Prospects for the measurement of the absolute neutrino mass in cosmology

Yvonne Y. Y. Wong
UNSW Sydney

FIPs 2022 Workshop, CERN, October 17 – 22, 2022

Measuring neutrino masses with cosmology...

Cosmological neutrino mass bounds go back a long way.

- Cowsik & McClelland (1972): $\sum m_\nu < 24\,\mathrm{eV}$
- Hinges on prediction of a **thermal background of neutrinos**.

VOLUME 29, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 1972

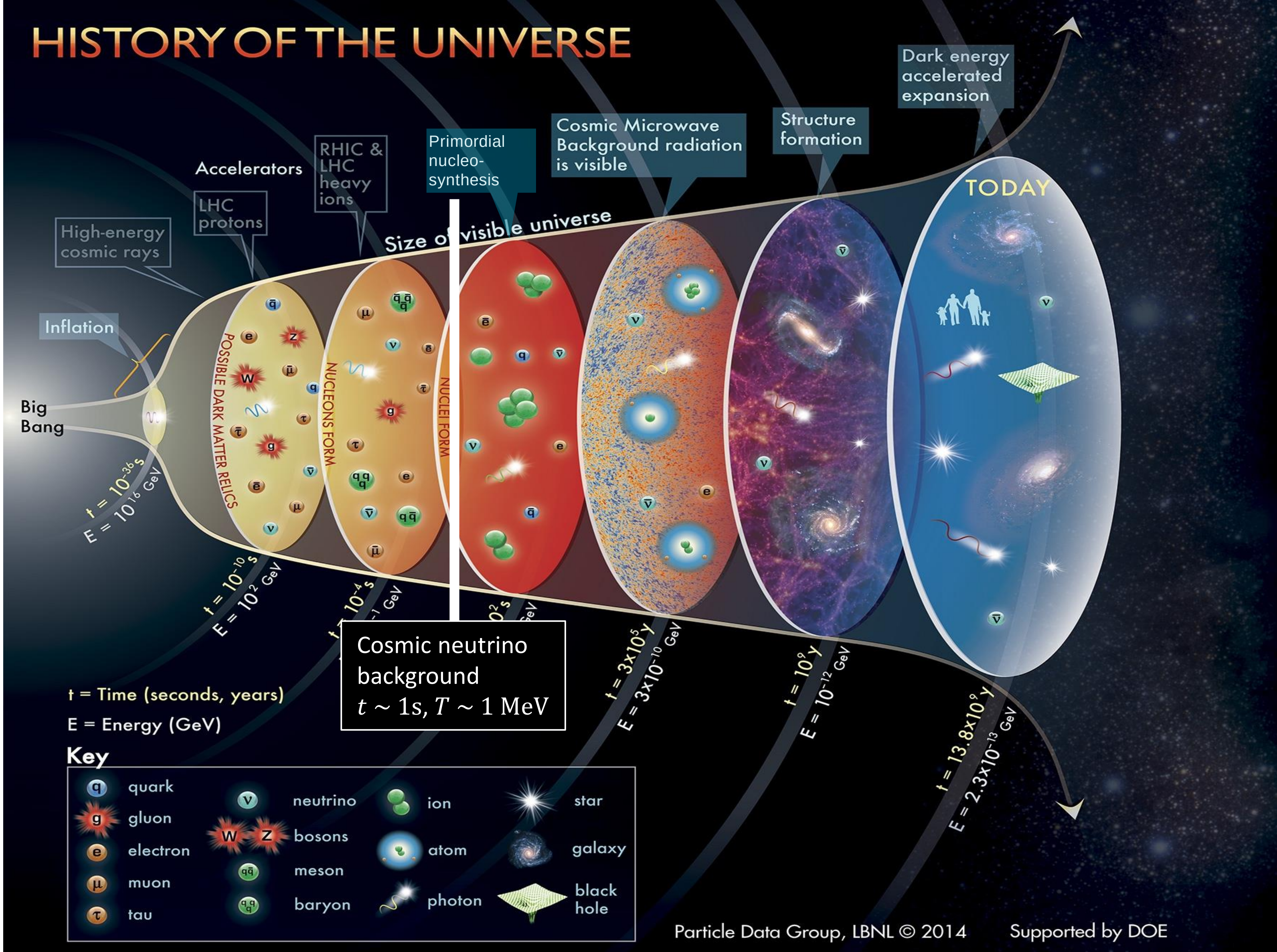
An Upper Limit on the Neutrino Rest Mass*

R. Cowsik† and J. McClelland

Department of Physics, University of California, Berkeley, California 94720

(Received 17 July 1972)

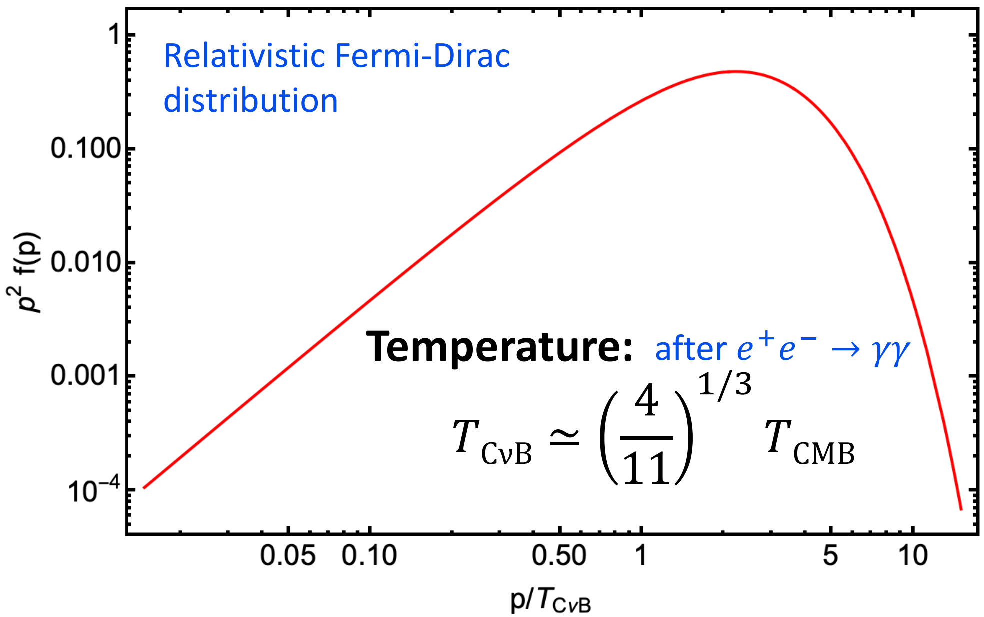
In order that the effect of graviation of the thermal background neutrinos on the expansion of the universe not be too severe, their mass should be less than 8 eV/c^2.



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
Primordial nucleo-synthesis
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 3\times10^{5}$ y
$E = 3\times10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8\times10^{9}$ y
$E = 2.3\times10^{-13}$ GeV
Cosmic neutrino background
$t \sim 1\mathrm{s}, T \sim 1$ MeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

The cosmic neutrino background…

Standard model predictions



Temperature: after $e^+e^- \rightarrow \gamma\gamma$

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

Number density: Per family of neutrinos +antineutrinos

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

Energy density: Per family

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

$$\rho_{C\nu B} \simeq \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} \rho_{CMB} \simeq 0.227\rho_{CMB}$$

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

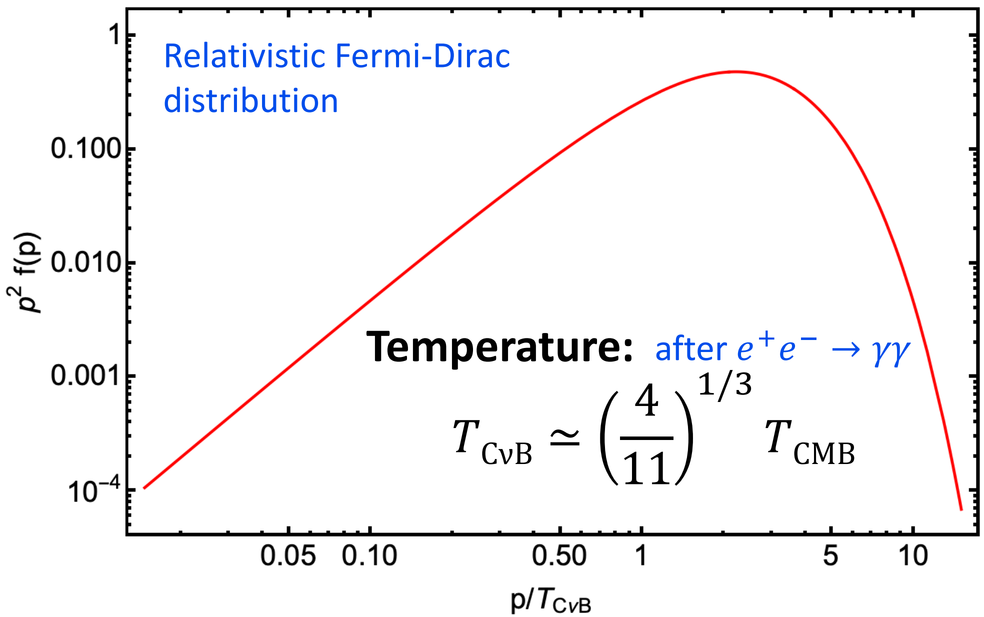
$$\Omega_{C\nu B} \simeq \frac{m_\nu}{93\ h^2 \text{ eV}}$$

Neutrino (hot) dark matter

Reduced Hubble parameter

The cosmic neutrino background…

Standard model predictions



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Reduced Hubble parameter

Demand no overclosure

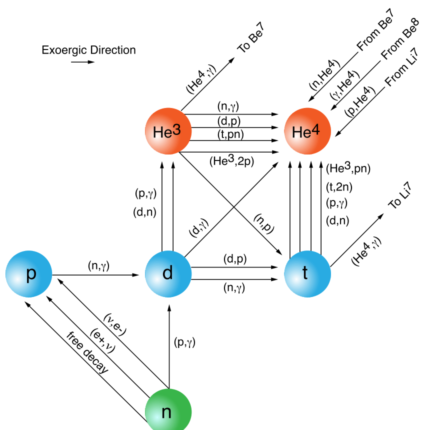
$$\sum m_\nu \lesssim 24 - 45\ \mathrm{eV} \Leftarrow \Omega_{C\nu B} \lesssim 1 \Leftarrow$$

Depending on h

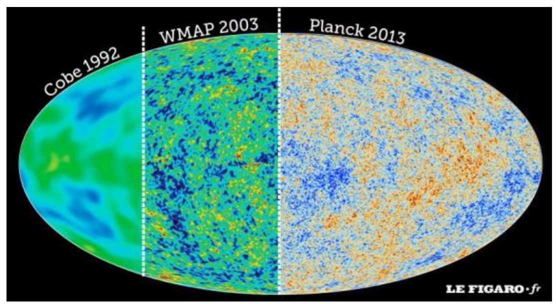
Modern cosmological neutrino mass bounds...

... are based on how the **properties of the CνB** affect the events that take place after its formation.

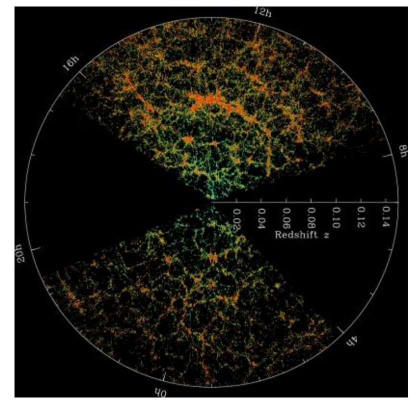
Light element abundances



CMB anisotropies



Large-scale matter distribution



Properties of the CνB probed:

N_{eff} (expansion rate)

N_{eff} (expansion rate)
$\sum m_\nu$ **(perturbation growth)**
Interactions (free-streaming)
Lifetime (free-streaming)

$\sum m_\nu$ **(perturbation growth)**

Neutrino masses & perturbation growth...

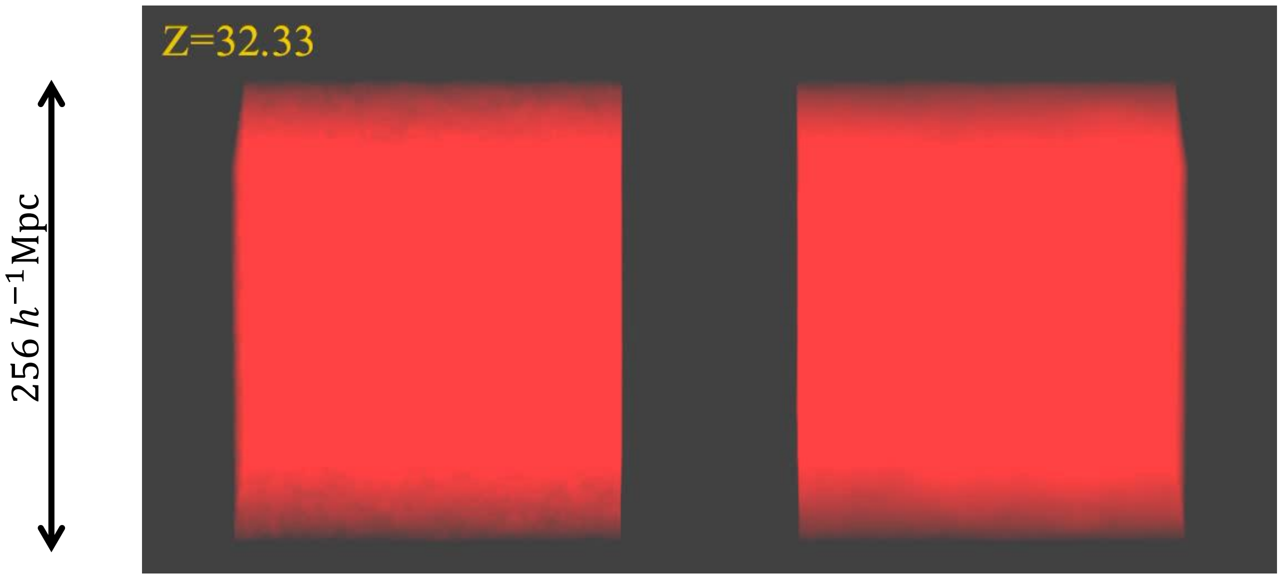
Cold dark matter only

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

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

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

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



Simulations by Troels Haugbølle

Neutrino masses & perturbation growth...

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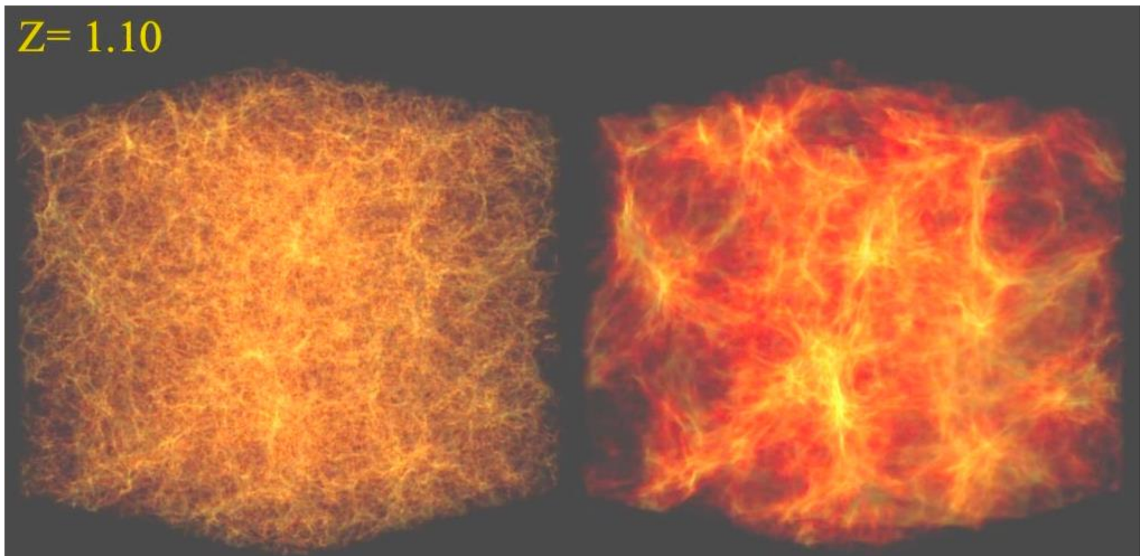
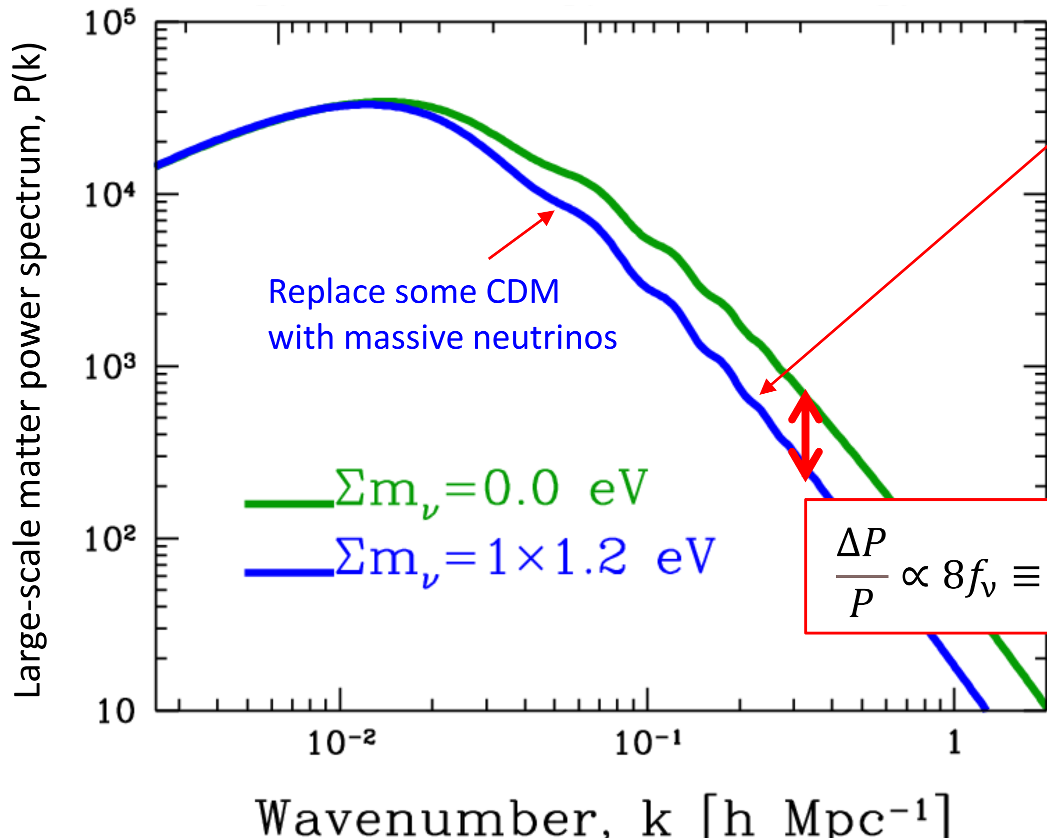
$256\ h^{-1}\mathrm{Mpc}$



Simulations by Troels Haugbølle

Large-scale matter power spectrum…

From linear perturbation theory



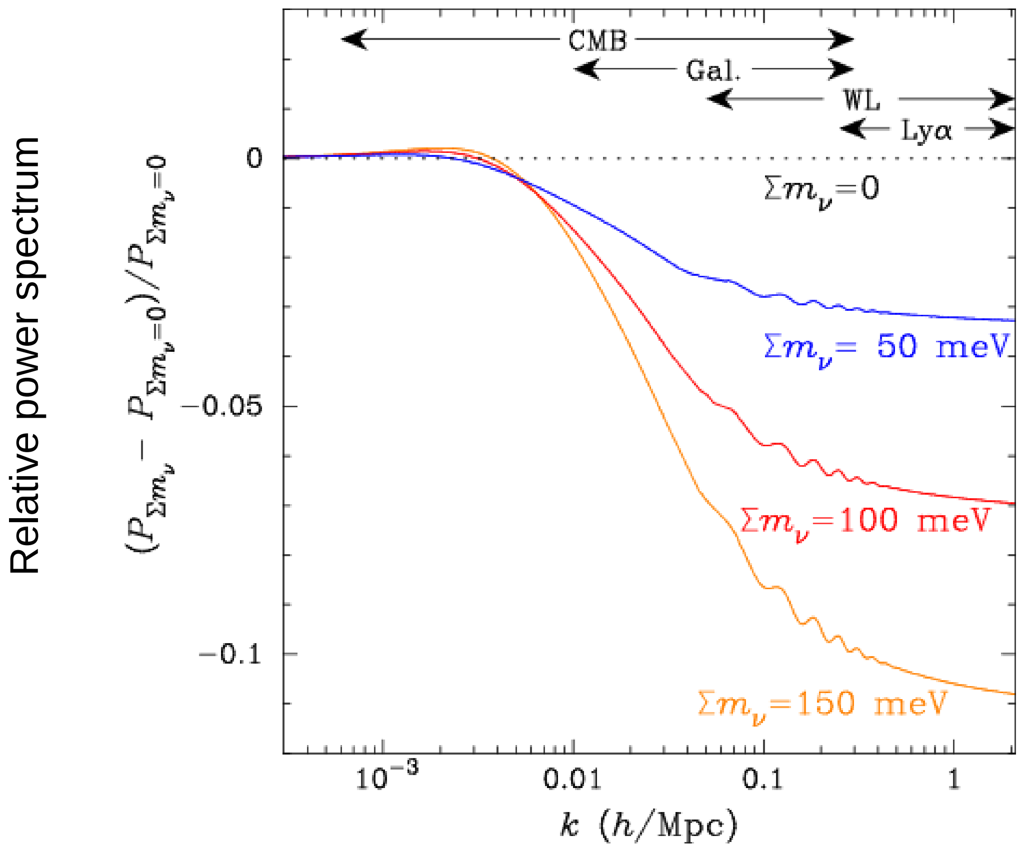
Suppression of power due to free-streaming induced potential decay

f_ν = Neutrino fraction

$$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$$

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\mathrm{eV}}$$

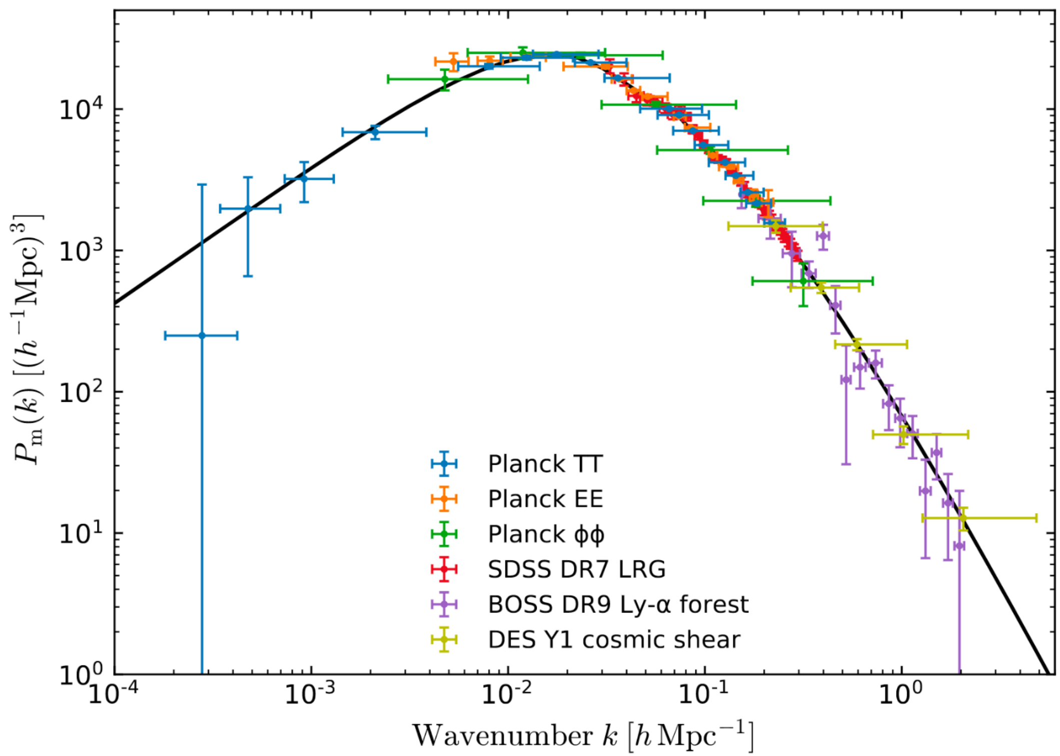
Large-scale matter power spectrum…



The larger the mass sum, the larger the suppression.

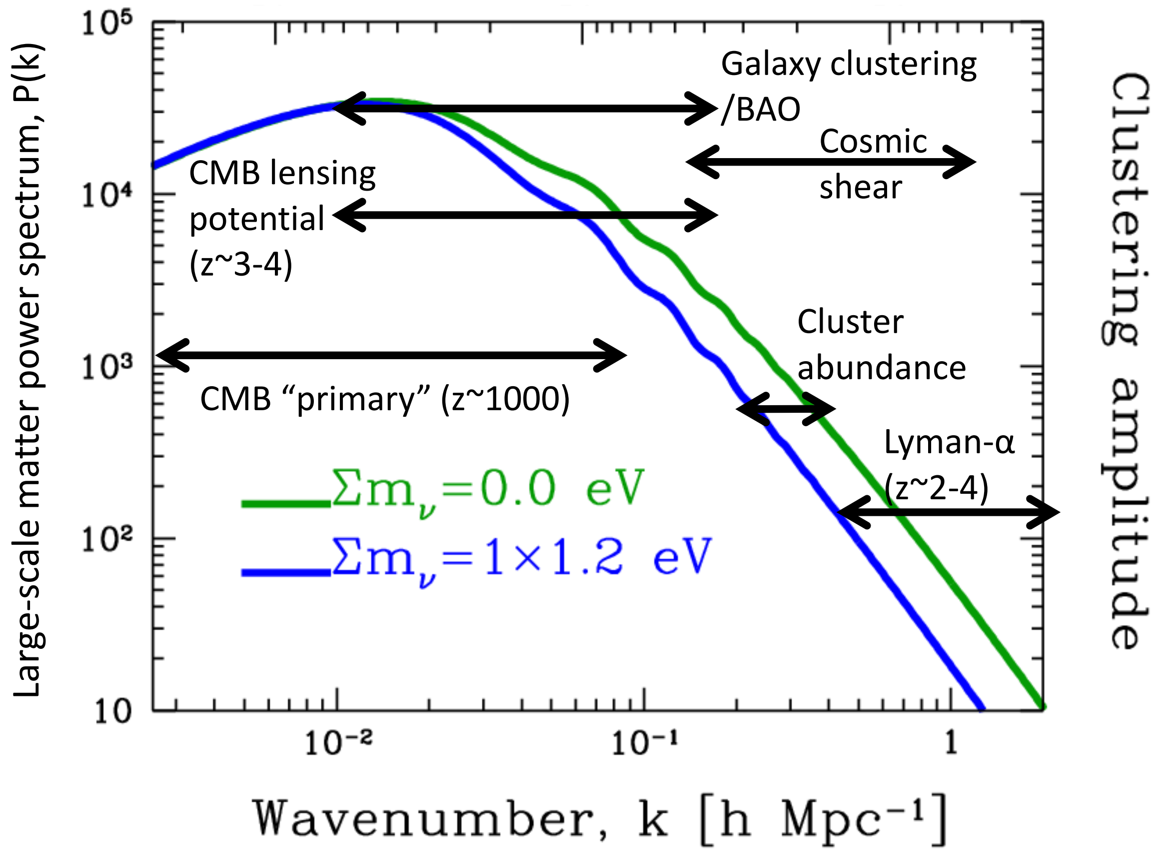
Who can measure it?

Large-scale power spectrum measurements circa 2018



Akrami et al. 2018

Who can measure it?

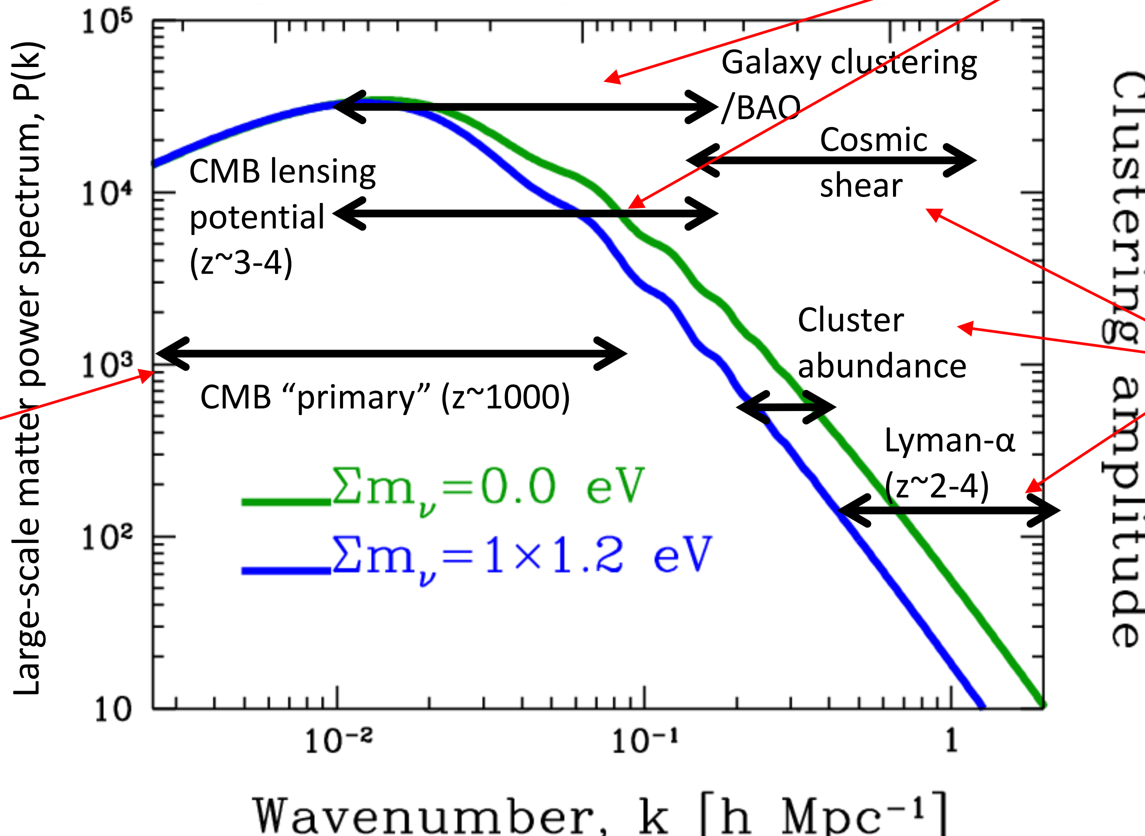


Who can measure it?

ω_m + geometry

Physical matter density

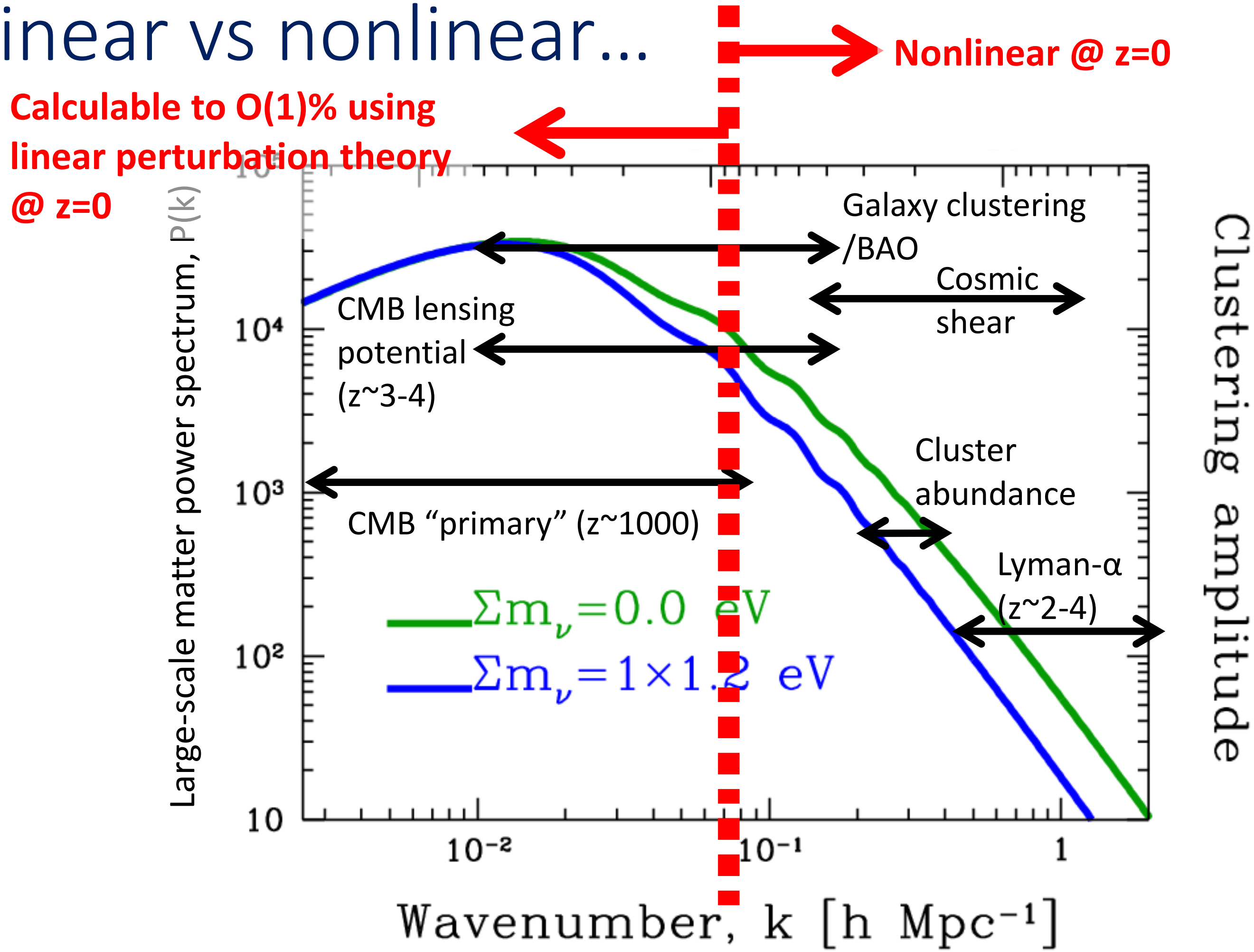
"Anchor" ΛCDM model parameters
$\omega_m, \omega_b, n_s,$
A_s, τ, h



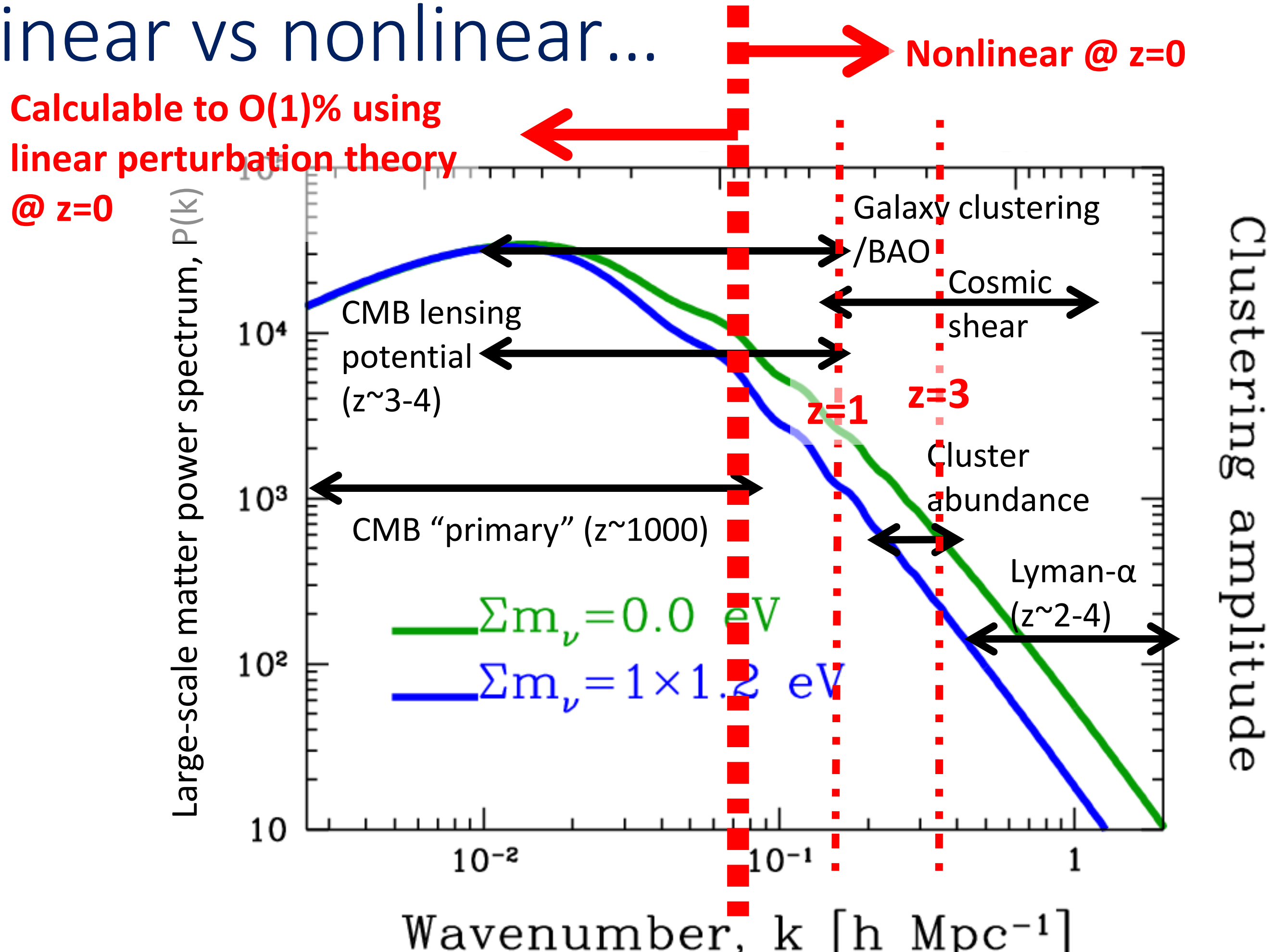
σ_8, Ω_m

Small-scale fluctuation amplitude

Linear vs nonlinear…



Linear vs nonlinear…



There are nonlinearities and nonlinearities…

	Nonlinear Dark matter (collisionless)	**Baryonic astrophysics @ k ~ O(1)/Mpc**	**Empirical tracers or proxies**
BAO	Mild	No	Mild
Cosmic shear	Yes	No	No
Galaxy power spectrum	Yes	No	Assume galaxy number density tracks DM density
Cluster abundance	Yes	No	X-ray temperature, cluster richness as proxies for cluster mass
Lyman alpha	Yes	Hydrogen distribution	No
Calculable from first principles (i.e., described by a Lagrangian)?	**Yes**	**No**	**No**

Constraints on the neutrino mass sum…

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

Two different high-ℓ likelihood functions

		+CMB lensing	+BAO (non-CMB)	+CMB lensing+BAO
Planck2018 TT+lowE	**0.54**	**0.44**	**0.16**	**0.13**
2015 number	0.72	0.68	0.21	n/a
Planck2018 TT +lowE+TE+EE	**0.26**	**0.24**	**0.13**	**0.12**
Planck2018 TT +lowE+TE+EE [CamSpec]	**0.38**	**0.27**	n/a	**0.13**
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Aghanim et al. [Planck] 2018
Ade et al. [Planck] 2015

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

Palanque-Delabrouille et al. 2015

Do you need to believe any of it?

Or to what extent should you trust these bounds?

There are certainly assumptions…

To even constrain neutrino mass cosmologically, there must be a cosmic neutrino background to begin with.

- There is **no reason** to think that this is not the case:
  - Cosmological data is consistent with there being 3 neutrino families.
  - Also consistent with them not interacting much amongst themselves or with other constituents.

- But even then there are caveats and some (small) room for play.

Caveat 1: which mass ordering...

Bounds on the mass sum do depend to an extent on the neutrino mass ordering assumed in the fit.

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

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

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

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

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

Official Planck benchmark: $\sum m_\nu < 0.12$ eV

Roy Choudhury & Hannestad 2019

Caveat 2: model dependence...

Official Planck benchmark:
$\sum m_\nu < 0.12$ eV

All bounds so far come from a ΛCDM+neutrino 7-parameter fit.

- Can test for how adding more fit parameters change the bound.

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

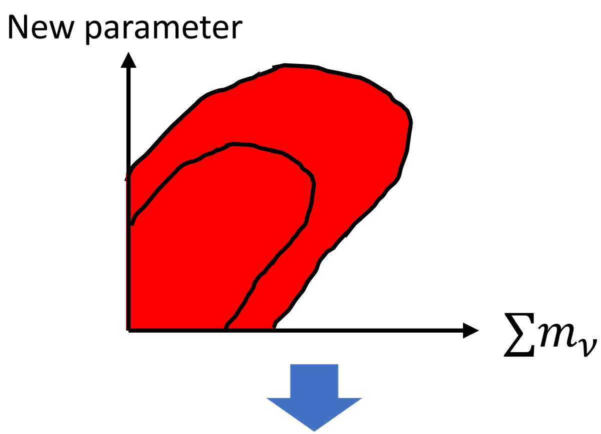
Roy Choudhury & Hannestad 2019

- This sort of game can buy you a factor ~2 relaxation, but typically no more.
- But it does not always work in the desired direction → blame it on **Bayesian stats**.

Blame it on Bayesian statistics…

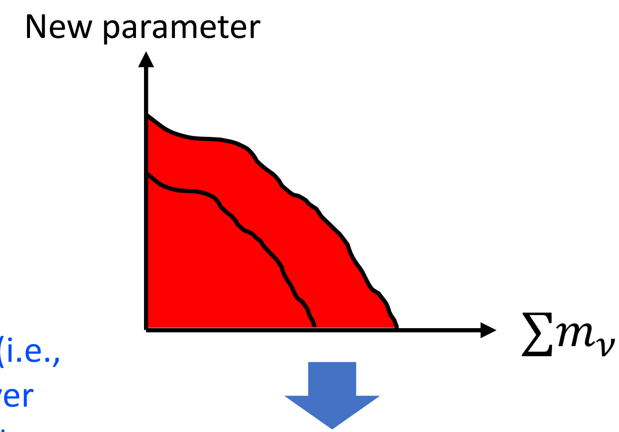
These X% credible intervals correspond to the **fractional area under the 1D marginalised posterior**.

- They depend on what degeneracy directions the additional parameters bring into the game.



Relaxed bound on $\sum m_\nu$

Marginalise (i.e., integrate) over new parameter



Tighter bound on $\sum m_\nu$

Caveat 3: more data ≠ improved bounds…

- Sometimes the extra data do bring in genuinely new physics info.
  - The resulting improvements are noticeably big.
  - **You need to pay attention to these**.

Constraints on the neutrino mass sum…

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Caveat 3: more data ≠ improved bounds…

- Sometimes the extra data do bring in genuinely new physics info.
  - The resulting improvements are noticeably big.
  - **You need to pay attention to these**.

- **Marginally improved bounds** (~20%) could be real physical effects, but are sometimes just accidents of marginal incompatibility of the different data sets
  - The inference process (and even how we define X% bounds) can end up translating the incompatibility into an "improved measurement".

  → It could easily have gone the other way to become a "worse measurement".
  - **You really shouldn't read too much into these**.

Constraints on the neutrino mass sum…

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

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Palanque-Delabrouille et al. 2015

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Caveat 4: non-standard neutrino physics…

You can also **alter the physics and properties of the CνB** to physically relax cosmological constraints.

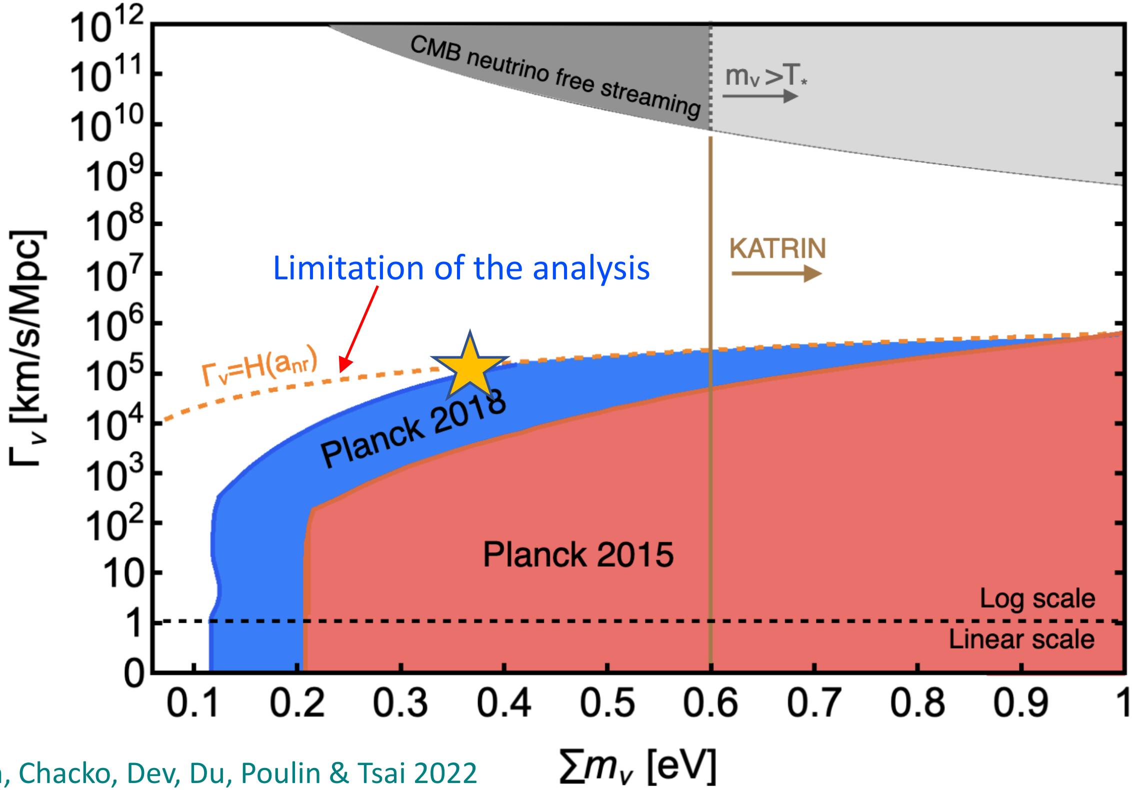
- Neutrino decay
- Neutrino spectral distortion
- Late-time neutrino mass generation
- …

These "physics" games can usually buy you more room for play, provided you are happy to accept the non-standard neutrino physics.

Non-relativistic neutrino decay…

… into dark radiation

Official Planck benchmark:
$\sum m_\nu < 0.12$ eV



Abellán, Chacko, Dev, Du, Poulin & Tsai 2022

If neutrinos decay with a **lifetime**

$$\tau_\nu \sim 0.1 \text{ Myr}$$

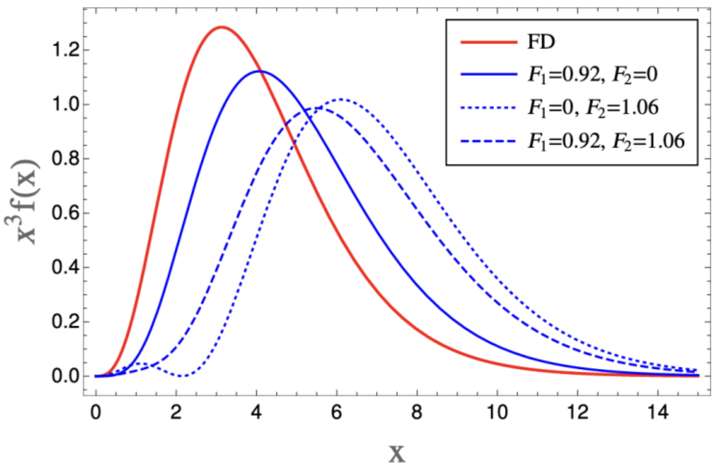
then it is possible to accommodate

$$\sum m_\nu \lesssim 0.42 \text{ eV}$$

Planck+BAO+SN

Neutrino spectral distortion…

Enhancing the average momentum (via decay, interaction, etc.) while maintaining the early-time neutrino energy density (i.e., N_{eff}) relaxes the neutrino mass bound.



Planck 2015

	TT+lowP (95 % CL)	TT+lowP+BAO (95 % CL)
FD	$\sum m_\nu < 0.73$ eV	$\sum m_\nu < 0.18$ eV
$F_1 = 0.92, F_2 = 0$	$\sum m_\nu < 0.95$ eV	$\sum m_\nu < 0.26$ eV
$F_1 = 0, F_2 = 1.06$	$\sum m_\nu < 1.45$ eV	$\sum m_\nu < 0.37$ eV
$F_1 = 0.92, F_2 = 1.06$	$\sum m_\nu < 1.34$ eV	$\sum m_\nu < 0.32$ eV

Oldengott, Barenboim, Kahlen, Salvado & Schwarz 2019

- If you're adventurous and take a Gaussian momentum distribution, you could even relax the bound to $\sum m_\nu \lesssim 3$ eV. Alvey, Escudero & Sabti 2022

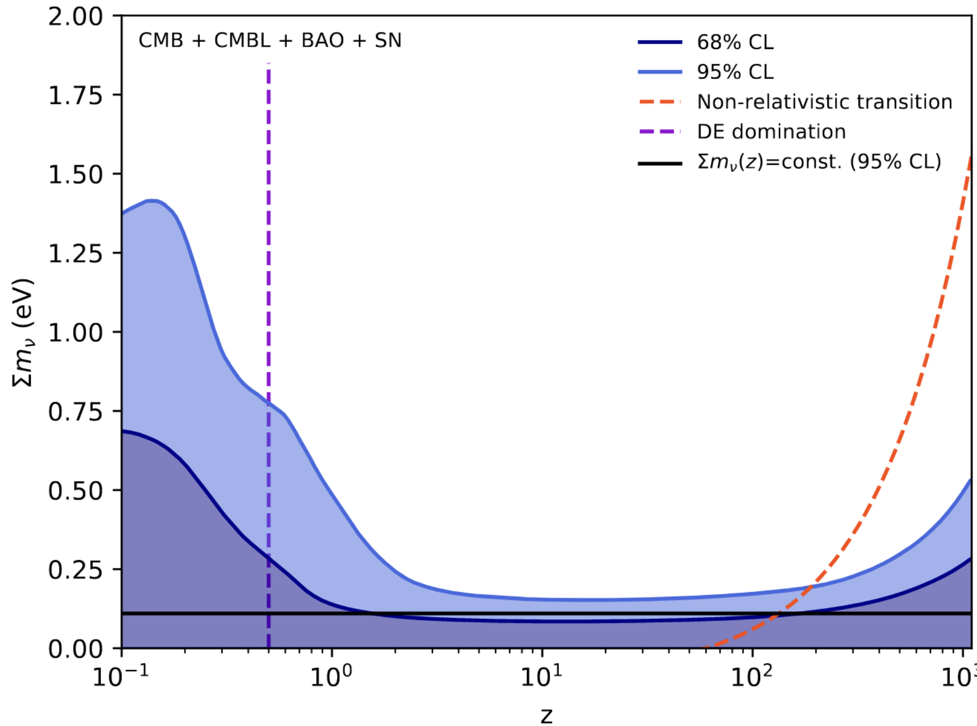
Late-time ν mass generation...

Official Planck benchmark:
$\sum m_\nu < 0.12$ eV

Late-time mass through a phase transition at $T{\sim}\text{meV}$ Dvali & Funcke 2016

- But phenomenologically, if neutrinos pick up masses only after $z{\sim}1$, then this is allowed:

$$\sum m_\nu \lesssim 1.46 \text{ eV}$$



Lorenz, Funcke, Löffler & Calabrese 2021

Take-home message…

Probably the best you can do now re cosmological neutrino mass bounds is to treat them as ballpark figures.

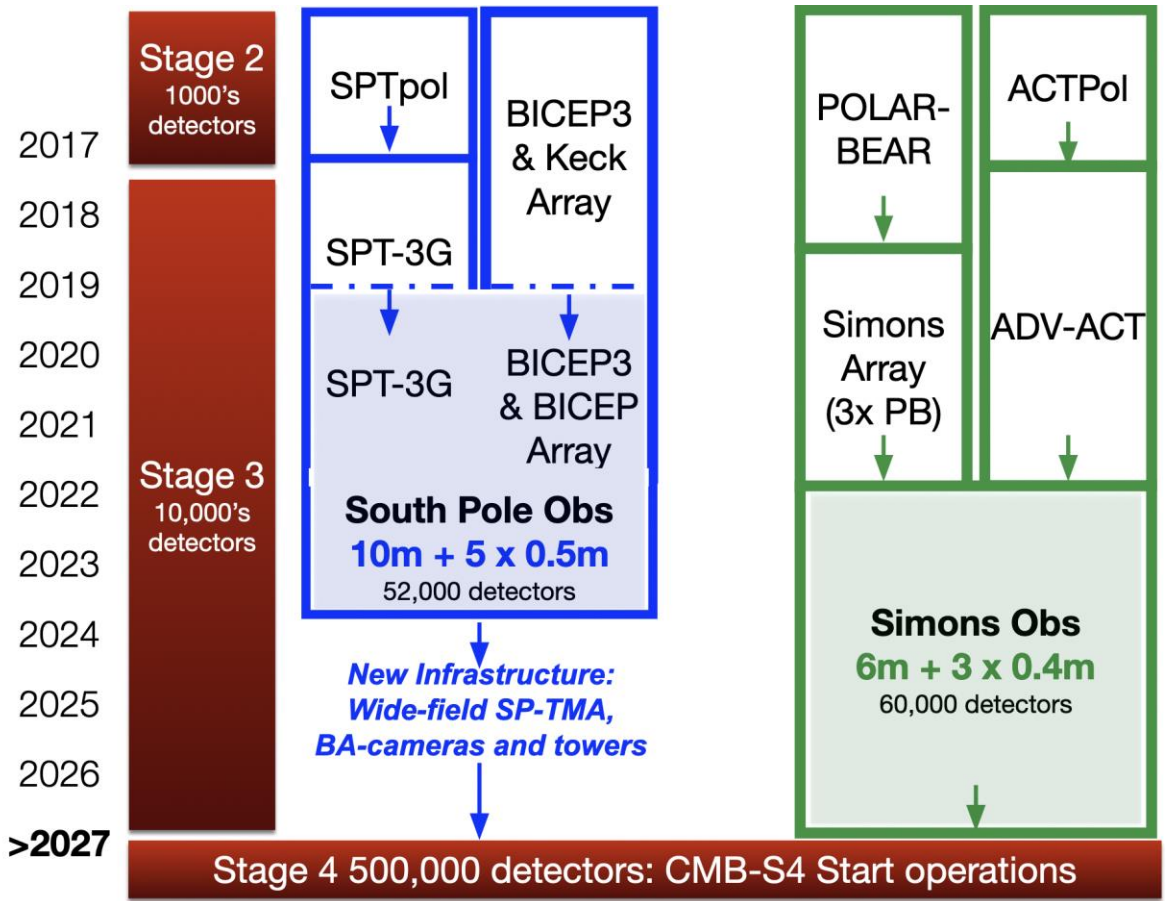
- You can evade the tightest constraints to a good extent, but **it's not like anything goes**.

- In the same vein, please **do not over-interpret bounds**.
  - That second significant digit doesn't mean much.
  - Anything from marginal incompatibility of data sets to a bad choice of fit parameters/priors could shift bounds by 10-20%.

Future probes…

What to expect in the future?

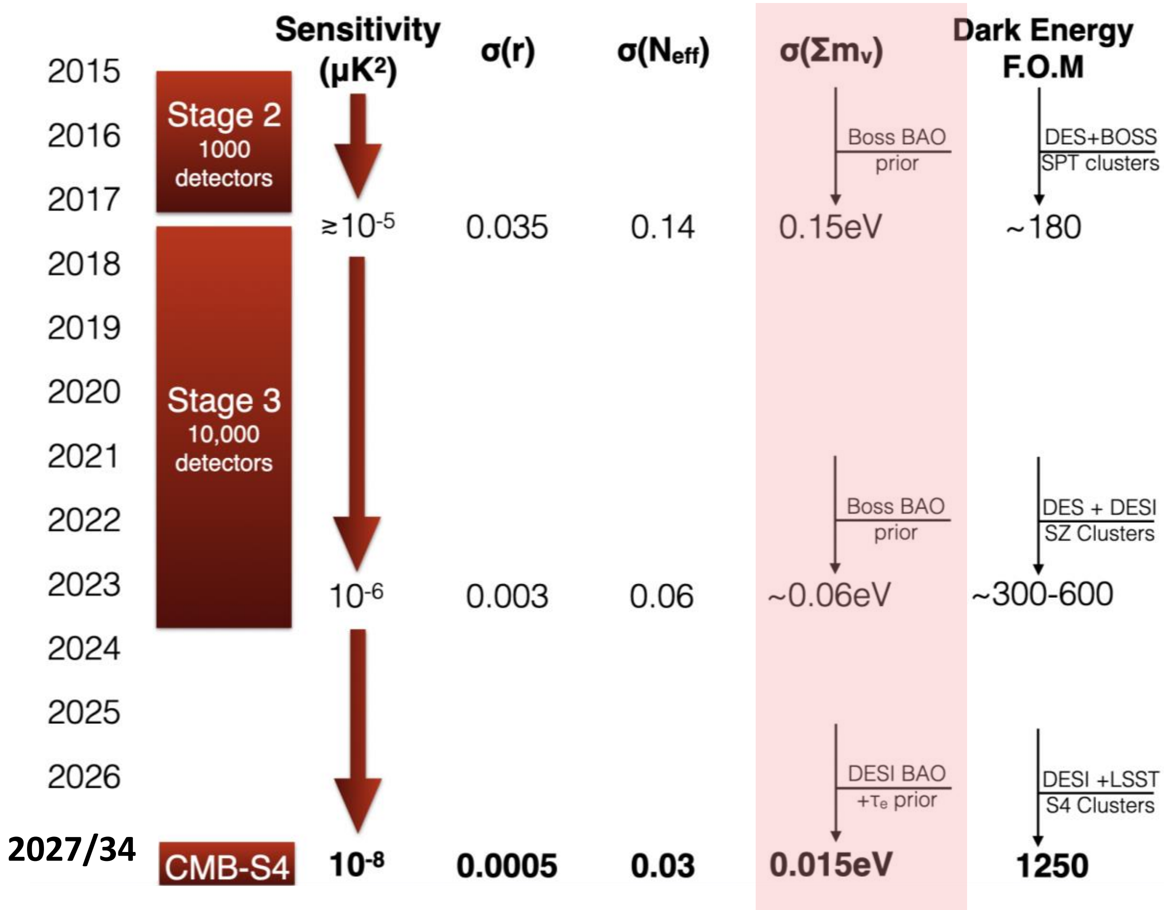
CMB observations



John Carlstrom

What to expect in the future?

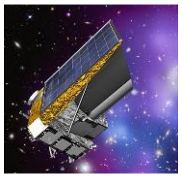
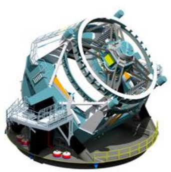
CMB observations



John Carlstrom

What to expect in the future?

Galaxies, cosmic shear, clusters, etc.

			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

These numbers mean, if the true neutrino mass sum is $\sum m_\nu = 0.06$ eV, then it is possible to measure it with $(3-5)\sigma$ significance.

Do you need to believe these forecasts?

Yes and no.

- Forecasts are just that: **an estimate** of what an instrument can do under an assumed set of conditions*.
  - * including our ability to predict theoretically the observables given an underlying cosmology theory.
  - Clearly, some observables are inherently under better control than others (see **nonlinearities** slide).
- So, again, your best bet is to treat these forecasted sensitivities as **ballpark figures**.

What it takes for me (Y^3W) to believe it?

Suppose one of these future probes announces a cosmological detection of the neutrino mass sum. Would I believe it?

- I might pay attention, depending on who is announcing it (again, refer to nonlinearities slide).

- But I won’t believe any of it until **multiple observations/data combinations** point to the same mass sum value with some statistical significance.

Summary…

These is no doubt that neutrino masses induce some non-trivial effects on cosmological observables.

- You can even turn this around and use cosmological observables to “measure” the neutrino mass.

- But please please please don’t over-interpret bounds or forecasted sensitivities. They are best treated as ballpark figures.

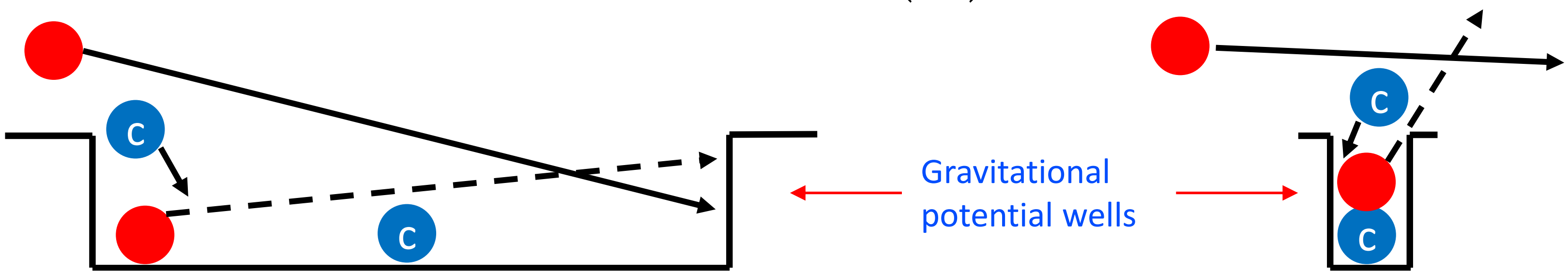
- Until **multiple observation**s have measured the same neutrino mass sum value, take all “measurements” *cum grano salis*.

Extra slides...

Why? Free-streaming suppression…

Neutrino thermal motion prevents efficient on small length scales.

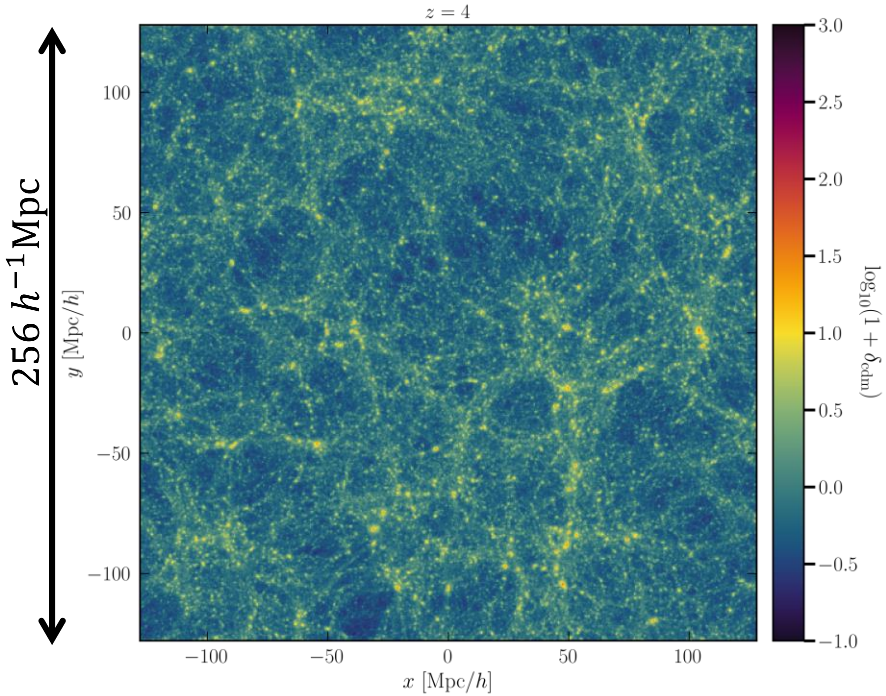
$$v_{\text{themal}} = \frac{T_{\text{C}\nu\text{B}}}{m_\nu} \approx 50\,(1+z)\left(\frac{\text{eV}}{m_\nu}\right)\text{km s}^{-1}$$



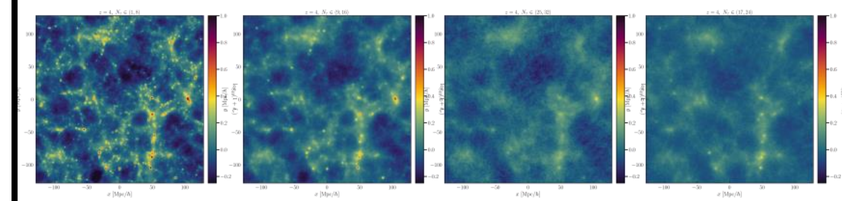
Free-streaming scale
(at any one time):

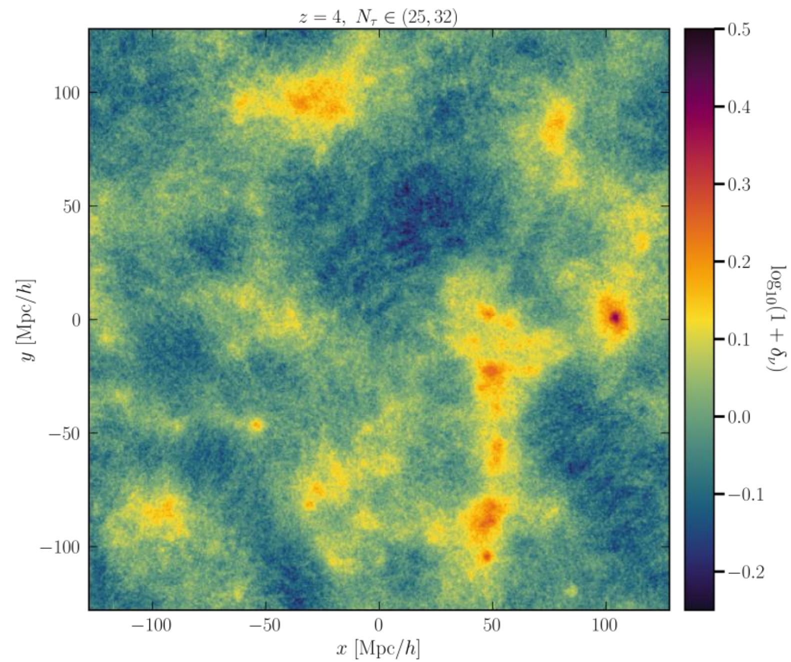
$$\lambda_{\text{fs}} \equiv \sqrt{\frac{8\pi^2 v_{\text{thermal}}^2}{3\Omega_m H^2}} \approx 4.2\sqrt{\frac{1+z}{\Omega_{m,0}}\left(\frac{\text{eV}}{m_\nu}\right)}\;h^{-1}\,\text{Mpc}$$

Cold dark matter component



Increasing neutrino momentum

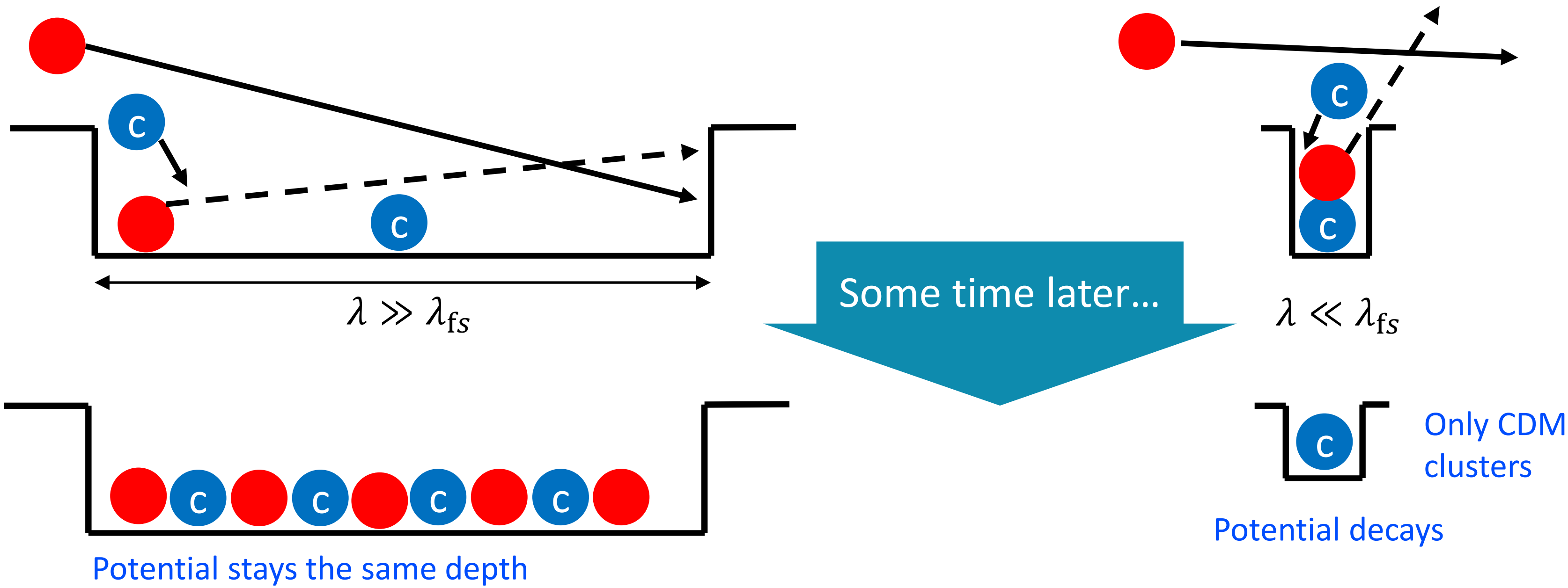




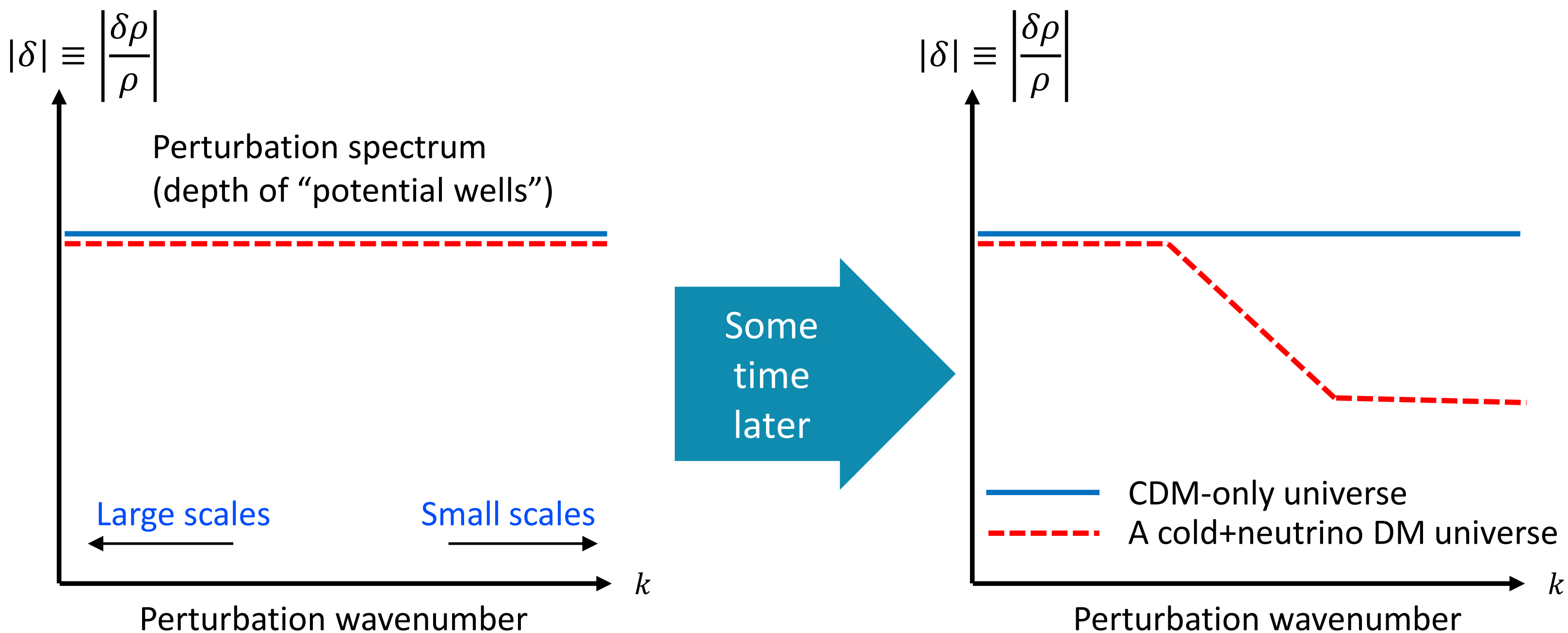
Neutrino component ($\sum m_\nu = 0.5$eV)

N-body code: Gadget-Hybrid:
Chen, Mosbech, Upadhye & Y[3]W, in prep
Post-processing/graphics: G. Pierobon

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



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



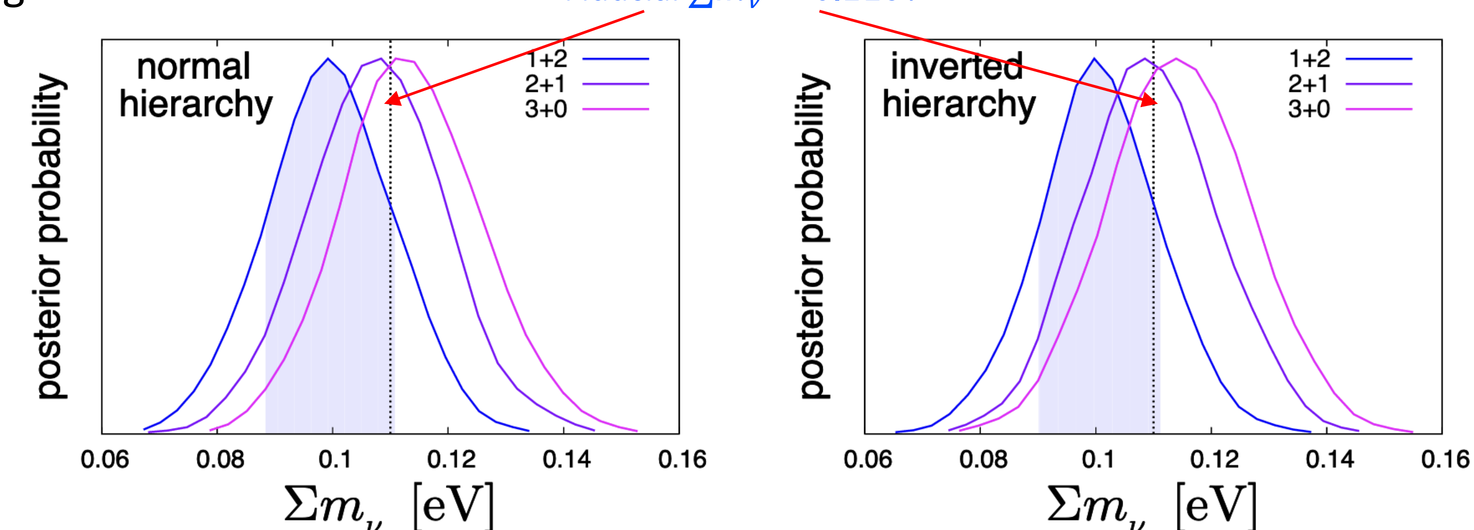
The presence of neutrino dark matter induces a step-like feature in the spectrum of gravitational potential wells.

Can you discern the mass spectrum?

Not for Euclid-like sensitivity.

- Fiducial model has 3 degenerate neutrinos
- Fitting 3 different mass spectra against fiducial data shows no statistically significant difference.

Fiducial $\sum m_\nu = 0.11\text{eV}$

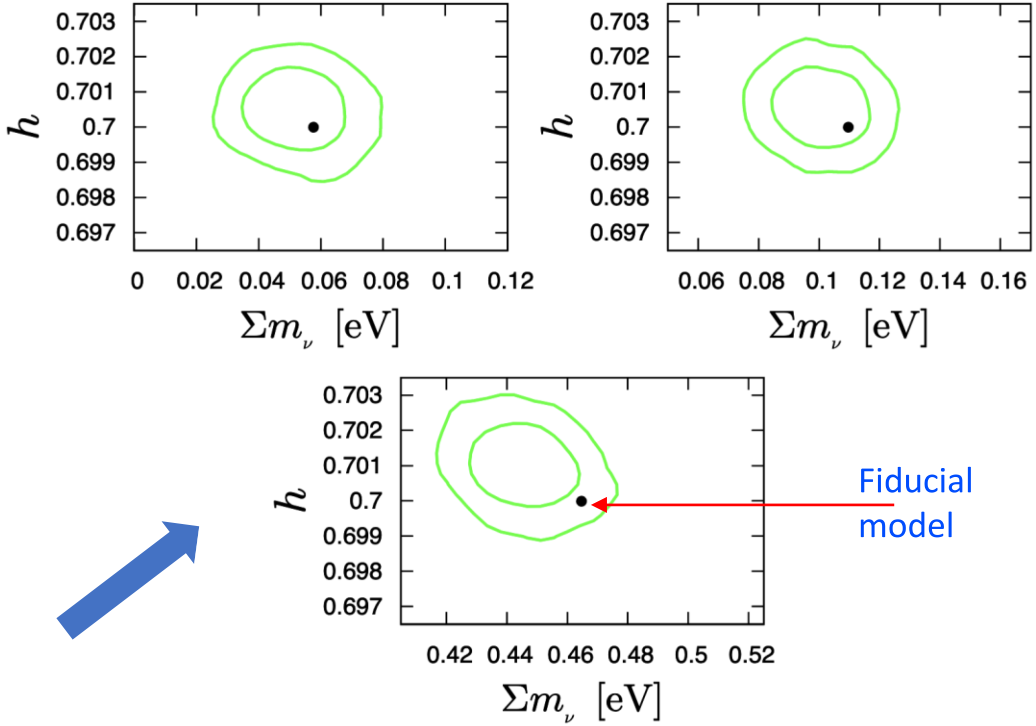


Hamann, Hannestad & Y[3]W 2012

Can you discern time evolution?

The presence of massive neutrinos leads **in theory** to a unique, time-dependent suppression of the matter power spectrum.

- **In practice**, a Euclid-like survey will not be able to pin this down with statistical significance.
- Fiducial data = correct time-dependence; Fit = no time-dependence.



Hamann, Hannestad & Y[3]W 2012