Observational status of the Galileon model from cosmological data and gravitational waves

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Outline

I. Presentation of the galileon model

II. Methodology

III. Constraints from cosmology

IV. GW170817

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Horndeski theories

- Simple principles for an extension of General Relativity :
  - Additional scalar field π coupled to the metric
  - 2nd order e.o.m : easy way to avoid Ostrogradski ghosts

$$\Downarrow$$

Horndeski lagrangians

$$\mathcal{L}_2^{(H)} = G_2\left(\pi, X\right)$$

$$\mathcal{L}_3^{(H)} = G_3\left(\pi, X\right)\left(\Box\pi\right)$$

$$\mathcal{L}_4^{(H)} = G_4\left(\pi, X\right) R - G_{4,X}\left(\pi, X\right)\left[2\left(\Box\pi\right)^2 - 2\pi_{;\mu\nu}\pi^{;\mu\nu}\right]$$

$$\mathcal{L}_5^{(H)} = G_5\left(\pi, X\right) G_{\mu\nu}\pi^{;\mu\nu} + \frac{1}{6} G_{5,X}\left(\pi, X\right)\left[\left(\Box\pi\right)^3 - 3\left(\Box\pi\right)\pi_{;\mu\nu}\pi^{;\mu\nu} + 2\pi_{;\mu}^{;\nu}\pi_{;\nu}^{;\rho}\pi_{;\rho}^{;\mu}\right]$$

- Where the G_i are arbitrary functions of π and X

A particular case : the galileon

- The galileon model is a particular case of Horndeski :
  - Galilean symmetry in Minkowskii space-time (inspired by DGP, massive gravity, ...) :

$$\pi \to \pi + c + b_\mu x^\mu$$

  - Simple expressions for the arbitrary functions :

$$G_2 = c_1 M^3 \pi + c_2 X, \qquad G_3 = \frac{c_3 X}{M^3}, \qquad G_4 = M_P^2 - \frac{c_4}{M^6} X^2, \qquad G_5 = \frac{3 c_5 X^2}{M^9}$$

  - The c_i are arbitrary parameters and $M^3 = M_P H_0^2$
  - Addition of direct couplings to matter : conformal and/or disformal

The galileon model

- The galileon action :

$$\mathcal{S}\left[\phi, g, \pi\right] = \mathcal{S}_{SM}\left[\phi, g\right] + \int d^4x\sqrt{-g}\left[\left(1 - 2c_0\frac{\pi}{M_P}\right)\frac{M_P^2}{2}R - \frac{1}{2}\sum_{i=1}^{5}\frac{c_i}{M^{3(i-2)}}\mathcal{L}_i - \frac{M_P}{M^3}c_G G^{\mu\nu}\pi_{;\mu}\pi_{;\nu}\right]$$

$$\mathcal{L}_1 = \pi$$

$$\mathcal{L}_2 = X$$

$$\mathcal{L}_3 = X\Box\pi$$

$$\mathcal{L}_4 = X\left[2\left(\Box\pi\right)^2 - 2\left(\pi_{;\mu\nu}\pi^{;\mu\nu}\right) - \frac{1}{2}XR\right]$$

$$\mathcal{L}_5 = X\left[\left(\Box\pi\right)^3 - 3\left(\pi_{;\mu\nu}\pi^{;\mu\nu}\right)\Box\pi + 2\left(\pi_{;\mu}^{;\nu}\pi_{;\nu}^{;\rho}\pi_{;\rho}^{;\mu}\right) - 6\left(\pi_{;\mu}\pi^{;\mu\nu}G_{\nu\rho}\pi^{;\rho}\right)\right]$$

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- The galileon action :

Five galileon parameters

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Tadpole (behaves like Λ so c_1=0)

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Disformal coupling

$\mathcal{L}_1=\pi$ ← Tadpole (behaves like Λ so c_1=0)

$\mathcal{L}_2=X$ ← Kinetic term

$\mathcal{L}_3=X\Box\pi$

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$\mathcal{L}_4 = X\left[2\left(\Box\pi\right)^2 - 2\left(\pi_{;\mu\nu}\pi^{;\mu\nu}\right) - \frac{1}{2}XR\right]$ ← Non-linear lagrangians

$\mathcal{L}_5 = X\left[\left(\Box\pi\right)^3 - 3\left(\pi_{;\mu\nu}\pi^{;\mu\nu}\right)\Box\pi + 2\left(\pi_{;\mu}^{;\nu}\pi_{;\nu}^{;\rho}\pi_{;\rho}^{;\mu}\right) - 6\left(\pi_{;\mu}\pi^{;\mu\nu}G_{\nu\rho}\pi^{;\rho}\right)\right]$

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Non-linear lagrangians ($\mathcal{L}_3$, $\mathcal{L}_4$, $\mathcal{L}_5$)

- Non-linear lagrangians screen the galileon at small scales through Vainshtein effect

The galileon model

- A popular modified gravity model :
  - Cosmological solution with accelerated expansion
  - No effect near massive bodies due to Vainshtein screening

  $\Rightarrow$ necessary to pass tests of gravity in the solar system
  - No ghost degrees of freedom
  - Simple construction principles and limit of other well motivated cosmological models
  - Only up to seven real parameters

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Galileon predictions

- Evolution in galileon gravity given by e.o.m of π and Einstein equations :

$$\frac{\delta \mathcal{S}}{\delta \pi} = 0 \qquad \text{and} \qquad G_{\mu\nu} = \kappa T_{\mu\nu}^{SM} + \kappa T_{\mu\nu}^{(\pi)}$$

- The galileon field is treated as a new fluid
- At first order $\Rightarrow$ background evolution necessary to compute cosmological distances
- At linear order $\Rightarrow$ perturbations evolution necessary to compute CMB powerspectra

Background evolution

- Cosmological background evolution :

$$\frac{dH}{d\ln a} = \frac{\omega\gamma - \lambda\beta}{\sigma\beta - \alpha\omega}$$

$$\frac{dx}{d\ln a} = -x + \frac{\alpha\lambda - \sigma\gamma}{\sigma\beta - \alpha\omega}$$

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functions of H and x

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- Scaling invariance :

$$\begin{array}{lll} c_i & \to & \bar{c}_i \equiv c_i B^i, \quad i = 2, ..., 5 \\ c_G & \to & \bar{c}_G \equiv c_G B^2 \\ x & \to & \bar{x} \equiv x/B \end{array}$$

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Perturbations evolution

- Scalar perturbations evolution in the synchronous gauge :

$$0 = f_1^{eom} \cdot \bar{\gamma}'' + f_2^{eom} \cdot \bar{\gamma}' + f_3^{eom} \cdot k^2\bar{\gamma} + f_4^{eom} \cdot k\mathcal{H}\mathcal{Z} + f_5^{eom} \cdot k\mathcal{Z}' + f_6^{eom} \cdot k^2\eta$$

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$$\delta\rho^{(\pi)} = f_1^{\chi} \cdot \gamma + f_2^{\chi} \cdot \gamma' + \frac{1}{\kappa a^2} \left(f_3^{\chi} \cdot k\mathcal{H}\mathcal{Z} + f_4^{\chi} \cdot k^2 \eta \right)$$

$$q^{(\pi)} = f_1^{q} + \frac{1}{\kappa a^2} f_2^{q} \cdot k^2 \left(\sigma - \mathcal{Z} \right)$$

$$\Pi^{(\pi)} = f_1^{\Pi} + \frac{1}{\kappa a^2} \left(f_2^{\Pi} \cdot k\mathcal{H}\sigma - f_3^{\Pi} \cdot k\sigma' + f_4^{\Pi} \cdot k^2 \phi \right)$$

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- Where the $f_i^{\chi,q,\Pi,eom}$ are functions of the background
- Barreira et al. 2013 showed that initial conditions for galileon perturbations can be taken as :

$$\gamma = \gamma' = 0 \qquad \text{at} \quad z \sim 10^{10}$$

Parameter space exploration

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    - Additional relation on parameters

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    - Attractor solutions
    - Additional relation on parameters
    - Analytical solution for the background evolution

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- MCMC exploration of the parameter space against cosmological observations using our modified version of CosmoMC :
  - Constraints on full galileon parameters $\{\mathrm{cosmo}, c_2, c_3, c_4, c_5, c_G, x_0\}$
  - Constraints on cubic galileon parameters $\{\mathrm{cosmo}, c_2, c_3, 0, 0, 0, x_0\}$
  - Common cosmological parameters $\{\Omega_b h^2, \Omega_c h^2, 100\theta_{\mathrm{MC}}, \tau, n_s, A_s\}$
  - Reject scenarios with instabilities in scalar or tensorial perturbations
  - No restriction to tracker solutions
- A posteriori comparison to GW speed constraint from GW170817

Outline

I. Presentation of the galileon model

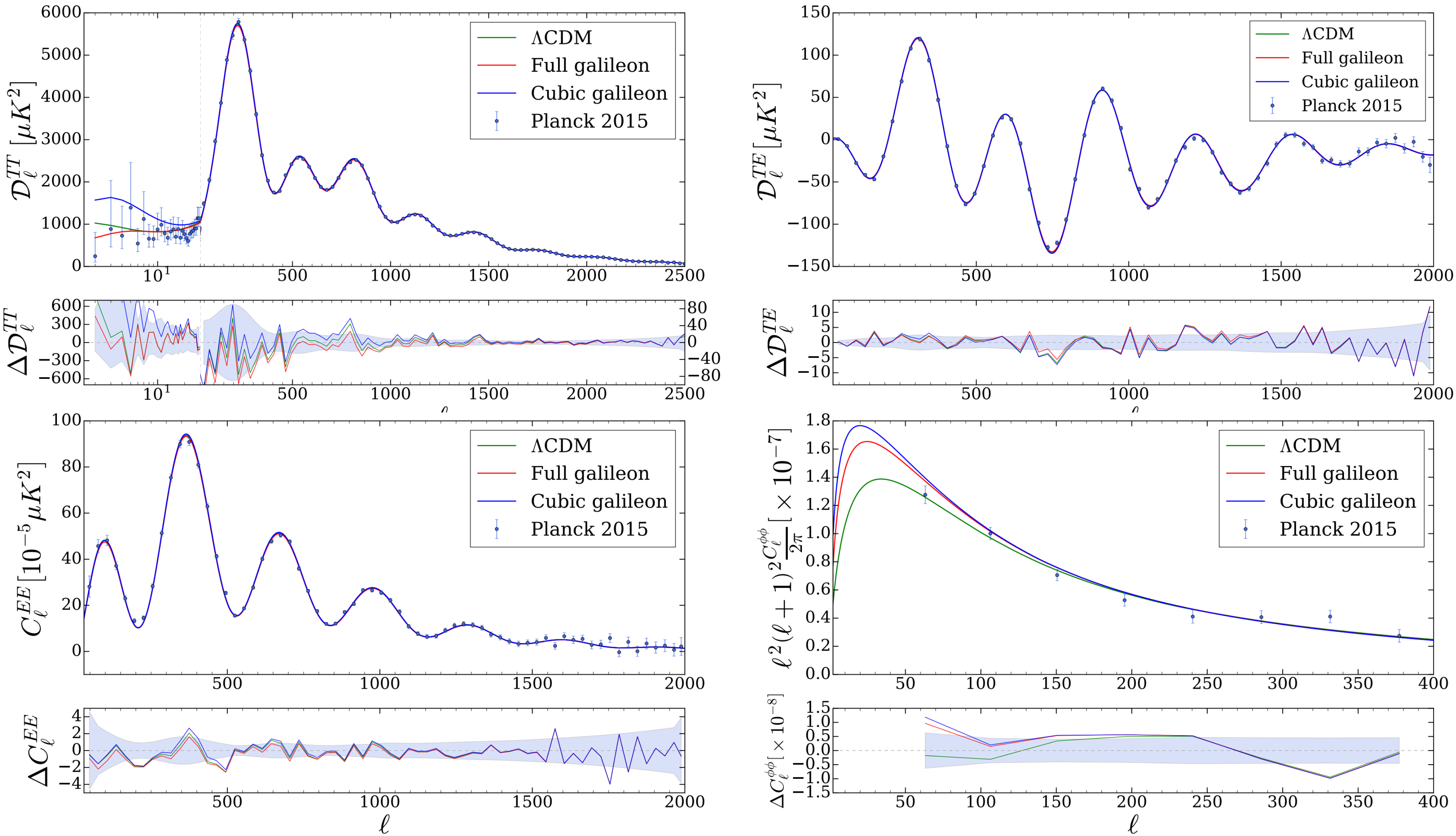
II. Methodology

III. Constraints from cosmology

IV. GW170817

Base models

➤ Fit to CMB data only :



Base models

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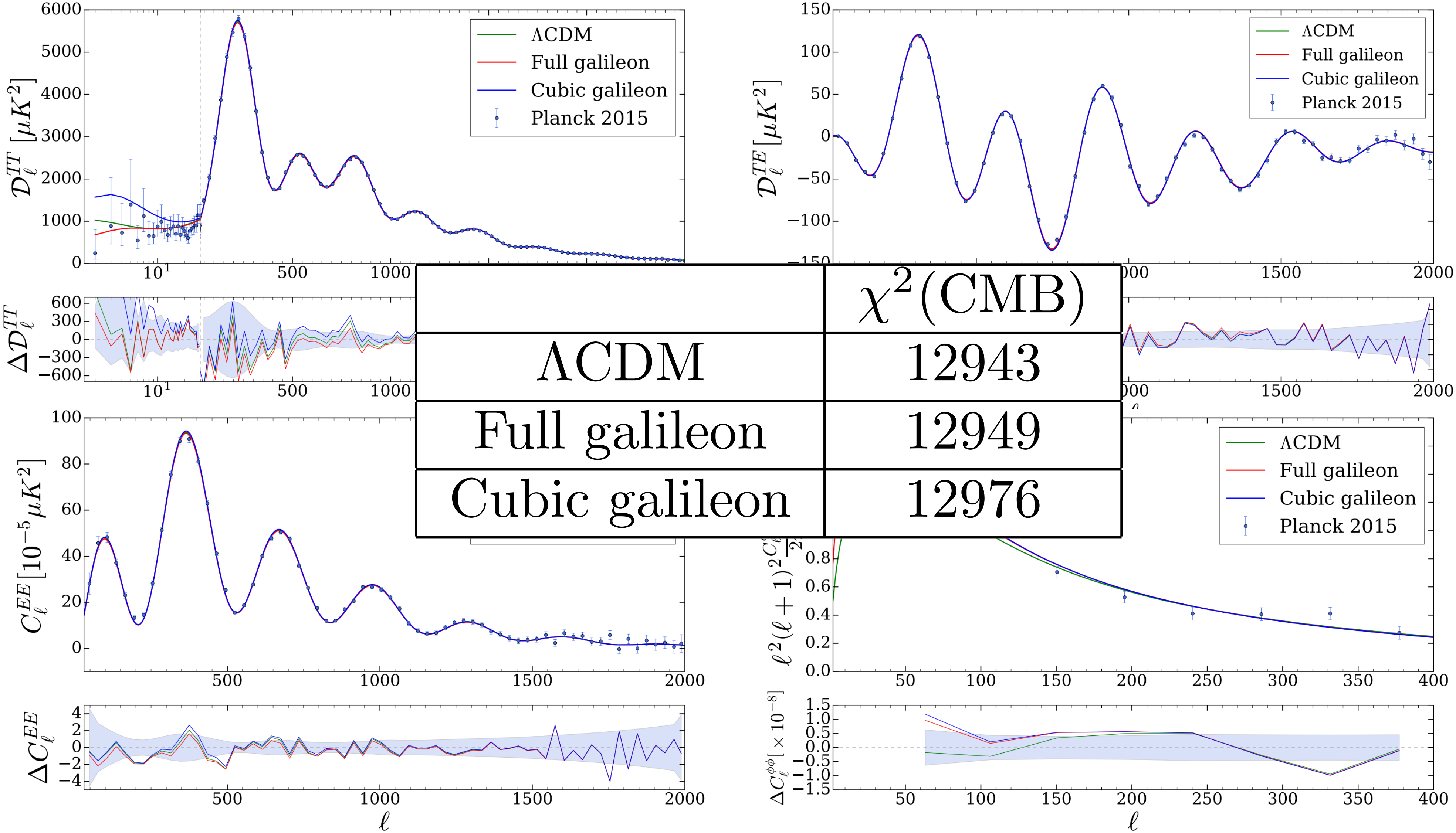
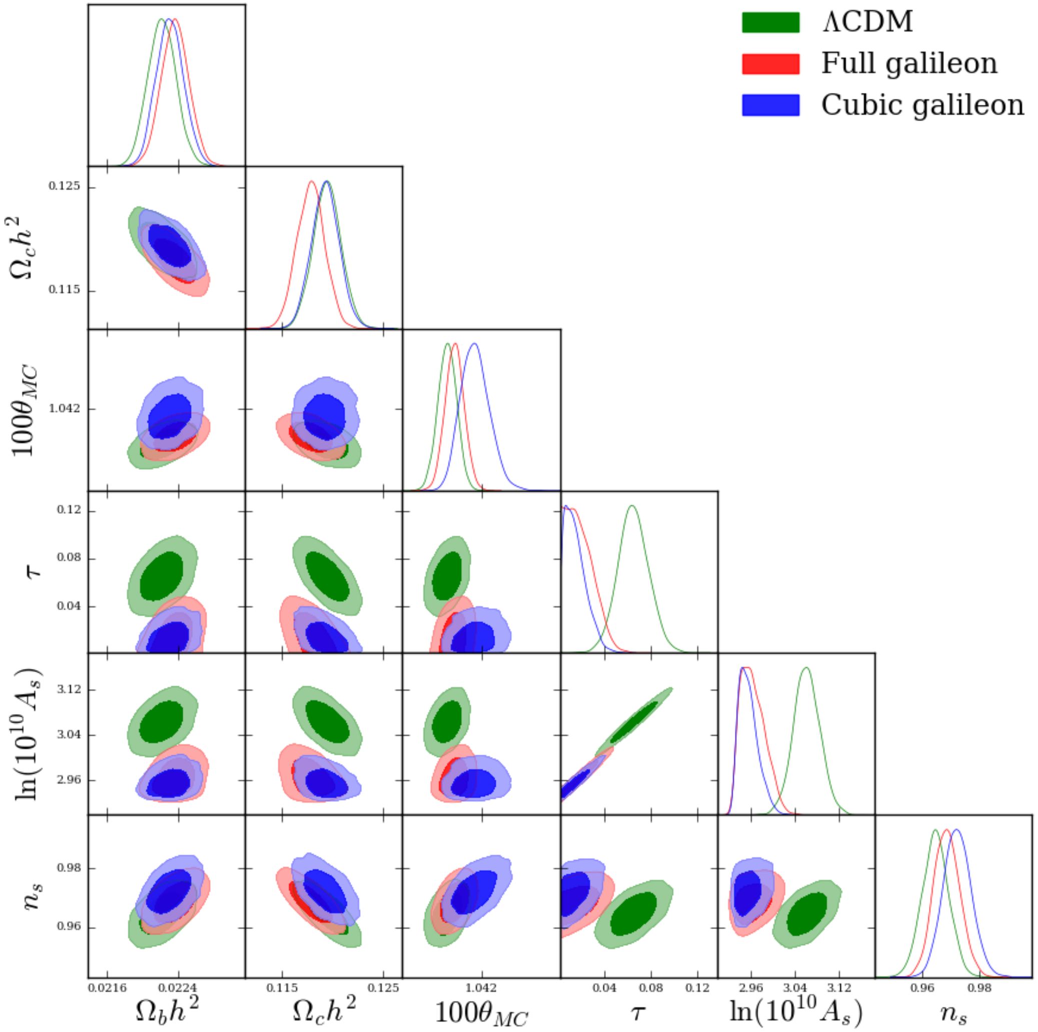


	χ^2(CMB)
ΛCDM	12943
Full galileon	12949
Cubic galileon	12976

Base models

- Fit to CMB data only :



Base models

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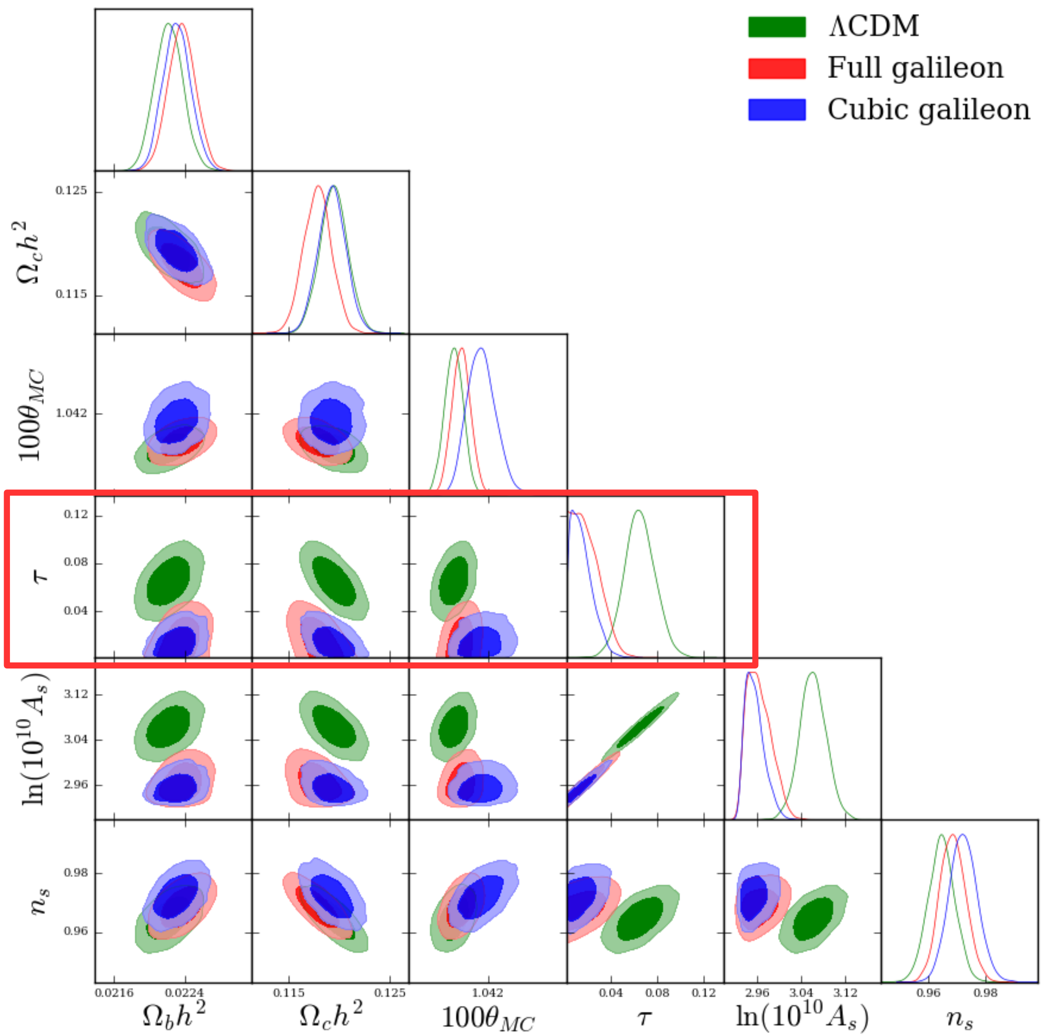

Base models

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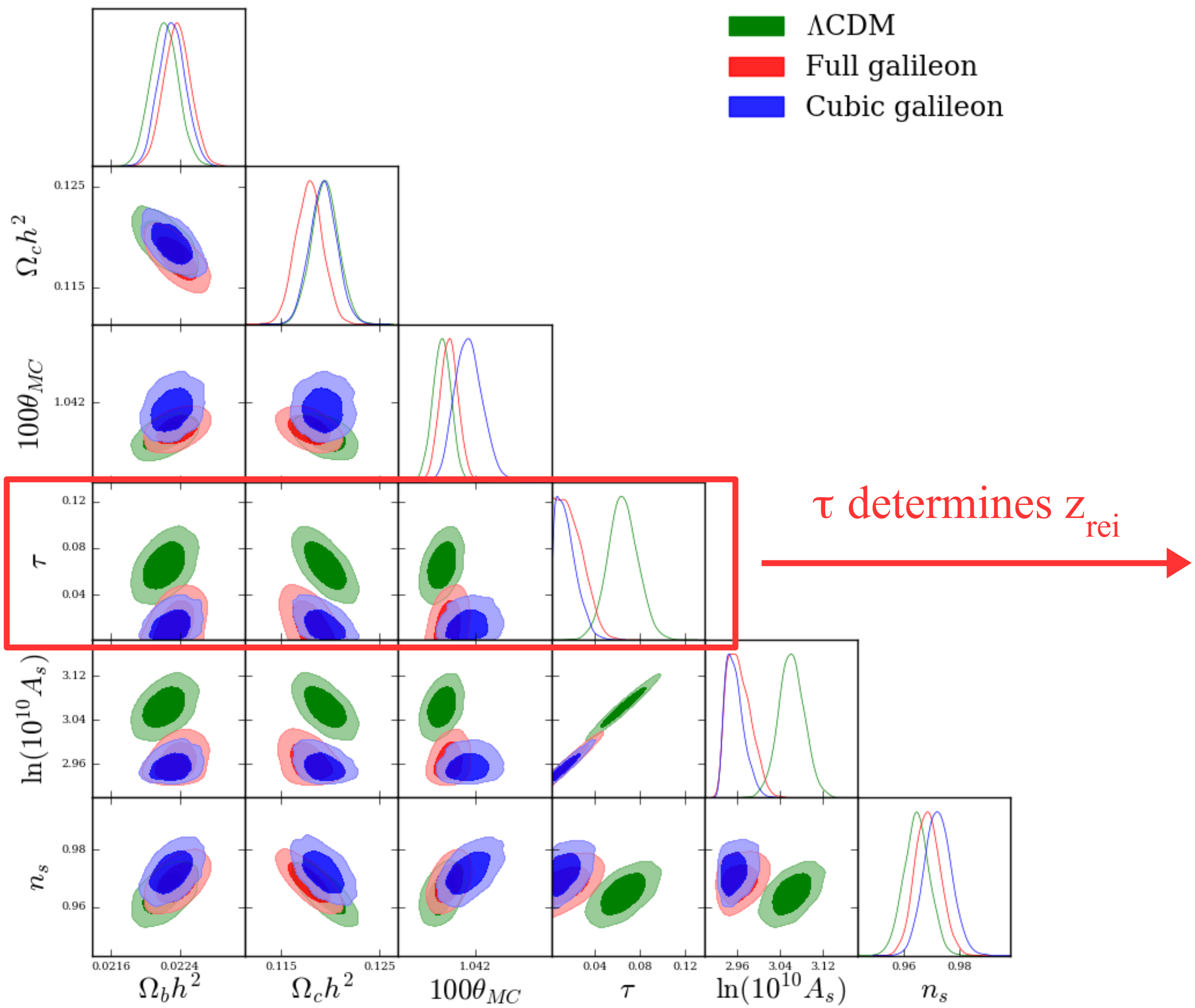

Base models

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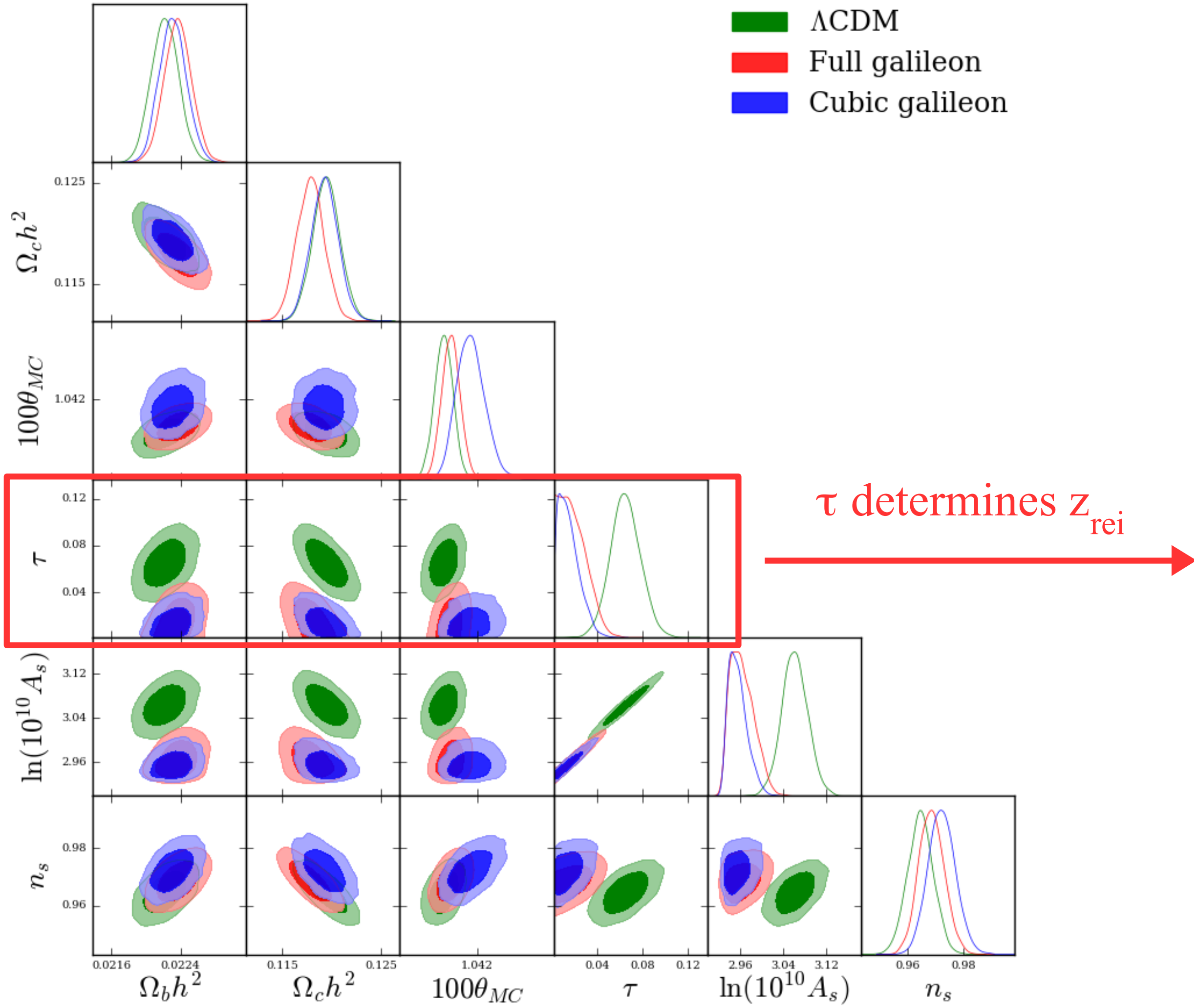

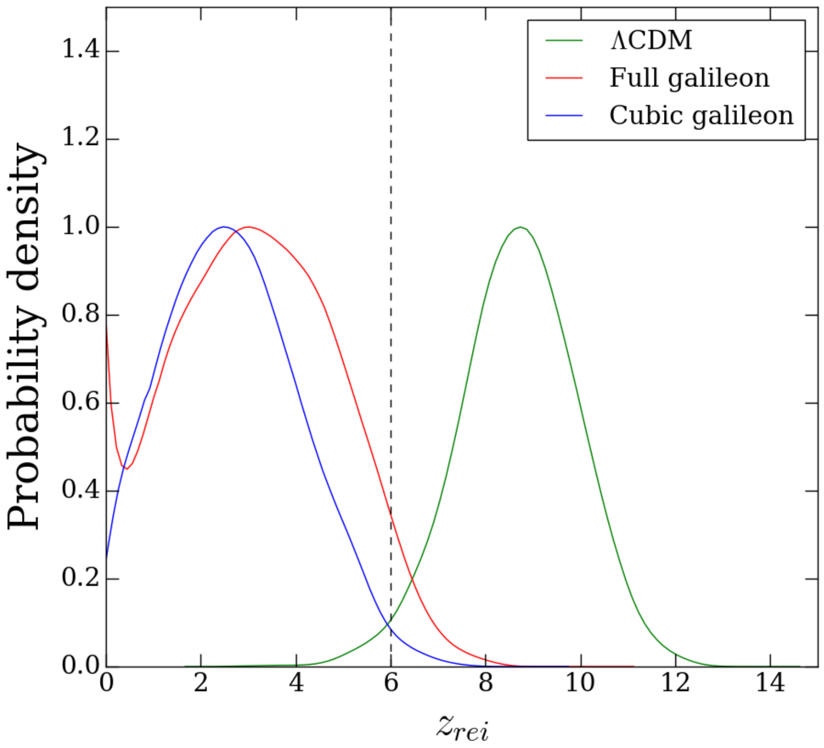

Base models

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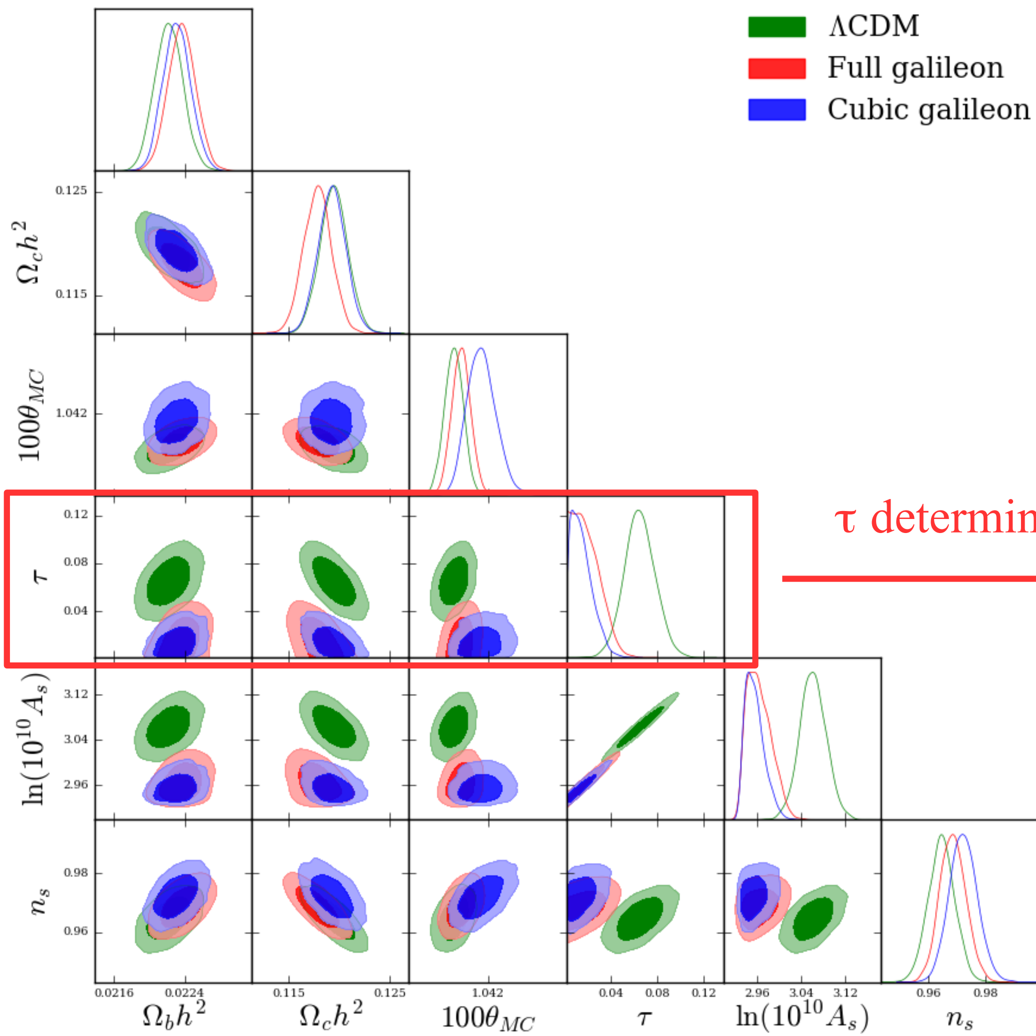
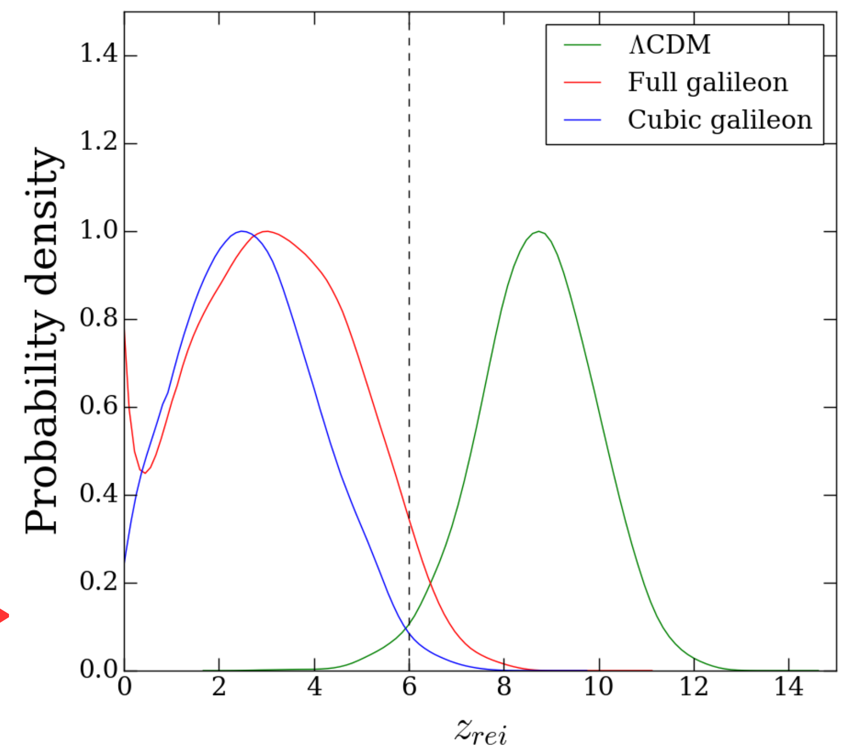


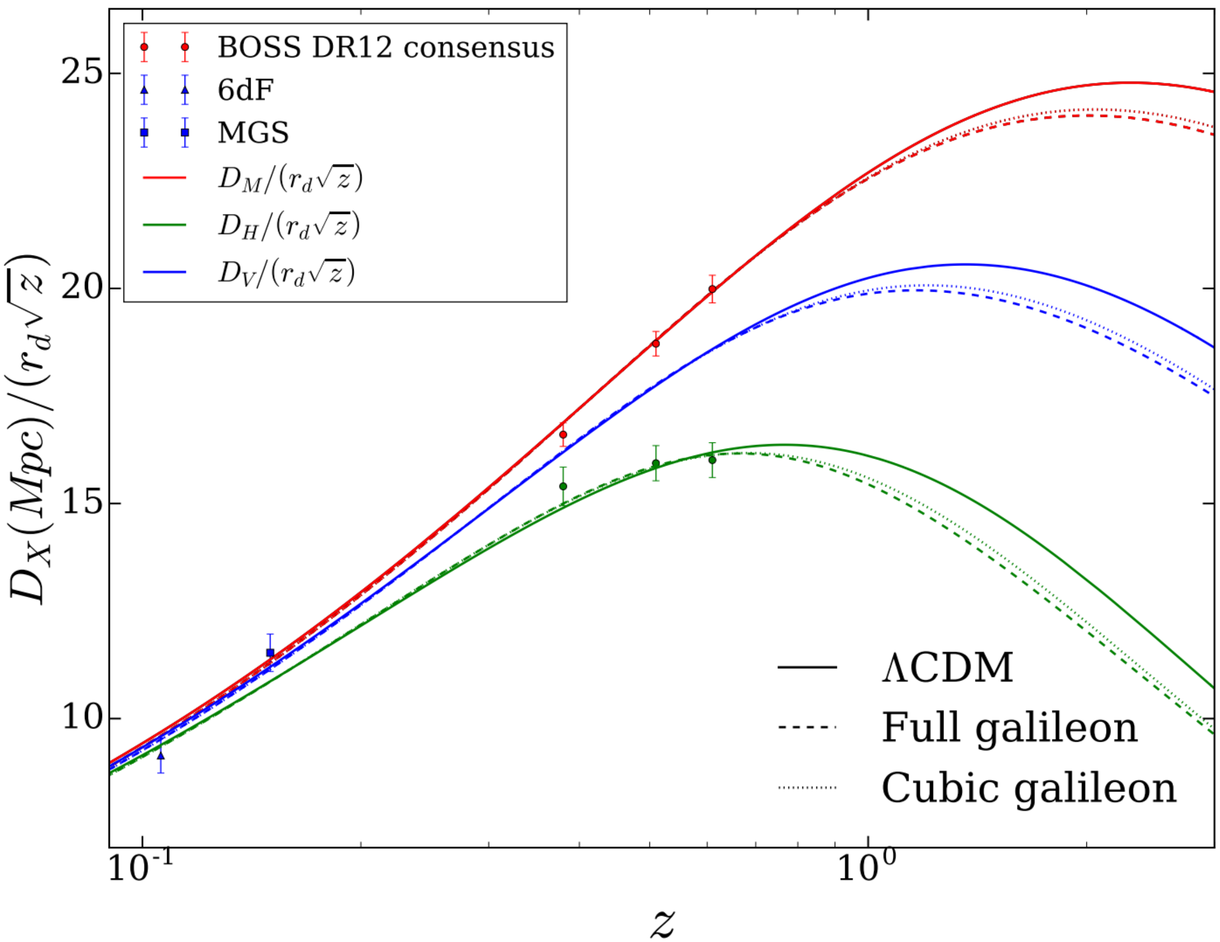
τ determines z_{rei}



- Astrophysical observations indicate that $z_{rei} > 6$ (e.g. astro-ph/0108097) :
  - Full galileon : ~1.5σ
  - Cubic galileon : ~3.5σ

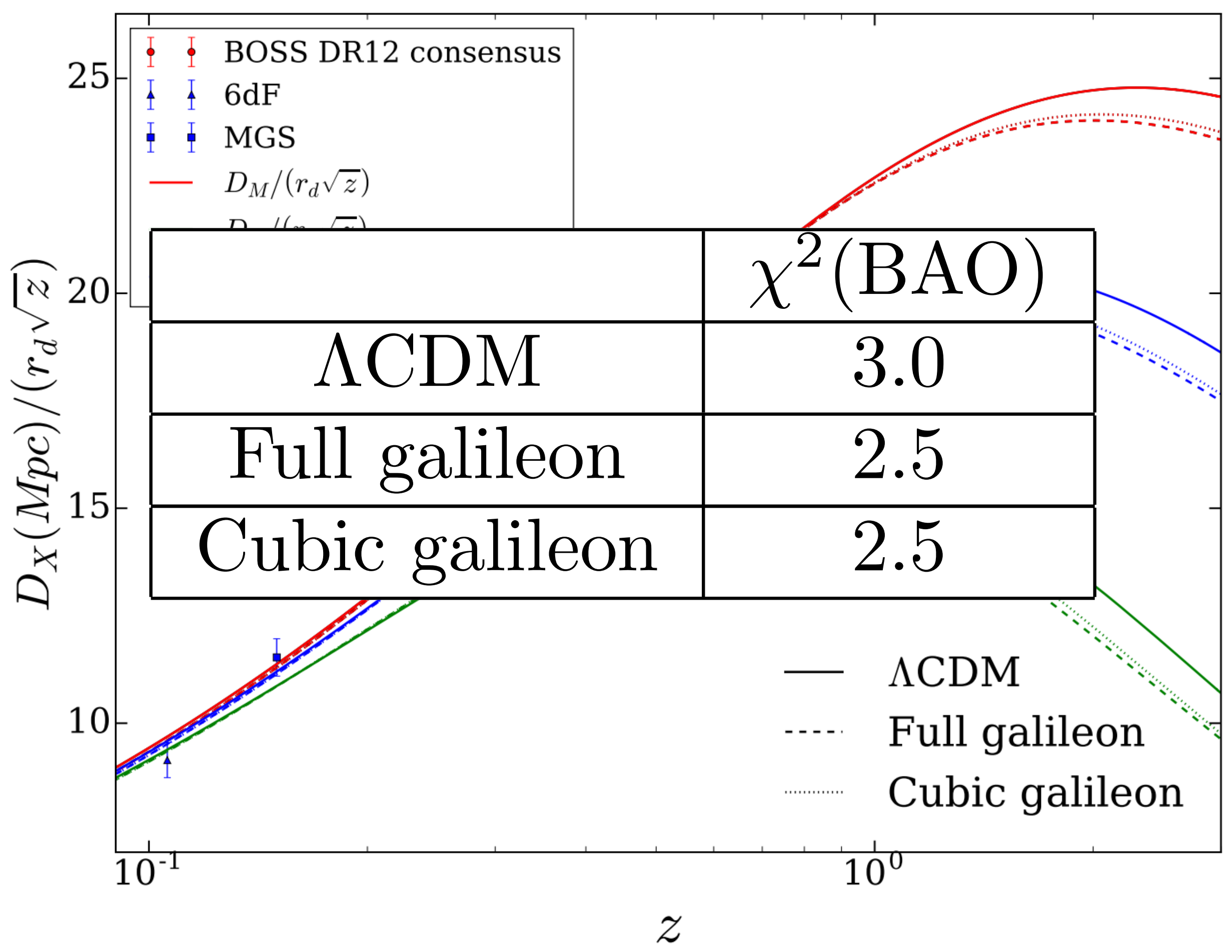
Base models

- Fit to BAO data only :



Base models

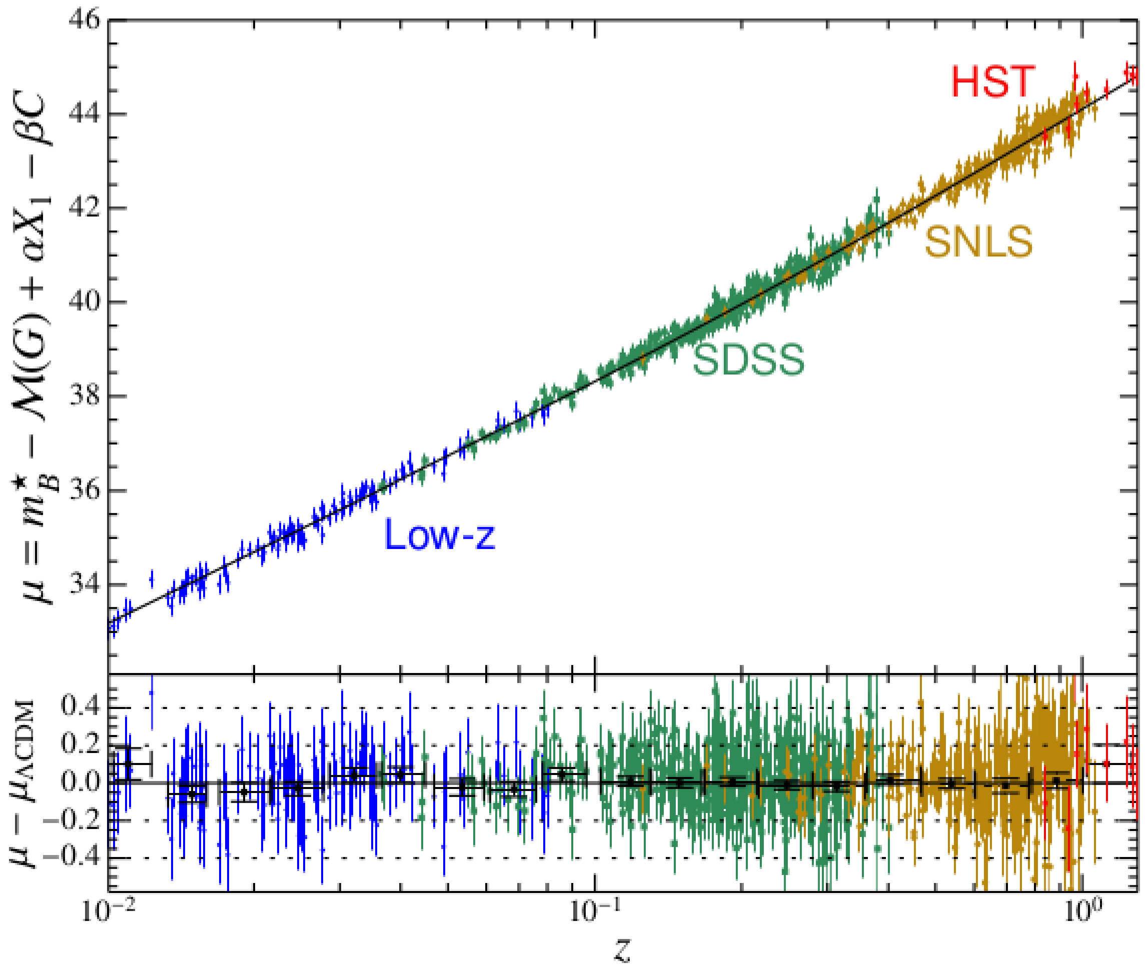
- Fit to BAO data only :



	χ^2(BAO)
ΛCDM	3.0
Full galileon	2.5
Cubic galileon	2.5

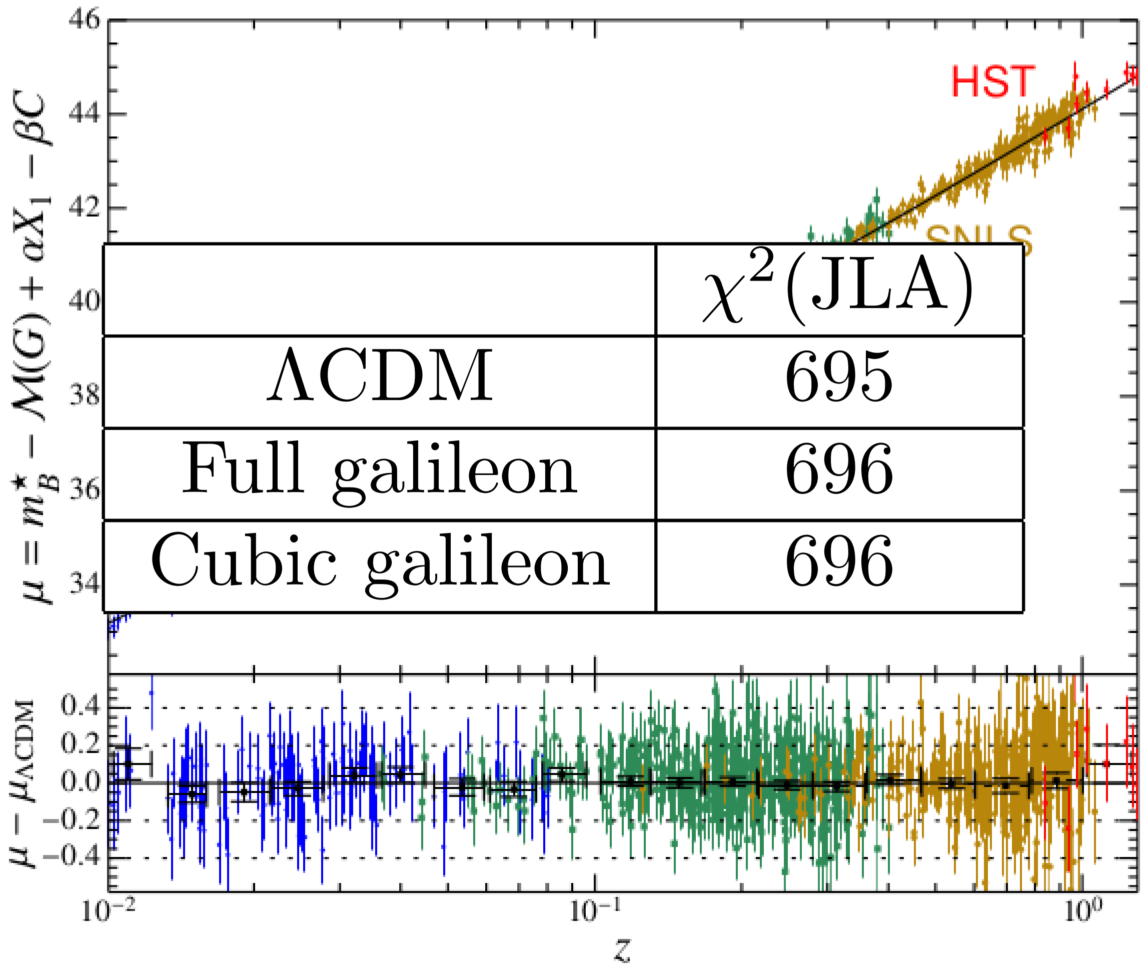
Base models

- Fit to JLA data only :



Base models

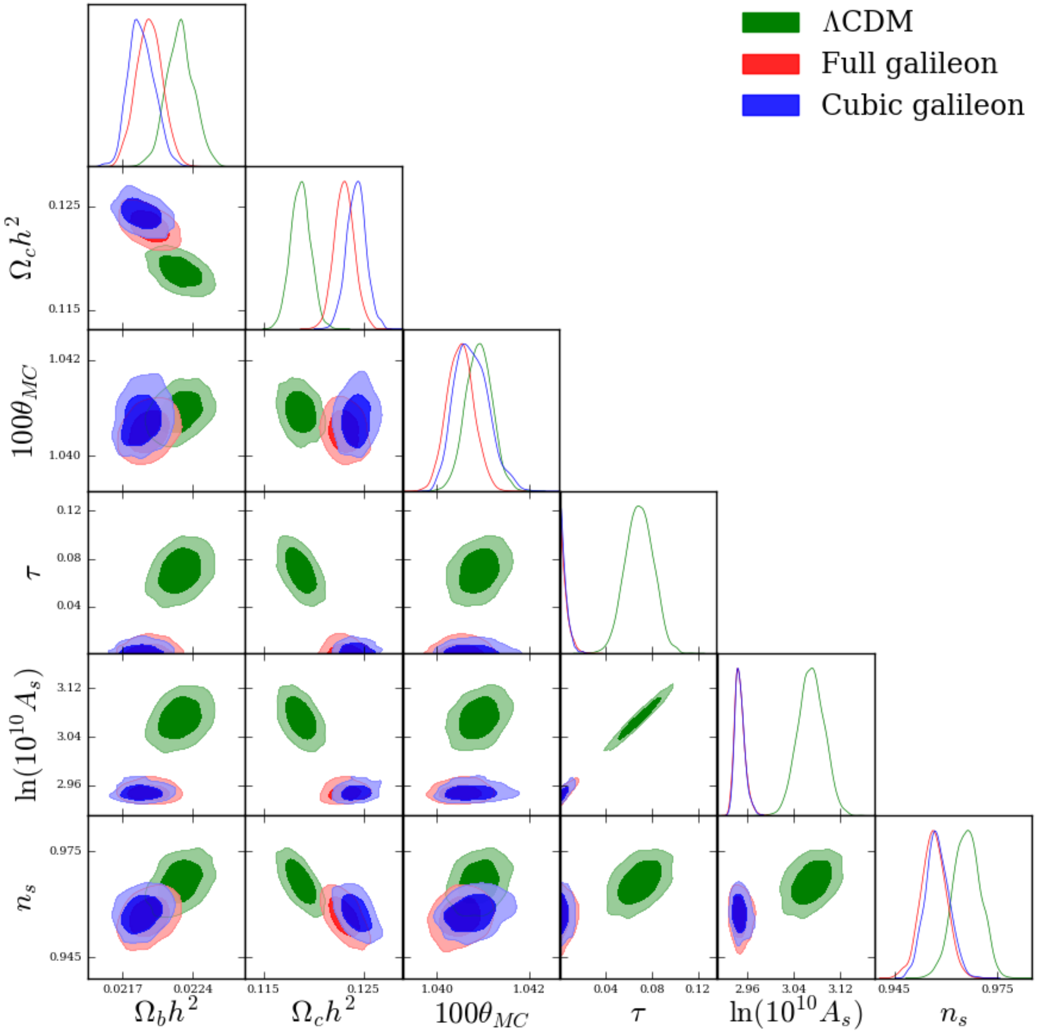
- Fit to JLA data only :



	χ^2(JLA)
ΛCDM	695
Full galileon	696
Cubic galileon	696

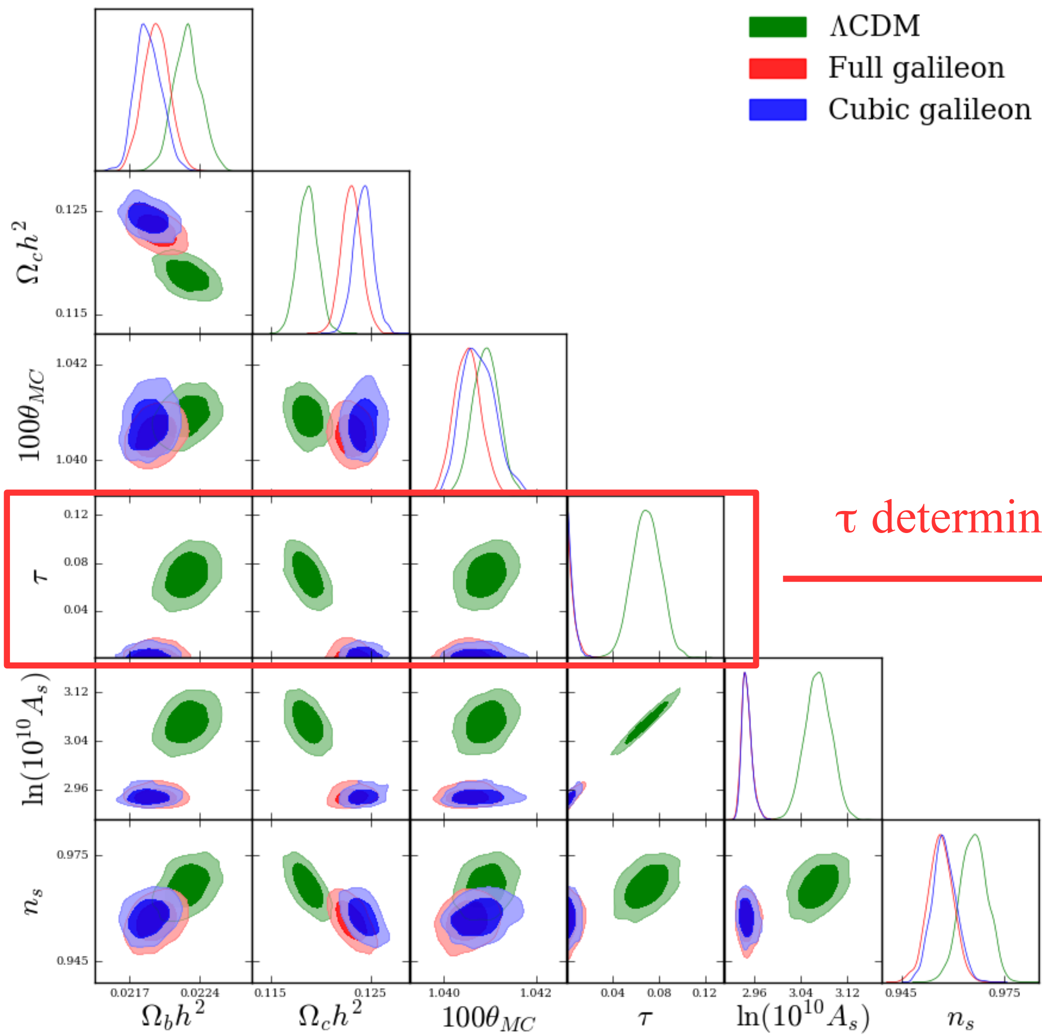
Base models

- Fit to combined cosmological data (CMB+BAO+JLA) :

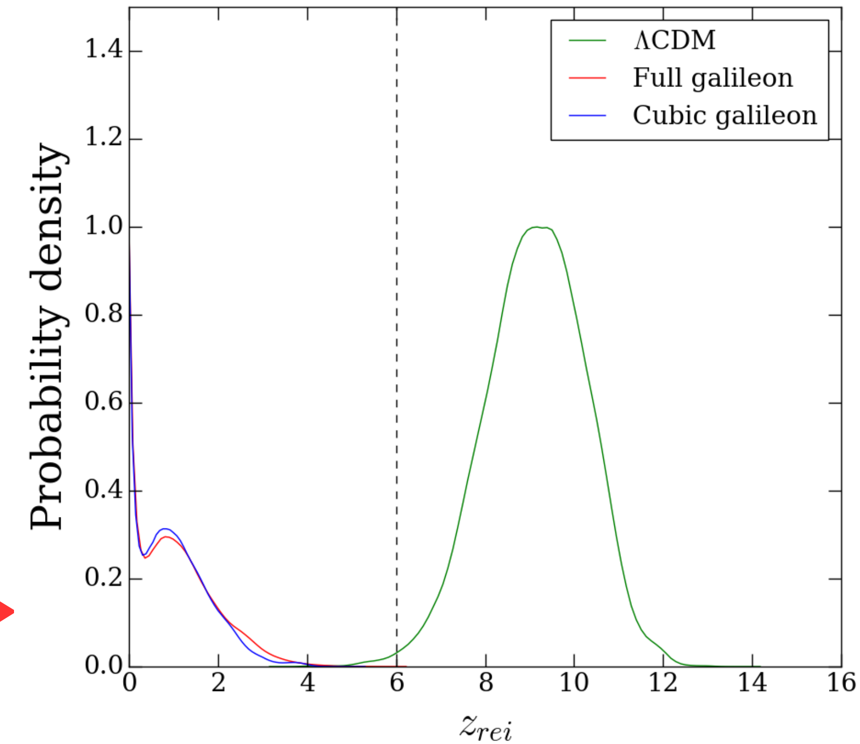


Base models

➤ Fit to combined cosmological data (CMB+BAO+JLA) :



τ determines z_{rei}



Base models

- Fit to combined cosmological data (CMB+BAO+JLA) :

	χ^2(CMB)	χ^2(BAO)	χ^2(JLA)
ΛCDM	12946	5.6	706.7
Full galileon	12966	30.4	723.3
Cubic galileon	12993	29.9	723.6

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8 data points only

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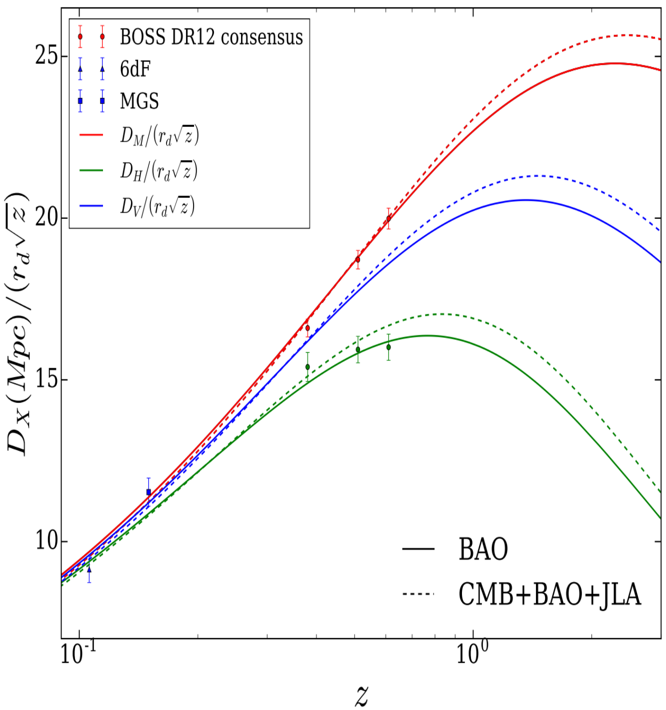
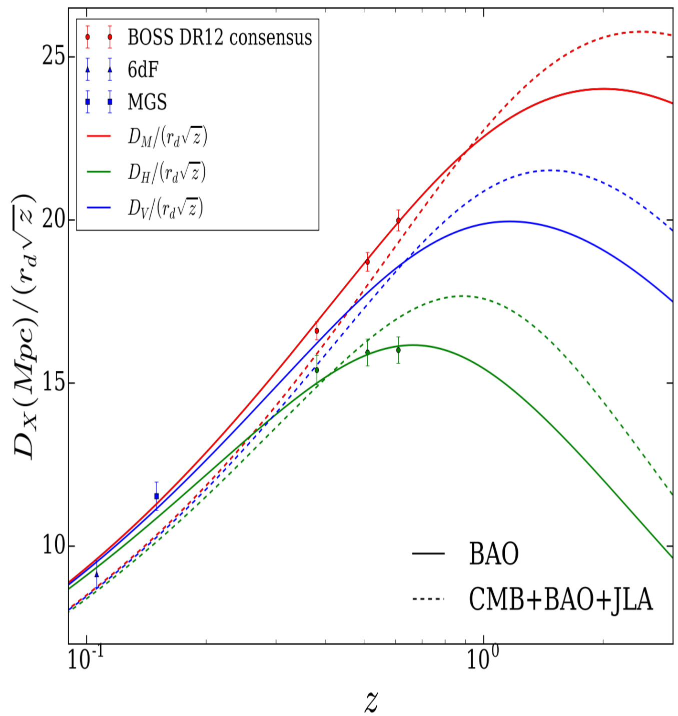
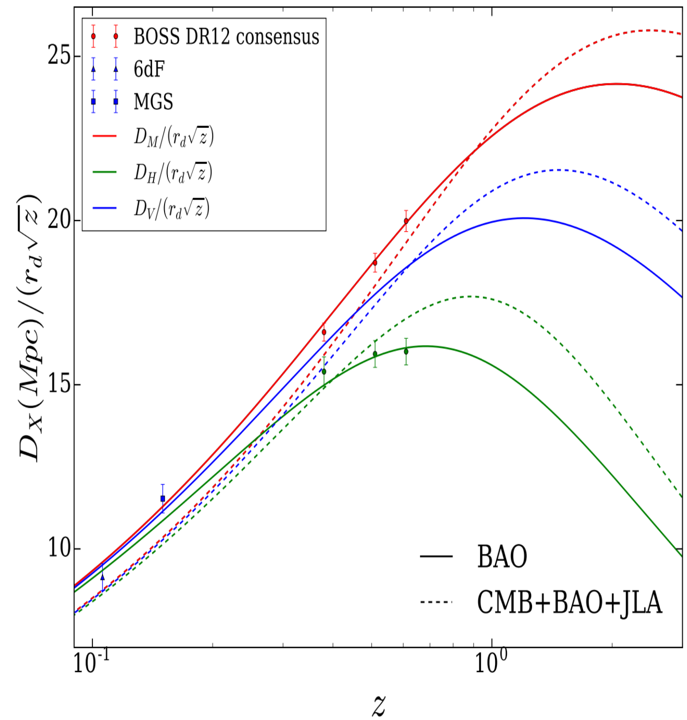
→ 8 data points only



ΛCDM



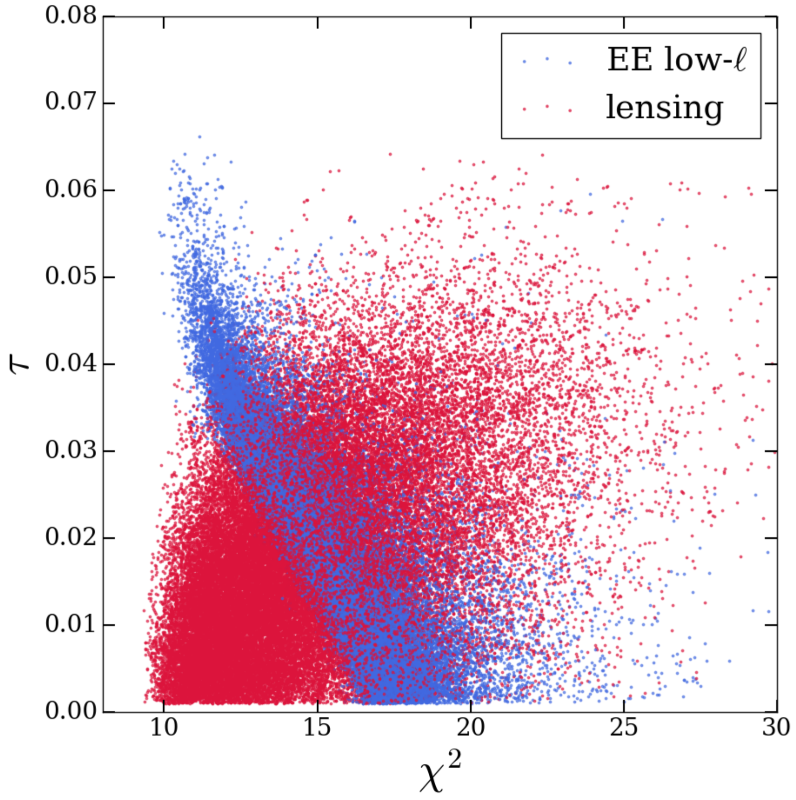
Full galileon



Cubic galileon

Tensions in base models

- Tension on τ due to :
  - lensing
  - low-ℓ of polarization



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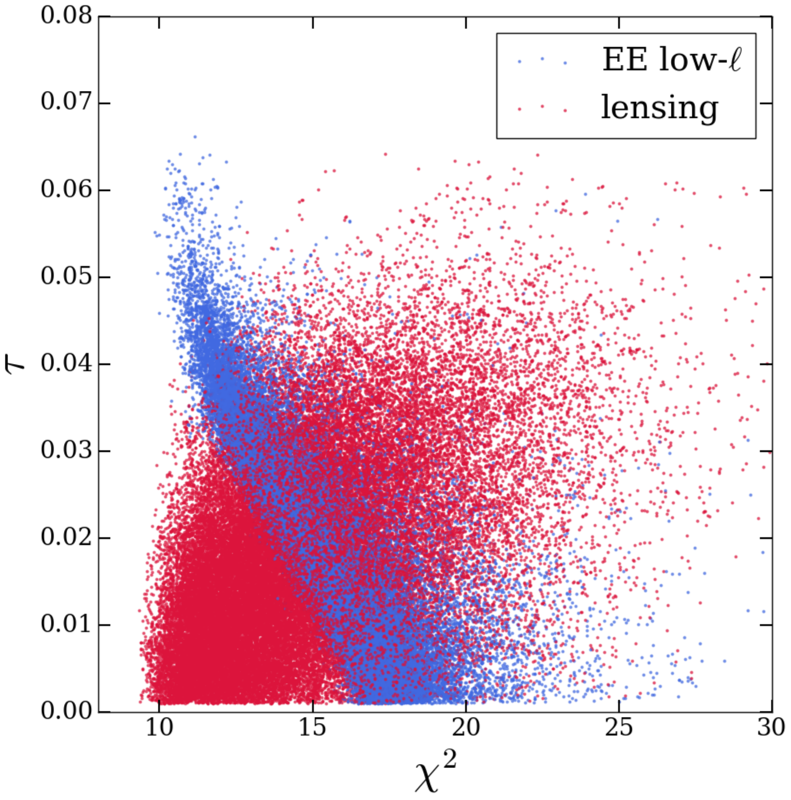
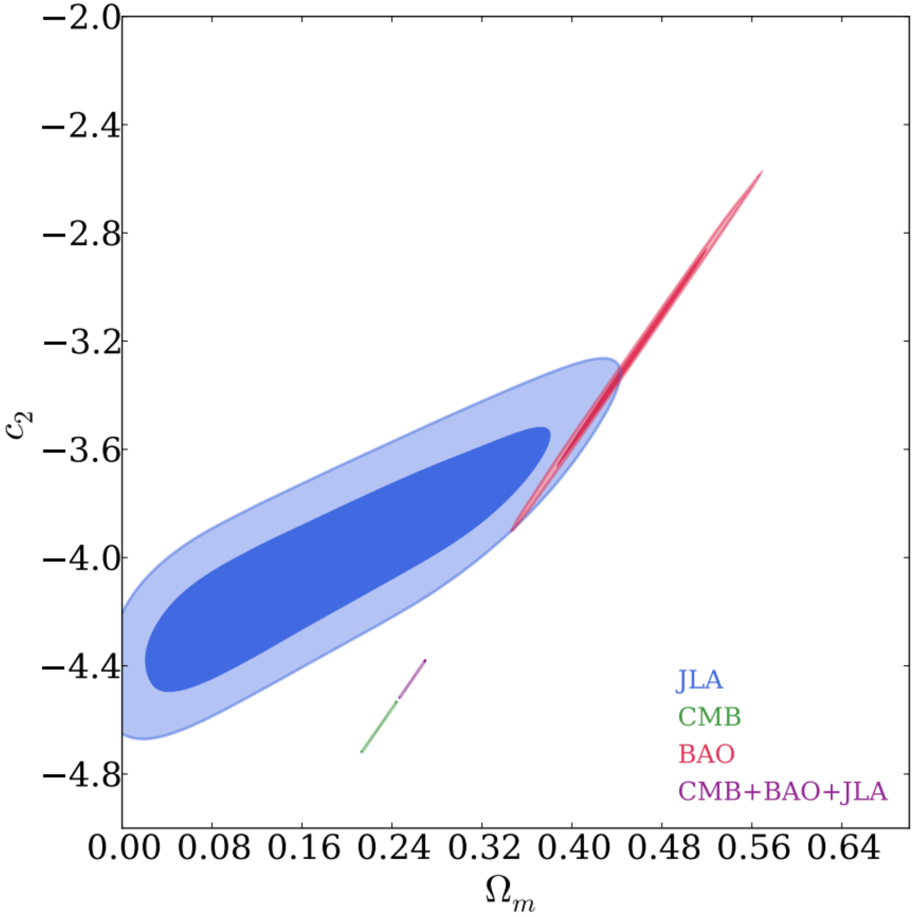
  - low-ℓ of polarization



- Tension between BAO and CMB :



Tensions in base models

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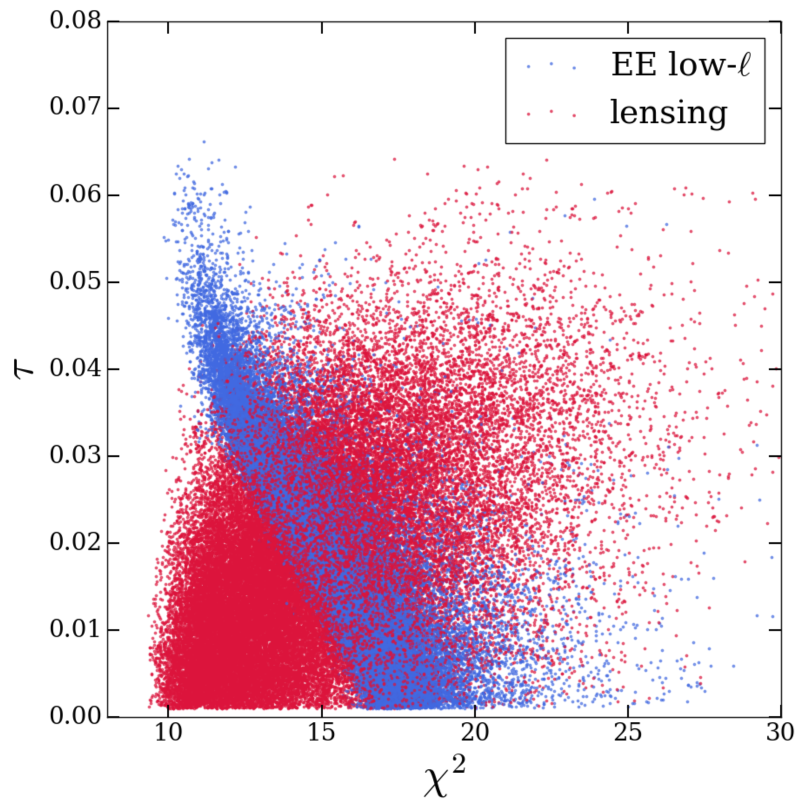
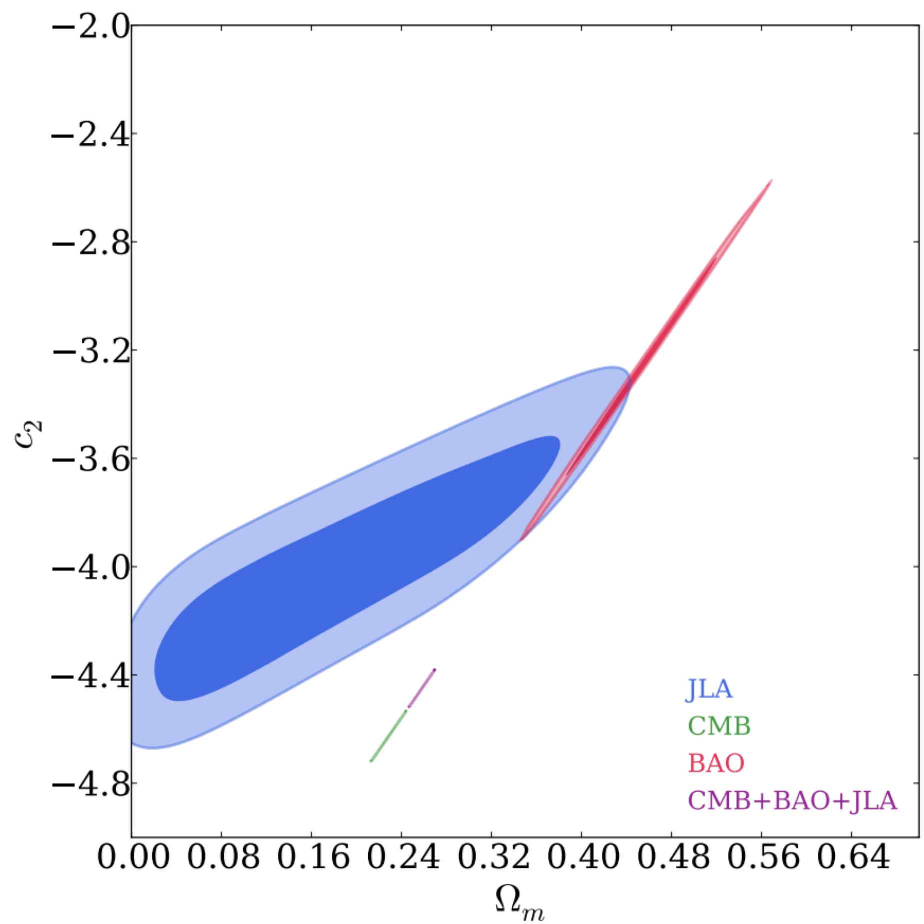


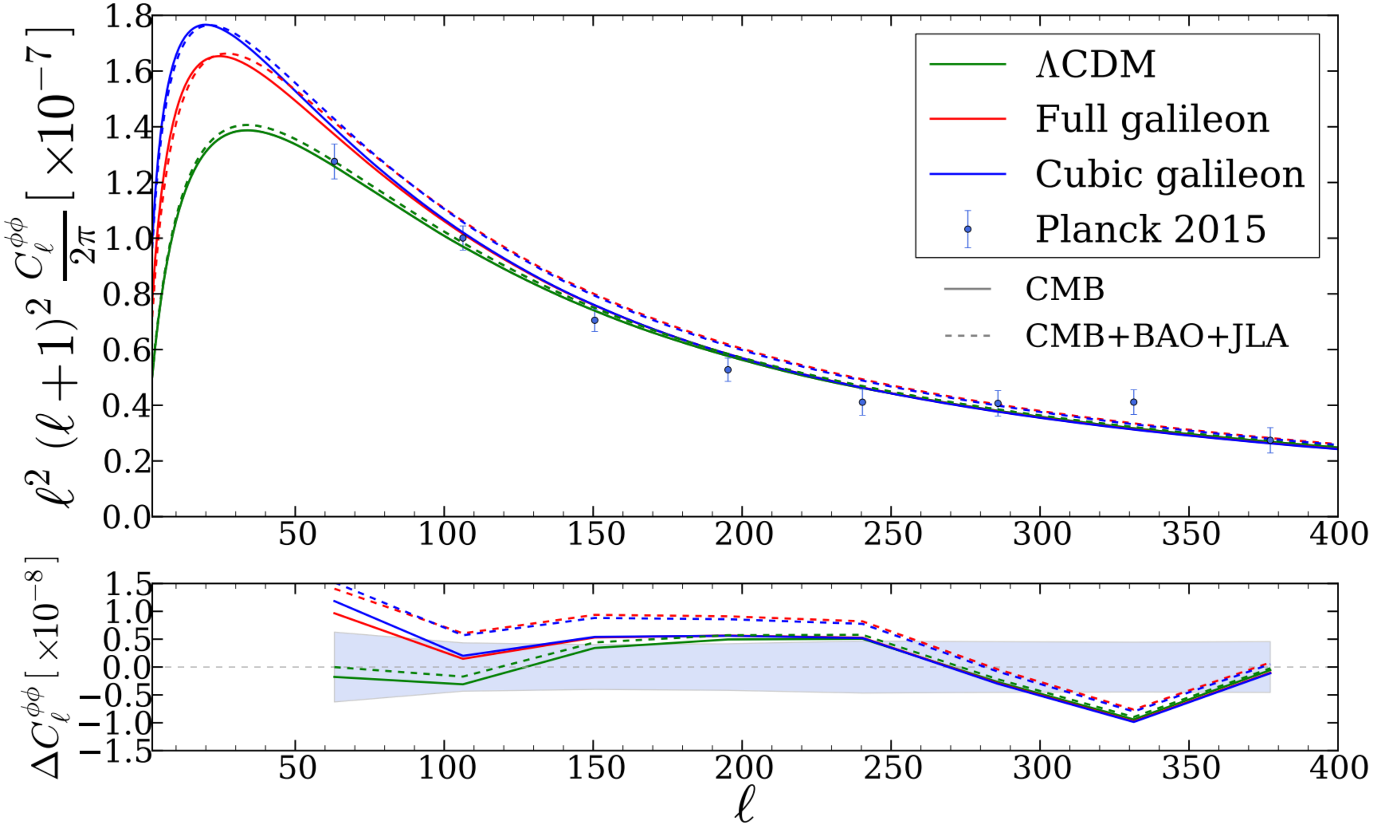
- Tension between BAO and CMB :



- Improve the situation with new parameters ?

Tensions in base models

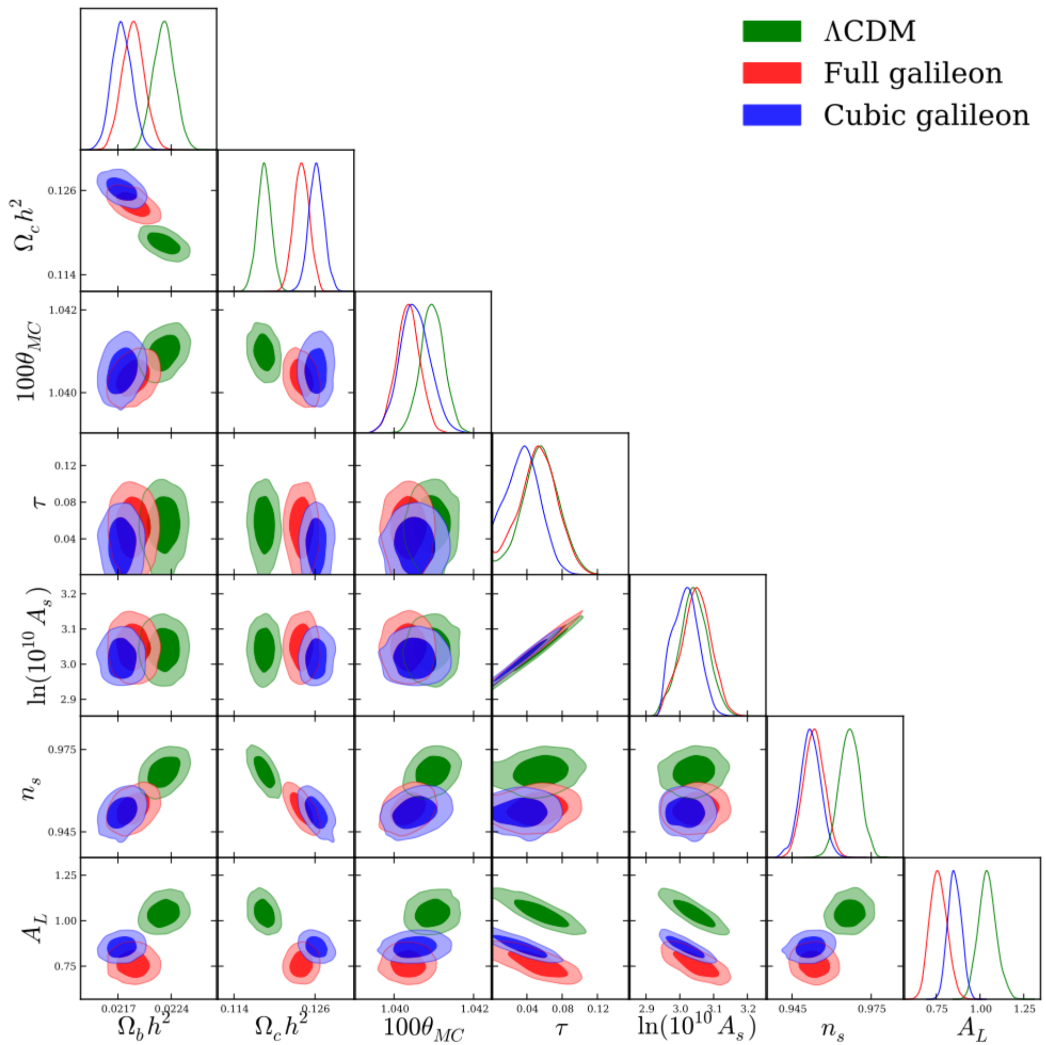
- CMB lensing power spectrum favours low A_s
- Because lensing effect stronger in galileon scenarios



- Additional parameters that have an effect on lensing normalization : A_L or Σm_ν

Extension to A_L

➤ Model extended to the parameter A_L :



Extension to A_L

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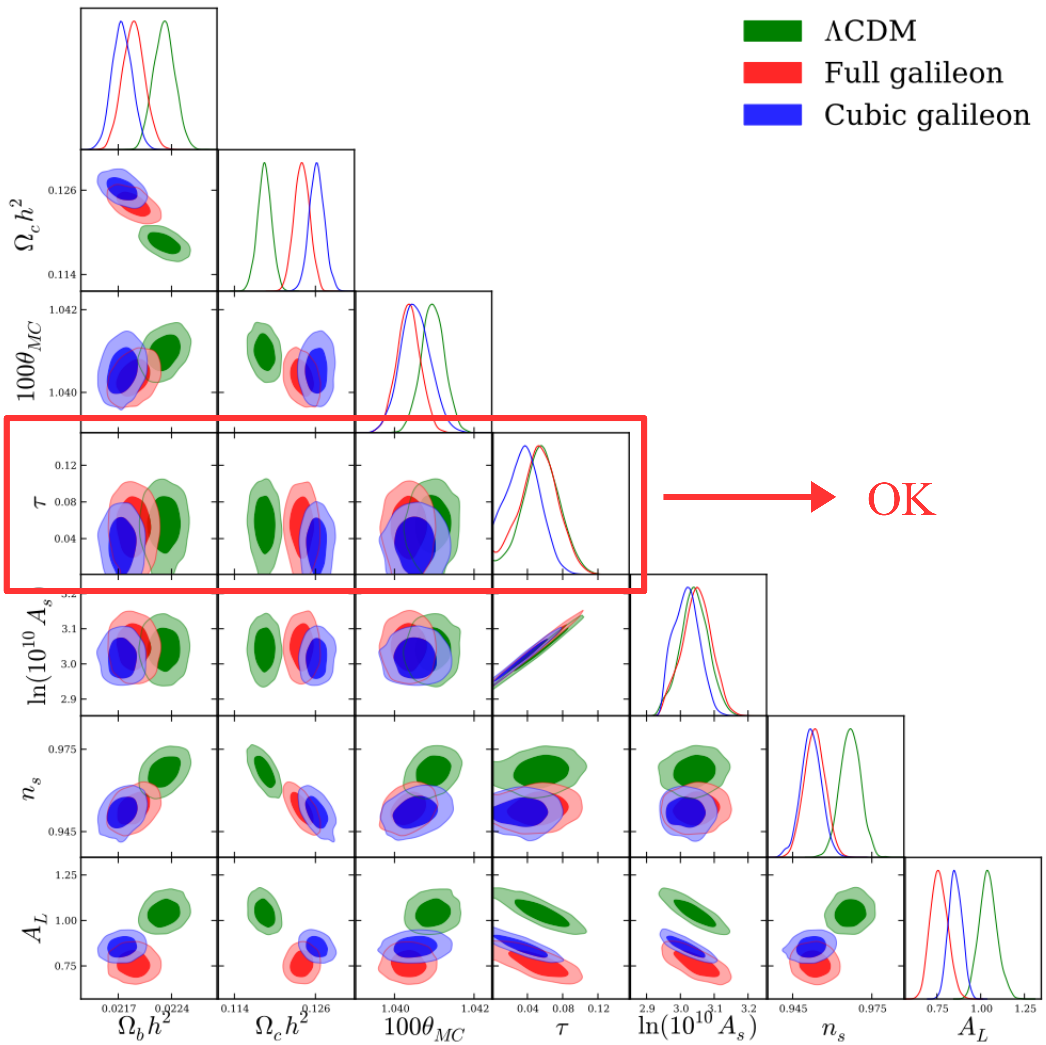

Extension to A_L

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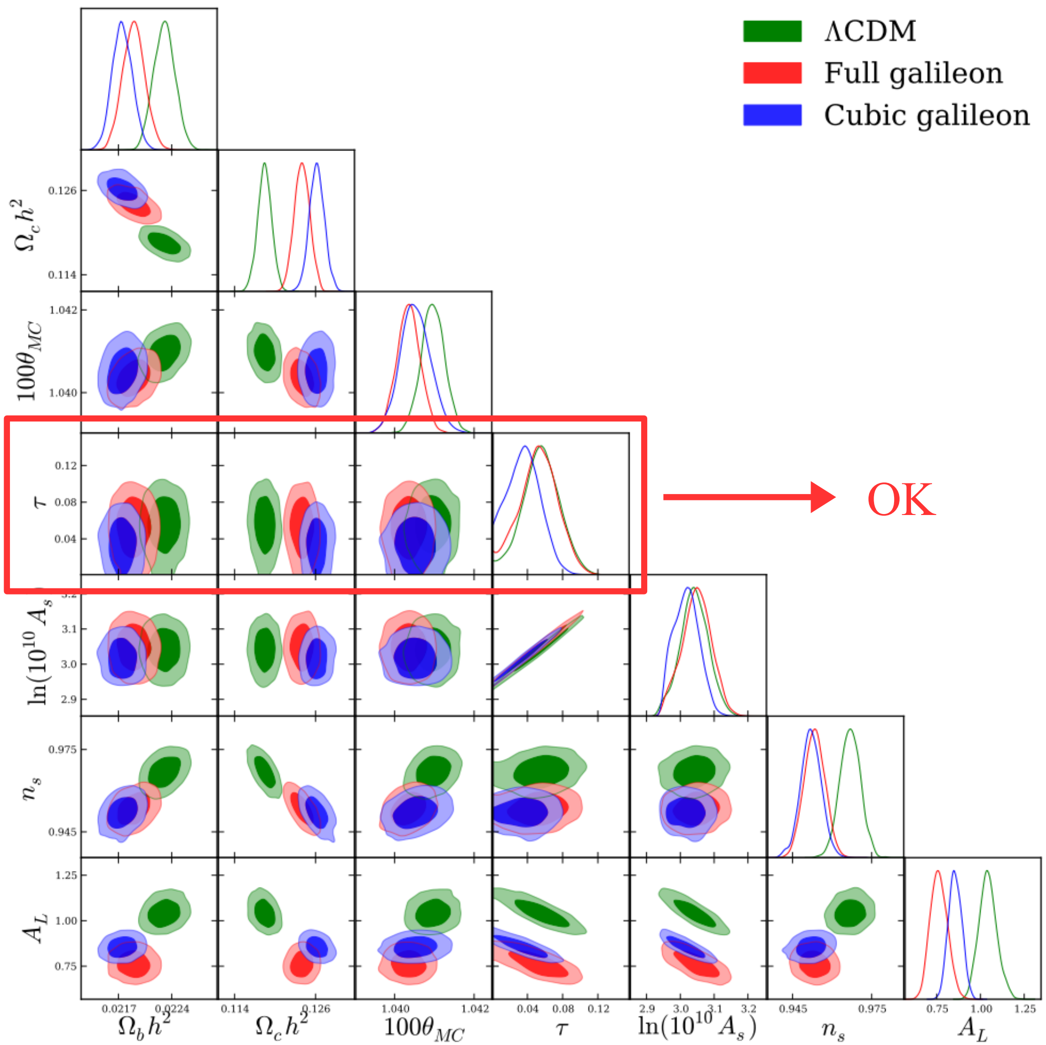
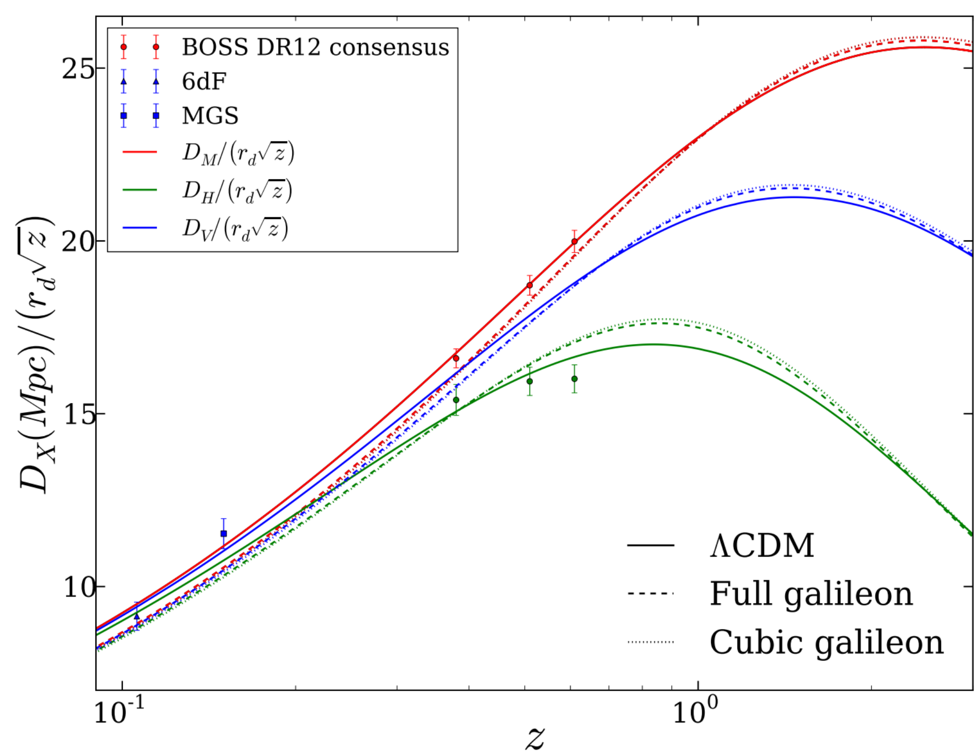
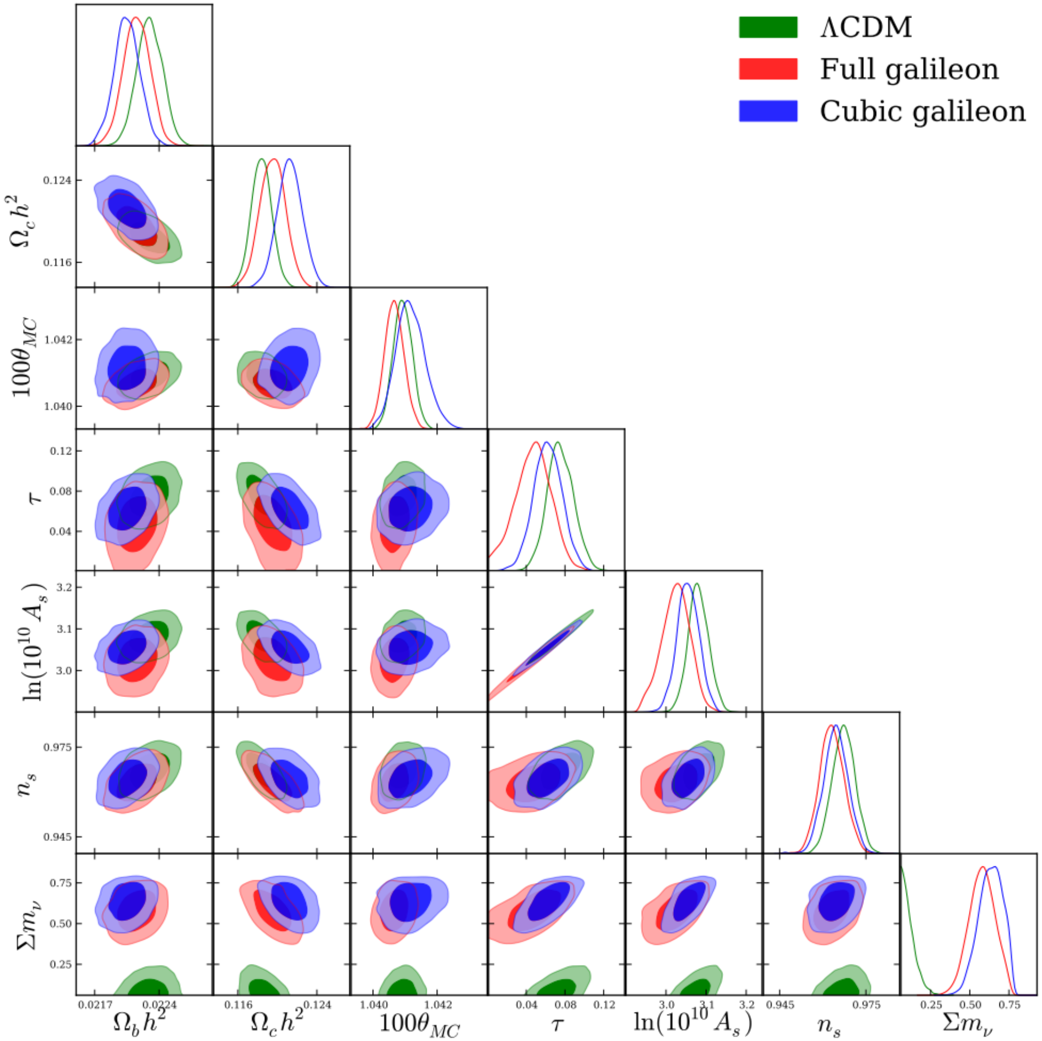


	χ^2(CMB)	χ^2(BAO)	χ^2(JLA)
ΛCDM	12945	5.2	706.6
Full galileon	12960	18.4	718.9
Cubic galileon	12984	22.5	721.6



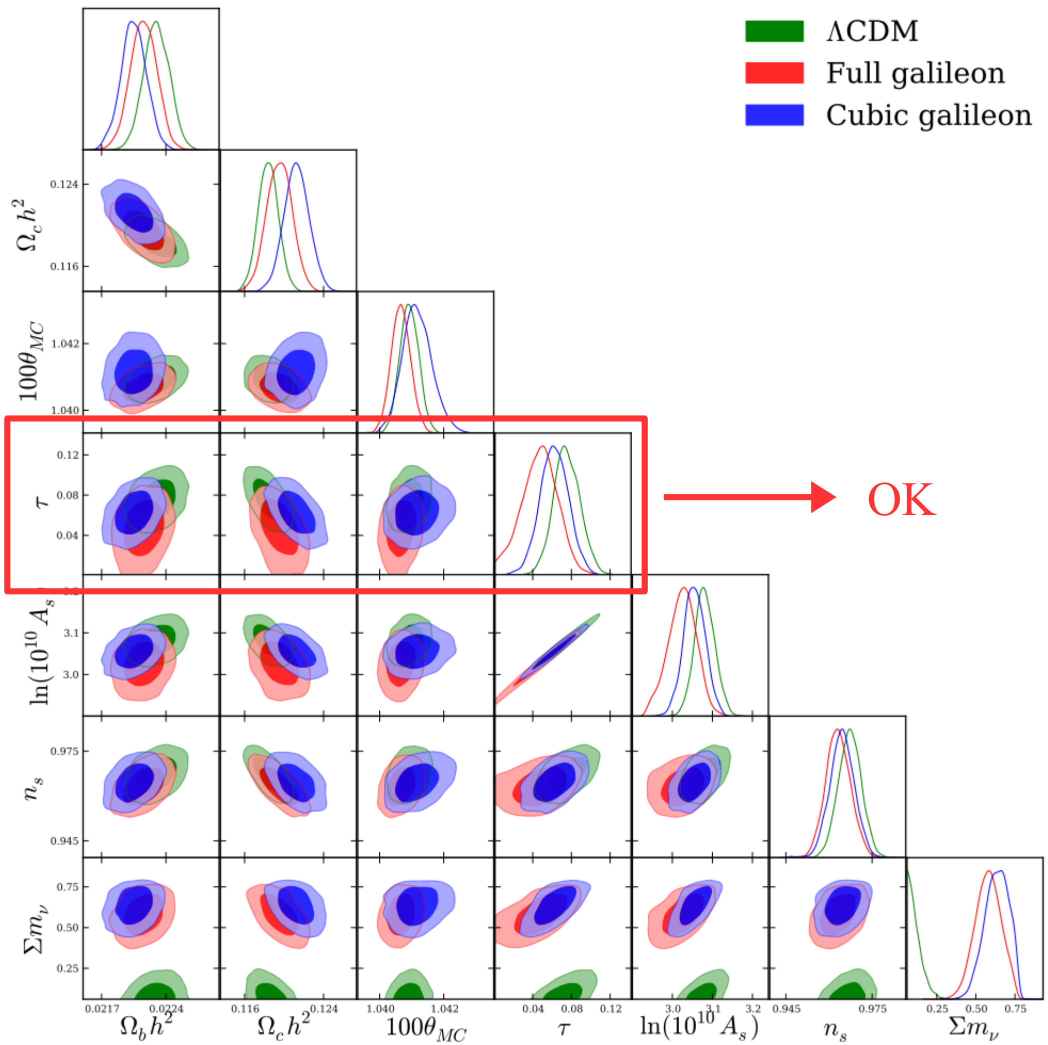
Extension to Σm_ν

➤ Model extended to the parameter Σm_ν :



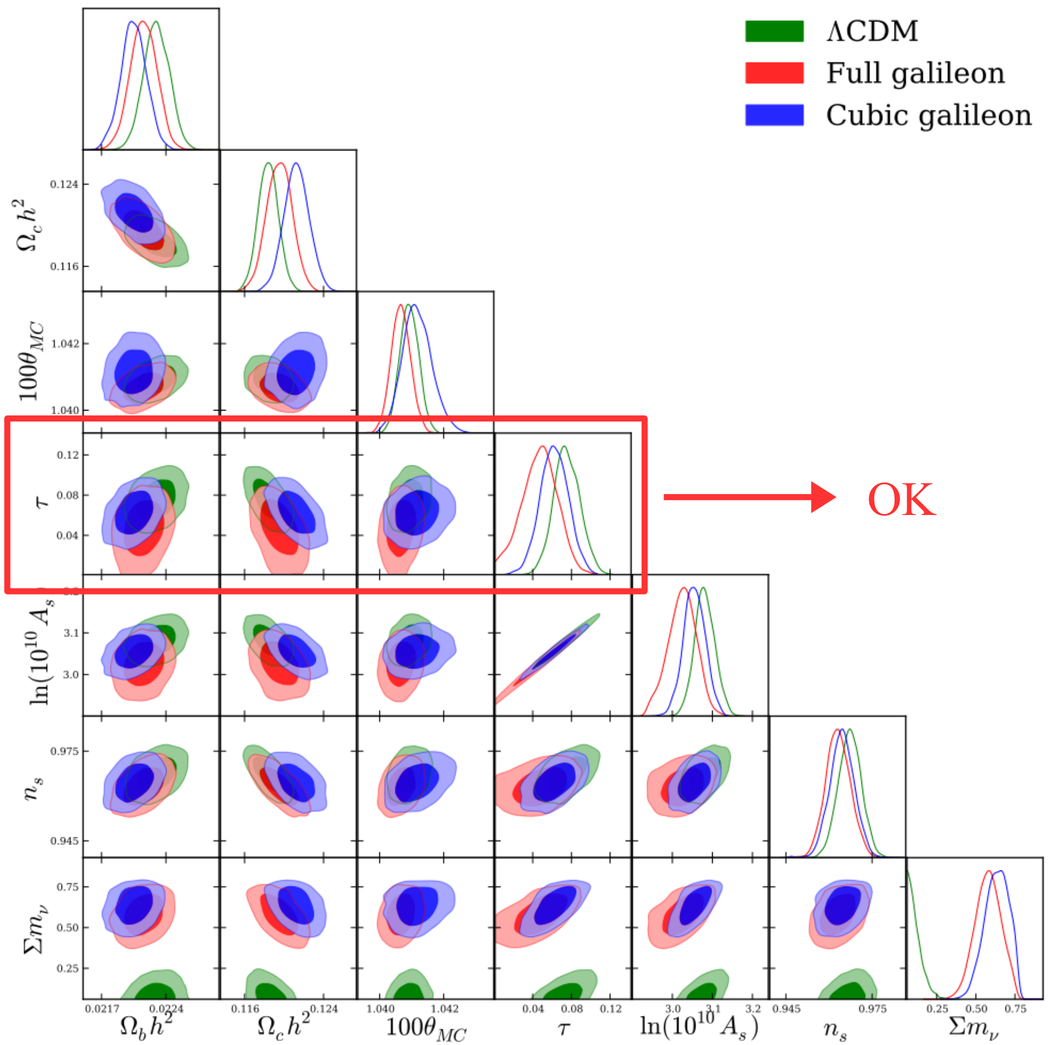
Extension to Σm_ν

➢ Model extended to the parameter Σm_ν :

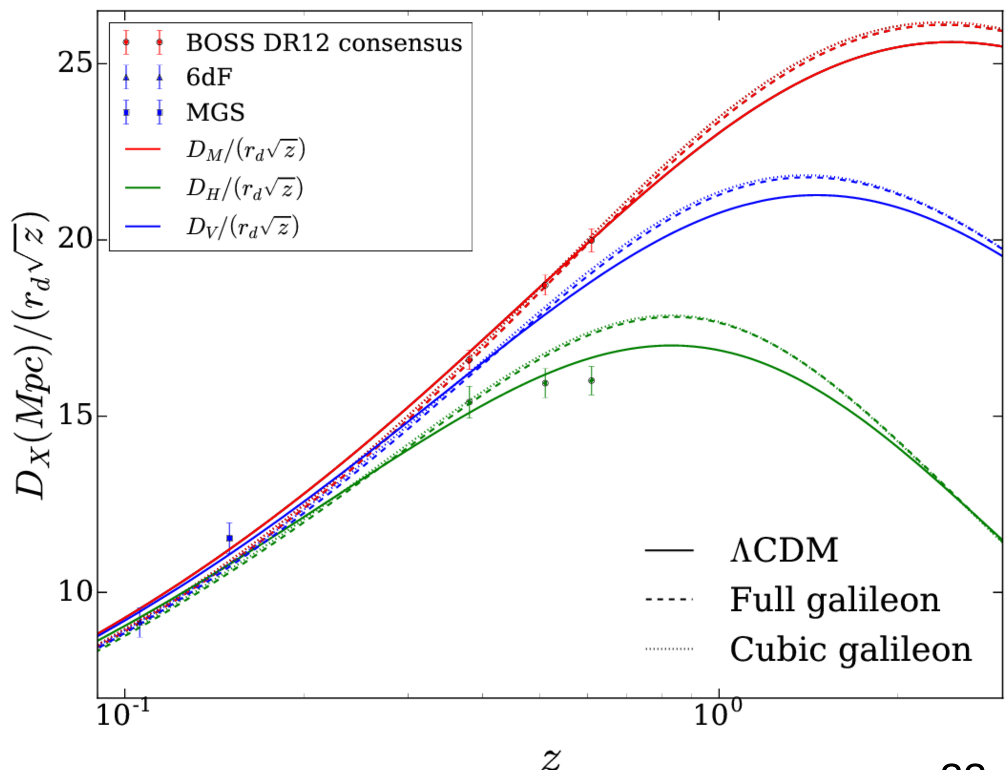


Extension to Σm_ν

- Model extended to the parameter Σm_ν :



	χ^2(CMB)	χ^2(BAO)	χ^2(JLA)
ΛCDM	12946	5.5	706.7
Full galileon	12950	16.8	717.2
Cubic galileon	12963	18.3	716.5



Outline

I. Presentation of the galileon model

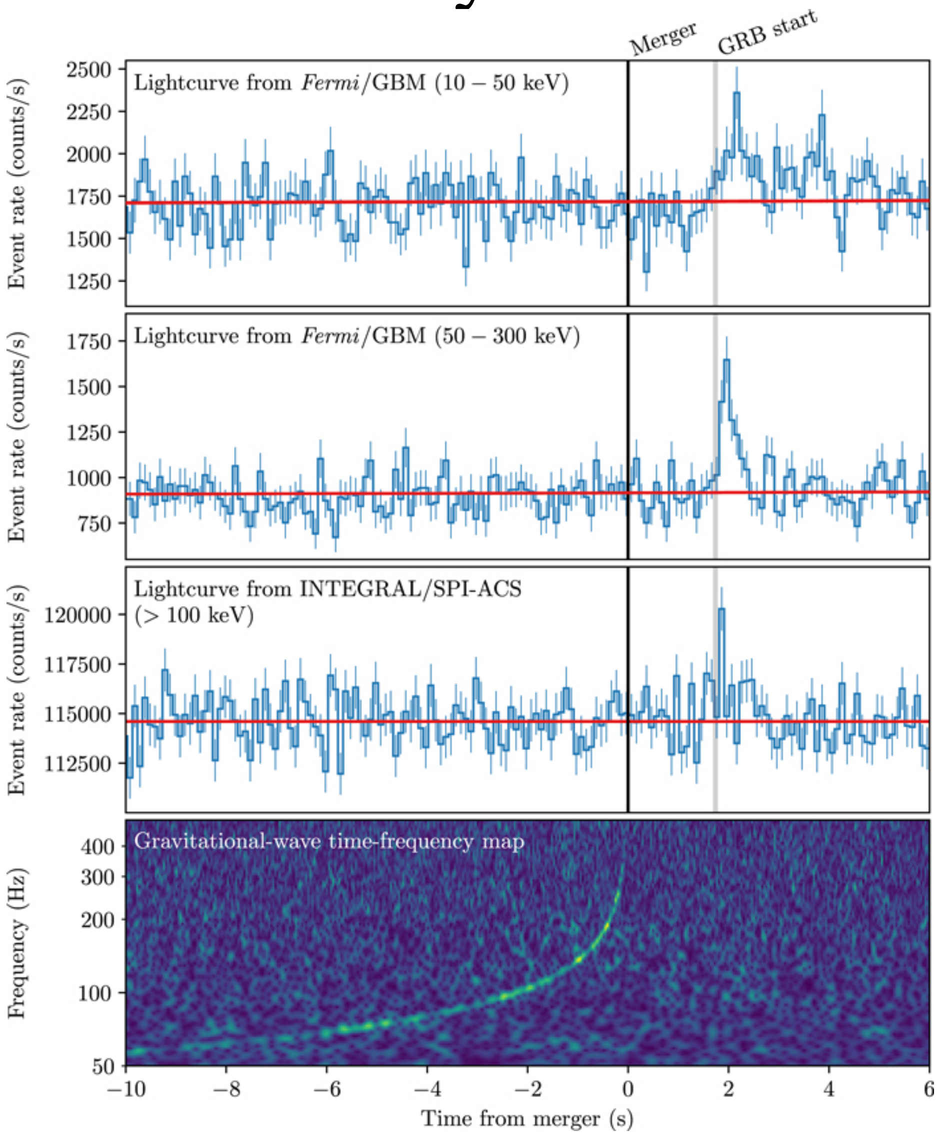
II. Methodology

III. Constraints from cosmology

IV. GW170817

Gravitational waves

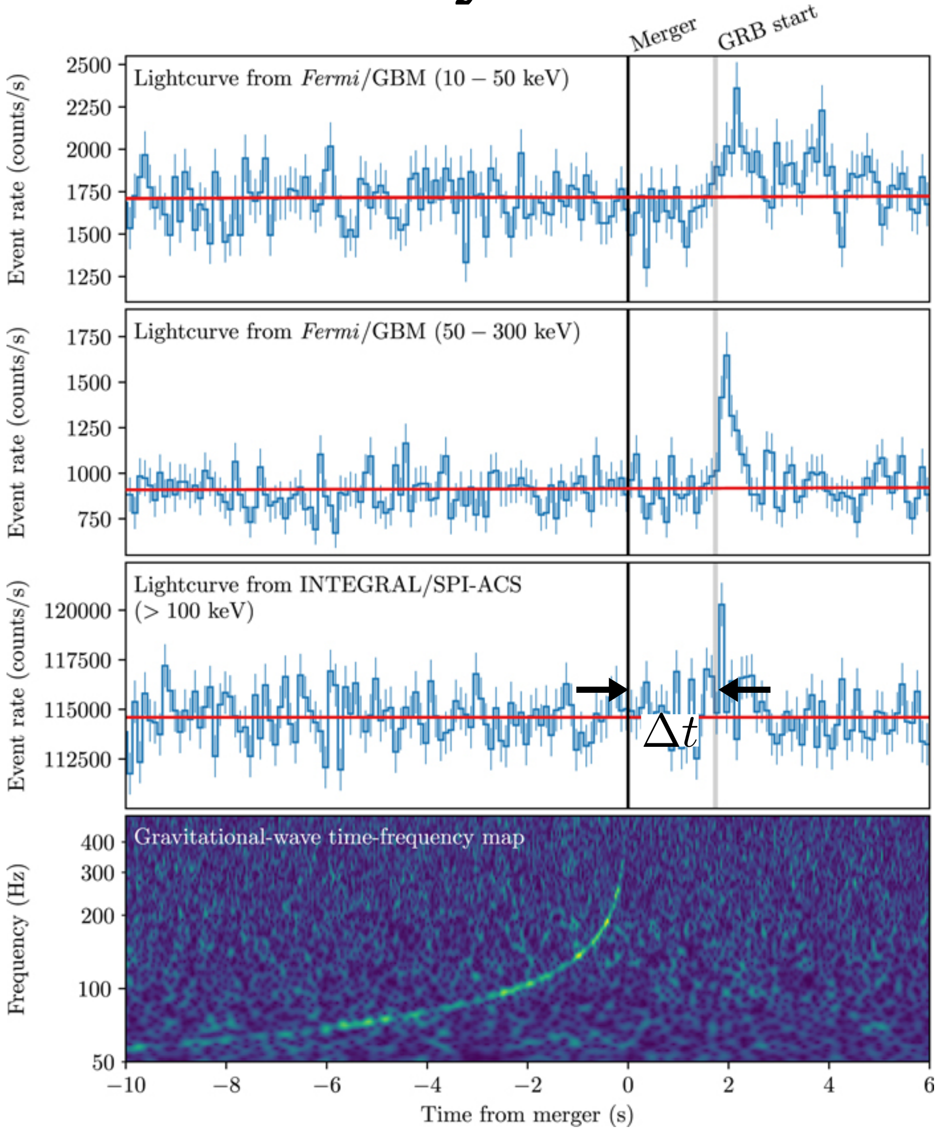
➢ Time delay between GW and light from GW170817



arXiv:1710.05834

Gravitational waves

- Time delay between GW and light from GW170817



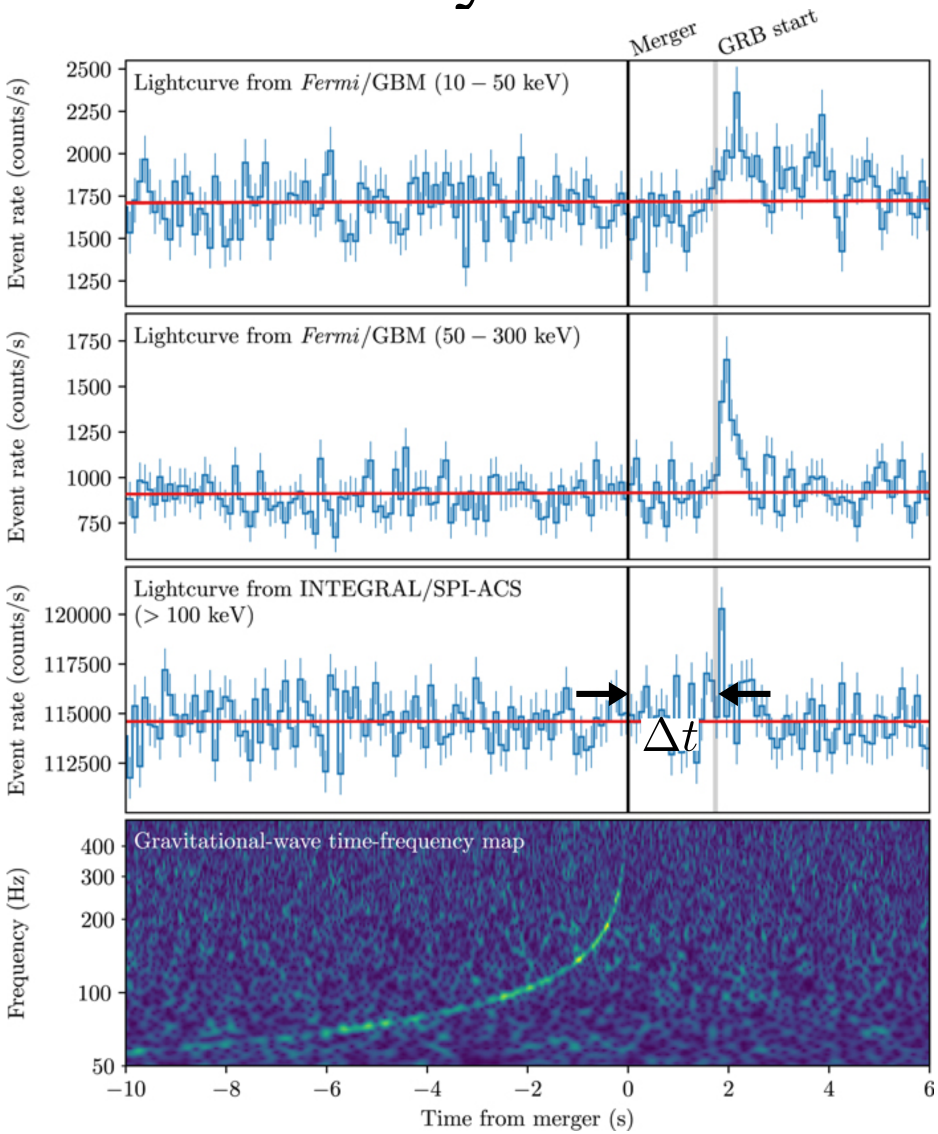
$$\Delta t = \int_{a_e}^{1} \frac{da}{aH}\left(1 - \frac{c}{c_g(a)}\right) + \delta t$$

$$= 1.74 \pm 0.05\text{s}$$

arXiv:1710.05834

Gravitational waves

- Time delay between GW and light from GW170817



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Speed of GW

arXiv:1710.05834

Gravitational waves

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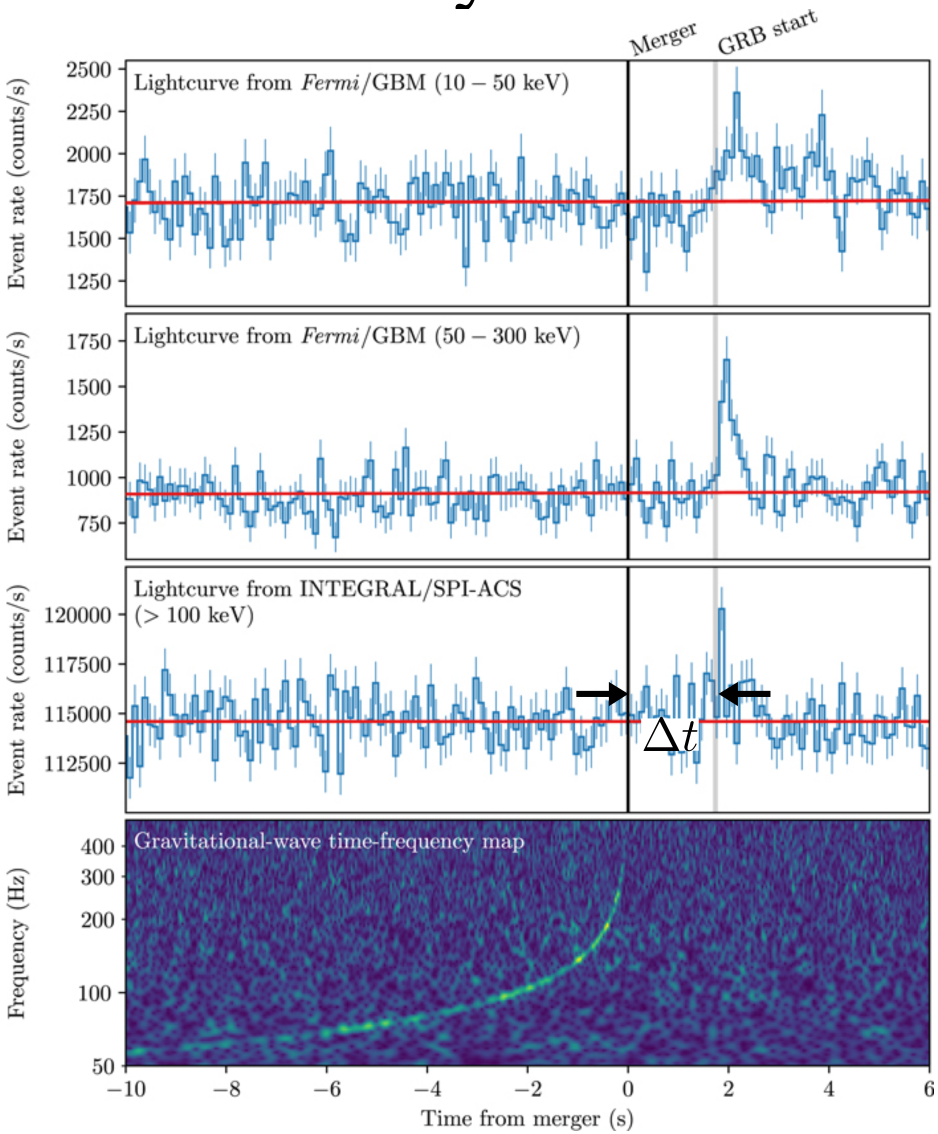


$$\Delta t = \int_{a_e}^{1} \frac{da}{aH}\left(1 - \frac{c}{c_g(a)}\right) + \delta t$$

$$= 1.74 \pm 0.05\text{s}$$

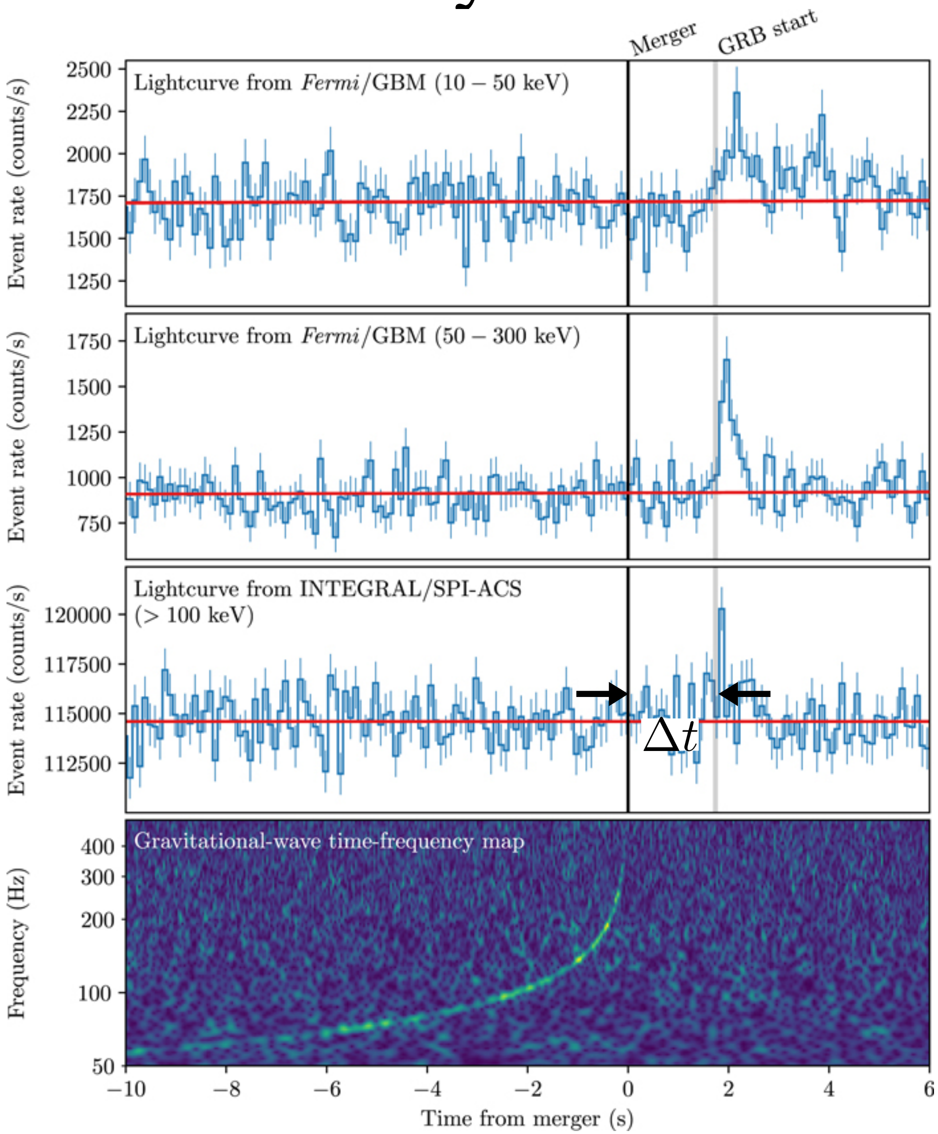
Speed of GW (c_g)

Redshift of host galaxy NGC4993 (a_e):
$z_e = 0.009787$

arXiv:1710.05834

Gravitational waves

- Time delay between GW and light from GW170817



$$\Delta t = \int_{a_e}^{1} \frac{da}{aH}\left(1 - \frac{c}{c_g(a)}\right) + \delta t$$

$$= 1.74 \pm 0.05\text{s}$$

Speed of GW

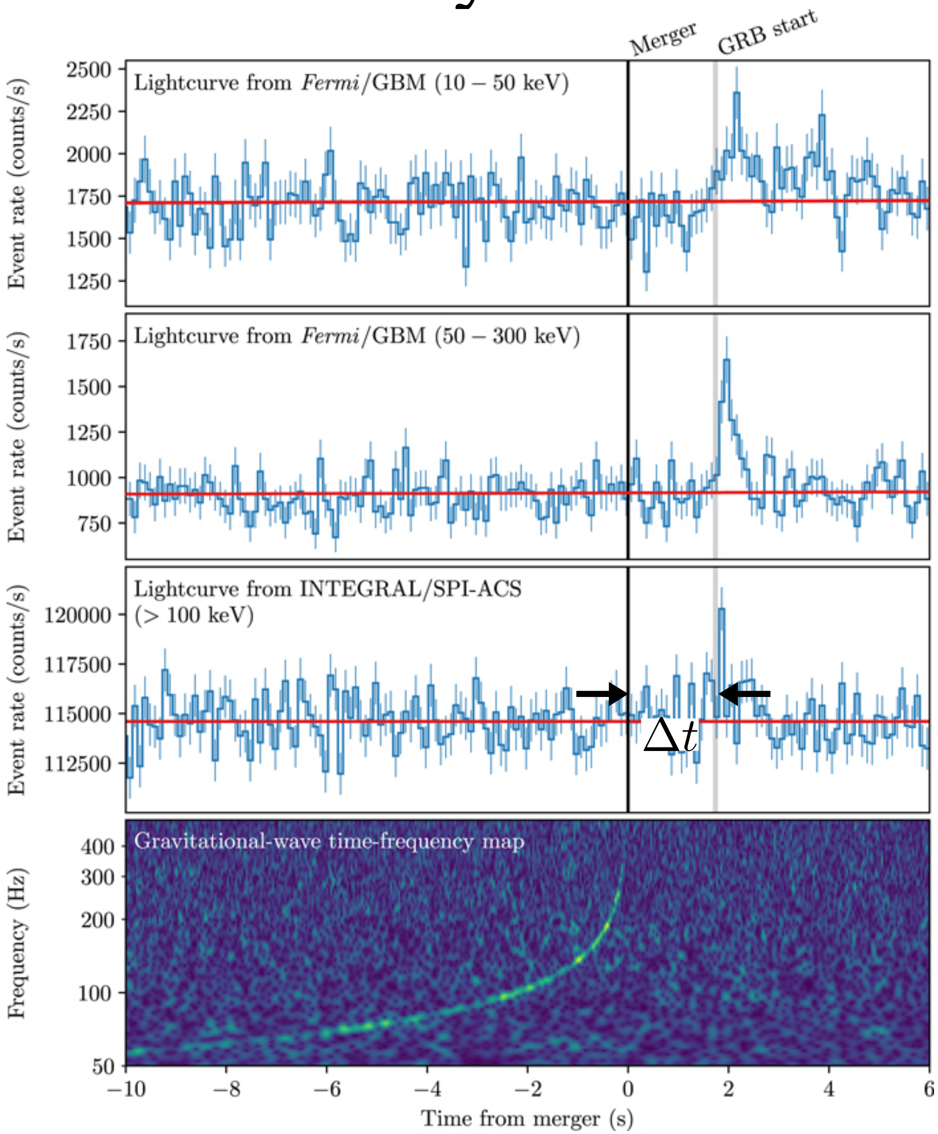
Redshift of host galaxy NGC4993 :
$z_e = 0.009787$

Time delay between GW emission and light emission.
Conservative assumption (arXiv:1710.05834) :
$\delta t \in [-1000\text{s}, 100\text{s}]$

arXiv:1710.05834

Gravitational waves

- Time delay between GW and light from GW170817



arXiv:1710.05834

$$\Delta t = \int_{a_e}^{1} \frac{da}{aH}\left(1 - \frac{c}{c_g(a)}\right) + \delta t$$

$$= 1.74 \pm 0.05\text{s}$$

Speed of GW

Redshift of host galaxy NGC4993 :
$z_e = 0.009787$

Time delay between GW emission and light emission.
Conservative assumption (arXiv:1710.05834) :
$\delta t \in [-1000\text{s}, 100\text{s}]$

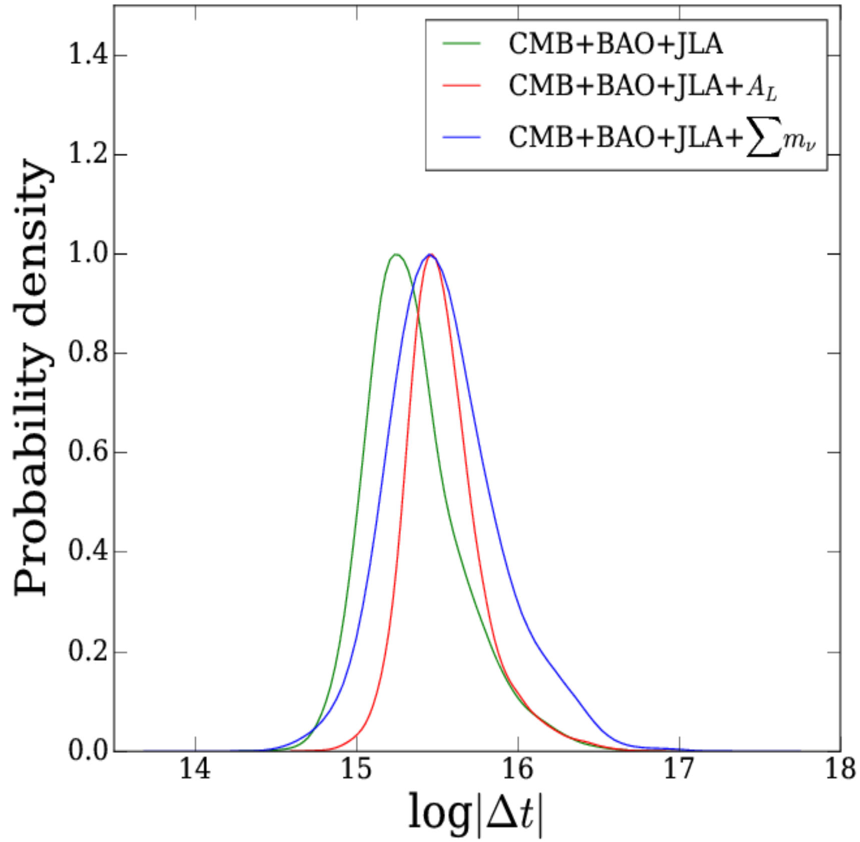
- In galileon cosmology :

$$\frac{c_g^2}{c^2} = \frac{\frac{1}{2} + \frac{1}{4}c_4\bar{H}^4x^4 + \frac{3}{2}c_5\bar{H}^5x^4 d\left(\bar{H}x\right)/\text{dlna} - \frac{1}{2}c_G\bar{H}^2x^2}{\frac{1}{2} - \frac{3}{4}c_4\bar{H}x^4 + \frac{3}{2}c_5\bar{H}^5x^5 + \frac{1}{2}c_G\bar{H}^2x^2}$$

Gravitational waves

- Modification of GW speed only due to c_4, c_5 and c_G

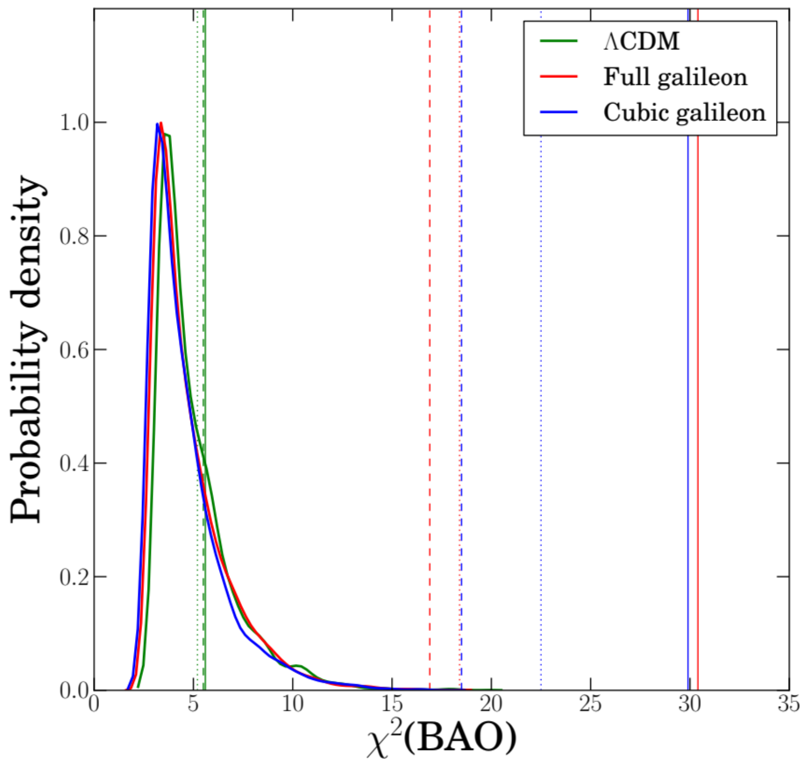
  $\Rightarrow$ affects only the full galileon model



- $\Delta t > 10^{14}$ sec ~ a few million years

Galileon status

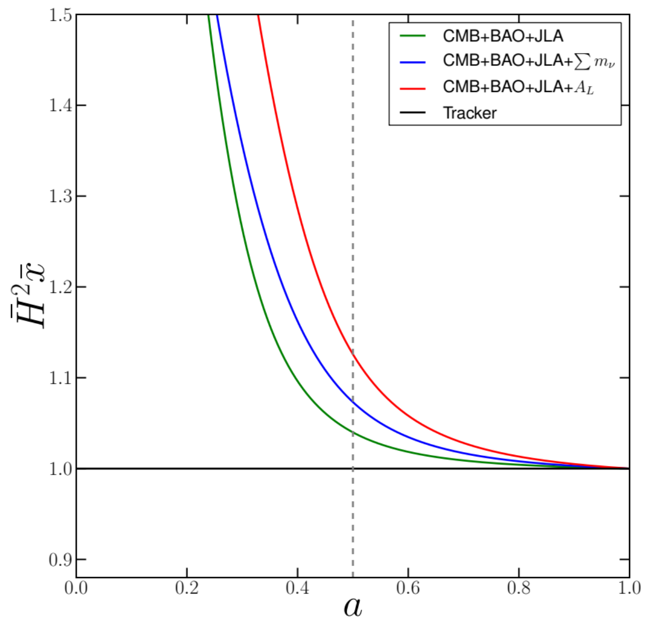
- Status of the general galileon model as of February 2019 (see Leloup et al. 2019) :
  - No galileon model can reproduce all cosmological data (especially BAO data)



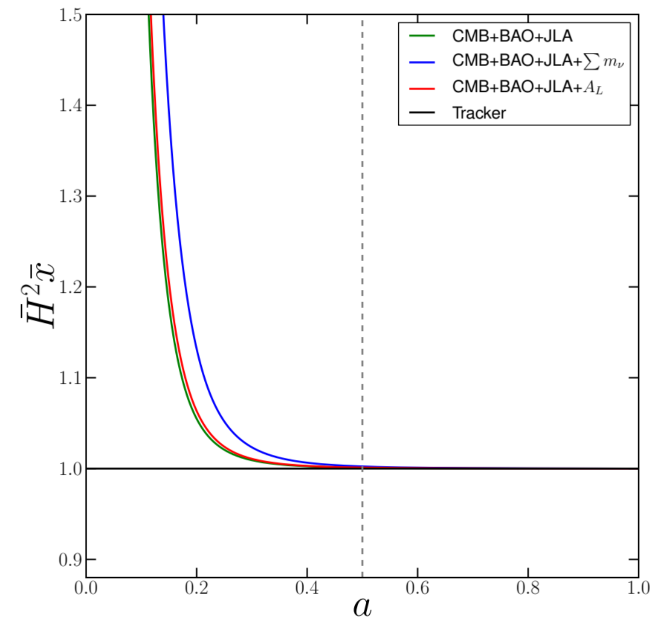
  - Full galileon model excluded by GW170817

Conclusion on tracker

- Was the full exploration of the parameter space useful ?
- Argued in Barreira et al. 2014 that tracker should be reached before the DE dominated era to reproduce correctly CMB TT



Full galileon



Cubic galileon

- Best fits of full galileon models converge towards tracker later

$\Rightarrow$ risk of missing interesting scenarios if tracker only

Thank you !

$$\tilde{g}_{\mu\nu} = A(\pi, X)\, g_{\mu\nu} + B(\pi, X)\, \nabla_\mu \pi \nabla_\nu \pi$$

Conformal transformation

$$\pi T^\mu_\mu$$

$$\downarrow$$

$$M_P c_0 \pi R$$

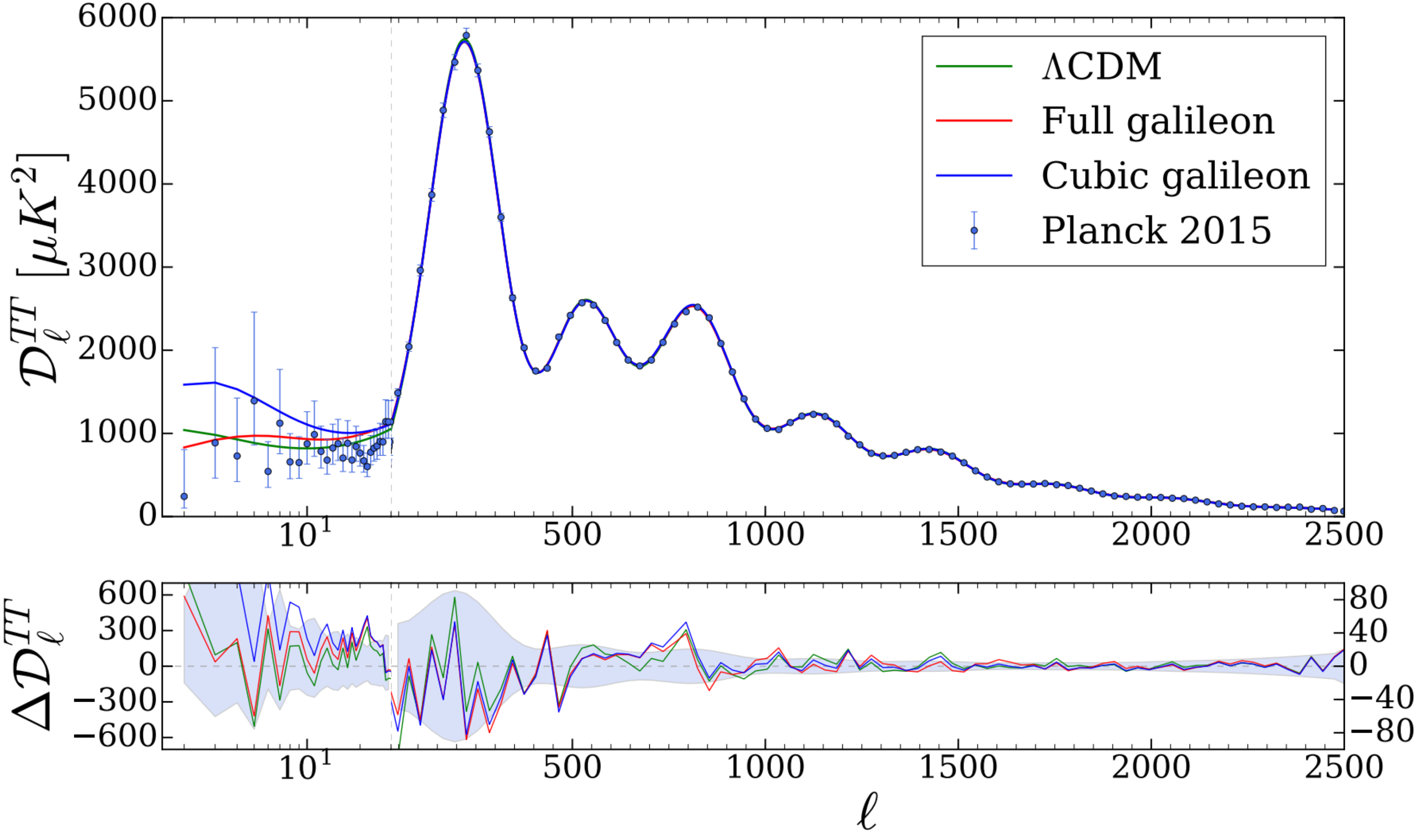
Disformal transformation

$$\nabla_\mu \pi \nabla_\nu \pi T^{\mu\nu}$$

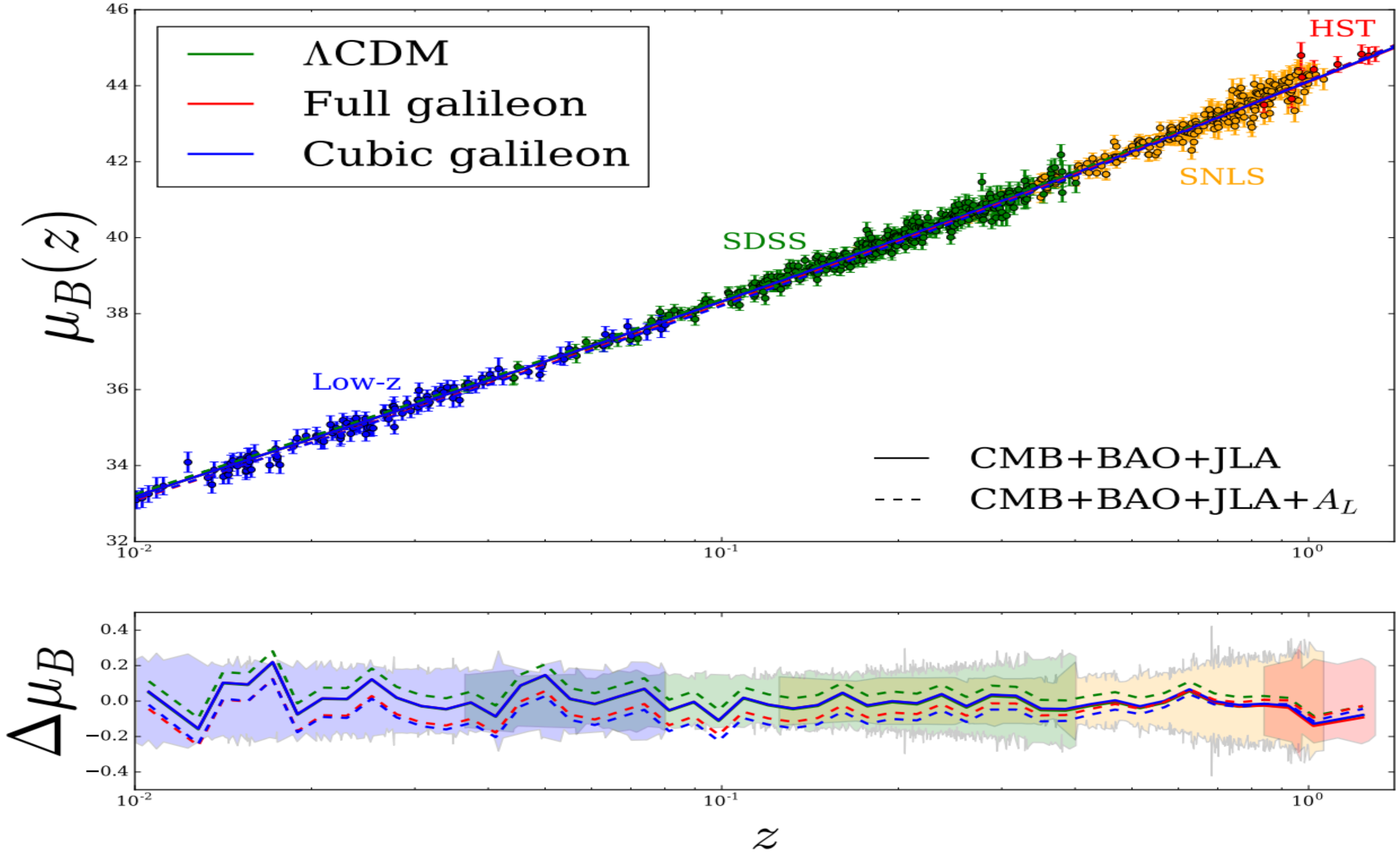
$$\downarrow$$

$$\frac{M_P}{M^3} c_G G^{\mu\nu} \nabla_\mu \pi \nabla_\nu \pi$$

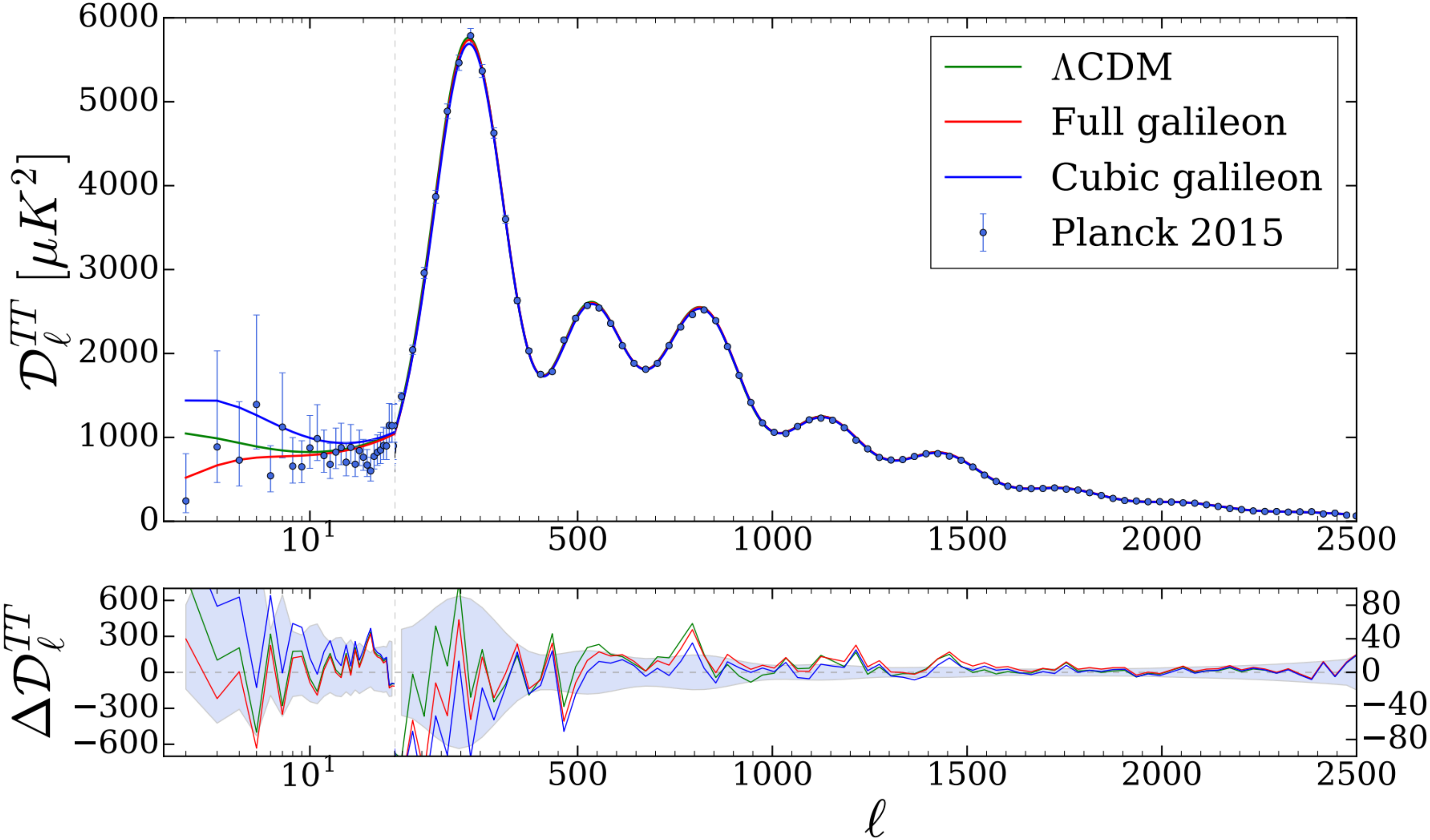
- TT powerspectrum with A_L



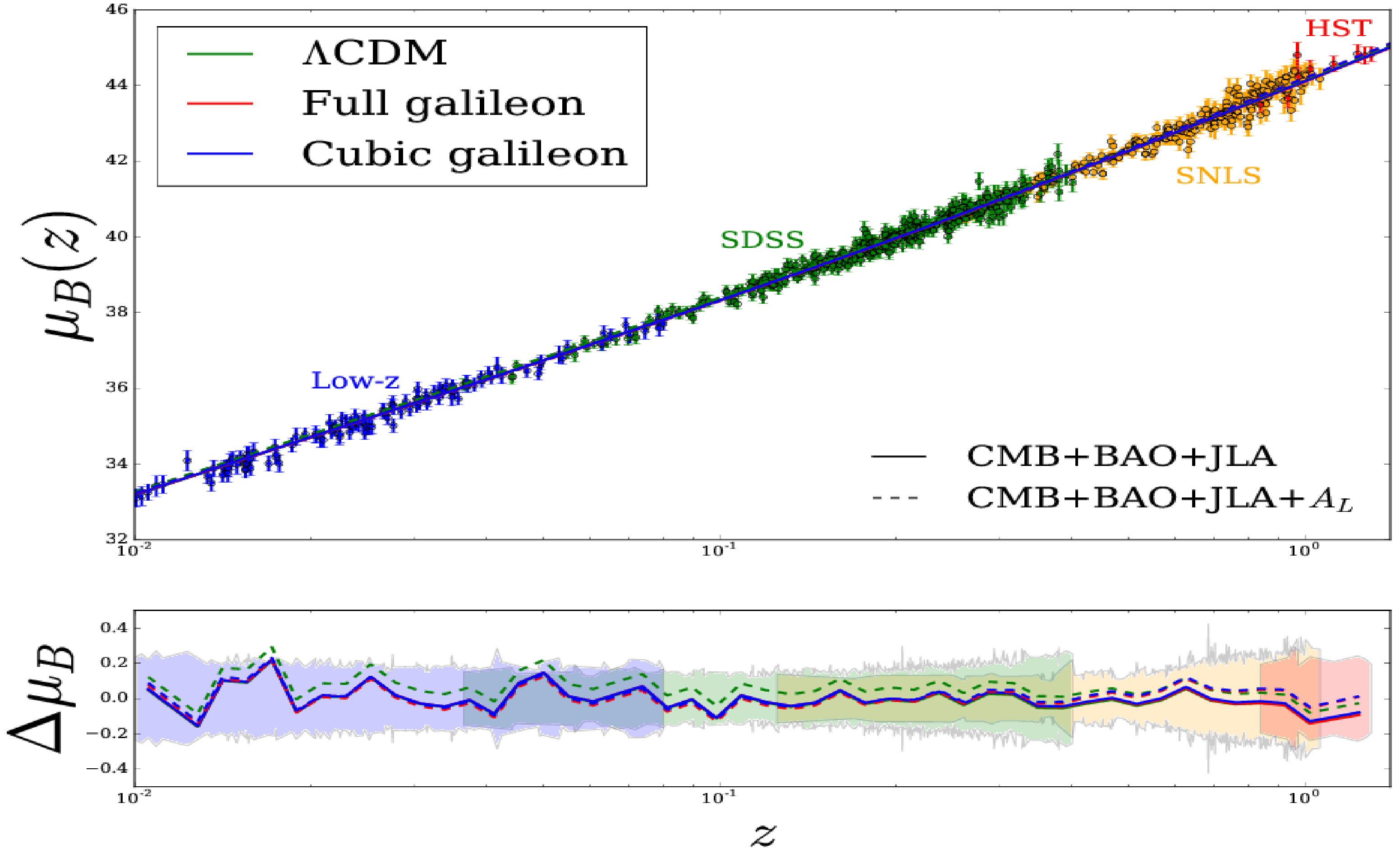
- SN hubble diagram with A_L

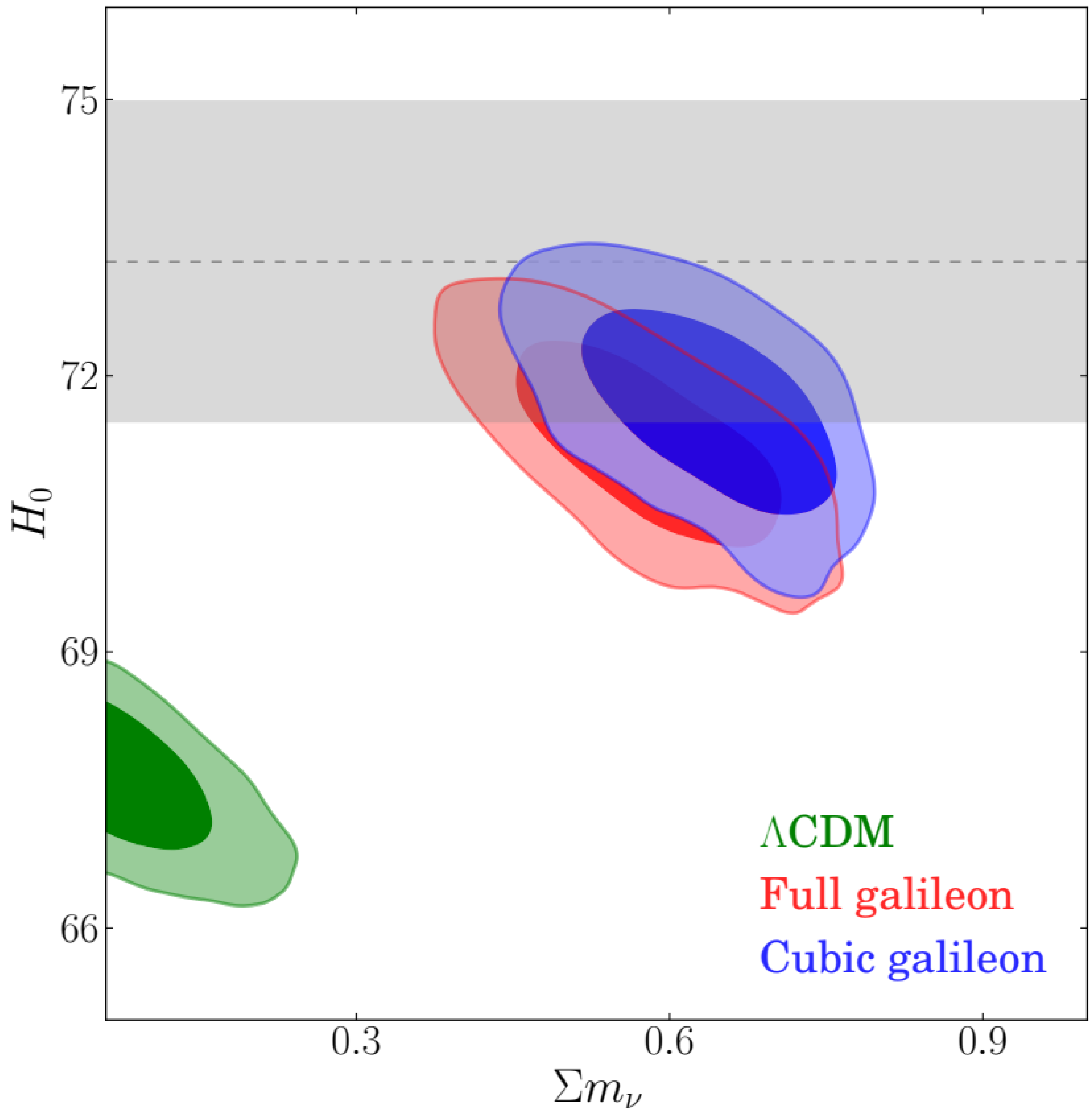


- TT powerspectrum with Σm_ν



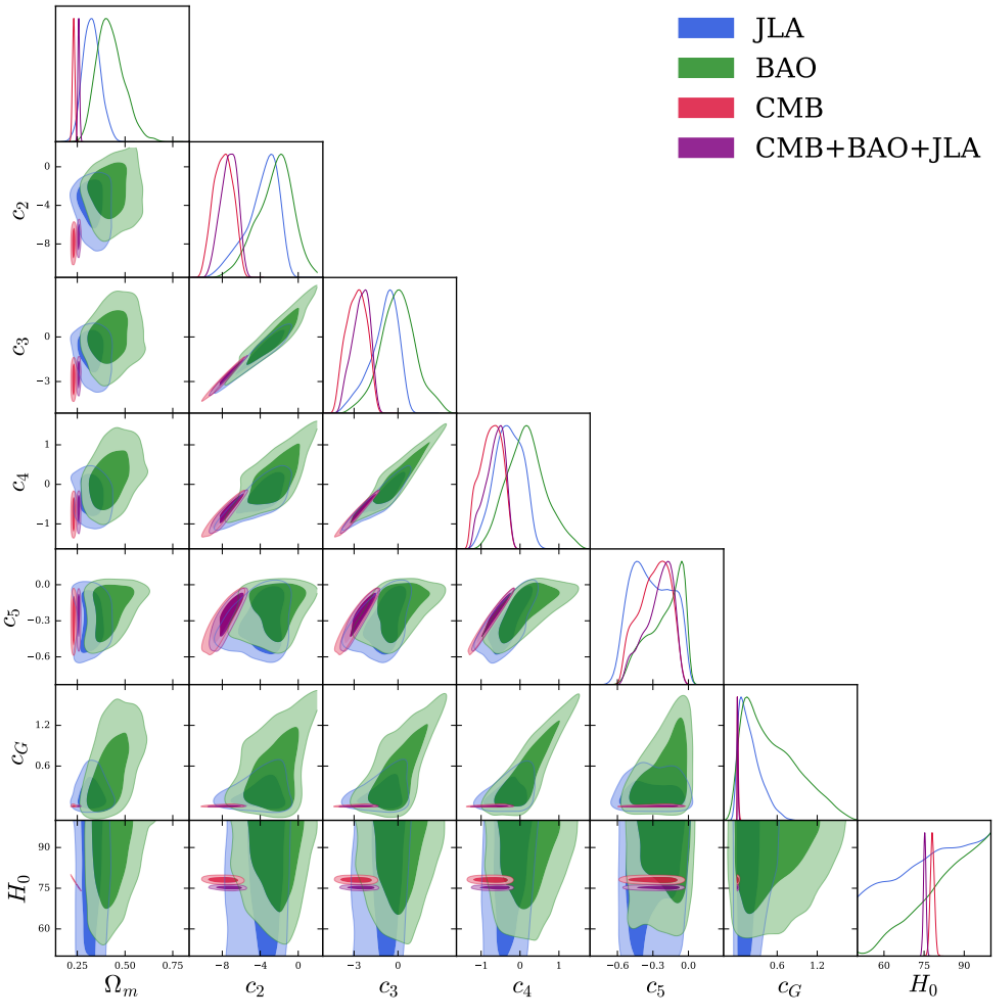
- SN hubble diagram with Σm_ν

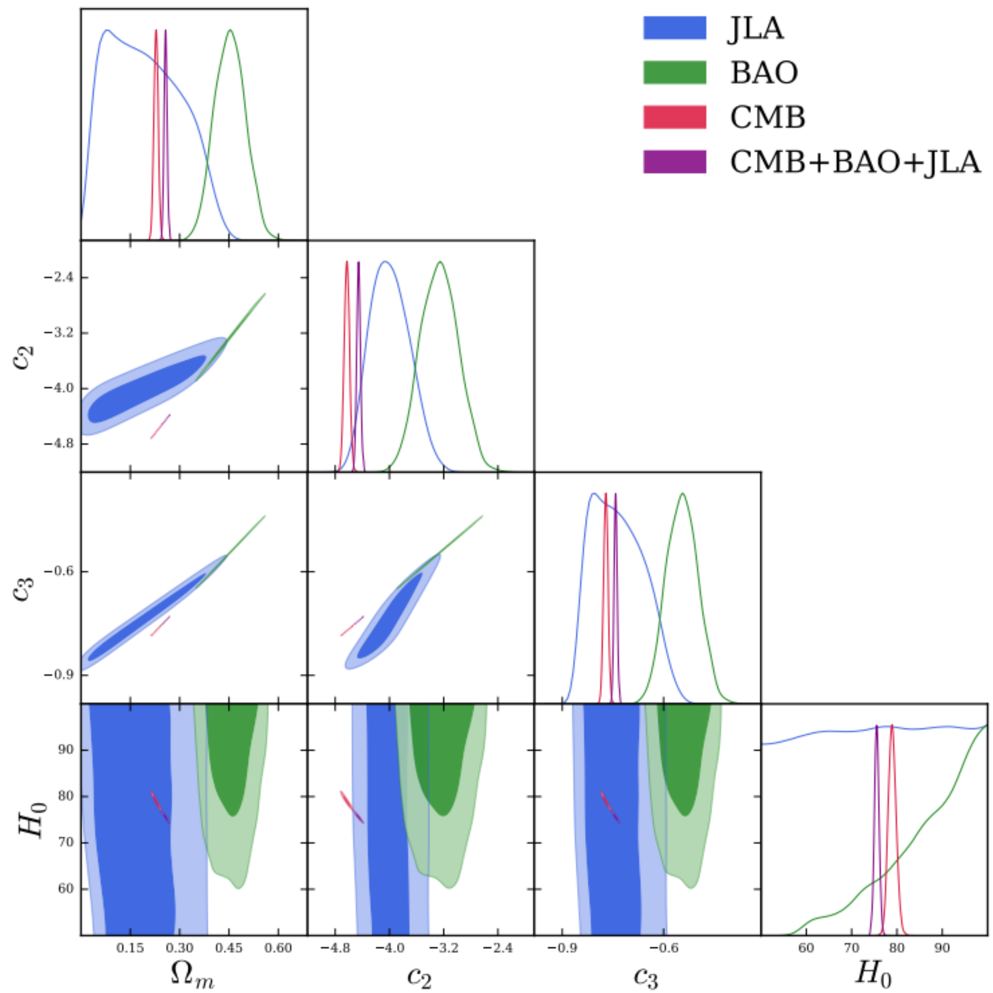




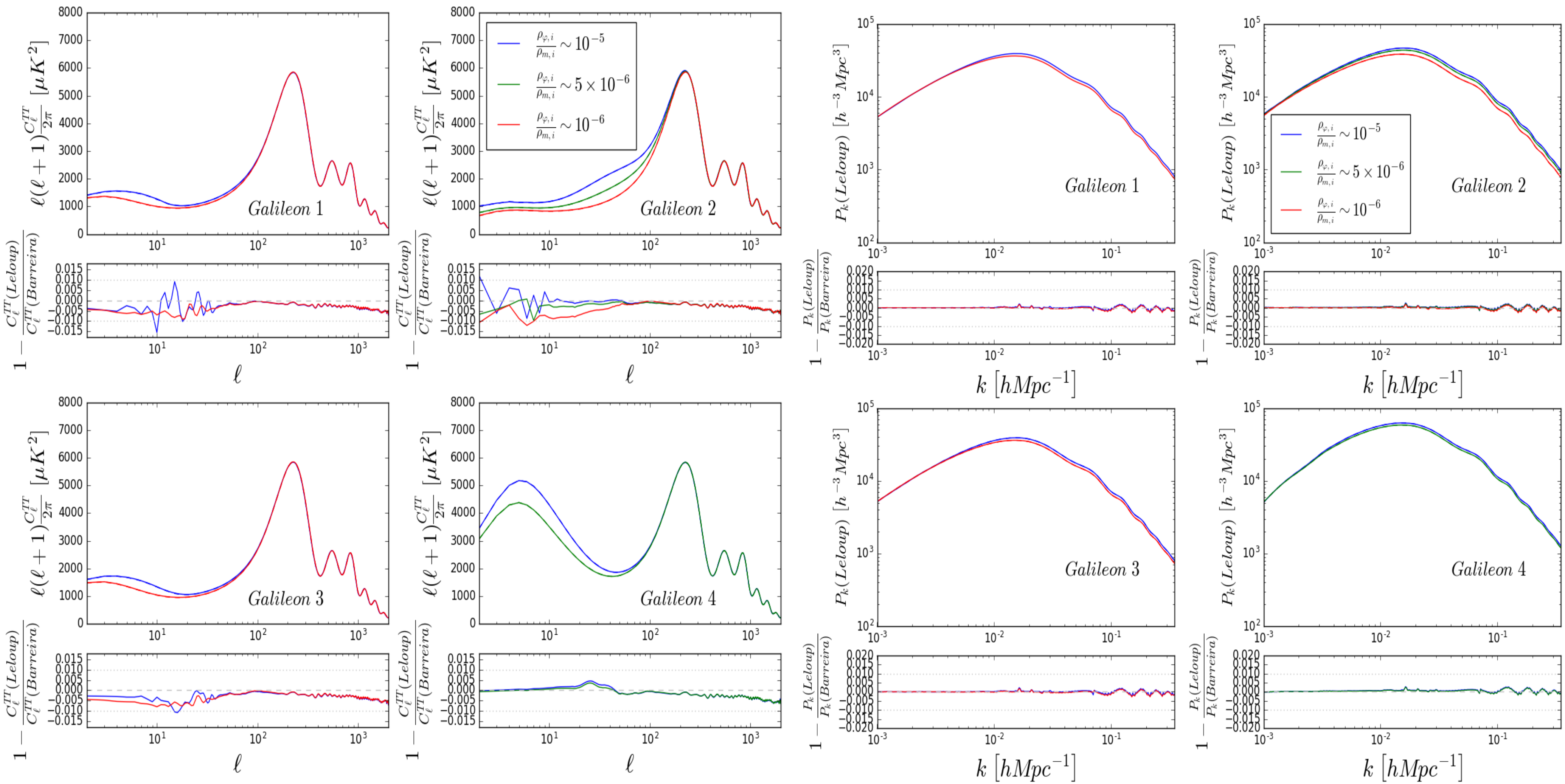
- CI on H0 from Riess et al. 2016

- Constraints on galileon parameters





➢ Validation of CAMB



$$\alpha = \frac{c_2}{6}\bar{H}x - 3c_3\bar{H}^3x^2 + 15c_4\bar{H}^5x^3 - \frac{35}{2}c_5\bar{H}^7x^4 - 3c_G\bar{H}^3x$$
$$\gamma = \frac{c_2}{3}\bar{H}^2x - c_3\bar{H}^4x^2 + 5\frac{5}{2}c_5\bar{H}^8x^4 - 2c_G\bar{H}^4x$$
$$\beta = \frac{c_2}{6}\bar{H}^2 - 2c_3\bar{H}^4x + 9c_4\bar{H}^6x^2 - 10c_5\bar{H}^8x^3 - c_G\bar{H}^4$$
$$\sigma = 2\bar{H} + 2c_3\bar{H}^3x^3 - 15c_4\bar{H}^5x^4 + 21c_5\bar{H}^7x^5 + 6c_G\bar{H}^3x^2$$
$$\lambda = 3\bar{H}^2 + \frac{\Omega_\gamma^0}{a^4} + \frac{p_\nu}{M_{Pl}^2H_0^2} + \frac{c_2}{2}\bar{H}^2x^2 - 2c_3\bar{H}^4x^3 + \frac{15}{2}c_4\bar{H}^6x^4 - 9c_5\bar{H}^8x^5 - c_G\bar{H}^4x^2$$
$$\omega = 2c_3\bar{H}^4x^2 - 12c_4\bar{H}^6x^3 + 15c_5\bar{H}^8x^4 + 4c_G\bar{H}^4x$$

1. $\chi^G = f_1^\chi \cdot \gamma + f_2^\chi \cdot \gamma' + \frac{1}{\kappa a^2}\left(f_3^\chi \cdot k\mathcal{H}\mathcal{Z} + f_4^\chi \cdot k^2\eta\right)$ with :

$$f_1^\chi = \frac{k^2}{\kappa a^2}\left[-2\frac{c_3}{a^2}x^2\bar{\mathcal{H}}^2 + 12\frac{c_4}{a^4}x^3\bar{\mathcal{H}}^4 - 15\frac{c_5}{a^6}x^4\bar{\mathcal{H}}^6 - 4\frac{c_G}{a^2}x\bar{\mathcal{H}}^2\right] \quad (A.1)$$
$$f_2^\chi = \frac{H_0}{\kappa a^2}\left[c_2x\bar{\mathcal{H}} - 18\frac{c_3}{a^2}x^2\bar{\mathcal{H}}^3 + 90\frac{c_4}{a^4}x^3\bar{\mathcal{H}}^5 - 105\frac{c_5}{a^6}x^4\bar{\mathcal{H}}^7 - 18\frac{c_G}{a^2}x\bar{\mathcal{H}}^3\right] \quad (A.2)$$
$$f_3^\chi = -2\frac{c_3}{a^2}x^3\bar{\mathcal{H}}^2 + 15\frac{c_4}{a^4}x^4\bar{\mathcal{H}}^4 - 21\frac{c_5}{a^6}x^5\bar{\mathcal{H}}^6 - 6\frac{c_G}{a^2}x^2\bar{\mathcal{H}}^2 \quad (A.3)$$
$$f_4^\chi = \frac{3}{2}\frac{c_4}{a^4}x^4\bar{\mathcal{H}}^4 - 3\frac{c_5}{a^6}x5\bar{\mathcal{H}}^6 - \frac{c_G}{a^2}x^2\bar{\mathcal{H}}^2 \quad (A.4)$$

2. $q^G = f_1^q + \frac{1}{\kappa a^2}f_2^q \cdot k^2(\sigma - \mathcal{Z})$ with :

$$f_1^q = \frac{k}{\kappa a^2}\left[c_2H_0x\bar{\mathcal{H}}\bar{\gamma} - \frac{c_3}{a^2}\left(-2x^2\bar{H}^2\bar{\gamma}' + 6H_0x^2\bar{\mathcal{H}}^3\bar{\gamma}\right) + \frac{c_4}{a^4}\left(-12x^3\bar{\mathcal{H}}^4\bar{\gamma}' + 18H_0x^3\bar{\mathcal{H}}^5\bar{\gamma}\right)\right.$$
$$\left. -\frac{c_5}{a^6}\left(-15x^4\bar{\mathcal{H}}^6\bar{\gamma}' + 15H_0x^4\bar{\mathcal{H}}^7\bar{\gamma}\right) - \frac{c_G}{a^2}\left(-4x\bar{\mathcal{H}}^2\bar{\gamma}' + 6H_0x\bar{\mathcal{H}}^3\bar{\gamma}\right)\right] \quad (A.5)$$
$$f_2^q = \frac{c_4}{a^4}x^4\bar{\mathcal{H}}^4 - 2\frac{c_5}{a^6}x^5\bar{\mathcal{H}}^6 - \frac{2}{3}\frac{c_G}{a^2}x^2\bar{\mathcal{H}}^2 \quad (A.6)$$

3. $\Pi^G = f_1^\Pi + \frac{1}{\kappa a^2}\left(f_2^\Pi \cdot k\mathcal{H}\sigma - f_3^\Pi \cdot k\sigma' + f_4^\Pi \cdot k^2\phi\right)$ with :

$$f_1^\Pi = \frac{k^2}{\kappa a^2}\left[\frac{c_4}{a^4}\left(4x^3\bar{\mathcal{H}}^4\bar{\gamma} - 6x^2\bar{\mathcal{H}}^3\left(\overset{o}{x\bar{\mathcal{H}}}\right)\bar{\gamma}\right) - \frac{c_5}{a^6}\left(12x^4\bar{\mathcal{H}}^6\bar{\gamma} - 3x^4\bar{\mathcal{H}}^5\overset{o}{\bar{\mathcal{H}}}\bar{\gamma} - 12x^3\bar{\mathcal{H}}^5\left(\overset{o}{x\bar{\mathcal{H}}}\right)\bar{\gamma}\right) + 2\frac{c_G}{a^2}\bar{H}\left(\overset{o}{x\bar{\mathcal{H}}}\right)\bar{\gamma}\right] \tag{A.7}$$

$$f_2^\Pi = \frac{c_4}{a^4}\left(3x^4\bar{\mathcal{H}}^4 - 6x^3\bar{\mathcal{H}}^3\left(\overset{o}{x\bar{\mathcal{H}}}\right)\right) - \frac{c_5}{a^6}\left(12x^5\bar{\mathcal{H}}^6 - 3x^5\bar{\mathcal{H}}^5\overset{o}{\bar{\mathcal{H}}} - 15x^4\bar{\mathcal{H}}^5\left(\overset{o}{x\bar{\mathcal{H}}}\right)\right) + 2\frac{c_G}{a^2}x\bar{H}\left(\overset{o}{x\bar{\mathcal{H}}}\right) \tag{A.8}$$

$$f_3^\Pi = \frac{c_4}{a^4}x^4\bar{\mathcal{H}}^4 + 3\frac{c_5}{a^6}x^4\bar{H}^5\left(\overset{o}{x\bar{\mathcal{H}}}\right) \tag{A.9}$$

$$f_4^\Pi = -\frac{c_4}{a^4}x^4\bar{\mathcal{H}}^4 - \frac{c_5}{a^6}\left(-6x^5\bar{\mathcal{H}}^6 + 6x^4\bar{H}^5\left(\overset{o}{x\bar{\mathcal{H}}}\right)\right) + 2\frac{c_G}{a^2}x^2\bar{\mathcal{H}}^2 \tag{A.10}$$

4. $0 = f_1^{eom}\cdot\bar{\gamma}'' + f_2^{eom}\cdot\bar{\gamma}' + f_3^{eom}\cdot k^2\bar{\gamma} + f_4^{eom}\cdot k\mathcal{H}\mathcal{Z} + f_5^{eom}\cdot k\mathcal{Z}' + f_6^{eom}\cdot k^2\eta$ with :

$$f_1^{eom} = c_2 - 12\frac{c_3}{a^2}x\bar{\mathcal{H}}^2 + 54\frac{c_4}{a^4}x^2\bar{\mathcal{H}}^4 - 60\frac{c_5}{a^6}x^3\bar{\mathcal{H}}^6 - 6\frac{c_G}{a^2}\bar{\mathcal{H}}^2 \tag{A.11}$$

$$f_2^{eom} = H_0\Bigg[2c_2\bar{\mathcal{H}} - \frac{c_3}{a^2}\left(12x\bar{\mathcal{H}}^2\overset{o}{\bar{\mathcal{H}}} + 12\bar{\mathcal{H}}^2(\overset{o}{x\bar{\mathcal{H}}})\right) + \frac{c_4}{a^4}\left(-108x^2\bar{\mathcal{H}}^5 + 108x^2\bar{\mathcal{H}}^4\overset{o}{\bar{\mathcal{H}}} + 108x\bar{\mathcal{H}}^4(\overset{o}{x\bar{\mathcal{H}}})\right)$$
$$-\frac{c_5}{a^6}\left(-240x^3\bar{\mathcal{H}}^7 + 180x^3\bar{\mathcal{H}}^6\overset{o}{\bar{\mathcal{H}}} + 180x^2\bar{\mathcal{H}}^6(\overset{o}{x\bar{\mathcal{H}}})\right) - 12\frac{c_G}{a^2}\bar{\mathcal{H}}^2\overset{o}{\bar{\mathcal{H}}}\Bigg] \tag{A.12}$$

$$f_3^{eom} = c_2 - \frac{c_3}{a^2}\left(4x\bar{\mathcal{H}}^2 + 4\bar{\mathcal{H}}(\overset{o}{x\bar{\mathcal{H}}})\right) + \frac{c_4}{a^4}\left(-10x^2\bar{\mathcal{H}}^4 + 12x^2\bar{\mathcal{H}}^3\overset{o}{\bar{\mathcal{H}}} + 24x\bar{\mathcal{H}}^3(\overset{o}{x\bar{\mathcal{H}}})\right)$$
$$-\frac{c_5}{a^6}\left(-36x^3\bar{\mathcal{H}}^6 + 24x^3\bar{\mathcal{H}}^5(\overset{o}{\bar{\mathcal{H}}}) + 36x^2\bar{\mathcal{H}}^5(\overset{o}{x\bar{\mathcal{H}}})\right) - \frac{c_G}{a^2}\left(2\bar{\mathcal{H}}\right) \tag{A.13}$$

$$f_4^{eom} = c_2x - \frac{c_3}{a^2}\left(6x^2\bar{\mathcal{H}}^2 + 4x\bar{\mathcal{H}}(\overset{o}{x\bar{\mathcal{H}}})\right) + \frac{c_4}{a^4}\left(-6x^3\bar{\mathcal{H}}^4 + 12x^3\bar{\mathcal{H}}^3\overset{o}{\bar{\mathcal{H}}} + 36x^2\bar{\mathcal{H}}^3(\overset{o}{x\bar{\mathcal{H}}})\right)$$
$$-\frac{c_5}{a^6}\left(-45x^4\bar{\mathcal{H}}^6 + 30x^4\bar{\mathcal{H}}^5\overset{o}{\bar{\mathcal{H}}} + 60x^3\bar{\mathcal{H}}^5(\overset{o}{x\bar{\mathcal{H}}})\right) - \frac{c_G}{a^2}\left(6x\bar{\mathcal{H}}^2 + 4x\bar{\mathcal{H}}\overset{o}{\bar{\mathcal{H}}} + 4\bar{\mathcal{H}}(\overset{o}{x\bar{\mathcal{H}}})\right) \tag{A.14}$$

$$f_5^{eom} = -2\frac{c_3}{a^2}x^2\bar{\mathcal{H}}^2 + 12\frac{c_4}{a^4}x^2\bar{\mathcal{H}}^4 - 15\frac{c_5}{a^6}x^4\bar{\mathcal{H}}^6 - 4\frac{c_G}{a^2}x\bar{\mathcal{H}}^2 \tag{A.15}$$

$$f_6^{eom} = \frac{c_4}{a^4}\left(-4x^3\bar{\mathcal{H}}^4 + 6x^2\bar{\mathcal{H}}^3(\overset{o}{x\bar{\mathcal{H}}})\right) - \frac{c_5}{a^6}\left(-12x^4\bar{\mathcal{H}}^6 + 3x^4\bar{\mathcal{H}}^5\overset{o}{\bar{\mathcal{H}}} + 12x^3\bar{\mathcal{H}}^5(\overset{o}{x\bar{\mathcal{H}}})\right)$$
$$-2\frac{c_G}{a^2}\bar{\mathcal{H}}(\overset{o}{x\bar{\mathcal{H}}}) \tag{A.16}$$

Existing constraints

- Barreira et al. (2014) and Renk et al. (2017)
  - Models : cubic, quartic, quintic
  - Tracker solutions only
  - $\sum m_\nu = 0.06$ eV and $\sum m_\nu \neq 0.06$ eV
  - Datasets : CMB spectra, BAO, ISW
  - Results :
    - All models need $\sum m_\nu \neq 0.06$ eV to fit CMB and BAO data
    - Cubic galileon in tension with ISW (7.2σ)
    - Quartic and quintic with $\sum m_\nu \neq 0.06$ eV comparable with ΛCDM

Existing constraints

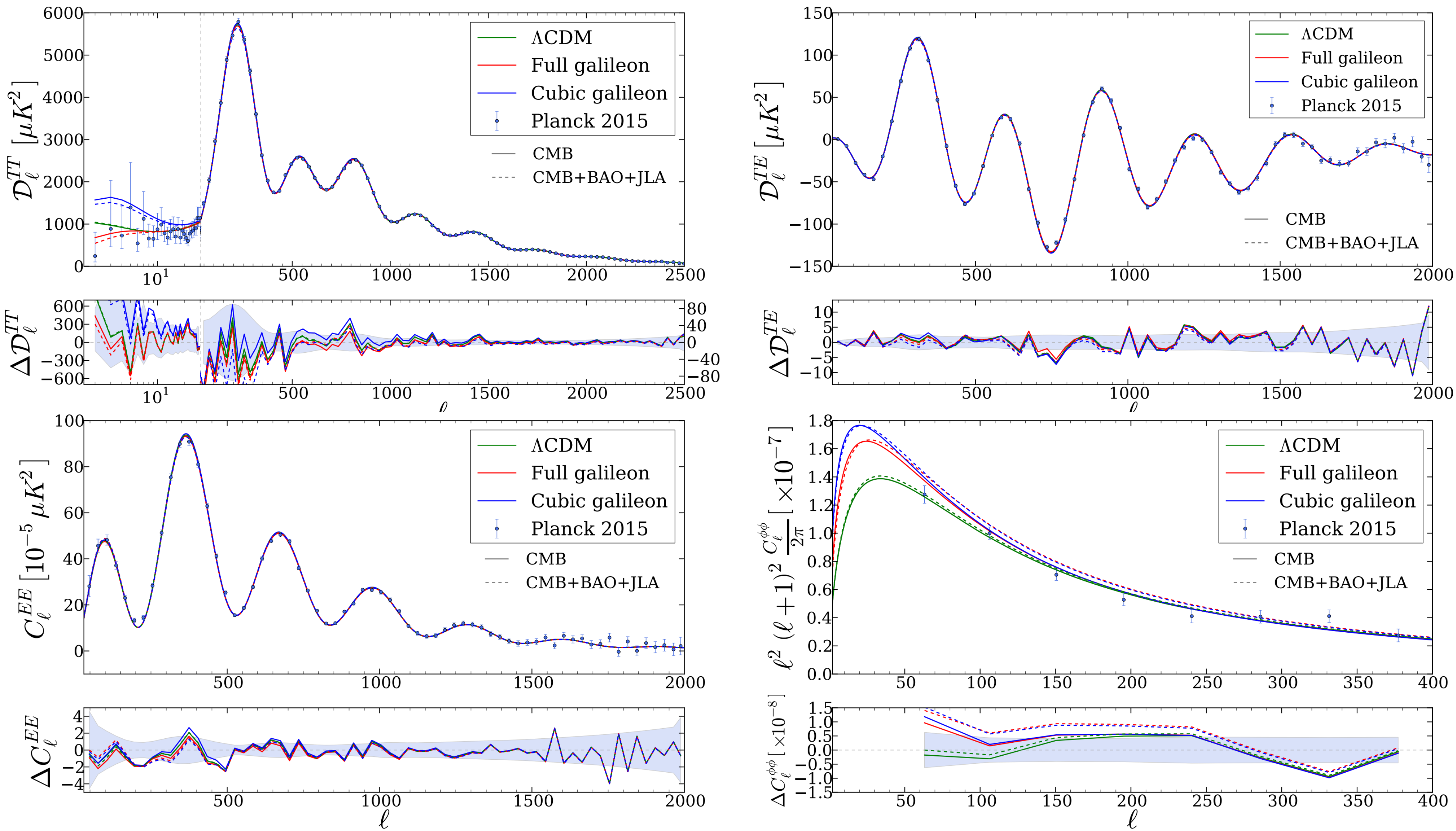
- Neveu et al. (2017)
  - Models : uncoupled, disformal, conformal, full
  - No restriction to tracker solutions
  - $\sum m_\nu = 0.06 \text{ eV}$
  - Datasets : CMB priors, BAO, SNIa, growth of structure
  - Results :
    - Conformal coupling is disfavored
    - Disformal coupling is slightly favored
    - Good agreement with data for all models

New constraints

- In the following (Leloup et al. in prep)
  - Models : cubic, full
  - No restriction to tracker solutions
  - $\sum m_\nu = 0.06$ eV and $\sum m_\nu \neq 0.06$ eV
  - Datasets :
    - CMB powerspectra (TT, TE, EE, lensing from Planck 2015)
    - BAO (SDSS MGS, 6dFGS, BOSS DR12)
    - SNIa (JLA sample)
    - GW170817

Base models

- Fit to CMB+BAO+JLA data :



Base models

- Fit to CMB+BAO+JLA data :