From Strongly Coupled SQFT to Quantum Gravity

Chiung Hwang

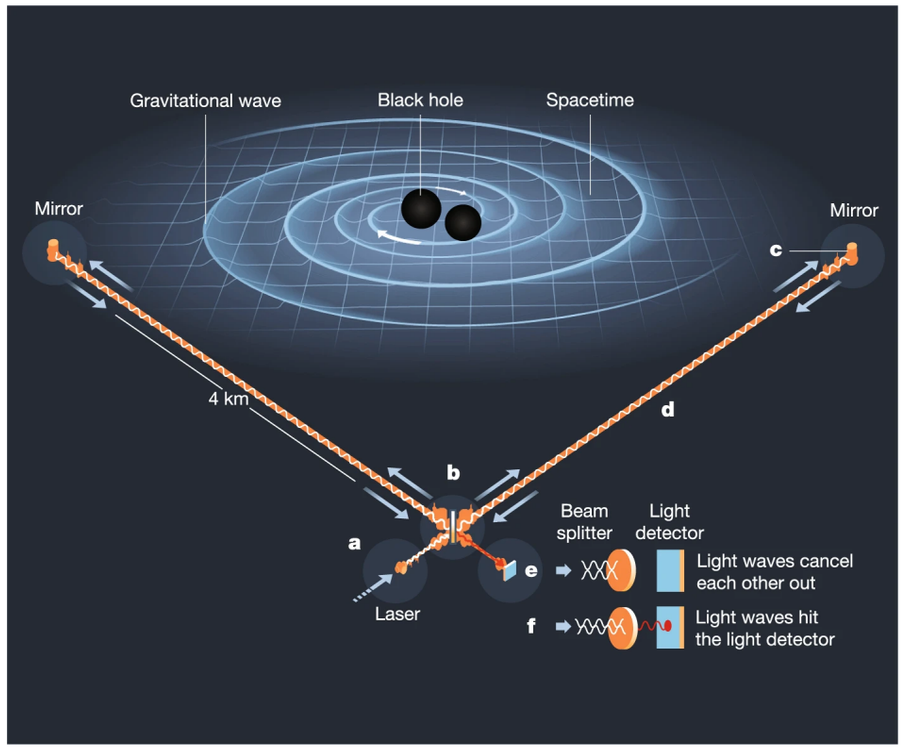
November 2 @ CTPU-PTC Welcome Workshop

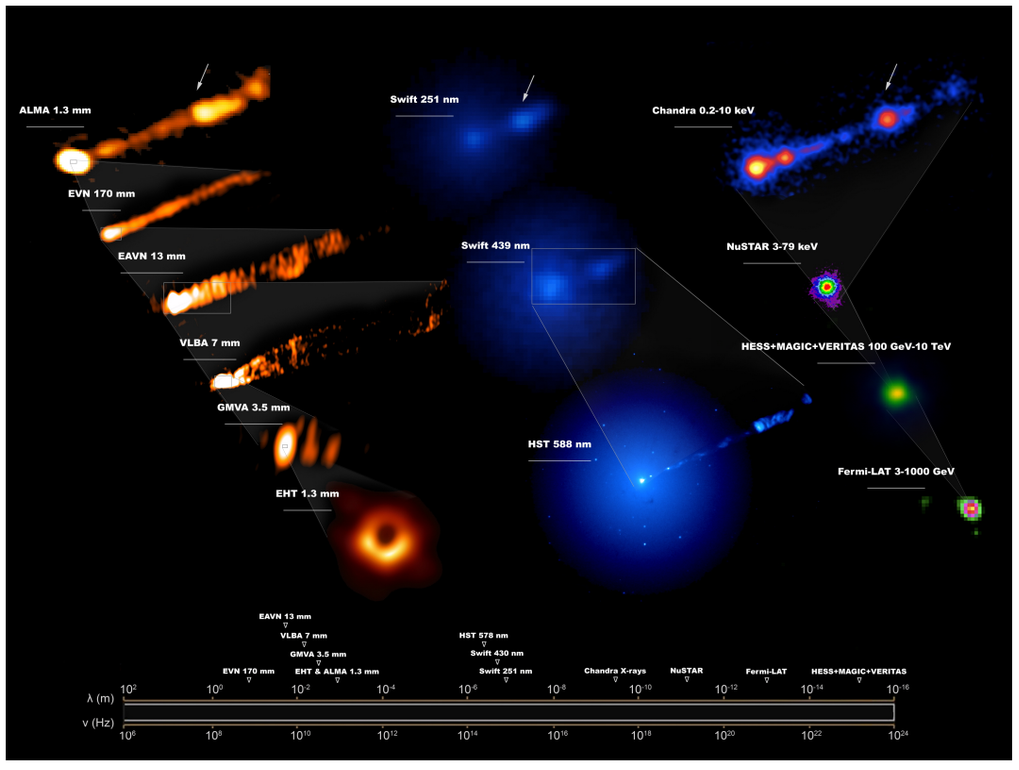
Who Am I?

- Chiung Hwang
- Joined CTPU in October as a Young Scientist Fellow
- My research interest is holography and duality of quantum field theory.

Academic Journey

Physics of Black Holes

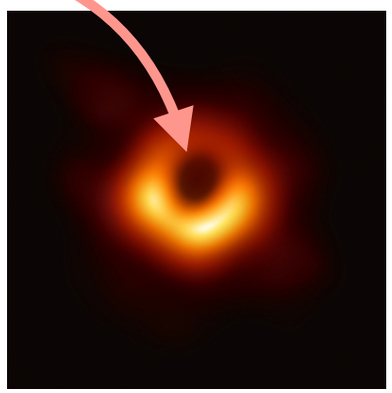

Gravitational wave
Black hole
Spacetime
Mirror
Mirror
c
4 km
d
b
a
e
Laser
Beam splitter
Light detector
Light waves cancel each other out
f
Light waves hit the light detector


ALMA 1.3 mm
Swift 251 nm
Chandra 0.2-10 keV
EVN 170 mm
EAVN 13 mm
Swift 439 nm
NuSTAR 3-79 keV
VLBA 7 mm
HESS+MAGIC+VERITAS 100 GeV-10 TeV
GMVA 3.5 mm
HST 588 nm
Fermi-LAT 3-1000 GeV
EHT 1.3 mm
EAVN 13 mm
VLBA 7 mm
GMVA 3.5 mm
EVN 170 mm
EHT & ALMA 1.3 mm
HST 578 nm
Swift 430 nm
Swift 251 nm
Chandra X-rays
NuSTAR
Fermi-LAT
HESS+MAGIC+VERITAS
λ (m)
ν (Hz)

- Still, a black hole is a mysterious object.
- A (classical) black hole vs. the 2nd law of thermodynamics

$$\Delta S \geq 0$$

Entropy S



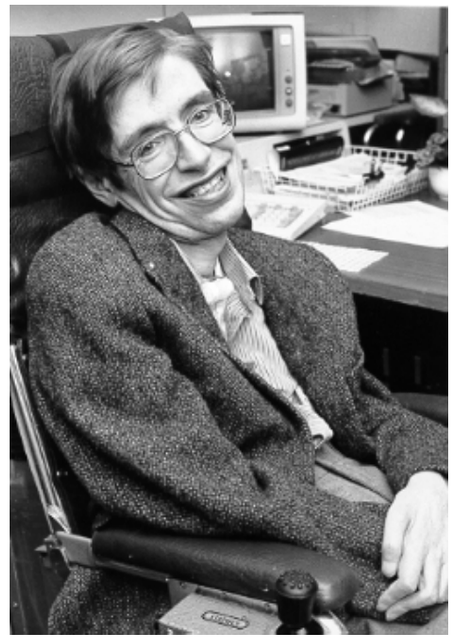
- The observable entropy seems to decrease.
- A violation of the 2nd law or non-zero entropy of a black hole?
- Signals non-zero temperature of a black hole—thermal radiation?

- Semi-classical analysis—the **quantum** fluctuation of fields around a classical black hole background

- Black holes do **radiate!** [Hawking 74]

- Thermal properties of a black hole

$$T_H = \frac{1}{8\pi M k_B} \qquad S_{BH} = \frac{1}{4} k_B A$$



- The ***microstates*** of a black hole? $e^{S/k_B} \sim e^{10^{44}}$ for 10 $M_\odot$

- On the other hand, everything is squeezed into a single point in a Schwarzschild black hole.

- Quantum nature of spacetime itself

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- Quantum nature of spacetime itself

Quantum gravity and black hole thermodynamics go side by side.

Black Hole Thermodynamics and Holographic Duality

Black Hole in the Anti-de Sitter Space

- The Hawking temperature

$$T_H = \frac{\hbar c^3}{8\pi G M k_B} \qquad \sim \frac{1}{M}$$

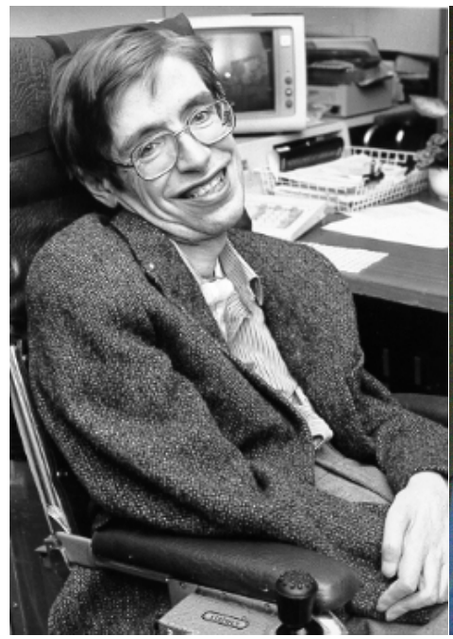
- A black hole in the flat spacetime -> negative specific heat
- The **Anti-de Sitter (AdS)** spacetime:

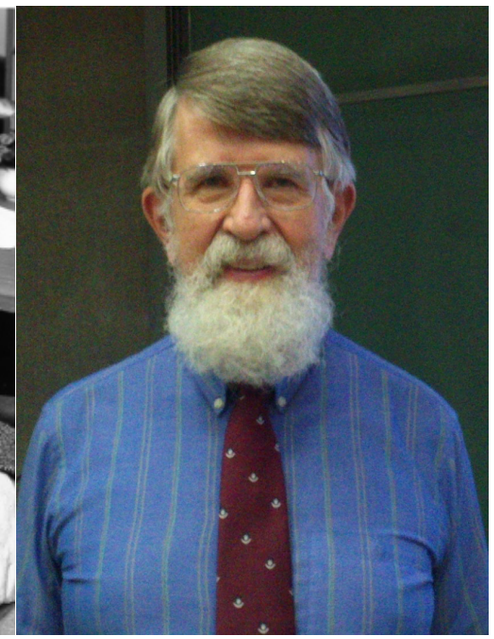
  the maximally symmetric solution to Einstein's equation with negative cosmological constant

- Positive specific heat, **thermodynamically stable**

Black Hole in the Anti-de Sitter Space

- Hawking-Page phase transition (1983)
  - $T < T_0$: thermal AdS in equilibrium
  - $T_0 < T < T_1$: thermal AdS preferred
  - $T_1 < T < T_2$: black hole preferred
  - $T_2 < T$: no equilibrium without a black hole





- Nontrivial phase structure with the 1st order transition

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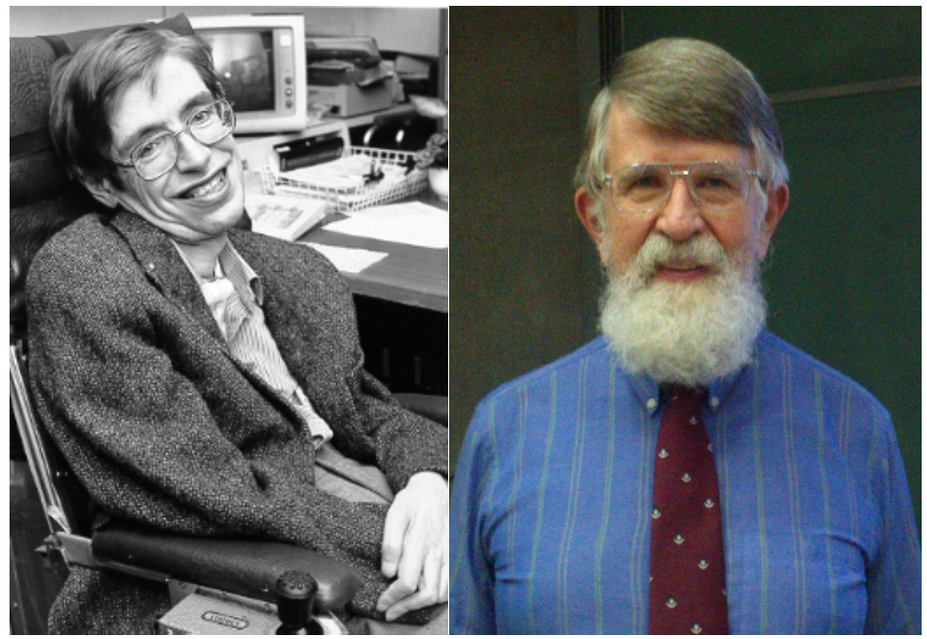


- Nontrivial phase structure with the 1st order transition

AdS is a nice playground to study black hole thermodynamics.

Holographic Duality

- A groundbreaking property of the AdS gravity [Maldacena 97]
- Also called: the AdS/CFT correspondence, the gauge/gravity duality, the Maldacena duality, …
- The most cited paper in INSPIRE (18,000 times)

The Large N Limit of Superconformal field theories and supergravity

Juan Maldacena[1]

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Abstract

We show that the large N limit of certain conformal field theories in various dimensions include in their Hilbert space a sector describing supergravity on the product of Anti-deSitter spacetimes, spheres and other compact manifolds. This is shown by taking

Holographic Duality

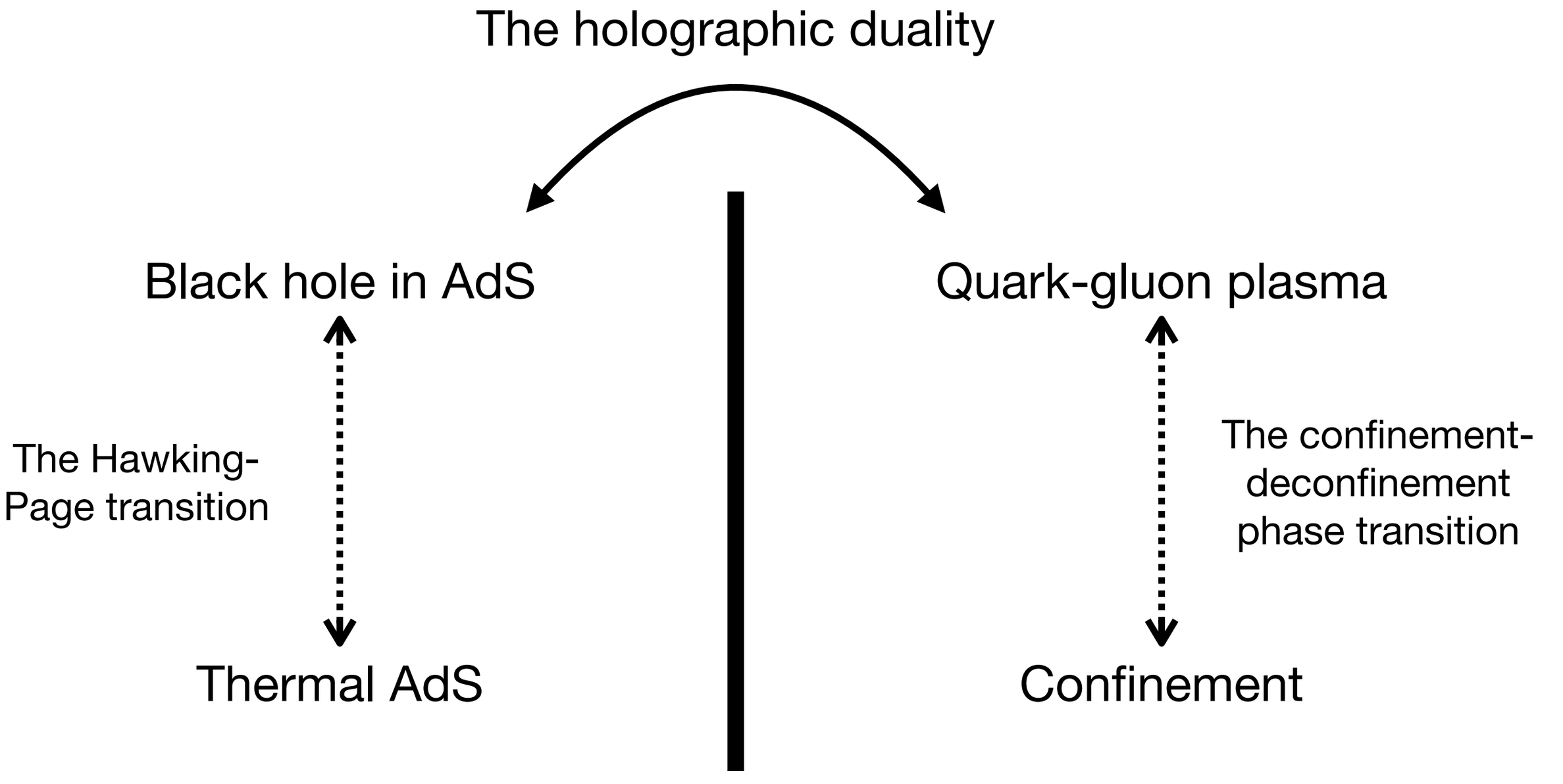
- **Duality between d-dimensional QFT and d+1-dimensional gravity**

3d Gauge Theory	4d AdS Gravity
More (Less) Gluons	Small (Large) Quantum Correction
Strong (Weak) Coupling	Small (Large) Higher Cuvature Correction

- Quantum gravity described by QFT
- Strongly coupled QFT described by gravity

Black Hole from Non-Perturbative Dynamics of QFT

Black Hole via Holographic Duality



Black Hole via Holographic Duality

Gravity side:

$\mathcal{N} = 8$ gauged supergravity

- An AdS black hole with (M, Q, J) satisfying $M = 4Q + J = \tilde{Q} + J$
- Black hole entropy [Choi-**CH**-Kim-Nahmgoong 18]

$$S = \frac{\pi}{2}\sqrt{\tilde{Q}^2 - \frac{8L^2}{G}\frac{J}{\tilde{Q}}}$$

QFT side:

- 2+1d $U(N)$ gauge theory with matter fields

(Dual of) the 2+1d maximally supersymmetric $U(N)$ Yang-Mills theory

- The grand canonical partition function

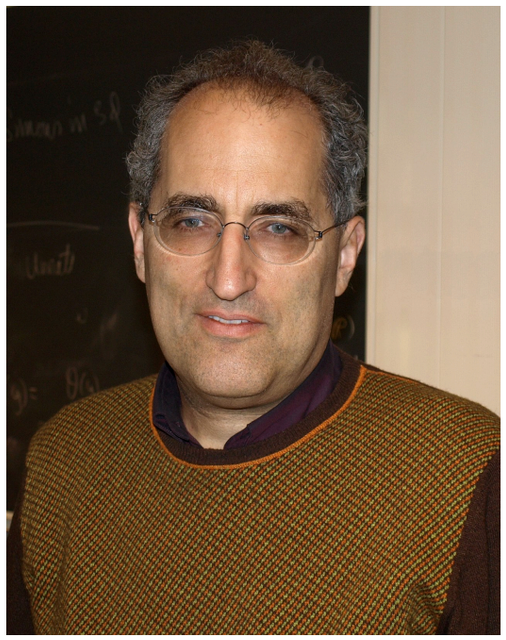
$$Z = \mathrm{Tr}_{E=\tilde{Q}+J}\, e^{-\Delta\tilde{Q}-\omega J}$$

→ Hard to compute for strongly coupled theories

Black Hole via Holographic Duality

- Witten (1982)

$$I = \mathrm{Tr}_{E=\tilde{Q}+J}(-1)^F e^{-\Delta\tilde{Q}-\omega J}$$



- Topological, exactly computable even if the theory is strongly coupled

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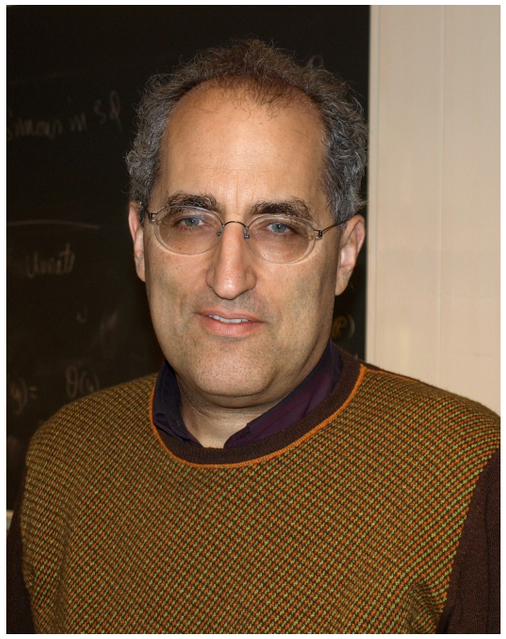

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Explore phases of the 2+1d gauge theory dual to 4-dimensional AdS gravity!

Confinement

1. The confinement phase [Bhattacharya-Minwalla 08, S.Kim 10]

- No isolated quark, only colorless bound states
- An order parameter for the confinement: the Polyakov loop

$$P \sim \mathrm{Tr}\, e^{\int A} = \sum_{k=1}^{N} e^{u_k}$$

# of gluons: $N \times N$

# of quarks: N

- The free energy of an isolated quark

$$F_{quark} \sim -\log \langle P \rangle$$

- In the confinement phase with $\langle u_k \rangle = 2\pi i k/N$

$$\langle P \rangle = 0\,, \qquad F_{quark} \to \infty \quad \Rightarrow \quad I_{QFT} = I_{graviton}$$

without a black hole

Deconfinement and Black Holes

2. The deconfinement phase [Choi-**CH**-Kim 19]

- A saddle point with $\langle P \rangle \neq 0$?
- *A long-standing problem over 10 years*

- Non-perturbative monopoles play a crucial role.
- A new saddle point with the monopole condensation

$$\langle P \rangle \sim e^{\sqrt{N}}$$

Deconfinement and Black Holes

2. The deconfinement phase [Choi-**CH**-Kim 19]

- The grand canonical partition function and the entropy

$$\log I \approx i\frac{4\sqrt{2}N^{\frac{3}{2}}}{3}\frac{\Delta^2}{\omega} \qquad S = \frac{\pi}{2}\sqrt{\tilde{Q}^2 - \frac{64}{9}\frac{N^3 J}{\tilde{Q}}}$$

Holographic dictionary: $\frac{L^2}{G} = \frac{2\sqrt{2}}{3}N^{\frac{3}{2}}$

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Quantum mechanical derivation of the black hole entropy

Deconfinement and Black Holes

- **The crucial effect of the monopole condensation**

- # of gluons: N^2

- # of quarks: N

→ The naive dof in the deconfinement: N^2

- The holographic dictionary predicts

$$\log I \sim \frac{1}{G} \sim N^{\frac{3}{2}}$$

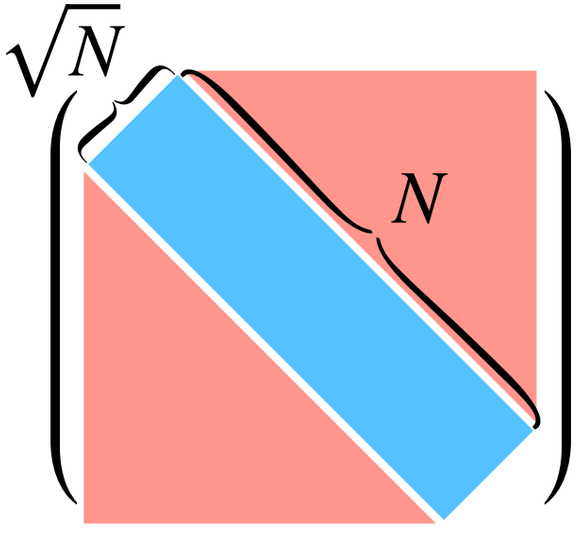
- N^2 vs $N^{\frac{3}{2}}$?

Deconfinement and Black Holes

- Effective mass of $N \times N$ gluons due to monopole condensation (Higgs mechanism)

$$M_{ab} \sim N^{-\frac{1}{2}} |\, a - b \,|$$

  - $|\, a - b \,| \lesssim N^{\frac{1}{2}}: \; M_{ab} \lesssim 1$
  - $|\, a - b \,| \gg N^{\frac{1}{2}}: \; M_{ab} \gg 1$



→ Only $N \times \sqrt{N}$ light gluons

- The free energy of N quarks

$$N \times F_{quark} \sim -N \log \langle P \rangle \sim -N^{\frac{3}{2}}$$

Deconfinement and Black Holes

- A number of results reporting $N^{\frac{3}{2}}$ for other non-perturbative observables in the literature [Gang-**CH**-Kim-Park 11, Cheon-Gang-**CH**-Nagaoka-Park 11, …]

- **The first physical understanding of the origin of $N^{\frac{3}{2}}$**

- The condensation of the monopole operator in the deconfinement phase

  -> ***partial*** deconfinement rather than full deconfinement

- Nontrivial prediction for strong dynamics of the 2+1d $U(N)$ gauge theory

- The 1st order phase transition between the **partial deconfinement** and the **confinement** expected

- Exactly (a supersymmetric version of) the Hawking-Page transition between **black hole** and **thermal AdS** phases in dual gravity

What Is Next?

- Holographic duality relates thermodynamics of gravity to strong dynamics of QFT.
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What are those states holographically dual to a black hole?

Classification of Black Hole States

- Much harder than counting
- Need some simplification
- More (super)symmetric states?
- Already classified and no deconfinement

4D MSYM & AdS5 Black Holes

- Instead, let's consider a **3+1d** maximally supersymmetric Yang-Mills theory.
- Dual to 5-dimensional AdS
- The states preserving more supersymmetry are not completely classified.

A New Black Hole?

- The known supersymmetric black hole solution in AdS5 preserves a minimal amount of supersymmetry.

- A black hole preserving **more supersymmetry**?

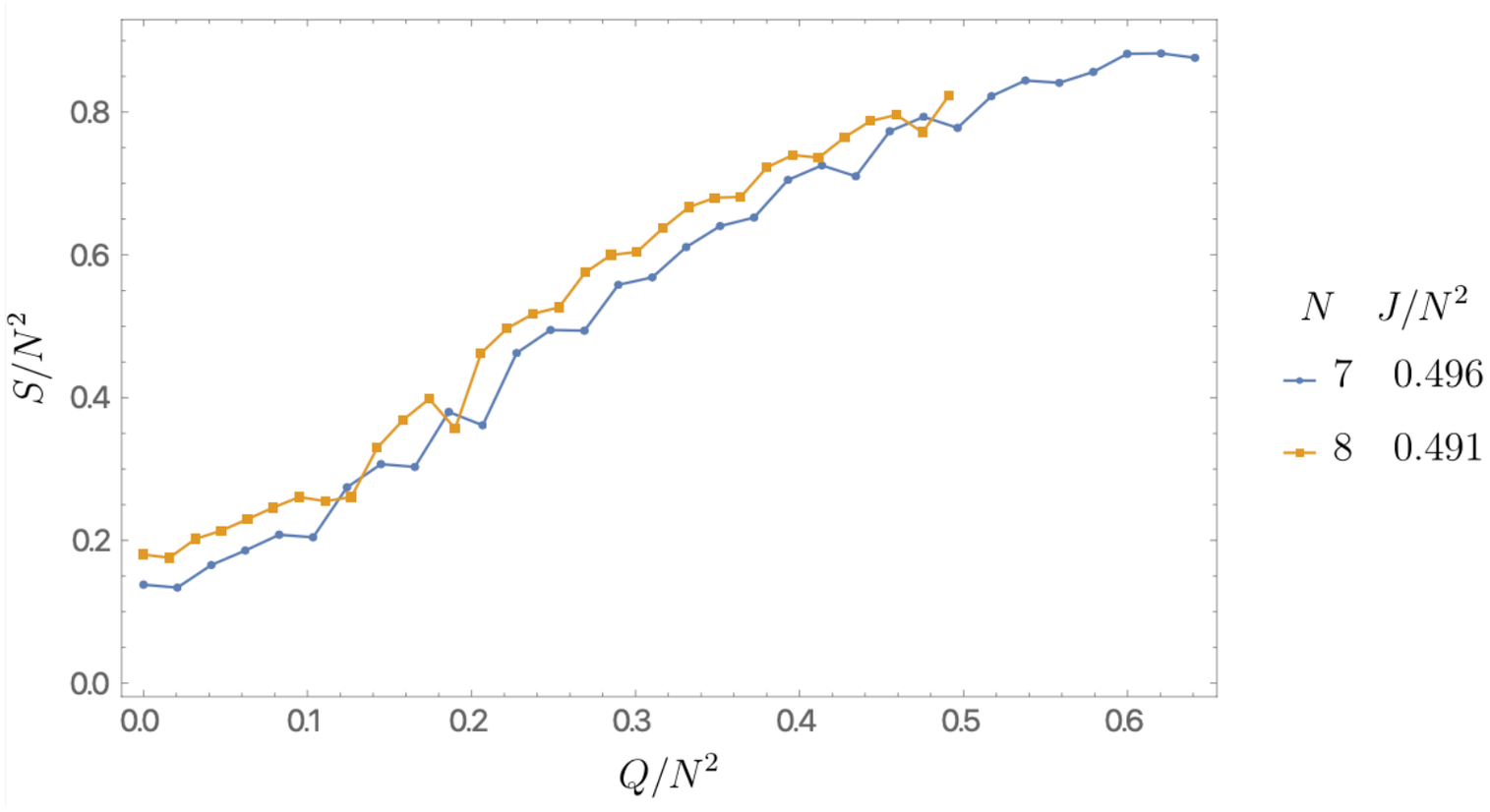
- More constraints on dual QFT states -> could be useful for a classification

- No known solution on the gravity side

- **Deconfinement** on the QFT side?

Black Hole with More Supersymmetry

- Work in progress with O. Dias, P. Mitra, J. Santos
- Explore the deconfinement phase ($\sim N^2$) in more supersymmetric sectors



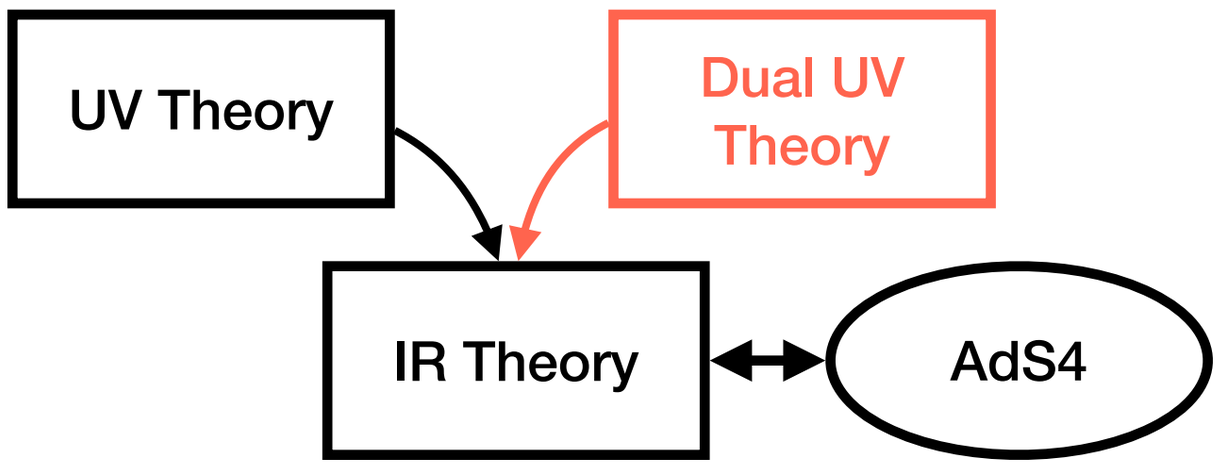
Black Hole with More Supersymmetry

- Predicts a ***new*** black hole—a guideline where to investigate to find a new black hole solution
- What is entropy?
- More constrained QFT states—a classification of **black hole states**?

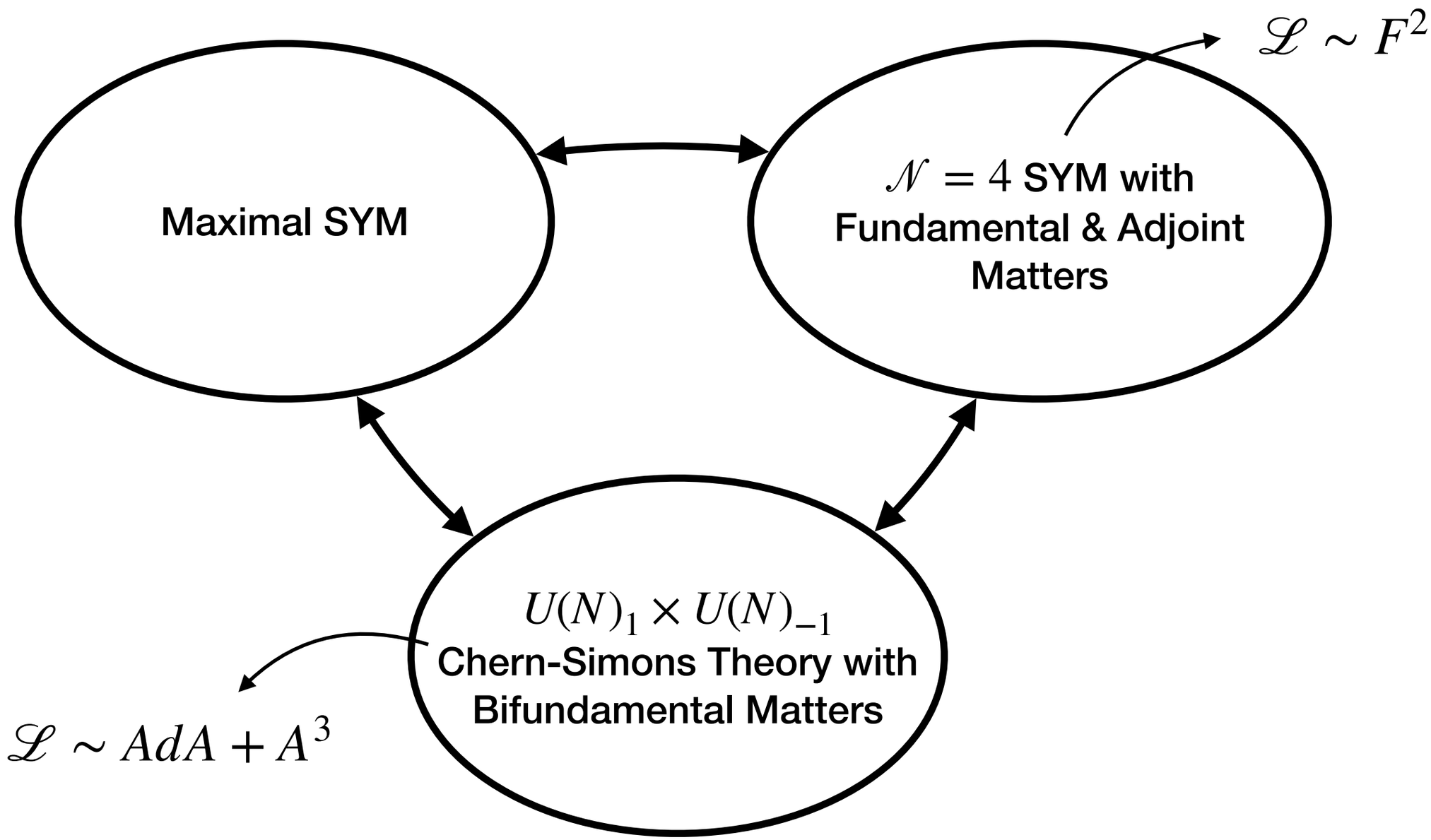
Duality—3D MSYM Theory Revisited

3D MSYM Revisited

- Recall the 2+1d maximally supersymmetric Yang-Mills theory
- Flows to a strongly interacting (conformal) field theory, which is dual to AdS4 gravity
- UV symmetry ≠ IR symmetry
- Not appropriate to study the dual black hole entropy
- Instead, a **dual** description flowing to the same IR CFT can be used!



3D MSYM Revisited



Mirror Symmetry

- A special case of **Mirror Symmetry** [Intriligator-Seiberg 96]
- A simple example: 2+1d supersymmetric QED
  - $\mathcal{N} = 4$ supersymmetric $U(1)$ gauge theory with N_f fundamental matters
  - $\mathcal{N} = 4$ supersymmetric $U(1)^{N_f - 1}$ gauge theory with $N_f - 2$ bifundamental and two fundamental matters
- More non-Abelian Yang-Mills examples

Mirror Symmetry

- Those dualities are motivated by *String Theory*
- Many nontrivial field-theoretic tests
- But no field-theoretic *derivation*
- Understanding at a more elementary level?

Theory vs. Fields

- A (Lagrangian) theory is defined in terms of fields & interactions
- Interactions are fixed by $\mathcal{N} = 4$ supersymmetry

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Can we dualize each elementary field rather than the whole theory?

Building Blocks of Mirror Symmetry

- Find new dualities between a theory of a **single free field** and an interacting gauge theory

- Depends on the representation of the field
  - A fundamental field
  - A bifundamental field

  } **CH**-Pasquetti-Sacchi 21, Bottini-**CH**-Pasquetti-Sacchi 21

  - An adjoint field — Work in progress

- A large class of mirror dual pairs can be derived from the fundamental duality & the bifundamental duality only

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Building blocks of mirror symmetry!

What Is Next?

- Application to holographic theories?
- E.g., the dualities of the MSYM
  - Dualization of an **adjoint** field?
  - **Chern-Simons** instead Yang-Mills?
- Better understand **the duality map of the states**
- Hints of black hole states?

Conclusion

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- The holographic duality relates gravity and QFT.
- Quantum aspects of black holes from non-perturbative dynamics of holographic QFTs
- Many useful tools: supersymmetry, duality, …

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A journey to a better/new understanding of strongly coupled QFT and quantum gravity!

Thank you