



# Clustering in growing neutrino quintessence

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TRR33 meeting: *the Dark Universe*  
20.06.09 Heidelberg

# C3!

- Amendola, Baldi, Wetterich 2007, Wetterich 2007 background
- D.F.Mota, V.Pettorino, G.Robbers, C.Wetterich 2008 linear perturbations
- Wintergerst, Pettorino, Mota, Wetterich in preparation non linear evolution
- Stern, Dent, Wetterich 2008
- Brouzakis, Tetradis, Wetterich 2008
- ...

# Dark energy and neutrinos

Significant influence in cosmology

Neutrinos naturally provide the right scale  
for dark energy



## Growing neutrinos:

Amendola et al 2007, Wetterich 2007, Mota et al 2008,  
Brouzakis et al 2007, Rubin et al 2008

## MAVANS:

Fardon et al 2004, Afshordi et al 2005, Bjaelde et al 2008,  
Brookfield et al 2007

# Dealing with a coupling

$$\nabla_\nu T_{(\alpha)\mu}^\nu = Q_{(\alpha)\mu}$$

For a multicomponent system, the stress energy tensor of the single species is in general not conserved.

$$\sum_\alpha Q_{(\alpha)\mu} = 0$$

Kodama&Sasaki 1984, Wetterich 1995, Amendola 2000, ...

DE and neutrinos

DE as a scalar field

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

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

$$\mathcal{L} = -\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - U(\phi) - m(\phi)\bar{\psi}\psi + \mathcal{L}_{kin}[\psi]$$

$$Q_{(\phi)\mu} = \frac{\partial \ln m(\phi)}{\partial \phi} (\rho - 3p) \partial_\mu \phi$$

The mass of the coupled species is a function of the DE scalar field

Exponential with a constant parameter  $\beta$

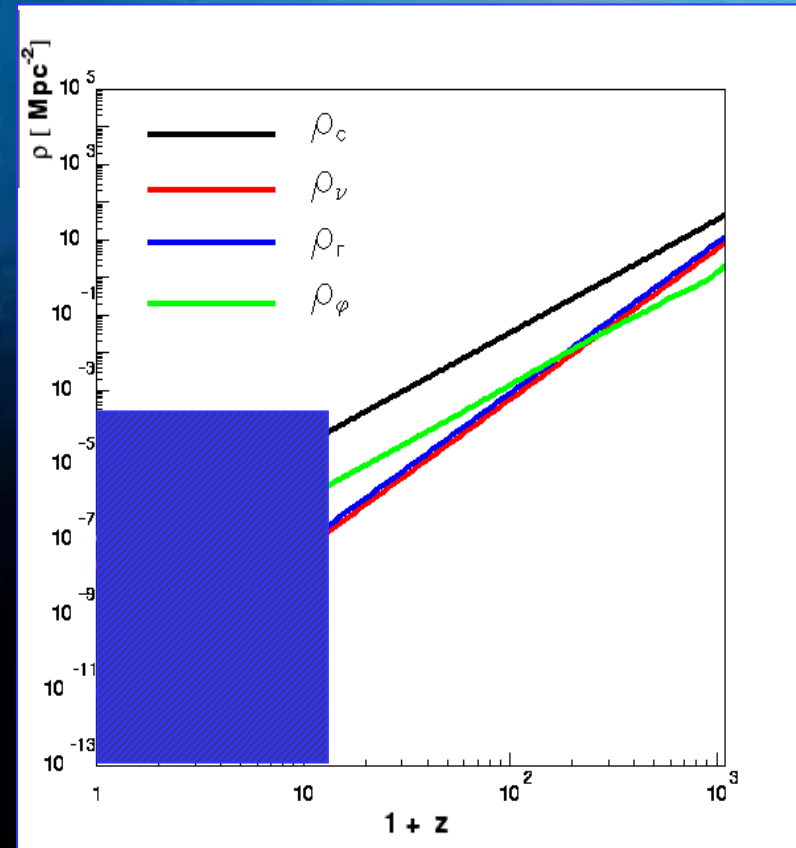
$$m(\phi) = m_0 e^{-\beta \frac{\phi}{M}}$$

$$m_\nu(\varphi) = \frac{\bar{m}_\nu M}{\epsilon(\varphi - \varphi_t)}$$

Wetterich 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~~

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

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

↓  
Neutrino mass grows ( $\beta < 0$ )

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

↓  
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# Neutrinos become non relativistic

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

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

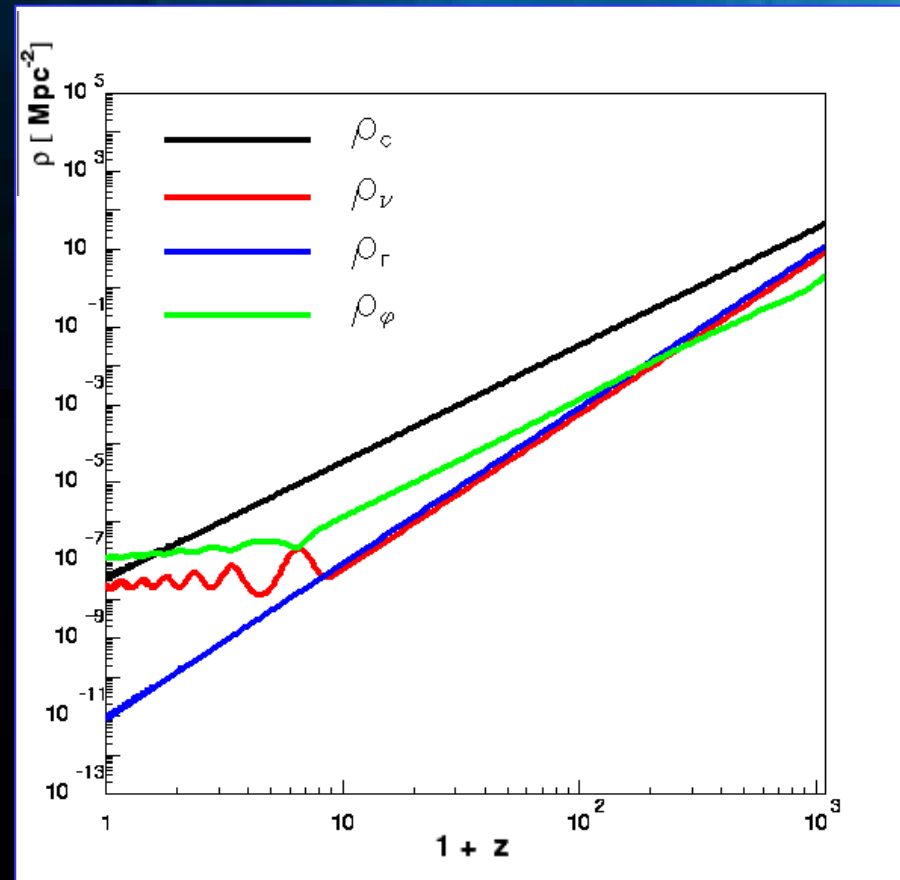
Neutrino mass grows ( $\beta < 0$ )

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

Neutrinos become non relativistic

The coupling to DE turns on and almost stops  $\phi$

# Coupling Dark Energy to neutrinos



Acceleration

# Dark energy - neutrino connection

Dark energy and neutrino properties are related!

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

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

DE- $\nu$  fluid equation of state

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

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

# Linear perturbations

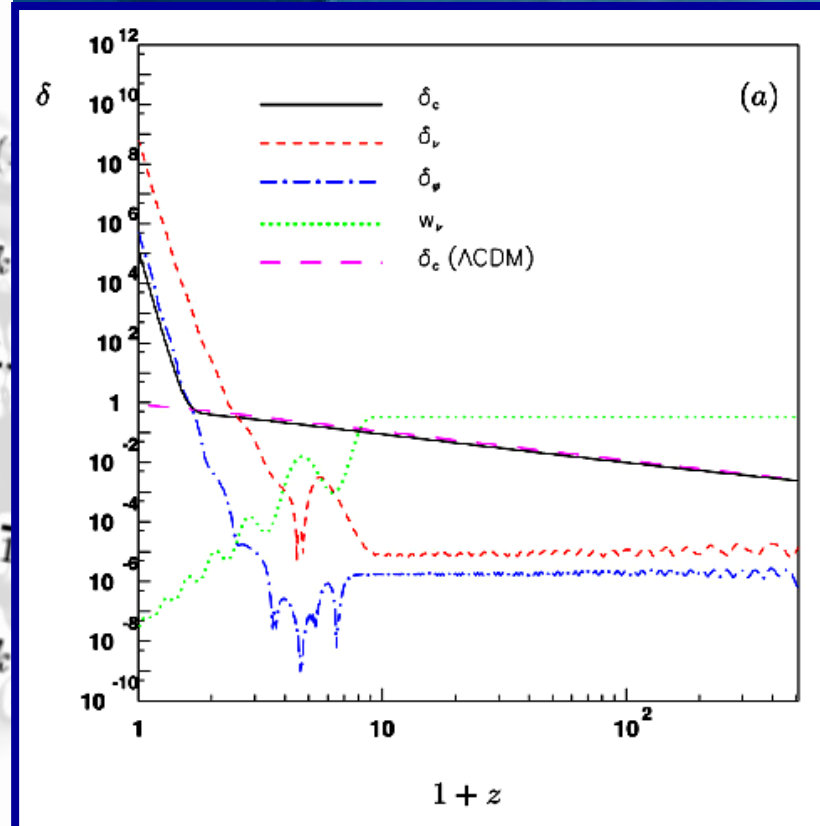
Implemented  
CMBEASY and CAMB  
to solve linear perturbations

$$\delta'_\phi = 3\mathcal{H}(w_\phi - c_\phi^2)\delta_\phi - \beta(\phi)\phi' \frac{\rho_\nu}{\rho_\phi} [(1 - 3c_\phi^2)\delta_\nu - (1 + w_\phi)(k v_\phi + \frac{\rho_\nu}{\rho_\phi}(1 - 3w_\phi) v'_\nu)]$$

$$v'_\phi = -\mathcal{H}(1 - 3w_\phi)v_\phi - \beta(\phi)\phi' \left[ \frac{w'_\phi}{1 + w_\phi} v_\phi + k c_\phi^2 \frac{\delta_\phi}{1 + w_\phi} + k \frac{2}{3} \frac{w_\phi}{1 + w_\phi} k \pi T_\phi + k \beta(\phi) \delta_\phi \frac{\rho_\nu}{\rho_\phi} \right]$$

$$\delta'_\nu = 3(\mathcal{H} - \frac{d\beta(\phi)}{d\phi})\delta_\nu - (1 + w_\nu) \left[ \frac{d\beta(\phi)}{d\phi} \delta_\phi + \frac{d\beta(\phi)}{d\phi} \frac{\rho_\nu}{\rho_\phi} \delta_\phi + \frac{d\beta(\phi)}{d\phi} \frac{\rho_\nu}{\rho_\phi} \delta_\phi + \frac{d\beta(\phi)}{d\phi} \frac{\rho_\nu}{\rho_\phi} \delta_\phi \right]$$

$$v'_\nu = (1 - 3w_\nu)(\beta(\phi)\phi' - \mathcal{H})v_\nu - \frac{2}{3}k \left[ k c_\nu^2 \frac{\delta_\nu}{1 + w_\nu} + k \Psi - \frac{2}{3}k \frac{d\beta(\phi)}{d\phi} \frac{\rho_\nu}{\rho_\phi} \delta_\phi \frac{1 - 3w_\nu}{1 + w_\nu} \right]$$



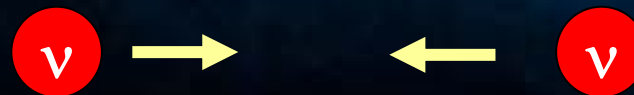
[Mota, Pettorino, Robbers, Wetterich 2008]

$k = 0.1 \text{ h/Mpc}$

# Effective attractive force

Neutrinos feel an extra attractive interaction mediated by the dark energy scalar field

$$\vec{F} = \beta \vec{\nabla} \delta\phi = \beta^2 \vec{\nabla} \Phi$$



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

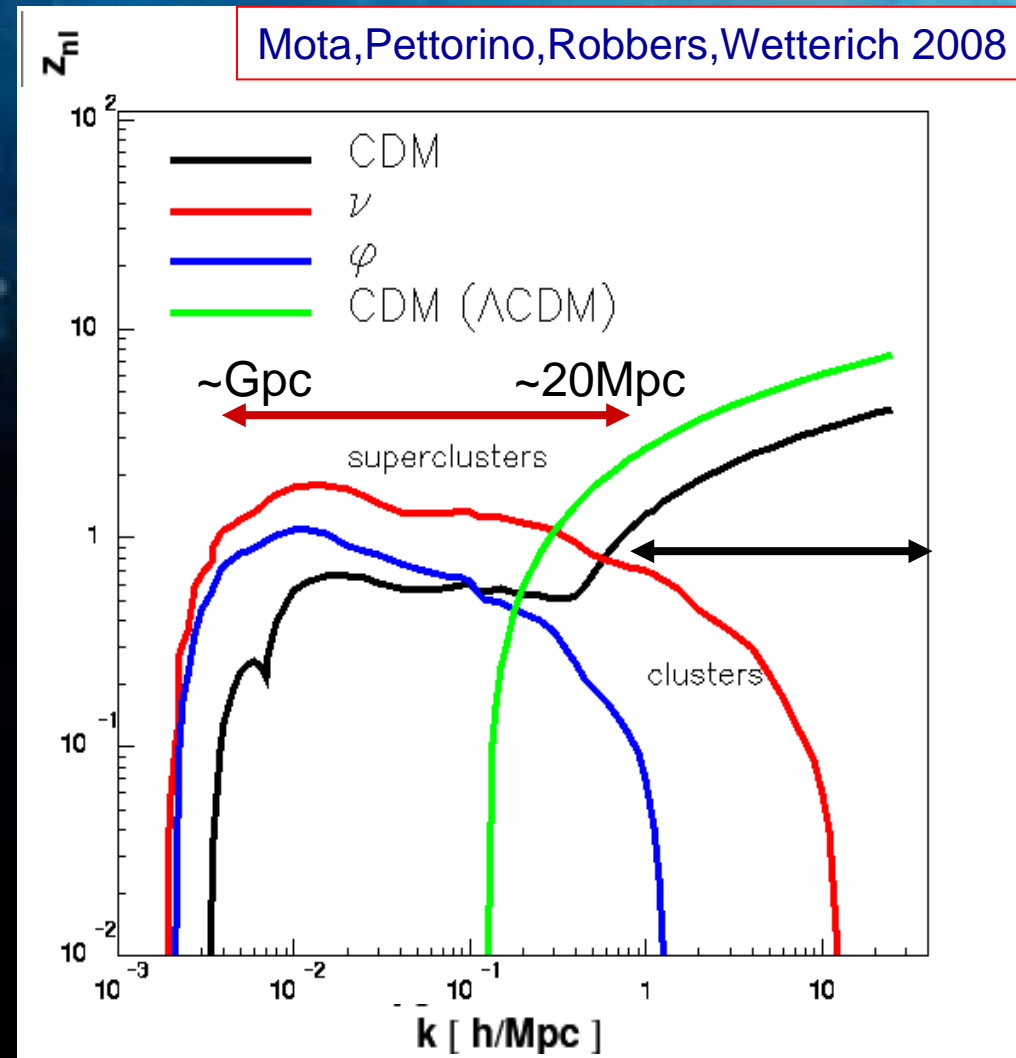
The dark energy scalar field - the cosmon - mediator of a fifth force acting on cosmological scales

Remember that neutrinos have become non relativistic and effectively behave as coupled cdm

# Neutrino clustering

- Neutrino structures become non linear at  $z \sim 1$  for supercluster scales
- At small scales neutrinos reduce CDM structures
- Stable neutrino lumps

Brouzakis et al 2007

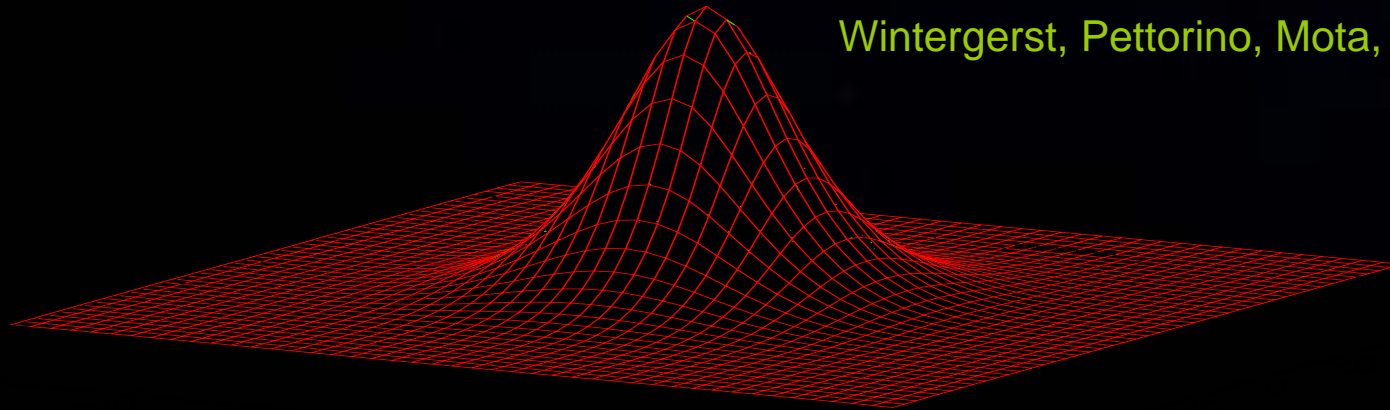


# Very large structures

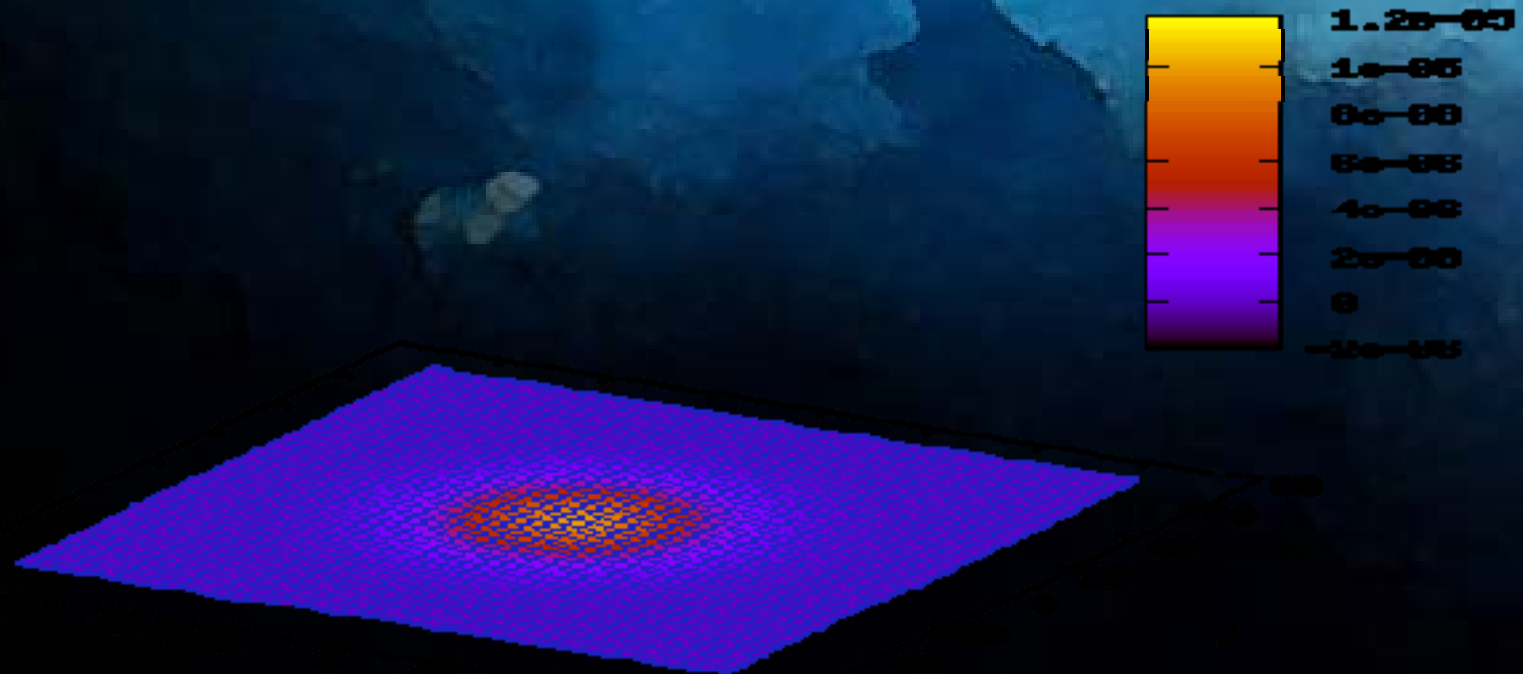
Prediction: formation of neutrino lumps  
at supercluster scales

Non linear investigation of neutrino lumps in real space

Wintergerst, Pettorino, Mota, Wetterich in preparation



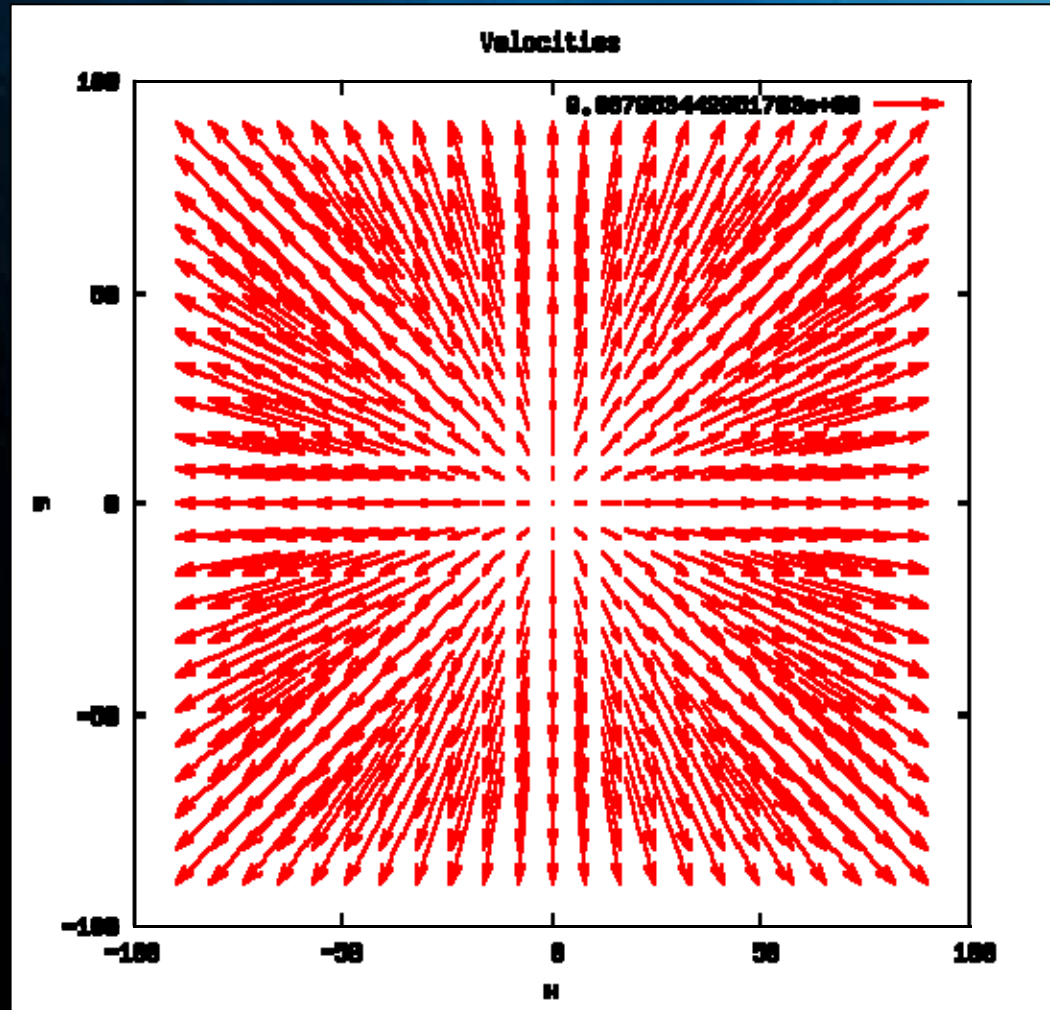
# Non linear evolution: overdensity



Formation of a lump under the effect of the fifth force

Wintergerst, Pettorino, Mota, Wetterich in preparation

# Non linear evolution: velocities



Wintergerst, Pettorino, Mota, Wetterich in preparation

# Conclusions

- Neutrinos play a crucial role in cosmology!
- $z \sim 10$ : neutrinos become non relativistic and activate the coupling. Transition from attractor to a cosmological constant like behavior.
- Dark energy and neutrino properties are related.
- Neutrinos cluster at  $z \sim 1$  at supercluster scales and beyond.
- 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.