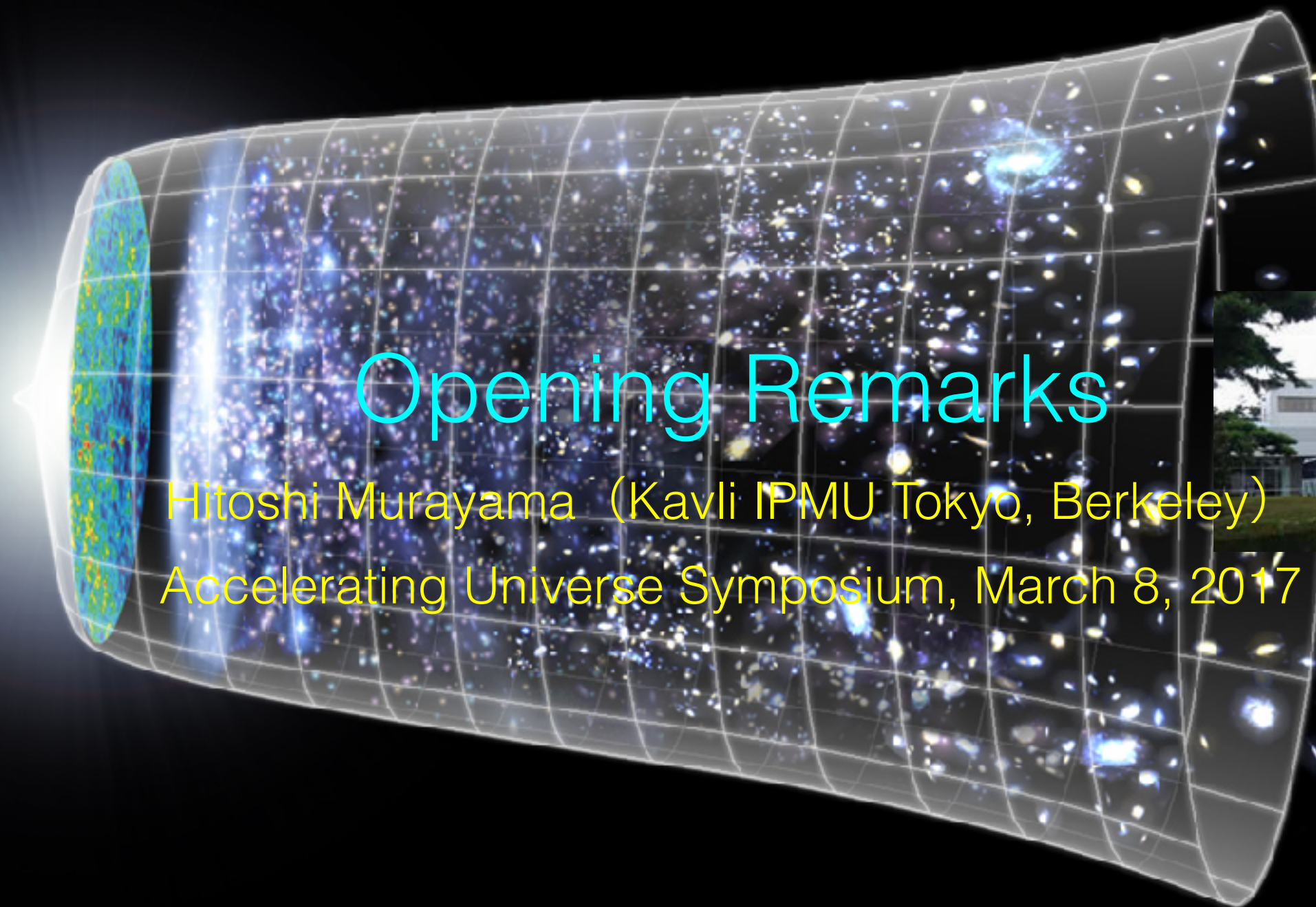
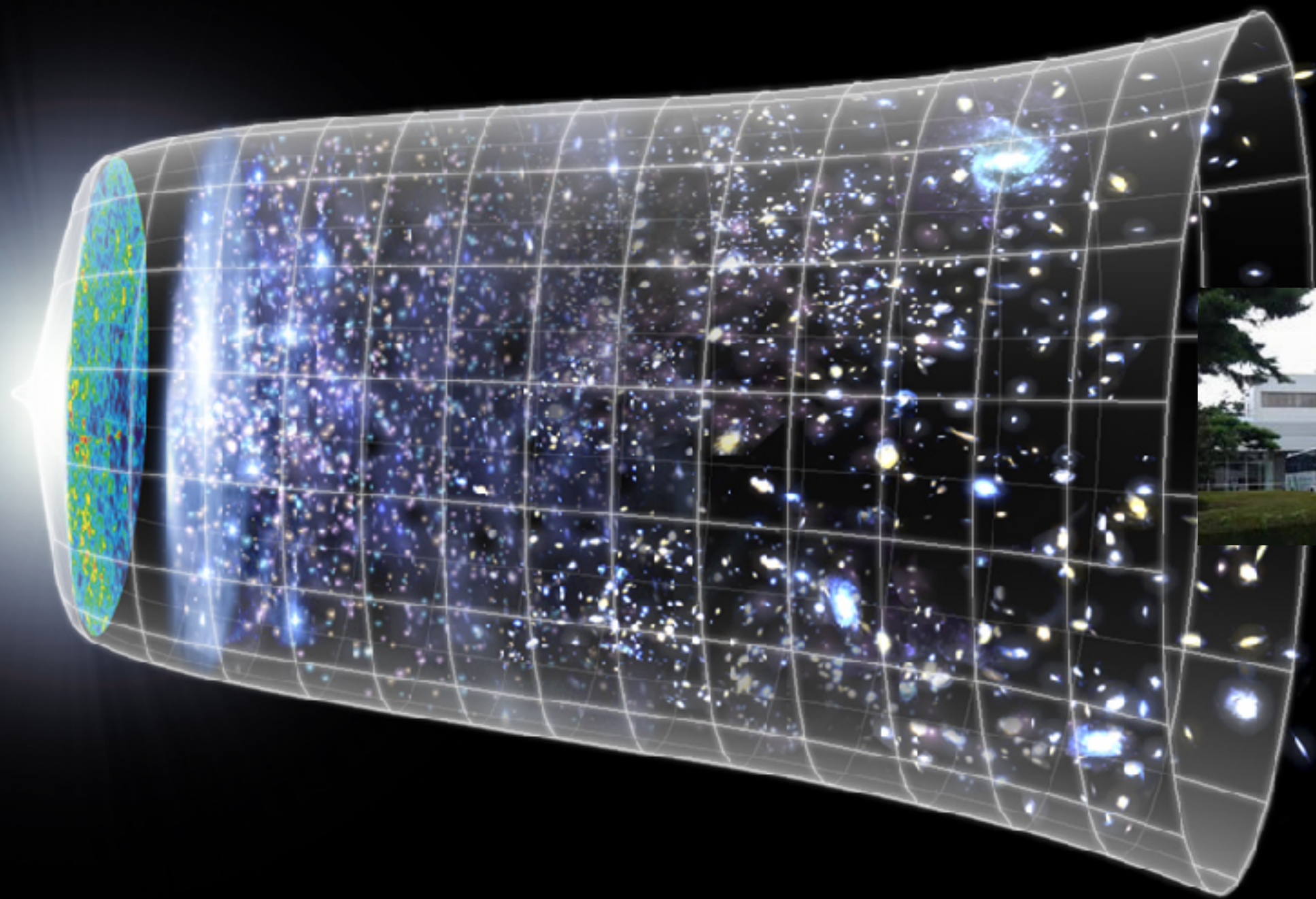




Opening Remarks

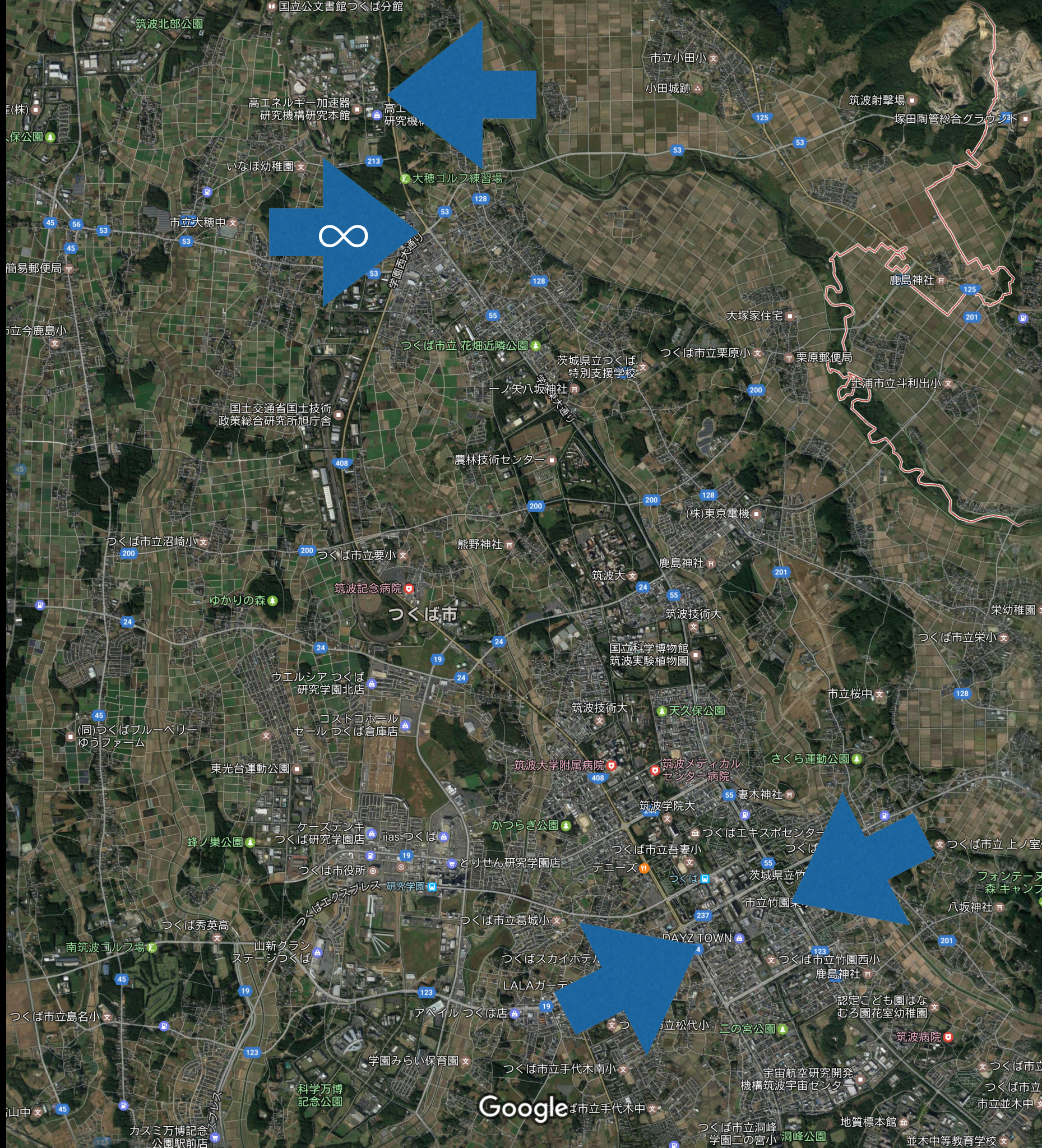
Hitoshi Murayama (Kavli IPMU Tokyo, Berkeley)
Accelerating Universe Symposium, March 8, 2017





Wow!

117 registrants



Google

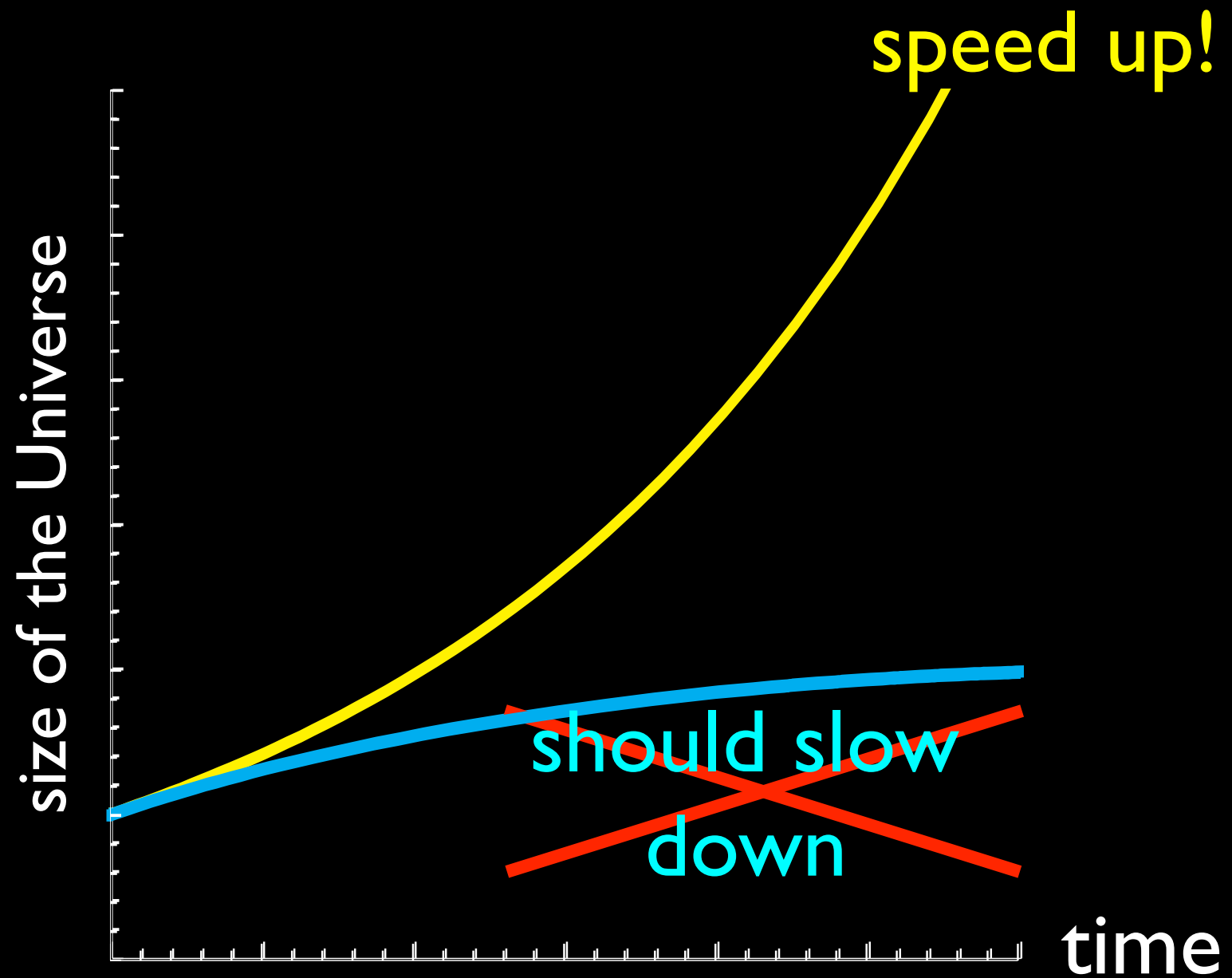
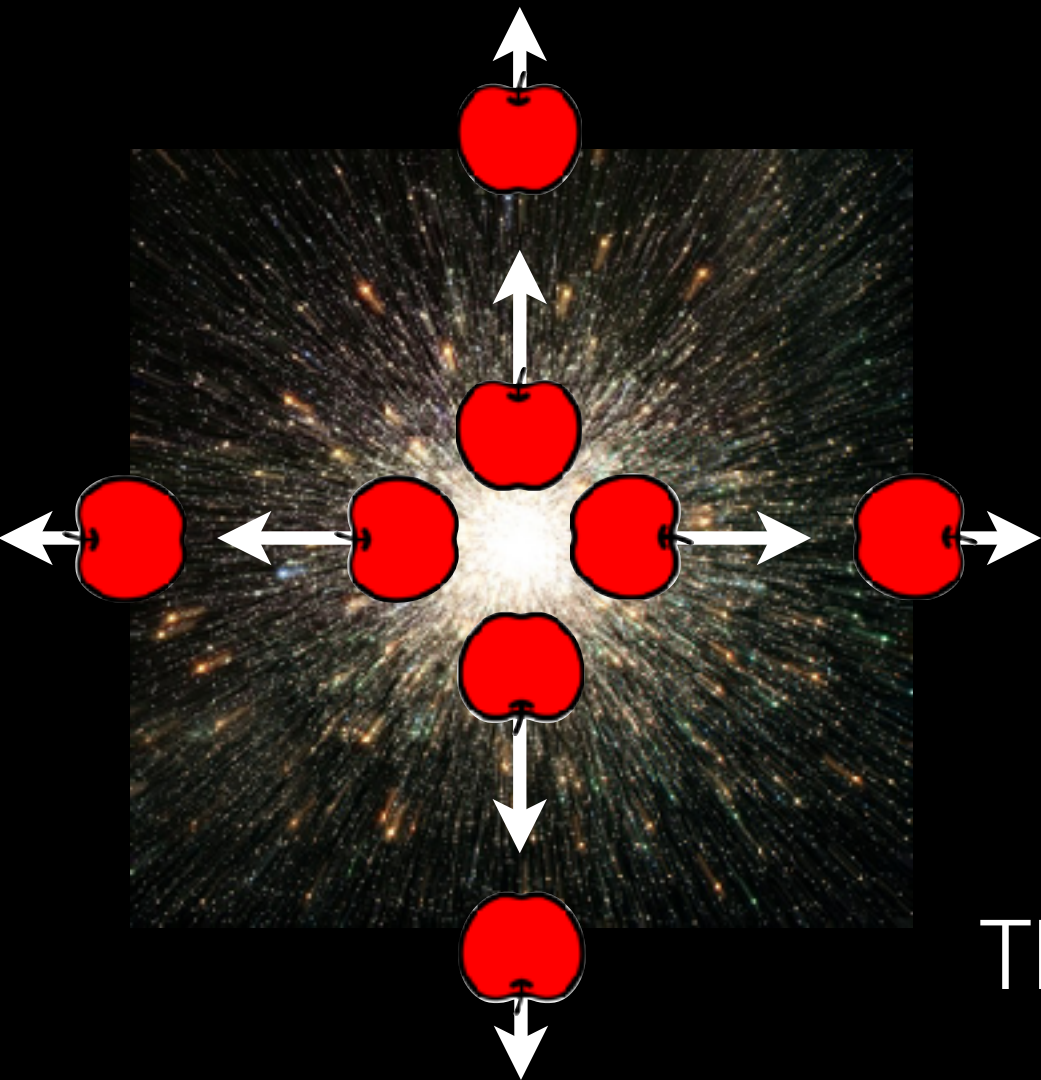
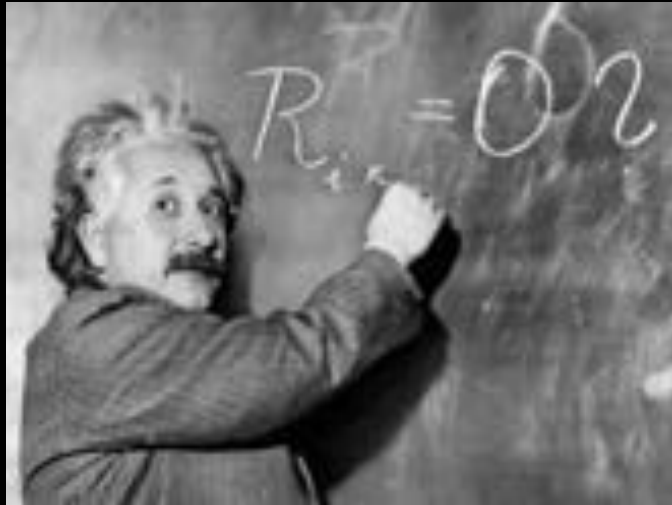
Why does the Universe speed up?— Comprehensive study and challenges to the future



PI : Hitoshi Murayama (Kavli IPMU Tokyo, Berkeley)

June 4, 2015

Cosmic Expansion



Gravity only pulls
Something is pushing the expansion
The biggest mystery in modern physics!



Phases of cosmic expansion

3 pillars of science

A03

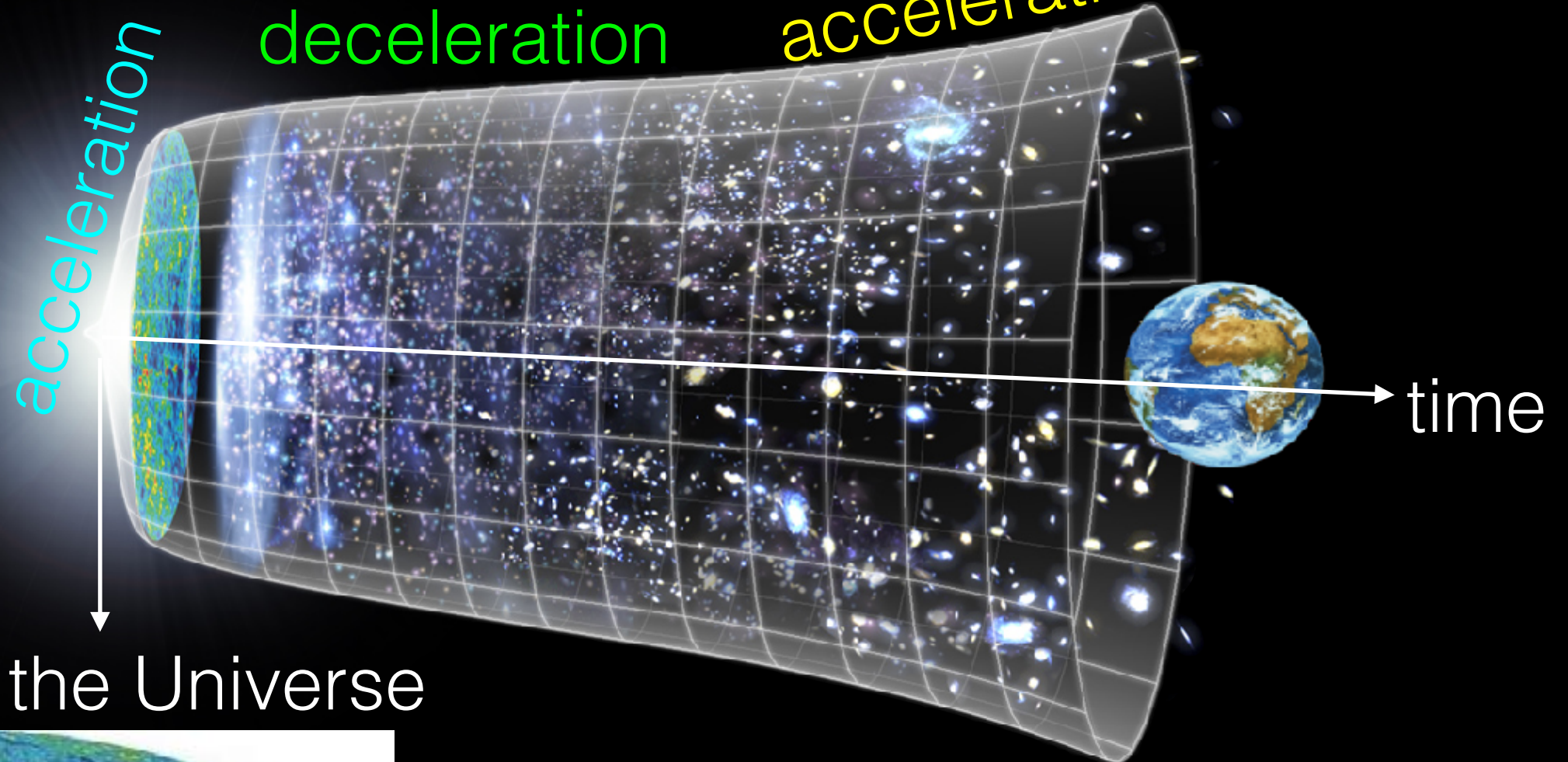
dark energy

A02 dark matter
deceleration

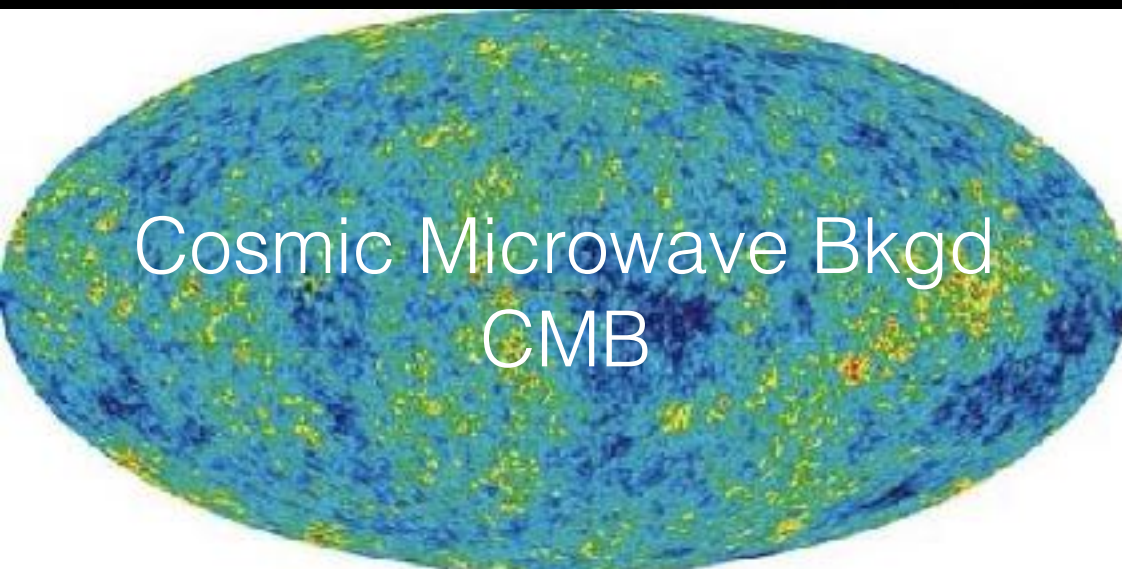
acceleration

A01
Inflation

acceleration



size of the Universe

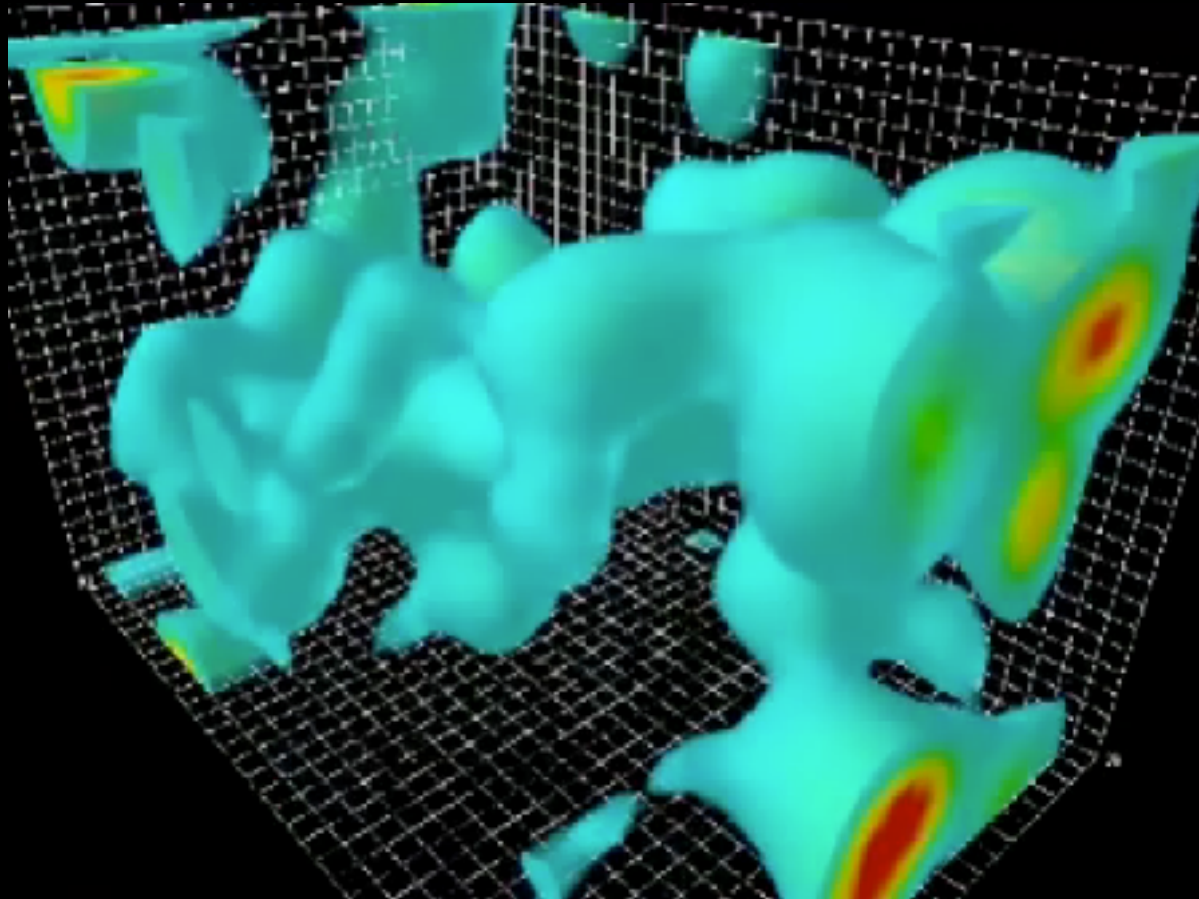


2011 Nobel Prize in Physics



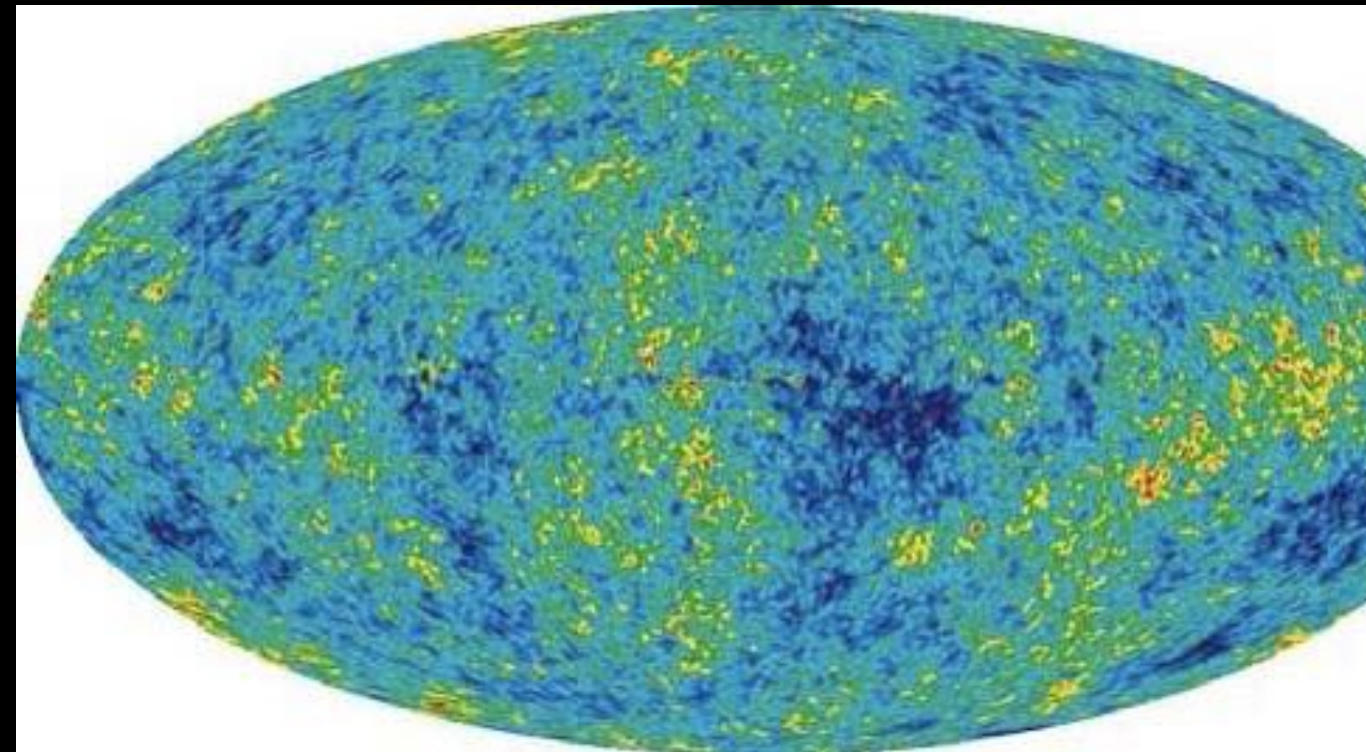
We are born from quantum fluctuation

Universe $< 10^{-26}$ cm



borrow & lend energy within
uncertainty principle

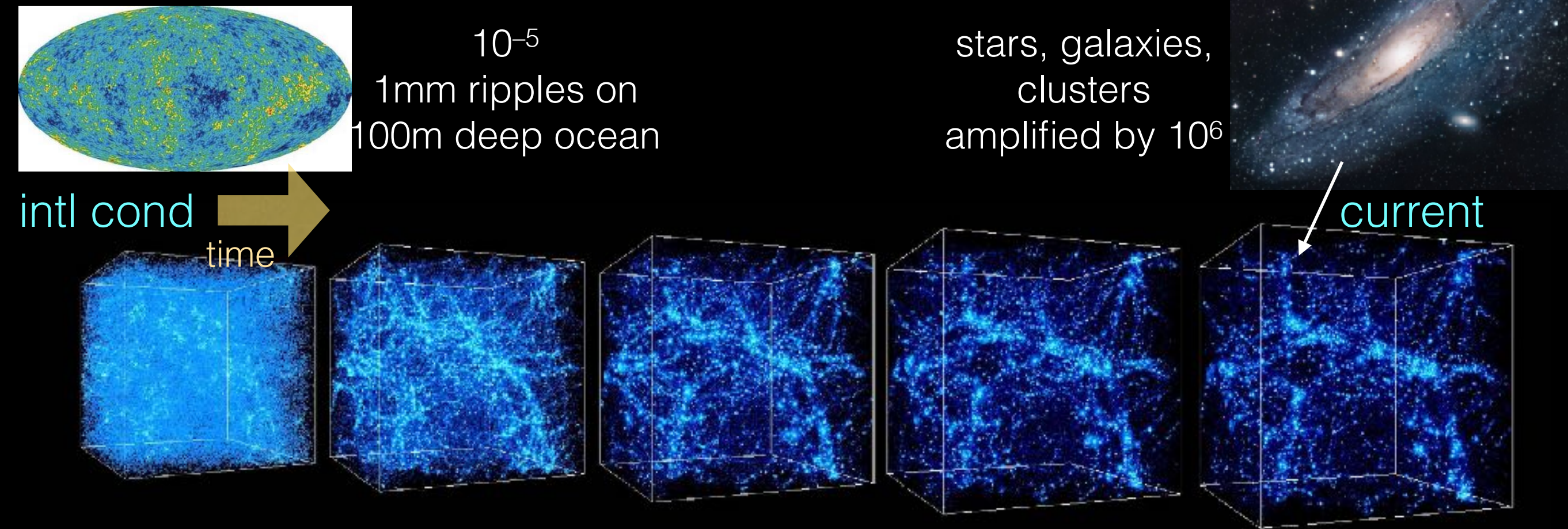
stretched to a macroscopic Universe



stuck with the energy borrowed or lent
fluctuation of 10^{-5}

Why, when did it accelerate?
How did it end acceleration and become hot?
quantum gravity?

Dark Matter is our Mom



Did dark matter really make stars & galaxies?
What is dark matter? Where did it come from?
Any relationship between dark matter & dark energy?

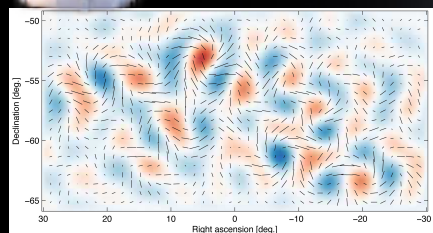
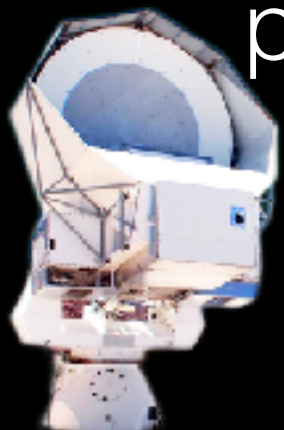
Universe being ripped apart



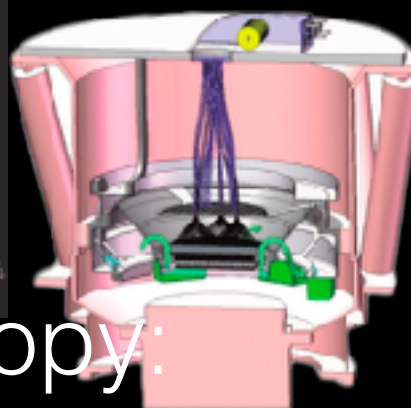
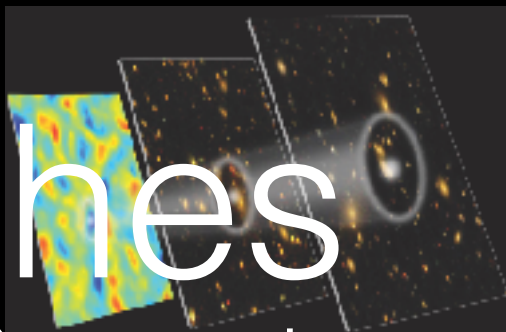
Why accelerate again? Was Einstein wrong?
Will the Universe end completely ripped apart?
Why “just right”? Multiverse?

4 Approaches

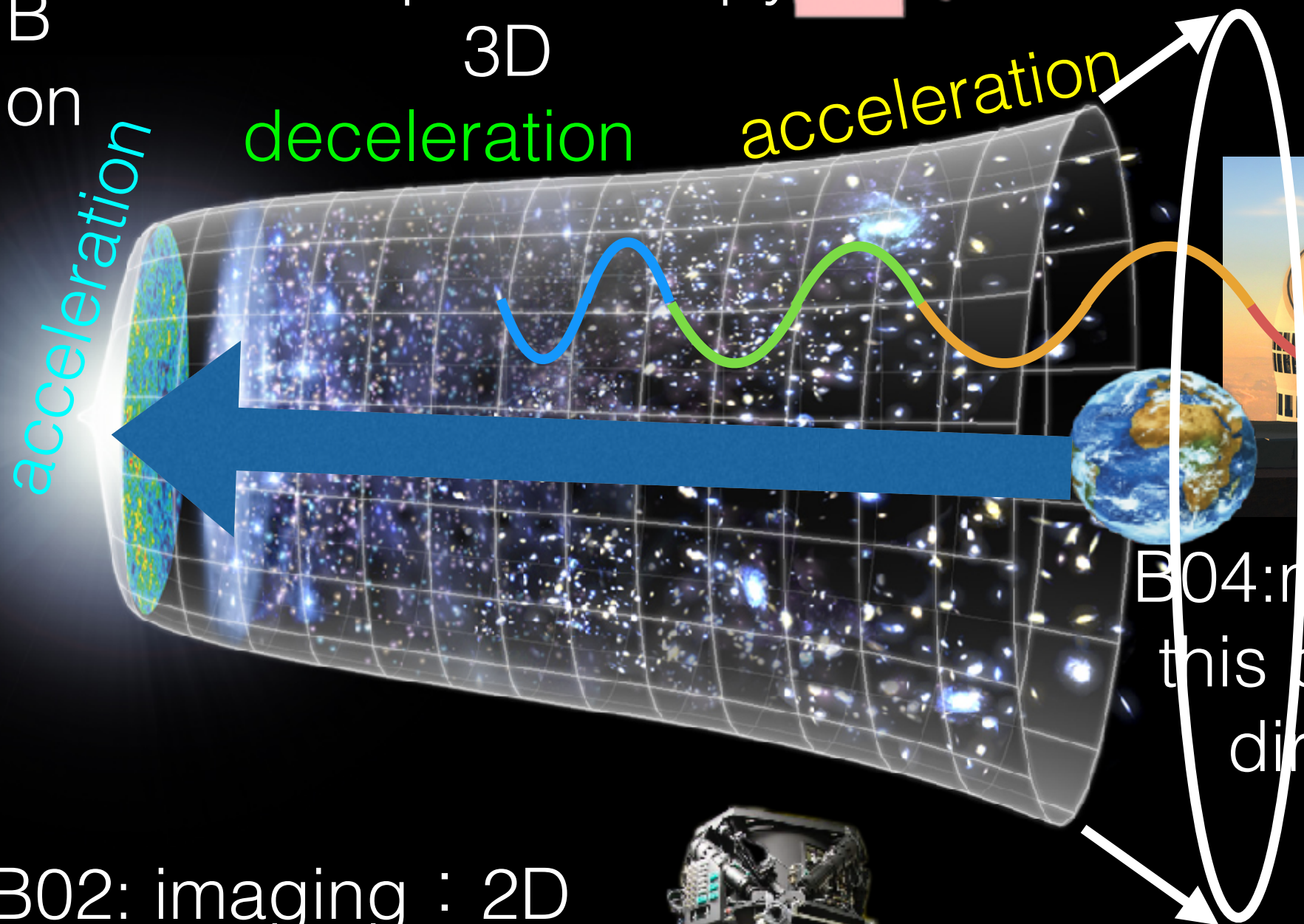
B01: CMB
polarization



B03: spectroscopy:
3D

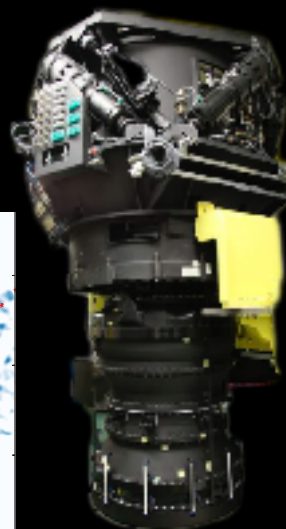
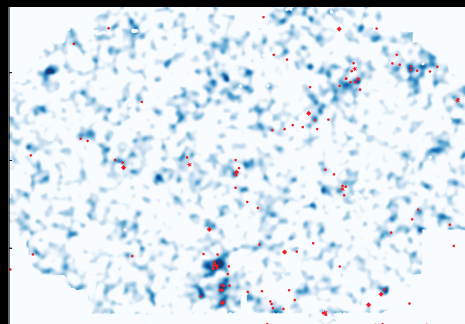


10 yrs later



B04: measure
this change
directly

B02: imaging : 2D



3 pillars of science (theory)

4 approaches (expt, obs)

	[A01] Inflation Sasaki (Kyoto)	[A02] fluent. & struct. Takahashi (Tohoku)	[A03] Dark Energy Sugiyama (Nagoya)
[B01] CMB polariz. Hazumi (KEK)	ζ, r, n_s direct evidence	CMB lensing isocurv. m_ν, N_ν	cosmo. params CMB lensing
[B02] Subaru galaxy imaging Miyazaki(NAOJ)	Lensing $\rightarrow b(k)$ $\rightarrow P_{\text{primod}}(k)$	weak lensing m_ν non-std. DM	weak lensing SNe, γ
[B03] galaxy spectroscopy Takada(KIPMU)	primord. NG Ω_K, n_s, α_s	isocurv. DM in dSph gals. $P(k), m_\nu$	BAO, RSD $\Omega_{\text{de}}(z), \gamma$
[B04] TMT Usuda (NAOJ)	QED coupling (α) space time var.	Lyman- α forests IGM	direct detection of acceleration

important observables at each intersection

C01: ultimate theory Ooguri(Caltech)

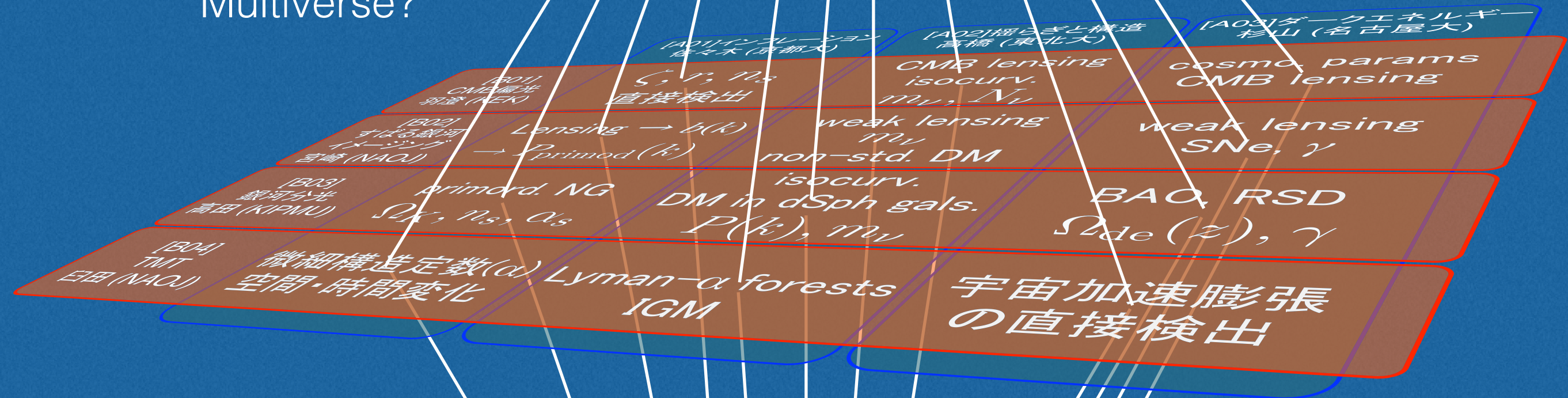
Universe before inflation?

Birth of time?

quantum gravity? string?

other dims? end of Universe?

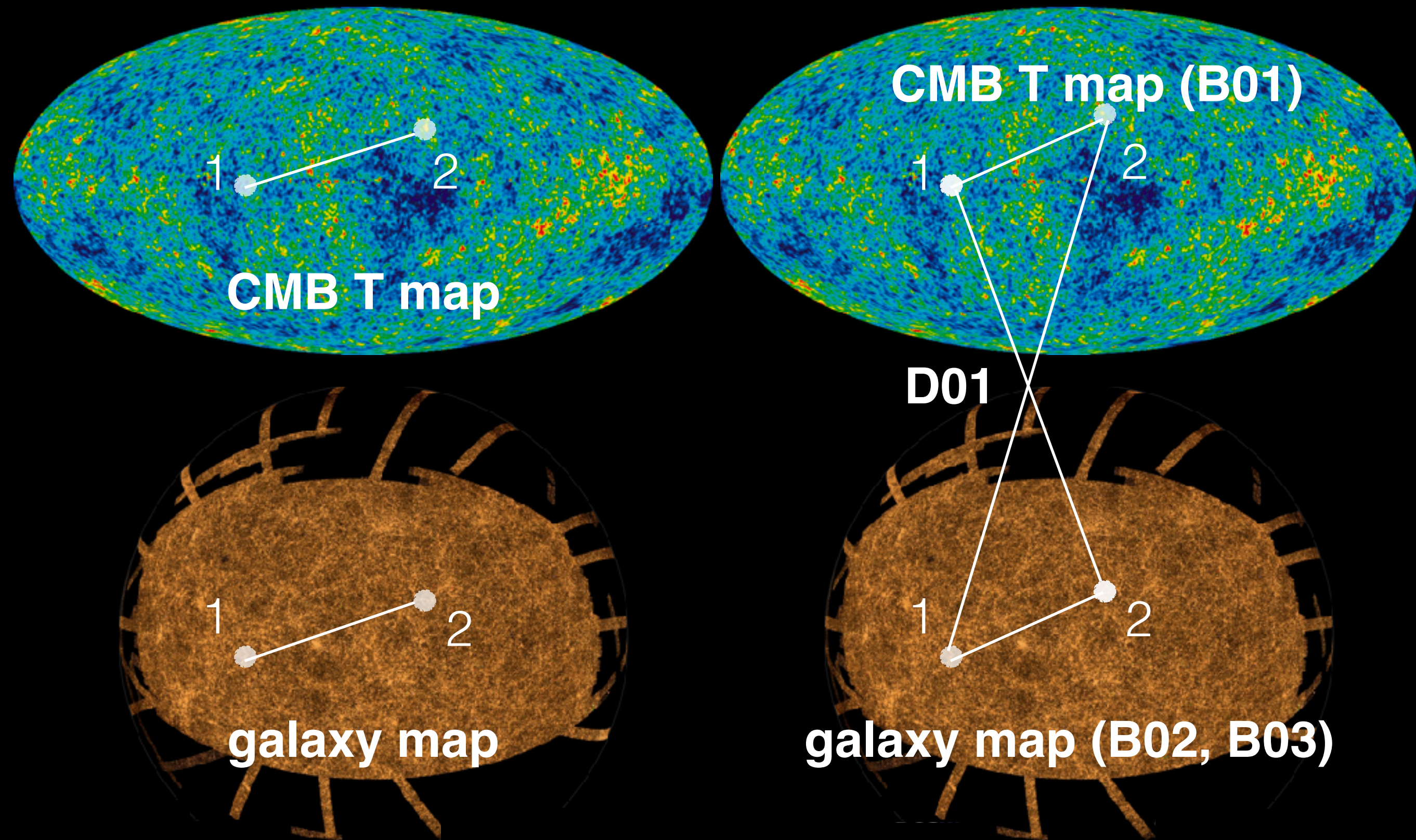
Multiverse?



X00: organization
Murayama (IPMU)

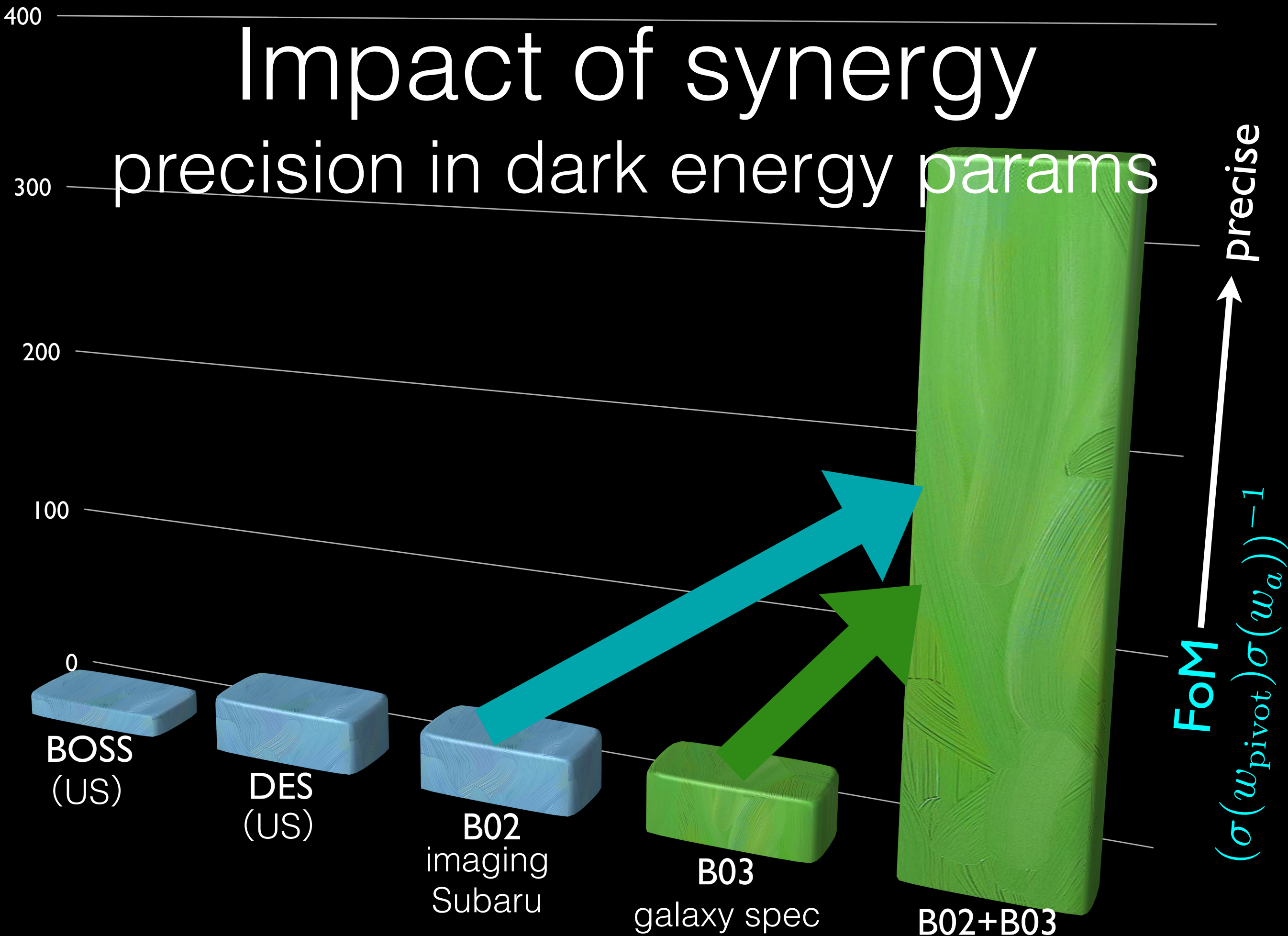
D01: ultimate analysis Komatsu(MPA)

D01: combination $\Rightarrow$ synergy



Impact of synergy

precision in dark energy params





HSC WFC



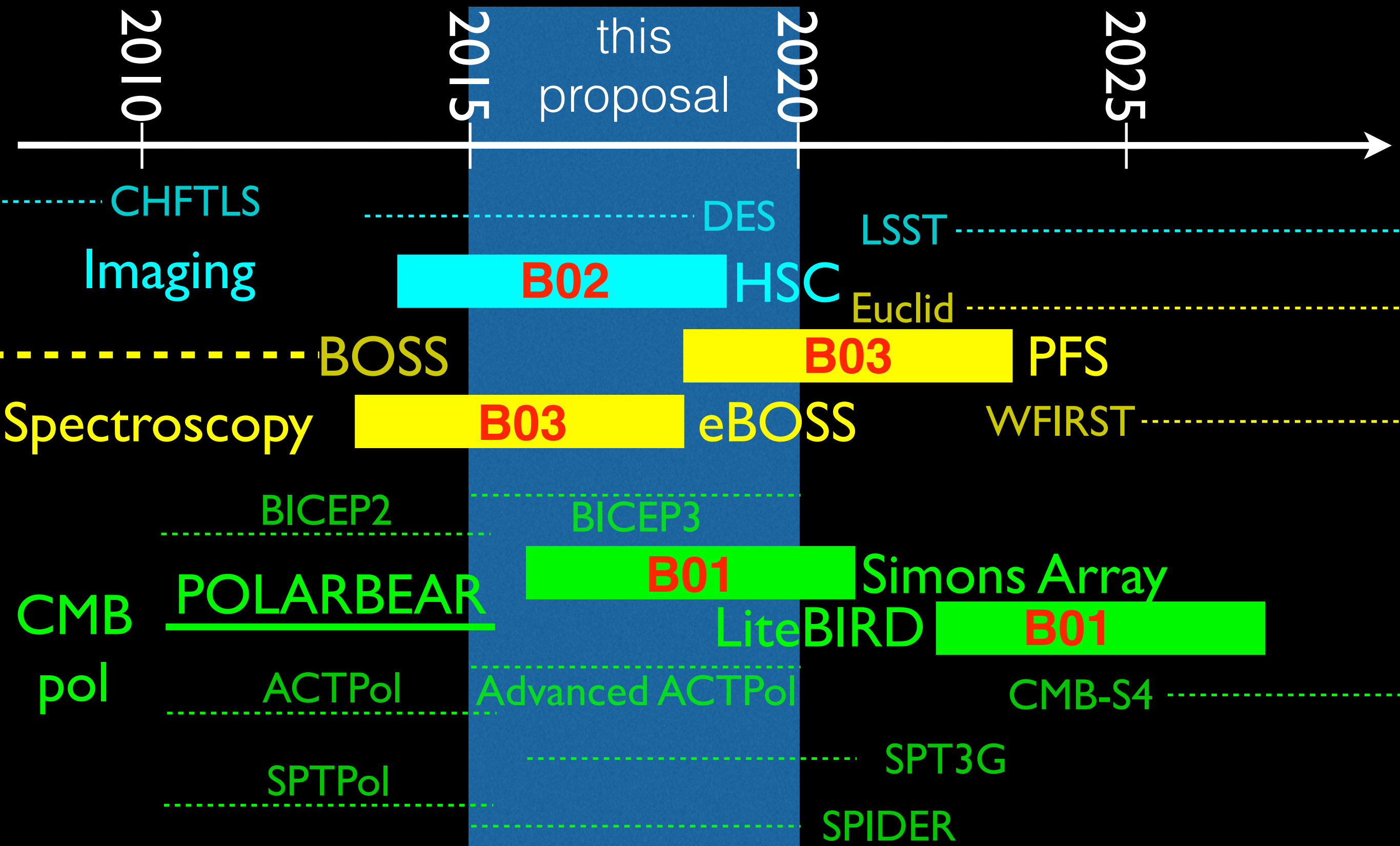
Example of readiness: B02

new camera on Subaru
2.5 hours in 3 colors

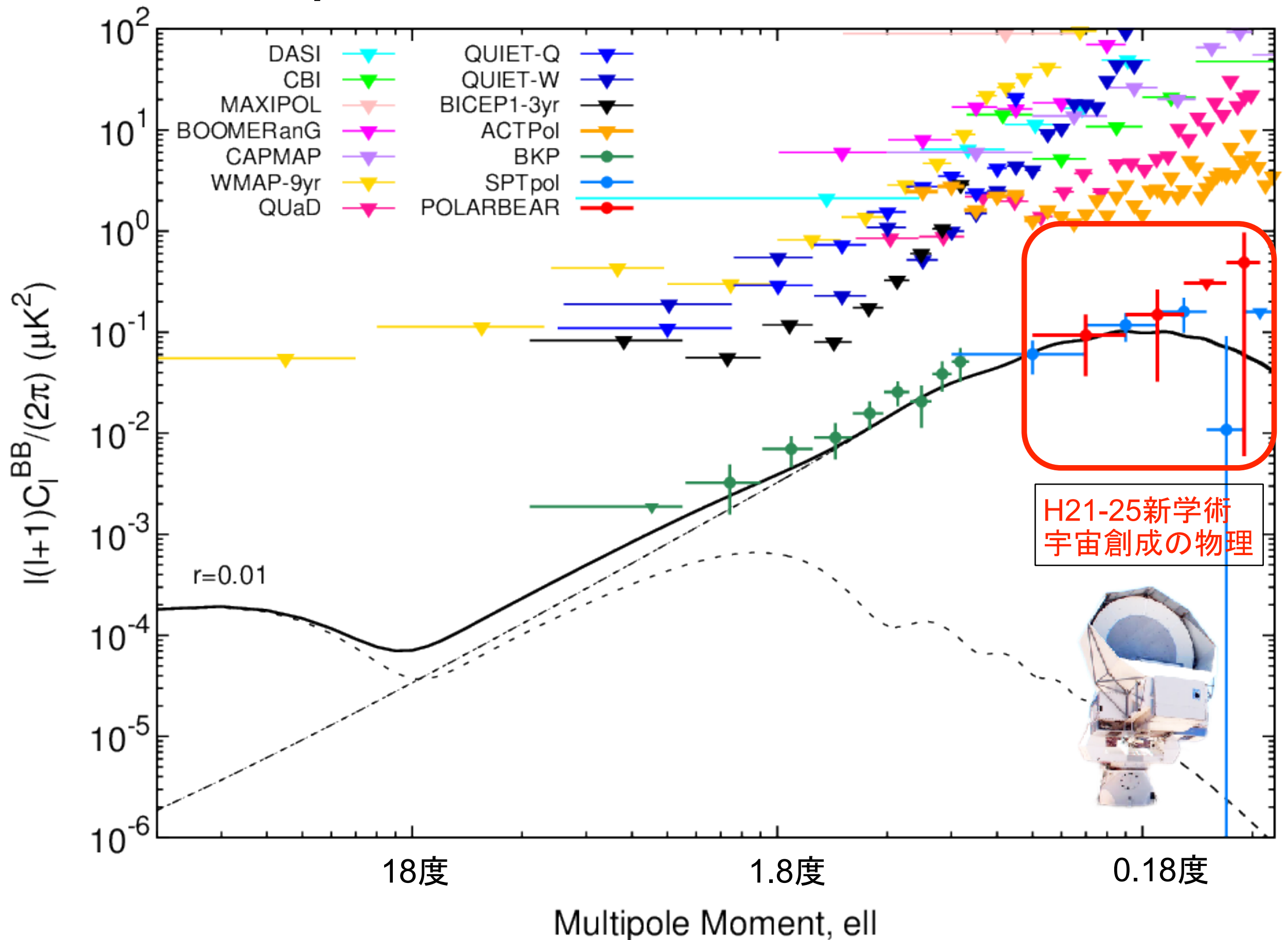
Hubble Space Telescope
500 hours in 1 color



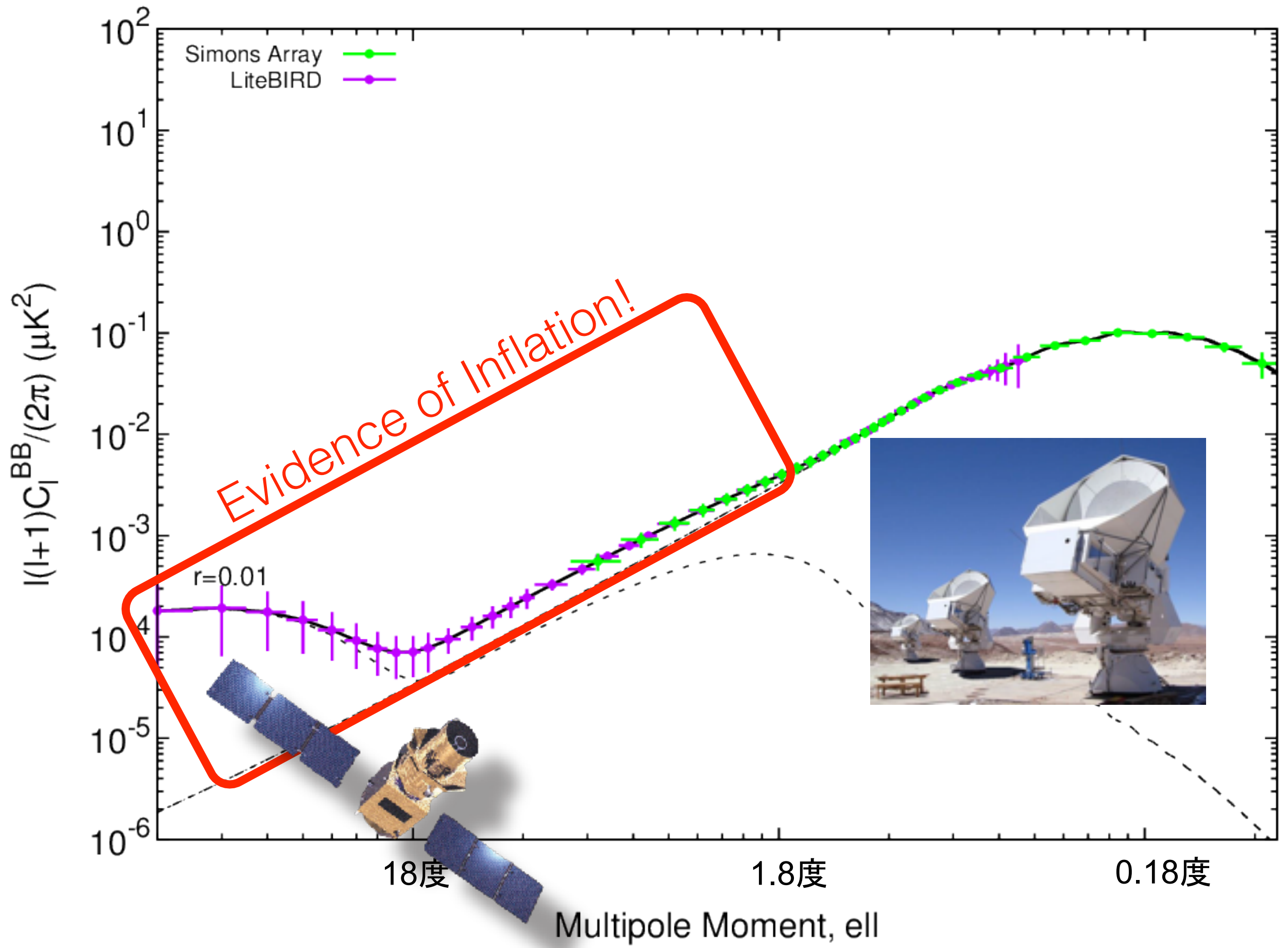
Intense Competition



Example of readiness: B01



And into the future: B01



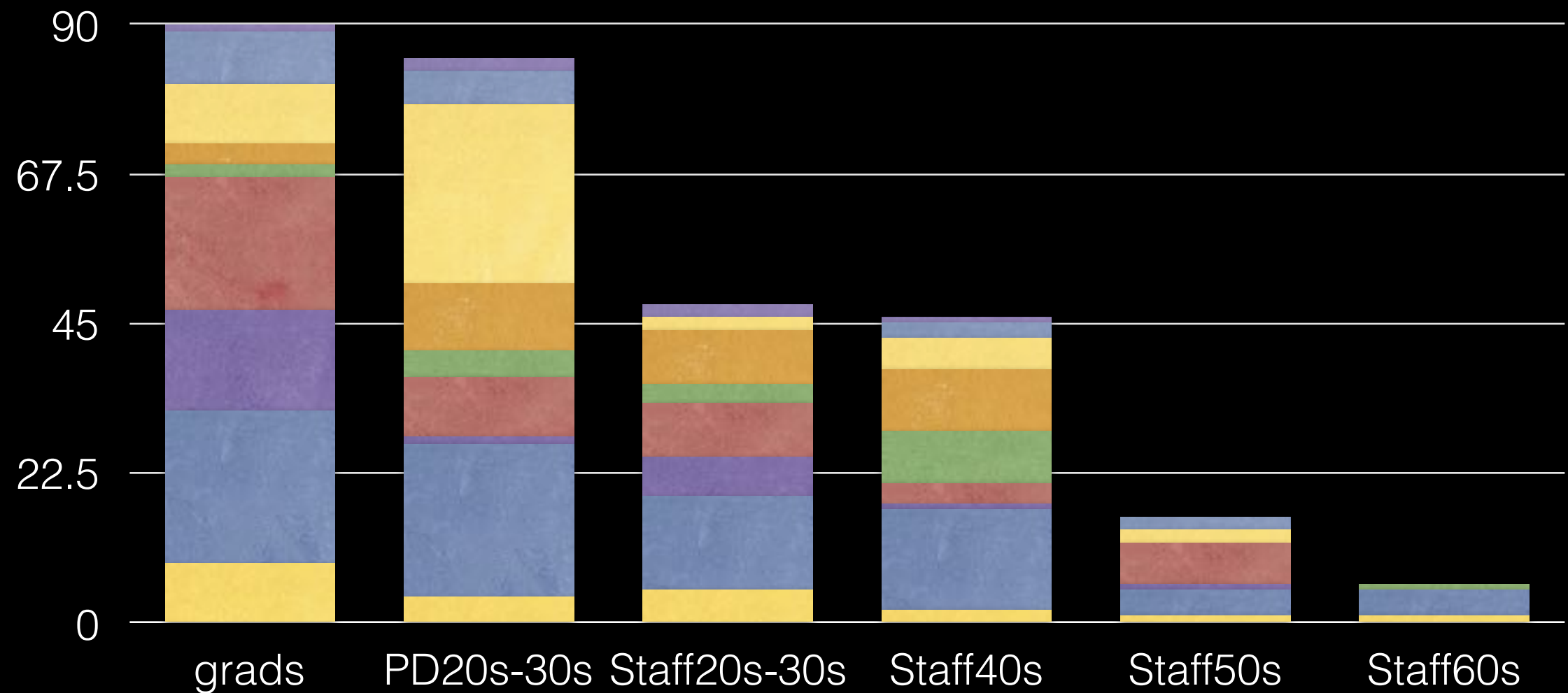
What result may come out

- *Possible within 5 years*
 - B01 detects primordial grav wave and proves inflation → Big challenge for string theory
 - B02 shows dark energy changes → Big Rip
- Preparation for future big discoveries
 - B03 measures curvature of space → Multiverse?
 - B04 detects variation in natl constants → strongly supports string
- evidence & new development in ultimate theory

All Star Team

Team	Name	Affiliation	Expertise
PI, organization	Murayama	Tokyo/Berkeley	particle theory
administration	Katayama	Tokyo	particle expt
A01	Sasaki	Kyoto	relativity
A02	Takahashi	Tohoku	particle theory
A03	Sugiyama	Nagoya	cosmology
B01	Hazumi	KEK	particle expt
B02	Miyazaki	NAOJ	observation, instrument
B03	Takada	Tokyo	cosmology
B04	Usuda	NAOJ	observation, instrument
C01	Ooguri	Tokyo/Caltech	particle
D01	Komatsu	Tokyo/MPA	cosmology

Age population

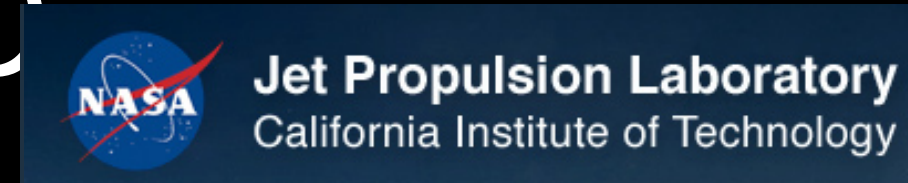
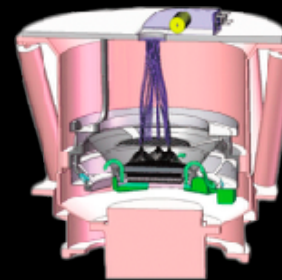
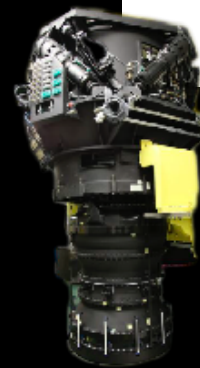
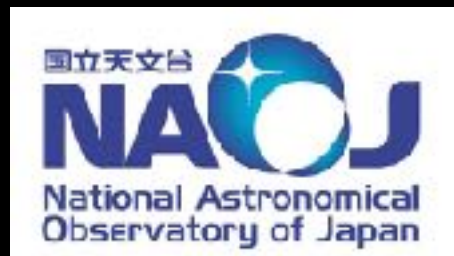
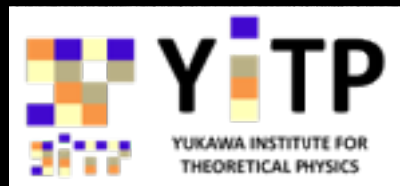


research led by grad students and researchers in 30s-40s

Japan

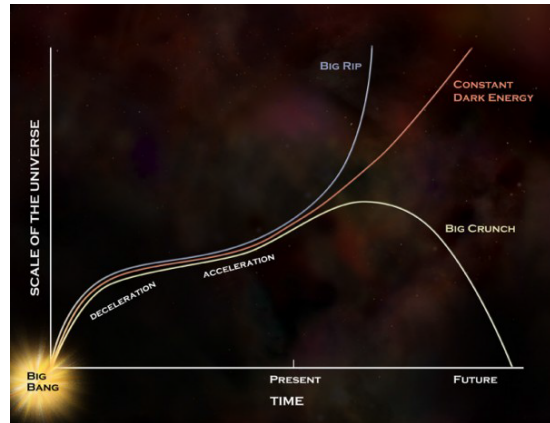
overseas

Intl collab



Strong Community Support

Comprehensive study of accelerating Universe



Ultimate Theory

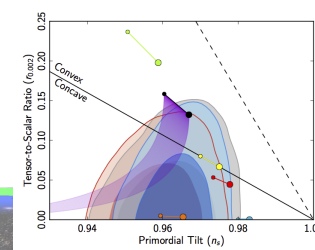
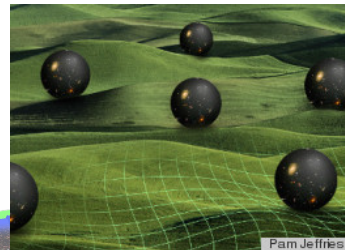
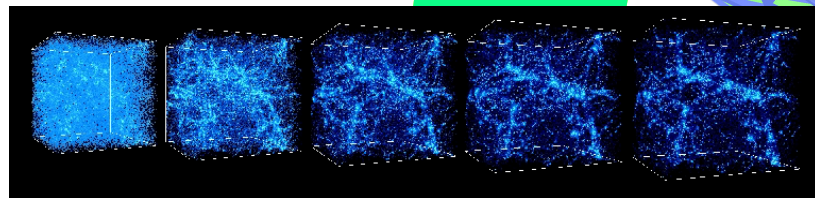
Ultimate Analysis

$$\frac{dz}{dt}$$

direct detection of acceleration (future)

TMT

Dark Energy



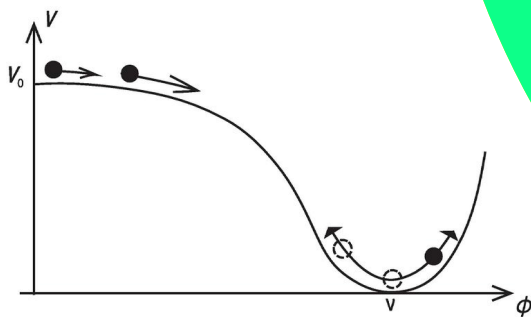
BAO, RSD

BOSS (finished)
eBOSS (H25 -)
MaNGA (H25 -)

PFS(future)

spectroscopy

Fluctuation & Structure



Inflation

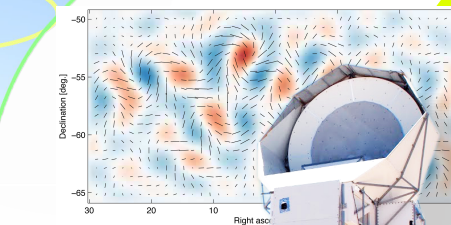


grav lensing
dark matter map



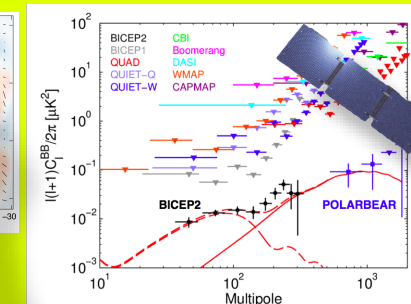
(H26-30)

Subaru HSC



CMB B-mode

Simons
Array (H27-)



CMB E-mode
primordial spectrum
primordial non-Gaussianity



LiteBIRD
(future)

CMB Pol.

Some of Activity

- Approved for ~¥1.5B
- Also “International Funds”
- First symposium September 20, 2015
- 24 research funded through open solicitation
- Meetings of the steering committee
- Nov 9-11, 2016 Autumn School on dark matter ~100 people
- We look at progress after 1.5 years today

A Small Fraction of
What's going on

3 pillars of science (theory)

4 approaches (expt, obs)

	[A01] Inflation Sasaki (Kyoto)	[A02] fluent. & struct. Takahashi (Tohoku)	[A03] Dark Energy Sugiyama (Nagoya)
[B01] CMB polariz. Hazumi (KEK)	ζ, r, n_s direct evidence	CMB lensing isocurv. m_ν, N_ν	cosmo. params CMB lensing
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[B04] TMT Usuda (NAOJ)	QED coupling (α) space time var.	Lyman- α forests IGM	direct detection of acceleration

important observables at each intersection

First Data Release of the Hyper Suprime-Cam Subaru Strategic Program

Hiroaki Aihara¹, Robert Armstrong², Steven Bickerton³, James Bosch², Jean Coupon⁴, Hisanori Furusawa⁵, Yusuke Hayashi⁵, Hiroyuki Ikeda⁵, Yukiko Kamata⁵, Hiroshi Karoji^{6,2}, Satoshi Kawanomoto⁵, Michitaro Koike⁵, Yutaka Komiyama^{5,7}, Robert H. Lupton², Sogo Mineo⁵, Hironao Miyatake^{8,9}, Satoshi Miyazaki^{5,7}, Tomoki Morokuma^{10,9}, Yoshiyuki Obuchi⁵, Yukie Oishi⁵, Yuki Okura^{11,12}, Paul A. Price², Tadafumi Takata^{5,7}, Manobu M. Tanaka¹³, Masayuki Tanaka^{5,*}, Yoko Tanaka¹⁴, Tomohisa Uchida¹³, Fumihiro Uraguchi⁵, Yousuke Utsumi¹⁵, Shiang-Yu Wang¹⁶, Yoshihiko Yamada⁵, Hitomi Yamanoi⁵, Naoki Yasuda⁹, Nobuo Arimoto^{14,7}, Masashi Chiba¹⁷, Francois Finet¹⁴, Hiroki Fujimori¹⁸, Seiji Fujimoto¹⁹, Junko Furusawa⁵, Tomotsugu Goto²⁰, Andy Goulding², James E. Gunn², Yuichi Harikane^{19,21}, Takashi Hattori¹⁴, Masao Hayashi⁵, Krzysztof G. Helminiak²², Ryo Higuchi¹⁹, Chiaki Hikage⁹, Paul T.P. Ho^{16,23}, Bau-Ching Hsieh¹⁶, Kuiyun Huang²⁴, Song Huang^{25,9}, Masatoshi Imanishi^{5,7}, Ikuru Iwata^{14,7}, Anton T. Jaelani¹⁷, Hung-Yu Jian¹⁶, Nobunari Kashikawa^{5,7}, Nobuhiko Katayama⁹, Takashi Kojima^{19,21}, Akira Konno¹⁹, Shintaro Koshida¹⁴, Alexie Leauthaud²⁵, C.-H. Lee¹⁴, Lihwai Lin¹⁶, Yen-Ting Lin¹⁶, Rachel Mandelbaum²⁶, Yoshiki Matsuoka^{5,27}, Elinor Medezinski², Shoken Miyama^{15,28}, Rieko Momose²⁰, Anupreeta More⁹, Surhud More⁹, Shiro Mukae¹⁹, Ryoma Murata^{9,1}, Hitoshi Murayama^{9,29,30}, Tohru Nagao²⁷, Fumiaki Nakata¹⁴, Hiroko Niikura^{1,9}, Atsushi J. Nishizawa³¹, Masamune Oguri^{32,9,1}, Nobuhiro Okabe^{33,15}, Yoshiaki Ono¹⁹, Masato Onodera¹⁴, Masafusa Onoue^{5,7}, Masami Ouchi^{19,9}, Tae-Soo Pyo¹⁴, Takatoshi Shibuya¹⁹, Kazuhiro Shimasaku²¹, Melanie Simet³⁴, Joshua Speagle^{35,9}, David N. Spergel^{2,36}, Michael A. Strauss², Yuma Sugahara^{19,21}, Naoshi Sugiyama^{37,9}, Yasushi Suto^{1,32}, Nao Suzuki⁹, Philip J. Tait¹⁴, Masahiro Takada⁹, Tsuyoshi Terai¹⁴, Yoshiki Toba¹⁶, Edwin L. Turner^{2,9,1}, Hisakazu Uchiyama⁷, Keiichi Umetsu¹⁶, Yuji Urata³⁸, Tomonori Usuda^{5,7}, Sherry Yeh¹⁴, Suraphong Yuma³⁹,

61.5 nights
out of
approved 300

~100M objects

~half Petabyte!

¹Department of Physics, University of Tokyo, Tokyo 113-0033, Japan

²Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane, Princeton, NJ 08544

³Orbital Insight, 100 W. Evelyn Ave. Mountain View, CA 94041

⁴Department of Astronomy, University of Geneva, ch. d'Écogia 16, 1290 Versoix, Switzerland

⁵National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

⁶National Institutes of Natural Sciences, 4-3-13 Toranomon, Minato-ku, Tokyo, JAPAN

⁷Department of Astronomy, School of Science, Graduate University for Advanced Studies (SOKENDAI), 2-21-1, Osawa, Mitaka, Tokyo 181-8588, Japan



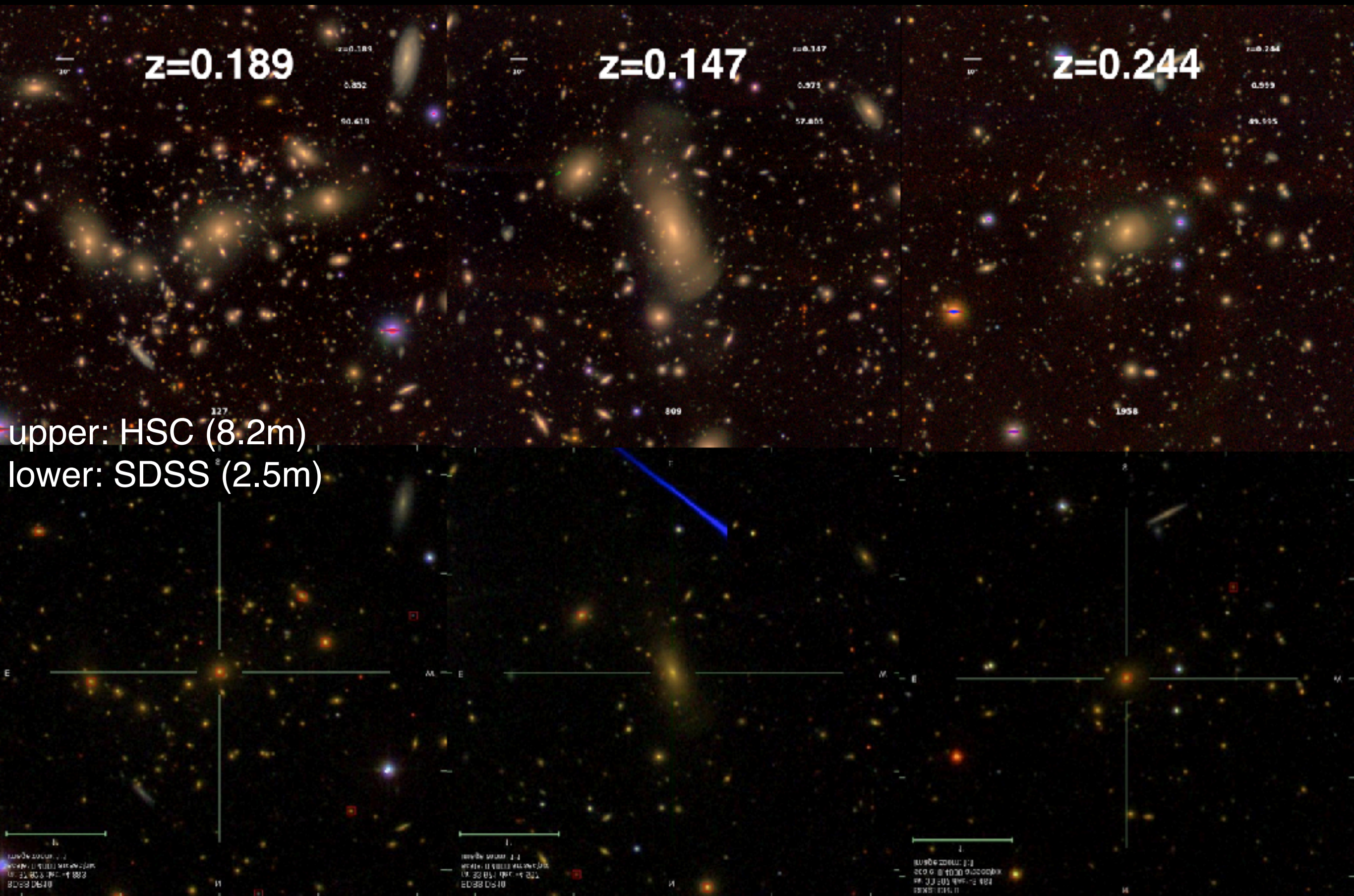
a small part of
COSMOS field
g, r, i
<27 mag!

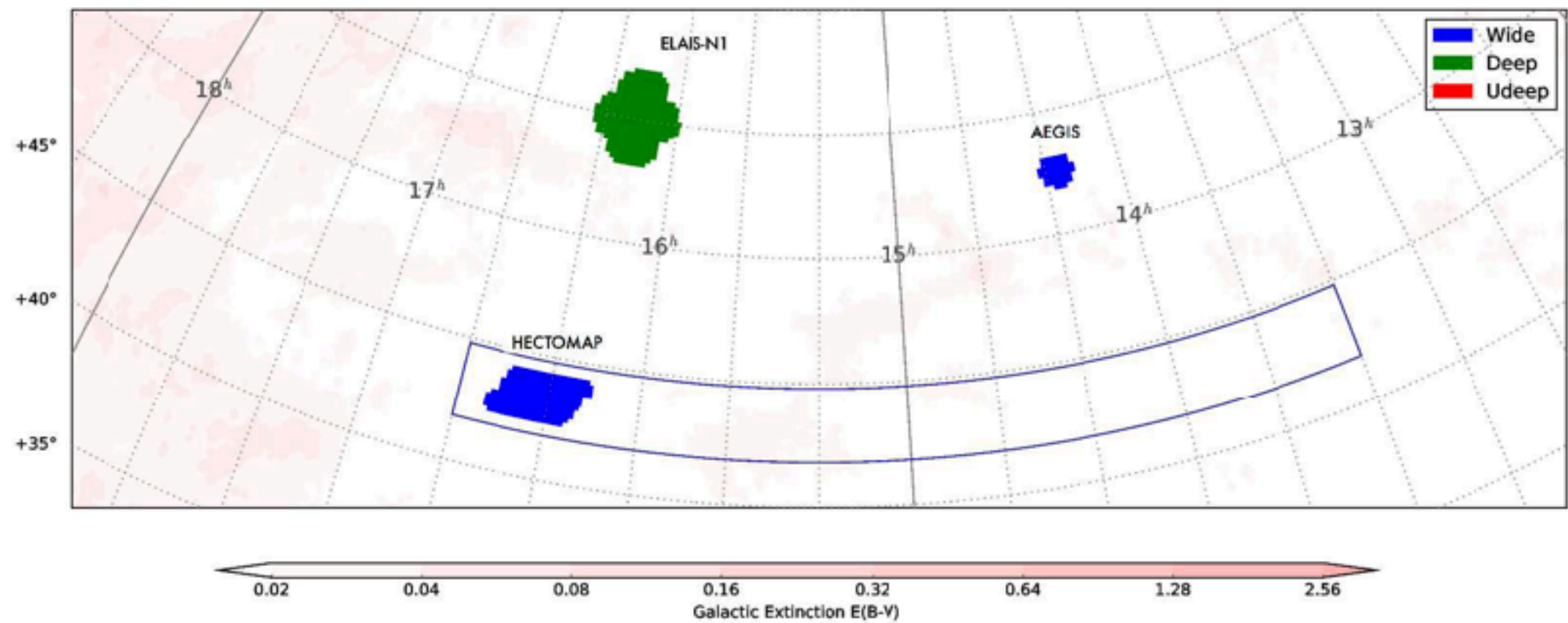
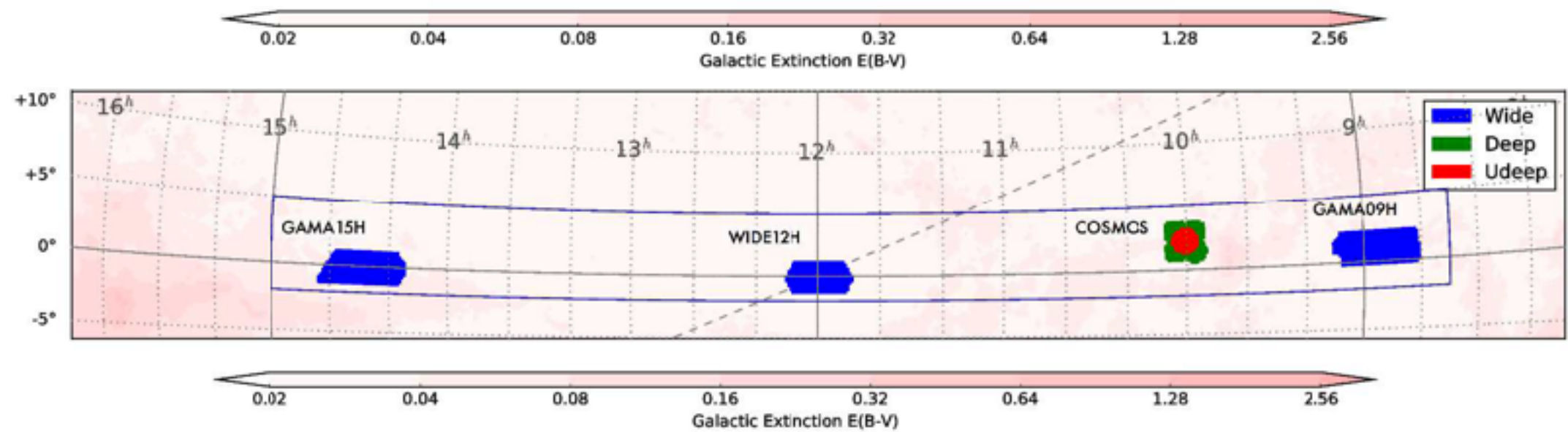
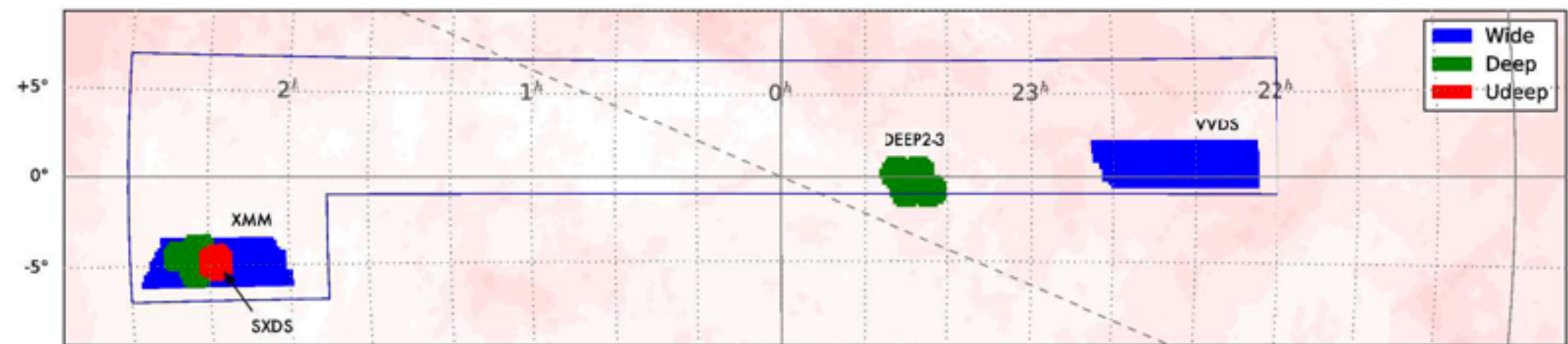


a massive cluster of galaxies $\sim 5.3 \text{ Glyr}$
g, r, i, composite, $\sim 0.6''$



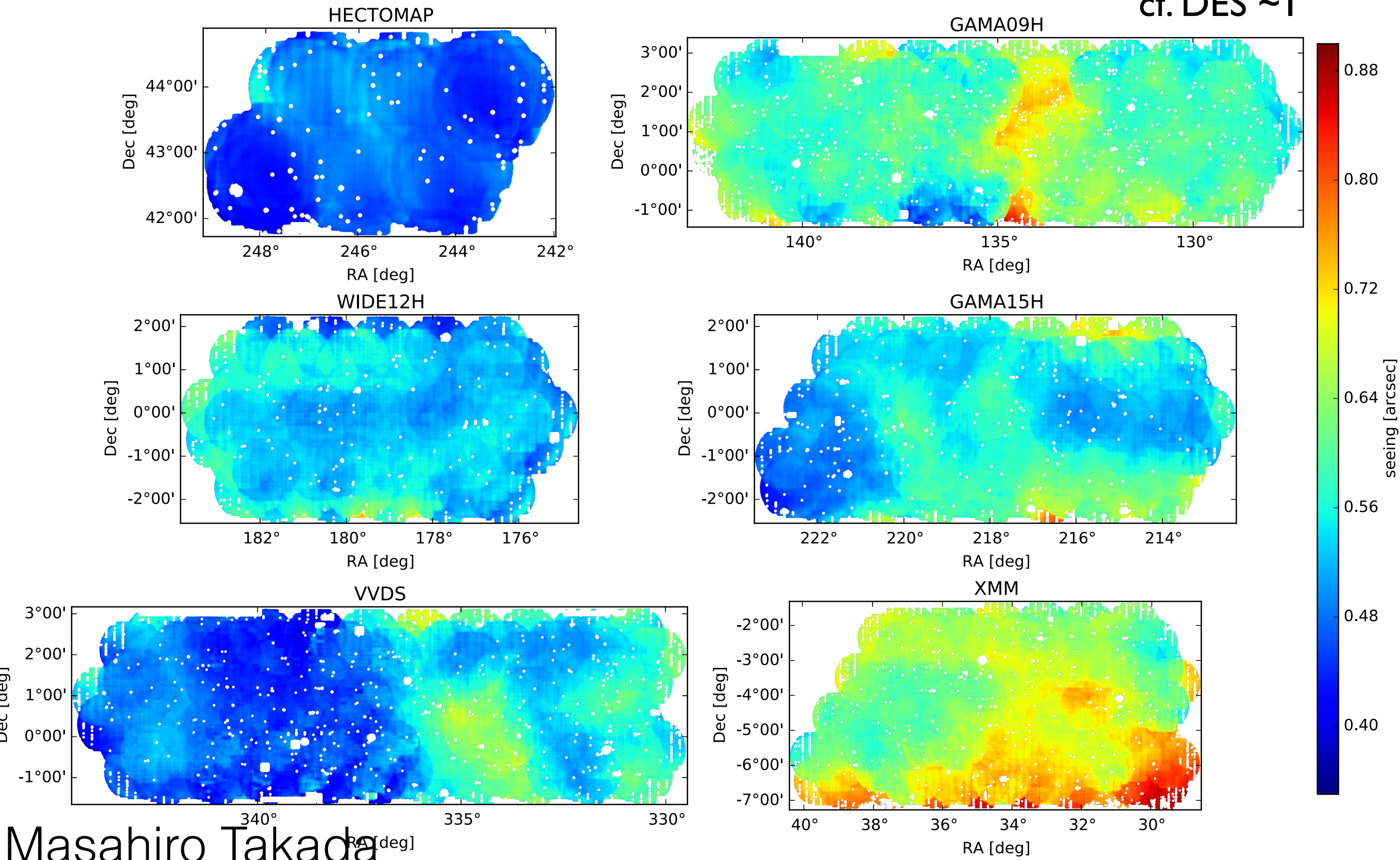
The Tadpole Galaxy $\sim 400\text{Mlyr}$
g, r, i, composite, $\sim 0.6''$



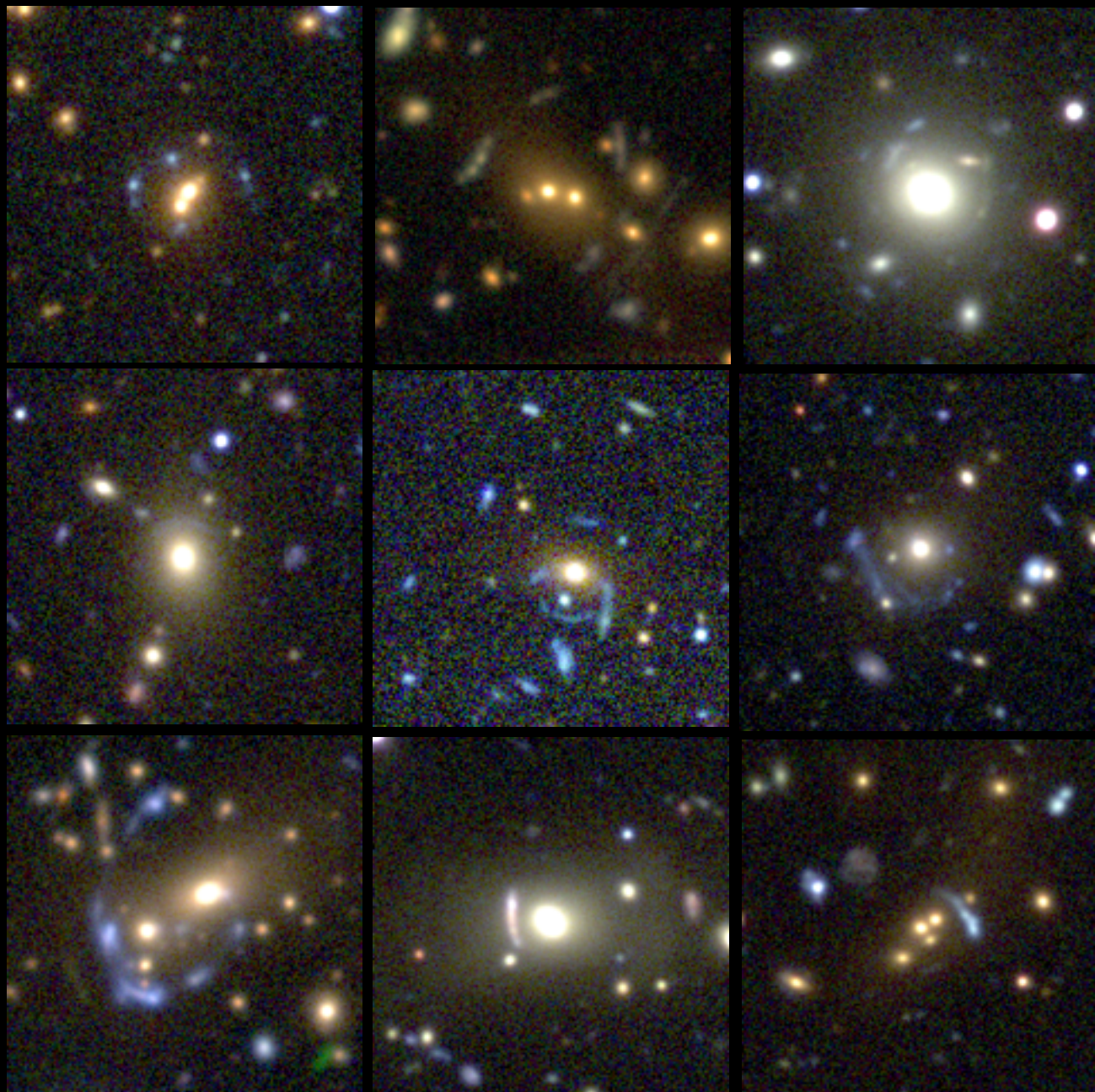


Now move forward to writing the 1st-year science papers with about **170 sq. degs.** (full color, full depth), typical seeing **~0.6"**, so far 100 nights

cf. DES ~1"



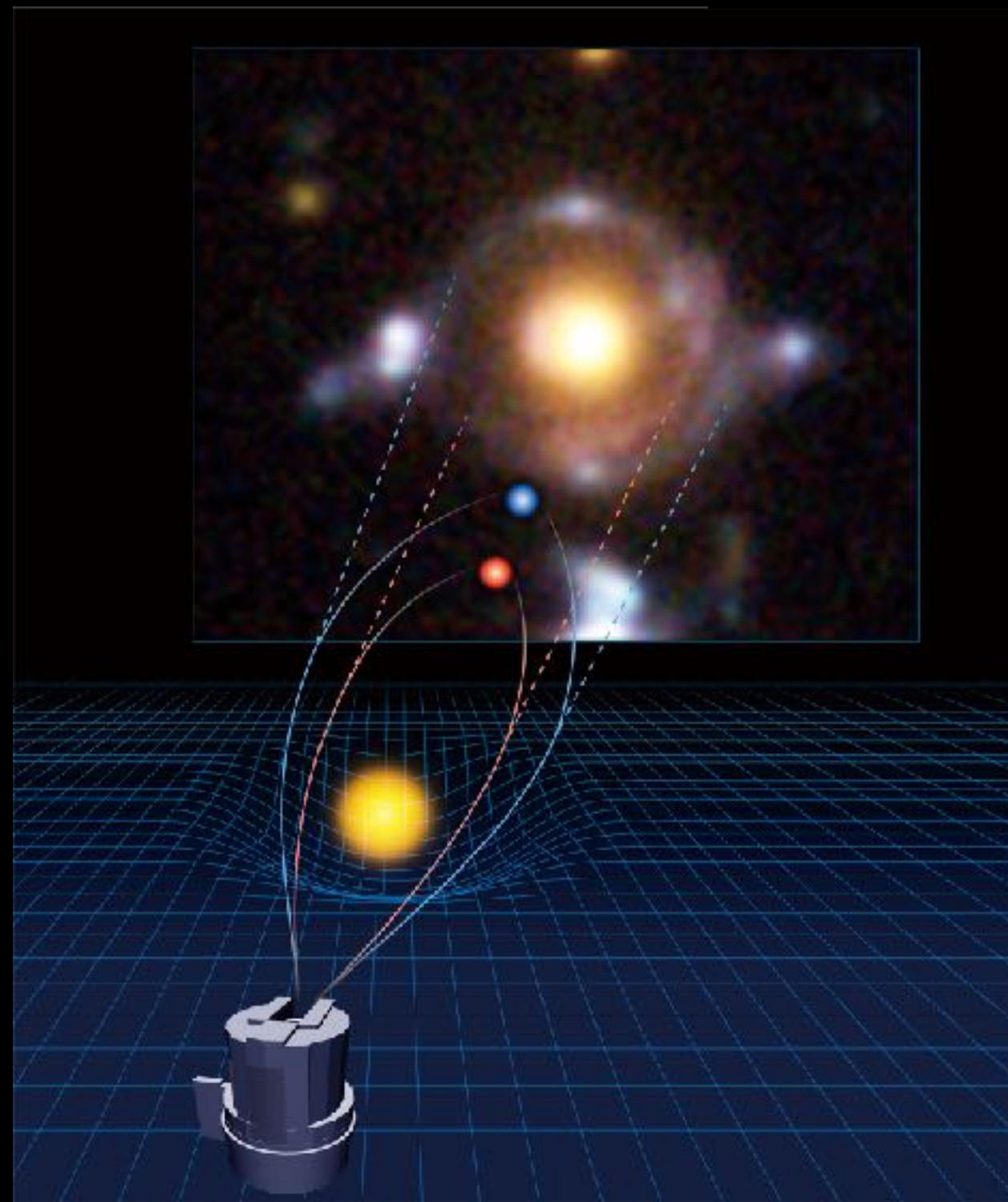
“Eye of Horus”



More et al. (in prep)

15 new strong lensing

Anupreeta More



Double Source Plane

Faster-Than-Expected Expansion of the Universe Supported by Results from Cosmic Lensing Research

$$\Omega_{\Lambda} = 0.62^{+0.24}_{-0.35}$$

January 27, 2017

Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU)

An international team of astronomers, including Kavli IPMU Project Researcher Alessandro Sonnenfeld, has used galaxies as giant gravitational lenses to make an independent measurement of how fast the Universe is expanding. Led by Sherry Suyu, the Max Planck @TUM professor at the Technical University Munich and Max Planck Institute for Astrophysics, Germany, the team used the NASA/ESA Hubble Space Telescope, the Subaru Telescope, and other telescopes in space and on the ground to study five galaxies [1].

The study arrived at an independent measurement of the Hubble constant—a fundamental quantity that describes the rate at which the Universe is expanding [2]. The new results are entirely independent and agree with other measurements of the Hubble constant in the local Universe, measurements that used as their reference points Cepheid variable stars and supernovae.

However, the findings from Suyu and her team, as well as those from the Cepheids and supernovae, differed from those made previously by the ESA Planck satellite—in the latter case, measurement of the Hubble constant was made for the early Universe by observing the cosmic microwave background. While the Planck measurements agree with our current understanding of the cosmos, the results emanating from measurements for the local Universe disagree with currently accepted theoretical models of the Universe.



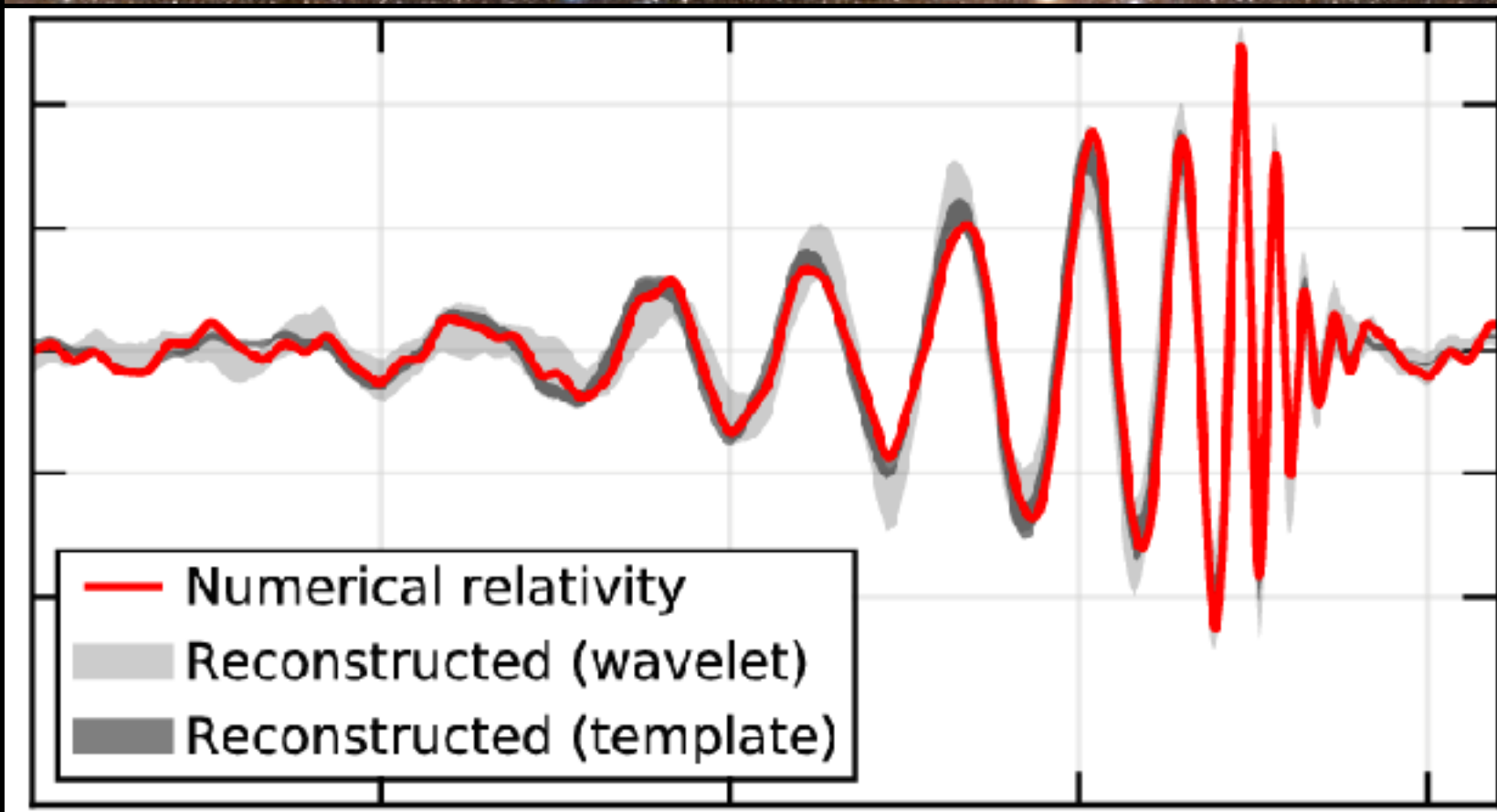
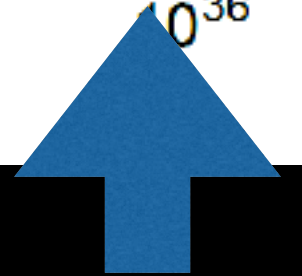
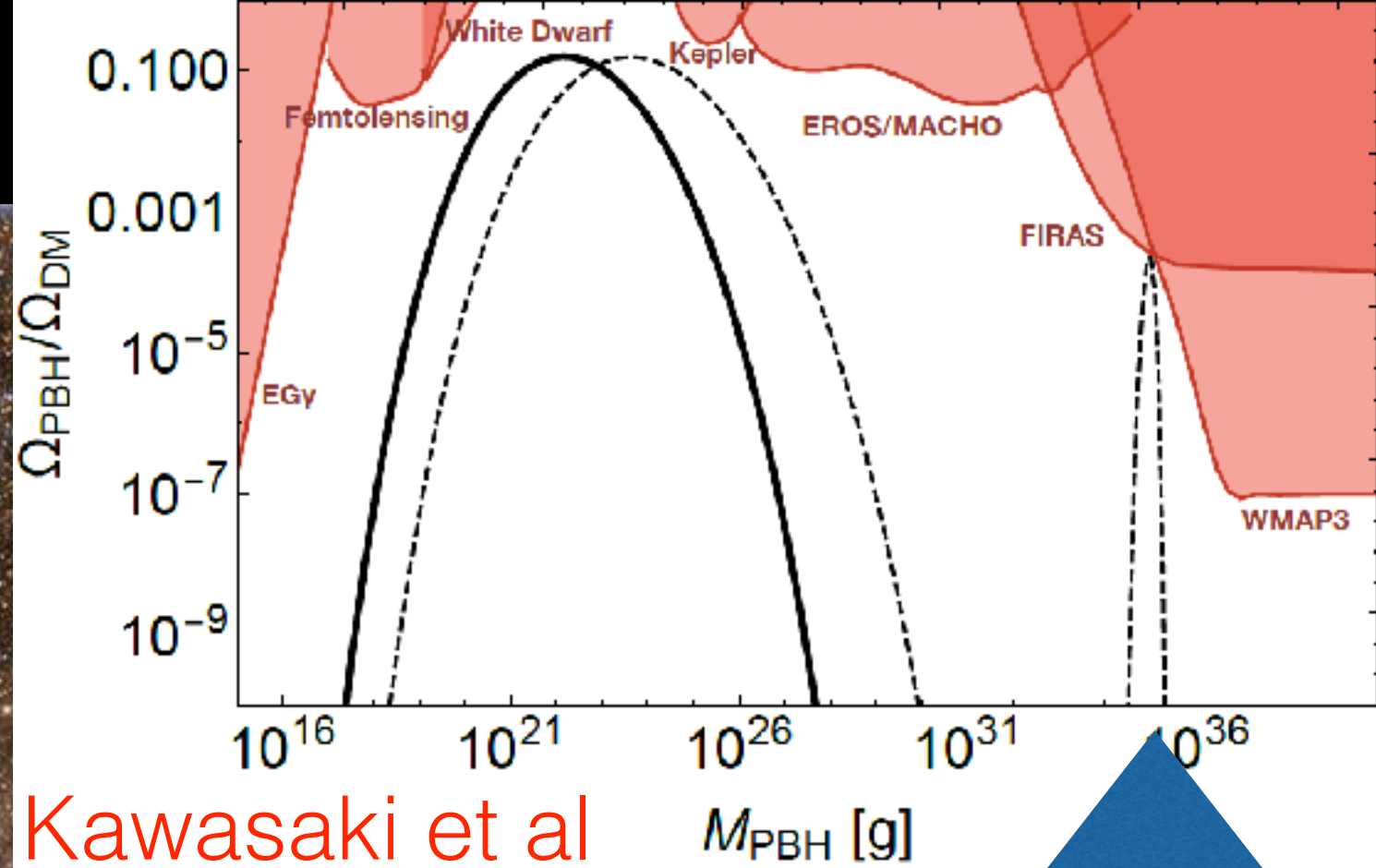
3 pillars of science (theory)

4 approaches (expt, obs)

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[B04] TMT Usuda (NAOJ)	QED coupling (α) space time var.	Lyman- α forests IGM	direct detection of acceleration

important observables at each intersection

LIGO



Primordial
Black Holes?

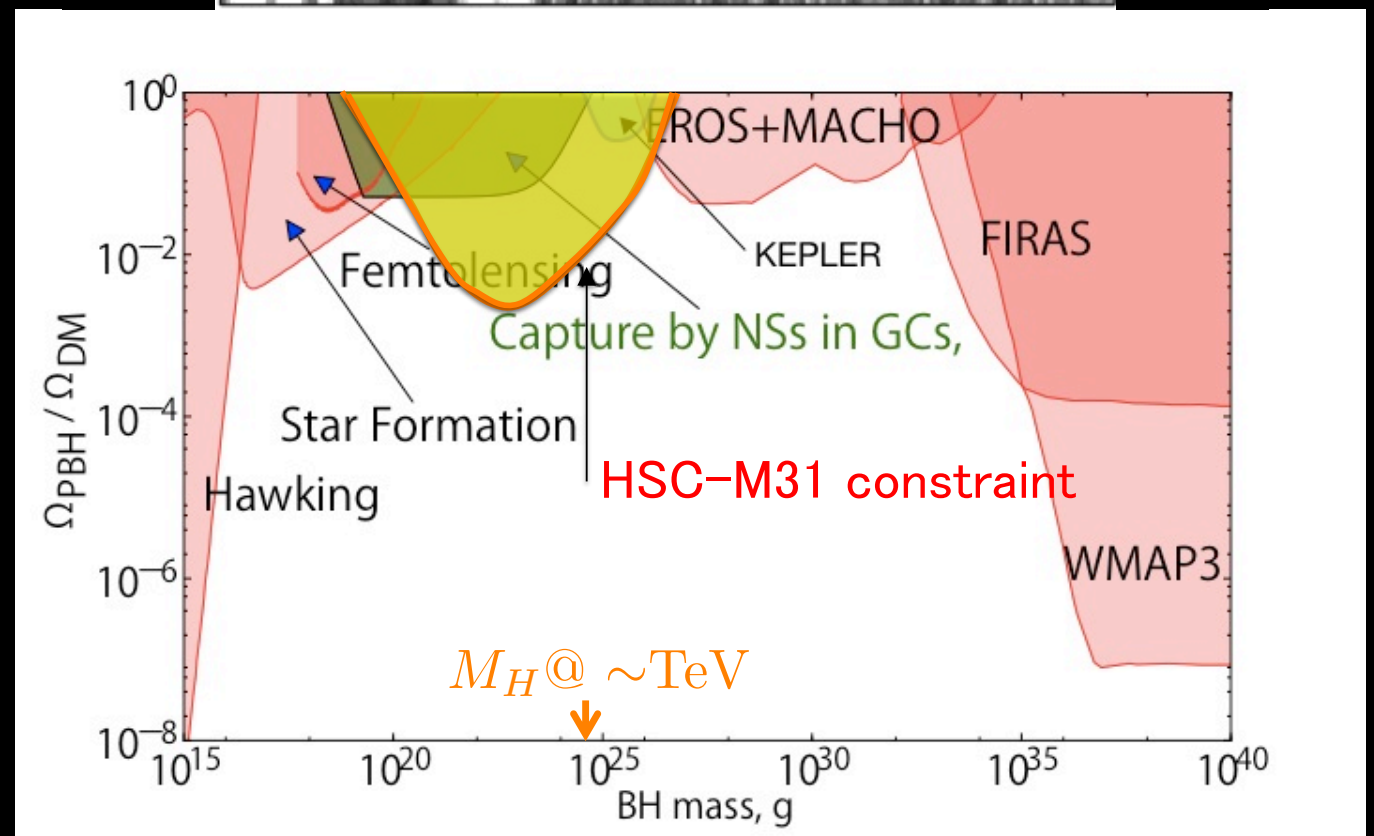
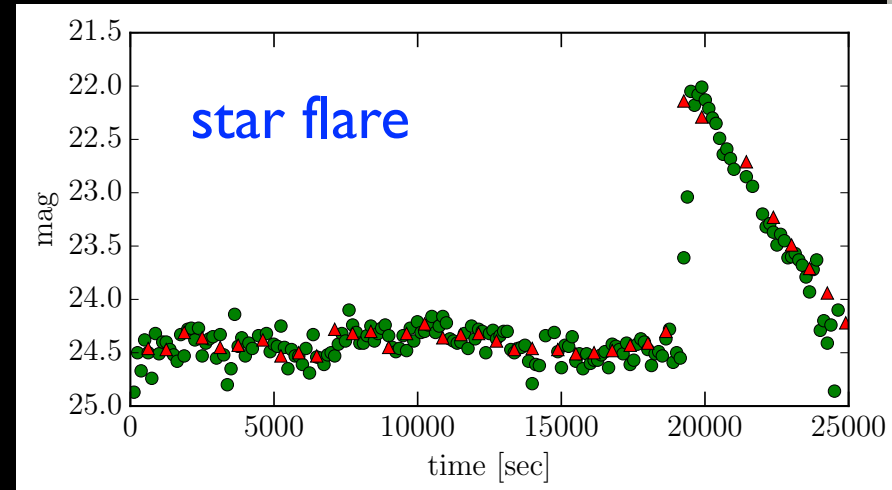
HSC result: Constraint on PBH

Niikura, MT et al., to submit soon
*started from conversation with Hitoshi
and Masahiro Kawasaki*

A dense cadence HSC obs. of M31
to search for microlensing due to
PBHs (just *one* night in Nov, 2015)

*No detection $\Rightarrow$ more stringent
upper bound, than 2yr Kepler data
(Griest et al.)*

Found many variable stars





$$\frac{n_{\text{DM}}}{s} = 4.4 \times 10^{-10} \frac{\text{GeV}}{m_{\text{DM}}}$$

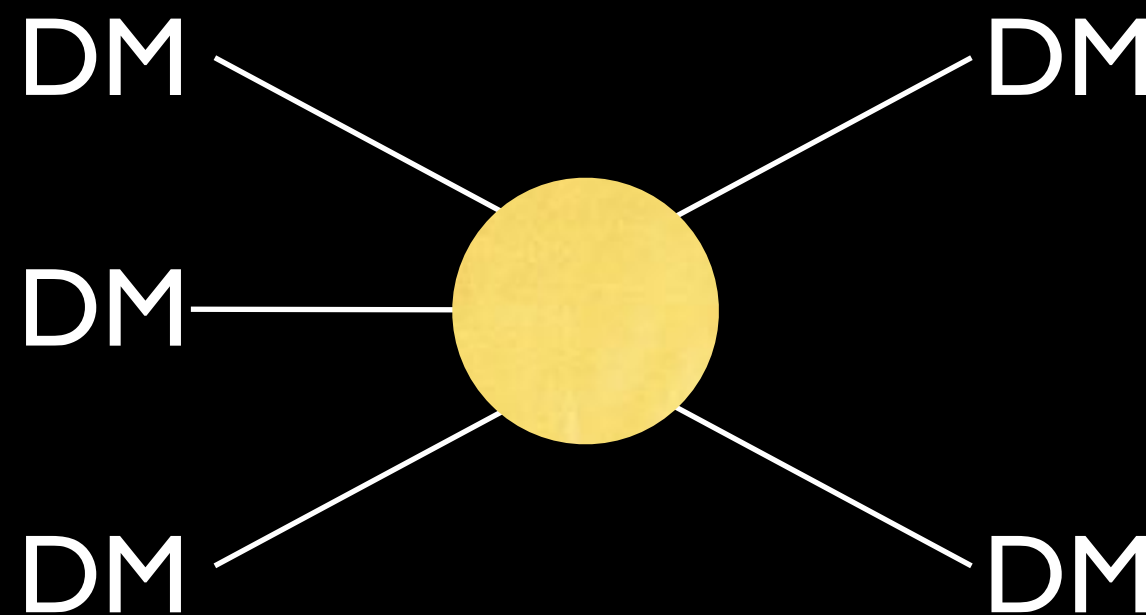
SIMPlEst Miracle

- Strongly Interacting Massive Particle $\sim 300\text{MeV}$
- Not only the mass scale is similar to QCD
- **dynamics itself can be QCD! Miracle³**
- DM = pions
- e.g. SU(2) theory with $N_f=4$
- SU(4)/Sp(4) = S⁵

$$\mathcal{L}_{\text{chiral}} = \frac{1}{16f_\pi^2} \text{Tr} \partial^\mu U^\dagger \partial_\mu U$$

$$\mathcal{L}_{\text{WZW}} = \frac{8N_c}{15\pi^2 f_\pi^5} \epsilon_{abcde} \epsilon^{\mu\nu\rho\sigma} \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\rho \pi^d \partial_\sigma \pi^e + O(\pi^7)$$

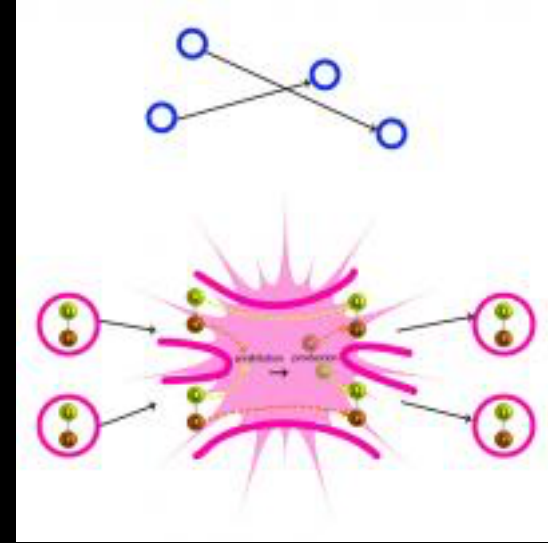
$$\pi_5(G/H) \neq 0$$



+HM

arXiv:1411.3727

self interaction

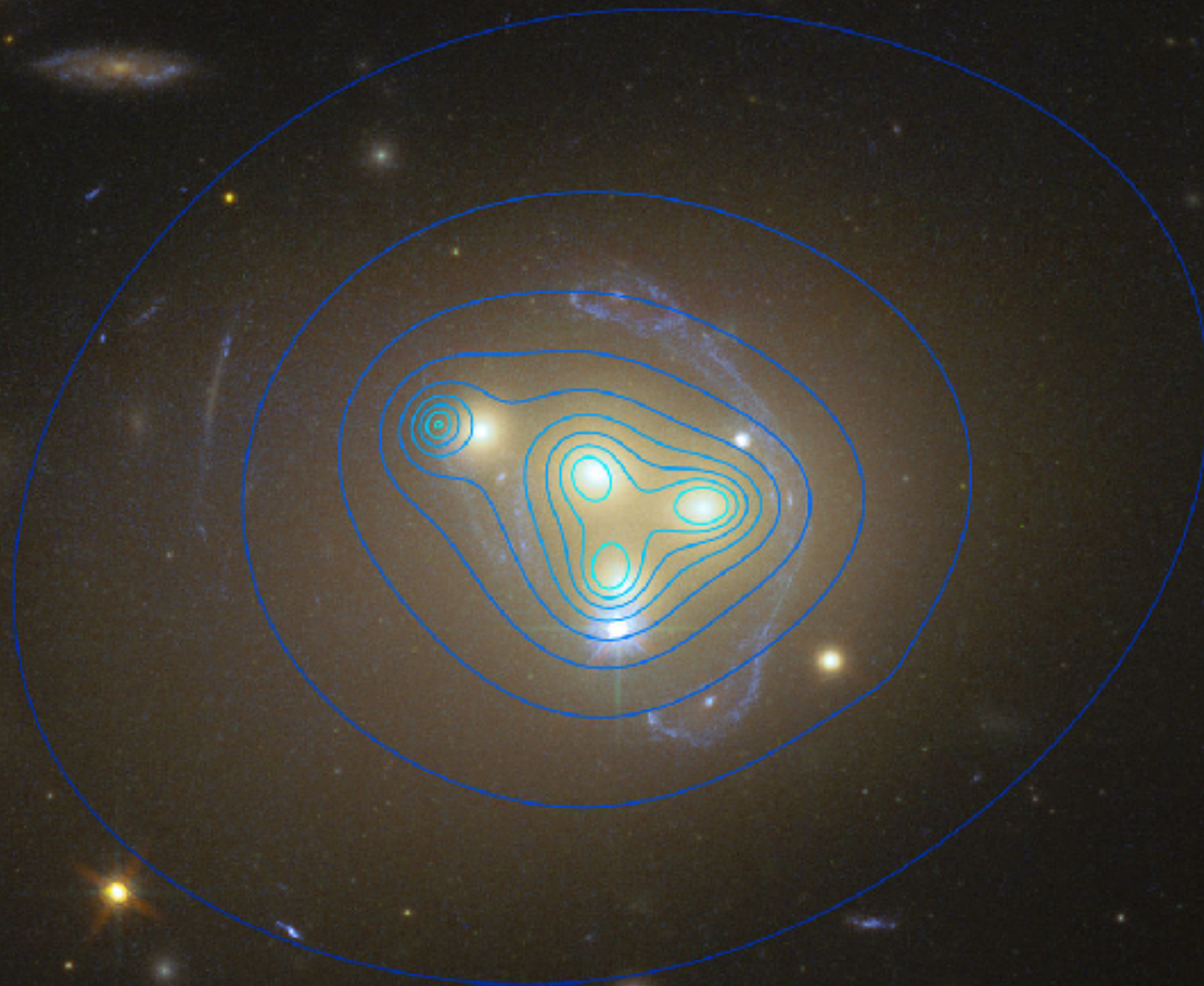


- self interaction of $\sigma/m \sim 10^{-24} \text{cm}^2 / 300 \text{MeV}$
- flattens the cusps in NFW profile
- actually desirable for dwarf galaxies?



$$\frac{\sigma}{m} \approx 1.5 \frac{\text{cm}^2}{g} = \frac{0.27\text{b}}{100\text{MeV}}$$

Sarkar et al

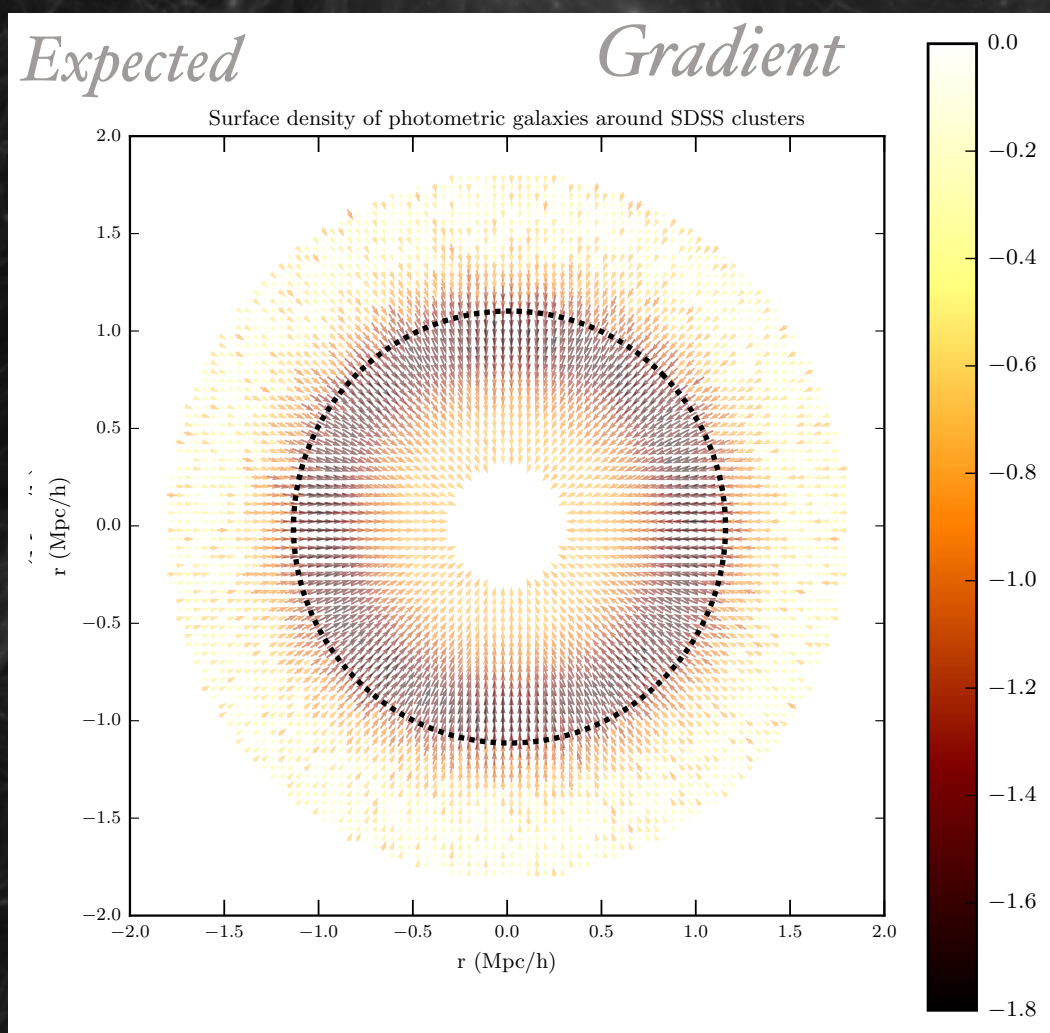


Massey et al

Galaxy distribution around SDSS galaxy clusters

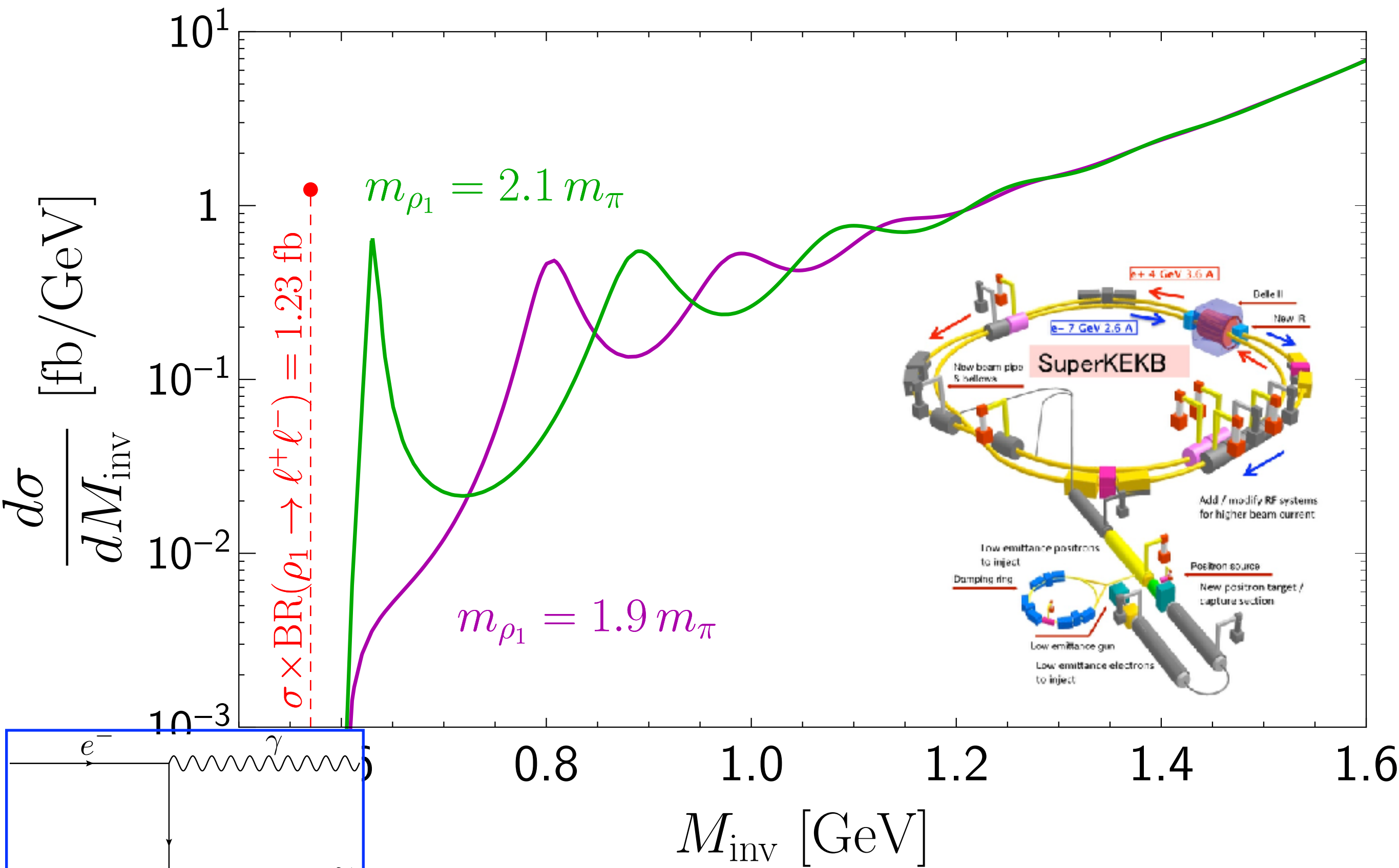


SM et al (2016), ApJ



- ✳ *Extremely well measured cross-correlation of galaxy clusters and faint photometric galaxies*
- ✳ *First detection of the halo edge!*
- ✳ *The edge is smaller than expected by about 20 percent (nominally 4-sigma confidence)*
- ✳ *Dark matter self-interactions(?!)*
- ✳ *Discussions with Dalal, Murayama and Matsumoto*

Surhud More



Yonit Hochberg, Eric Kuflik, HM

3 pillars of science (theory)

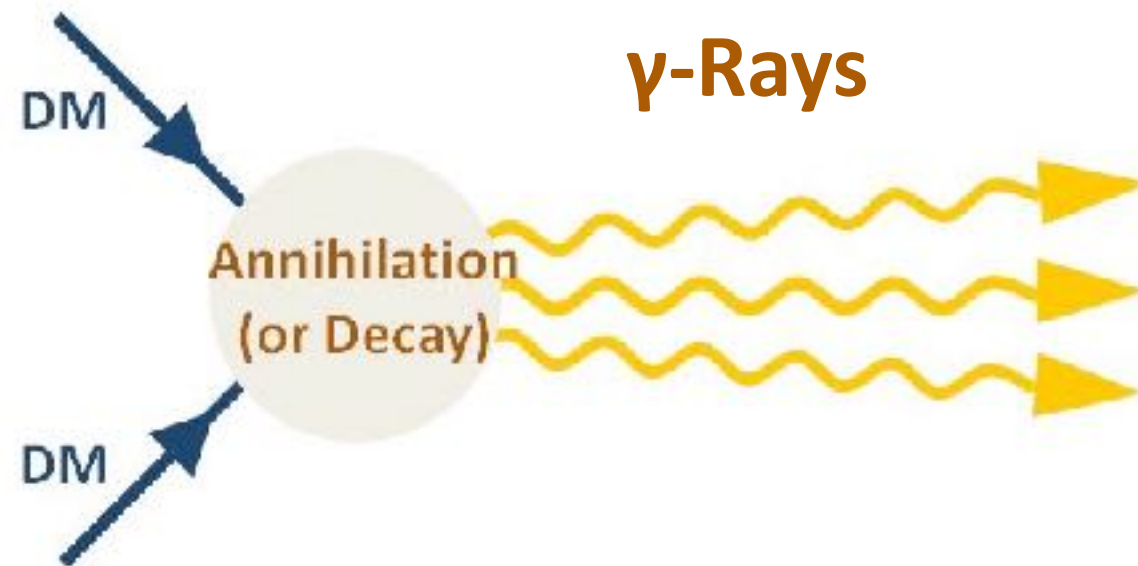
4 approaches (expt, obs)

	[A01] Inflation Sasaki (Kyoto)	[A02] fluent. & struct. Takahashi (Tohoku)	[A03] Dark Energy Sugiyama (Nagoya)
[B01] CMB polariz. Hazumi (KEK)	ζ, r, n_s direct evidence	CMB lensing isocurv. m_ν, N_ν	cosmo. params CMB lensing
[B02] Subaru galaxy imaging Miyazaki(NAOJ)	Lensing $\rightarrow b(k)$ $\rightarrow P_{\text{primod}}(k)$	weak lensing m_ν non-std. DM	weak lensing SNe, γ
[B03] galaxy spectroscopy Takada(KIPMU)	primord. NG Ω_K, n_s, α_s	isocurv. DM in dSph gals. $P(k), m_\nu$	BAO, RSD $\Omega_{\text{de}}(z), \gamma$
[B04] TMT Usuda (NAOJ)	QED coupling (α) space time var.	Lyman- α forests IGM	direct detection of acceleration

important observables at each intersection

Dark Matter Detection by Gamma-Ray

Dwarf galaxy



$$\underbrace{\Phi(E, \Delta\Omega)}_{\text{Observed } \gamma\text{-Ray Flux}} = \underbrace{\left[\frac{\langle\sigma v\rangle}{8\pi m_{\text{DM}}^2} \sum_f \text{Br}(\text{DM DM} \rightarrow f) \left(\frac{dN_\gamma}{dE} \right) \right]}_{\text{DM Property}} \underbrace{\left[\int_{\Delta\Omega} d\Omega \int_{\text{l.o.s}} dl \rho^2(l, \Omega) \right]}_{\text{Halo Profile (J-factor)}}$$

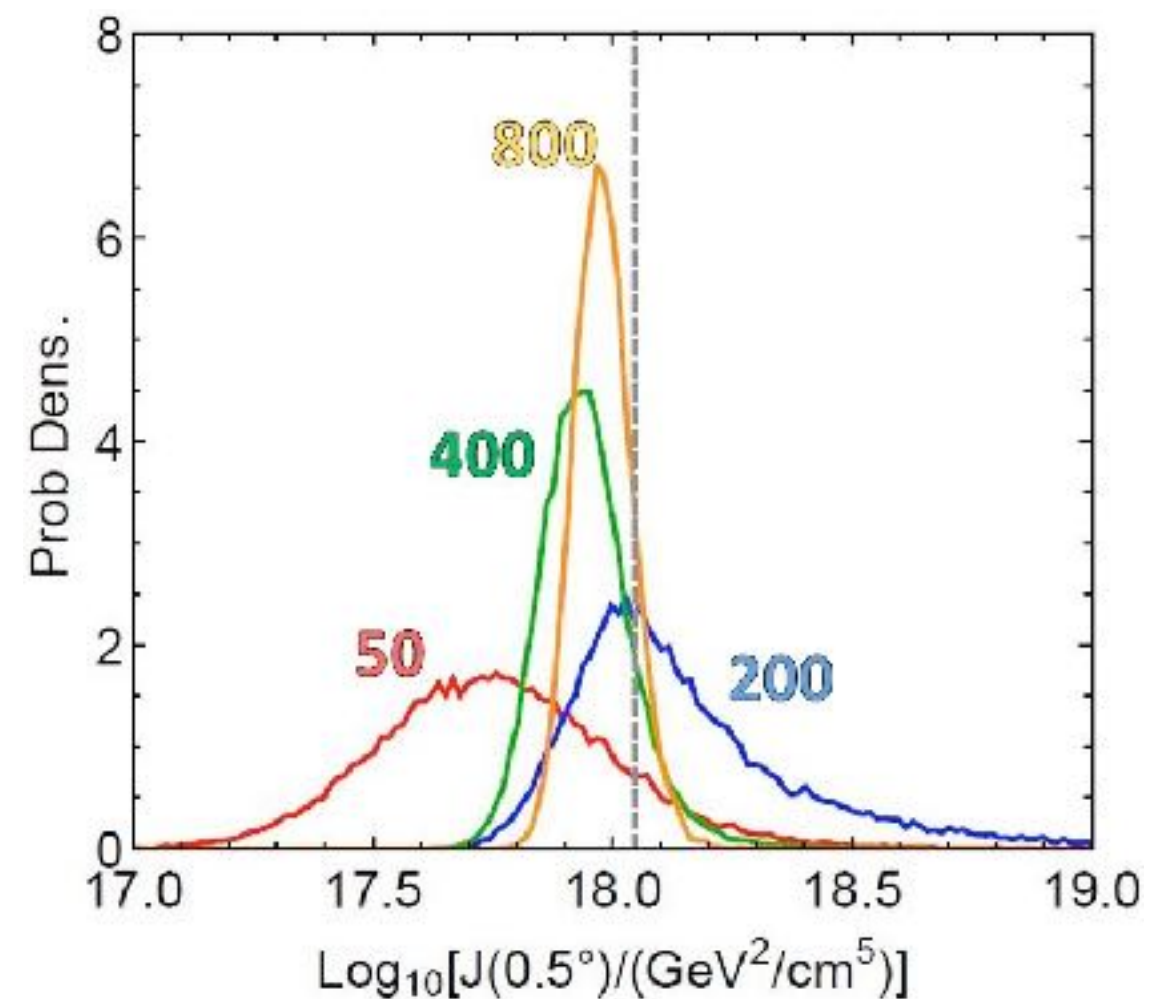
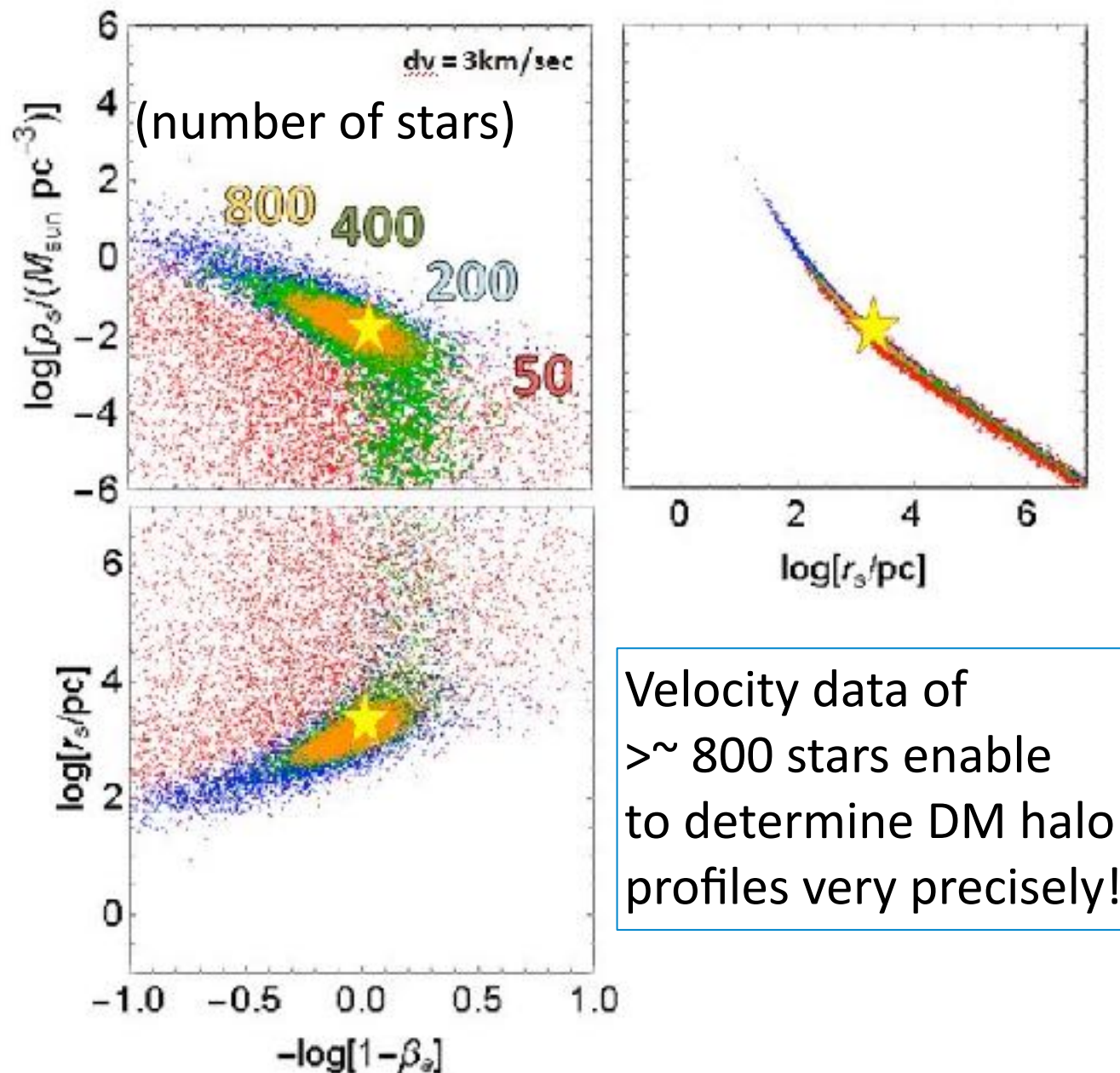
Determination of J-factor is essential
to constrain the DM property

Precise measurement of DM Halo Profiles

Stellar Velocity Data $\longleftrightarrow$ DM Gravitational Potential
Fit

DM Halo: $\rho(r) = \rho_s(r/r_s)^{-1}(1 + r/r_s)^{-2}$

J-factor = $\left[\int_{\Delta\Omega} d\Omega \int_{l.o.s} dl \rho^2(l, \Omega) \right]$



J-factor is determined very precisely!
 $\Rightarrow$ nature of DM

Hayashi, Ibe, Ichikawa, Ishigaki, Matsumoto, Sugai(2016)]

3 pillars of science (theory)

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[B04] TMT Usuda (NAOJ)	QED coupling (α) space time var.		

important observables at each intersection

3 pillars of science (theory)

4 approaches (expt, obs)

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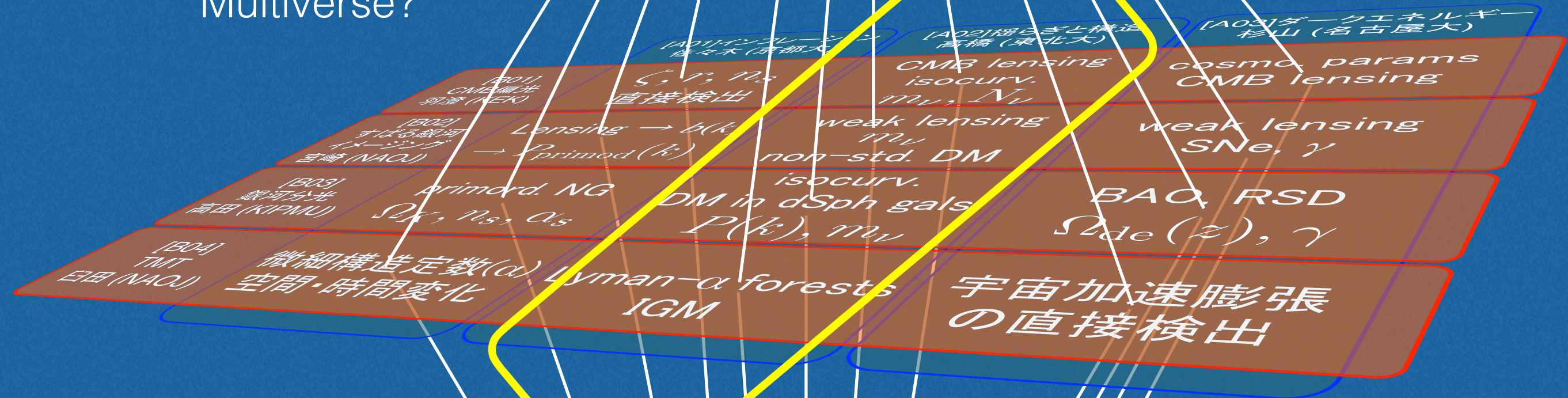
important observables at each intersection

Modified Gravity

- Horndeski theory?
- Genesis? Big Rip?
- Signal on galaxy clustering,
Redshift Space Distortion?

C01: ultimate theory Ooguri(Caltech)

Universe before inflation?
Birth of time?
quantum gravity? string?
other dims? end of Universe?
Multiverse?



X00: organization
Murayama (IPMU)

D01: ultimate analysis Komatsu(MPA)

Emergent Gravity and the Dark Universe

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The Netherlands

Abstract

Recent theoretical progress indicates that spacetime and gravity emerge together from the entanglement structure of an underlying microscopic theory. These ideas are best understood in Anti-de Sitter space, where they rely on the area law for entanglement entropy. The extension to de Sitter space requires taking into account the entropy and temperature associated with the cosmological horizon. Using insights from string theory, black hole physics and quantum information theory we argue that the positive dark energy leads to a thermal volume law contribution to the entropy that overtakes the area law precisely at the cosmological horizon. Due to the competition between area and volume law entanglement the microscopic de Sitter states do not thermalise at sub-Hubble scales: they exhibit memory effects in the form of an entropy displacement caused by matter. The emergent laws of gravity contain an additional ‘dark’ gravitational force describing the ‘elastic’ response due to the entropy displacement. We derive an estimate of the strength of this extra force in terms of the baryonic mass, Newton’s constant and the Hubble acceleration scale $a_0 = cH_0$, and provide evidence for the fact that this additional ‘dark gravity force’ explains the observed phenomena in galaxies and clusters currently attributed to dark matter.

new matter?
new force?





Symmetry? Multiverse?

Looking forward to
exciting talks!