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]]

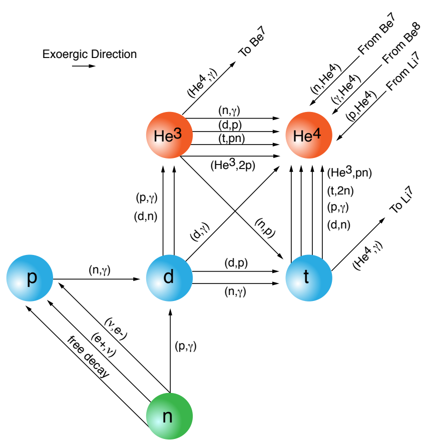
Yvonne Y. Y. Wong, UNSW Sydney

Current Topics in Astroparticle Physics, November 9 – 11, 2022

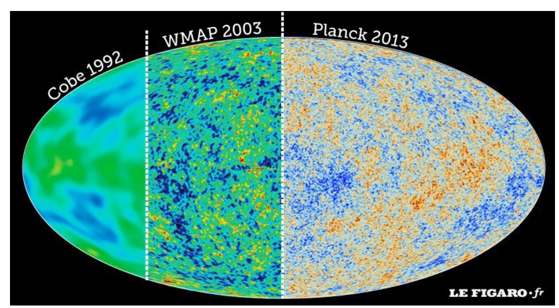
Why the topic of precision cosmology?

I got into the business of **using precision cosmological observables**, particularly the CMB anisotropies and the large-scale matter distribution, **to constrain BSM physics** while a postdoc at MPP in 2005—2008.

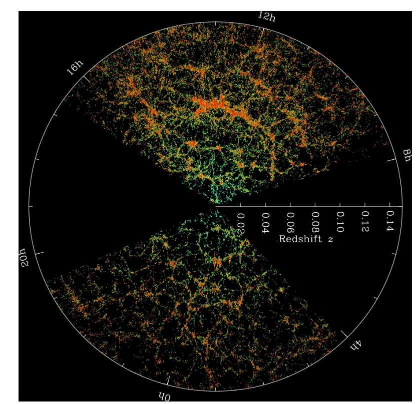
Light element abundances



CMB anisotropies



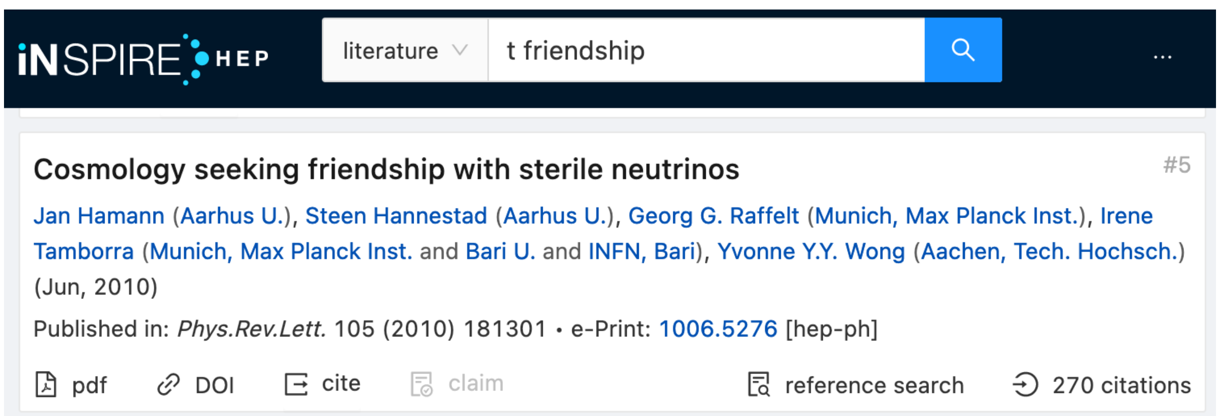
Large-scale matter distribution



Precision cosmological constraints on neutrino mass, $N_{\rm eff}$, light sterile neutrinos, hot axions, axion isocurvature, and combinations thereof.

- M. Archidiacono, T. Basse, J. Hamann, S. Hannestad, G. Raffelt and Y. Y. Y. Wong, ``Future cosmological sensitivity for hot dark matter axions,'' JCAP 05 (2015), 050 [arXiv:1502.03325 [astro-ph.CO]].
- M. Archidiacono, S. Hannestad, A. Mirizzi, G. Raffelt and Y. Y. Y. Wong, ,``Axion hot dark matter bounds after Planck,'' JCAP 10 (2013), 020 [arXiv:1307.0615 [astro-ph.CO]].
- J. Hamann, S. Hannestad, G. G. Raffelt and Y. Y. Y. Wong,, `Sterile neutrinos with eV masses in cosmology: How disfavoured exactly?,'' JCAP 09 (2011), 034 [arXiv:1108.4136 [astro-ph.CO]].
- J. Hamann, S. Hannestad, G. G. Raffelt, I. Tamborra and Y. Y. Y. Wong, ``Cosmology seeking friendship with sterile neutrinos,'' Phys. Rev. Lett. 105 (2010), 181301 [arXiv:1006.5276 [hep-ph]].
- S. Hannestad, A. Mirizzi, G. G. Raffelt and Y. Y. Y. Wong, ``Neutrino and axion hot dark matter bounds after WMAP-7,'' JCAP 08 (2010), 001 [arXiv:1004.0695 [astro-ph.CO]].
- J. Hamann, S. Hannestad, G. G. Raffelt and Y. Y. Y. Wong,``Isocurvature forecast in the anthropic axion window,'' JCAP 06 (2009), 022 [arXiv:0904.0647 [hep-ph]].
- S. Hannestad, A. Mirizzi, G. G. Raffelt and Y. Y. Y. Wong, ``Cosmological constraints on neutrino plus axion hot dark matter: Update after WMAP-5,'' JCAP 04 (2008), 019 [arXiv:0803.1585 [astro-ph]].
- S. Hannestad, A. Mirizzi, G. G. Raffelt and Y. Y. Y. Wong, ``Cosmological constraints on neutrino plus axion hot dark matter,'' JCAP 08 (2007), 015 [arXiv:0706.4198 [astro-ph]].
- J. Hamann, S. Hannestad, G. G. Raffelt and Y. Y. Y. Wong, ``Observational bounds on the cosmic radiation density,'' JCAP 08 (2007), 021 [arXiv:0705.0440 [astro-ph]].

One for the classifieds?



The oldest paper on INSPIRE-HEP with the word “friendship” in the title

CMB constraints on the neutrino lifetime…

To my knowledge this is the first work:

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

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Constraining invisible neutrino decays with the cosmic microwave background

Steen Hannestad and Georg G. Raffelt
Phys. Rev. D **72**, 103514 – Published 14 November 2005

The gist of it is, for $m_{\nu H} \lesssim O(1)\mathrm{eV}$, the CMB anisotropies places a lower limit on the lifetime of ν_H from the relativistic decay $\nu_H \to \nu_l + \phi$:

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

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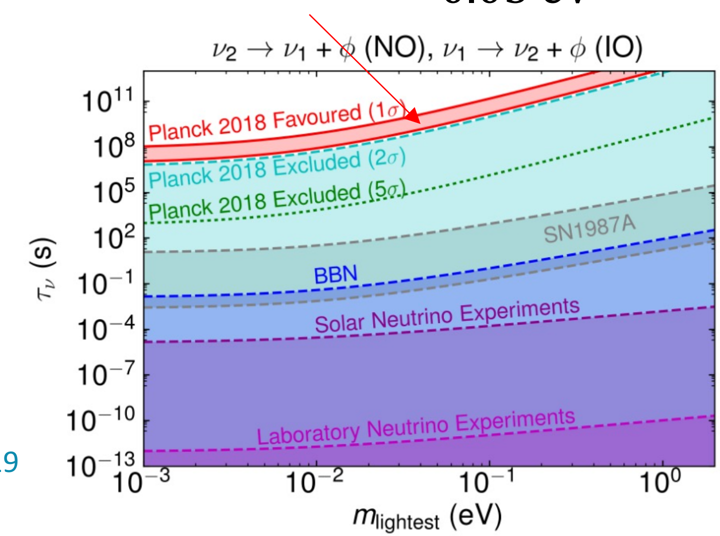

Escudero & Fairbairn 2019

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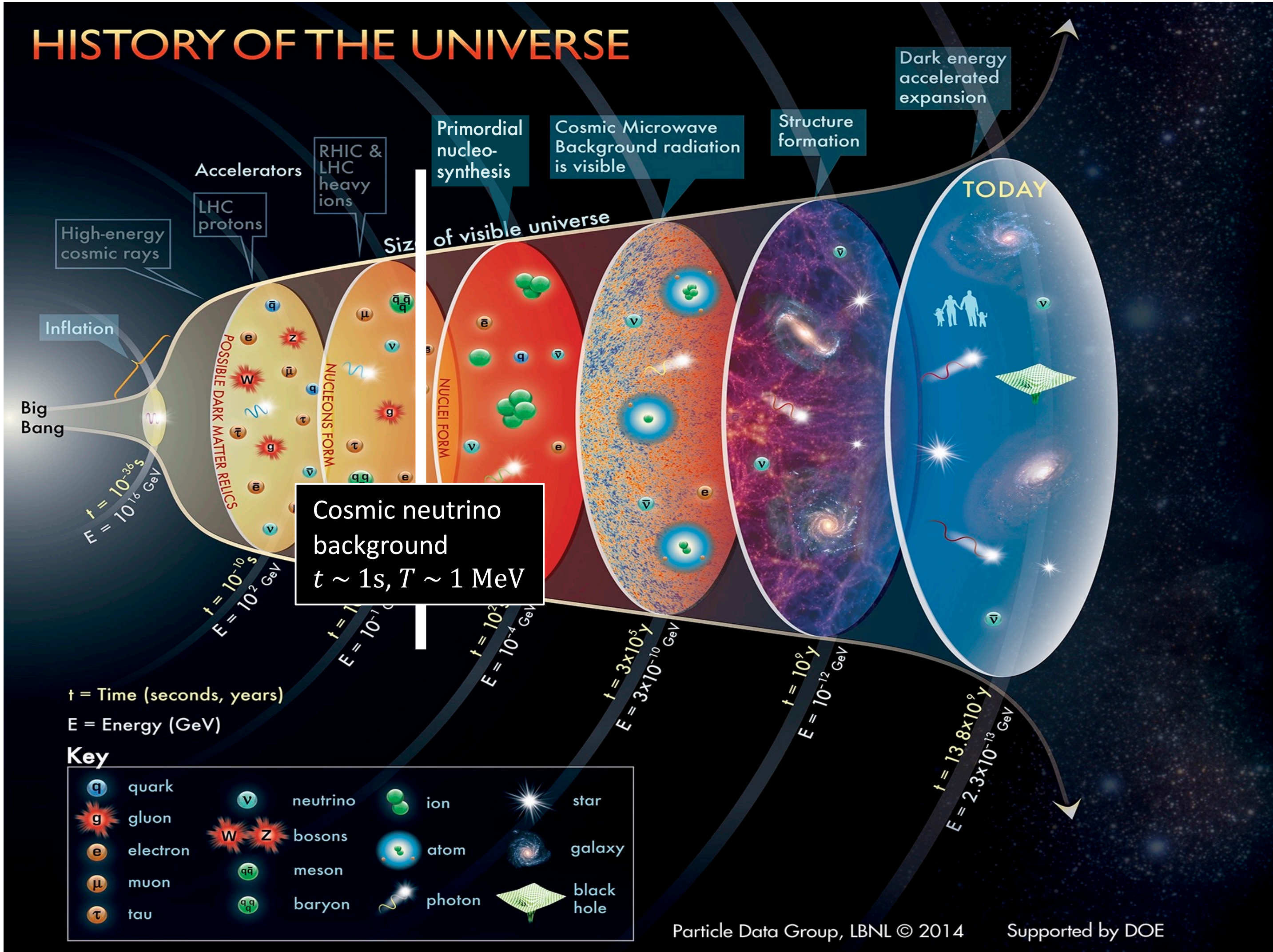
- Hopeless for other probes to compete…
- But, we revisited the scenario in Barenboim, Chen, Hannestad, Oldengott, Tram & Y^{3}W 2021 and Chen, Oldengott, Pierobon & Y^{3}W 2022, and **found a rather different outcome**… ← This talk

So, here we go…

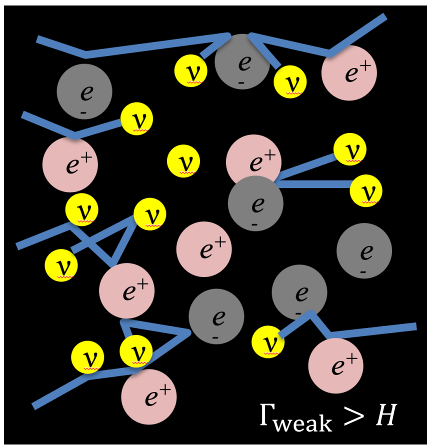

HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
Primordial nucleo-synthesis
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Big Bang
Size of visible universe
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
Cosmic neutrino background
$t \sim 1\text{s}, T \sim 1\ \text{MeV}$
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 3\text{x}10^{5}$ y
$E = 3\text{x}10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8\text{x}10^{9}$ y
$E = 2.3\text{x}10^{-13}$ 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
Particle Data Group, LBNL © 2014
Supported by DOE

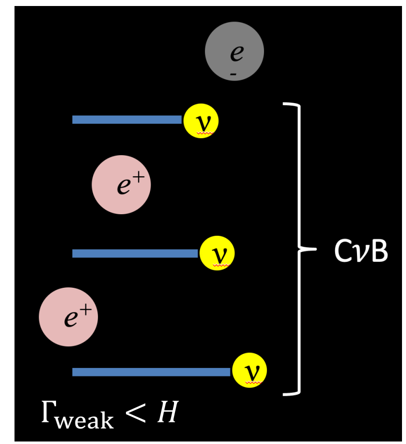
Interaction rate: $\Gamma_{\text{weak}} \sim G_F^2 T^5$

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.





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.

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

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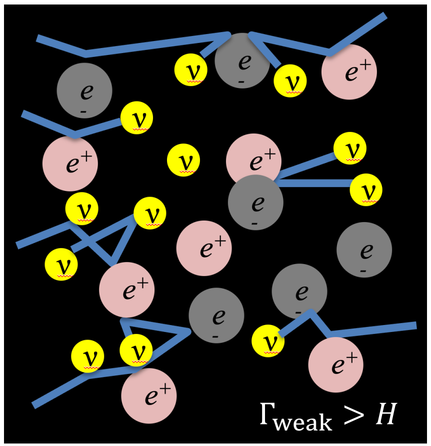

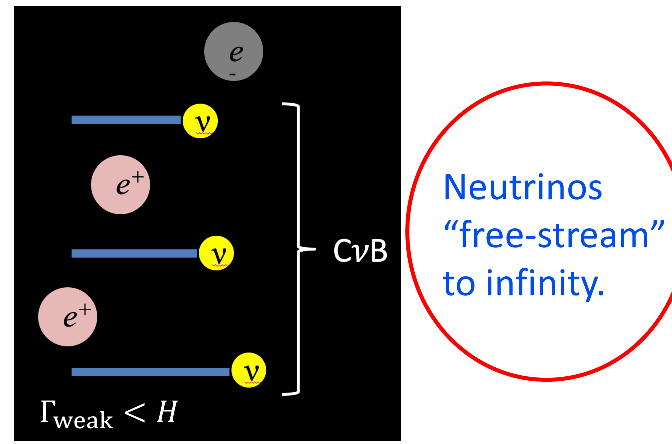

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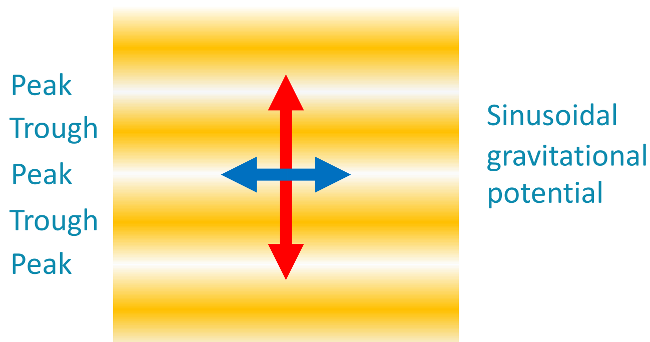
Free-streaming in inhomogeneities…

Standard Model neutrinos free-stream after decoupling.

- Free-streaming in a spatially inhomogeneous background induces shear stress (or momentum anisotropy).

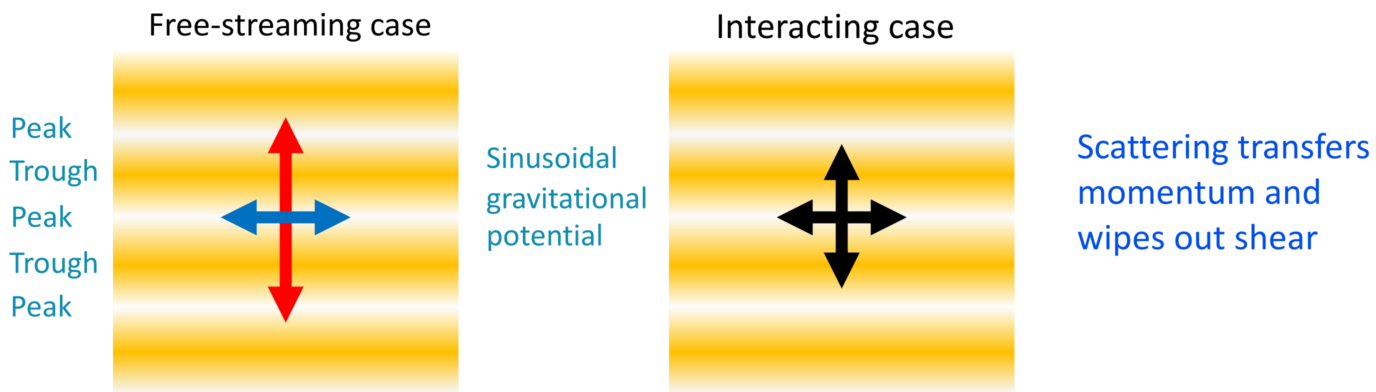
Free-streaming case



Free-streaming in inhomogeneities…

Standard Model neutrinos free-stream after decoupling.

- 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 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.

Scale factor

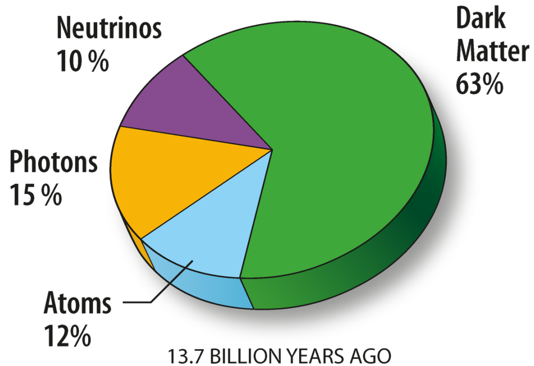
Conformal Newtonian gauge

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

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

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

Mean energy density & pressure



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Mean energy density & pressure → $\bar{\rho}$, $\bar{P}$

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

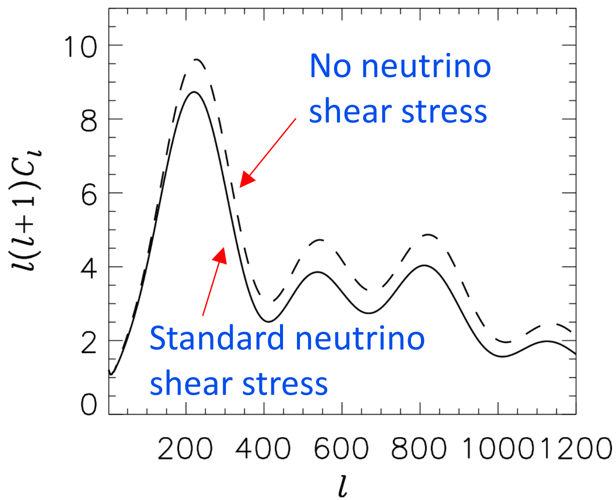
- The **CMB temperature fluctuations** respond to changes in $(\phi - \psi)$

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

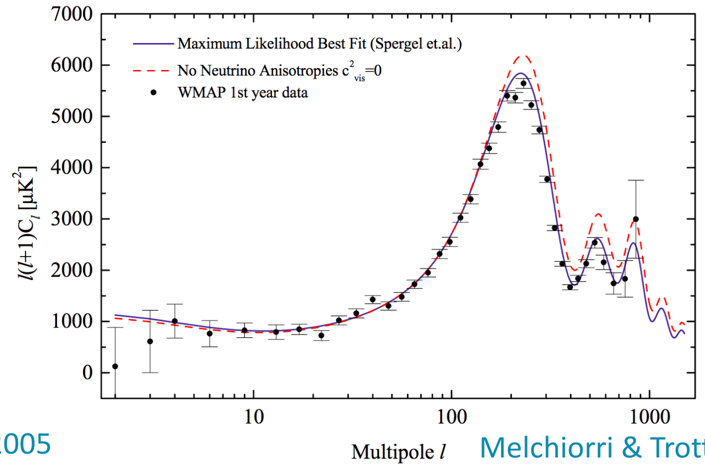
  → Good probe of neutrino interactions at CMB formation times $(t \sim 400\ \mathrm{kyr})$

Neutrino free-streaming & the CMB…

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



Hannestad 2005



Melchiorri & Trotta 2005

- The trickly 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 an interaction?

Computing the isotropisation timescale…

Given an interaction Lagrangian, the **isotropisation timescale is calculable**.

- Write down the Boltzmann equation:

$$P^\mu \frac{\partial f_i}{\partial x^\mu} - \Gamma^\nu_{\rho\sigma} P^\rho P^\sigma \frac{\partial f_i}{\partial P^\nu} = \frac{1}{2} \left(\prod_j^N \int g_j \frac{\mathrm{d}^3 \mathbf{n}_j}{(2\pi)^3 2E_j(\mathbf{n}_j)} \right) \left(\prod_k^M \int g_k \frac{\mathrm{d}^3 \mathbf{n}_k}{(2\pi)^3 2E_k(\mathbf{n}_k)} \right)$$

$$\times (2\pi)^4 \, \delta_D^{(4)} \left(p + \sum_j^N n_j - \sum_k^M n'_k \right) |\mathcal{M}_{i+j_1+\cdots+j_N \leftrightarrow k_1+\cdots+k_M}|^2$$

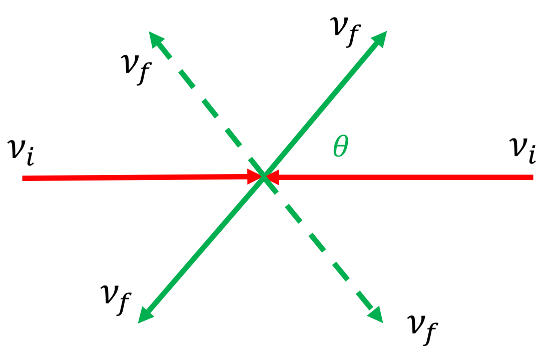
$$\times [f_{k_1} \cdots f_{k_N} (1 \pm f_i)(1 \pm f_{j_1}) \cdots (1 \pm f_{j_N}) - f_i f_{j_1} \cdots f_{j_N} (1 \pm f_{k_1}) \cdots (1 \pm f_{k_M})]$$

- Sum over momentum and decompose in a Legendre series
- The damping rate of the quadrupole ($\ell = 2$) moment of the ensemble is the **isotropisation rate**.

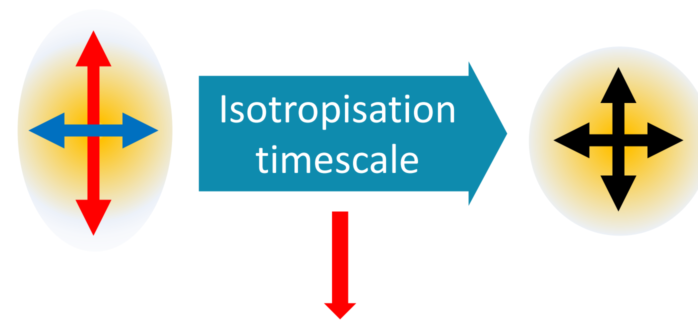
Tedious stuff, but this is really the only correct way to calculate these things, else you can get it very wrong…
However, the result can usually be understood in simple terms. → **Next slide**

Warm-up: Isotropisation from 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

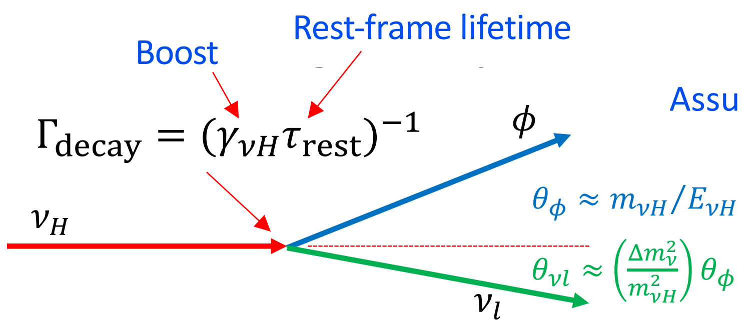
- The probability of ν_f emitted at any angle θ is the same for all $\theta \in [0, \pi]$.

That was easy….
Now let’s try relativistic decay.

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 lifetime of ν_H.)

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



Assuming a massless ϕ

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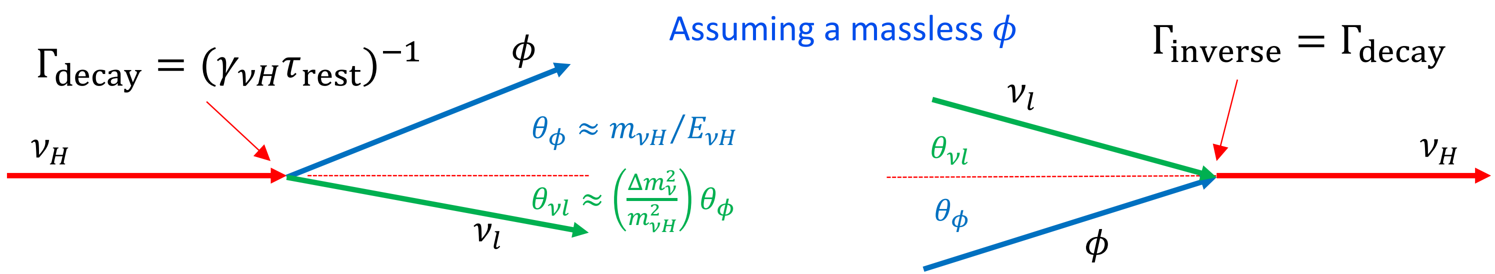
- Inverse decay also only happens when the daughter particles meet **strict momentum/angular requirements**.



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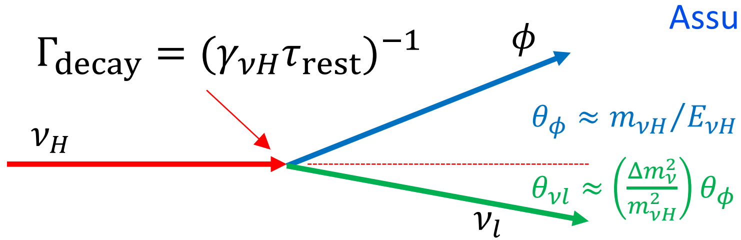

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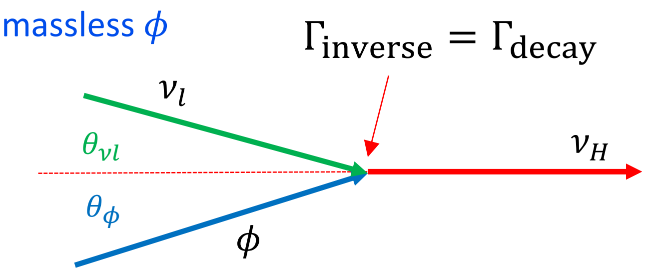
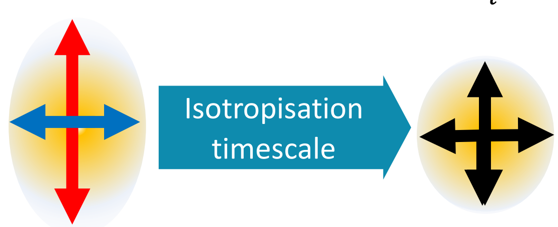


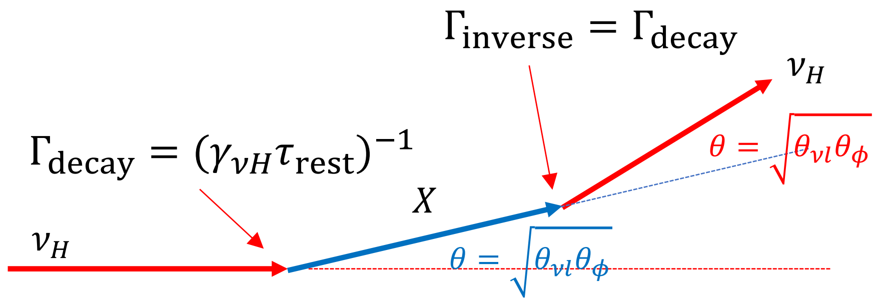


→ Isotropisation is going to take a loooong time compared with the ν_H lifetime.

So how long?

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

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



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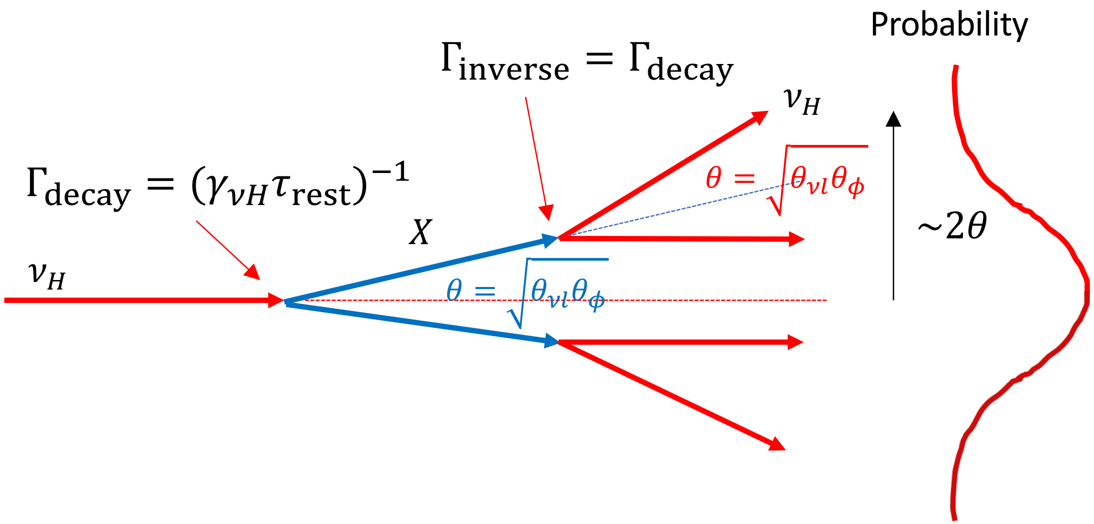

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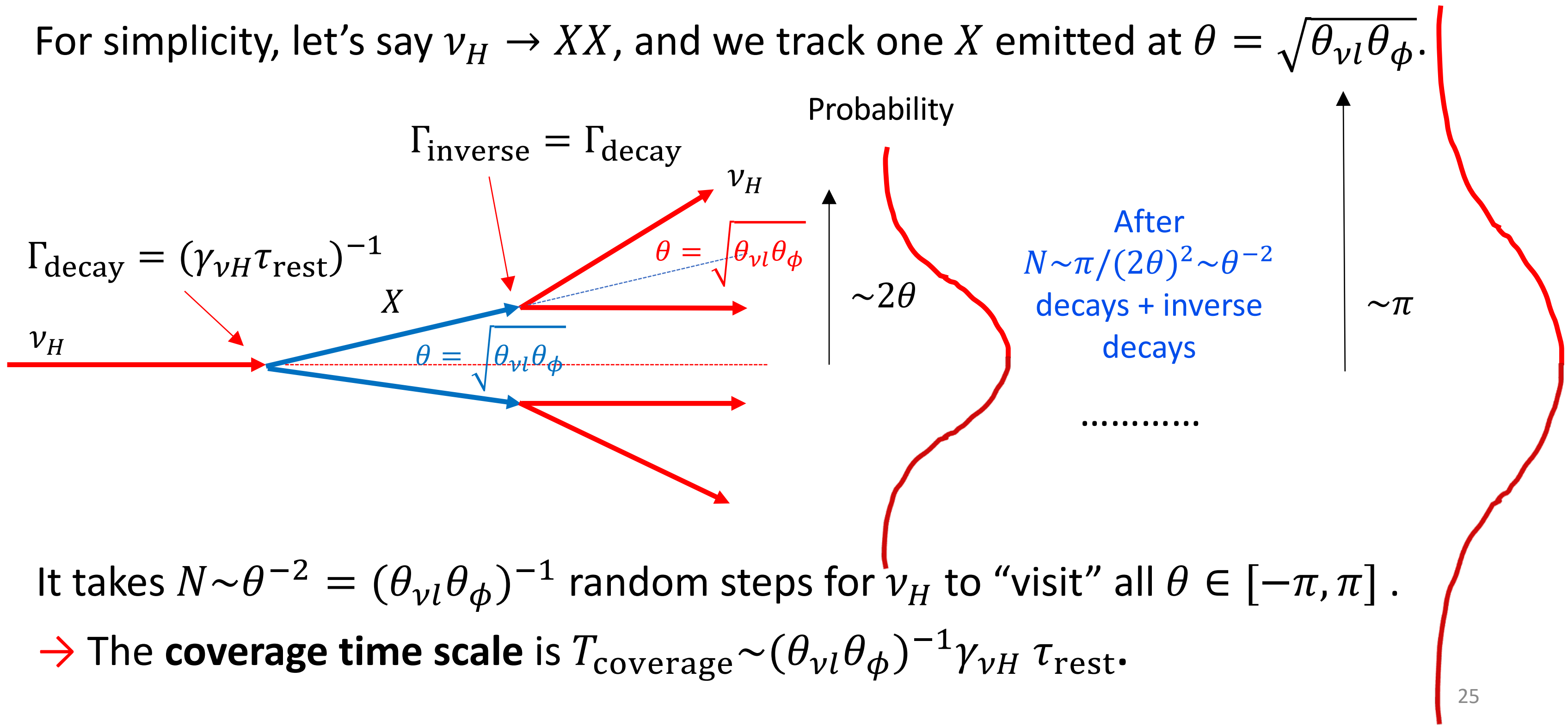

- It takes $N \sim \theta^{-2} = (\theta_{\nu l}\theta_\phi)^{-1}$ random steps for ν_H to "visit" all $\theta \in [-\pi, \pi]$.

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

Is T_{coverage} the isotropisation time scale?

Chacko, Hall, Okui & Oliver 2004
Hannestad & Raffelt 2005

Considering only massless decay products, early works identify T_{coverage} with the isotropisation time scale.

- **But it is NOT and here's the reason.**

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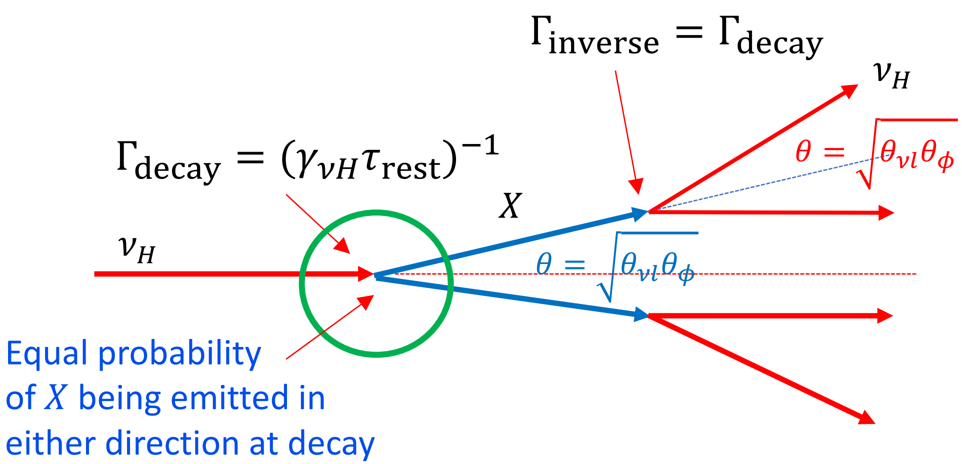

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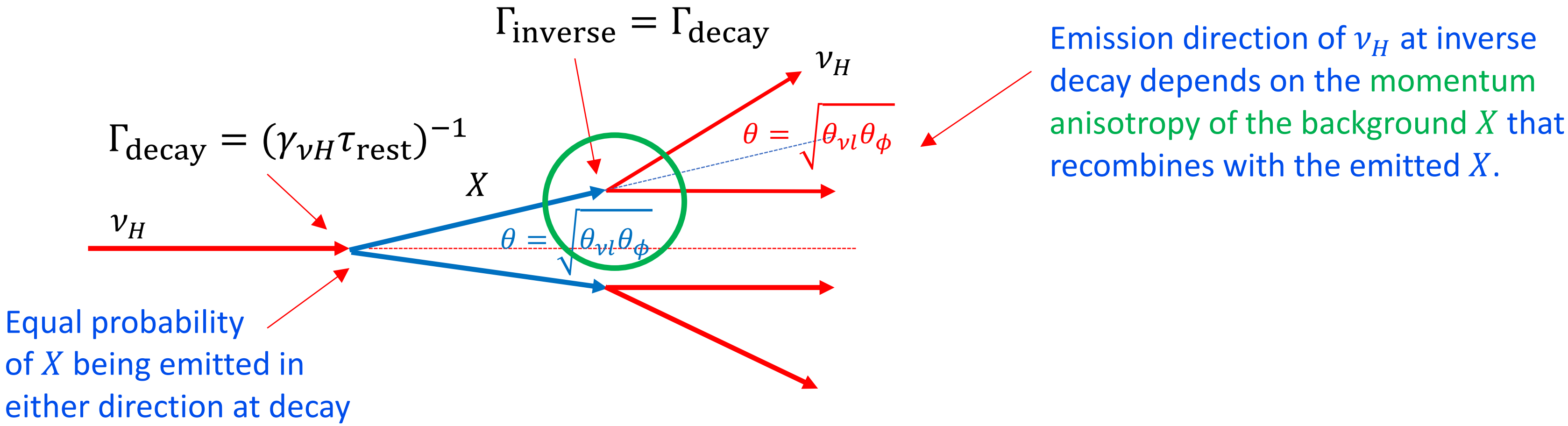

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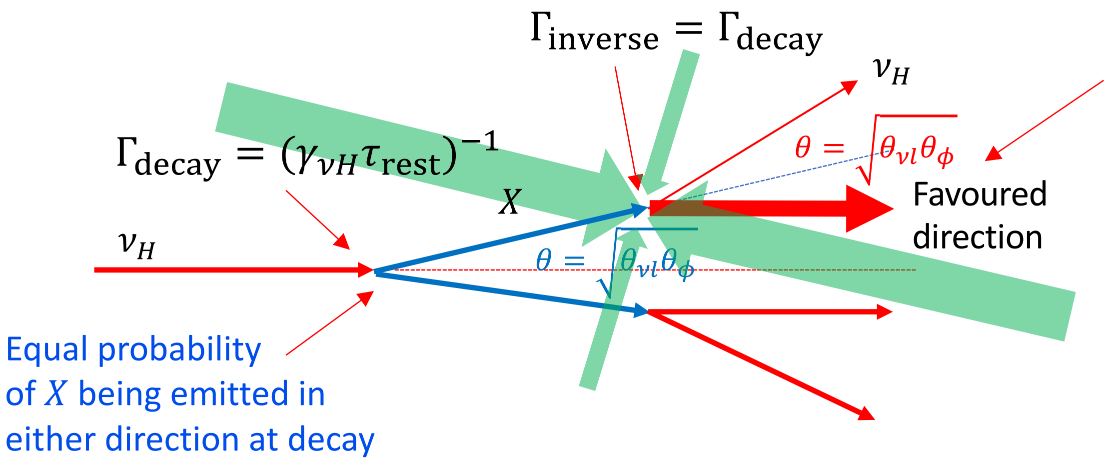

Emission direction of ν_H at inverse decay depends on the momentum anisotropy of the background X that recombines with the emitted X.
→ Random walk of ν_H in θ space is biased towards the anisotropy of X.

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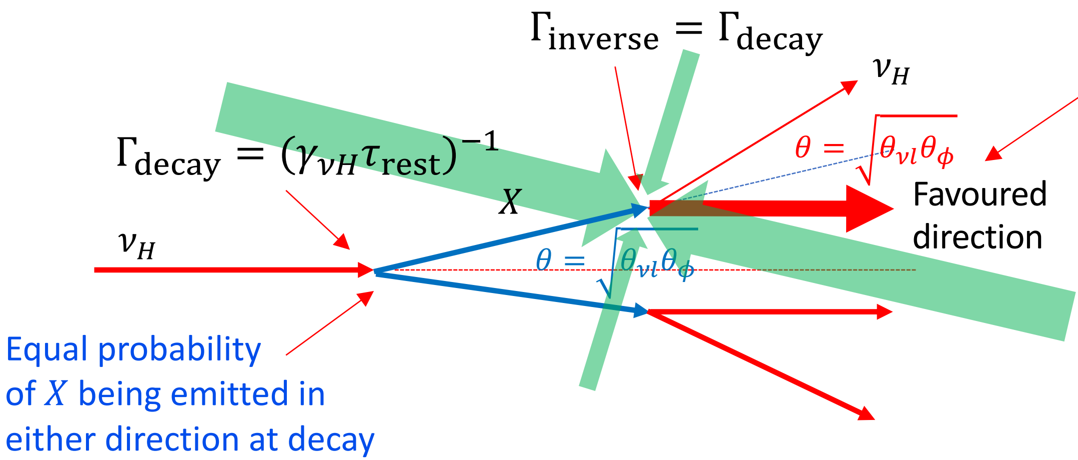
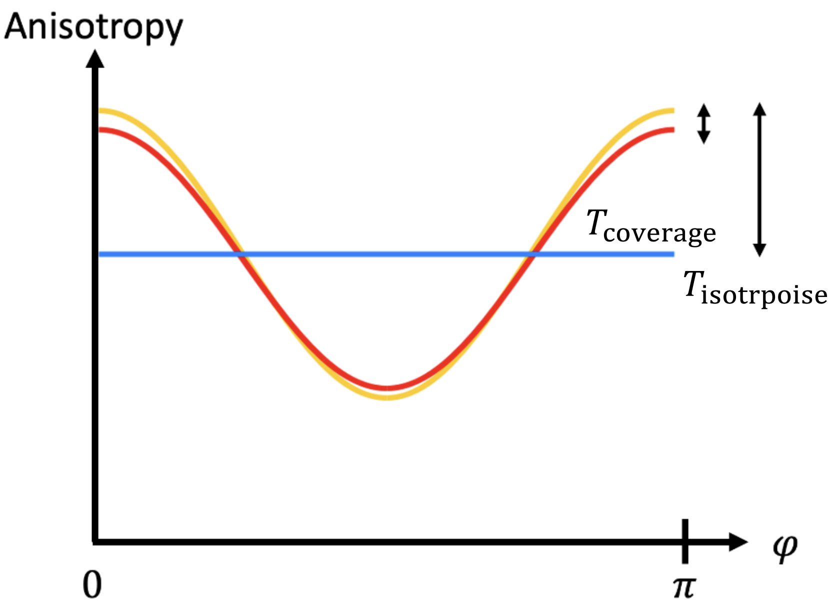


Emission direction of ν_H at inverse decay depends on the momentum anisotropy of the background X that recombines with the emitted X.
→ Random walk of ν_H in θ space is biased towards the anisotropy of X.

→ After T_{coverage}, the momentum distribution of ν_H will **not** be isotropic, but will merely reflect the anisotropy of X with a small twist…

.... 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 $\pm\theta$ relative to X in an inverse decay.



- Smearing over $\sim\theta$ **reduces the peak anisotropy** by an amount:

$$\text{Peak}_{\text{new}} - \text{Peak}_{\text{old}} \sim O(\theta^2)$$

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

→ **True isotropisation time scale**:

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

OK, that was hand-waving. But…

The isotropisation rate is calculable…

Given an interaction Lagrangian, the isotropisation timescale is calculable.

- Write down the Boltzmann equation:

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

- Sum over momentum and decompose in a Legendre series
- The damping rate of the quadrupole ($\ell = 2$) moment of the ensemble 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…

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 $\nu_H \rightarrow \nu_l + \phi$ and its inverse:

$\sim(\theta_\phi \theta_{\nu l})^2$

T_0 = comoving neutrino temperature

$$\frac{d\mathcal{F}_{\ell\geq2}}{dt} = -\alpha_\ell \tilde{\Gamma}_{\mathrm{dec}} \left(\frac{a m_{\nu H}}{T_0}\right)^4 \Phi\left(\frac{m_{\nu l}}{m_{\nu H}}\right) \mathfrak{F}\left(\frac{a m_{\nu H}}{T_0}\right) \mathcal{F}_{\ell\geq2}$$

O(1) prefactor

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

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

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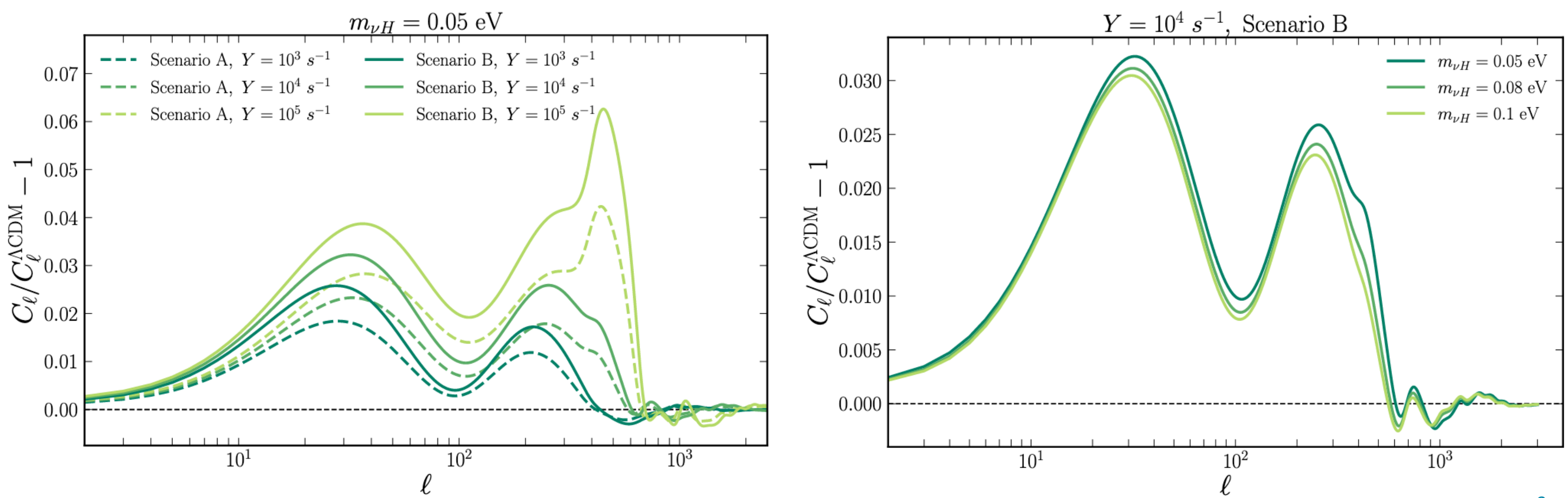
Signatures in the CMB TT power spectrum…

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



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Effective isotropisation rate: $Y = 6.55C\times10^{10}\Phi(m_{\nu l}/m_{\nu H})\left(\frac{m_{\nu H}}{0.05eV}\right)^5 \tau_{\mathrm{rest}}^{-1}$

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

Revised constraints on the neutrino lifetime…

CMB lower bounds on the neutrino lifetime...

Using the Planck 2018 CMB TTTEEE+low+lensing data, **our revised lifetime constraint** is:

Rel to non-rel factor

$$\tau_{\rm rest} \gtrsim 1.2{\times}10^6\, \mathfrak{F}\left[0.12\left(\frac{m_{\nu H}}{0.05\ {\rm eV}}\right)\right]\Phi\left(\frac{m_{\nu l}}{m_{\nu H}}\right)\left(\frac{m_{\nu H}}{0.05\ eV}\right)^5 {\rm s}$$

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

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- Or equivalently:

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

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

$\nu_2 \rightarrow \nu_1 + \phi$

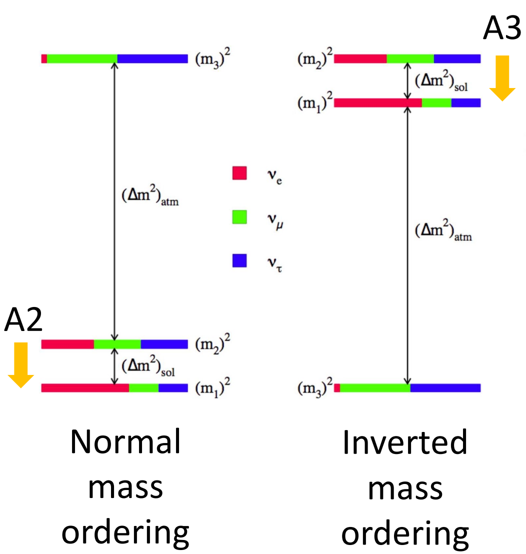
$$\tau_{\rm rest} \gtrsim (400 - 500){\rm s}$$

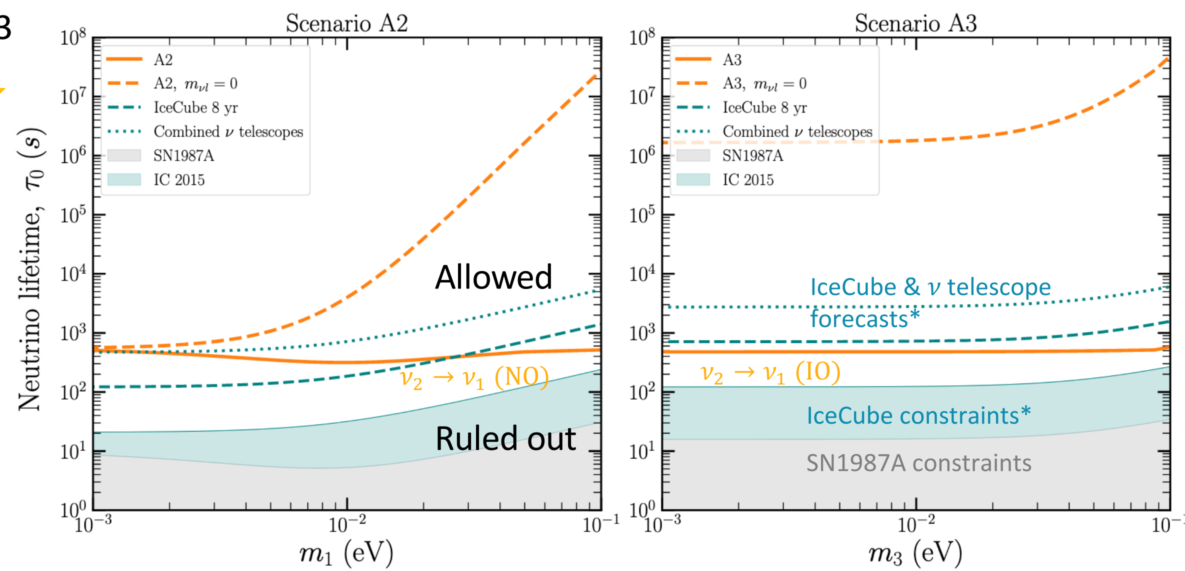
Cf old constraints (which misidentified $T_{\rm coverage}$ with $T_{\rm isotropise}$):

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

CMB lower bounds on the neutrino lifetime…

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





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

* IceCube constraints & forecasts from Song et al. 2021

Summary…

- It has been known for 15+ years that **precision cosmological observables** can be used to constrain invisible neutrino decay.

- But **mapping the decay rate** to the transport rates that ultimately change the CMB observable can be a tricky task.

- We have calculated the transport rates from first-principles and revised the CMB constraint on the neutrino lifetime by many orders of magnitude.