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"VORTICES IN QUANTUM FLUIDS: A NEW SPIN ON PHYSICS"

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ABSTRACT

Astrophysical systems such as neutron stars represent some of the most extreme environments in the universe, yet their vast distances typically hundreds of light-years away make direct exploration impossible. Our understanding of these dense stellar remnants is therefore limited to indirect observations, including the radiation they emit and the gravitational effects they imprint on nearby celestial bodies. Developing methods to simulate neutron-star physics in controlled laboratory settings would revolutionize our ability to probe their internal structure and dynamics. A similar challenge arises in condensed-matter physics, where strongly correlated electron phenomena such as the integer and fractional quantum Hall effects give rise to entirely new states of matter under extreme magnetic fields and ultralow temperatures. Although these conditions can be engineered on Earth using two-dimensional heterostructures and quantum wells, current experimental tools cannot track the microscopic motion of individual electrons within these complex systems. Advancing our ability to emulate and resolve such strongly correlated behavior would therefore mark a major breakthrough in uncovering the fundamental mechanisms that govern both astrophysical and quantum-material phenomena.

KEYWORDS: Neutron stars, Quantum fluids, strongly correlated systems, Quantum Hall effect, Vortex dynamics, and Extreme environments.

INTRODUCTION

Many of the universe's most extraordinary physical phenomena occur under conditions that are far beyond our ability to access directly. Neutron stars, for example, host extreme densities, intense magnetic fields, and rapidly rotating superfluids, yet the nearest one lies about 400 light years away. As a result, their internal dynamics can only be inferred indirectly through emitted radiation and gravitational effects, leaving many key questions unresolved.

Similar challenges arise in condensed-matter physics, where strongly correlated electron systems such as those exhibiting the integer and fractional quantum Hall effects—form new collective states of matter under ultralow temperatures and strong magnetic fields. Although these systems can be realized in the laboratory, our current tools cannot track the microscopic behavior of individual electrons with sufficient precision. These limitations in both astrophysics and quantum materials have motivated the development of quantum simulators and laboratory-based analogues capable of recreating aspects of such extreme environments. By emulating the relevant physics on Earth, these platforms offer a promising path toward uncovering the fundamental mechanisms governing complex, strongly correlated, and otherwise inaccessible systems.

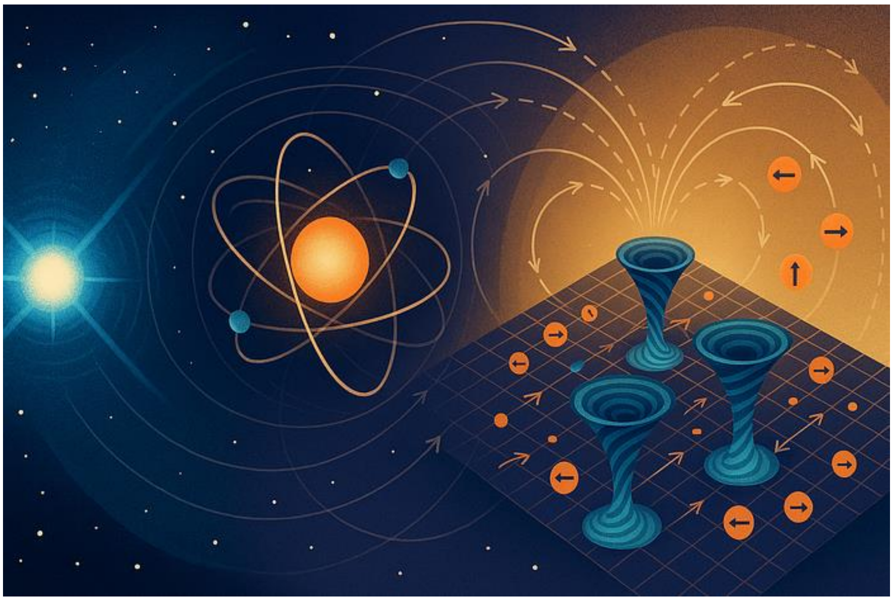

Fig.1 spinning neutron stars and rotating ultracold dipoles

The illustration depicts a conceptual bridge between **atomic-scale physics** and **large-scale space-time or field dynamics**.

- **Left Side (Quantum/Atomic World):**

You can see a stylized atom with a bright nucleus at the center and electrons orbiting around it. Waves radiate outward into space, suggesting quantum fields, radiation, or fundamental forces.

- **Right Side (Spacetime / Field Theory):**

The grid represents a spacetime or field landscape. Three blue funnel-like structures rise upward, resembling vortices**,** wormholes**, or** topological defects.

Orange particles and arrows show the movement or flow of field lines, illustrating how these structures influence surrounding fields.

- **Middle Transition:**

The curved white and orange arrows connect the atomic region to the field/vortex region, symbolizing how microscopic physics (like quantum behavior) may connect to macroscopic phenomena (like spacetime geometry, vortices, or quantum fluids).

1.1 Neutron stars

A neutron star is the ultra-dense remnant left behind after a massive star (typically 8–20 times the mass of the Sun) explodes in a supernova. When the core collapses, protons and electrons merge into neutrons, packing matter so tightly that a teaspoon of neutron-star material would weigh billions of tons.

Despite containing more mass than the Sun, a neutron star is only about 20 km wide. Its gravity is enormous, its magnetic fields can be trillions of times stronger than Earth's, and it rotates incredibly fast some spin hundreds of times per second.

Neutron stars emit powerful beams of radiation. If these beams sweep across Earth, we detect them as pulsars. They are laboratories of extreme physics, helping us study dense matter, quantum fluids, superconductivity, and strong gravitational fields that cannot be recreated on Earth.

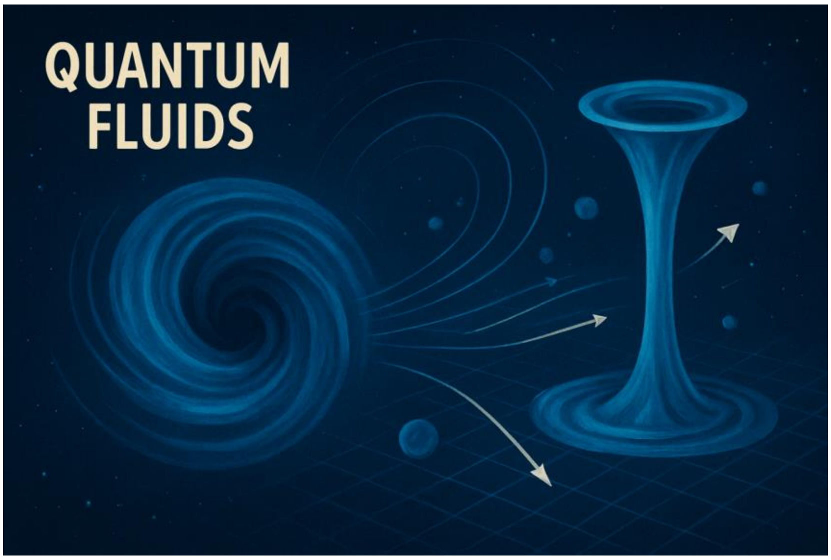

Fig.2 spinning neutron stars and rotating ultra cold dipoles

1.2 Quantum fluids

Quantum fluids behave like matter that has decided to follow the rules of a dream rather than everyday physics. They are real, measurable systems, but they move and flow in ways that look almost magical because they obey quantum mechanics on a macroscopic scale**.**

A quantum fluid like superfluid helium**,** ultracold atomic gases**,** or the interior of a neutron **star** can do things that ordinary fluids never attempt. A superfluid can climb walls, flow without friction, and form perfectly quantized vortices: tiny whirlpools whose rotation is locked to the rules of quantum mechanics. In neutron stars, these vortices live inside a nuclear soup so dense that a single cubic centimeter outweighs a mountain.

The strange charm of quantum fluids is that they reveal how collective behavior emerges from individual particles. The fluid becomes a single, coordinated quantum object, a bit like a marching band of atoms all stepping perfectly in phase. This makes them wonderful playgrounds for studying phenomena such as superconductivity, entanglement, and the microscopic origins of turbulence.

1.3 Strongly correlated systems

Strongly correlated systems are materials in which particles usually electrons—interact with each other so strongly that their behaviour cannot be explained by treating each electron independently. Instead, the entire system must be considered as a collective, because one particle's motion strongly depends on all the others.

These strong interactions lead to unusual and emergent phenomena, such as:

- Mott insulators (materials that should conduct electricity but don't)
- High-temperature superconductors
- Quantum spin liquids
- Heavy-fermion materials
- Fractional quantum Hall states

1.4 Quantum Hall Effect (QHE)

The Quantum Hall Effect is a phenomenon that occurs when electrons move in a very thin (2D) material under low temperatures and strong magnetic fields. Under these conditions, the electrical resistance across the material becomes quantized—it takes on precise, universal values.

Hall resistance becomes quantized: $R_H = \frac{h}{e^2 n}$

Where n is an integer and h/e^2 is a fundamental constant. This is called the Integer Quantum Hall Effect.

1. Plateaus:

As the magnetic field increases, the Hall resistance shows flat plateaus at these quantized values instead of changing smoothly.

2. Landau **levels:**

The magnetic field forces electrons into discrete energy levels called Landau levels, causing the quantization.

Fractional Quantum Hall Effect (FQHE)

Discovered later, this is even more exotic:

$R_H = \frac{h}{e^2 \ p/q}$

with fractional values (e.g., 1/3, 2/5).

This happens because electrons strongly interact and form new collective states with fractionally charged quasiparticles.

1.5 **Vortex Dynamics**

Vortex dynamics refers to the study of how vortices regions where a fluid circulates around a central core form, move, interact, and decay. Vortices appear in both classical fluids (like air and water) and quantum fluids (like super fluid helium and Bose Einstein condensates), but their behaviour is very different.

In Classical Fluids

- Vortices can have any size and speed.
- Their motion is governed by the Navier–Stokes equations, viscosity, turbulence, and instabilities.
- They can stretch, merge, reconnect, and dissipate energy.

In Quantum Fluids

Quantum fluids have special properties such as super fluidity, leading to unique vortex behavior:

1. Quantized Circulation

Vortices have a fixed amount of circulation:

$\Gamma=hm$

This means vortex strength comes in discrete units not continuous.

2. Vortex Cores are Tiny

The core size is on the order of nanometres (in helium) or micrometers (in BECs).

3. Vortex Lattices

When rotated, quantum fluids arrange vortices into a beautiful triangular lattice.

4. Vortex Reconnections

When two vortices collide, they "snap" and reconnect important in understanding quantum turbulence.

5. Collective Dynamics

Because quantum fluids are highly coherent, vortex motion reveals information about:

- super fluid density
- excitations
- interactions in strongly correlated systems

1.6 Extreme Environments

In physics, **extreme environments** are conditions far beyond what we experience on Earth. These include **very** high pressures, temperatures, densities, magnetic fields, or gravitational forces. Studying matter in such regimes helps us understand how physical laws behave when pushed to their limits.

Examples of Extreme Environments

1. Neutron Stars

- Density equivalent to packing the mass of the Sun into a city-sized sphere.
- Contain superfluid neutrons, superconducting protons, and quantized vortices.
- Magnetic fields trillions of times stronger than Earth's.

2. Early Universe Conditions

- Temperatures greater than 10^{10} K.
- Quark–gluon plasma, where quarks and gluons move freely.

3. High-Pressure Physics

- Conditions inside giant planets like Jupiter, where hydrogen becomes metallic.
- Laboratory experiments using diamond-anvil cells and high-intensity lasers.

4. Ultracold Quantum Gases

- Temperatures near absolute zero (10^{-9} K).
- Quantum fluids and Bose–Einstein condensates show quantized vortices and superfluidity.

5. Strongly Correlated Materials

- Materials with immense electron–electron interaction.
- Display exotic phases like Mott insulators, quantum spin liquids, and unconventional superconductors.

CONCLUSION

Astrophysical objects like neutron stars and strongly correlated quantum systems share a common challenge: their extreme conditions are largely inaccessible to direct observation. Despite this, both fields have revealed that under such extremes, matter exhibits novel and often unexpected behaviours ranging from quantized vortices in rapidly rotating super fluids to the emergence of exotic collective states in two-dimensional electron systems. Advances in experimental techniques, particularly the development of quantum simulators and laboratory analogues, offer a promising avenue to probe these otherwise unreachable phenomena. By bridging the gap between theory and experiment, these platforms not only enhance our understanding of fundamental physics but also provide insights that may unify concepts across astrophysics, condensed-matter physics, and quantum technology. Ultimately, the study of extreme environments continues to illuminate the rich complexity of the universe, demonstrating how collective interactions shape matter in ways that challenge our conventional understanding.

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