Testing Chern-Simons interaction with AliCPT

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Outline

1. Current status of dark energy
2. Interacting dark energy: Chern-Simons coupling
3. Probes dynamics of dark energy with AliCPT

宇宙从60亿年前开始
加速膨胀！

2011

Photo: Ariel Zambelich, Copyright © Nobel Media AB
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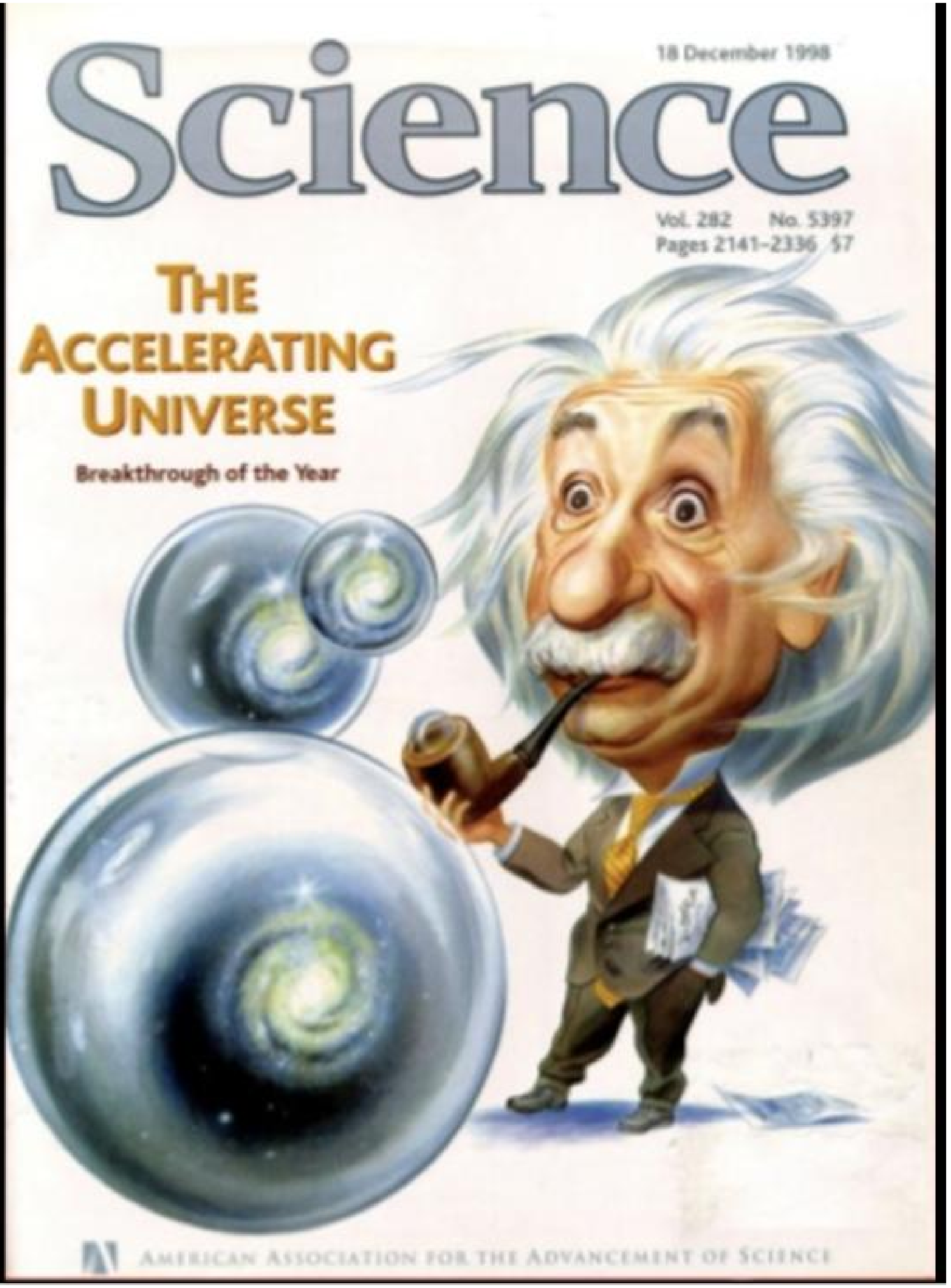
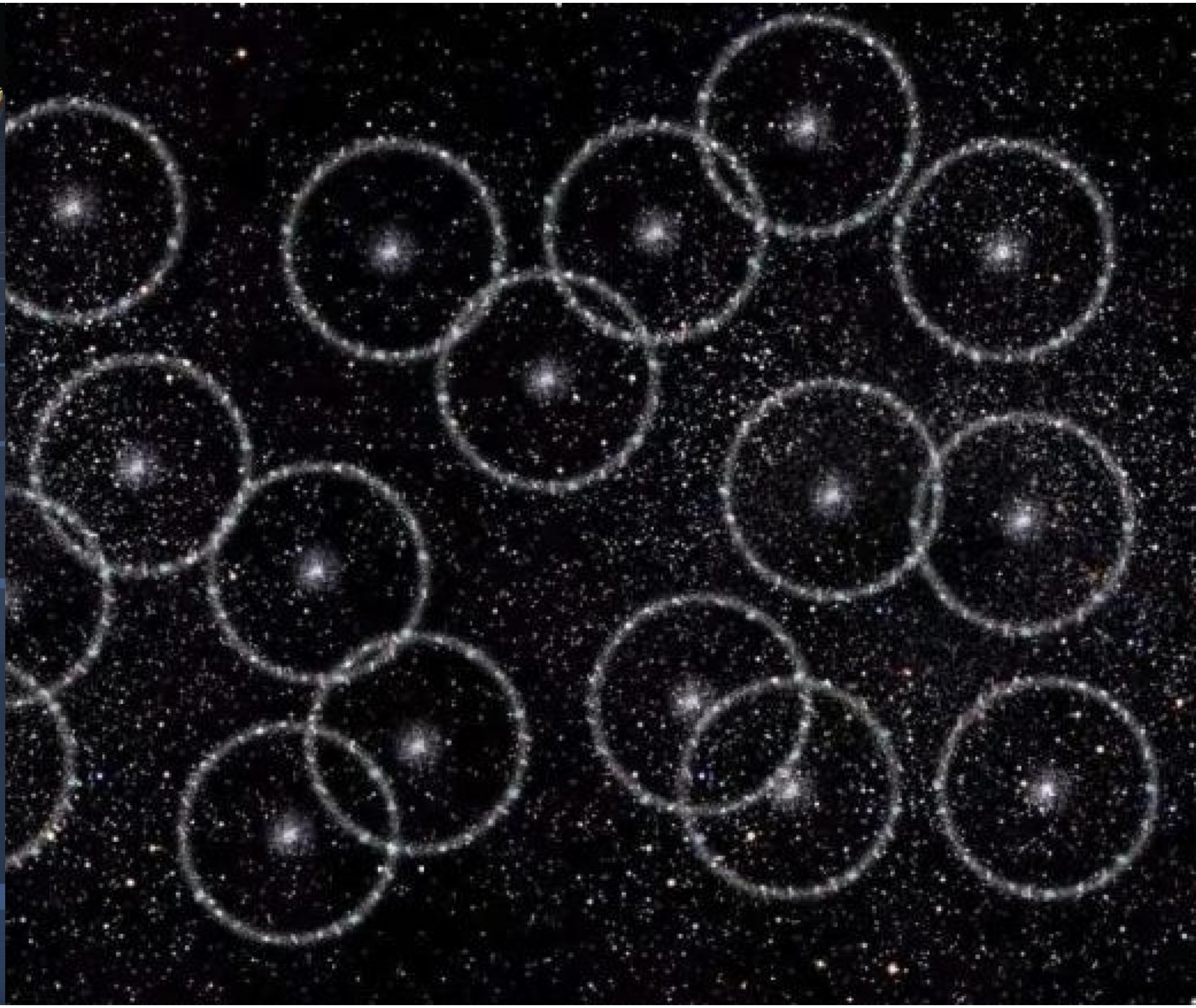
Photo: Belinda Pratten, Australian National University
Brian P. Schmidt

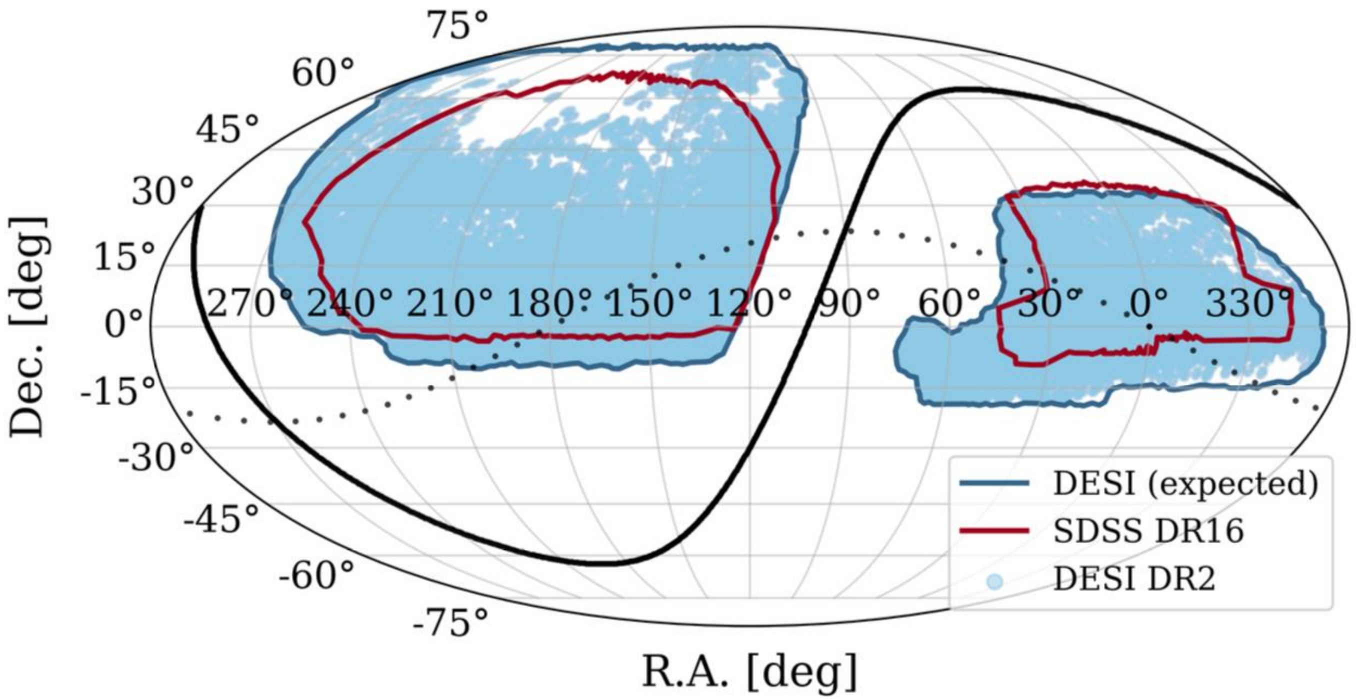
Photo: Homewood Photography
Adam G. Riess



Lots of efforts and data



DESI release DR2: 3-years observation



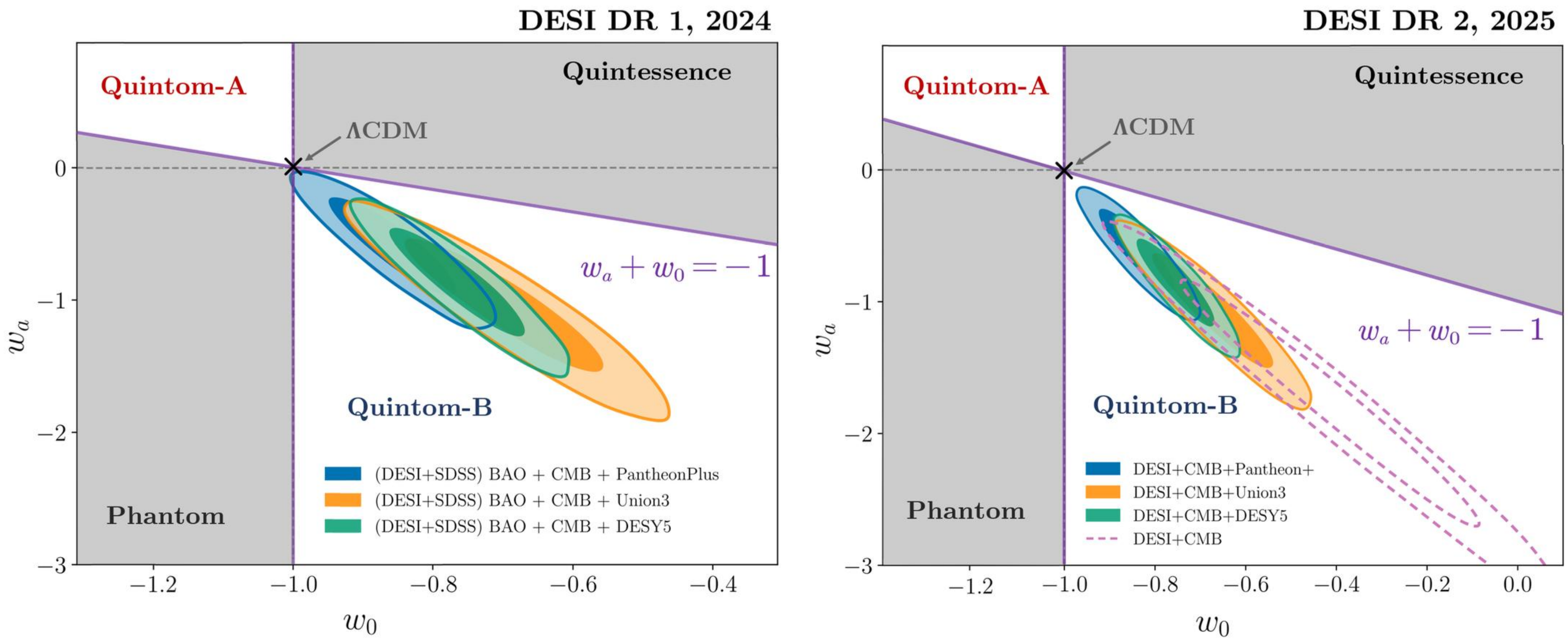
Dark Energy Spectroscopic Instrument (DESI),
Kitt Peak National Observatory

30 million galaxies and quasars in 3 years of operation,
DR2 cover galaxies at higher redshif, significant expanding galaxy sample

DESI collaboration, JCAP 02 (2025) 021, arxiv:2404.03002, DESI collaboration, arxiv: 2503.14738

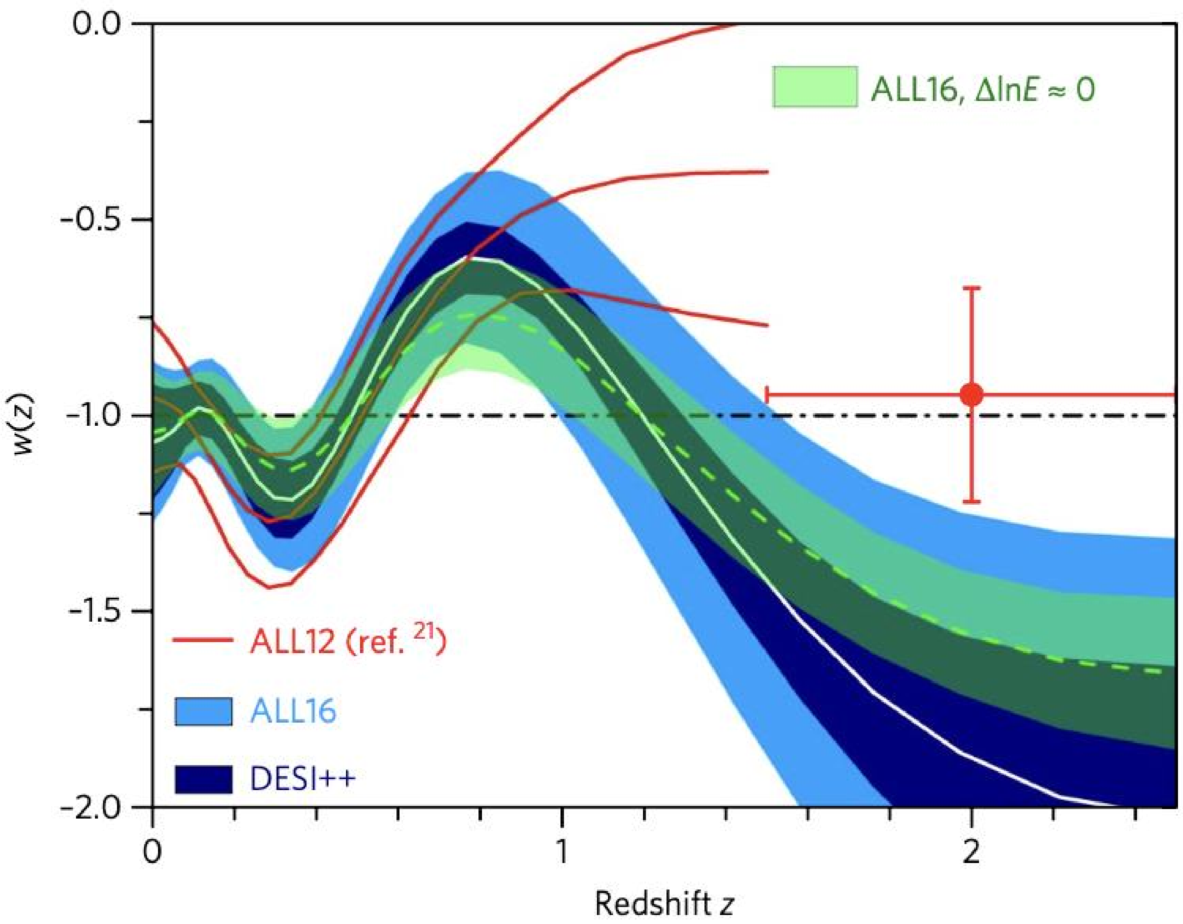
New constraints on dark energy from DESI DR2

- DESI-DR2 show a stronger preference of a time-varying dark energy EoS, at > 4σ , challenging w= -1 (e.g., the cosmological constant, Λ)



Yifu Cai, et al. , The Quintom theory of dark energy after DESI DR2, arxiv: 2505.24732

Various method yield consistent evolutionary trend



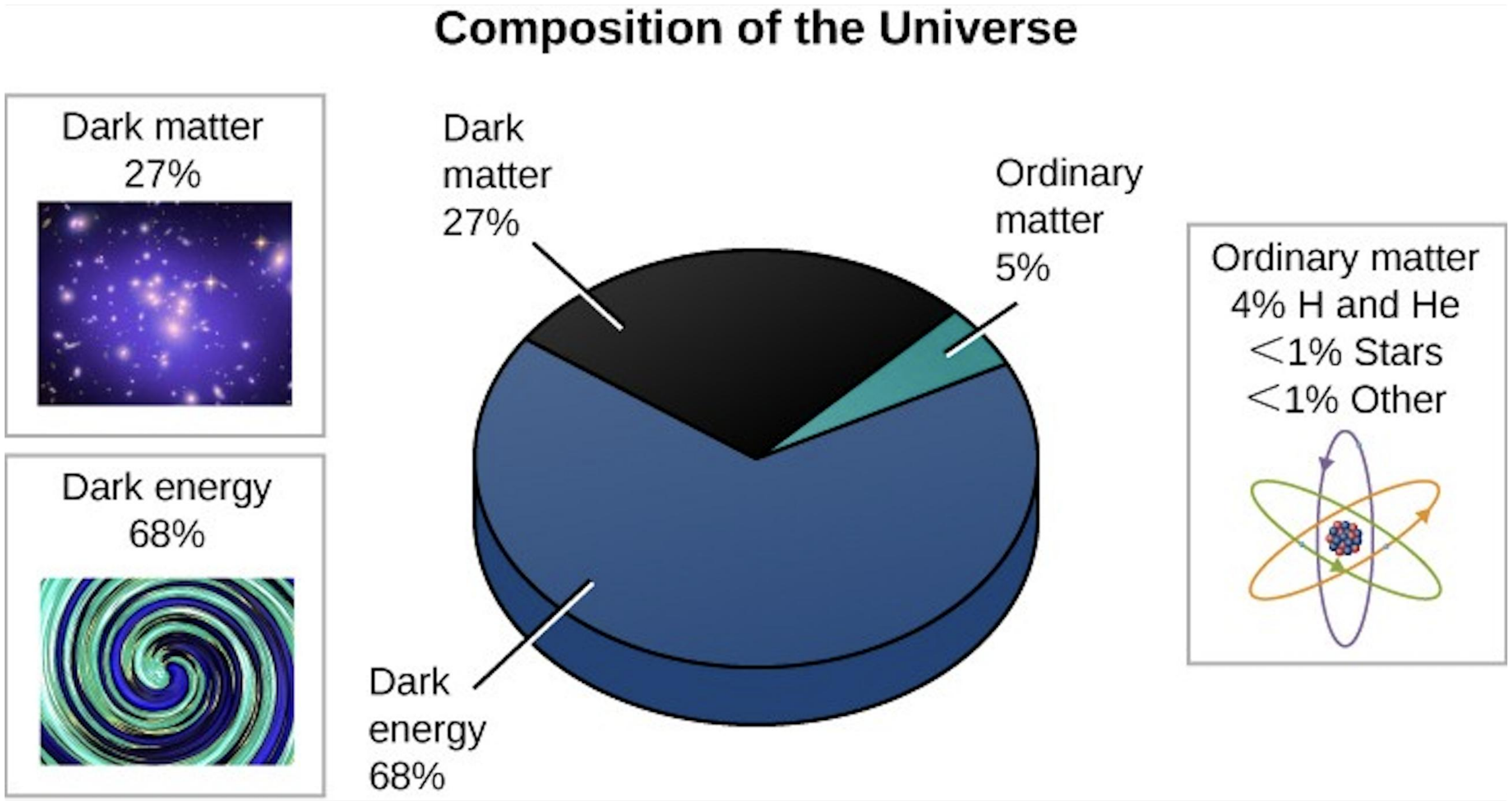
- **2012: 2.5 σ**
  (*Zhao et al*, PRL)
- **2017: 3.5 σ**
  (*Zhao et al*, Nat. Astron.)
- **2025: 4.3 σ**
  (*Gu et al*, DESI, 2025)

Strongly suggest possible dynamics in DE !

G. Zhao, R. Crittenden, L. Pogosian, X. Zhang （PRL, **2012**） (2.5 σ)
G. Zhao, et.al. （BOSS 合作组）Nature Astronomy, 1, 627-632, (**2017**) (3.5 σ)
G. Gu, et al., （DESI 合作组） arXiv:2504.06118,(**2025**) (4.3 σ)

Dark energy may have interactions

- ***Theoretically, it is implausible that a dynamical background field, constituting 68% of the universe's energy budget, would remain completely decoupled from other cosmic components !!!***



Interacting DE: a new pathway to understand DE

□ Building on a dynamical framework

- **I:** Precise measurement of the dark energy equation of state
  - More data：DESI、LSST、Euclid、CSST、ESST…
- **II：model building**
  - Quintom model building、cosmic evolution…
- **III：Investigate the potential interaction** between dynamical dark energy and ordinary matter
  - Interaction： Opening a new window into the physical nature of dark energy

Interacting DE: a new pathway to understand DE

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Chern-Simons interaction between DE and photon

$$\mathcal{L}_{CS} \sim p_\mu A_\nu \widetilde{F}^{\mu\nu}$$

- **Derivative of Scalar Field:** $p_\mu \sim \partial_\mu f(\phi)$
- **Dual Electromagnetic field Tensor:** $\widetilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$

☐ *The derivative coupling has the advantage of naturally incorporating shift symmetry: efficiently avoiding long-range forces*

Peccei-Quinn mechanism

$$\mathcal{L}_{int} \sim \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G^{a,\mu\nu}}$$

- Introduce $\mathrm{U(1)_{PQ}}$ symmetry, to solve strong CP problem
- Axion is the predicted scalar

$\mathcal{L}_{CS}$ modify Maxwell's equation

$$\mathcal{L}_{QED} \sim -\frac{1}{4}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu} \boxed{-\frac{1}{4}\alpha\phi F_{\mu\nu}\tilde{F}^{\mu\nu}}, \quad \alpha = c/M$$

$$\partial_\nu F^{\mu\nu} + \boxed{\frac{c}{M}\partial_\nu \phi \tilde{F}^{\mu\nu}} = 0, \quad \ddot{A} - \nabla^2 A + \boxed{\frac{c}{M}[-\dot{\phi}(\nabla \times A) + (\nabla\phi) \times \dot{A}]} = 0$$

$$\ddot{A}_\pm + (\kappa^2 \boxed{\mp \kappa \frac{c}{M}\dot{\phi}})A_\pm = 0$$

- **Induce a polarization rotation in photon**

$$\beta = \int \frac{c}{M}\partial_\mu \phi d\chi^\mu = \frac{c}{M}\Delta\phi$$

depends on both the photon propagation distance and the variation of the associated DE field

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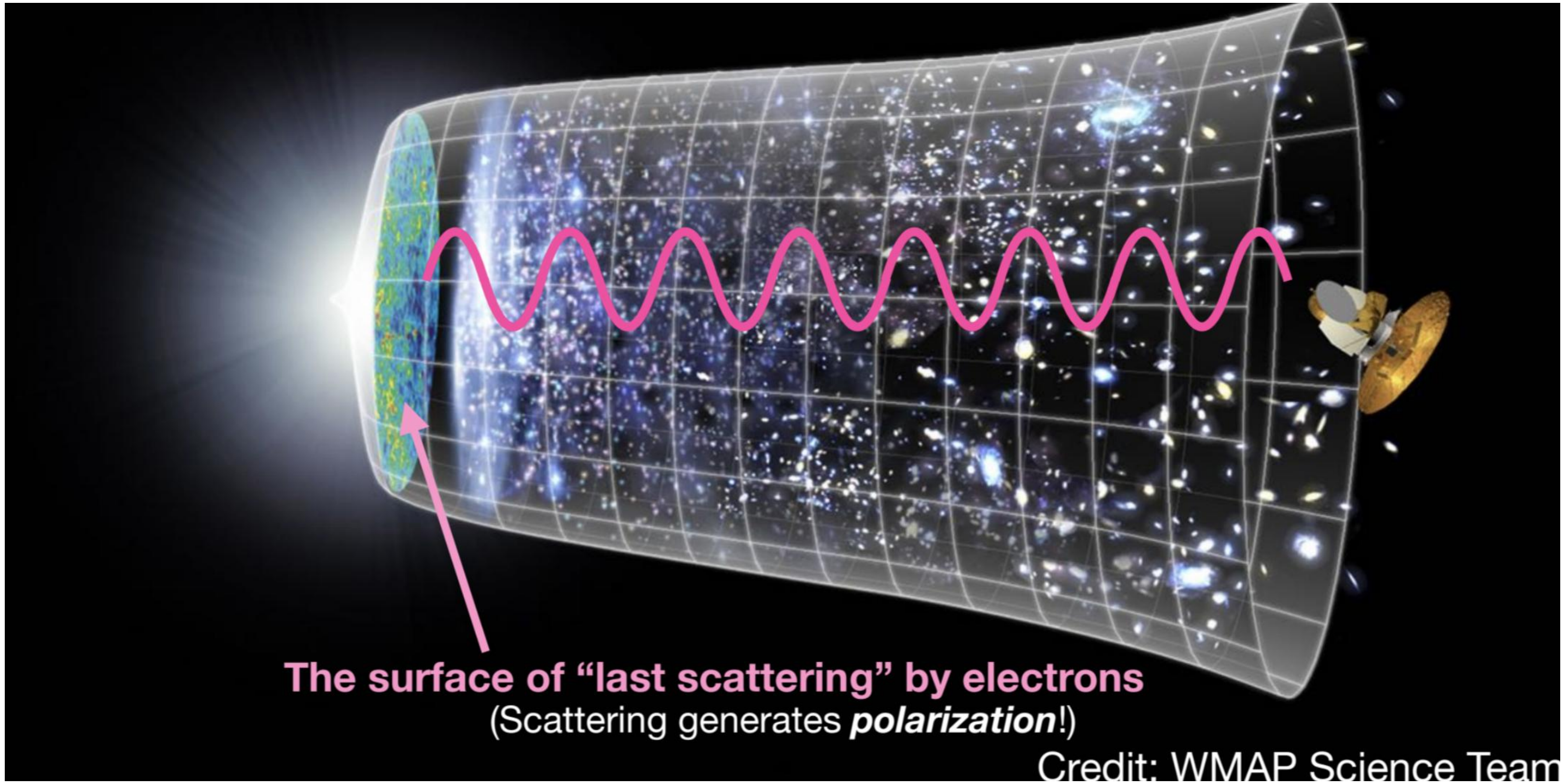
- **Induce a polarization rotation in photons**

$$\beta = \int \frac{c}{M}\partial_\mu \phi d\chi^\mu = \frac{c}{M}\Delta\phi$$

depends on both the photon propagation distance and the variation of the associated

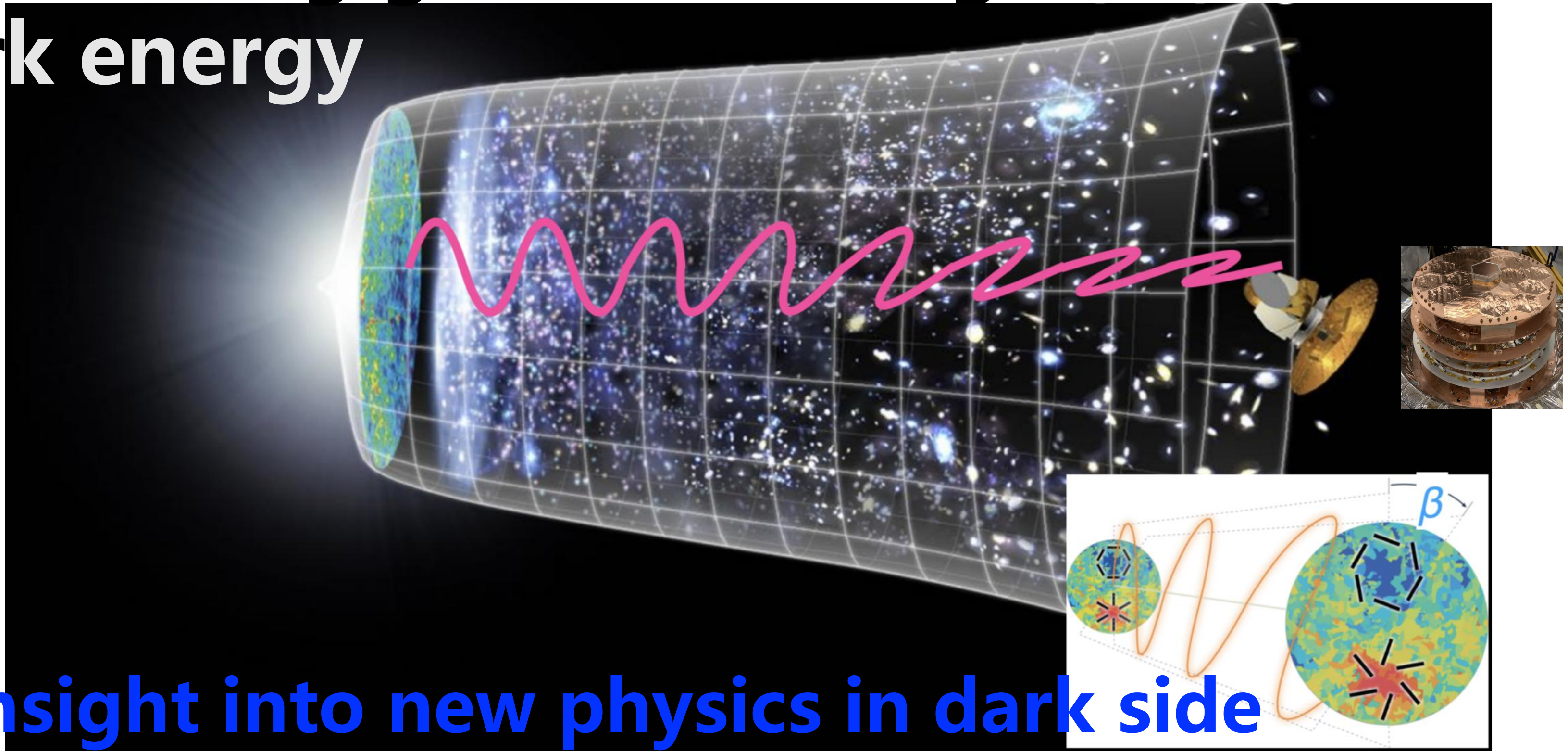
CMB photons


The surface of "last scattering" by electrons
(Scattering generates *polarization*!)
Credit: WMAP Science Team

Rotation Angles in CMB Photons: A window into cosmic history

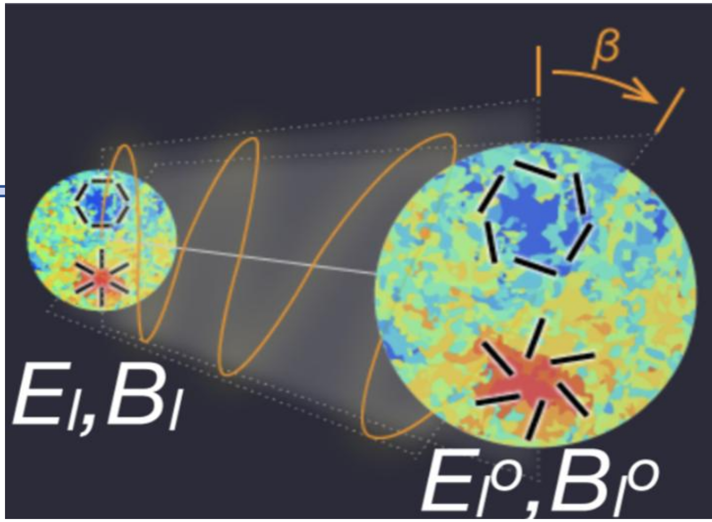
$$\beta = \int \frac{c}{M}\, \partial_\mu \phi\, d\chi^\mu = \frac{c}{M}\, \Delta\phi$$

$\Delta\phi$: providing a smoking gun for tracing the cosmic evolution of dark energy

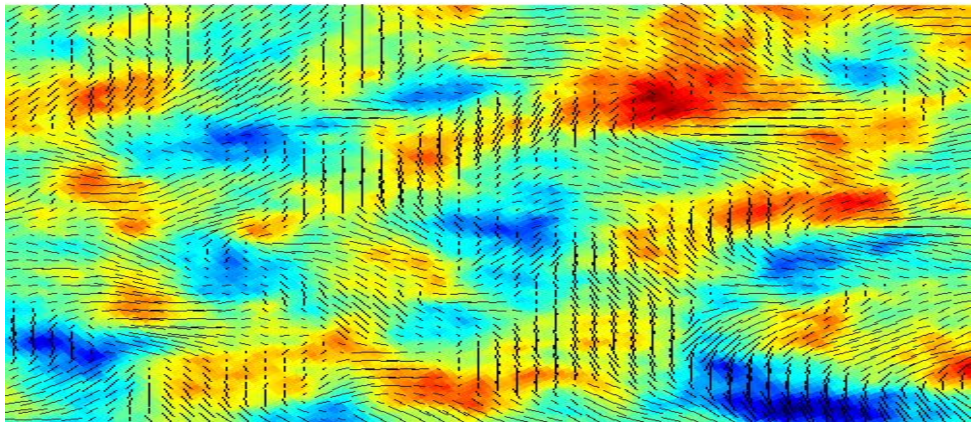


Insight into new physics in dark side

Non-zero TB，EB



$$Q^o \pm iU^o = (Q \pm iU)e^{\pm 2i\beta}$$



$$C^o{}_\ell{}^{TB} = C_\ell{}^{TE}\sin 2\bar{\beta}$$

Arthur Lue, et al. (1999);

$$C^o{}_\ell{}^{EB} = \frac{1}{2}\left(C_\ell{}^{EE} - C_\ell{}^{BB}\right)\sin 4\bar{\beta}$$

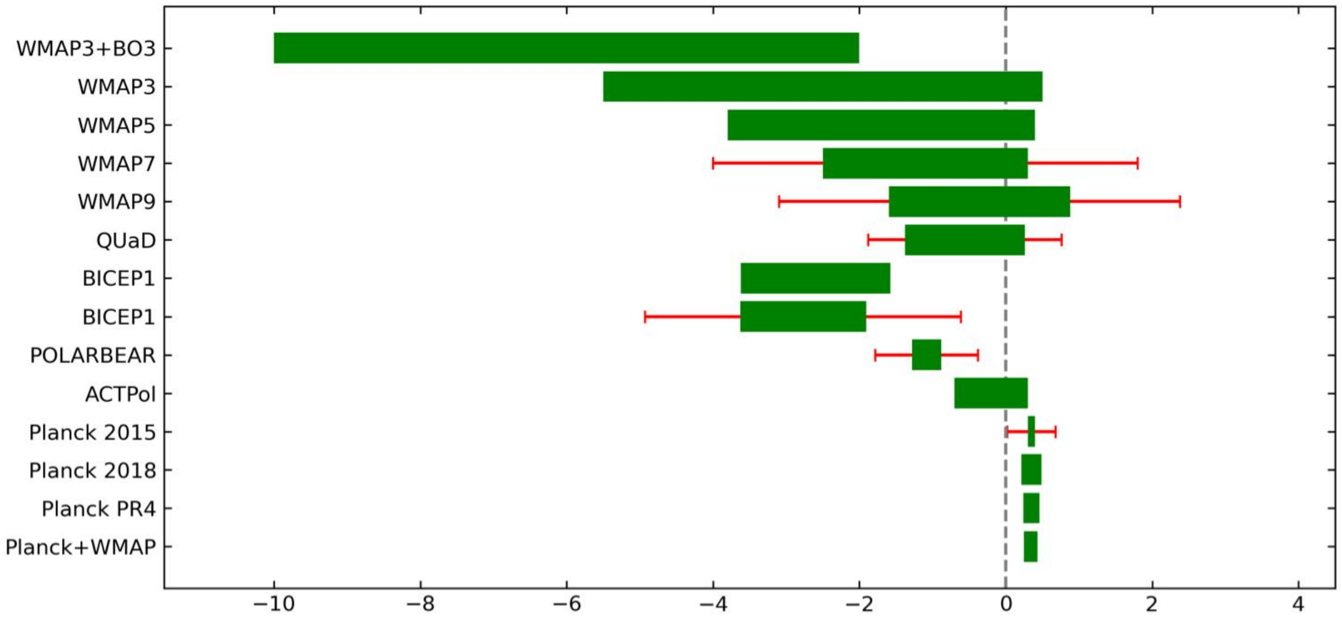
$$C^o{}_\ell{}^{TE} = C_\ell{}^{TE}\cos 2\bar{\beta}\ ,$$

$$C^o{}_\ell{}^{EE} = C_\ell{}^{EE}\cos^2 2\bar{\beta} + C_\ell{}^{BB}\sin^2 2\bar{\beta}$$

$$C^o{}_\ell{}^{BB} = C_\ell{}^{BB}\cos^2 2\bar{\beta} + C_\ell{}^{EE}\sin^2 2\bar{\beta}$$

Feng, H. Li, M.Z. Li, X.M. Zhang, (2005)

Summary of the Measurements from CMB Experiments



	Data	$\alpha + \sigma_\alpha^{stat} + \sigma_\alpha^{sys}$
1	WMAP3+BOOMERANG	$-6^\circ \pm 4^\circ$
2	WMAP3	$-2.5^\circ \pm 3^\circ$
3	WMAP5	$-1.7^\circ \pm 2.1^\circ$
4	WMAP7	$-1.1^\circ \pm 1.4^\circ \pm 1.5^\circ$
5	WMAP9	$-0.36^\circ \pm 1.24^\circ \pm 1.5^\circ$
6	QuaD	$-0.56^\circ \pm 0.82^\circ \pm 0.5^\circ$
7	BICEP1	$-2.6^\circ \pm 1.02^\circ$
8	BICEP1	$-2.77^\circ \pm 0.86^\circ \pm 1.3^\circ$
9	POLARBEAR	$-1.08^\circ \pm 0.2^\circ \pm 0.5^\circ$
10	ACTPol	$-0.2^\circ \pm 0.5^\circ$
11	Planck 2015	$0.35^\circ \pm 0.05^\circ \pm 0.28^\circ$
12	Planck 2018	$0.35^\circ \pm 0.14^\circ$
13	Planck PR4	$0.35^\circ \pm 0.11^\circ$
14	Planck + WMAP	$0.342^{\circ}{}^{+0.094^\circ}_{-0.091^\circ}$

Latest measurement：non-zero @3.6σ

Refs：

[1]Feng, et.al., 2006, PRL 96, 221302
[2]Cabella, et.al., J. 2007, PRD, 76, 123014
[3]Komatsu, et.al., 2009, ApJS, 180, 330-376
[4]Komatsu, et.al., 2011, ApJS, 192, 18
[5]Hinshaw, et.al., 2013, ApJS, 208, 19
[6]QUaD Collaboration, et.al., 2009, PRL, 102, 161302
[7]XIA, et.al., 2010, PLB 687, 129
[8]BICEP1 Collaboration, et.al., 2014, PRD, 89,062006
[9]The POLARBEAR Collaboration, et.al., 2014, ApJ, 794, 171
[10]Naess, et.al., 2014, JCAP, 10, 007
[11]Planck Collaboration, arXiv:1605.08633
12Yuto,et.al., 2020, PRL. 125, 221301
13P. Diego-Palazuelos, et.al., arXiv:2203.04830
14 Johannes, et.al., 2022, PRD,106, 063503

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Focus: Testing a Universal Symmetry

Published June 12, 2006 | Phys. Rev. Focus **17**, 21 (2006) | DOI: 10.1103/PhysRevFocus.17.21

The cosmic microwave background that fills the Universe provides a test for asymmetries in the laws of physics.

The laws of physics show many symmetries. No matter what direction you toss a ball, for example, its interactions with Earth's gravity follow the same rules. But theorists looking for ways to connect quantum theory with relativity have suggested that a fundamental symmetry known as *CPT* might be violated, even though it underlies all of modern physics. In the 9 June *PRL*, researchers describe a new way to test this basic principle using measurements of the microwave glow leftover from the big bang. Their analysis shows a small *CPT* violation, although it is statistically consistent with no violation. Still, experts say the paper shows a new way to test fundamental symmetries, and it will continue to be useful as better data become available.

All known interactions in particle physics heed a rule known as *CPT* invariance. Start with a collection of interacting particles, then create a mirror-image version (parity reversal, *P*), change the signs on all electrical charges (*C*), and let time run backward (*T*). Under *CPT* invariance, the interactions among the particles in these two complementary situations–before and after the *CPT* reversals–are identical, as are the probabilities for each possible outcome. Because *CPT* involves space and time operations, it turns out that any violation of *CPT* invariance would disrupt the spacetime symmetries embodied in relativity theory.

In effect, *CPT* violation would mean that not all directions in space are equivalent. There would be one special direction in space, and electromagnetic radiation would propagate differently depending on its orientation relative to this special direction. To look for this effect, Bo Feng of the National Astronomical Observatories in Beijing and his colleagues scrutinized recent measurements of the cosmic microwave background or CMB–radiation filling the universe that arose from the big bang.

Data from the satellite-borne Wilkinson Microwave Anisotropy Probe (WMAP) and the BOOMERANG instrument, flown by balloon over Antarctica, include detailed measurements across the sky of the direction of the electric field, or polarization, of the CMB. If *CPT* symmetry is violated, then all polarizations will rotate with respect to the special space direction as the radiation travels through the universe.

Although we can't follow a single CMB photon to see if its polarization changes over time, Feng and his colleagues realized that polarization rotation would generate a relationship among CMB polarizations measured at different points on the sky. That is, polarization at two points would not be randomly related but would have a specific type of correlation with each other. They found signs of this correlation in their analysis, but statistically speaking, it could have arisen from random chance.

Even if further measurements were to confirm the correlation, Feng is quick to admit, it would not be a definitive demonstration of *CPT* violation. His team's test, strictly speaking, detects a P violation in the way photons propagate. However, there is no P-violating theory for photons that doesn't also violate *CPT*, says Feng. Moreover, *CPT* violation of this type may have a natural connection to the "dark energy" that cosmologists have recently postulated to explain novel features of cosmic expansion.

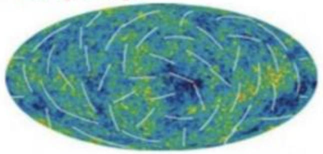
Marc Kamionkowski of the California Institute of Technology in Pasadena says that until recently, looking for exotic phenomena such as *CPT* violation was mostly regarded as "a fishing expedition–a waste of time." But since nobody has any clue what dark energy is, he adds, previously unthinkable hypotheses have gained some credibility. Though their results are as yet inconclusive, the Chinese team has performed "a nice measurement," he says, and their efforts should prompt further scrutiny of the available data.

–David Lindley

David Lindley is a freelance science writer in Alexandria, Virginia.

Searching for *CPT* Violation with Cosmic Microwave Background Data from WMAP and BOOMERANG
Bo Feng, Mingzhe Li, Jun-Qing Xia, Xuelei Chen, and Xinmin Zhang
Phys. Rev. Lett. **96**, 221302 (2006)
Published June 7, 2006

+Enlarge image



NASA/WMAP Science Team

Physics test. An analysis of the polarization (white lines) of the cosmic microwave background measured across the entire sky can test for violations of the fundamental symmetry known as *CPT*.

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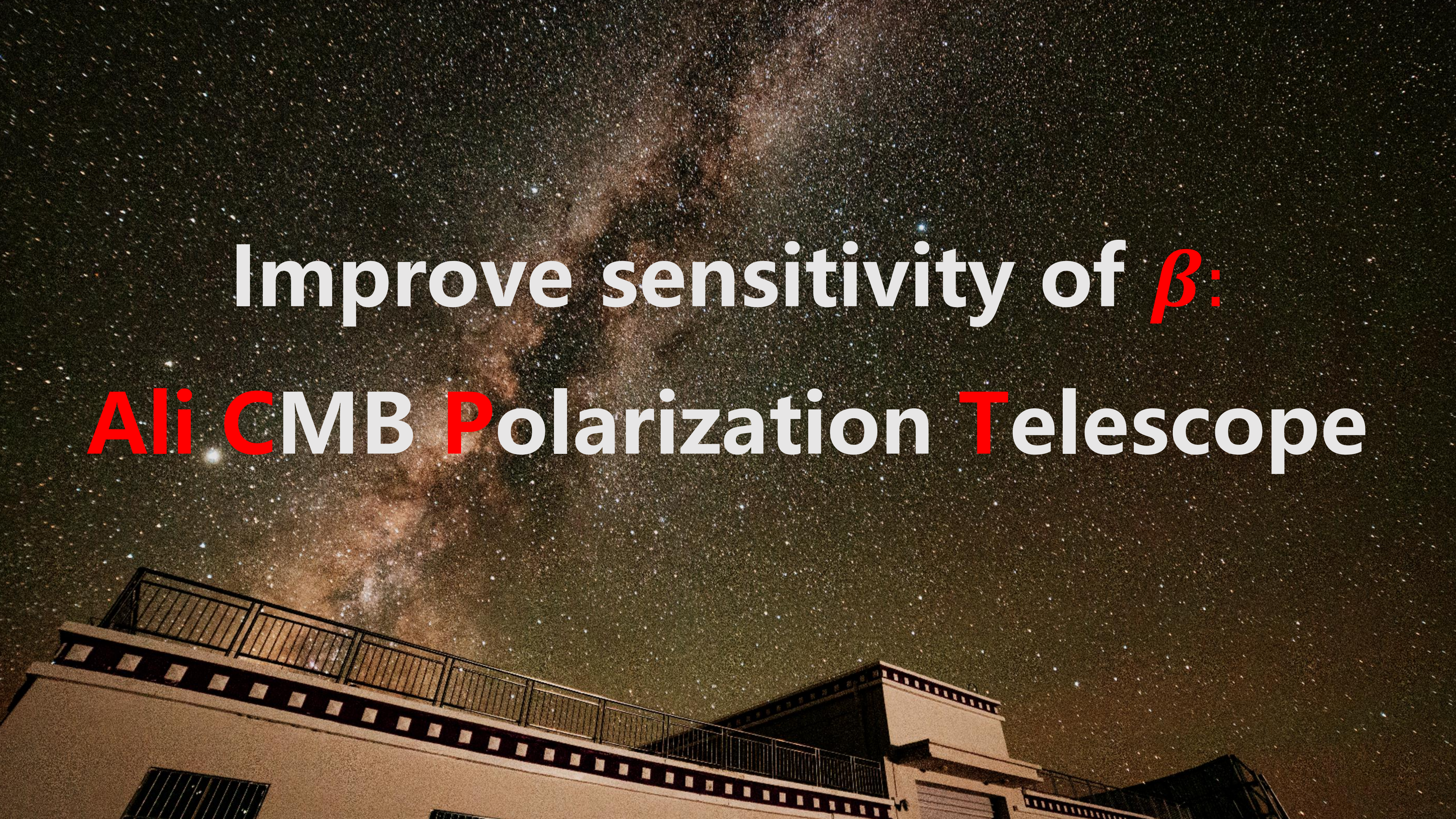
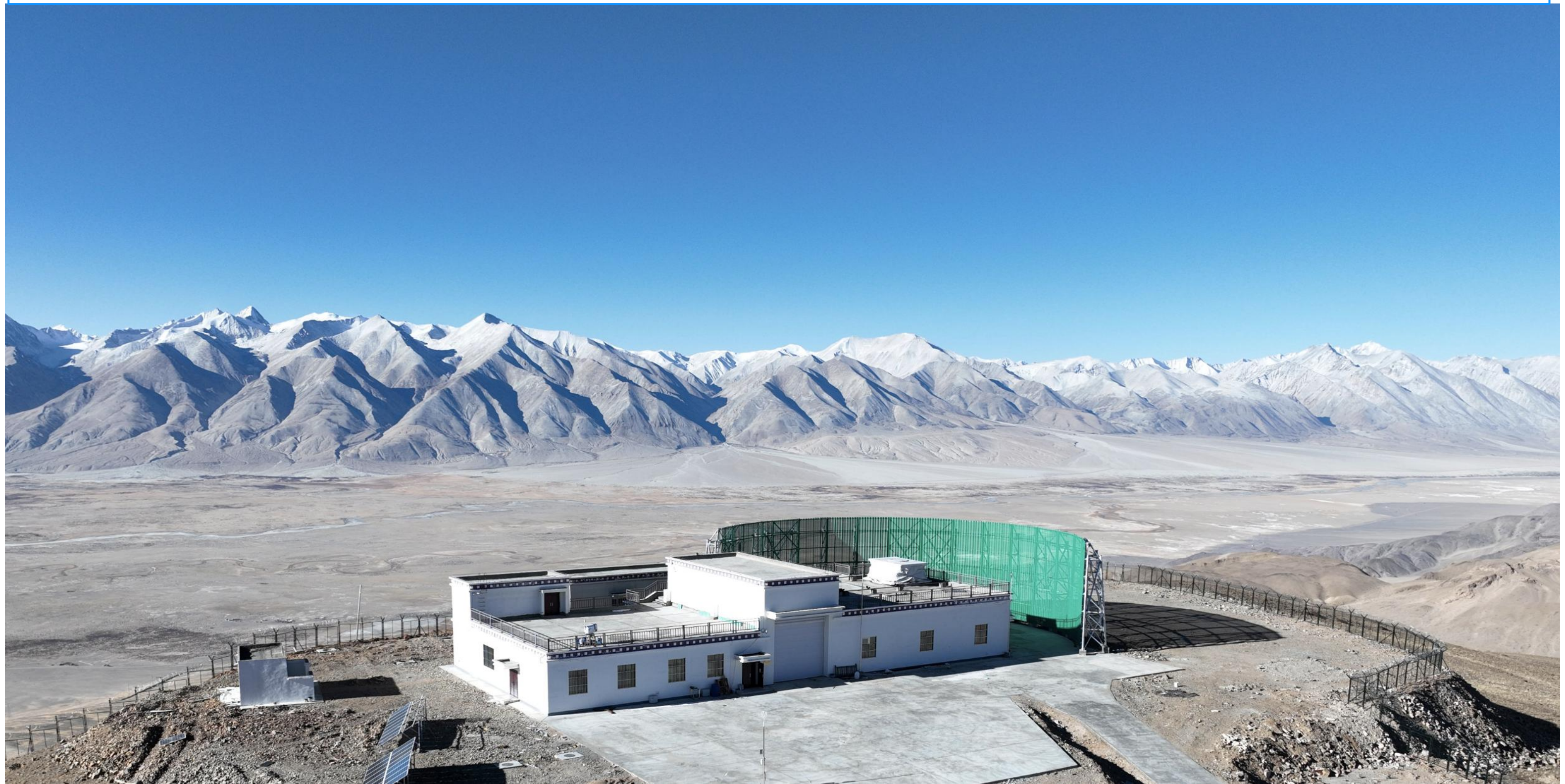
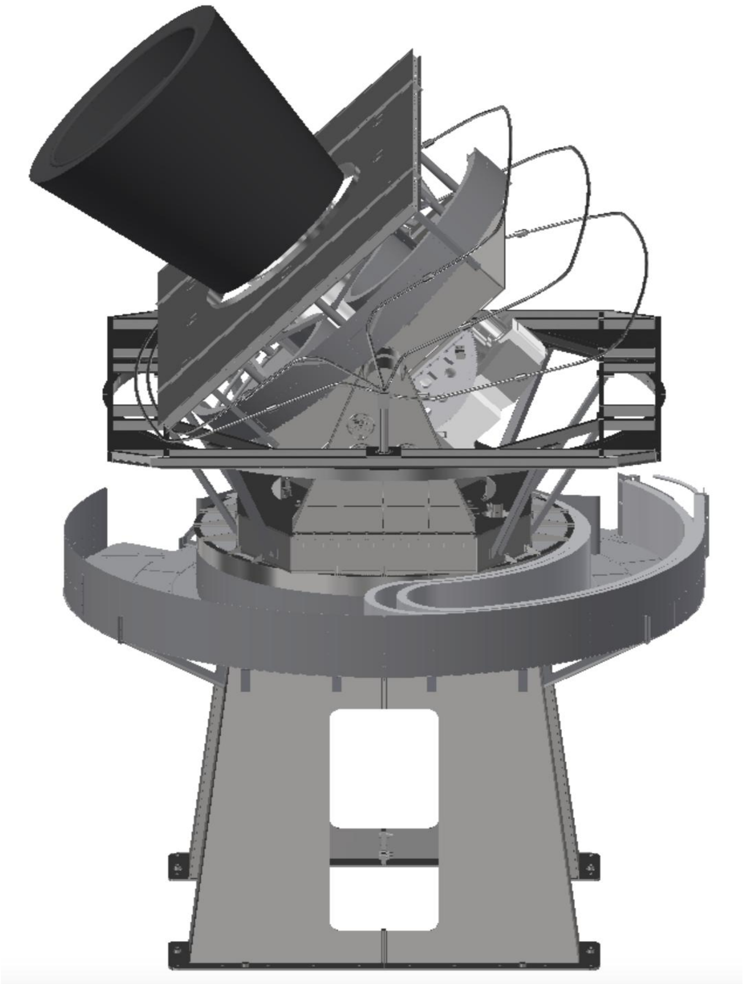

Improve sensitivity of β:
Ali CMB Polarization Telescope

Ali CMB Polarization Telescope (AliCPT)

AliCPT is an international CMB project, located in Ali region of Tibet at an elevation of 5,250m. It is dedicated to the precise measurements of the CMB polarization, with the goal of detecting the Primordial Gravational Waves (PGWs), measuring the CMB Polarization Rotation (CPR) angle, etc.



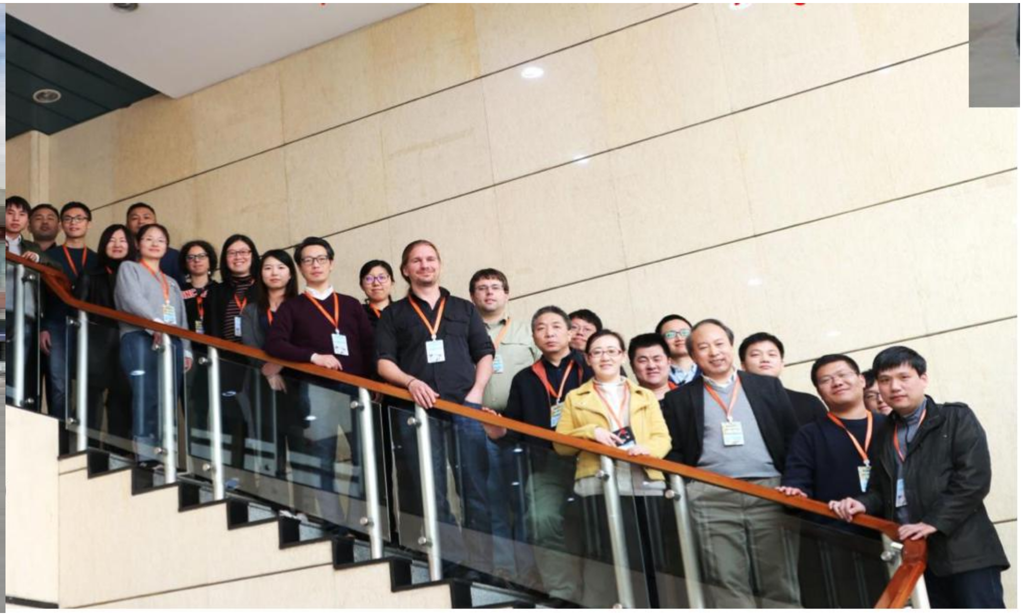


AliCPT Collaboration since 2016

Institute of High Energy Physics(IHEP), Stanford University,

National astronomical observatory(NAOC), NIST, ASU,

CNRS/APC, SJTU, BNU, NTU, ……

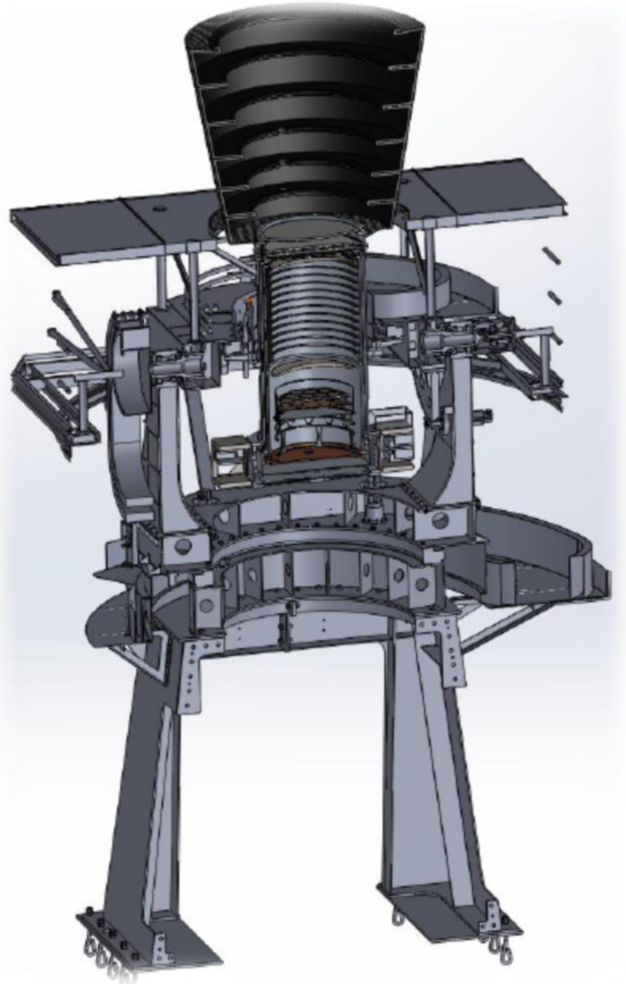


Summary for AliCPT design parameters

Table of designed parameters

Frequencies	90GHz	150GHz
Center Frequency (GHz)	91.4	145
Bandwidth (GHz)	38	40
Optical TES count	16,188	16,188
P_{sat} (pW)	7.0	12.0
NEP Phonons (aW/$\sqrt{Hz}$)	19	25
NEP Photons (aW/$\sqrt{Hz}$)	33	46
NEP Total (aW/$\sqrt{Hz}$)	38	53
Resolution (FWHM)	19'	11'
NET CMB ($\mu K\sqrt{s}$)	274	348

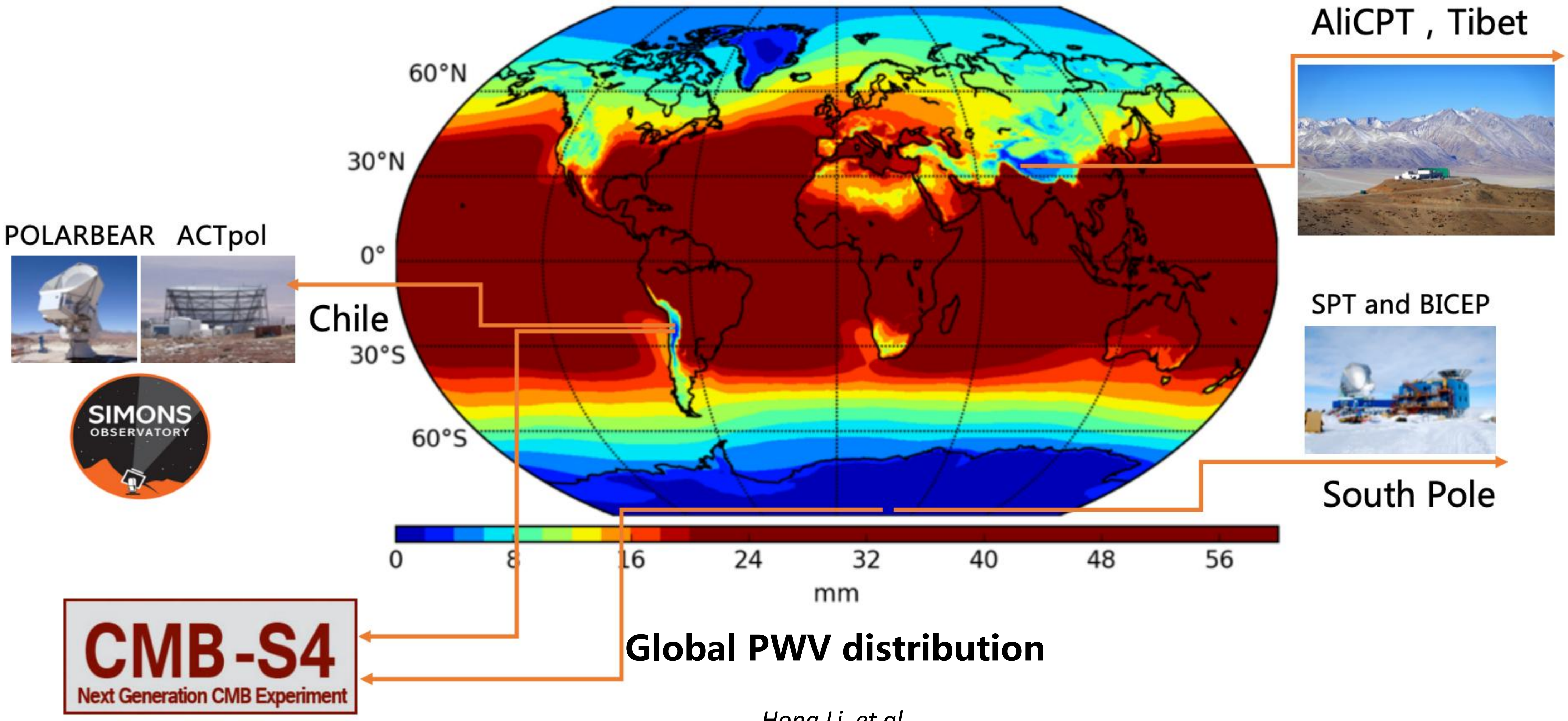
Maria Salatino ,et al. IEEE Transactions on Applied Superconductivity



receiver & mount

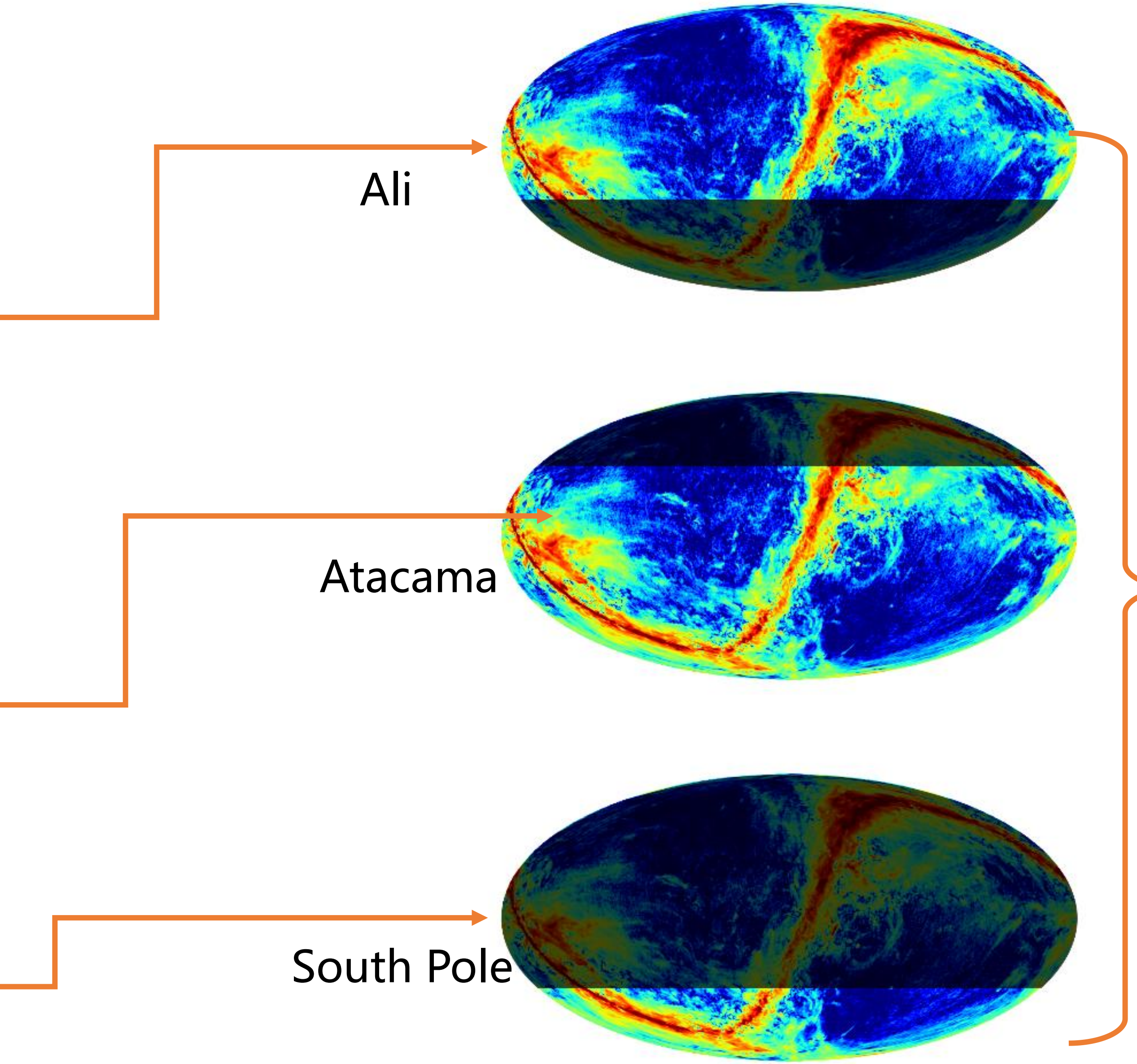
Ali in the North Offers a great site for CMB

- CMB observations require locations with low Precipitable Water Vapor (PWV)

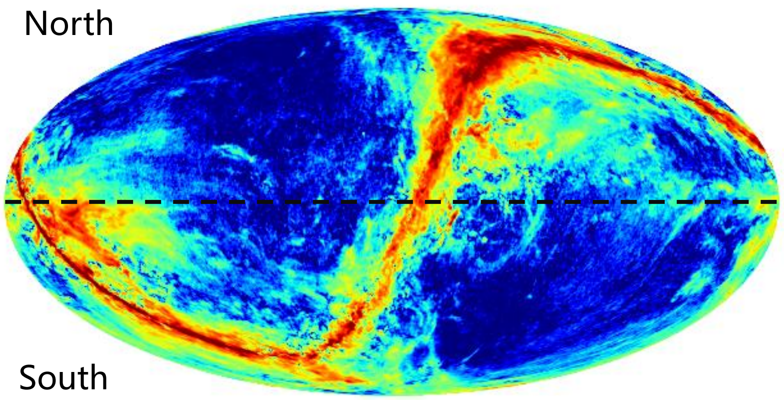


Global PWV distribution

Hong Li, et al.



- AliCPT can serve as a complement to the telescopes in the South Pole and Chile:
  - ~64% of whole sky
  - There is sky overlap
  - Good chance for cross check

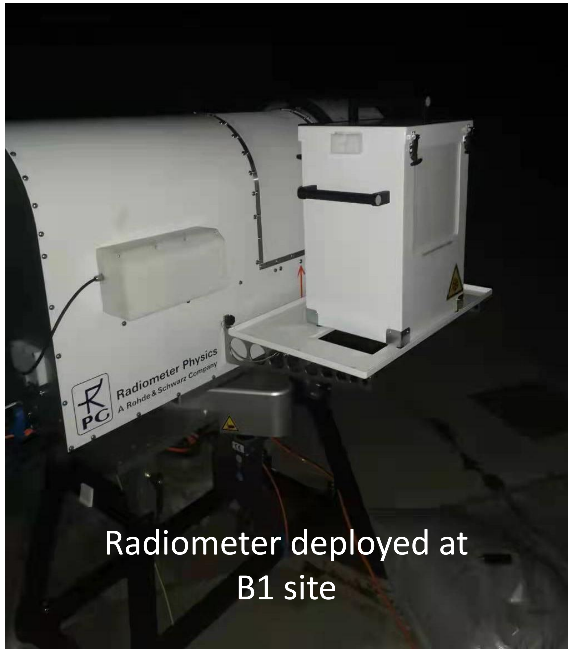


- AliCPT :
  - ~10% clean patch for deep survey of r

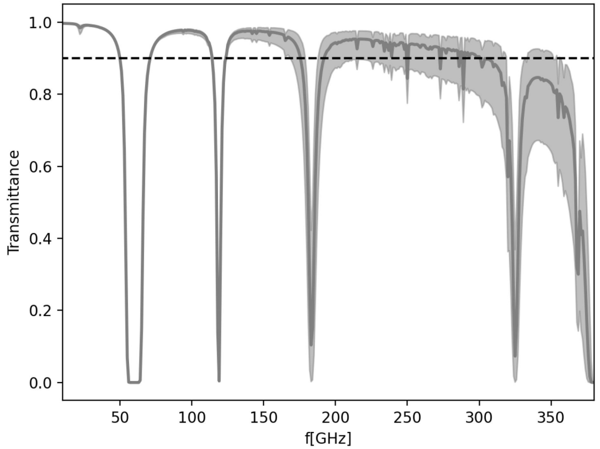
With the three sits on earth → Full sky coverage

Ali Site: Water Vapor is comparable with Atacama

Median value of the Precipitable Water Vapor (mm)						
Data	Nov.	Dec.	Jan.	Feb.	Mar.	Oct. ~ Mar.
MERRA-2 (2011- 2017)	**1.06**	**0.80**	**0.78**	**1.01**	**1.39**	**1.08**
Radiosondes (2015 - 2016, 7:00, 19:00)	**1.19**	**0.56**	**0.59**	**0.61**	**1.40**	**0.92**
FTS (2017 - 2021)	**-**	**-**	**-**	**-**	**-**	**0.90**
RPG (2021)	**0.72**	**0.64**	**0.87**	**0.81**	**0.98**	**0.78** (Nov. ~ Mar.)



Radiometer deployed at B1 site

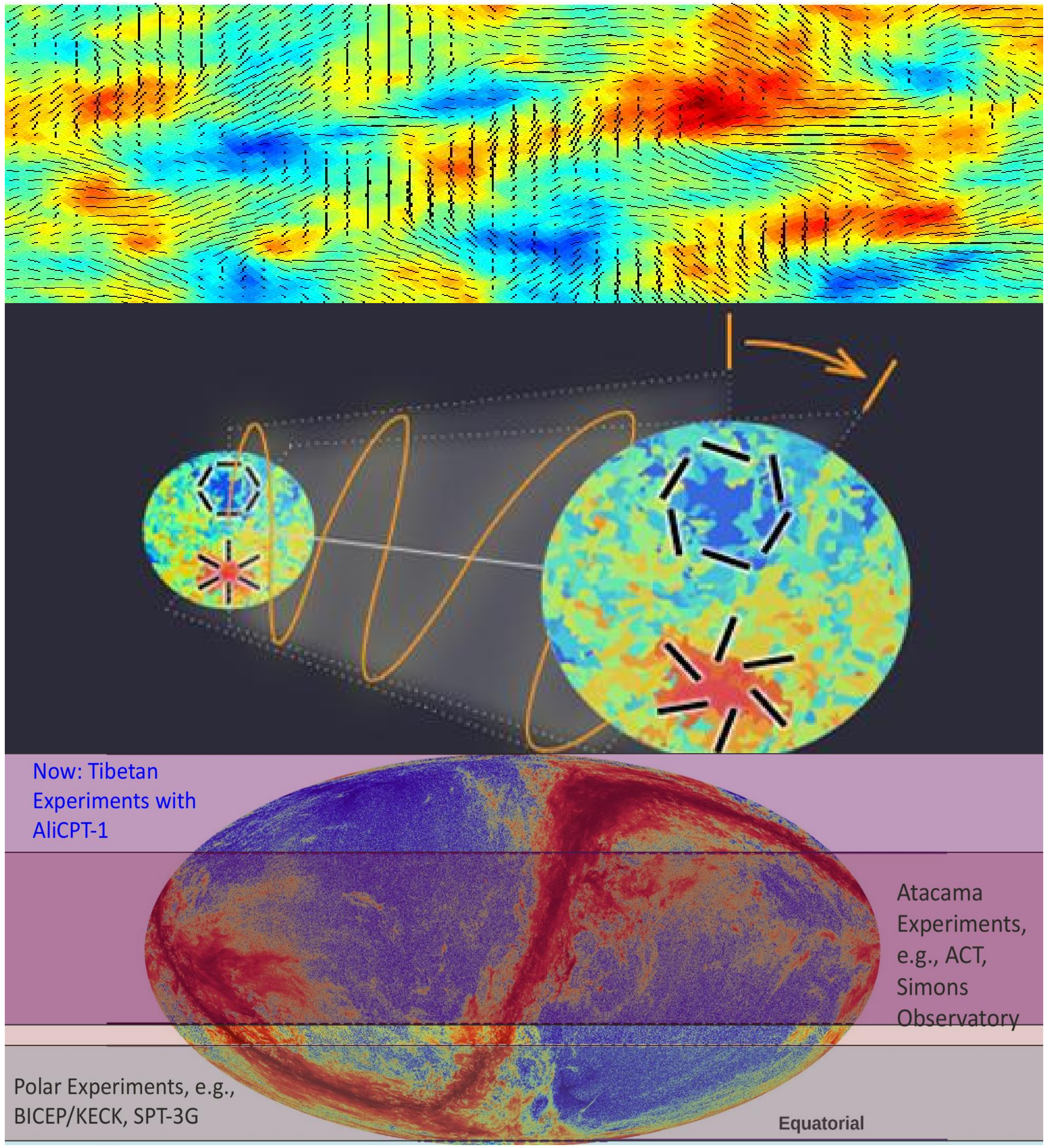


Atmospheric transmittance for AliCPT site

- All these measurements are highly consistent, indicating low PWV
- Median PWV value is below 1 mm through out the observational season (early October to end of March.)
- This makes it ideal observation at 90 and 150 GHz, and even better for low frequencies.

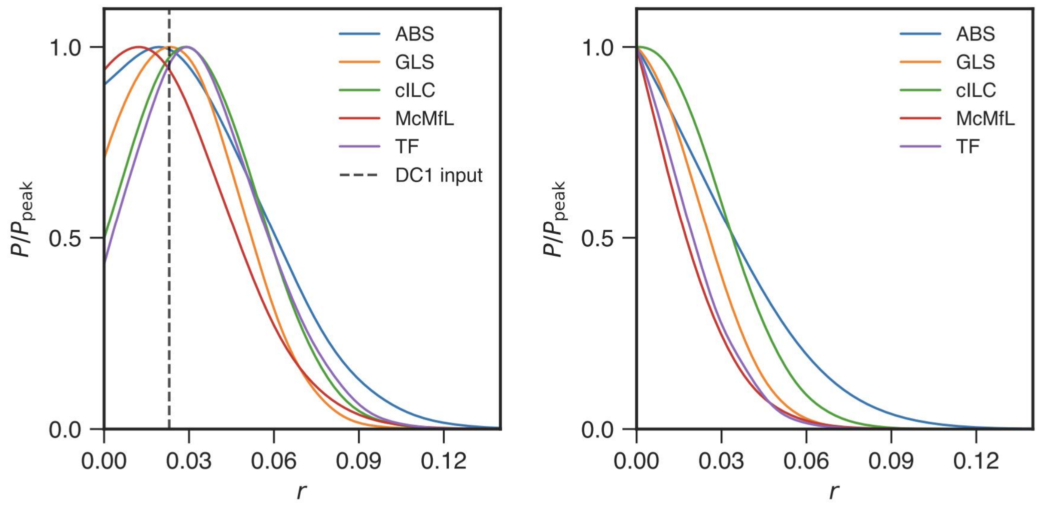
Science goals of AliCPT

- Measuring CMB BB spectra
  - Searching for Primordial Gravitational Waves
  - Testing inflationary theories and early Universe models
- Measuring CMB TB & EB spectra
  - Measuring CMB polarization rotation angle
  - Testing Chern-Simons Theory and CPT symmetry
- Measuring CMB EE spectra
  - Study the early dark energy
  - Precisely test the LCDM
- Millimeter-wave Northern Sky Survey
  - CMB lensing reconstruction
  - Cross correlation with Large Scale Structure
  - Galactic foreground, magnetic fields science
  - Time-domain astronomy
- Joint analysis with full sky coverage from ground missions



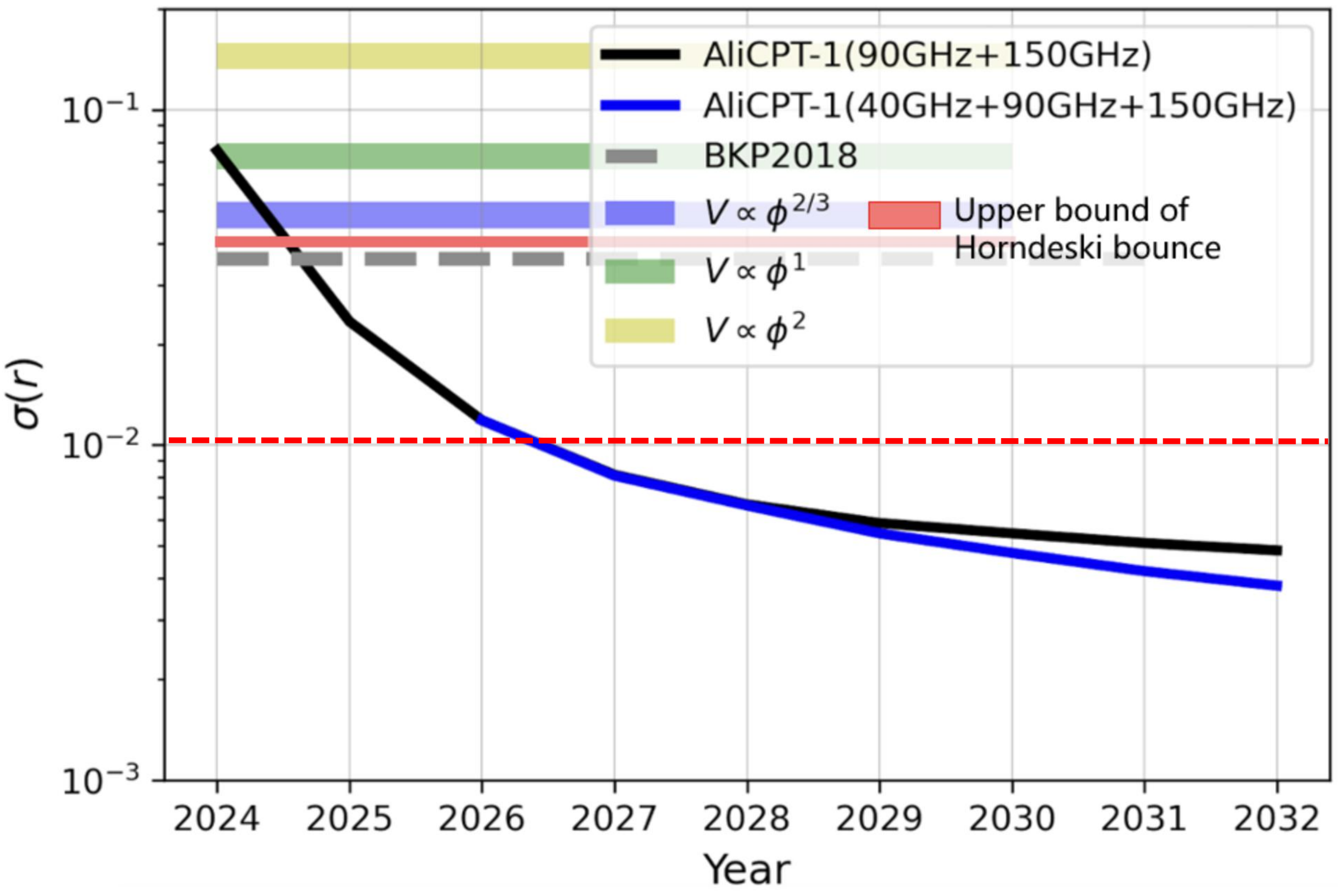
Science goal: r sensitivity

Data Challenge Results with 4mody data



Method	ABS	GLS	cILC	McMfL	TF (p16)
$\boldsymbol{r}$ [MAP]	0.019	0.023	0.024	0.012	0.029
ℓ range	[20,200]	[40,200]	[40,200]	[50,250]	[20,200]
$\chi^2_{\rm min}$/DOF	4.3/8	2.4/3	2.9/3	219.6/214	248.3/236
$\boldsymbol{r}$ [MMSE]	$0.036^{+0.025}_{-0.025}$	$0.030^{+0.019}_{-0.020}$	$0.025^{+0.016}_{-0.016}$	$0.026^{+0.019}_{-0.019}$	$0.035^{+0.021}_{-0.021}$

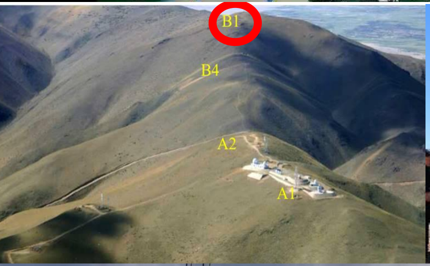
AliCPT-1 collaboration:JCAP10(2022)063

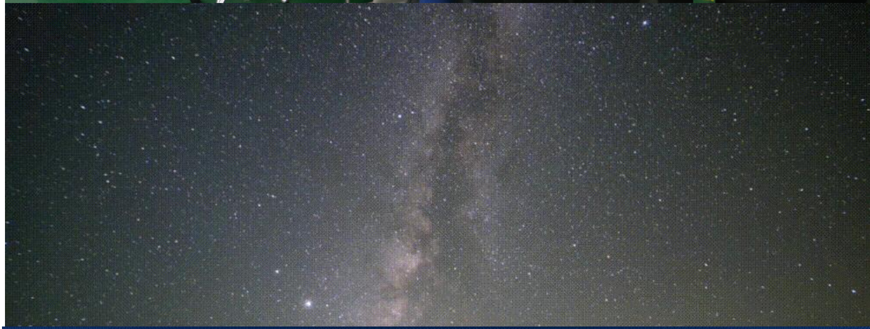


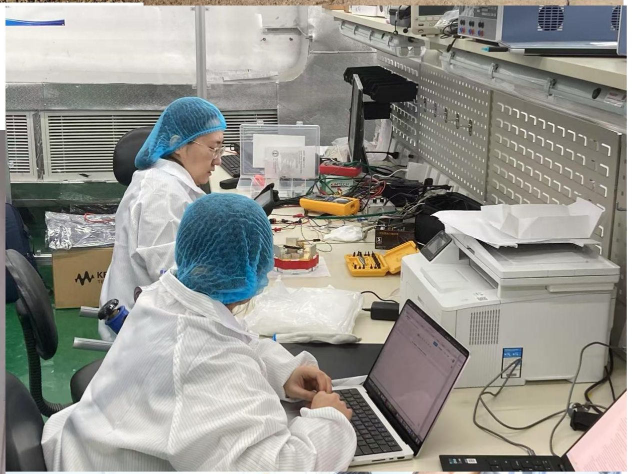
Forecast on PGWs (r) based on AliCPT schedule

- All results from our post-map pipeline are consistent and successfully meet the data challenge

First Light in April

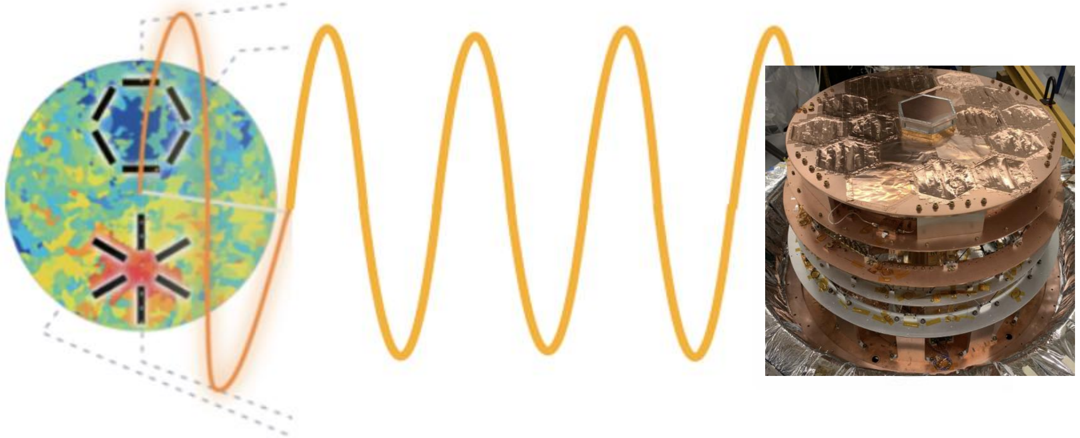


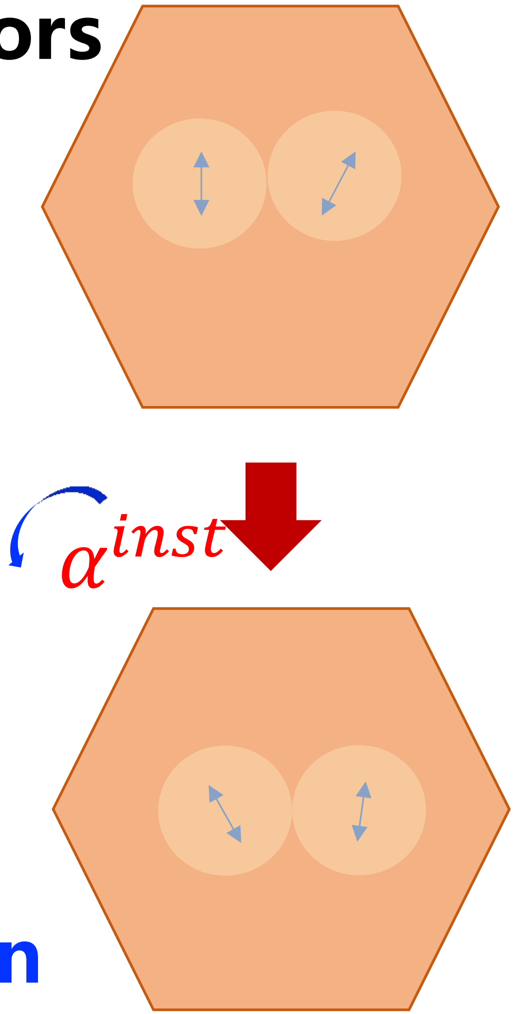




Improve CMBP-RA sensitivity

- Isotropic CMB polarization rotation angle is highly degenerates with an intrinsic angle of detectors



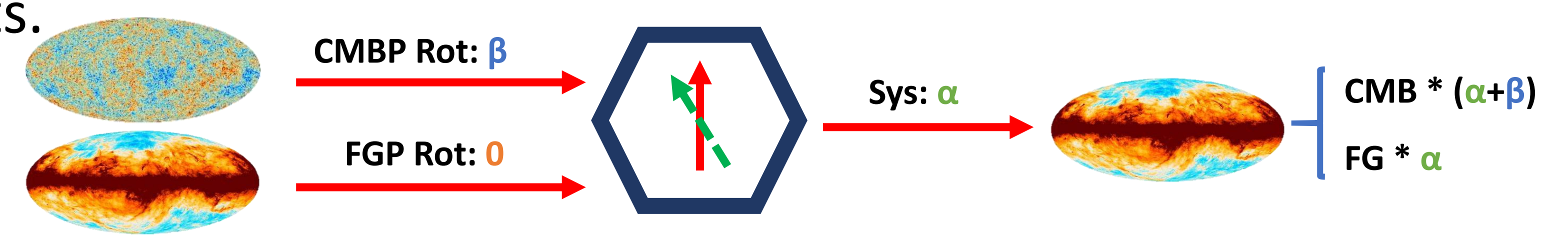


$$\beta^{o} = \beta + \alpha^{inst}$$

- Strategy: break the associated degeneracy provides a way for achieving higher-precision

Break degeneracy: using foreground emission

- Foreground emissions, originating from nearby polarized sources, exhibit negligible intrinsic rotation effects , making them ideal calibration sources for CMB polarization measurements.



- A joint analysis of foreground emission can break the efficiently

- **Recent studies:**

Reference/Data	Rotation angle $\bar{\alpha}$
[1]Planck 2018	$0.35° \pm 0.14°$
[2]Planck PR4	$0.35° \pm 0.11°$
[3]Planck+WMAP	$0.342°\,^{+0.094°}_{-0.091°}$

[1]Yuto,et.al., 2020, PRL. 125, 221301

[2]P. Diego-Palazuelos, et.al., arXiv:2203.04830

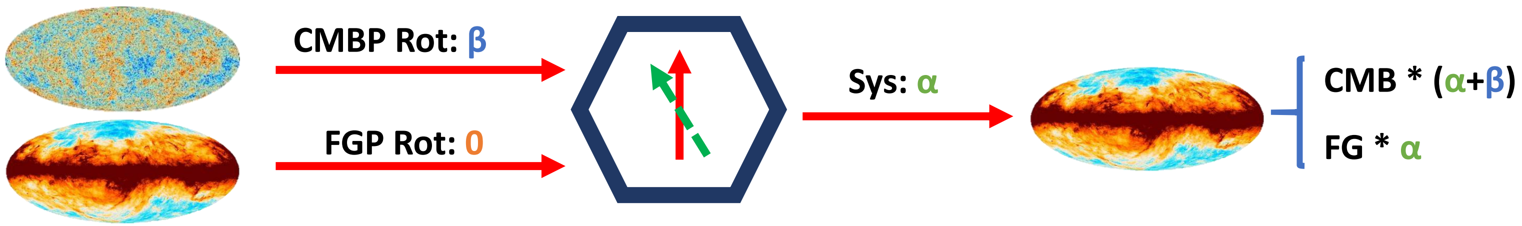
[3]Johannes, et.al., 2022, PRD,106, 063503

Non- zero at 3.6 σ

Break degeneracy: Calibrate Intrinsic pol. angle

- Several polarization sources have been used to calibrate intrinsic polarization angle of detectors.

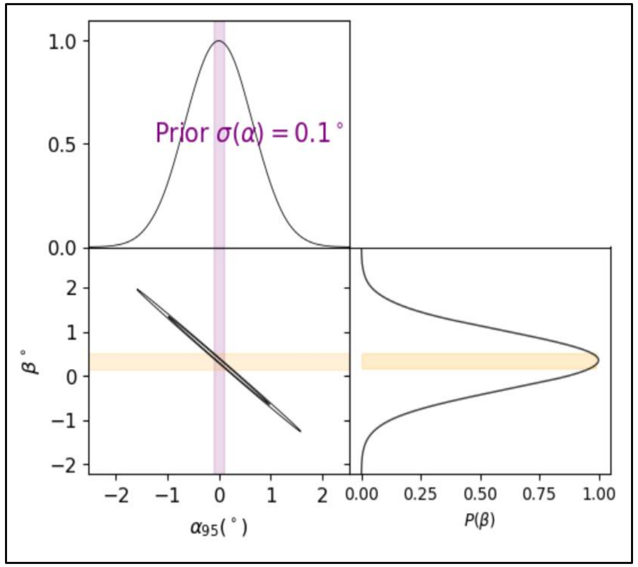
Sources	Expts	Current precision
Self calibration	BICEP series	Assume $\beta = 0$. Minimizing TB EB power spectra.
Optical model ray tracing	ACTPol	$\sigma_\alpha \sim 0.1°$
Artificial sources	BICEP3	$\sigma_\alpha \sim 0.3°$
	CLASS, SO	$\sigma_\alpha \sim 0.1°$
Celestial sources	POLARBEAR	$\sigma_\alpha \sim 0.5°$
Polarized foreground	PLANCK + WMAP	$\sigma_\alpha \sim 0.1°$ $\left(\beta = -0.342°{}^{+0.094°}_{-0.091°},\ 3.6\sigma\right)$



Break degeneracy：A good artificial source

AliCPT：

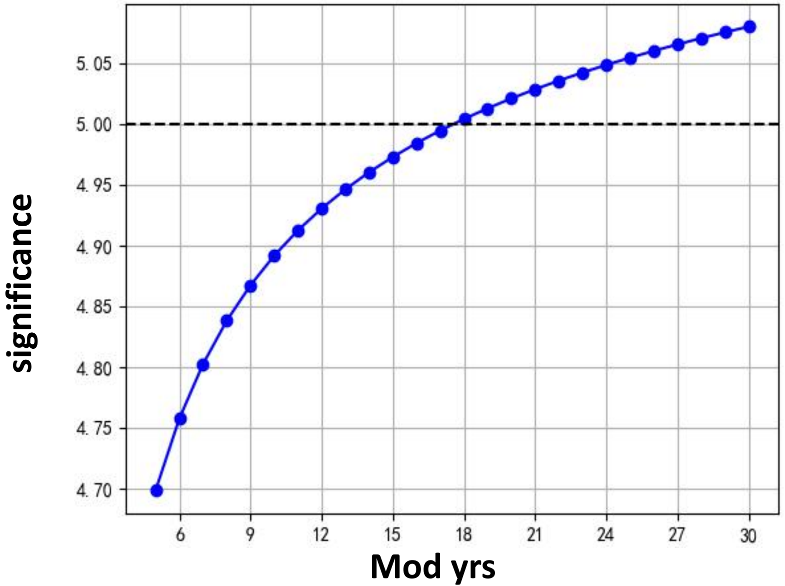
- Artificial source with the precision less than 0.1 deg
- Joint analysis with foreground emission



Forecast：

- With five module-years of AliCPT-1 observations and polarized calibration sources, the polarization rotation angle can be measured with a precision of 4.6σ.
- With additional modules, the polarization rotation angle measurement could soon achieve 5σ precision

AliCPT + PLK HFI + pol calib. (0.1 deg)



Precision measurement of CMB polarization angle

Rotation angle:

$$\beta = \int_{x_{lss}}^{x_0} \frac{c}{M} \partial_\mu \phi d\chi^\mu = \boxed{\frac{c}{M} \Delta\phi}$$

track the time evolution of dark energy

Dynamic equation of ϕ:

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

characterize its dynamics

Summary

- DESI has provided strong hints for dynamical dark energy
- Interacting dark energy (IDE) offer a new pathway to detecting the dynamics — very similar to how dark matter particles are detected through their interactions.
- ALICPT could contribute to the understanding of the "dark sector"

谢谢！