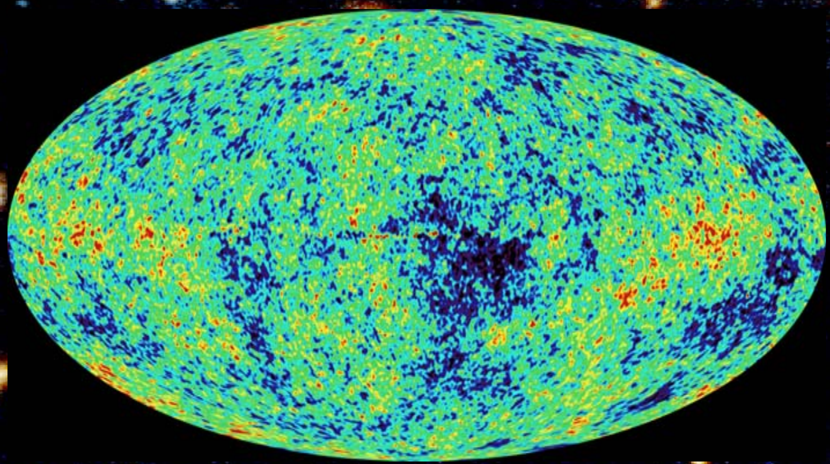
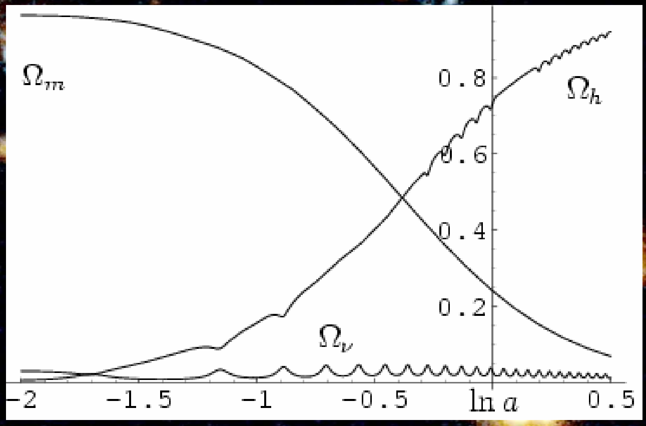
Growing neutrinos and cosmological selection





Quintessence

C.Wetterich

A.Hebecker, M.Doran, M.Lilley, J.Schwindt,
C.Müller, G.Schäfer, E.Thommes,
R.Caldwell, M.Bartelmann,
K.Kharwan, G.Robbers,T.Dent, S.Steffen,
L.Amendola, M.Baldi

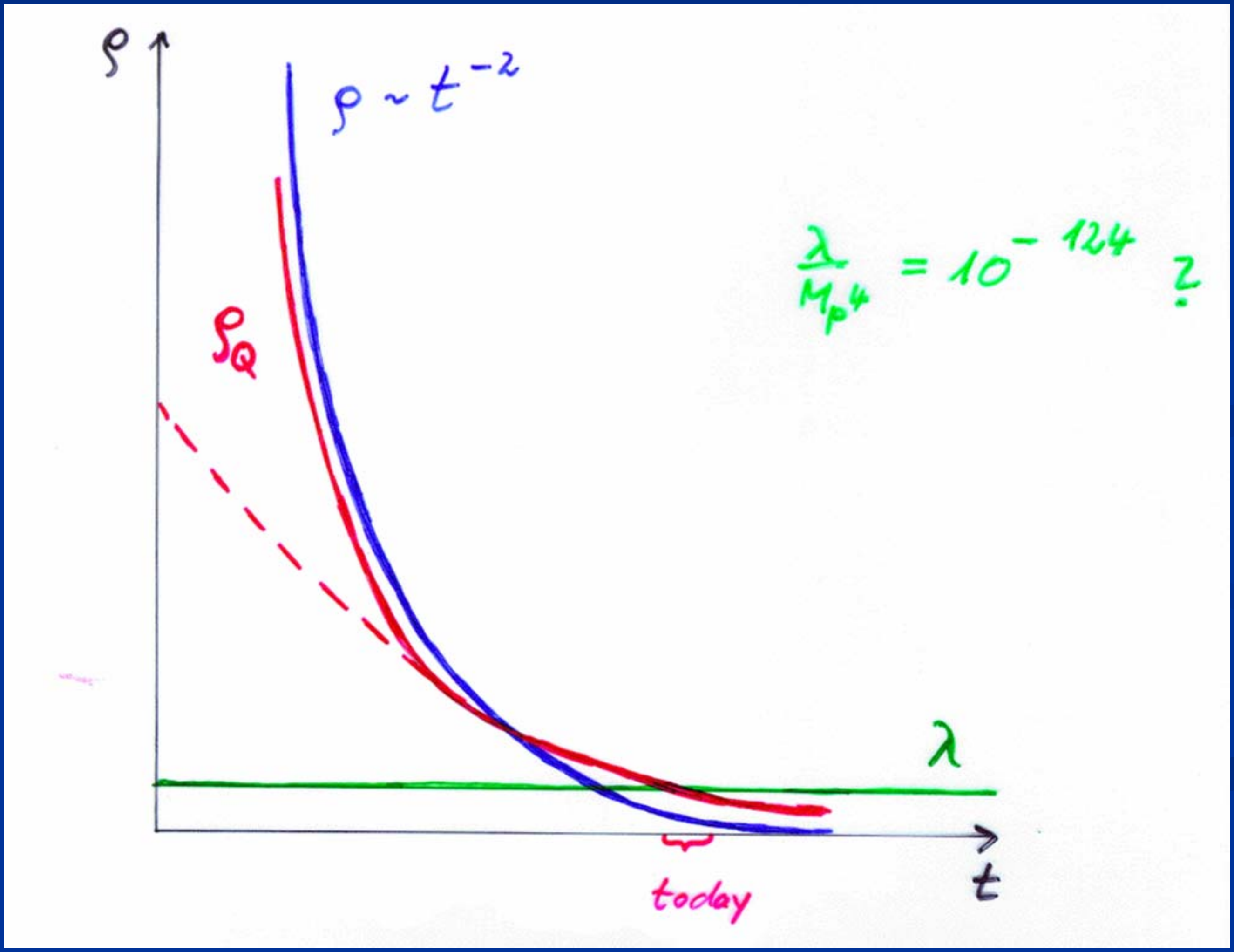
Why now ?

coincidence problem

Why does dark energy become important
in present cosmological epoch ?

Cosm. Const. | Quintessence

static | dynamical



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

here : cosmon coupling to neutrinos

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(φ) determines details of the model

V(φ) =M^4 exp(- αφ/M)

for increasing φ the potential decreases towards zero !

Cosmic Attractors

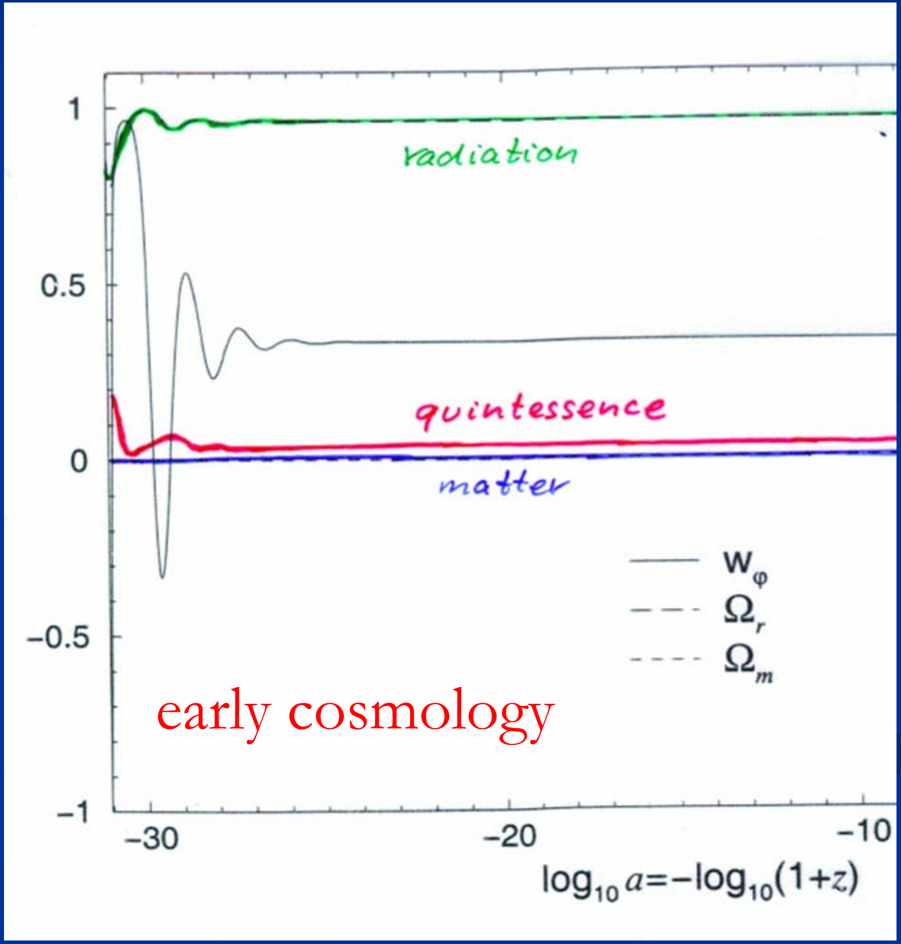
Solutions independent of initial conditions

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

$\varphi \sim \ln(t)$

$\Omega_h \sim$ const.

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



exponential potential ➡ constant fraction in dark energy

$$\Omega_h = n/\alpha^2$$

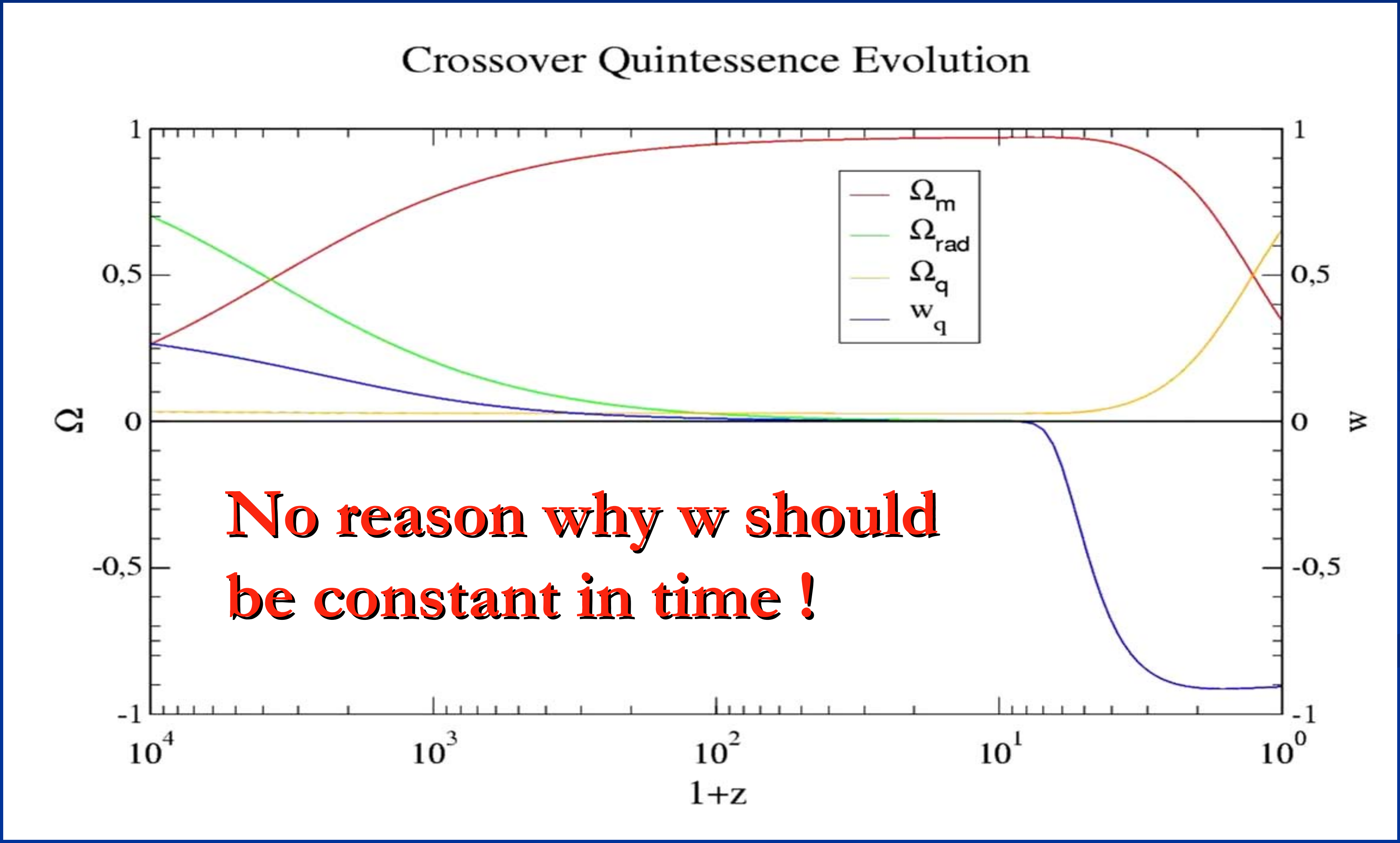
can explain order of magnitude of dark energy !

realistic quintessence

fraction in dark energy has to increase in "recent time" !

cosmic coincidence

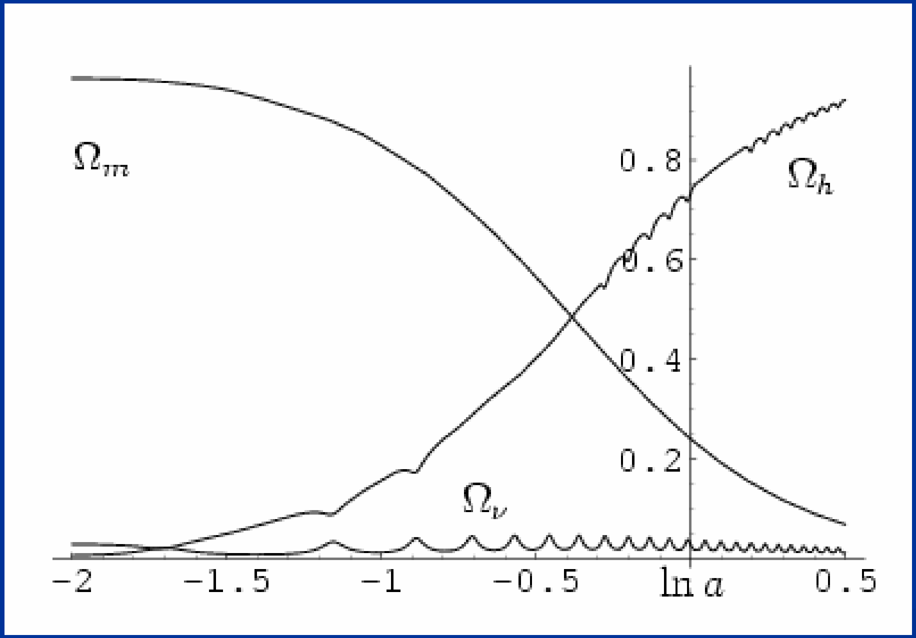
Quintessence becomes important "today"

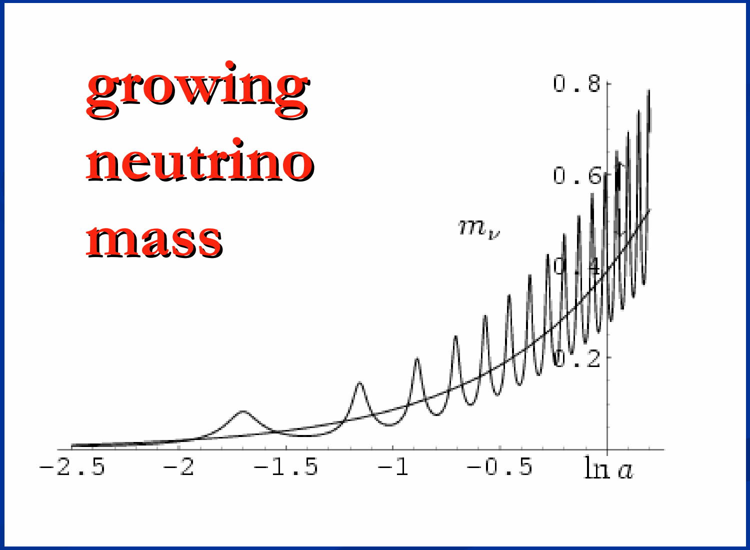


coincidence problem

What is responsible for increase of Ω_h for $z < 6$?

growing neutrino mass triggers transition to almost static dark energy





cosmological selection

- present value of dark energy density set by cosmological event :

  neutrinos become non – relativistic

- not given by ground state properties !

connection between dark energy and neutrino properties

$$[\rho_h(t_0)]^{\frac{1}{4}} = 1.07 \left(\frac{\gamma m_\nu(t_0)}{eV} \right)^{\frac{1}{4}} 10^{-3} eV$$

present dark energy density given by neutrino mass

present equation of state given by neutrino mass !

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

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 β

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

variable neutrino - cosmon coupling

basic ingredient :

cosmon coupling to neutrinos

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 ω in solar system.
- Only very small influence on cosmology.

Cosmon coupling to neutrinos

- can be large !
- 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

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

varying neutrino – cosmon coupling

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

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

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

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 ~ $\gamma \frac{d^2}{M_t^2}$

M.Magg , …
G.Lazarides , Q.Shafi , …

triplet expectation value ~ doublet squared

varying neutrino mass

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

ε ≈ -0.05

triplet mass depends on cosmon field φ

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

➡ neutrino mass depends on φ

"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 $\varphi \rightarrow \varphi_t$

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

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

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

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

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

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 cosmon 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
- ß 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 $\varphi \longrightarrow \varphi_t$!

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

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

effective cosmological constant

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

realistic value
for
$\alpha\, \varphi_t / M \approx 276$

$\Longleftrightarrow$

$$\epsilon = -\frac{\alpha \ln \tau}{276}$$

effective cosmological constant linked to neutrino mass

realistic value $\alpha \varphi_t / M \approx 276$:
needed for neutrinos to become non-relativistic in recent past -
as required for observed mass range of neutrino masses

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

dark energy fraction determined by neutrino mass

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

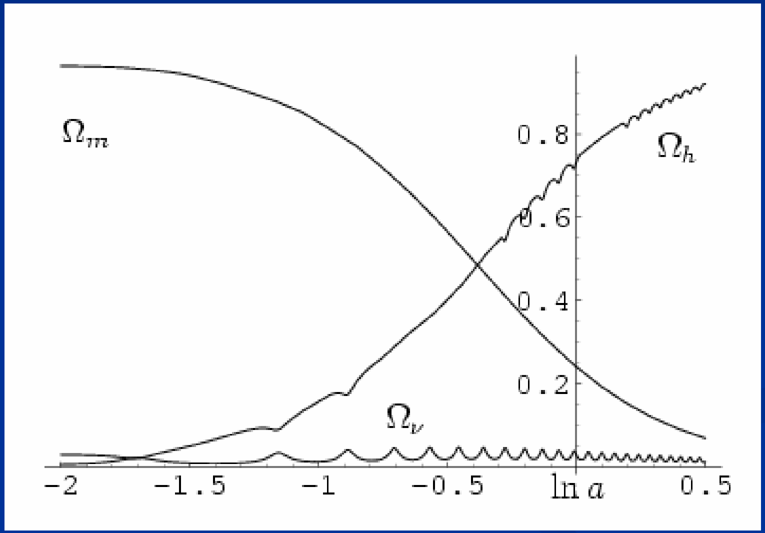
$$\gamma = -\frac{\beta}{\alpha}$$

constant neutrino - cosmon coupling β

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

variable neutrino - cosmon coupling

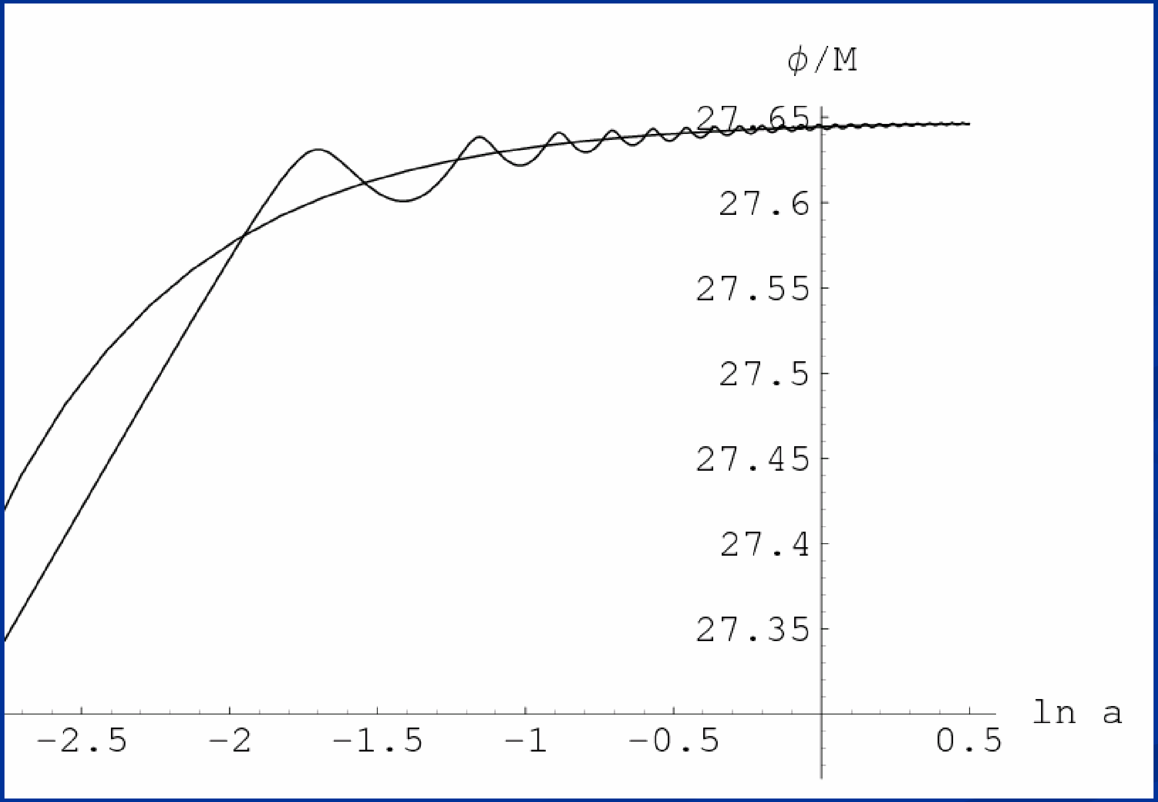
crossover to dark energy dominated universe



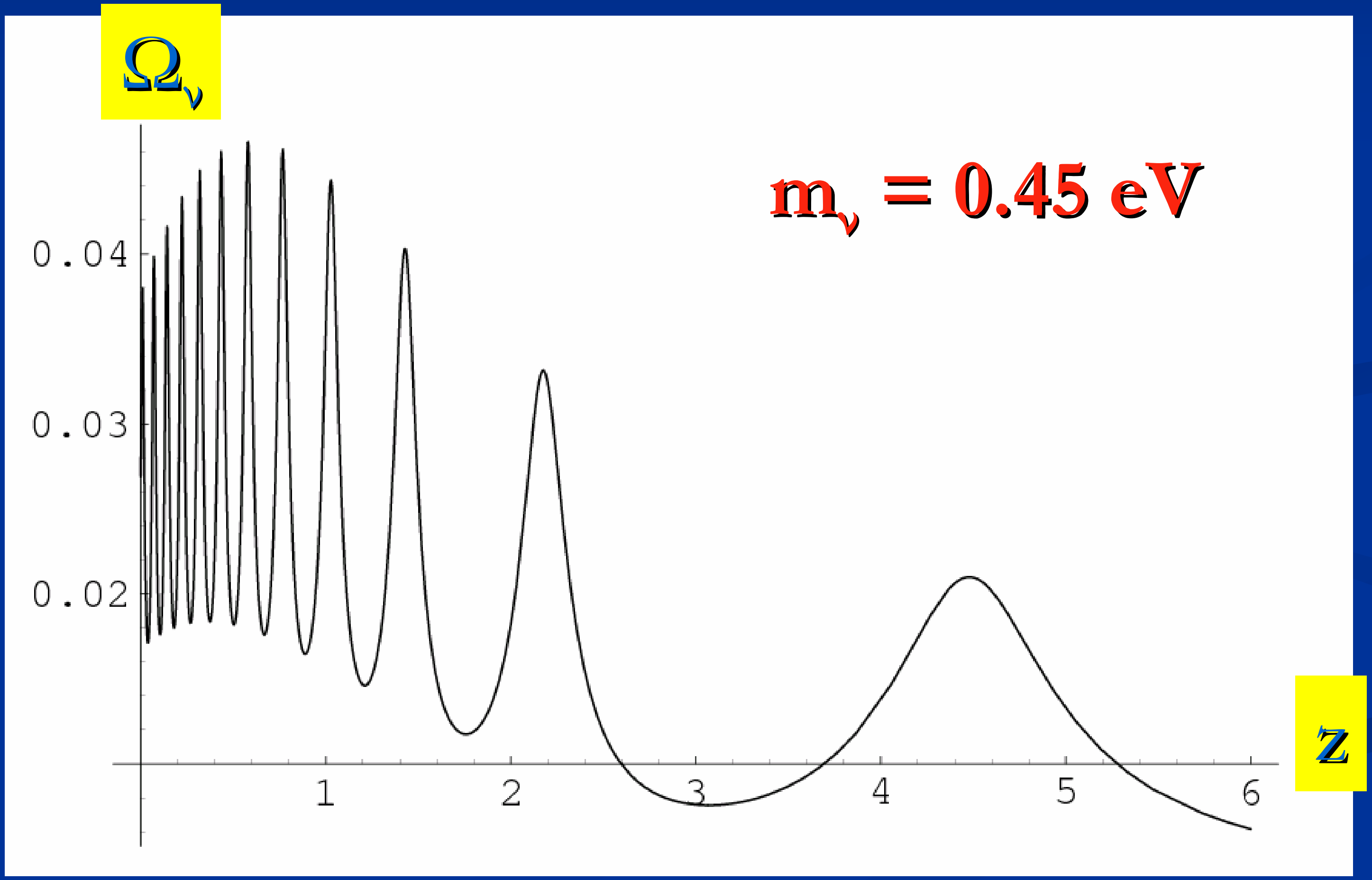
starts at time when "neutrino force" becomes important for the evolution of the cosmon field

cosmological selection !

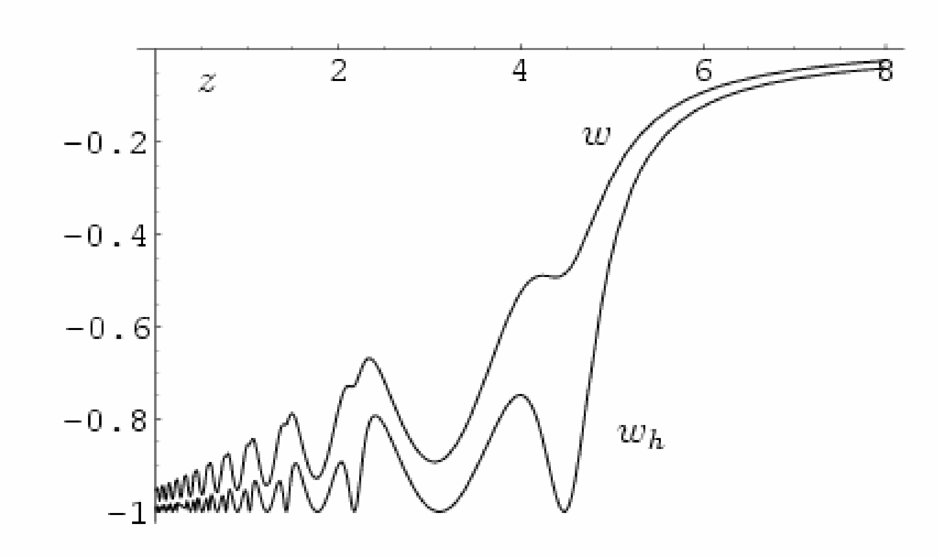
cosmon evolution



neutrino fraction remains small



equation of state

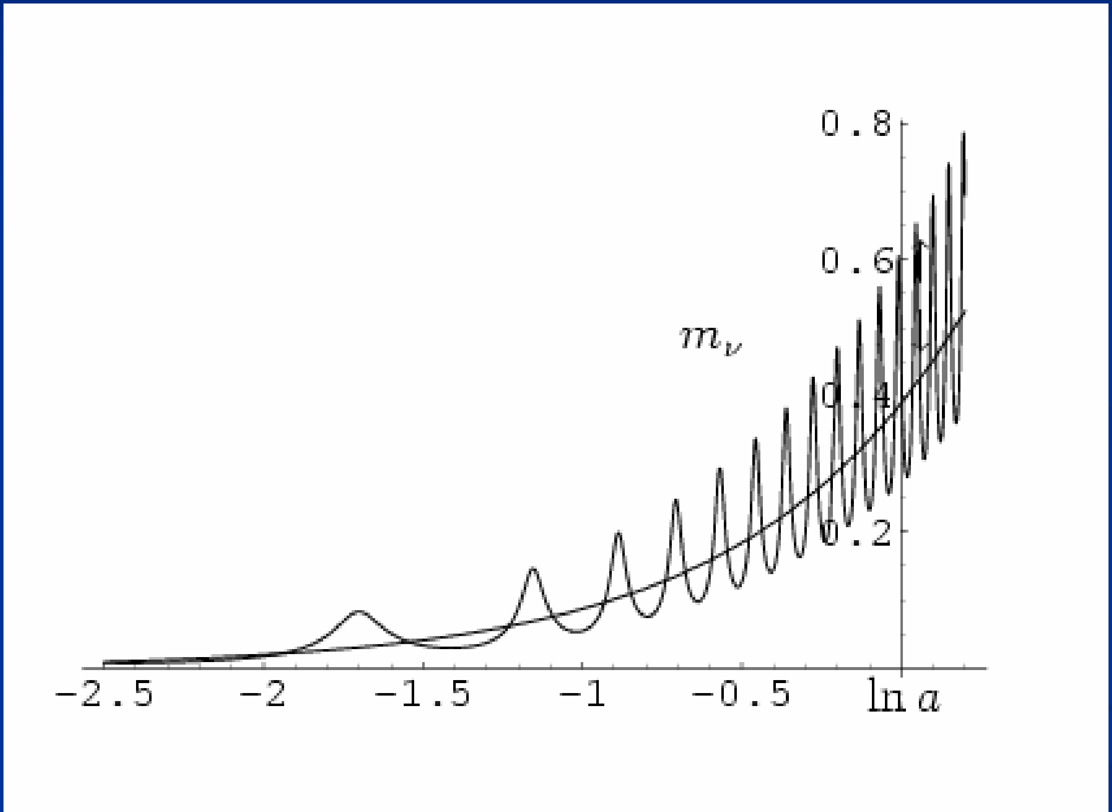


$$w = \frac{T - V + w_\nu \rho_\nu}{T + V + \rho_\nu} \approx -1 + \frac{\rho_\nu}{V} \approx -1 + \frac{\Omega_\nu}{\Omega_h},$$

present equation of state given by neutrino mass !

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

oscillating neutrino mass



crossing time

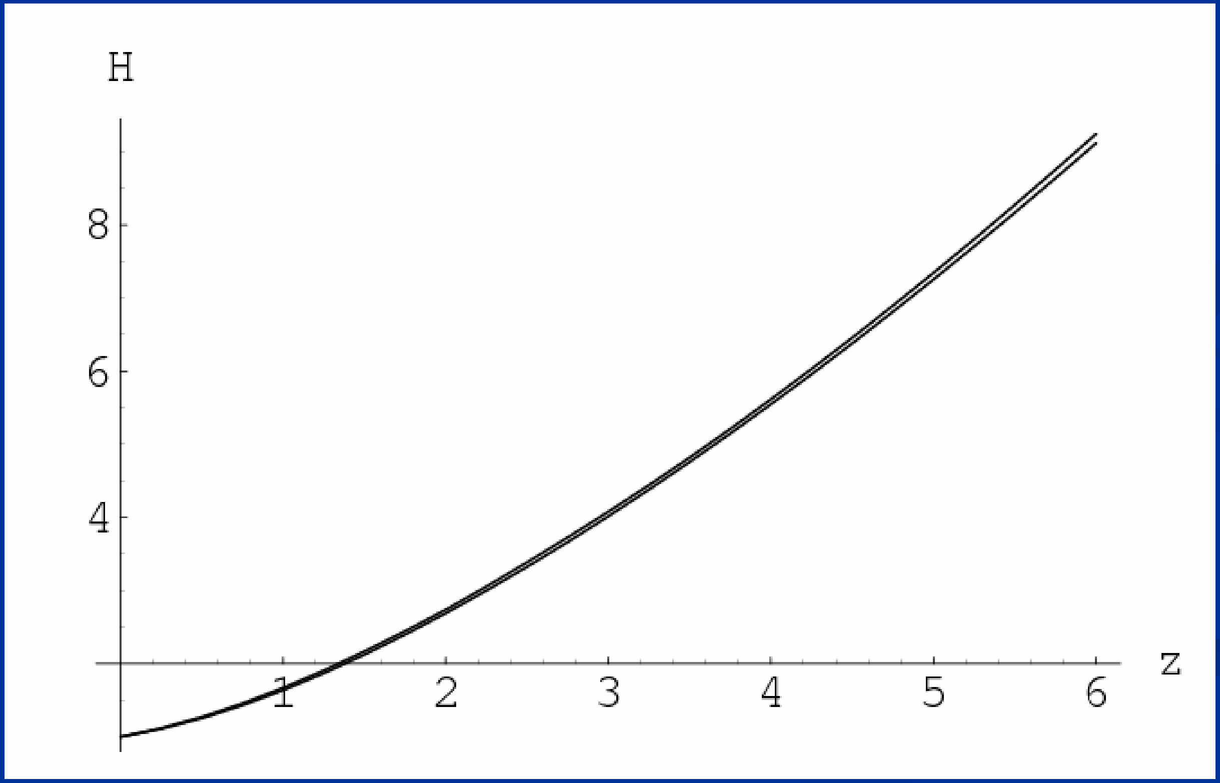
from matching between
early solution and late solution

$$V_t \approx V(t_c) \approx \frac{3}{2}\Omega_{h,e} M^2 H^2(t_c)$$
$$= \frac{9}{2\alpha^2} M^2 H^2(t_c) = \frac{2M^2}{\alpha^2 t_c^2}$$

$$t_c^2 H_0^2 = \frac{2}{3\Omega_{h,0}\alpha^2} \approx \frac{8}{9\alpha^2}$$

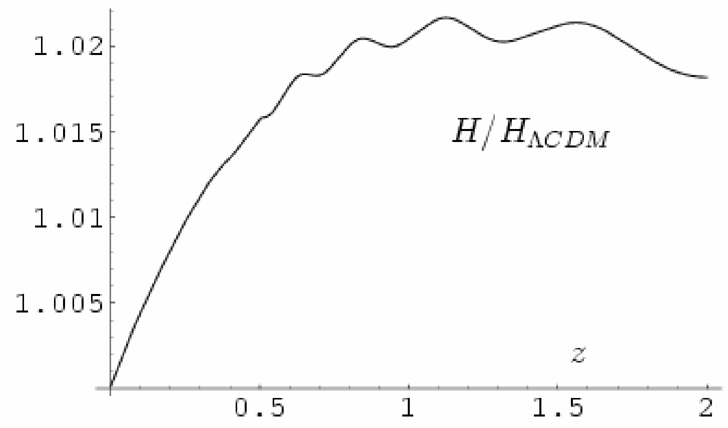
Hubble parameter

as compared to ΛCDM



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 ΛCDM !

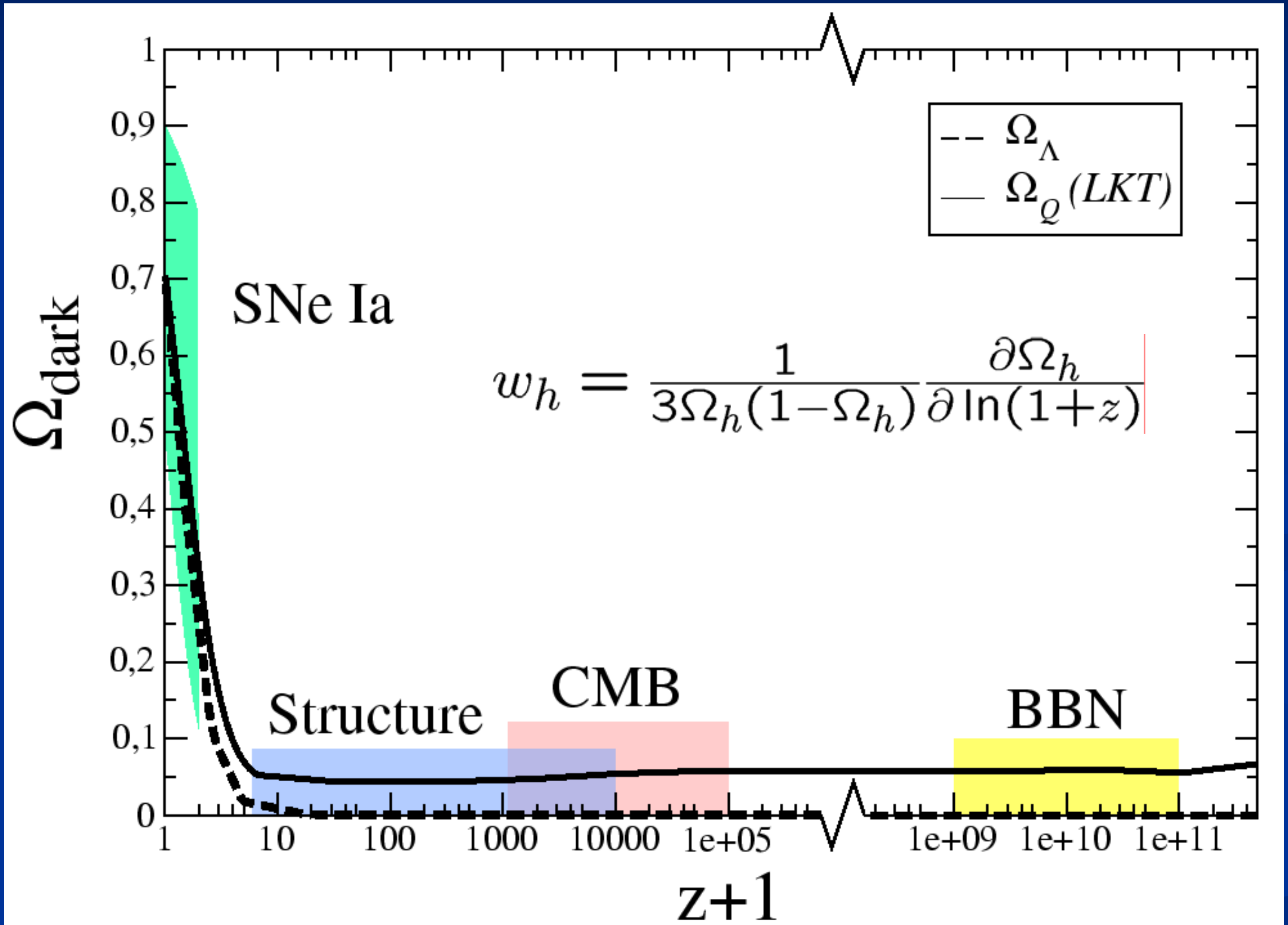
Can time evolution of neutrino mass be observed ?

- Experimental determination of neutrino mass may turn out higher than upper bound in model for cosmological constant

(KATRIN, neutrinoless double beta decay)

How can quintessence be distinguished from a cosmological constant ?

Time dependence of dark energy



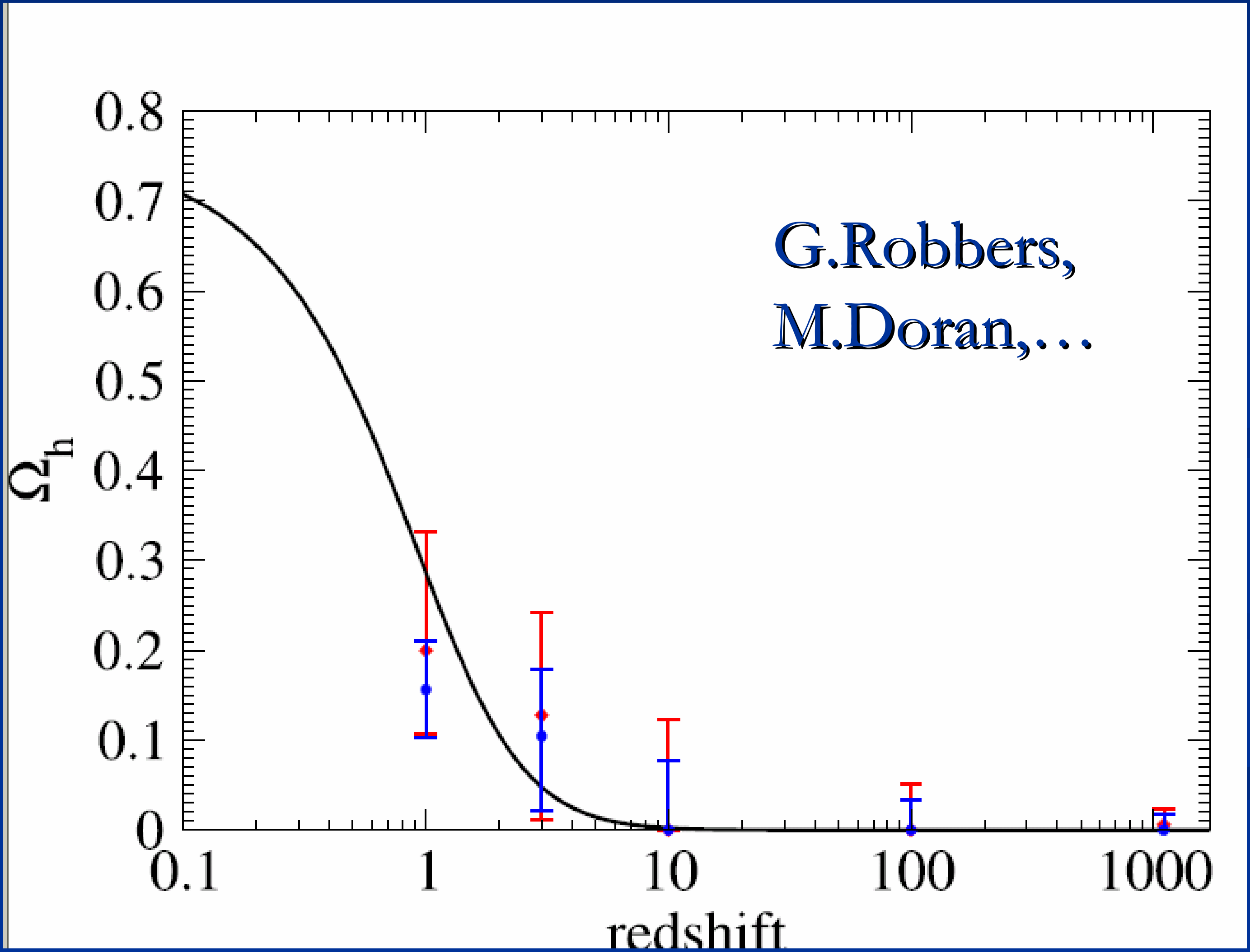
cosmological constant : $\Omega_h \sim t^2 \sim (1+z)^{-3}$

M.Doran,…

effects of early dark energy

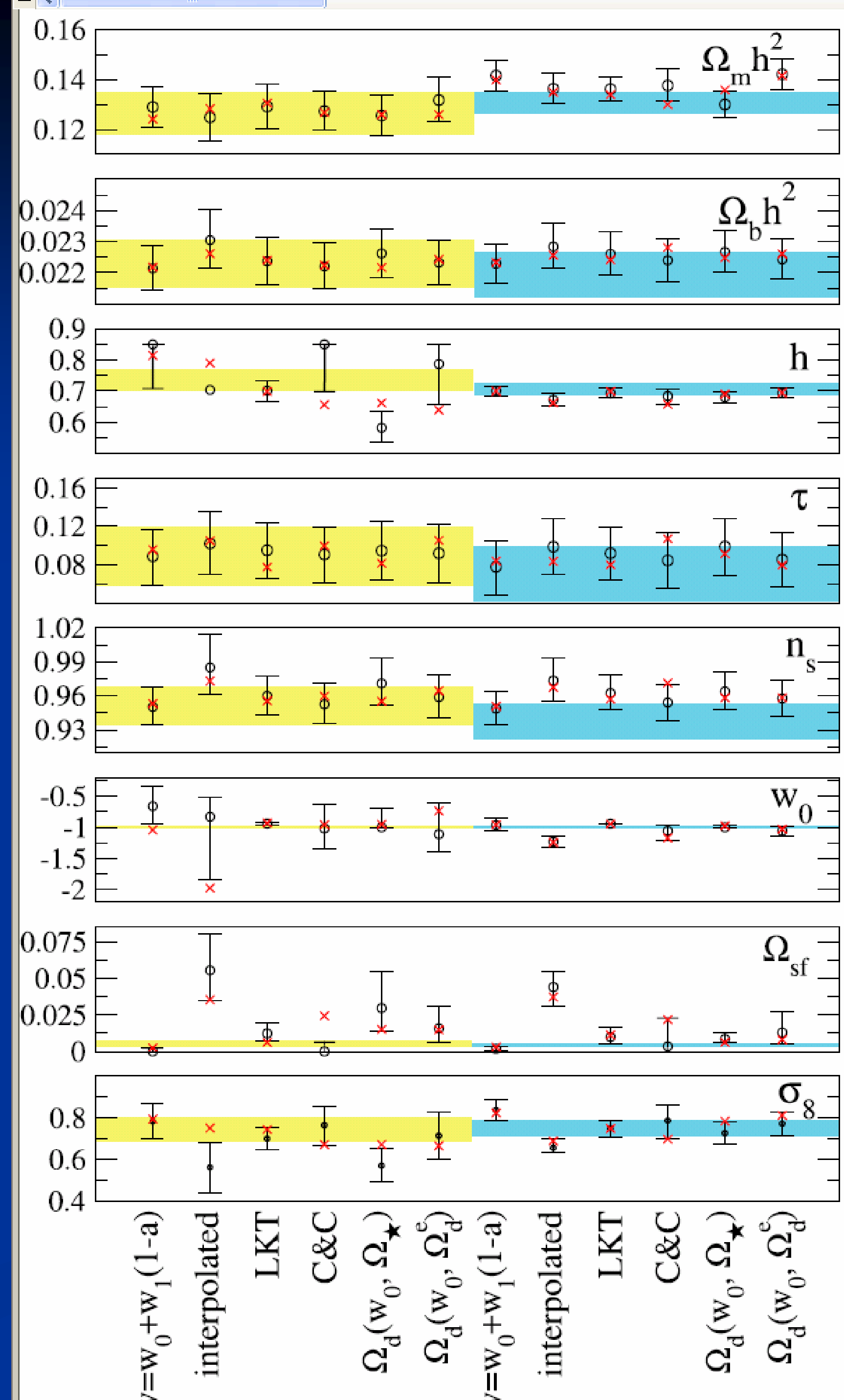
- modifies cosmological evolution (CMB)
- slows down the growth of structure

interpolation of Ω_h

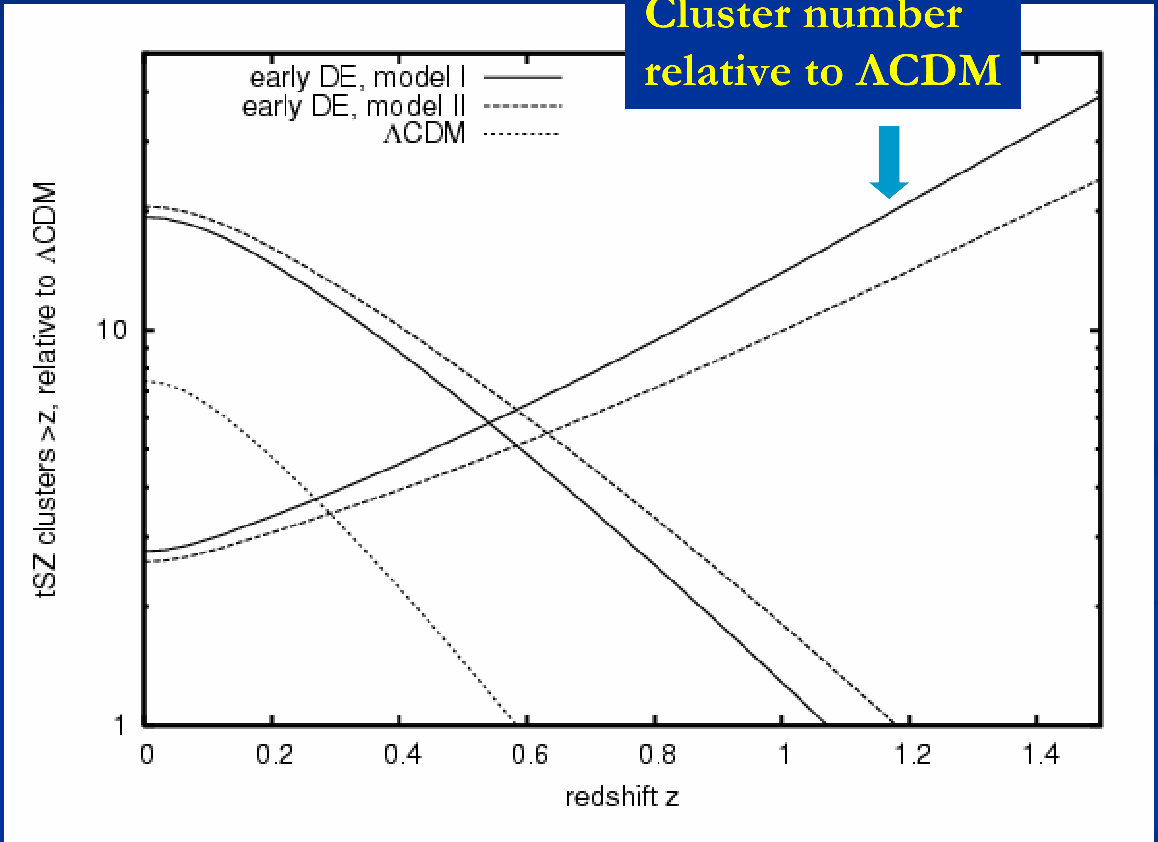


bounds on
Early Dark Energy
after WMAP'06

G.Robbers,M.Doran,…



Little Early Dark Energy can make large effect ! Non – linear enhancement



Cluster number relative to ΛCDM

Two models with 4% Dark Energy during structure formation

Fixed σ_8 (normalization dependence !)

More clusters at high redshift !

Bartelmann,Doran,…

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

Quintessence and solution of cosmological constant problem should be related !

A few references

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approximate late solution

variables :

$$\begin{aligned} s &= -\alpha(\varphi - \varphi_t)/M, \\ x &= \ln a \end{aligned}$$

$$\partial_x \ln \rho_\nu + \partial_x \ln s = -3 \ , \ \ \partial_x \ln \rho_m = -3$$

$$\rho_\nu = \frac{c_\nu}{s a^3} \ , \ \ \rho_m = \frac{\rho_{m,0}}{a^3}$$

approximate smooth solution
(averaged over oscillations)

$$s^{(0)}(x) = \left(\frac{c_\nu}{V_t}\right)^{1/2} e^{-\frac{3x}{2}} = \frac{\tilde{\rho}_\nu(x)}{V_t}$$

$$s_0^{(0)} = \left(\frac{c_\nu}{V_t}\right)^{1/2} = \frac{\tilde{\rho}_{\nu,0}}{V_t} \approx \frac{\Omega_\nu(t_0)}{\Omega_h(t_0)}$$

dark energy fraction

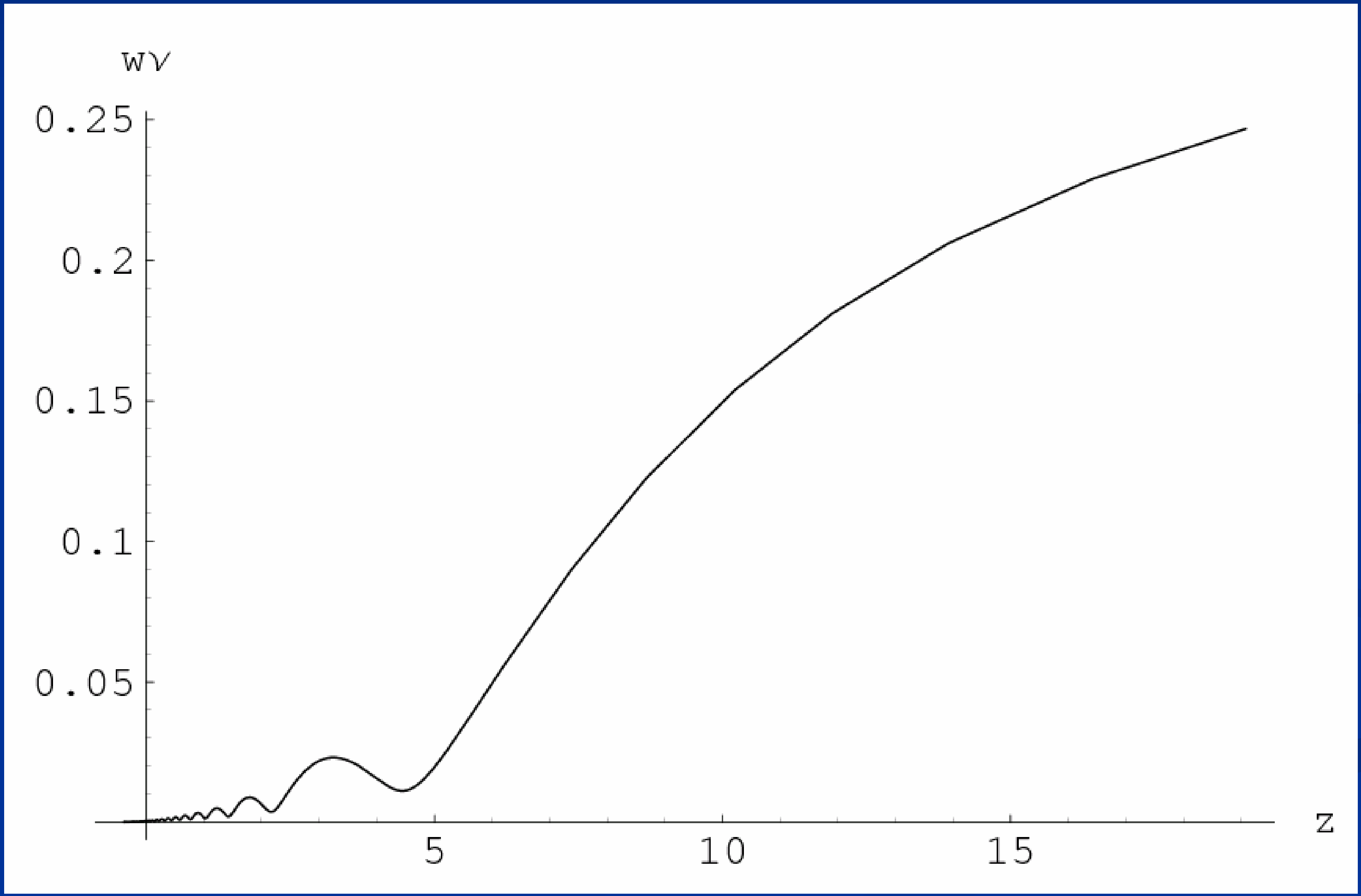
$$\tilde{\Omega}_h(a) = \begin{cases} \frac{\tilde{\Omega}_{h,0} a^3 + 2\Omega_{\nu,0}(a^{3/2} - a^3)}{1 - \tilde{\Omega}_{h,0}(1 - a^3) + 2\Omega_{\nu,0}(a^{3/2} - a^3)} & \text{for } a > a_c \\ \frac{3}{\alpha^2} & \text{for } a < a_c \end{cases}$$

neutrino fluctuations

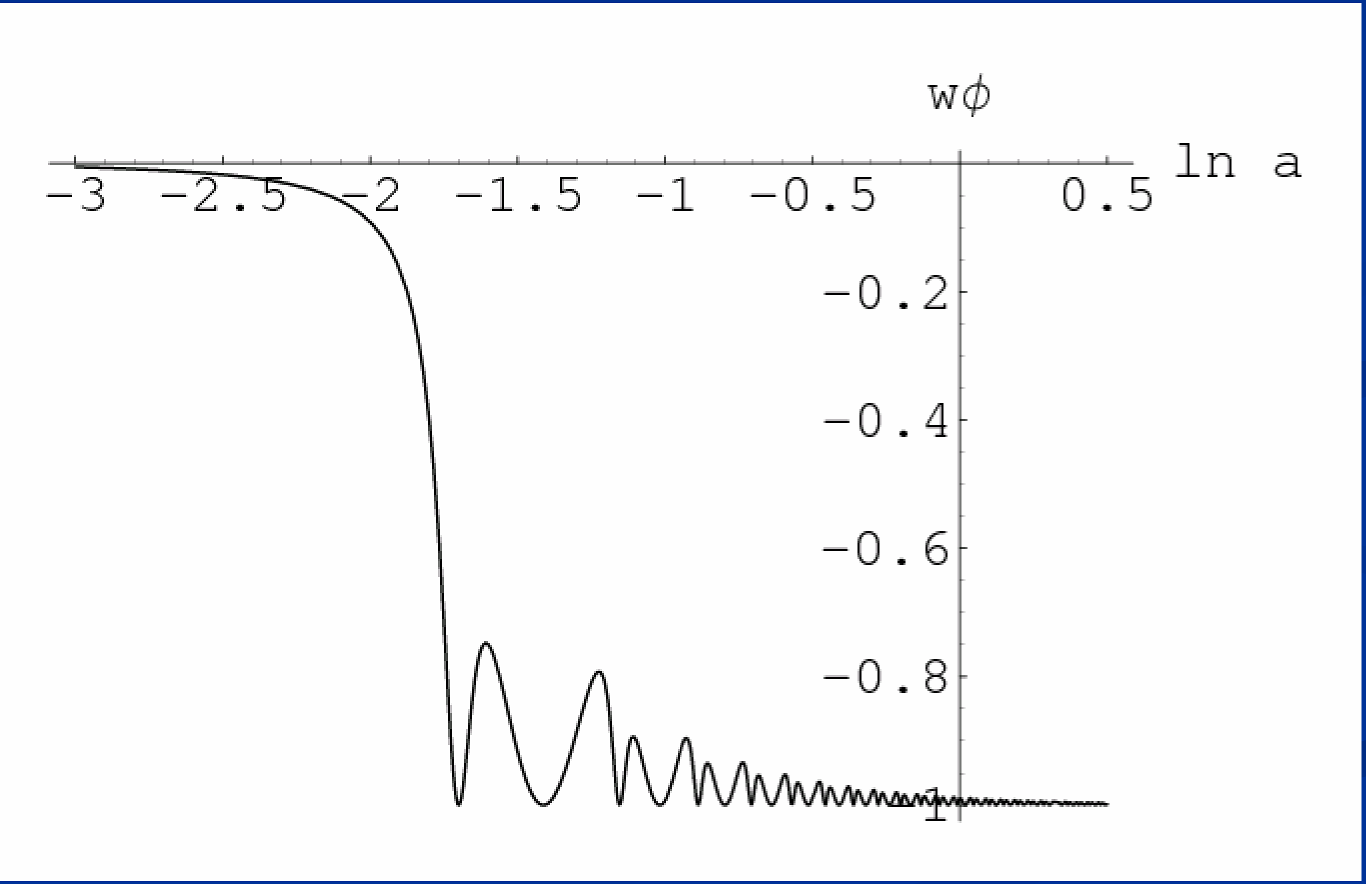
- time when neutrinos become non – relativistic
- sets free streaming scale

$$a_R = \left(\frac{\tilde{m}_\nu(t_0)}{3T_{\nu,0}}\right)^{-\frac{2}{5}} = 0.05\left(\frac{\tilde{m}_\nu(t_0)}{eV}\right)^{-2/5}$$

neutrino equation of state



cosmon equation of state



fixed point behaviour : apparent tuning

$$V(\varphi) = U_0(\varphi) - \frac{\lambda d_0^4 \gamma^2}{2(\lambda M_t^2(\varphi) - \gamma^2)}$$

$$V(\varphi) = U_0(\varphi) - \frac{m_\nu(\varphi) d^2 \gamma}{2 h_L}$$