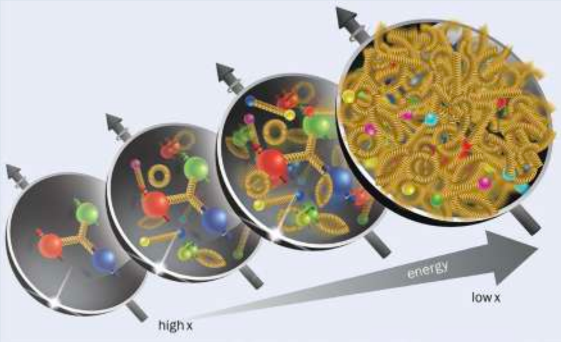
ICTS
INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES
NEWS
VOLUME X
ISSUE 1
2024
TATA INSTITUTE OF FUNDAMENTAL RESEARCH

TO SEE THE UNIVERSE IN A GRAIN OF SAND: UNCOVERING THE FUNDAMENTAL STRUCTURE OF VISIBLE MATTER WITH AN ELECTRON-ION COLLIDER

ABHAY DESHPANDE AND RAJU VENUGOPALAN

An Electron-Ion Collider (EIC) School and Workshop was held at ICTS from January 29 to February 9, 2024, attracting approximately 80 participants, evenly divided amongst students and postdocs, and professors, with 75% of the attendees from India and the rest from overseas. So, what is the Electron-Ion Collider, and why is it interesting?



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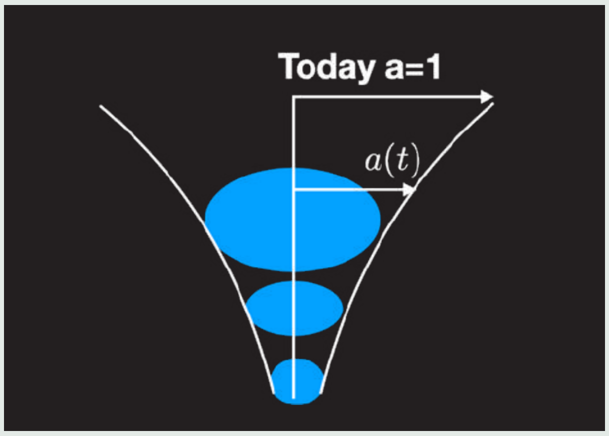
CONSTRAINING THE EXPANDING UNIVERSE

SHADAB ALAM

The concept of an expanding universe has evolved dramatically over the past century, from a static model to one of accelerated expansion. Recent findings from the Dark Energy Spectroscopic Instrument (DESI[1]) may be poised to revolutionize our understanding once again. This article traces the history of this field and explores the latest developments.



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FROM 15TH CENTURY MADHAVA TO 20TH CENTURY FEYNMAN: STRINGING PI

ANINDA SINHA

Madhava's pi

As every middle-schooler knows, pi is a number that cannot be written as the ratio of two integers. The popular form 22/7 is just an approximation, convenient for hand-made calculations. It is not unusual to show-off to one's friends at that age (and beyond!), how many decimal places one can

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ICTS HOSTS SECOND SUMMER SCHOOL FOR WOMEN IN PHYSICS

SUPURNA SINHA

This summer (June 3-14, 2024) the ICTS held the second Summer School for Women in Physics (SSWP). The first one was SSWP2023, a pilot school that was confined to 26 women from Karnataka colleges. This year we expanded the reach of the school and invited 60 students from colleges all over India.

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CONSTRAINING THE EXPANDING UNIVERSE

SHADAB ALAM

Historical context

Alexander Friedmann, Georges Lemaître and Edwin Hubble are the three pillars who changed the world view of the static universe to an expanding universe by proposing theoretical ideas and showing observational evidence between 1920-1930. They together showed that the universe is expanding and it can be explained using Einstein's General Relativistic framework.

An expanding universe was a big surprise and generated a lot of interest in general relativity as well as raised many new questions about the universe. One of the first things physicists wondered about is whether the universe is expanding at a constant rate or slowing down. The general understanding developed over the next few decades was that the Universe's expansion must be slowing down because gravity is an attractive force, and the dominant one at the cosmological scale and hence gravitational force must decelerate the universe.

Discovery of Accelerating Expansion

A lot of focus went into observing this deceleration which led to another big surprise. The universe's expansion rate was slightly slower in the distant past than recently, indicating an accelerated expansion. The High-z supernova search and the supernova cosmology project independently performed these measurements around 1999. Michael Turner introduced the term "Dark Energy" to explain this phenomenon. Saul Perlmutter, Brian Schmidt and Adam Riess were awarded the Nobel Prize in physics in 2011 for this discovery.

Current Research

This fundamental change in our understanding threw a new puzzle termed dark energy to explain the physics and nature of this acceleration. A key question emerged: can the acceleration be explained by a constant energy density, or does this mysterious component evolve with time? This is often expressed in terms of the equation of state (w), where w = -1 indicates constant dark energy. The equation of state relates the pressure of dark energy to its density, providing insight into its physical nature.

Over the last 25 years, scientists have developed various methods to measure potential deviations of w from -1. Recently, the Dark Energy Spectroscopic Instrument (DESI) released their first analysis of 1/5th of their data, showing a hint of deviation from w = -1 at a significance of 2.6-4 sigma. In scientific terms, sigma represents the level of confidence in a result, with 5 sigma typically considered the threshold for a definitive discovery. While DESI's finding is not yet at this level, it could be as significant as the first discovery of accelerated expansion if confirmed with more data.

Nature of Acceleration as Seen by DESI

The scale factor of the universe (denoted by a) represents the relative expansion of the universe over time, set to 1 at the present day. The figure shows how the scale factor evolves for different scenarios, with the bottom panel showing the acceleration of the universe (second derivative of scale factor).

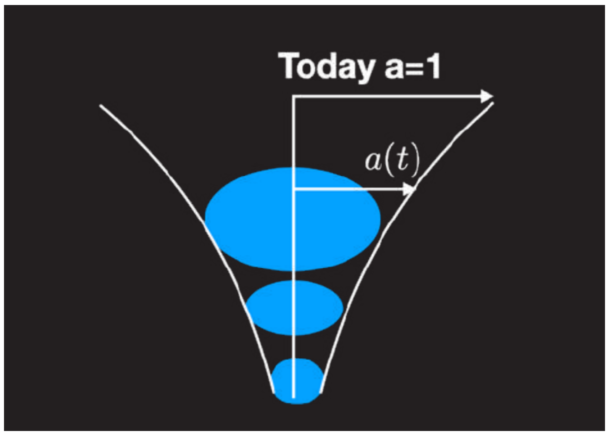

Figure 1: This illustrates an expanding universe showing how scale factor categorizes the expansion of the universe. The vertical axis denotes flow of time and the horizontal axis denotes spatial expansion of the universe.

The horizontal axis looks back in time relative to today. Hence the x-axis below 1 shows past time in the universe whereas x-axis above 1 indicates the future of the universe. The different scenarios are discussed below. One thing to notice is that the evolution of scale factors in the past are very similar and only recently they start to deviate although the acceleration shown in the bottom panel separates the different scenarios better.

Now if you consider the expanding universe which means a is increasing with time and hence the first derivative of a is positive ($\dot{a} > 0$). Our expectation prior to discovery of dark energy was that since gravity is an attractive force it must slow down the expansion of universe and hence $\dot{a}$ will decrease with time which will imply $\ddot{a} < 0$. This is shown with an orange line in the figure.

The first surprise seen in 1999 implied that $\ddot{a} > 0$ and hence the accelerated expansion of the universe. If this surprise is combined with the hypothesis that energy density of dark energy is constant then that will refer to the cosmological constant scenario shown as the white line in the figure. But the result at the time was not precise enough to separate different scenarios and only showed that recently the universe was in an accelerated phase. The new result from DESI (shown with red line in the figure) implies that the universe was accelerating and just going into a transition from accelerating phase to a decelerating phase, in the future this acceleration will approach zero. This is the best fit model from DESI data and has a number of implications to how we view the universe.

Fundamental Physics of the Universe

Dark energy, which explains the observed accelerated expansion of the universe, could have many physical origins. One way to distinguish between them is by examining the ratio of pressure to energy density, known as the equation of state of dark energy (w(t)).

The most popular scenario was that of a cosmological constant, with w = -1. Given DESI has measured w ≠ -1, if confirmed at higher significance, this would rule out the cosmological constant as an explanation for dark energy.

DESI's results suggest w crosses -1, which is even more intriguing. When w > -1, dark energy density decreases over time, potentially explained by an additional scalar field or fluid. When w < -1, dark energy density increases over time, leading to theoretical challenges.

Crossing w = -1 is impossible with a single scalar field or fluid. If confirmed, this would necessitate multi-field theories of dark energy, representing a major shift in theoretical paradigms.

Measurements from DESI

DESI is a spectroscopic galaxy survey that measures the optical spectra of galaxies. These spectra allow precise distance measurements using redshift - the stretching of light due to cosmic expansion. By measuring distances to millions of galaxies, DESI creates a three-dimensional map of the universe, enabling measurements of expansion at large scales.

A galaxy spectrum is like the fingerprint of a galaxy, where the light coming from the galaxy gets spread as the function of wavelength and intensities are recorded for a range of wavelengths. Such spectra are fairly expensive to observe and one of the main technical

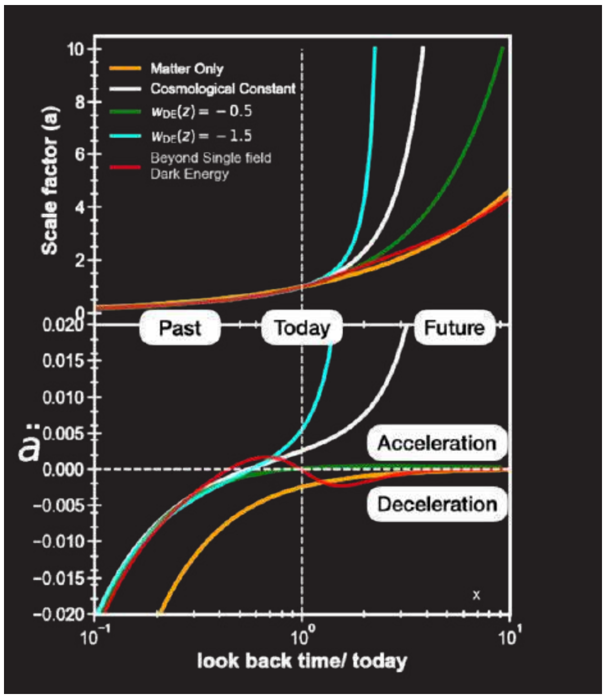

Figure 2: The time evolution of the scale factor of the universe characterizes the nature of gravity and ingredients of the universe such as dark matter, radiation and dark energy. The top panel shows the time evolution of scale factor for different physical models and bottom panel shows the second derivative of the scale factor and hence acceleration of the universe.

The orange line is for the universe with no dark energy. The white line is when dark energy density is constant and cosmological constant. Green line is where dark energy density decreases with time (single field models) and cyan line is where dark energy density increases with time and hence phantom scenarios.

The red line shows the current best estimate from DESI recent DESI analysis.

achievements of DESI is that it is an instrument which can measure 5000 such spectra at once. This allows DESI to measure 40 million extragalactic objects in 5 years. The spectrum of galaxies has a wealth of knowledge which the DESI collaboration is looking at currently. They can tell you about the total mass of stars in the galaxy, masses of central black-holes and most importantly precise distances of the galaxies using redshift (see illustration). Measuring distances of so many galaxies allow us to create a three-dimensional map of the universe which then helps us measure strengths of universe expansion by looking at the structures at very large scales. This is what DESI has done using data collected in its first year of operations which gave us the current interesting insight about dark energy.

DESI already has three years of data which the collaboration is analyzing to refine their measurement of dark energy. Eventually it is going to observe the universe for five years which should give us an improved constraint on dark energy and if the current results hold then these will be at higher significance bringing a paradigm shift in understanding the expansion of our universe.

Conclusion

DESI's groundbreaking results, if confirmed, could fundamentally alter our understanding of dark energy and cosmic expansion. As the collaboration analyzes more data, we may be on the cusp of a new era in cosmology, challenging existing theories and opening doors to new physics. DESI is expected to release its analysis of the full 5 years of data by 2027 at which point the precision of measurement will be significantly better. Ongoing experiments, such as the Euclid space telescope and the Vera C. Rubin Observatory, will build on DESI's work, potentially providing even more precise measurements of dark energy's properties. These efforts may lead us to a more complete theory of gravity and the universe's evolution, reshaping our cosmic perspective once again.

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Footnote

1. A summary of technical papers from DESI collaboration can be found at the following webpage: https://www.desi.lbl.gov/2024/04/04/desi-y1-results-april-4-guide/

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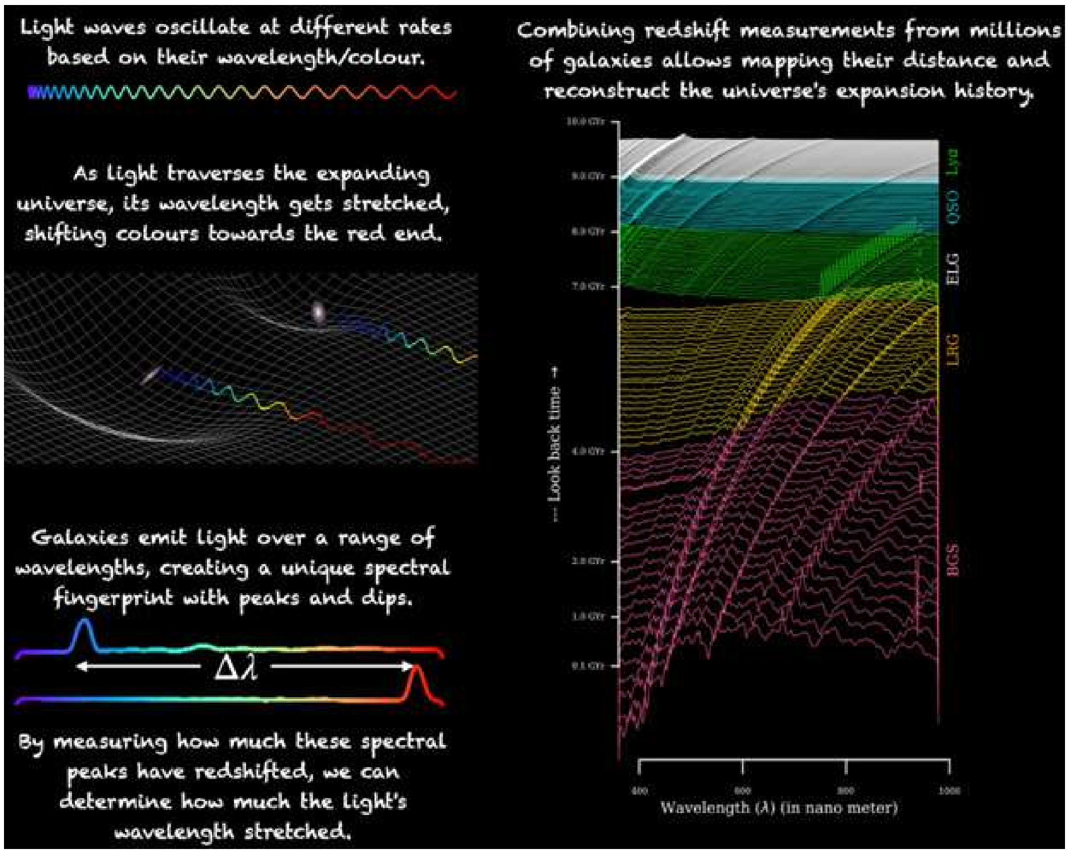

Figure 3: An illustration of redshift and example of galaxy spectra across cosmic history measured by DESI

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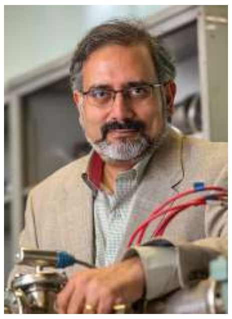


The EIC is a US $2 Billion (Rs 20 K crores) machine that is about to begin construction at Brookhaven National Laboratory in the United States. The machine will collide beams of electrons with energies up to 18 giga electron volts (18 GeV) on ion beams, with proton energies up to 275 GeV and light and heavy atomic nuclei of maximum energy 110 GeV/nucleon. The electrons, protons, and even some light ions will be polarized; the EIC will be the world's first electron-nucleus collider and its first polarized electron-polarized ion collider. The layout of the Electron-Ion Collider is shown in Figure 1.

According to Heisenberg's uncertainty principle, the basic idea underlying smashing such energetic beams of electrons on light and heavy ions is that probing very small distances requires very high energies. In such "deeply inelastic scattering" (DIS) experiments one is probing the structure of matter at distance scales down to 10^{-19} meters, 1 part in 10,000 of the size of a proton! Highly energetic polarized ion beams and beams of heavy nuclei add novel elements in exploring the spin couplings and many-body interactions of nuclear forces at these tiny distance scales.

DIS experiments first performed at the Stanford Linear Accelerator Center (SLAC) discovered the fundamental quark constituents of matter, resulting in a Nobel Prize in physics to Friedman, Kendall and Taylor in 1990. In addition, so-called scaling violation patterns observed by the experiments also provided strong hints for the existence of gluons as force carriers of the strong force. In the decade following the first SLAC experiments, the development of polarized electron (and muon) beams on the one hand, and polarized proton (and neutron) targets on the other, led to pioneering polarized DIS experiments by Vernon Hughes and collaborators at SLAC, and later at CERN, exploring how quark spins contribute to the proton's spin.

The DIS experiments played a critical role in establishing Quantum Chromodynamics (QCD) as the fundamental theory of the strong force in nature. According to QCD, all strongly interacting matter, protons and neutrons, up to the heaviest atomic nuclei, are fundamentally made up of quarks that are held together by gluons, the latter being the force carriers of the strong force. A fundamental consequence of DIS experiments therefore was that > 98% of visible matter in the universe is made up of quarks and gluons! A further surprise was that simple quark model descriptions of the proton's spin proved woefully inadequate, hinting at a much richer dynamical picture of the proton's internal structure predicted by QCD, involving quark and gluon distributions, their spins and angular momenta.

The SLAC experiments only provided indirect evidence for the existence of gluons, with direct evidence for their existence coming nearly 15 years later in electron-positron collisions at the Positron-Electron Ring Accelerator (PETRA) at DESY in Germany. To understand the role of glue, it is useful to compare it to that of photons in Quantum Electrodynamics (QED), the quantum theory of electromagnetism. In QED, the fundamental matter constituents are leptons (electrons, muons and tau-particles) that exchange virtual photons and radiate real ones, with energies ranging from heat to gamma-rays. As we know from light rays, photons are massless, and are spin-1 particles. They do not interact with each other, as anyone who has seen light rays criss-cross a room knows. Gluons too are massless spin-1 particles, mediating the interactions of quarks with each other. However, a profound difference between photons and gluons exists that, it is not an overstatement to say, is responsible for the universe as we know it. Gluons carry a colour charge (they form a colour-octet), as do quarks (forming a colour-triplet), and interact with each other through such coloured interactions. In mathematical parlance, this is what makes QCD a non-Abelian theory of quantum (quark and gluon) fields, while QED is an Abelian theory of quantum (electron and photon) fields.

The self-interaction of gluons causes the strong force to become very weak at short distances (or high energies) and live up to the strong force moniker at large distances (low energies), in contrast to QED, where the opposite is true. The discovery of this "asymptotic freedom" of QCD led to the award of the 2004 Nobel Prize in physics to Gross and Wilczek, and to Politzer. The weak coupling of quarks and gluons at short distances provides powerful insight into the quark-gluon structure of matter revealed in a generation of DIS and hadron

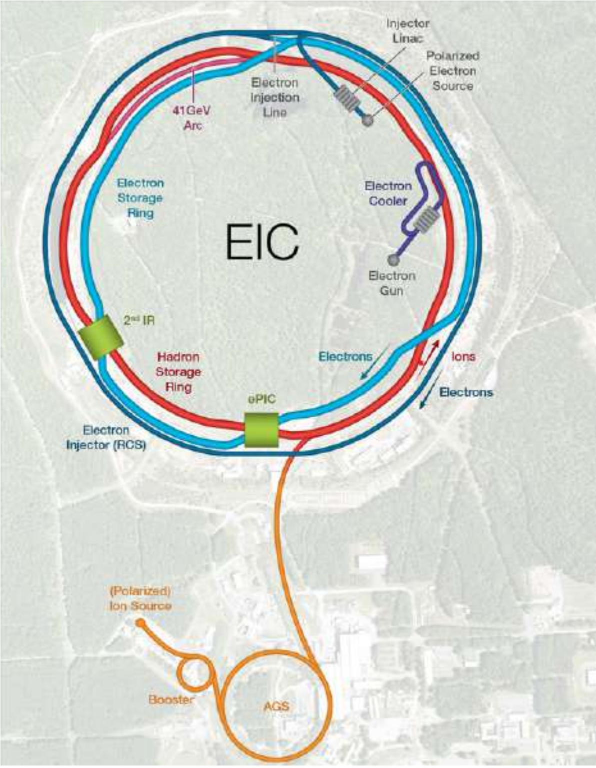


Figure 1: The EIC will be located inside the tunnel built previously for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. Ions ranging from proton to uranium will (including polarized light ions) will be produced from an Electron Beam Ion Source (EBIS), accelerated to velocities through the Alternating Gradient Synchrotron (AGS), and injected into the red RHIC ring with velocities up to 99.999% of the speed of light. The electron beams are generated by an electron "gun" and injected into the blue ring, also at highly ultra-relativistic velocities. The two beams are steered to collisions at 6 o'clock, with measurements taken by the EPIC detector. The site of a possible second detector is located at 8 o' clock, as shown.

collider experiments, and into remarkable phenomena such as jets, properly described as the highly energetic collimated flow of quarks and gluons. Polarized proton-proton collisions at BNL Relativistic Heavy Ion Collider (RHIC) have provided first evidence for the helicity distribution of gluons in the proton. The Large Hadron Collider (LHC), colliding beams of protons at the highest collider energies ever, is a "gluon factory" and precision QCD comparisons with LHC data form the backbone of searches beyond the standard model of physics.

Asymptotic freedom also has profound consequences for our understanding of nature not just at sub-femtometer scales but on macroscopic scales as well. For instance, in the words of Nobelist Steven Weinberg, it "lifted the veil" shadowing the big bang enabling access not only to a quark-gluon plasma (QGP) occupying the universe at time scales a 10th of a microsecond, but also to earlier, hotter, phase transitions in the structure of matter. Famously, as well, it suggested that the innermost recesses of neutron stars may be comprised of quark matter. The QGP was discovered at RHIC (and subsequently confirmed at the LHC) in collisions of ultra-relativistic heavy-ion beams. Its most remarkable feature is that it is a nearly perfect fluid, with its resistance to flow being the lowest amongst any fluid known in nature. Heavy-ion experiments at lower energies, and astronomical observatories (including gravitational wave observatories!) now allow for deeper investigations of strongly interacting matter at the high baryon densities of neutron star matter.

QCD, however, contains a central mystery that has baffled physicists since the very inception of the theory. This is "infrared slavery", the counterpart of asymptotic freedom at large distances. The very strong coupling of quarks and gluons at large distances means that they can never be observed in isolation, in the same manner as one studies electrons, photons, and even wispy neutrinos. Instead, coloured quarks and gluons confine into hadrons consisting of colourless meson (quark-antiquark), baryon (three quark) and exotic (recently discovered multi-quark, and conjectured glueball and hybrid quark-gluon) states. The tremendous progress in first-principles numerical simulations of QCD now allows us to reproduce (and even predict) the hadron spectrum. Lately, they have made possible first explorations of the three-dimensional quark-gluon structure of the proton. Despite this tremendous progress, how quark and gluon confinement occurs dynamically in time is poorly understood.

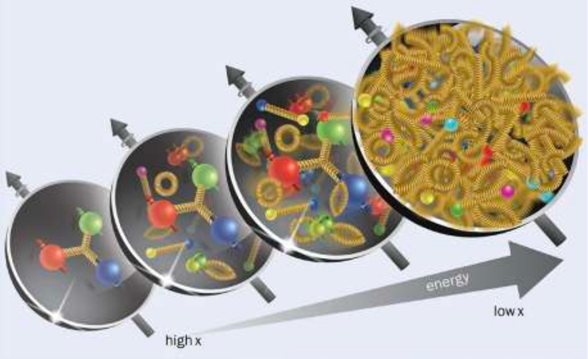


Figure 2: "Snap shots" that will be taken by the EIC of quark and gluon distributions inside a (polarized) proton. In red, blue and green, are shown the three "coloured" valence quarks that carry fractional electric charges. (The two up quarks carry +2/3 charge each and the third down quark carries charge -1/3.) In a quark model, the proton's spin is primarily made up of the valence quark spins. As the proton is boosted to higher energies, snap shots with fine resolution show an increasingly complex picture of coloured gluons (in yellow) and quark-antiquark pairs, each carrying small fractions (x) of the proton's momentum.

As an example, quarks and gluons produced in high energy collisions create string-like configurations as they evolve in time. The spins of the hadrons produced and their masses obey simple patterns that demand a first-principles understanding. The masses of hadrons themselves are one to several orders of magnitude greater than those of the light up, down and strange quark flavors of QCD. The explanation by Yochiro Nambu (for which he was awarded the Nobel Prize in 2008), inspired by similar phenomena in superconductivity, is that the vacuum of QCD is a remarkably complex object that breaks a handedness (chiral) symmetry possessed by the quarks. The relation of this dynamical breaking of chiral symmetry to the stringy confining picture remains a puzzle.

Underlying these puzzles is the fact that hadrons are fundamentally quantum states whose nature depends on how they are probed. As clearly demonstrated in DIS experiments at the Hadron Electron Ring Accelerator (HERA) at DESY, high energy electron probes of protons obtain completely different snapshots of their quark-gluon structure depending on how rapidly they are being accelerated. A boosted hadron will appear as a many-body entangled system containing copious numbers of gluons and quark-antiquark pairs. A sketch of the many-body structure of the proton is shown in Figure 2. Though they all individually contain intrinsic spins, quarks and gluons spin in concert, in a complex and subtle interplay with the QCD vacuum, to generate the proton's unique spin-1/2. Further, theoretical studies predict that the "snapshots" taken by the probe can uncover evidence for an over-occupied state of gluons, a Color Glass Condensate (CGC). This state has features akin to a Bose-Einstein condensate but evolves slowly on subatomic time scales in a manner reminiscent of glassy materials. The connection of strongly correlated CGC matter to the dynamics of confinement is a further outstanding puzzle.

Advancing our understanding of confinement, resolving the many puzzling features of nature's strong force, and perhaps uncovering novel ones, is the central mission of the Electron-Ion Collider. The EIC comes powerfully equipped for this purpose. In addition to its ability to probe at high energies deeply within nuclei, the EIC will be 1000 times brighter than the previous HERA DIS collider. In layman terms, the luminosity of the EIC will enable it to collect in far less than a year the entire dataset accumulated by HERA in its 15 years of running. This will allow us to perform far more differential measurements that are cleaner and more precise than any attempted previously. In particular, we will be able to extract 3-D tomographic images of the spatial and momentum distributions of polarized and unpolarized quark and gluon distributions in protons and heavier nuclei. The clean collider environment of the EIC can also offer fresh insight into the hadron spectroscopy of the exotic states noted previously, to complement ongoing intensive studies underway at Jefferson Lab in the US, at CERN, and at BELLE II (Japan) and BES III (China).

EIC science, as the reader may have gathered, has strong overlap with a very broad range of physics sub-disciplines. This includes heavy-ion physics that explores the properties of the QGP and the QCD phase diagram. Precise extractions of quark and gluon distributions and explorations of electroweak phenomena at the EIC may significantly impact searches for physics beyond the standard model. As hinted above, strikingly novel entanglement measures at the EIC can provide unique insight into the role of quantum information in how quarks and gluons confine.

The many-body correlations explored at the EIC have overlap with ultracold atom physics and in the study of quantum phase transitions, and it has the potential to uncover novel topological features of quantum field theories. A further unanticipated development are the quantitative relations between QCD scattering amplitudes and gravitational amplitudes, which opens a new interdisciplinary window into the potential impact of precision QCD studies on gravitational wave observations. EIC science therefore has the potential to create powerful new interdisciplinary connections across fields exploring widely differing energy scales in nature.

In summary, the unique and versatile features of the Electron-Ion Collider herald an unprecedented opportunity to settle central mysteries of the standard model. The history of DIS experiments is replete with unanticipated surprises and we can anticipate more of these at the EIC. We hope that the vibrant community of Indian physicists we interacted with at the

ICTS school and workshop will grow further and engage strongly with EIC science, contributing significantly to its future success.

Abhay Deshpande is a SUNY Distinguished Professor of Physics and Director of the Center for Frontiers in Nuclear Science (CFNS) at Stony Brook University, USA . He is also Director of Science for the Electron Ion Collider at Brookhaven National Laboratory, USA.

Raju Venugopalan is Distinguished Scientist at Brookhaven National Laboratory, USA and Director of BNL EIC Theory Institute

BETWEEN THE SCIENCE

SUBHRO BHATTACHARJEE received a joint Indo-Swedish International Mobility Grant together with his collaborator at KarlStad University, Sergej Moroz.

BRATO CHAKRABORTY and his collaborator Anke Lindner (ESPCI-Paris) received one of the Scientific High Level Visiting Fellowships from the French Institute in India.

RAMA GOVINDARAJAN and her collaborator, Prashant Valluri from the University of Edinburgh, have been awarded the selective Vaibhav Collaborative Fellowship of the DST/SERB, Government of India.

RAJESH GOPAKUMAR has been awarded the INSA Distinguished Lecture Fellowship (2024) in Physics.

AKSHIT GOYAL received the Ramanujan Fellowship from DST, Government of India.

MANAS KULKARNI was awarded the Institute of Physics CNRS Guest Researcher for 2024. He will be a visiting professor at the Laboratory of Theoretical Physics and Statistical Models (LPTMS), Paris-Saclay in June 2024 and will be hosted by Satya Majumdar.

AJITH PARAMESWARAN received the 2024 INSA Associate Fellowship. He was also elected as a Fellow of the Indian Academy of Sciences.

ANINDA SINHA | *continued from Page 1 ...*

FROM 15TH CENTURY MADHAVA TO 20TH CENTURY FEYNMAN: STRINGING PI

ANINDA SINHA

memorize: 3.14159265..... The oldest series representation of pi was given to us by the famous Indian mathematician, Madhava in the 14th or 15th century, before the invention of calculus (see [1] and the incredible book [2]). Madhava's series for pi (historically referred to as the Madhava-Leibniz series as it was rediscovered by Leibniz in the 17th century) takes the form:

$$\pi = 4\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1} = 4 - \frac{4}{3} + \frac{4}{5} - \frac{4}{7} + \cdots \tag{1}$$

This form of the series converges very slowly to the actual value. Later refinements were attempted by many luminaries, including Newton, who found different series [3] using calculus and spent leisure hours calculating up to 15 decimal places of pi! Pi is an example of what is called a transcendental number in mathematics, a quantity that does not satisfy a polynomial equation with rational coefficients. Like pi, there are other similar transcendental numbers like Euler's e and Euler's Zeta function, which makes an appearance in the famous unsolved Riemann hypothesis. This function was invented by the Swiss mathematician, Leonhard Euler in the 18th century. Euler also invented a quantity called the Beta function [4], which made an unusual appearance in physics in the late 1960s and 1970s. In addition, pi and Zeta function appear as specific limits of this famous function.

Euler-Beta Function in Physics

The surprising appearance of the Euler-Beta function in physics is as follows. In physics, we learn about what things are made of by scattering particles of them. For instance, we see things by shining light, which is nothing but a scattering experiment. The Heisenberg Uncertainty Principle taught us that to have higher resolving power, we need to pump in more energy. Quantum theory also teaches us that we can excite virtual particles in such scattering experiments. In recent times, one such famous particle detected in experiments conducted in the Large Hadron Collider in CERN, was the 2012 discovery of the Higgs boson. In principle, there is nothing that prevents us from going to higher and higher energies, where we would see a plethora of higher mass particles. In 1968, motivated by the almost linear relation between the spin of observed resonances in pion scattering and their mass-squared, Gabriele Veneziano observed that the Euler-Beta function is a possible amplitude with similar features. This eventually led to the birth of string theory.

Re-interpreting the Euler-Beta Function using Quantum Field Theory

What has all this got to do with pi and Zeta functions? If we try to write pi as a sum of rational numbers, we will require an infinite number of them as otherwise the sum of a finite number of rational numbers is rational. It turns out that each such term can be interpreted as arising due to a specific virtual particle being exchanged in the theory of strings. But so what? What does one learn from such a physics interpretation of the series formulas? There is another twist in the story. When we describe the physics of relativistic particles, we think of the particles as arising from a field. For example, the quantum of the electromagnetic field is the photon, that of the Higgs field is the Higgs boson and so on. These fields are an intermediary in the description of what is actually observed, and their specific choices should not affect the actual physics. This freedom of what specific field variables to use gives rise to a parametric ambiguity in the answers describing scattering. These ambiguities do not show up in physical answers after we sum over all the virtual particles, just as the choice of coordinates we use in space-time cannot affect the actual physics. In turn, these ambiguities are expected to show up in the formulas for pi and Zeta functions — if we truncate the series, the ambiguities manifest themselves but if we sum over all terms, they go away. No such formulas for the Beta function and the associated transcendental numbers, which resemble this expectation from quantum physics arguments, were known in the literature prior to this work.

The New Representation and Feynman Diagrams

For the first time in the 300-year history of the Euler-Beta function, this work finds such a parametric representation for this function (manifestly showing the singularities) and hence the associated pi and Zeta functions using physics considerations. The importance of such parametric representation can also be paraphrased as follows. Imagine we are trying to measure the probability of scattering, but we are limited by how much energy we can pump into our experiments. Thus, we cannot excite a very highly massive virtual particle as it would need energies beyond what we have access to. What is the best possible way to describe the physics in such an experiment? The parametric formulas found in this paper enable a quantitative answer to such a question. The explicit formula that emerges for the open superstring amplitude is [5]:

$$\frac{\Gamma(-s_1)\,\Gamma(-s_2)}{\Gamma(1-s_1-s_2)} = \sum_{n=0}^{\infty} \frac{1}{n!} \left(\frac{1}{s_1-n} + \frac{1}{s_2-n} + \frac{1}{\lambda+n} \right) \left(1-\lambda+\frac{(s_1+\lambda)(s_2+\lambda)}{\lambda+n} \right)_{n-1} \tag{2}$$

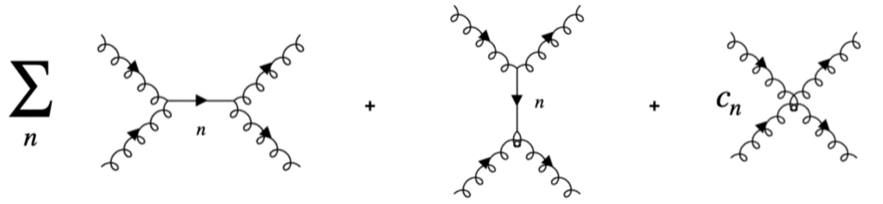
Here on the left-hand side, we see the amplitude as ratios of Gamma functions (a slight generalization of the Beta function, a similar formula exists for the Beta function itself). This is a function of two variables s_1 and s_2, which are relativistic kinematic invariants usually referred to as the Mandelstam variables. On the right-hand side, we present a series expansion which can be thought of as a Feynman-diagram-like expansion. Apart from the factorial function, we also see the Pochhammer symbol or rising factorial defined via:

$$(a)_n = a(a+1)(a+2)\cdots(a+n-1) \qquad n \geq 0$$

$$(a)_{-1} = \frac{1}{a-1}$$

For the series to converge, a simple Gauss ratio test shows that the real part of lambda has to be bigger than -1, with no restrictions on s_1 or s_2.

Pictorially we have for the rhs of eq(2):



s-channel t-channel contact diagrams

Each term in the series pertains to a process where two particles are scattering and exchanging a massive particle whose mass is proportional to an integer n—then we sum over all such processes. The key features are that the series expansion makes manifest the singularities of the amplitude in both variables. The presence of the parameter lambda (denoted by the Greek symbol) in the series is vital. It enables us to interpolate between various physical pictures. For instance, when lambda is set equal to $-s_2$ we have an expansion in terms of the singularities in s_1 only. Namely we have:

$$\frac{\Gamma(-s_1)\Gamma(-s_2)}{\Gamma(1-s_1-s_2)} = \sum_{n=0}^{\infty} \frac{1}{n!} \frac{(1+s_2)_{n-1}}{s_1-n}$$

Connection with Dual Resonance Models and the Origins of String Theory

However, this series converges only when the real part of s_2 is less than -1. As a result, the singularities in s_2 are not visible! To make these visible, one needs to resum the infinite series and then perform an analytic continuation (a way to bypass singularities in the complex plane by moving through gaps between the singularities — this is what makes complex analysis so powerful!) to make the other singularities manifest. This is usually the familiar form that is discussed in almost all string theory literature and goes by the name of dual resonance models. The terminology arises since the singularities in one set of diagrams (the s-channel in the picture above), after resumming can reproduce the singularities in the other set (the t-channel). This feature is also what gave rise to the so-called worldsheet interpretation of string theory [6]. In the worldsheet picture, we calculate only one diagram unlike the multitudes of Feynman diagrams displayed above. We can visualize the worldsheet as a kind of a disc made of putty and stretching the putty in different ways would give the multitudes of Feynman diagrams.

For other choices of lambda, we have what can be termed as the Feynman diagram picture. While it may appear as if the worldsheet picture is more efficient since in that picture we calculate only one diagram (and not separately the s, t channels and contact diagrams as in the Feynman diagram picture above), one should also note that to recreate the mathematical features of the full amplitude, one will need to sum over an infinite number of terms in the resulting series expansion. From the perspective of a quantum field theorist, this would appear to be undesirable: after all, if we are interested in describing physics up to a particular energy scale, say million electron volts, why should we put in the information of particles at trillion electron volts? The new representation in eq (2) enables us to consider the physics up to a particular energy scale, without needing to incorporate the knowledge of an infinite number of particles.

As an aside, the originators of the dual resonance models, Dolen, Horn and Schmid [7] had in fact suggested the possibility of a form similar to eq (2) — this fact is rarely mentioned in the modern (or that matter of fact older!) literature. The worldsheet picture which led to the invention of string theory [8,9] and later got reinterpreted as a consistent theory of quantum gravity [10, 11], never managed to explain hadron scattering satisfactorily, which in fact was the original motivation for the researchers in the late 1960's and 1970's. The new series representation opens the possibility of re-examining the origins of string theory, while trying to maintain a connection with experiments.

A New Formula for pi Which Connects with the Madhava Series, Quantum Field Theory and String Theory

While the story above was the actual motivation for us to pursue this line of research, we landed up getting a nice connection with Madhava's work!

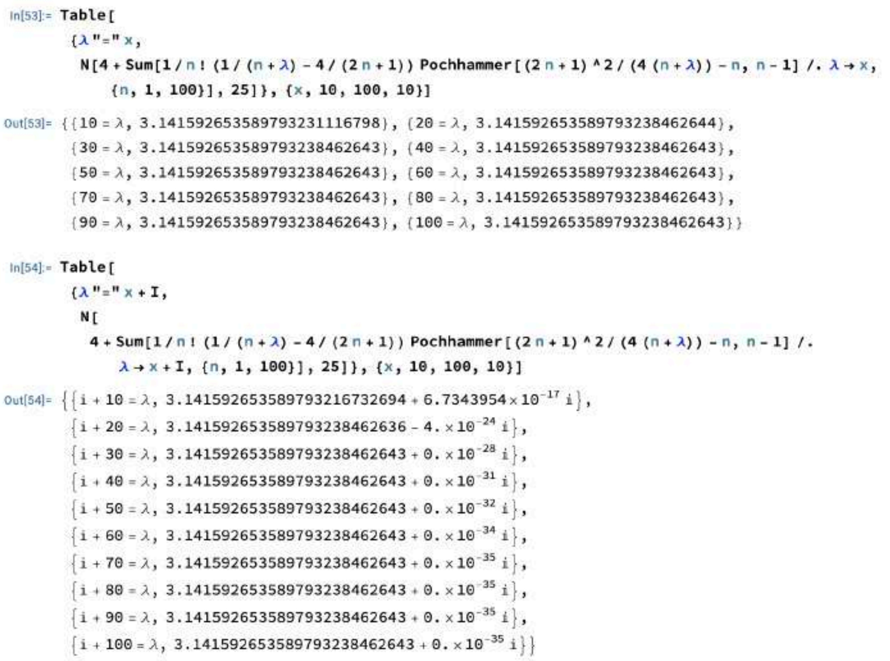
As physics undergraduates, we learn that the square-root of pi emerges from the Gamma function evaluated at the argument ½. Then from the formula above, getting a formula for pi is literally child's play! We just set s_1 and s_2 to be – ½ . Then we have our new formula for pi:

$$\pi = 4 + \sum_{n=1}^{\infty} \frac{1}{n!} \left(\frac{1}{n+\lambda} - \frac{4}{2n+1} \right) \left(\frac{(2n+1)^2}{4(n+\lambda)} - n \right)_{n-1} . \tag{3}$$

In both equations (2) and (3) displayed above, we need the real part of lambda to be bigger than -1. Remarkably, both formulas hold for any lambda, real or complex, as long as this condition holds (see the Mathematica outputs below). Just to remind the reader, this presence of the parameter is precisely what we anticipated from physics considerations described above. When we sum over all n's the dependence on lambda drops out as expected. As such, we have an intriguing (infinite) family of formulas for these classical functions. The parameter lambda plays a dual role: on the one hand it interpolates between the string worldsheet picture and the Feynman diagram picture; on the other hand, it enables us to optimize the formulas to get the best convergence. When the parameter lambda for a fixed summand is taken to be very large, we find that the summand is exactly the one in the Madhava series in equation (1)!

The state of affairs can be explained in the figure for pi below. On the horizontal axis, we depict the number of terms in the series — the larger the number of terms we use, the harder it is to compute. The vertical axis represents the extra physics inspired parameter that was described above. As we dial the parameter, in the middle of the figure, the number of terms needed and hence the difficulty minimizes. As the parameter becomes large, we get the 15th century Madhava series (using which calculating pi is a very hard task as an answer to 10 decimal places needs 5 billion terms). As the parameter becomes small, we get a description in terms of the traditional string picture. However, the most efficient representation [12] is in terms of Feynman diagrams, which is what the middle of the figure conveys (10 decimal places needs around 40 terms)!

Playing with the series on Mathematica is fun and addictive—we give sample outputs below:



```
In[53]:= Table[
           {λ "=" x,
            N[4 + Sum[1 / n ! (1 / (n + λ) - 4 / (2 n + 1)) Pochhammer[(2 n + 1) ^ 2 / (4 (n + λ)) - n, n - 1] /. λ → x,
               {n, 1, 100}], 25]}, {x, 10, 100, 10}]
Out[53]= {{10 = λ, 3.141592653589793231116798}, {20 = λ, 3.141592653589793238462644},
          {30 = λ, 3.141592653589793238462643}, {40 = λ, 3.141592653589793238462643},
          {50 = λ, 3.141592653589793238462643}, {60 = λ, 3.141592653589793238462643},
          {70 = λ, 3.141592653589793238462643}, {80 = λ, 3.141592653589793238462643},
          {90 = λ, 3.141592653589793238462643}, {100 = λ, 3.141592653589793238462643}}

In[54]:= Table[
           {λ "=" x + I,
            N[
             4 + Sum[1 / n ! (1 / (n + λ) - 4 / (2 n + 1)) Pochhammer[(2 n + 1) ^ 2 / (4 (n + λ)) - n, n - 1] /.
                λ → x + I, {n, 1, 100}], 25]}, {x, 10, 100, 10}]
Out[54]= {{i + 10 = λ, 3.141592653589793216732694 + 6.7343954 × 10^-17 i},
          {i + 20 = λ, 3.141592653589793238462636 - 4. × 10^-24 i},
          {i + 30 = λ, 3.141592653589793238462643 + 0. × 10^-28 i},
          {i + 40 = λ, 3.141592653589793238462643 + 0. × 10^-31 i},
          {i + 50 = λ, 3.141592653589793238462643 + 0. × 10^-32 i},
          {i + 60 = λ, 3.141592653589793238462643 + 0. × 10^-34 i},
          {i + 70 = λ, 3.141592653589793238462643 + 0. × 10^-35 i},
          {i + 80 = λ, 3.141592653589793238462643 + 0. × 10^-35 i},
          {i + 90 = λ, 3.141592653589793238462643 + 0. × 10^-35 i},
          {i + 100 = λ, 3.141592653589793238462643 + 0. × 10^-35 i}}
```

Such a family of representations of pi arising out of physics considerations did not exist in the mathematics literature—after our work came out, recently, an independent proof of our formulas, without using dispersion relations or the physics considerations described above was found by mathematicians [13]—however, the physics considerations provide the motivation for looking for such parametric representations in the first place. More importantly, this picture enables us to think about ways to retain some of the nice features of string theory (it is after all a consistent theory of quantum gravity) while abandoning some of the unwanted ones (e.g. exponential softness in amplitudes). In particular, it will enable a re-examination of some of the roots of string theory and either establish them as the unique direction forward or enable a search for a new realistic perspective of nature.

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[2] Ranjan Roy, "Series and products in the development of Mathematics," *Cambridge University Press, 2021.*

[3] https://www.scientificamerican.com/article/the-long-search-for-the-value-of-pi/

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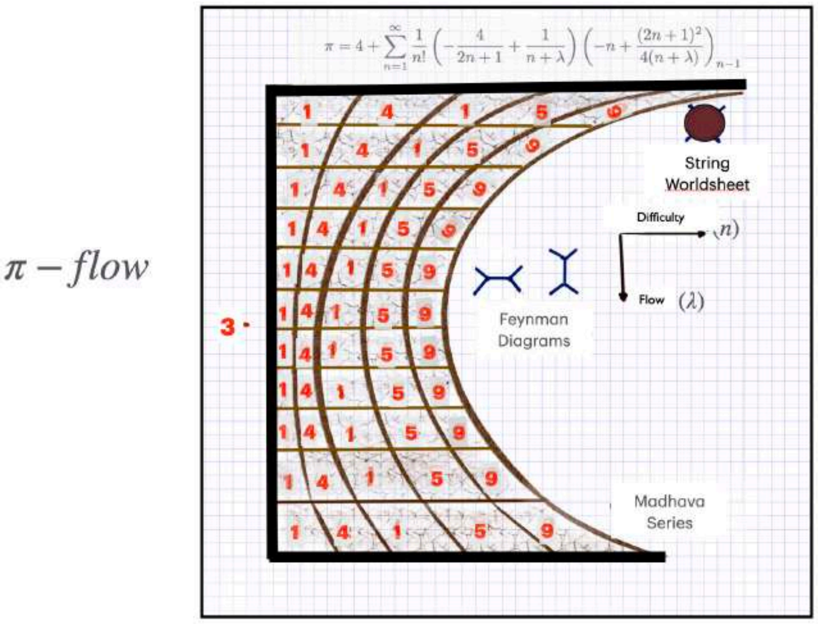

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[6] M.B. Green, J. H. Schwarz, E. Witten, "Superstring theory 1,2", *Cambridge University Press, 1987.*

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[11] J. Scherk and J. H. Schwarz, "Dual Models for Nonhadrons," Nucl. Phys. B 81 (1974) 118-144.

[12] Our objective was not to find the fastest converging representation! There are many known series representations which converge very fast.

[13] H. Rosengren in mathoverflow.net (https://mathoverflow.net/questions/474141/proof-of-possible-new-series-for-pi-without-use-of-physics)

Aninda Sinha is a Professor of Physics at the Centre for High Energy Physics, Indian Institute of Science, Bengaluru

SUPURNA SINHA | *continued from Page 1 ...*

ICTS HOSTS SECOND SUMMER SCHOOL FOR WOMEN IN PHYSICS

SUPURNA SINHA

Following the successful pattern of SSWP2023, the school was centered around demos and experiments. This year the experimental component was strengthened, more focussed and quantitative. The experimental kits were designed meticulously at the HBCSE, Mumbai. The demos were developed in the JC Bose laboratory at ICTS. The idea was to get the participants to ask questions based on the observations they made while doing the experiments. There were theory sessions where we introduced the students to mathematics and theoretical physics related to the experiments the students performed. In particular, we discussed matrices, units and dimensions, Fourier transforms, optimisation, symmetry and error analysis. We also had an interesting session on Polya's "How to Solve It", introducing the students to strategies in solving problems.

In addition, we had special sessions in the evenings which were designed to develop problem solving skills. Many of the participants appreciated these sessions where the students came to the board and discussed the problems in an enabling environment with the facilitators.

There were general talks by researchers on a variety of topics: Perspectives in Math and Art, Patterns and Order in Randomness, Making Materials on the Computer, A Journey in Archaeometallurgy, How is Quantum Information Localized in Quantum Gravity, Quantum Science and Technology With Ultra-Cold Atoms, How do Shampoos, Lotions and Clays Flow when Pushed.

Some talks involved demos developed at the JC Bose Lab, ICTS, while some delved into the professional journeys of the women speakers. The students were very interactive and asked a lot of questions which livened up the sessions.

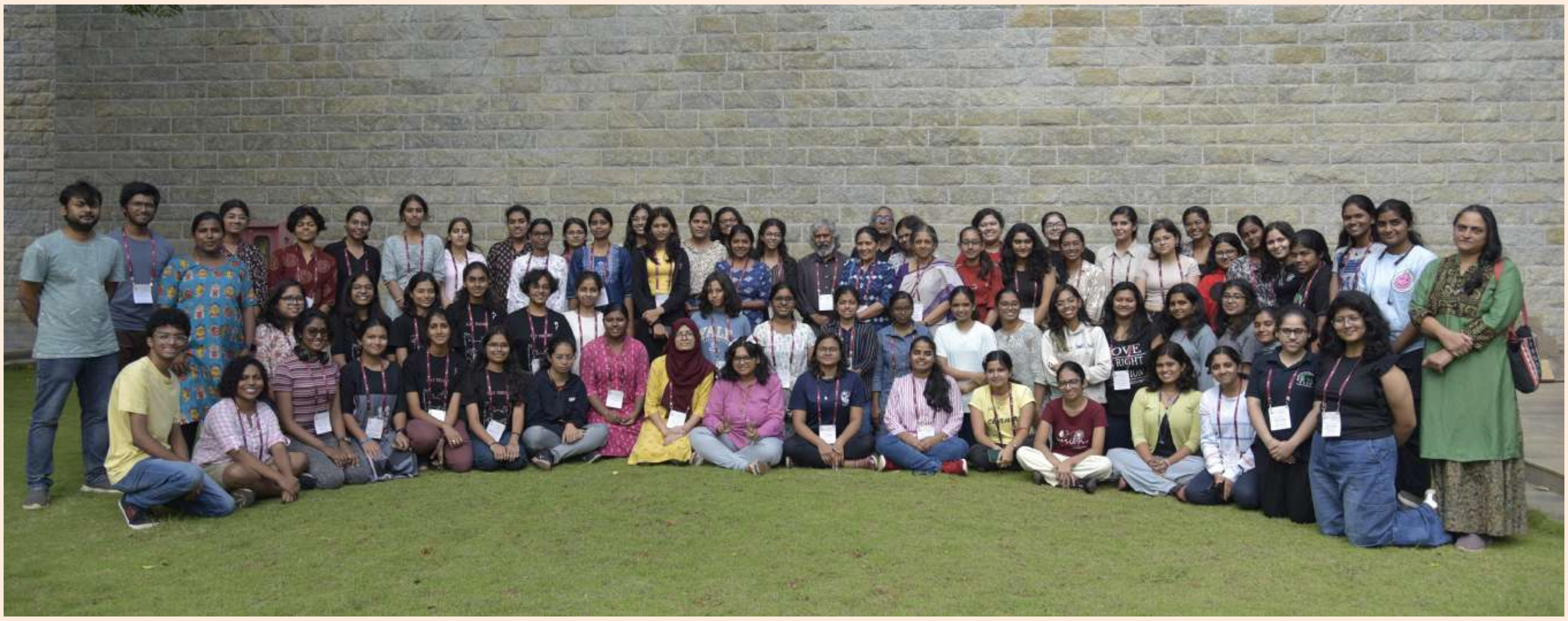
The first day started with a set of soap film demos which set the tone for the rest of the school. The notion of optimisation was introduced through concrete demos. It was clear that the participants started actively thinking about the observations they made during the demos. We invited questions and many of the students participated enthusiastically in the discussions.

Following the pattern of SSWP2023, the students were engaged in experiments during the morning half of each day and the afternoon half was devoted to theoretical discussions and talks. The sixty participants were divided into fifteen groups named after pioneering women scientists. The division into groups enabled greater interaction between participants from different parts of the country and from different universities. The participants gave talks on the lives and works of the pioneering women scientists their groups were named after. This session was particularly special. All the participants spoke confidently and they did a remarkable job considering that they had only a few days to do research.

We expect this experience will go a long way towards encouraging them to take up science in general and physics in particular as a career. As in the 2023 Summer School, there was a cultural program by the participants. This was great as an ice-breaker and led to a wonderful event at the Chandrasekhar Auditorium, where the participants showcased their talents in dance, singing and instrumental music. The visual artists showcased their work on poster boards in the foyer in front of the JC Bose Lab. It was a memorable event that brought the community together.

The success of the program was due in a large part to the help received from the ICTS program office, the AV team, the students and staff.

Supurna Sinha is Professor of Physics at the Raman Research Institute, Bengaluru



PROGRAMS

Emerging Infectious Diseases: Ecology and Evolution

1-12 July 2024 ✦ *Organizers* — Uma Ramakrishnan (NCBS, Bengaluru), Farah Ishtiaq (Tata Institute of Genetics and Society) and Ansil BR (NCBS, Bengaluru)

Summer School on Gravitational-Wave Astronomy

1-12 July 2024 ✦ *Organizers* — Parameswaran Ajith (ICTS-TIFR, Bengaluru), K. G. Arun (CMI, Chennai), Bala R. Iyer (ICTS-TIFR, Bengaluru) and Prayush Kumar (ICTS-TIFR, Bengaluru)

Summer School for Women in Mathematics and Statistics

17-28 June 2024 ✦ *Organizers* — Siva Athreya (ICTS-TIFR, Bengaluru and Indian Statistical Institute, Bengaluru), Rhythm Grover (IIT Guwahati) and Dootika Vats (IIT Kanpur)

Summer School for Women in Physics 2024

3-14 June 2024 ✦ *Organizers* — S. Annapoorni (Delhi University), Ranjini Bandyopadhyay (RRI, Bengaluru), Dipankar Bhattacharya (Ashoka University, Sonepat), Mahua Ghosh (Mount Carmel College, Bengaluru), Kripa Gowrishankar (Azim Premji University, Bengaluru), Sushan Konar (NCRA-TIFR, Pune), Rajaram Nityananda (ICTS-TIFR, Bengaluru), Shirish Pathare (HBCSE, TIFR, Mumbai), Sumathi Rao (ICTS-TIFR, Bengaluru), Joseph Samuel (ICTS-TIFR, Bengaluru), T. R. Seshadri (Delhi University) and Supurna Sinha (RRI, Bengaluru)

Theoretical and Practical Perspectives in Geophysical Fluid Dynamics

20-31 May 2024 ✦ *Organizers* — Manita Chouksey (Institut für Ostseeforschung Warnemünde, Germany), Hossein Amini Kafiabad (Durham University, UK), Han Wang (University of Edinburgh, UK) and Jim Thomas (ICTS-TIFR and TIFR-CAM, Bengaluru)

Theoretical and Empirical Approaches to Understand Polygenic Adaptation

6-17 May 2024 ✦ *Organizers* — Kavita Jain (JNCASR, Bengaluru), Christian Schlötterer (Vetmeduni Vienna, Austria) and Sam Yeaman (University of Calgary, Canada)

Workshop on Data Assimilation in Weather and Climate Models

6-17 May 2024 ✦ *Organizers* — Govindan Kutty (Indian Institute of Space Science and Technology, Valiamala), A. Chandrasekar (Indian Institute of Space Science and Technology, Valiamala) and Amit P Kesarkar (National Atmospheric Research Laboratory)

Understanding the Universe Through Neutrinos

22 April-3 May 2024 ✦ *Organizers* — Amol Dighe (TIFR. Mumbai), Srubabati Goswami (PRL, Ahmedabad), Alex Himmel (Fermilab, USA), Rukmani Mohanta (University of Hyderabad) and Sanjay Kumar Swain (NISER, Bhubaneswar) |

School for Advanced Topics in Particle Physics (SATPP): Selected Topics in Effective Field Theories

8-19 April 2024 ✦ *Organizers* — Rick Sandeepan Gupta (TIFR, Mumbai), Tuhin S. Roy (TIFR, Mumbai) and Sudhir Vempati (IISc, Bengaluru)

Theoretical Approaches in Cancer Progression and Treatment

11-22 March 2024 ✦ *Organizers* — Helen Byrne (Oxford University, UK), Shaon Chakrabarti (NCBS-TIFR, Bengaluru), Mohit Kumar Jolly (IISc, Bengaluru) and Franziska Michor (Harvard University, USA)

Future Roadmap Vision 2047 - Chintan Shivir

5-9 March 2024 ✦ *Organizers* — Heads of Aided Institutes of DAE

Predictability in General Relativity

28-29 February 2024 ✦ *Organizers* — Shalabh Gautam (ICTS-TIFR, Bengaluru), Prayush Kumar (ICTS-TIFR, Bengaluru), Kartik Prabhu (RRI, Bengaluru) and Sumati Surya (RRI, Bengaluru & current president of the IAGRG)

Recent Advances on Control Theory of PDE Systems

12-23 February 2024 ✦ *Organizers* — Shirshendu Chowdhury (IISER Kolkata), Debayan Maity (TIFR-CAM, Bengaluru) and Debanjana Mitra (IIT Bombay, Mumbai)

Sixth Bangalore School on Population Genetics and Evolution

12-23 February 2024 ✦ *Organizers* — Deepa Agashe (NCBS, Bengaluru) and Kavita Jain (JNCASR, Bengaluru)

International School and Workshop on Probing Hadron Structure at the Electron-Ion Collider

29 January-9 February 2024 ✦ *Organizers* — Abhay Deshpande (CFNS, Stony Brook University and BNL), Bedangadas Mohanty (NISER, Bhubaneswar), Asmita Mukherjee (IIT Bombay, Mumbai) and Marco Radici (INFN Pavia, Italy)

Stability of Quantum Matter in and out of Equilibrium at Various Scales

15-26 January 2024 ✦ *Organizers* — Arnab Das (IACS, Kolkata), Roderich Moessner (Max Planck Institute for the Physics of Complex Systems, Dresden, Germany), Anatoli Polkovnikov (Boston University, USA), Tomaz Prosen (University of Ljubljana, Slovenia) and Dibyendu Roy (RRI, Bengaluru)

Zariski Dense Subgroups, Number Theory and Geometric Applications

1-12 January 2024 ✦ *Organizers* — Gopal Prasad (University of Michigan, USA), Andrei Rapinchuk (University of Virginia, USA), B Sury (Indian Statistical Institute, Bengaluru) and Aleksy Tralle (University of Warmia and Mazury, Poland)

DISCUSSION MEETINGS

Cosmic Revelations: A Joint DESI and eROSITA Symposium

22 May 2024 ✦ *Organizers* — Shadab Alam (TIFR, Mumbai) and Subha Majumdar (TIFR, Mumbai)

Gravitational Wave Open Data Workshop

18-20 April 2024 ✦ *Organizers* — Parameswaran Ajith (ICTS-TIFR, Bengaluru), Ankur Barsode (ICTS-TIFR, Bengaluru), Bala Iyer (ICTS-TIFR, Bengaluru), Prayush Kumar (ICTS-TIFR, Bengaluru) and Akash Maurya (ICTS-TIFR, Bengaluru)

9th Indian Statistical Physics Community Meeting

3 -5 April 2024 ✦ *Organizers* — Ranjini Bandyopadhyay (RRI, Bengaluru), Abhishek Dhar (ICTS-TIFR, Bengaluru), Kavita Jain (JNCASR, Bengaluru), Rahul Pandit (IISc, Bengaluru), Samriddhi Sankar Ray (ICTS-TIFR, Bengaluru), Sanjib Sabhapandit (RRI, Bengaluru) and Prerna Sharma (IISc, Bengaluru)

Grothendieck Teichmüller Theory

26 February-1 March 2024 ✦ *Organizers* — Pierre Lochak (CNRS and IMJ-PRG, Paris, France) and Devendra Tiwari (Bhaskaracharya Pratishthana, Pune)

Turbulence and Vortex Dynamics in 2D Quantum Fluids

26 February-1 March 2024 ✦ *Organizers* — Dario Ballarini (CNR NANOTEC, Italy), Iacopo Carusotto

(CNR-INO, BEC Center, Trento), Alessandra S. Lanotte (CNR NANOTEC and INFN, Lecce, Italy), Samriddhi Sankar Ray (ICTS-TIFR, Bengaluru) and Daniele Sanvitto (CNR NANOTEC, Italy)

ICTS-NETWORKS Workshop "Challenges in Networks"
26 February-1 March 2024 ✦ *Organizers* — Pierre Lochak (CNRS and IMJ-PRG, Paris, France) and Devendra Tiwari (Bhaskaracharya Pratishthana, Pune)

LECTURE SERIES

DISTINGUISHED LECTURES

Principles of Evolutionary Overdesign and Underperformance
10 May 2024 ✦ *Speaker* — Michael Lynch *(Center for Mechanisms of Evolution, Arizona State University)*

The Evolutionary Enigma of Sex
16 February 2024 ✦ *Speaker* — Sarah Otto *(University of British Columbia, Canada)*

Statistical Mechanics of Mutilated Sheets and Shells
18 August 2023 ✦ *Speaker* — David R. Nelson *(Lyman Laboratory of Physics, Harvard University)*

VISHVESHWARA LECTURES

Gravitational-wave Astronomy: New Discoveries, Puzzles & Prospects
3 January 2024 ✦ *Speaker* — B.S. Sathyaprakash *(Penn State University, USA & Cardiff University, Wales)*

PUBLIC LECTURES

Evolution of Women Over the Last 50 Years
18 June 2024 ✦ *Speaker* — Sudha Murty *(Founder of Infosys Foundation, Author, Philanthropist, Chairperson of Murty Trust and Rajya Sabha MP)*

The Forever War Against Cancer
11 March 2024 ✦ *Speaker* — Herbert Levine *(Northeastern University)*

KAAPI WITH KURIOSITY

Hyperbolicity
28 July 2024 ✦ *Speaker* — Indira Chatterji *(Université Côte d'Azur à Nice, France)* ✦ *Venue* — J. N. Planetarium, Bangalore

Secrets of the Indian Savanna
30 June 2024 ✦ *Speaker* — Abi T Vanak *(Ashoka Trust for Research in Ecology and the Environment (ATREE)* ✦ *Venue* — J. N. Planetarium, Bangalore

Sudha Murty interacts with young students at ICTS-TIFR, Bengaluru. Photo credit: AS Sumukh

The Accelerating Expanding Universe: Dark Matter, Dark Energy, and Einstein's Cosmological Constant
26 May 2024 ✦ *Speaker* — Bharat Ratra *(Kansas State University, USA)* ✦ *Venue* — J. N. Planetarium, Bangalore

When Big Meets Small: The Connection Between Particle Physics and Cosmology
28 April 2024 ✦ Speaker — Yvonne Wong *(University of New South Wales, Sydney)* ✦ *Venue* — J. N.Planetarium, Bangalore

What Does Not Kill Cancer Can Make it Stronger: Investigating Cancer as a Complex System
17 March 2024 ✦ *Speaker* — Mohit Kumar Jolly *(Indian Institute of Science, Bengaluru)* ✦ *Venue* — J. N. Planetarium, Bangalore

Fitness Landscapes and the Predictability of Evolution
25 February 2024 ✦ Speaker — Claudia Bank *(Institute of Ecology and Evolution, University of Bern)* ✦ *Venue* — J. N.Planetarium, Bangalore

Understanding the Glue - the "Super-God Particle" - That Binds Us All
28 January 2024 ✦ *Speaker* — Abhay Deshpande *(Stony Brook University, USA)* ✦ *Venue* — J. N. Planetarium, Bangalore

VIGYAN ADDA

Experimental Evolution
30 May 2024 ✦ *Speaker* — Christian Schlötterer *(Institute of Population Genetics, Vienna)*

EINSTEIN LECTURES

The Plasma Universe
27 February 2024 ✦ *Speaker* — Pallavi Bhat (ICTS - TIFR, Bengaluru) ✦ *Maharani Lakshmi Ammanni College For Women Autonomous*

BETWEEN THE SCIENCE

ASHOKE SEN received the 2024 International Congress of Basic Sciences (ICBS) Frontiers of Science Award.

SPENTA WADIA was elected to the American Academy of Arts and Sciences (AAA&S) as an International Honorary Member.

Graduate students **SOUVIK JANA** and **RITWIK MUKHERJEE** received the selective pan-TIFR Sarojini Damodaran International Student Travel Fellowship. Ritwik was also selected for the Visting Doctoral Student Program of the Academy of Complex Systems, Université Côte d'Azur.

Graduate student **BIKRAM PAIN** was awarded the NORDITA Visiting PhD Fellowship. He will collaborate with Ivan Khaymovich at NORDITA and Jens Bardarson at KTH in Stockholm during the period of his scholarship.

First-year Physics of Life program student **NITESH KUMAR PATRO** topped his masters physics class at Utkal University and received a gold medal from the President of India.