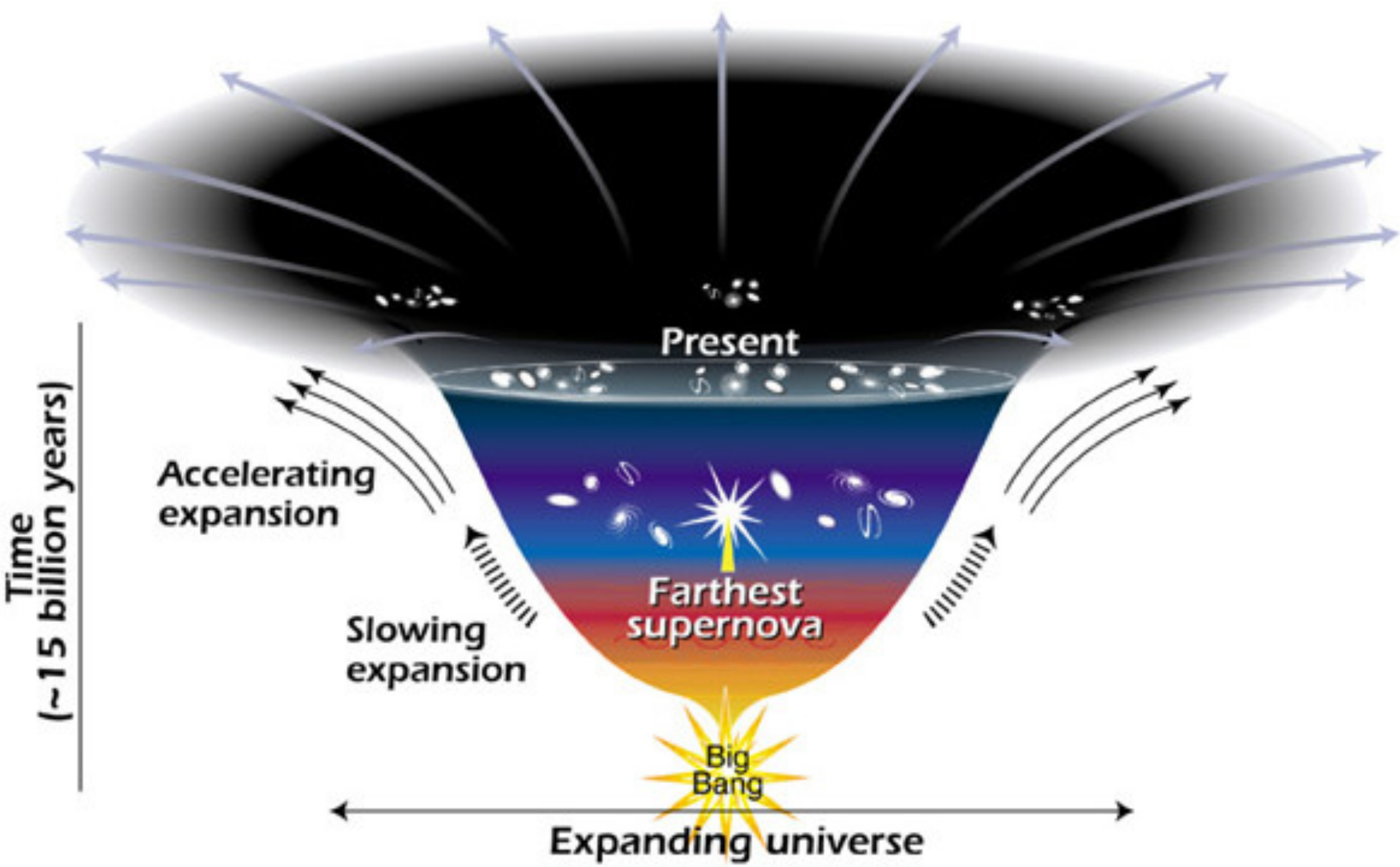
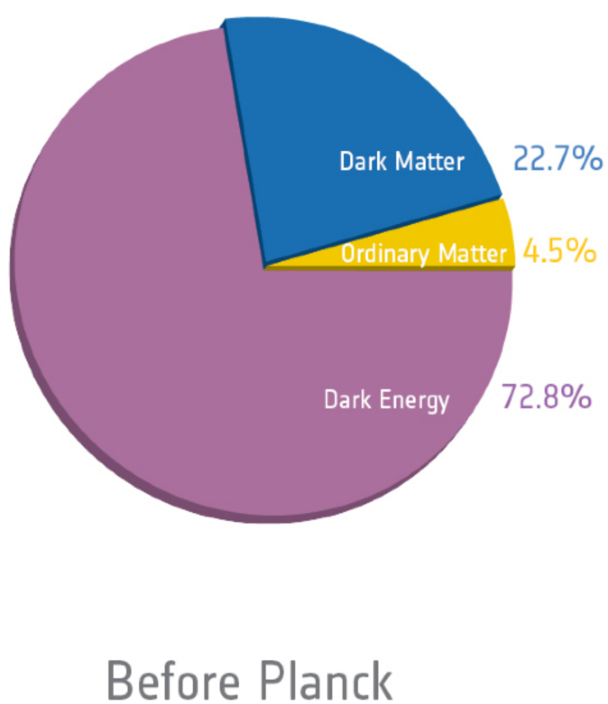


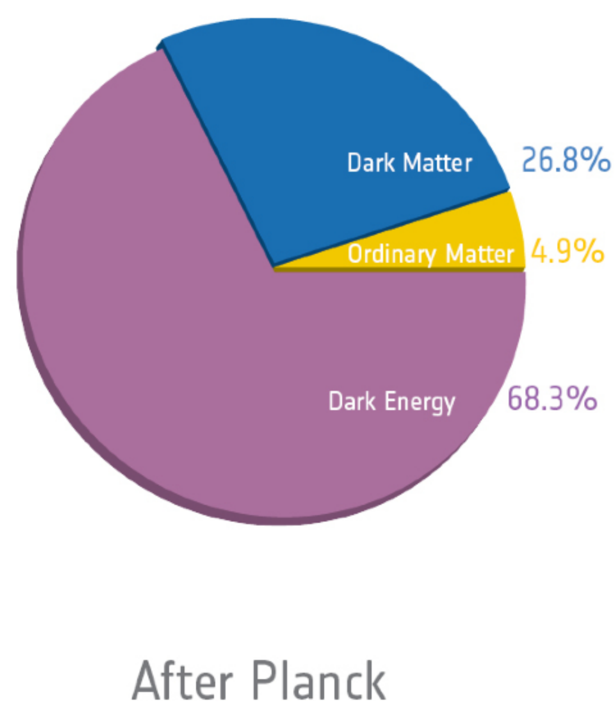
Constraining interacting dark energy with CMB and BAO future surveys

Santos, L. et al, PRD, 96,103529 (2017)

Larissa Santos

The standard cosmological model

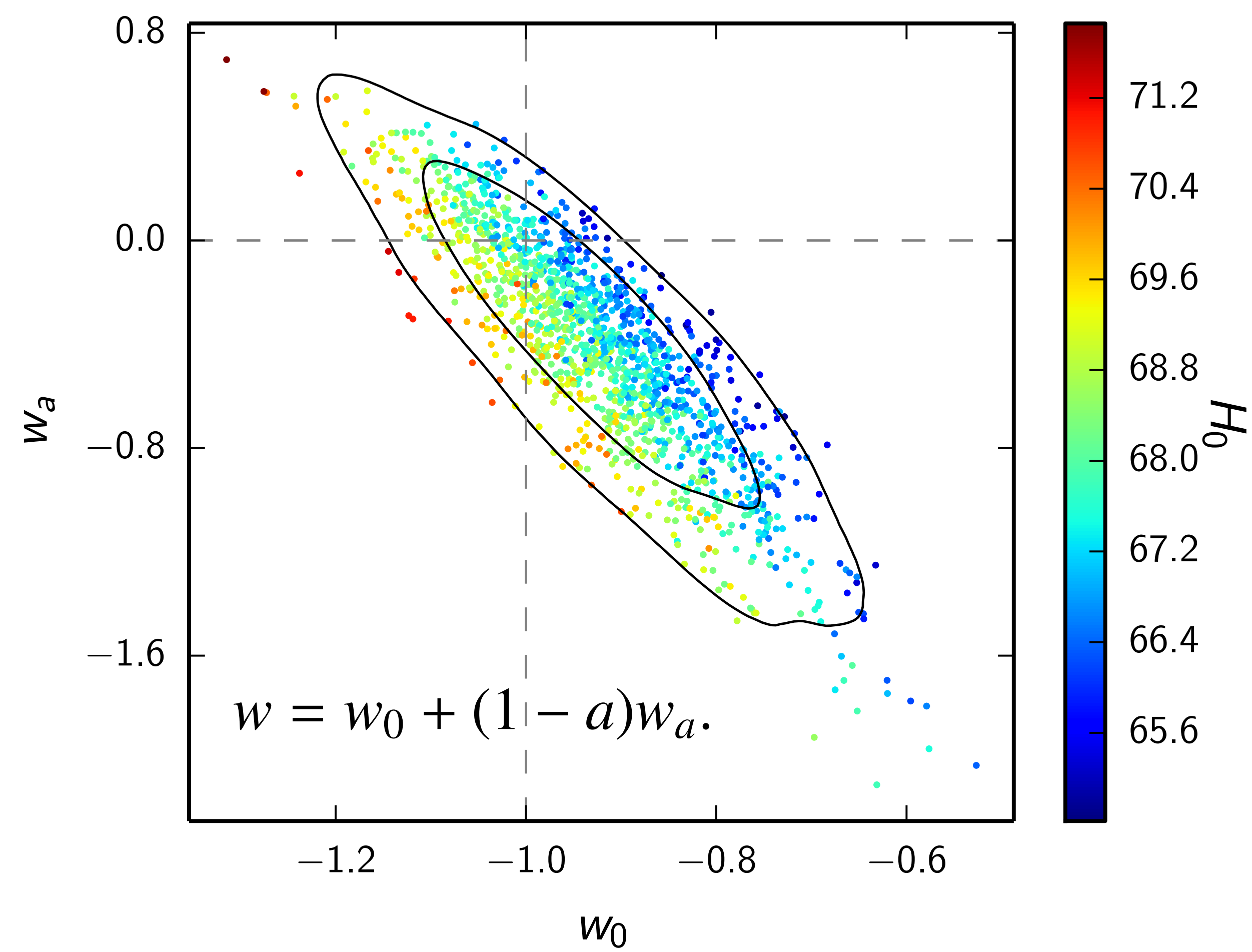




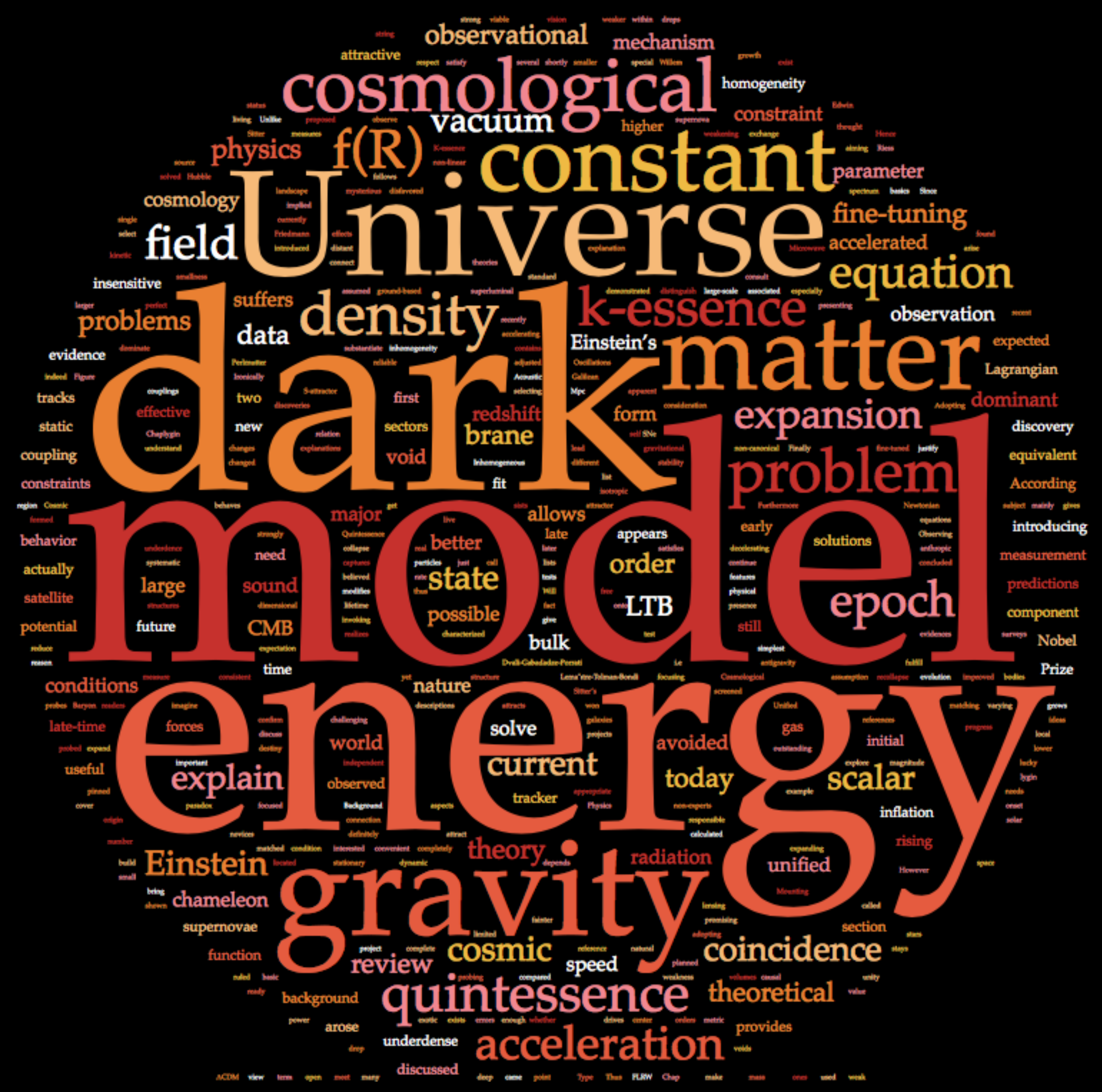
$$w = -1.023^{+0.091}_{-0.096} \quad \textit{Planck}\ \text{TT+lowP+ext},$$
$$w = -1.006^{+0.085}_{-0.091} \quad \textit{Planck}\ \text{TT+lowP+lensing+ext},$$
$$w = -1.019^{+0.075}_{-0.080} \quad \textit{Planck}\ \text{TT, TE, EE+lowP+lensing+ext}.$$

- Planck data is consistent with a cosmological constant scenario

Planck collaboration 2015



But a quick search on dark energy shows…



Problems in the standard scenario

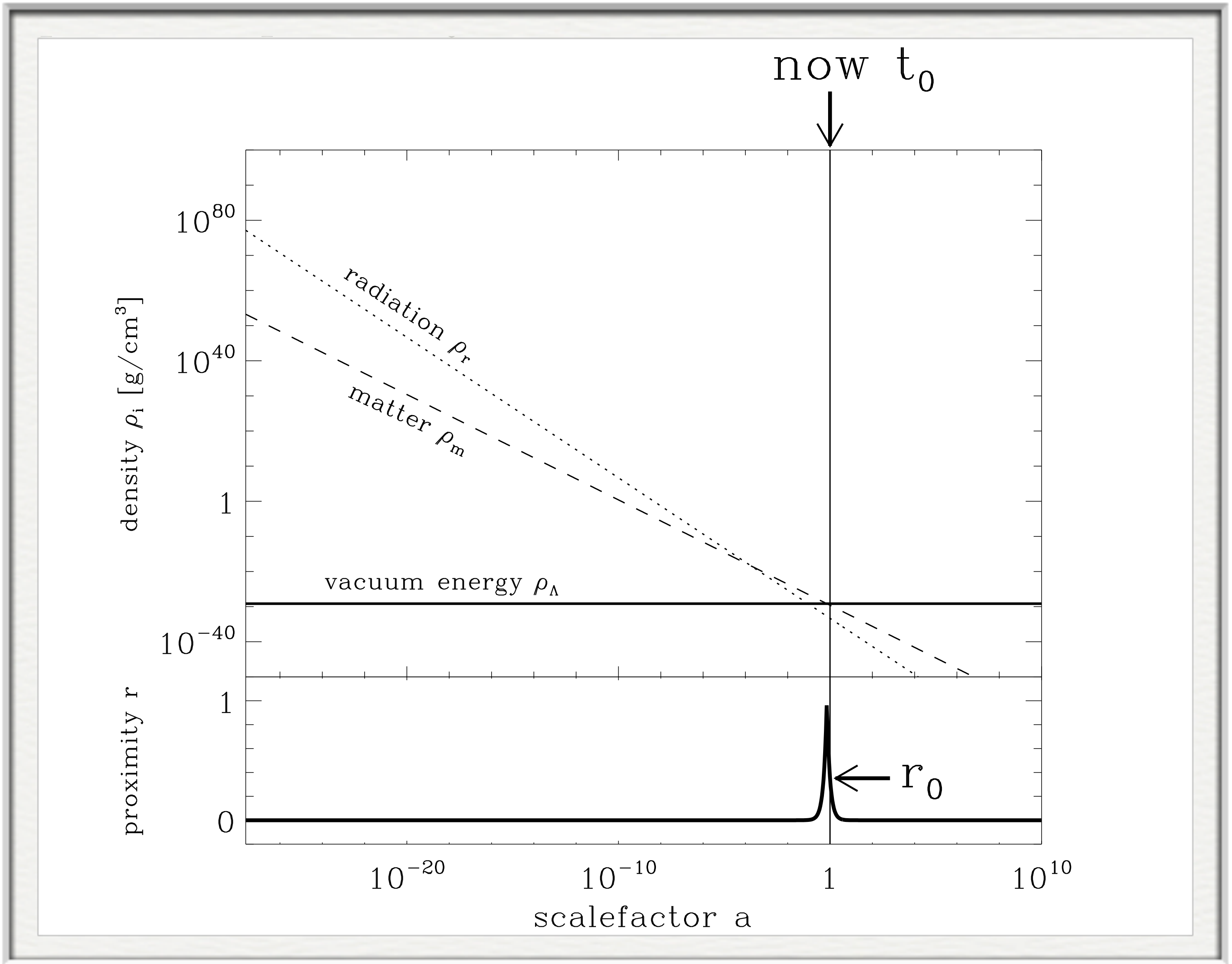
- We need a very **fine-tuned** particle physics theory that makes the vacuum energy density extremely small but still different from 0

$$\rho_\Lambda^{obs} \leq (10^{-12} GeV)^4 \sim 2 \times 10^{-10} erg/cm^3.$$

- There is a 120 orders of magnitude difference between the theoretical expectation and the observational value

Coincidence problem

- The cosmological constant energy density is **coincidentally** of the same order of magnitude as the present mass density of the universe
  - Why does cosmic acceleration happen to begin now and not at some point in the past or in the future?



Anthropic considerations?

The conditions for the existence of observers in an ensemble set upper bounds on the dark energy density

Alternative Dark Energy scenarios: Why not?

For a review and references: Yi-Fu Cai et al (2010), arXiv: 0909.2776

- To solve the problems regarding the cosmological constant many alternatives are discussed in the literature
  - Cosmological constant
  - Quintessence
  - Phantom
  - Quintom
  - Modified gravity…

Interacting dark energy

- An interacting DM and DE scenario would affect the overall evolution of the universe and its expansion history

- The equation of evolution of the background of DM and DE densities are then given by

$$\boxed{\begin{aligned} \dot{\rho}_{\rm DM} + 3H\rho_{\rm DM} &= +Q \\ \dot{\rho}_{\rm DE} + 3H(1+w_{\rm DE})\rho_{\rm DE} &= -Q \end{aligned}}$$

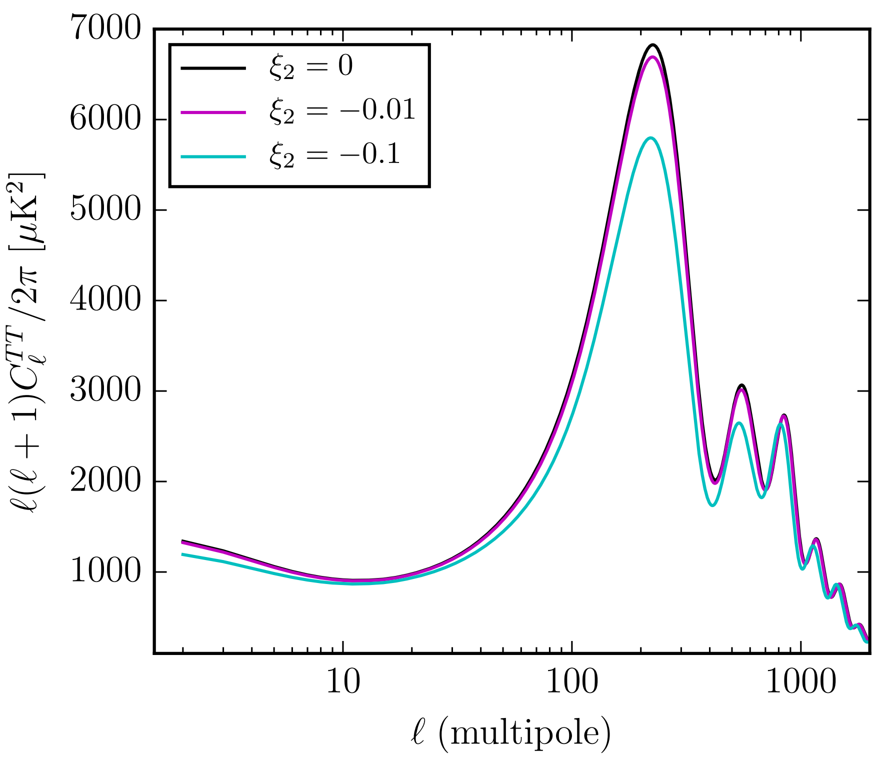
coupling coefficients

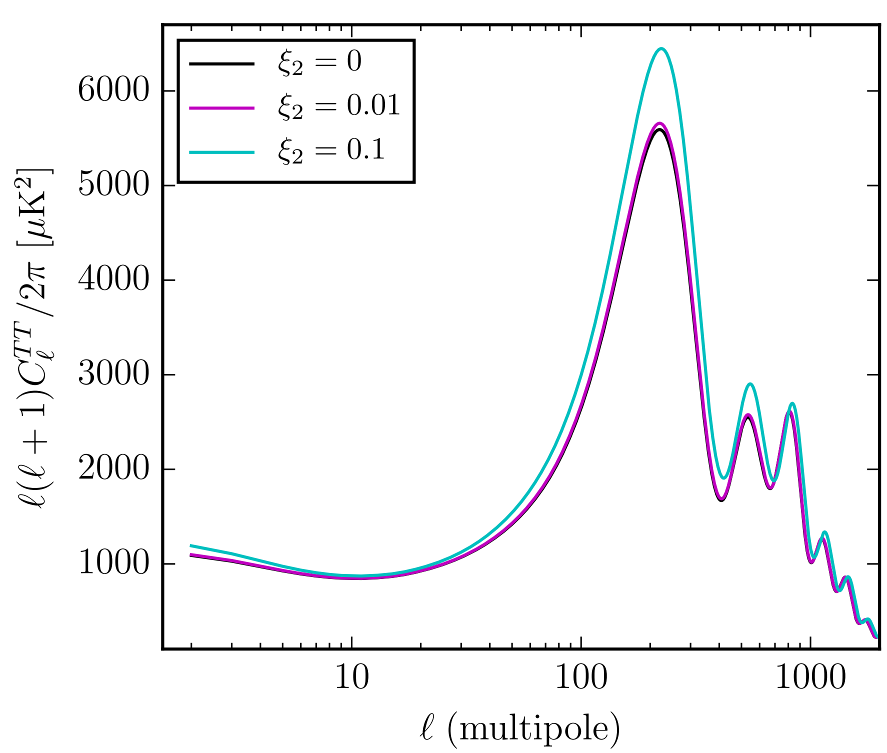
$$\boxed{Q = 3H(\xi_1\rho_{\rm DM} + \xi_2\rho_{\rm DE})}$$

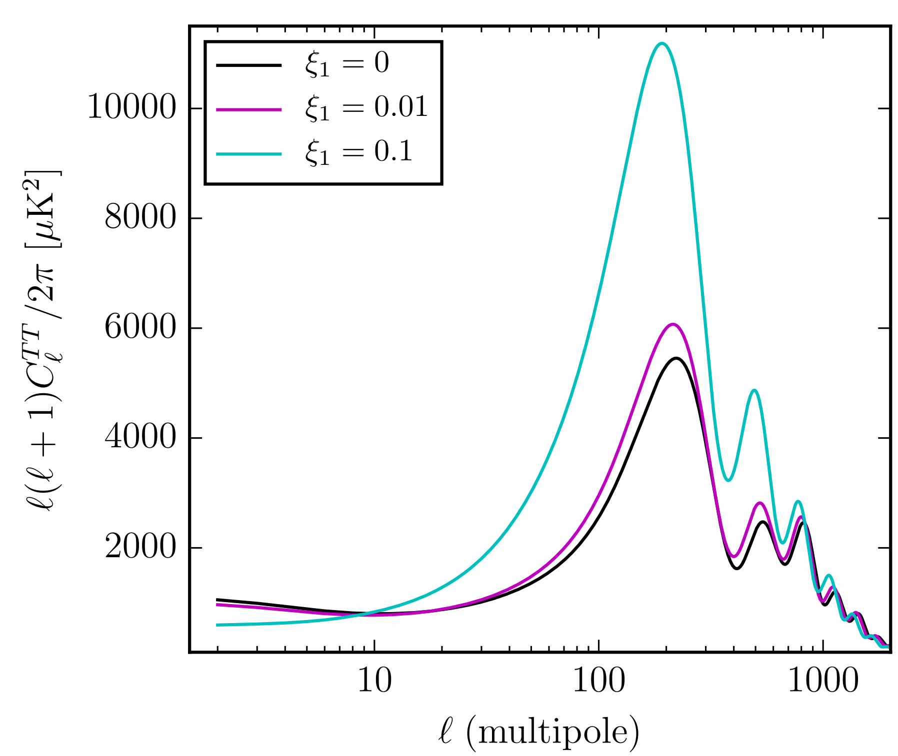
- For Q>0 the energy flows from DE $\longrightarrow$ DM
- For Q<0 the energy flows from DM $\longrightarrow$ DE

Models J. H. He, B. Wang and E. Abdalla (2009)

Model	Q	DE EoS
1	$3\xi_2 H \rho_{\rm DE}$	$-1 < w_{\rm DE} < -1/3$
2	$3\xi_2 H \rho_{\rm DE}$	$w_{\rm DE} < -1$
3	$3\xi_1 H \rho_{\rm DM}$	$w_{\rm DE} < -1$







Motivations

- The coincidence problem could be solved by imposing the requirement that the ratio of the energy densities of DM and DE is a constant in the expansion history of the universe, such that $\rho = \rho c/\rho d$
- It is observationally distinguishable from the ΛCDM model
- Check if future experiments will be able to distinguish between different cosmological models

Models evolution

- When one allows for an energy flow between DE and DM, the energy densities present a different evolution for each model

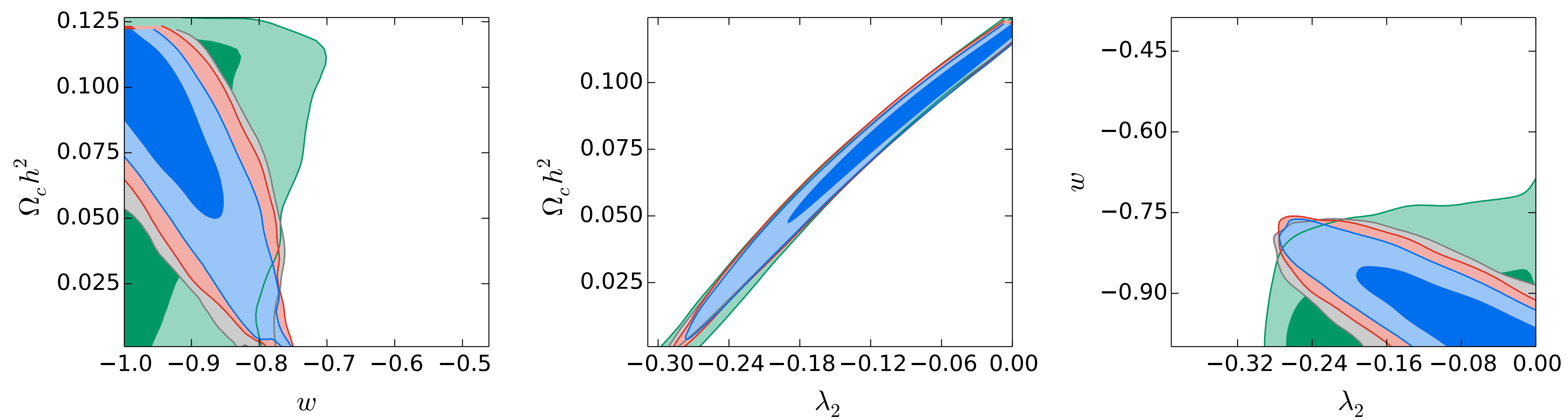
  - Models 1 and 2:

$$\rho_{\mathrm{DE}} = (1+z)^{3(1+w_{\mathrm{DE}}+\xi_2)}\rho^0_{\mathrm{DE}}\,,$$
$$\rho_{\mathrm{DM}} = (1+z)^3 \times \left\{ \frac{\xi_2\left[1-(1+z)^{3(\xi_2+w_{\mathrm{DE}})}\right]\rho^0_{\mathrm{DE}}}{\xi_2+w_{\mathrm{DE}}} + \rho^0_{\mathrm{DM}} \right\}$$

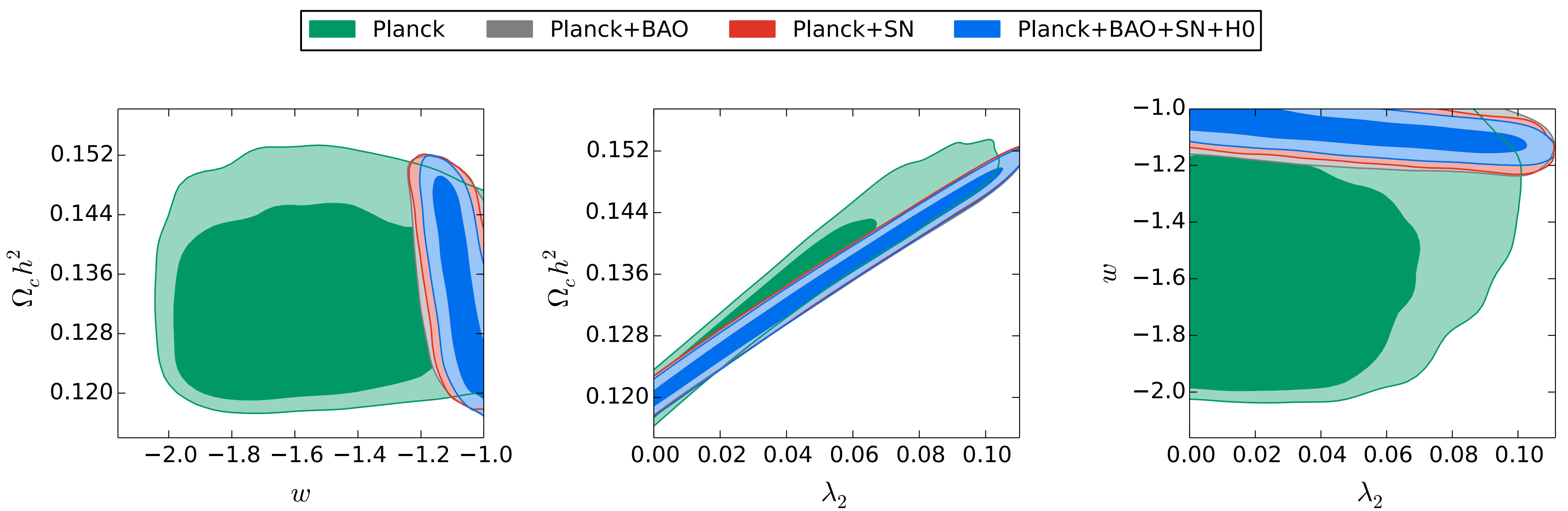
  - Model 3:

$$\rho_{\mathrm{DE}} = (1+z)^{3(1+w_{\mathrm{DE}})}\left(\rho^0_{\mathrm{DE}} + \frac{\xi_1\rho^0_{\mathrm{DM}}}{\xi_1+w_{\mathrm{DE}}}\right) - \frac{\xi_1}{\xi_1+w_{\mathrm{DE}}}(1+z)^{3(1-\xi_1)}\rho^0_{\mathrm{DM}}\,,$$
$$\rho_{\mathrm{DM}} = \rho^0_{\mathrm{DM}}(1+z)^{3-3\xi_1}\,,$$

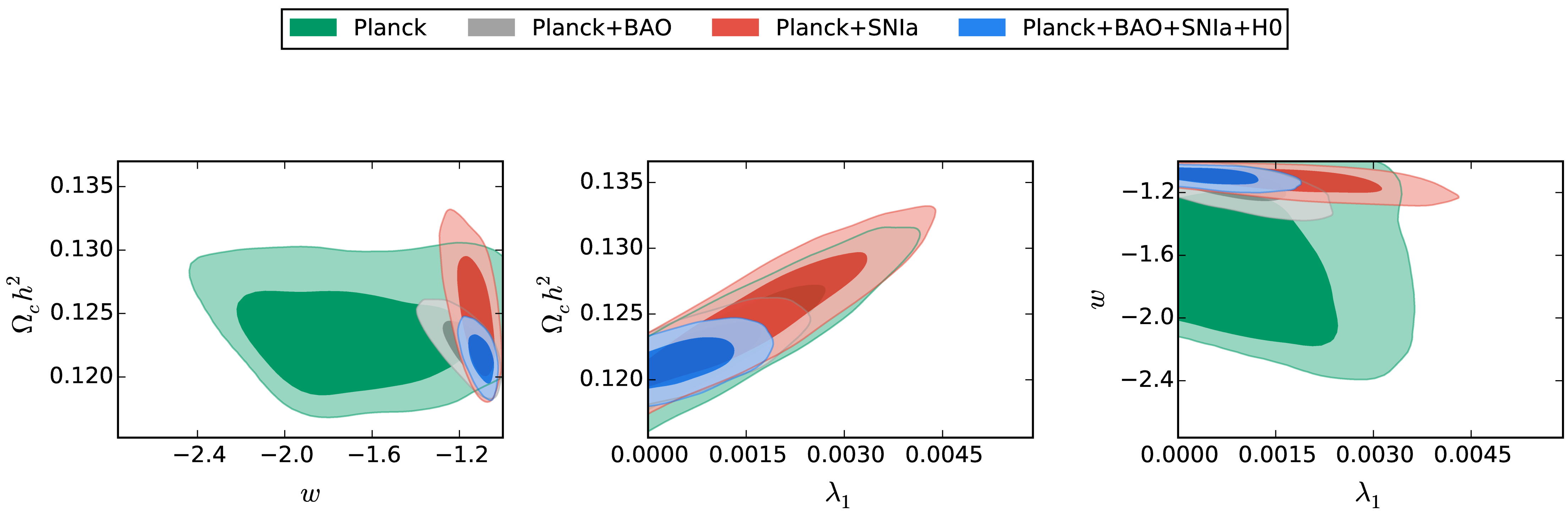
Current constraints A. A. Costa et. al (2017)



(a) Model I



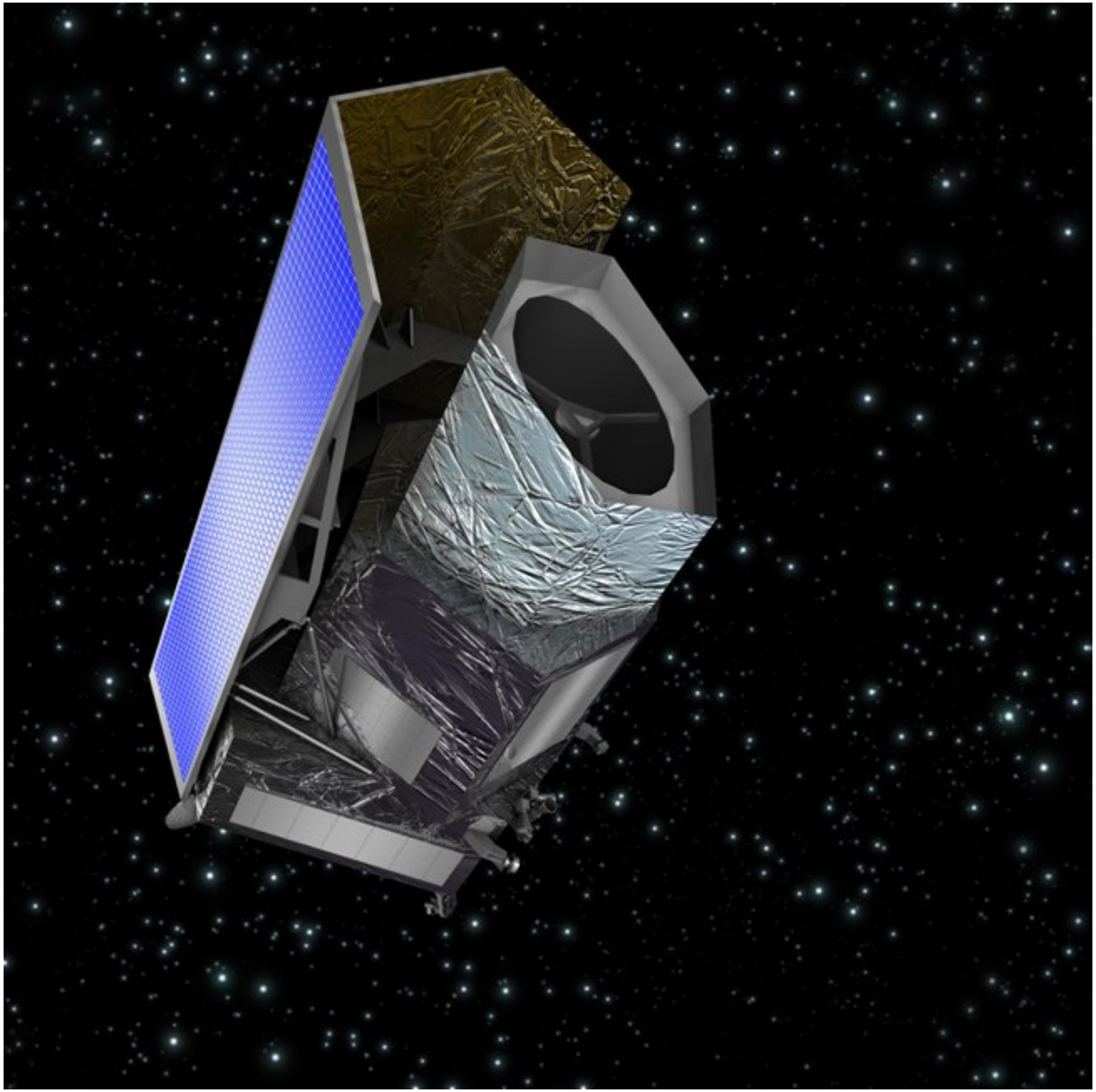
(b) Model II

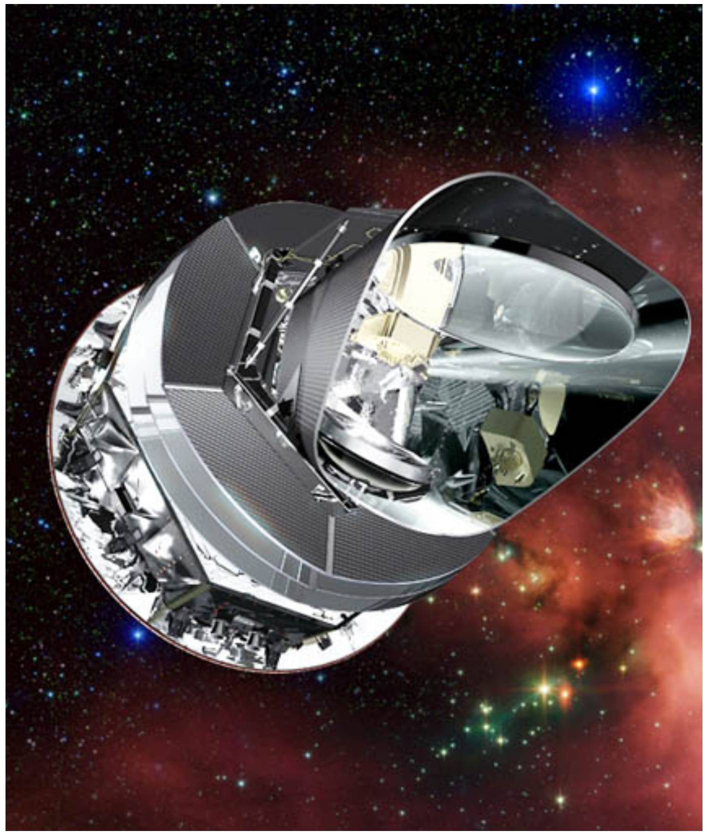


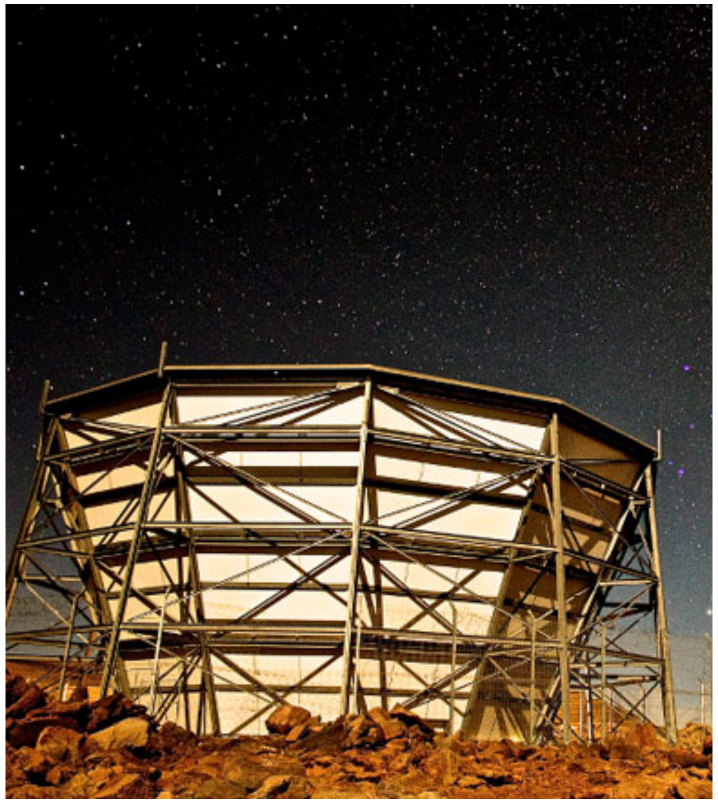
(c) Model III

- Present observations, however, are not able to confidently distinguish between these alternative interacting DE models and ΛCDM

- Since DM and DE are currently only measured gravitationally and since gravity only probes the total energy momentum tensor, degeneracies in the cosmological parameters are inevitable.







Can future cosmological experiments distinguish alternative models from the LCDM?

The Fisher matrix

- Fisher matrices are frequently used to constraint cosmological parameters using different data sets

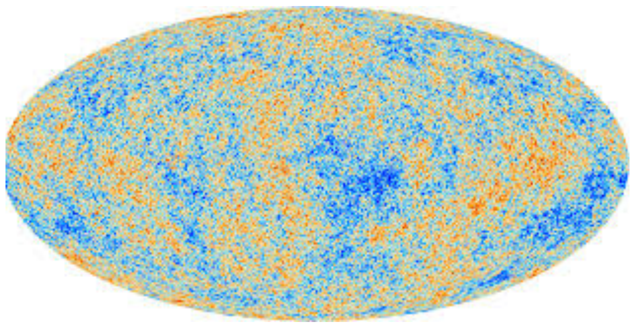
- The inverse of the Fisher matrix is the covariance matrix

$$[F]^{-1} = [C] = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{bmatrix}$$

  - Where σ_x and σ_y are the 1- σ uncertainties in the parameters x and y respectively.

The observables: the CMB

$$F_{ij} = \sum_{\ell} \sum_{X,Y} \frac{\partial C_\ell^X}{\partial p_i} (\mathrm{Cov}_\ell^{-1})_{XY} \frac{\partial C_\ell^Y}{\partial p_j}$$



Zaldarriaga & Seljak 1997

$$[\mathrm{Cov}_\ell] = \frac{2}{(2\ell+1) f_{\mathrm{sky}}} \begin{bmatrix} \Xi_\ell^{TTTT} & \Xi_\ell^{TTEE} & \Xi_\ell^{TTTE} \\ \Xi_\ell^{TTEE} & \Xi_\ell^{EEEE} & \Xi_\ell^{EETE} \\ \Xi_\ell^{TTTE} & \Xi_\ell^{EETE} & \Xi_\ell^{TETE} \end{bmatrix},$$

AdvACT

Frequency [GHz]	θ_{beam}	$\sigma_T[\mu\mathrm{K}\text{-arcmin}]$
90	$2.2'$	7.8
150	$1.3'$	6.9
230	$0.9'$	25

$$
\begin{aligned}
\Xi_\ell^{TTTT} &= \left(\mathcal{C}_\ell^{TT}\right)^2 \, , \\
\Xi_\ell^{EEEE} &= \left(\mathcal{C}_\ell^{EE}\right)^2 \, , \\
\Xi_\ell^{TETE} &= \left(\mathcal{C}_\ell^{TE}\right)^2 + \mathcal{C}_\ell^{TT}\mathcal{C}_\ell^{EE} \, , \\
\Xi_\ell^{TTEE} &= \left(C_\ell^{TE}\right)^2 \, , \\
\Xi_\ell^{TTTE} &= C_\ell^{TE}\mathcal{C}_\ell^{TT} \, , \\
\Xi_\ell^{EETE} &= C_\ell^{TE}\mathcal{C}_\ell^{EE} \, .
\end{aligned}
$$

$$
\begin{aligned}
N_\ell^{TT} &= \sum_\nu \frac{1}{w_T(\nu) B_\ell(\nu)^2} \\
N_\ell^{PP} &= \sum_\nu \frac{1}{w_P(\nu) B_\ell(\nu)^2}
\end{aligned}
$$

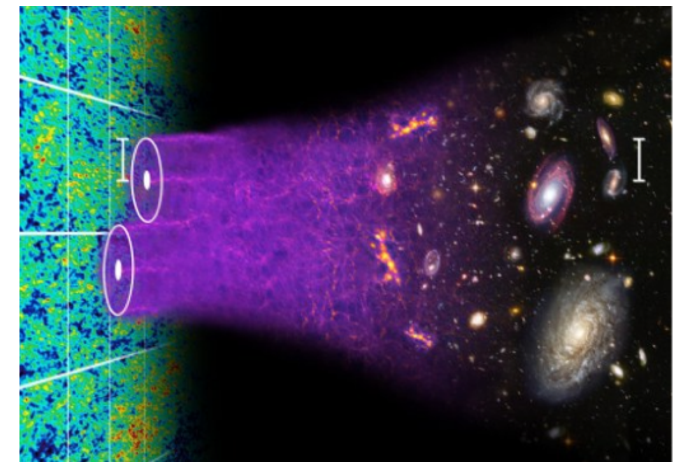
$$
B_\ell(\nu)^2 = \exp\left[\frac{-\ell(\ell+1)\theta_{\rm beam}(\nu)^2}{8\ln 2}\right]
$$

$$
\begin{aligned}
w_T(\nu) &= \frac{1}{[\theta_{\rm beam}(\nu)\sigma_T(\nu)]^2} \\
w_P(\nu) &= \frac{1}{[\theta_{\rm beam}(\nu)\sigma_P(\nu)]^2}
\end{aligned}
$$

The BAO

$$F_{ij} = \int_{\vec{k}_{\min}}^{\vec{k}_{\max}} \frac{\partial \ln P(\vec{k})}{\partial p_i} \frac{\partial \ln P(\vec{k})}{\partial p_j} V_{\mathrm{eff}}(\vec{k}) \frac{d\vec{k}}{2(2\pi)^3}$$
$$= \int_{-1}^{1} \int_{k_{\min}}^{k_{\max}} \frac{\partial \ln P(k,\mu)}{\partial p_i} \frac{\partial \ln P(k,\mu)}{\partial p_j} V_{\mathrm{eff}}(k,\mu) \frac{2\pi k^2 dk d\mu}{2(2\pi)^3}$$

M. Tegmark (1997)



$$P_{\mathrm{obs}}(k_\perp^{(\mathrm{ref})}, k_\parallel^{(\mathrm{ref})}) = \left(\frac{D_A^{(\mathrm{ref})}(z)}{D_A(z)}\right)^2 \left(\frac{H(z)}{H^{(\mathrm{ref})}(z)}\right) \times P_g(k_\perp, k_\parallel) + P_{\mathrm{shot}} ,$$

H. J. Seo and D. J. Eisenstein (2003)

$$V_{\mathrm{eff}}(k,\mu) = \left[\frac{\bar{n} P_g(k,\mu)}{1 + \bar{n} P_g(k,\mu)}\right]^2 V_{\mathrm{survey}}$$

Euclid specifications

area: 15000 $\deg^2$

redshift accuracy: $\sigma z/(1+z) = 0.001$

redshift range: $0.5 \le z \le 2.1$

Linear redshift space distortion parameter

Growth function

$$P_g(k_\perp^{(\mathrm{ref})}, k_\parallel^{(\mathrm{ref})}) = b^2(z)\left(1+\beta\mu^2\right)^2\left(\frac{G(z)}{G(z=0)}\right)^2 \times P_{\mathrm{matter},\, z=0}(k)\, e^{-k^2\mu^2\sigma_r^2}.$$

Galaxy bias

Exponential damping factor due to redshift uncertainties

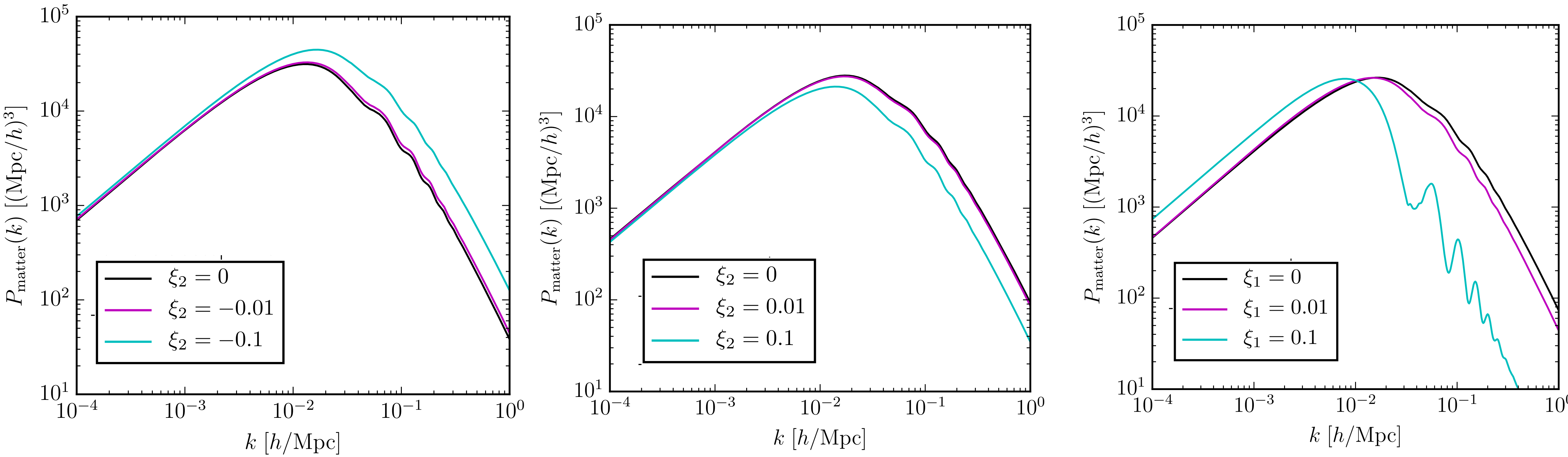
- We define $\mu \equiv \mathbf{k}\cdot\hat{\mathbf{r}}/k$, where **r** is the unit vector along the line of sight

- The wavenumbers across and along the line of sight in the true cosmology are denoted by $k_\perp$ and $k_\parallel$

- They are related to the ones in the reference cosmology by $k_\perp^{(\mathrm{ref})} = k_\perp D_A(z)/D^{(\mathrm{ref})}(z)$ and $k_\parallel^{(\mathrm{ref})} = k_\parallel H^{(\mathrm{ref})}(z)/H(z)$.

- The set of parameters of interest to obtain constraints on the dark sector is

$$\{\omega_{\rm b} \equiv h^2\Omega_{\rm b}, \omega_{\rm c}, h, H(z_i), D_A(z_i), G(z_i), \beta(z_i), P^i_{\rm shot}\}$$



- Finally, we must derive the errors on H(z) and $D_A(z)$ to later propagate them into the desired dark sector parameters for the interacting DE models.

$$F_{mn}^{\mathrm{DE}} = \sum_{\alpha,\,\beta} \frac{\partial p_\alpha}{\partial q_m} F_{\alpha\beta}^{(\mathrm{sub})} \frac{\partial p_\beta}{\partial q_n} \,,$$

- The final set of parameters are

$$\mathcal{Q} = \{\omega_{\mathrm{b}}, \omega_{\mathrm{c}}, h, w_{\mathrm{DE}}, \xi_2\}$$ For models 1 and 2

$$\mathcal{Q} = \{\omega_{\mathrm{b}}, \omega_{\mathrm{c}}, h, w_{\mathrm{DE}}, \xi_1\}$$ For model 3

Combined forecast

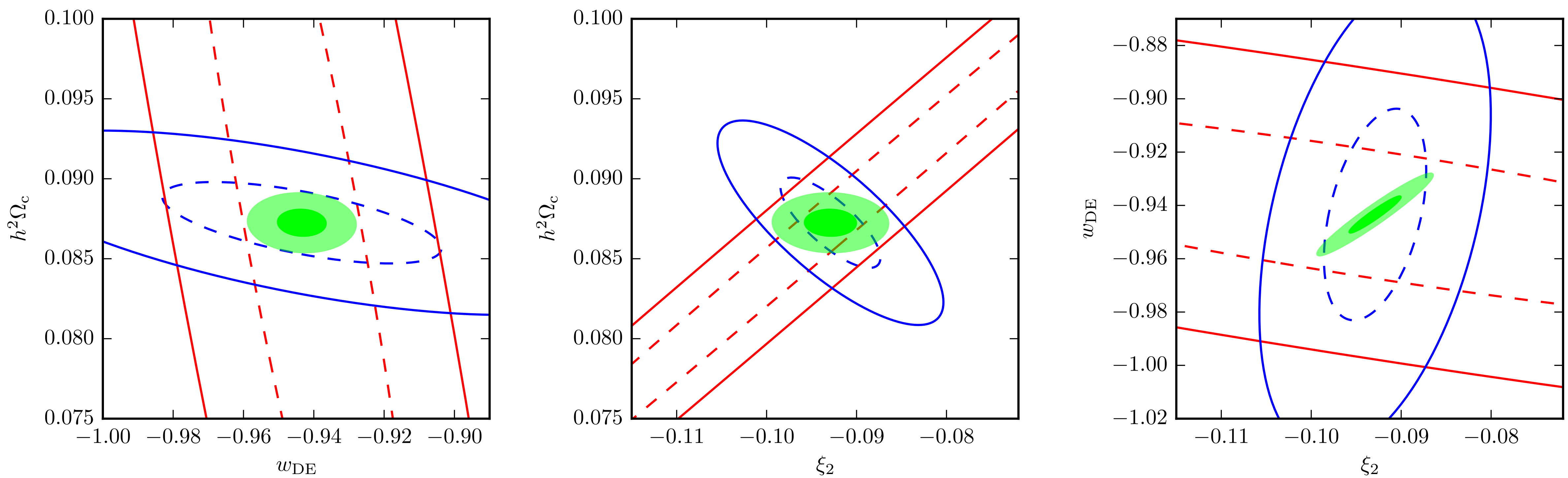
$$F_{ij}^{\mathrm{total}} = F_{ij}^{\mathrm{BAO}} + F_{ij}^{\mathrm{CMB}}$$

- Future generation of astronomical ground- and space-based experiments as well as future CMB experiments will be able to precisely perform consistency tests of the ΛCDM model and significantly improve constraints on alternative scenarios, including the interacting DE models.

- We aim to test the ability of the BAO information obtained from an updated Euclid-like experiment and the primary CMB fluctuations from a possible future experiment like AdvACT to constrain the phenomenological interacting DE models described here and determine how their combination can help break the degeneracies between the different cosmological parameters.

Results: model 1

Parameter	Fiducial value	AdvACT (CMB)	Euclid (BAO)	AdvACT + Euclid
$\omega_{\rm b}$	0.02224	3.86e-05	0.00028	3.69e-05
$\omega_{\rm c}$	0.08725	0.017	0.0017	0.00053
h	0.6845	0.0079	0.0055	0.0014
$w_{\rm DE}$	-0.9434	0.028	0.026	0.0044
ξ_2	-0.0929	0.045	0.0037	0.0019



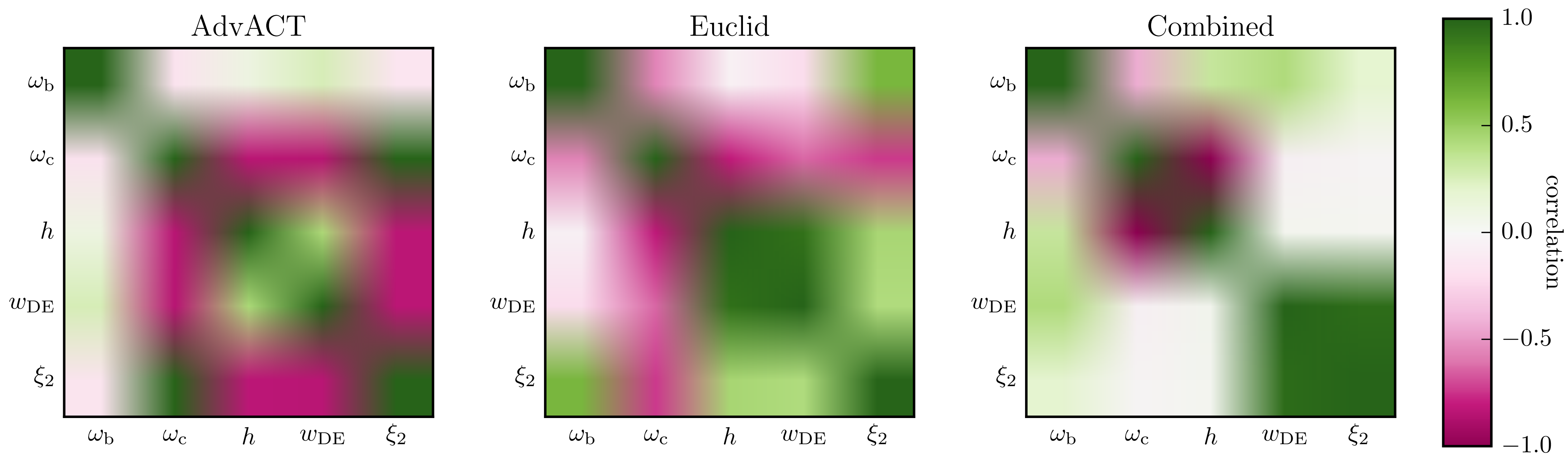
- Present constraints are found to be

$$\omega_c = 0.0792^{+0.0348}_{-0.0166} \qquad \omega_{DE} = -0.9191^{+0.0222}_{-0.0839} \qquad \xi_2 = -0.1107^{+0.085}_{-0.0506}$$

- We notice that the marginalized error for the dark sector parameters would be drastically improved for such combined forecast, being $\sigma(\omega_c) = 0.00053$, $\sigma(w_{DE}) = 0.0044$ and $\sigma(\xi_2) = 0.0019$

- Let's introduce the correlation matrix, which measures the correlation between two parameters

$$\rho_{ij} = \frac{\mathrm{Cov}_{ij}}{\sqrt{\mathrm{Cov}_{ii}\mathrm{Cov}_{jj}}} \quad \text{where} \quad \mathbf{Cov} \equiv \mathbf{F}^{-1}$$



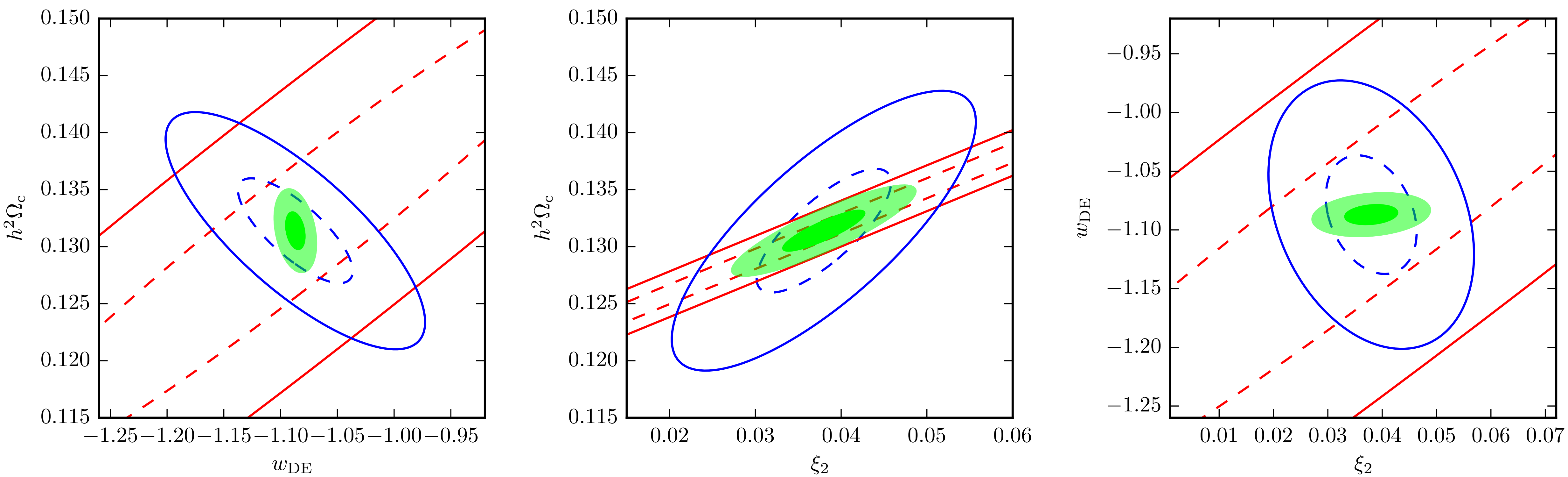
- For CMB information alone, we can see that the correlation between w_{DE} and ξ_2 is 0.8 (in absolute value) and it is very large (≈ 1) between ω_c and ξ_2 .

- These degeneracies are considerably weakened when BAO information is added.

- The correlations between ω_c and ξ_2 and between ω_c and w_{DE} are reduced to ≈ −0.026 and ≈ −0.059, respectively, for the combined forecast (AdvACT + Euclid).

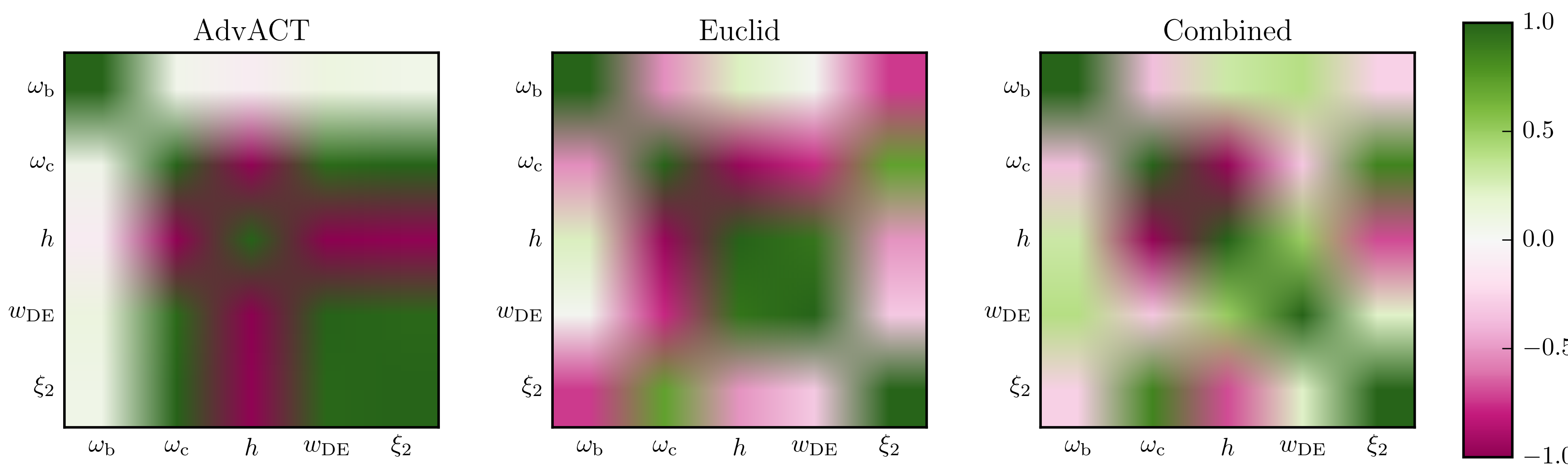
Results: model 2

Parameter	Fiducial value	AdvACT (CMB)	Euclid (BAO)	AdvACT + Euclid
$\omega_{\rm b}$	0.02229	3.85e-05	0.00022	3.76e-05
$\omega_{\rm c}$	0.1314	0.015	0.0030	0.0010
h	0.6876	0.075	0.0068	0.0019
$w_{\rm DE}$	-1.087	0.19	0.033	0.0053
ξ_2	0.03798	0.055	0.0055	0.0031



- The combined forecast leads to stringent constraints on ω_c, w_{DE}, and ξ_2, the latter being $\sigma(\xi_2) = 0.00310$.

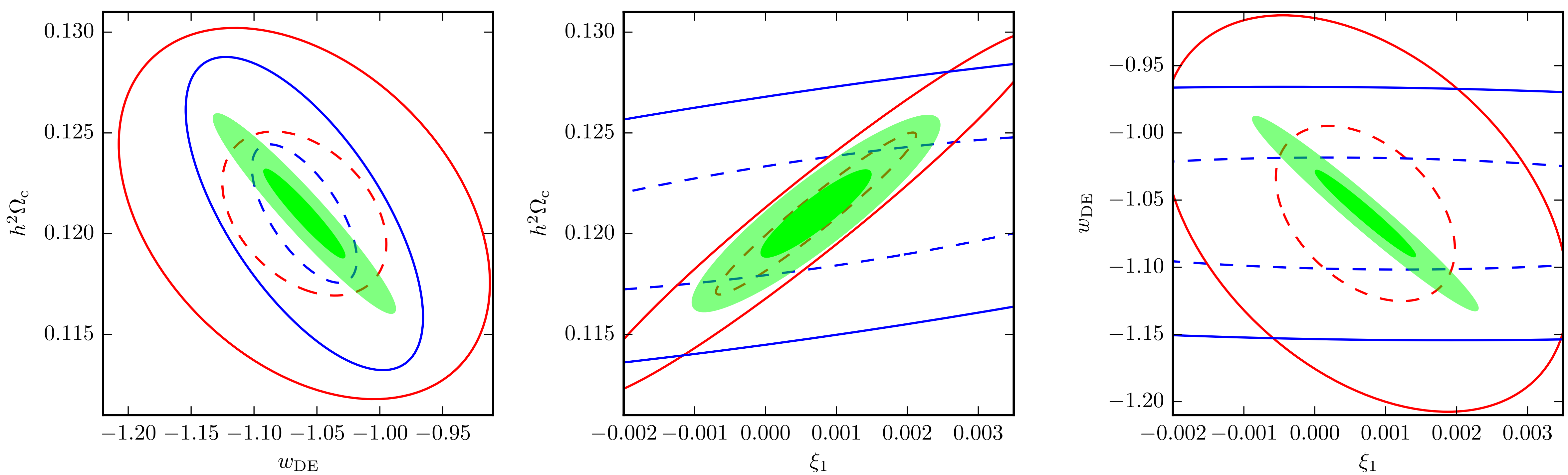
- Present constraints $\xi_2 = 0.02047^{+0.00565}_{-0.00667}$ are improved by a factor of ~ 2



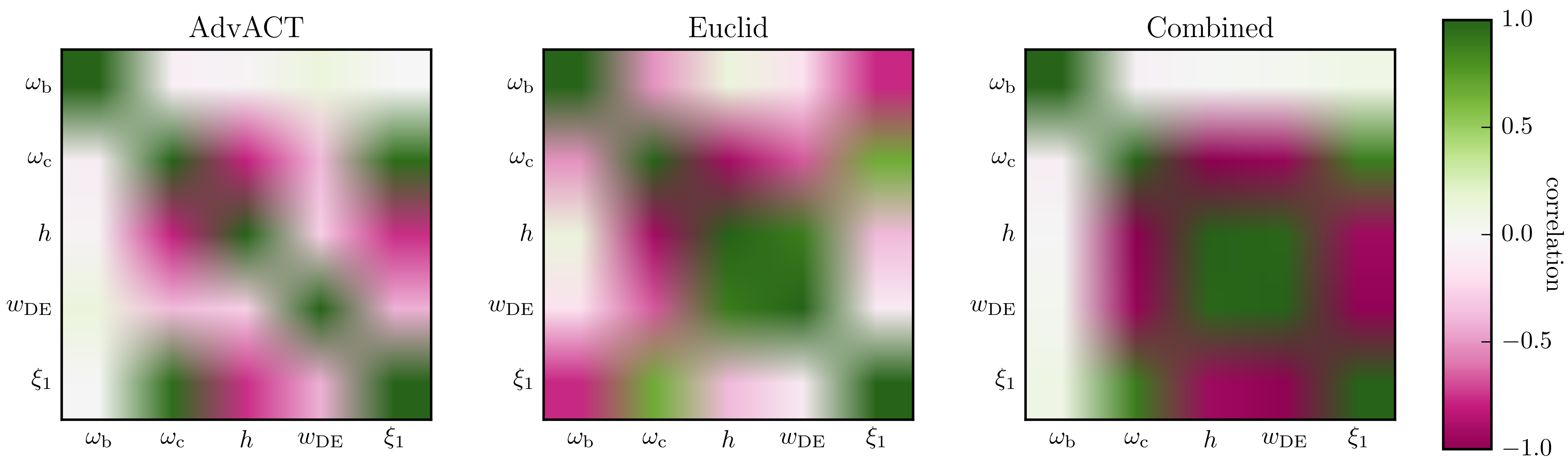
- All the correlations become milder for the combined analysis, and this happens for all the degenerate parameters w_{DE}, ξ_2, and ω_c almost equally.

Results: model 3

Parameter	Fiducial value	AdvACT (CMB)	Euclid (BAO)	AdvACT + Euclid
ω_{b}	0.02232	3.83e-05	0.00021	3.59e-05
ω_{c}	0.121	0.0027	0.0022	0.0014
h	0.6793	0.018	0.0055	0.0041
w_{DE}	-1.06	0.043	0.027	0.021
ξ_1	0.0007127	0.00083	0.00400	0.00046



- CMB plays an important role in constraining ξ_1, revealing that the interaction between DE and DM is already well constrained by CMB data before the inclusion of information about H(z) evolution



- For model 3, w_{DE} and ξ_1 are not degenerate at present times.

  - BAO does not help a lot to break remaining degeneracies.

Conclusions

- For models 1 and 2
  - Since the interaction is proportional to the DE energy density, stringent constraints were found in the dark sector parameters for the combined probes, especially for the coupling constant.
  - The combination of future CMB and BAO experiments, such as presented here, would probably be able to exclude the null interaction
  - Degeneracies, which limits the constraining power of CMB information alone, can be broken by the addition of Euclid-like BAO measurements

- For model 3
  - The interaction, proportional to the DM energy density, is not improved as much by the combination of future CMB and BAO experiments compared with its constraint derived by present datasets.
  - Extra information is still necessary for probing this model, and one could consider introducing the CMB lensing power spectra (possibly including higher order corrections) and/or the convergence power spectrum from weak cosmic shear