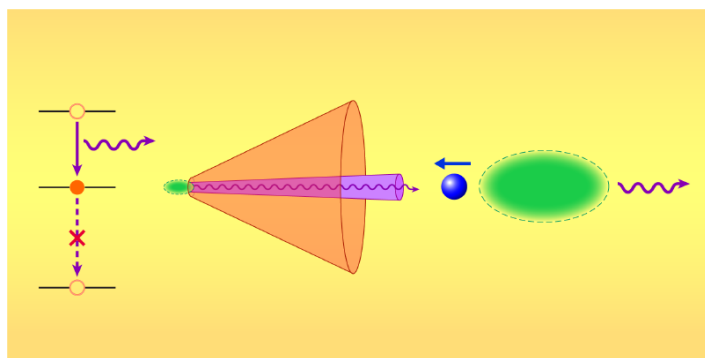


# To Lase or Not to Lase: The Question of Neutrino Superradiance

Two studies find that fundamental quantum constraints rule out a previously proposed neutrino-laser scheme.

By Ana Maria Rey, James K. Thompson, and Haoqing Zhang

One of the most striking demonstrations of collective quantum behavior is superradiance. When photons emitted by many particles carry no information about which particle produced them, the different emission pathways interfere constructively, and the ensemble radiates far more



**Figure 1:** In the neutrino-laser scheme proposed in 2025, each rubidium atom in a Bose-Einstein condensate decays into a krypton atom and a neutrino [1]. Ketterle and his colleagues have identified three issues facing the development of such a laser [2, 3]. Left: During the first decay, the system's collective state changes (straight purple arrow), and a neutrino is emitted (wavy purple arrow). But the Pauli exclusion principle prevents further decay into the same mode. Center: The tiny neutrino wavelength causes the condensate (green) to have an emission cone (purple) that is vanishingly small compared with that typically observed for optical photons (orange). Right: The produced krypton atom (blue) rapidly recoils out of the condensate, destroying coherence before collective emission can build up.

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intensely than independent emitters would. Last year, scientists proposed that this principle could extend from photons to neutrinos, potentially enabling the first neutrino laser (see [Viewpoint: Envisioning a Neutrino Laser](#)) [1]. The idea was especially appealing because neutrinos are otherwise extremely difficult to control and detect, owing to their weak interactions with matter. Now Wolfgang Ketterle and his colleagues at MIT have demonstrated that this vision of neutrino superradiance runs up against fundamental constraints—ones imposed not by engineering challenges but by quantum mechanics itself [2, 3].

Superradiance is a collective enhancement of spontaneous emission [4]. An isolated atom emits at its natural rate  $\gamma$ , so  $N$  independent atoms radiate at a total rate  $N\gamma$ . But when all the atoms radiate into the same mode, constructive interference of the different emission pathways can cause the maximum emission rate to scale as  $N^2\gamma$ . This superradiant regime can occur when the atoms occupy a region much smaller than the radiation's wavelength or when an optical cavity forces them to couple to a common mode [5–7]. Such collective emission can also arise in extended atomic systems, where it becomes directional and is shaped by propagation effects. This extended-ensemble superradiance has been observed in free space [8] and in waveguides [9].

In last year's proposal of a neutrino laser, the researchers sought to exploit the same physics using a Bose-Einstein condensate of about one million radioactive rubidium-83 atoms [1]. These atoms decay into krypton-83 atoms through a process called nuclear electron capture. In this process, a proton in the nucleus captures an electron, transforming into a

neutron while releasing a neutrino. The team predicted that the neutrino emission could become superradiant, shortening the half-life of the rubidium atoms from 86 days to roughly 2.5 minutes—corresponding to a nearly 50,000-fold increase in the characteristic neutrino emission rate.

Ketterle and his colleagues scrutinized the idea in two complementary studies. In the first study, they considered the most favorable possible scenario: All neutrinos are emitted into the same mode, while atomic recoil and other sources of decoherence are entirely absent [2]. In this simplified case, each decay leaves no information about which rubidium atom produced the neutrino—preserving the emission indistinguishability that is essential for superradiance. The team then explored a hypothetical situation in which both the rubidium and krypton atoms are bosons—even though the considered krypton atoms are in fact fermions. Under these assumptions, indeed, successive decays move the system through a sequence of collective states, beginning with all atoms as rubidium and ending with all atoms as krypton. The collective enhancement is strongest near the midpoint of this sequence, where the maximum emission rate scales as  $N^2$ .

The researchers then imposed the actual quantum statistics: While the rubidium-83 atoms are bosons, the produced krypton-83 atoms are fermions. Since the Pauli exclusion principle forbids identical fermions from occupying the same quantum state, the chain of collective emission stops after the first decay (Fig. 1, left). This blockage prevents the  $N^2$  scaling and leaves a maximum emission rate proportional only to  $N$ , the same scaling as for independent emitters.

In the second study, the team continued to treat the krypton atoms hypothetically as bosons and asked whether a Bose-Einstein condensate can support the single-mode emission required for neutrino superradiance [3].

Unlike an optical cavity, free space provides no fixed emission mode. Superradiant enhancement occurs only when the emission from different atoms adds coherently, in directions set by the condensate's geometry and the neutrino wavelength [10]. For an elongated condensate, the emission forms a narrow beam along the condensate's long axis, characterized by a beam waist and a Rayleigh range—the distance over which the mode remains approximately collimated.

Two limiting cases illustrate the challenge of achieving superradiance. One possibility is to match the Rayleigh range to the condensate's length, which is typically tens of micrometers. Doing so, however, requires a beam waist of just a few nanometers, so that only a tiny fraction of the atoms can participate in the collective emission. Alternatively, one could select a beam waist comparable to the transverse size of the condensate. That choice yields an emission cone with an angular width  $\vartheta$  proportional to the neutrino wavelength. The wavelength of the highly relativistic neutrinos produced in nuclear decay is of the order of picometers—vastly smaller than the condensate—meaning that, unfortunately, the cone is extremely narrow (Fig. 1, center). The fraction of emitted neutrinos captured by the collective mode, known as the cooperativity  $C$ , scales as  $\vartheta^2$ , and superradiance requires  $NC \gg 1$ . The neutrino wavelength gives  $C \sim 10^{-12}$ . Thus, even one million atoms yield only  $NC \sim 10^{-6}$ , far below the threshold for collective emission.

The tiny neutrino wavelength creates a further problem: It corresponds to a high momentum, which, because of momentum conservation, gives the produced krypton atoms a recoil velocity of a few thousand meters per second. These atoms move across the condensate in less than a microsecond, which is much shorter than the time required for collective emission to build up (Fig. 1, right). This atomic motion encodes in each emitted neutrino information about which atom produced it, destroying collective coherence long before a superradiant burst can develop.

The significance of these two studies extends beyond the fate of the proposed neutrino laser. Together, they highlight the essential ingredients required for collective quantum emission: indistinguishable emission pathways, sufficiently large cooperativity, and coherence that persists long enough for collective dynamics to emerge.

Understanding why an appealing proposal fails can be as instructive as showing that it works. Although this neutrino-laser scheme seems unworkable, the search for one has illuminated the deep interplay among quantum statistics, coherence, and collective behavior. These lessons may guide the development of future quantum systems in which analogous phenomena can be engineered and explored.

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