Neutrinos in cosmology:

A match made in the Heavens

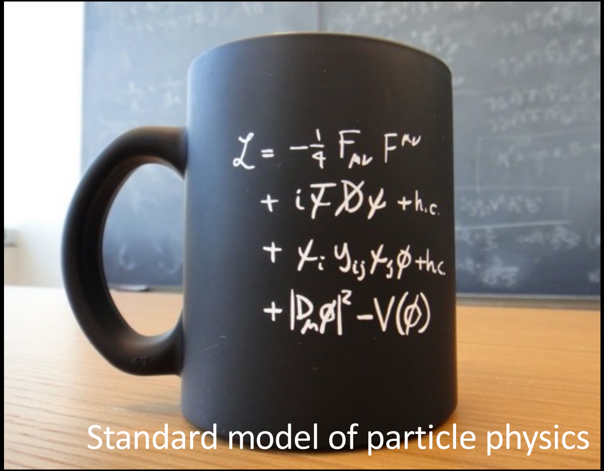
Yvonne Y. Y. Wong, UNSW Sydney

Snowmass neutrino colloquium IV, May 4, 2022

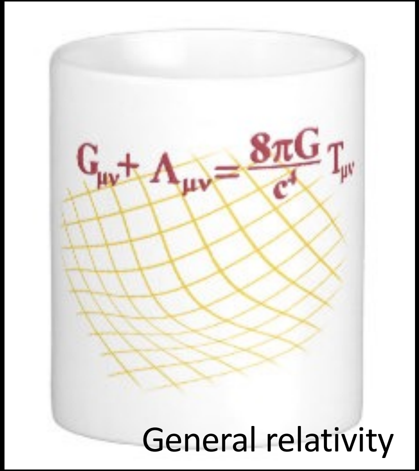
An unlikely partnership?

Neutrino = one of the lightest and most weakly-interacting known particles

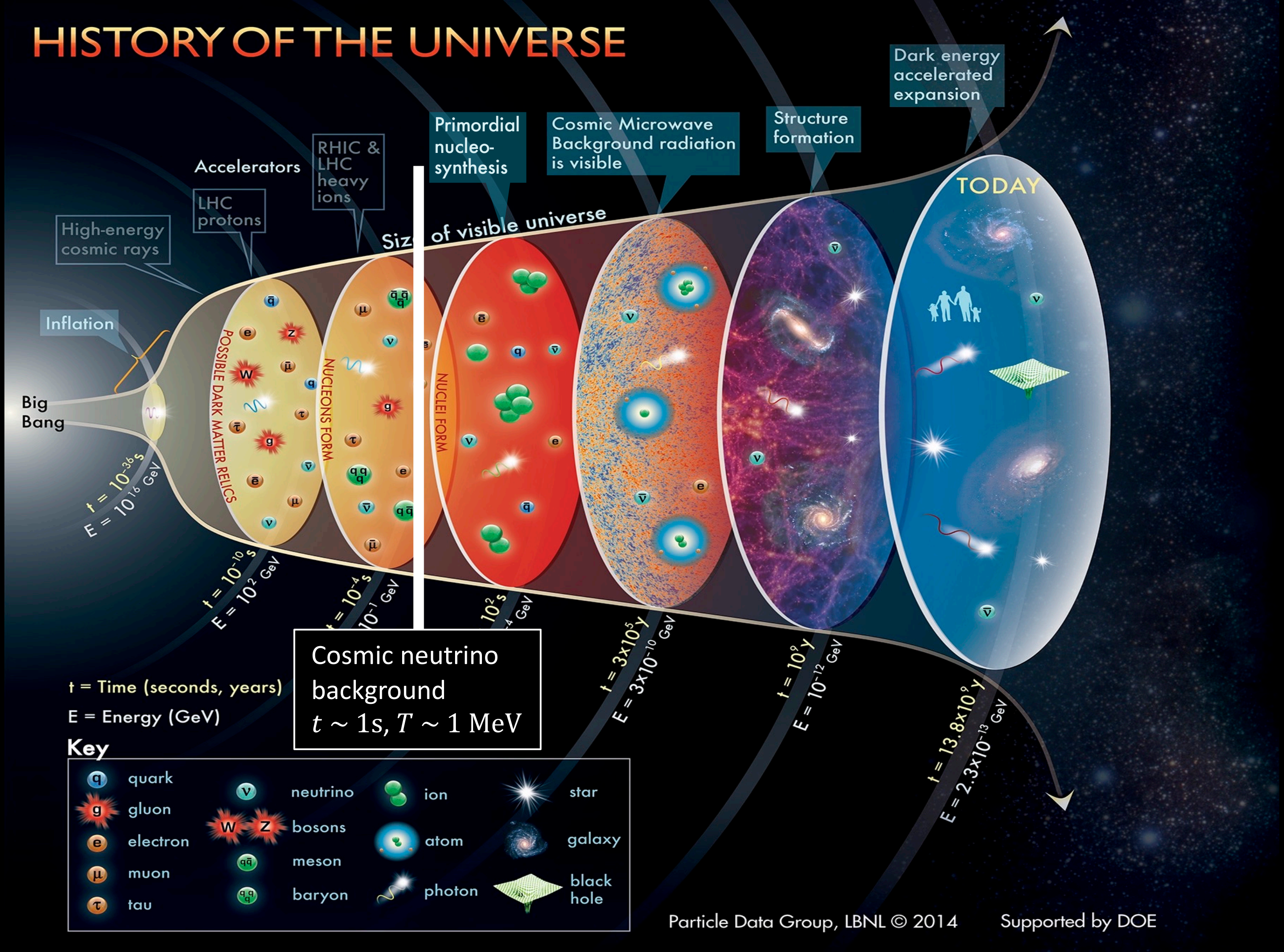
Cosmology = gravitation on the largest observable scales



Standard model of particle physics



General relativity



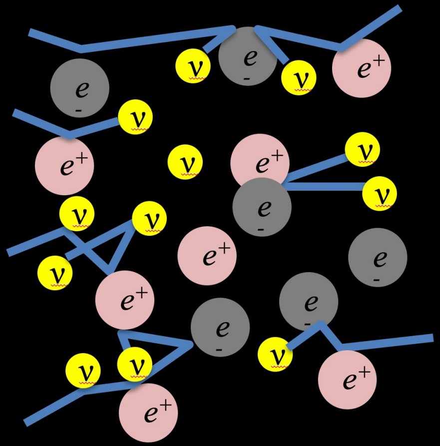
Cosmic neutrino background

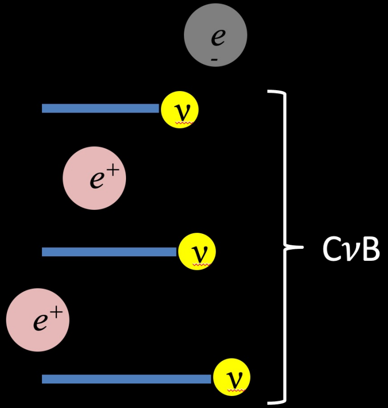
$t \sim 1\text{s}, T \sim 1\ \text{MeV}$

Particle Data Group, LBNL © 2014 Supported by DOE

Formation of the CνB…

The CνB is formed when neutrinos decouple from the cosmic plasma.





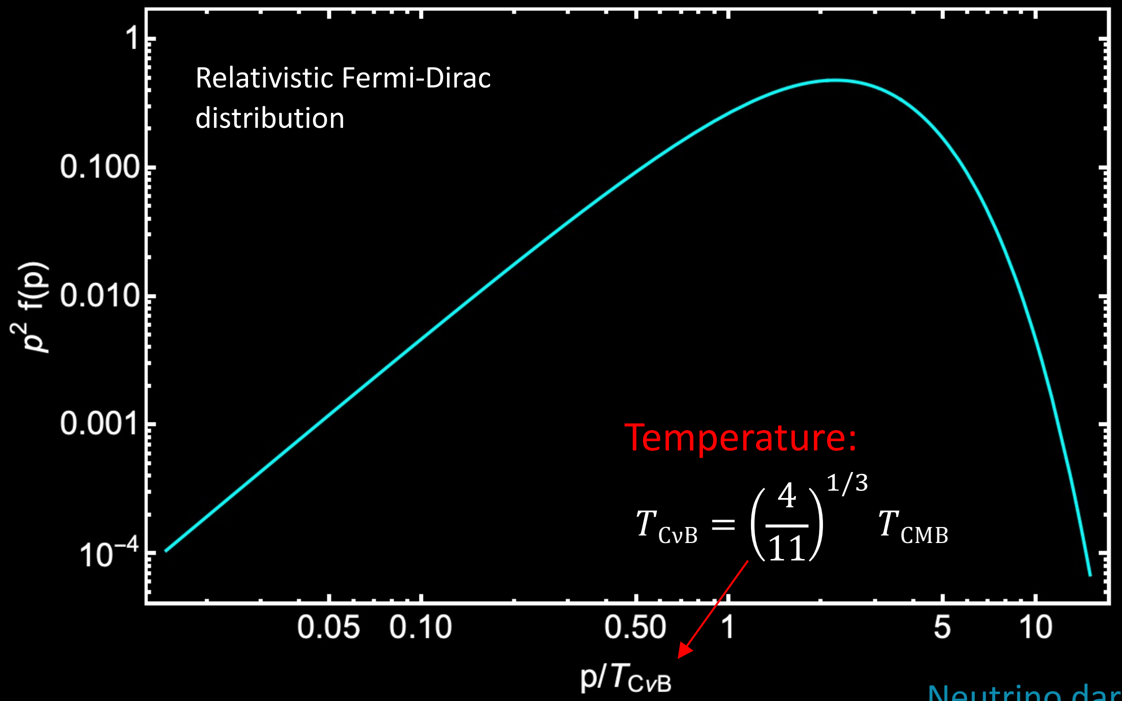
Neutrinos “free-stream” to infinity.

Above $T \sim 1\ \mathrm{MeV}$, even weakly-interacting neutrinos can be produced, scatter off e^+e^- and other neutrinos, and attain thermodynamic equilibrium

Below $T \sim 1\ \mathrm{MeV}$, expansion dilutes plasma, and reduces interaction rate: the universe becomes transparent to neutrinos.

The cosmic neutrino background…

Standard model predictions



Temperature:

$$T_{\mathrm{C\nu B}} = \left(\frac{4}{11}\right)^{1/3} T_{\mathrm{CMB}}$$

Number density:

Per family of neutrinos +antineutrinos

$$n_{\mathrm{C\nu B}} \simeq 110\ \mathrm{cm}^{-3}$$

Energy density:

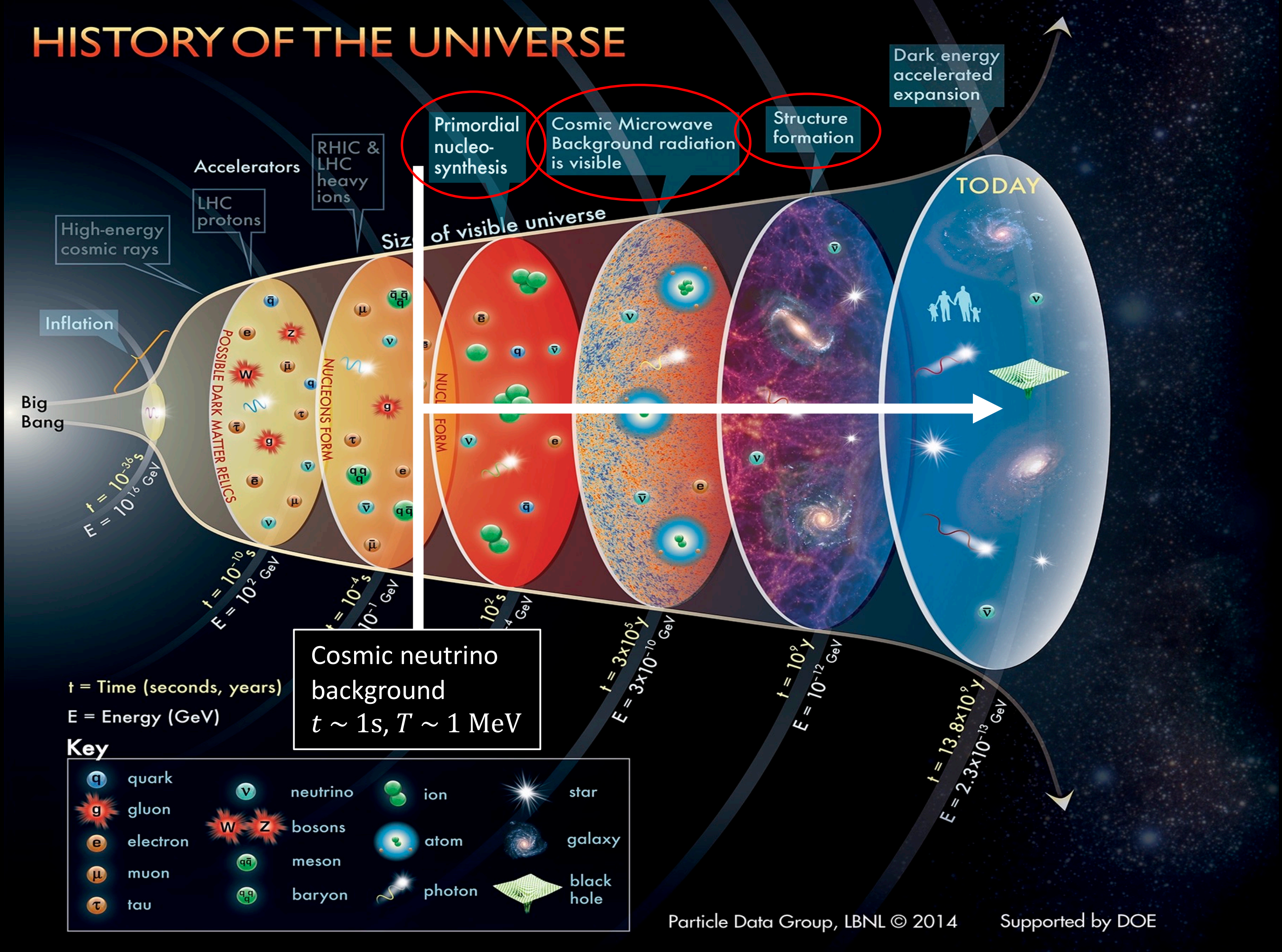
- Relativistic (if $T_{\mathrm{C\nu B}} \gg m_\nu$):

$$\rho_{\mathrm{C\nu B}} \simeq \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_{\mathrm{CMB}}$$

- Non-rel (if $T_{\mathrm{C\nu B}} \ll m_\nu$):

$$\Omega_{\mathrm{C\nu B}} \simeq \frac{m_\nu}{93\ h^2\ \mathrm{eV}}$$

Neutrino dark matter



Cosmic neutrino background
$t \sim 1\text{s}, T \sim 1\ \text{MeV}$

Particle Data Group, LBNL © 2014 Supported by DOE

What can cosmology do for neutrino physics?

Precision cosmological observations allow us to infer the properties of the cosmic neutrino background, from which to determine :

- **Absolute neutrino mass scale,** $\sum m_\nu$
- **Number of neutrino families,** N_{eff}
  - Deviations from SM prediction of $N_{\text{eff}} \approx 3$
  - e.g., test for the existence of light sterile states

“Standard” tests (even a *raison d’être*)

- **Neutrino decay/lifetime,** τ_0
- **Non-standard neutrino interactions**
  - Self, neutrino-dark matter, neutrino-dark energy
  - …

More exotic, but of growing interest

What can neutrino physics do for cosmology?

From the theoretical perspective:

- **Origin of dark matter** = keV sterile neutrinos as a dark matter candidate
- **Origin of the matter-antimatter asymmetry** = leptogenesis linked to neutrino mass generation

More directly, neutrino experiments can also help to pin down parameters of the CνB.

- Allow us to gain more precise and accurate information about the other stuff in the universe.

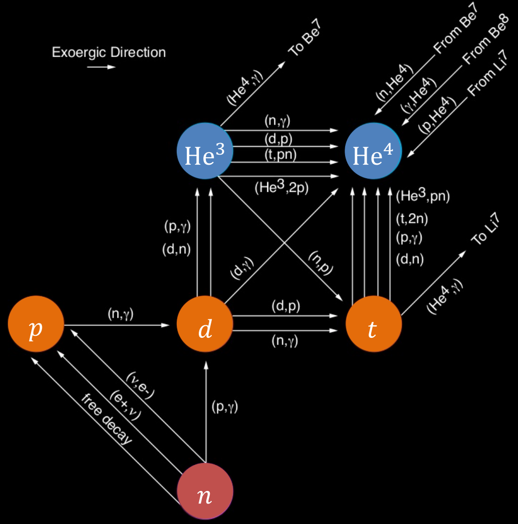
1. What can cosmology do for neutrino physics?

Cosmological observables…

+ Supernova Ia, local H_0, etc.

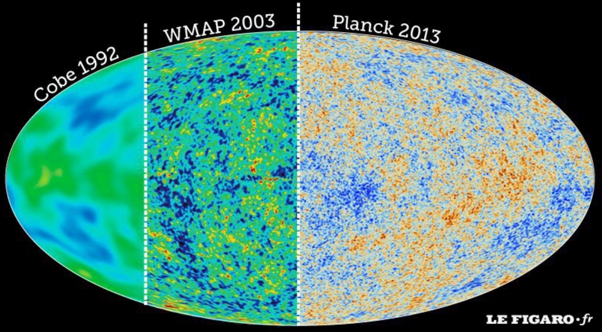
(No direct neutrino effects)

Light element abundances from primordial nucleosynthesis



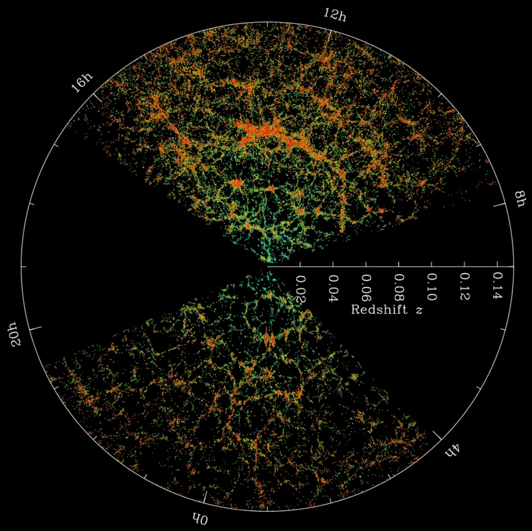
N_{eff} (expansion rate)

Cosmic microwave background anisotropies



N_{eff} (expansion rate)
Interactions (free-streaming)
Lifetime (free-streaming)

Large-scale matter distribution

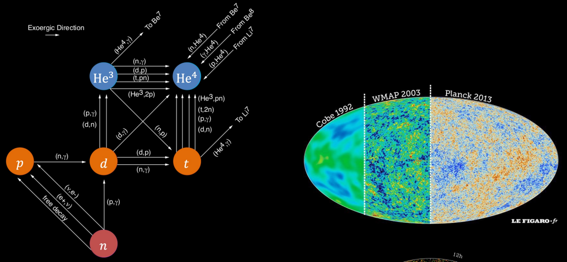


$\sum m_\nu$ (perturbation growth)

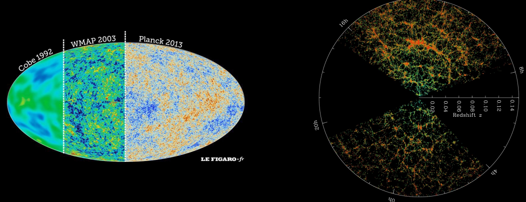
What do these probes really probe?

They may look different, but ultimately the information contained is

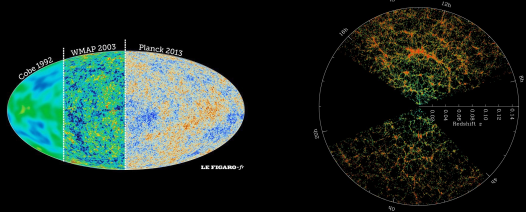
- Universal expansion rate at different times
  - How much matter, radiation, "in-between" (e.g., neutrinos), vacuum energy, etc.



- Growth of fluctuations under gravity
  - Kinematic properties and interactions of the various types of stuff in the universe; good for neutrino physics



- Distance measurements
  - Spatial geometry, dark energy; not directly relevant for neutrino physics but has indirect effects on inference



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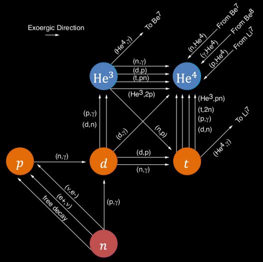

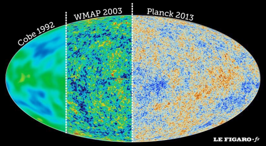

Neutrinos & the expansion rate…

The Hubble expansion rate depends on the energy content of the universe:

$$H^2(a(t)) = H_0^2(\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \Omega_k a^{-2} + \cdots)$$

Scale factor

Matter

Radiation

Cosmological constant

Spatial curvature

Neutrinos = radiation at early times
= matter at late times

Neutrinos & the expansion rate…

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Scale factor

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Radiation

Cosmological constant

Spatial curvature

Standard cosmology

$$\rho_{\mathrm{CMB}} + \sum \rho_{\mathrm{C\nu B}} = \left[1 + N_{\mathrm{eff}} \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right] \rho_{\mathrm{CMB}}$$

$N_{\mathrm{eff}}^{\mathrm{SM}} = 3.0440 \pm 0.0002$

Bennett et al, 2020, 2021;
Froustey, Pitrou & Volpe, 2020

For 3 SM families, includes m_e/T corrections, non-instantaneous decoupling, finite-temperature QED, and neutrino oscillations.

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Scale factor

Matter

Radiation

Cosmological constant

Spatial curvature

$$\rho_{\rm other} + \rho_{\rm CMB} + \sum \rho_{{\rm C}\nu{\rm B}} = \left[1 + N_{\rm eff} \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]\rho_{\rm CMB}$$

Any relativistic, feebly-interacting, thermalised particle species **will look like a neutrino** cosmologically, e.g., light sterile neutrinos, thermal axions, etc.

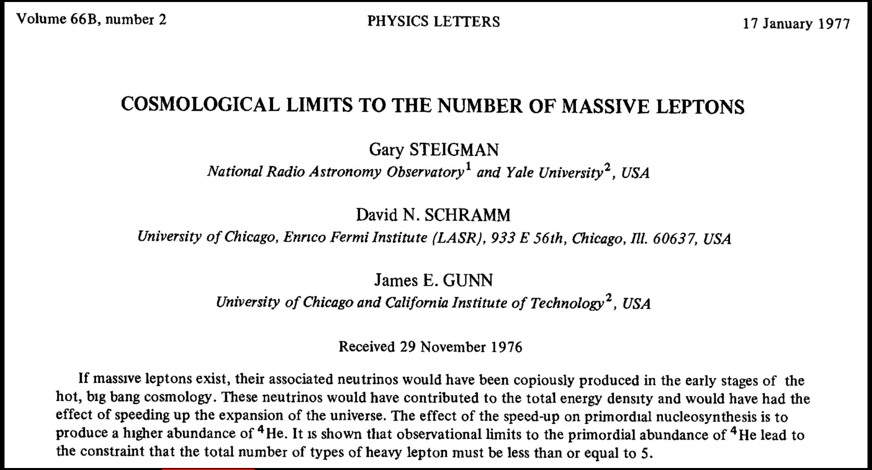
$N_{\rm eff}^{\rm SM} = 3.0440 \pm 0.0002$

Bennett et al, 2020, 2021; Froustey, Pitrou & Volpe, 2020

For 3 SM families, includes m_e/T corrections, non-instantaneous decoupling, finite-temperature QED, and neutrino oscillations.

Nucleosynthesis & N_{eff}…

Constraining N_{eff} with the primordial elemental abundances has a long history.



Volume 66B, number 2 PHYSICS LETTERS 17 January 1977

COSMOLOGICAL LIMITS TO THE NUMBER OF MASSIVE LEPTONS

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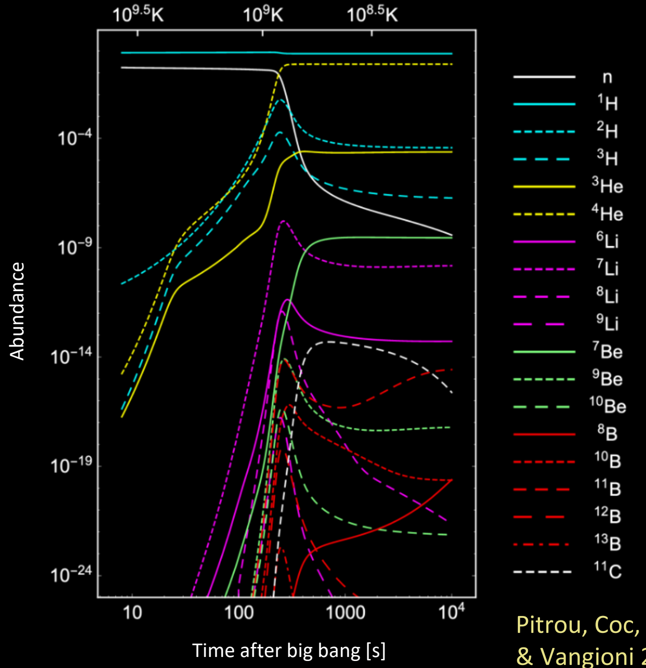
University of Chicago and California Institute of Technology[2], *USA*

Received 29 November 1976

If massive leptons exist, their associated neutrinos would have been copiously produced in the early stages of the hot, big bang cosmology. These neutrinos would have contributed to the total energy density and would have had the effect of speeding up the expansion of the universe. The effect of the speed-up on primordial nucleosynthesis is to produce a higher abundance of ^{4}He. It is shown that observational limits to the primordial abundance of ^{4}He lead to the constraint that the total number of types of heavy lepton must be less than or equal to 5.

$N_{\text{eff}} < 5$



Pitrou, Coc, Uzan & Vangioni 2018

How much of these elements is produced depends on how fast the universe expands.

Nucleosynthesis & N_{eff}…

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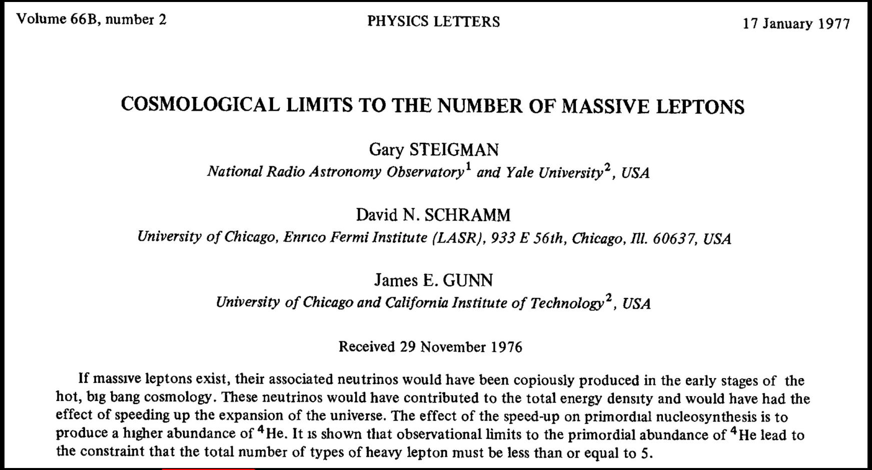

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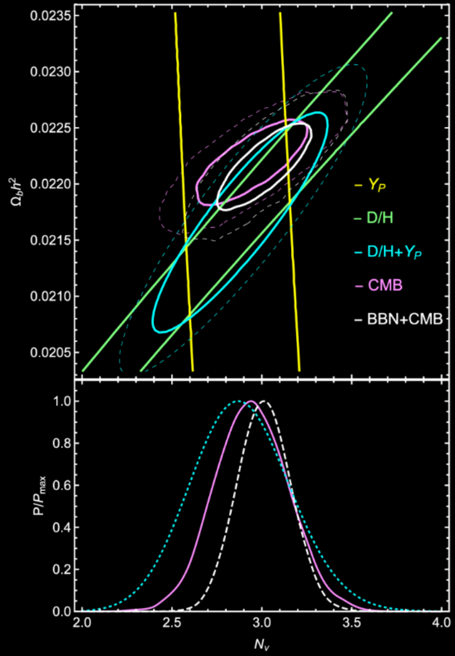
$$\boxed{N_{\text{eff}} < 5}$$



D/H = Deuterium
Y_p = Helium-4

Pitrou, Coc, Uzan & Vangioni 2018

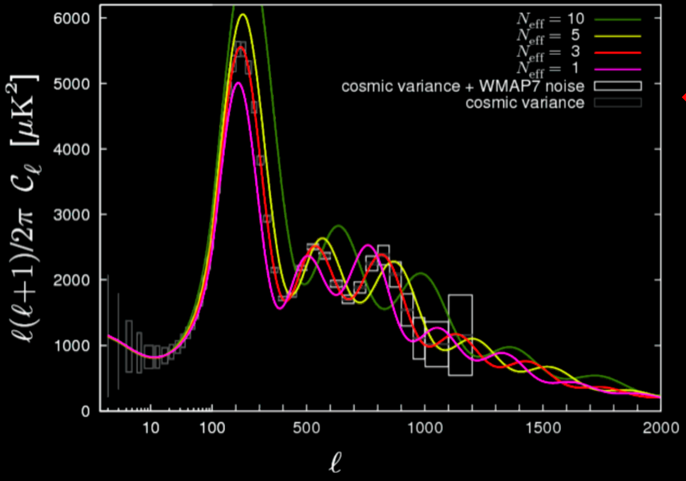
$$\boxed{N_{\text{eff}} = 2.88 \pm 0.27\ (68\%\ \text{CL})}$$

At face value a strong statement against thermalised light sterile neutrinos ($N_{\text{eff}} = 4$).

CMB anisotropies & N_{eff}…

N_{eff} also affects the expansion rate at recombination.

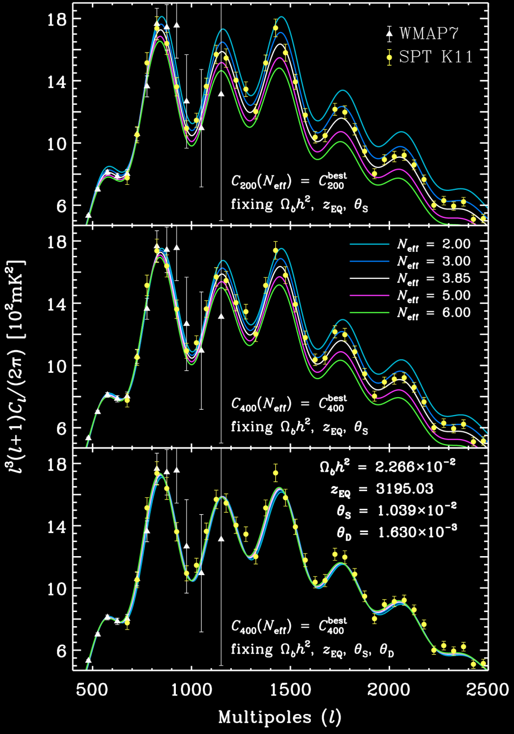
- Observable in the CMB temperature power spectrum



“Naïve” signature

“Irreducible” signature is in the CMB damping tail

Hou, Keisler, Knox, Millea & Reichardt 2013



Planck TTTEEE+lowE +lensing+BAO; 7-parameters

$$\boxed{N_{\text{eff}} = 2.99 \pm 0.34 \; (95\% \; \text{CL})}$$

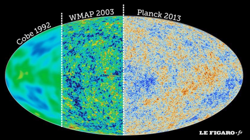
Aghanim et al. [Planck] 2021

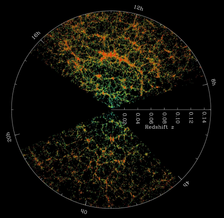
Remarkably consistent with Standard Model prediction $N_{\text{eff}} \approx 3$

What do these probes really probe?

They may look different, but ultimately the information contained is

- Growth of fluctuations under gravity
  - Kinematic properties and interactions of the various types of stuff in the universe; good for neutrino physics





Neutrino masses, $\sum m_\nu$ (large-scale structure)
Neutrino decay/lifetime, τ_0 (CMB)
Non-standard neutrino interactions (CMB)

Neutrino masses & large-scale structure...

Cold dark matter only

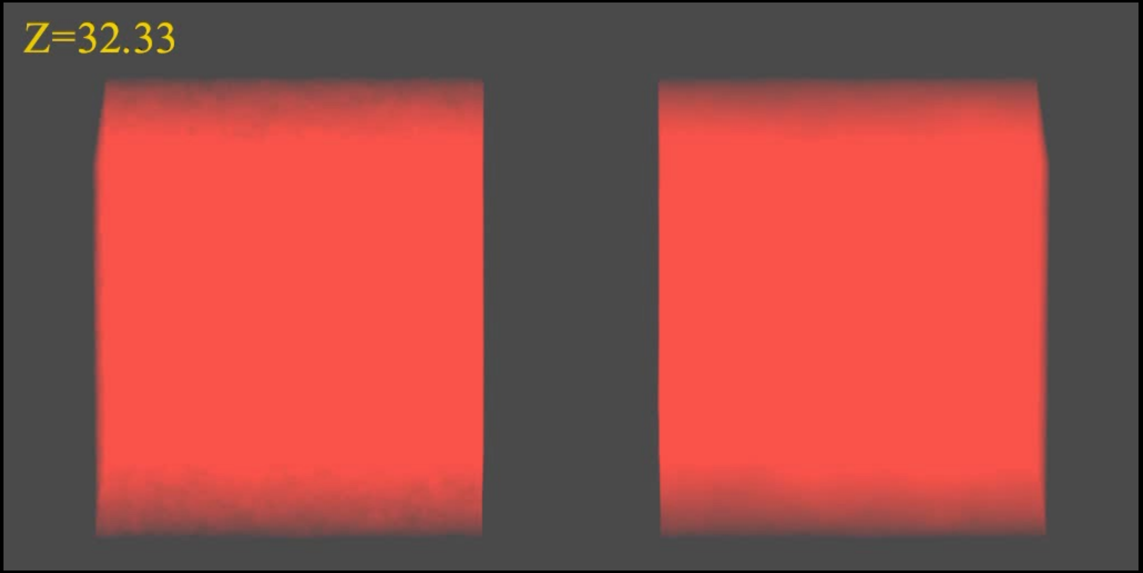
$\Omega_{\mathrm{CDM}} \approx 25\%$

Cold dark matter + neutrinos ($\sum m_\nu = 6.9\ \mathrm{eV}$)

$\Omega_{\mathrm{CDM}} \approx 10\%$

$\Omega_\nu = \dfrac{\sum m_\nu}{93\ h^2} \approx 15\%$

$256\ h^{-1}\mathrm{Mpc}$



Simulations by Troels Haugbølle

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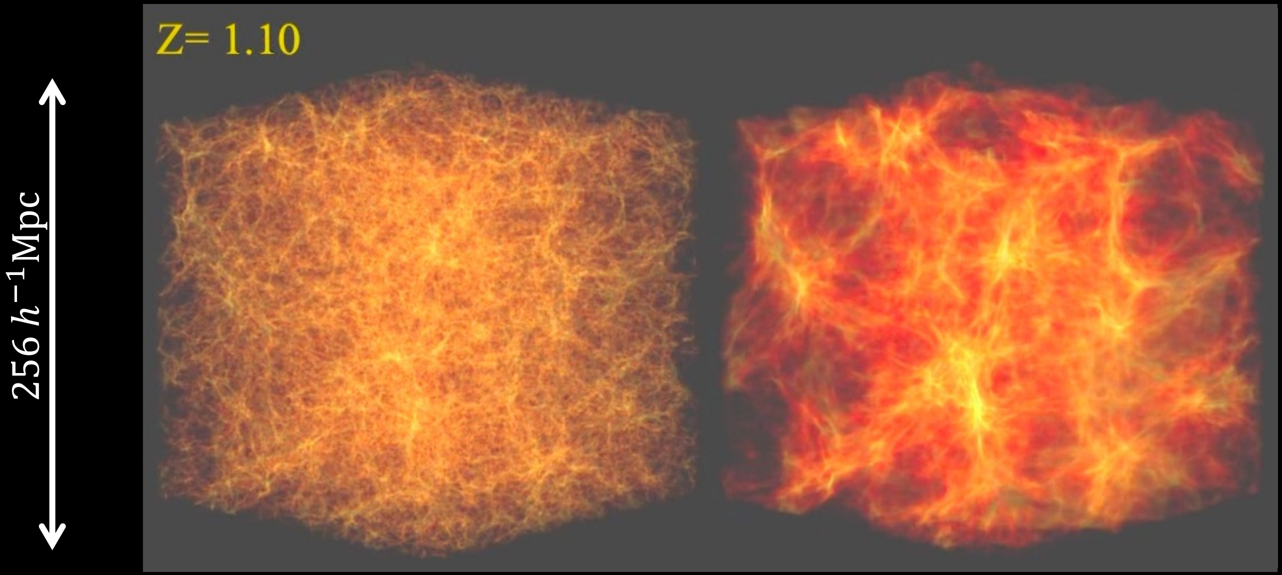
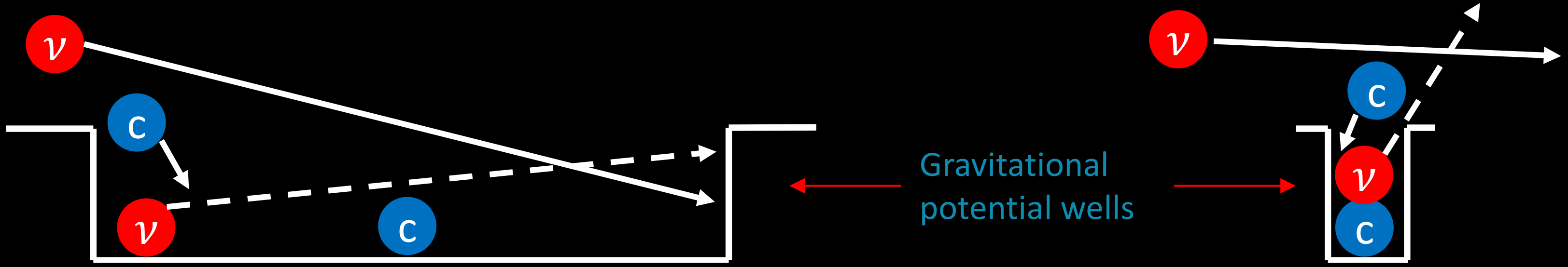


Simulations by Troels Haugbølle

Why? Free-streaming suppression…

Neutrino thermal motion prevents efficient clustering on small length scales.

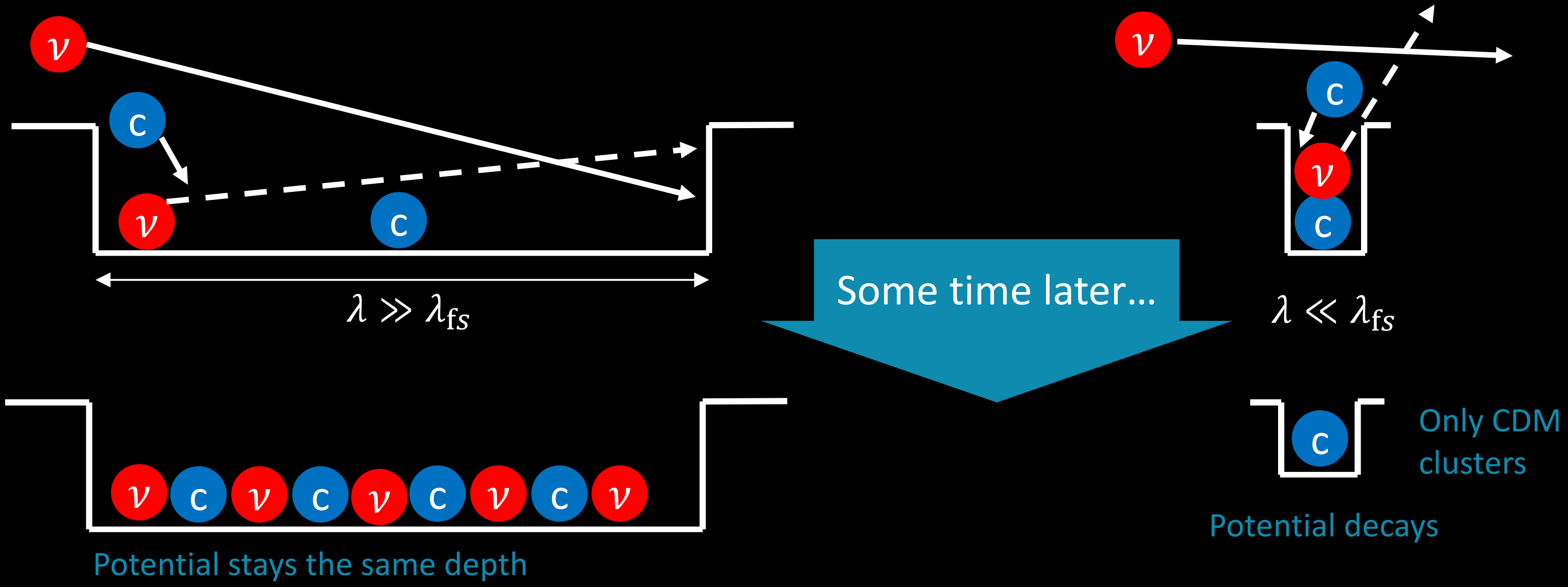
$$v_{\text{themal}} = \frac{T_{\mathrm{C\nu B}}}{m_\nu} \approx 50\,(1+z)\left(\frac{\mathrm{eV}}{m_\nu}\right)\mathrm{km\ s^{-1}}$$



Gravitational potential wells

Free-streaming scale: $$\lambda_{\mathrm{fs}} \equiv \sqrt{\frac{8\pi^2 v_{\text{thermal}}^2}{3\Omega_m H^2}} \approx 4.2\sqrt{\frac{1+z}{\Omega_{m,0}}\left(\frac{\mathrm{eV}}{m_\nu}\right)}\;h^{-1}\,\mathrm{Mpc}$$

A neutrino and a cold DM particle encounter 2 gravitational potential wells of different physical sizes in an expanding universe:



$\lambda \gg \lambda_{\mathrm{fs}}$

$\lambda \ll \lambda_{\mathrm{fs}}$

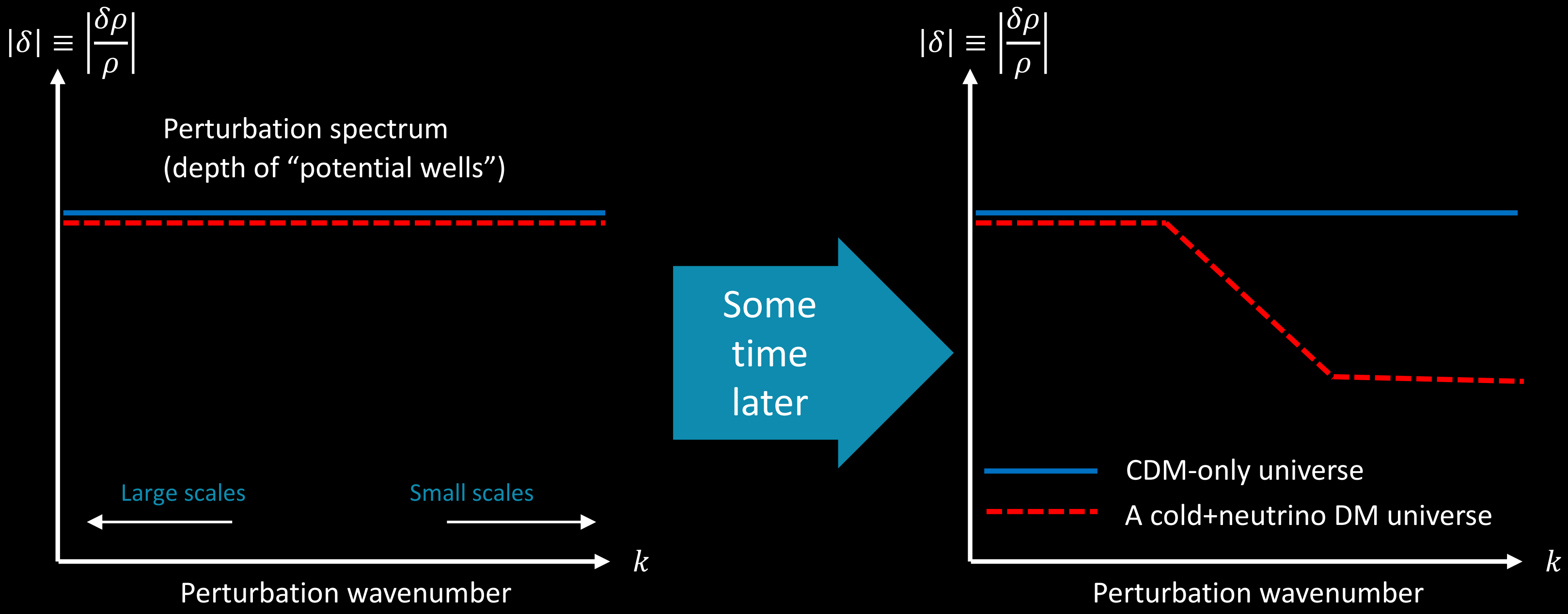
Some time later…

Potential stays the same depth

Only CDM clusters

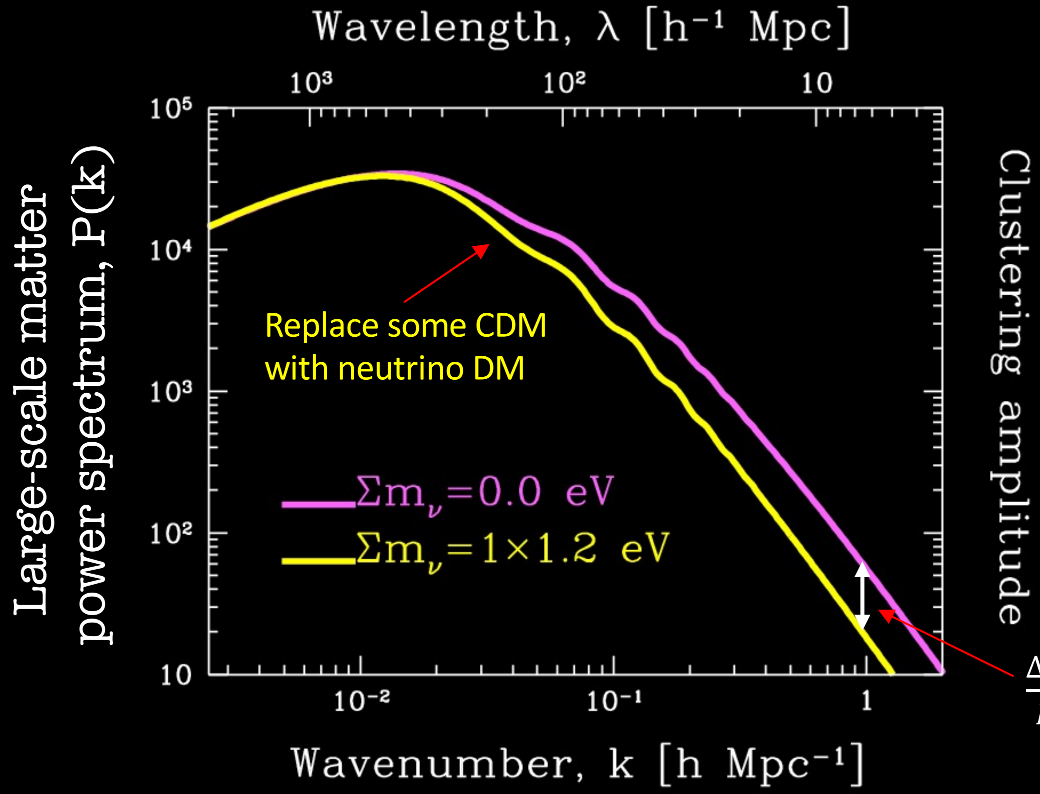
Potential decays

Free-streaming induces gravitational potential decay on length scales $\lambda \ll \lambda_{\mathrm{FS}}$.



The presence of neutrino dark matter induces a step-like feature in the spectrum of gravitational potential wells.

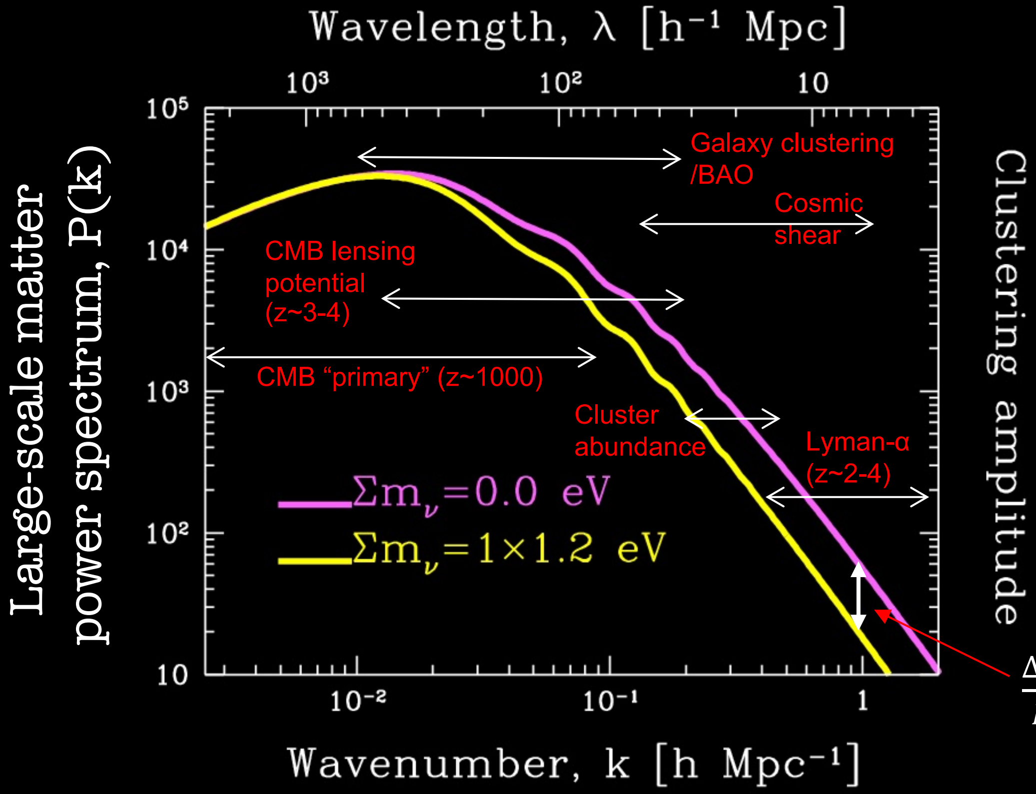
A real matter power spectrum calculated from linear perturbation theory…



Replace some CDM with neutrino DM

$$\frac{\Delta P}{P} \propto \frac{\Omega_\nu}{\Omega_m} \propto \sum m_\nu$$

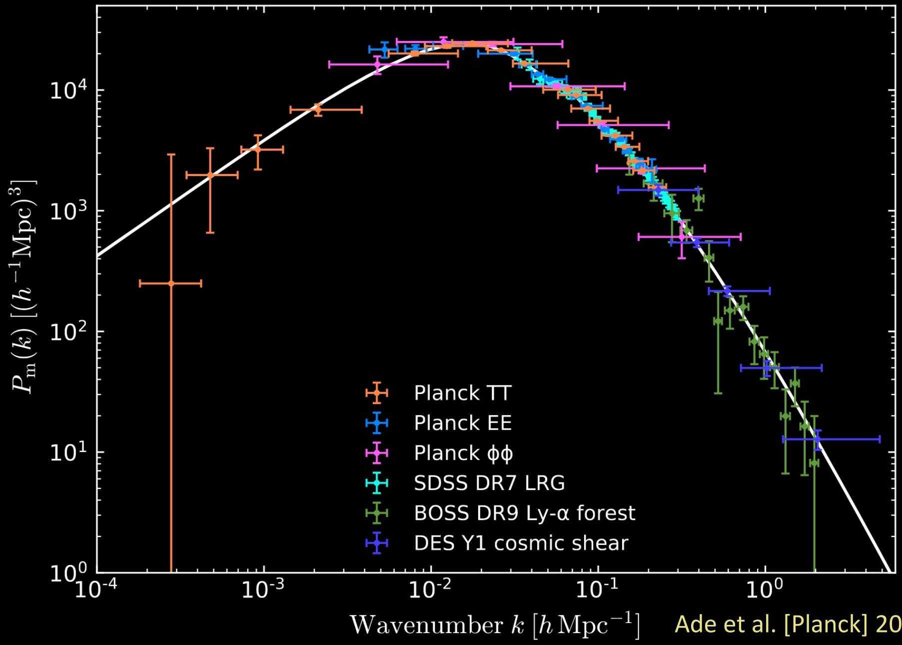
A real matter power spectrum calculated from linear perturbation theory…



$$\frac{\Delta P}{P} \propto \frac{\Omega_\nu}{\Omega_m} \propto \sum m_\nu$$

Neutrino mass from cosmology…

Large-scale matter power spectrum measurement ca. 2018



Ade et al. [Planck] 2018

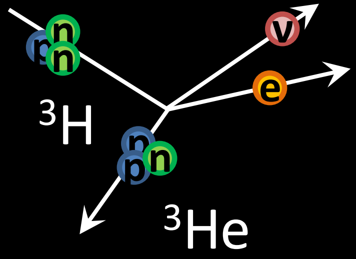
Planck TTTEEE+lowE+lensing+BAO;
7-parameters

$$\boxed{\sum m_\nu < 0.12 \text{ eV } (95\% \text{ CL})}$$

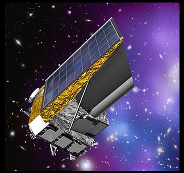
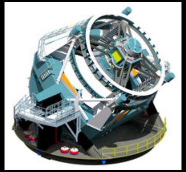
Aghanim et al. [Planck] 2021

At face value a factor of 30 tighter than current lab bound from KATRIN, $\sum m_\nu < 3$ eV.

Aker et al. [KATRIN] 2019



Future cosmological probes…

			1σ sensitivity to $\sum m_\nu$	1σ sensitivity to $N_{\rm eff}$
	**ESA Euclid**	2024	$0.011 - 0.02$ eV	0.05
	**LSST**	2024	0.015 eV	0.05
	**CMB-S4**	2027	0.015 eV	$0.02 - 0.04$

Minimum $\sum m_\nu = 0.06$ eV

From neutrino oscillations
(assuming normal mass ordering)

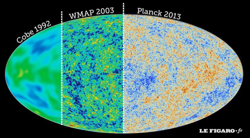
→

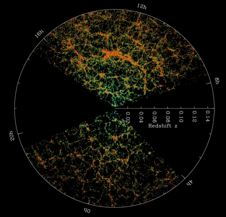
Detection of the absolute
neutrino mass may be possible!

What do these probes really probe?

They may look different, but ultimately the information contained is

- Growth of fluctuations under gravity
  - Kinematic properties and interactions of the various types of stuff in the universe; good for neutrino physics





Neutrino masses, $\sum m_\nu$ (large-scale structure)

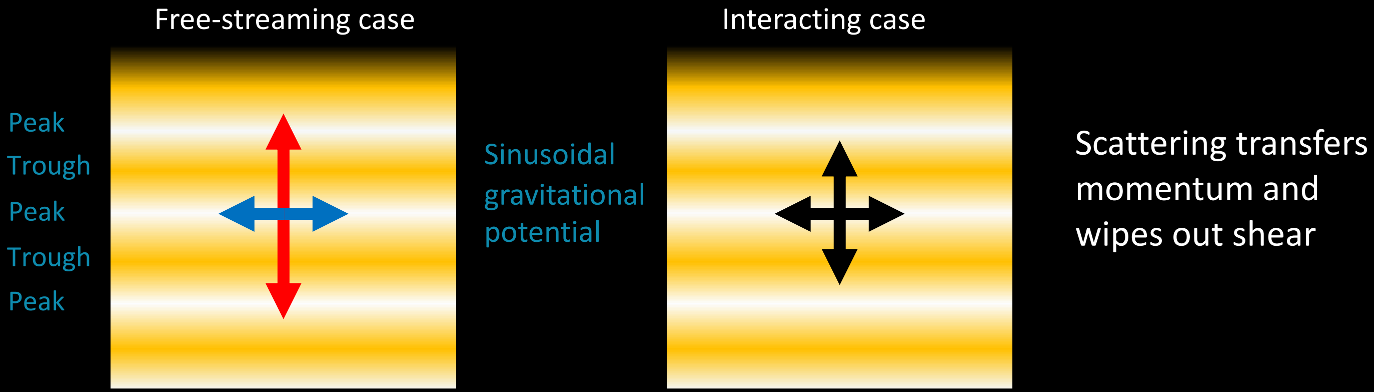
Neutrino decay/lifetime, τ_0 (CMB)

Non-standard neutrino interactions (CMB)

Neutrino free-streaming & the CMB…

Standard neutrinos free-stream.

- Free-streaming in a spatially inhomogeneous background induces shear stress
- Conversely, interactions transfer momentum and wipe to out shear.

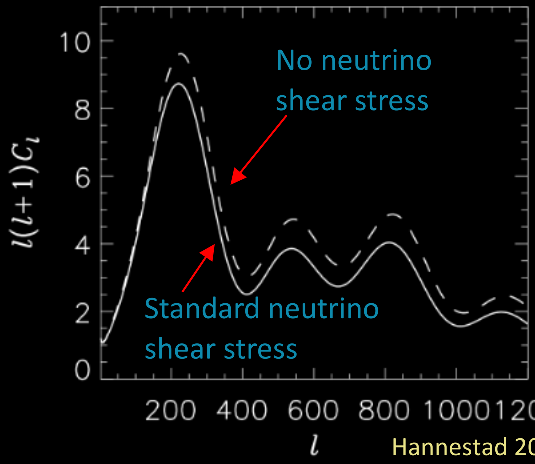


Scattering transfers momentum and wipes out shear

- Neutrino shear stress (or lack thereof) leave distinct imprints on the spacetime metric.
  - Affects the evolution of CMB perturbations; observable in the TT spectrum.

Neutrino free-streaming & the CMB…

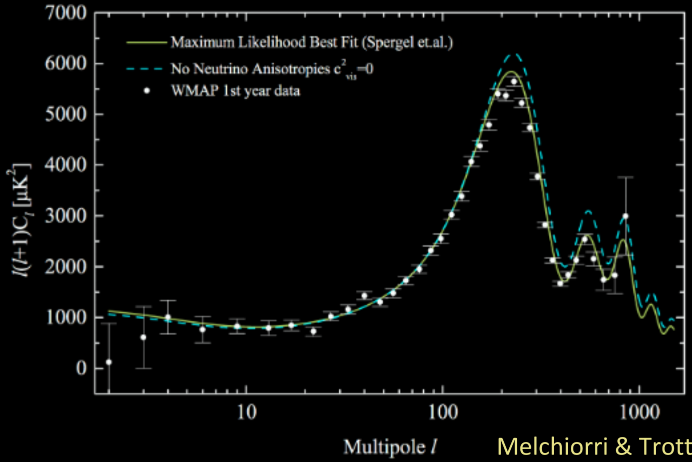
That CMB prefers neutrino shear stress to no shear stress is well known.



No neutrino shear stress

Standard neutrino shear stress

Hannestad 2005



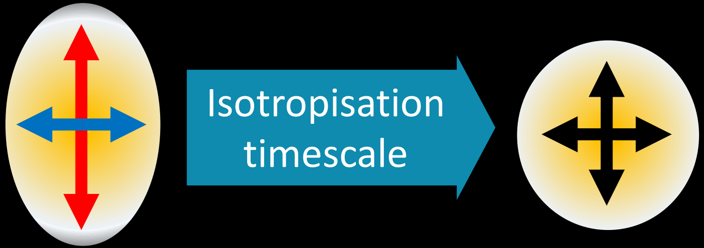
Melchiorri & Trotta 2005

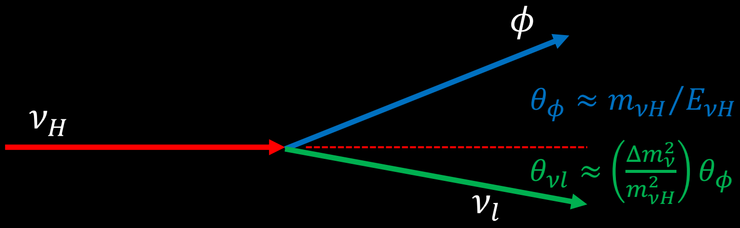
- The trick is in translating this preference to constraints on the fundamental parameters of a non-standard neutrino interaction → What is the isotropisation timescale?
  - Isotropisation timescale should not be longer than the CMB timescale (400k years).

Isotropisation from relativistic (inverse) decay…

Consider $\nu_H \rightarrow \nu_l + \phi$ and its inverse process.

- Isotropisation timescale = How long it takes for decay and inverse decay to wipe out the momentum anisotropy in a fluid element.





In relativistic decay, the decay products are beamed. Inverse decay can also only happen when the daughter particles satisfy strict momentum/angular requirements.

→Isotropisation is a looooong process:

$$T_{\text{isotropise}} \sim \left(\theta_\phi \theta_{\nu l}\right)^{-2} \gamma_{\nu H}\, \tau_{\text{rest}}$$

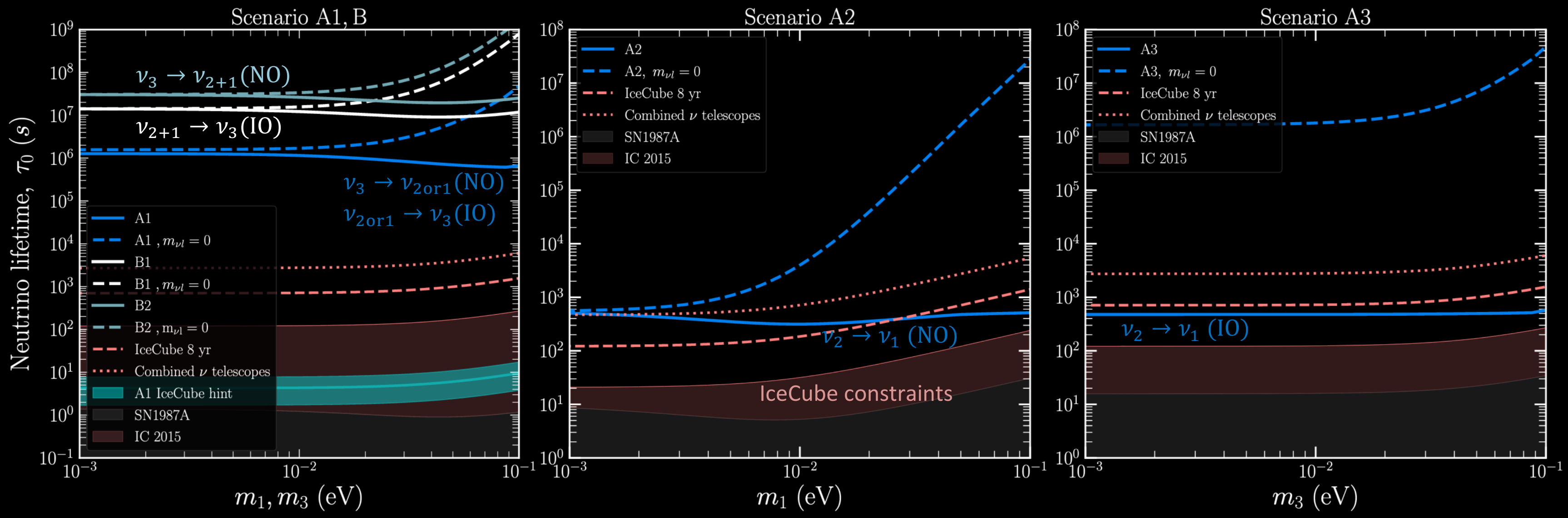
Rest-frame lifetime

Boost

Chen, Oldengott, Pierobon & Y^{3}W 2022

CMB lower bounds on the neutrino lifetime…

Mass-spectrum consistent constraints on invisible neutrino decay $\nu_H \to \nu_l + \phi$.



Chen, Oldengott, Pierobon & Y^{3}W 2022

- In some scenarios, neutrino telescopes and CMB probe the same parameter space.

2. What can neutrino physics do for cosmology?

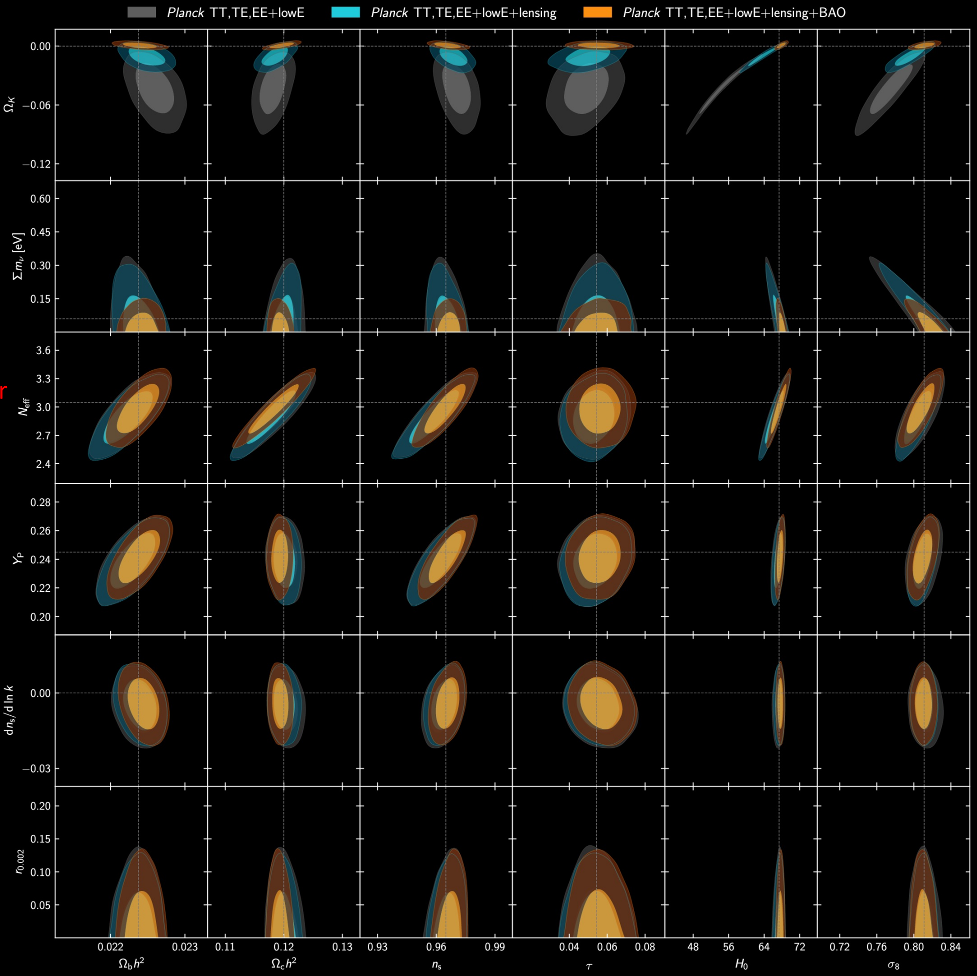
What can neutrino physics do for cosmology?

Parameter estimation from cosmological observations is based on statistical inference.

- Observations don't actually measure the dark matter density or the dark energy equation of state, and much less anything about inflation.

- Inference always assumes a model:
  - The less the model uncertainty, the more precise and accurate the parameter estimates.

- Neutrinos are unique in that they are the only cosmologically significant component that has a precise prediction within the Standard Model and whose properties can be independently measured in a laboratory.
  - Eliminating uncertainty in the neutrino sector will help us pin down other cosmological parameter inaccessible in the laboratory.



Neutrino mass

Effective number of neutrinos

A direct neutrino mass measurement or even a confirmation of the inverted mass ordering (minimum $\sum m_\nu = 0.11\ \mathrm{eV}$) by oscillation experiments would help to shrink these ellipses.

Establishing the existence (or not) of light sterile neutrino states through oscillation experiments would shrink the uncertainty in N_{eff} from the neutrino sector.

More accurate estimates of parameters inaccessible in the lab.

Aghanim et al. [Planck] 2021

Dark matter density

Spectral index

Hubble parameter

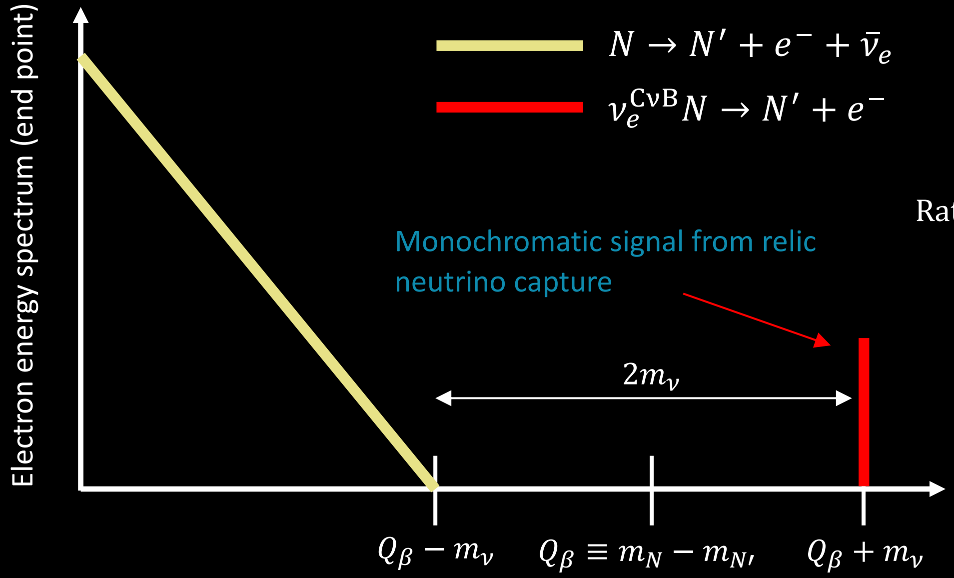
Fluctuation amplitude

What can neutrino physics do for cosmology?

Ultimate prize = Direct detection of the CνB itself

- Best idea uses the β-decay end-point spectrum → Goes hand-in-hand with direct neutrino mass detection.

Weinberg 1962
Cocco, Mangano & Messina 2007



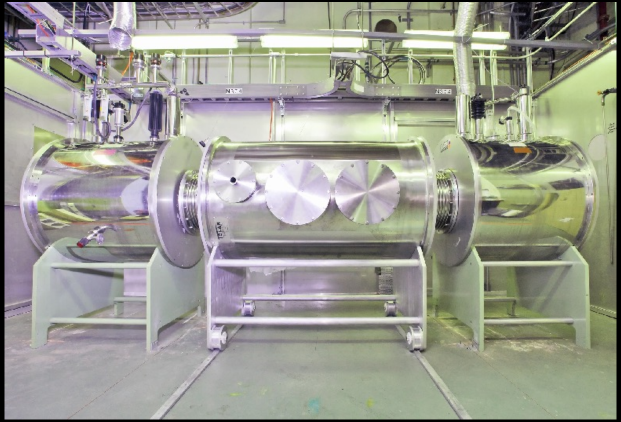
$\mathrm{Rate} \sim 7.5/\mathrm{year}\ /(100\ \mathrm{tritium})$

KATRIN source:
~ 0.1 mg tritium

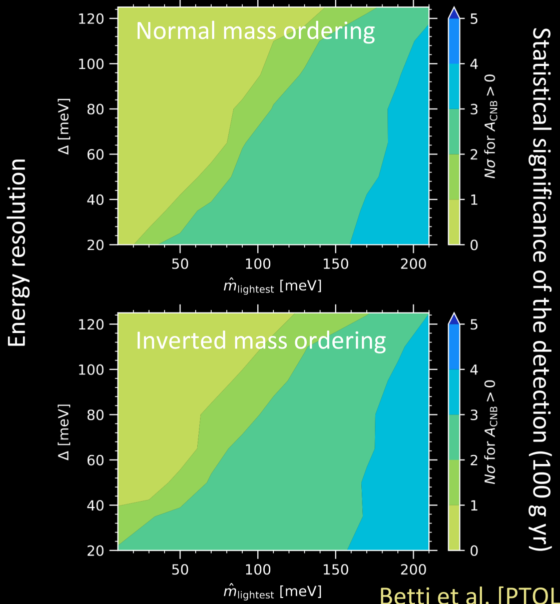
What can neutrino physics do for cosmology?

Ultimate prize = Direct detection of the CνB itself

- Best idea uses the β-decay end-point spectrum → Goes hand-in-hand with direct neutrino mass detection.
- Ptolemy Experiment



The PTOLEMY prototype at the Princeton Plasma Physics Laboratory



Betti et al. [PTOLEMY] 2019

Summary…

- The existence of a cosmic neutrino background is a fundamental prediction of SM+FLRW cosmology.
  - Precision cosmological observations have allowed us to infer the properties of this background, from which to determine neutrino properties.
  - e.g., masses, effective number of neutrinos, non-standard interactions, lifetime.

- Conversely, better determination of neutrino properties in laboratory experiments will allow us to eliminate some model uncertainty in the cosmological parameter inference exercise.
  - More precise and accurate constraints on the dark matter density, dark energy properties, inflationary physics, and other cosmological physics inaccessible in the laboratory.