Large-scale structure of magnetic currents strongly correlates with confinement

Modern data analysis methods combined with state-of-the-art supercomputing allows us to tackle head-on one of the most challenging open problems in theoretical particle physics.

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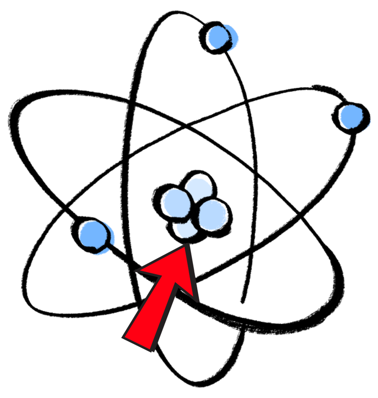
A. The confinement problem

Quarks and gluons are tiny, fundamental building blocks of matter. Everything around us (including you!) is made of atoms. Inside their nucleus, atoms consist of quarks bound together into clumps. In some ways, quarks and gluons are similar to electrons (electricity) and photons (light) but they have a peculiar tendency to only travel around in groups of 2 or more.



Inside the nucleus, each proton and neutron consists of 3 quarks.

In every experiment we've ever performed, no single quark has ever been isolated - we call this phenomenon **confinement**. The problem is that we don't have a mathematical explanation for why this effect happens! How do we even begin to tackle this problem?

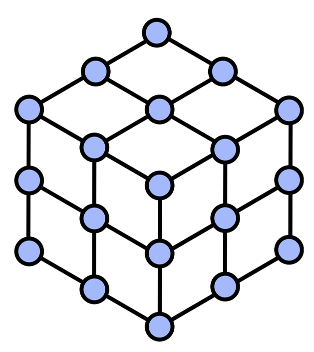
A quark and anti-quark are held together by a string-like object called a **flux tube**. The more you try and pull the quarks apart, the more they want to stick together!

The confinement problem is so challenging that it has even been included in the Clay Mathematics Institute's millenium problems!

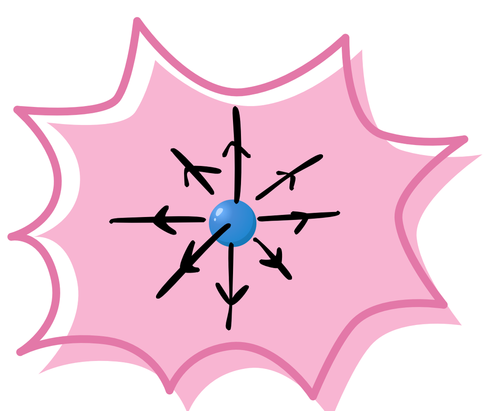
One promising avenue of research involves theoretical particles called **monopoles...**

B. Supercomputers vs. super small particles

By discretising space and time into a grid, we are able to simulate a pixelated version of gluons. This allows us to study their behaviour. As we make the simulation bigger, we get closer to the real-world physics. To do something physically meaningful, we need a big computer: a **supercomputer**! We find that our simulation contains magnetic particles called monopoles.



Each edge of the grid represents a little piece of the gluons.

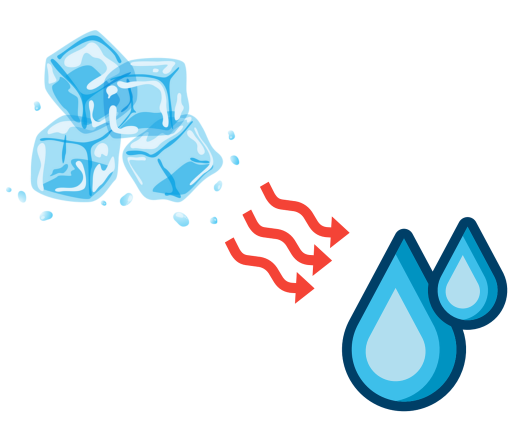


A **monopole** is a point-like source of the magnetic field.

C. An interesting phase transition

As you increase the temperature of the gluons, something interesting happens: **the system changes phase**. This is directly analogous to ice melting into water.

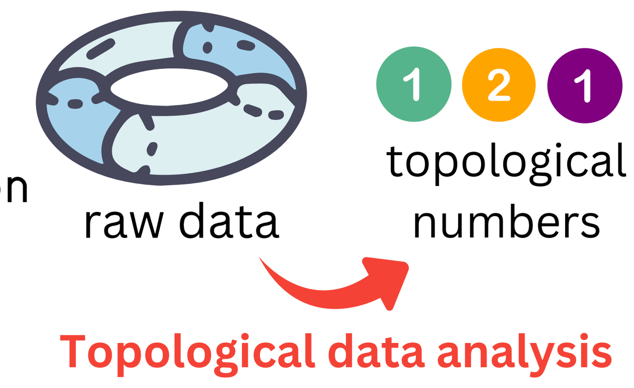
One phase represents confined gluons: we find monopoles forming a large, dense gas. The other phase represents free gluons: we find monopoles melting into smaller structures.



Ice melting into water is a classic example of a first order phase transition.

D. Topology to the rescue

Monopoles are particularly difficult to analyse because they self-organise into large structures that change depending on the phase of the system.



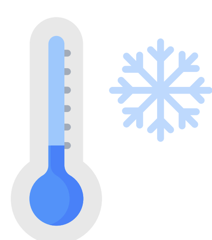
Using **topological data analysis,** a cutting-edge field of mathematics combining algebraic topology and data science, we have been able to quantitatively analyse monopole structures with high precision.

Topological data analysis allows us to compute the **number of lumps** and the **number of loops** formed by monopoles.

Topology is a branch of mathematics that deals with fundamental properties of shapes. For example, the number of holes in a shape is a "topological invariant".

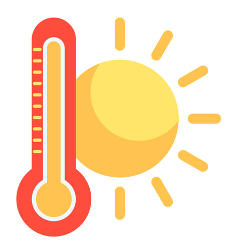
Topology has allowed us to very precisely follow monopoles across the phase transition.

COLD PHASE



the number of lumps is very low and the number of loops is very high

the number of lumps increases and the number of loops decreases



HOT PHASE

We have been able to estimate the critical temperature of the phase transition (like the melting point of ice at 0°C). In fact, we have achieved a **higher precision** than standard methodologies.

The topology of monopoles is clearly a very good way to study the confinement phase transition!

This hints at the potential role that monopoles have to play in the microscopic mechanism underpinning confinement.

E. A new phase of matter?

The real-world contains matter and so our next step is to repeat our methodology in the more complicated theory of both quarks and gluons.

Recently, numerical evidence has hinted at the existence of a new phase but it has been difficult to verify with standard methods.

Our hypothesis is that our methods may help confirm the existence of this new phase.

If this were to be the case, in future, experiments like the heavy-ion collisions at the Large Hadron Collider at CERN might be able to detect this new phase!

Heavy-ion collisions could temporarily create this conjectured new phase.

MORE INFO

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