Gauge/gravity duality and applications

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Plan

- QCD, large Nc limit
- Gauge/gravity duality
- Quark/gluon plasma, viscosity
- Applications to condensed matter physics

QCD: nonperturbtive part of the Standard Model

$$SU(3) \times \underbrace{SU(2) \times U(1)}$$

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electroweak interactions
Glashow-Weinberg-Salam

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electroweak interactions
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strong interactions

Asymptotic freedom Gross Politzer Wilczek 1972

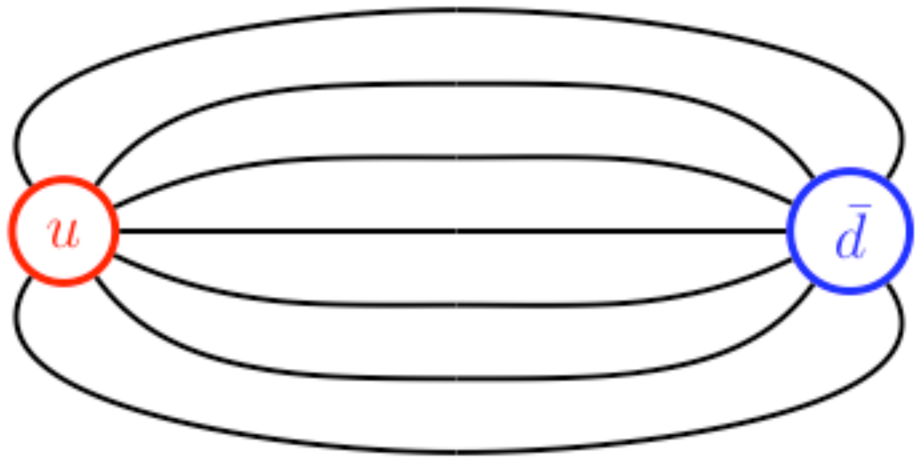
Asymptotic states are hadrons, not quarks and gluons

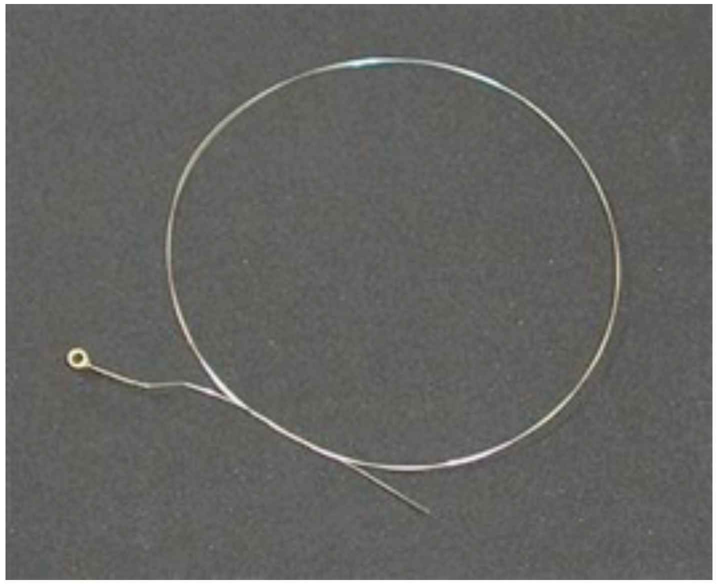
't Hooft large Nc limit

$$N_c \to \infty, \quad g \to 0, \quad g^2 N_c = \text{fixed}$$

Only planar diagrams survive
look like string worldsheets

Effective string theory description of large Nc QCD?





fat flux tube vs elementary string

Gauge gravity duality

- Maldacena 1997: equivalence

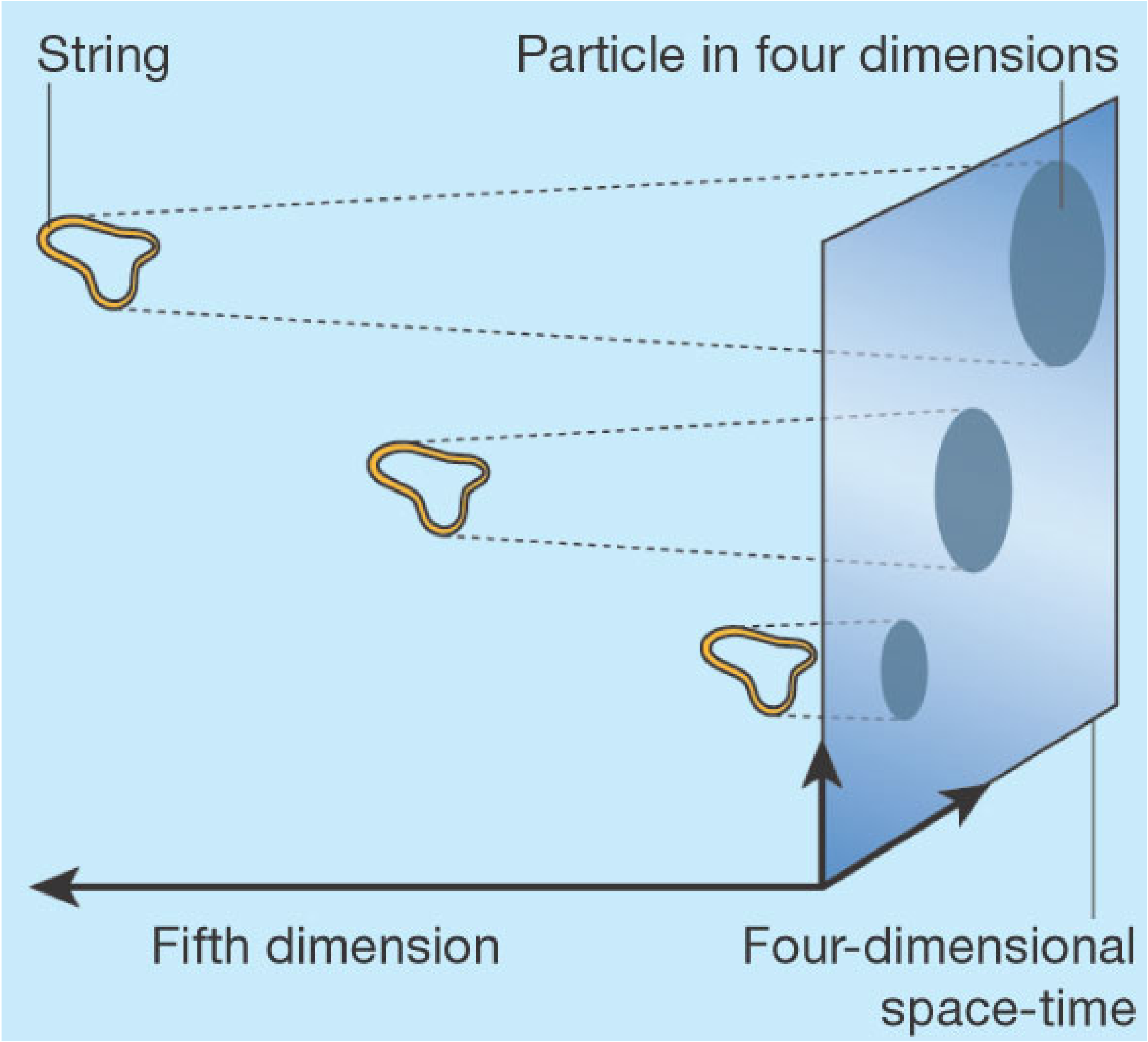
Strongly coupled QFT in 3+1 dimensions	$\Longleftrightarrow$	String theory in 10 dimensions

Complete surprise:

- Different numbers of dimensions
- Role of gravity

$$g^2 N_c \gg 1 \qquad \Longleftrightarrow \qquad \text{Einstein's gravity}$$

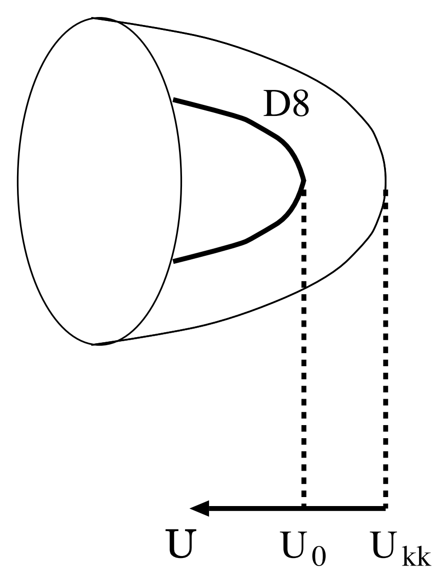
“Holography”



String
Particle in four dimensions
Fifth dimension
Four-dimensional space-time

Approaching QCD

- "Bottom-up" approach: modify the gravitational background to have confinement and chiral symmetry breaking
  - Erlich, Katz, Son, Stephanov "QCD and a holographic model of hadrons" 2005
  - Da Rold, Pomarol "χSB from 5D spaces" 2005
- "Top-down" approach: find string theory solutions with properties of QCD
  - Sakai-Sugimoto model



Viscosity of the quark gluon plasma

- Very high-temperatures: hadrons melt to quarks and gluons: quark-gluon plasma
- Goal of RHIC and LHC heavy ion experiments
- Surprise of RHIC and LHC: QGP behaves like an almost ideal fluid
- Holography: QGP ~ black hole in AdS space

“Prediction” of gauge-gravity duality

$$\frac{\eta}{s} = \frac{\hbar}{4\pi}$$

“Prediction” of gauge-gravity duality

viscosity
fluid mechanics

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entropy per unit volume
thermodynamics

“Prediction” of gauge-gravity duality

viscosity
fluid mechanics

quantum mechanics

$$\frac{\eta}{s} = \frac{\hbar}{4\pi}$$

entropy per unit volume
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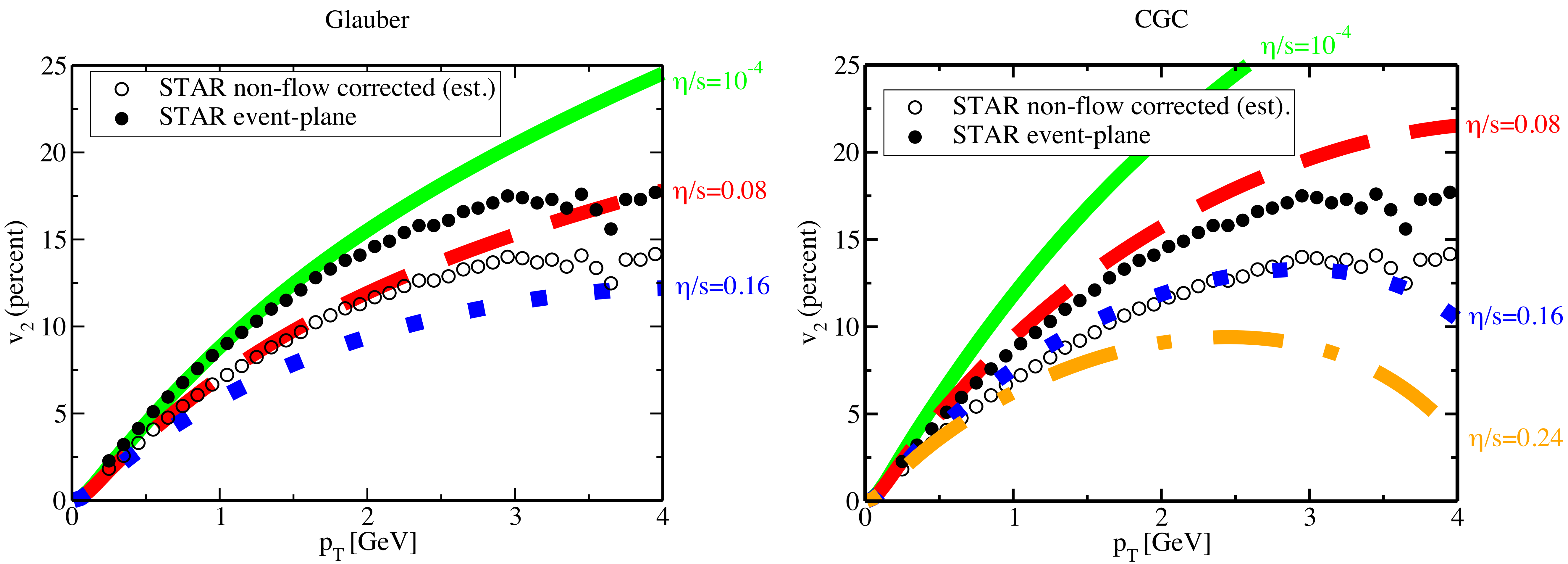
Viscosity of the QGP



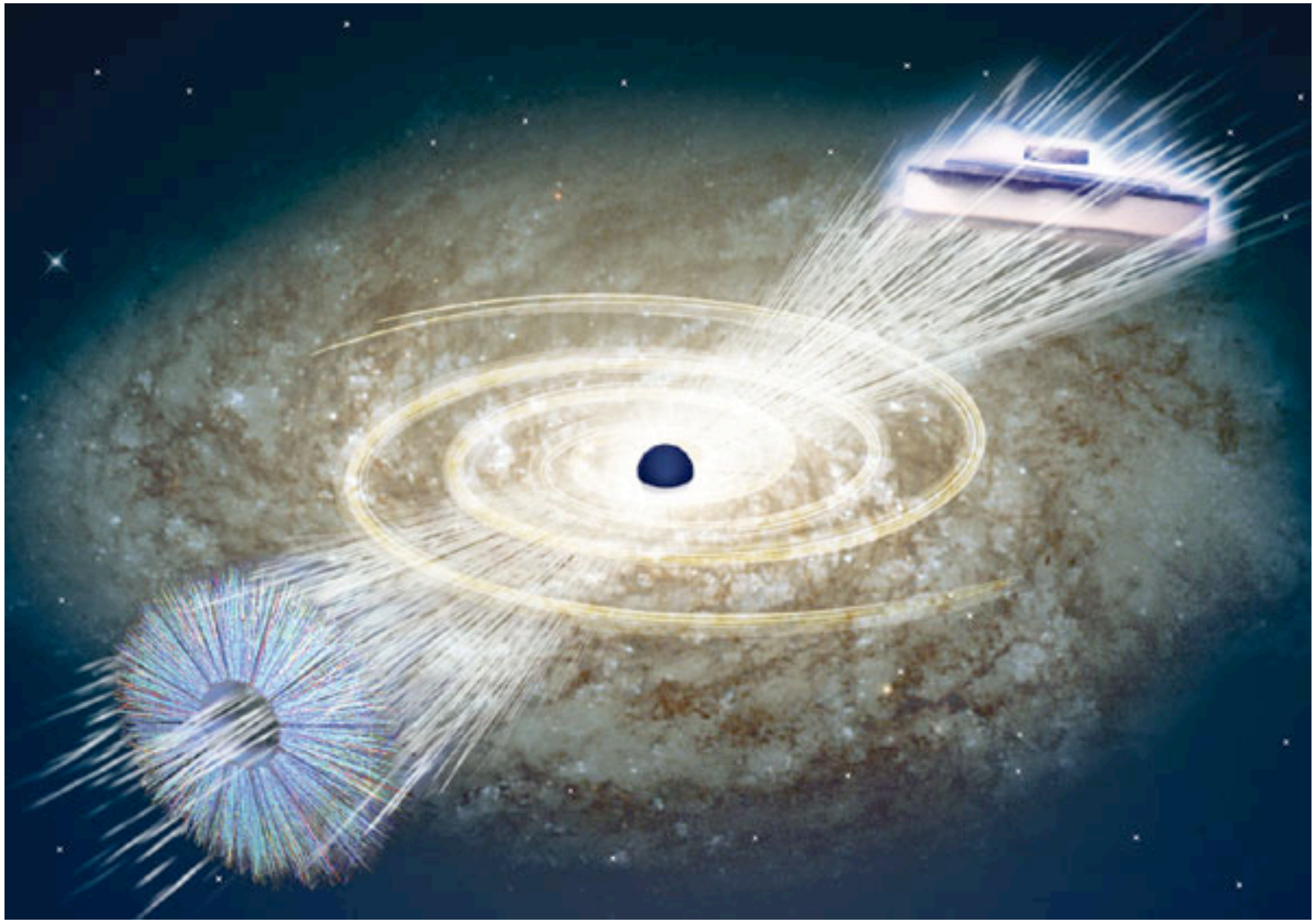
Romatschke and Luzum

$$\frac{\eta}{s} = 0.1 \pm 0.1(\text{th}) \pm 0.08(\text{exp})$$

Not too far away from 1/4π

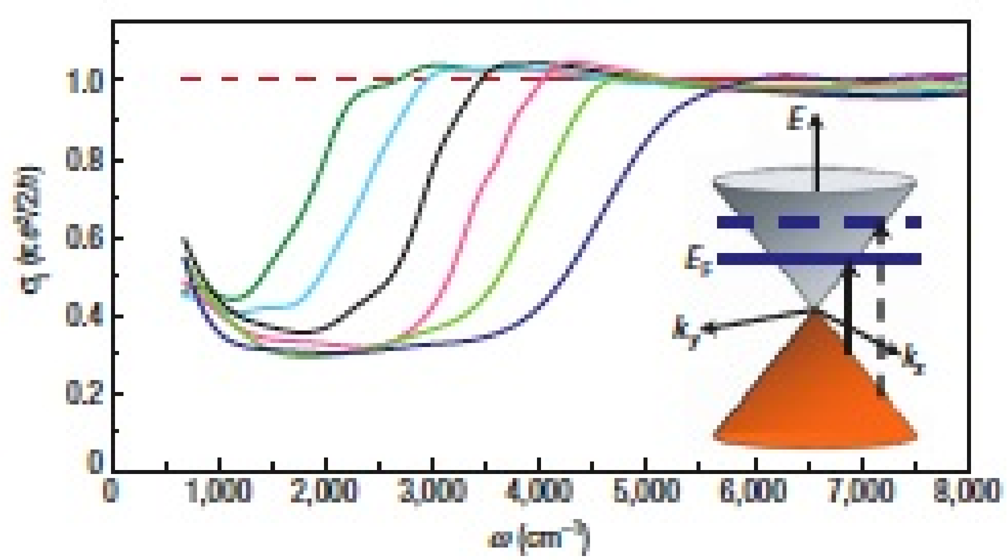
QGP is strongly coupled (sQGP)

Applications to condensed-matter physics?

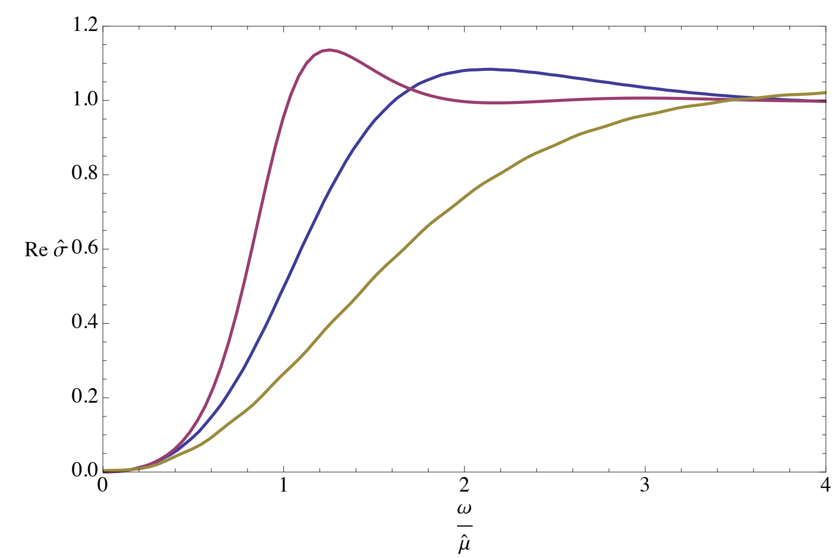


Strongly coupled superconductors

- Motivation: high-Tc superconductivty
  - Normal phase with nontrivial properties ("strange metal")
- Gauge/gravity duality: enables studies of some models of strongly coupled superconductors

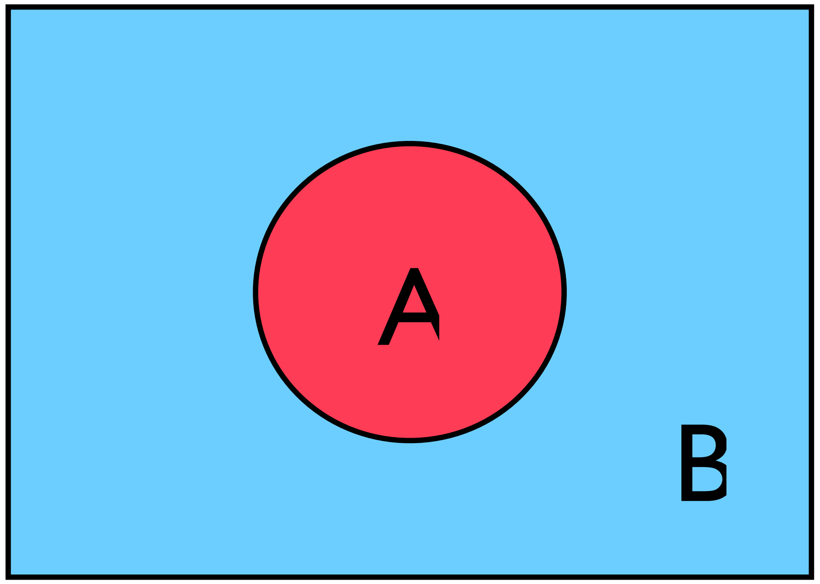


[Li, Henriksen, Jiang, Hao, Martin, Kim, Stormer, Basov '04]



Herzog, Harnoll, Horowitz

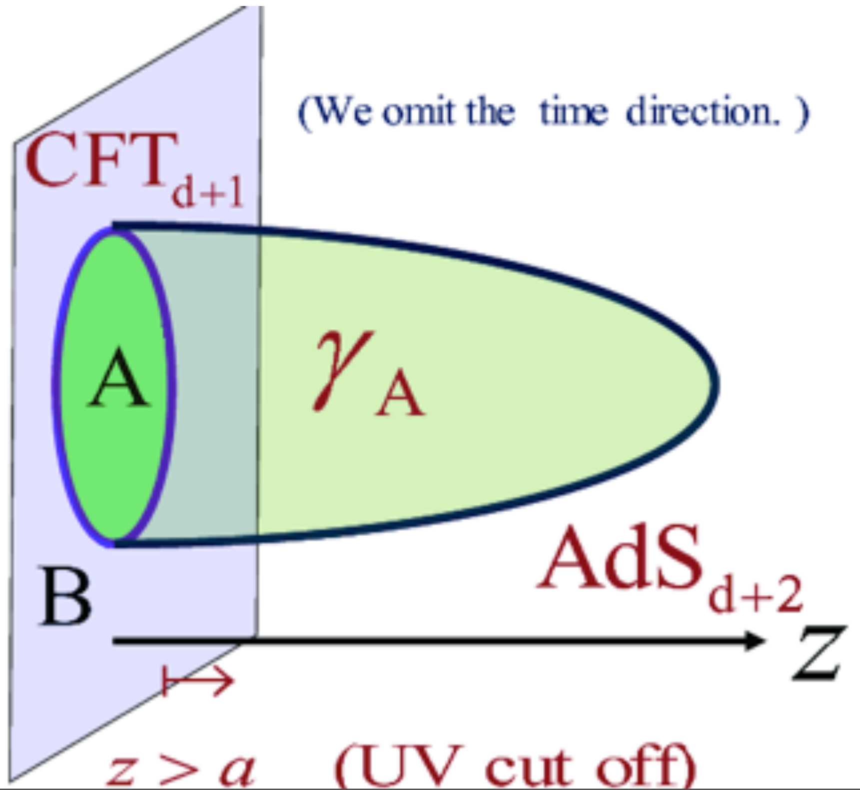
Entanglement entropy



$$\rho_A = \mathrm{tr}_B\, \rho_{\mathrm{tot}}$$

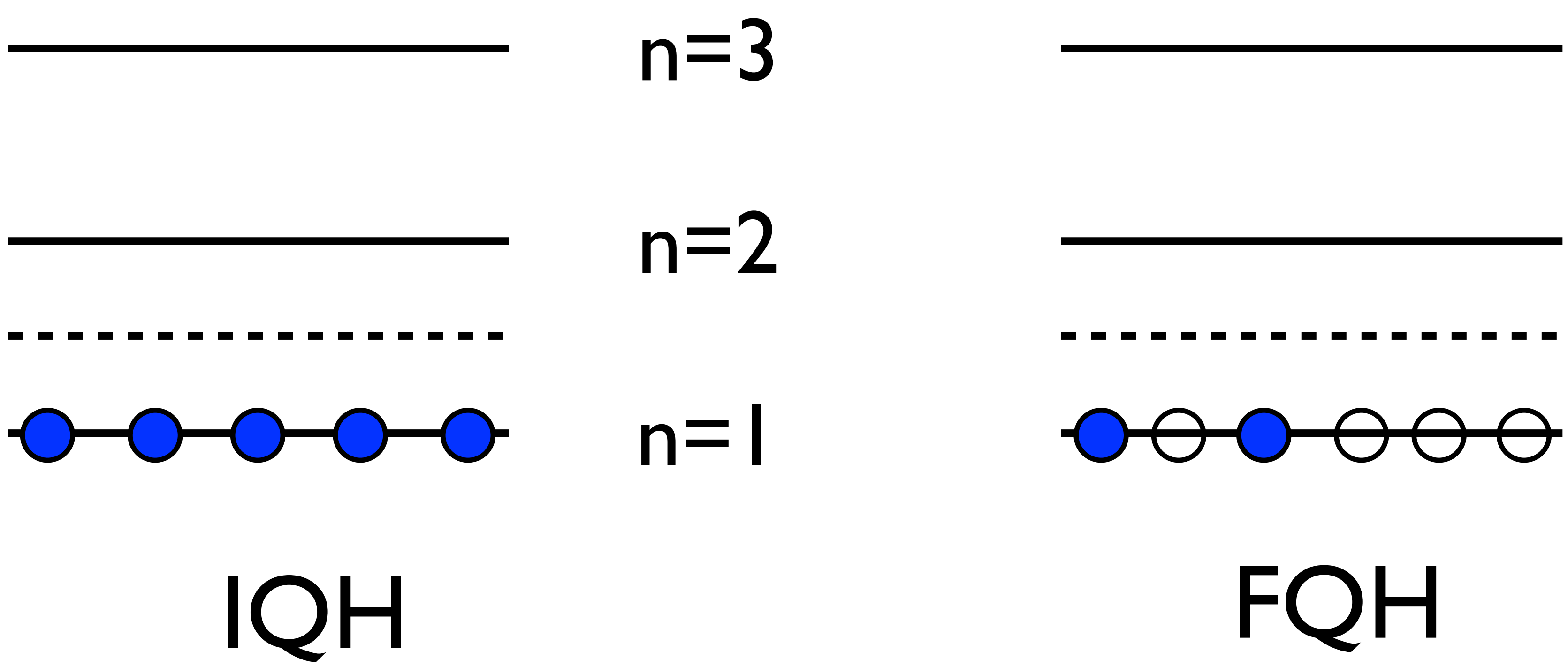
$$S_A = -\mathrm{tr}\, \rho_A \ln \rho_A$$

Entanglement entropy from holography (Ryu-Takanayagi)



Gravity in quantum Hall effect?

- 2 types of quantum Hall effects
  - integer QHE (von Klitzing 1980)
  - fractional QHE (Tsui, Stormer 1982)



Excitations in FQH systems

- Ground state degeneracy lifted by interactions
- Excitations
  - fractionally charged quasiparticles
  - neutral magneto-rotons

Physics is strongly nonperturbative (cf. QCD)

Useful gravitational dual?

Gravity for QHE

- The theory of QHE can be formulated to be frame-independent, like General Relativity
- A convenient framework: Newton-Cartan's geometry

Cartan 1923-1924

Reformulation of Newton's theory of gravity

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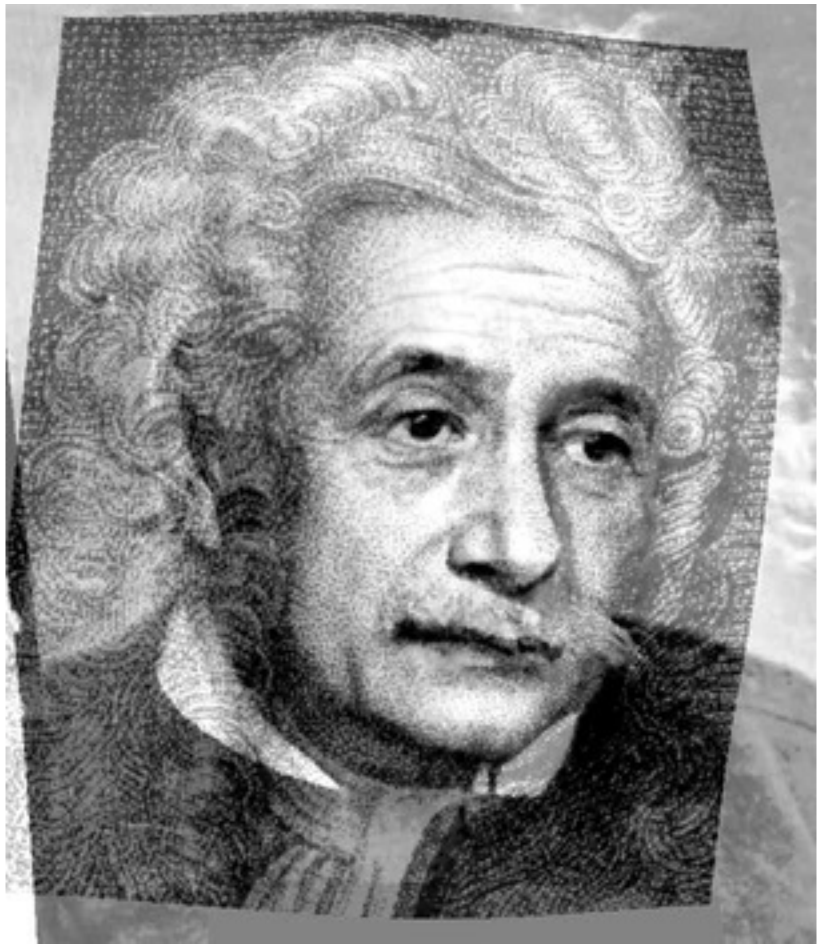
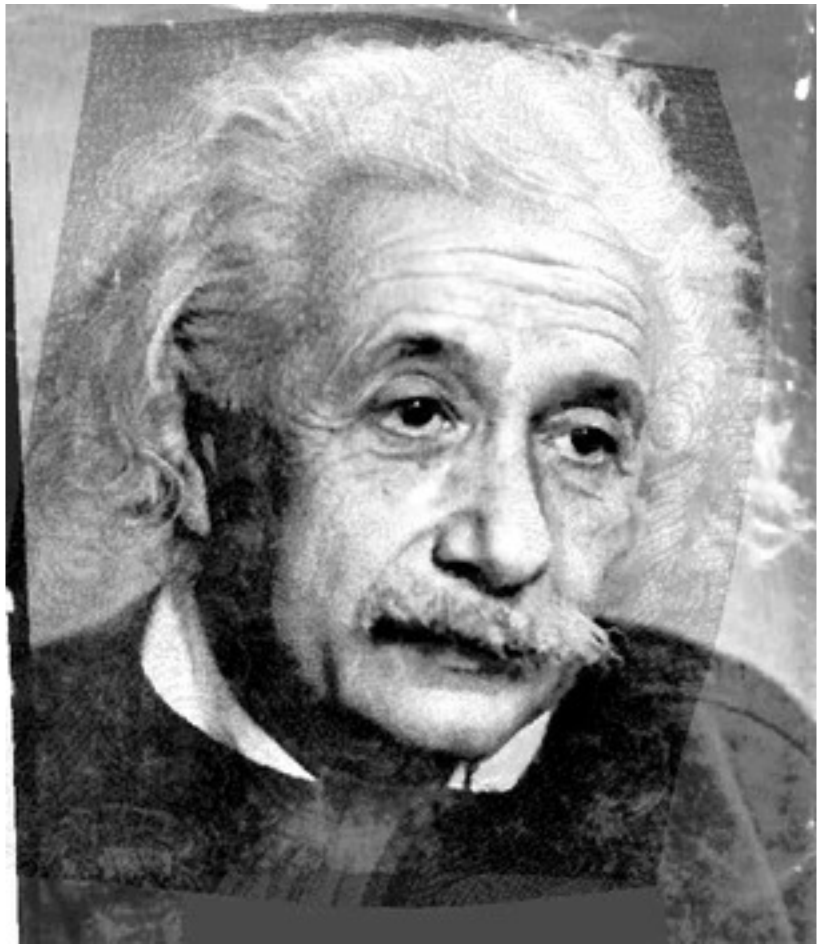


Cartan 1923-1924

Reformulation of Newton's theory of gravity



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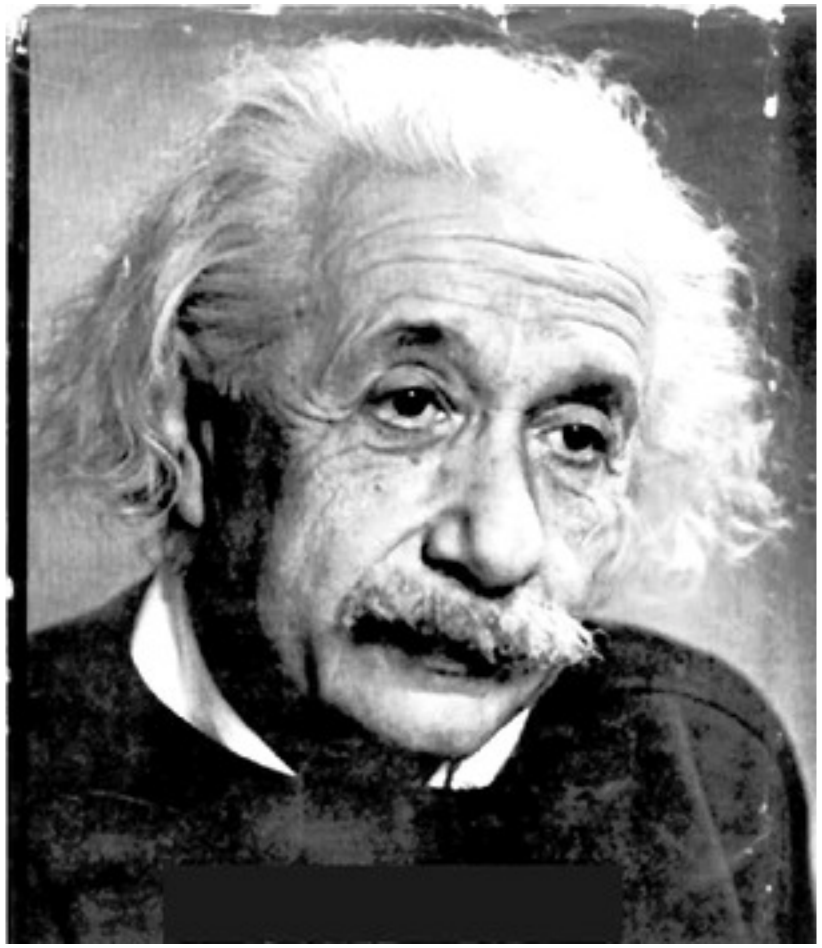
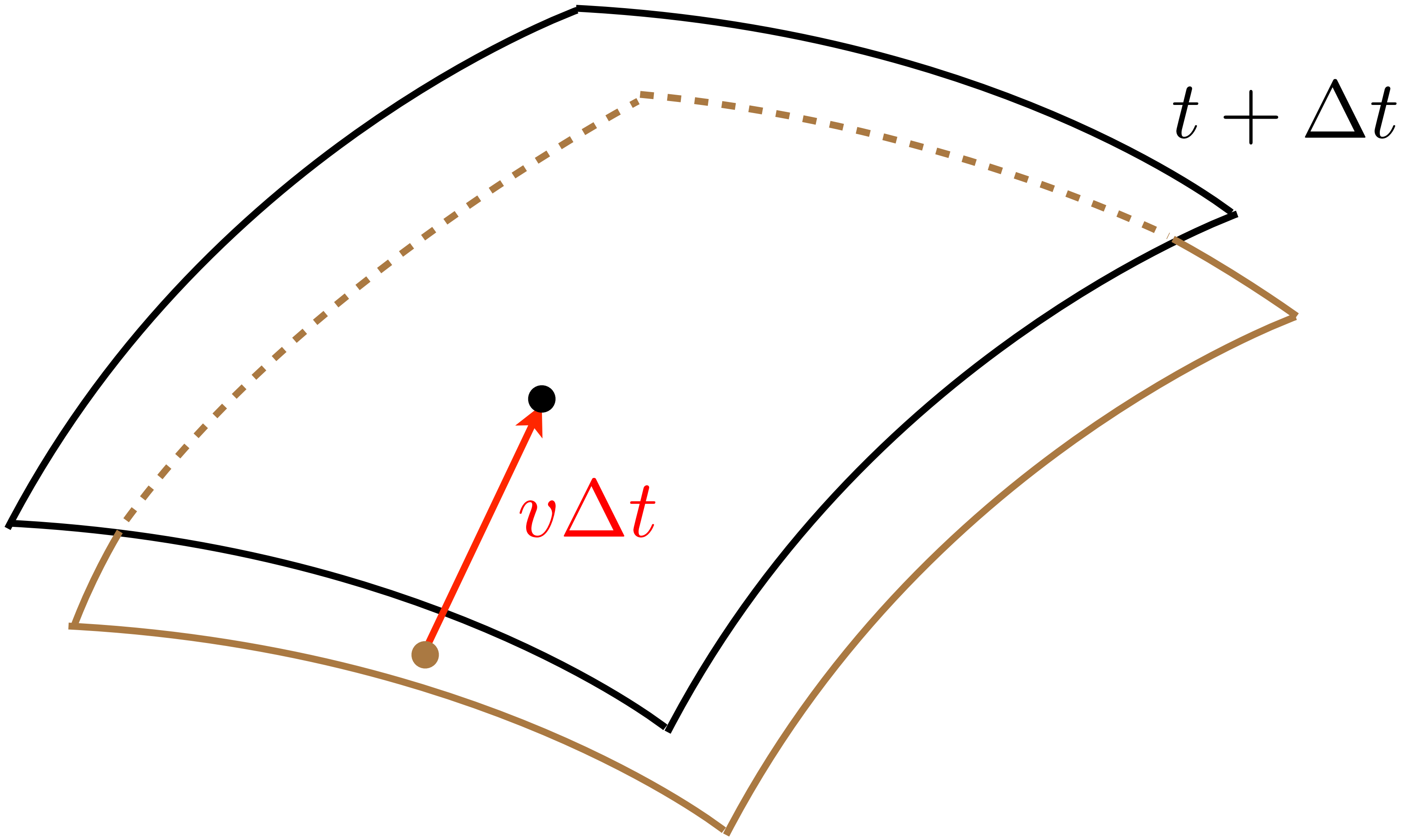
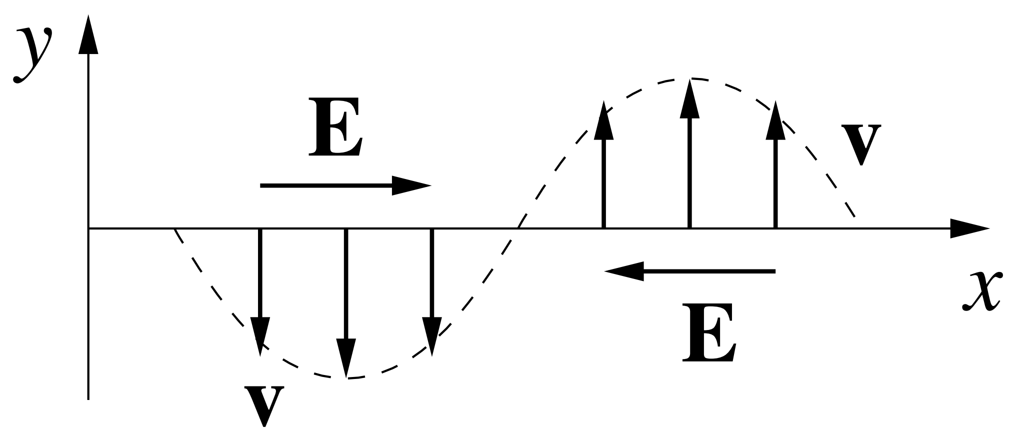




$$g_{ij}, \quad v^i$$

A prediction of Newton-Cartan formalism

Hall conductivity at nonzero wavenumber



$$E_x = E\,\mathrm{e}^{iqx}$$

$$j_y = \sigma_{xy}(q) E_x$$

$$\frac{\sigma_{xy}(q)}{\sigma_{xy}(0)} = 1 + C_2 (q\ell)^2 + \mathcal{O}(q^4\ell^4)$$

Carlos Hoyos, DTS 2011
DTS 2013

universal coeff.

$$C_2 = \frac{1}{4\nu} - 1, \;\; \nu = \frac{1}{2p+1}$$

Magnetoroton as emergent graviton?

- Haldane: there is a hidden metric in FQH systems
- A graviton, made massive by a gravitational Higgs mechanism S.Golkar, Nguyễn Xuân Dũng, DTS, to appear

$$(\partial_i u_j + \partial_j u_i + h_{ij})^2$$

fluid displacement = NG boson (eaten)

magnetoroton = graviton
magnetoroton at q=0 has spin polarization

Conclusion

- Gauge/gravity duality: connections between seemingly unrelated systems
- Black holes in AdS space as rough model of the strongly coupled QGP
- Maybe useful for condensed matter physics
- Fractional quantum Hall systems: a system with emergent massive graviton?