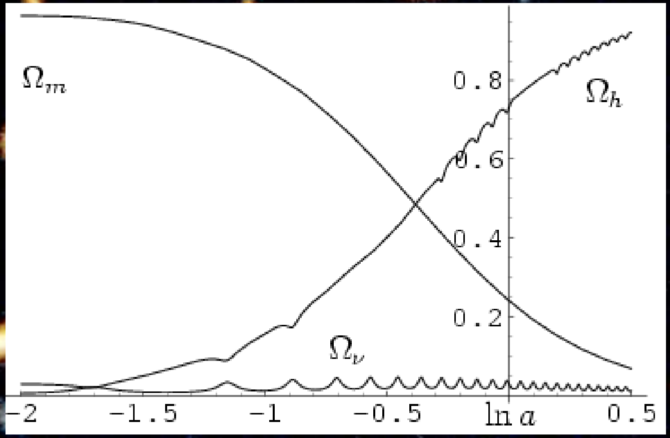
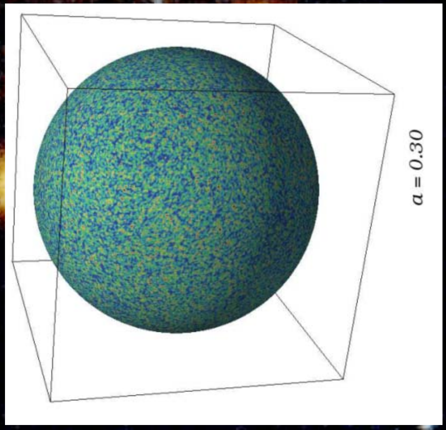
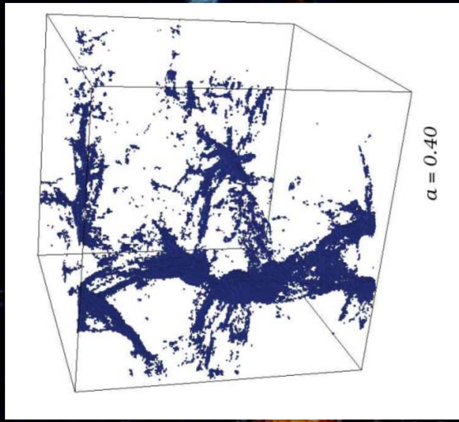
Have neutrinos to do with Dark Energy ?







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 .

Neutrino energy density not much smaller than Dark Energy density .

Neutrinos can have substantial **coupling to Dark Energy.**

connection between dark energy and neutrino properties

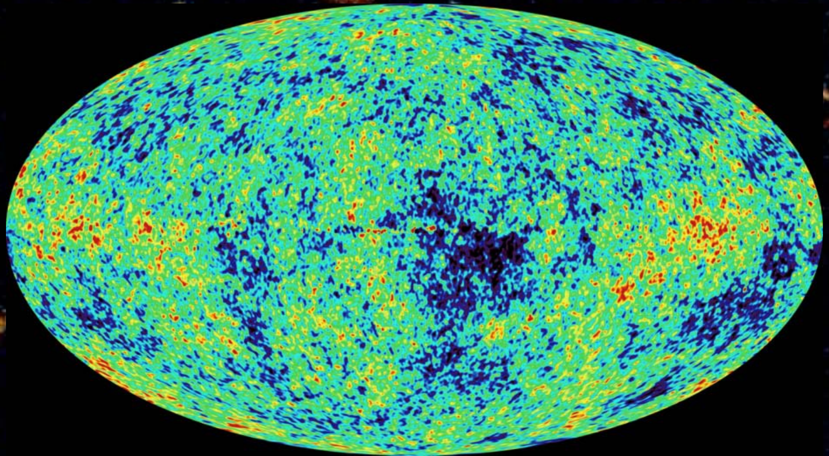
$$[\rho_h(t_0)]^{\frac{1}{4}} = 1.27 \left(\frac{\gamma m_\nu(t_0)}{eV}\right)^{\frac{1}{4}} 10^{-3} eV$$

present dark energy density given by neutrino mass

present equation of state given by neutrino mass !

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

What do we know about Dark Energy ?



Dark Energy dominates the Universe

Energy - density in the Universe

=

Matter + Dark Energy

25 % + 75 %

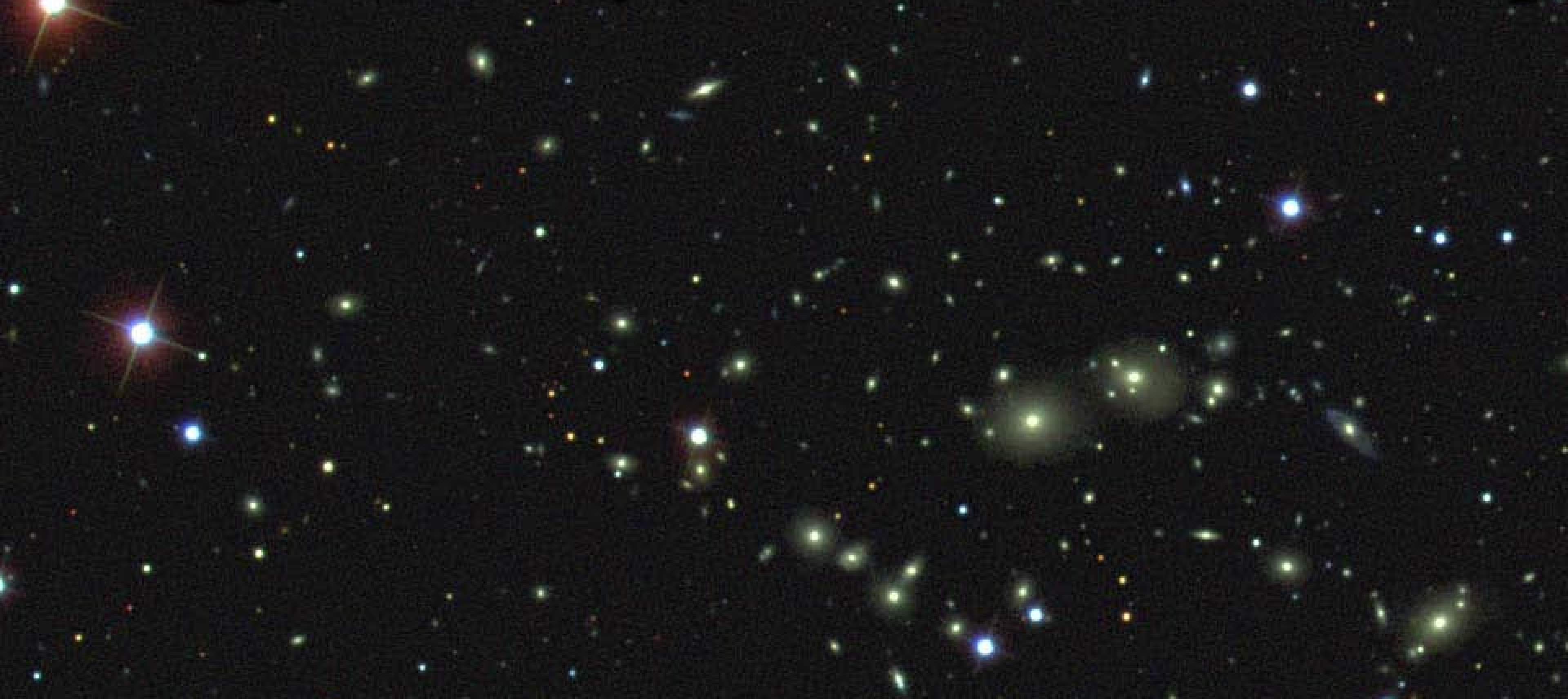
Composition of the universe

Atoms : $\Omega_b = 0.045$

Dark Matter : $\Omega_{dm} = 0.225$

Dark Energy : $\Omega_h = 0.73$

Dark Energy :
Energy density that does not clump



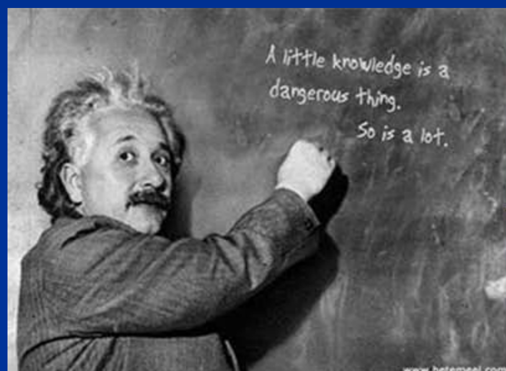
Photons , gravitons : insignificant

Space between clumps
is not empty :

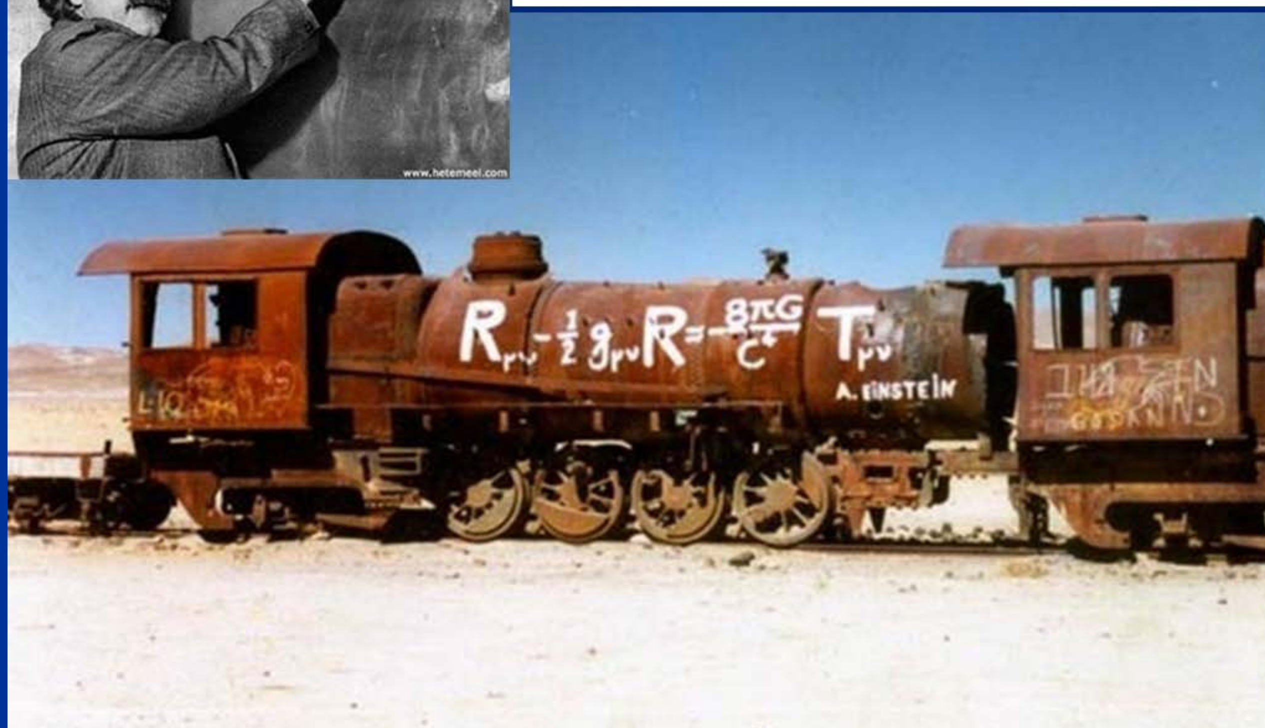
Dark Energy !

Dark Energy : Homogeneously distributed

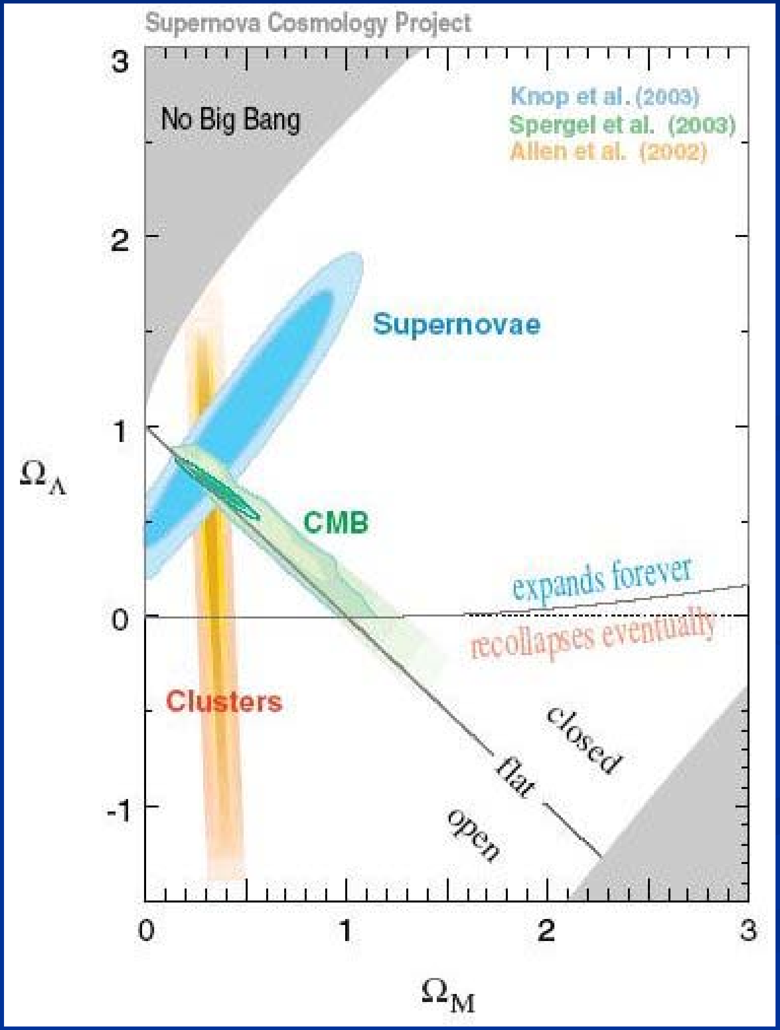
Einstein's equations :
(almost) static Dark Energy predicts accelerated expansion of Universe



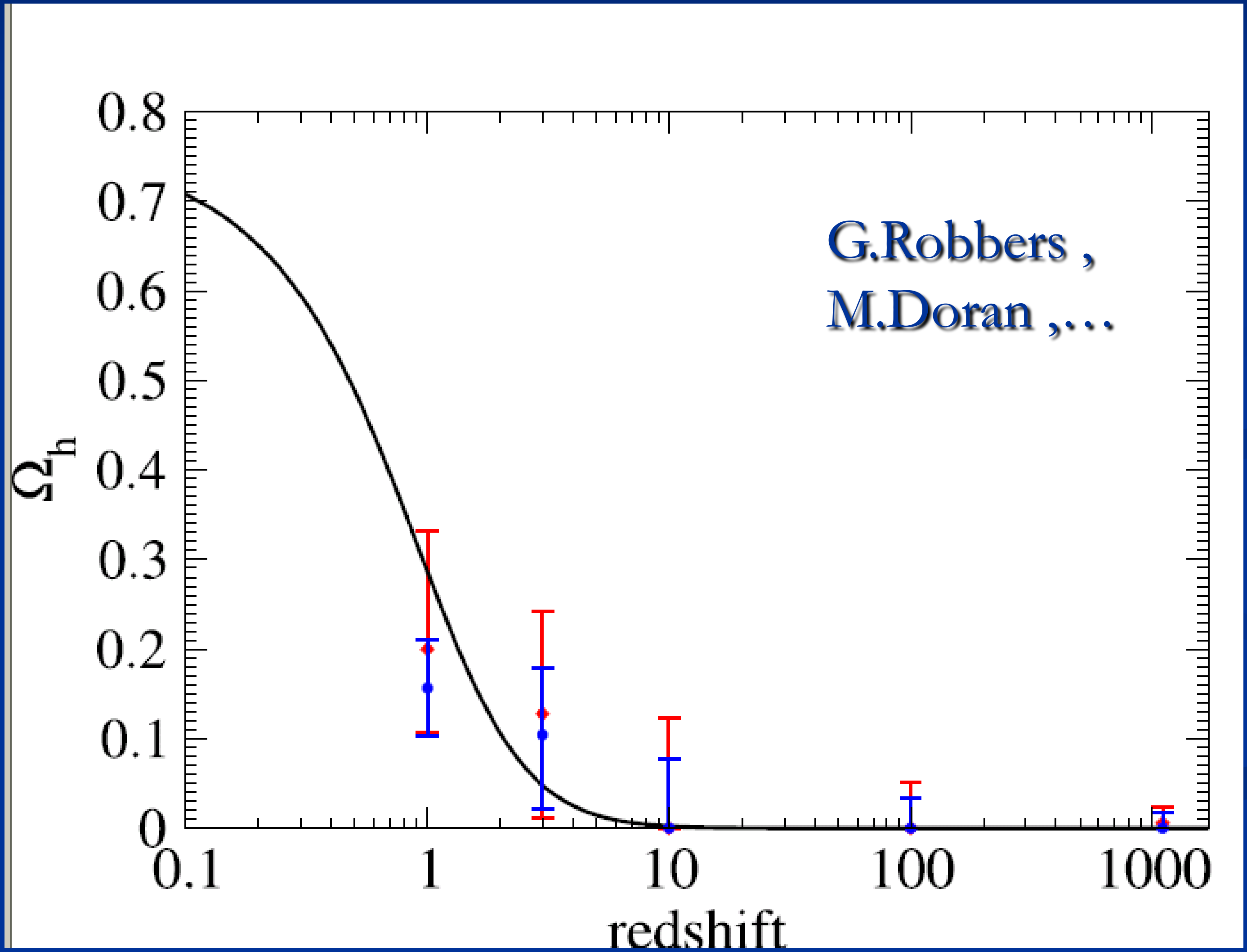
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$



Dark Energy : observations fit together !

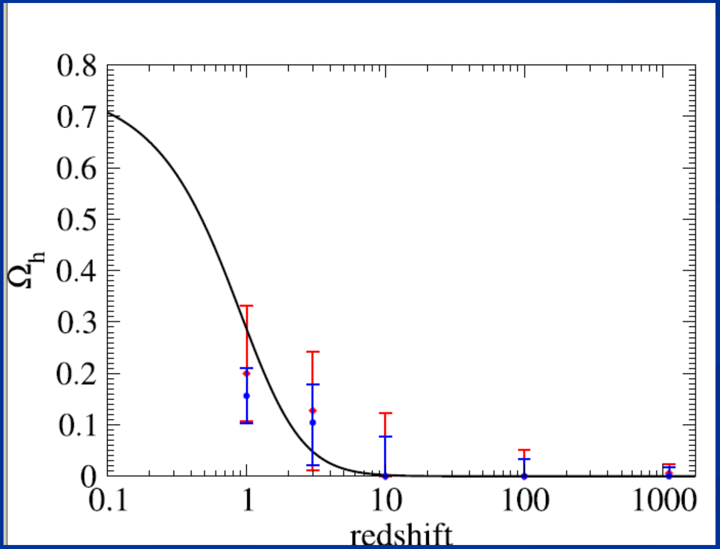


Observational bounds on Ω_h



Why now problem

Why does fraction in Dark Energy increase in present cosmological epoch ,
and not much earlier or much later ?



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 ?

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: $\rho_h/M^4 = 7 \; 10^{-121}$

matter: $\rho_m/M^4 = 3 \; 10^{-121}$

Time evolution

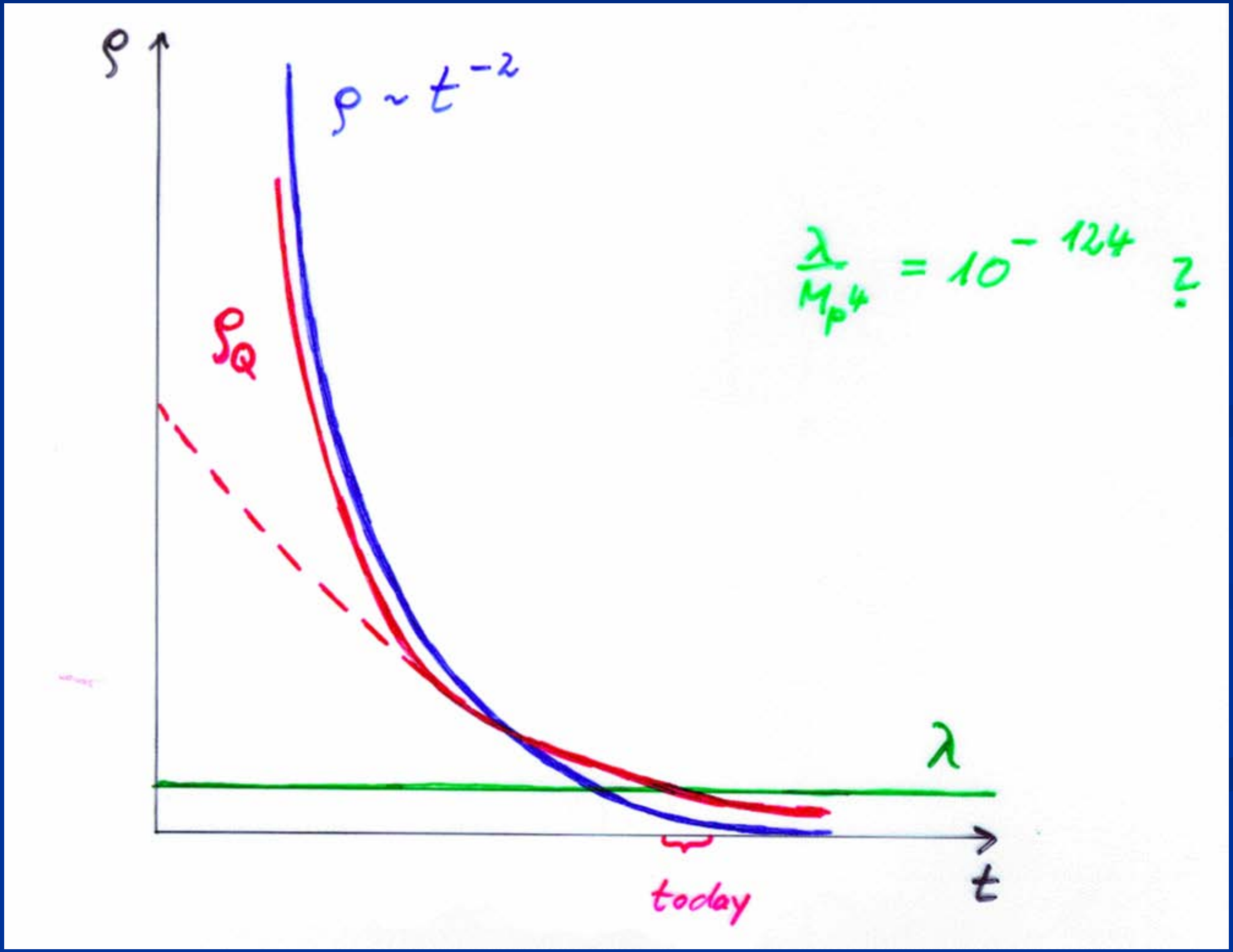
- $\varrho_m / M^4 \sim a^{-3} \sim$
  - t^{-2} matter dominated universe
  - $t^{-3/2}$ radiation dominated universe

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

Huge age → small ratio

Same explanation for small dark energy?

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

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 !

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

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

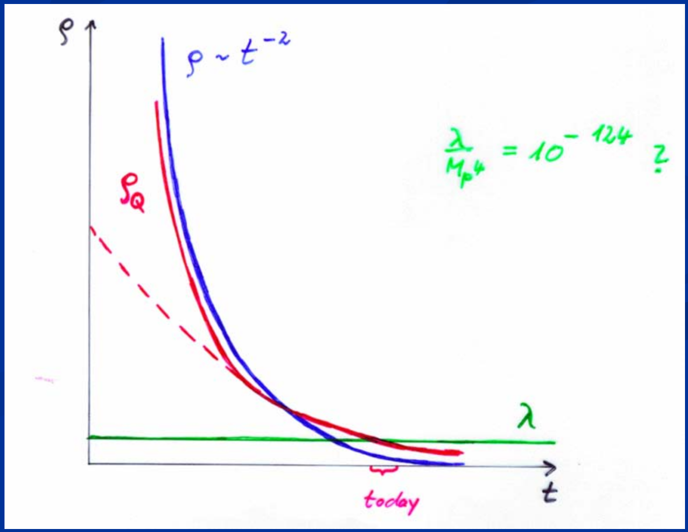
for increasing φ the potential decreases towards zero !

exponential potential ⇒ 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 !



Neutrinos in cosmology

only small fraction of energy density

→

only sub-leading role ?

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.

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

neutrino mass

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

(?) ….

C.Wetterich, Nucl.Phys.B187 (1981) 343

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

cascade (seesaw II) mechanism

M.Magg, C.W. 1980

Neutrino cosmon coupling

- realized by dependence of neutrino mass on value of cosmon field

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

- $\beta \approx 1$: cosmon mediated attractive force between neutrinos has similar strength as gravity

growing neutrino quintessence

growing neutrinos change cosmon evolution

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

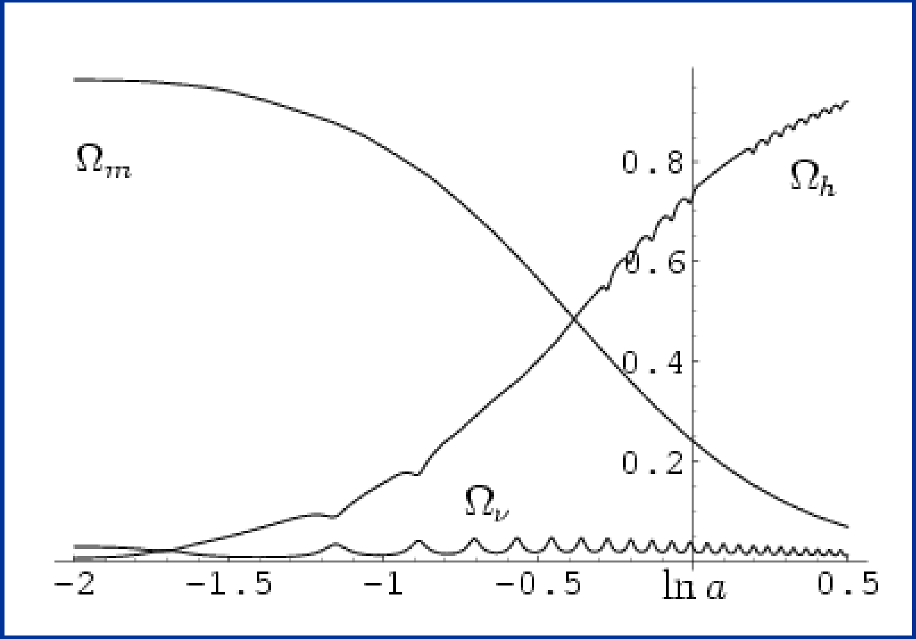
$$\beta(\varphi) = -M\frac{\partial}{\partial \varphi}\ln m_\nu(\varphi) = \frac{M}{\varphi - \varphi_t}$$

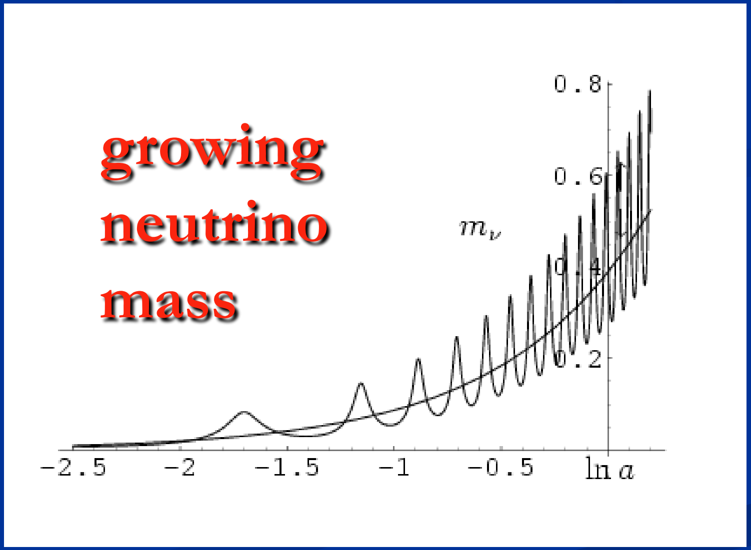
modification of conservation equation for neutrinos

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

$$= -\frac{\dot{\varphi}}{\varphi - \varphi_t}(\rho_\nu - 3p_\nu)$$

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 !

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

cosmological selection

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

  neutrinos become non – relativistic

- not given by ground state properties !

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,…

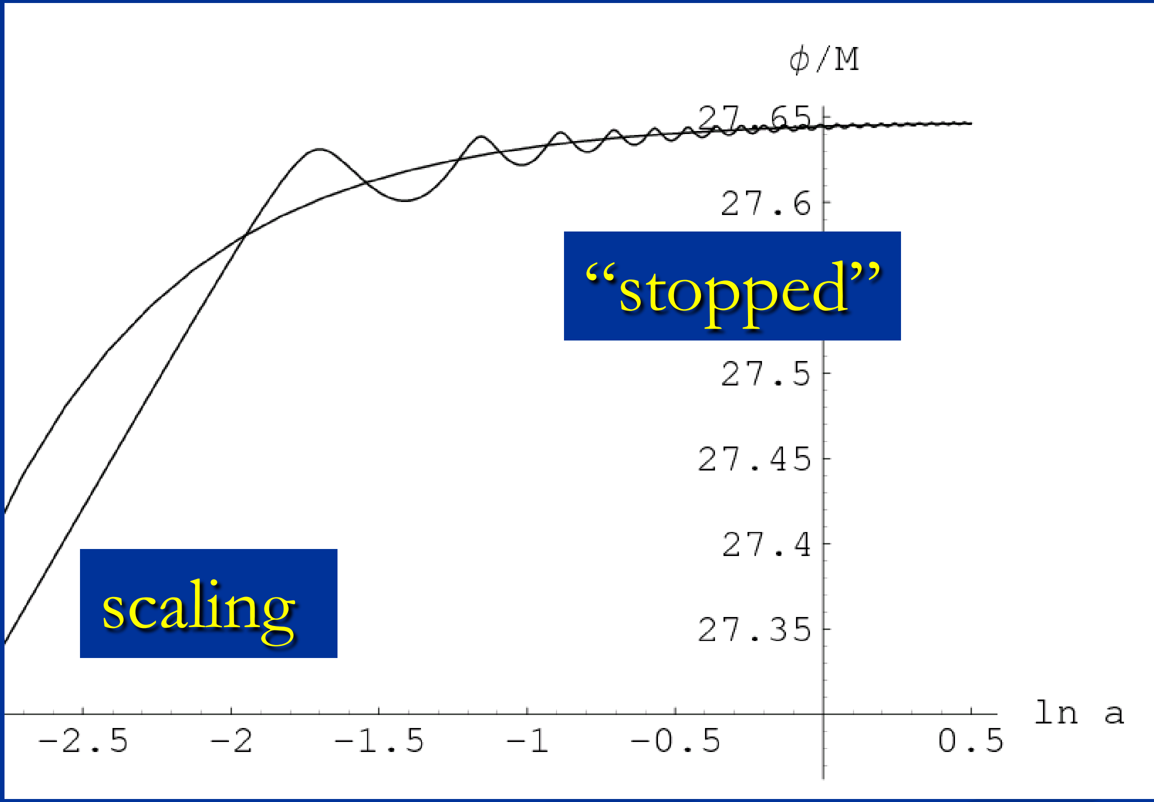
stopped scalar field mimicks a cosmological constant (almost …)

rough approximation for dark energy :

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

  (cosmological constant)

cosmon evolution

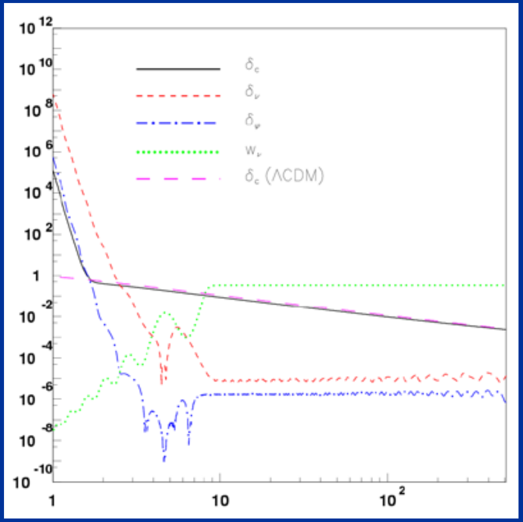


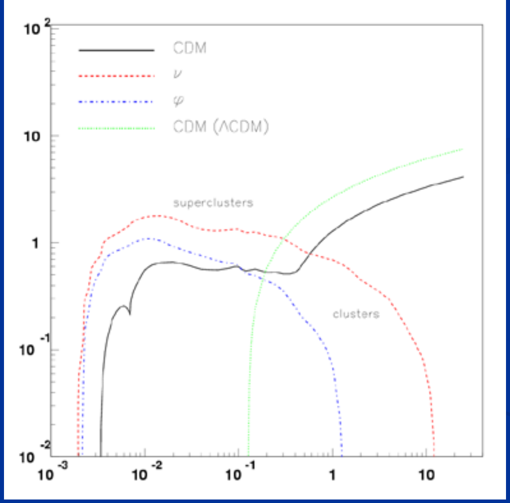
neutrino lumps

neutrino fluctuations

neutrino structures become nonlinear at z~1 for supercluster scales

D.Mota , G.Robbers , V.Pettorino , …

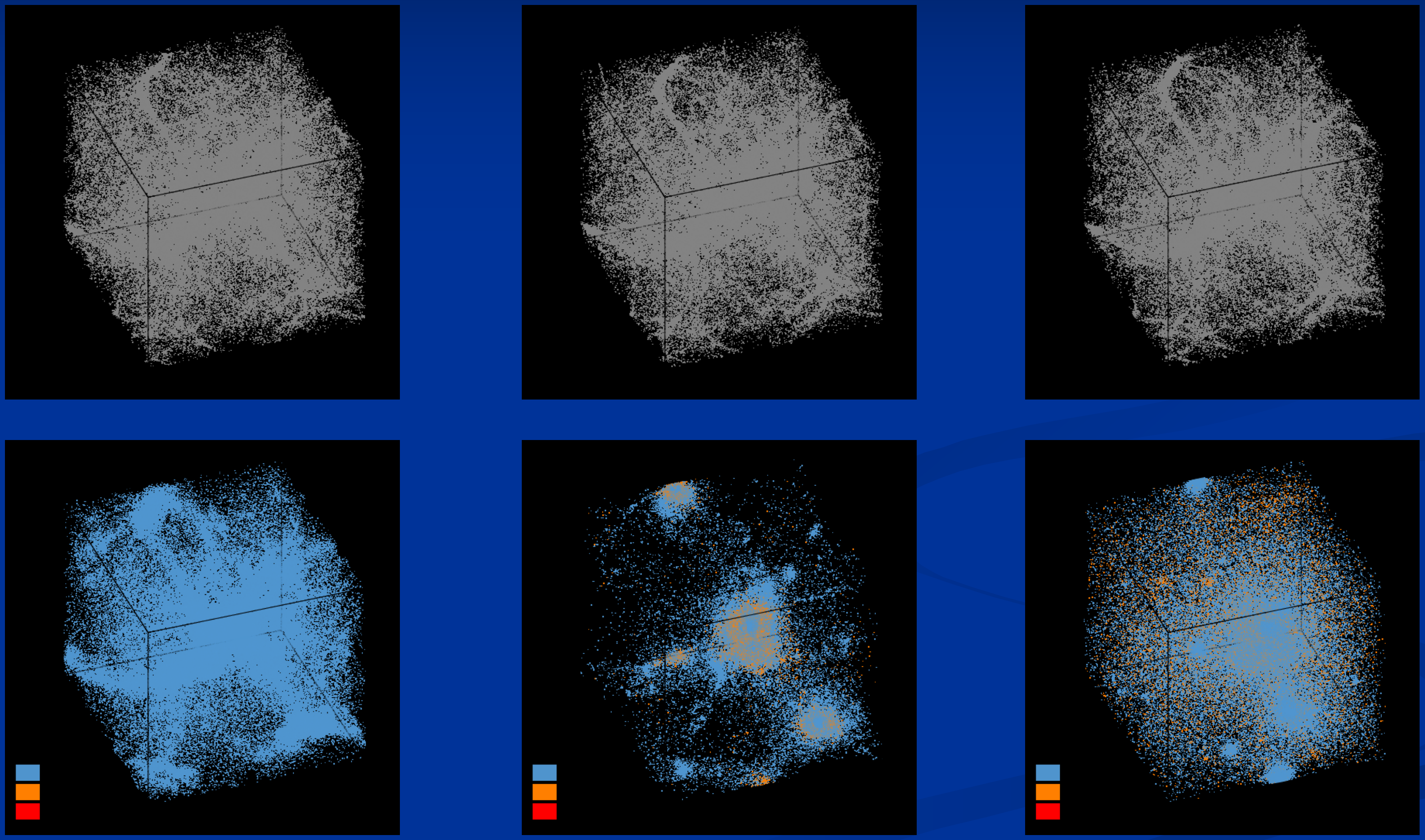




stable neutrino-cosmon lumps exist

N.Brouzakis , N.Tetradis ,… ; O.Bertolami ; Y.Ayaita , M.Weber,…

Formation of neutrino lumps



N- body simulation M.Baldi et al

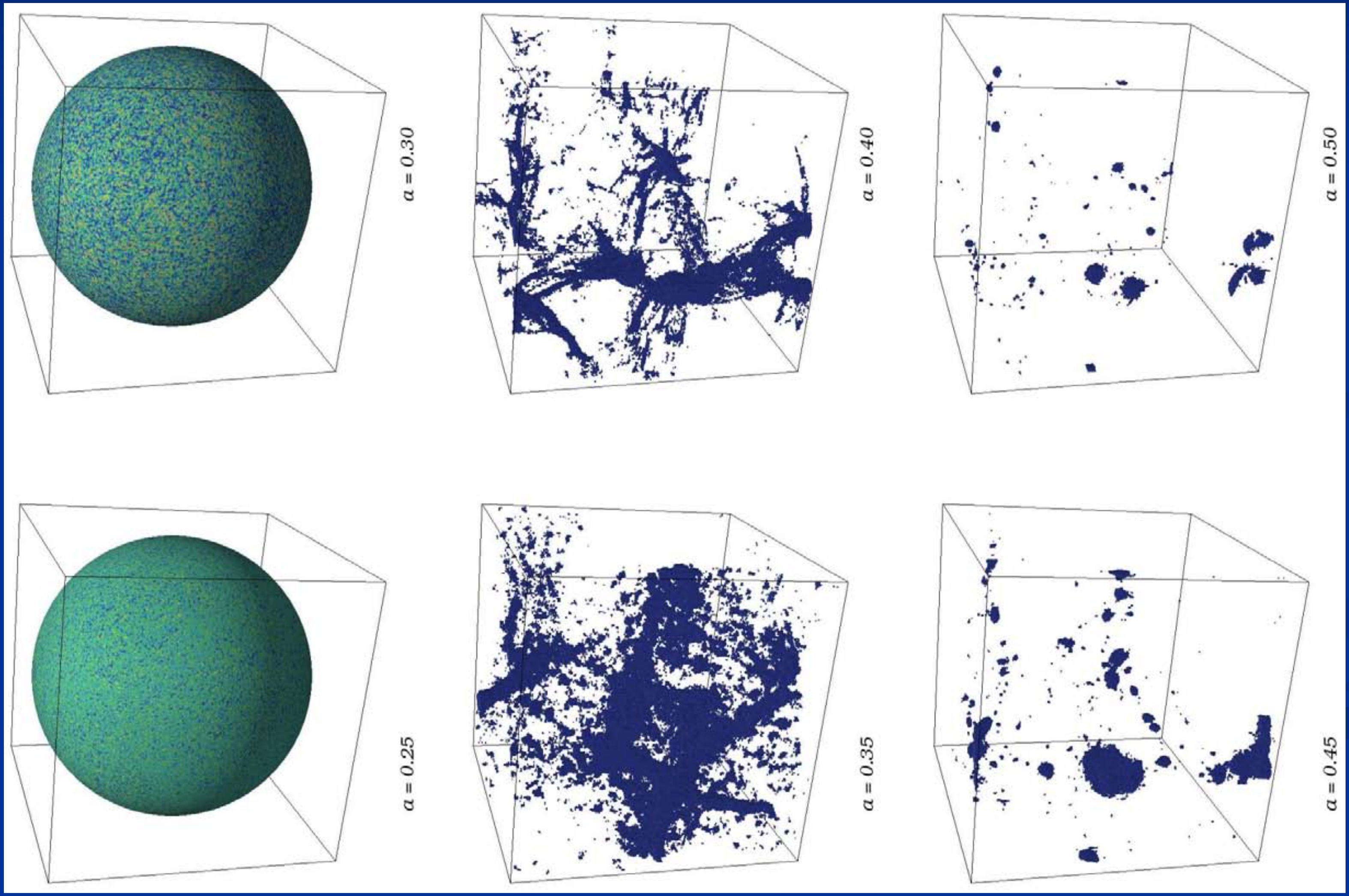
N-body code with fully relativistic neutrinos and backreaction

one has to resolve local value of cosmon field and then form cosmological average;
similar for neutrino density, dark matter and gravitational field

Y.Ayaita,M.Weber,…

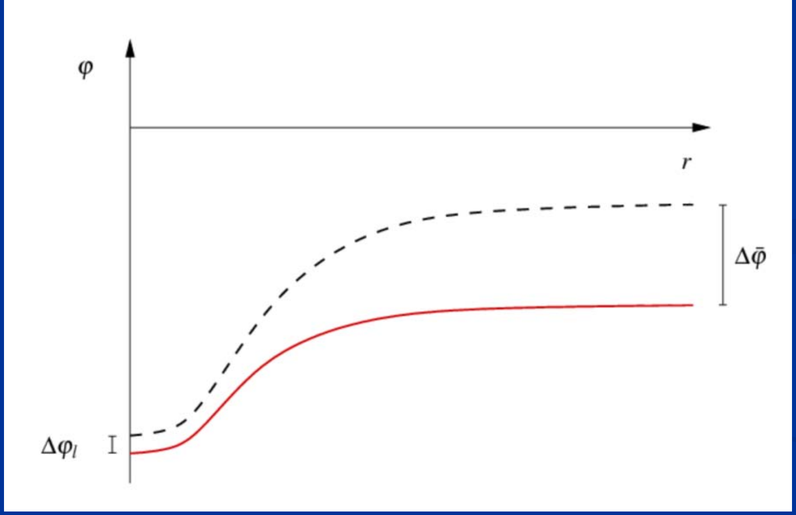
Formation of neutrino lumps

Y.Ayaita,M.Weber,…



backreaction

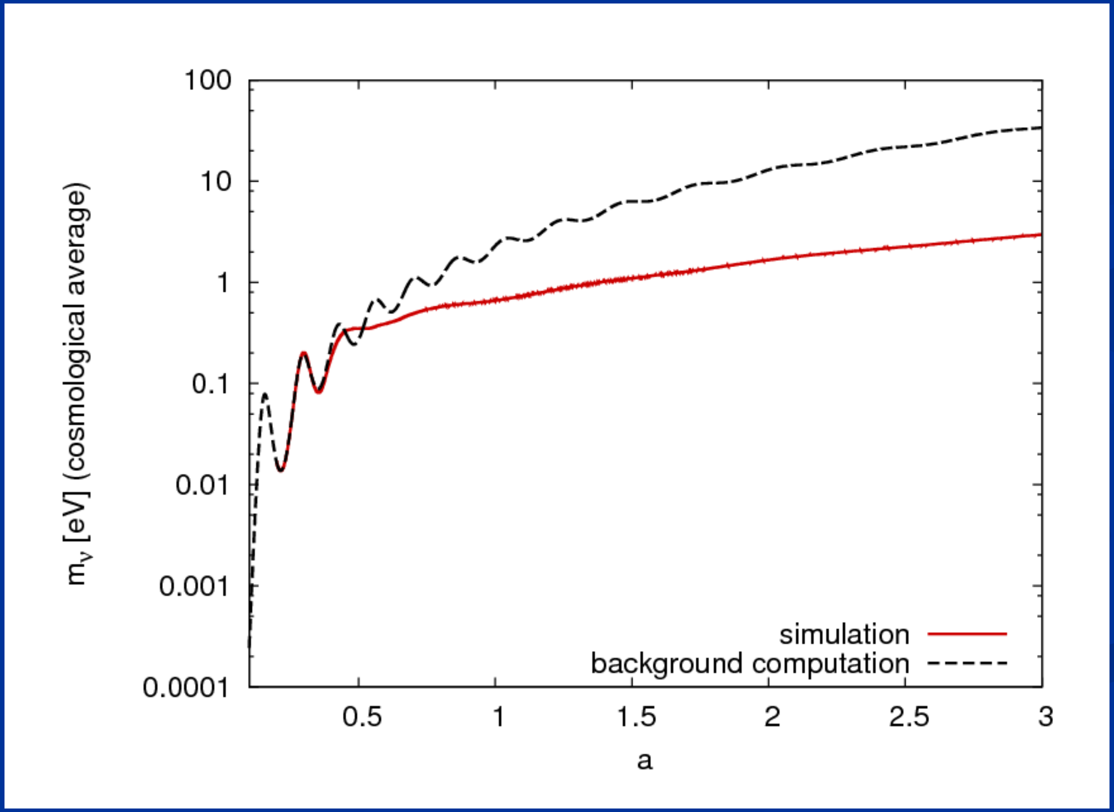
cosmon field inside lumps does not follow cosmological evolution



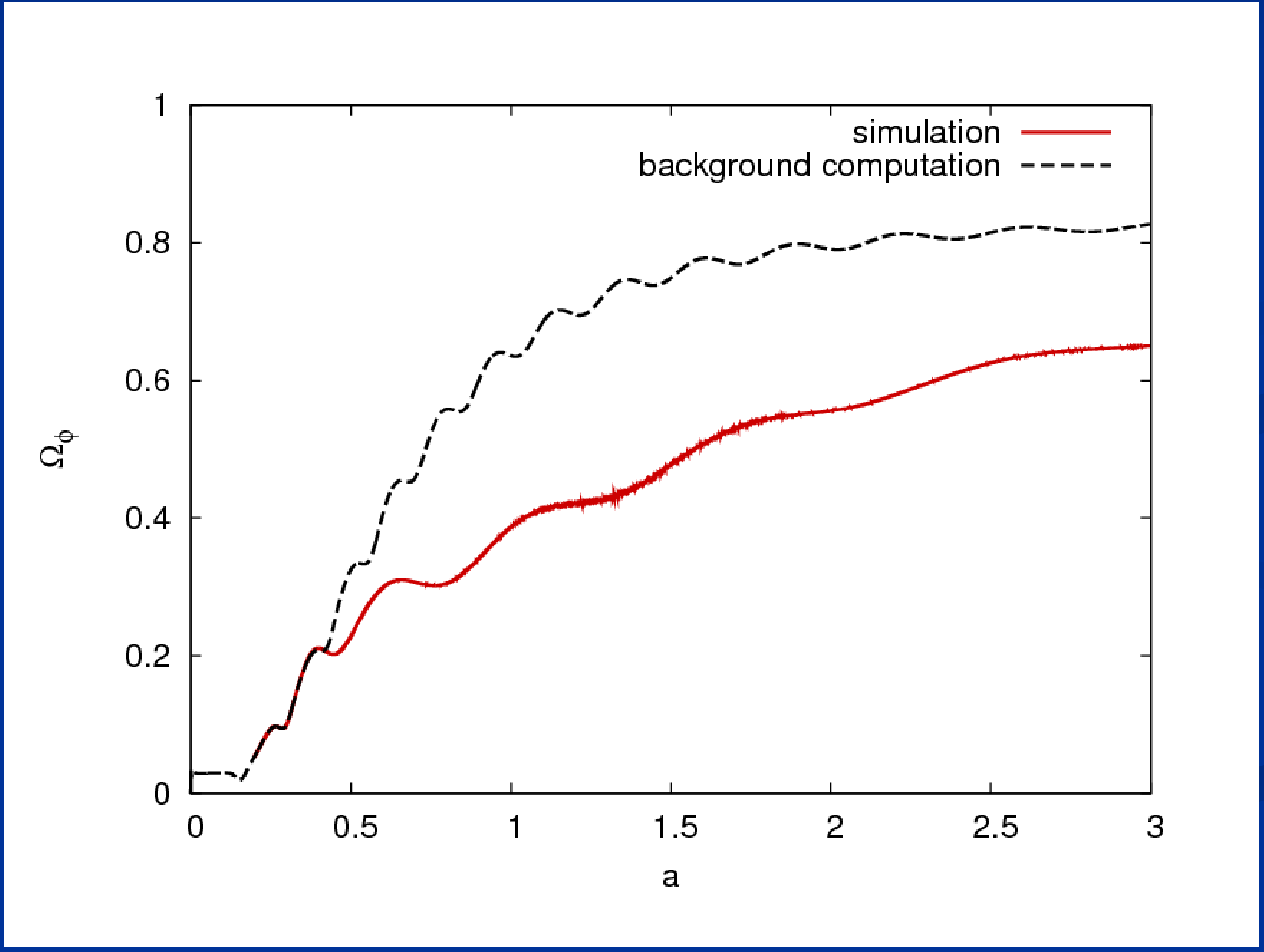
neutrino mass inside lumps smaller than in environment   L.Schrempp, N.Nunes,…

importance of backreaction : cosmological average of neutrino mass

Y.Ayaita , E.Puchwein,…

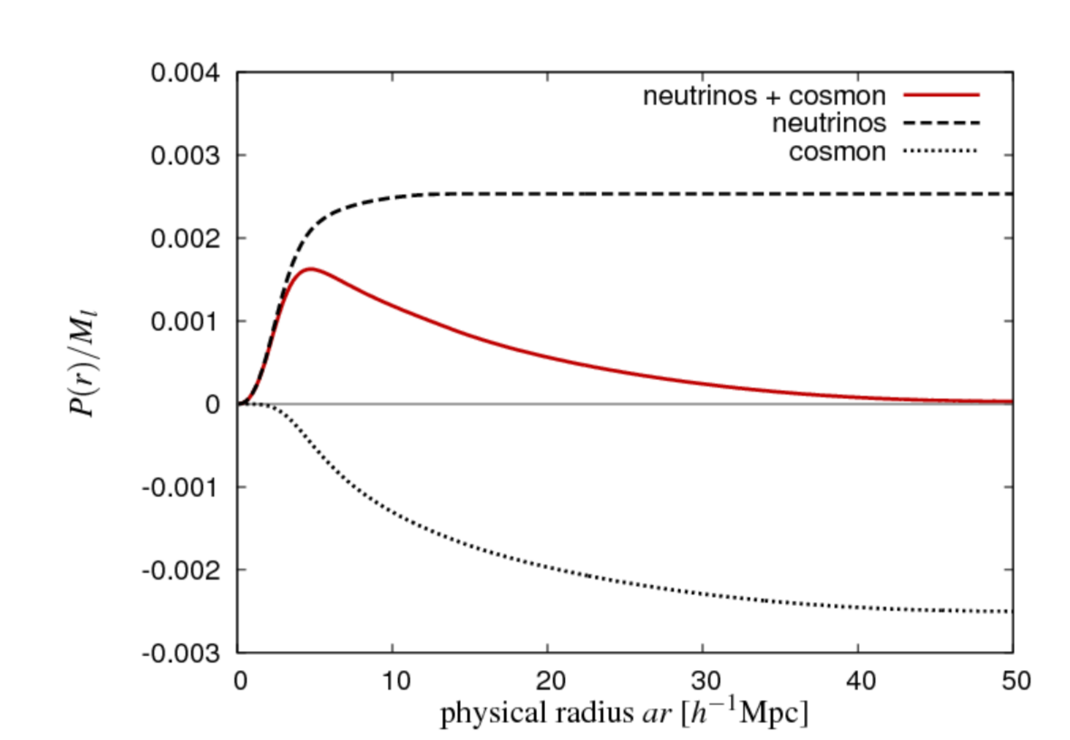


importance of backreaction : fraction in Dark Energy

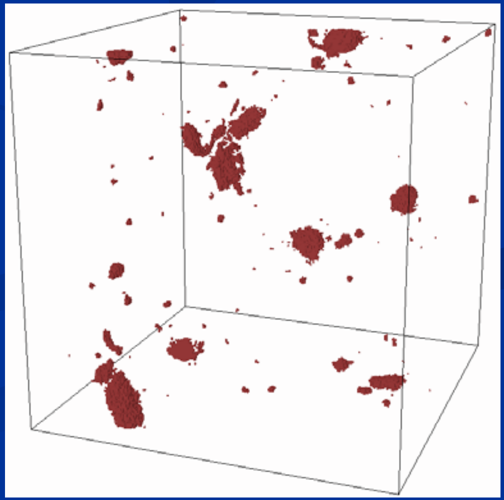


neutrino lumps

behave as non-relativistic fluid with effective coupling to cosmon



Y.Ayaita, M.Weber,…



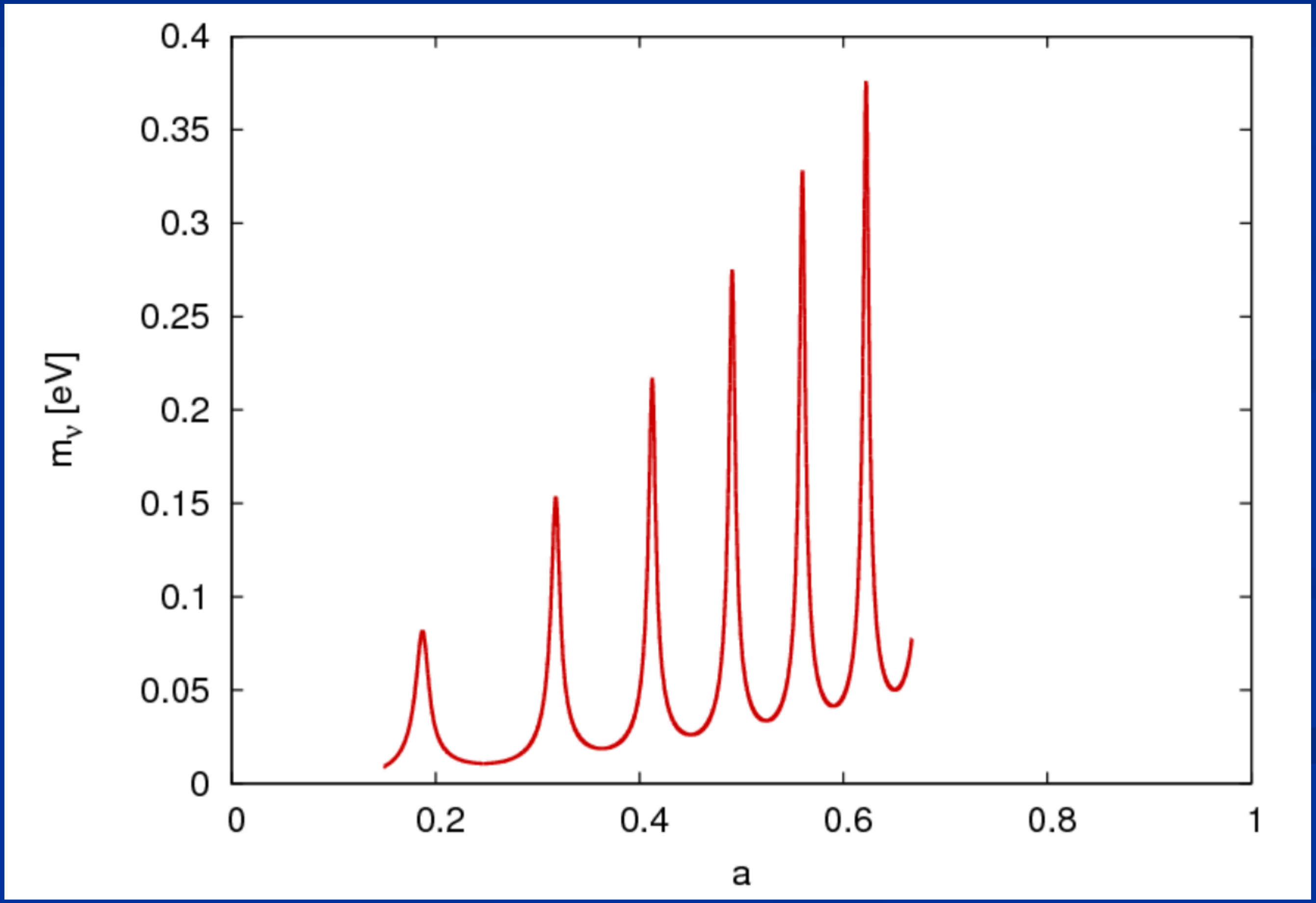
φ - dependent neutrino – cosmon coupling

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

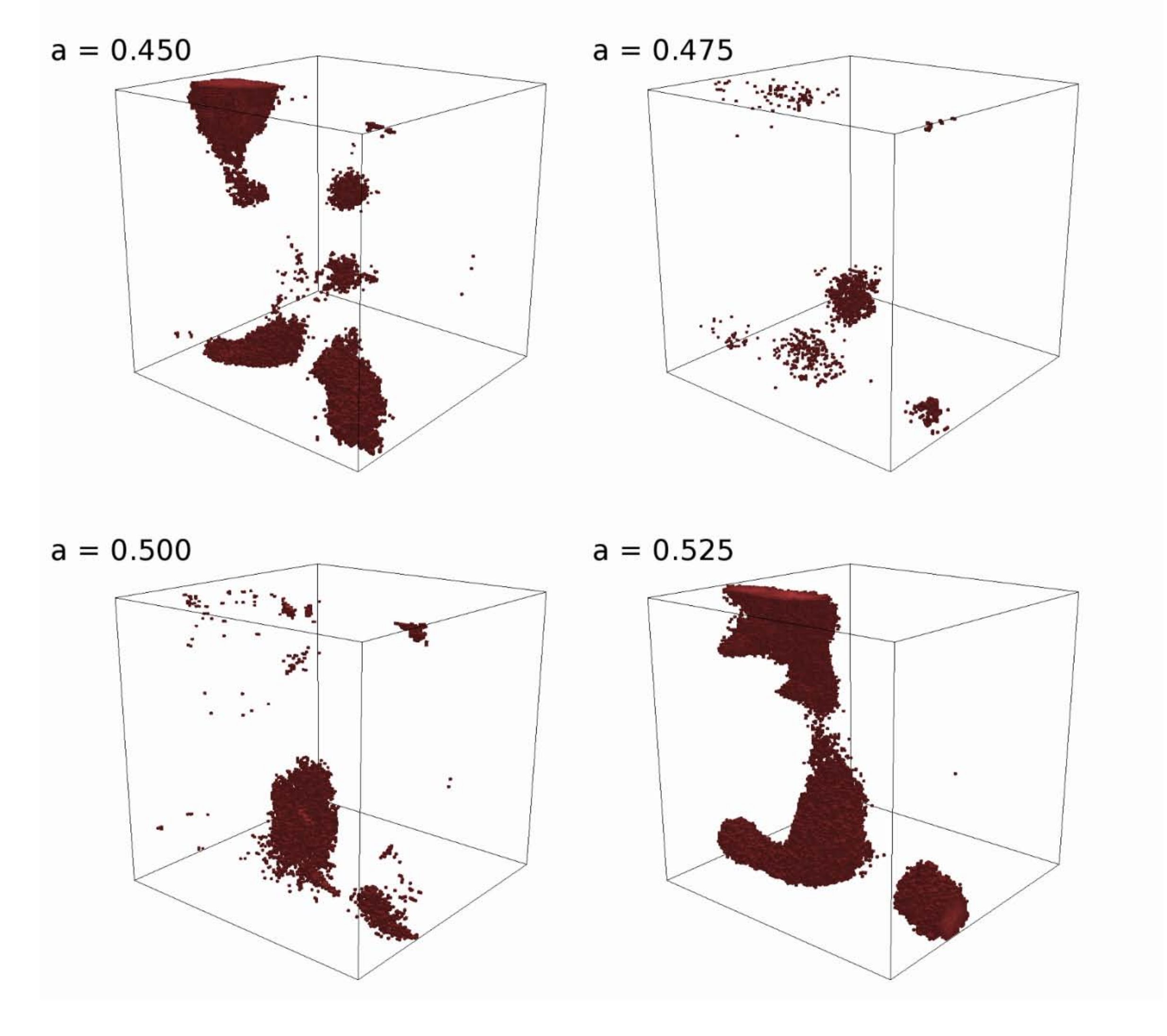
neutrino lumps form and are disrupted by oscillations in neutrino mass

smaller backreaction

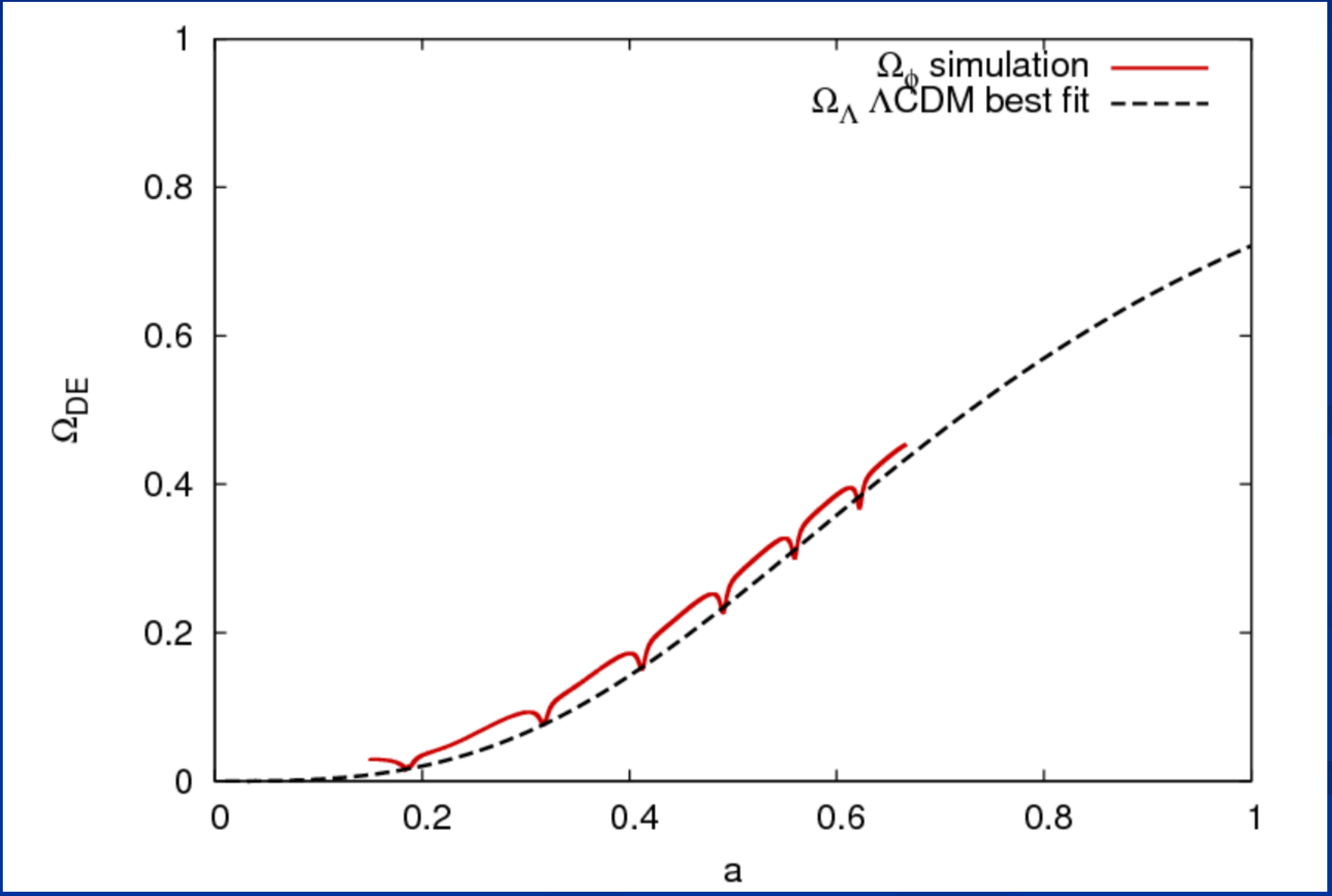
oscillating neutrino mass



oscillating neutrino lumps



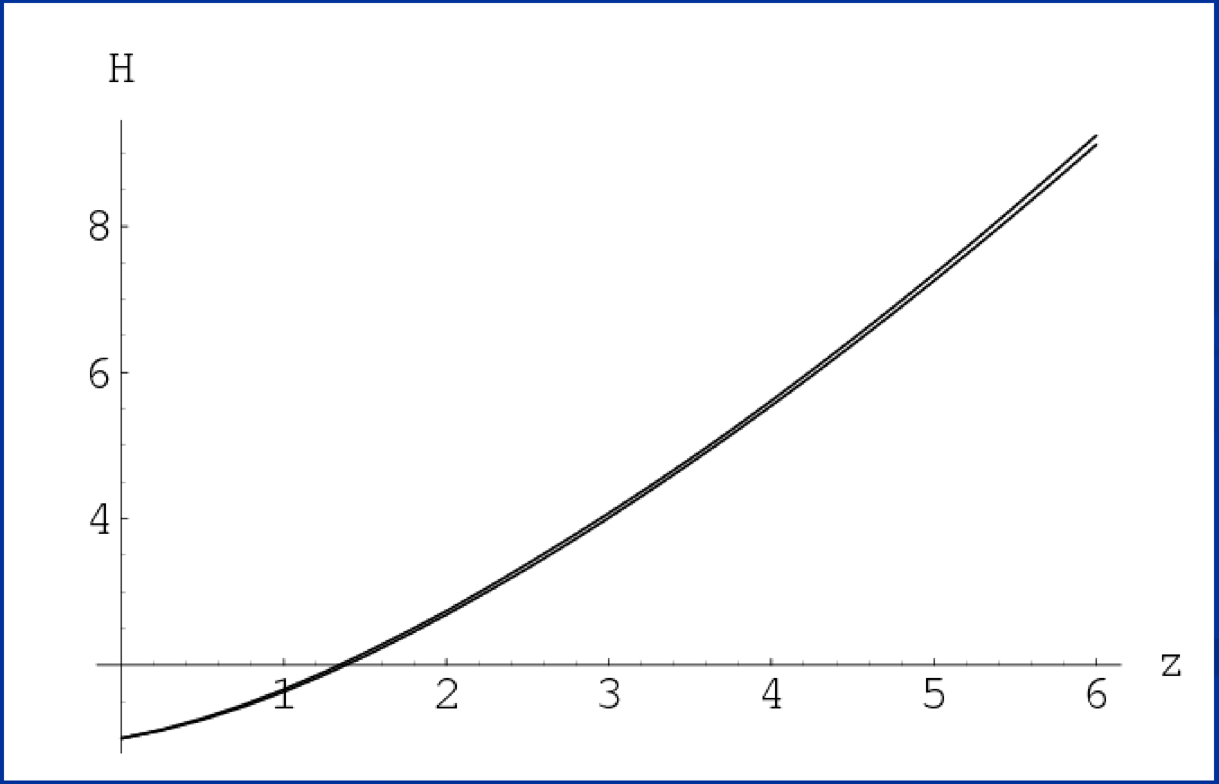
small oscillations in dark energy



Tests for growing neutrino quintessence

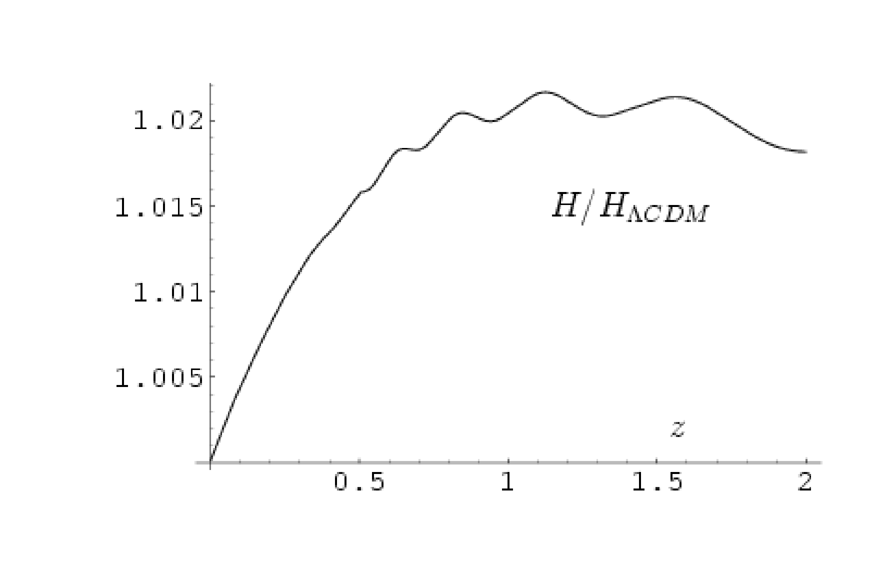
Hubble parameter

as compared to ΛCDM



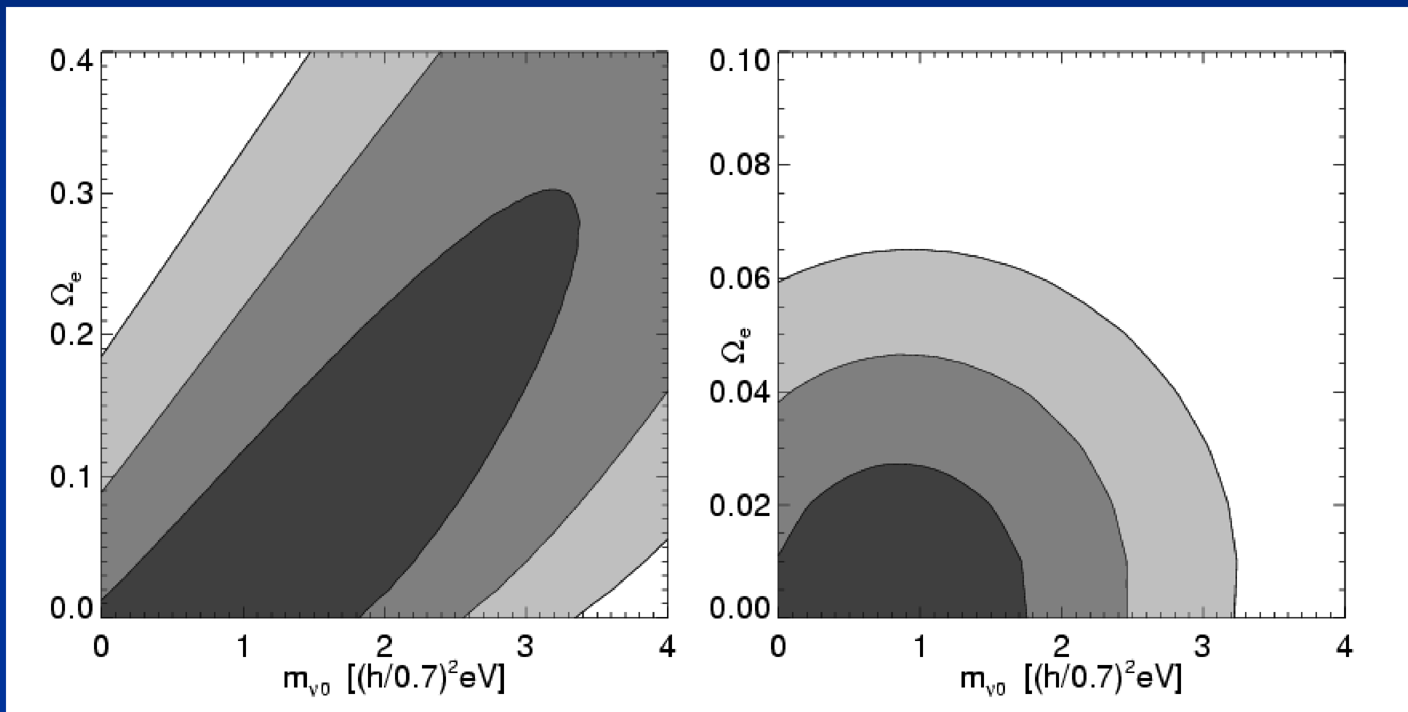
Hubble parameter (z < z_c)

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



only small difference from ΛCDM !

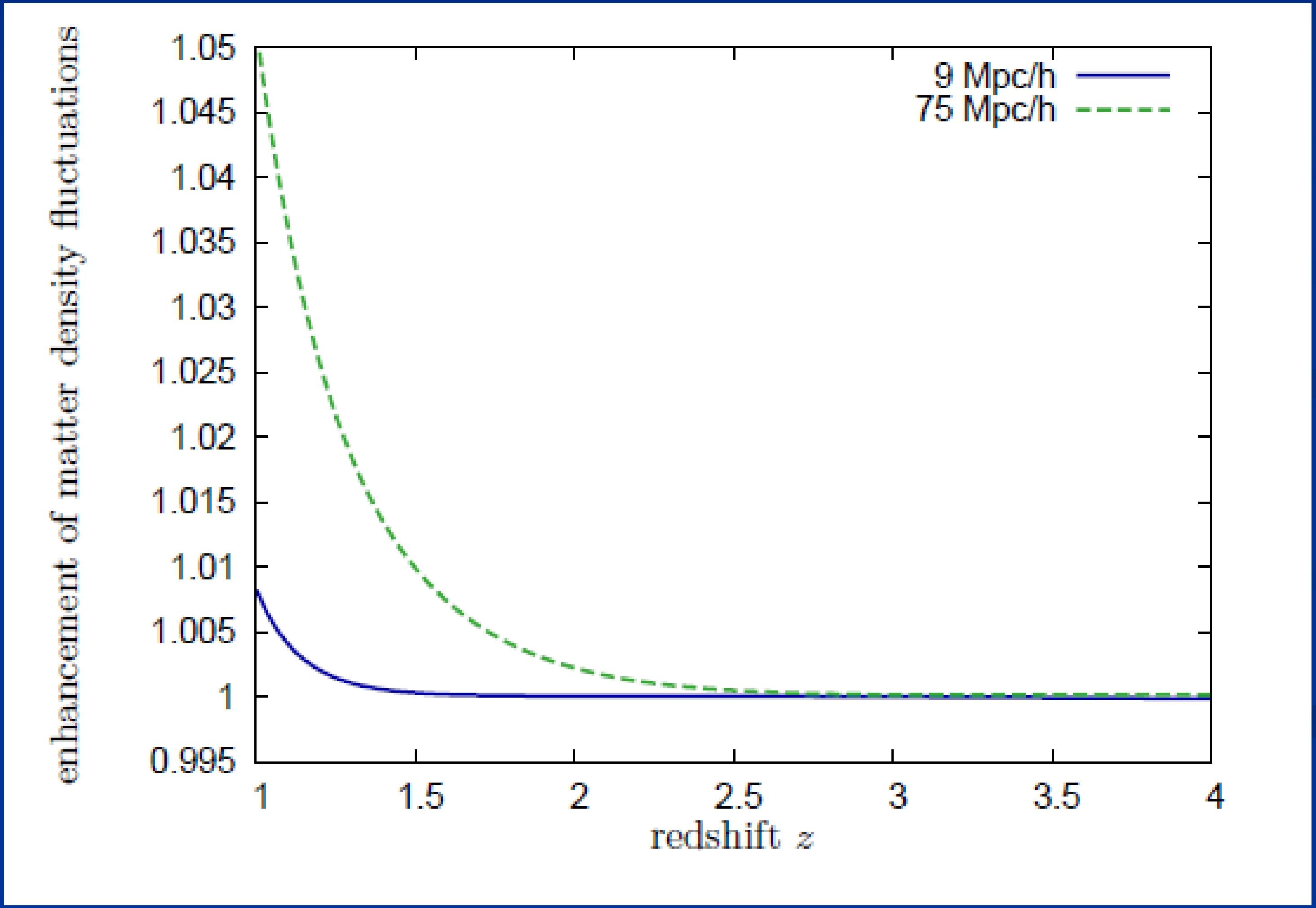
bounds on average neutrino mass



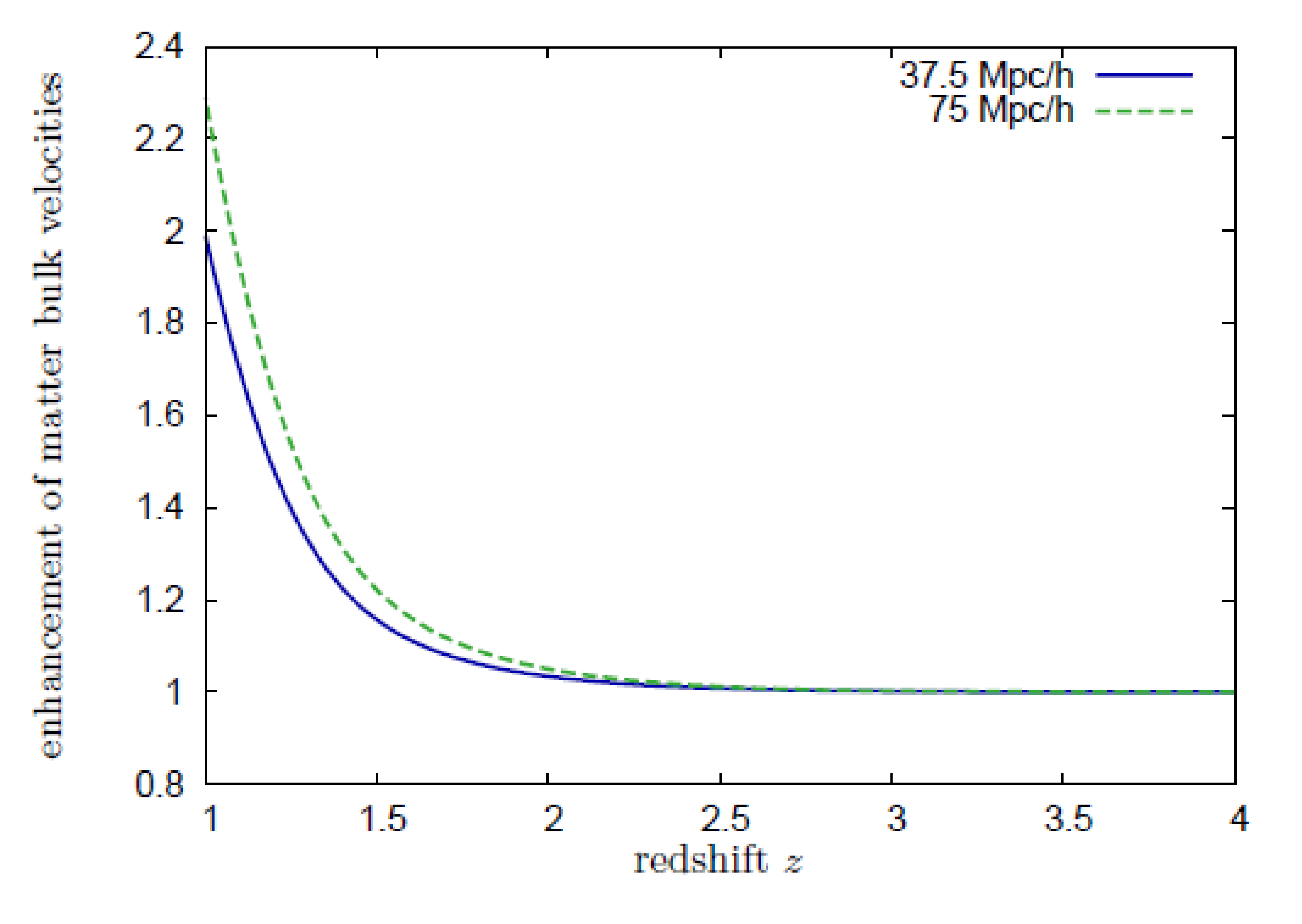
Looking Beyond Lambda with the Union Supernova Compilation

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)

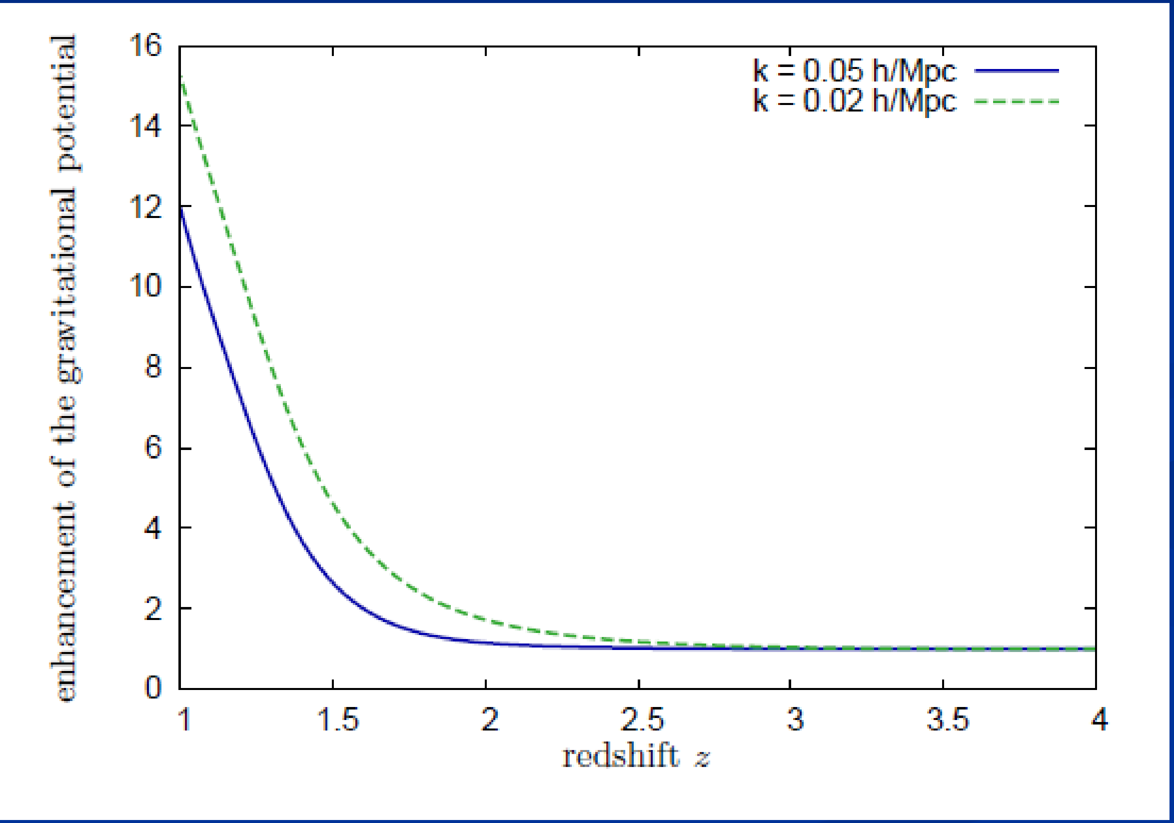
Small induced enhancement of dark matter power spectrum at large scales



Enhanced bulk velocities



Enhancement of gravitational potential

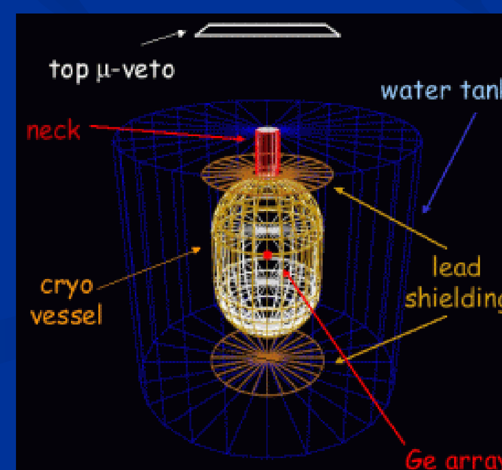


Test of allowed parameter space by ISW effect

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

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

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 :*

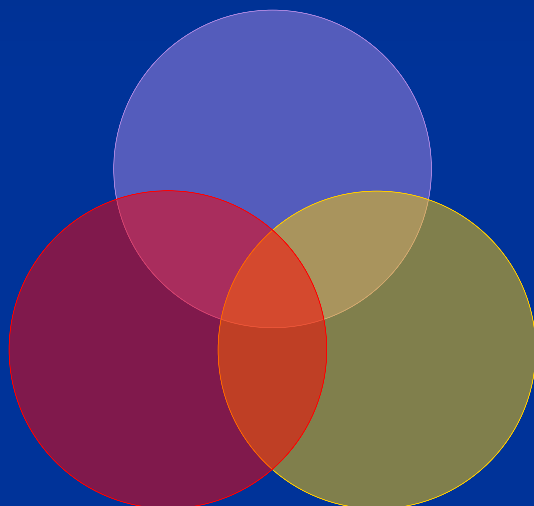
  $\varrho_h(t)$ *decreases with time !*

Cosmon

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

"Fundamental" Interactions

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

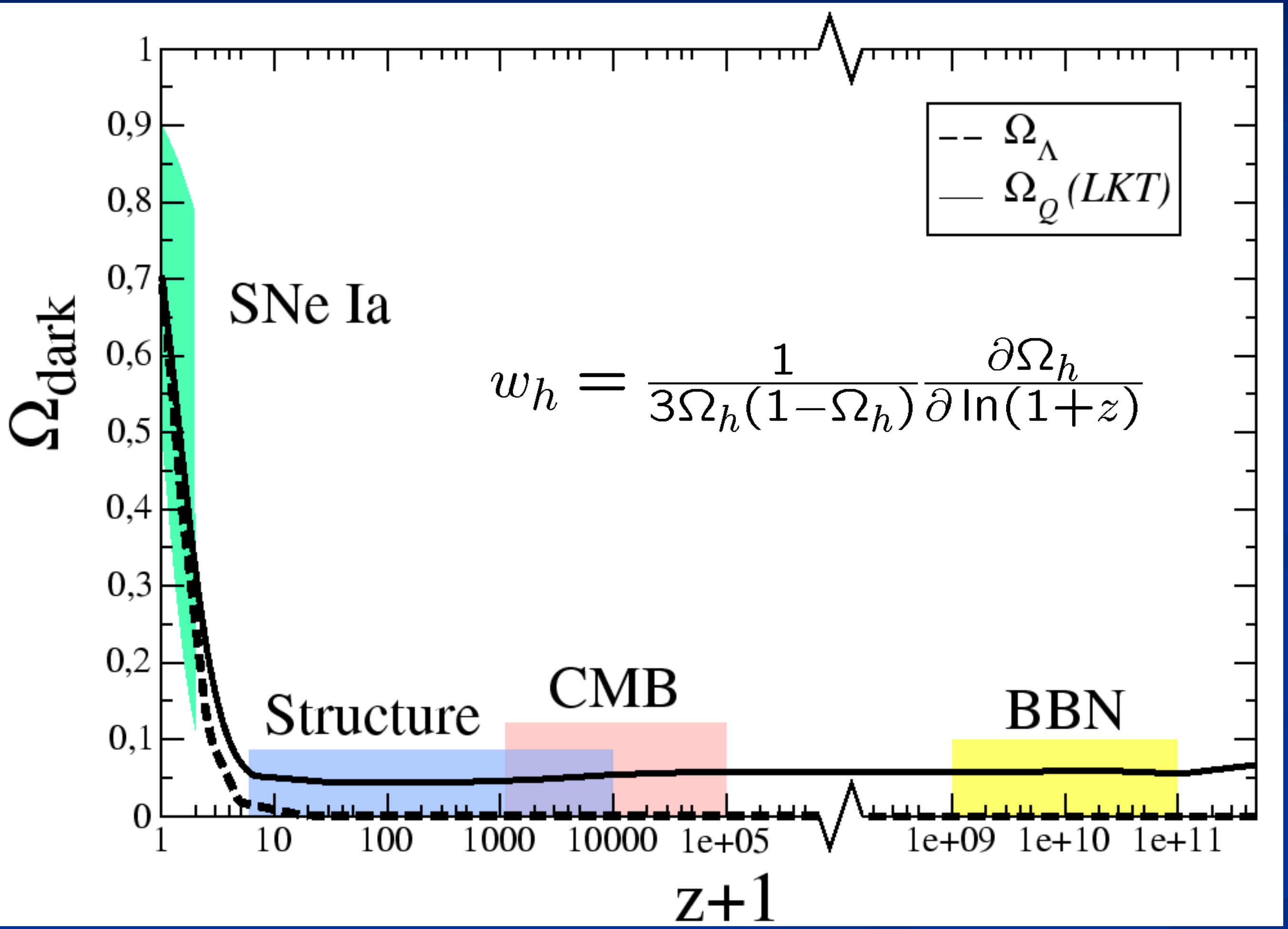
On astronomical length scales:

graviton

+

cosmon

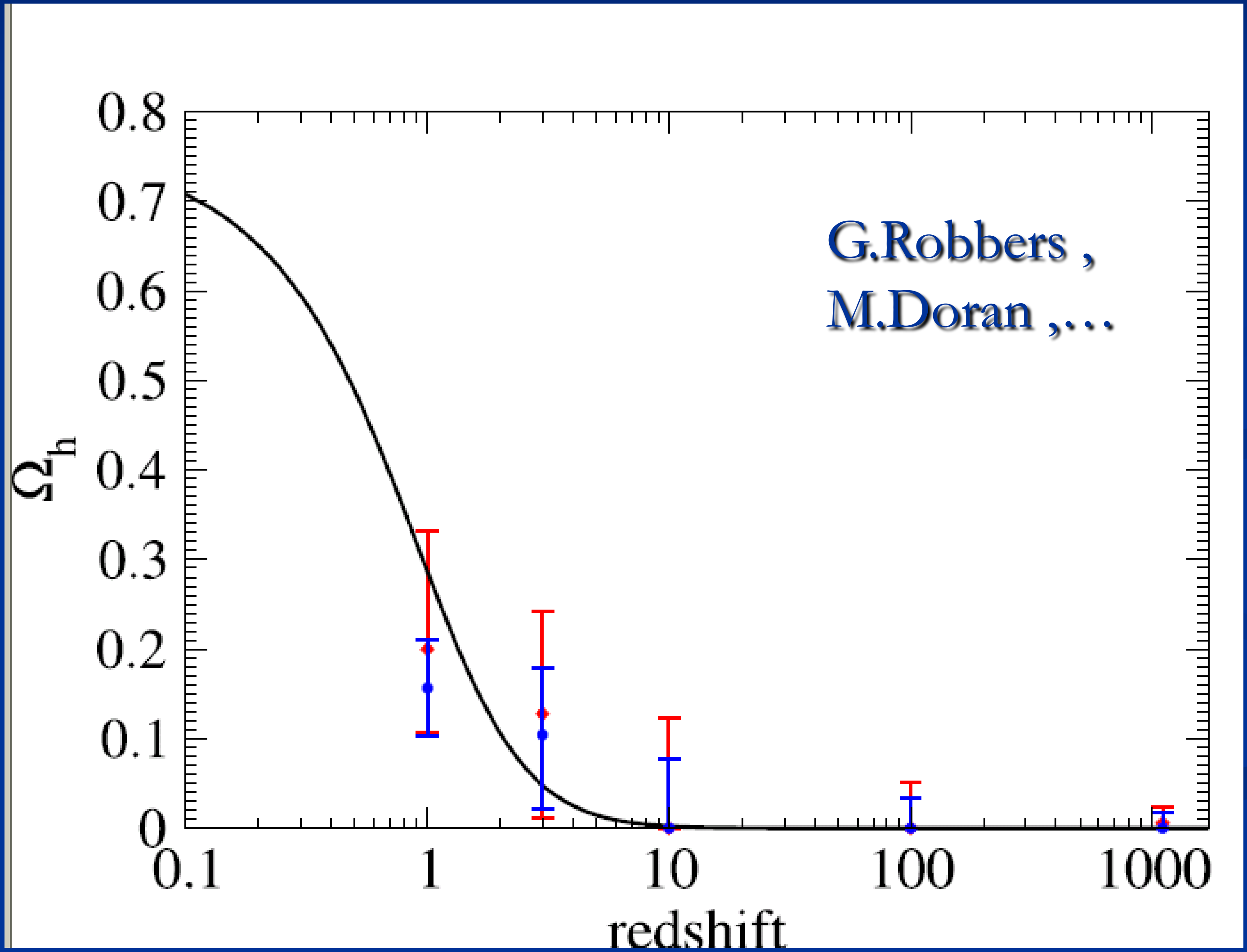
Early Dark Energy



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

M.Doran,…

Observational bounds on Ω_h



Cosmic Attractors

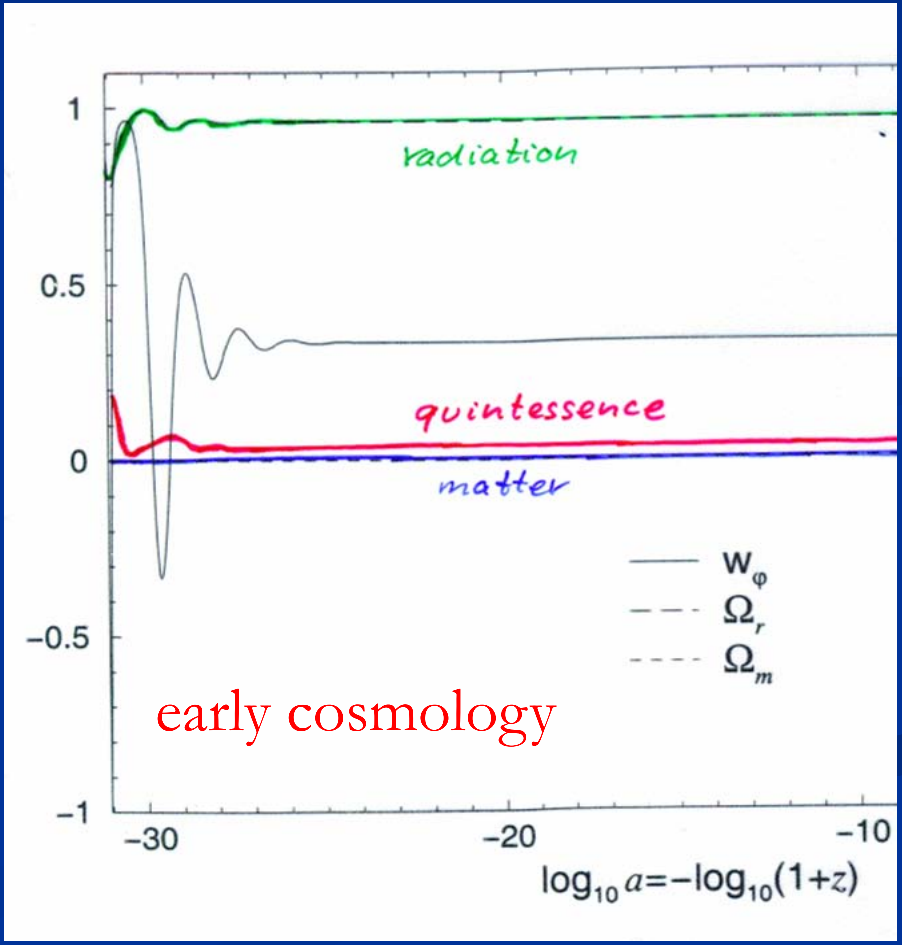
Solutions independent of initial conditions

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

$\varphi \sim \ln(t)$

$\Omega_h \sim$ const.

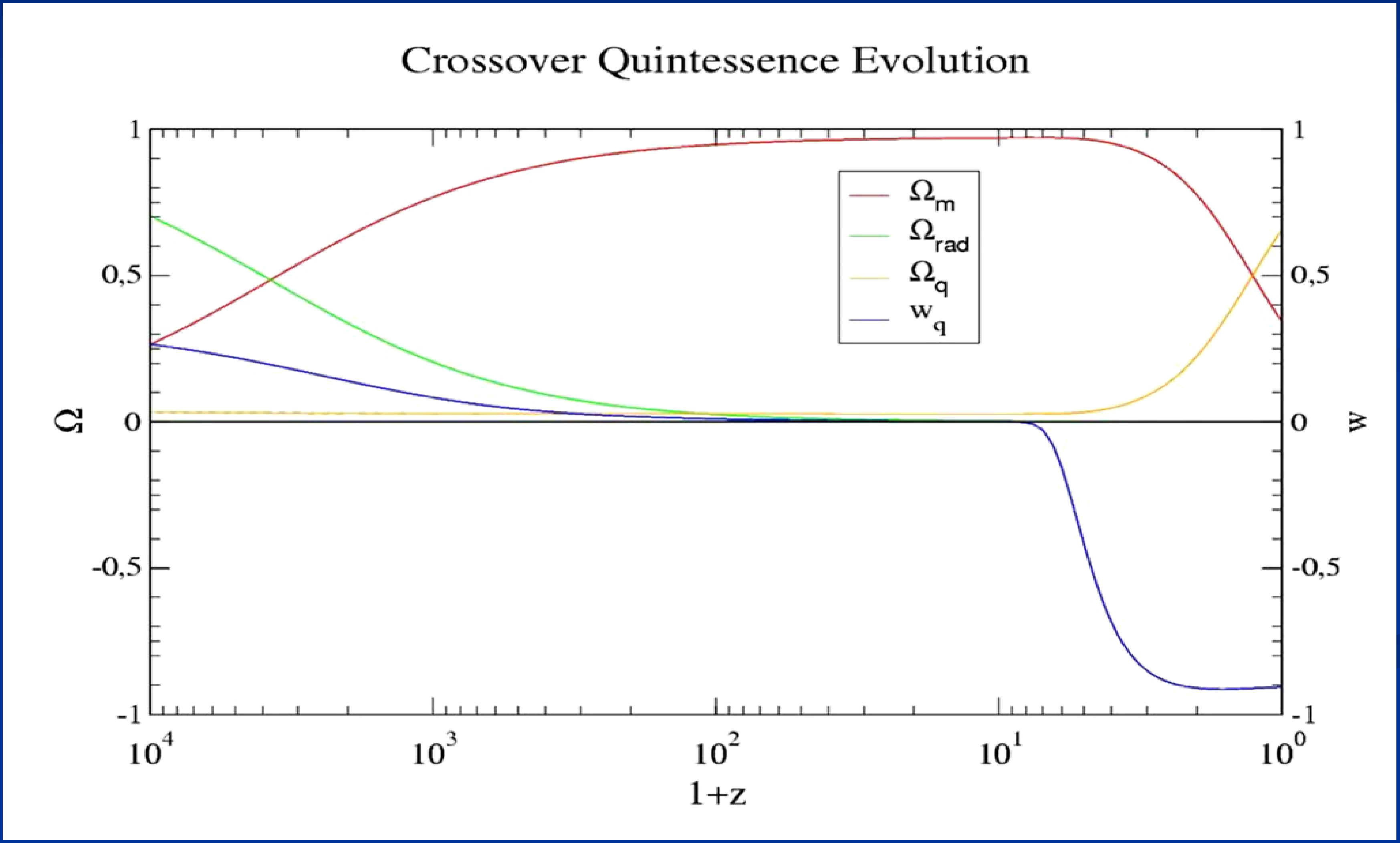
details depend on $V(\varphi)$ or kinetic term



realistic quintessence

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

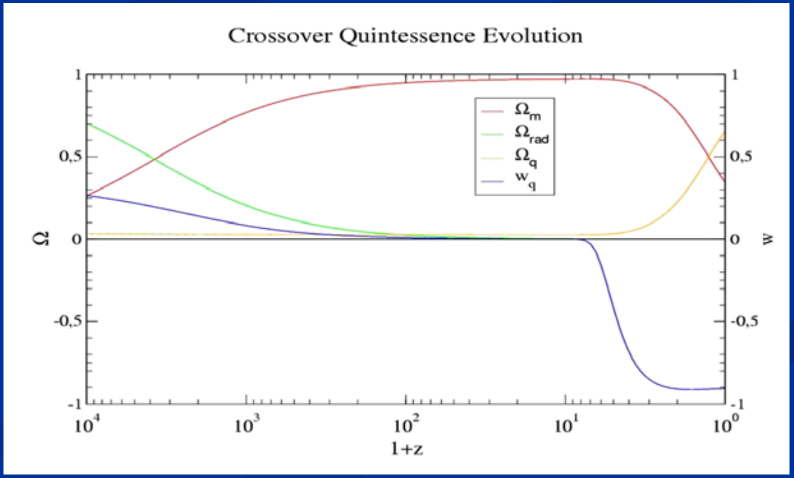
Quintessence becomes important "today"



coincidence problem

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

Why now ?



Cosmon – neutrino coupling

- Can be somewhat stronger than gravitational coupling
- Neutrino mass depends on value of cosmon field

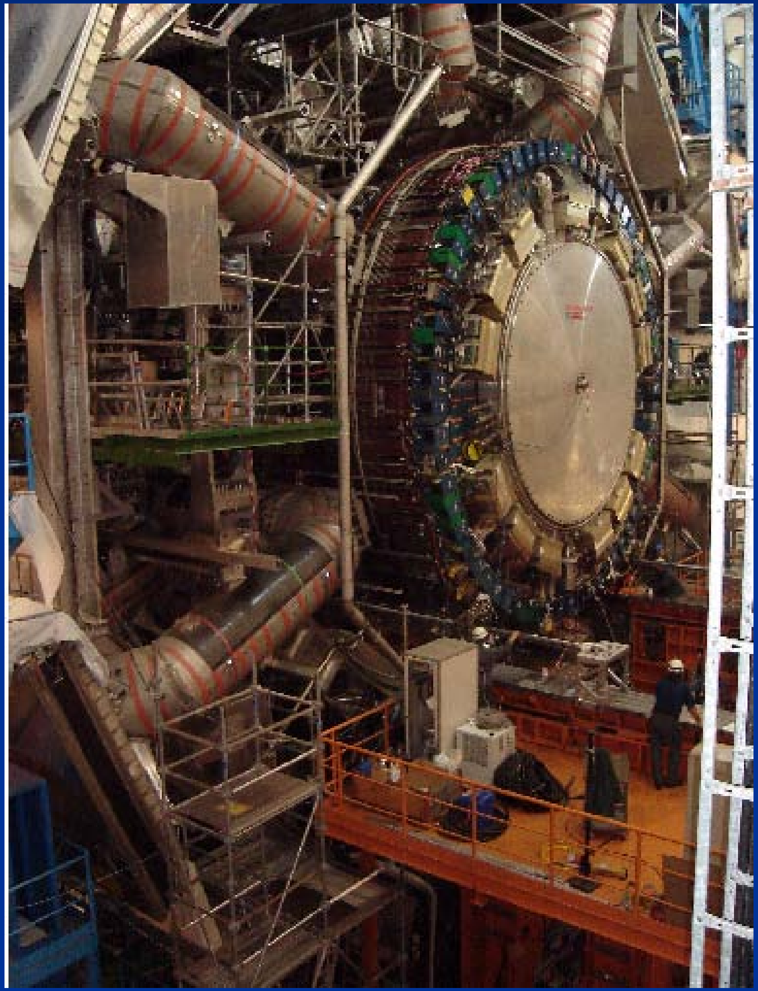
In contrast : cosmon – atom coupling must be weaker than gravity

Fundamental couplings in quantum field theory

Masses and coupling constants are determined by properties of ***vacuum*** *!*

Similar to Maxwell – equations in matter

Spontaneous symmetry breaking confirmed at the LHC



Have coupling constants in the early Universe other values than today ?

Yes !

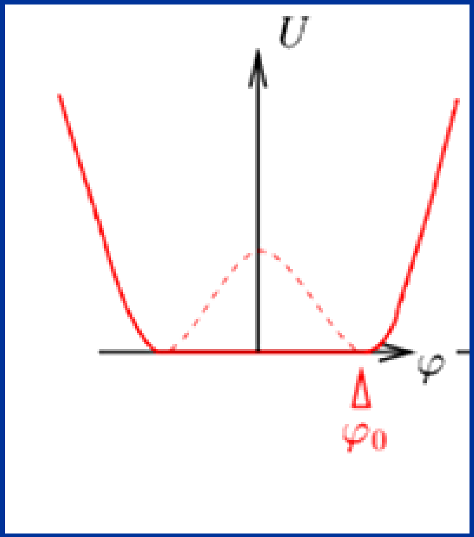
Restoration of symmetry at high temperature in the early Universe

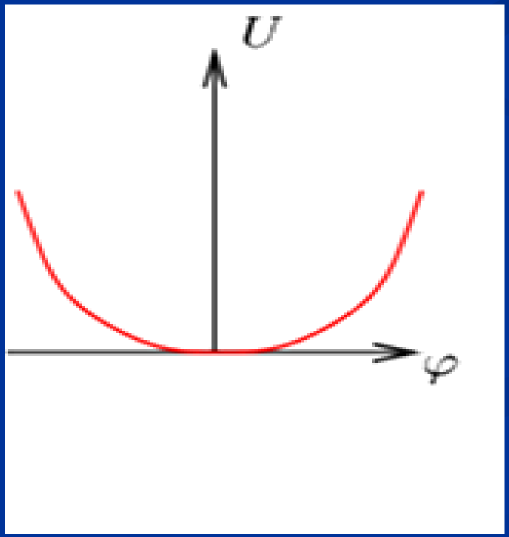
Low T
SSB
$<\varphi>=\varphi_0 \neq 0$

High T
SYM
$<\varphi>=0$

high T :
Less order
More symmetry

Example:
Magnets





In hot plasma
of early Universe :

masses of electron und muon
not different!

similar strength of electromagnetic
and weak interaction

Varying couplings

only question :

How strong is **present** variation of couplings ?

Particle masses in quintessence cosmology

can depend on value of cosmon field

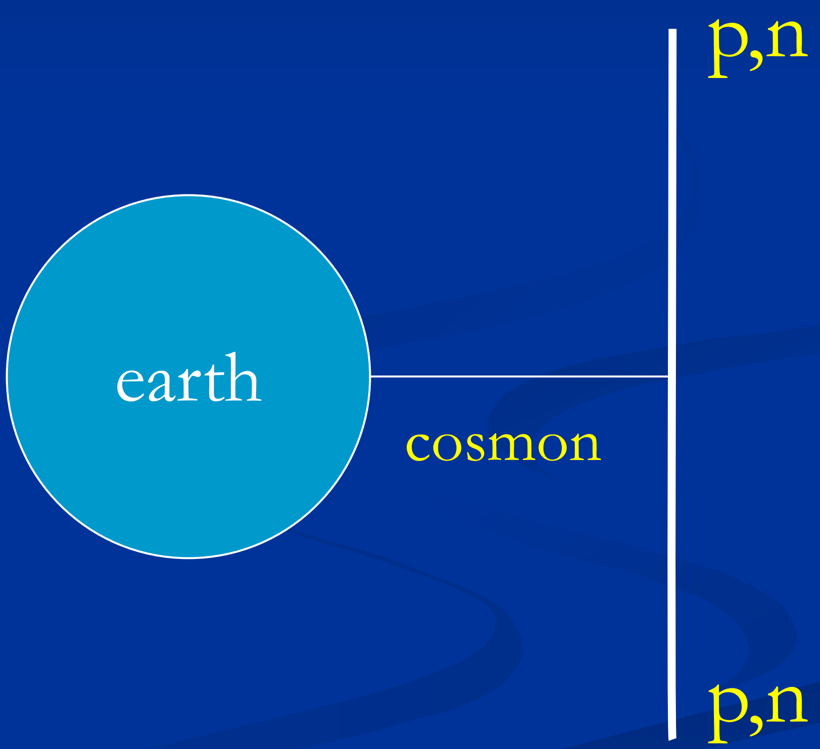
similar to dependence on value of Higgs field

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" !

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

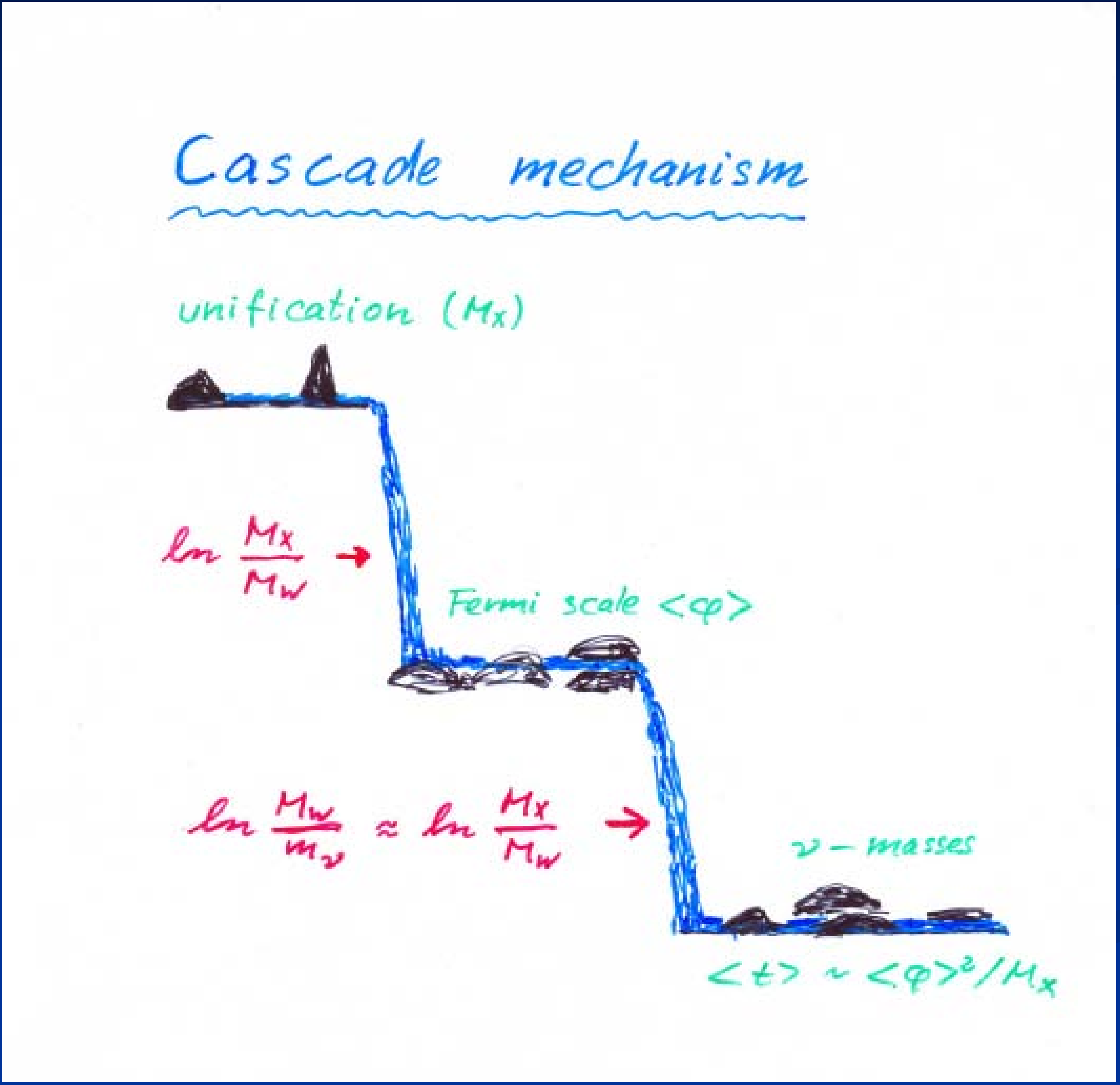
cascade mechanism

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

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

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

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

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 $\varphi \longrightarrow \varphi_t$!

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

A few early references on quintessence

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