From string theory to exotic materials

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At a string theory conference this year
‘Elementary’ particles

- Established high energy physics is built on the notion of particles.
String theory on one slide

- String theory embeds established physics into a bigger structure.
- Each particle (e.g. graviton, photon, etc.) $\Rightarrow$ tower of string states.
A triangle of dualities

- Extra structure of string theory allows it to act as a bridge between gravitational and non-gravitational physics.
Universal attraction + cosmic speed limit ⇒ black holes
Black hole growth is irreversible

- Things fall into black holes but they cannot get out again

- It is plausible, then, that the area of black holes necessarily gets larger over time (proven by Hawking, 1970s)

- Black hole growth is therefore irreversible.

- Irreversible processes are familiar ...

- Irreversibility is usually characterized by an increase in entropy.
Black hole entropy

- Theoretical acrobatics by Bekenstein and Hawking showed that black holes have an entropy given by
  \[ S = k_B \frac{1}{4} \frac{A}{\ell_P^2}. \]

- Two unusual and important properties:
  - The entropy scales with the area, not volume.
  - The entropy is in Planck units and therefore huge. E.g. solar mass black hole: \(10^{18}\) times more entropy than the sun.

- Entropy too large to be accounted for by conventional matter.

- Need more degrees of freedom ...
Stringy Physics

Entropy counting
[Strominger-Vafa, ... ]

Black Holes

Gauge Theory
• In certain mathematically idealized circumstances
  ⇒ String states exactly account for black hole entropy.

• Generally: parametrically enough stringy states to build black hole.
  (Susskind ’93; Horowitz-Polchinksy ’97)

\[ S = k_B \frac{A}{4 L_P^2} \]
Gauge theories

- Generalisations of electromagnetism

- Most famously arise in quantum chromodynamics (theory of protons, neutrons, quarks, etc.)

- May also arise in exotic solid state systems (possibly high temperature superconductors?) ...
Fractionalization (gauge theories in exotic materials)

- Electrons have spin and charge
- In some circumstances, spin and charge can move independently
- Can imagine the electron being split up into ‘spinons’ and ‘holons’.
- Need to remember that the spin and charge are ultimately joined together into physical electrons. They are joined by lines of flux.
Stringy Physics

Black Holes

Gauge Theory

Flux tubes
[old string theory, Polyakov, Maldacena, ...]
Gestalt switch

- Flip the background and the foreground.
From gluons to flux tubes

- Strong interactions
  ⇒ Quanta of gauge field cannot retain an individual existence.

- ‘Gestalt switch’: Consider lines of flux as the basic quantities.
Stringy Physics

Black Holes

Gauge Theory

Dissipation on horizon
[Damour, Policastro-Son-Starinets, ...]
Black holes from the outside

- When a black hole horizon is excited
  $\Rightarrow$ Relaxes back to equilibrium like a dissipative fluid.

- Relaxation timescale characteristic of a ‘quantum critical’ medium
  \[ \tau \sim \frac{\hbar}{k_B T}. \]
Holography Duality

- The connection between gravity and gauge theories has been made very sharp in the Holographic Correspondence. (Maldacena ’97)
Exotic materials we would like to understand

- The normal state of unconventional superconductors is not normal.
  - e.g. cuprates, pnictides, heavy fermions, organics.

- We would like a theory of these (ab)normal states.
- Given such a theory we would like to understand the emergence of superconductivity at low temperatures.
These weeks at the KITP ...

- These (ab)normal states exhibit quantum criticality and may possibly have a description as a gauge theory.

- A current program at the KITP is exploring the extent to which the connection between gauge theories and black holes may be useful for understanding these materials.
Example: electrical resistivity

- Electrical resistivity: energy lost to heat (entropy)

- The holographic way to calculate the resistivity:
Holographically, superconductivity emerges when at low temperatures, charge is sucked out of the black hole.
Summary

- String theory: *stringy structure* built onto particle physics
- Strings have enough *entropy* to make up black holes
- Strings can also play the role of *flux tubes* in gauge theory
- **Holographic duality**: Black holes describe dissipative processes in gauge theories (e.g. electrical resistivity)
- Gauge theories may be relevant for understanding *exotic materials*
- Can black holes offer conceptual and computational insight into ill-understood unconventional superconductors?