宇宙論を実証する

Introduction to

Experimental Cosmology

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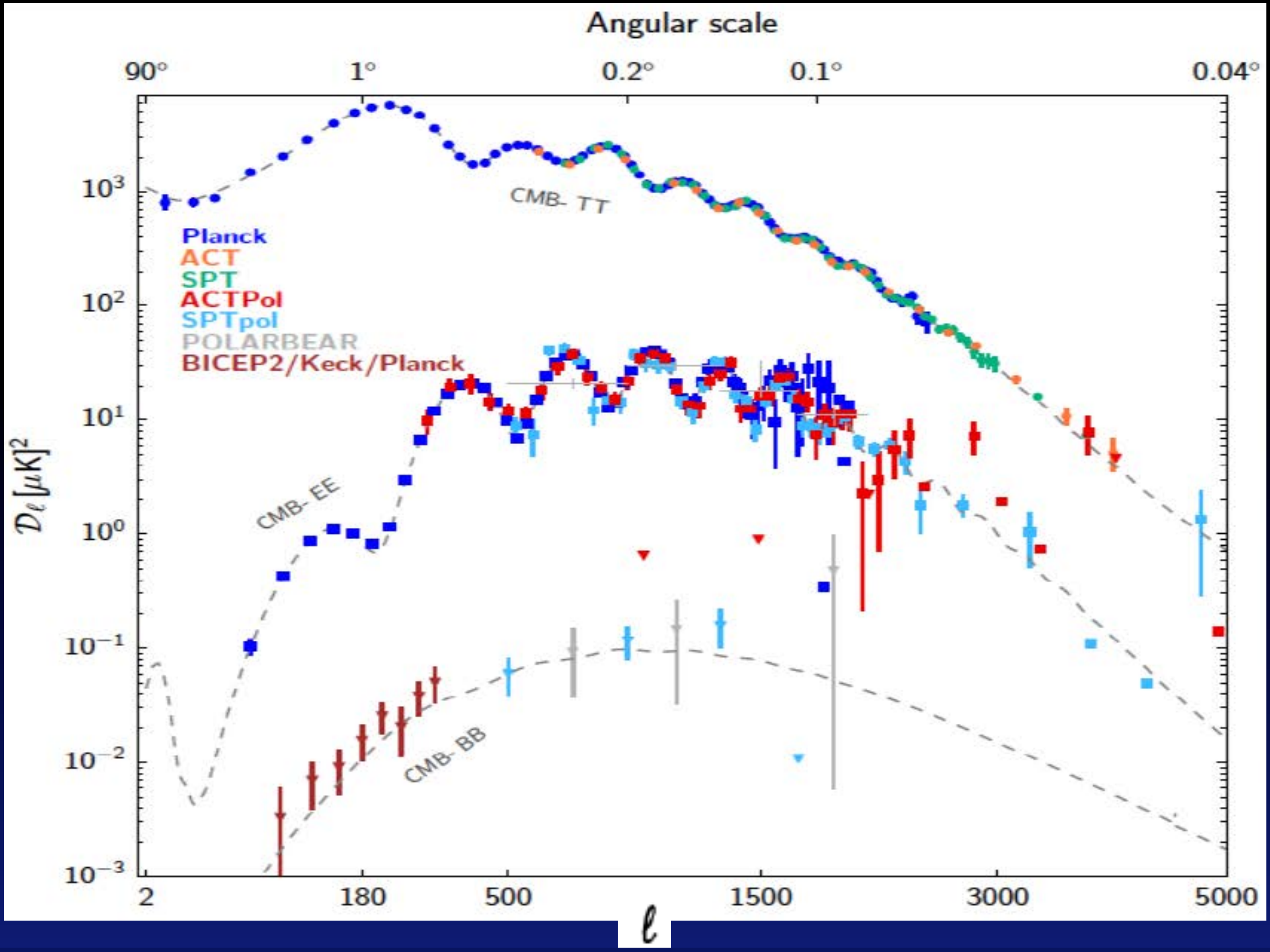
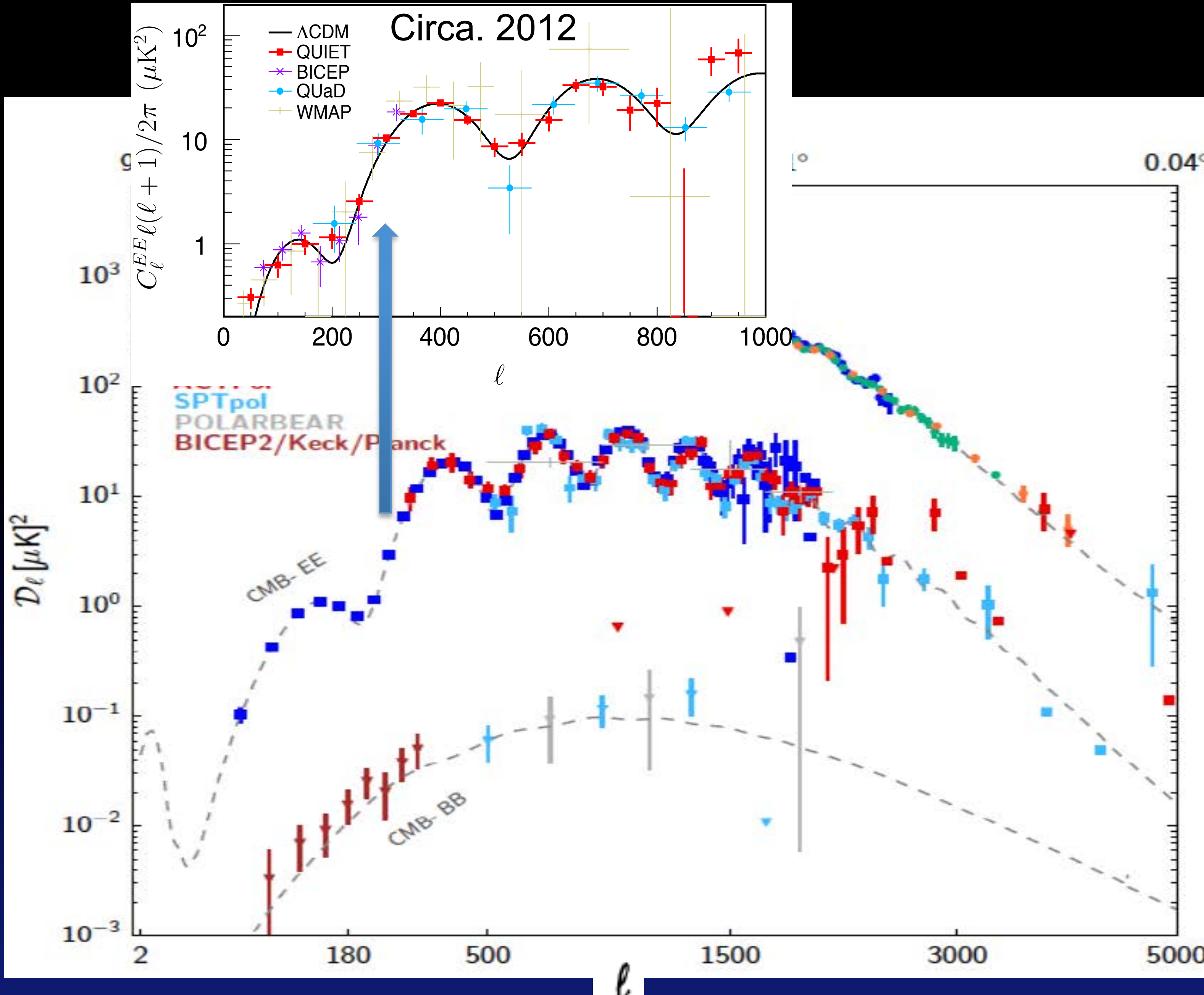
(KEK / Kavli IPMU / SOKENDAI)

GR @ 100

CMB @ 50

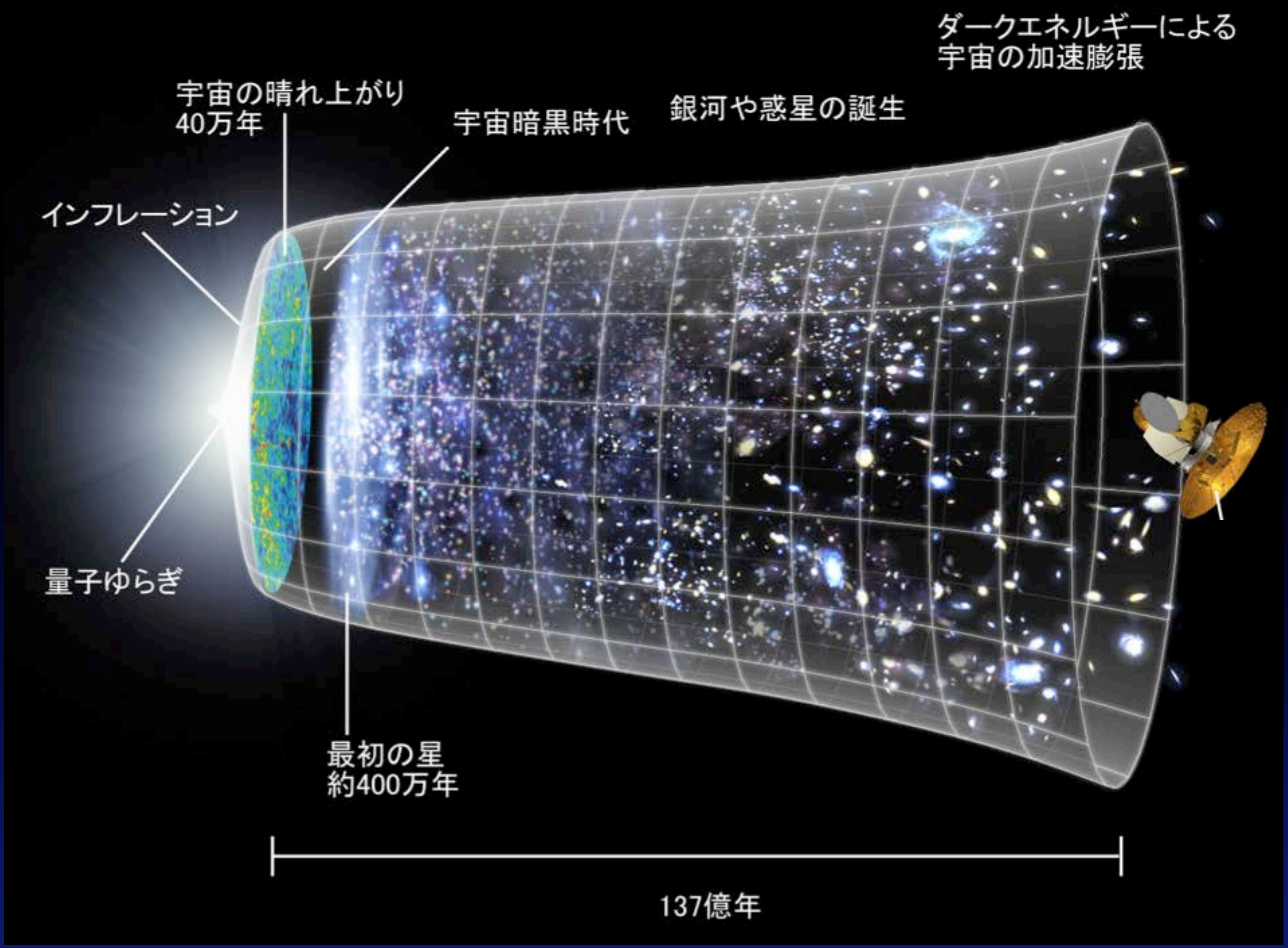
CMB Power Spectra Today





Circa. 2012
ΛCDM
QUIET
BICEP
QUaD
WMAP
$C_\ell^{EE}\ell(\ell+1)/2\pi\ (\mu K^2)$
10^2
10
1
0
200
400
600
800
1000
ℓ
0.04°
SPTpol
POLARBEAR
BICEP2/Keck/P anck
CMB- EE
CMB- BB
$\mathcal{D}_\ell\ [\mu K]^2$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
2
180
500
1500
3000
5000
ℓ

Golden Age of Cosmology



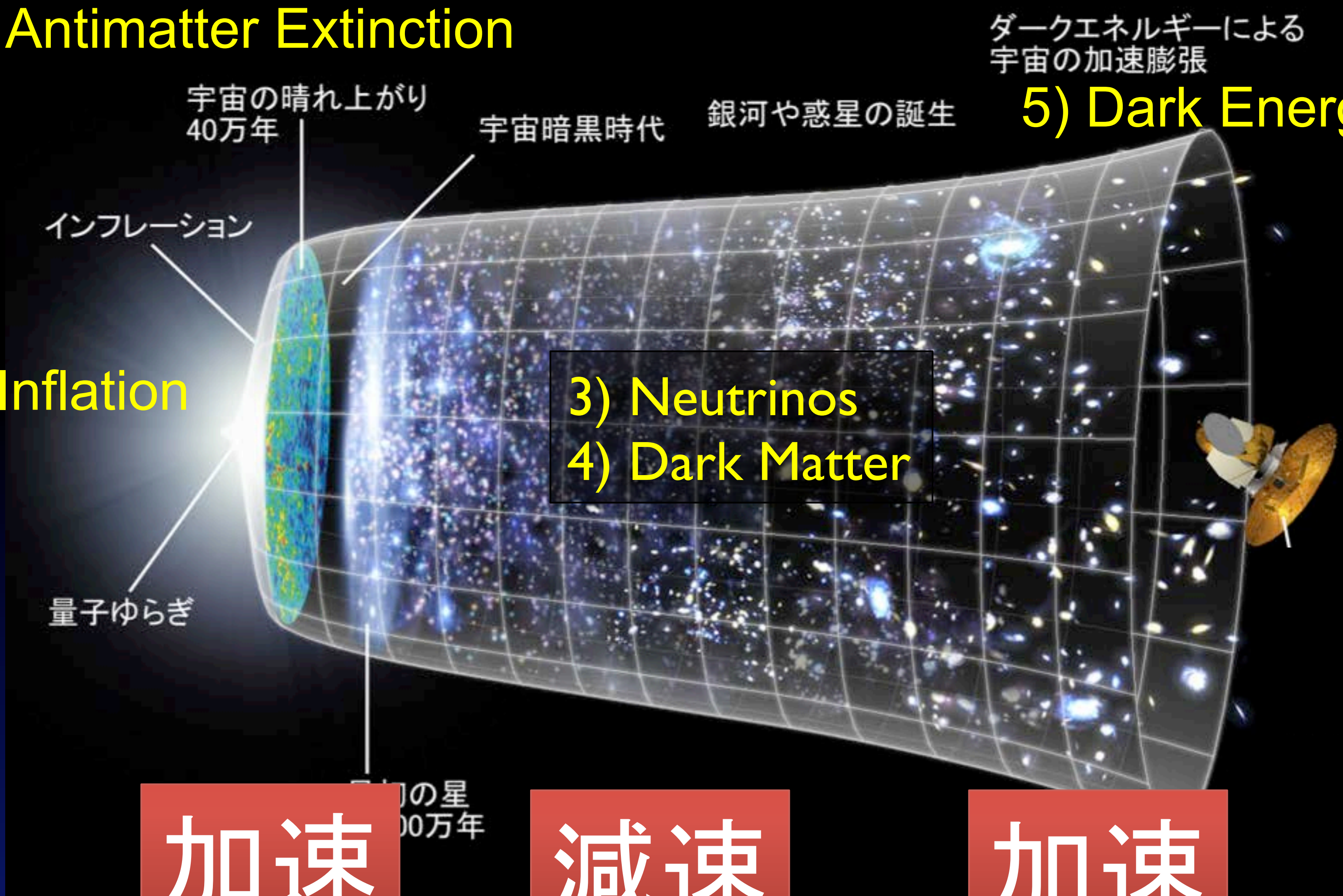
Five Mysteries from Particle Physics Viewpoint

2) Antimatter Extinction

5) Dark Energy

1) Inflation

3) Neutrinos
4) Dark Matter

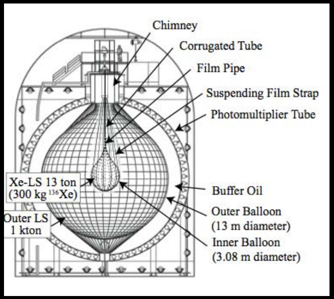


加速 減速 加速

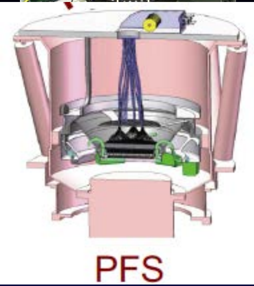
Beyond the Standard Model is mandatory !

Example Projects w/ Key Japanese Contributions

2) Antimatter Extinction

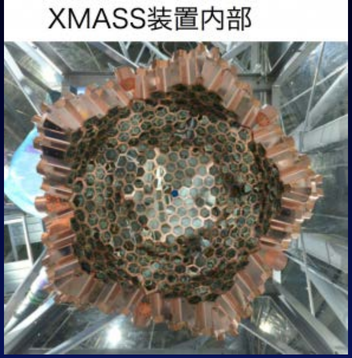


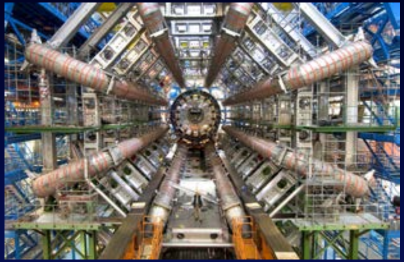
5) Dark Energy

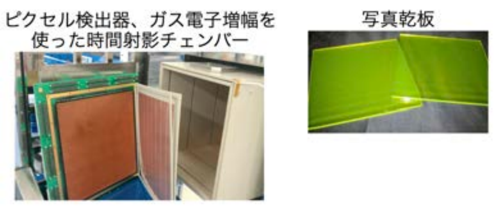


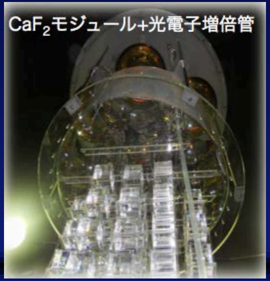
1) Inflation

3) Neutrinos
4) Dark Matter









Quantum Gravity is Essential !

- Cosmic Acceleration is the clue
  - Inflation
  - Dark Energy

e.g.
Inflation models motivated by String Theory can be tested !

Inflation

量子重力理論

インフレーションモデル

宇宙の初期条件

量子重力効果が
反映されている

宇宙の組成

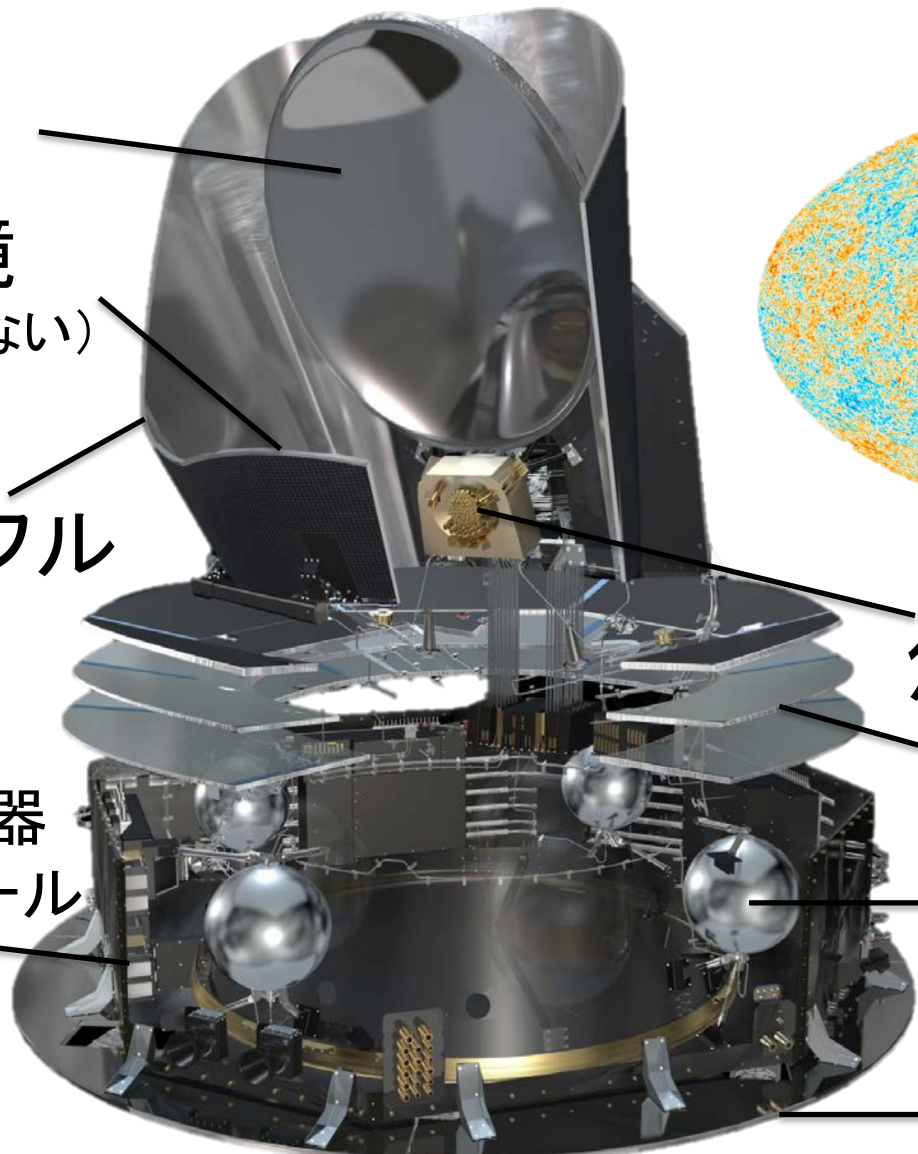
暗黒成分が
反映されている

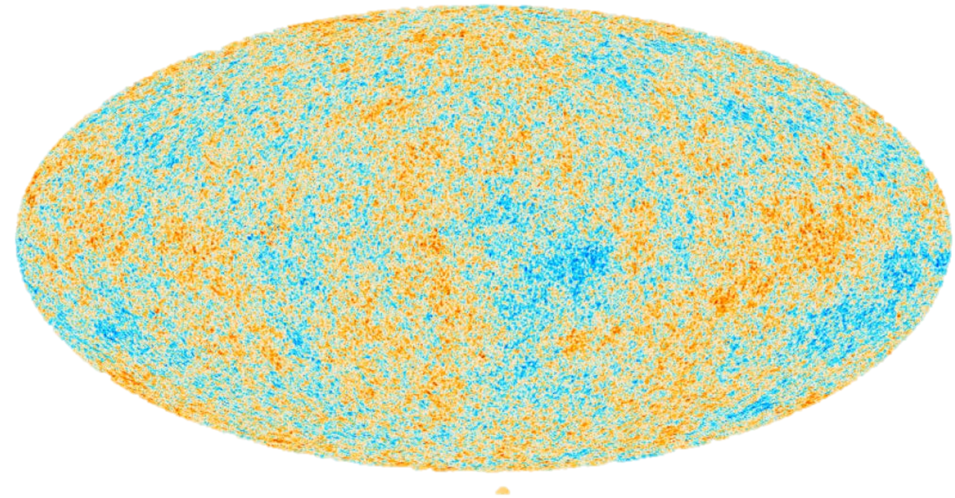
パワースペクトル

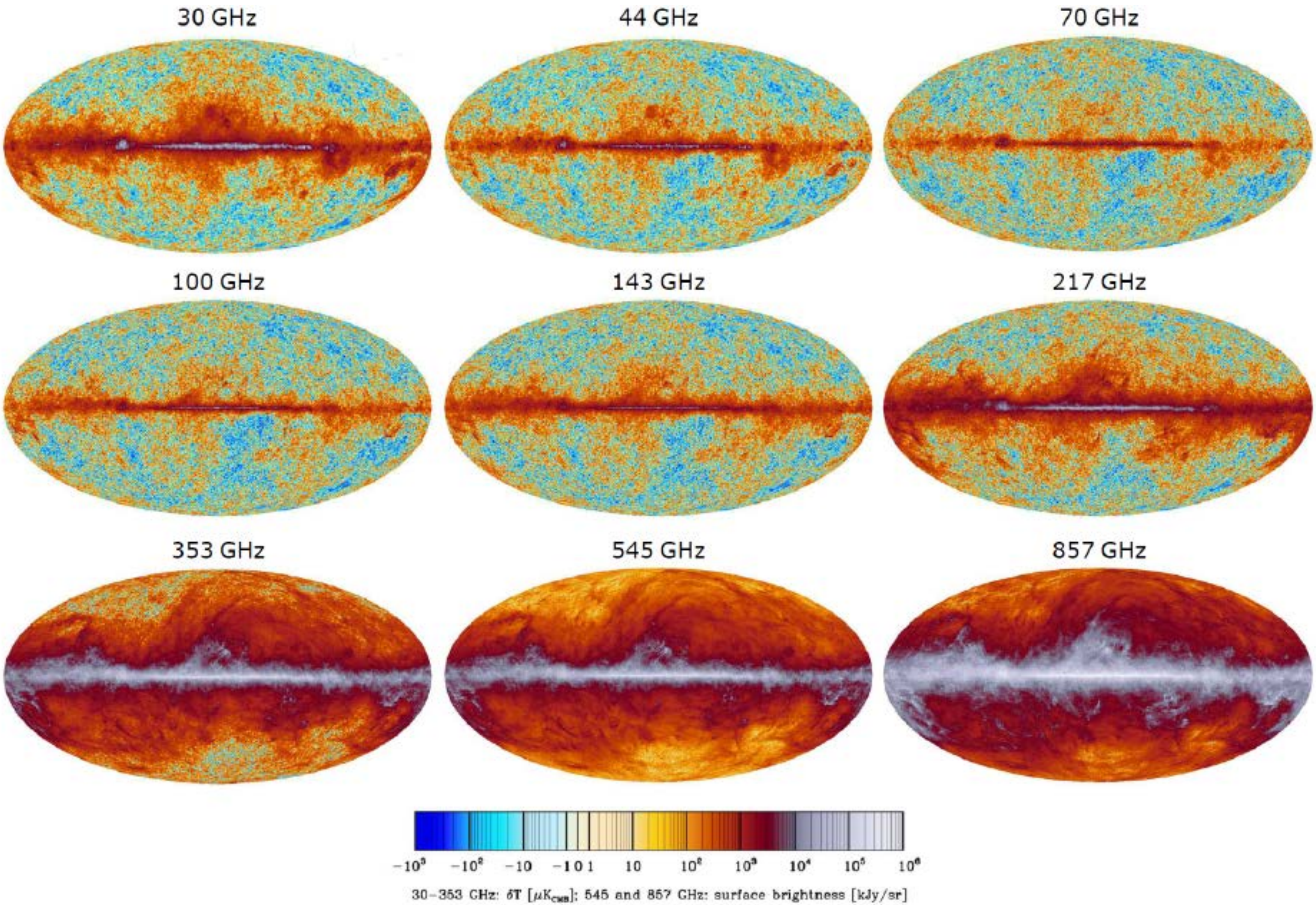
逆問題
を解く

CMB観測

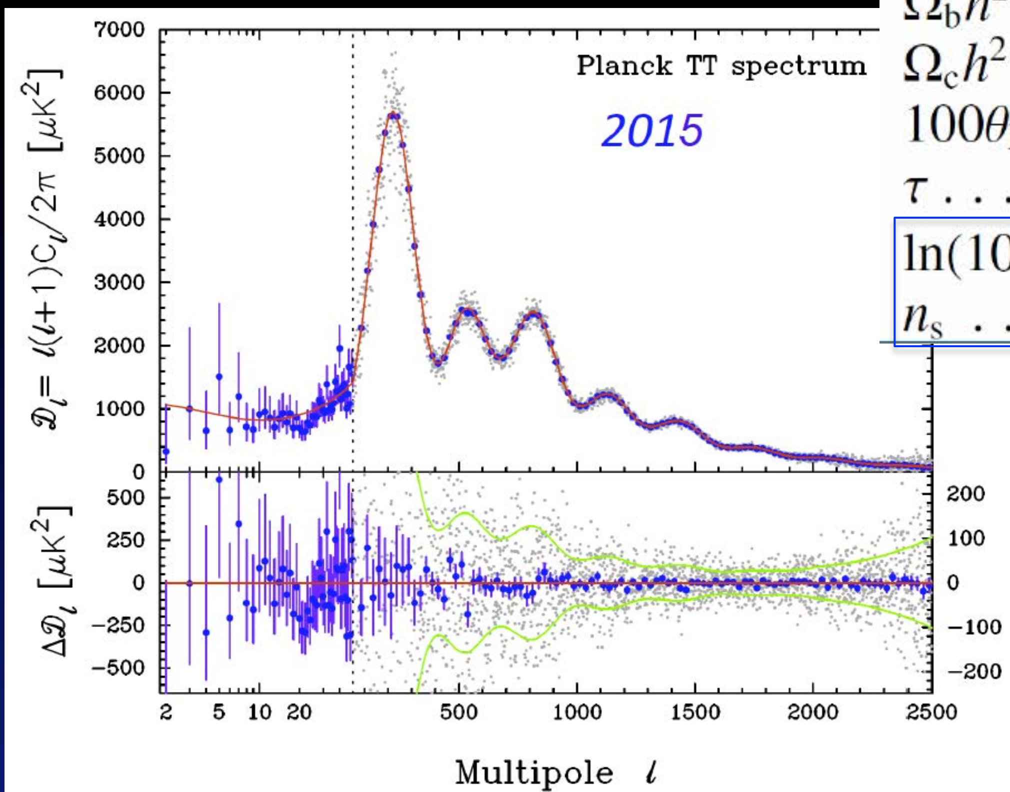
Planck衛星（2013年に初期観測結果発表）






30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
−10³ −10² −10 −1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶
30−353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]

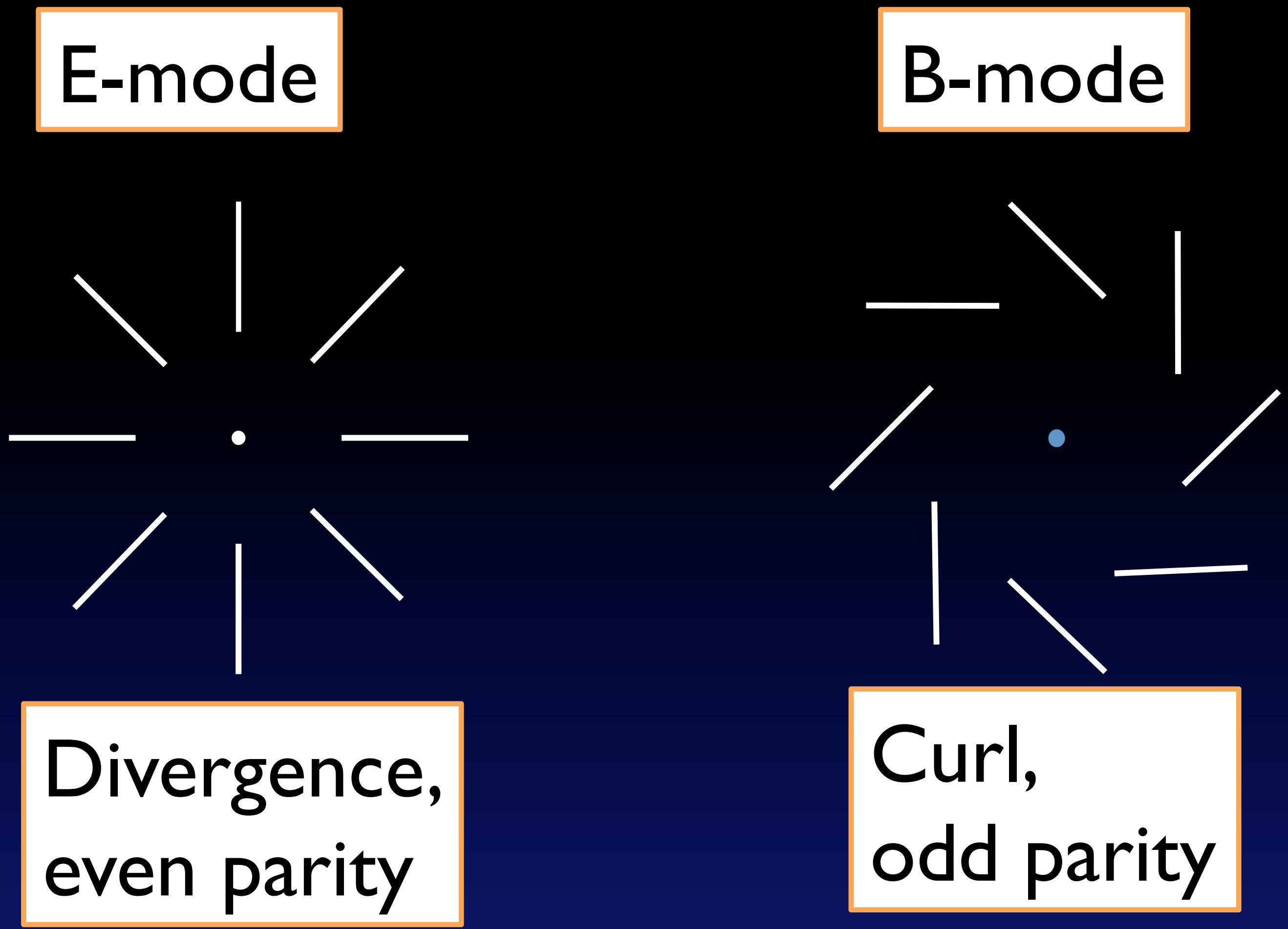
ΛCDM
The Standard Model of Cosmology



Parameter	[1] *Planck* TT+lowP
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062

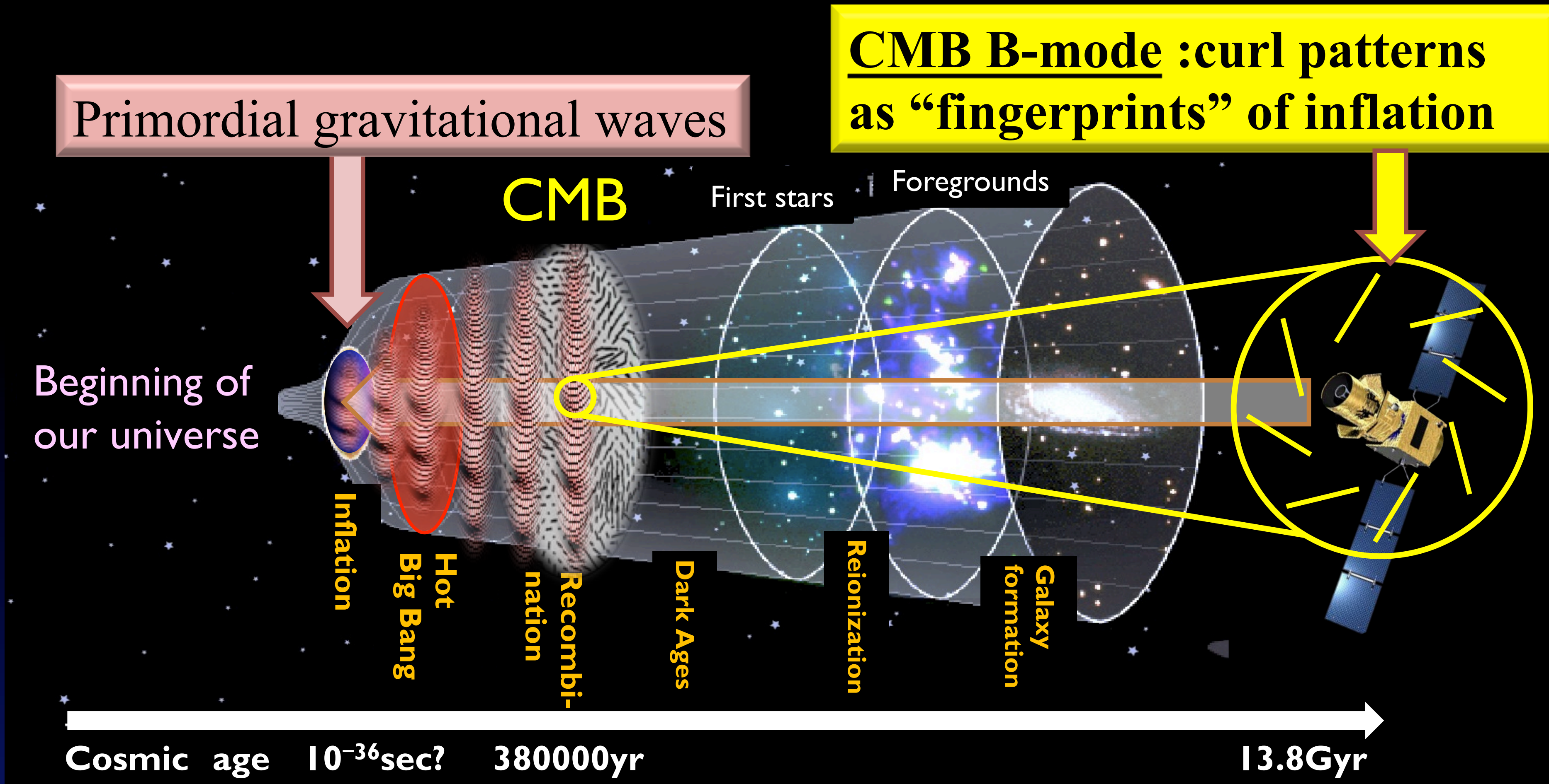
曲率ゆらぎの振幅とベキ
（インフレーションに起因）

E-mode and B-mode



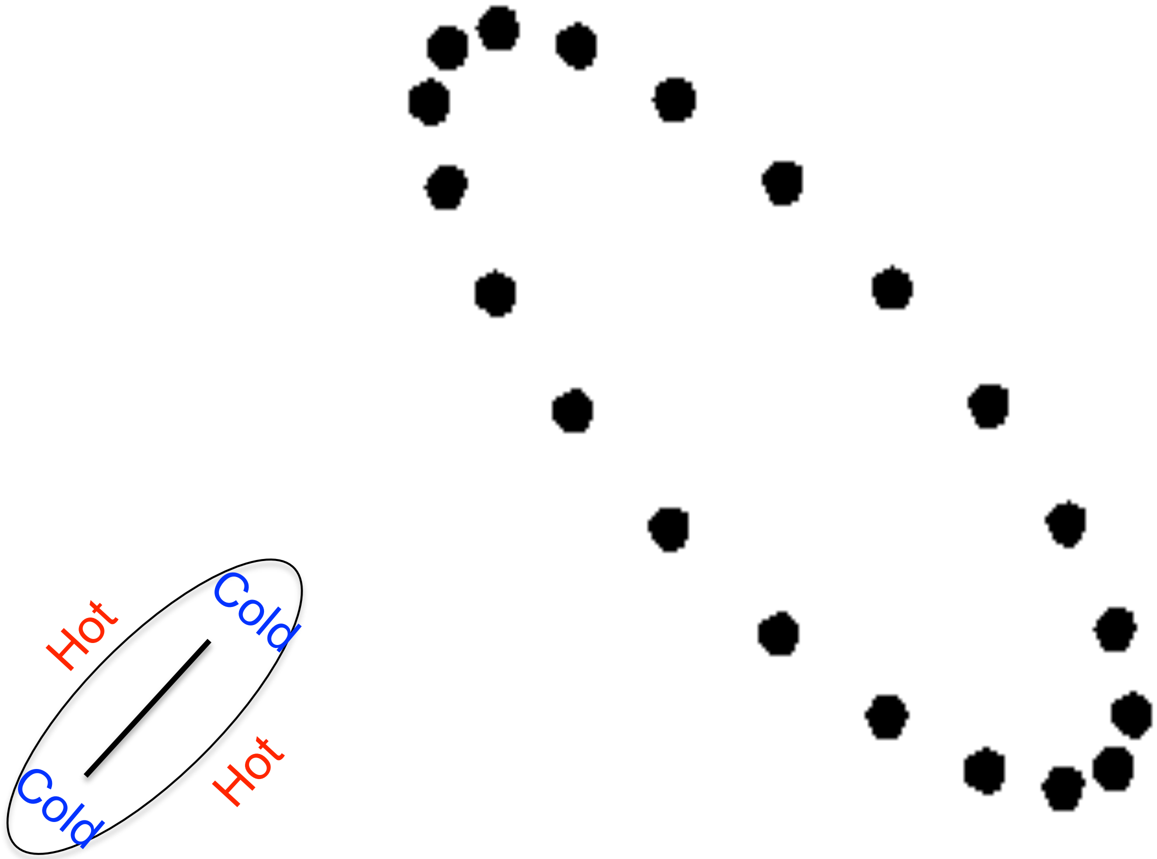
Polarization map is decomposed into E-mode and B-mode.

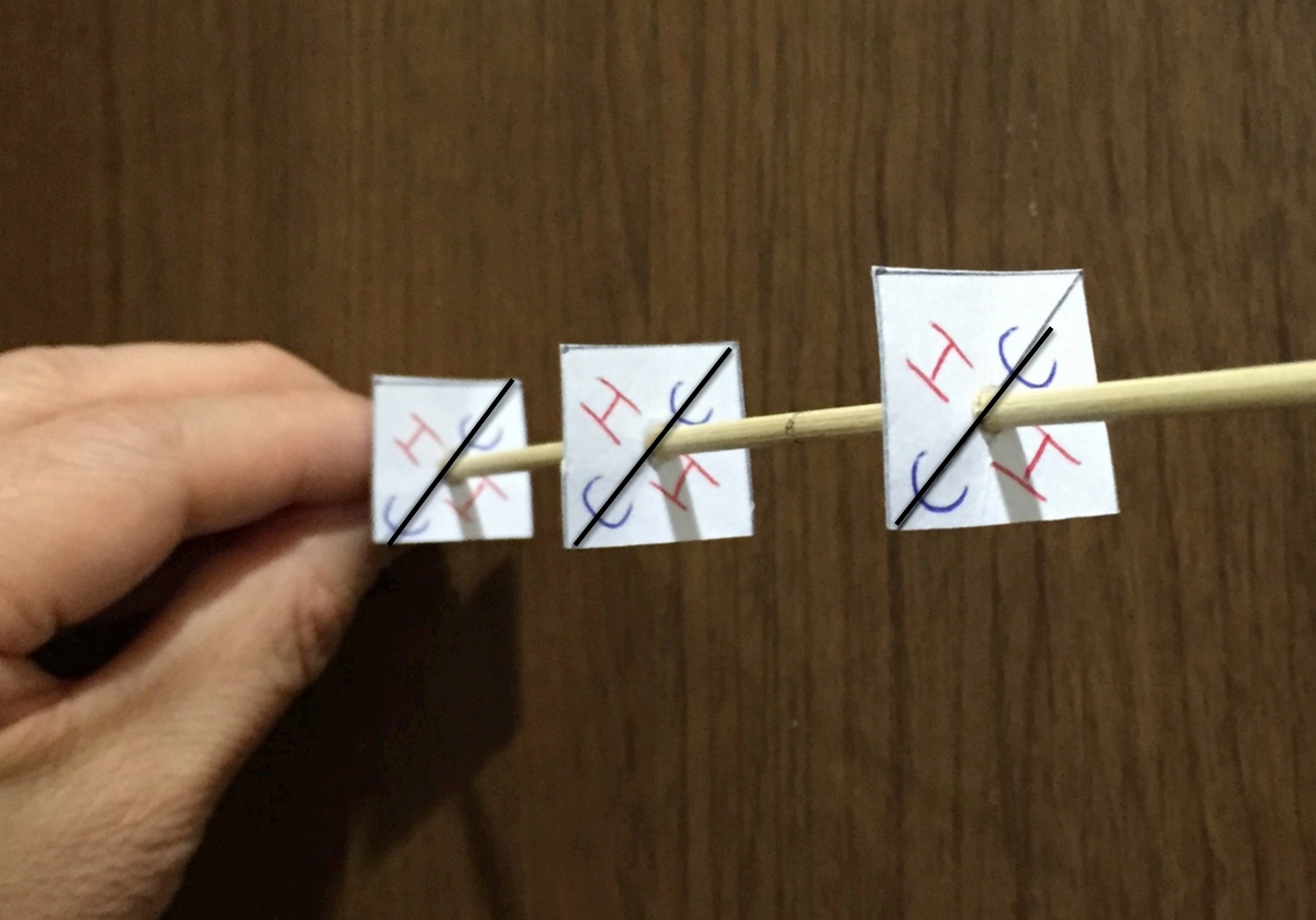
Probing cosmic inflation with CMB polarization



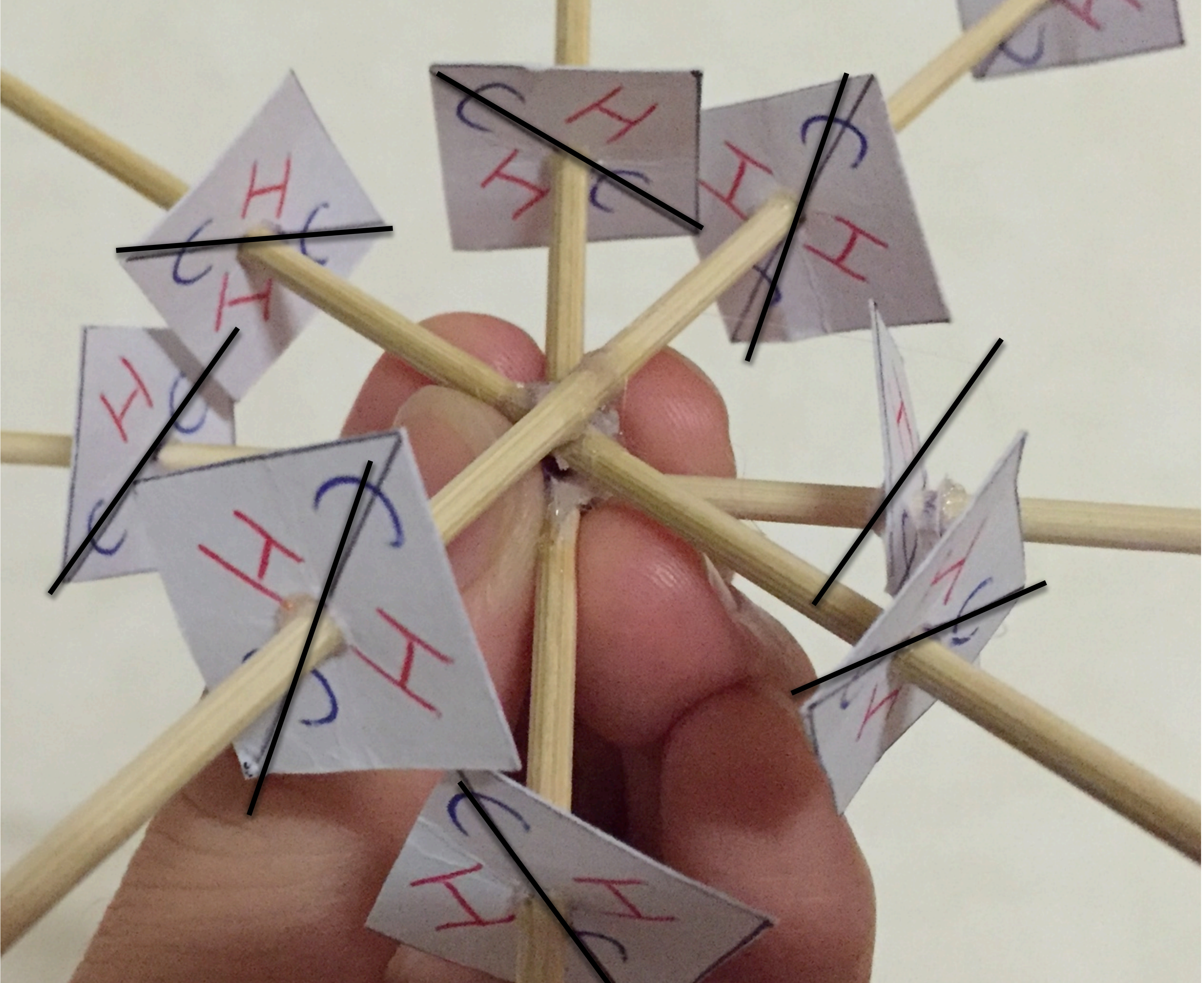
CMB B-mode is the best probe for primordial gravitational waves

Gravitational waves





H
C
C
H
H
C
C
H
H
C
C
H



Physics of CMB B-mode

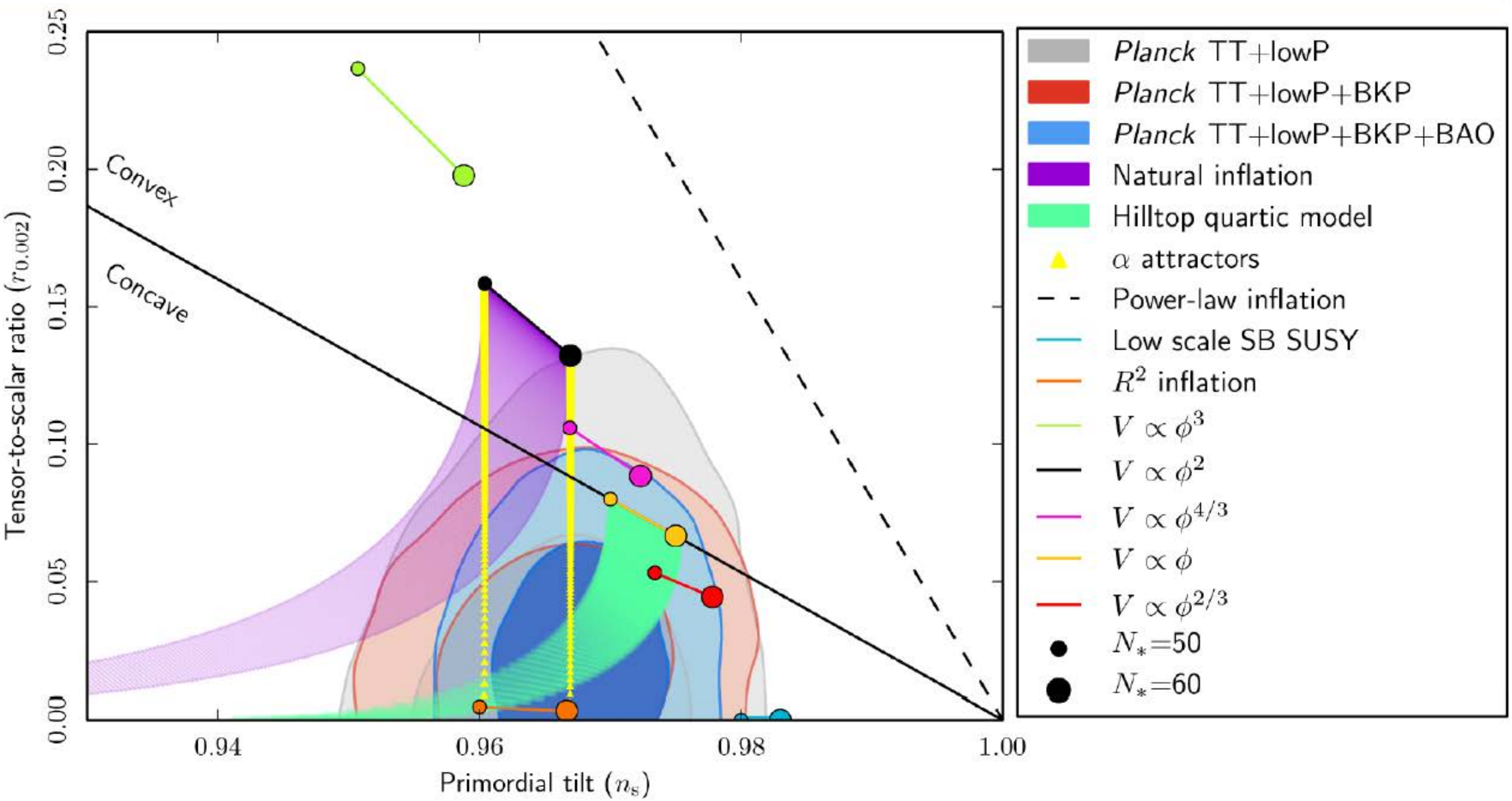
- Direct evidence for cosmic inflation

- GUT-scale physics

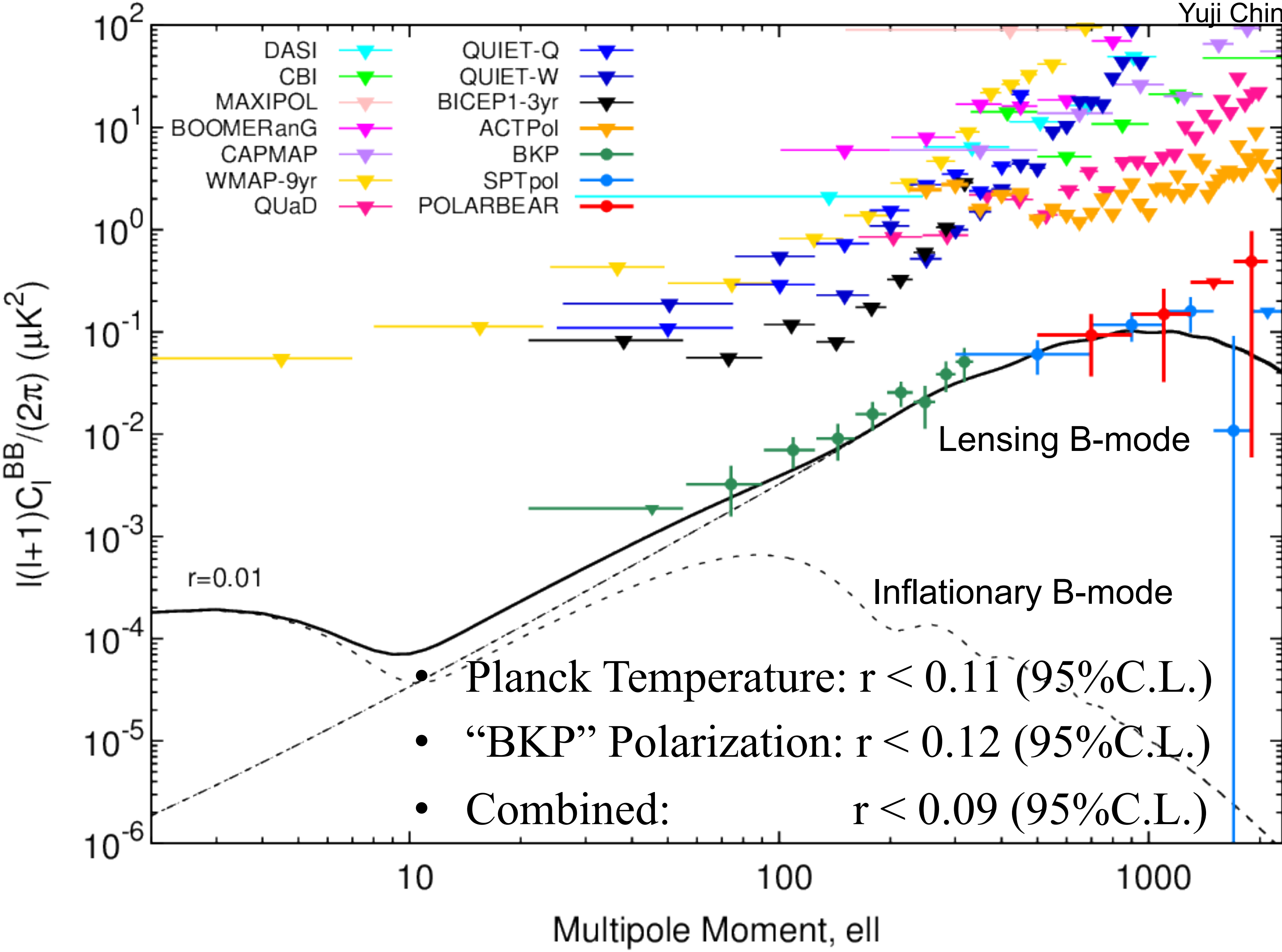
$$V^{1/4} = 1.06 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} \text{[GeV]}$$

- Arguably the first observation of quantum fluctuation of space-time !

Current Constraint

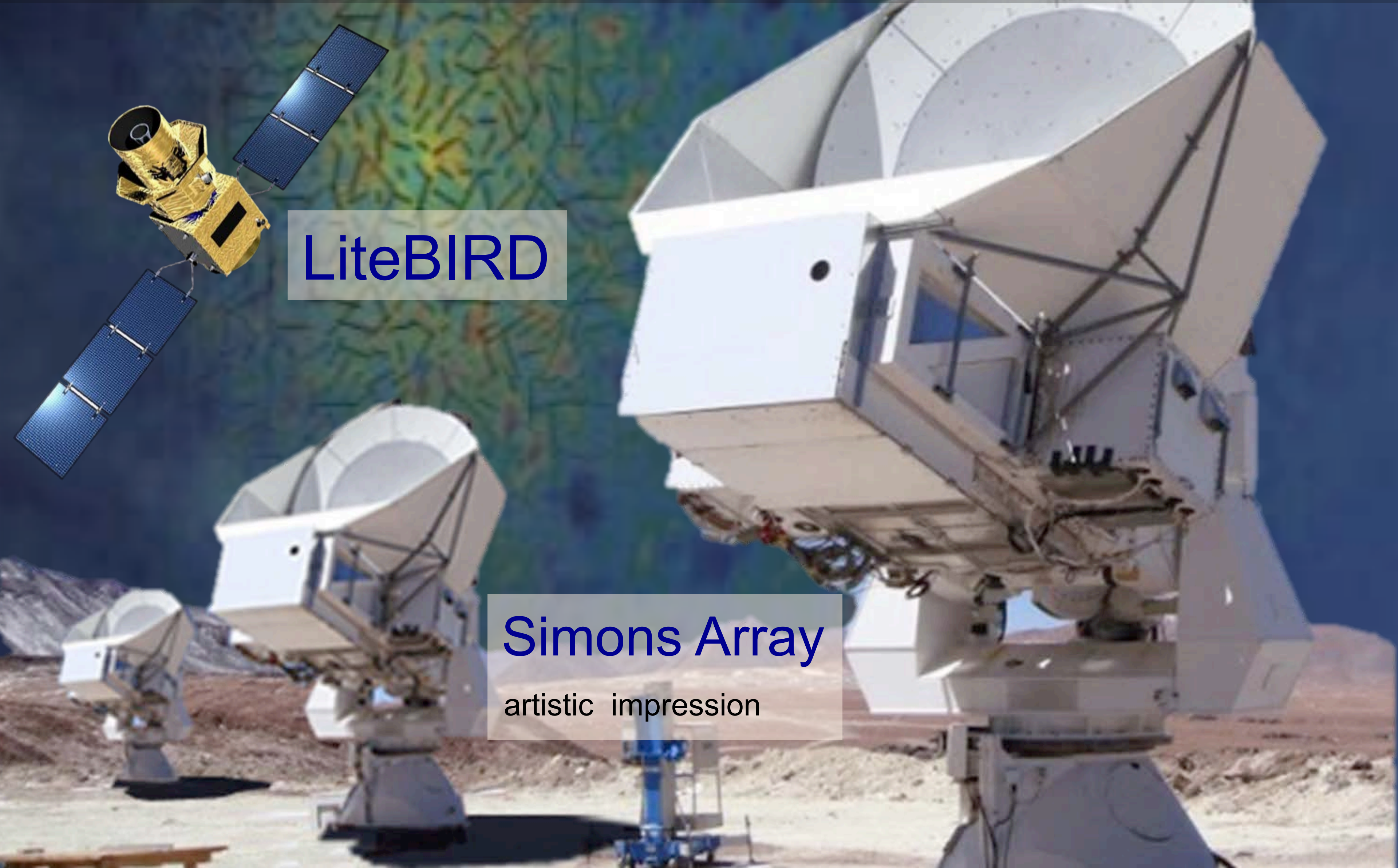


Planck 2015

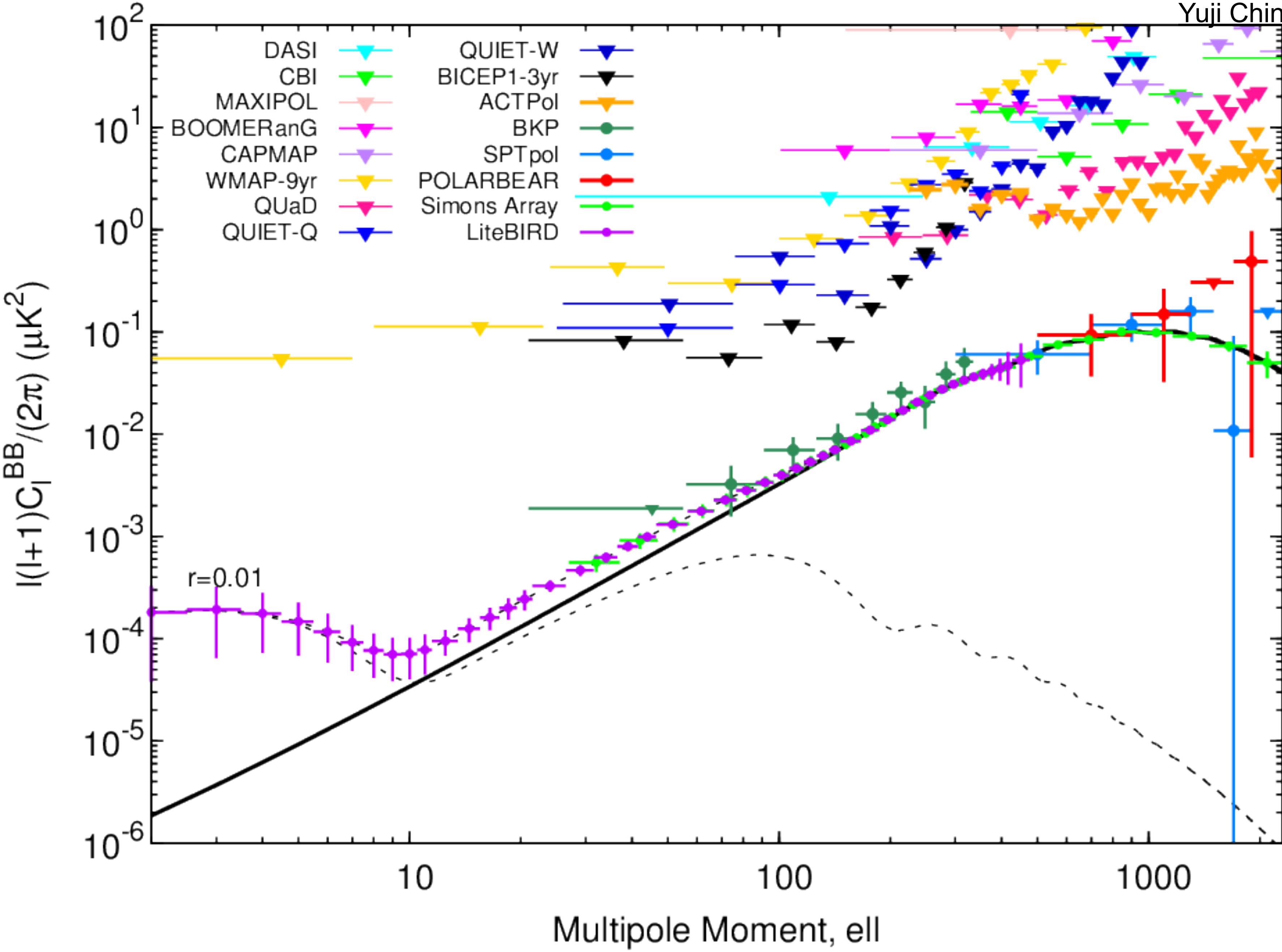


- Planck Temperature: r < 0.11 (95%C.L.)
- "BKP" Polarization: r < 0.12 (95%C.L.)
- Combined: r < 0.09 (95%C.L.)

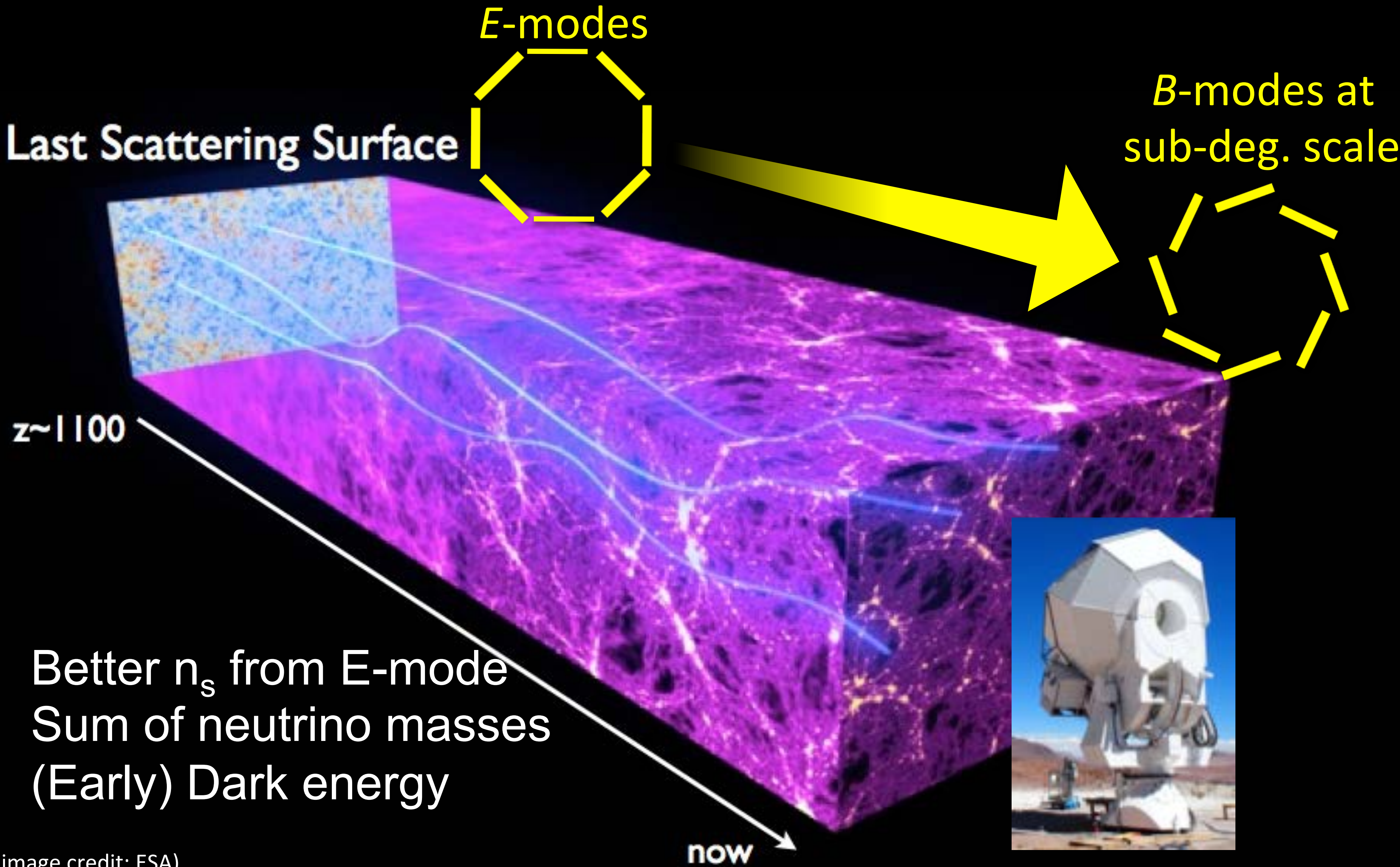
Future large-area CMB surveys for studies of cosmic acceleration and large-scale structure



Yuji Chinone



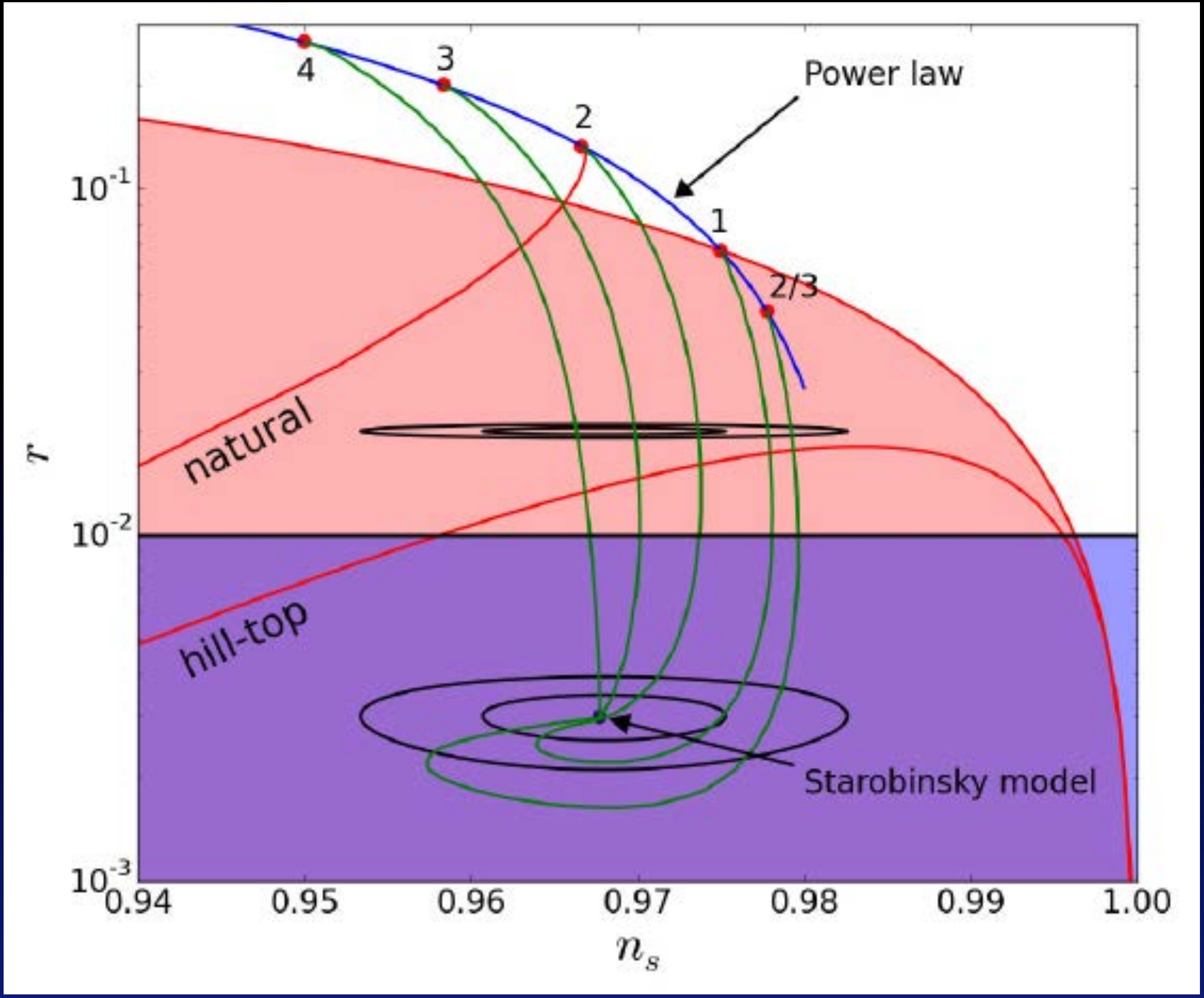
Lensing *B*-modes *by Weak lensing*



- Better n_s from E-mode
- Sum of neutrino masses
- (Early) Dark energy

(image credit: ESA)

LiteBIRD constraints on r vs. n_s plane (15 bands)



Why is LiteBIRD targeting σ(r) < 0.001 ?

- Many models predict r>0.01 → >10σ discovery.
- What if we do not see the signal ?
  - Focus on the simplest models based on Occam's razor principle.
  - Single field models that satisfy slow-roll conditions give

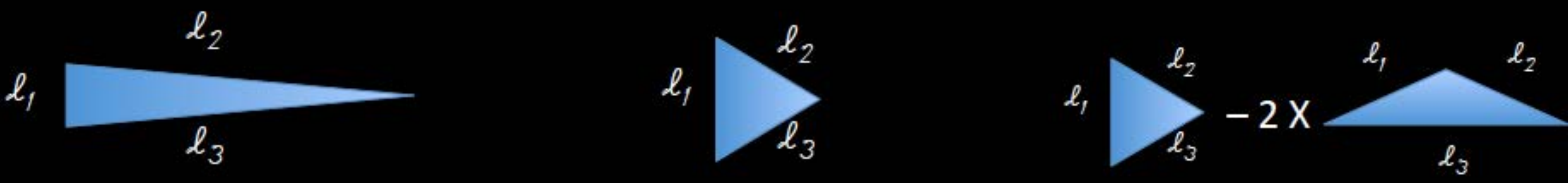
$$r \simeq 0.002 \left(\frac{60}{N}\right)^2 \left(\frac{\Delta\phi}{m_{pl}}\right)^2$$

N: e-folding, m_{pl}: reduced Planck mass

  - Establishing a bound r < 0.002 (95%C.L.) will rule out large field models. Setting this limit is a very significant contribution to cosmology and fundamental physics.
    - More model-dependent studies come to the same conclusion

Non-Gaussianity

- Another important observable (bispectrum) to distinguish between single-field and multi-field models



Ortho. = Equil. – 2 X Flat.

Inflation Models

	$f_{NL}^{loc} \lesssim 1$	$f_{NL}^{loc} \gtrsim 1$
$f_{NL}^{eq,\,orth} \lesssim 1$	Single-field slow-roll	Multi-field
$f_{NL}^{eq,\,orth} \gtrsim 1$	Single-field non-slow-roll	Multi-field

Target for space missions
(e.g. SPHEREX)

Planck 2015

$$f_{NL}^{local} = 0.8 \pm 5.0$$

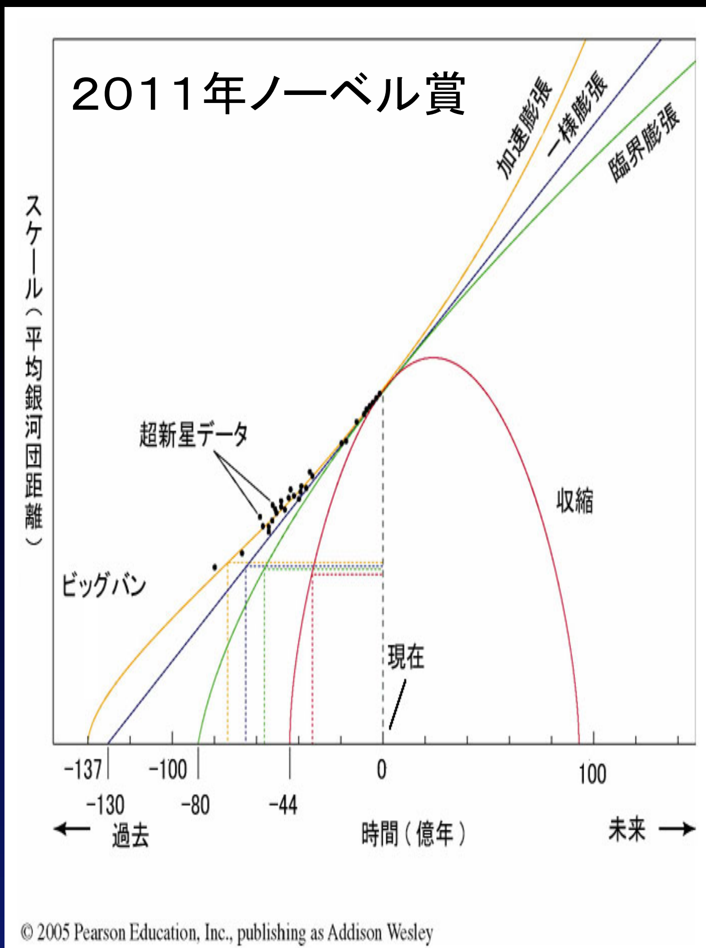
$$f_{NL}^{equil} = -4 \pm 43$$

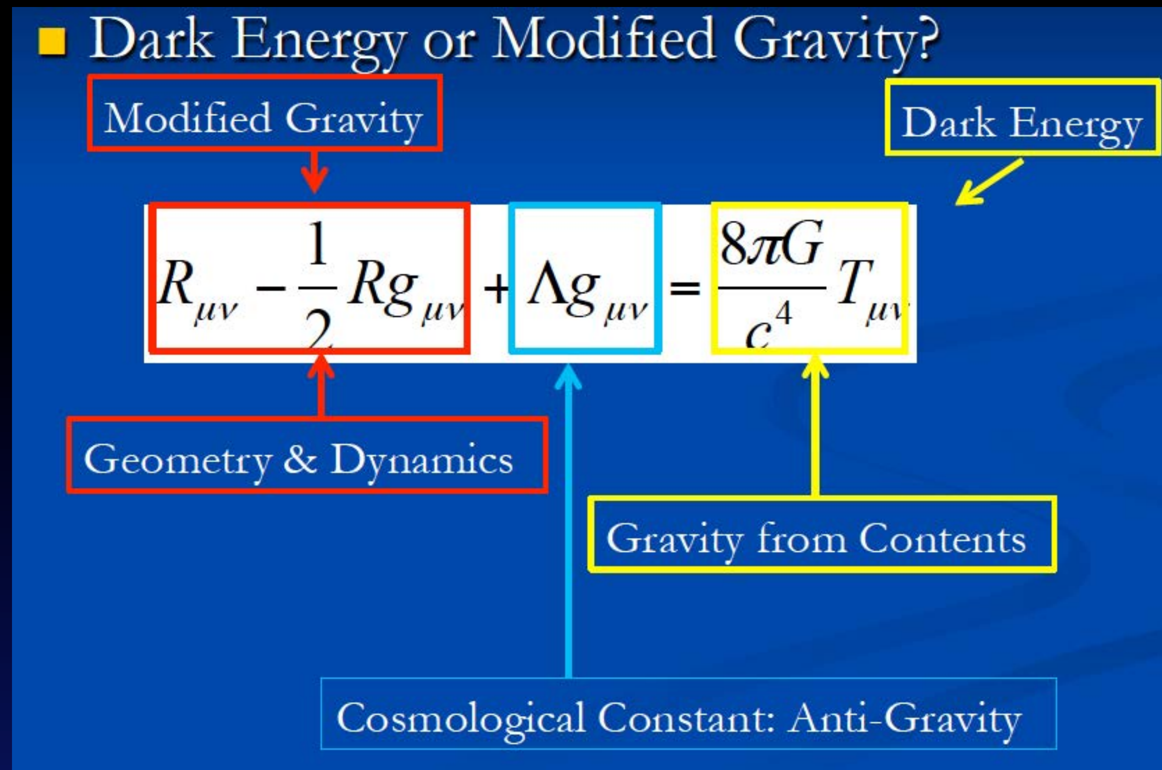
$$f_{NL}^{ortho} = -26 \pm 21$$

Dark Energy

Overview

Discovery of Acceleration





N. Sugiyama

Dark Energy Probes and Target

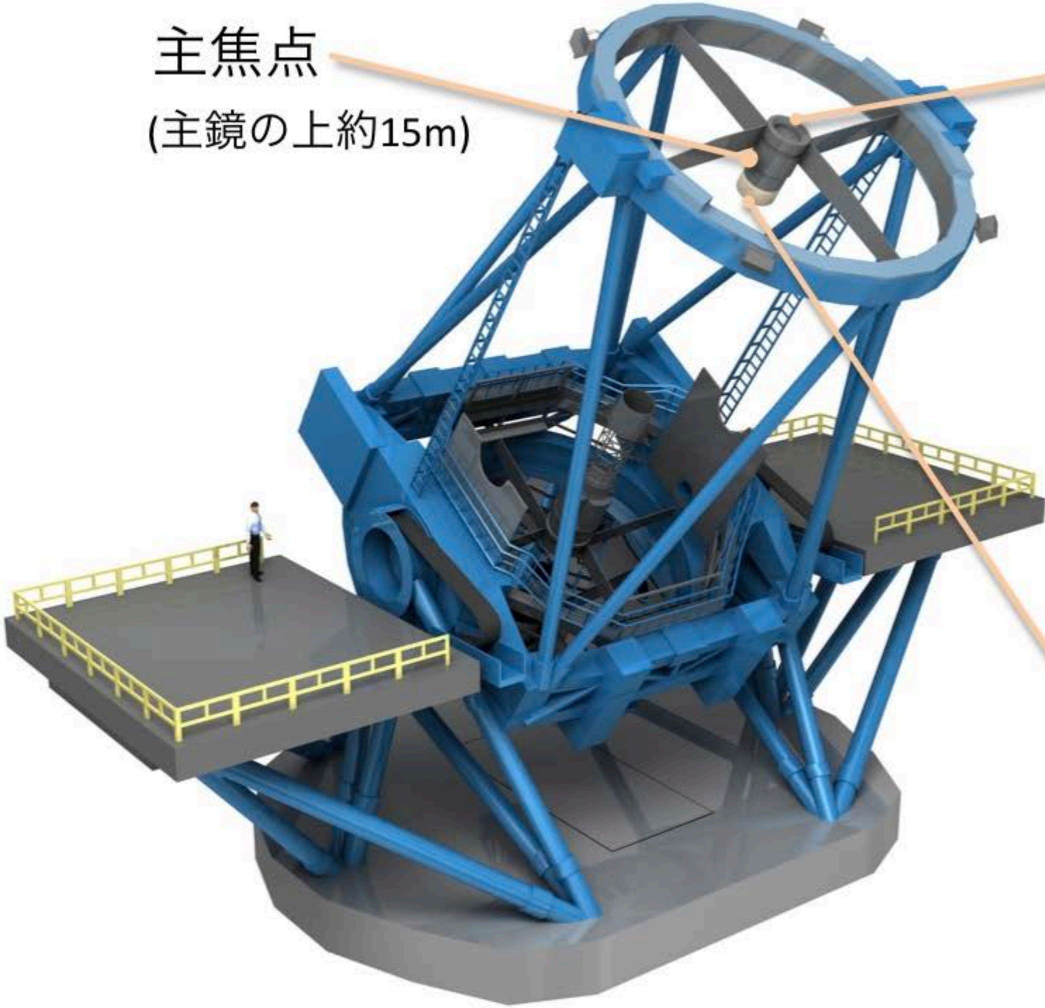
- Probes
  - SNe
  - Weak Lensing
  - Baryon Acoustic Oscillation
  - Sunyaev Zel'dovich Effect
- Target

$$w(a) \equiv \frac{p}{\rho} = w_0 + (1-a)w_a$$

時間変化するかどうか知りたい → ３次元マップ

主焦点

(主鏡の上約15m)

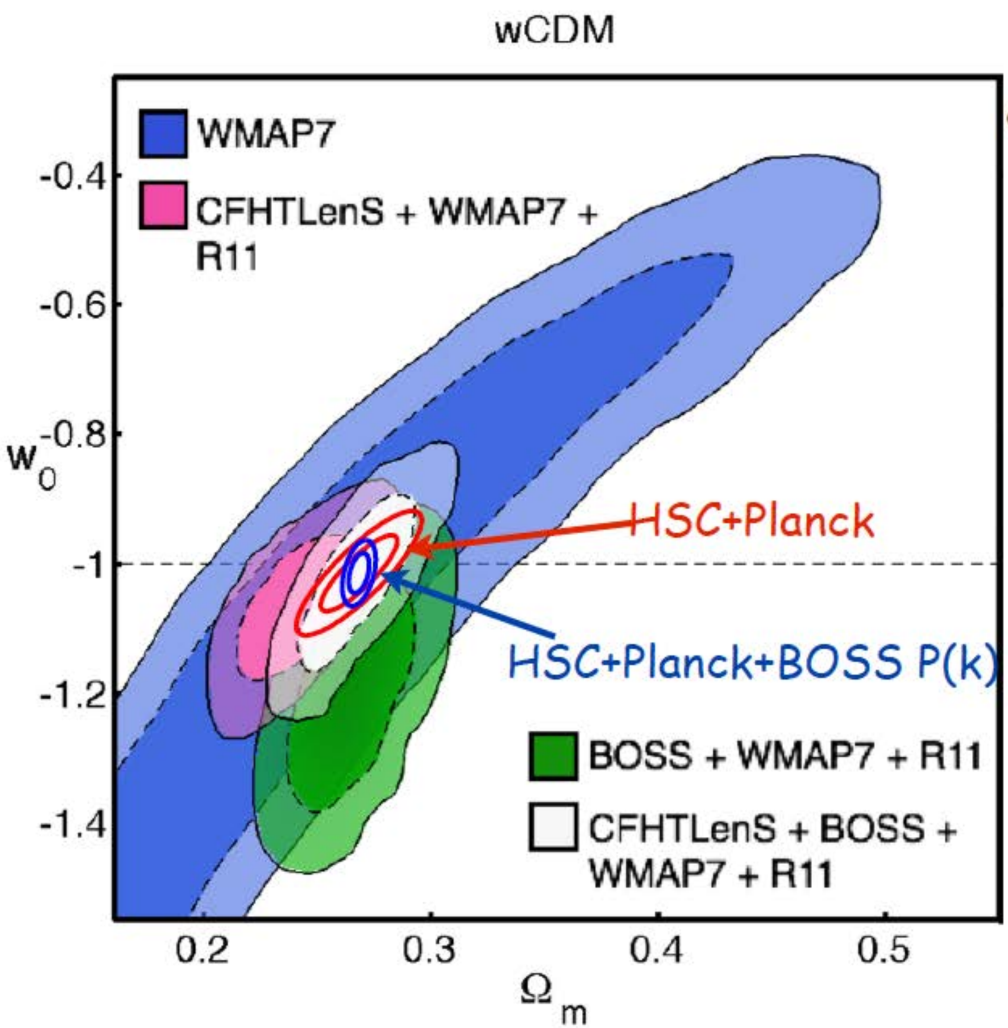


すばる望遠鏡

Hyper Suprime-Cam

(高さ約３m、重さ約３トン)

Cosmology through WL (Forecast)

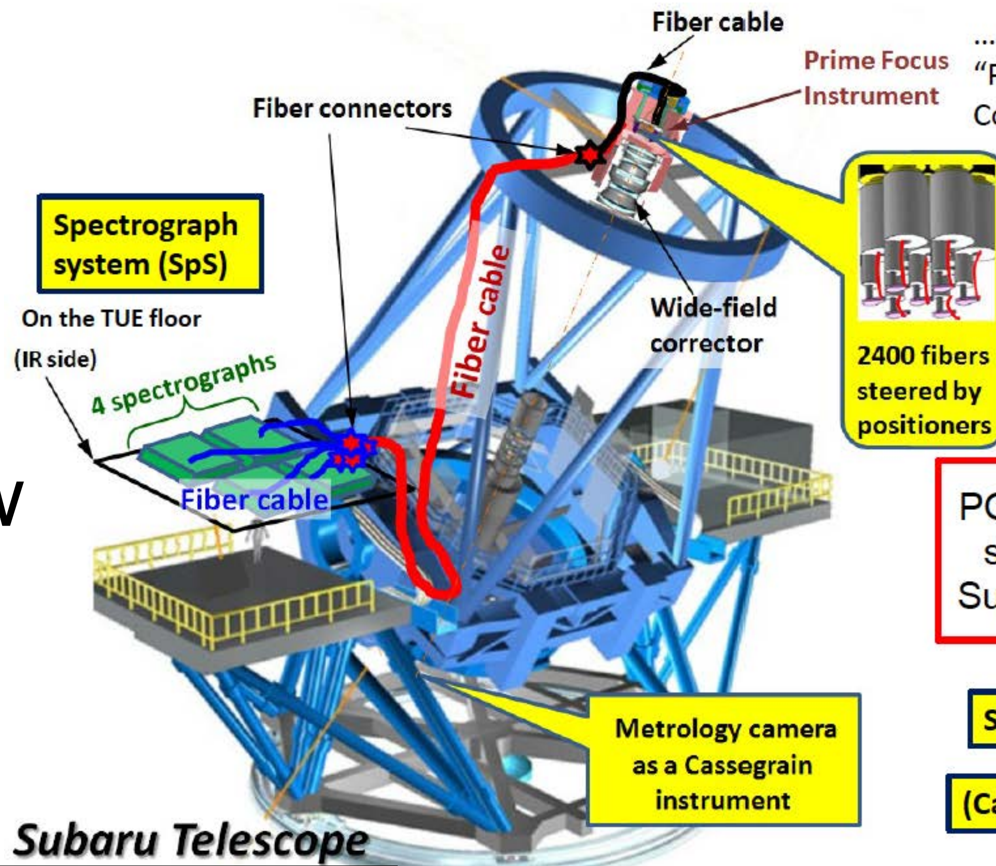


- 3 times improvement compared with CFHT Lensing Survey (Heymans et al. 13): 154deg2、2003-2008

N

Miyazaki

PFS Overview



POpt2 & WFC will be shared with Hyper Suprime Cam (HSC).

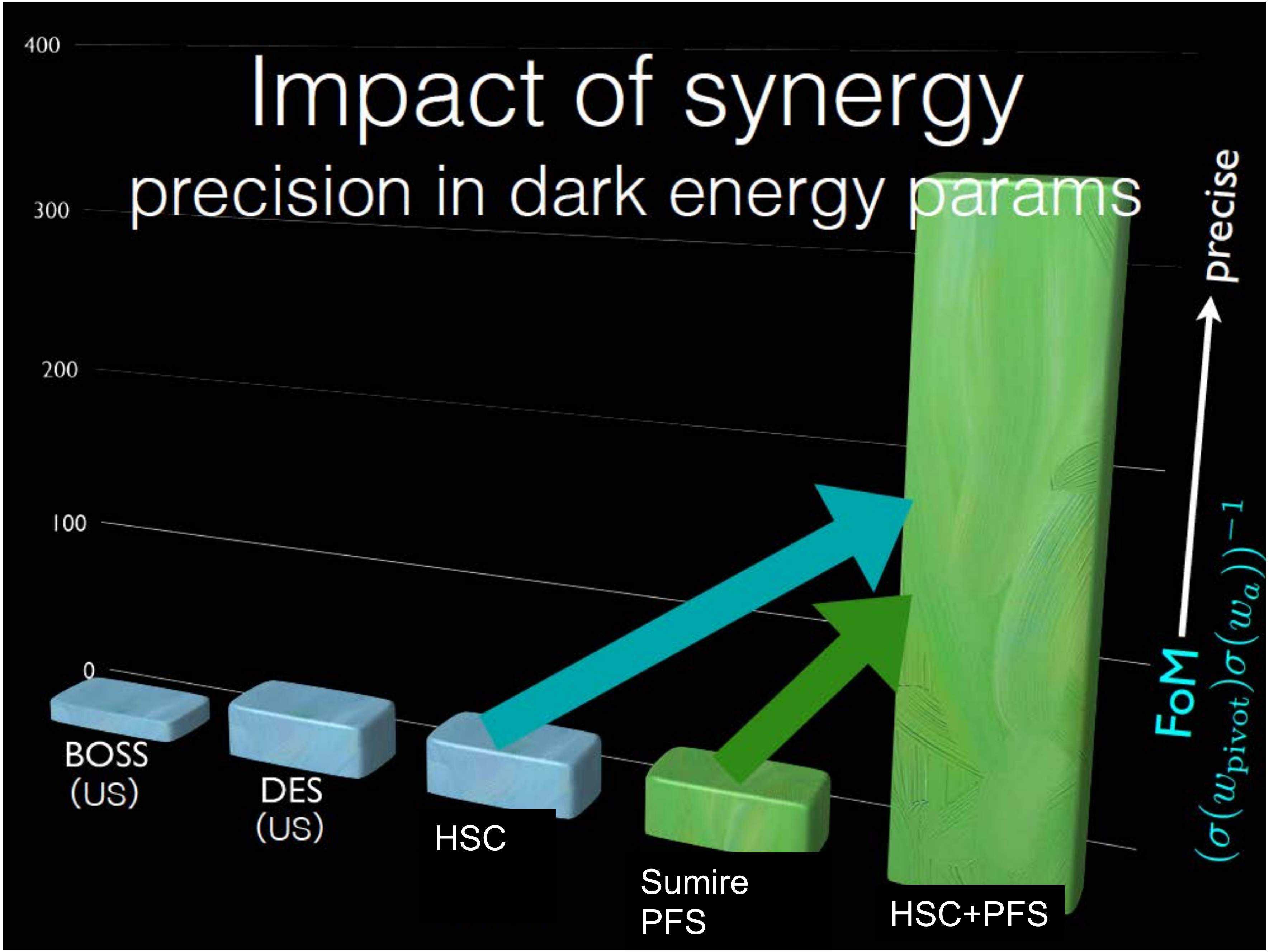
Software system

(Calibration system)

- Subaru *Prime Focus Spectrograph*
  - Wide field: *~1.3 deg* diameter
  - Highly multiplexed: *2400 fibers*
  - Quick fiber reconfiguration: *~60 sec* (TBC)
  - Optical-NIR coverage: *380-1260nm simultaneously*
- Developed by *international* collaboration, under the initiative of *Kavli IPMU*
- ***Cosmology***, ***Galaxy/AGN evolution***, ***Galactic Archaeology*** as the key science areas in the PFS collaboration
- Aiming to start science operation from *2019*, as *a facility instrument* on Subaru.

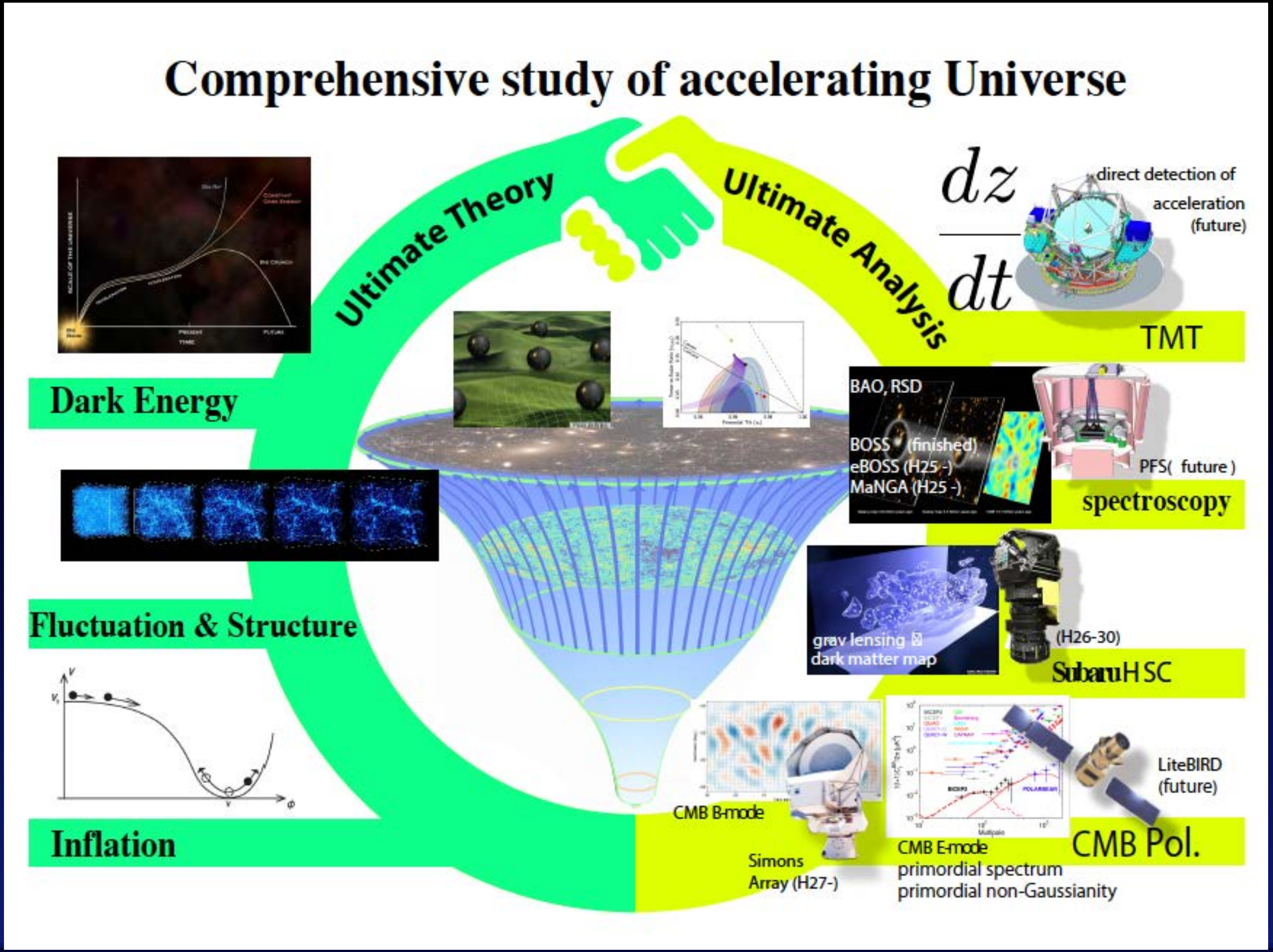
Impact of synergy

precision in dark energy params



新学術領域「加速宇宙」H27-H31

代表：村山斉（カブリIPMU）



Summary

- We are in the Golden Age of Cosmology;
  - Thanks Einstein and all who contributed !
- Yet we have 5 mysteries from particle physics viewpoint.
  → New physics is mandatory !
- Ultimately Quantum Gravity should be understood to solve the mysteries.
- Two eras of acceleration, Inflation and Dark Energy, are the clue.
- New projects (CMB polarization, Galaxy surveys etc.) will much improve the current precision.

Exciting time is ahead of us !