Physics and properties of relic neutrinos

Yvonne Y. Y. Wong
The University of New South Wales
Sydney, Australia

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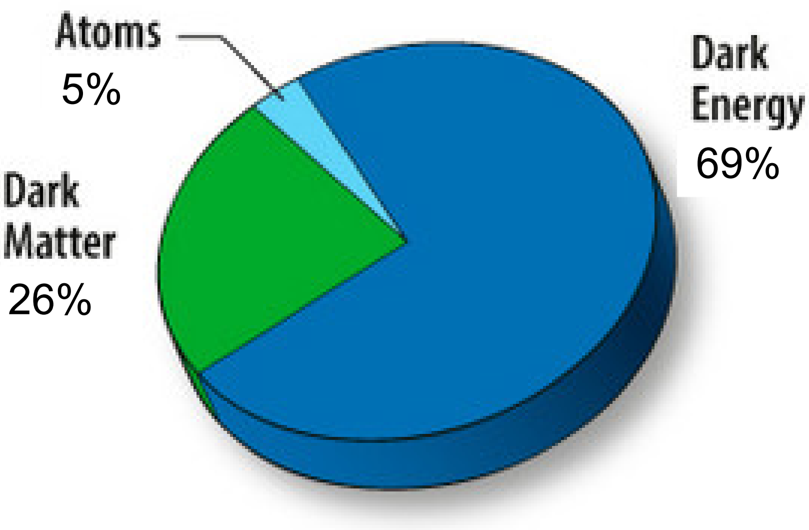
The concordance flat ΛCDM model...

The simplest model consistent with **present observations**.

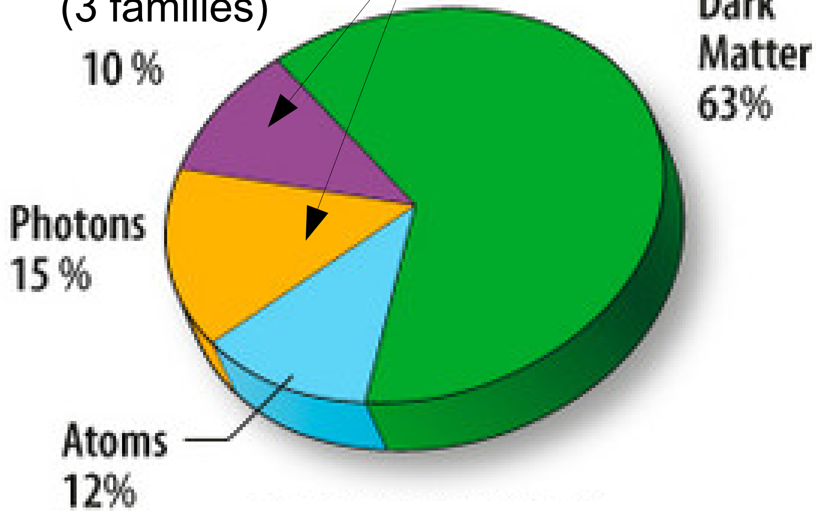
Min. value from $\sum m_\nu = 0.06\,\mathrm{eV}$ oscillations experiments

(Nearly) Massless Neutrinos (3 families)

ν-to-γ energy density ratio fixed by SM physics



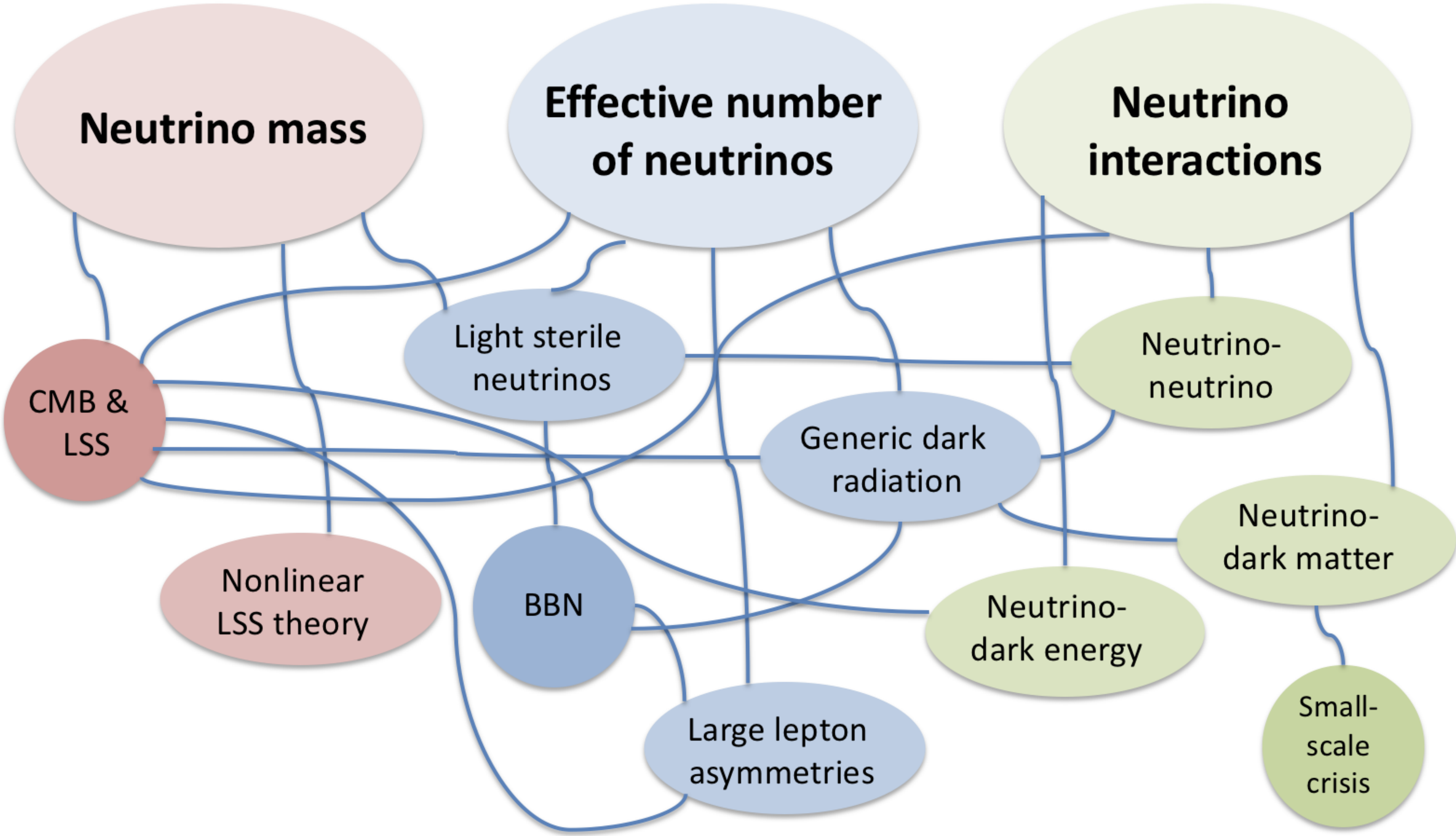
Composition today



13.4 billion years ago
(at photon decoupling)

Plus flat spatial geometry+initial conditions from single-field inflation

The neutrino sector beyond ΛCDM...



This talk...

- Generic standard model predictions

- CMB and other large-scale structure constraints on neutrino properties

  - Masses
  - Effective number of neutrinos
  - Interactions

- Relic neutrino distribution on galaxy/cluster scales

1. Generic standard model predictions...

Generic predictions of the standard hot big bang...

- Neutrino decoupling at $T \sim O(1)$ MeV. ← Fixed by weak interactions
- After e^+e^- annihilation ($T \sim 0.5$ MeV):
  - **Temperature**: $$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$ ← Assuming $T_{dec} >> m_e$
  - **Energy density** per flavour: $$\rho_\nu = \frac{7}{8}\frac{\pi^2}{15} T_\nu^4 = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$ ← $\frac{3\rho_\nu}{\rho_\gamma} \sim 0.68$

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- If massive, then at $T << m_\nu$: $\rho_\nu = m_\nu n_\nu$ → $$\Omega_{\nu,0} h^2 = \sum \frac{m_\nu}{93\,\text{eV}}$$
  - **Energy density in neutrino dark matter**

From neutrino oscillations → $$0.1\,\% < \Omega_{\nu,0} < 7\,\%$$ ← From KATRIN

$$\min \sum m_\nu = 0.06\,\text{eV}$$

$$m_e \equiv \left(\sum_i |U_{ei}|^2 m_i^2\right)^{1/2} < 1.1\ \text{eV}$$

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    (High-z; say, $z > 10^6$)

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  - **Energy density in neutrino dark matter**
    (Low-z; say, $z < 10^6$)

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Some small tweaks...

This is not a very good approximation.

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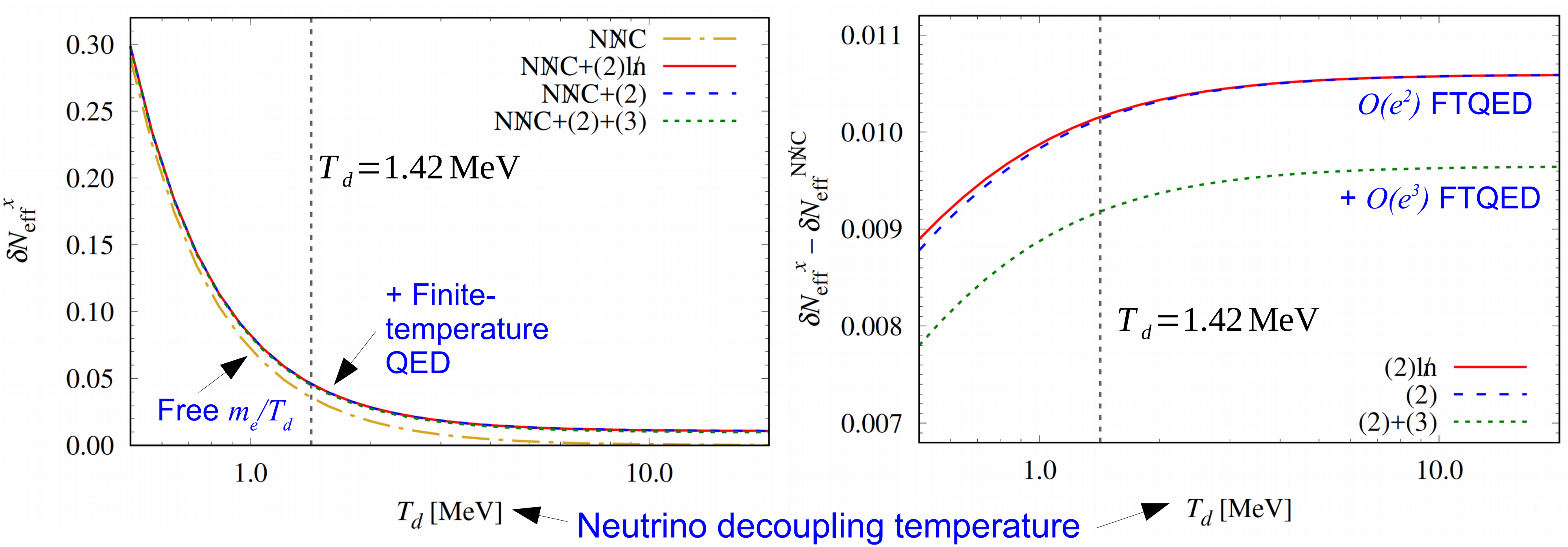
    (High-z; say, $z > 10^6$)

    Finite-temperature corrections to the QED equation of state

- Lump all corrections into the **effective number of neutrino** $N_{\rm eff}$ parameter:

$$\sum \rho_\nu = N_{\rm eff} \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma = (3 + \delta N_{\rm eff}) \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$

Effective number of neutrinos: SM corrections...



Bennett, Buldgen, Drewes & Y[3]W, in prep.

- **SM prediction** of the $N_{\rm eff}$ parameter including $O(e^3)$ FTQED:

Certain about this digit.

$$N_{\rm eff}^{\rm SM} = 3.043$$

Last digit preliminary

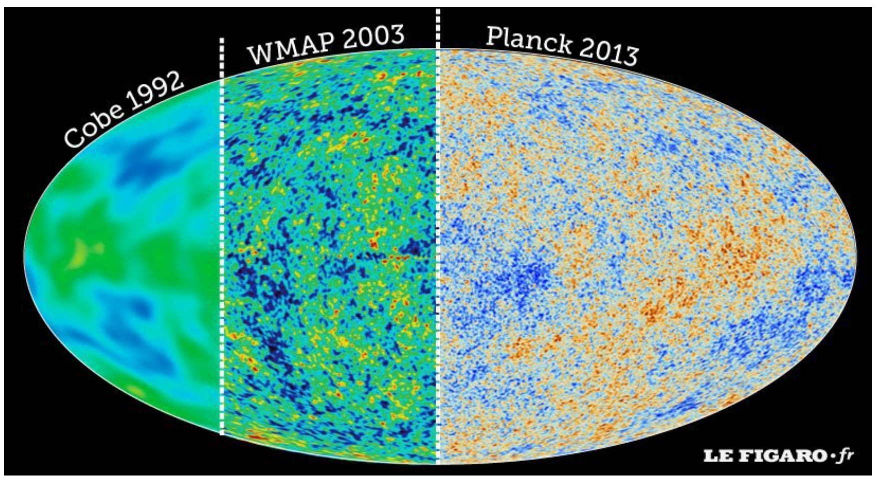
Bennett, de Salas, Gariazzo, Pastor & Y[3]W, in prep.

2. CMB and large-scale structure constraints…

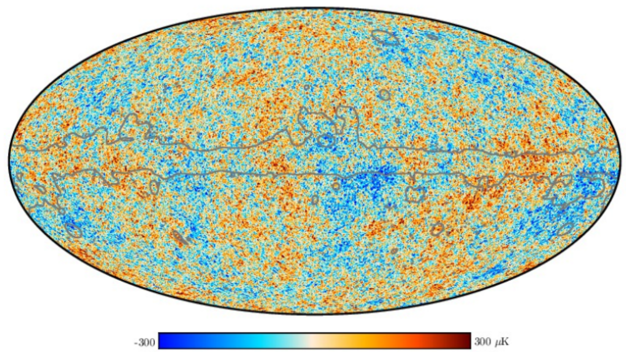
Observable 1: CMB anisotropies...

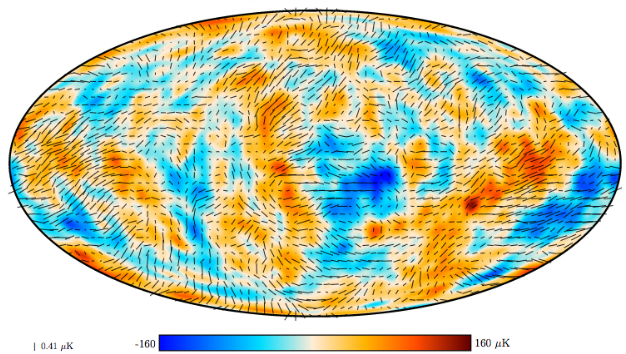
ESA Planck mission: State-of-the-art measurements of the temperature and polarisation fluctuations in the **cosmic microwave background**.

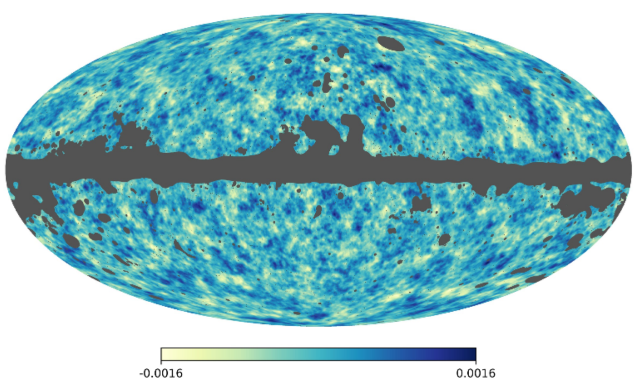
- Final data release results 2018
- Main driver behind cosmological constraints on neutrino physics



Three CMB observables...







Temperature:

- Sensitive to m_ν, $N_{\rm eff}$, ν interactions
- Cosmic-variance-limited to ℓ ~ 2000 since 2013 (i.e., nothing more to be done here)

Polarisation:

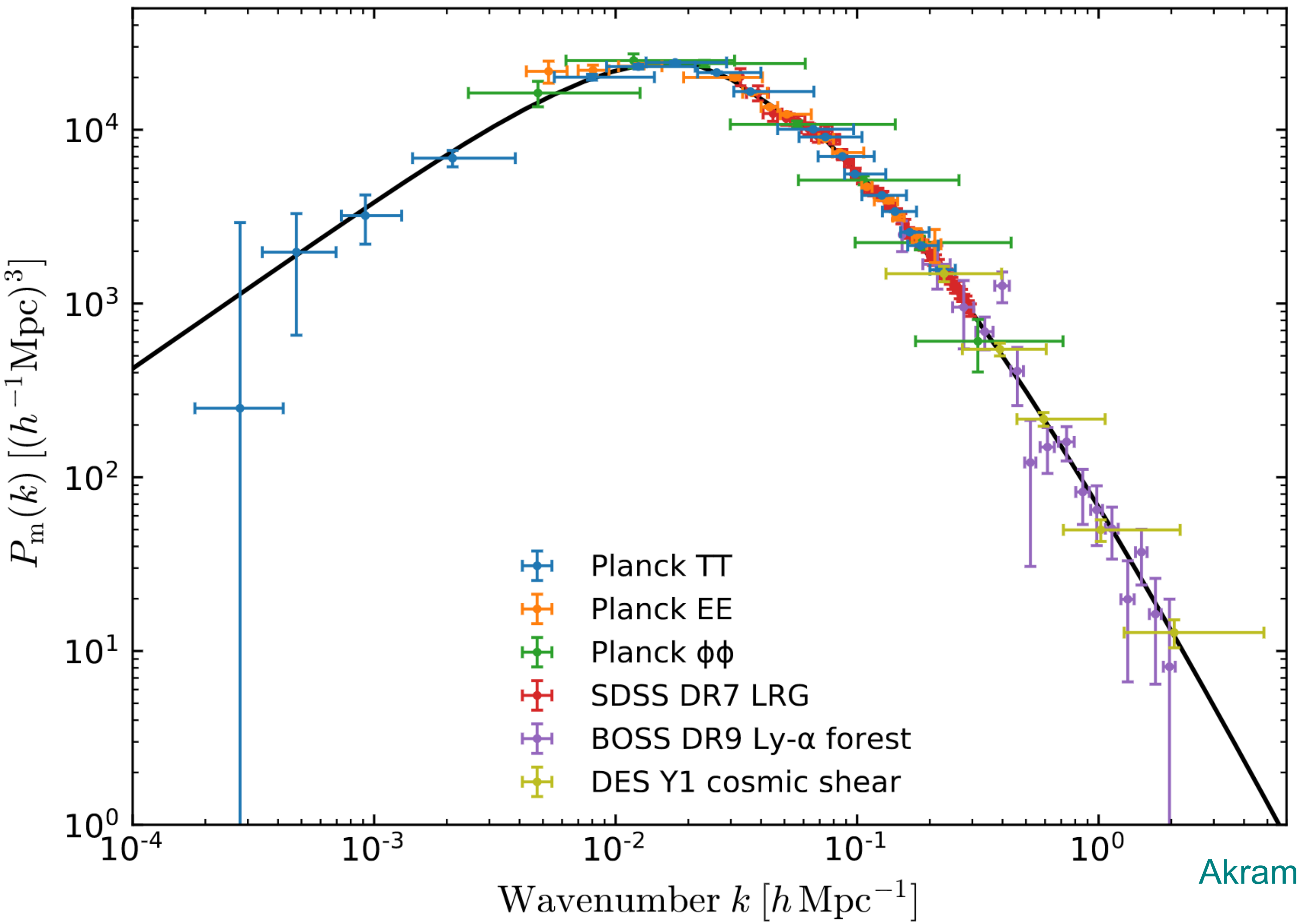
- No independent info on m_ν, $N_{\rm eff}$ (interactions?)
- Low multipoles lifts A_s-τ degeneracy, which helps to tighten other parameter constraints.

Lensing potential:

- Secondary observable reconstructed from temperature and/or polarisation (future) maps.
- Independent signatures of neutrino physics; particularly good for m_ν

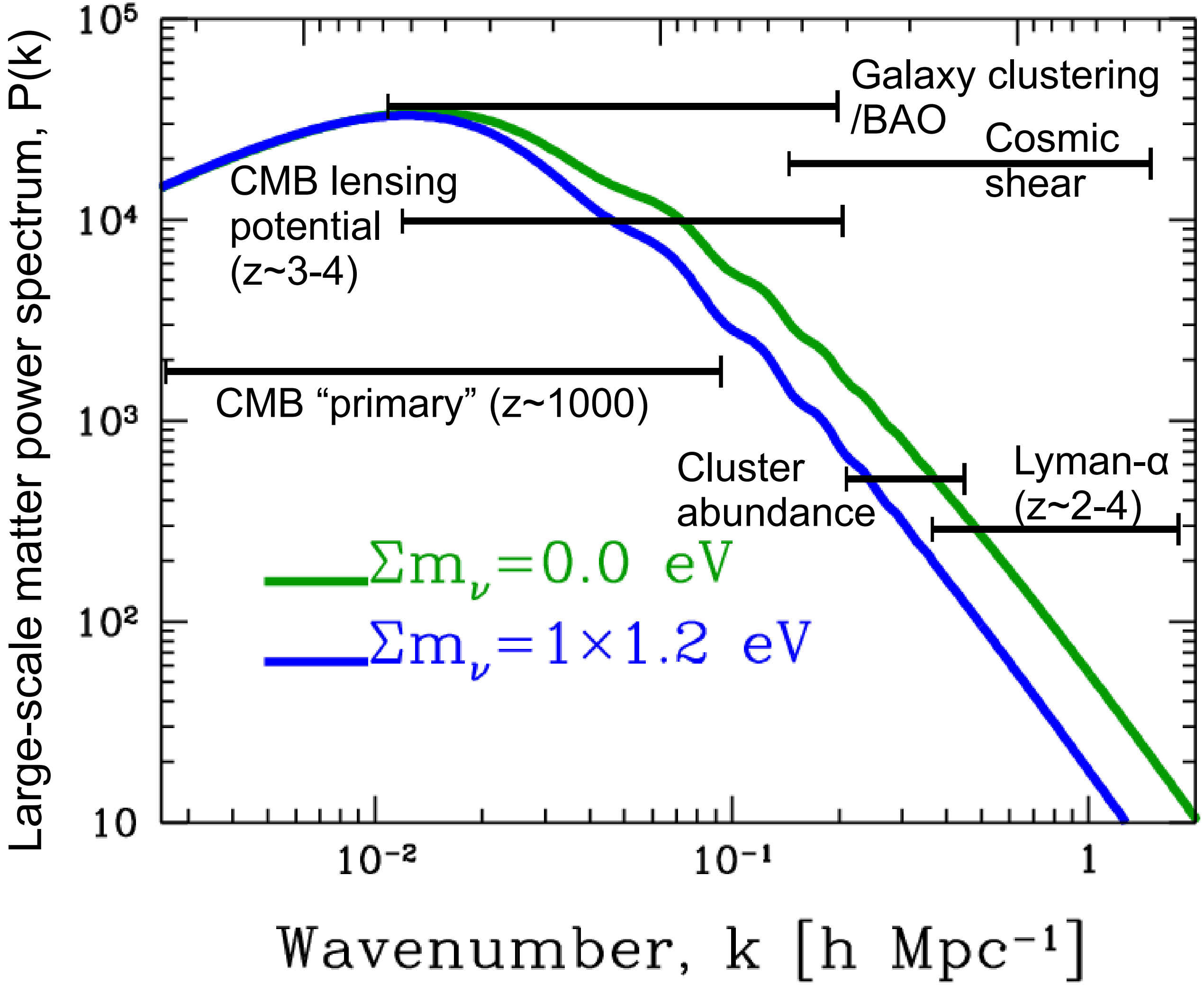
Observable 2: large-scale matter power spectrum...

Large-scale matter power spectrum measurements circa 2018



Akrami et al. 2018

Observable 2: large-scale matter power spectrum...



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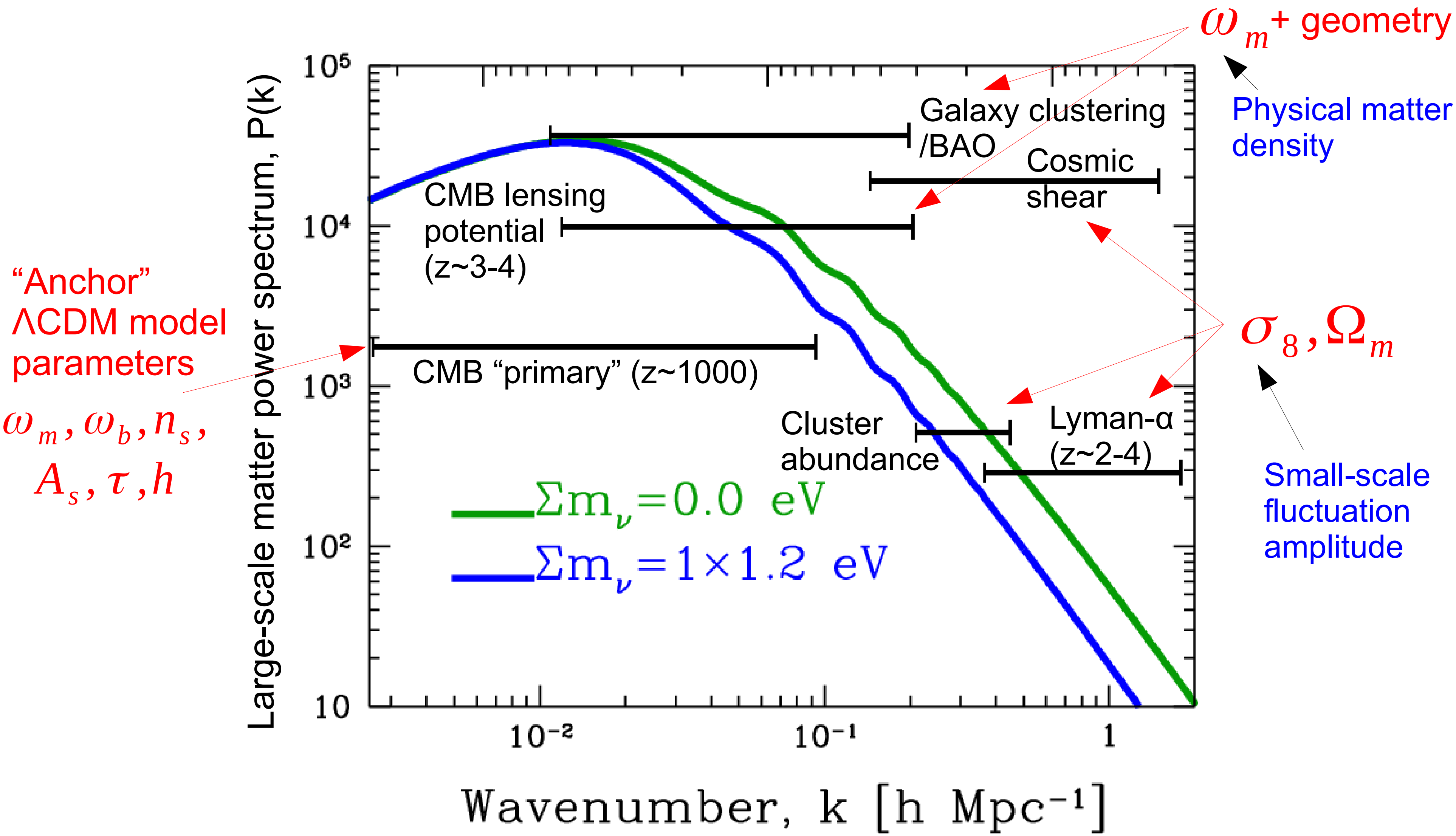


Constraints on the neutrino mass sum…

ΛCDM+neutrino mass 7-parameter fit; 95% C.L. on $\sum m_\nu$ in [eV].

Low-ℓ polarisation only

		+Lensing	+BAO (non-CMB)	+Lensing+BAO
Planck2018 TT+lowE	**0.54**	**0.44**	**0.16**	**0.13**
2015 numbers	0.72	0.68	0.21	n/a

Plus high-ℓ polarisation

Two different high-ℓ likelihood functions

		+Lensing	+BAO (non-CMB)	+Lensing+BAO
Planck2018 TT +lowE+TE+EE	**0.26**	**0.24**	**0.13**	**0.12**
Planck2018 TT +lowE+TE+EE [CamSpec]	**0.38**	**0.27**	n/a	**0.13**
2015 numbers	0.49	0.59	0.17	n/a

Planck2015 TT+lowP+Lyα $\sum m_\nu < 0.13 \text{ eV}$

Palanque-Delabrouille et al. 2015

Aghanim et al. [Planck] 2018
Ade et al. [Planck] 2015

Caveat 1 of 2 : which mass hierarchy...

Mass bounds reported in official Planck papers have all been derived assuming 3 neutrino families with degenerate masses.

- Using **different mass orderings** in the fit actually does change the bounds by up to ~40%.
- ΛCDM+neutrino mass 7-parameter fit; 95% C.L. on $\sum m_\nu$ in [eV]:

Planck 2018 TT+TE+EE+ lowE+lensing + BAO

$$\sum m_\nu < 0.121 \text{ eV}$$ Degenerate

$$\sum m_\nu < 0.146 \text{ eV}$$ Normal hierarchy

$$\sum m_\nu < 0.172 \text{ eV}$$ Inverted hierarchy

Roy Choudhury & Hannestad 2019

Caveat 2 of 2: model dependence...

All bounds so far have been derived from a ΛCDM+neutrino mass 7 parameter fits.

- Can make the fit model more complicated in order to "relax" the bounds.

	Model	Degenerate	Normal	Inverted
	Baseline ΛCDM+Σm_ν	**0.121**	**0.146**	**0.172**
Primordial tensors	+ r	0.115	0.142	0.167
Dynamical dark energy	+ w	0.186	0.215	0.230
Dynamical dark energy	+ $w_0 w_a$	0.249	0.256	0.276
Dynamical dark energy	+ $w_0 w_a$, $w(z) > -1$	0.096	0.129	0.157
Spatial curvature	+ Ω_k	0.150	0.173	0.198

Roy Choudhury & Hannestad 2019

  - However, this sort of game doesn't gain you that much. (Some relaxation, but it's not like you can squeeze in a 1 eV neutrino.)
  - **It doesn't always work in the desired direction**.

Constraints on N_{eff} ...

Aghanim et al. [Planck] 2018
Ade et al. [Planck] 2015

Planck-inferred $N_{\rm eff}$ compatible with 3.046 at better than 2σ.

ΛCDM+Neff 7-parameter fit	Planck 2018 (95%)	Planck2015 (95%)
TT+lowE	$\mathbf{3.00^{+0.57}_{-0.53}}$	3.13±0.64
+lensing+BAO	$\mathbf{3.11^{+0.44}_{-0.43}}$	n/a
TT+lowE+TE+EE	$\mathbf{2.92^{+0.36}_{-0.37}}$	2.99±0.40
+lensing+BAO	$\mathbf{2.99^{+0.34}_{-0.33}}$	n/a

ΛCDM+Neff+neutrino mass 8-parameter fit

$$N_{\rm eff} = 2.96^{+0.34}_{-0.33}$$
$$\sum m_\nu < 0.12 \ \ {\rm eV}$$

95% C. L.
Planck TT+TE+EE+lowE +lensing+BAO

N_{eff} and the H_0 tension...

3.6σ discrepancy between the Planck-inferred H_0 and local measurements:

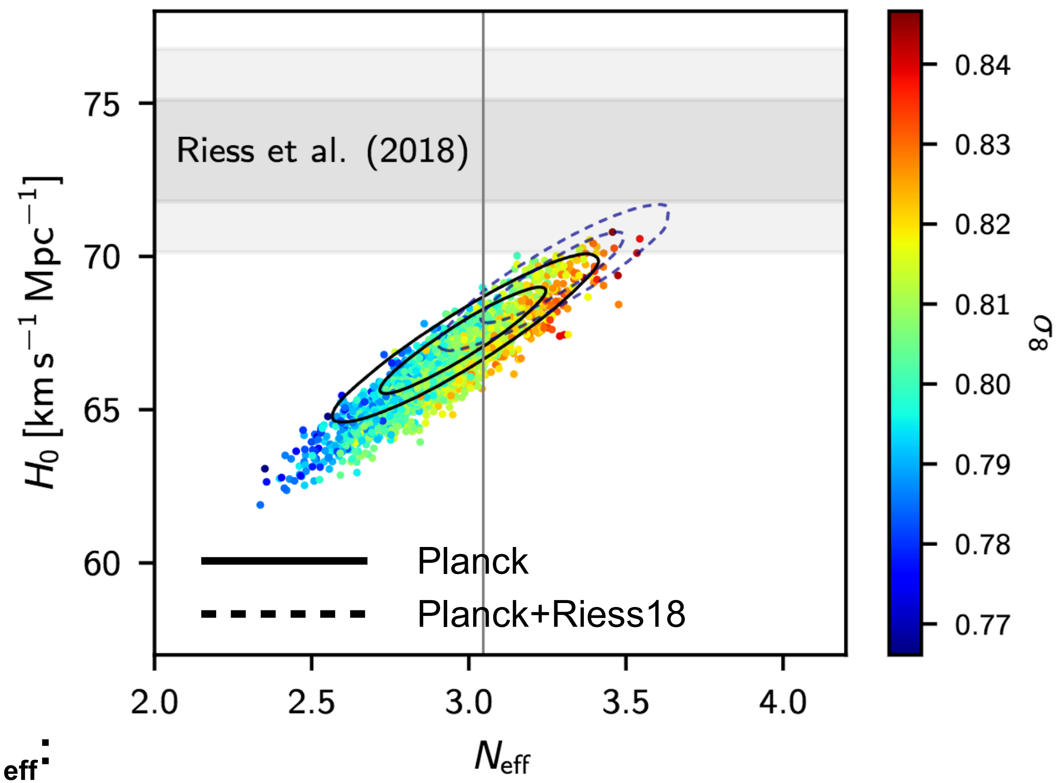
- **TT+TE+EE+lowE+lensing**

$$H_0 = 67.36 \pm 0.54\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

- **Local measurement**:

$$H_0 = 73.52 \pm 1.62\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Riess et al. 2018



Joint Planck+Riess 2018 fit varying N_{eff}:

$$N_{eff} = 3.27 \pm 0.15$$
$$H_0 = 69.32 \pm 0.97\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

68% C. L.
Planck TT+TE+EE+lowE
+lensing+BAO+Riess

Exotica 1: neutrino self-interaction...

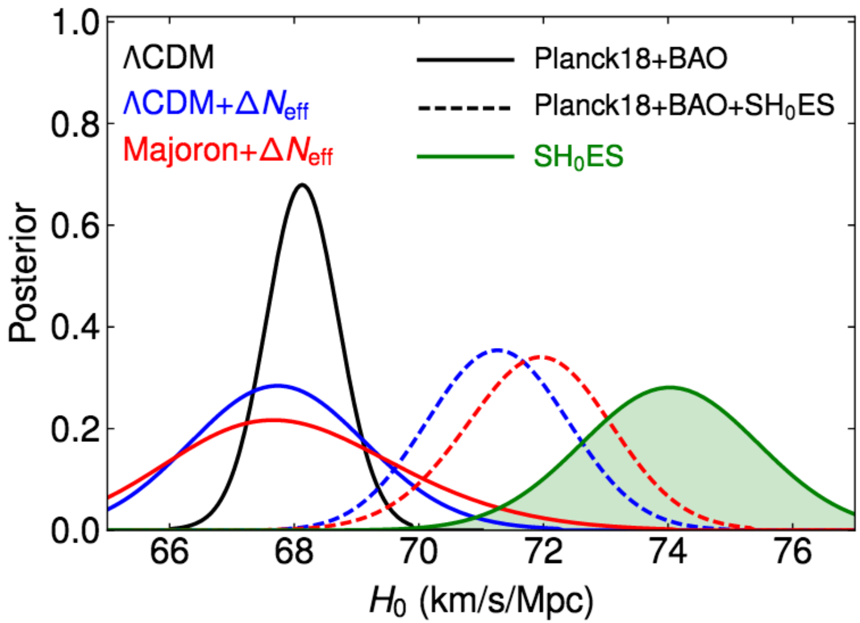
Originally investigated for academic interest in two limits:

- 4-fermion contact interaction — Cyr-Racine & Sigurdson 2014; Lancaster et al. 2017; Oldengott, Tram, Rampf & Y³W 2017
- Massless mediator — Oldengott, Rampf & Y³W 2015; Forasteri, Lattanzi & Natoli 2015, 2019

More recently, **proposed as a solution to the H_0 tension**, with fine prints:

- Only works in conjunction with a non-standard $N_{\rm eff}$
- Need at least $G_{\rm eff} = 10^{-4}$ MeV^{-2}
- Does not fare well with high-ℓ polarisation.

Kreisch, Cyr-Racine & Dore 2019
Escudero & Witte 2019



Exotica 2: neutrino-dark matter elastic scattering...

Originally proposed as an alternative to Warm Dark Matter to solve the small-scale crisis.

- Collisional damping has similar gross features as free-streaming on small scales.

Boehm, Riazuelo, Hansen & Schaeffer 2002
Boehm, Fayet & Schaeffer 2001

Recently revived as **a solution to the H_0 tension**. Di Valentino, Boehm, Hivon & Bouchet 2018

- As in the case of neutrino self-interaction, still need a non-standard $N_{\rm eff}$ to make the scenario work.

- Does not fare well with high-ℓ polarisation data.

3. Relic neutrino distribution on galaxy/cluster scales...

Not a well-studied subject, although obviously important for direct detection of the relic neutrino background (next talk)

"Toy model" of relic neutrino gravitational clustering...

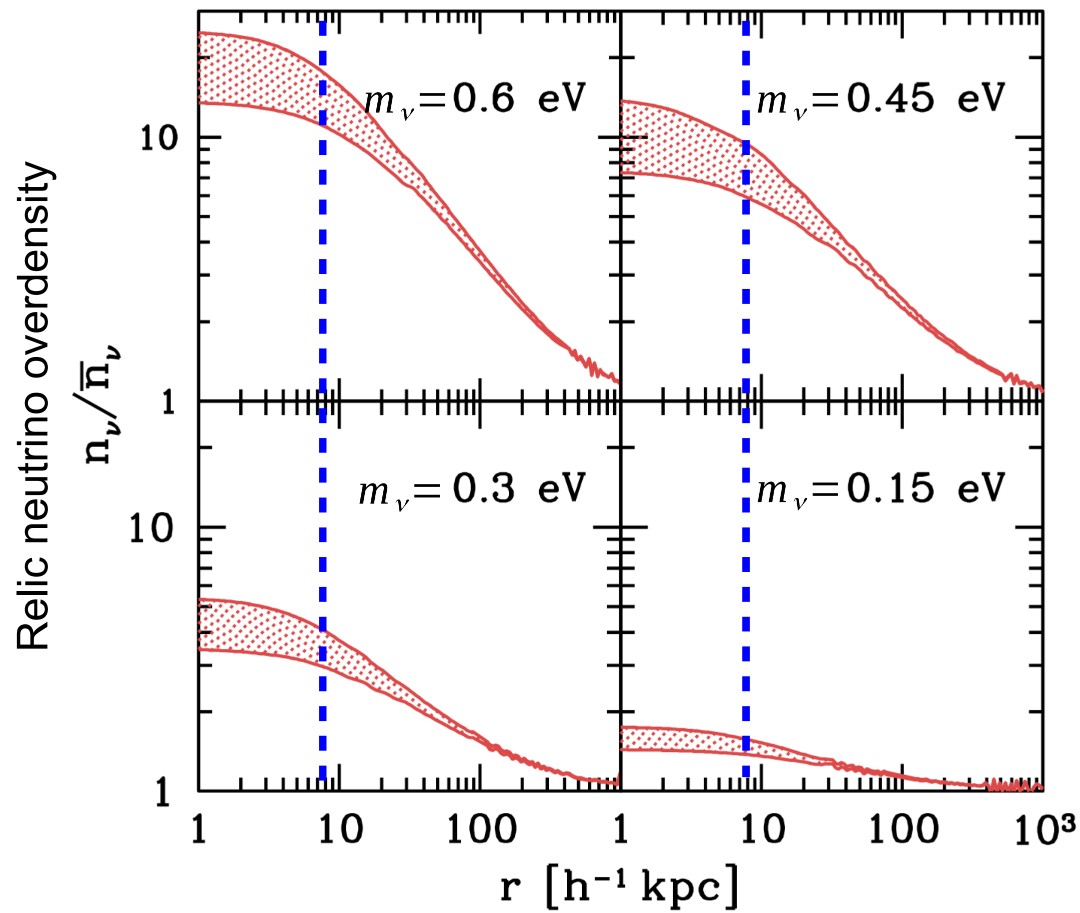
… in a Milky Way-like object

Overdensity expected at the solar system (~10 kpc from GC) depends strongly on the individual neutrino mass.

- For neutrino masses consistent with cosmological bounds, expect no more than factor of 2 enhancement.

- Caveat: calculations assumed SM neutrinos. Can non-standard interaction improve overdensity?

Ringwald & Y^3W 2004



Distance from the Galactic centre

"Toy model" of relic neutrino gravitational clustering...

… in a Milky Way-like object

De Salas, Gariazzo, Lesgourgues & Pastor 2017

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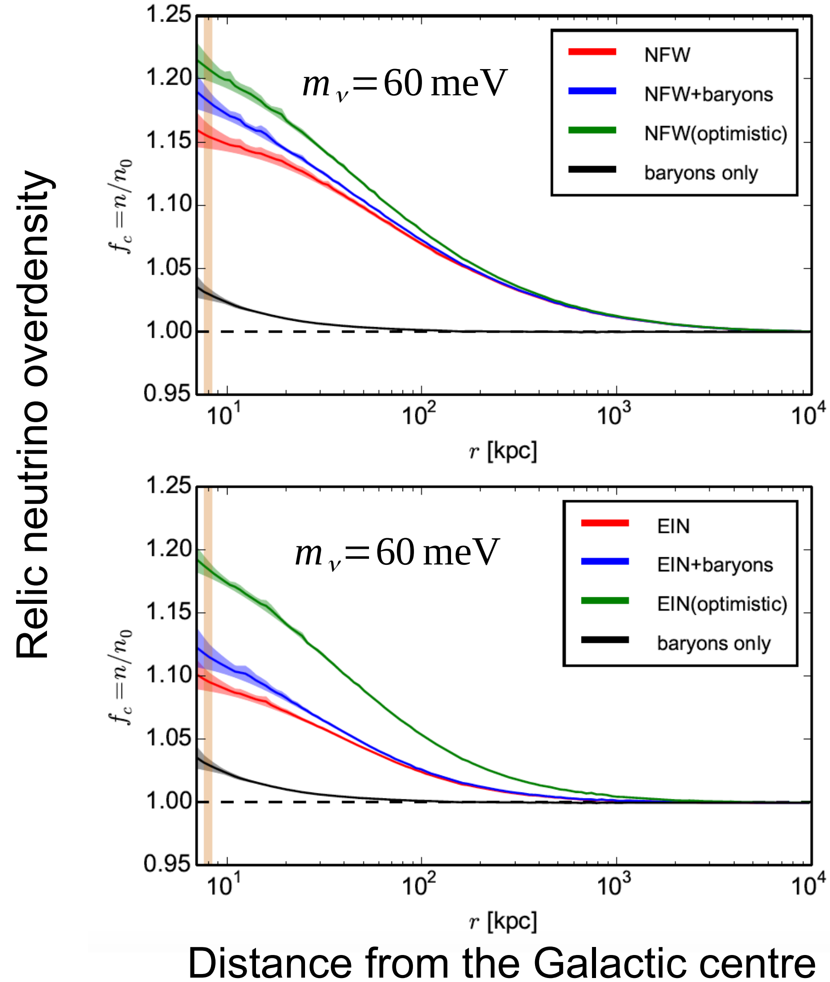

Summary...

- **Relic neutrinos** = a necessary consequence of embedding the SM in cosmology

- **Strong constraints** can be obtained on the neutrino mass sum, the effective number of neutrinos, and non-standard interactions from CMB and large-scale structure observations

  - Neutrino physics may contribute to an extent to alleviating the H_0 tension.

- CMB/large-scale structure constraints on neutrino mass sum also imply **limited enhancement in the local (Milky Way) relic neutrino density**, if neutrinos only have SM interactions.

  - How non-standard interactions affect the local relic neutrino density has yet to be explored.