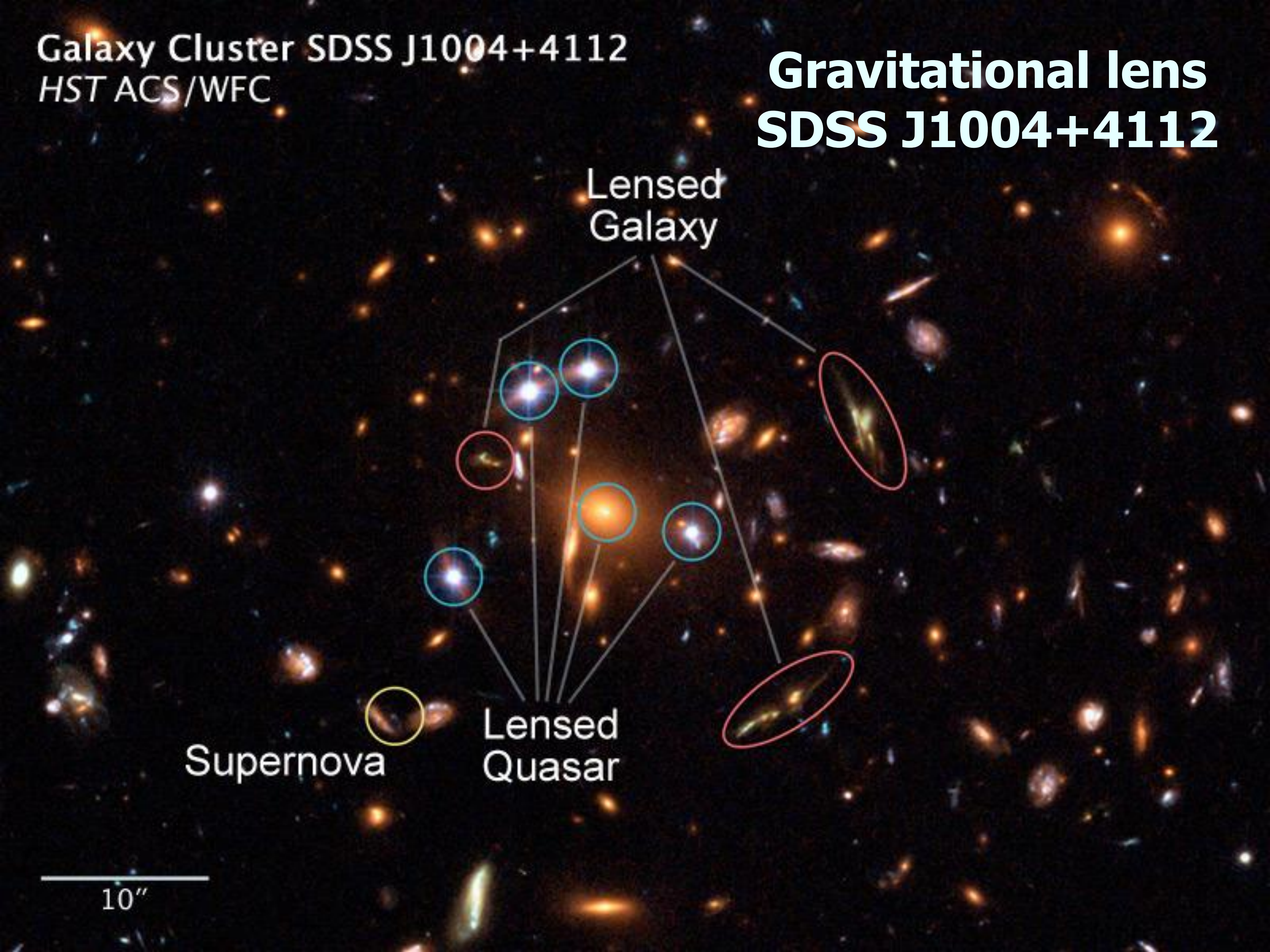
Discovered by N.Inada and M.Oguri at Univ. of Tokyo in 2003 from SDSS images
and then confirmed by Subaru and Keck
Inada et al. Nature 426(2003)810

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



Gravitational lens
SDSS J1004+4112 :
general relativistic mirage

Gravitational lens SDSS J1004+4112

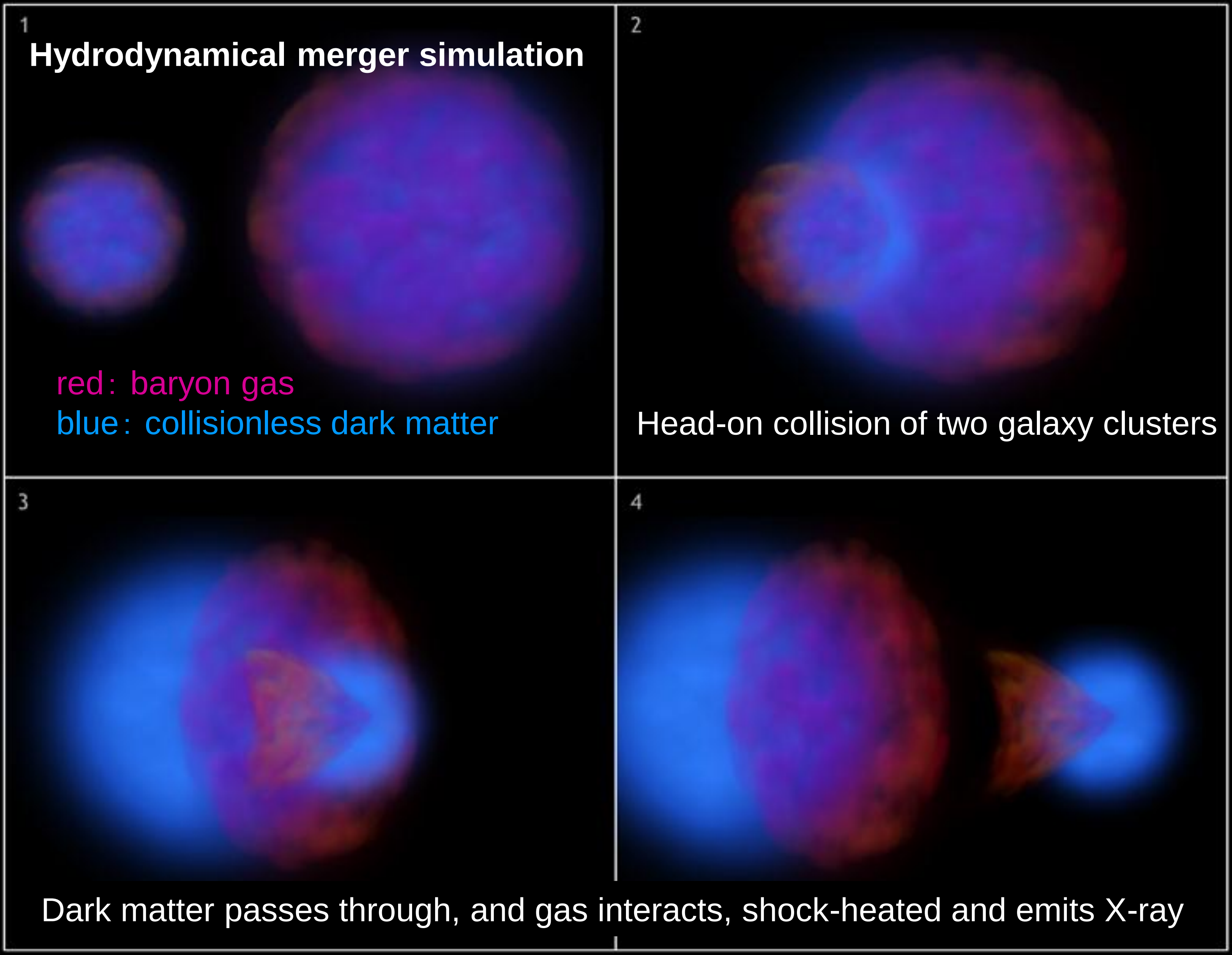


Gravitationally Lensed Quasar in Galaxy Cluster SDSS J1004+4112 *HST* ▪ ACS/WFC

NASA, ESA, K. Sharon (Tel Aviv University) and E. Ofek (Caltech) STScI-PRC05-23

Bullet cluster (1E 0657-56)

Implies *collisionless* dark matter



Dark matter: from astronomy to physics

- **Astronomical observations** unambiguously proved the existence of dark matter
  - *Astronomy does not require any specific form of Lagrangian of dark matter particles*
  - ***From unknown unknowns to known unknowns***
- On-going/up-coming **physics experiments** will identify the elementary particle responsible for dark matter in the universe
  - *Particle physics will specify the Lagrangian*
  - ***From known unknowns to known knowns***

Dark energy
in the universe

Are there any unknown unknowns that distribute homogeneously in the universe ?

- 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
- Is it possible to identify the existence of a homogeneously distributed component ?
  - differential measurements in time domain (cosmic acceleration, structure growth)

Expanding the expanding universe

- *Expand* the "size" of the universe around now

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

  - current size:

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

  - current expansion rate: the Hubble constant

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

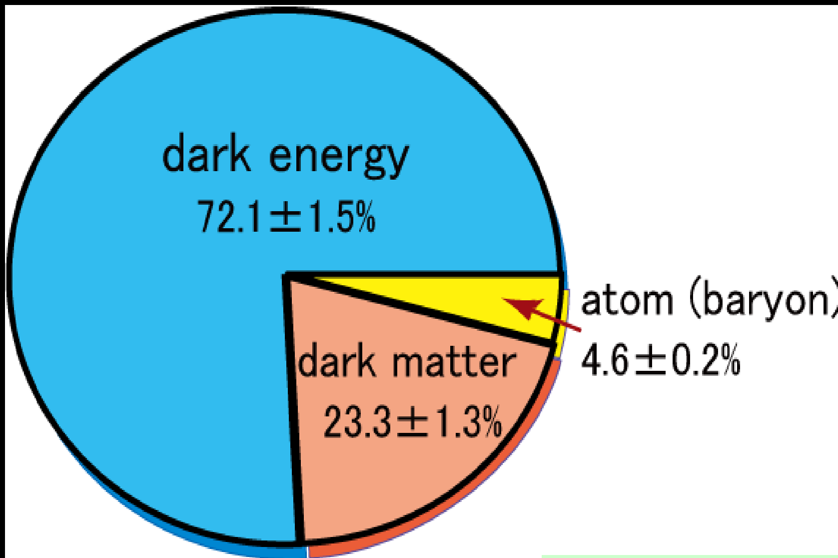
    ⇔ unpredictable: basically determined by the initial condition (can be either negative or positive)

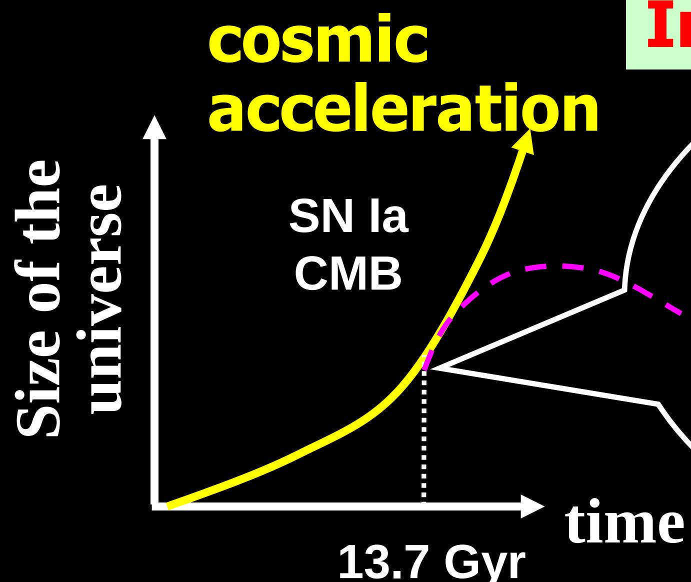
  - current acceleration rate: the deceleration parameter

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

    ⇔ 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 inaccurate at cosmological scales ? (modified gravity theories)**

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 :

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

$w<-1/3 \Rightarrow$ repulsion force

w=-1 or not: that is the question

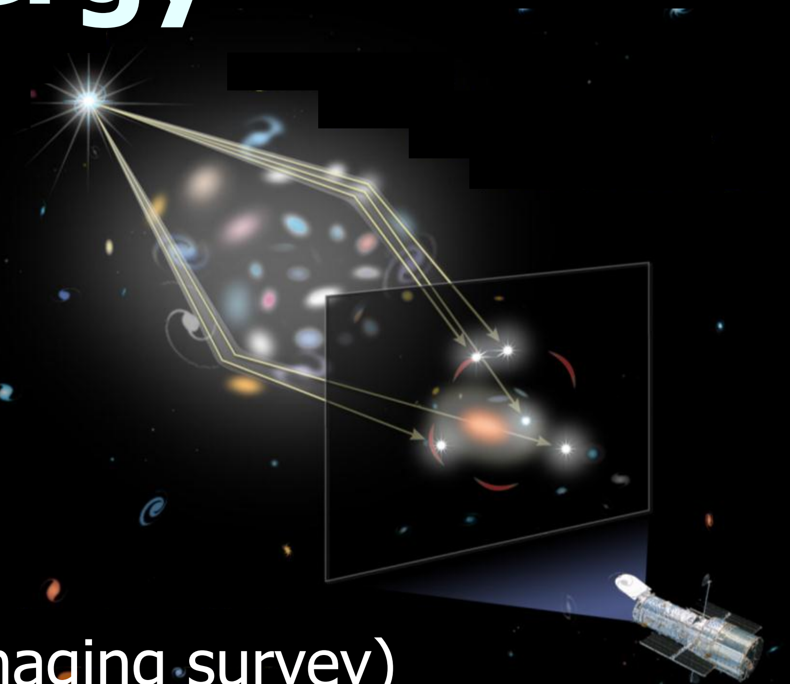
- $p=w\rho$ ($w<-1/3$)
  - Negative pressure: dark energy
  - More generally w may change with time
- conventional but not unique parameterization:

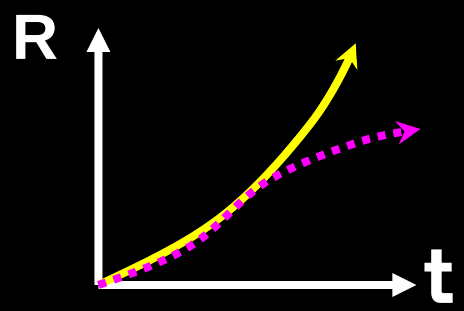
$w(a)= w_0+w_a(1-a)$ where $a=1/(1+z)$

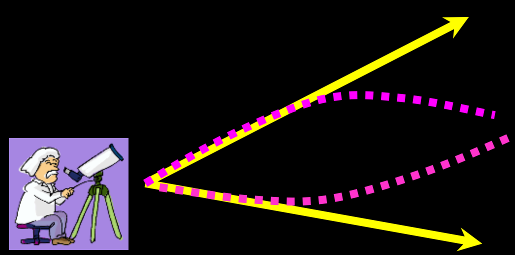
  - $w_0=-1$ or not ???
  - $w_a=0$ or not ???
  - $w_0=-1$ & $w_a=0$??? (cosmological constant)

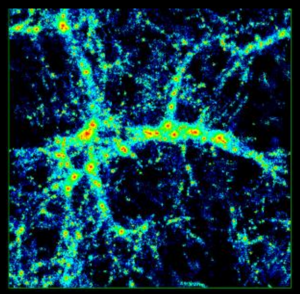
Observational signatures of dark energy

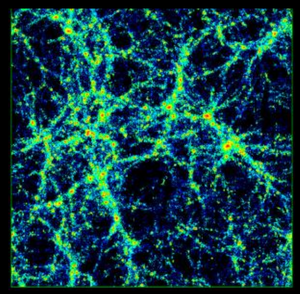
- **cosmic acceleration**
- **geometry of the universe**
- **evolution of structure**
- **4 major probes**
  - Supernova Hubble diagram
  - Cosmic Microwave Background
  - Gravitational lensing (galaxy imaging survey)
  - *Baryon Acoustic Oscillation (galaxy redshift survey)*



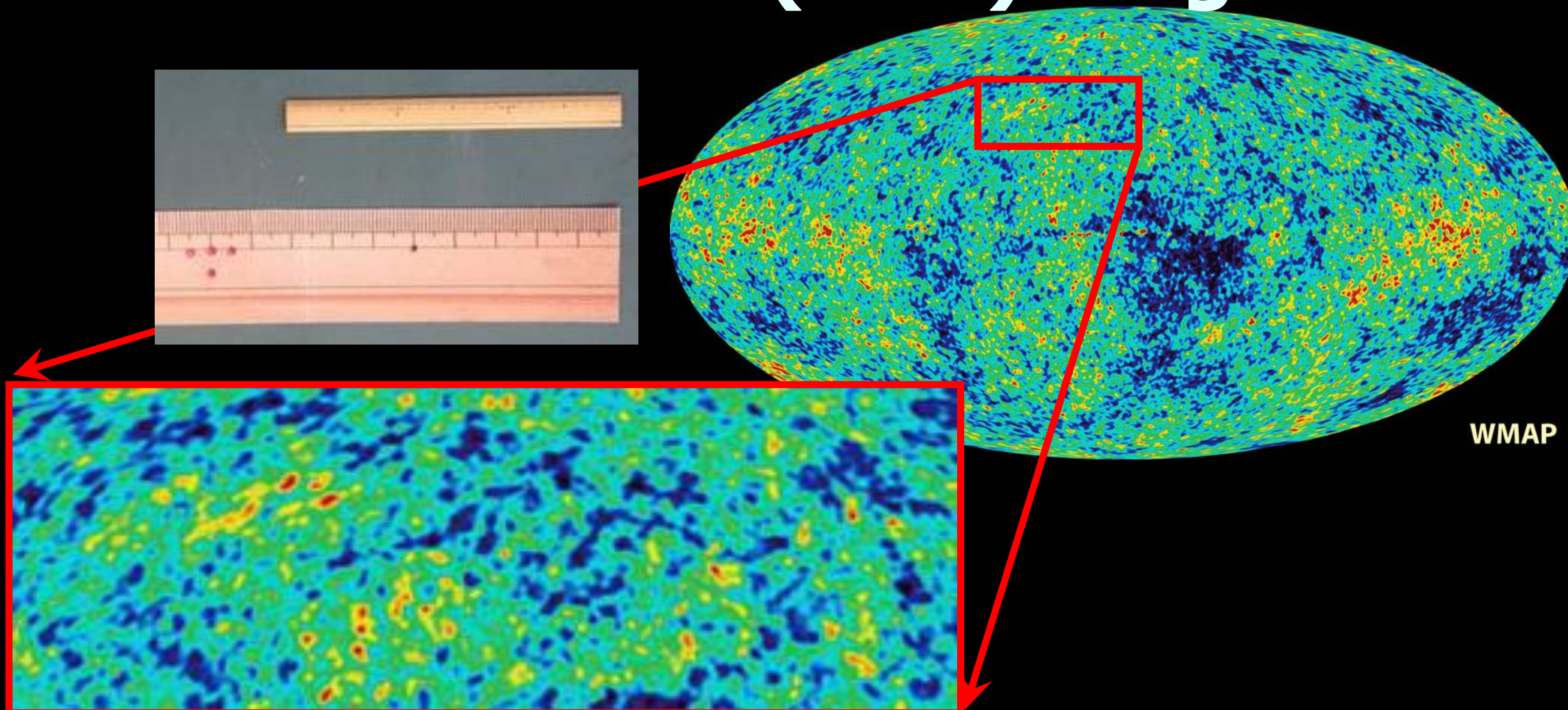








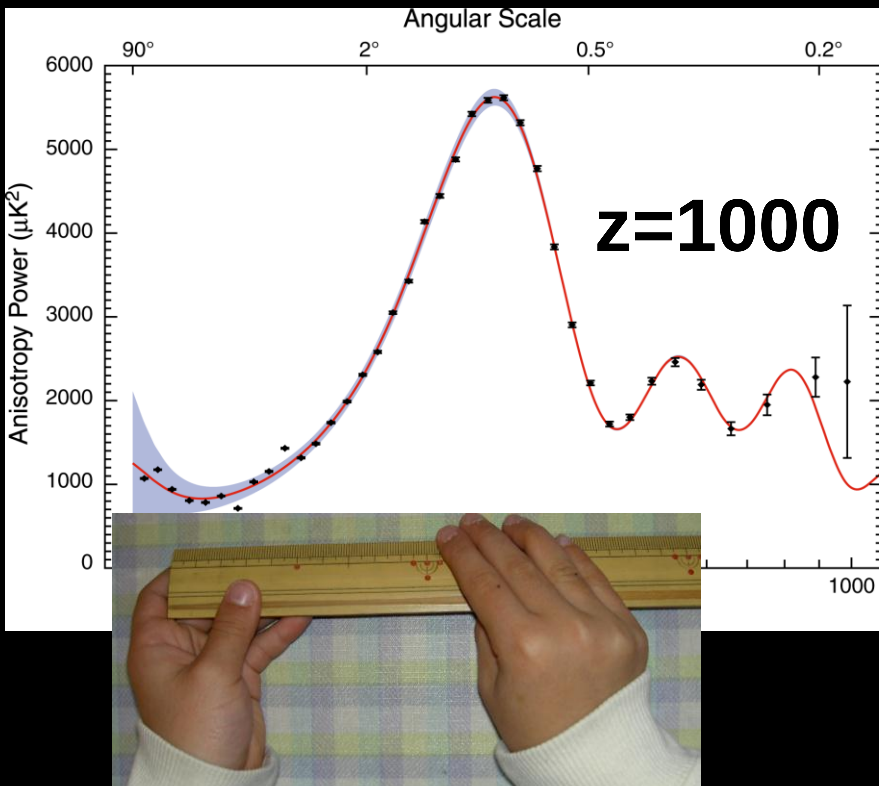
Standard ruler: baryon acoustic oscillation (BAO) length

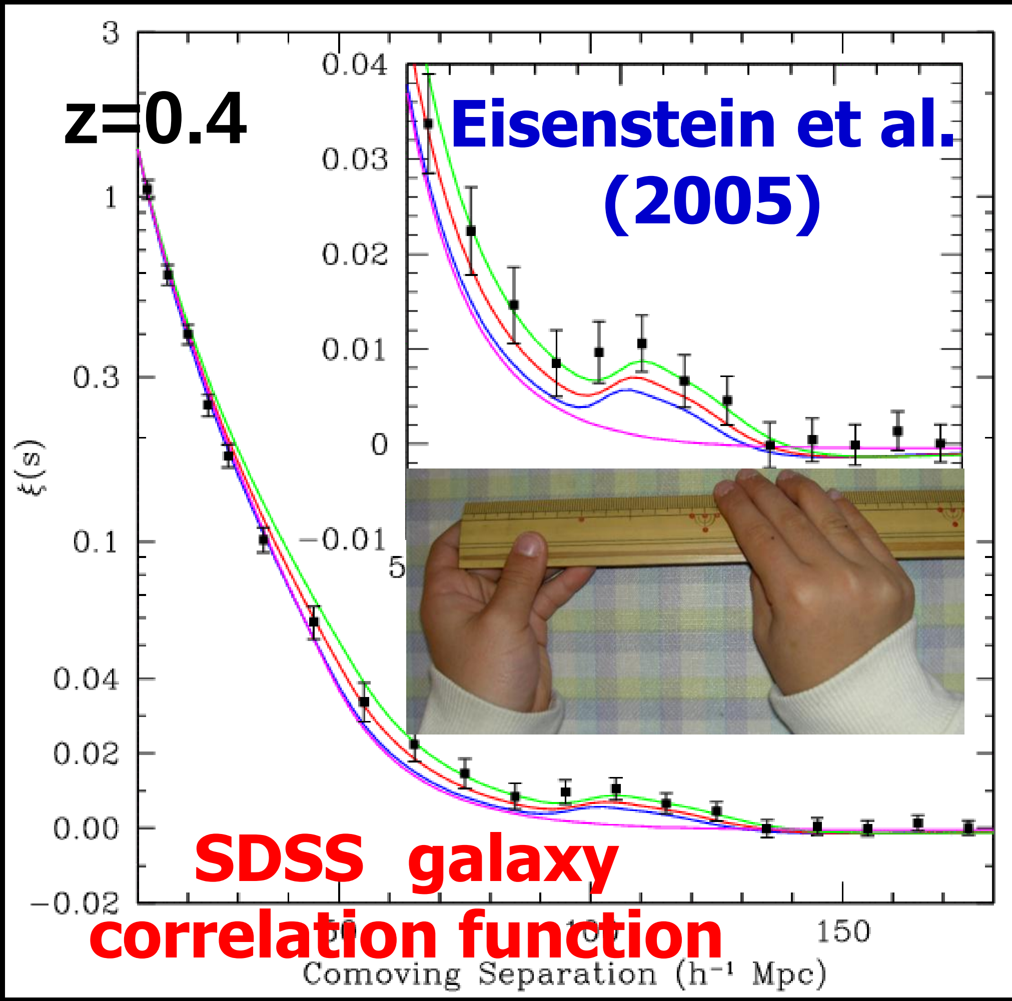


- **Sound horizon length at recombination（≒c_s×0.37Myr）**
  - $r_s = 147\ (\Omega_m h^2 / 0.13)^{-0.25}\ (\Omega_b h^2 / 0.024)^{-0.08}$ **Mpc**
- **Estimate the distance to the CMB last-scattering surface using the above as a standard ruler**

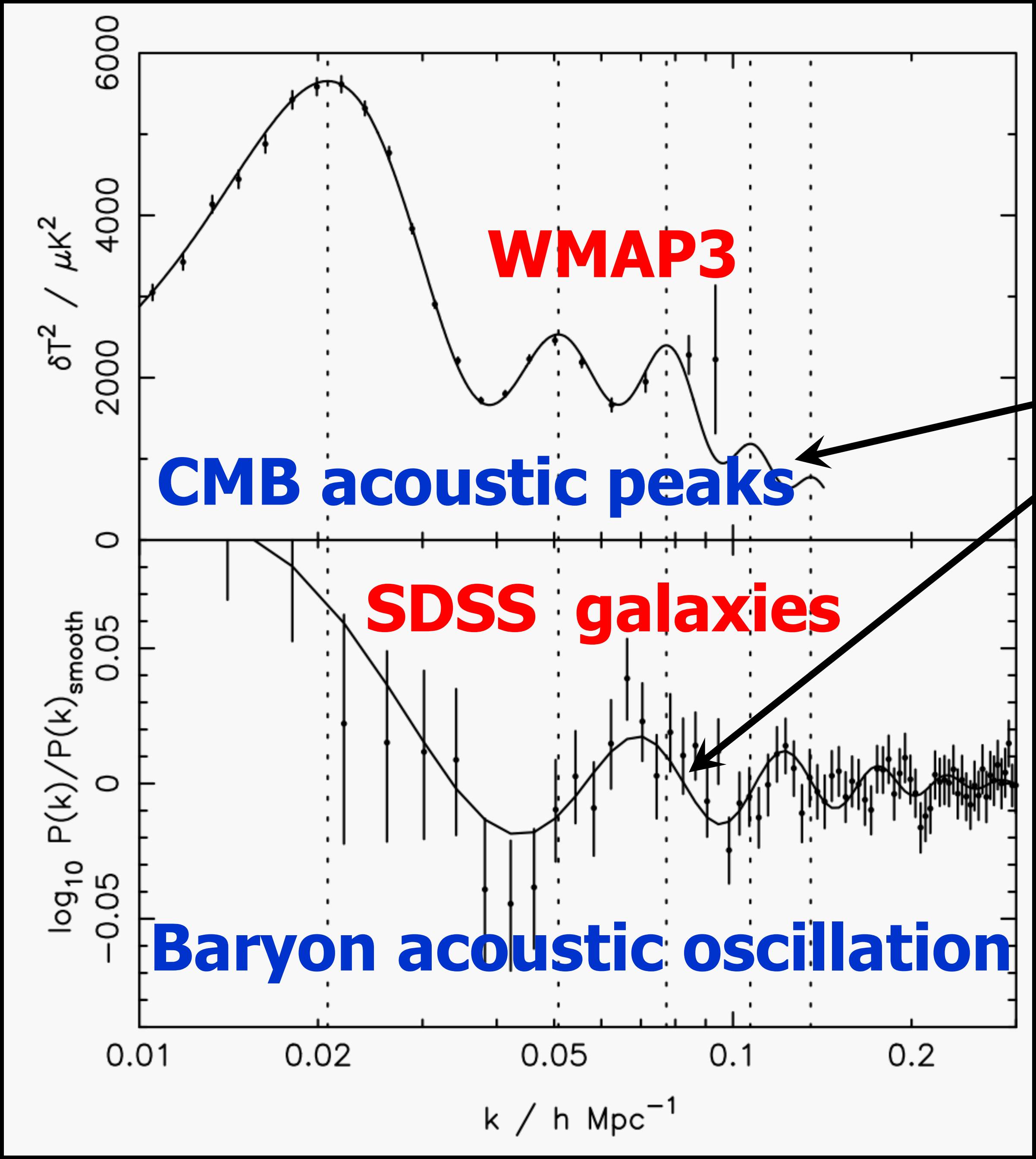
Acoustic oscillations detected

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





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

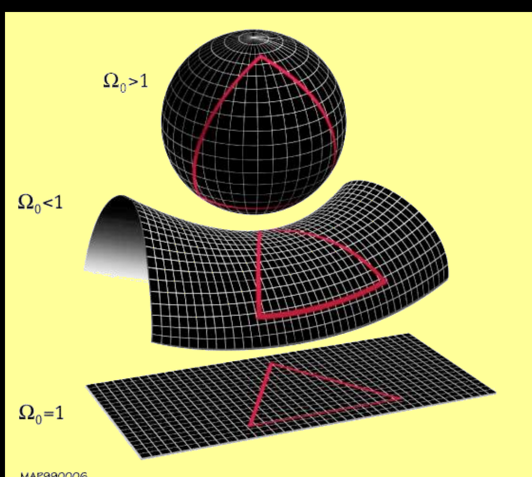


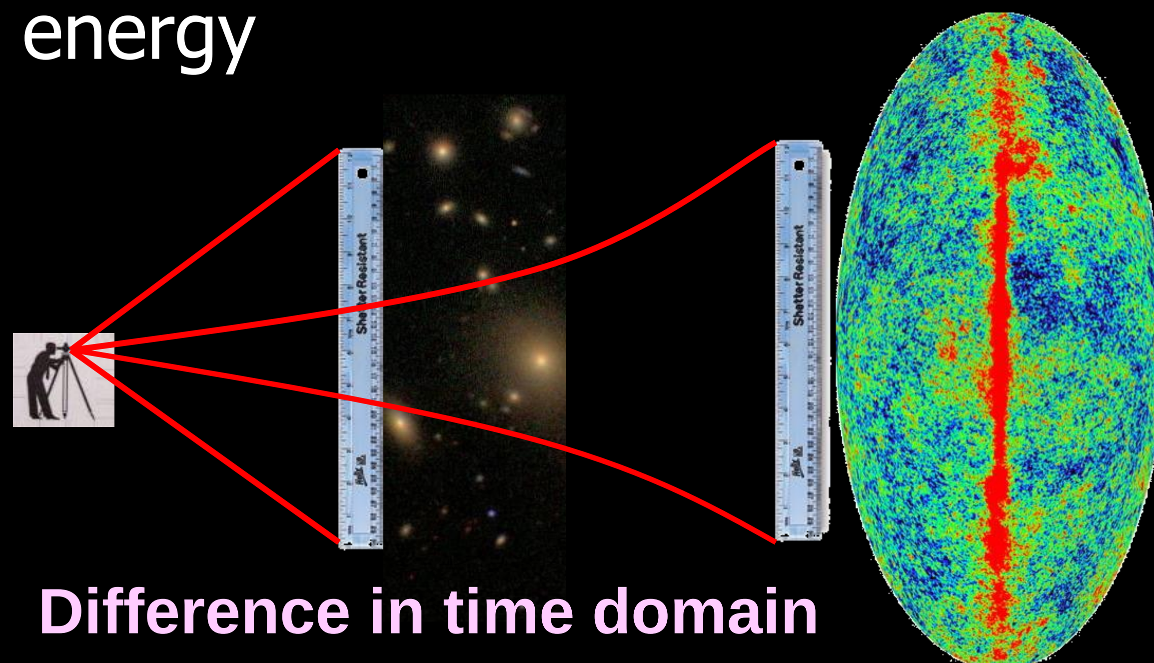
Percival et al. (2007)

Baryon acoustic oscillation (BAO) as a standard ruler

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

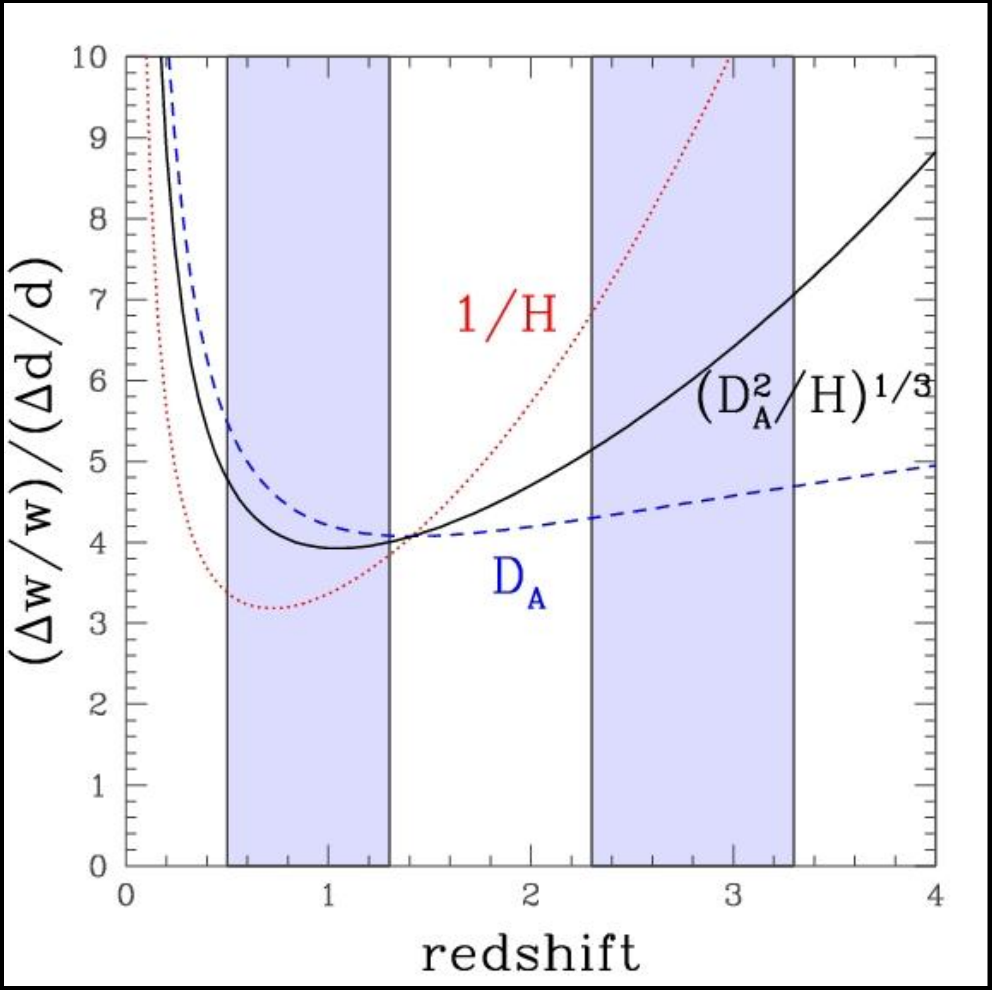
- Distance measurement at different epochs
- Promising methodology to observationally constrain dark energy





Picture credit: Bob Nichol

Required accuracy of the BAO scale measurement to constrain w

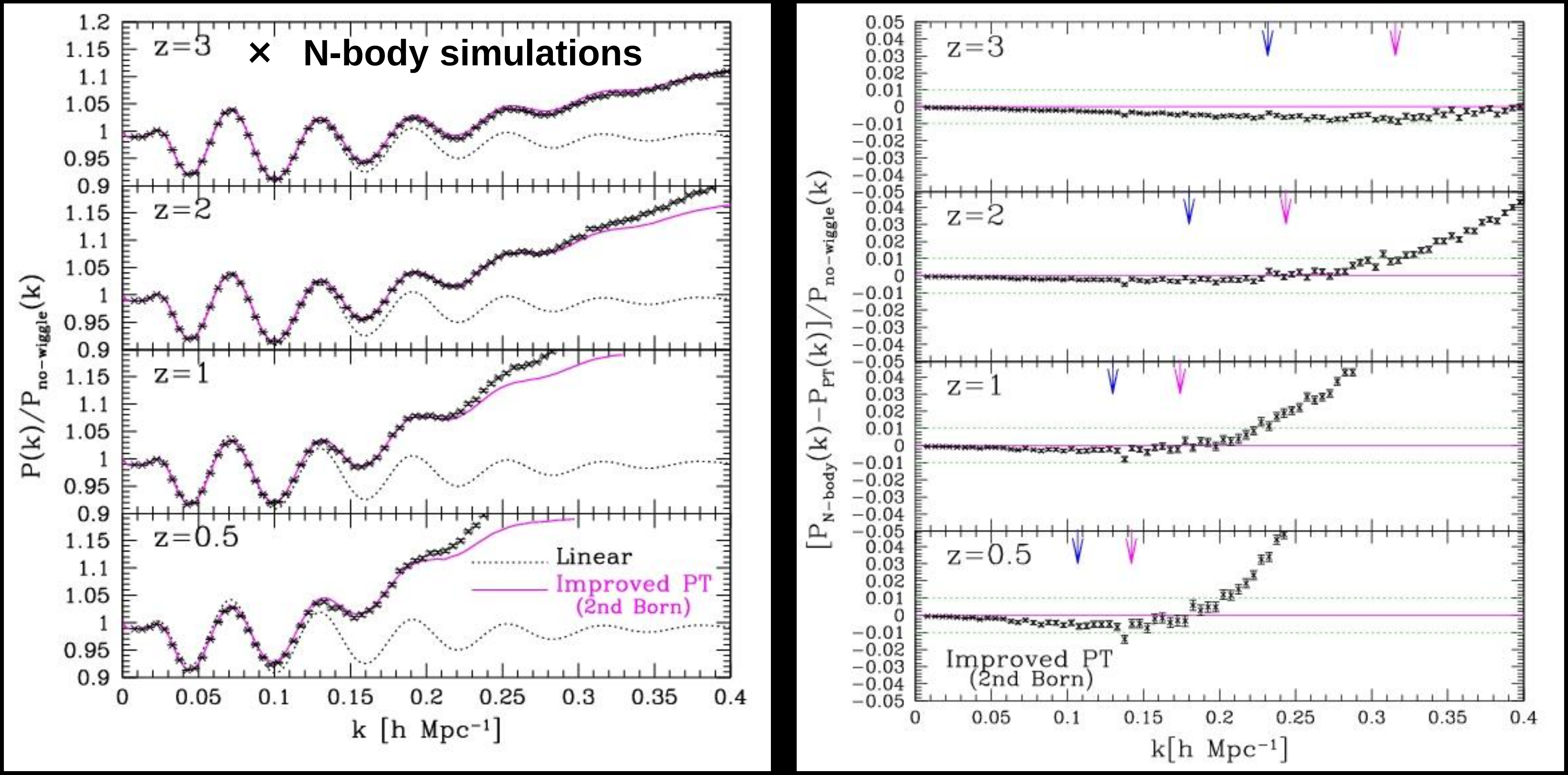


- 3% accuracy of w requires to determine BAO scale at z=1 within <1%
- ***⇒ Needs bigger surveys of galaxies***

Nishimichi et al. (2007)

Sub-percent level accuracy is demanding even for theoretical templates

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



International Research Network for Dark Energy (JSPS, core-to-core program 2007-2012)

DENET

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

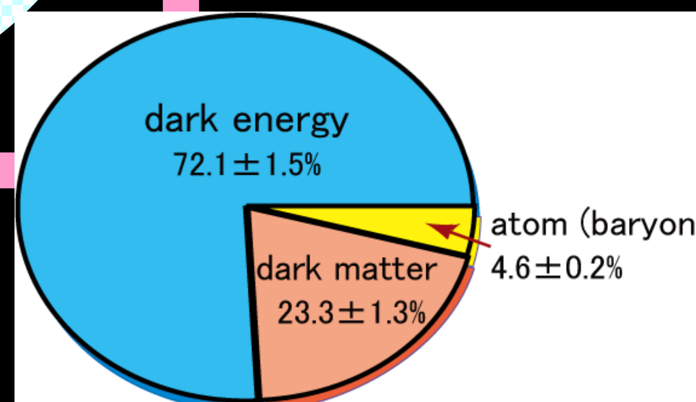
Tohoku Univ.
NAOJ
Hiroshima Univ.
Kyoto Univ.
Nagoya Univ.

Institut d'Astrophysique de Paris
coordinator
Jerome Martin

Modified gravity
Extra-dimension
backreaction

Edinburgh U.
Royal Obs.
coordinator
John Peacock

Theoretical model
Baryon oscillation
Weak lens mapping



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+, 2016-?)
  - Imaging galaxy survey
  - 20000 deg^2@Chile 8.4m dedicated telescope
- SuMIRe HSC: Hyper Suprime-Cam (Subaru+Princeton+Taiwan, 2012-)
  - Imaging galaxy survey (1.5deg FOV)
  - 1500 deg^2@Subaru 8m telescope
- SuMIRe PFS: Prime Focus Spectrograph (Subaru+US,France,Taiwan,Brazil,,, 2016-???)
  - Spectroscopic galaxy survey (1.3deg FOV)
  - 2500 fibers, 10000 galaxy redshifts a night

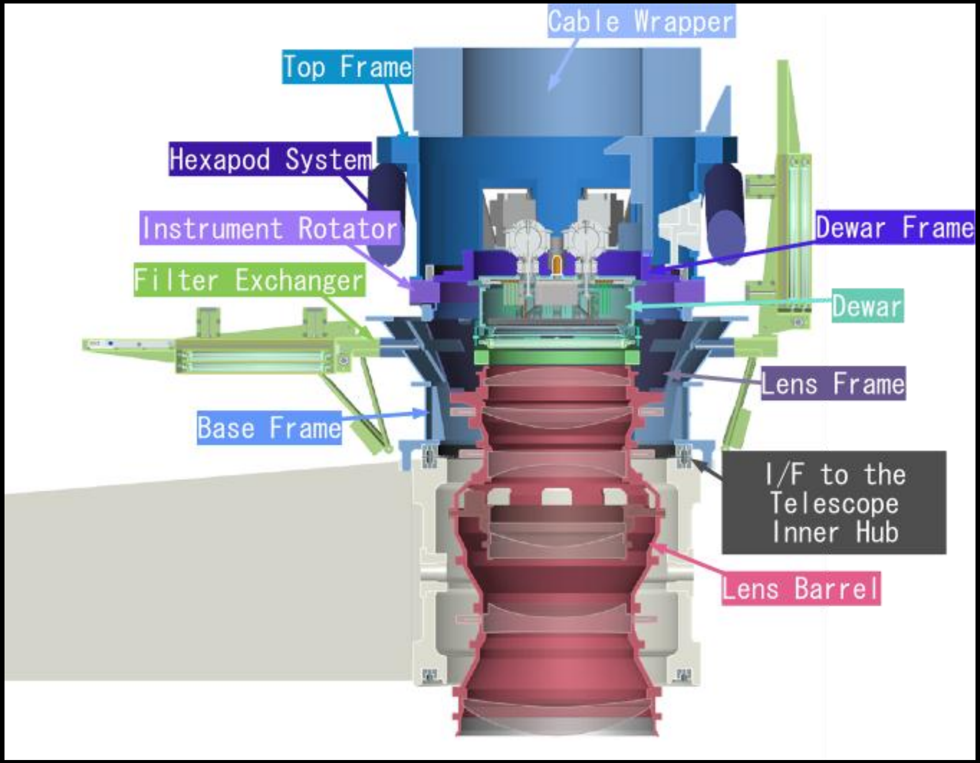
Galaxy survey project: SuMIRe

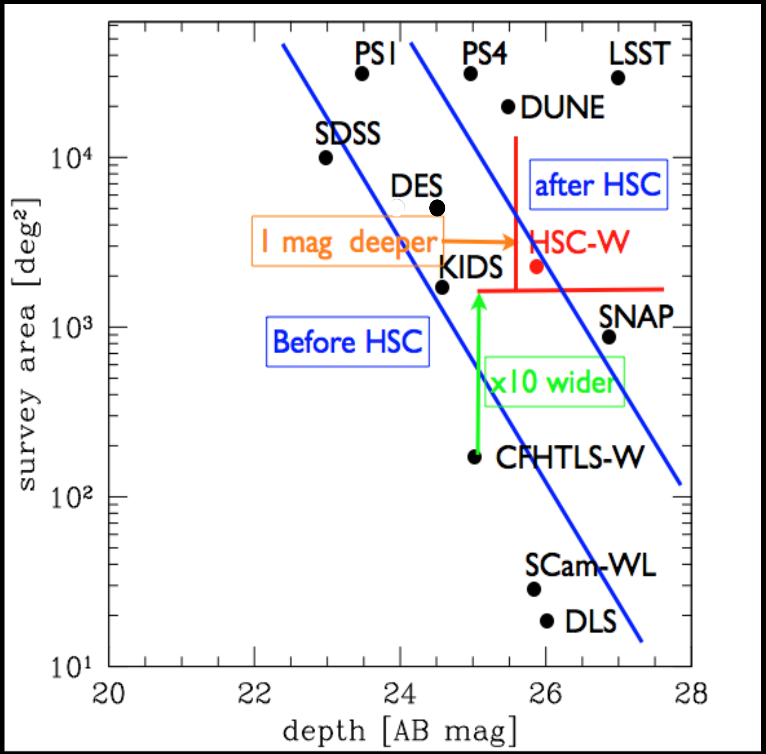
***Su*baru *M*easurement of *I*maging and *Re*dshift of the universe**

- 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 + US, Taiwan, France, Brazil,,,

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

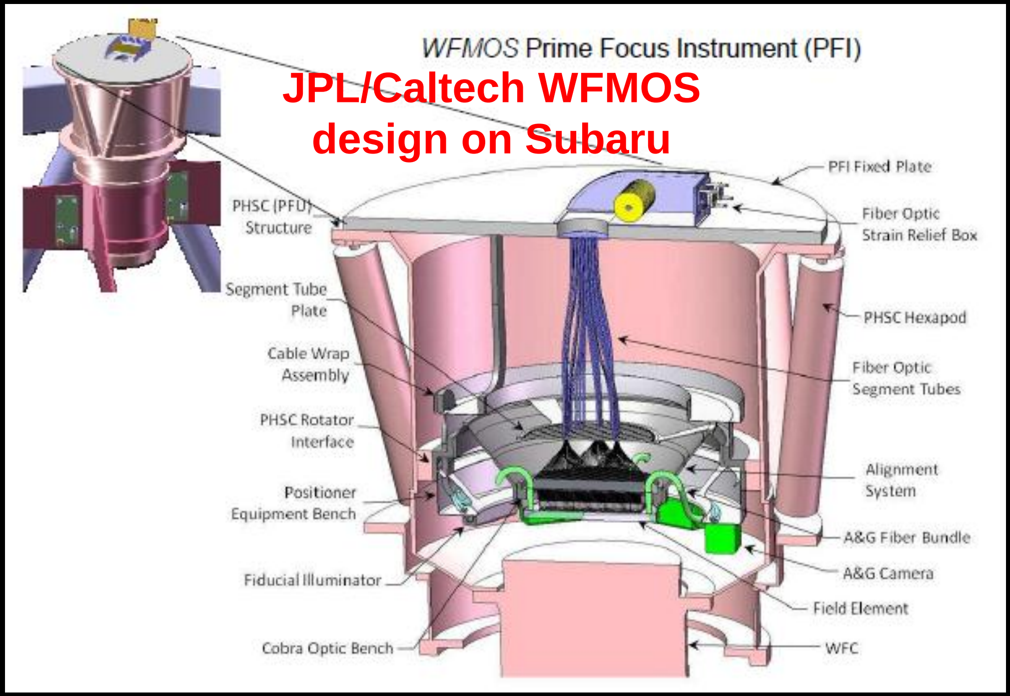




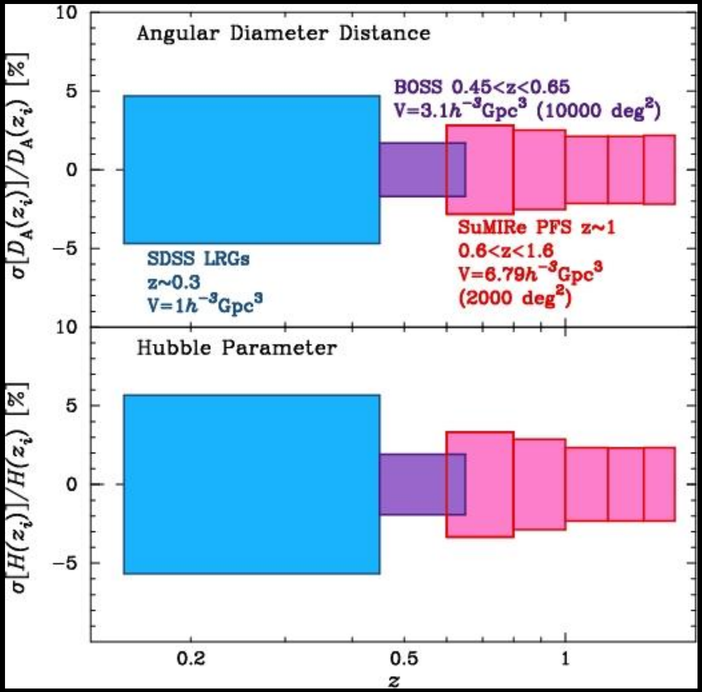
Presented at DENET-Princeton conference (2009) by Satoshi Miyazaki (NAOJ)

PFS: Prime Focus Spectrograph

- **Japan+ (2016-2020 ???)**
  - 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)

Digression and summary

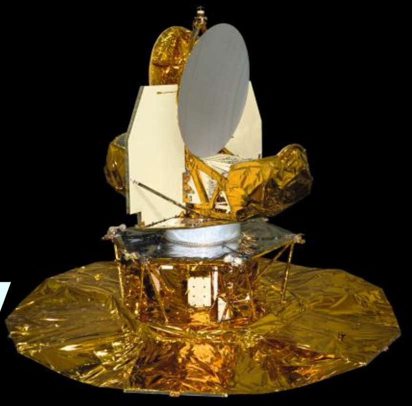
Dark energy research is good or bad for astronomy ?

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, personal perspective and/or preference, a matter of taste**

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

Which is happier, the town mouse or the country mouse ?

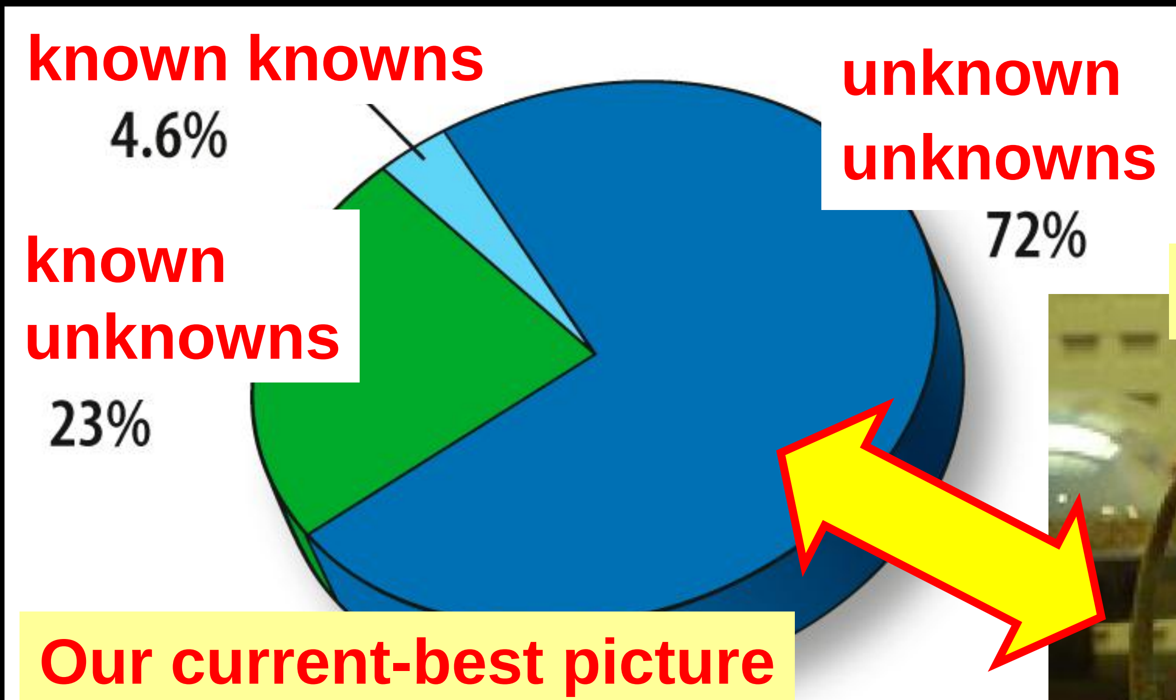
Town mouse ?	Country mouse ?
Large Hadron Collider experiments	High-intensity laser experiments
High-energy physicists	Amateur astronomers
Germany in EU	Greece in EU
dark energy cosmology	extrasolar planet hunting

Towards bigger science or downsizing ?

Without dark sky,
one could have never
imagined …

what dominates our world

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



Our current-best picture of the universe

Ancient Indian picture

Have we made progress at all ?