Tomography of cosmic birefringence induced by 3-form dark energy

KK, Tucker Manton (HIAS-UCAS), arXiv: 2608.05296 [astro-ph.CO]

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Slide Background Courtesy: H. Oide

1. Introduction — Cosmic Birefringence —
2. Tomographic Approach to Cosmic Birefringence
3. The Case with 3-form Dark Energy
4. Summary

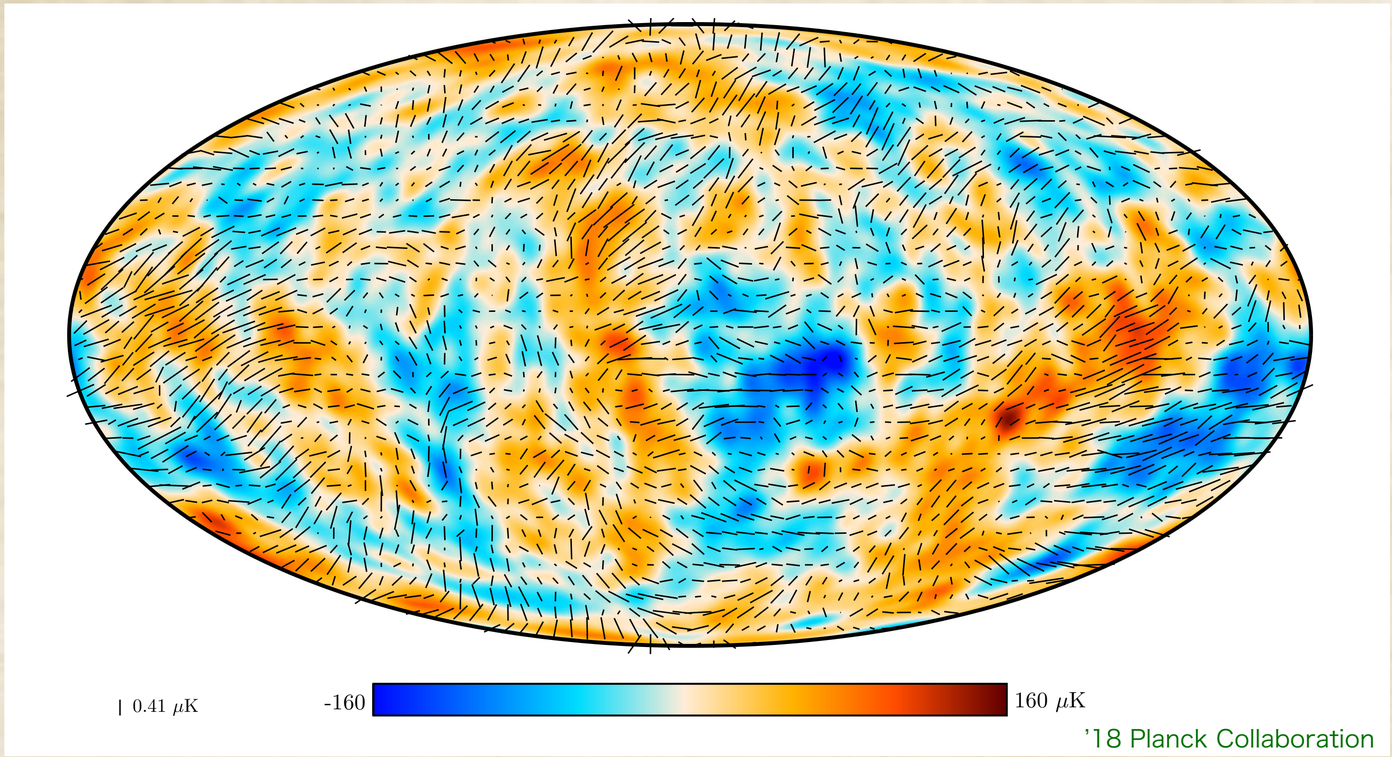
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Introduction — Cosmic Birefringence —

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Cosmic Microwave Background

…carries several information of the early Universe.



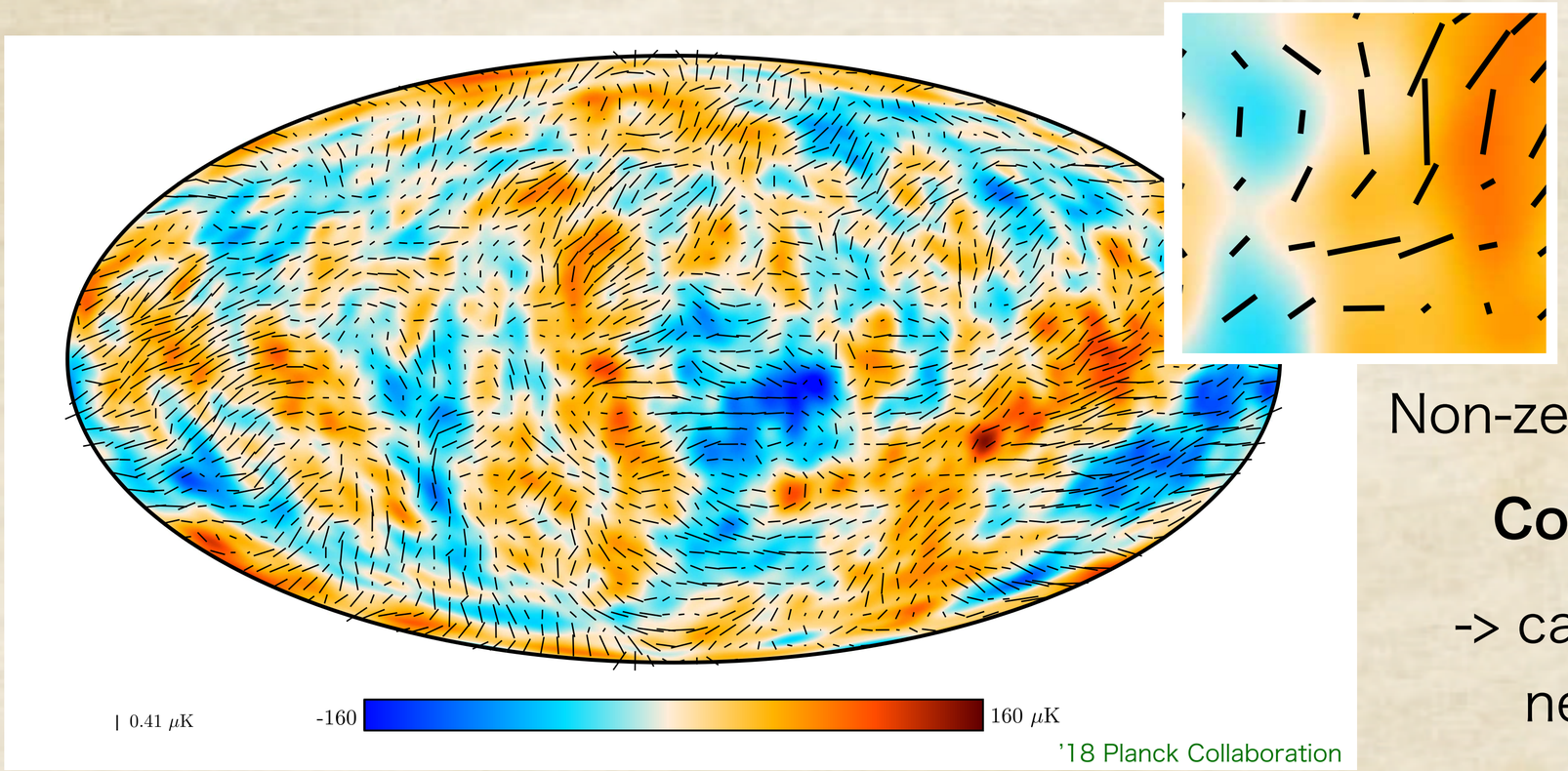
All-sky intensity and polarization map of CMB by Planck

color : temperature, line segments: polarization

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Cosmic Microwave Background (CMB)

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Non-zero C_ℓ^{EB} correlation

Cosmic Birefringence!

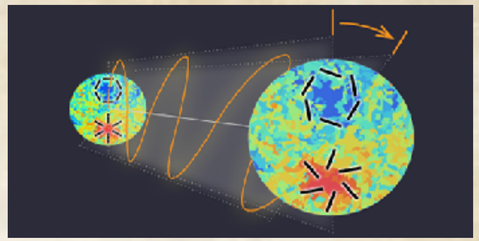
-> calls for parity-violating new physics?

All-sky intensity and polarization map of CMB by Planck

color : temperature, line segments: polarization

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(Isotropic) Cosmic Birefringence



'20 Minami & Komatsu

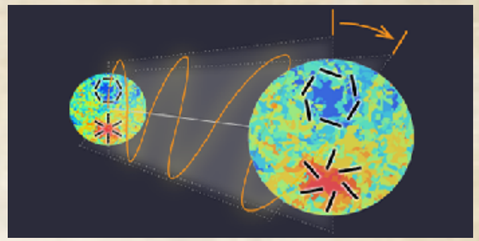
- No initial EB or TB correlation
- Constant rotation of the polarization plane of the CMB photons by a constant angle β

$$C_l^{EB,o} = \frac{1}{2}(C_l^{EE,o} - C_l^{BB,o})\tan(4\beta).$$

$$C_l^{\Theta B,o} = C_l^{\Theta E,o}\tan(2\beta).$$

Slide Background Courtesy: H. Oide

(Isotropic) Cosmic Birefringence



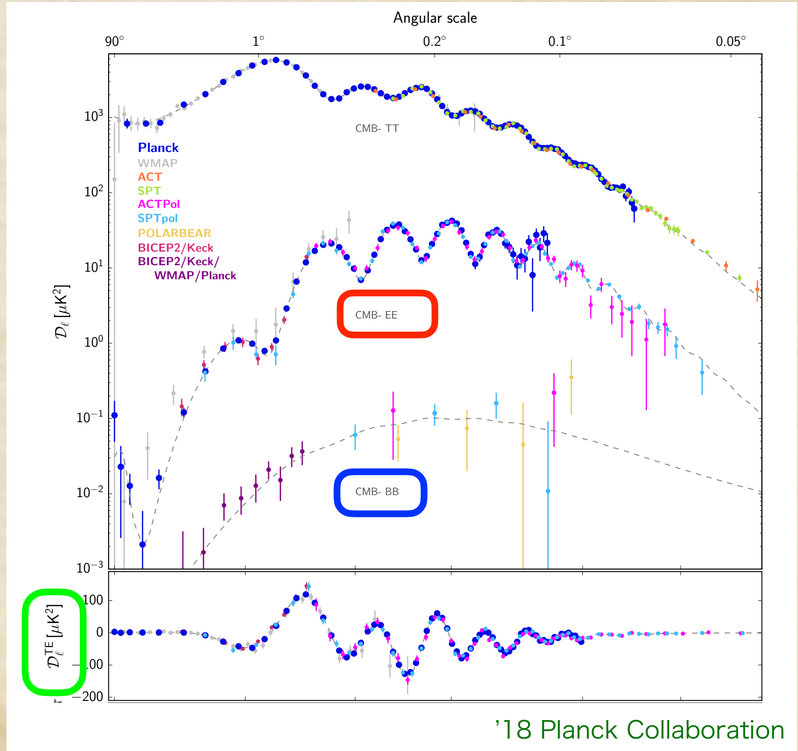
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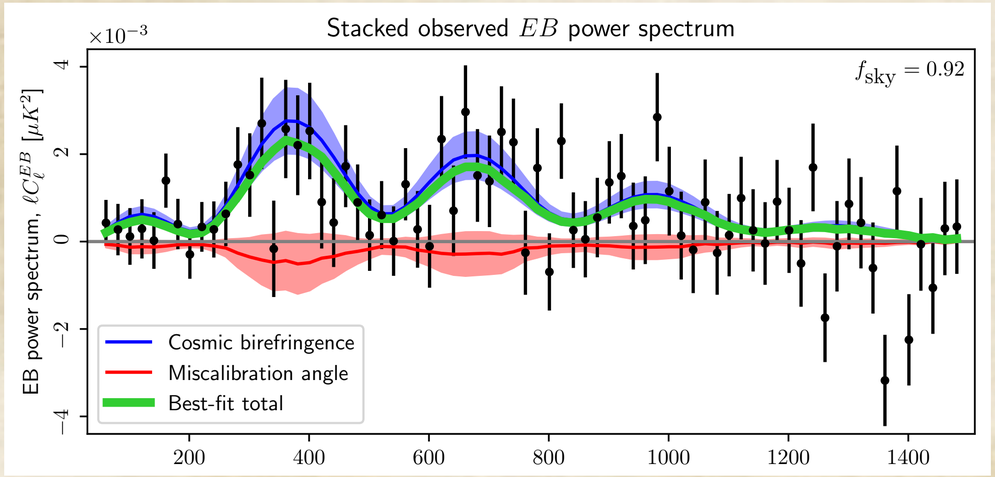
If we observe non-zero C_ℓ^{EB} or $C_\ell^{\Theta B}$,
fitted by this formula,
we determine the birefringence angle β



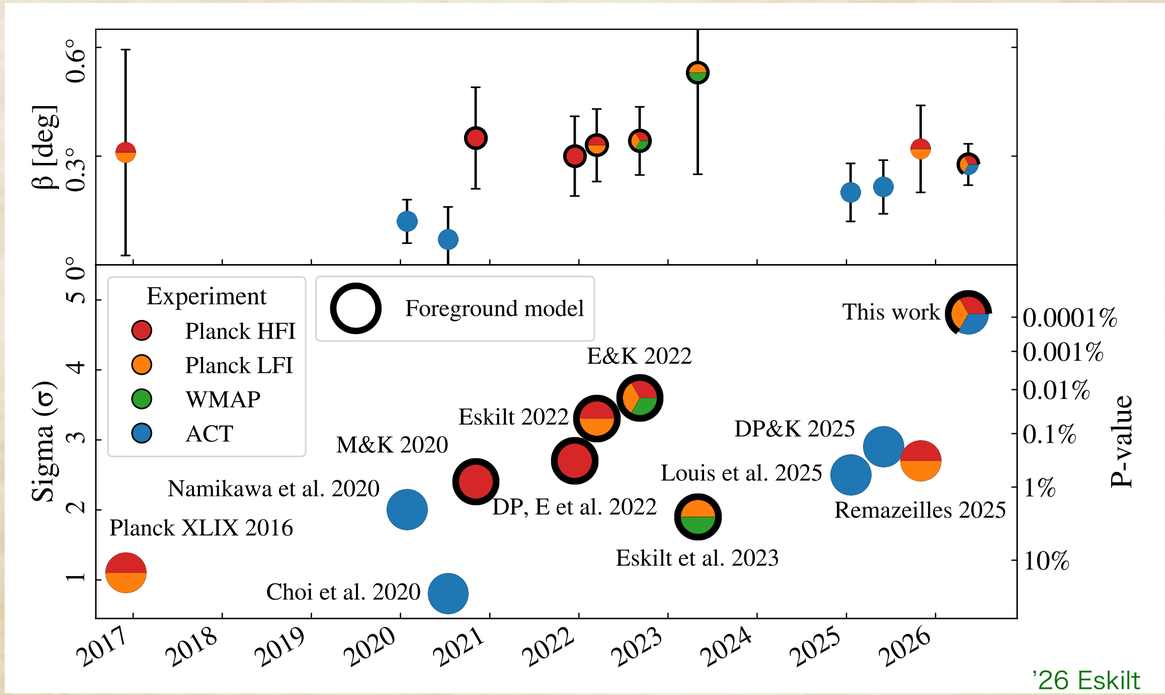
'18 Planck Collaboration

Slide Background Courtesy: H. Oide

Non-zero β has been observed?



'22 Eskilt & Komatsu



'26 Eskilt

$\beta = 0.277^\circ \pm 0.057^\circ$ is suggested, excluding $\beta = 0^\circ$ at $4.8\,\sigma$.

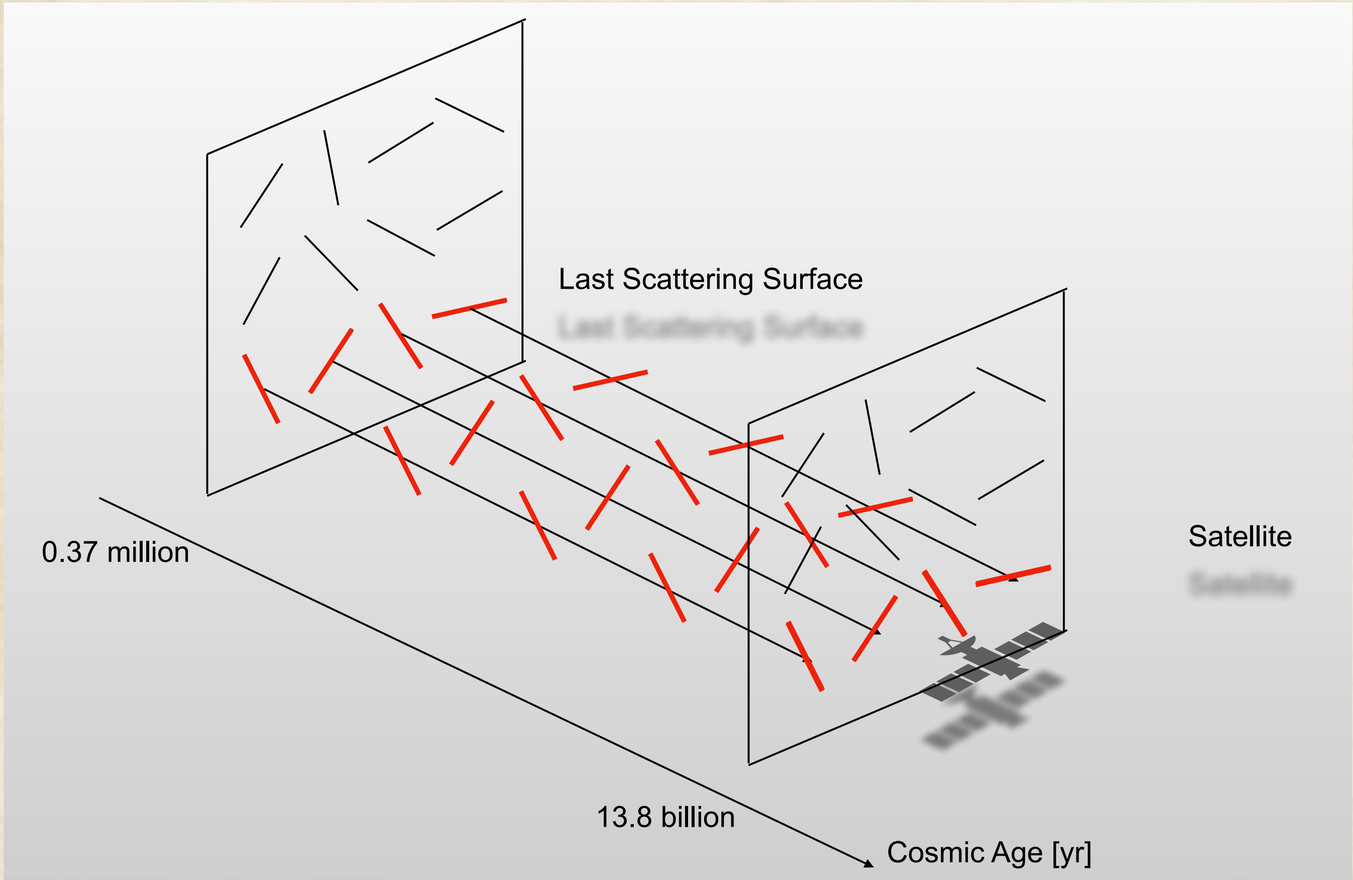
'26 Eskilt, w/ Planck DR4 & ACT DR6

Slide Background Courtesy: H. Oide

Tomographic Approach to Cosmic Birefringence

Slide Background Courtesy: H. Oide

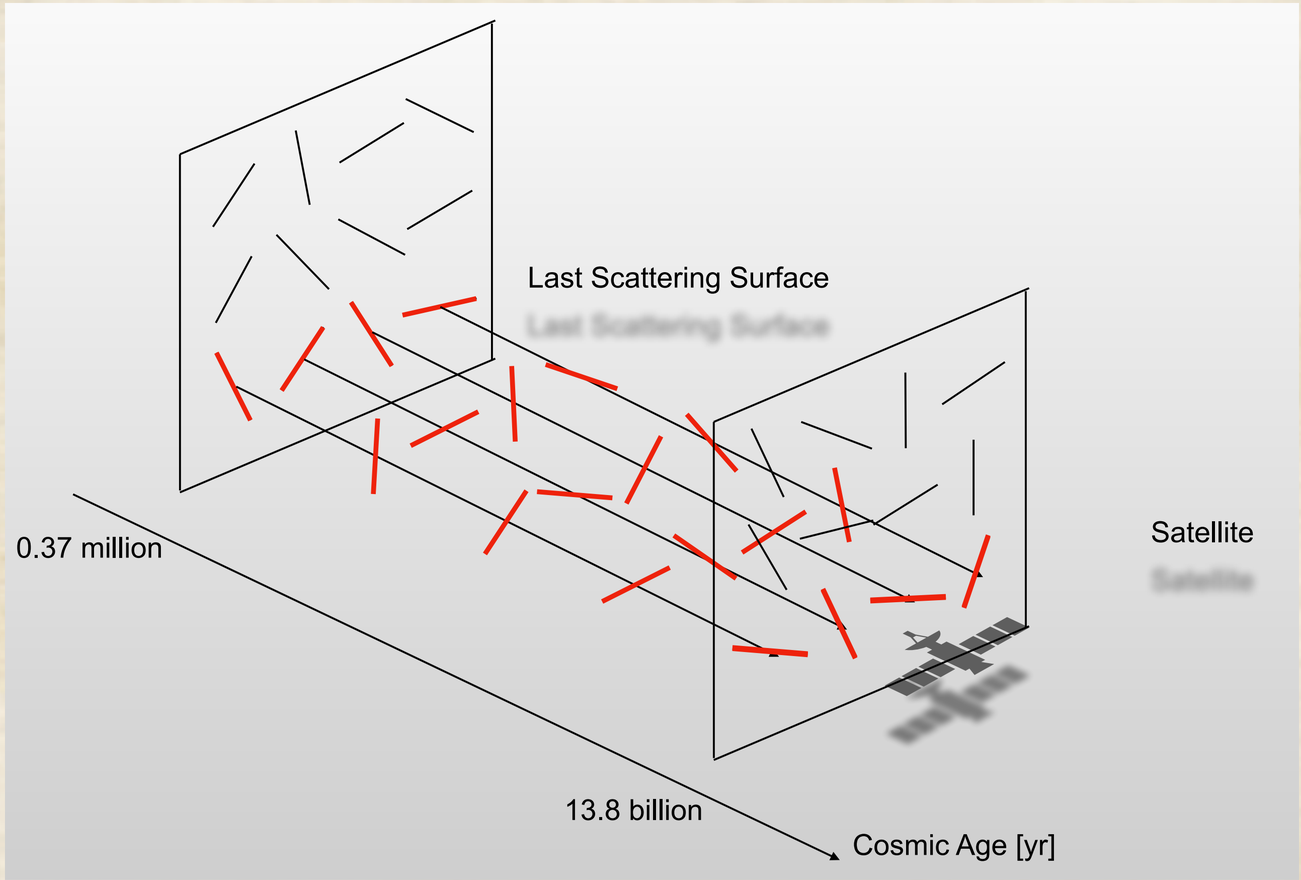
The analysis examined the difference of the polarization plane between the recombination and today



Coutesy: Fumihiro Naokawa

Slide Background Courtesy: H. Oide

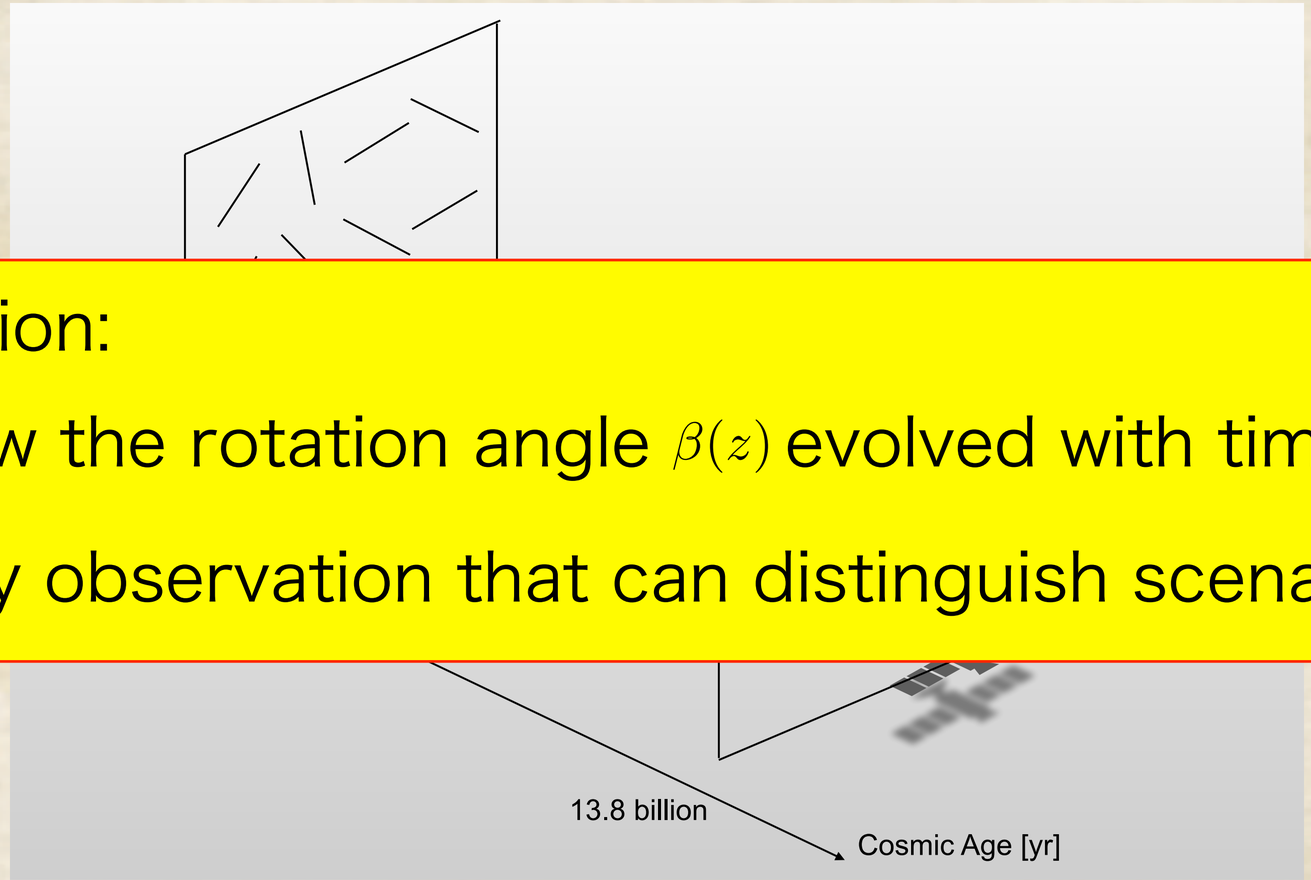
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Question:

How the rotation angle $\beta(z)$ evolved with time?

Any observation that can distinguish scenarios?

Coutesy: Fumihiro Naokawa

Slide Background Courtesy: H. Oide

The origin of cosmic birefringence

Consider an equation of motion for photons
in the presence of some interactions with external background media

$$\ddot{A}_\pm + (k^2 + \lambda_\pm \varphi(t) k) A_\pm = 0, \quad \lambda_\pm = \pm 1$$

in the circular polarization basis.

Slide Background Courtesy: H. Oide

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“Phase birefringence”⋯ different dispersion relation, $\omega_\pm^2 = k^2 + \lambda_\pm \varphi(t) k$

leads to the rotation of the polarization angle:

$$\beta(z) = \frac{1}{2} \int_{t_{\rm LSS}}^{t(z)} \mathrm{d}t (\omega_- - \omega_+) \simeq -\frac{1}{2} \int_{t_{\rm LSS}}^{t(z)} \mathrm{d}t \varphi(t)$$

Slide Background Courtesy: H. Oide

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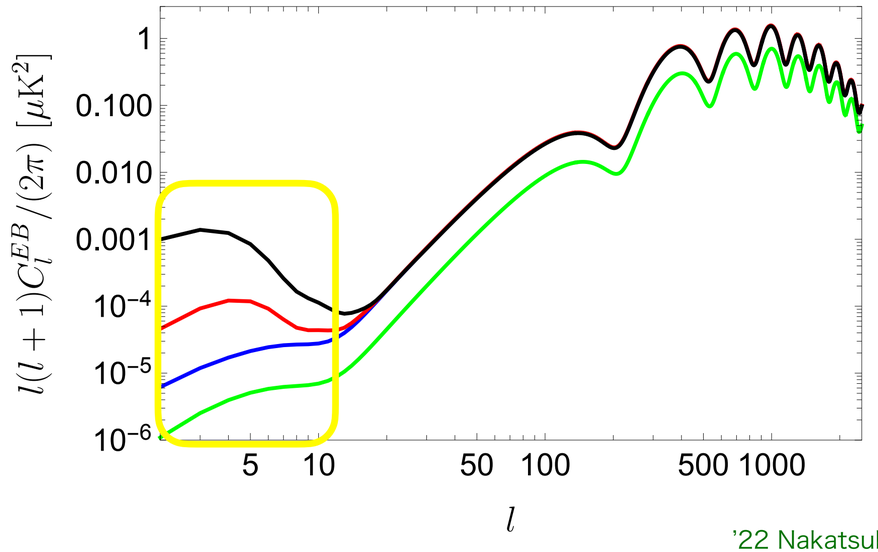
The case with Axion-Like Particle (ALP)

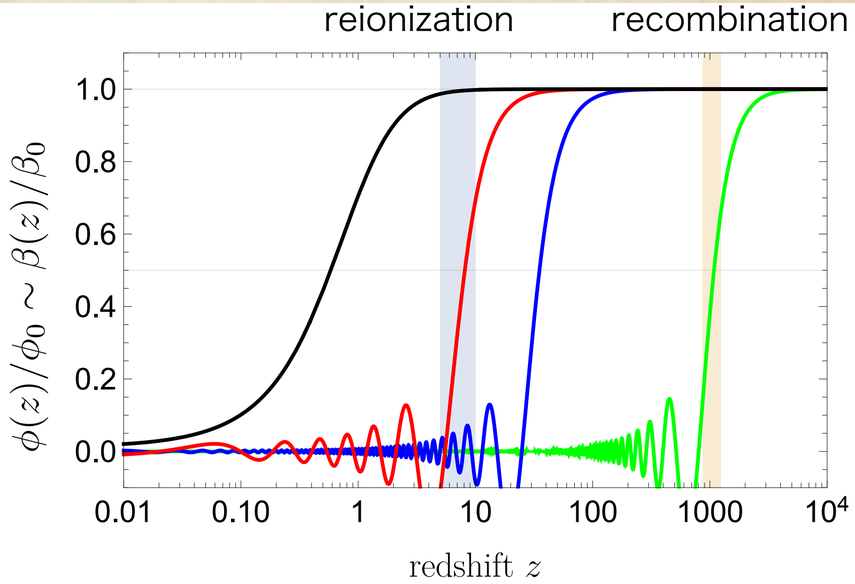
$$\mathcal{L} \ni -\frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \rightarrow \beta(z) = \frac{1}{2} g_{\phi\gamma} \int_{t_{\rm LSS}}^{t(z)} \mathrm{d}t \dot{\phi} = \frac{1}{2} g_{\phi\gamma} (\phi(t(z)) - \phi(t_{\rm LSS}))$$

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CMB Tomography

If $\beta(z)$evolves mainly between the recombination and reionization, reionization bump in the C_ℓ^{EB} disappears.





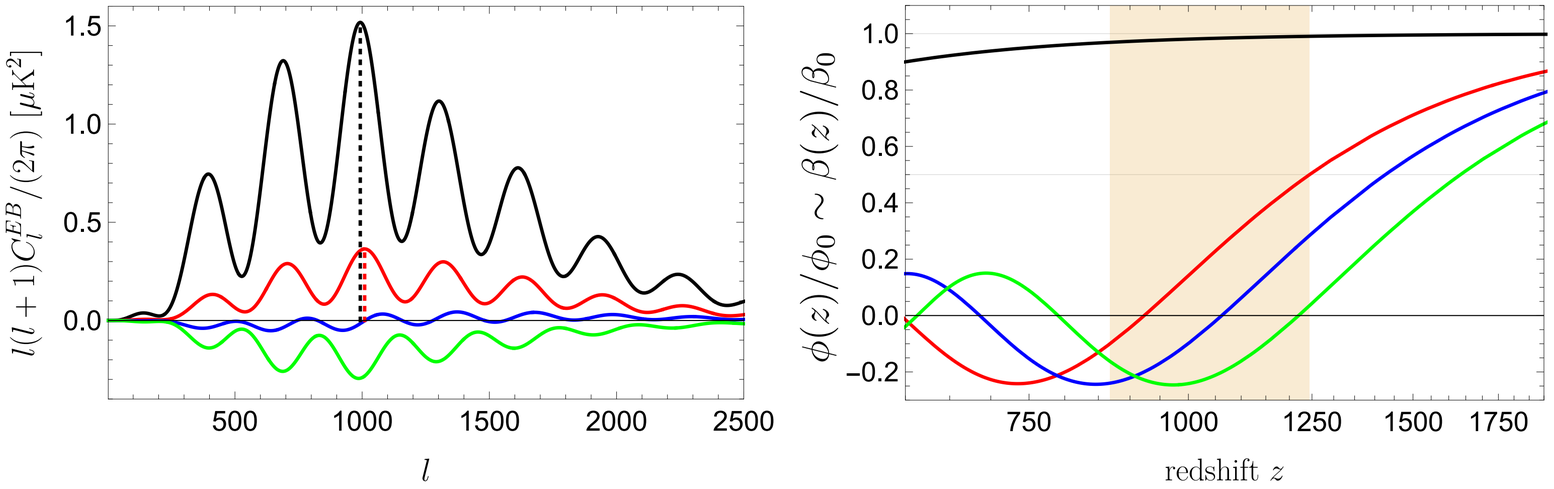
'22 Nakatsuka, Namikawa, Komatsu

Case with ALP, a concrete example.

Slide Background Courtesy: H. Oide

CMB Tomography

If $\beta(z)$evolves mainly during recombination,
modulation of C_ℓ^{EB}at $\ell \sim 10^3$ can determine the time evolution of relatively precisely.



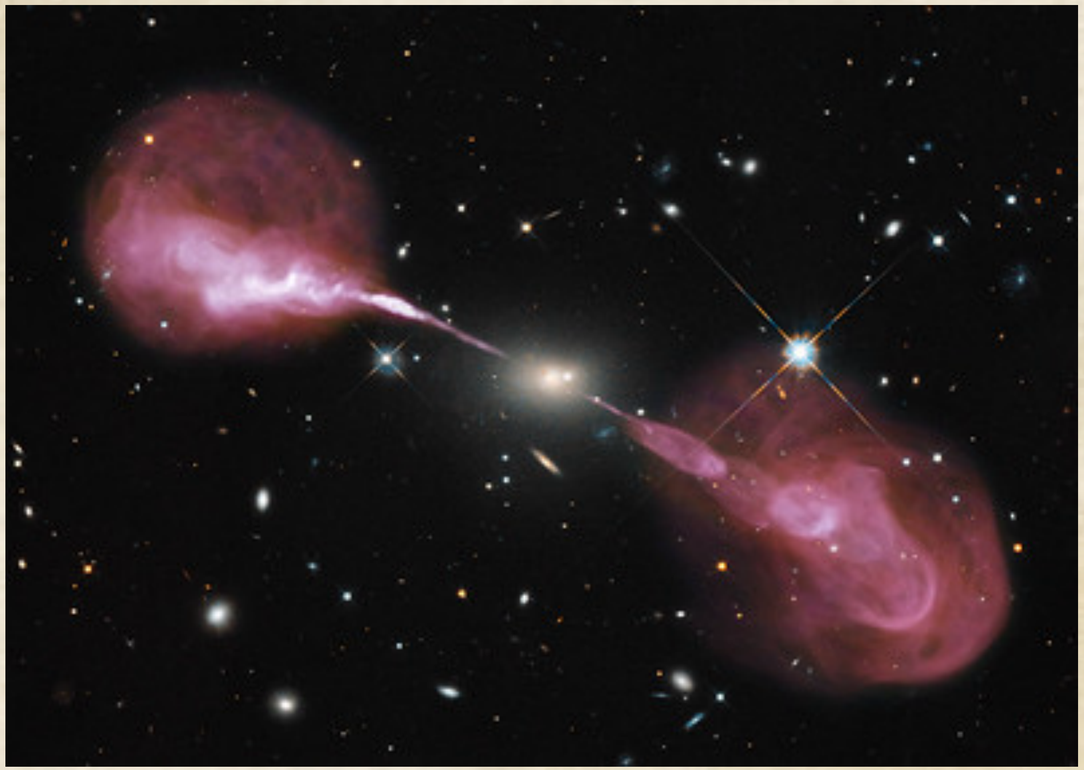
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Tomography with radio galaxies '90 Carroll, Field, Jackiw '97 Carroll & Field, '98 Carroll, '26 Naokawa

… source of polarized photons at low redshift; another “Standard Cross”

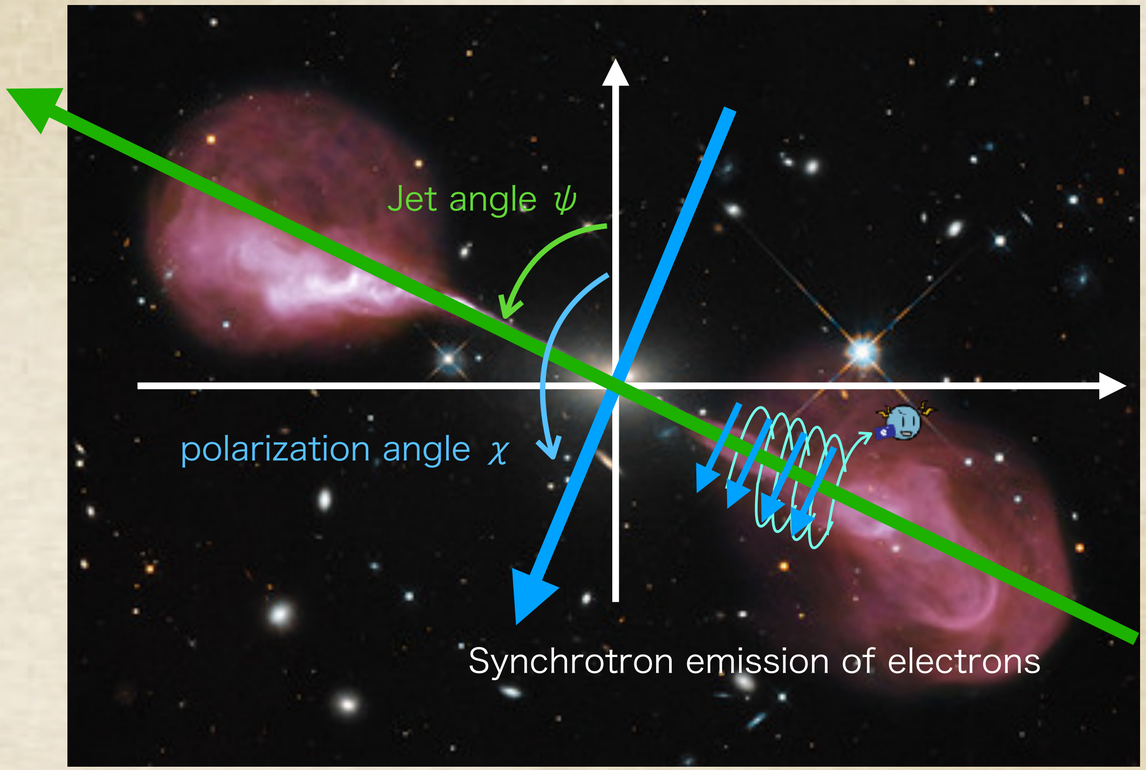


A Multi-Wavelength View of Radio Galaxy Hercules A
Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley andW. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team
(STScI/AURA) https://www.flickr.com/photos/gsfc/8230235118/in/photostream/ CC BY 2.0 Generic https://creativecommons.org/licenses/by/2.0/

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The polarization angle of synchrotron emission from radio galaxies should be orthogonal to jet angle, $\chi - \psi \sim 90°$

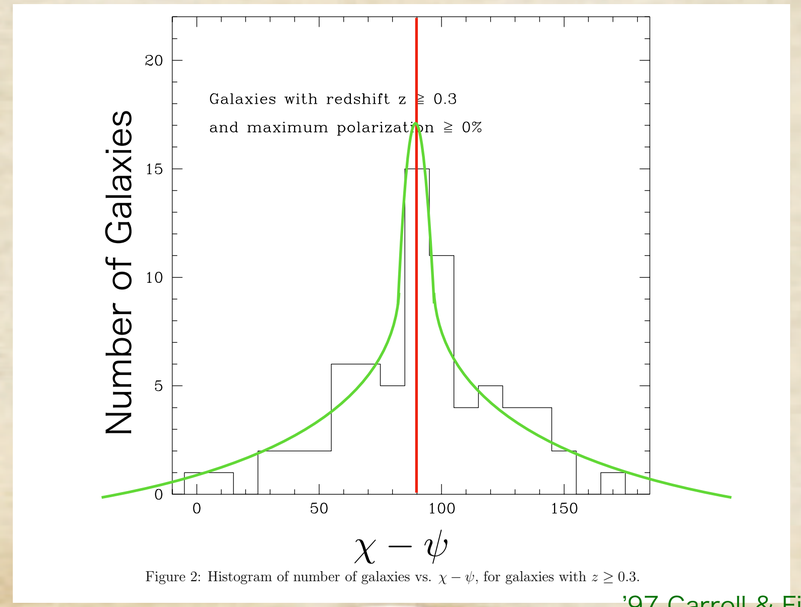


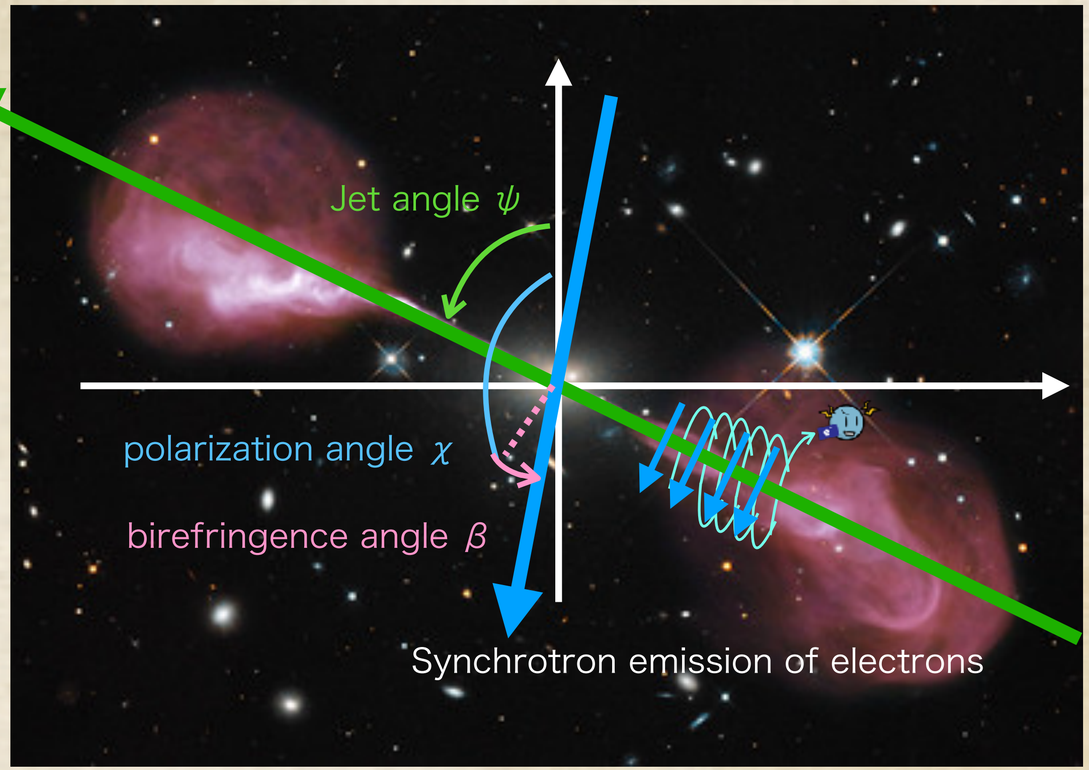
Figure 2: Histogram of number of galaxies vs. $\chi - \psi$, for galaxies with $z \geq 0.3$.

'97 Carroll & Field,

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If we have birefringence between the radio galaxies and us, the histogram should shift by β

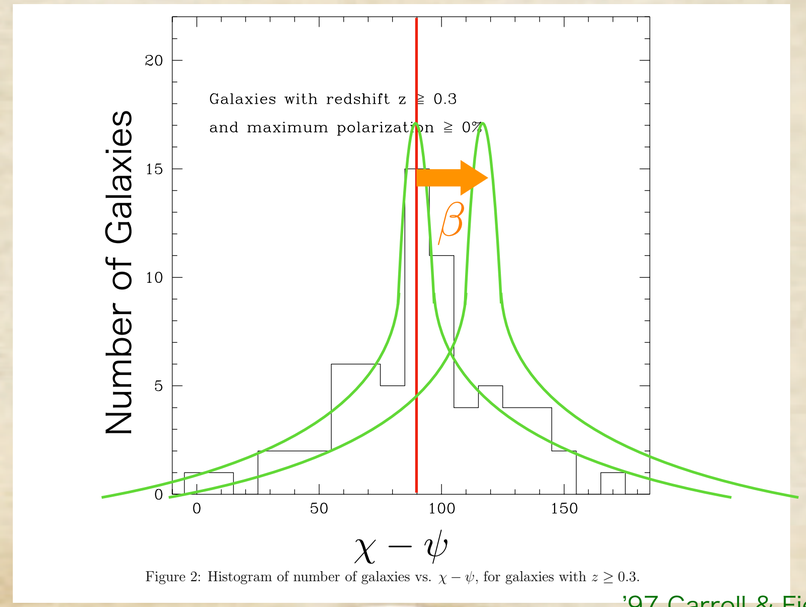


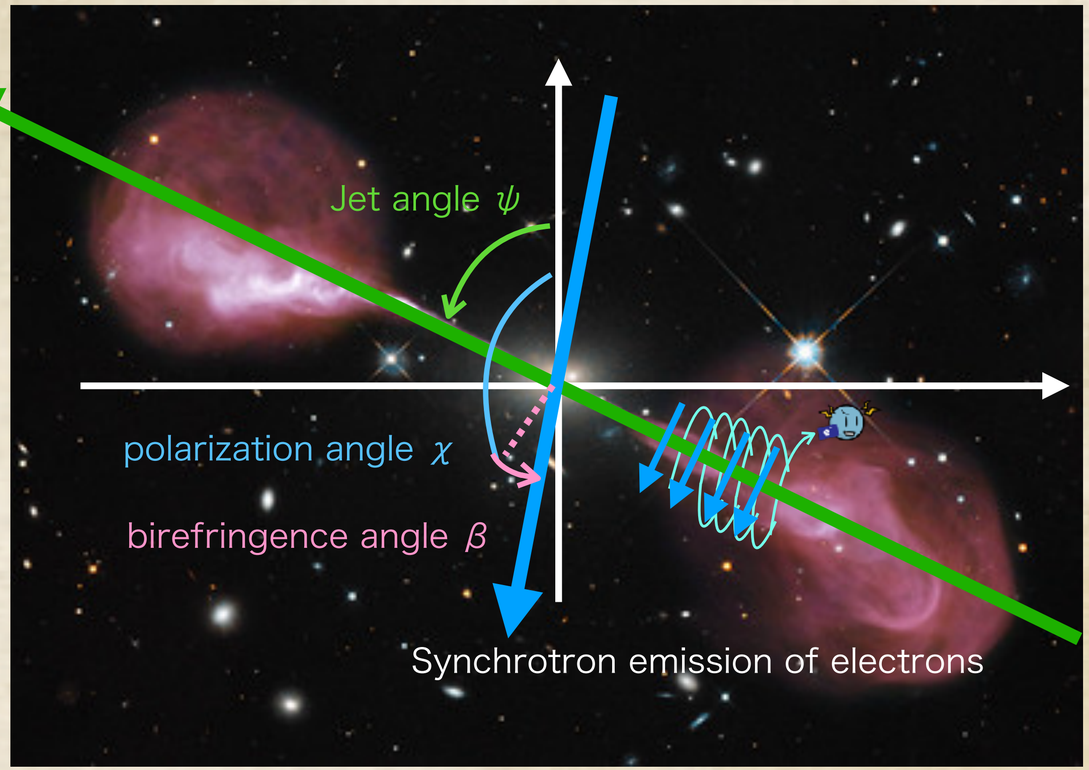
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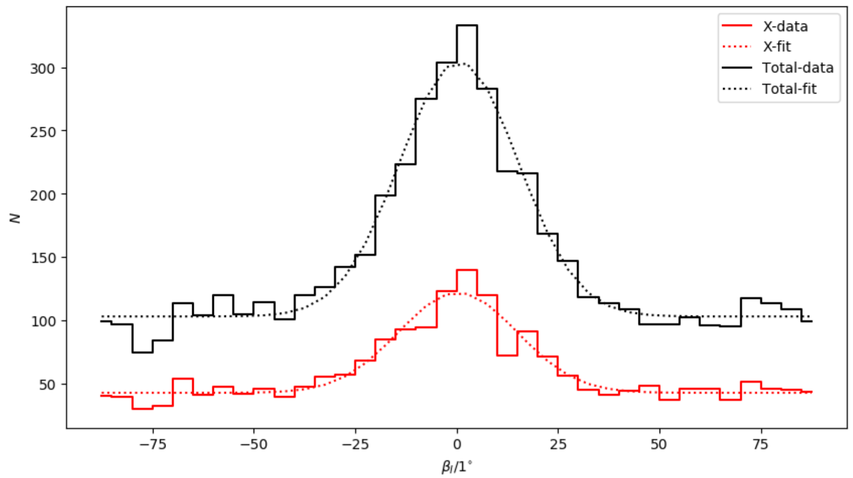
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Recent analysis w/ 2111 samples

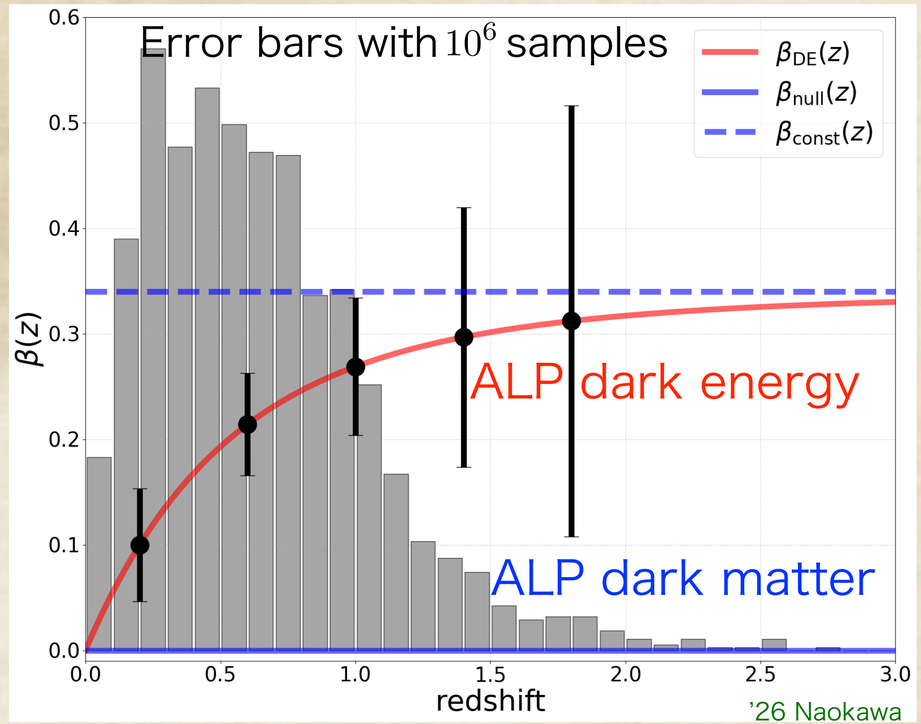


$\mu_\beta = (0.2 \pm 1.0)^\circ \quad \sigma_\beta = (14.7 \pm 1.1)^\circ$ '26 Battye+

Slide Background Courtesy: H. Oide

Tomography with radio galaxies '90 Carroll, Field, Jackiw '97 Carroll & Field, '98 Carroll, '26 Naokawa

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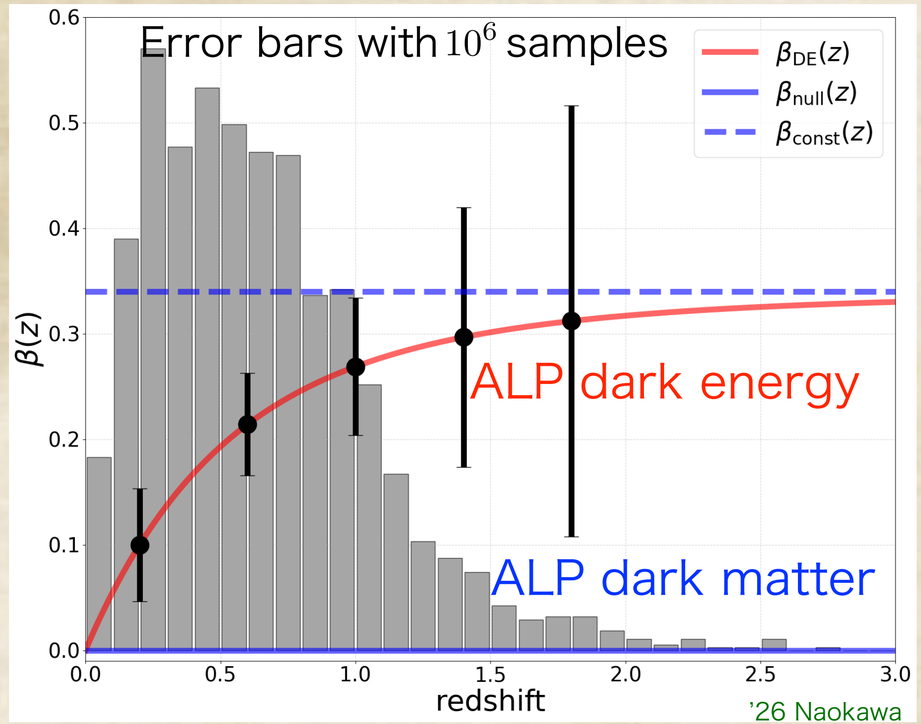
Naokawa showed that in the case of ALP,
especially for the radio galaxy, $z \lesssim 10$
profile of $\beta(z)$ has a Universal profile,
independent of the ALP potential,
as long as $\beta_0 \simeq 0.3^\circ$ '26 Naokawa

assuming the redshift distribution of the samples
are the same to the one in LOFAR LoTSS DR2 (~2500 samples)

Slide Background Courtesy: H. Oide

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Future observations at ASKAP POSSUM survey may identify $10^{5\sim6}$ samples, sufficient to distinguish ALP DM and ALP DE !

assuming the redshift distribution of the samples
are the same to the one in LOFAR LoTSS DR2 (~2500 samples)

Slide Background Courtesy: H. Oide

What is found for ALP:

ALP DM: reionization bump is absent in C_ℓ^{EB}

modulation of C_ℓ^{EB} at $\ell \sim 10^3$ can be sensitive to $V(\phi)$

ALP DE: reionization bump exists in C_ℓ^{EB}

radio galaxy will find the Universal profile.

DE + Cosmic Birefringence = Universal Profile in Radio Galaxies

Slide Background Courtesy: H. Oide

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DE + Cosmic Birefringence = Universal Profile in Radio Galaxies ?

Slide Background Courtesy: H. Oide

The case with 3-form Dark Energy

Slide Background Courtesy: H. Oide

A possible model of DE that also induces cosmic birefringence

3-form Dark Energy

’09 Kovisto & Nunes, ’09 Germani & Kehagias, ’12 De Felice+, ’25, ’26 Bouhmadi-Lopez+, ⋯

which is of interest in its own right.

Slide Background Courtesy: H. Oide

3-form field ⋯ totally antisymmetric covariant tensor field of rank 3: $C_{\mu\nu\rho}$

$$\mathcal{L} = -\frac{1}{48} G_{\mu\nu\rho\sigma} G^{\mu\nu\rho\sigma} - V(C^2) \qquad G_{\mu\nu\rho\sigma} = \nabla_{[\mu} C_{\nu\rho\sigma]}$$

Dynamical solution appears; homogeneous & isotropic one in the FRW Univ.

$$C_{ijk} = a^3 \chi(t) \epsilon_{ijk}, \quad G_{0ijk} = a^4 (\dot{\chi} + 3H\chi) \epsilon_{ijk} \Rightarrow \ddot{\chi} + 3\frac{\mathrm{d}}{\mathrm{d}t}[H\chi] + \frac{\mathrm{d}V}{\mathrm{d}\chi} = 0$$

Slide Background Courtesy: H. Oide

3-form dark energy

$$\rho = \frac{1}{2}(\dot{\chi} + 3H\chi)^2 + V$$

$$p = -\frac{1}{2}(\dot{\chi} + 3H\chi)^2 - V + \chi V'$$

$$w = -1 + \frac{\chi V'}{\frac{1}{2}(\dot{\chi} + 3H\chi)^2 + V}$$

cosmological constant

in the limit of $V' = 0$

Can cause phantom divide? ’25, ’26 Bouhmadi-Lopez+

But fluctuation becomes ghost. ’12 De Felice+,

Slide Background Courtesy: H. Oide

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Background dependent dynamics:

$$\ddot{\chi} + 3\frac{\mathrm{d}}{\mathrm{d}t}[H\chi] + \frac{\mathrm{d}V}{\mathrm{d}\chi} = 0 \quad \Rightarrow \quad \ddot{\chi} + 3H\dot{\chi} + \left(1 - (\chi/\chi_c)^2\right)\frac{\mathrm{d}V}{\mathrm{d}\chi} = \frac{3}{2M_{\rm pl}^2}\left(\rho_m + \frac{4}{3}\rho_r\right)\chi \qquad \chi_c \equiv \sqrt{\frac{2}{3}}M_{\rm pl}$$

During the radiation and matter dominated era,

χ dynamics is dominated by the tachyonic mass induced by the BG,

while keeping the energy density almost constant for sufficiently small V'.

Slide Background Courtesy: H. Oide

Dynamics of 3-form dark energy

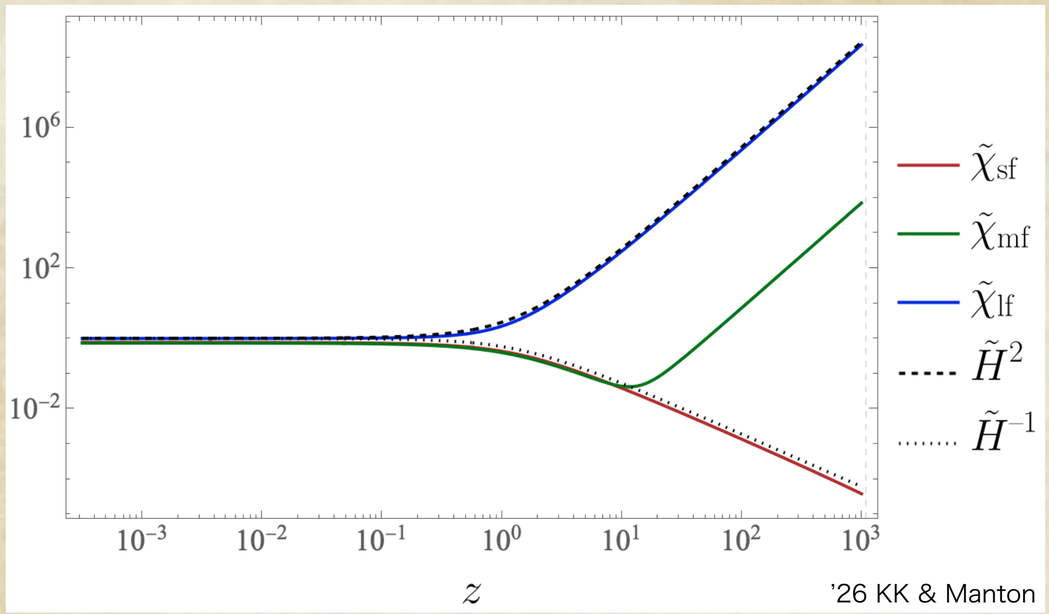
If we set (tune) $\rho_\chi^{\rm ini} \simeq 3H_0^2 M_{\rm pl}^2$, χ can explain the present dark energy.

$V = \frac{1}{2} m_\chi^2 \chi^2$

Two (attractor) solutions:

$$\chi_{\rm lf} = \chi_{\rm eq}^{\rm lf} \exp[-3(N - N_{\rm eq})] \propto H^2, \quad \text{with} \quad \chi_{\rm eq}^{\rm lf} \gg \chi_c,$$

$$\chi_{\rm sf} = \chi_{\rm eq}^{\rm sf} \exp[3(N - N_{\rm eq})/2] \propto H^{-1}, \quad \text{with} \quad \chi_{\rm eq}^{\rm sf} \ll \chi_c,$$



Dynamics at $z \gg 1$
is dominated by BG;
Recent dynamics depends on V
but looks almost independent.

Slide Background Courtesy: H. Oide

Dynamics of 3-form dark energy

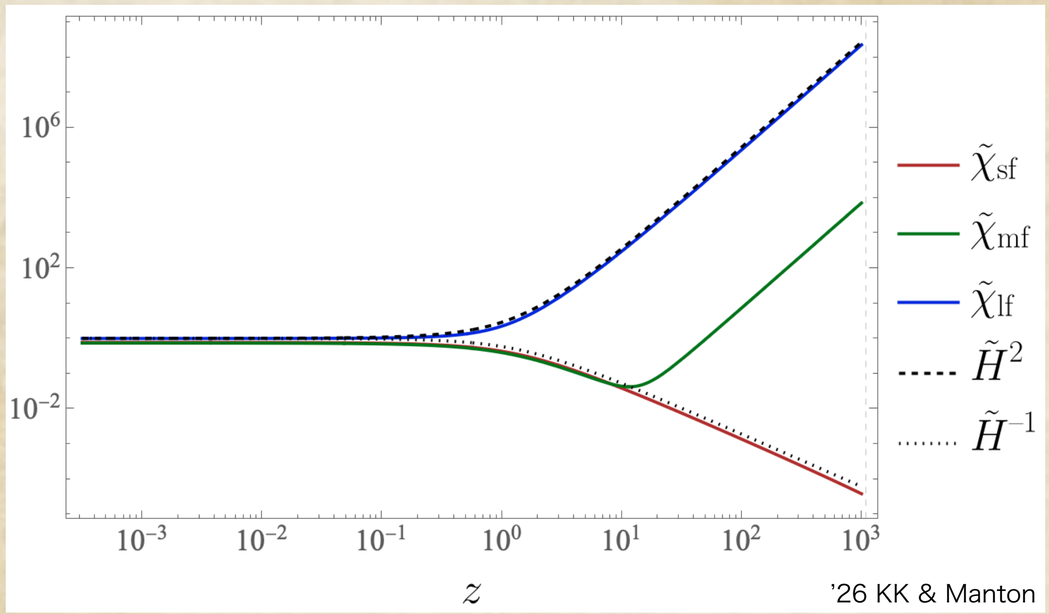
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is dominated by BG;
Recent dynamics depends on V
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Equation of state is sensitive;
Can be tested BAO?

Slide Background Courtesy: H. Oide

Effective interactions of 3-form field and cosmic birefringence

1. Dimension-6 (healthy) operator:

$$\mathcal{L}_{int} = -\frac{\epsilon}{4\Lambda^2} G_{\mu\nu\rho\sigma} F^{\mu\nu} F^{\rho\sigma},$$

Photon EOM:

$$\ddot{A}_{k,\pm} + H\dot{A}_{k,\pm} + (\tfrac{k^2}{a^2} \pm \tfrac{k}{a}\alpha(t))A_{k,\pm} = 0,$$

$$\alpha(t) = \frac{\epsilon}{\Lambda^2}(\ddot{\chi} + 3\frac{\mathrm{d}}{\mathrm{d}t}(H\chi)).$$

Slide Background Courtesy: H. Oide

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Birefringence is induced:

$$\beta = -\frac{\epsilon}{2\Lambda^2}\int_{t_{\rm LSS}}^{t_0} \mathrm{d}t\dot{X} = -\frac{\epsilon}{2\Lambda^2}\Big(X(t_0) - X(t_{\rm LSS})\Big). \qquad X = \dot{\chi} + 3H\chi,$$

Slide Background Courtesy: H. Oide

Effective interactions of 3-form field and cosmic birefringence

1. Dimension-6 (healthy) operator:

$$\mathcal{L}_{int} = -\frac{\epsilon}{4\Lambda^2} G_{\mu\nu\rho\sigma} F^{\mu\nu} F^{\rho\sigma},$$

Can it explain $\beta_0 \simeq 0.3^\circ$?

$$\chi \sim \chi_c \sim M_{\rm pl} \Rightarrow X \sim H\chi \sim H_0 M_{\rm pl} \quad \Rightarrow \quad \beta_0 \propto \frac{H_0 M_{\rm pl}}{\Lambda^2} \sim \frac{10^{-24}\ {\rm GeV}^2}{\Lambda^2}.$$

Cutoff scale Λ should be much smaller than the energy scale of DE $10^{-3}{\rm eV}$

Conclusion: Dimension-6 operator likely cannot explain observationally suggested cosmic birefringence $\beta_0 \simeq 0.3^\circ$

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Effective interactions of 3-form field and cosmic birefringence

2. Dimension-4 symmetry-breaking operator:

$$\mathcal{L}_{int} = \epsilon\lambda C_{\mu\nu\rho} F^{\mu\nu} A^{\rho},$$

Photon EOM:

$$\ddot{A}_{k,\pm} + H\dot{A}_{k,\pm} + (\tfrac{k^2}{a^2} \pm \tfrac{k}{a}\epsilon\lambda\chi(t))A_{k,\pm} = 0,$$

Birefringence is induced:

$$\beta = -\frac{\epsilon\lambda}{2}\int_{t_{\rm LSS}}^{t_0} dt\chi(t) = -\frac{\epsilon\lambda}{2}\int_{N_{\rm LSS}}^{0} \frac{dN}{H(N)}\chi(N).$$

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Can it explain $\beta_0 \simeq 0.3^\circ$?

$$\beta \propto \lambda \frac{M_{\rm pl}}{H_0} \sim \lambda \times 10^{60}.$$

➡ $\lambda \simeq 10^{-62}$ can explain $\beta_0 \simeq 0.3^\circ$

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Is it large or small, from viewpoint of gauge symmetry breaking?

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A Stückelberg trick for the gauge symmetry restoration

Let us introduce a scalar field π , which transforms under gauge trans.

$$\pi \to \pi - m_\gamma \alpha.$$

such that a combination

$$A_\mu \to A_\mu + \frac{1}{m_\gamma} \nabla_\mu \pi,$$

is gauge invariant.

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The gauge invariant Lagrangian is then

$$\begin{aligned}\mathcal{L}_{GI} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_\gamma^2(A_\mu + \tfrac{1}{m_\gamma}\nabla_\mu\pi)(A^\mu + \tfrac{1}{m_\gamma}\nabla^\mu\pi) \\ &- \lambda C_{\mu\nu\rho}F^{\mu\nu}(A^\rho + \tfrac{1}{m_\gamma}\nabla^\rho\pi) - A_\mu J^\mu_{\text{matter}}\end{aligned}$$

m_γ : photon mass

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A Stückelberg trick for the gauge symmetry restoration (Cont'd.)

The decoupling limit can be taken as $m_\gamma \to 0$

To keep the smooth decoupling of the interaction to 3-form field, we require

$$\lambda \sim \frac{m_\gamma}{M_{\rm pl}}$$

such that the Lagrangian in the decoupling limit is

$$\mathcal{L}_{\rm dec} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{48}G_{\mu\nu\rho\sigma}G^{\mu\nu\rho\sigma} - U(C^2)$$
$$- \frac{1}{2}(\nabla_\mu \pi)^2 - \frac{1}{M_p}C_{\mu\nu\rho}F^{\mu\nu}\nabla^\rho \pi.$$

Just a Planck-suppressed interaction

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non-zero m_γ acts as a light photon mass

Just a Planck-suppressed interaction

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Cosmic Birefringence with massive photon?

$$\lambda \simeq 10^{-62} \quad \text{for} \quad \beta_0 \simeq 0.3^\circ$$

corresponds to

$$m_\gamma \sim H_0 \simeq 10^{-33}\mathrm{eV}$$

See the PDG constraint, $m_\gamma < 10^{-18}\mathrm{eV}$

Conclusion: Dimension-4 operator can explain
observationally suggested cosmic birefringence
with a byproduct of present Hubble scale photon mass.

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Tomography of cosmic birefringence from 3-form DE

Two attractor solutions & intermediate solution:

$$\chi_{\rm lf} = \chi^{\rm lf}_{\rm eq} \exp[-3(N - N_{\rm eq})] \propto H^2, \quad \text{with} \quad \chi^{\rm lf}_{\rm eq} \gg \chi_c,$$

$$\chi_{\rm sf} = \chi^{\rm sf}_{\rm eq} \exp[3(N - N_{\rm eq})/2] \propto H^{-1}, \quad \text{with} \quad \chi^{\rm sf}_{\rm eq} \ll \chi_c,$$

$$\chi_{\rm mf} \simeq \mathcal{A}\,\chi_{\rm sf} + \mathcal{B}\,\chi_{\rm lf},$$

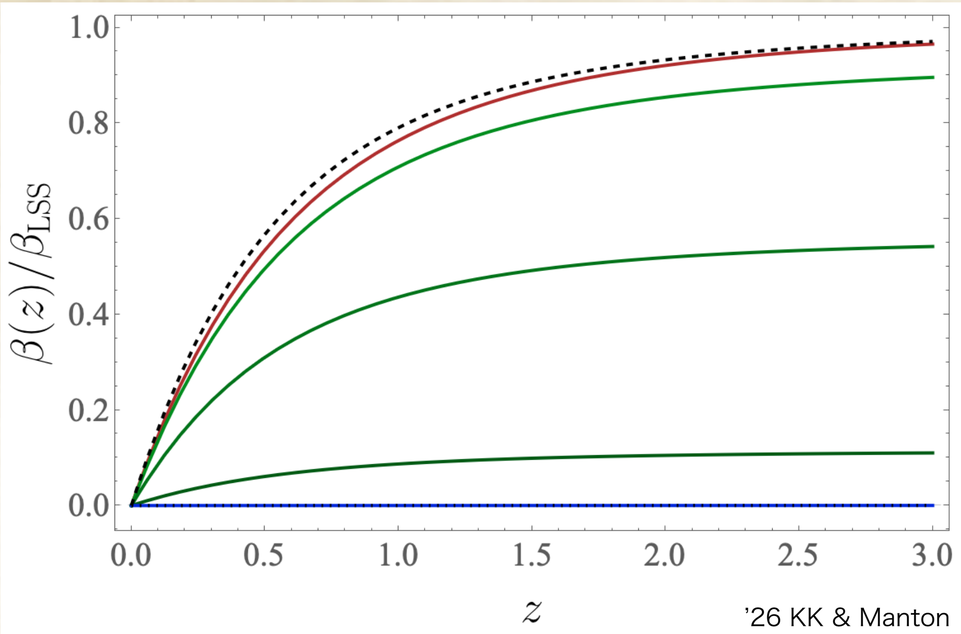
$$\begin{aligned}
\beta(z) &= -\frac{\epsilon\lambda}{2}\int_{t(z)}^{t_0} {\rm d}t\chi(t) \\
&= -\frac{\epsilon\lambda}{2}\int_0^z {\rm d}z' \frac{\chi(z')}{(1+z')H(z')} \\
&= -\frac{\epsilon\lambda\chi_c}{2} \times \begin{cases} \int_0^z \frac{H_0}{(1+z')H(z')^2} & \text{small field solution} \\ \int_0^z \frac{H(z')}{(1+z')H_0^2} & \text{large field solution} \end{cases}
\end{aligned}$$

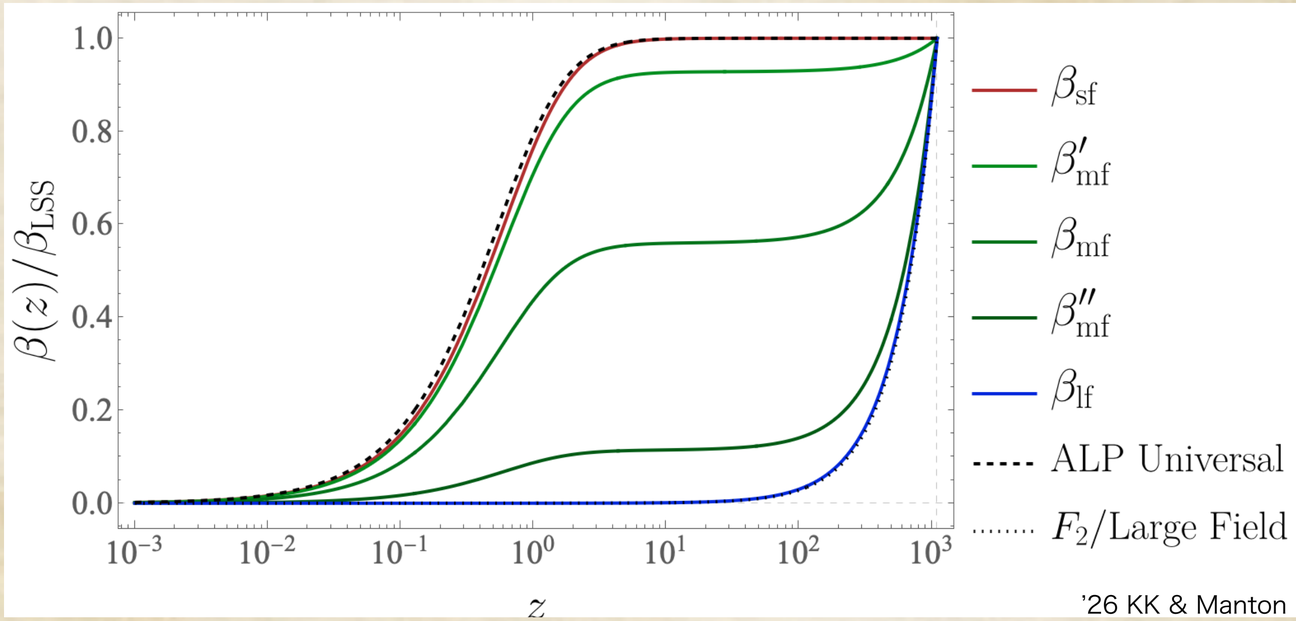
Potential independent! once more.

Small-field case is identical to ALP case.

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Tomography of cosmic birefringence from 3-form DE

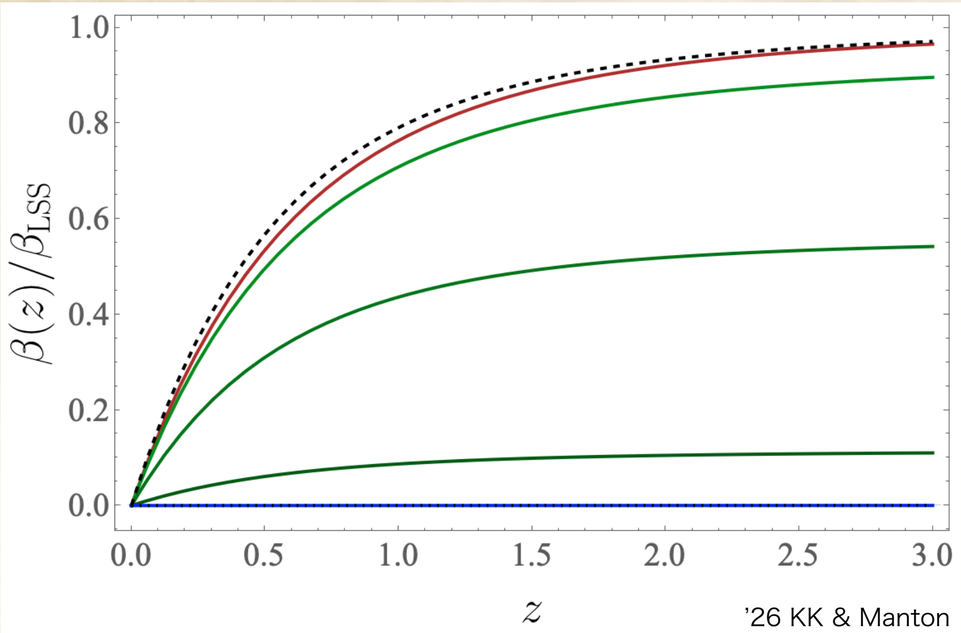


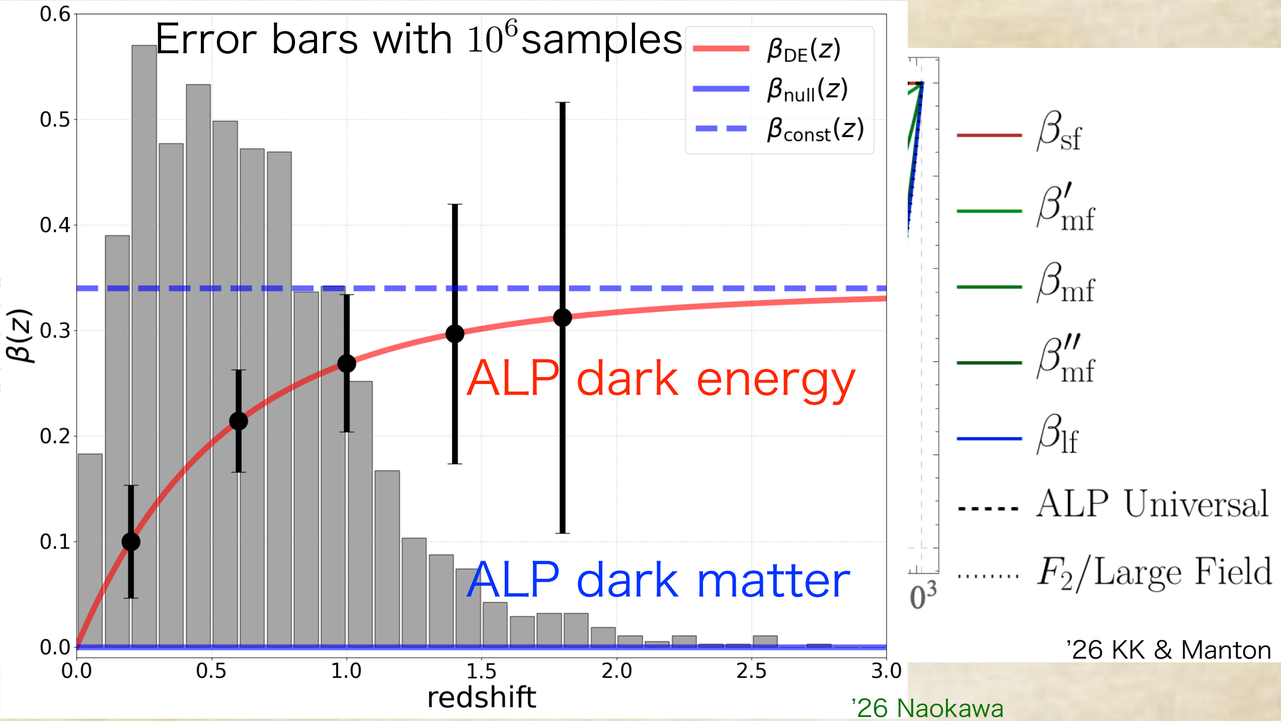


- Small field: identical to ALP DE - Intermediate: Distinct behavior
- Large field: similar to ALP DM -> interesting to see CMB C_ℓ^{EB}

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Tomography of cosmic birefringence from 3-form DE





- Small field: identical to ALP DE
- Intermediate: Distinguishable behavior
- Large field: similar to ALP DM -> interesting to see CMB C_ℓ^{EB}

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Summary

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- 3-form DE can mimic ΛCDM, quintessence.
- EFT-inspired coupling produce cosmic birefringence, possibly with different evolution of $\beta(z)$
- Dim-6 coupling too small to explain $\beta_0 \simeq 0.3^\circ$
- Dim-4 coupling candidate explanation, excites photon mass, smooth decoupling tells $m_\gamma \sim H_0 \simeq 10^{-33}\mathrm{eV}$
- Tomography of $\beta(z)$ can mimic ALP DE, ALP DM, or distinguishable for radio galaxies
- The ALP DM-like case is of interest for future CMB C_ℓ^{EB} analysis.

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Appendix

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3-form field ⋯ totally antisymmetric covariant tensor field of rank 3: $C_{\mu\nu\rho}$

$$\mathcal{L} = -\frac{1}{48} G_{\mu\nu\rho\sigma} G^{\mu\nu\rho\sigma}$$

$$G_{\mu\nu\rho\sigma} = \nabla_{[\mu} C_{\nu\rho\sigma]}$$

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$$\mathcal{L} = -\frac{1}{48} G_{\mu\nu\rho\sigma} G^{\mu\nu\rho\sigma} \qquad G_{\mu\nu\rho\sigma} = \nabla_{[\mu} C_{\nu\rho\sigma]}$$

with the gauge symmetry $C \to C + \mathrm{d}\Lambda$ potential term is forbidden.

-> Solution of EOM is a cosmological constant.

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