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NEUTRINOS ASTROPHYSICS:
from core-collapse supernovae and kilonovae to the discovery of the diffuse supernova neutrino background

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Abstract

Core-collapse supernovae and binary neutron star mergers are the most powerful sources of low energy neutrinos. In such astrophysical environments, shock waves, turbulence, neutrino self-interactions and unknown neutrino properties influence the neutrino time signal and energy spectra while neutrinos propagate in the medium. Understanding their impact is important for the future observation of the neutrino signal from an (extra)galactic explosion and the discovery of the diffuse supernova neutrino background, for the longstanding open questions of the core-collapse supernovae explosion mechanism and for identifying the site(s) for r-process nucleosynthesis. The recent GW170817 has given evidence that r-process elements are produced in kilonovae. In their (dynamical, viscous, neutrino-driven) winds, neutrinos modify the electron-fraction, a key parameter for r-process nucleosynthesis. The future supernova neutrino luminosity curve and spectra precise measurements will give key information on the astrophysical sources. Theoretical developments are necessary to answer these fundamental and observational open questions and to support the coming decade of crucial measurements of core-collapse supernova neutrinos, gravitational waves from binary neutron star mergers, and kilonovae.

White paper

The neutrino oscillation discovery has deeply modified our understanding of neutrino propagation in vacuum, in cosmological and astrophysical environments – the Sun, core-collapse supernovae, accretion disks around black holes and binary compact mergers. The deficit of high energy solar neutrinos is nowadays understood as an adiabatic resonant flavour conversion phenomenon due to neutrino coupling with matter – the Mikheev-Smirnow-Wolfenstein (MSW) effect, which has become essential to describe neutrino flavour conversion in media. Reactor, accelerator and solar experiments have precisely determined the mixing angles of the Pontecorvo-Maki-Nakagawa-Sakata matrix relating the flavour to the mass basis, as well as the mass-squared differences and one sign. Crucial open issues remain, including the neutrino Dirac versus Majorana nature, the neutrino absolute mass and mass ordering, the existence of CP violation in the lepton sector and of sterile neutrinos.

Concerning astrophysical neutrinos, important open questions have been challenging theorists since more than a decade :

* How do neutrinos modify their flavor in dense environments ? What are the associated effects on the time signal and on the neutrino spectra and, consequently, the impact on

observations, on the core-collapse supernova dynamics and on nucleosynthetic abundances in r-process candidate sites, i.e. core-collapse supernovae, accretion disks around compact objects - black holes, binary neutron star mergers (BNS)? How are the neutrino time signal and the energy spectra modified by unknown neutrino properties (e.g. the neutrino mass ordering, the neutrino magnetic moment, non-standard interactions or sterile neutrinos)? What can we learn on the neutrino sources ?

Such neutrinos are tightly linked to two longstanding questions in astrophysics :

* What is the explosion mechanism of core-collapse supernovae ?
* What are the sites for r-process nucleosynthesis ?

The present proposal is complementary to the proposals *"Understanding the core collapse supernova explosion mechanism"*, *"Probing extreme matter physics with gravitational waves"* (GT04) and *"The Super-Kamiokande Gadolinium experiment"* (GT06).

The measurement of twenty-five electron anti-neutrinos events from SN1987A has brought key information on the supernova mechanism, favoring the delayed neutrino driven mechanism (Bethe-Wilson 1985) over the prompt explosion [1], as well as on neutrino properties. For r-process nucleosynthesis, GW170817 has provided first evidence for the gravitational wave signal from a BNS in coincidence with a short Gamma-Ray-Burst and a kilonova [2]. The electromagnetic signal gives the first evidence for ejecta with r-process elements (actinides and lanthanides) in a BNS. Ejecta are compatible with a dynamical pre-merger component and viscous and neutrino-driven winds ejecta from the post-merger phase. Flavor evolution impacts electron-fraction and nucleosynthetic abundances in such sites.

Since more than a decade, theorists have shown that neutrino flavor evolution in dense environments is much more complex than the case of our Sun. This is due to the presence of shock waves and of turbulence in exploding astrophysical environments and of sizeable neutrino self-interaction, since core-collapse supernovae and kilonovae are among the most powerful neutrino sources in the Universe. As a consequence, neutrino propagation in such sites is a complex many-body problem. Novel flavor conversion mechanisms are being uncovered that can influence the time signal and energy spectra with observational implications. Predictions require demanding numerical simulations, due to stiffness, multi-dimensionality and the non-linearity of the problem [3].

While many aspects have been understood on neutrino flavor evolution in dense environments, open questions still need to be addressed for a definite answer about the conditions and scales for flavor instabilities, the competition of flavor mixings and collisions, the role of gravity, just to mention a few, and the consequent impact on observations. It is noteworthy that the description of flavor evolution in dense environments has obvious tight connections with cosmological neutrinos at the epoch of Big-bang nucleosynthesis.

In the future the discovery of the diffuse supernova neutrino background is expected with the start of Super-Kamiokande with Gadolinium project in Japan, which is sensitivite to both the star formation rate and on the redshifted neutrino spectra [4]. Gravitational wave observations from LIGO and Virgo should observe new BNS events, precisely measuring BNS rate, and new kilonovae. This will bring essential information to assess the sites and conditions where weak and strong r-process can take place [5]. Finally, if a core-collapse supernova blows up in our galaxy or nearby, an ensemble of observatories both in the Supernova Early Warning System (SNEWS), including Super-Kamiokande, ICECUBE, JUNO, KM3NET and beyond, like Dark-Side, DUNE and the future Hyper-Kamiokande will precisely measure the time and energy signal for the three neutrino flavors. The precise measurement of the time signal can confirm/refute the delayed neutrino driven mechanism aided by SASI (Standing-Accretion-Shock Instability). The determination of the neutrino time signal and spectra gives the unique possibility to understand flavor evolution in dense environments, to learn about unknown neutrino properties, the properties of the newly born neutron star (e.g. gravitational binding energy, mass-radius and EOS, gravitational binding energy-radius, cooling and phase transitions) and new physics. Theoretical developments are essential to address these fundamental issues, and support the coming decade of crucial observations.

References

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