Constraints on massive vector dark energy models from ISW-galaxy cross-correlations

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Based on PRD 99, 063533 (2019)

Outline

- Introduction to vector-tensor theories
- ISW effect as probe of dark energy models
- Observational constraints
- Summary

Introduction

- Our universe is accelerating now.

  ⇨ The source of this acceleration is dubbed "dark energy (DE)"

GR

- ΛCDM model ⇨ cosmological constant, H0 tension...

spin0

- Scalar-tensor theories ⇨ scalar field coupled to gravity

  (e.g.) Horndeski theories

spin1

- Vector-tensor theories ⇨ vector field coupled to gravity

  (e.g.) Generalized Proca theories

Horndeski theories: a scalar field coupled to gravity

The most general scalar-tensor theories with 2nd-order EoMs:

$$\mathcal{L}_H = G_2(\pi, X) + G_3(\pi, X)\,\Box\pi + G_4(\pi, X)\,R + G_{4,X}(\pi, X)[(\Box\pi)^2 - \pi^{;\mu\nu}\pi_{;\mu\nu}]$$
$$+G_5(\pi, X)G_{\mu\nu}\pi^{;\mu\nu} - \frac{1}{6}\,G_{5,X}(\pi, X)[(\Box\pi)^3 - 3(\Box\pi)\pi_{;\mu\nu}\pi^{;\mu\nu} + 2\pi_{;\mu\nu}\pi^{;\mu\sigma}\pi^{;\nu}{}_{;\sigma}]$$

where

π : scalar field with kinetic energy $X = -\nabla_\mu\pi\nabla^\mu\pi/2,$

$G_2,\, G_3,\, G_4,\, G_5$: arbitraly function

R : Ricci scalar, $G_{\mu\nu}$: Einstein tensor

DOFs: 2 tensors + 1 scalar

Horndeski theories: a scalar field coupled to gravity

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The GW170817 event constrained the speed of gravitational waves to be very close to that of light.

Demanding that $c_T = c$

$$\mathcal{L}_H = G_2(\pi, X) + G_3(\pi, X)\Box\pi + G_4(\pi)R$$

In GR, $G_4 = M_{\rm pl}^2/2$

Degrees of freedom for vector fields (Minkowski space-time)

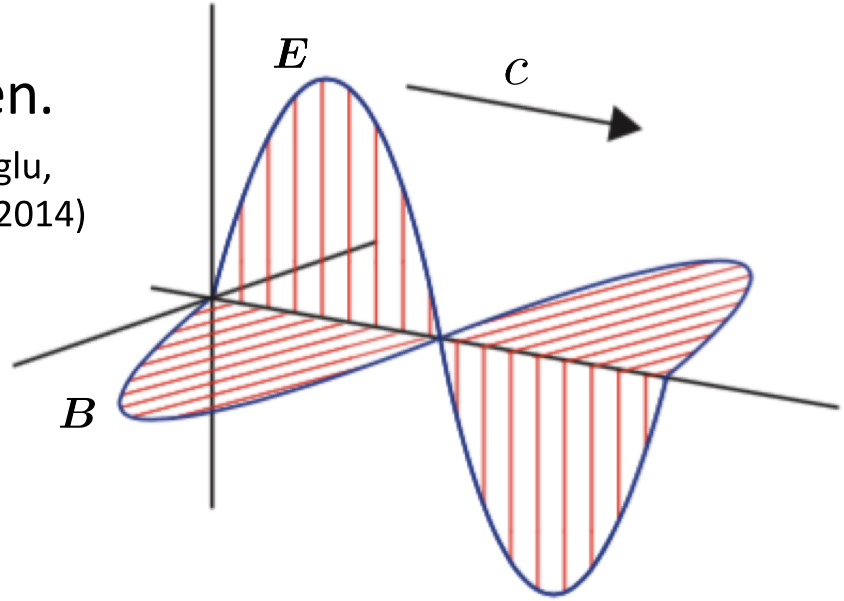
・U(1) gauge field (massless)

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \, , \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

⇨ DOFs: 2 transverse polarizations.

⇨ If we keep U(1) gauge symmetry,
Galileon-like interactions are forbidden.

C. Deffayet, A. E. Gumrukcuoglu,
S. Mukohyama and Y. Wang (2014)



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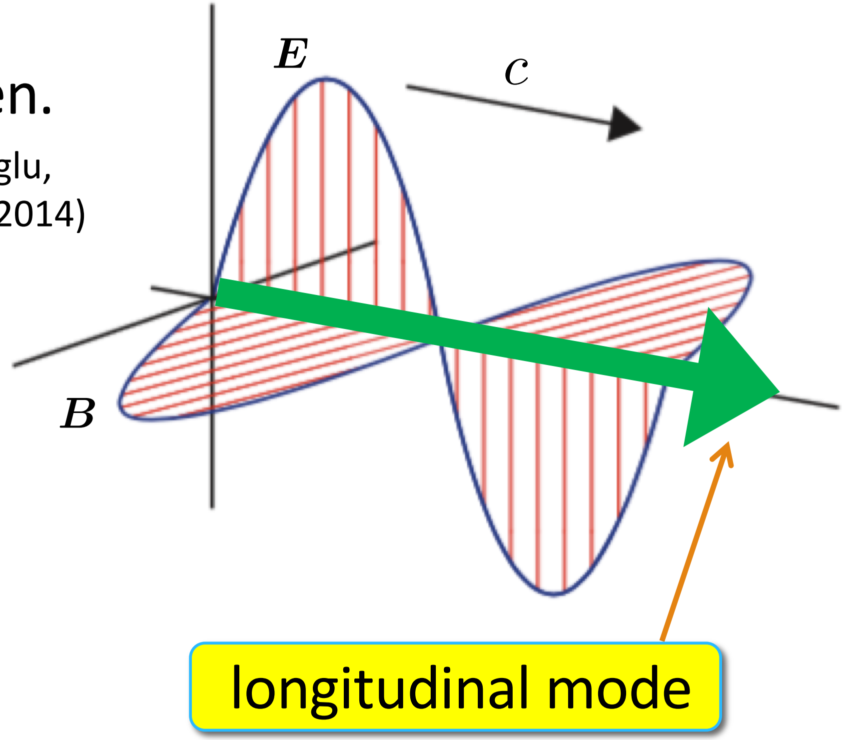
- Proca field (massive) (3 DOFs)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \underline{- \frac{1}{2}m^2 A_\mu A^\mu}\,,$$

⇨ U(1) symmetry is broken.

⇨ DOFs:2 transverse polarizations
+ 1 longitudinal mode.



Generalized Proca theories: a vector field coupled to gravity

G. Tasinato (2014), L. Heisenberg (2014), J. B. Jimenez and L. Heisenberg (2016)

$$\mathcal{L}_{\rm GP} = \sum_{i=2}^{6} \mathcal{L}_i \,,$$

Intrinsic vector mode

$$\mathcal{L}_2 = G_2(X, F, Y) \,,$$

$$\mathcal{L}_3 = G_3(X) \nabla_\mu A^\mu \,,$$

$$\mathcal{L}_4 = G_4(X) R + G_{4,X}(X) \left[(\nabla_\mu A^\mu)^2 - \nabla_\rho A_\sigma \nabla^\sigma A^\rho \right] ,$$

$$\mathcal{L}_5 = G_5(X) G_{\mu\nu} \nabla^\mu A^\nu - \frac{1}{6} G_{5,X}(X) [(\nabla_\mu A^\mu)^3 - 3 \nabla_\mu A^\mu \nabla_\rho A_\sigma \nabla^\sigma A^\rho + 2 \nabla_\rho A_\sigma \nabla^\gamma A^\rho \nabla^\sigma A_\gamma]$$

$$- g_5(X) \tilde{F}^{\alpha\mu} \tilde{F}^\beta{}_\mu \nabla_\alpha A_\beta \,,$$

$$\mathcal{L}_6 = G_6(X) L^{\mu\nu\alpha\beta} \nabla_\mu A_\nu \nabla_\alpha A_\beta + \frac{1}{2} G_{6,X}(X) \tilde{F}^{\alpha\beta} \tilde{F}^{\mu\nu} \nabla_\alpha A_\mu \nabla_\beta A_\nu \,,$$

Intrinsic vector modes

The EOMs are second-order on general space-time with 5 DOFs.

where $X = -\frac{A_\mu A^\mu}{2}$, $F = -\frac{F_{\mu\nu} F^{\mu\nu}}{4}$, $Y = A^\mu A^\nu F_\mu{}^\alpha F_{\nu\alpha}$, $\tilde{F}^{\mu\nu} = \frac{1}{2} \mathcal{E}^{\mu\nu\alpha\beta} F_{\alpha\beta}$, $L^{\mu\nu\alpha\beta} = \frac{1}{4} \mathcal{E}^{\mu\nu\rho\sigma} \mathcal{E}^{\alpha\beta\gamma\delta} R_{\rho\sigma\gamma\delta}$.

$\mathcal{E}^{\mu\nu\alpha\beta}$: Levi-Civita tensor

- DOFs: 2 tensors + 2 vectors + 1 scalar
- In the limit ($A_\mu \to \nabla_\mu \phi$), $\mathcal{L}_{\rm GP}$ reduces to the shift-symmetric Horndeski theories.

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Cosmological background in Generalized Proca theories

Action: $\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2} + G_2(X,F,Y) + G_3(X)\nabla_\mu A^\mu + \mathcal{L}_6\right] + \mathcal{S}_M\,,$

Metric: $ds^2 = -dt^2 + a^2(t)\delta_{ij}dx^i dx^j\,.$

$c_T = c$

A vector field with the perturbations:

$X \equiv -A_\mu A^\mu/2 = \phi^2/2$

$$A^\mu = \left(\phi(t) + \delta\phi,\ \frac{1}{a^2}\delta^{ij}\partial_j\chi_V + E^i\right)$$

⇦ From isotropy of the background

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⇦ From isotropy of the background

The background equations of motion:

$\phi=\phi(H)$

$$g_{00}:3M_{\rm pl}^2H^2=-G_2+\rho_m+\rho_r\,,\quad A^\mu:\ \phi\left(G_{2,X}+3G_{3,X}H\phi\right)=0\,,$$

- Intrinsic vector modes do not appear at the background level.
- $\phi\neq 0$ ⇨ There exist de Sitter solutions characterized by

$\phi=\text{constant}$ and $H=\text{constant}.$

A simple dark energy model in vector-tensor theories

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{M_{\rm pl}^2}{2} R + F + G_2(X) + G_3(X) \nabla_\mu A^\mu \right] + \mathcal{S}_M \,,$$

where

$$G_2(X) = b_2 X^{p_2} \,, \quad G_3 = b_3 X^{p_3} \,,$$

$b_2,\, b_3,\, p_2,\, p_3$: constants.

→ The cubic vector Galileon corresponds to the case with $p_2 = p_3 = 1$.

When $\phi \neq 0$, there are the solutions characterized by

$\phi^p H = \text{constant}$ with $p = 1 - 2p_2 + 2p_3 > 0$

→ ϕ grows with the decrease of H to give rise to the late-time cosmic acceleration.

Dark energy equation of state in our model

$$w_{\rm DE} = -\frac{3(1+s)+s\Omega_r}{3(1+s\Omega_{\rm DE})}$$

Radiation era : $w_{\rm DE} = -1 - 4s/3$

Matter era : $w_{\rm DE} = -1 - s$

de Sitter era : $w_{\rm DE} = -1$

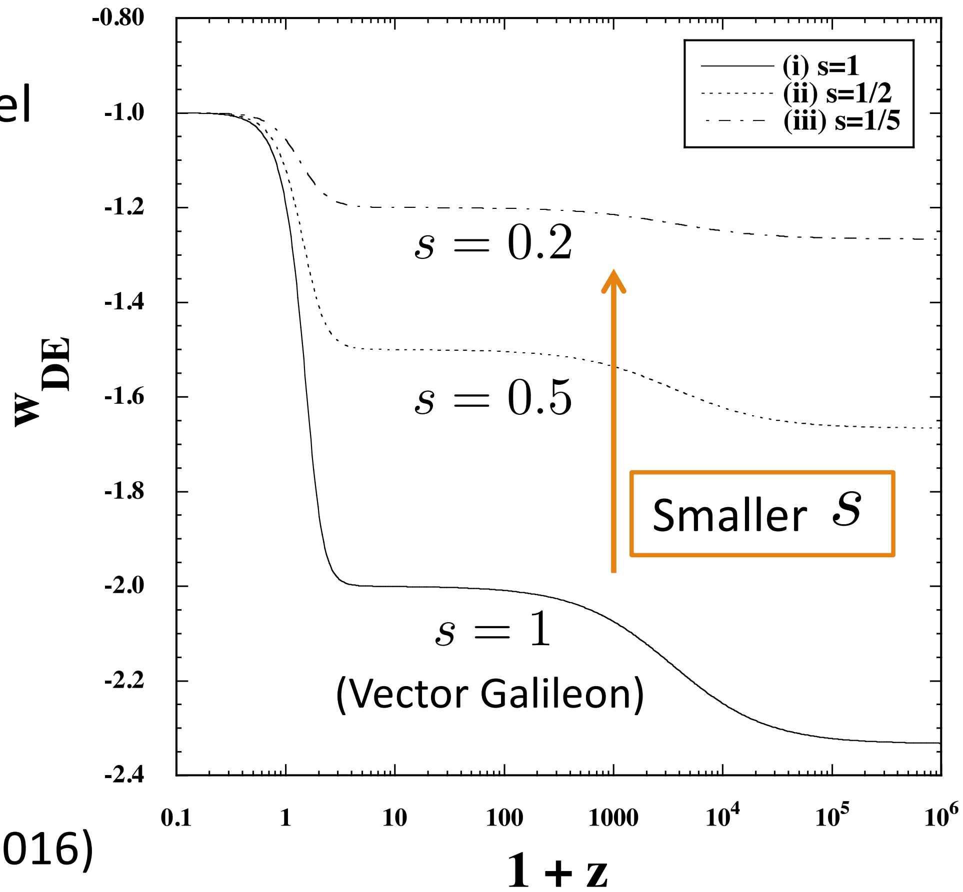
$s \equiv p_2/p$: Deviation from ΛCDM model

Ω_r : Radiation density parameter

$\Omega_{\rm DE}$: DE density parameter

The ΛCDM limit: $s = 0$

The solutions converge to a de Sitter attractor.



A. De Felice et al (2016)

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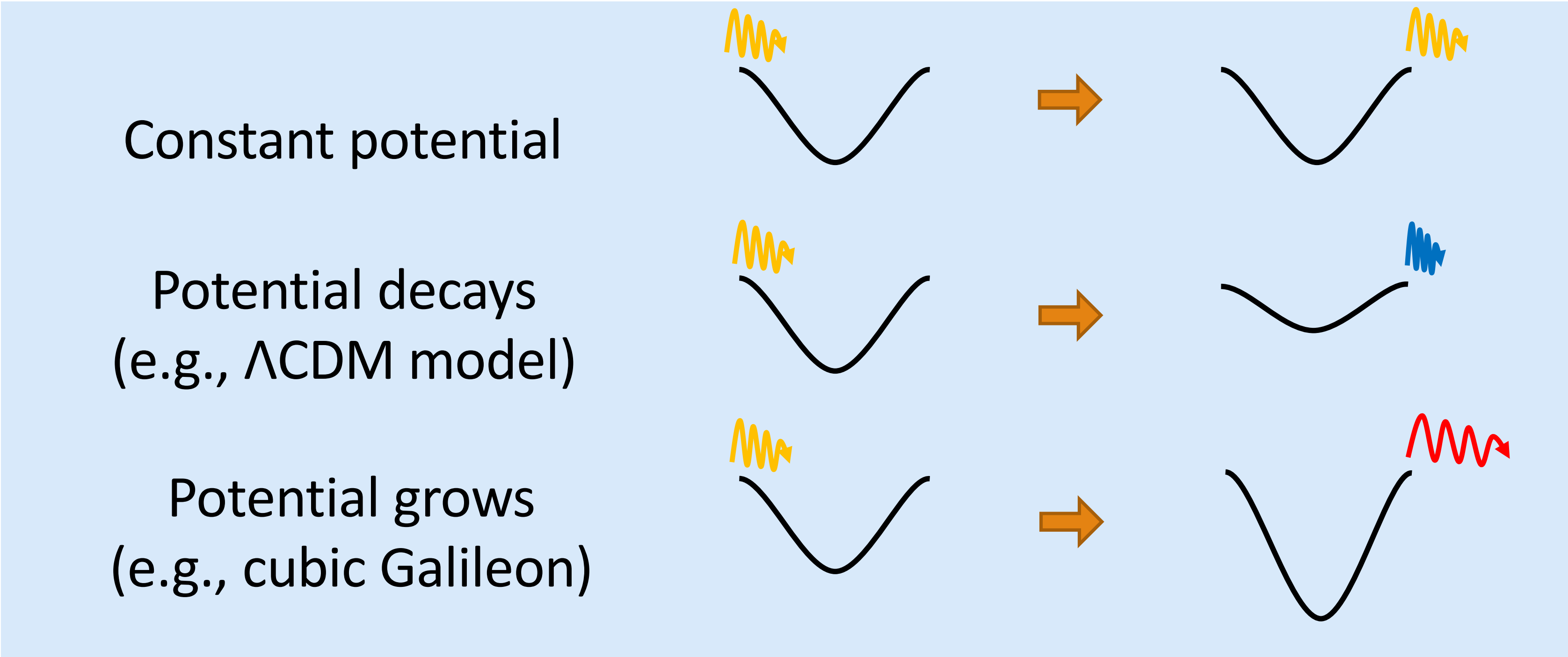
Integrated Sachs-Wolfe (ISW) effect



- Detection of late-time ISW effect in a flat universe is independent evidence for dark energy.
- Taking the cross-correlation between the CMB anisotropy and the galaxy distributions, we can separate the ISW signal from the CMB anisotropy.

Dark energy model with $c_T = c$

The cross-correlation between ISW effect in CMB and galaxy distributions is given by

$$\left\langle \underbrace{\frac{\Delta T_{\rm ISW}(\hat{n})}{T}}_{\text{CMB temperature anisotropy}} \underbrace{\frac{\Delta N_{\rm Galaxy}(\hat{n}')}{N}}_{\text{Galaxy number density fluctuations}} \right\rangle = \sum_{l=0}^{\infty} \frac{2l+1}{4\pi} C_l^{\rm IG} \mathcal{P}_l(\cos\theta)\,,$$

CMB temperature anisotropy   Galaxy number density fluctuations

This cross-correlation can distinguish the different dark energy models:

GR
- ΛCDM model ⇒ The ISW-galaxy cross-correlation is positive.

spin0
- Cubic-order scalar-tensor theories

Example: Kinetic Gravity Braiding (scalar-tensor theories)

R. Kimura, T. Kobayashi and K. Yamamoto (2012)

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R + K(\tilde{X}) - G(\tilde{X})\Box\varphi\right] + S_M$$

where

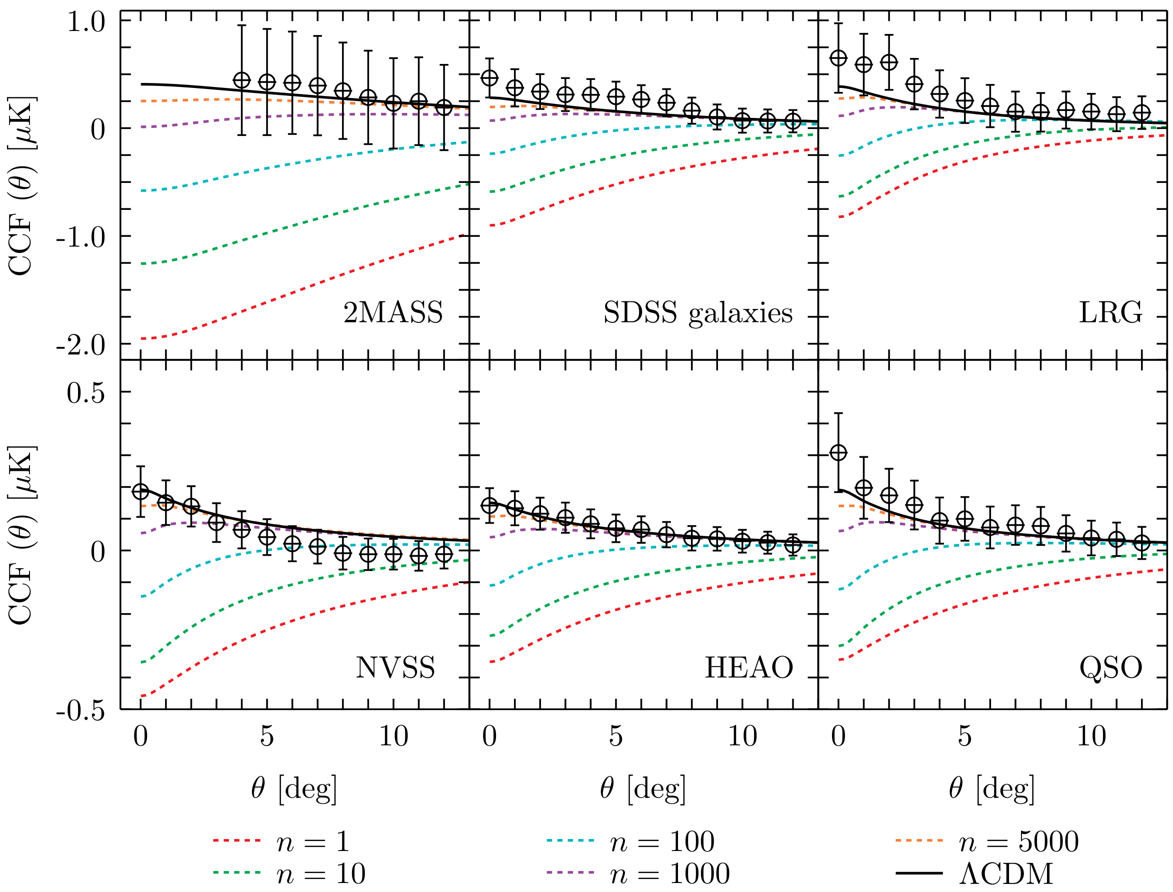
$$K(\tilde{X}) = -\tilde{X}\,, \quad G(\tilde{X}) \propto \tilde{X}^n$$

φ : scalar field

$$\tilde{X} \equiv -\partial_\mu\varphi\partial^\mu\varphi/2$$

The data of ISW-galaxy cross-correlation constrain the power in range

$$n \gtrsim \mathcal{O}(100)$$



➡ Cubic Galileon $(n=1)$ is excluded.

Dark energy model with $c_T = c$

The cross-correlation between ISW effect in CMB and galaxy distributions is given by

$$\left\langle \frac{\Delta T_{\rm ISW}(\hat{n})}{T} \frac{\Delta N_{\rm Galaxy}(\hat{n}')}{N} \right\rangle = \sum_{l=0}^{\infty} \frac{2l+1}{4\pi} C_l^{\rm IG} \mathcal{P}_l(\cos\theta)\,,$$

CMB temperature anisotropy ($\frac{\Delta T_{\rm ISW}(\hat{n})}{T}$) — Galaxy number density fluctuations ($\frac{\Delta N_{\rm Galaxy}(\hat{n}')}{N}$)

This cross-correlation can distinguish the different dark energy models:

GR • ΛCDM model ⇨ The ISW-galaxy cross-correlation is positive.

spin0 • Cubic-order scalar-tensor theories

⇨ The ISW-galaxy cross-correlation can be negative.

spin1 • Cubic-order vector-tensor theories ⇨ positive or negative?

Evolution of matter density perturbations

We introduce gauge-invariant gravitational potentials: $\Psi,\ \Phi$

In Fourier space with the comoving wave number k,
these potential are related with the matter density contrast δ, as

Newtonian potential: $$\frac{k^2}{a^2}\Psi = -4\pi G\,\mu\,\rho_m\delta\,, \qquad \mu \equiv G_{\rm eff}/G$$

Weak lensing potential: $$\frac{k^2}{a^2}\psi_{\rm eff} = 8\pi G\,\Sigma\,\rho_m\delta\,, \qquad \psi_{\rm eff} \equiv \Phi - \Psi$$

The density contrast obeys $\ddot{\delta} + 2H\dot{\delta} - 4\pi G\mu\rho_m\delta \simeq 0$

In GR, $\mu = \Sigma = 1$

Cross-correlation amplitude

$$\left\langle \frac{\Delta T_{\rm ISW}(\hat{n})}{T} \frac{\Delta N_{\rm Galaxy}(\hat{n}')}{N} \right\rangle = \sum_{l=0}^{\infty} \frac{2l+1}{4\pi} C_l^{\rm IG} \mathcal{P}_l(\cos\theta)\,,$$

$$\frac{\Delta T_{\rm ISW}(\hat{n})}{T} \equiv \int_{\eta_r}^{\eta_0} d\eta \frac{\partial}{\partial \eta}[\Psi - \Phi] = \int_0^{z_r} dz \frac{\partial \psi_{\rm eff}}{\partial z}$$

Under the small angle approximation, the cross-correlation amplitude is given by

$$C_l^{\rm IG} \simeq \frac{3\Omega_{m0} H_0^2}{l_{12}^2 D_0^2} \int d\mathcal{N} e^{-\mathcal{N}} H\, \mathcal{W}\, b_s\, D\, \Sigma\, \mathcal{F}\, P(l_{12})$$

$$\mathcal{N} \equiv \ln a(t)$$

$$\mathcal{F} \equiv 1 - \frac{D'}{D} - \frac{\Sigma'}{\Sigma} = 1 - (\ln D\Sigma)'\,.$$

$l_{12} \equiv l + 1/2$

$\mathcal{W}$: window function

b_s: bias

D : growth factor

P : the matter power spectrum

This quantity determines the sign of the cross-correlation power spectrum.

Gravitational coupling related to light bending

In our models, $\mathcal{S}=\int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R+F+b_2X^{p_2}+b_3X^{p_3}\nabla_\mu A^\mu\right]+\mathcal{S}_M\,,$

$$\Sigma = 1 + 1 \Big/ \left[f(s,\, p,\, \Omega_{\rm DE}) + \left(\frac{2}{3^{1/p}}\right)^{1/(1+s)} \frac{1}{\lambda_V} \frac{1}{\Omega_{\rm DE}^{1/[p(1+s)]}} \right]$$

where λ_V is associated with the intrinsic vector mode such that

$$\lambda_V \equiv q_V \left[\left(\frac{\phi}{M_{\rm pl}}\right)^p \frac{H}{m} \right]^{2/[p(1+s)]} ,$$

$\phi \propto H^{-1/p}$

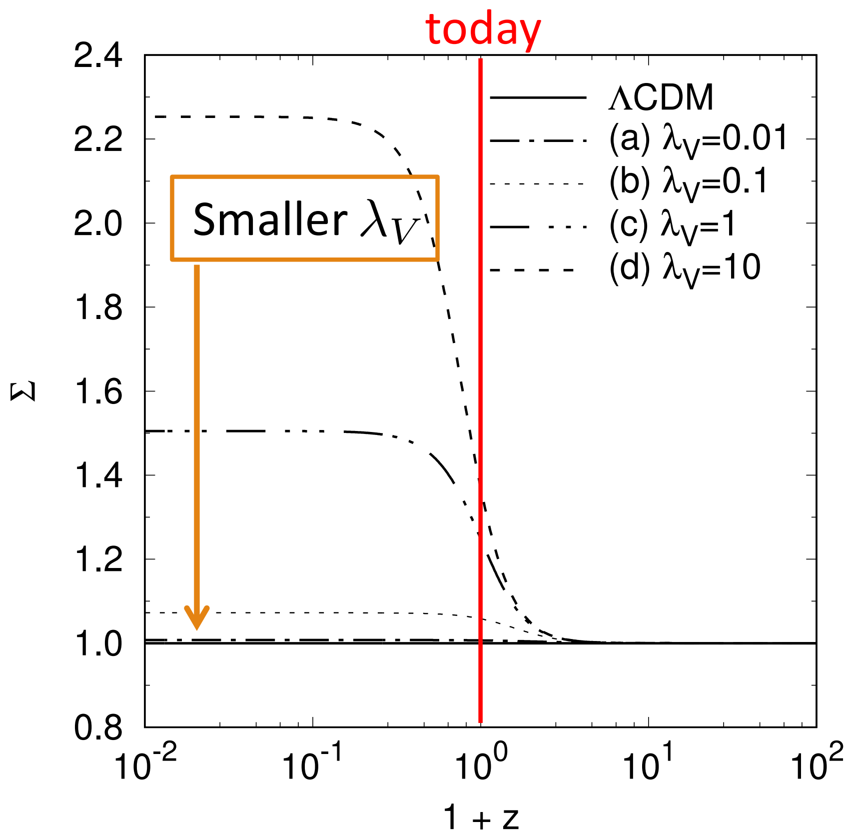
q_V : coefficient of kinetic term of vector perturbation

- In the limit $\lambda_V \to 0$, the evolution of perturbation is similar to that in ΛCDM.
- In the limit $\lambda_V \to \infty$, this model reduces to a subclass of scalar-tensor theories.

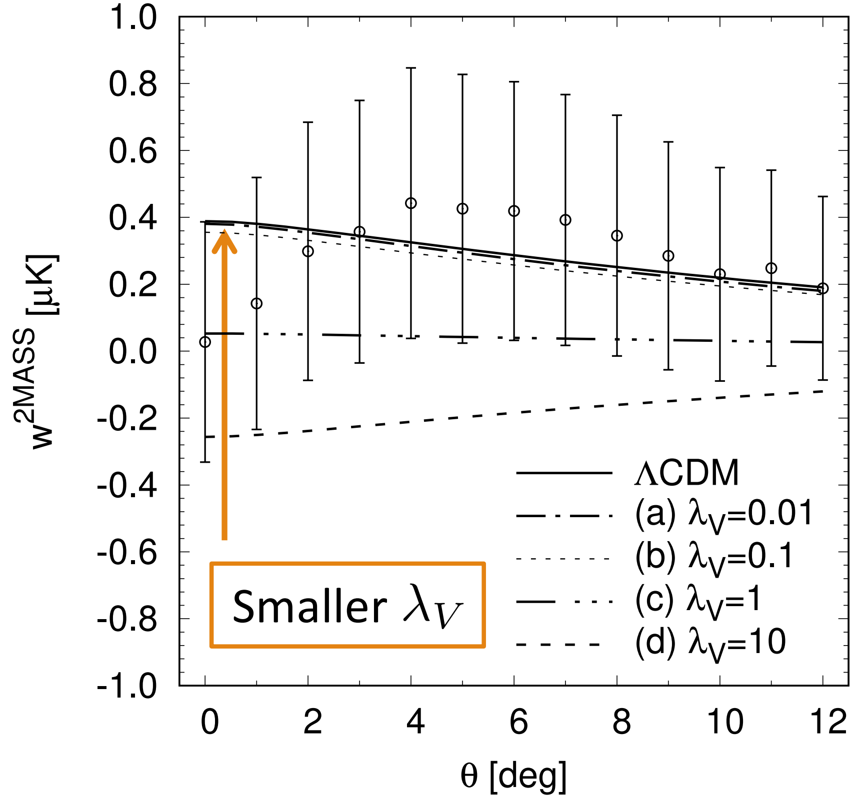
ISW-galaxy cross-correlations in concrete models

$$\Sigma_{\rm dS} = 1 + \left[\frac{1-ps}{ps} + \left(\frac{2}{3^{1/p}}\right)^{1/(1+s)} \frac{1}{\lambda_V}\right]^{-1}$$

SN, A. De Felice, R. Kase and S. Tsujikawa (2018)



Cross-correlation function



The intrinsic vector mode can give rise to positive cross-correlations compatible with the data.

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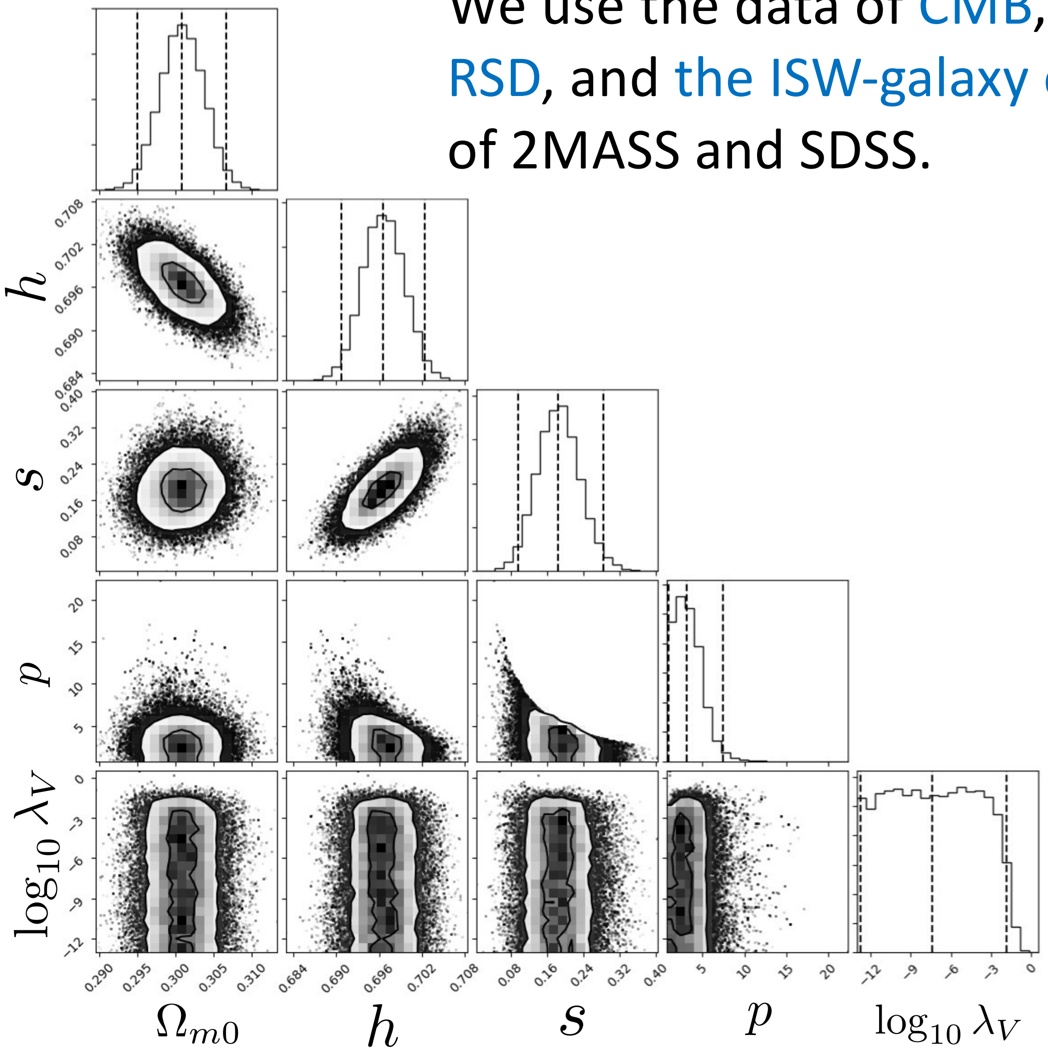
Observational constraints

SN, A. De Felice, R. Kase and S. Tsujikawa (2018)



We use the data of CMB, BAO, SN Ia, Hubble expansion rate, RSD, and the ISW-galaxy cross-correlations with the catalogues of 2MASS and SDSS.

$$\Omega_{m0} = 0.301^{+0.006}_{-0.006}\,,$$
$$h = 0.697^{+0.006}_{-0.006}\,,$$
$$s = 0.185^{+0.100}_{-0.089}\,,$$
$$p = 3.078^{+4.317}_{-2.119}\,,$$
$$\bar{\lambda}_V \le \lambda_V < 0.015\,, \quad (95\%\,\mathrm{CL})$$

$\phi \propto H^{-1/p}$

The model with $s > 0$ still fits the data better than the ΛCDM model.

Best-fit: $\mathrm{BIC} = 651.2$

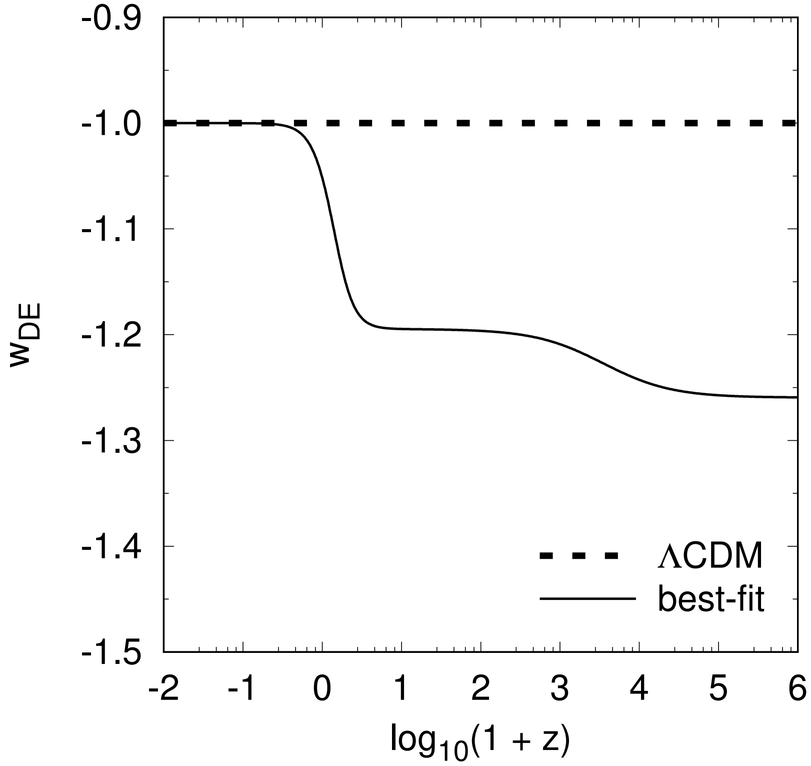
ΛCDM: $\mathrm{BIC} = 655.6$

Best-fit case in massive vector dark energy model

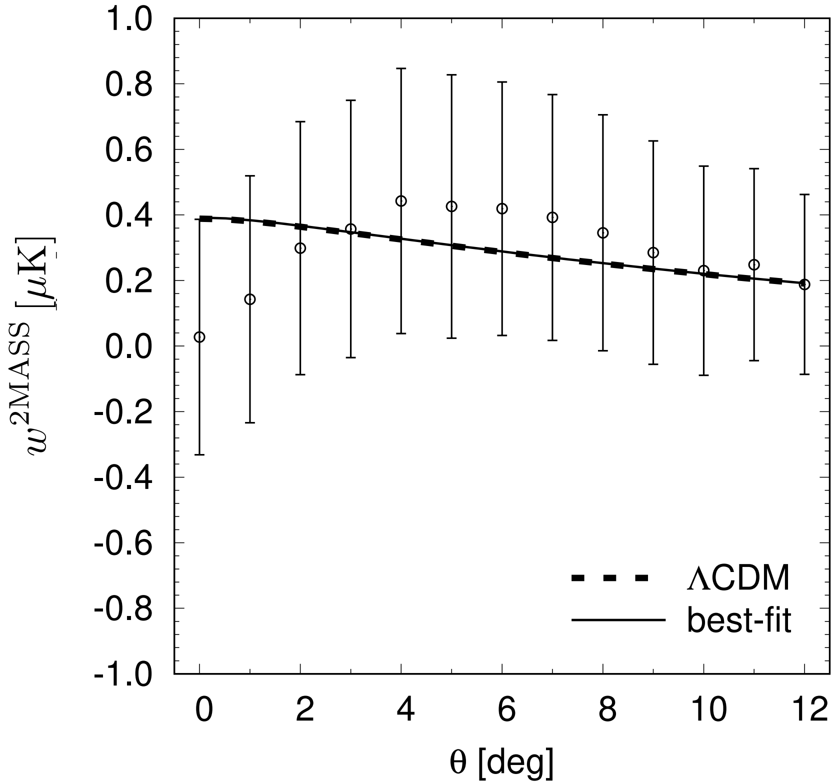
$$\Omega_{m0} = 0.301,\ h = 0.697,\ s = 0.185,\ p = 3.078,\ \log_{10}\lambda_V = -7.359 \quad \Longrightarrow \quad \mathrm{BIC} = 651.2$$

The background dynamics in our model is different from that in ΛCDM, while the perturbation dynamics is almost the same as that in ΛCDM.

$$w_{\mathrm{DE}} = -\frac{3(1+s) + s\Omega_r}{3(1+s\Omega_{\mathrm{DE}})}$$



Cross-correlation function



Summary

- We studied observational constraints on a dark energy model in cubic-order generalized Proca theories by using the data of CMB, BAO, SN Ia, RSD and ISW-galaxy cross-correlation.

- Due to the existence of intrinsic vector mode, the ISW-galaxy cross-correlation can be positive even for cubic interactions unlike that in scalar-tensor theories.

- The model with $s > 0$ still fits the data better than the ΛCDM model even by including the ISW-galaxy cross-correlation data.

- It remains to be seen whether future high-precision observations show some evidence that the dark energy model in the vector-tensor theories is favored over the ΛCDM model.