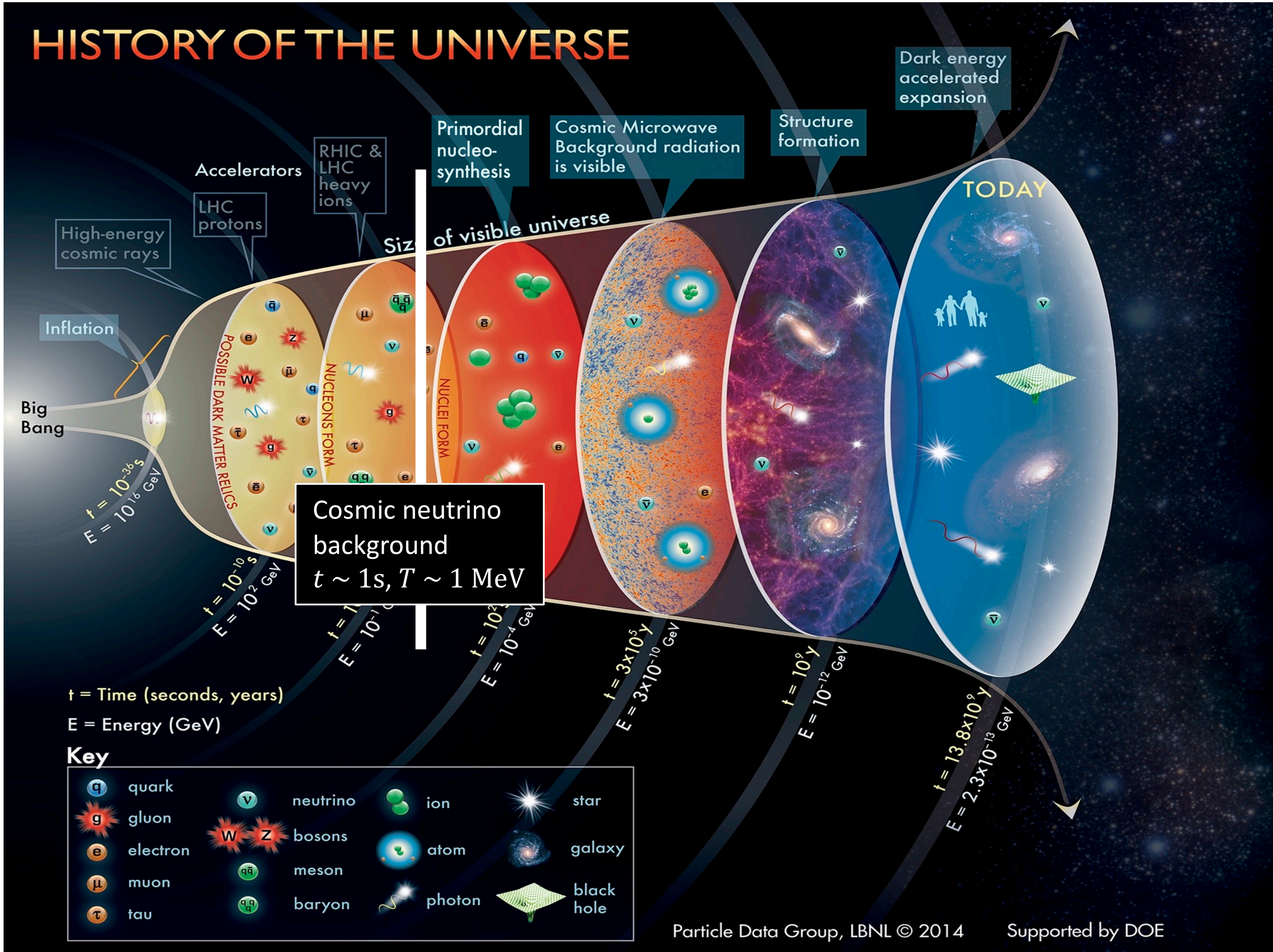
Constraining the neutrino lifetime with precision cosmology

Barenboim, Chen, Hannestad, Oldengott, Tram & Y^{3}W, *JCAP* 03 (2021) 087 [arXiv:2011.01502 [astro-ph.CO]]
Chen, Oldengott, Pierobon & Y^{3}W, *EPJC* 82 (2022) 7, 640 [arXiv:2203.09075 [hep-ph]]

Yvonne Y. Y. Wong, UNSW Sydney

Neutrino Frontiers Focus Week, GGI Florence, July 1 - 5, 2024



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
Big Bang
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
Cosmic neutrino background
$t \sim 1\mathrm{s}, T \sim 1$ MeV
$t = 10^{-36}$ 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
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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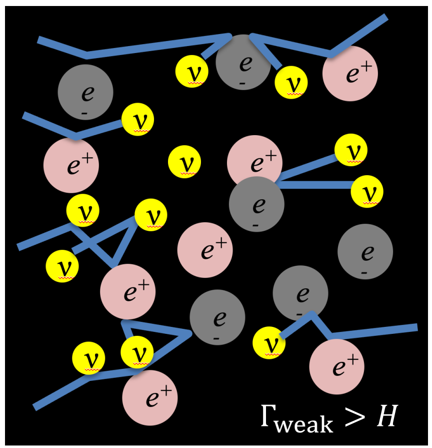
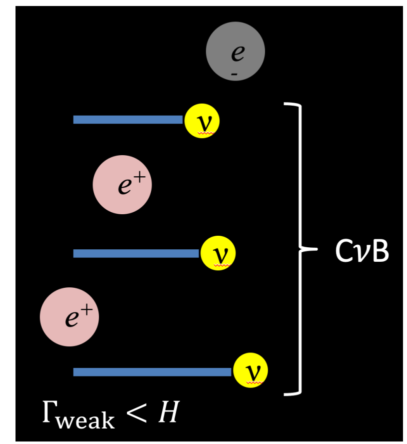
Formation of the CνB…

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.

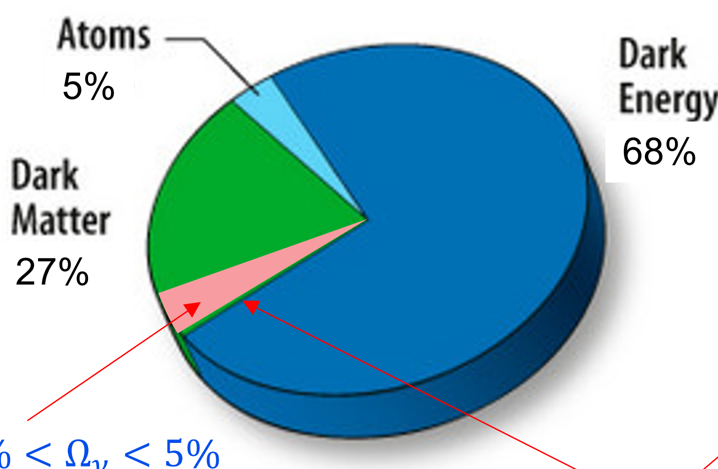
Above $T \sim 1$ MeV, even the Weak Interaction occurs efficiently enough to allow neutrinos to scatter off e^+e^- and other neutrinos, and attain thermodynamic equilibrium.

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

Three key predictions of the CνB…

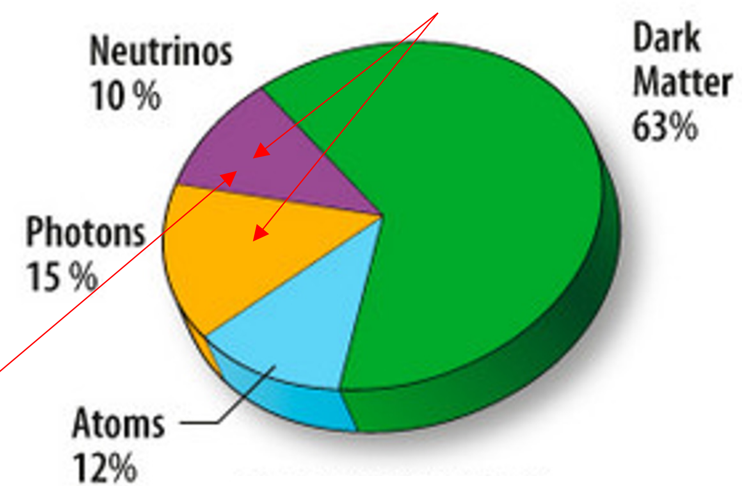
… assuming the SM of particle physics + neutrino masses.

$\frac{\rho_\nu}{\rho_\gamma}$~0.68 or $N_{\mathrm{eff}} = 3.0440$ is fixed by SM physics



A $0.1\% < \Omega_\nu < 5\%$ subdominant dark matter component in SM massive neutrinos

Composition today



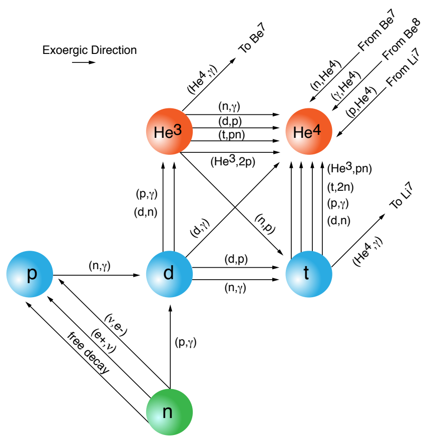
The neutrinos free-stream, i.e., they do not interact except gravitationally

13.4 billion years ago
(at photon decoupling)

Testing CνB predictions against observations…

We cannot (yet) detect the CνB in the lab. But we can look its imprints on cosmological observables to see if they are consistent with expectations

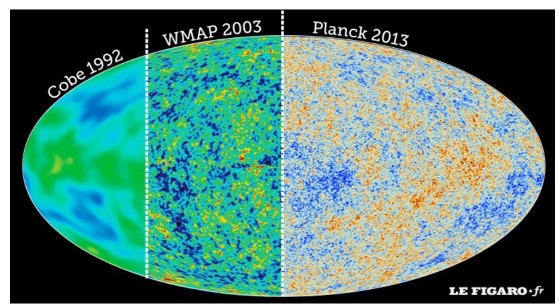
Light element abundances



Properties of the CνB probed:

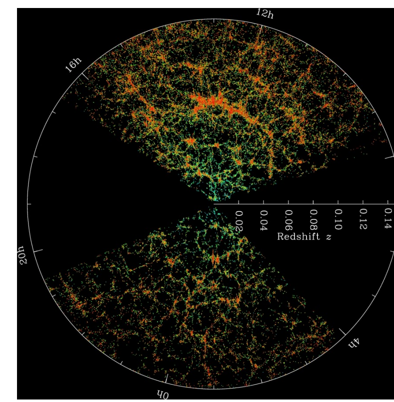
$N_{\rm eff}$ (expansion rate)

CMB anisotropies



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

Large-scale matter distribution



$\sum m_\nu$ (perturbation growth)

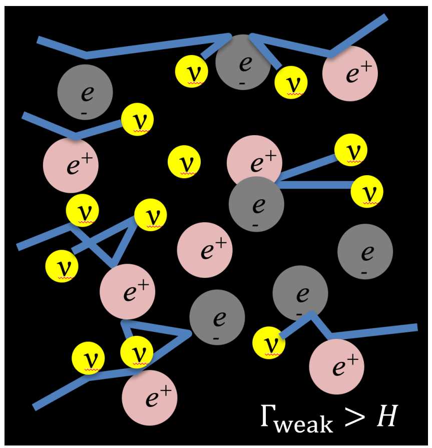
Testing relativistic neutrino free-streaming…

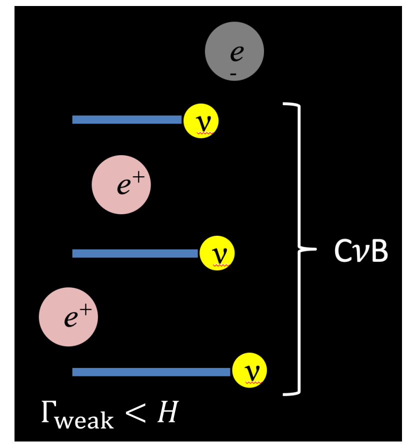
Interaction rate: $\Gamma_{\text{weak}} \sim G_F^2 T^5$

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

Formation of the CνB…

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





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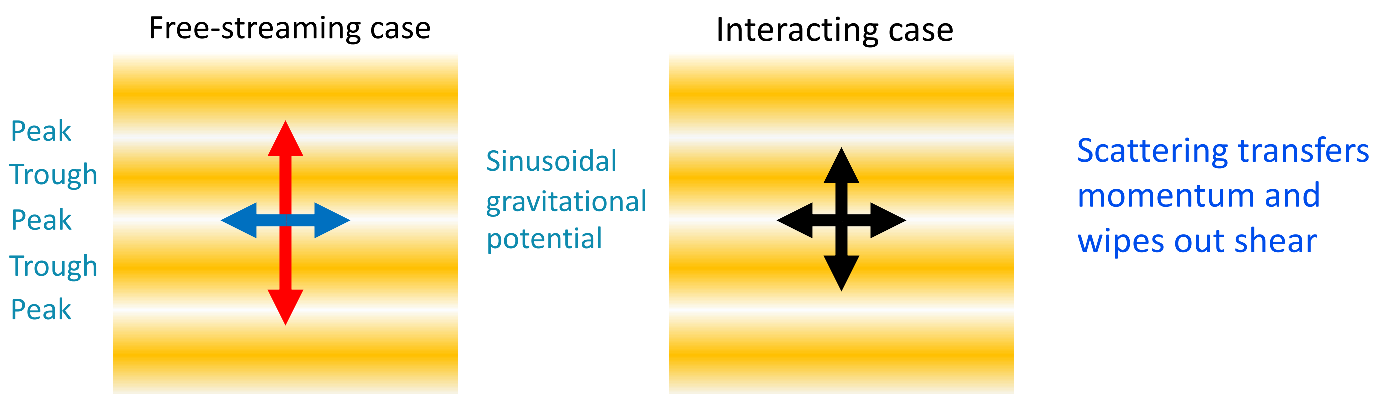
Above $T \sim 1$ MeV, even the Weak Interaction occurs efficiently enough to allow neutrinos to scatter off e^+e^- and other neutrinos, and attain thermodynamic equilibrium.

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

Free-streaming in inhomogeneities…

Standard Model neutrinos free-stream after decoupling.

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



Why is this interesting for the CMB?

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

Conformal Newtonian gauge

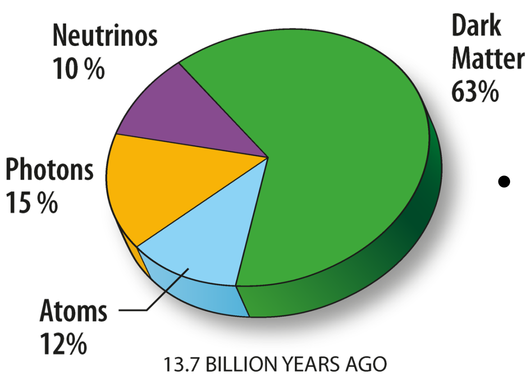
Scale factor

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

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

Shear stress
At CMB times, mainly from ultra-relativistic neutrinos and photons.

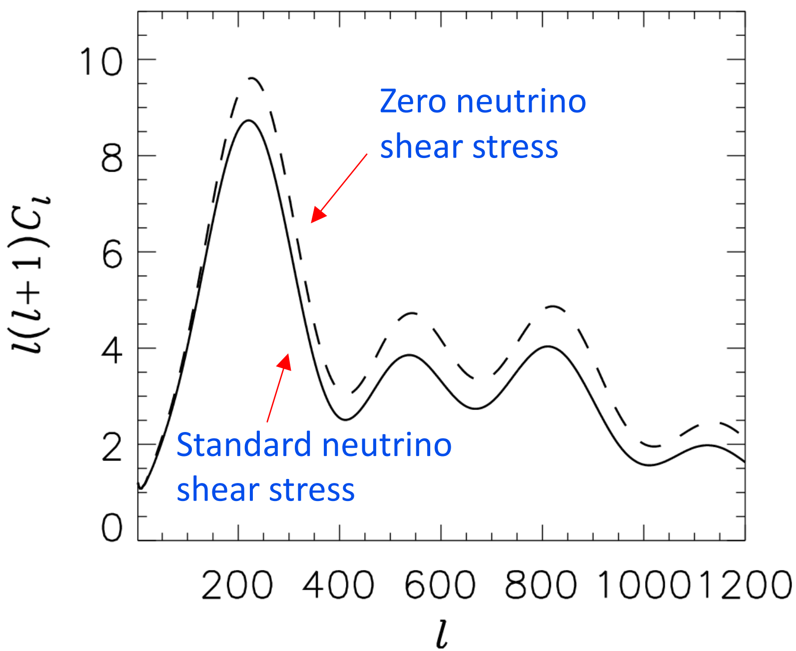
Mean energy density & pressure



- The **CMB temperature fluctuations** respond to changes in $(\phi - \psi)$

→ Observable effects in the **CMB TT power spectrum**

Neutrino shear & the CMB TT spectrum…

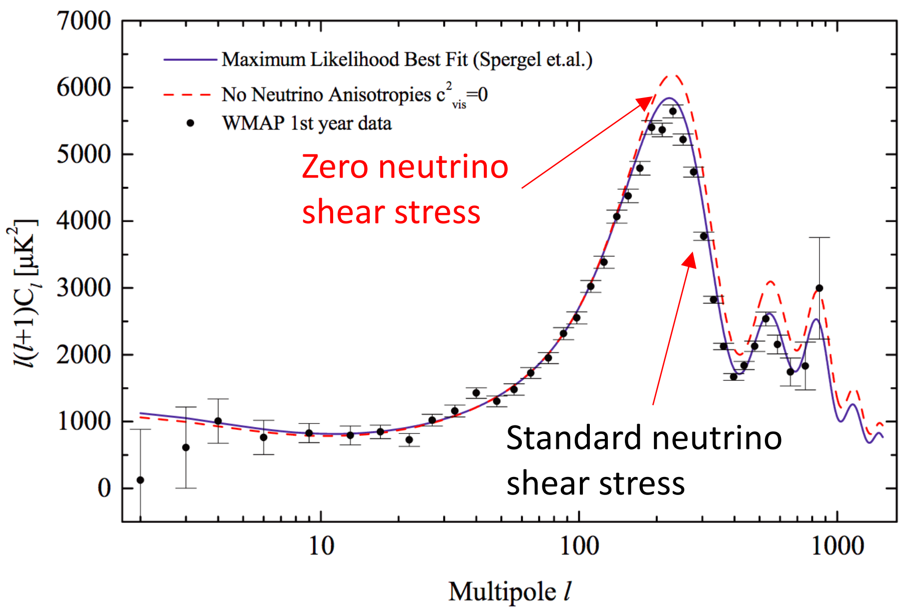


Hannestad 2005

Removing neutrino shear stress enhances power at multipoles $\ell \gtrsim 200$.

- Effect is mildly degenerate with the primordial fluctuation amplitude and spectral tilt.
- But even with **WMAP-1st year data**, it was already possible to exclude zero neutrino shear stress at $\gtrsim 2\sigma$.

Neutrino shear & the CMB TT spectrum…



Melchiorri & Trotta 2005

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- But even with **WMAP-1st year data**, it was already possible to exclude zero neutrino shear stress at $\gtrsim 2\sigma$.

A more modern take…

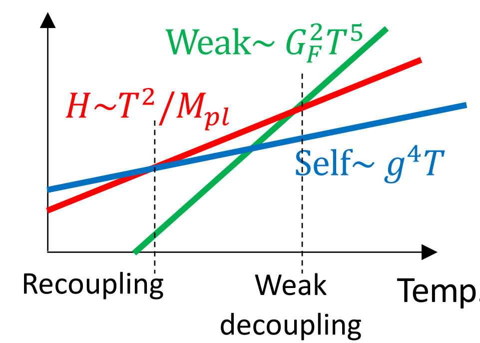
Recent analyses usually split the discussion of relativistic free-streaming constraints on neutrino self-interactions into two limiting behaviours:

- **Decoupling** scenario:
  - Realised, by, e.g., 2-to-2 contact interaction
  - Delay neutrino decoupling to CMB temperatures ($T \sim 0.2 - 1$ eV) i.e., neutrinos enter the CMB epoch with no anisotropic stress.

  → **How late** into the CMB epoch can data tolerate no anisotropic stress?

- **Recoupling** scenario:
  - Realised by, e.g., 2-to-2 scattering with light or massless mediator, relativistic 2-to-1 decay.

  → **How early** in the CMB epoch can neutrinos begin to lose anisotropic stress?



Recoupling from relativistic invisible neutrino decay …

Invisible neutrino decay…

Invisible here means the decay products do **not** include a photon.

- **SM $1 \to 3$ decay:** $\nu_j \to \nu_i \nu_k \bar{\nu}_k$, but the rate is suppressed by m_ν^6.

  → For sub-eV neutrino masses, the neutrino lifetime would be $> 10^{10}$ longer than the present age of the universe, i.e., not very interesting. Bahcall, Cabibbo & Yahil 1972

- **Beyond SM**: generically one could consider

$$\nu_H \to \nu_l + \phi$$

SM neutrinos (sub-eV masses)

Some almost massless boson (scalar, pseudo-scalar, vector)

  - More freedom with the coupling strength and hence lifetime.
  - Predicted by a many extensions to the SM (mostly linked to neutrino mass generation or dark matter). Gelmini & Roncadelli 1981; Chikashige, Mohapatra & Peccei 1981; Schechter & Valle 1982; Dror 2020; Ekhterachian, Hook, Kumar & Tsai 2021; etc.

Isotropisation timescale…

Given the decay process, the **key to using relativistic free-streaming requirements** to constrain invisible neutrino decay is knowing the rate at which neutrino shear stress is lost due to the interaction.

→ What is the **isotropisation timescale** given a specific interaction?

Tracking neutrino perturbations…

The standard approach is to use the **relativistic Boltzmann equation** to describe the neutrino phase space distribution $f_i(x^\mu, P^i)$.

Liouville operator

$$P^\mu \frac{\partial f_i}{\partial x^\mu} - \Gamma^\nu_{\rho\sigma} P^\rho P^\sigma \frac{\partial f_i}{\partial P^\nu} = 0$$

Gravitational effects

- **Split** into $f_i(x^\mu, P^i) = \bar{f}_i(x^0, |P^i|) + F_i(x^\mu, P^i)$
- **Linearise** and go to Fourier space $x^i \leftrightarrow k^i$
- **Decompose** $F_i(x^o, k^i, P^i)$ into a Legendre series in $k \cdot P$.

Integrate in momentum:
$\ell = 0 \rightarrow$ density and pressure perturbations
$\ell = 1 \rightarrow$ velocity perturbations
$\ell \geq 2 \rightarrow$ anisotropies

Ma & Bertschinger 1995

Adding a short-range particle interaction…

To describe a **short-range interaction**, add a collision integral to the RHS of the relativistic Boltzmann equation for $f_i(x^\mu, P^i)$.

Liouville operator

$$P^\mu \frac{\partial f_i}{\partial x^\mu} - \Gamma^\nu_{\rho\sigma} P^\rho P^\sigma \frac{\partial f_i}{\partial P^\nu} = C[f]$$

Collision integral

Gravitational effects

Integrate in momentum:
$\ell = 0 \rightarrow$ density and pressure perturbations
$\ell = 1 \rightarrow$ velocity perturbations
$\ell \geq 2 \rightarrow$ anisotropies

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- **Decompose** $F_i(x^o, k^i, P^i)$ into a Legendre series in $k \cdot P$.

Ma & Bertschinger 1995

Collision integral and the isotropisation rate…

Given an interaction Lagrangian, the collision integral for $f_i(x^\mu, P^i)$ is

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

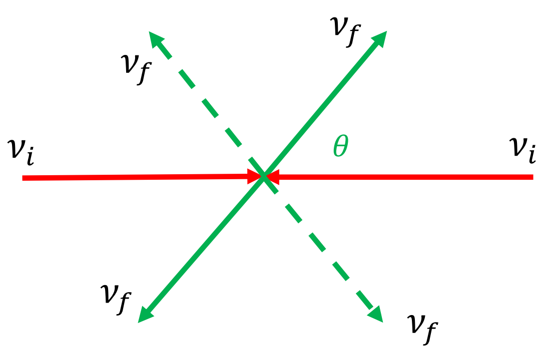
- **To compute the isotropisation rate**, follow the previous procedure of linearisation and decomposition into a Legendre series.

→ The damping rate of the quadrupole ($\ell = 2$) moment represents the lowest-order isotropisation rate of the neutrino ensemble.

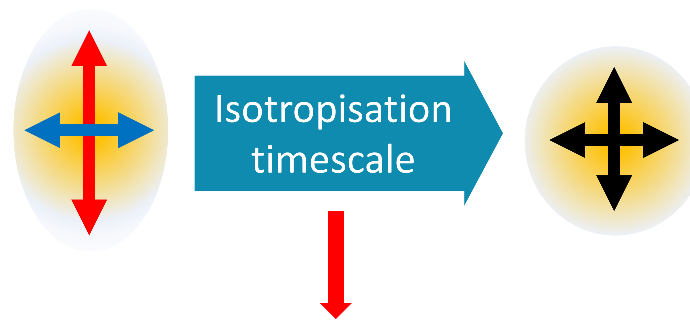
Tedious stuff, but this is really the only correct way to calculate these things, else you can get it very wrong…
However, the result can usually be understood in simple terms. → **Next slide**

Warm-up: Isotropisation from self-interaction...

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



→ 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

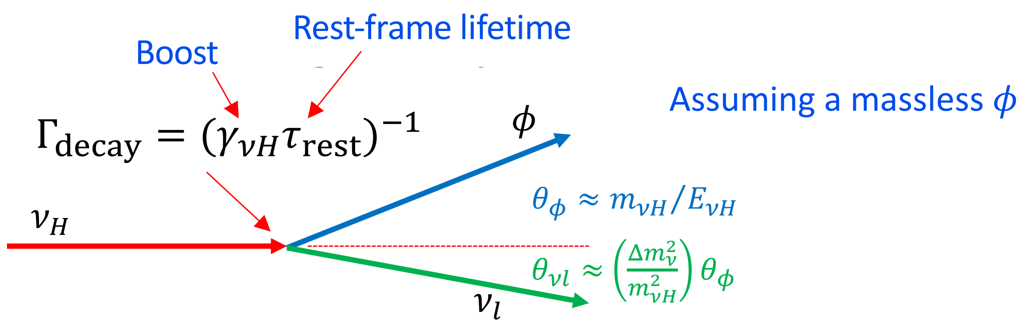
- The probability of ν_f emitted at any angle θ is the same for all $\theta \in [0, \pi]$.

That was easy…. Now let's try relativistic $1 \to 2$ decay+inverse…

Isotropisation from relativistic $1 \rightarrow 2$ 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 lifetime of ν_H.)

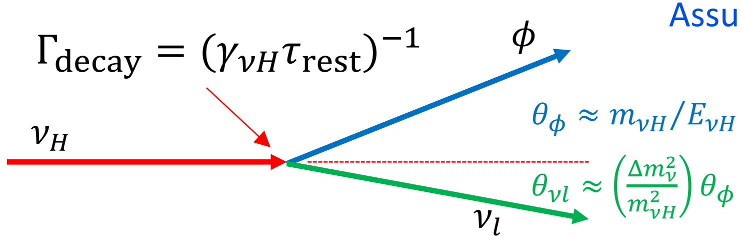
- In relativistic decay, the decay products are **beamed**.



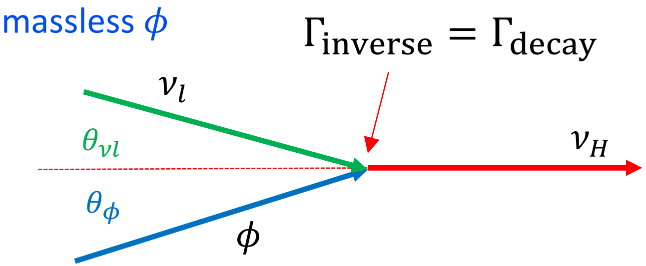
Isotropisation from relativistic $1 \rightarrow 2$ decay…

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 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**.



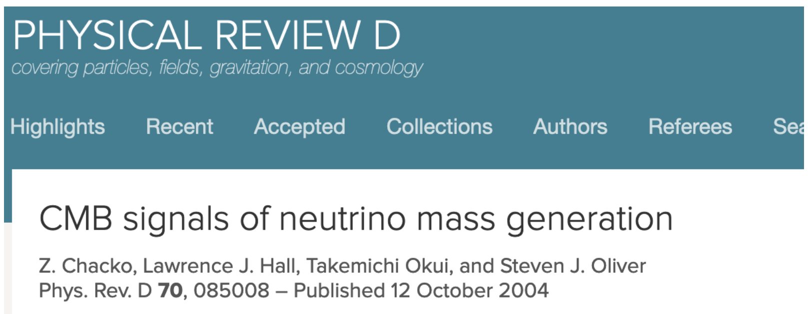
Assuming a massless ϕ



→ Isotropisation is going to take a loooong time compared with the ν_H lifetime.

How long? Part 1

Two works in the 2000s that considered how long it would take relativistic $1 \rightarrow 2$ decay and inverse decay to isotropise a neutrino ensemble.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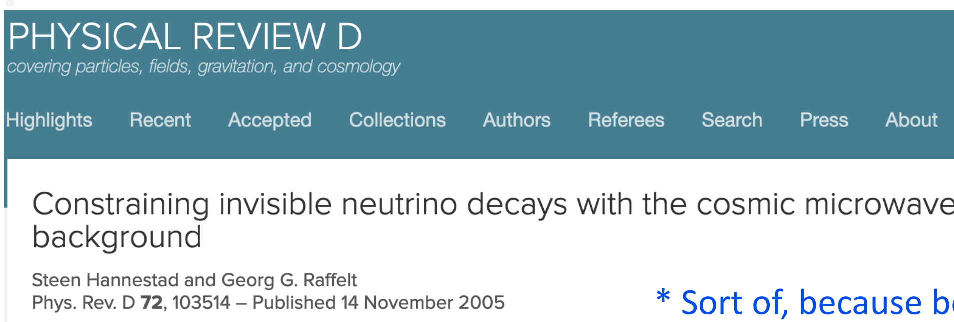
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Constraining invisible neutrino decays with the cosmic microwave background

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- **Neither** work actually calculated it… But this is the isotropisation timescale they (sort of*) used:

$$T \sim (\theta_{\nu l}\theta_{\phi})^{-1}\gamma_{\nu H}\,\tau_{\text{rest}}$$

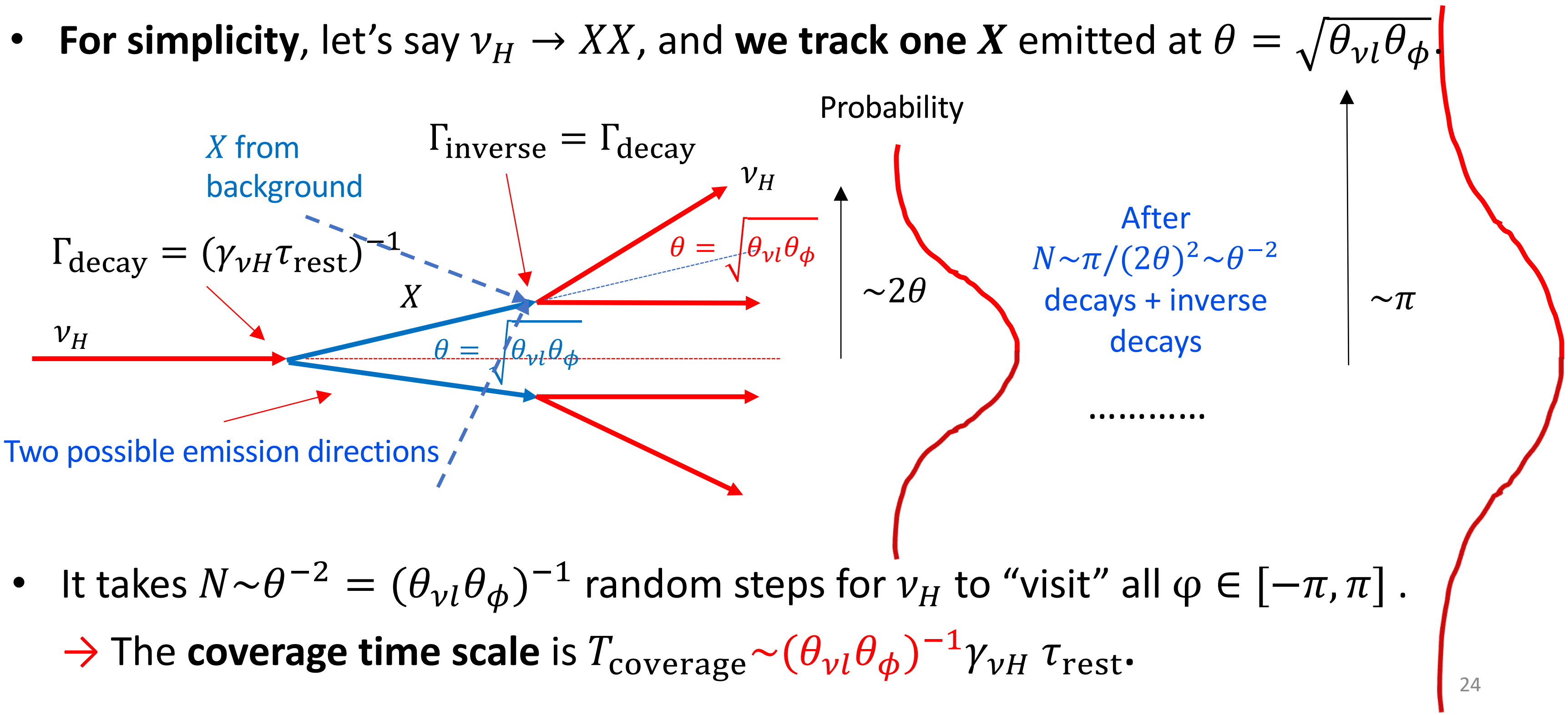
- Their argument is as follows.

* Sort of, because both works assumed two massless daughters.

How long? Part 1

Let's look at what happens to ν_H after one decay and inverse decay.

- **For simplicity**, let's say $\nu_H \to XX$, and **we track one X** emitted at $\theta = \sqrt{\theta_{\nu l}\theta_\phi}$.



- It takes $N \sim \theta^{-2} = (\theta_{\nu l}\theta_\phi)^{-1}$ random steps for ν_H to "visit" all $\varphi \in [-\pi, \pi]$.

  → The **coverage time scale** is $T_{\text{coverage}} \sim (\theta_{\nu l}\theta_\phi)^{-1} \gamma_{\nu H}\, \tau_{\text{rest}}$.

How long? Part 1

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- Taking T_{coverage} to be the isotropisation timescale and assuming massless decay products, the free-streaming bound on the ν_H **rest-frame lifetime** was found to be:

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

Hannestad & Raffelt 2005

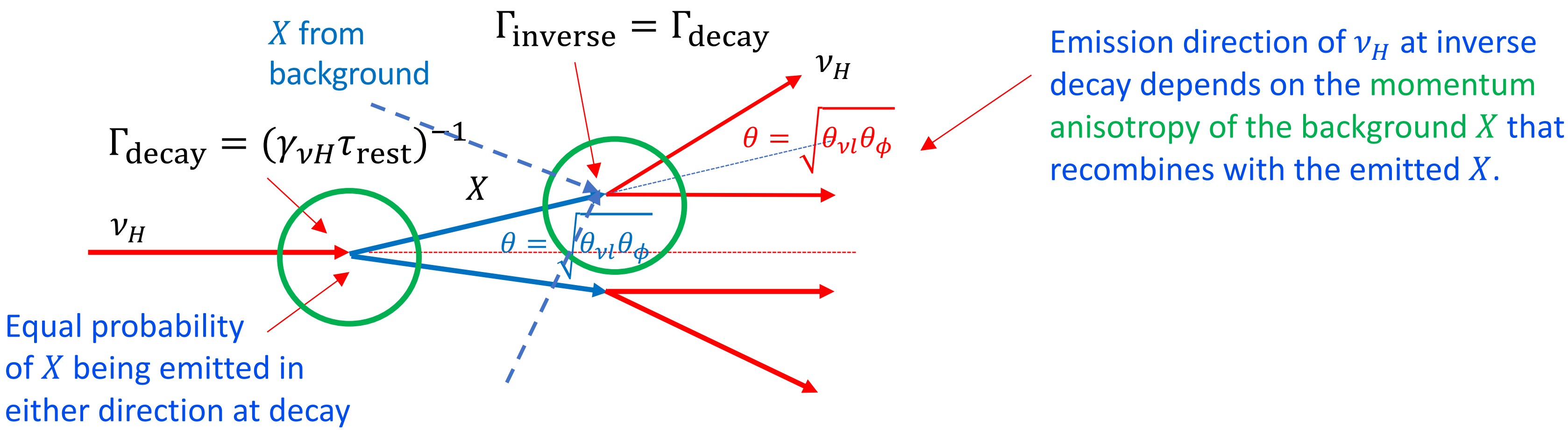
Many updates to the number since (e.g., WMAP to Planck), but no one really questioned the modelling behind this bound in the next 15 years…

Is T_{coverage} the isotropisation time scale?

Barenboim, Chen, Hannestad, Oldengott, Tram & Y[3]W 2021
Chen, Oldengott, Pierobon & Y[3]W 2022

Actually, T_{coverage} is only the first half of the story!

- **It is NOT the isotropisation time scale and here's the reason.**



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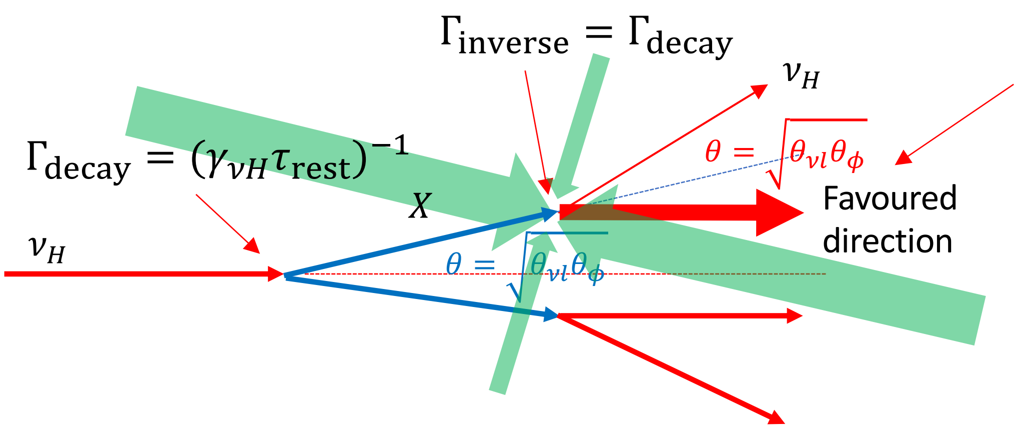

Emission direction of ν_H at inverse decay depends on the momentum anisotropy of the background X that recombines with the emitted X.
→ Random walk of ν_H in θ space is biased towards the anisotropy of X.

Is T_{coverage} the isotropisation time scale?

Barenboim, Chen, Hannestad, Oldengott, Tram & Y[3]W 2021
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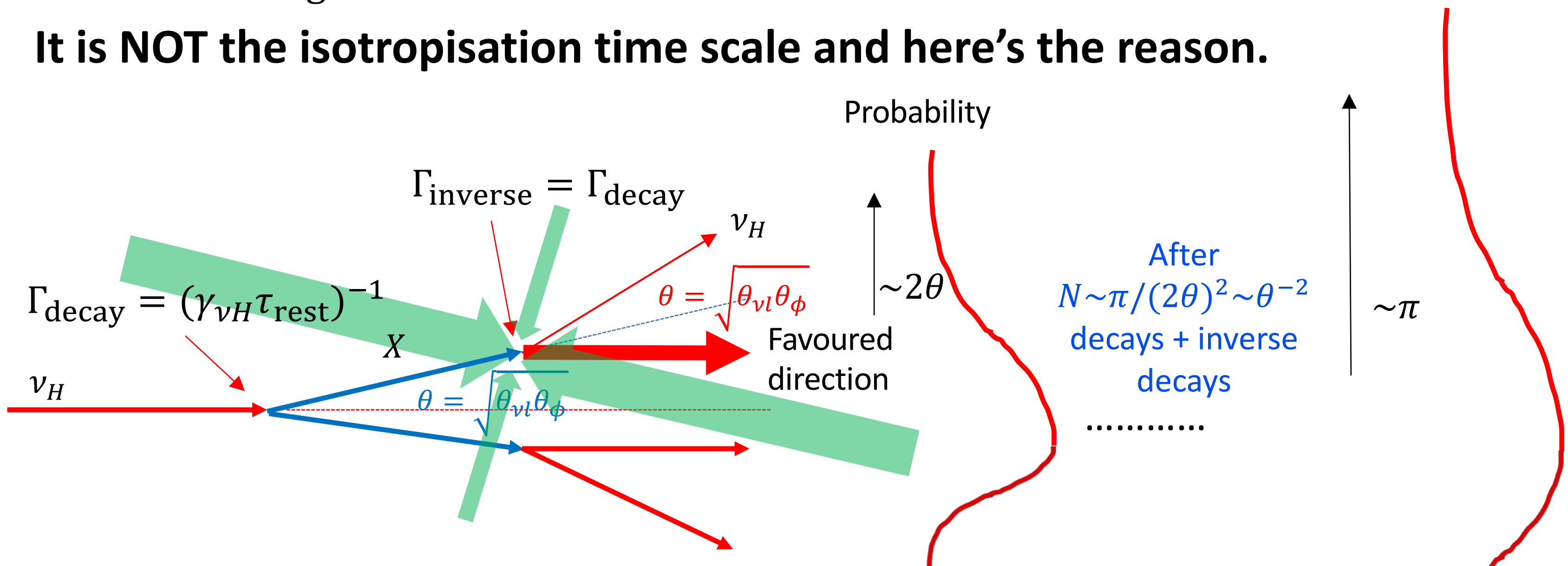
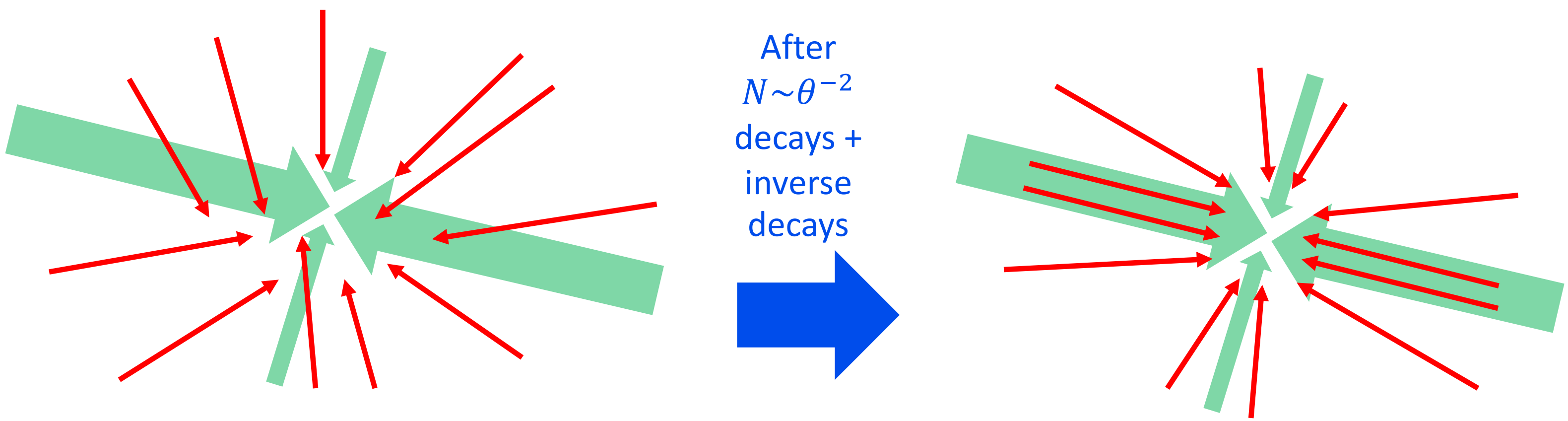


→ For a 10^{-5} anisotropy, ν_H will still need $N \sim \theta^{-2}$ steps to visit all $\varphi \in [-\pi, \pi]$, but there will be a **higher concentration of steps** in the anisotropy's direction.

Is T_{coverage} the isotropisation time scale?

That was for just one particle ν_H.

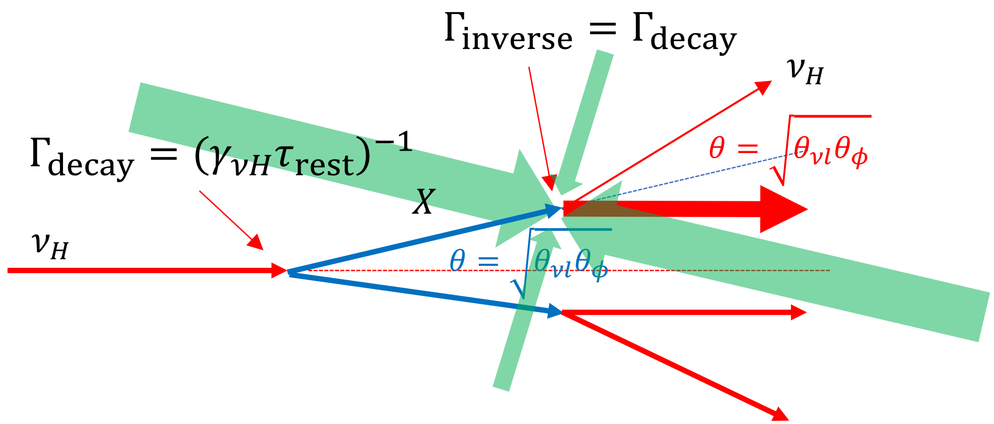
- Suppose now we have a whole ensemble of ν_Hs random-walking in the same anisotropic background.



- Thus, after T_{coverage}, the ν_H ensemble **will not become isotropic**, but will end up **almost** as anisotropic as the background…

Almost as anisotropic (or how long part 2)...

After one coverage time, the anisotropy of ν_H will be smeared over $\sim\theta = \sqrt{\theta_{\nu l}\theta_\phi}$ relative to the anisotropy of X, because ν_H is **always emitted at an angle $\pm\boldsymbol{\theta}$** relative to X in an inverse decay.

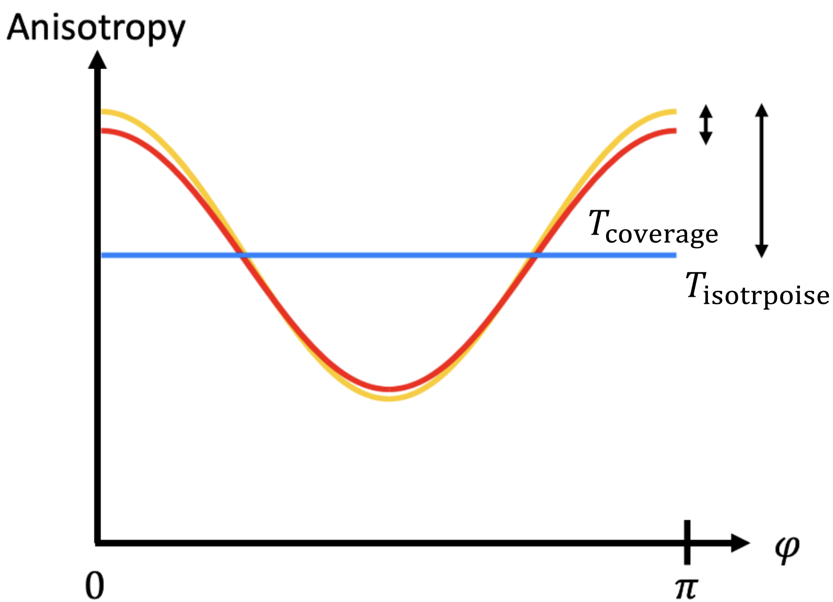


→ Even though total isotropisation of ν_H is not possible after one coverage time, a small amount of anisotropy is inevitably lost as a result.

Almost as anisotropic (or how long part 2)...

Smearing over $\sim\theta$ **reduces the peak anisotropy** after one coverage time by an amount:

$$\mathrm{Peak_{new}} - \mathrm{Peak_{old}} \sim O(\theta^2)$$



→ Need to **repeat** coverage $M \sim \theta^{-2} = (\theta_{\nu l}\theta_{\phi})^{-1}$ times to completely rid the (ν_H, ν_l, ϕ) ensemble of anisotropy.

→ **True isotropisation time scale**:

$$T_{\mathrm{isotropise}} \sim (\theta_{\phi}\theta_{\nu l})^{-1} T_{\mathrm{coverage}} \sim (\theta_{\phi}\theta_{\nu l})^{-2} \gamma_{\nu H}\, \tau_{\mathrm{rest}}$$

OK, that was hand-waving. But…

The isotropisation rate is calculable…

Given an interaction Lagrangian, the collision integral for $f_i(x^\mu, P^i)$ is

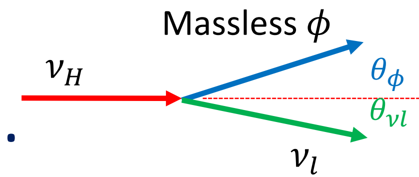
$$C[f] = \frac{1}{2}\left(\prod_j^N \int g_j \frac{\mathrm{d}^3\mathbf{n}_j}{(2\pi)^3 2E_j(\mathbf{n}_j)}\right)\left(\prod_k^M \int g_k \frac{\mathrm{d}^3\mathbf{n}_k}{(2\pi)^3 2E_k(\mathbf{n}_k)}\right)$$
$$\times (2\pi)^4 \delta_D^{(4)}\left(p + \sum_j^N n_j - \sum_k^M n'_k\right) |\mathcal{M}_{i+j_1+\cdots+j_N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

- **To compute the isotropisation rate**, follow the previous procedure of linearisation and decomposition into a Legendre series.

→ The damping rate of the quadrupole ($\ell = 2$) moment represents the lowest-order isotropisation rate of the neutrino ensemble.

In fact, we calculated the rate loooong before we understood what was going on physically…

The isotropisation rate is calculable…



With some reasonable approximations (e.g., separation of scales), we have calculated the damping rate of the ℓth neutrino kinetic moment from relativistic $\nu_H \to \nu_l + \phi$ and its inverse process:

It's model-independent in the sense that the interaction structure is contained in $\Gamma_{\rm dec}$.

T_0 = comoving neutrino temperature

$$\frac{d\mathcal{F}_{\ell\geq 2}}{dt} = -\alpha_\ell \tilde{\Gamma}_{\rm dec} \underbrace{\left(\frac{a m_{\nu H}}{T_0}\right)^4 \Phi\left(\frac{m_{\nu l}}{m_{\nu H}}\right)}_{\sim(\theta_\phi \theta_{\nu l})^2} \mathfrak{F}\left(\frac{a m_{\nu H}}{T_0}\right) \mathcal{F}_{\ell\geq 2}$$

O(1) prefactor

Boosted decay rate, $\sim(\gamma_{\nu H}\tau_{\rm rest})^{-1}$

Phase space factor $\sim \frac{1}{3}\left(\frac{\Delta m_\nu^2}{m_{\nu H}^2}\right)^2$

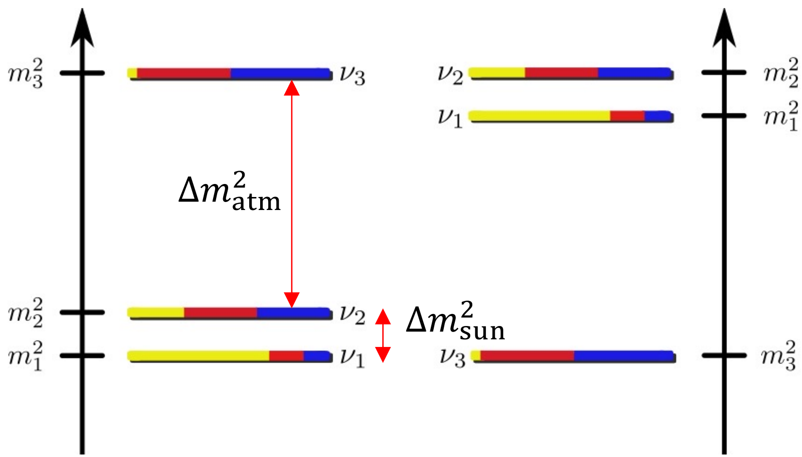
Bonus: Relativistic to non-relativistic transition:
~ 1-10 when relativistic;
drops to 0 when non-relativistic

Barenboim, Chen, Hannestad, Oldengott, Tram & Y[3]W 2021 (massless ν_l)
Chen, Oldengott, Pierobon & Y[3]W 2022 (massive ν_l + full Boltzmann hierarchy)

Revised constraints on the neutrino lifetime…

Decay scenarios…

Global neutrino oscillation data currently point to two possible orderings of neutrino masses → **several possible decay/free-streaming patterns**.



Normal mass ordering   Inverted mass ordering

		FS	Decay	Gap	Min $m^2_{\nu H}$
Scenario A: one decay channel					
A1	NO	ν_1	$\nu_3 \to \nu_2$	$\Delta m^2_{32}\|_{\rm N}$	$\|\Delta m^2_{31}\|_{\rm N}$
		ν_2	$\nu_3 \to \nu_1$	$\|\Delta m^2_{31}\|_{\rm N}$	
	IO	ν_2	$\nu_1 \to \nu_3$	$\|\Delta m^2_{31}\|_{\rm I}$	$\|\Delta m^2_{31}\|_{\rm I}$
		ν_1	$\nu_2 \to \nu_3$	$\Delta m^2_{23}\|_{\rm I}$	$\Delta m^2_{23}\|_{\rm I}$
A2	NO	ν_3	$\nu_2 \to \nu_1$	Δm^2_{21}	Δm^2_{21}
A3	IO	ν_3	$\nu_2 \to \nu_1$		$\Delta m^2_{23}\|_{\rm I}$
Scenario B: two decay channels					
B1	NO	–	$\nu_3 \to \nu_2, \nu_1$	$\|\Delta m^2_{31}\|_{\rm N}$	$\|\Delta m^2_{31}\|_{\rm N}$
B2	IO	–	$\nu_1, \nu_2 \to \nu_3$	$\|\Delta m^2_{31}\|_{\rm I}$	$\|\Delta m^2_{31}\|_{\rm I}$

Free-streaming   Decay pairs

Decay scenarios…

These scenarios look very different from one another…

- Phenomenologically, however, there are only two independent parameters.

Relativistic to NR transition

$$\frac{d\mathcal{F}_{\ell\geq 2}}{d\tau} = -\alpha_\ell \, a^6 \, Y \, \mathfrak{F}(aX)\mathcal{F}_{\ell\geq 2}$$

"Mass" of decaying neutrino

$$X = 298\left(\frac{m_{\nu H}}{0.05eV}\right)$$

Effective isotropisation rate

$$Y = 6.55C\times 10^{10}\Phi\left(\frac{m_{\nu_l}}{m_{\nu H}}\right)\left(\frac{m_{\nu H}}{0.05eV}\right)^5 \tau_{\rm rest}^{-1}$$

Mass gap

Lifetime

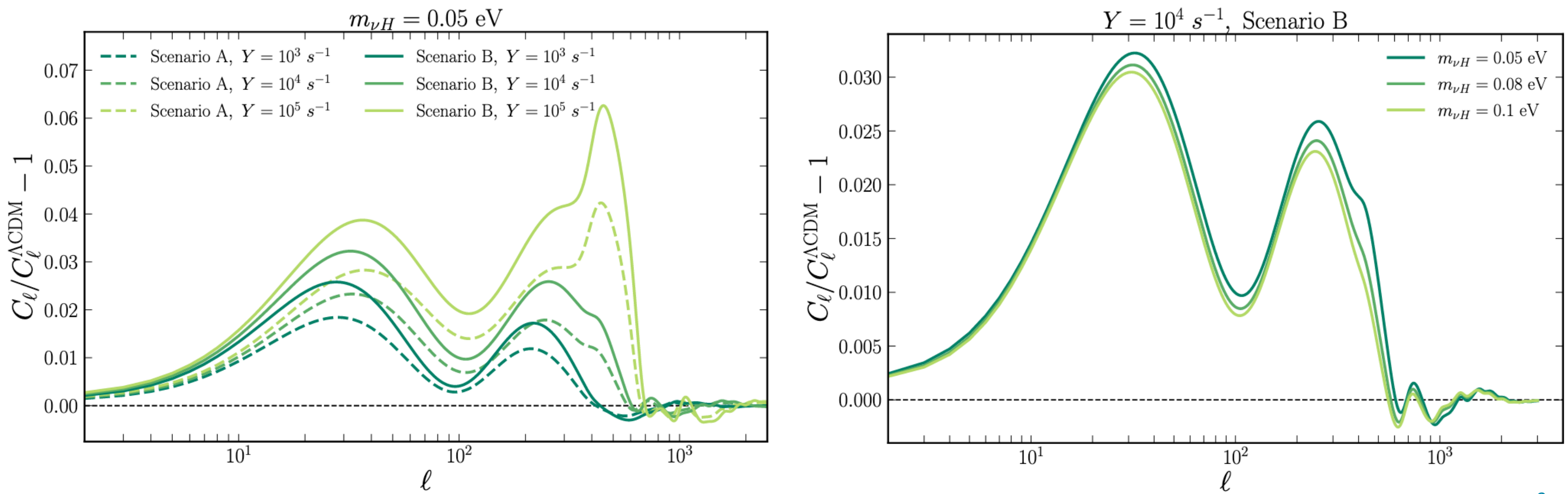
		FS	Decay	Gap	Min $m^2_{\nu H}$
Scenario A: one decay channel					
A1	NO	ν_1	$\nu_3 \to \nu_2$	$\Delta m^2_{32}\|_{\rm N}$	$\|\Delta m^2_{31}\|_{\rm N}$
		ν_2	$\nu_3 \to \nu_1$	$\|\Delta m^2_{31}\|_{\rm N}$	
	IO	ν_2	$\nu_1 \to \nu_3$	$\|\Delta m^2_{31}\|_{\rm I}$	$\|\Delta m^2_{31}\|_{\rm I}$
		ν_1	$\nu_2 \to \nu_3$	$\Delta m^2_{23}\|_{\rm I}$	$\Delta m^2_{23}\|_{\rm I}$
A2	NO	ν_3	$\nu_2 \to \nu_1$	Δm^2_{21}	Δm^2_{21}
A3	IO	ν_3	$\nu_2 \to \nu_1$		$\Delta m^2_{23}\|_{\rm I}$
Scenario B: two decay channels					
B1	NO	–	$\nu_3 \to \nu_2, \nu_1$	$\|\Delta m^2_{31}\|_{\rm N}$	$\|\Delta m^2_{31}\|_{\rm N}$
B2	IO	–	$\nu_1, \nu_2 \to \nu_3$	$\|\Delta m^2_{31}\|_{\rm I}$	$\|\Delta m^2_{31}\|_{\rm I}$

Free-streaming

Decay pairs

Signatures in the CMB TT power spectrum…

Fractional deviations in the CMB TT power spectrum from ΛCDM for various the effective isotropisation rate Y and ν_H masses.



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

Effective isotropisation rate: $Y = 6.55C \times 10^{10} \Phi(m_{\nu l}/m_{\nu H}) \left(\frac{m_{\nu H}}{0.05eV}\right)^5 \tau_{\mathrm{rest}}^{-1}$

Scenario A = 2 neutrinos participate in decay/inverse decay; Scenario B = all 3 participate

CMB lower bounds on the neutrino lifetime…

We derive constraints on Y at a set of fixed X using Planck 2018 TTTEEE+ low+lensing, and translate the constraints to a **revised lower bound on the neutrino lifetime**:

Rel to non-rel factor

$$\tau_{\rm rest} \gtrsim 1.2\times10^6\, \mathfrak{F}\left[0.12\left(\frac{m_{\nu H}}{0.05\ {\rm eV}}\right)\right] \Phi\left(\frac{m_{\nu l}}{m_{\nu H}}\right)\left(\frac{m_{\nu H}}{0.05\ {\rm eV}}\right)^5 {\rm s}$$

Phase space factor $\sim \frac{1}{3}\left(\frac{\Delta m_\nu^2}{m_{\nu H}^2}\right)^2$

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

- Or equivalently:

For $m_\nu < 0.2$ eV

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

$$\tau_{\rm rest} \gtrsim (6-10)\times10^5 {\rm s}$$

$\nu_2 \to \nu_1 + \phi$

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

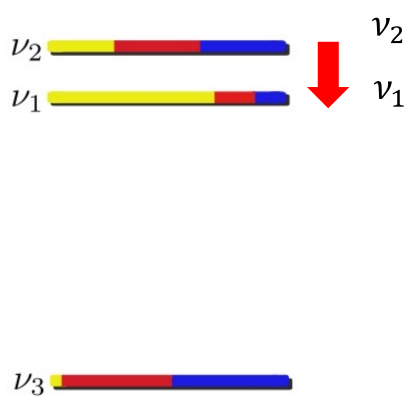
Cf old constraints (which misidentified $T_{\rm coverage}$ with $T_{\rm isotropise}$):

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

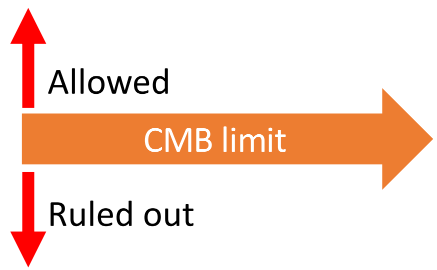
Hannestad & Raffelt 2005

CMB lower bounds on the neutrino lifetime…

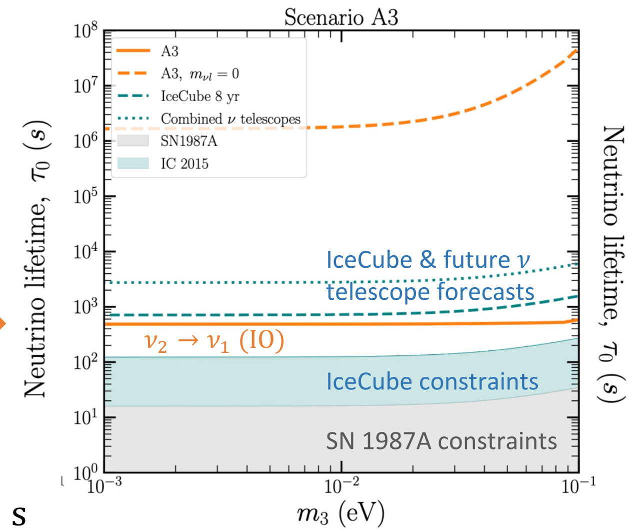
… currently the best limits on invisible neutrino decay $\nu_H \rightarrow \nu_l + \phi$.



Inverted mass ordering



BBN: $\tau_0 \gtrsim 10^{-2} \rightarrow 10^{-1}$ s
Solar ν: $\tau_0 \gtrsim 10^{-5} \rightarrow 10^{-4}$ s
Lab ν: $\tau_0 \gtrsim 10^{-13} \rightarrow 10^{-11}$ s



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

* IceCube constraints & forecasts from Song et al. 2021

CMB lower bounds on the neutrino lifetime…

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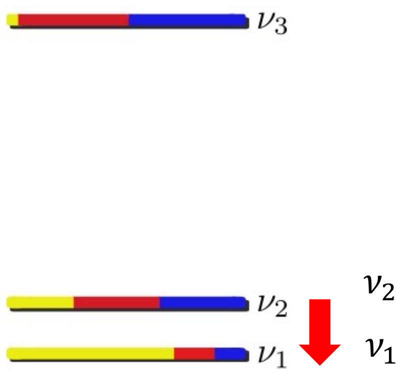
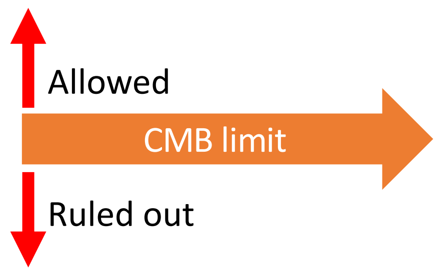


Normal mass ordering



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

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

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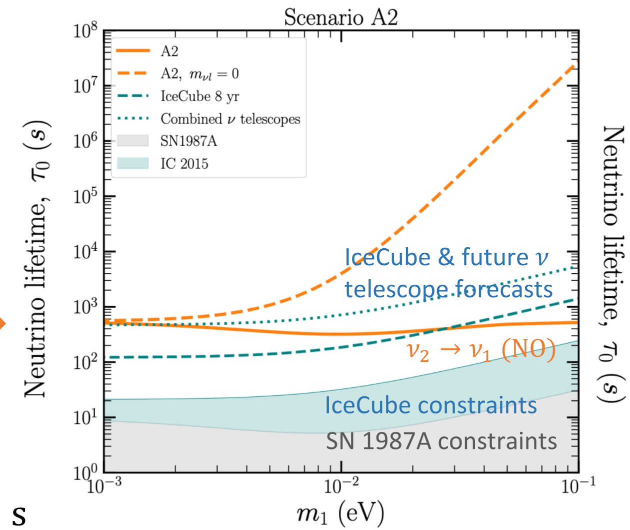

Chen, Oldengott, Pierobon & Y[3]W 2022

* IceCube constraints & forecasts from Song et al. 2021

Summary…

- We can use **precision cosmological observables** to constrain non-standard neutrino properties like relativistic invisible neutrino decay.
- But **mapping the decay rate** to the isotropisation rate that ultimately changes the CMB observable can be a tricky task.
- We have calculated the isotropisation rate from first-principles and relaxed the CMB constraint on the neutrino lifetime by several orders of magnitude relative to old works using an incorrect rate.
  - Barenboim et al. 2021: massless daughters; 3 orders of magnitude bound relaxation at $m_\nu = 0.05$ eV.
  - Chen et al. 2022: massive daughters + full Boltzmann hierarchy + “hand-waving” explanation; up to another 5 orders of magnitude relaxation.