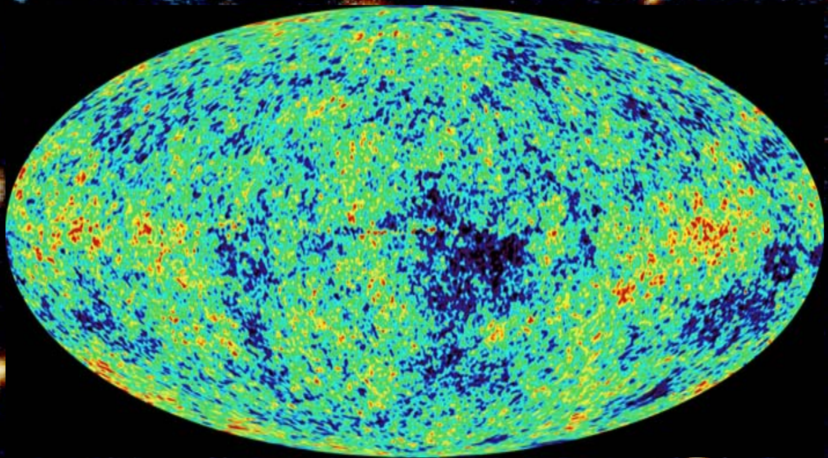
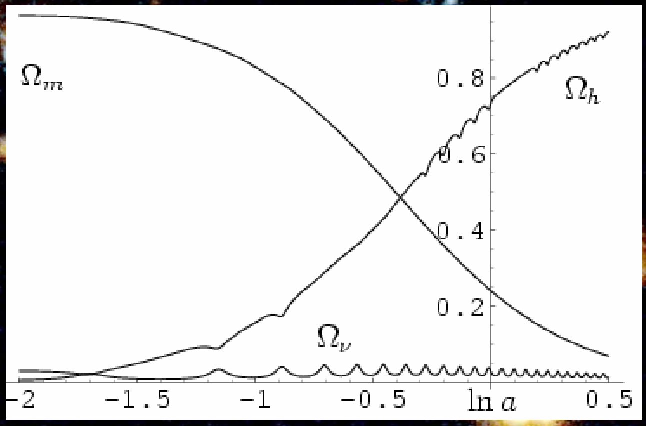
Growing neutrinos and cosmological selection





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

What is our universe made of ?

Dark Energy dominates the Universe

Energy - density in the Universe

=

Matter + Dark Energy

25 % + 75 %

Matter : everything that clumps

Dark Energy density is
the same at every point of space

“ homogeneous “

Space between clumps
is not empty

Composition of the Universe

$\Omega_b = 0.045$	visible	clumping
$\Omega_{dm} = 0.2$	invisible	clumping
$\Omega_h = 0.75$	invisible	homogeneous

What is Dark Energy ?

Cosmological Constant
or
Quintessence ?

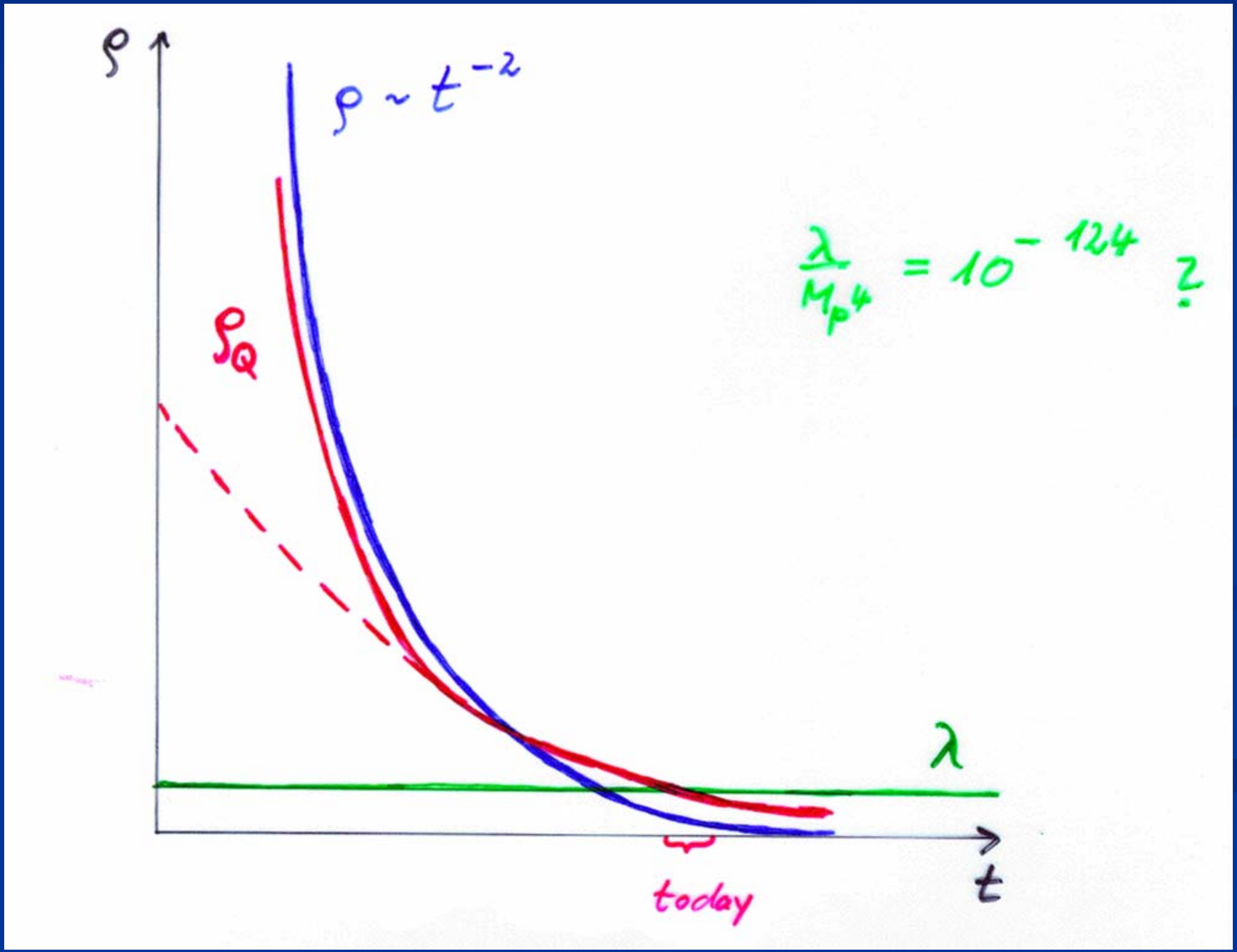
Cosmological Constant
- Einstein -

- Constant λ compatible with all symmetries
- No time variation in contribution to energy density

- Why so small ? $\lambda/M^4 = 10^{-120}$

- Why important just today ?

Cosm. Const. | Quintessence
static | dynamical



Cosmological mass scales

- Energy density

  $\rho \sim (\ 2.4\times10^{-3}\ \mathrm{eV}\ )^{-4}$

- Reduced Planck mass

  $M=2.44\times10^{18}\mathrm{GeV}$

- Newton's constant

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

Only ratios of mass scales are observable !

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

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

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

Quintessence

Cosmon – Field $\varphi(x,y,z,t)$

Homogeneous und isotropic Universe : $\varphi(x,y,z,t)=\varphi(t)$

Potential und kinetic energy of the cosmon -field contribute to a dynamical energy density of the Universe !

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*
- *Time - variable dark energy :*

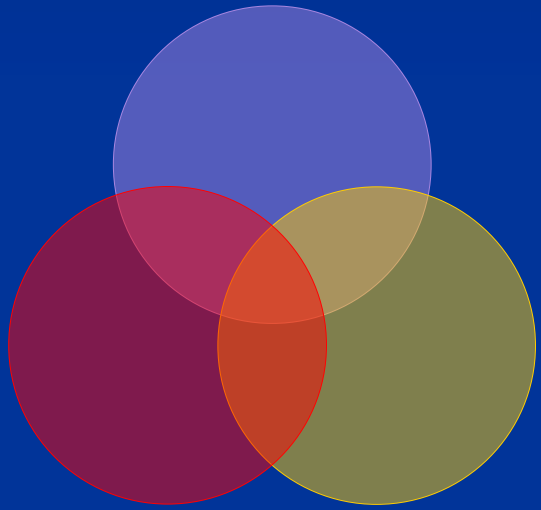
  $\rho_h(t)$ *decreases with time !*

Cosmon

- *Tiny mass*
- $m_c \sim H$
- *New long - range interaction*

"Fundamental" Interactions

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

On astronomical length scales:

graviton

+

cosmon

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

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

for increasing φ the potential decreases towards zero !

Cosmic Attractors

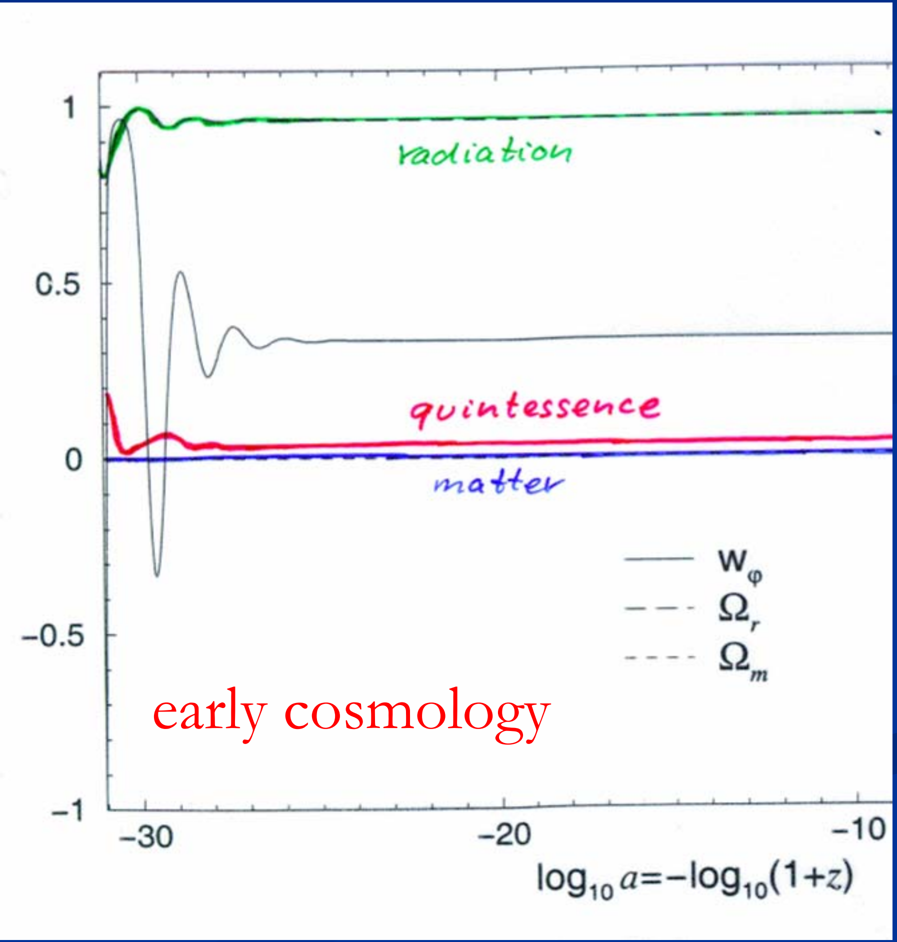
Solutions independent of initial conditions

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

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

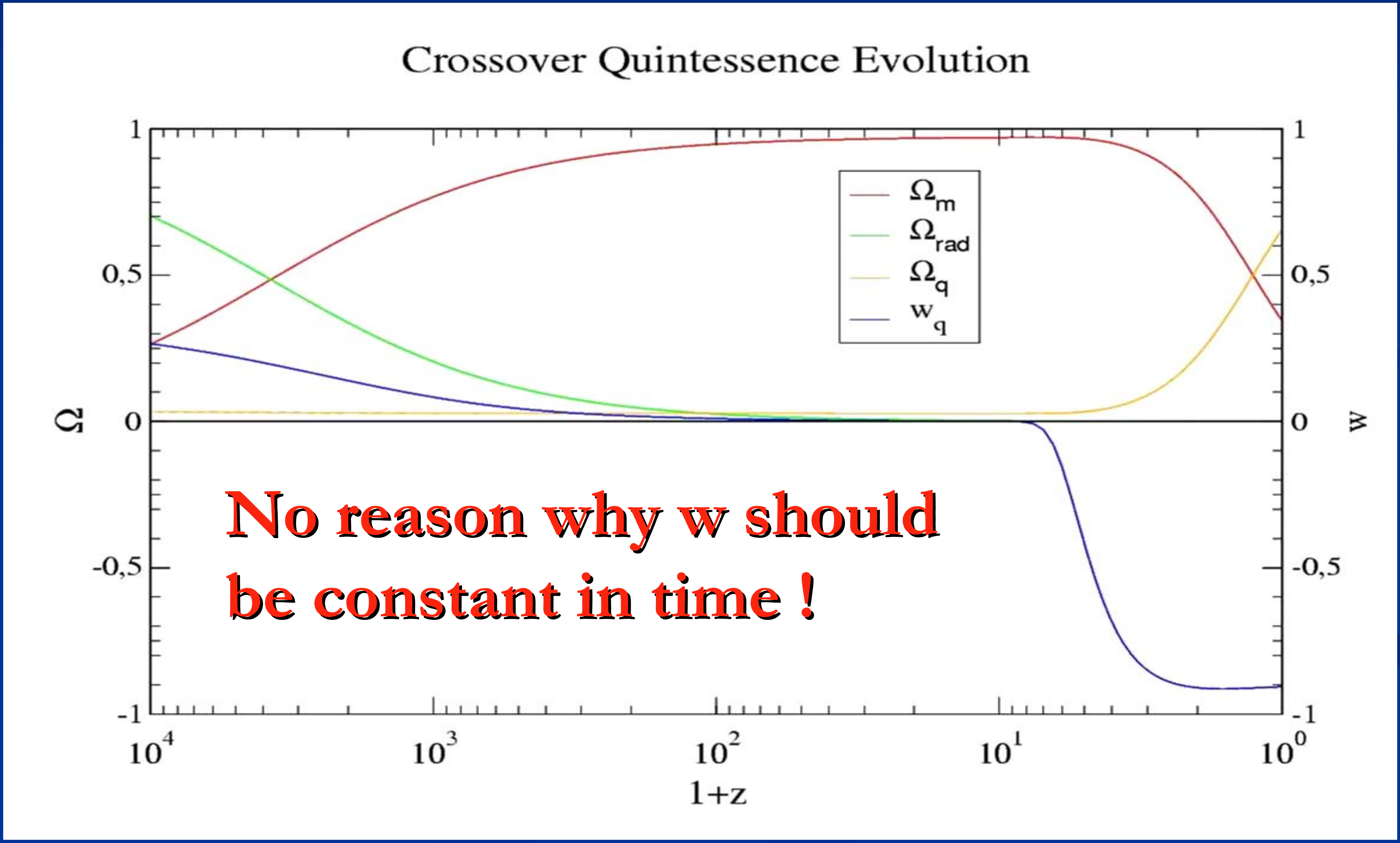
can explain order of magnitude of dark energy !

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 $z < 6$?

a) Properties of cosmon potential or kinetic term

Late quintessence

- w close to -1
- Ω_h negligible in early cosmology
- needs tiny parameter, similar to cosmological constant

Early quintessence

- Ω_h changes only modestly
- w changes in time

transition

- special feature in cosmon potential or kinetic term becomes important “now”
- tuning at ‰ level

b) Quintessence reacts to some special event in cosmology

- Onset of matter dominance

K- essence

Amendariz-Picon, Mukhanov, Steinhardt

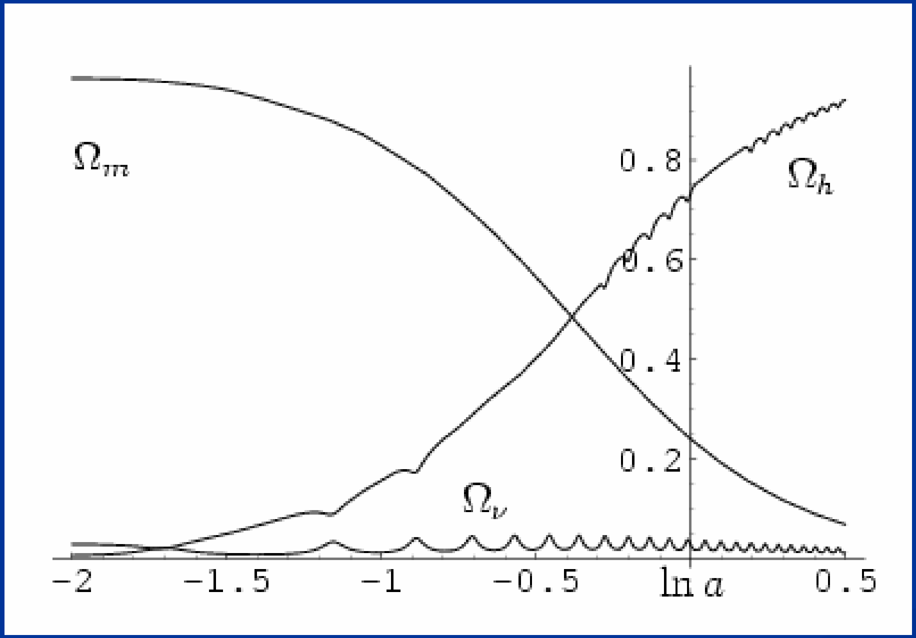
needs higher derivative kinetic term

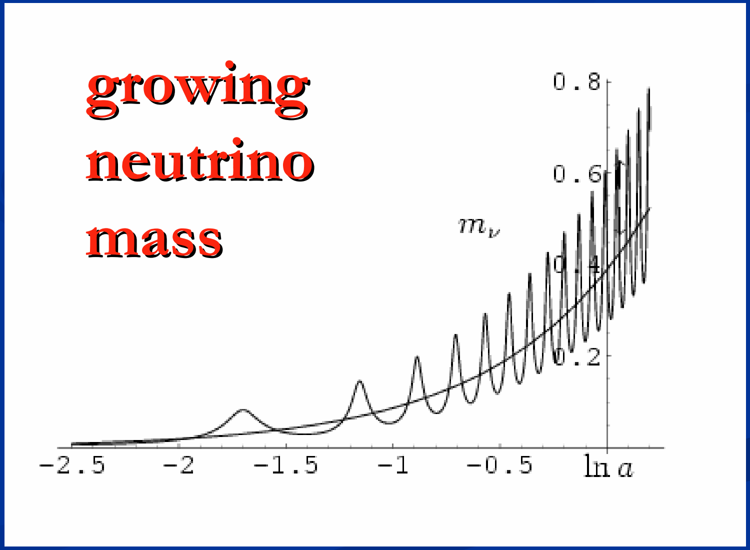
- Appearance of non-linear structure

Back-reaction effect

needs coupling between Dark Matter and Dark Energy

growing neutrino mass triggers transition to almost static dark energy





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 Dark Matter

- Only bounded by cosmology
- Substantial coupling possible
- Can modify scaling solution and late cosmology
- Role in clustering of extended objects ?

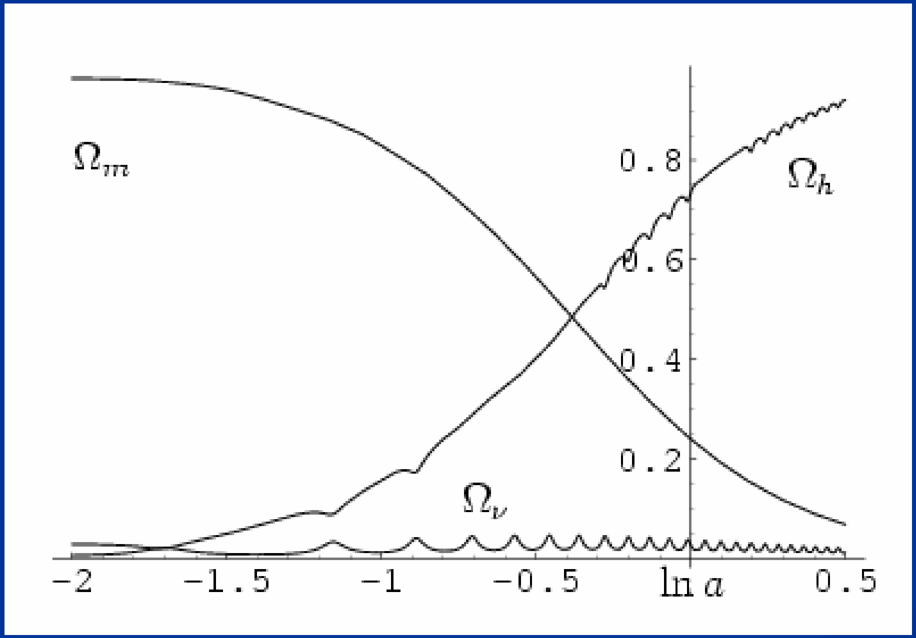
L. Amendola

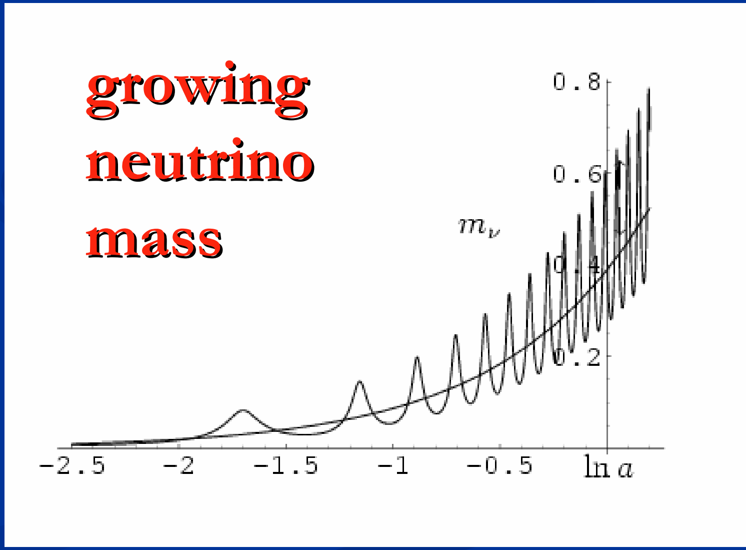
Cosmon coupling to neutrinos

- 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 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 !

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

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

M.Magg , …
G.Lazarides , Q.Shafi , …

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

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

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

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

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

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

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

early scaling solution (tracker solution)

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

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

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

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 $\varphi \rightarrow \varphi_t$!

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

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

effective cosmological constant

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

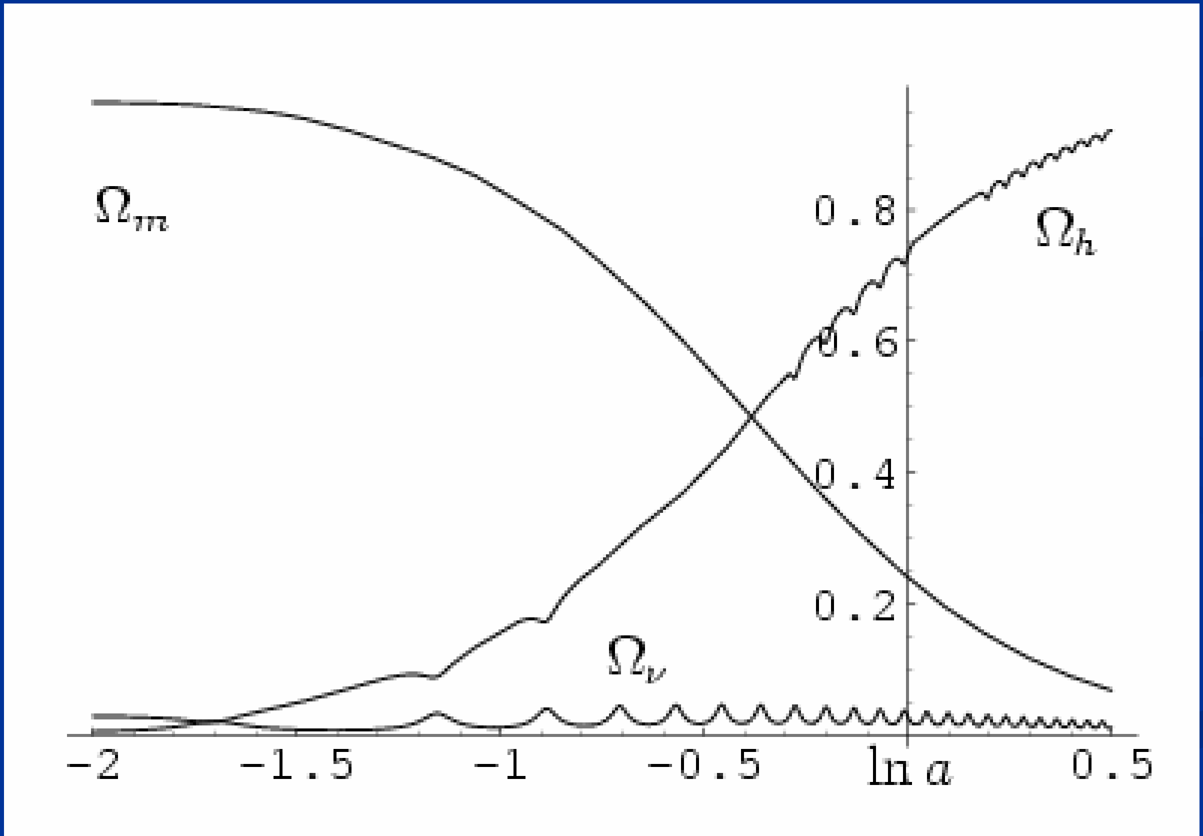
realistic value
for
$\alpha\ \varphi_t / M \approx 276$

⟺

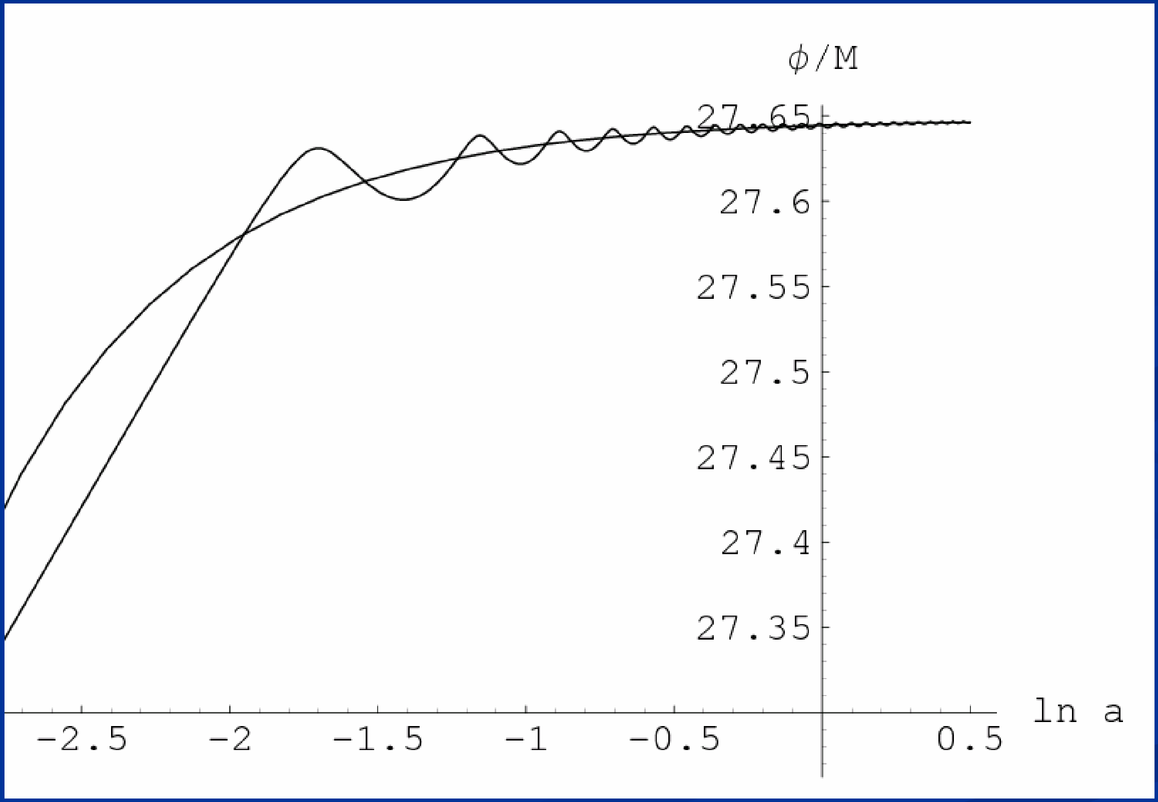
$$\epsilon = -\frac{\alpha \ln \tau}{276}$$

cosmological selection !

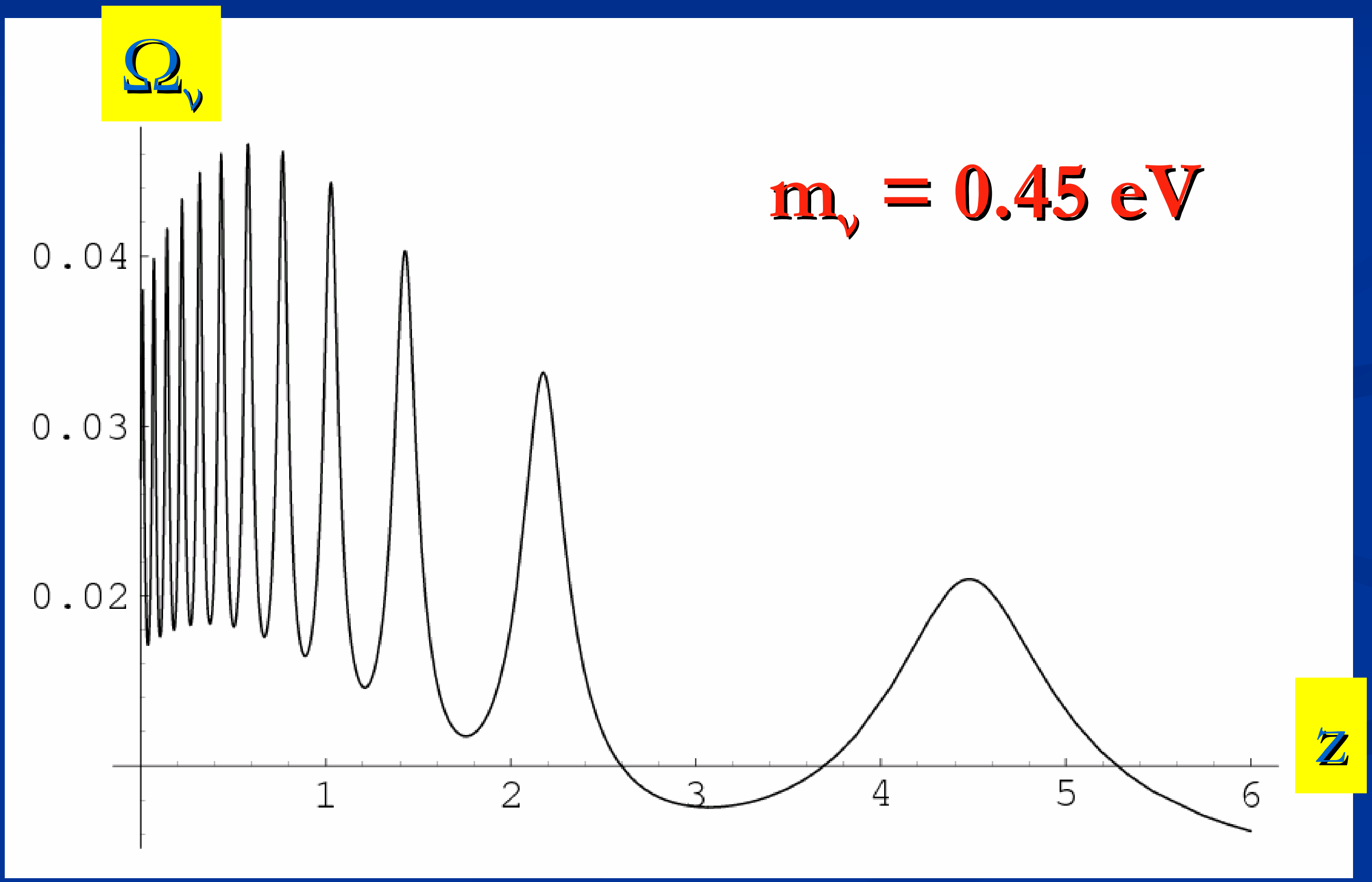
crossover to dark energy dominated universe



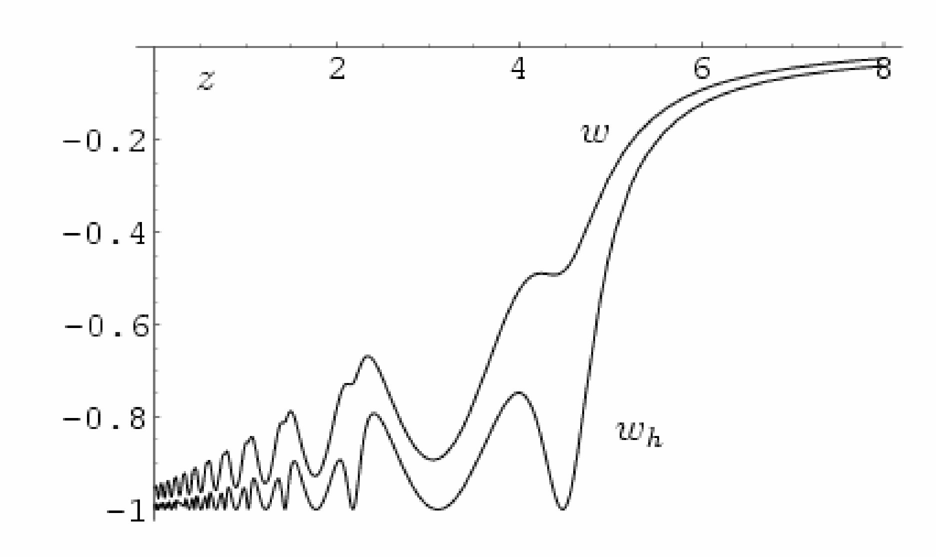
cosmon evolution



neutrino fraction remains small



equation of state

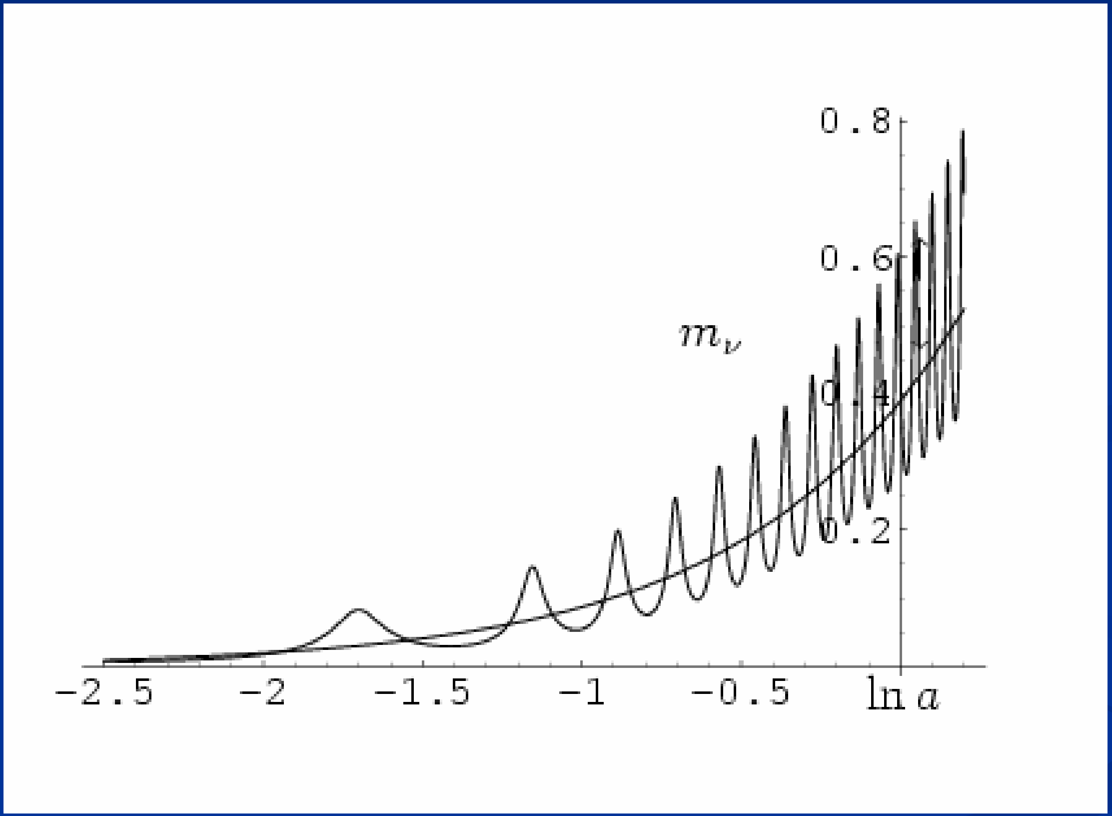


$$w = \frac{T - V + w_\nu \rho_\nu}{T + V + \rho_\nu} \approx -1 + \frac{\rho_\nu}{V} \approx -1 + \frac{\Omega_\nu}{\Omega_h},$$

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

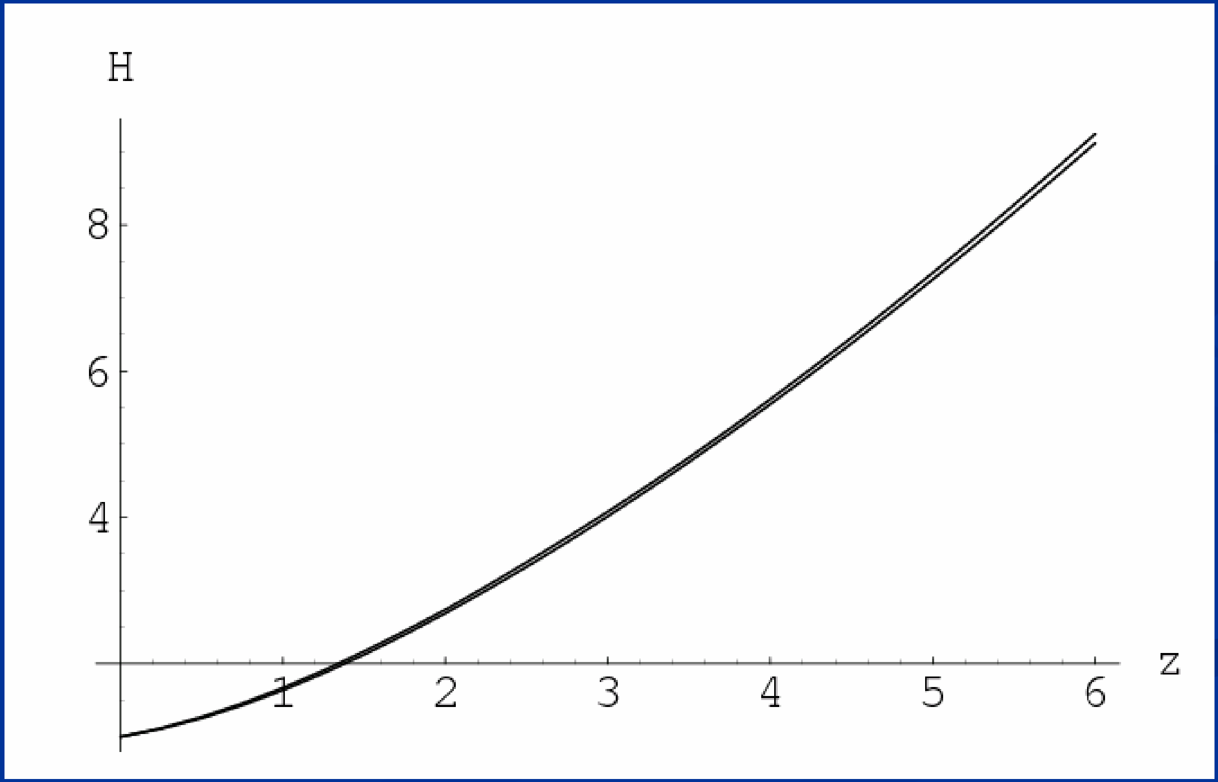
early solution and late solution

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

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

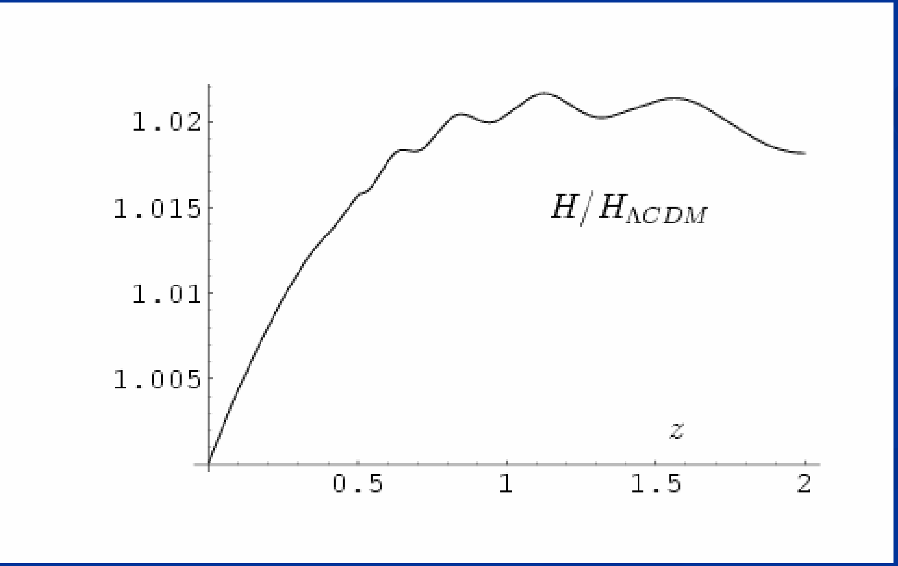
Hubble parameter

as compared to ΛCDM



Hubble parameter (z < z$_c$)

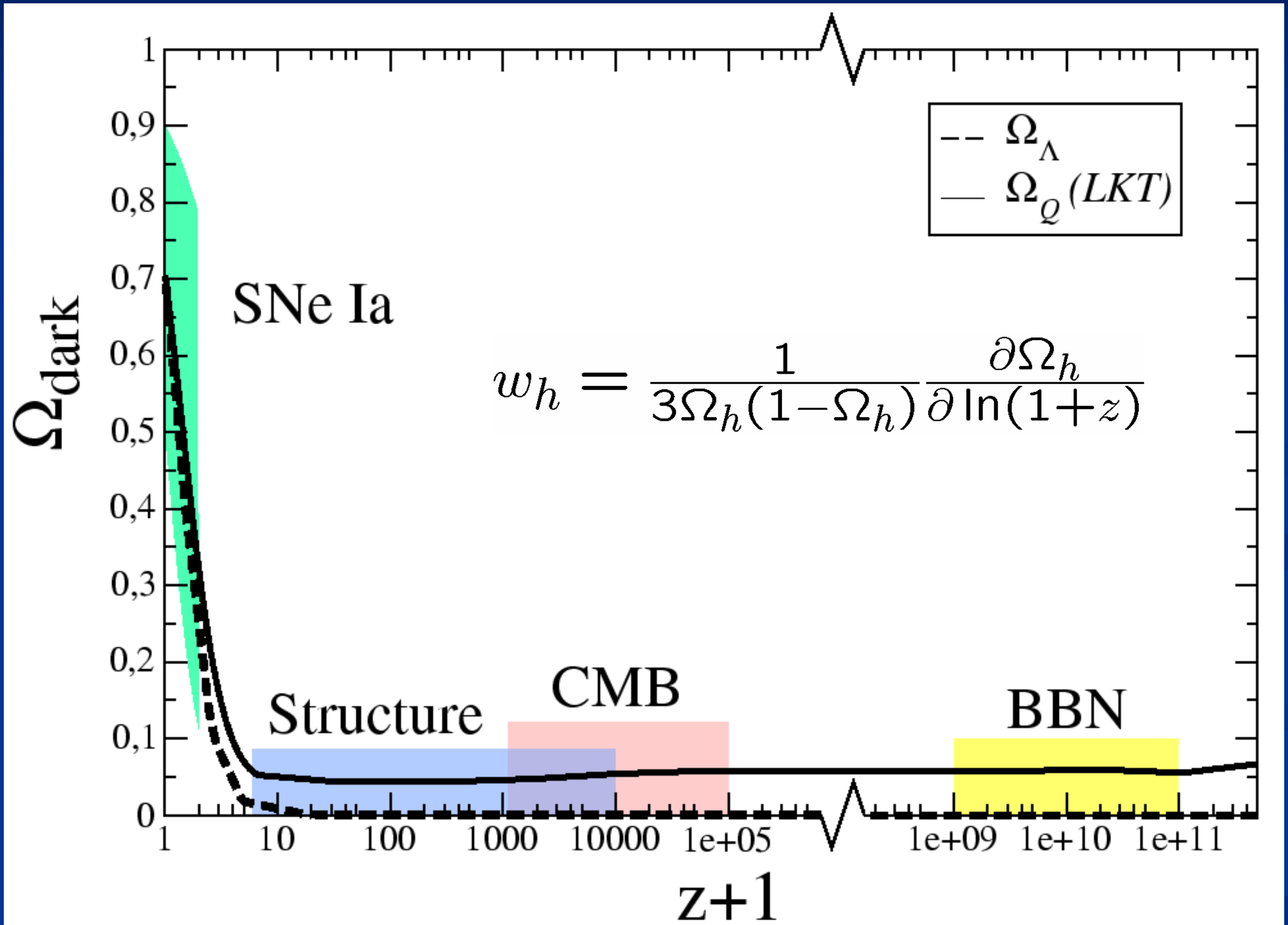
$$H^2 = \frac{1}{3M^2}\left\{V_t + \rho_{m,0}a^{-3} + 2\tilde{\rho}_{\nu,0}a^{-\frac{3}{2}}\right\}$$



only small difference from ΛCDM !

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,…

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

Growth of density fluctuations

- Matter dominated universe with constant Ω_h :

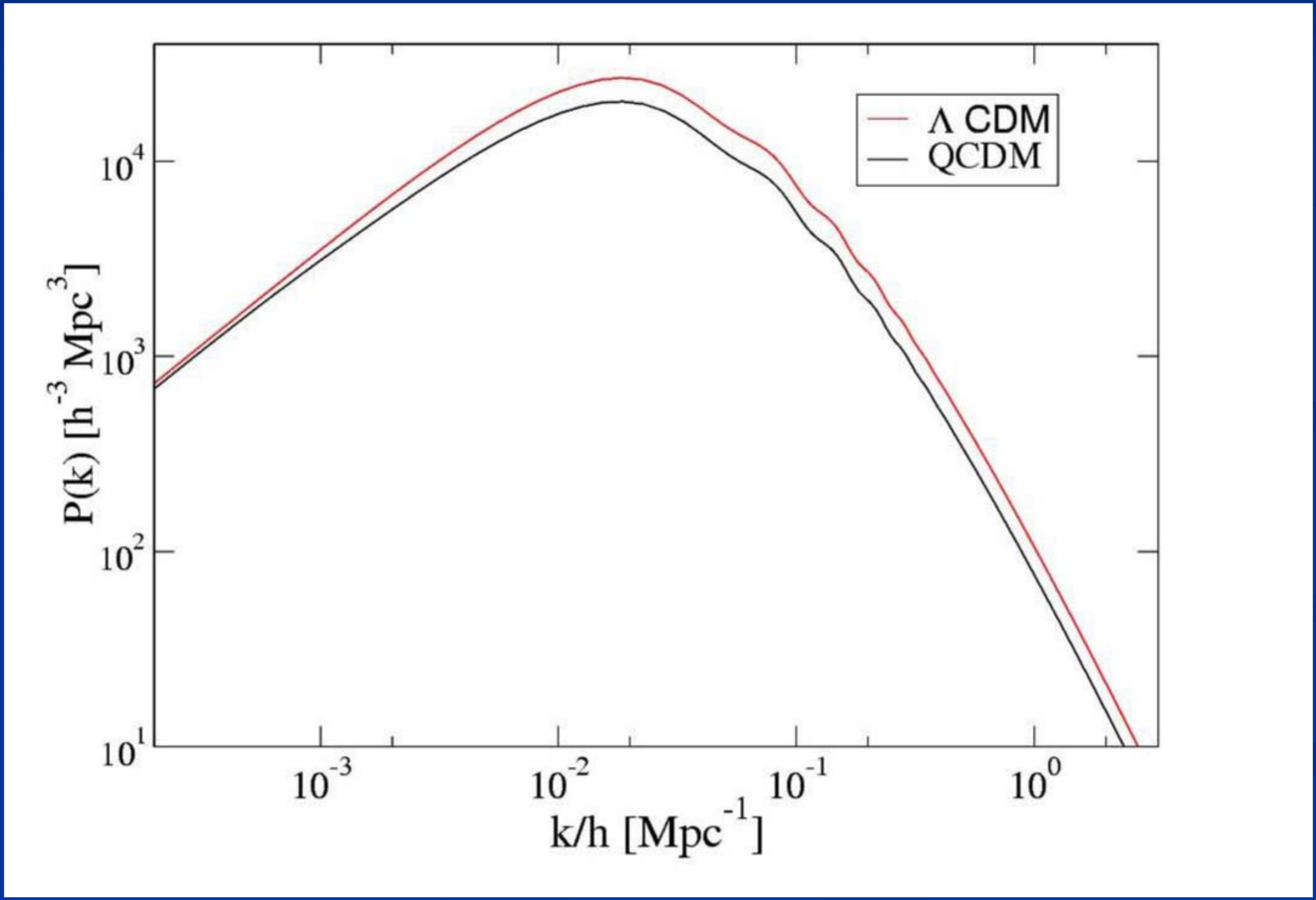
$$\Delta\rho \sim a^{1-\frac{\epsilon}{2}}\ ,\ \epsilon = \frac{5}{2}\left(1 - \sqrt{1 - \frac{24}{25}\Omega_h}\right)$$

P.Ferreira,M.Joyce

- Dark energy slows down structure formation

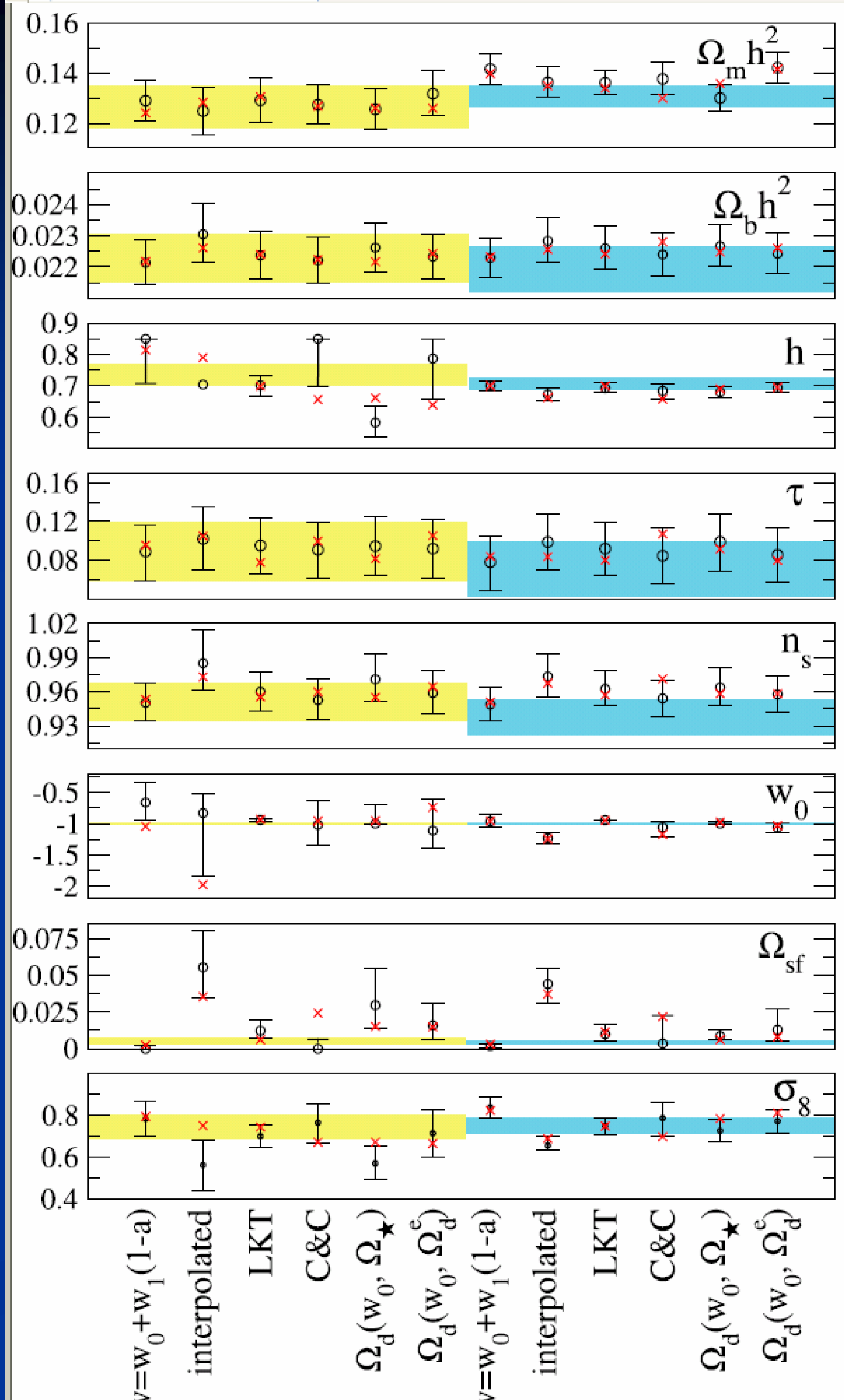
  ⟶ $\Omega_h < 10\%$ during structure formation

Early quintessence slows down the growth of structure

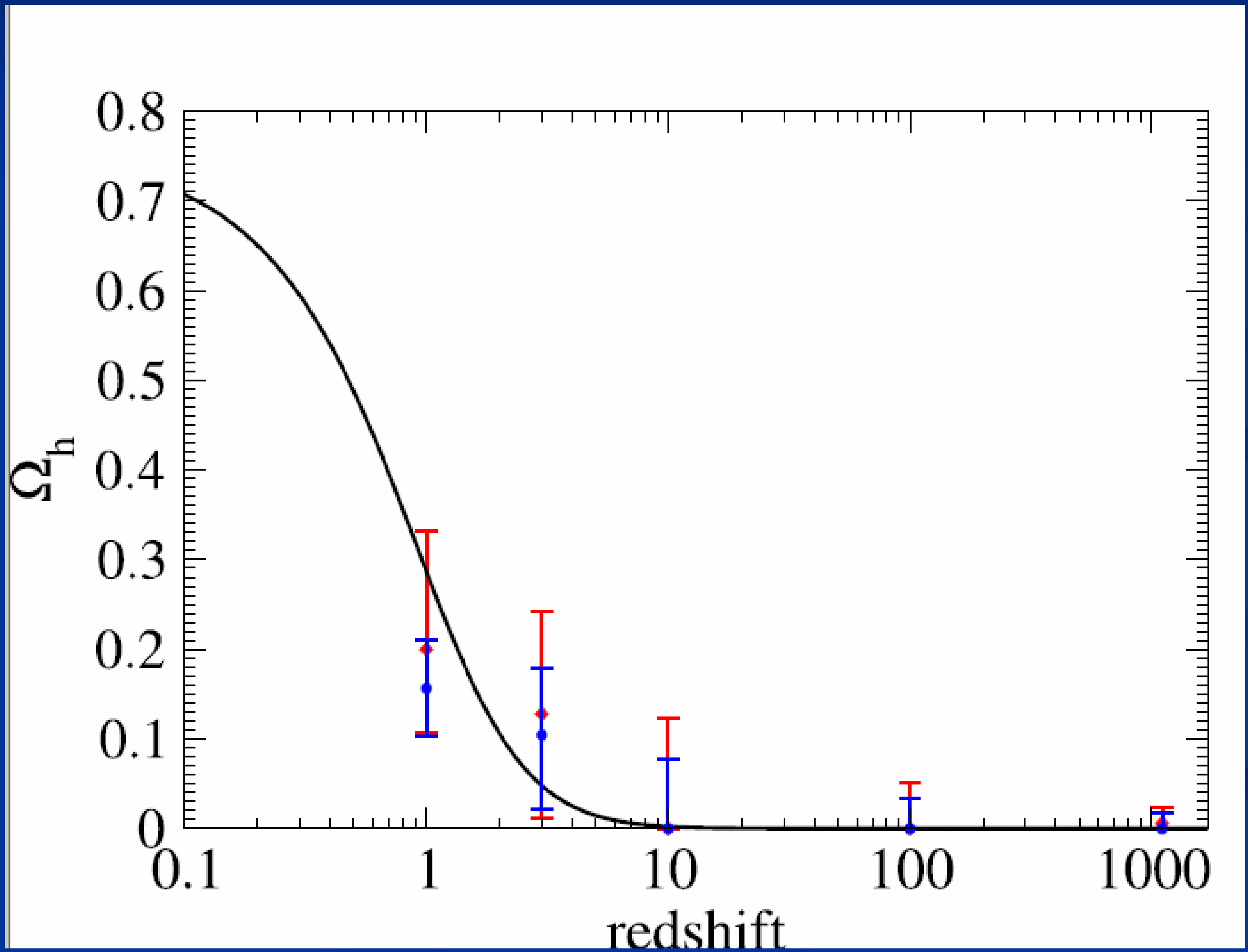


bounds on
Early Dark Energy
after WMAP'06

G.Robbers,M.Doran,…

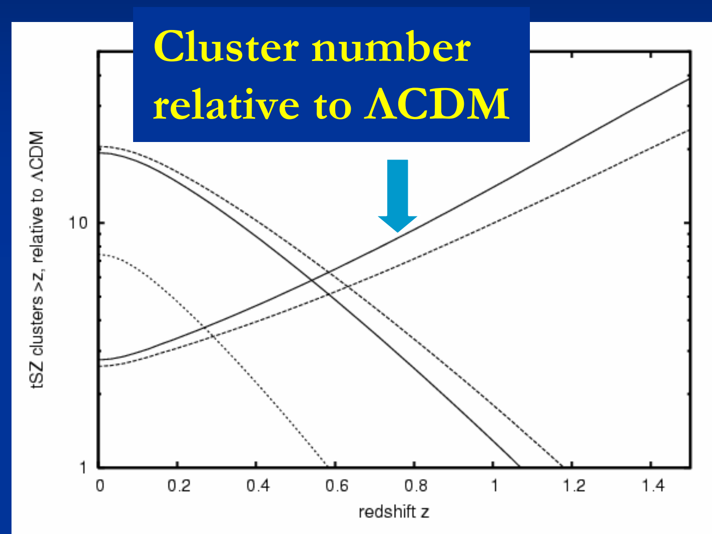


interpolation of Ω_h



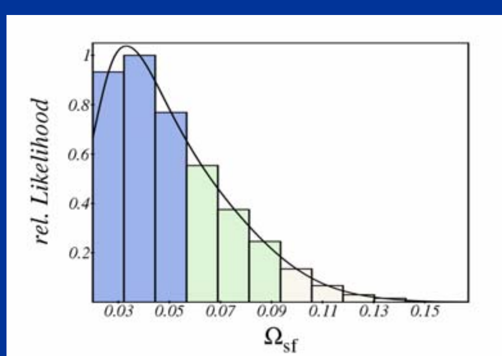
Little Early Dark Energy can make large effect !

More clusters at high redshift

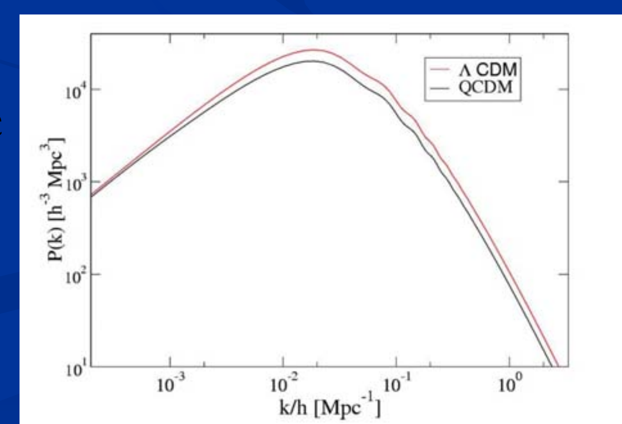


Two models with 4% Dark Energy during structure formation

Fixed σ_8 (normalization dependence !)

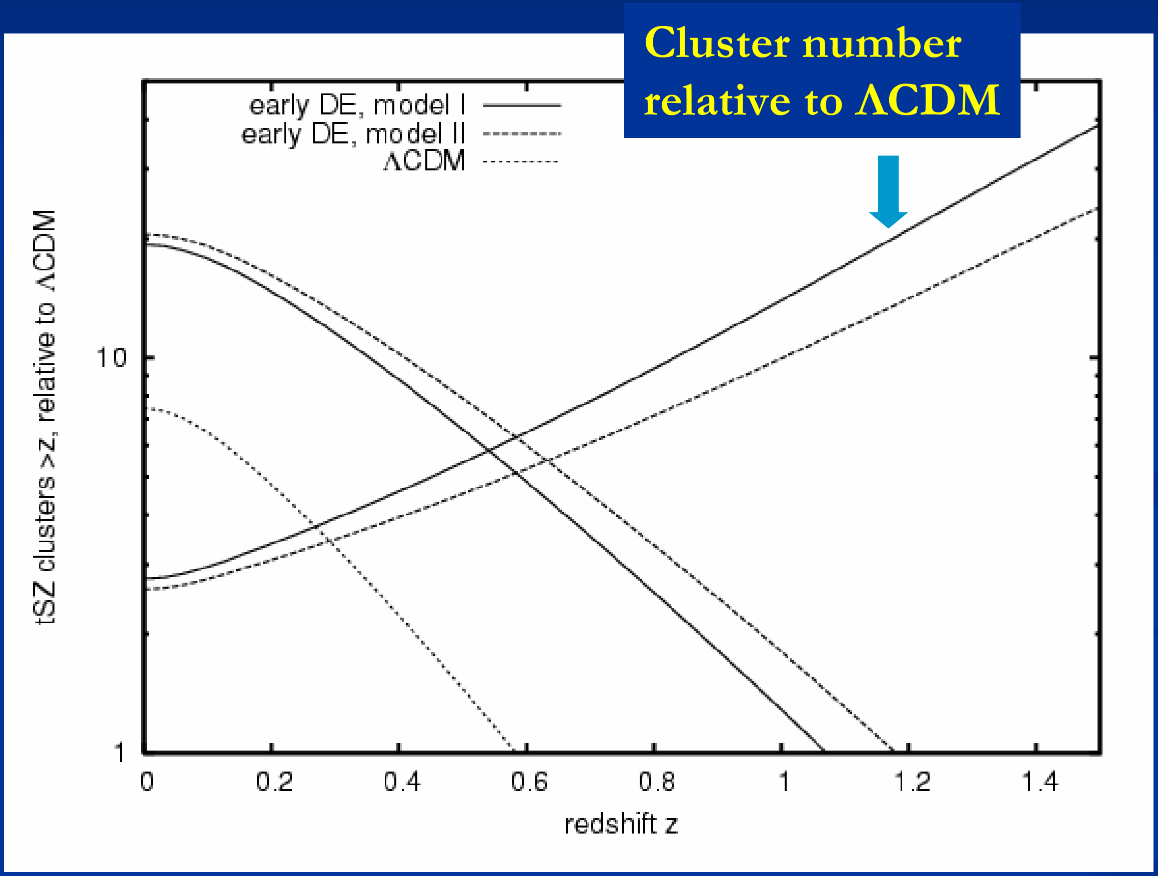


Early Quintessence slows downs the growth of structure



Dark Energy during structure formation

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



Two models with 4% Dark Energy during structure formation

Fixed σ_8 (normalization dependence !)

More clusters at high redshift !

Bartelmann,Doran,…

How to distinguish Q from Λ ?

A) Measurement $\Omega_h(z)$ ⟺ $H(z)$

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

Cosmodynamics

Cosmon mediates new long-range interaction

Range : size of the Universe – horizon

Strength : weaker than gravity

photon	electrodynamics
graviton	gravity
cosmon	cosmodynamics

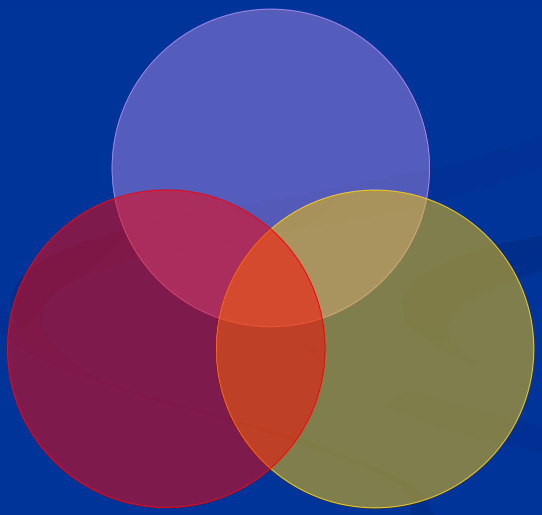
Small correction to Newton's law

Quintessence and time variation of fundamental constants

Generic prediction

Strength unknown

C.Wetterich , Nucl.Phys.B302,645(1988)



Time varying constants

- It is not difficult to obtain quintessence potentials from higher dimensional or string theories
- Exponential form rather generic

  (after Weyl scaling)
- But most models show too strong time dependence of constants !

Are fundamental “constants” time dependent ?

Fine structure constant α (electric charge)

Ratio electron mass to proton mass

Ratio nucleon mass to Planck mass

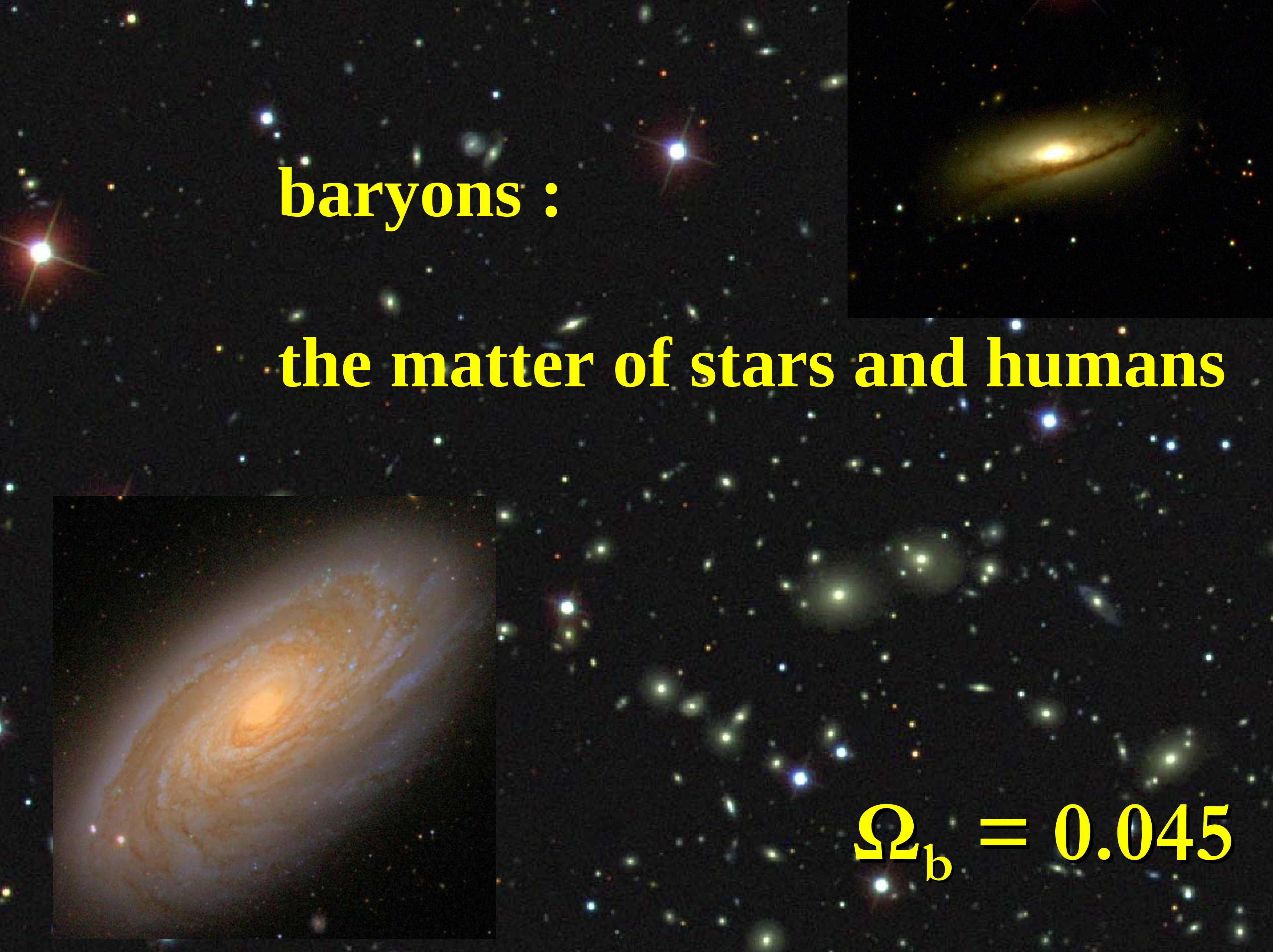
Quintessence and Time dependence of "fundamental constants"

- 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 φ → Time evolution of α

Jordan,…

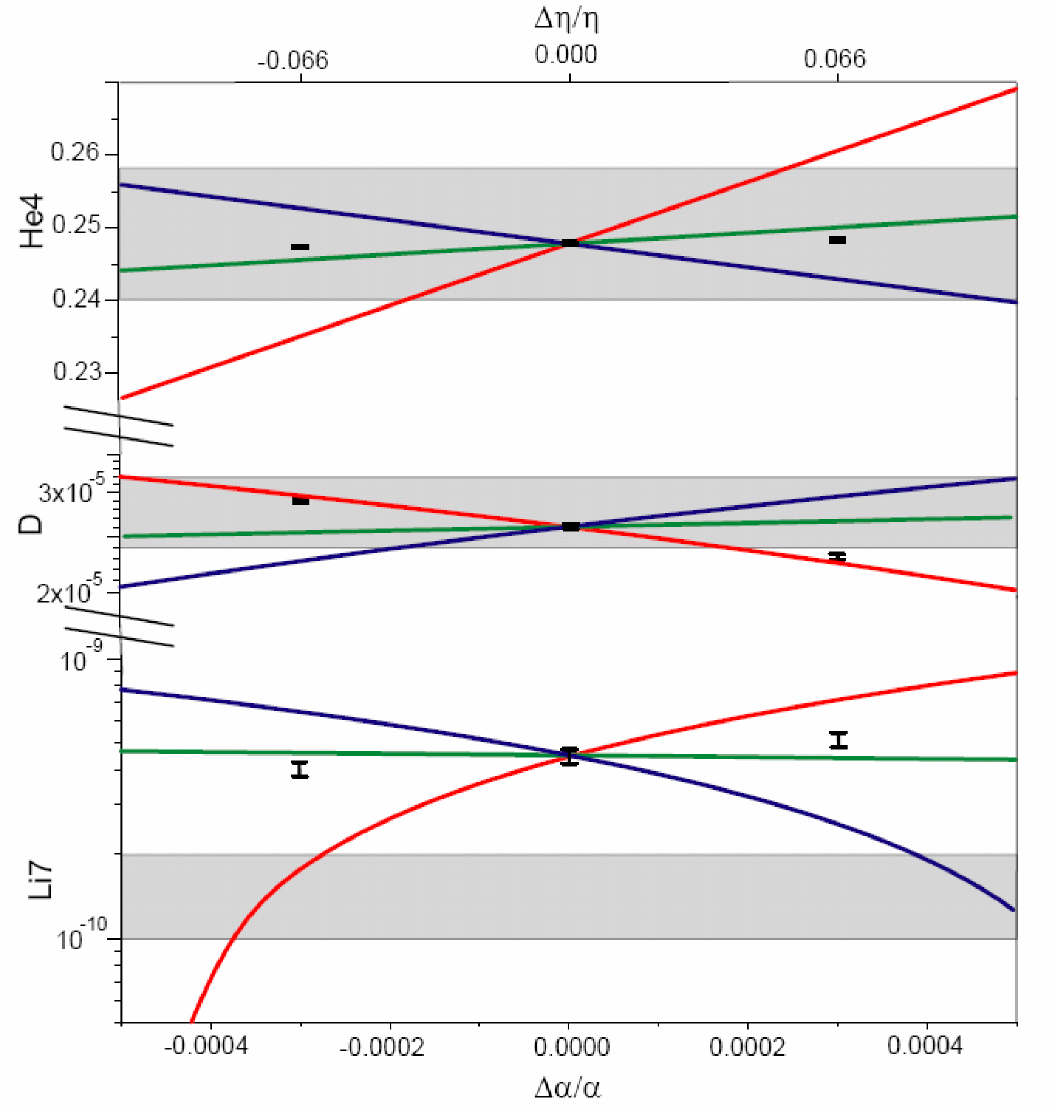

baryons :
the matter of stars and humans
$\Omega_b = 0.045$

primordial abundances for three GUT models

He

D

Li



present observations : 1σ

T.Dent, S.Stern,…

three GUT models

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

$\Delta\alpha/\alpha \approx 4\ 10^{-4}$ 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

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

Time variation of coupling constants must be tiny –

would be of very high significance !

Possible signal for Quintessence

Summary

- $\Omega_h = 0.75$

- Q/Λ : dynamical und static dark energy will be distinguishable

- growing neutrino mass can explain why now problem

- Q : time varying fundamental coupling "constants"
  violation of equivalence principle

????????????????????????

Are dark energy and dark matter related ?

Can Quintessence be explained in a fundamental unified theory ?

Quintessence and solution of cosmological constant problem should be related !

End

A few references

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Transition to cosmon dominated universe

- Large value k >> 1 : universe is dominated by scalar field
- k increases rapidly : evolution of scalar fied essentially stops
- Realistic and natural quintessence:

  k changes from small to large values after structure formation

approximate late solution

variables :

$$s = -\alpha(\varphi - \varphi_t)/M,$$
$$x = \ln a$$

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

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

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

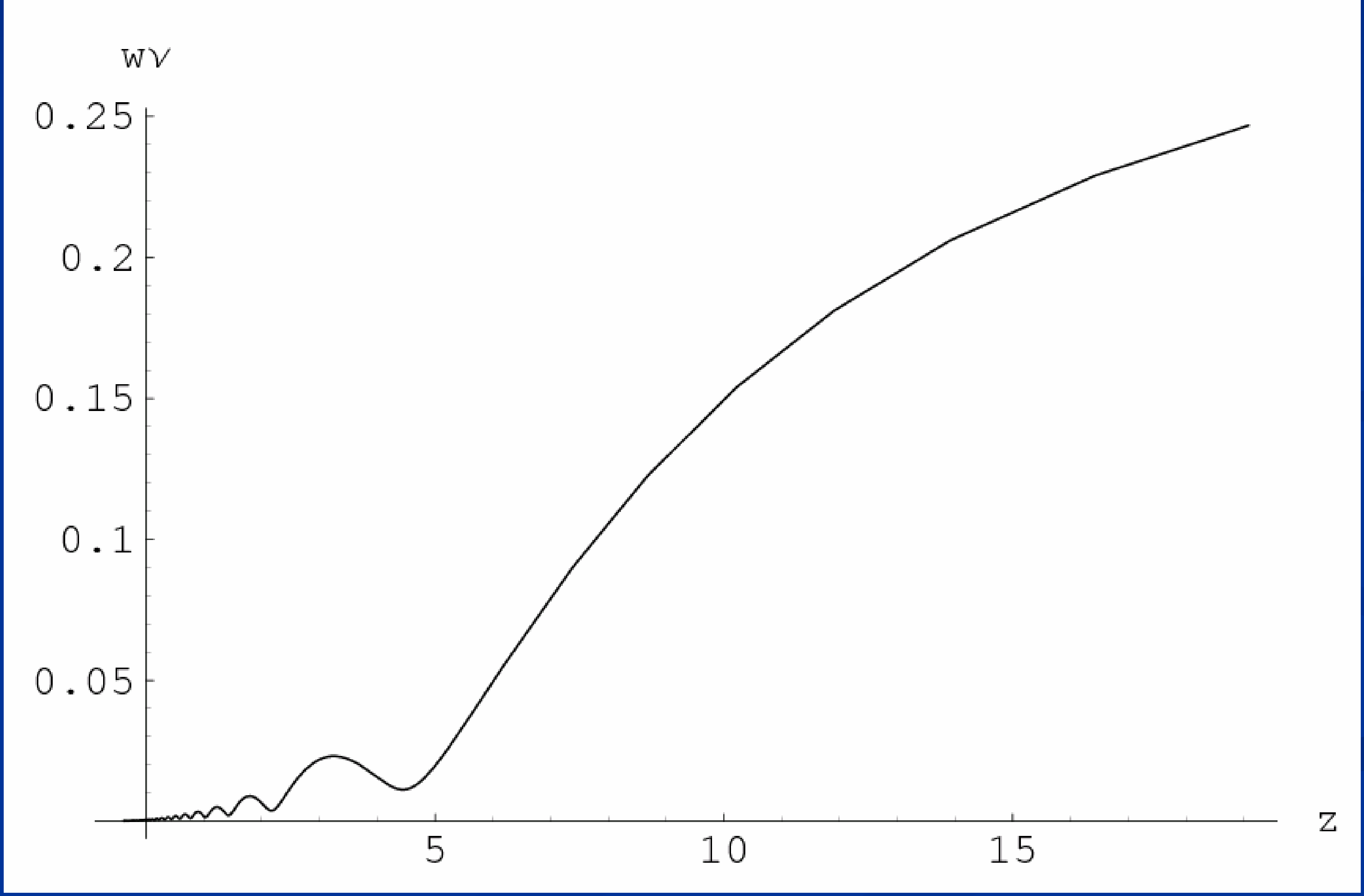
$$\tilde{\Omega}_h(a) = \begin{cases} \frac{\tilde{\Omega}_{h,0}a^3+2\Omega_{\nu,0}(a^{3/2}-a^3)}{1-\tilde{\Omega}_{h,0}(1-a^3)+2\Omega_{\nu,0}(a^{3/2}-a^3)} & \text{for } a > a_c \\ \frac{3}{\alpha^2} & \text{for } a < a_c \end{cases}$$

neutrino fluctuations

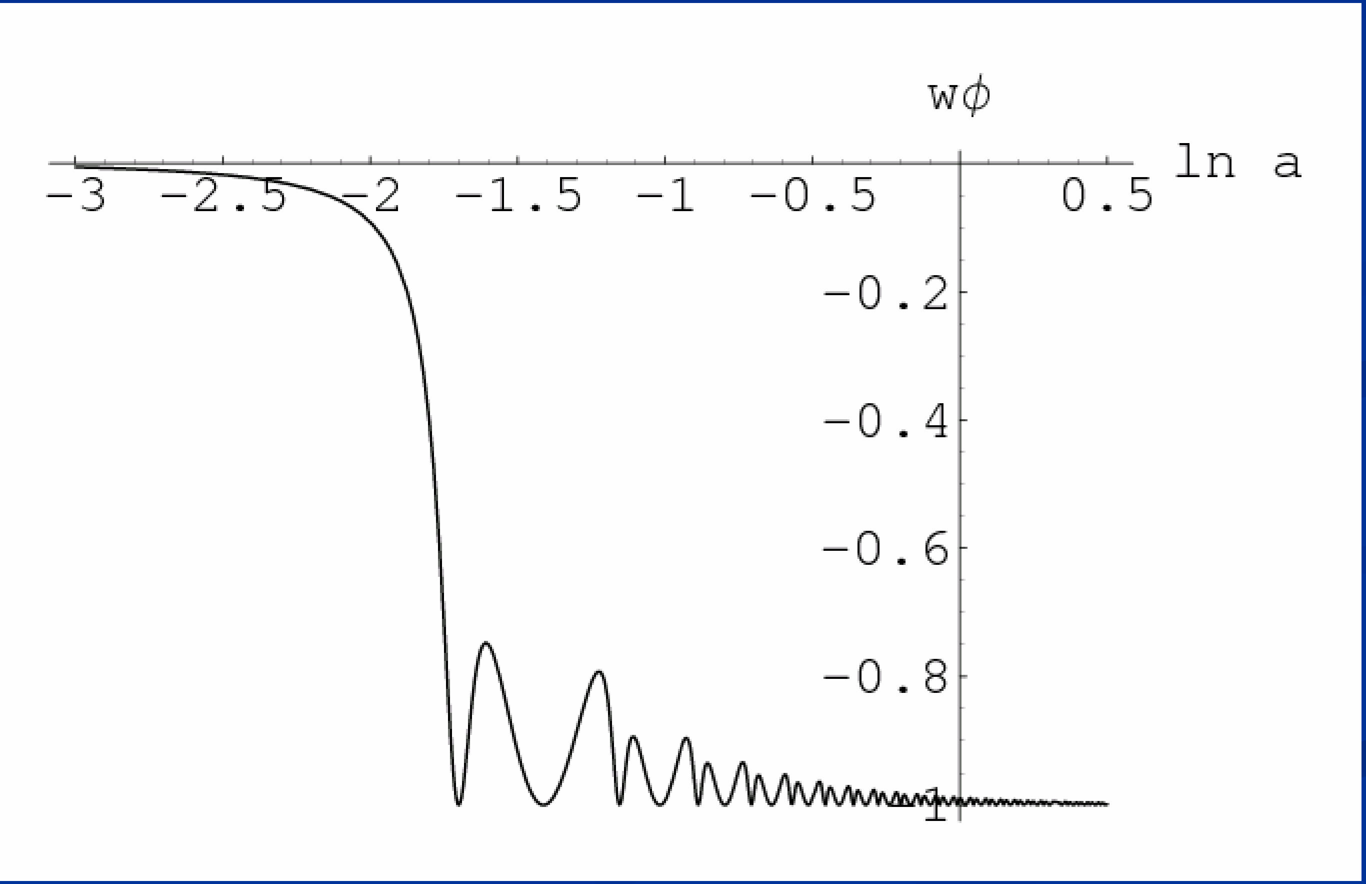
- time when neutrinos become non – relativistic
- sets free streaming scale

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

neutrino equation of state



cosmon equation of state



fixed point behaviour : apparent tuning

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

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