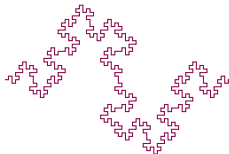


Growing Neutrino Quintessence

Youness Ayaita
Institute for Theoretical Physics
Heidelberg University



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Growing neutrino quintessence¹

- ▶ Motivation: coincidence problem for standard quintessence.

Trigger event for dark energy domination:
cosmic neutrinos becoming nonrelativistic.

- ▶ (average) neutrino mass dependence $m_\nu(\varphi) \propto \exp(-\beta\varphi)$,
in general $\beta(\varphi) = -d \log m_\nu / d\varphi$.
- ▶ corresponds to energy-momentum exchange

$$\nabla_\beta T_{(\varphi)}^{\alpha\beta} \propto \beta(\rho_\nu - 3p_\nu)$$

⇒ only effective once $w_\nu < 1/3$ (around $z \approx 5-10$);

- ▶ dark energy domination similar to Λ CDM.

¹Amendola, Baldi, Wetterich: 0706.3064; Wetterich: 0706.4427

Cosmological dynamics

- ▶ Cosmon-neutrino coupling $\beta \sim -10^2$,
- ▶ attractive force between neutrinos $|\mathbf{F}| \sim 2\beta^2 |\mathbf{F}_{\text{gravity}}|$.

Attempts to study cosmological dynamics:

- ▶ Linear perturbation theory: *breaks down*.²
- ▶ Newtonian N-body: *particles become relativistic*.³

Neglected but important effects⁴:

1. Relativistic motion of neutrino particles,
2. local mass variations $m_\nu(\varphi(\mathbf{x}))$,
3. backreaction.

²Mota, Pettorino, Robbers, Wetterich: 0802.1515

³Baldi, Pettorino, Amendola, Wetterich: 1106.2161

⁴Nunes, Schrempp, Wetterich: 1102.1664

Result: Formation of nonlinear neutrino structures

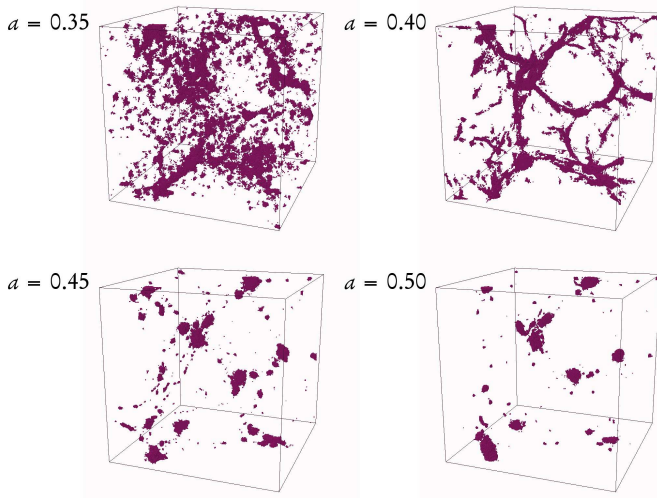


Figure: Simulation volume: $V = 600^3 h^{-3} \text{Mpc}^3$; fields: Ψ , Φ , $\delta\varphi$ on fixed grid $N_c = 256^3$; background: $\bar{\varphi}$, \mathcal{H} ; parameter $\beta = -52$.

1. Relativistic motion

$$\frac{du^\alpha}{d\tau} + \Gamma_{\rho\sigma}^\alpha u^\rho u^\sigma = \beta \partial^\alpha \varphi + \beta u^\lambda \partial_\lambda \varphi u^\alpha.$$

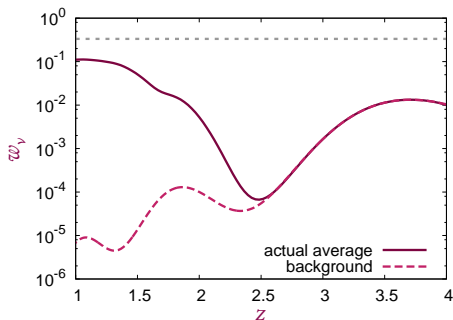


Figure: Increasing w_γ due to nonlinear clustering.

⇒ Backreaction.

2. Cosmon perturbations

$$\Delta \delta \varphi - a^2 V_{,\varphi\varphi}(\bar{\varphi}) \delta \varphi + 2\Psi(\bar{\varphi}'' + 2\mathcal{H}\bar{\varphi}') = -a^2 \beta (\delta \rho_\nu - 3\delta p_\nu)$$

Suppressed $m_\nu \propto \exp(-\beta\varphi(\mathbf{x})) \Rightarrow$ backreaction.

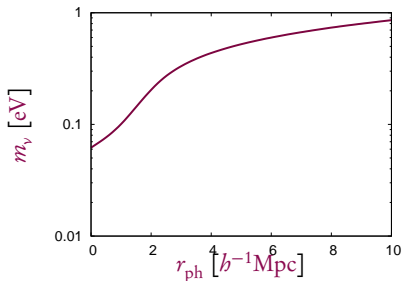
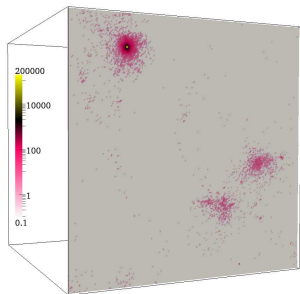


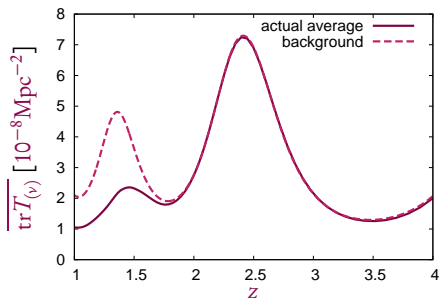
Figure: Number density contrast (left), mass profile (right).

3. Backreaction

$$\bar{\varphi}'' + 2\mathcal{H}\bar{\varphi}' + a^2 V_{,\varphi}(\bar{\varphi}) = -a^2 \beta (\bar{\rho}_\nu - 3\bar{p}_\nu)$$

$$-(\bar{\rho}_\nu - 3\bar{p}_\nu) = \overline{\text{tr}T_{(\nu)}} = \frac{\int_V d^3x \sqrt{\tilde{g}} \text{tr}T_{(\nu)}}{\int_V d^3x \sqrt{\tilde{g}}} = -\frac{1}{a^3 V} \sum_p \frac{m_{\nu,p}}{\gamma_p}.$$

⇒ Systematically $m_{\nu,p} = m_\nu(\varphi(\mathbf{x}_p)) < m_\nu(\bar{\varphi})$ and $\gamma_p > 1$.



Outlook: Confrontation with observations

- ▶ Equation for cosmon perturbation $\delta\varphi$ is highly nonlinear

$$\Delta\delta\varphi - a^2 V_{,\varphi\varphi}(\bar{\varphi})\delta\varphi + \dots = -a^2\beta [\delta\rho_\nu(\delta\varphi) - 3\delta p_\nu(\delta\varphi)].$$

- ▶ Iterative scheme \rightarrow unstable for $z \lesssim 1$.
 - ▶ 1D BVP for spherically symmetric structures:
 $\frac{d\varphi}{dr}(r=0) = 0, \quad \varphi(r \rightarrow \infty) = \varphi_{\text{out}}$.
 - ▶ Semi-analytical investigation of isolated, spherical structures.
- ▶ Observable consequences:
 - ▶ *Directly*: ISW, weak lensing, ...
 - ▶ *Indirectly*: Matter perturbations, peculiar velocities.

Growing neutrino quintessence is...

- ▶ theoretically appealing,
- ▶ technically challenging.

Special thanks to:

- ▶ Maik Weber,
- ▶ Christof Wetterich,
- ▶ Marco Baldi.