Galileons compatible with current cosmological data

(but maybe nothing else??)

Alex Barreira
Max Planck Institute for Astrophysics

Based on

Renk, Montaneri, Zumalacarregui,Barreira 2017 (arXiv:1707.02263)

In this talk ...

1) The Galileon model

2) Methodology: CMB, BAO and ISW constraints

3) Results

4) What is there next ?

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1) The Galileon model

2) Methodology: CMB, BAO and ISW constraints

3) Results

4) What is there next ?

"As it stands, cosmological data has not been shown to rule out Galileon gravity

but

there are plenty of other problems and possible ways to do so ! "

The Galileon model

Action

*Most general Galilean symmetric 4D action with 2nd order field equations of motion in Minkowskii space (**Nicolis et al 2009**), augmented with curvature-coupling counter-terms (**Deffayet et al 2009**) to keep 2nd order nature in FRW spacetime.*

$$S[g_{\mu\nu},\phi] = \int \mathrm{d}^4x\,\sqrt{-g}\left[\sum_{i=2}^{5}\mathcal{L}_i[g_{\mu\nu},\phi] + \mathcal{L}_{\mathrm{m}}[g_{\mu\nu},\psi_{\mathrm{m}}]\right]$$

$$\mathcal{L}_2 = c_2 X - \frac{c_1 M^3}{2}\phi\,,$$

$$\mathcal{L}_3 = 2\frac{c_3}{M^3}X\Box\phi\,,$$

$$\mathcal{L}_4 = \left(\frac{M_{\mathrm{Pl}}^2}{2} + \frac{c_4}{M^6}X^2\right)R + 2\frac{c_4}{M^6}X\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right]\,,$$

$$\mathcal{L}_5 = \frac{c_5}{M^9}X^2 G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{3}\frac{c_5}{M^9}X\left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\right]$$

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No free functions; 5 dimensionless free parameters

Has GR limit, but not LCDM limit

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Take c1 = 0

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Tracker background evolution

Tracker evolution *characterized by:*

$$\frac{\dot{\phi} H}{M_{\mathrm{Pl}} H_0^2} \equiv \xi = \text{constant}$$

Unacceptable CMB-TT if the tracker isn't reached early enough

Barreira et al (2013) ; 1302.6241

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We'll assume the tracker at all times by simplicity

$$\left(\frac{H(a)}{H_0}\right)^2 = \frac{1}{2}\left[\Omega_{\mathrm{fluid}}(a) + \sqrt{[\Omega_{\mathrm{fluid}}(a)]^2 + 4\Omega_{\phi 0}}\right]$$

Admits analytical expression for H(a)

Galileon subspace of parameters

$$\left\{ \xi, \; c_2, \; c_3, \; c_4, \; c_5 \right\}$$

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Fixed by

Conditions for spatial flatness and to be on the tracker:

$$\Omega_{\phi 0} = \frac{c_2}{6}\xi^2 - 2c_3\xi^3 + c_4\frac{15}{2}\xi^4 + c_5\frac{7}{3}\xi^5$$

$$c_2\xi - 6c_3\xi^2 + 18c_4\xi^3 + 5c_5\xi^4 = 0$$

Galileon subspace of parameters

$$\xi \rightarrow B\xi$$
$$c_n \rightarrow c_n/B^n$$

Leaves equations unchanged

Take c2 = -1 to break unphysical scaling degeneracy.

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Free parameters

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Leaves equations unchanged

Take c2 = -1 to break unphysical scaling degeneracy.

Organize the results by constraining separately three "corners" of the model:

$$\{\xi,\ c_2,\ c_3,\ c_4,\ c_5\}$$

$$\begin{aligned} \text{Cubic Galileon } (Gal3) &: \quad c_4 = c_5 = 0 \\ \text{Quartic Galileon } (Gal4) &: \quad c_5 = 0 \\ \text{Quintic Galileon } (Gal5) &: \quad \text{all free} \end{aligned}$$

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Methodology: CMB, BAO, ISW constraints

Methodology steps

1) MCMC constraints with CMB (TT, lensing) and BAO13

2) Scan the chains and compute the cross-spectra of CMB and WISE galaxies to measure the ISW effect.

Wide-field Infrared Survey Explorer
Wright et al , arXiv:1008.0031

Methodology steps

1) MCMC constraints with CMB (TT, lensing) and BAO13

Parameters varied:

$$\left\{\Omega_c h^2, \Omega_b h^2, h, n_s, A_s, \tau, \Sigma m_\nu\right\} + \text{Galileon params.}$$

MontePython + hi_class (Zumalacarregui et al; arXiv:1605.06102)

2) Scan the chains and compute the cross-spectra of CMB and WISE galaxies to measure the ISW effect.

Wide-field Infrared Survey Explorer
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WISE-ISW signal

CMB T – galaxy cross spectrum

$$C_\ell^{\mathrm{Tg}} = 4\pi \int \frac{dk}{k} \Delta_\ell^{\mathrm{ISW}}(k) \Delta_\ell^{\mathrm{g}}(k) \mathcal{P}_{\mathcal{R}}(k)$$

WISE-ISW signal

CMB T – galaxy cross spectrum

$$C_\ell^{\mathrm{Tg}} = 4\pi \int \frac{dk}{k} \Delta_\ell^{\mathrm{ISW}}(k) \Delta_\ell^{\mathrm{g}}(k) \mathcal{P}_{\mathcal{R}}(k)$$

ISW kernel

$$\Delta_\ell^{\mathrm{ISW}} = \int_{\tau_*}^{\tau_0} d\tau \left(\Phi' + \Psi'\right) j_\ell$$

Galaxy distribution kernel

$$\Delta_\ell^{g} = \int_0^{\tau_0} \mathrm{d}\tau \; W_g(\tau) b_g(\tau) \delta(\tau, k) j_\ell$$

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Galaxy bias

Signal is degenerate with galaxy bias: need to fit for b_g first !

Galaxy bias with CMB lensing

CMB lensing – galaxy cross spectrum

$$C_\ell^{\kappa g} = 4\pi \int \frac{dk}{k} \Delta_\ell^\kappa(k) \Delta_\ell^g(k) \mathcal{P}_\mathcal{R}(k)$$

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$$\Delta_\ell^\kappa = -\frac{\ell(\ell+1)}{2} \int_{\tau_*}^{\tau_0} d\tau \, \frac{\tau - \tau_*}{(\tau_0 - \tau)(\tau_0 - \tau_*)} \, (\Phi + \Psi) \, j_\ell$$

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Galaxy bias

Use this data to fit for the galaxy bias !

Galaxy bias with CMB lensing

CMB lensing – galaxy cross spectrum

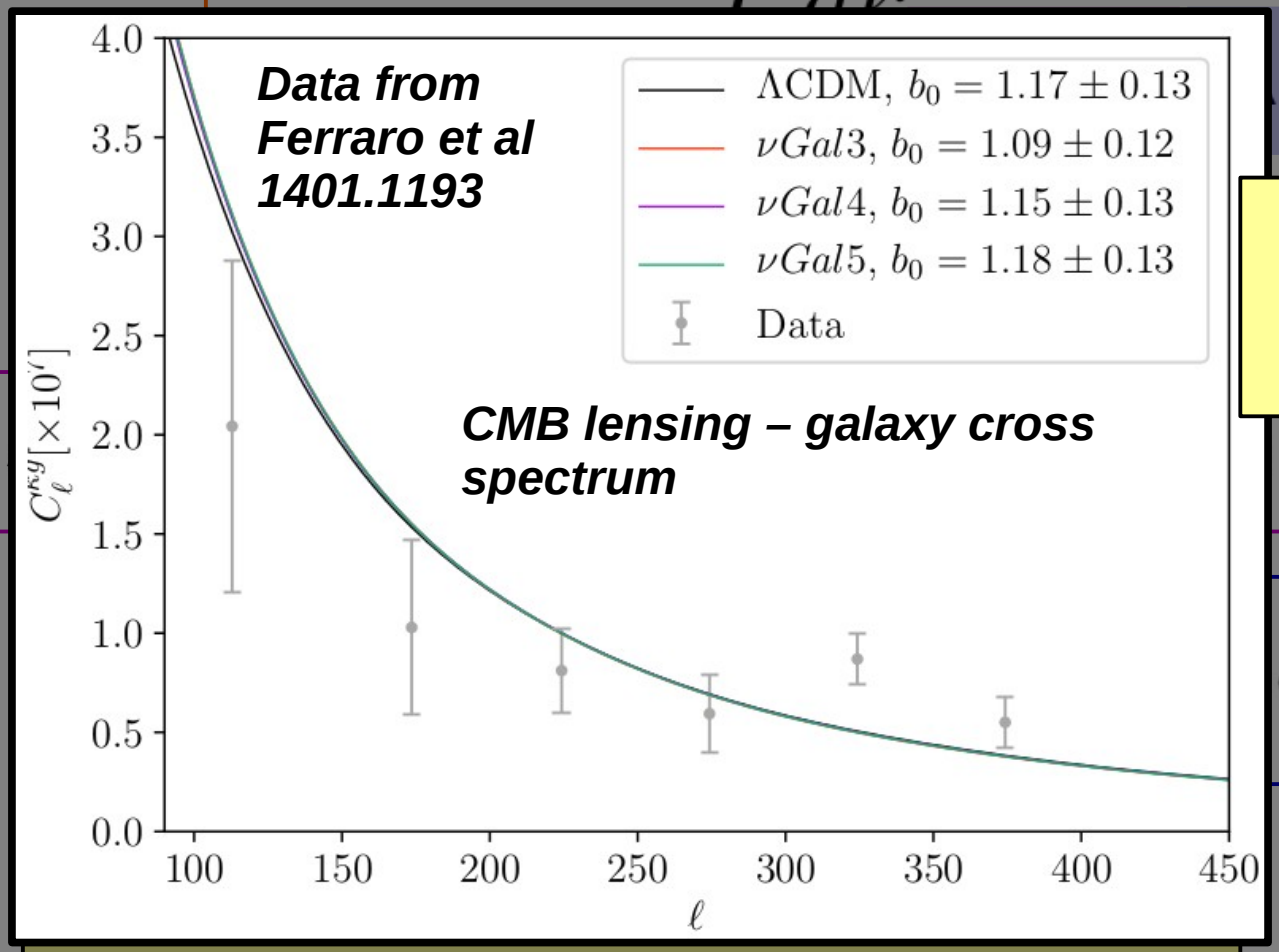
$$\int dk \; {}^{g}_{\ell}(k)\mathcal{P}_{\mathcal{R}}(k)$$

$$j_\ell$$

kernel

$$\mathrm{d}\tau \; W_g(\tau) b_g(\tau) \delta(\tau, k) j_\ell$$

Galaxy bias



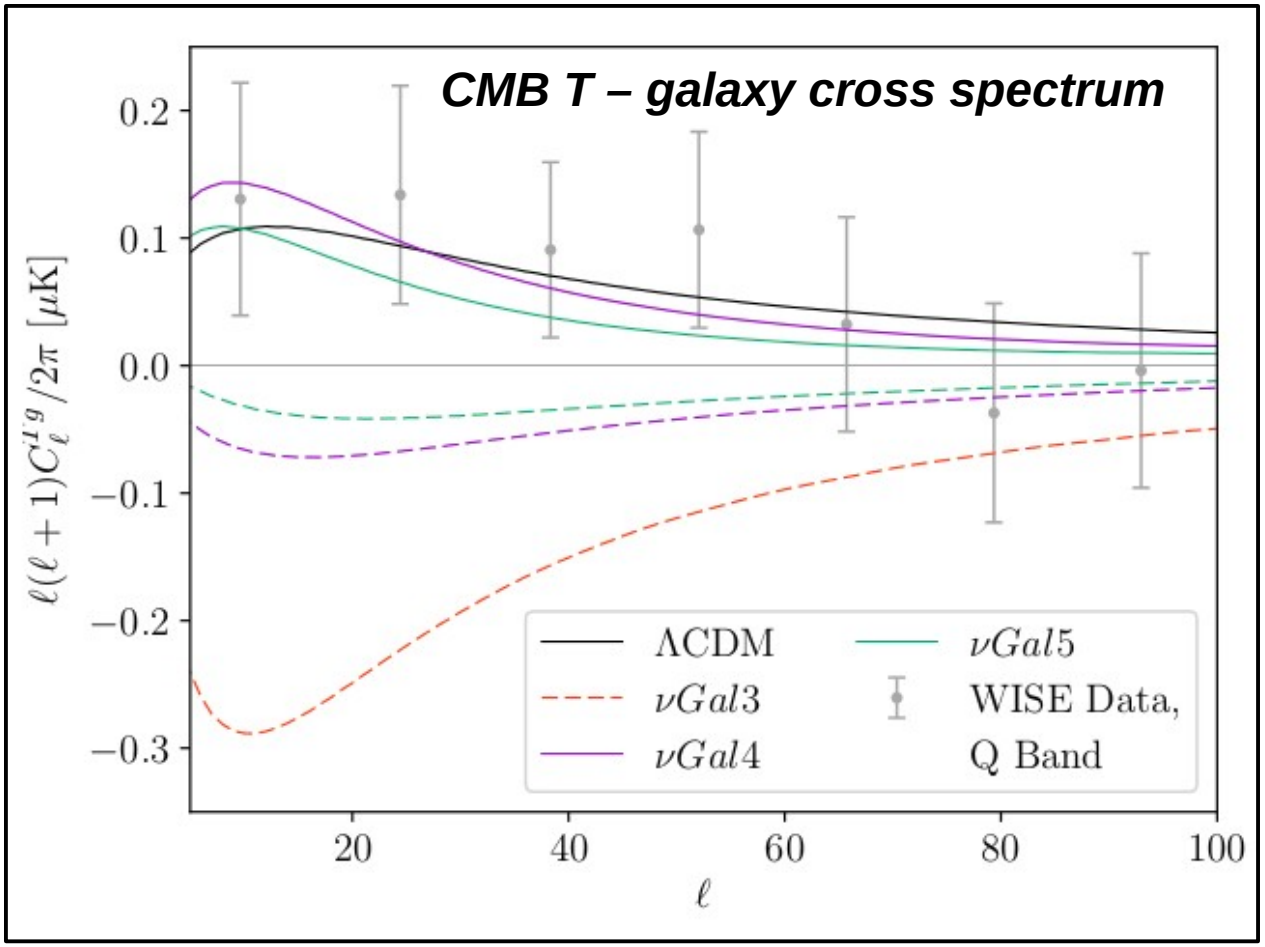
Different bias values for different gravity models, as expected .

Use this data to fit for the galaxy bias !

WISE-ISW signal

CMB TT – galaxy cross spectrum

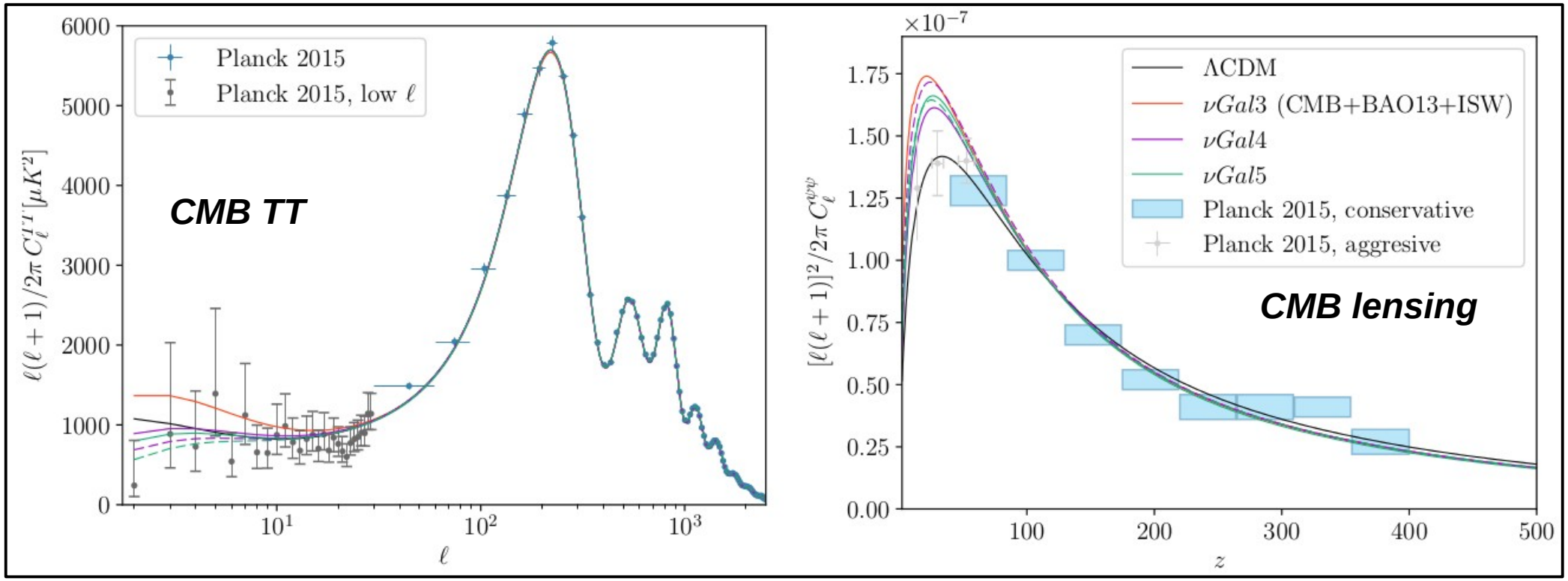
$$C_\ell^{\mathrm{Tg}} = 4\pi \int \frac{dk}{k} \Delta_\ell^{\mathrm{ISW}}(k) \Delta_\ell^{\mathrm{g}}(k) \mathcal{P}_{\mathcal{R}}(k)$$



Data from Ferraro et al 1401.1193

Results

CMB+BAO constraints



Galileons display the same goodness-of-fit as LCDM to these data !

Barreira et al 1406.0485
Renk et al 1707.02263

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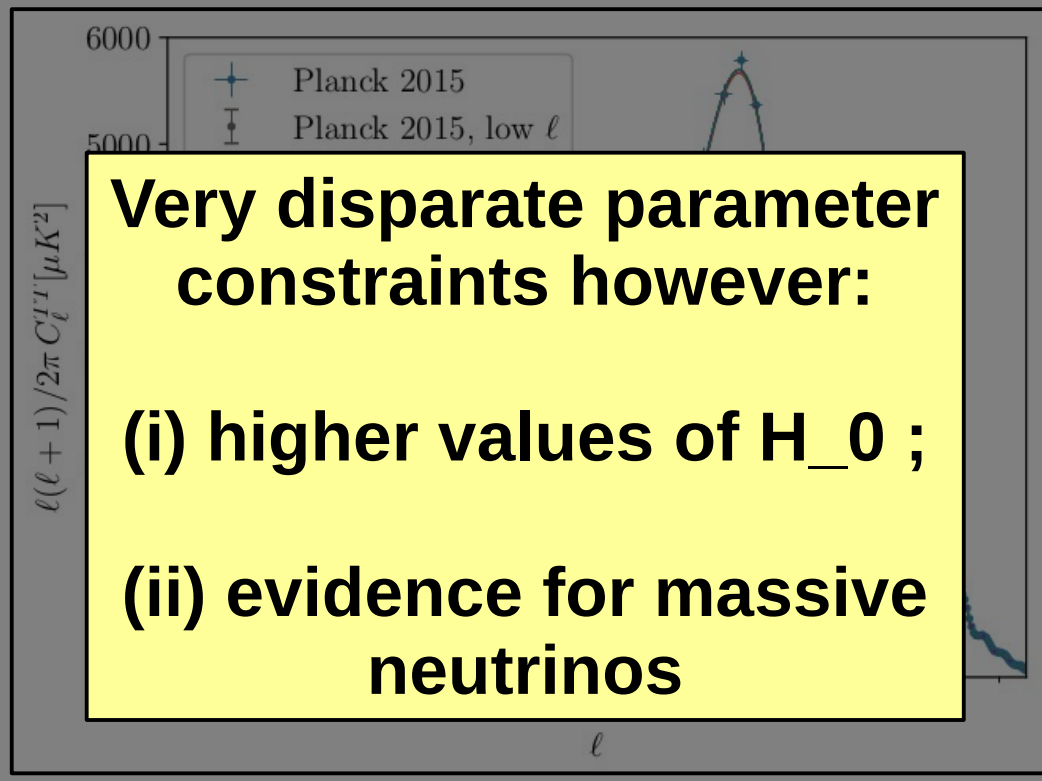
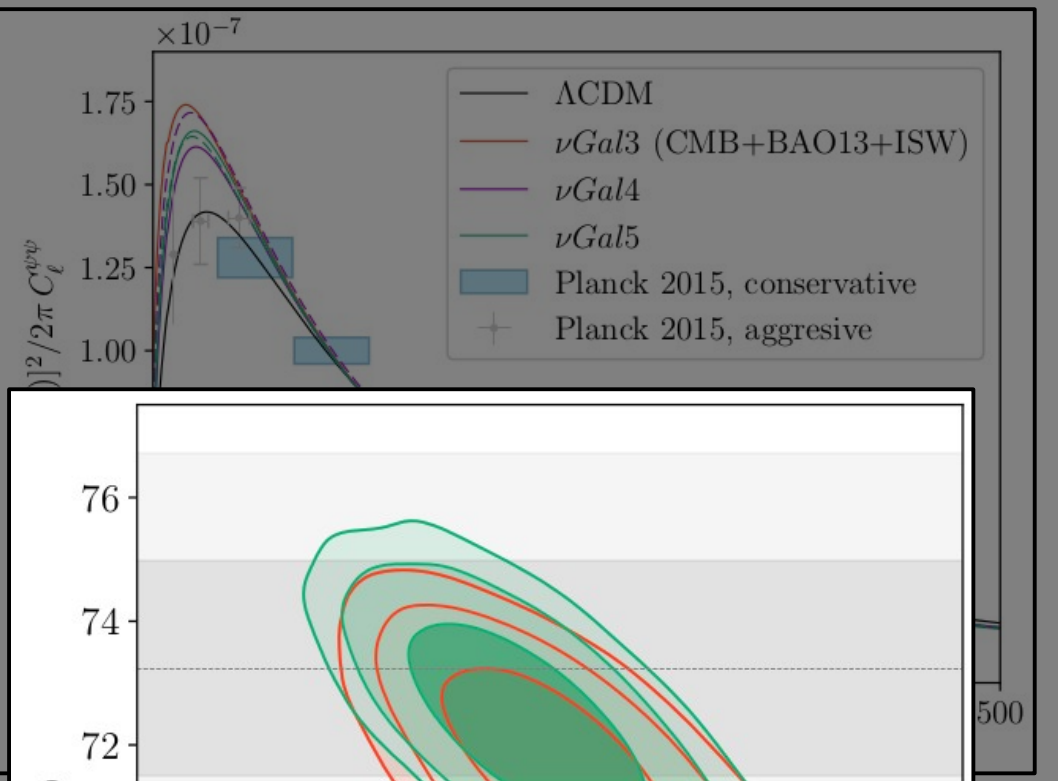
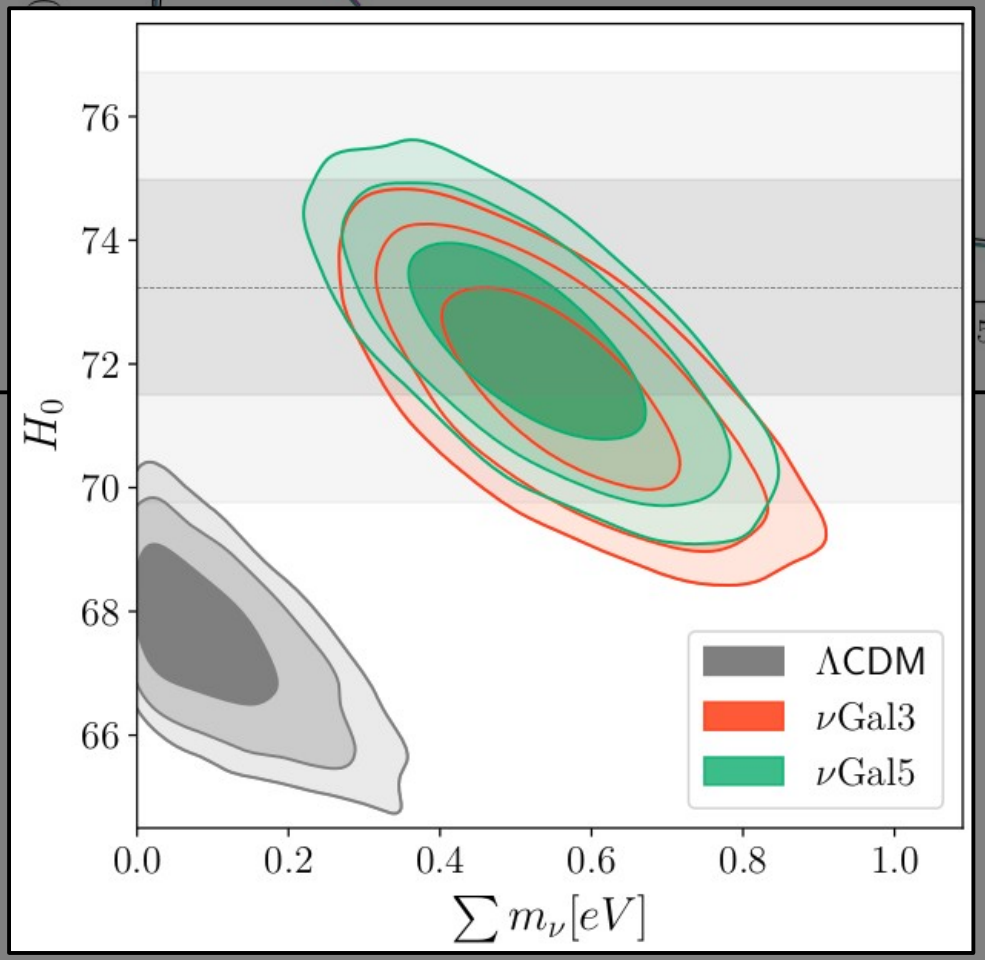




Very disparate parameter constraints however:

(i) higher values of H_0 ;

(ii) evidence for massive neutrinos



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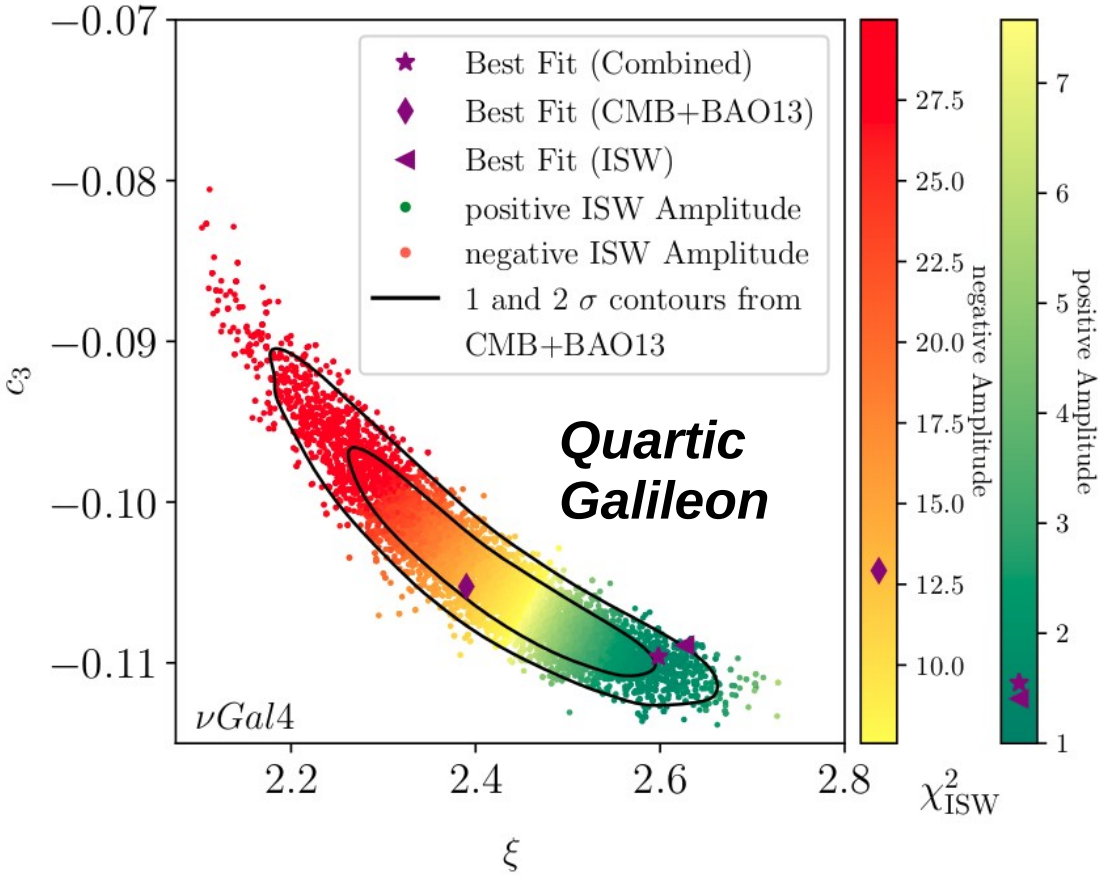
ISW constraints: Quartic



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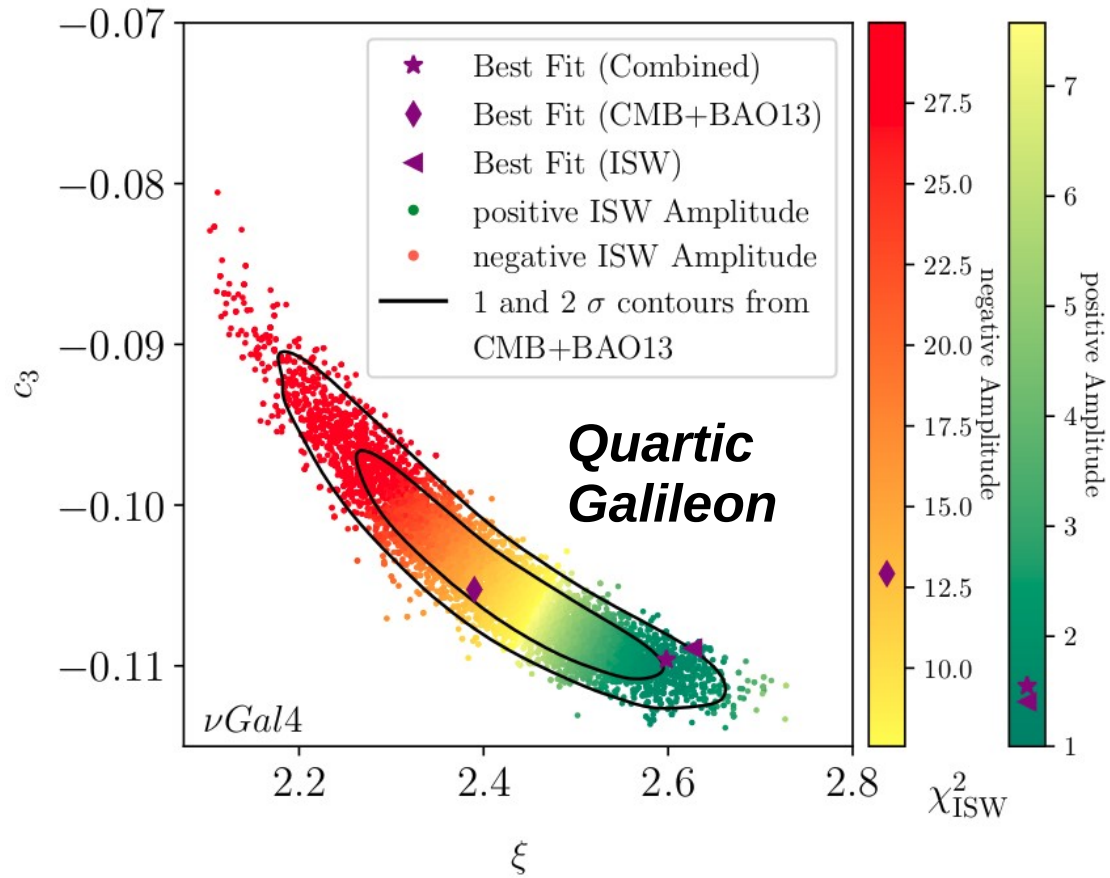
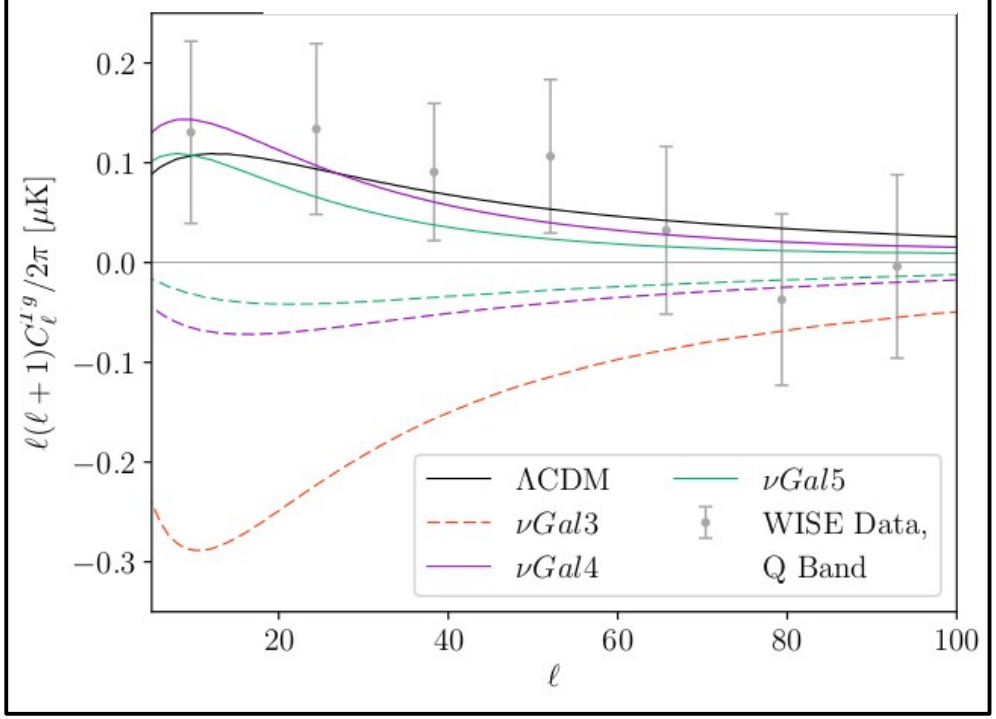


Define ISW amplitude

$$A_{\rm ISW} = \frac{\sum_i t_i}{\sum_i d_i}, \quad i = \{\ell\ bins\}$$

$A_{\rm ISW} < 0$ $A_{\rm ISW} > 0$

CMB T – galaxy cross spectrum



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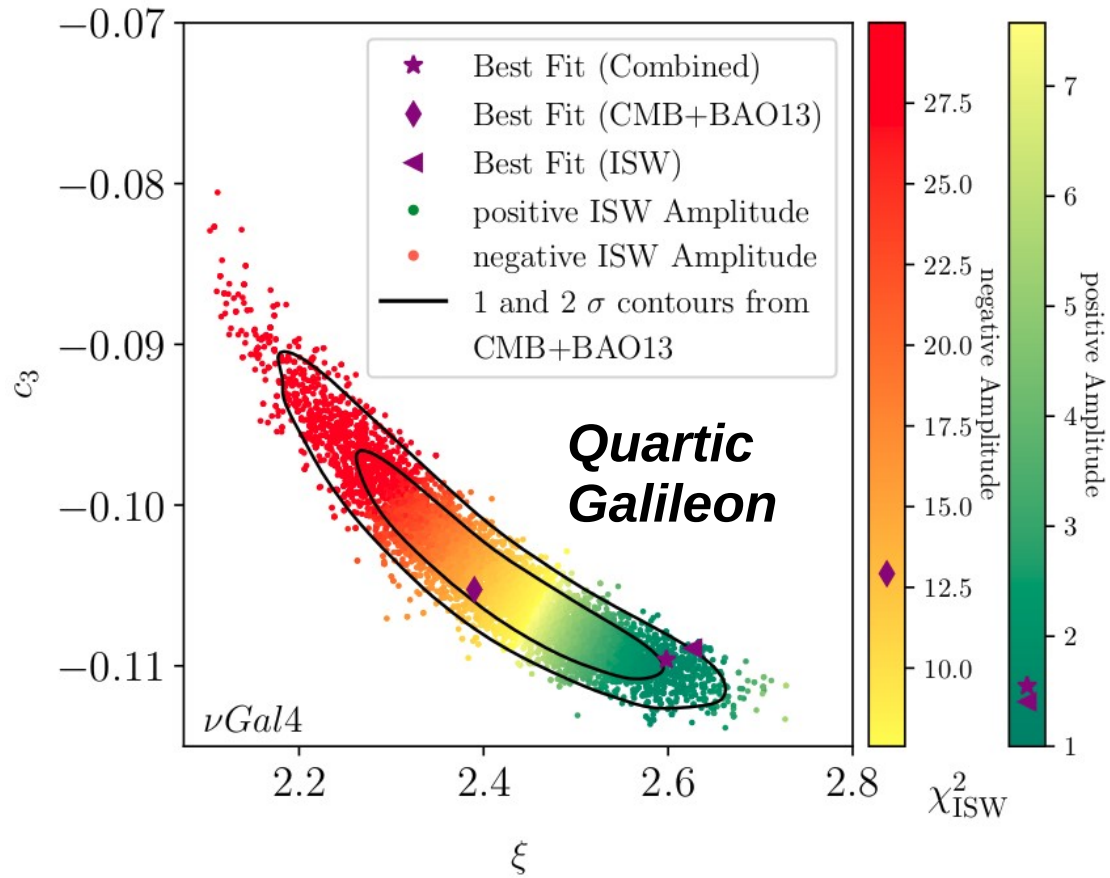

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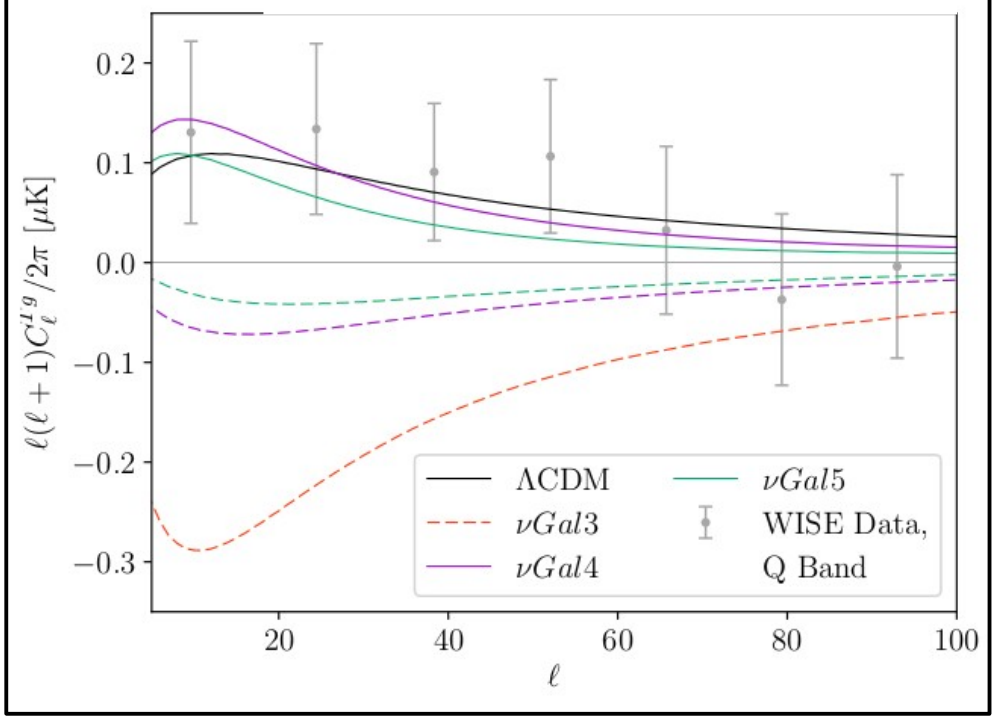

Quartic/Quintic yield good fits to ISW within CMB+BAO13 contours !

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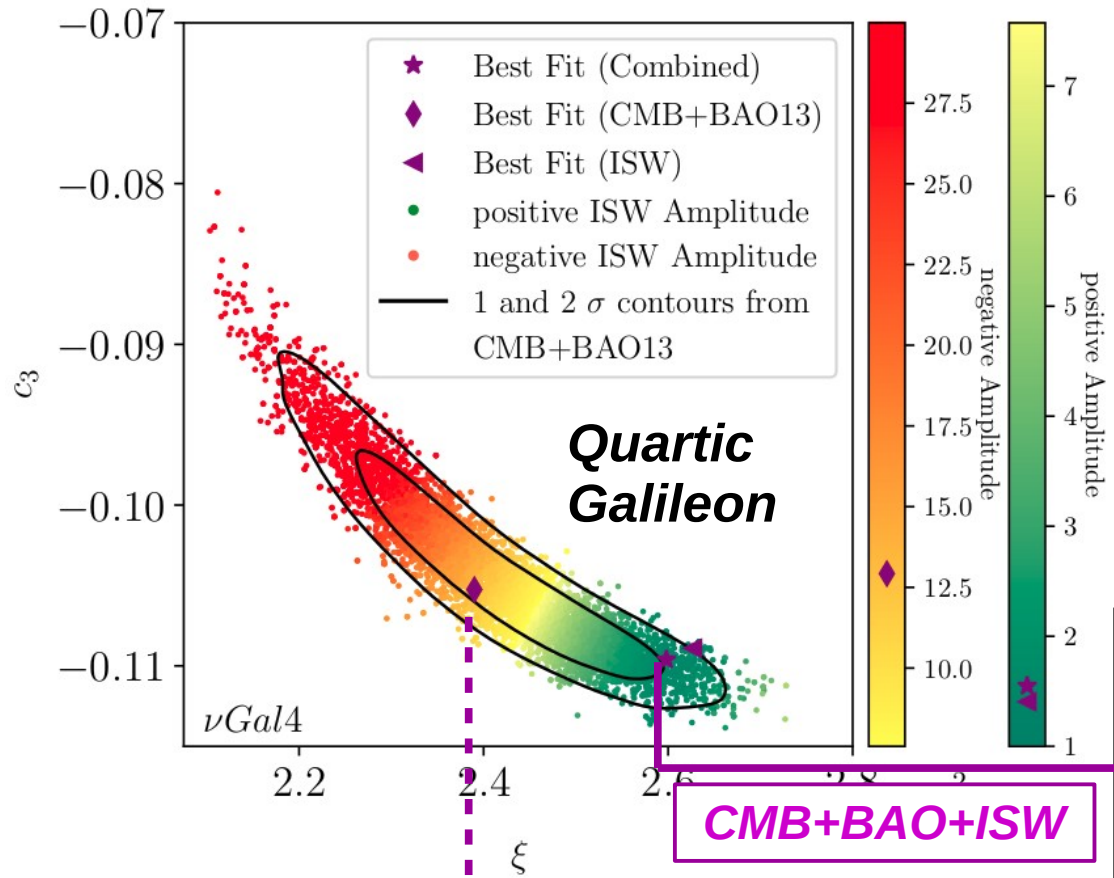

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CMB+BAO+ISW

CMB+BAO

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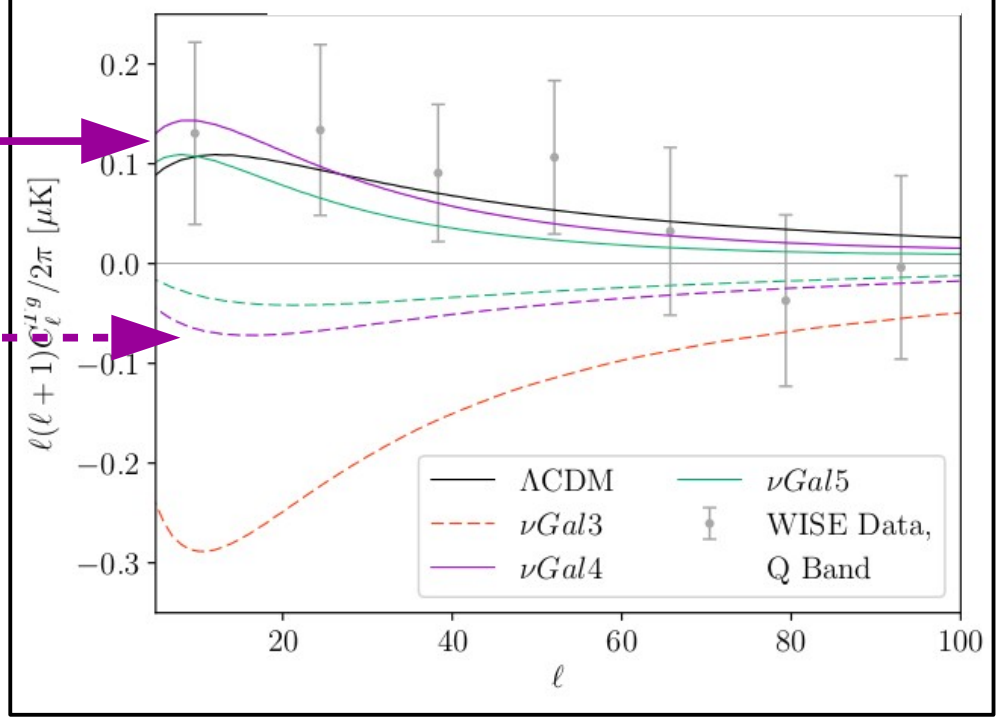

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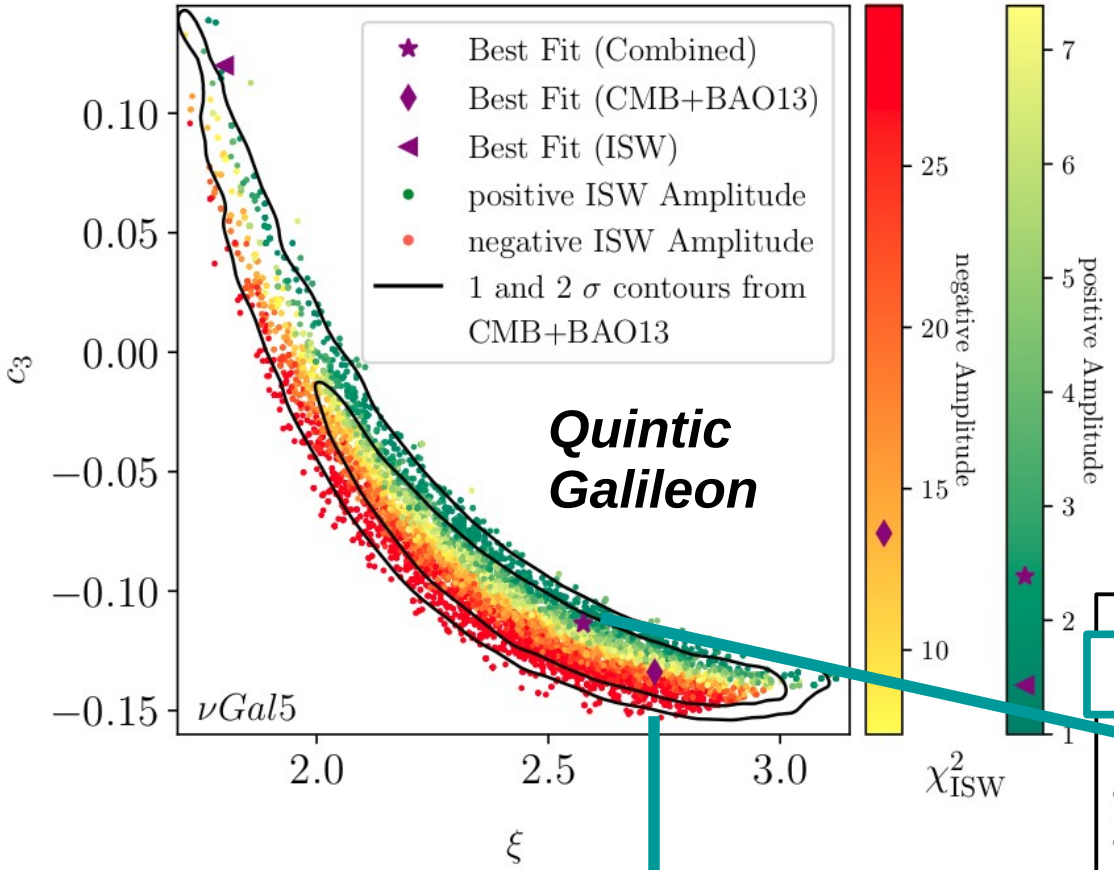

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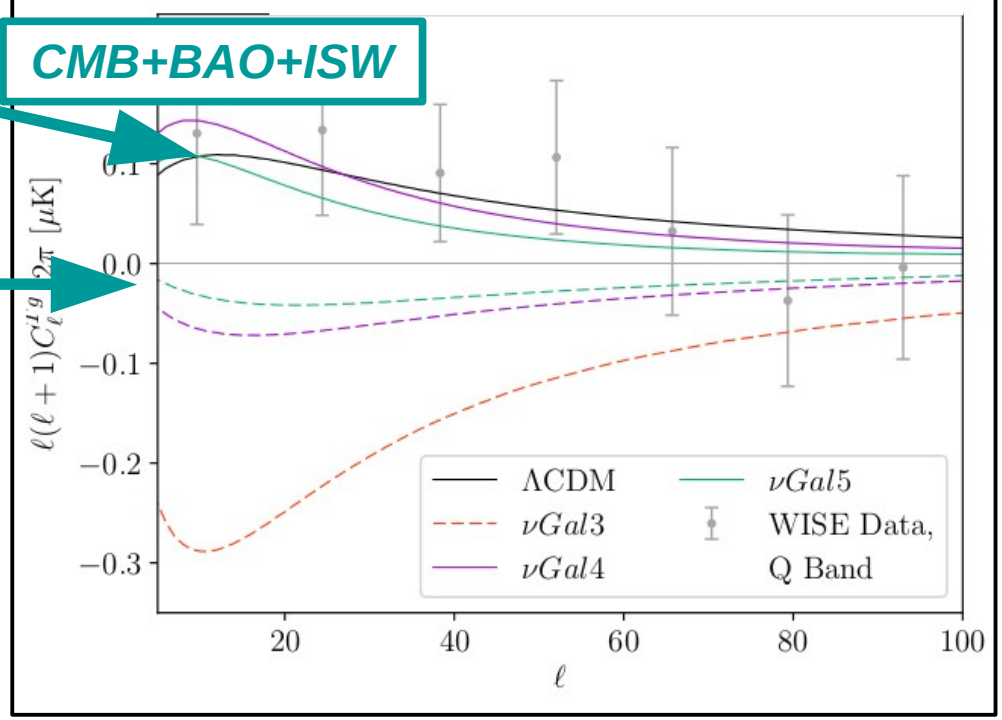

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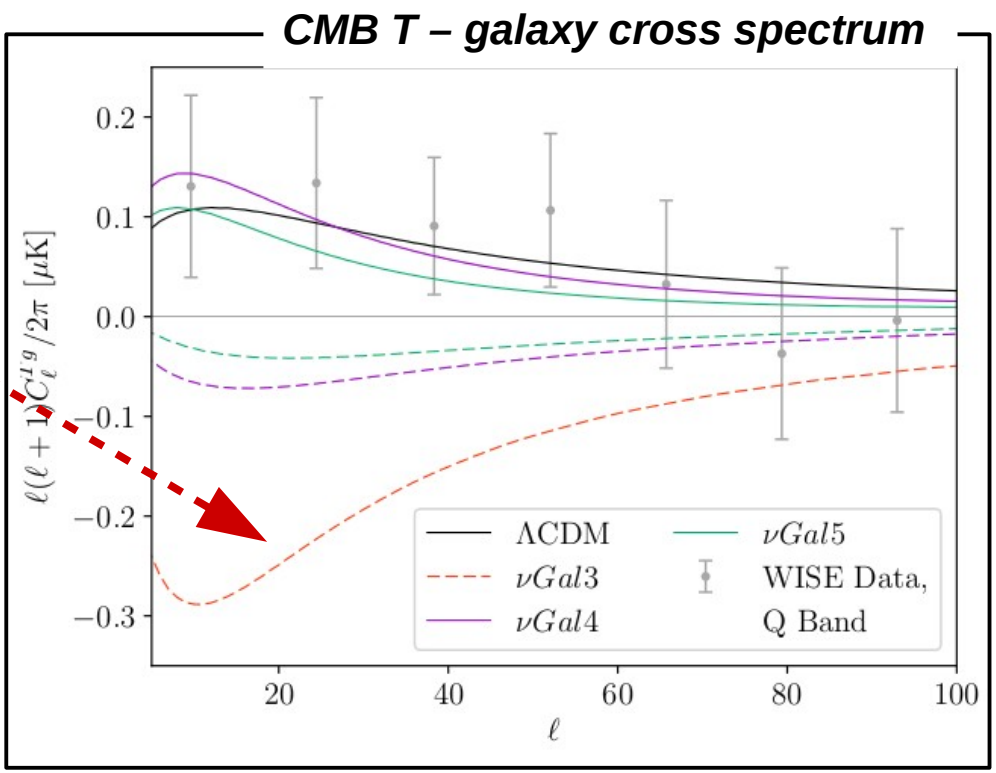
ISW constraints: Cubic

The covariant Cubic Galileon model is ruled out : 8sigma tension !

Best-fitting Cubic Galileon model to the WISE-ISW data !



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$$X\Box\phi \longrightarrow X^n\Box\phi$$

Transforming G3 in this way yields good fits for large *n though*

Best-fitting Cubic Galil
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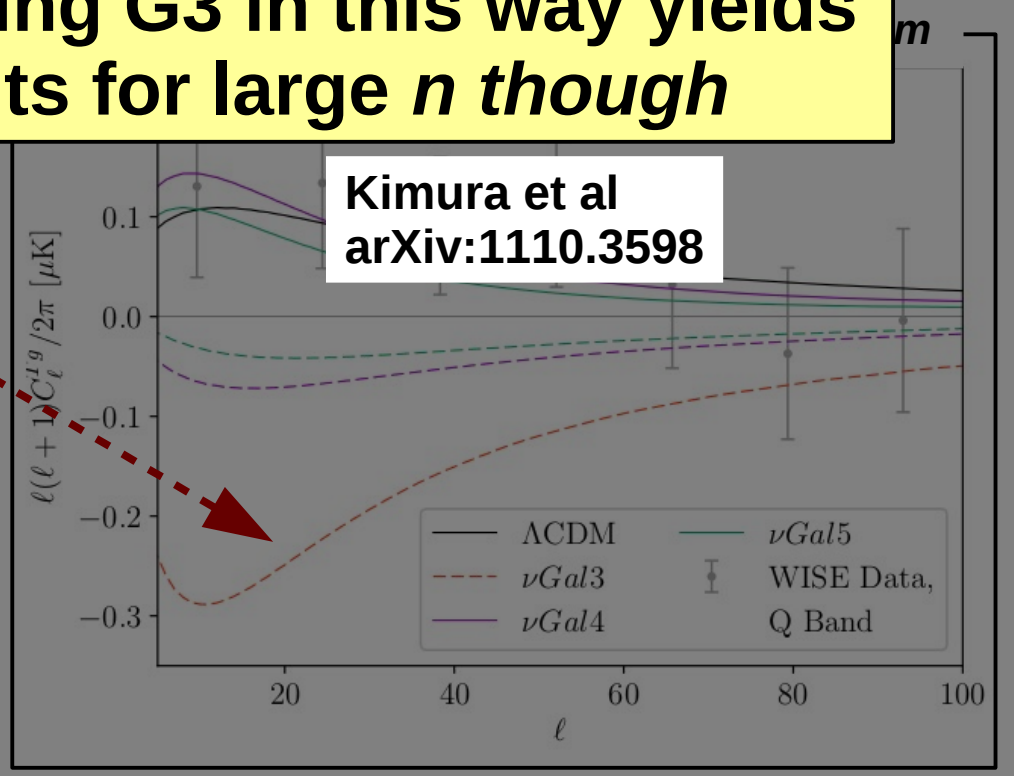
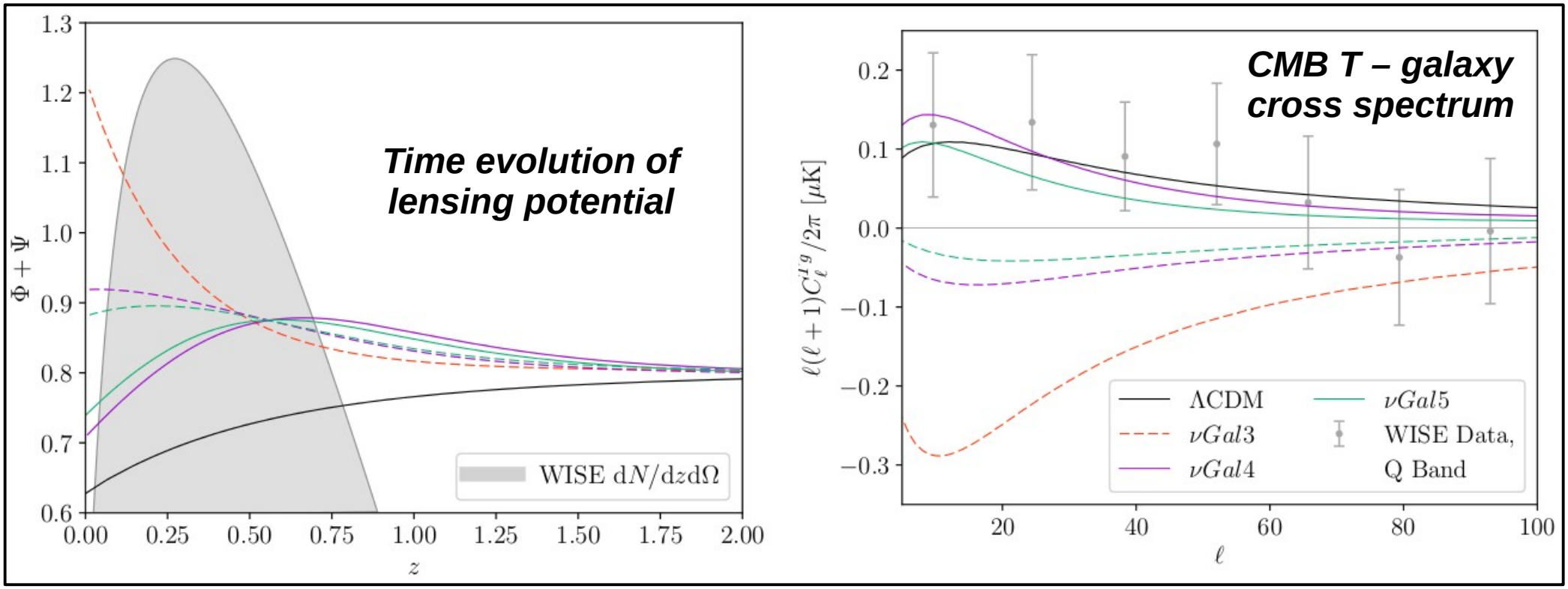


Physical explanation



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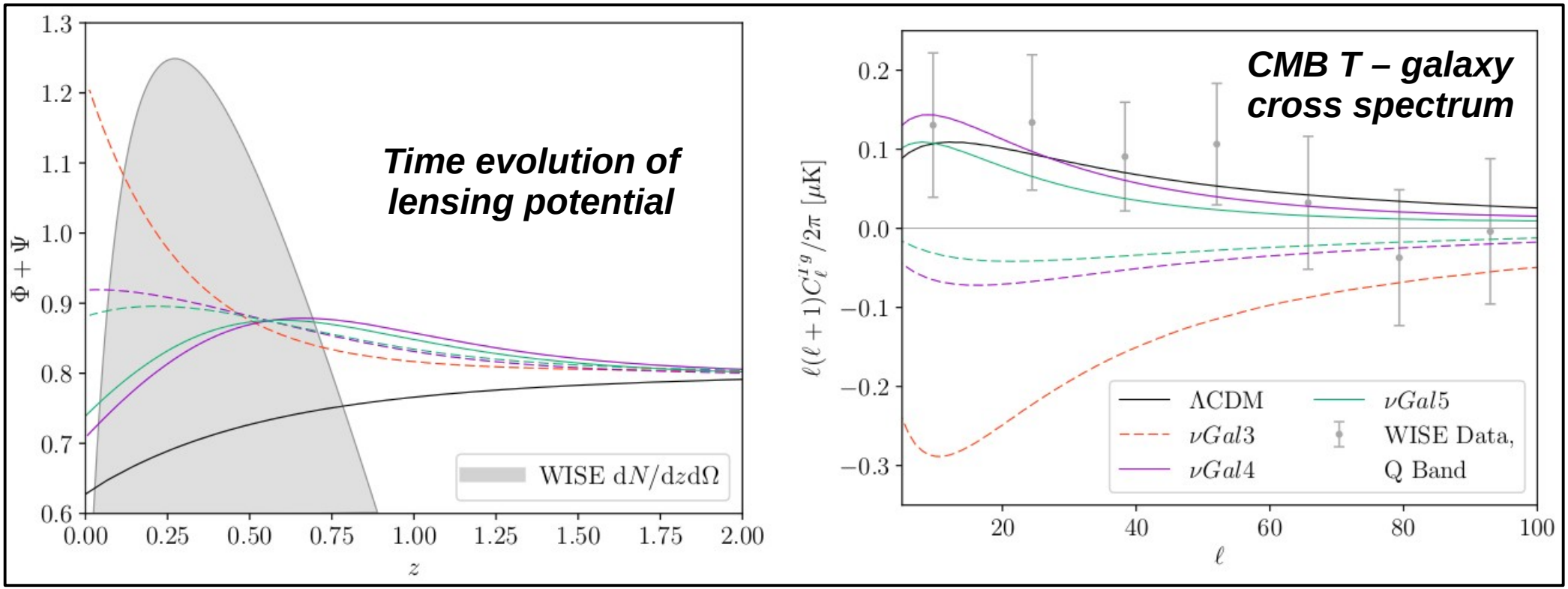
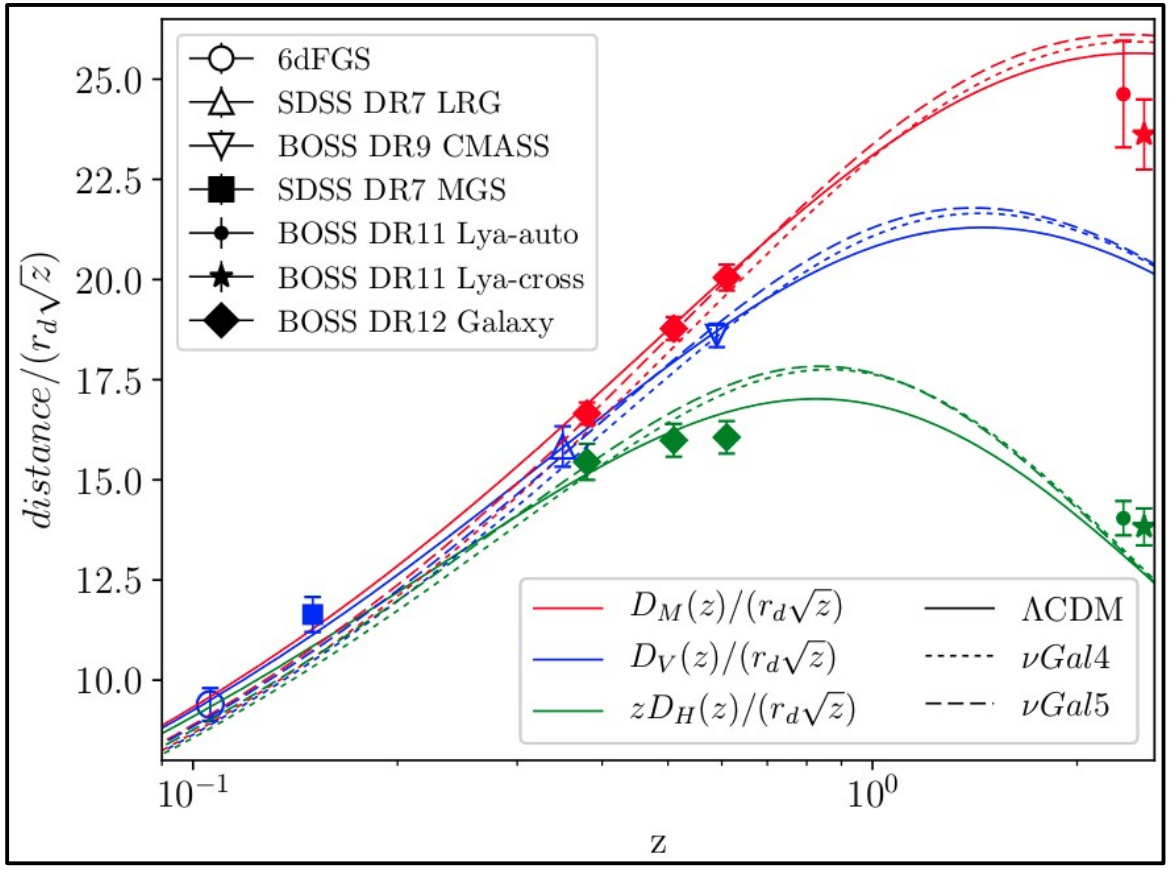


Only decaying lensing potentials in the WISE z-range survive !

Cubic Galileon is not flexible enough to get decaying potentials .

Tension with BAO data



- ***Open:*** *BAO13 – used in our MCMCs;*
- ***Filled:*** *BAO16 – more recent measurements;*

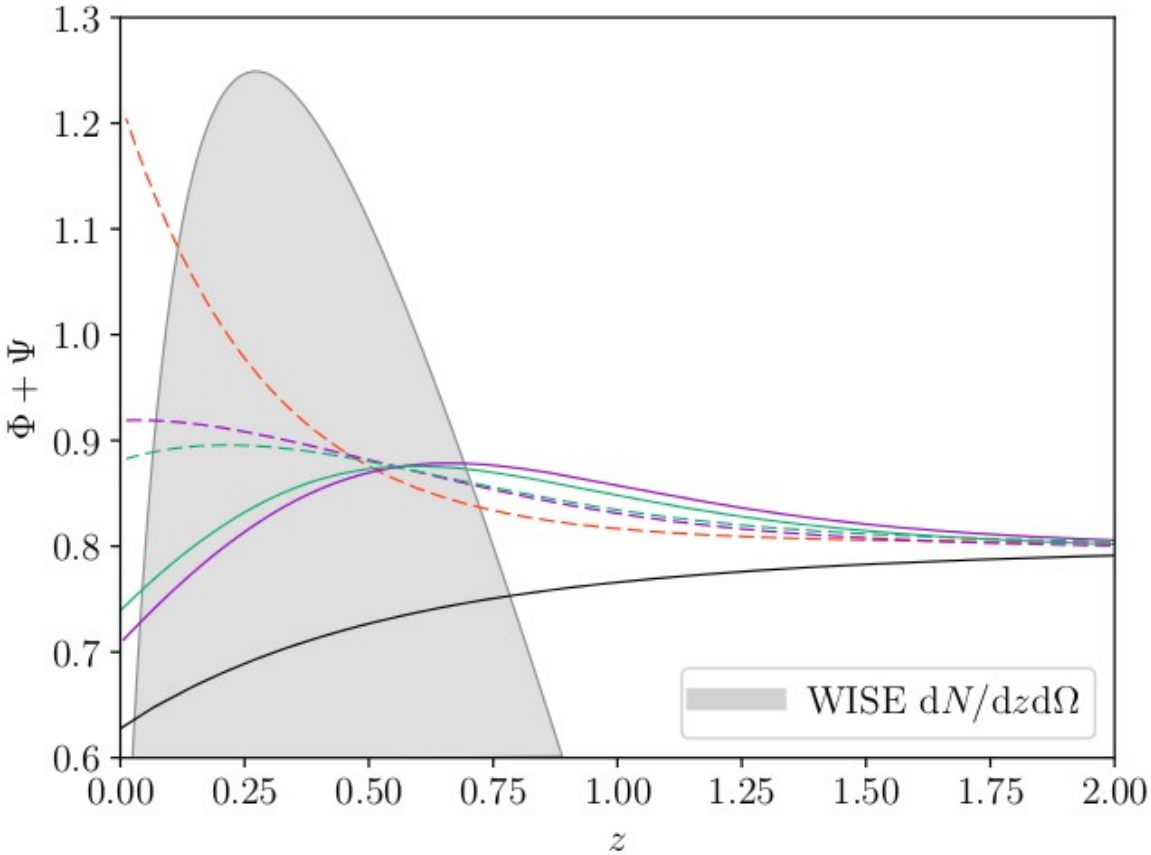
Quartic/Quintic are already in some tension with recent BAO data !

	$\chi^2_{\rm MGS}$	$\chi^2_{\rm DR12}$	$\chi^2_{\rm Ly\alpha-auto}$	$\chi^2_{\rm Ly\alpha-cross}$
data points	1	6	2	2
ΛCDM	1.98	5.02	4.95	4.78
$\nu Gal4$	5.82	12.69	5.35	3.61
$\nu Gal5$	3.45	12.90	6.05	4.26

What is there next ?

ISW tomography

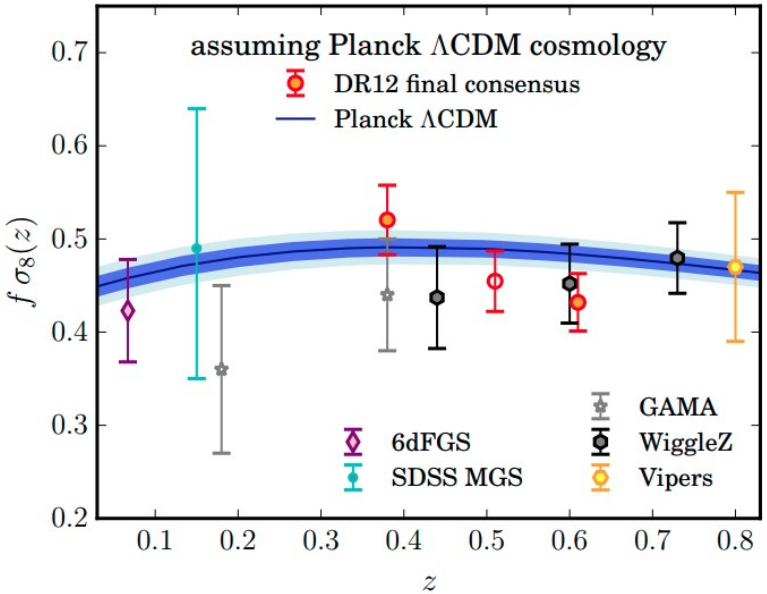
Time evolution of lensing potential



*Sign of the **<u>ISW effect is redshift dependent</u>** in Quartic/Quintic models*

Cross-correlate CMB-T with galaxies at varying z-ranges to test nontrivial evolutions

Why not other cosmological data?



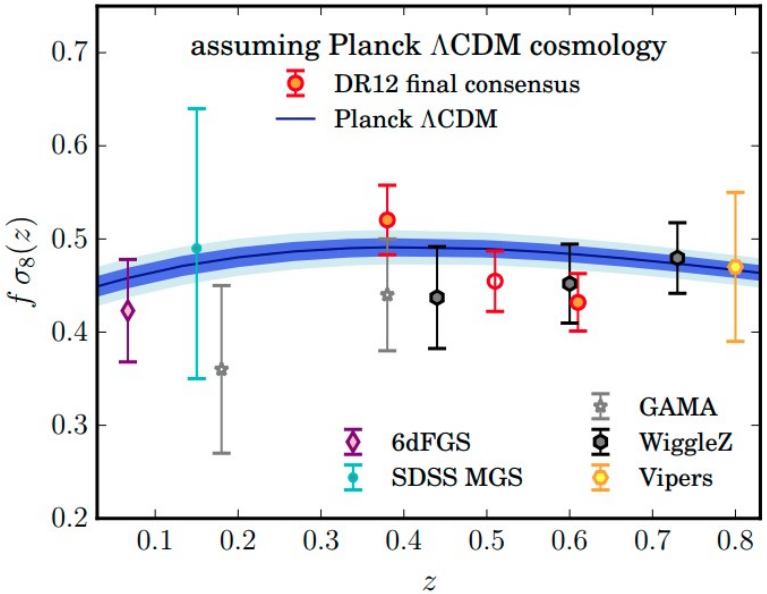
Growth rate

Data points are derived ***under LCDM assumptions !***

Need to validate observational analysis with galaxy mocks of Galileon gravity.

Barreira et al, 1605.03965
Bose et al, 1702.02348

Why not other cosmological data?

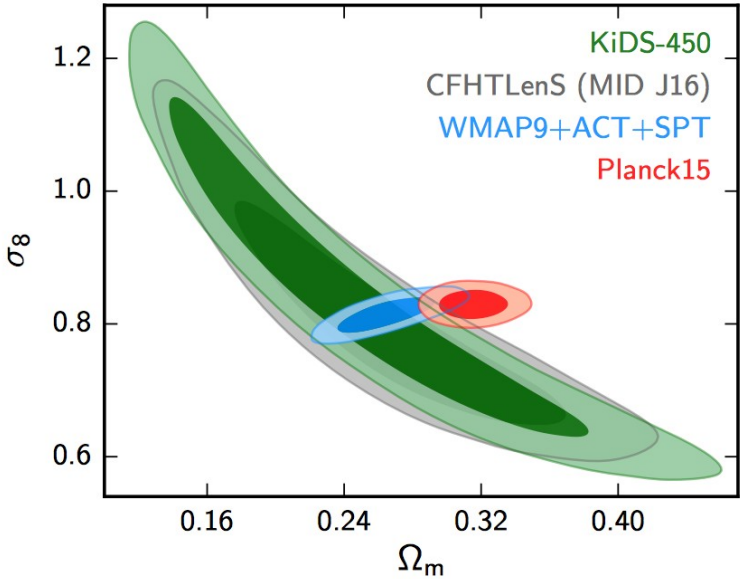


Growth rate

Data points are derived ***under LCDM assumptions !***

Need to validate observational analysis with galaxy mocks of Galileon gravity.

Barreira et al, 1605.03965
Bose et al, 1702.02348



Cosmic Shear

Currently there are no prescriptions for ***nonlinear structure formation.***

Needs further work or apply large-scale cuts.

Guns pointed at Quartic/Quintic

Lunar Laser Ranging

In the Quartic Galileon for instance:

$$\nabla^2\Psi = 4\pi\Big(f(\dot{\bar{\varphi}}) + g(\nabla^2\varphi)\Big)G\delta\rho_m + h(\nabla^2\varphi)$$

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Is this true though ?

Guns pointed at Quartic/Quintic

Lunar Laser Ranging

Light vs GW speed

*If c_t < c , **observed cosmic rays should have decayed away** into gravitons by Cherenkov-like emmision.*

Moore & Nelson 2001
Kimura & Yamamoto 1112.4284

*Potentially tighter constraints will be made possible in the **event of detections of GW with known optical origin.***

Guns pointed at Quartic/Quintic

Lunar Laser Ranging

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Does screening have any impact on these tests ?

Is this

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Guns pointed at Quartic/Quintic

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Absence of solutions in the nonlinear regime

In the Quartic Galileon for instance:

Light vs GW speed

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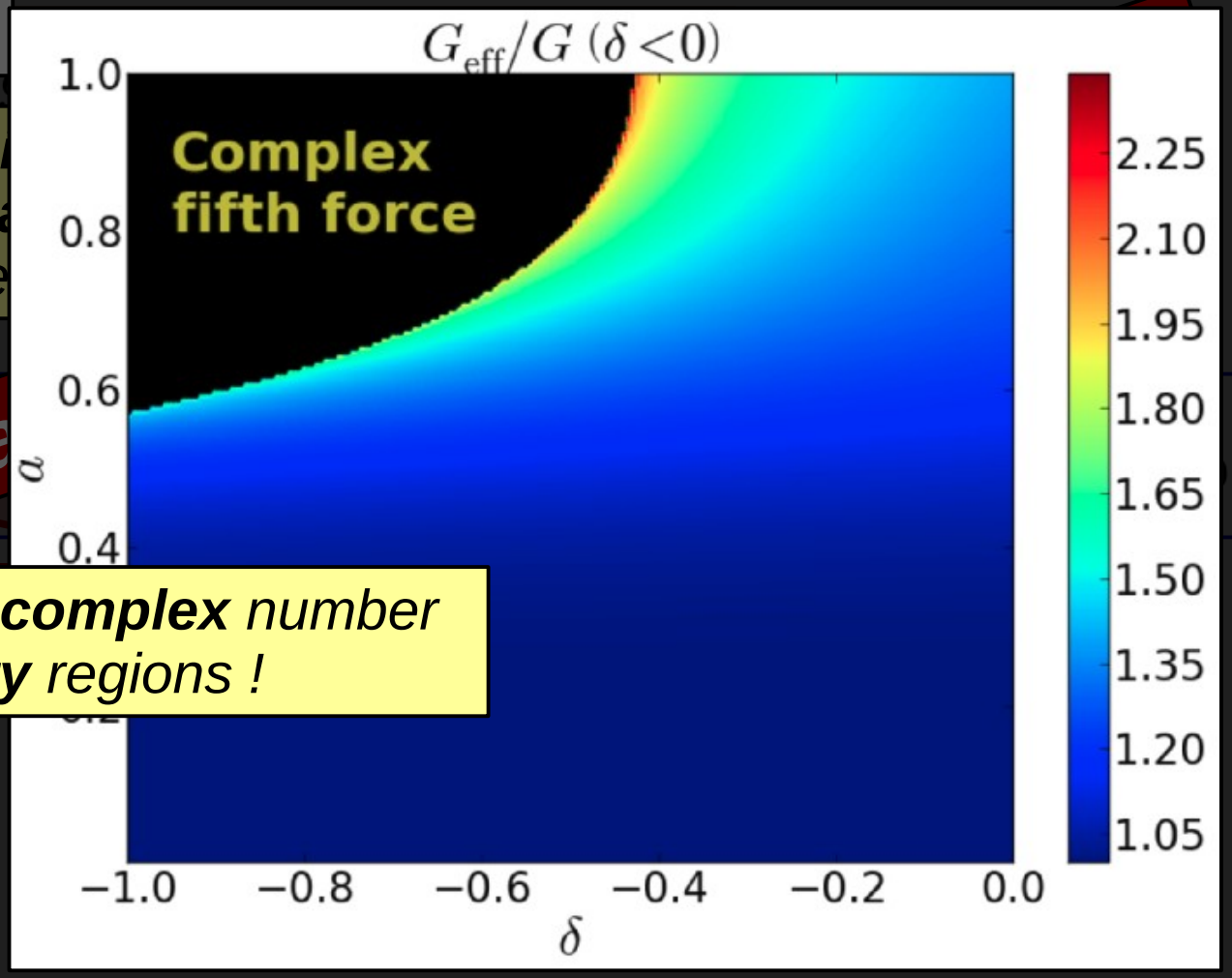
Do screening ha

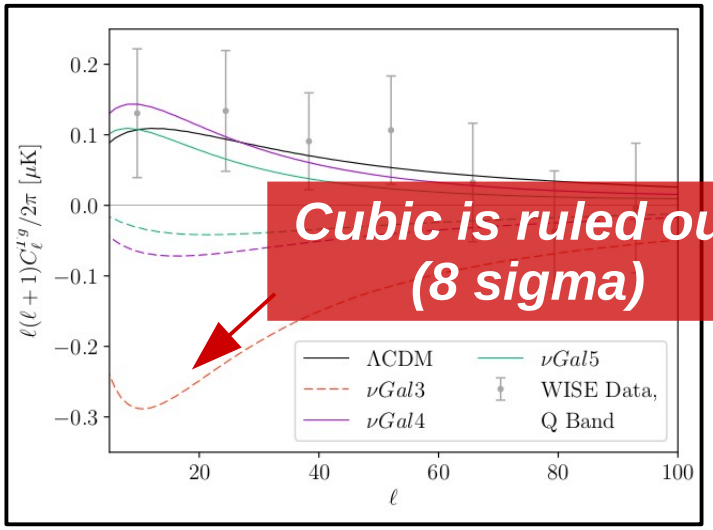
*Solution becomes a **complex** number in **low-density** regions !*

Barreira et al 1308.3699



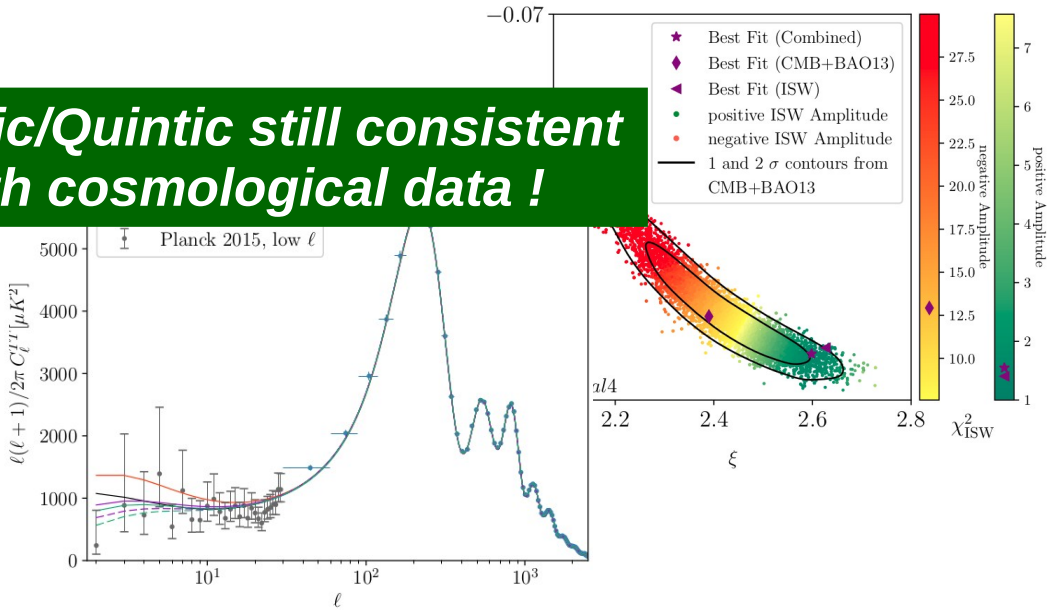
Summary

CMB+BAO+ISW constraints



Cubic is ruled out! (8 sigma)

Quartic/Quintic still consistent with cosmological data !



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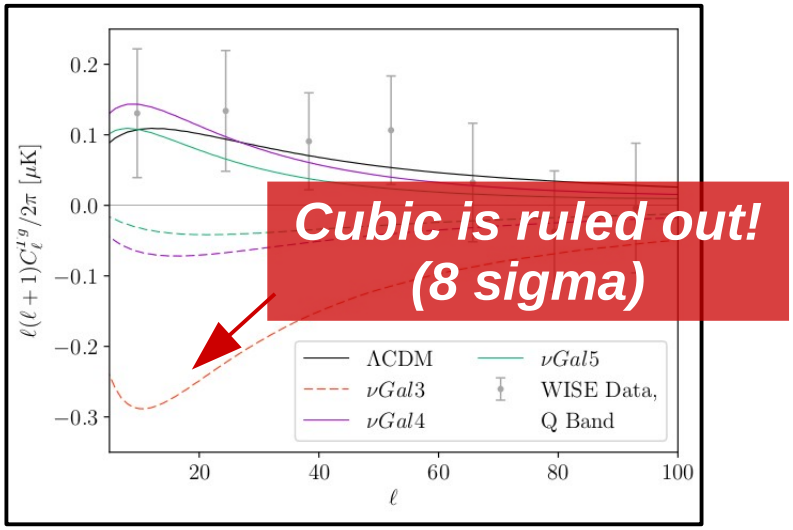

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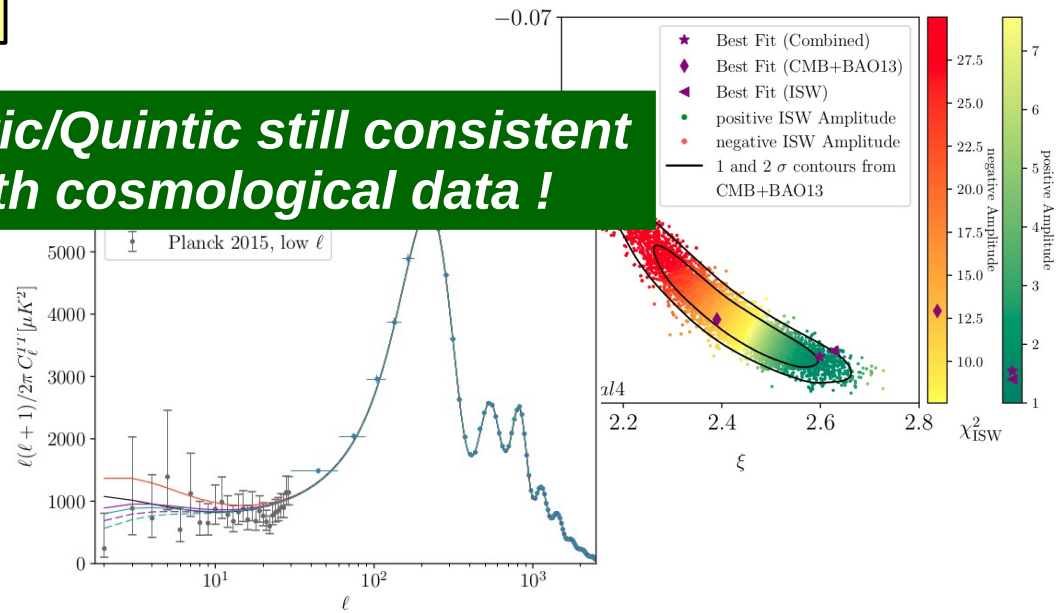

But are the Quartic/Quintic consistent with other data ?

Cosmology

- *ISW tomography*
- *Tighter BAO measurements*
- *Cosmic shear*
- *Growth rate*

Astrophysics

- *Lunar Laser Ranging*
- *Cherenkov-like radiation*
- *LIGO GW & known optical origin*

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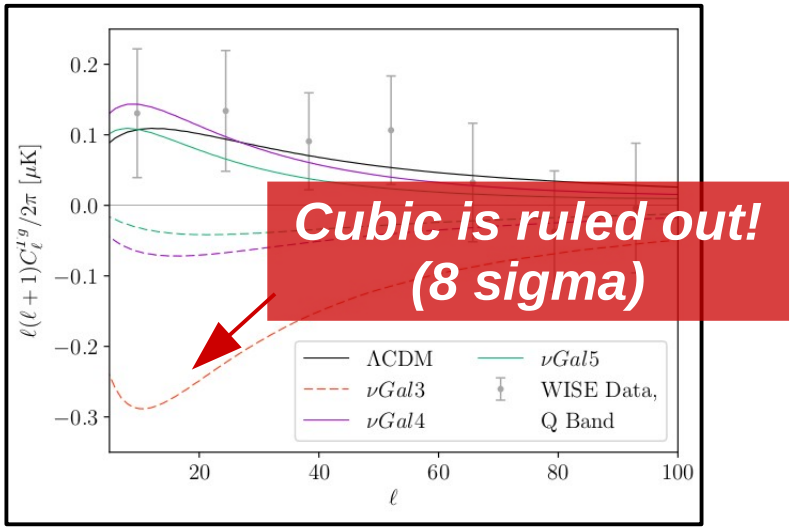

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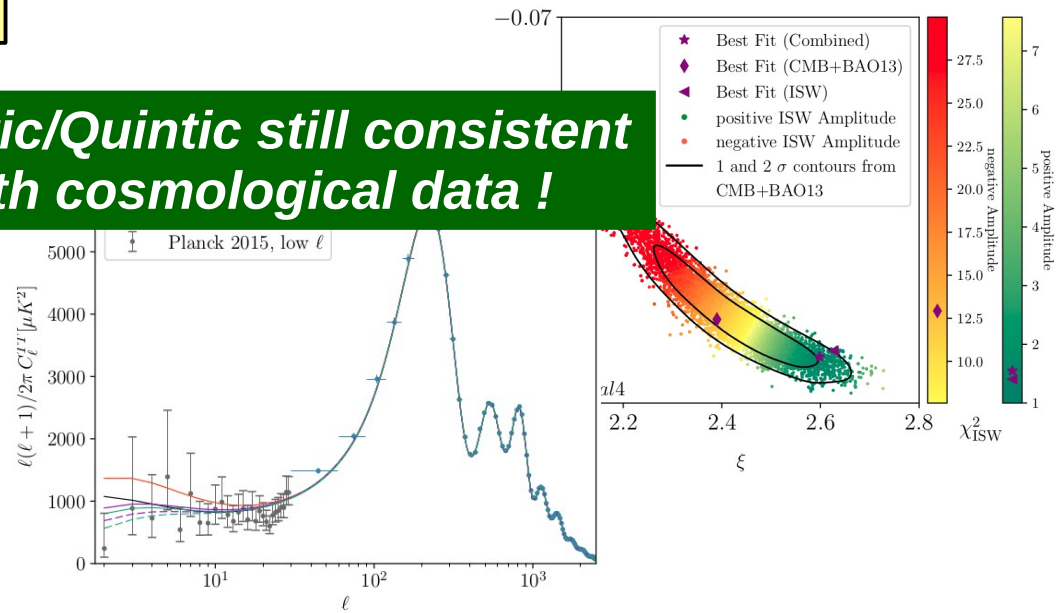

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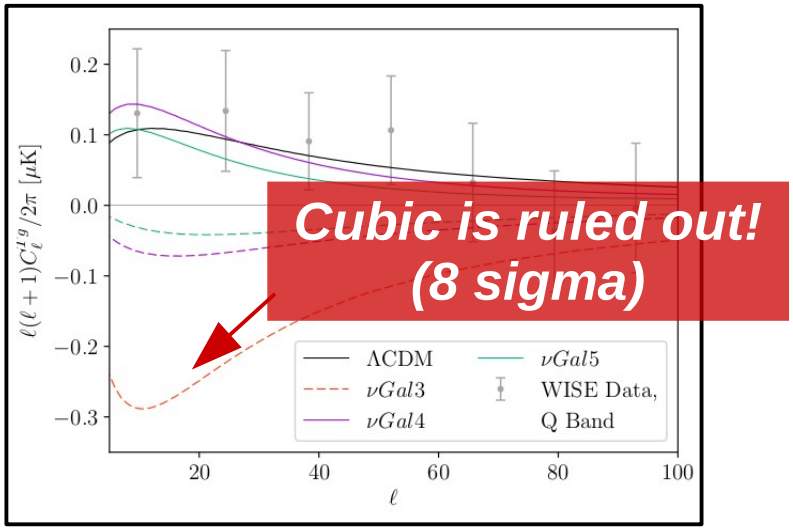

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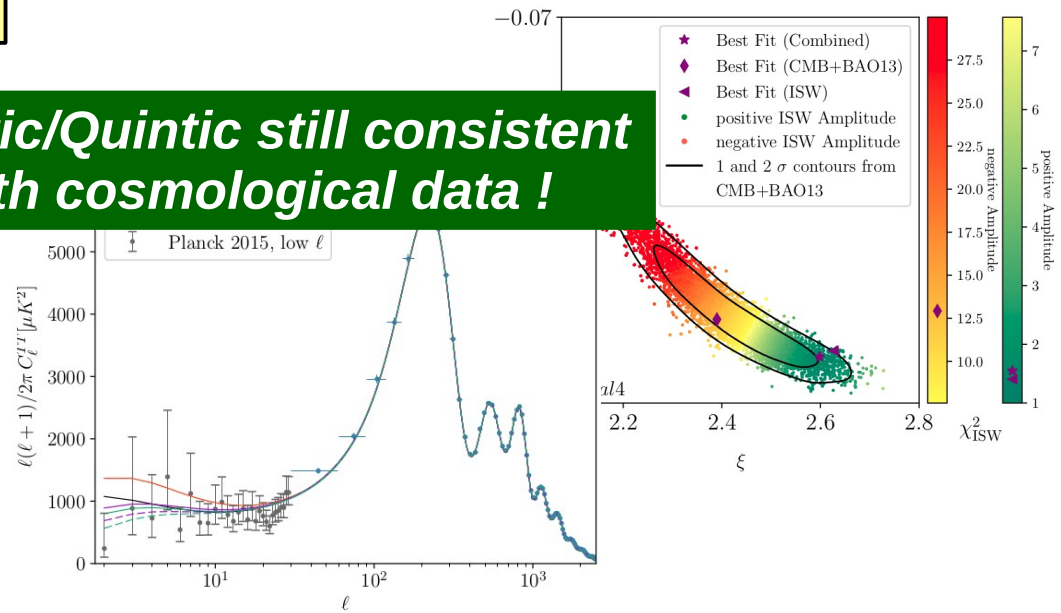

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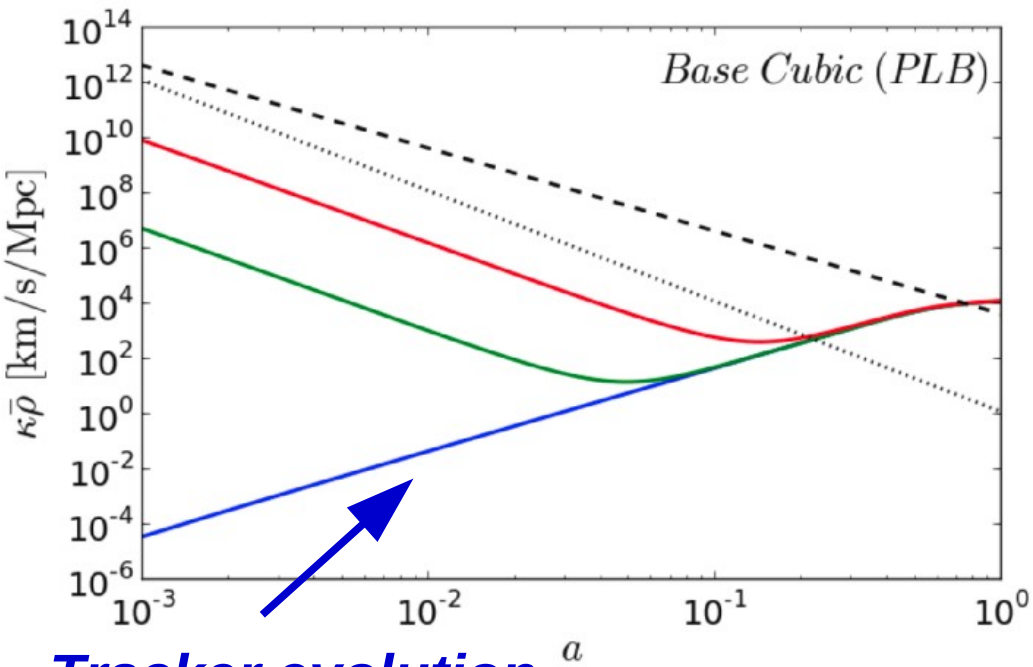
Tracker background evolution

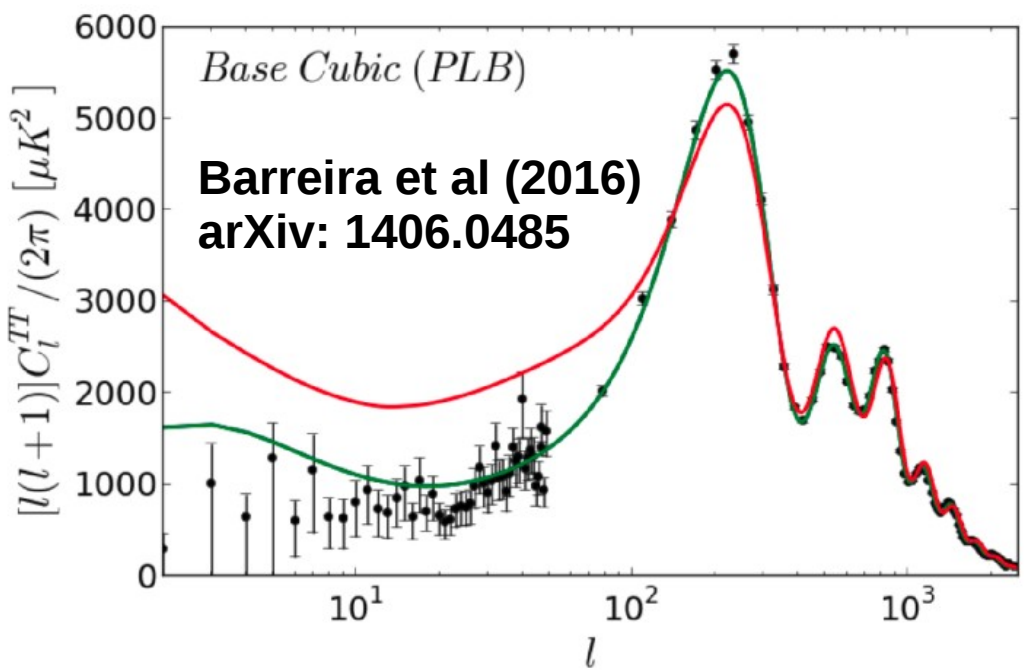
***Tracker evolution** characterized by:*

$$\frac{\dot{\phi} H}{M_{\mathrm{Pl}} H_0^2} \equiv \xi = \text{constant}$$

Unacceptable CMB-TT if the tracker isn't reached early enough

Barreira et al (2013) ; 1302.6241





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