Clustering in interacting Dark Energy cosmologies

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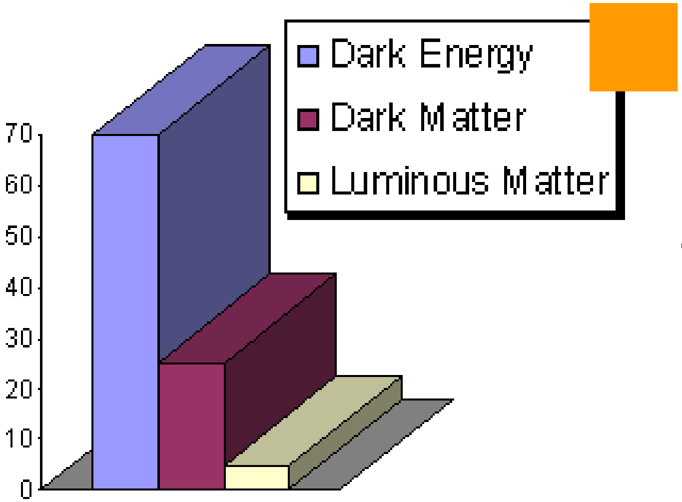
Overview

- Introduction
- Interacting dark energy
  - Gravity
  - Cold dark matter
  - Neutrinos
- Conclusions and future prospects

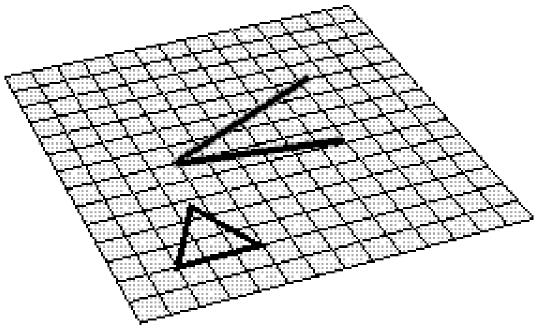
Dark ?

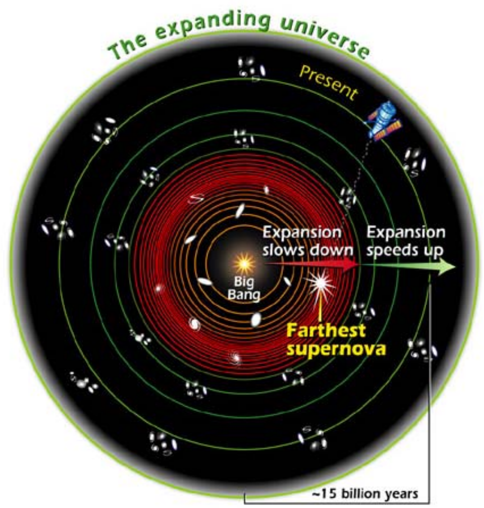
Flat ?

Accelerating



$\Omega_{tot} \approx 1$





Hopes and troubles

Cosmological constant

↓

Quintessence

Wetterich 1988,
Ratra & Peebles 1988

↓

Attractor solutions

Steinhardt, Wang and Zlatev 1999,
Liddle & Scherrer 1999

$\rho_{DE}/M^4 \sim 6.5 \times 10^{-121}$

$\rho_m/M^4 \sim 3.5 \times 10^{-121}$

$M = 2.44 \times 10^{18}$ GeV

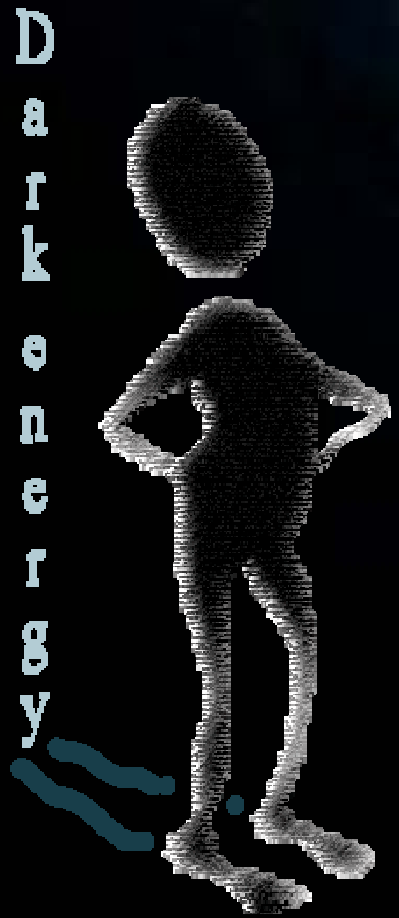
Why so small?

Why important just today?

Solutions are independent on the initial conditions for ϕ and ϕ'

Details depend on $V(\phi)$ or on the kinetic term

Interacting dark energy



The stringent difficulties of quintessence models and the lack of a clear explanation of the dark issue, encourage to pursue new ways of approaching the Dark Energy problem

The interaction keeps the dark energy density closer to matter fields

Interacting Dark Energy

- Coupling to gravity
  - Cosmological bounds
  - role in clustering?

[Boisseau etal 2000]
[Faraoni 2000]
[Perrotta, Baccigalupi 2002]
[Riazuelo Uzan 2002]
[Pettorino, Baccigalupi 2008]
and references therein

- Coupling to dark matter
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[Wetterich 1995]
[Amendola 2000, 2004]
[Mangano Miele Pettorino 2005]
[Quartin etal 2008]
[Bean etal 2008]

- Coupling to neutrinos
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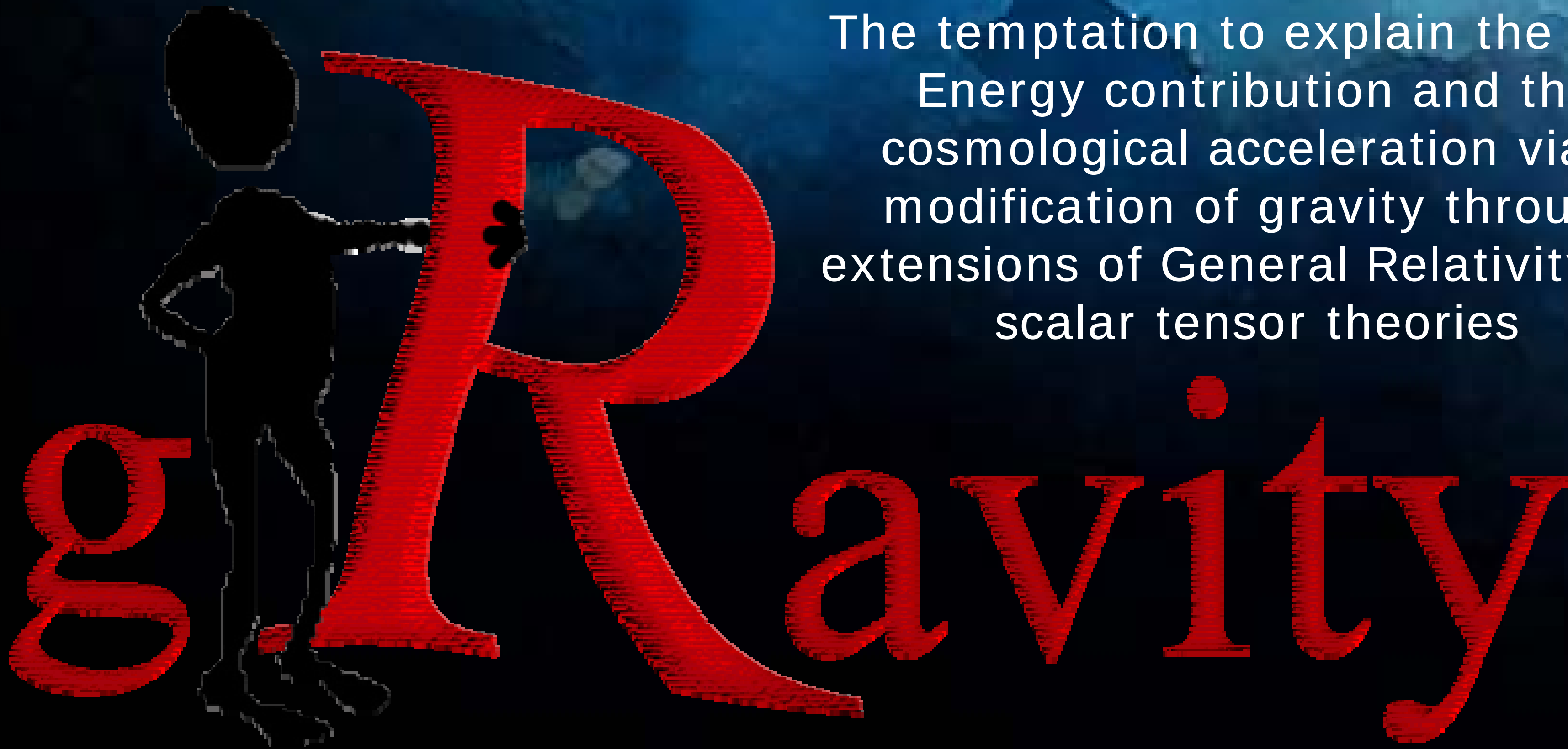
Generalized theories of...



The temptation to explain the Dark Energy contribution and the cosmological acceleration via a modification of gravity through extensions of General Relativity like scalar tensor theories

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa} f(\phi, R) - \frac{1}{2} Z(\phi) g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) + \mathcal{L}_{\text{fluid}} \left[\psi_m ; g_{\mu\nu} \right] \right]$$

Weyl scaling

Coupling a scalar field to gravity

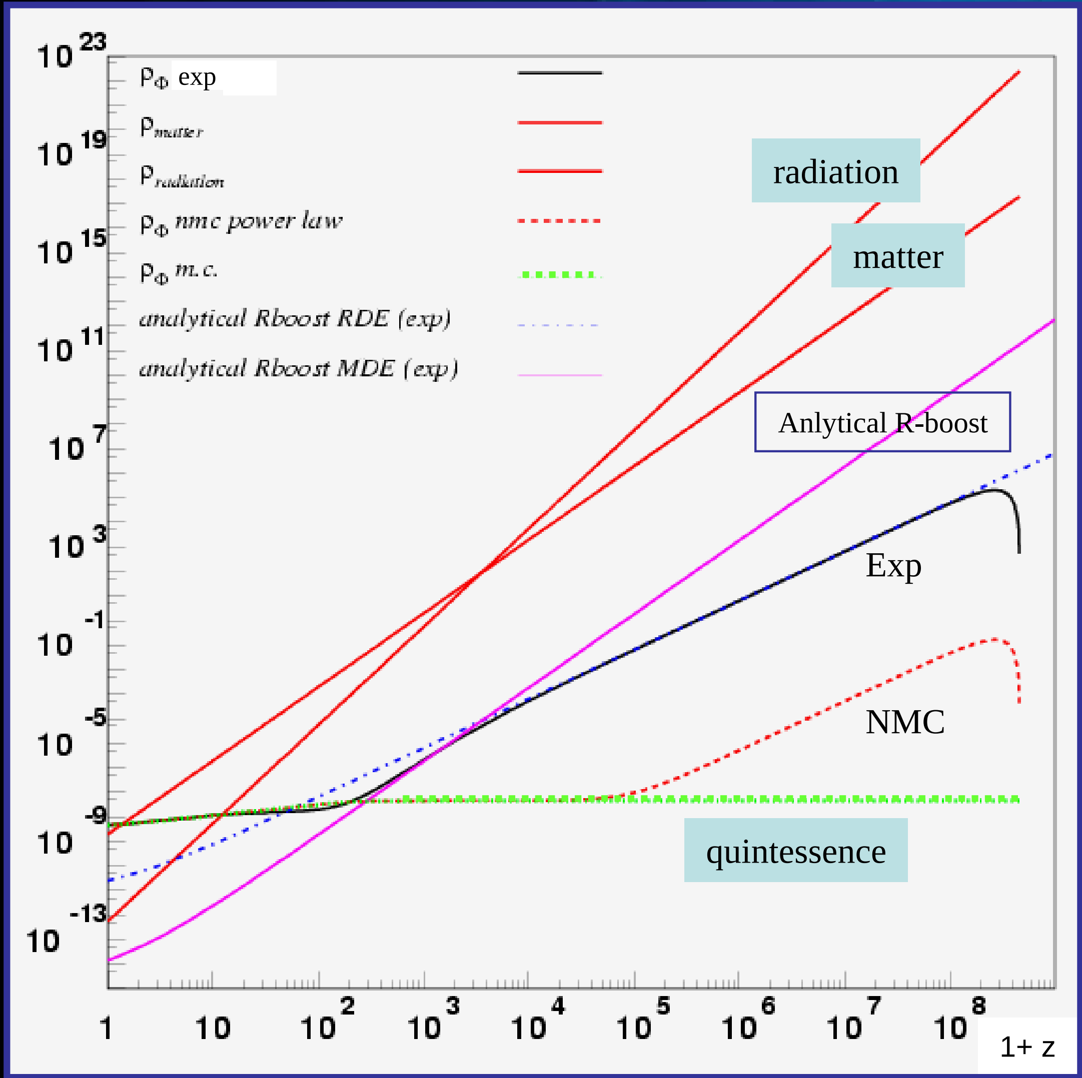
⇕

GR + coupling to all matter fields

$$m(\phi) = m_0 e^{-\frac{\beta}{M}(\phi - \phi_0)}$$

The coupling to baryons is constrained

Background



$$\omega_{JBD} \equiv F\left(\frac{dF}{d\phi}\right)^{-2} = -\frac{1}{\gamma - 1} \geq 4\times10^4$$

$$\phi'' + 2\mathcal{H}\phi' = \frac{a^2 F_\phi R}{2} - a^2 V_\phi$$

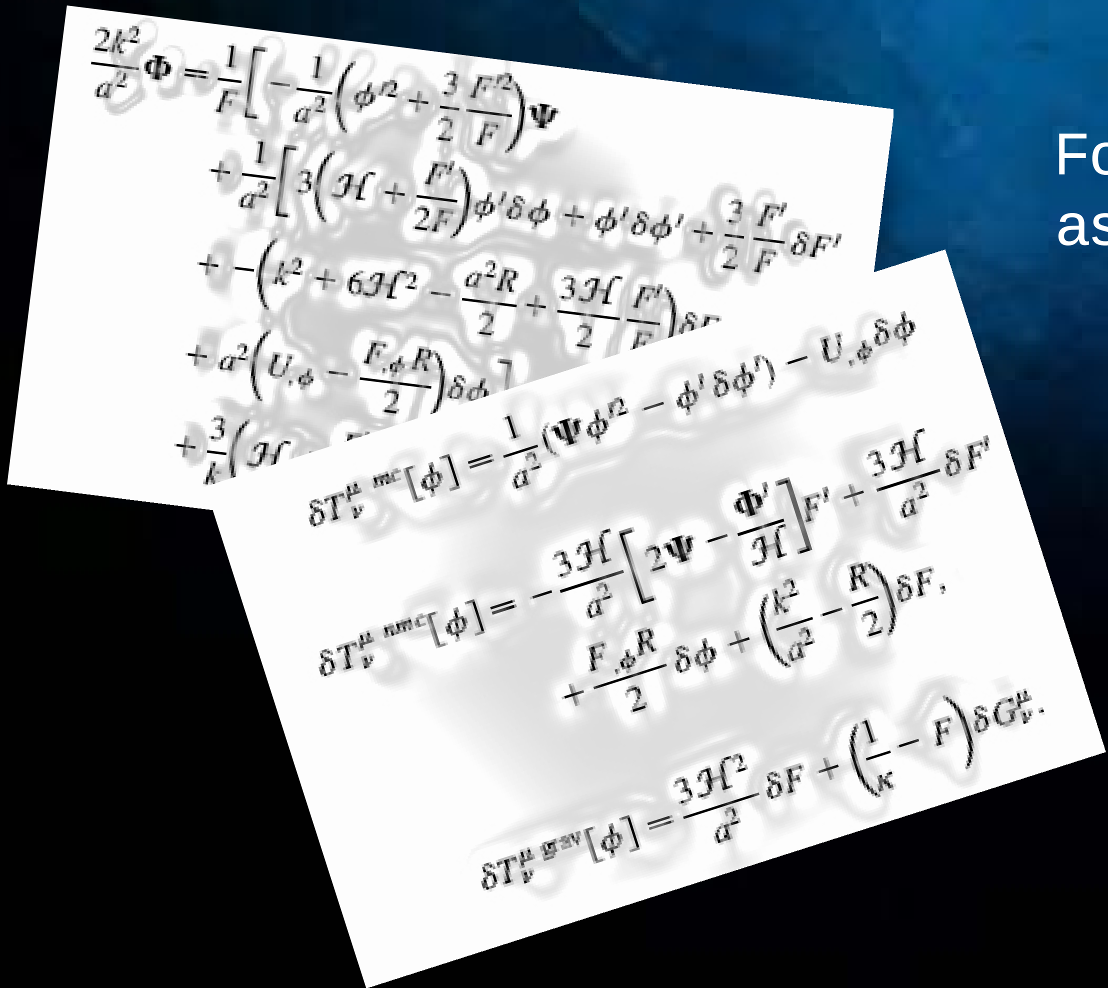
EXP
$$\frac{F(\phi)R}{2} = \frac{R}{16\pi G}\exp\left(\frac{\xi(\phi-\phi_0)}{M_P}\right)$$

NMC
$$F(\phi)R = \frac{R}{16\pi G} + \xi\phi^2 R$$

Attractor solutions

[Pettorino, Baccigalupi, Mangano 2004]
[Pettorino, Baccigalupi, Perrotta 2005]

Linear perturbations



Formally the same equations as in GR but...

$$\nabla^2 \Phi_E = -\frac{4\pi G}{F} a^2 \rho_f \delta_f$$

[Pettorino, Baccigalupi 2008]

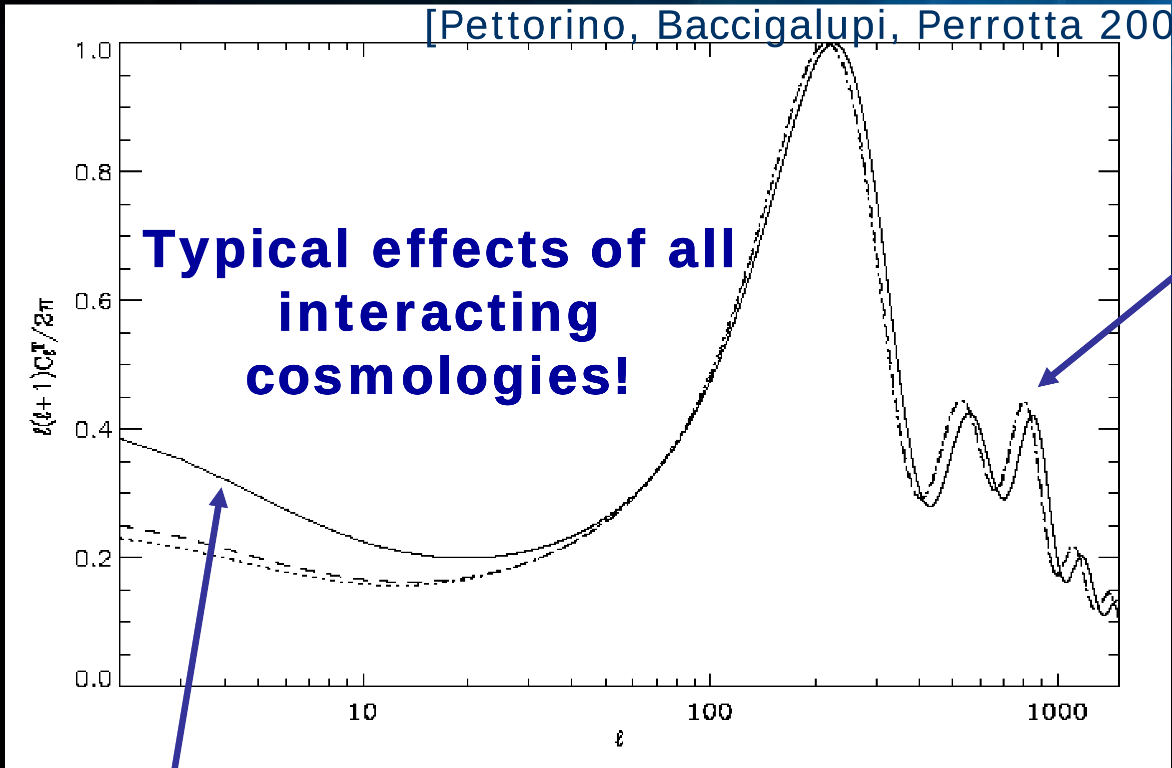
...with an effective gravitational ‘constant’

$$\tilde{G} = \frac{2(F + 2F_{,\phi}^2)}{(2F + 3F_{,\phi}^2)} \frac{1}{8\pi F}$$

Effects on the CMB

The angular scale is proportional to the horizon: $\theta \propto H^{-1}$

[Pettorino, Baccigalupi, Perrotta 2005]



Typical effects of all interacting cosmologies!

Projection effect

Larger LISW

DEfast

an implementation of CMBfast which allows to study minimal and non-minimal coupled quintessence scenarios.

[Baccigalupi etal 2000]

It takes into account the gravitational redshift (blueshift) of photons climbing out time varying gravitational potential wells along the line of sight when DE occurs to dominate

Relevant effects at the non linear level might be observable

Nbody simulations for EQ

GADGET [V.Springel 2005] has been implemented:

1. Different background expansion, computed with DEfast
2. Different linear growth factors used to rescale initial conditions
3. Effective gravitational interaction between all particles

[Dolag, Pettorino, Moscardini, Baccigalupi, Bartelmann, Meneghetti] in progress

$$\tilde{G} = \frac{2(F + 2F_{,\phi}^2)}{(2F + 3F_{,\phi}^2)} \frac{1}{8\pi F}$$

Hidrodynamical simulations have been carried out

- $L_{box} = 300$ Mpc/h, $n_p = 2 \times 768^3$, $\epsilon_G = 7.5$ kpc/h

$\Rightarrow$ $m_{DM} = 3.7 \times 10^9 M_\odot/h$ and $m_{gas} = 7.3 \times 10^8 M_\odot/h$

Data analysis in progress!

Coupled quintessence

Background

Consider dark energy as a quintessence scalar field

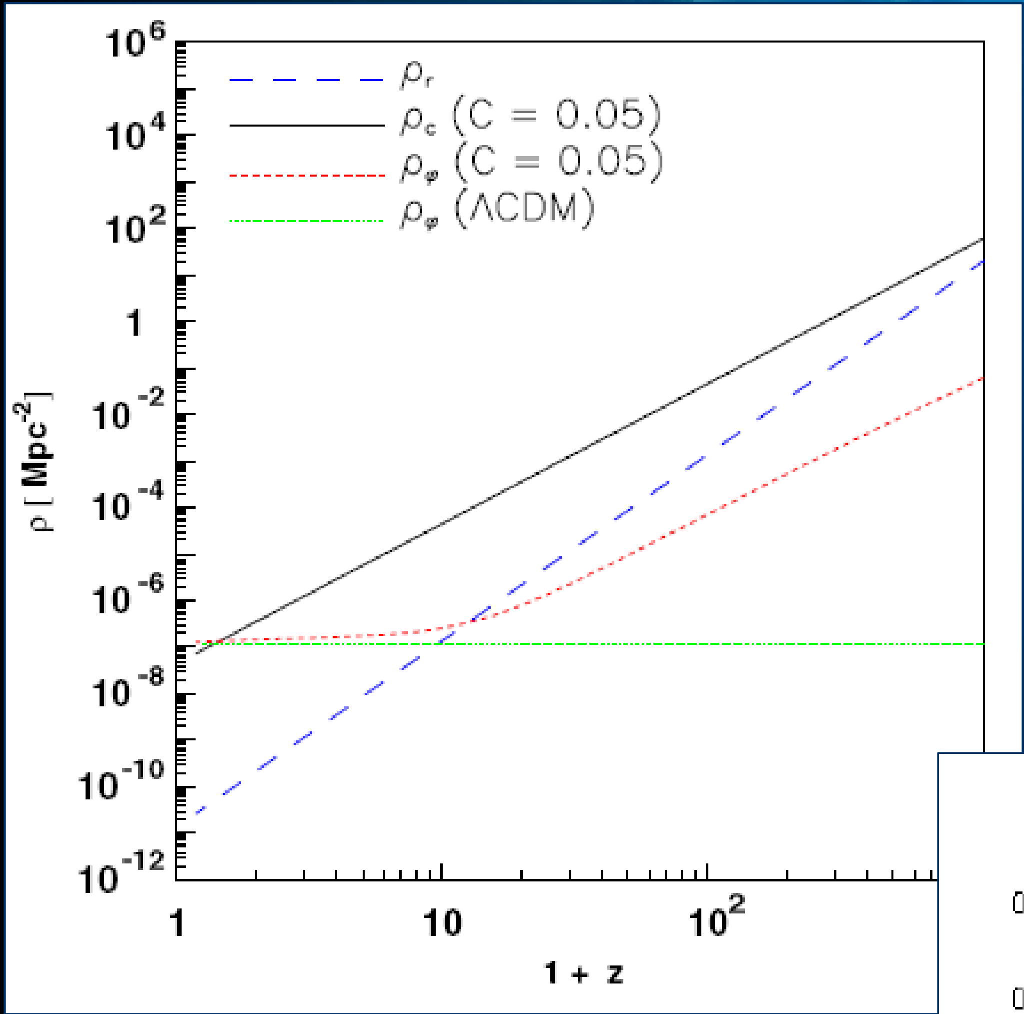
$$\rho_\phi = \frac{\phi'^2}{2a^2} + V(\phi)$$

[Rhatra and Peebles 1988]
[Wetterich 1988]

coupled to a species whose mass is now function of ϕ

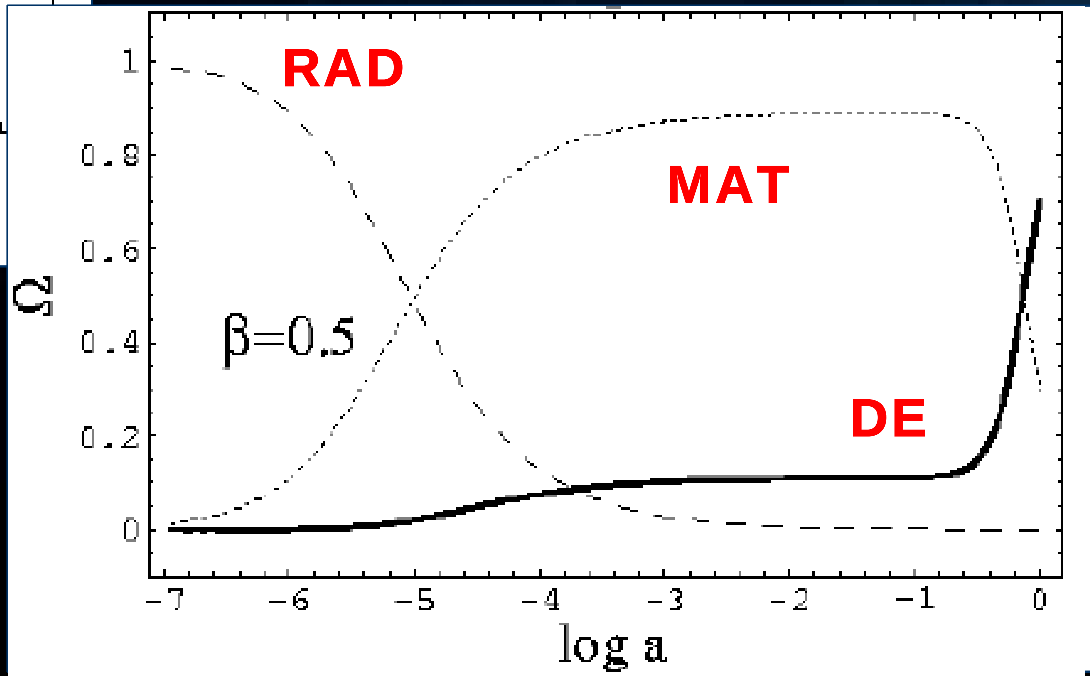
$$m_c = \bar{m} e^{-\tilde{\beta}\phi}$$

[Wetterich 1995]
[Amendola 2000, 2004]
[Mangano, Miele, Pettorino 2005]



Pattern for the background similar to extended quintessence

Non negligible amount of dark energy in the past



Linear perturbations

$$\delta\rho'_\phi + 3\mathcal{H}(\delta\rho_\phi + \delta p_\phi) + kh_\phi v_\phi + 3h_\phi \mathbf{\Phi}' = \frac{\beta(\phi)}{M}\rho_c\delta\phi' + \frac{\beta(\phi)}{M}\phi'\delta\rho_c + \frac{\beta_{,\phi}}{M}\phi'\delta\phi\rho_c$$

$$\delta\rho'_c + 3\mathcal{H}\delta\rho_c + k\rho_c v_c + 3\rho_c\mathbf{\Phi}' = -\frac{\beta(\phi)}{M}\rho_c\delta\phi' - \frac{\beta(\phi)}{M}\phi'\delta\rho_c - \frac{\beta_{,\phi}}{M}\phi'\delta\phi\rho_c$$

$$h_\phi v'_\phi + \left(h'_\phi + 4\mathcal{H}h_\phi\right)v_\phi - k\delta p_\phi - kh_\phi\mathbf{\Psi} = k\frac{\beta(\phi)}{M}\rho_c\delta\phi$$

$$v'_c + \left(\mathcal{H} - \frac{\beta(\phi)}{M}\phi'\right)v_c - k\mathbf{\Psi} = -k\frac{\beta(\phi)}{M}\delta\phi$$

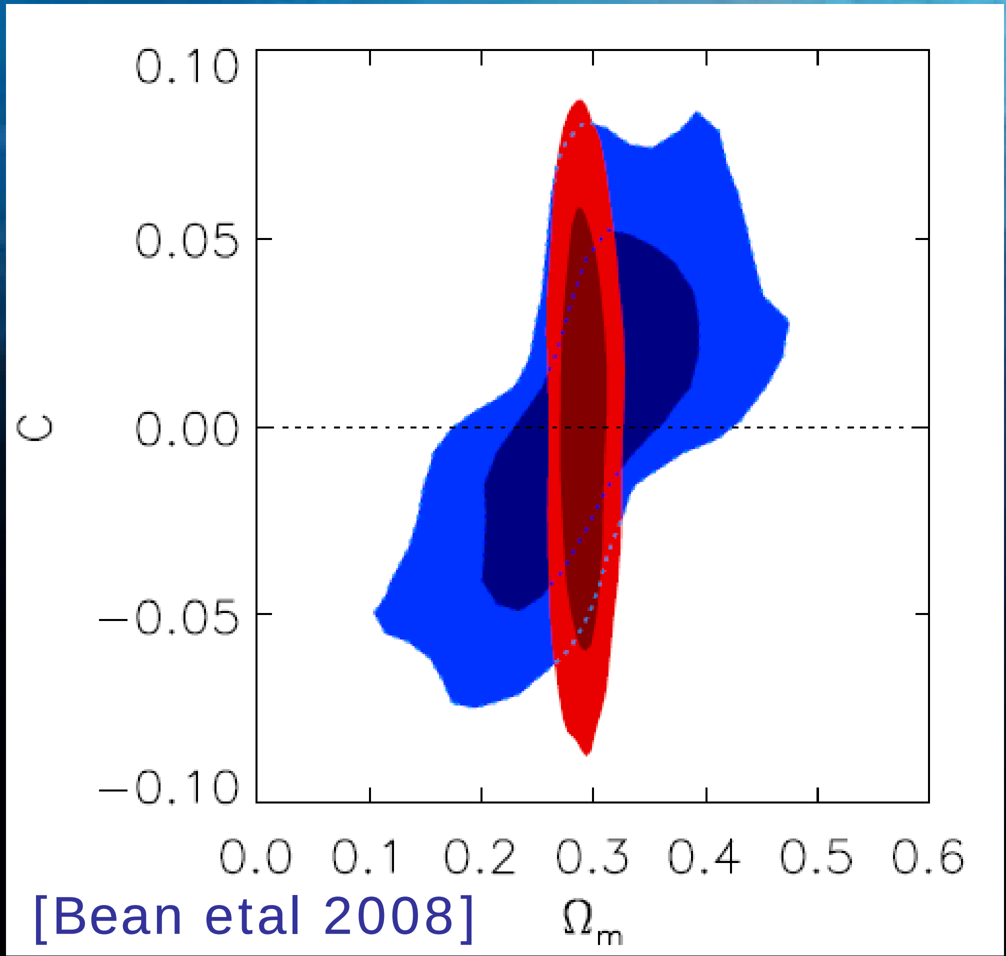
Generalized coupled quintessence

Constraints to the coupling from CMB data $\beta \leq 0.1$ (for a constant coupling)

[Bean etal 2008] →

WARNING:
constraints for constant coupling models

Implementation of CMBEASY to include general coupling mass function $m(\phi)$

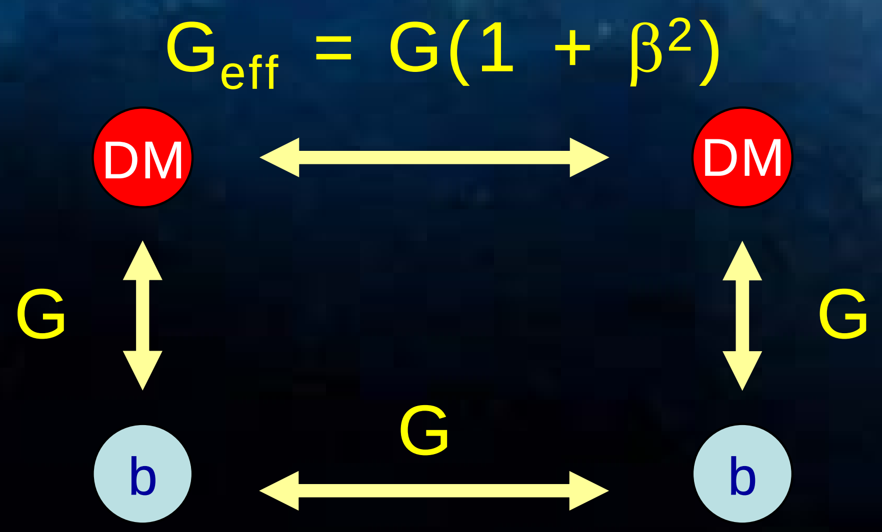


Monte Carlo analysis in progress!
[Robbers, Pettorino]

Recipe for N-body codes

Extra interaction between cdm particles, mediated by the quintessence scalar field

1. Effective gravitational interaction between DM particles
2. The mass of DM particles varies
3. An extra friction term is present



$$\delta_c'' + \left(\mathcal{H} - \beta\phi'\right)\delta_c' - \frac{3}{2}\mathcal{H}^2\left[\left(1 + 2\beta^2\right)\Omega_c\delta_c + \Omega_b\delta_b\right] = 0$$

Nbody simulations for CQ

M.Baldi, V.Pettorino, G.Robbers
in preparation, very soon to come!

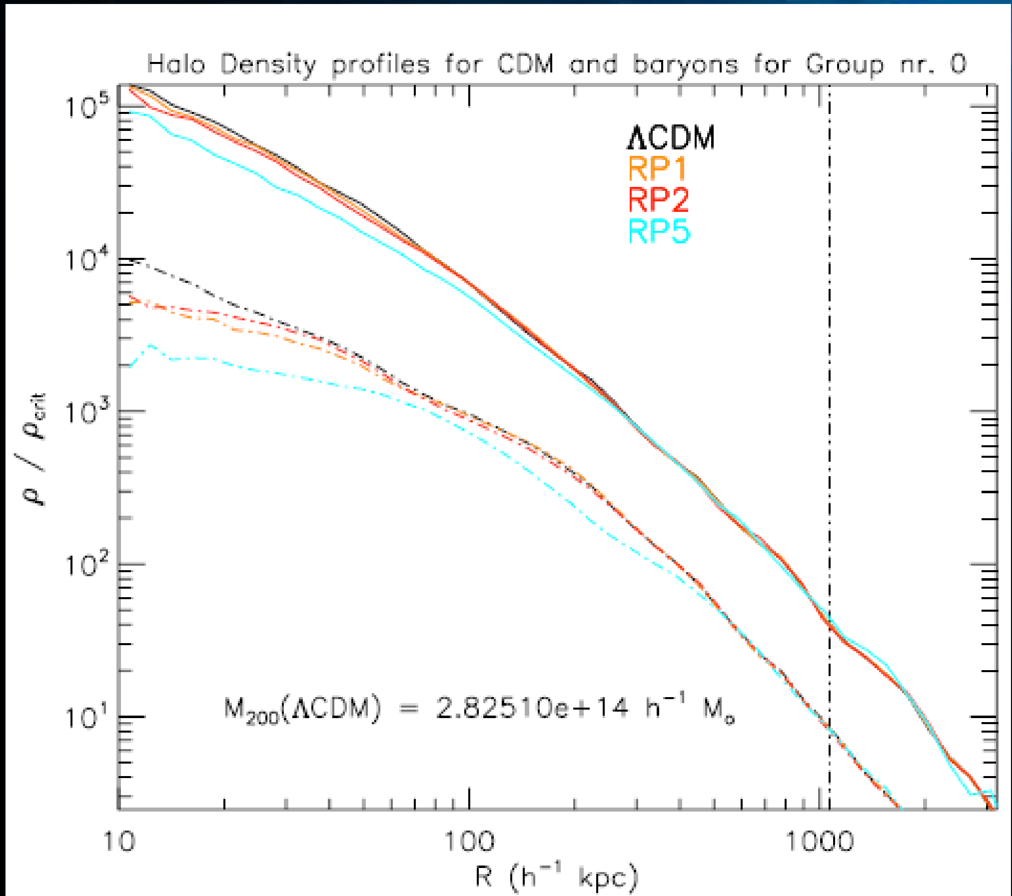
$L_{\rm box} = 80\,{\rm h}^{-1}{\rm Mpc}$	$m_c(z=0) \sim 2 \cdot 10^8\,{\rm h}^{-1}{\rm M}_\odot$
$N = 2 \times 512^3$	$m_b \sim 5 \cdot 10^7\,{\rm h}^{-1}{\rm M}_\odot$
$\epsilon_g = 3.5\,{\rm h}^{-1}{\rm kpc}$	$z_i = 60$

All the corrections have been implemented in GADGET

[V.Springel 2005]

- Less steep density profiles
- Lower halo concentrations
- Scale dependent bias between baryons and cdm

Result~~s~~: density profiles



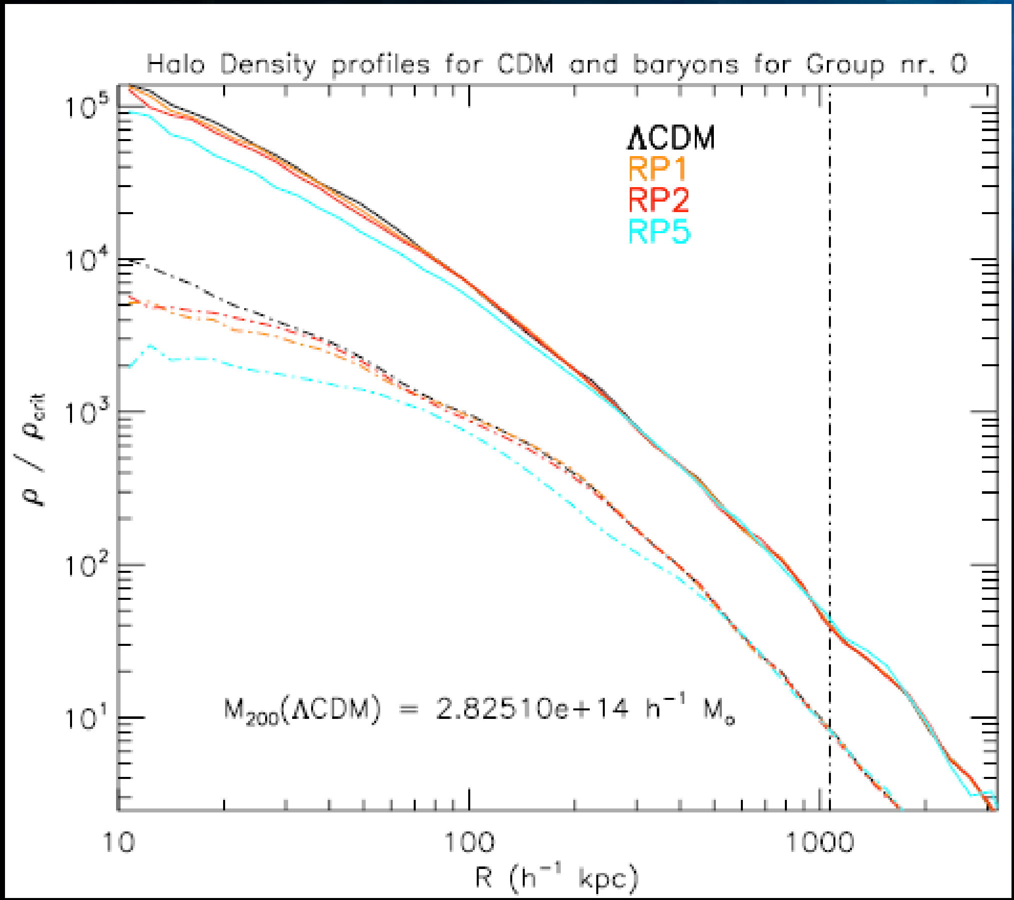
Baldi Pettorino Robbers
in preparation

The inner density decreases with increasing coupling both for cdm and for baryons

Results in contrast with Macciò etal 2004

More on scale dependent bias and halo concentration...

Results: density profiles



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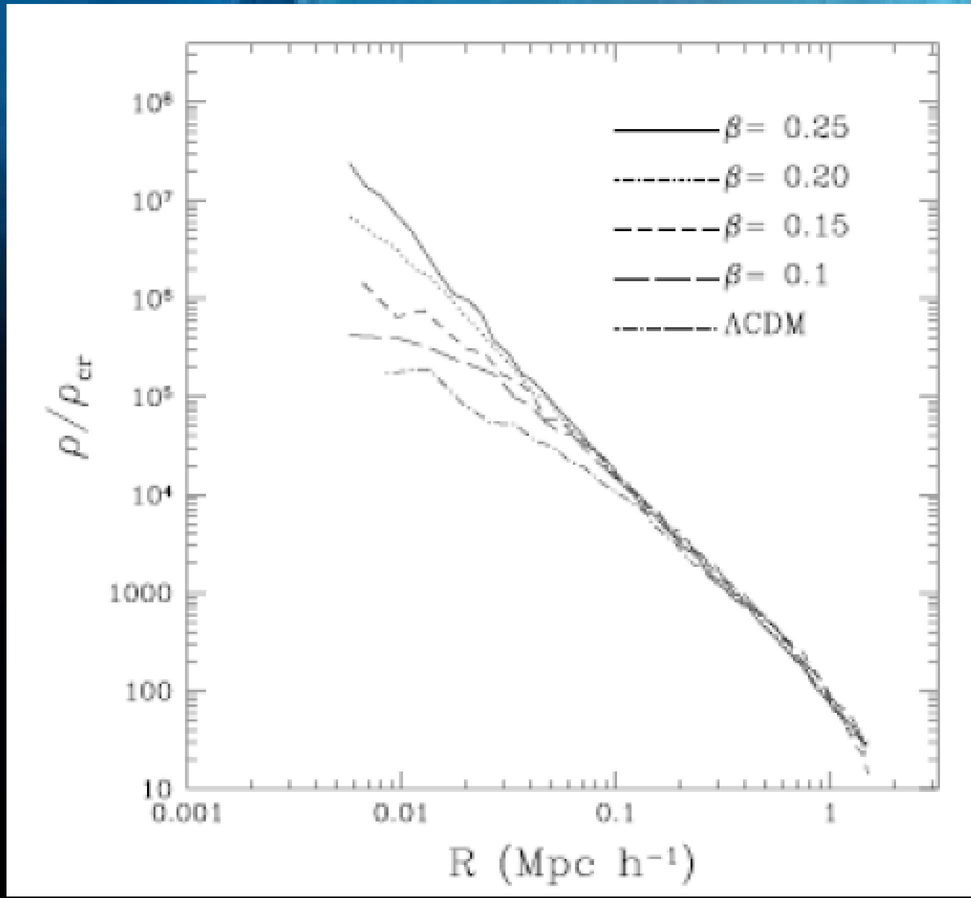
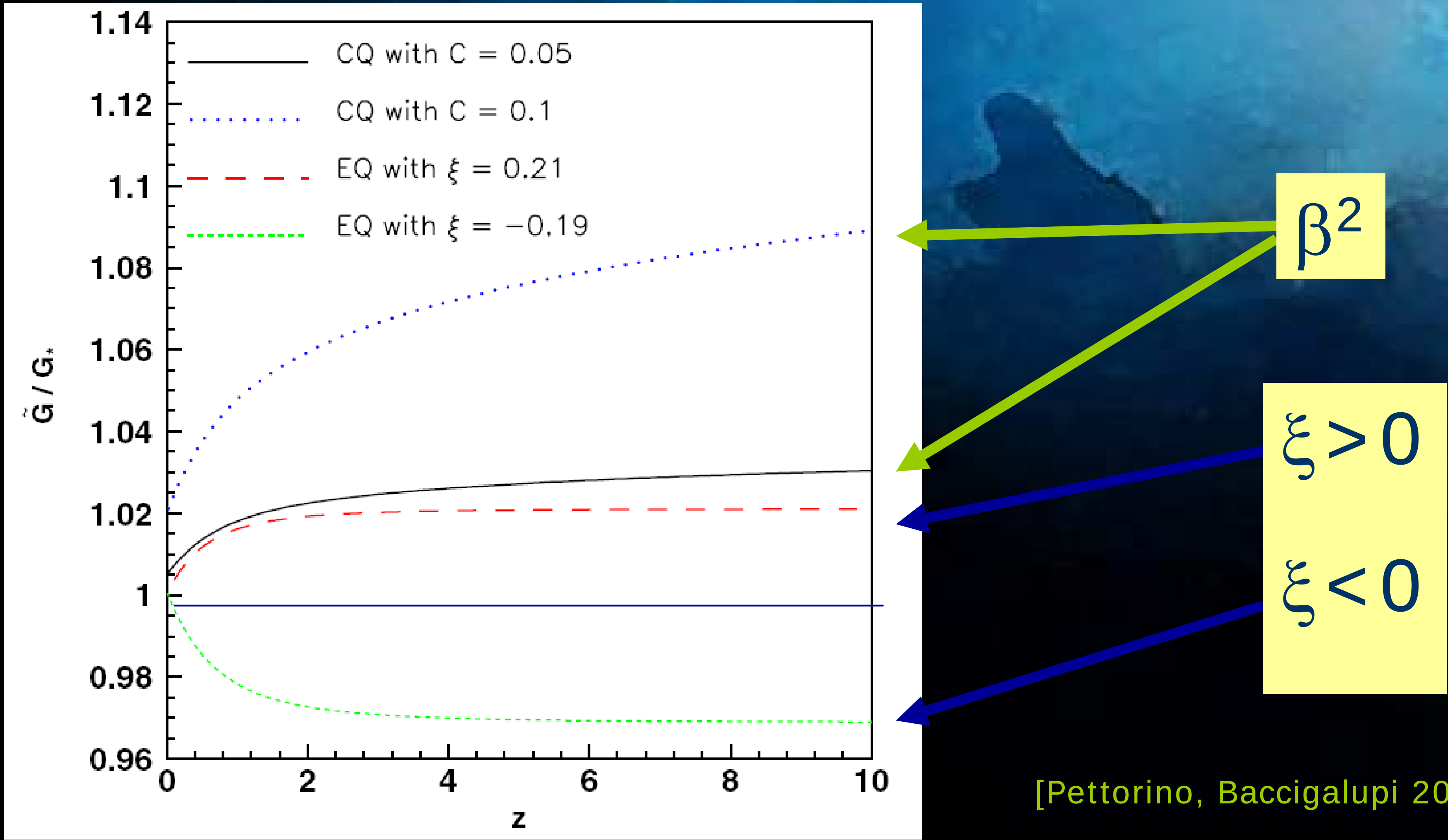


Macciò etal 2004

Note that...



[Pettorino, Baccigalupi 2008]

In constant coupling CQ the effective gravitational constant is always stronger than G

Growing neutrino quintessence

Interaction with neutrinos

Coupling to neutrinos

can have a significant influence in cosmology (Wetterich 2007)

MAVANS: Fardon etal 2004, Afshordi etal 2005, Bjaelde etal 2008, Brookfield etal 2007, ...

Growing neutrinos: Amendola etal 2007, Wetterich 2007, Mota etal 2008, Brouzakis etal 2007

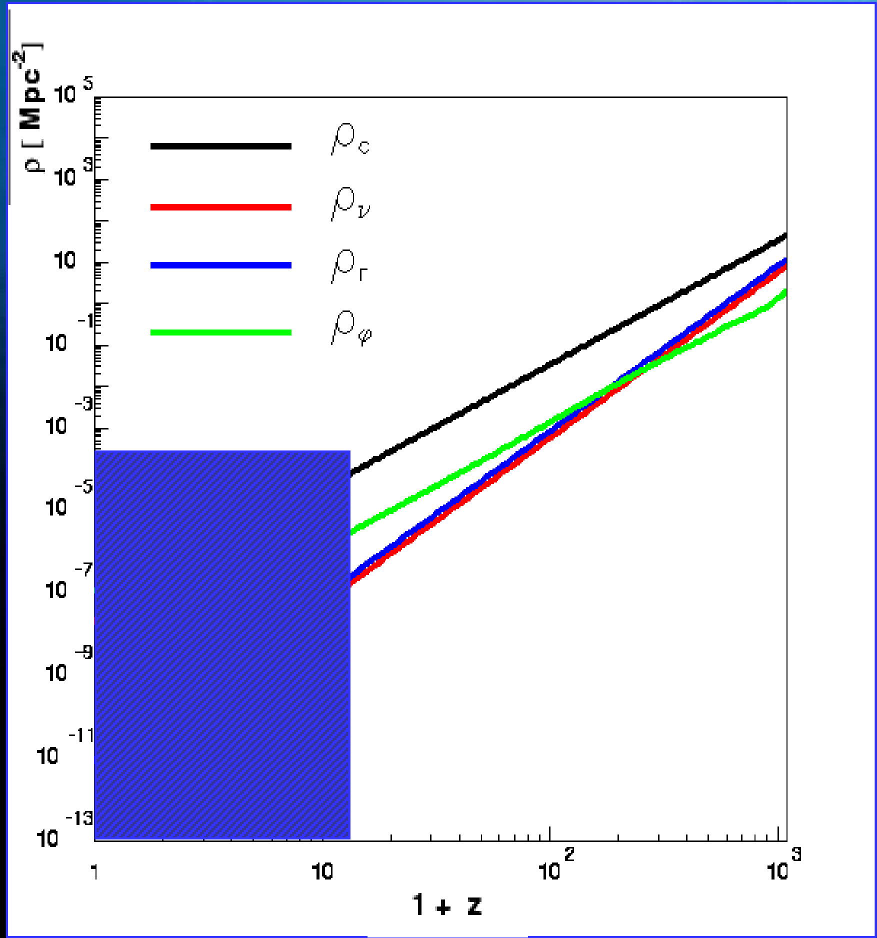
Exponential potential

- $V(\phi) = M^4 \exp(-\alpha\phi)$

- Solutions independent of the initial conditions
- DE scales as a constant fraction tracking the background:

  $\Omega_\phi = n/\alpha^2$

  with n = 3(4) in MDE (RDE)



Need a cosmological event that triggers the end of the attractor era

Neutrinos become non relativistic

Attractor with constant fraction of DE + ~~coupling~~

$$\rho'_\phi = -3\mathcal{H}(1+w_\phi)\rho_\phi + \beta(\phi)\phi'(1-3w_\nu)\rho_\nu$$

$$\rho'_\nu = -3\mathcal{H}(1+w_\nu)\rho_\nu - \beta(\phi)\phi'(1-3w_\nu)\rho_\nu$$

$$\phi'' + 2\mathcal{H}\phi' + a^2\frac{dU}{d\phi} = a^2\beta(\phi)(\rho_\nu - 3p_\nu)$$

$$\beta(\phi) \equiv -\frac{d\ln m_\nu}{d\phi}$$

Neutrino mass grows (β < 0)

$$m_\nu = \bar{m}_\nu e^{-\tilde{\beta}(\phi)\phi}$$

Neutrinos become non relativistic

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$$\rho'_\phi = -3\mathcal{H}(1+w_\phi)\rho_\phi + \beta(\phi)\phi'(1-3w_\nu)\rho_\nu$$
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Neutrino mass grows ($\beta < 0$)

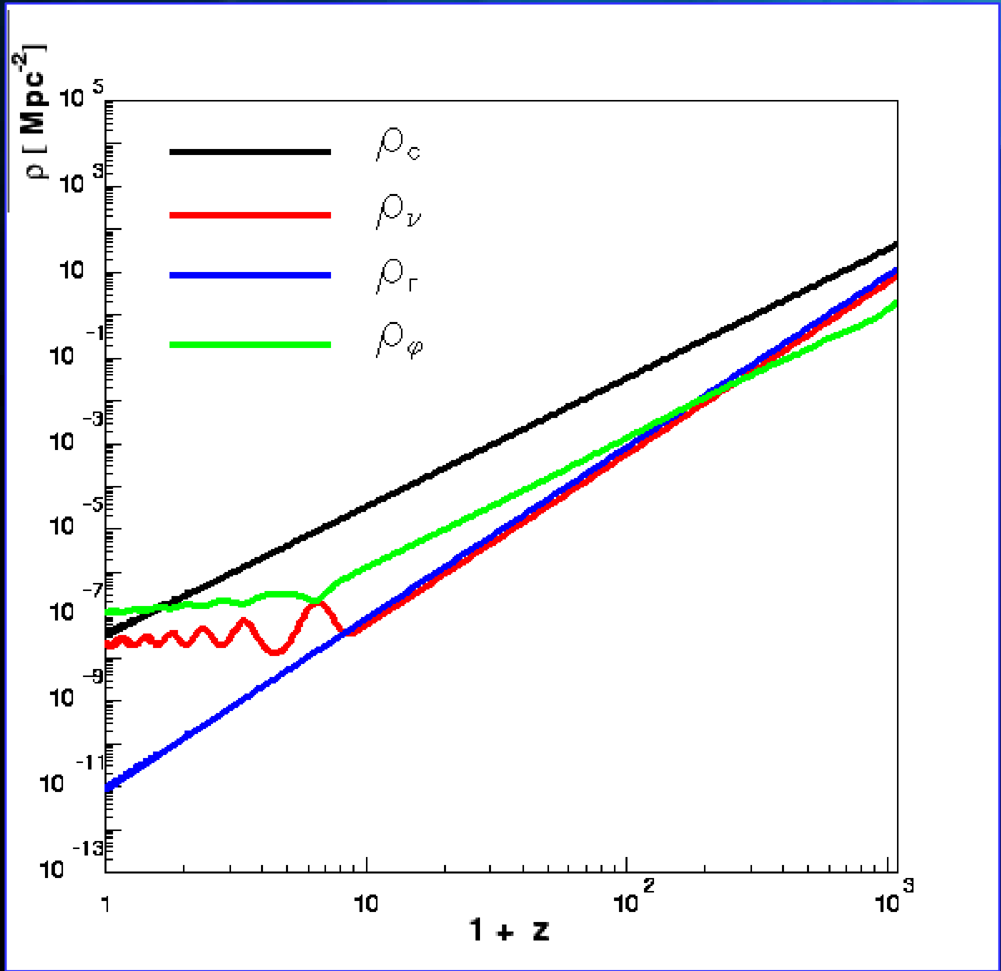
$$m_\nu = \bar{m}_\nu e^{-\tilde{\beta}(\phi)\phi}$$

Neutrinos become non relativistic

The coupling to DE turns on and almost stops ϕ

Acceleration

Coupling Dark Energy to neutrinos



Dark energy - neutrino connection

- Dark energy and neutrino properties are related

$$\Omega_h(t_0) \approx \frac{\gamma m_\nu(t_0)}{16eV}$$

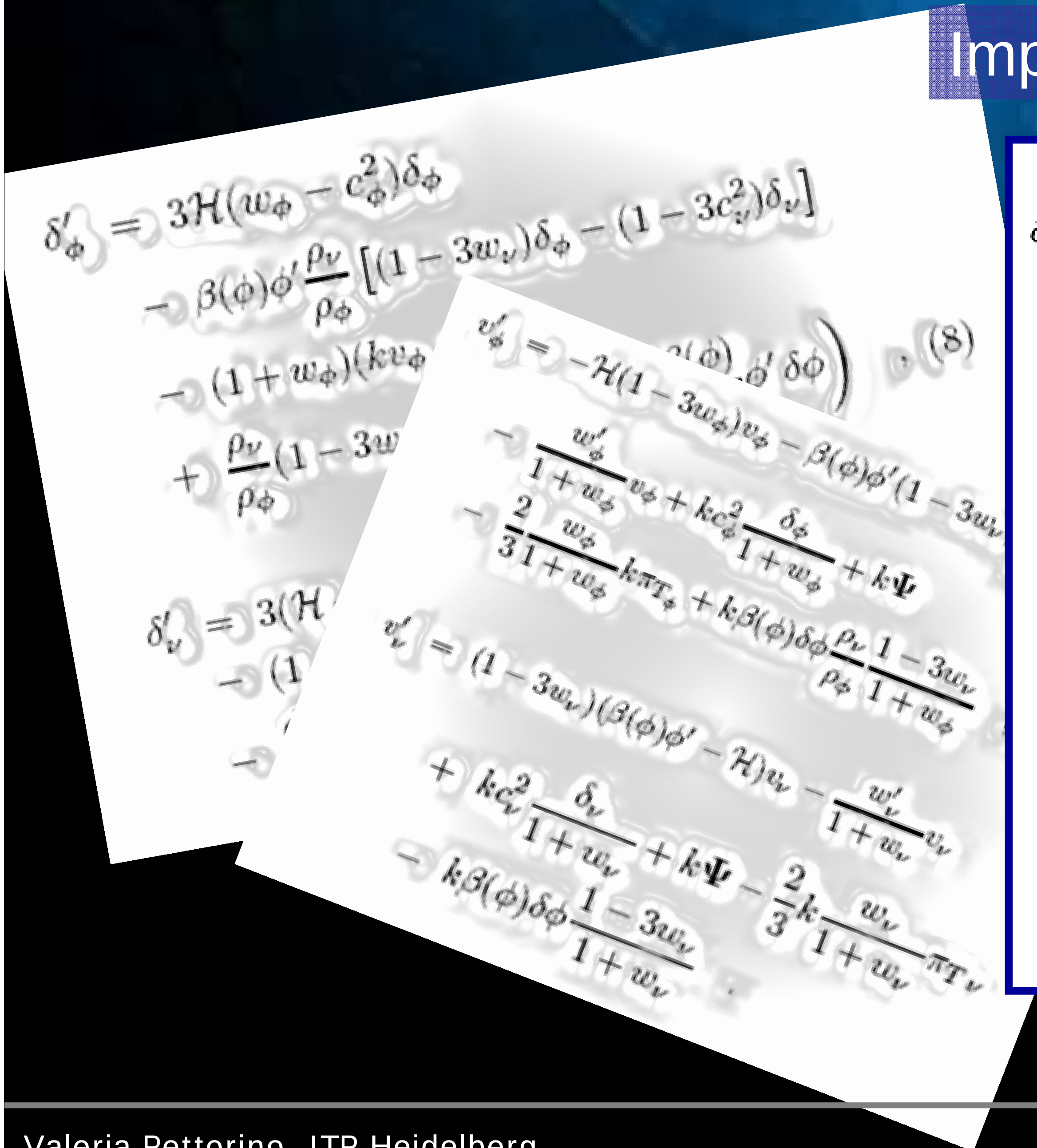
The present amount of DE is set by a cosmological event and not by ground state properties

$$\gamma = -\frac{\beta}{\alpha}$$

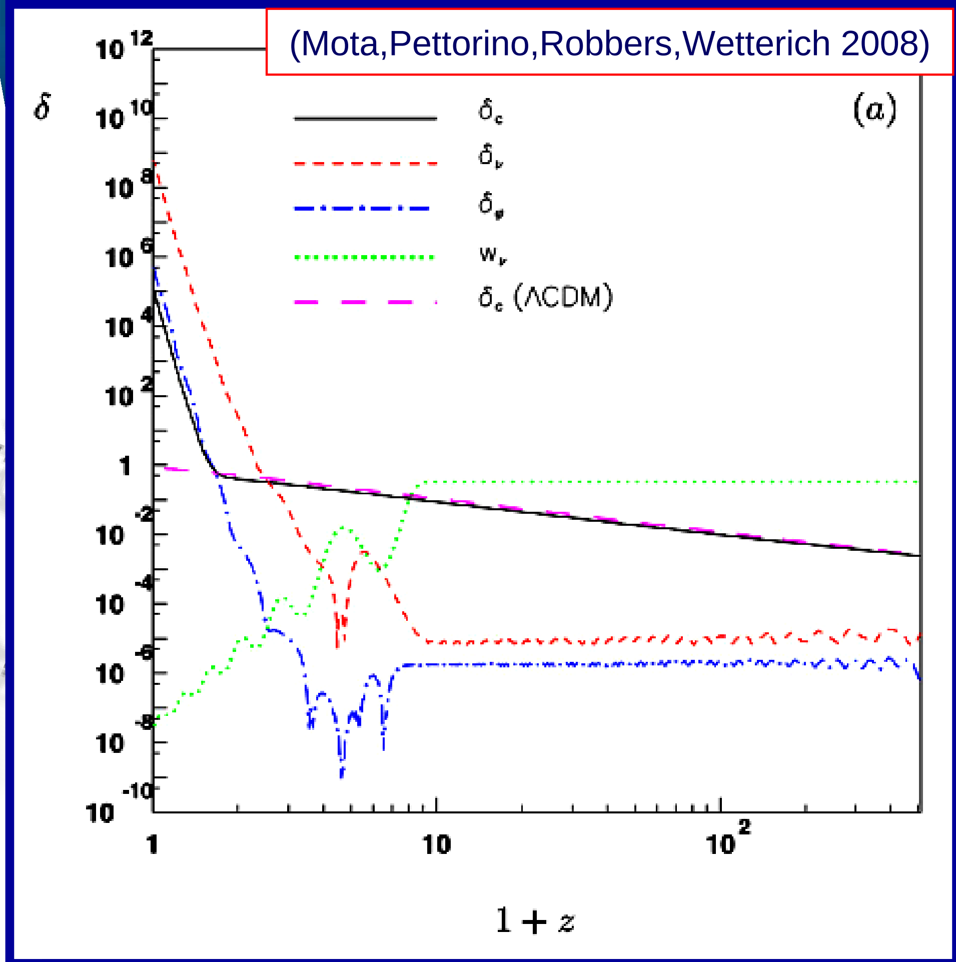
DE-ν fluid equation of state

$$w_0 \approx -1 + \frac{m_\nu(t_0)}{12\mathrm{eV}}$$

Linear perturbations



Implement CMBEASY, CAMB…



k = 0.1 h/Mpc

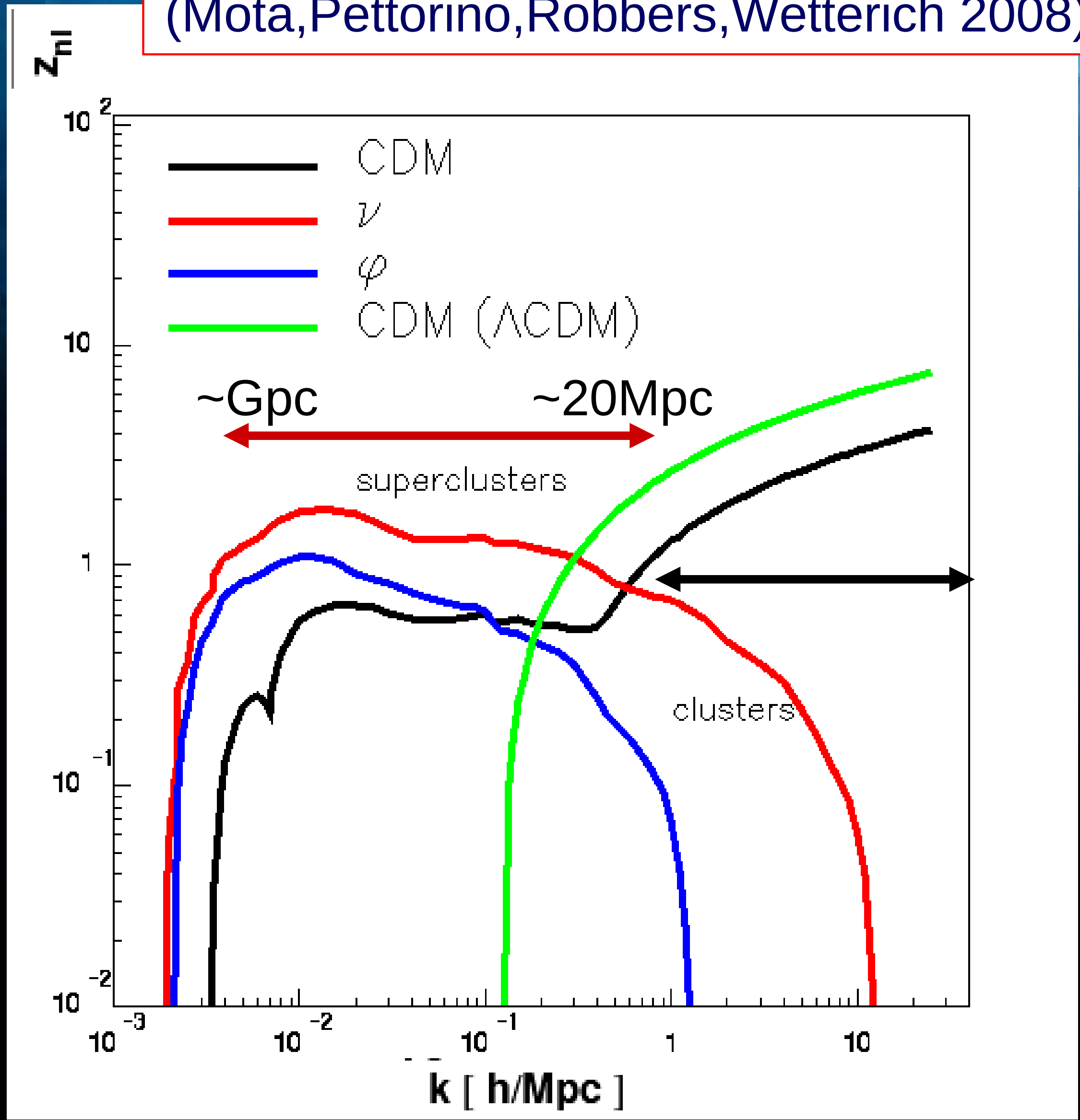
Neutrino clustering

- Neutrino structures become non linear at z ~ 1 for supercluster scales

- At small scales neutrinos reduce CDM structures

- Stable neutrino lumps (Brouzakis etal 2007)

(Mota,Pettorino,Robbers,Wetterich 2008)



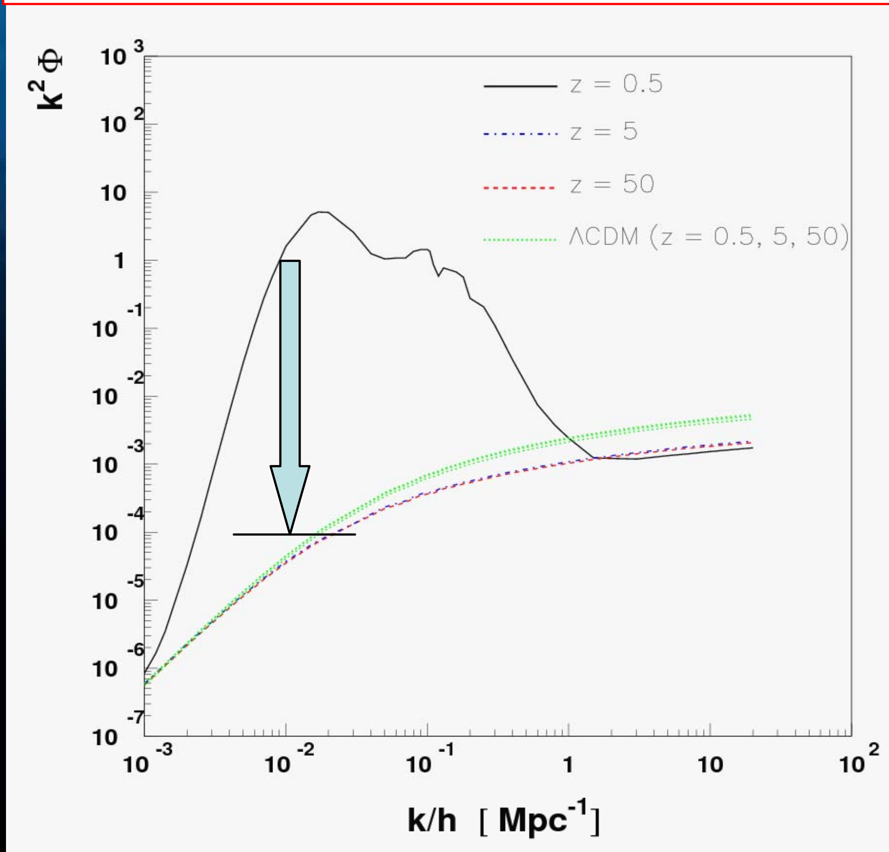
Gravitational potential

• Linear analysis is not sufficient. The gravitational potential is not realistic and can lead to a huge ISW in CMB. However...

• There aren't many neutrinos!

• If they distribute more or less homogeneously in more lumps, the gravitational potential can be significantly reduced

(Mota,Pettorino,Robbers,Wetterich 2008)



Essential to have a knowledge of the realistic gravitational potential due to the presence of a distribution of virialized neutrino lumps

Non linear analysis...

Work in progress!

- Non linear analysis of structure formation, from semi analytical approaches to N-body simulations

Non linear evolution of the primordial overdensities driven by the fifth force

Φ

N.Wintergest, V.Pettorino, D.F.Mota, L.Schrempp, C.Wetterich

- Use data to constrain the coupling (or the neutrino mass)

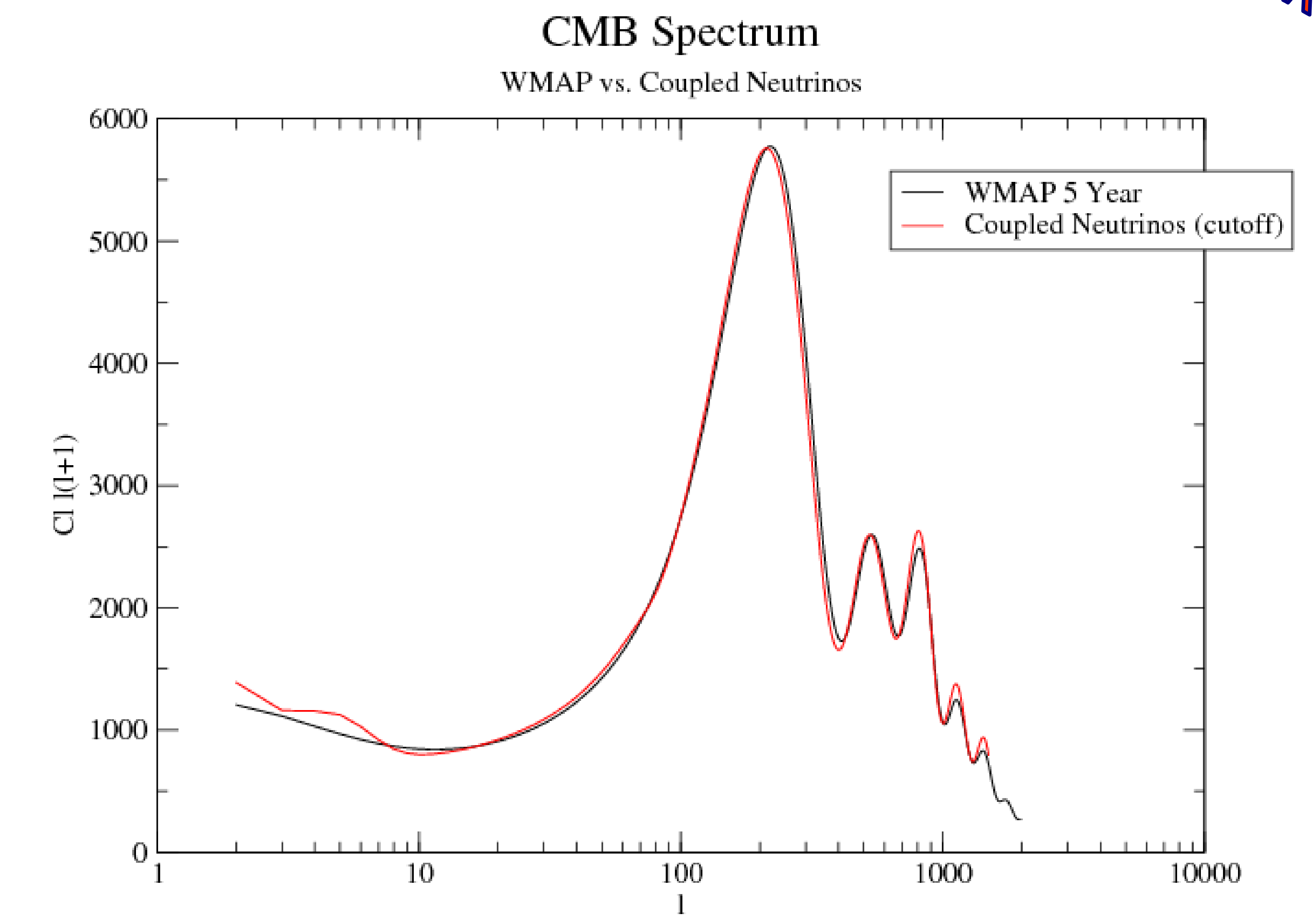
...and CMB

SNae bounds in Rubin etal 2008

E.Carlesi, D.Mota, V.Pettorino, G.Robbers, C.Wetterich

Work in progress!

...first results are encouraging



Work in progress!

Monte Carlo analysis necessary!

Work in progress!

E.Carlesi, D.Mota, V.Pettorino, G.Robbers, C.Wetterich

Summary

Interacting Dark Energy	Linear	Non Linear
Gravity	√	~ data analysis of Nbody in progress
CDM	√	coming soon: Baldi etal
Neutrinos	√	Under investigation

Conclusions for DE - neutrinos

- When neutrinos become non relativistic, they activate the coupling.
- Transition from attractor to an almost static dark energy, independent of ground state properties.
- Neutrinos first cluster at z ~ 1 at supercluster scales and beyond.
- At small scales, neutrinos don’t contribute to the clumping but they reduce cdm structures.
- Detection of such a population of large scale structures via gravitational potential or correlation with CMB can be an indication for a new attractive force stronger than gravity.

Future prospects

- Non linear features of interacting dark energy models
- Data analysis of N-body simulations
- Cross correlation with CMB
- Applications and forecast for future dark energy missions

NASA JOINT DARK ENERGY MISSION
Beyond Einstein Program

ESA Cosmic Vision Program