Cosmic Birefringence
&
Electroweak Axion Dark Energy

Work in collaboration with Weikang Lin, Luca Visinelli and Tsutomu Yanagida
Phys. Rev. D **104**, L101302 [arXiv:2106.12602]

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IBS-CTPU, PTC seminar
Dec 1, 2021

Cosmic Birefringence

- Recently, non-vanishing rotation angle of CMB linear polarization was reported (isotropic birefringence)
  → $\beta = 0.35 \pm 0.14$deg Y. Minami and E. Komatsu (2011.11254)

- A pseudo-scalar field A coupled to photon via

$$\mathcal{L}_{\rm eff} \supset -c_\gamma \frac{g_{\rm em}^2}{16\pi^2} \frac{A}{F_A} F^{\mu\nu} \tilde{F}_{\mu\nu} .$$

can induce $\beta \neq 0$ F. Takahashi, W. Yin (2012.11576)

$$\beta = 0.42\,{\rm deg} \times \frac{c_\gamma}{2\pi} \times \frac{A(t_0) - A(t_{\rm LSS})}{F_A}$$

How to have β~O(0.1)deg?

- For the case with

$$\mathcal{L}_{\rm eff} \supset -c_\gamma \frac{g_{\rm em}^2}{16\pi^2}\frac{A}{F_A}F^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{V_0}{2}\left[1-\cos\left(\frac{A}{F_A}\right)\right]$$

the easiest way to have β ~ O(0.1)deg is

$$\beta = 0.42\,{\rm deg} \times \frac{c_\gamma}{2\pi} \times \frac{A(t_0)-A(t_{\rm LSS})}{F_A}$$

c_γ ~ 10 → ΔA ~ O(0.1)F_A with $A(t_{LSS}) \simeq \pi F_A$

- Hilltop - inflection point ~ 1.5F_A → slow-roll to date

- → $-1 < w_A \equiv P_A / \rho_A < 0$ → quintessence DE?

Quintessence Dark Energy candidate?

- A good candidate for a quintessence?
  → very light?! → pNGB → axion?

- When an axion couples to instanton with $S_{inst} \sim 2\pi/\alpha(\rho)$, the instanton generates the potential $\sim M_P{}^4 e^{-S_{inst}} e^{iA}$

- QCD axion potential height is too large for Λ_{DE}~2meV

- Then the question is…
  could we have EW axion as dark energy candidate?

EW Axion DE? - dominant small size instanton

- $U(1)_{B+L}$ is anomalous w.r.t $SU(2)_L$
  → can make axion massless
  → assume gauge invariant operator $\mathcal{O}$ = $QQQL/M_P^2$

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$$V \sim \int^{\infty} \frac{d\rho}{\rho^5}\, e^{\frac{-2\pi}{\alpha(\rho)}} = \int^{\infty} \frac{d\rho}{\rho^5}\, e^{\frac{-2\pi}{\alpha(\rho_0)}} \left(\frac{\rho}{\rho_0}\right)^{-b}$$

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b = -7 for QCD

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IR domination

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- For SU(2) in SM with QQQL operator,

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Net negative power of ρ

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UV domination ← Net negative power of ρ

EW Axion DE? - the back of the envelope estimates

- $\Lambda_{DE}{}^4 \sim (2\text{meV})4 \sim M_P{}^4 10^{-120}$
- For $SU(2)_L$, instanton of size $\rho \sim M_P{}^{-1}$ dominates
- In SM, $\Lambda_a{}^4 \sim M_P{}^4 e^{-S_{inst}} \rightarrow M_P{}^4 e^{-(-2\pi/(1/44))} \rightarrow M_P{}^4 10^{-130}$

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Quite interesting to some people at 1990s

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- For our work, we consider $SU(2)_L$ in MSSM
- From $\rho_{DE} \sim (2\text{meV})^4 \sim (m_A F_A)^2$,
  expect $m_A \sim 10^{-33}$eV and $F_A \sim O(10^{17})$GeV

EW Axion DE - symmetry

- Symmetry Group

Y. Nomura, T. Watari, T. Yanagida (2000)

$$G = G_{\rm SM} \otimes Z_{4R} \otimes U(1)_F \otimes U(1)_X$$

- $U(1)_F$ is an approximate global symmetry
  → already explicitly broken down by QQQL operator

- Z_{4R} is the gauged discrete R-symmetry

- $U(1)_X$ is the global symmetry
  → SSB results in quintessence axion

EW Axion DE - particle contents

	Q	$\overline{U}$	$\overline{D}$	L	$\overline{E}$	H_u	H_d	$e^{-8\pi^2\tau}$	$\mathcal{D}^2$	$\overline{\mathcal{D}}^2$	Ψ	$\overline{\Psi}$	Φ	$\overline{\Phi}$	X	H'_u	H'_d	Σ	Σ'	$\epsilon \equiv \langle\phi\rangle/M_P$
$U(1)_Y$	1/6	-2/3	1/3	-1/2	1	1/2	-1/2	-	-	-	-	-	-	-	-	1/2	-1/2	-	-	-
$SU(2)_L$	□	-	-	□	-	□	□	-	-	-	□	□	-	-	-	□	□	Ad	Ad	-
Z_{4R}	3/5	3/5	1/5	1/5	3/5	4/5	6/5	-2	-2	$+2$	1	1	0	0	$+2$	$-6/5$	6/5	0	$+2$	-
$U(1)_F$	$(2,1,0)$	$(2,1,0)$	$(1,0,0)$	$(1,0,0)$	$(2,1,0)$	-	-	$+10$	-	-	-	-	-	-	-	-	-	-	-	-1
$U(1)_X$	-	-	-	-	-	-	-	-	-	-	-1	-	+1	-1	-	-	-	-	-	-

- MSSM → Q, U-bar, D-bar, L, E-bar, H_u, H_d
- Ψ, Ψ-bar, Φ, Φ-bar
  → for axion coupling to $SU(2)_L$ anomaly
- Hu’, Hd’
  → makes the mixed anomaly of Z_{4R} x $[SU(2)_L]^2$ vanish
- Σ, Σ’
  → enhances $\alpha_2(M_P)$

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Spurion for $U(1)_F$

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EW Axion DE - SU(2) gauge and PQ sector

- Superpotential (SU(2) gauge and PQ sector)

$$W \supset \frac{\tau}{4}\mathcal{W}^{a\alpha}\mathcal{W}^{a}_{\alpha} + \Phi\Psi\overline{\Psi} + X(\Phi\overline{\Phi} - 2F_A) \qquad \tau = \frac{1}{g_2^2} + i\frac{\Theta}{8\pi^2} - \frac{2m_{1/2}}{g_2^2}\theta^2$$

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- SSB of $U(1)_X$ leads to

$$\begin{aligned} \langle\Phi\rangle &= (F_A/\sqrt{2})\exp[\mathcal{A}/F_A] \\ \langle\overline{\Phi}\rangle &= (F_A/\sqrt{2})\exp[-\mathcal{A}/F_A] \end{aligned}$$

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- SSB of $U(1)_X$ leads to

$$\mathcal{L} \supset \int d^2\theta\left(\frac{1}{32\pi^2}\frac{\mathcal{A}}{F_A}\mathcal{W}^{a\alpha}\mathcal{W}^a_\alpha + \text{h.c.}\right)$$

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- assume gauge invariant QQQL operator
  → explicitly breaks $U(1)_{B+L}$
- QQQL can induce the proton decay

  Sakai-Yanagida (1982), Weinberg (1982)

  → should be sufficiently suppressed
  → use the approximate $U(1)_F$ symmetry
  with $\varepsilon = \langle \phi \rangle / M_P \sim 1/17$

  Sato-Yanagida (1998)

EW Axion DE - axion potential

- Good reference → arXiv:hep-ph/9809286
  "Small Instanton Contribution to the Axion Potential in Supersymmetric Models"
  K. Choi and H. Kim

- The effective Lagrangian at $\rho^{-1} \sim M_P$

$$\begin{aligned}
\mathcal{L} \;=\; & \int d^2\theta d^2\bar{\theta} \left[\sum_r Z_r \Phi_r^\dagger \Phi_r + \sum_i \frac{Y_i}{M_{\rm pl}^{d_i-2}} \mathcal{O}_i \right] \\
& + \left[\int d^2\theta \left(\tilde{\mu} H_u H_d + \sum_j \frac{\tilde{Y}_j}{M_{\rm pl}^{\tilde{d}_j-3}} \tilde{\mathcal{O}}_j \right) + \text{h.c.} \right] \\
& + \left[\int d^2\theta \frac{1}{4} \left(S + \frac{1}{8\pi^2} \frac{\Phi_{\mathcal{A}}}{F_{\mathcal{A}}} \right) W^{a\alpha} W^a_\alpha + \text{h.c.} \right],
\end{aligned}$$

$$\begin{aligned}
Z_r &= 1 - m_r^2 \theta^2 \bar{\theta}^2, \\
Y_i &= \left(1 + C_i \theta^2 + C_i^* \bar{\theta}^2 + |D_i|^2 \theta^2 \bar{\theta}^2\right) \eta_i, \\
\tilde{\mu} &= \left(1 + B\theta^2\right) \mu, \\
\tilde{Y}_j &= \left(1 + A_j \theta^2\right) \lambda_j, \\
S &= \frac{1}{g^2} + i \frac{\Theta}{8\pi^2} - \frac{2m_{1/2}}{g^2} \theta^2,
\end{aligned}$$

EW Axion DE - axion potential

- After integrating out superfields with vanishing vev,

$$\mathcal{L} = \int d^2\theta d^2\bar\theta \left[e^{-\left(8\pi^2 S + \frac{\Phi_{\mathcal{A}}}{F_{\mathcal{A}}}\right)} K_{\rm eff}(\Phi_r, \Phi_r^\dagger, \mathcal{D}^\alpha, \bar{\mathcal{D}}_{\dot\alpha}, Z_r, Y_i, \tilde\mu, \tilde\mu^\dagger, \tilde Y_j, \tilde Y_j^\dagger, e^{S+S^\dagger}; \rho) + {\rm h.c.} \right]$$
$$+ \left[\int d^2\theta e^{-\left(8\pi^2 S + \frac{\Phi_{\mathcal{A}}}{F_{\mathcal{A}}}\right)} W_{\rm eff}(\Phi_r, \tilde\mu, \tilde Y_j; \rho) + {\rm h.c.} \right],$$

(

- Under Z_{4R} transformation, θ shifts by 2α
  → R-charge of $e^{-8\pi^2\tau}$ is -2
  → $R[K_{\rm eff}]=2$ and $R[W_{\rm eff}]=4$

EW Axion DE - axion potential

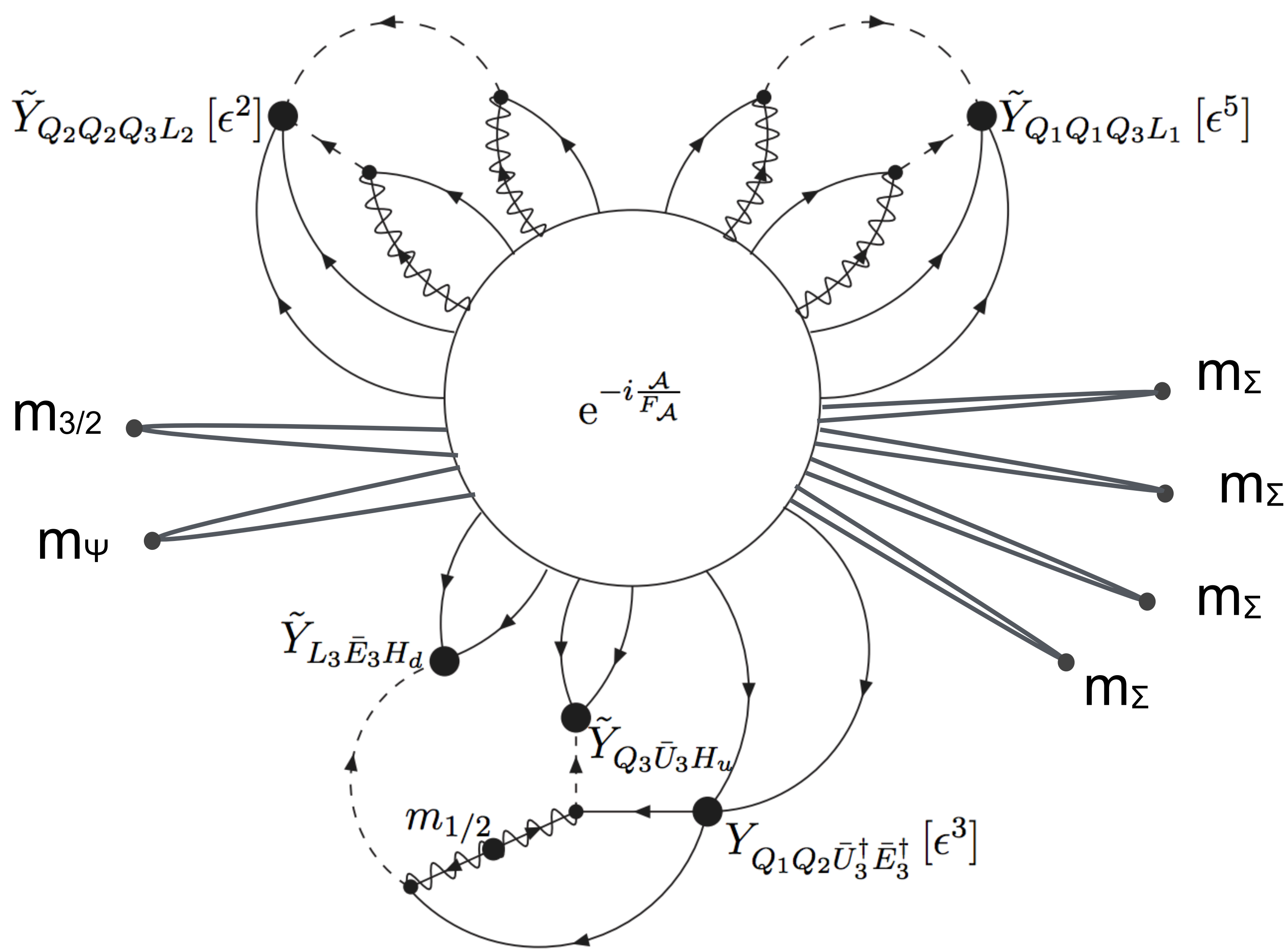
- R-charges of two covariant derivatives = 2
- Mass dimension of two covariant derivatives = 1

$$K_{\mathrm{eff}} = \rho^{-2}\left(\rho\bar{\mathcal{D}}^2\right) f\left(Z_r,\ \frac{Y_i}{(\rho M_{\mathrm{pl}})^{d_i-2}},\ \frac{\tilde{Y}_j}{(\rho M_{\mathrm{pl}})^{\tilde{d}_j-3}},\ \frac{\tilde{Y}_j^\dagger}{(\rho M_{\mathrm{pl}})^{\tilde{d}_j-3}},\ \mathrm{e}^{S+S^\dagger}\right)$$

- "f" is expanded in terms of dimensionless quantities
  → contains couplings constants and coefficients
  of operators used for closing fermion zero modes

EW Axion DE - axion potential

$$\mathcal{O} = Q_1 Q_2 \bar{U}_3^\dagger \bar{E}_3^\dagger,\ \tilde{\mathcal{O}} = Q_1 Q_1 Q_3 L_1,\ Q_2 Q_2 Q_3 L_2,\ Q_3 \bar{U}_3 H_u \text{ and } L_3 \bar{E}_3 H_d$$



EW Axion DE - axion potential

- Eventually one obtains

$$
\begin{aligned}
{\Lambda_{\mathcal{A}}}^4 &\simeq c\, e^{-\frac{2\pi}{\alpha_2(M_P)}} \epsilon^{10} m_{\rm SUSY}^3 M_P \\
&\quad \times \left(\frac{m_{3/2}}{M_P}\right)^{2T(\Box)} \left(\frac{m_\Psi}{M_P}\right)^{2T(\Box)} \left(\frac{m_\Sigma}{M_P}\right)^{2T(\rm Ad)} \\
&\simeq c\, e^{-\frac{2\pi}{\alpha_{2,\rm MSSM}(M_P)}} \epsilon^{10} m_{\rm SUSY}^3 M_P \\
&\simeq c\epsilon^{10} (1\,{\rm eV})^4 \,,
\end{aligned}
$$

F_A and $\alpha_2(M_P)$?

- Slow-roll for Quintessence M. Ibe, M. Yamazaki, T. Yanagida (2018)

$$\ddot{a} + 3H_0\dot{a} = -V'(a),$$

F_A and $\alpha_2(M_P)$?

- Slow-roll for Quintessence M. Ibe, M. Yamazaki, T. Yanagida (2018)

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→ For quintessence, better to have F_A as large as M_P

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- For $F_A \sim M_P$, $\alpha_2(M_P) \sim 1 > \alpha_{2,\rm MSSM}(M_P)$

- Hu',Hd', Ψ, Ψ-bar helps enhancing α_2, but not enough!
  → Introduce heavy $SU(2)_L$ triplets Σ and Σ'
  (with $m_\Sigma \sim O(10^7)$GeV)

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- Can EW axion DE explain β = 0.35 deg?

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$C_\gamma > \sim 2\pi$?

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- In the current model, c_γ is at most 1
→ introduce Ω charged both under $U(1)_X$ and $U(1)_Y$
→ The number of Ω is limited by $\alpha_1(M_P)<1$
→ $c_\gamma \equiv \sum_{i=\Psi,\Omega} Q_{X,i} Q^2_{\mathrm{em},i}$ is limited as well

- From model's point of view,
for each F_A, there is corresponding m_Ω and this changes $\#_\Omega$ and (and $\#_{\Omega\text{-bar}}$) satisfying $\alpha_1(M_P)=1$
→ different F_A corresponds to different c_γ

Mapping w_{DE} to β/c_γ

F_A

dA/dt=0 at LSS + $\delta A(t) = \pi F_A - A(t)$

$$\ddot{A} + 3H\dot{A} + \frac{\partial V(A)}{\partial A} = 0$$

$\delta A(t_0)$

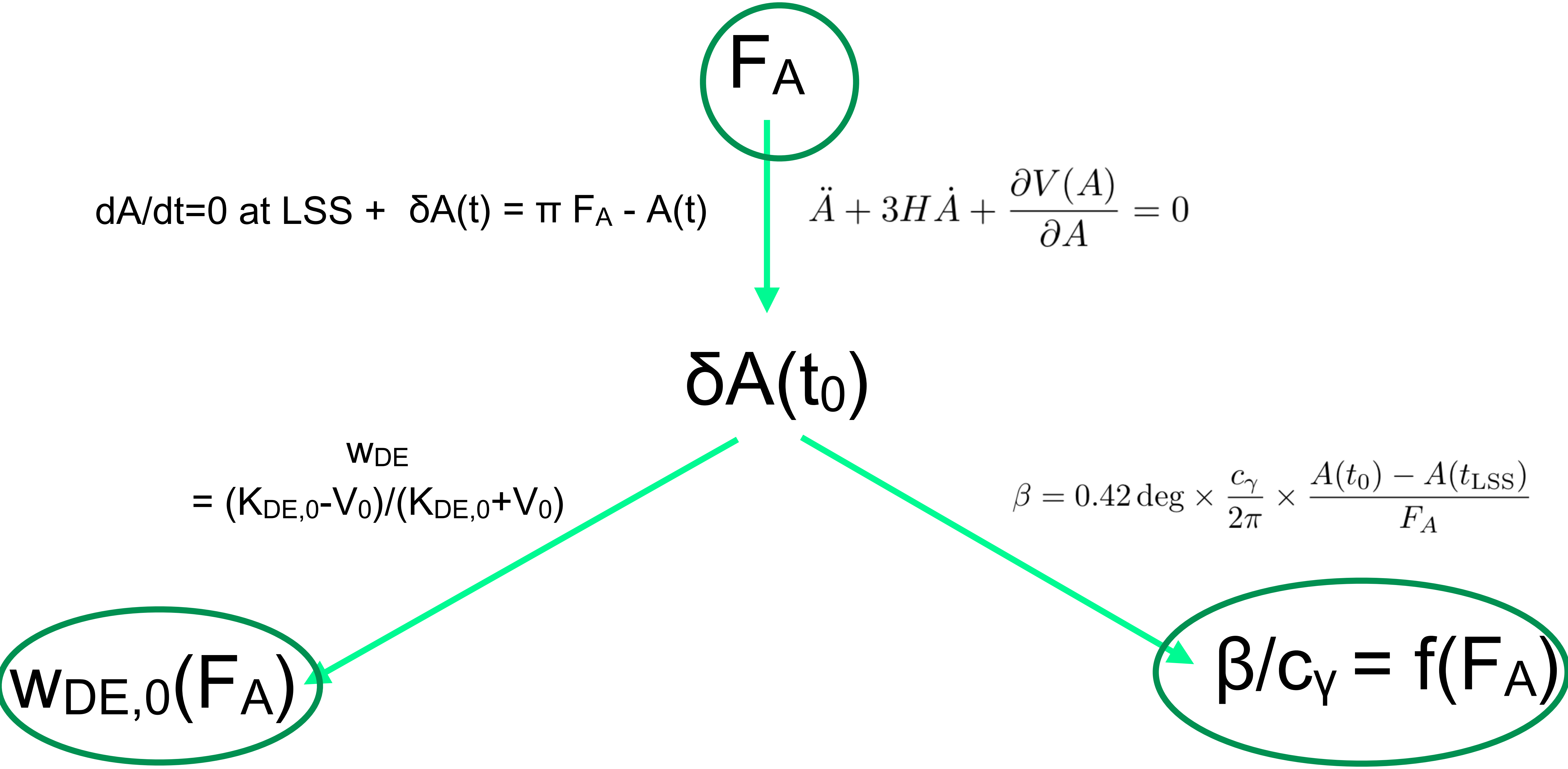
$w_{DE,0}$
$= (K_{DE,0}-V_0)/(K_{DE,0}+V_0)$

$$\beta = 0.42\,\mathrm{deg} \times \frac{c_\gamma}{2\pi} \times \frac{A(t_0) - A(t_{\mathrm{LSS}})}{F_A}$$

$w_{DE,0}(F_A)$

$\beta/c_\gamma = f(F_A)$

Mapping w_{DE} to β/c_γ



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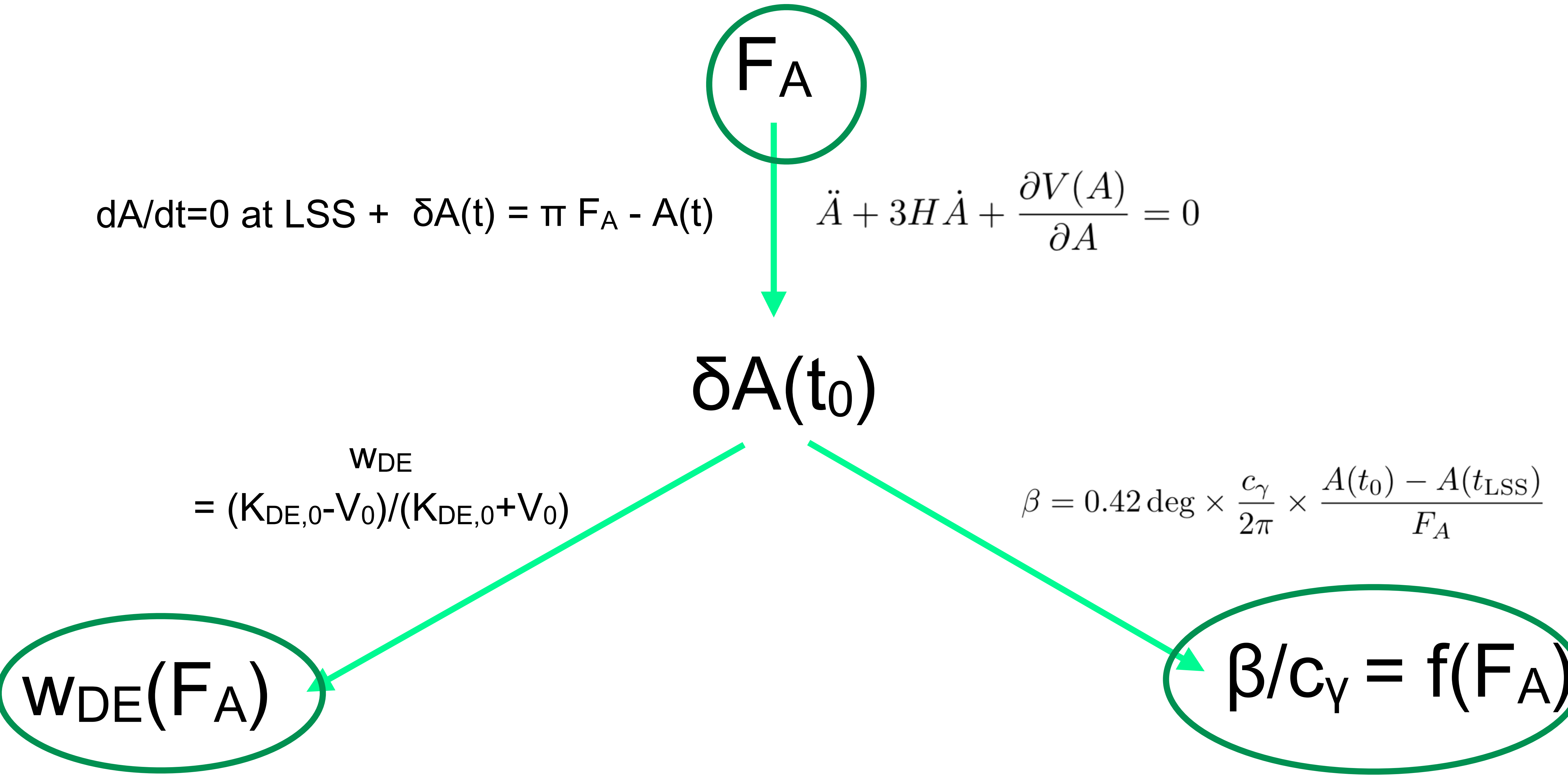


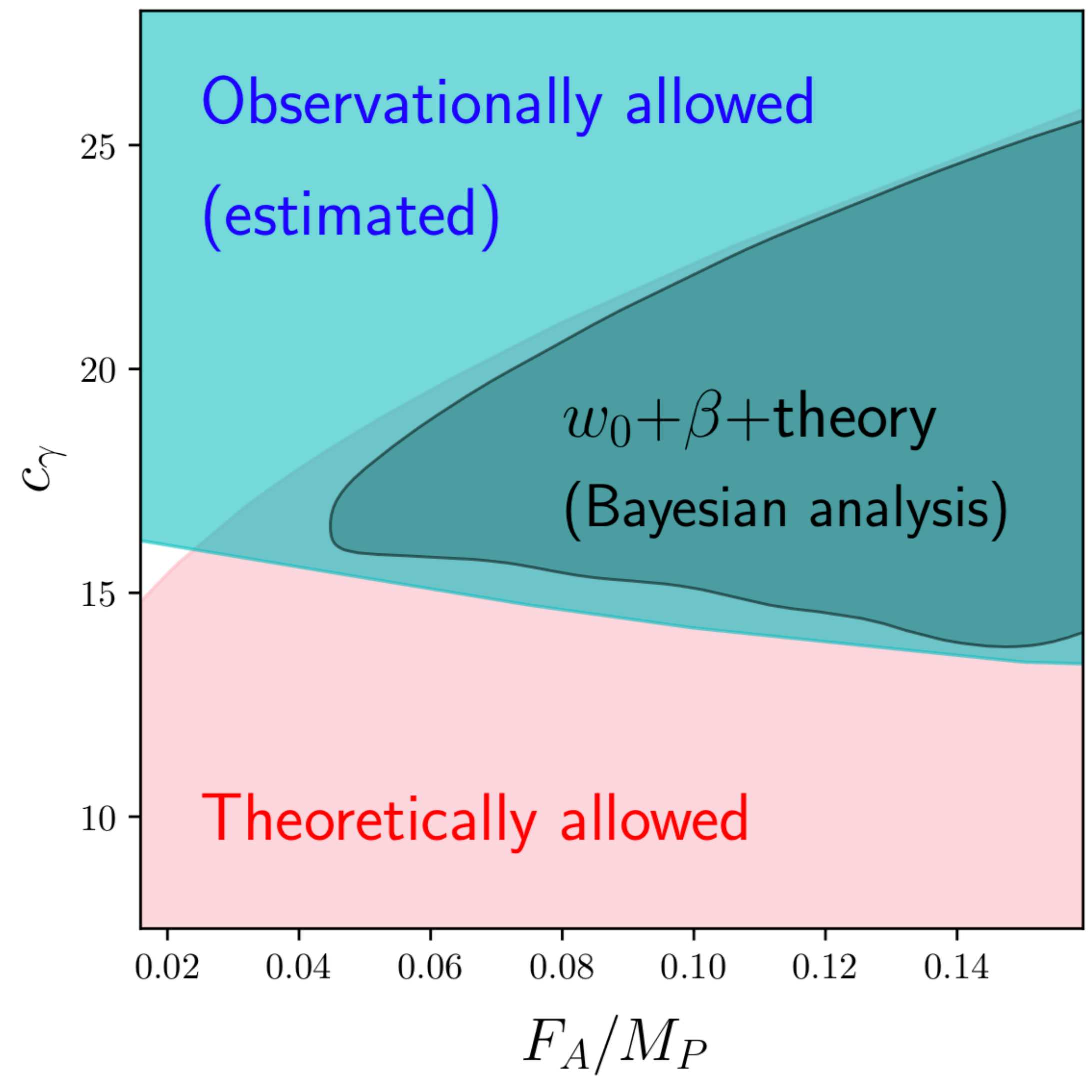
$$w_{\mathrm{DE},0} = -1 + 2\pi^2\xi^2 \left(\frac{\beta/c_\gamma}{0.42\,\mathrm{deg}} \right)^2$$

F_A/M_P	0.3	0.25	0.2	0.15	0.1	0.075	0.05	0.025	$\to 0$
ξ	0.85	0.82	0.80	0.81	0.85	0.89	0.93	0.96	1

Constraining EoS (w_{DE})

- Applying
  1. $w_{DE,0}$<-0.95, β=0.35deg to the relation
     (Planck TT,TE,EE+lowE+lensing+BAO+SN w/ prior $w_{DE,0} \geq -1$)
  2. $c_{\gamma,th}$ ensuring perturbativity of $U(1)_Y$

- We obtain c_γ consistent with cosmic birefringence, constraint on EoS of quintessence DE, and perturbativity of the model
  → $-0.994 < w_{DE,0} < -0.968$ (68% C.L.)



Summary

- Cosmic Birefringence can be a hint for a quintessence dark energy
- Electroweak axion can be a candidate for the quintessence DE ($m_A \sim 10^{-33}$eV, $F_A \sim O(10^{17})$GeV)
- Model's prediction for $\Lambda_{DE} \sim O(1)$meV is insensitive to a UV structure of the model
- Explaining β=0.35deg, the model predicts $-0.994 < w_{DE,0} < -0.968$ (68% C.L.)
- If $\delta\beta \sim O(10^{-2})$ is achieved in near-future CMB missions, $-0.982 < w_{DE,0} < -0.961$ (68% C.L.)