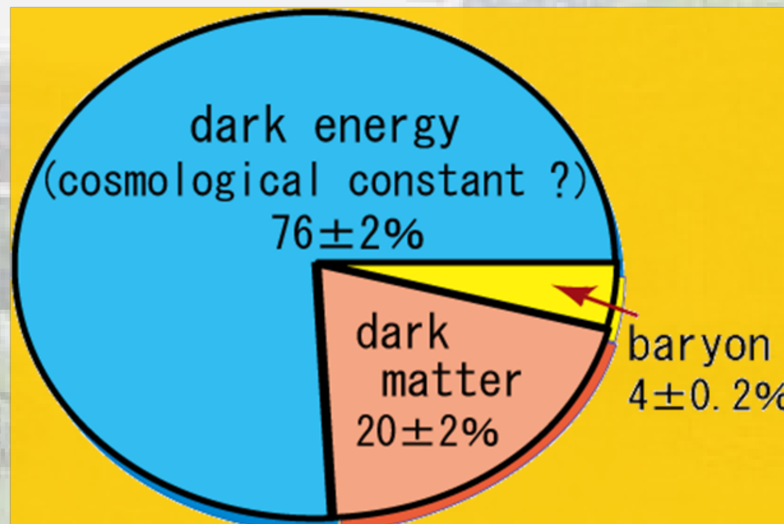
四季の湯
強羅静雲荘

RESCEU & JSPS core-to-core program DENET Summer School

Dark energy in the universe

September 1-4, 2007

Introducing DENET, HSC, & WFMOS



Yasushi Suto

Department of Physics, The University of Tokyo

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

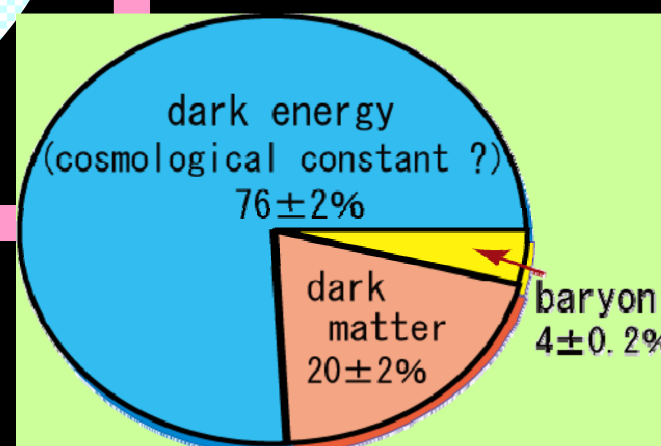
Tohoku Univ.
NAOJ
Hiroshima Univ.
Kyoto Univ.
Nagoya Univ.

Caltech
Dept. of Astron.
coordinator
Richard Ellis

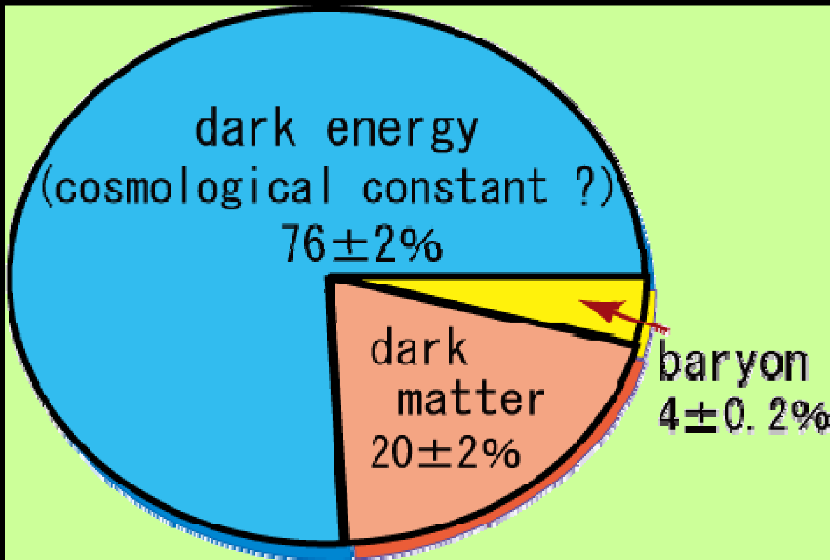
Supernova
Weak lens mapping

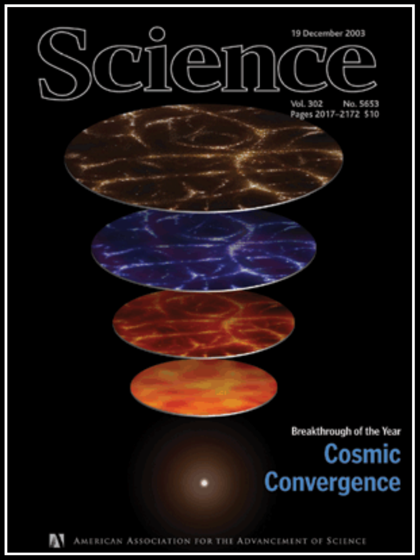
Edingburgh U.
Royal Obs.
coordinator
John Peacock

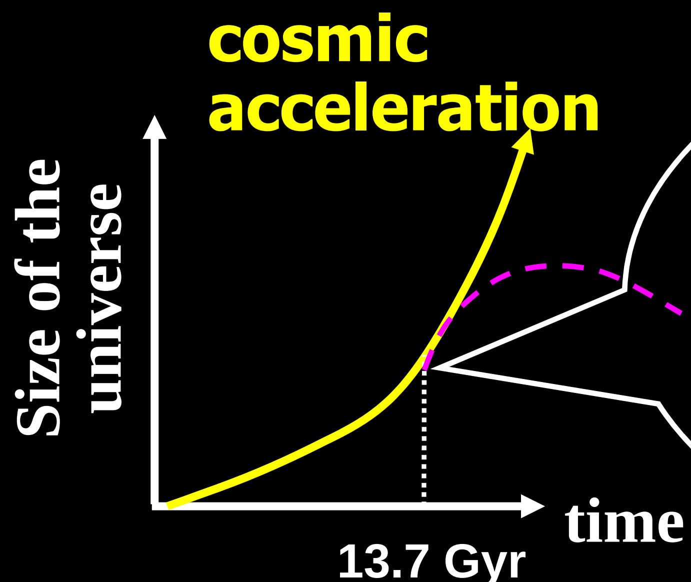
Theoretical model
Baryon oscillation
Weak lens mapping



Dark energy in the universe



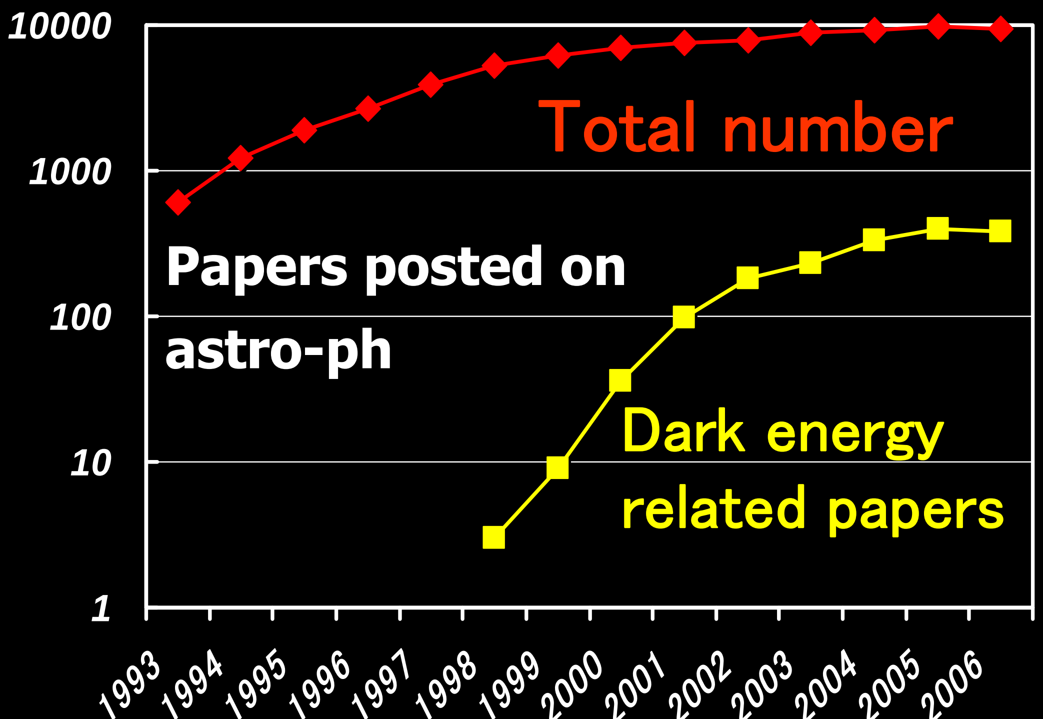




Universal repulsion?
Cosmological constant?
Dark energy?
Modified gravity?

Why important ?

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



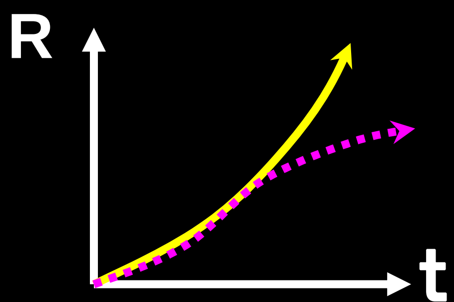
- **Steven Weinberg** *"Right now, not only for cosmology but for elementary particle theory this is the bone in the throat"*
- **Edward Witten** *"Would be number one on my list of things to figure out"*
- **Frank Wilczek** *"Maybe the most fundamentally ysterious thing in basic science"*

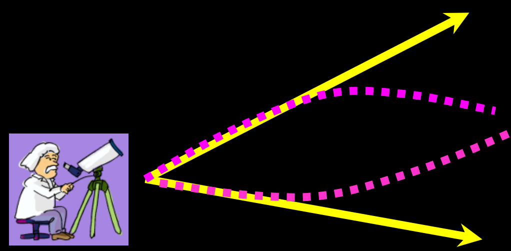
Why observable ?

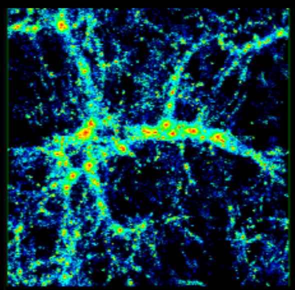
- **Objects are usually identified only through differential observations**
  - Visible matter: contrast between dark and bright regions
  - Dark matter: spatial inhomogeneities dynamically and gravitationally traced by visible stars, galaxies and quasars
- **Dark energy, if exists in a completely homogeneous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

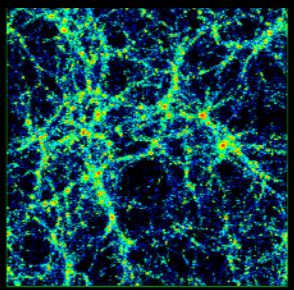
Signatures of dark energy

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









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 :

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

    $w<-1/3 \Rightarrow$ 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 ≠0 ???**
  - **w_0=-1 or ≠-1 ???**
- physical models desperately needed
  - My colleagues told me that DGP (Dvali-Gabadadze-Porrati) model is approximated by

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

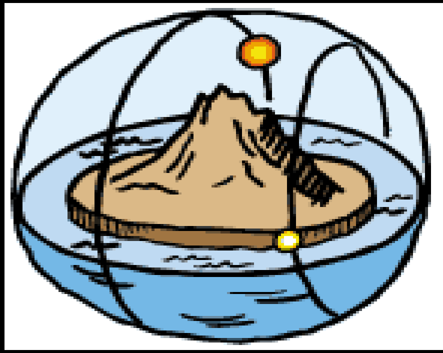
$$\Rightarrow \quad w_0 = -0.78, w_a = 0.32 \quad \text{for} \quad \Omega_m = 0.27$$

although I cannot even pronounce their names…

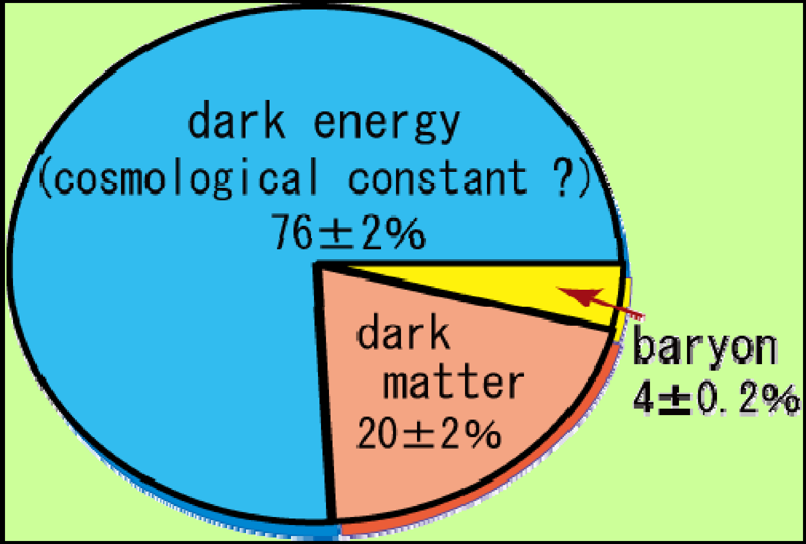
Did we make progress at all ?

Egypt

Chinese



Indian



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

Towards better 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
5. repeat the above steps 1～4 until you become tired (or retire) for n=1,2,3,4,5…

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

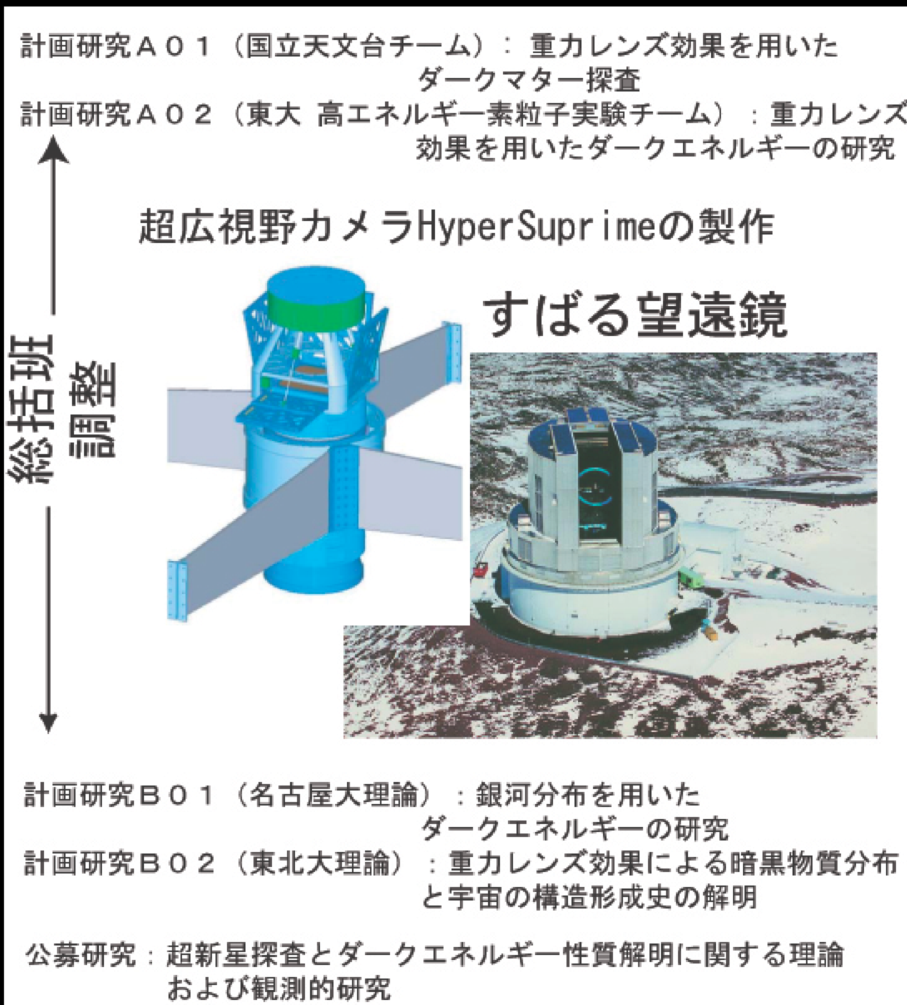
- Meaningful theoretical breakthroughs are unlikely during this century

  ⇒ 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

future dark energy survey projects

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

Hyper Suprime-Cam project



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

WFMOS proposal: Subaru+Gemini spectroscopic survey

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

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, but…**