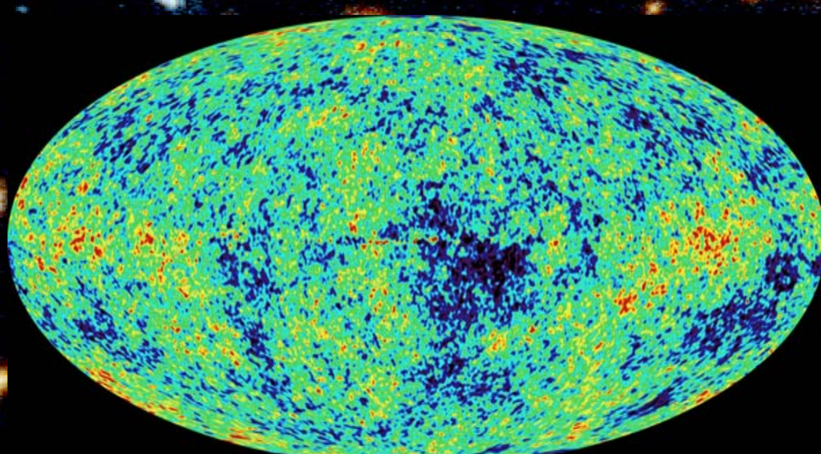
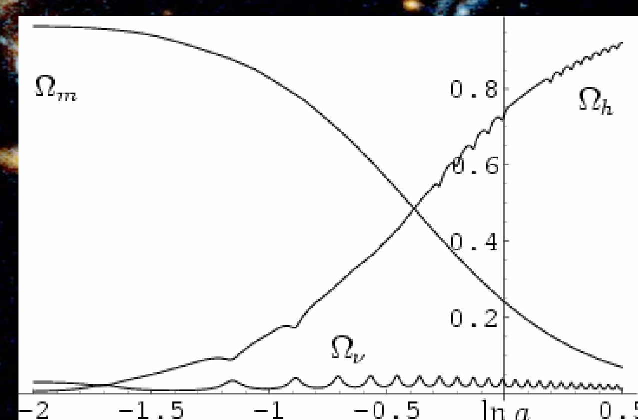
Growing Neutrinos as a solution of the why now problem of Dark Energy





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 given by neutrino mass

present equation of state given by neutrino mass !

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

Dark Energy
and the
Why now problem

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

What is Dark Energy ?

Cosmological Constant

or

Quintessence ?

Cosmological Constant
- Einstein -

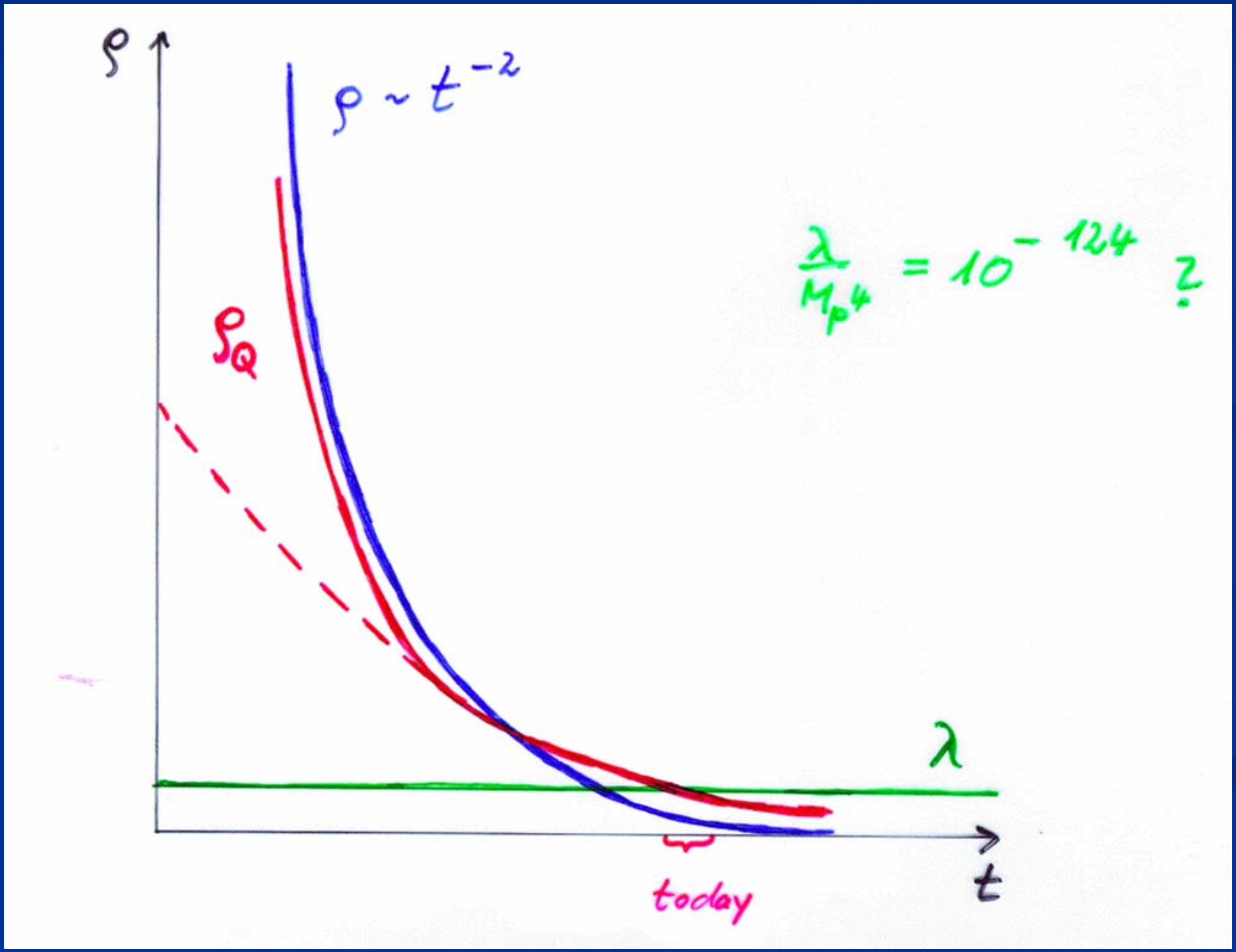
- Constant λ compatible with all symmetries
- No time variation in contribution to energy density

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

- Why important just today ?

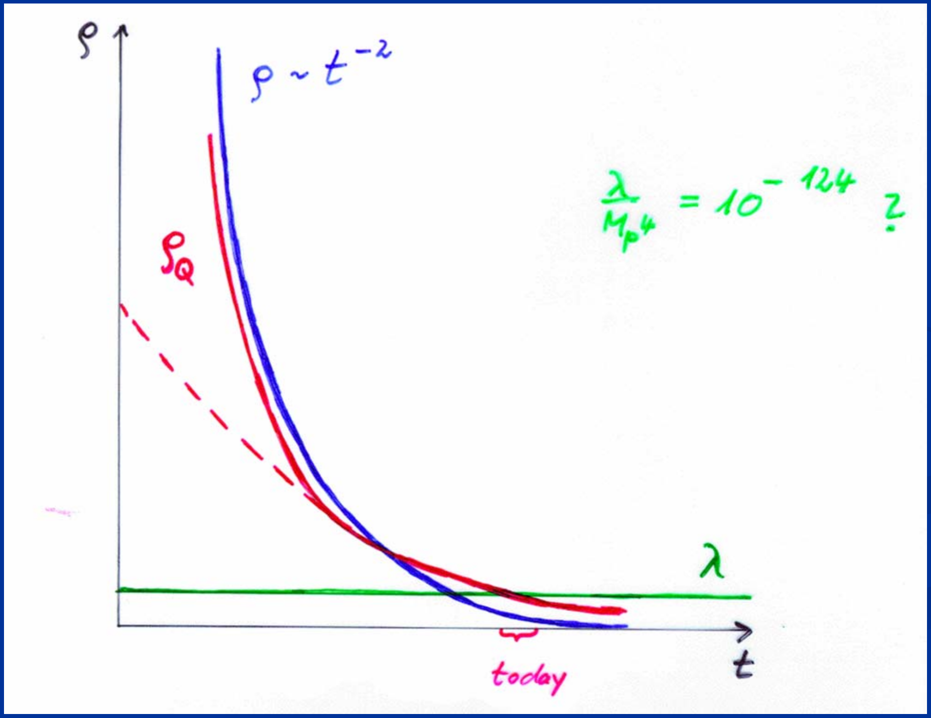
Cosm. Const | Quintessence

static | dynamical



Why now problem

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



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

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 given by neutrino mass

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

neutrino masses and dark energy density depend on time !

Time evolution

- $\rho_m/M^4 \sim a^{-3} \sim$
  - t^{-2} matter dominated universe
  - $t^{-3/2}$ radiation dominated universe

- $\rho_r/M^4 \sim a^{-4} \sim t^{-2}$ radiation dominated universe

Huge age ⇨ small ratio

Same explanation for small dark energy?

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

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*

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

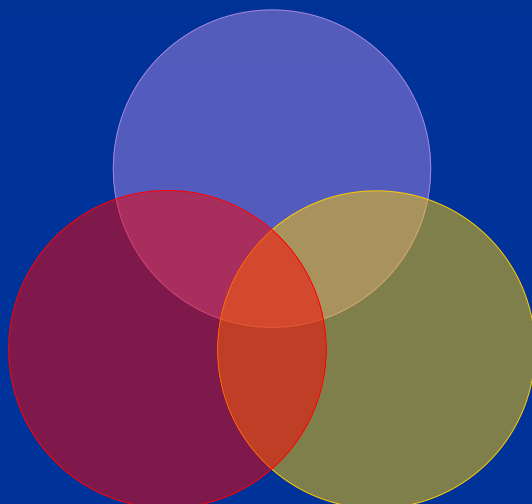
- *Time - variable dark energy :*

  $\rho_h(t)$ decreases with time !

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

"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

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

for increasing φ the potential decreases
towards zero !

Cosmic Attractors

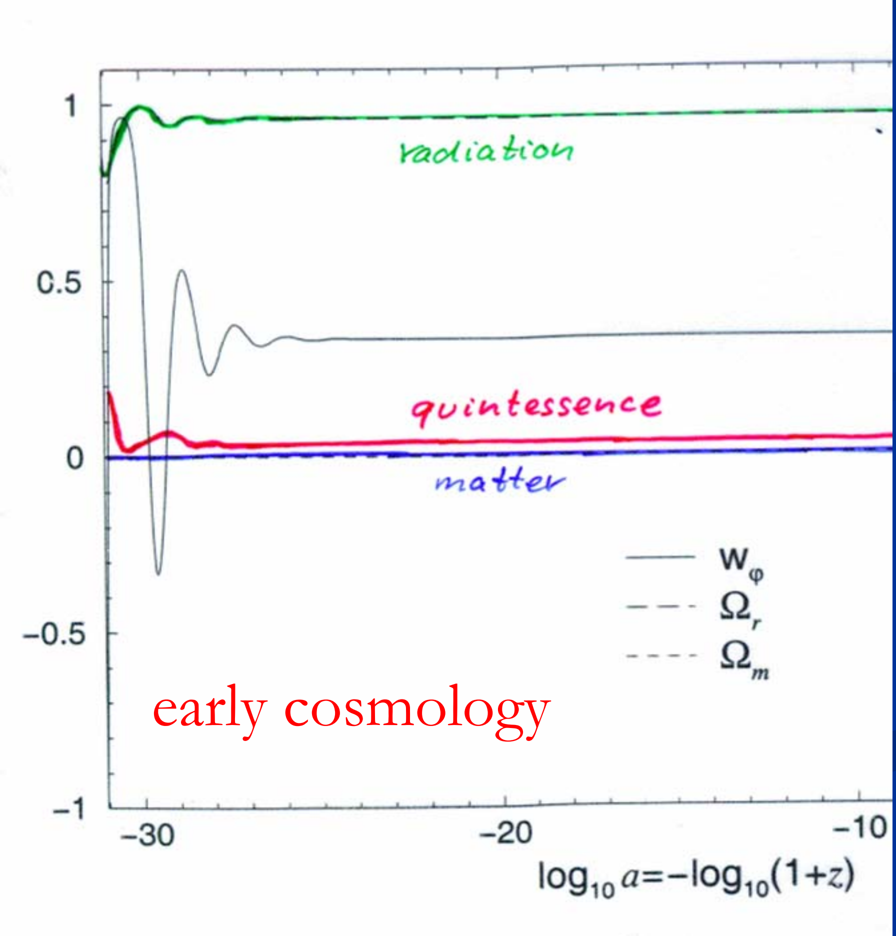
Solutions independent of initial conditions

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

$\varphi \sim \ln(t)$

$\Omega_h \sim$ const.

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



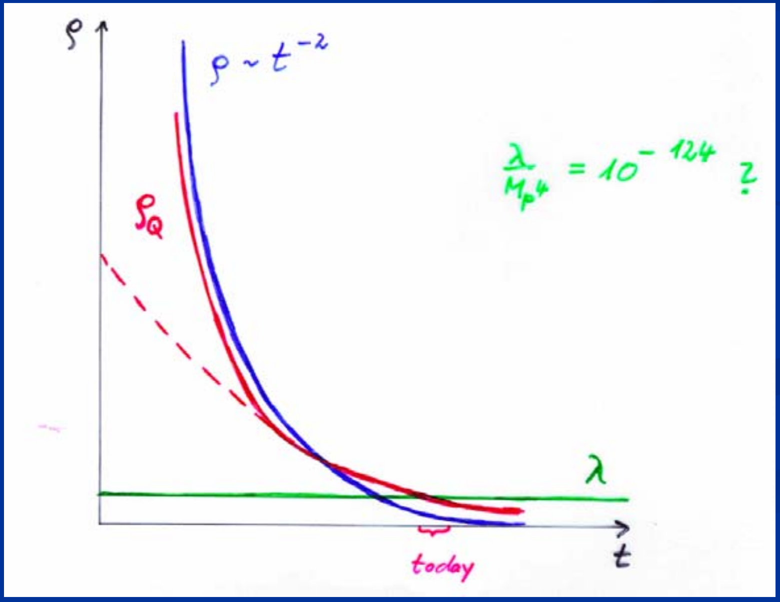
exponential potential ⟹ constant fraction in dark energy

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

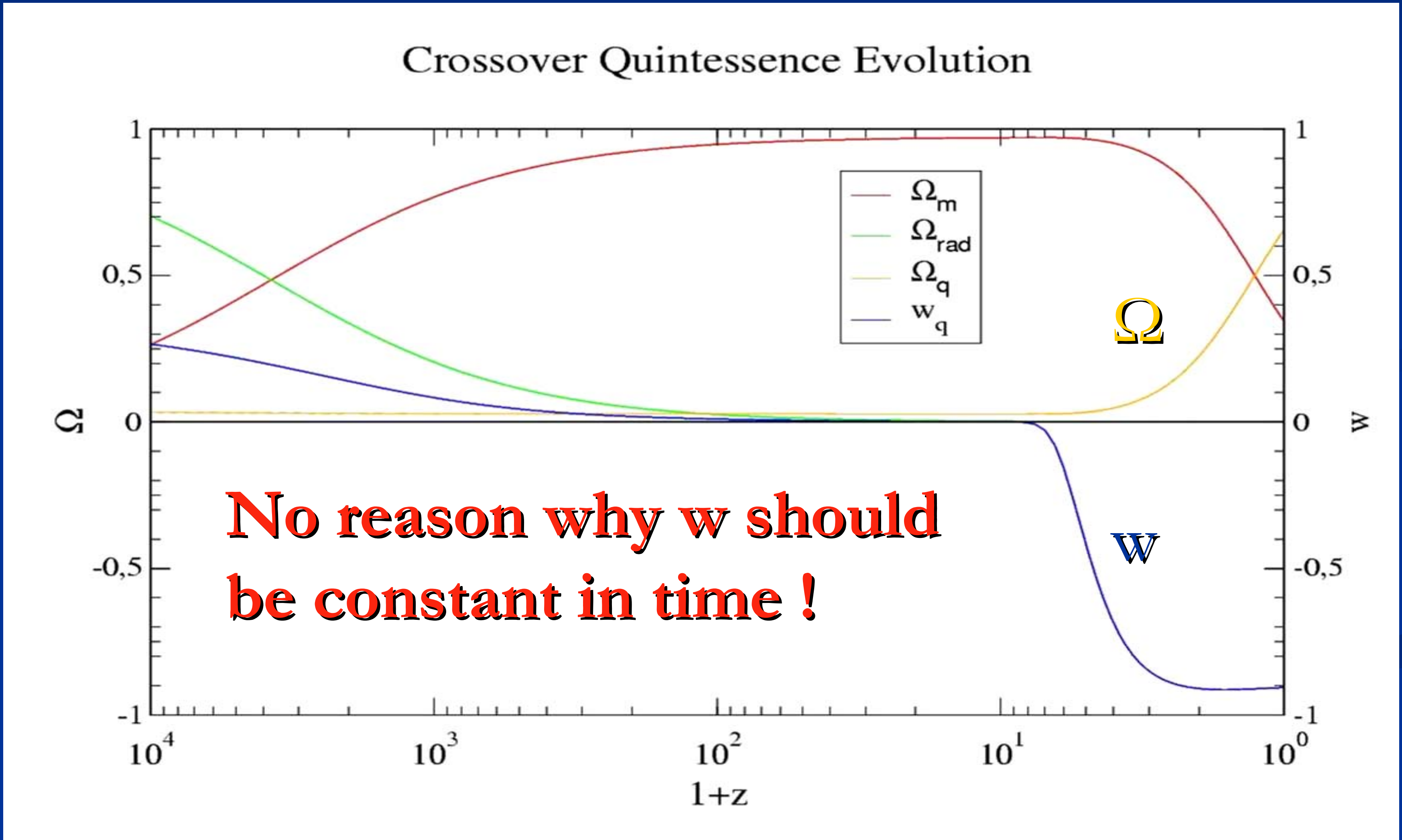
can explain order of magnitude of dark energy !

realistic quintessence

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



Quintessence becomes important “today”

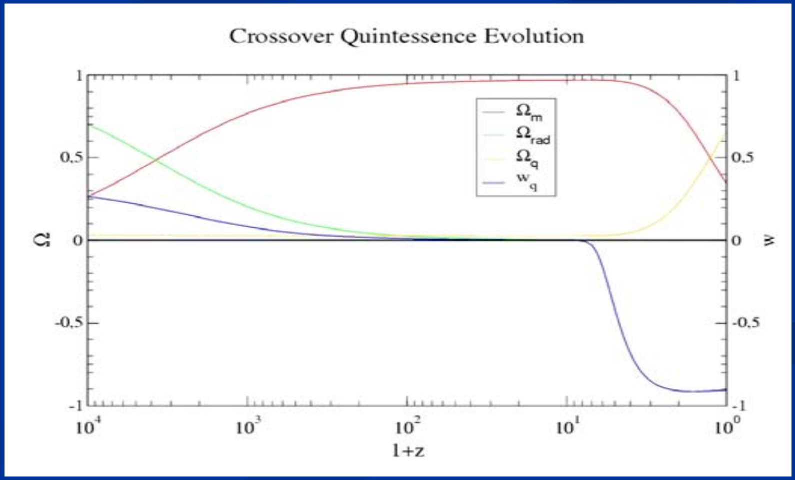


cosmic coincidence

coincidence problem

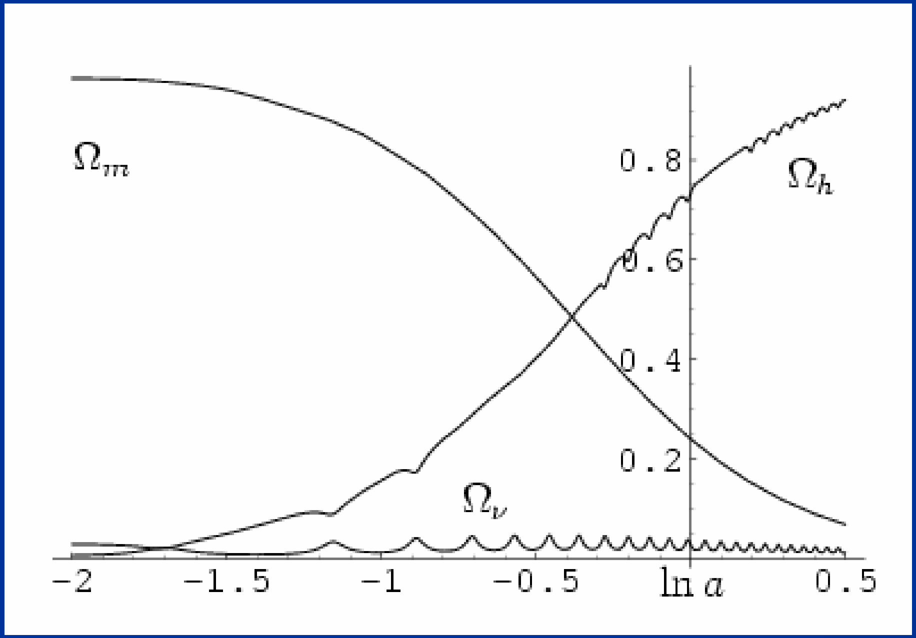
What is responsible for increase of Ω_h for $z < 6$?

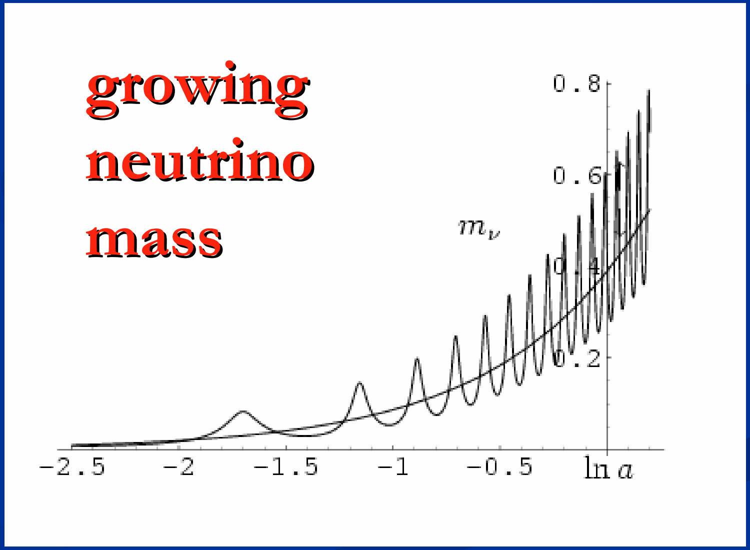
Why now ?



A new role for neutrinos in cosmology ?

growing neutrino mass triggers transition to almost static dark energy

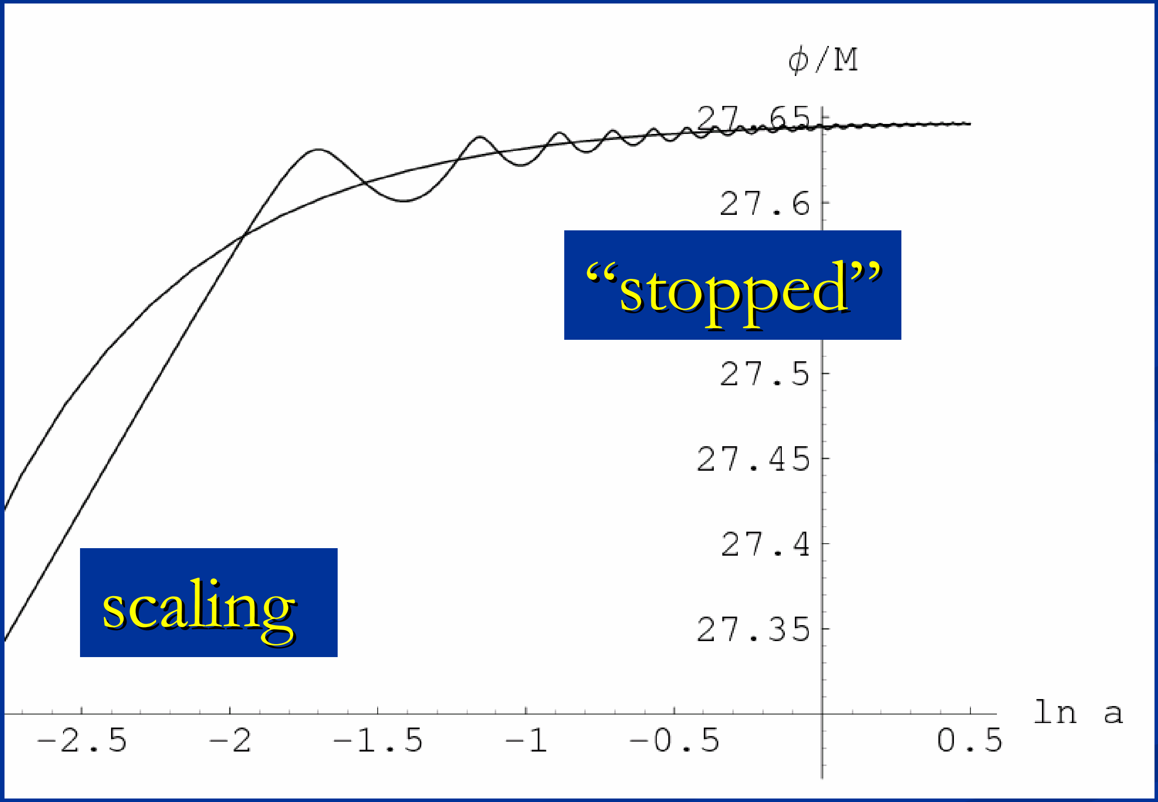




effective cosmological trigger for stop of cosmon evolution : neutrinos get non-relativistic

- 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

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
- cosmon 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 !

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 given by neutrino mass

present equation of state given by neutrino mass !

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

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

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

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

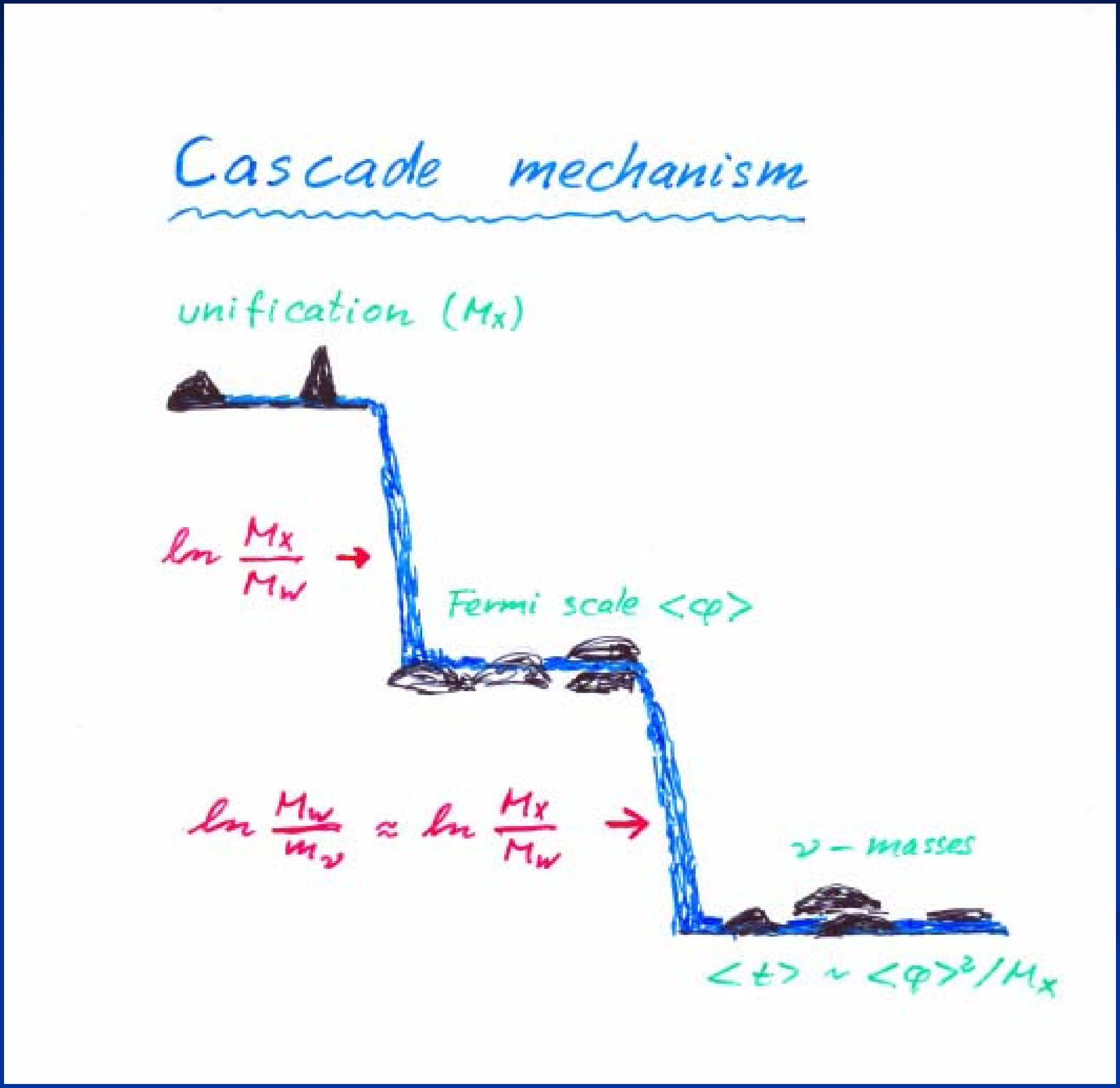
$$U = U_0(\varphi) + \frac{\lambda}{2}(d^2 - d_0^2)^2 + \frac{1}{2}M_t^2(\varphi)t^2 - \gamma d^2 t$$

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

M.Magg , …

G.Lazarides , Q.Shafi , …

cascade



Cascade mechanism
unification (M_X)
$\ln \frac{M_X}{M_W}$
Fermi scale $\langle \varphi \rangle$
$\ln \frac{M_W}{m_\nu} \approx \ln \frac{M_X}{M_W}$
ν – masses
$\langle t \rangle \sim \langle \varphi \rangle^2 / M_X$

varying neutrino mass

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

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

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

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

“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 $\varphi \longrightarrow \varphi_t$

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

typical present value : $\beta \approx 50$ ⇒
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 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 !

dark energy fraction determined by neutrino mass

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

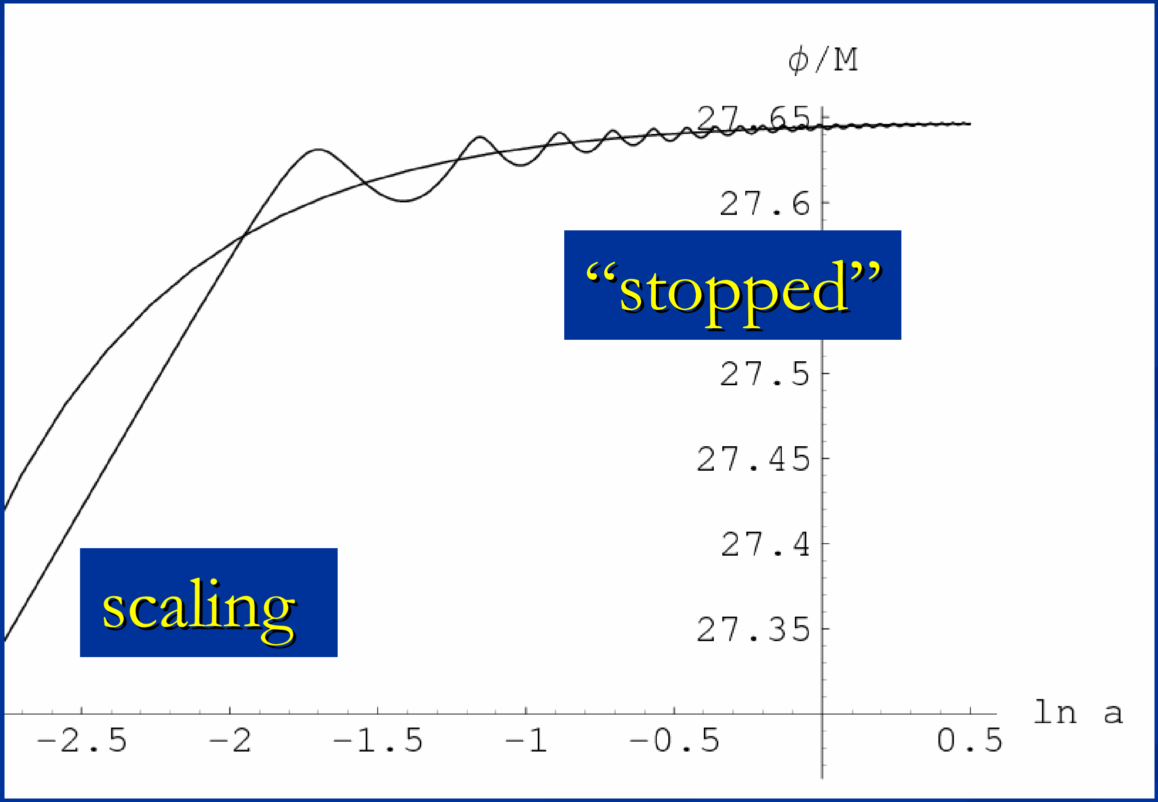
$$\gamma = -\frac{\beta}{\alpha}$$

constant neutrino - cosmon coupling β

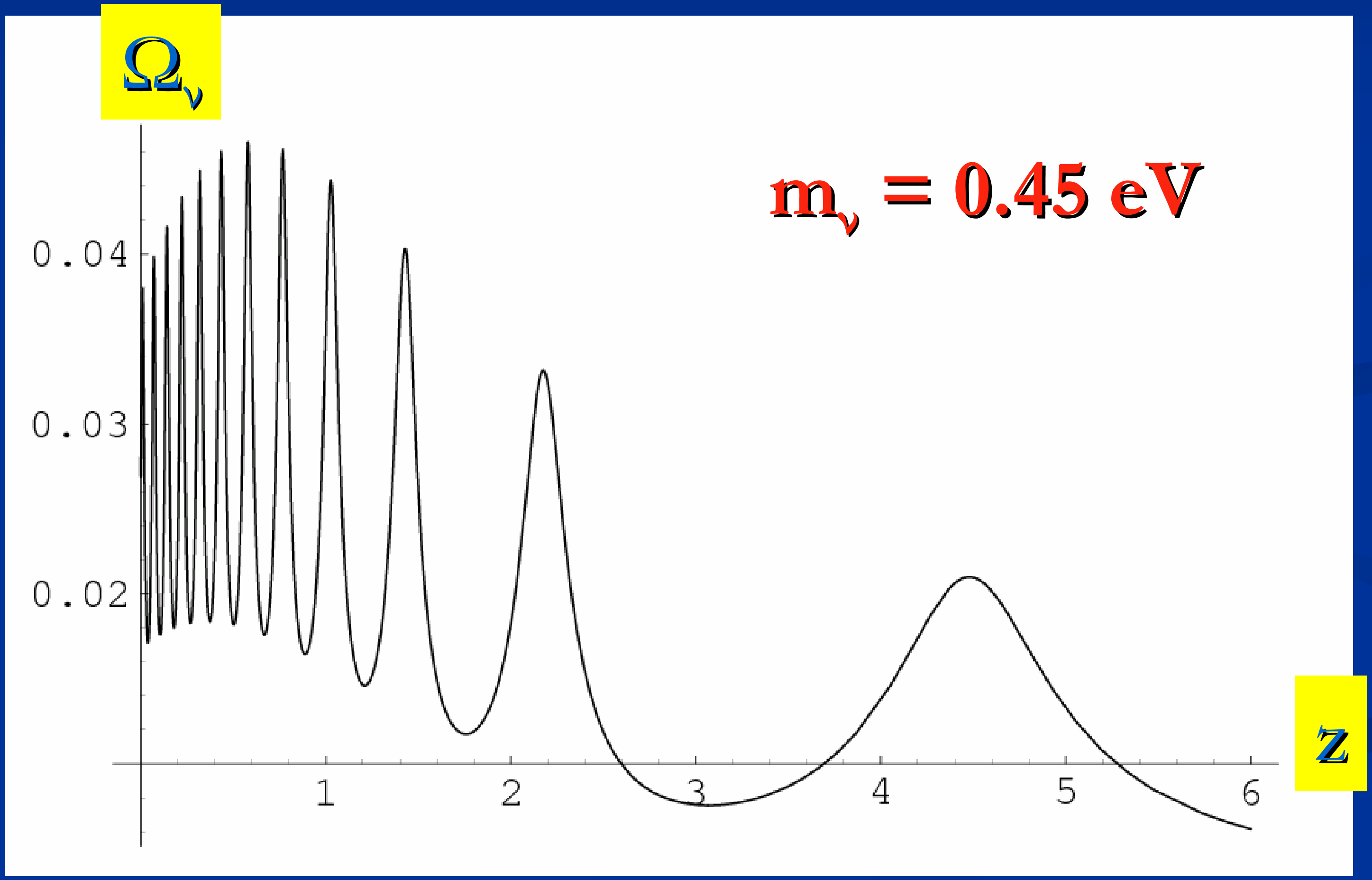
$$\Omega_h(t_0) \approx -\frac{\epsilon}{\alpha} \frac{m_\nu(t_0)}{\bar{m}_\nu} \frac{m_\nu(t_0)}{16eV}$$

variable neutrino - cosmon coupling

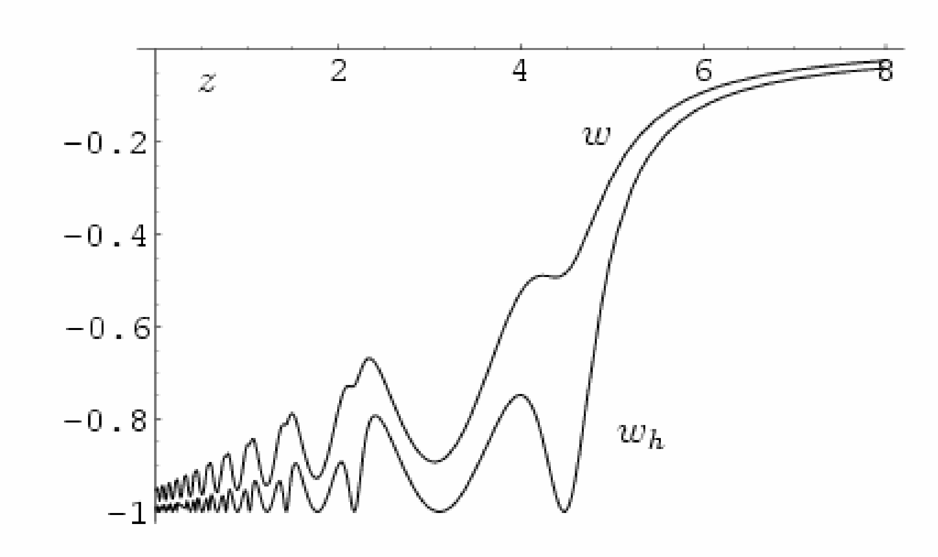
cosmon evolution



neutrino fraction remains small



equation of state

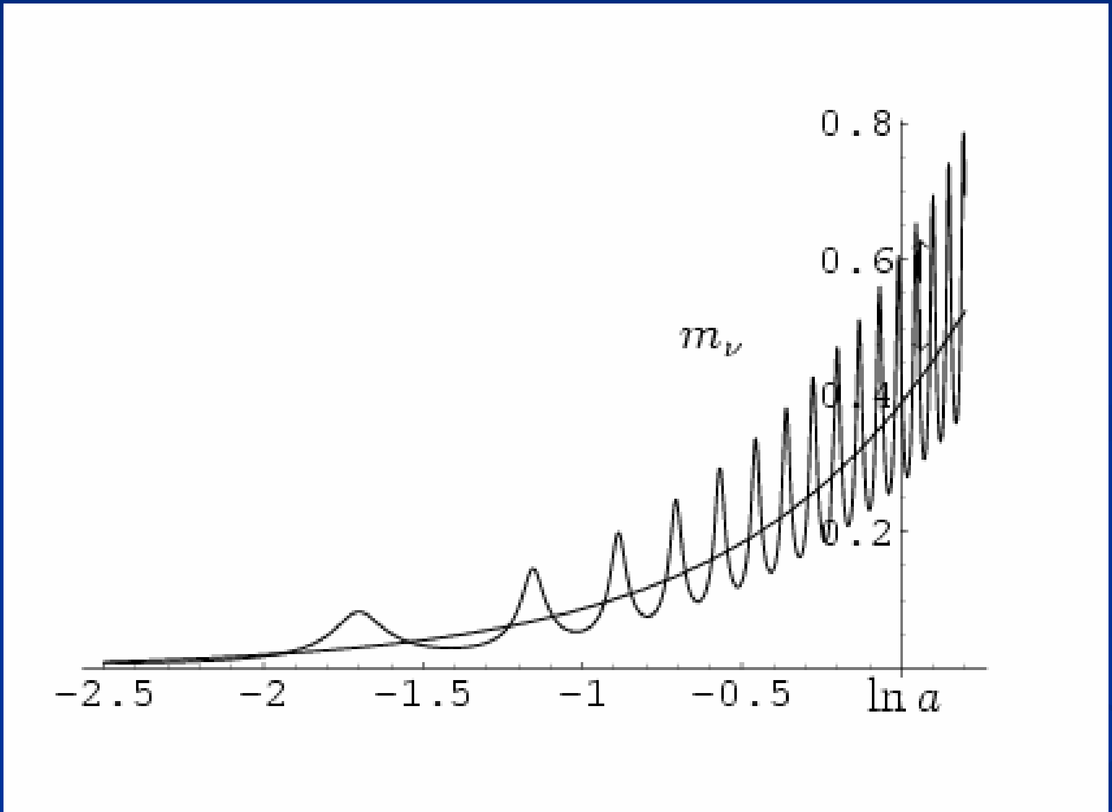


$$w = \frac{T - V + w_\nu \rho_\nu}{T + V + \rho_\nu} \approx -1 + \frac{\rho_\nu}{V} \approx -1 + \frac{\Omega_\nu}{\Omega_h},$$

present equation of state given by neutrino mass !

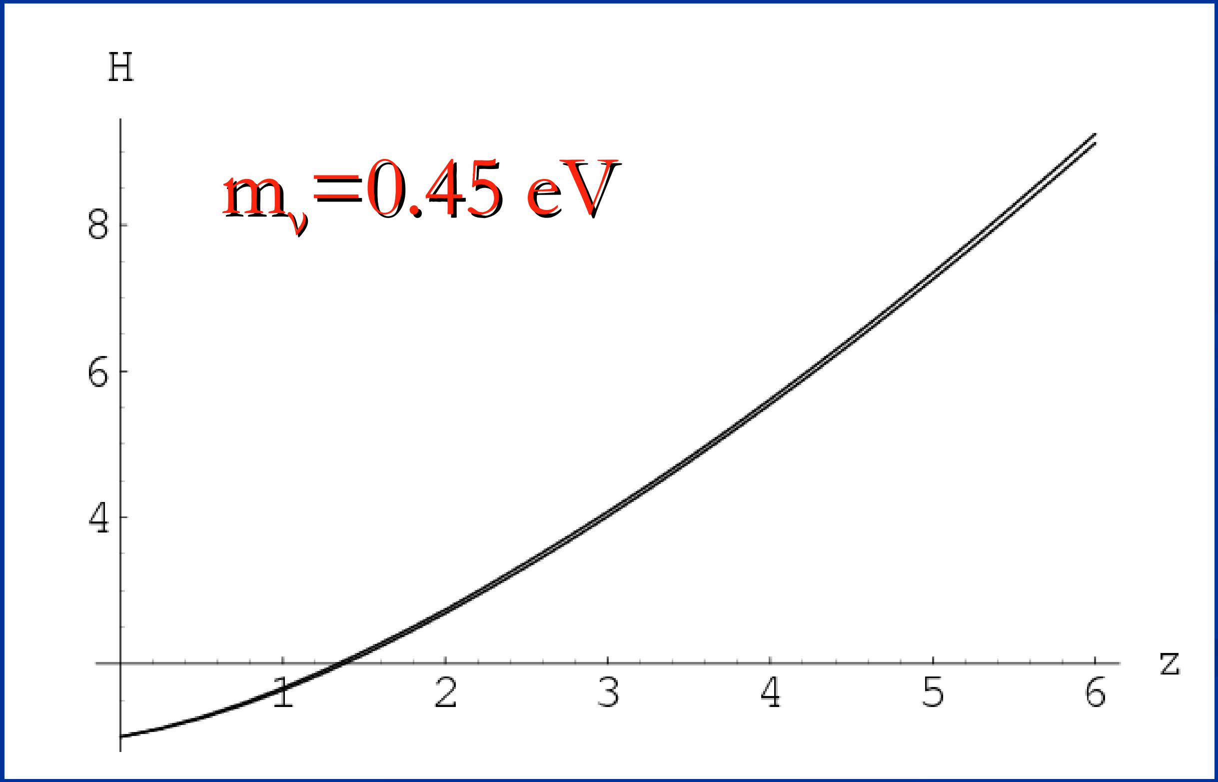
$$w_0 \approx -1 + \frac{m_\nu(t_0)}{12\mathrm{eV}}$$

oscillating neutrino mass



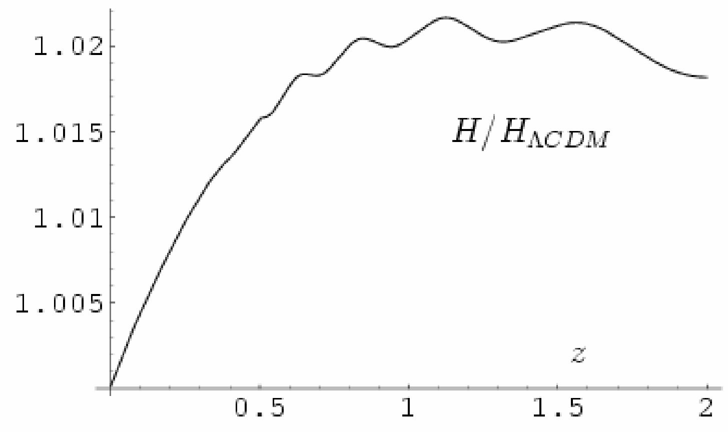
Hubble parameter

as compared to ΛCDM



Hubble parameter ($z < z_c$)

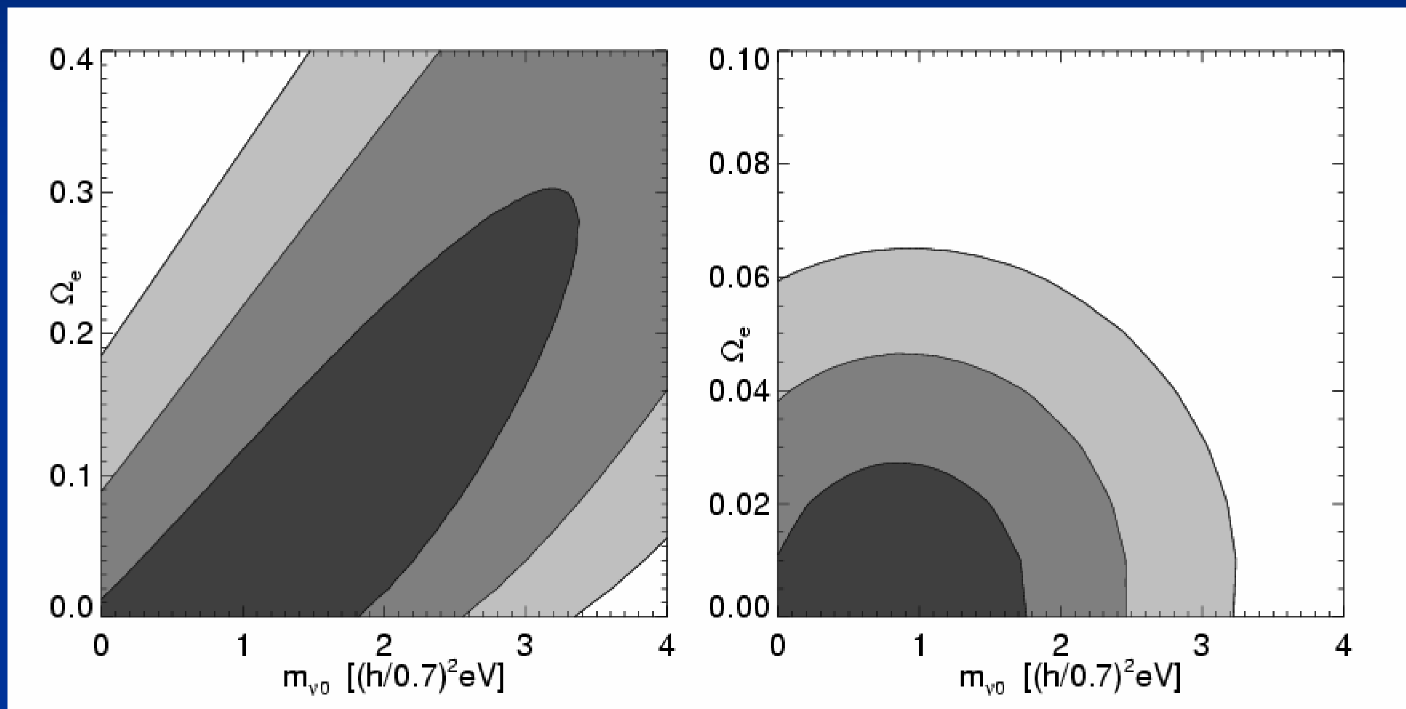
$$H^2 = \frac{1}{3M^2}\left\{V_t + \rho_{m,0}a^{-3} + 2\tilde{\rho}_{\nu,0}a^{-\frac{3}{2}}\right\}$$



m_ν=0.45 eV

only small difference from ΛCDM !

bounds on average neutrino mass



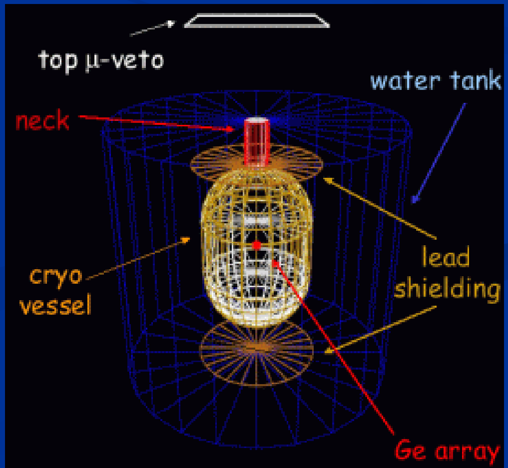
Looking Beyond Lambda with the Union Supernova Compilation

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

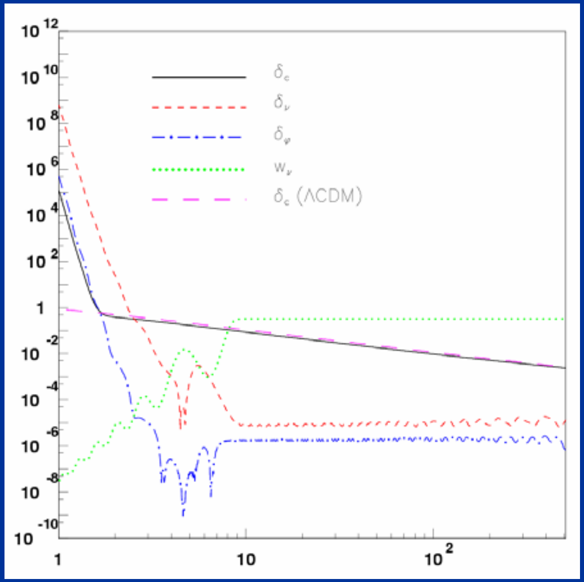


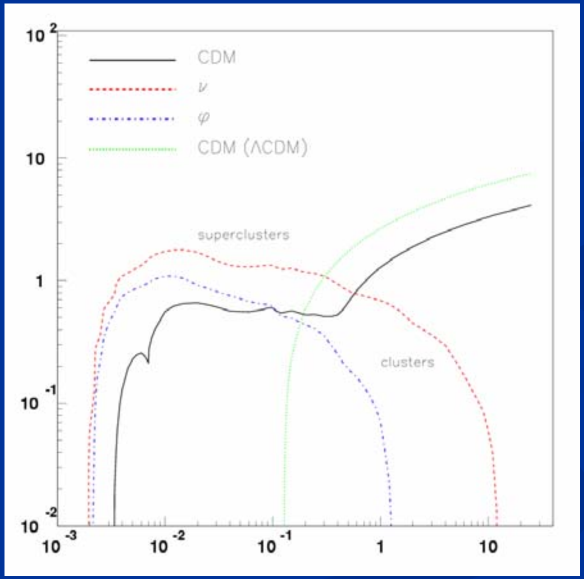
GERDA

neutrino fluctuations

neutrino structures become nonlinear at z~1 for supercluster scales

D.Mota , G.Robbers , V.Pettorino , …





stable neutrino-cosmon lumps exist

N.Brouzakis , N.Tetradis ,…

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

two key features

1) Exponential cosmon potential and scaling solution

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

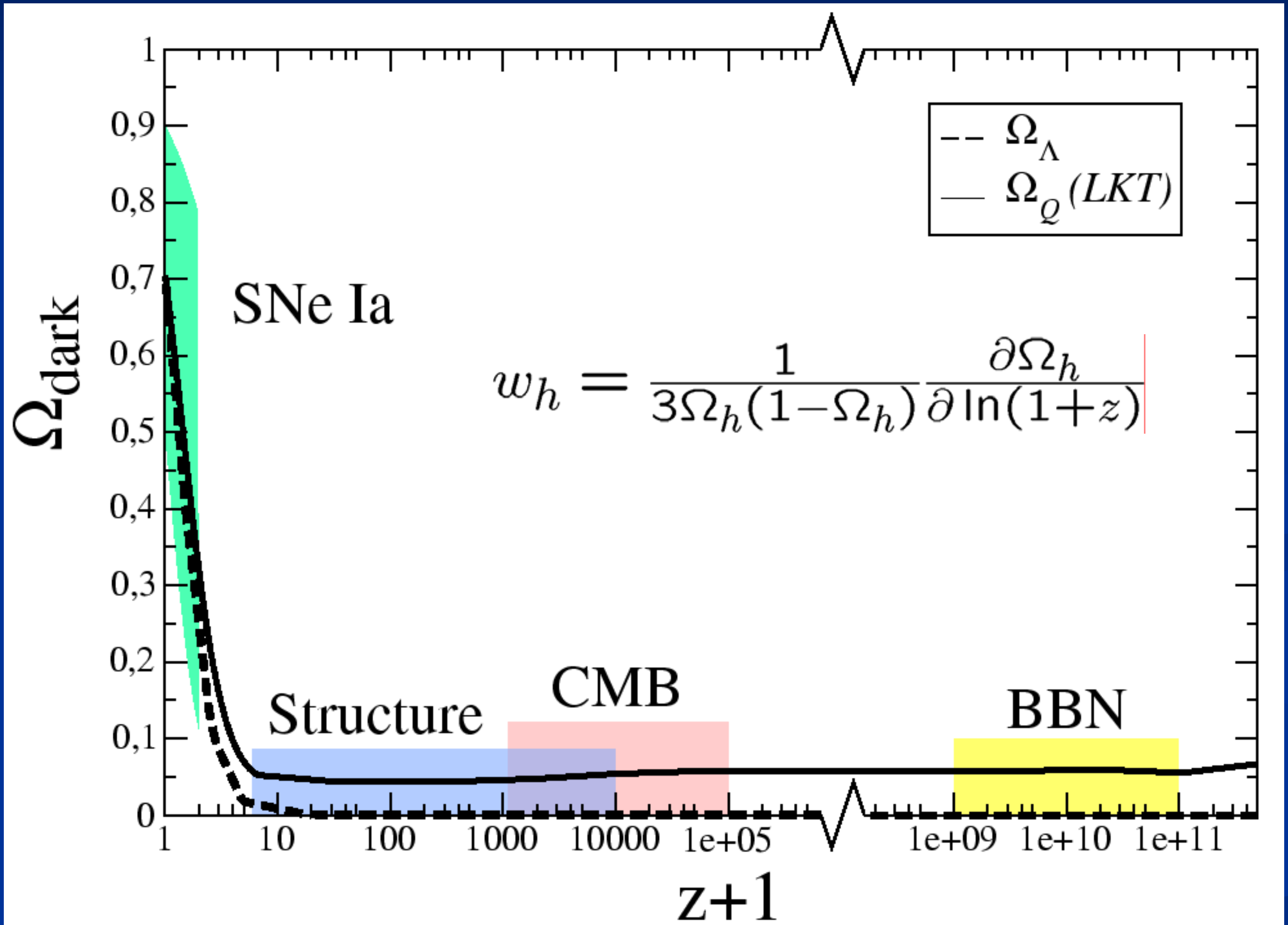
$$V(\varphi \to \infty) \to 0 \ \ !$$

2) Stop of cosmon evolution by cosmological trigger

End

How can quintessence be distinguished from a cosmological constant ?

Time dependence of dark energy



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

M.Doran,…

small early and large present dark energy

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

→

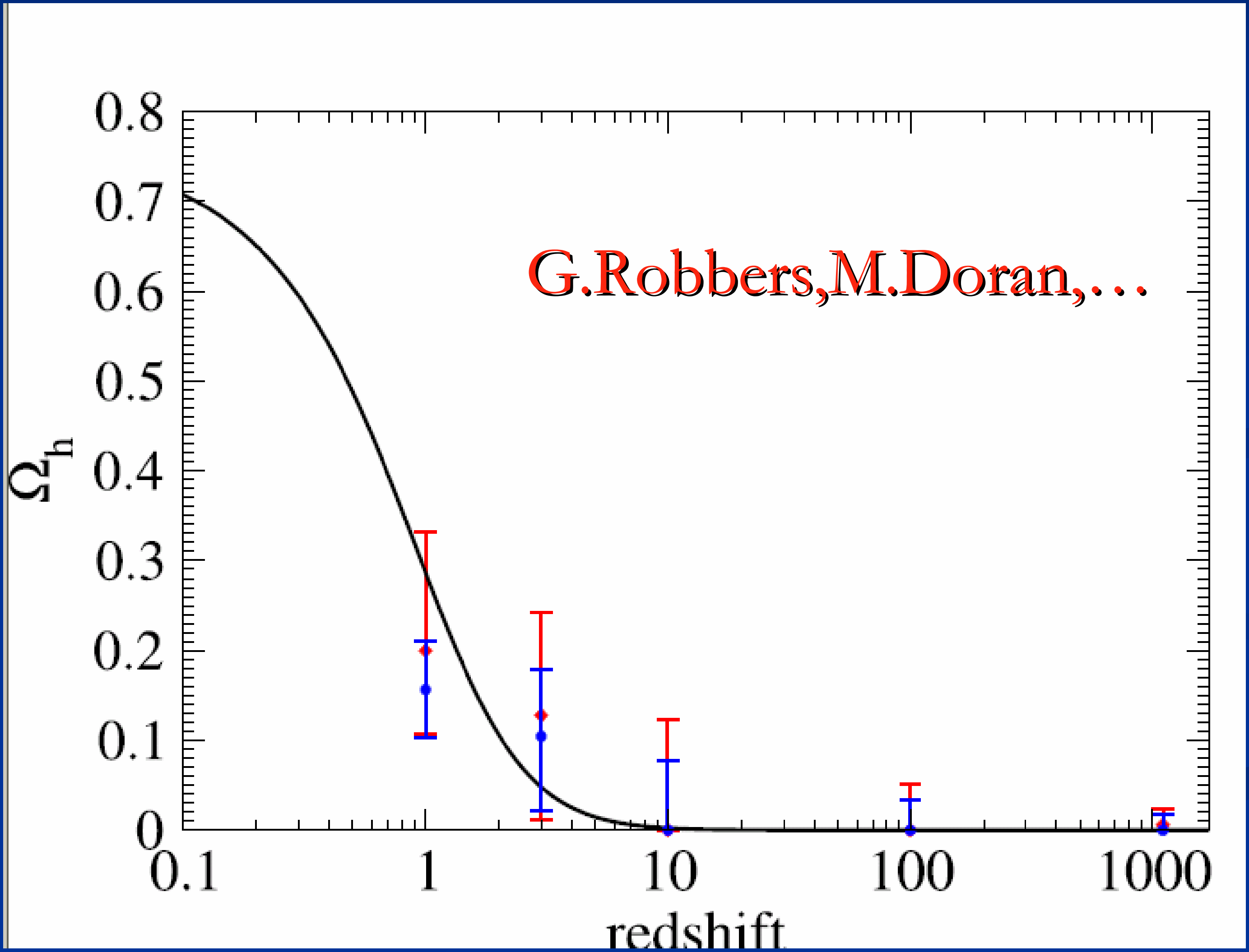
expansion of universe accelerates in present epoch

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

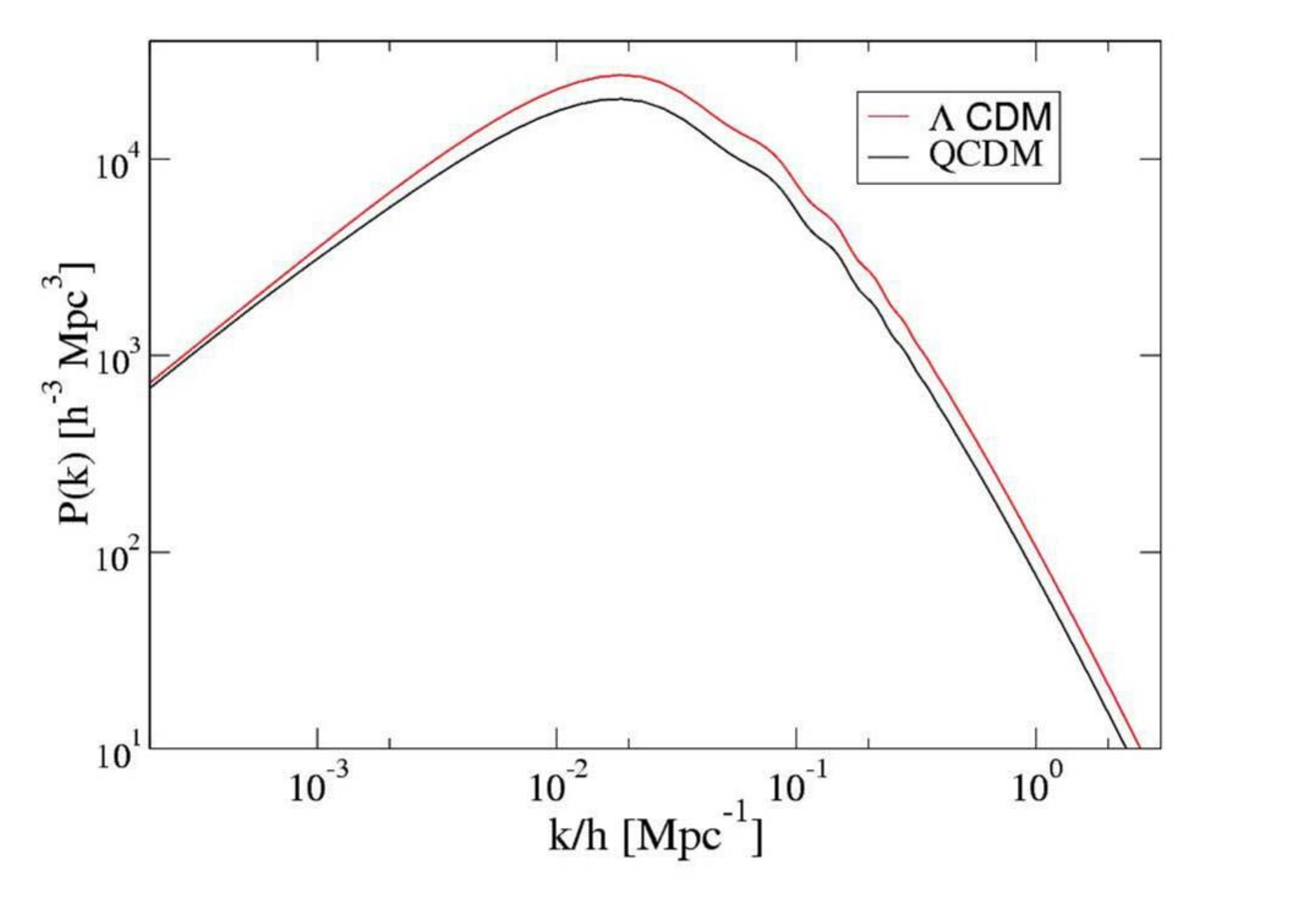
effects of early dark energy

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

interpolation of Ω_h



Early quintessence slows down the growth of structure



time variation of “fundamental constants”

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

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(today) > -1

B) Time variation of fundamental "constants"

C) Apparent violation of equivalence principle

D) Possible coupling between Dark Energy and Dark Mater

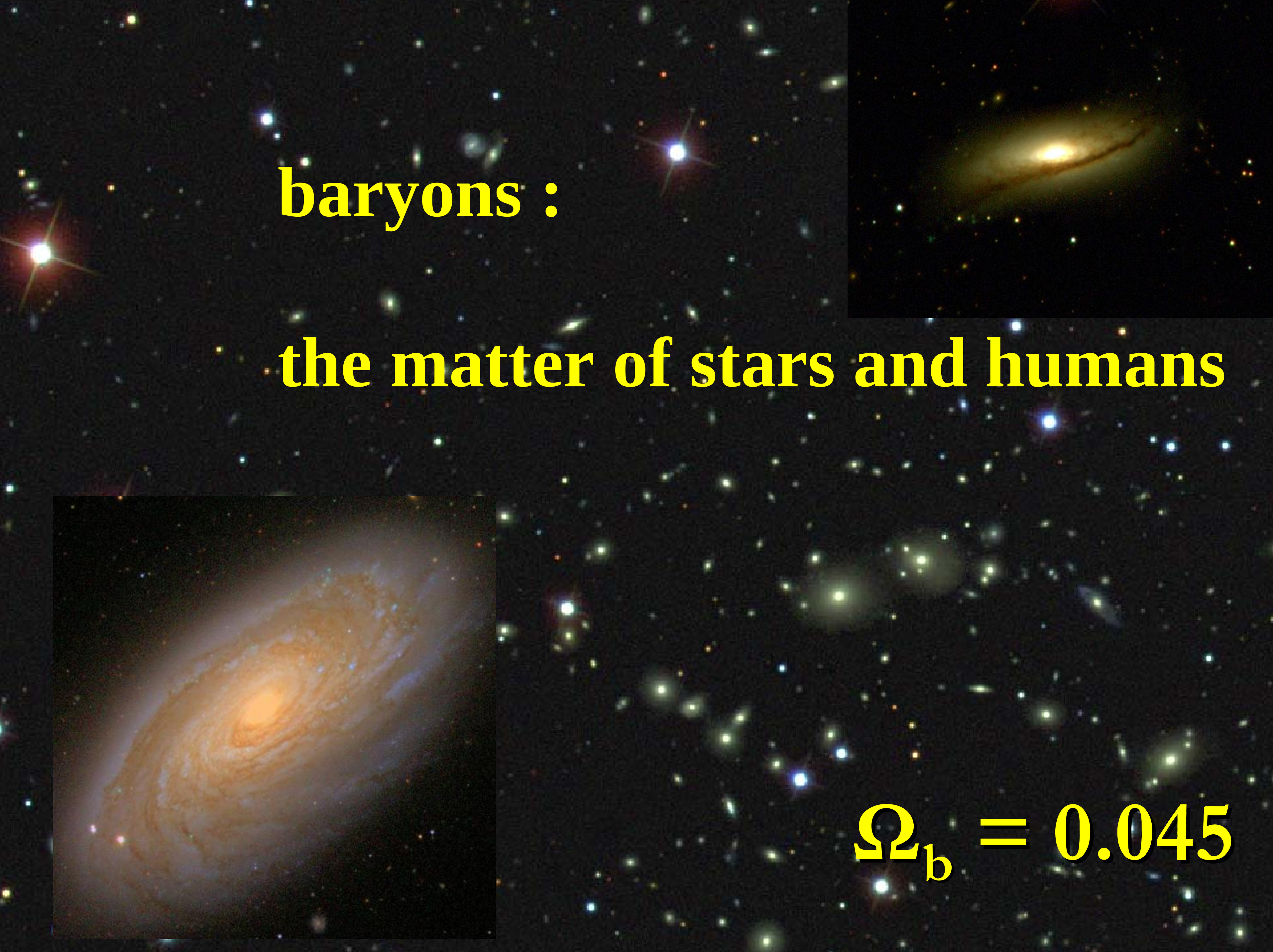
Quintessence and Time dependence of "fundamental constants"

- 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 φ ⟹ Time evolution of α

Jordan,…

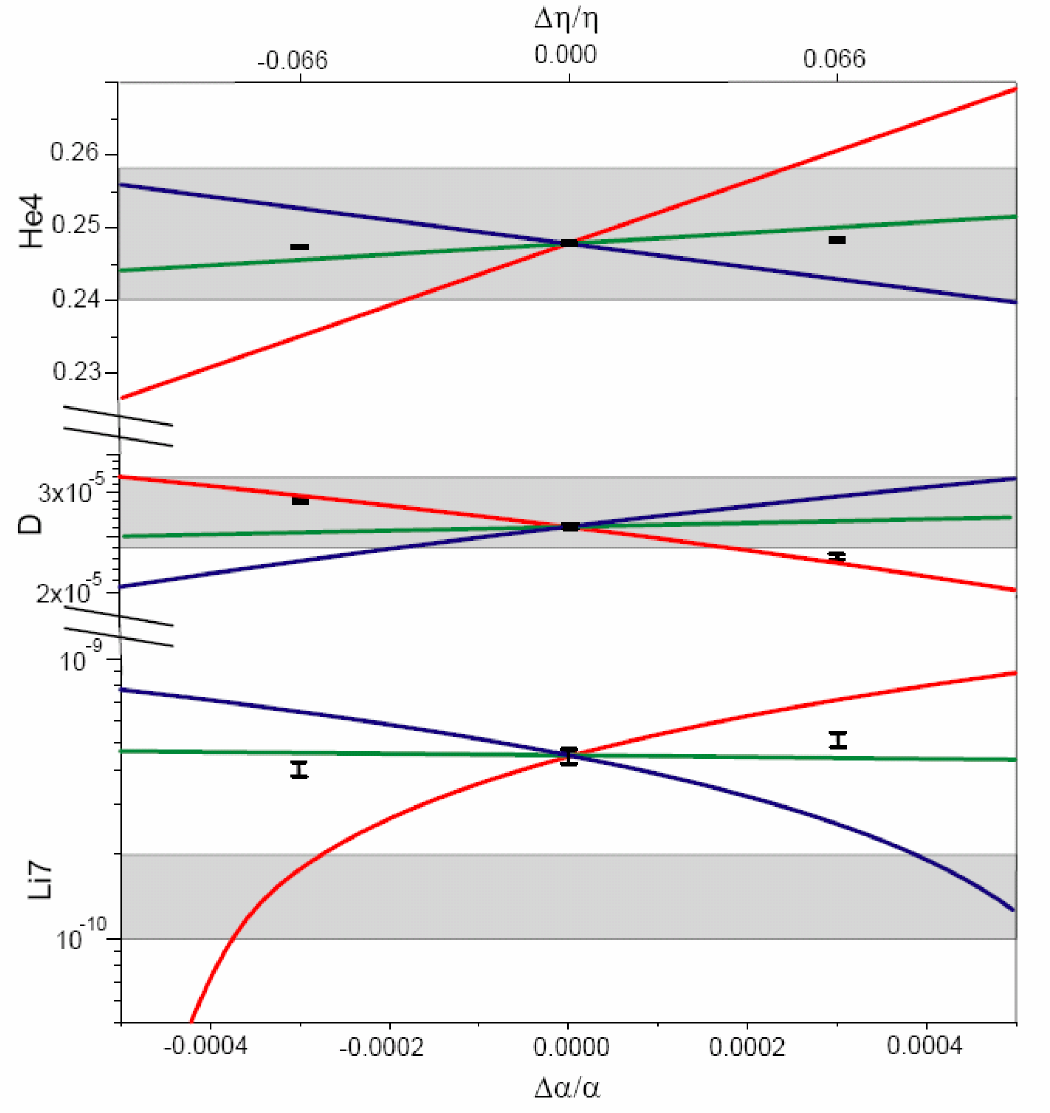

baryons :
the matter of stars and humans
$\Omega_b = 0.045$

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

Quintessence and solution of cosmological constant problem should be related !

End

A few references

C.Wetterich , Nucl.Phys.B302,668(1988) , received 24.9.1987

P.J.E.Peebles,B.Ratra , Astrophys.J.Lett.325,L17(1988) , received 20.10.1987

B.Ratra,P.J.E.Peebles , Phys.Rev.D37,3406(1988) , received 16.2.1988

J.Frieman,C.T.Hill,A.Stebbins,I.Waga , Phys.Rev.Lett.75,2077(1995)

P.Ferreira, M.Joyce , Phys.Rev.Lett.79,4740(1997)

C.Wetterich , Astron.Astrophys.301,321(1995)

P.Viana, A.Liddle , Phys.Rev.D57,674(1998)

E.Copeland,A.Liddle,D.Wands , Phys.Rev.D57,4686(1998)

R.Caldwell,R.Dave,P.Steinhardt , Phys.Rev.Lett.80,1582(1998)

P.Steinhardt,L.Wang,I.Zlatev , Phys.Rev.Lett.82,896(1999)

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 ,N.Brouzakis ,N.Tetradis,
V.Pettorino, D.Mota, M.Neubert, T.Krueger

fixed point behavior : apparent tuning

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

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

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

effective cosmological constant

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

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

⟺

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

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

φ_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 !

crossing time

from matching between

early solution and late solution

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

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

neutrino fluctuations

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

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

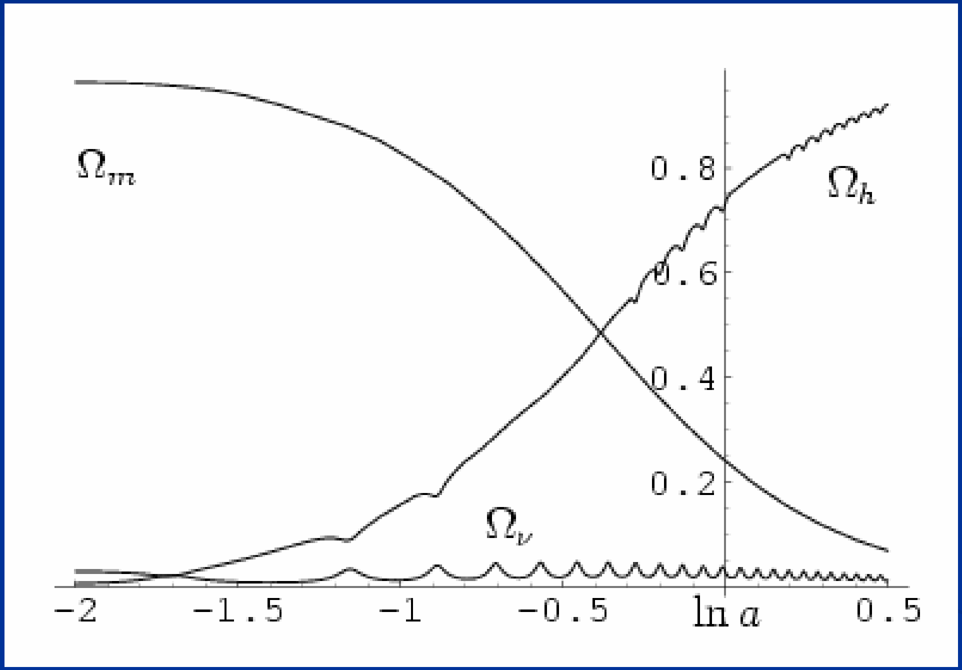
- neutrino structures become nonlinear at z~1 for supercluster scales

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

- stable neutrino-cosmon lumps exist

  N.Brouzakis , N.Tetradis ,…

crossover to dark energy dominated universe



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

cosmological selection !