Supernovae could enable the discovery of new Muonic physics

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Artistic illustration of SN1987a. Credit: NRAO/AUI/NSF, B. Saxton.

A supernova, the explosion of a white-dwarf or massive star, can create as much light as billions of normal stars. This transient astronomical

phenomenon can occur at any point after a star has reached its final evolutionary stages.

Supernovae are thought to be associated with extreme physical conditions, far more extreme than those observed during any other known astrophysical phenomenon in the universe, excluding the Big Bang. In supernovae that involve a massive star, the star's core can collapse into a neutron star, while the rest of it is expelled in the explosion.

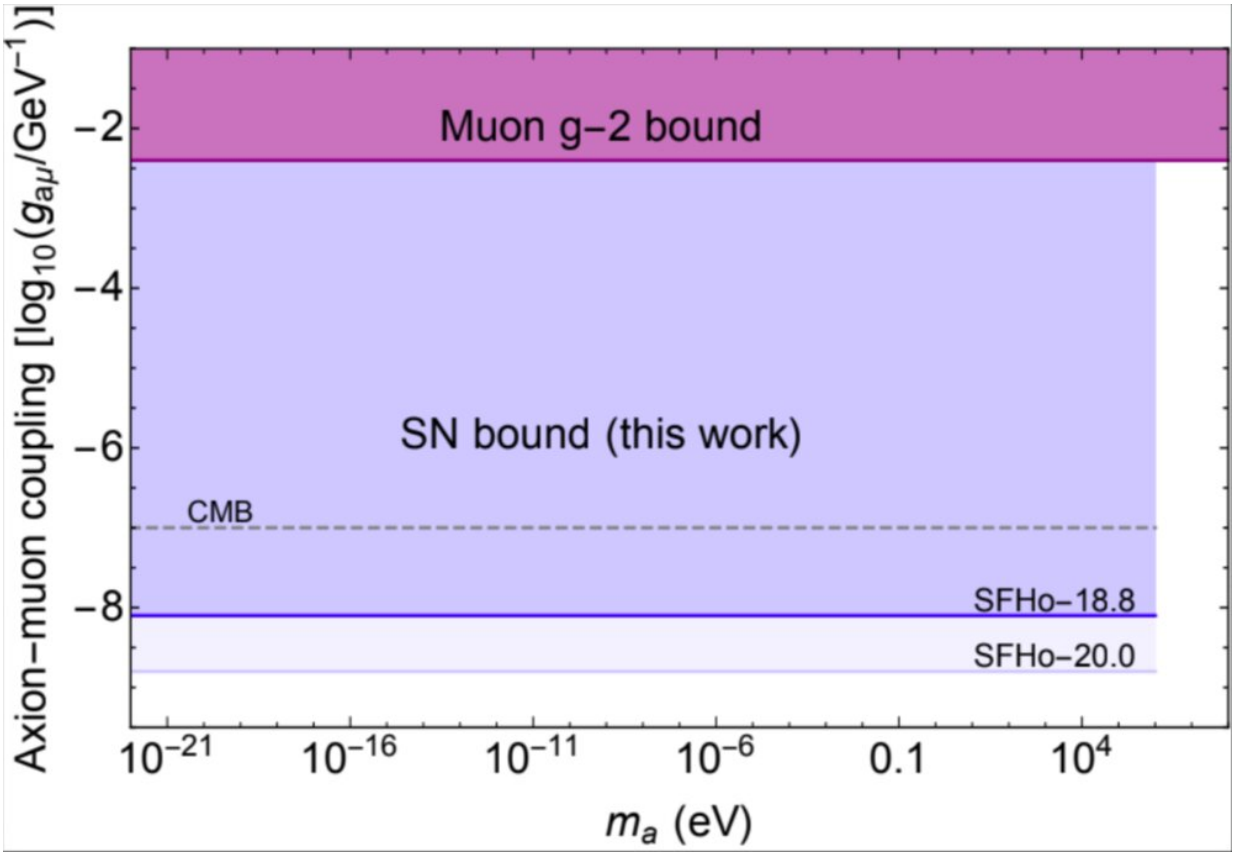
During these violent stellar explosions, temperatures in the newborn neutron star can reach over 600 billion degrees, and densities can be up to 10 times greater than those in atomic nuclei. The hot neutron star resulting from this type of supernova is a significant source of neutrinos and could thus be an ideal model for particle physics studies.

For several decades, astronomers and astrophysicists have been trying to prepare for the occurrence of a supernova, devising theoretical and computational models that could aid the current understanding of this fascinating cosmological event. These models could help to analyze and better understand new data collected using state-of-the-art detectors and other instruments, particularly those designed to measure neutrinos and gravitational waves.

Back in 1987, researchers were able to observe neutrinos produced in a supernova for the first and, so far, only time, using instruments known as neutrino detectors. These neutrinos had traveled to Earth over a time period of approximately ten seconds, thus, their observation provided a measurement of the rate at which the remains of a supernova were able to cool down.

For decades now, this measurement was seen as the limit in how quickly exotic particles can cool a supernova remnant. Since it was first

introduced in 1987, this point of reference, known as the "supernova cooling constraint," has been extensively used to investigate extensions of the standard model, the primary theory of particle physics describing fundamental forces in the universe.



Credit: Bollig et al.

Researchers at the Max Planck Institute for Astrophysics in Germany and Stanford University have recently carried out a study investigating the potential of supernovae as platforms to unveil new physics beyond the standard model. Their paper, published in *Physical Review Letters*, specifically explores the role that muons, particles that resemble

electrons but have far larger masses, could play in the cooling of supernova remnants.

"While the concept of 'supernova cooling constraints' has been around for decades, the community has only recently begun to appreciate the role that muons can play in supernovae, and as a result, very little work had been done on how new particles that couple primarily to muons could affect the cooling," William DeRocco, one of the researchers who carried out the study, told Phys.org. "We realized that by running cutting-edge simulations of muons in supernovae, we could place a cooling bound on these exotic couplings, and that was how the project was born."

The recent study featured in *Physical Review Letters* was the result of a collaboration between two teams of researchers, one at the Max Planck Institute and one at Stanford. The team at the Max Planck Institute, comprised by Robert Bolling and Hans-Thomas Janka, ran a series of supernova simulations that included Muonic effects, while also incorporating some of the most recent findings about the physics of supernovae.

These simulations led to the creation of the largest existing library of supernova profiles including muons, which is now publicly available and can be accessed by all astrophysics researchers worldwide. Subsequently, De Rocco and the rest of the team at Stanford used this library to compute production rates of axion-like particles, trying to determine where in the parameter space their production would violate the cooling constraint delineated in 1987.

"More and more detailed models of the complex processes in supernovae still allow us to use the 33-year-old neutrino measurements connected with Supernova 1987A to learn new aspects about particle phenomena, which are difficult to explore in lab experiments," Janka told Phys.org.

"William and Peter contacted my postdoc Robert and myself with their novel ideas by email, so we teamed up to join forces on this research project during the COVID-19 lockdown on both sides, communicating via email and in video meetings."

DeRocco, Janka, and their colleagues demonstrated that supernovae could be powerful laboratory models to hunt for new muonic physics, something that was not fully appreciated until now. Their work has already inspired other research teams to seek for exotic physics beyond the standard model by studying muons in supernovae. In the future, this paper could thus pave the way towards new fascinating discoveries about particles in the universe and cosmological phenomena.

"I think there's a still a wealth of information that supernovae can provide us on possible extensions of the standard model," DeRocco said. "So far, we have only seen the neutrinos of one galactic supernova, but the rate at which supernovae go off in our galaxy is estimated to be about twice per century, so we have a good chance of seeing another in the next few decades. With the significantly advanced detectors that we built since 1987, the information we would receive from the observation of the next galactic supernova is vast and exciting to speculate on. Perhaps it is in supernova neutrinos that we will make our first observation of beyond standard model physics!"

More information: Robert Bollig et al. Muons in Supernovae: Implications for the Axion-Muon Coupling, *Physical Review Letters* (2020). DOI: 10.1103/PhysRevLett.125.051104