Title: Clustering in interacting dark energy cosmologies

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Abstract: I will illustrate the case of interacting dark Energy, that is to say cosmologies in which the dark energy scalar field interacts with other things in the universe (gravity, cold dark matter or neutrinos). After briefly presenting the status of our work for the first two classes of models, regarding both linear perturbations and Nbody simulations, I will in particular focus on the case of \'growing neutrinos\': in these models, neutrinos with a mass increasing with time might be driven to cluster at very large scales, due to a new interaction stronger than gravity and mediated by the dark energy scalar field.

Clustering in interacting Dark Energy cosmologies

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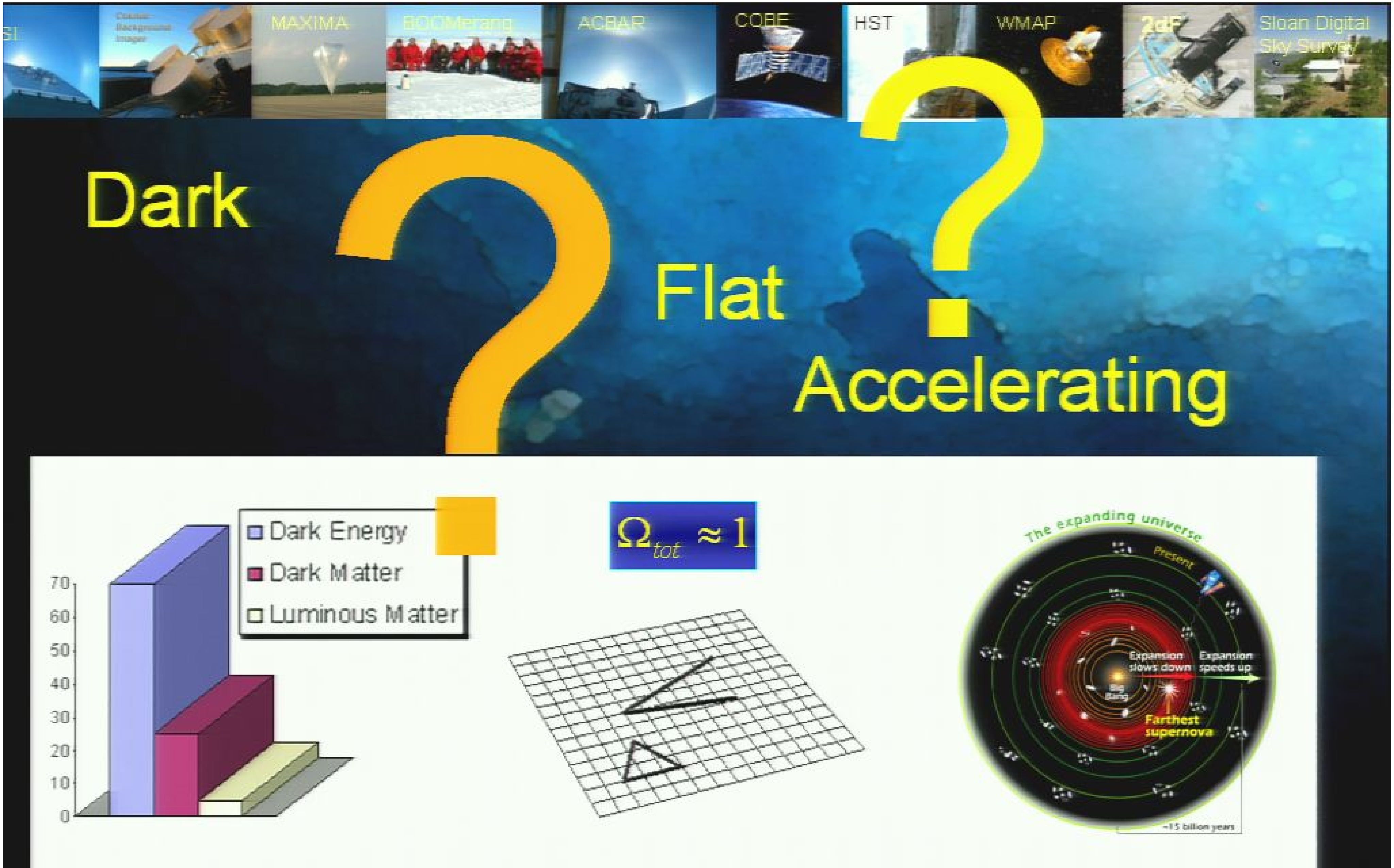
Overview

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


MAXIMA
BOOMerang
ACBAR
COBE
HST
WMAP
2dF
Sloan Digital Sky Survey
Dark
Flat
Accelerating
Dark Energy
Dark Matter
Luminous Matter
70
60
50
40
30
20
10
0
$\Omega_{tot} \approx 1$
The expanding universe
Present
Expansion slows down
Expansion speeds up
Farthest supernova
~15 billion years

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**
  - cosmological bounds
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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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  - role in clustering?

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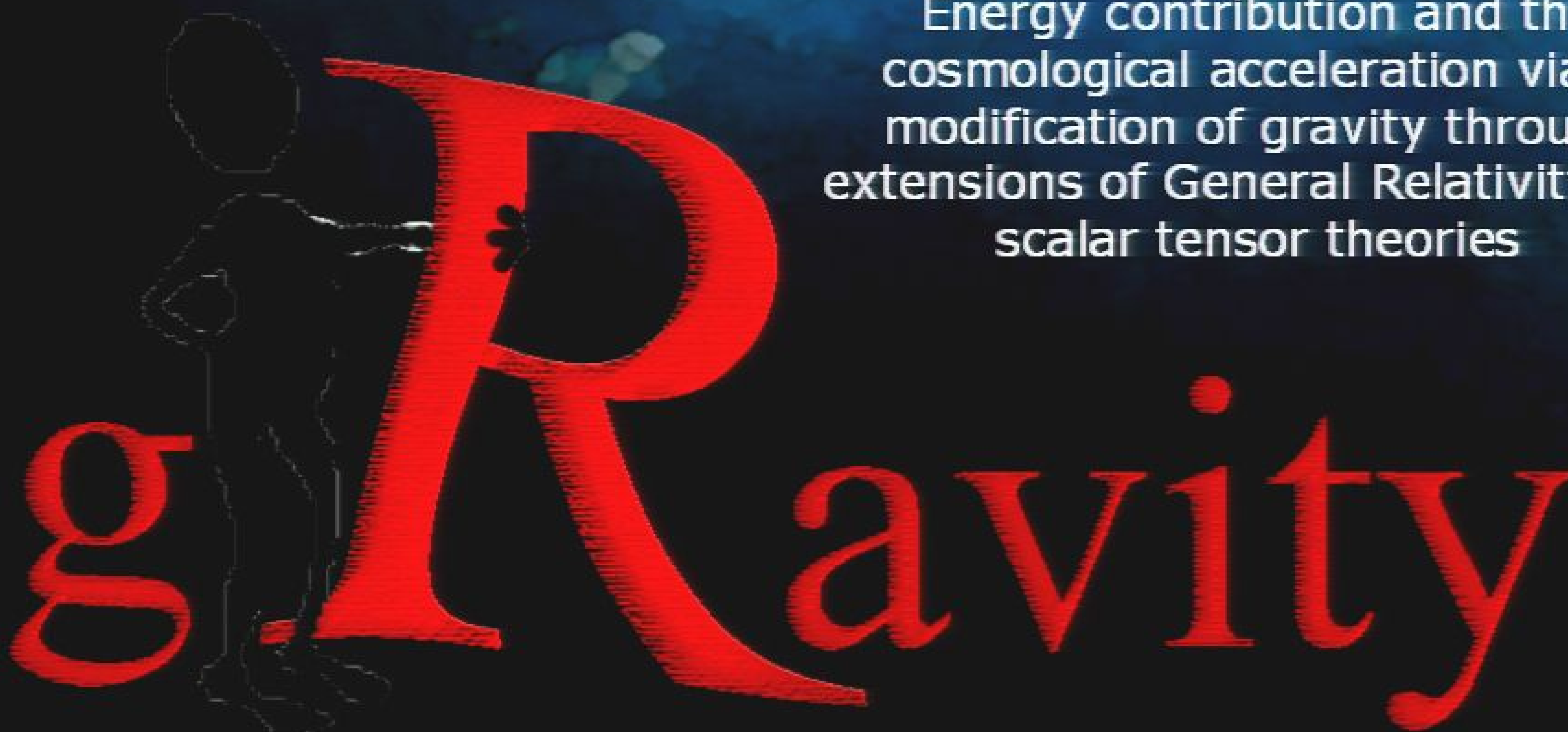
Generalized theories of…

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



Extended quintessence

Scalar field

Ricci scalar $\rightarrow$ metric tensor $g_{\mu\nu}$

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

$\kappa = 8\pi G$

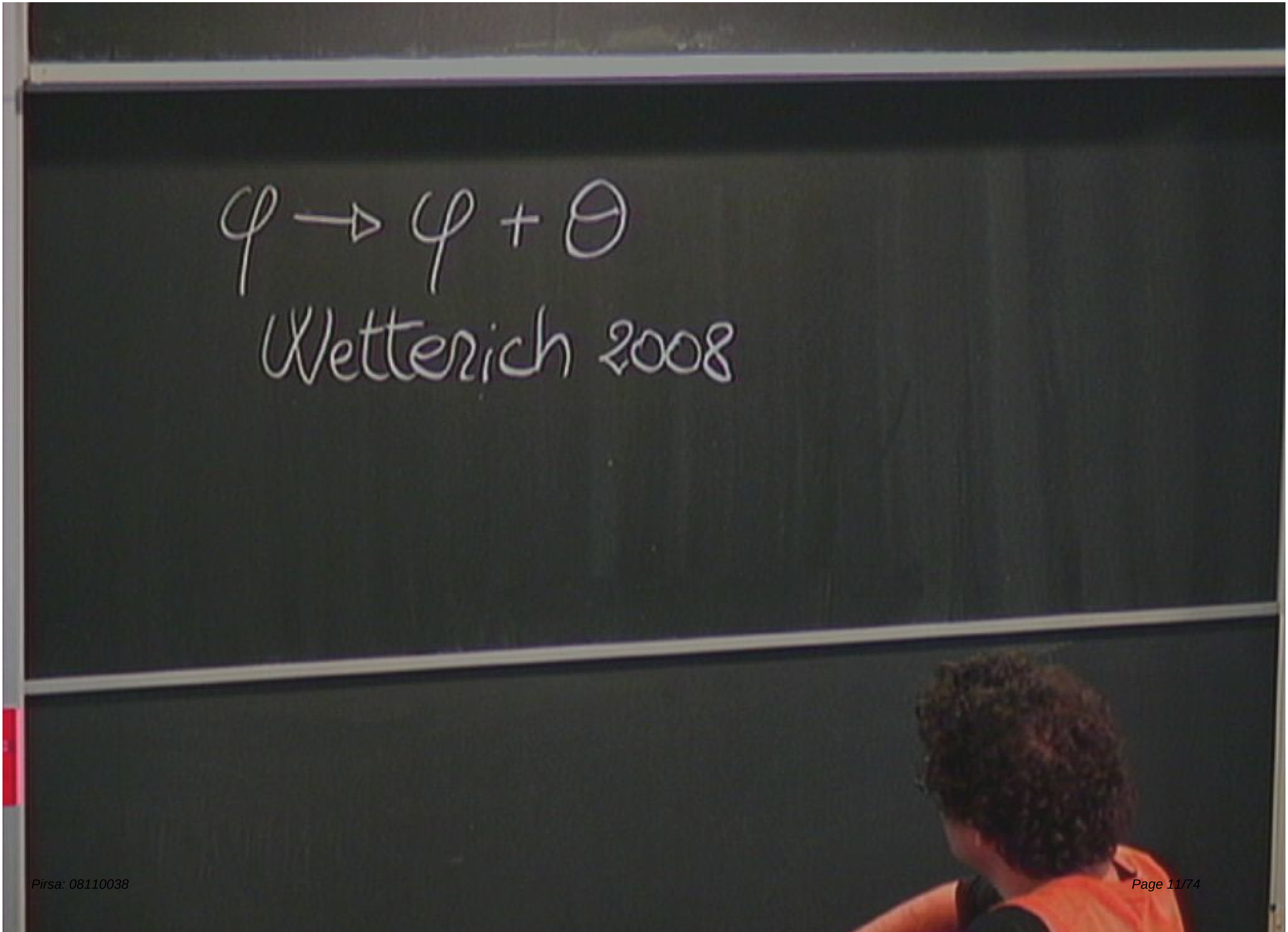
$$F(\phi) \equiv \frac{1}{\kappa} \frac{\partial f}{\partial R}$$

$Z = 1$

$$\mathcal{L}_{\text{fluid}} = -i\bar{\psi} g^{\mu\nu} \gamma_\nu \nabla_\mu \psi + m\bar{\psi}\psi$$

The relevant equations change both for the background and for perturbations

Baccigalupi Matarrese Perrotta 2000, Riazuelo Uzan 2002, Bartolo Pietroni 2000...


$\varphi \to \varphi + \theta$
Wetterich 2008

Weyl scaling

Coupling a scalar field to gravity

↕

GR + coupling to all matter fields

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

Weyl scaling

Coupling a scalar field to gravity

⇕

GR + coupling to all matter fields

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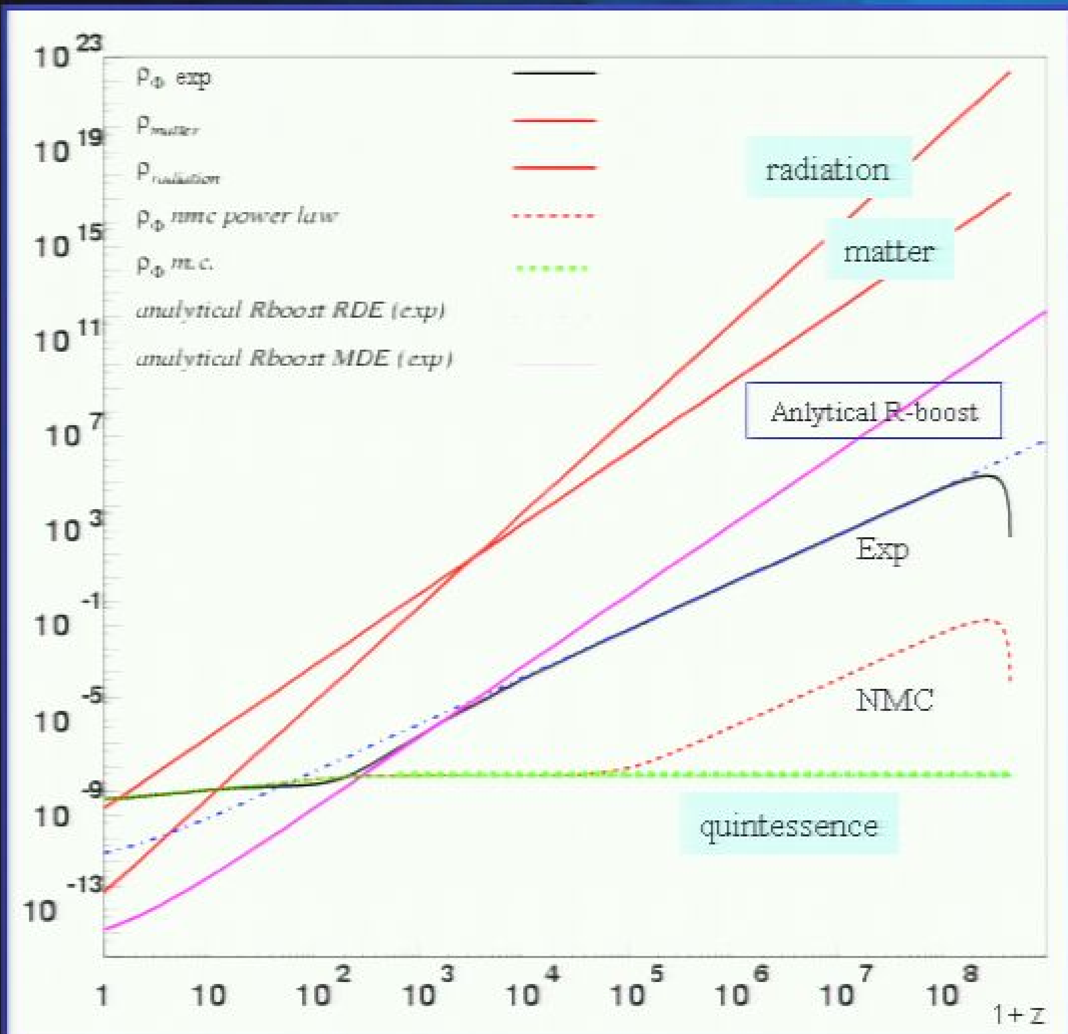
Background



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

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

$$R_{RDE} \cong \frac{1}{F}\frac{\rho_{mnr\,0}}{a^3} \neq 0$$

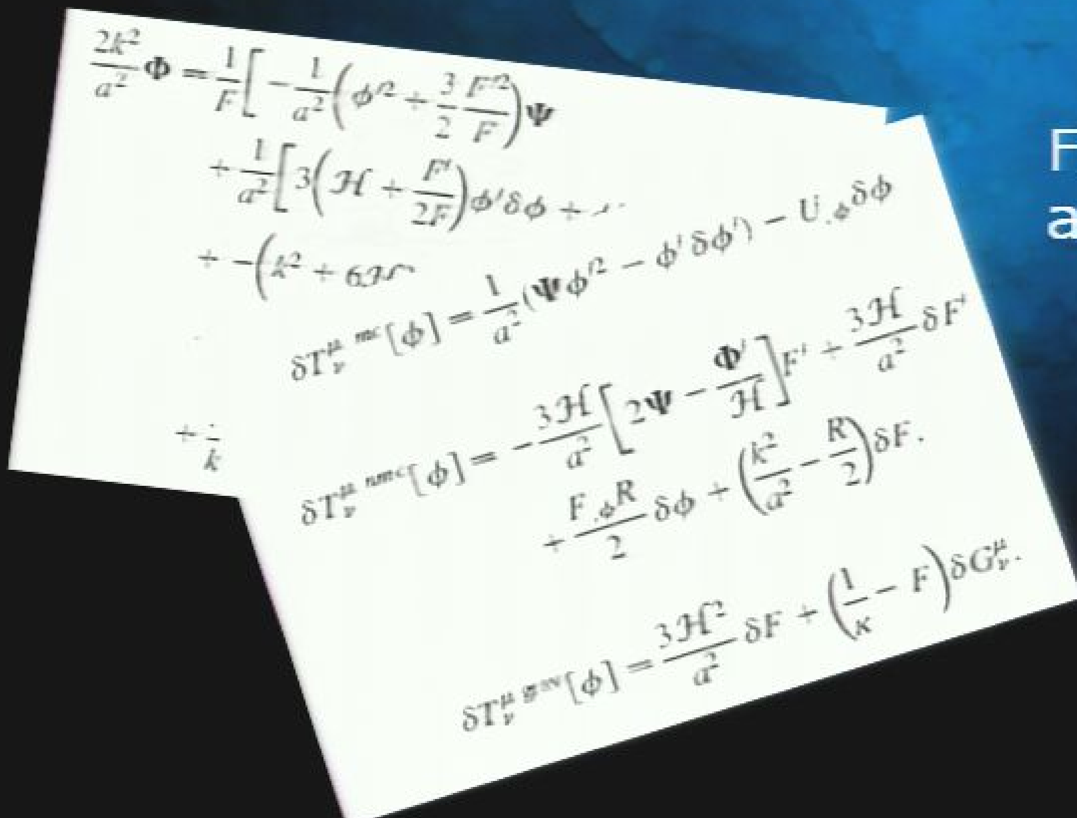
EXP $$\frac{F(\phi)R}{2} = \frac{R}{16\pi G}\exp\left(\frac{\xi(\phi-\phi_0)}{M_p}\right)$$

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


$$\frac{2k^2}{a^2}\Phi = \frac{1}{F}\Big[-\frac{1}{a^2}\Big(\phi'^2 + \frac{3}{2}\frac{F'^2}{F}\Big)\Psi + \frac{1}{a^2}\Big[3\Big(\mathcal{H} + \frac{F'}{2F}\Big)\phi'\delta\phi + \dots$$

$$\delta T^{\mu\ \mathrm{mc}}_{\nu}[\phi] = \frac{1}{a^2}(\Psi\phi'^2 - \phi'\delta\phi') - U_{,\phi}\delta\phi$$

$$\delta T^{\mu\ \mathrm{nmc}}_{\nu}[\phi] = -\frac{3\mathcal{H}}{a^2}\Big[2\Psi - \frac{\Phi'}{\mathcal{H}}\Big]F' + \frac{3\mathcal{H}}{a^2}\delta F' + \frac{F_{,\phi}R}{2}\delta\phi + \Big(\frac{k^2}{a^2} - \frac{R}{2}\Big)\delta F.$$

$$\delta T^{\mu\ \mathrm{gsw}}_{\nu}[\phi] = \frac{3\mathcal{H}^2}{a^2}\delta F + \Big(\frac{1}{\kappa} - F\Big)\delta G^{\mu}_{\nu}.$$

Formally the same equations as in GR but...

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

[Pettorino, Baccigalupi 2008]

...with an effective gravitational 'constant'

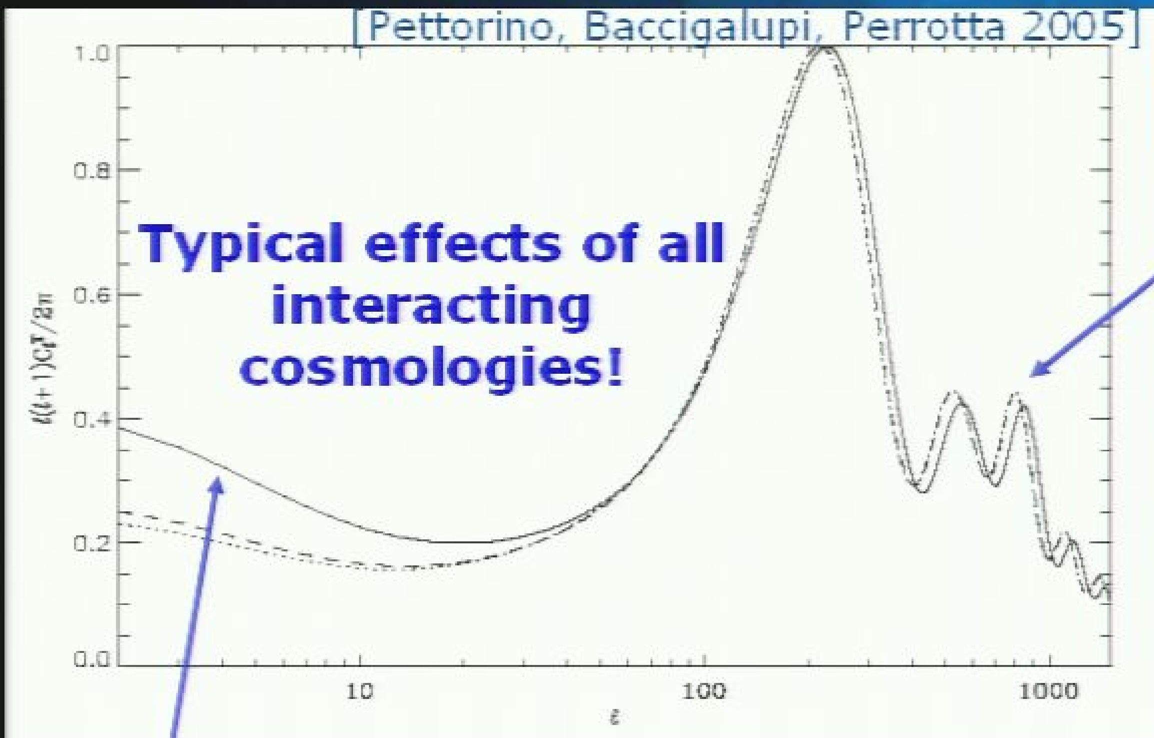
$$\tilde{G} = \frac{2(F + 2F_{,\phi}^2)}{(2F + 3F_{,\phi}^2)}\frac{1}{8\pi F}$$

$$\mathcal{H}^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3F}\left(a^2\rho_{fluid} + \dots\right.$$

...already visible from the background equations

Effects on the CMB

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



Projection effect

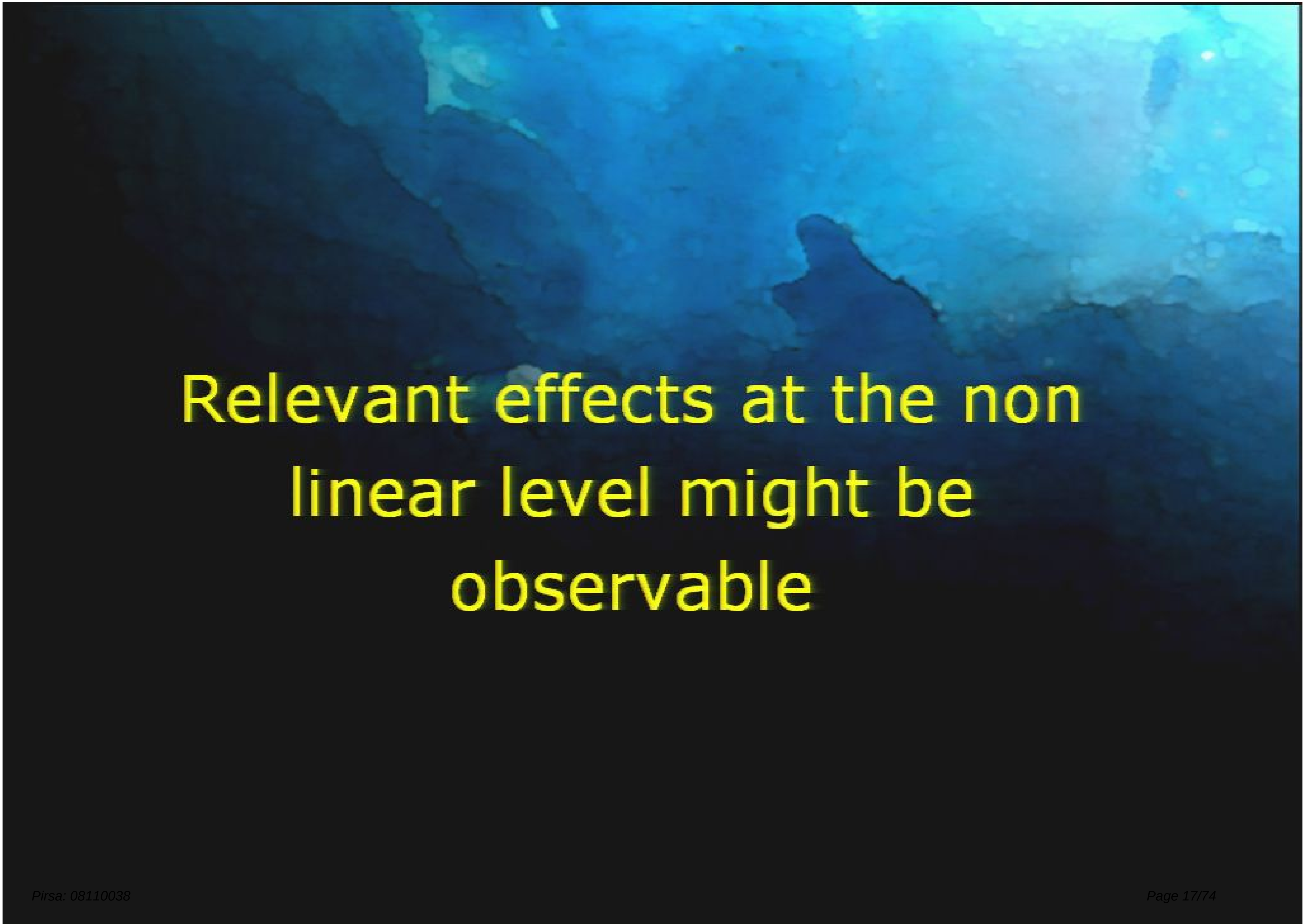
Larger LISW

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

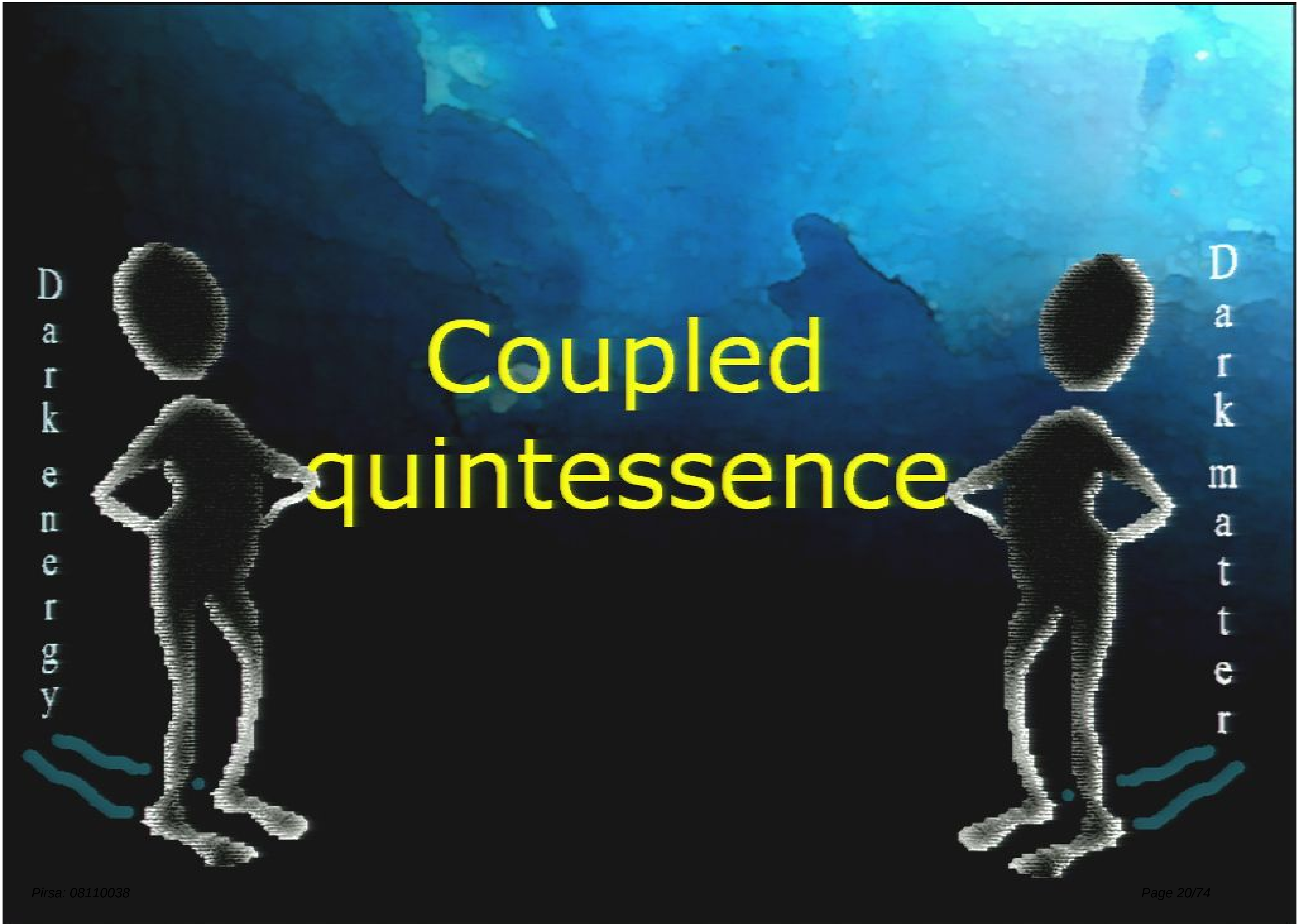
- $L_{box} = 300$ Mpc/h, $n_p = 2 \times 768^3$, $\epsilon_G = 7.5$ kpc/h

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

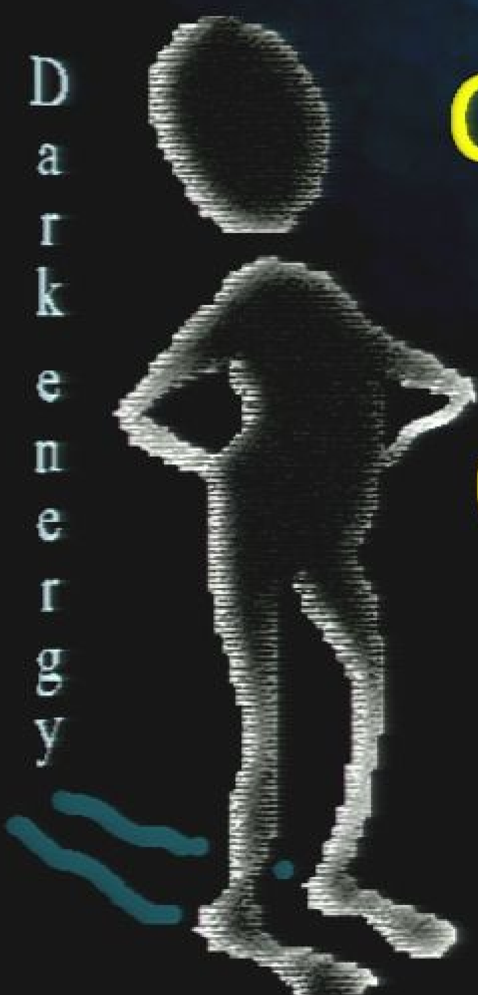
Data analysis in progress!

Conclusions for Extended Quintessence

- Attractor properties due to a gravitational effect
- Two main effects on CMB (difficult to see within bounds!)
- Nbody simulations with:
  - dynamical gravitational 'constant' felt by all particles


Coupled quintessence
Dark energy
Dark matter

Coupled quintessence = quintessence + cdm (only)



Background

Consider dark energy as a quintessence scalar field

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

[Rhatra and Peebles 1988]
[Wetterich 1988]

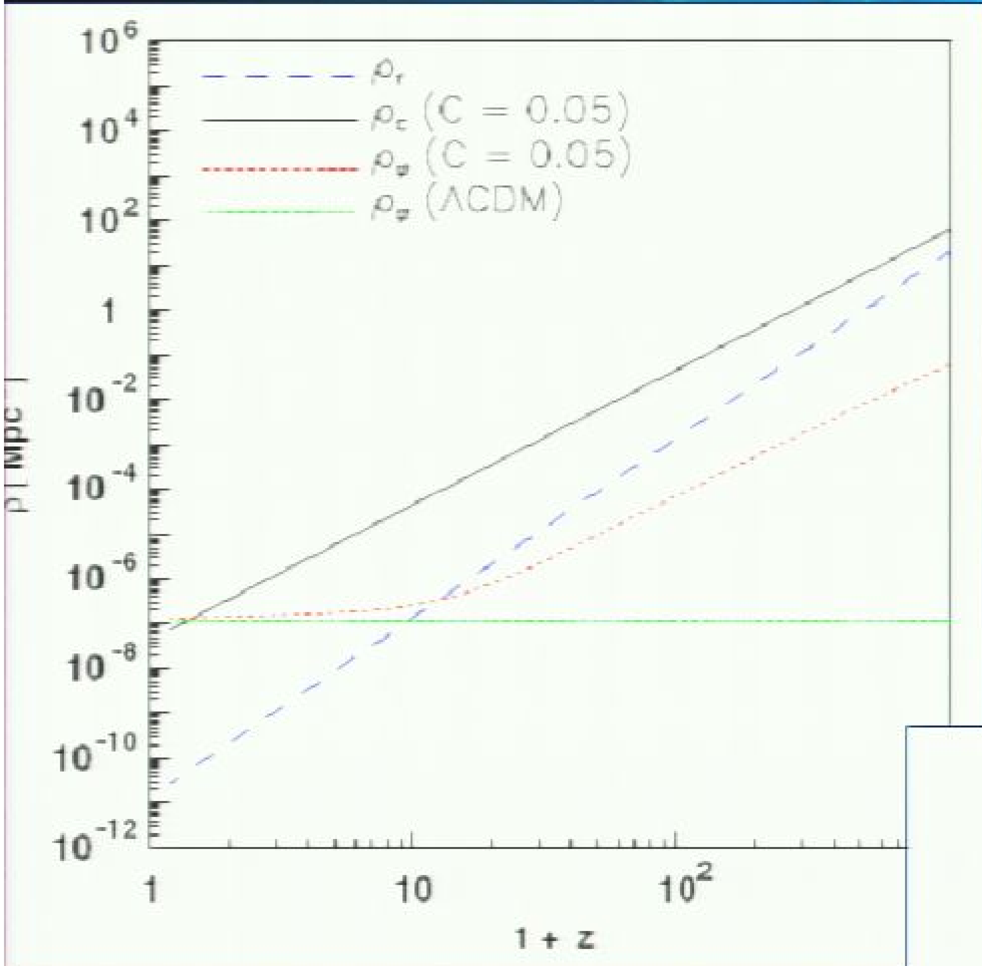
coupled to a species whose mass is now function of ϕ

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

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa} R - \frac{1}{2} \phi^{;\mu} \phi_{;\mu} - U(\phi) - m(\phi)\bar{\psi}\psi + \mathcal{L}_{\mathrm{kin},\psi} \right]$$

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

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

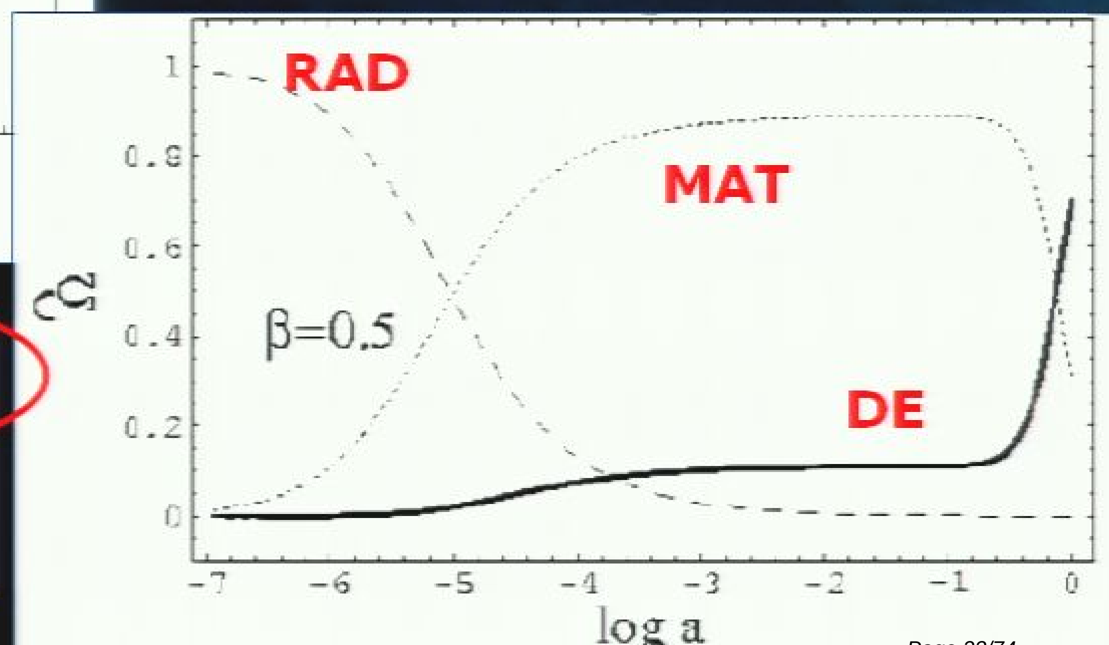


Pattern for the background similar to extended quintessence

Non negligible amount of dark energy in the past

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

$$\rho'_c = -3\mathcal{H}\rho_c - \beta(\phi)\phi'\rho_c$$



Linear perturbations

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

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

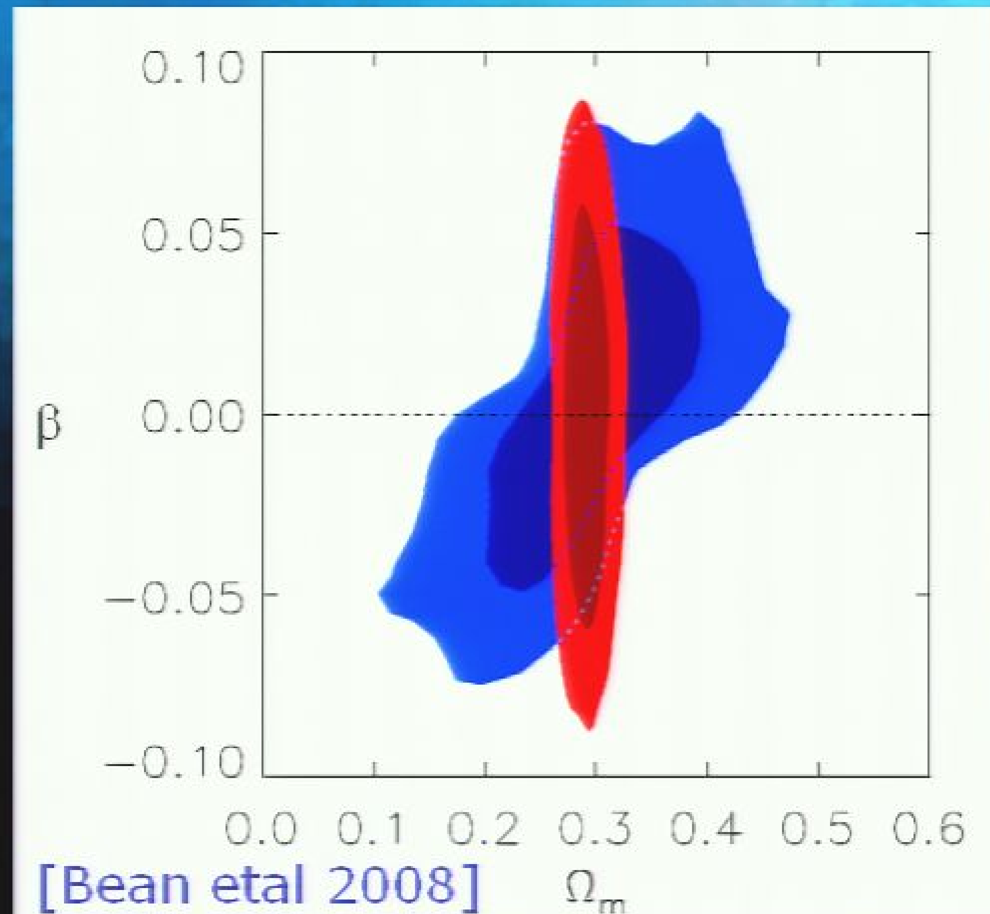
$$h_\phi v'_\phi + \left(h'_\phi + 4\mathcal{H}h_\phi\right)v_\phi - k\delta p_\phi - k h_\phi \mathbf{\Psi} = k\frac{\beta(\phi)}{M}\rho_c\delta\phi$$

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

CMB constraints

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

$$G_{eff} = G(1 + \beta^2)$$

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

Nbody simulations for CQ

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

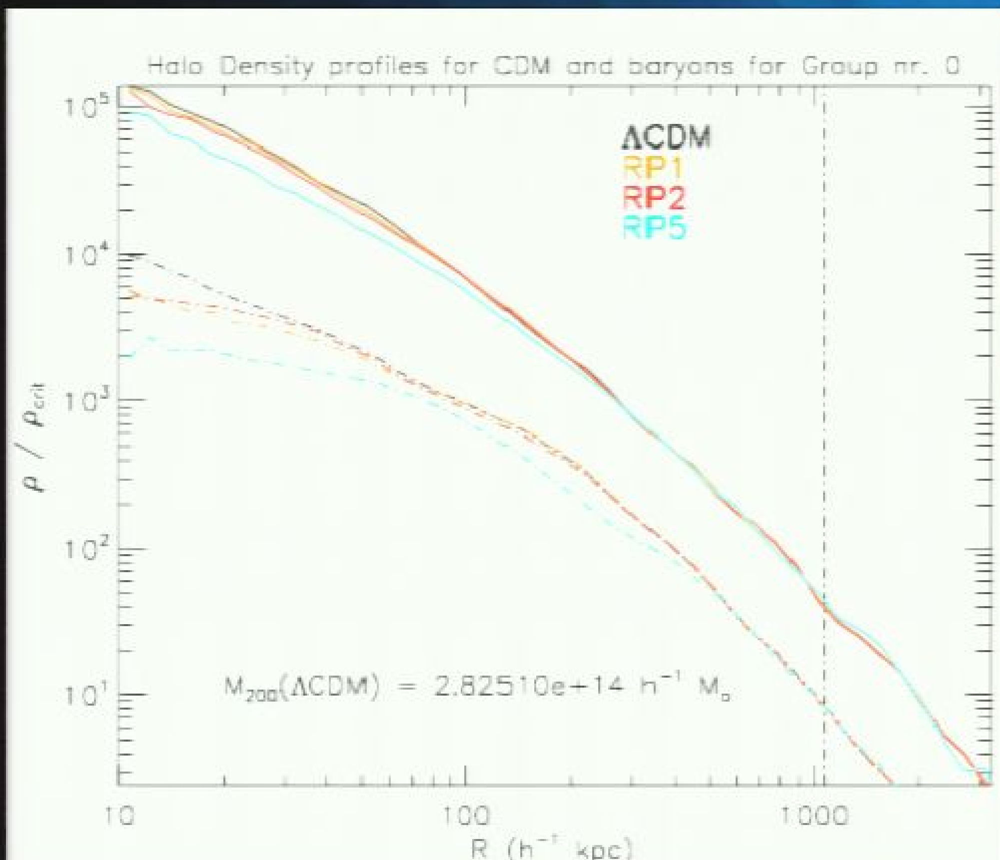
$L_{\rm box} = 80\,{\rm h}^{-1}{\rm Mpc}$	$m_c(z=0) \sim 2 \cdot 10^8\,{\rm h}^{-1}{\rm M}_\odot$
$N = 2 \times 512^3$	$m_b \sim 5 \cdot 10^7\,{\rm h}^{-1}{\rm M}_\odot$
$\epsilon_g = 3.5\,{\rm h}^{-1}{\rm kpc}$	$z_i = 60$

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

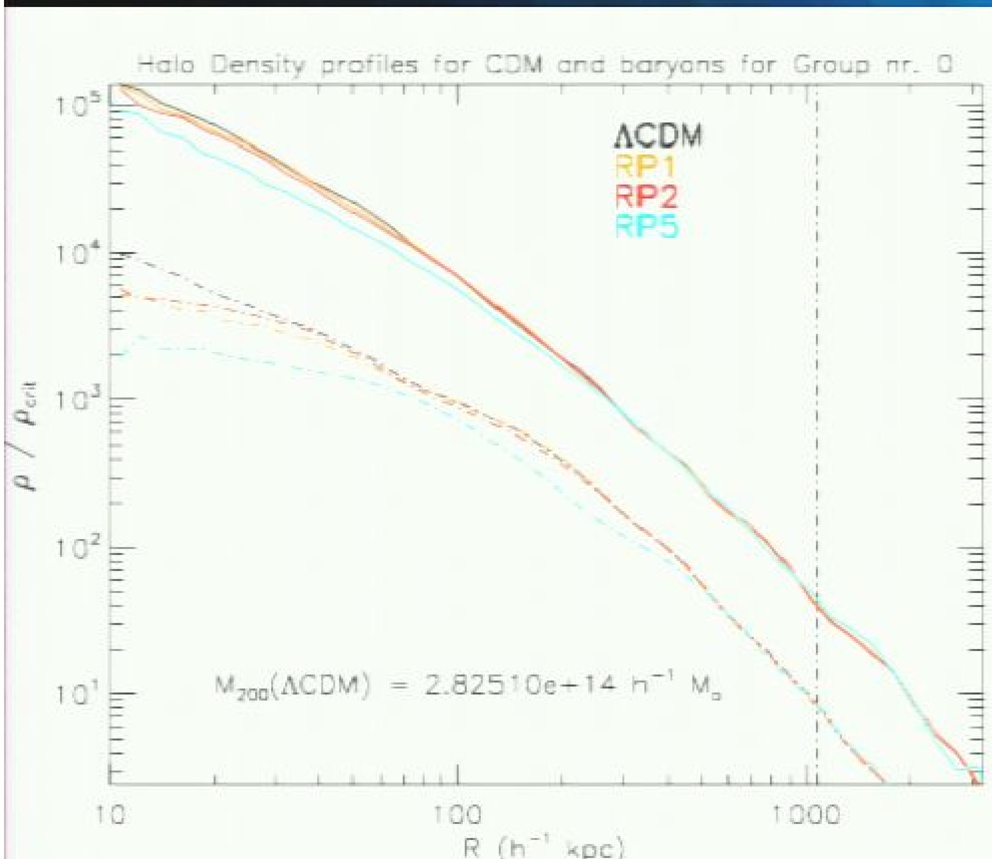


Baldi Pettorino Robbers
in preparation

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

Results in contrast with Macciò etal 2004

Results: density profiles



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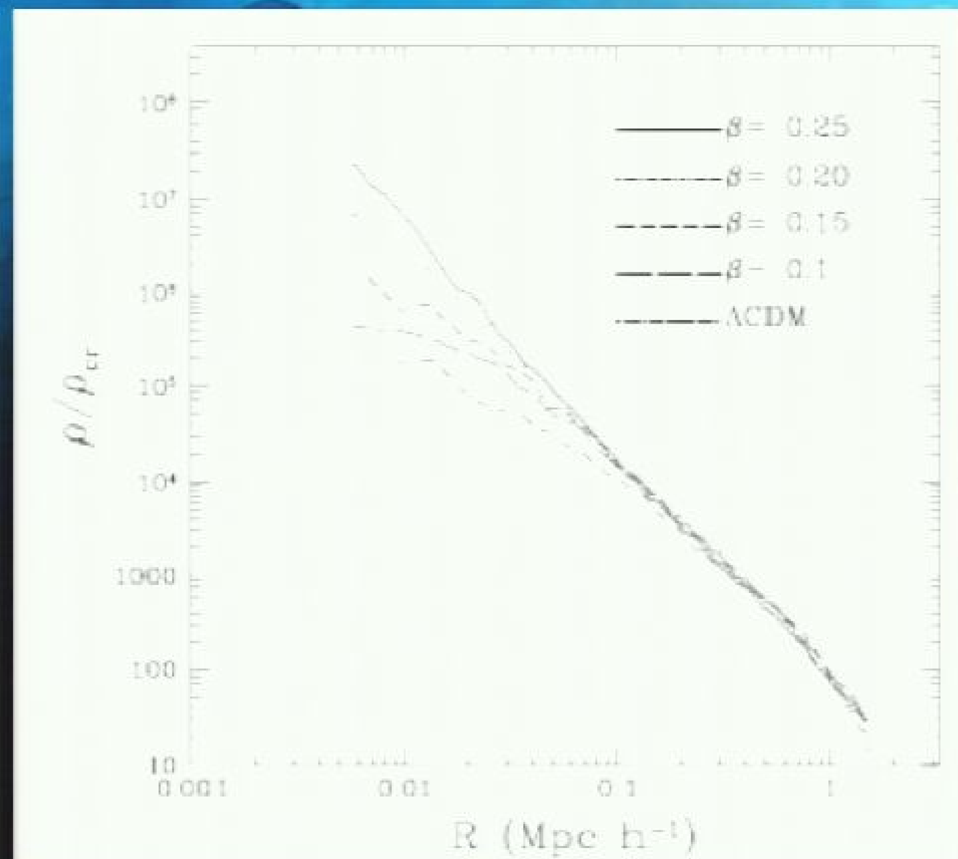

Macciò etal 2004

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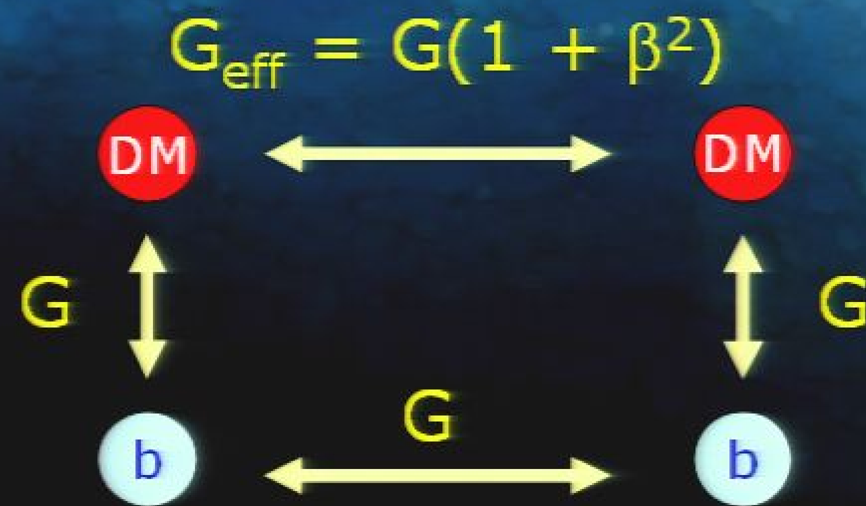
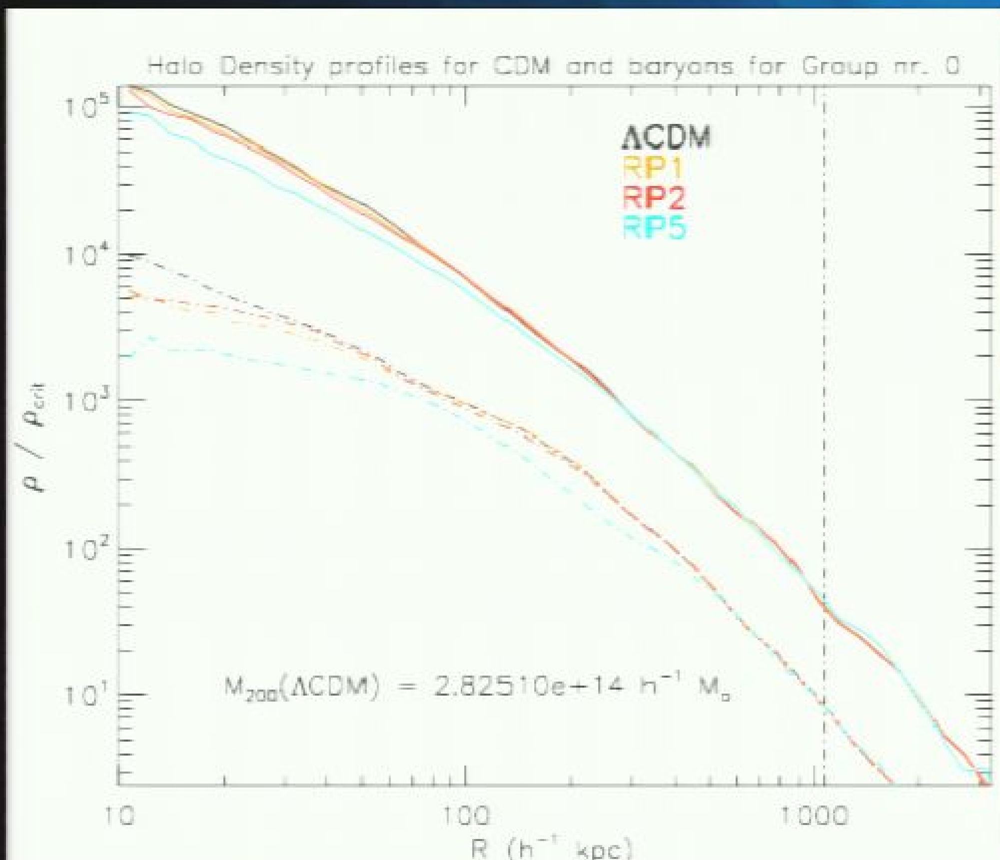


$$\delta_c'' + (\mathcal{H} - \beta\phi')\,\delta_c' - \frac{3}{2}\mathcal{H}^2\left[(1+2\beta^2)\,\Omega_c\delta_c + \Omega_b\delta_b\right] = 0$$

Results: density profiles



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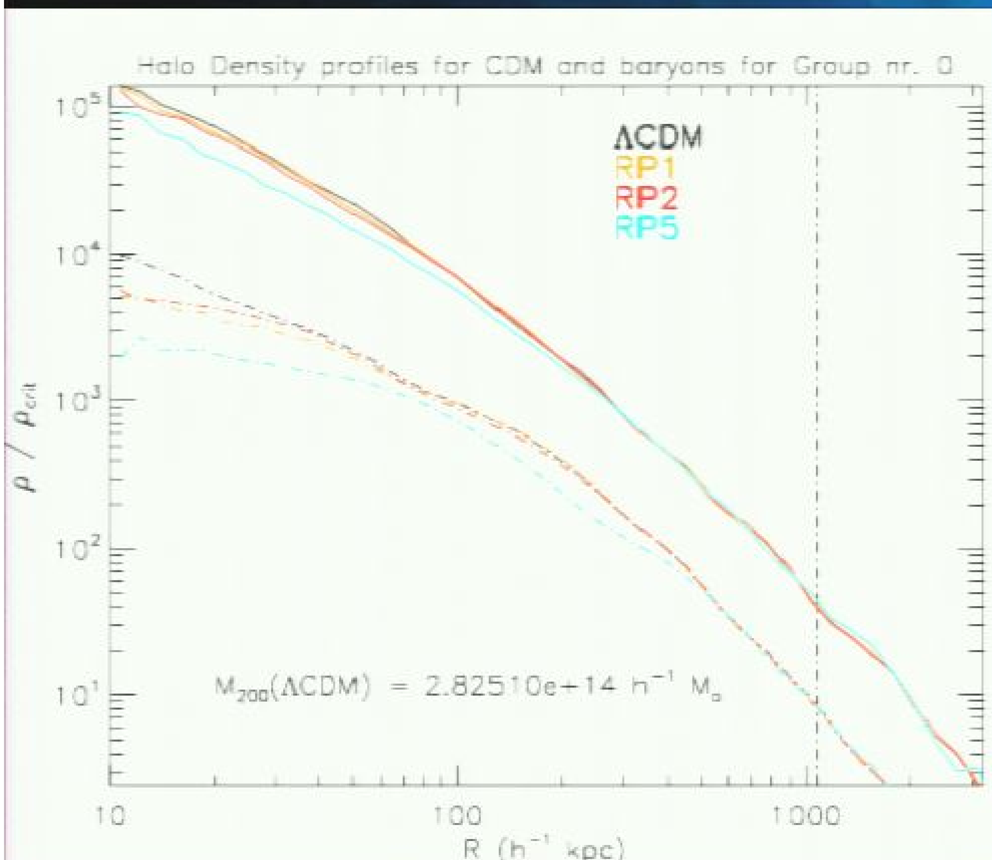

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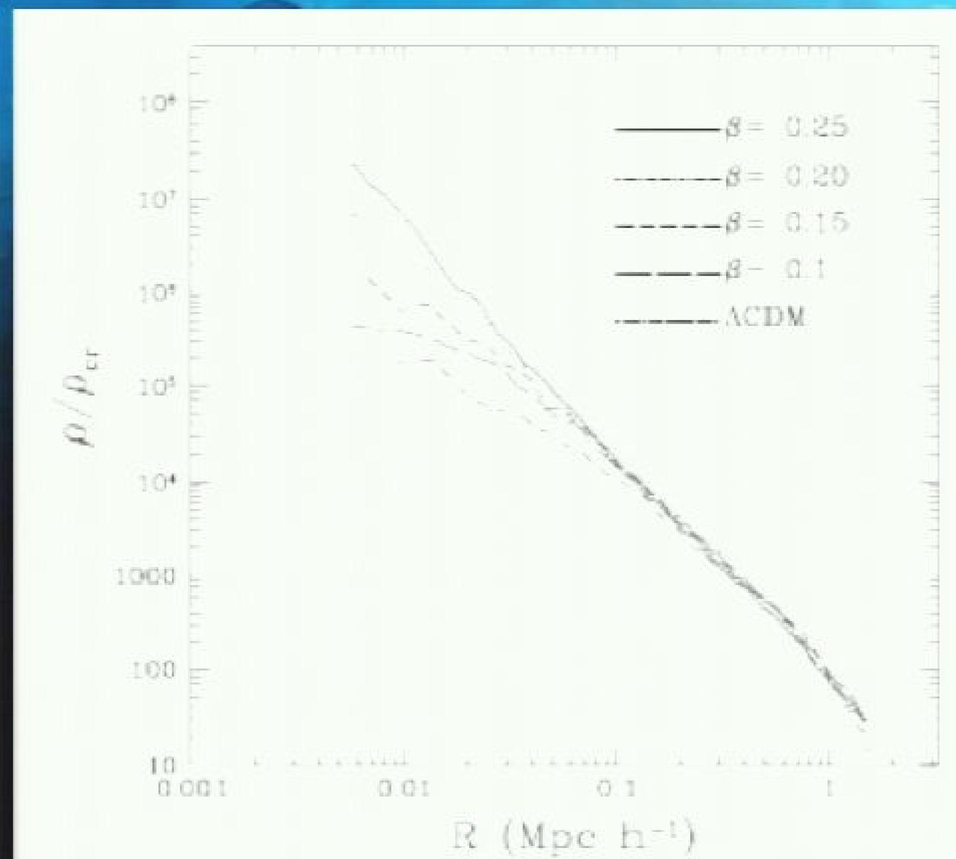
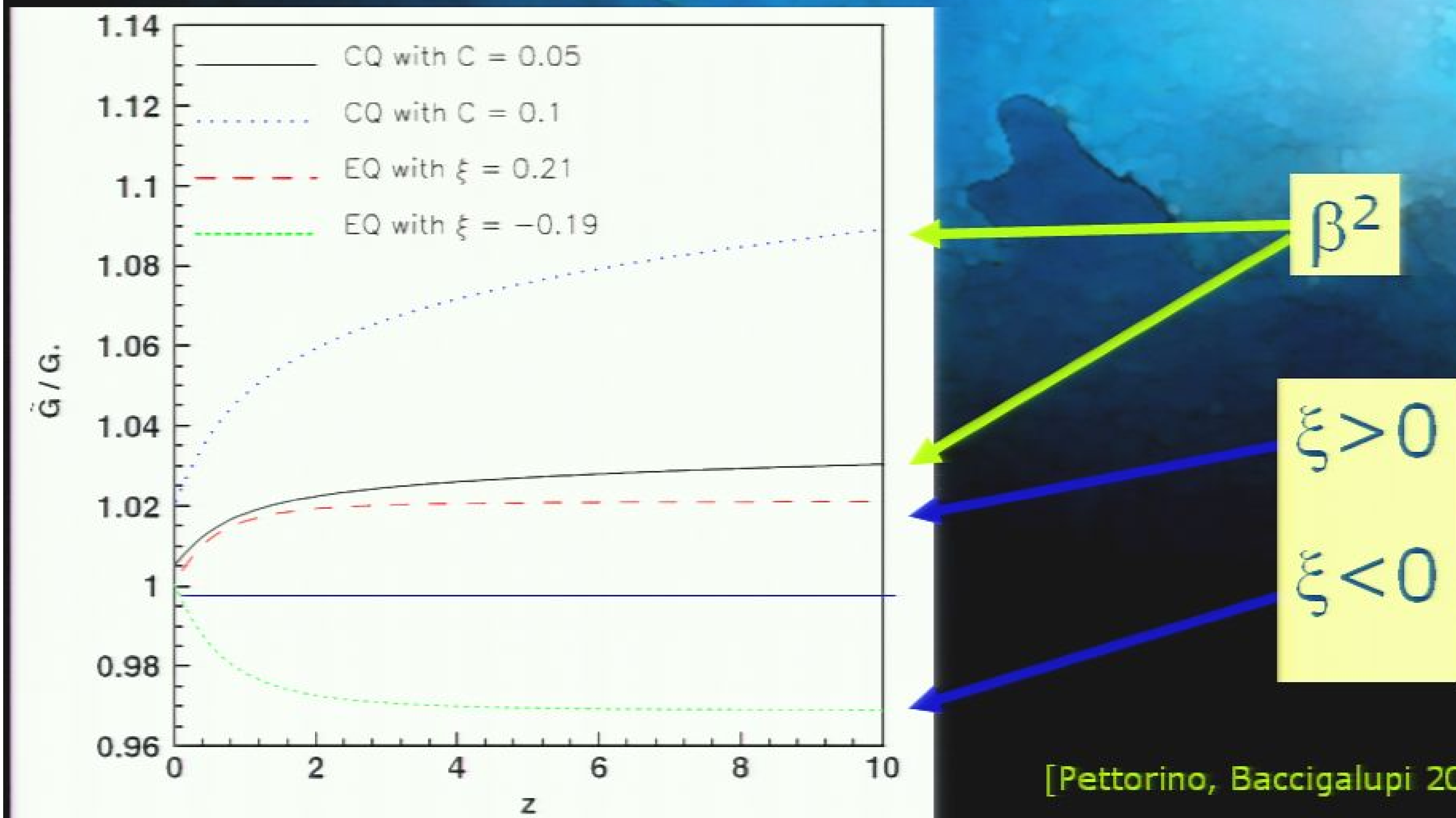


Macciò etal 2004

Note that...



[Pettorino, Baccigalupi 2008]

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

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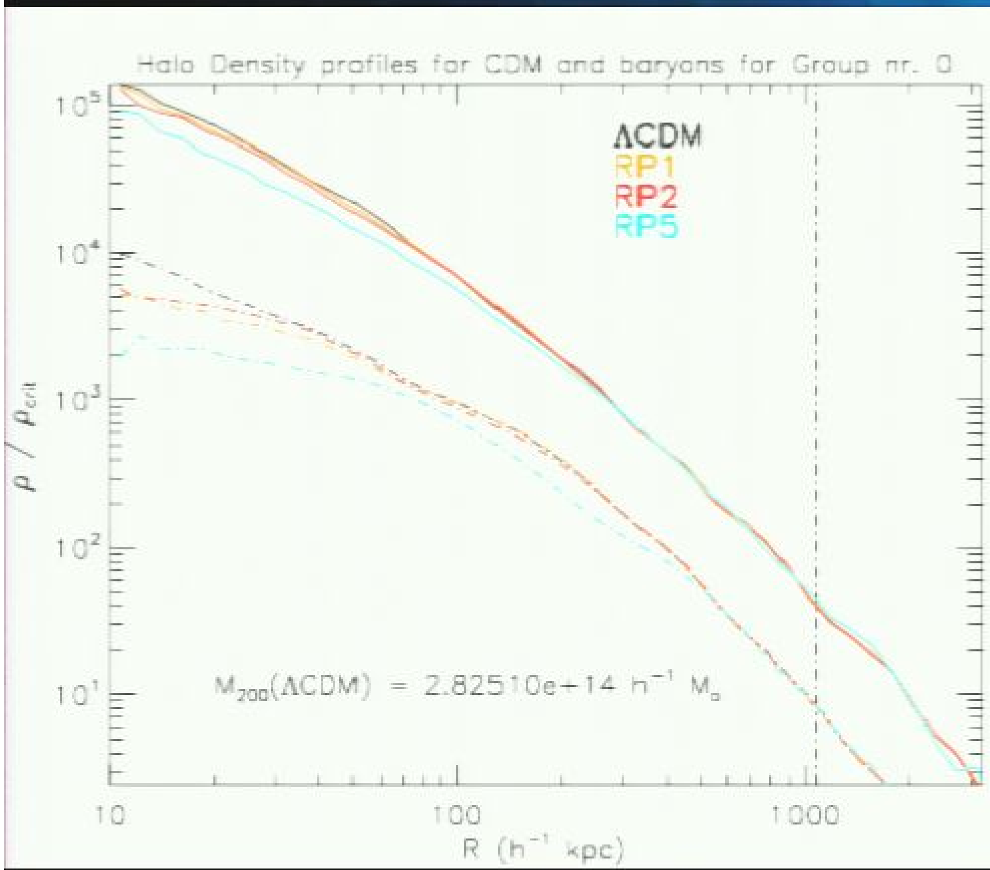

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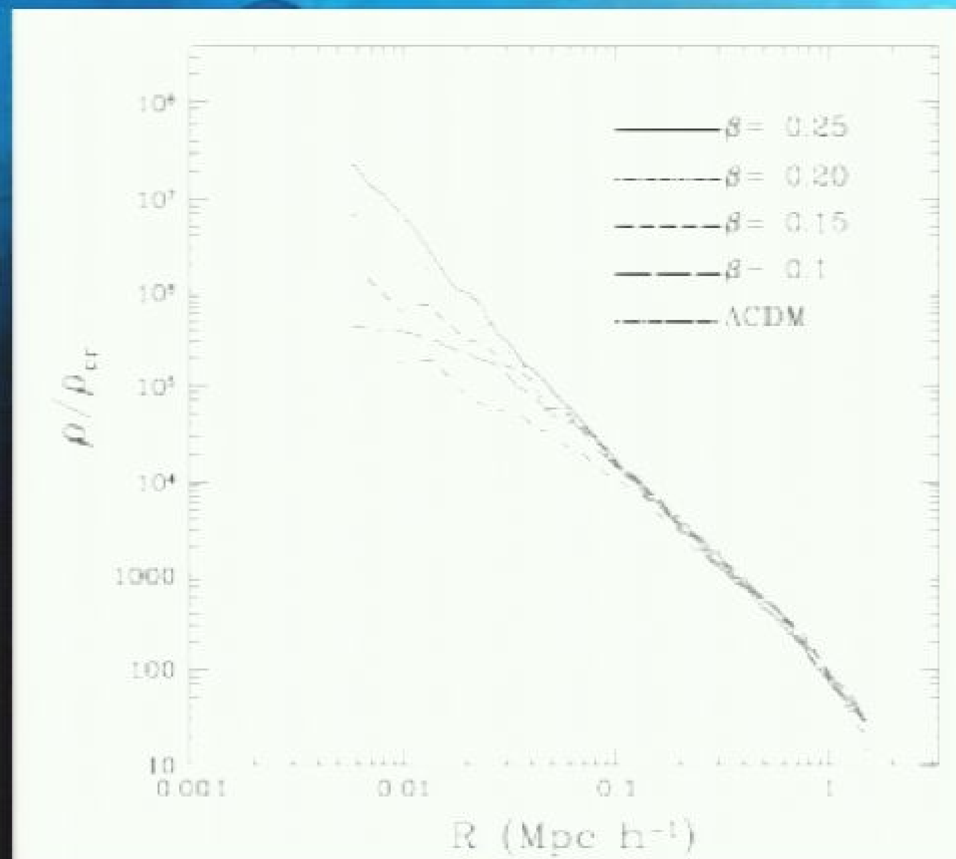

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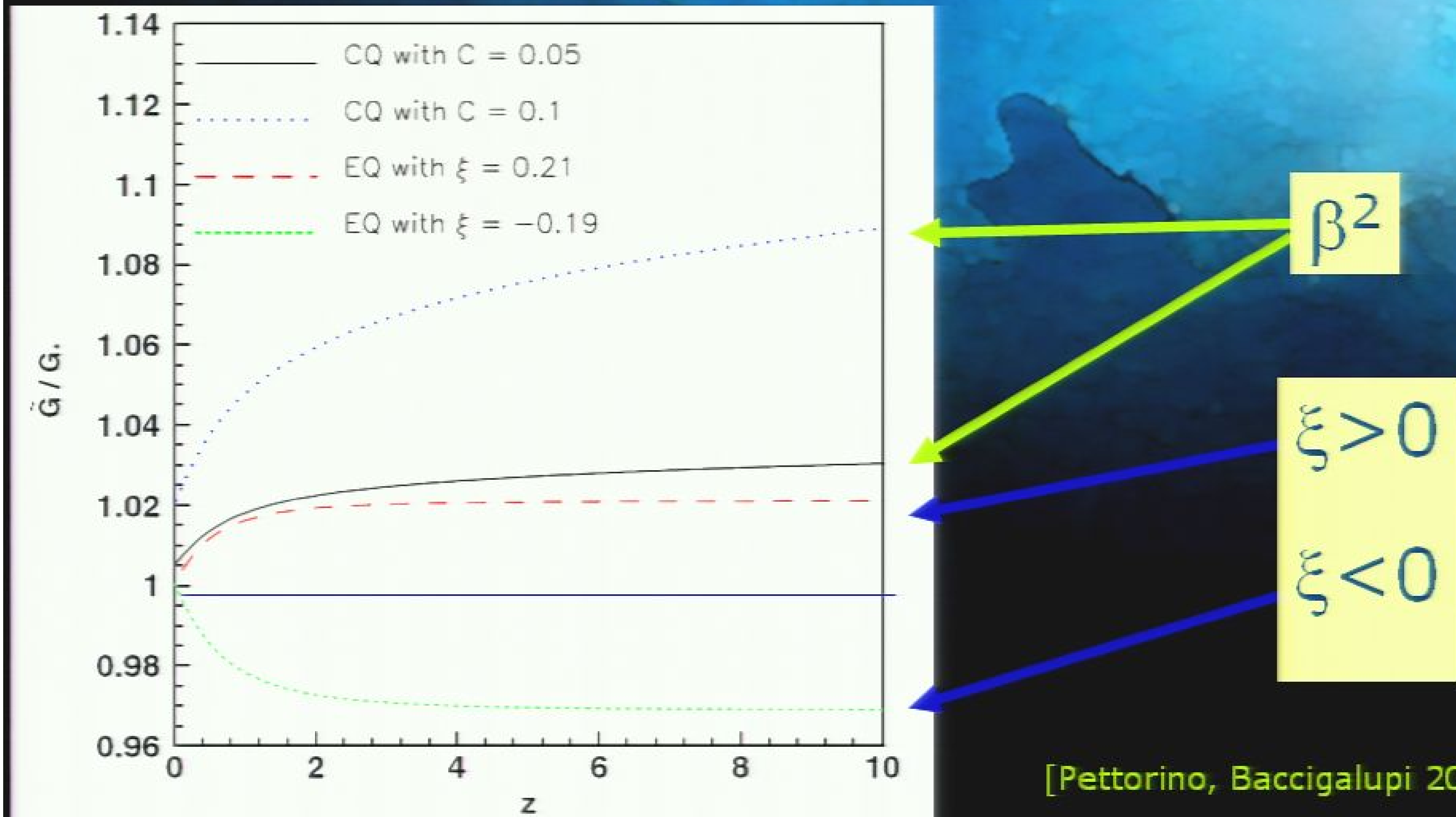


[Pettorino, Baccigalupi 2008]

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

Conclusions for Quintessence - CDM

- Interaction keeps DE and DM closer in the background evolution

See also Mangano, Miele, Pettorino 2005

- Attractor solutions
- Constrains by CMB
- Three features implemented in the Nbody code:
  - bigger gravitational 'constant' felt by DM particles
  - varying mass of DM
  - extra friction term in the direction of the velocity
- Three main results:
  - less clumpy inner profiles, smaller halo concentrations, scale dependent bias

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, ...

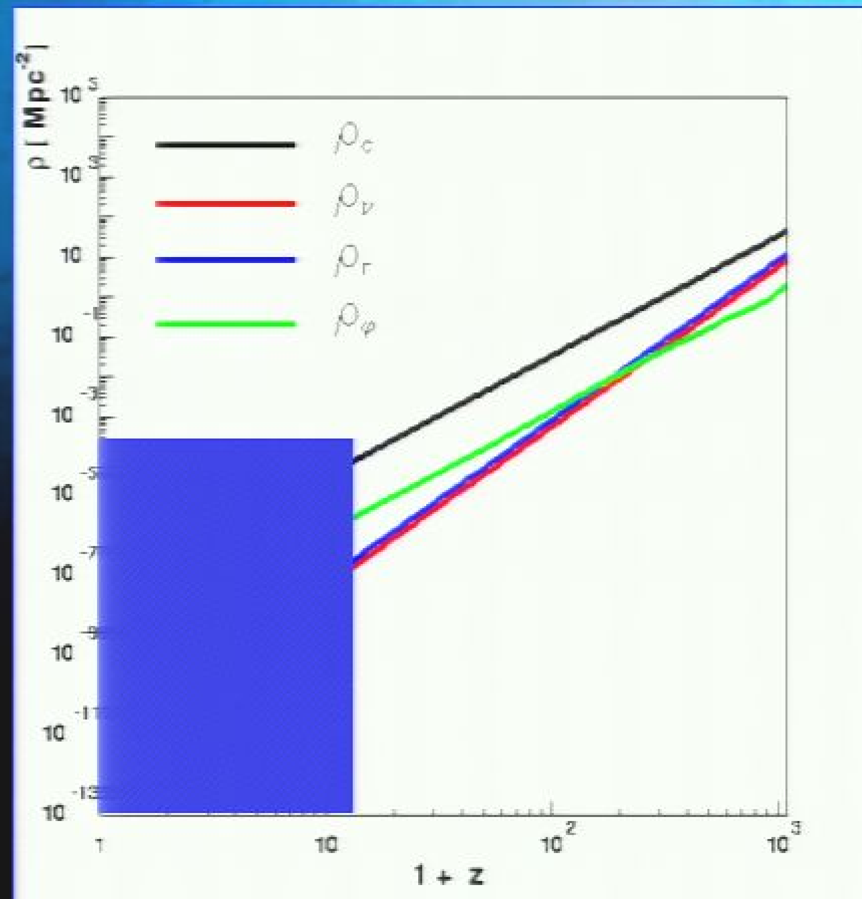
Growing neutrinos: Amendola etal 2007, Wetterich 2007, Mota etal 2008, Brouzakis etal 2007

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)



Steinhardt, Wang and Zlatev 1999, Liddle & Scherrer 1999, Wetterich 1995, Amendola 2000, ...

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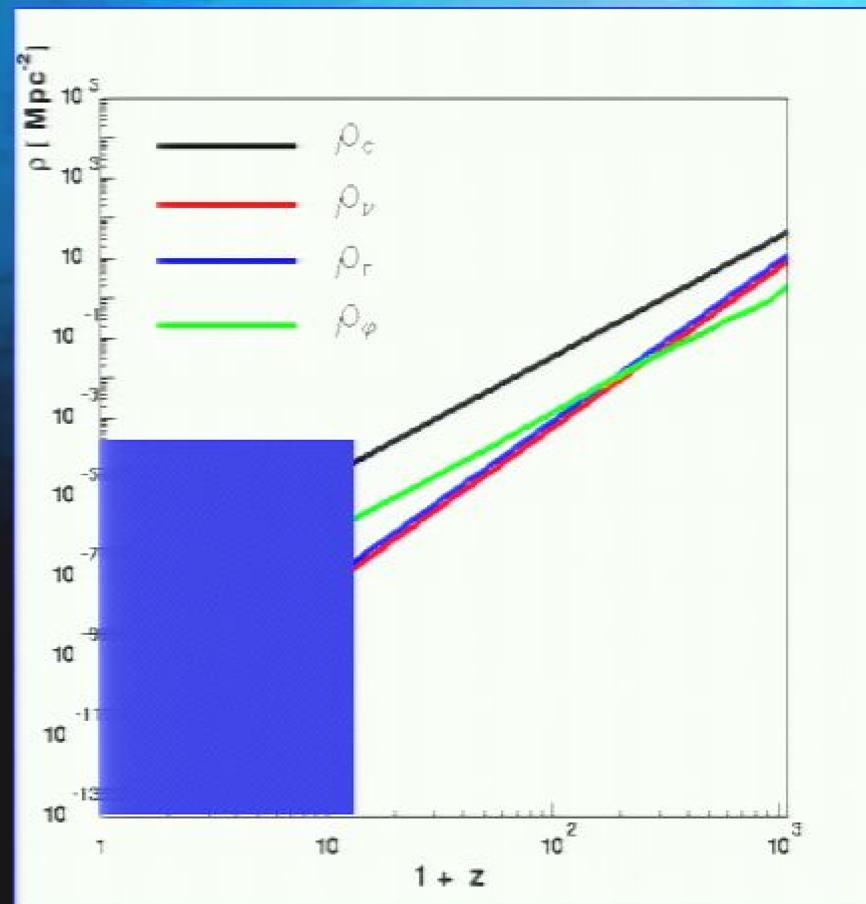

Need a cosmological event that triggers the end of the attractor era

Neutrinos become non relativistic

Attractor with constant fraction of DE + coupling

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

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

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

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

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Neutrino mass grows ($\beta < 0$)

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

↓

Neutrino mass grows ($\beta < 0$)

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

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

↓

Neutrinos become non relativistic

↓

The coupling to DE turns on and almost stops ϕ

Neutrinos become non relativistic

Attractor with constant fraction of DE + coupling

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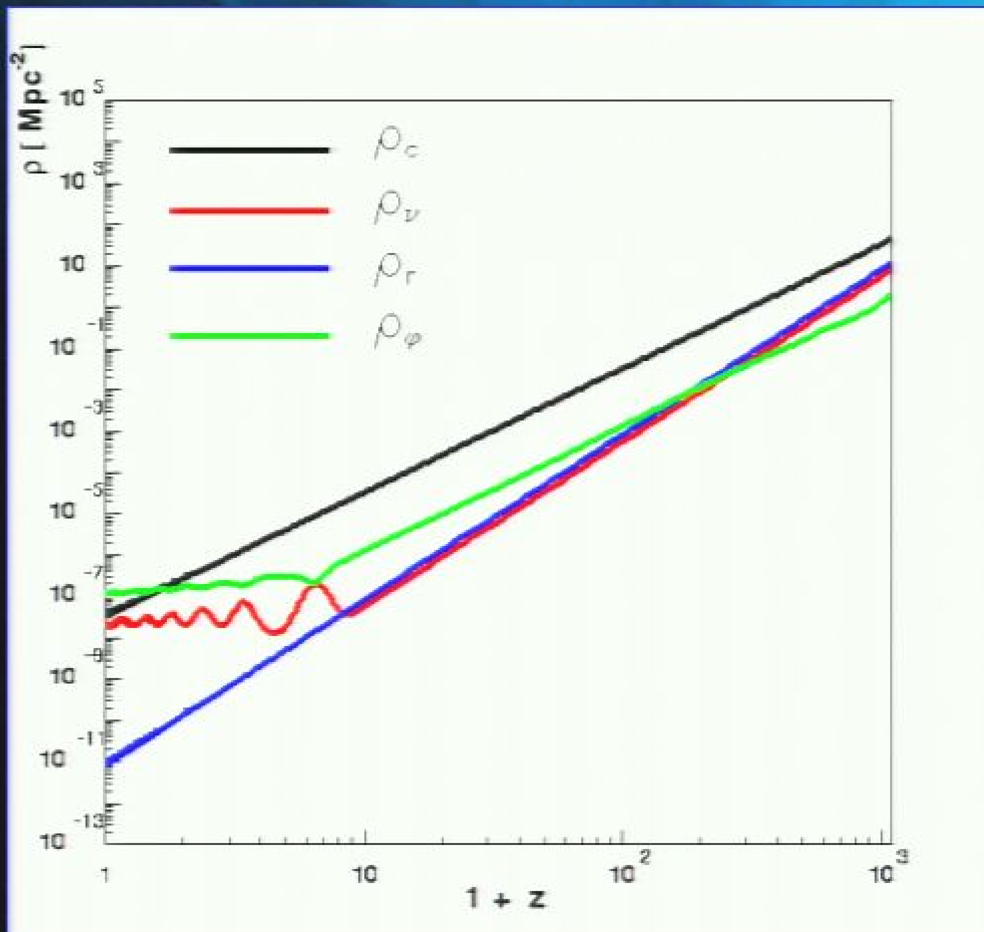
Acceleration

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

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

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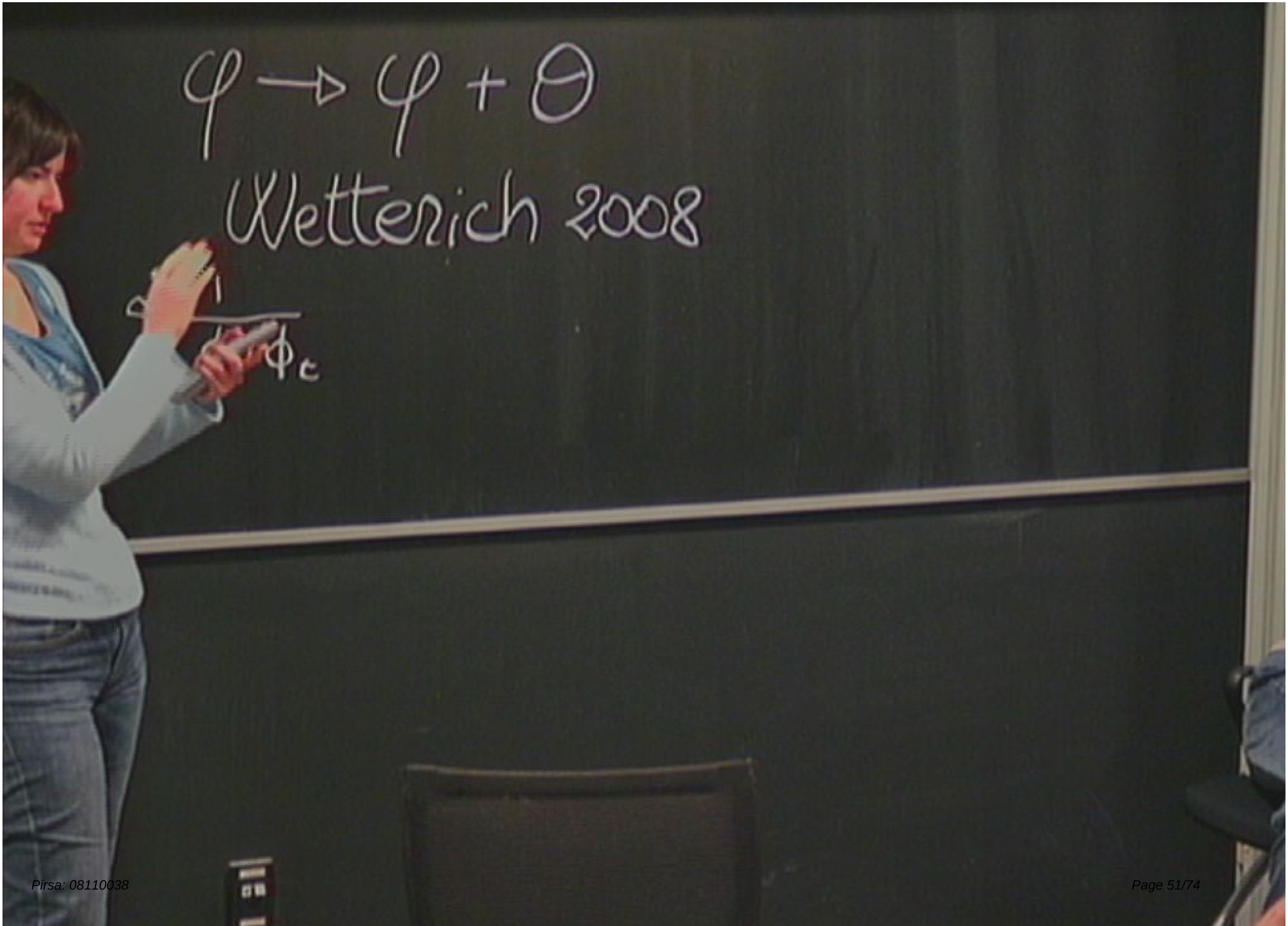
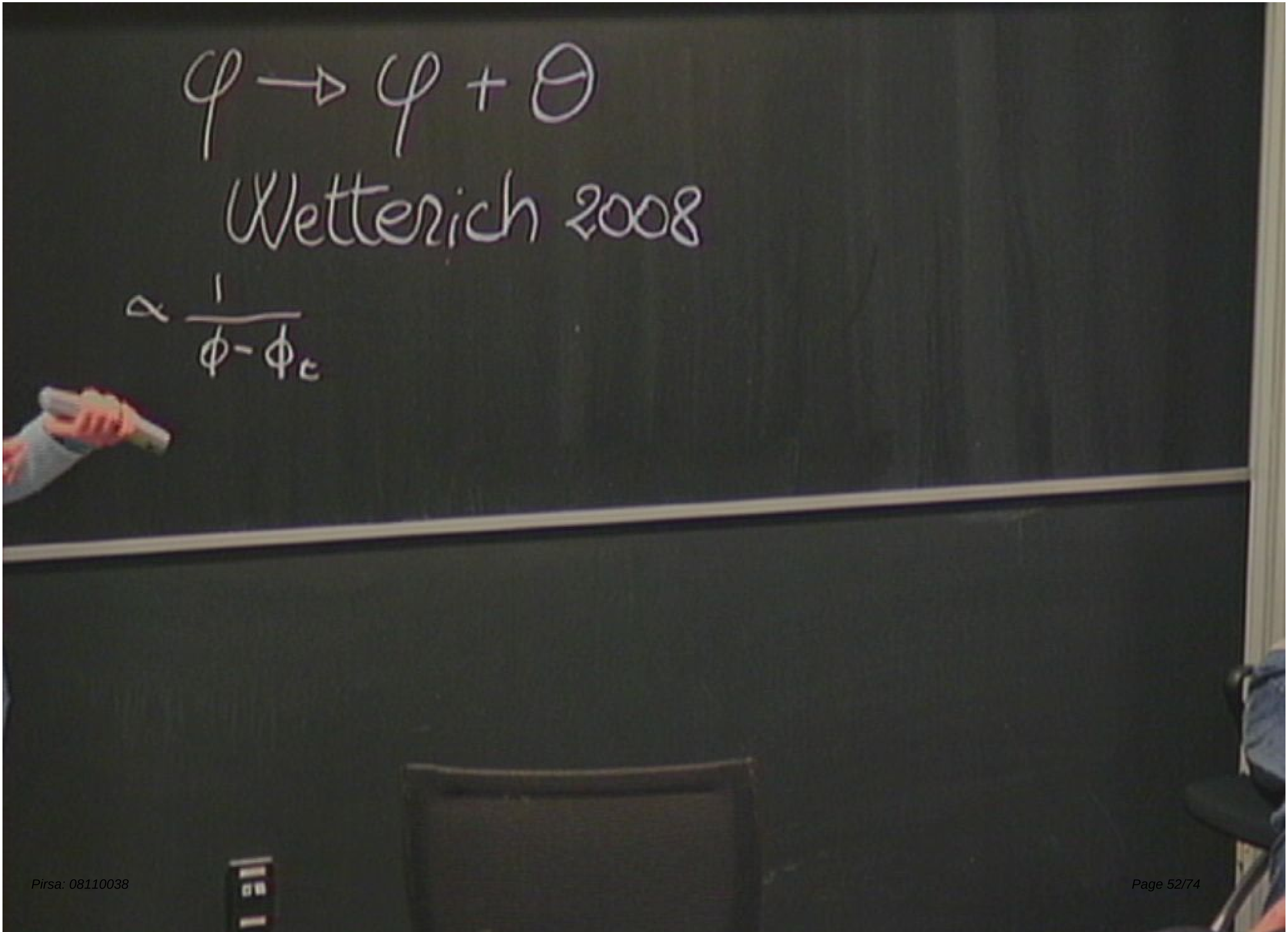
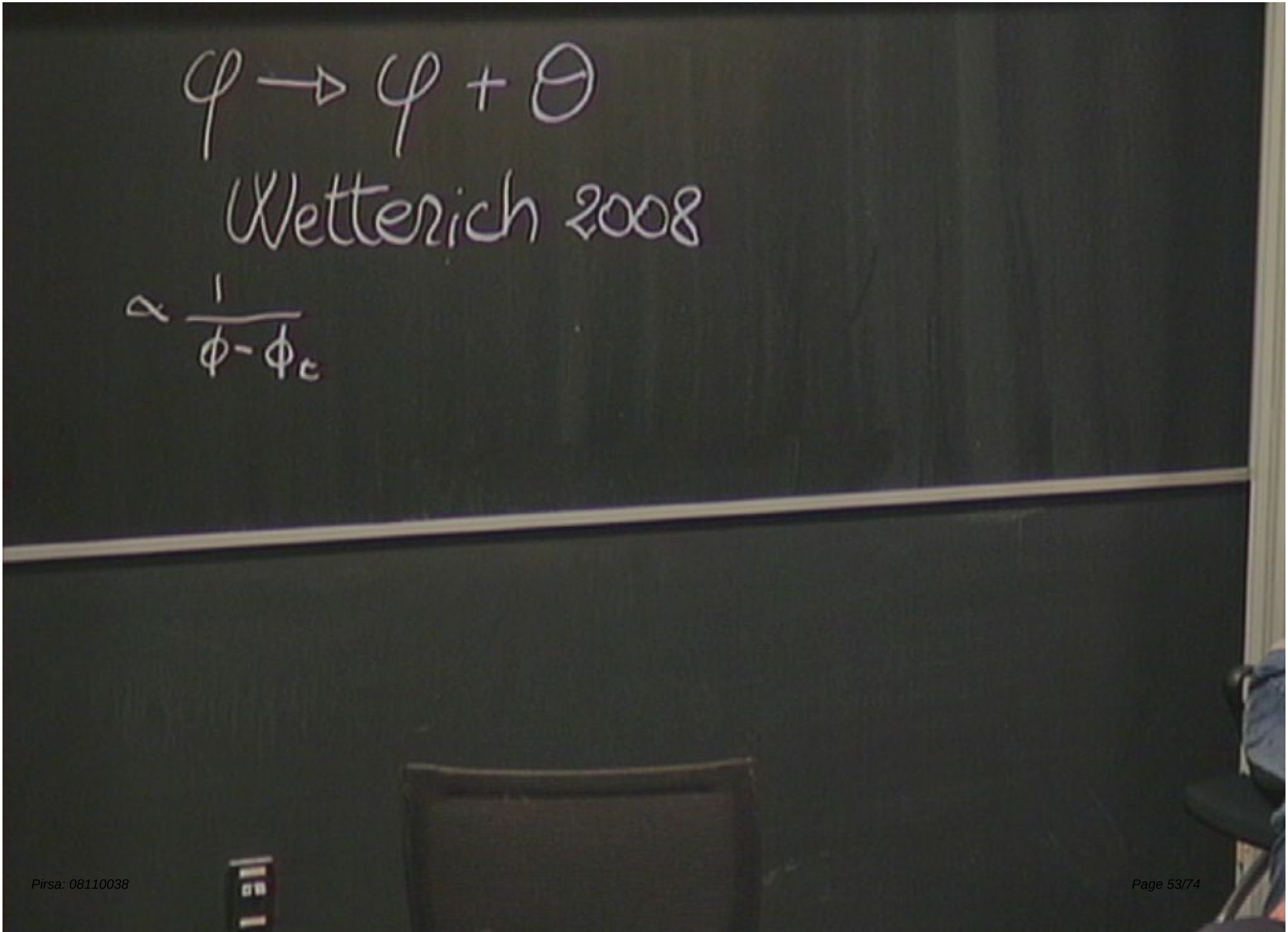

φ → φ + θ
Wetterich 2008


φ → φ + θ
Wetterich 2008
∝ 1/(φ − φ_c)


$\varphi \rightarrow \varphi + \theta$
Wetterich 2008
$\propto \frac{1}{\phi - \phi_c}$

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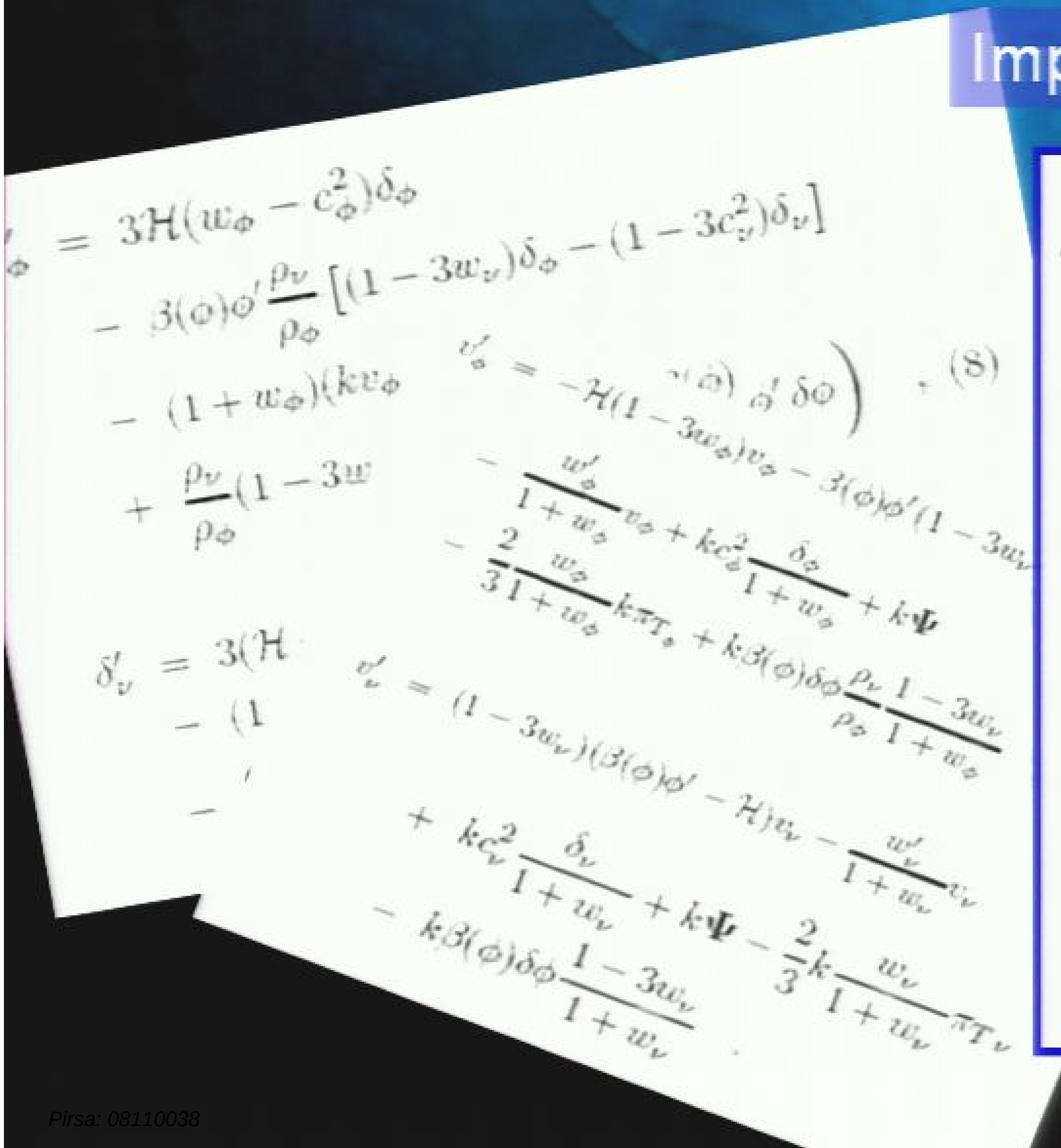
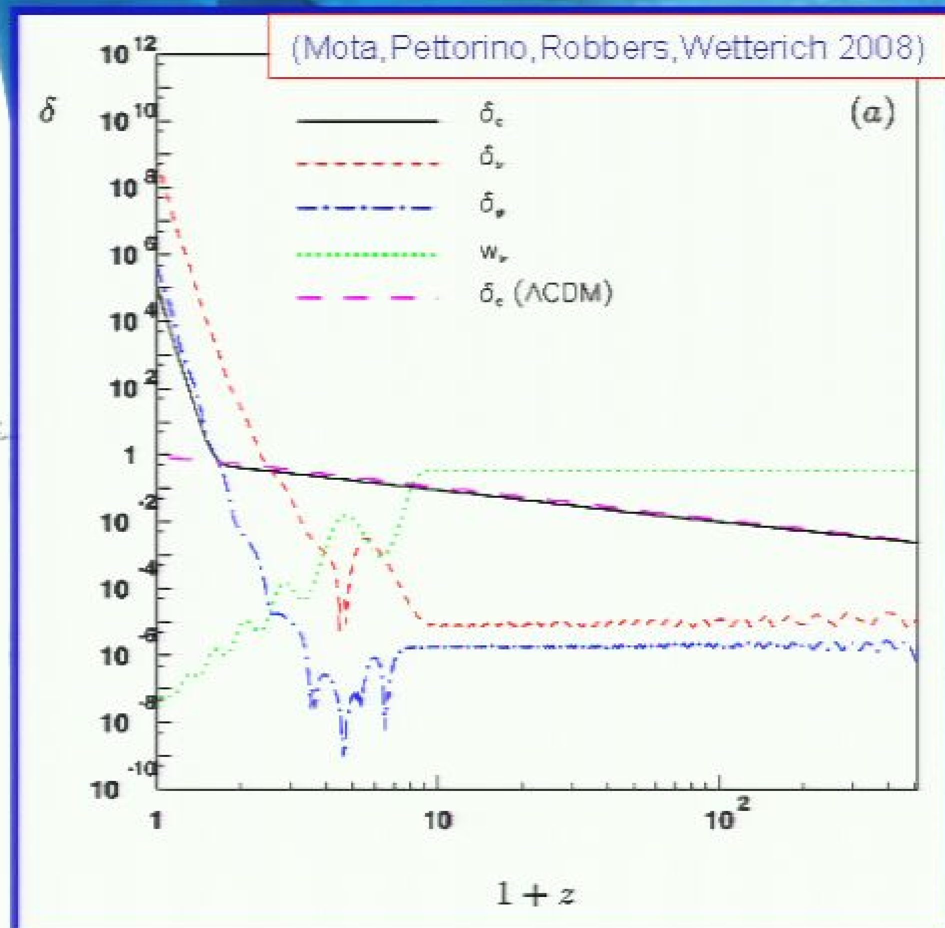
Linear perturbations

Implement CMBEASY, CAMB…



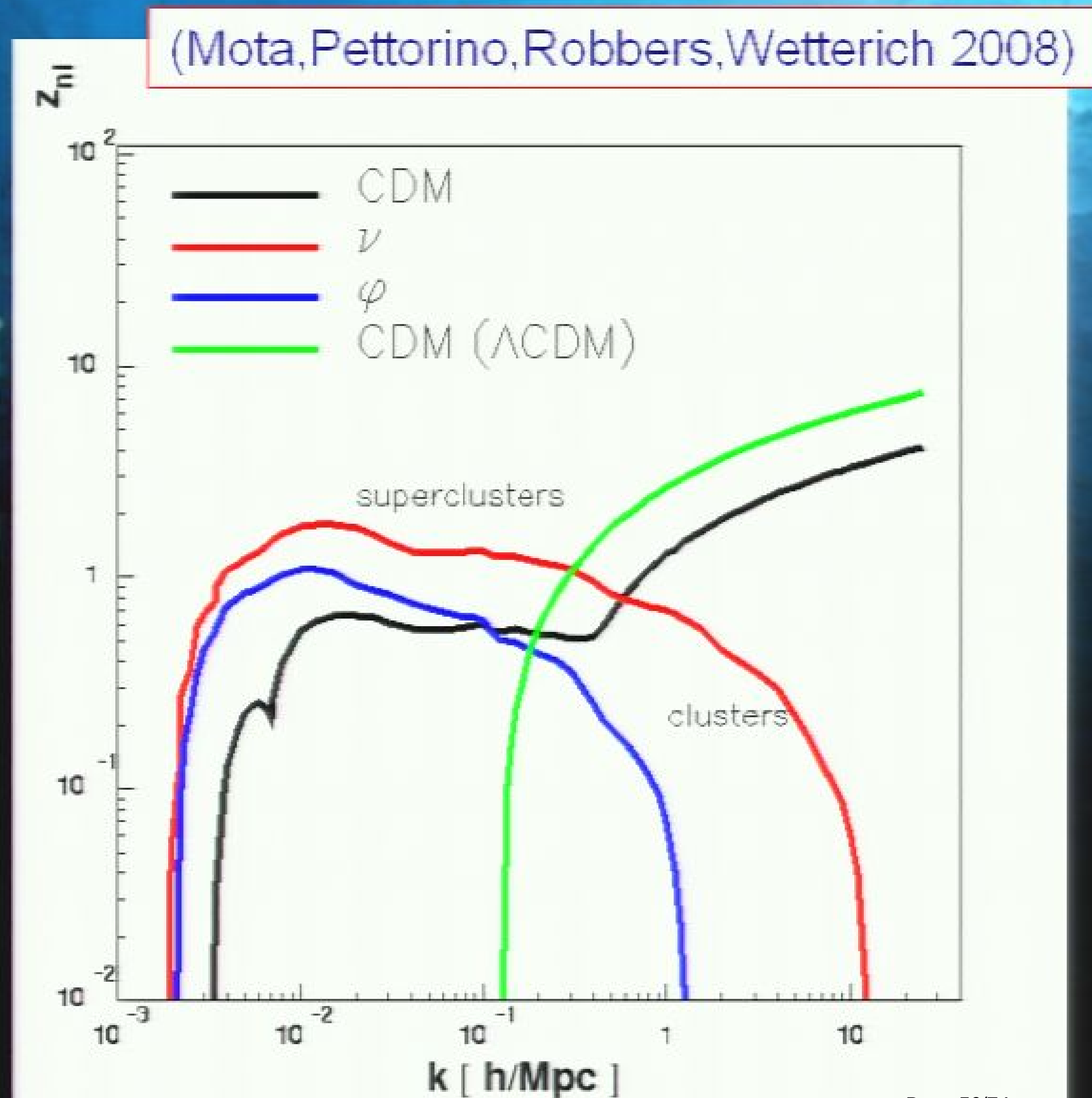


k = 0.1 h/Mpc

Neutrino clustering

- Neutrino structures become non linear at z ~ 1 for supercluster scales
- At small scales neutrinos reduce CDM structures
- Stable neutrino lumps/nuggets

Afshordi etal 2005
Brouzakis etal 2007



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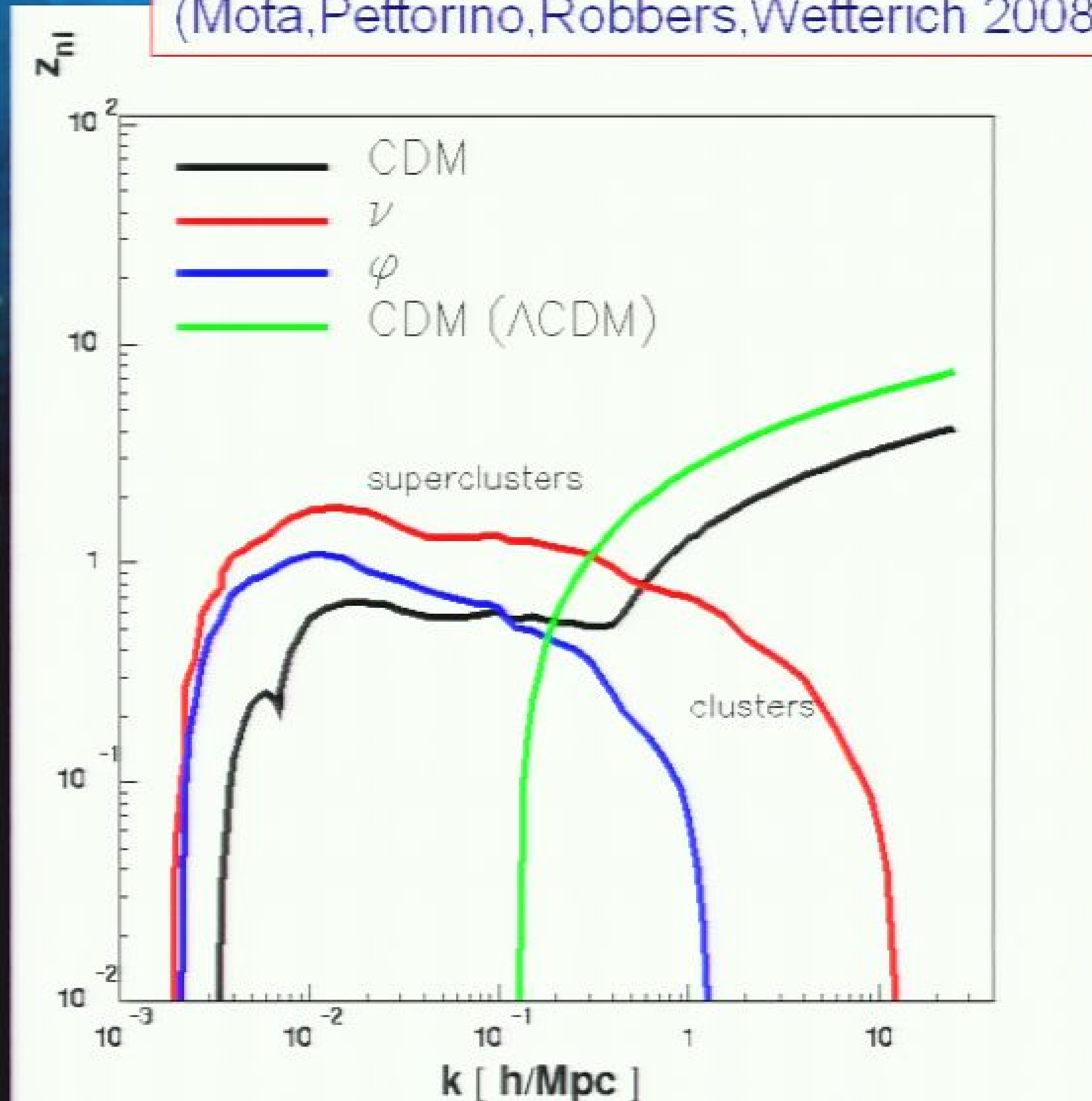

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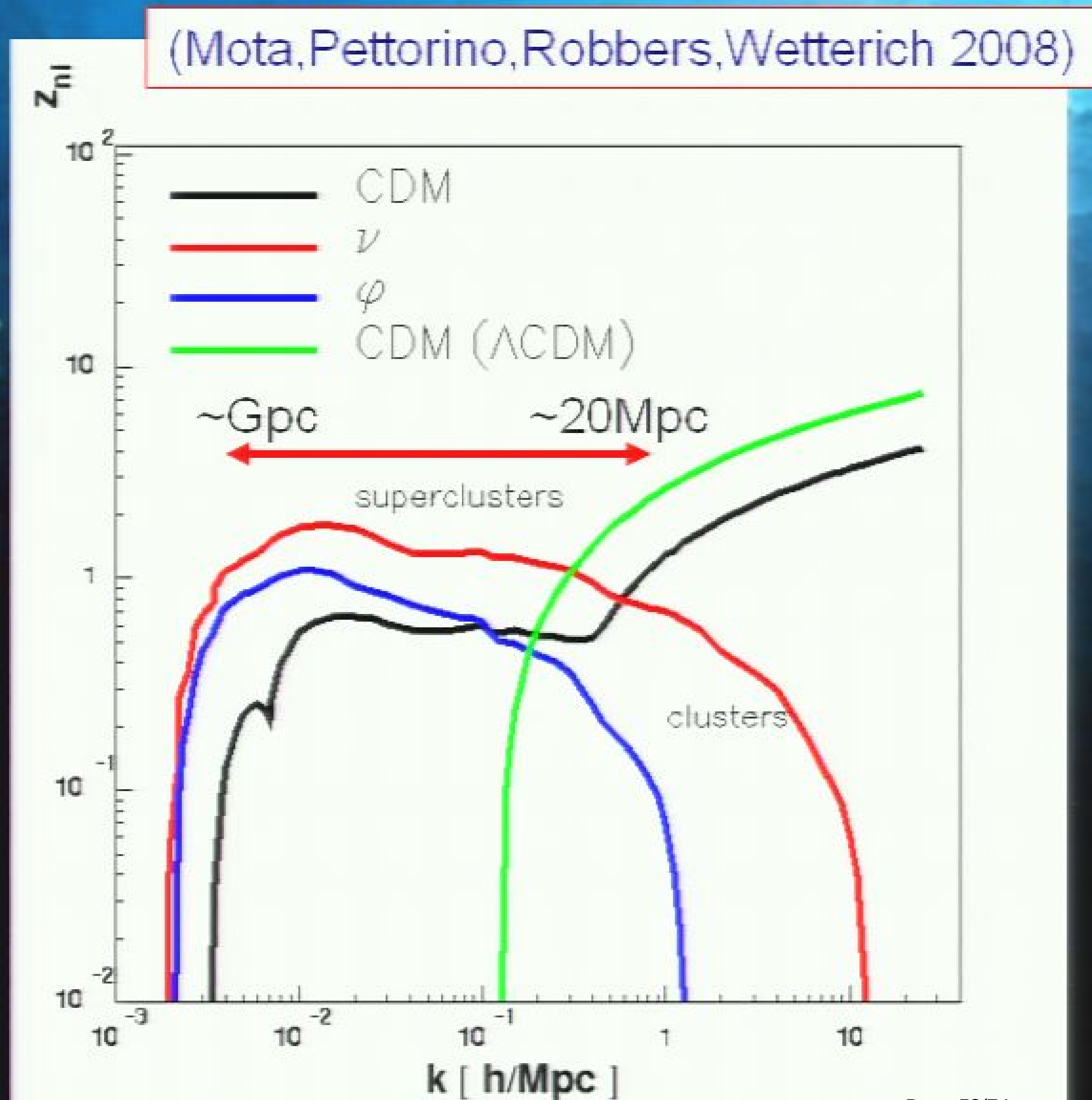
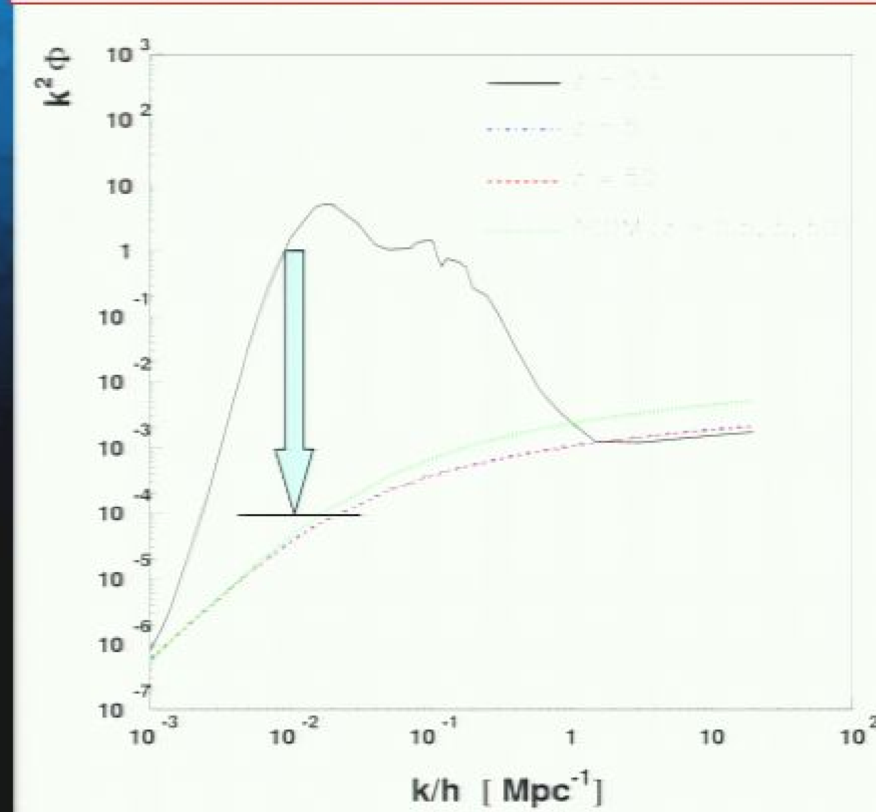


Gravitational potential

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

(Mota,Pettorino,Robbers,Wetterich 2008)



- There aren't many neutrinos!
- If they distribute more or less homogeneously in more lumps, the gravitational potential can be significantly reduced

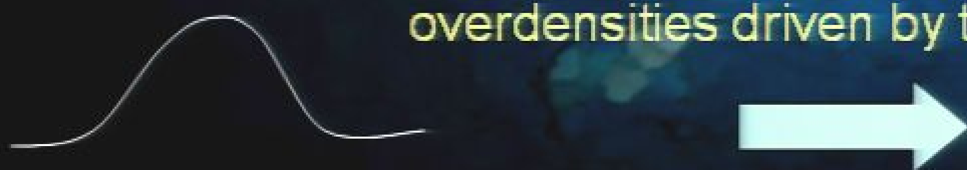
Essential to have a knowledge of the realistic gravitational potential due to the presence of a distribution of virialized neutrino lumps

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

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

...first results are encouraging

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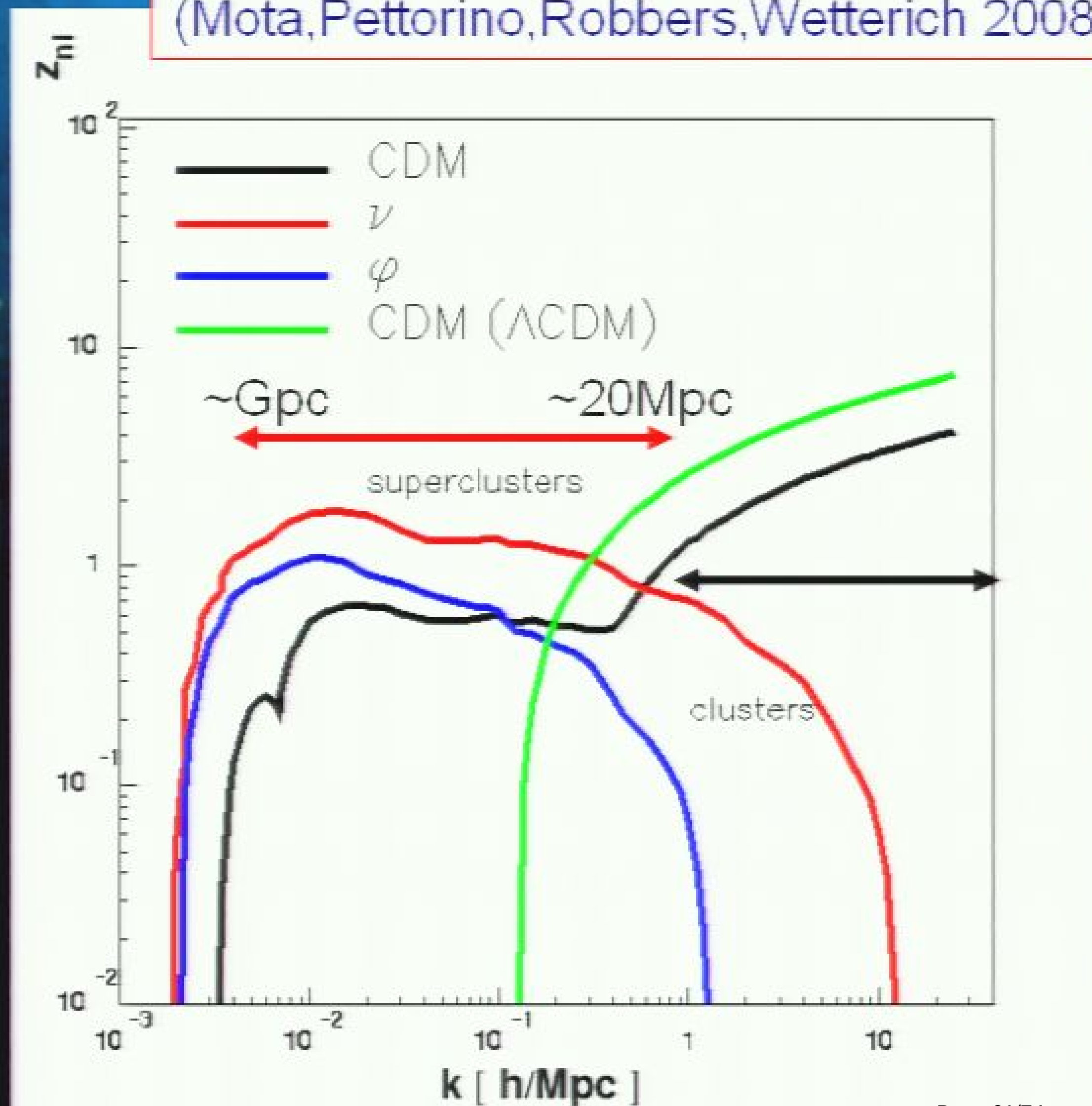

Afshordi etal 2005
Brouzakis etal 2007

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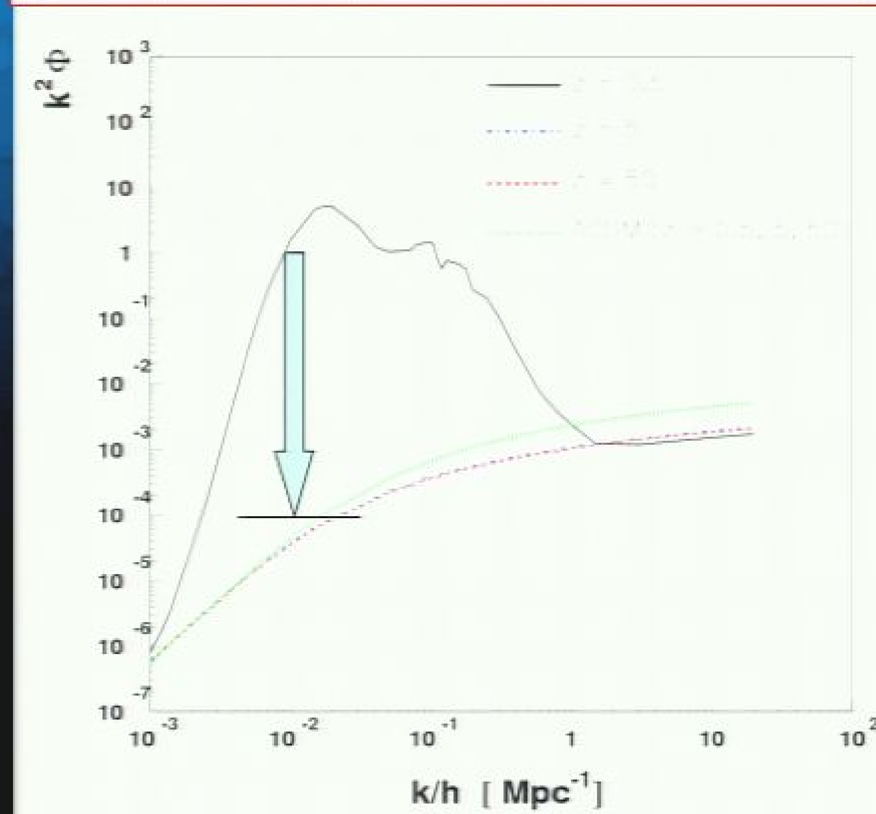

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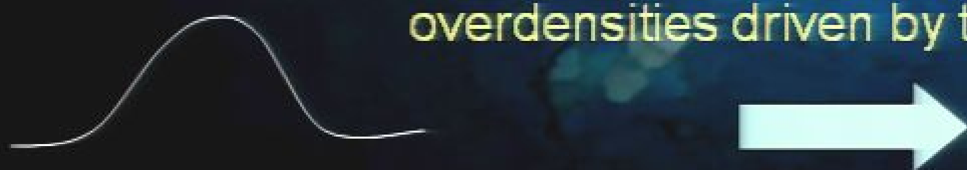

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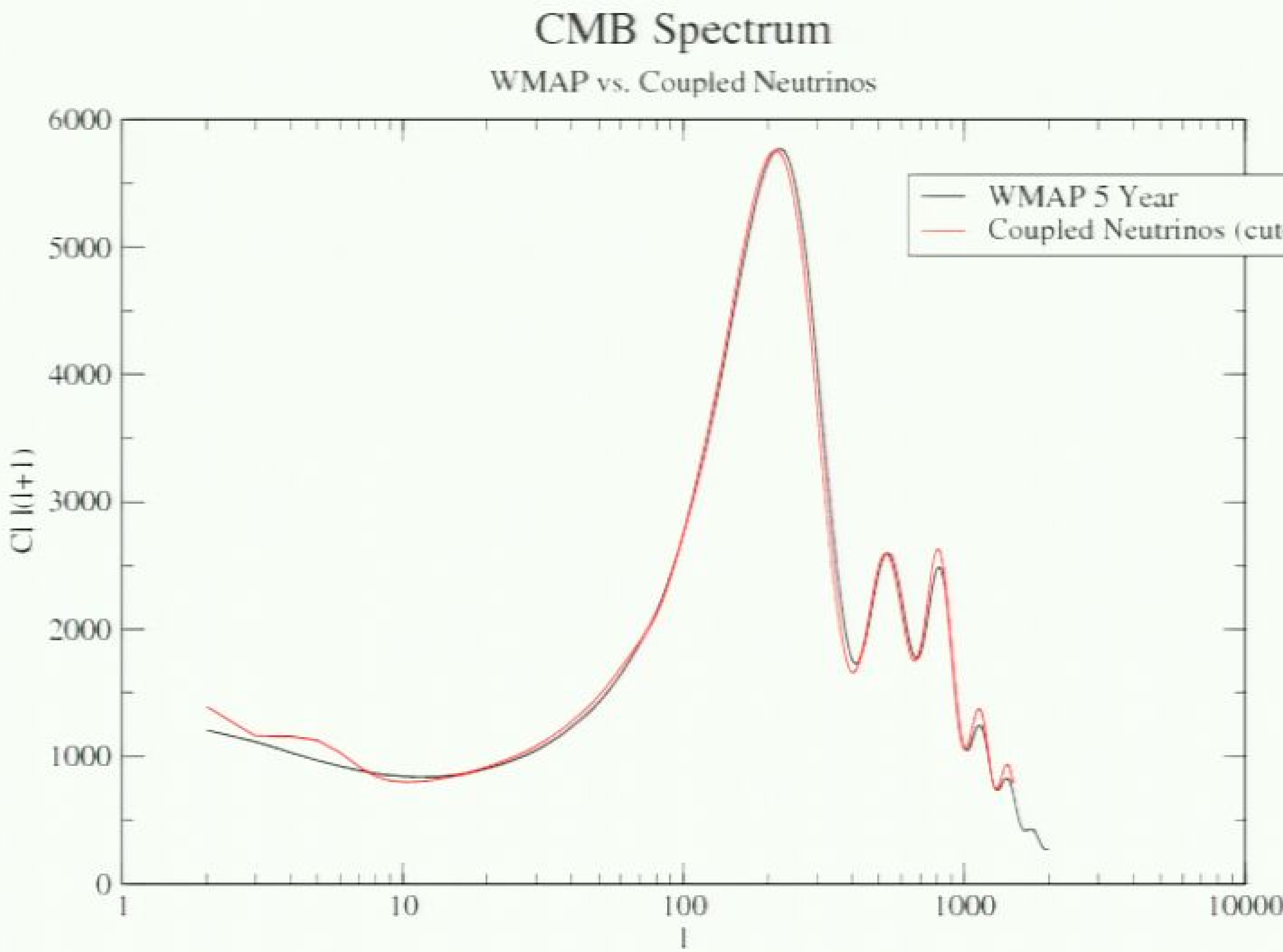


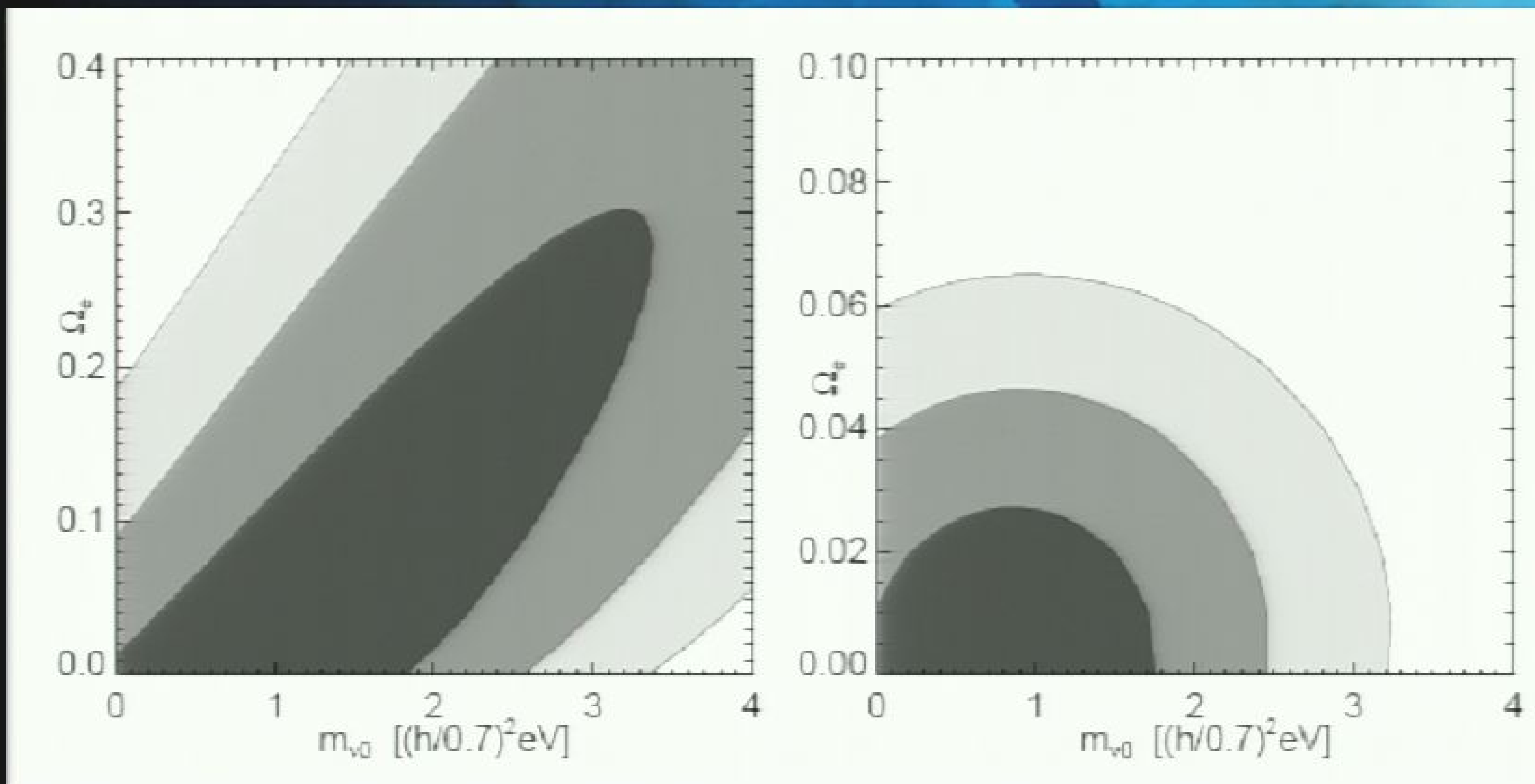
Work in progress!

Monte Carlo analysis necessary!

Work in progress

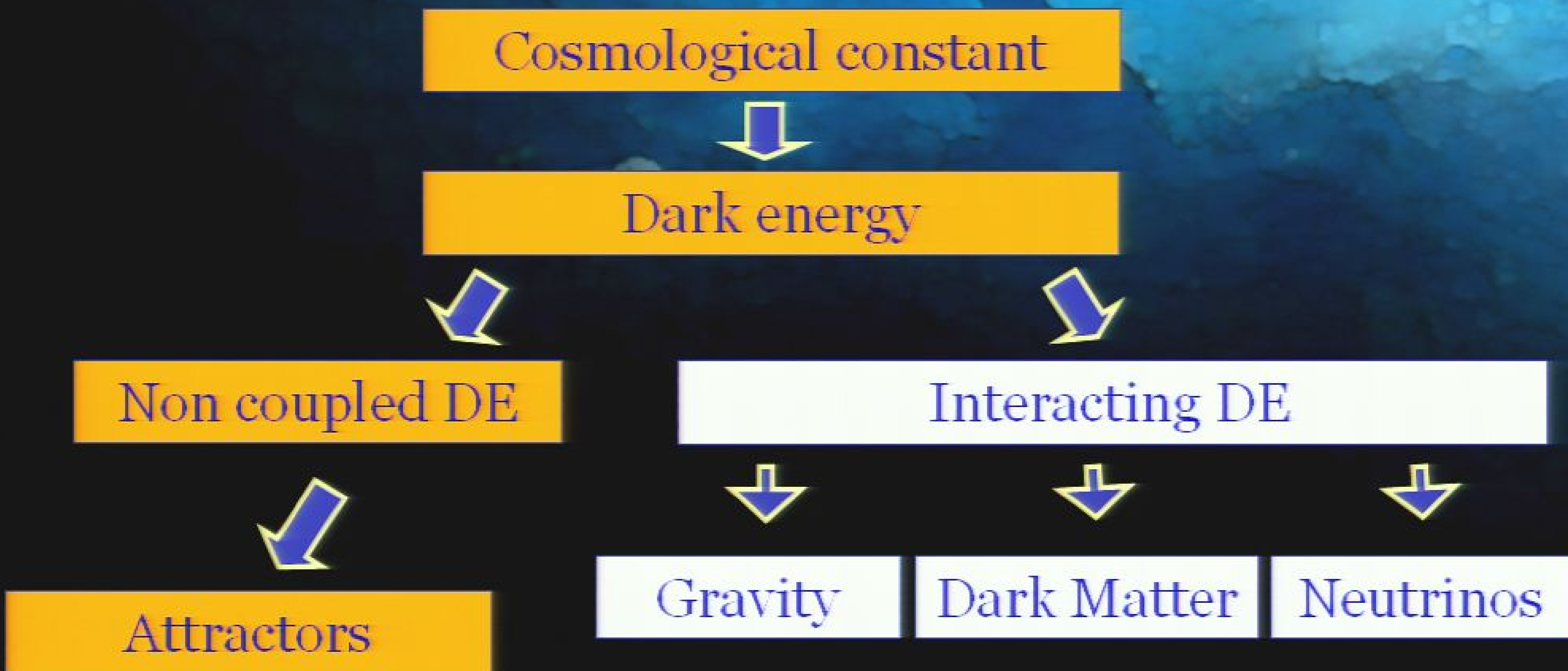
E.Carlesi, D.Mota, V.Pettorino, G.Robbers, C.Wetterich

Supernovae constraints



Rubin etal 2008

Dark energy



Cosmological constant
Dark energy
Non coupled DE
Interacting DE
Attractors
Gravity
Dark Matter
Neutrinos

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 $z \sim 1$ 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

DUNE Euclid SPACE

NASA JOINT DARK ENERGY MISSION
Beyond Einstein Program

ESA Cosmic Vision Program

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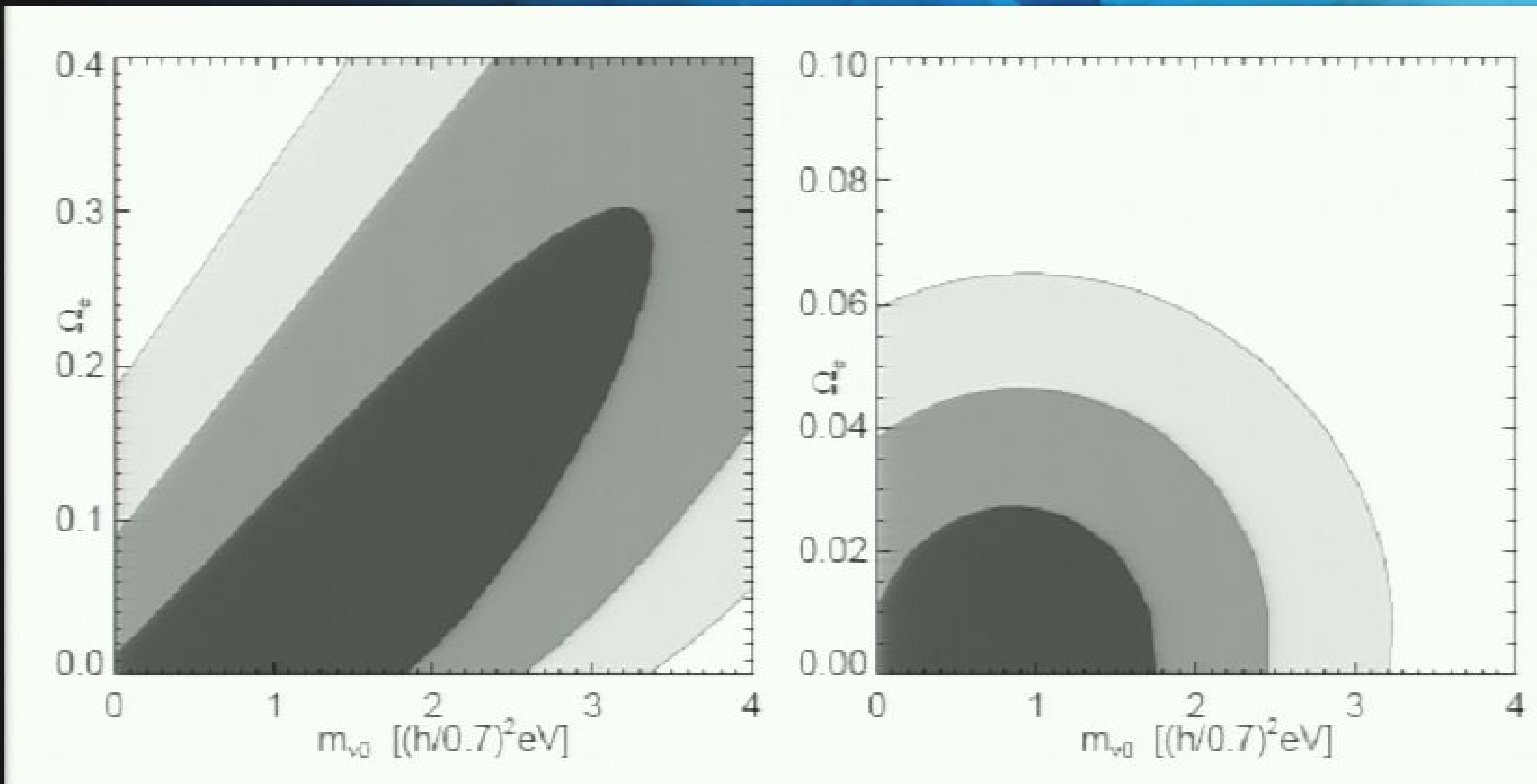

Rubin etal 2008

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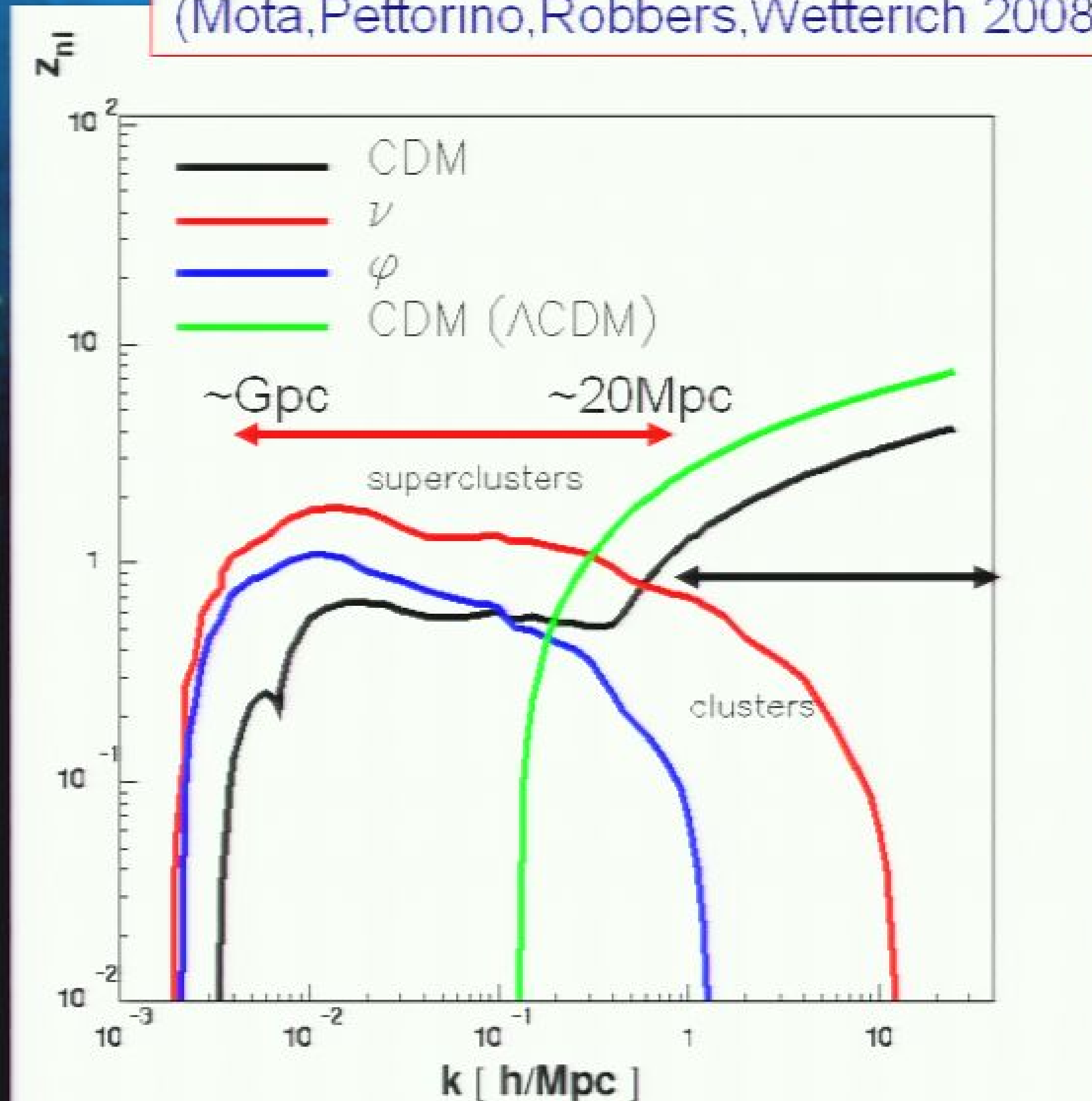

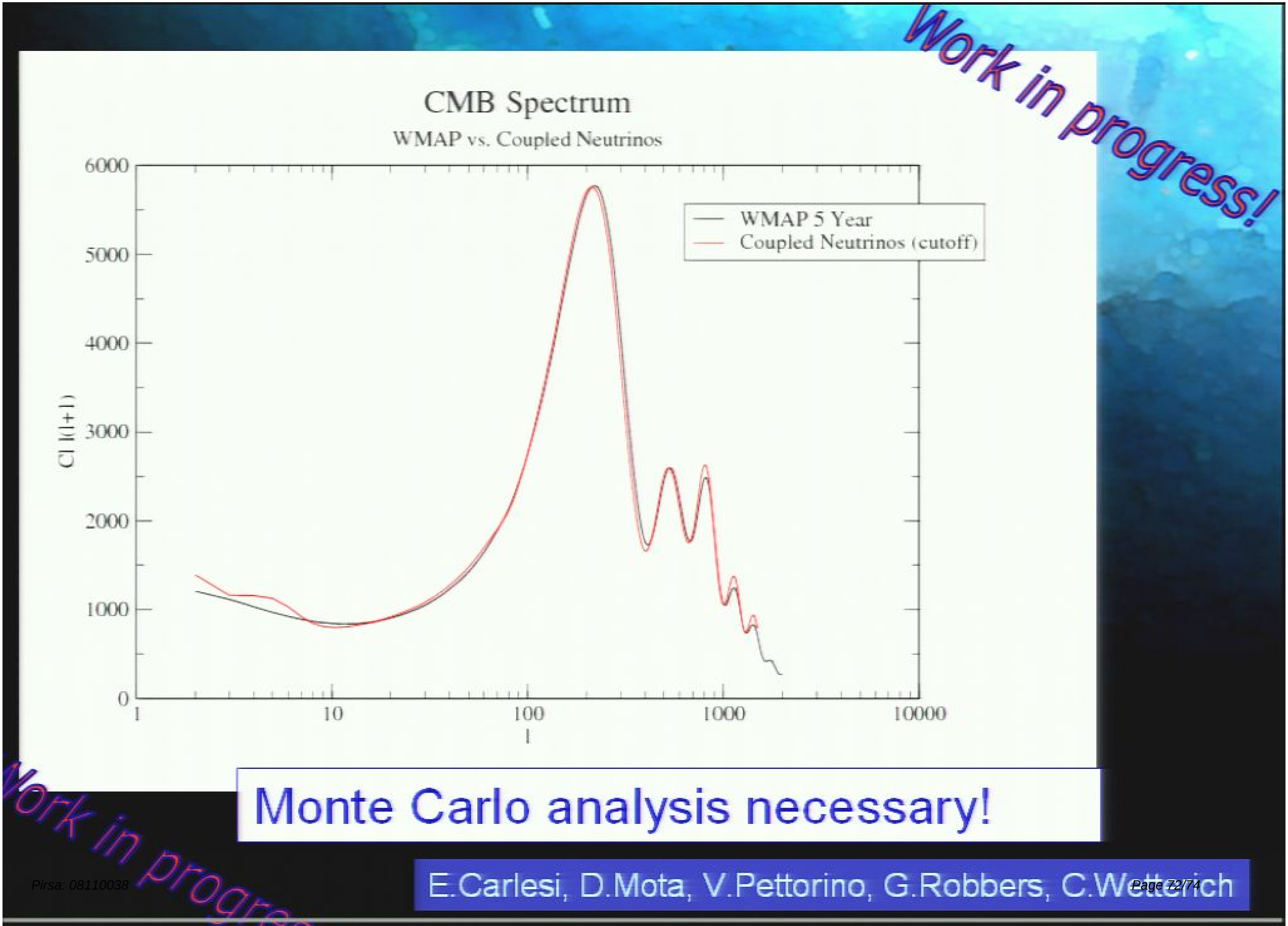
Work in progress!
CMB Spectrum
WMAP vs. Coupled Neutrinos
WMAP 5 Year
Coupled Neutrinos (cutoff)
Cl l(l+1)
6000
5000
4000
3000
2000
1000
0
1
10
100
1000
10000
l
Work in progress
Monte Carlo analysis necessary!
E.Carlesi, D.Mota, V.Pettorino, G.Robbers, C.Wetterich

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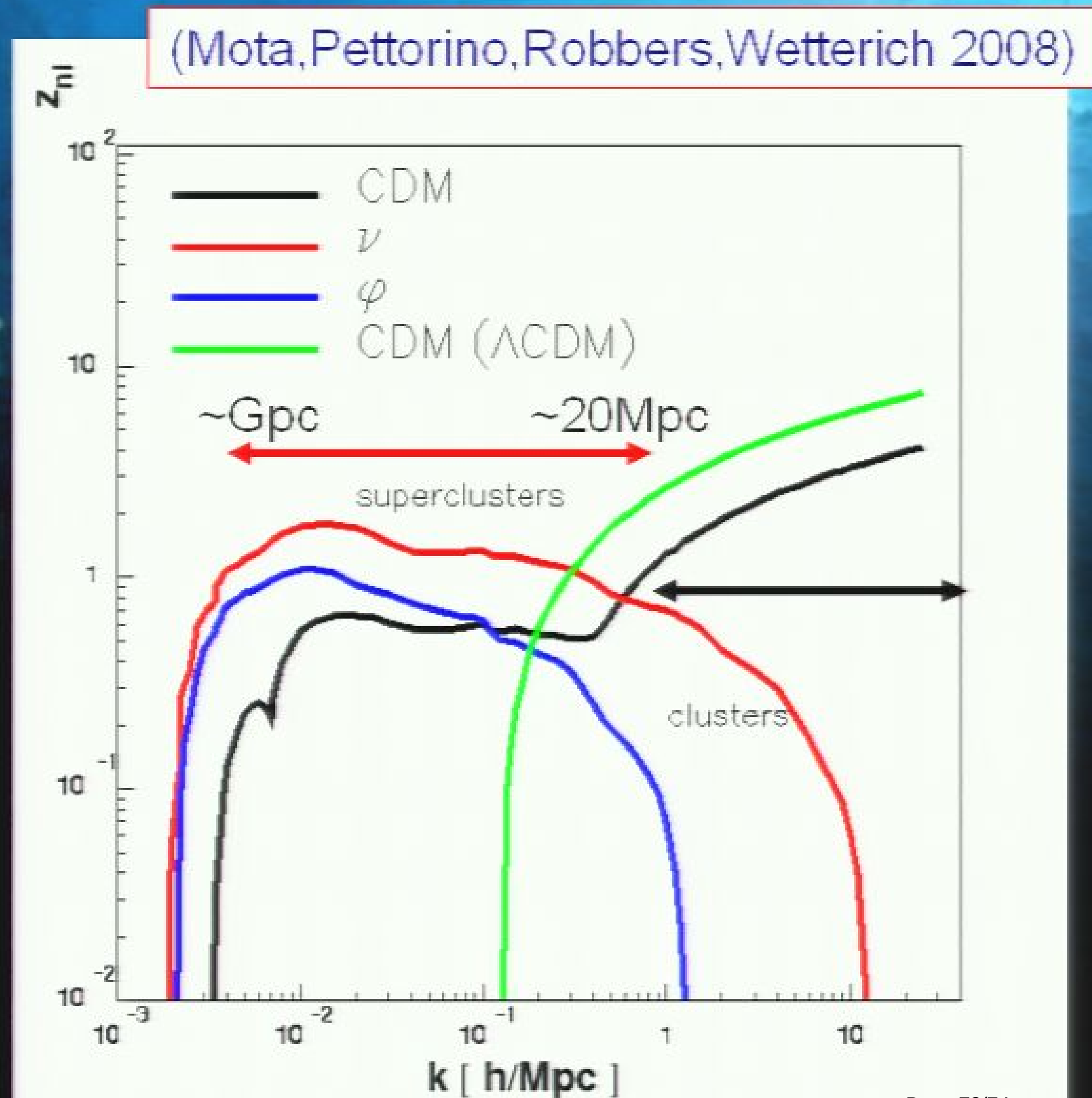

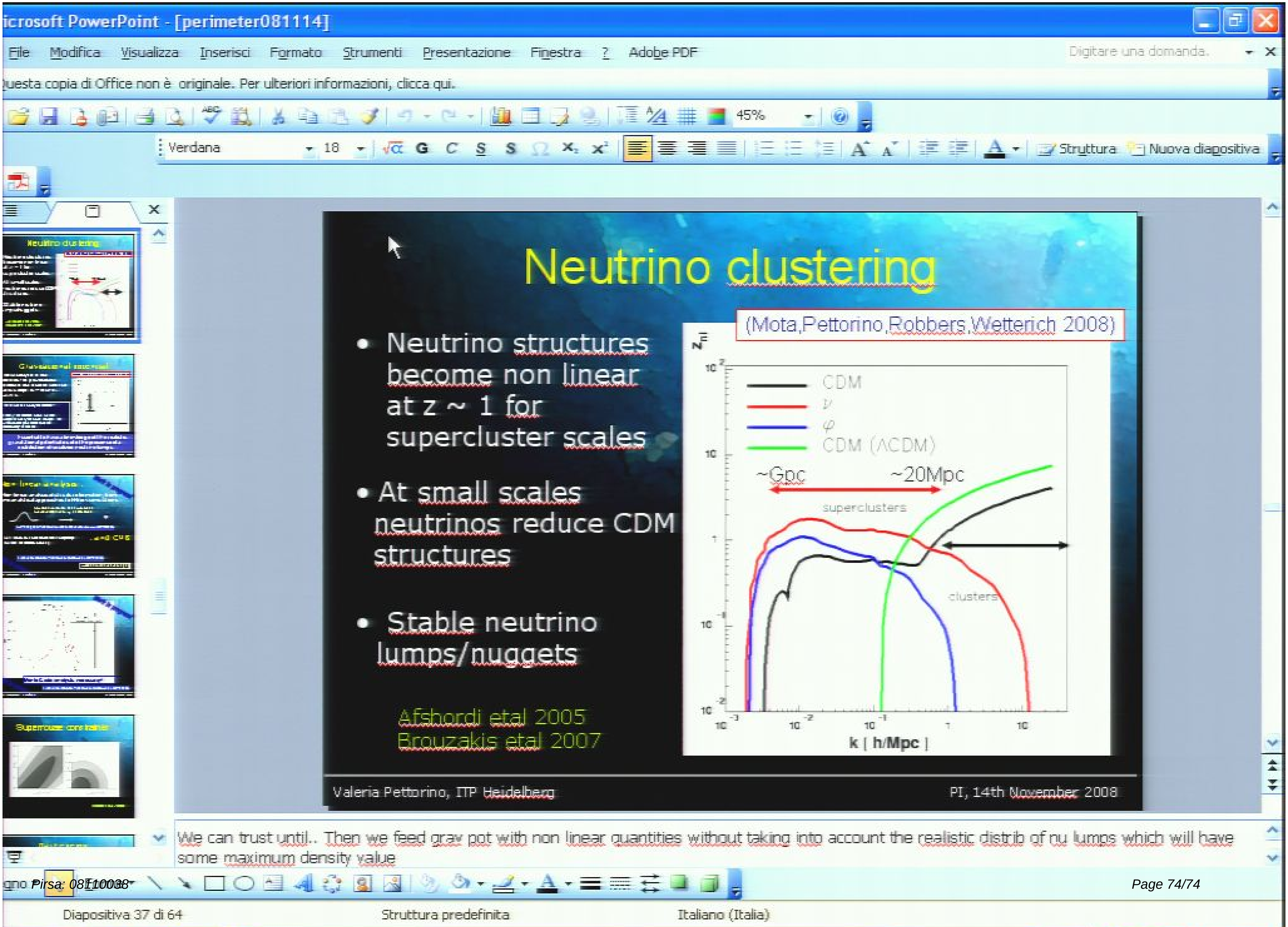
Microsoft PowerPoint - [perimeter081114]
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Brouzakis etal 2007
CDM
ν
φ
CDM (ΛCDM)
~Gpc
~20Mpc
superclusters
clusters
k [h/Mpc]
Valeria Pettorino, ITP Heidelberg
PI, 14th November 2008
We can trust until.. Then we feed grav pot with non linear quantities without taking into account the realistic distrib of nu lumps which will have some maximum density value
Diapositiva 37 di 64
Struttura predefinita
Italiano (Italia)