# Hunting for the cosmic neutrino background

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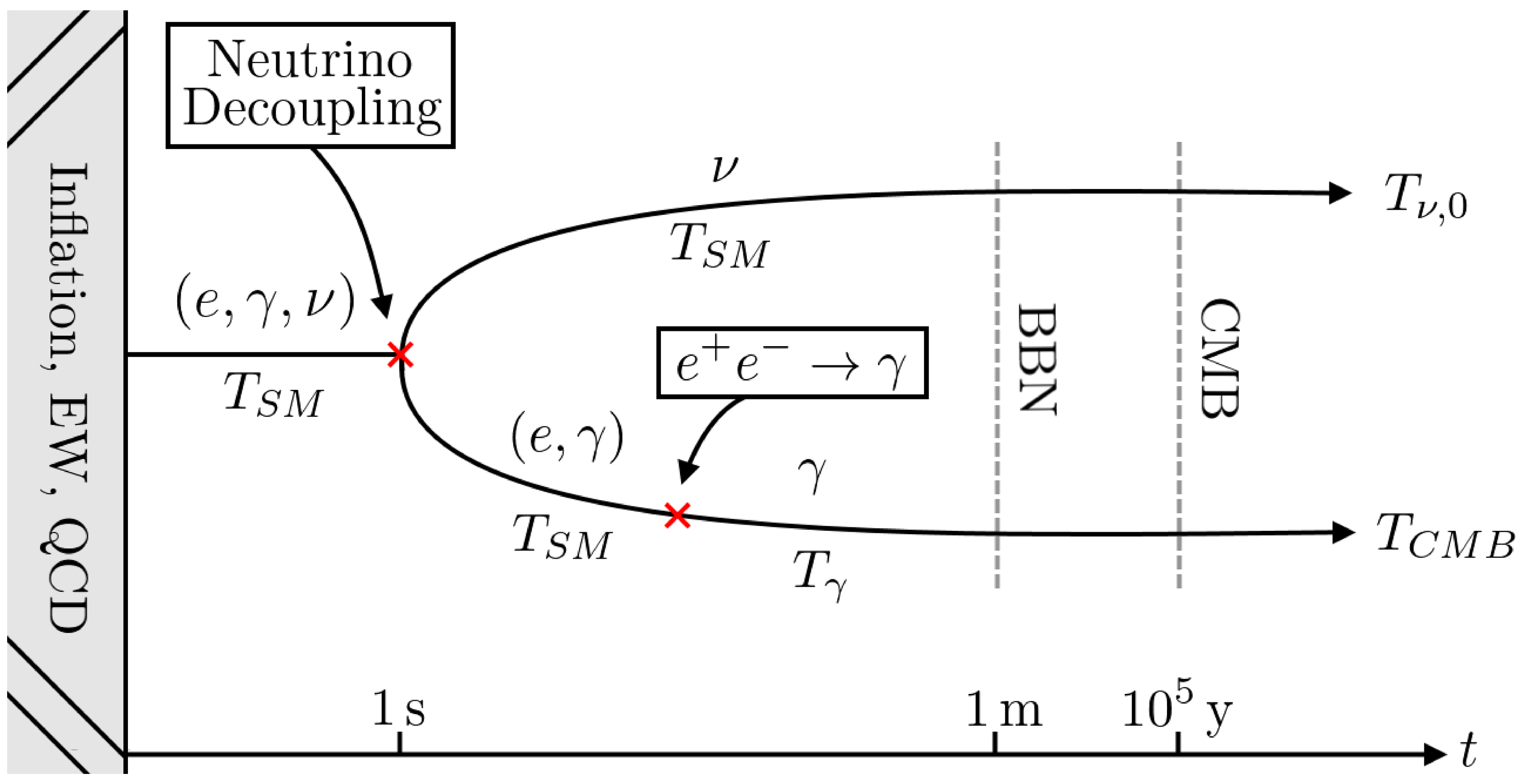
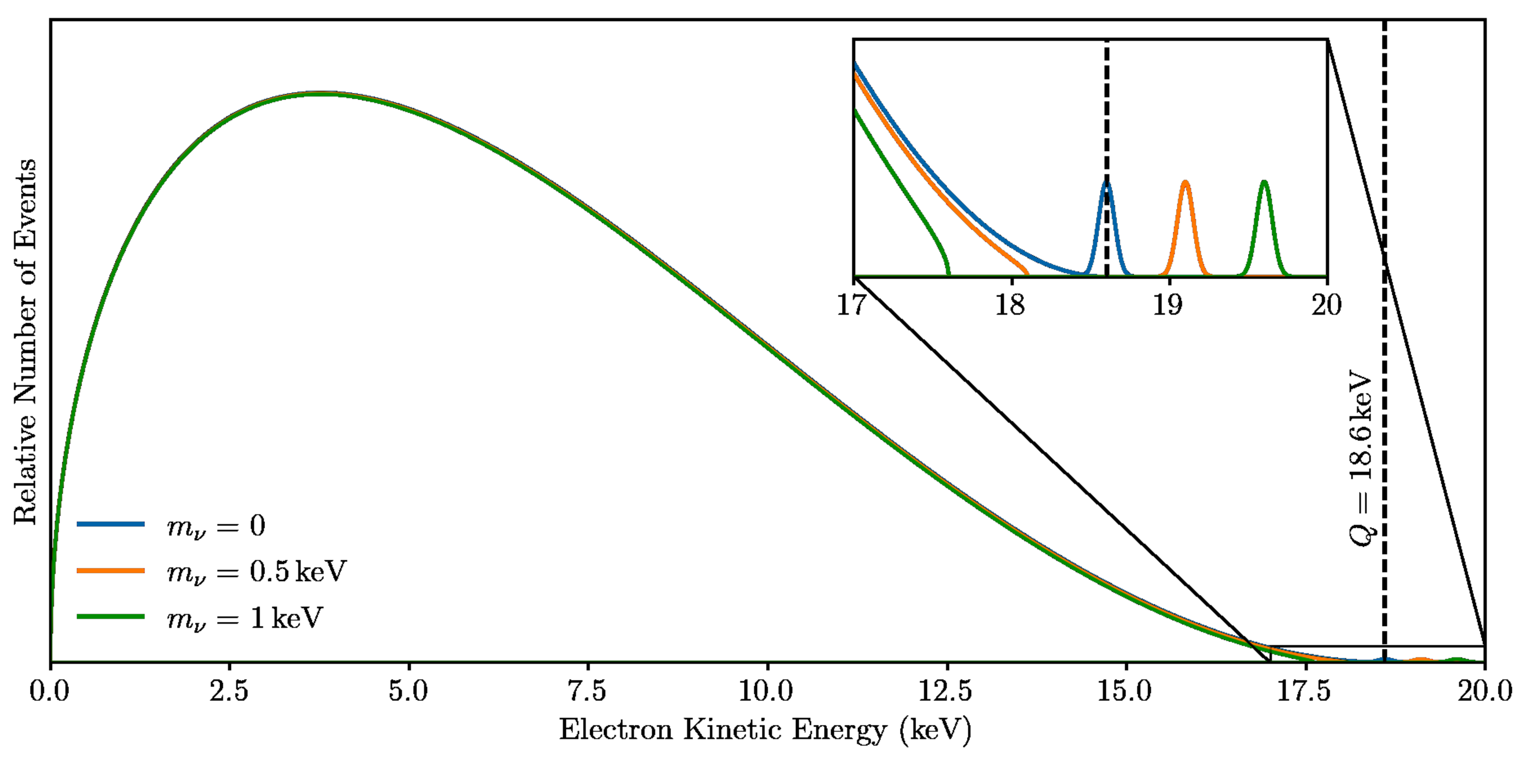
## The Cosmic Neutrino Background

- Neutrinos were abundant in the early radiation dominated universe, in thermal equilibrium with electrons and photons.
- As the universe expanded and cooled, neutrinos fell out of equilibrium with electrons and photons, leaving behind the cosmic neutrino background (C$\nu$B).
- Relic neutrinos played a key role in Big Bang nucleosynthesis (BBN), and left imprints on the cosmic microwave background (CMB).
- Today, C$\nu$B neutrinos are expected to be non-relativistic with average momentum less than 1 meV. This makes them impossible to detect at conventional neutrino experiments.
- As a result, we need to completely rethink neutrino detection. Fortunately, many detection proposals exist.
- A successful detection of the C$\nu$B would give key insights into the evolution of the universe, and may offer a window into the dark sector.
- Due to the low energy of relic neutrino, many C$\nu$B detection proposals are also sensitive to the neutrino mass, as well as the Dirac or Majorana nature of neutrinos.




## PTOLEMY

- The idea is to capture neutrinos on tritium, using the thresholdless process $^3\text{H} + \nu_e \to {}^3\text{He}^+ + e^-$, and observe the outgoing electron with kinetic energy $E_k \simeq 18.6\,\text{keV} + m_\nu$.
- The signal is a peak displaced from the $\beta$-decay endpoint by $2m_\nu$.




- With 100 g of tritium we expect $\sim$ 4 events per year for Dirac neutrinos, or $\sim$ 8 for Majorana neutrinos.

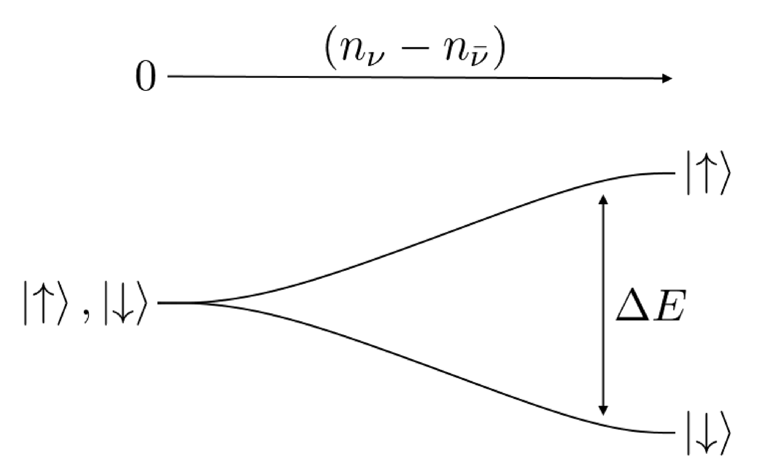
S. Weinberg, *Universal Neutrino Degeneracy*, Phys. Rev. **128** (1962), 1457-1473.

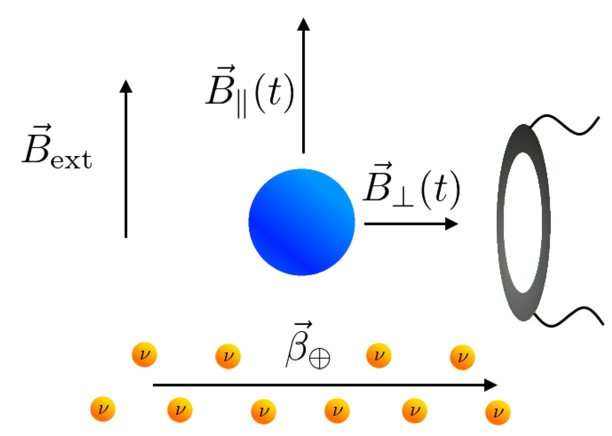
## The Stodolsky Effect

- A background of neutrinos causes a spin-dependent shift in the energy of nucleons or electrons, analogous to the Zeeman effect.
- Its magnitude is proportional either the neutrino-antineutrino or left-right helicity asymmetry in the background

$$\Delta E \sim G_F \beta_\oplus (n_\nu - n_{\bar{\nu}}) \tag{1}$$

- Helicity effect is largest, and leads to a splitting $\Delta E \simeq 10^{-35}\,\text{eV}$.




- This is $\mathcal{O}(10^{-30}\,\text{eV})$ smaller than the Zeeman effect, so how do we see it?
- The splitting causes target spins to precess transverse to the incident neutrino wind.
- Target develops a tiny, time-dependent magnetisation transverse to an applied magnetic field, detectable with a SQUID.

L. Stodolsky, *Speculations on Detection of the Neutrino Sea*, Phys. Rev. Lett. **34** (1975), 110.

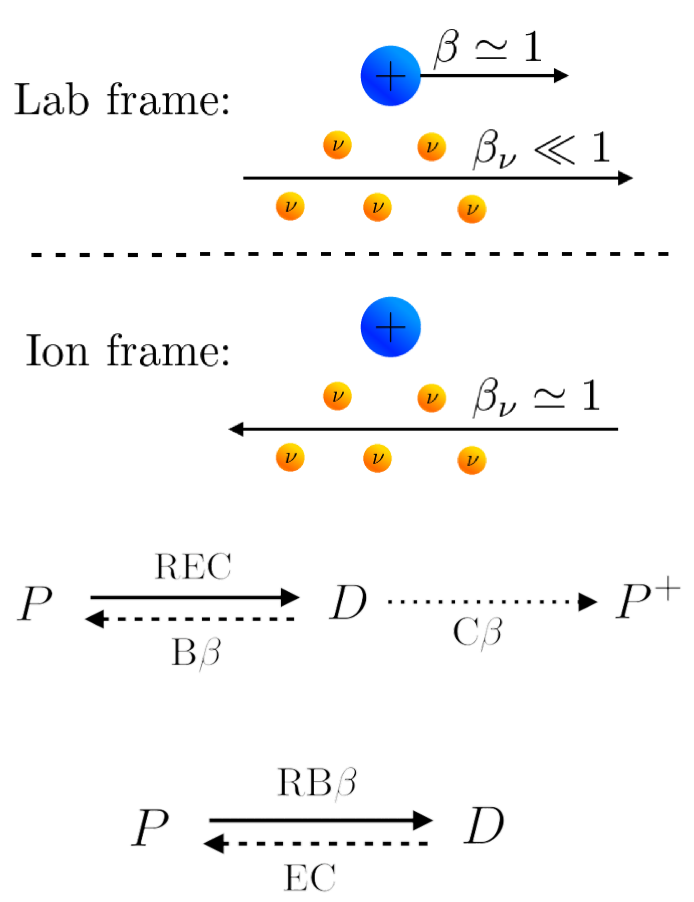
## Accelerator

- In the rest frame of an ultrarelativistic ion, relic neutrinos are ultrarelativistic. This allows us to capture neutrinos on stable targets.
- Using an accelerated beam of ions, we are also able to tune the energy to a resonance, resulting in huge capture cross sections.
- We consider the resonant electron capture (REC) and bound beta (RB$\beta$) processes

$$^A_ZP + e^-\,(\text{bound}) + \bar{\nu}_e \to {}^A_{Z-1}D, \tag{2}$$

$$^A_ZP + \nu_e \to {}^A_{Z+1}D + e^-\,(\text{bound}). \tag{3}$$

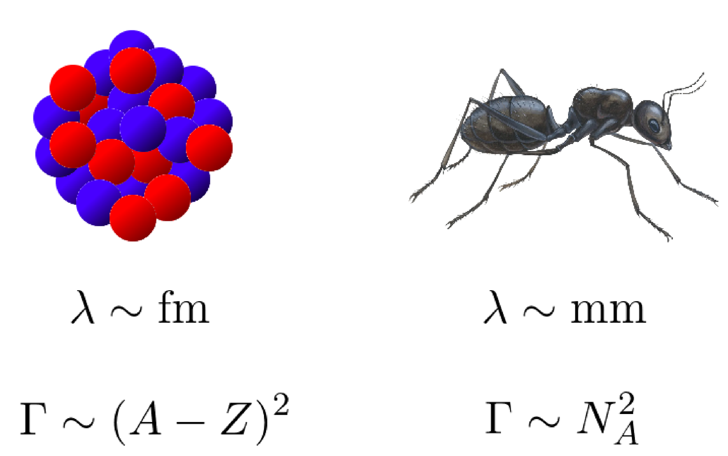
- With threshold $Q$, the capture cross section scales as $Q^{-2}$ and the capture rate as $Q^{-7}$.
- Success requires small $Q$ targets, *e.g.* excited initial states. Improvements can also be made by considering more complex "3-state" systems.




M. Bauer and J. D. Shergold, *Relic neutrinos at accelerator experiments*, Phys. Rev. D **104** (2021) no.8, 083039.

## Coherent Scattering

- The de Broglie wavelength, $\lambda$, of particles scales inversely with their momentum, $p$.
- Consequently, particles scattering with low momentum "see" a larger target and scatter with larger cross sections.
- The coherent scattering rate scales as $N^2$, if there are $N$ targets within the coherent volume $\lambda^3 \sim 1/p^3$.




- Coherent elastic neutrino-nucleus scattering (CE$\nu$NS) has been measured at COHERENT. Here, $p \lesssim 50\,\text{MeV}$ and $\lambda \sim$ fm, the size of an atomic nucleus, giving an enhancement factor approximately equal to the number of nucleons in the target, $A \sim 100$.
- Relic neutrinos have momenta $p \simeq 0.5\,\text{meV}$, corresponding to macroscopic wavelengths $\lambda \sim$ mm and an enhancement factor of order the Avogadro number, $N_A = 6 \cdot 10^{23}$.
- Relic neutrino scattering rates are $\mathcal{O}$(kHz), each transferring a tiny momentum to the target. The resulting acceleration of the target may be measured with a torsion balance.

R. Opher, *Coherent scattering of cosmic neutrinos*, Astron. Astrophys. **37** (1974) no.1, 135-137.

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