ABSTRACT

Answering well-known fundamental questions is usually regarded as the major goal of science. Discovery of other unknown and fundamental questions is, however, even more important. Recognition that “we didn’t know anything” is the basic scientific driver for the next generation. Cosmology indeed enjoys such an exciting epoch.

What is the composition of our universe? This is one of the well-known fundamental questions that philosophers, astronomers and physicists have tried to answer for centuries. Around the end of the last century, cosmologists finally recognized that “We didn’t know anything”. Except for atoms that comprise slightly less than 5% of the universe, our universe is apparently dominated by unknown components; 23% is the known unknown (dark matter), and 72% is the unknown unknown (dark energy).

In the course of answering a known fundamental question, we have discovered an unknown, even more fundamental, question: “What is dark matter? What is dark energy?” There are a variety of realistic particle physics models for dark matter, and its experimental detection may be within reach. On the other hand, it is fair to say that there is no widely accepted theoretical framework to describe the nature of dark energy. This is exactly why astronomical observations will play a key role in unveiling its nature.

I will review our current understanding of the “dark sky”, and then present on-going Japanese project, SuMIRe, to discover even more unexpected questions.

Keywords: Cosmology, dark energy, galaxy survey, BAO, HSC, PFS, SuMIRe

1. INTRODUCTION

Darkness is the key to understanding our world in both literal and metaphorical senses. Philosophy, astronomy, and therefore physics should have started by thinking in the dark in the ancient era. I believe that this still applies now at the frontier of the contemporary science. Serious scientific investigations for another element, another Earth, and another life have have opened new research fields in astronomy; dark matter, dark energy, extrasolar planet, and astrobiology.

In his well-known novella Nightfall Issac Asimov considered a planet “Lagash” with six different “Suns” on which “night” comes only every 2049 years at the occasion of the total eclipse of a Sun in the sky. People on the planet understood the real world, for the first time, only during Lagash’s brief and rare dark night (Fig. 1).

“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.”

Indeed the story tells us in a convincing fashion that we usually do not realize that we do not know anything when we get so used to what we directly see. If our planet were always covered by blue sky, we would have never dreamed of the presence of numerous stars behind it.

It is exactly why until relatively recently we have never imagined the fact that darkness in the night sky is dominated by something we do not know; dark matter and dark energy. The combined analysis of the Hubble diagram of type Ia supernovae, the angular power spectrum of CMB (cosmic microwave background) temperature...
anisotropies, and the baryon acoustic oscillation in galaxy power spectrum among other indications unveiled the precise composition of the present universe.

Maybe even more surprisingly, baryons in the present universe have largely evaded the direct detection so far, i.e., most of the baryons are dark. The majority of those cosmic dark baryons in the present universe are thought to take the form of the warm-hot intergalactic medium with $10^5 \text{K} < T < 10^7 \text{K}$ that does not exhibit any strong observational signature.

In summary, our universe is apparently dominated by unknown dark components as shown in Figure 2. The current situation may be well described by a controversial press briefing given by former US Defense Secretary Donald H. Rumsfeld on February 12, 2002.

There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don’t know. But there are also unknown unknowns. There are things we don’t know we don’t know.

I am always a bit concerned by the fact that many colleagues in the cosmology community tend to show something like Figure 2 even proudly, indicating that our understanding of the universe is amazingly precise.
It may be true in some sense, but you might well consider it as a paraphrase of the old Indian picture of the universe (Fig. 3). Have we made progress at all since then? Maybe yes, but we have to recognize that we still do not know something. This is why we should move on and try to unveil the nature of the dark universe.

In what follows, I basically focus on dark energy with particular emphasis on our on-going project with Subaru telescope. A complementary and more comprehensive discussion on imaging surveys of galaxies, especially that with LSST (Large Synoptic Survey Telescope), is presented by Prof. Tony Tyson in these proceedings.

![Figure 3. Ancient Indian idea of the universe (courtesy of Chiharu Ishizuka, Osaka Science Museum, Japan).](image)

2. DARK ENERGY

2.1 Cosmic Acceleration

The discovery of the accelerated expansion of the current universe\textsuperscript{6, 7, 8} required a fundamental modification of the standard picture. This can be understood as follows. Let us denote the scale factor of the universe by \( a(t) \), and expand it in a Taylor series around the present time \( t_0 \):

\[
a(t) = a(t_0) + \left. \frac{da}{dt} \right|_0 (t - t_0) + \frac{1}{2} \left. \frac{d^2 a}{dt^2} \right|_0 (t - t_0)^2 + \cdots. \tag{1}
\]

The normalization of the first term \( a_0 \equiv a(t_0) \) is arbitrary, and thus has no direct physical meaning (conventionally it is set to unity, \( a_0 = 1 \)). The second and third terms are related to observable cosmological parameters, the Hubble constant \( H_0 \), and the deceleration parameter \( q_0 \) as follows:

\[
H_0 = \frac{1}{a_0} \left. \frac{da}{dt} \right|_0, \tag{2}
\]
\[
q_0 = -\frac{1}{a_0 H_0^2} \left. \frac{d^2 a}{dt^2} \right|_0. \tag{3}
\]

Indeed the nature of the above two parameters is intrinsically different. The value of \( H_0 \) is a purely observationally determined parameter that cannot be predicted at all by theory. This is even true for its signature. Observations indicate that \( H_0 \) is positive, implying that our present universe is expanding. Even if the measured value of \( H_0 \) were negative, however, it would simply mean that the universe is contracting. So we would not be surprised even if \( H_0 \) were negative; the value and signature of the expansion velocity are just a manifestation of the initial conditions, but not of physical laws.

This is not the case for \( q_0 \). In the standard homogeneous isotropic cosmology, one obtains

\[
\frac{1}{a} \frac{d^2 a}{dt^2} = -\frac{4\pi G}{3} (\rho + 3p), \tag{4}
\]
where $\rho = \rho(t)$ and $p = p(t)$ denote the mean density and pressure of the universe. As long as both $\rho$ and $p$ are positive, the left-hand-side of equation (4) is negative, and $q_0$ defined by equation (3) is positive. This is in contradiction of the accelerated expansion of the present universe; observationally $q_0$ is approximately $-0.6$. The second derivative is dictated by laws of physics, and thus it was long believed that $q_0$ should be positive.

One solution to the apparent contradiction is to introduce an unknown additional constituent with $\rho_{DE}(>0)$ and $p_{DE}(<0)$. Then equation (4) is rewritten as

$$\frac{1}{a} \frac{d^2 a}{d t^2} = -\frac{4\pi G}{3}(\rho + 3p + \rho_{DE} + 3p_{DE}).$$

(5)

Thus if we are generous enough to accept such a strange component, coined “dark energy”, the cosmic acceleration can be accounted for if $p_{DE} < -p - (\rho + \rho_{DE})/3$. In this context, a widely used parameterization of the equation of state of dark energy is

$$w_{DE} \equiv \frac{p_{DE}}{\rho_{DE}}.$$  

(6)

Apart from dark energy, the present universe is known to be approximately dominated by non-relativistic matter (baryons and dark matter) with $\rho_m$ and negligible pressure. In this case, equation (5) reduces to

$$\frac{1}{a} \frac{d^2 a}{d t^2} = -\frac{4\pi G}{3} \left[ \rho_m + (1 + 3w_{DE})\rho_{DE} \right] = -\frac{H_0^2}{2} \left[ \Omega_m \frac{a}{a^0} + (1 + 3w_{DE})\Omega_{DE} \exp \left( 3 \int_{a_0}^a \frac{1 + w_{DE}}{a} da \right) \right],$$

(7)

where

$$\Omega_m = \frac{8\pi G}{3H_0^2}\rho_m(t_0), \quad \Omega_{DE} = \frac{8\pi G}{3H_0^2}\rho_{DE}(t_0)$$

(8)

are the present ($a = a_0$) values of the dimensionless density parameters of matter and dark energy, respectively.

If the parameter $w_{DE}$ does not depend on $t$, equation (7) indicates that the deceleration parameter is written in terms of the other parameters as

$$q_0 = \Omega_m + \frac{1 + 3w_{DE}}{2} \Omega_{DE}.$$  

(9)

All the currently available data are surprisingly consistent with $w_{DE} = -1$, which corresponds to the cosmological constant, $\Lambda$, that Einstein originally introduced in 1917 for a completely different reason. In this case, the condition for the cosmic acceleration ($q_0 < 0$) is

$$\Omega_{DE} = \Omega_\Lambda > \frac{\Omega_m}{2}.$$  

(10)

Therefore the cosmic acceleration implies that our present universe should be dominated by a peculiar unknown component that behaves very similarly as Einstein’s cosmological constant; various observations point to $\Omega_\Lambda \approx 0.72$ and $\Omega_m \approx 0.28$. Is dark energy really a cosmological constant? In other words, $w_{DE} = -1$ or not, that is the question. This is one of the crucial questions on dark energy that we would like to answer within a decade from now.

Another solution is to assume that general relativity is not strictly valid on cosmological scales, commonly referred to as modified gravity theories. Equation (4) with $p = 0$ may be rewritten as

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

(11)

indicating that this is nothing but the inverse square law of gravitation. While dark energy models abandon the idea that our universe is dominated by normal components with positive pressure, modified gravity models abandon the validity of the inverse square law on cosmological scales.

The two different solutions to the cosmic acceleration should lead to different predictions on growth history of structures in the universe, which can be tested against the galaxy survey data as will be discussed below.
2.2 Baryon Acoustic Oscillation (BAO)

The baryon acoustic oscillation (BAO) is an oscillation of photon-baryon fluid imprinted in the matter spectrum, which was detected in the SDSS and 2dFGRS galaxy distribution in 2005 (e.g., Refs. 9, 10). The characteristic scale imprinted in the BAO is basically the sound horizon at recombination:

$$r_s(z_{rec}) = \int_{z_{rec}}^{\infty} \frac{dz}{H(z)} = \frac{2}{3k_{eq}} \sqrt{\frac{6}{R_{eq}}} \ln \frac{\sqrt{1 + R_{rec}} + \sqrt{R_{rec} + R_{eq}}}{1 + \sqrt{R_{eq}}} \approx 147(\Omega_m h^2/0.13)^{-0.25}(\Omega_b h^2/0.024)^{-0.08}\text{Mpc},$$

where $c_s(z)$ is the sound speed at redshift $z$, and $z_{rec}$ is the redshift at recombination ($\simeq 1089$). In the second equality, $k_{eq}$ is the horizon scale at the matter-radiation equality epoch, $z_{eq}$, $R_{rec} = R(z_{rec})$ and $R_{eq} = R(z_{eq})$ are the ratio of the baryon to photon momentum densities at $z_{rec}$ and $z_{eq}$. Finally the last equality is an approximate fit where $\Omega_m$ and $\Omega_b$ are the density parameters of matter and baryon, and $h$ is the Hubble constant in units of $100\text{km s}^{-1}\text{Mpc}^{-1}$.

The BAO length scale is a good tracer of $w_{DE}$, and also of modified gravity theories. The BAO scale measured from a redshift survey of galaxies provides estimates of the angular diameter distance, $D_A(z)$, and the inverse of the Hubble parameter, $1/H(z)$, which correspond to the scales perpendicular and parallel to the line-of-sight direction, respectively. They in turn can be translated into the estimate of $w_{DE}$. Figure 4 shows how the fractional errors of three important scales, the angular diameter distance $D_A(z)$, the inverse of Hubble parameter $1/H(z)$ and their average over three dimensions, $(D_A^2(z)/H(z))^{1/3}$, propagate to that of $w_{DE}$. The two shaded regions show the approximate targeted redshift ranges of a galaxy redshift survey, WFMOS (Wide-field Fiber-fed Multi-Object Spectrograph), which is basically the same as SuMIRe PFS redshift surveys discussed in §3. Typically a ratio of $\Delta w/w$ and $\Delta d/d$ around $z = 1$ ranges from 3 to 5.

Figure 4. The error propagation from measured scales, $d$, to the dark energy equation of state parameter, $w_{DE}$, as a function of redshift. We choose $1/H(z)$ (dotted), and $D_A(z)$ (dashed) for $d$, which correspond to the separations parallel and perpendicular to the line-of-sight direction. We also plot the three dimensional average, $(D_A^2(z)/H(z))^{1/3}$ (solid) for $d$. The shaded regions indicate the targeted redshift ranges of a future galaxy survey, WFMOS (reproduced from Ref. [12]).

Figure 4 indicates that determining $w_{DE}$ within 3% accuracy requires the sub-percent accuracy/precision in determining the BAO scale. This is a very demanding requirement for on-going galaxy surveys, and the reliable theoretical predictions to that level of accuracy are non-trivial to make. This is why various authors have been developing different semi-analytic models to compute power spectra of galaxies taking account of nonlinear gravitational evolution, biasing with respect to dark matter, and redshift-space distortion. Since the standard perturbation theory (PT) breaks down even at a relatively weak nonlinear regime, those approaches are exploring different new re-summation techniques so that a class of infinite series of higher-order corrections can be incorporated even empirically by modifying the standard PT.
Figure 5. Comparison between N-body results and improved PT predictions. From top to bottom, the results at $z = 3, 2, 1$ and 0.5 are shown. The improved PT predictions plotted here include the corrections up to the second-order Born approximation of the mode-coupling term, $P^{MC2}$. Left: ratio of power spectrum to the smoothed reference spectra, $P(k)/P_{\text{no-wiggle}}(k)$. Solid and dotted lines are improved PT and linear theory predictions, respectively. Right: difference between N-body and improved PT results normalized by the no-wiggle formula, $[P_{\text{N-body}}(k) - P_{\text{PT}}(k)]/P_{\text{no-wiggle}}(k)$. In each panel, vertical arrows represent the wavenumber $k_{1\%}$ for the leading-order predictions of standard and improved PT from left to right (reproduced from Ref. 23).

One of the most successful methods (see Refs. 19, 20 for systematic comparison between simulations and different analytic methods) is based on the closure theory widely used in describing turbulence. Atsushi Taruya and his collaborators applied the methodology to cosmological perturbation theory for the first time.21, 22 Their results of dark matter in real space23 are shown in Figure 5 as specific examples of the BAO features. The comparison between the model and simulations indicate that the sub-percent level accuracy is now achieved for dark matter spectra in real space. Nevertheless the clustering statistics measured from actual galaxy surveys have to be computed in redshift space with galaxy biasing. It is also important to formulate those methods in modified gravity theories so as to see any departure from dark energy models.24 Thus there are still many aspects that should be improved theoretically, and the efforts towards the direction are being explored intensively.

3. SUBARU MEASUREMENT OF IMAGES AND REDSHTFS (SUMIRE)
The Subaru Measurement of Images and Redshifts (SuMIRe) of the universe is an international galaxy survey project, which comprises a wide-field imaging survey with Hyper Suprime-Cam (HSC) and a redshift survey with Prime-Focus Spectrograph (PFS). One of the major goals of SuMIRe is to probe the evolution of cosmic structures, and thereby to unveil the nature of dark energy and/or test general relativity at cosmological scales. For that purpose, we combine four different methods; weak gravitational lensing, BAO, cluster counting statistics, and the redshift – magnitude relation of distant type-Ia supernovae. The imaging survey with HSC will observe a billion of galaxies, and the spectroscopic survey with PFS will determine redshifts of a few millions of galaxies (and QSOs as well). The combined SuMIRe survey will complete a three-dimensional map of dark matter, galaxies and clusters over a wide range of redshifts up to $z \approx 1.6$. 
3.1 Brief history of SuMIRe

The HSC was originally proposed by Satoshi Miyazaki and his colleagues at NAOJ (National Astronomical Observatory of Japan) as one of next-generation instruments on Subaru 8.2 m telescope at Mauna Kea, Hawaii. They completed the conceptual design and concluded that the field size of up to 2 degree in diameter is technically feasible\cite{5}. Based on their studies, the first major funding proposal (P.I. Hiroshi Karoji, NAOJ) was submitted in 2005 to Japanese Ministry of Education, and was approved as a 6 year project (September 2006 – March 2012). Later ASIAA (Academia Sinica Institute of Astronomy and Astrophysics) and Department of Astrophysical Sciences, Princeton University officially joined the project. We expect to have the HSC first light at the end of 2011, and hope to start imaging surveys around mid-2012.

In contrast, PFS has a long and complicated history. The original idea of PFS should be traced back to KAOS (Kilo-Aperture Optical Spectrograph), a prime focus wide-field multi-object fiber spectrograph concept for one of the Gemini Telescopes in 2002. In 2003, KAOS was renamed as WF MOS (Wide-field Fiber-fed Multi-Object Spectrograph), and proposed as one of Gemini’s next-generation instruments at Aspen. Soon later, however, it was recognized that the Gemini telescope cannot mechanically support such a heavy instrument at Prime Focus. In 2004 Hiroshi Karoji, the director of Subaru Observatory at that time, suggested a possibility that WFMOS should be installed on Subaru. Karoji’s suggestion was taken very seriously by a group of people in the Gemini community, and White paper by the WFMOS Feasibility Study Dark Energy Team\cite{6} was released in 2005.

In December 2005, the Gemini observatory started a WFMOS conceptual design study. While it was once suspended in May 2006 due to the budget uncertainty, it was resumed in May 2007, and in February 2009, a JPL/Caltech team (P.I. Richard Ellis, Caltech) was selected for the design group. In May 2009, however, the Gemini Board finally decided to cancel WFMOS due to the budget problem.

Just after that, the Japanese government announced the stimulus funding program that will select 30 top-researchers in Japan and provide $2.7 \times 10^{11}$ yen in total for the next 5 years. The director of IPMU (Institute of Physics and Mathematics of the Universe, The University of Tokyo), Hitoshi Murayama, proposed “Revealing the past and future of the universe: unveiling the nature of dark matter and dark energy with ultra-wide-field imaging and spectroscopy”, which was approved on September 5, 2009, 6 days after the historical defeat of Japan Liberal Democratic Party at the Japanese general election on August 30, 2009.

The proposal is a joint project of HSC and PFS, and indeed is the current SuMIRe project. Incidentally “Sumire” is the Japanese name of a flower (“violet” in English). I invented the acronym first, and later David Spergel of Princeton University came up with the full name “SUbaru Measurement of Images and REdshift of the universe” for it.

Of course, this is not the end of the story. On September 16, 2009, new Japanese government started, and on October 17, 2009, it reduced the total budget of the stimulus package (for 30 projects) from $2.7 \times 10^{11}$ yen to $1.0 \times 10^{11}$ yen. Nevertheless we are supposed to complete PFS in the international collaboration scheme in any way. At the time of this writing, therefore, we are pursuing a variety of possibilities to secure the funding necessary for PFS, and hope to start the collaboration within a year or so.

3.2 Hyper Suprime-Cam (HSC)

Hyper Suprime-Cam (HSC) is an upgrade of the existing camera Suprime-Cam (SC) installed at the Prime Focus of Subaru Telescope. The field-of-view of HSC is nearly an order-of-magnitude larger than than of SC, while maintaining the equivalent image quality. Combined with the fact that Subaru’s median seeing is better than 0.7 arcsec (FWHM), HSC will be a very unique and powerful instrument particularly for weak lensing survey. The basic specifications of HSC are summarized in Table\cite{7} and the configuration of its major components are shown in Figure\cite{8} (courtesy of Satoshi Miyazaki). See Ref.\cite{9} for further details of HSC.

The HSC wide-field, multi-color (grizy) survey covering 1500 $\sim$ 2000 square degree sky is expected to start in mid-2012 for 5 years. The depths of the survey correspond to $g < 26$, $r < 25.9$, $i < 25.8$, $z < 25$, and $y < 24$ (5σ limit), respectively, and probe galaxies up to $z = 1.5$. The planned dark energy experiments with the HSC surveys (and also with PFS) include weak lensing, cluster counting statistics, and SNe, which are summarized in Table\cite{10}.
Field of View | 1.5 degree diameter | Vignetting allowed up to 25 % at the edge
| Dead area (CCD gap) fraction ≤ 5 %
Instrument PSF size | ≤ 0".4 for g', r', i', z'
| FWHM, Telescope Elevation > 30 deg.
Pixel scale | ≤ 0".2 /pix
System Throughput | ≥ 50 % for g'
| ≥ 65 % for r'
| ≥ 65 % for i'
| ≥ 40 % for z'
| ≥ 20 % for Y
Primary Mirror × Wide Field Corrector × Filter × CCD
at the center of the field
Minimum Exposure time | 2 sec (1 sec goal)
| Time accuracy ≤ ± 1 %
Min. interval of Exposures | 20 sec (15 sec goal)
| Including CCD readout and wipe
pointing change
Min. number of filter holders | 4
Filter Exchange Time | < 10 minutes

Table 1. Specifications of Hyper Suprime-Cam (reproduced from Ref. [27]).

Figure 6. Cross sectional view of Hyper Suprime-Cam unit mounted on telescope’s top end hub (reproduced from Ref. [27]).

| Methods | Dominant systematic errors | SuMIRe approaches |
|---------|--------------------------|------------------|
| Weak lensing | Photo-z errors | PFS data (spectroscopic calibration sample) |
| | Shape measurements | Subaru image-quality, methods & algorithms |
| | Small-scale clustering | A suite of high-resolution simulations |
| Clusters | Mass-observable relations | Sunyaev-Zel’dovich-optical-lensing cross calibration |
| | Selection function | PFS spectroscopic calibration of BCGs |
| BAO | Galaxy biases | Lensing-galaxy cross-correlations |
| | Nonlinearities | A suite of simulations & refined analytical methods |
| Type-Ia supernovae | Photometric calibration | Calibration strategy, spectroscopic calibration |

Table 2. SuMIRe Dark Energy Experiments (courtesy of Masahiro Takada and John D. Silverman)
3.3 Prime Focus Spectrograph (PFS)

The basic design of PFS is as follows; in total 2000–3000 fibers to target 2200 galaxies per field-of-view. The spectral resolution is $R \approx 3000$ for wavelength 600–1000nm in order to survey galaxies over redshift range $0.6 < z < 1.6$ and to detect absorption/emission lines of each galaxies with enough signal-to-noise ratios $(S/N > 5–10)$. Thus it is possible to perform a multi-object spectroscopic survey of early-type galaxies and emission line galaxies up to $z \approx 1.6$.

The PFS will carry out another dark energy experiment through BAO from the measured three-dimensional galaxy distribution, which bears a great synergy with the HSC survey. The deep, multi-color HSC data sets can deliver an ideal catalog to find target galaxies for the PFS redshift survey based on the same telescope. To maximize the synergy of HSC and PFS surveys, we choose, as the target galaxies, red galaxies (BCGs and early-type galaxies) in cluster regions and star-forming blue galaxies. By targeting emission-line galaxies exhibiting [OII] (3726Å, 3729Å) with red-band sensitive CCD chips, we can probe the three-dimensional galaxy distribution over a wide range of redshifts, $0.6 < z < 1.6$. The spectral resolution of $R \approx 3000$ is important to discriminate [OII] emission lines from OH sky lines in red bands beyond 8000Å. The resulting survey is complementary to the ongoing BOSS (Baryon Oscillation Spectroscopic Survey) with redshift range $0.4 < z < 0.65$ and 10000 square degree area (mostly in the northern hemisphere sky); we can combine the spectroscopic data sets from the BOSS and PFS surveys to accurately estimate photometric redshift errors and cluster selection function. This will significantly reduce the systematic errors in the weak lensing and cluster experiments.

Figure 7 shows the expected accuracies of measuring the angular diameter distances and the Hubble expansion rate for each redshift slices. The PFS BAO survey can achieve a few percent accuracies of the distance measurements and is quite complementary to the SDSS and BOSS surveys, yielding a wider coverage of redshifts out to $z \approx 1.6$. The dark energy contribution to the cosmic expansion is thought to be insignificant at $z > 1$, if dark energy is the cosmological constant, and therefore the PFS survey combined with the SDSS and BOSS can open up a window to test early dark energy models up to $z \approx 1.6$.

Thus the SuMIRe (HSC + PFS) survey will aim at probing the nature of dark energy and/or testing gravity theories via weak lensing, BAO, galaxy clustering statistics, galaxy clusters, and supernovae, in addition to at constraining or even detecting neutrino mass and primordial non-Gaussianity for the first time.
4. CONCLUSION

Observational cosmology in the last decade clearly reminded us of the fact that one could have never imagined what dominates our world without dark nights. This may sound quite obvious now, but we do not seem to have fully appreciated the fact until very recently. The discovery of the cosmic acceleration indicates either an unknown component in the universe or an unknown law of gravity on cosmological scales. This poses a previously unknown and fundamental question in our world. Various on-going and up-coming international galaxy survey projects will answer the question in the next decade by taking photos of darkness, exactly in the same spirit of Simon & Garfunkel’s *The Sound of Silence*: “Hello darkness, my old friend. I’ve come to talk with you again”. I hope that we will come to understand better our old dark friend in due course.

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