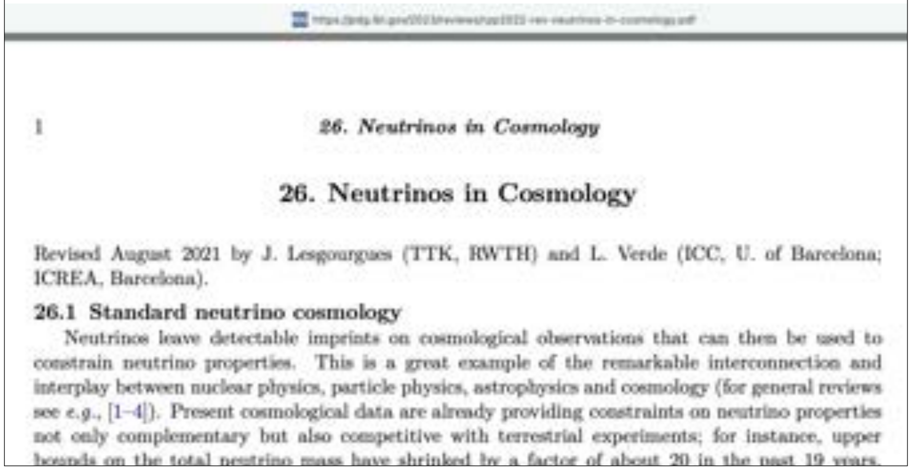
Collection of Nonsense Blather
Cosmic Neutrino Background

Douglas Scott (UBC)
Varenna, July 2023

For more information, see this mini-review

Lesgourgues & Verde, 2022
in "Review of Particle Physics" (aka "Particle Data Book")



1 *26. Neutrinos in Cosmology*

26. Neutrinos in Cosmology

Revised August 2021 by J. Lesgourgues (TTK, RWTH) and L. Verde (ICC, U. of Barcelona; ICREA, Barcelona).

26.1 Standard neutrino cosmology

Neutrinos leave detectable imprints on cosmological observations that can then be used to constrain neutrino properties. This is a great example of the remarkable interconnection and interplay between nuclear physics, particle physics, astrophysics and cosmology (for general reviews see *e.g.*, [1–4]). Present cosmological data are already providing constraints on neutrino properties not only complementary but also competitive with terrestrial experiments; for instance, upper bounds on the total neutrino mass have shrinked by a factor of about 20 in the past 19 years.

Let's start with a coincidence

Cosmological density of massive neutrinos:
$\Omega_\nu=\Sigma m_\nu/93.14h^2$eV

For the normal hierarchy, $\Omega_\nu\simeq0.0014$
(cf. $\Omega_b\simeq0.0490$, $\Omega_c\simeq0.2610$)

But average density of stars, $\Omega_*\simeq0.0015$
(e.g. Fukugita & Peebles 2004)

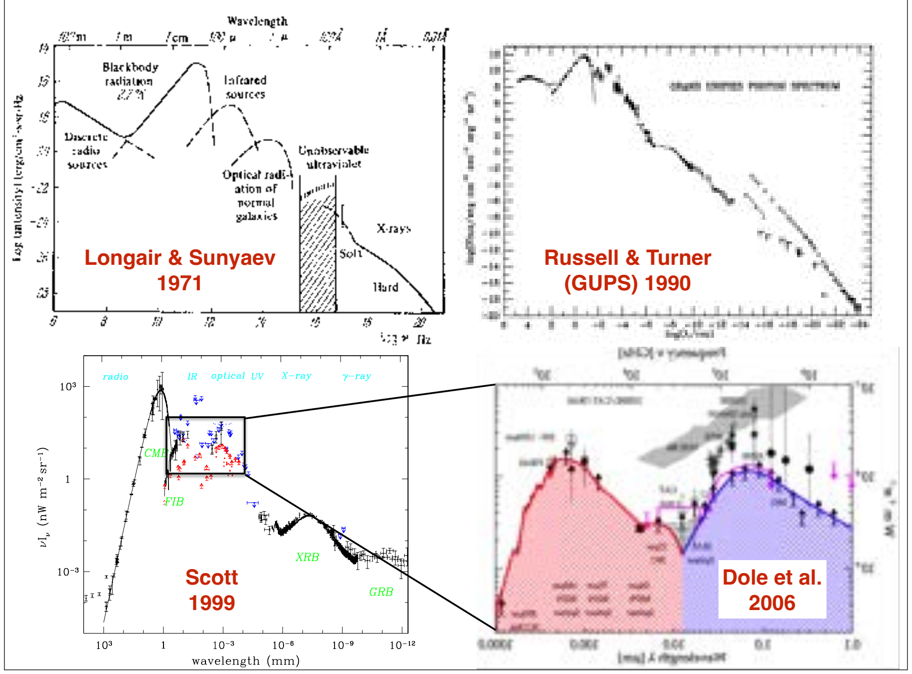
These are essentially the same!

So neutrinos are some of the dark matter!

And they're at the point of being impossible to ignore in cosmology

Another way of saying the same thing:
if neutrinos were more massive, they would be the ideal dark matter particles

Let’s think about the CNB, by starting with the photon backgrounds



Longair & Sunyaev 1971

Russell & Turner (GUPS) 1990

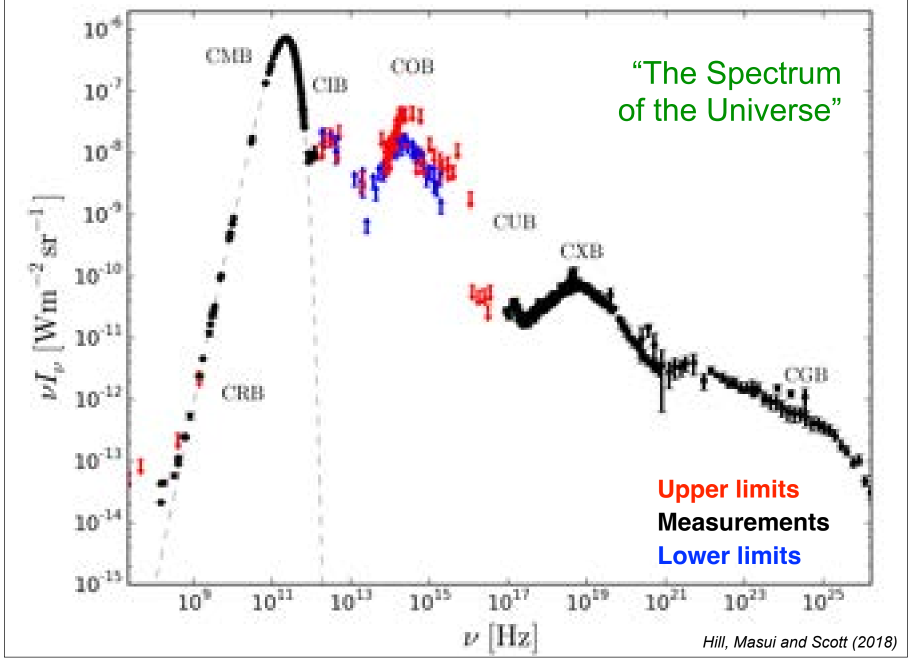
Scott 1999

Dole et al. 2006

- **Learn about the integrated history of electromagnetic radiation emission:**

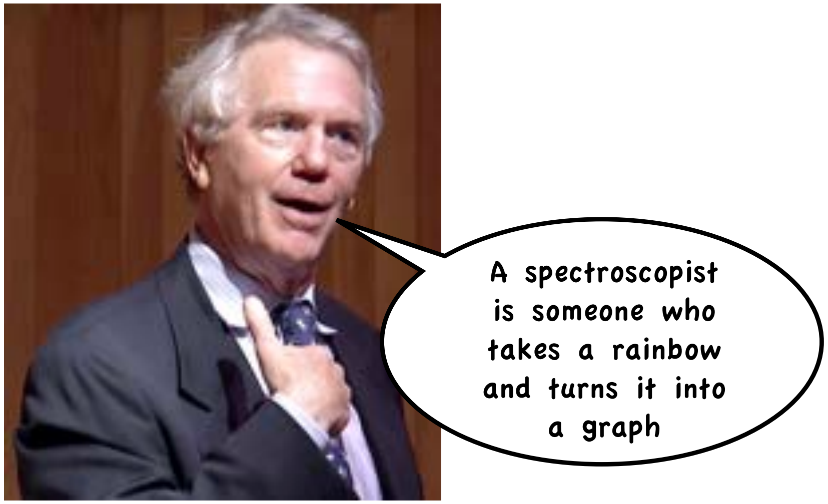
$$I = \left(\frac{c}{4\pi}\right) \int_0^\infty \mathcal{L}(z) \left|\frac{dt}{dz}\right| \frac{dz}{1+z}$$

- **For the CIB, for example, this constrains the history of star formation, metal production, black hole accretion, …**
- **And potentially new populations of sources, exotic processes, such as DM decay, annihilation …**
- **But the absolute level (aka DC, monopole) is hard to measure**

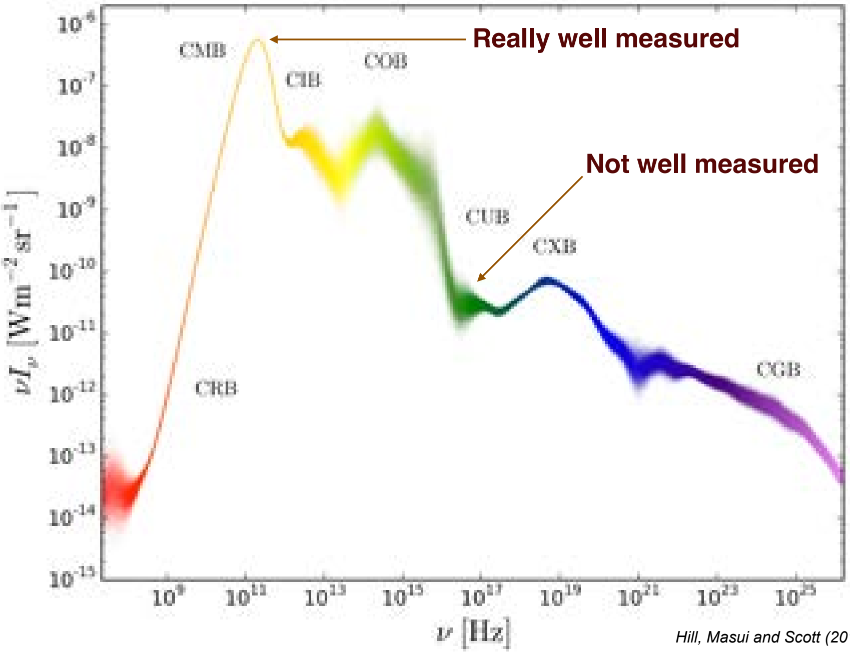


“The Spectrum of the Universe”

Hill, Masui and Scott (2018)



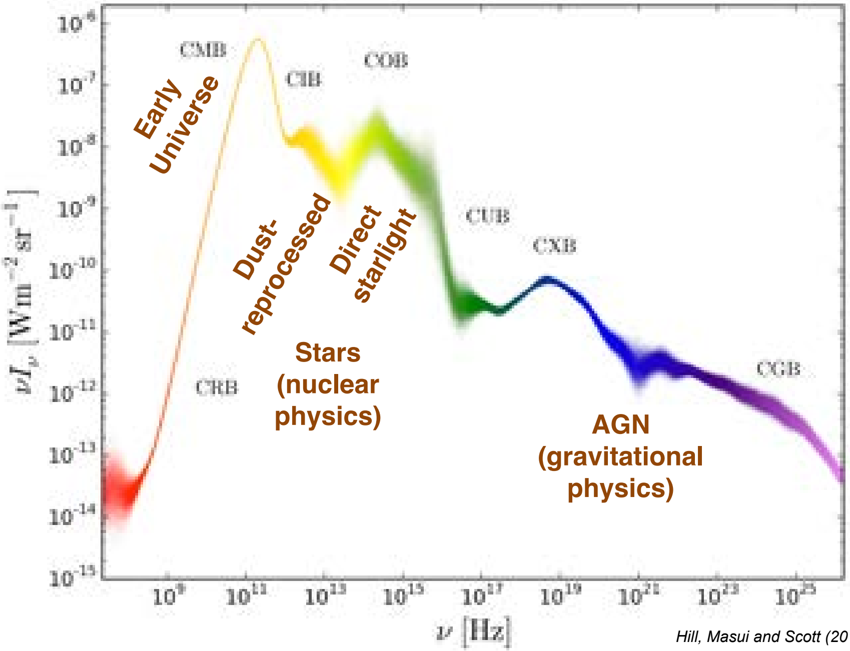
Bob Kirshner
(supernova astronomer)



Really well measured

Not well measured

Hill, Masui and Scott (2018)



Early Universe

Dust-reprocessed

Direct starlight

Stars (nuclear physics)

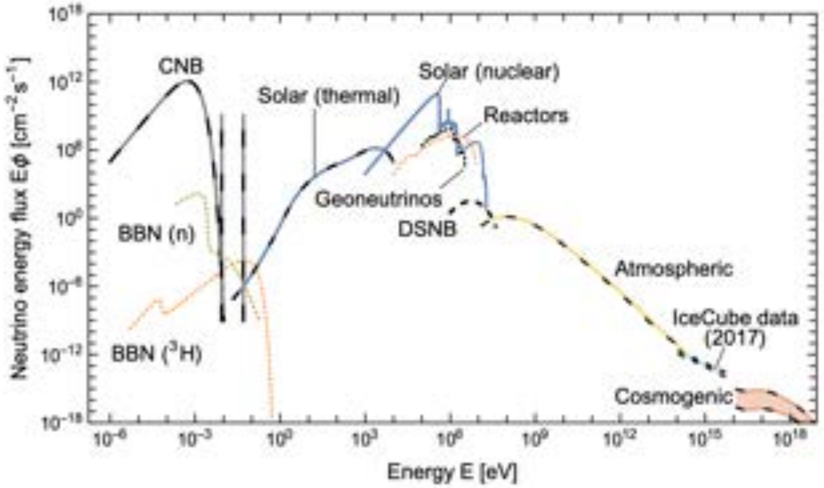
AGN (gravitational physics)

Hill, Masui and Scott (2018)

And now the neutrino backgrounds

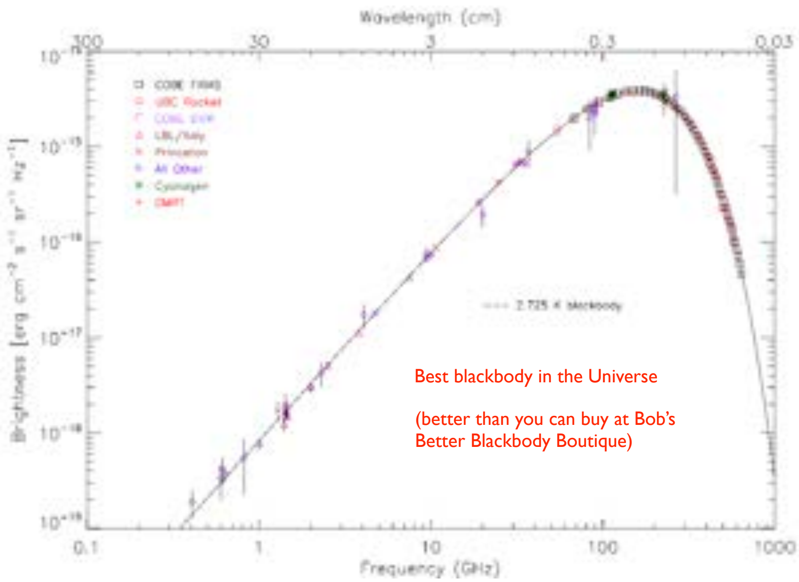
Grand Unified Neutrino Spectrum

(Vitagliano, Tamborra & Rafelt, arXiv:1910.11878)



But not all of this is “cosmic” (and we could multiply by E)

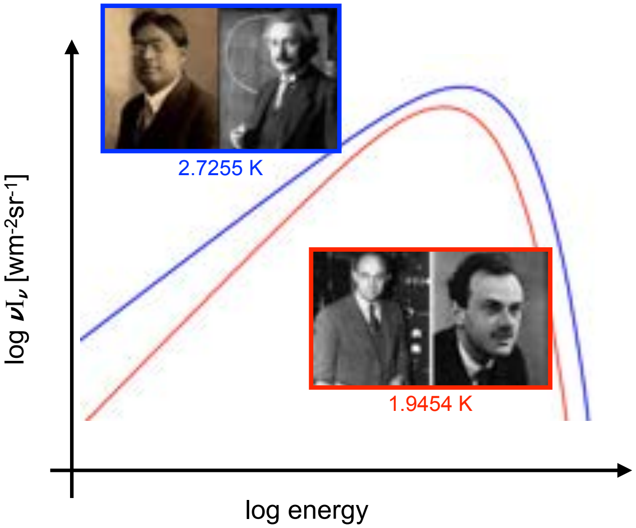
CMB Spectrum



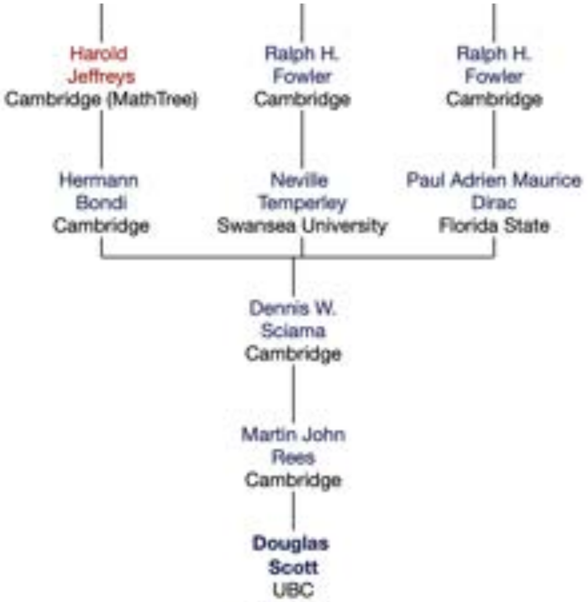
Best blackbody in the Universe

(better than you can buy at Bob’s
Better Blackbody Boutique)

CNB Spectrum



academictree.org



Harold
Jeffreys
Cambridge (MathTree)

Ralph H.
Fowler
Cambridge

Ralph H.
Fowler
Cambridge

Hermann
Bondi
Cambridge

Neville
Temperley
Swansea University

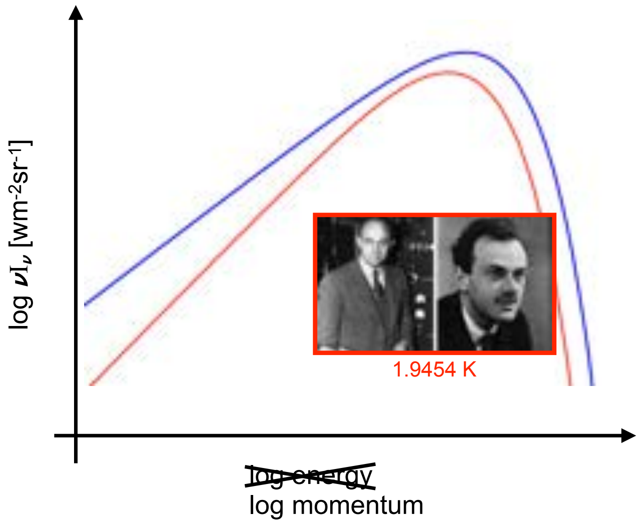
Paul Adrien Maurice
Dirac
Florida State

Dennis W.
Sciama
Cambridge

Martin John
Rees
Cambridge

Douglas
Scott
UBC

CNB Spectrum



But neutrinos are more complicated!

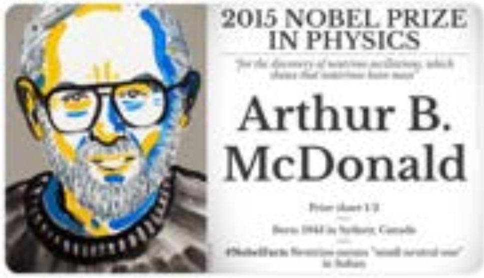
Mass states aren't flavour states

In other words, it's non-trivial to answer questions like: "what's the mass of the electron neutrino"?

Who can we turn to for an explanation of neutrino flavour?

Lots of things are associated with Canada

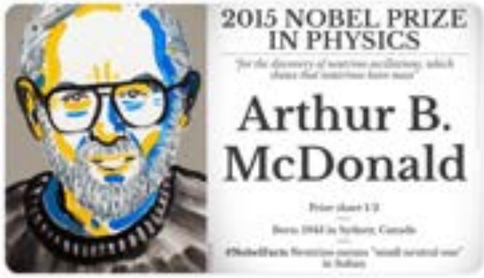
Let's focus on these two Canadian icons



Art McDonald

Timbits

Look it up on youtube as “Neutrino timbits”



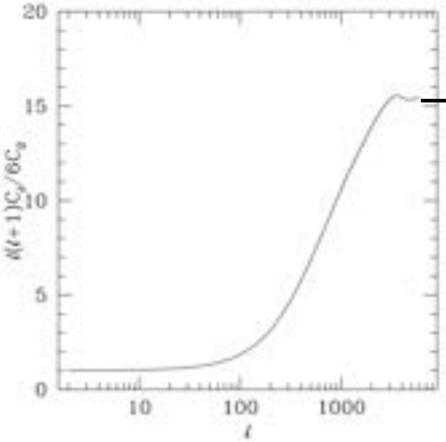
Art McDonald

Timbits

CNB will also contain anisotropies

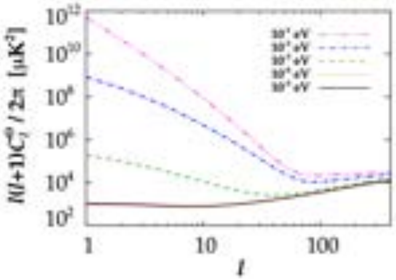
First published prediction in 1995:

Hu, Scott, Sugiyama & White,
“The Effect of Physical Assumptions on the Calculation of Microwave Background Anistropies”
astro-ph/9504043, PRD, 52, 5498 (1995)
“Le bon Dieu est dans le detail” - Gustave Flaubert

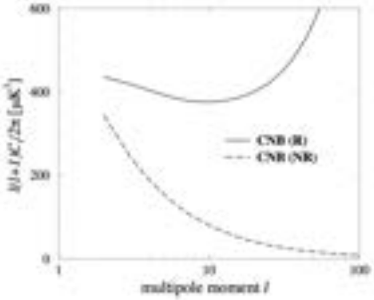


ℓ~10^8

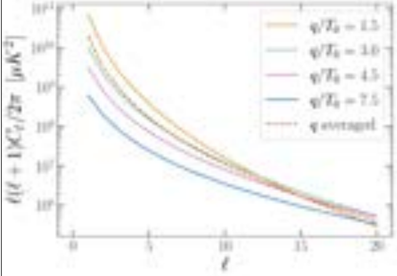
- Anisotropy amplitudes are ~10^{-5}
- Rise in power spectrum because of “early ISW”
- Damping at scales corresponding to neutrino decoupling, at multipoles ~10^8
- (milli-arcseconds!)
- Additionally should have “late ISW” at low multipoles

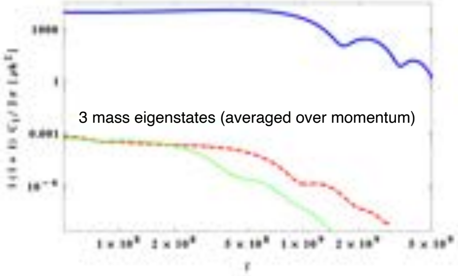


Hannestad & Brandbyge 2010



Michney & Cladwell 2007





3 mass eigenstates (averaged over momentum)

Tully & Zhang 2021

Elham Alipour, UBC PhD thesis, 2015

Cosmic Neutrino Background

- But neutrinos decouple in flavour eigenstates, propagate in mass eigensttates and then are detected in flavour eigenstates again!
- And distributions are in terms of momentum, not energy
- Each momentum evolves differently
- So calculations are complicated!

- And results are at ~10^{-5} level of an already-impossible-to-detect signal!

Good luck measuring the anisotropies!

Dipole is ~10^{-3}, so maybe that's easier?

ν LSS at t~1s, but can be <u>closer</u> than γ LSS!

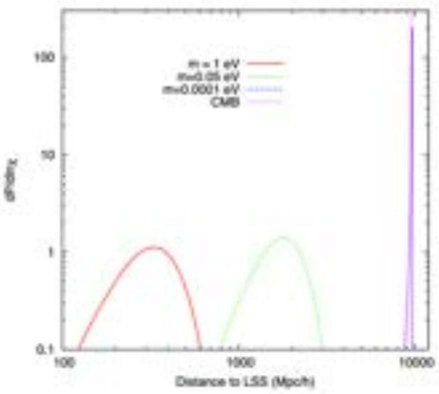


FIG. 2: The probability that a neutrino with mass m last scatters at a given comoving distance from us (the visibility function). Massive neutrinos travel more slowly than massless neutrinos so arrive here from much closer distances. Also shown is the last scattering surface of the cosmic microwave background, virtually indistinguishable from that of an $m_\nu = 10^{-4}$ eV neutrino.

Neutrinos of different masses (and momenta) arrive from different distances

Plus lensing deflections can be much bigger!

Bisnovatyi-Kogan and Seidov, 1983

Dodelson & Vesterinen, 2009 [arXiv:0907.2887]

Let's end with cosmological limits on neutrino properties

Can easily constrain 1-parameter extensions to LCDM, e.g. N_{eff} and Σm_ν

Expectation for effective number of neutrino species (contributing to cosmic background):

detailed calculations, including non-instantaneous decoupling, oscillation effects, finite-temperature effects, etc., give

$$N_{\rm eff} = 3.0440 \pm 0.0002$$

Bennett et al., 2021, JCAP, 04, 073
[arXiv:2012.02726]

$N_{\rm eff}$ effects are mostly on the distance scale
For Planck data, uncertainty is $\Delta N_{\rm eff}$~0.3.
⇒ detection of CNB to high significance:

$$N_{\rm eff} = 2.99 \pm 0.34\ (95\,\%)$$

(for Planck power spectra + BAO).

Additionally, Planck data constrain CNB sound speed and anisotropic stress,

$$c^2_{\rm eff} = c^2_{\rm vis} = \frac{1}{3},$$

to 2% and 10%, respectively.

For neutrino mass, cosmological effects depend almost entirely just on Σm_ν

Minimal expectation for sum of neutrino masses: Σm_ν~0.06eV

Neutrino mass effects on Planck data:
1. changes distance to CMB last-scatering
2. smoothing of power spectra
3. changing shape of lensing power spectrum

CMB lensing power spectrum particularly important

Combination of CMB power spectra (including lensing) and BAO gives

$$\Sigma m_\nu < 0.12\,{\rm eV}(95\,\%)$$

(precise bound depends on choice of data).

What about sterile neutrinos?

A complication is that cosmology constrains the contributions to

$N_{\rm eff}$ & Σm_ν

but direct experiments constrain (say)

Δm^2_{41} & $\sin^2 2\theta_{14}$

Volume effects, sampling and priors need to be considered carefully to combine cosmological and experimental limit

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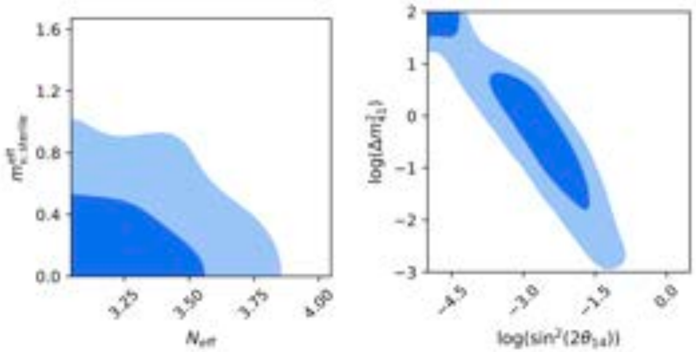

Figure 2. *Left panel: Planck* 68% and 95% CL constraints in the cosmology parameter space using *Planck* CMB TT+lowTEB data. Priors are flat in the ranges $3.046 \leq N_{\rm eff} \leq 4.046$ and $0 \leq m^{\rm eff}_{\nu,\rm sterile} \leq 3$ eV. *Right panel:* The procedure explained in section 3.2 is used to calculate the particle parameters from the original cosmology chains. The region of low mass and mixing angle appears to be ruled out, but these constraints are not robust, since this is a result of poor sampling.

Knee, Contreras & Scott, 2019

“Cosmological constraints on sterile neutrino oscillations from Planck”

Current generation cosmology experiments look set to measure Σm_ν (even in normal-ordering)

Ω_ν seems set to become the 7th (or 8th including T0) parameter of the SMC

The elephant in the Fermi Room

Will direct-detection neutrino physicists believe a cosmological measurement of Σm_ν?

That's for you to answer!

Extra slides

Notes fron earlier lectures

- T_dec~1Mev, ~1s
- n_nu=3/11 n_gamma
- behave like matter flor m_nu>>T_nu
- n_nu=3339.5cm^-3
- T_nu=1.95K, <p>=3.15T_nu
- Omega_nu h^2=m_nu/93.14eV
- >6e-4 (NO) or e-3 (IO)
- 5th most abundant comp by energy, 2nd by number
- rho_R=[1+7/8(4/11)^4/3N_eff]rho_gamma
- N_eff=3.044 from theory
- =2.92+0.36-0.37 for Planck+
- Everything consiste with rel fluid with no viscosity
- Delta N_eff tests for new particles

- More complicated in perturbed universe
- Damping of perts below nu free-streaming scale
- Free-streaming scale is dynamic quantity
- Free-streaming horizon is an integrated quantity
- P(k) same as CDM for k<k_nr
- suppressed by factor [1+…] for k>k_nr
- cosmology not expected to be sensitive enough to how Sum is split

- Nu number density large, 2nd most abundant species
- Become non-rel after decoupling and do not annihilate
- Affects scales up to 10s of Mpc
- Neutrinos do not cluster much
- Non-linearities produce features in matter P(k)
- Expect best place to look is IGM, e.g. Ly alpha forest

- Omega_nu=Sum m_nu,i/93.14h^2eV
- When looking at effects of mass, set N_eff=3.046
- Assume full degeneracy in neutrino mass hierarchy, Sum=3m_nu
- 3 scales: equivalence delayed - (1) a_eq = a_eq^f=0 (1-f_nu)^-1

(2) non-rel transition, 1+z_nr=1890m_nu/1eV,
after baryon-radiation decoupling for sub-eV nus
(3) free-streaming scale lambda_fs=a(t) \int_t_i^t v_th dt'/a(t')
lambda_fs(t)=2pi\sqrt{(2/3)v_th(t)/H(t)}

- Perturbation growth…
- Effects on power spectrum (e.g. Euclid Forecasts, Blanchard et al.)
- Massive nus introduce a scale dependence to D and f