THE PAST AND FUTURE OF NEUTRINO PHYSICS

Sheldon Lee Glashow
Harvard & Boston Univerities, emeritus

It is an honor to present the opening talk at the 19th edition of the International Workshop on Neutrino Telescopes, the fourth such workshop I've been privileged to attend.
My earlier experiences in Venice were all instructive, enjoyable and graciously hosted by Milla Baldo-Ceolin.
They took place mostly on dry land, but partly on water when Venice was flooded This time, for a change, our proceedings must be mostly on air.

Neutrino physics has begun its vigorous ninth decade, with Milla's dream of neutrino astronomy now realized in full. Today, I offer neither pictures, graphs, equations nor new theoretical insights. Instead, my talk begins with a timeline of our enchanting endeavor, mentioning some highlights of its history with which my younger listeners might not be familiar. Please forgive the many errors, omissions and indelicacies of an elder if not wiser colleague.

1930: Wolfgang Pauli chose not to travel to a physics conference, sensibly opting for a Christmas Ball in Zurich instead. In a letter of apology to the assembled "radioaktive damen und herren" in Tubingen, he described his "desperate remedy" for the vexing problem of the continuity of beta decay spectra. He dared propose the existence of a new light and neutral particle to solve both the energy and statistics problems. Three years later Enrico Fermi dubbed Pauli's putative particles neutrinos. He put them and their antiparticles to very good use in his theory of weak interactions.

1946: Bruno Pontecorvo proposed the radiochemical Chlorine experiment which Ray Davis would later use to observe and study solar neutrinos.

1955: Ray Davis' null experiment at the Savannah River nuclear reactor showed neutrinos & antineutrinos to be distinct particles.

In 1956, also at that reactor, Clyde Cowan & Fred Reines triumphantly detected reactor antineutrinos. Pauli was delighted, as was every physicist of a certain age. In that same year, Mme. Wu, following the counsel of her Columbia colleague T.D. Lee, became the first to show that weak interactions violate mirror symmetry, and that neutrinos are left-handed. An American postage stamp with a flattering image of her has just been issued.

1957: My thesis advisor Julian Schwinger proposed that a triplet of vector bosons could mediate both the weak and electromagnetic interactions. He left the detail for me to work out. Furthermore, the V-A theory was devised by Sudarshan & Marshak. An identical theory was proposed, not quite independently, by Feynman & Gell-Mann. Later in 1957, Sid Bludman suggested the first gauge theory of the weak interactions, just as John Sakurai had done for the strong. Neither of these precocious gauge theories would long survive.

1958: My high-school buddy Gary Feinberg, assuming weak interactions to be mediated by vector bosons, showed why the observed absence of radiative muon decay demands electron and muon neutrinos to be distinct particles. During my thesis oral exam that summer, C.N. Yang, a member of my exam committee learned from Schwinger how electron and muon neutrinos, if they were different, could be experimentally distinguished from one another.

1960: I proposed the gauge group SU(2)XU(1) to underline electroweak forces, thereby predicting neutral currents, but not acceptable ones. The GIM mechanism would undo the damage almost a decade later..

1962: My late friends Leon Lederman, Mel Schwartz and Jack Steinberger designed and performed a brilliant experiment proving muon and electron neutrinos to be distinct particles.

1966: Stirling Colgate & Richard White deduced that about 99% of the energy release of a core-collapse supernova is emitted as a brief but intense burst of neutrinos, such as would be observed 21 years later.

1968: Theorist John Bahcall and experimenter Ray Davis uncovered a puzzling deficit in the observed flux of solar neutrinos. Was it due to a flaw in Bahcall's solar model? Or a systematic error in Davis's experiment? Or did neutrino flavors oscillate, as Pontecorvo first suggested? The Solar Neutrino Problem would challenge physicists for decades.

1972-74: Neutrino interactions studied at Gargamelle confirmed that quarks have fractional charges. They also discovered the neutral current interactions that had been predicted by the electroweak theory. Fermilab would soon confirm the dramatic discovery.

1975: Samios's group at Brookhaven claimed to have discovered the first charmed particle: a baryon produced by a neutrino impact whose measured mass lay close both to its actual value, and to its predicted value. One year later, charmed mesons aplenty were seen at SLAC.

1979: Larry Sulak and his friends conceived, designed and created the first massive underground imaging water Cerenkov detector. Such devices enabled the spectacular achievements of IMB, KamiokandeAntares, Super-Kamiokande, Kamland, IceCube, and SnoLab, as well as those of future facilities like Hyper-Kamiokande.

1987: An intense neutrino burst from a relatively nearby supernova was observed by IMB in Ohio, Kamiokande in Japan and the Baksan neutrino observatory in Russia, confirming our understanding of supernovae. Later on the event was seen in visible light, X-rays and gamma rays, thereby initiating the notion of multi-messenger neutrino astronomy.

1988: From its study of Zo decays, CERN measured the number of active neutrino species to be three to within 0.2%, in excellent agreement with astrophysical estimates, and more importantly, with nature.

1990: GALLEX in Italy and the Soviet-American experiment SAGE offered firm confirmations of Davis's observed deficit of solar neutrinos.

1997: Fermilab's DONUT experiment managed to detect the interactions of tau neutrinos, whose existence no one had doubted.

1998: Super-Kamiokande published a neutrino image of the sun. More important was its astonishing (but anticipated) discovery of atmospheric neutrino oscillations, which proved that neutrinos have mass. Announced at the 1998 Takayama neutrino conference, the work earned a standing ovation, a rare event at physics conferences.

2001: The Sudbury Neutrino Observatory in Canada ingeniously measured the fluxes of solar neutrinos of all flavors. Along with Super-K data, their result confirmed the standard solar model. The decades-old Solar Neutrino Problem had finally been put to rest.

2012: The Daya Bay and RENO experiments in China and South Korea measured theta-31, the third of the four angles of the Pontecorvo-Maki-Nakagawa-Sakata neutrino mass matrix... a rather mysterious multiple eponym, but one that may need revision if not-quite-sterile eV-scale neutrinos are found to exist.

2017: At the South Pole, the IceCube Observatory's detection of a high-energy cosmic-ray neutrino triggered other observers to detect gamma rays and electromagnetic signals from a blazar. IceCube had located the first known source of cosmic rays and high-energy neutrinos.

2019: IceCube detected one likely instance of the so-called Glashow resonance, which I imagined over 60 years ago. Let them see another!

2020: Hyper-Kamiokande was approved for construction. Meanwhile, the T2K experiment severely constrained the CP-violating phase of the PMNS matrix. The absence of CP violation amongst neutrinos was excluded at the 95% confidence level, much encouraging neutrino experimenters.

2021: At least twelve eV-scale sterile neutrino searches are underway in Antarctica, Asia, Russia, Western Europe and the United States. "As a result of [this] surge of interest in sterile neutrinos," wrote the CERN Courier, "detector technology has improved to the point that they may be used to monitor nuclear reactors." With this reminder that even the least practical pursuits of particle physicists can be of benefit to society, we reach the end of our timeline.

I turn briefly to the principal focus of this Workshop, the future of neutrino physics.

Why such fervid interest in the possible existence of hypothetical spin 1/2 neutral fermions, also known as sterile neutrinos? While only three active neutrino states participate in the standard theory, several sensible arguments suggest the existence of additional sterile or quasi-sterile neutrino states. To wit:

(i) Right-handed neutrino states are needed Standard Model neutrinos are to be Dirac fermions. Neutrino masses would then be lepton-number conserving and the mechanism for neutrinoless double beta decay would be disabled. However, these are not the sterile neutrino states that interest my experimental colleagues, nor do we know how we can search for them directly.

(ii) Quasi-sterile neutrinos with large Majorana masses and small mixings with active neutrinos are essential to implement the most popular mechanism for generating neutrino masses. But neither are these the eV-scale neutrino states being sought... although their decays might provide targets for the LHC, or they might be cosmologically signifigant.

(iii) What actually motivates all those searches for eV-scale quasi-sterile neutrinos are several otherwise inexplicable `anomalies' reported by LSND MiniBooNE, Gallex and SAGE, as well as various shortfalls and bumps in the measured fluxes of reactor antineutrinos. We may search for them at our pleasure, but eV-scale quasi-sterile neutrinos have no known theoretical raison d'etre, and experimental anomalies are often otherwise explained.

Several substantive questions remain about our three known neutrino states. We know a lot about their squared-mass differences, but we don't yet know their actual masses. Astrophysicists set upper bounds on the sum of their masses which, they say, cannot exceed about 120 meV or milli-electron volts. On the other hand, we know their sum must exceed 60 meV for the normal hierarchy, or 100 meV for the inverted. The squeeze is on, with the astrorophysical constraint likely to tighten.

We shall soon learn which hierarchy nature favors. Equally important is delta, the measure of CP violation in the neutrino sector, which T2K has recently constrained but not measured. I expect that the challenge to determine delta shall also soon be met.

Are neutrino masses Dirac, Majorana or a bit of both? They would be Majorana if neutrinoless double beta decay were detected. This beyond the standard model lepton-number violating process was first discussed in 1939 by my erstwhile Harvard colleague Wendell Furry. Ever more sensitive but fruitless searches for this rare or forbidden decay mode have been made, the most sensitive, I believe, being the Japanese-American-French collaboration KamLAND-Zen. It claims the NDBD lifetime for Xenon-136 to exceed 10^26 years, and the e-e entry of the neutrino mass matrix to be less than 100 meV, in concord with astrophysical constraints. Future experiments will target lifetime limits as much as 100 times greater... or better yet, may result in the dramatic discovery of lepton number violation.

Three ambitious and costly research facilities are to be completed this decade: the Jiangmen Underground Neutrino Experiment (JUNO) in China, Hyper-Kamiokande, to be hosted by Japan, and the Deep Underground Neutrino Experiment (DUNE), to be sited at Fermilab and Sanford Lab in the United States. All three labs will be international facilities, involving scientists from at least 39 different nations, and counting, You will hear much more about them in the next few days. It's likely that experiments there and elsewhere may deal with all of the issues I mentioned, hopefully posing new puzzles as well.

However, I believe the grandest challenge for both neutrino experimenters and theorists is to ask and answer those questions about neutrinos that we have not yet been imaginative enough to think of. Surely there will be many more exciting discoveries in neutrino physics, and there will be many more Workshops on Neutrino Telescopes to discuss them. Hopefully they will take place in La Serenissima di Venezia, whether it be flooded or not. Thank you all for your kind attention.