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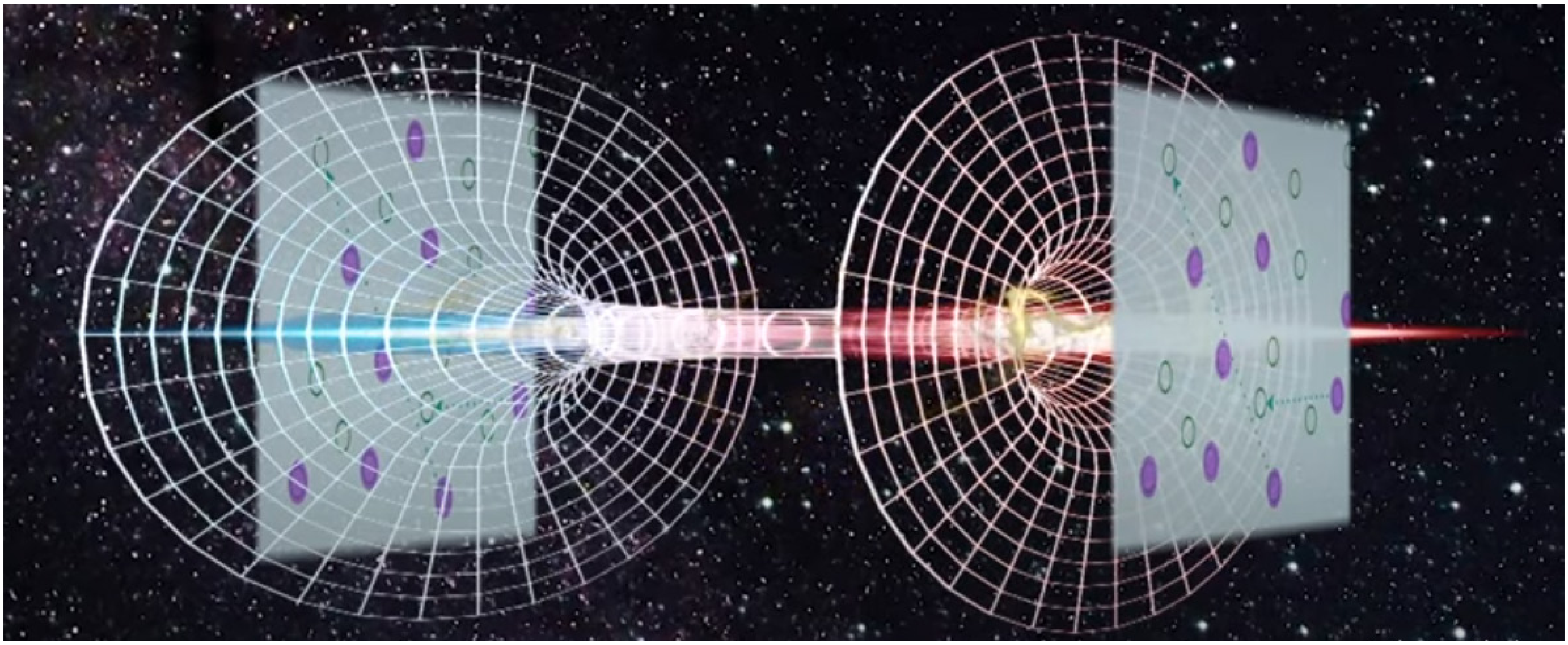

STATISTICAL MECHANICS OF STRANGE METALS AND BLACK HOLES

SUBIR SACHDEV

The meeting of the American Physical Society in New York in 1987 celebrated the discovery of high temperature superconductivity in the cuprate series of compounds. I was fortunate to be present as a young postdoc at this 'Woodstock' meeting. Physicists were confidently applying the till-then highly successful methods of condensed matter physics to these materials, expecting a rapid explanation of their remarkable properties. But the ensuing decades have shown that new paradigms of the collective quantum behavior of electrons would be needed, which would take years to develop. The biggest mystery, as became evident early on, was the unusual metallic state of these materials, above the superconducting critical temperature. This 'strange metal' as it has since come to be called, displayed unusual temperature and frequency dependencies in its properties, which indicated that the strange metal was an entangled many-body quantum state without 'quasiparticles'. Almost all of condensed matter physics is built on the idea of quasiparticles: it allows us to account for the Coulomb interactions between electrons, by assuming their main effect is to renormalize each electron with a cloud of electron-hole pairs, after which we can treat each electron as a nearly independent quasiparticle. This decomposition of the excitations of a many-body system into a composite of simple quasiparticle excitations is an assumption so deeply engrained in the theoretical framework that it is usually left unstated.

Complex many-particle quantum entanglement is also a central theme in another major puzzle in theoretical physics. In 1974, Stephen Hawking [1] combined heretofore distinct pillars of physics: the quantum theory of microscopic particles like the electron, and Einstein's theory of general relativity which applies on astrophysical scales. He argued that the application of quantum theory to the black hole solutions of general relativity led to the remarkable conclusion that each black hole had a non-zero temperature, and an associated entropy (which had been postulated earlier by Bekenstein [2]). Hawking's arguments were based upon semiclassical methods, related to the old quantum theory of Bohr and Sommerfeld. It was not at all clear whether Hawking's results were compatible with the microscopic quantum theory of Schrödinger and Heisenberg, which is known today to apply without change to all the microscopic constituents of our universe. Indeed, Hawking famously stated in the early days that perhaps the Schrödinger-Heisenberg quantum theory broke down near black holes. Today, there is an emerging consensus that the Schrödinger-Heisenberg quantum theory is indeed compatible with general relativity and black holes, and complex and chaotic many-particle quantum entanglement is the key to resolving the difficulties in the semiclassical description.

The last few decades have seen much progress in our understanding of the remarkable physical consequences of many-particle quantum entanglement, coming from a synthesis of ideas from quantum condensed matter theory, quantum information science, quantum field theory, string theory, and also from modern mathematical ideas built on category theory. Here, I will discuss some of the insights that have emerged from a study of the Sachdev-Ye-Kitaev (SYK) model. I proposed a closely related model with the same physical properties in 1992, some of which were described in a paper with my first graduate student, Jinwu Ye [3]. Alexei Kitaev [4] proposed a modification in 2015 which simplified its solution and enabled important insights from a more refined analysis [5–16]. My motivation in 1992 was to write down the simplest model of a metal without quasiparticles, as a starting point towards addressing the strange metal problem of the cuprates. Additional properties of the SYK model were described by Olivier Parcollet and Antoine Georges in Refs. [17, 18] in 1999-2001, and in 2010 I pointed out [19] that the SYK model also provided a remarkable description of the low temperature properties of certain black holes [20]. This connection has since undergone rapid development and has been made quite precise. The SYK model shows that the quantum entanglement responsible for the absence of quasiparticles in strange metals is closely connected to that needed for a microscopic quantum theory of black holes.

Foundations by Boltzmann

Let's start by recalling two foundational contributions by Boltzmann to statistical mechanics.

First, in 1870, Boltzmann gave a precise definition of the thermodynamic entropy S in statistical terms:

$$S = k_B ln W \qquad (1)$$

Where k_B is Boltzmann's constant, and W is number of microstates consistent with macroscopically observed properties. The value of W diverges exponentially with the volume of the system, and so S is extensive *i.e.,* proportional to the volume. Boltzmann was thinking in terms of a dilute classical gas of molecules, as found in the atmosphere. But Boltzmann's definition works also for quantum systems, upon replacing W by $D(E)$, the density of the energy eigenstates of the many-body quantum system per unit energy interval; then we have

$$D(E) \sim \exp(S(E)/k_B) \qquad (2)$$

where $S(E)$ is the thermodynamic entropy in the microcanonical ensemble with extensive energy E.

Second, in 1872, Boltzmann's equation gave a correct description of the time evolution of the observable properties of a dilute gas in response to external forces. He applied Newton's laws of motion to individual molecules, and obtained an equation for $f_{\mathbf{p}}$, the density of particles with momentum $\mathbf{p}$. In a spatially uniform situation, Boltzmann's equation takes the form

$$\frac{\partial f_{\mathbf{p}}}{\partial t} + \mathbf{F} \cdot \nabla_{\mathbf{p}} f_{\mathbf{p}} = \mathcal{C}[f] \qquad (3)$$

where t is time, and F is the external force. The left-hand-side of (3) is just a restatement of Newton's laws for individual molecules. Boltzmann's innovation was the right-hand-side, which describes collisions between the molecules. Boltzmann introduced the concept of 'molecular chaos', which asserted that in a sufficiently dilute gas successive collisions were statistically independent. With this assumption, Boltzmann showed that

$$\mathcal{C}[f] \propto \int_{\mathbf{p}_{1,2,3}} \cdots \left[f_{\mathbf{p}} f_{\mathbf{p}_1} - f_{\mathbf{p}_2} f_{\mathbf{p}_3} \right] \qquad (4)$$

for a collision between molecules as shown in Fig. 1. The statistical independence of collisions is reflected in the products of the densities in (4), and the second term represents the time-reversed collision.

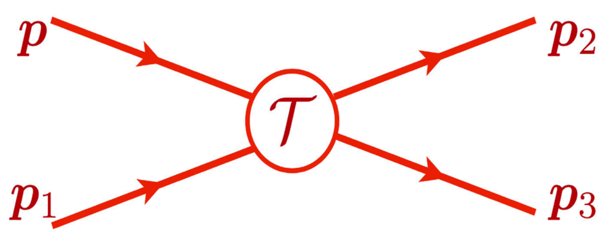

Fig. 1: Collision between two molecules. The collision term in the Boltzmann equation is proportional to the absolute square of the T-matrix.

Ordinary and strange metals

The remarkable fact is that Boltzmann's equation also applies, with relatively minor modifications, in situations very different from the dilute classical gas: it also applies to the dense quantum gas of electrons found in ordinary metals. Now collisions become rare because of Pauli's exclusion principle, and the statistical independence of collisions is assumed to continue to apply. The main modification is that the collision term in (4) is replaced by

$$\mathcal{C}[f] \propto \int_{\mathbf{p}_{1,2,3}} \cdots \left[f_{\mathbf{p}} f_{\mathbf{p}_1} (1 - f_{\mathbf{p}_2})(1 - f_{\mathbf{p}_3}) \right. \qquad (5)$$
$$\left. - f_{\mathbf{p}_2} f_{\mathbf{p}_3} (1 - f_{\mathbf{p}})(1 - f_{\mathbf{p}_1}) \right]$$

where the additional (1-f) factors ensure that the final states of collisions are not occupied. Now the $f_{\mathbf{p}}$ measure the distribution of electronic quasiparticles, and the cloud of particle-hole pairs around each electron only renormalizes the microscopic scattering cross-section. Such a quantum

Boltzmann equation is the foundation of the quasiparticle theory of the electron gas in metals, superconductors, semiconductors, and insulators, and indeed almost all of condensed matter physics before the 1980's. One of its important predictions is that as temperature $T \to 0,$, the typical time between collisions, t_c , diverges as $t_c \sim 1/T^2$.

One can now ask, how short can we make t_c before we cannot ignore the quantum interference between successive collisions, and the concept of quasiparticles does not make sense? An energy-time uncertainty-principle argument indicates that *any* many-body quantum system should have a relaxation time [21]

$$t_r \geq \alpha \frac{\hbar}{k_B T} \quad , \quad T \to 0 \, , \qquad (6)$$

where α is a dimensionless, T - independent constant. For systems with quasiparticles, we expect $t_c \sim t_r$, and we have introduced a general relaxation time t_r to allow a more general discussion in systems without quasiparticles. From studies of various quantum critical systems, it was argued [21] that the inequality in (6) becomes an equality when quasiparticles are absent, as in strange metals. Recent experiments [22] on the strange metal in cuprate superconductors have measured a particular relaxation time by connecting it to the angle dependence of the resistivity in a magnetic field, and indeed found it obeys (6) as an equality, with $\alpha \approx 1.2$. This is often stated as the strange metal exhibiting 'Planckian time' dynamics [23].

Quantum black holes and holography

We can write the quantum theory of black holes as a Feynman path integral over the spacetime metric $g_{\mu\nu}$, and the electromagnetic gauge field a_μ : this involves computing the partition function

$$\mathcal{Z} = \int \mathcal{D}g_{\mu\nu}\mathcal{D}a_\mu \exp(-\frac{1}{\hbar}\int d^d x \int_0^{\hbar/(k_B T)} d\tau \sqrt{g}\,\mathcal{L}_d[g_{\mu\nu}, a_\mu]) \qquad (7)$$

over fields in (d+1) -dimensional spacetime, with $\mathcal{L}_d$ the Lagrangian of classical Einstein-Maxwell theory in d+1 spacetime dimensions, and g the determinant of the metric. Here τ is time analytically continued to the imaginary axis, which is taken to lie on a circle of circumference $\hbar/(k_B T)$, where $\hbar$ is Planck's constant. This constraint on imaginary time follows from the correspondence between the evolution operator $U(t)$ for real time t in quantum mechanics, and the Boltzmann-Gibbs partition function $\mathcal{Z}$ for a quantum system with Hamiltonian H:

$$U(t) = \exp(-iHt/\hbar) \quad \Leftrightarrow$$
$$Z = Tr \exp(-H/(k_B T)) \qquad (8)$$

In imaginary time, the spacetime geometry outside a black hole is that of a 'cigar' as shown in Fig. 2.

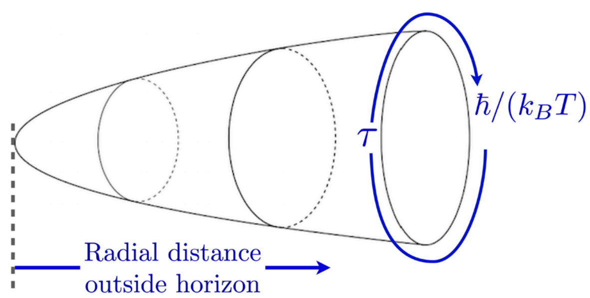

Fig. 2: Spacetime geometry outside a black hole. Only the radial direction and the imaginary time direction τ are shown, and the two angular directions are not shown.

Note that all dependence of (7) on $\hbar$ and T is explicit, and there is no $\hbar$ or T in the Lagrangian $\mathcal{L}_d$.

Formally, the path integral in (7) is pathological because it includes infinities that cannot be controlled by the usual renormalization tricks of quantum field theory. Nevertheless, Gibbons and Hawking [24] boldly decided to evaluate it in the semiclassical limit, where one only includes the contribution of the cigar saddle point in Fig. 2. For a black hole, they also imposed the requirement that spacetime was smooth at the horizon in imaginary time. From this relatively simple computation, they were able to obtain the thermodynamic properties of a black hole, including its temperature and entropy. For a neutral black hole of mass M in d = 3 they found

$$\frac{S}{k_B} = \frac{Ac^3}{4G\hbar} \quad , \quad \frac{k_B T}{\hbar} = \frac{c^3}{8\pi G M} \qquad (9)$$

where c is the velocity of light, G is Newton's gravitational constant, and $A = 4\pi R^2$ is the *area* of the black hole horizon with $R = 2GM/c^2$ the horizon radius.

The revolutionary results in (9) raised many more questions than they answered. Is this semiclassical computation of thermodynamics compatible with Boltzmann's fundamental statistical interpretation of entropy in (2)? Can one compute the energy eigenvalues of a quantum Hamiltonian whose density of states $D(E)$ yields a $S(E)$ that is consistent with (9) and the partition function $\mathcal{Z}$ in (7)? With the energy E shifted so that E=0 for the ground state, $\mathcal{Z}$ is related to $D(E)$ by

$$\mathcal{Z} = \int_{0^-}^{\infty} dE D(E) \exp\left(-\frac{E}{k_B T}\right). \qquad (10)$$

Many other questions are raised when one considers the fate of the black hole as it evaporates while emitting blackbody radiation at the temperature in (9), and computes the entanglement entropy of the Hawking radiation.

A remarkable feature of the entropy in (9) is that it is proportional to the surface *area* of the black hole. This contrasts with extensive volume proportionality of the entropy, mentioned below (1), obeyed by all other quantum systems. Attempts to understand this feature led to the idea of holography [25-27] illustrated in Fig. 3.

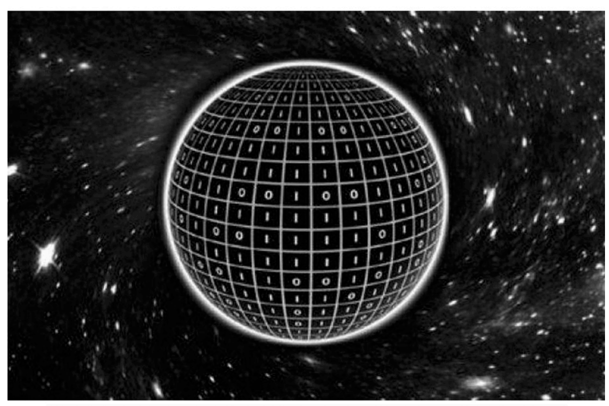

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Fig. 3: Holography: the number of qubits required for the quantum simulation of a black hole is proportional to its surface area.

Let us try to build a quantum simulation of a black hole by simple two-level systems *i.e.* qubits. How many qubits will we need? As N qubits can describe 2^N linearly-independent quantum states, the formula in (2) tells us that the number of qubits is proportional to the entropy, and hence the area of the black hole. So the qubits realize a many-body quantum system which we can imagine residing on its surface *i.e.* the qubits are a faithful $(d\text{-}1)$ - dimensional hologram of the complete quantum gravitational theory of the black hole in d spatial dimensions.

A particular realization of such qubits was found in string theory for 'extremal' black holes (defined below) with low energy supersymmetry [28]. This realization has a ground state with an exponentially large degeneracy, and special features of the supersymmetry were employed to compute this degeneracy, yielding

$$D(E) = [\exp(S(E)/k_B)]\delta(E) + \dots \qquad (11)$$

where... refers to a continuum above an energy gap. The value of $S(0)$ was found to be precisely that in the Hawking formula in (9) [29]. However, the zero energy delta-function in (11) is now known [16] to be a special feature of theories with low energy supersymmetry, and is not a property of the generic semiclassical path integral over Einstein gravity in (7), as we will discuss below (see Fig. 5).

To move beyond supersymmetric string theory, we ask if there are any general constraints that must be obeyed by the many-body system realized by the interactions between the qubits. An important constraint comes from an earlier result by Vishveshwara [30]. He computed the relaxation time, t_r of quasi-normal modes of black holes in Einstein's classical theory; this is the time in which a black hole relaxes exponentially back to a spherical shape after it has been perturbed by another body:

$$t_r = \alpha\prime \frac{8\pi GM}{c^3}, \qquad (12)$$

where α' is a numerical constant of order unity dependent upon the precise quasi-normal mode. Comparing Vishveshwara's result in (12) with Hawking's result in (9), we can write

$$t_r = \alpha\prime \frac{\hbar}{k_B T} \qquad (13)$$

which is exactly of the form in (6) for many body quantum systems without quasiparticles! This is a key hint that the holographic qubit description of a black hole must involve a quantum system without quasiparticle excitations, if it is reproducing basic known features of black hole dynamics. At this point, it is interesting to note that measurements of t_r in binary black hole mergers by LIGO-Virgo [31] do indeed fall around the value of $\hbar/(k_B T)$.

The SYK model

The Hamiltonian of a version SYK model is illustrated in Fig. 4. We take a system with fermions $\psi_i, i = 1 \dots N$ states. Depending upon physical realizations, the label i could be position or an orbital, and it is best to just think of it as an abstract label of a fermionic qubit with the two states $|0\rangle$ and $\psi_i^+|0\rangle$. We now place QN fermions in these states, so that a density $Q \approx 1/2$ is occupied, as shown in Fig. 4.

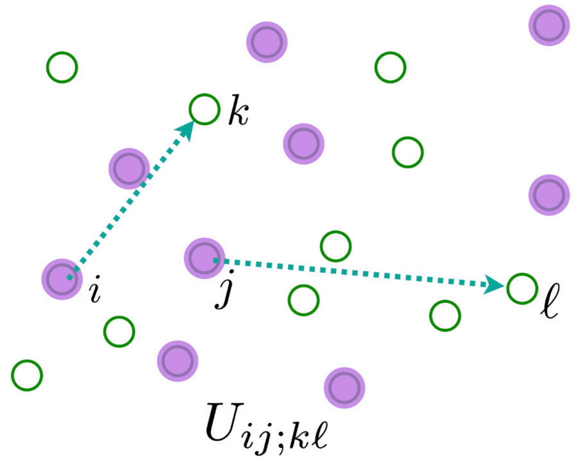

Fig. 4: The SYK model: fermions undergo the transition ('collision') shown with quantum amplitude $U_{ij;kl}$.

The quantum dynamics is restricted to *only* have a 'collision' term between the fermions, analogous to the right-hand-side of the Boltzmann equation. However, in stark contrast to the Boltzmann equation, we will not make the assumption of statistically independent collisions, and will account for quantum interference between successive collisions: this is the key to building up a many-body state with non-trivial entanglement. So a collision in which fermions move from sites i and j to sites k and l is characterized not by a probability, but by a quantum amplitude $U_{ij;k\ell}$, which is a complex number.

The model so defined has a Hilbert space of order 2^N states, and a Hamiltonian determined by order N^4 numbers $U_{ij;k\ell}$. Determining the spectrum or dynamics of such a Hamiltonian for large N seems like an impossibly formidable task. But if we now make the assumption that the $U_{ij;k\ell}$ are statistically independent random numbers, remarkable progress is possible. Note that we are not considering an ensemble of SYK models with different $U_{ij;k\ell}$, but a single fixed set of $U_{ij;k\ell}$. Most physical properties of this model are self-averaging at large N, and so as a technical tool, we can rapidly obtain them by computations on an ensemble of random $U_{ij;k\ell}$. In any case, the analytic results we now describe have been checked by numerical computations on a computer for a fixed set of $U_{ij;k\ell}$. We recall that even for the Boltzmann equation, there was an ensemble average over the initial positions and momenta of the molecules that was implicitly performed.

Using these methods, key properties of the SYK model have been established (for complete references to the literature, please see the review in Ref. [32]):

- There are no quasiparticle excitations, and it exhibits quantum dynamics with a Planckian relaxation time obeying (13) at $T \ll U$, where $U/N^{3/2}$ is the root-mean-square value of the U_{ijkl} . In particular, the relaxation time is *independent* of U , a feature not present in any ordinary metal with quasiparticles.

- At large N, the many-body density of states is (see Fig. 5a)

$$D(E) \sim \exp(N s_0) \sinh(\sqrt{2N\gamma E}). \qquad (14)$$

Here s_0 is a universal number dependent only on Q ($s_0 = 0.4648476991708051 \dots$ for $Q = 1/2$), and $\gamma \sim 1/U$ is the only parameter dependent upon the strength of the interactions.

Given $D(E)$, we can compute the partition function from (10) at a temperature T, and hence the low T dependence of the entropy

$$\frac{S(T)}{k_B} = N(s_0 + \gamma k_B T) - \frac{3}{2}\ln\left(\frac{N^{1/3}U}{k_B T}\right) + \cdots \qquad (15)$$

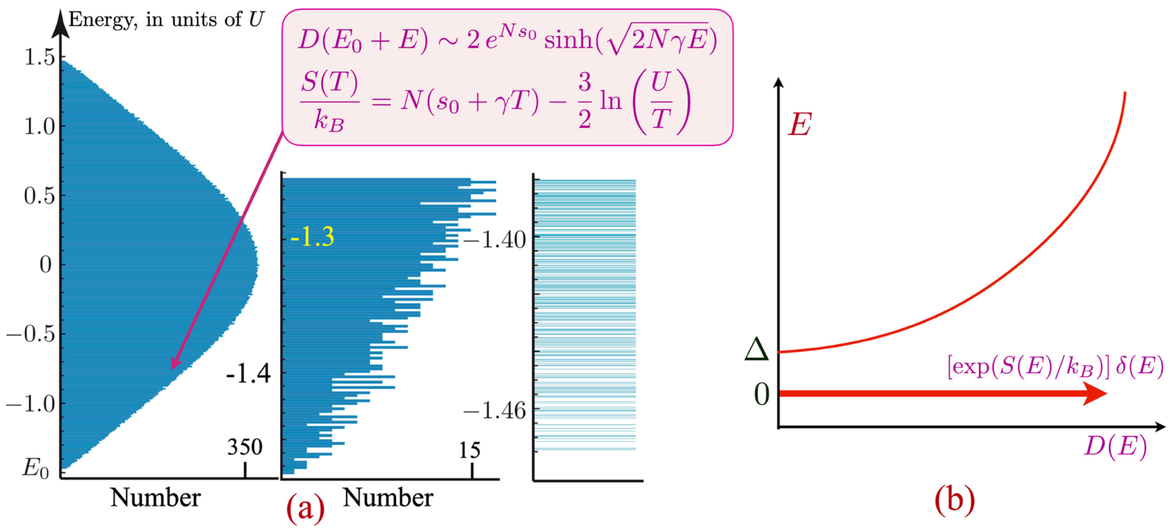

Fig. 5: a) 65536 many-body eigenvalues of a N=32 Majorana SYK Hamiltonian. The coarse-grained low energy and low temperature behavior is described by (14) and (15). The lower energy part of this density of states is argued to apply to the semiclassical path integral in (7) for charged black holes at low T (i.e., extremal black holes).

(b) Schematic of the lower energy density of states of the supersymmetric string theory description of extremal black holes [28] in (11). The energy gap is proportional to the inverse of S\left(E=0\right).

(the $N^{1/3}$ in the argument of the logarithm has been introduced following Ref. [33]). The limit $\lim_{T\to 0}\lim_{N\to\infty} S(T)/(k_B N) = s_0$ is non-zero, implying an energy level spacing exponentially small in N near the ground state. This is very different from systems with quasiparticle excitations, whose energy level spacing vanishes with a positive power of $1/N$ near the ground state. However, there is no exponentially large degeneracy of the ground state itself in the SYK model, unlike the ground states of the string theory solutions leading to (11), and the ground states in Pauling's model of ice [34]. Obtaining the ground state degeneracy requires the opposite order of limits between T and N, and numerical studies show that the entropy density does vanish in such a limit for the SYK model. The density of states (14) implies that any small energy interval near the ground state contains an exponentially large number of energy eigenstates with an exponentially small spacing in energy (see Fig. 5a). The wavefunctions of these eigenstates in Fock space change chaotically from one state to the next, providing a realization of maximal many-body quantum chaos [35] in a precise sense. This structure of eigenstates is very different from systems with quasiparticles, for which the lowest energy eigenstates differ only by adding and removing a few quasiparticles.

• The E dependence of the density of states in (14) is associated with a time reparameterization mode, and (14) shows that its effects are important when E~$1/N$. We can express the low energy quantum fluctuations in terms of a path integral which reparameterizes imaginary time $\tau \to f(\tau)$, in a manner analogous to the quantum theory of gravity being expressed in terms of the fluctuations of the spacetime metric. There are also quantum fluctuations of a phase mode $\phi(\tau)$, whose time derivative is the charge density, and so we have the partition function

$$\mathcal{Z}_{SYK} = e^{Ns_0}\int \mathcal{D}f\mathcal{D}\phi \; \exp\Big(-\frac{1}{\hbar}\int_0^{\hbar/(k_BT)} d\tau\,\mathcal{L}_{SYK}[f,\phi]\Big) \qquad (16)$$

The Lagrangian $\mathcal{L}_{SYK}$ is known, and involves a Schwarzian of $f(\tau)$. Remarkably, despite its non-quadratic Lagrangian, the path integral in (16) can be performed exactly [12], and leads to (14).

From the SYK model to black holes

Can we use insights from the path integral over time reparameterizations of the SYK model in (16) to evaluate the path integral over spacetime metrics of black holes in (7)? Remarkably, for a black hole with a non-zero fixed total charge Q , the answer is yes (for complete references to the literature in the discussion below, please see the review in Ref. [32]).

The saddle-point solution of the Einstein-Maxwell action for a charged black hole has the form shown in Fig. 6: while the spacetime is 3+1 dimensional flat Minkowski far from the black hole, it factorizes into a 1+1 dimensional spacetime involving the radial direction ζ , and a 2-dimensional space of non-zero angular momentum modes around the spherical black hole.

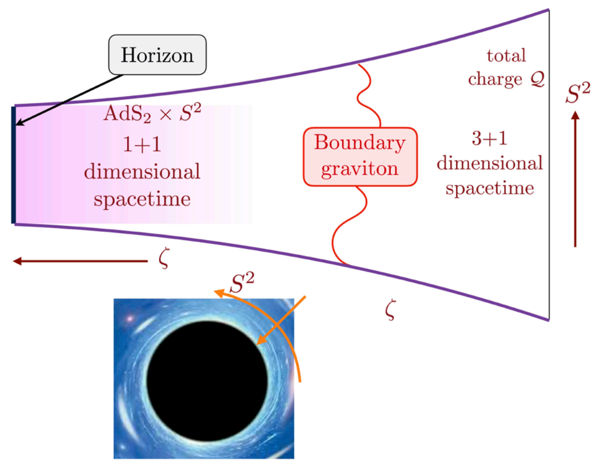

Fig. 6: Two views of the spacetime outside a charged black hole. S^2 is the sphere, and $\mathbf{AdS_2}$ is anti-de Sitter space with metric $ds^2 = (d\zeta^2 + d\tau^2)/\zeta^2$.

As the black hole temperature $T \to 0$ (also known as the extremal limit), the angular momentum modes become unimportant, and we can write the partition function of the charged black hole purely as a theory of quantum gravity in 1+1 spacetime dimensions, which is an extension of a theory known as Jackiw-Teitelboim (JT) gravity; then (7) reduces to

$$\mathcal{Z}_{JT} = e^{A_0c^3/(4\hbar G)}\int \mathcal{D}g_{\mu\nu}\mathcal{D}a_\mu \exp\left(-\frac{1}{\hbar}\int d\zeta \int_0^{\hbar/(k_BT)} d\tau\sqrt{g}\,\mathcal{L}_1[g_{\mu\nu},a_\mu]\right), \qquad (17)$$

where A_0 is the area of the black hole horizon at T=0. The (1+1) -dimensional spacetime saddle point of $\mathcal{Z}_{JT}$ has a uniform negative curvature: it is the anti-de Sitter space AdS_2, noted in Fig. 6. Quantum gravity in 1+1 dimensions is especially simple because there is no graviton, and it is possible to make an explicit holographic mapping to a quantum system in 0+1 dimensions. It turns out that the holographic quantum realization of the 1+1 dimensional theory in $\mathcal{Z}_{JT}$ (17) is exactly the 0+1 dimensional SYK model partition function in $\mathcal{Z}_{SYK}$ in (16). The fluctuations of the metric in the boundary region between the 1+1 dimensional and

3+1 dimensional spacetimes (denoted 'boundary graviton' in Fig. 6) are described by the time reparameterization $f(\tau)$, and the boundary value of a_μ becomes the phase field $\phi(\tau)$. This powerful connection enables us to proceed beyond the semiclassical results of Hawking in (9) for black holes with non-zero charge Q. Applying this mapping from $\mathcal{Z}_{JT}$ to $\mathcal{Z}_{SYK}$, we obtain a density of states $D(E)$ with precisely the E dependence in (14), which also corresponds to that shown for the SYK model in Fig. 5a. This should be contrasted with the supersymmetric result in (11) and Fig. 5b [15,16]. The parameters in the black hole $D(E)$ can be deduced by comparing the SYK entropy in (15) with the low T limit of the entropy of a charged black hole in asymptotically 3+1 dimensional Minkowski spacetime, which is

$$\frac{S(T)}{k_B} = \frac{1}{\hbar G}\left(\frac{A_0 c^3}{4} + \frac{\sqrt{\pi} A_0^{3/2} c^2}{2}\frac{k_B T}{\hbar}\right) - \frac{3}{2}\ln\left(\frac{c^2}{A_0^{1/6}(\hbar G)^{1/3}(k_B T/\hbar)}\right) + \dots \quad (18)$$

The terms in (18) are in one-to-one correspondence with those in (15), and now the expansion is in small $\hbar G$ in place of large N for the SYK model. (The A_0 factor within the logarithm has been obtained by matching to the SYK model, but there are additional in (A_0) terms for black holes that are not contained in (18) [15,36].) In this manner, we obtain an expression for the low energy density of states of a charged black hole in asymptotically 3+1 dimensional Minkowski spacetime, corresponding to (14) for the SYK model;

$$D(E) \sim \exp\left(\frac{A_0 c^3}{4\hbar G}\right)\sinh\left(\left[\frac{\sqrt{\pi} A_0^{3/2} c^2}{\hbar^2 G} E\right]^{1/2}\right); \quad (19)$$

this is very different from the result in (11) obtained from string theory. Recall that A_0 is the area of the black hole horizon at $T=0$; all other parameters in (19) are fundamental constants of nature. The result in (19) is a rare formula which combines Planck's constant $\hbar$ with Newton's gravitational constant G: the exponential prefactor was obtained by Hawking, and the sinh follows from developments ensuing from the solution of the SYK model. In particular, the time reparameterization mode is important when the sinh in (19) becomes of order unity and such corrections address [15,16] issues raised in Ref. [37].

We have now answered one of the questions raised by Hawking's semiclassical computation of black hole entropy, at least for the case of a charged black hole at low T. There is a perfectly well-defined quantum system, with precise and discrete energy levels, whose many body density of states $D(E)$ is described at low energies by a gravitational theory expressed in terms of the semiclassical fluctuations of a spacetime metric: this is the SYK model. This connection has enabled computation of the logarithmic correction to black hole entropy in (18) and the density of states in (19), and has led to some understanding of the key role played by many-body quantum chaos in the black hole microstates [38]. The random couplings in the SYK model mainly play the role of a powerful computational tool for accessing the physics of chaotic behavior, as was also the case in single-particle problems such as 'quantum billiards' [39]. The quantities being studied here self-average in a single realization of the random couplings, and are not sensitive to the particular member chosen from the random ensemble. It is also worth noting here that the Boltzmann equation also involves an implicit average over an ensemble of initial conditions for the quasiparticles.

The connection between the SYK model and black holes does *not* imply that the ultimate high energy and short distance physics is described by the SYK model. That likely requires string theory, in which supersymmetry is restored at high energies. Nevertheless, the SYK model provides a much simpler quantum simulation of the low energy physics in certain cases, including the complex quantum entanglement and the maximal many-body quantum chaos. The semiclassical path integral over Einstein gravity can capture certain coarse-grained properties of the underlying Schrödinger-Heisenberg quantum theory, and is not sensitive to all the microscopic details at the smallest length scales. Recent work [40,41] has shown that the path integral over Einstein gravity can also consistently describe the time evolution of the entanglement entropy of an evaporating black hole, provided we also include the contributions of 'wormhole' solutions of Einstein gravity. Such wormholes can also be realized by the quantum states of the SYK model. The idea that Einstein quantum gravity is a coarse-grained description of the microscopics has also led to many theoretical advances by employing averages over ensembles of consistent, microscopic, quantum theories [42].

From the SYK model to strange metals

To conclude, we return to the original motivation for studying the SYK model, to the strange metal phase of the cuprate superconductors and related compounds. Realistic models of the lattice scale physics of these materials involve mobile electrons with strong interactions. These models can be solved by methods closely related to those of the SYK model, after they are extended to large spatial dimension d, and upon including random spin exchange interactions. These large d models display strange metal phases with many similarities to observations [32]. In particular, such strange metals do have a time reparameterization low energy mode, and this mode leads to a linear-in-temperature resistivity at the smallest T [43], as is observed in the strange metals of the cuprates.

Other works have focused on the strange metal directly in d=2 dimensions, which is the physically relevant dimension for the cuprates. Rather than departing from the SYK model, physically realistic models of such strange metals can be built from 'Yukawa-SYK' models of fermions and bosons with Yukawa couplings [32]. An important consideration is the role of the Fermi surface: for free electrons, this is the surface which divides occupied and empty electron states in momentum space. A suitably defined Fermi surface is also present when there are interactions between the electrons in an ordinary metal, and also when quasiparticles are no longer present in a strange metal. An interesting and much studied strange metal is obtained when the interactions between the Fermi surface excitations are mediated by the exchange of a boson with a gapless energy spectrum. Such a boson may be the order parameter of a symmetry-breaking quantum phase transition, or an emergent gauge field in a correlated metal. However, this strange metal has a zero resistance because the low energy theory has a continuous translation symmetry. But recent studies [44-46] have shown that adding a SYK-like randomness to the boson-electron coupling does lead to a linear-in-temperature resistivity as $T \to 0$. Such randomness can arise from impurities in the strange metal, and quantifying the role of randomness is an important direction for the further study of strange metals.

Acknowledgements

I thank Matthew Heydeman, G. Joaquin Turiaci and Spenta Wadia for important comments on the manuscript. This research has been supported by the U.S. National Science Foundation, most recently under grant No. DMR-2002850.

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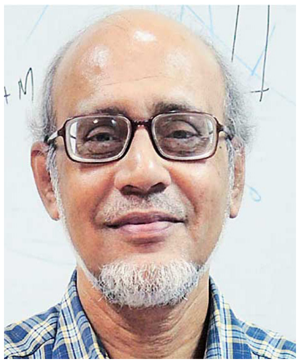
GENES AS A GUIDE TO HUMAN HISTORY AND CULTURE

PARTHA P. MAJUMDER



We have always been interested in questions about our past, such as, where do we come from? where did we move to and when? Whom did we mix with? Scientists of various disciplines – palaeontology, archaeology, prehistory, anthropology, linguistics, genetics – have used their own toolkits and have attempted to answer these questions. In this narrative, we shall focus on genetics as the toolkit. This story is in two parts. The first part spans about five million years and the second one about hundred and fifty thousand or two hundred thousand years

About 5 million years ago, a population of African apes split into two distinct lines of descent. One of these led to the evolution of the gorilla, chimpanzee and bonobo, and the other line of descent led to the human (Fig. 1).

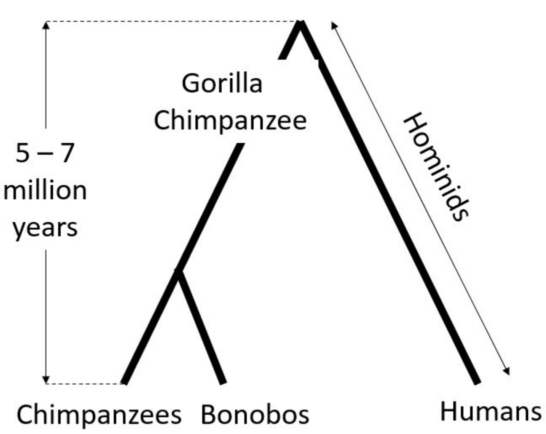


Fig. 1: Lines of evolutionary descent that separated about five million years ago leading to the arrival of modern humans.

More than four million years ago, one of the species on the evolutionary path to humans began spending most of its time on two feet. This was the genus *Australopithecus*; the most famous species in this genus being the *afarensis*. Remains of *Australopithecus afarensis* in the fossilized form were found in Hadar, Ethiopia, in 1991. This fossil has been famously named "Lucy." Lucy walked upright on earth about 3.2 million years ago. How do we know that Lucy walked upright? Footprints of an individual that were testimony to an upright gait were found on a volcanic ash bed, which was dated to approximately the same period of time when *Australopithecus afarensis* roamed in that region of Africa.

This upright stance seems to have set in motion a profound evolutionary trend. It resulted in greater visibility over higher underbrush of the forests in Africa. This meant that predators could be spotted when they were at a distance. Hands became free to use for manipulation. For example, Lucy and her relatives could throw stones to ward off predators and thereby save their own lives. Freeing of hands resulted in the ability to make tools. There was simultaneous increase in their brain size. We will never know for certain whether a larger brain size provided novel abilities or whether exploration to perform new activities resulted in larger brain size. The most important upshot of bipedality is that our ancestors were able to survive longer.

The genus *Homo* evolved a little over 2 million years ago. Once the first species in the genus *Homo appeared, it began to spin off new varieties of Homo*. Between the appearance of the first species of *Homo* to the appearance of *Homo sapiens* – that is us, the modern man – there were many other species that arose and evolved into newer species, but eventually went extinct. These species included *Homo robustus, habilis, ergaster, erectus, heidelbergensis and neanderthalensis. Homo nearderthalensis* is famously called the Neanderthal man. There was a lot of speculation about how the Neanderthal man disappeared.

Modern man, *Homo sapiens*, evolved shortly after the appearance of the Neanderthal man. Modern man and the Neanderthal man lived together for many thousands of years. It was speculated that the modern man, with larger brain size and greater abilities, killed the Neanderthal man in large numbers that resulted in their disappearance. Today, we know through some extraordinary genetic studies that this speculation is false. *Homo sapiens* interbred with *Homo neanderthalensis* and absorbed them; simply put, the children that resulted from a mating between modern man and a Neanderthal became a part of the family of modern man. Over a period of time, the size of the Neanderthal group declined, but their genes became a part of the genetic constitution of modern man. All this took place about 100,000 years ago. However, when we cite these dates, we need to remember that these are estimates and can actually be off by some thousands of years; the estimates have large standard deviations.

Part two of this story begins now. Modern methods of genetics have provided fantastic tools for the study of human history. Palaeontologists, scientists who study fossils and draw scientific inferences by systematically studying them, often have to base their inferences using fragmentary evidence – one broken bone, a skull or a jaw. Geneticists, on the other hand, are able to gather vast amounts of heritable information – information that is passed on from parents to their offspring nearly intact – by analysing DNA contained in the cells. The DNA is passed on from one generation to another, largely unchanged. Sometimes random changes occur due to, for example, exposure to ultraviolet radiation or some chemicals. When a change occurs, that change is passed on to the next generations. We roughly know how often such changes in the DNA take place during a fixed length of time. This enables us to also estimate times of acquisition of changes and track the evolution of DNA over time.

Anatomically modern humans arose in Africa about 130,000 years ago. May be 150,000 or 110,000 years ago; the date is a little uncertain. We, the modern humans, are less heavily built and have higher cognitive flexibility than the ancestral species from which we evolved. We are also unusual animals with a wide geographical distribution. We have adapted ourselves to a wide range of environmental conditions and now occupy every nook and corner of the world.

We also started organizing ourselves into groups. Resulting from this organization, our 'mating structure' also underwent reorganization. Instead of being one large inter-mating group, we started to choose mates from within "our own group." This in turn resulted in genetic distinctions between groups. As a result of humans tending to mate within their own groups, genetic variations that arose in individuals within a group tended to remain within the group, since these variations had little chance to cross group-boundaries. This is because individuals carrying these variants did not generally mate with individuals of a different group. Genes, as we know, move with people. Therefore, if movement of individuals was restricted because they tended to remain within their own group, then genes also tended to have restricted movement. An individual usually avoids mating with another who does not share her or his own some physical, cultural and linguistic attributes. In other words, cultural and linguistic differences are barriers to admixture. In addition, geographical barriers also act as barriers to admixture.

Since genetic changes appear in individuals within a group and these changes accumulate over time within a group, one expects that a contemporary group that has a lot of genetic diversity is an "old" genetic group, i.e., has evolved for a long period of time. If we consider the overall human genetic diversity at the continental level, we find that Africa has the highest genetic diversity followed by Asia (Fig. 2).

MANJUL BHARGAVA PROVES 86-YEAR-OLD CONJECTURE

ICTS International Advisory Board member and Princeton University professor, Manjul Bhargava has, in a recent preprint, proved an 86-year-old conjecture originally formulated by the Dutch mathematician B. L. Van der Waerden. Consider the $(2H+1)^n$ polynomials $x^n + a_1 x^{\{n-1\}} + \dots a_n$, where $a_1, a_2 \dots a_n$ are all integers of modulus less than or equal to H. Most of these polynomials have roots that are all, for many purposes, completely interchangeable (e.g., the roots of the polynomial x^2-7). However, some relatively special polynomials have roots that are clearly not interchangeable (e.g., the roots 2 and 3 of the polynomial x^2-5x+6). How many of these polynomials are of this relatively special sort? Technically, how many of these polynomials have an associated Galois group that is not the full symmetric group S_n? In 1936 Van der Warden conjectured that the number of such special polynomials was bounded from above by a number of order $H^{(n-1)}$. In his recent work, Bhargava has presented a proof of this long-standing conjecture.

This is consistent with the claim that Africa is the cradle of humankind. Indeed, genetic diversity of both Y-chromosomal genetic variants that are passed on along the male lineage, and mitochondrial genetic variants that are passed on by a mother to all her children with no contribution from their father, are the highest in Africa and also decay with increasing geographical distance from Africa through Asia to the new world. These facts are consistent with the evolution of humankind in Africa and their subsequent dispersal from Africa to other parts of the world. Asia – in particular, India – was one of the earliest regions that modern humans occupied after moving out-of-Africa.

India has served as a major corridor for the migration of modern humans who started to disperse out-of-Africa about 100,000 (perhaps, sometime between 110,000 and 60,000) years ago. Nevertheless, the date of entry of modern humans into India remains uncertain. It is quite certain, based on human remains, that by the middle of the Palaeolithic period (50,000–20,000 years before present) humans had spread to many parts of the Indian subcontinent. Thus, India has been peopled by contemporary humans at least for the past 55,000 years. Genetic evidence indicates that a major population expansion of modern humans took place within India.

A little over ten years ago, some of us interested in understanding "where do we come from?" initiated a project to estimate the genetic diversity and decipher the genetic structures of ethnic populations of Asia by interrogating for each individual the presence or absence of a very large number of genetic variants. We noted a high degree of genetic diversity in populations of India, and indeed their antiquities estimated from the genomic data turned out to be the deepest compared to other Asian populations. Overall, Asia seemed to have been founded by seven or eight genetically distinct ancestral populations.

We wished to estimate, using genetic data, how many genetically distinct ancestral populations may have contributed to the pool of genes that comprise the diversity

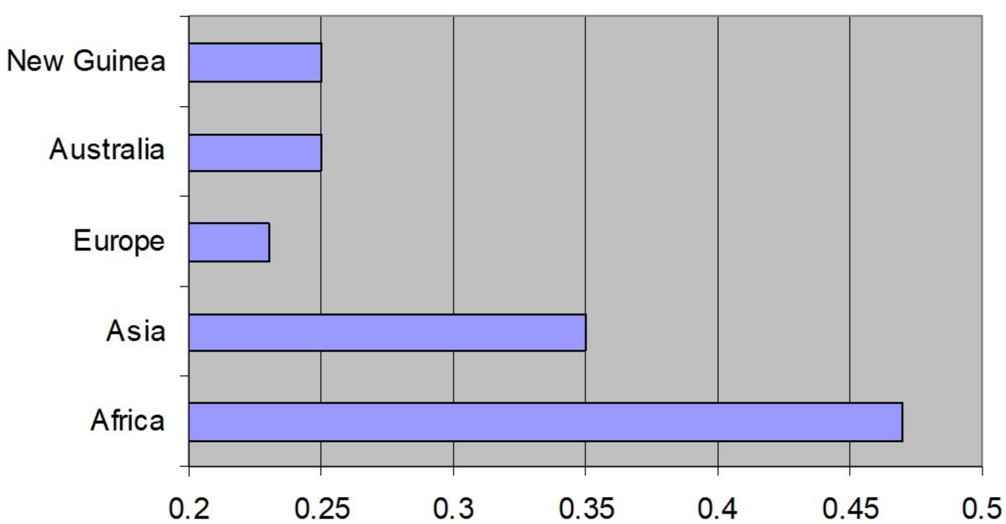


Fig. 2: Extent of genetic diversity among human populations of different continental regions..

of ethnic groups – tribal, caste and migrant – of India. Contemporary India is a rich tapestry of largely intra-marrying ethnic groups. As estimated by nationwide surveys conducted by the Anthropological Survey of India, there are about 400 tribal groups in India, about 4000 caste and sub-caste groups, and about 150 migrant and religious groups.

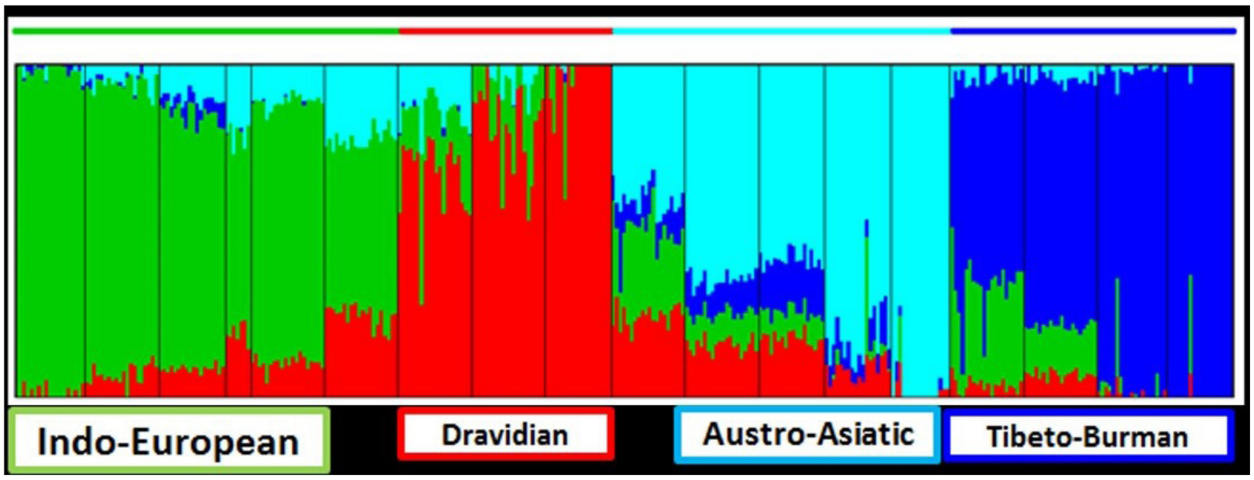


Fig. 3: Genetic analysis of admixture in individuals belonging to different ethnic groups of India, who speak languages of different linguistic families or resident in different regions of India reveal that (a) four distinct ancestral populations (indicated by different colours) have contributed to the gene pool of contemporary Indians, and (b) only one ancestral population has predominantly contributed to the gene pool of populations of each geographical region or equivalently among populations who speak a similar language.

The tribal groups have a simple social organization and carry out simple occupations, primarily slash-and-burn agriculture. The caste and the migrant populations have a complex, often hierarchical, social organization and are engaged in a variety of occupations. Linguistically, all groups in the northern region of India speak Indo-European languages; in the southern region, Dravidian languages; and, in north-east India Tibeto-Burman languages.

The tribal groups of central India, such as the Munda, speak dialects that belong to the Austro-Asiatic linguistic family. None of the non-tribal groups speak Austro-Asiatic languages. I underscore that there is confounding of geography and language in India.

We sampled individuals, with informed consent, from a large number of ethnic groups – tribal, caste, religious and migrant – from throughout the country and obtained a blood sample from each. We then analysed the DNA of each individual, either by interrogating a large number of genetic variants or by DNA sequencing. By use of a variety of statistical analyses, we estimated that four ancestral populations contributed to the gene-pool of mainland India (i.e., excluding the island populations).

These ancestral populations cannot be identified with any of the contemporary ethnic groups. However, it is evident (Fig. 3) that each of the four distinct ancestral populations has contributed to the overall gene-pool; with one ancestral population contributing largely to populations that speak languages belonging to one of the four distinct linguistic families

This evidence can also be interpreted as – in view of the confounding of geography and language in India – that distinct ancestral populations have contributed to the gene pools of contemporary ethnic groups occupying northern, southern, central and north-eastern regions. Thus, in spite of the diverse tapestry that is ethnic India, there is a discernible genetic unity as revealed by genetic contributions of only four ancestral populations to the large numbers of ethnic groups.

Genes can also provide evidence of major human cultural innovations and their spread. Arguably, farming was a major innovation of modern humans. Organized farming arose in the Fertile Crescent region – the region where Syria, Lebanon, Turkey are located. Subsequently, it spread to many places fairly rapidly and eventually to all parts of the world.

Was the spread of farming by word of mouth or did farmers take the technology and culture of farming physically to distant lands? This was an enigma until about two decades ago when genetic studies provided evidence consistent with human dispersal to be associated with the spread of agriculture. Just to be sure, even at the risk of being repetitive, that no one thinks that the practice of agriculture is in the genes, I would like to point out that the spread of agriculture was associated with the movement of people; agriculturists took the practice of farming to new regions and taught it to the locals in the new region. Movement of people implies movement of genes. Some migrants ‘export’ their genes to a new region by taking spouses from the new region and producing children with them who stay in the new region. We can never be sure that the attribution of agriculture having been introduced to the Indian subcontinent by migrants is fully true. However, genetic data do support this model, especially of the spread of modern, organized agriculture. A male genetic (Y-chromosomal) signature, called haplogroup J, was shown to be associated with the spread of modern agriculture. This signature has its highest frequency in the Fertile Crescent region where the technology of modern agriculture was invented about 7,000-10,000 years ago. This signature is associated with individuals who invented agriculture. The frequency of this signature diminishes as one moves away from the Fertile Crescent region, consistent with the paradigm that farmers actually dispersed from the Fertile Crescent region and carried the culture and technology of farming to new areas. As they went far and wide, the strength of the original band of migrating farmers diminished and the genetic signature they carried with them diluted (Fig. 4). Collection of deeper data showed that this signature is quite heterogeneous and is composed of sub-signatures, one of which – haplogroup J2b2 – is confined to the India-Pakistan region (Fig. 5). This sub-signature arose over 13000 years ago and hence its introduction into India could not have been by migrants who introduced modern agriculture into India. The haplogroup J2b2 possibly arose in India, because the highest frequency of this haplogroup is found in India. We discovered multiple epicentres of this haplogroup in India and interestingly these epicentres nearly coincided with the seats of invention of early forms of agriculture in India (as evidenced by the study of fossilized pollen grains by palynologists).

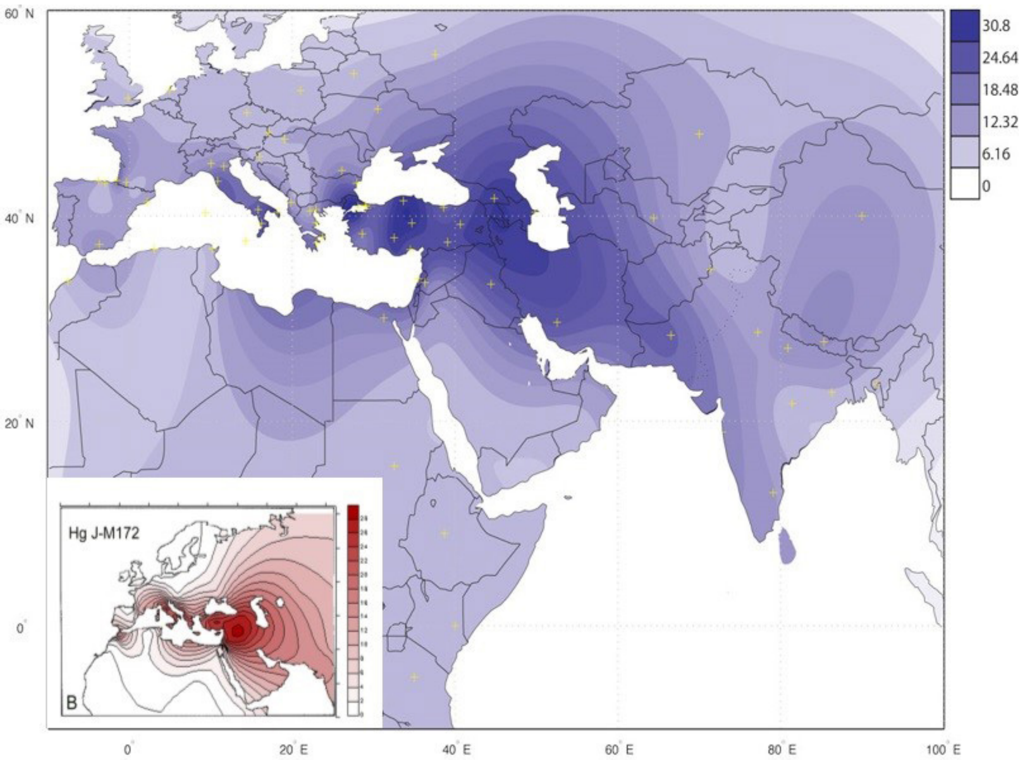


Fig. 4: The frequency of the male genetic signature, haplogroup J, is the highest (darkest in colour) in the Fertile Cresent region where modern farming was invented. The frequency of this signature declines with increase in distance from the Fertile Cresent region and is associated with the global spread of farming through human dispersal.

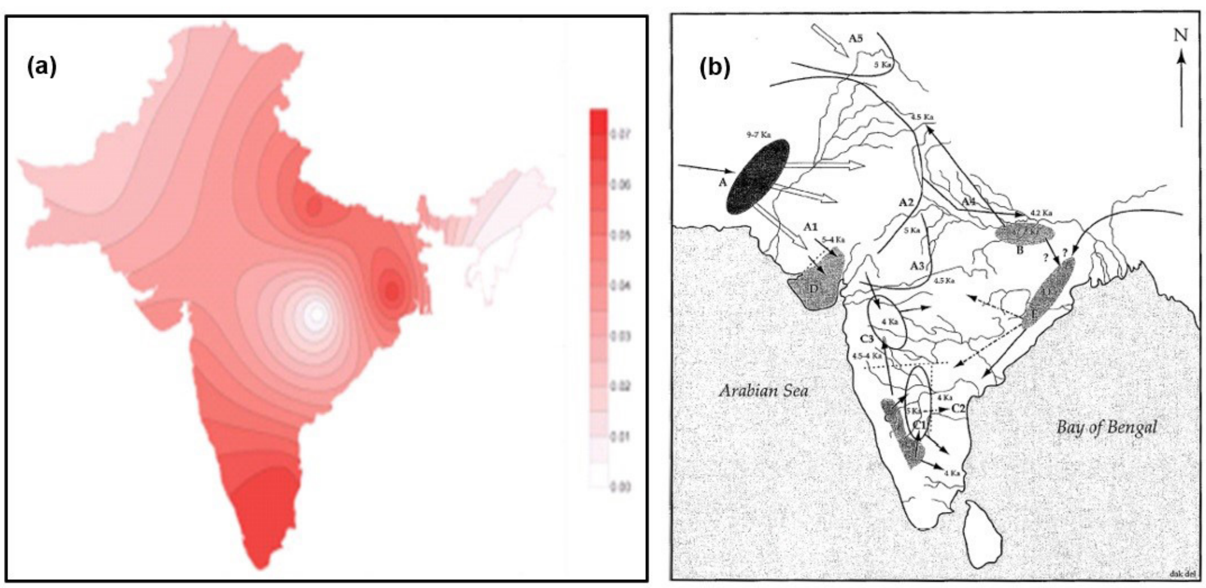


Fig. 5: The frequency of the male genetic signature, haplogroup J2b2, that arose before the invention of modern farming has (a) multiple epicentres within India that nearly coincide with (b) the locations where ancient agriculture was invented in India and spread locally, but not far and wide.

Rudimentary forms of agriculture may have been invented independently in multiple geographical regions within India. However, it is notable that these early forms of agriculture did not spread far and wide, and remained largely confined to India and Pakistan region.

Through our studies of ethnic groups of India and elsewhere, I have learnt that there is genomic unity in the midst of all the cultural and linguistic diversity that is ethnic India. The number of ancestral populations to which we can trace ourselves back is only four. We must celebrate our diversity keeping our unity in focus. We must join our voices with the African-American poet, Maya Angelou: *"It is time for the preachers, the rabbis, the priests and pundits, and the professors to believe in the awesome wonder of diversity so that they can teach those who follow them. It is time for parents to teach young people early on that in diversity there is beauty and there is strength. We all should know that diversity makes for a rich tapestry, and we must understand that all the threads of the tapestry are equal in value no matter their color; equal in importance no matter their texture."*

Remembering that all of us are rooted in Africa, we must also recognize that there is a *fundamental* genomic unity of all humankind, bolstering UNESCO's call to *"respect and promote the practice of solidarity towards individuals, families and population groups..."* [Article 17 of The Universal Declaration on the Human Genome and Human Rights (UNESCO, 2000)].

Partha P. Majumder is a National Science Chair, Govt. of India, Distinguished Professor & Founder, National Institute of Biomedical Genomics, Kalyani and Emeritus Professor Indian Statistical Institute, Kolkata.

This article has been adapted from the 238th Foundation Day lecture delivered by the author at the Asiatic Society, Kolkata.

BETWEEN THE SCIENCE

ANIRBAN BASAK ICTS faculty member, was awarded the INSA Medal for Young Scientists (Mathematics), 2021. The prestigious medal is awarded by the Indian National Science Academy (INSA) to young scientists in recognition of notable contributions to any branch of science and technology.

RIDDHIPRATIM BASU ICTS faculty member, was awarded the 2021 NASI Platinum Jubilee Young Scientist Award for his contributions to probability theory. Basu's interests are specifically in first and last passage percolation, interacting particle systems and models of self-organized criticality. BASU also received the SERB MATRICS grant.

SUBHRO BHATTACHARJEE ICTS faculty member, received the prestigious Swarnajayanti Fellowship of the Department of Science and Technology, Govt. of India, in the physical sciences category. BHATTACHARJEE was also awarded a VAJRA grant of SERB as co-PI with Tanusri Saha-Dasgupta of SN Bose National Centre for Basic Sciences, Kolkata. Their proposed work is titled 'Tuning Quantum Materials with Strain.' This grant will host Arun Paramekanti of the University of Toronto as the overseas VAJRA Faculty.

RAHUL CHAJWA Former ICTS graduate student, received the TAA-Geeta Udgaonkar Award (2021) for the best thesis in physical sciences within TIFR. Rahul's thesis, titled 'Driven Stokesian Suspensions: Particle Anisotropy, Effective Inertia and Transient Growth' is based on experimental and theoretical work done under the supervision of Profs. Rama Govindarajan (ICTS-TIFR), Narayanan Menon (University of Massachusetts, Amherst) and Sriram Ramaswamy (IISc).

MANAS KULKARNI ICTS faculty member, was featured in the book 75 Under 50: Scientists Shaping Today's India, published by the Department of Science and Technology, Govt of India. This coffee table book, highlighting 75 scientists below 50 years of

BETWEEN THE SCIENCE

age, was released on National Science Day, as part of the golden jubilee celebrations of DST. KULKARNI and ABHISHEK DHAR also received one of the exclusive VAJRA grant, for their proposed work titled 'Hydrodynamic Behaviour of Low-Dimensional Systems.' Herbert Spohn of Technische Universitat Munchen, Germany, will be the overseas VAJRA Faculty. This grant will enable international collaborations over a period of three years and will host Herbert Spohn at ICTS.

RAMA GOVINDARAJAN ICTS faculty member, was elected a Fellow of the Indian National Science Academy (INSA). Govindarajan has contributed over many different aspects of fluid mechanics, including instabilities in viscosity-stratified flows and the ubiquitous multiphase flows involving the dynamics of bubbles, drops and particles in fluid.

VIJAY KUMAR KRISHNAMURTHY ICTS faculty member, was part of a global cohort of interdisciplinary researchers who have been awarded a prestigious Templeton Foundation Grant to investigate new conceptual frameworks for understanding 'Agency, Directionality and Function' in living systems. Krishnamurthy and ICTS Senior Associate Vidyanand Nanjundiah are part of the project 'Cellular Agency in Multicellular Development and Cancer' led by Stuart Newman of New York Medical College.

ANUPAM KUNDU ICTS faculty member has received the SERB MATRICS grant. The SERB MATRICS grants are given by the Department of Science and Technology, Government of India, for research in theoretical sciences for a period of three years. KUNDU also received the SERB-Core Research Grant (SERB-CRG).

BIKRAM PAIN ICTS first year I-Phd student was awarded the gold medal by the Indian Association of Physics Teachers (IAPT) for his stellar performance in the National Graduate Physics Examination (NGPE-21). The NGPE was started in 1989 to encourage bright students to take up careers in physics. The exam is held across 270 centres.

BETWEEN THE SCIENCE

MYTHILY RAMASWAMY NASI Platinum Jubilee Senior Scientist, was awarded the prestigious P.C. Mahalanobis Medal of the Indian National Science Academy (INSA) in 2021. This medal is a lifetime achievement award given in recognition of her many contributions to mathematics. Ramaswamy received this medal jointly with Prof. Arup Bose of the Indian Statistical Institute, Kolkata.

SAMRIDDHI SANKAR RAY , ICTS faculty member postdoctoral fellow SIDDHARTHA MUKHERJEE and PhD student RAHUL K. SINGH'S work (in collaboration with Martin James), titled Anomalous Diffusion and Levy Walks Distinguish Active from Inertial Turbulence, was highlighted as Editors' Suggestion in Physical Review Letters. The work has also been featured in the APS Physics Magazine. RAY was also awarded the new prestigious SERB-Science and Technology Award for Research (SERB-STAR). The SERB-STAR is instituted by SERB to recognize and reward outstanding performance of Principal Investigators of SERB Projects. The award is given to young researchers for stellar performances in frontier areas of science and engineering. He also received the SERB-CRG.

ASHOKE SEN ICTS-Infosys Madhava Chair, was awarded the prestigious Atul Chandra Gupta Distinguished Alumnus Award of the Presidency University Alumni Association.

SHASHI THUTUPALLI ICTS Joint Faculty (with NCBS), was selected PI for one of four Infosys-TIFR 'Leading Edge' Grants across all TIFR centres. The team of co-PIs and collaborators includes Jimreeves David (postdoc at NCBS), Sandeep Krishna (NCBS) and Prasad Perlekar (TCIS-TIFR, Hyderabad). Thutupalli and his collaborators have proposed to bring together theory and experiment to elucidate the coupled roles of mechanics and chemistry in the growth dynamics of microbial populations on viscoelastic substrates. TTHUTUPALLI also became an Associate Editor for EPJ E: Soft Matter and Biological Physics.

CELEBRATING THE SCIENCE OF GIORGIO PARISI, PHYSICS NOBEL LAUREATE 2021: ROLE OF DISORDER AND FLUCTUATIONS IN COMPLEX SYSTEMS

SMARAJIT KARMAKAR

Giorgio Parisi is one of the pioneers in the field of statistical mechanics. He is also probably one of the most versatile living physicists who has worked in the areas, ranging from physics of sub-atomic particles to molecules, animal migratory behavior to climate science, computer sciences, etc. Giorgio made seminal contributions in all the fields with a high degree of originality. His contributions in these different areas had an overarching effect on the future development of science in general. This year, he has been awarded the most prestigious award, the Nobel Prize, for his “discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales” [1]. The prize underlines the importance of basic research in addressing the pressing problems of our time.

Giorgio was born on 4th August 1948 in Rome, Italy. He obtained his Bachelor’s and Master’s Degree from the University of Rome - La Sapienza, and then went on to do his doctoral studies in the same university under the supervision of Nicola Cabibbo, a pioneering high energy physicist, famously known for his work on the weak decays of strange particles, Cabibbo universality, and Cabibbo angle [2]. Giorgio finished his doctoral thesis in 1970 at the tender age of 22 years. He then worked in various institutes before becoming a full professor of Theoretical Physics at the University of Rome, Tor Vergata in 1981. He moved back to the University of Rome, La Sapienza in 1992 as a full professor of Quantum Theories, and continues to date at the same position. Since 2016, Giorgio Parisi has been a leading face in the movement of “Salviamo la Ricerca Italiana” which advocates the increase of funding in basic research in Italy. He also served as the president of the Accademia dei Lincei from 2018 until 2021.

The illustrious scientific career of Giorgio has been celebrated with many notable prizes and awards including, the Boltzmann Medal in 1992 and the Dirac Medal (ICTP) in 1999. Some of the other prestigious awards include the Enrico Fermi Prize (2002), the Nonino Prize “An Italian Master of our Time” (2005), Microsoft Award (2007), the Lagrange Prize (2009), Max Planck Medal (2011), the High Energy and Particle Physics Prize – EPS HEPP Prize (2015), the Lars Onsager Prize

(2016), the Wolf Prize (2021) [3]. These awards vividly acknowledge his versatility and deep original insights. He has seminal contributions, with a high degree of innovation, in several fields, such as spin glasses, scaling violations in deep inelastic processes, growing interface, turbulence, climate modelling, bird flocking, developing various simulation methods for enhanced sampling, etc. Despite these problems being very far from each other, one common theme of Giorgio’s research interest has been the emergence of complex collective behavior from simple elementary rules of interaction among the constituent particles.

This is a recurrent theme in physics and biology, and the Nobel Prize recognizes his profound contributions in this direction. I will briefly discuss some of them to give a flavor of the broadness of his research interest and his ingenuity in solving different complex problems.

Replica Theory of Spin Glasses

Parisi’s works on disorder systems, particularly the spin-glass problem and his famous replica symmetry breaking ansatz [4, 5] are probably one his most influential works. Spin glasses are magnetic systems with local static impurities (quenched disorder) together with disorder coming in terms of frustrations in the ferromagnetic and anti-ferromagnetic interactions between interacting spins in the crystal. These systems show a sudden freezing of the spin directions below a critical temperature (T_c) with no detectable long-range order in the spin orientation. This led to the discovery of a new type of phase transition in magnetic materials whose physics are very non-trivial to understand using the standard statistical mechanics frameworks and the famous Landau-Ginzberg theory of phase transition. As quenched disorder plays an essential role in these systems, a new method was devised (known as the replica trick) to compute the free energy of the system. It turns out that if one considers replica symmetric solutions for a model of spin glass (e.g. the well-known Sherington-Kirkpatrick model [6]), then one indeed observes an emergence of spin-glass phase with non-zero value of the Edward-Anderson order parameter [7] below T_c, and zero above. But one of the major problems of this solution is that the entropy of the spin-glass phase becomes negative at lower temperatures, and the whole spin-glass phase becomes unstable [8]. This is when Parisi’s work [9] came to the rescue and solved the abovementioned issues. He proposed breaking the replica symmetry and considering the spin-glass phase to be a replica symmetry broken state, signalling a major change in the physics concept. He then offered how to correctly perform the replica symmetry breaking calculations leading to the correct

free energy of the system. Later this was shown mathematically to be the exact procedure for the SK spin-glass model [10]. Thus replica symmetry breaking ansatz of Parisi is an important method to obtain the essential physics of various spin-glass model systems.

However, a rigorous proof for general model systems is still lacking. It is important to mention that there are many competing theories for the spin-glass transition – the most famous being the Droplet theory [11]. This theory suggests that the spin-glass phase is a unique ground state of the problem in short-range models, and the phase completely disappears even under a small magnetic field. Some of these controversies remain unresolved to date, although there are big computational efforts to resolve them in the near future, the most talked-about one being the Janus project [12].

The spin-glass theories have immense impacts on the understanding of structural glasses. The disorder in the latter is self-generated, thus annealed (changes with time) and not quenched. Yet, the dynamics in structural glasses have remarkable similarities with that of a specific spin-glass model, the p-spin spherical spin-glass model, for which 1RSB solution seems to be exact [13]. Subsequent calculations for the dynamics of the p-spin model lead to the well-known Mode Coupling Theory (MCT) for structural glasses, developed by Götze and others [14, 15]. One of us (SK) and Giorgio performed the replica calculations on a model structural glass with quenched-disorder in the form of random pinning [16] and showed that the theory of p-spin spin-glass indeed has a quantitative similarity with structural glasses.

Stochastic Resonance in Climate modelling

Next, I want to briefly discuss yet another seminal work of Parisi that has surely played an important role in climate modelling, for which Syukuro Manabe and Klaus Hasslemann got the other half of the Nobel Prize. This suggests that Parisi's work indeed encompasses a broad spectrum of complex systems. The title of the work is "Stochastic resonance in climate change [17]." The main achievement of this work is that this work, for the first time, predicted a plausible answer for the observed periodicity in the mean temperature of earth with a periodicity of 105 years as concluded from the time series of continental ice volume variation over last 106 years that shows that glaciation sequence has a periodicity of about 105 on average. Now the question is, what is this astronomically long timescale? The answer turns out to be the modulation period of the earth's orbital eccentricity primarily caused by the planetary gravitational perturbations.

This modulation of earth's orbital eccentricity results in variations of total solar energy flux that incident on earth at about 0.1%. Then the question is whether enhancement of climate sensitivity to such a small external periodic perturbation is possible or not? Parisi and collaborators were able to show that a stochastic process coupled to a small periodic perturbation can lead to resonance-like phenomena where the system flips back and forth between two stable states under the stochastic noise with the same periodicity of the small external periodic perturbation. The phenomenon later turned out to be ubiquitous in nature and plays an important role in various complex systems, including many biological processes.

Multifractality in Fully Developed Turbulence

Turbulence refers to the fluid flow with chaotic changes in pressure and velocity. When inertia is large compared to viscous forces, the small-scale fluctuations become increasingly significant and lead to very complex chaotic behavior in the fluid flow, known as the fully developed turbulence. This is a classic example of complex systems and has implications for modeling atmospheric and climate properties. Kolmogorov's theory, proposed in 1941 (hereafter K41) [18], predicted universal scaling properties for the small-scale turbulent flows. The bases of the K41 theory are two crucial assumptions: the system is locally isotropic and homogeneous. Frisch, Sulem, and Nelkin [19] showed that these properties imply a detailed balance of energy transfer. That is, input and output energies balance at every length scale. Deviations from the K41 theory were observed and commonly attributed to intermittency that was first pointed out by Landau [20]. Intermittency implies that the small-scale structure becomes irregular and distinct from the large scale. In the eighties, Parisi and collaborators proposed that if one relaxes the constraint of the detailed balance of energy transfer, allowing for intermittency, one must have a hierarchy of systems with different scaling properties [21].

This is the celebrated multifractal description of fully developed turbulence: it assumes a continuous spectrum of scaling exponents, each belonging to a specific set. The energy transfer, of course, must be constrained, not via the detailed balance but on average. The theory makes precise predictions. Comparing with experiments, the authors showed that "multifractal sets are indeed necessary to describe the properties of" turbulent flows [21]. The application of multifractality has been an elegant, remarkable, and novel theoretical description, applied in many branches of statistical physics and complex and disordered systems.

Kardar-Parisi-Zhang (KPZ) Equation for a Growing Interface

This article will not be complete if the famous Kardar-Parisi-Zhang (KPZ) equation for the growth of an interface is not discussed, at least briefly. The growth dynamics of a rough interface has great practical importance. It appears in the biological growth process of bacteria and cancerous cells [22], the fire propagation in a forest, solid-state surfaces, oil recovery through porous media, erosion of Earth's surface [23], passive scalars in fluctuating medium [24], gene segregation during bacterial growth [25], etc. The problem is also of great theoretical importance, as it involves a multitude of statistical physics concepts. In a ground-breaking work in 1986, Kardar-Parisi-Zhang (KPZ) proposed a model "for the evolution of the profile of a growing interface" [26]. KPZ theory provides a description of the height of a growing interface as functions of space-time. This work paved the way for a new direction in nonequilibrium statistical physics. Many of the kinetic roughening phenomena and random growth processes can be mapped into the KPZ universality class in the Renormalization Group sense [23]. Universality classes in physics play a crucial role. Roughly speaking, if two problems belong to the same universality class, the results of one problem applies to the other. Thus, the KPZ universality class allows analysis of these diverse physical problems within a unified framework leading to deeper insights.

Interactions in Active Matter

Active matter, where the constituent particles consume energy and perform some work, is a field of nonequilibrium physics of great current interest due to their applications in biology. Many biologically crucial processes, such as wound healing, cancer progression, collective cellular dynamics in epithelia, etc. can be conveniently modelled via active matter. Moreover, the large-scale migratory behavior of various animals such as bird flocks, fish schools, mammal herds, and synthetic systems, like a system of vertically vibrated rods, are naturally represented as active matter. In addition, these behaviors are also important in very different fields of science like control theory, economics, and social sciences. Starting from the seminal work of Vicsek and colleagues in 1995 [27], this field has risen to great prominence. Giorgio has influential contributions in this field, specifically in understanding the nature of interactions in flocking behavior. Flocking refers to the coherent, ordered motion of many creatures in a single direction [28]. The transition from a disordered to a flocking state can happen even in two spatial dimensions (2D). Note that in equilibrium systems with shortranged interactions spontaneous order cannot appear in 2D due to fluctuations, but active matter is a nonequilibrium system. However, it points towards a novel phenomenon in these systems. Theoretical and numerical works showed that collective behavior arises from simple local rules of interaction; for example, the direction of a particle's movement depends on the average direction of its neighbours. However, the details of such interactions were not clear, and experimental tests of different theoretical hypotheses were lacking. Parisi's fieldwork with colleagues on the collective behavior of a flock of starlings near the Termini station in Rome between December 2005 and February 2006 [29] showed that the interactions in a flock do not depend on the distance between different birds. In fact, "*each bird interacts on average with a fixed number of neighbors (six to seven)*." Via simulations, they showed that a flock breaks more easily when the interaction among the particles depends on their physical distance against their topological distance (i.e., whether or not neighbors). Analysis of their field data showed that bird flocks, in fact, follow the latter rule, which they argued should be advantageous in scenarios

when they are in search of food or under attack by, say, a falcon. They further showed that velocity correlations in a flock are scale-free [30], that is, the range of the interaction scales with the size. This long-range velocity correlation has also been found in other systems and is a defining property of active systems.

Parallel Tempering (Replica exchange) and Swap Monte Carlo Methods

We finally highlight another central contribution of Parisi in understanding the physics of deeply supercooled liquids by proposing extremely efficient Monte Carlo techniques to accelerate the equilibration in these systems. The relaxation time, τ increases extremely rapidly (by 10 – 14 orders of magnitude) as the system approaches glass transition temperature, T_g. The precise mechanism of glass transition continues to be debated. Simulations have provided crucial insights into the problem. However, as τ becomes very large, close to T_g, it becomes hard to equilibrate systems in simulations. Therefore, an efficient simulation method to accelerate the equilibration process is imperative to gain crucial insights into the mechanism behind the rapid dynamical slowing down. Parisi and Marinari [31] developed such a process known as the parallel tempering on replica exchange method. Briefly, the basic idea is as follows. A system at a high temperature, T_1, will equilibrate fast by exploring a large number of microstates. Now, there is a finite probability that the system will have same equilibrium configuration at different temperature, T_2. This probability will be larger if T_1 if T_2 is very close to T_1. Thus if the system exchanges configurations between these two different equilibrium states maintaining detailed balance conditions then it is possible that the system will be able to explore different parts of the phase space in more efficient manner leading to faster equilibration even at temperature T_2. This is the essence of the replica-exchange method, where one starts with a large number of systems (replicas) at slightly varying T such that their P(E) have substantial overlap and exchange the configurations among themselves following certain rules. This leads to substantially quick equilibration at lower T. Beyond glasses, the method is also useful in simulations of many complex systems, including biomolecular simulations of protein in various liquid mediums. Another simulation technique for faster equilibration, known as the "swap Monte Carlo" method, was proposed by Grigera and Parisi. Complex systems often get stuck in their local minima in the rugged energy landscape. The equilibration process can immensely speed up if one tries to swap two different types (sizes) of particles in the system following some rules. The initial paper contained some results showing faster equilibration in a model binary glass-forming liquids, but the system quickly crystallizes within the simulation time. The acceptance rate of swap moves was very low for other binary models, and the method did not show much improvement. Thus, it did not get much attention in the initial years. When I was working with Giorgio in Rome, he suggested to me that the method could be much faster for ternary (consisting of three different types/sizes of particles) or polydisperse models (with a continuous size distribution). This is because the size ratio between two distinct particles is small. Such models do not readily crystallize either. I could not implement this idea immediately as I moved to India to join TIFR Hyderabad as an assistant professor. Next year, when I was visiting Weizmann Institute of Science (WIS) in Israel for a joint TIFR-WIS meeting, I discussed this idea with Itamar Procaccia, and then jointly performed the first swap Monte Carlo simulation on a ternary system.

Surprisingly, as predicted by Giorgio, the swap moves lead to an impressive speed-up of dynamics, and the system could be equilibrated at a T, which could have taken nearly 105 days for current-day computers. This impressive speed-up helped to study the very low-temperature phase of glassy systems, including the investigation of the growth of static many-body correlation length, which may be one of the primary players in the rapid growth of τ in supercooled liquids [32]. Subsequently, Berthier *et al* took this up for polydisperse systems and tuned the model parameters, and further optimized the swap Monte Carlo method. The recent works on polydisperse models claim to have achieved a speed-up of nearly 1010 in three dimensional (3D) systems, exceeding all the expectations.

This method has allowed some of the fascinating studies in the field of glassy dynamics leading to many crucial results, such as the lack of finite T glass transition in 2D [33], ductile to brittle yielding transition in glassy systems [34]. These results provide further insights into the glassy systems.

Giorgio Parisi - Beyond Science

Finally, I want to end this article by sharing some of my personal interactions with him as my postdoctoral mentor. Giorgio is an inspiration to many young and not-so-young scientists worldwide. Giorgio is probably one of the smartest (scientifically) persons I have ever interacted with till now.

Just to highlight one occasion, when Prof. G Szamel from Colorado university was visiting Giorgio, we had a joint discussion. Then Giorgio wrote down a differential equation that both Szamel and I had not seen before, and he then explained the origin of this equation. Near the end of the discussion, Giorgio thought for some time and suddenly wrote down the possible form of the solution of this complicated differential equation. We then worked through the night to see whether the proposed solution of Giorgio satisfies the differential equation. We were amazed that it did. The next day, Prof. Szamel said that either Giorgio is a genius or knew the solution be-forehand. My take will be that he is a genius; otherwise, it will be difficult to explain how he managed to finish his doctoral thesis with Prof. Nicola Cabibbo at an early age of 22 years. In spite of being one of the living legends in theoretical physics, Giorgio is a simple, down-to-earth person with a delightful and affectionate personality.

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PROGRAMS

Future Flavours: Prospects for Beauty, Charm and Tau
17-28 January 2022 ✦ *Organizers* — B. Ananthanarayan, Thomas Browder, Amol Dighe, Jim Libby, Namit Mahajan, Gagan Mohanty, Soumitra Nandi, Nita Sinha, Sanjay Kumar Swain, Guy Wilkinson

Classical and Quantum Transport Processes: Current State and Future Directions
17-28 January 2022 ✦ *Organizers* — Alberto Imparato, Anupam Kundu, Carlos Mejia-Monasterio, Lamberto Rondoni

Fifth Bangalore School on Population Genetics and Evolution
17-28 January 2022 ✦ *Organizers* — Deepa Agashe and Kavita Jain

Kavli Asian Winter School (KAWS) on Strings, Particles and Cosmology
10-23 January 2022 ✦ *Organizers* — Francesco Benini, Bartek Czech, Dongmin Gang, Sungjay Lee, Cheng Peng, Pavel Putrov, Loganayagam R, Aninda Sinha, Tadashi Takayanagi, Masahito Yamazaki

Physics of the Early Universe (Hybrid)
3-12 January 2022 ✦ *Organizers* — Robert Brandenberger, Jerome Martin, Subodh Patil, L. Sriramkumar

ICTP-ICTS Winter School on Quantitative Systems Biology
6-17 December 2021 ✦ *Organizers* — Vijaykumar Krishnamurthy, Venkatesh N. Murthy (Harvard University, Sharad Ramanathan, Sanjay Sane, and Vatsala Thirumalai

DISCUSSION MEETINGS

Waves, Instabilities and Mixing in Rotating and Stratified Flows
4-8 April 2022 ✦ *Organizer* — Thierry Dauxois, Sylvain Joubaud, Manikandan Mathur, Philippe Odier, Anubhab Roy

APS Satellite Meeting at ICTS (Hybrid)
15-18 March 2022 ✦ *Organizers* — Ranjini Bandyopadhyay, Subhro Bhattacharjee, Arindam Ghosh, Shobhana Narasimhan, Sumantra Sarkar

Complex Lagrangian Problems of Particles in Flows
14-18 March 2022 ✦ *Organizers* — Massimo Cencini, Kristian Gustafsson, Filippo De Lillo, Samriddhi Sankar Ray

Workshop on Climate Studies (Hybrid)
1-3 March 2022 ✦ *Organizers* — Rama Govindarajan, Sandeep Juneja, Ramalingam Saravanan, Sandip Trivedi

Statistical Physics: Recent Advances and Future directions
14-15 February 2022 ✦ *Organizers* — Rajesh Gopakumar and Spenta R. Wadia

Neuroscience, Data Science and Dynamics
7-10 February 2022 ✦ *Organizers* — Amit Apte, Neelima Gupte, Ramakrishna Ramaswamy

Celebrating the Science of Giorgio Parisi
15-17 December 2021 ✦ *Organizers* — Chandan Dasgupta, Abhishek Dhar, Smarajit Karmakar and Samriddhi Sankar Ray

Hunting SUSY @ HL-LHC
22-26 November 2021 ✦ *Organizers* — Satyaki Bhattacharya, Rohini Godbole, Kajari Majumdar, Prolay Mal, Seema Sharma, Ritesh K. Singh and Sanjay Kumar Swain

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Topological Aspects of Strong Correlations and Gauge Theories
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Hydrodynamics and Fluctuations - Microscopic Approaches in Condensed Matter Systems
6-10 September 2021 ✦ *Organizers* — Abhishek Dhar, Keiji Saito and Tomohiro Sasamoto

LECTURE SERIES

TMC DISTINGUISHED LECTURES

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Video release: 30 March 2022; Interactive session: 20 April 2022 ✦ *Speaker* — Melanie Matchett Wood *(Harvard University)*

INFOSYS-ICTS TURING LECTURES

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1-3 March 2022 ✦ *Speaker* — J. Srinivasan *(Divecha Centre for Climate Change, Indian Institute of Science, Bengaluru)*

FOUNDATION DAY LECTURES

The Future of Our Universe
27 December 2021 ✦ *Speaker* — Ashoke Sen *(ICTS-TIFR, Bengaluru)*

DISTINGUISHED LECTURES

Putting Order into Disorder: An Application to the Chronology of my Work
16 December 2021 ✦ *Speaker* — Giorgio Parisi *(Sapienza University, Rome, Italy)*

A Scientific Summary of the 2021 Nobel Prize in Physics
2 November 2021 ✦ *Speaker* — John Wettlaufer *(Yale University, USA & Nordic Institute for Theoretical Physics, Sweden)*

OUTREACH

KAAPI WITH KURIOSITY

The lecture series has been temporarily renamed Kuriosity During Kuarantine. All the lectures are being livestreamed on the ICTS YouTube channel, unless otherwise mentioned.

Perspectives in Math and Art
24 April 2022 ✦ *Speaker* — Supurna Sinha *(Raman Research Institute, Bengaluru)* ✦ *Venue* — J. N. Planetarium, Bangalore

Tilings
27 March 2022 ✦ *Speaker* — Mahuya Datta *(Indian Statistical Institute, Kolkata)*

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28 February 2022 ✦ *Speaker* — Varun Bhalerao *(IIT Bombay)*

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9 January 2022 ✦ Speaker — R Shankar *(The Institute of Mathematical Sciences, Chennai)*

To Paint the Lily, Mathematically
12 December 2021 ✦ *Speaker* — L. Mahadevan *(De Valpine Professor of Applied Mathematics, Professor of Organismic and Evolutionary Biology, Professor of Physics, Harvard University)*

Autism and "Astro"logy: New Insights From Recordings in Human Brain Cells
7 November 2021 ✦ *Speaker* — Sumantra Chattarji *(Senior Professor, NCBS-TIFR, Bengaluru & Visiting Professor, Simons Initiative for the Developing Brain, University of Edinburgh, UK)*

Science of the Indian Kitchen
17 October 2021 ✦ Speaker — Krish Ashok *(Author of 'Masala Lab')*

The Art and Science of Secret Messages: Some Glimpses
19 September 2021 ✦ *Speaker* — Geetha Venkataraman *(Dr. B. R. Ambedkar University Delhi, Delhi)*

VIGYAN ADDA

The Finite Part of Infinity

24 October 2021 ✦ *Speaker* — Joseph Samuel *(RRI & ICTS-TIFR, Bengaluru)*

Steven Weinberg: The Physicist and his Physics

2 September 2021 ✦ *Speaker* — Rohini M. Godbole *(Indian Institute of Science, Bengaluru)*

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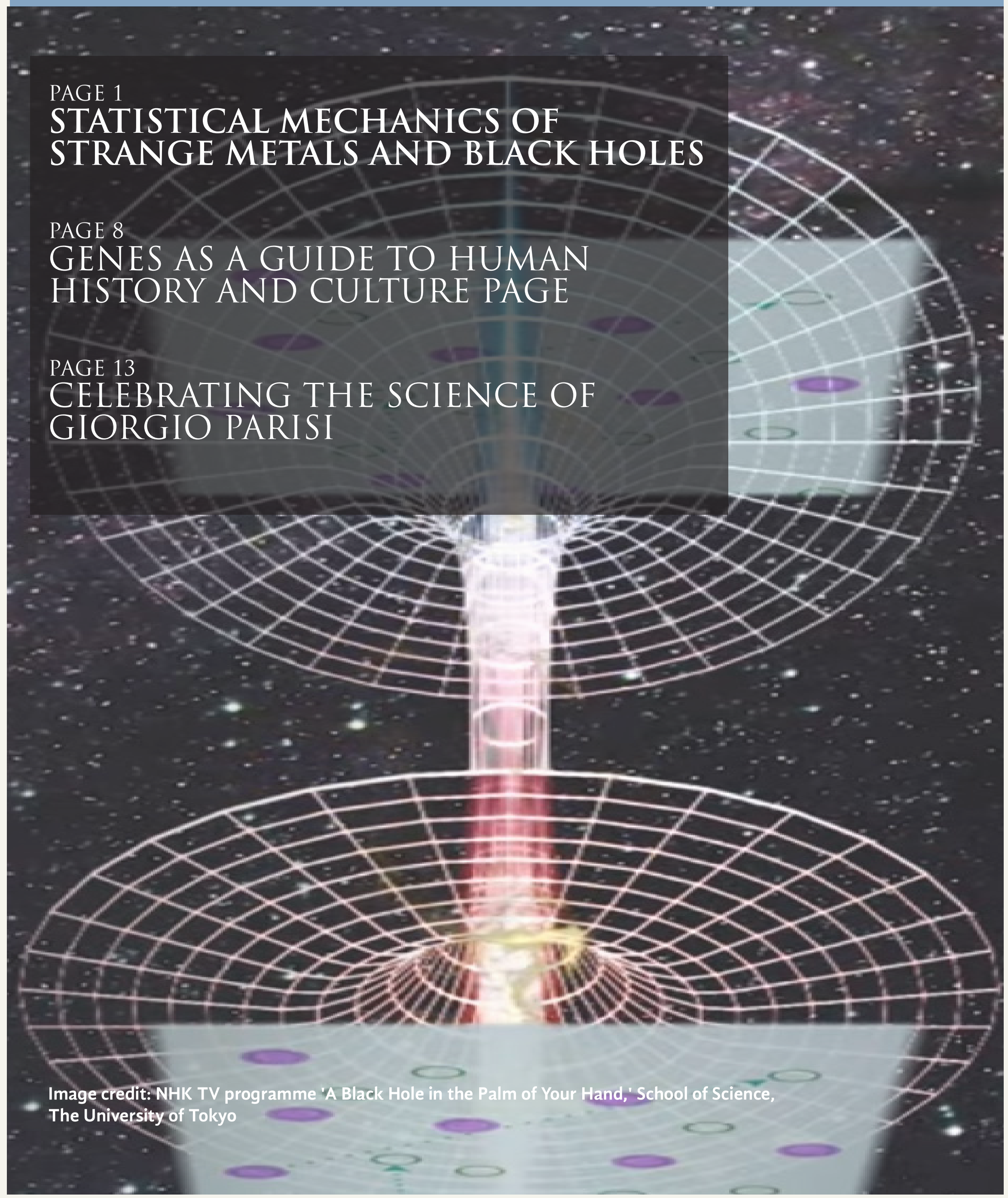
TATA INSTITUTE OF FUNDAMENTAL RESEARCH

PAGE 1
STATISTICAL MECHANICS OF STRANGE METALS AND BLACK HOLES

PAGE 8
GENES AS A GUIDE TO HUMAN HISTORY AND CULTURE PAGE

PAGE 13
CELEBRATING THE SCIENCE OF GIORGIO PARISI



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