From string theory to exotic materials

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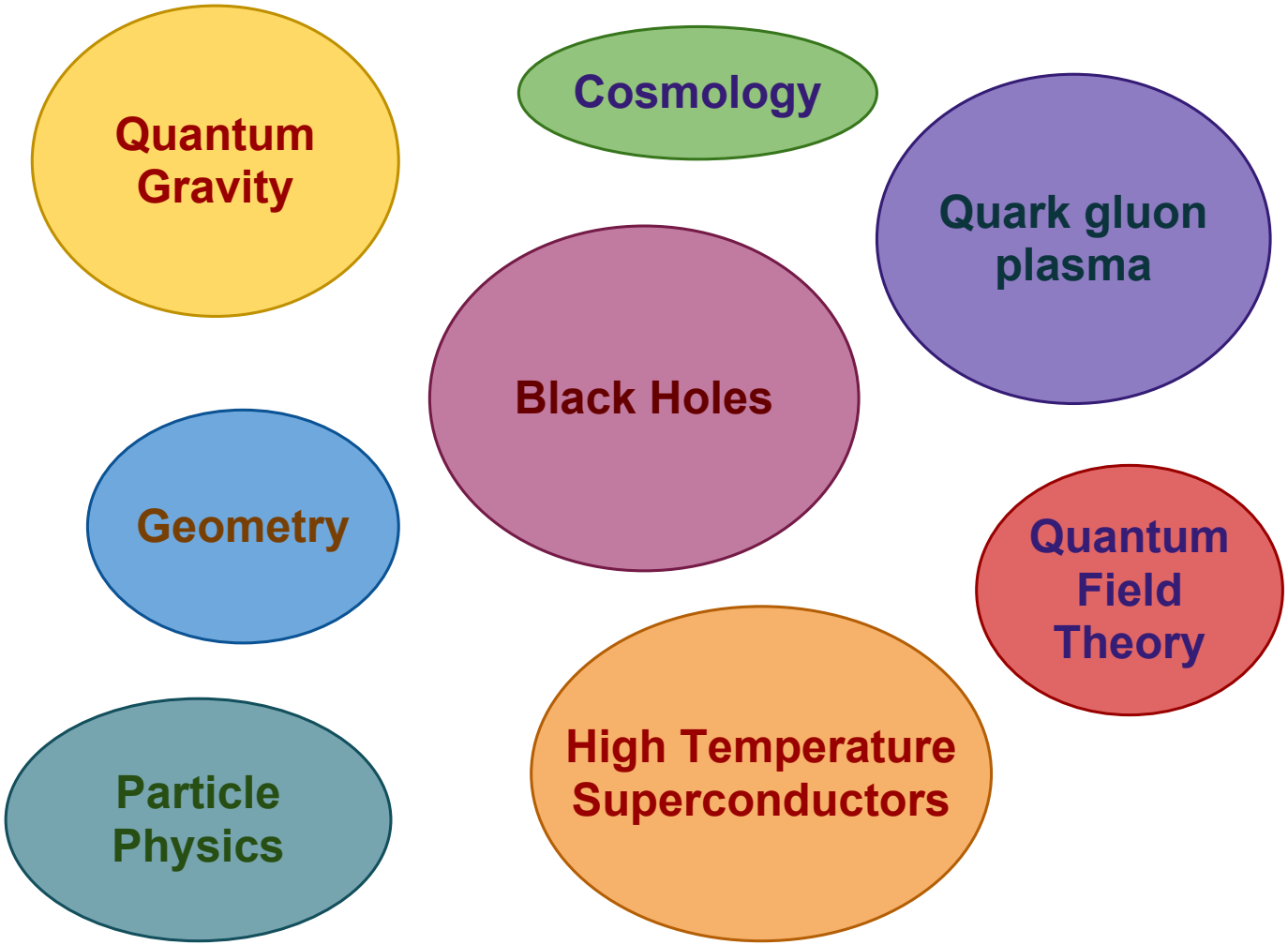
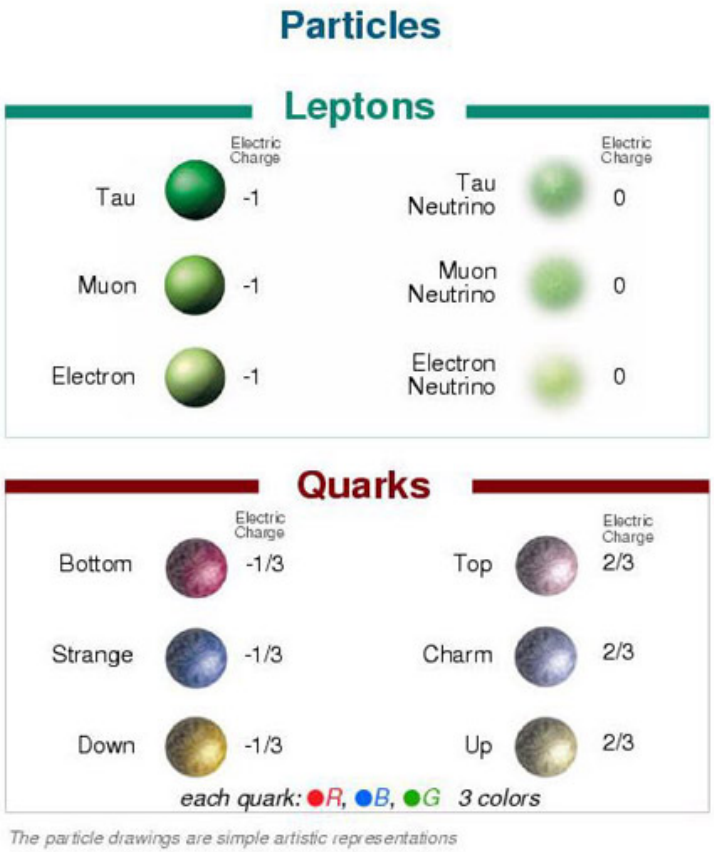
October 2011 – KITP

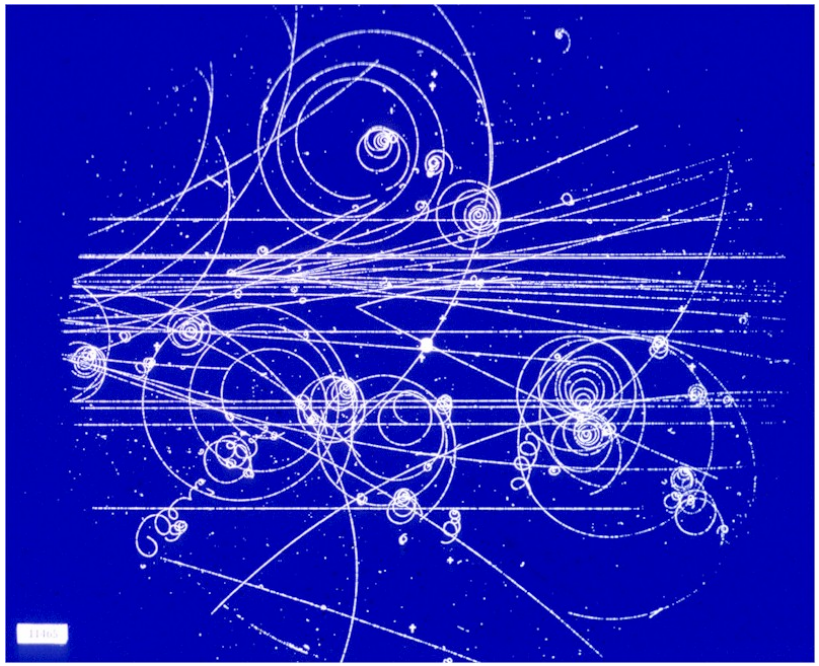
At a string theory conference this year



‘Elementary’ particles

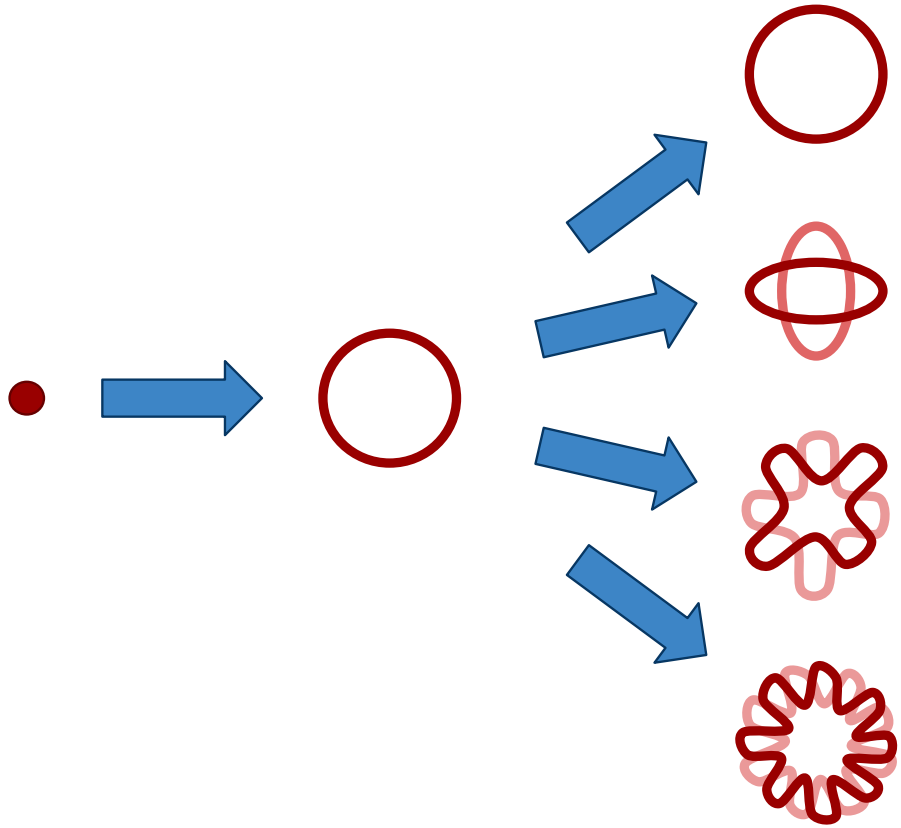
- Established high energy physics is built on the notion of particles.





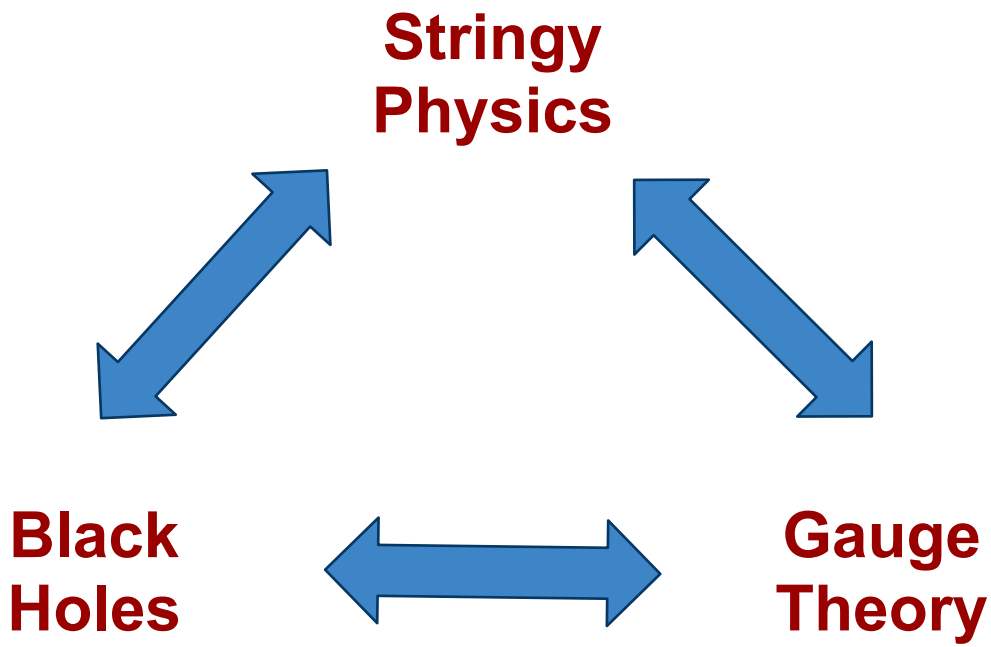
String theory on one slide

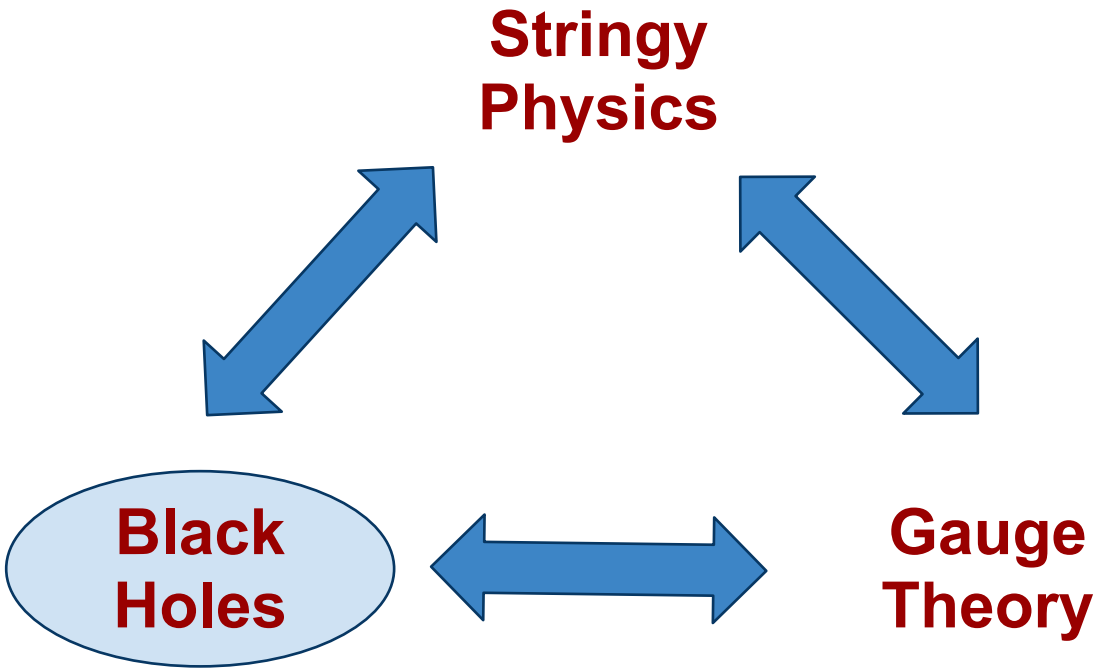
- String theory embeds established physics into a bigger structure.
- Each particle (e.g. graviton, photon, etc.) $\Rightarrow$ tower of string states.



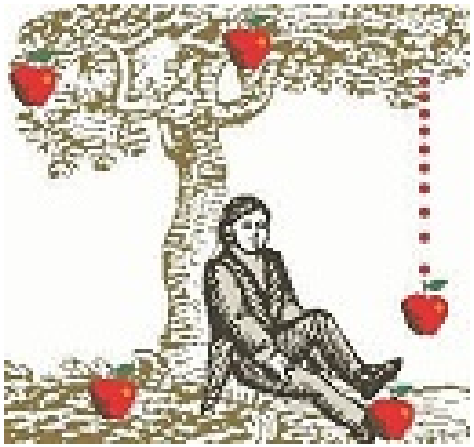
A triangle of dualities

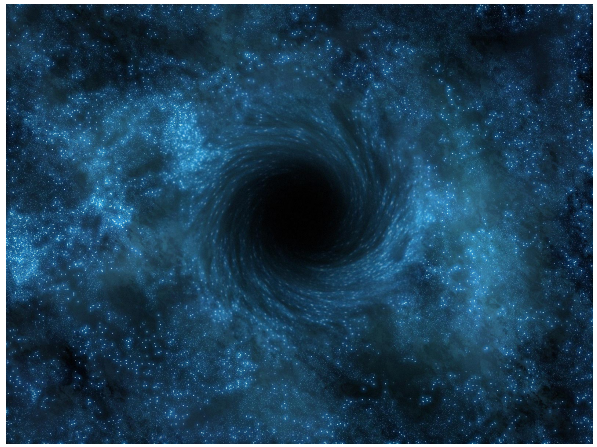
- Extra structure of string theory allows it to act as a bridge between gravitational and non-gravitational physics.




Stringy
Physics
Black
Holes
Gauge
Theory

Universal attraction + cosmic speed limit ⇒ black holes





Black hole growth is irreversible

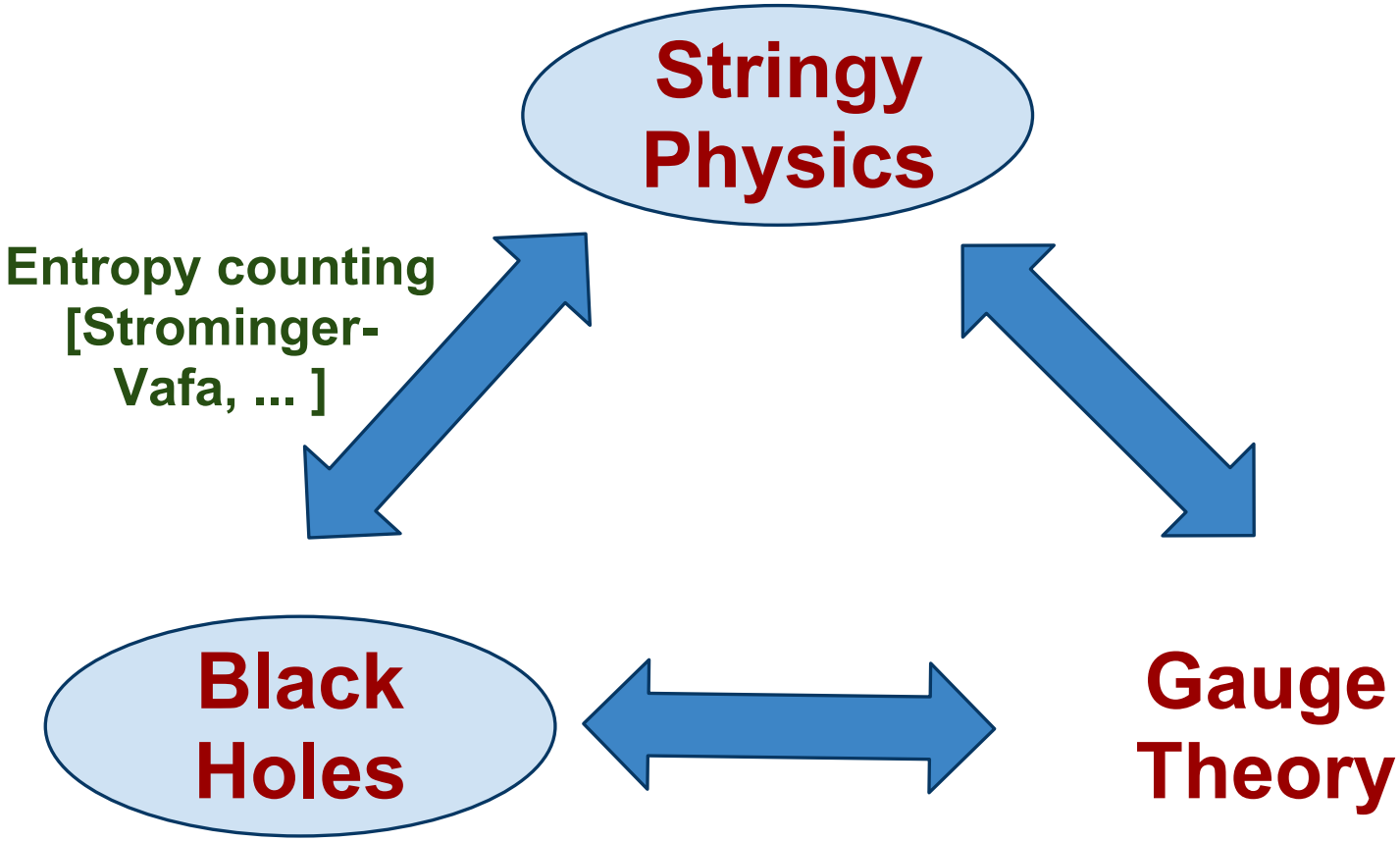
- Things fall into black holes but they cannot get out again
- It is plausible, then, that the area of black holes necessarily gets larger over time (proven by Hawking, 1970s)
- Black hole growth is therefore irreversible.
- Irreversible processes are familiar ...
- Irreversibility is usually characterized by an increase in entropy.

Black hole entropy

- Theoretical acrobatics by Bekenstein and Hawking showed that black holes have an entropy given by

$$\boxed{S = k_B \frac{1}{4} \frac{A}{\ell_P^2} .}$$

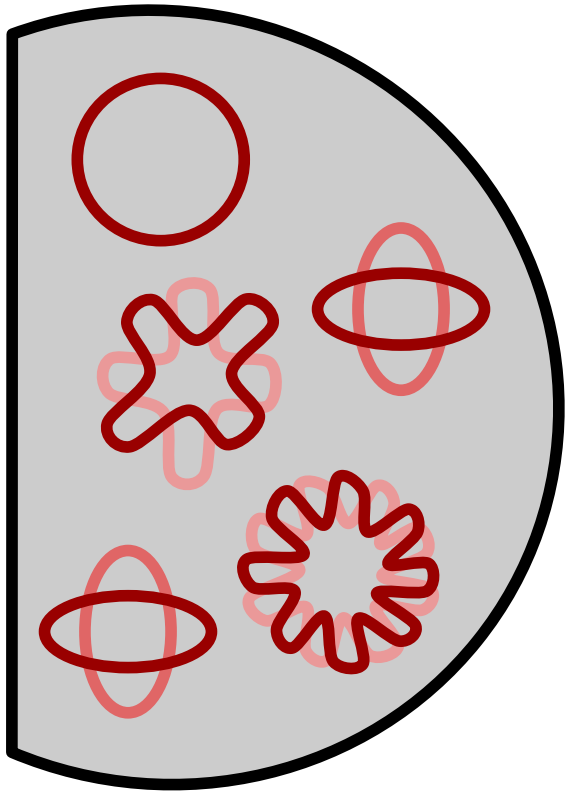
- Two unusual and important properties:
  - The entropy scales with the area, not volume.
  - The entropy is in Planck units and therefore huge. E.g. solar mass black hole: 10^{18} times more entropy than the sun.
- Entropy too large to be accounted for by conventional matter.
- Need more degrees of freedom ...


Stringy Physics
Entropy counting [Strominger-Vafa, ...]
Black Holes
Gauge Theory

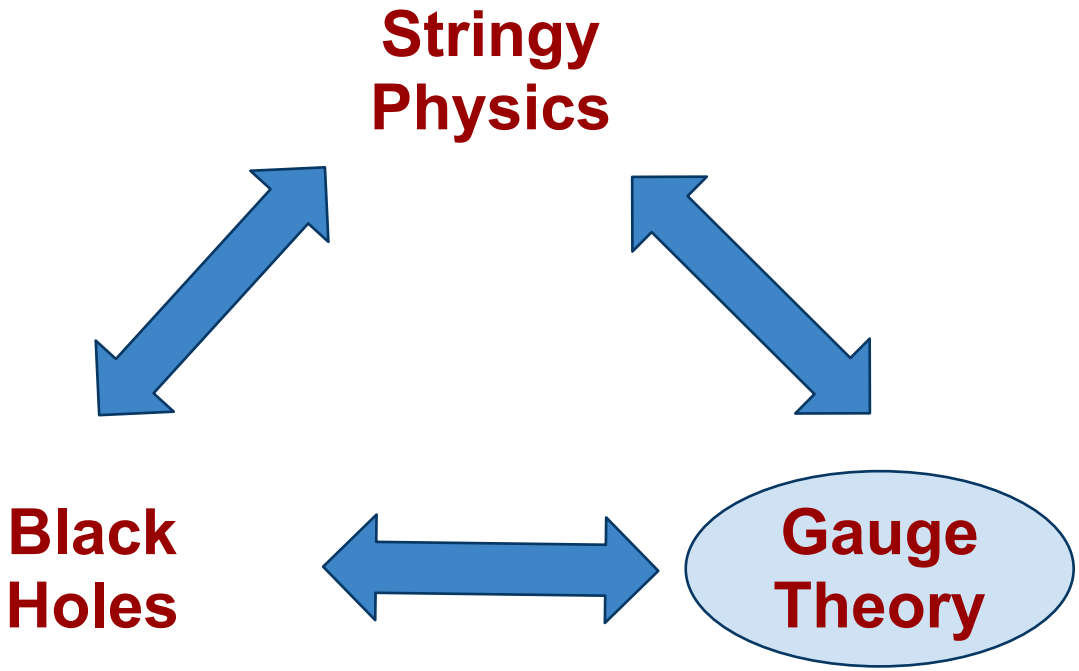
Black holes 'from the inside'

- In certain mathematically idealized circumstances
  $\Rightarrow$ String states exactly account for black hole entropy.

- Generally: parametrically enough stringy states to build black hole. (Susskind '93; Horowitz-Polchinksi '97)



$$S = k_B \frac{A}{4 L_P^2}$$


Stringy
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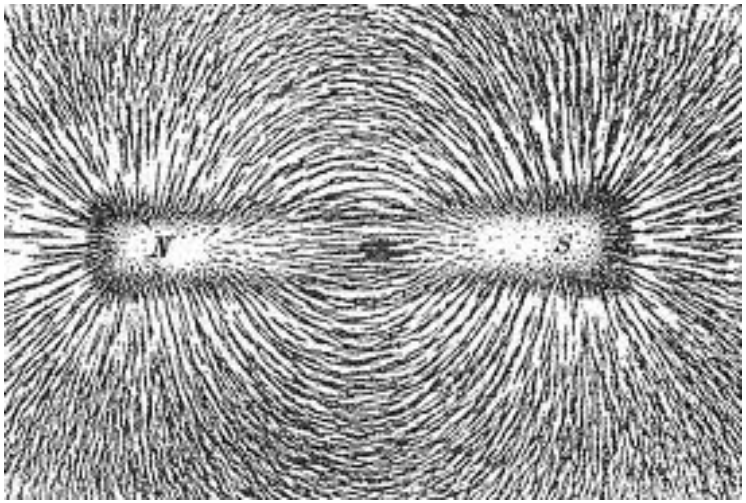
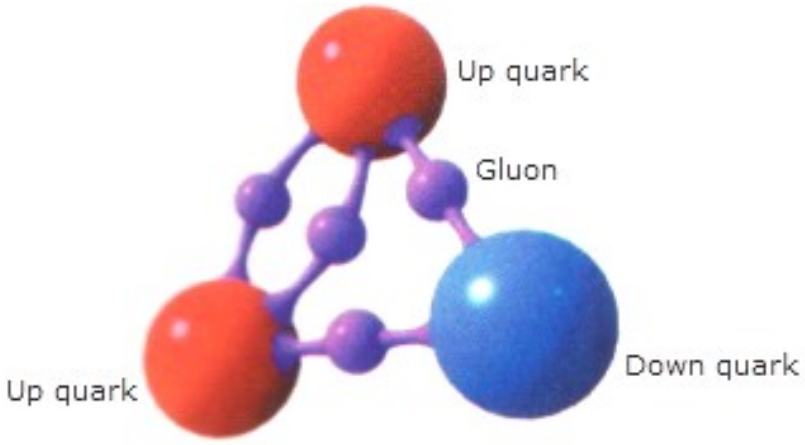
Gauge theories

- Generalisations of electromagnetism



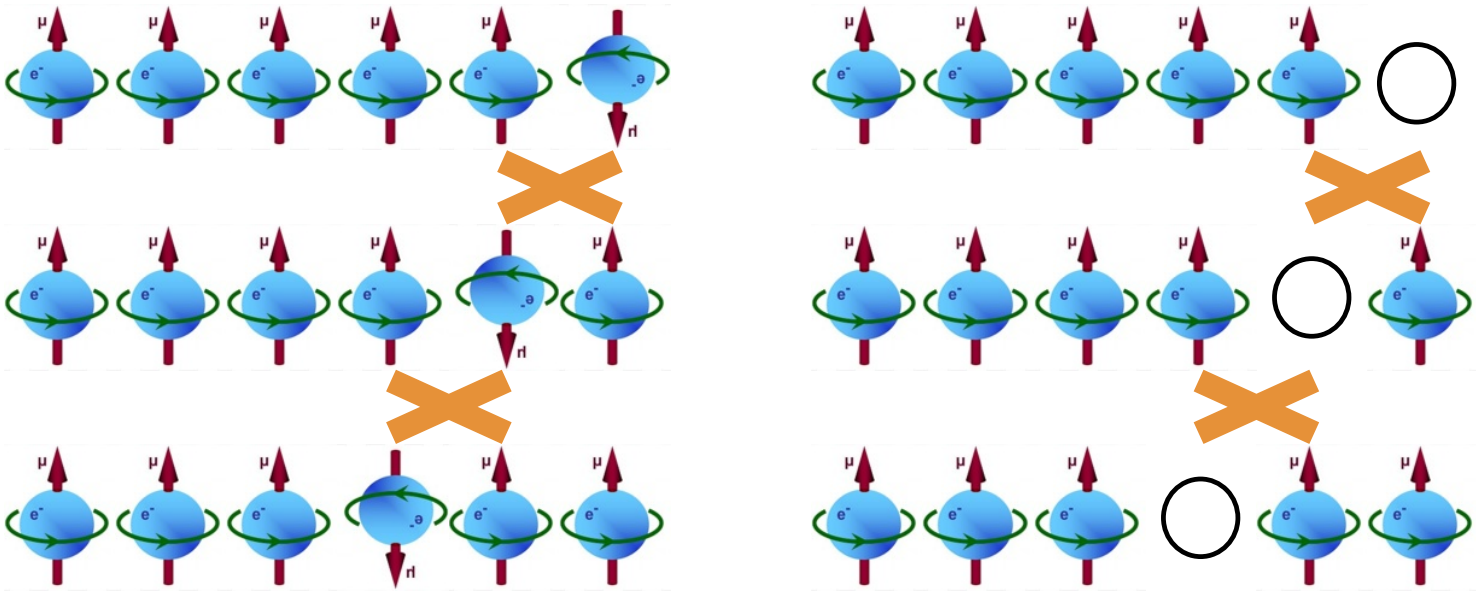


Gluons holding quarks together to form a proton
(diagram from *Scientific American*)

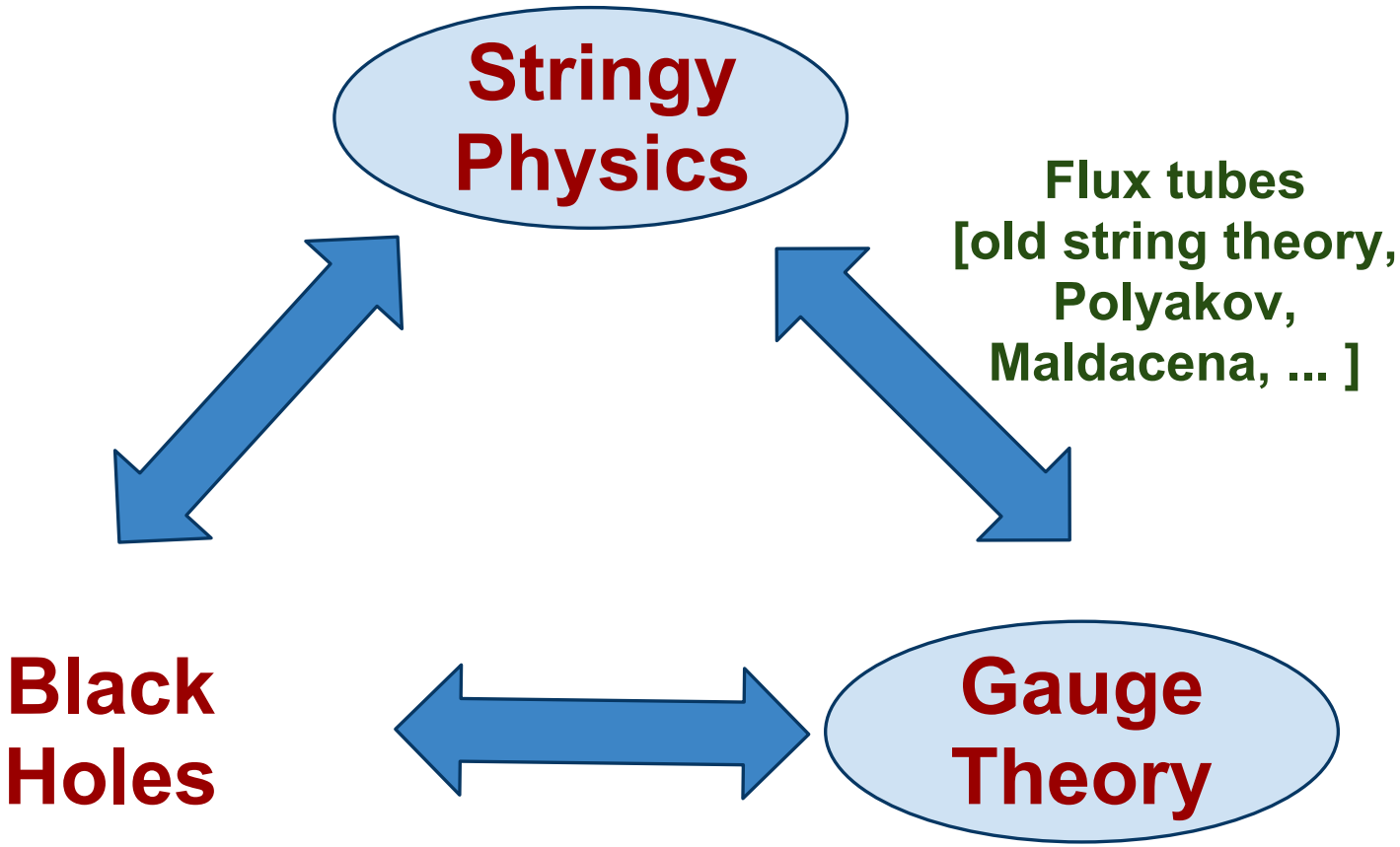
- Most famously arise in quantum chromodynamics (theory of protons, neutrons, quarks, etc.)
- May also arise in exotic solid state systems (possibly high temperature superconductors?) ...

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
Flux tubes [old string theory, Polyakov, Maldacena, ...]
Black Holes
Gauge Theory

Gestalt switch

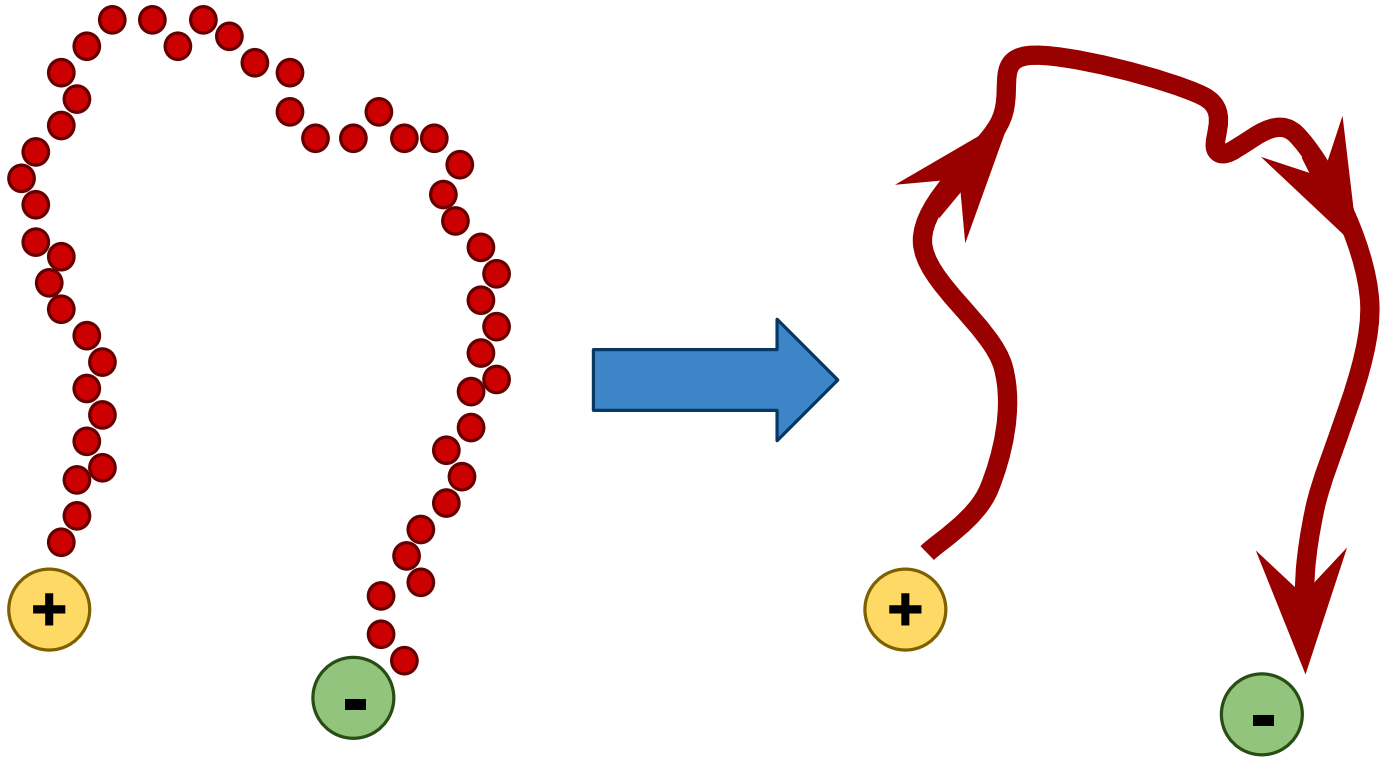
- Flip the background and the foreground.

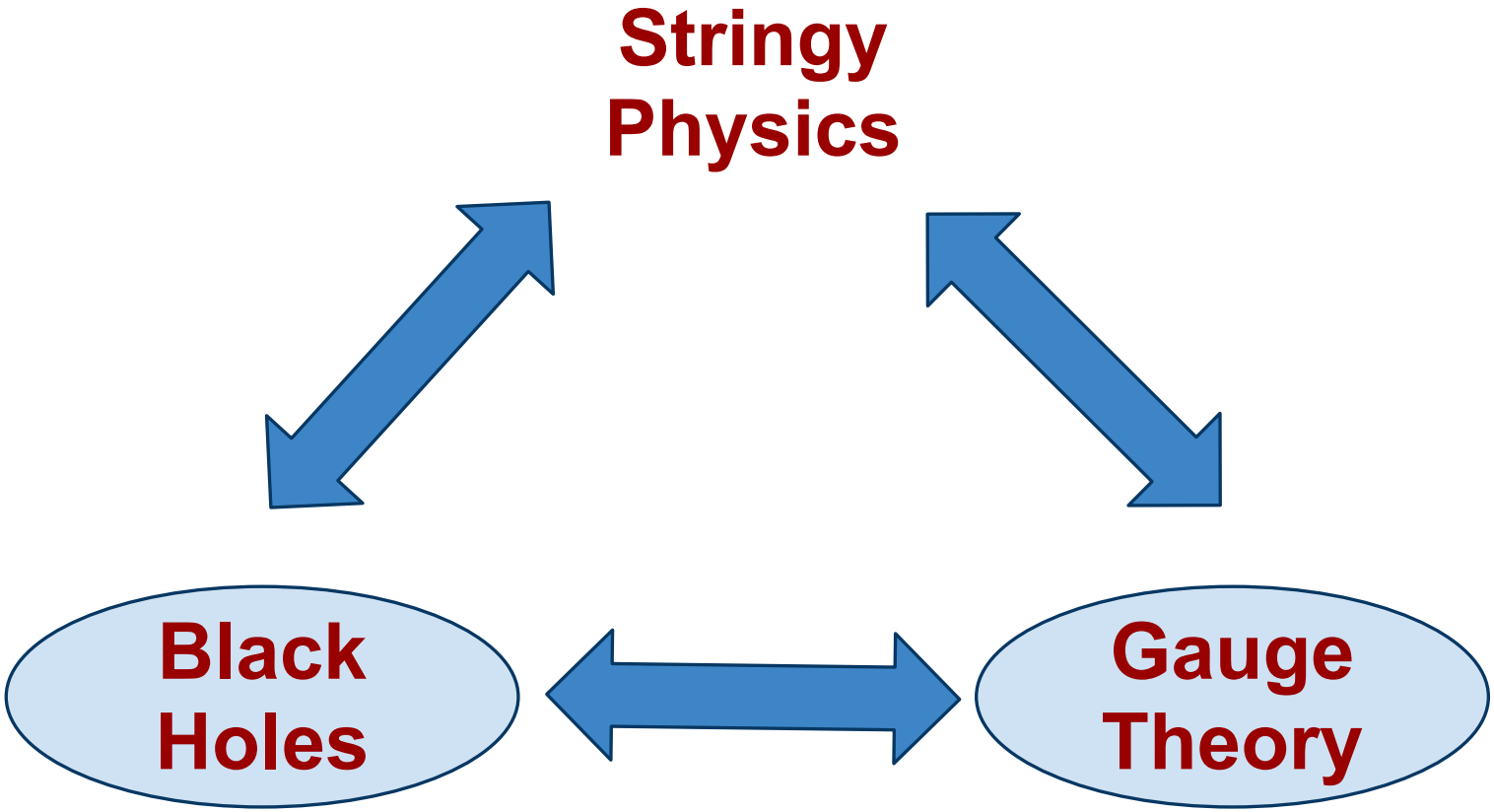
From gluons to flux tubes

- Strong interactions

  $\Rightarrow$ Quanta of gauge field cannot retain an individual existence.

- 'Gestalt switch': Consider lines of flux as the basic quantities.





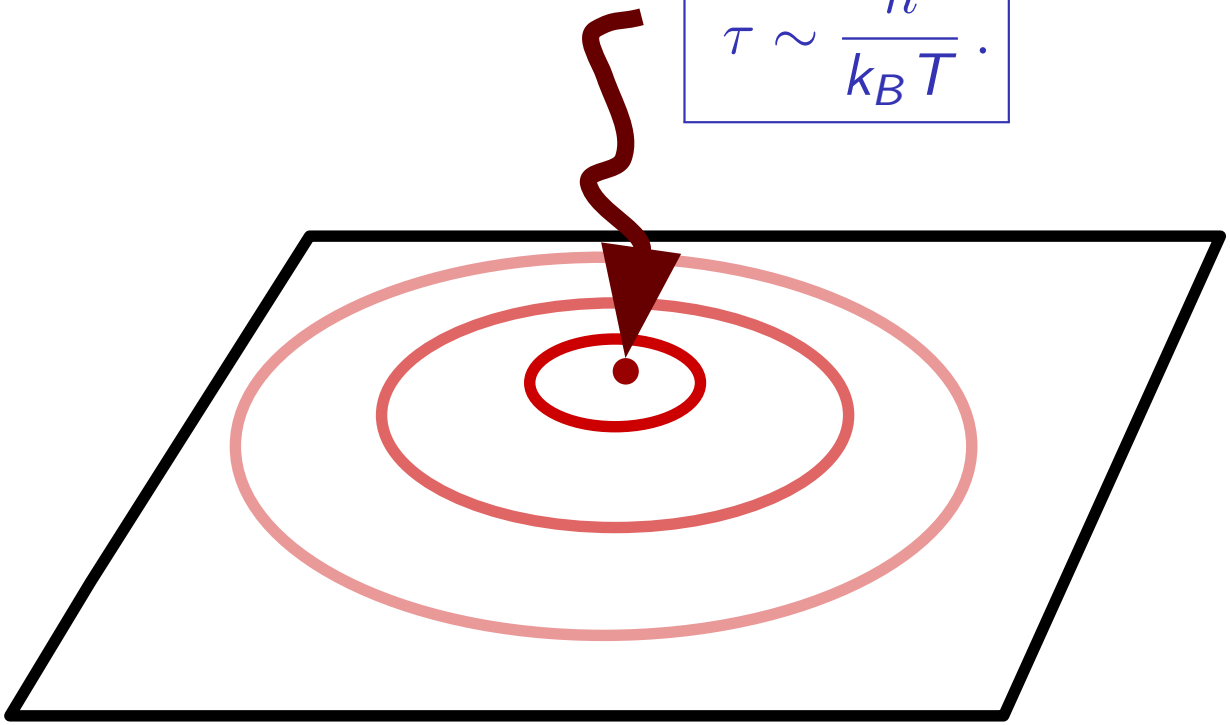
Dissipation on horizon
[Damour, Policastro-Son-Starinets, ...]

Black holes from the outside

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

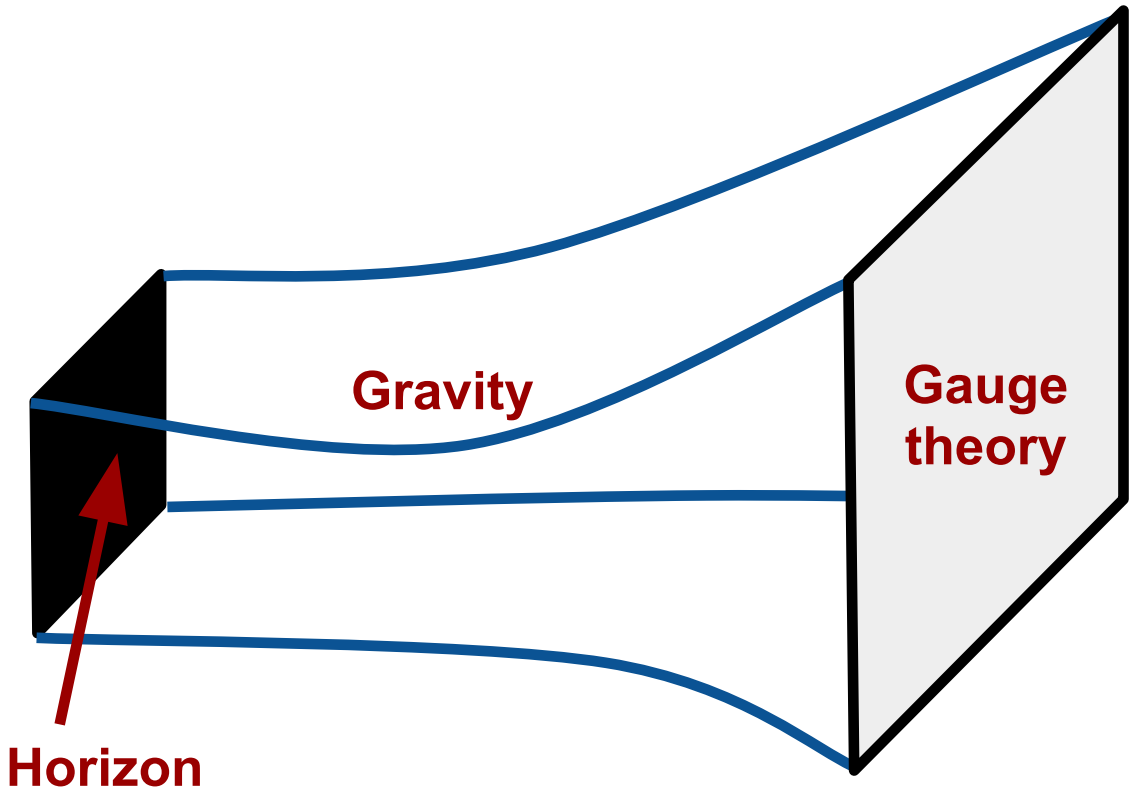
- Relaxation timescale characteristic of a 'quantum critical' medium

$$\tau \sim \frac{\hbar}{k_B T}.$$



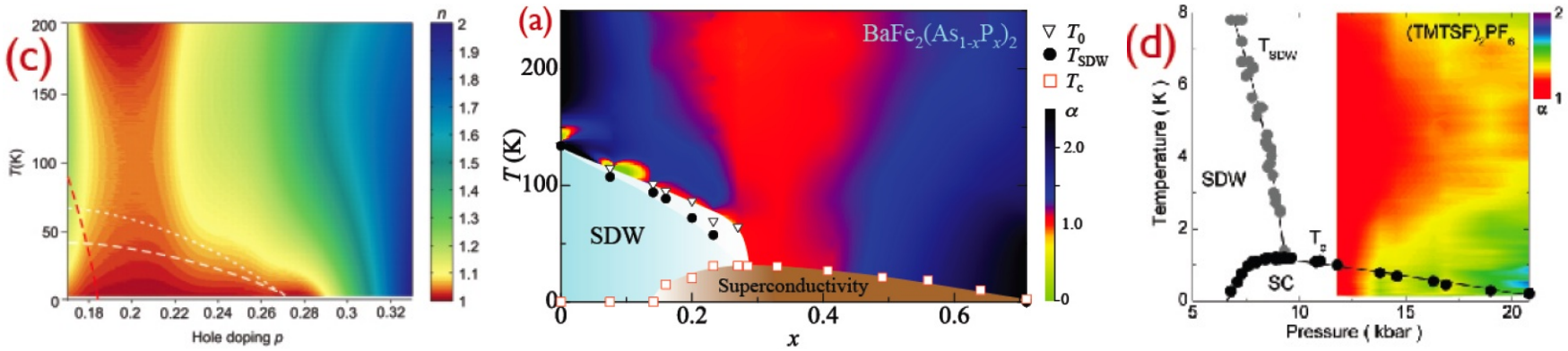
Holography Duality

- 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.

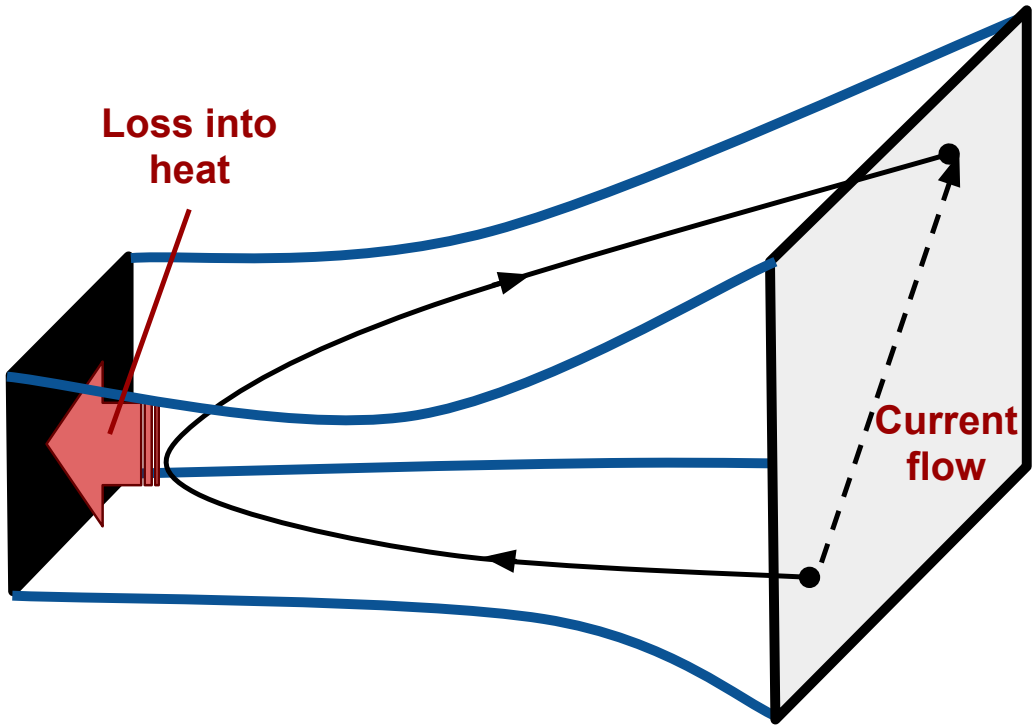
These weeks at the KITP ...

- 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.

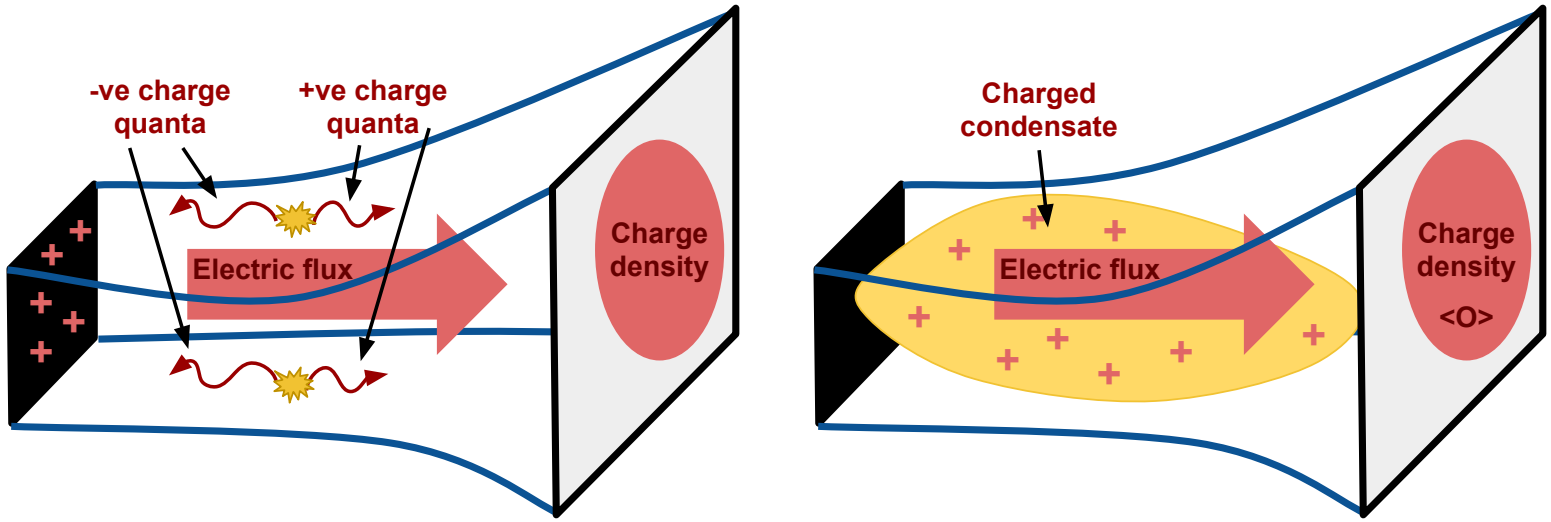
Example: electrical resistivity

- Electrical resistivity: energy lost to heat (entropy)
- The holographic way to calculate the resistivity:



Example: emergence of superconductivity

- 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?