# On the dark contents of the Universe: a Euclid survey approach

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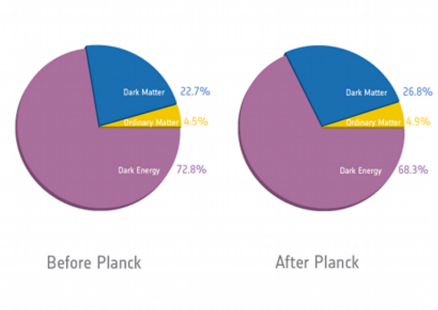
# Introduction

**Current standard model in cosmology: $\Lambda$CDM model.**




**Good phenomenological fit to current cosmological data:**

- SNIa (Perlmutter et al. 1999; Riess et al. 1998)
- BAO (Anderson et al. 2014; Ross et al. 2015)
- $P(k)$ (Gil-Marín et al. 2015)
- CMB (Planck Collaboration et al. 2015a)

# Introduction

**Many sources of constraints:**

- Galaxy rotation curves (Persic et al. 1996)
- Gravitational-lensing (Lefor et al. 2013)
- Halo properties (Moore 1994; Jee et al. 2014)
- CMB and LSS data (Yang 2015)

**But no direct detection of DM, neither of DE as a Cosmological Constant.**

$\Rightarrow$ There is room for studying models departing from this ideal case.

# Dark Content(s) of the Universe

## Models under study

**General assumptions:**

- Flat Universe
- FLRW metric
- $P_i = w_i \rho_i$, with $w_i$ constant for $i =$ DM, DE
- Non-interacting fluids
- Fixed radiation contribution:

$$\Omega_r = \Omega_\gamma (1 + 0.2271 N_{eff} f)$$

with $N_{eff} = 3.046$, $\Omega_\gamma = 2.469 \times 10^{-5} h^{-2}$ and $f = \left(1 + \left(0.3173 \cdot 187 \times 10^3 \left(\frac{m_\nu}{94}\right)\left(\frac{1}{1+z}\right)\right)^{1.83}\right)^{\frac{1}{1.83}}$ (Komatsu et al. 2011)

# Dark Content(s) of the Universe

## Models under study

$w$**CDM model:** Accounting for DE with $w \neq -1$ (but constant).

$$\frac{H^2(z)}{H_0^2} = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + (1-\Omega_r-\Omega_m)(1+z)^{3(1+w)}$$

$\epsilon$**CDM model:** Accounting for DM with $w \neq 0$ (but constant).

$$\frac{H^2(z)}{H_0^2} = \Omega_r(1+z)^4 + \Omega_b(1+z)^3 + (\Omega_m-\Omega_b)(1+z)^{3(1+\epsilon)} + (1-\Omega_r-\Omega_m)$$

$w\Lambda$**CDM model:** Accounting for an extra DE term with a constant eq. of state parameter $w_{DE'}$.

$$\frac{H^2(z)}{H_0^2} = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_{DE'}(1+z)^{3(1+w_{DE'})} + (1-\Omega_r-\Omega_m-\Omega_{DE'})$$

$\epsilon w$**CDM model:** Accounting for $w_{DM} \neq 0$ and $w_{DE} \neq -1$ (but both constant).

$$\frac{H^2(z)}{H_0^2} = \Omega_r(1+z)^4 + \Omega_b(1+z)^3 + (\Omega_m-\Omega_b)(1+z)^{3(1+\epsilon)} + (1-\Omega_r-\Omega_m)(1+z)^{3(1+w)}$$

# Dark Content(s) of the Universe

## Method and data samples

**Method:**

- $\chi^2$ minimization (using MIGRAD from MINUIT) to determine the constraints on the parameters:

$$\chi^2 = (\mathbf{u} - \mathbf{u}_{data}) C^{-1} (\mathbf{u} - \mathbf{u}_{data})^T$$

- $\mathbf{u}$ is the vector of the compressed likelihood parameters for the cosmological probe.
- Combining probes: we minimize the sum of the corresponding $\chi^2$ functions.

**SNIa:**

- Sample of 740 SNIa from SDSS, SNSL and HST (Betoule et al. 2014).
- To use a reduced sample for the compressed likelihood:

$$\chi^2 = \mathbf{r} C_b^{-1} \mathbf{r}^T$$

with $\mathbf{r} = \boldsymbol{\mu}_b - M - 5\log_{10} D_L(\mathbf{z}_b)$, where $\boldsymbol{\mu}_b$ is the vector of distance modulus at the binned redshifts $\mathbf{z}_b$, $M$ is a free normalization parameter, $C_b$ is the covariance matrix of $\boldsymbol{\mu}_b$ and $D_L$ is the luminosity distance.

# Dark Content(s) of the Universe

## Method and data samples

**BAO:**

- We analyze it through:

$$d_z = \frac{r_s(z_{drag})}{D_v(z)}, \quad \text{with} \quad D_v(z) = \left((1+z)^2 D_A^2 \frac{cz}{H(z)}\right)^{1/3}$$

  - $D_A$ is the angular-diameter distance.
  - $z_{drag}$ is the redshift at which the baryons released from the Compton drag of the photons in terms of a weighted integral over the Thomson scattering rate (Eisenstein & Hu 1998).
  - $r_s(z_{drag}) = \int_{z_{drag}}^{\infty} \frac{c_s(z)\,\mathrm{d}z}{H(z)}$, where $c_s(z) = c(3(1+R_b(z)))^{-1/2}$ and $R_b(z) = 3\rho_b/(4\rho_\gamma)$

- We use BAO measurements at $z = 0.106$, $z = 0.35$ and $z = 0.57$ (Beutler et al. 2011, Padmanabhan et al. 2012, Anderson et al. 2012).

**CMB:**

- We consider the following parameters (Wang & Mukherjee 2007):
  - Scaled distance to recombination: $R \equiv \sqrt{\Omega_m H_0^2} \int_0^{z_{CMB}} \frac{\mathrm{d}z}{H(z)}$, where $z_{CMB}$ is the redshift of the last scattering epoch (Hu & Sugiyama 1996).
  - Angular scale of the sound horizon at recombination: $l_a \equiv \pi \frac{\int_0^{z_{CMB}} \frac{\mathrm{d}z}{H(z)}}{r_s(z_{CMB})}$
  - Reduced density parameter of the baryons: $\omega_b \equiv \Omega_b h^2$
- We use Planck data plus lensing information (Wang & Wang 2013).

**$\epsilon$CDM and $\epsilon w$CDM models:**

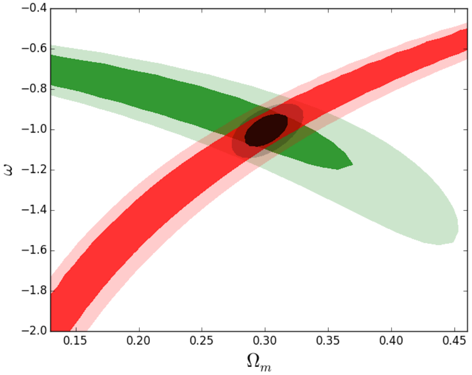
We modify the matter component and it has an extremely important role in the CMB-era $\Rightarrow$ we adapt the computation of the corresponding parameters:

- $z_{CMB}$ and $z_{drag}$: we change $(\Omega_m - \Omega_b) \rightarrow (\Omega_m - \Omega_b)(1 + z_{CMB})^{3\epsilon} \approx (\Omega_m - \Omega_b)(10^3)^{3\epsilon}$
- $R = \sqrt{(\Omega_b + (\Omega_m - \Omega_b)(1 + z_{CMB})^{3\epsilon})H_0^2} \int_0^{z_{CMB}} \frac{\mathrm{d}z}{H(z)}$

# Dark Content(s) of the Universe

## Results

**$w$CDM model:**



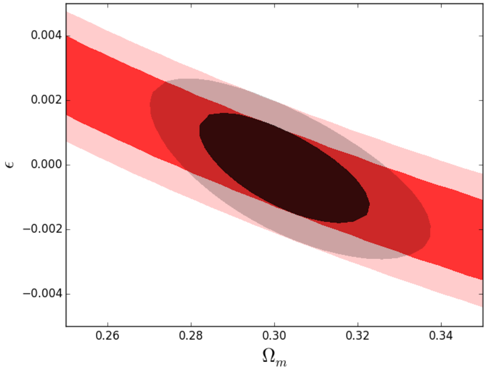

- Contours at 68% and 95% ($\Delta\chi^2 = 2.30$, $\Delta\chi^2 = 6.17$, respectively).
- Marginalization over $H_0$ and $\omega_b$.
- Main constraints come from the CMB (red) and the SNIa (green).
- Consistent with Betoule et al. 2014 with slightly smaller errors.

$$\Omega_m = 0.300 \pm 0.012, \quad w = -1.003 \pm 0.055$$

# Dark Content(s) of the Universe

## Results

### $\epsilon$CDM model:



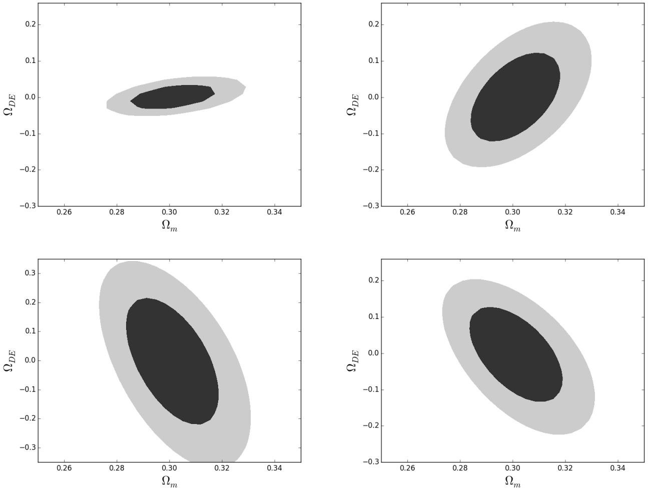

- Contours at 68% and 95% ($\Delta\chi^2 = 2.30$, $\Delta\chi^2 = 6.17$, respectively).
- Marginalization over $H_0$ and $\omega_b$.
- Main constraint comes from the CMB (red).
- No correlation between $\omega_b$ and $\epsilon$.

$$\Omega_m = 0.301 \pm 0.014, \;\; \epsilon = -0.0001 \pm 0.0011$$

# Dark Content(s) of the Universe

## Results

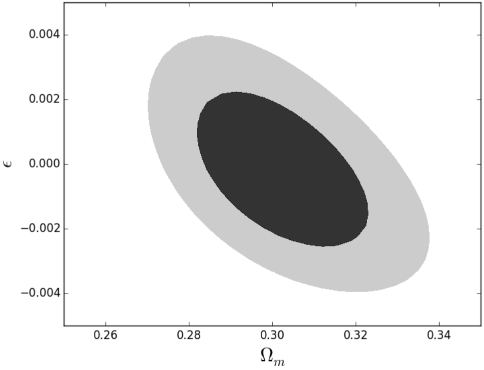
**$w\Lambda$CDM model:**



# Dark Content(s) of the Universe

## Results

**$\epsilon w$CDM model:**



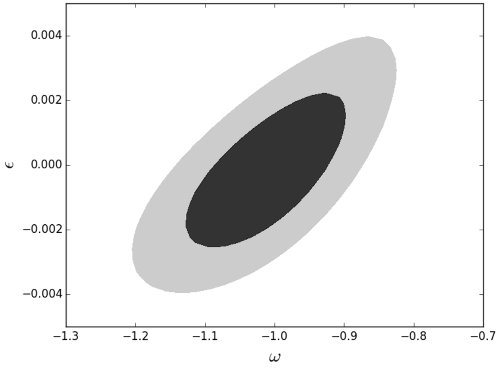

- Contours at 68% and 95% ($\Delta\chi^2 = 2.30$, $\Delta\chi^2 = 6.17$, respectively).
- Marginalization over $H_0$, $\omega_b$ and $w$.
- Slightly larger error for $\epsilon$ than in the $\epsilon$CDM model (introduction of the $w$ d.o.f.).

$$\Omega_m = 0.302 \pm 0.014, \;\; \epsilon = -0.0003 \pm 0.0016$$

# Dark Content(s) of the Universe

## Results

**$\epsilon w$CDM model:**




- Contours at 68% and 95% ($\Delta\chi^2 = 2.30$, $\Delta\chi^2 = 6.17$, respectively).
- Marginalization over $H_0$, $\omega_b$ and $\Omega_m$.
- Slightly larger error for $w$ than in the $w$CDM model (introduction of the $\epsilon$ d.o.f.).

$$w = -1.011 \pm 0.077, \;\; \epsilon = -0.0003 \pm 0.0016$$

**Main conclusion:** All the presented models are compatible with the ΛCDM model, but it is clear that the assumptions made on the dark matter sector ($\epsilon$ parameter) are not independent of the assumptions on the dark energy sector ($w$ parameter).

**Idea:** Galaxy power spectrum Euclid survey forecast using a Fisher matrix formalism in a parameterized cosmological model, considering $H(z)$ and $D_A(z)$ as observables.

**Forecast construction:**

- Matter power spectrum (Amendola et al. 2013):
  $P_{\rm matter}(k,z) = \frac{8\pi^2 c^4 k_0 \Delta_R^2(k_0)}{25 H_0^4 \Omega_m^2} T^2(k) \left[\frac{G(z)}{G(z{=}0)}\right]^2 \left(\frac{k}{k_0}\right)^{n_s}$
- Observed power spectrum (Seo & Eisenstein 2003):
  $P_{\rm obs}(k_\perp, k_\parallel, z) = \frac{D_A(z)^2_{\rm ref} H(z)}{D_A(z)^2 H(z)_{\rm ref}} P_g(k_\perp, k_\parallel, z) + P_{\rm shot}$, with
  $P_g(k_\perp, k_\parallel, z) = b(z)^2 \left[1 + \beta(z) \frac{k_\parallel^2}{k_\parallel^2 + k_\perp^2}\right] P_{\rm matter}(k,z)$

**Forecast construction:**

- Fisher matrix for a given redshift interval (Tegmark 1997):
$F_{ij} = \int_{-1}^{1} \int_{k_{\rm min}}^{k_{\rm max}} \frac{\partial \ln P_{\rm obs}(k,\mu)}{\partial p_i} \frac{\partial \ln P_{\rm obs}(k,\mu)}{\partial p_j} V_{\rm eff}(k,\mu) \frac{2\pi k^2 \, {\rm d}k \, {\rm d}\mu}{2(2\pi)^3}$, with
$V_{\rm eff}(k,\mu) = \int \left[ \frac{n(\mathbf{r})P(k\mu)}{n(\mathbf{r})P(k,\mu)+1} \right]^2 {\rm d}\mathbf{r} = \left[ \frac{nP(k,\mu)}{nP(k,\mu)+1} \right]^2 V_{\rm survey}$
- Propagate the Fisher matrix from observables $p_i$, $p_j$ to parameters $q_\alpha$, $q_{\alpha'}$ (Wang et al. 2010): $F_{\alpha\alpha'} = \sum_{ij} \frac{\partial p_i}{\partial q_\alpha} F_{ij} \frac{\partial p_j}{\partial q_{\alpha'}}$
- The Fisher matrix for all the redshift range is the sum of all the Fisher matrices.
- The inverse of the resulting Fisher matrix gives us the errors and the correlations on the parameters.

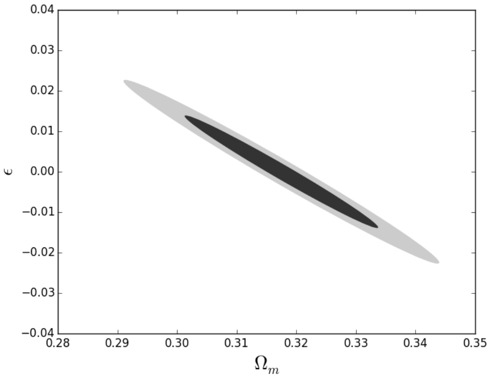
**Forecast construction for the Euclid survey:**

- 5 parameters: $z_{\rm min} = 0.7$, $z_{\rm max} = 2.1$, area=15000 sq. deg, $N = 50 \times 10^6$ galaxies, $\sigma_z/(1+z) \leq 0.1\%$ (Laureijs et al. 2011).
- Reference cosmology: Planck 2014.
- Bias evolution: $b(z) = \sqrt{1+z}$ (Amendola et al. 2013).
- Bin width: 0.1 in redshift.
- $k_{\rm min} = 0$ and $k_{\rm max}$ interpolated from Seo & Eisenstein 2003.

# Dark Content(s) of the Universe: a Euclid Forecast

## Results

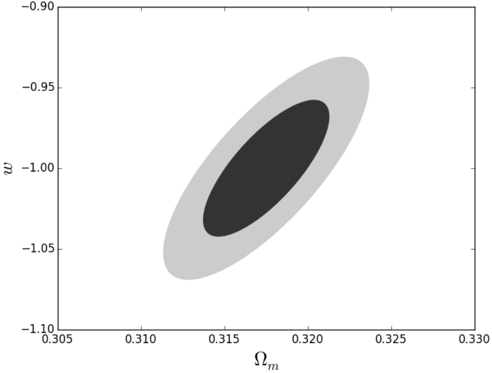
**$\epsilon$CDM model:**




- Contours at 68% and 95%.
- Marginalization over $H_0$. $\omega_b$ fixed at the reference value.
- Larger error for $\epsilon$ than in present-day data (we do not account for the most constraining probe: the CMB).

$$\Omega_m = 0.318 \pm 0.011, \;\; \epsilon = 0.0000 \pm 0.0092$$

## $w$CDM model:



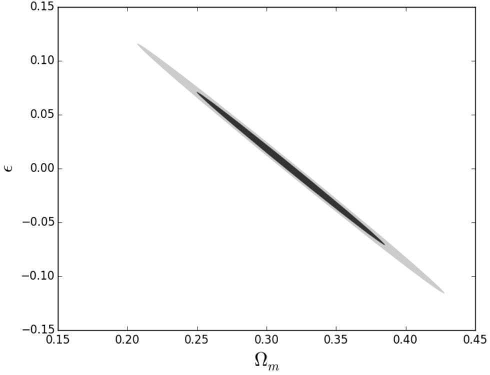

- Contours at 68% and 95%.
- Marginalization over $H_0$.
- Smaller errors than in present-day data even only considering the BAO for the forecast.

$$\Omega_m = 0.3175 \pm 0.0025, \;\; w = -1.000 \pm 0.028$$

# Dark Content(s) of the Universe: a Euclid Forecast

## Results

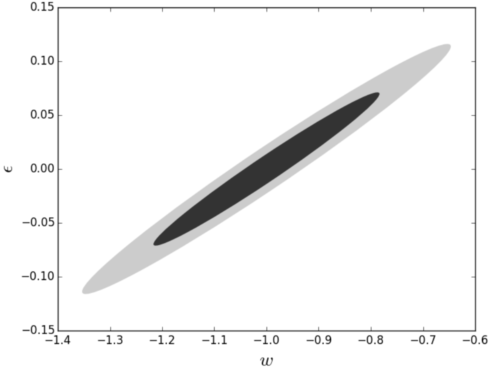
### $\epsilon w$CDM model:




- Contours at 68% and 95%.
- Marginalization over $H_0$ and $w$. $\omega_b$ fixed at the reference value.
- Larger errors than in present-day data (we do not consider the CMB).

$$\Omega_m = 0.318 \pm 0.045, \;\; \epsilon = 0.000 \pm 0.047$$

## $\epsilon w$CDM model:




- Contours at 68% and 95%.
- Marginalization over $H_0$ and $\Omega_m$. $\omega_b$ fixed at the reference value.
- Larger errors than in present-day data (we do not consider the CMB).

$$w = -1.00 \pm 0.14, \;\; \epsilon = 0.000 \pm 0.047$$

**Main conclusions:**

- The dark matter and the dark energy sectors are still not uncoupled.
- The **estimated** constraint on $w_{DE}$ is very poor if we allow $w_{DM} \neq 0$. $\Rightarrow$ Two options for the Euclid survey: assume $\epsilon = 0$ or add CMB information.

# Alternative Description of the Dark Sector

**Gravity probes only the total energy-momentum tensor, which leads to a degeneracy for generalized dark energy models. Because of it, the matter density parameter cannot be measured** (Kunz 2009).

- We only measure $H(z)$ and $\Omega_k$ (geometrical analyses (Zolnierowski & Blanchard 2015)).
- $\rho$ is obtained from their difference (assuming GR) $\Rightarrow$ we cannot distinguish observationally the components of a $\rho$ parameterization.

# Alternative Description of the Dark Sector

**New approach:**

$$\rho(a) = a^{-4} \sum_{n \geq 0} \alpha_n a^n$$

- Theoretically motivated: $\rho$ treatment as a whole + $\alpha_n$ reinterpretation ($\Omega_r$, $\Omega_m$, $\Omega_\Lambda$).
- $w > 0$ components killed by the CMB.
- All $\rho$ models proposed can be approximated by a polynomial $\Rightarrow$ new approach still general.

# Alternative Description of the Dark Sector

Direct testing:

**Present-day data (marginalization over $\omega_b$ and $H_0$):**

- $\alpha_1, \alpha_4 \to (\Omega_m, \Omega_\Lambda) \to$ ΛCDM: OK
- $\alpha_1, \alpha_2, \alpha_4 \to (\Omega_m, \Omega_{w=-1/3}, \Omega_\Lambda)$: OK
- $\alpha_1, \alpha_2, \alpha_3, \alpha_4 \to (\Omega_m, \Omega_{w=-1/3}, \Omega_{w=-2/3}, \Omega_\Lambda)$:

$$\alpha_1 = 0.300 \pm 0.012 \quad \alpha_2 = 0.011 \pm 0.074 \quad \alpha_3 = -0.04 \pm 0.27$$

- $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5 \to (\Omega_m, \Omega_{w=-1/3}, \Omega_{w=-2/3}, \Omega_\Lambda, \Omega_{w=-4/3})$: degenerate

**Euclid Forecast (marginalization over $H_0$):**

- $\alpha_1, \alpha_2, \alpha_3, \alpha_4$:

$$\alpha_1 = 0.318 \pm 0.064 \quad \alpha_2 = 0.00 \pm 0.34 \quad \alpha_3 = 0.00 \pm 0.68$$

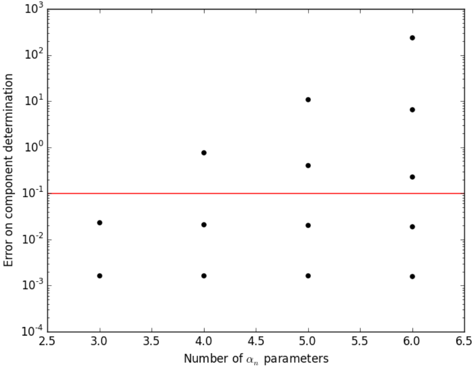
- $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$: degenerate

# Alternative Description of the Dark Sector

## PCA Approach for the Euclid Forecast:

**Main idea:** Select only the best determined components coming from a linear combination of the $\alpha_n$ parameters.

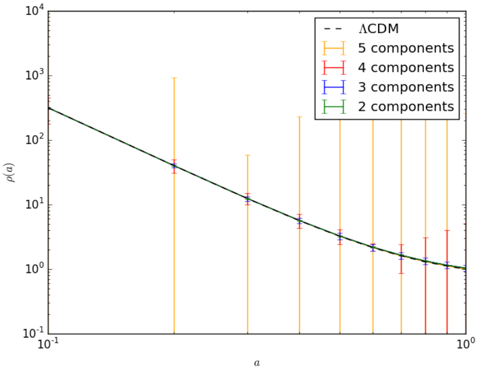
- Select the eigenvectors of the $\alpha_n$ covariance matrix with the lowest eigenvalues and reconstruct $\rho(a)$ with them.



# Alternative Description of the Dark Sector

## PCA Approach for the Euclid Forecast:

**ΛCDM input:**

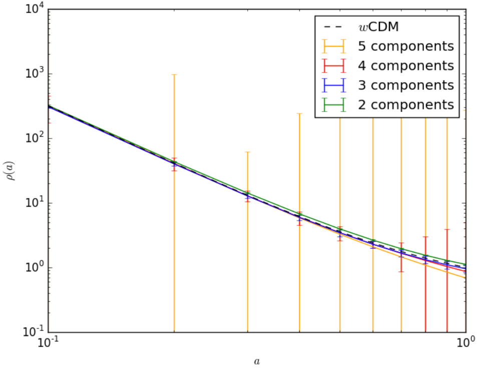



- Errors obtained from bootstrap ($10^4$ iterations).
- More components ⇒ Larger errors (allowing bad-constrained components).
- 2 principal components ⇒ Good reconstruction.

# Alternative Description of the Dark Sector

## PCA Approach for the Euclid Forecast:

**$w$CDM input ($w = -0.8$):**




- Least squares fit to obtain a polynomial approximation to the $w$CDM $\rho$ (error below 0.03%).
- Bias in the 2 component reconstruction (PCA problem).
- Good reconstruction with 3 components.

# Conclusions

- The assumptions done on the dark matter sector are not independent of the ones done on the dark energy sector.
- We can only measure $\rho$ from cosmological observations (Kunz 2009).
- We propose a theoretically motivated decomposition for $\rho$ which treats it as a whole.
- Our decomposition leads us to reconstruct the input $\rho$ in a galaxy power spectrum Euclid forecast with good precision through a PCA approach.