# Constraining parameters of general dark energy models in the non-linear regime.

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**Gravity at the Largest Scales, Heidelberg, 28.10.2015**

# Motivation

- Future LSS probes:
- Euclid, positions, shapes and spectroscopic redshifts of ~$10^7$ galaxies over 15,000 sq.deg. Many more photometric z.

- SKA2 and LSST, allegedly 30,000 sq.deg and provide $10^9$ redshifts. Intensity mapping is a promising method. Deep, wide, sample variance-limited surveys.

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- → Predict interesting features at the nonlinear level of structure formation.
- Either test these signatures by N-body simulations and then fitting functions or calculating perturbatively the non-linear power spectrum.
- → On the way there we have to understand much more about systematics, bias and baryonic features.

# Outline

- **Working on an interface between simulations, perturbation theory and forecasts for future LSS surveys.**

**Main topic of the talk:**

- Coupled DE models, fitting functions for the non-linear PS.
- → Improve forecasts on the coupling parameter, using information from N-body simulations[1].
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- Clustered structures affect the background evolution[2].

**[1]S.C, L.A, V.P., Marco Baldi, A.V, 1508.07208; col.: [2]C.Wetterich, F.Führer; [3]M.Pietroni; [4]M.Kunz, M.Martinelli**

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- Fisher forecasts for Euclid and LSS probes, testing several models of DE, scale-dependence[4] , code comparisons and Fisher Taylor expansions.

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- Let's take the N-body simulations we have available and create fitting functions, which then can be used in forecasts.
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- The caveat is that we have to be careful with numerical and theoretical uncertainties.

→ Show that even being very conservative, we can improve, by more than one order of magnitude, the present constraints on the coupling.

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# Short review on coupled quintessence

- Dark Matter is coupled to a scalar field through its mass

$$S=\int d^4x \sqrt{-g} \left[\frac{1}{16\pi G} R + -\frac{1}{2} g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi) - m(\phi)\overline{\psi}\psi + \mathcal{L}_{kin,\psi}\right]$$

- Mass of DM particles depends on value of field, this defines the coupling strength as:

$$Q(\phi) = -\frac{d\ln m(\phi)}{d\phi}$$

- Baryons are not coupled, radiation is traceless. Total $T_{\mu\nu}$ is conserved:

$$\nabla_\mu T^\mu_{\nu(c)} = +Q_c(\phi)T_{(c)}\nabla_\nu\phi \ , \ \nabla_\mu T^\mu_{\nu(b)} = 0 \ , \ \nabla_\mu T^\mu_{\nu(\phi)} = -Q_c(\phi)T_{(c)}\nabla_\nu\phi$$

- We use an exponential potential and assume a constant coupling:

$$V(\phi) = V_0 e^{-\alpha\phi} \qquad \beta = \sqrt{3/2}Q$$

- Interesting background tracking solutions, helps to alleviate the coincidence problem and predicts characteristic features at the perturbative level.

# CQ at the perturbation level

- Effective gravitational constant affecting only DM particles:

$$\tilde{G}_{CQ} = G_N(1 + 2\beta^2)$$

- Modified Hubble friction term in the Euler equation:

$$\tilde{H}\mathbf{v} = H(1 - \beta\dot{\phi}/H)\mathbf{v}$$

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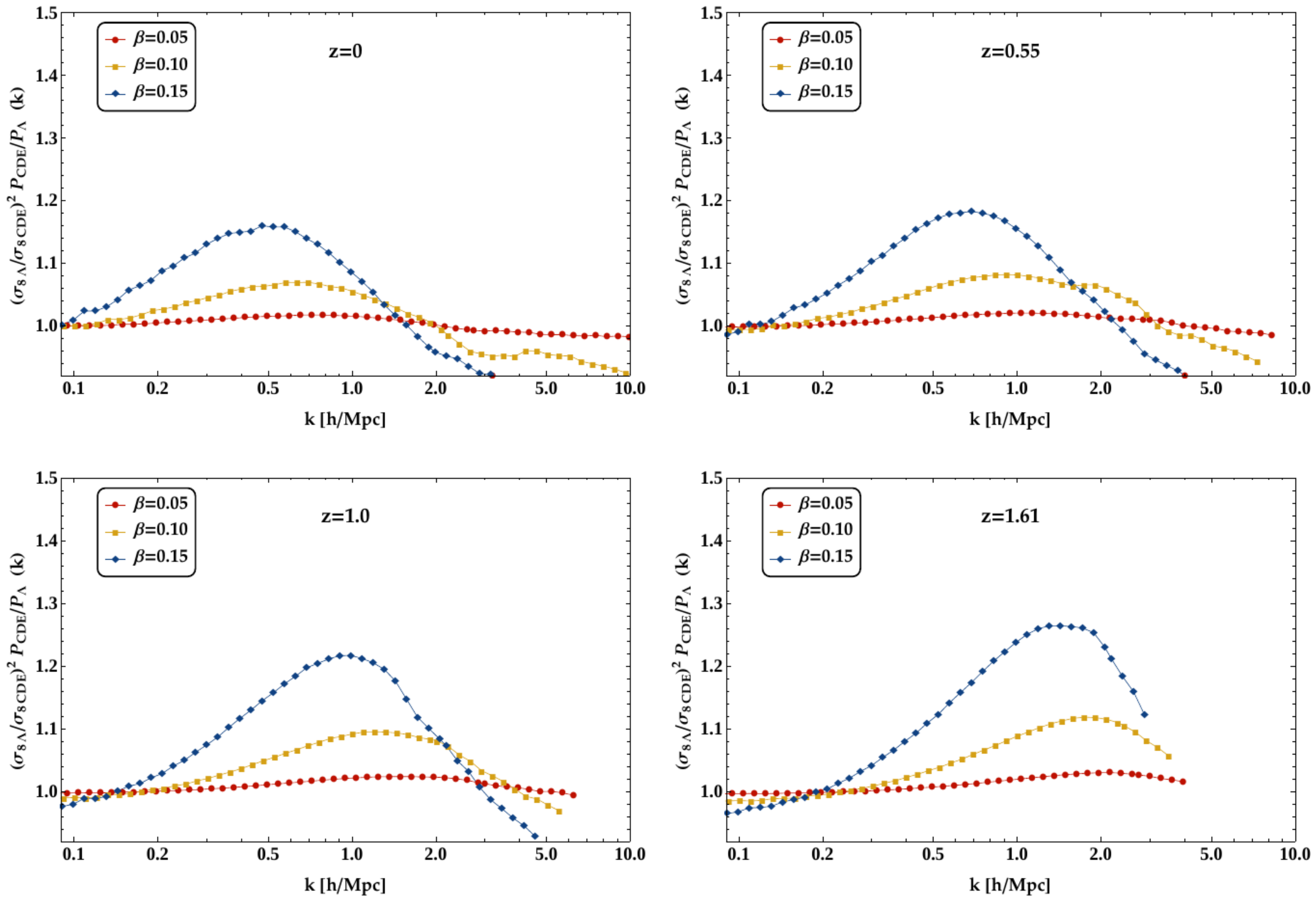
**This has been implemented in N-body simulations, yielding interesting results for modified structure formation:**

- Gravitational bias between baryons and DM at the linear level, decreasing baryon fraction in halos.
- Increase of number density of high-mass objects compared to $\Lambda CDM$ at all z.
- Lower concentration of halos, emptier voids
- Modifications of the small scale power spectrum

See among others: Maccio et al. (2004), Baldi et al. (2010), Li et al. (2011), Carlesi et al. (2014)

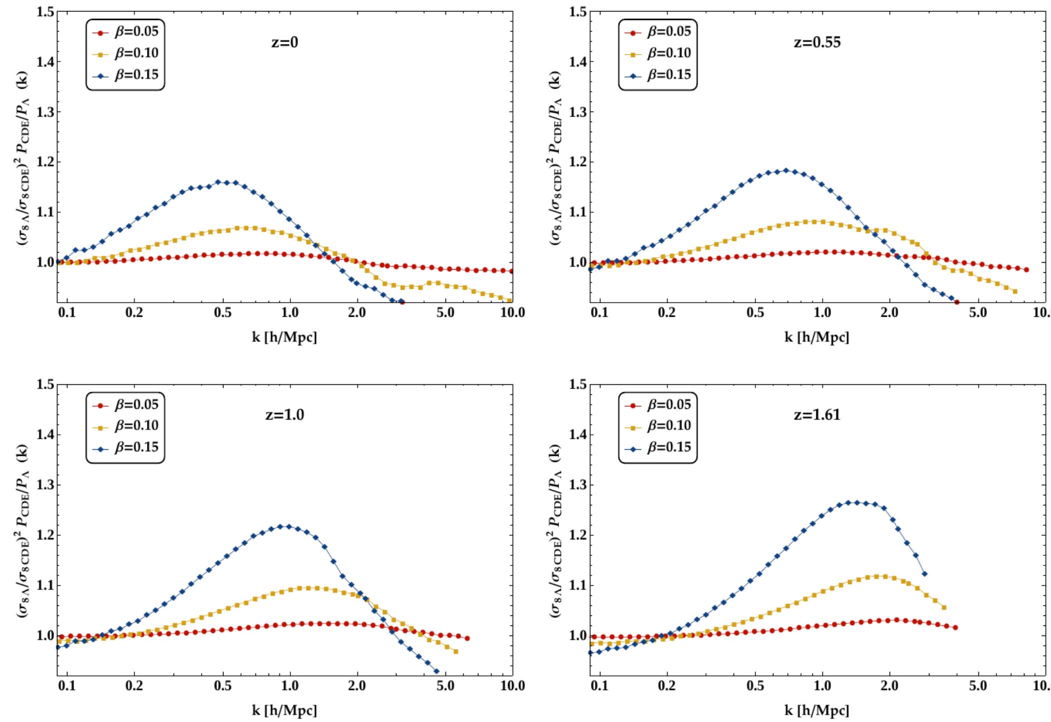
# The nonlinear power spectrum in CQ



# The nonlinear power spectrum in CQ

- After normalizing to the same $\sigma 8$ , compared to $\Lambda CDM$ there is a “bump” that increases its amplitude with increasing coupling while its maximum locates at smaller scales for higher redshifts.

**We want to use this characteristic feature to test how well a future mission like Euclid is able to measure it and distinguish this particular CQ from other classes of models.**



# What do we need to forecast using the nonlinear power spectrum?

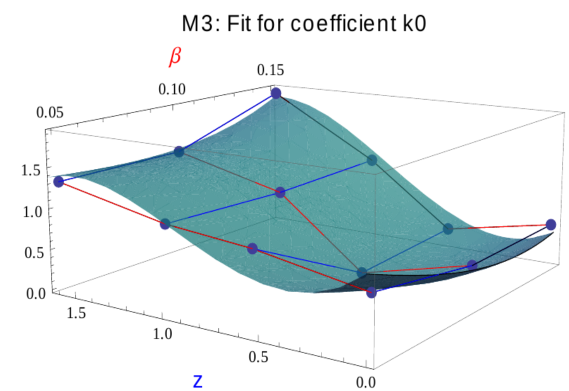
- We cannot run N-body simulations varying all interesting cosmological parameters.
- Perturbation Theory or Effective Theories of LSS do not reach yet the interesting range in k for this particular case. Furthermore it is complicated to include beyond-$\Lambda$CDM models[1]. (discussed later in this talk)
- We need fitting functions that can be varied w.r.t. cosmological parameters.

[1]We have tried to use an implementation by A.Vollmer of cDE in TRG, but not very successfully.

# Fitting functions

- Use CoDECS[1] EXP simulations with three different couplings.
- We developed an automatic method that corrects numerical anomalies around the Nyquist frequency.
- Multidimensional nonlinear fit: Tested 8 “sigmoidal” models for goodness of fit, each with 5 coefficients depending polynomially (3rd order) on the parameters.

| Model Name | Analytical expression | $N_p$ |
|---|---|---|
| M1 | $f(k) = 1 + a_0 + a_1 \cdot k + c \cdot k \cdot \tanh((k - k_0) \cdot b)$ | 5 |
| M2 | $f(k) = 1 + a_0 + a_1 \cdot k + c \cdot k \cdot \arctan((k - k_0) \cdot b)$ | 5 |
| M3 | $f(k) = 1 + a_0 + a_1 \cdot k + c \cdot k \cdot \mathrm{Gudermannian}((k - k_0) \cdot b)$ | 5 |
| M4 | $f(k) = 1 + a_0 + a_1 \cdot k + c \cdot k \cdot \mathrm{erf}((k - k_0) \cdot b)$ | 5 |
| M5 | $f(k) = 1 + a_0 + a_1 \cdot k + \frac{c \cdot k}{1+e^{-(k-k_0)\cdot b}}$ | 5 |
| M6 | $f(k) = 1 + a_0 + a_1 \cdot k + c \cdot k \cdot (\frac{1}{4} + e^{(-b+(k-k_0))^2})$ | 5 |
| M7 | $f(k) = 1 + a_0 + a_1 \cdot k + c \cdot k \cdot \frac{b \cdot (k-k_0)}{\sqrt{1+b^2 \cdot (k-k_0)^2}}$ | 5 |
| M8 | $f(k) = h - a_1 \cdot k + c \cdot \left( A + \frac{(K-A)\cdot k}{\left(1+Q \cdot e^{-B(k-M)}\right)^{1/\nu}} \right)$ | 9 |




The Gudermannian function is something like Integrate[dt/cosh(t)]. Inverse of Mercator projection.

# Fitting functions

- Use CoDECS[1] EXP simulations with three different couplings.
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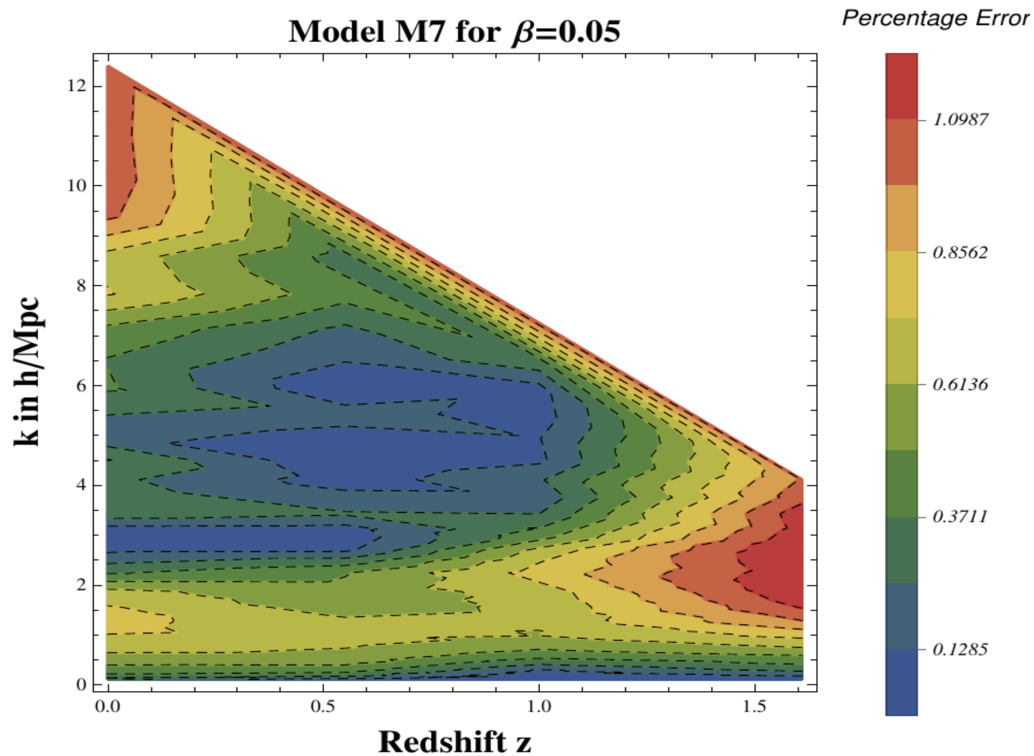
- Multidimensional nonlinear fit: Tested 8 models for goodness of fit.
- Accuracy goal: 1-2%



# Fisher Forecast

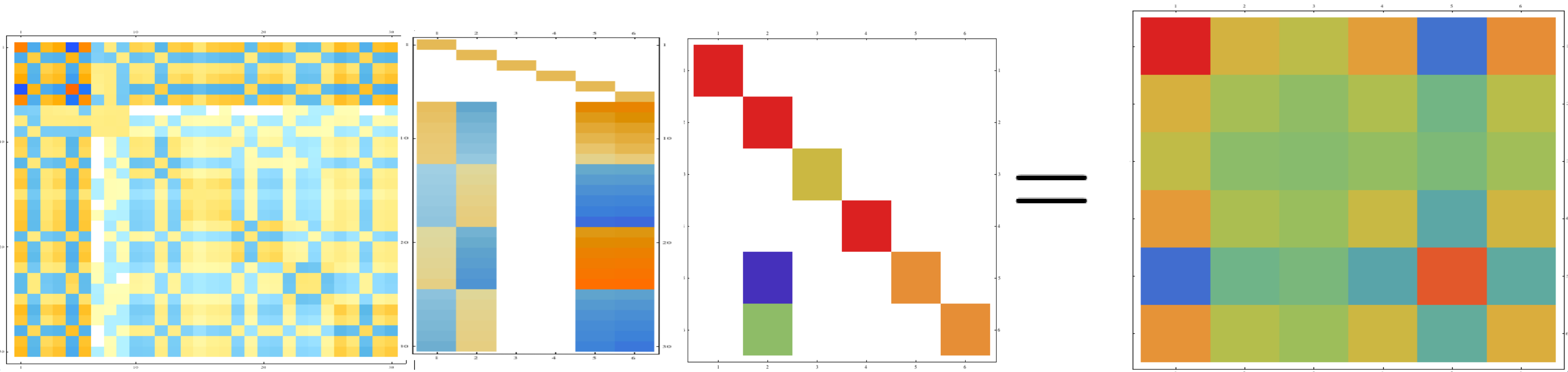
- We use 6 cosmological parameters:

$$\{\beta^2,\ h,\ \log A,\ n_s, \omega_b,\ \omega_c\}$$

- The observed power spectrum for galaxy clustering:

$$P_{\rm obs}\left(z,k,\mu;\theta\right) = P_{\rm s}(z) + \frac{D_A^2(z)_{ref} H(z)}{D_A^2(z) H(z)_{ref}} b^2(z)\left(1+\beta(z)\mu^2\right)^2 P(k,z) e^{-k^2\mu^2(\sigma_z^2/H(z)+\sigma_v^2(z))}$$

- Using information on the Growth, the Hubble function, the Angular Diameter Distance and the Growth Rate at 6 redshift bins, using Euclid specifications.

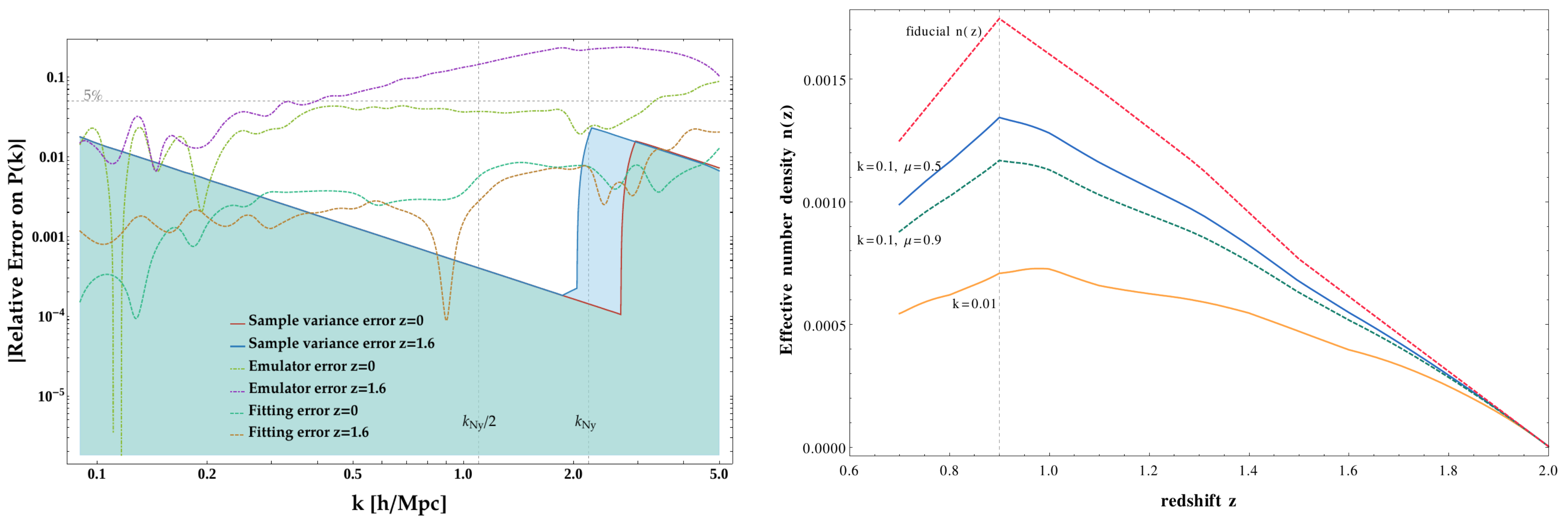


We include a first order correction on the Kaiser formula, due to non-linear peculiar velocity dispersion.

# Inclusion of errors

- We include in our Fisher analysis the errors on the PS coming from the fitting functions, the cosmic emulator and the sample variance of the N-body PS.
- These errors add noise to the Fisher matrix in the form of an effective galaxy number density:

$$n_{eff}(k,z) = n(z)/(1+n(z)\sigma_p(k,z))$$




- We will perform the analysis using two different cuts in k: at the Nyquist frequency and at half of the Nyquist frequency (conservative).

# Fisher Forecast for WL

- Fisher matrix for the WL multipoles:

$$F_{\alpha\beta} = f_{sky} \sum_{\ell}^{\ell_{max}} \sum_{i,j,k,m} \frac{(2\ell+1)\Delta\ell}{2} \frac{\partial P_{ij}(\ell)}{\partial\theta_\alpha} C^{-1}_{jk} \frac{\partial P_{km}(\ell)}{\partial\theta_\beta} C^{-1}_{mi}$$

- Here the matter power spectrum enters the game:

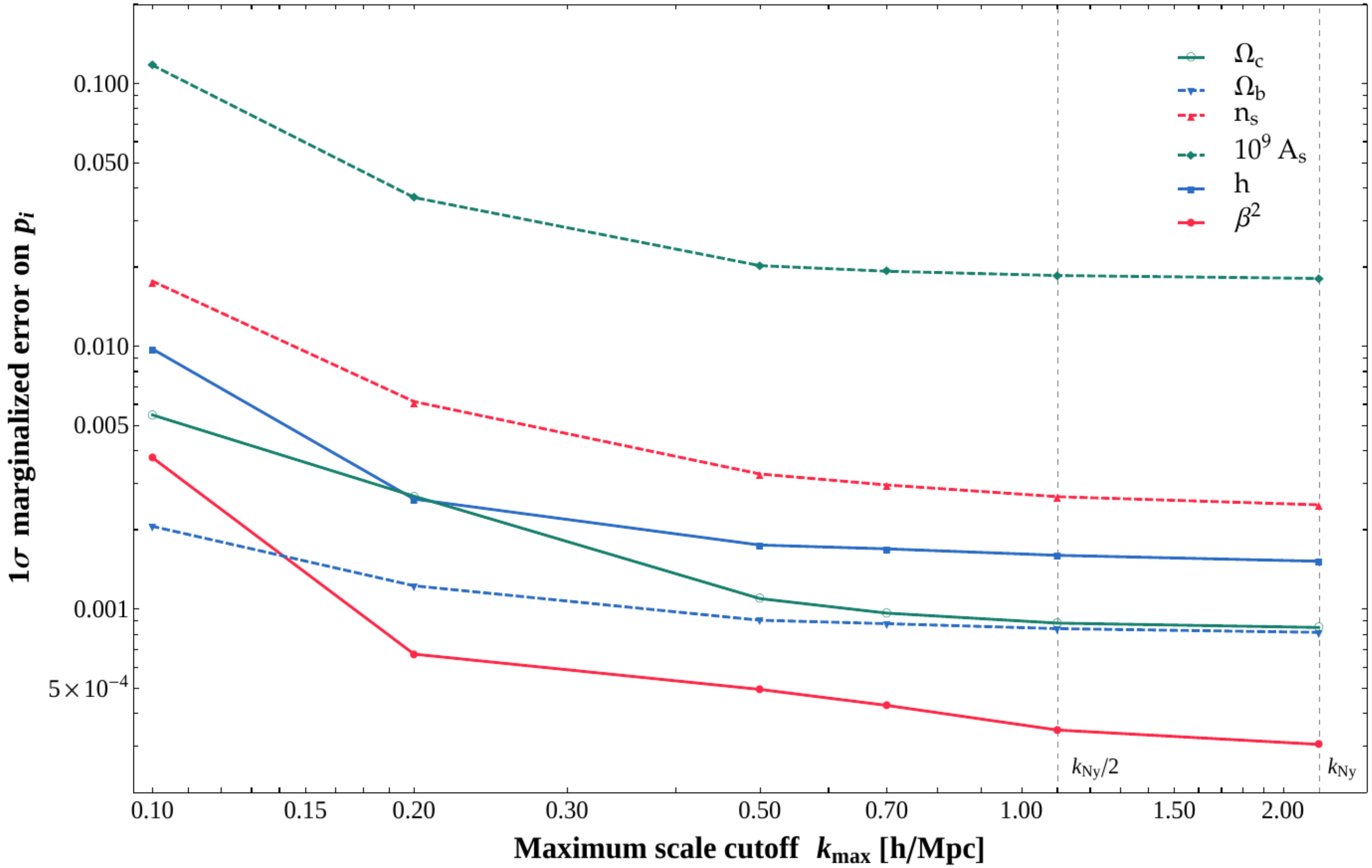
$$P_{ij}(\ell) = \frac{9}{4} \int_0^\infty \mathrm{d}z \, \frac{W_i(z) W_j(z) H^3(z) \Omega_m^2(z)}{(1+z)^4} P_m(\ell/r(z))$$

- We include an “error” matrix K in the covariance to account for the cut in k, which translates into a cut in multipoles depending on z.

$$C_{ij}(\ell) = P_{ij}(\ell) + \delta_{ij} \gamma_{int}^2 n_i^{-1} + K_{ij}(\ell)$$

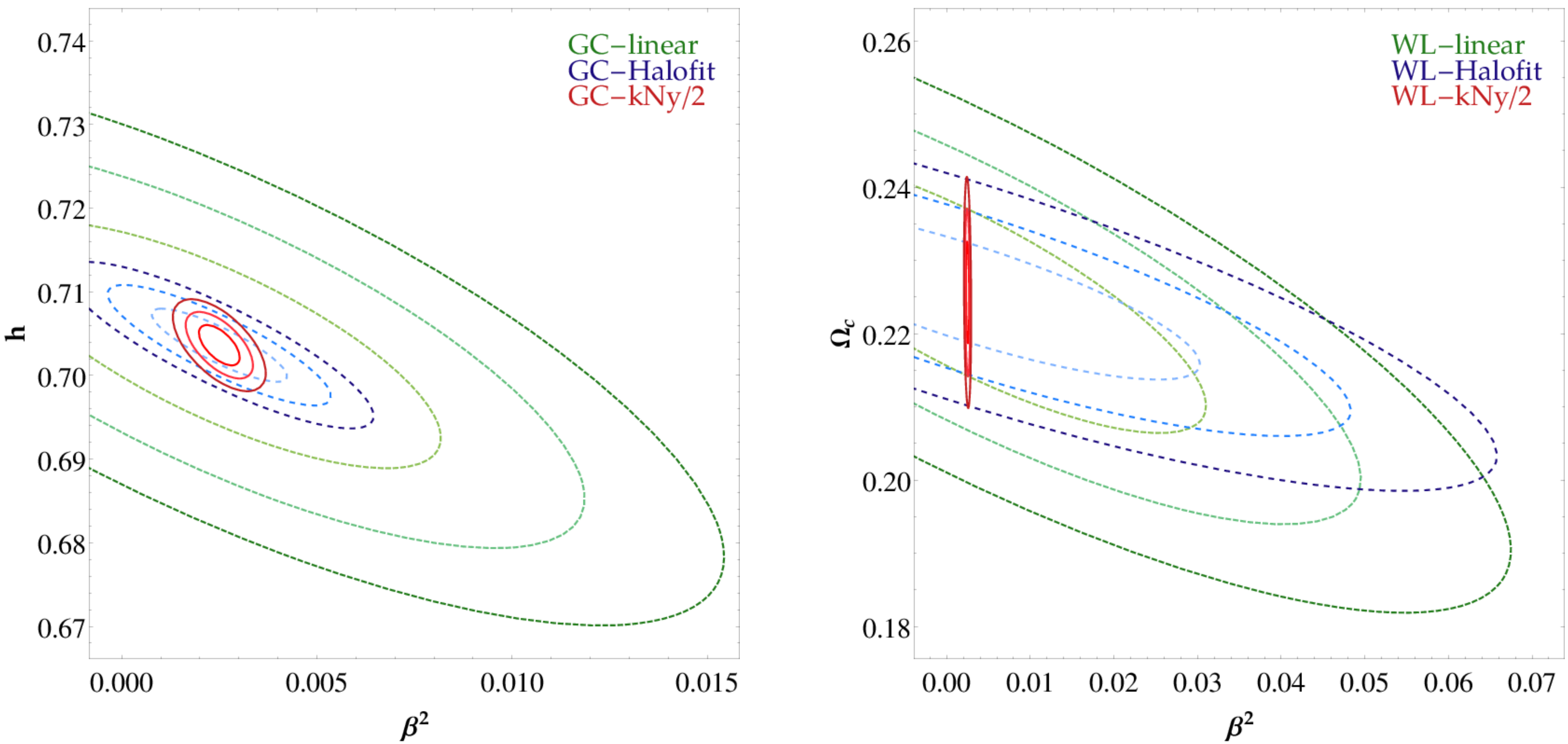
# Results

- Including more of the nonlinear scales, improves considerably the constraints on the cosmological parameters, especially on $\beta^2$.
- At small scales, information from initial conditions is lost due to mode-mode coupling, but signal from the DE coupling starts being important.



# Results

- Including more of the nonlinear scales, improves considerably the constraints on the cosmological parameters, especially on $\beta^2$
- When using only linear PS + Halofit, there is not much gain on the errors on $\beta$, since there is no extra information contained in there.




It is still important to check what is the parameter estimation bias by doing this.

# Results

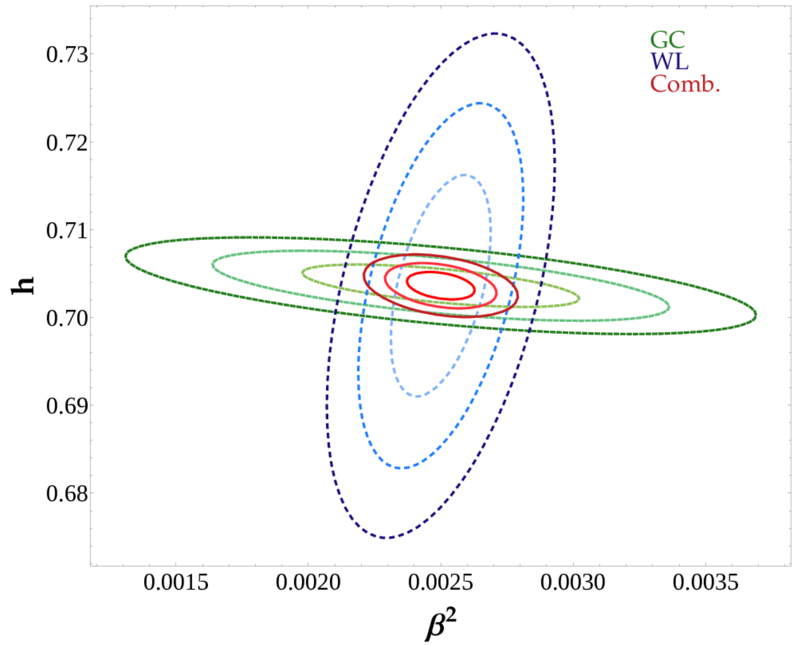
The constraint on the DM-DE coupling would be of the same order as the present constraint on the DE-baryon coupling in the Solar System.

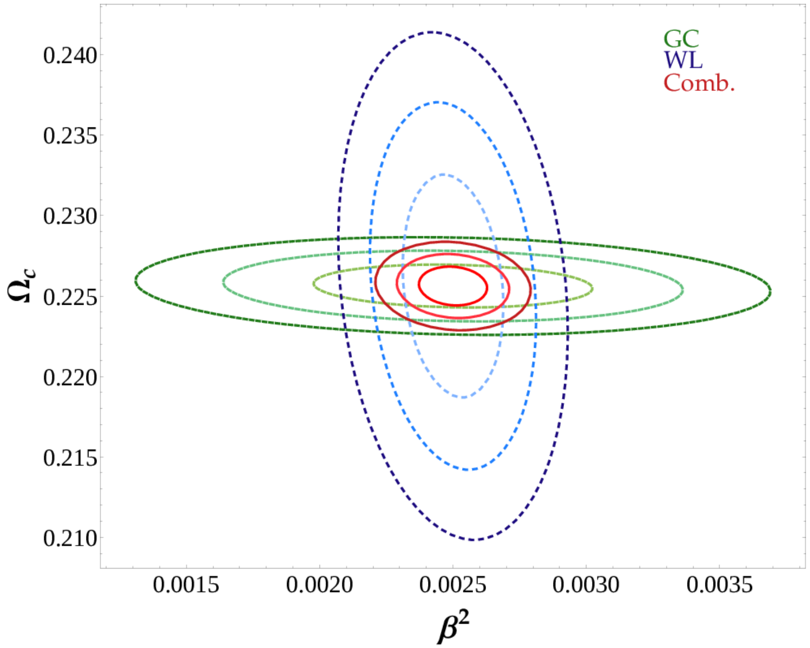
| **Parameter** | $\beta^2$ | $h$ | $10^9 \mathscr{A}_s$ | $n_s$ | $\Omega_b$ | $\Omega_c$ |
|---|---|---|---|---|---|---|
| fiducial | 0.0025 | 0.7036 | 2.42 | 0.966 | 0.04503 | 0.2256 |
| **WL: 1-$\sigma$ abs. error, using:** | | | | | | |
| linear CDE | 0.0189 | 0.040 | 0.221 | 0.0139 | 0.0062 | 0.0127 |
| linear CDE+Halofit | 0.0184 | 0.044 | 0.256 | 0.0109 | 0.0066 | 0.0079 |
| non-linear CDE fitting functions | 0.000125 | 0.00835 | 0.112 | 0.0105 | 0.0032 | 0.0046 |
| **GC: 1-$\sigma$ abs. error, using:** | | | | | | |
| linear CDE | 0.0038 | 0.0097 | 0.117 | 0.0176 | 0.0021 | 0.0055 |
| linear CDE+Halofit | 0.0011 | 0.0029 | 0.024 | 0.0023 | 0.0007 | 0.0006 |
| non-linear CDE fitting functions | 0.00035 | 0.0016 | 0.018 | 0.0027 | 0.0008 | 0.0009 |

## Old results[1], linear PS

| Parameter | $\sigma_i$ CMB | $\sigma_i$ $P(k)$ | $\sigma_i$ WL |
|---|---|---|---|
| $\beta^2$ | 0.0094 | 0.0015 | 0.012 |
| $\alpha$ | 0.55 | 0.12 | 0.083 |
| $\Omega_c$ | 0.022 | 0.010 | 0.012 |
| $h$ | 0.15 | 0.036 | 0.039 |
| $\Omega_b$ | 0.00087 | 0.0022 | 0.010 |
| $n_s$ | 0.014 | 0.034 | 0.026 |
| $\sigma_8$ | - | 0.0084 | 0.024 |
| $\log A$ | 0.0077 | - | - |

[1] Amendola, Pettorino, Quercellini, Vollmer (2012).




**Weak Lensing and Galaxy Clustering observables are complimentary and break some parameter degeneracies.**

**If we manage to understand the nonlinear power spectrum accurately, Euclid will be a powerful tool.**

# FisherTools and Cosmomathica

- Fisher forecasting led me to develop a set of very flexible Mathematica packages for computing, analyzing and plotting GC and WL Fisher forecasts.

- It interacts with Cosmomathica, a code started by Adrian Vollmer, which I now constantly extend and maintain. It creates a very useful interface between Mathematica and codes like CAMB, (CLASS*), CosmicEmulator, Copter, Halofit, Eisenstein&Hu TF, without the need to import/export text files constantly.

- The FisherTools code was used for the Euclid Fisher Code Comparison Project.
  If you want to participate and benchmark your Fisher matrices, go to WP6 and follow the instructions.

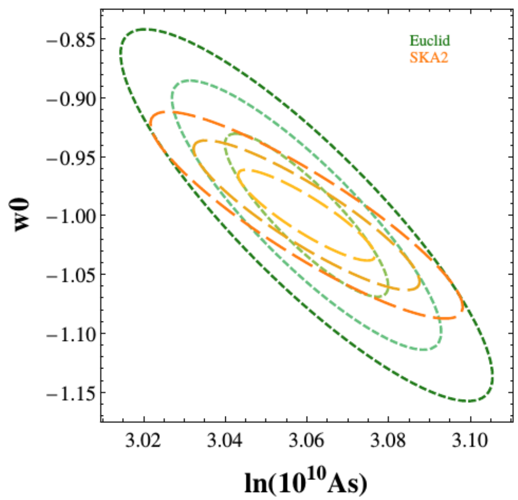
https://github.com/santiagocasas/cosmomathica.git

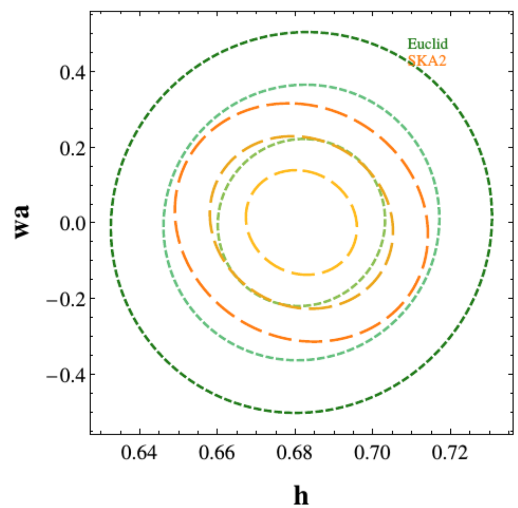
CURLY: http://www.thphys.uni-heidelberg.de/~cosmo/dokuwiki/doku.php/codes

* Still in beta-testing phase.

# What else can we do with Fisher forecasts?

## SKA2 and Euclid comparison + Planck priors



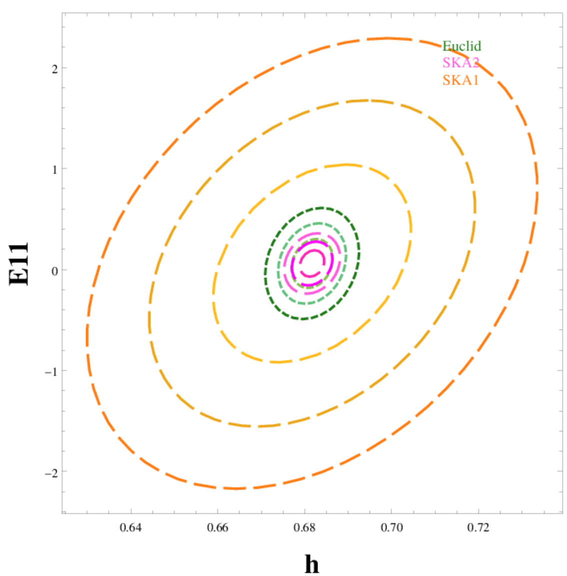



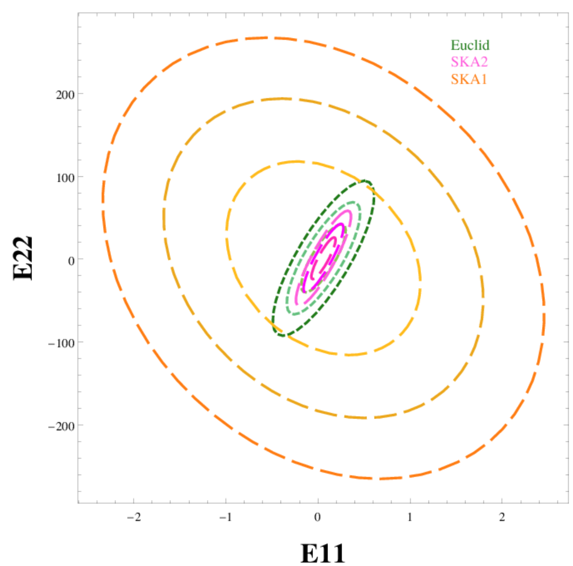

## Planck DE paper 2015

$$\mu(a,k) = 1 + f_1(a)\frac{1 + c_1(\lambda H/k)^2}{1 + (\lambda H/k)^2}$$

$$\eta(a,k) = 1 + f_2(a)\frac{1 + c_2(\lambda H/k)^2}{1 + (\lambda H/k)^2}$$

## SKA1-MID, SKA2, Euclid

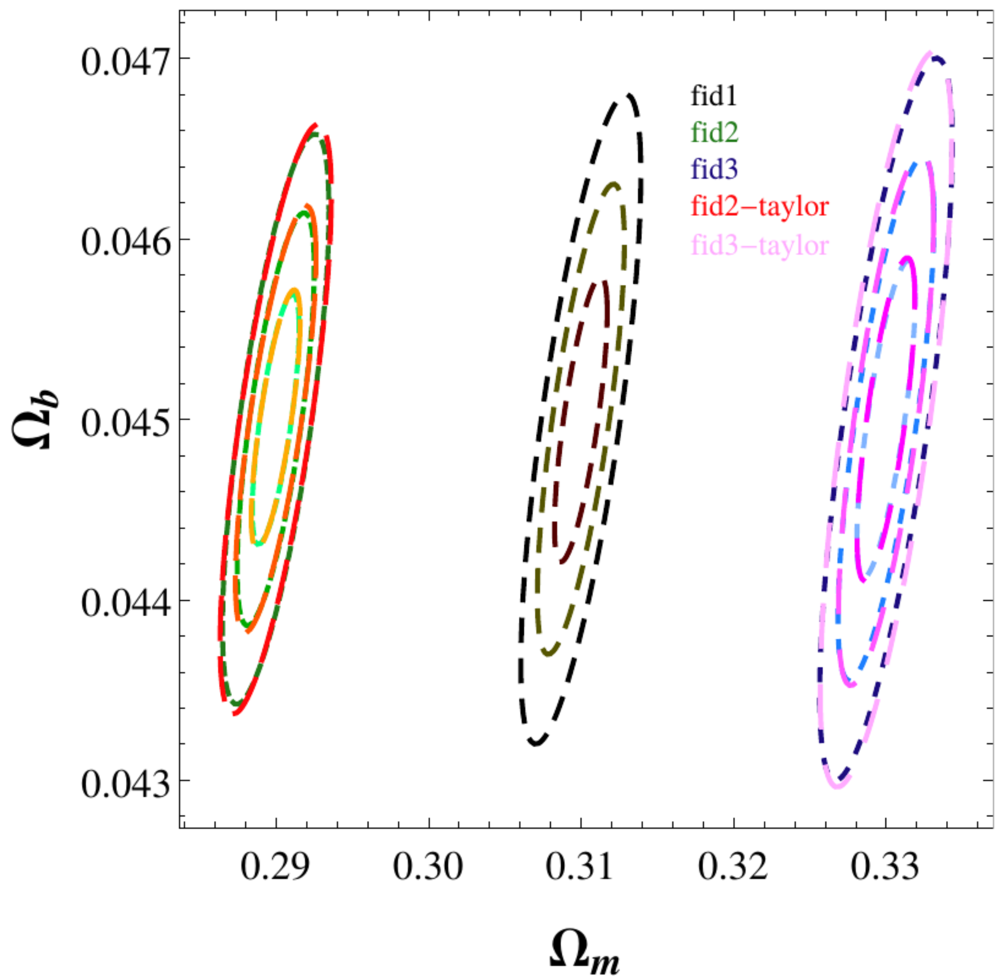



In collaboration with M.Kunz, M.Martinelli and V. Pettorino

# What else can we do with Fisher forecasts?

Predict Fisher ellipses at different fiducial points without the need to recompute them. Using “Fisher-Taylor tensors”.



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- As we have shown before, especially for WL, using the wrong non-linear modeling can bias the results or simply not give any useful constraints.
- In principle we need to take care of the P(k) covariances and take non-Gaussian variables into account. Higher order statistics are another challenge.

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✓ In some models and parametrizations of Modified Gravity we can try to get the mildly non-linear regime using eikonal Renormalized Perturbation Theory. (?)

→ For other models, we have little hope of capturing the non-linear dynamics analytically --> Go back to Nbodys.[1]

[1] See for example Growing Neutrino Quintessence at the end of the talk.

# Horndeski-like theories in the "quasistatic" limit

- In general Horndeski models, assuming the quasistatic limit, the anisotropic stress and the "effective gravitational constant" can be expressed as[1]:

$$\eta(k,a) = -\frac{\Phi}{\Psi} = h_2\left(\frac{1+k^2h_4}{1+k^2h_5}\right) \qquad Y(k,a) = -\frac{2k^2\Psi}{3\Omega_m\delta_m} = h_1\left(\frac{1+k^2h_5}{1+k^2h_3}\right)$$

- This modified Poisson's equation will have an effect on structure formation of DM that we would like to study at the mildly nonlinear scales.

- We will just take general functions of time $h_i(t)$ which given a particular model, can always be specified.

[1] Other EFT's of DE can be parametrized in a similar way (alphas). Important here is the scale dep. dependence

# Fluid equations and approximations

- **Continuity** $$\frac{\partial \delta_c}{\partial \tau} + \nabla \cdot [(1+\delta_c)\,\mathbf{v}] = 0$$
- **Euler** $$\frac{\partial \mathbf{v}}{\partial \tau} + \mathcal{H}(\mathbf{v} + [\mathcal{A}\mathbf{v}]) + (\mathbf{v}\cdot\nabla)\,\mathbf{v} = -\nabla\Psi$$
- **Poisson** $$\nabla^2\Psi = \frac{3}{2}\mathcal{H}^2\Omega_c(\tau)\,(\delta_c + [\mathcal{B}\delta_c])$$

- These equations are only valid in the **single stream approximation.** We neglected initial vorticity and the stress tensor from the Vlasov-Poisson system.

$$\varphi_a(\mathbf{k},\eta) = e^{-\eta}\begin{pmatrix}\delta_m(\mathbf{k},\eta)\\ -\theta(\mathbf{k},\eta)/\mathcal{H}\end{pmatrix} \qquad \Omega_{ab}(\mathbf{k},\eta) = \begin{pmatrix}1 & -1\\ -\frac{3}{2}\Omega_m(\eta)(1+\mathcal{B}(\mathbf{k},\eta)) & 2+\frac{\mathcal{H}'}{\mathcal{H}}+\mathcal{A}(\mathbf{k},\eta)\end{pmatrix}$$

$$\partial_\eta\varphi_a(\mathbf{k},\eta) = \underbrace{-\Omega_{ab}(\mathbf{k},\eta)\varphi_b(\mathbf{k},\eta)}_{\text{Linear perturbation theory}} + \underbrace{e^{\eta}\gamma_{abc}(\mathbf{k},-\mathbf{p},-\mathbf{q})\varphi_b(\mathbf{p},\eta)\varphi_c(\mathbf{q},\eta)}_{\text{Non-linear terms, mode coupling, causing trouble}}$$

Linear perturbation theory

Non-linear terms, mode coupling, causing trouble

# eRPT Resummation

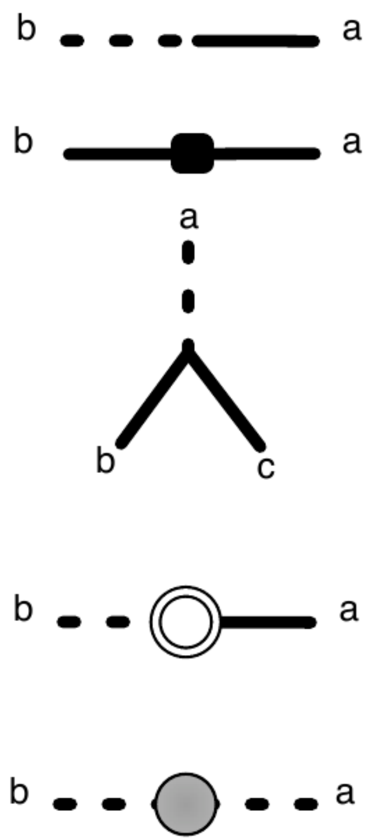
- Resummation method developed by Stefano Anselmi and Massimo Pietroni, "...A leap beyond the BAO scale" (2012). We use here the eikonal approximation.

- We start with the evolution equation for the PS in this method, but add scale dependence and a "Horndeski modified" propagator:

$$g(\mathcal{X},\mathcal{X}') = \Theta(\mathcal{X}-\mathcal{X}')\left[\frac{1}{2+3Y}\begin{pmatrix}3Y & 2\\ 3Y & 2\end{pmatrix} + \frac{1}{2+3Y}\begin{pmatrix}2 & -2\\ -3Y & 3Y\end{pmatrix} e^{-\frac{(2+3Y)}{2}(\mathcal{X}-\mathcal{X}')}\right]$$

$$\begin{aligned}\partial_{\mathcal{X}}\tilde{P}_{ab}(k;\mathcal{X}) &= -\tilde{\Omega}_{ac}(\mathbf{k};\mathcal{X})\tilde{P}_{cb}(\mathbf{k};\mathcal{X}) - \tilde{\Omega}_{bc}(\mathbf{k};\mathcal{X})\tilde{P}_{ac}(\mathbf{k};\mathcal{X})\\ &+ H_{\mathbf{a}}(k;\mathcal{X},\mathcal{X}_{in})\tilde{P}_{\mathbf{a}b}(\mathbf{k};\mathcal{X}) + H_{\mathbf{b}}(k;\mathcal{X},\mathcal{X}_{in})\tilde{P}_{a\mathbf{b}}(\mathbf{k};\mathcal{X})\\ &+ \int \mathrm{d}s\left[\tilde{\Phi}_{ad}(k;\mathcal{X},s)G^{eik}_{bd}(k;\mathcal{X},s) + G^{eik}_{ad}(k;\mathcal{X},s)\tilde{\Phi}_{db}(k;\mathcal{X},s)\right]\end{aligned}$$

Time variable has to be changed from usual $D_+$ back to the scale factor a.




propagator tree-level: $-iG^{eik}_{ab}(\mathbf{k};\eta_a,\eta_b)$

power spectrum tree-level: $P^{eik}_{ab}(\mathbf{k};\eta_a,\eta_b)$

interaction vertex: $-ie^{\eta}\gamma_{abc}(\mathbf{k}_a,\mathbf{k}_b,\mathbf{k}_c)$

counter term propagator: $i\Sigma^{eik}_{ab}(\mathbf{k};\eta_a,\eta_b)$

counter term power spectrum: $-\Phi^{eik}_{ab}(\mathbf{k};\eta_a,\eta_b)$

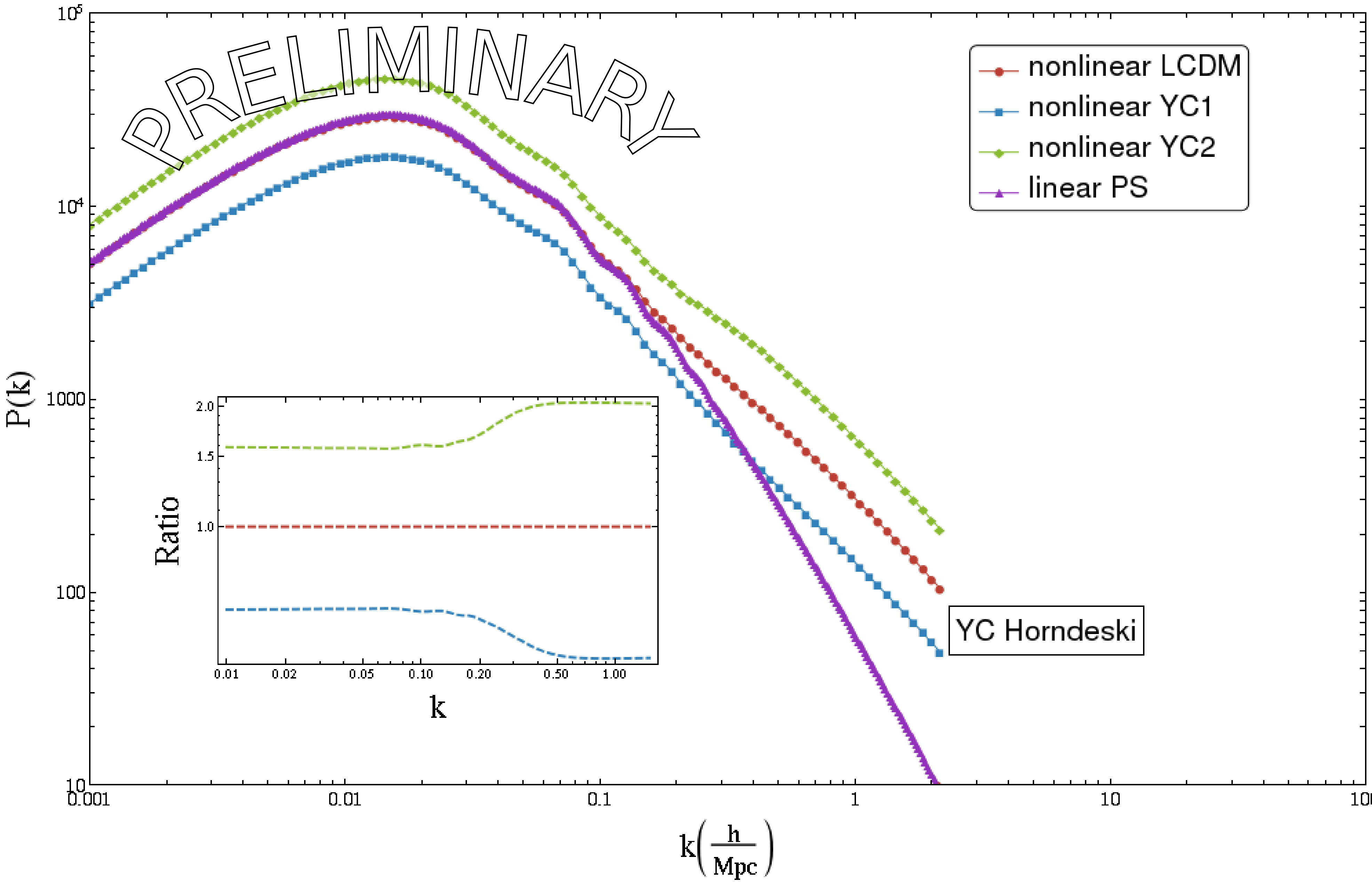
Quantities can be obtained by performing functional derivatives of a generating functional that has the same dynamical structure as SPT:

$$Z[J_a,\,K_b;\,P^0] = \int \mathcal{D}\varphi_a \mathcal{D}\chi_b \exp\Big\{-\tfrac{1}{2}\int d\eta_a d\eta_b \chi_a P^0_{ab}\delta(\eta_a)\delta(\eta_b)\chi_b + i\int d\eta\,\left[\chi_a g^{-1}_{ab}\varphi_b - e^{\eta}\,\gamma_{abc}\chi_a\varphi_b\varphi_c + J_a\varphi_a + K_b\chi_b\right]\Big\}$$

$$\left.\frac{\delta^2 W}{\delta J_a\,\delta J_b}\right|_{J_a,\,K_b=0} = i\,\delta_D(\mathbf{k}+\mathbf{k}')P_{ab}\,,$$

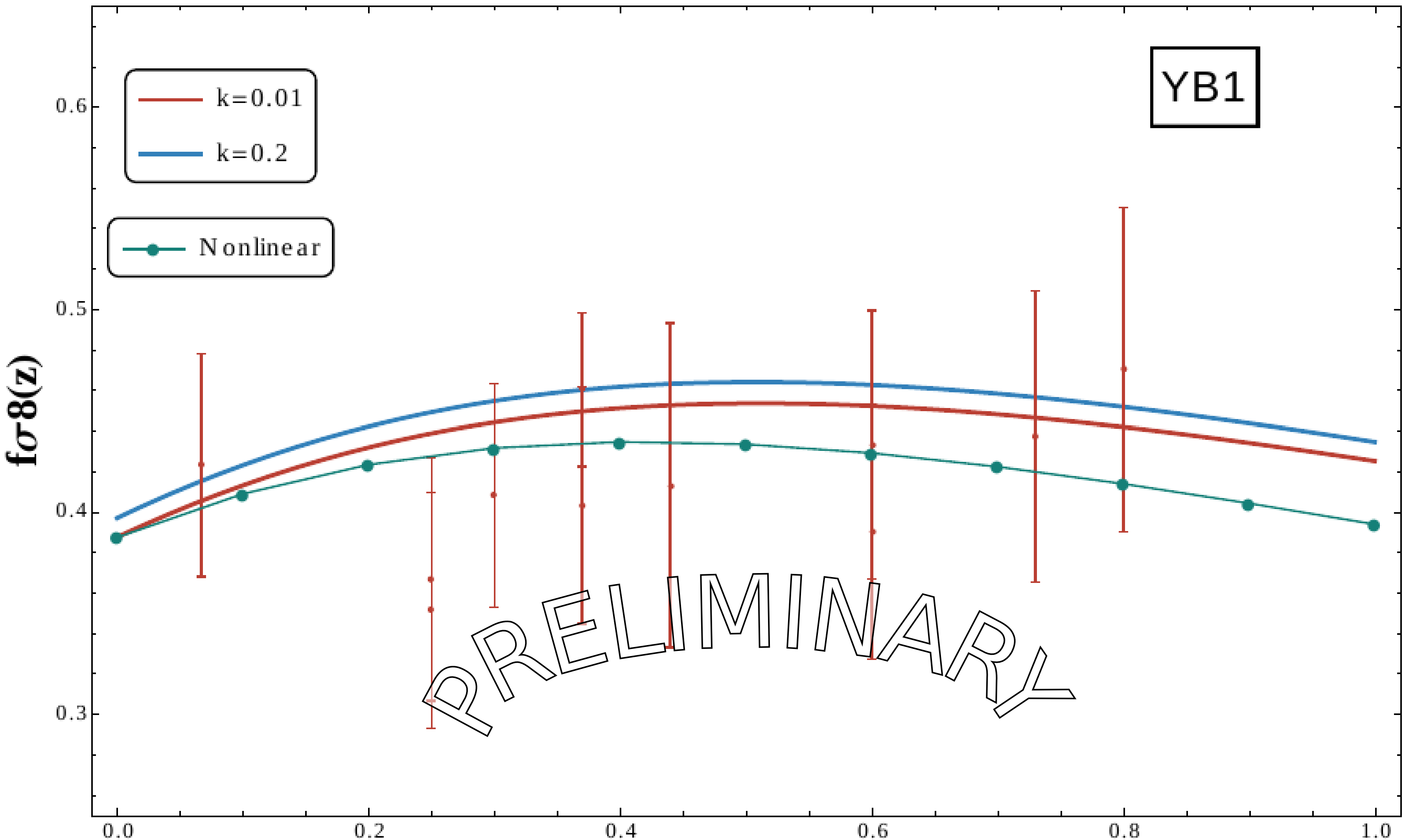
$$\left.\frac{\delta^2 W}{\delta J_a\,\delta K_b}\right|_{J_a,\,K_b=0} = -\delta_D(\mathbf{k}+\mathbf{k}')G_{ab}$$

[1] For more details: Next-to-leading resummations in cosmo. pert. theory, Anselmi, Matarrese, Pietroni. (2010).




Of course I need to compare with actual N-body simulations (f(R), Gallileons, etc.)

Some common observational quantities are modified when including the non-linear scale dependent predictions:




[1] To calculate cosmological quantities from the models, we will use the Hi-CLASS output by Zumalacarregui et al..

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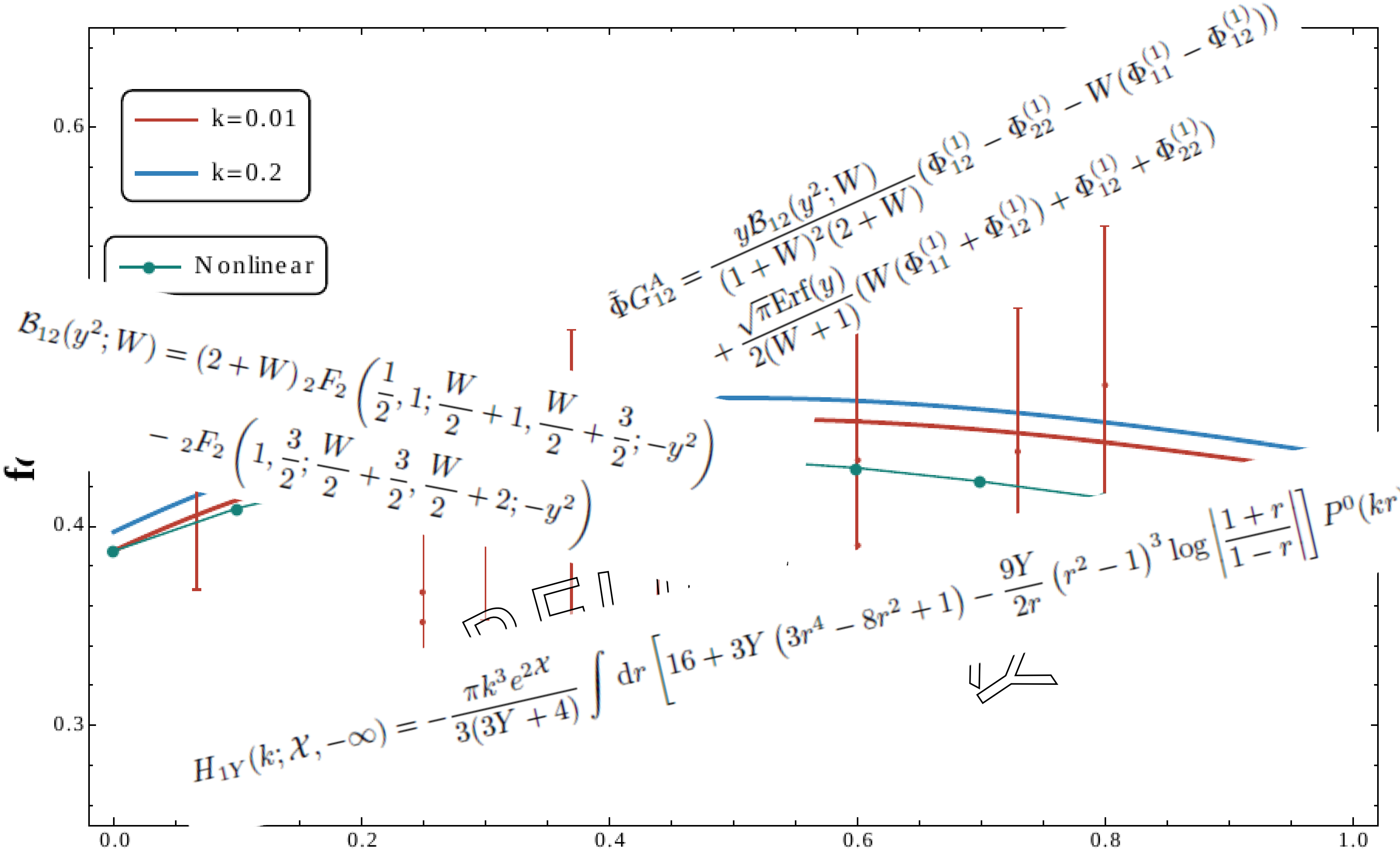


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# Growing Neutrino Quintessence

- Model of coupled quintessence, motivated by the fact that the energy density of dark energy and neutrino masses, are not that far away: 2x10$^{-3}$ eV.
- Addresses the CC and the "why now" problem.

Coupling through the mass

$$\beta = -\frac{d\, ln(m_\nu)}{d\varphi} < 0$$

Modified Klein-Gordon eqn.

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = -\beta T_\nu$$

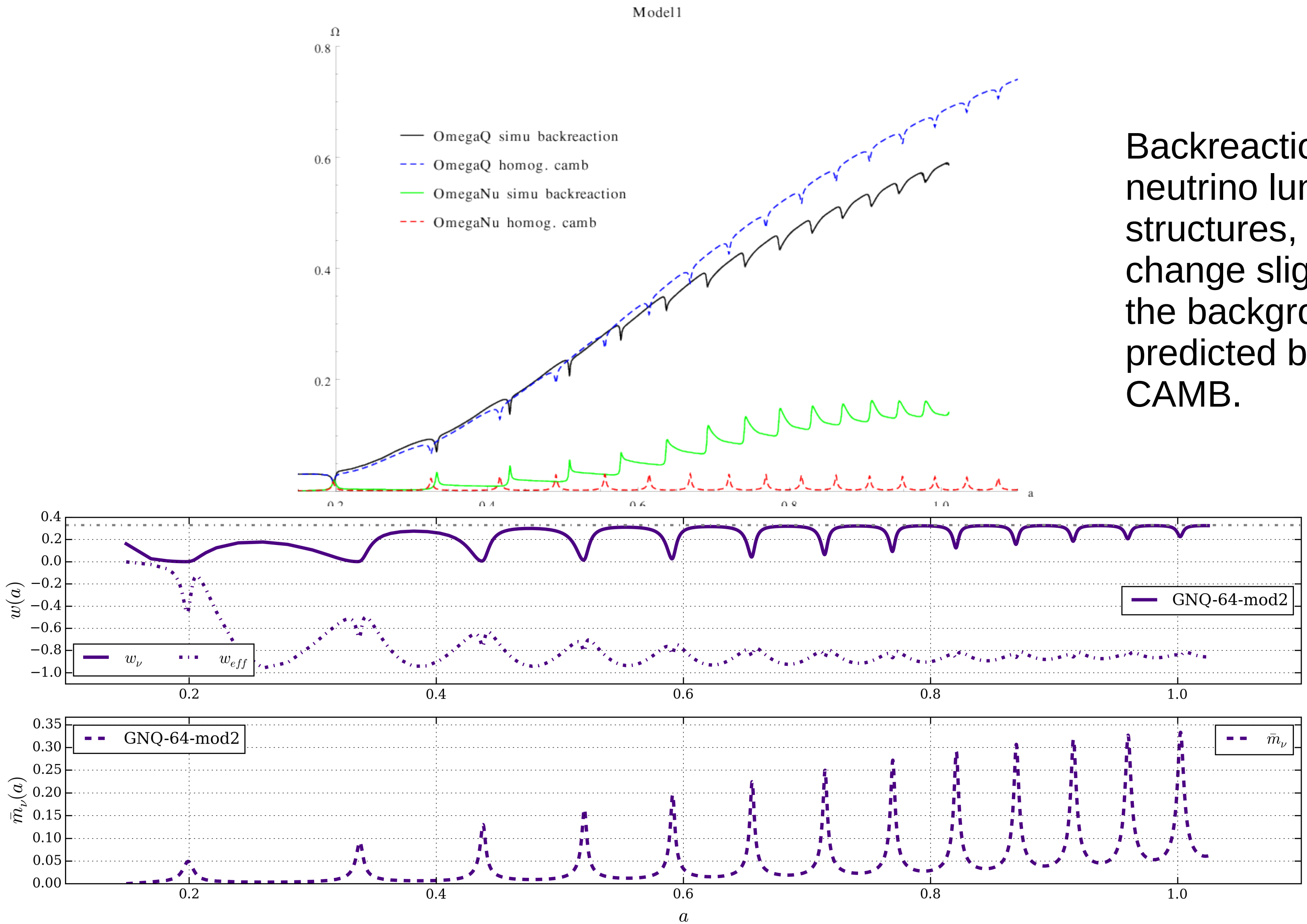
Modified continuity eqn.

$$\dot{\rho_\varphi} + 3H(\rho_\varphi + P_\varphi) = -\beta T_\nu \dot{\varphi}$$

Varying beta model

$$m_\nu = \frac{\bar{m}}{\varphi_{\rm crit} - \varphi} \qquad \beta = -\frac{1}{\varphi_{\rm crit} - \varphi}$$

# Growing Neutrino Quintessence

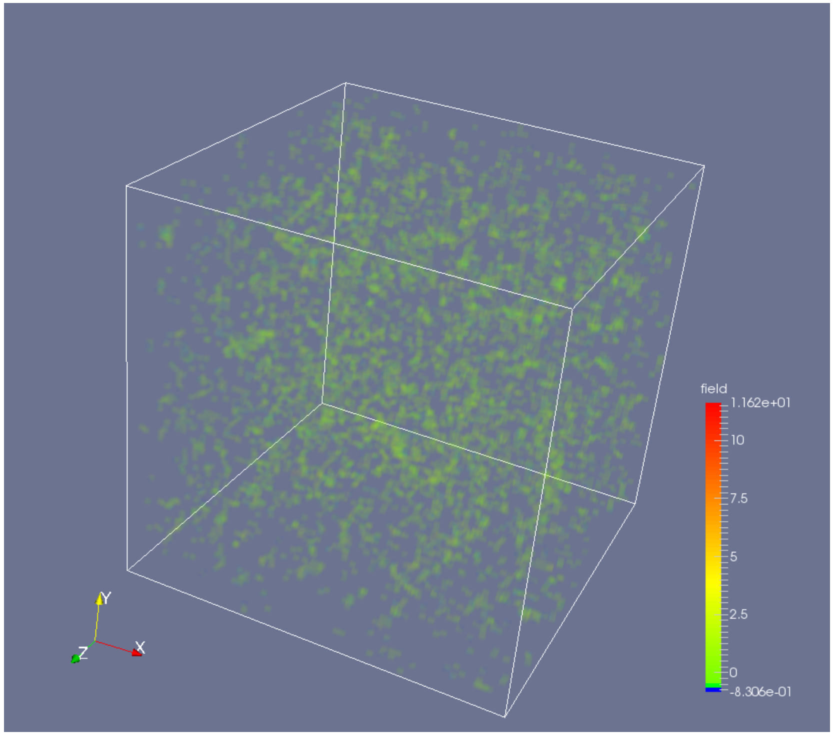


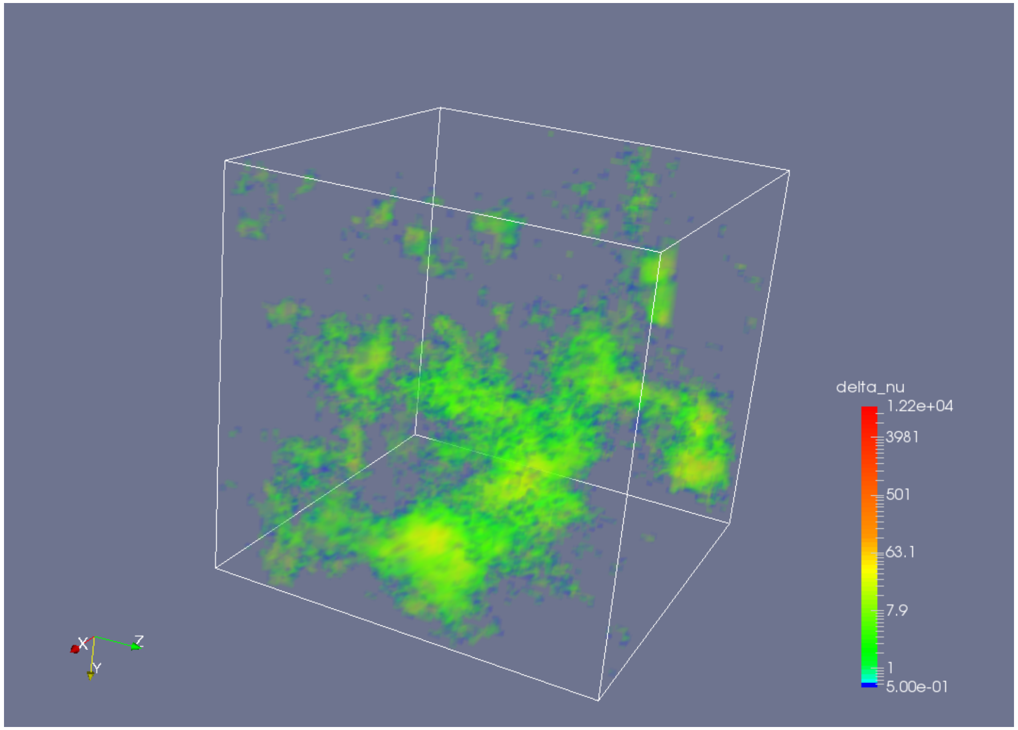

Backreaction of neutrino lump structures, change slightly the background predicted by CAMB.

# Growing Neutrino Quintessence

- For small neutrino masses, lumps form and dissolve rapidly.
- We have discovered that for high neutrino masses > 1eV, the neutrinos do not oscillate between relativistic and non-relativistic, forming always larger and denser lumps.
- We need better resolution and therefore a decent parallelization.

→ Collaboration with gevolution code by the Geneva group?



# Main Conclusions:

- N-body simulations together with semi-analytical methods are a powerful way of estimating the predictions of DE theories in the nonlinear regime.
- Using information from nonlinear PS, where there is a characteristic feature coming from MG improves strongly the estimation of parameters using future LSS surveys.
- For some models we cannot hope to have a semi-analytic solution, we need a way of running relativistic MG simulations. Ideally, the raw datasets should be analyzed within that framework too.
- It is still necessary to do this consistently for all viable models, also taking into account massive neutrinos, baryonic feedback, etc. Other systematics related to GC and WL are still mostly unresolved.


Thanks!

# Backup Slides

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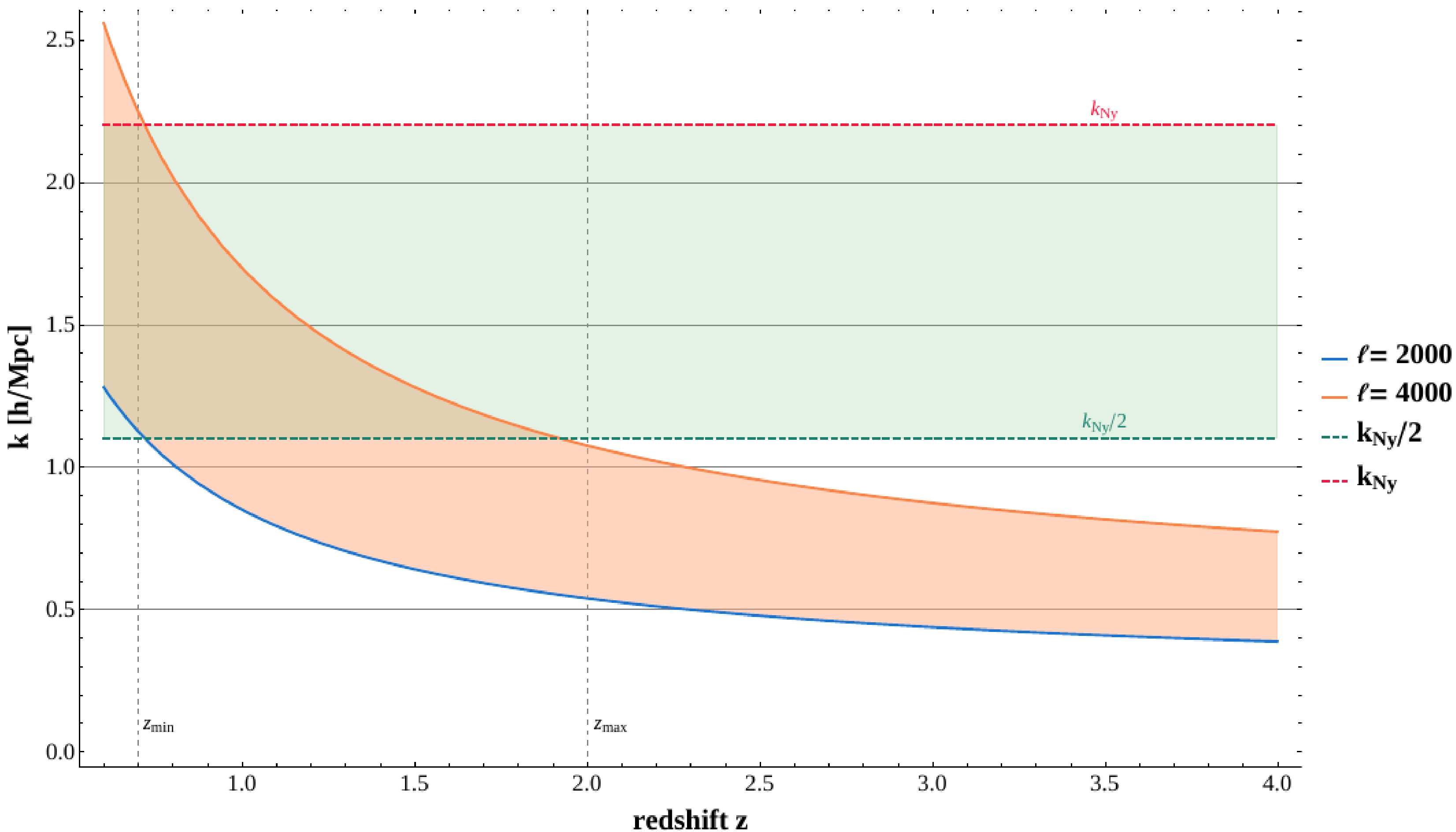


# Fitting functions

- Use CoDECS[1] EXP (exponential potential) simulations with three different values of the DM-DE coupling.

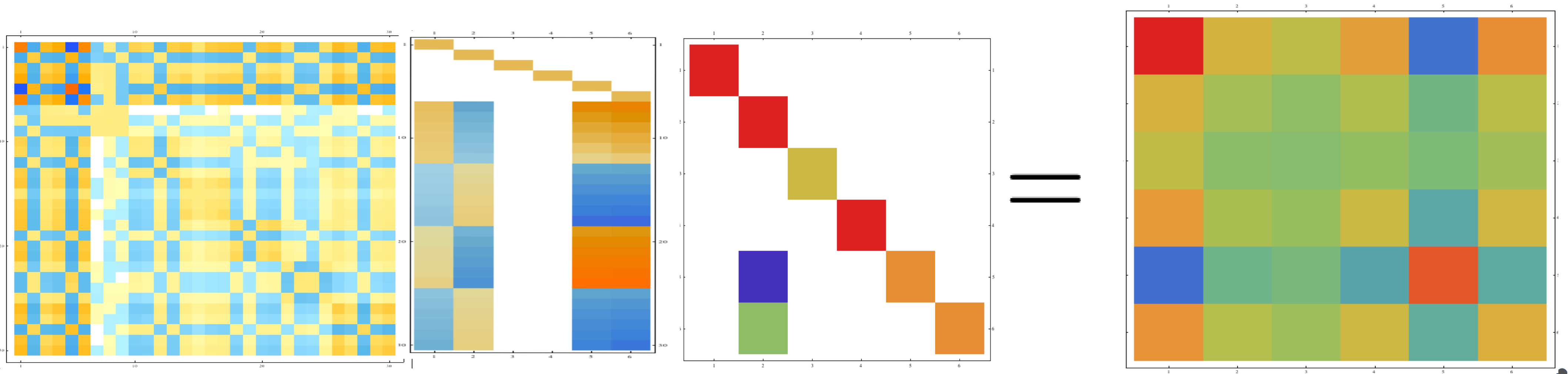
| Model | Potential | $\alpha$ | $\beta_0$ | $\beta_1$ | Scalar field normalization | Potential normalization | $w_\phi(z=0)$ | $\mathcal{A}_s(z_{\rm CMB})$ | $\sigma_8(z=0)$ |
|---|---|---|---|---|---|---|---|---|---|
| $\Lambda$CDM | $V(\phi) = A$ | – | – | – | – | $A = 0.0219$ | $-1.0$ | $2.42 \times 10^{-9}$ | 0.809 |
| EXP001 | $V(\phi) = Ae^{-\alpha\phi}$ | 0.08 | 0.05 | 0 | $\phi(z=0) = 0$ | $A = 0.0218$ | $-0.997$ | $2.42 \times 10^{-9}$ | 0.825 |
| EXP002 | $V(\phi) = Ae^{-\alpha\phi}$ | 0.08 | 0.1 | 0 | $\phi(z=0) = 0$ | $A = 0.0218$ | $-0.995$ | $2.42 \times 10^{-9}$ | 0.875 |
| EXP003 | $V(\phi) = Ae^{-\alpha\phi}$ | 0.08 | 0.15 | 0 | $\phi(z=0) = 0$ | $A = 0.0218$ | $-0.992$ | $2.42 \times 10^{-9}$ | 0.967 |
| EXP008e3 | $V(\phi) = Ae^{-\alpha\phi}$ | 0.08 | 0.4 | 3 | $\phi(z=0) = 0$ | $A = 0.0217$ | $-0.982$ | $2.42 \times 10^{-9}$ | 0.895 |
| SUGRA003 | $V(\phi) = A\phi^{-\alpha}e^{\phi^2/2}$ | 2.15 | -0.15 | 0 | $\phi(z \to \infty) = \sqrt{\alpha}$ | $A = 0.0202$ | $-0.901$ | $2.42 \times 10^{-9}$ | 0.806 |

# Fisher Forecast for GC

- Fisher matrix is a Gaussian approximation at the “minimum” of the likelihood:

$$F_{ij} = \frac{V_{survey}}{8\pi^2}\int_{-1}^{+1} \mathrm{d}\mu \int_{k_{min}}^{k_{max}} \mathrm{d}k\, k^2 \frac{\partial \ln P_{obs}(k,\mu,z)}{\partial \theta_i}\frac{\partial \ln P_{obs}(k,\mu,z)}{\partial \theta_j}\left[\frac{n(z)P_{obs}(k,\mu,z)}{n(z)P_{obs}(k,\mu,z)+1}\right]^2$$

- From the Euclid specifications, the most important are the survey volume, 15,000 sq.deg. and the n(z) function which peaks at around z=0.8.
- We marginalize over the bias b(z) which is estimated from mock galaxy simulations.



# Implement into Fisher Forecast

- We have fitting functions that describe the effect of the DM-DE coupling in CQ on the nonlinear power spectrum.
- Since we want to extract information at high-k there is no better option than using fitting functions that describe the nonlinear PS for $\Lambda$CDM.
- Halofit[2] introduces errors higher than 15% at the scales of interest, therefore we use the FrankenEmu from the Cosmic Emulator project[1].*

[1] Heitmann et al. (2014), [2]Takahashi et al. (2012). *Other recent approaches: HMCode and PkANN.

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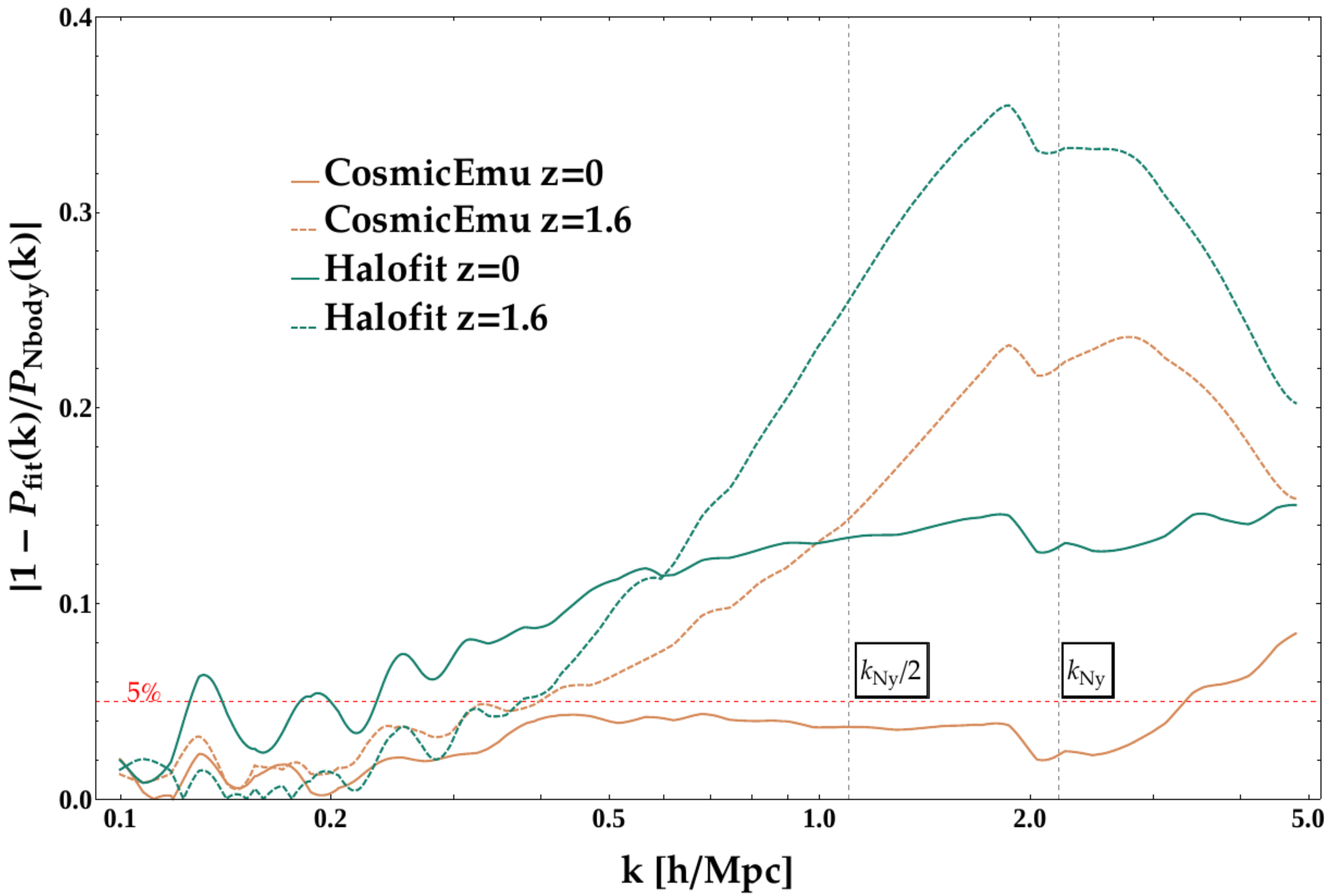
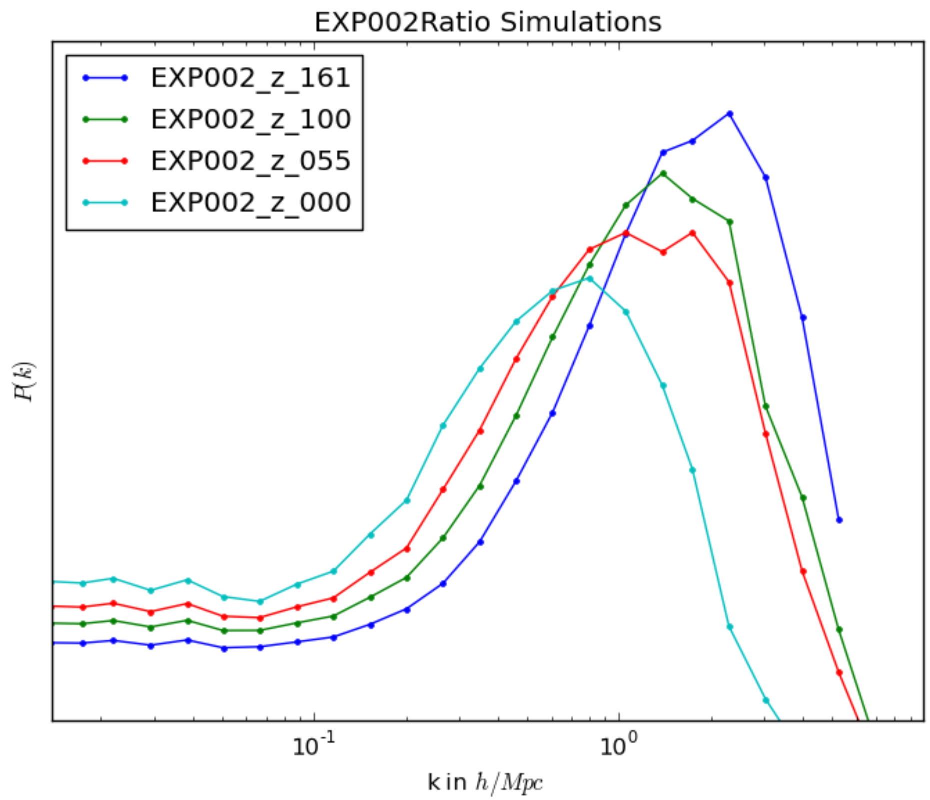


# Fitting functions

- Use CoDECS EXP simulations with three different couplings.
- We need to estimate the nonlinear PS with much more accuracy than previously. We developed an automatic method that corrects numerical anomalies around the Nyquist frequency. Reduce aliasing and improve the folding method[1]. → Improve convergence of fitting functs.




1: Colombi et al., Mon. Not. R. Astron. Soc.393, (2009)