Title: The Cosmic Neutrino Background

Speakers: Douglas Scott

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

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Abstract:

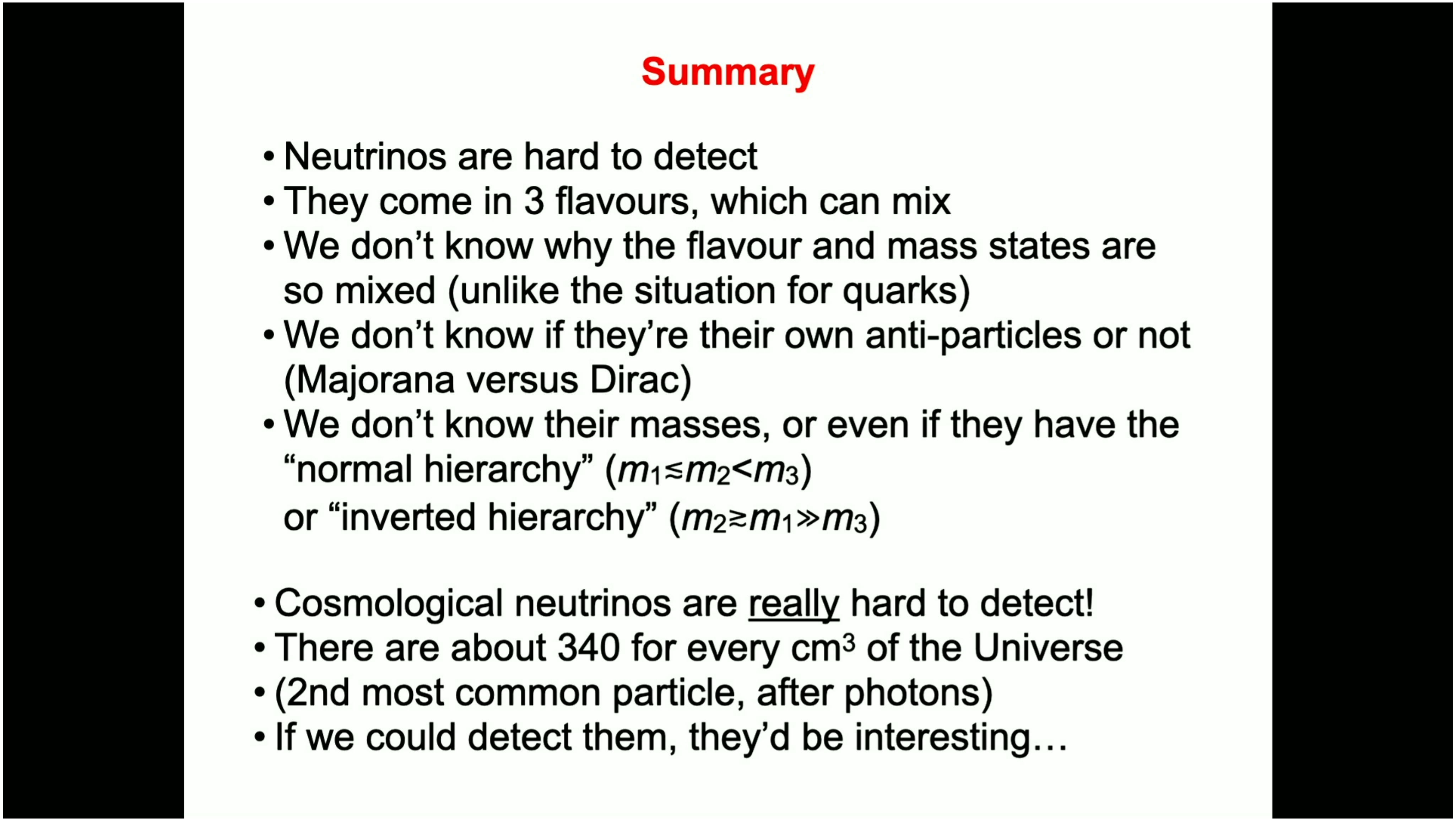
The cosmic neutrino background is like the cosmic microwave background, but less photon-y and more neutrino-ey. The CNB is also less talked about than the CMB, mostly because it's nearly impossible to detect directly. But if it could be detected, it would be interesting in several ways that are discussed.

Cosmic Neutrino Background

Douglas Scott (UBC)
March 2025

My new (least?) favourite spot
in Kitchener/Waterloo

Map of the County of Waterloo 1879



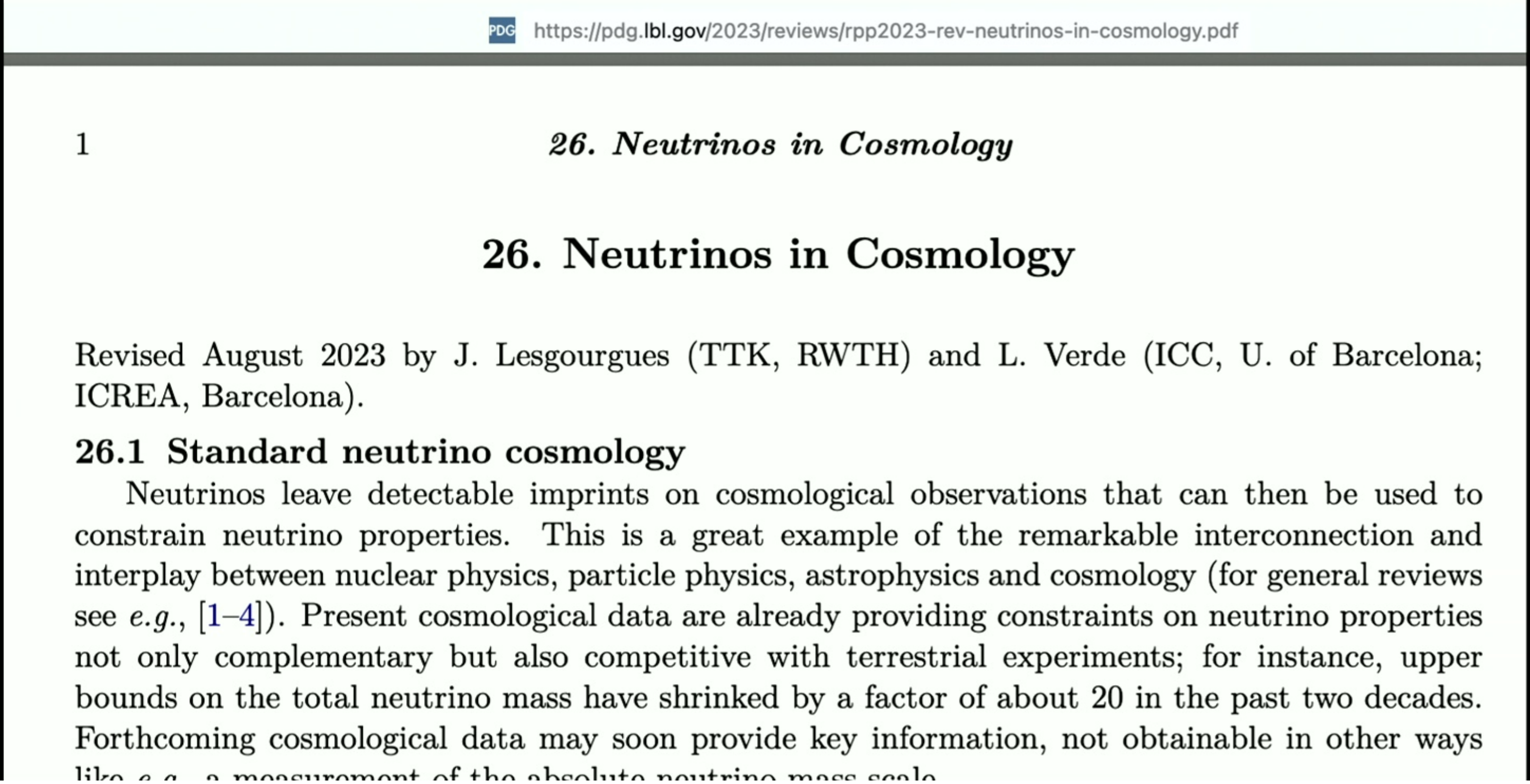
Summary

- Neutrinos are hard to detect
- They come in 3 flavours, which can mix
- We don't know why the flavour and mass states are so mixed (unlike the situation for quarks)
- We don't know if they're their own anti-particles or not (Majorana versus Dirac)
- We don't know their masses, or even if they have the "normal hierarchy" ($m_1 \lesssim m_2 < m_3$)
  or "inverted hierarchy" ($m_2 \gtrsim m_1 \gg m_3$)

- Cosmological neutrinos are <u>really</u> hard to detect!
- There are about 340 for every cm^3 of the Universe
- (2nd most common particle, after photons)
- If we could detect them, they'd be interesting…

For more information, see this mini-review

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



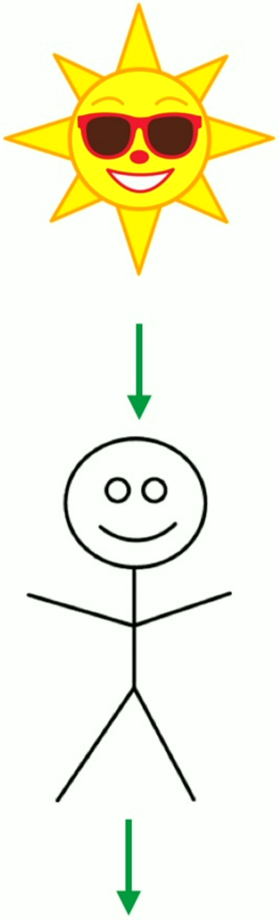
26. Neutrinos in Cosmology

Revised August 2023 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 two decades. Forthcoming cosmological data may soon provide key information, not obtainable in other ways like *e.g.*, a measurement of the absolute neutrino mass scale.

Neutrinos are hard to detect



They're produced prodigiously
in nuclear reactions in the Sun

Number entering your body per second
$\sim 10^{15}$

And

Number leaving your body per second
$\sim 10^{15}$

Cosmic Gall (John Updike)

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids through a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed-you call
It wonderful; I call it crass.

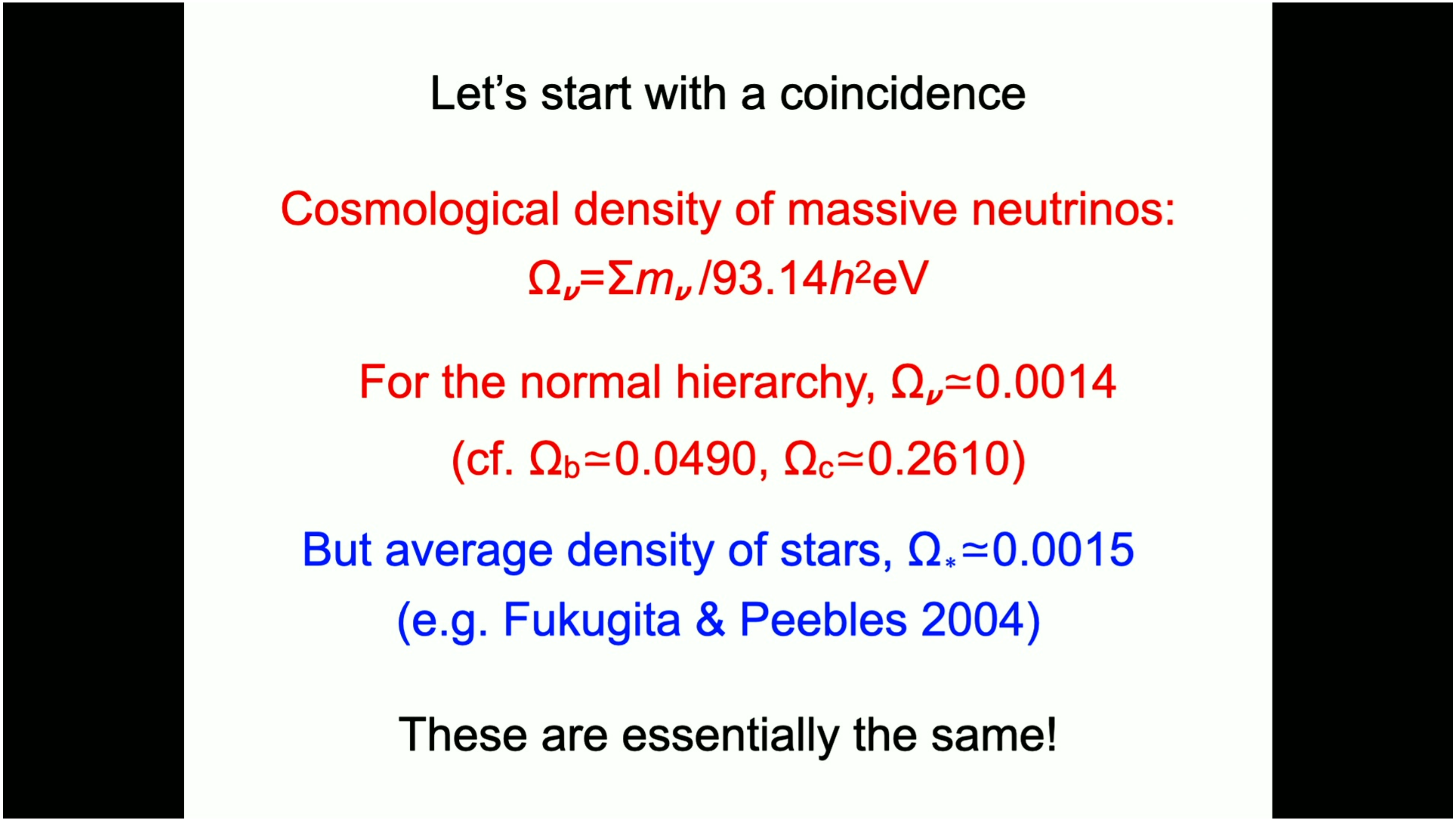
New Yorker Magazine, 1960

~20 neutrinos detected from SN1987A

Most passed through the Earth and up into the detector!

What about neutrinos in cosmology?

The CNB or CνB



Let’s start with a coincidence

Cosmological density of massive neutrinos:

$\Omega_\nu = \Sigma m_\nu / 93.14 h^2 \mathrm{eV}$

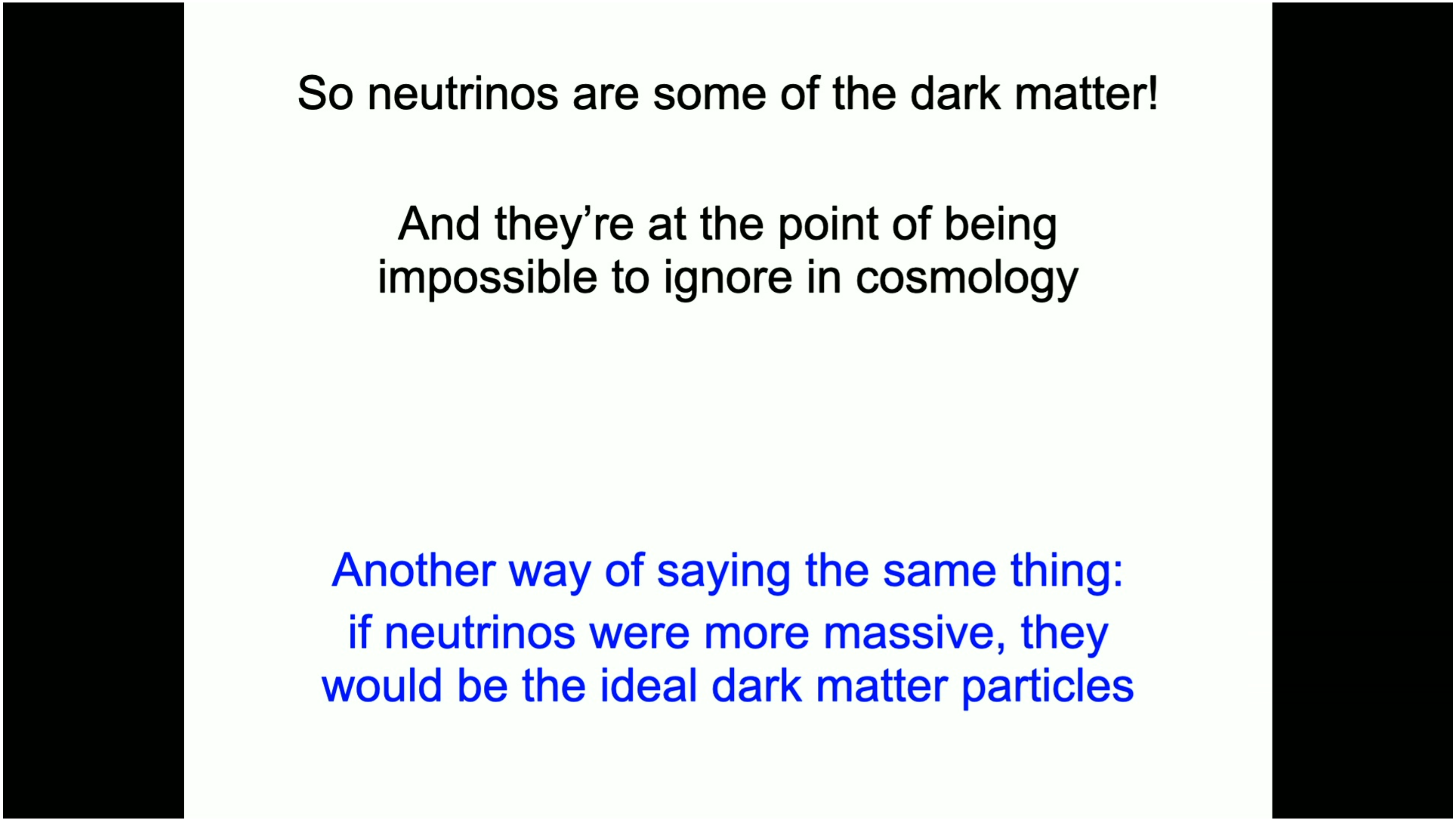
For the normal hierarchy, $\Omega_\nu \simeq 0.0014$

(cf. $\Omega_b \simeq 0.0490$, $\Omega_c \simeq 0.2610$)

But average density of stars, $\Omega_* \simeq 0.0015$

(e.g. Fukugita & Peebles 2004)

These are essentially the same!

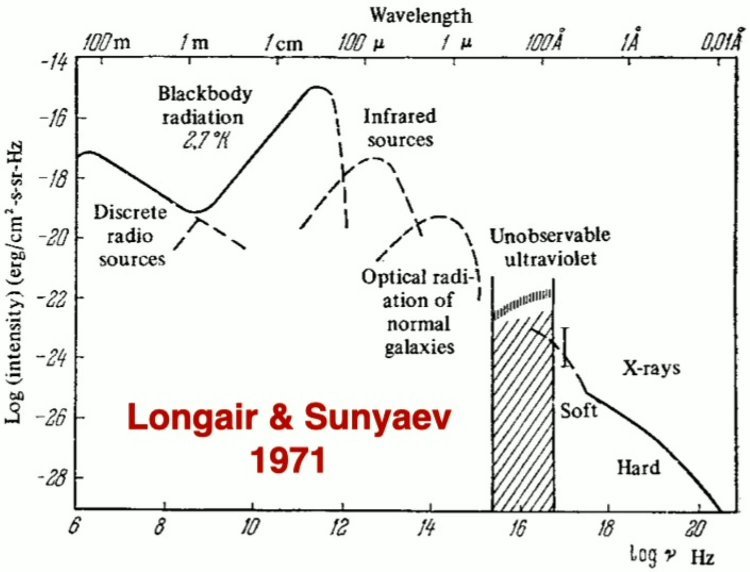


So neutrinos are some of the dark matter!

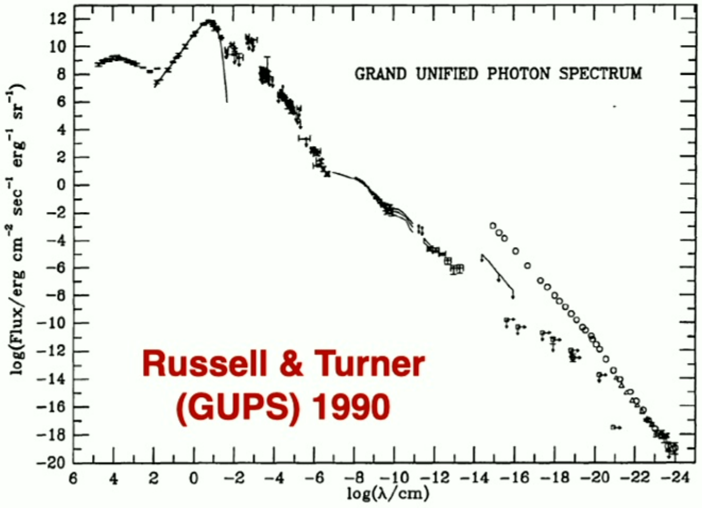
And they’re at the point of being impossible to ignore in cosmology

Another way of saying the same thing:

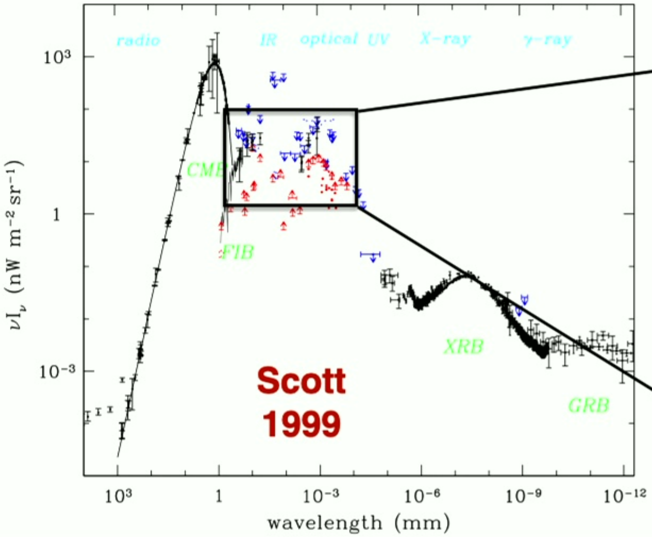
if neutrinos were more massive, they would be the ideal dark matter particles



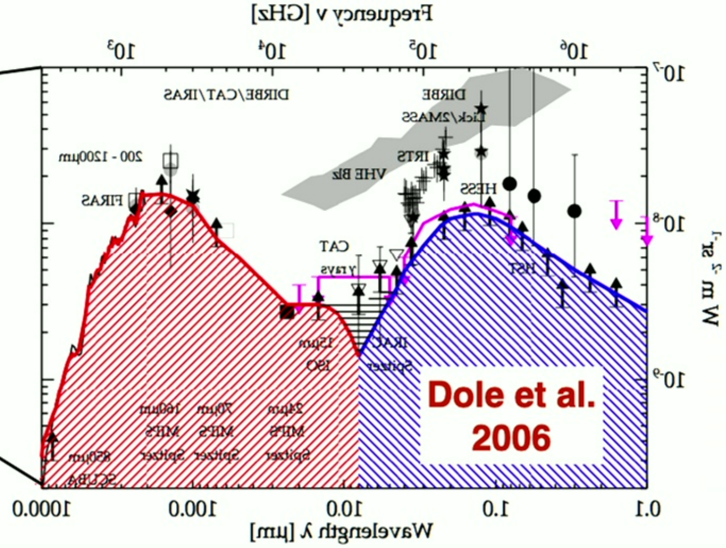
Longair & Sunyaev 1971



Russell & Turner (GUPS) 1990



Scott 1999

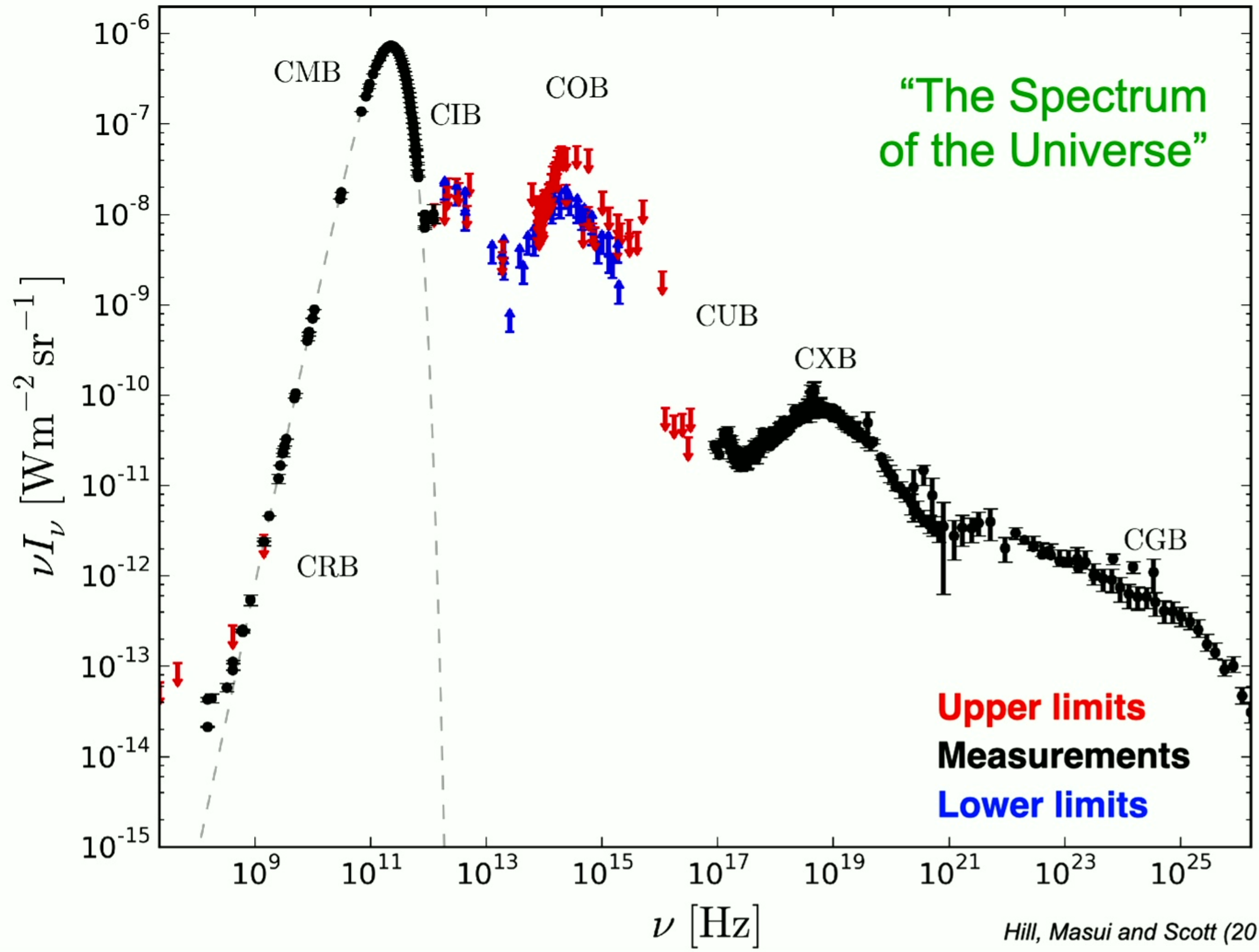


Dole et al. 2006

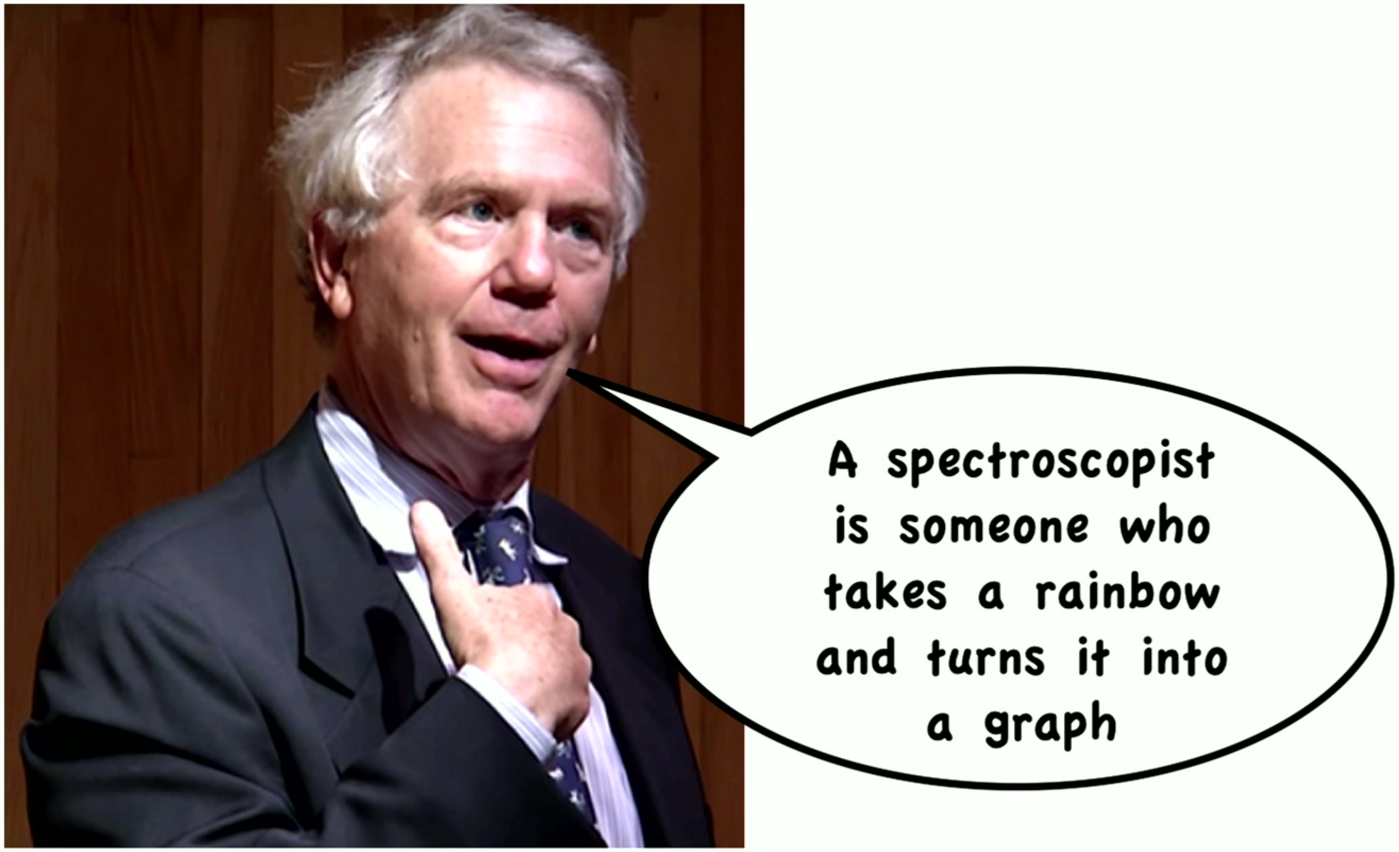
- Learn about the integrated history of electromagnetic radiation emission:

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

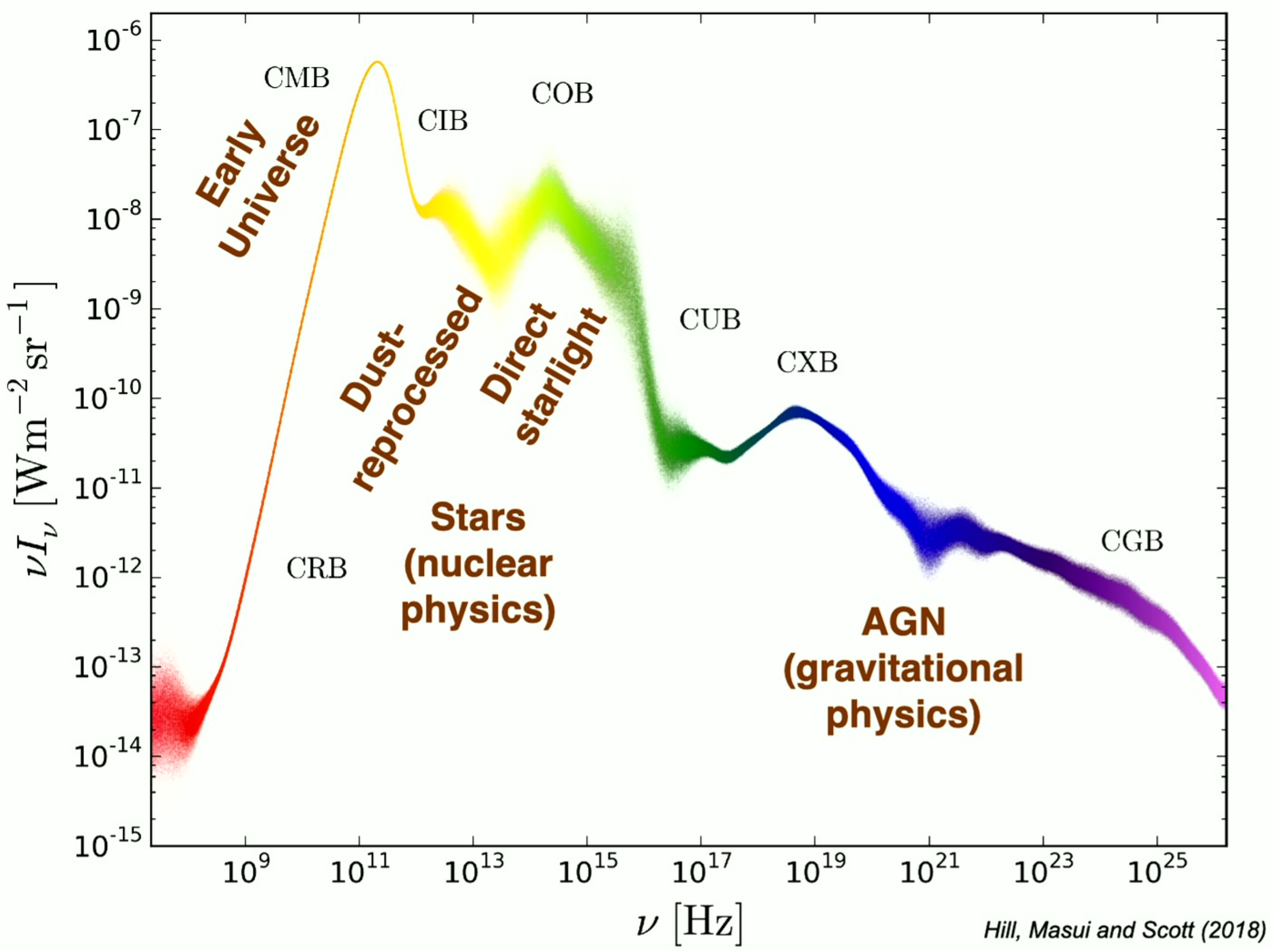
- For the CIB, for example, this constrains the history of star formation, metal production, black hole accretion, …
- And potentially new populations of sources, exotic processes, such as DM decay, annihilation, …
- But the absolute level (aka DC, monopole) is hard to measure



Hill, Masui and Scott (2018)

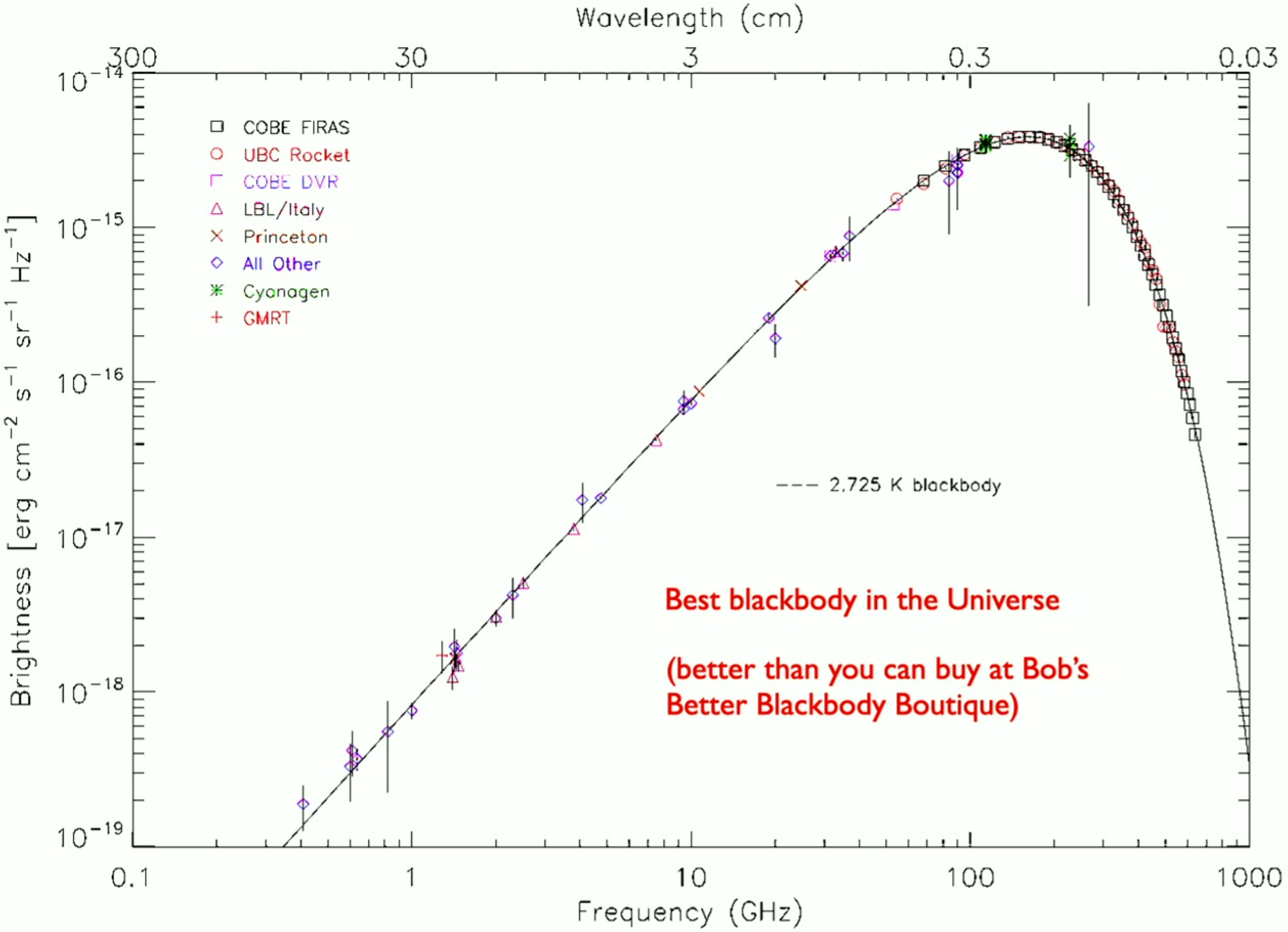


Bob Kirshner
(supernova astronomer)



Hill, Masui and Scott (2018)

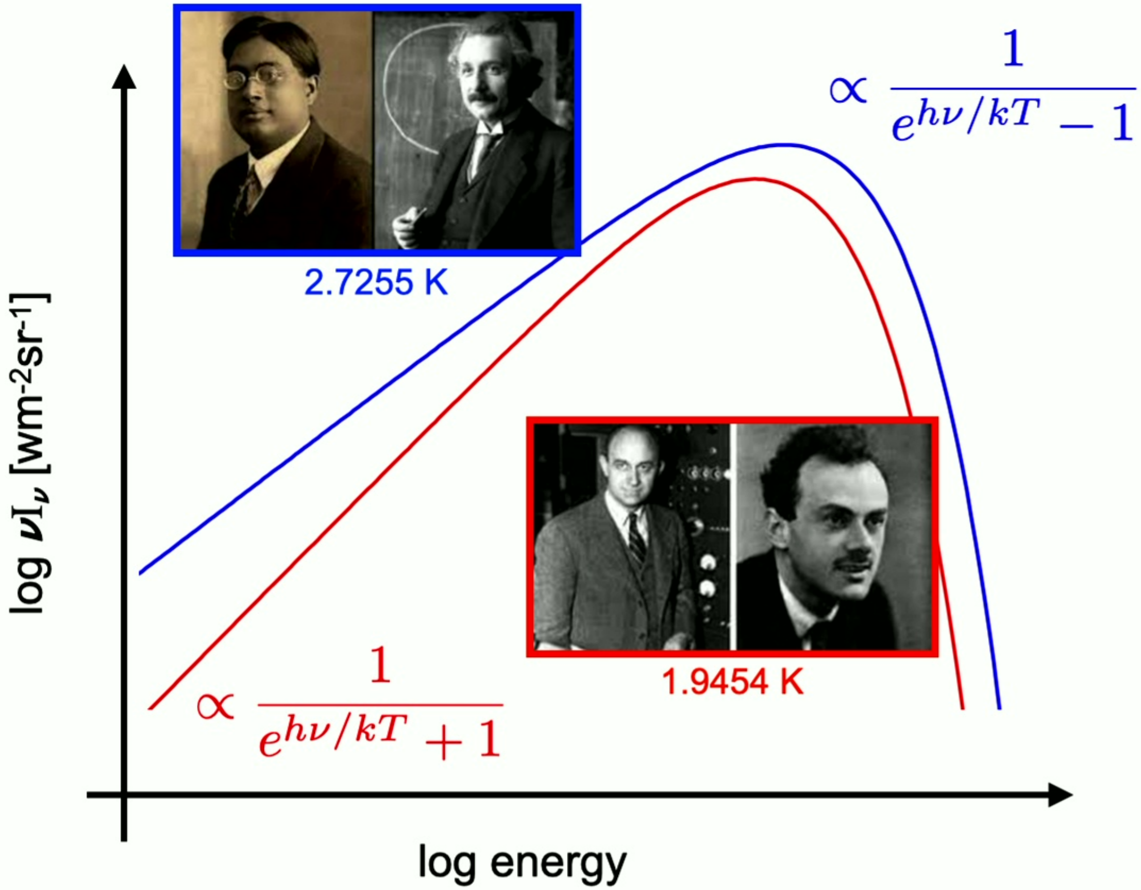
CMB Spectrum



Best blackbody in the Universe

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

CMB and CNB Spectra



CNB Spectrum

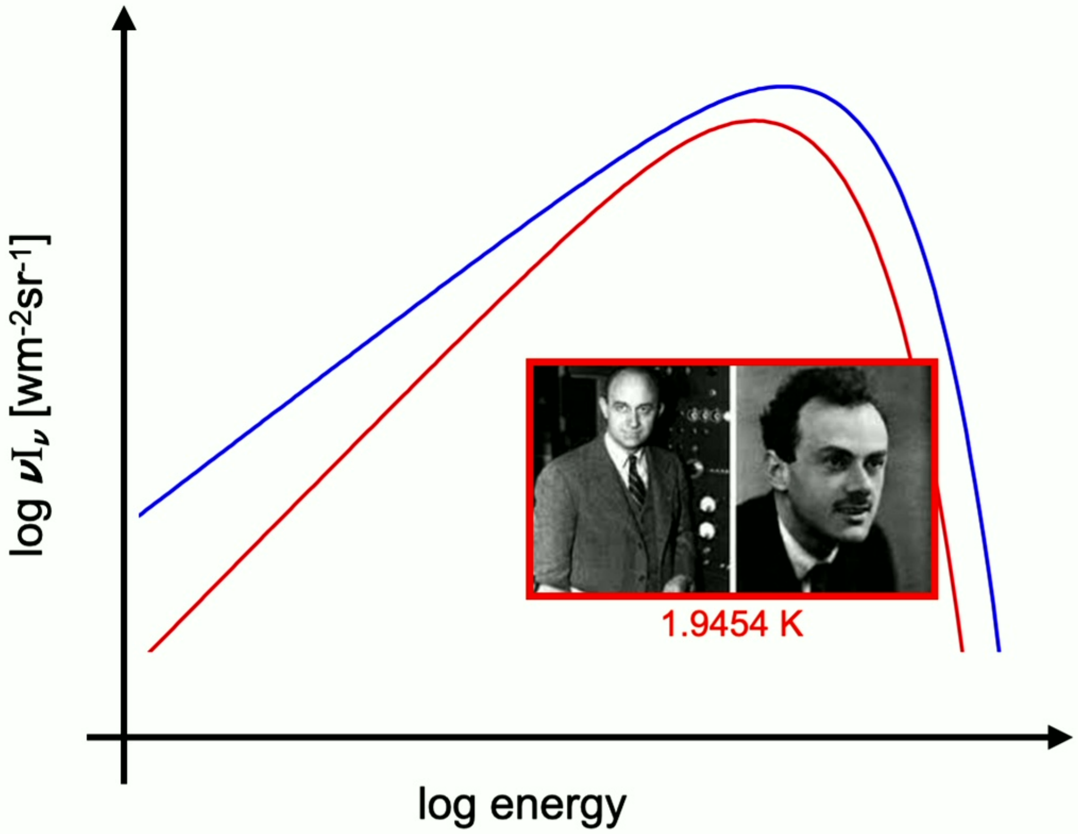
Why 1.9454 K?

Neutrino decoupling at *T*~1MeV, *t*~1s, which is <u>before</u> e^+-e^- annihilation

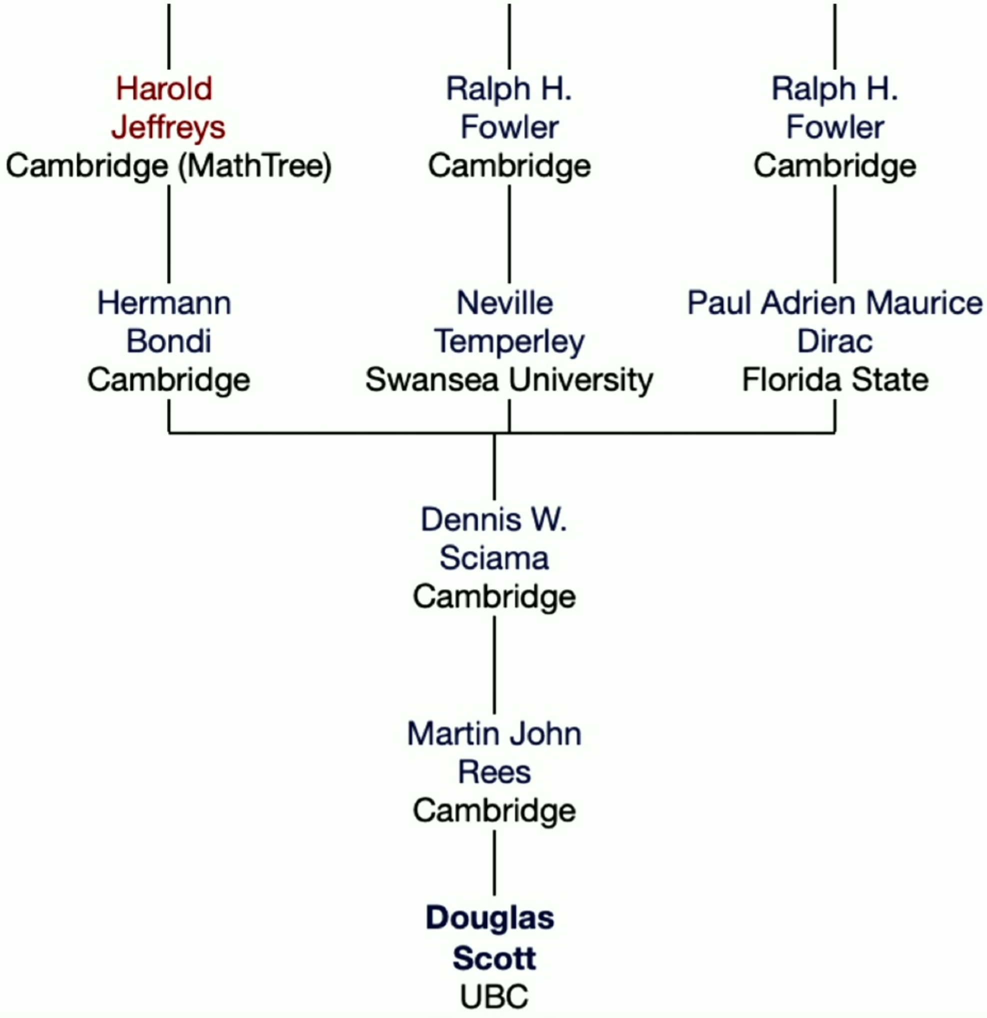
Annihilation boosts photon temperature relative to neutrino temperature

Calculation (comparing entropies before and after ν decoupling), gives factor of $(4/11)^{1/3}$

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

For photons in an expanding universe

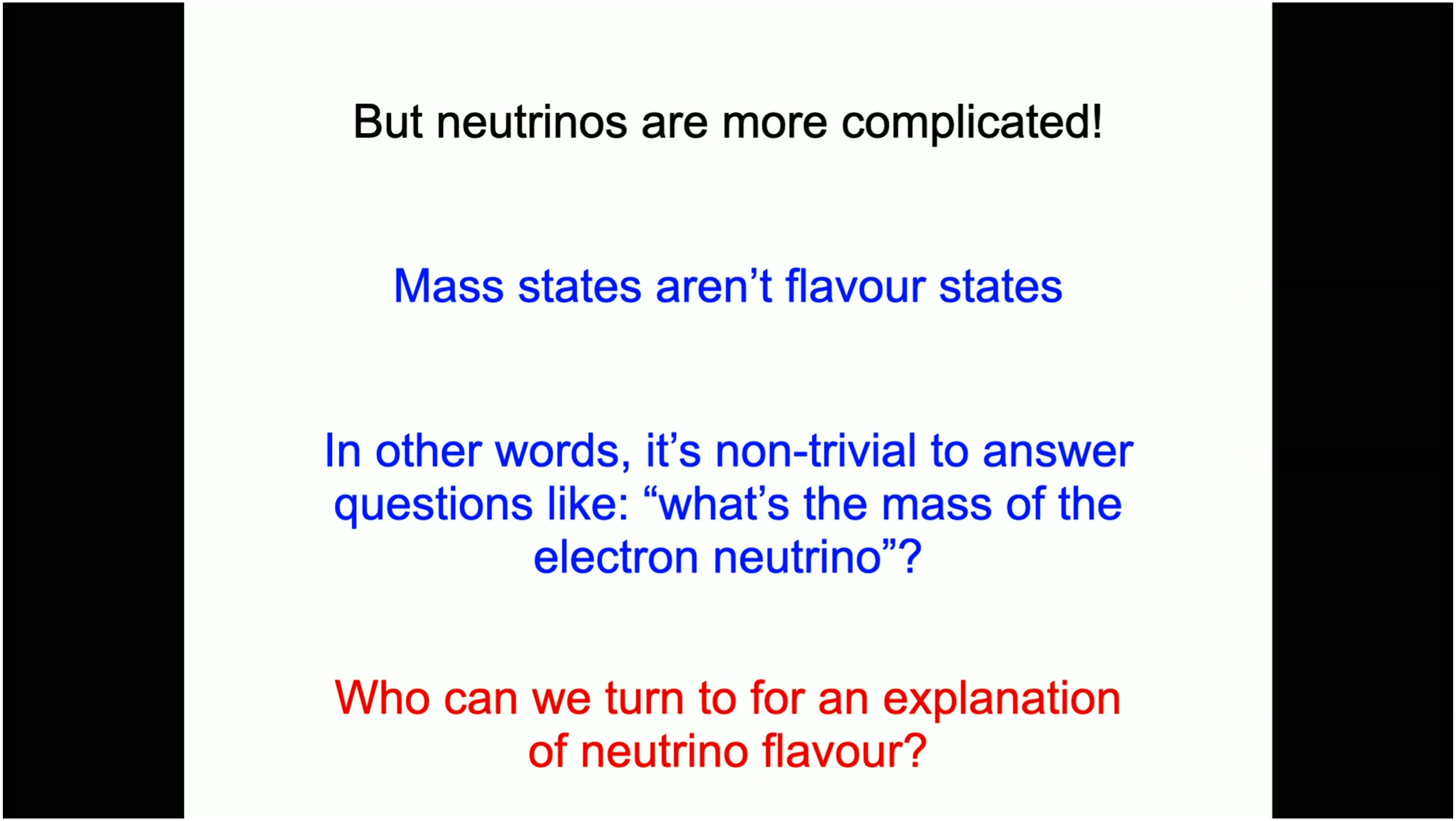
$T(z) = T_0(1+z)$ and $\nu(z) = \nu_0(1+z)$

so $\dfrac{1}{e^{h\nu/kT}-1}$ keeps its shape

Works whether you consider energy or momentum to be the thing that redshifts

For neutrinos, it turns out it's really momentum that redshifts

so $\dfrac{1}{e^{pc/kT}+1}$ keeps its shape



But neutrinos are more complicated!

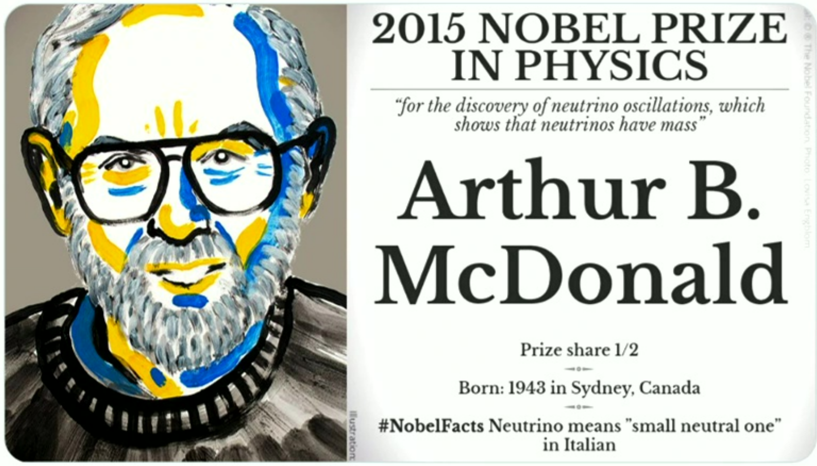
Mass states aren’t flavour states

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



2015 NOBEL PRIZE IN PHYSICS

“for the discovery of neutrino oscillations, which shows that neutrinos have mass”

Arthur B. McDonald

Prize share 1/2

Born: 1943 in Sydney, Canada

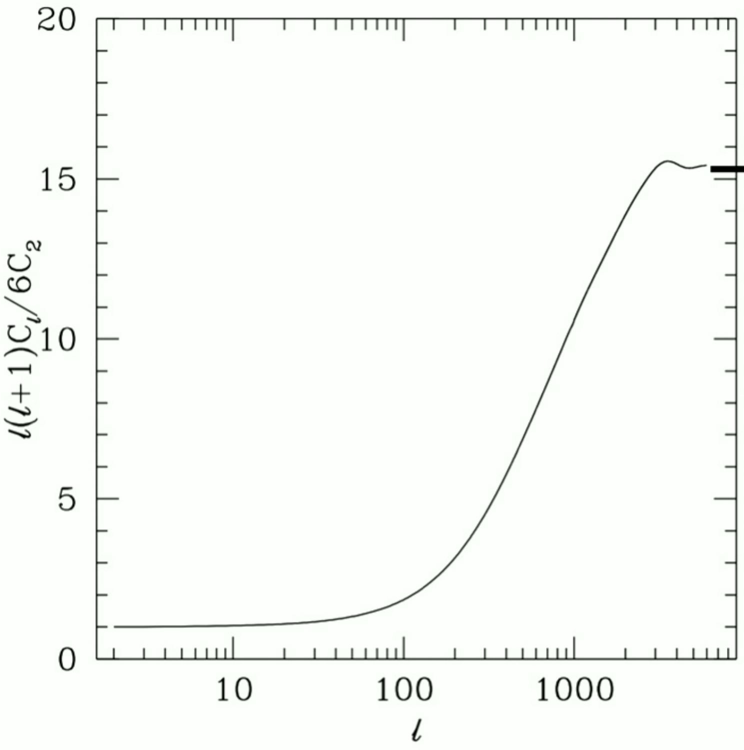
#NobelFacts Neutrino means "small neutral one" in Italian

Art McDonald

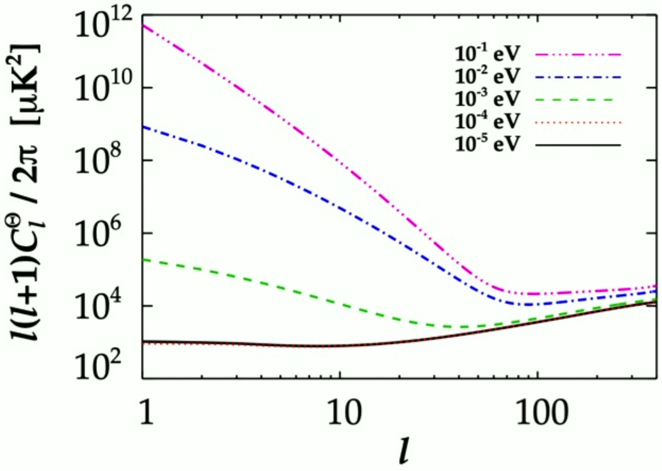
Timbits

First published prediction in 1995:

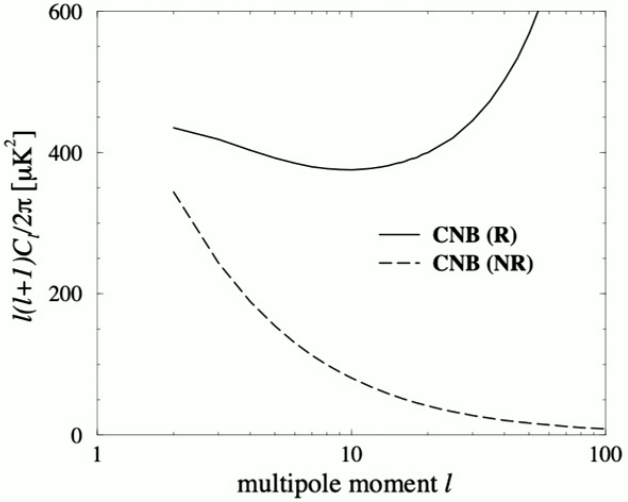
Hu, Scott, Sugiyama & White,
“The Effect of Physical Assumptions on the Calculation of Microwave Background Anistropies”
astro-ph/9504043, PRD, 52, 5498 (1995)
“Le bon Dieu est dans le detail” - Gustave Flaubert



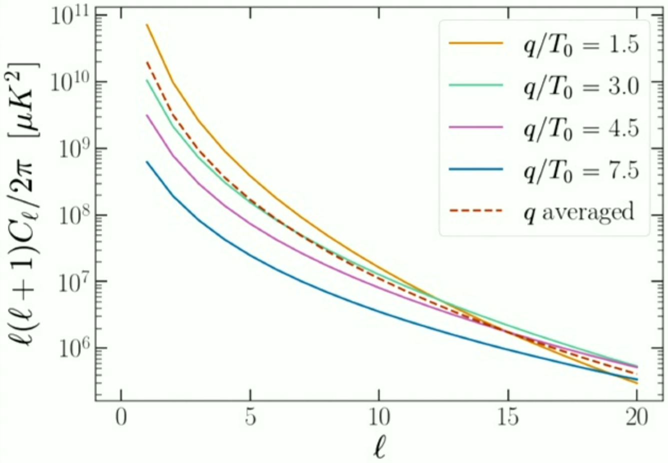
- Anisotropy amplitudes are ~10^{-5}
- Rise in power spectrum because of “early ISW”
- Damping at scales corresponding to neutrino decoupling, at multipoles ~10^8
- (milli-arcseconds!)
- Additionally should have “late ISW” at low multipoles



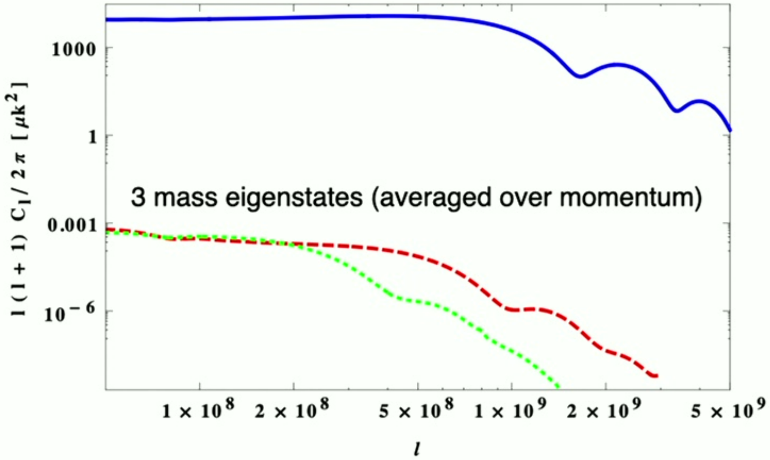
Hannestad & Brandbyge 2010



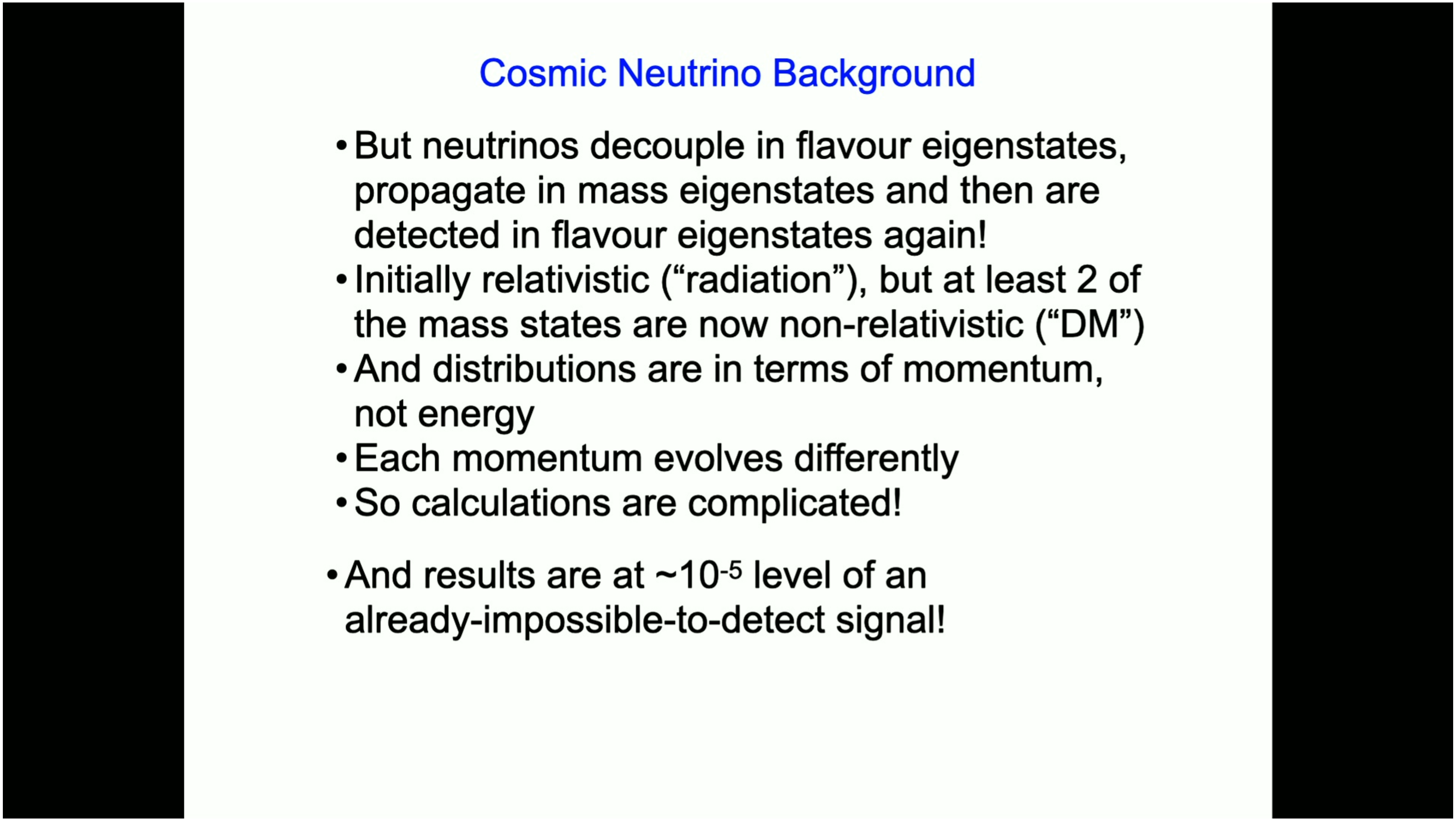
Michney & Cladwell 2007



Tully & Zhang 2021



Elham Alipour, UBC PhD thesis, 2015



Cosmic Neutrino Background

- But neutrinos decouple in flavour eigenstates, propagate in mass eigenstates and then are detected in flavour eigenstates again!
- Initially relativistic (“radiation”), but at least 2 of the mass states are now non-relativistic (“DM”)
- 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!

ν LSS at t~1s, but can be closer than γ LSS!

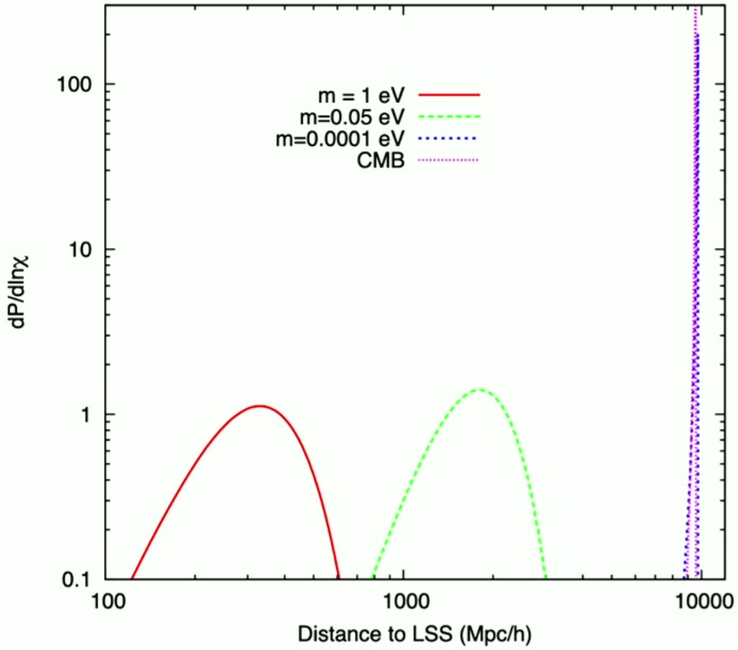


FIG. 2: The probability that a neutrino with mass m last scatters at a given comoving distance from us (the visibility function). Massive neutrinos travel more slowly than massless neutrinos so arrive here from much closer distances. Also shown is the last scattering surface of the cosmic microwave background, 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 & Seidov, 1983

Dodelson & Vesterinen, 2009
[arXiv:0907.2887]

Yao-Yu Lin & Holder, 2020
[arXiv:1910.03550]

ν anisotropies are even more complicated!

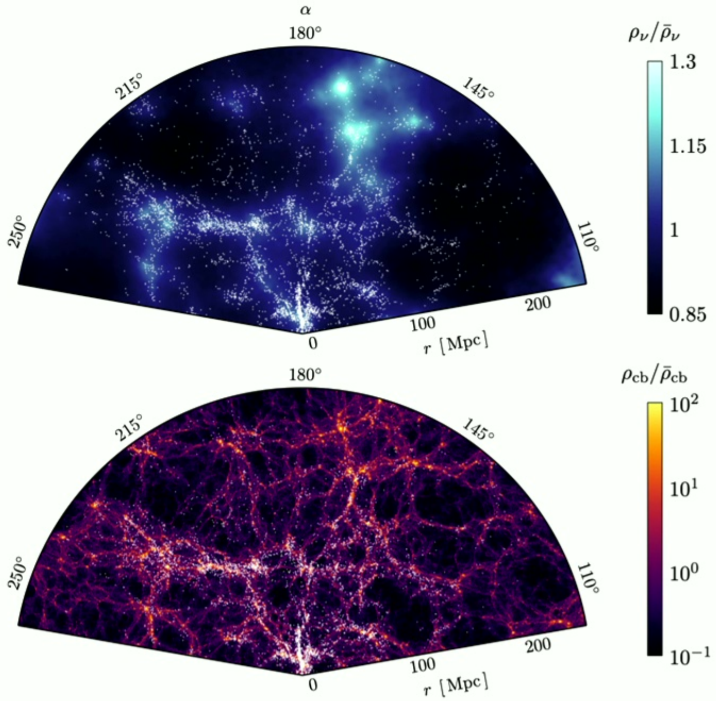


Figure 1: Slices of the expected neutrino (top) and dark matter (bottom) densities with right ascension $100° \leq \alpha \leq 260°$ within $r \leq 250\,\mathrm{Mpc}$, assuming $\sum m_\nu = 0.06\,\mathrm{eV}$. The white dots are galaxies from the `2M++` catalogue. From Earth, one would see a deficit in neutrino flux along lines of sight that intersect massive structures, due to the trapping of neutrinos in the surrounding neutrino clouds.

Elbers et al., 2023, "Where shadows lie: reconstruction of anisotropies in the neutrino sky" [arXiv:2307.03191]

- Cold DM anisotropies come from structure formation (halos, tidal streams, etc.)
- CMB photon distribution contains primordial anisotropies, plus line-of-sight "secondaries"
- νs are "hot" DM,

  combining both promordial anisotropies and capture by massive structures

Maybe we just need a better detector to detect cosmological neutrinos?

(like Geordi La Forge's visor in Star Trek)

But MeV νs from the Sun are hard enough to detect

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

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

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

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

N_{eff} effects are mostly on the distance scale

For Planck data, uncertainty is ΔN_{eff}~0.3.

⇒ detection of CNB to high significance:

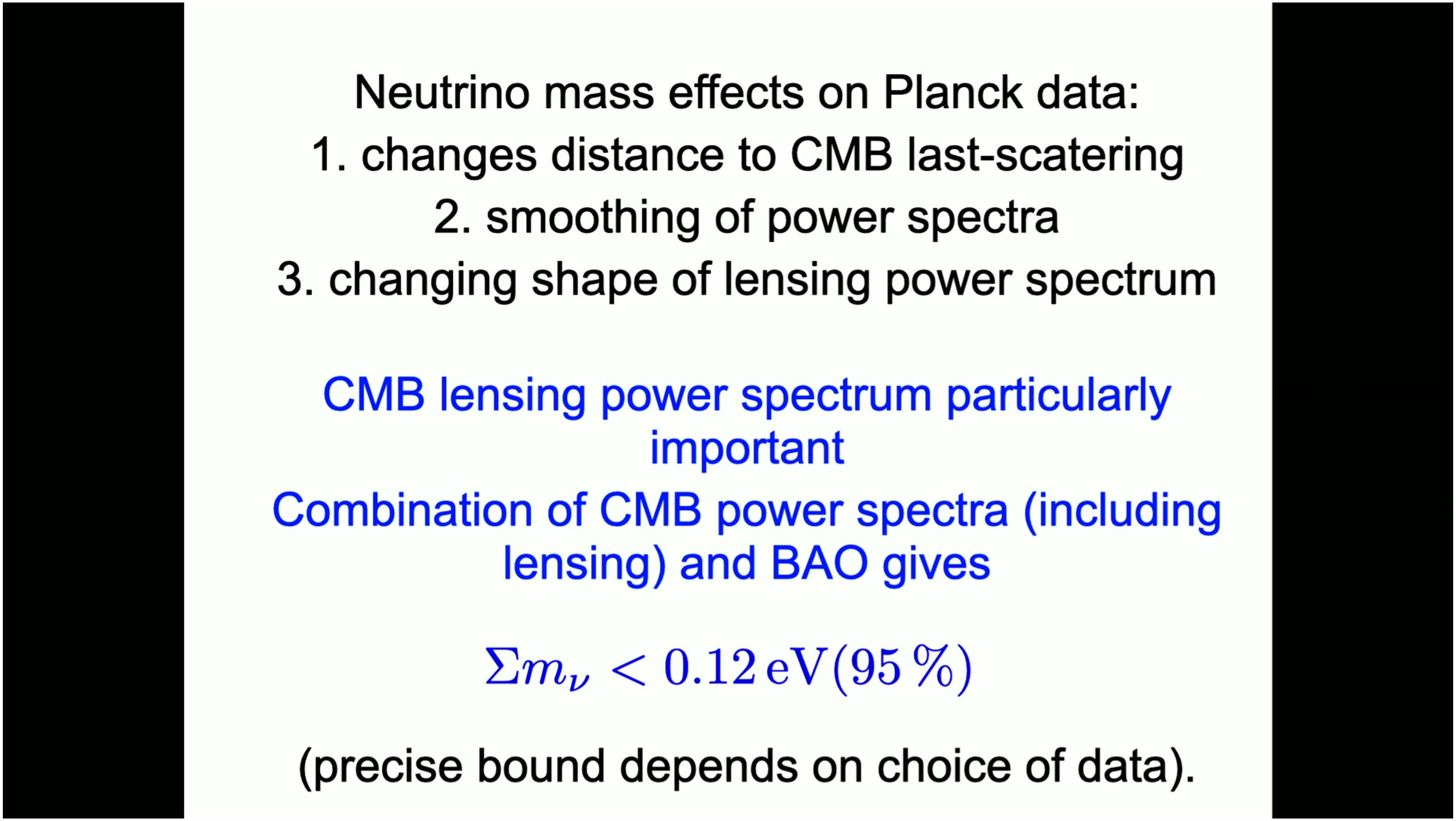
$$N_{\text{eff}} = 2.99 \pm 0.34 \ (95\,\%)$$

(for Planck power spectra + BAO).

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

$$c_{\text{eff}}^2 = c_{\text{vis}}^2 = \frac{1}{3},$$

to 2% and 10%, respectively.



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

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

(precise bound depends on choice of data).

What about sterile neutrinos?

A complication is that cosmology constrains the contributions to

$$N_{\mathrm{eff}} \ \& \ \Sigma m_\nu$$

but direct experiments constrain (say)

$$\Delta m^2_{41} \ \& \ \sin^2 2\theta_{14}$$

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

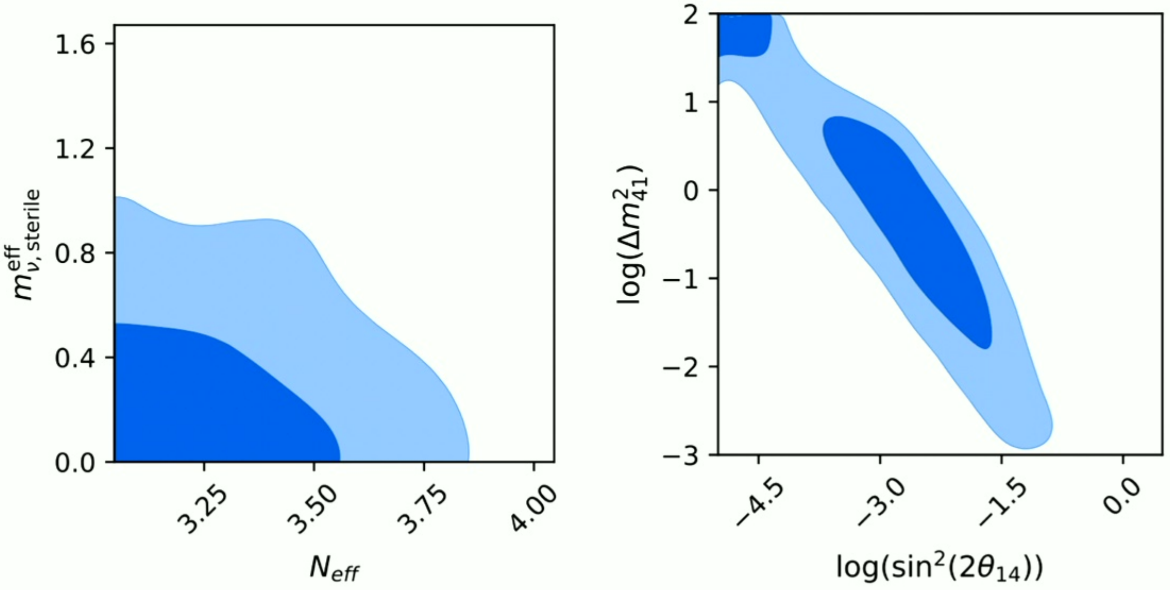


Figure 2. *Left panel*: *Planck* 68% and 95% CL constraints in the cosmology parameter space using *Planck* CMB TT+lowTEB data. Priors are flat in the ranges $3.046 \leq N_{\mathrm{eff}} \leq 4.046$ and $0 \leq m^{\mathrm{eff}}_{\nu,\mathrm{sterile}} \leq 3$ eV. *Right panel*: The procedure explained 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 T_0) parameter of the SMC

the Room
(in Varenna)

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

Time will tell!