Cosmological constraint on neutrino decay lifetime

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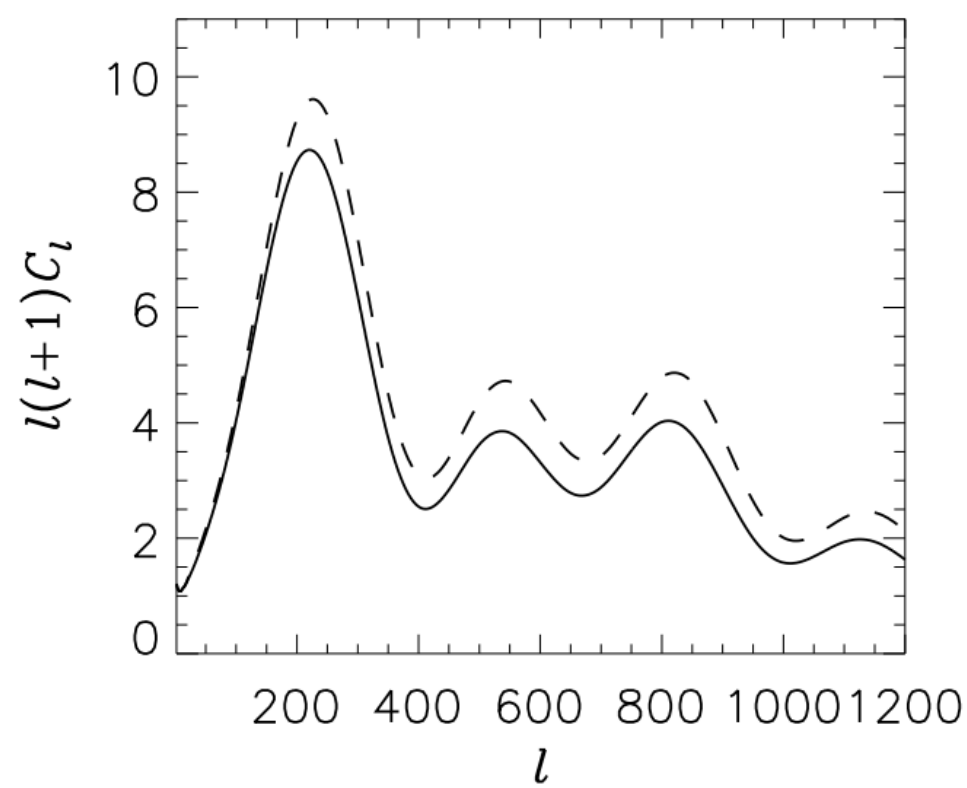
Cosmic Relic Neutrinos

- Relic neutrino background (CνB): 3 generations ($N_{\text{eff}} = 3.0440$).
- After weak decoupling: free-streaming species.
- Cosmic microwave background (CMB) is sensitive to neutrino free-streaming behaviour $\Longrightarrow$ sensitive to any exotic interactions that affects neutrino free-streaming.



Solid line: free-streaming neutrinos
dashed line: strongly interacting neutrinos
Figure from S. Hannestad
(astro-ph/0411475)

Relativistic Neutrino Decay

- Neutrino - Majoron decay $(\nu_H \to \nu_l \phi)$: $\mathscr{L} \sim \mathfrak{g}_{ij} \nu_i \bar{\nu}_j \phi$
- Assume: light Majoron (i.e. $m_\phi = 0$), universal coupling $(\mathfrak{g}_{ij} \sim \mathfrak{g})$.
- Recouple when mother neutrino is ultra-relativistic $T(z_{\rm rc}) \gg m_{\nu H}$. Inverse decay process is kinematically allowed.
- The inverse decay allows transporting momentum in transverse direction and isotropise the neutrino-Majoron combined fluid $\implies$ stops free-streaming.
- Can use CMB's preference on neutrino free-streaming to place constraints on the decay coupling $\mathfrak{g}$ / lifetime $\tau_0 \equiv 1/\Gamma^0_{\rm dec}$.

Decay Modelling

- Collisional Boltzmann equation.

- Anisotropic stress, $\ell \geq 2$ moments in the multipole expansion.

$$\dot{F}_{i,0} = -\frac{|\mathbf{q}||\mathbf{k}|}{\epsilon_i} F_{i,1} + \frac{1}{6}\frac{\partial \bar{f}_i}{\partial \ln |\mathbf{q}|}\dot{h} + \left(\frac{\mathrm{d}f_i}{\mathrm{d}\tau}\right)^{(1)}_{C,0},$$

$$\dot{F}_{i,1} = \frac{|\mathbf{q}||\mathbf{k}|}{\epsilon_i}\left(-\frac{2}{3}F_{i,2} + \frac{1}{3}F_{i,0}\right) + \left(\frac{\mathrm{d}f_i}{\mathrm{d}\tau}\right)^{(1)}_{C,1},$$

$$\dot{F}_{i,2} = \frac{|\mathbf{q}||\mathbf{k}|}{\epsilon_i}\left(-\frac{3}{5}F_{i,3} + \frac{2}{5}F_{i,1}\right) - \frac{\partial \bar{f}_i}{\partial \ln |\mathbf{q}|}\left(\frac{2}{5}\dot{\eta} + \frac{1}{15}\dot{h}\right) + \left(\frac{\mathrm{d}f_i}{\mathrm{d}\tau}\right)^{(1)}_{C,2},$$

$$\dot{F}_{i,\ell>2} = \frac{|\mathbf{k}|}{2\ell+1}\frac{|\mathbf{q}|}{\epsilon_i}\left[\ell F_{i,\ell-1} - (\ell+1)F_{i,\ell+1}\right] + \left(\frac{\mathrm{d}f_i}{\mathrm{d}\tau}\right)^{(1)}_{C,\ell}.$$

Decay Terms

Neutrino/Majoron distribution function
$i \in \{\nu_H, \nu_l, \phi\}$

Collision Integral

- In general, the decay collision integrals are very complicated, numerically difficult to solve.

$$m_i \left(\frac{\mathrm{d}f_i}{\mathrm{d}\sigma}\right)_C = \frac{1}{2}\int \mathrm{d}\mathbf{\Pi}_j(\mathbf{n}) \int \mathrm{d}\mathbf{\Pi}_k(\mathbf{n}')\,(2\pi)^4\,\delta_D^{(4)}(p-n-n')$$
$$\times\,|\mathcal{M}_{i\leftrightarrow j+k}|^2\,[f_j f_k(1\pm f_i) - f_i(1\pm f_j)(1\pm f_k)]$$

- Even if the quantum statistics are dropped, the integro-differential system is still too stiff to solve with brute force.

Effective Collision Integral

- (Escudero, Fairbairn 2019): $\frac{\partial \mathcal{F}_\ell}{\partial \tau} = \cdots - a\Gamma_{\rm T}\mathcal{F}_\ell$, damping of the $\ell \geq 2$ moments.

- The time scale is determined by the 'transport rate'

$$\Gamma_{\rm T} \simeq \Gamma^0_{\rm dec} \left(\frac{m_{\nu H}}{E_{\nu H}}\right)^3 .$$

1 for time dilation
2 for relativistic beaming

- The bound on the decay lifetime from the above modelling

$$\tau_0 \gtrsim (0.3 \to 1.2) \times 10^9\,{\rm s}\,(m_{\nu H}/50\,{\rm meV})^3,$$

the daughter neutrino is assumed massless.

Effective Collision Integral

- Assumptions:
  1. Thermal background dist: $\bar{f}_i(|\mathbf{q}|) = e^{-(\epsilon_i - \mu_i)/T_0}$,

  2. Separable ansatz: $F_{i,\ell}(|\mathbf{k}|, |\mathbf{q}|) \simeq -\frac{1}{4}\frac{\mathrm{d}\bar{f}_i}{\mathrm{d}\ln|\mathbf{q}|}\mathcal{F}_{i,\ell}(|\mathbf{k}|)$,

  3. Common perturbations: $\mathcal{F}_{\nu H,\ell}(|\mathbf{k}|) \simeq \mathcal{F}_{\nu l,\ell}(|\mathbf{k}|) \simeq \mathcal{F}_{\phi,\ell}(|\mathbf{k}|) \simeq \mathcal{F}_{\ell}(|\mathbf{k}|)$,

- Result:

$$\left(\frac{\mathrm{d}\mathcal{F}}{\mathrm{d}\tau}\right)_{C,\ell} = -\,\alpha_\ell\, a\,\tilde{\Gamma}_{\mathrm{dec}}\left(\frac{a m_{\nu H}}{T_0}\right)^4 \mathscr{F}\left(\frac{a m_{\nu H}}{T_0}\right)\Phi\left(\frac{m_{\nu l}}{m_{\nu H}}\right)\mathcal{F}_\ell .$$

$$\sim -a\Gamma^0_{\mathrm{dec}}\left(\frac{a m_{\nu H}}{T_0}\right)^5 \mathcal{F}_\ell$$

5 powers of Lorentz suppression instead of the 3

$$\Phi(y) = \frac{1}{1-y^2}\left(1 - y^4 + 4\,y^2\ln y\right),$$

$$\tilde{\Gamma}_{\mathrm{dec}} = \frac{1}{12}\,\frac{(a^4\bar{\rho}_{\nu H})}{(a^4\bar{\rho}_{\nu\phi})}\,\frac{a m_{\nu H}}{T_0}\,\Gamma^0_{\mathrm{dec}},$$

$$\alpha_\ell = \frac{1}{32}\left(3\ell^4 + 2\ell^3 - 11\ell^2 + 6\ell\right)$$

Possible Scenarios

- Three neutrino mass states, two oscillation mass splitting bounds, inverted or normal hierarchy

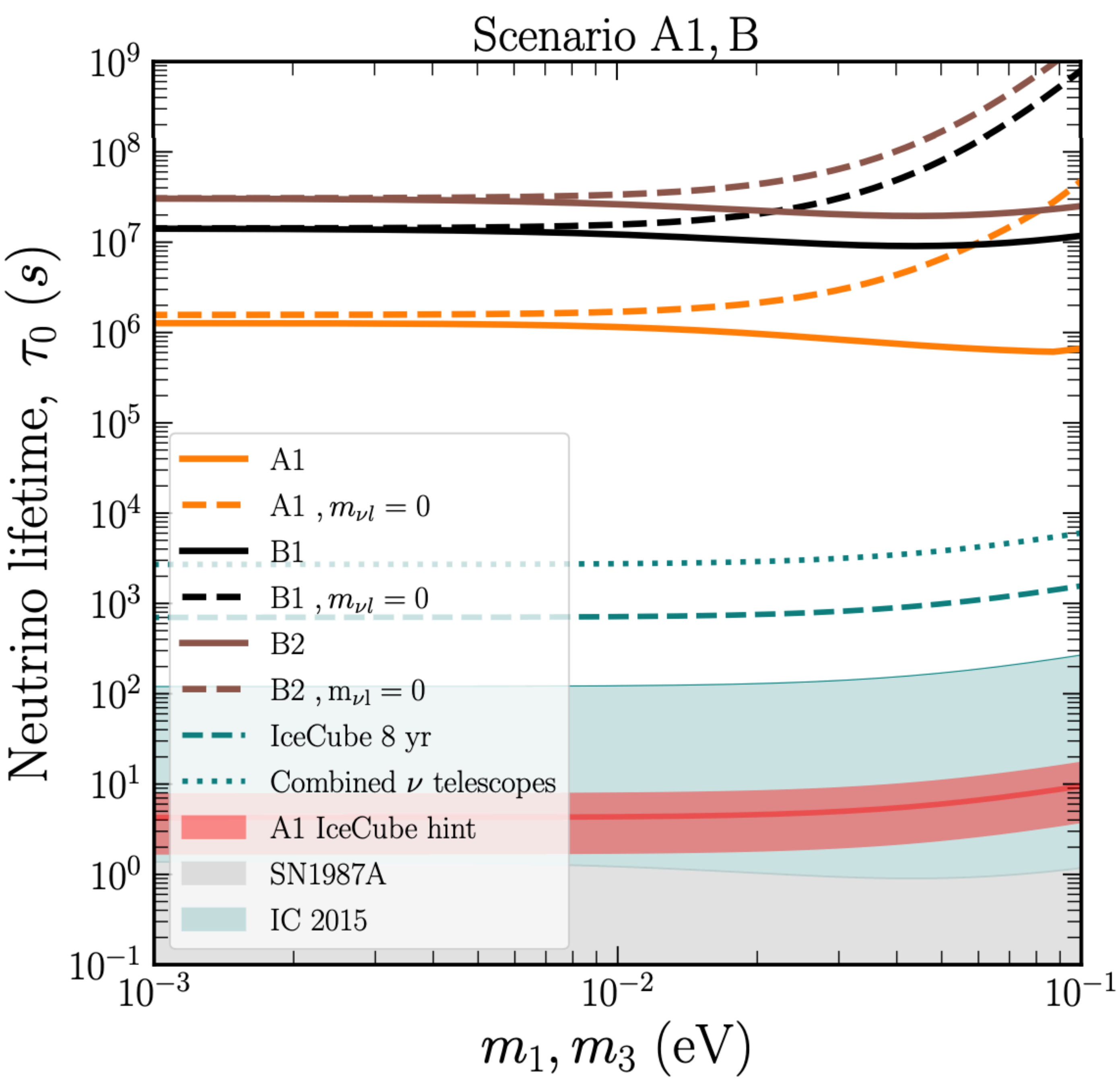
- Scenario A: 1 free-streaming state, 2 decay coupled states (1 decay channel).

- Scenario B: All 3 states are coupled by the decay (2 decay channels). Assume the two solar mass splitting separated states are effectively degenerate (three-to-two states apprxoimation).

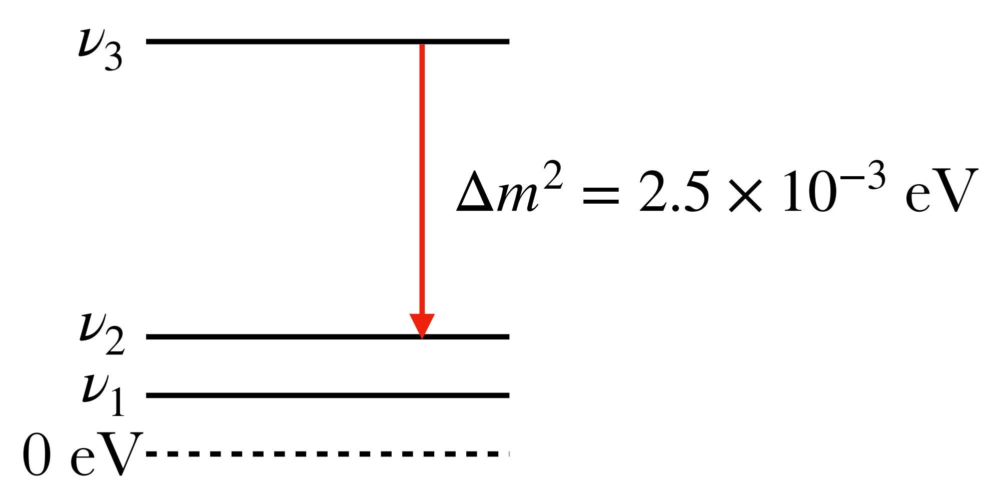
- Implented into CLASS for the purpose of MCMC scan.

Updated Lifetime Constraints

- Planck 2018 data release: TT+TE+EE+lowE+lensing



Scenario A1:
(orange lines)
- 1 free-streaming state
- 2 decay coupled states
- Normal ordering hierarchy



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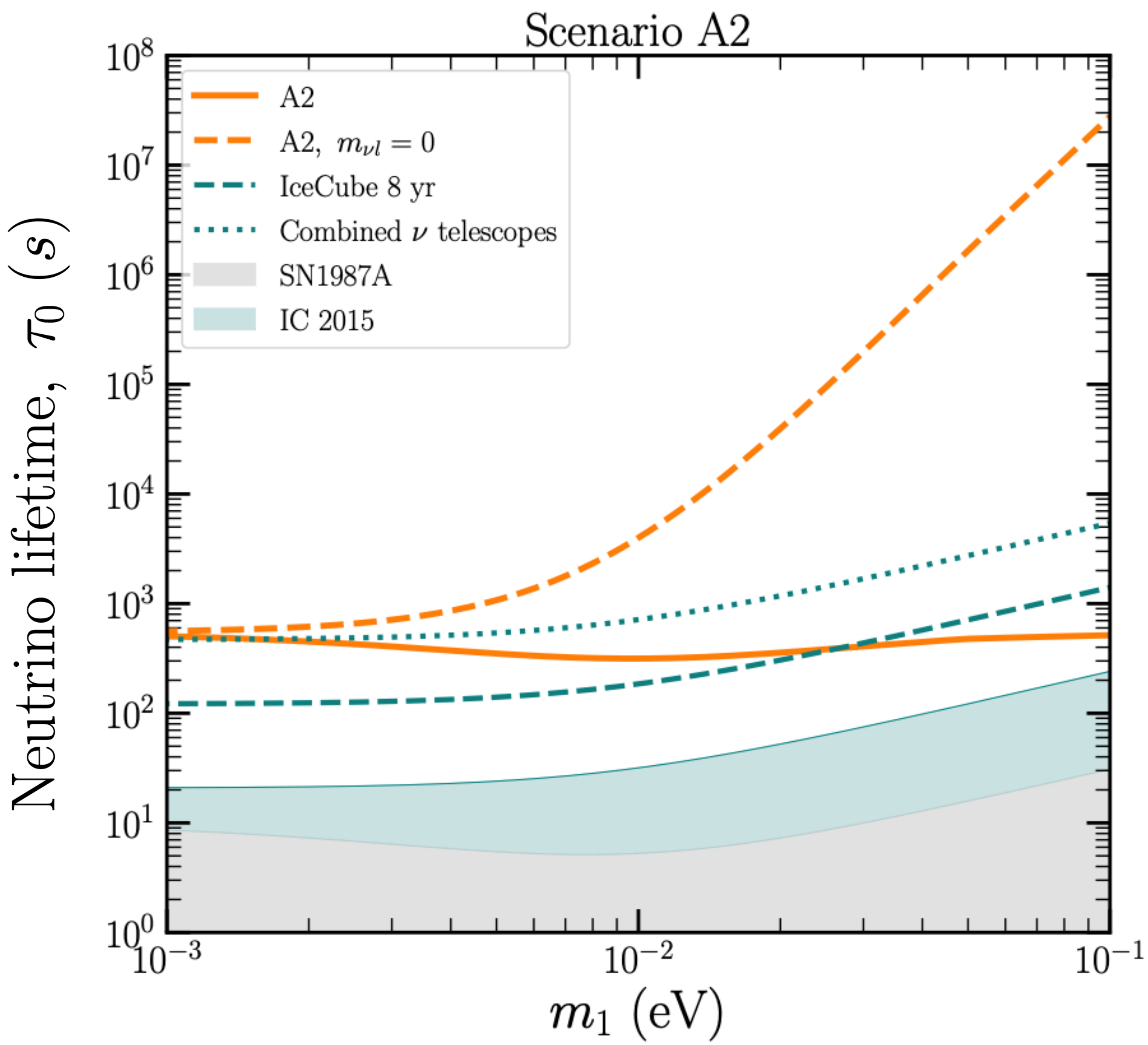
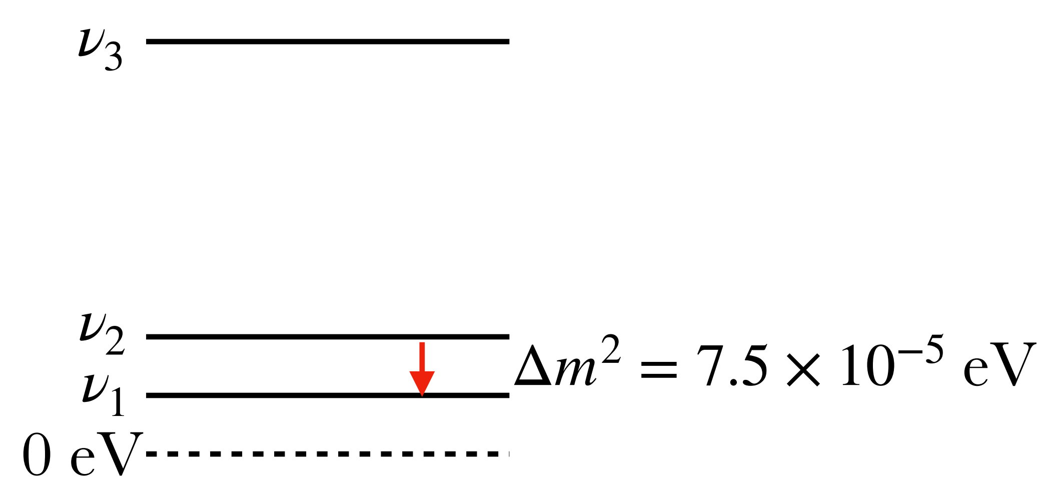


Scenario A2:
(orange lines)
- Normal ordering hierarchy
- 1 free-streaming state
- 2 decay coupled states



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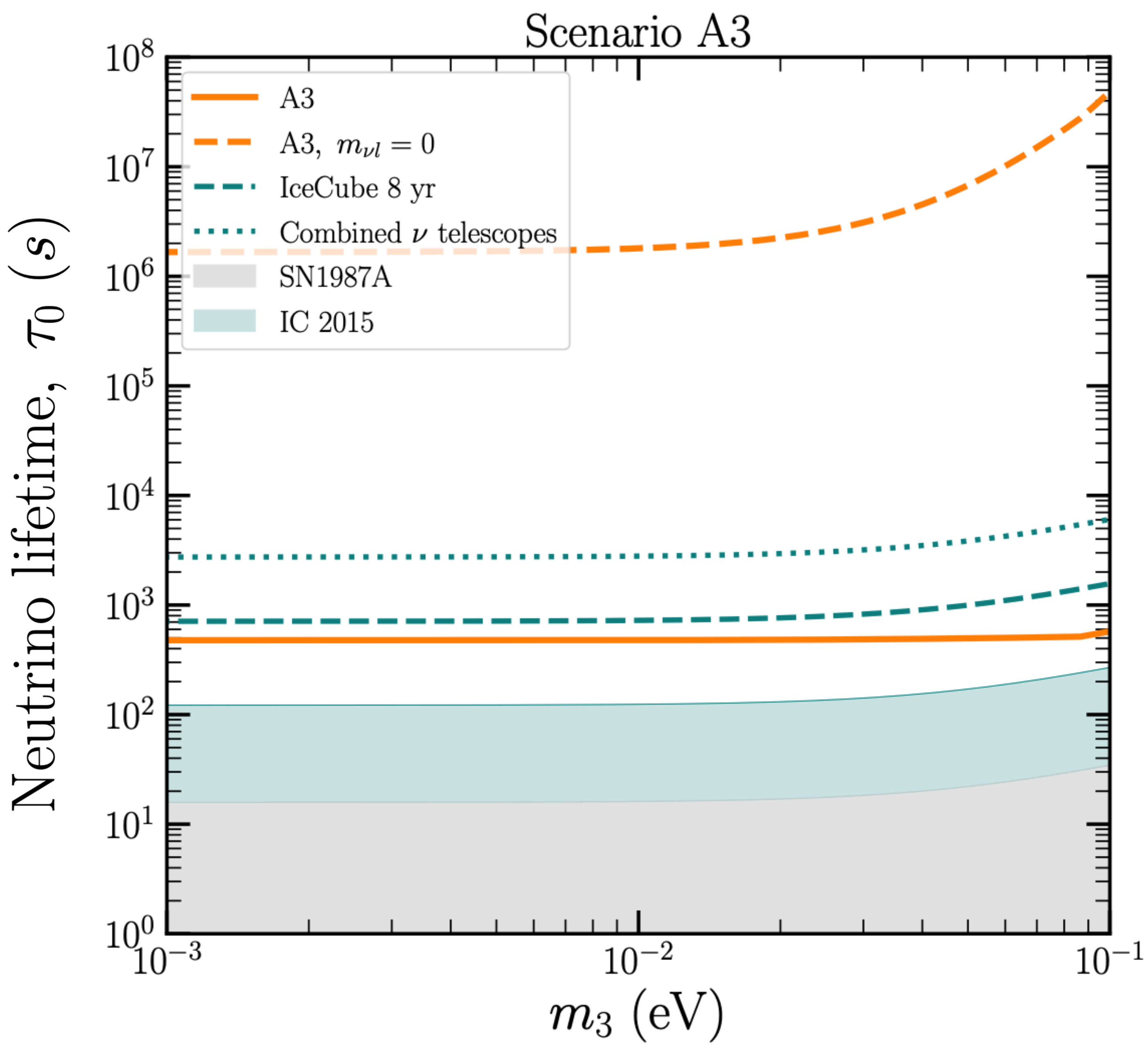


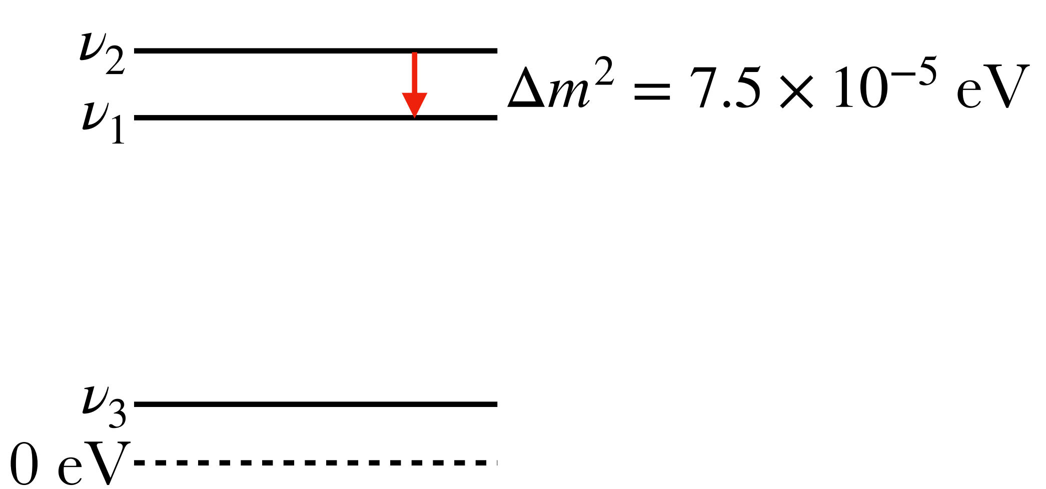
Scenario A3:

(orange lines)

- Inverted ordering hierarchy

- 1 free-streaming state

- 2 decay coupled states



Summary

- The decay lifetime can be constrained with the CMB data's preference for free-streaming neutrinos around recombination.
- The modelling of the decay with the full collisional Boltzmann hierarchy can be done in the form of relaxation time.
- The transport rate we derived is $\Gamma_{\mathrm{T}}^{\mathrm{new}} = (am_{\nu H}/T_0)^5\,\Gamma_{\mathrm{dec}}^0$ differ from the old $\Gamma_{\mathrm{T}}^{\mathrm{old}} = (am_{\nu H}/T_0)^3\,\Gamma_{\mathrm{dec}}^0$.
- Neutrino lifetime constraint from cosmology is significantly relaxed, $\tau_0^{\mathrm{old}} \sim 10^9 (m_{\nu H}/E_{\nu H})^3\,\mathrm{s} \to \tau_0^{\mathrm{new}} \sim 10^2 \to 10^6\,\mathrm{s}$
- Terresterial telescope bounds in the near future will be competitive with cosmological bounds.

The Random Walk Picture

- The old ‘transport rate’ argument is based on the picture that one random walker in a homogeneous background.

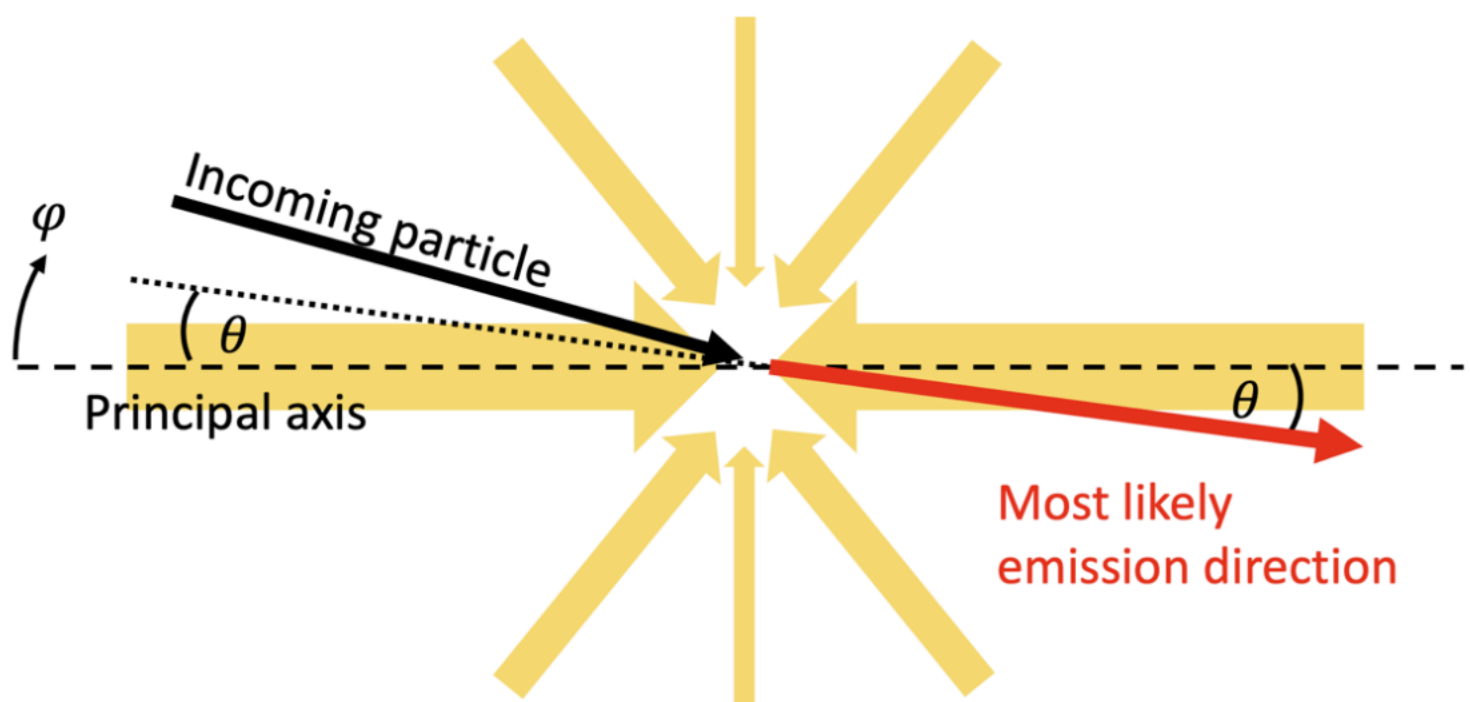
- If each ‘collision’ between the walker and a particle in the background shifts the momentum vector by $\theta = (m/E)$, it takes on average $T_2 = \theta^2$ number of collisions to turn the momentum 90 degrees from its initial direction.

- There is technically nothing stopping the process from contiuning and turn the momentum vector 180 degrees, and thus wiping out any dipole anisotropy.

The Random Walk Picture

- Consider the population separated in two groups, one being the walkers, one being the background.

- The background is anisotropic, and hence would bias the emission from the inverse decay collisions of the walkers.



The Random Walk Picture

- The collisions could shift the momentum vector by $\theta = (m/E)$.
- After $N = 1/\theta^2$, the walker group would look like the background with a slight 'blur' in the anisotropy by θ.
- The entire fluid would only isotropise after many iterations.