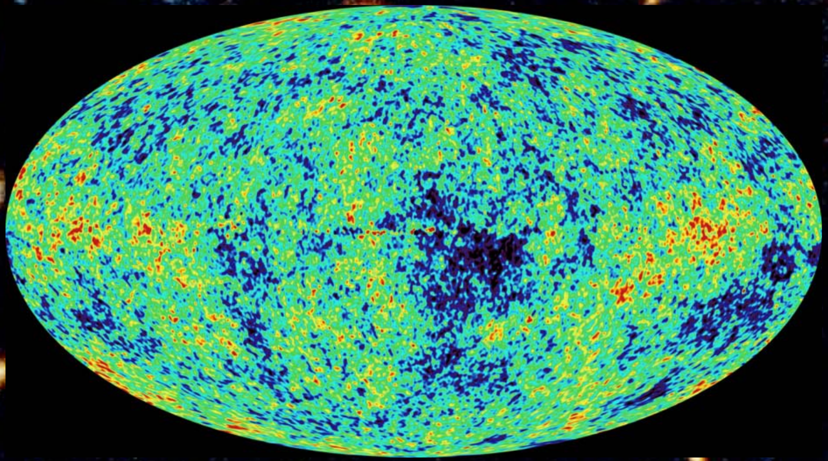
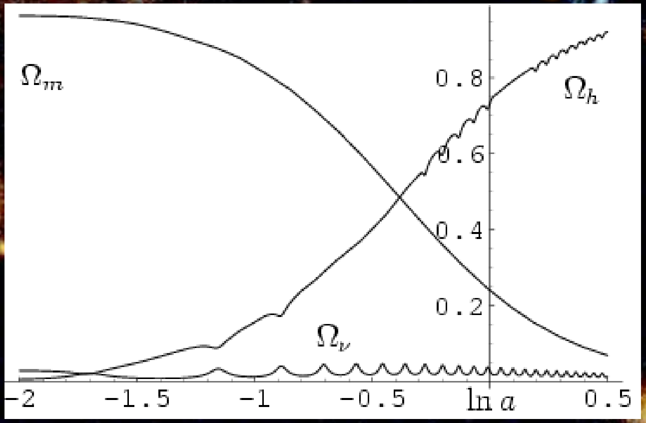
Dynamical Dark Energy





What is dynamical dark energy ?

What do we know about Dark Energy ?

Dark Energy dominates the Universe

Energy - density in the Universe

=

Matter + Dark Energy

25 % + 75 %

Dark Energy :
Energy density that does not clump

Photons , gravitons : insignificant

Dark Energy

$\Omega_m + X = 1$

Ω_m : 25%

Ω_h : 75% Dark Energy

h : homogenous , often Ω_Λ instead of Ω_h

Space between clumps
is not empty :

Dark Energy !

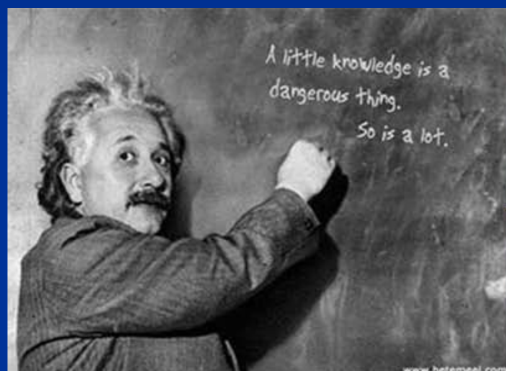
Dark Energy : Homogeneously distributed

Dark Energy density is
the same at every point of space

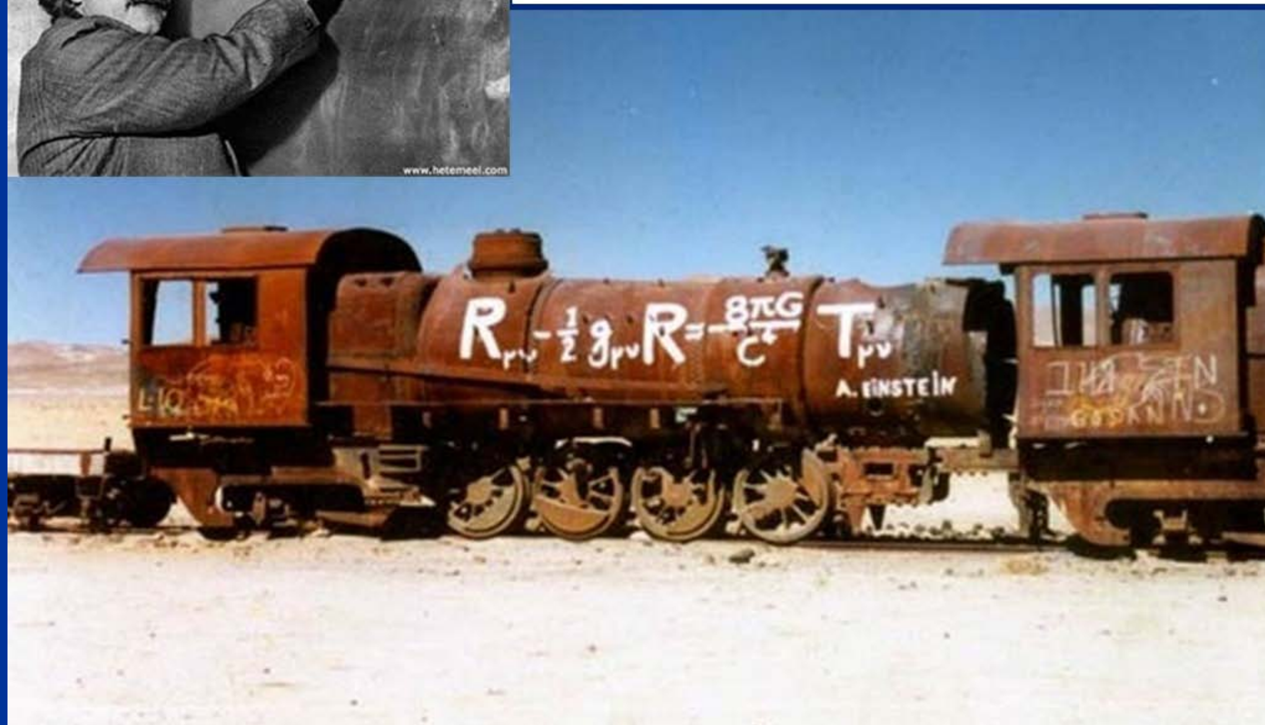
“ homogeneous “

No force in absence of matter –
“ In what direction should it draw ? “

Einstein's equations : static or slowly evolving Dark Energy predicts accelerated expansion of Universe



$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

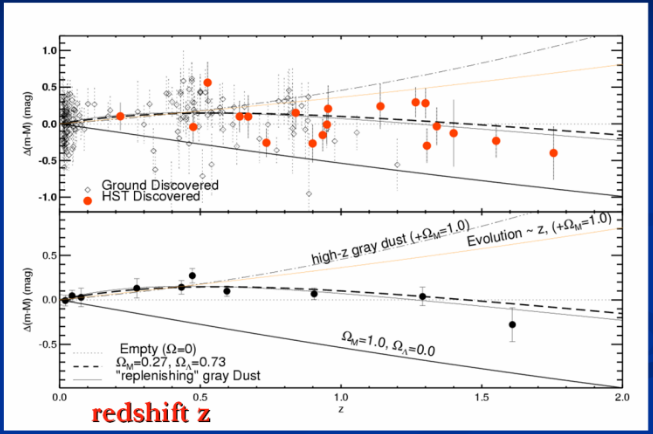


Predictions for dark energy cosmologies

The expansion of the Universe

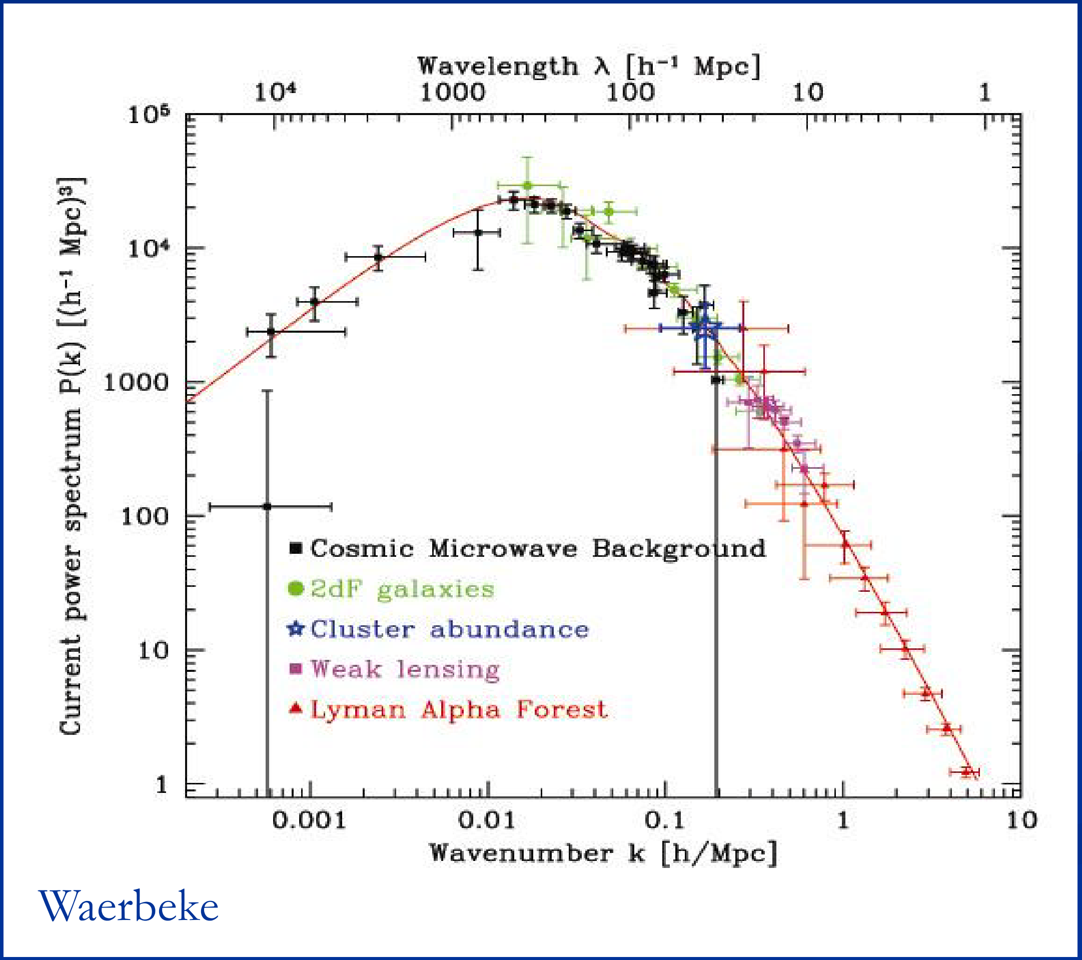
accelerates today !

Supernovae 1a Hubble diagram



Riess et al. 2004

Structure formation :
One primordial fluctuation spectrum



CMB agrees with

Galaxy distribution

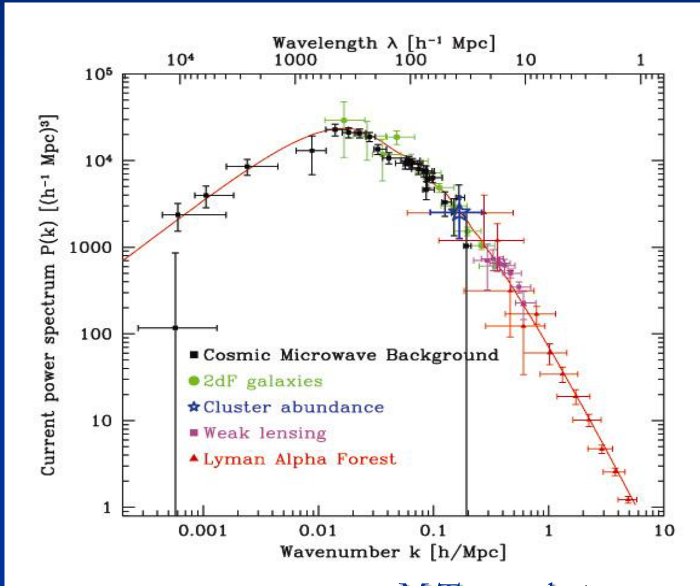
Lyman – α

and

Gravitational Lensing !

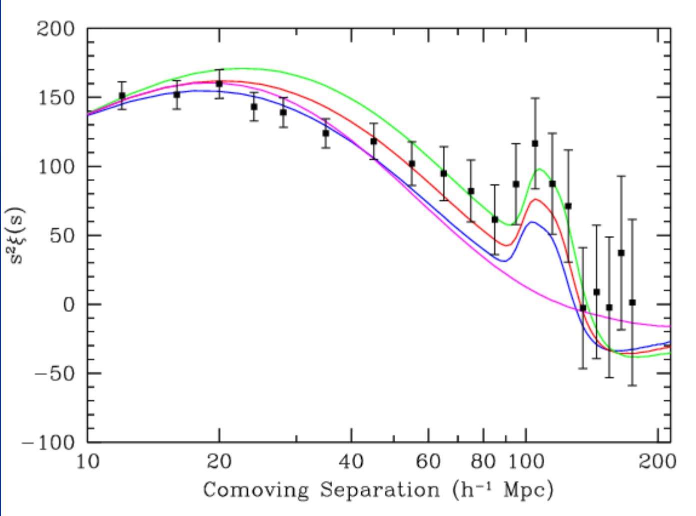
Power spectrum

Baryon - Peak



M.Tegmark + …

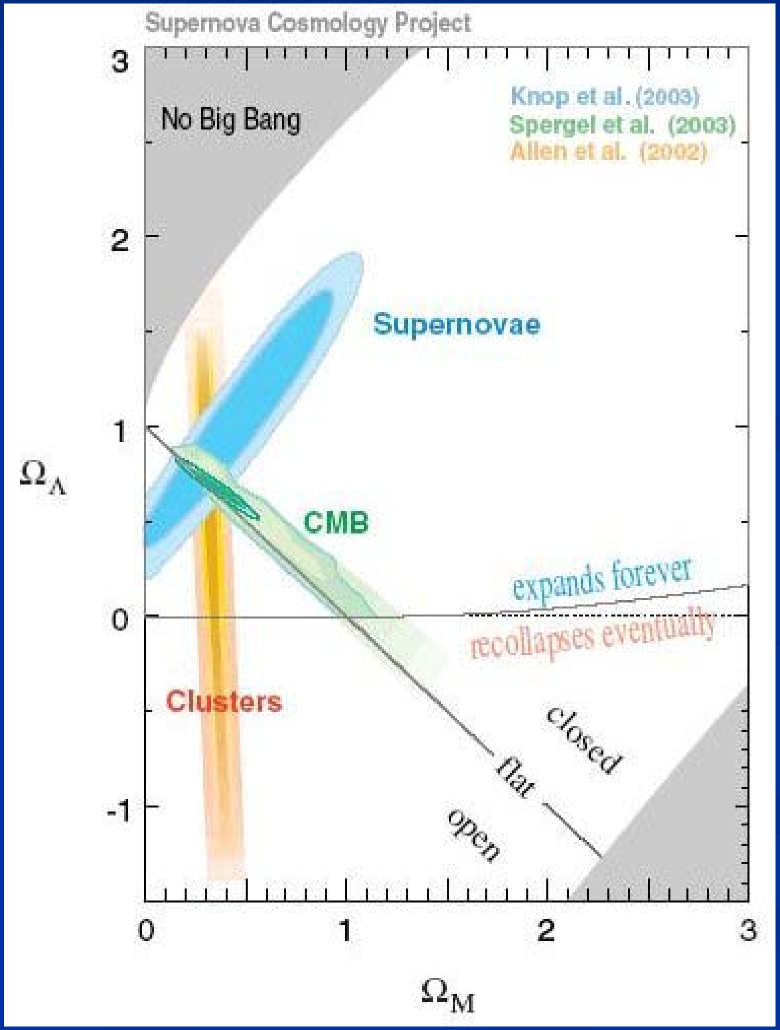
galaxy –
correlation –
function



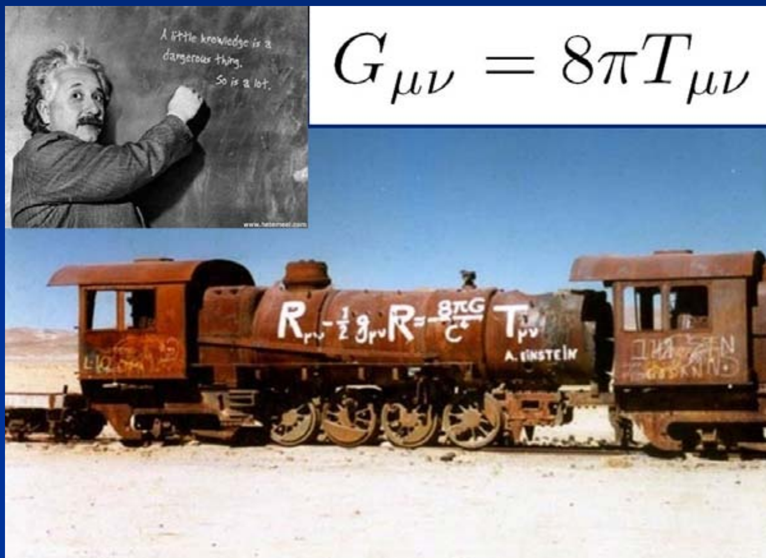
Structure formation :
One primordial
fluctuation- spectrum

SDSS

Dark Energy : observations fit together !



energy momentum tensor



One can always write the gravitational field equation in this form !

T: matter (dark matter and atoms), photons, neutrinos + dark component

universal description of dark energy

- dark energy density : 0,0-component of dark component of energy momentum tensor
- includes cosmological constant, quintessence, modified gravity, backreaction, …
- Einstein frame with constant Planck mass has also essentially constant couplings and masses in standard model of particle physics

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 ?

dynamical dark energy

dark component of energy momentum tensor changes with time

(homogeneous in space)

What is dynamical dark energy good for ?

What is dynamical dark energy good for ?

Dynamical dark energy can explain the size of the dark energy density

Cosmological mass scales

- Energy density

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

- Reduced Planck mass

  $M = 2.44 \times 10^{27}$ eV

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

Time evolution

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

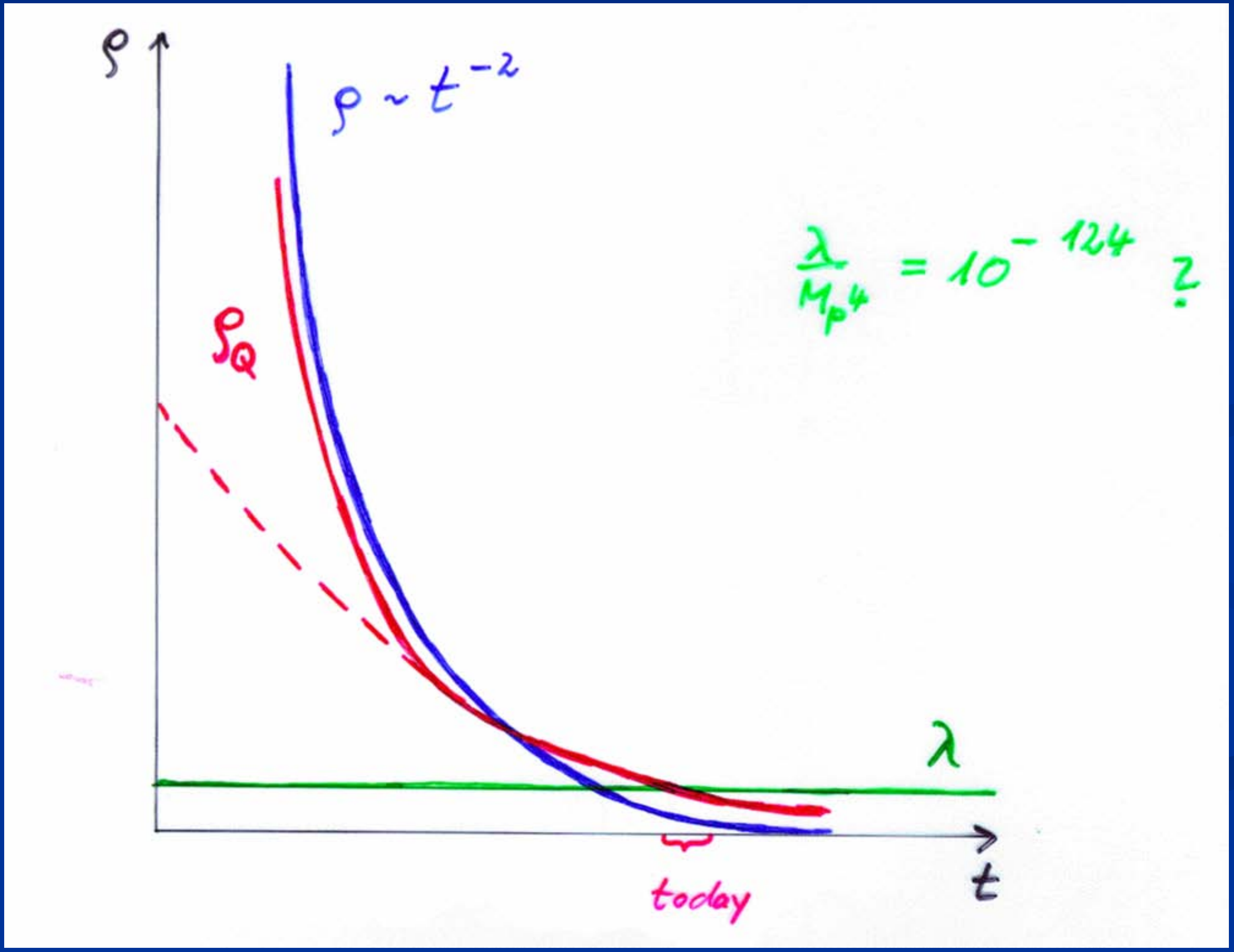
- $\varrho_r/M^4 \sim a^{-4} \sim t^{-2}$ radiation dominated universe

Huge age $\Rightarrow$ small ratio

Same explanation for small dark energy?

Cosm. Const. | Quintessence

static | dynamical



Fields

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 $\varphi(x,y,z,t)$

similar to electric field , but no direction (scalar field)

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 :*

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

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 φ the potential decreases towards zero !

Different possibilities (1)

- Scalar field
- 0 – component of vector field
- higher tensor fields

homogeneous cosmological value of field must be invariant under rotations

only transformation property matters , origin arbitrary

scalar field

scalar field may be “fundamental”,

or it may express higher order gravity (many models of modified gravity), or non-local gravity,

or back-reaction, or higher dimensional properties ,

or other composite degrees of freedom

use simple degrees of freedom whenever you can !

(scalars, vectors etc.)

good coordinates for differential equations !

different possibilities (2)

- more involved kinetic term

  k- essence , ….
- non-minimal coupling to gravity

  (in Einstein frame)

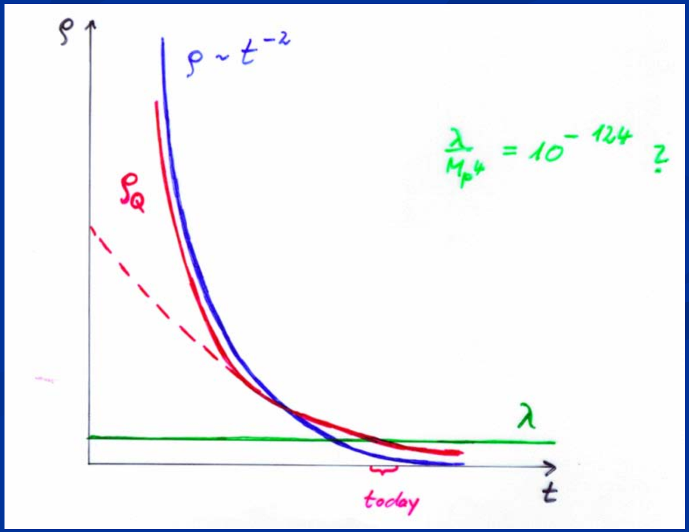
Early dark energy

exponential potential $\Rightarrow$ constant fraction in dark energy

$$\Omega_h = 3/\alpha^2$$

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

can explain order of magnitude of dark energy !



Cosmic Attractors

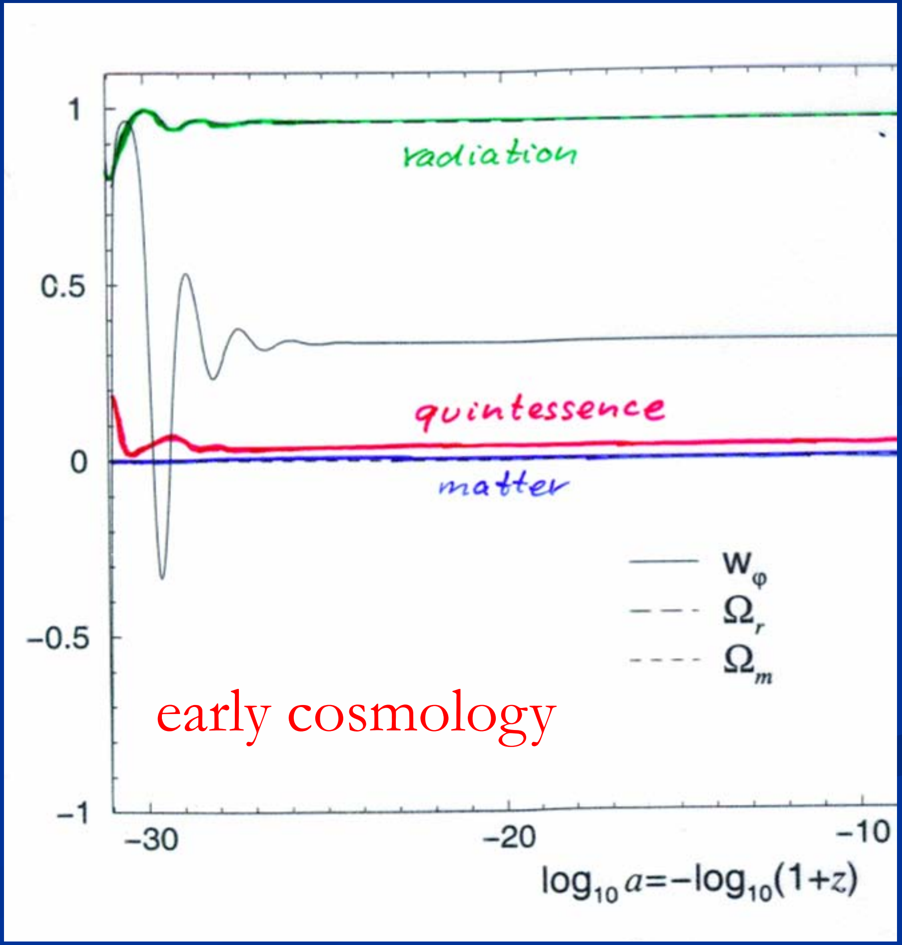
Solutions independent of initial conditions

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

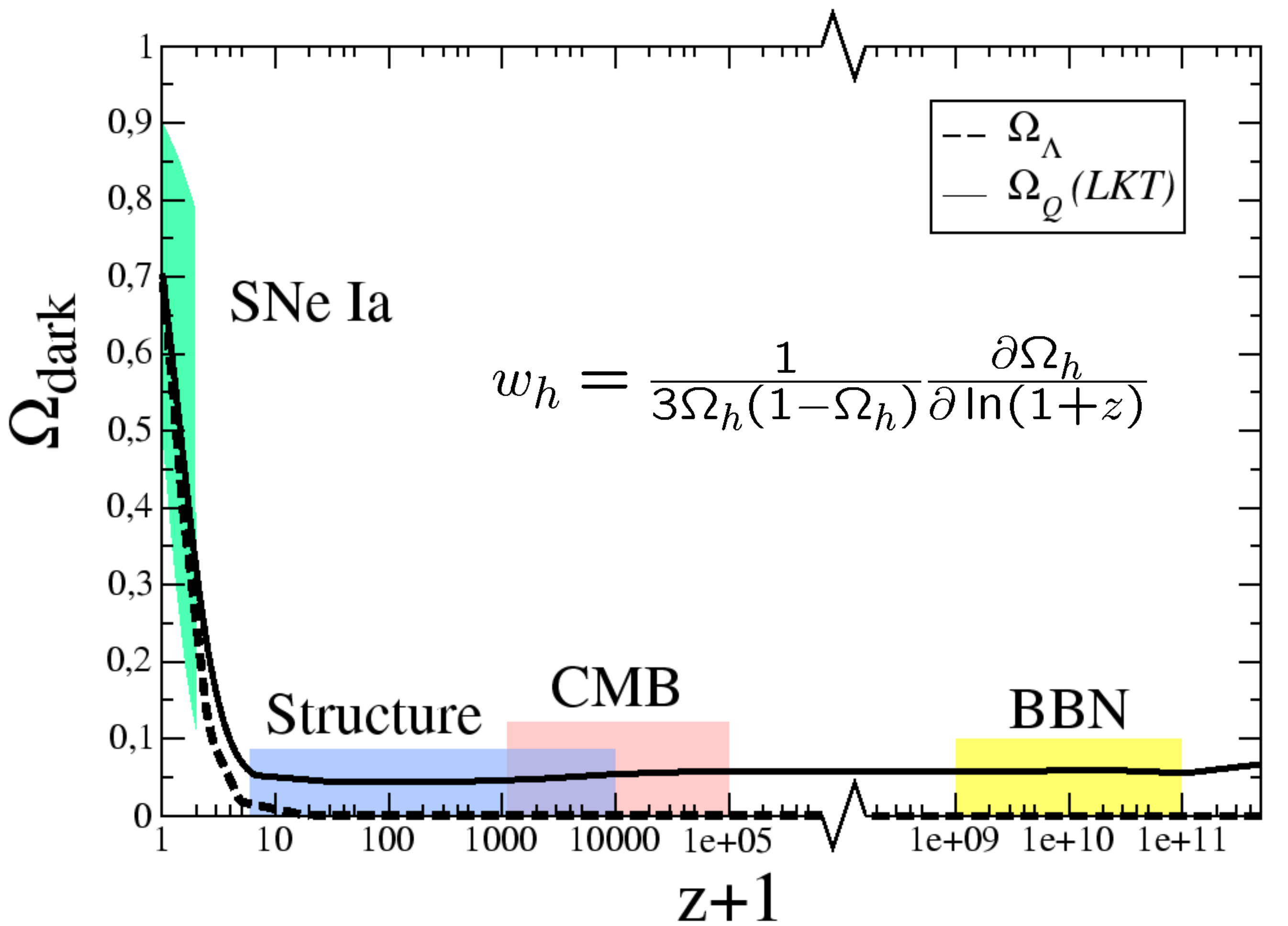
$\varphi \sim \ln(t)$

$\Omega_h \sim$ const.

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



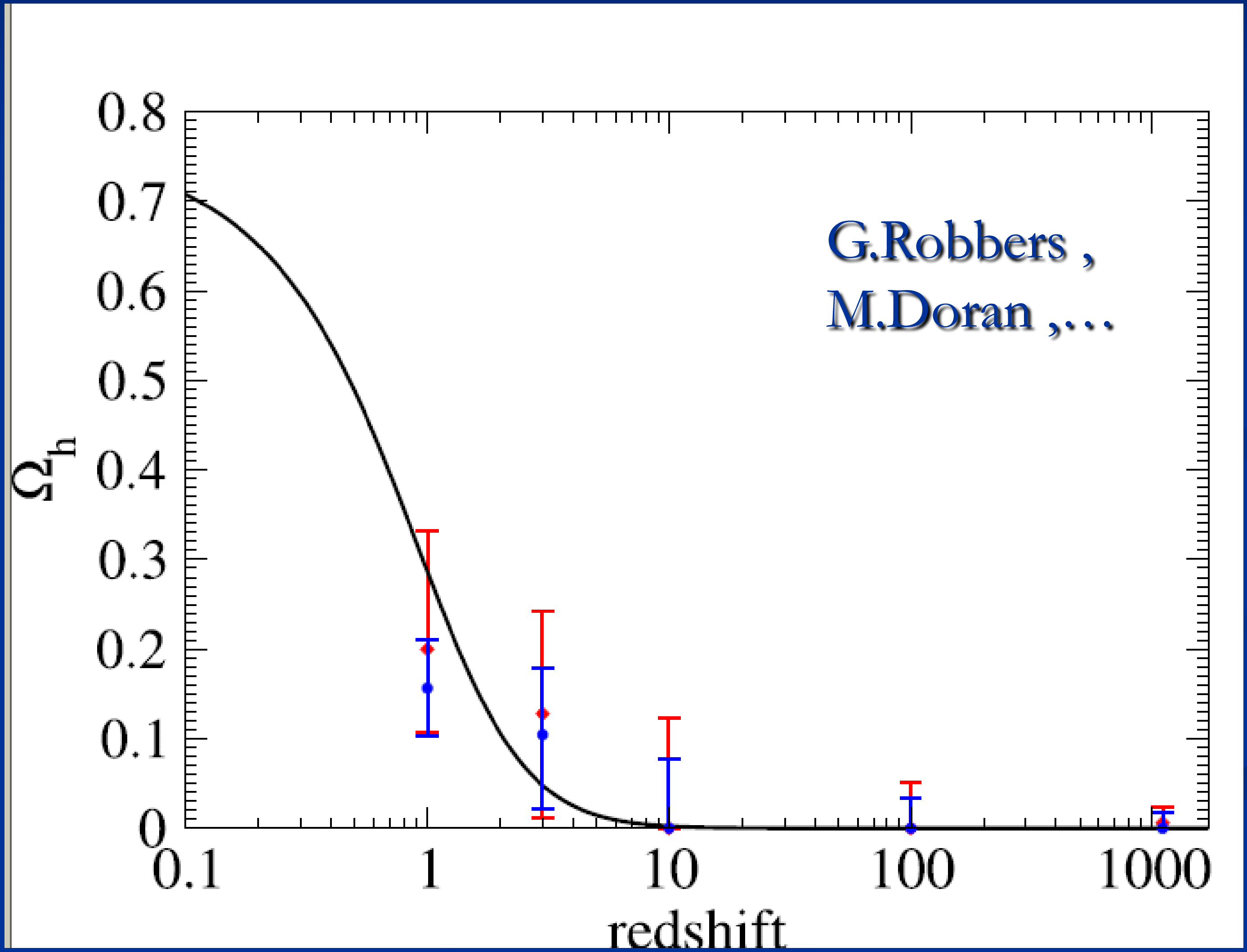
Early Dark Energy



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

M.Doran,…

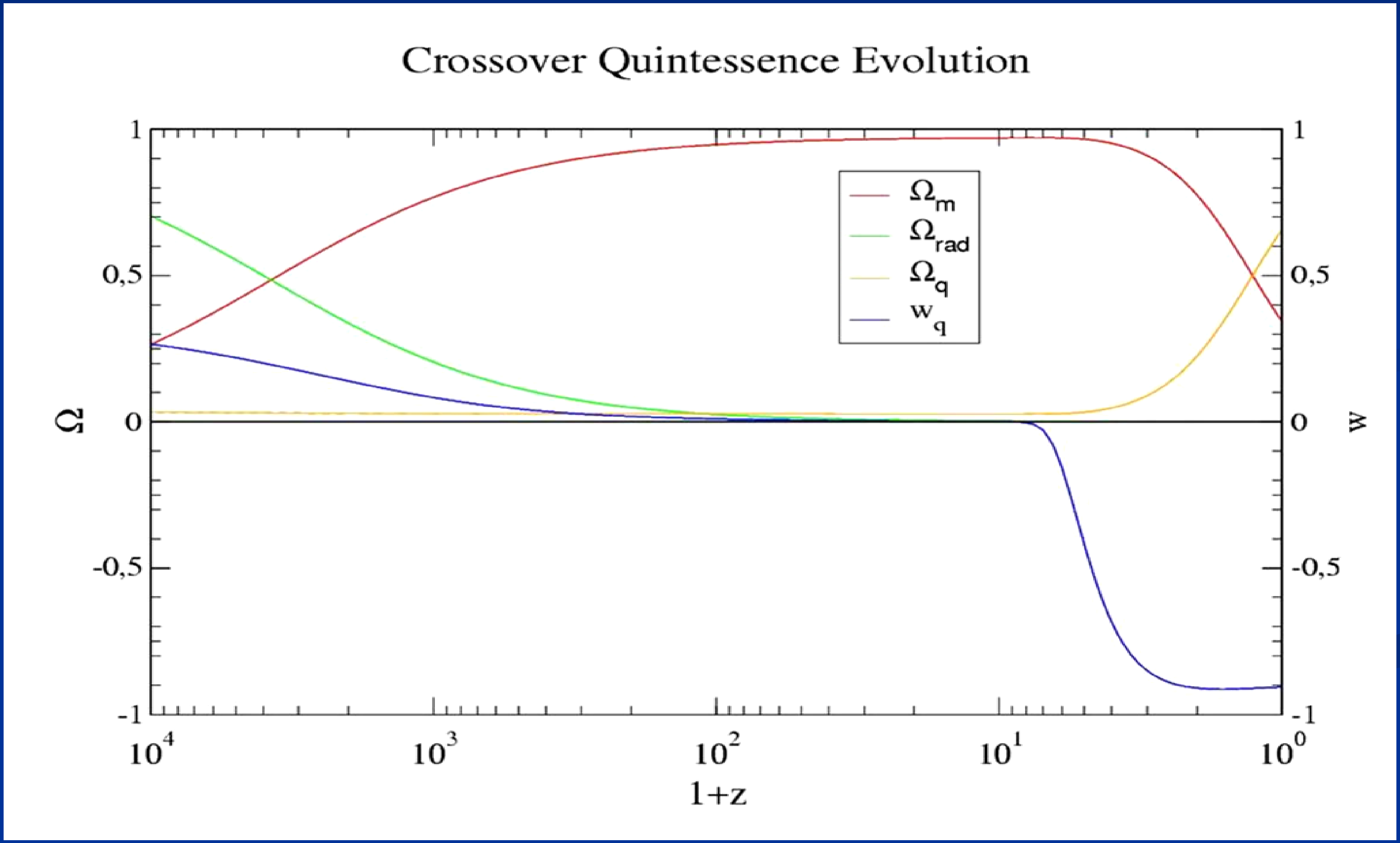
Observational bounds on Ω_h



realistic quintessence

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

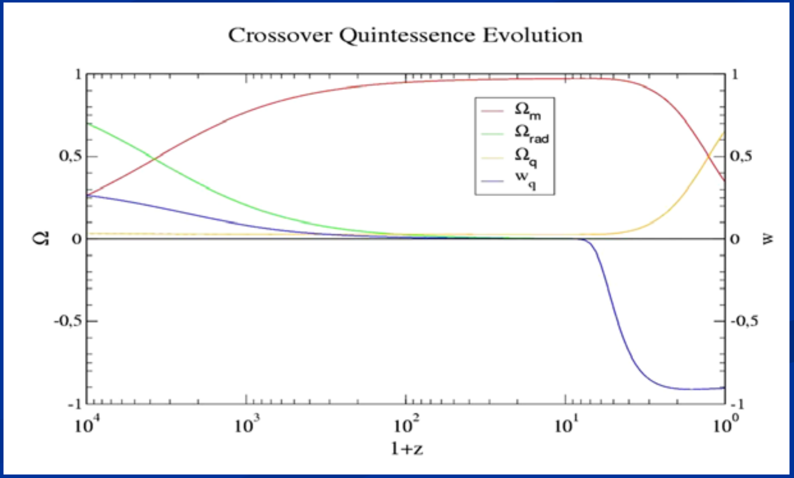
Quintessence becomes important "today"



coincidence problem

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

Why now ?



Coupled dark energy

coupled dark energy

C.Wetterich , Astron.Astrophys.301(1995)321
L.Amendola,Phys.Rev.62(2000)043511

cosmon coupling to atoms much smaller than gravity
cosmon coupling to dark matter restricted by cosmological observation (somewhat smaller than gravity)
cosmon coupling to neutrinos can be substantially stronger than gravity (Fardon,Nelson,Weiner)

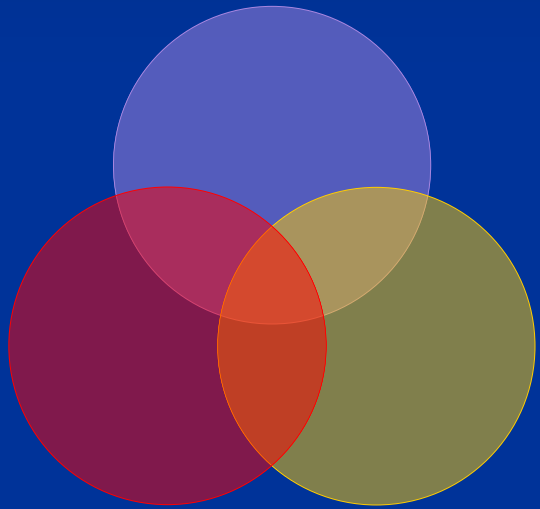
larger couplings allowed if chameleon effect operates

Cosmon

- *Tiny mass*
- $m_c \sim H$ *(depends on time !)*
- *New long - range interaction*

"Fundamental" Interactions

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

On astronomical length scales:

graviton

+

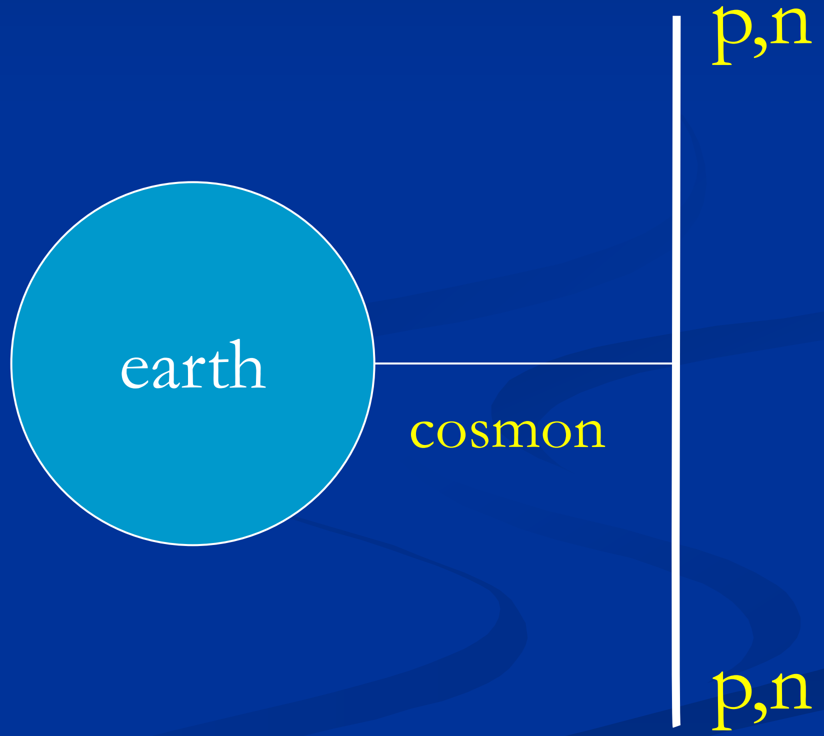
cosmon

Cosmon – atom coupling induces violation of equivalence principle

Different couplings of cosmon to proton and neutron

Differential acceleration

"Violation of equivalence principle"



only apparent : new "fifth force" !

Neutrino cosmon coupling

- Strong bounds on atom-cosmon coupling from tests of equivalence principle or time variation of couplings.
- No such bounds for neutrino-cosmon coupling.
- In particle physics : Mass generation mechanism for neutrinos differs from charged fermions. Seesaw mechanism involves heavy particles whose mass may depend on the value of the cosmon field.

growing neutrino quintessence

Why neutrinos may play a role

Mass scales :

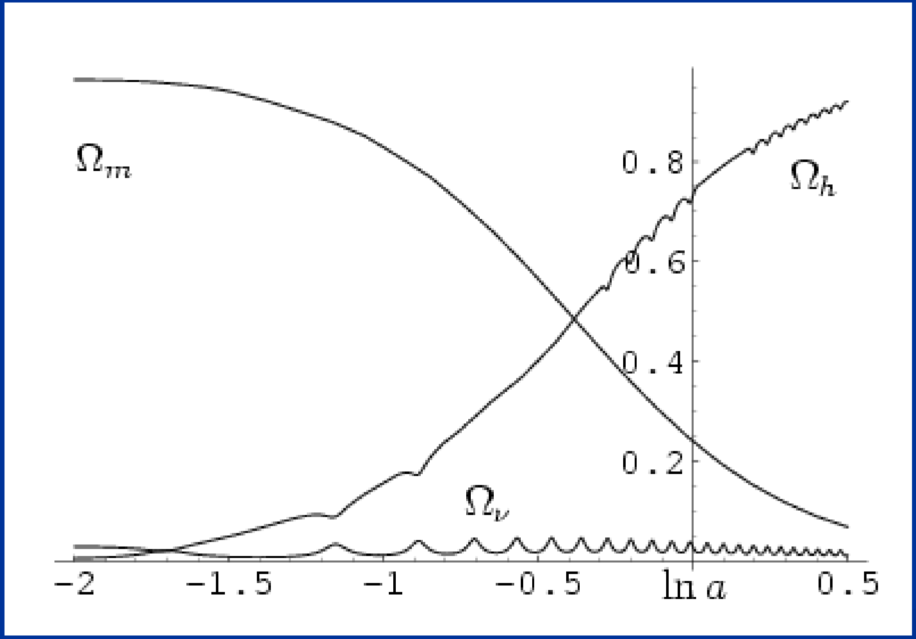
Dark Energy density : $\varrho \sim (2 \times 10^{-3}\ \mathrm{eV})^{-4}$.

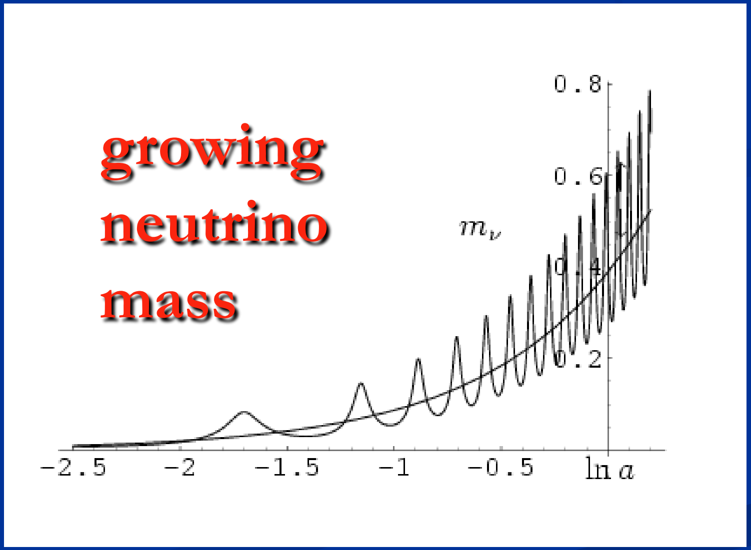
Neutrino mass : eV or below.

Cosmological trigger : Neutrinos became non-relativistic only in the late Universe .

Neutrinos can have coupling to cosmon stronger than gravity.

growing neutrino mass triggers transition to almost static dark energy





L.Amendola, M.Baldi,…

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

- this has happened recently !
- sets scales for 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 !

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

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

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

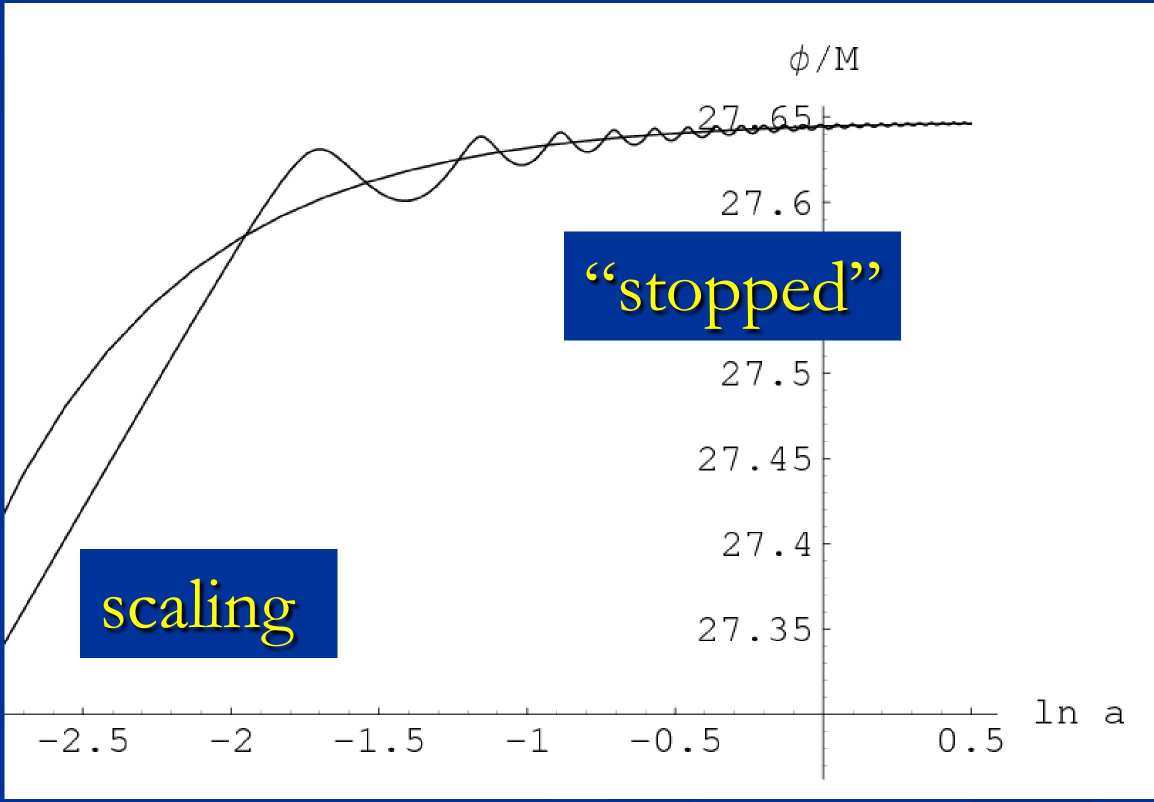
stopped scalar field mimicks a cosmological constant (almost …)

rough approximation for dark energy :

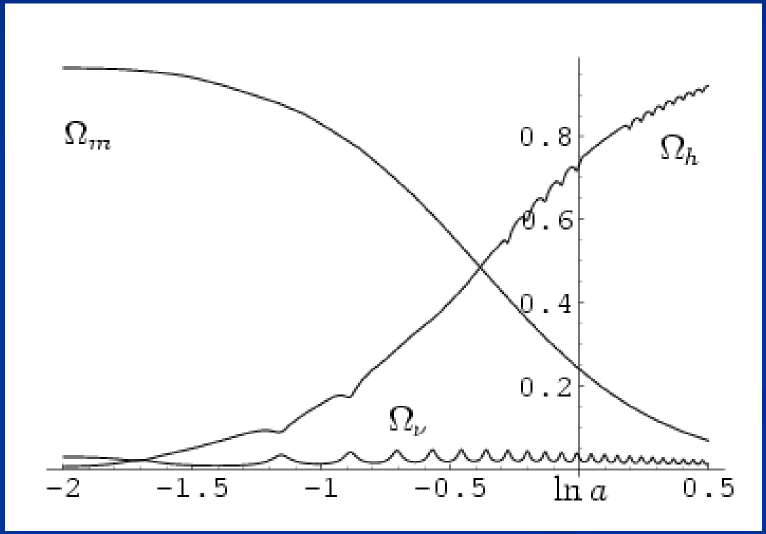
- before redshift 5-6 : scaling (dynamical)
- after redshift 5-6 : almost static

  (cosmological constant)

cosmon evolution



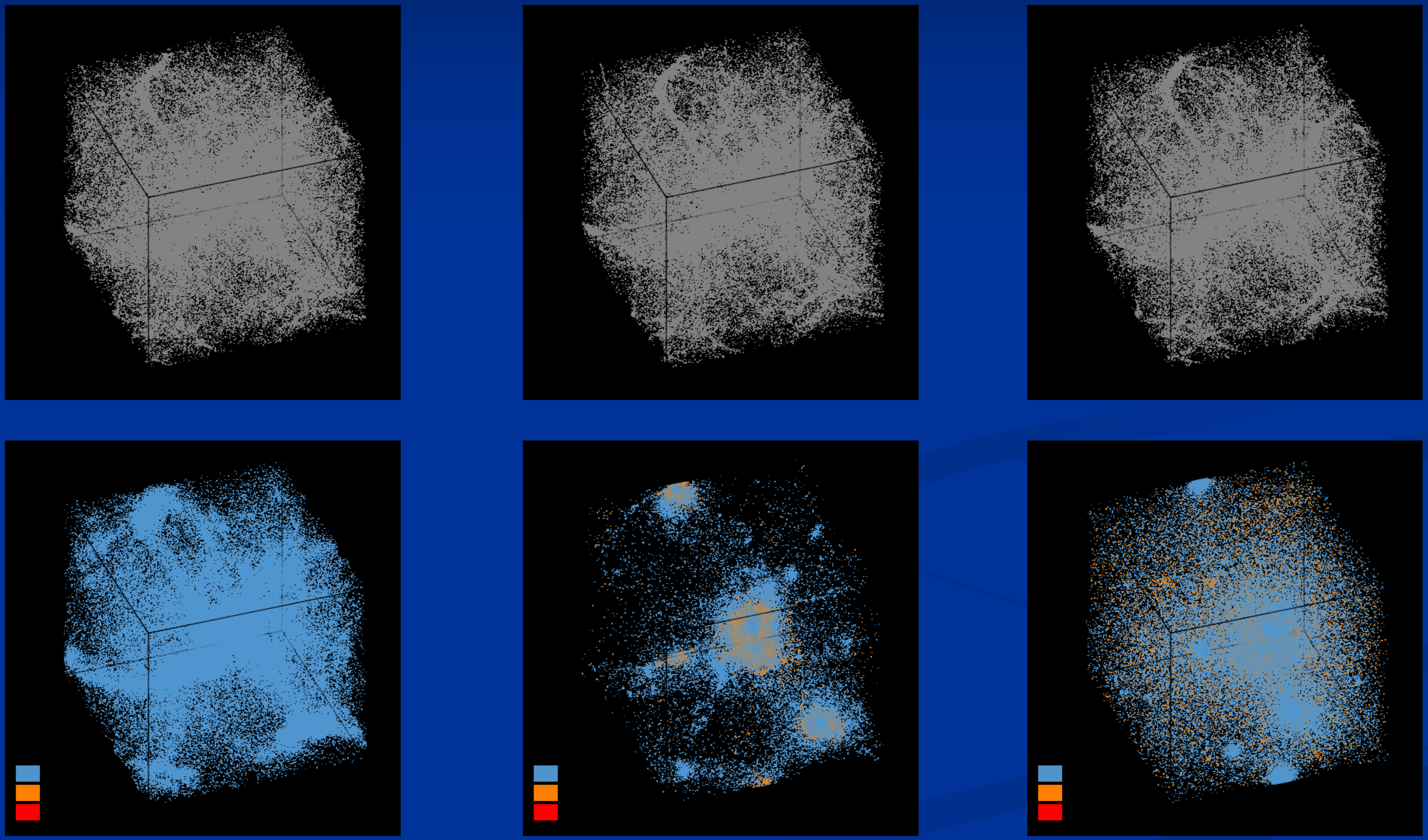
crossover to dark energy dominated universe



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

cosmological selection !

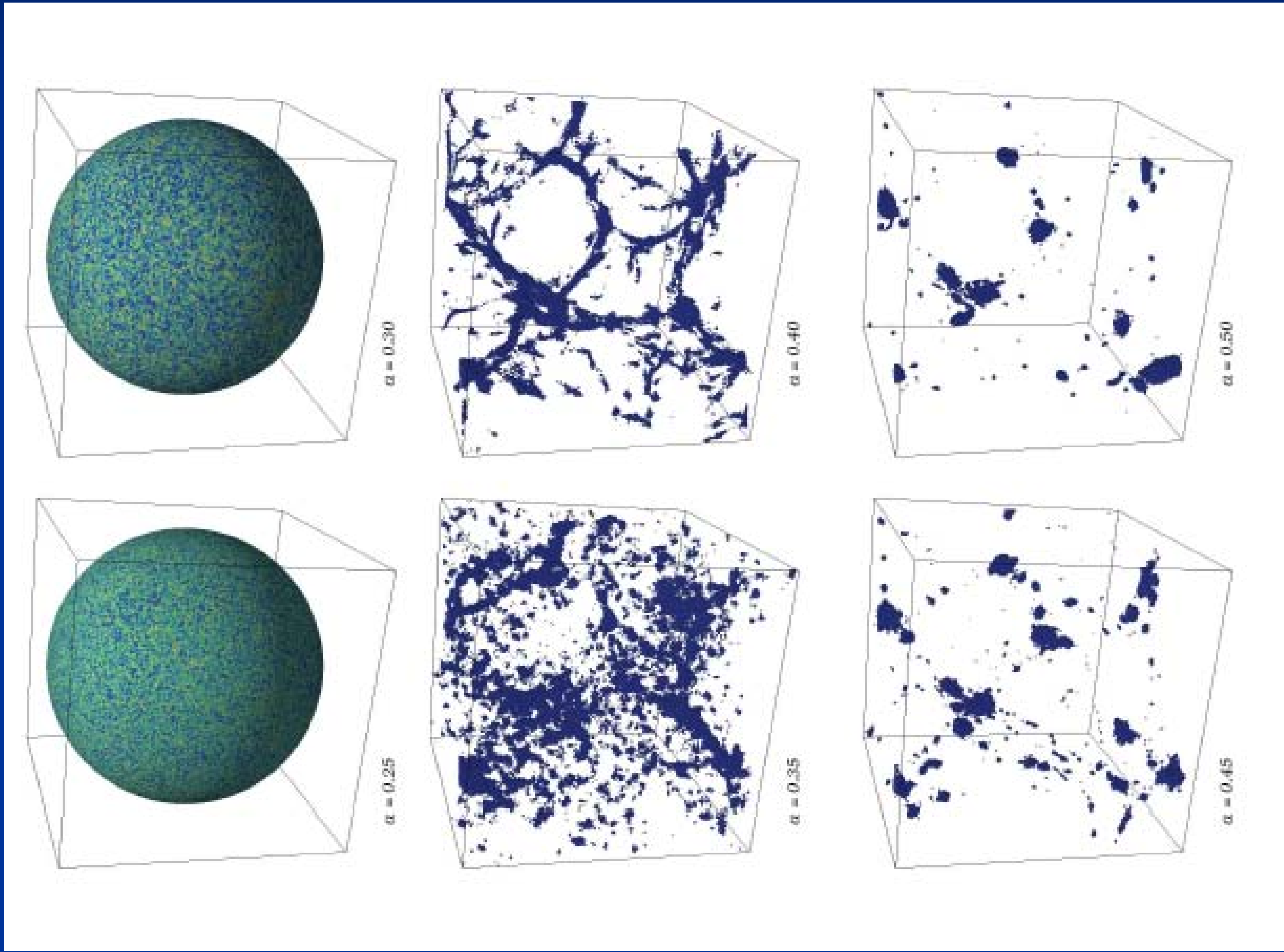
Formation of neutrino lumps



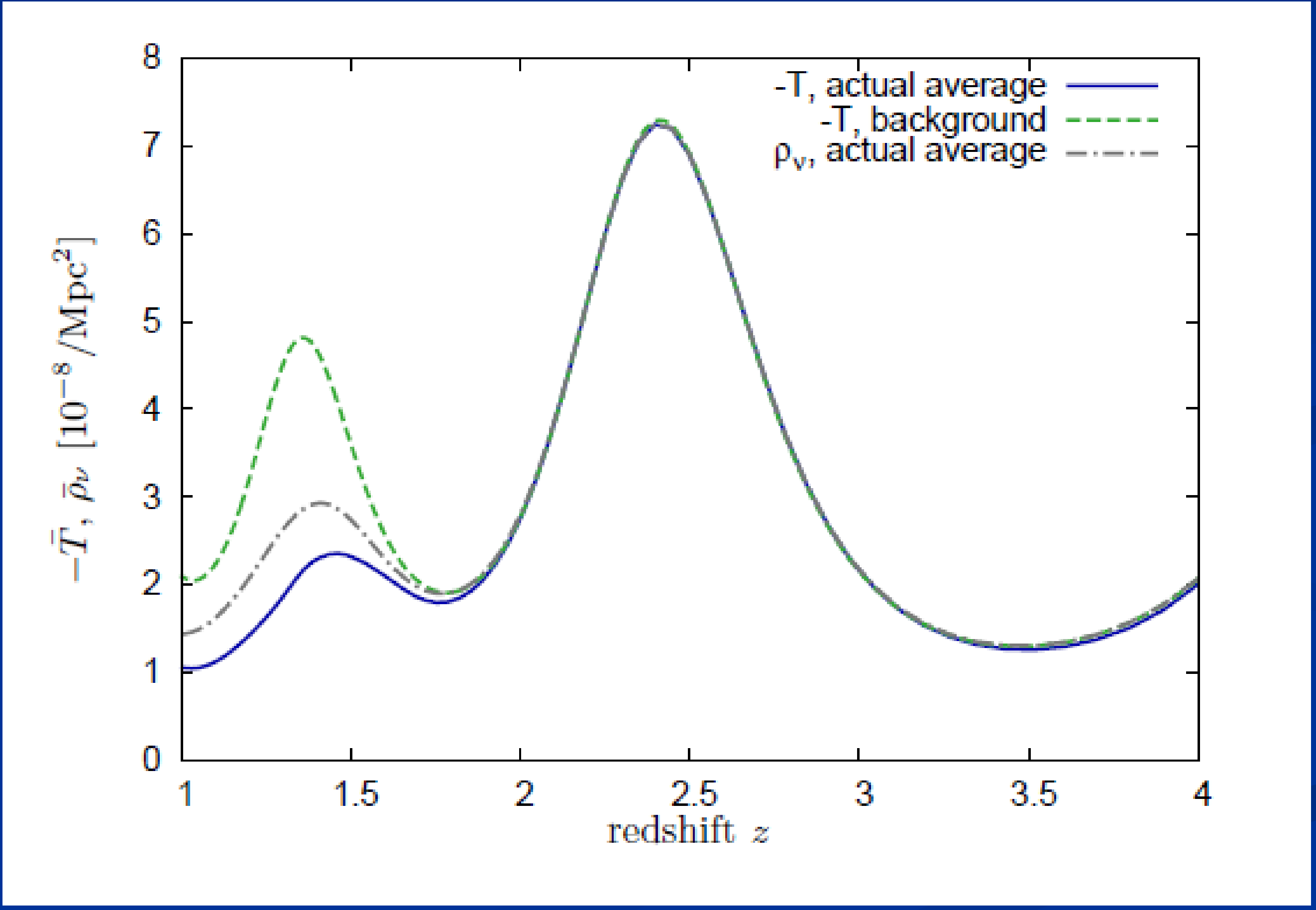
N- body simulation M.Baldi et al

Formation of neutrino lumps

Y.Ayaita,M.Weber,…



back-reaction : energy momentum tensor of neutrinos



Key questions for quintessence

- Why does cosmon potential vanish for infinite time ?
  $V(\varphi) = M^4 \exp(- \alpha\varphi/M)$

  Dilatation symmetry in higher dimensions – not today

- Why is time variation of fundamental couplings small ?
  (e.g. fine structure constant , electron-proton mass ratio)

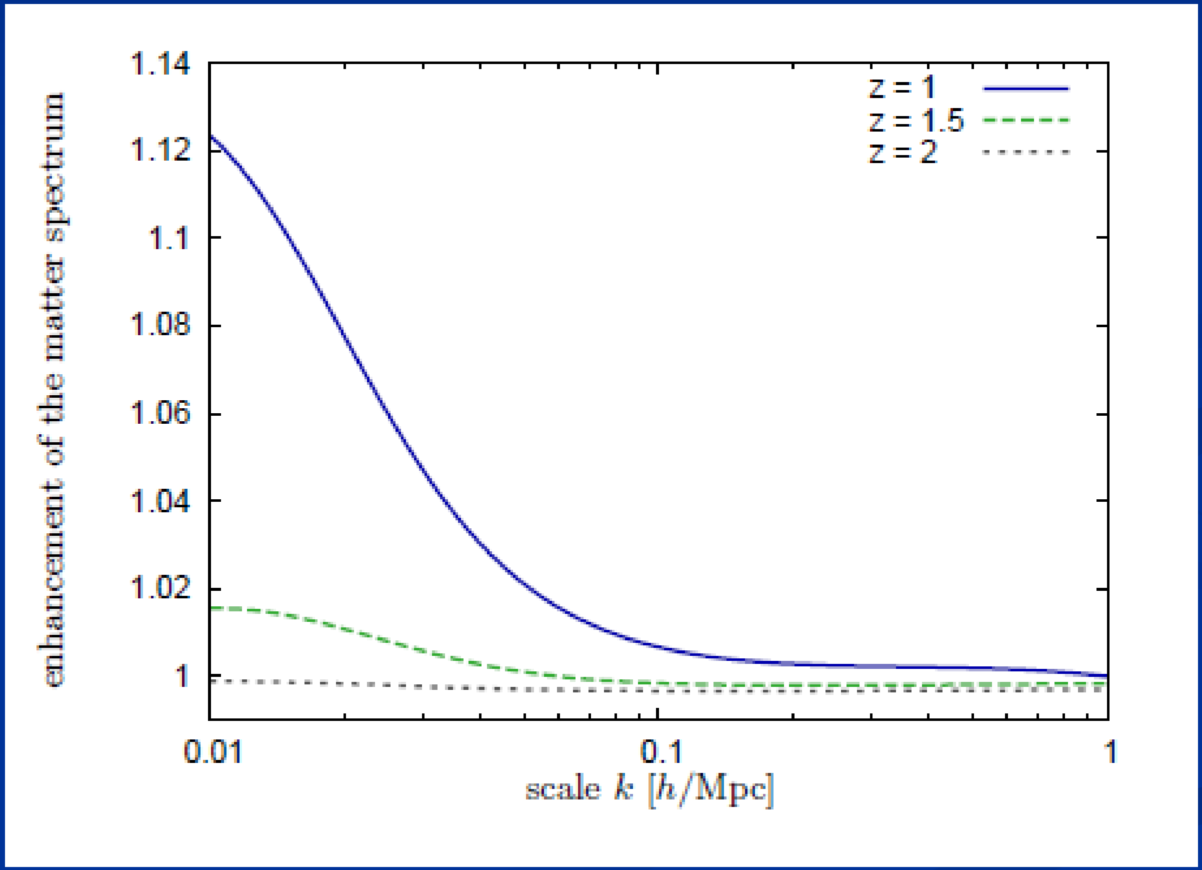
  Fixed point behavior – not today

- Why does Dark Energy dominate only in recent cosmology
  (Why now ? – problem)

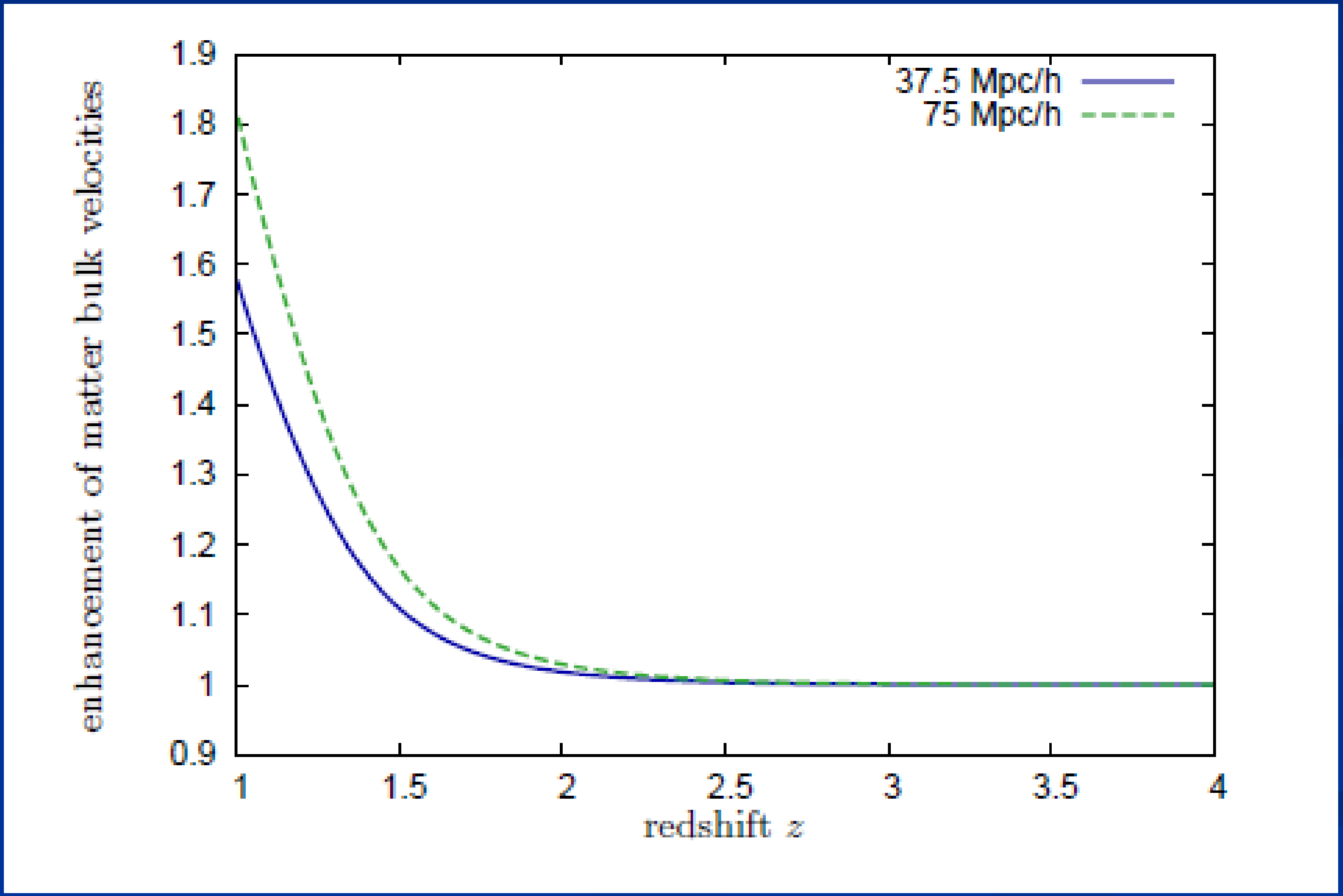
  Growing neutrino mass - today

End

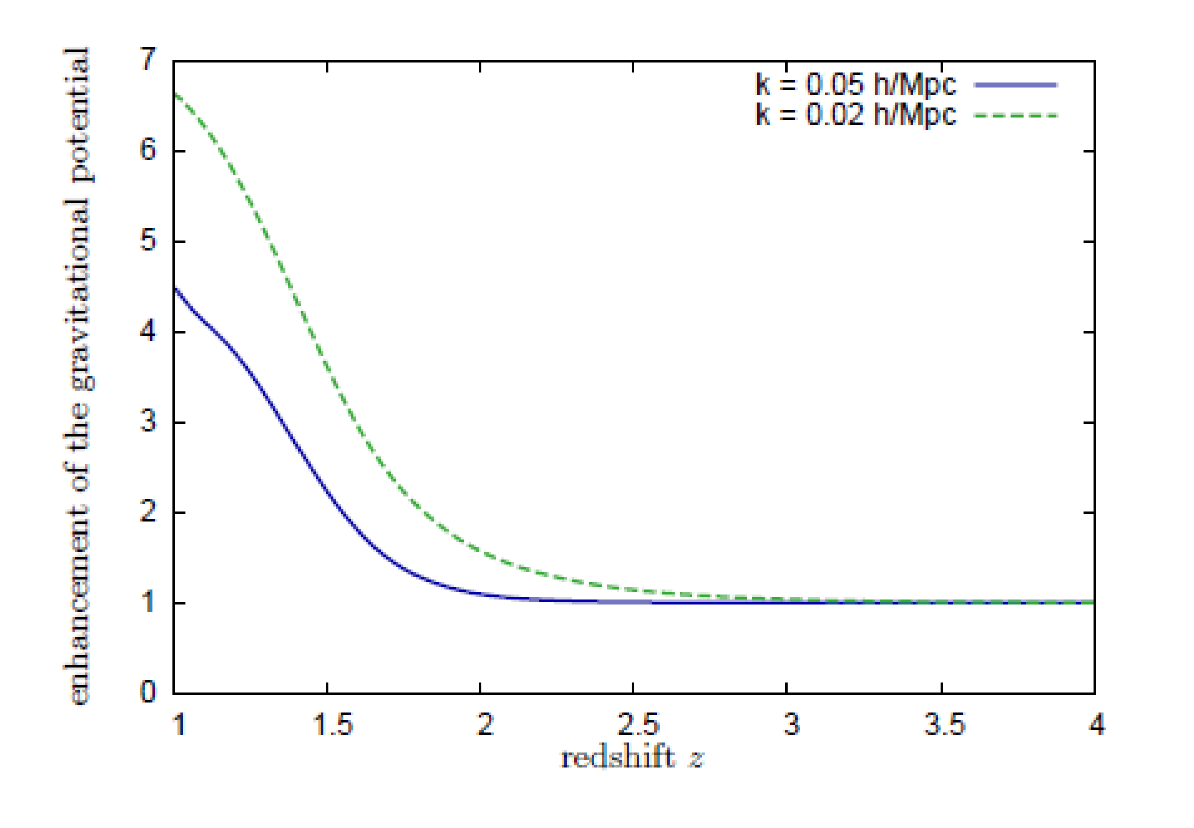
Small induced enhancement of dark matter power spectrum at large scales



Enhanced bulk velocities

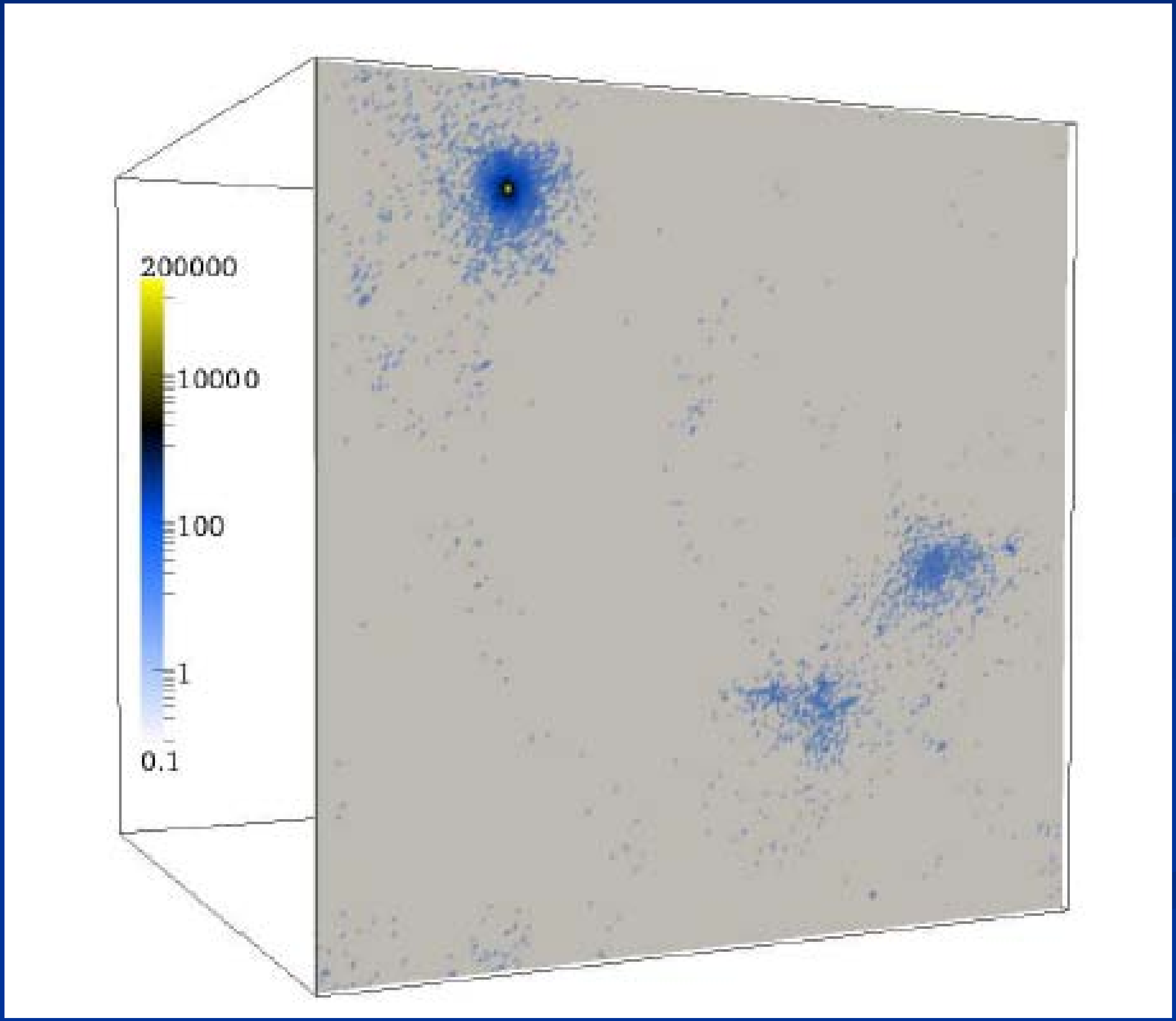


Enhancement of gravitational potential

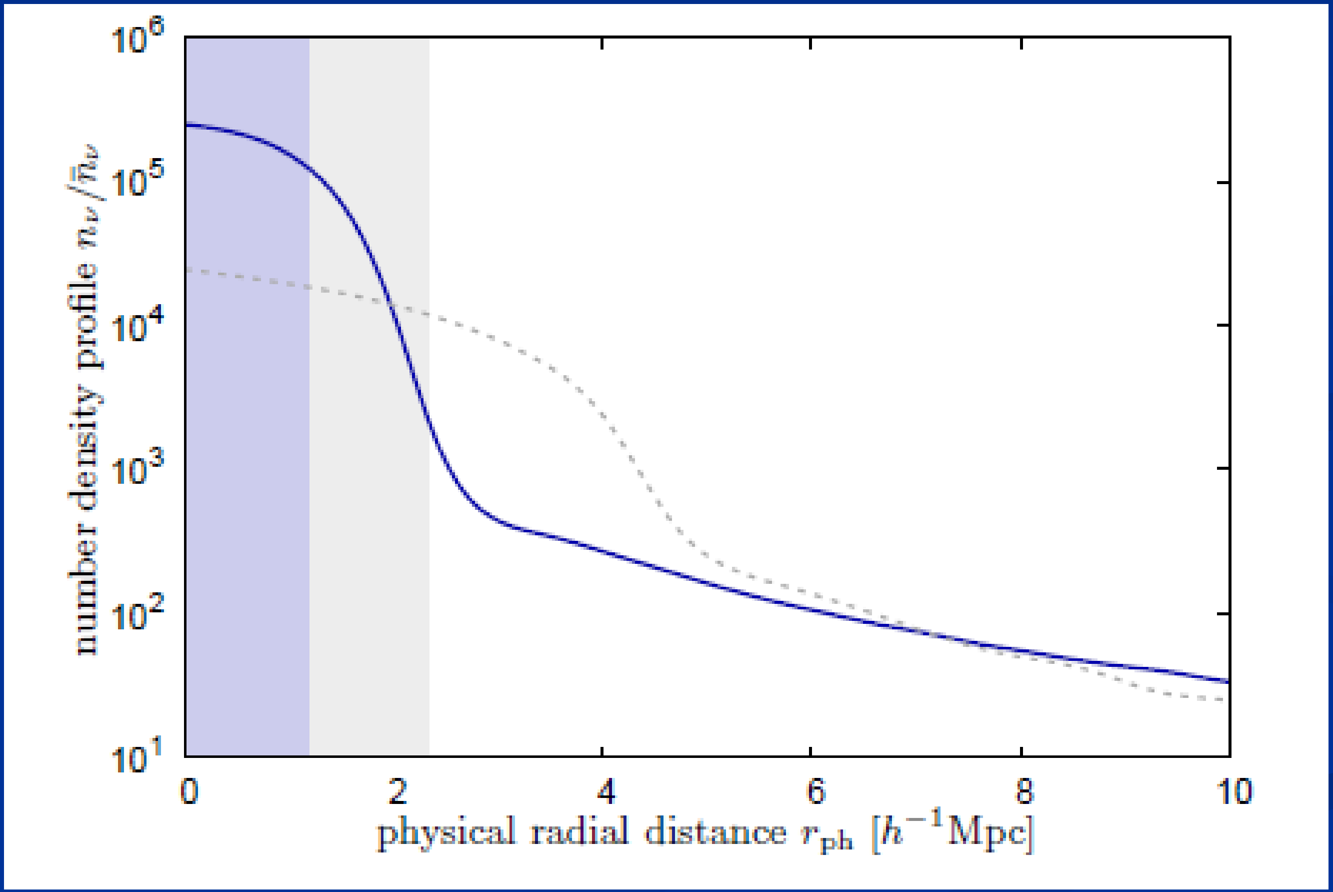


Test of allowed parameter space by ISW effect

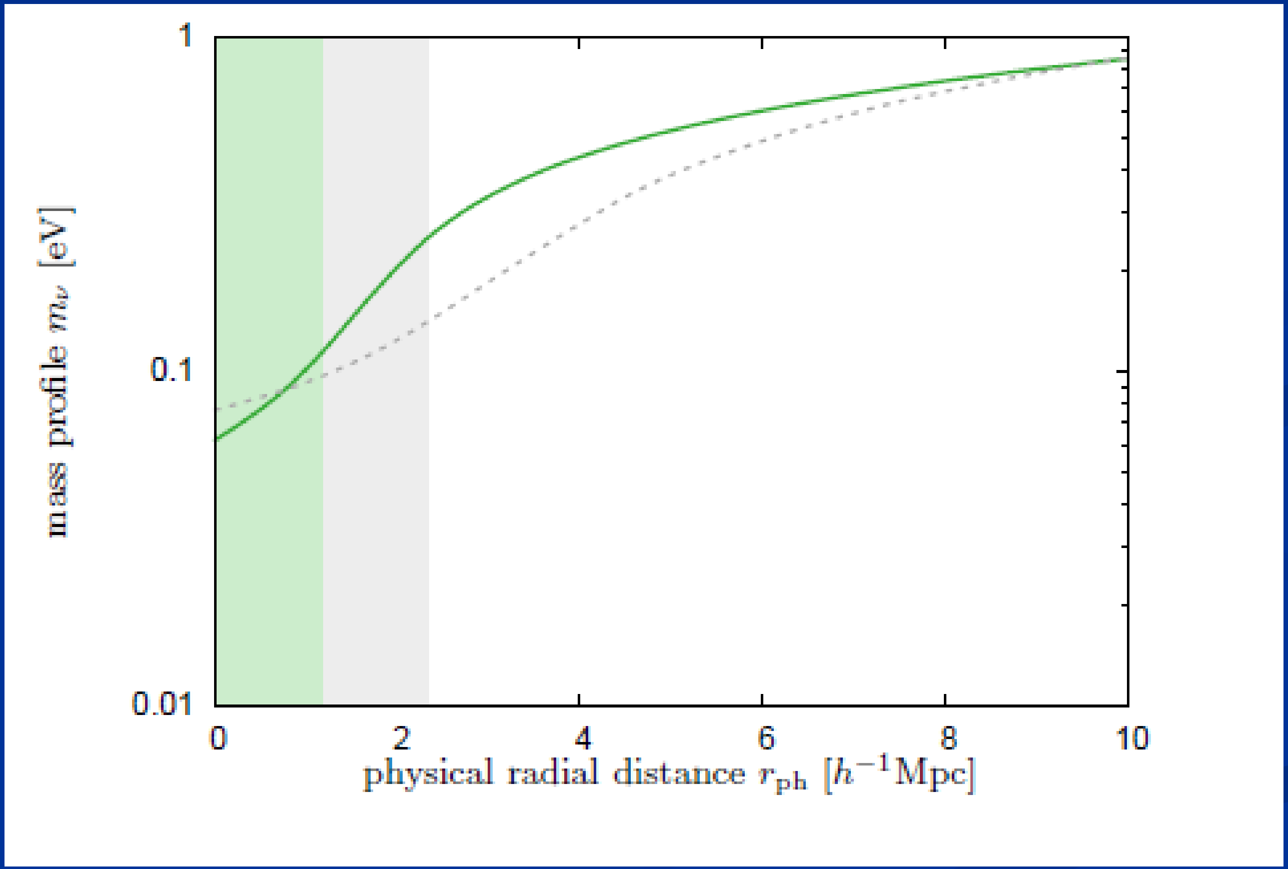
neutrino lumps



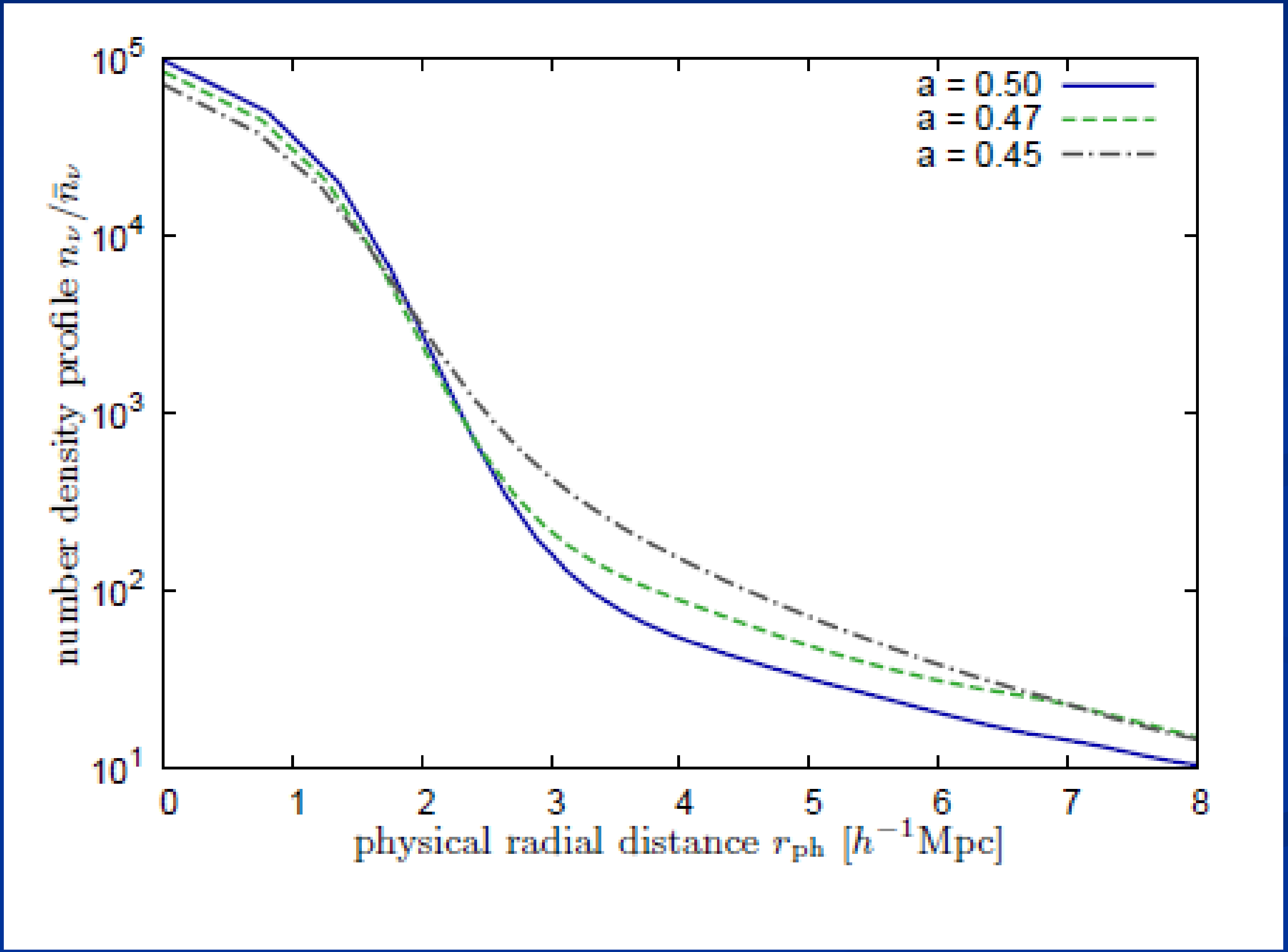
number density profile of neutrino lumps



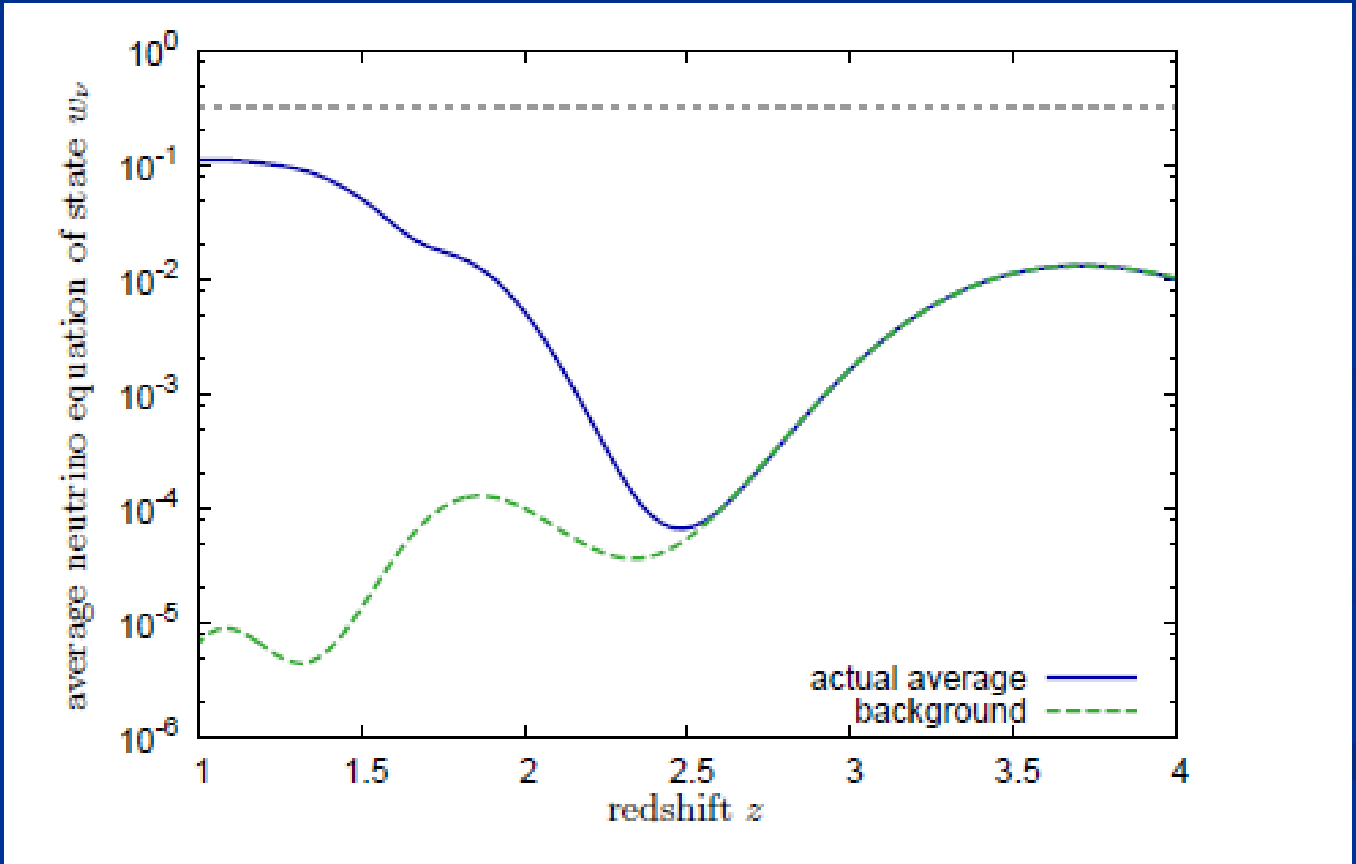
mass profile in neutrino lumps



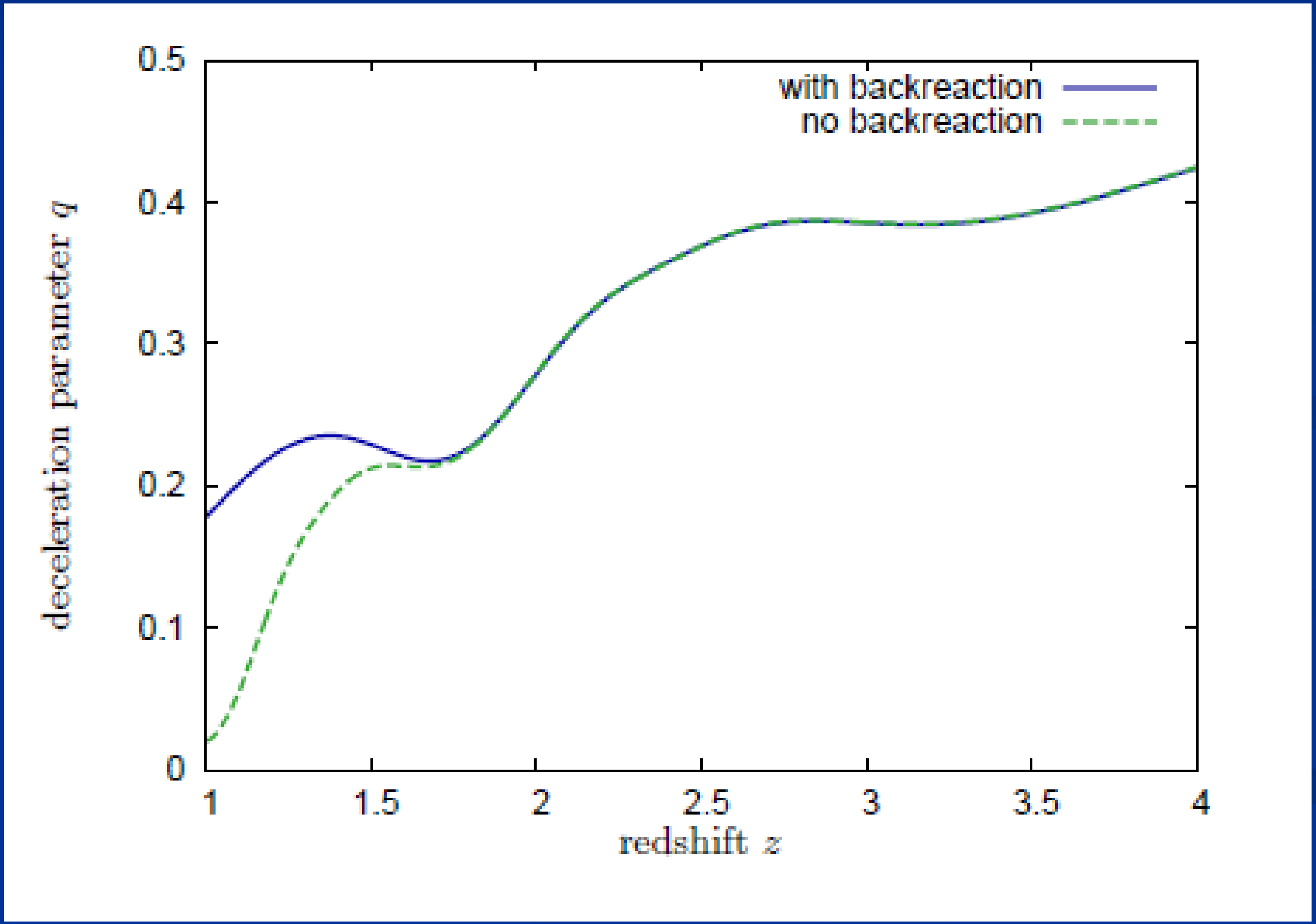
time dependence of neutrino distribution in lumps



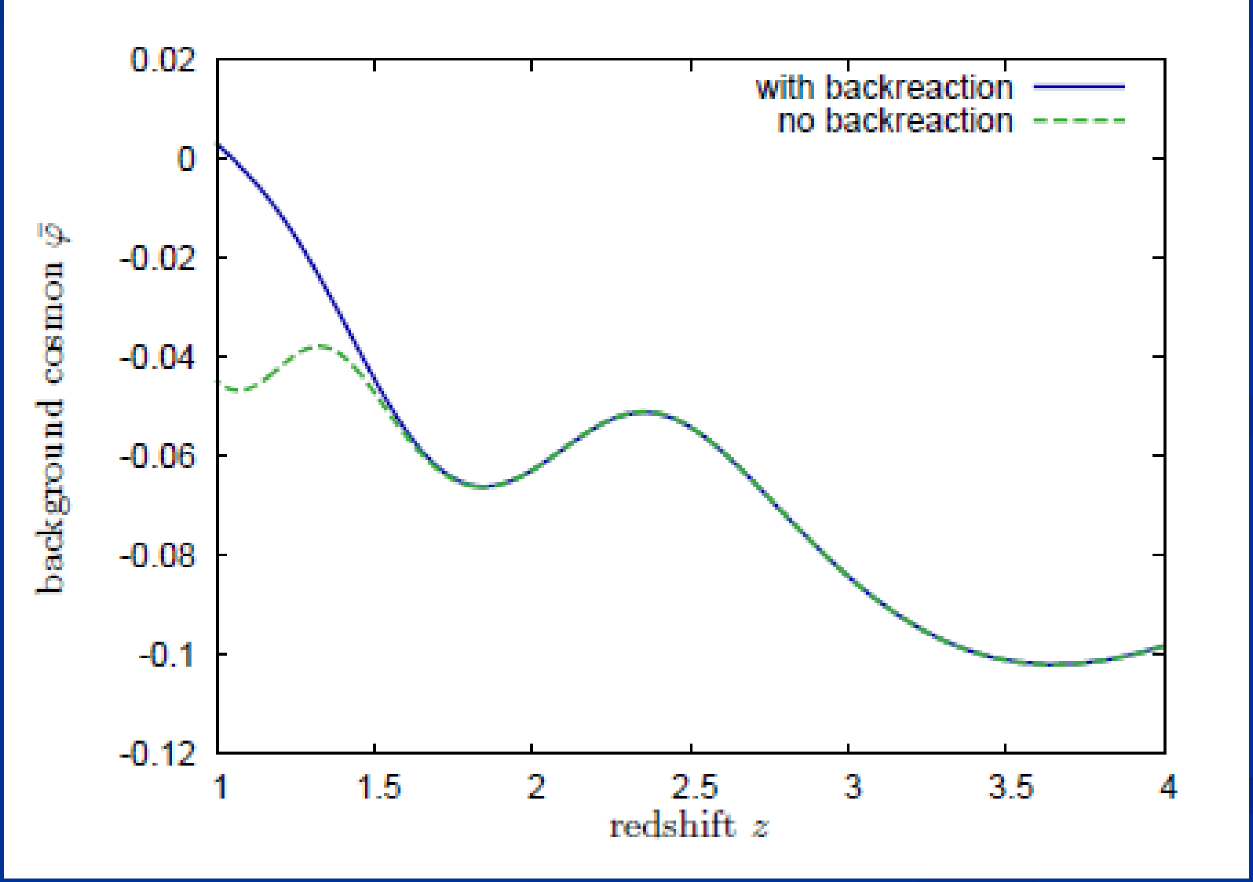
back-reaction : neutrino equation of state



back-reaction : decelaration parameter



back-reaction: cosmon field



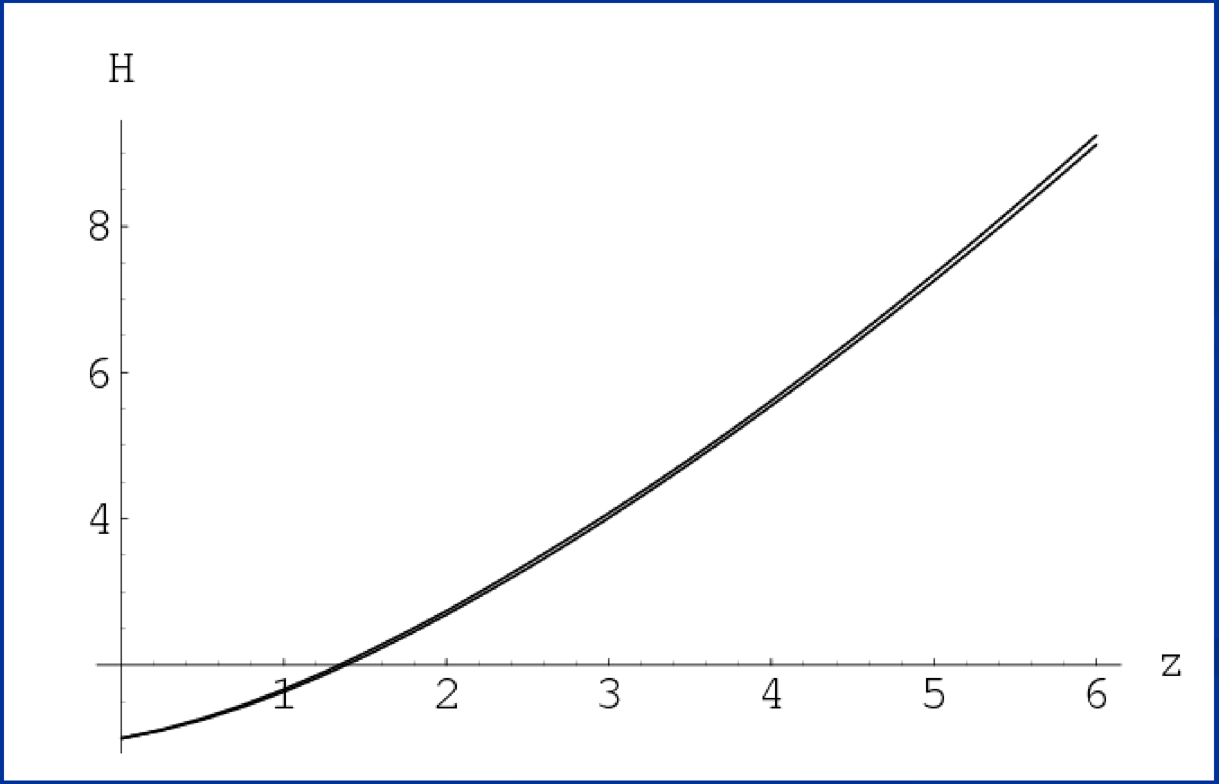
Conclusions

- 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

Tests for growing neutrino quintessence

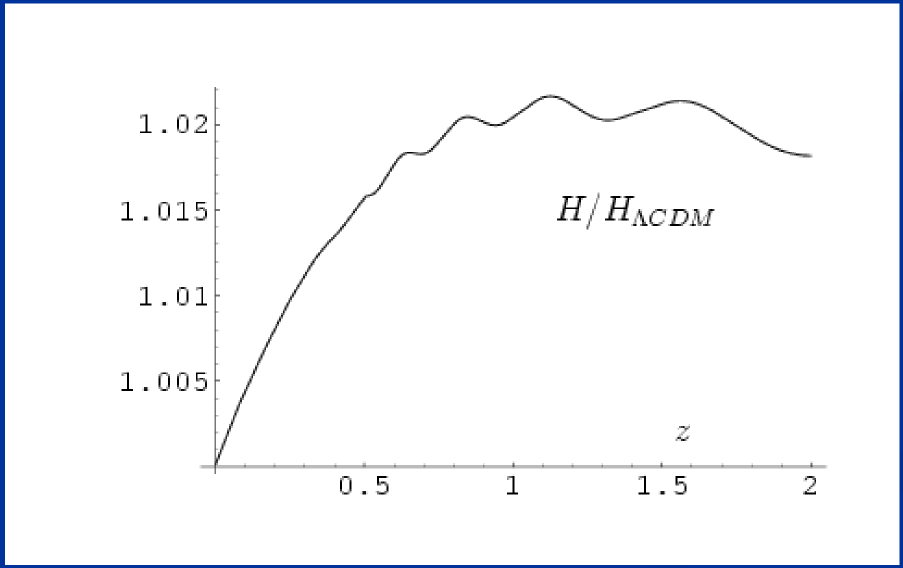
Hubble parameter

as compared to ΛCDM



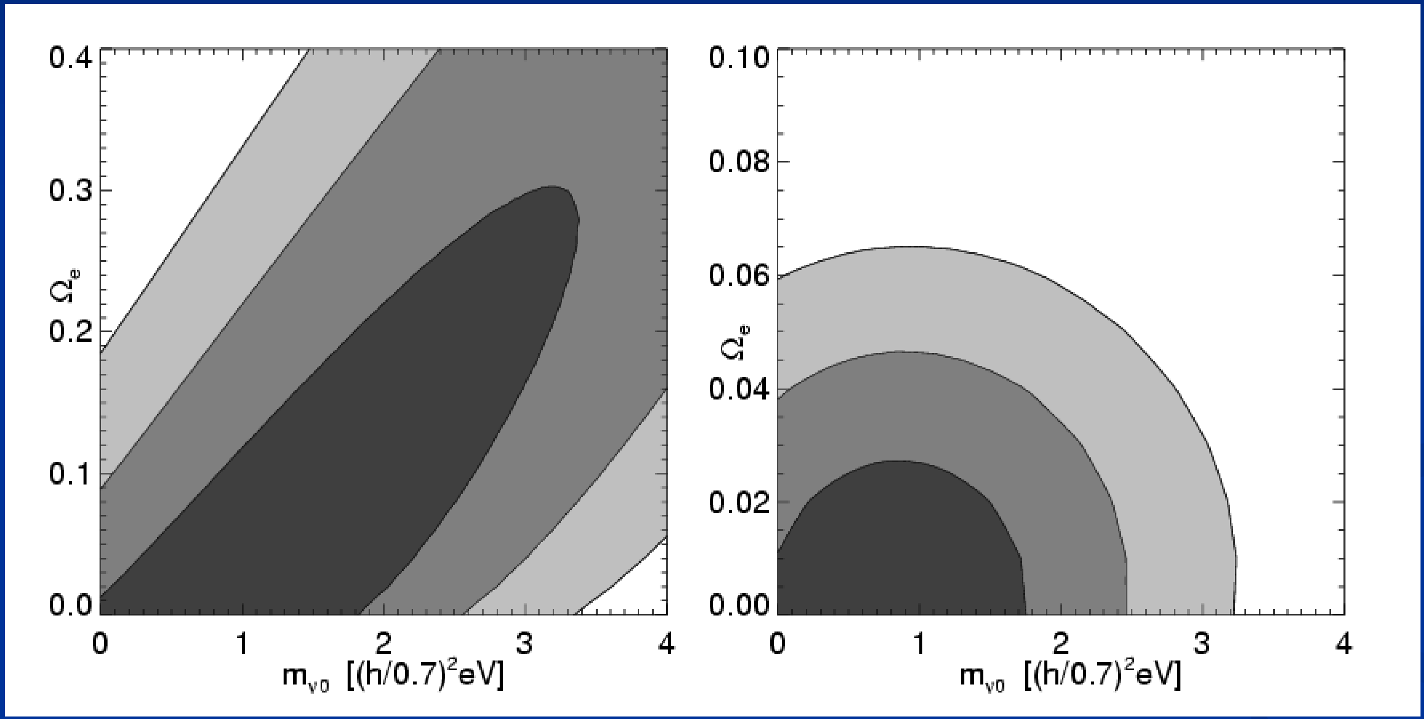
Hubble parameter ($z < z_c$)

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



only small difference from ΛCDM !

bounds on average neutrino mass



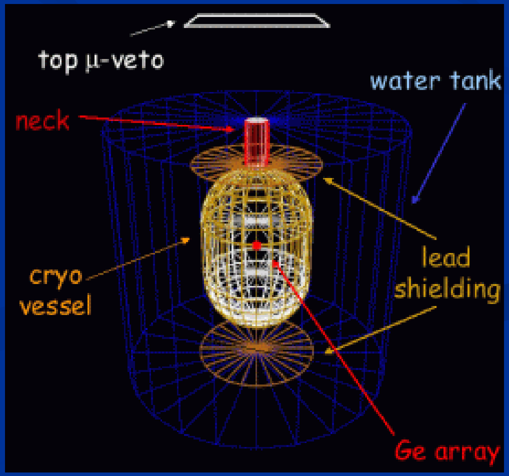
Looking Beyond Lambda with the Union Supernova Compilation

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 cosmological upper bound in model with constant neutrino mass

(KATRIN, neutrino-less double beta decay)

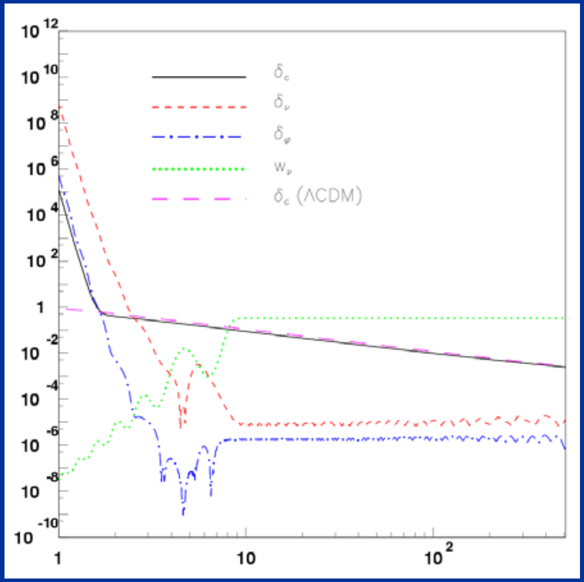


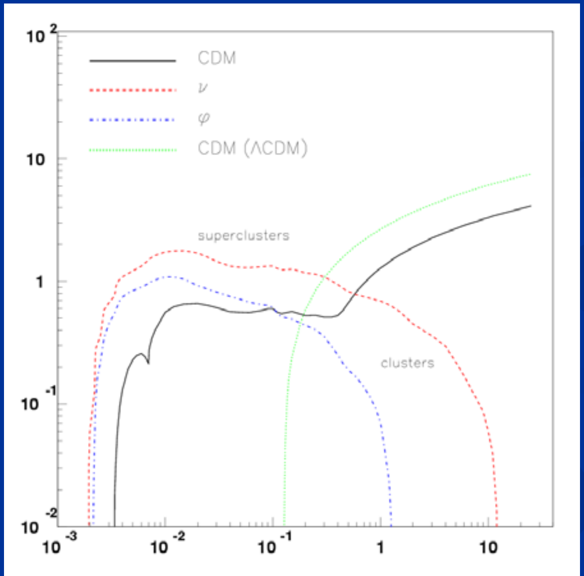
GERDA

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 ,…

Equation of state

p=T-V pressure

ϱ=T+V energy density

kinetic energy

$$T = \frac{1}{2}\dot{\phi}^2$$

Equation of state

$$w = \frac{p}{\rho} = \frac{T-V}{T+V}$$

Depends on specific evolution of the scalar field

Negative pressure

- $w < 0$ Ω_h increases (with decreasing z)

late universe with
small radiation component :

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

- $w < -1/3$ expansion of the Universe is accelerating

- $w = -1$ cosmological constant

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