Growing Neutrino Dark Energy

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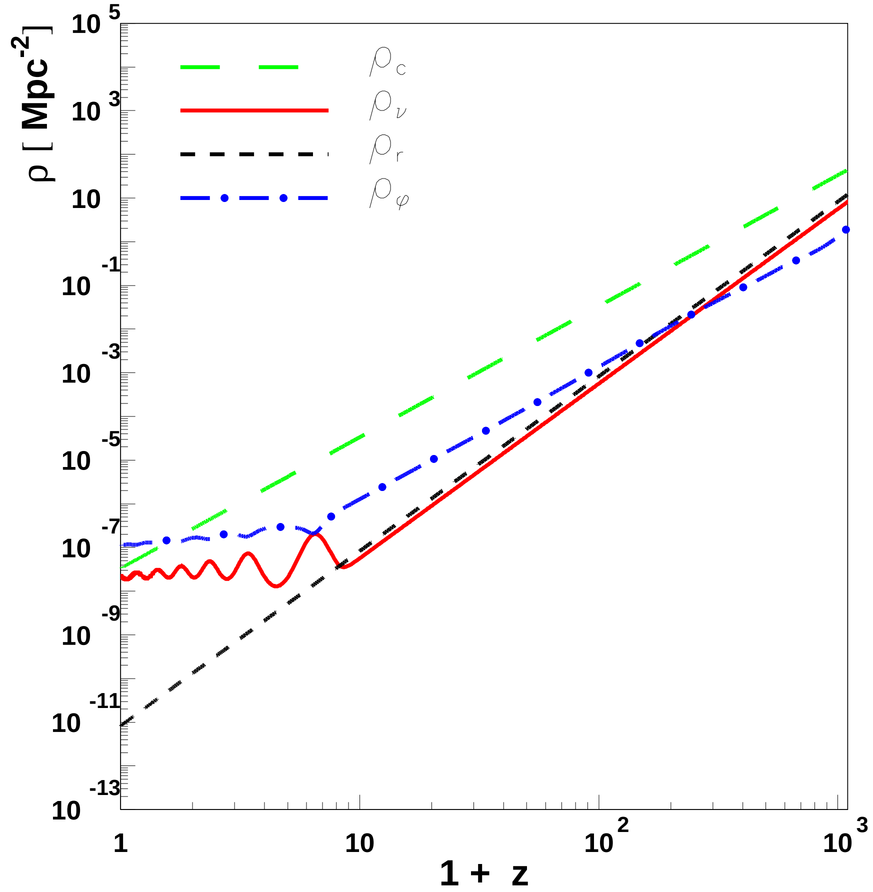
Nunes, Schrempp, Wetterich, PRD, arXiv:1102.1664

Growing neutrino dark energy

Amendola, Baldi, Wetterich (2007);
Wetterich (2007)

- Interaction between a scalar field and neutrinos;
- Rolling field generates time dependent neutrino mass;
- Neutrinos interact via a new fifth force.
- Scalar field is today's dark energy.



Growing neutrino dark energy

Amendola, Baldi, Wetterich (2007);
Wetterich (2007)

Scalar potential:

$$V(\phi) = M^4 \exp\left(-\alpha \frac{\phi}{M}\right)$$

Neutrino mass:

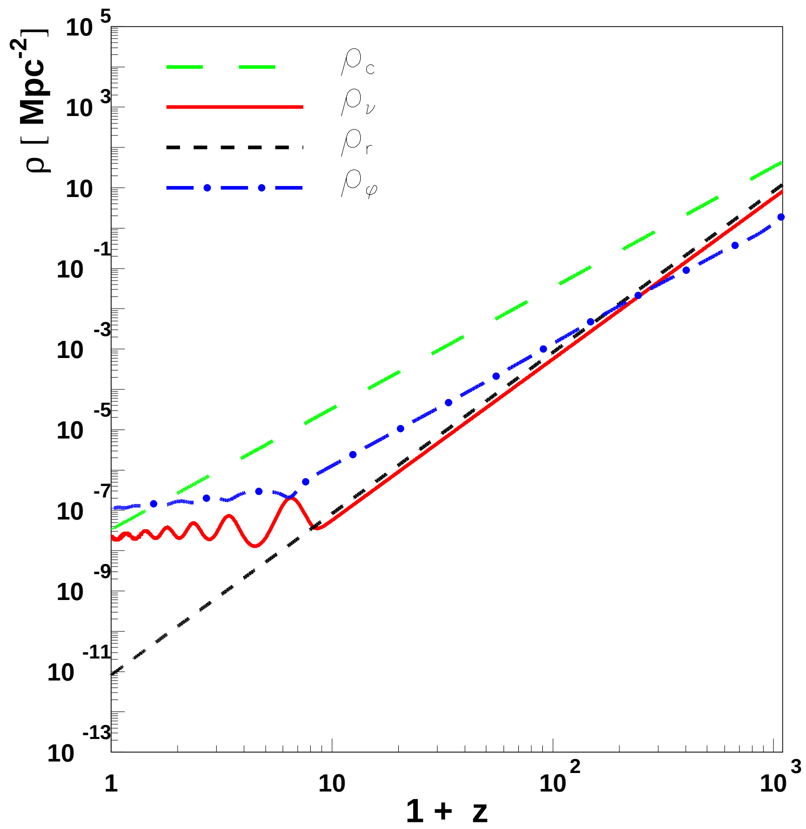
$$m_\nu(\phi) = \hat{m} \exp\left(-\beta \frac{\phi}{M}\right)$$

Scalar field equation of motion:

$$\ddot{\bar{\phi}} + 2\mathcal{H}\dot{\bar{\phi}} + a^2 \frac{dV}{d\bar{\phi}} = a^2 \frac{\beta}{M}(\rho_\nu - 3p_\nu)$$

Continuity equation for neutrinos:

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



Growing neutrino dark energy

While neutrinos are relativistic, $p_\nu = \rho_\nu/3$:

- No coupling. Field in cosmic attractor defined by the potential;
- Neutrinos decay as $\rho_\nu \propto a^{-4}$;
- Solution independent of initial conditions;
- Constant fraction in dark energy,

$$\Omega_\phi = \frac{3(4)}{\alpha^2}$$

When neutrinos become non-relativistic, $p \approx 0$:

- Coupling turns on;
- Neutrino mass grows with time;
- Field dynamics approaches the acceleration attractor

$$\Omega_\phi = 1 - \frac{1}{\gamma} + \frac{3}{\alpha^2\gamma^2}$$

with $\gamma = 1 - \beta/\alpha$.

We use $\alpha = 10$, $\beta = -52$.

Neutrino lump formation

- Non-relativistic neutrinos interact via fifth force enhanced by $(1 + 2\beta^2)$ compared to gravity;

- This force drives rapid growth of neutrino perturbations;

- Neutrino perturbations on supercluster scales grow non-linear around $z \approx 2$.

Mota, Pettorino, Robbers, Wetterich (2008);
Wintergerst, Pettorino, Mota, Wetterich (2010)

Neutrino distribution

Neutrino distribution compatible with Navarro-Frenk-White profile

Wintergerst, Pettorino, Mota, Wetterich (2010)

$$n_{\rm NFW}(r) = \frac{n_s}{(r/r_s)\,(1+r/r_s)^2}$$

We also consider that infall of neutrinos stops after a characteristic time such that

$$n_{\rm step}(r) = \begin{cases} n_{\rm NFW}(r)\,, & r < c\,r_s \\ 0\,, & r > c\,r_s \end{cases}$$

where c is concentration parameter.

And in the background

$$\bar{n}_\nu(z) = \bar{n}_{\nu 0}\,(1+z)^3$$

In general:

$$n_\nu(z,r) = n_{\rm NFW}(r)\,\theta(c\,r_s - r) + \bar{n}_\nu(z)$$

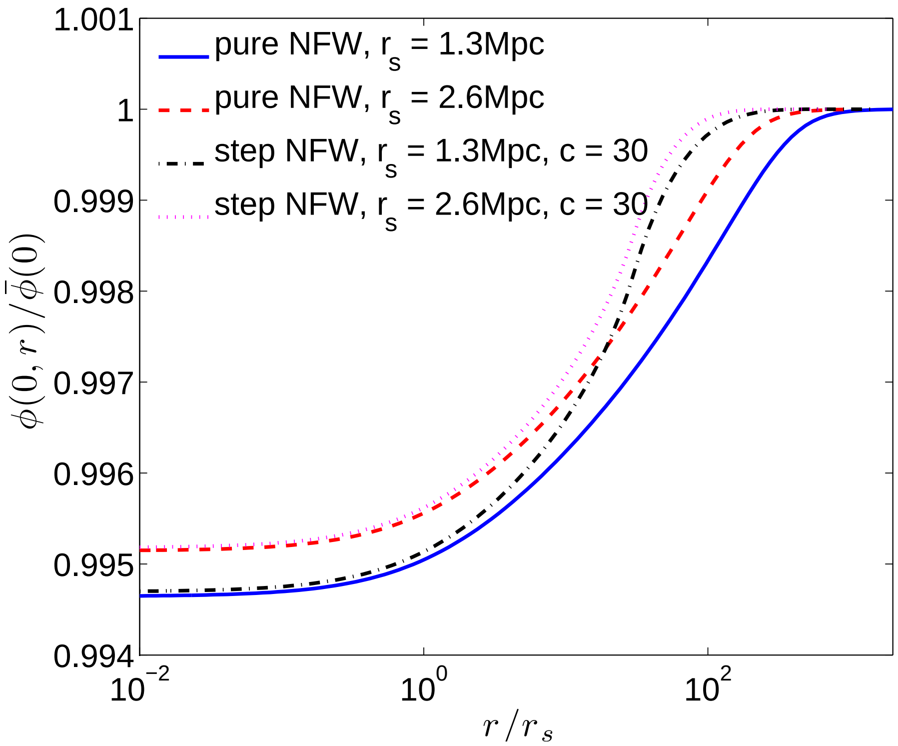
Spatial profiles

Assuming a spherical neutrino lump

$$\phi'' + \frac{2}{r}\phi' = \frac{dV(\phi)}{d\phi} - \frac{\beta}{M} n_\nu(r)\, m_\nu(\phi)$$

with boundary conditions

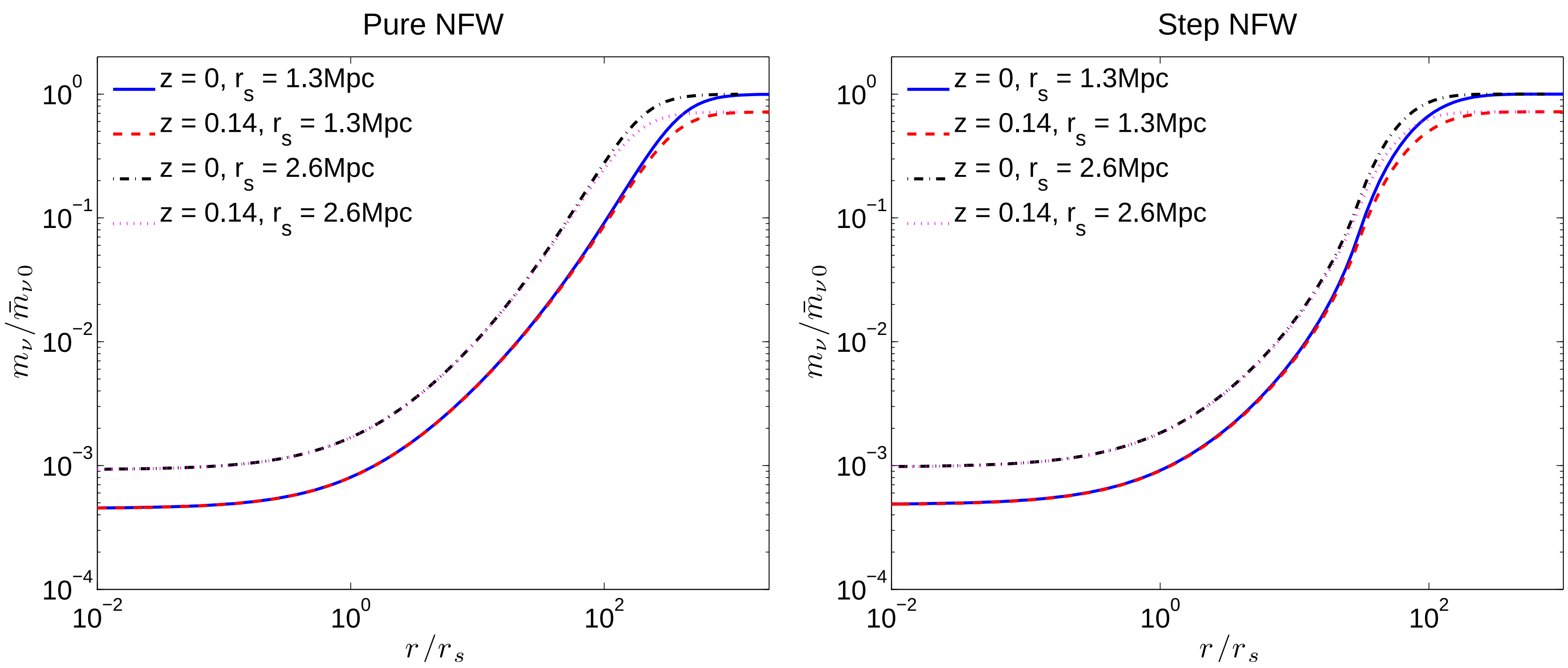
$$\phi'(r)|_{r=0} = 0 \quad \text{and} \quad \phi(r)|_{r\to\infty} = \bar{\phi}$$



No chameleon thin-shell mechanism!

Neutrino masses

$$m_\nu(\phi) = \hat{m}\exp\left(-\beta\frac{\phi}{M}\right)$$



Neutrino mass suppressed inside a lump!

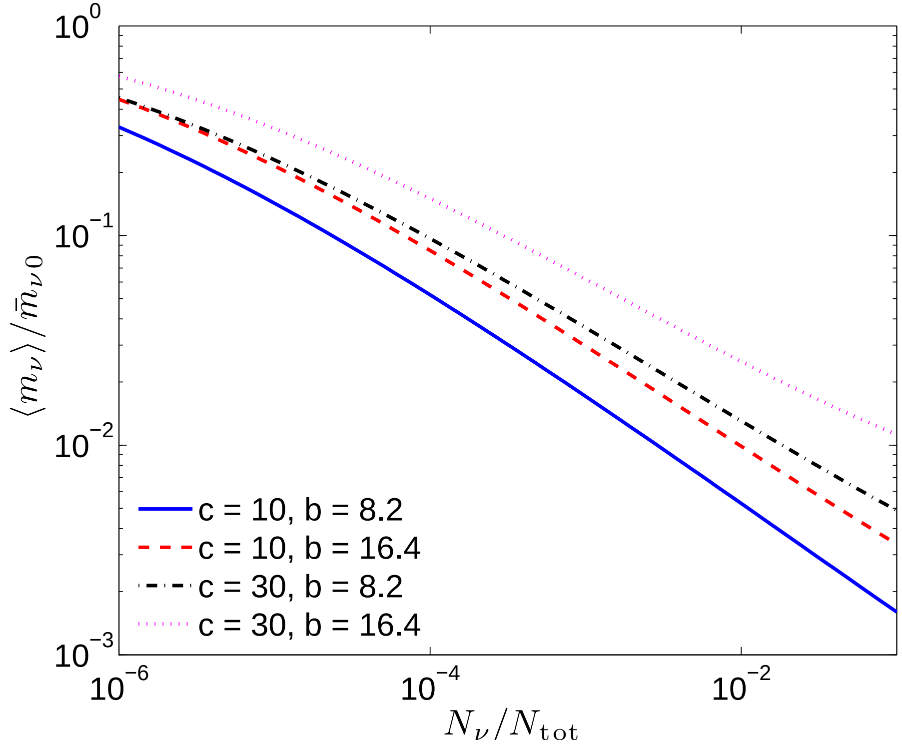
Average neutrino mass

How the average mass depends on the number of the neutrinos in a lump, or equivalently, on the size of the lump?

$$\langle m_\nu \rangle = \frac{4\pi}{N_\nu} \int_0^{c\, r_s} dr\, r^2 n_\nu(r) m_\nu(\phi(r))$$

$$r_s = b \left(\frac{N_\nu}{N_{\rm tot}\, F(c)} \right)^{1/3} \text{Mpc}$$

$$F(c) = \ln(1+c) - c/(1+c)$$



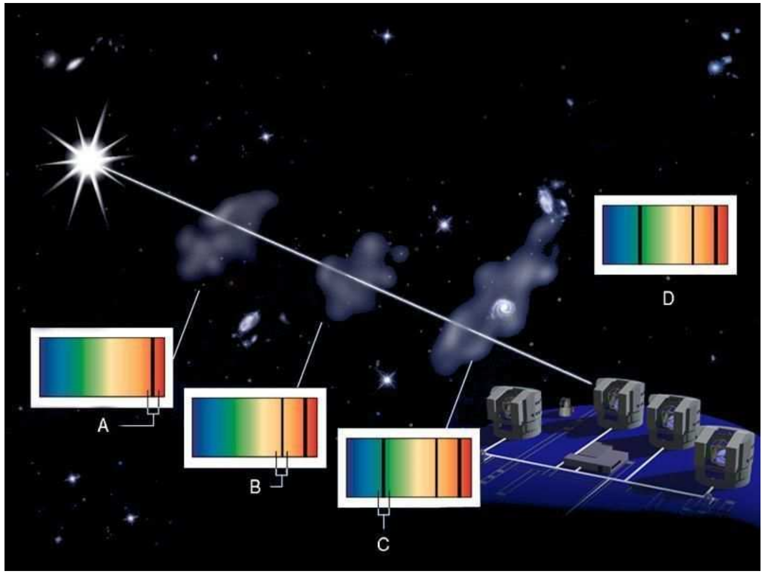
The gravitational potential of a neutrino lump:

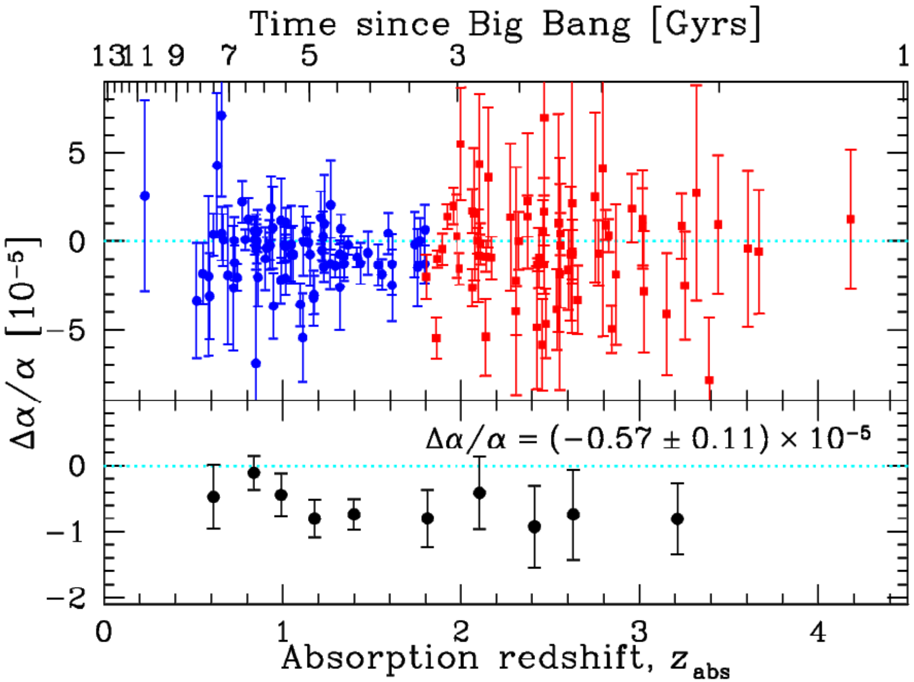
$$\Phi_\nu(r) = -G\frac{N_\nu \langle m_\nu \rangle}{r} \ll \frac{\langle m_\nu \rangle}{\bar{m}_{\nu 0}}\, \Phi_\nu(r)|_{m_\nu = \bar{m}_{\nu 0}}$$

Cosmological variation of alpha?

Keck/Hires high resolution spectra from distant quasars

Murphy, Webb, Flambaum (2003)
Murphy et al. (2004)

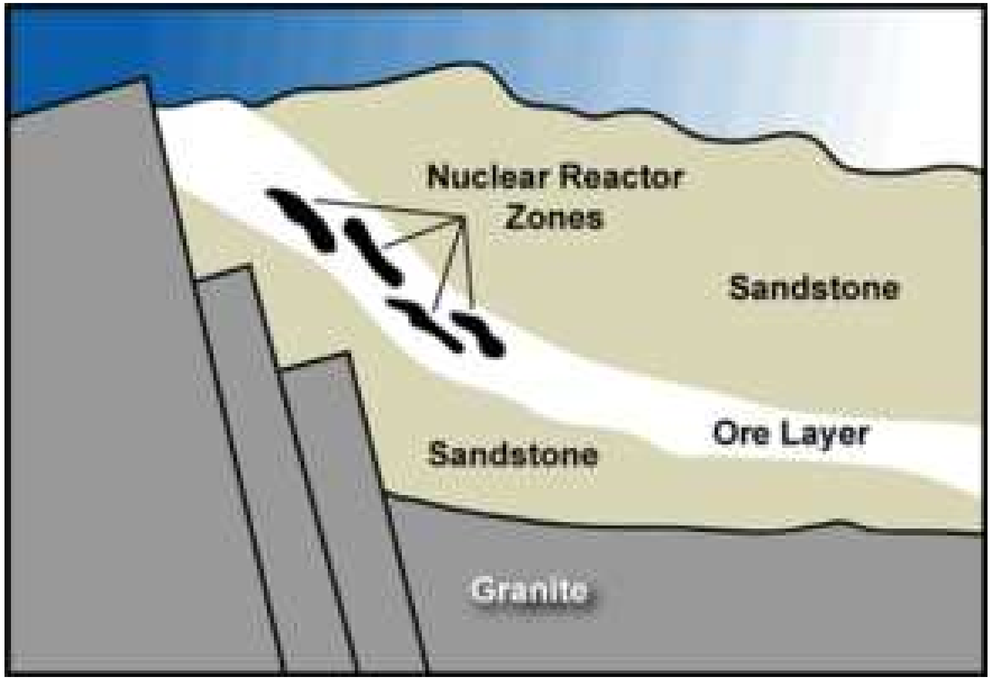


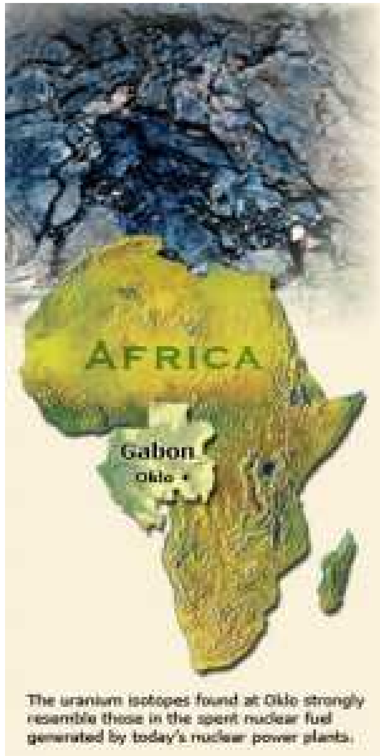


$$\frac{\Delta\alpha}{\alpha} \equiv \frac{\alpha - \alpha_0}{\alpha} = -(5.7 \pm 1.1) \times 10^{-6}$$

Local constraints on variation of alpha

Oklo Nuclear Reactor: The rate of radioactive decay and isotope abundances of Samarium constrain the variation of alpha at corresponding redshift $z = 0.14$ (1.8 Gyr ago).





$$\frac{\Delta\alpha}{\alpha} = (0.7 \pm 1.8) \times 10^{-8}$$

$$\frac{\Delta\alpha}{\alpha} = (0.6 \pm 6.2) \times 10^{-8}$$

Gould, Sharapov, Lamoreaux (2006)

Petrov et al. (2006)

Local constraints versus cosmological variation

Oklo:

$$\left(\frac{\Delta\alpha}{\alpha}\right)_{\rm Oklo} = (0.7 \pm 1.8) \times 10^{-8}$$

Keck/Hires:

$$\left(\frac{\Delta\alpha}{\alpha}\right)_{\rm cloud} = -(5.7 \pm 1.1) \times 10^{-6}$$

A linear dependence of $\Delta\alpha/\alpha$ with redshift reveals incompatibility between these two constraints.

- α must freeze at low redshift or...
- Spatial variation of α.

Coupling the field with electromagnetism

The coupling

$$\mathcal{L}_{\phi F} = -\frac{1}{4} B_F(\phi) F_{\mu\nu} F^{\mu\nu}$$

Gauge kinetic function

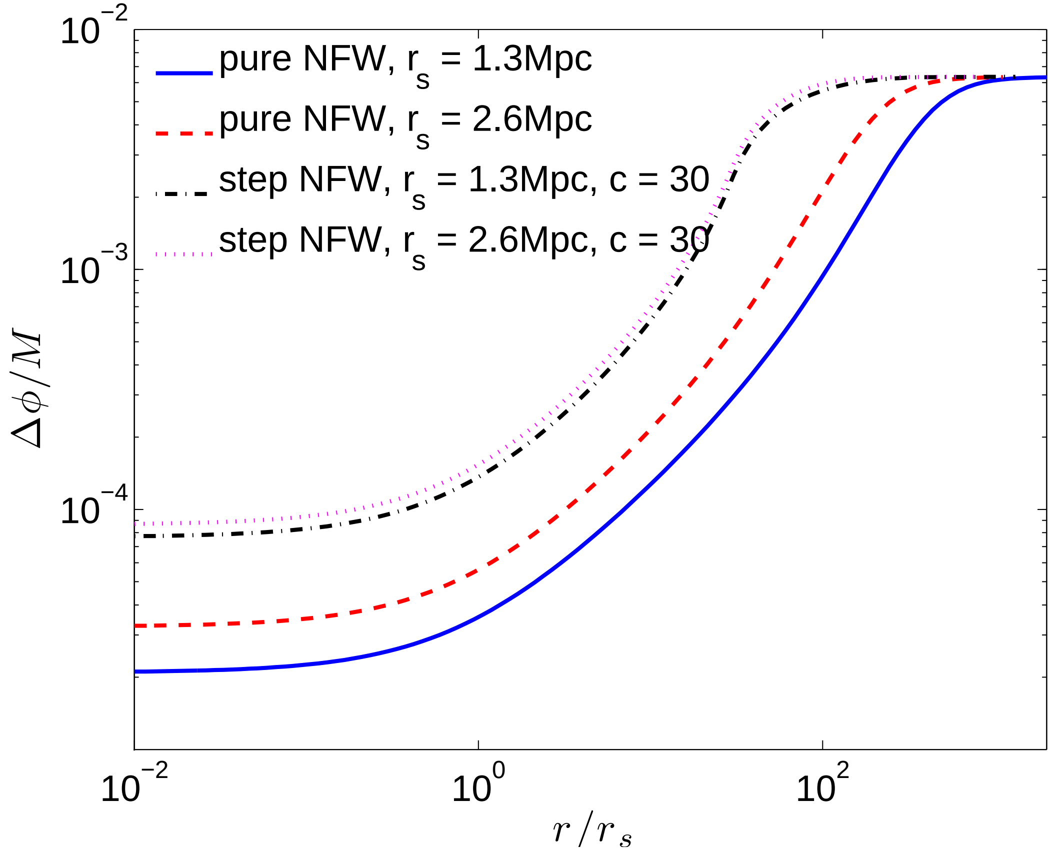
$$B_F(\phi) = 1 - \zeta(\phi - \phi_0)$$

Variation in α

$$\alpha = \frac{\alpha_0}{B_F(\phi)} \qquad \Rightarrow \qquad \frac{\Delta\alpha}{\alpha} \equiv \frac{\alpha - \alpha_0}{\alpha_0} = \zeta(\phi - \phi_0)$$

Relative evolution of the field

$$\Delta\phi = \phi(z=0,r) - \phi(z=0.14,r)$$



The fields evolves slower inside the lump than in the background!

Comparing constraints

In terms of the scalar field:

$$\left(\frac{\Delta\alpha}{\alpha}\right)_{\rm Oklo} = \frac{\zeta}{M}\left[\phi(z=0.14,r) - \phi(z=0,r)\right]$$

$$\left(\frac{\Delta\alpha}{\alpha}\right)_{\rm cloud} = \frac{\zeta}{M}\left[\phi(z_c=2,R_c) - \phi(z=0,r)\right]$$

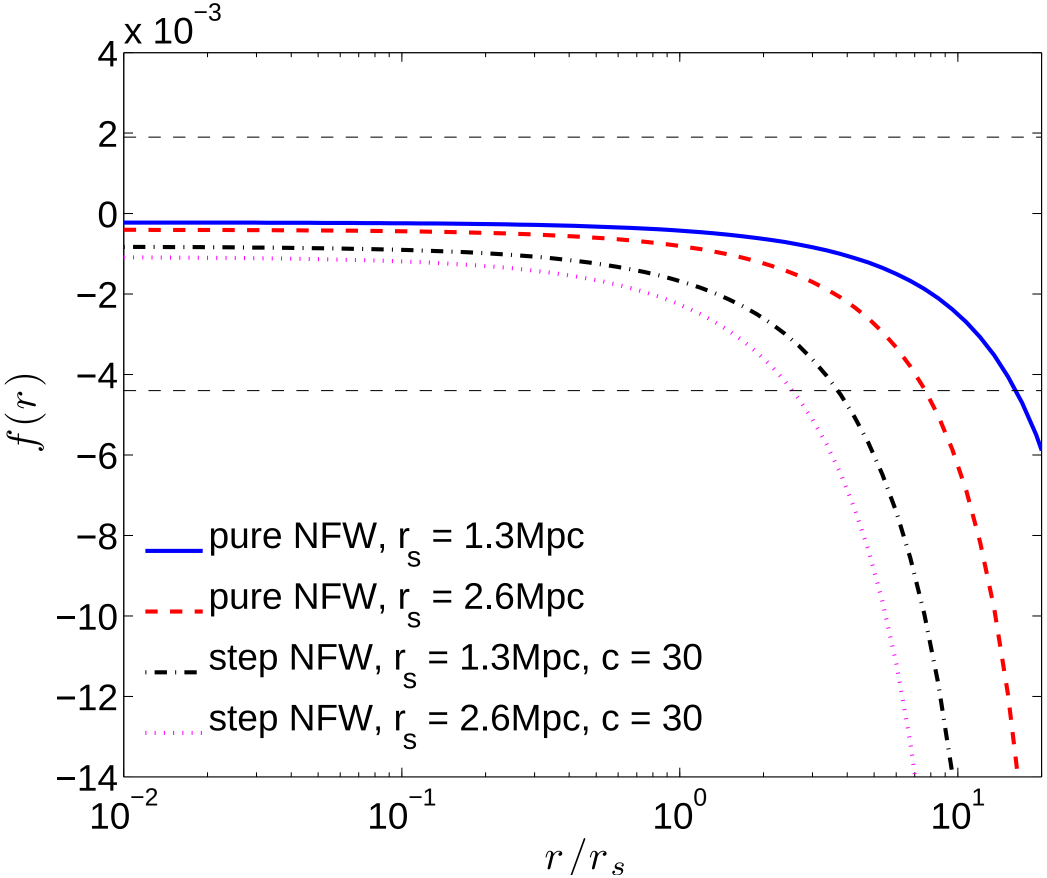
With $f(r) \equiv (\Delta\alpha/\alpha)_{\rm Oklo}/(\Delta\alpha/\alpha)_{\rm cloud}$

$$f(r) \equiv \frac{\phi(z=0.14,r) - \phi(z=0,r)}{\bar{\phi}(z_c=2) - \phi(z=0,r)}$$

From the observations we have:

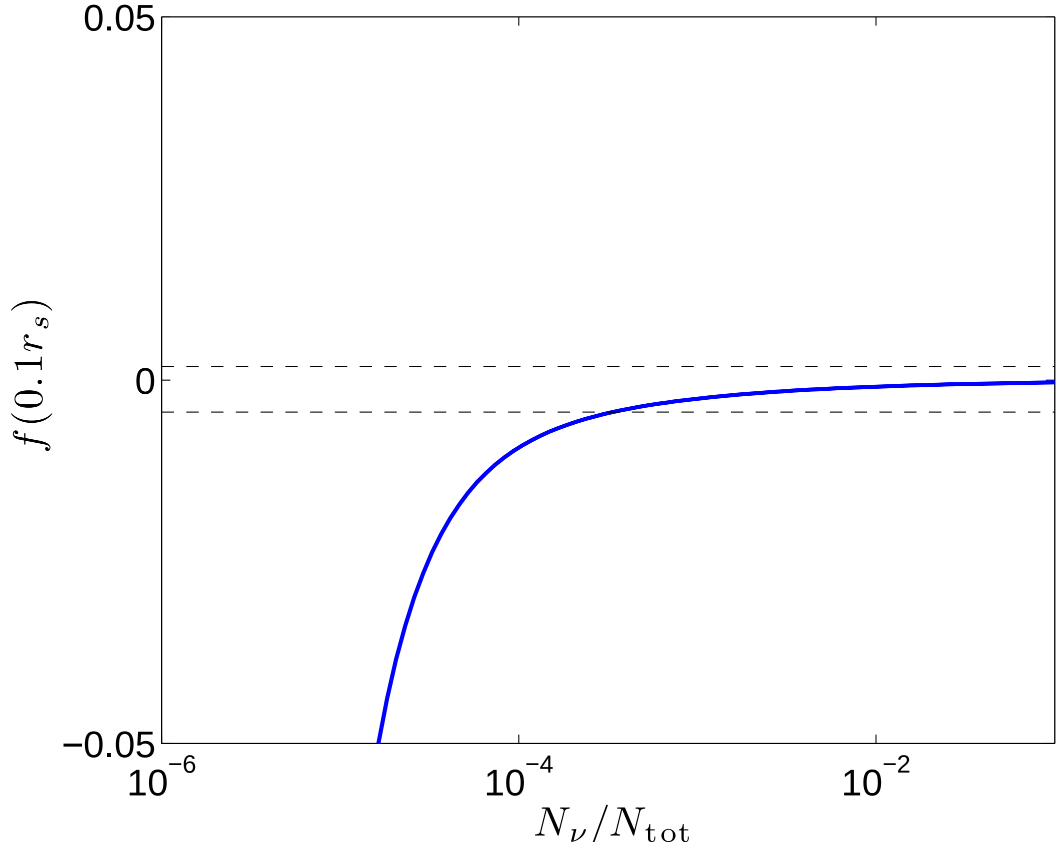
$$-4.4\times10^{-3} \lesssim f(r) \lesssim 1.9\times10^{-3}$$

Comparing constraints



The constraints can be satisfied for $r \lesssim r_s$!

Dependence with number of neutrinos



Constraints are more easily satisfied for larger neutrino lumps!

Conclusions

Growing Neutrino Dark energy

- Non linear effects resulting from scalar-neutrino interaction stronger than gravity;
- Within a neutrino lump, field and neutrino mass are nearly frozen;
- Gravitational potential is suppressed;
- Time variation of fundamental parameters significantly reduced;
- Stronger suppression for larger lumps;
- Study effects on ISW and bulk flow of peculiar velocities.