Universe without Expansion

The Universe is shrinking

The Universe is shrinking …

while Planck mass and particle masses are increasing

Two models of “ Variable Gravity Universe “

- Scalar field coupled to gravity
- Effective Planck mass depends on scalar field
- Simple scalar potential :

  quadratic (model A)

  cosmological constant (model B)
- Nucleon and electron mass proportional to Planck mass
- Neutrino mass has different dependence on scalar field

Model A

- Inflation : Universe expands
- Radiation : Universe shrinks
- Matter : Universe shrinks
- Dark Energy : Universe expands

Model B

- Inflation : Universe expands
- Radiation : Static Minkowski space
- Matter : Universe expands
- Dark Energy : Universe expands

Compatibility with observations

- Both models lead to same predictions for radiation, matter , and Dark Energy domination, despite the very different expansion history
- Different inflation models:

  A: $n=0.97$, $r=0.13$ B: $n=0.95$, $r=0.04$
- Almost same prediction for radiation, matter, and Dark Energy domination as ΛCDM
- Presence of small fraction of Early Dark Energy
- Large neutrino lumps

Cosmon inflation

Unified picture of inflation and dynamical dark energy

Cosmon and inflaton are the same field

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

Merits of variable gravity models

- Economical setting
- No big bang singularity
- Arrow of time
- Simple initial conditions for inflation

Model A

$$S = \int_x \sqrt{g} \left\{ -\frac{1}{2}\chi^2 R + \frac{1}{2} K(\chi) \partial^\mu \chi \partial_\mu \chi + V(\chi) \right\}$$

$$V(\chi) = \mu^2 \chi^2$$

$\mu = 2 \cdot 10^{-33}$ eV

$$K(\chi) = \frac{4}{\tilde{\alpha}^2} \frac{m^2}{m^2 + \chi^2} + \frac{4}{\alpha^2} \frac{\chi^2}{m^2 + \chi^2} - 6$$

Scalar field equation:

additional force from R counteracts potential gradient : increasing χ !

scalar field eq.

$$-D_\mu(K\partial^\mu\chi) = -\frac{\partial V}{\partial \chi} + R\chi$$

Robertson-Walker metric

$$K\left(\ddot{\chi} + 3H\dot{\chi} + \frac{\partial \ln K}{\partial \chi}\dot{\chi}^2\right) = -\frac{\partial V}{\partial \chi} + R\chi$$

Modified Einstein equation

New term with derivatives of scalar field

gravitational field eq.

$$\chi^2\left(R_{\mu\nu}-\frac{1}{2}Rg_{\mu\nu}\right)+(\chi^2)_{;\rho}^{;\rho}g_{\mu\nu}-(\chi^2)_{;\mu\nu}$$

$$+\frac{1}{2}K\partial^\rho\chi\partial_\rho\chi g_{\mu\nu}-K\partial_\mu\chi\partial_\nu\chi+Vg_{\mu\nu}=T_{\mu\nu}$$

$$\Rightarrow$$

$$\chi^2R=3(\chi^2)_{;\mu}^{;\mu}+K\partial^\mu\chi\partial_\mu\chi+4V-T_\mu^\mu$$

Curvature scalar and Hubble parameter

Robertson Walker metric

$$\chi^2 R = 4V - (K+6)\dot{\chi}^2 - 6\chi\ddot{\chi} - 18H\chi\dot{\chi} - T^{\mu}_{\mu}$$

$$(\chi^2)_{;\rho}^{;\rho} = -2\dot{\chi}^2 - 2\chi\ddot{\chi} - 6H\chi\dot{\chi}$$

0-0-component

$$3\chi^2 H^2 + 6H\chi\dot{\chi} = \frac{1}{2}K\dot{\chi}^2 + V + T_{00}$$

Scaling solutions

(for constant K)

$$H = b\mu \; , \; \chi = \chi_0 \exp(c\mu t).$$

Four different scaling solutions for inflation, radiation domination, matter domination and Dark Energy domination

Scalar dominated epoch, inflation

$$c = \pm \frac{2}{\sqrt{(K+6)(3K+16)}}$$

$$K > -\frac{16}{3}.$$

$$\begin{aligned} b &= \pm\sqrt{\frac{1}{3} + \frac{K+6}{6}c^2} - c \\ &= \pm\frac{K+4}{\sqrt{(K+6)(3K+16)}} = \frac{K+4}{2}c. \end{aligned}$$

Universe expands for K > 4, shrinks for K < 4.

No big bang singularity

$$R_{\mu\nu\rho\sigma} = b^2\mu^2(g_{\mu\rho}g_{\nu\sigma} - g_{\mu\sigma}g_{\nu\rho})$$

Radiation domination

$$c = \frac{2}{\sqrt{K+6}}$$ $$b = -\frac{c}{2}.$$

Universe shrinks !

$$T_{00} = \rho = \bar{\rho}\mu^2\chi^2.$$

$$\bar{\rho}_r = -3\frac{K+5}{K+6}.$$ $$K < -5$$

scaling of particle masses

mass of electron or nucleon is proportional to variable Planck mass χ !

effective potential for Higgs doublet h

$$\tilde{V}_h = \frac{1}{2}\lambda_h(\tilde{h}^\dagger\tilde{h} - \epsilon_h\chi^2)^2$$

cosmon coupling to matter

$$-D_\mu(K\partial^\mu\chi) = -\frac{\partial V}{\partial\chi} + \frac{1}{2}\frac{\partial F}{\partial\chi}R + q_\chi ;$$

$$q_\chi = -(\rho - 3p)/\chi$$

Matter domination

$$c = \sqrt{\frac{2}{K+6}},$$

$$b = -\frac{1}{3}\sqrt{\frac{2}{K+6}} = -\frac{1}{3}c,$$

Universe shrinks !

$$\bar{\rho}_m = -\frac{2(3K+14)}{3(K+6)}$$

$$K < -14/3$$

Dark Energy domination

neutrino masses scale differently from electron mass

$$m_\nu = \bar{c}_\nu \chi^{2\tilde{\gamma}+1}$$

$$\chi q_\chi = -(2\tilde{\gamma}+1)(\rho_\nu - 3p_\nu)$$

$$\frac{\rho_\nu}{\chi^2} = \bar{\rho}_\nu \mu^2$$

$$b = \frac{1}{3}(2\tilde{\gamma}-1)c.$$

new scaling solution. not yet reached.

at present : transition period

Model B

$$\Gamma = \int d^4x\sqrt{g}\left\{-\frac{1}{2}F(\chi)R + \frac{1}{2}K(\chi)\partial^\mu\chi\partial_\mu\chi + V(\chi)\right\}$$

$$F(\chi) = \chi^2 + m^2\,,\ V(\chi) = \bar{\lambda}_c$$

$$\frac{\bar{\lambda}_c}{M^4} \approx 7\cdot 10^{-121}\,,\ (\bar{\lambda}_c)^{1/4} = 2\cdot 10^{-3}eV$$

$$K + 6 = \frac{16}{\tilde{\alpha}^2}\frac{m^2}{m^2+\chi^2} + \frac{16}{\alpha^2}\frac{\chi^2}{m^2+\chi^2}$$

Radiation domination

Flat static Minkowski space ! H=0 !

$$\chi = 2\sqrt{\frac{\lambda_c}{K+6}}(t+t_0).$$

exact regular solution ! (constant K)

constant energy density

$$\frac{\bar{\rho}}{\bar{\lambda}_c} = -\frac{3(K+2)}{K+6}.$$

$$K < -2.$$

Matter domination

$$H = \frac{1}{3}\dot{s}.$$

$$\dot{\chi}^2 = \frac{2}{K+6}\bar{\lambda}_c;$$

$$\frac{14-3K}{6}\dot{\chi}^2 = \bar{\lambda}_c + \bar{\rho}$$

$$\frac{\bar{\rho}}{\lambda_c} = -\frac{2(2+3K)}{3(K+6)}$$

$$K < -\frac{2}{3}$$

Weyl scaling

$$\Gamma = \int d^4x\sqrt{g}\left\{-\frac{M^2}{2}R + \frac{k^2}{2}\partial^\mu\varphi\partial_\mu\varphi + M^4\exp\left(-\frac{\alpha\varphi}{M}\right)\right\}$$

$$k^2 = \frac{\alpha^2(K+6)}{4}.$$

$$\varphi = \frac{2M}{\alpha}\ln\left(\frac{\chi}{\mu}\right)$$

Kinetial

$$k^2(\varphi) = \left(\frac{\alpha^2}{\tilde{\alpha}^2} - 1\right) \frac{m^2}{m^2 + \mu^2 \exp(\alpha\varphi/M)} + 1.$$

scalar σ with
standard normalization

$$\frac{d\sigma}{d\varphi} = k(\varphi).$$

$$\Gamma = \int d^4x \sqrt{g} \left\{ -\frac{M^2}{2} R + \frac{k^2}{2} \partial^\mu \varphi \partial_\mu \varphi + M^4 \exp\left(-\frac{\alpha\varphi}{M}\right) \right\}$$

$$k^2 = \frac{\alpha^2 (K+6)}{4}.$$

Inflation : Slow roll parameters

$$\epsilon = \frac{M^2}{2}\left(\frac{\partial \ln V}{\partial \sigma}\right)^2 = \frac{M^2}{2k^2}\left(\frac{\partial \ln V}{\partial \varphi}\right)^2 = \frac{\alpha^2}{2k^2}$$

$$\eta = \frac{M^2}{V}\frac{\partial^2 V}{\partial \sigma^2} = 2\epsilon - \frac{M}{\alpha}\frac{\partial \epsilon}{\partial \varphi}$$

For large $\alpha \gg 1$ and small $\tilde{\alpha} \ll 1$ we can approximate

$$\epsilon = \frac{\tilde{\alpha}^2}{2}\left(1 + \frac{\mu^2}{m^2}\exp(\alpha\varphi/M)\right),$$

$$\eta = \epsilon + \frac{\tilde{\alpha}^2}{2}.$$

End of inflation at $\varepsilon = 1$

$$\exp\left(\frac{\alpha\varphi_f}{M}\right) = \frac{2m^2}{\tilde{\alpha}^2\mu^2}$$

Number of e-foldings before end of inflation

$$N(\varphi) = \frac{1}{\alpha M} \int_{\varphi}^{\varphi_f} d\varphi' k^2(\varphi')$$

$$= \frac{\alpha(\varphi_f - \varphi)}{\tilde{\alpha}^2 M} - \left(\frac{1}{\tilde{\alpha}^2} - \frac{1}{\alpha^2}\right) \ln\left(\frac{m^2 + \mu^2 \exp(\alpha\varphi_f/M)}{m^2 + \mu^2 \exp(\alpha\varphi/M)}\right)$$

ε, η, N can all be computed from kinetial alone

Spectral index and tensor to scalar ratio

Model A

$$n = 1 - 6\epsilon + 2\eta = 1 - \frac{2}{N}$$
$$r = 16\epsilon = \frac{8}{N} = 4(1-n).$$

$$n \approx 0.97\ ,\ \ r \approx 0.13$$

Amplitude of density fluctuations

$$24\pi^2\Delta^2 = \frac{V}{\epsilon M^4} = 2N\exp\left(-\frac{\alpha\varphi}{M}\right) \approx 5\cdot 10^{-7}.$$

$$\exp\left(-\frac{\alpha\varphi}{M}\right) \approx 4\cdot 10^{-9},$$

$$\frac{\tilde{\alpha}^2\mu^2}{m^2} \approx \frac{2}{3}\cdot 10^{-10}$$

Einstein frame , model B

$$\varphi = \frac{M}{\alpha} \ln \frac{(\chi^2 + m^2)^2}{\bar{\lambda}_c},$$

$$k^2 = 1 + \alpha^2 \left(\frac{1}{\tilde{\alpha}^2} - \frac{3}{8} \right) \frac{m^2}{\chi^2}$$

for large χ :
no difference to model A

$$\Gamma = \int d^4x \sqrt{g} \left\{ -\frac{M^2}{2} R + \frac{k^2}{2} \partial^\mu \varphi \partial_\mu \varphi + M^4 \exp\left(-\frac{\alpha\varphi}{M} \right) \right\}$$

inflation model B

approximate relation between r and n

$$r = \frac{16(1-n)\exp\big(-N(1-n)\big)}{1-3\big[N(1-n)-1\big]\exp\big(-N(1-n)\big)}$$

n=0.95 , r=0.035

conclusion 1

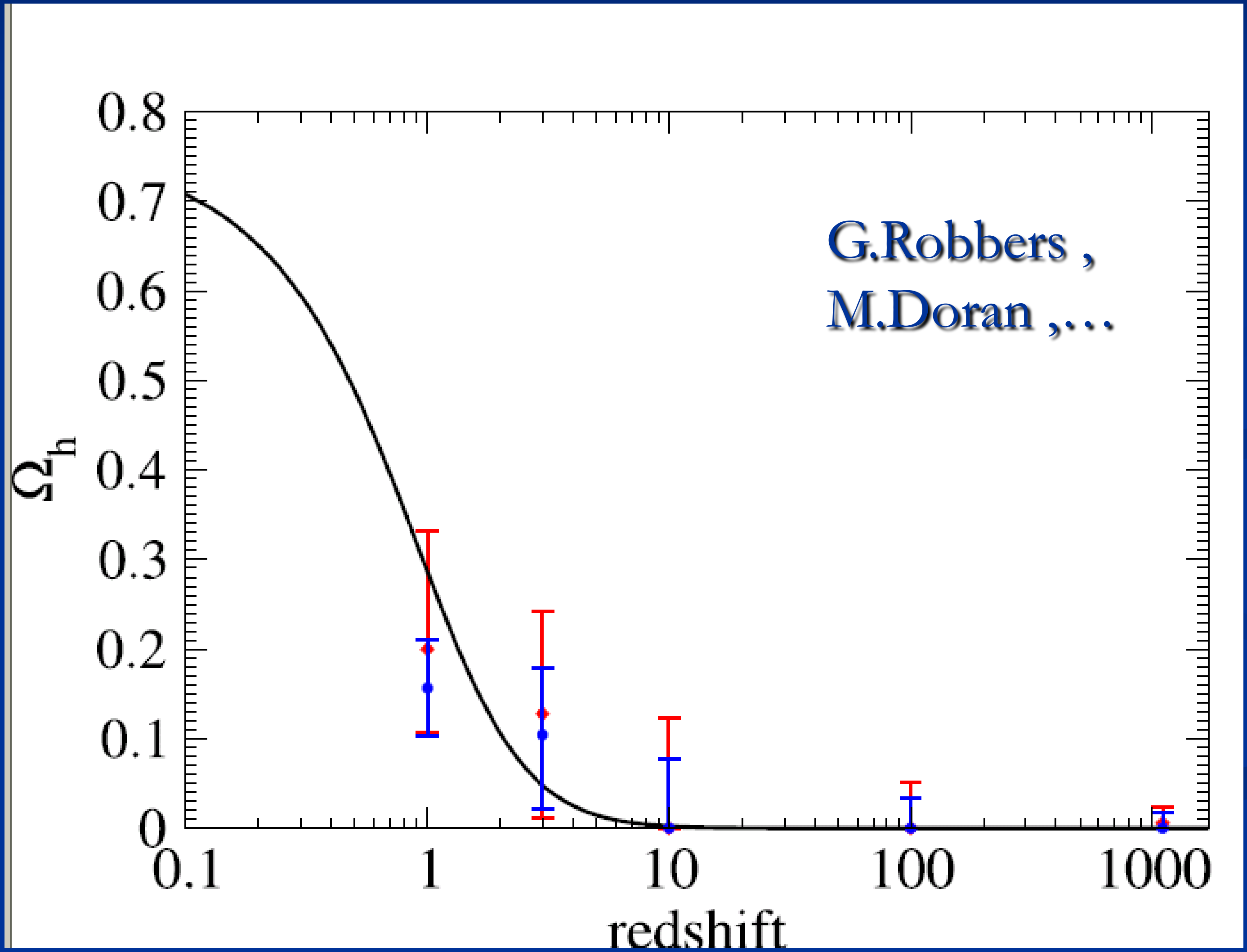
- cosmon inflation :
- compatible with observation
- simple
- no big bang singularity
- stability of solution singles out arrow of time
- simple initial conditions

$$\Gamma = \int d^4x \sqrt{g} \left\{ -\frac{1}{2} F(\chi) R + \frac{1}{2} K(\chi) \partial^\mu \chi \partial_\mu \chi + V(\chi) \right\}$$

$$F(\chi) = \chi^2 + m^2 \,, \; V(\chi) = \bar{\lambda}_c$$

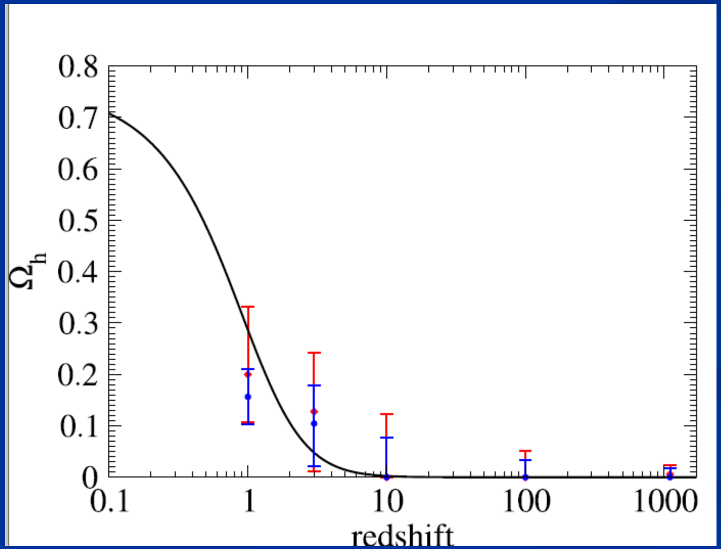
Growing neutrino quintessence

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 ?



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 !

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

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

M.Magg, C.W. 1980

Neutrino cosmon coupling

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

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

- β ≈ 1 : cosmon mediated attractive force between neutrinos has similar strength as gravity

growing neutrinos change cosmon evolution

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

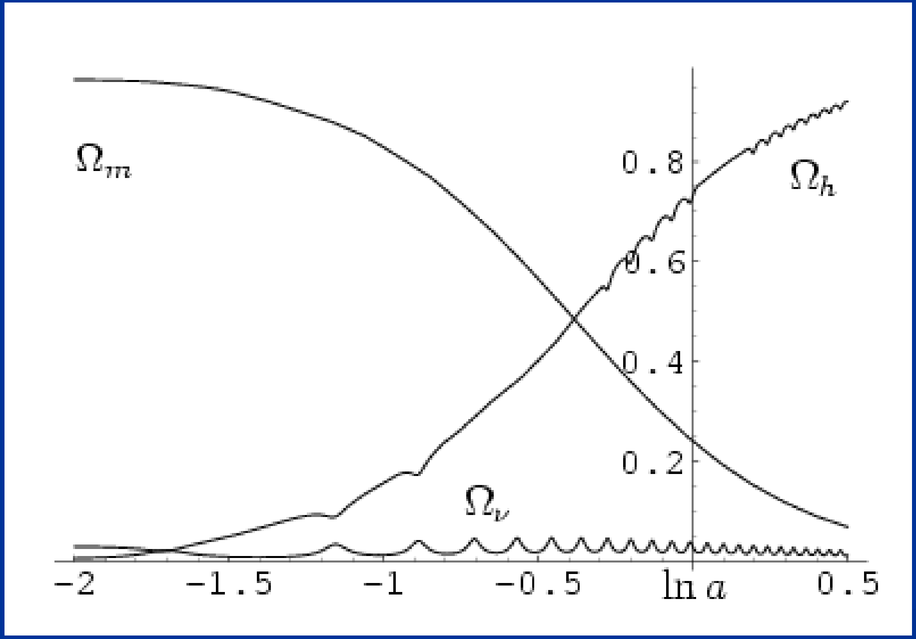
$$\beta(\varphi) = -M\frac{\partial}{\partial \varphi}\ln m_\nu(\varphi) = \frac{M}{\varphi - \varphi_t}$$

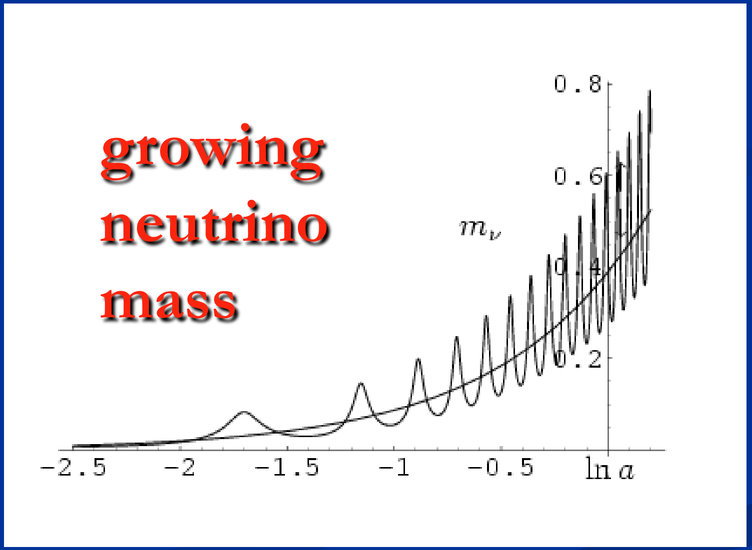
modification of conservation equation for neutrinos

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

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

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 !

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

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,…

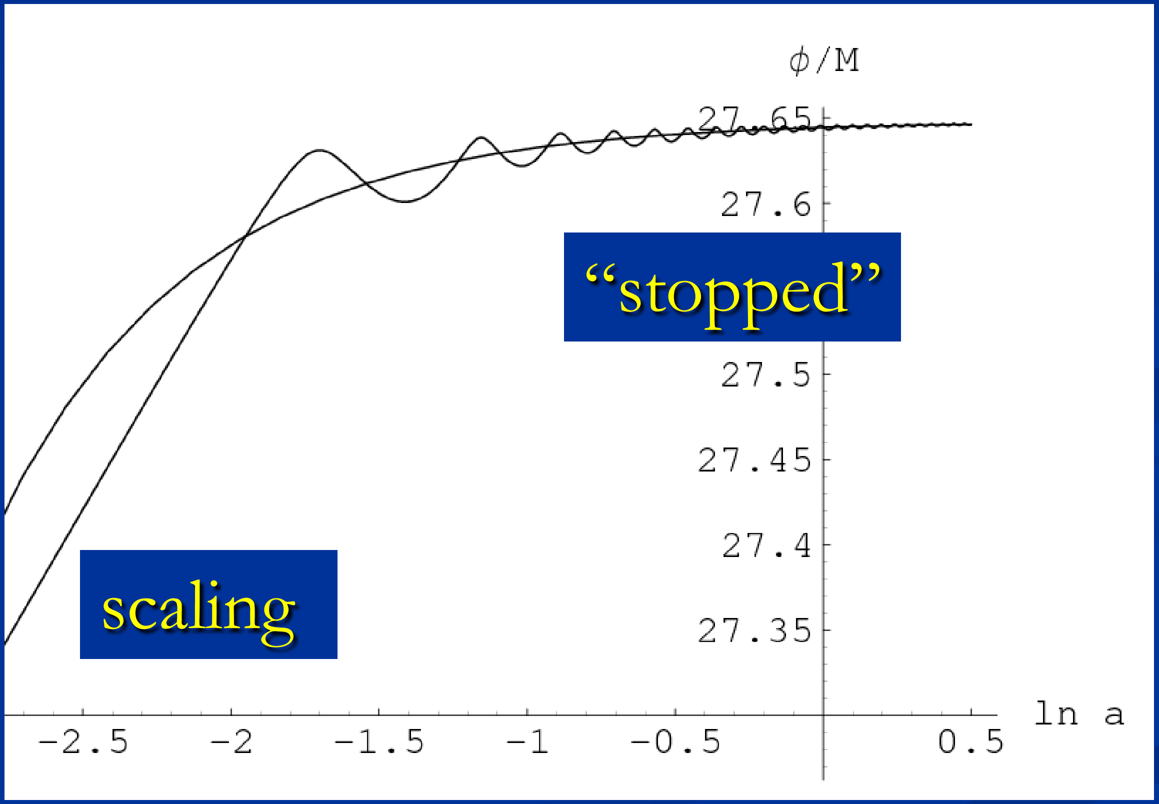
stopped scalar field mimicks a cosmological constant (almost …)

rough approximation for dark energy :

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

  (cosmological constant)

cosmon evolution

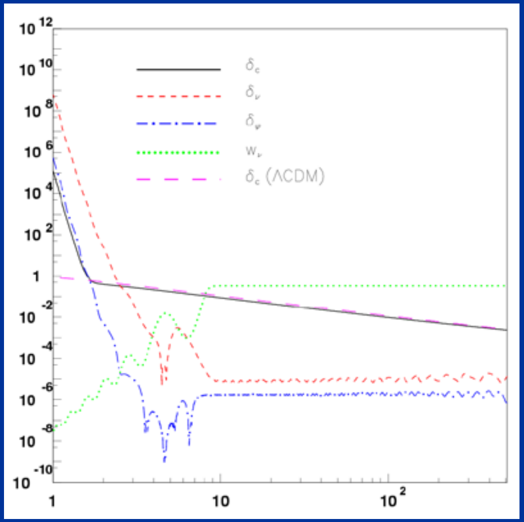


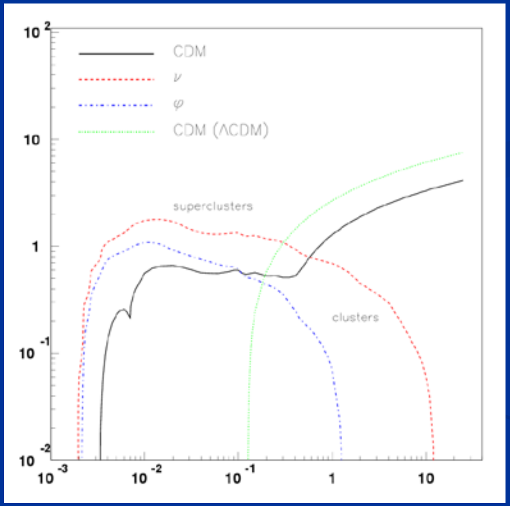
neutrino lumps

neutrino fluctuations

neutrino structures become nonlinear at z~1 for supercluster scales

D.Mota , G.Robbers , V.Pettorino , …

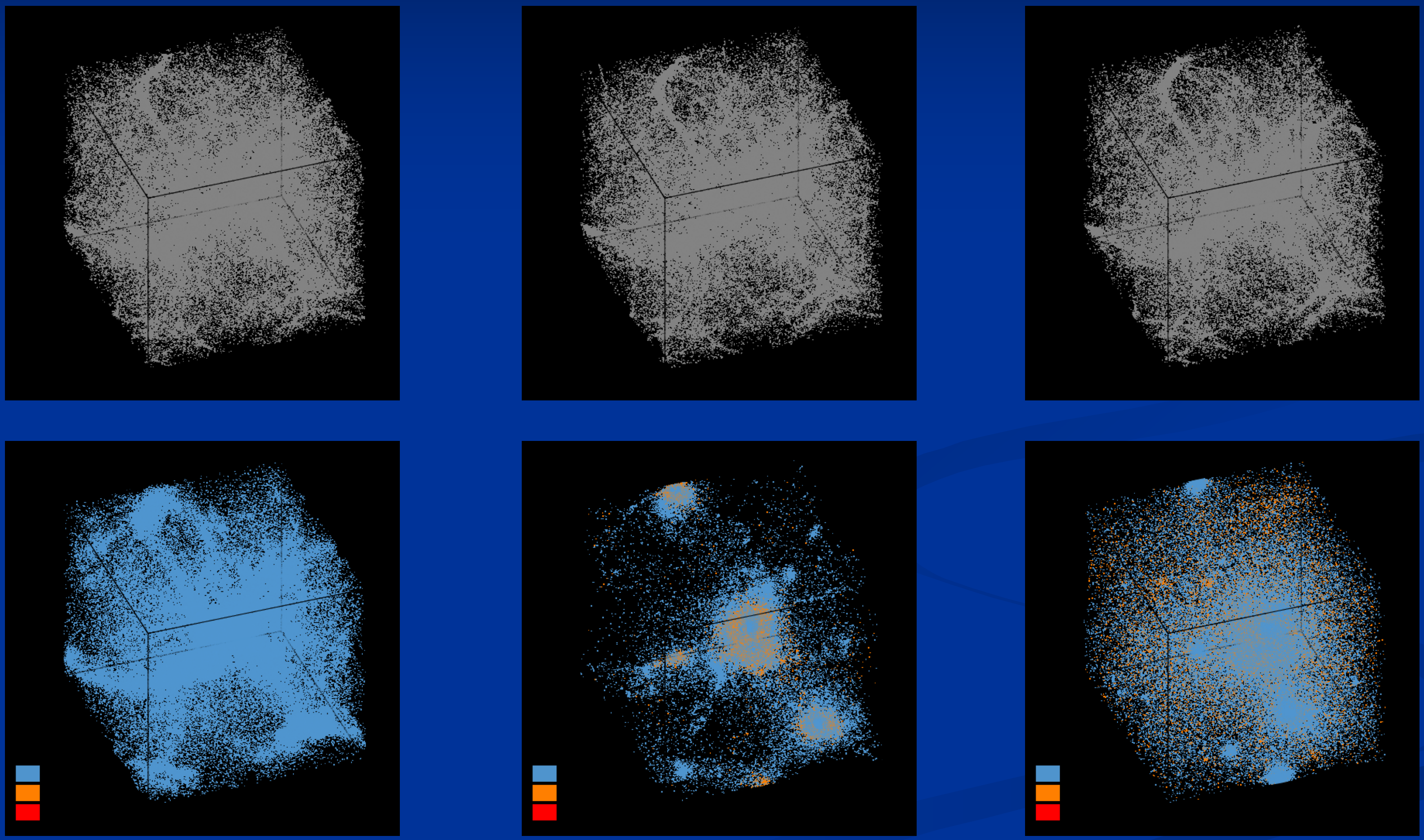




stable neutrino-cosmon lumps exist

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

Formation of neutrino lumps



N- body simulation M.Baldi et al

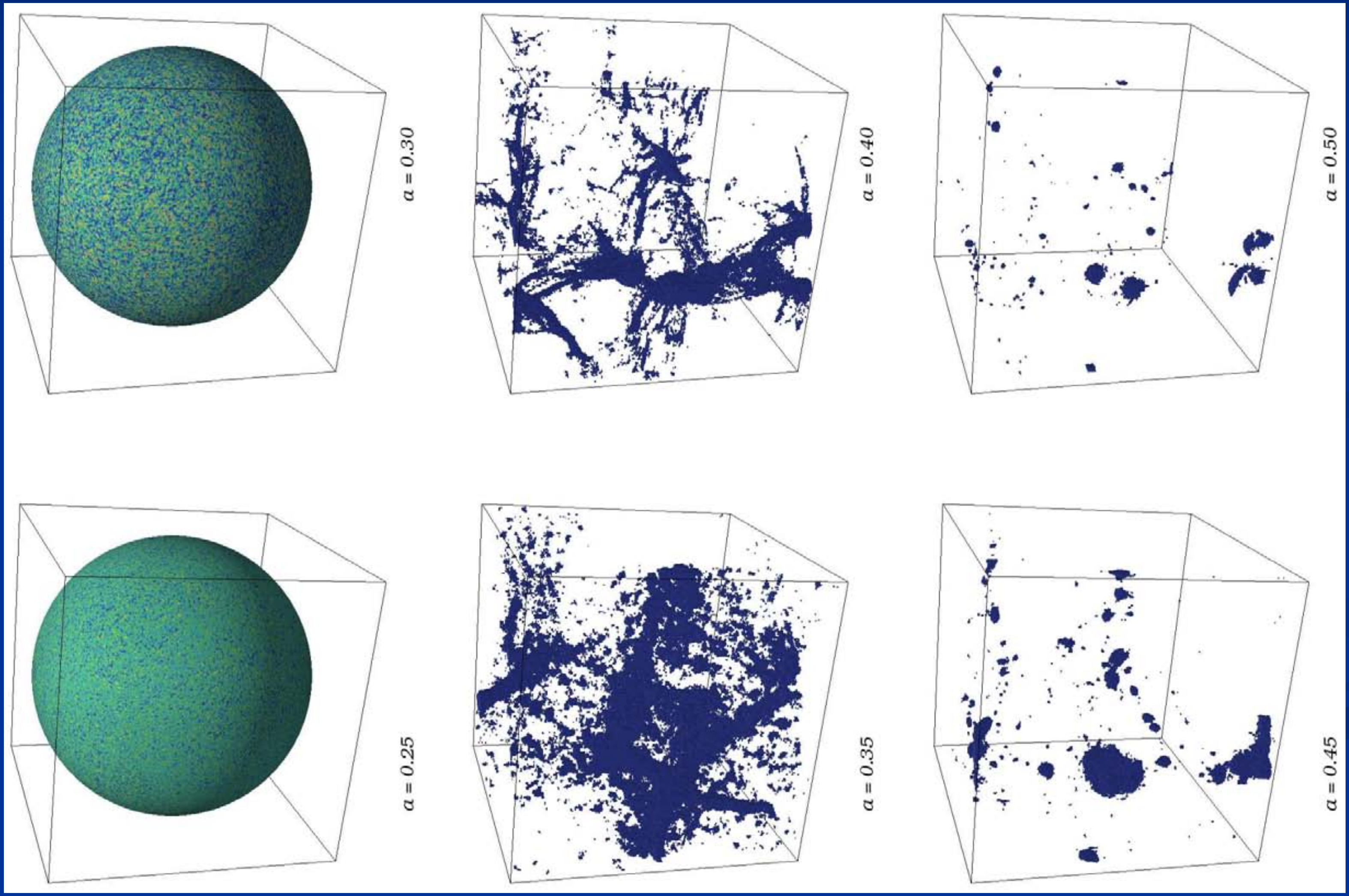
N-body code with fully relativistic neutrinos and backreaction

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,…

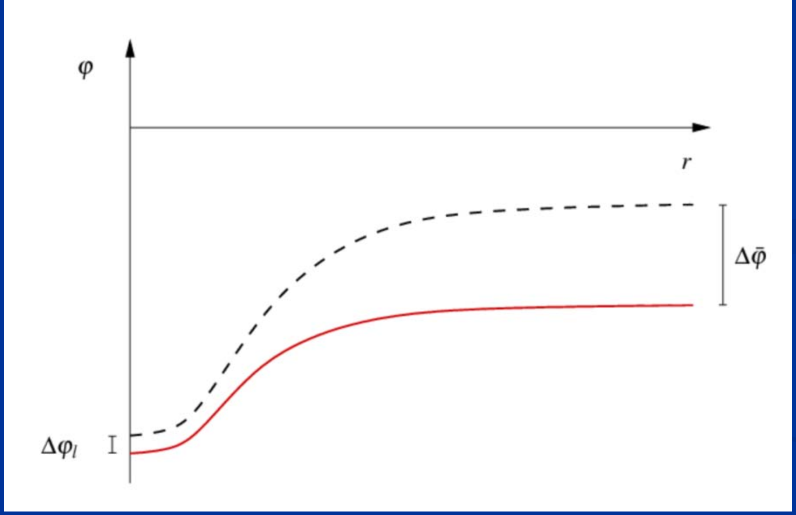
Formation of neutrino lumps

Y.Ayaita,M.Weber,…



backreaction

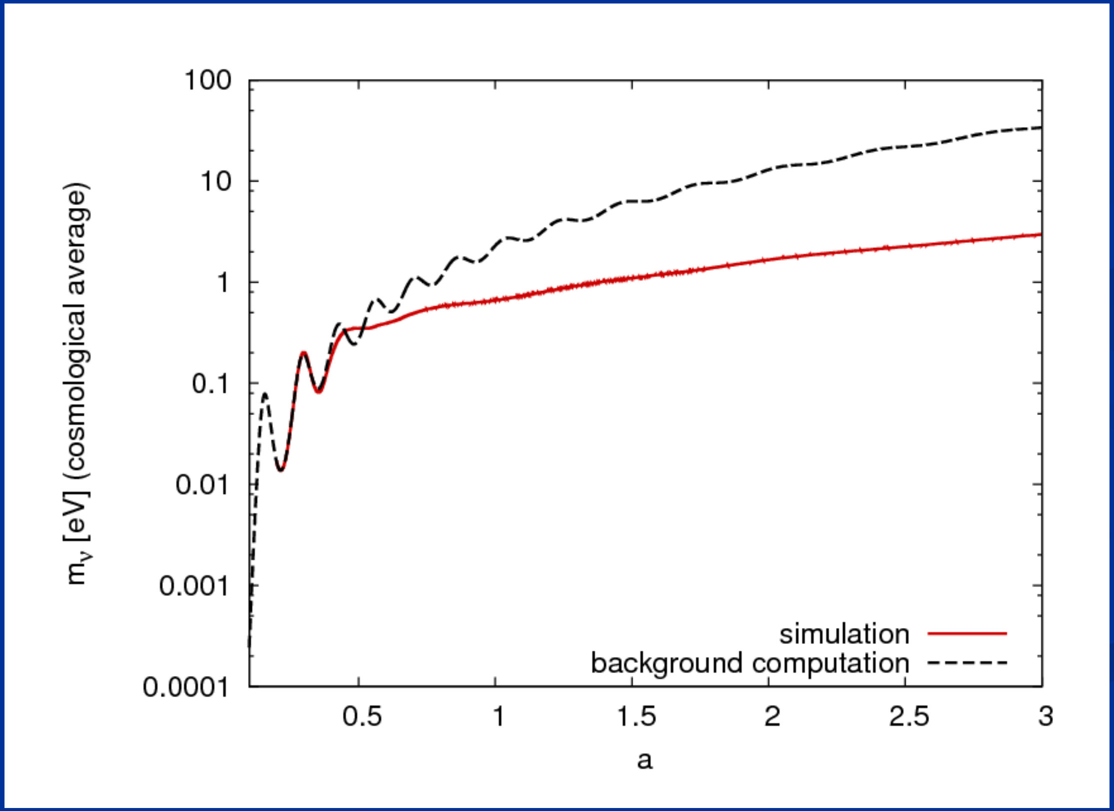
cosmon field inside lumps does not follow cosmological evolution



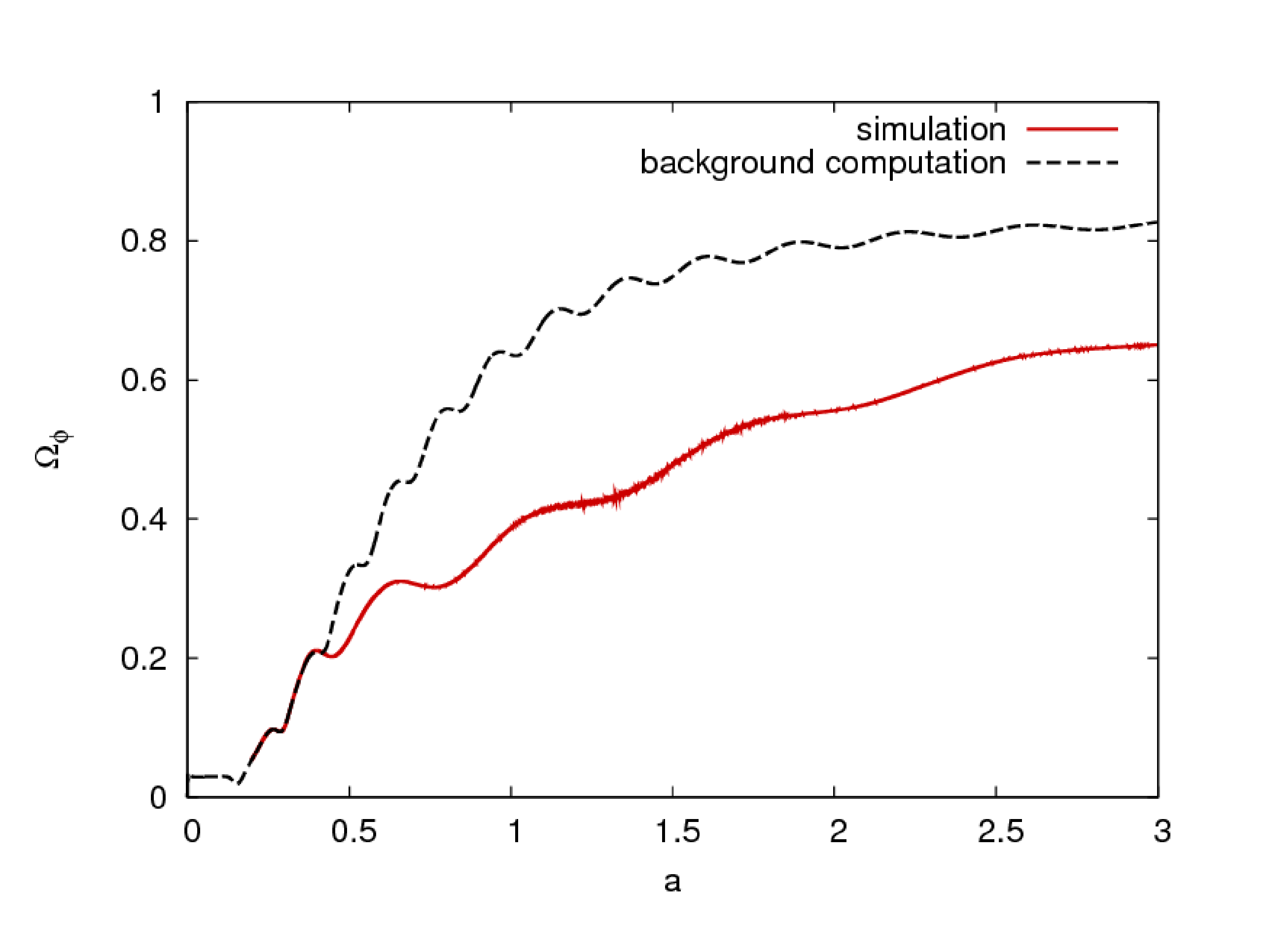
neutrino mass inside lumps smaller than in environment   L.Schrempp, N.Nunes,…

importance of backreaction : cosmological average of neutrino mass

Y.Ayaita , E.Puchwein,…

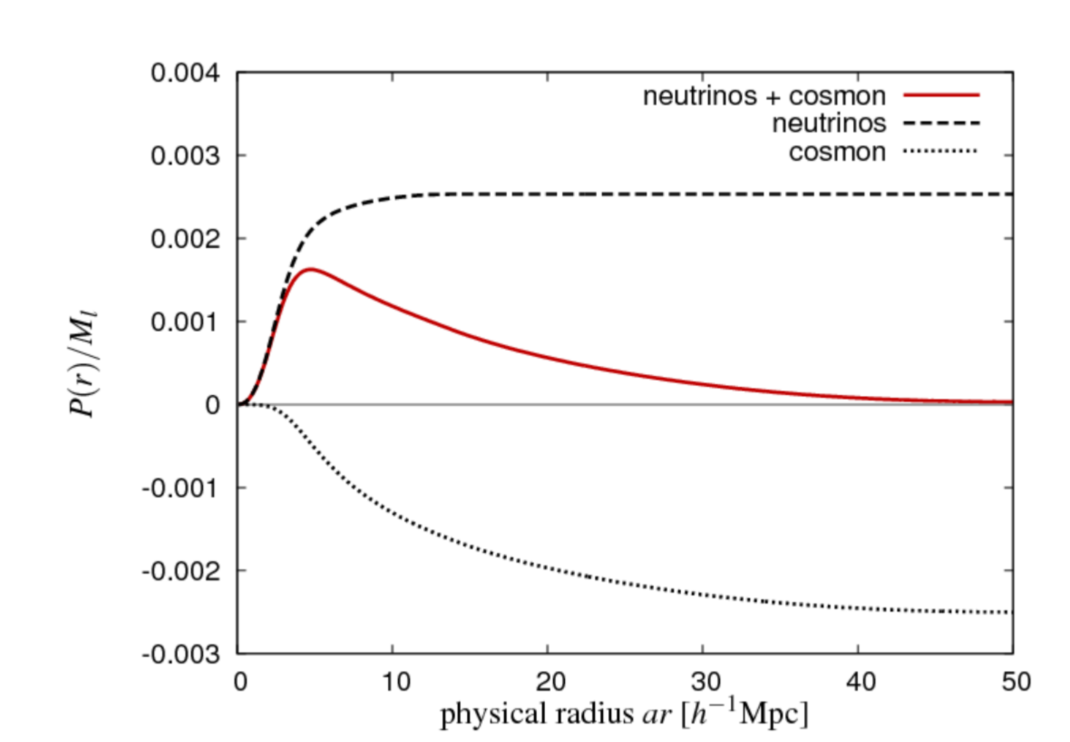


importance of backreaction : fraction in Dark Energy

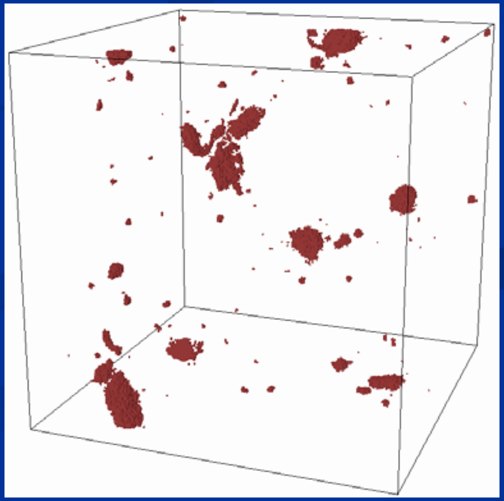


neutrino lumps

behave as non-relativistic fluid with effective coupling to cosmon



Y.Ayaita, M.Weber,…



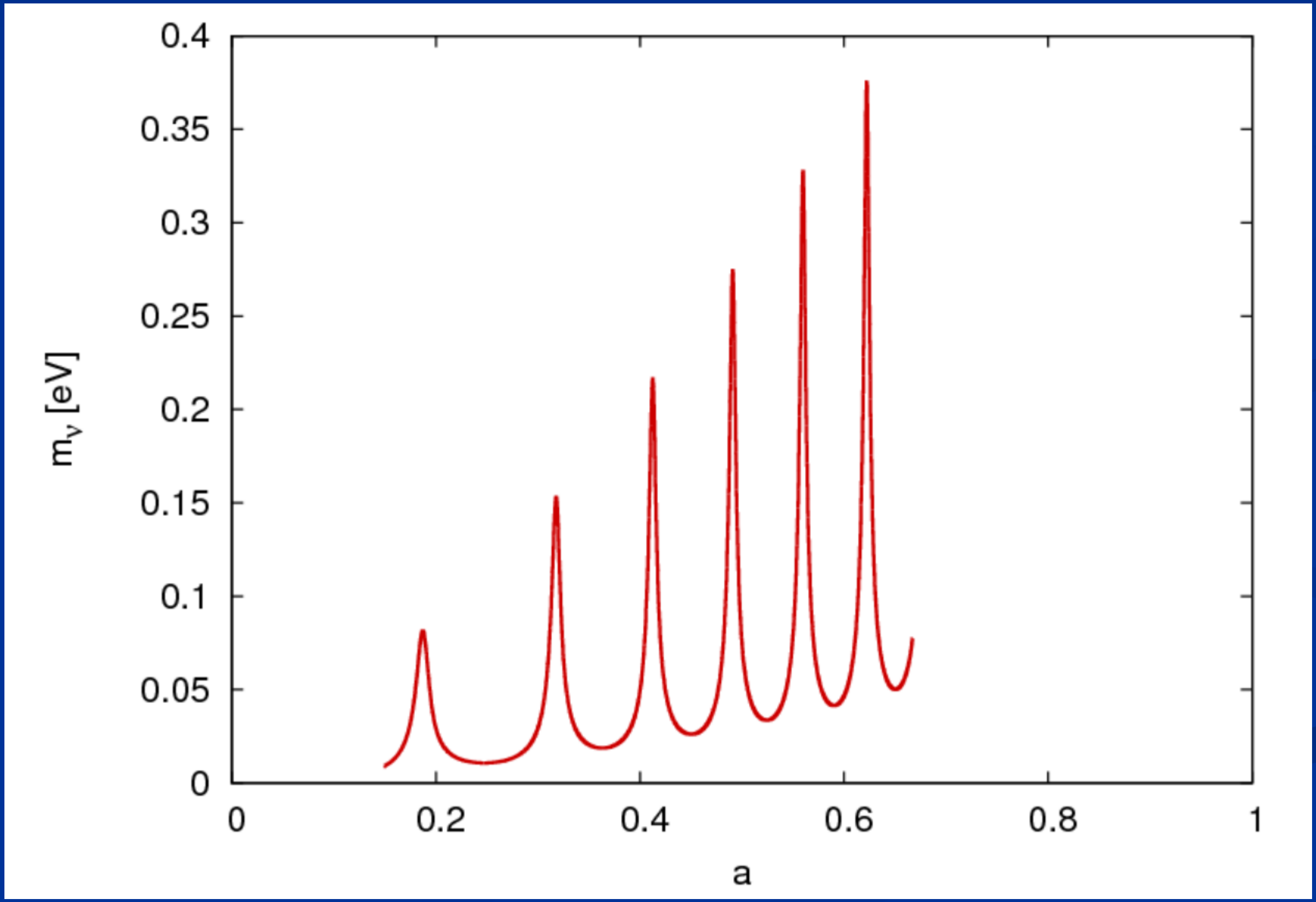
φ - dependent neutrino – cosmon coupling

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

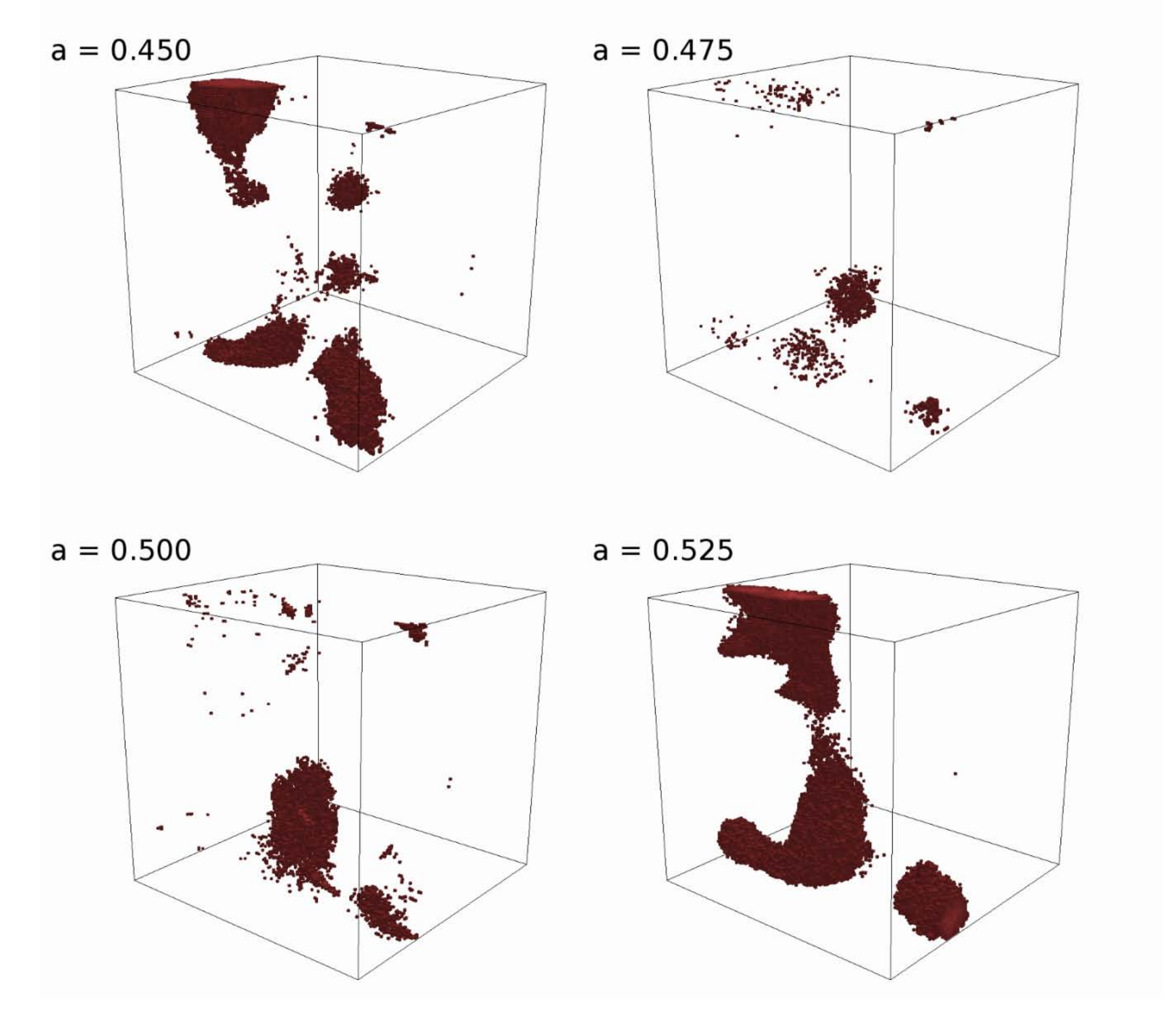
neutrino lumps form and are disrupted by oscillations in neutrino mass

smaller backreaction

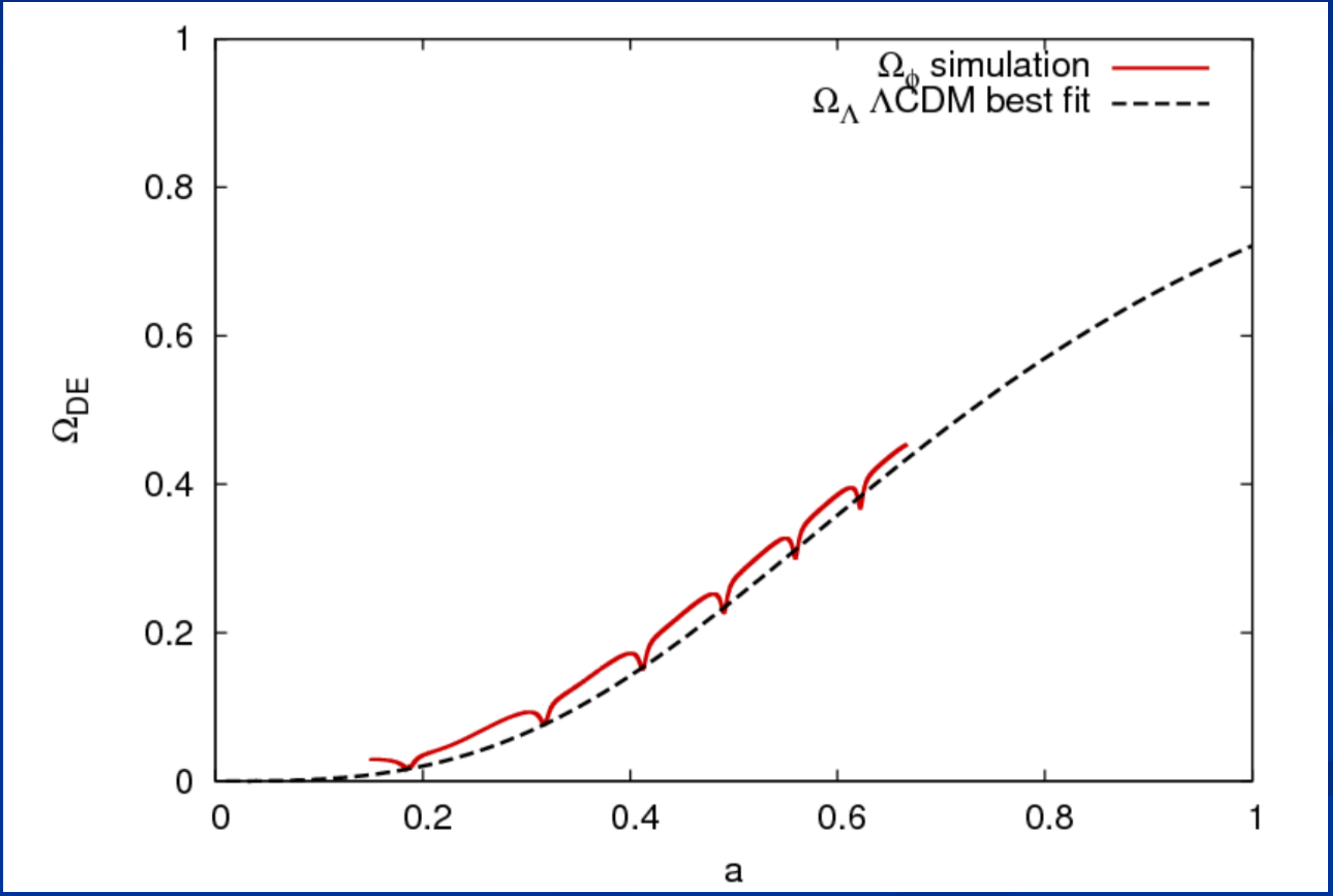
oscillating neutrino mass



oscillating neutrino lumps



small oscillations in dark energy



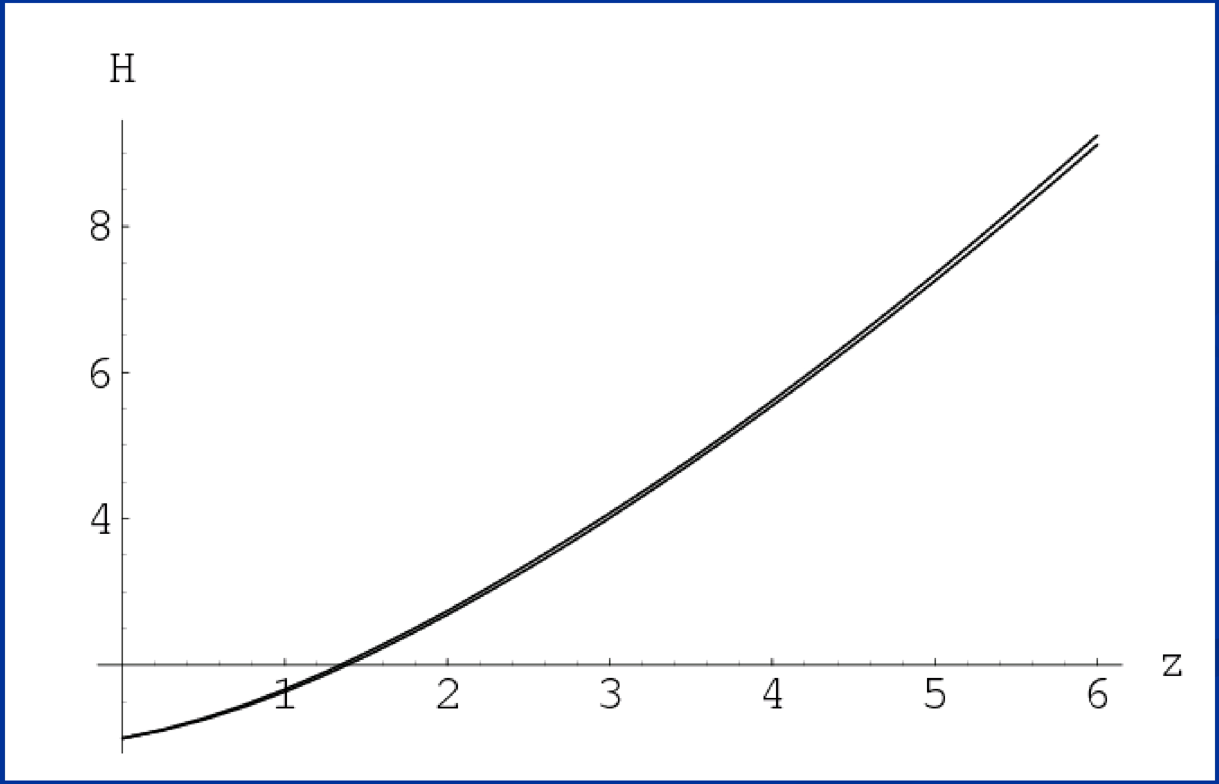
conclusions

- Variable gravity cosmologies can give a simple and realistic description of Universe
- Compatible with tests of equivalence principle and bounds on variation of fundamental couplings if nucleon and electron masses are proportional to variable Planck mass
- Different cosmon dependence of neutrino mass can explain why Universe makes a transition to Dark Energy domination now
- characteristic signal : neutrino lumps

Tests for growing neutrino quintessence

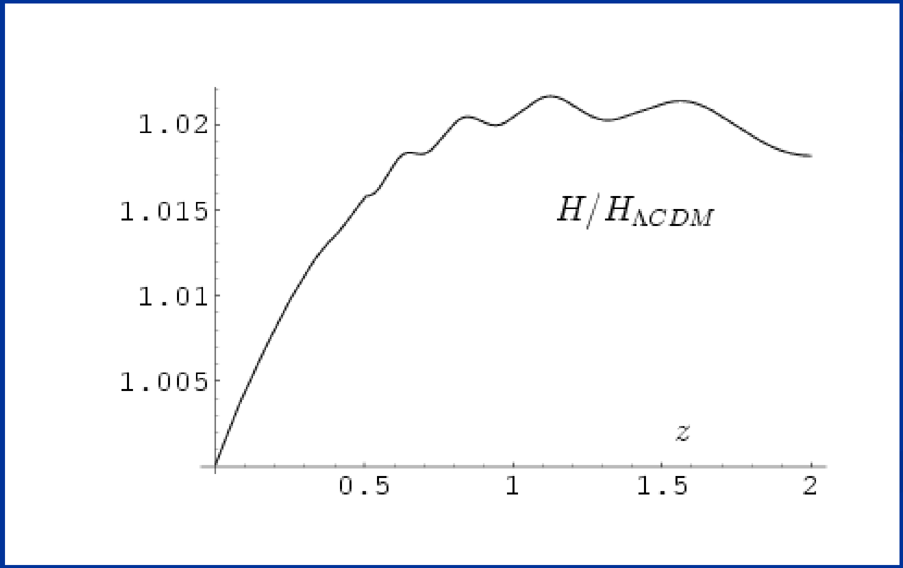
Hubble parameter

as compared to ΛCDM



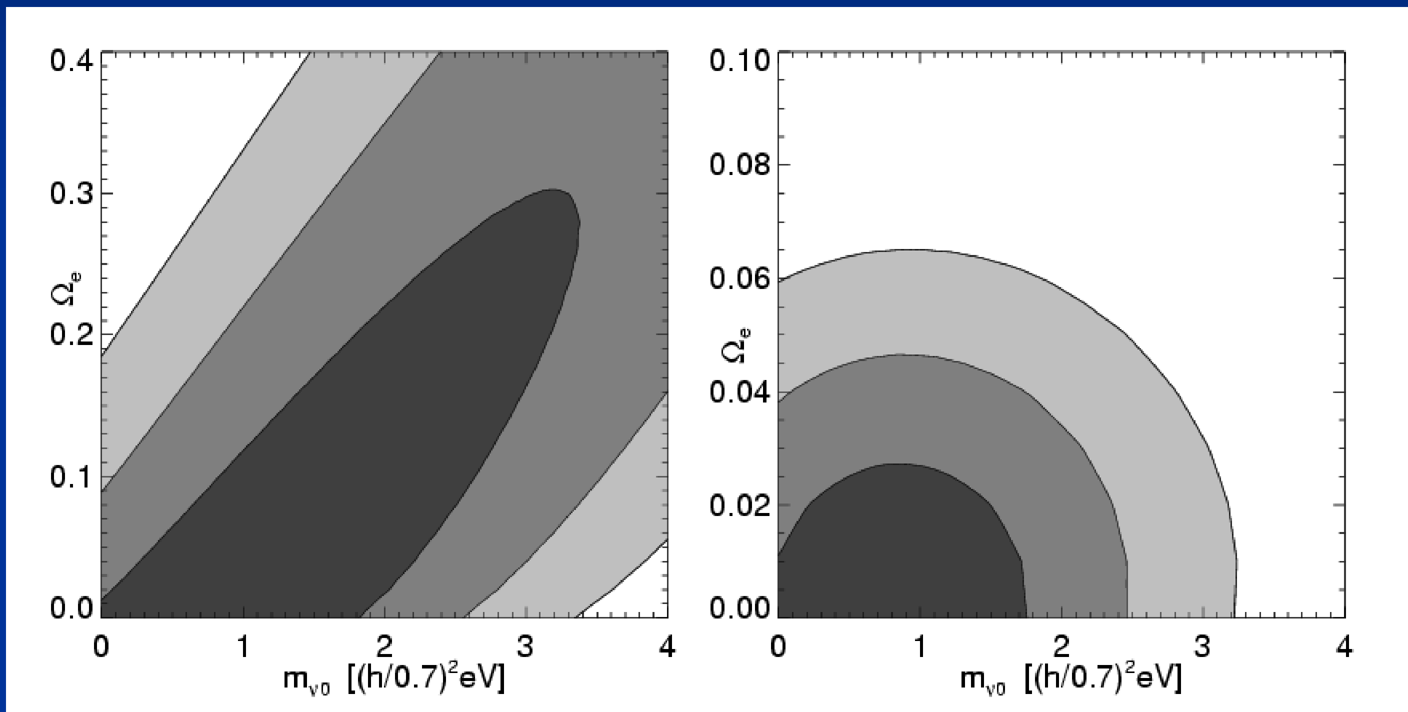
Hubble parameter ($z < z_c$)

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



only small difference from ΛCDM !

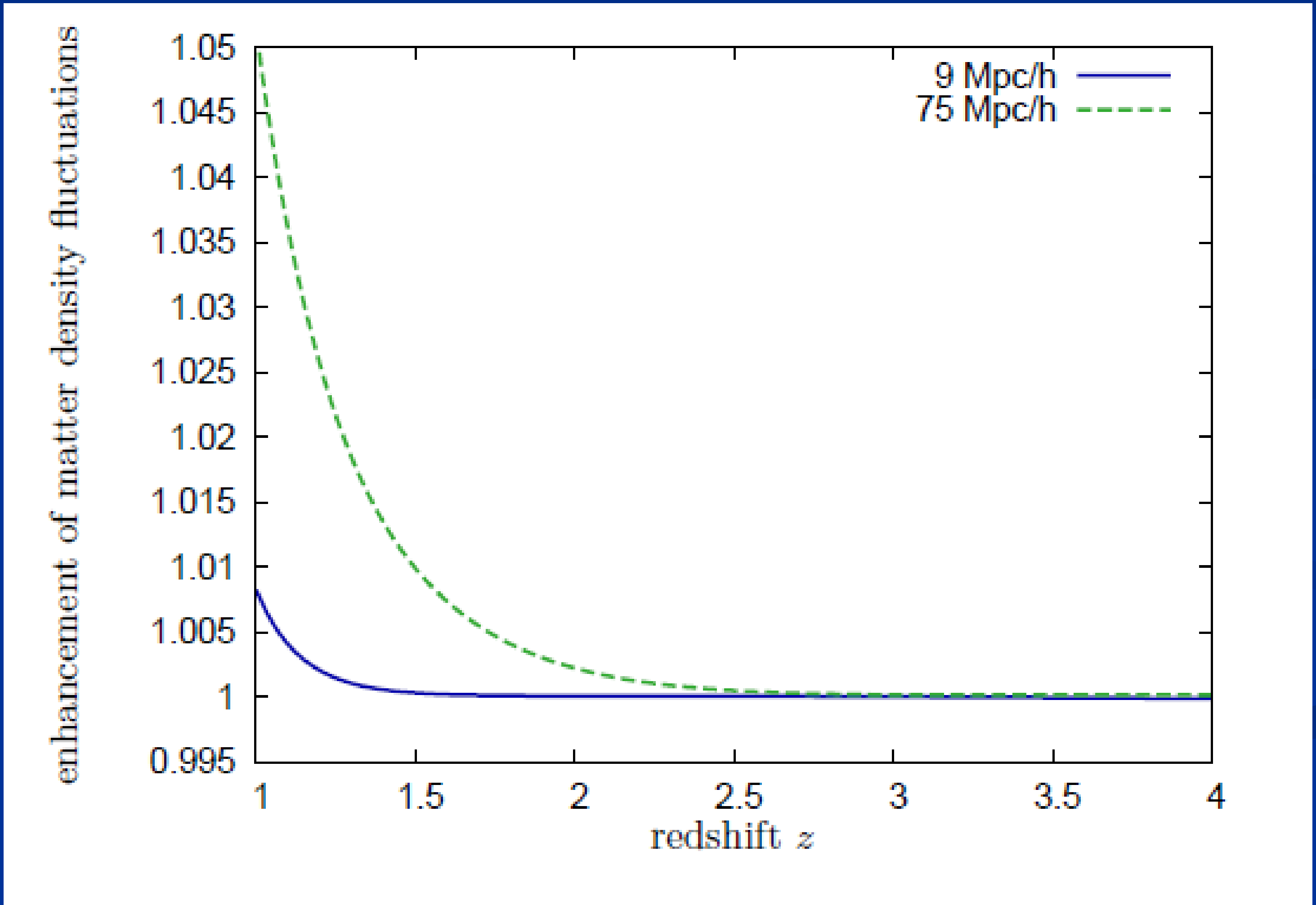
bounds on average neutrino mass



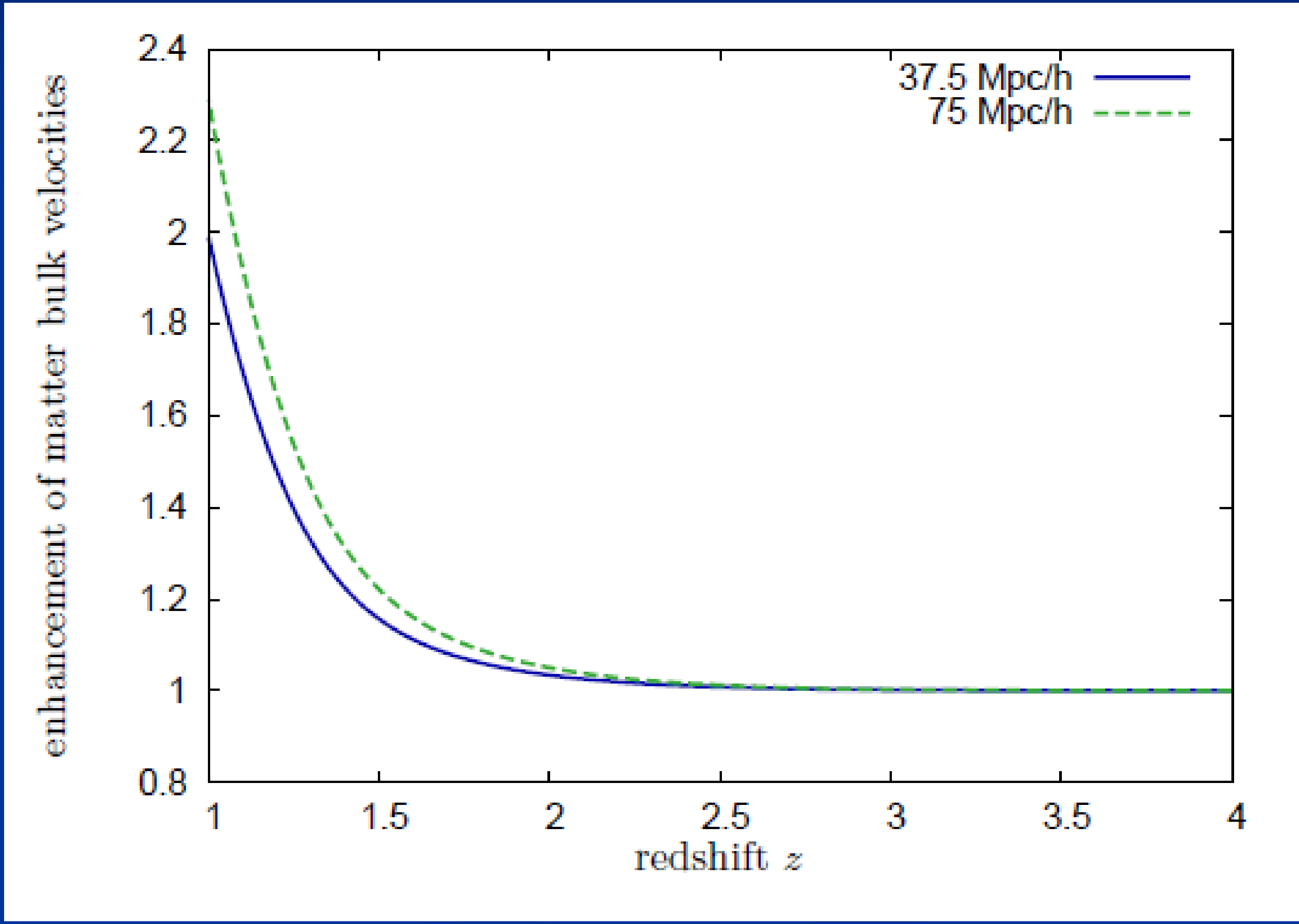
Looking Beyond Lambda with the Union Supernova Compilation

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)

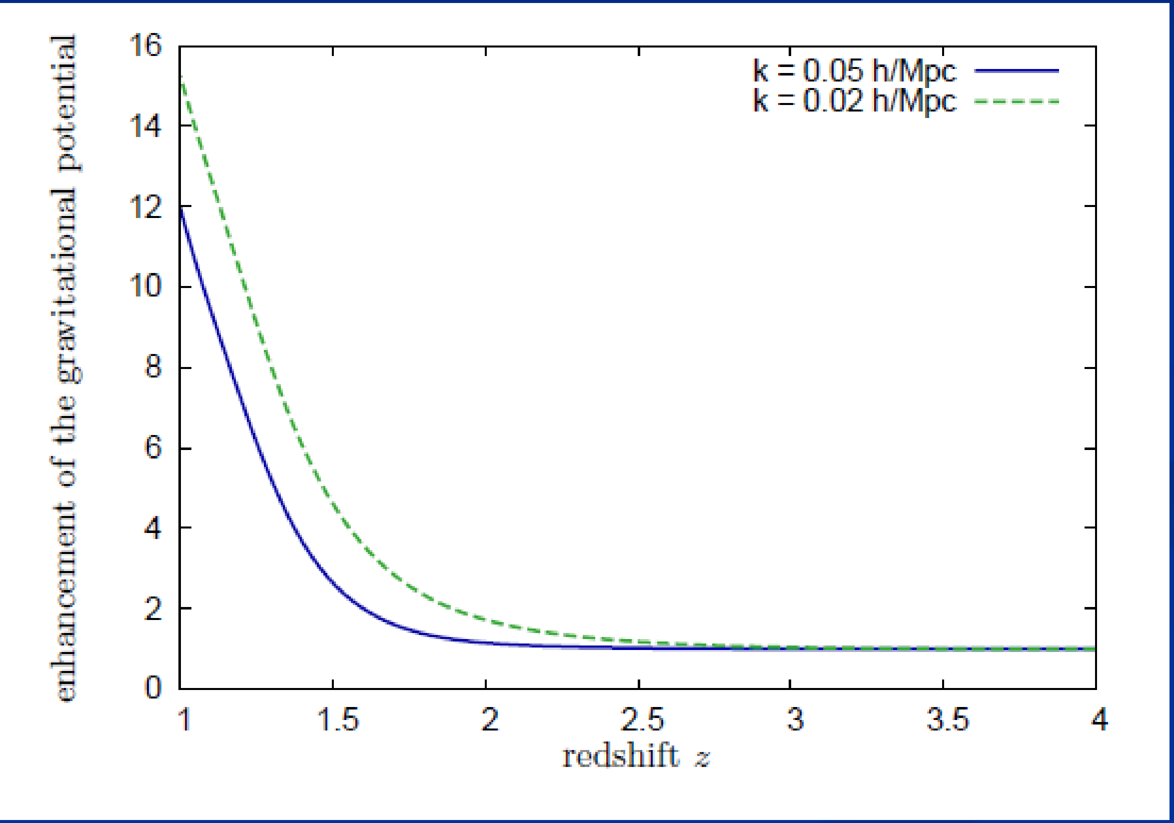
Small induced enhancement of dark matter power spectrum at large scales



Enhanced bulk velocities



Enhancement of gravitational potential

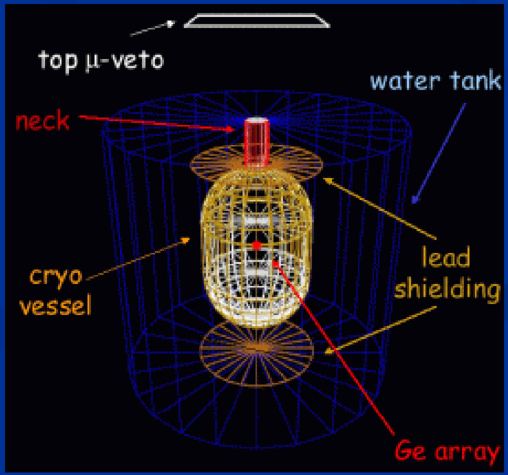


Test of allowed parameter space by ISW effect

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

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

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

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 $\varphi \longrightarrow \varphi_t$!

A few early references on quintessence

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