Symposium of Dark Matter and Dark energy

AliCPT 检验Dark Energy-Chern-Simons 理论

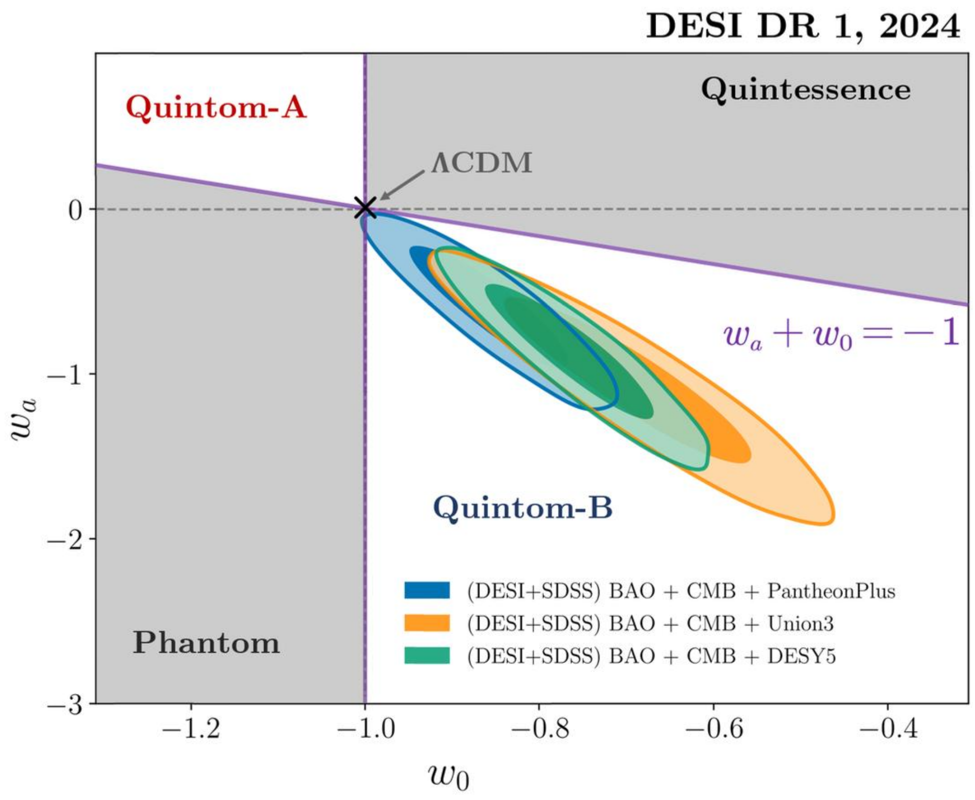
李 虹

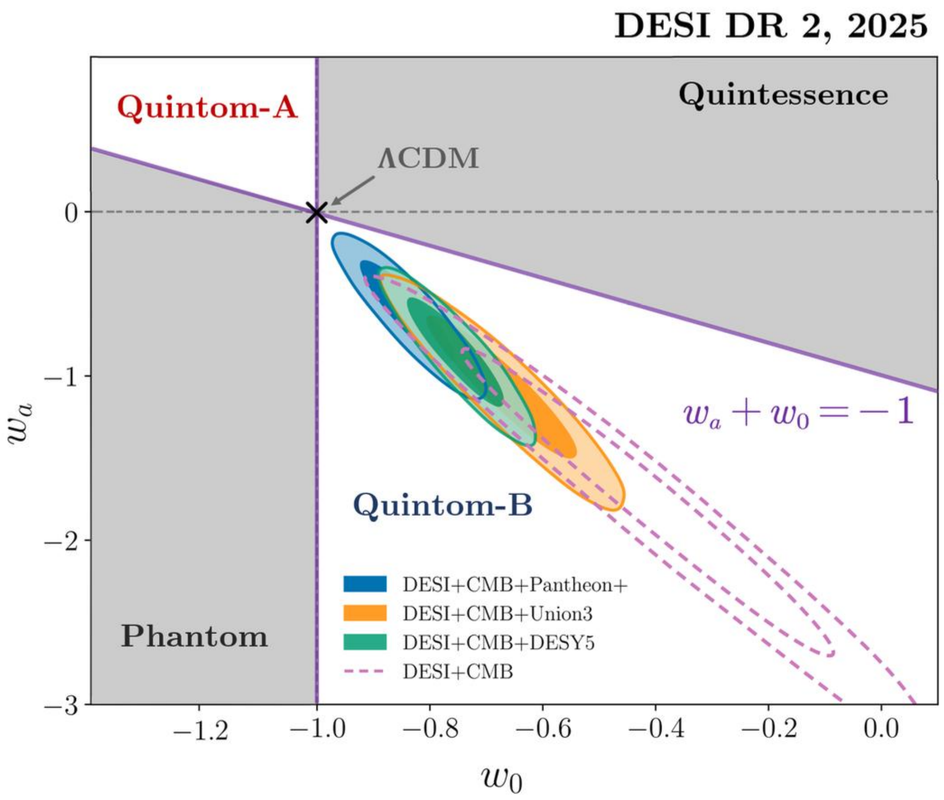
IHEP

2025.6

暗能量状态方程测量现状

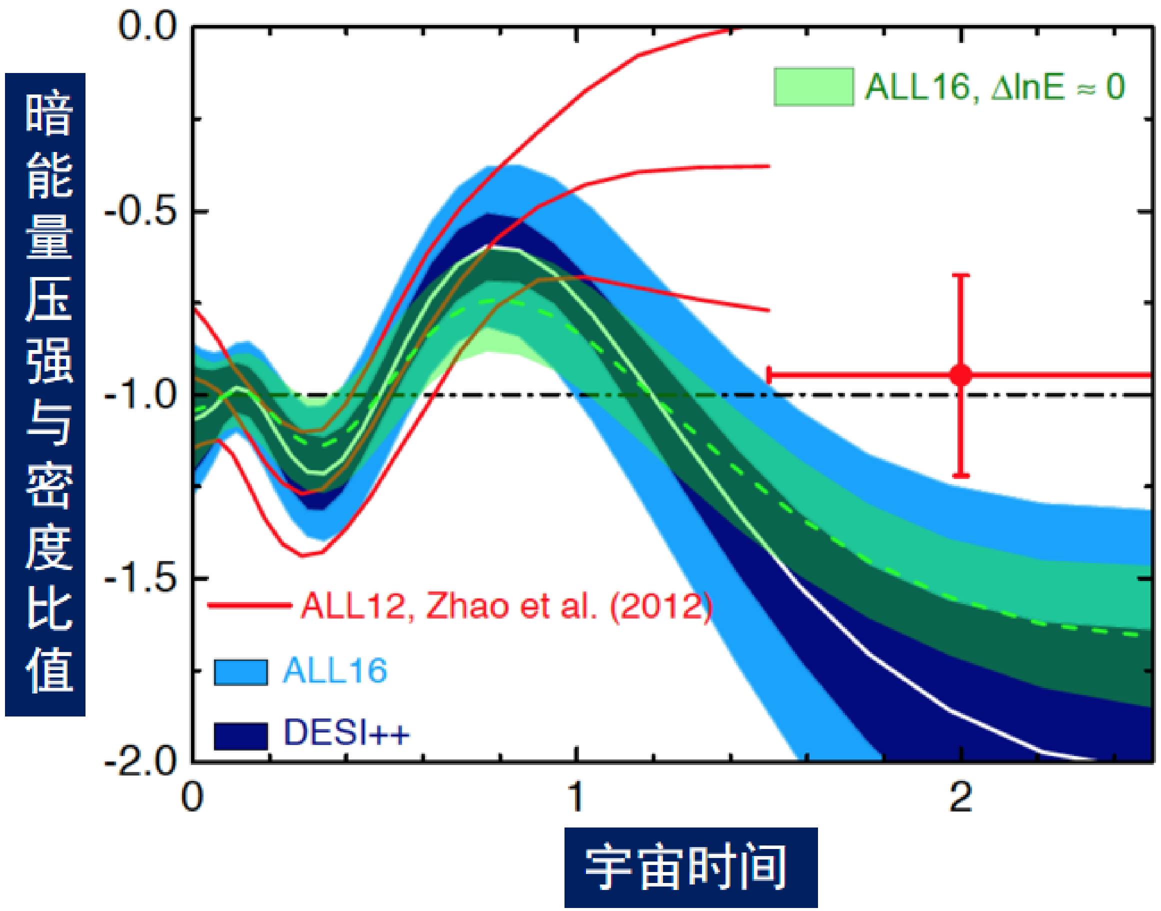
- **Dark Energy Spectroscopic Instrument (DESI): favor a time-varying nature of dark energy, at > 4σ, challenging w= -1 (e.g., the cosmological constant, Λ)**





DESI collaboration, JCAP 02 (2025) 021, arxiv:2404.03002
DESI collaboration, arxiv: 2503.14738
Gu, et al., arXiv:2504.06118

PCA方法分析结果



- **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**)

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)

进一步探索暗能量的动力学

- In near future, how to reveal further the nature of DE ?

进一步探索暗能量的动力学

□ In near future, how to reveal further the nature of DE?

- **方向I：精确测量暗能量状态方程**

积累数据，提升测量精度：DESI、LSST、Euclid、CSST、ESST…

- **方向II：深入研究暗能量状态方程越过w=-1的Quintom理论**

Quintom model building、cosmic evolution…

- **方向III：研究动力学暗能量与通常物质的相互作用**

相互作用：打开对暗能量物理本质认识的新窗口

见中国科学院理论所
彭桓武前沿科学论坛
报告
原初引力波与暗能量
张新民
2025.6.18

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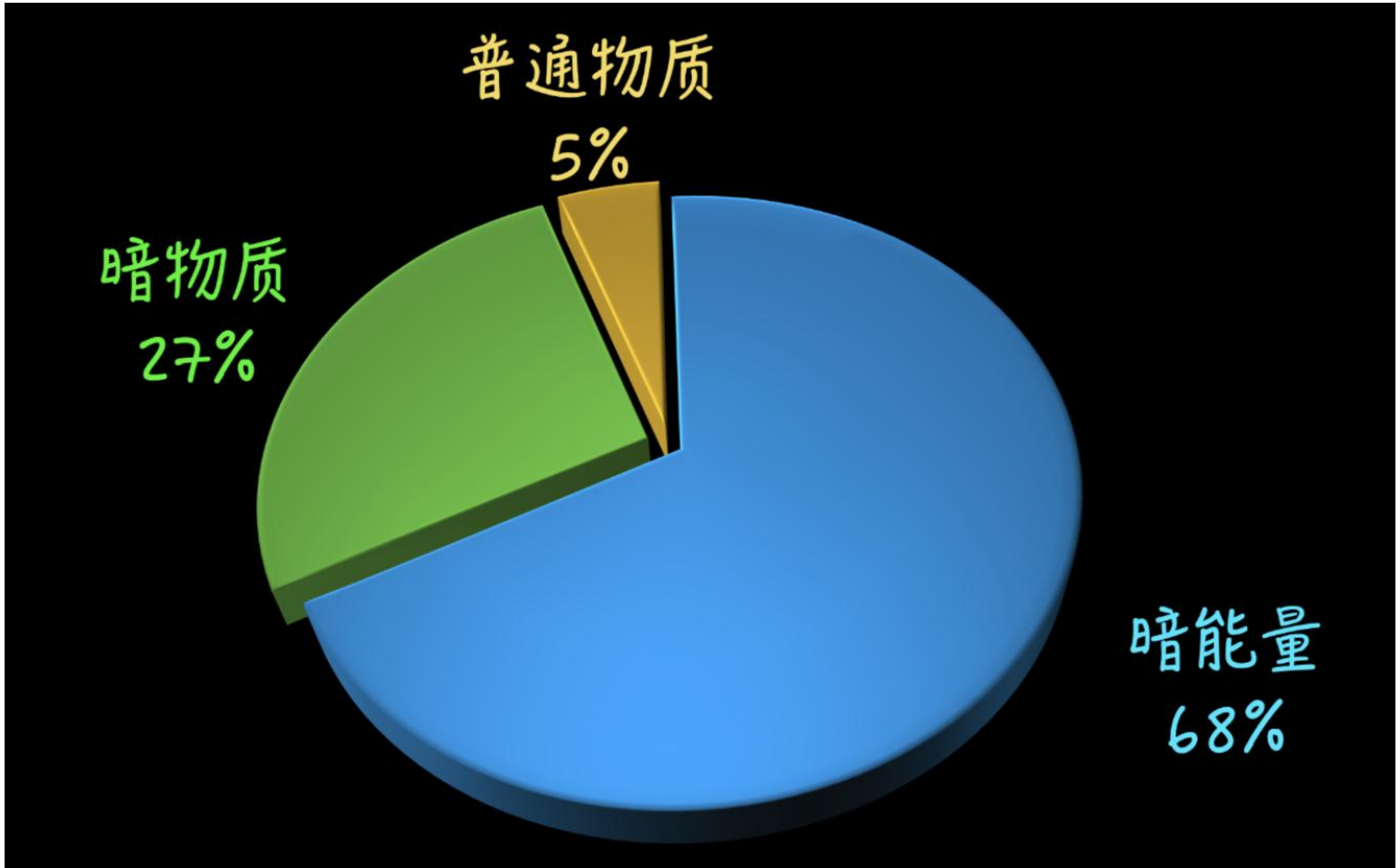
进一步探索暗能量的动力学

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



提 纲

1 暗能量与通常物质的可能相互作用

2 AliCPT实验最新进展

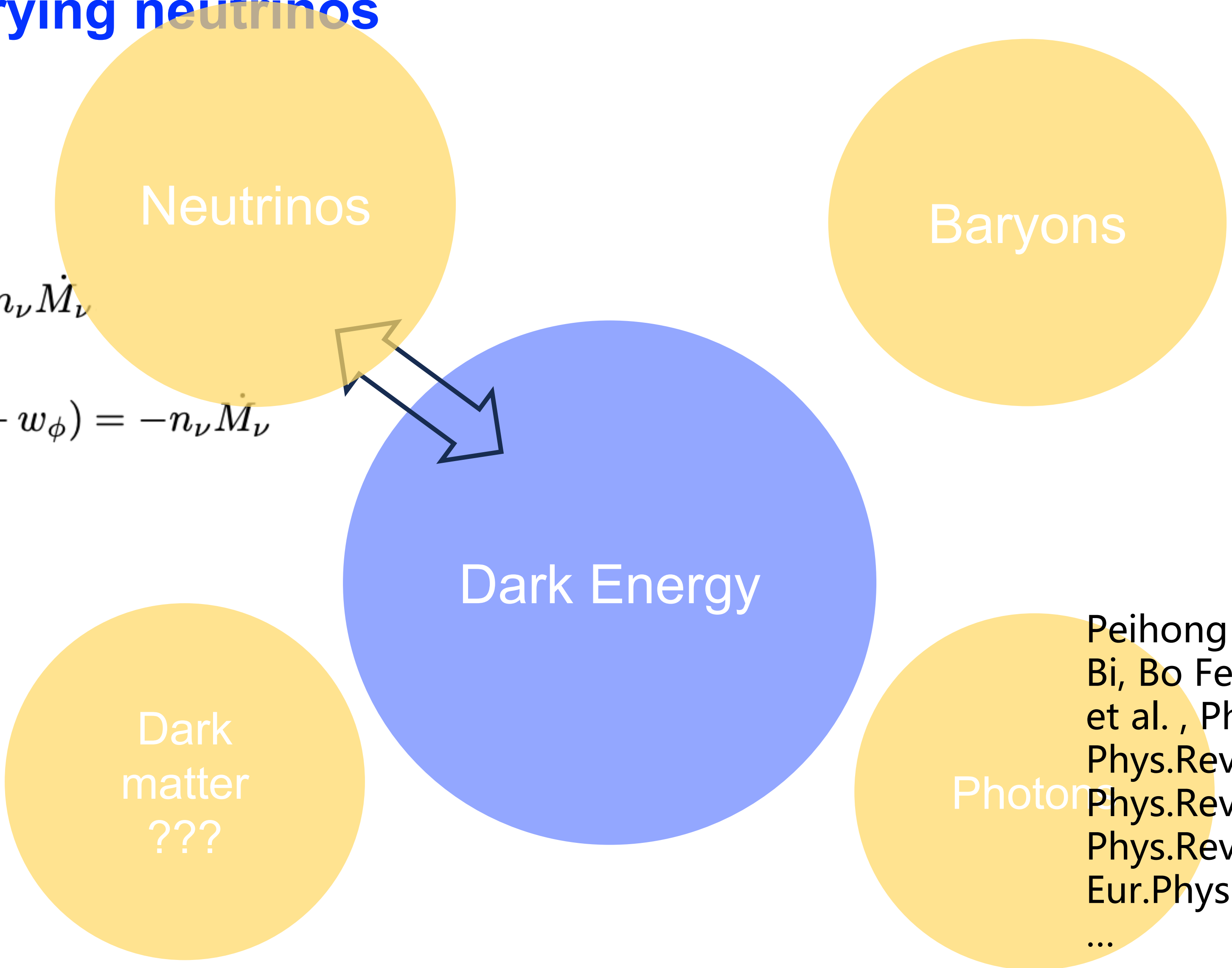
3 基于AliCPT实验的暗能量研究

1. DE 与 neutrino 相互作用

- **Mass varying neutrinos**

$$\dot{\rho}_\nu + 3H\rho_\nu = n_\nu \dot{M}_\nu$$

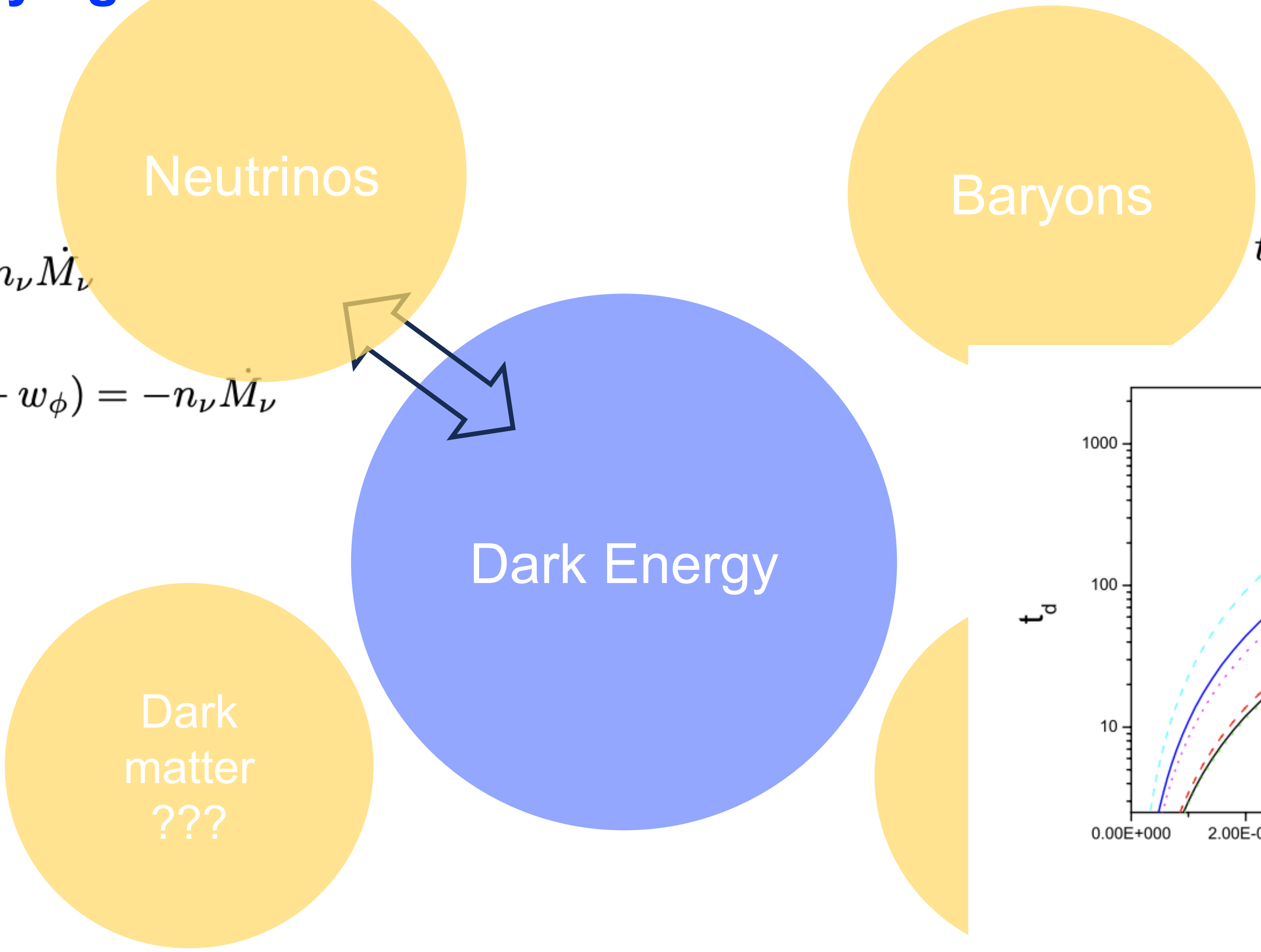
$$\dot{\rho}_\phi + 3H\rho_\phi(1 + w_\phi) = -n_\nu \dot{M}_\nu$$



Peihong Gu, Xiulian Wang, Xiao-Jun Bi, Bo Feng, Hong Li, Xinmin Zhang et al. , Phys.Rev.D 68(2003);
Phys.Rev.D 69(2004);
Phys.Rev.D 71(2005);
Phys.Rev.D 73(2006);
Eur.Phys.J.C50(2007);
...

1. DE 与 neutrino 相互作用

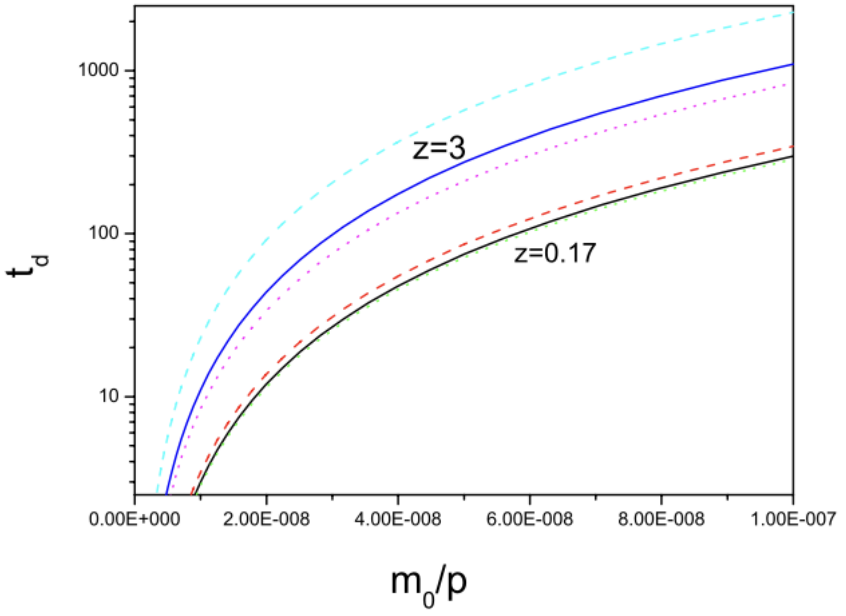
➢ Mass varying neutrinos



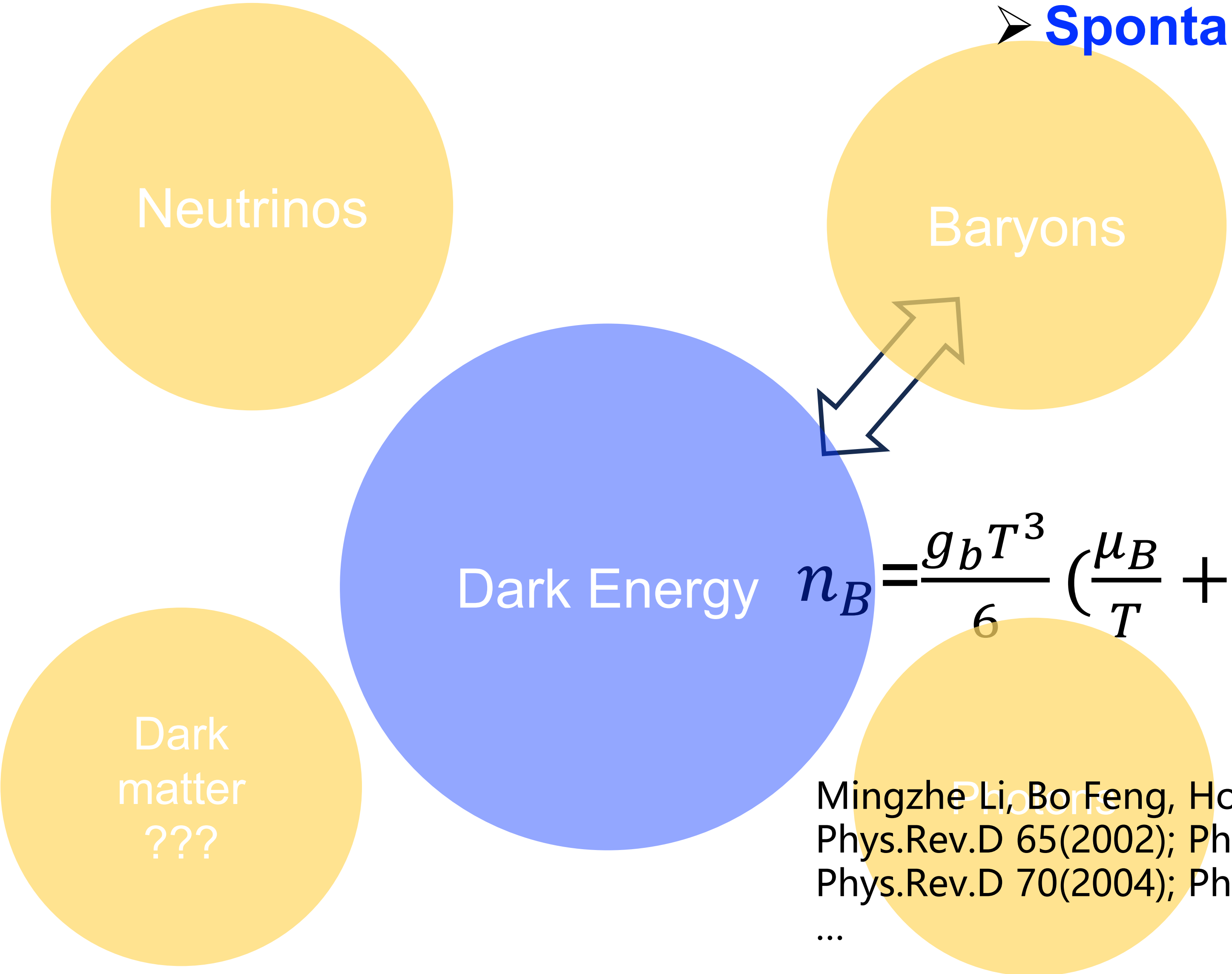
$$\dot{\rho}_\nu + 3H\rho_\nu = n_\nu \dot{M}_\nu$$

$$\dot{\rho}_\phi + 3H\rho_\phi(1+w_\phi) = -n_\nu \dot{M}_\nu$$

$$t_d \approx \int_t^{t_0} a(t')dt' \frac{1}{2}\frac{m^2}{p^2}$$



2. DE 与 baryon 相互作用



➢ **Spontaneous Baryogenesis**

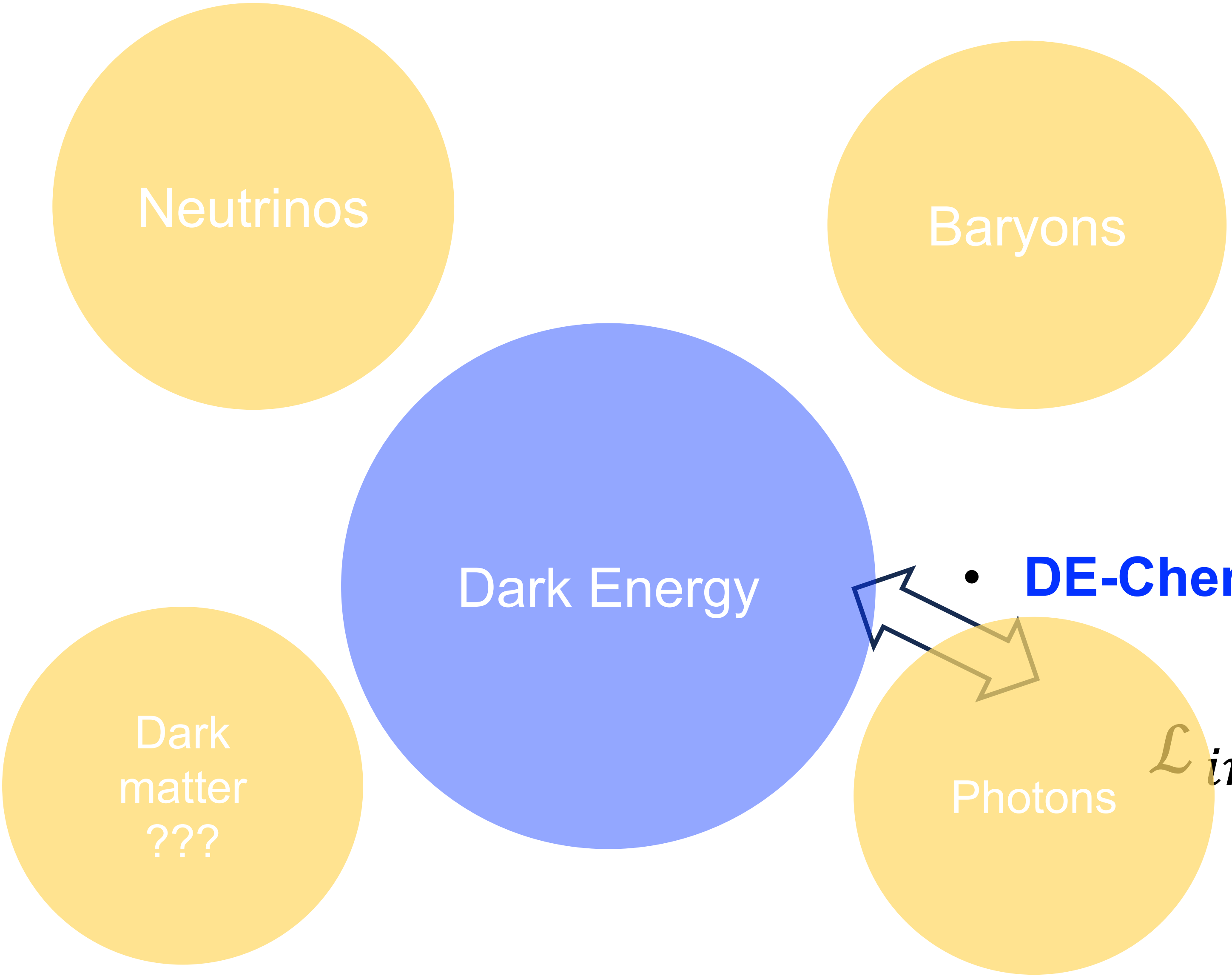
$$c\frac{\partial_\mu \phi}{M} J_B^\mu$$

$$\mu_B = -c\frac{\dot{\phi}}{M} = -\mu_{\bar{B}}$$

$$n_B = \frac{g_b T^3}{6}\left(\frac{\mu_B}{T} + \mathcal{O}\left(\frac{\mu_B}{T}\right)^3\right) \simeq c\frac{g_b \dot{\phi} T^2}{6M}$$

Mingzhe Li, Bo Feng, Hong Li, Xinmin Zhang et al. ,
Phys.Rev.D 65(2002); Phys. Lett. B573(2003);
Phys.Rev.D 70(2004); Phys. Lett. B620(2005);
…

3. DE 与光子的相互作用



- **DE-Chern-Simons interaction**

$$\mathcal{L}_{int} \sim \frac{c}{M}\phi\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

DE-Chern-Simons interaction

- The dynamic dark energy field couples to photons derivatively will take the form of Axion-Chern-Simons coupling

$$\mathcal{L}_{CS} \sim \frac{c}{M}\phi\, F_{\mu\nu}\tilde{F}^{\mu\nu}, \qquad \tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$$

Peccei-Quinn 机制与轴子

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

- Peccei和Quinn 1977年提出：

 - 引入$U(1)_{PQ}$对称性，解决strong CP problem

 - 预言了Axion粒子

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

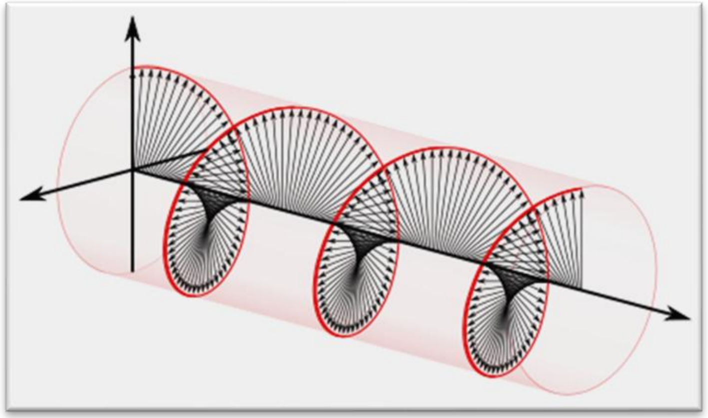
$$\mathcal{L}_{QED} \sim -\frac{1}{4}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu} \boxed{-\frac{1}{4}\alpha\int d\chi^4 \phi\, F_{\mu\nu}\tilde{F}^{\mu\nu}}, \quad \alpha = c/M$$

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

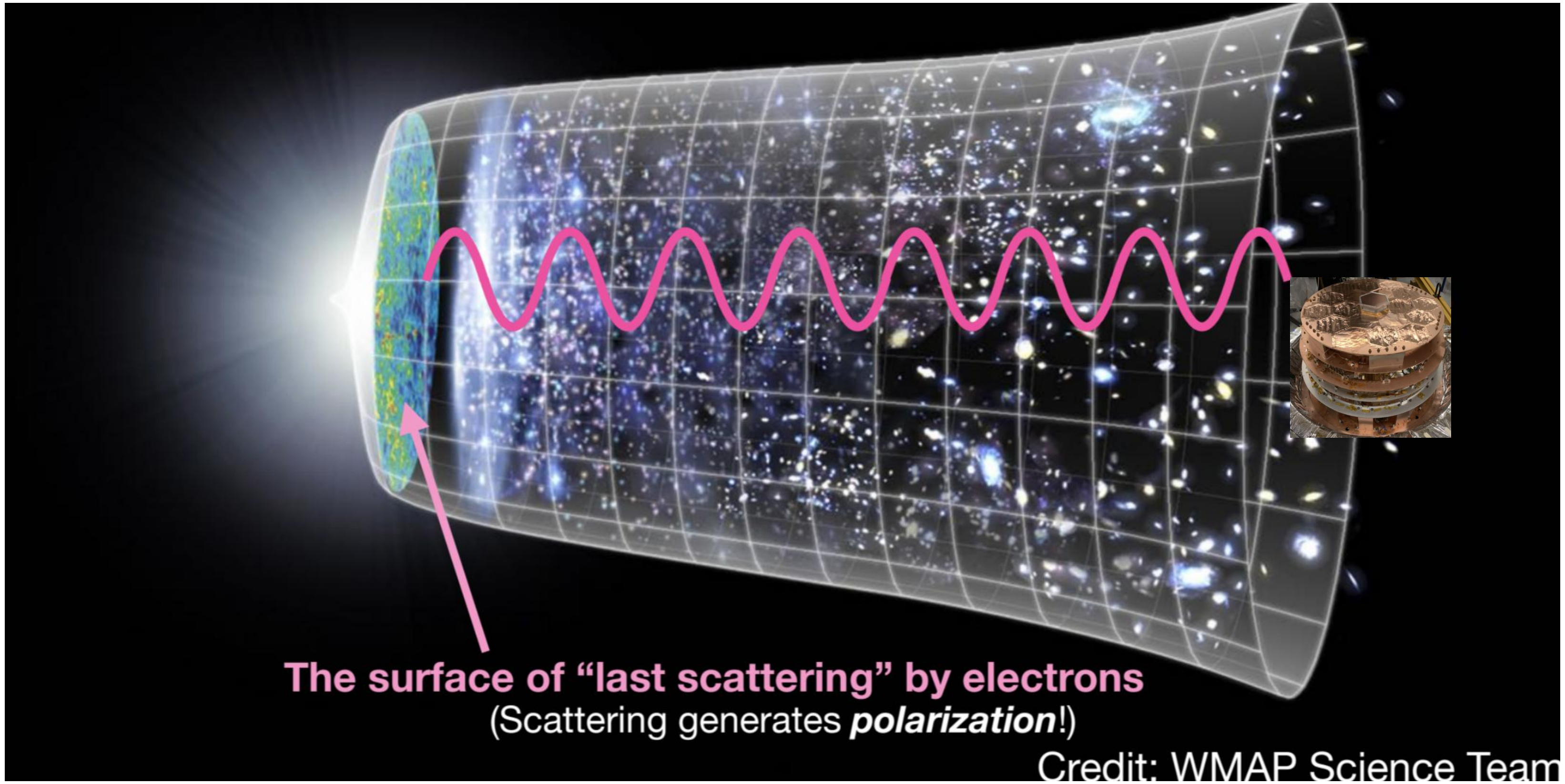
$$\ddot{A}_\pm + (\kappa^2 \boxed{\mp \kappa \frac{c}{M}\dot{\phi}})A_\pm = 0$$

- **Induce a polarization rotation in photons**

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



Precision measurement of CMB rotation angle



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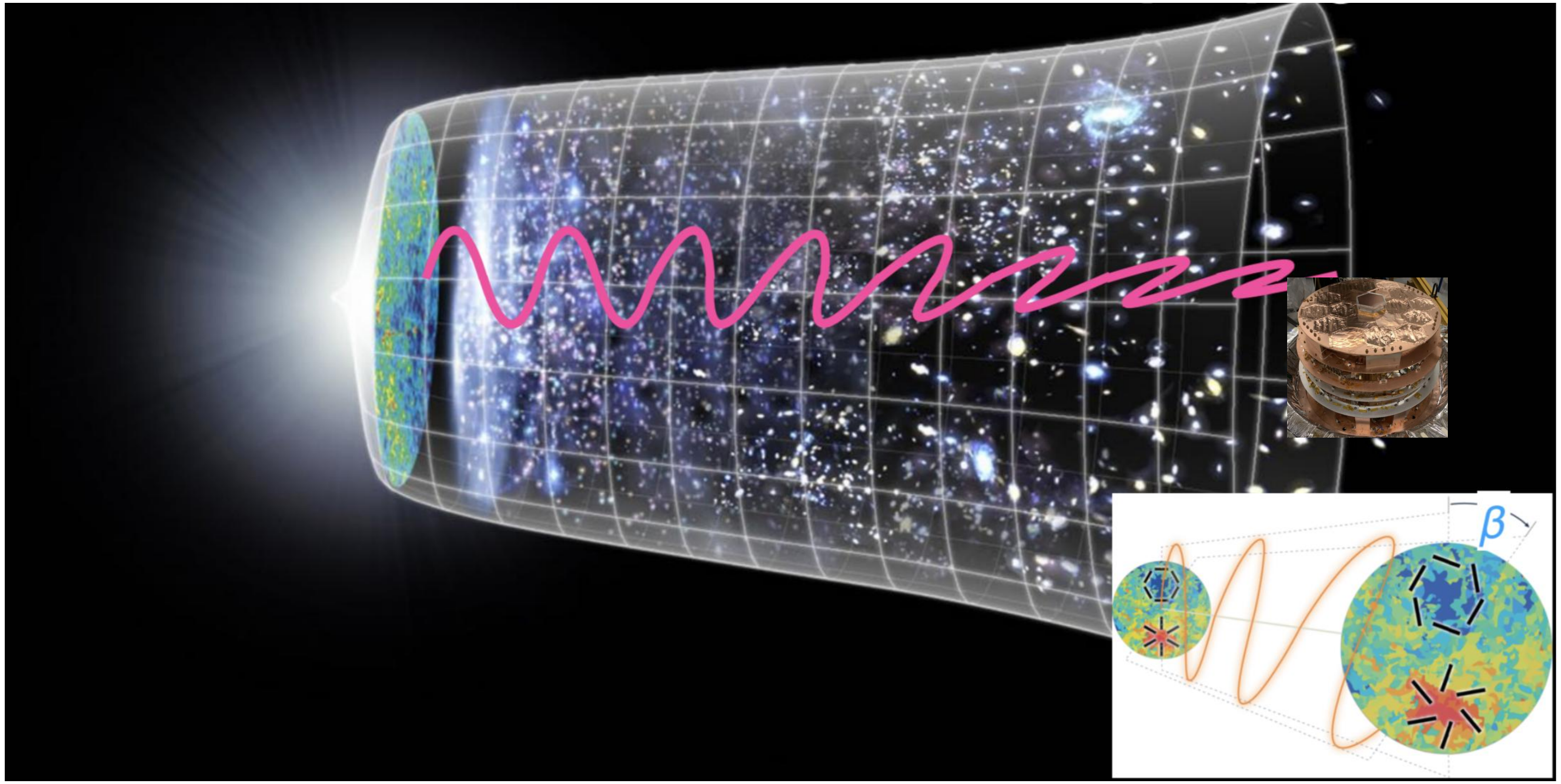
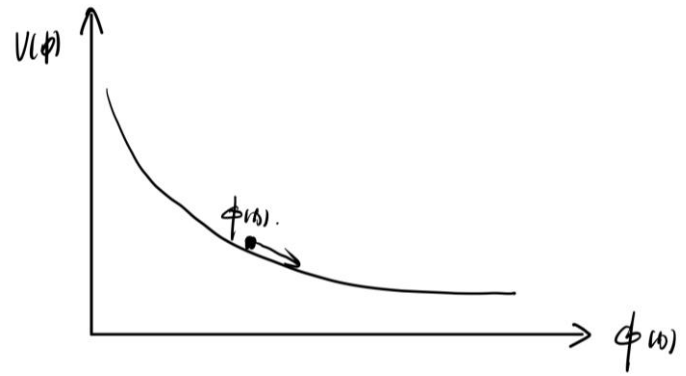


Cosmological CPT violation



$$\partial_\mu \phi(x) \longrightarrow \langle \partial_0 \phi(x) \rangle$$

For RW universe, time dependent vacuum expectation.

$$\partial_\mu \phi(x) K^\mu \longrightarrow \langle \partial_0 \phi(x) \rangle \, K^0$$

Under CPT transformation:

$$\langle \partial_\mu \phi(x) \rangle \, K^\mu \xrightarrow{\text{CPT}} -\langle \partial_\mu \phi(x) \rangle \, K^\mu$$

So now:

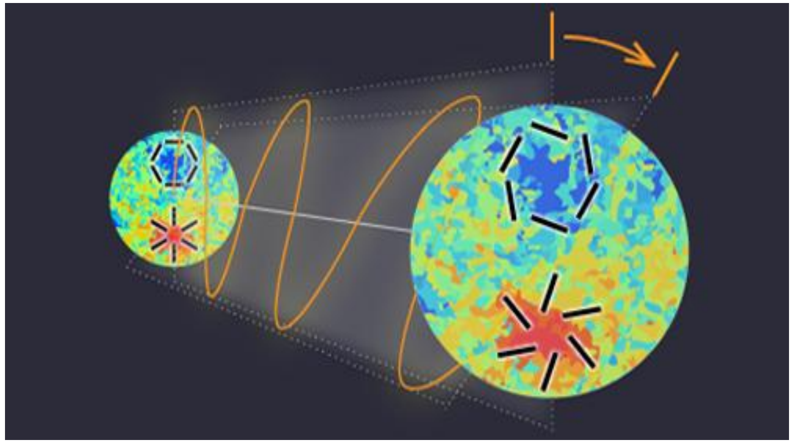
$$\mathcal{L}_{QED} \sim -\frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu} + \partial_\mu \phi K^\mu$$

CMB polarization rotation angle

- **A new probe for the dynamics of DE:**

$$\mathcal{L}_{CS} \sim \frac{c}{M} \phi \, F_{\mu\nu} \widetilde{F^{\mu\nu}}$$

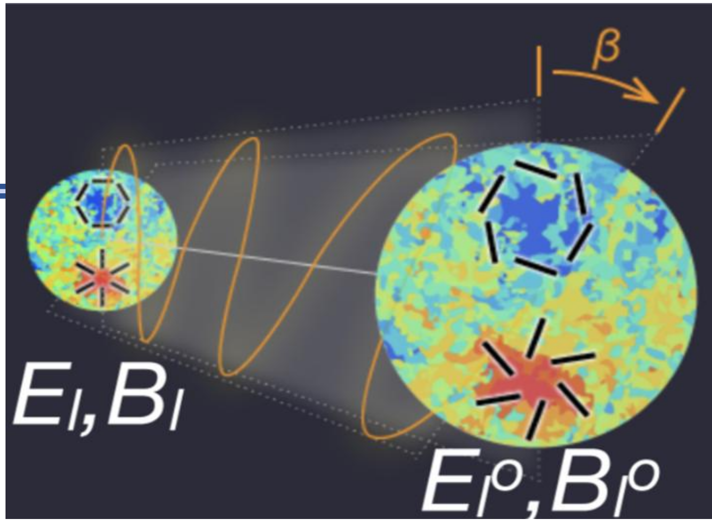
ϕ: **the dynamical dark energy ?**



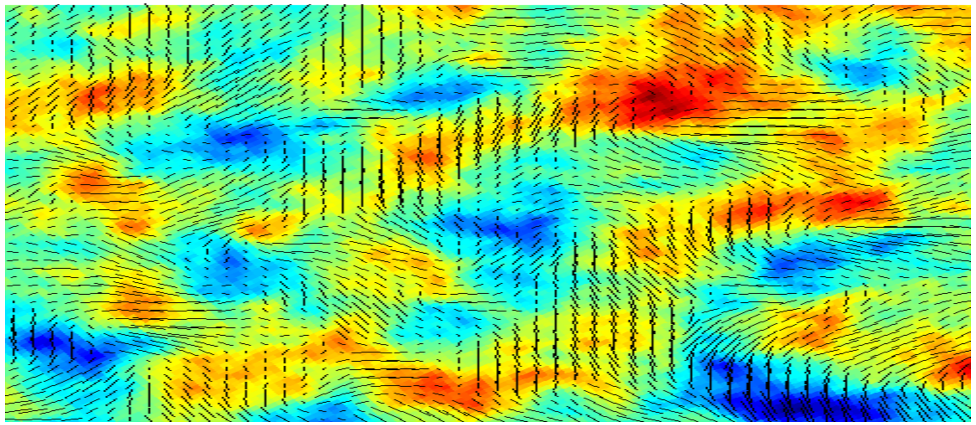
- **New physics in the dark side:**

~~CPT~~, cosmologically

Measurement of a Non-zero TB，EB



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



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

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

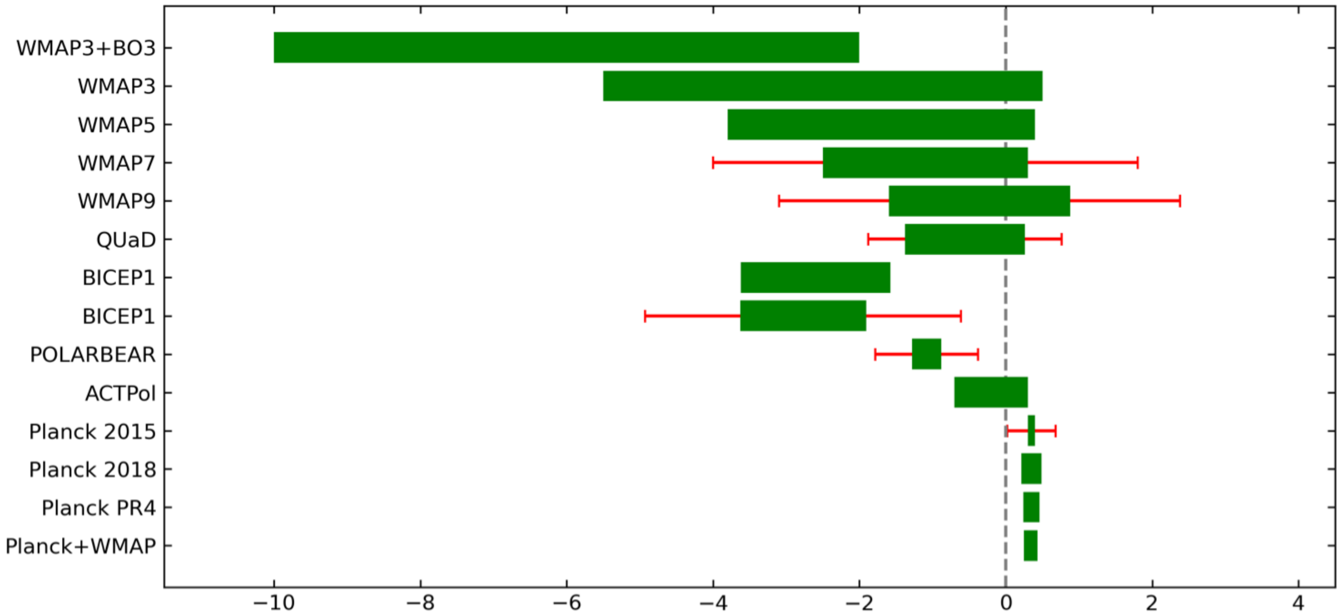
$$C^{o}{}_{\ell}^{TE} = C_{\ell}^{TE} \cos 2\bar{\beta}\ ,$$

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

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

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

国际CMB实验测量CMB极化旋转角结果汇总



	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	$0.342^{\circ}{}^{+0.094^\circ}_{-0.091^\circ}$

最新测量结果：3.7σ 不为0

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

《Physical review focus》 report this paper

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.

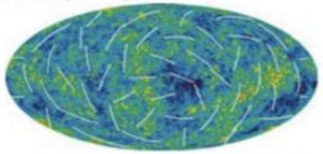
Marc Kamionkowski of the California Institute of Technology in Pasadena says that until recently, looking for exotic phenomena such as *CPT* violation was mostly regarded as "a fishing expedition–a waste of time." But since nobody has any clue what dark energy is, he adds, previously unthinkable hypotheses 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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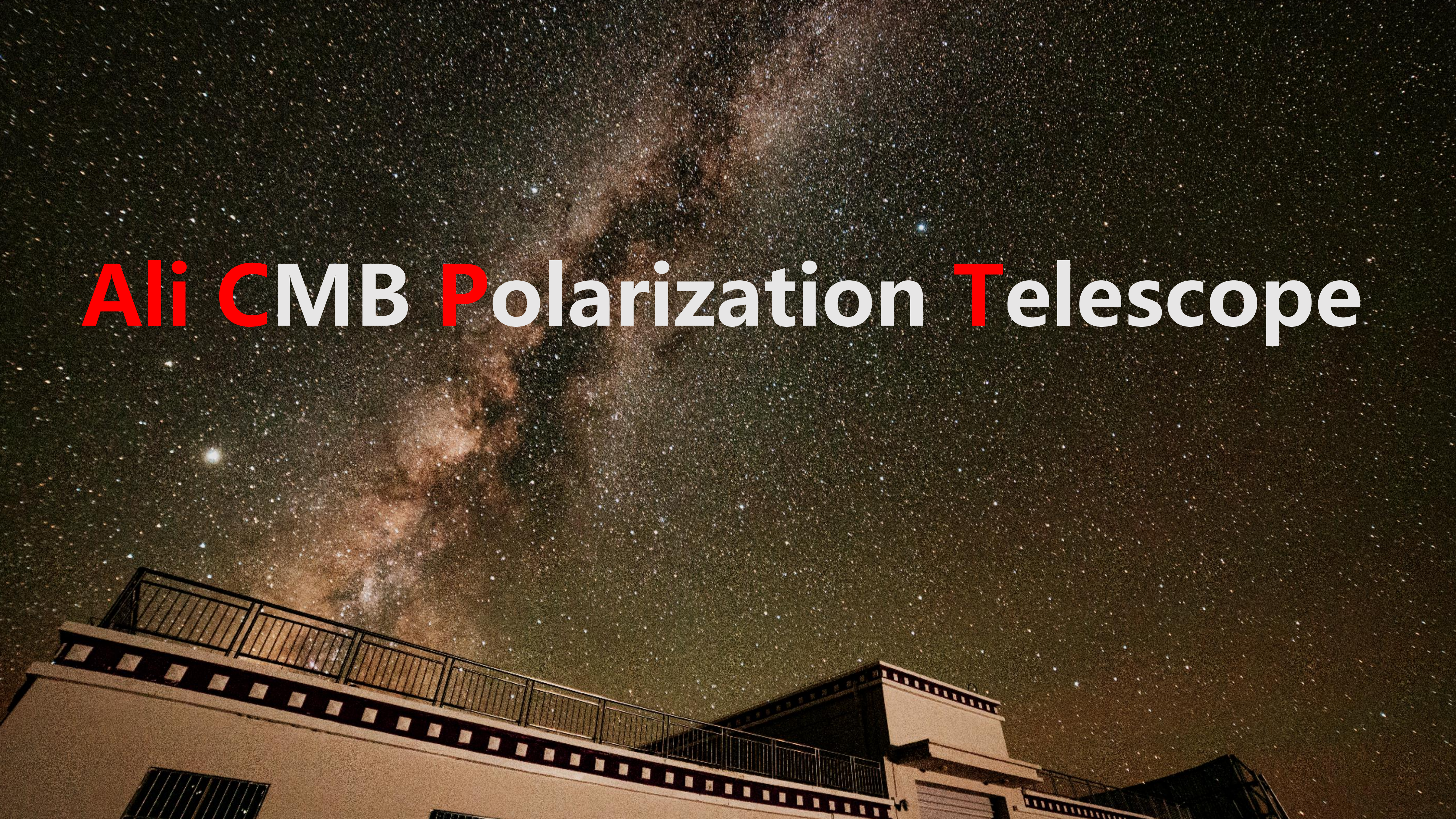
Ali CMB Polarization Telescope

AliCPT：中国首个原初引力波探测实验

- 世界屋脊之眼：建于西藏阿里天文台（海拔5,250米），全球海拔最高的原初引力波观测站，大气透射率与智利相当

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- 北半球唯一：填补北天区地面原初引力波探测空白，与南极、智利的探测阵列形成互补，打造CMB观测的三大基地

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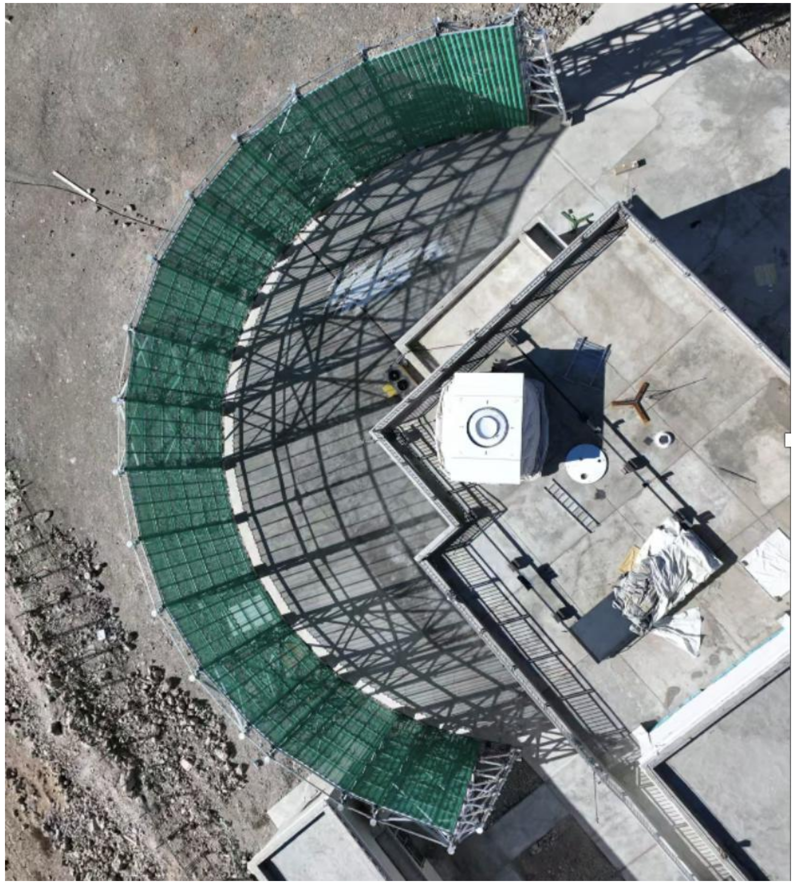
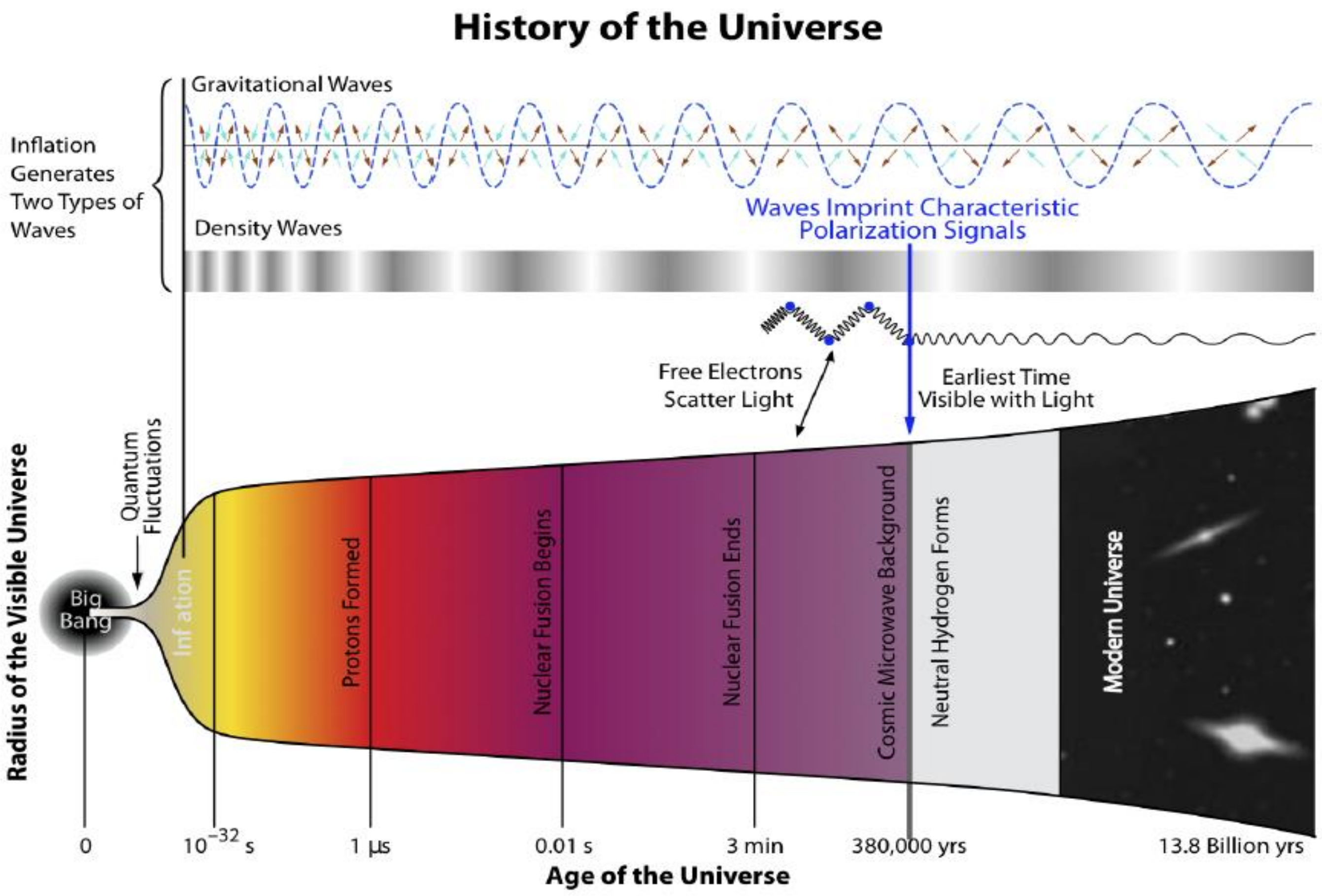
- **北半球唯一：填补北天区地面原初引力波探测空白，与南极、智利的探测阵列形成互补，打造CMB观测的三大基地**
- **2025年4月，成功首光！**

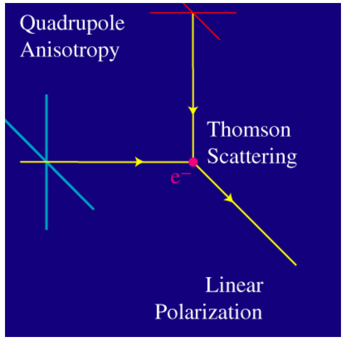
AliCPT：
a new CMB polarization observation in northern hemisphere

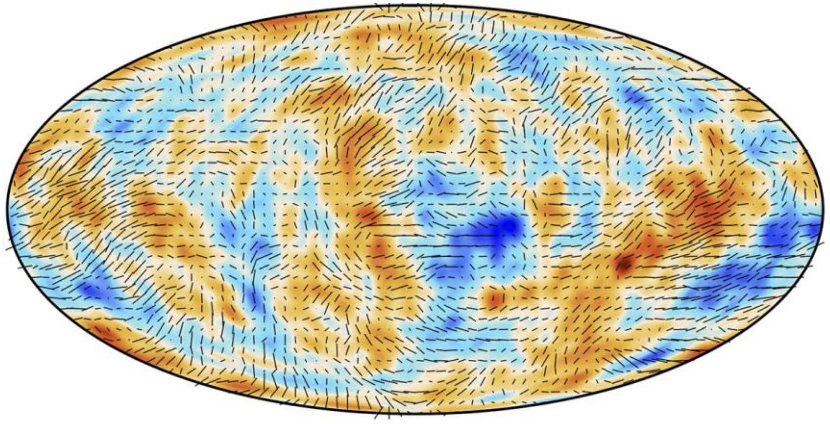
- 精确测量CMB 极化天图，探测原初引力波，探索宇宙起源

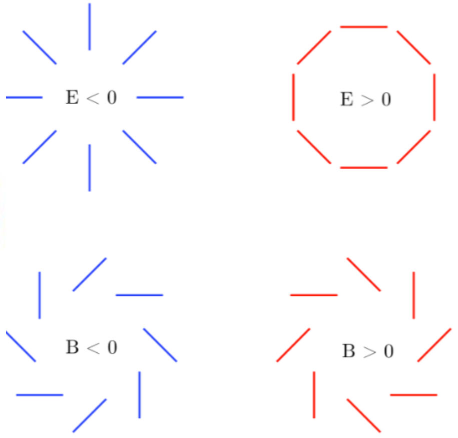


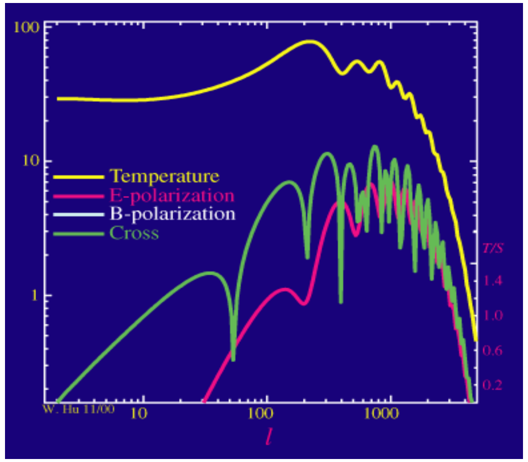


CMB 实验前沿：B mode 科学两大目标









C_l^{BB}

C_l^{TB}

C_l^{EB}

r

$\beta \equiv \overline{\beta} + \delta\beta$

- r: 张标比

目标一：测量原初引力波r，检验Inflation理论

- β: CMB 极化旋转角

目标二：测量CMB极化旋转角，检验Chern-Simons理论

阿里计划大事记：

2014年5月： 张新民团队提出阿里原初引力波探测计划

2016年10月： 阿里计划项目经理部及项目办公室成立

2016年12月： 阿里计划被列为中美高能物理会谈确定的合作项目

2017年3月： 观测站奠基，时任中国科学院院长白春礼一行亲临现场，指导工作

2017年8月： 时任中共中央政治局委员、国务院副总理刘延东亲临现场，视察并指导工作

2017年12月： 高能所与斯坦福大学签署 Ali CMB Polarization Telescope (AliCPT) 望远镜接收机研制合作协议

2018年底： 观测站建设完成（两年时间）

2018年~2021年： 完成 AliCPT-1望远镜及 CMB 实验各分系统（基座、控制系统、微波准光路系统及恒温器、探测器模块、数据分析平台等）的设计和研制（**三年半**）

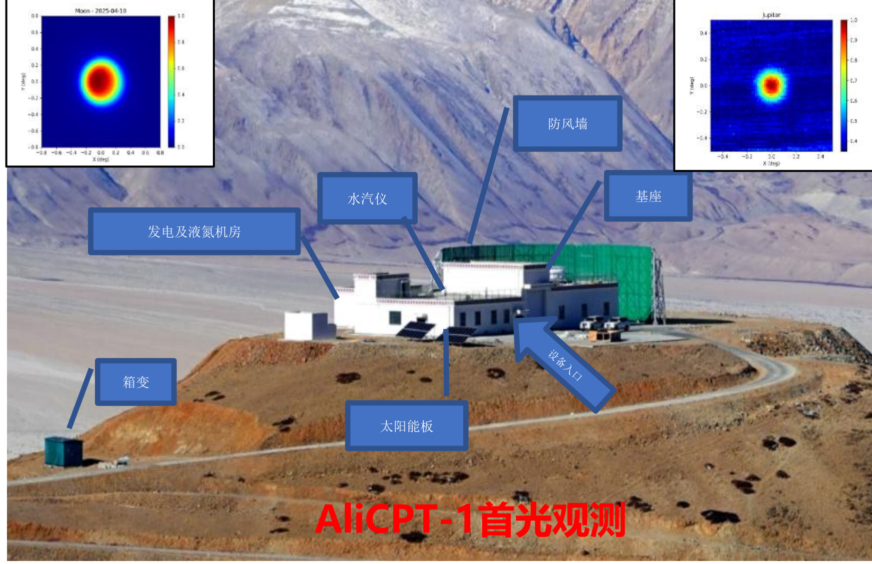
2021年~2024年： AliCPT-1 望远镜接收机在斯坦福大学实验室集成与测试，办理出口许可

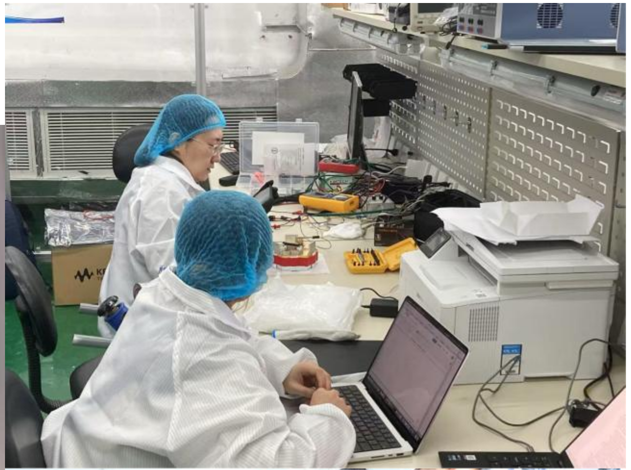
2024年11月30日： AliCPT-1 接收机运抵阿里原初引力波观测站

2025年4月10日： AliCPT-1 实现首光观测

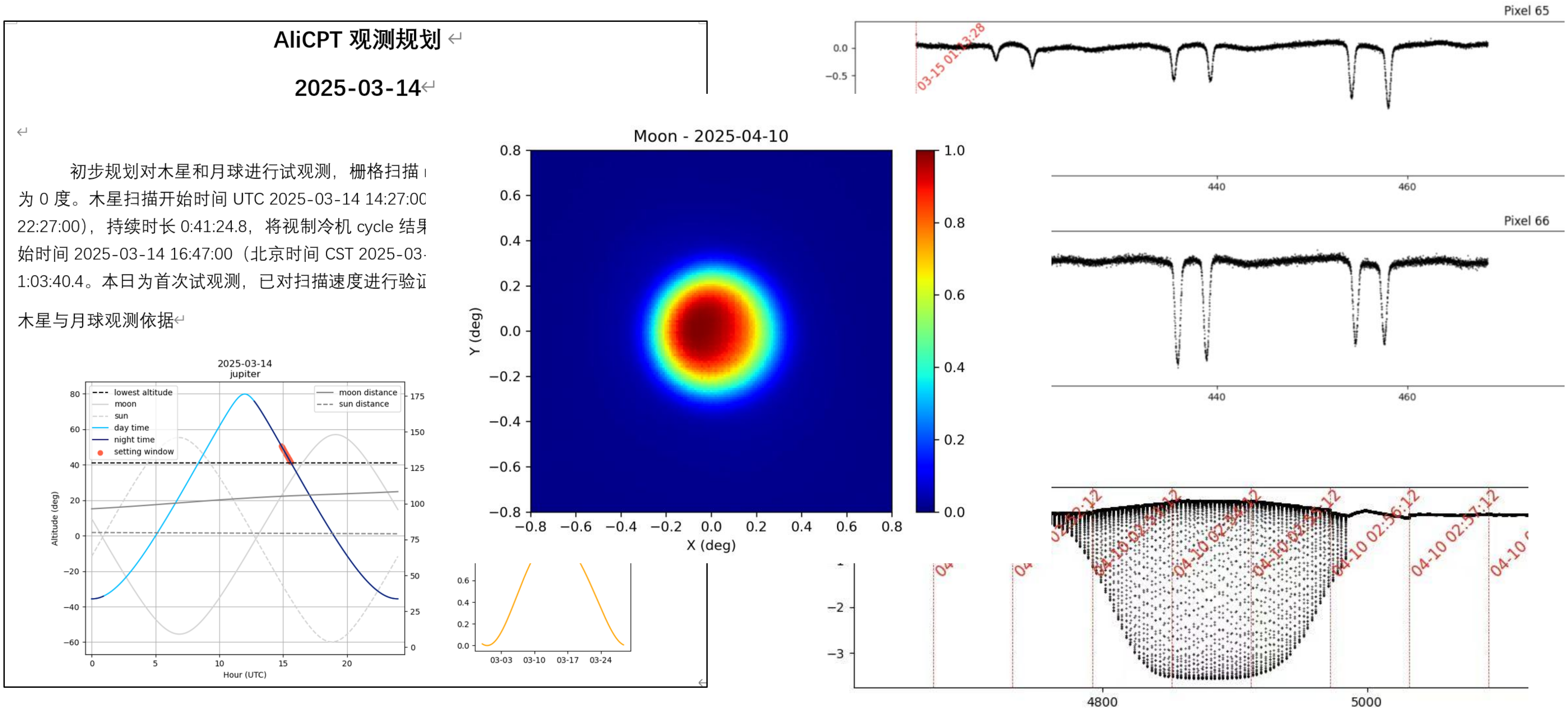
我国首台CMB望远镜从提出到建成~10年！

AliCPT-1建设发展历程



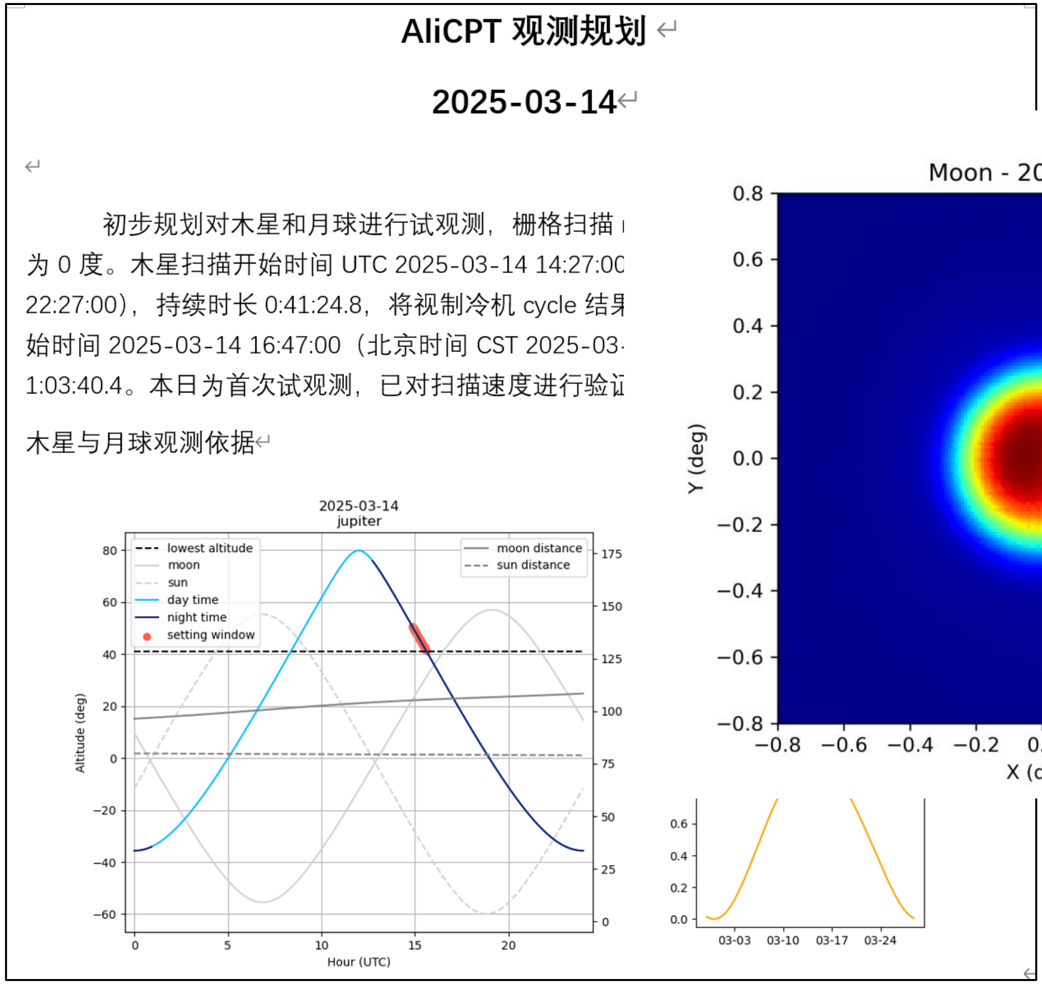


AliCPT-1 的天体源观测： 3 月 15 日首次观测月亮



☐ 积累数据，获取月球观测更高信噪比的天图，进一步验证了数据处理系统的可靠性

AliCPT-1 的天体源观测： 4 月 11 日首次观测木星

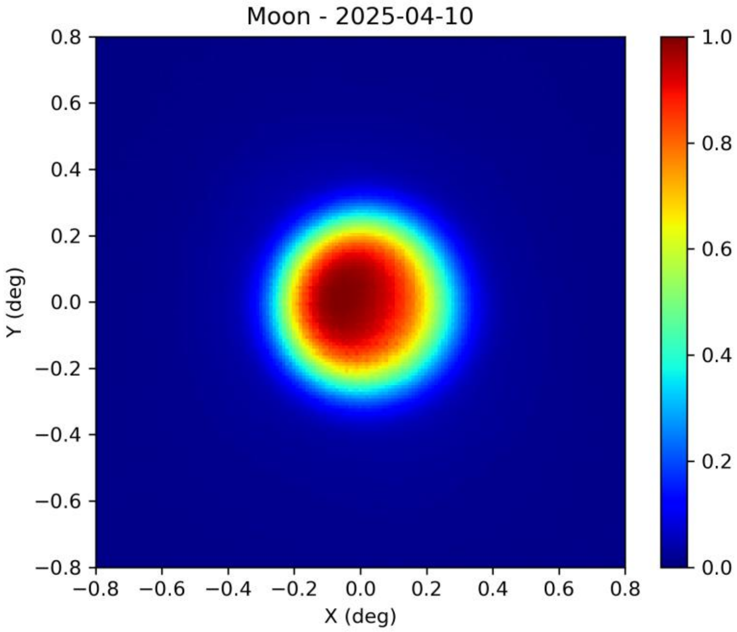


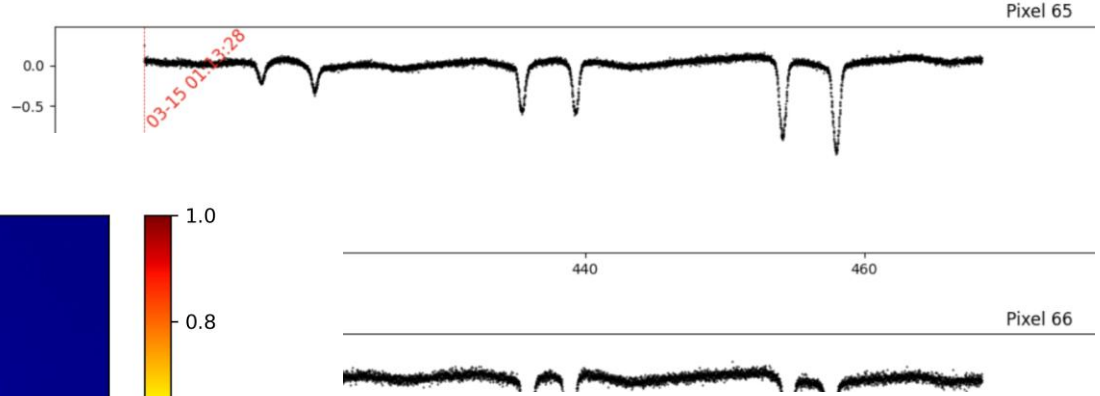
AliCPT 观测规划

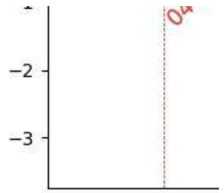
2025-03-14

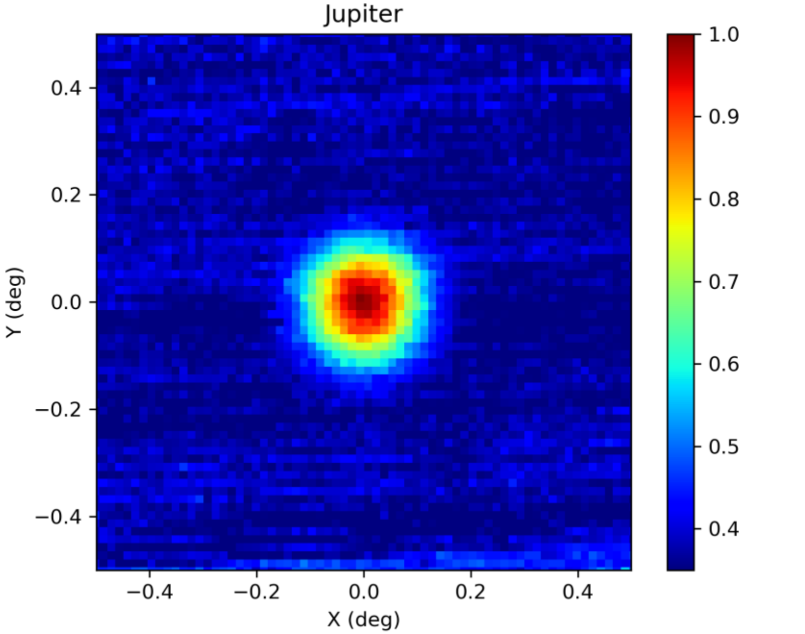
初步规划对木星和月球进行试观测，栅格扫描
为 0 度。木星扫描开始时间 UTC 2025-03-14 14:27:00
22:27:00)，持续时长 0:41:24.8，将视制冷机 cycle 结束
始时间 2025-03-14 16:47:00（北京时间 CST 2025-03-
1:03:40.4。本日为首次试观测，已对扫描速度进行验证

木星与月球观测依据









- ☐ **AliCPT-1首次实现对点源的观测！**

AliCPT-1 的CMB扫描： 3 月 17 日完成首次CMB扫描

AliCPT 观测规划

2025-03-17

CMB 观测开始时间 2025-03-17 17:49:39（北京时间 CST 2025-03-18 01:49:39），持续时间 7 小时 20 分钟。整个扫描过程持续总时长 12:24:17.2，DK 为 0 度。观测木星分为 4 轮，栅格扫描 raster scan 方位轴速度分别为 1、1、2、3 度/秒。观测火星分为 3 轮，栅格扫描 raster scan 方位轴速度分别为 1、2、3 度/秒。木星扫描开始时间 UTC 2025-03-17 12:44:00（北京时间 CST 2025-03-17 20:44:00），持续约 2 小时 40 分钟。火星扫描开始时间 2025-03-17 15:30:00（北京时间 CST 2025-03-17 23:30:00），持续约 2 小时。

```
scans = [
["2025-03-17 12:47:00", "cali_celest_CES", ["jupiter", 0, 8, 1, "down"]],
["2025-03-17 13:30:00", "cali_celest_CES", ["jupiter", 0, 8, 2, "down"]],
["2025-03-17 14:09:00", "cali_celest_CES", ["jupiter", 0, 8, 3, "down"]],
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["2025-03-17 15:30:00", "cali_celest_CES", ["mars", 0, 8, 1, "down"]],
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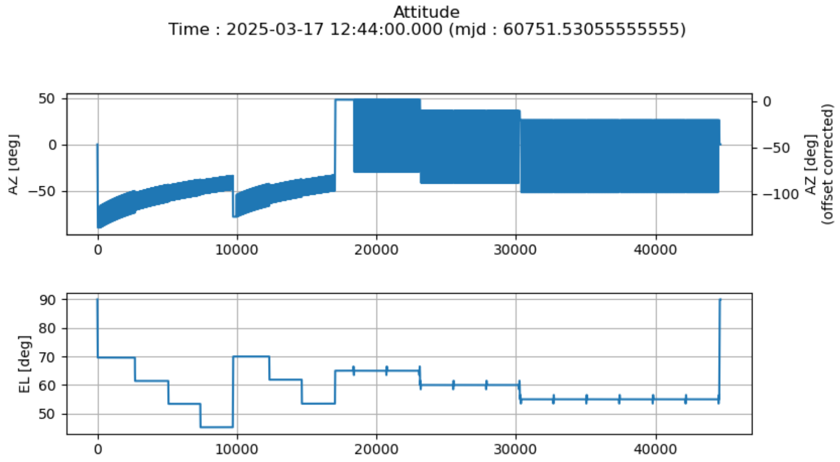
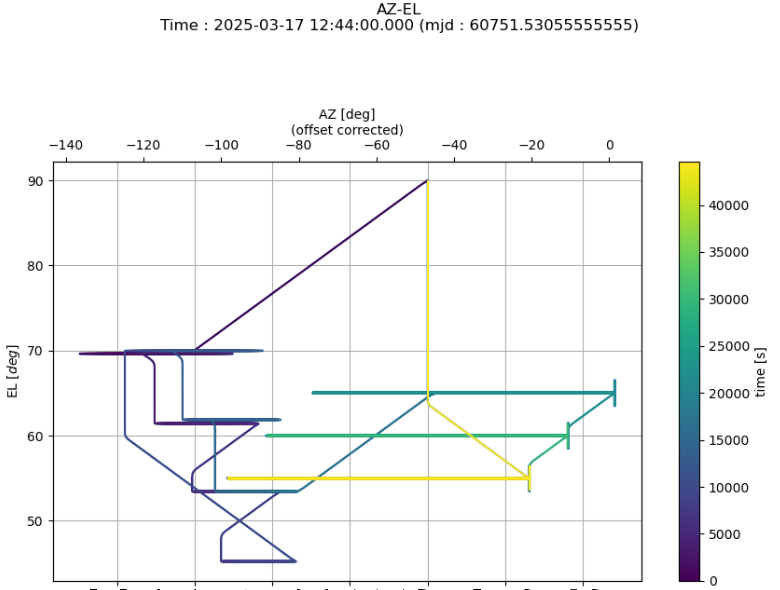
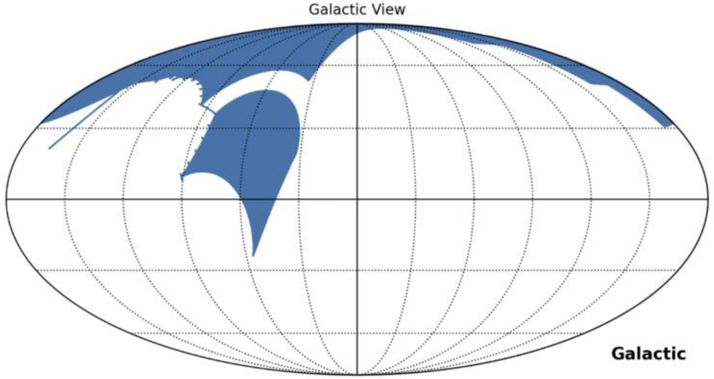
优化针对目标天区的观测策略





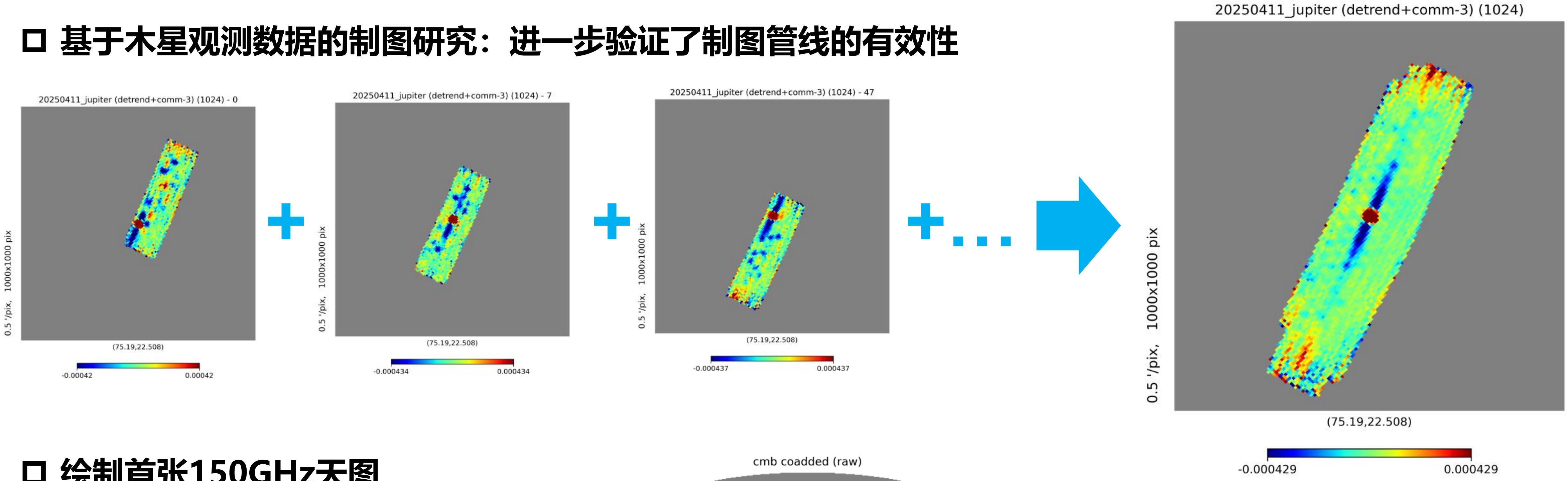
制定望远镜的姿态参数，锁定对目标源的指向跟踪

实现望远镜多自由度运动模式的精确配置与闭环控制，观测CMB



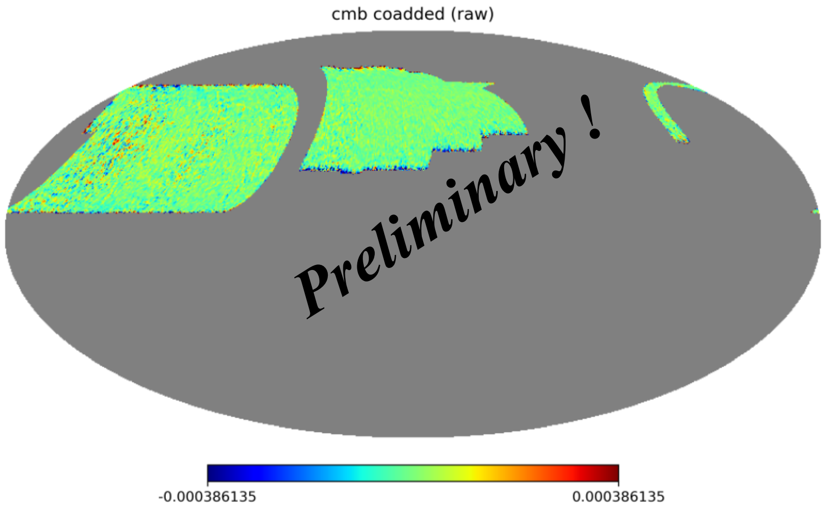
绘制AliCPT-1首张天图

□ 基于木星观测数据的制图研究：进一步验证了制图管线的有效性



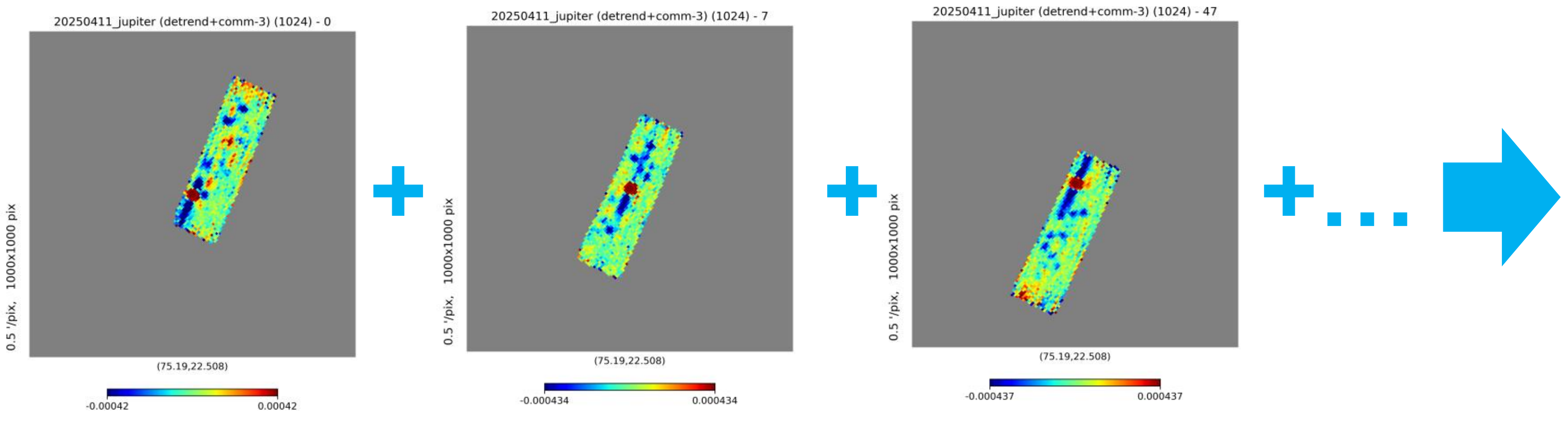
□ 绘制首张150GHz天图

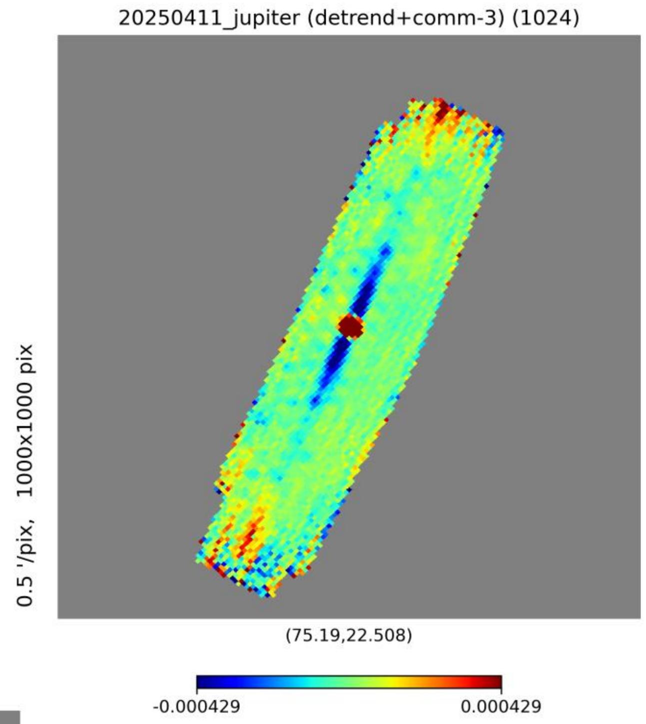
4.14/15/16/17/21/22/23/26几个观测夜的CMB扫描数据，叠加得到首个观测季得到的天图



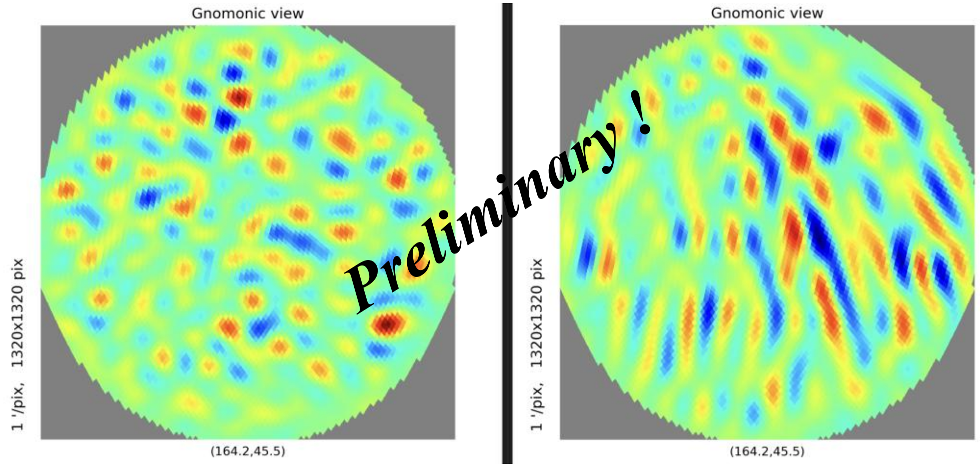
绘制AliCPT-1首张天图

- □ 基于木星观测数据的科学制图研究：进一步验证了制图管线的有效性



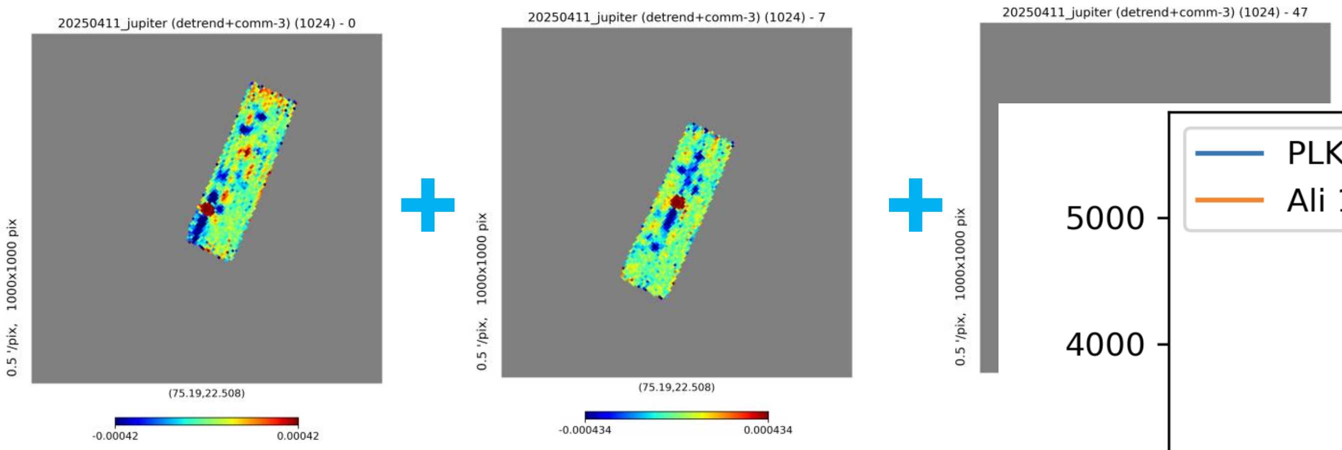


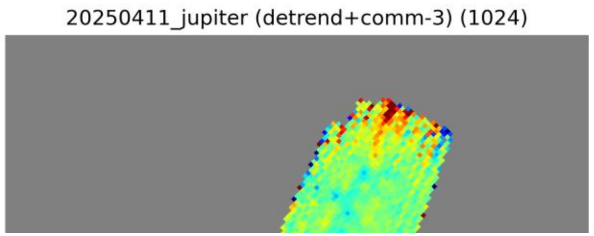
- □ 绘制首张150GHz天图



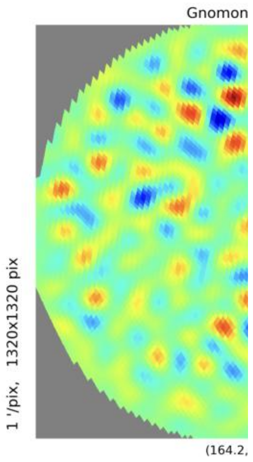
绘制AliCPT-1首张天图

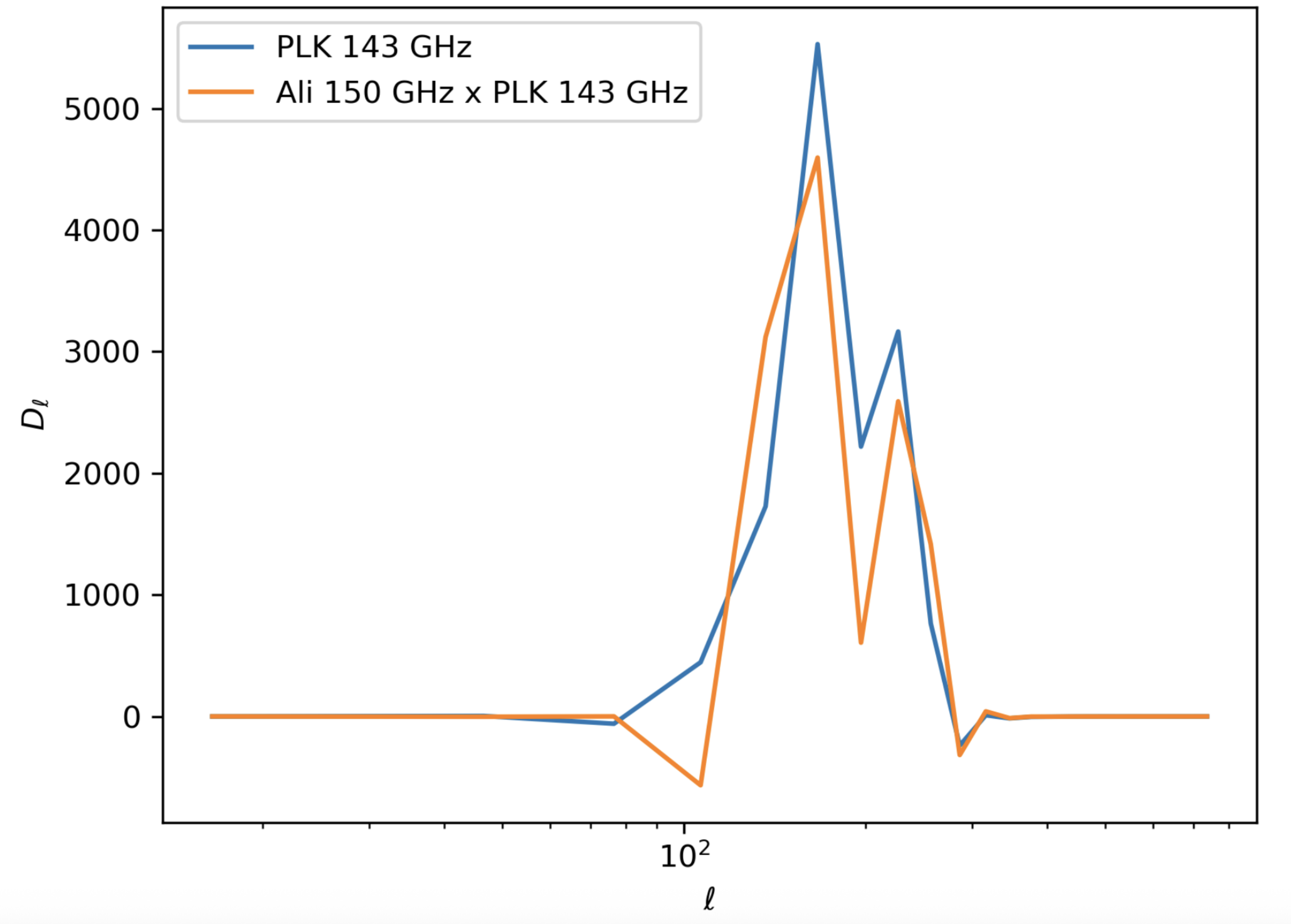
- 基于木星观测数据的科学制图研究：进一步验证了制图管线的有效性





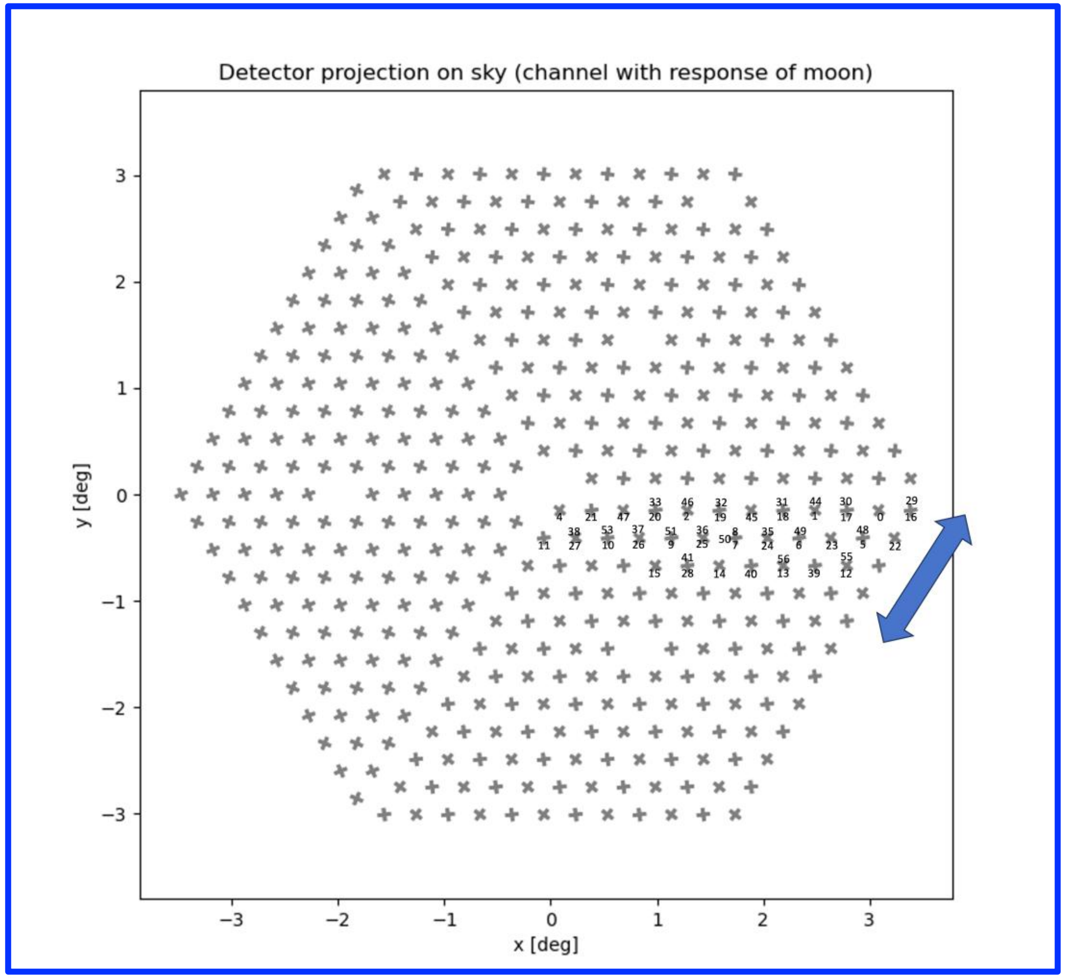
- 绘制首张150GHz天图

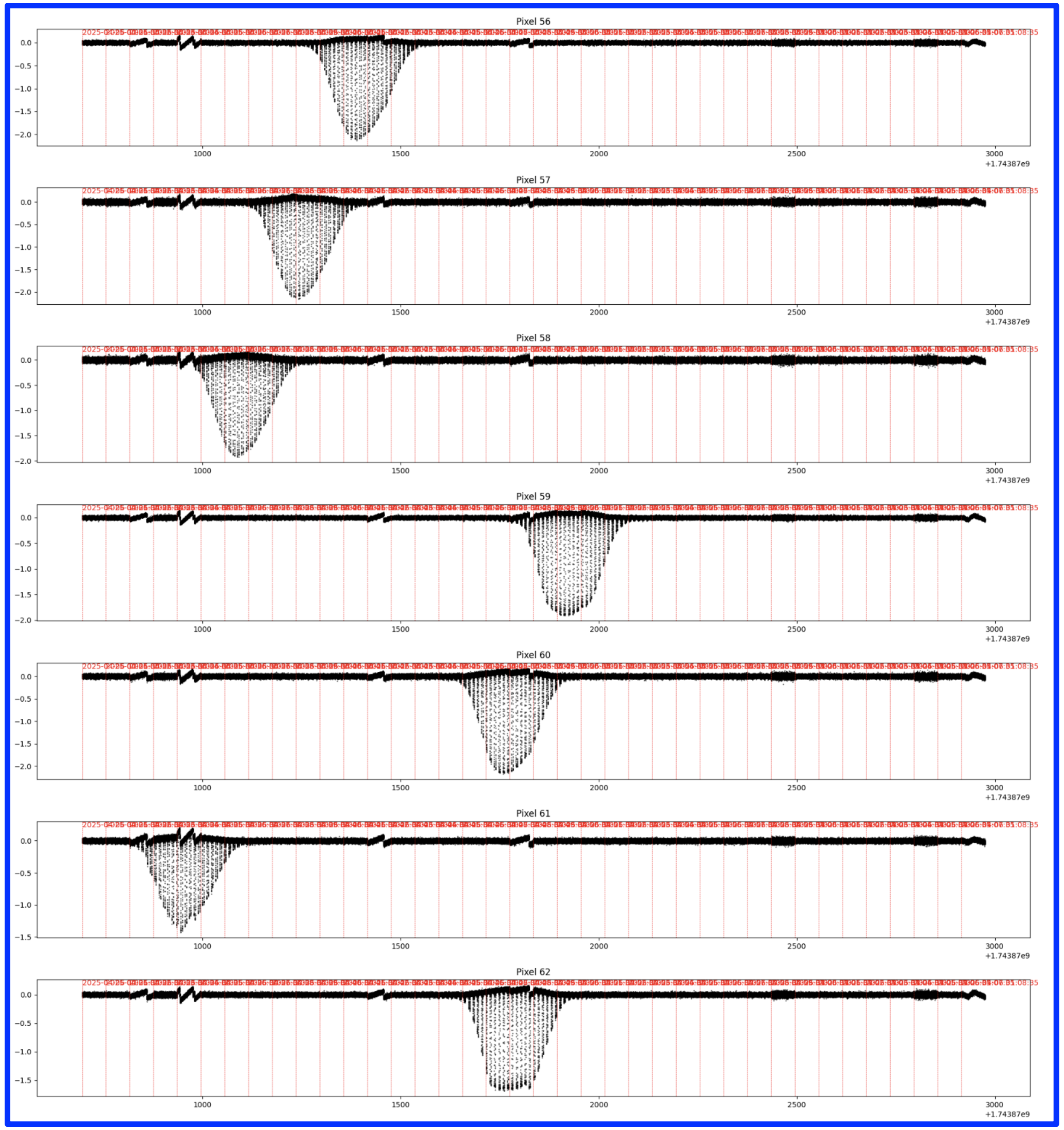




Data-driven标定分析：

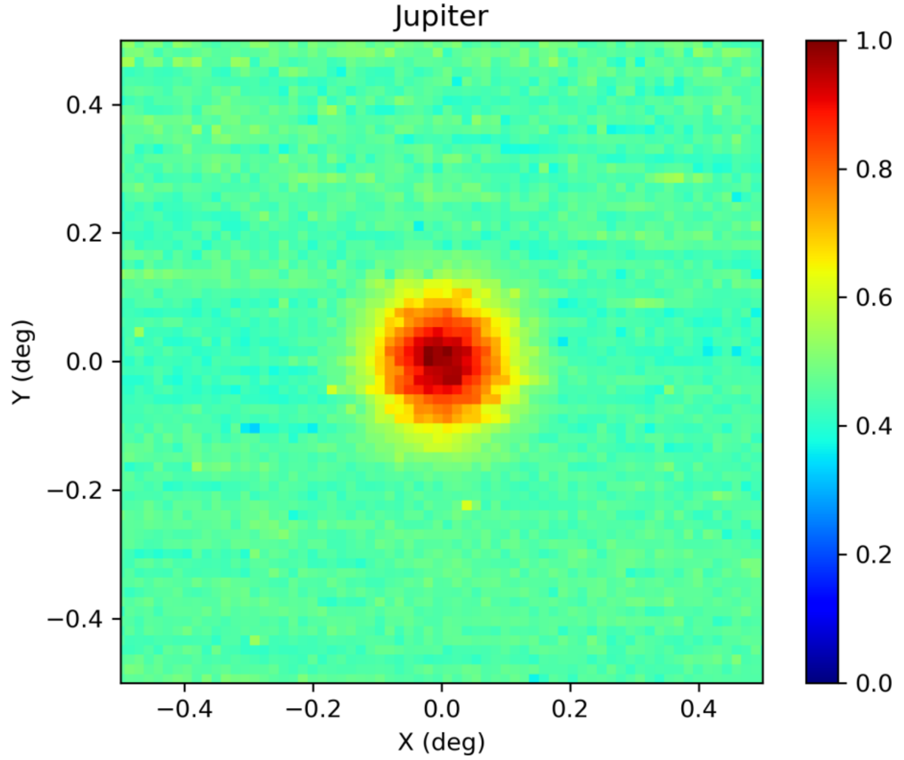
- **Detector mapping：天体源信号在TOD上的分布可以用来认证TeSes在焦平面上的位置分布**

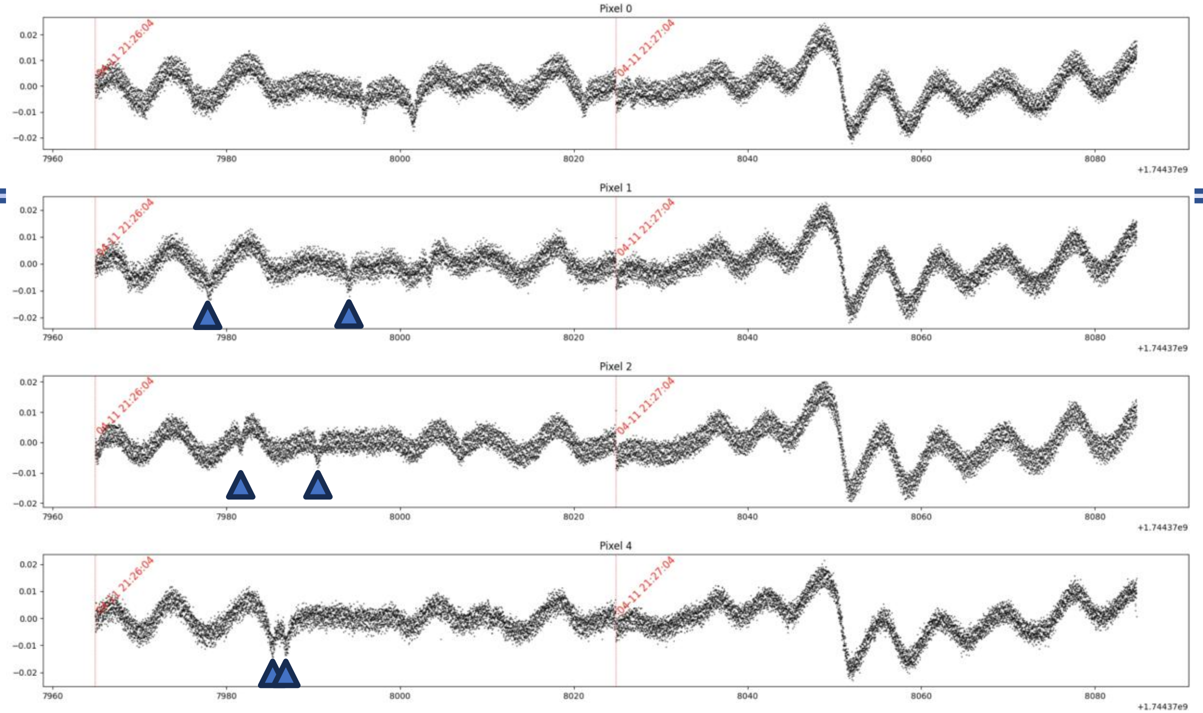


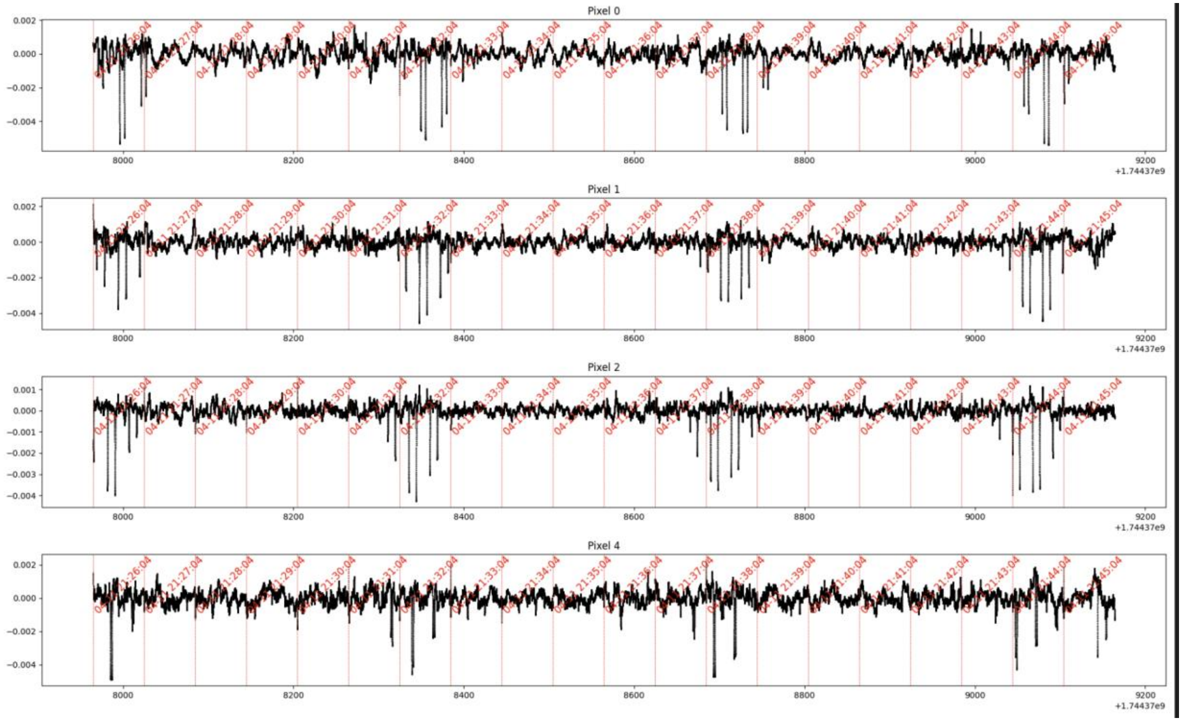


Data-driven标定分析：

- 利用对木星的观测数据，标定 AliCPT-1 beam：10.09 角分 @150GHz



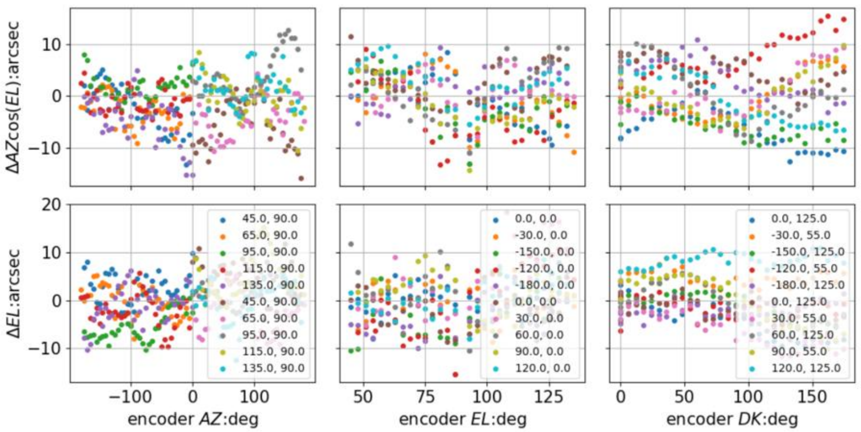




指向标定: 星敏数据标定结果

Residue rms =7.2角秒

Pointing model：16 参数



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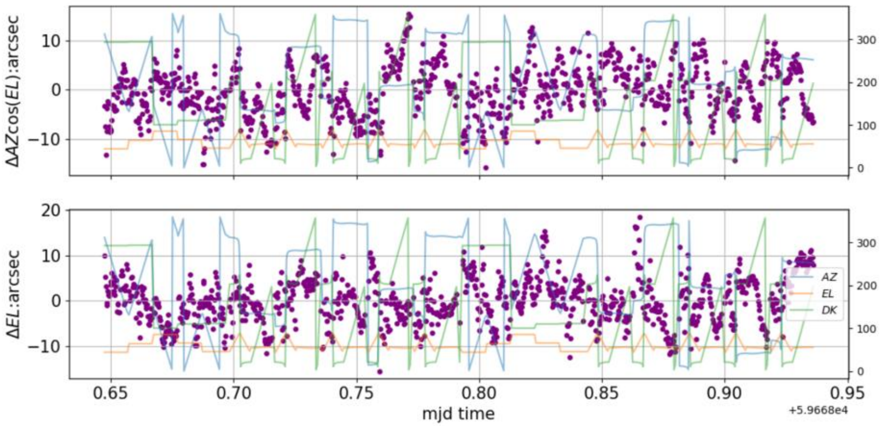
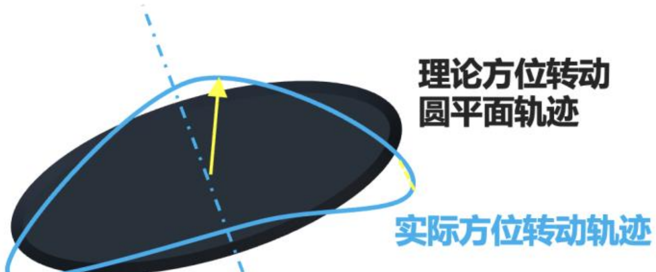
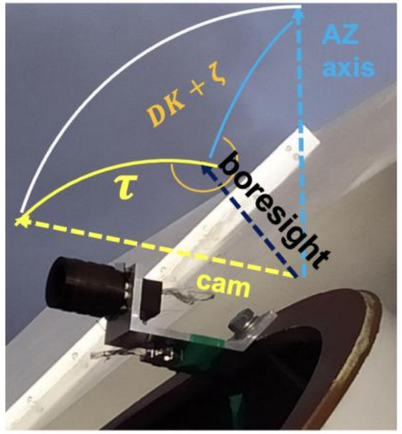


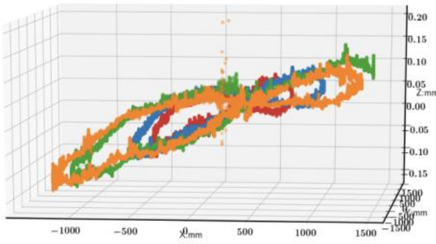
Residue ~time variation

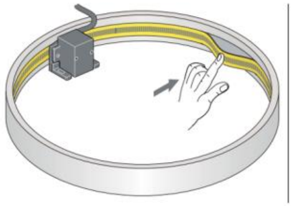


方位转台不平整参数

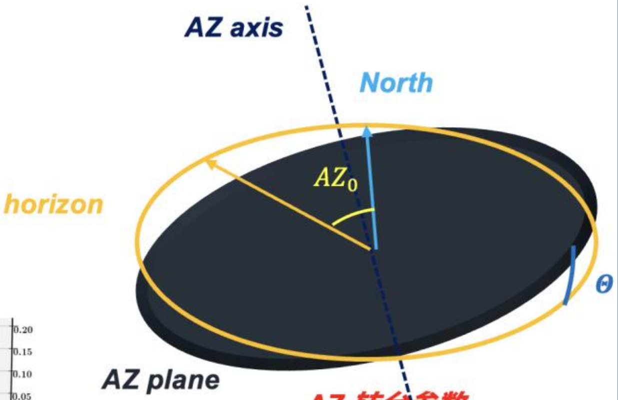


星敏与视轴不平行参数

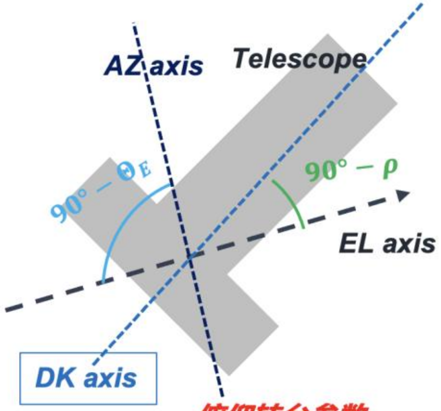




方位读数误差：光栅尺
安装直径与名义直径偏离



AZ 转台参数



俯仰转台参数

AliCPT-1初光观测标志着我国开启CMB观测的新纪元

运行AliCPT-1望远镜，进一步提升其精度：

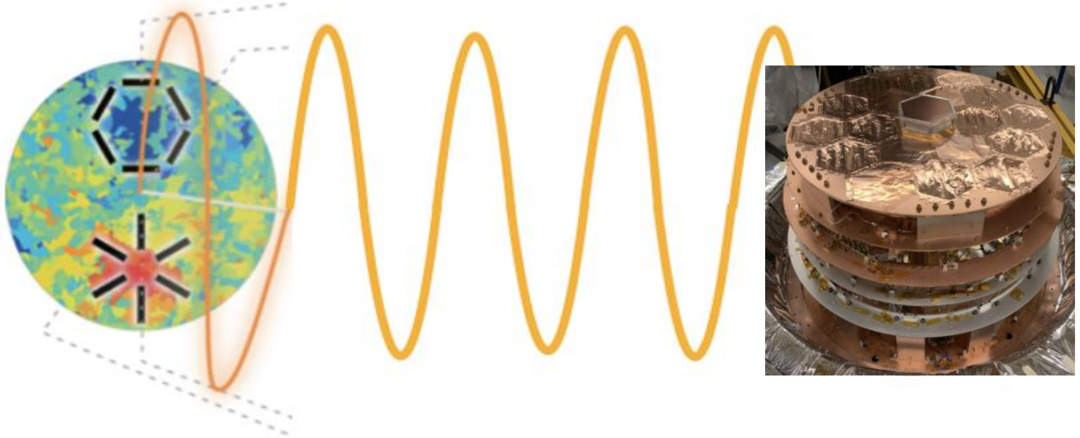
- 精确测量CMB极化信号；
- 利用TB/EB功率谱观测，检验Axion-Chern-Simons理论的物理效应；
- 基于EE功率谱的高精度测定，验证ΛCDM宇宙学模型的预测；
- 结合毫米波巡天数据，开展前景辐射成分及时域天文现象的深入研究；
- 通过BB功率谱的精确测量，约束原初引力波信号；

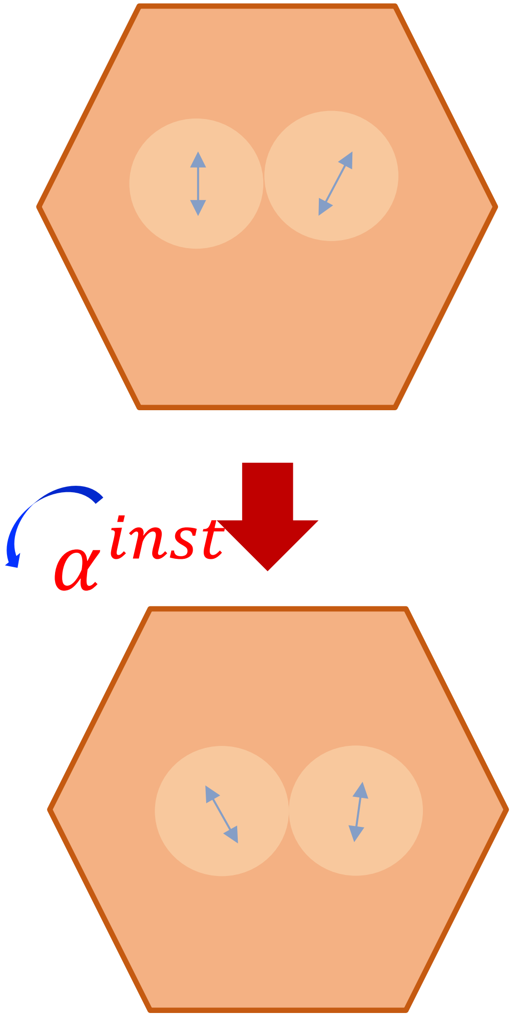
挖掘CMB极化科学，产出高水平的科学成果：

- 好于 Planck 的北天区的CMB极化天图
- 5sigma 置信度水平上测得极化旋转角（具有中国特色：陈省身先生的数学理论，张新民团队国际上首次测量）
- E 模式物理、检验早期暗能量理论 （特色：北天独立测量）
- 北天毫米波巡天和前景科学（特色：北天唯一）
- 精确测量原初引力波参数 r ~0.01 （特色：北天独立测量）

CS 旋转角与探测器固有极化角

- CS 诱导的极化旋转角的测量值与TeS探测器的固有极化角是强简并的

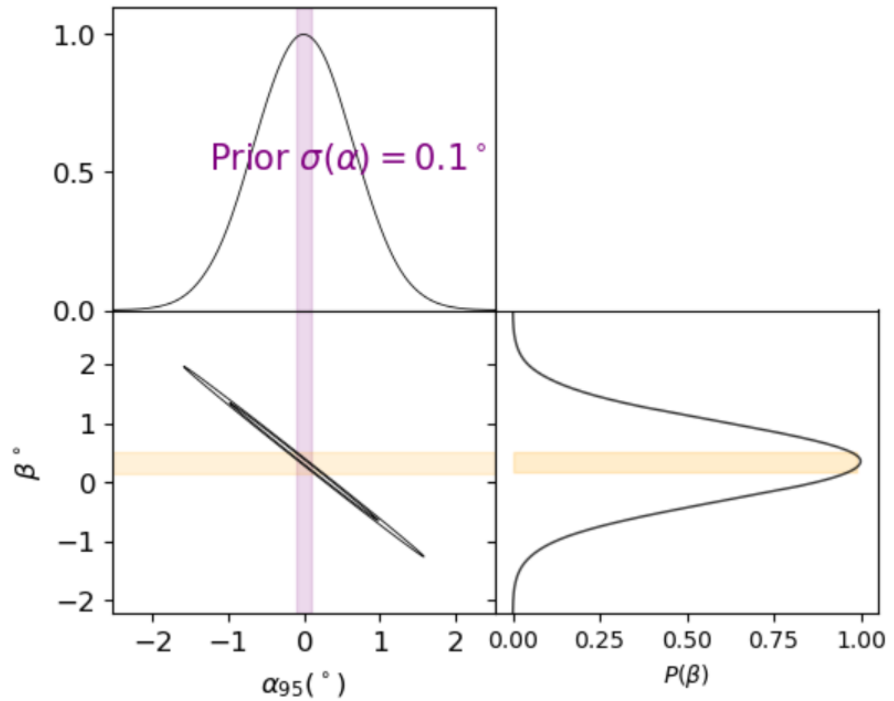




$$\beta^{0} = \beta + \alpha^{inst}$$

- 测量值 = CS 诱导的极化旋转角 + TeS 的固有极化角

α 与 β 高度简并

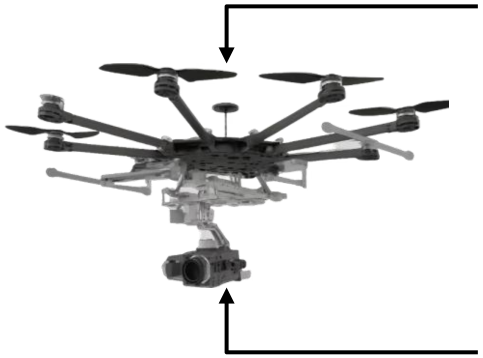


α 与 β 高度简并

α 的独立标定将极大提升对β的探测精度

AliCPT远场极化标定新方案

研究路线：利用无人机运载极化源，利用摄影测量法和卫星定位系统确定无人机以及极化源的位置和姿态。实现对极化角标定精度到 0.1度。



无人机平台：

卫星定位系统

摄影测量系统

云台增稳系统

人工微波极化源：

微波噪声源

线栅

具备基础：

1. 已经具有远场极化源
2. AliCPT-1即将初光，在非观测季可进行标定测试

AliCPT 验证DE-Chern-Simons dynamics

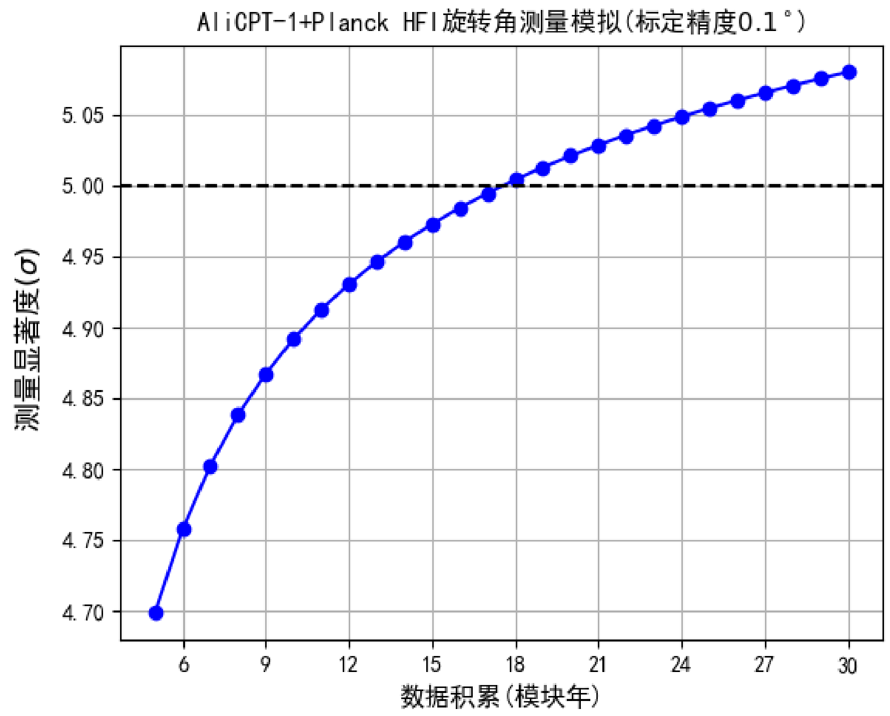
新方法：新建一个高精度 CMB 极化标定源，比如无人机携带的，精度 0.1度

模拟结果：

1. AliCPT-1观测5年 + 极化标定源，到2030年，

极化旋转角的测量精度可到 4.6 sigma

2. 如果增加模块， 极化旋转角测量精度很快到 5 sigma



AliCPT 验证DE-Chern-Simons dynamics

Dynamic equation of ϕ: $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$

$$(Q \pm iU)' = e^{\pm 2i\alpha}(Q \pm iU)$$

Rotation angle:

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

Frequency independent

The dynamics of dark energy

总结

- DESI 发现动力学暗能量 -> 引力效应
- Dark energy field 与通常物质的相互作用 -> 探测暗能量的新方法 （类似暗物质的直接/间接探测，基于与物质相互作用）
- 提出了AliCPT探测暗能量的新方案 -> 2030年前有望测到5σ

谢谢！