How neutrinos can kill cosmological models
or
Bad νs for quintessence

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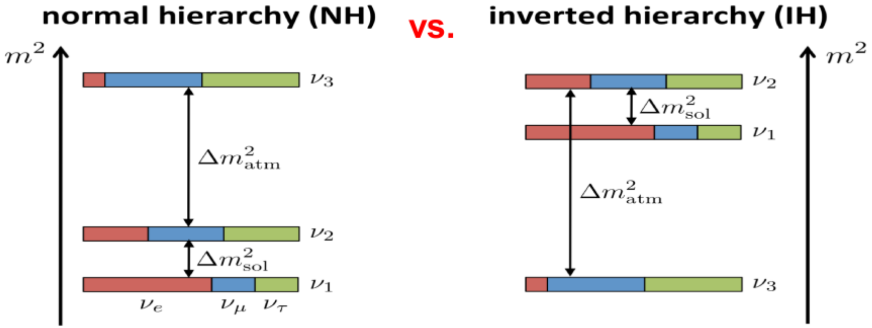
Advances in theoretical cosmology in light of data
Stockholm, July 2017

“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



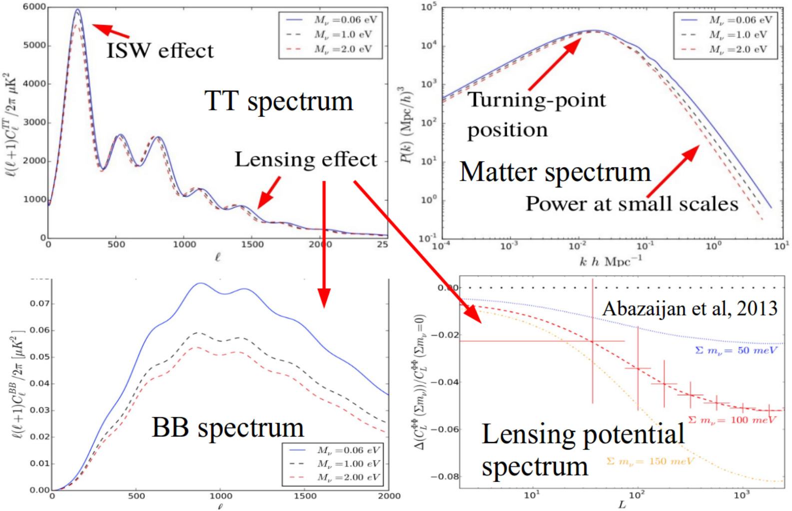
$\Sigma m_\nu > 0.06$ eV

$\Sigma m_\nu > 0.10$ eV

Idea: neutrinos as a test of cosmological models

- Choose your favourite cosmological model
- Parametrize it appropriately if needed
- Derive bounds on M_ν within your chosen model **imposing a lower prior $\mathbf{M_\nu > 0\,eV}$** (ignore oscillation measurements)
- Are your bounds consistent with oscillation data ($M_\nu > 0.06\,\mathrm{eV}$)?
  Gonzalez-Garcia et al. 2014; Forero et al. 2014; Esteban et al. 2016; Capozzi et al. 2016, 2017
  - **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

Turning-point position

Matter spectrum

Power at small scales

BB spectrum

Abazaijan et al, 2013

Lensing potential spectrum

Courtesy of Martina Gerbino

Quintessence

Single, **minimally-coupled** scalar ϕ, 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**:

$$w_\phi = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \geq \mathbf{-1}$$

Quintessence

Essentially two classes of quintessence models:

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

THAWING

e.g. Scherrer & Sen 2008

- 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

e.g. Scherrer 2006

- 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:

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

FREEZING

7CPL parametrization:

Pantazis et al. 2016

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

Dark energy density:

$$\rho_q(a) = \rho_{\mathrm{DE},0} a^{-3(1+w_0+w_a)} \times e^{-3w_a\left(H_7 - 7a\,{}_3F_2\,(1,1,-6;2,2;a)\right)}$$

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-ℓ polarization (*PlanckTT+lowP*), BAO measurements (DR11 CMASS and LOWZ, 6dFGS, MGS), and supernovae luminosity distances (JLA)

THAWING

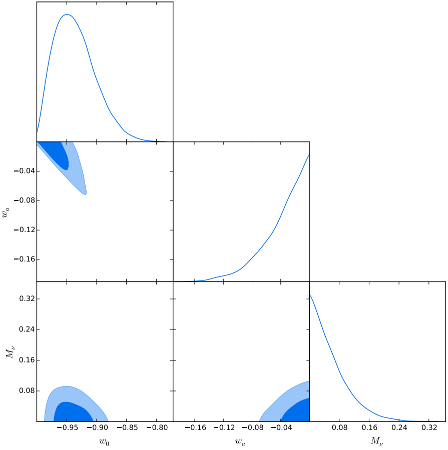
- $w_0 = -0.936^{+0.019}_{-0.038}$ (68% C.L.)
- $-0.037 < w_a < 0$ (95% C.L.)
- $\mathbf{M_\nu < 0.058\,eV}$ (95% C.L.)

FREEZING

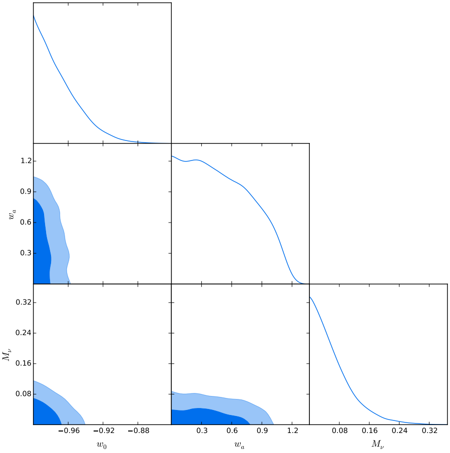
- $-1 < w_0 < -0.969$ (95% C.L.)
- $0 < w_a < 0.567$ (95% C.L.)
- $\mathbf{M_\nu < 0.063\,eV}$ (95% C.L.)

Results

THAWING



FREEZING



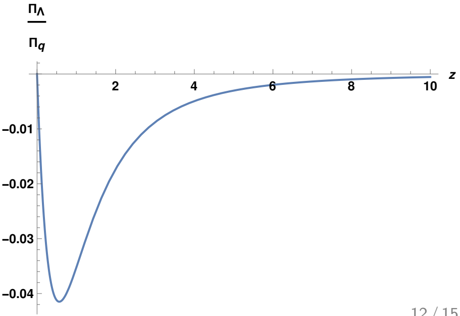
Physical explanation

- 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 ΛCDM...
- ...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 Λ/quintessence

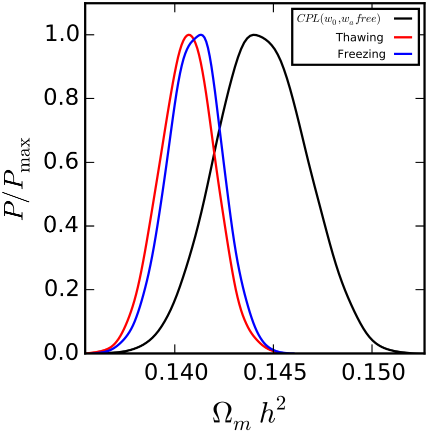
$$\Pi_{m,\Lambda}(z) \equiv \frac{\rho_m(z)}{\rho_m(z) + \rho_\Lambda(z)}$$

$$\Pi_{m,q}(z) \equiv \frac{\rho_m(z)}{\rho_m(z) + \rho_q(z)}$$



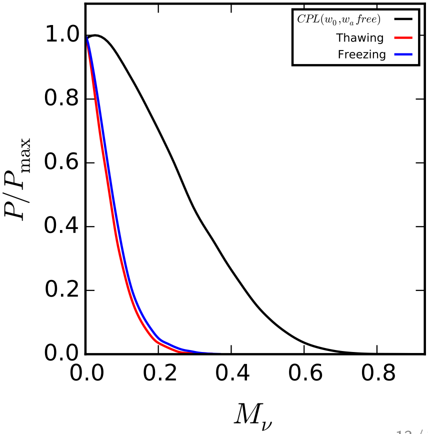
Physical explanation

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



Corresponding shift in M_ν since:

$$\Omega_m h^2 \supset \Omega_\nu h^2 \approx \frac{M_\nu}{93\,\mathrm{eV}}$$



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:

$$\mathbf{M_\nu < 0.059\,eV} \quad \text{(95\% C.L.)}$$

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_ν in conflict with oscillation data ($M_\nu < 0.06\,\mathrm{eV}$)
- 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)