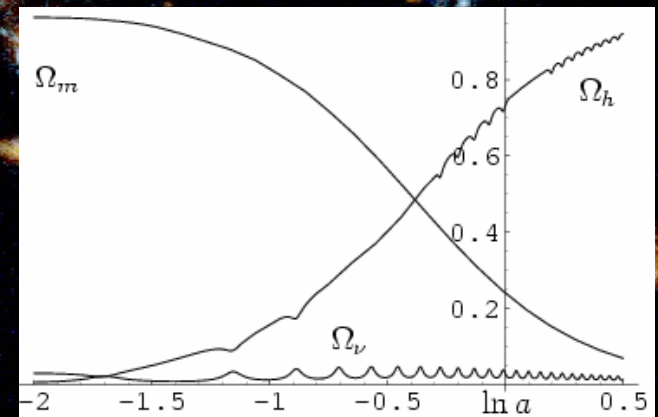
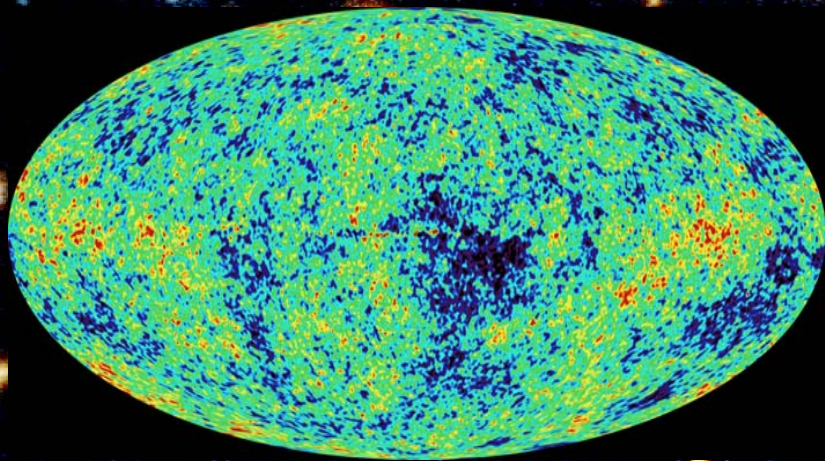


# Neutrino lumps



# connection between dark energy and neutrino properties

$$[\rho_h(t_0)]^{\frac{1}{4}} = 1.27 \left( \frac{\gamma m_\nu(t_0)}{eV} \right)^{\frac{1}{4}} 10^{-3} eV$$

present dark energy density computable  
in terms of neutrino mass

present equation  
of state given by  
neutrino mass !

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

# Cosmological mass scales

- Energy density

$$\rho \sim (2.4 \times 10^{-3} \text{ eV})^{-4}$$

- Reduced Planck mass

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

- Newton's constant

$$G_N = (8\pi M^2)$$

Only ratios of mass scales are observable !

homogeneous dark energy:  $\rho_h/M^4 = 6.5 \cdot 10^{-121}$

matter:  $\rho_m/M^4 = 3.5 \cdot 10^{-121}$

# connection between dark energy and neutrino properties

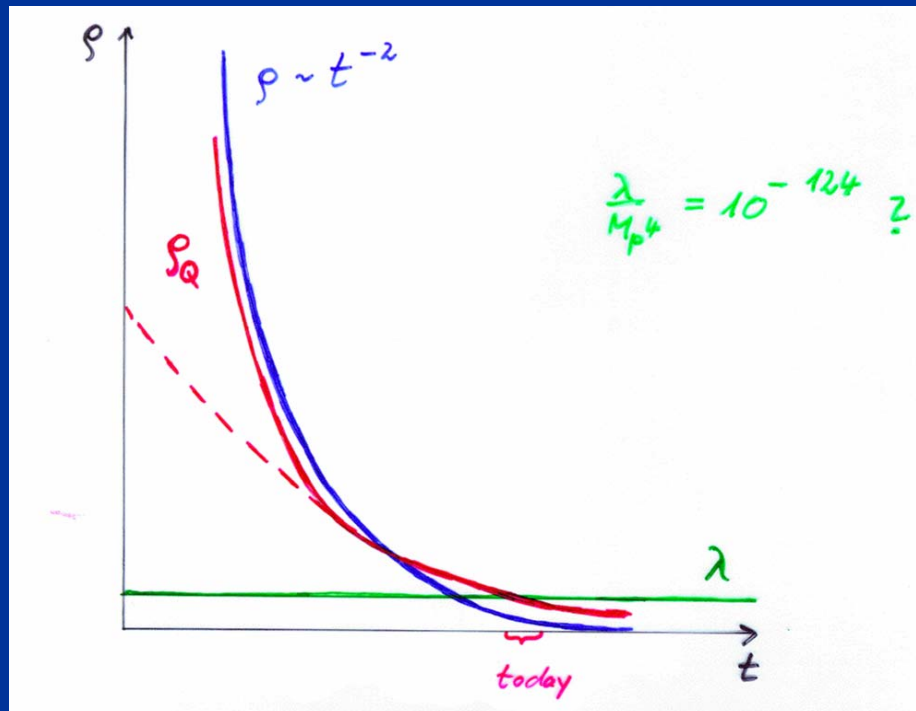
$$[\rho_h(t_0)]^{\frac{1}{4}} = 1.27 \left( \frac{\gamma m_\nu(t_0)}{eV} \right)^{\frac{1}{4}} 10^{-3} eV$$

present dark energy density computable  
in terms of neutrino mass

Energy density :  $\rho^{1/4} \sim 2.4 \times 10^{-3} eV$

# Why now problem

- Why is dark energy important now and not in the past?



**neutrino masses and  
dark energy density  
depend on time !**

# Quintessence

Dynamical dark energy ,  
generated by scalar field

(cosmon)

C.Wetterich,Nucl.Phys.B302(1988)668, 24.9.87

P.J.E.Peebles,B.Ratra,ApJ.Lett.325(1988)L17, 20.10.87

**Prediction :**

**homogeneous dark energy  
influences recent cosmology**

**- of same order as dark matter -**

Original models do not fit the present observations  
.... modifications



# Evolution of cosmon field

Field equations

$$\ddot{\phi} + 3H\dot{\phi} = -dV/d\phi$$

$$3M^2H^2 = V + \frac{1}{2}\dot{\phi}^2 + \rho$$

Potential  $V(\varphi)$  determines details of the model

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

for increasing  $\varphi$  the potential decreases  
towards zero !

# Cosmic Attractors

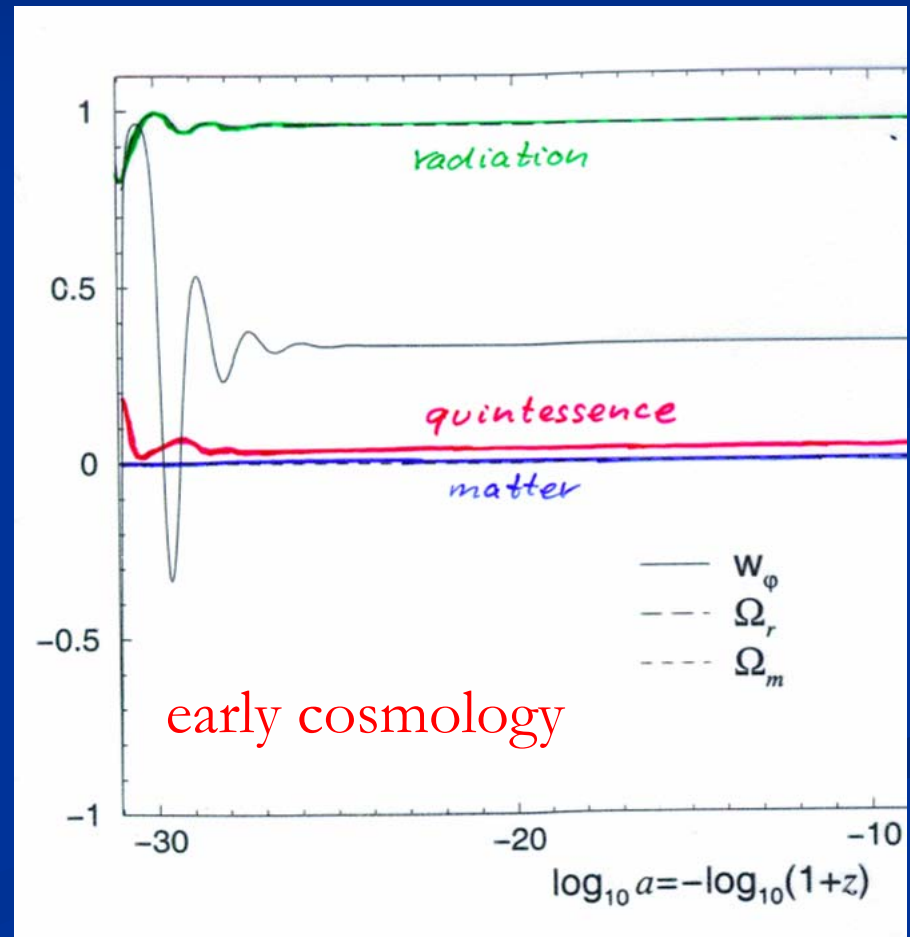
Solutions independent  
of initial conditions

typically  $V \sim t^{-2}$

$\varphi \sim \ln(t)$

$\Omega_h \sim \text{const.}$

details depend on  $V(\varphi)$   
or kinetic term



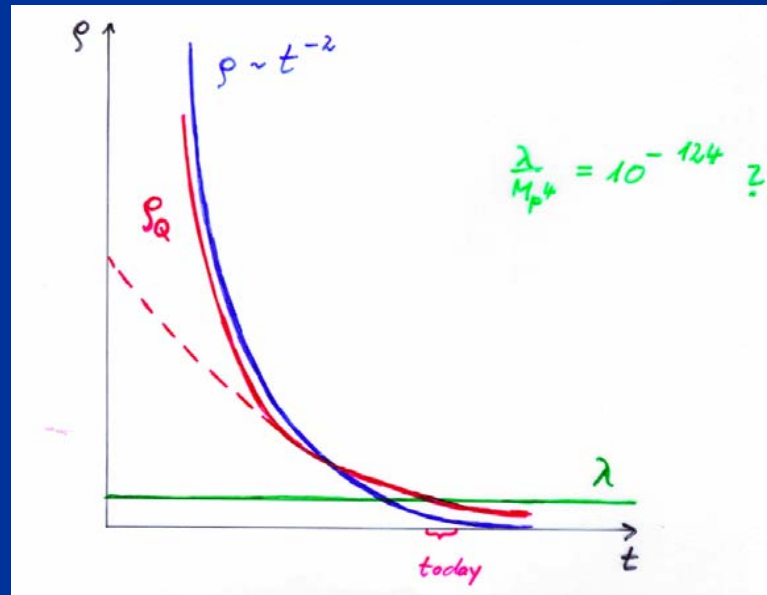
exponential potential →  
constant fraction in dark energy

$$\Omega_h = 3(4)/\alpha^2$$

can explain order of magnitude  
of dark energy !

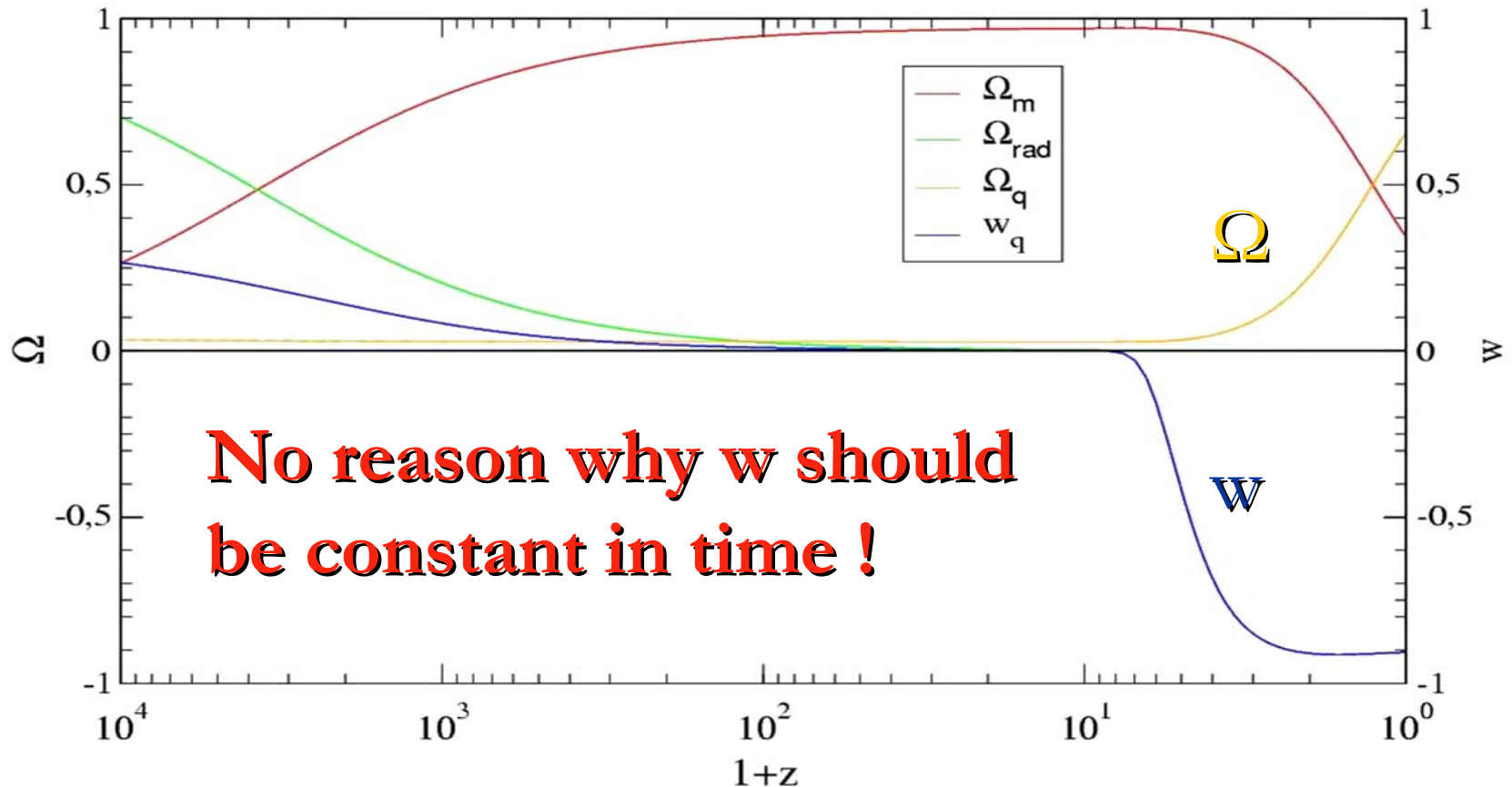
# realistic quintessence

fraction in dark energy has to increase in “recent time” !



# Quintessence becomes important “today”

Crossover Quintessence Evolution

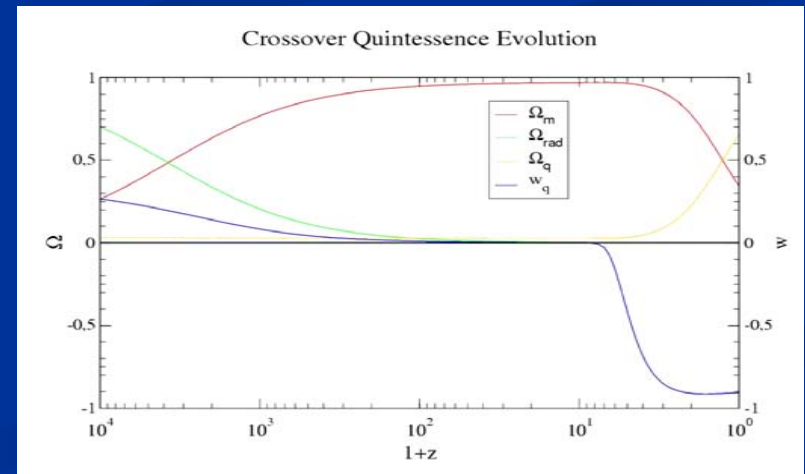


**cosmic coincidence**

# coincidence problem

What is responsible for increase of  $\Omega_h$  for  $z < 6$  ?

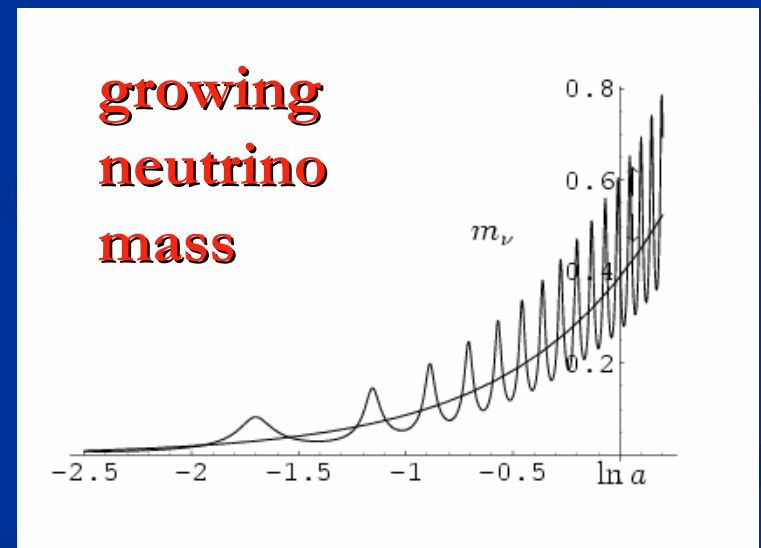
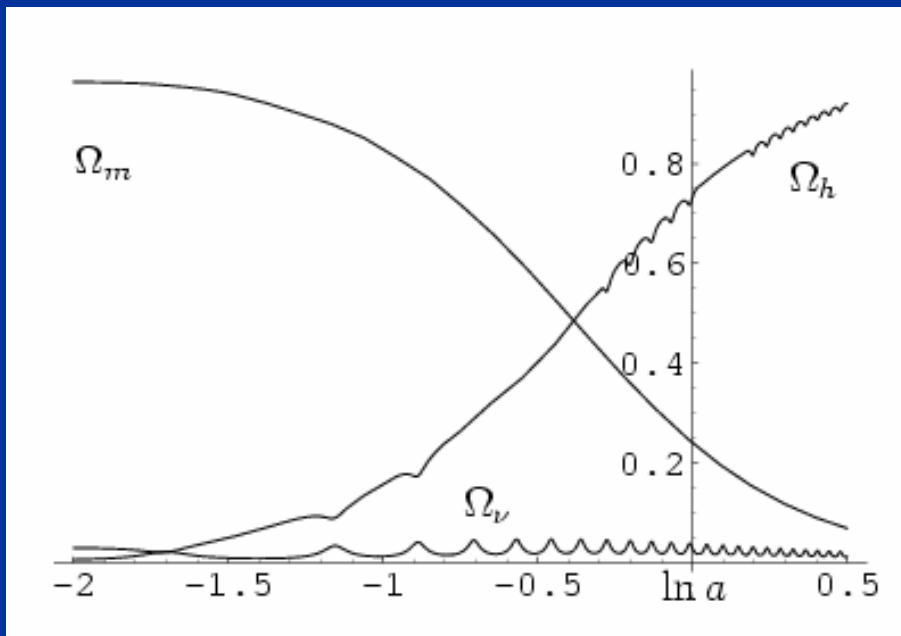
Why now ?



A new role for  
neutrinos  
in cosmology ?



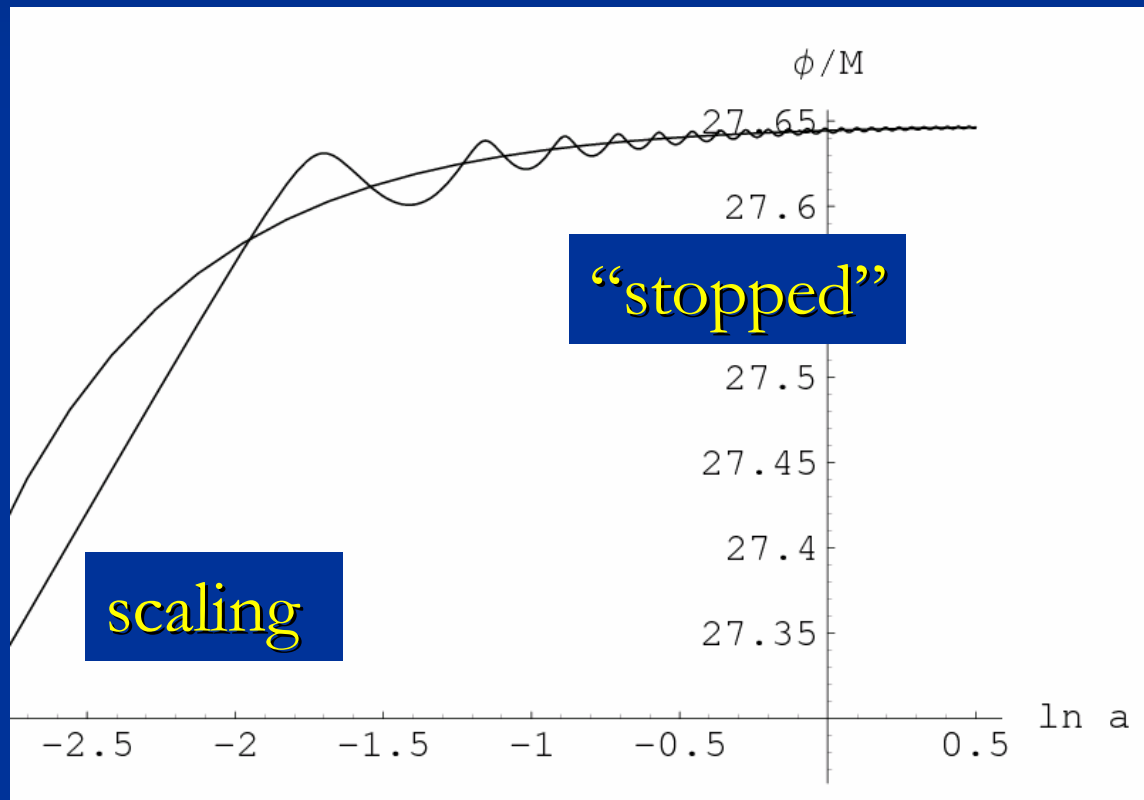
# growing neutrino mass triggers transition to almost static dark energy



effective cosmological trigger  
for stop of cosmon evolution :  
neutrinos get non-relativistic

- this has happened recently !
- sets scales for dark energy !

# cosmon evolution



stopped scalar field  
mimicks a  
cosmological constant  
( almost ... )

rough approximation for dark energy :

- before redshift 5-6 : scaling ( dynamical )
- after redshift 5-6 : almost static  
( cosmological constant )

basic ingredient :

**cosmon coupling to neutrinos**

# Cosmon coupling to neutrinos

- can be large !

Fardon, Nelson, Weiner

- interesting effects for cosmology if neutrino mass is growing
- growing neutrinos can stop the evolution of the cosmon
- transition from early scaling solution to cosmological constant dominated cosmology

L. Amendola, M. Baldi, ...

**growing neutrinos**

# varying neutrino – cosmon coupling

- specific model
- can naturally explain why neutrino – cosmon coupling is much larger than atom – cosmon coupling



# cascade mechanism

$$U = U_0(\varphi) + \frac{\lambda}{2}(d^2 - d_0^2)^2 + \frac{1}{2}M_t^2(\varphi)t^2 - \gamma d^2 t$$

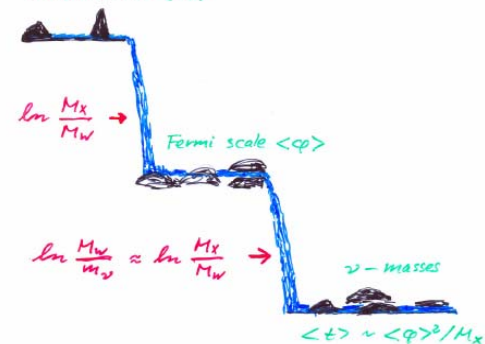
triplet expectation value  $\sim \gamma \frac{d^2}{M_t^2}$

M.Magg , ...

G.Lazarides , Q.Shafi , ...

Cascade mechanism

unification ( $M_x$ )



# varying neutrino mass

$$M_t^2 = c_t M_{GUT}^2 \left[ 1 - \frac{1}{\tau} \exp\left(-\epsilon \frac{\varphi}{M}\right) \right] \quad \epsilon \approx -0.05$$

triplet mass depends on cosmon field  $\varphi$

$$m_\nu(\varphi) = \bar{m}_\nu \left\{ 1 - \exp\left[-\frac{\epsilon}{M}(\varphi - \varphi_t)\right] \right\}^{-1}$$

→ neutrino mass depends on  $\varphi$

# “singular” neutrino mass

$$M_t^2 = c_t M_{GUT}^2 \left[ 1 - \frac{1}{\tau} \exp\left(-\epsilon \frac{\varphi}{M}\right) \right]$$

triplet mass vanishes for  $\varphi \rightarrow \varphi_t$

$$\frac{\varphi_t}{M} = -\frac{\ln \tau}{\epsilon}$$

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

➔ neutrino mass diverges for  $\varphi \rightarrow \varphi_t$

strong effective  
neutrino – cosmon coupling  
for  $\varphi \rightarrow \varphi_t$

$$\beta(\varphi) = -M \frac{\partial}{\partial \varphi} \ln m_\nu(\varphi) = \frac{M}{\varphi - \varphi_t}$$

typical present value :  $\beta \approx 50$   $\rightarrow$   
cosmon mediated attraction between neutrinos  
is about  $50^2$  stronger than gravitational attraction

**crossover from  
early scaling solution to  
effective cosmological constant**

# early scaling solution ( tracker solution )

$$V(\varphi) = M^4 \exp\left(-\alpha \frac{\varphi}{M}\right)$$

$$\varphi = \varphi_0 + (2M/\alpha) \ln(t/t_0)$$

$$\Omega_{h,e} = \frac{n}{\alpha^2}$$

neutrino mass unimportant in early cosmology

# growing neutrinos change cosmological evolution

$$\ddot{\varphi} + 3H\dot{\varphi} = -\frac{\partial V}{\partial \varphi} + \frac{\beta(\varphi)}{M}(\rho_\nu - 3p_\nu),$$
$$\beta(\varphi) = -M \frac{\partial}{\partial \varphi} \ln m_\nu(\varphi) = \frac{M}{\varphi - \varphi_t}$$

modification of conservation equation for neutrinos

$$\dot{\rho}_\nu + 3H(\rho_\nu + p_\nu) = -\frac{\beta(\varphi)}{M}(\rho_\nu - 3p_\nu)\dot{\varphi}$$
$$= -\frac{\dot{\varphi}}{\varphi - \varphi_t}(\rho_\nu - 3p_\nu)$$

# effective stop of cosmon evolution

cosmon evolution almost stops once

- neutrinos get non-relativistic
- $\beta$  gets large

$$\ddot{\varphi} + 3H\dot{\varphi} = -\frac{\partial V}{\partial \varphi} + \frac{\beta(\varphi)}{M}(\rho_\nu - 3p_\nu)$$

$$\beta(\varphi) = -M \frac{\partial}{\partial \varphi} \ln m_\nu(\varphi) = \frac{M}{\varphi - \varphi_t}$$

$$m_\nu(\varphi) = \frac{\beta(\varphi)}{\epsilon} \bar{m}_\nu$$

**This always  
happens  
for  $\varphi \rightarrow \varphi_t$  !**



effective cosmological trigger  
for stop of cosmon evolution :  
neutrinos get non-relativistic

- this has happened recently !
- sets scales for dark energy !

# dark energy fraction determined by neutrino mass

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

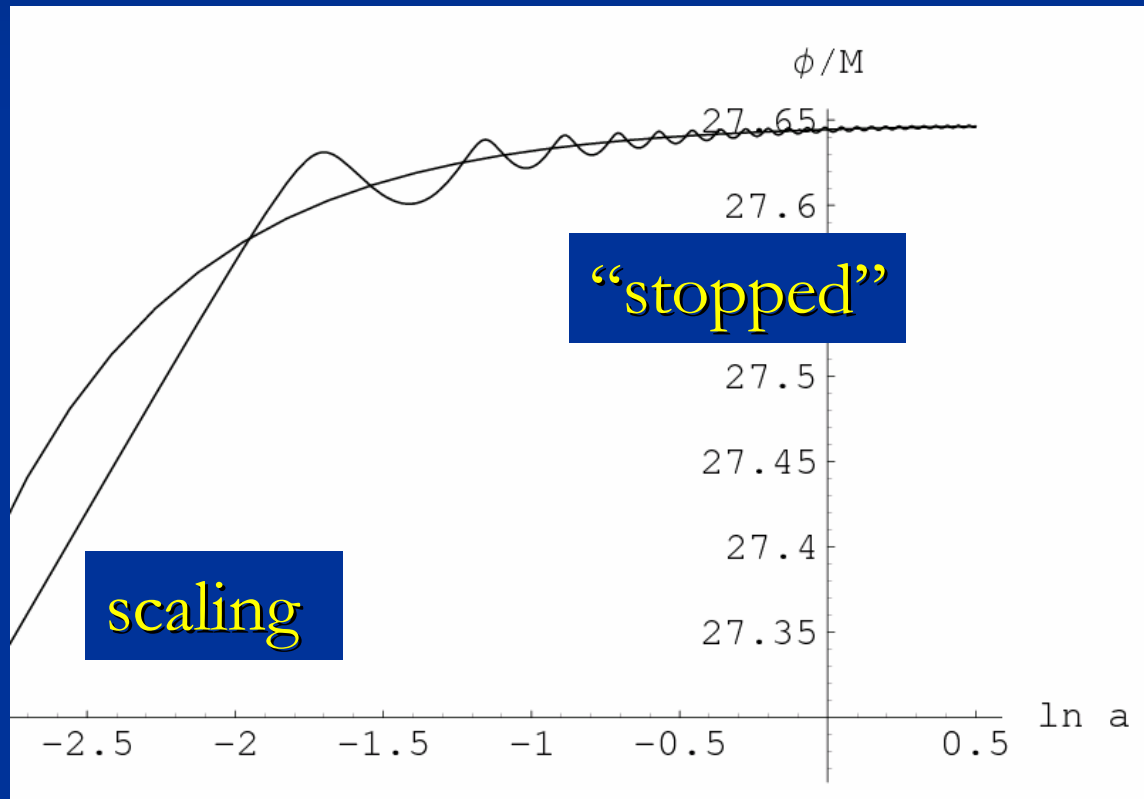
$$\gamma = -\frac{\beta}{\alpha}$$

constant neutrino - cosmon coupling  $\beta$

$$\Omega_h(t_0) \approx -\frac{\epsilon}{\alpha} \frac{m_\nu(t_0)}{\bar{m}_\nu} \frac{m_\nu(t_0)}{16eV}$$

variable neutrino - cosmon coupling

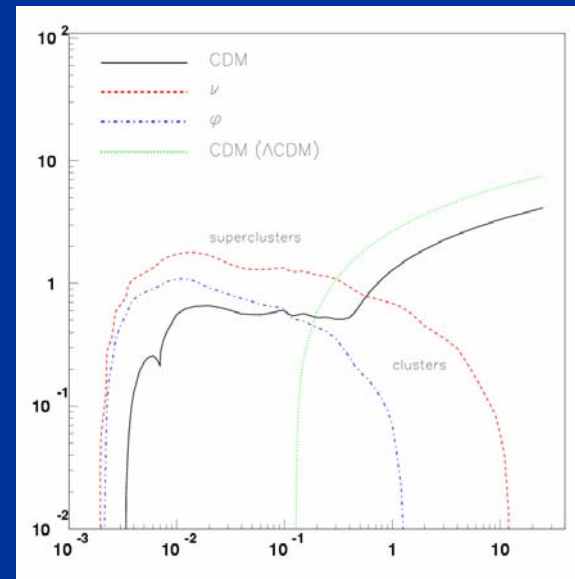
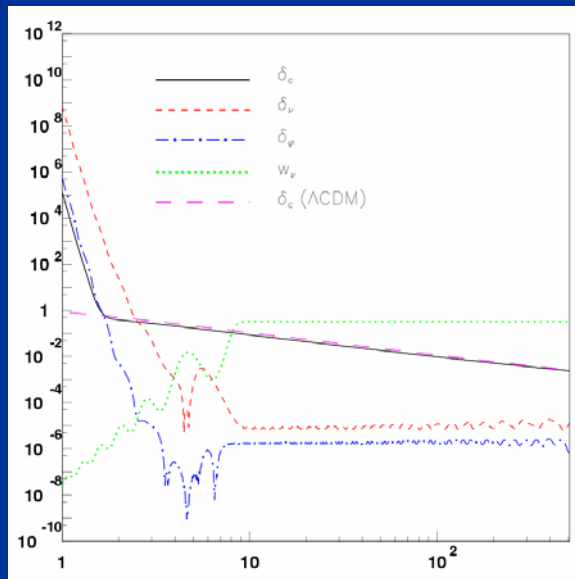
# cosmon evolution



# neutrino fluctuations

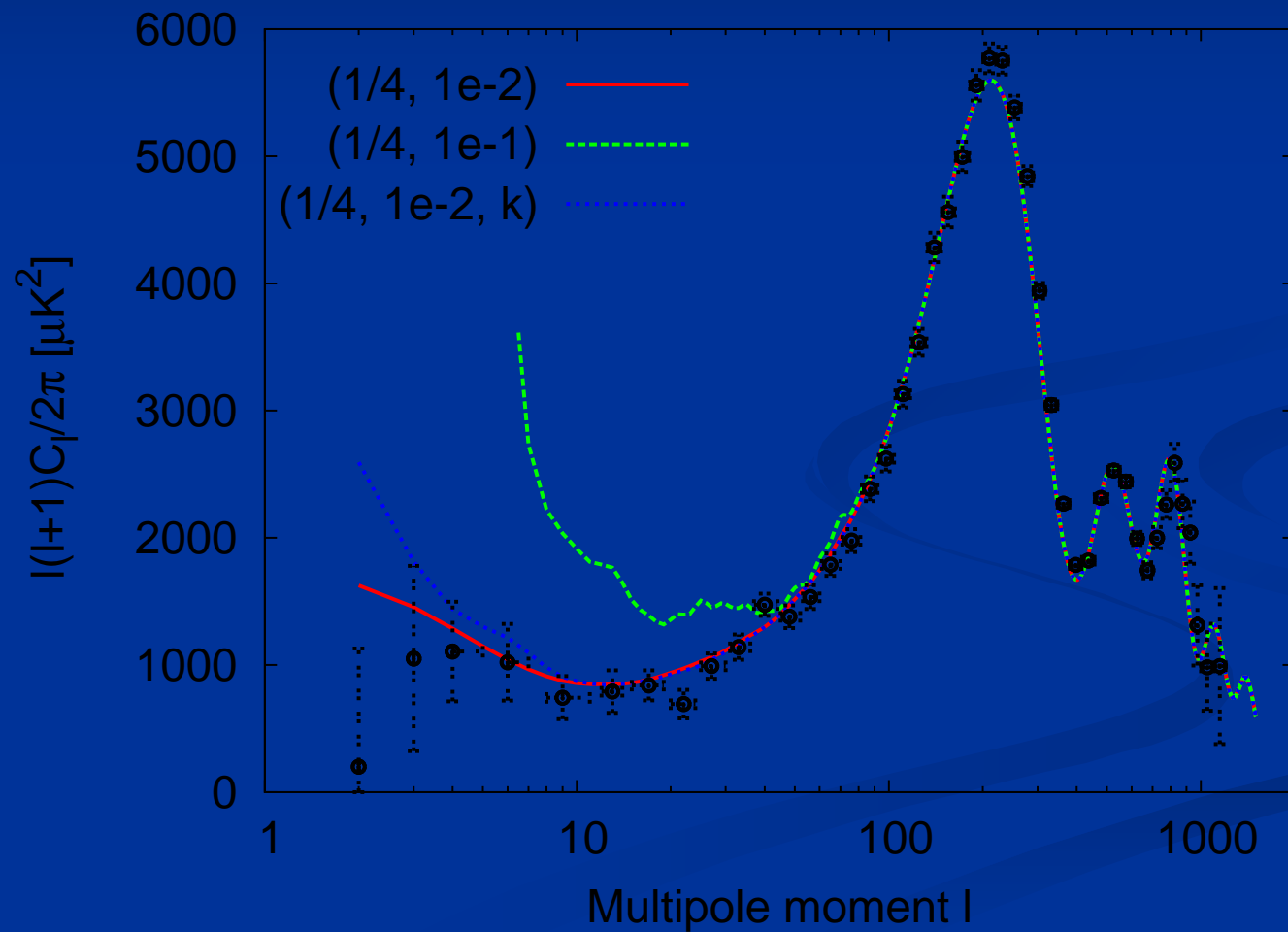
neutrino structures become nonlinear at  $z \sim 1$  for  
supercluster scales

D.Mota , G.Robbers , V.Pettorino , ...



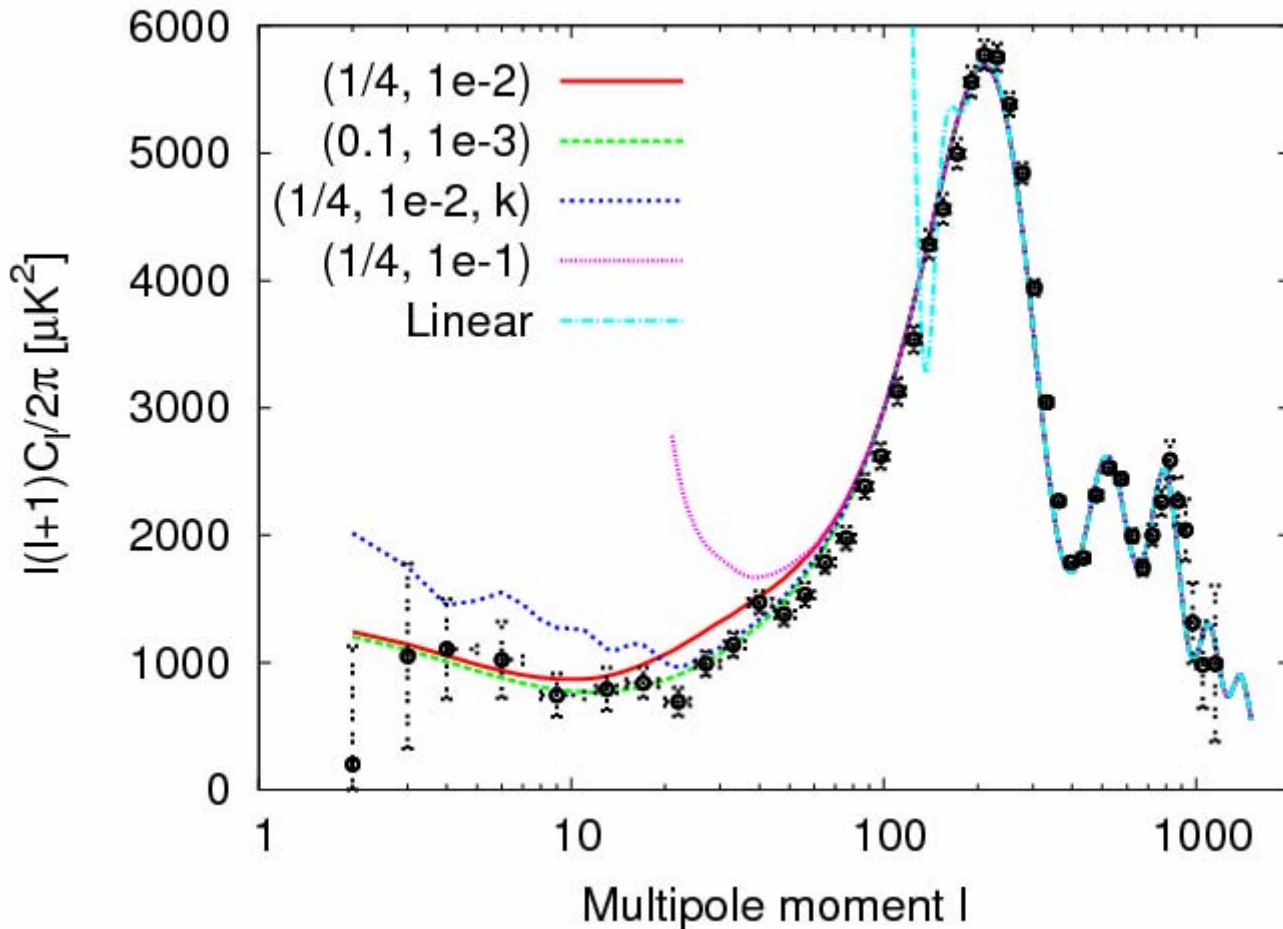
stable neutrino-cosmon lumps exist

N.Brouzakis , N.Tetradis , ... Bertolami



**How to compute the CMB ?**

# Linear approximation breaks down



# cosmon attraction

- much stronger than gravitational attraction
- neutrino mass changes with time
  
- new methods need to be developed
- non-linear hydro-dynamical equations
- N-body simulations for coupled quintessence
- renormalization group improved resummations

Pettorino, Wintergerst, Mota , Amendola , Baldi, Catena ,  
Schrempp, Nunes , ...

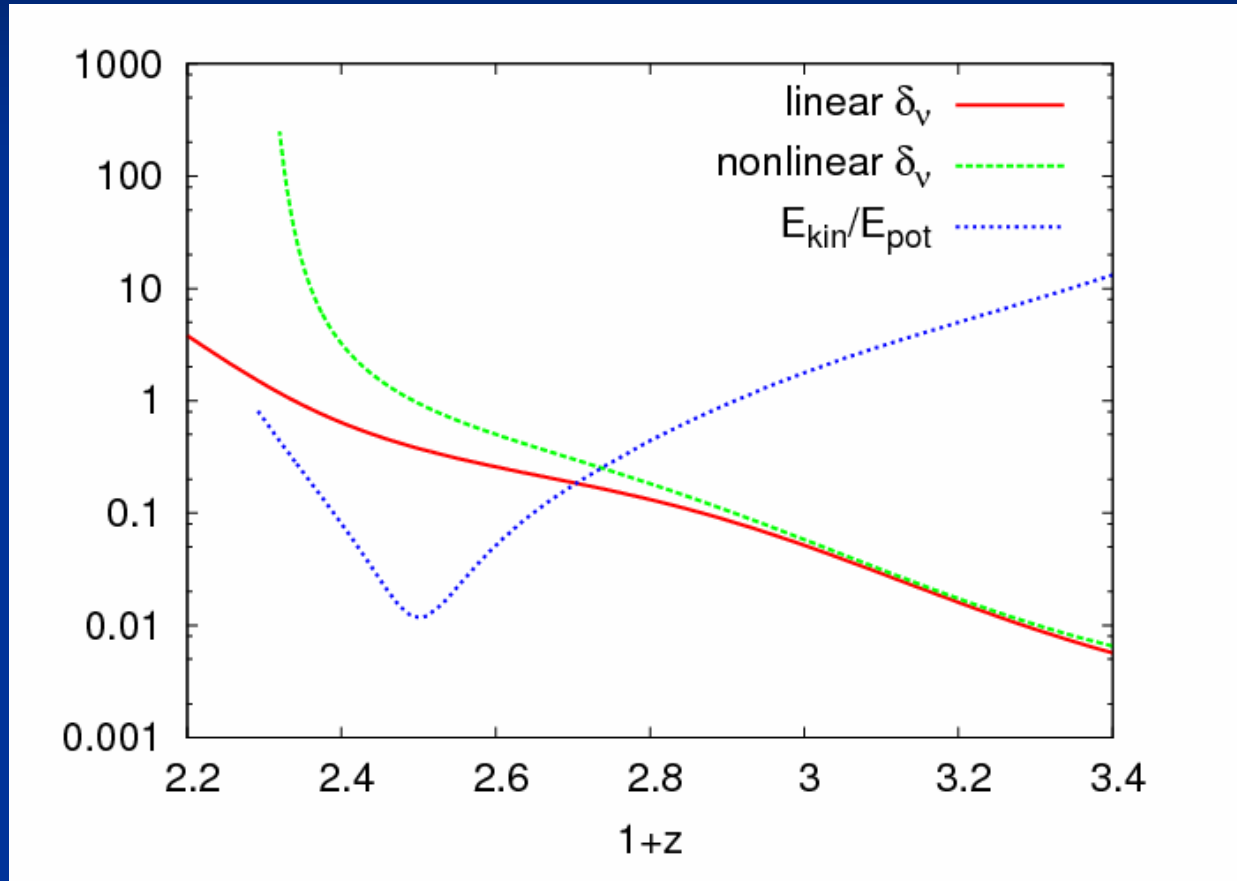


# non-linear fluid equations

$$\begin{aligned}\delta'_\nu &= -\mathbf{v}_\nu \cdot \nabla \delta_\nu - (1 + \delta_\nu) \nabla \cdot \mathbf{v}_\nu \quad , \\ \mathbf{v}'_\nu &= -(\mathcal{H} - \beta \phi') \mathbf{v}_\nu - (\mathbf{v}_\nu \cdot \nabla) \mathbf{v}_\nu \\ &\quad + \nabla(\Phi_\nu + \beta \delta\phi) \quad , \\ \Delta \delta\phi &= -\beta a^2 \delta_\nu \bar{\rho}_\nu \quad , \\ \Delta \Phi_\nu &= -\frac{a^2}{2} \delta_\nu \bar{\rho}_\nu \quad .\end{aligned}$$

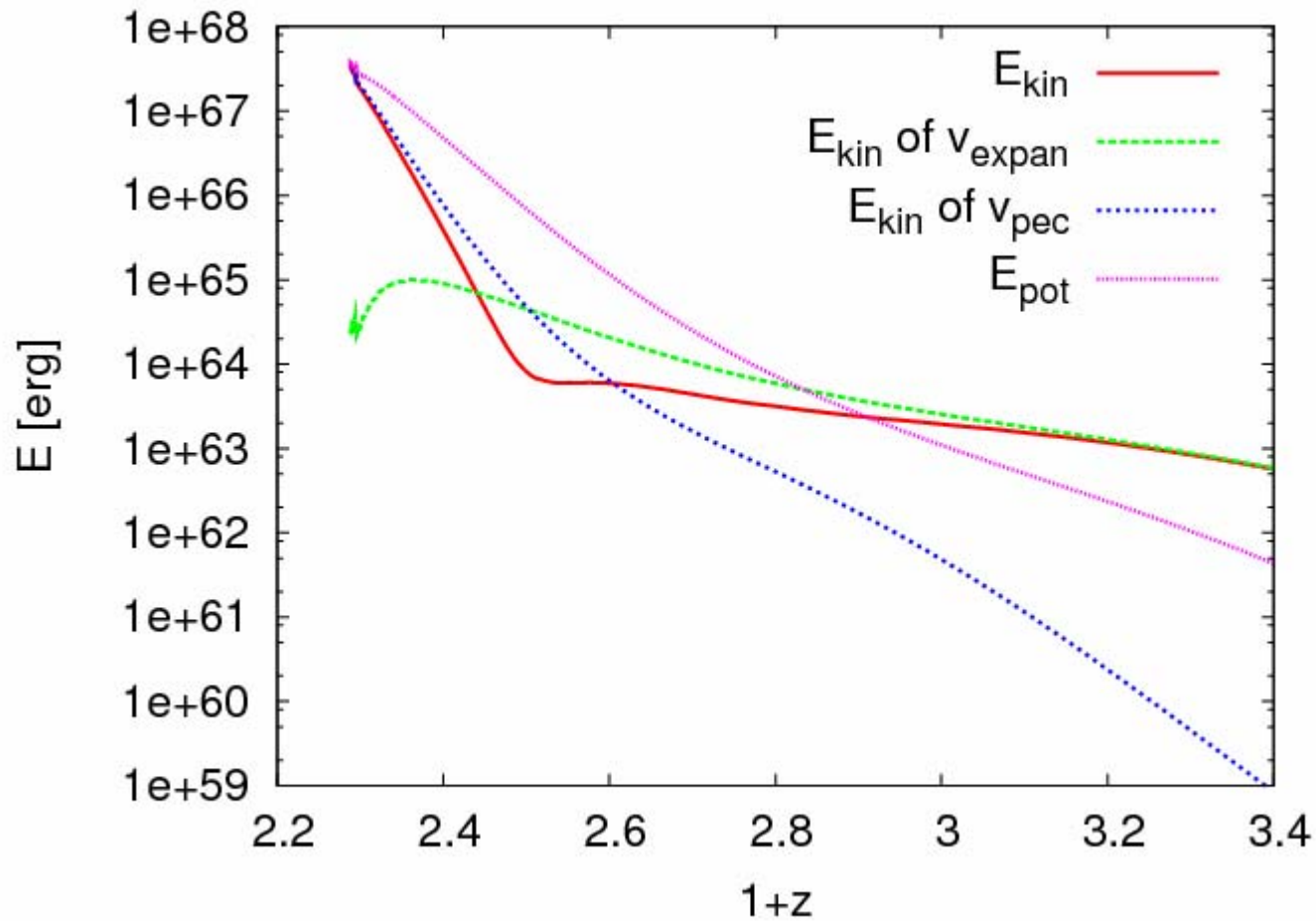
local scalar potential :  $2\beta^2$  stronger  
than gravitational potential

# evolution of single neutrino lump

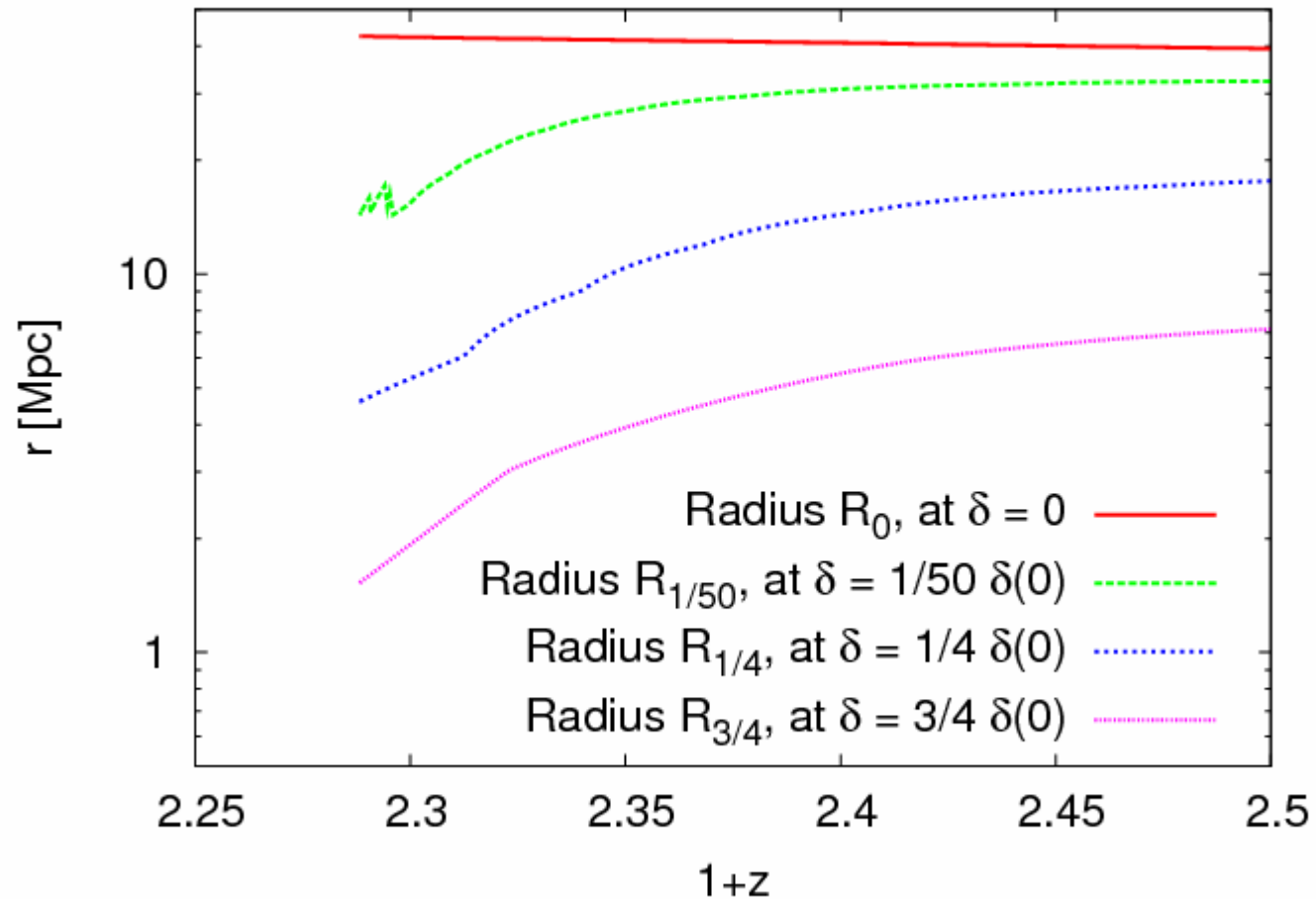


Wintergerst, Pettorino, Mota,...

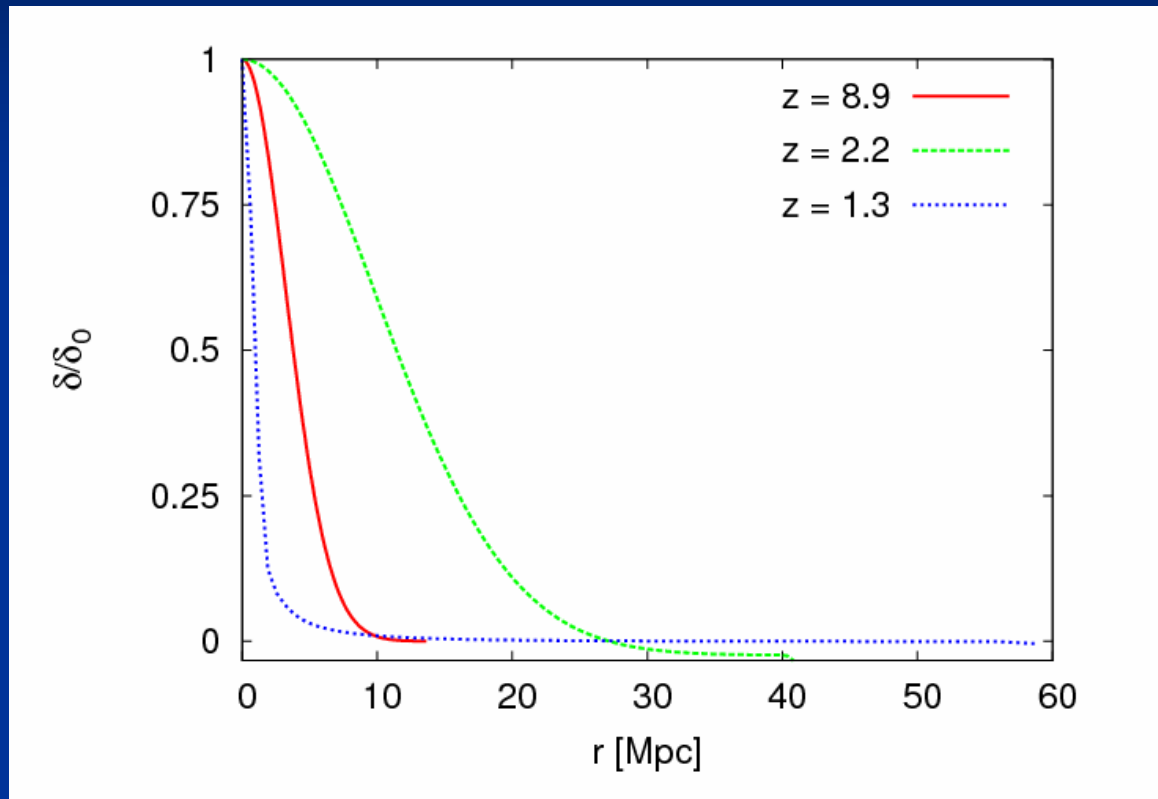
# virialization



# shrinking of radius

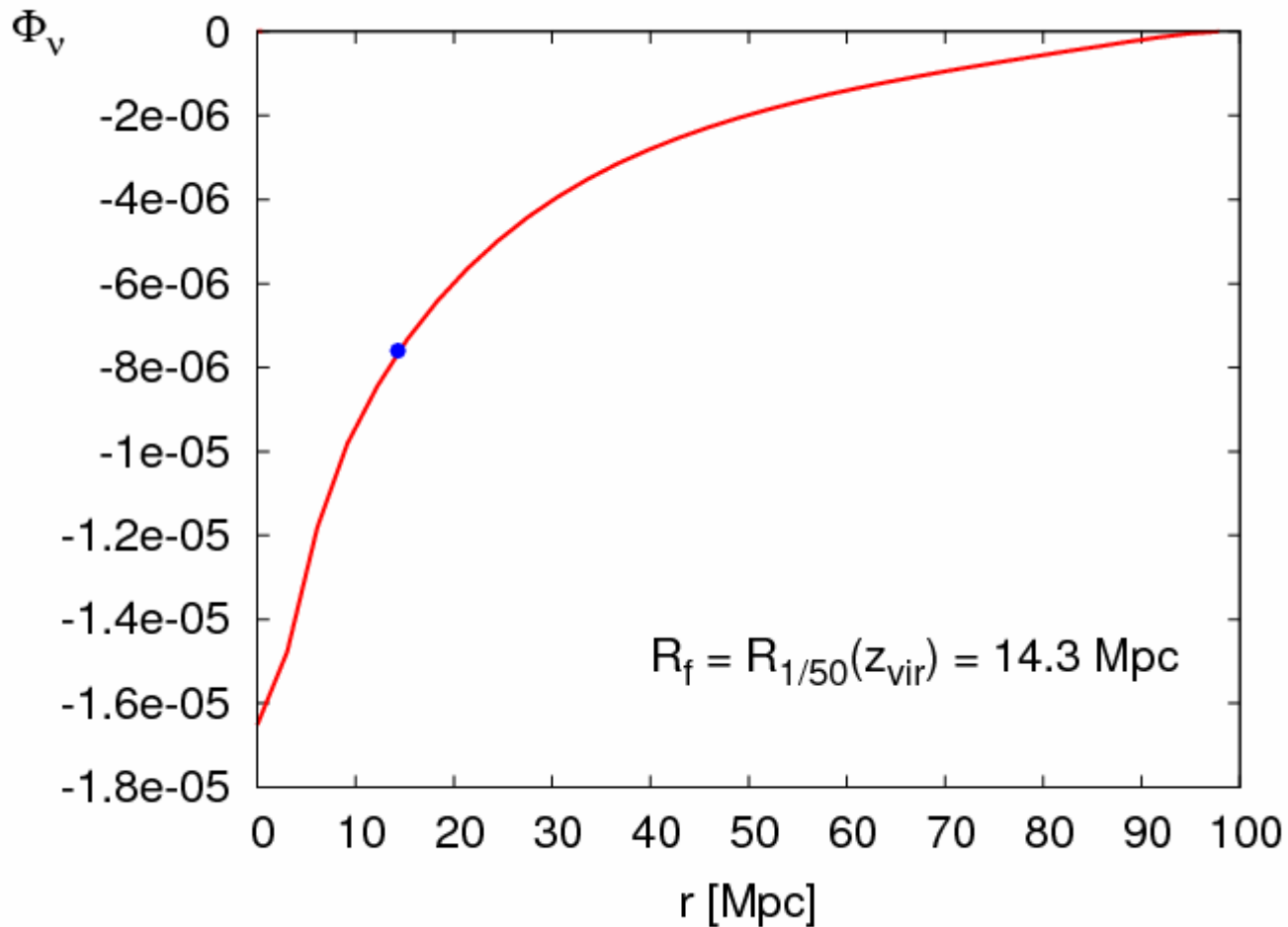


# density profile

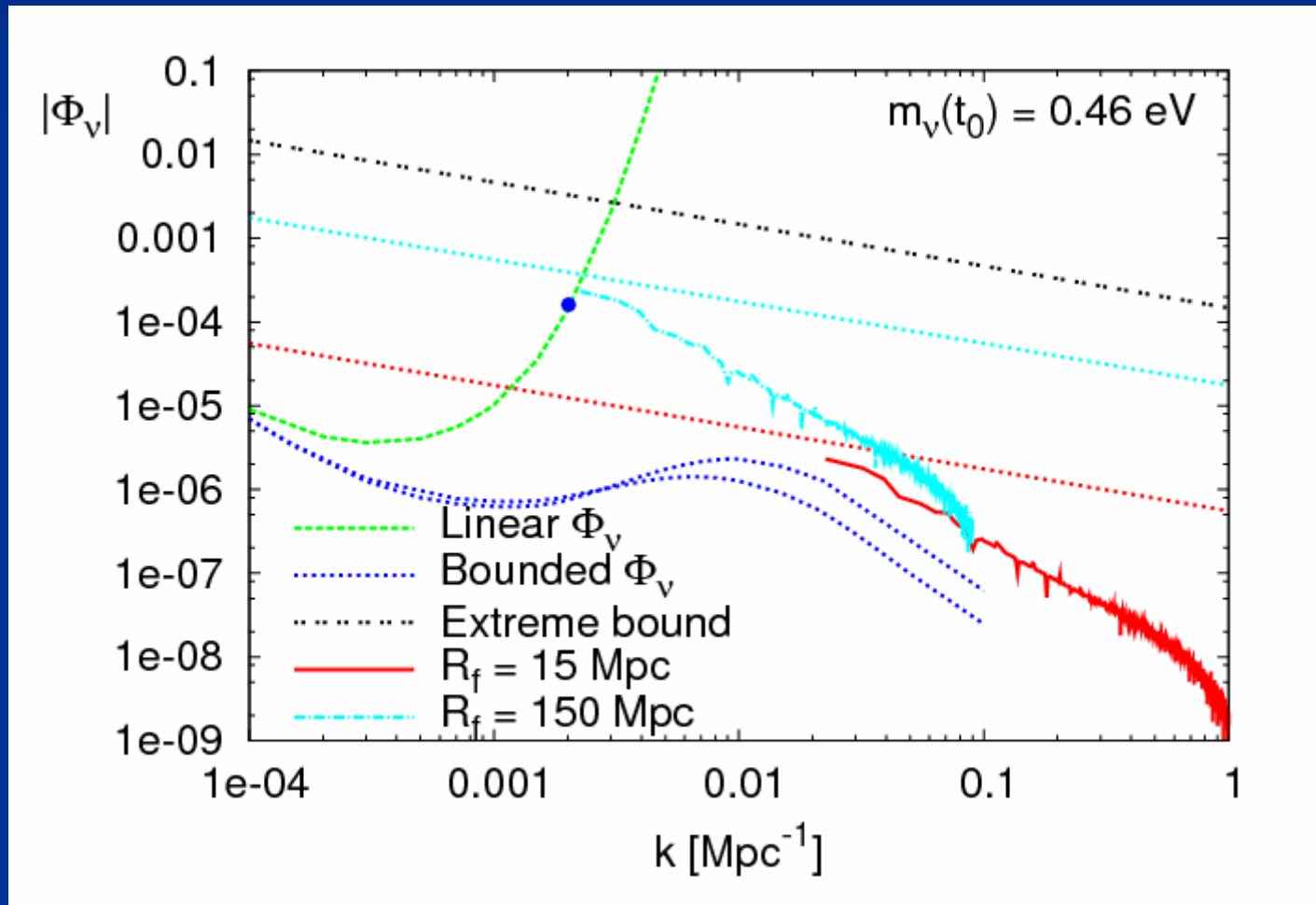


normalized to 1 in the center of the lump

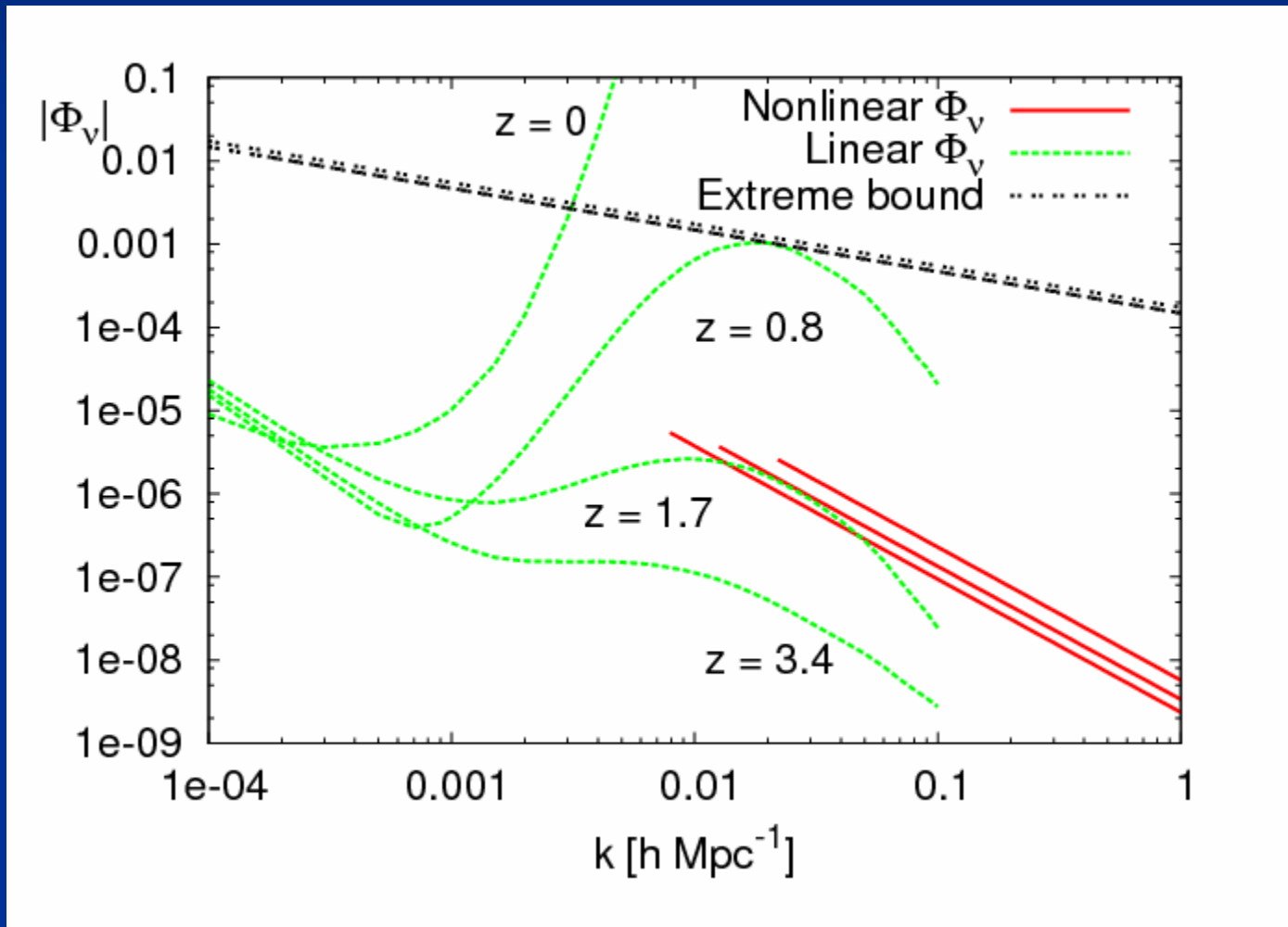
# gravitational potential



# cosmological gravitational potential induced by neutrino lumps



# time evolution of linear and non-linear gravitational potential





# backreaction

- neutrino-mass inside lump different from cosmological neutrino-mass ( smaller )
- effective coupling  $\beta$  smaller
- freezing of growth

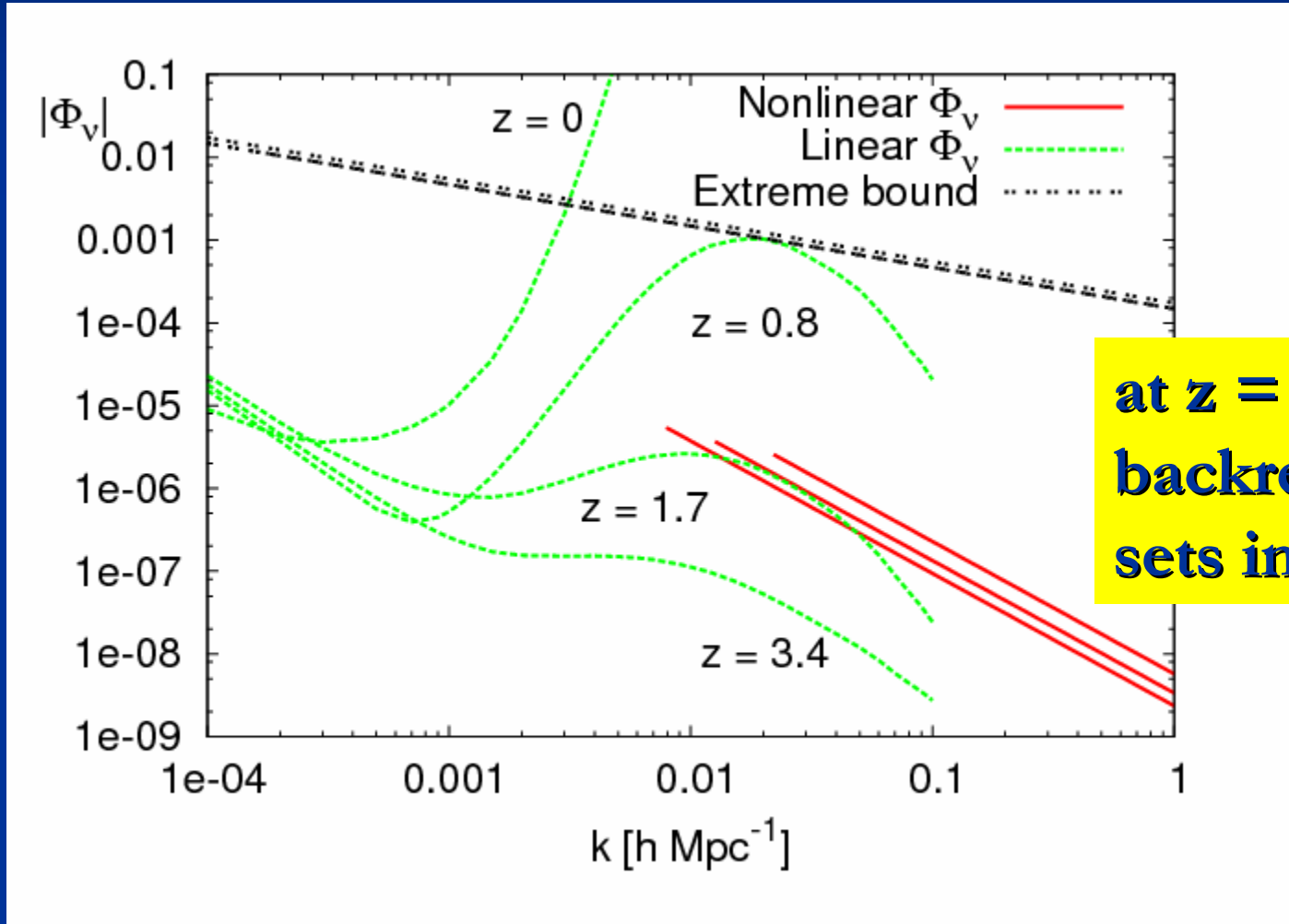
criterion for backreaction effects :

local  $\beta \delta\Phi$  order one

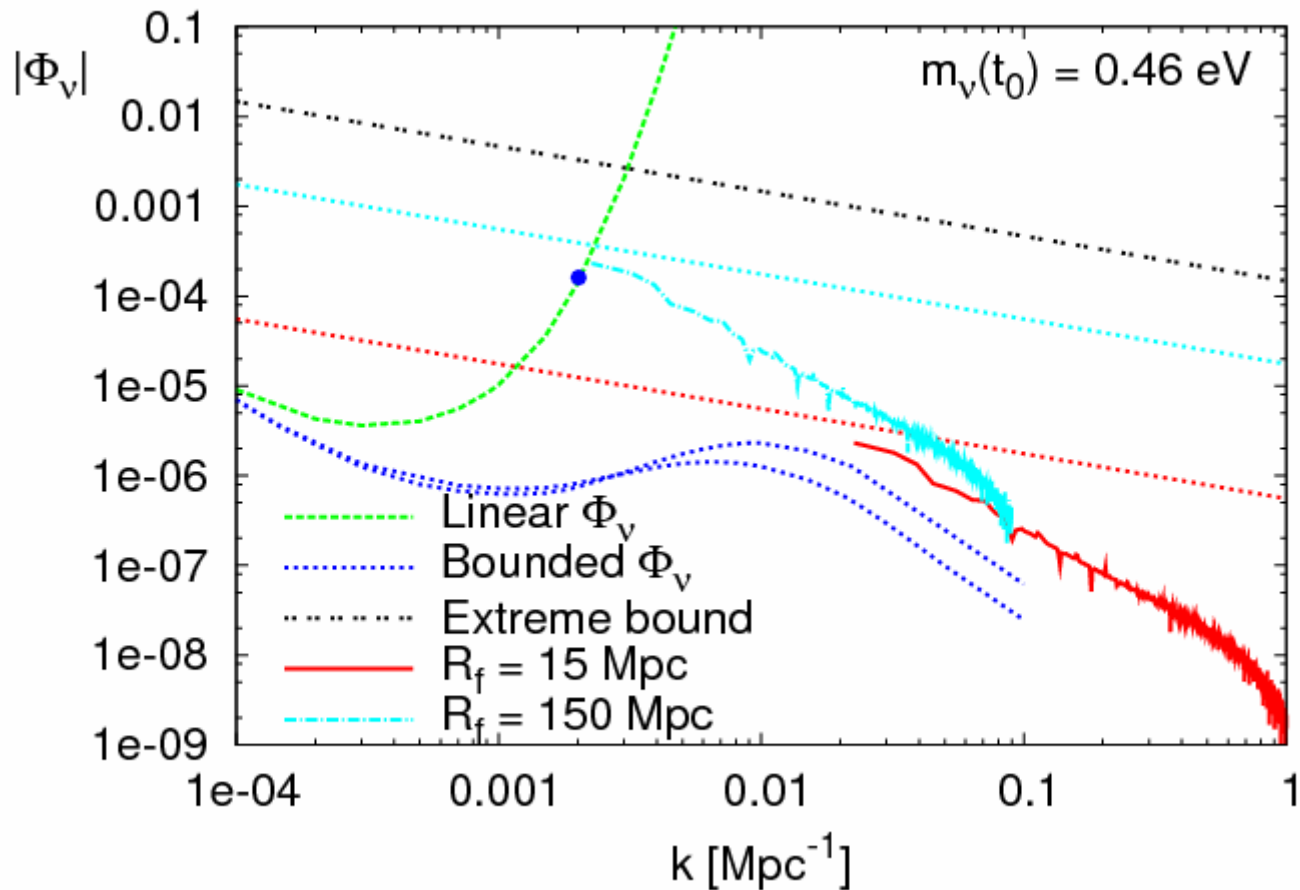
cosmological  $\beta \delta\Phi$  order  $10^{-3}$

- stop growth of a  $k$ -modes with  $k < k_b$  if  $k_b$  hits bound

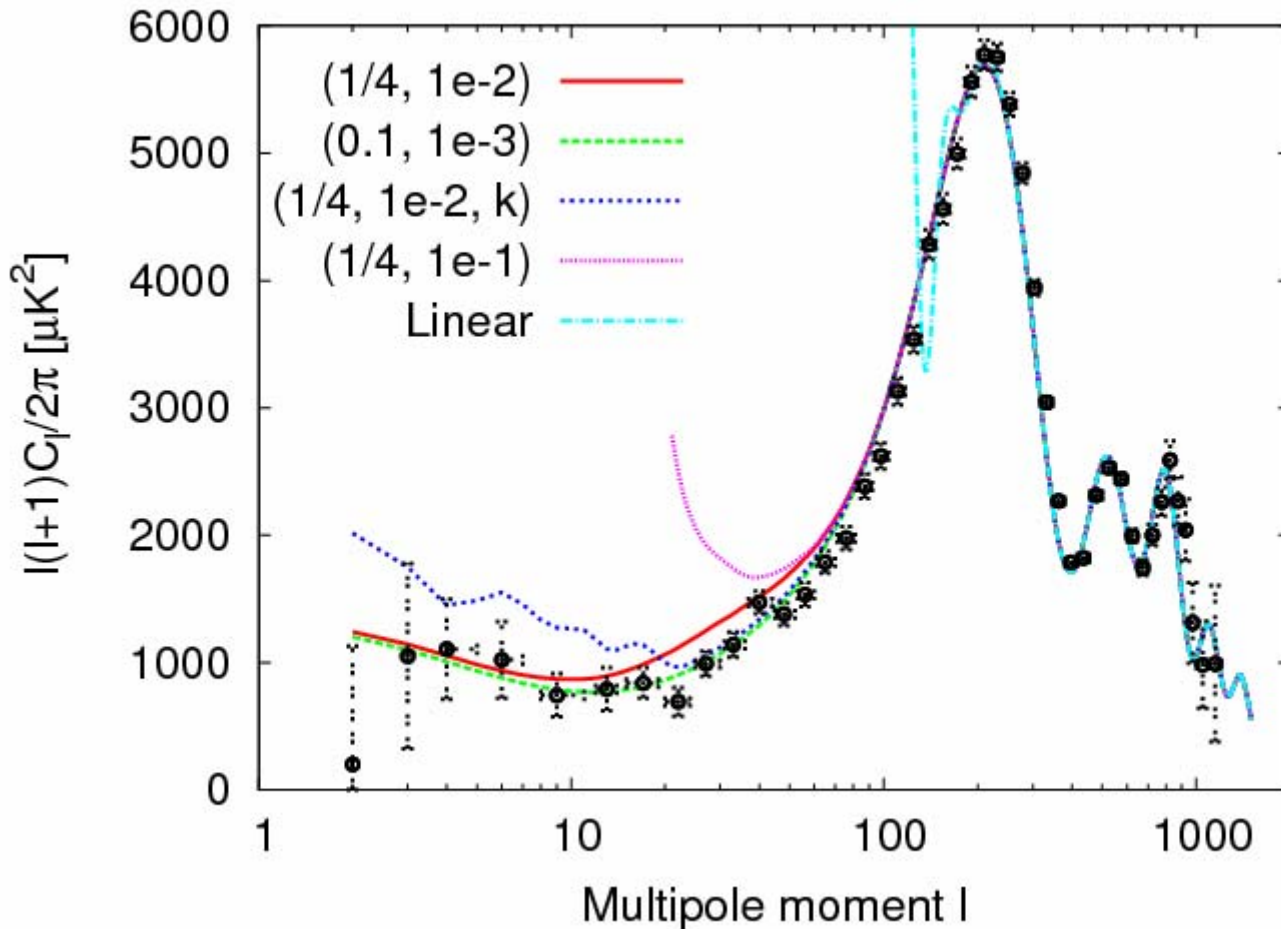
# time evolution of linear and non-linear gravitational potential



# cosmological gravitational potential induced by neutrino lumps



# Linear approximation breaks down

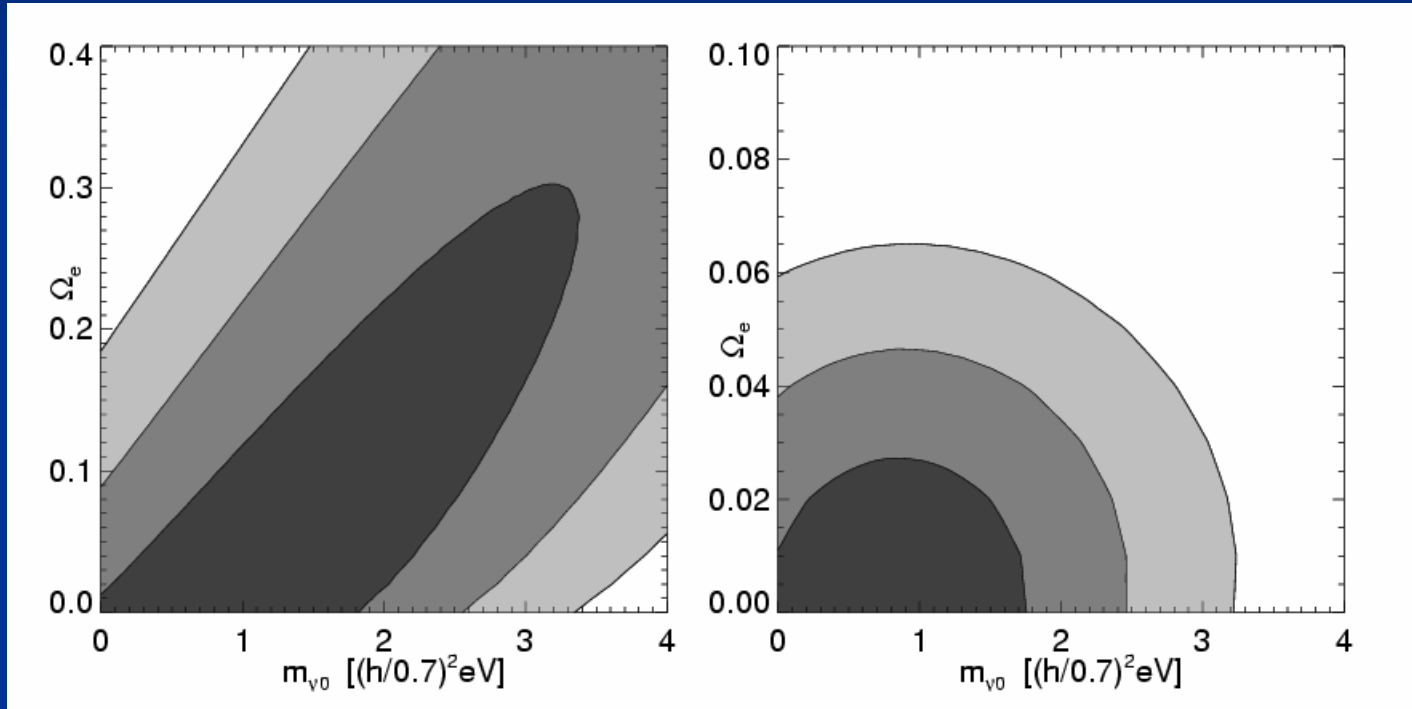


enhanced peculiar velocities  
in bulk flow

modification of ISW correlations

chances for observation

# bounds on average neutrino mass

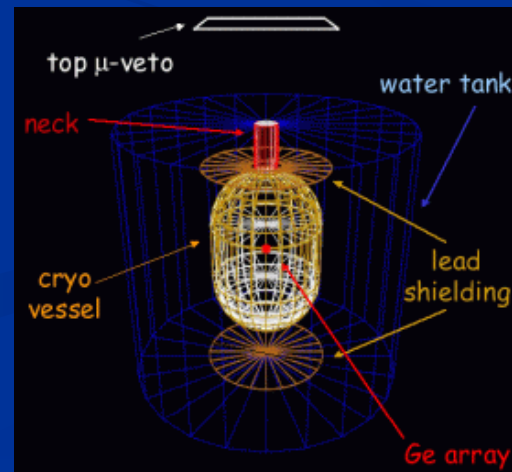


## Looking Beyond Lambda with the Union Supernova Compilation

D. Rubin<sup>1,2</sup>, E. V. Linder<sup>1,3</sup>, M. Kowalski<sup>4</sup>, G. Aldering<sup>1</sup>, R. Amanullah<sup>1,3</sup>, K. Barbary<sup>1,2</sup>,  
N. V. Connolly<sup>5</sup>, K. S. Dawson<sup>1</sup>, L. Faccioli<sup>1,3</sup>, V. Fadeyev<sup>6</sup>, G. Goldhaber<sup>1,2</sup>, A. Goobar<sup>7</sup>,  
I. Hook<sup>8</sup>, C. Lidman<sup>9</sup>, J. Meyers<sup>1,2</sup>, S. Nobili<sup>7</sup>, P. E. Nugent<sup>1</sup>, R. Pain<sup>10</sup>, S. Perlmutter<sup>1,2</sup>,  
P. Ruiz-Lapuente<sup>11</sup>, A. L. Spadafora<sup>1</sup>, M. Strovink<sup>1,2</sup>, N. Suzuki<sup>1</sup>, and H. Swift<sup>1,2</sup>  
(Supernova Cosmology Project)

# Can time evolution of neutrino mass be observed ?

- Experimental determination of neutrino mass may turn out higher than upper bound in model for cosmological constant  
( KATRIN, neutrino-less double beta decay )



GERDA

# Conclusions

- Cosmic event triggers qualitative change in evolution of cosmon
- Cosmon stops changing after neutrinos become non-relativistic
- Explains why now
- Cosmological selection
- Model can be distinguished from cosmological constant





End

# two key features

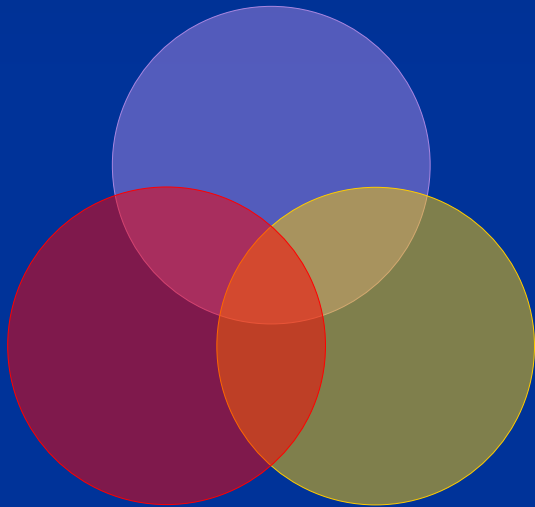
- 1) Exponential cosmological potential and scaling solution

$$V(\varphi) = M^4 \exp(-\alpha\varphi/M)$$
$$V(\varphi \rightarrow \infty) \rightarrow 0 !$$

- 2) Stop of cosmological evolution by cosmological trigger

# “Fundamental” Interactions

Strong, electromagnetic, weak interactions



gravitation

cosmodynamics

On astronomical length scales:

graviton

+

cosmon

# Cosmon

- *Scalar field changes its value even in the **present** cosmological epoch*
- *Potential und kinetic energy of cosmon contribute to the energy density of the Universe*

$$3M^2H^2 = V + \frac{1}{2}\dot{\phi}^2 + \rho$$

- *Time - variable dark energy :  
 $\rho_b(t)$  decreases with time !*

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

# end of matter domination

- growing mass of neutrinos



- at some moment energy density of neutrinos becomes more important than energy density of dark matter



- end of matter dominated period
- similar to transition from radiation domination to matter domination
- this transition happens in the recent past
- cosmology plays crucial role

# cosmological selection

- present value of dark energy density set by cosmological event  
( neutrinos become non – relativistic )
- not given by ground state properties !

# neutrino mass

$$M_\nu = M_D M_R^{-1} M_D^T + M_L$$

$$M_L = h_L \gamma \frac{d^2}{M_t^2}$$

seesaw and  
cascade  
mechanism

triplet expectation value  $\sim$  doublet squared

$$m_\nu = \frac{h_\nu^2 d^2}{m_R} + \frac{h_L \gamma d^2}{M_t^2}$$

omit generation  
structure

# cascade mechanism

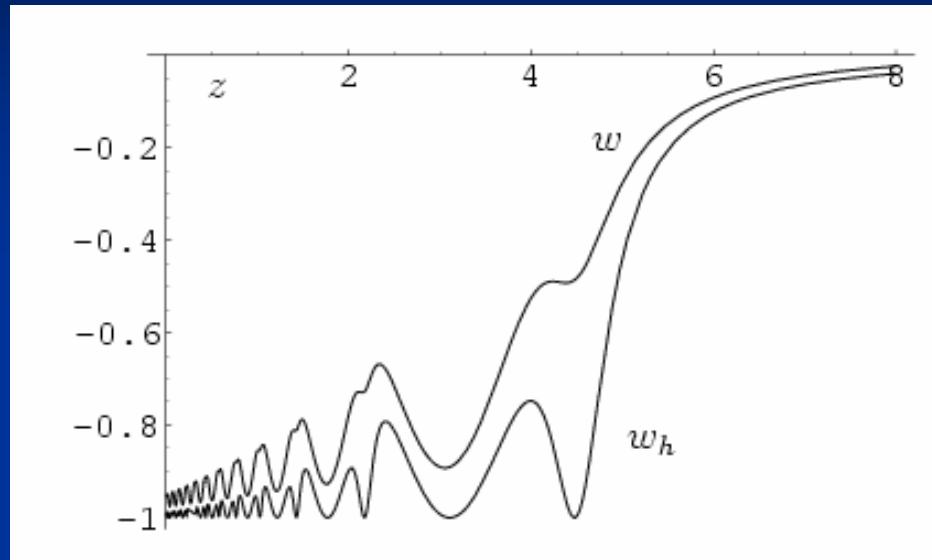
$$U = U_0(\varphi) + \frac{\lambda}{2}(d^2 - d_0^2)^2 + \frac{1}{2}M_t^2(\varphi)t^2 - \gamma d^2 t$$

triplet expectation value  $\sim \frac{d^2}{M_t^2}$

$$M_t^2(\varphi) = \bar{M}_t^2 \left[ 1 - \exp\left(-\frac{\epsilon}{M}(\varphi - \varphi_t)\right) \right]$$



# equation of state



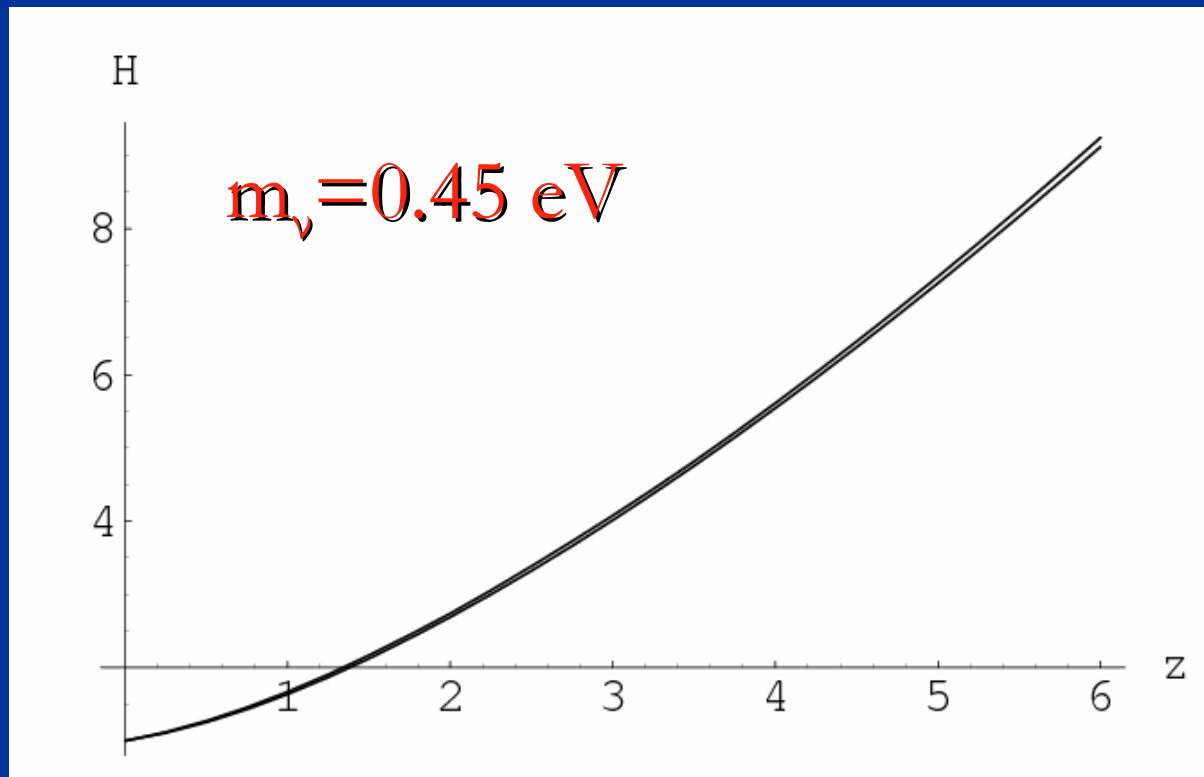
$$w = \frac{T - V + w_\nu \rho_\nu}{T + V + \rho_\nu} \approx -1 + \frac{\rho_\nu}{V} \approx -1 + \frac{\Omega_\nu}{\Omega_h},$$

**present equation  
of state given by  
neutrino mass !**

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

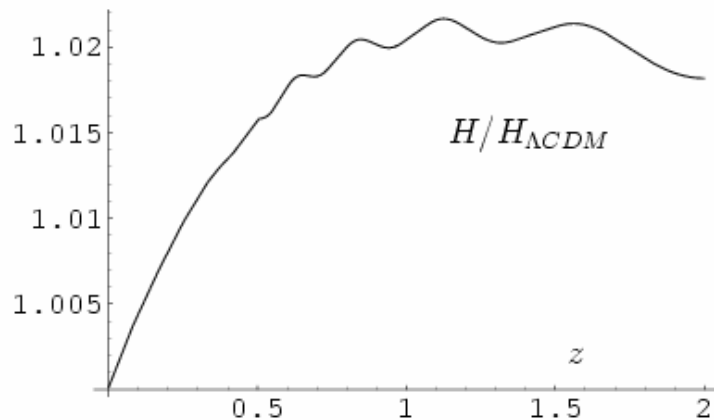
# Hubble parameter

as compared to  $\Lambda$ CDM



# Hubble parameter ( $z < z_c$ )

$$H^2 = \frac{1}{3M^2} \left\{ V_t + \rho_{m,0} a^{-3} + 2\tilde{\rho}_\nu,0 a^{-\frac{3}{2}} \right\}$$

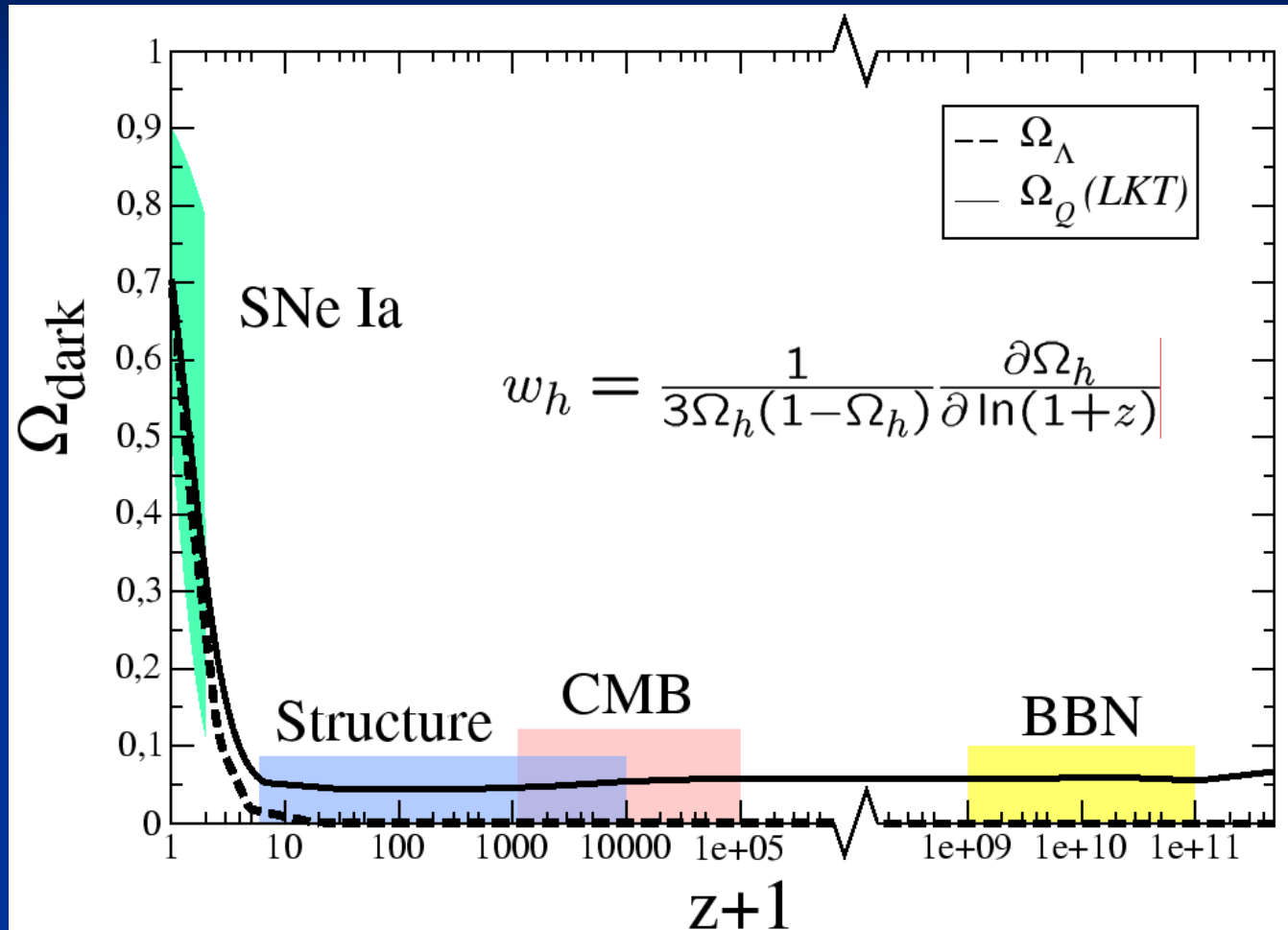


only small  
difference  
from  
 $\Lambda$ CDM!

$$m_\nu = 0.45 \text{ eV}$$

How can quintessence be distinguished from a cosmological constant ?

# Time dependence of dark energy



cosmological constant :  $\Omega_h \sim t^2 \sim (1+z)^{-3}$

# small early and large present dark energy

fraction in dark energy has substantially  
increased since end of structure formation



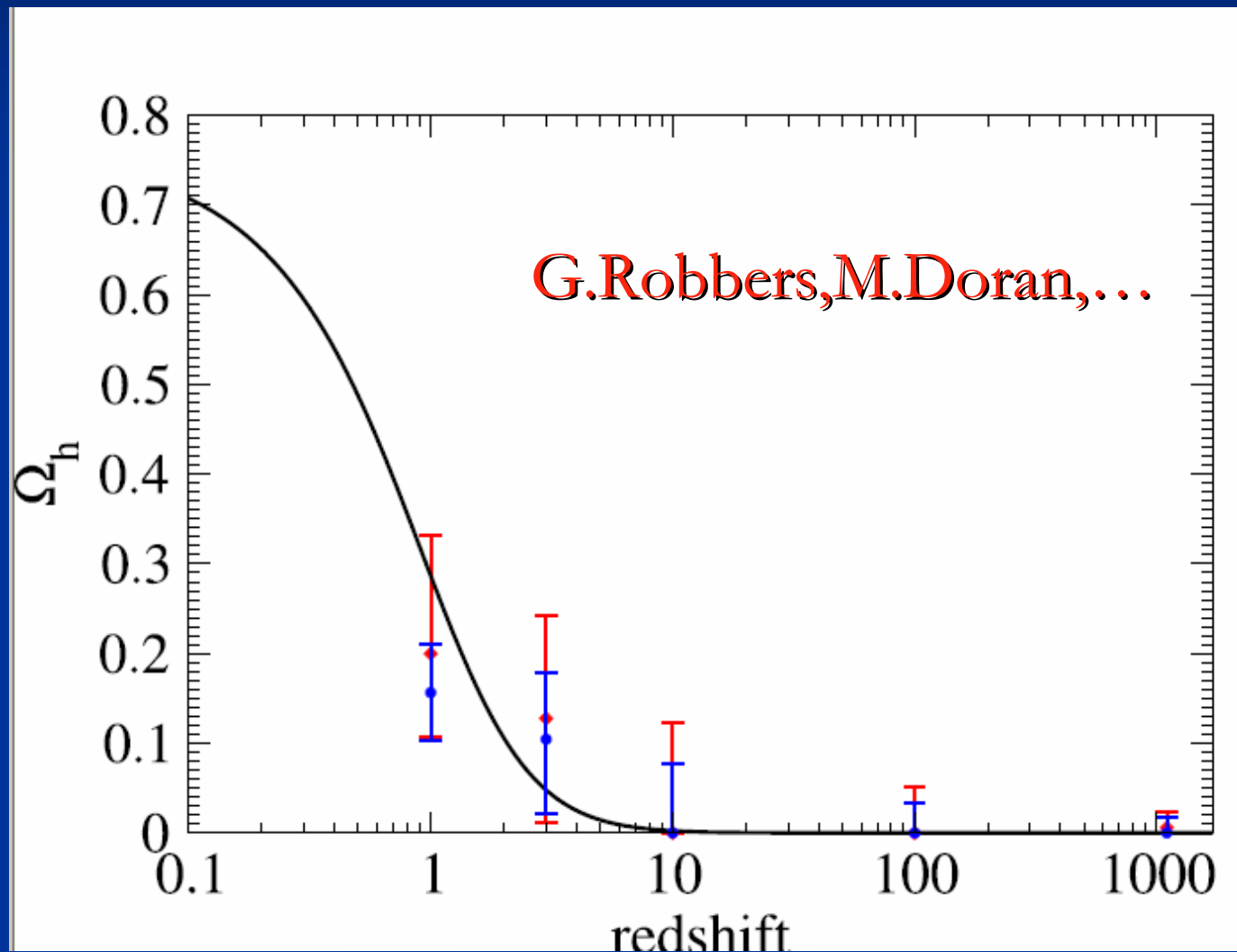
expansion of universe accelerates in present  
epoch

$$w_h = \frac{1}{3\Omega_h(1-\Omega_h)} \frac{\partial \Omega_h}{\partial \ln(1+z)}$$

# effects of early dark energy

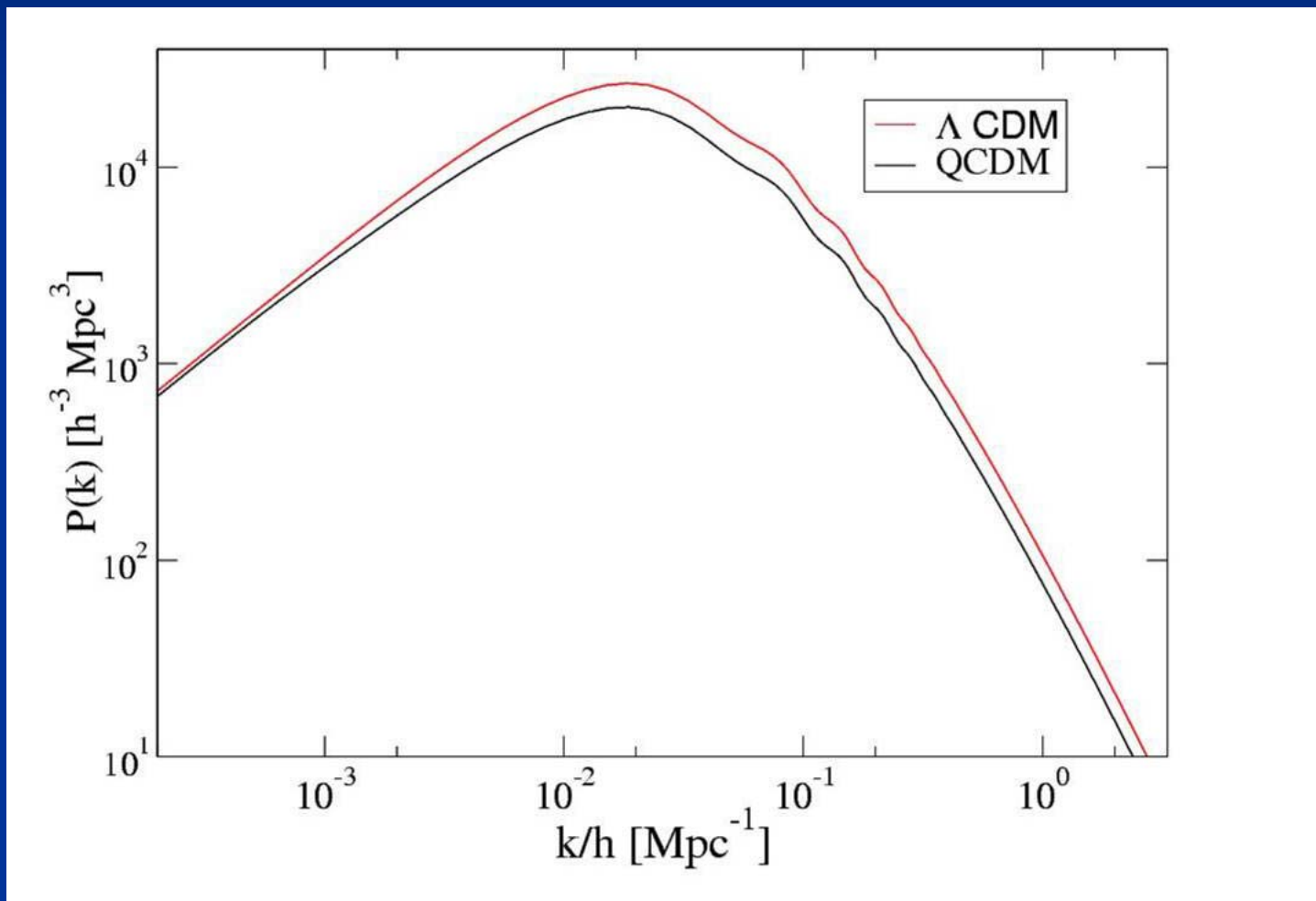
- modifies cosmological evolution (CMB)
- slows down the growth of structure

# interpolation of $\Omega_h$





# *Early quintessence slows down the growth of structure*



# Cosmon coupling to atoms

- Tiny !!!
- Substantially weaker than gravity.
- Non-universal couplings bounded by tests of equivalence principle.
- Universal coupling bounded by tests of Brans-Dicke parameter  $\omega$  in solar system.
- Only very small influence on cosmology.

# time variation of “fundamental constants”

M.Mueller , G.Schaefer , T.Dent , S.Steffen , ...

# How to distinguish Q from $\Lambda$ ?

A) Measurement  $\Omega_h(z) \iff H(z)$

i)  $\Omega_h(z)$  at the time of structure formation, CMB - emission or nucleosynthesis

ii) equation of state  $w_h(\text{today}) > -1$

B) Time variation of fundamental “constants”

C) Apparent violation of equivalence principle

D) Possible coupling between Dark Energy and Dark Mater

# Quintessence and Time dependence of “fundamental constants”

- Fine structure constant depends on value of  
cosmon field :  $\alpha(\varphi)$

*(similar in standard model: couplings depend on  
value of Higgs scalar field)*

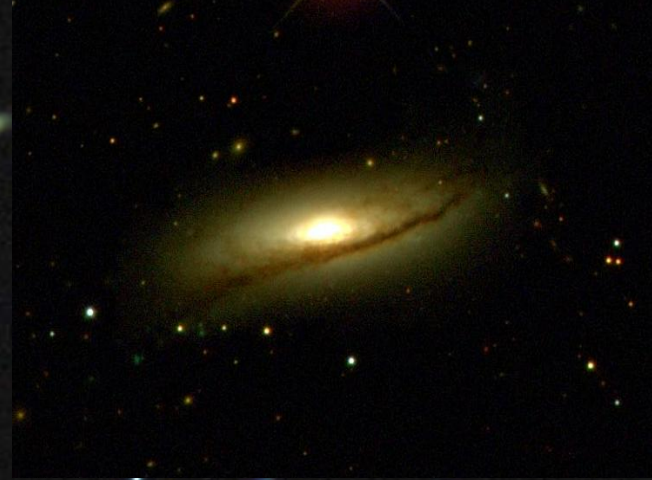
- Time evolution of  $\varphi$    
Time evolution of  $\alpha$

Jordan,...

**baryons :**

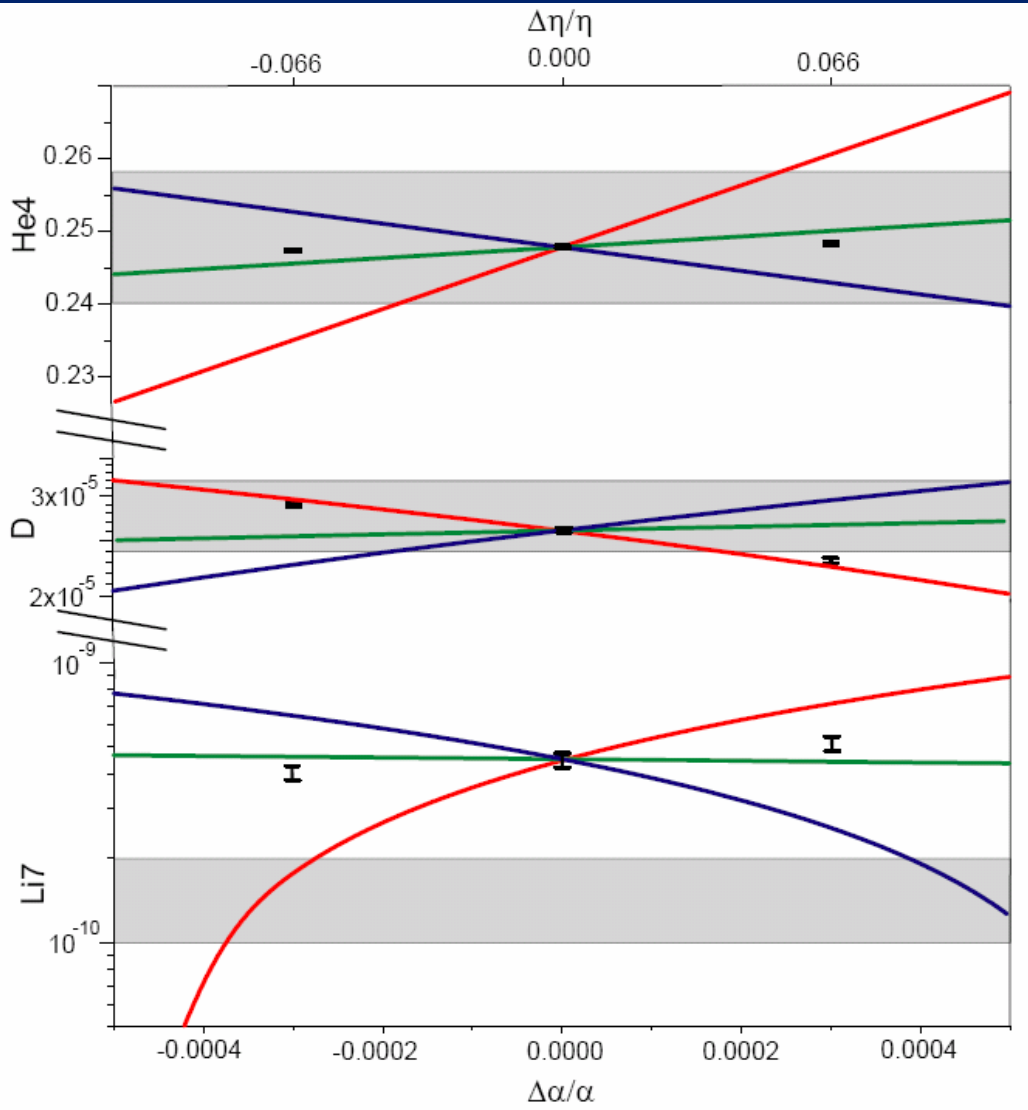
**the matter of stars and humans**

$$\Omega_b = 0.045$$



# primordial abundances for three GUT models

He



D

Li

present  
observations :  
 $1\sigma$

T.Dent,  
S.Stern,...

# three GUT models

- unification scale  $\sim$  Planck scale
- 1) All particle physics scales  $\sim \Lambda_{\text{QCD}}$
- 2) Fermi scale and fermion masses  $\sim$  unification scale
- 3) Fermi scale varies more rapidly than  $\Lambda_{\text{QCD}}$

$\Delta\alpha/\alpha \approx 4 \cdot 10^{-4}$  allowed for GUT 1 and 3 , larger for GUT 2

$\Delta\ln(M_n/M_p) \approx 40 \Delta\alpha/\alpha \approx 0.015$  allowed



# time varying Fermi scale

$$U = U_0(\varphi) + \frac{\lambda}{2}(d^2 - d_0^2)^2 + \frac{1}{2}M_t^2(\varphi)t^2 - \gamma d^2 t$$

$$M_t^2(\varphi) = \bar{M}_t^2 \left[ 1 - \exp\left(-\frac{\epsilon}{M}(\varphi - \varphi_t)\right) \right]$$

yields triplet expectation value  
as function of doublet

$$t = \gamma \frac{d^2}{M_t^2}$$

insert :

$$U(\varphi, d, t(d, \varphi)) = U_0(\varphi) + \frac{\lambda}{2}(d^2 - d_0^2)^2 - \frac{\gamma^2 d^4}{2M_t^2(\varphi)}$$

$$d^2(\varphi) = d_0^2 \left( 1 - \frac{\gamma^2}{\lambda M_t^2(\varphi)} \right)^{-1}$$

# time varying electron mass

$$\partial_t \ln m_e \approx -\frac{R}{2} \partial_t \ln s \approx -\frac{R}{2} \partial_t \ln \rho_\nu \approx \frac{3R}{4} H$$

$$R = \gamma^2 / (\lambda M_t^2)$$

time variation of quantities  
not related to triplet

$$\frac{\delta X}{X} = -\frac{m_\nu(t_0)}{12\text{eV}} \frac{\delta}{\alpha} ((1+z)^{3/2} - 1)$$

Time variation of coupling constants  
must be tiny –

would be of very high significance !

**Possible signal for Quintessence**

## A few references

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# effective cosmological constant linked to neutrino mass

realistic value  $\propto \varphi_t / M \approx 276$  :

needed for neutrinos to become non-relativistic in  
recent past -

as required for observed mass range of neutrino masses

$\varphi_t / M$  : essentially determined by present neutrino mass

adjustment of one dimensionless parameter  
in order to obtain for the present time the  
correct ratio between dark energy and neutrino  
energy density

**no fine tuning !**

