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Neutron Stars as Cosmic Laboratories: Probing QCD, Dark Matter and Axions in the Multi-Messenger Era

Neutron stars are poised to become precision tools for nuclear and particle physics. In the era of multi-messenger astronomy, observations of gravitational waves, electromagnetic radiation, and neutrinos from neutron stars are transforming our understanding of matter under extreme conditions. In the first part of this talk, I will explore how radio and x-ray observations of neutron stars in our galaxy, and gravitational waves from neutron star mergers from the universe can illuminate the QCD phase diagram at low temperatures and high baryon densities, a regime inaccessible to terrestrial experiments. We'll discuss how multi-messenger data constrain the equation of state and hint at potential phase transitions deep within neutron star cores. In the second part, I'll shift focus to the role of QCD axions—hypothetical particles motivated by the strong CP problem. I will present recent theoretical developments suggesting that axions may condense inside neutron stars. We'll consider how such axion condensates could alter observable properties of these stars and point toward new physics beyond the Standard Model. Together, these threads weave a picture of neutron stars not just as endpoints of stellar evolution, but as cosmic laboratories for nuclear and particle physics

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Originally from Bengaluru, Sanjay Reddy attended St. Joseph's Indian High School before earning a B.Sc. in Physics from St. Stephen's College, Delhi University, and a Master's degree from IIT Madras. He completed his Ph.D. in Physics at SUNY Stony Brook in 1998, followed by postdoctoral positions at the Institute for Nuclear Theory (INT) at the University of Washington and the Center for Theoretical Physics at MIT. From 2002 to 2011, he was a Staff Scientist at Los Alamos National Laboratory. Since 2011, he has been a Senior Fellow at INT and Professor of Physics at the University of Washington, Seattle.

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