Neutrinos in cosmology:

A match made in the Heavens

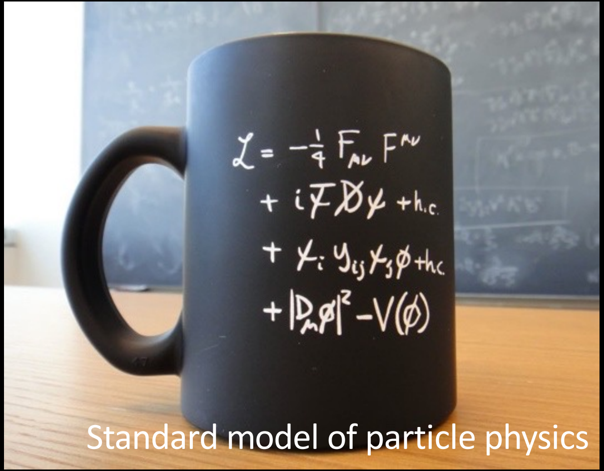
Yvonne Y. Y. Wong, UNSW Sydney

Colloquium, CP3 Louvain, October 12, 2022

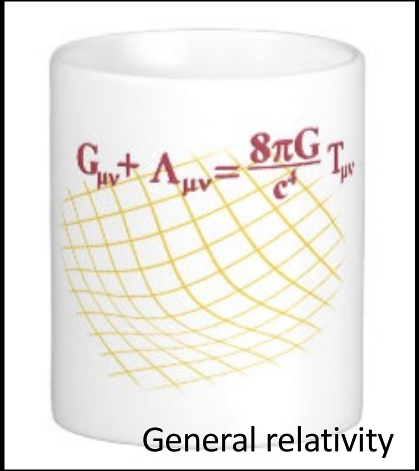
An unlikely partnership?

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

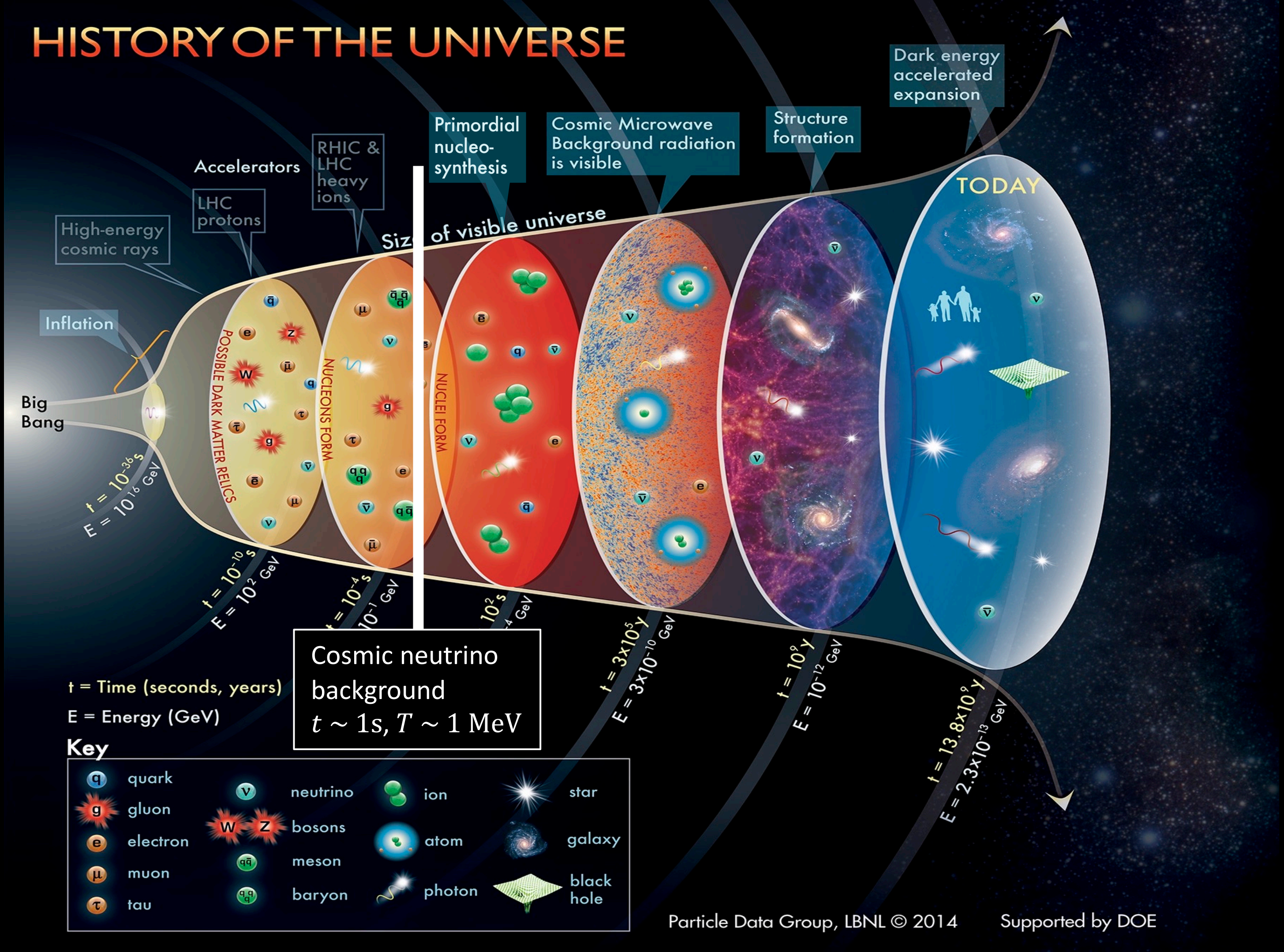
Cosmology = gravitation on the largest observable scales



Standard model of particle physics



General relativity



Particle Data Group, LBNL © 2014 Supported by DOE

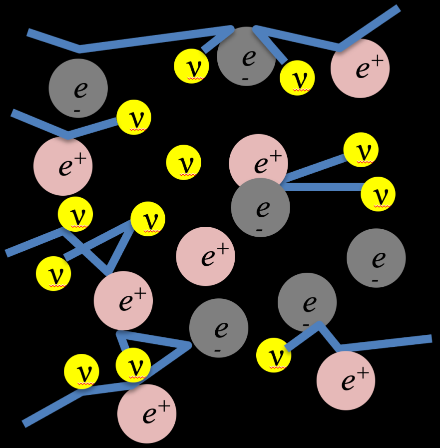
Cosmic neutrino background
$t \sim 1\text{s}, T \sim 1\ \text{MeV}$

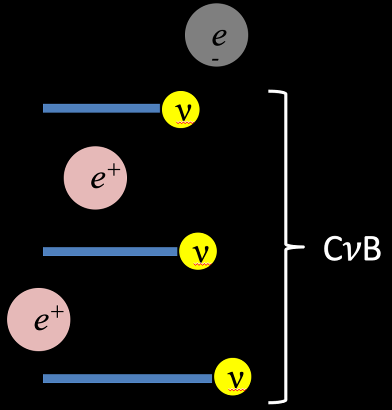
Formation of the CνB…

Interaction rate: $\Gamma_{\text{weak}} \sim G_F^2 T^5$

Expansion rate: $H \sim M_{\text{pl}}^{-2} T^2$

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





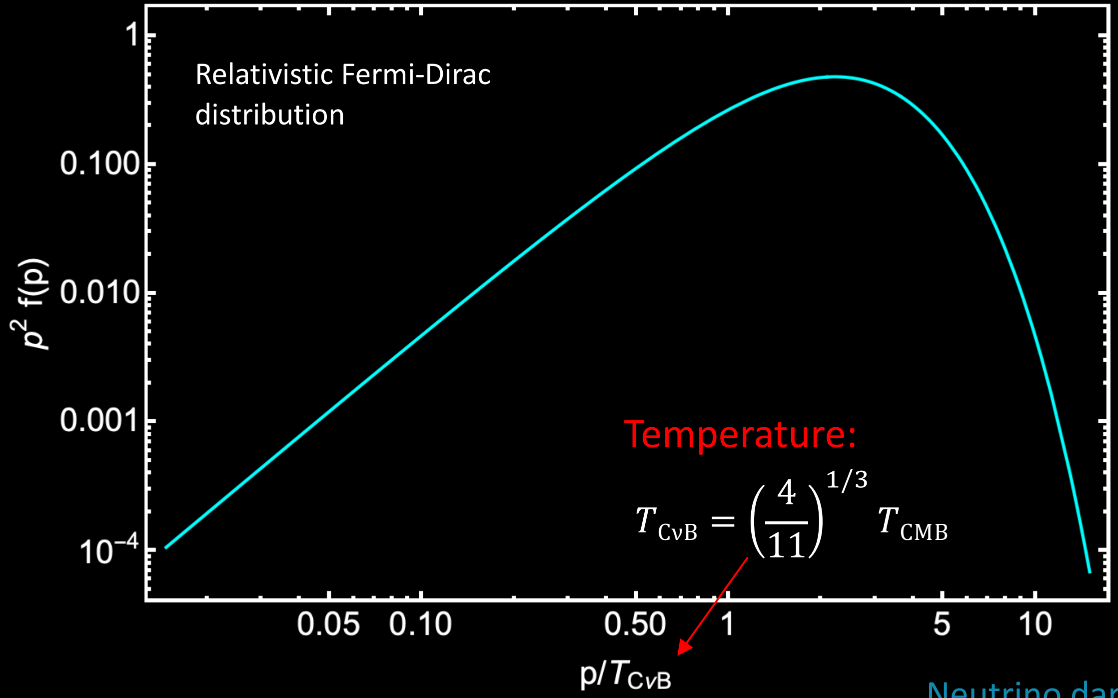
Neutrinos "free-stream" to infinity.

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

Below $T \sim 1$ 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:

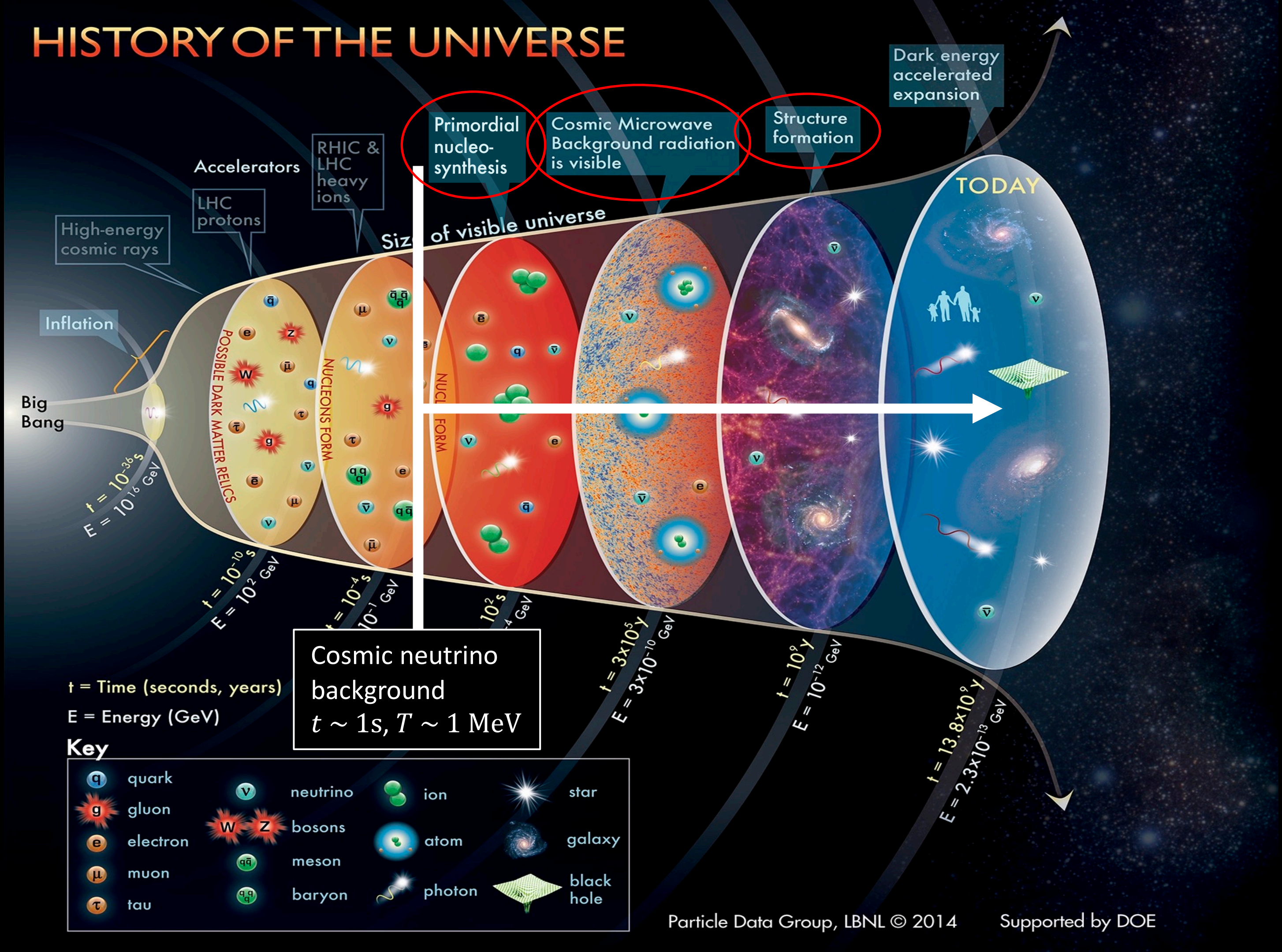
- Relativistic (if $T_{\mathrm{C\nu B}} \gg m_\nu$):

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

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

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,** $N_{\rm eff}$
  - Deviations from SM prediction of $N_{\rm eff} \approx 3$
  - e.g., test for the existence of light sterile states

"Standard" tests

- **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.

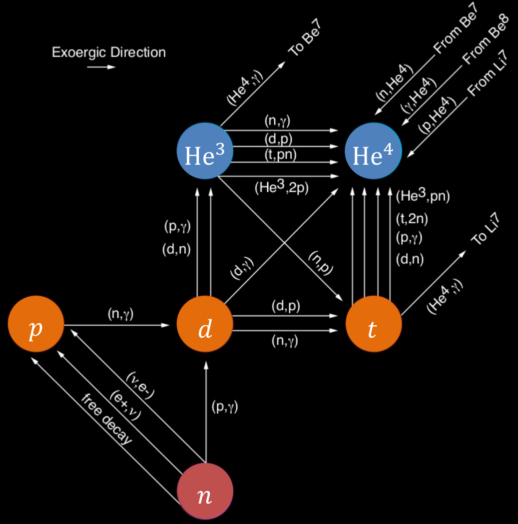
- Allow us to gain more precise and accurate information about the other stuff in the universe.

1. What can cosmology do for neutrino physics?

Cosmological observables...

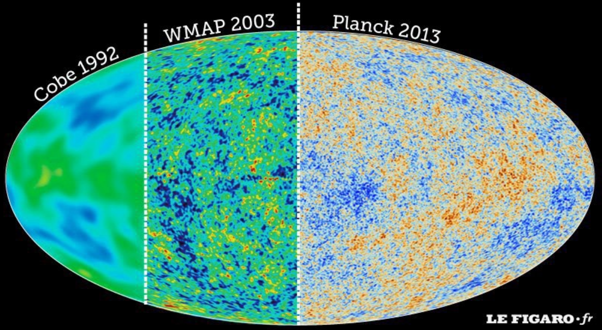
+ Supernova Ia, local H_0, etc.
(No direct neutrino effects)

Light element abundances from primordial nucleosynthesis



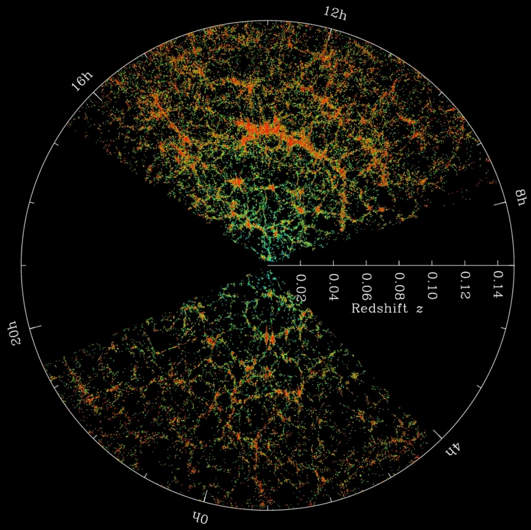
$N_{\rm eff}$ (expansion rate)

Cosmic microwave background anisotropies



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

Large-scale matter distribution

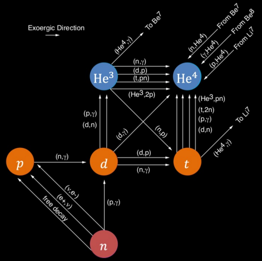


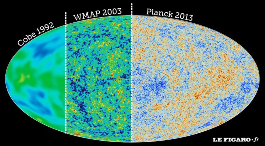
$\sum m_\nu$ (perturbation growth)

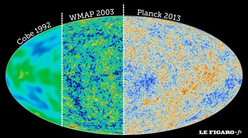
What do these probes really probe?

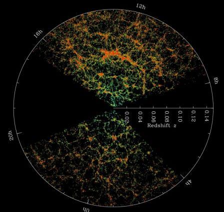
They may look different, but ultimately the information contained is

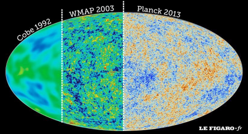
- Universal expansion rate at different times
  - How much matter, radiation, “in-between” (e.g., neutrinos), vacuum energy, etc.
- Growth of fluctuations under gravity
  - Kinematic properties and interactions of the various types of stuff in the universe; good for neutrino physics
- Distance measurements
  - Spatial geometry, dark energy; not directly relevant for neutrino physics but has indirect effects on inference

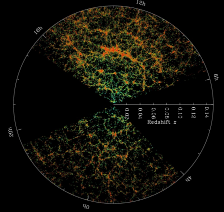












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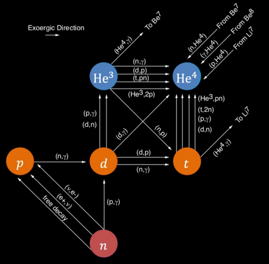
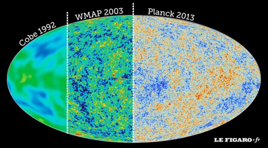




Neutrinos & the expansion rate…

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…

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

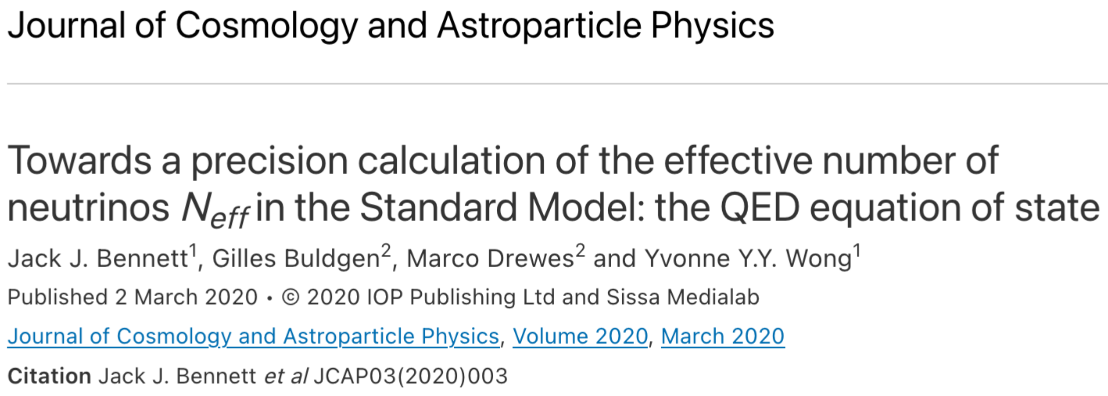
Standard cosmology

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

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

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.



Journal of Cosmology and Astroparticle Physics

Towards a precision calculation of the effective number of neutrinos N_{eff} in the Standard Model: the QED equation of state

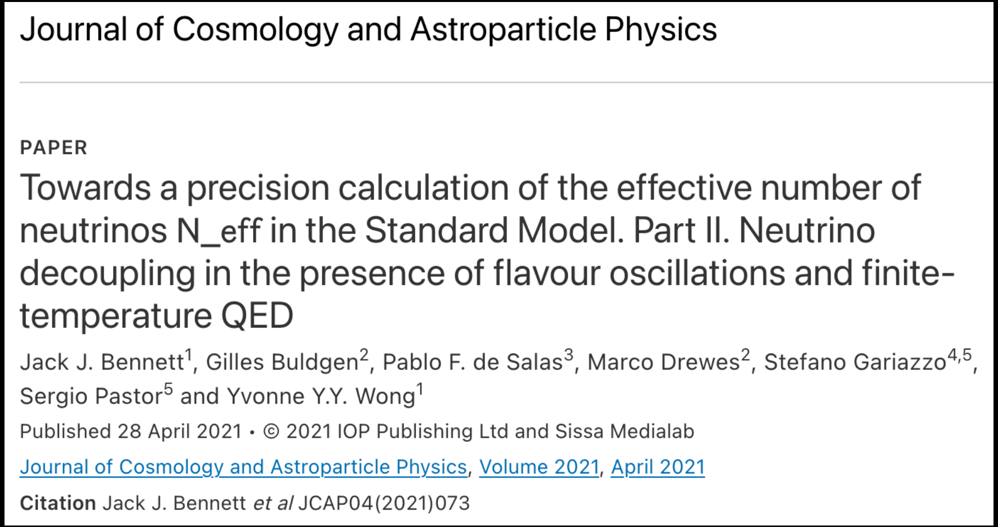
Jack J. Bennett[1], Gilles Buldgen[2], Marco Drewes[2] and Yvonne Y.Y. Wong[1]

Published 2 March 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab

Journal of Cosmology and Astroparticle Physics, Volume 2020, March 2020

Citation Jack J. Bennett *et al* JCAP03(2020)003

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



Journal of Cosmology and Astroparticle Physics

PAPER

Towards a precision calculation of the effective number of neutrinos N_eff in the Standard Model. Part II. Neutrino decoupling in the presence of flavour oscillations and finite-temperature QED

Jack J. Bennett[1], Gilles Buldgen[2], Pablo F. de Salas[3], Marco Drewes[2], Stefano Gariazzo[4,5], Sergio Pastor[5] and Yvonne Y.Y. Wong[1]

Published 28 April 2021 • © 2021 IOP Publishing Ltd and Sissa Medialab

Journal of Cosmology and Astroparticle Physics, Volume 2021, April 2021

Citation Jack J. Bennett *et al* JCAP04(2021)073

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

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

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

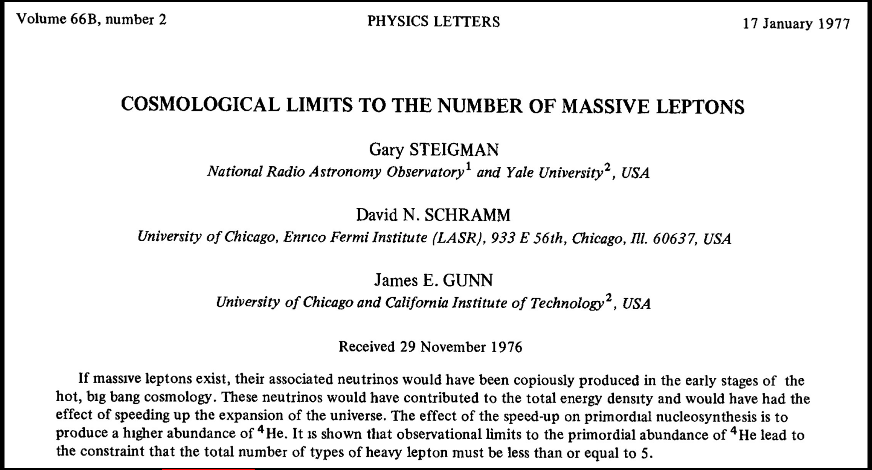
$N_{\mathrm{eff}}^{\mathrm{SM}} = 3.0440 \pm 0.0002$

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.

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

Gary STEIGMAN
National Radio Astronomy Observatory[1] *and Yale University*[2], *USA*

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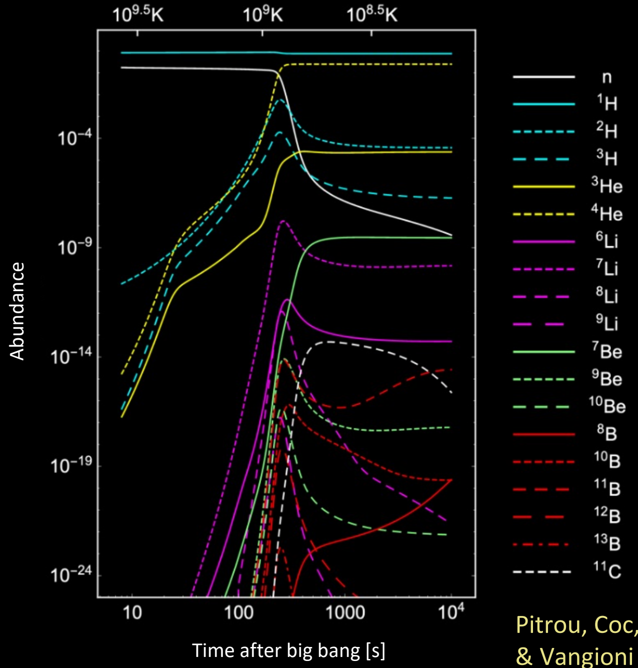
James E. GUNN
University of Chicago and California Institute of Technology[2], *USA*

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.

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

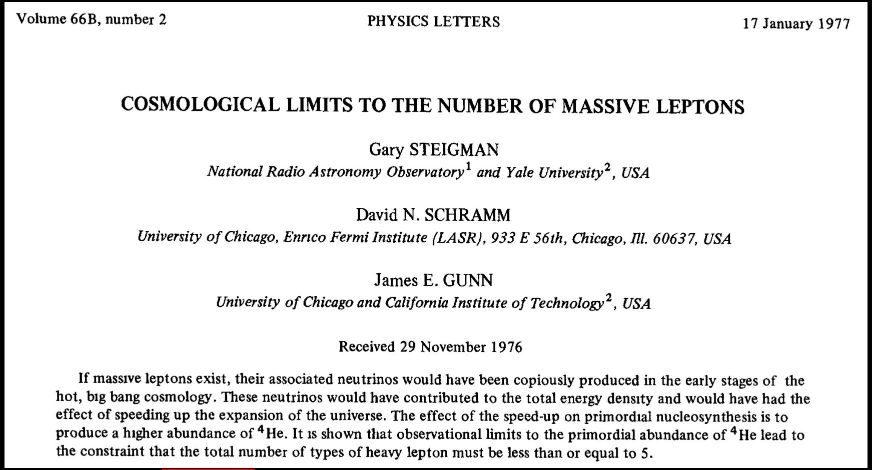


Pitrou, Coc, Uzan & Vangioni 2018

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

Nucleosynthesis & N_{eff}…

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



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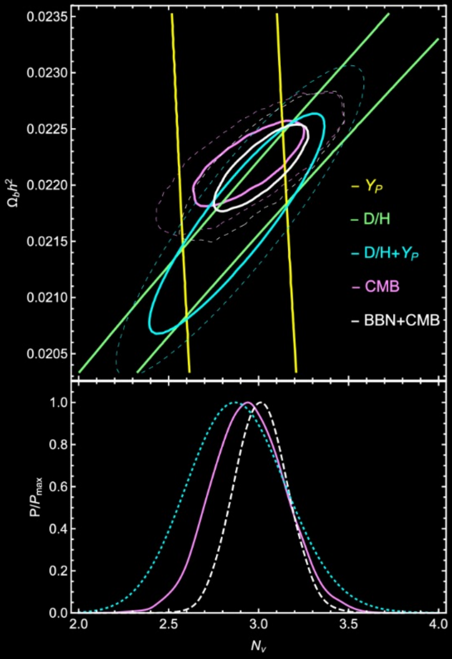
$$N_{\mathrm{eff}} < 5$$



D/H = Deuterium
Y_p = Helium-4

Pitrou, Coc, Uzan
& Vangioni 2018

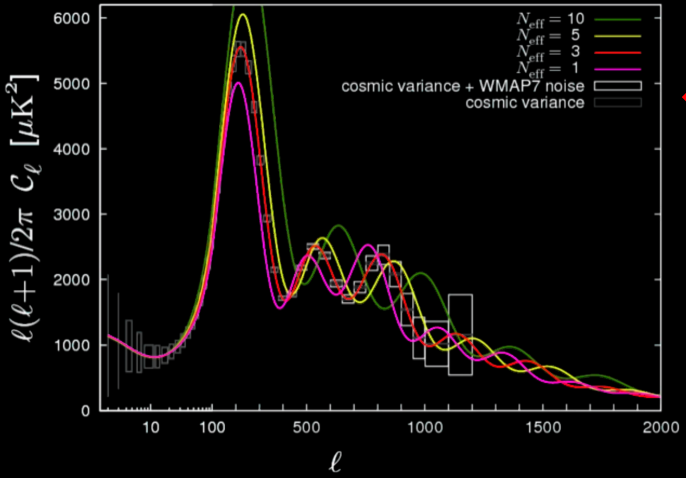
$$N_{\mathrm{eff}} = 2.88 \pm 0.27 \text{ (68\% CL)}$$

Consistent with Standard Model prediction $N_{\mathrm{eff}} \approx 3$

CMB anisotropies & N_{eff}…

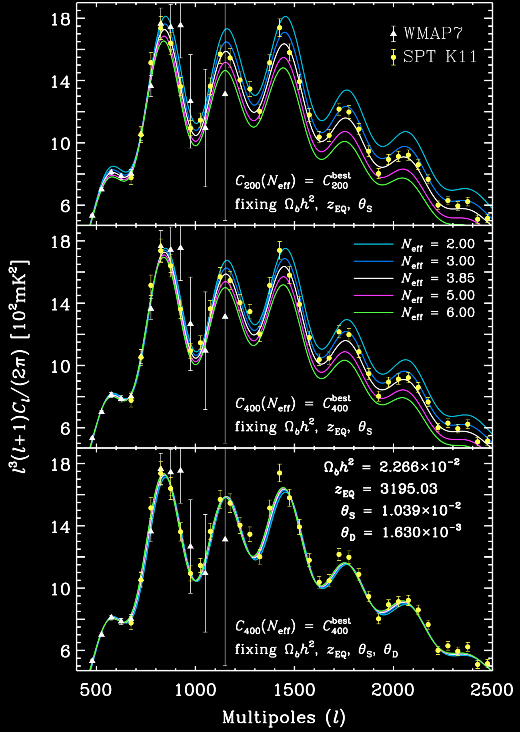
N_{eff} also affects the expansion rate at recombination.

- Observable in the CMB temperature power spectrum



"Naïve" signature

Hou, Keisler, Knox, Millea & Reichardt 2013



"Irreducible" signature is in the CMB damping tail

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

$$N_{\mathrm{eff}} = 2.99 \pm 0.34\ (95\%\ \mathrm{CL})$$

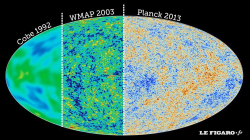
Aghanim et al. [Planck] 2021

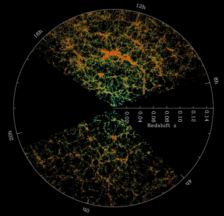
Remarkably consistent with Standard Model prediction $N_{\mathrm{eff}} \approx 3$

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

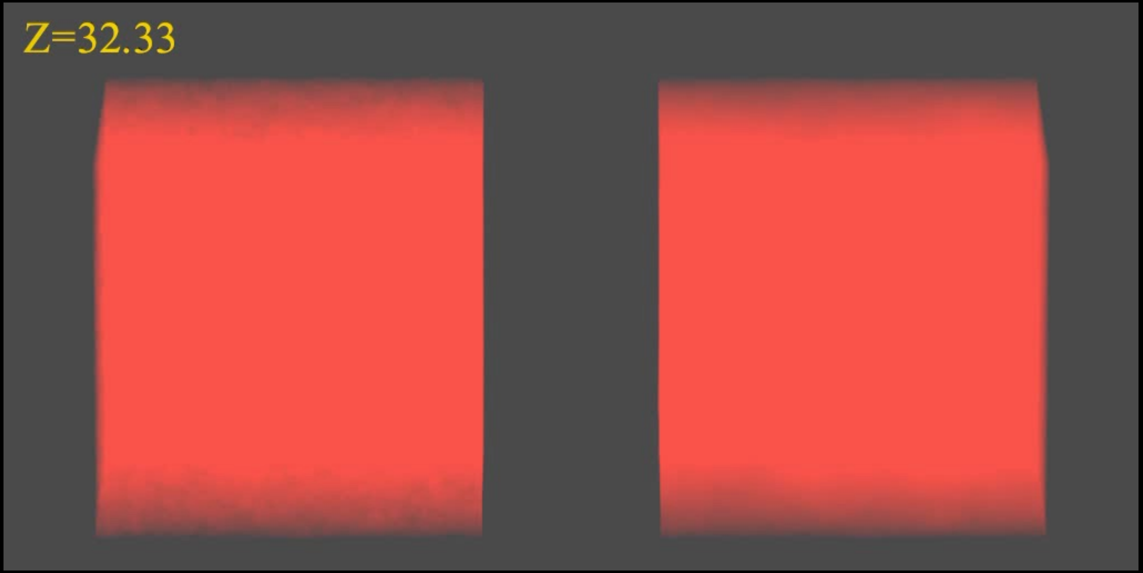
$\Omega_{\mathrm{CDM}} \approx 25\%$

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

Neutrino masses & large-scale structure...

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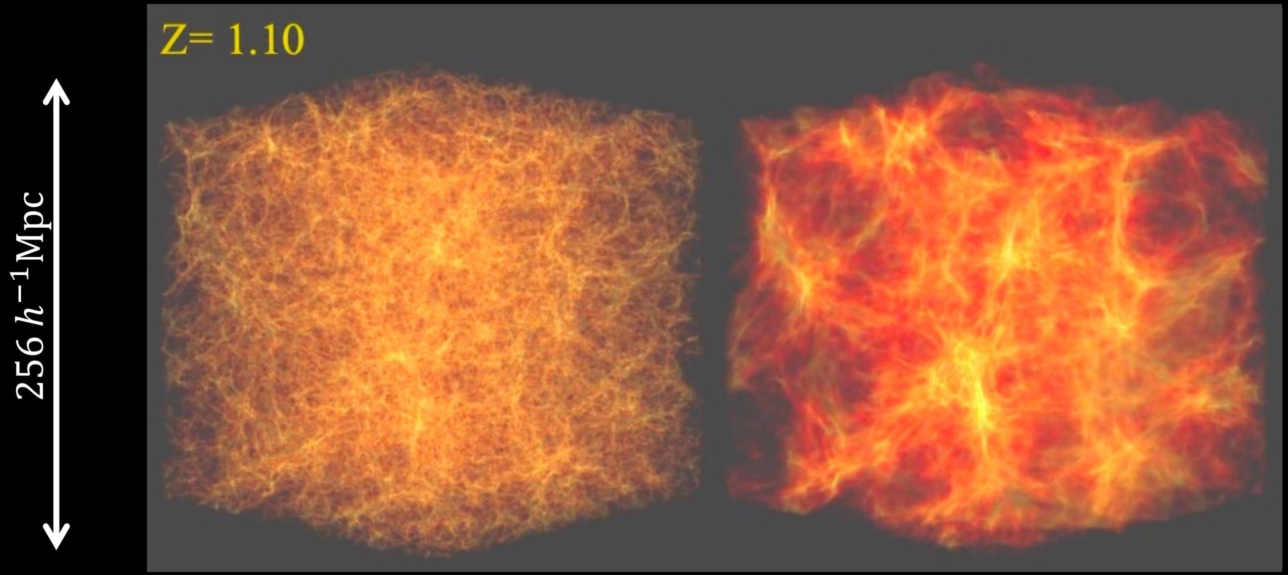
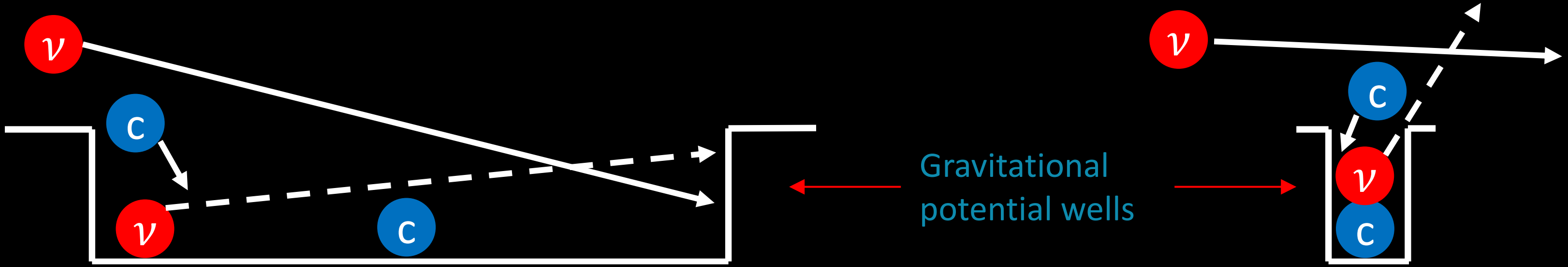


Simulations by Troels Haugbølle

Why? Free-streaming suppression…

Neutrino thermal motion prevents efficient clustering on small length scales.

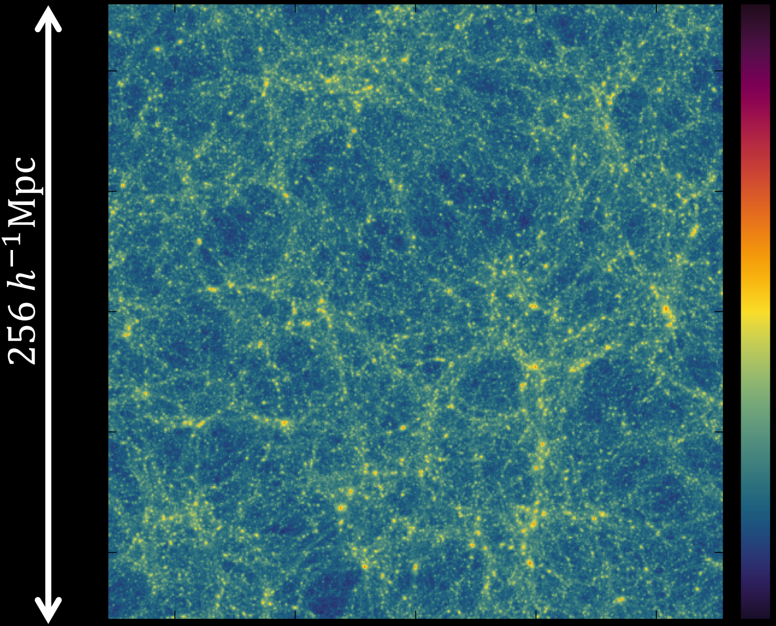
$$v_{\text{themal}} = \frac{T_{\text{C}\nu\text{B}}}{m_\nu} \approx 50\,(1+z)\left(\frac{\text{eV}}{m_\nu}\right)\text{km s}^{-1}$$



Gravitational potential wells

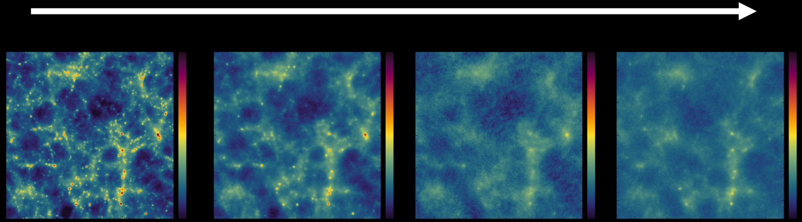
Free-streaming scale: $$\lambda_{\text{fs}} \equiv \sqrt{\frac{8\pi^2 v_{\text{thermal}}^2}{3\Omega_m H^2}} \approx 4.2\sqrt{\frac{1+z}{\Omega_{m,0}}\left(\frac{\text{eV}}{m_\nu}\right)}\;h^{-1}\,\text{Mpc}$$

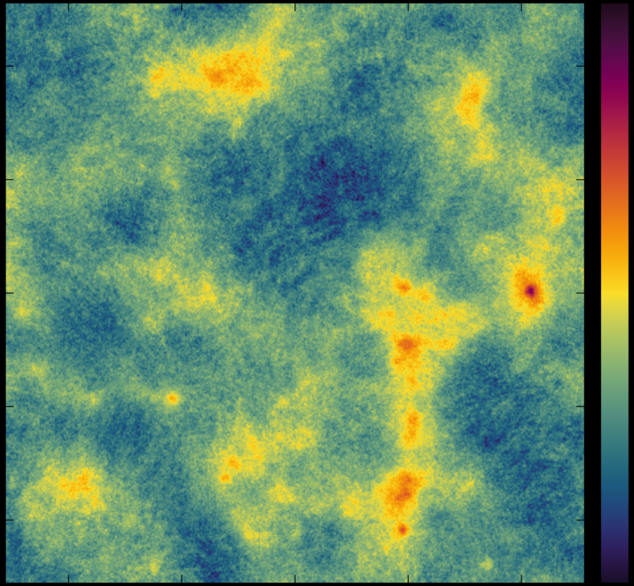
Cold dark matter component



N-body code: Gadget-Hybrid
Chen, Mosbech, Upadhye & Y^{3}W, in prep
Post-processing/graphics: Pierobon

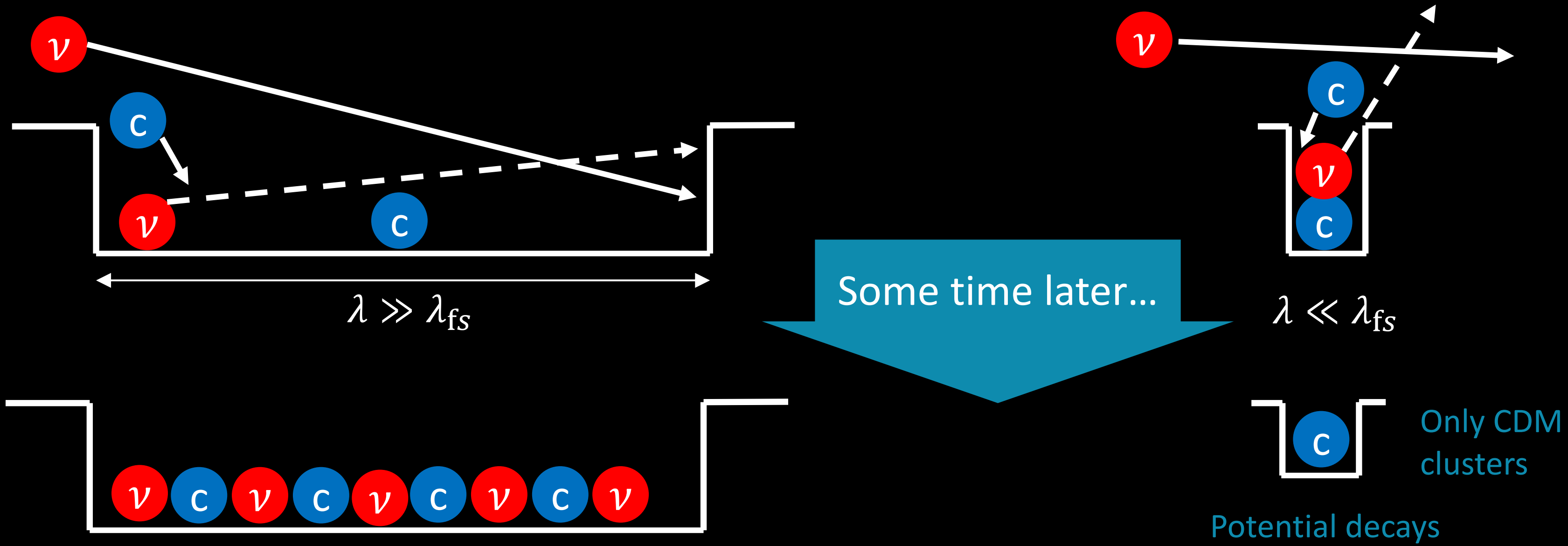
Increasing neutrino momentum





Neutrino component ($\sum m_\nu = 0.5\mathrm{eV}$)

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



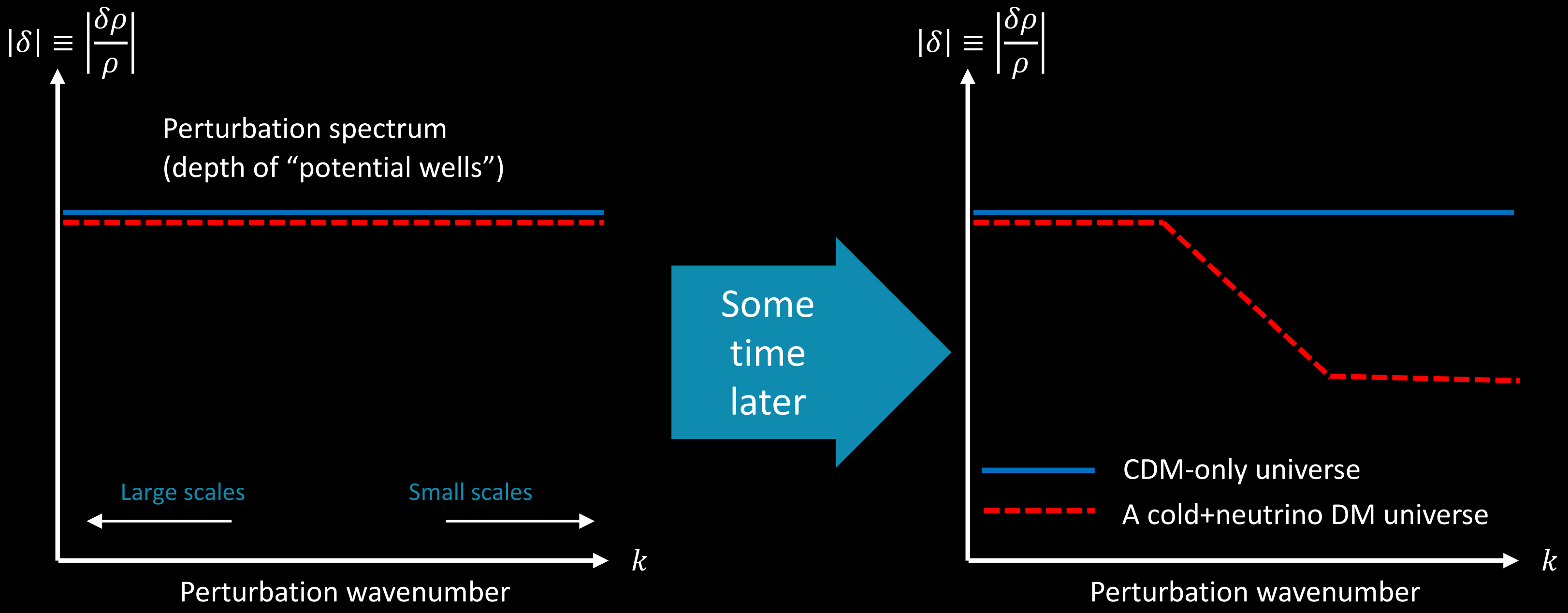
Some time later…

Only CDM clusters

Potential decays

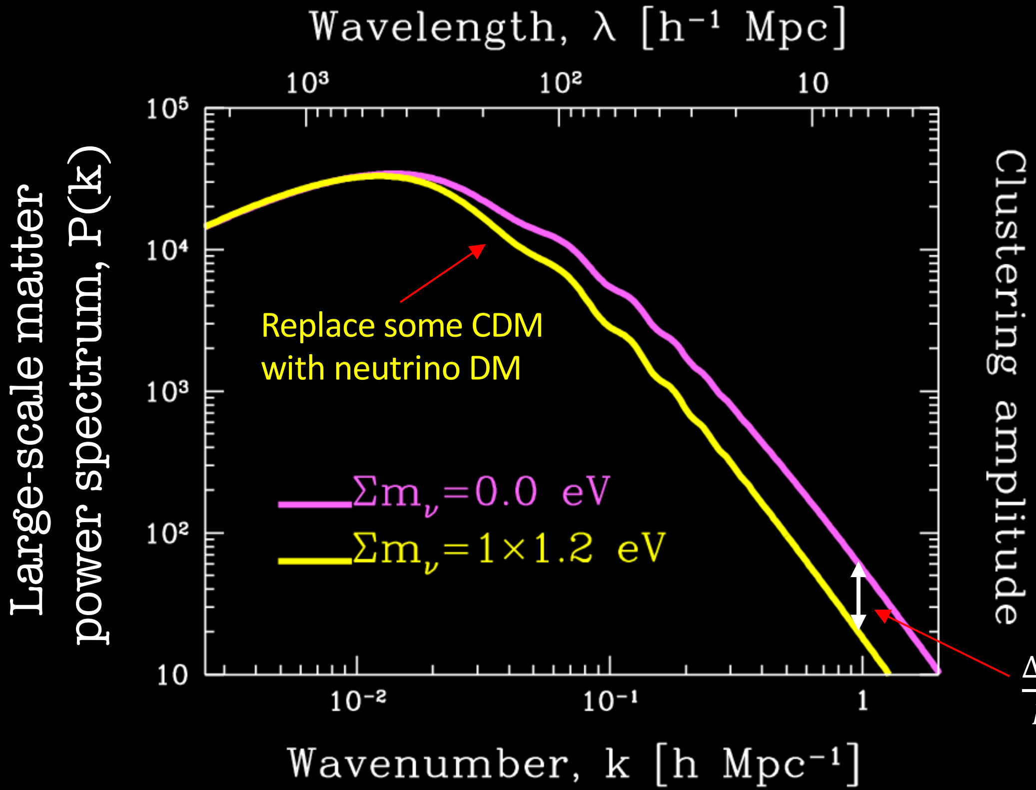
Potential stays the same depth

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



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

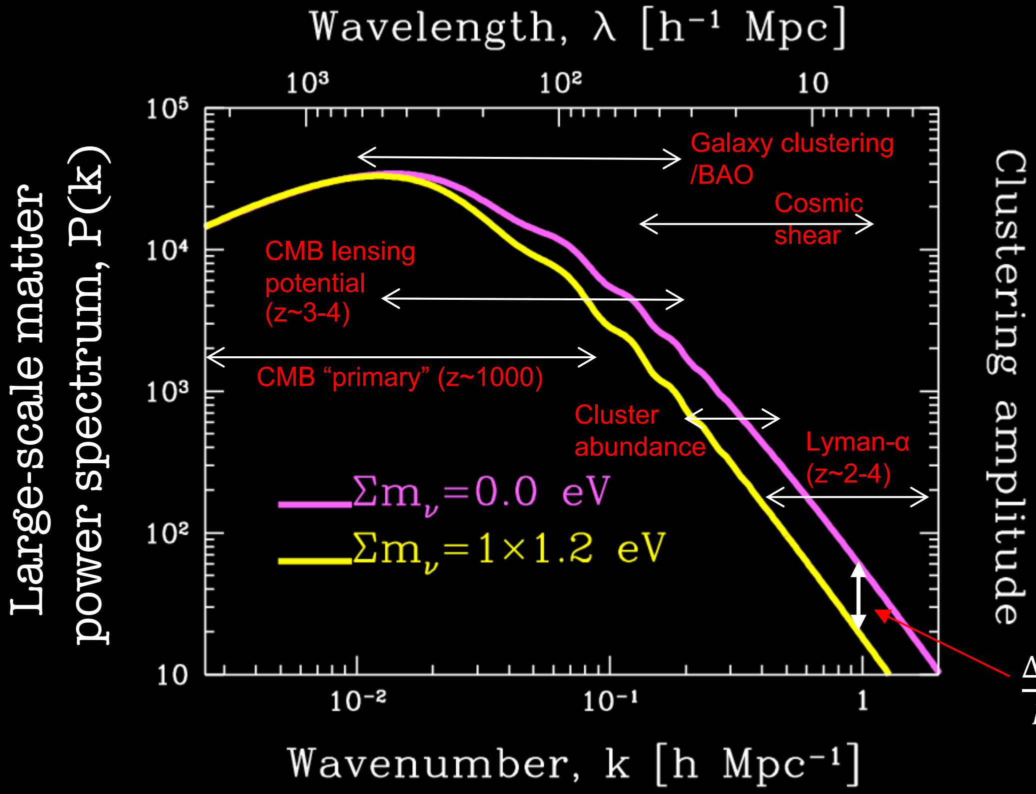
A real matter power spectrum calculated from linear perturbation theory…



Replace some CDM
with neutrino DM

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

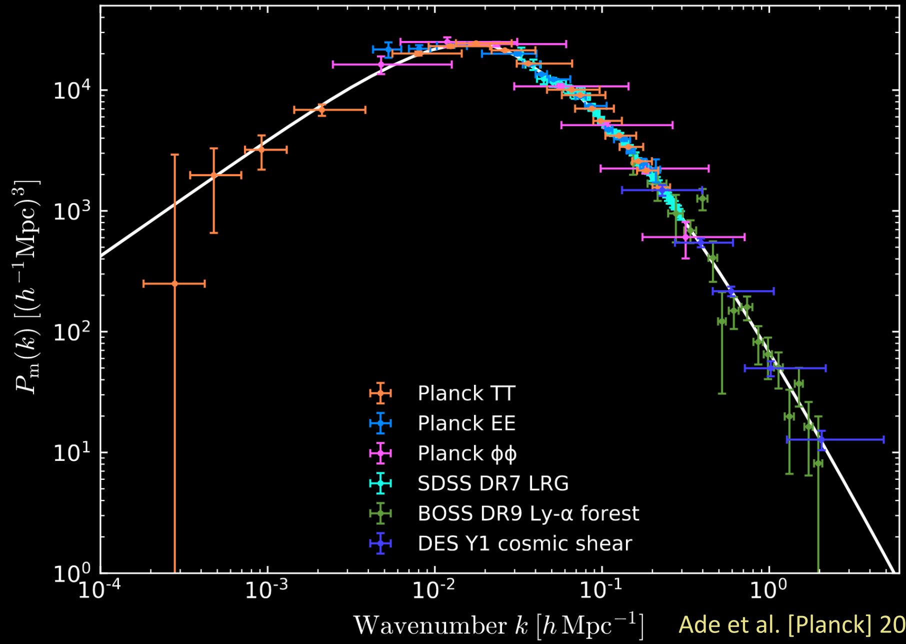
A real matter power spectrum calculated from linear perturbation theory…



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

Neutrino mass from cosmology…

Large-scale matter power spectrum measurement ca. 2018



Ade et al. [Planck] 2018

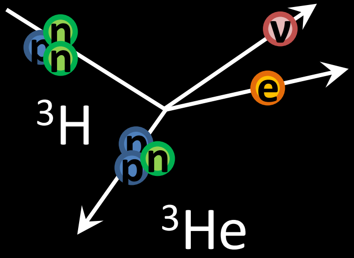
Current cosmological limits on the neutrino mass sum typically fall in the range:

$$\sum m_\nu < O(0.1\ - 0.5)\mathrm{eV}\ (95\%\ \mathrm{CL})$$

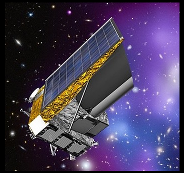
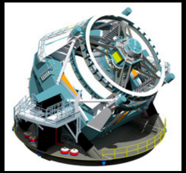
Aghanim et al. [Planck] 2021

At face value a factor of 6 tighter than current lab bound from KATRIN, $\sum m_\nu < 3$ eV.

Aker et al. [KATRIN] 2019



What to expect in the future?

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

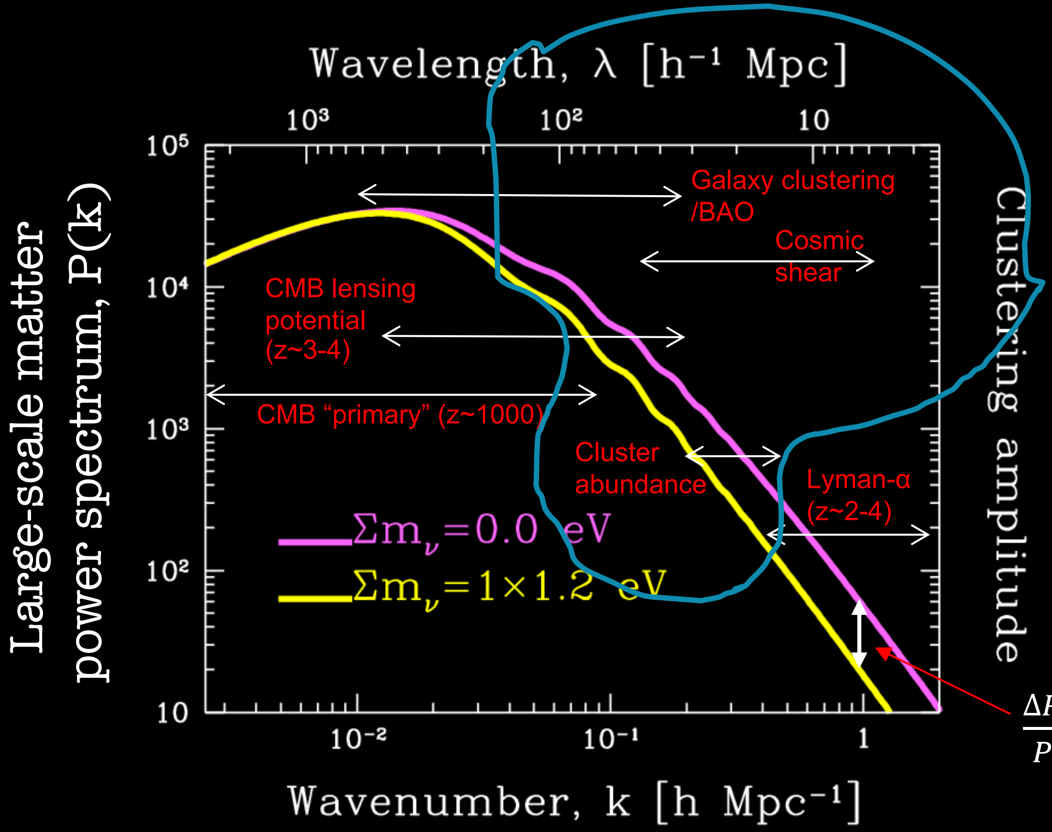
Minimum $\sum m_\nu = 0.06\ \mathrm{eV}$

From neutrino oscillations
(assuming normal mass ordering)

→

Detection of the absolute
neutrino mass may be possible!

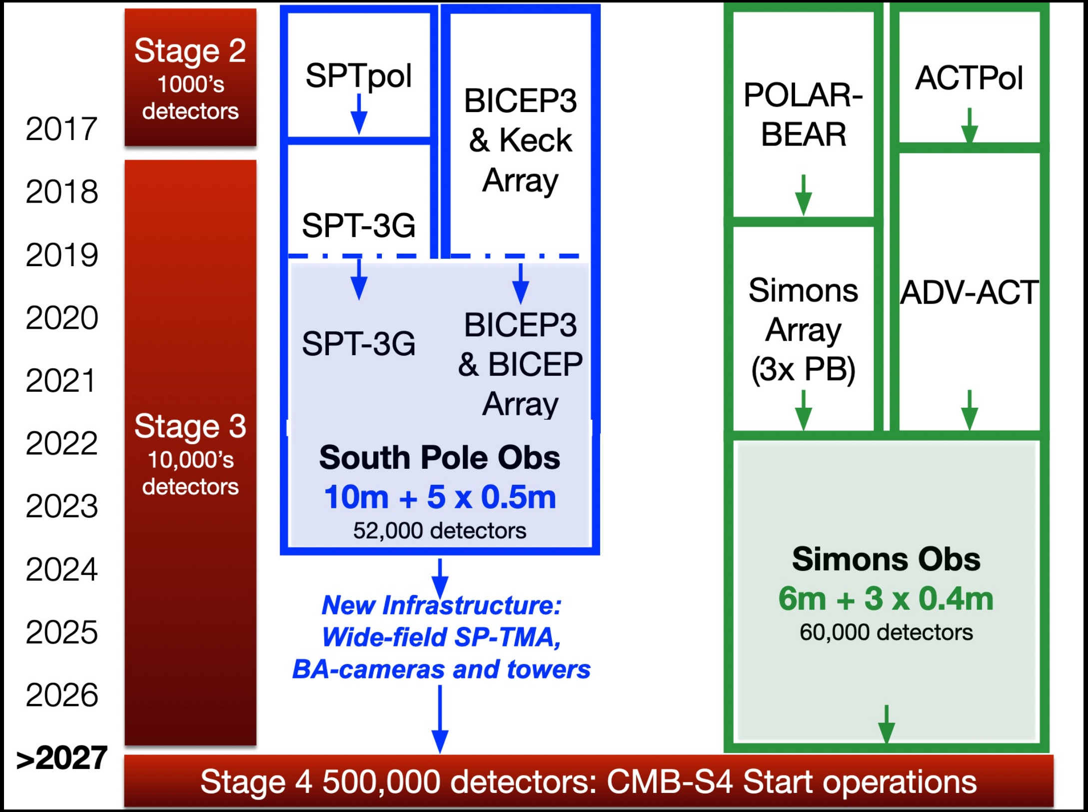
A real matter power spectrum calculated from linear perturbation theory…



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

What to expect in the future?

CMB experiments



2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
>2027

Stage 2
1000's detectors

Stage 3
10,000's detectors

SPTpol → SPT-3G → SPT-3G

BICEP3 & Keck Array → BICEP3 & BICEP Array

South Pole Obs
10m + 5 x 0.5m
52,000 detectors

New Infrastructure: Wide-field SP-TMA, BA-cameras and towers

POLAR-BEAR → Simons Array (3x PB)

ACTPol → ADV-ACT

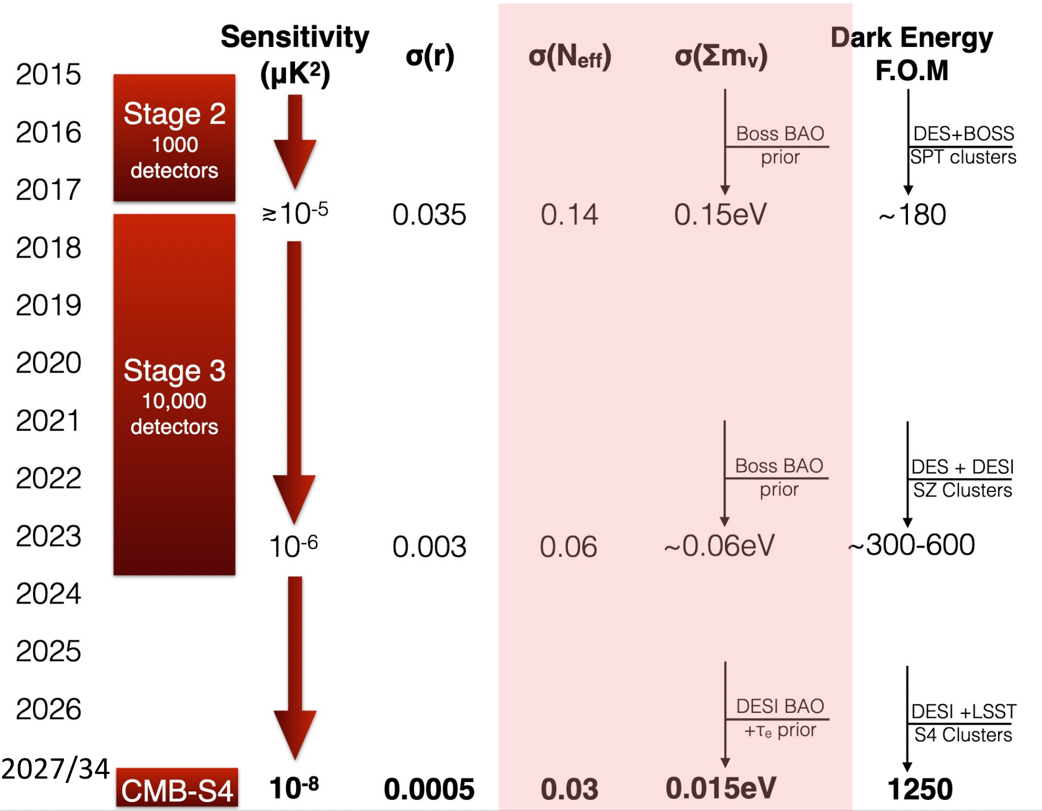
Simons Obs
6m + 3 x 0.4m
60,000 detectors

Stage 4 500,000 detectors: CMB-S4 Start operations

John Carlstrom

What to expect in the future?

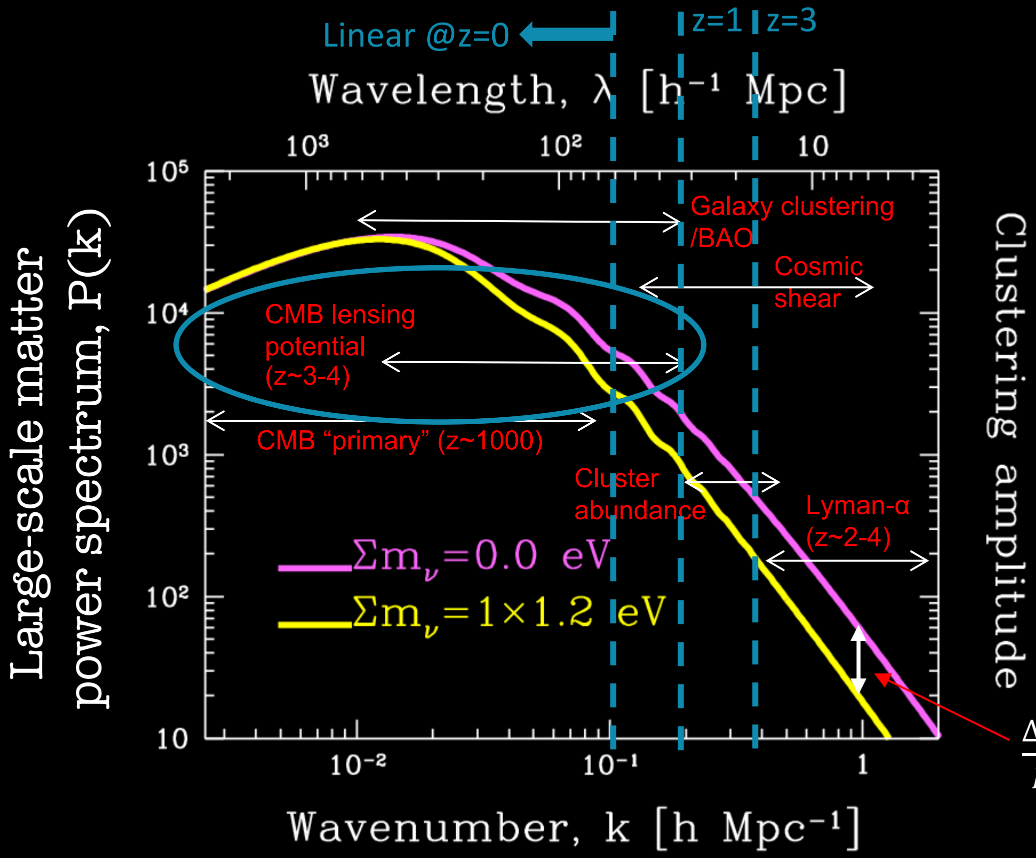
CMB experiments



		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{\mathrm{eff}})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors					
2016					Boss BAO prior	DES+BOSS SPT clusters
2017		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2018	Stage 3 10,000 detectors					
2019						
2020						
2021						
2022					Boss BAO prior	DES + DESI SZ Clusters
2023		10^{-6}	0.003	0.06	~0.06eV	~300-600
2024						
2025						
2026					DESI BAO +T_e prior	DESI +LSST S4 Clusters
2027/34	**CMB-S4**	**10^{-8}**	**0.0005**	**0.03**	**0.015eV**	**1250**

John Carlstrom

A real matter power spectrum calculated from linear perturbation theory…

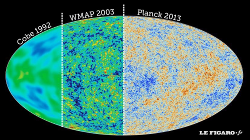


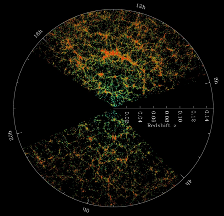
$$\frac{\Delta P}{P} \propto \frac{\Omega_\nu}{\Omega_m} \propto \sum m_\nu$$

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)

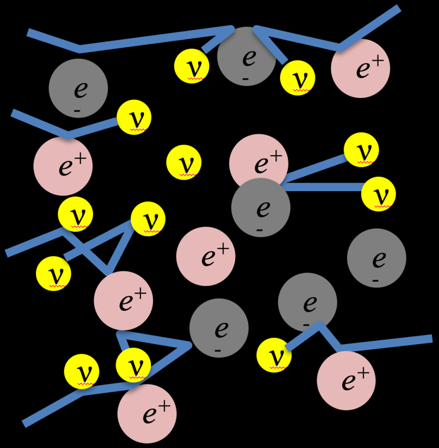
➡ Non-standard neutrino interactions (CMB)

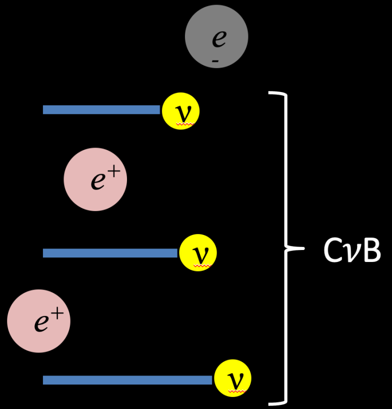
Formation of the CνB…

Interaction rate: $\Gamma_{\text{weak}} \sim G_F^2 T^5$

Expansion rate: $H \sim M_{\text{pl}}^{-2} T^2$

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





Neutrinos "free-stream" to infinity.

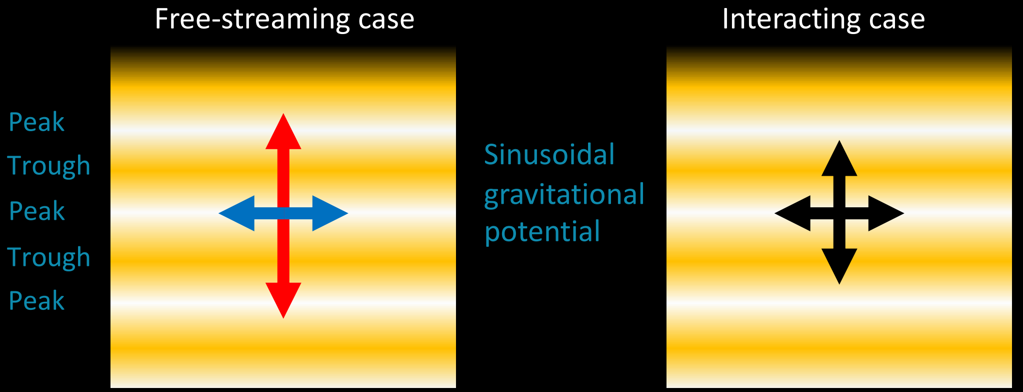
Above $T \sim 1$ MeV, even weakly-interacting neutrinos can be produced, scatter off e^+e^- and other neutrinos, and attain thermodynamic equilibrium

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

Neutrino free-streaming & the CMB…

Standard neutrinos free-stream.

- Free-streaming in a spatially inhomogeneous background induces shear stress (or momentum anisotropy).
- Conversely, interactions transfer momentum and, if sufficiently efficient, can wipe to out shear.



Scattering transfers momentum and wipes out shear

Neutrino free-streaming & the metric…

Neutrino shear stress (or lack thereof) leaves distinct imprints on the spacetime metric perturbations.

Scale factor

Conformal Newtonian gauge

$$ds^2 = a^2(\tau)[-(1+2\psi)d\tau^2 + (1-2\phi)dx^i dx_i]$$

where $$k^2(\phi - \psi) = 12\pi G a^2(\bar{\rho} + \bar{P})\sigma$$

Mean energy density & pressure

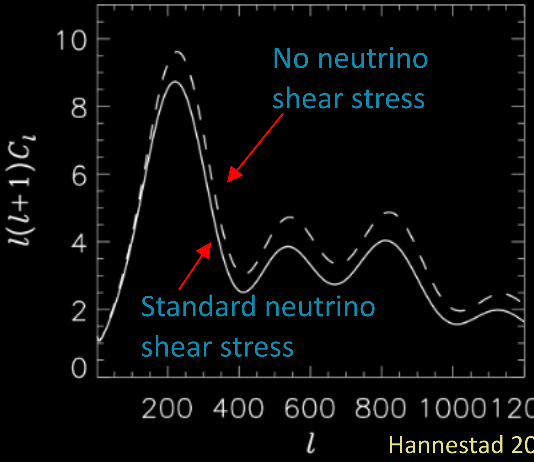
Shear stress

In ΛCDM, mainly from ultra-relativistic neutrinos and photons.

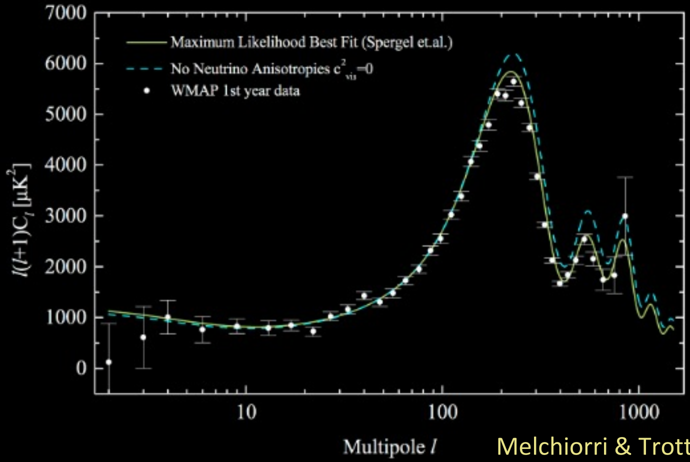
- Changes to $(\phi - \psi)$ affect the evolution of CMB perturbations and are observable in the **CMB TT power spectrum**.
- Good probe of neutrino interactions around CMB formation times $(t \sim 400\ \mathrm{kyr})$ when the CνB still constitutes a substantial fraction of the relativistic energy density.

Neutrino free-streaming & the CMB…

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



Hannestad 2005



Melchiorri & Trotta 2005

- The tricky part is, how do you translate this preference to constraints on the fundamental parameters of a non-standard neutrino interaction

  → What is the isotropisation timescale given a fundamental process?

Isotropisation timescale…

Given an interaction Lagrangian, the isotropisation timescale is calculable.

- Write down the Boltzmann equation:

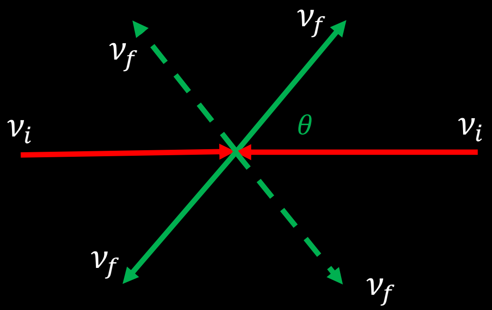
$$
\begin{aligned}
P^\mu \frac{\partial f_i}{\partial x^\mu} - \Gamma^\nu_{\rho\sigma} P^\rho P^\sigma \frac{\partial f_i}{\partial P^\nu} =& \frac{1}{2} \left(\prod_j^N \int g_j \frac{\mathrm{d}^3 \mathbf{n}_j}{(2\pi)^3 2E_j(\mathbf{n}_j)} \right) \left(\prod_k^M \int g_k \frac{\mathrm{d}^3 \mathbf{n}_k}{(2\pi)^3 2E_k(\mathbf{n}_k)} \right) \\
& \times (2\pi)^4 \, \delta_D^{(4)} \left(p + \sum_j^N n_j - \sum_k^M n'_k \right) \, |\mathcal{M}_{i+j_1+\cdots+j_N \leftrightarrow k_1+\cdots+k_M}|^2 \\
& \times [f_{k_1} \cdots f_{k_N} (1 \pm f_i)(1 \pm f_{j_1}) \cdots (1 \pm f_{j_N}) - f_i f_{j_1} \cdots f_{j_N} (1 \pm f_{k_1}) \cdots (1 \pm f_{k_M})]
\end{aligned}
$$

- Decompose in a Legendre series
- The damping rate of the quadrupole ($\ell = 2$) moment is the **isotropisation rate**.

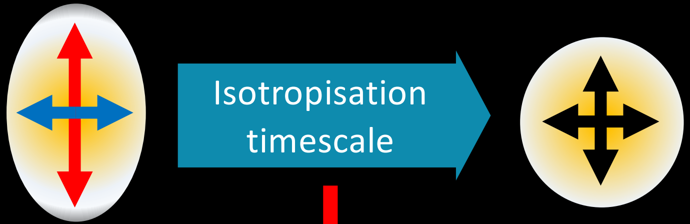
Tedious stuff, but this is really the only correct way to calculate these things, else you can get it very wrong…
However, the result can usually be understood in simple terms. → **Next slide**

Isotropisation from ν self-interaction…

Consider a 2-to-2 scattering event $\nu_i + \nu_i \rightarrow \nu_f + \nu_f$.



→ Particles in two head-on ν_i beams need only scatter once to transfer their momenta equally in all directions.



$T_{\text{isotropise}} \sim 1/\Gamma_{\text{scattering}}$

Scattering rate

- The probability of ν_f emitted at any angle θ is the same for all $\theta \in [0, \pi]$.

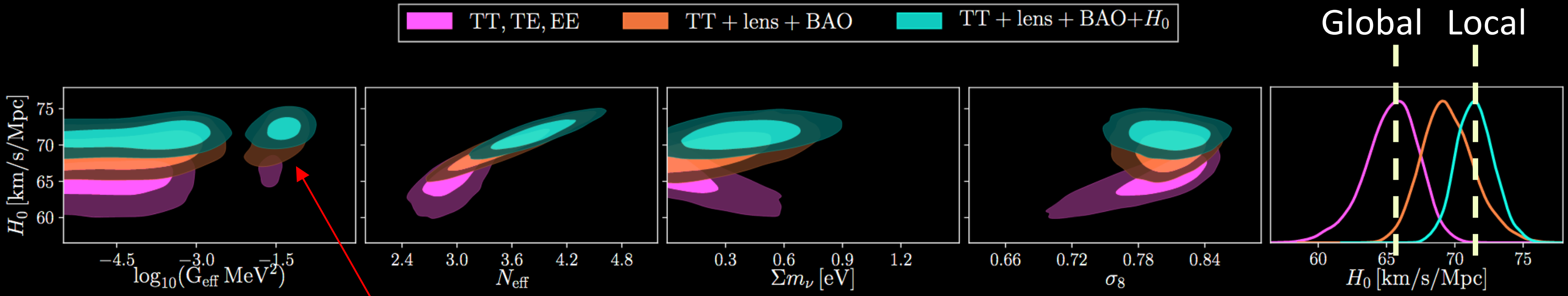
Cyr-Racine & Sigurdson 2014; Oldengott, Rampf & Y³W 2015; Lancaster, Cyr-Racine, Knox & Pan 2017; Oldengott, Tram, Rampf & Y³W 2017; Kreisch, Cyr-Racine & Dore 2019; Forastieri et al. 2019; etc.

ν self-interaction and the H_0 tension…

Kreisch, Cyr-Racine & Dore 2019

Recent claim that self-interaction **alleviates the Hubble tension**.

- **Local/late time**: Cepheid-calibrated SNIa (SH0ES) and strong-lensing time delays (H0liCOW); $H_0 = (73.5 \pm 1.4)\ \mathrm{km/s/Mpc}$
- **Global/early time**: Statistical inference from CMB anisotropies (Planck), weak lensing, BAO; $H_0 = (67.4 \pm 0.5)\ \mathrm{km/s/Mpc}$



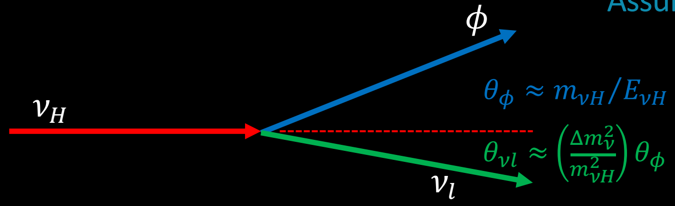
Global Local

This island:
$G_{\rm eff} \sim 10^{10} G_F$

Isotropisation from relativistic (inverse) decay…

How long does it take $\nu_H \rightarrow \nu_l + \phi$ and its inverse process to wipe out momentum anisotropies? (Hint: it's not the rest-frame lifetime of ν_H.)

- In relativistic decay, the decay products are **beamed**.



Assuming a massless ϕ

$\theta_\phi \approx m_{\nu H}/E_{\nu H}$

$\theta_{\nu l} \approx \left(\frac{\Delta m_\nu^2}{m_{\nu H}^2}\right)\theta_\phi$

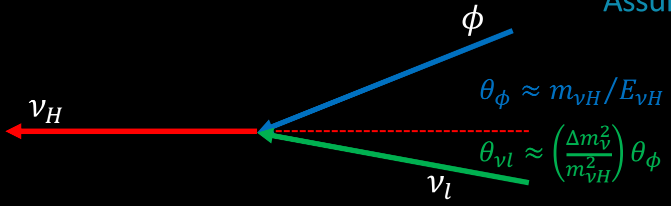
Barenboim, Chen, Hannestad, Oldengott, Tram & Y^{3}W 2021
Chen, Oldengott, Pierobon & Y^{3}W 2022

Isotropisation from relativistic (inverse) decay…

How long does it take $\nu_H \rightarrow \nu_l + \phi$ and its inverse process to wipe out momentum anisotropies? (Hint: it's not the rest-frame lifetime of ν_H.)

- In relativistic decay, the decay products are **beamed**.
- Inverse decay also only happens when the daughter particles meet **strict momentum/angular requirements**.

Assuming a massless ϕ



$\theta_\phi \approx m_{\nu H}/E_{\nu H}$

$\theta_{\nu l} \approx \left(\frac{\Delta m_\nu^2}{m_{\nu H}^2}\right)\theta_\phi$

Boost

Rest-frame lifetime of ν_H

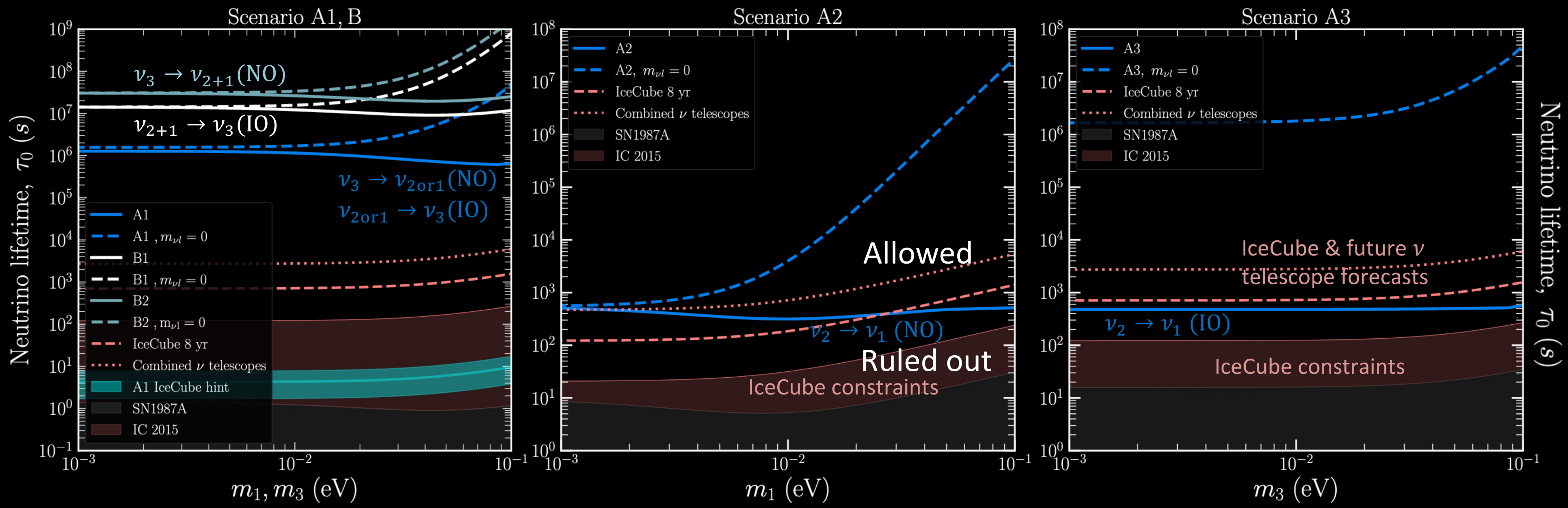
→ Isotropisation is a looooong process: $T_{\text{isotropise}} \sim (\theta_\phi \theta_{\nu l})^{-2}\, \gamma_{\nu H}\, \tau_{\text{rest}} \gtrsim 400\ \text{kyr}$

Barenboim, Chen, Hannestad, Oldengott, Tram & Y³W 2021
Chen, Oldengott, Pierobon & Y³W 2022

→ Lower bound on τ_{rest} as a function of $m_{\nu H}$ and $m_{\nu l}$.

CMB lower bounds on the neutrino lifetime…

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

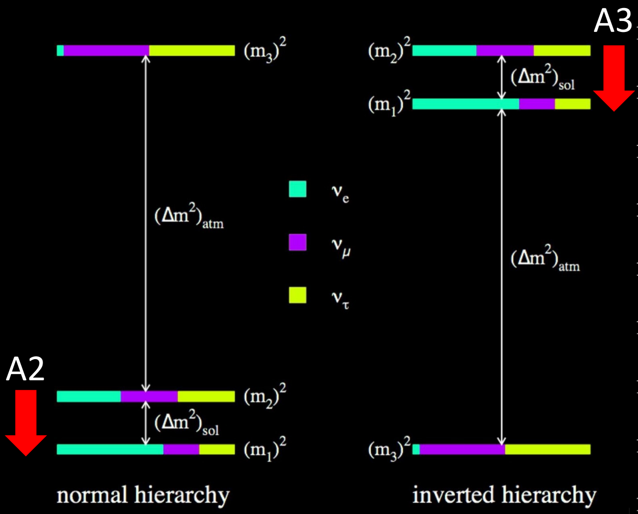


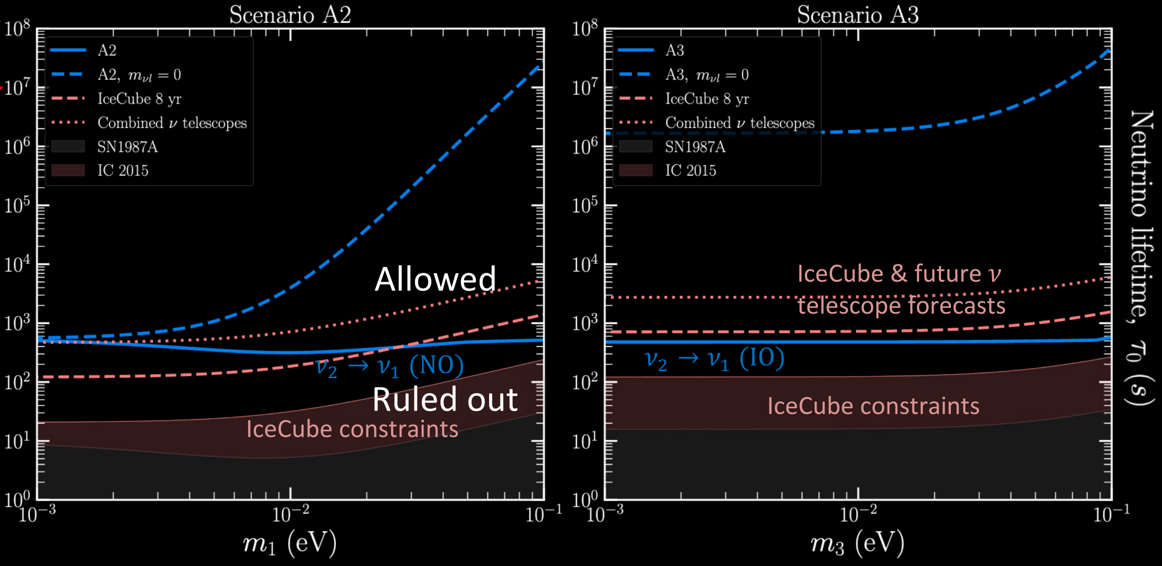
Chen, Oldengott, Pierobon & Y^{3}W 2022

* IceCube constraints & forecasts from Song et al. 2021

CMB lower bounds on the neutrino lifetime…

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





Chen, Oldengott, Pierobon & Y^3W 2022

- For $\nu_2 \rightarrow \nu_1 + \phi$, neutrino telescopes and CMB probe the same parameter space.

Why I like this so much…

Previous CMB constraints on the neutrino lifetime were based on an (heuristic) isotropisation rate that turns out to be too large.

→ Resulting lower limit is too strong:

$$\tau_{\mathrm{rest}} \gtrsim 10^9 \left(\frac{m_\nu}{0.05\ \mathrm{eV}}\right)^3 \mathrm{s}$$

e.g.,
Hannestad & Raffelt 2005
Basboll, Bjaelde, Hannestad & Raffelt 2009
Escudero & Fairbairn 2019

- Compare this with our revised limits: Chen, Oldengott, Pierobon & Y^{3}W 2022

$\nu_3 \to \nu_{1,2} + \phi$ (NO)
$\nu_{1,2} \to \nu_3 + \phi$ (IO)

$$\tau_{\mathrm{rest}} \gtrsim (6 - 10)\times 10^5 \mathrm{s}$$

$\nu_2 \to \nu_1 + \phi$

$$\tau_{\mathrm{rest}} \gtrsim (400 - 500)\mathrm{s}$$

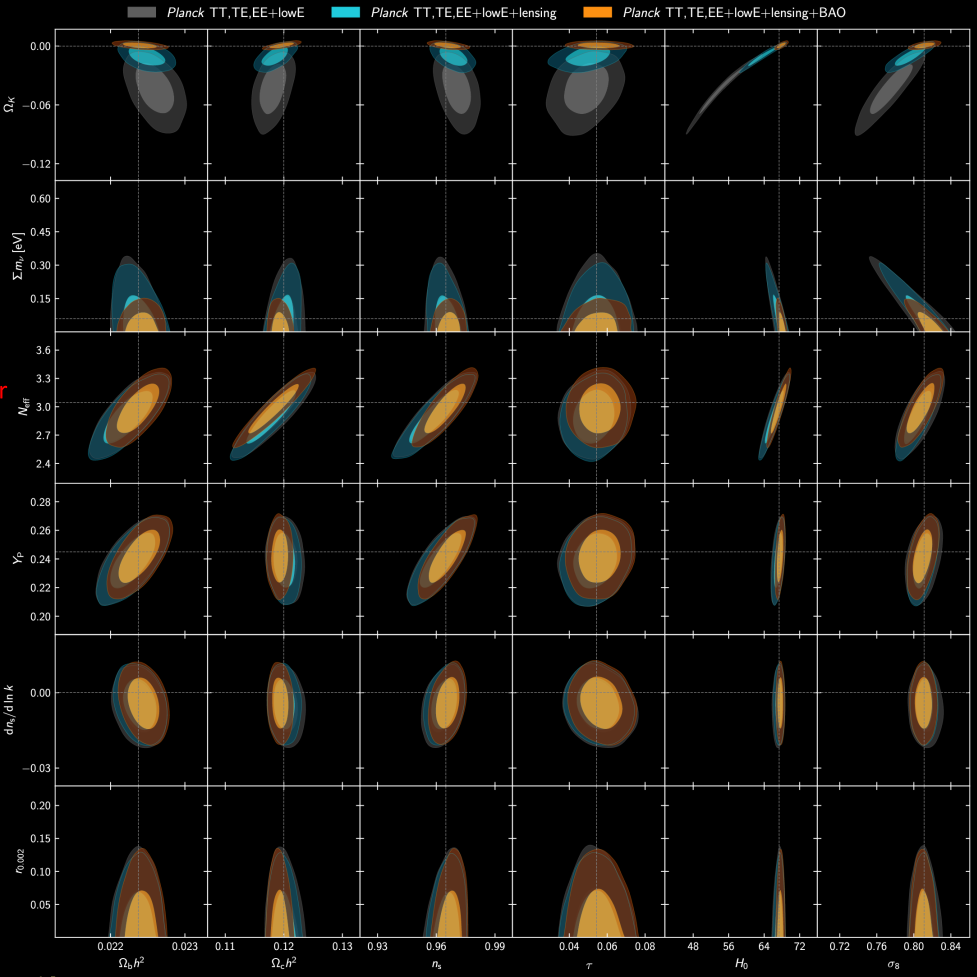
There's now some hope that other experiments can probe this process too.

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

Aghanim et al. [Planck] 2021

Dark matter density

Spectral index

Hubble parameter

Fluctuation amplitude

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.

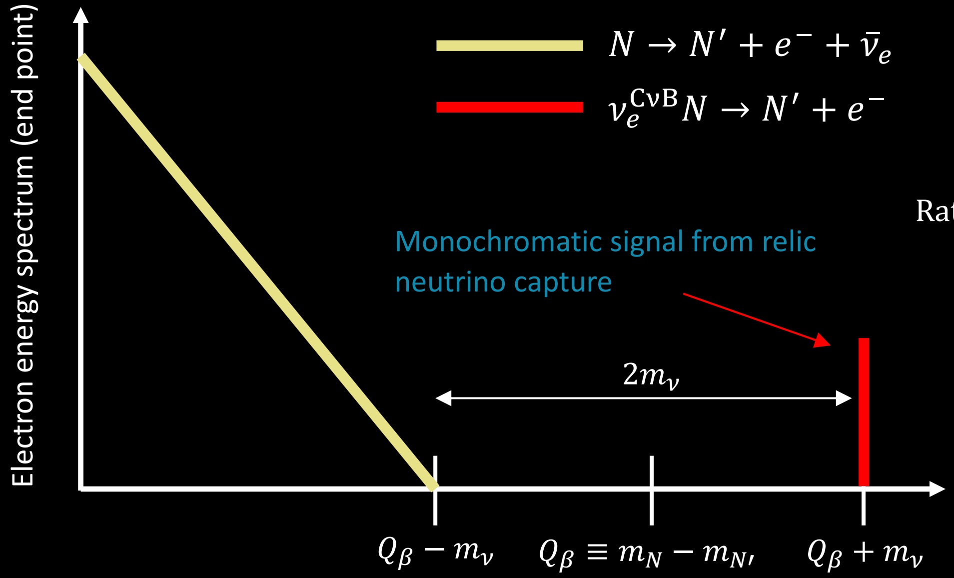
More accurate estimates of parameters inaccessible in the lab.

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



Monochromatic signal from relic neutrino capture

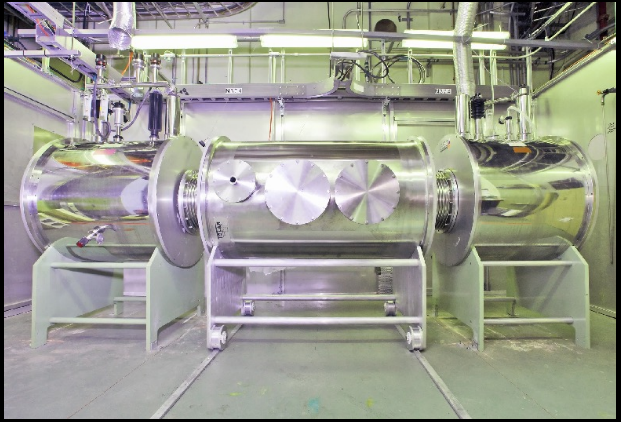
$\mathrm{Rate} \sim 7.5/\mathrm{year}\ /(100\ \mathrm{tritium})$

KATRIN source:
~ 0.1 mg tritium

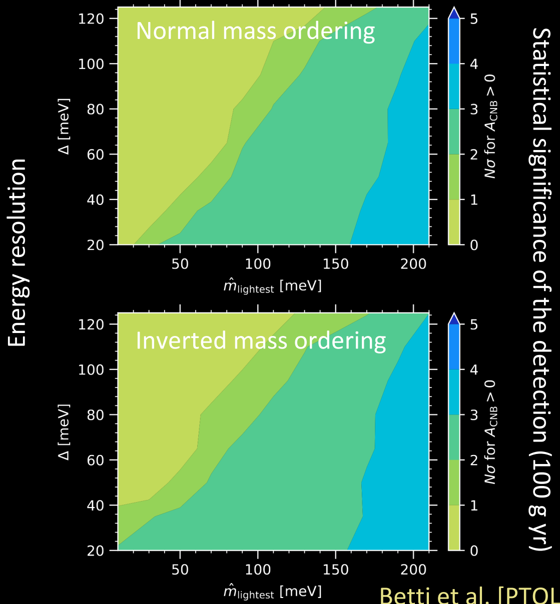
What can neutrino physics do for cosmology?

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.