Neutrino (and other particle) physics in large-scale structure

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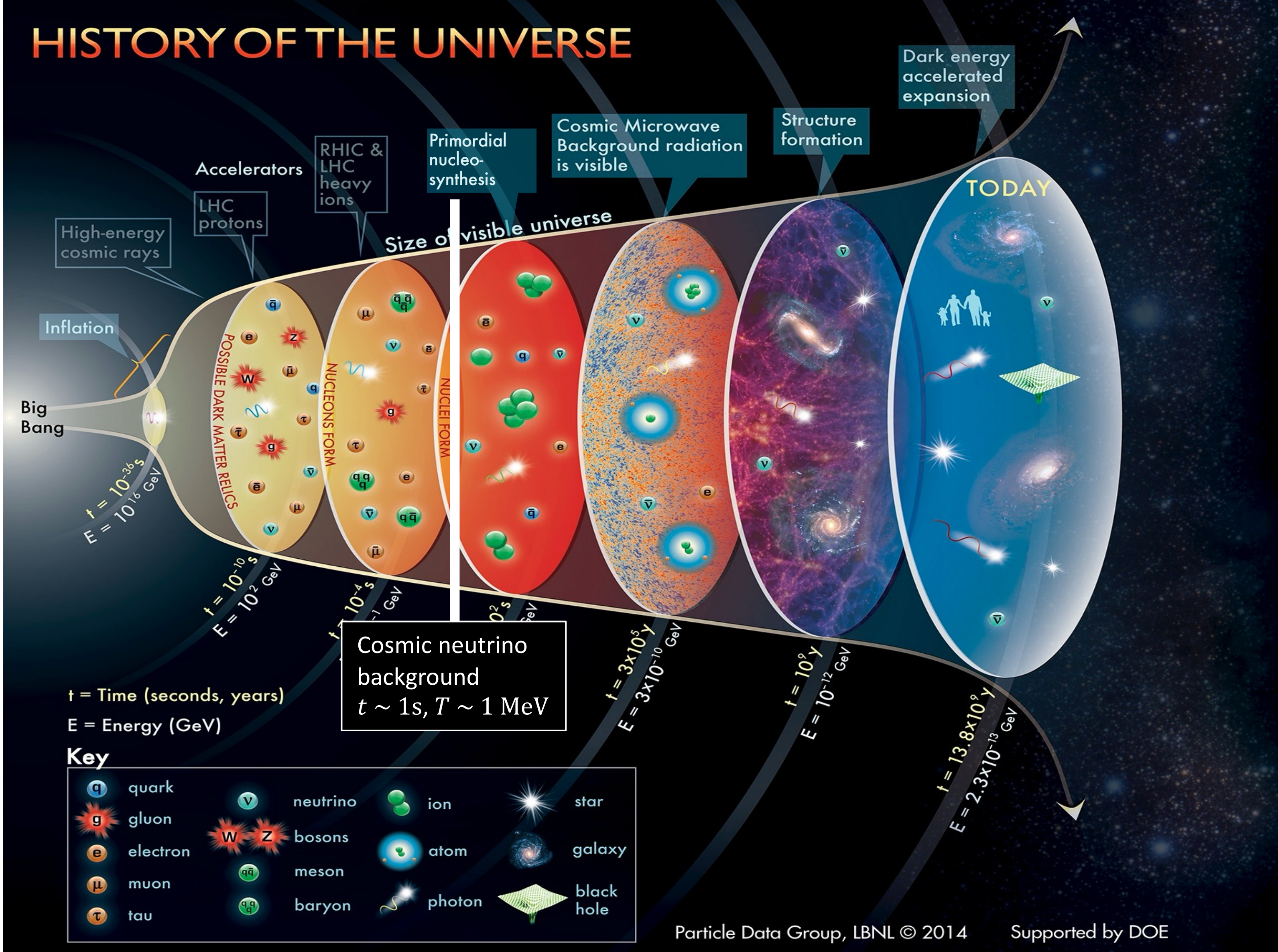
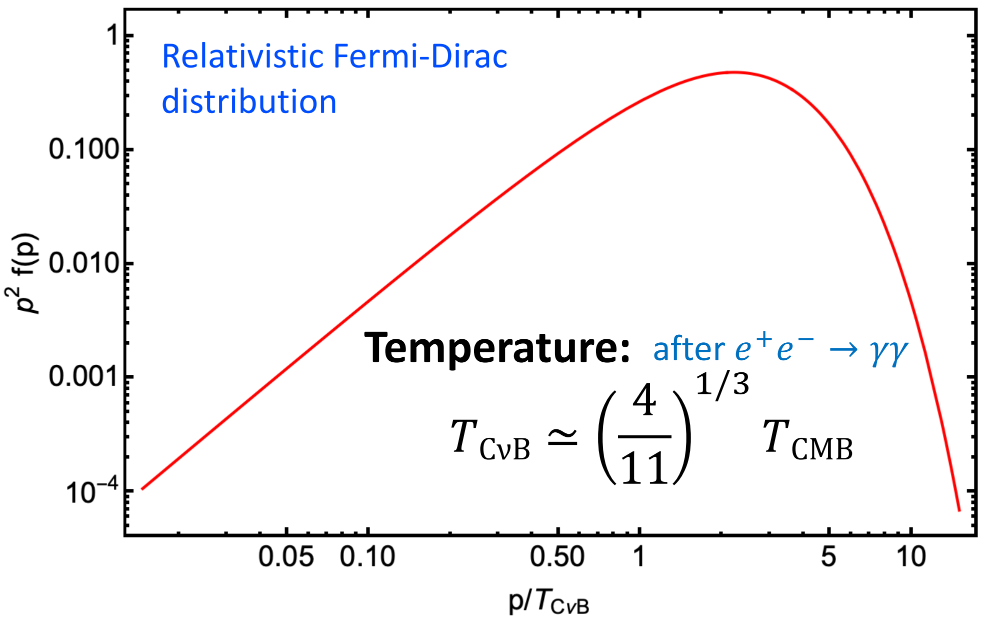


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
Primordial nucleo-synthesis
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
Cosmic neutrino background
$t \sim 1$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 $e^+e^- \to \gamma\gamma$

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

Number density: Per family of neutrinos +antineutrinos

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

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 $T_{C\nu B} \ll m_\nu$):

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

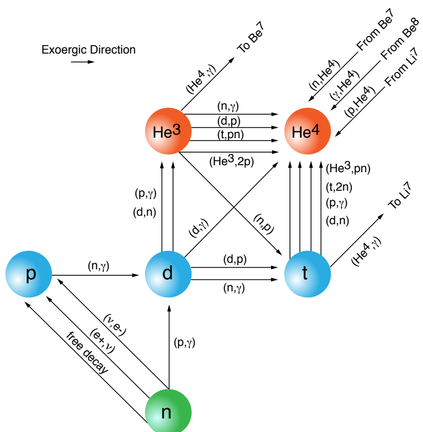
Neutrino (hot) dark matter

Reduced Hubble parameter

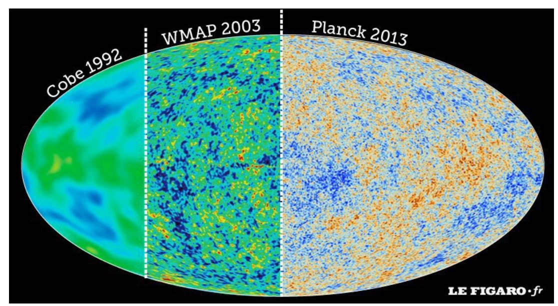
Cosmological bounds on neutrino physics...

How the CνB affects the events that take place after its formation can be **exploited to constrain its properties**.

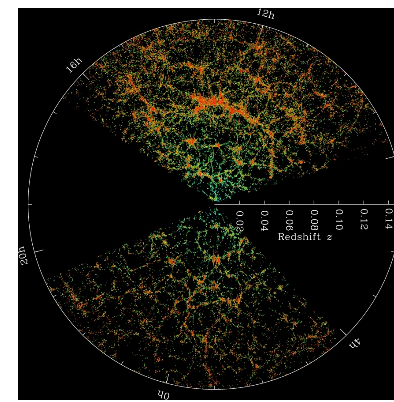
Light element abundances



CMB anisotropies



Large-scale matter distribution



Properties of the CνB probed:

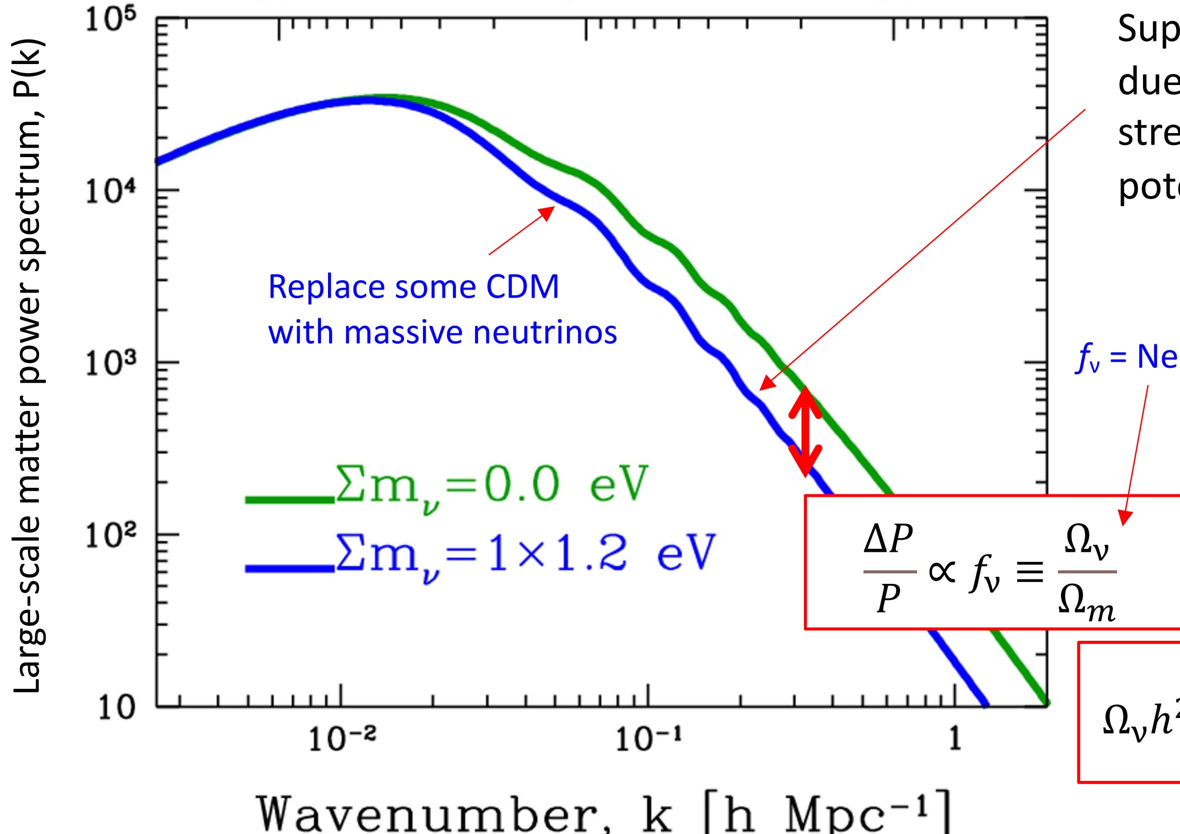
N_{eff} (expansion rate)

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

$\sum m_\nu$ (perturbation growth)
Interactions (free-streaming)
Lifetime (free-streaming)

See talk by A. Upadhye

E.g., neutrino masses & perturbation growth...



Suppression of power due to neutrino free-streaming induced potential decay

f_ν = Neutrino fraction

The larger the mass sum, the larger the suppression.

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

Constraints on the neutrino mass sum…

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

		+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**
2015 number	0.49	0.59	0.17	n/a

Two different high-ℓ likelihood functions

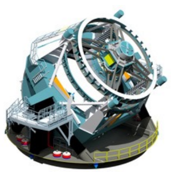
Planck2015 TT+lowP+Lyα $\sum m_\nu < 0.13$ eV

Palanque-Delabrouille et al. 2015

Aghanim et al. [Planck] 2018
Ade et al. [Planck] 2015

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

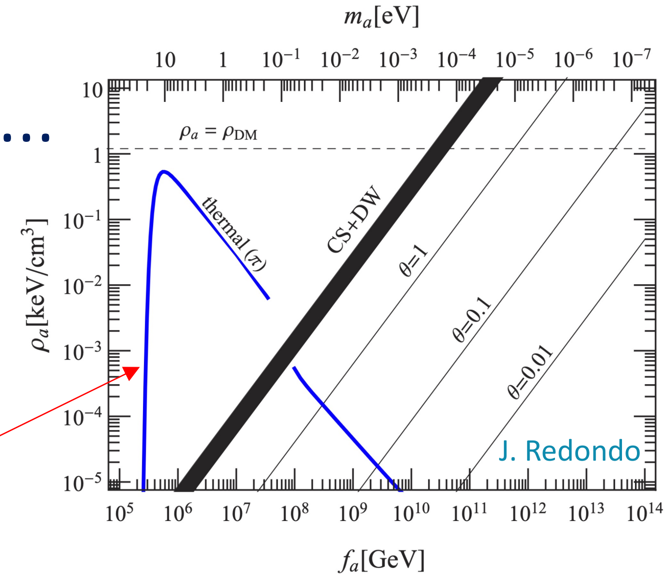
These numbers mean, if the true neutrino mass sum is $\sum m_\nu = 0.06$ eV (minimum number required by neutrino oscillation experiments), then it will be possible to measure it with $(3-5)\sigma$ significance.

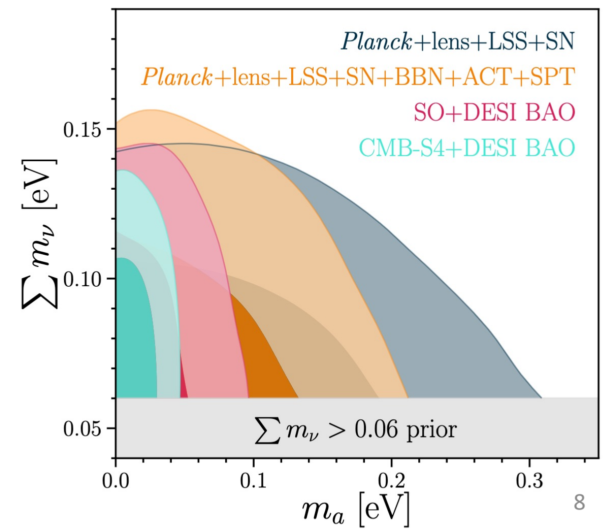
Variants on the same theme…

Some other BSM particle physics scenarios can also be constrained in the same way.

- E.g., for sufficiently **small axion decay constants** f_a, a thermal background of QCD axions can be produced via $\pi + \pi \to \pi + a$ in the early universe ($T \sim \Lambda_{\rm QCD} \sim 200$ MeV).
- **Analogous to the CνB** → the axion mass m_a can be constrained in the same way as $\sum m_\nu$.

Bianchini, Cortona & Valli 2023
Also:
Notari, Rompineve & Villadoro 2023
D'Eramo et al. 2022
Hannestad, Mirizzi, Raffelt & Y[3]W 2007, 2008, 2010, 2013, etc.





Cosmological bounds on neutrino physics...

How the CνB affects the events that take place after its formation can be **exploited to constrain its properties**.

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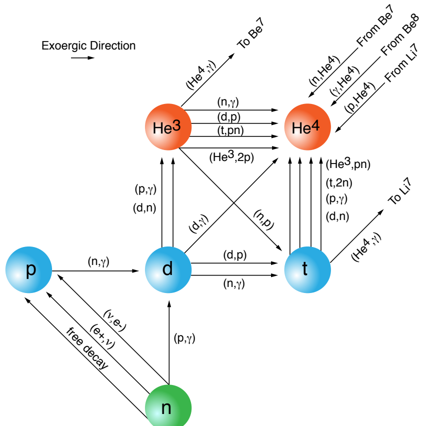
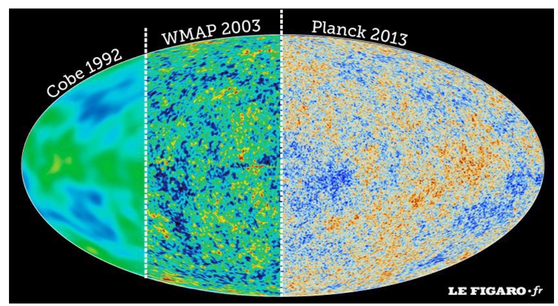
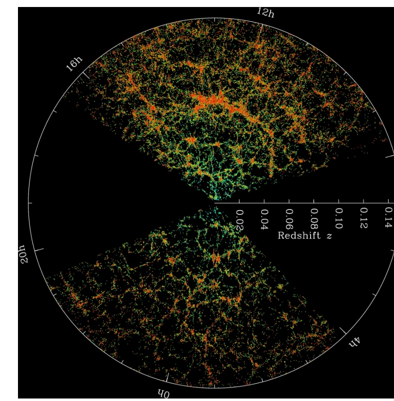


CMB anisotropies



Large-scale matter distribution



Properties of the CνB probed:

Light element abundances: $N_{\rm eff}$ (expansion rate)

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

Large-scale matter distribution:
- $\sum m_\nu$ (perturbation growth)
- **Interactions (free-streaming)**
- **Lifetime (free-streaming)**

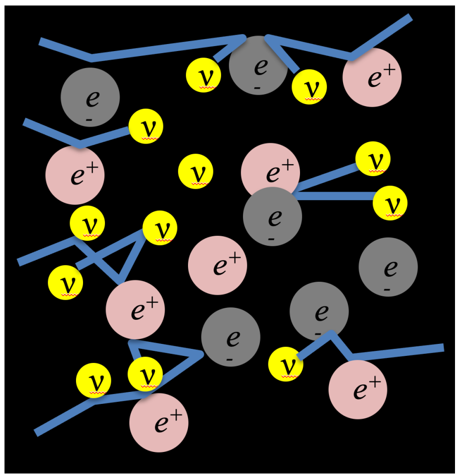
Constraining non-standard neutrino interactions & lifetime…

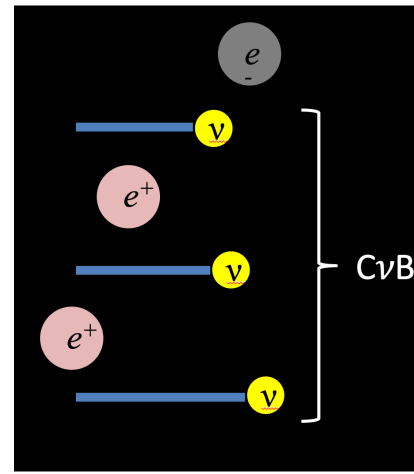
Cosmic neutrino background …

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.

($T_{\odot\text{core}} \sim 1$ keV)

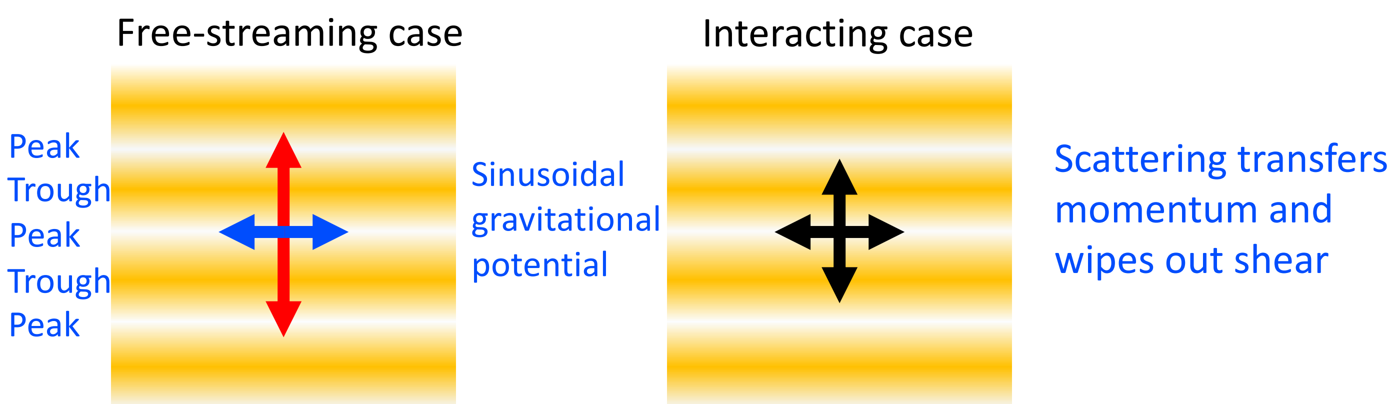
Above $T \sim 1$ MeV, even weakly-interacting neutrinos can be produced, scatter off e^+e^- and other neutrinos, and attain thermodynamic equilibrium

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

Neutrino free-streaming vs interactions…

Standard-model neutrinos free-stream.

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



Neutrino shear stress & the metric...

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

Scale factor

Conformal Newtonian gauge

$$\mathrm{d}s^2 = a^2(\tau)[-(1+2\psi)\mathrm{d}\tau^2 + (1-2\phi)\mathrm{d}x^i\mathrm{d}x_i]$$

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

Shear stress

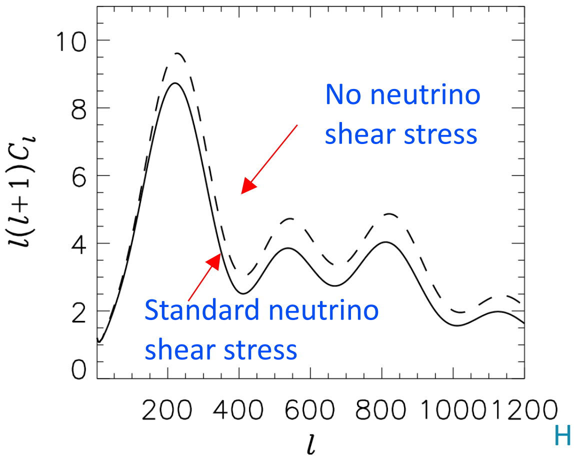
In ΛCDM, mainly from ultra-relativistic neutrinos and photons.

Mean energy density & pressure

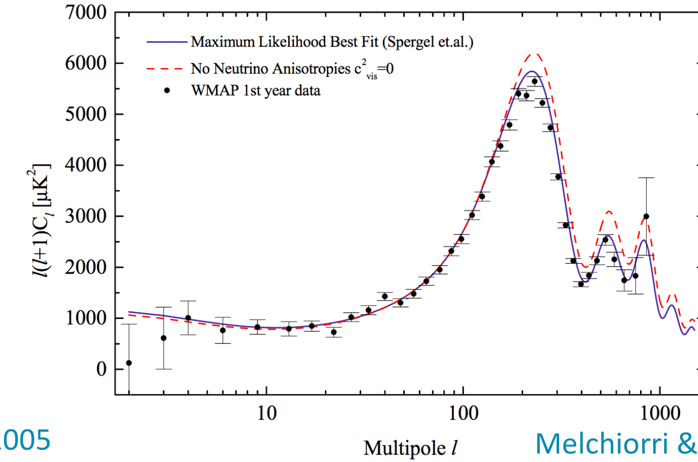
- Changes to $(\phi - \psi)$ at CMB formation times affect the evolution of CMB perturbations and are observable in the **TT power spectrum**.
- In turn, the evolution of ϕ and ψ individually can influence **growth of matter perturbations**.

Neutrino shear stress & the CMB…

That the CMB prefers neutrino shear stress to no shear stress has been known for a long time.



Hannestad 2005



Melchiorri & Trotta 2005

- The tricky part is in translating this preference to constraints on the fundamental parameters of a non-standard neutrino interaction

→ What is the **isotropisation timescale** given an interaction?

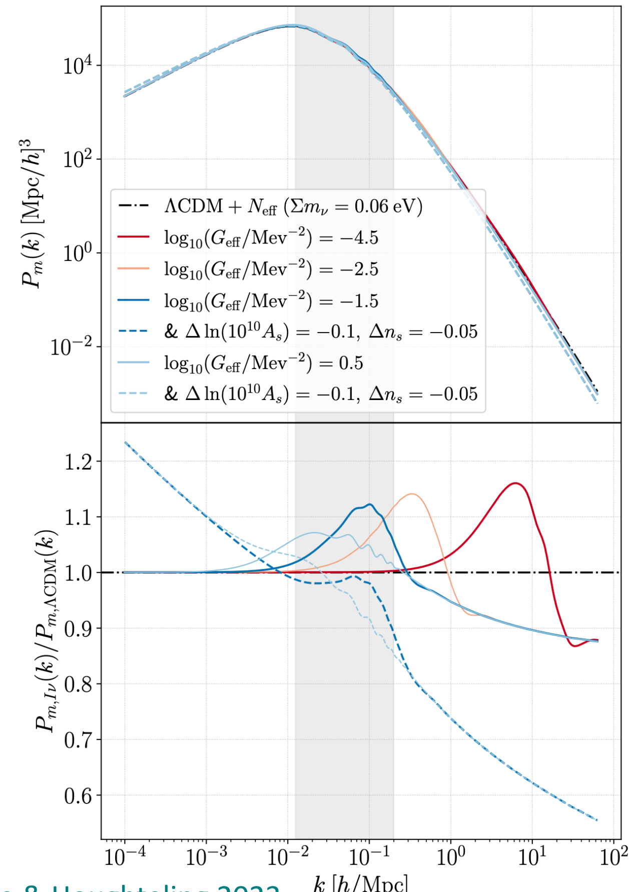
I'll come back to this in a bit.

Neutrino shear stress & LSS power spectrum…

Neutrino shear stress (or lack thereof) also has a signature in the mildly-nonlinear part of the matter power spectrum.

- Large neutrino shear stress expected only **during and shortly after radiation domination**, when neutrinos are ultra-relativistic.
  - Observable signatures are thus confined to small scales that entered the horizon at the said times.

- There is however room for improvement in the modelling of the LSS signature….



Camarena, Cyr-Racine & Houghteling 2023

Isotropisation timescale $T_{\mathrm{isotropise}}$…

The key to **connecting anisotropic stress loss to a non-standard neutrino interaction** lies in the isotropisation timescale.

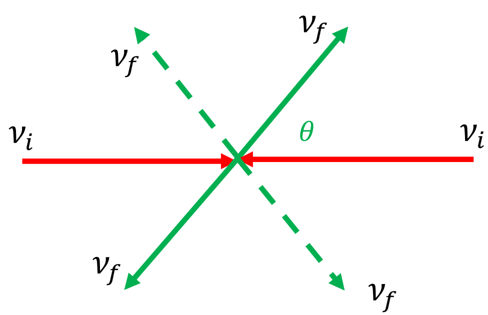
- Given an interaction Lagrangian, $T_{\mathrm{isotropise}}$ is calculable.
- Write down the Boltzmann equation:

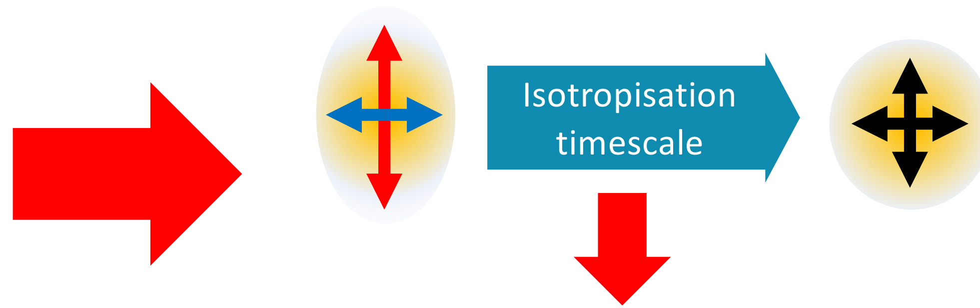
$$P^\alpha \frac{\partial f}{\partial x^\alpha} - \Gamma^\gamma_{\alpha\beta} P^\alpha P^\beta \frac{\partial f}{\partial P^\gamma} = \frac{1}{2} \left(\prod_j^N \int g_j \frac{\mathrm{d}^3 \mathbf{n}_j}{(2\pi)^3 2E_j(\mathbf{n}_j)} \right) \left(\prod_k^M \int g_k \frac{\mathrm{d}^3 \mathbf{n}_k}{(2\pi)^3 2E_k(\mathbf{n}_k)} \right)$$
$$\times (2\pi)^4 \delta_D^{(4)} \left(p + \sum_j^N n_j - \sum_k^M n'_k \right) |\mathcal{M}_{i+j_1+\cdots+j_N \leftrightarrow k_1+\cdots+k_M}|^2$$
$$\times [f_{k_1} \cdots f_{k_N} (1 \pm f_i)(1 \pm f_{j_1}) \cdots (1 \pm f_{j_N}) - f_i f_{j_1} \cdots f_{j_N} (1 \pm f_{k_1}) \cdots (1 \pm f_{k_M}$$

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

Example 1: ν self-interaction…

Isotropisation from 2-to-2 scattering $\nu_i + \nu_i \rightarrow \nu_f + \nu_f$.





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

Scattering rate

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

$$\gtrsim 400 \text{ kyr}$$

→ Upper limit on $\Gamma_{\text{scattering}}$ (hence coupling).

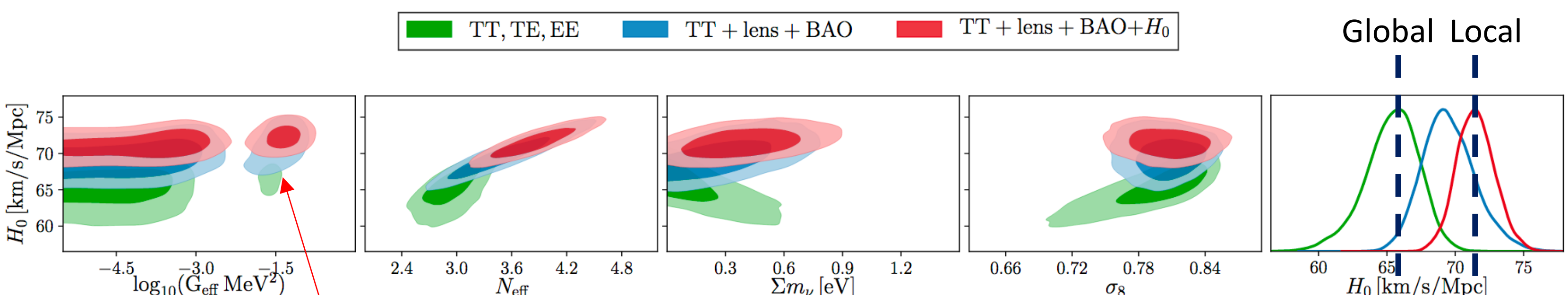
Cyr-Racine & Sigurdson 2014; Oldengott, Rampf & Y[3]W 2015; Lancaster, Cyr-Racine, Knox & Pan 2017; Oldengott, Tram, Rampf & Y[3]W 2017; Kreisch, Cyr-Racine & Dore 2019; Forastieri et al. 2019; etc.

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; $H_0 = (67.4 \pm 0.5)\ \mathrm{km/s/Mpc}$



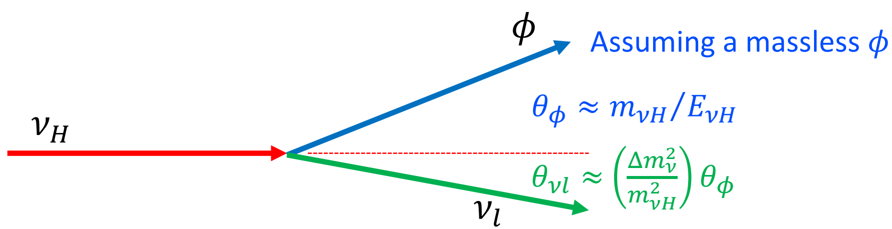
This island:
$G_{\rm eff} \sim 10^{10} G_F$

For now this is mainly a CMB result. But the scenario can be further tested in the mildly-nonlinear part of the matter power spectrum.

Example 2: Relativistic ν decay…

Some boson

Isotropisation can also happen via $\nu_H \to \nu_l + \phi$ and its inverse process $\nu_l + \phi \to \nu_H$, but the rate is a bit more complicated.



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

Inverse decay can also only happen when the daughter particles satisfy **strict momentum/angular requirements**.

Boost   Rest-frame lifetime

→ Isotropisation takes a loooooong time:

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

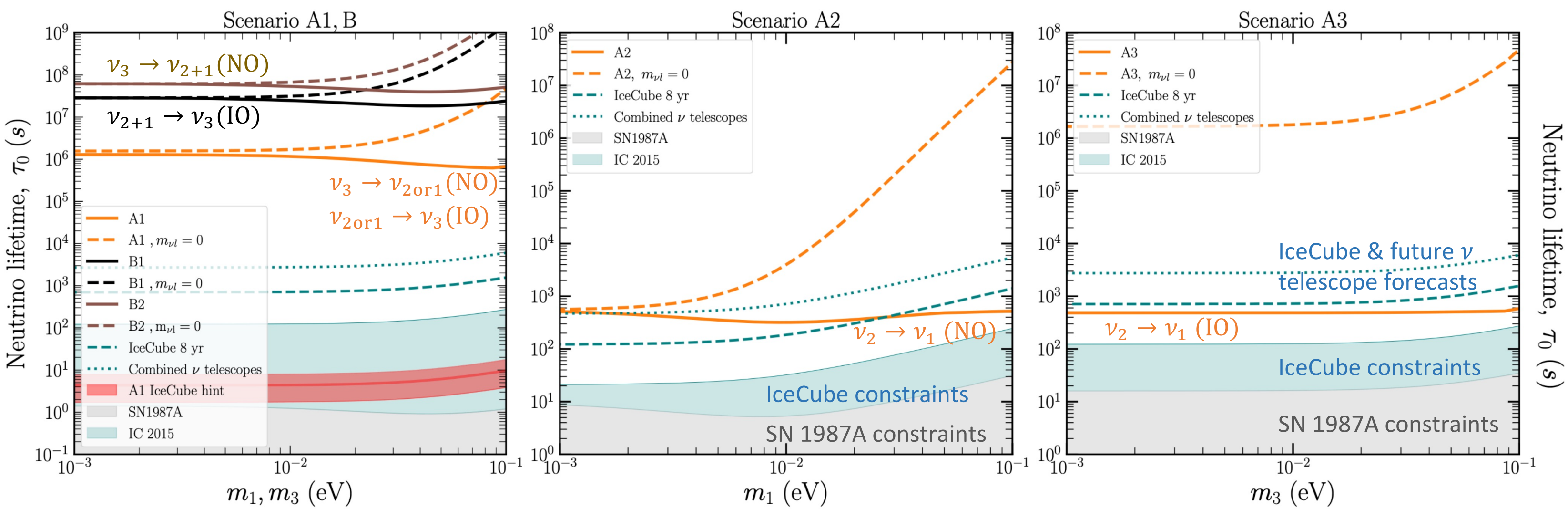
$$\gtrsim 400 \text{ kyr}$$

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

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

Lower bounds on the neutrino lifetime…

CMB currently gives the best limits on invisible neutrino decay $\nu_H \rightarrow \nu_l + \phi$.



NO = Normal mass ordering
IO = Inverted mass ordering

Chen, Oldengott, Pierobon & Y[3]W 2022

* IceCube constraints & forecasts from Song et al. 2021

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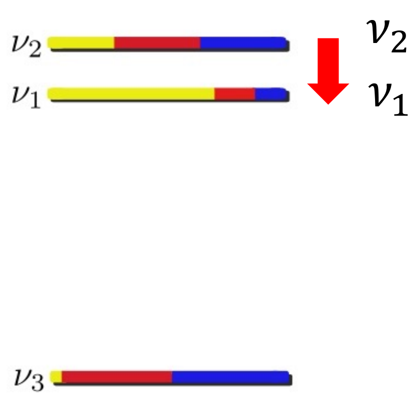
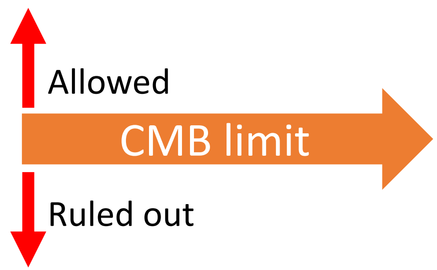


Inverted mass ordering

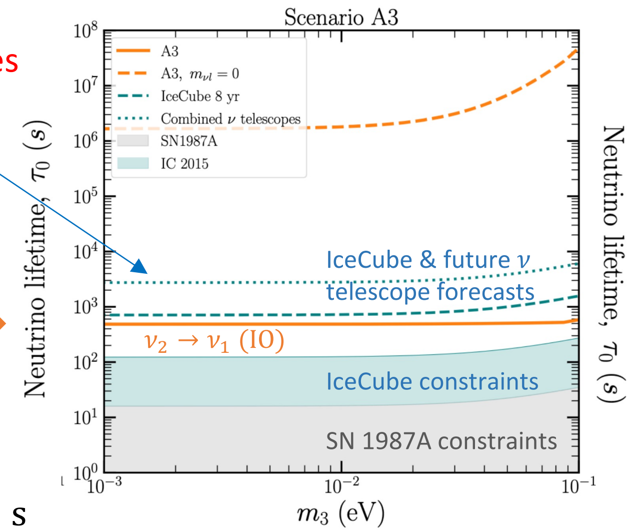
However, depending on the exact decay scenario, neutrino telescopes may become competitive in the future! Watch this space!



BBN: $\tau_0 \gtrsim 10^{-2} \to 10^{-1}$ s

Solar ν: $\tau_0 \gtrsim 10^{-5} \to 10^{-4}$ s

Lab ν: $\tau_0 \gtrsim 10^{-13} \to 10^{-11}$ s



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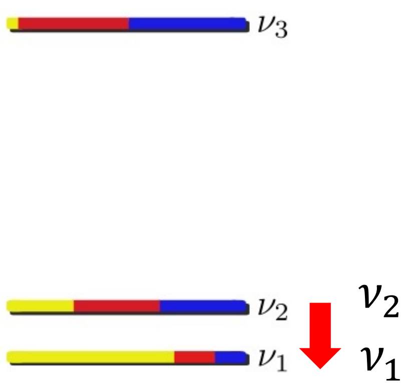

Normal mass ordering

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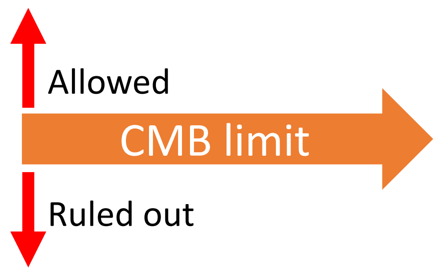

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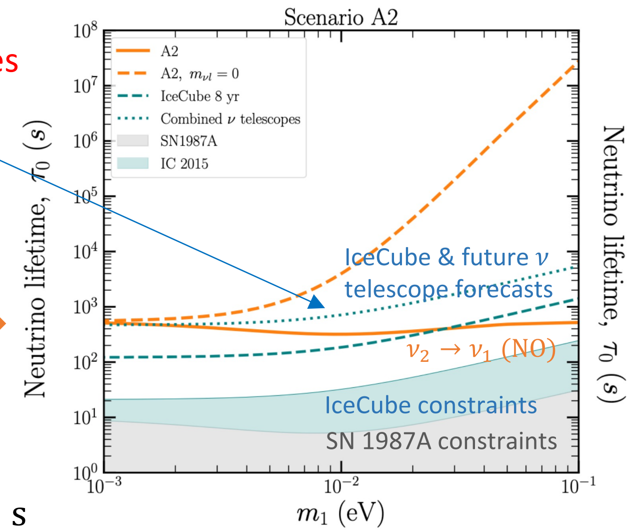

Chen, Oldengott, Pierobon & Y[3]W 2022

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Summary…

It is well known that CMB/large-scale structure observations can set very competitive upper limits on the neutrino mass sum.

- But there are also other well-motivated particle physics scenarios, e.g., the QCD axion, that can be constrained in the same way.

- Furthermore, besides mass limits, CMB/LSS observations can also be used to probe non-standard neutrino interactions and to constrain the neutrino lifetime.
  - However, more work on modelling is required to predict the precise LSS signatures of these scenarios.