How neutrinos can kill cosmological models

or

Bad $\nu$s for quintessence

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Advances in theoretical cosmology in light of data

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“What can neutrinos do for cosmology?”

Michael Turner, Advances in Theoretical Cosmology in Light of Data, week 1
Idea: neutrinos as a test of cosmological models

\[ \Sigma m_\nu > 0.06 \text{ eV} \quad \text{vs.} \quad \Sigma m_\nu > 0.10 \text{ eV} \]
Idea: neutrinos as a test of cosmological models

- Choose your favourite cosmological model
- Parametrize it appropriately if needed
- Derive bounds on $M_\nu$ within your chosen model **imposing a lower prior** $M_\nu > 0 \text{ eV}$ (ignore oscillation measurements)
- Are your bounds consistent with oscillation data ($M_\nu > 0.06 \text{ eV}$)?
  - **YES**: Great! Your model isn’t ruled out (yet)!
  - **NO**: Might want to reconsider your model...

How can cosmology measure neutrino masses?

ISW effect

TT spectrum

Lensing effect

Matter spectrum

Power at small scales

Turning-point position

Abazajian et al, 2013

BB spectrum

Lensing potential spectrum

Courtesy of Martina Gerbino
Quintessence

**Single, minimally-coupled scalar \( \phi \), with canonical kinetic term**

Ratra & Peebles 1988; Wetterich 1988; Caldwell, Dave & Steinhardt 1998

Lagrangian:

\[
\mathcal{L}_{\phi} = -\frac{1}{2} \partial^{\mu} \phi \partial_{\mu} \phi - V(\phi)
\]

Pressure and energy density:

\[
\rho_{\phi} = \frac{1}{2} \dot{\phi}^2 + V(\phi), \quad P_{\phi} = \frac{1}{2} \dot{\phi}^2 - V(\phi)
\]

Equation of state is **non-phantom**:

\[
w_{\phi} = \frac{\frac{1}{2} \dot{\phi}^2 - V(\phi)}{\frac{1}{2} \dot{\phi}^2 + V(\phi)} \geq -1
\]
Quintessence

Essentially two classes of quintessence models:

Caldwell & Linder 2005; Linder 2006; Huterer & Peiris 2007

**THAWING**

- φ frozen at early times due to Hubble friction
- φ starts rolling at late times when friction is subdominant
- $w \approx -1$ at early times
- $w > -1$ at late times
- $w(z)$ monotonically convex decreasing function of $z$ and non-phantom

**FREEZING**

- φ rolls at early times due to steep potential
- φ frozen at late times due to shallower potential
- $w > -1$ at early times
- $w \approx -1$ at late times
- $w(z)$ monotonically convex increasing function of $z$ and non-phantom
Quintessence parametrizations

**THAWING**

1CPL parametrization:
Chevallier & Polarski 2001; Linder 2003

\[ w(z) = w_0 + w_a \frac{z}{1 + z} \]

Dark energy density:

\[ \rho_q(a) = \rho_{DE,0} a^{-3(1+w_0+w_a)} \times e^{-3w_a(1-a)} \]

**FREEZING**

7CPL parametrization:
Pantazis et al. 2016

\[ w(z) = w_0 + w_a \left( \frac{z}{1 + z} \right)^7 \]

Dark energy density:

\[ \rho_q(a) = \rho_{DE,0} a^{-3(1+w_0+w_a)} \times e^{-3w_a\left(H_7 - 7a_3 F_2(1,1,-6;2,2;a)\right)} \]
Quintessence priors

**THAWING**

1CPL parametrization:

\[ w(z) = w_0 + w_a \frac{z}{1 + z} \]

Thawing priors:
- \( w_0 > -1 \)
- \( w_a < 0 \)
- \( w_0 + w_a > -1 \)

**FREEZING**

7CPL parametrization:

\[ w(z) = w_0 + w_a \left( \frac{z}{1 + z} \right)^7 \]

Freezing priors:
- \( w_0 > -1 \)
- \( w_a > 0 \)
Results

Data: Planck temperature and low-\( \ell \) polarization (\( Planck TT + lowP \)), BAO measurements (DR11 CMASS and LOWZ, 6dFGS, MGS), and supernovae luminosity distances (JLA)

THAWING
- \( w_0 = -0.936^{+0.019}_{-0.038} \) (68% C.L.)
- \( -0.037 < w_a < 0 \) (95% C.L.)
- \( M_\nu < 0.058 \) eV (95% C.L.)

FREEZING
- \( -1 < w_0 < -0.969 \) (95% C.L.)
- \( 0 < w_a < 0.567 \) (95% C.L.)
- \( M_\nu < 0.063 \) eV (95% C.L.)
Results

THAWING

FREEZING
Physical explanation

- As $w(z) > -1$ and moves towards 0, the behaviour of quintessence may resemble that of matter.
- Another way to see this is that there is more dark energy in the near past than for simple $\Lambda$CDM...
- ...so the relative energy density of matter has to decrease...
- and hence the contribution of massive neutrinos!

$\Pi_{m,\Lambda}(z)/\Pi_{m,q}(z)$ relative contribution to energy density of matter for $\Lambda$/quintessence

\[
\Pi_{m,\Lambda}(z) \equiv \frac{\rho_m(z)}{\rho_m(z) + \rho_{\Lambda}(z)}
\]

\[
\Pi_{m,q}(z) \equiv \frac{\rho_m(z)}{\rho_m(z) + \rho_q(z)}
\]
Physical explanation

Shift in $\Omega_m h^2$ to lower values due to having more dark energy in the past with quintessence than with $\Lambda$

Corresponding shift in $M_\nu$ since:

$$\Omega_m h^2 \supset \Omega_\nu h^2 \approx \frac{M_\nu}{93 \text{ eV}}$$
Non-phantom dark energy beyond quintessence?

Assume:

- CPL parametrization: \( w(z) = w_0 + w_a \frac{z}{1+z} \)
- Non-phantom priors: \( w_0 > -1 \) and \( w_0 + w_a > -1 \)
- Same datasets used previously

Result:

\[ M_\nu < 0.059 \text{ eV} \quad (95\% \text{ C.L.}) \]

**Note**: the CPL parametrization is used by essentially the whole cosmology community, including big current and future collaborations (e.g. Planck, BOSS, KiDS, etc.), as it is an excellent low-redshift parametrization of most smooth dark energy models.
Conclusions

- Neutrinos can be used as a consistency check of cosmological models
- Neutrinos provide a robust tool to test dark energy models
- Quintessence models appear to need low values of $M_\nu$ in conflict with oscillation data ($M_\nu < 0.06$ eV)
- Same results seem to apply to smooth non-phantom dynamical dark energy models
- **Is this the end of quintessence or maybe more generally non-phantom dark energy?** (let you decide)