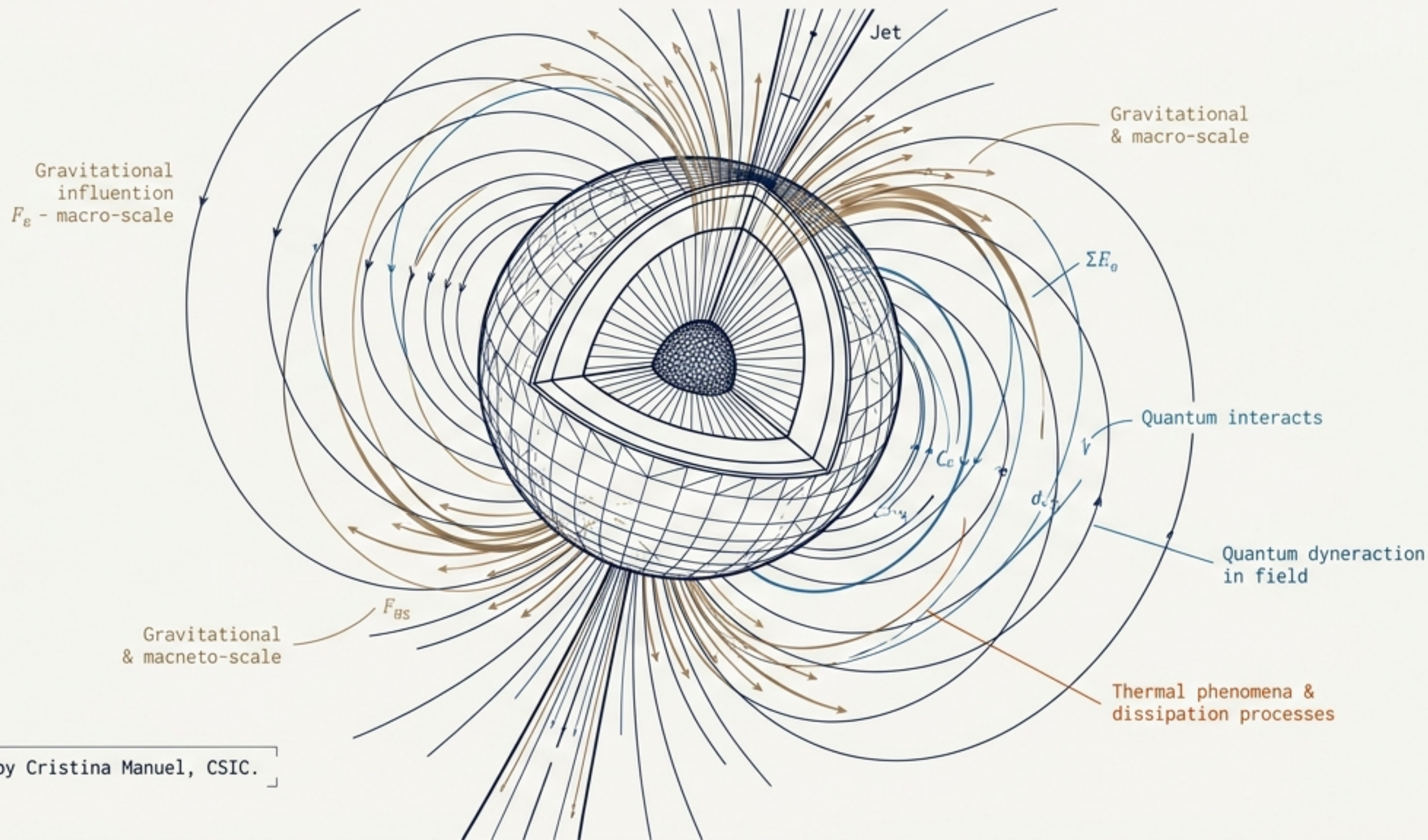


Transport Phenomena in Neutron Stars

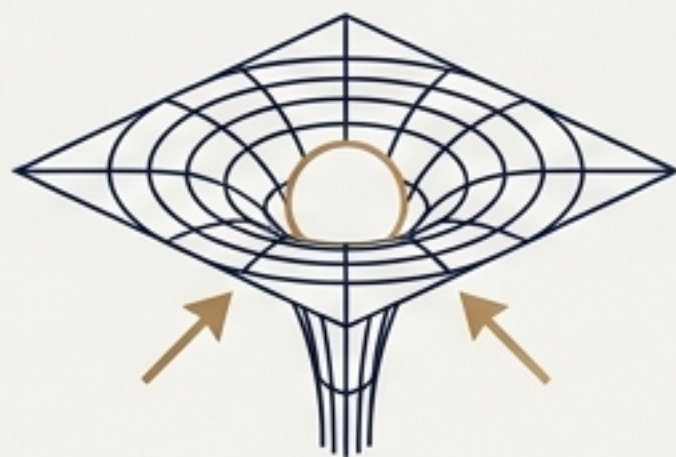
Bridging Microscopic Quantum Physics with Macroscopic Astrophysical Observables.



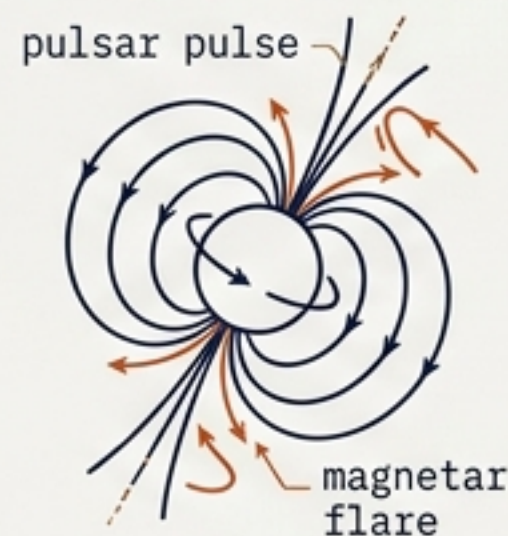
Based on research by Cristina Manuel, CSIC.

Gravity

Holds the star together.
Extreme spacetime curvature.



Electromagnetism



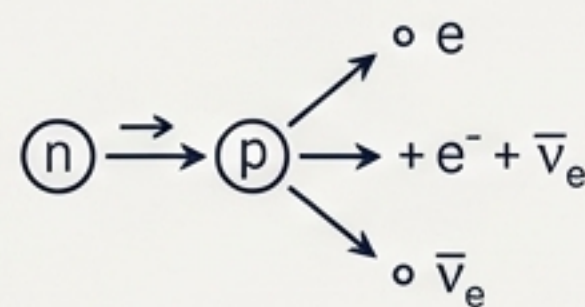
Makes pulsars pulse and magnetars flare.

Strong Interactions

Determines the internal composition (QCD matter).



Electroweak Interactions

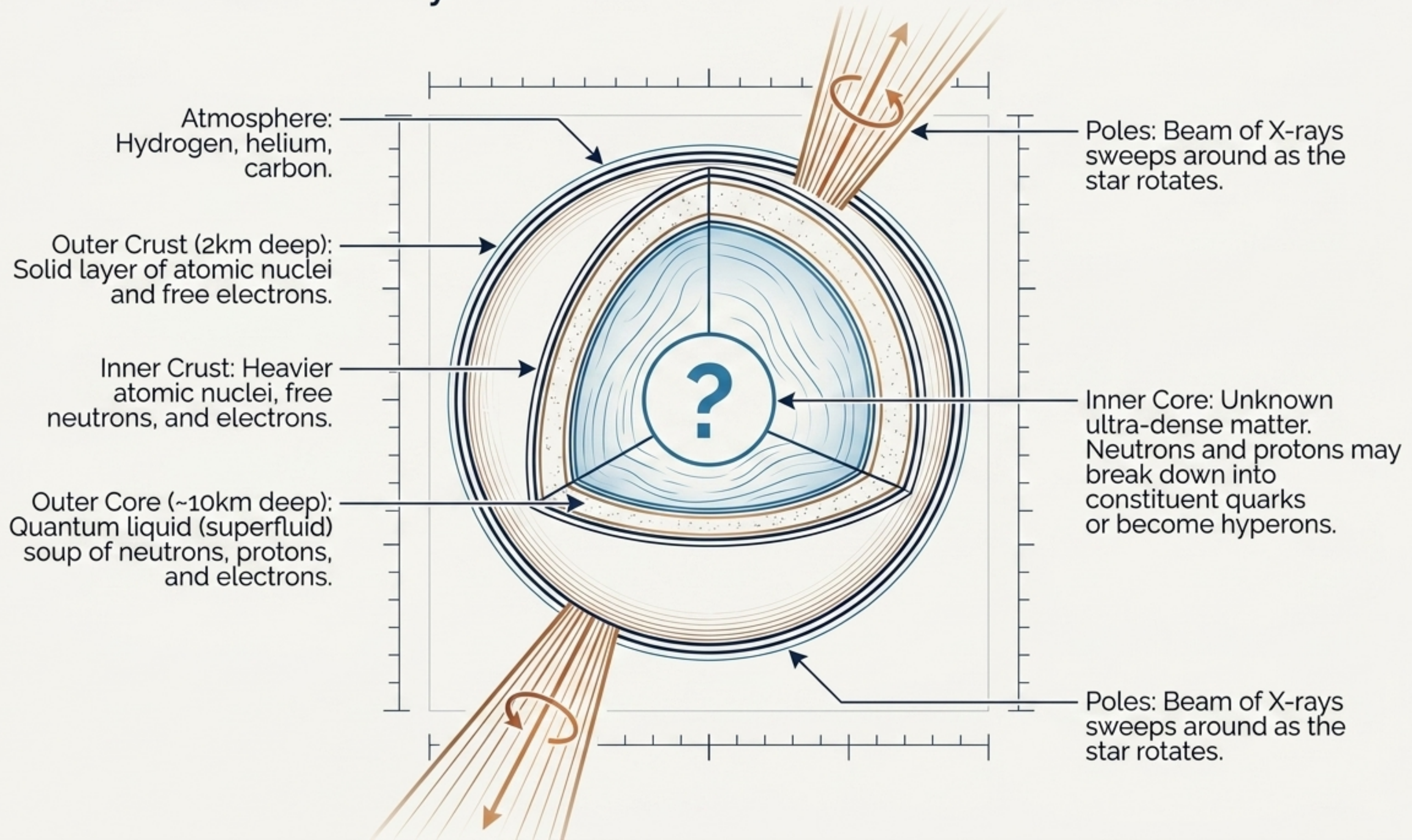


Affects the reaction rates and neutrino emission.

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Neutron stars push all fundamental forces to the extreme, making them the ultimate laboratory for physics that cannot be replicated on Earth.

Architectural Astrodynamics: Neutron Star Cross-Section



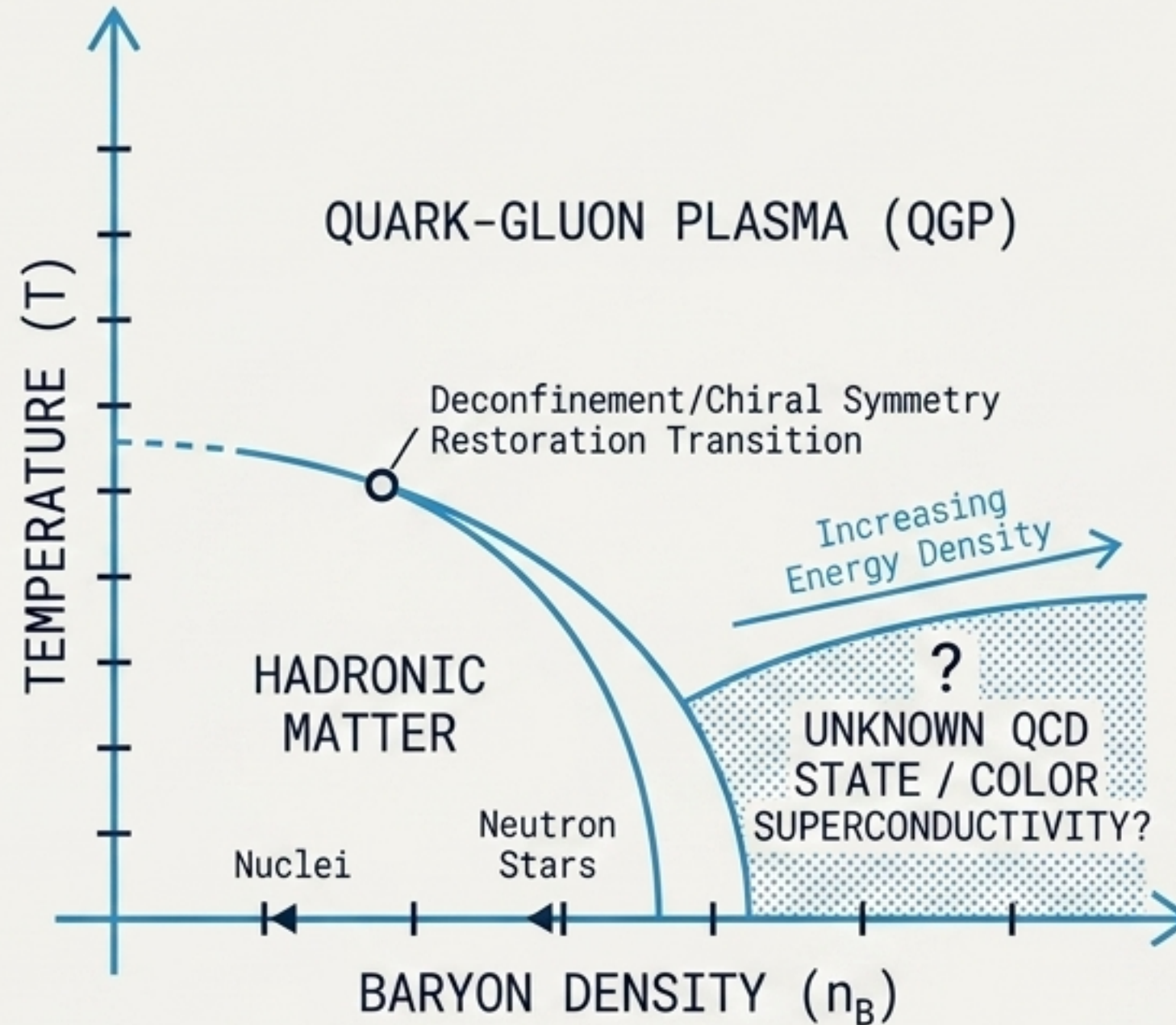
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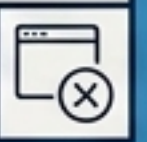
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The QCD Puzzle

Strong nuclear interactions (Quantum Chromodynamics) have never been tested at these extreme densities.



Traditional numerical algorithms used to study QCD in a vacuum fail entirely at finite density. The strength of the interaction breaks standard analytical tools.

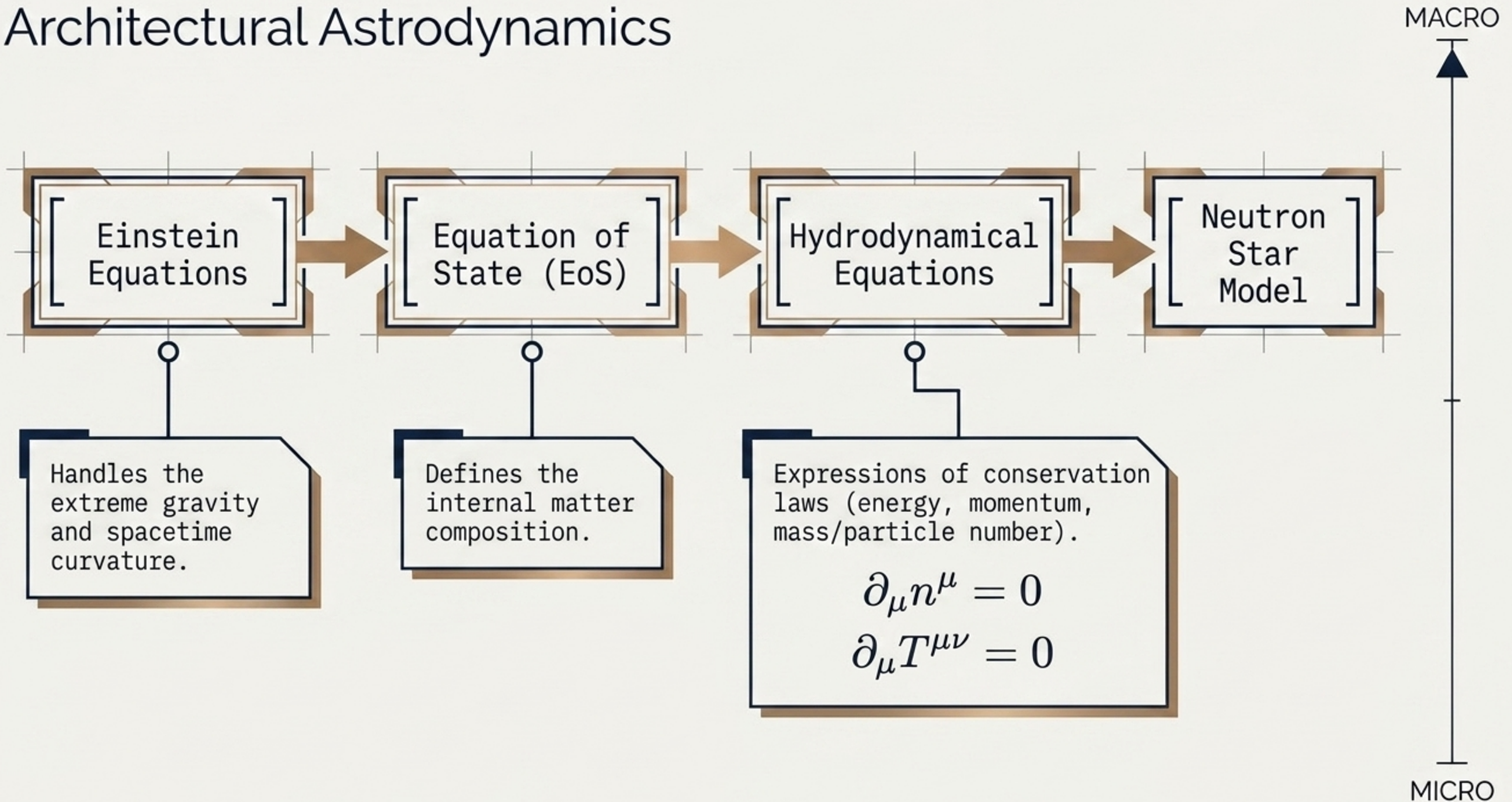


Because we cannot test this directly on Earth, we must rely on complex mathematical models and observable macroscopic clues.

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Architectural Astrophysics



Fluid Comparison: Ideal vs. Real Dynamics

Ideal Fluid

Requires only the Equation of State (EoS).

Valid only when the Knudsen number is small.



Real (Dissipative) Fluid

Requires EoS + Transport Coefficients.

Accounts for non-equilibrium processes and the transfer of conserved quantities.



Dynamical properties of the star actively require knowing these specific transport coefficients.

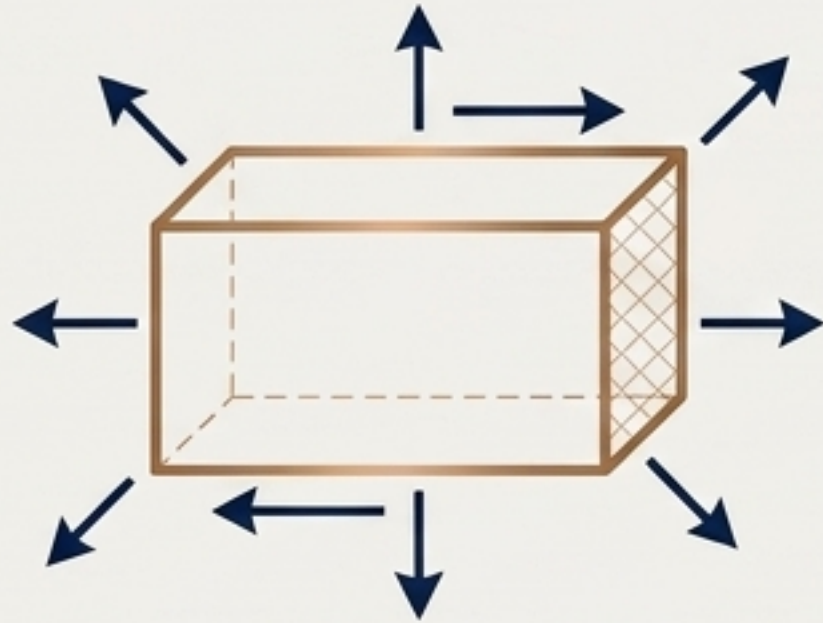
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zoom-reticle

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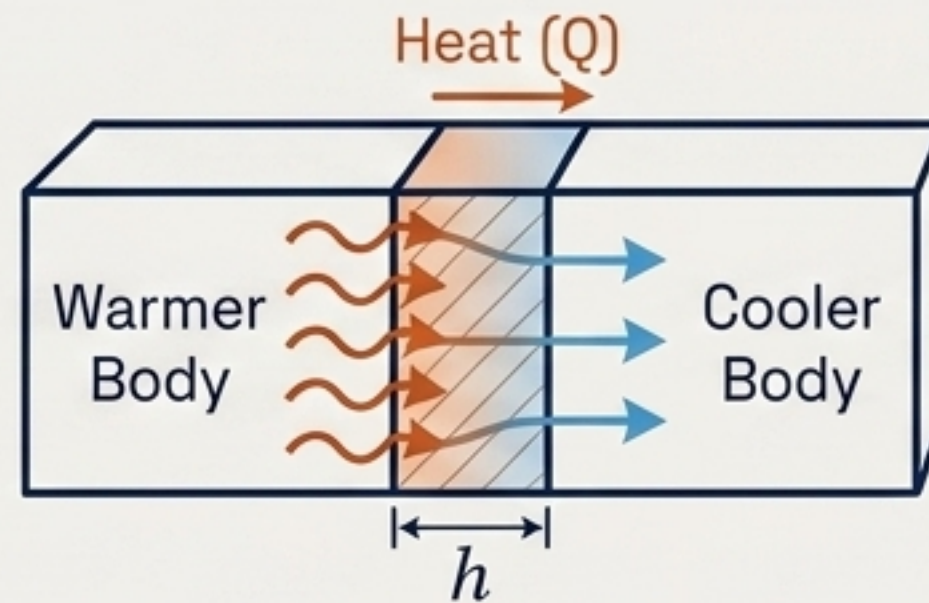
Defining the Translators: Transport Coefficients

Shear & Bulk Viscosity



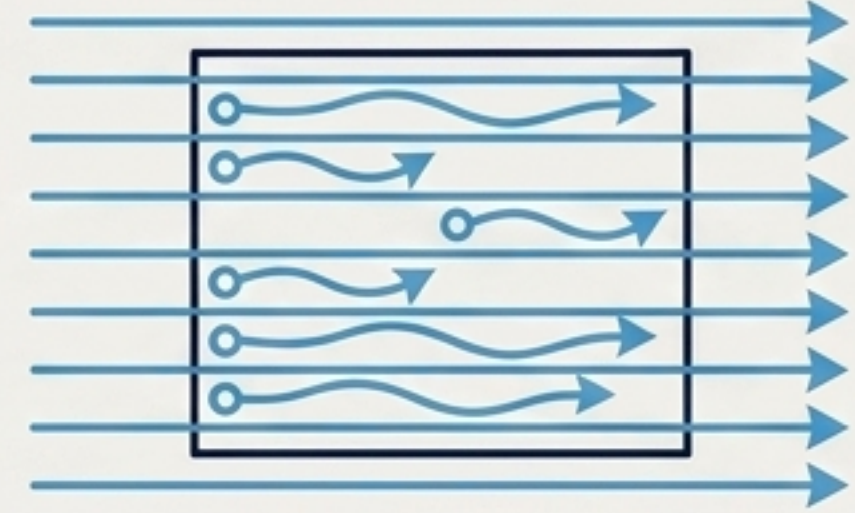
Resistance to gradual deformation

Thermal Conductivity



The property of a material to conduct heat.

Electrical Conductivity



Measures the ability to conduct an electric current.

Core Insight: These macroscopic coefficients are determined entirely by microscopic particle collisions.

The Relativistic Roadblock

Navier-Stokes

For fluid velocities close to the speed of light, a naive generalization of Navier-Stokes equations becomes completely acausal and unstable.



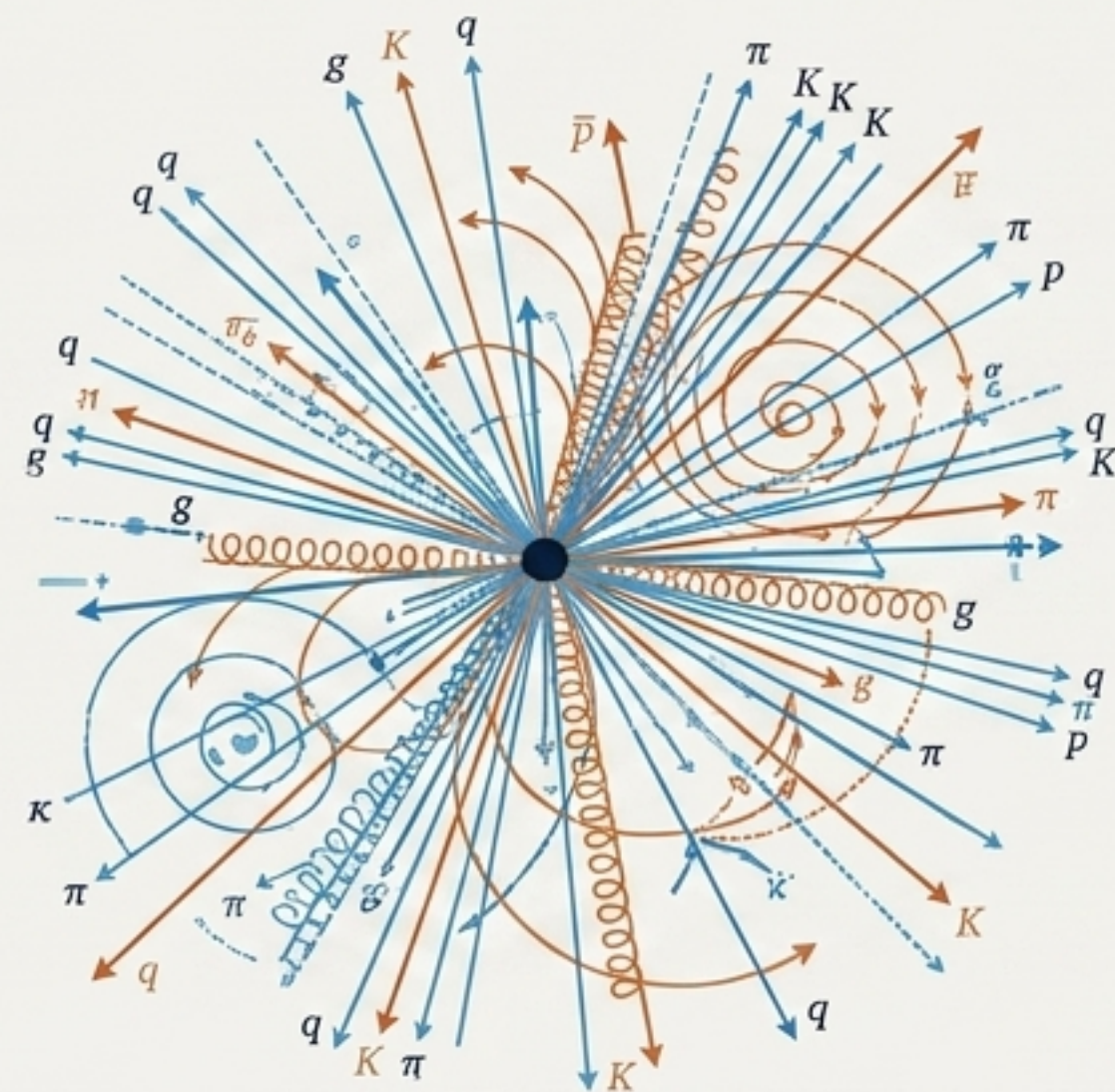
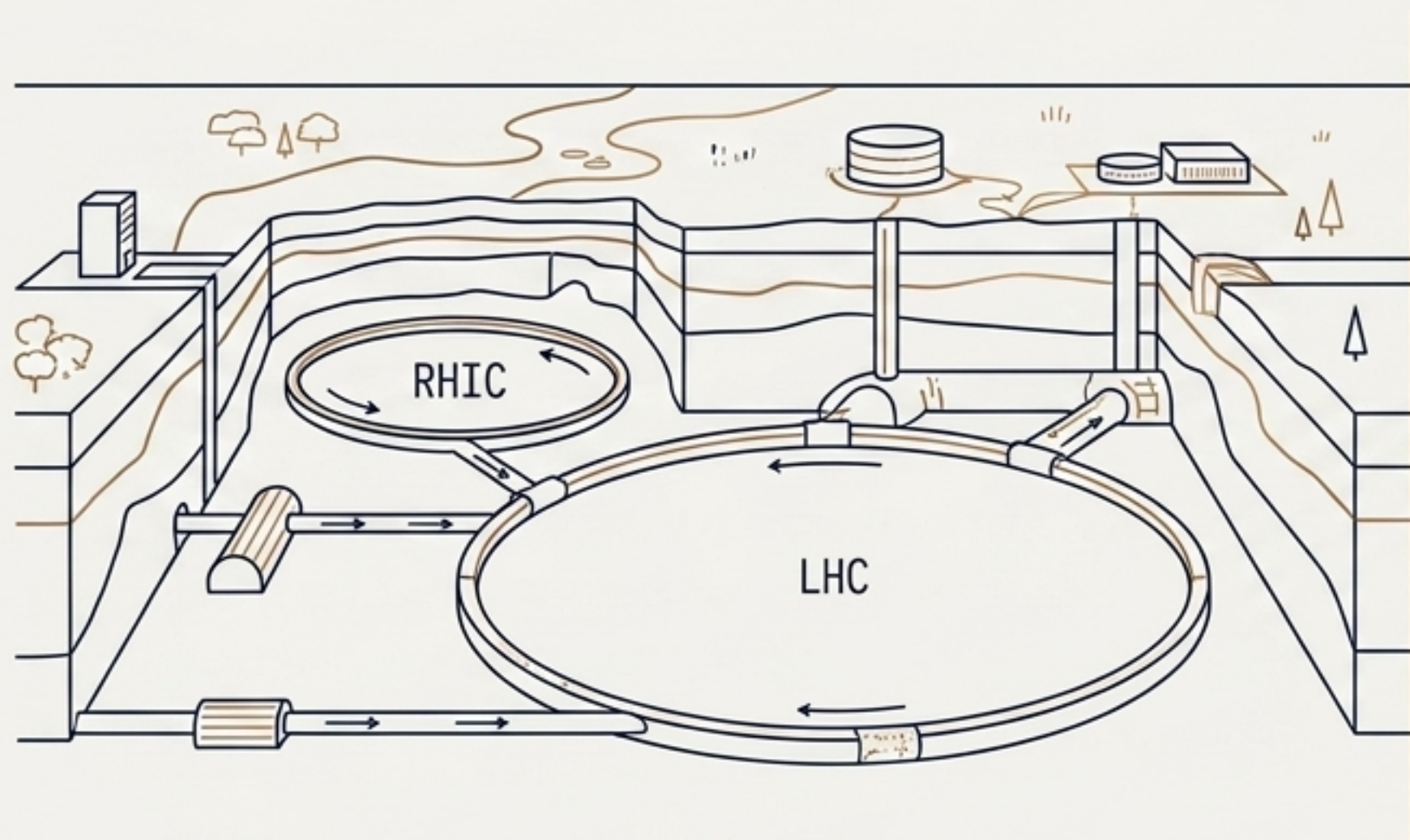
Israel-Stewart

Introduces second-order transport coefficients (relaxation times) to solve this instability.

$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - g^{\mu\nu}P + T_{dis}^{\mu\nu}$$

Context: This tensor formulation accounts for general relativistic effects and high magnetic fields, succeeding where traditional fluids fail.

The Earthly Analog

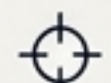


How do we test Israel-Stewart hydrodynamics?
Through Heavy Ion Collisions (HIC) on Earth.

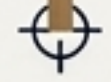
These colliders create Quark-Gluon Plasma. Even though these systems are only a few femtometers in size, hydrodynamical models accurately describe the data.

Surprise finding: Shear viscosity in these tiny collisions has been measured and directly challenges naively predicted values, directly informing stellar-scale models.

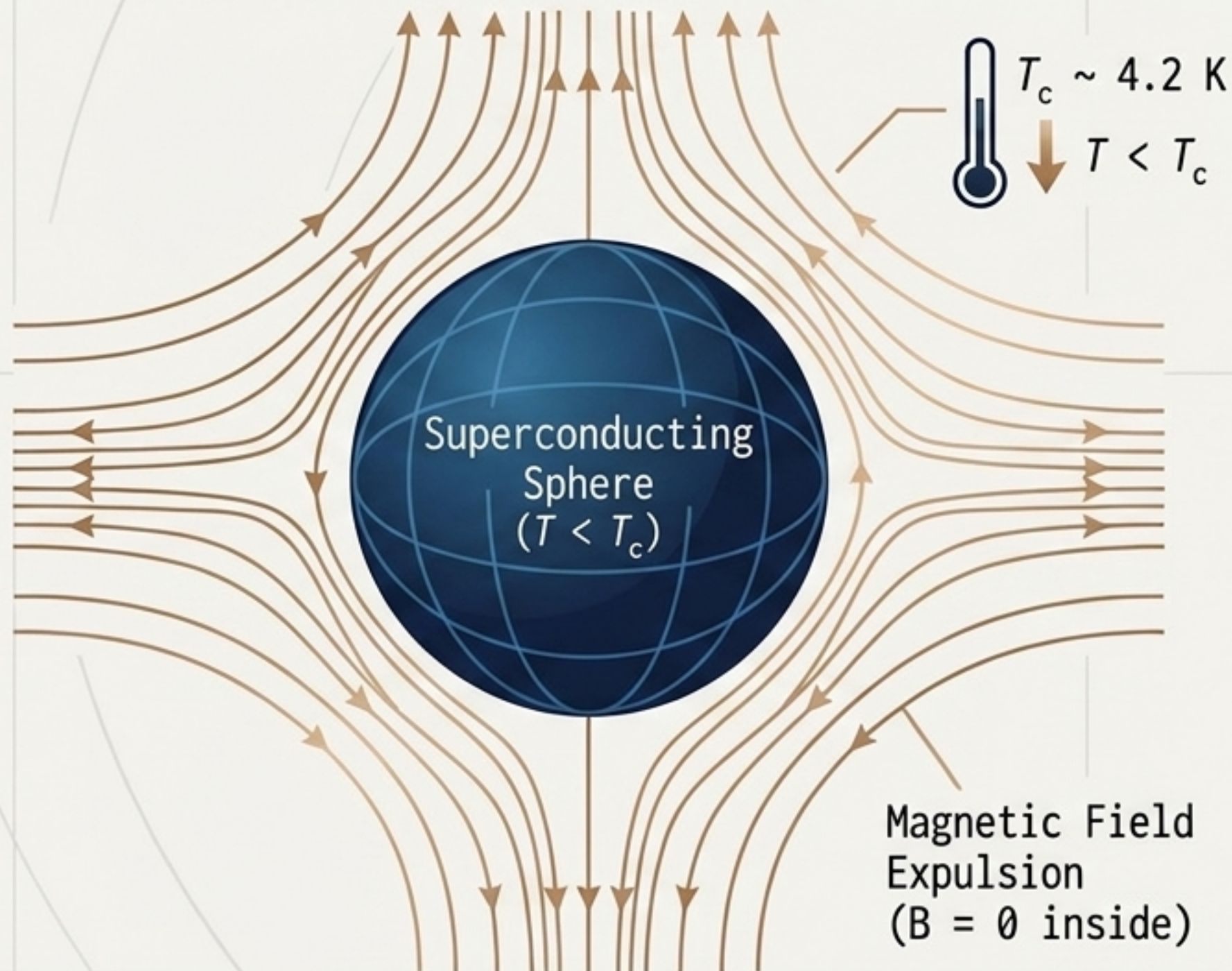
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Quantum Complications I: Superconductivity



Origins:

Discovered in 1911 by H.K. Onnes (electric resistance of mercury drops to ~ 0 at $T_c \sim 4.2 \text{ K}$).

Mechanism:

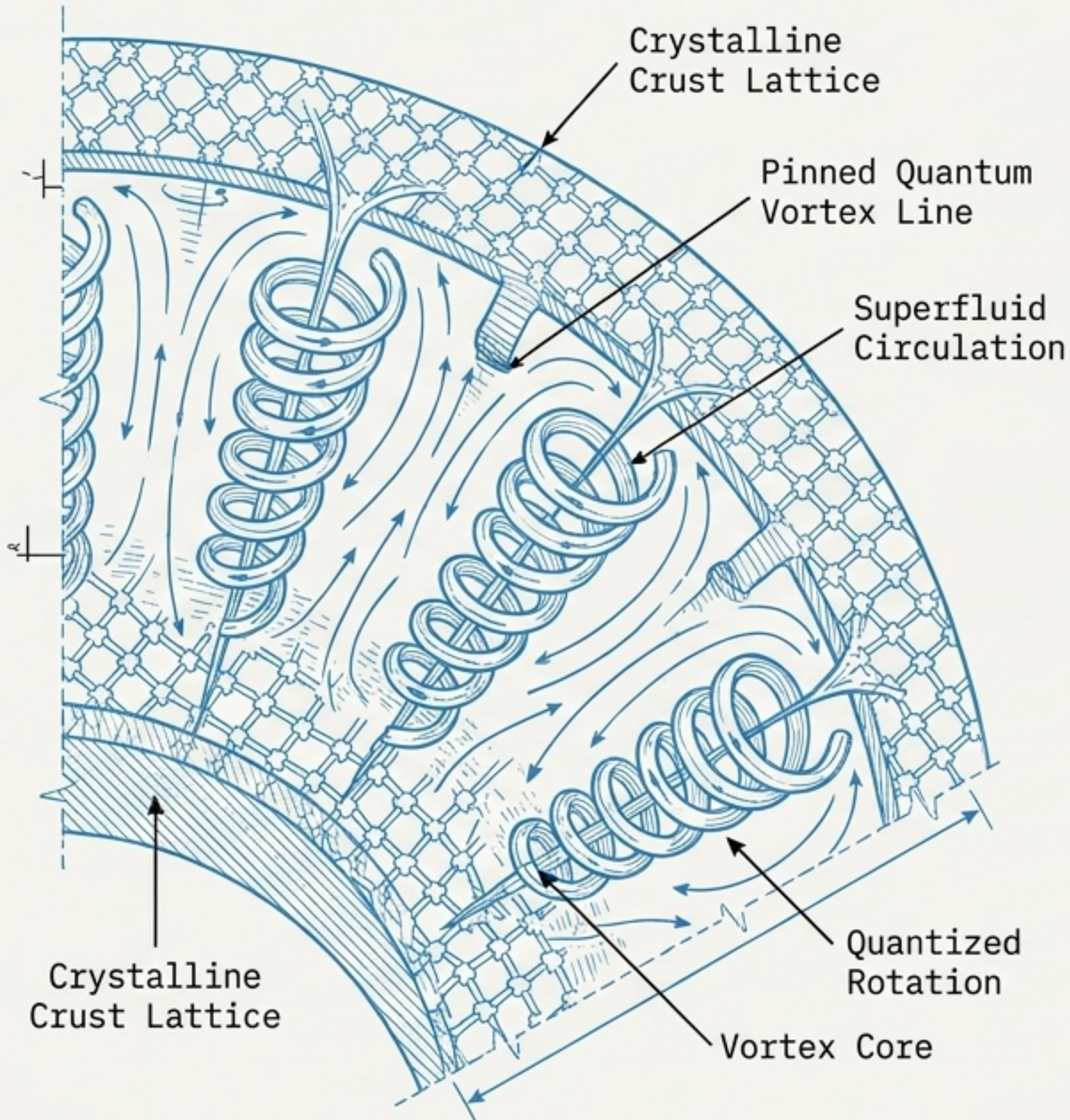
Below critical temperature (T_c), electron heat capacity is exponentially suppressed, indicating a gap in the energy spectrum.

Neutron Star Impact:

Exhibits Type I superconductivity, where magnetic fields are fundamentally prevented from penetrating the stellar interior.

Quantum Complications II: Superfluidity

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The Mechanism:

Superfluidity depends on the excitation spectrum dynamics. If the excitation energy is negative, the fluid loses energy.

The Crucial Paradox:

Superconductivity and Superfluidity have **minimal effects** on the star's macroscopic **Equation of State** (EoS). However, they drastically and fundamentally alter the **hydrodynamical equations**, **transport coefficients**, and **rotational properties** of the star.

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SYNTHESIS: The Transport Phenomenology Matrix

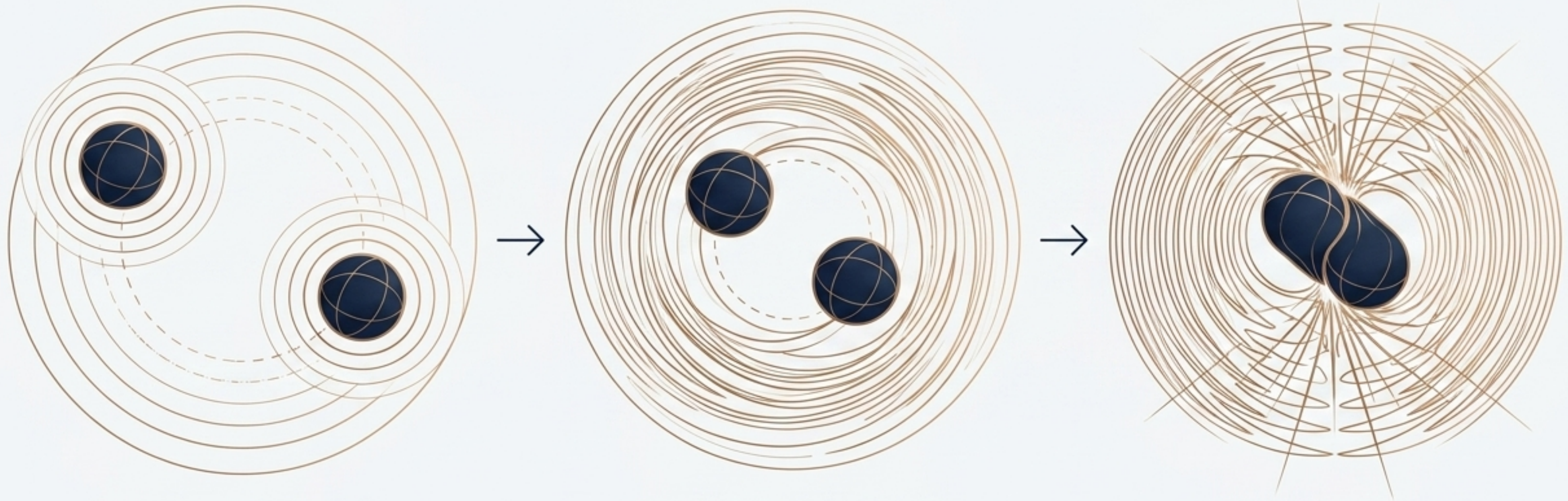
Macroscopic Phenomenon (Telescope view)	Transport Process (Math view)	Coefficient (Micro view)
Oscillatory Modes	Dissipation	Shear & Bulk Viscosities
Thermal Radiation / Cooling	Heat Transport / Neutrino Emissivity	Thermal Conductivity
Magnetic Field Evolution	Current Flow	Electrical Conductivity
Pulsar Glitches	Vortex Pinning	Superfluid Transport
Core-Collapse Supernovae	Neutrino-nucleus reactions	Neutrino Transport

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The New Frontier: Neutron Star Mergers

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Event Focus:

GW170817—the first detection of neutron star mergers via gravitational waves.

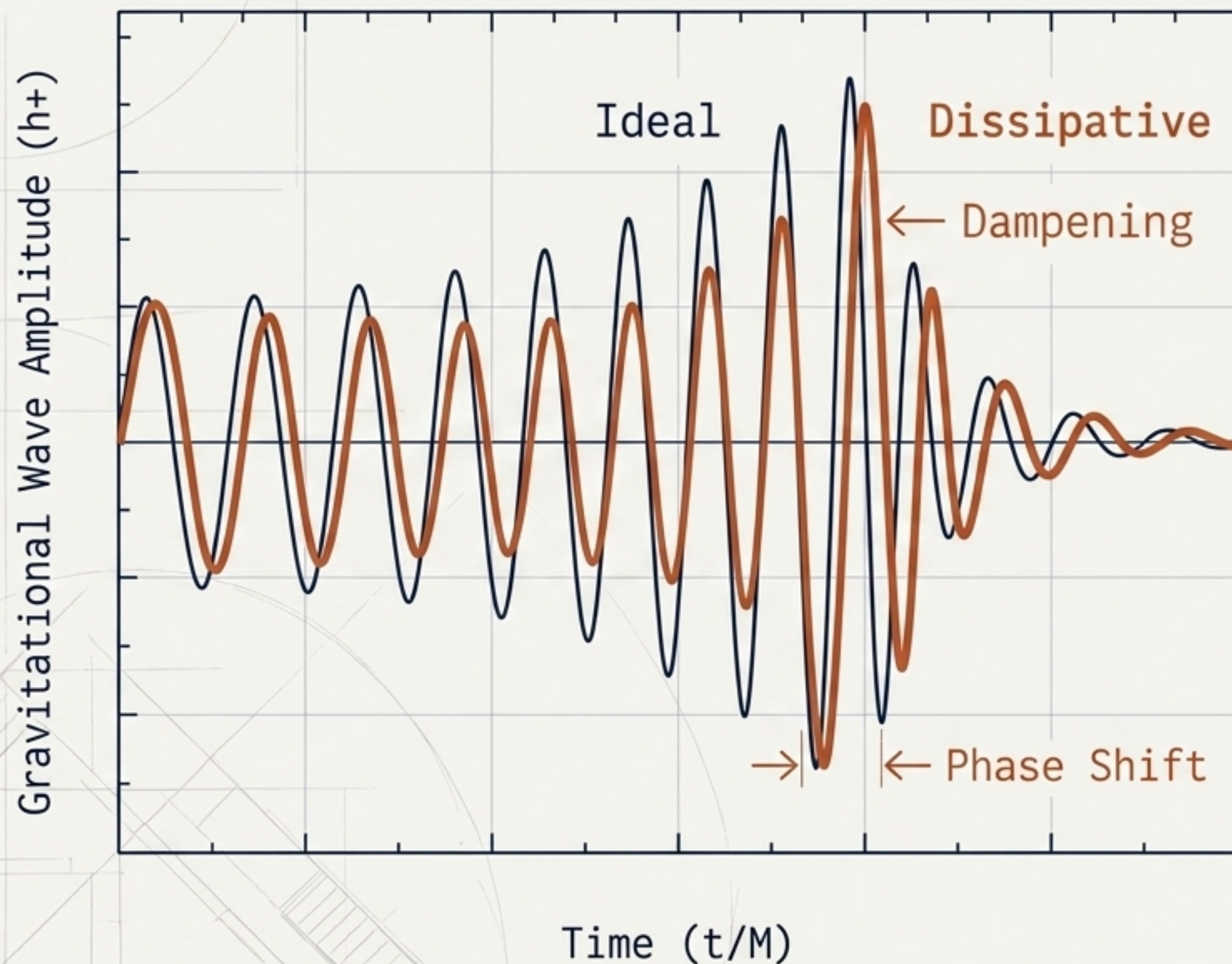
The Ultimate Stress Test:

Mergers provide extreme physical conditions. Modern numerical simulations now track both **Gravitational Wave (GW)** propagation and extreme **matter evolution** simultaneously.

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Dissipation in Action

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The Breakthrough:

Recent simulations prove that ideal fluid models are not enough.

The Evidence:

Strong indications show that dissipation effects—specifically **bulk viscosity**—are critical for accurately predicting merger dynamics.

Citation:

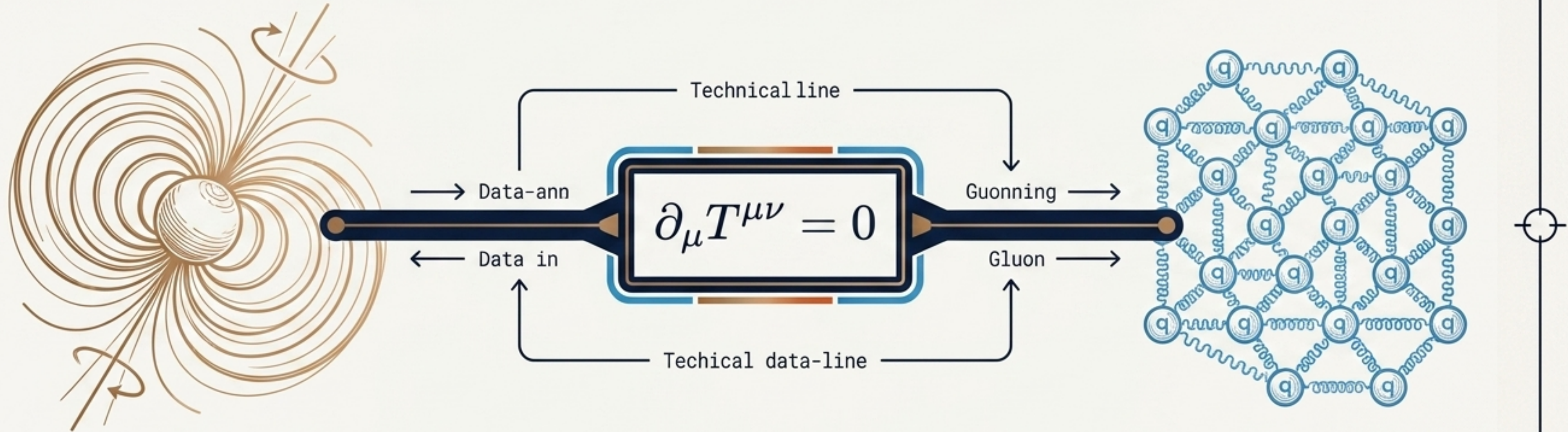
Highlights pioneering work by Dietrich et al. (2021) and Chabanov & Rezzolla, marking the first successful attempts to include bulk viscosity in merger simulations.

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The Micro-Macro Bridge Completed

MACRO: Pulsar & Gravitational Waves

MICRO: Quark-Gluon Matter



Reverse-Engineering the Quantum World

We cannot test ultra-dense QCD matter in a lab. But by observing macroscopic phenomena (pulsar glitches, gravitational waves) and applying relativistic, dissipative hydrodynamics, we can reverse-engineer the microscopic quantum world.

Cosmic Translators

Transport coefficients are not just mathematical corrections; they are the cosmic translators unlocking the densest matter in the universe.