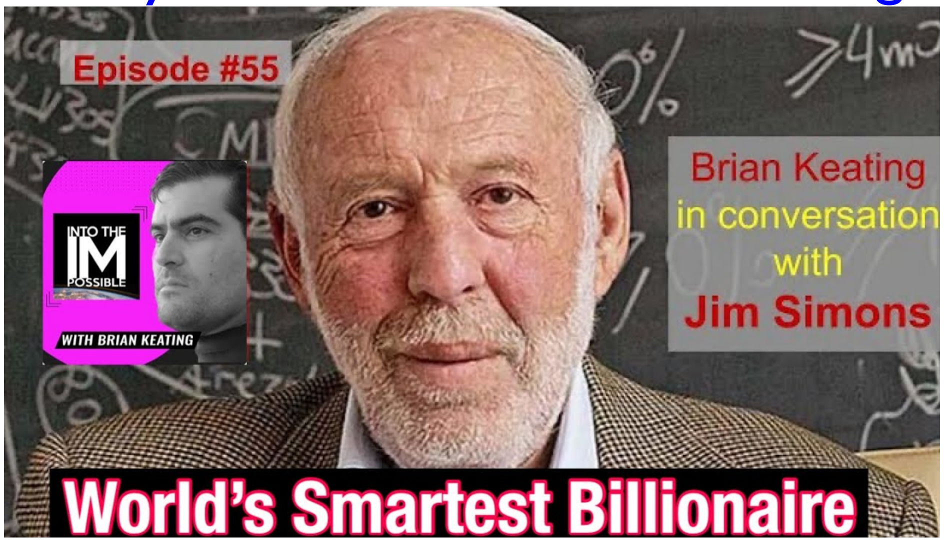
Beyond Chern-Simons: Historical & Background Experimental techniques Challenges

https://briankeating.com/cb

Brian Keating
Department of Physics
University of California, San Diego

Milan
11/5/24

Subscribe to my YouTube Channel for interviews with geniuses:
www.youtube.com/DrBrianKeating



Join my

mailing list for

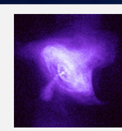
10 Life-Lessons

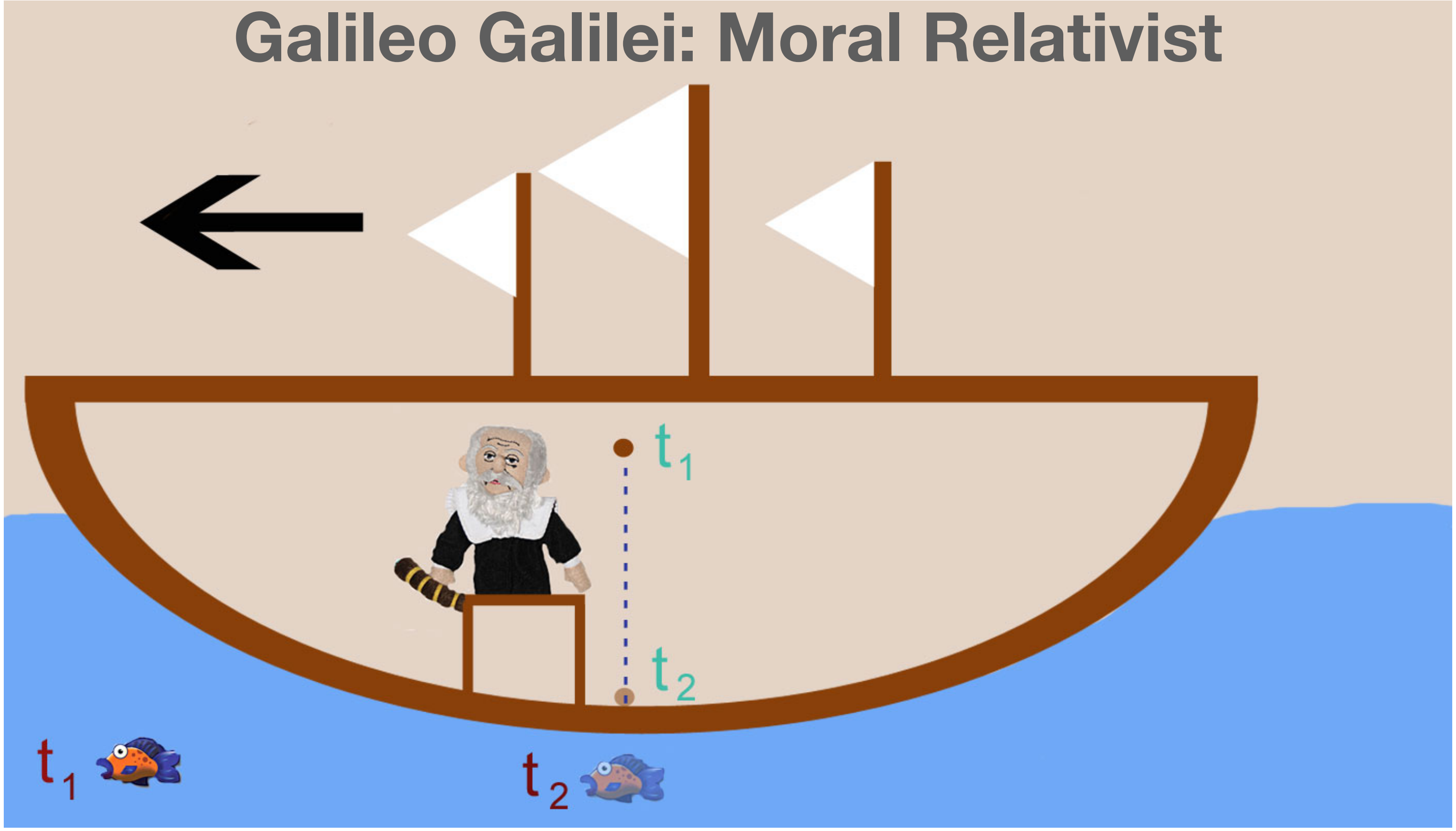
from 14 Nobel Prize winners

briankeating.com/edu

bitly

Outline

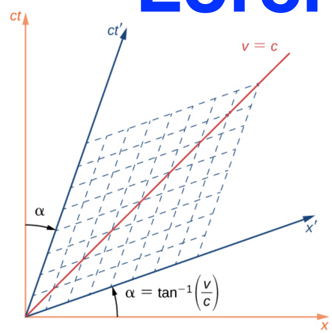
- Cosmology with CMB Polarization
- Cosmic birefringence
- Experimental Results
-  PolCal Drones!
-  Future



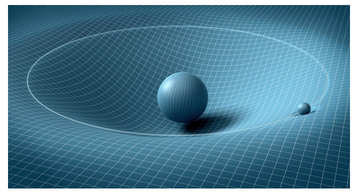
Galileo used this experiment to demonstrate that Earth could, in fact, move without conflicting with our everyday sense of the world. Even if the Earth were moving, everything on its surface would move at the same speed. Consequently, doing these experiments in the geocentric universe of the Church and the heliocentric universe Galileo had in mind would be indistinguishable. Galileo had stumbled upon a type of relativity that now bears his own name. Reflecting upon several simple mechanical experiments like the falling ball, Galileo concluded: You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still.

https://www.physicscentral.com/explore/plus/galilean-relativity.cfm

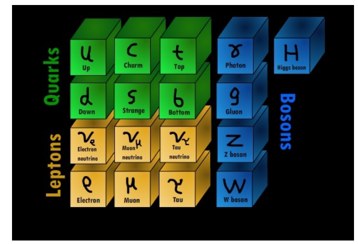
Lorentz invariance violation?



General Relativity (GR)



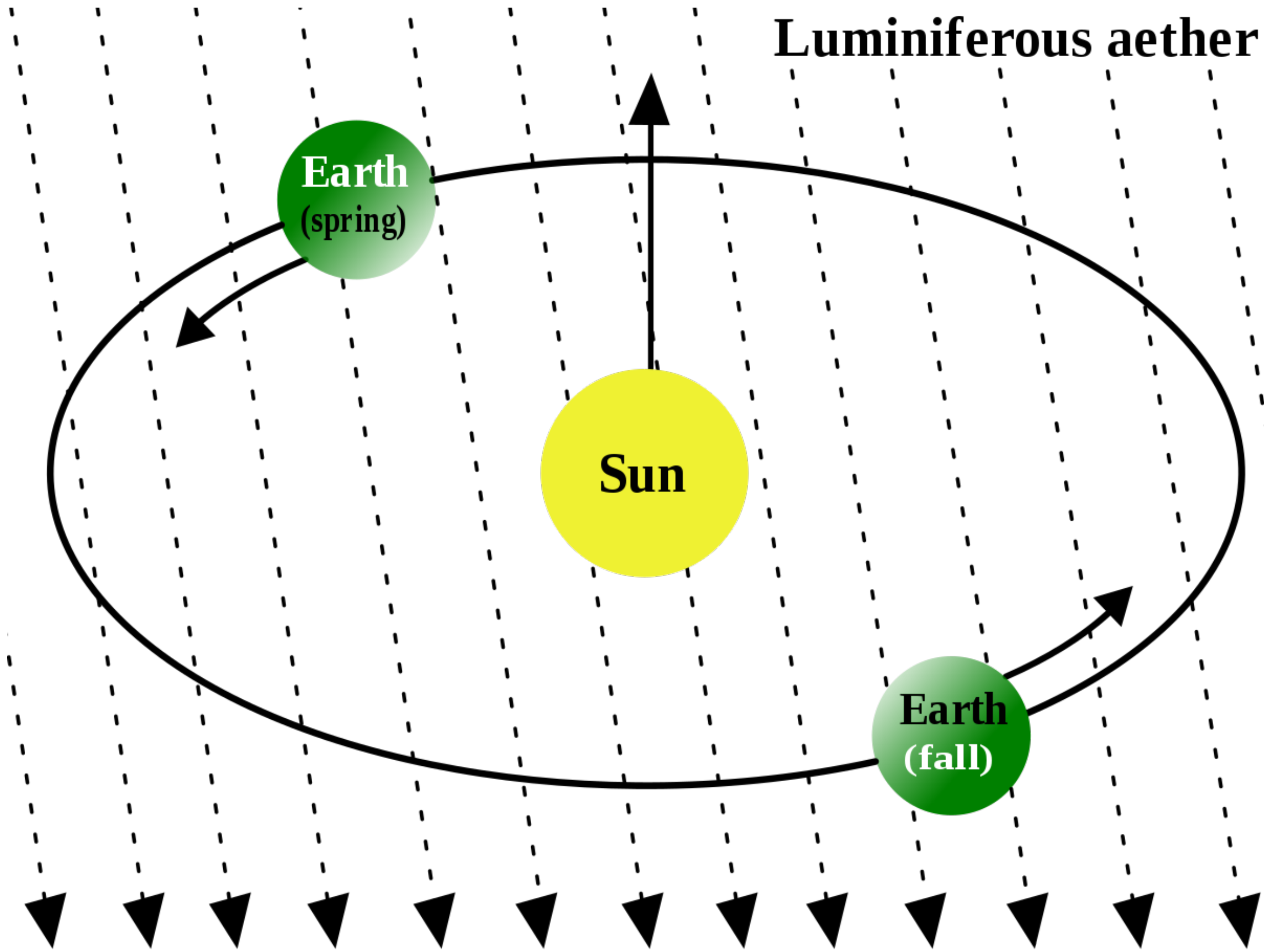
Standard Model (SM)



- Both GR and SM *assume* Lorentz Symmetry (special relativity, relativistic quantum theory, QFT)
- But GR and Quantum Field Theory/Standard Model are not unified!

Violations of Lorentz symmetry, if detected, would point us toward new physics, quantum gravity!

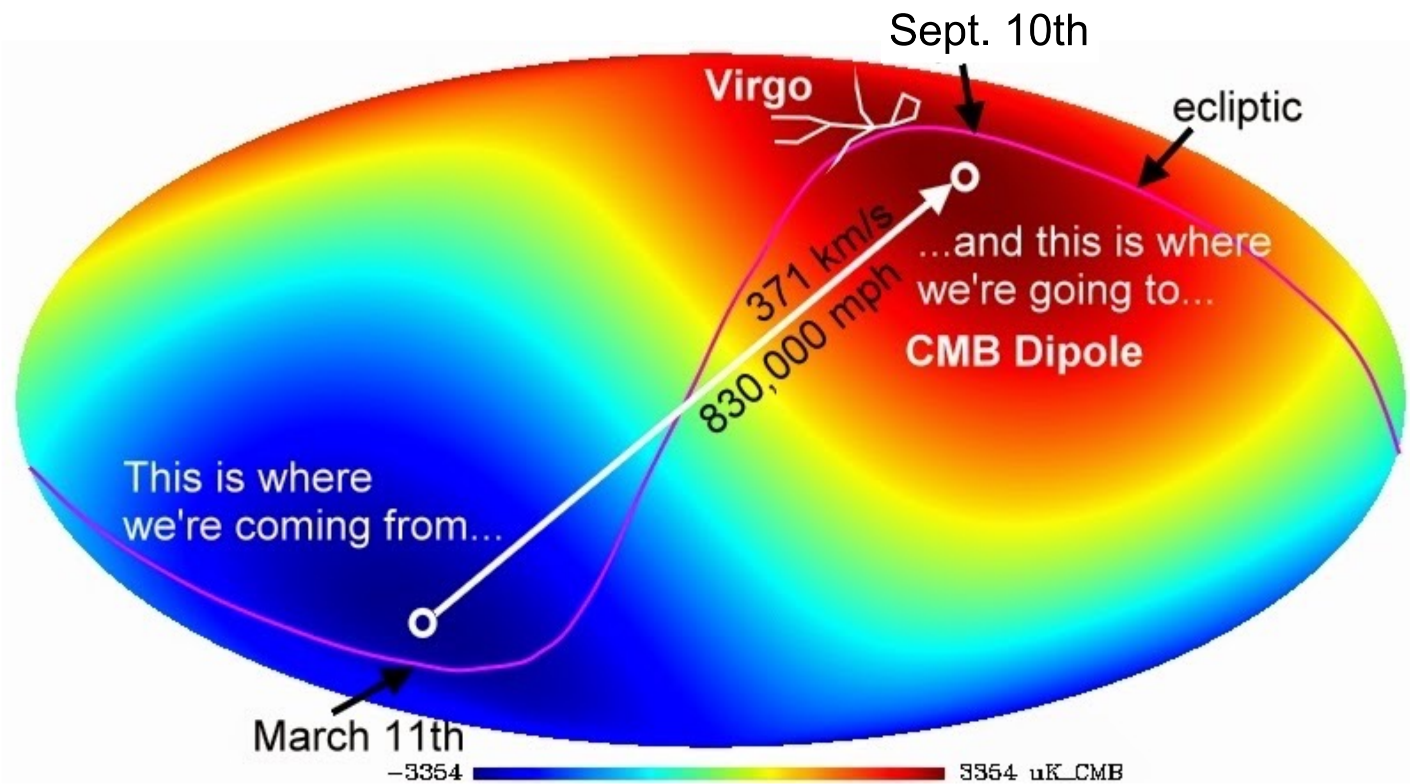
Michelson-Morley: Hold my aether!



Are we sure there isn’t a preferred reference frame?

CMB DIPOLE

- **CMB temp. map has dipole distortion.**
- Each point on sky has blackbody spectrum, but spectrum is redshifted/blueshifted in different halves of the sky.
- Due to Doppler shift caused by net motion of satellite with respect to frame in which CMB is isotropic. **Net motion toward Virgo cluster!**



Is Parity violated? Yes!

- Cobalt-60 cooled to 3 mK (!)
- Applied magnetic field to align all atoms
- Measured electron emission
- Reversed the magnetic field, reversing the spin
- Saw the same anisotropic electron emission
- Preferred emission direction is opposite to the nuclear spin
- Thus we can tell a “mirrored” world from our own – parity NOT conserved

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

The question of p ... ined. Possible
experiments are sug

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

In a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would provide the necessary evidence for parity conservation or nonconservation. In beta decay, one could measure the angular distribution of the electrons coming from beta decays of polarized nuclei. If an asymmetry in the distribution between θ and $180°-\theta$ (where θ is the angle between the orientation of the parent nuclei and the momentum of the electrons) is observed, it provides unequivocal proof that parity is not conserved in beta decay. This asymmetry effect has been observed in the case of oriented Co^{60}.

It has been known for some time that Co^{60} nuclei can be polarized by the Rose-Gorter method in cerium magnesium (cobalt) nitrate, and the degree of polarization detected by measuring the anisotropy of the succeeding gamma rays.[2] To apply this technique to the present problem, two major difficulties had to be over-

sotropy alone provides a reliable measure of nuclear polarization. Specimens were made by taking good single crystals of cerium magnesium nitrate and growing on the upper surface only an additional crystalline layer containing Co^{60}. One might point out here that since the allowed beta decay of Co^{60} involves a change of spin of

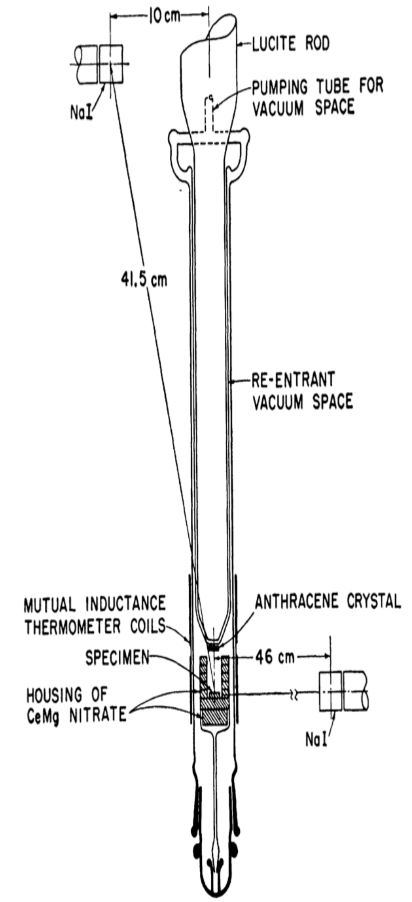


Fig. 1. Schematic drawing of the lower part of the cryostat.

Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998)

Cosmic Birefringence

The effect accumulates over the distance

- If the Universe is filled with a pseudo-scalar field (e.g., an axion field) coupled to the electromagnetic tensor via a Chern-Simons coupling:

Turner & Widrow (1988)

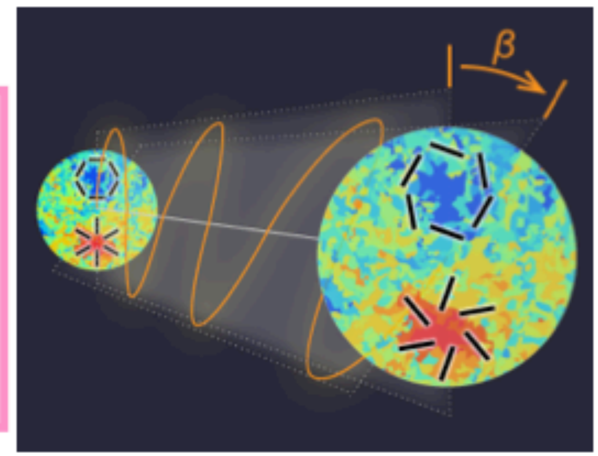
the effective Lagrangian for axion electrodynamics is

Chern-Simons term

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad (3.7)$$

$$\tilde{F}^{\mu\nu} = \sum_{\alpha\beta} \frac{\epsilon^{\mu\nu\alpha\beta}}{2\sqrt{-g}} F_{\alpha\beta}$$

where g_a is a coupling constant of the order α, and the vacuum angle $\theta = \phi_a / f_a$ (ϕ_a = axion field). The equations



$$\beta = 2g_a \int_{t_{\text{emission}}}^{t_{\text{observed}}} dt\ \dot{\theta}$$

The larger the distance the photon travels, the larger the effect becomes.

Komatsu "Cosmology Talks" YouTube

HAPPY BIRTHDAY TO CARROLL, FIELD, & JACKIW (1990)
(Galileo Galilei's 426th BIRTHDAY🎉)

PHYSICAL REVIEW D VOLUME 41, NUMBER 4 15 FEBRUARY 1990

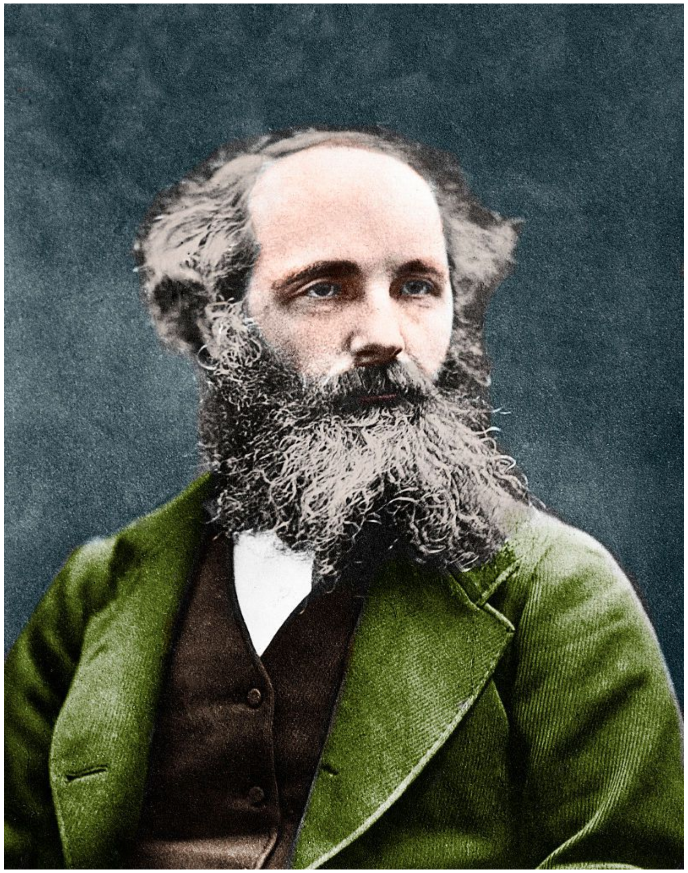
Limits on a Lorentz- and parity-violating modification of electrodynamics

Sean M. Carroll and George B. Field
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138

Roman Jackiw*
Department of Physics, Columbia University, New York, New York 10027
(Received 5 September 1989)

The Chern-Simons Lagrangian has been studied previously in (2+1)-dimensional spacetime, where it is both gauge and Lorentz invariant. In 3+1 dimensions, this term couples the dual electromagnetic tensor to an external four-vector. If we take this four-vector to be fixed, the term is gauge invariant but not Lorentz invariant. In this paper, we examine both the theoretical consequences of such a modification and observational limits we can put on its magnitude. The Chern-Simons term would rotate the plane of polarization of radiation from distant galaxies, an effect which is not observed. From the observations we deduce that the magnitude of the vector is $<1.7\times10^{-42}h_0$ GeV, where h_0 is the Hubble constant in units of 100 km sec^{-1} Mpc^{-1}.

https://www.researchgate.net/publication/13277928_Limits_on_a_Lorentz-_and_parity-violating_modification_of_electrodynamics



James Clerk Maxwell

(born June 13, 1831, Edinburgh, Scotland—died November 5, 1879, Cambridge, Cambridgeshire, England)

I. INTRODUCTION

Gauge and Lorentz invariance are two symmetries of Maxwell's electrodynamics that have come to dominate all fundamental physical theory. They provide physical principles that guide the invention of models describing fundamental phenomena, and their experimental status—within electromagnetism—is well established. The properties of electromagnetic radiation, both in a natural setting and in high-energy accelerators, are precisely described by Lorentz-invariant dynamics. Gauge invariance, interpreted as the masslessness of the photon, is validated by stringent limits on the photon mass.

Experimental tests of such well-established and universal physical ideas are best discussed within a theoretical framework that allows departures to be governed by arbitrary parameters; experimental data then set limits on the magnitude of these symmetry-breaking parameters. Thus, violations of gauge invariance are parametrized by a mass μ for the photon field A_ν. A mass term is hypothesized to modify the electromagnetic Maxwell Lagrange density $\mathcal{L}_{\rm EM}$,

$$\mathcal{L}_{\rm EM}=-\tfrac{1}{4}F_{\nu\lambda}F^{\nu\lambda} \quad (1)$$

so that the photon becomes massive:

$$\mathcal{L}_\mu=-\tfrac{1}{4}F_{\nu\lambda}F^{\nu\lambda}+\frac{\mu^2}{2}A^\nu A_\nu\ . \quad (2)$$

Here $F_{\nu\lambda}$ is the electromagnetic tensor $F_{\nu\lambda}=\partial_\nu A_\lambda-\partial_\lambda A_\nu$, and the field equations in the presence of a conserved current J_ν read

$$\Box A_\nu+\mu^2A_\nu=4\pi J_\nu,\quad \partial_\nu A^\nu=0\ , \quad (3)$$

where $\Box$ is the d'Alembertian $\Box=\partial_t^2-\nabla^2$. (We set c equal to unity throughout.) Gauge invariance

$$A_\nu\rightarrow A_\nu+\partial_\nu\chi \quad (4)$$

is clearly lost. Geomagnetic data then set the limit[1] $\mu\leq 3\times10^{-24}$ GeV; observations of the galactic magnetic field set the more stringent bound[2] of $\mu\leq 3\times10^{-36}$ GeV; see below.

In this paper we explore the experimental limits on another modification of Maxwell theory, which also involves a mass parameter p_α, but respects gauge invariance—rather, it is Lorentz invariance that is violated.

The modification we consider involves adding to the Maxwell Lagrange density a Chern-Simons term:

$$\mathcal{L}_p=\mathcal{L}_{\rm EM}+\mathcal{L}_{\rm CS}\ . \quad (5)$$

The Chern-Simons term is given by

$$\mathcal{L}_{\rm CS}=-\tfrac{1}{2}p_\alpha A_\beta\tilde{F}^{\alpha\beta}\ , \quad (6)$$

where $\tilde{F}^{\alpha\beta}$ is the dual electromagnetic tensor, $\tilde{F}^{\alpha\beta}=\frac{1}{2}\epsilon^{\alpha\beta\mu\nu}F_{\mu\nu}$. This modification couples the electromagnetic field to an (as yet unspecified) four-vector p_α.

When electromagnetic phenomena are confined to a plane, as in the quantum Hall effect and high-T_c superconductivity, the approximation can be made that no interesting dynamical motion takes place in the direction perpendicular to the plane. Then the external vector p_α may be chosen to lie in that direction as well, and (6) reduces to an unconventional electrodynamic action that is Lorentz and gauge invariant in a three-dimensional spacetime, i.e., boosts in the plane leave dynamics unchanged. It was in this context that the Chern-Simons term was initially investigated as a "topological mass" term for gauge fields in (2+1)-dimensional spacetime.[3] Models in which $\mathcal{L}_{\rm CS}$ is taken to be the entire gauge field action have found application in examinations of the quantum Hall effect[4] and high-T_c superconductivity.[5] Moreover, several purely mathematical applications for $\mathcal{L}_{\rm CS}$ have also been found.[6]

In this paper we shall consider the (3+1)-dimensional case, where considerations of both Lorentz and gauge invariance play a crucial role.

The action S of Chern–Simons theory is proportional to the integral of the Chern–Simons 3-form

$$S = \frac{k}{4\pi}\int_M \mathrm{tr}\,(A \wedge dA + \tfrac{2}{3} A \wedge A \wedge A).$$

The constant k is called the *level* of the theory. The classical physics of Chern–Simons theory is independent of the choice of level k.

Classically the system is characterized by its equations of motion which are the extrema of the action with respect to variations of the field A. In terms of the field curvature

$$F = dA + A \wedge A$$

the field equation is explicitly

$$0 = \frac{\delta S}{\delta A} = \frac{k}{2\pi} F.$$

CS Action

$$S_{CS} = p \times F \wedge F$$

$$\vec{p} = p_\mu = (p_0, \vec{p})$$

$$F \wedge F = dK$$

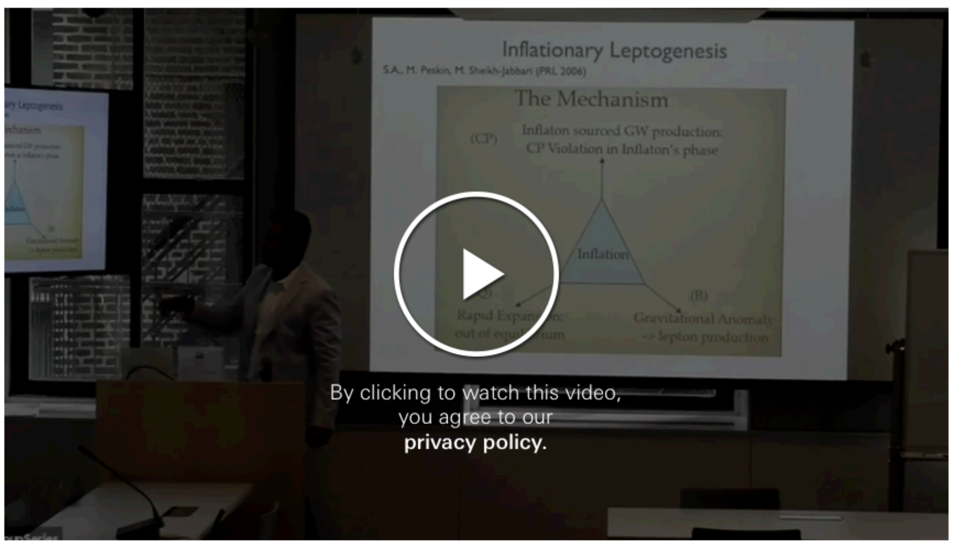
where K is the Chern-Simons three-form:

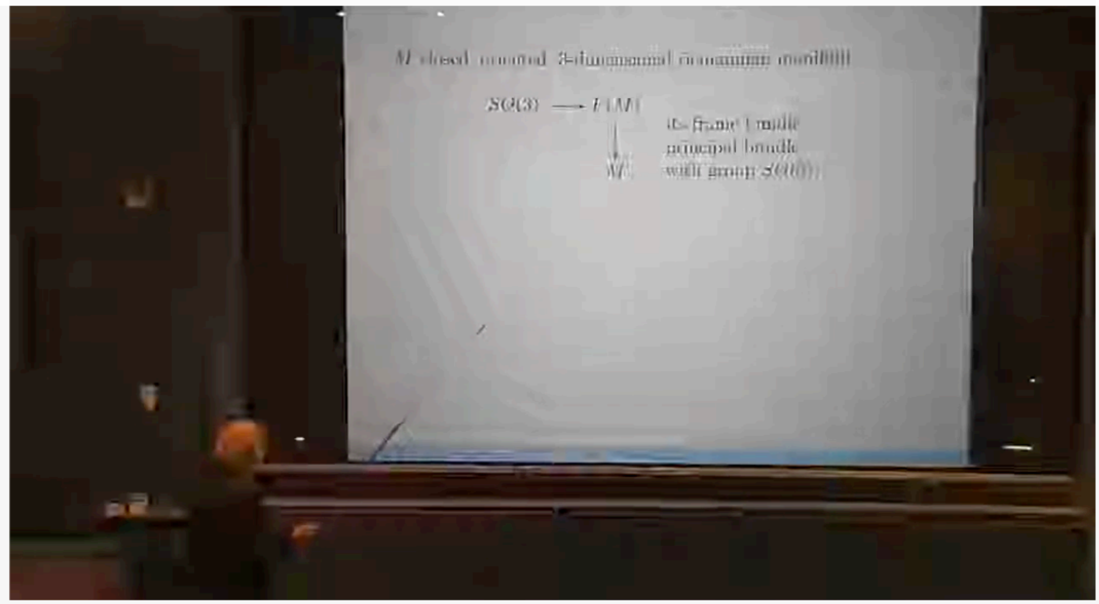
$$K = A \wedge F$$

Can break both parity and Lorentz Invariance symmetry

CCA Groups Projects News Events J

Stephon Alexander: The Theory of a Halo: Chern Simons Theory – Dark Genesis and Inflation





C. Vafa, M. Freedman, C. Kane, Jim Simons - Applications of Chern-Simons Theory (April 25, 2018)

906 views • Feb 6, 2019 20 0 SHARE SAVE

Simons Foundation 7.13K subscribers SUBSCRIBED

1. Introduction and Preliminaries

Electromagnetic Field Tensor and Forms

- Electromagnetic 2-form: $F = \frac{1}{2} F_{\mu\nu}\, dx^\mu \wedge dx^\nu$, with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
- Hodge dual: $\tilde{F} = \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}\, dx_\mu \wedge dx_\nu$
- 4D Action Term:

$$S = \int d^4x\, P(x) F \wedge F \tag{1}$$

- $P(x)$ is a pseudoscalar field, $F = dA$

2. Chern-Simons Current and 3D Reduction

Rewriting the Action

- $F \wedge F = dK$, where $K = A \wedge F$
- $S = \int d^4x \, dP \wedge K$
- For $P(t)$ (time-dependent):

$$S = \int d^4x \, (\partial_0 P(t)) \epsilon^{ijk} A_i F_{jk}$$

Physical Implication

- Modification to photon propagation in 4D space-time
- Not symmetric under spatial parity, leading to polarization asymmetry

3. Physical Interpretation and Final Form

Electromagnetic Interpretation

- $K^0 = \epsilon^{ijk} A_i F_{jk}$ as magnetic helicity density
- Topological measure of magnetic field linkage and twist

Axion-Coupled Action

- $S = -\int d^4x \, (\partial_0 a(t)) K^0$
- Observable effect: cosmic birefringence (rotation of CMB polarization)

Birefringence Generating Mechanisms

New fields (such as axions) with Chern-Simons couplings

Polarization rotation for a single photon:

- $\Delta\theta \propto g_{\gamma\phi}(\phi_{absorbed} - \phi_{emitted})$

Some axion masses cause polarization oscillation on the timescale of hours - months

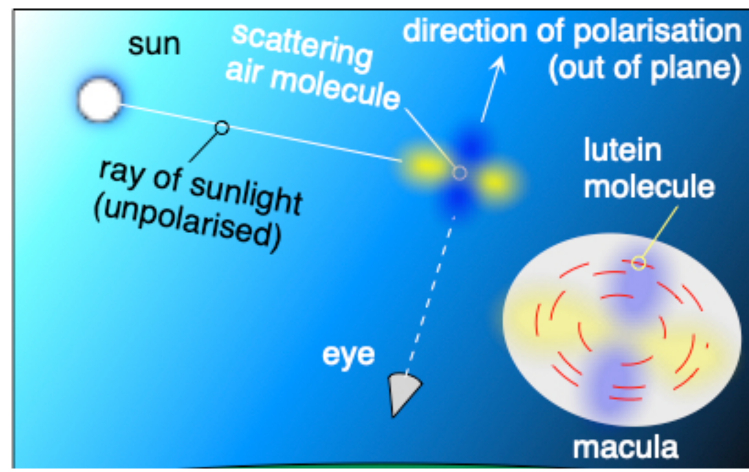
particle (e.g. axion) field

EM field

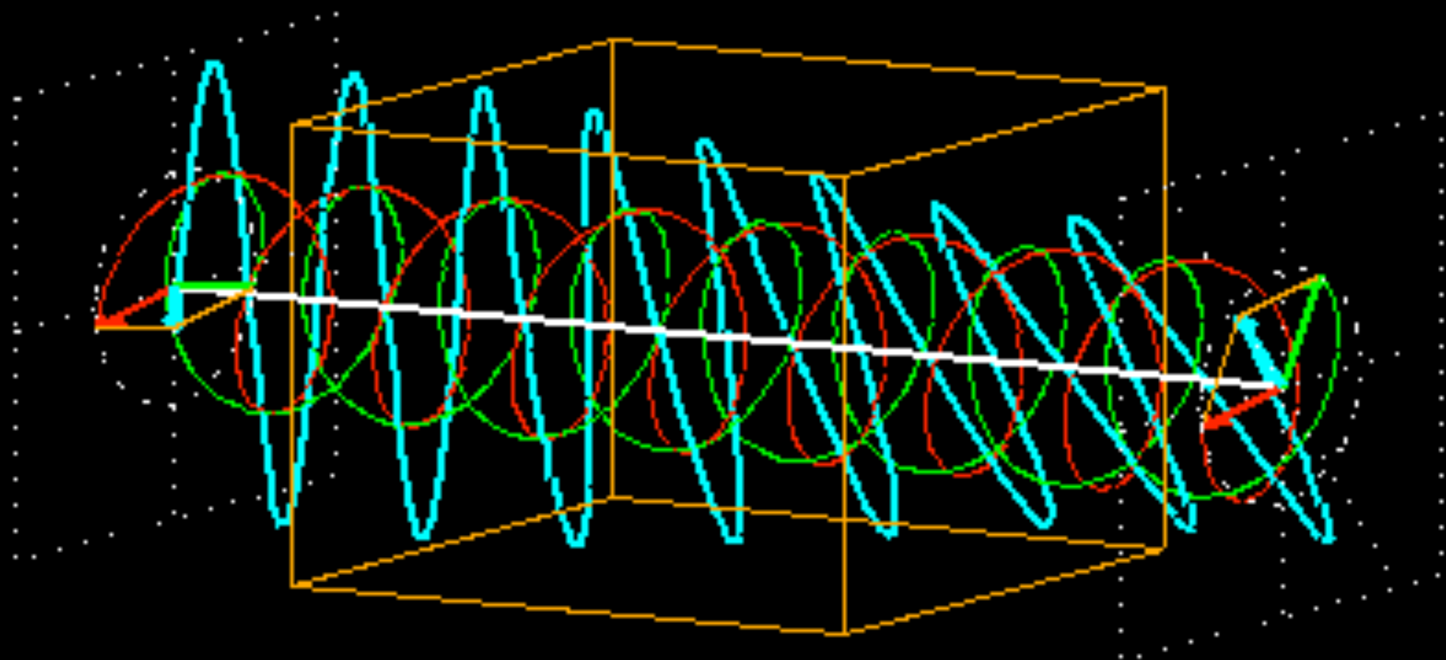
coupling

$$-\frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

Chern-Simons term in the action coupling EM field and axion field



Can we test Lorentz Invariance with the CMB?



Look for a preferred direction in spacetime!

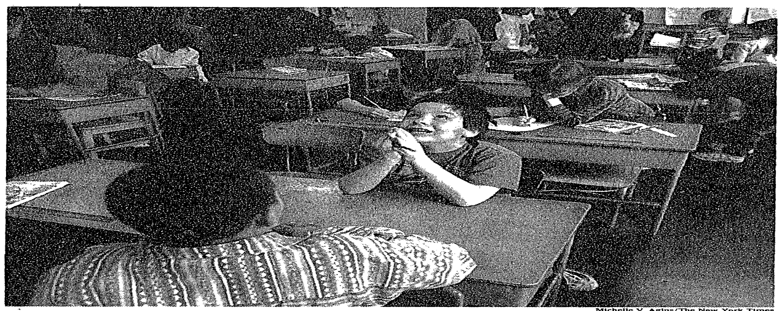
(Discovered already???)

"All the News That's Fit to Print"

The New York Times

Late Edition
New York: **Today**, windy, showers, thunder. High 50. **Tonight**, windy, rain, possible wet snow. Low 41. **Tomorrow**, cloudy, breezy. High 54. **Yesterday**, high 57, low 47. Details, page A27.

VOL. CXLVI . . . No. 50,766 | NEW YORK, FRIDAY, APRIL 18, 1997 | $1 beyond the greater New York metropolitan area. | 60 CENTS



Michelle V. Agins/The New York Times

'Oh, If You Will Just Let Me Pass'

A citywide reading test meant anxiety yesterday for students in grades three through eight. Schools Chancellor Rudy Crew will measure the results against new goals he has set for literacy. Daniel Hessel, a third grader at Public School 75 in Manhattan, sought help from a higher power. Page B1.

PATAKI REMOVING MCCAUGHEY ROSS FROM 1998 TICKET

WIDE G.O.P. SPLIT IS SEEN

Governor Suggests 2 Women as Possible Replacements for Re-election Effort

By RICHARD PÉREZ-PEÑA

ALBANY, April 17 — Three years after choosing a running mate who confounded even her allies with unpredictable actions and who refused to play the quiet, pliant second, Gov. George E. Pataki said today that Lieut. Gov. Betsy McCaughey Ross would be dropped from the Republican ticket when he runs for re-election next year.

In a letter to Ms. McCaughey Ross, Mr. Pataki said he could no longer work with a Lieutenant Governor who did not share his philosophy, and he made it clear that he considered her a disruptive force in his administration.

"Unfortunately, you have demonstrated through your decisions that you do not share my vision for the state," he wrote. Recounting his record on taxes, government spending and crime, he added, "Your unwillingness and, in fact, outright refusal to work as part of our united team to build on these historic achievements has been disappointing."

In an interview this evening, Ms. McCaughey Ross said the Governor's announcement had caught her off guard. "I have always wanted to work more closely with the Governor, and I was surprised that he did not want to."

The Lieutenant Governor said Mr. Pataki, who has routinely gone weeks, even months, without speaking to her, informed her of his decision only this afternoon. "The Governor called me this afternoon with a short statement that he would be choosing someone else as his running mate in 1998," she said. "It was the first time he had talked to me in months. I actually thought he was

Continued on Page B2, Column 1

Schumer Sets Sights On a D'Amato Race

Representative Charles E. Schumer, the Brooklyn Democrat, has dropped plans to run for governor and will challenge Senator Alfonse M. D'Amato. The decision suggests he views Mr. D'Amato as more vulnerable than Gov. George E. Pataki.

Article, page B2.

C-Span via Associated Press

House Speaker Newt Gingrich speaking in the House yesterday.

State Dept. Set For Reshaping, Pleasing Helms

By STEVEN LEE MYERS

WASHINGTON, April 17 — President Clinton today approved a plan to reorganize the State Department, senior Administration officials said, a decision that responds to a long-standing demand by Senator Jesse Helms that has snarled foreign policy decisions.

The plan, which was disclosed only hours after Mr. Helms finally agreed to allow a Senate vote on a long-delayed chemical weapons ban, would consolidate the Arms Control and Disarmament Agency and the United States Information Agency into the State Department over the next two years, the officials said.

The United States Agency for International Development, which distributes foreign aid, would remain a distinct agency, but its director would come under the direct authority of the Secretary of State and some functions would be consolidated.

Senator Helms and other conservatives have long demanded that these agencies be brought under the direct control of the State Department, complaining that they are bloated and unaccountable and that their roles sometimes overlap with State Department functions.

Vice President Al Gore, who has overseen the Administration's efforts to reorganize the Government but who opposed a similar proposal two years ago, presented the plan to Mr. Clinton today and the President approved it, the officials said. The White House did not announce it publicly.

The President's approval of the plan, which officials discussed on condition of anonymity, came on the day the Senate agreed to schedule a vote next Thursday on a treaty to ban the manufacture, stockpiling

GINGRICH WILL GET A LOAN FROM DOLE TO PAY HOUSE FINE

1ST PAYMENT DUE IN 2005

Former Senate Leader Says the $300,000 Is an Investment in 'Future of Our Party'

By ADAM CLYMER

WASHINGTON, April 17 — Speaker Newt Gingrich announced today that he would pay his $300,000 fine to the House by borrowing the money from Bob Dole, who called his action "not only an opportunity to support a friend, but a long-term investment in the future of our party."

The terms of the loan must still be approved by the ethics committee, which levied the fine. But under the plan announced today, Mr. Gingrich would not have to pay a penny before 2005, two years after he plans to leave Congress. But he could pay the 10 percent annual interest or part of the principal earlier if he wished.

Mr. Gingrich's lawyer, J. Randolph Evans, told reporters the Speaker intended to repay the loan from increased earnings he anticipates after leaving Congress, not from money people might give him. Mr. Evans said collateral would be provided, but he would not say what it would be or whether it would include the Speaker's house in Georgia.

"All the parameters that would apply to a private personal loan from the bank down the street are going to be applied," Mr. Evans said.

The intervention of Mr. Dole, the former Senate leader whom the Speaker called "a close personal friend of impeccable integrity," was the day's most stunning development. Mr. Dole, the Republican Presidential candidate last year, told reporters this afternoon that he did it to "help the party and help Newt."

Although Republicans grumbled that Mr. Dole's campaign hurt them last fall and House Republicans publicly conceded he would lose, Mr. Dole's loyalty to his party has always been deep, and this move only renews it.

But Mr. Dole's views of the Speaker, who once called him the "tax collector for the welfare state," have gone down and up, and he was plainly impatient at Mr. Gingrich's strategy of shutting down the Government to force President Clinton to make a budget deal in 1994 and 1995.

Mr. Dole conceded today that the Speaker's troubles were affecting the party's agenda. Indeed, there has been no sign of any legislative agenda in the House. Ever since Mr. Gingrich barely won re-election as Speaker in January, his leadership has been hobbled by the question of how he would pay the fine. It was imposed when he admitted bringing discredit on the House through use of tax-exempt money for political purposes and by providing untrue information about the case.

Democrats and many Republicans, including Mr. Dole, said Mr. Gingrich should set an example and pay from his own money. He could use campaign money or a legal de-

NETANYAHU FIGHTS REPORT BY POLICE

Israeli Premier Accuses Labor of Trying to Foment Crisis

By SERGE SCHMEMANN

JERUSALEM, April 17 — Prime Minister Benjamin Netanyahu went on the counteroffensive today against police recommendations that he be indicted for breach of the public trust, defiantly vowing to a gathering of political allies that "this Government is not going anywhere."

At the same time, the initial shock of the disclosure that Mr. Netanyahu had been implicated by the police in what has come to be called the "Bar-On Affair" was followed by widespread questioning of the gravity of the charges, especially after senior police officers confirmed that their recommendation was based largely on the testimony of one witness.

The affair was centered on allegations that Mr. Netanyahu appointed a lawyer named Roni Bar-On as Attorney General last January under pressure from an influential member of his coalition, Aryeh Deri, who evidently expected the appointment to help him in his corruption trial. After complaints from lawyers that Mr. Bar-On was unqualified, he resigned after one day.

But the exact nature of the accusations against Mr. Netanyahu were still unknown today because the police report was not made public. Without further details some Israelis wondered how the affair crossed from political haggling to illegality.

That decision whether to bring charges was left to the current Attorney General, Elyakim Rubinstein, a former judge and Government official, and the State Attorney, Edna

Continued on Page A9, Column 1

More Money, Less Tax

The number of Americans who make more than $200,000 but pay no Federal income tax has grown twice as fast as the number who earn more than $200,000.

The information casts doubt on the effectiveness of the alternative minimum tax, a system intended to insure that the wealthy pay at least some income taxes.

Article, page A21.

On the Internet: www.nytimes.com

Tory Leader, in Election Gamble, Embraces an Anti-Europe Stance

By WARREN HOGE

LONDON, April 17 — In a high-risk maneuver to invigorate his flagging re-election campaign, Prime Minister John Major yielded today to the increasingly vocal anti-European wing of his party and declared his opposition to current proposals for Britain's integration into Europe.

With only two weeks to go before the May 1 vote and various polls showing the Conservatives 17 to 25 points behind Labor, Mr. Major suggested that his rival, Tony Blair, would sell out British interests to the French and the Germans if he became Prime Minister.

Mr. Blair responded that the action by Mr. Major proved he was unable to control his party and reflected poorly on his ability to continue running the country. "If you are engaged in fighting with your own party 14 days before an election, something is wrong," he said.

Standing at a news conference before the illuminated legend "You Can't Trust Labor on Europe," Mr. Major held aloft a draft review of European Union treaties to be discussed at a summit meeting in the Netherlands in June and said most of them were "quite literally unthinkable" for Britain.

Mr. Major stood by his position that it was best for Britain to take part in talks about the proposed monetary union, even if the ultimate decision was against joining.

But he dropped his objections to Tory candidates campaigning against his approach and aligned himself with their attitudes. "Centralism, federalism, more decisions taken by bureaucrats and politicians in Brussels and the European Parliament rather than here in the British Parliament is frankly a route that is not acceptable to us," he said.

Listing his own achievements as a shrewd negotiator, he said that the Labor Party may "claim these days not to wave the red flag, but they'd certainly go to Amsterdam and wave the white flag."

He told the news conference at Conservative Party headquarters that Labor would "play the game of 'follow my European leader,'" and Malcolm Rifkind, his Foreign Minister, supplied the names. "Chancellor

Continued on Page A12, Column 1

Serbian Leader Bounces Back, to Foes' Dismay

By CHRIS HEDGES

BELGRADE, Serbia, April 16 — President Slobodan Milosevic of Serbia, the Balkans' wiliest political escape artist, appears once again to have defied the expectations of his opponents and reasserted his grip on power.

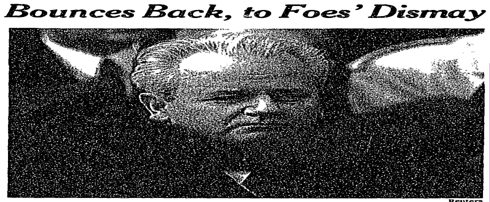
Mr. Milosevic, who was knocked off stride by months of protests by the political opposition, is now moving to limit criticism of him by the independent news media. He has sidelined those who were disloyal to him in his moment of weakness and appointed a long-time loyalist as chairman of the electoral commission.

He has capitalized on disarray in the ranks of the opposition, which began squabbling almost immediately after they took power in many of Serbia's largest cities.

And, to the consternation of his critics, he is preparing to run for the Yugoslav Presidency. The post is now largely ceremonial. But many in Serbia believe that Mr. Milosevic will maintain his sweeping powers if he is elected by the Federal Parliament, which is dominated by members of his Socialist Party.

Yugoslavia is made up of Montenegro and Serbia, and Serbia's Constitution bars Mr. Milosevic from serving a third term in Serbia.

The heady excitement of the daily street marches, called after Mr.



Reuters

Slobodan Milosevic has capitalized on the opposition's disarray.

Milosevic nullified opposition victories in November in several large cities, including Belgrade, has dissipated in the smoggy, slate-colored skies that hover over the capital.

"We failed as a people, as a country," said Miomir Brkic, the editor-in-chief of the independent daily Nasa Borba. "We should have formed a movement during the street protests to build a united, nonpartisan front to fight for a democratic, parliamentary system. Instead we followed politicians who lacked vision, who cared only for power and who now spend their time bickering among themselves like street vendors. We have a terrible deficit of leaders."

To be sure, Mr. Milosevic is weaker than he was a year ago. He lost his top security chief, Radovan Stojicic, who was assassinated last

Continued on Page A12, Column 1

'This Side Up' May Apply To the Universe, After All

By JOHN NOBLE WILFORD

Measurements by scientists have suggested for the first time that the universe has an "up" and a "down."

The observation, if correct, would be one of the most surprising and fundamental new insights about the universe to emerge in recent years. The notion that space is uniform, that it is the same in all directions, with no north and south or up and down, is a major tenet of modern cosmology, backed by Einstein's theory of relativity.

The findings could force scientists to reconsider aspects of Einstein's theory, rethink some ideas about the birth of the universe and the possible existence of other universes. They also raise questions about the speed of light, especially whether it may not be always precisely the same.

In an analysis of radio waves from 160 distant galaxies, physicists at the University of Rochester and the University of Kansas made the startling discovery that the radiations rotate as they move through space, in a subtle corkscrew pattern unlike anything observed before.

A complete turn of the corkscrew appeared to occur every one billion miles the radio waves travel. These effects are in addition to what is known as the Faraday effect, a polarization of light caused by intergalactic magnetic fields.

Even more surprisingly, the magnitude of these newly observed rotations appear to depend on the angle at which the radio waves move in relation to a kind of axis of orientation running through space. The more parallel the direction of travel of the wave is with the axis, the greater the rotation. The reason for this remains unknown.

This axis of orientation is not a physical entity, but rather defines a direction of space that somehow determines how light travels through the universe. As observed from Earth, the discoverers said, the axis runs one way toward the constellation Sextans and the other toward the constellation Aquila. Which way is up and which way down, whether to-

Continued on Page A22, Column 3

INSIDE

F.B.I. Spy Chase Criticized
The Justice Department says the Federal Bureau of Investigation was derelict in pursuing leads in the Aldrich H. Ames spying case. Page A16.

Chaim Herzog Dies
Chaim Herzog, who as President of Israel from 1983 to 1993 strove to expand the largely ceremonial office, is dead at 78. Page A26.

Jets Make a Deal
The Jets traded the No. 1 choice the National Football League draft the Rams for the No. 6 choice over and three other picks. Page B7.

'This Side Up' May Apply To the Universe, After All

Continued From Page A1

ward Sextans or Aquila, would be a matter of arbitrary choice.

The discovery was made by Dr. Borge Nodland of Rochester and Dr. John Ralston of Kansas, using radio-wave observations made by different astronomers around the world. In a report to be published on Monday in Physical Review Letters, the two physicists concluded on a note of excitement tempered with caution.

"Barring hidden systematic bias in the data," they wrote, the behavior of electromagnetic radiation propagating over vast distances "indicates a new cosmological effect."

In an announcement by the University of Rochester yesterday, Dr. Nodland said: "The big news is that perhaps not all space is equal, for as far back as we can peer in time. This work defies the notion that there is no 'up' or 'down' in space."

Dr. Ralston said, "Our observational data suggest that there is a mysterious axis, a kind of cosmological north star that orients the universe."

Few other physicists and cosmologists have had a chance to read the journal report, but they agreed that the research must be tested thoroughly before the conclusions can be accepted.

"It would be a really profound change in physics, if it is true," said Dr. P. James E. Peebles, a Princeton University astrophysicist.

Dr. Stephen P. Maran, an astronomer at the Goddard Space Flight Center in Greenbelt, Md., said: "Anytime you find a new effect globally in the sky, the crucial issue is always whether you have correctly taken account of systematic errors in the observations. And any result of this potential magnitude is going to be viewed with considerable skepticism until new experiments can be done to verify it."

In their report, Dr. Nodland and Dr. Ralston constructed a mathematical theory that could explain the observations. The data indicate that light actually travels through space at two slightly different speeds. Such a mismatch in speeds would cause the polarization plane to rotate in a certain familiar manner. It is the way physics students see when they pass light through corn syrup and look at the light with polarizing filters.

The physicists say the axis of orientation they have inferred would appear to be along different lines in different parts of the universe, but they would be parallel to the one observed from Earth.

Because the findings run counter to the idea that all space is uniform and that the speed of light in a vacuum is always the same, the implications of the research could be enormous. For example, scientists might have to reconsider the concept that the Big Bang, the theorized moment of cosmic origin, was completely symmetric.

"Perhaps it was not a perfect Big Bang, but a Big Bang with a twist to space and time," Dr. Ralston said. "Such a twist would be seen today as a ripple of nonuniformity, perhaps as the axis represents."

Dr. Nodland also speculated that the observed rotations could be the first evidence for physicists who have theorized the existence of other universes. If the universe in which people live was asymmetric at creation, he said, it raises the possibility of the simultaneous creation of another universe with an opposite twist.

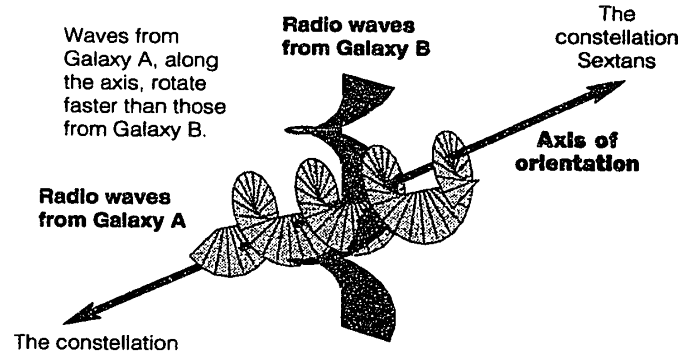
Concluding a summary of the findings for the Internet, Dr. Nodland said, "At this point, the question of what is truly underlying the effect we see is as wide open as space itself."

A CLOSER LOOK

A Universe With Ups and Downs?

Scientists have discovered that radio waves traveling in one direction across the universe behave differently from radio waves traveling at right angles to that direction. This implies that the universe is not uniform in all directions. Astrophysicists have generally assumed it is uniform.

Surprisingly, the radio waves corkscrew faster when they travel along an apparent axis of orientation, running in a direction roughly between the constellation Sextans and the constellation Aquila, with Earth in the middle. This could mean that there is an "up" and a "down" in the universe, but which is which remains purely arbitrary.



Source: Dr. Borge Nodland, University of Rochester

The New York Times

Master Equation: cosmic birefringence x 4

$\gamma(\omega, t, \hat{n})$: Coupling terms

- Cross-terms between different effects
- Example: $\gamma \propto \boldsymbol{\alpha}(\hat{n}) \cdot \hat{n} \times \omega^n$
- Higher-order corrections

The total rotation angle including all possible birefringence effects can be expressed as:

$$\Delta\phi(\vec{r}, \hat{n}, \omega, t) = \int_0^r \Big[\underbrace{\alpha_0}_{\text{constant isotropic}} + \underbrace{\boldsymbol{\alpha}(\hat{n})}_{\text{direction-dependent}} \cdot \hat{n} + \underbrace{\beta(\omega)}_{\text{frequency-dependent}} + \underbrace{\alpha(t)}_{\text{time-varying}} + \underbrace{\gamma(\omega, t, \hat{n})}_{\text{coupling terms}} \Big] dr'$$

α_0: Constant isotropic birefringence

- Uniform rotation independent of direction and frequency
- Simplest case of cosmic birefringence
- Units: [rad/Mpc]

$\boldsymbol{\alpha}(\hat{n})$: Anisotropic birefringence tensor

- Direction-dependent rotation
- Can be decomposed into spherical h
- $\boldsymbol{\alpha}(\hat{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{n})$

$\alpha(t)$: Time-varying component

- Can be periodic: $\alpha(t) = \alpha_1 \cos(\Omega t)$
- Or monotonic: $\alpha(t) = \alpha_1 t$

$\beta(\omega)$: Frequency-dependent term

- Accounts for dispersive effects
- Generally modeled as power law: $\beta(\omega) \propto \omega^n$
- Important for multi-frequency observations

Notes

- Integration is along the photon path from emission to observation
- $\hat{n}$ represents the direction of observation
- ω is the photon frequency
- Effects can be constrained through CMB observations

Example 1: Constant Isotropic cosmic birefringence

$\gamma(\omega, t, \hat{n})$: Coupling terms

- Cross-terms between different effects
- Example: $\gamma \propto \boldsymbol{\alpha}(\hat{n}) \cdot \hat{n} \times \omega^n$
- Higher-order corrections

The total rotation angle including all possible birefringence effects can be expressed as:

$$\Delta\phi(\vec{r}, \hat{n}, \omega, t) = \int_0^r \Big[\underbrace{\alpha_0}_{\text{constant isotropic}} + \underbrace{\boldsymbol{\alpha}(\hat{n})}_{\text{direction-dependent}} \cdot \hat{n} + \underbrace{\beta(\omega)}_{\text{frequency-dependent}} + \underbrace{\alpha(t)}_{\text{time-varying}} + \underbrace{\gamma(\omega, t, \hat{n})}_{\text{coupling terms}} \Big] dr'$$

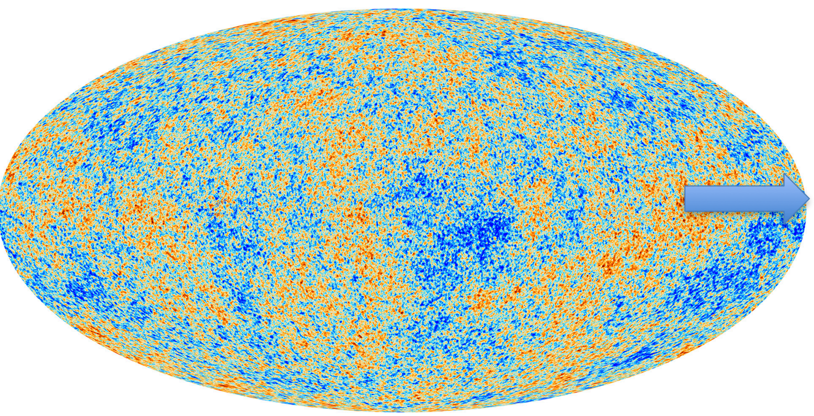
α_0: Constant isotropic birefringence

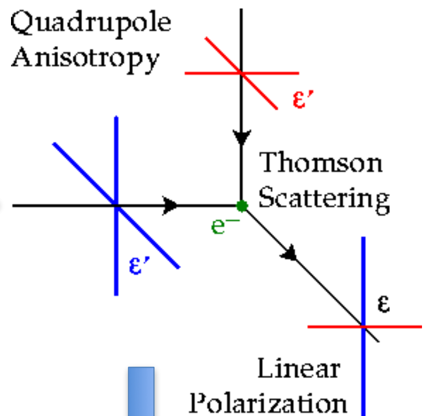
- Uniform rotation independent of direction and frequency
- Simplest case of cosmic birefringence
- Units: [rad/Mpc]

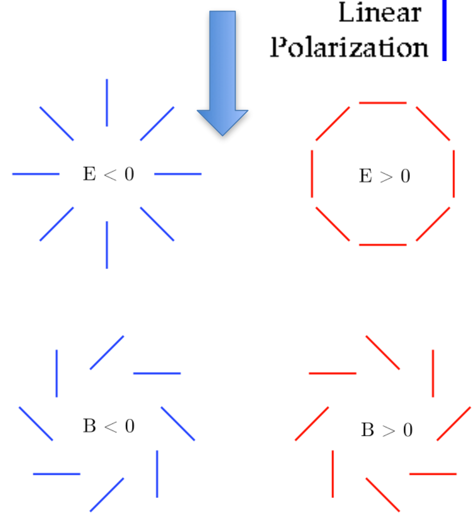
Notes

- Integration is along the photon path from emission to observation
- $\hat{n}$ represents the direction of observation
- ω is the photon frequency
- Effects can be constrained through CMB observations

Cosmic Microwave Background polarization



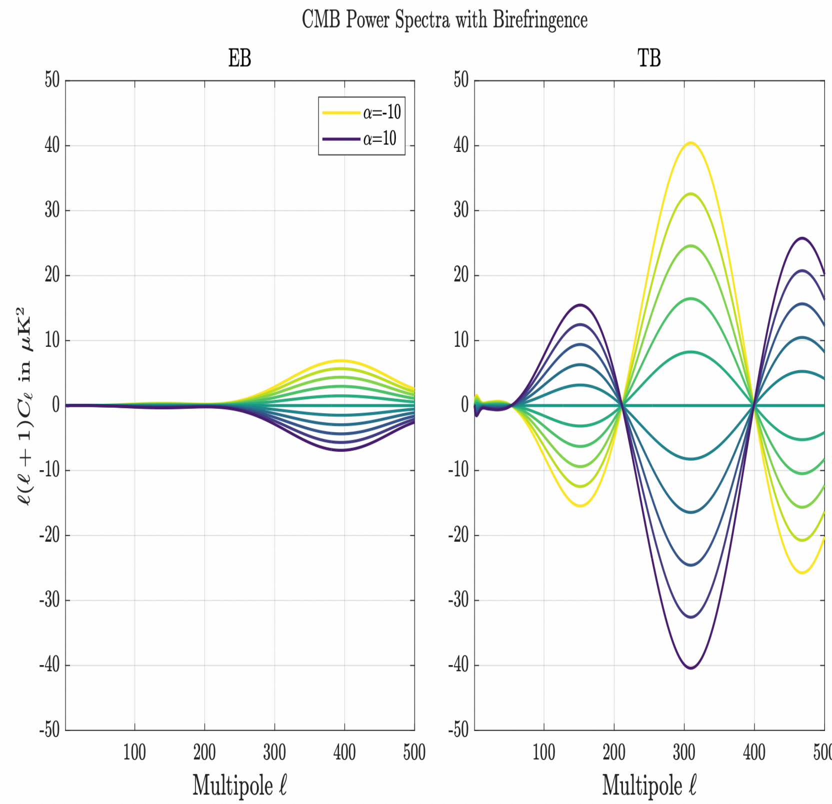




No TB or EB correlations in the standard model

$$C_\ell^{\prime TB} = C_\ell^{TE} \sin(2\alpha)$$

$$C_\ell^{\prime EB} = \frac{1}{2}\left(C_\ell^{EE} - C_\ell^{BB}\right)\sin(4\alpha)$$



BICEP/Keck XVIII: Measurement of BICEP3 polarization angles and consequences for constraining cosmic birefringence and inflation
https://arxiv.org/pdf/2410.12089

August 2009

Xia et al. claim a *first* detection of CPT violation!
Parameterized by Chern-Simons rotation angle α

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Probing CPT violation with CMB polarization measurements

Jun-Qing Xia[a,*], Hong Li[b,c], Xinmin Zhang[b,c]

[a] Scuola Internazionale Superiore di Studi Avanzati, Via Beirut 2-4, I-34014 Trieste, Italy
[b] Institute of High Energy Physics, Chinese Academy of Science, P.O. Box 918-4, Beijing 100049, PR China
[c] Theoretical Physics Center for Science Facilities (TPCSF), Chinese Academy of Science, PR China

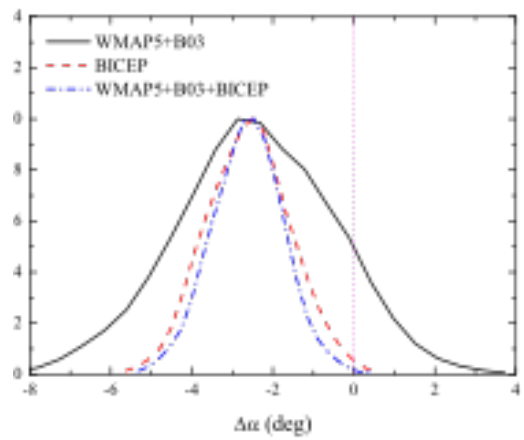
ARTICLE INFO

Article history:
Received 12 October 2009
Received in revised form 9 March 2010
Accepted 10 March 2010
Available online 16 March 2010
Editor: M. Trodden

Keywords:
Observational cosmology
Lorentz and Poincaré invariance
Charge conjugation, parity, time reversal, and other discrete symmetries

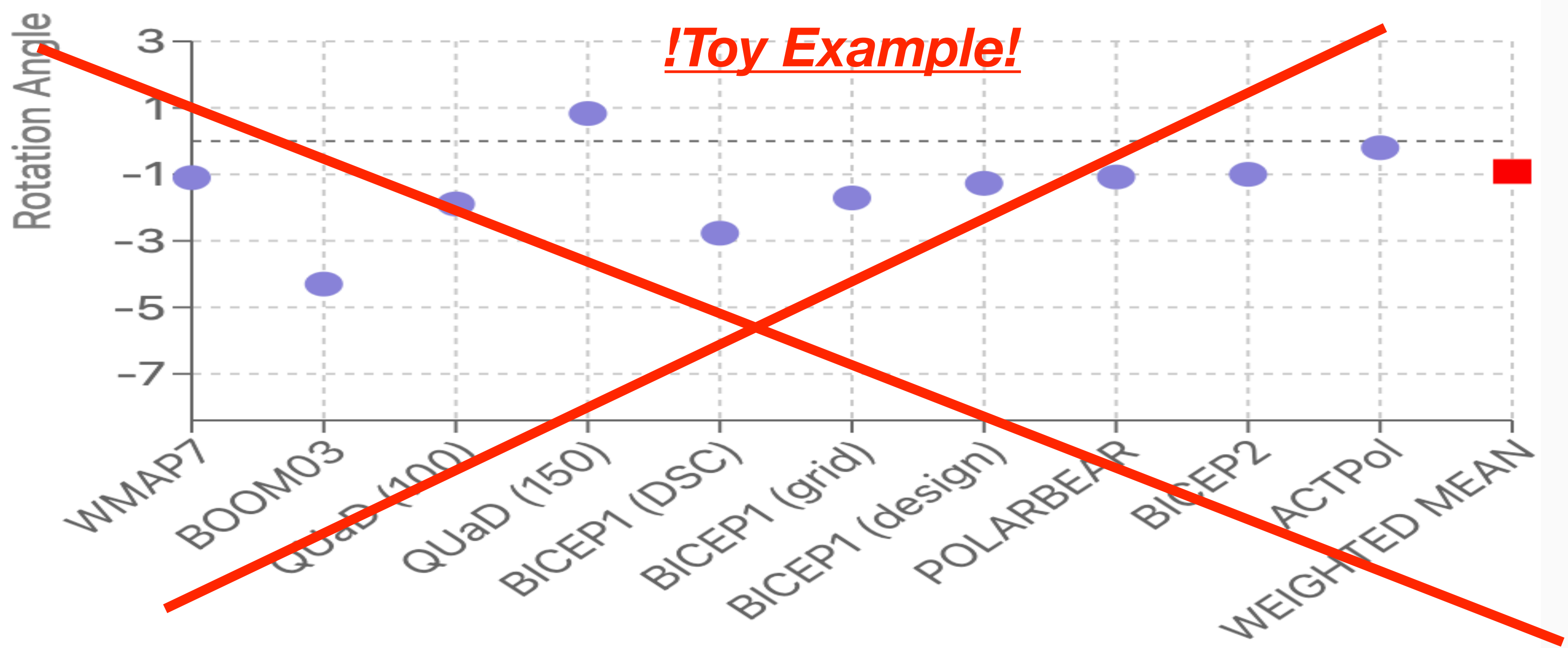
ABSTRACT

The electrodynamics modified by the Chern–Simons term $\mathcal{L}_{cs} \sim p_\mu A_\nu \tilde{F}^{\mu\nu}$ with a non-vanishing p_μ violates the *Charge-Parity-Time Reversal* symmetry (CPT) and rotates the linear polarizations of the propagating *Cosmic Microwave Background* (CMB) photons. In this Letter we measure the rotation angle $\Delta\alpha$ by performing a global analysis on the current CMB polarization measurements from the *five-year Wilkinson Microwave Anisotropy Probe* (WMAP5), *BOOMERanG 2003* (B03), BICEP and QUaD using a Markov Chain Monte Carlo method. Neglecting the systematic errors of these experiments, we find that the results from WMAP5, B03 and BICEP all are consistent and their combination gives $\Delta\alpha = -2.62 \pm 0.87$ deg (68% C.L.), indicating a 3σ detection of the CPT violation. The QUaD data alone give $\Delta\alpha = 0.59 \pm 0.42$ deg (68% C.L.) which has an opposite sign for the central value and smaller error bar compared to that obtained from WMAP5, B03 and BICEP. When combining all the polarization data together, we find $\Delta\alpha = 0.09 \pm 0.36$ deg (68% C.L.) which significantly improves the previous constraint on $\Delta\alpha$ and test the validity of the fundamental CPT symmetry at a higher level.



ne-dimensional posterior distributions of the rota-
derived from various data combinations. The dot-
al line illustrates the unrotated case (Δα = 0) to
.

CMB Rotation Angle Measurements from Different Experiments



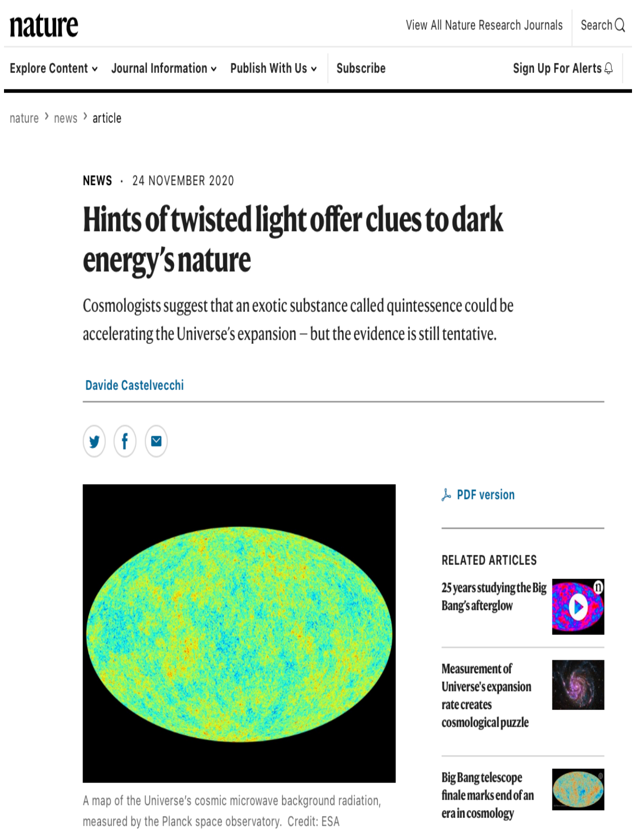
Assumes all are independent, ignores systematics etc…
5.4 sigma (BEFORE Minami and Komatsu 2020)

Error bars show total uncertainty (statistical and systematic combined in quadrature where both are available)

Weighted mean: −0.914° ± 0.169° (χ^2/dof = 7.6/9)

Parity Violation in E&M: Minami & Komatsu PRL 2020:
New extraction of the cosmic birefringence from the Planck 2018 polarization data

β=+0.35±0.14 deg (68%CL)….excludes β=0 @ 99.2%~CL.


nature | View All Nature Research Journals | Search
Explore Content | Journal Information | Publish With Us | Subscribe | Sign Up For Alerts
nature › news › article

NEWS · 24 NOVEMBER 2020

Hints of twisted light offer clues to dark energy's nature

Cosmologists suggest that an exotic substance called quintessence could be accelerating the Universe's expansion – but the evidence is still tentative.

Davide Castelvecchi

A map of the Universe's cosmic microwave background radiation, measured by the Planck space observatory. Credit: ESA

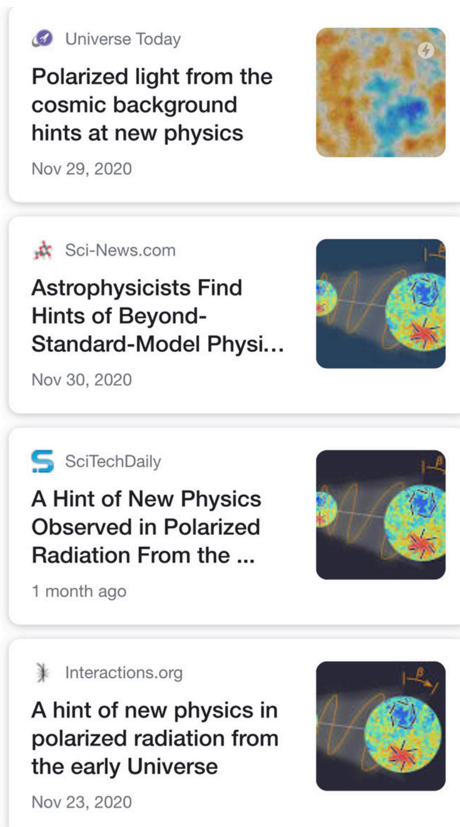
PDF version

RELATED ARTICLES

25 years studying the Big Bang's afterglow

Measurement of Universe's expansion rate creates cosmological puzzle

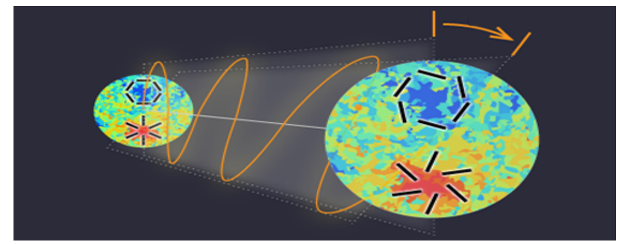
Big Bang telescope finale marks end of an era in cosmology

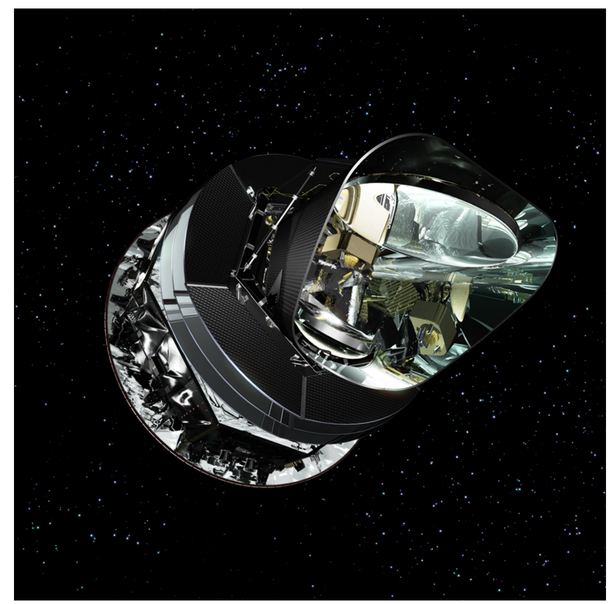

Universe Today
Polarized light from the cosmic background hints at new physics
Nov 29, 2020

Sci-News.com
Astrophysicists Find Hints of Beyond-Standard-Model Physi...
Nov 30, 2020

SciTechDaily
A Hint of New Physics Observed in Polarized Radiation From the ...
1 month ago

Interactions.org
A hint of new physics in polarized radiation from the early Universe
Nov 23, 2020

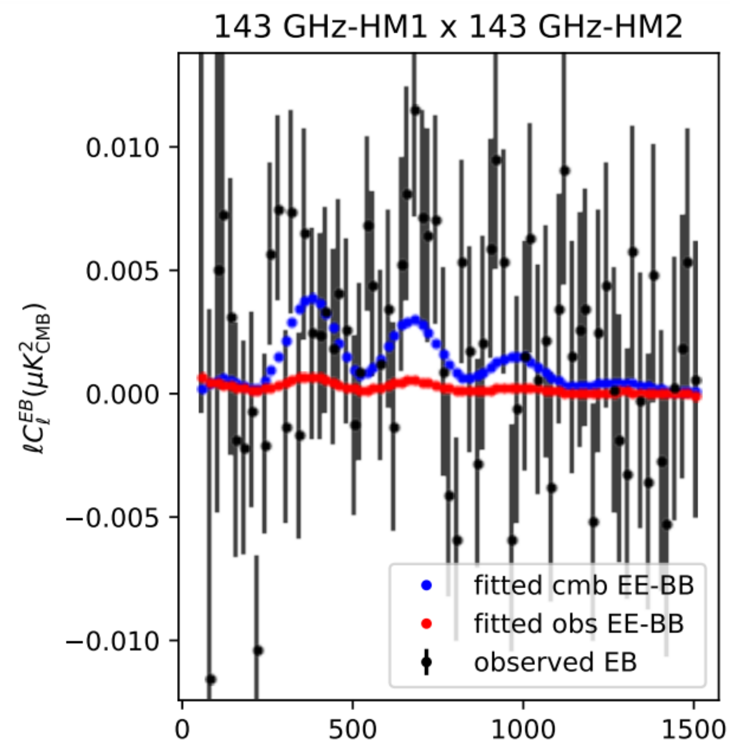




Planck (ESA)

Minami & Komatsu (2020) using Planck 2018 data

- Isotropic rotation of each CMB photon's polarization plane:
- **0.35° ± 0.14° (excludes zero at 2.4σ level/99.2%)**
- Distinguishes between CMB birefringence and telescope angle miscalibration.
- Key idea: galactic foregrounds are local; should not be rotated by birefringence mechanism.



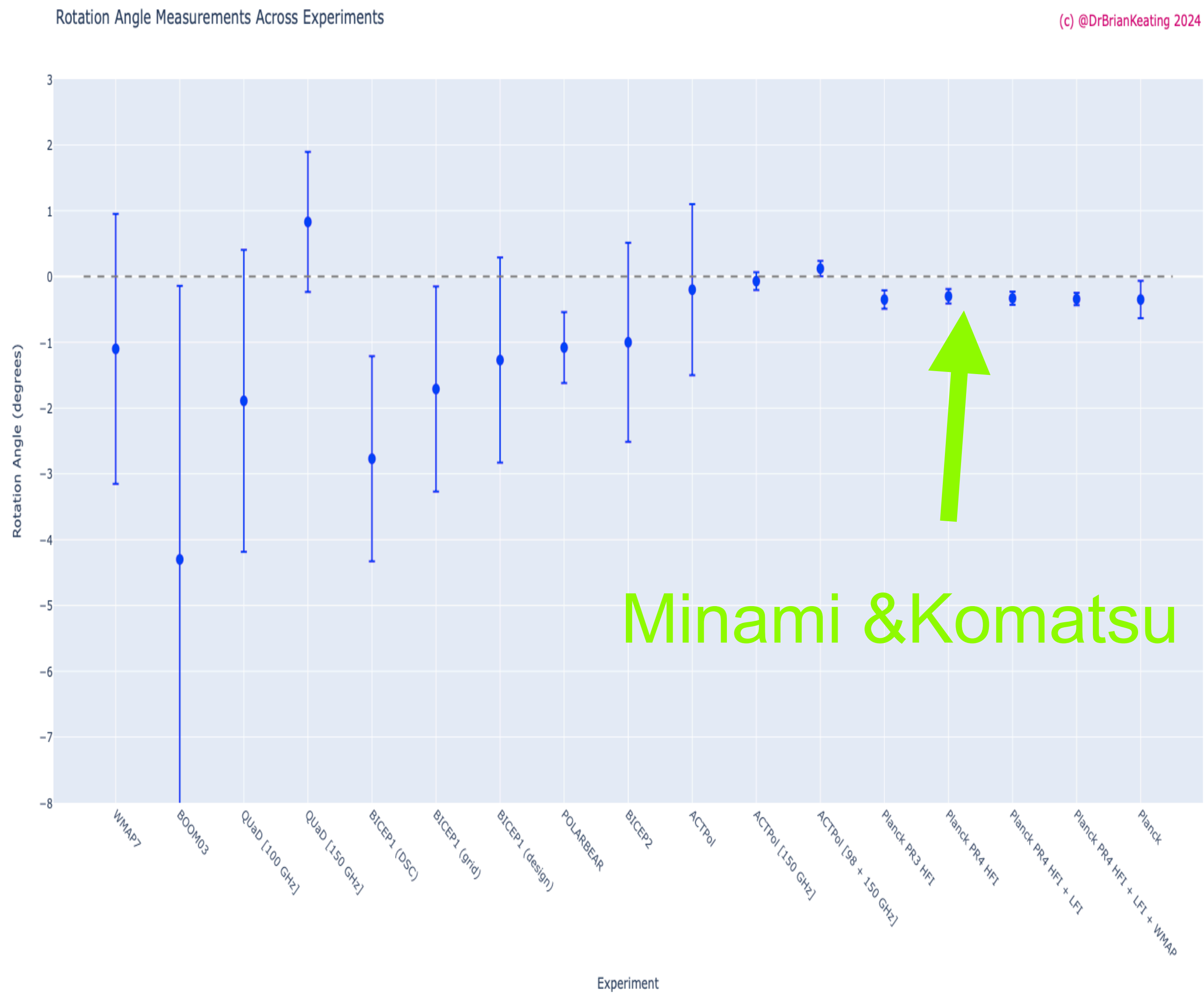
Part of fig. 2 from *Minami and Komatsu.* Blue: correlation with CMB birefringence angle. Red: correlation with telescope miscalibration angle.

M&K 2020 Pipeline validation did not include any foregrounds: "Since the FFP10 simulation does not have foreground maps convolved with realistic beam effects such as the I→P leakage, we only consider CMB and noise realizations of the HM maps."

Their validation only shows that these foreground-less simulations didn't yield any bias in α_v or β.

This likelihood is a long stretch from the 5-sigma confidence needed for a discovery, but next-generation CMB detectors using the new method could strengthen the result.

Data on my website: https://briankeating.com/cb



https://briankeating.com/cb

Experiment/Dataset	Frequency [GHz]	ℓ range	$\alpha \pm \mathrm{stat}(\pm\mathrm{syst})[^\circ]$	Measurement Method
QUaD[26]	100	200–2000	$-1.89 \pm 2.24(\pm 0.5)$	Polarized source
	150		$+0.83 \pm 0.94(\pm 0.5)$	
BOOM03[27]	143	150–1000	$-4.3 \pm 4.1(\pm 0.69)$	Pre-flight polarized source
ACTPol	146	500–2000	$-0.2 \pm 0.5(-1.2)$	As-designed
WMAP9[28]	23–94	2–800	$0.36 \pm 1.24(\pm 1.5)$	Pre-launch polarized source / Tau A
BICEP2[29]	150	30–300	$-1 \pm 0.2(\pm 1.5)$	Dielectric Sheet
BICEP1[30]	100+150	30–300	$-2.77 \pm 0.86(\pm 1.3)$	Dielectric sheet
			$-1.71 \pm 0.86(\pm 1.3)$	Polarized source
			$-1.08 \pm 0.86(\pm 1.3)$	As-designed
POLARBEAR[31]	150	500–2100	$-1.08 \pm 0.2(\pm 0.5)$	Tau A
Planck[32]	30–353	100–1500	$-0.35 \pm 0.05(\pm 0.28)$	Pre-flight source / Tau A [33, 34]
ACTPol (Choi et al., Murphy et al.)[14, 15]	150	600–1800	$-0.07 \pm 0.09(\pm \sim 0.1)$	Metrology+modeling+point sources
ACTPol (Namikawa et al., Murphy et al.)[15, 25]	98 + 150	200–2048	$0.12 \pm 0.06(\pm \sim 0.1)$	Metrology+modeling+point sources
Planck PR3 HFI (Minami et al.)[19])	100–353	50–1500	-0.35 ± 0.14	Galactic foregrounds
Planck PR4 HFI (Diego-Palazuelos et al.)[20]	100–353	50–1500	-0.30 ± 0.11	Galactic foregrounds
Planck PR4 HFI + LFI (Eskilt et al.)[21]	30–353	50–1500	-0.33 ± 0.10	Galactic foregrounds
Planck PR4 HFI + LFI + WMAP (Eskilt et al.)[22]	23–353	50–1500	$-0.342^{+0.094}_{-0.091}$	Galactic foregrounds
BICEP3 2-year (this work)	95	40–500	$\alpha \pm 0.078(\pm 0.3)$	Polarized source
Forecast: BICEP3 7-year + RPS improved performance	95	40–500	$\alpha \pm 0.055(\pm \sim 0.07)$	Polarized source

BICEP/*Keck* XVIII: Measurement of BICEP3 polarization angles and consequences for constraining cosmic birefringence and inflation

BICEP/*Keck* Collaboration: P. A. R. Ade,[1] Z. Ahmed,[2,3] M. Amiri,[4] D. Barkats,[5] R. Basu Thakur,[6] C. A. Bischoff,[7] D. Beck,[8] J. J. Bock,[6,9] H. Boenish,[5] V. Buza,[10] J. R. Cheshire IV,[11] J. Connors,[12] J. Cornelison,[5,*] M. Crumrine,[13] A. J. Cukierman,[8] E. Denison,[12] L. Duband,[14] M. Eiben,[5] B. D. Elwood,[15,5] S. Fatigoni,[6] J. P. Filippini,[16,17] A. Fortes,[8] M. Gao,[6] C. Giannakopoulos,[7] N. Goeckner-Wald,[8] D. C. Goldfinger,[8] J. A. Grayson,[8] P. K. Grimes,[5] G. Hall,[13,8] G. Halal,[8] M. Halpern,[4] E. Hand,[7] S. A. Harrison,[5] S. Henderson,[2,3] J. Hubmayr,[12] H. Hui,[6] K. D. Irwin,[8] J. H. Kang,[6] K. S. Karkare,[2,3] S. Kefeli,[6] J. M. Kovac,[15,5] C. Kuo,[8] K. Lau,[6] M. Lautzenhiser,[7] A. Lennox,[17] T. Liu,[8] K. G. Megerian,[9] L. Minutolo,[6] L. Moncelsi,[6] Y. Nakato,[8] H. T. Nguyen,[9,6] R. O'brient,[9,6] A. Patel,[6] M. A. Petroff,[5] A. R. Polish,[15,5] T. Prouve,[14] C. Pryke,[13] C. D. Reintsema,[12] T. Romand,[6] M. Salatino,[8] A. Schillaci,[6] B. Schmitt,[5] B. Singari,[13] A. Soliman,[9,6] T. St Germaine,[5] A. Steiger,[6] B. Steinbach,[6] R. Sudiwala,[1] K. L. Thompson,[8] C. Tsai,[5] C. Tucker,[1] A. D. Turner,[9] C. Vergès,[5,†] A. G. Vieregg,[10] A. Wandui,[6] A. C. Weber,[9] J. Willmert,[13] W. L. K. Wu,[3,2] H. Yang,[8] C. Yu,[8,3] L. Zeng,[5] C. Zhang,[6] and S. Zhang[6]

[1] *School of Physics and Astronomy, Cardiff University, Cardiff, CF24 3AA, United Kingdom*
[2] *Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305*
[3] *SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA*
[4] *Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, V6T 1Z1, Canada*
[5] *Center for Astrophysics | Harvard & Smithsonian, Harvard University, Cambridge, MA 02138, USA*
[6] *Department of Physics, California Institute of Technology, Pasadena, CA 91125, USA*
[7] *Department of Physics, University of Cincinnati, Cincinnati, OH 45221, USA*
[8] *Department of Physics, Stanford University, Stanford, CA 94305, USA*
[9] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*
[10] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*
[11] *Minnesota Institute for Astrophysics, University of Minnesota, Minneapolis, MN 55455, USA*
[12] *National Institute of Standards and Technology, Boulder, CO 80305, USA*
[13] *School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*
[14] *Service des Basses Temperatures, Commissariat a l'Energie Atomique, 38054 Grenoble, France*
[15] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[16] *Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*
[17] *Department of Astronomy, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*

We use a custom-made calibrator to measure individual detectors' polarization angles of BICEP3, a small aperture telescope observing the cosmic microwave background (CMB) at 95GHz from the South Pole. We describe our calibration strategy and the statistical and systematic uncertainties associated with the measurement. We reach an unprecedented precision for such measurement on a CMB experiment, with a repeatability for each detector pair of 0.02°. We show that the relative angles measured using this method are in excellent agreement with those extracted from CMB data. Because the absolute measurement is currently limited by a systematic uncertainty, we do not derive cosmic birefringence constraints from BICEP3 data in this work. Rather, we forecast the sensitivity of BICEP3 sky maps for such analysis. We investigate the relative contributions of instrument noise, lensing, and dust, as well as astrophysical and instrumental systematics. We also explore the constraining power of different angle estimators, depending on analysis choices. We establish that the BICEP3 2-year dataset (2017–2018) has an on-sky sensitivity to the cosmic birefringence angle of $\sigma_\alpha = 0.078°$, which could be improved to $\sigma_\alpha = 0.055°$ by adding all of the existing BICEP3 data (through 2023). Furthermore, we emphasize the possibility of using the BICEP3 sky patch as a polarization calibration source for CMB experiments, which with the present data could reach a precision of 0.035°. Finally, in the context of inflation searches, we investigate the impact of detector-to-detector variations in polarization angles as they may bias the tensor-to-scalar ratio r. We show that while the effect is expected to remain subdominant to other sources of systematic uncertainty, it can be reliably calibrated using polarization angle measurements such as the ones we present in this paper.

BICEP3 (James C.)

Example 2: Time-varying isotropic cosmic birefringence

$\gamma(\omega, t, \hat{n})$: Coupling terms

– Cross-terms between different effects
– Example: $\gamma \propto \boldsymbol{\alpha}(\hat{n}) \cdot \hat{n} \times \omega^n$
– Higher-order corrections

The total rotation angle including all possible birefringence effects can be expressed as:

$$\Delta\phi(\vec{r}, \hat{n}, \omega, t) = \int_0^r \Big[\underbrace{\alpha_0}_{\text{constant isotropic}} + \underbrace{\boldsymbol{\alpha}(\hat{n})}_{\text{direction-dependent}} \cdot \hat{n} + \underbrace{\beta(\omega)}_{\text{frequency-dependent}} + \underbrace{\alpha(t)}_{\text{time-varying}} + \underbrace{\gamma(\omega, t, \hat{n})}_{\text{coupling terms}} \Big] dr'$$

α_0: Constant isotropic birefringence

– Uniform rotation independent of direction and frequency
– Simplest case of cosmic birefringence
– Units: [rad/Mpc]

$\boldsymbol{\alpha}(\hat{n})$: Anisotropic birefringence tensor

– Direction-dependent rotation
– Can be decomposed into spherical h
– $\boldsymbol{\alpha}(\hat{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{n})$

$\alpha(t)$: Time-varying component

– Can be periodic: $\alpha(t) = \alpha_1 \cos(\Omega t)$
– Or monotonic: $\alpha(t) = \alpha_1 t$

$\beta(\omega)$: Frequency-dependent term

– Accounts for dispersive effects
– Generally modeled as power law: $\beta(\omega) \propto \omega^n$
– Important for multi-frequency observations

Notes

- Integration is along the photon path from emission to observation
- $\hat{n}$ represents the direction of observation
- ω is the photon frequency
- Effects can be constrained through CMB observations

Axion Signal in the CMB

- Oscillating classical field description:

$$\phi(\vec{x},t) = \phi_0(\vec{x},t)\sin\left(m_\phi t + \theta(\vec{x})\right)$$

Oscillation period: days-months

- Cosmic birefringence:

$$\beta = \frac{g_{\phi\gamma}}{2}\left(\phi(\vec{x}_{\rm abs}, t_{\rm abs}) - \phi(\vec{x}_{\rm emit}, t_{\rm emit})\right)$$

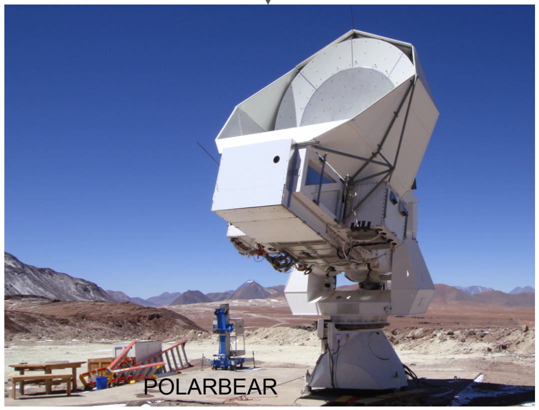
- CMB polarization angle rotation: (Federreke et. al., PRD 2019)

$$\beta_{\rm CMB}(t) = \frac{g_{\phi\gamma}\phi_0}{2}\sin(m_\phi t + \theta)$$

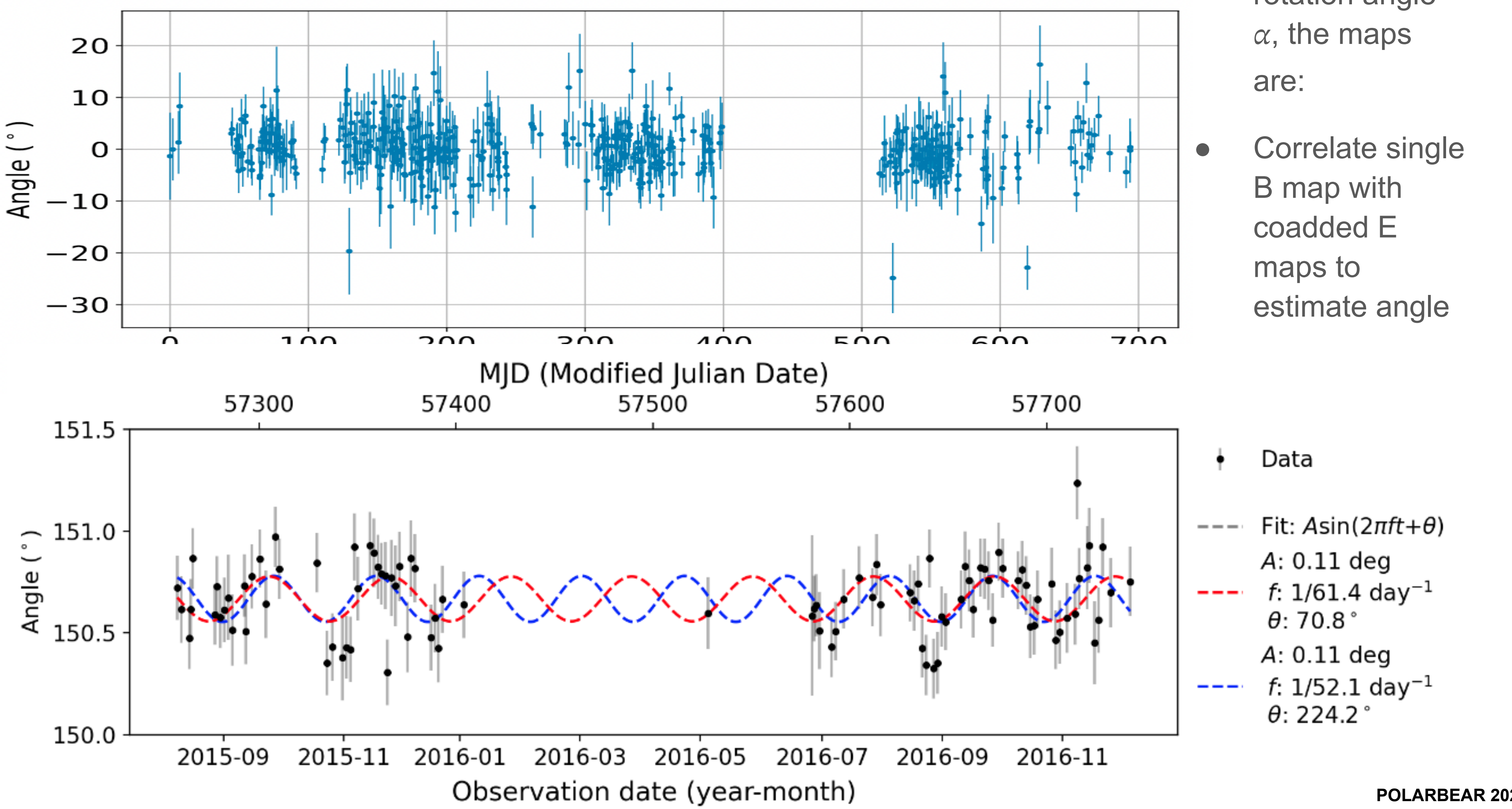
Sinusoidal rotation effect: **this work**

6523 Lyrs

CMB absorbed by POLARBEAR 1



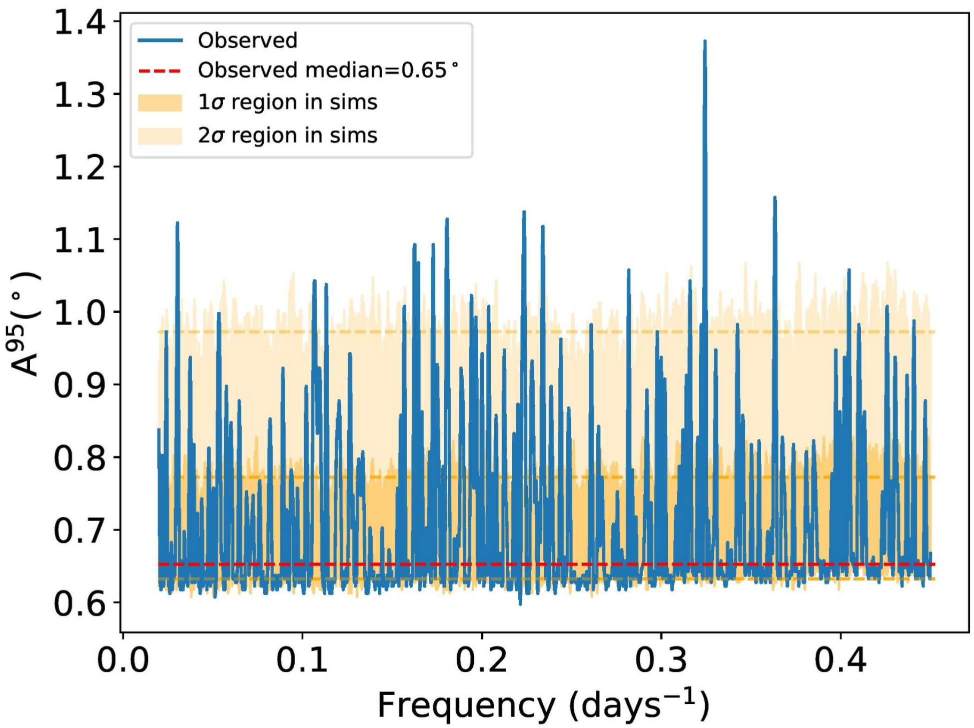
Estimating an Angle for Each Observation



- Under small rotation angle α, the maps are:
- Correlate single B map with coadded E maps to estimate angle

POLARBEAR 2024

Results: No Detection

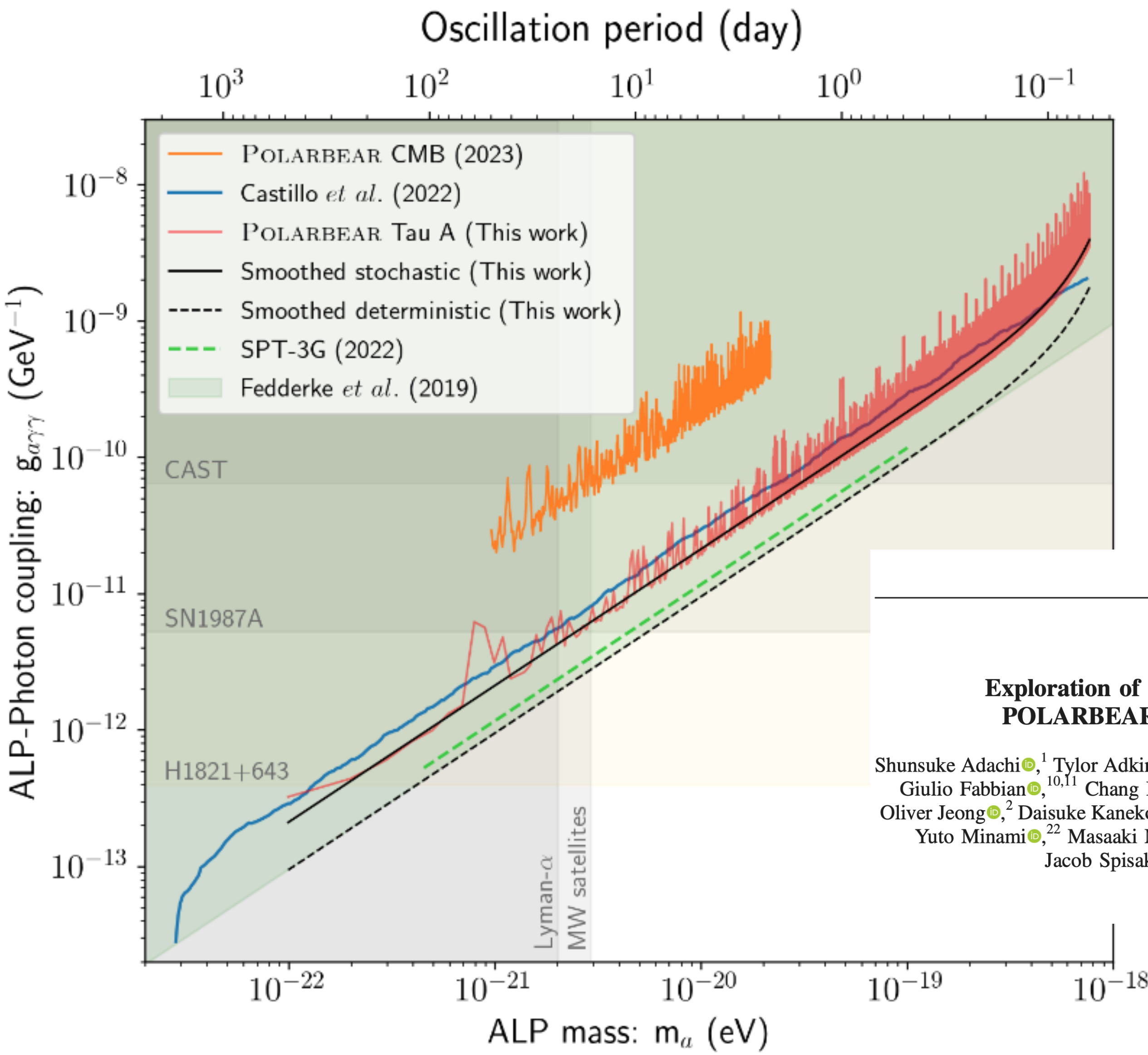


POLARBEAR 2023

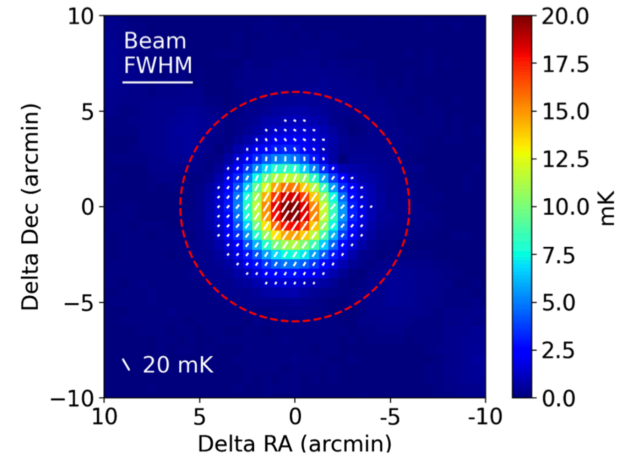
- Test for presence of signal:

$$\Delta\chi^2 \equiv \chi^2(A=0) - \chi^2(A^{\rm mle}, f^{\rm mle}, \theta^{\rm mle})$$

- Compare to a simulated distribution
- σ_{PTE} = 1.7: no significant detection
- Place 95% upper confidence limit on sinusoid amplitude A_{95} across frequency range



Adachi et al Crab Nebula 2024



PHYSICAL REVIEW D **110,** 063013 (2024)

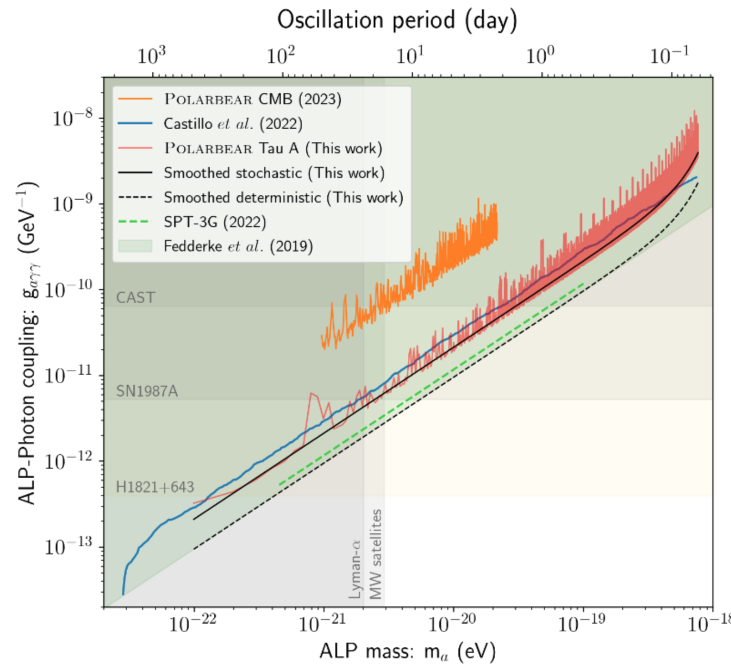
Exploration of the polarization angle variability of the Crab Nebula with POLARBEAR and its application to the search for axionlike particles

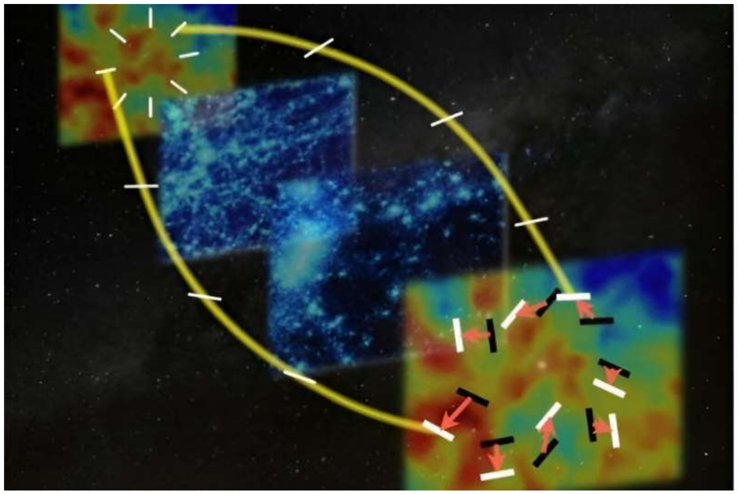
Shunsuke Adachi,[1] Tylor Adkins,[2] Carlo Baccigalupi,[3,4,5] Yuji Chinone,[6,7] Kevin T. Crowley,[8] Josquin Errard,[9] Giulio Fabbian,[10,11] Chang Feng,[12,13] Takuro Fujino,[14] Masaya Hasegawa,[15,6,16] Masashi Hazumi,[6,15,7,17,16] Oliver Jeong,[2] Daisuke Kaneko,[6] Brian Keating,[8] Akito Kusaka,[18,19,7,20] Adrian T. Lee,[2,19] Anto I. Lonappan,[21] Yuto Minami,[22] Masaaki Murata,[18] Lucio Piccirillo,[23] Christian L. Reichardt,[24] Praween Siritanasak,[25] Jacob Spisak,[8] Satoru Takakura,[26] Grant P. Teply,[8] and Kyohei Yamada[18,*]

(POLARBEAR Collaboration)

Conclusion

- Well-motivated from fundamental physics and from dark matter
- Constraints coming in
- Reminds me of early days of BICEP and inflation searches
- First they ignore you, then they laugh at you, then they fight you, then they join you, then you win.





END

Data 👇

https://briankeating.com/cb