Neutrinos and WDM in cosmology

Martin Kunz
University of Geneva
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.
spatial curvature: $\Omega_k = 0.000 \pm 0.005$ (95%)

flat $\Lambda$CDM: 
(1σ errors)

baryons: $\omega_b = 0.0222 \pm 0.0002$

CDM: $\omega_{cdm} = 0.120 \pm 0.002$

Hubble constant: 
$H_0 = 67.3 \pm 0.7$ [km/s/Mpc]

relative dark energy density today
relative matter density today
light particles during radiation dom.

\[ N_{\text{eff}} = 3.13 \pm 0.32 \quad \text{Planck TT+lowP}; \]
\[ N_{\text{eff}} = 3.15 \pm 0.23 \quad \text{Planck TT+lowP+BAO}; \]
\[ N_{\text{eff}} = 2.99 \pm 0.20 \quad \text{Planck TT, TE, EE+lowP}; \]
\[ N_{\text{eff}} = 3.04 \pm 0.18 \quad \text{Planck TT, TE, EE+lowP+BAO} \]

\[ \sum m_\nu < 0.23 \text{ eV} \quad (\text{95\%, Planck TT+lowP+lensing+ext.}) \]

- no neutrinos \((N_{\text{eff}}=0)\) is clearly not acceptable
- mass not yet measured but strong constraint

\( (\beta\text{-decay}: < 2\text{eV [PDG 17]}) \)
outline

1. modeling cosmological dark matter
2. neutrinos
   - constraints on linear perturbations
   - non-linear neutrino clustering (relativistic N-body simulations)
3. (Warm) dark matter and the CMB
4. Conclusions
modeling dark matter

fluid: EMT conservation equations (+ Einstein)
\( T_{\mu \nu} = 0 \) -- one set for each type (matter, radiation, DE, …)

\[
\delta'_i = 3(1 + w_i) \phi' - \frac{V_i}{Ha^2} - \frac{3}{a} \left( \frac{\delta p_i}{\rho_i} - w_i \delta_i \right)
\]

\[
V'_i = -(1 - 3w_i) \frac{V_i}{a} + \frac{k^2}{Ha} \left( \frac{\delta p_i}{\rho_i} + (1 + w_i)(\psi - \sigma_i) \right)
\]

\( w = p/\rho, \, \delta p \sim c_s^2 \delta \rho, \sigma \sim c_{vis}^2 \): determines physical nature of fluid

Collisionless particles are in general not well described by a fluid, better to use 1-particle distribution function \( f(x,q,t) \rightarrow \) Boltzmann eq (lin. / N-body)

\( \rho, p, \delta \rho, \delta p, \sigma \) are then integrals over the distribution function, eg.

\[
\bar{\rho}(a) a^4 \propto \int dq q^2 \varepsilon(q, a) f_0(q, a),
\]

\[
\bar{\rho}(a) a^4 \propto \int dq q^2 \frac{q^2}{3 \varepsilon(q, a)} f_0(q, a)
\]

\( \varepsilon(p, t) \equiv a \sqrt{p^2 + m^2} \quad q = p/a \)

‘higher’ quantities have higher powers of \( q/\varepsilon \) and are suppressed for cold species [so size of \( \sigma \) can be a diagnostic if higher terms are needed]
neutrino properties

- significant detection of “primordial neutrino anisotropies”
- compatible with expected values
Future large surveys should see neutrino mass in flat ΛCDM

(These are relatively old Euclid GC forecasts, update in progress)

Neutrinos have degeneracies with other model parameters (eg DE), which can degrade errors seriously [cosmology is nearly always model dependent!]

Need to control systematics, obtain reliable predictions in non-linear regime ... need N-body simulations
Neutrinos cluster less than CDM – but they do cluster

→ need to go beyond linear treatment

But neutrinos fill full 6D phase space and are relativistic
→ need lots of particles and small time steps

(WDM is even much worse)
non-linear neutrino clustering with *gevolution*

arXiv:1707.06938

Need accurate predictions to exploit next-gen surveys, but are Newtonian N-body simulations and fitting formula based on them good enough?

(16h wallclock on 16k CPU cores)

*gevolution* is a weak-field GR relativistic N-body code for cosmological simulations

- no superluminal neutrinos
- include anisotropic stress, etc
- consistent initial conditions
- simple! fast! public! 😊

https: //github.com/gevolution-code/gevolution-1.1.git

\[
\frac{dq_i}{d\tau} = -\sqrt{q^2 + m^2a^2} \left( \Psi_i + \frac{q^2}{q^2 + m^2a^2} \Phi_i + \frac{q^j B_{j,i}}{\sqrt{q^2 + m^2a^2}} - \frac{1}{2} \frac{q^j q^k h_{j,k,i}}{q^2 + m^2a^2} \right)
\]
halo fit okay (~1%) for relative spectra, not so good for absolute spectra
• cosmic emulator just the opposite
→ fitting formula work within their specifications, but is that good enough?
looking at halos

halo power spectrum shows $\sim 1\%$ effect of different hierarchy ... could this be detectable? (but observationally degenerate with other total mass?)

a bright future for neutrinos ... now back to the dark side
Planck: additional thermalized neutrinos are not favoured – except if they look like CDM

How much like CDM do they need to look?
results for generalized DM

arXiv:1604.05701

1. Just include $w$, $c_s^2$ and $c_{\text{vis}}^2$ as free DM parameters, using Planck+ext
   - $w = (-0.26 \pm 0.68) \times 10^{-3}$
   - $\log_{10} c_s^2 < -5.9$, $\log_{10} c_{\text{vis}}^2 < -5.7$ at 99%
     (consistent with Thomas+ arXiv:1601.05097)
   using ‘linearized’ weak lensing (CFHTLenS) does not change much

2. Physically expect a $1/a^2$ redshifting behaviour in non-relativistic regime
   - strong suppression at late times
   - today $\log_{10}[w, c_s^2, c_{\text{vis}}^2] < \sim -10$
   - implies DM non-relativistic at decoupling
     \[ w(z_{\text{rec}}) \sim 10^{-3} \] (same for $c_s^2$, $c_{\text{vis}}^2$)
   - CMB lensing gives $c_s^2 < 10^{-6}$ at low-$z$
   - these are model-independent constraints
   - Weak lensing more powerful, but more systematics, should see non-linear velocity dispersion soon
implications for WDM

free streaming scale today:

$$k_{FS,0} = \sqrt{\frac{3}{2}} \frac{H_0}{c_{s0}} > 81 \ h \text{Mpc}^{-1}$$

$$k_{FS}(z_{\text{rec}}) > 1h/\text{Mpc}$$

implied ‘primordial’ velocity dispersion:

$$\sigma_{v0} = \frac{3}{\sqrt{5}} c_{s0} < 2.0 \ \text{km/s}$$

actually measured dispersion (CMB lensing):

$$\sigma_{v}^{\text{late}} < 450 \ \text{km/s}$$

implied limits for both hot and cold freeze-out are about

$$m \gtrsim 100 \ eV$$

but also Ly-α: $k_{FS}(z \sim 5) > 10/\text{Mpc}$ or $m > 3.3 \text{keV}$, Fermi pressure: $m > 400 \ eV$

(Viel+,arXiv:1306.2314)

(Tremain & Gunn 79)
conclusions

- The CMB sees the neutrino background (and neglecting neutrinos in analyses biases the results significantly)
- Its properties are consistent with standard expectations
- Upper mass limits from cosmology are around 0.25 eV
- Future obs need non-linear scales (Newtonian N-body OK)
- Viable WDM generically doesn’t improve CMB fit
- $c_s^2 < 10^{-10}$ today [Ly-$\alpha$: $10^{-14}$]; at $z_{\text{rec}}$: $w$, $c_s^2 < \sim 10^{-3}$
- Implies ‘linear’ limits $m_{\text{DM}} > \sim 100$ eV [Ly-$\alpha$: 3.3 keV, Tremaine-Gunn: >400 eV]
- Future large surveys should be able to detect the neutrino mass and strongly constrain WDM properties / see CDM velocity dispersion – if systematics are under control (non-linear behaviour, astrophysics, likelihood, …)
- Cosmology is a useful tool for particle physics! 😊
Thank you