Backreaction in Growing Neutrino Cosmology

Florian Führer

Institut für Theoretische Physik

Universität Heidelberg

Based on

FF, C. Wetterich Phys. Rev. D 91, 123542

Y. Ayaita, M. Baldi, FF, E. Puchwein, C. Wetterich 1407.8417

Content

1.Dark Energy
2.(Growing Neutrino) Quintessence
3.Constant Coupling Model
4.Varying Coupling Model

Expansion of the Universe

Scale factor $$a = \frac{d_{\text{physical}}}{d_{\text{coordinate}}}$$

Friedman equation $$\frac{\dot{a}}{a} = H = \frac{1}{\sqrt{3}M_{\text{Pl}}}\sqrt{\rho}$$

Continuity equation $$\dot{\rho} + 3H(\rho + P) = 0$$ $$w = \frac{P}{\rho}$$

(Non-relativistic) matter/dust $$w = 0$$ $$\rho \propto a^{-3}$$

Volume grows

Radiation/Relativistic species $$w = \frac{1}{3}$$ $$\rho \propto a^{-4}$$

Volume grows
+redshift

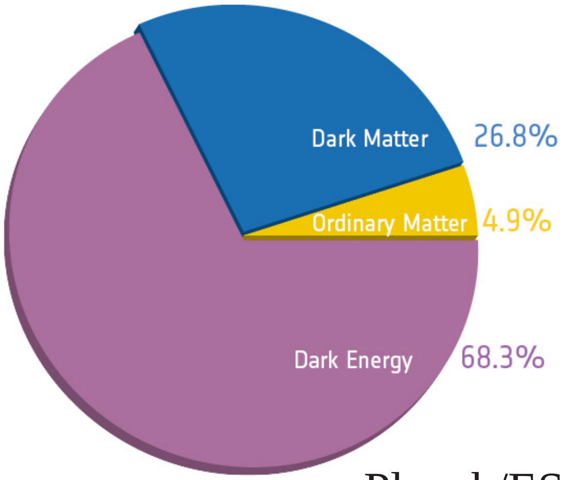
Accelerated expansion $$w < -\frac{1}{3}$$

Dark Energy

Accelerated expansion of the universe discovered in 1998/1999
by the Super Nova Search Team/Super Nova Cosmology Project

Dark Energy density $\Omega \approx 0.7$

Constant energy density $w = -1$



Planck/ESA

Obvious candidate cosmological constant $\frac{\Lambda}{M_{\mathrm{Pl}}^4} \sim 10^{-120}$

Quintessence can explain the small number, but not the accelerated expansion

Coupling between the cosmon and neutrinos can act as trigger

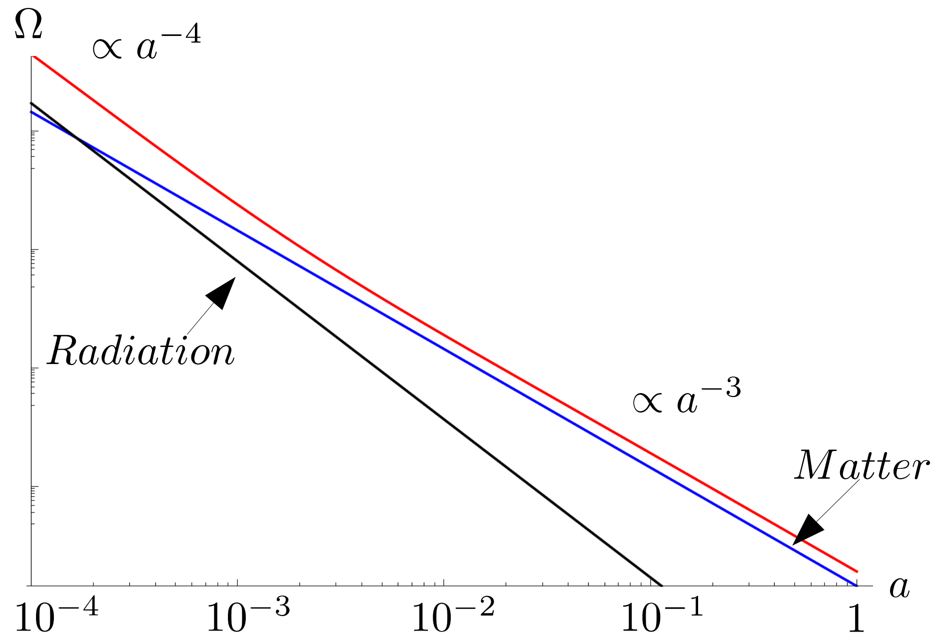
Quintessence

Scalar field as Dark Energy

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0$$

$$\rho_\varphi = \frac{1}{2}\dot{\varphi}^2 + V(\varphi)$$

$$P_\varphi = \frac{1}{2}\dot{\varphi}^2 - V(\varphi)$$

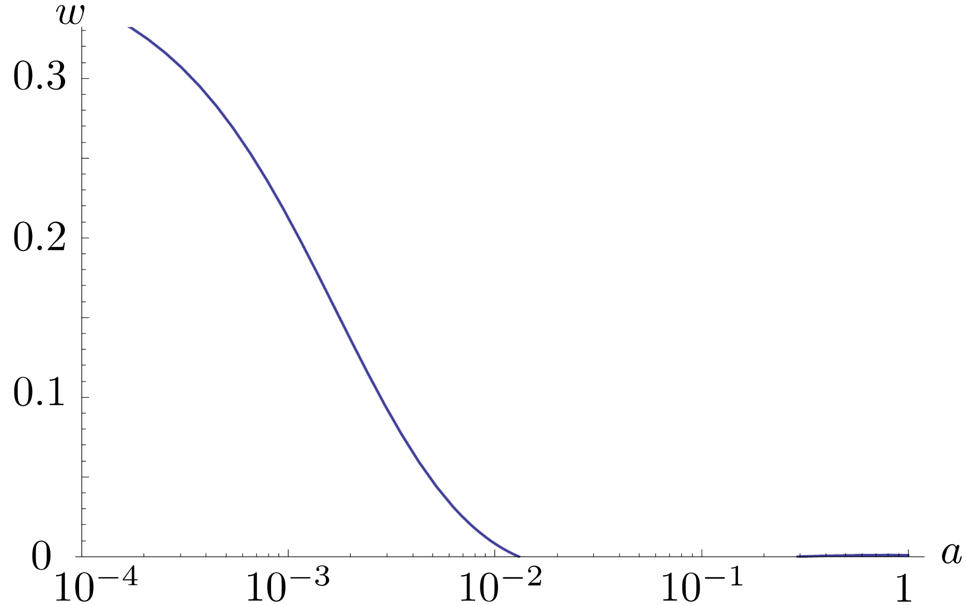


With V$\propto e^{-\alpha\varphi}$

Approaches scaling solution

RD: $\Omega_\varphi = \frac{4}{\alpha^2}$ $\quad w = \frac{1}{3}$

MD: $\Omega_\varphi = \frac{3}{\alpha^2}$ $\quad w = 0$



Growing Neutrino Quintessence

Coupling between ν and φ $\qquad \beta = -\frac{d\,ln(m_\nu)}{d\varphi} < 0$

Leads to φ-dependent mass $\qquad m_\nu = m_i e^{-\beta\varphi} \longrightarrow$ Mass grows with time

Modified Klein-Gordon equation

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = -\beta T_\nu$$

Modified continuity equations

$$\dot{\rho_\nu} + 3H(\rho_\nu + P_\nu) = \beta T_\nu \dot{\varphi}$$

$$\dot{\rho_\varphi} + 3H(\rho_\varphi + P_\varphi) = -\beta T_\nu \dot{\varphi}$$

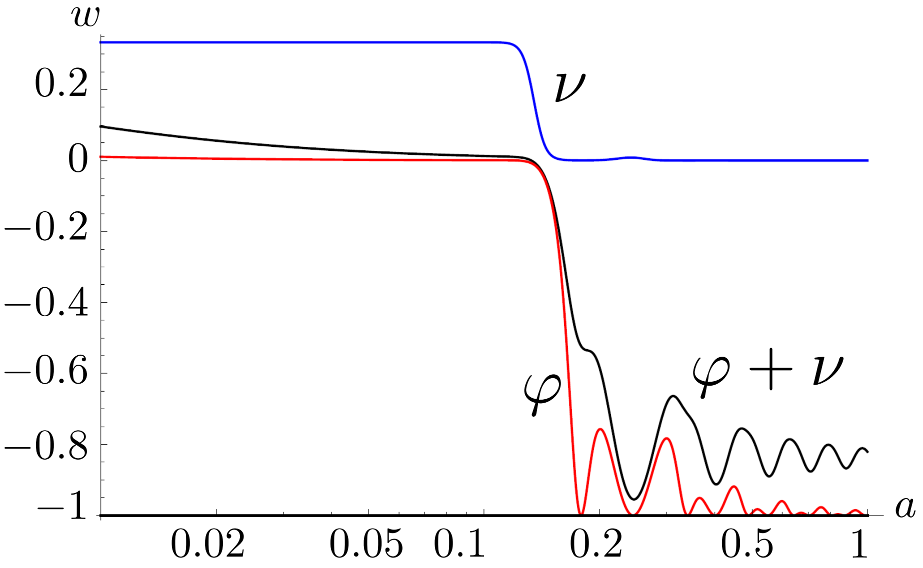
ν and φ can exchange Energy $\longrightarrow$ Form one “Fluid”

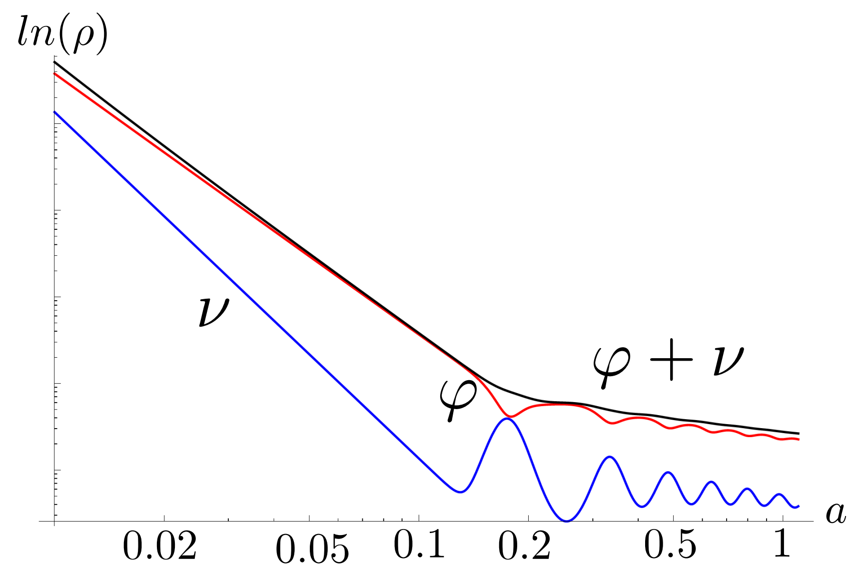
Transition to Dark Energy

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = -\beta T_\nu$$

$$T_\nu = -\rho_\nu(1 - 3w_\nu) = \begin{cases} 0 & \text{While Relativistic} \\ -\rho_\nu & \text{While Non-Relativistic} \end{cases}$$

Transition triggers DE





Need $-\beta \sim 5\alpha$ Bounds on Early Dark Energy require $\alpha \gtrsim 10$

Perturbations

Split into homogenous field and perturbation $\varphi = \bar{\varphi} + \delta\varphi$

Homogenous equation $\ddot{\bar{\varphi}} + 3H\dot{\bar{\varphi}} + V'(\bar{\varphi}) = -\beta T_\nu(\bar{\varphi})$

Perturbation equation (gravitational potentials suppressed)

$$\delta\ddot{\varphi} + 3H\delta\dot{\varphi} - a^{-2}\nabla^2\delta\varphi + V'(\varphi) - V'(\bar{\varphi}) = -\beta\left(T_\nu(\varphi) - T_\nu(\bar{\varphi})\right)$$

Neglect

Highly non-linear

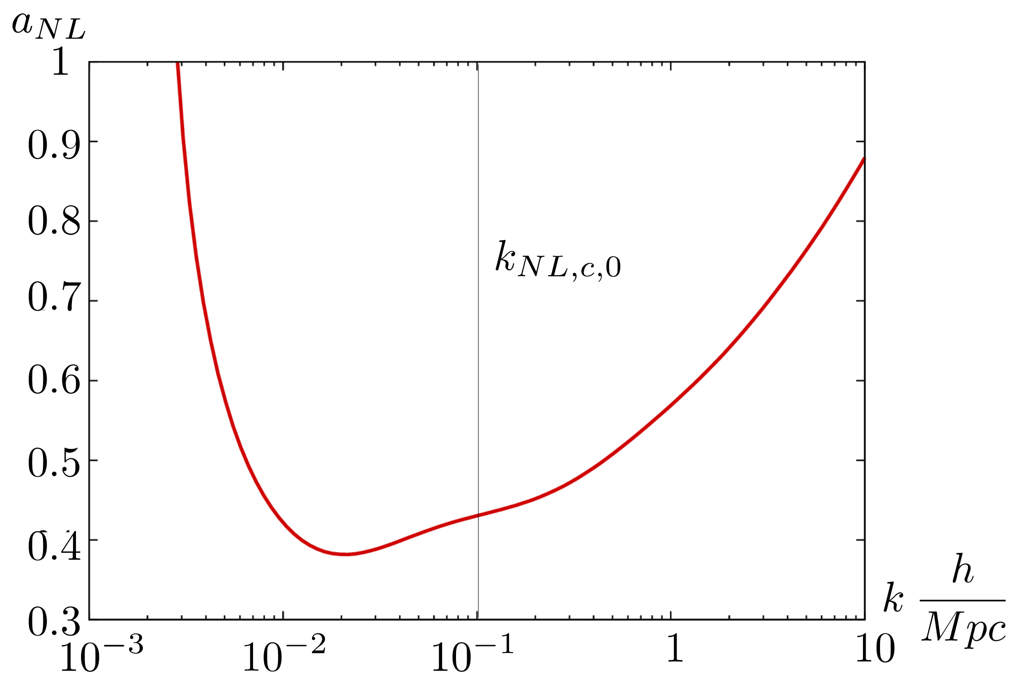
Attractive force

Neutrino equation of motion: $$\frac{du^\eta}{d\eta} + \Gamma^\mu_{\nu\lambda}u^\lambda u^\nu = \beta\left(\partial^\mu\varphi + u^\nu\partial_\nu\varphi u^\mu\right)$$

Gravity

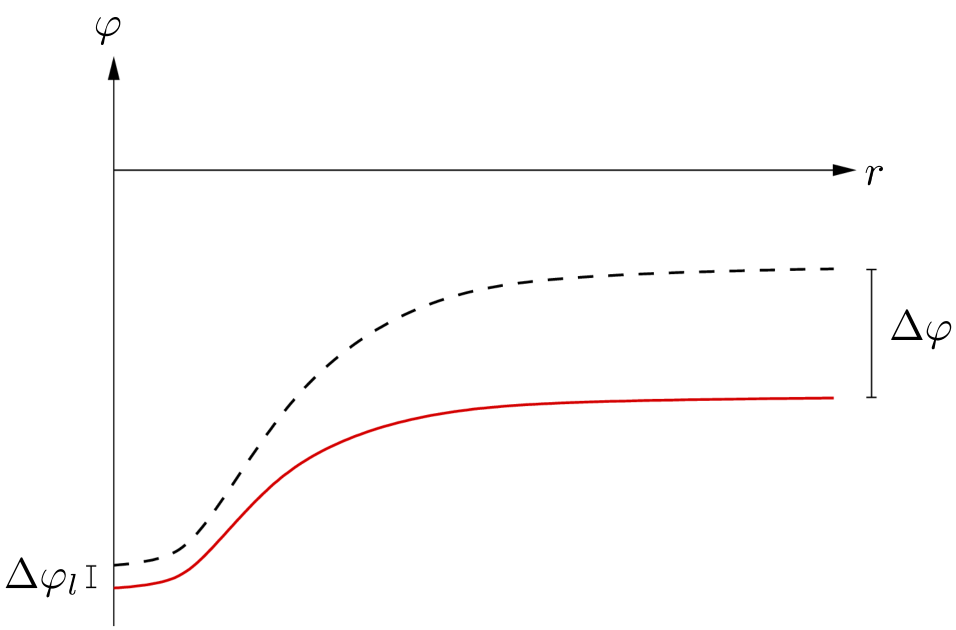
Ensures momentum conservation

Structure Formation



Strong attractive force $F_\varphi \sim \beta^2 F_{\text{Gravity}}$

Neutrinos form lumps after becoming non-relativistic



Most neutrinos are bound in lumps

Average neutrino mass $\overline{m_\nu(\varphi)} < m(\bar{\varphi})$

Neutrinos inside lumps are relativistic

Mota et. al. 2008
Baldi et al. 2011
Nunes, Schrempp, Wetterich 2011
Ayaita,Weber, Wetterich 2011

Backreaction

Use volume average as background $\bar{f} = \frac{1}{V}\int_V d^3x\, f(x)$

Averaged Klein-Gordon equation

$$\ddot{\bar{\varphi}} + 3H\dot{\bar{\varphi}} + a^{-2}\overline{\nabla^2\delta\varphi} + \overline{V'(\varphi)} = -\beta\bar{\rho}_\nu(1-3w_\nu)$$

$$\sim 0.1$$

$\longrightarrow$ Field starts to evolve again

Average energy density and pressure

$$\overline{\rho_\varphi} = \underbrace{\frac{1}{2}\overline{\dot{\varphi}^2}}^{\approx \frac{1}{2}\dot{\bar{\varphi}}^2} + \underbrace{\frac{1}{2}a^{-2}\overline{(\nabla\varphi)^2}}_{\sim O(0.5)V(\bar{\varphi})} + \overbrace{\overline{V(\varphi)}}^{\approx V(\bar{\varphi})}$$

$$\overline{P_\varphi} = \frac{1}{2}\overline{\dot{\varphi}^2} - \frac{1}{6}a^{-2}\overline{(\nabla\varphi)^2} + \overline{V(\varphi)}$$

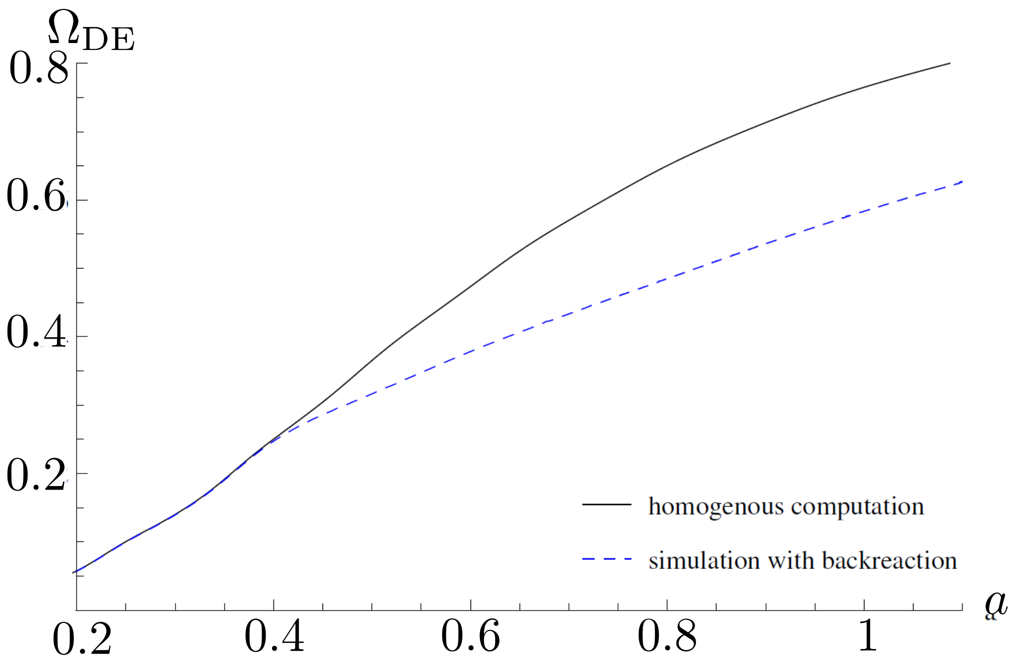
$\longrightarrow$ $w_{\nabla\varphi} = -\frac{1}{3}$

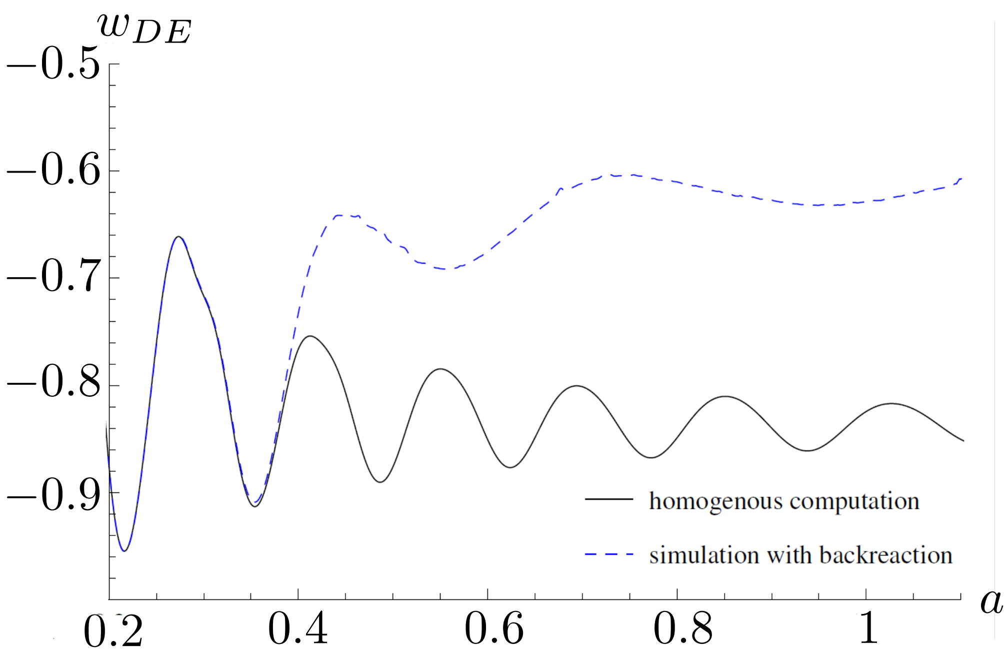
Virialized structures behave like a non-relativistic fluid

Baumann et al. 2012
Ayaita, Weber, Wetterich 2012

Backreaction

$$\alpha = 10$$
$$\beta = -52$$
$$m_i = 2.75\, eV$$

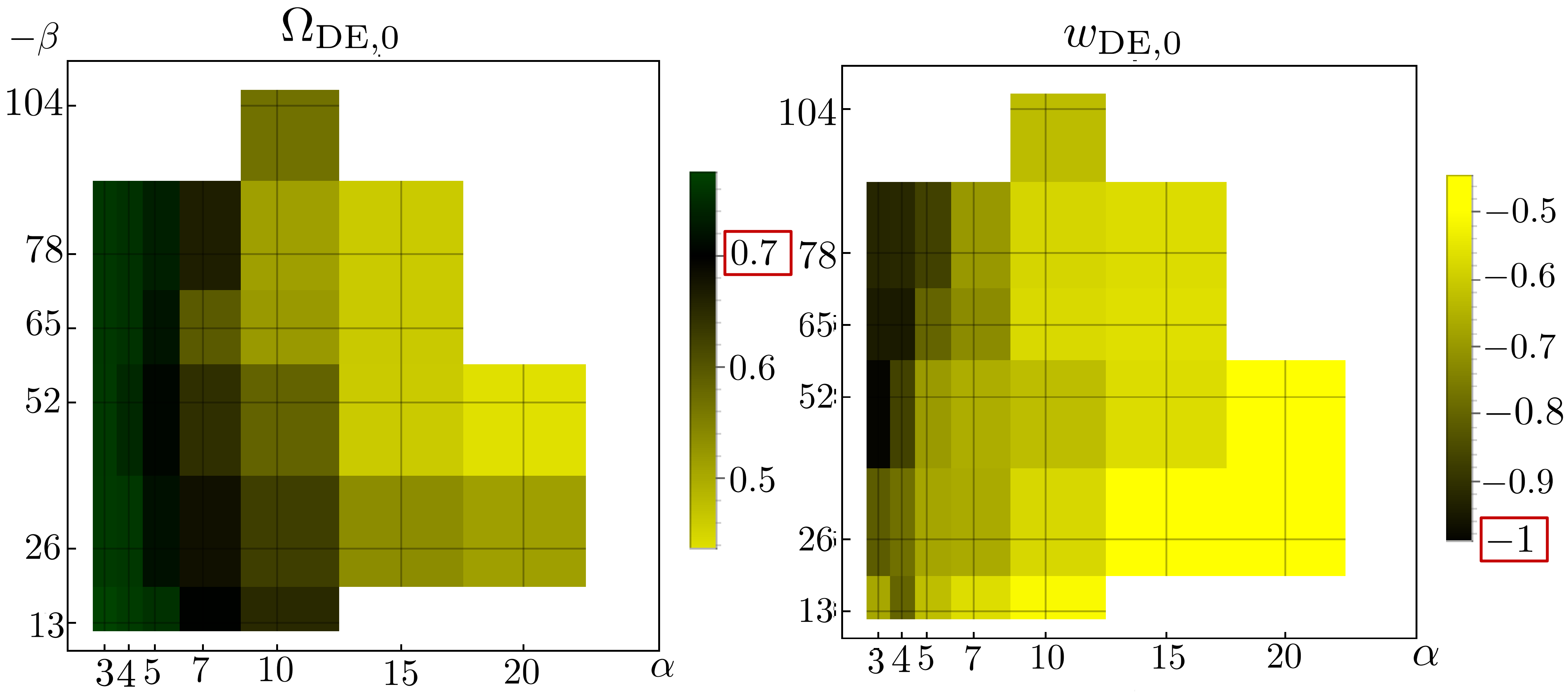




Comparison of the cosmon+neutrino energy density and equation of state obtained from the simulation compared to the homogenous result

Viable Parameters?

$m_i = 2.75\, eV$



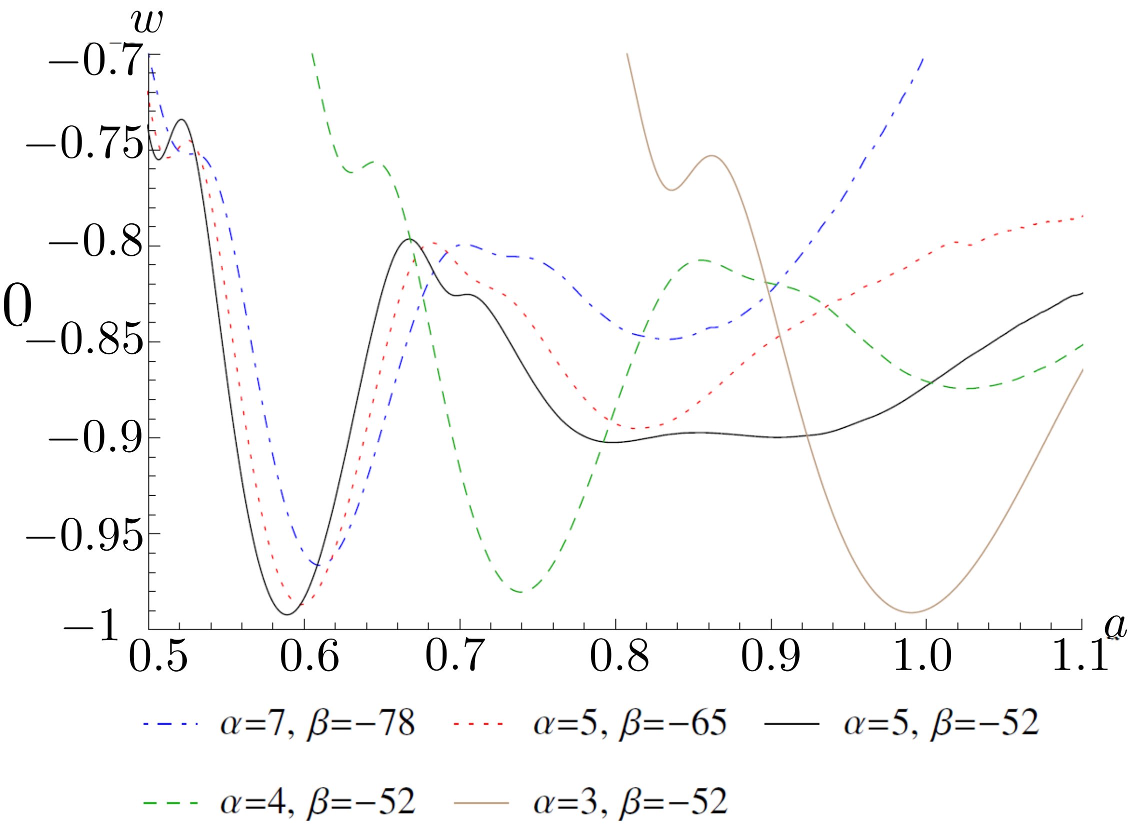
Viable Parameters?

Sufficiently small w $\alpha \lesssim 5$

Correct amount of DE $5 \lesssim \alpha \lesssim 10$

Too much EDE $\alpha \lesssim 10$

→ Probably not viable



For small α neutrinos become non-relativistic late

→ Cosmon evolution stops late

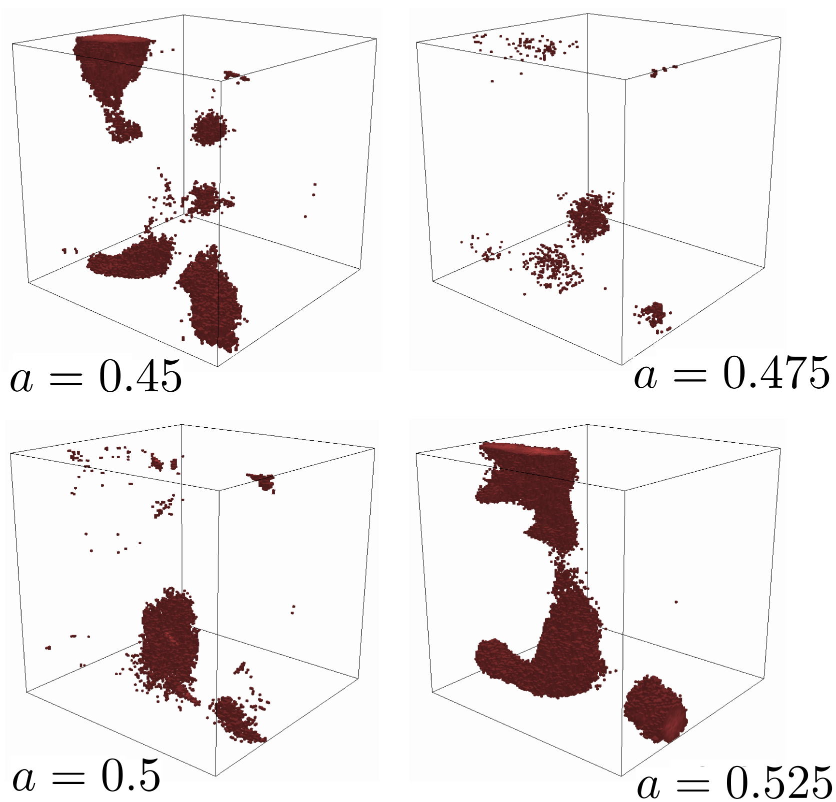
→ Lumps form late

→ Lumps have no time to grow large
no large backreaction effects

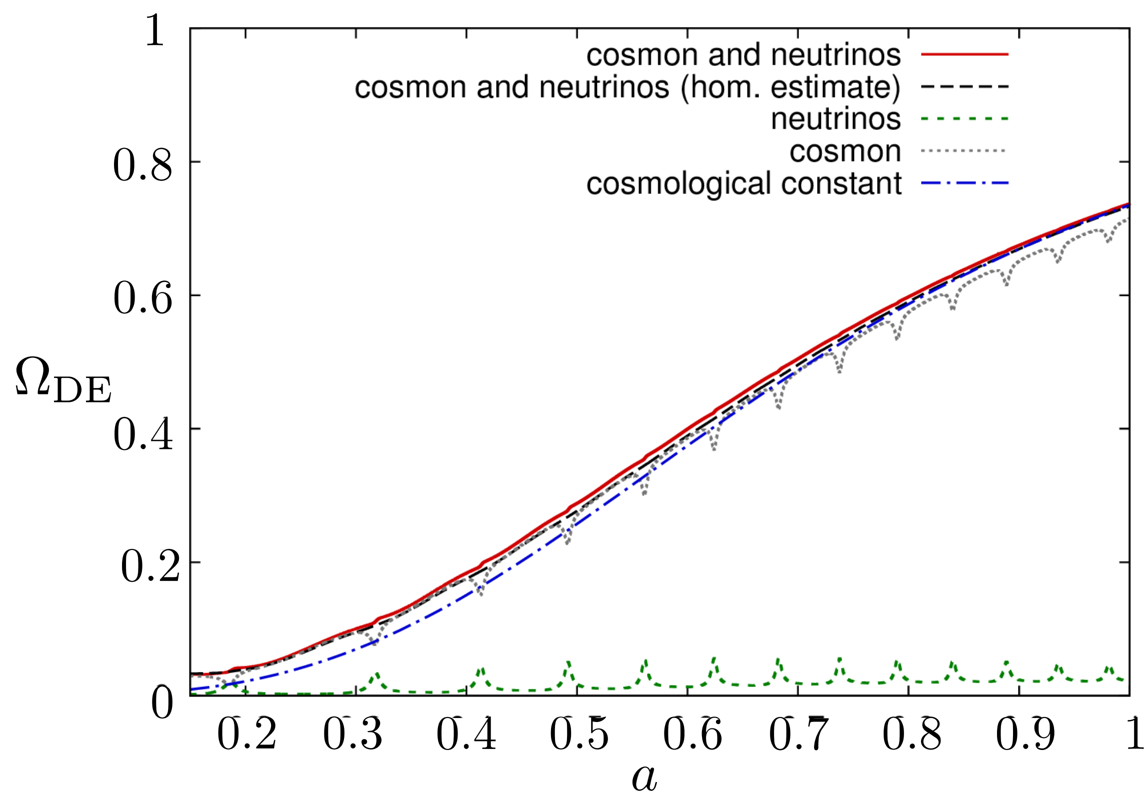
Varying Beta

With a field dependent coupling lumps form and dissolve periodically

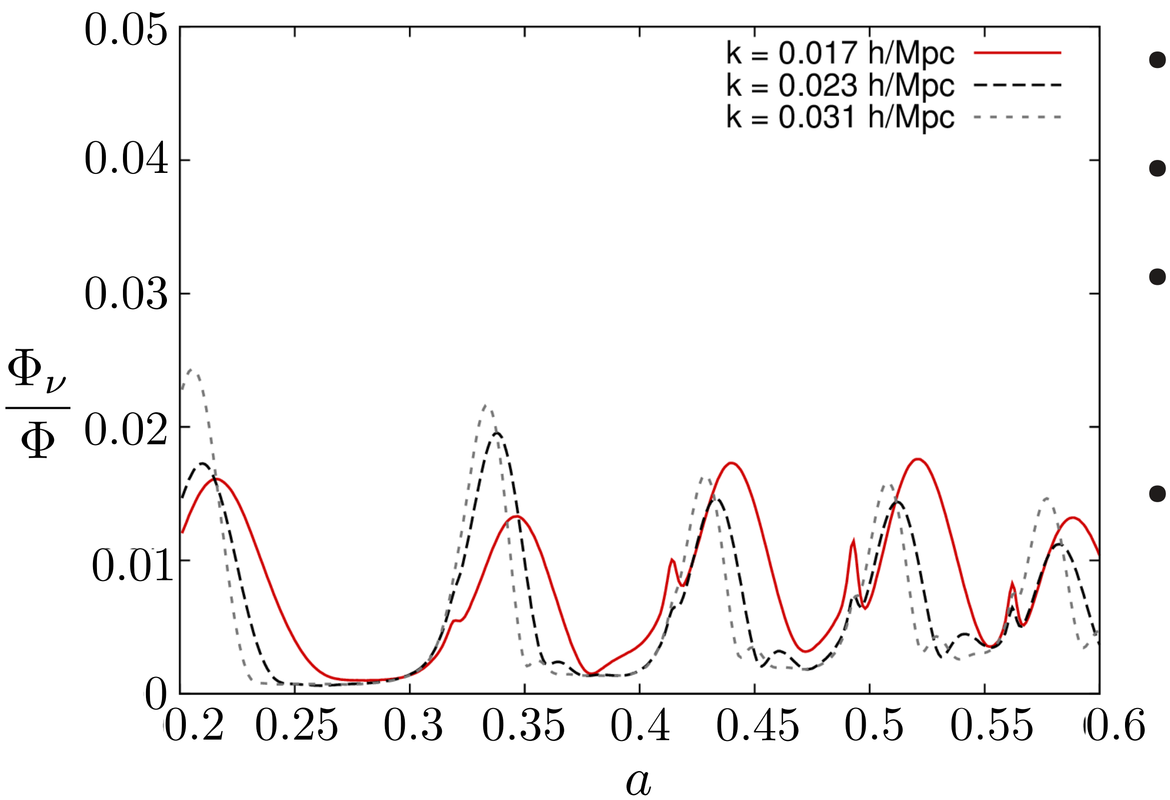
$$m_\nu = \frac{\bar{m}}{\varphi_{\mathrm{crit}} - \varphi} \qquad \beta = -\frac{1}{\varphi_{\mathrm{crit}} - \varphi}$$



$n_\nu > 5\bar{n}_\nu$



Observational Tests



- Early Dark Energy
- Features from transition?
- Different imprint of neutrinos on matter perturbations
- Lumps observable via gravitational potentials

Integrated Sachs-Wolf-Effect $$\frac{\Delta T_{\mathrm{ISW}}}{T} = \int_{t_{\mathrm{dec}}}^{t_0} dt \left(\dot{\Phi} + \dot{\Psi}\right)(t, \mathbf{x}(t))$$

Conclusion

- GNQ addresses CC-problem
- Interesting physical effects
  - Virialized structures of relativistic particles
  - Backreaction effects
- Testable through gravitational potentials
- Constant coupling model probably not viable
- Varying coupling model similar to ΛCDM
  - Dynamics very different