SPACETIME FROM QUANTUM INFORMATION

AMIR KHOSRAVI

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Raboud University, Nijmegen, The Netherlands

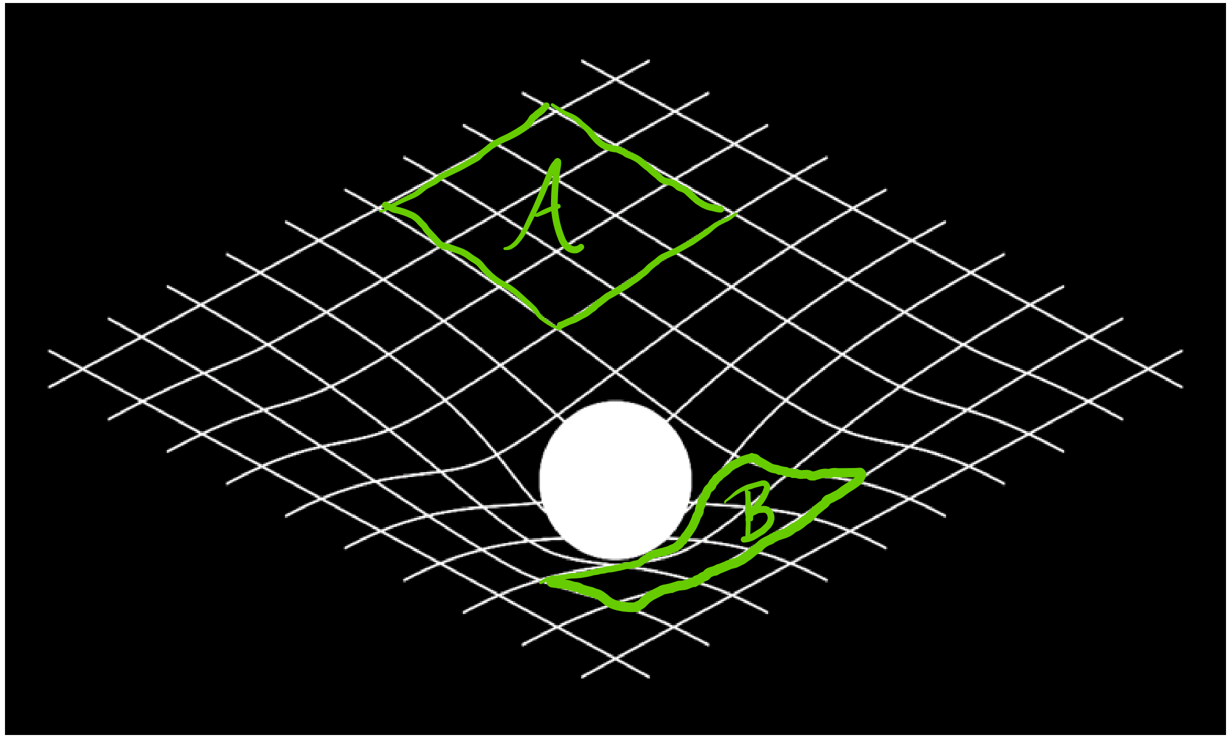
OUTLINE

- Part I:
  - Quantum curse upon spacetime?
  - An Interesting approach towards emergent spacetime: info-graphs
- Part II:
  - Unitarity => Spacetime Can’t be Discrete

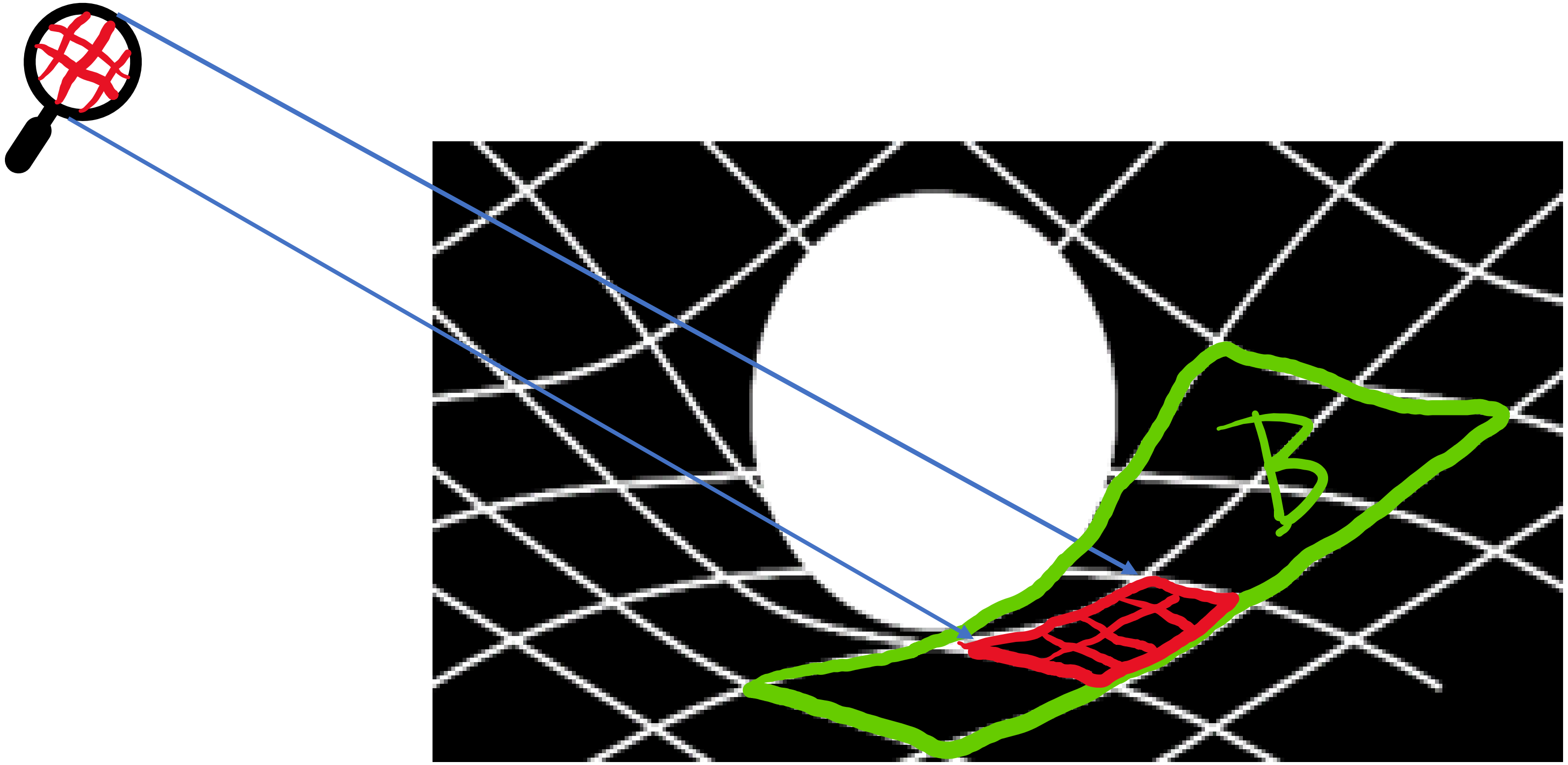
Part I

Quantum curse upon spacetime?

- Quantum corrections to the Bekenstein-Hawking entropy



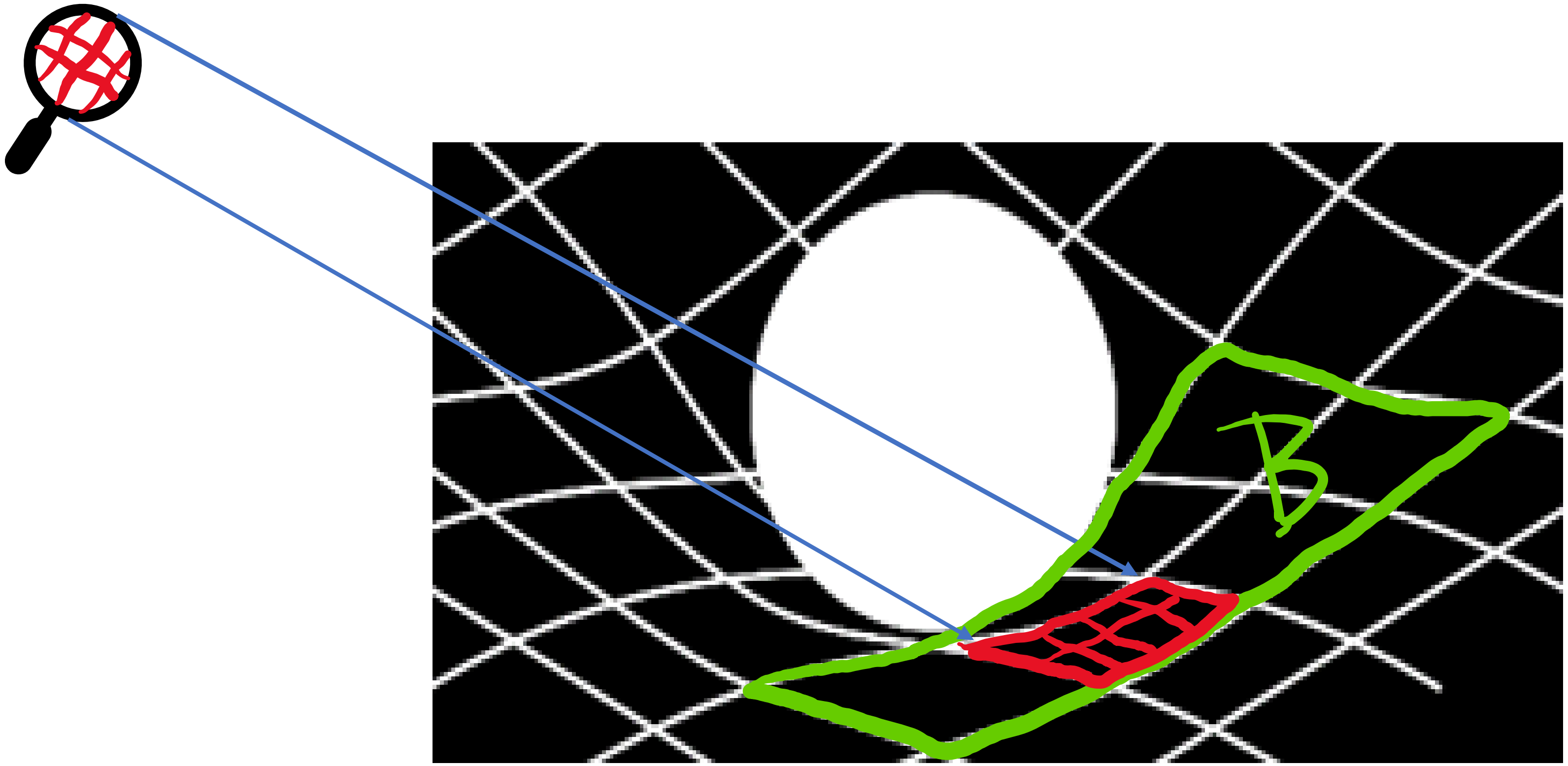
Quantum curse upon spacetime?



$$S_{BH} = S_{HB}$$

$$= \frac{A}{l_P^2}$$

Quantum curse upon spacetime?



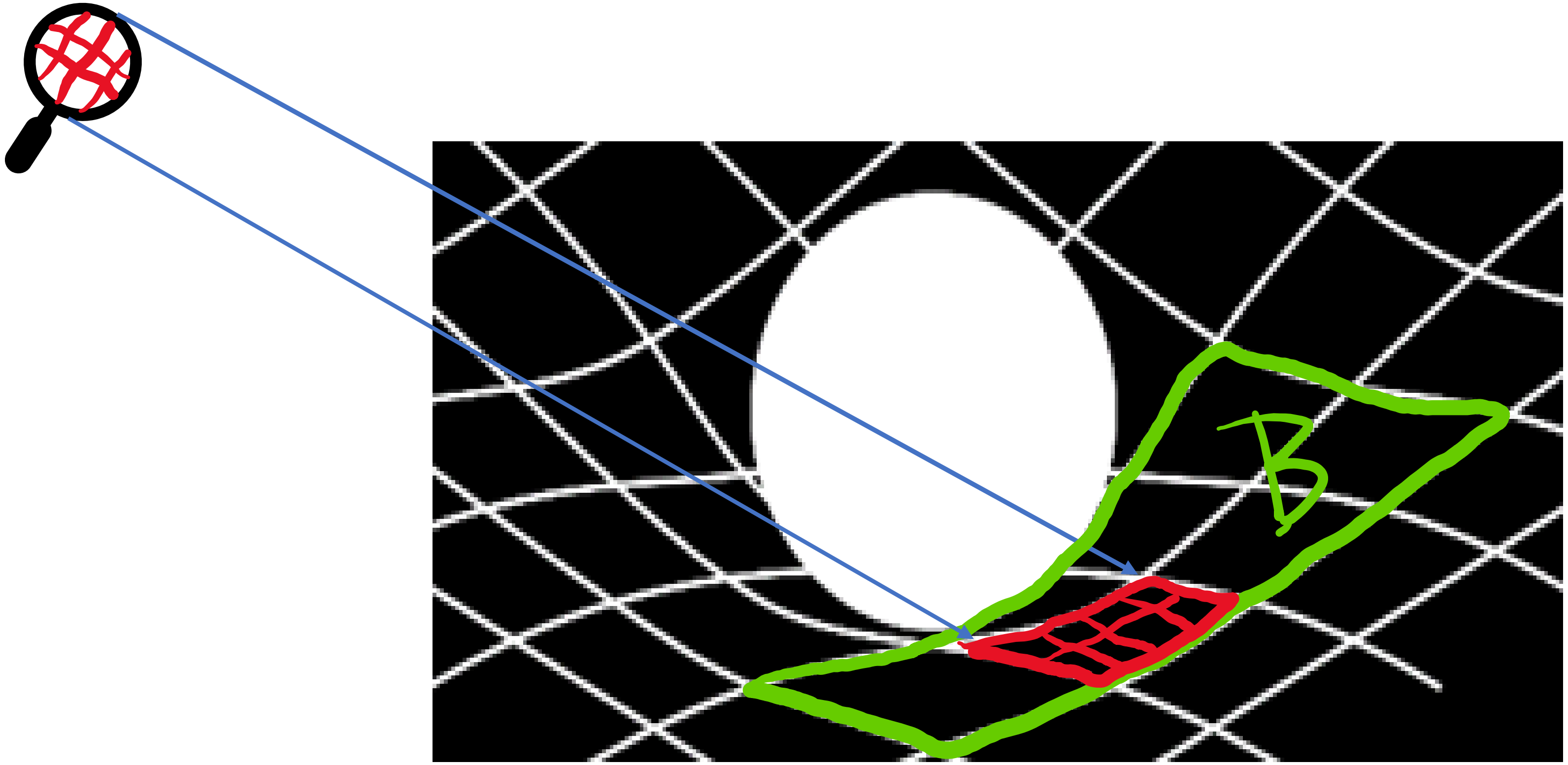
$$S_{BH} = S_{HB} + S_{ent}$$

$$= \frac{A}{l_p^2} + S_{ent}$$

$$S_{ent}^{(out)} \equiv -Tr\left[\rho_{out} \log \rho_{out}\right] = A/\epsilon^2$$

$$\rho_{out} = Tr_{in}[\rho]$$

Quantum curse upon spacetime?



$$S_{BH} = \overset{\mathrm{IR}}{S_{HB}} + \overset{\mathrm{UV}}{S_{ent}}$$

$$= \frac{A}{l_p^2} + S_{ent}$$

$$S_{ent}^{(out)} = -\mathrm{Tr}\left[\rho_{out} \log \rho_{out}\right] = A/\epsilon^2$$

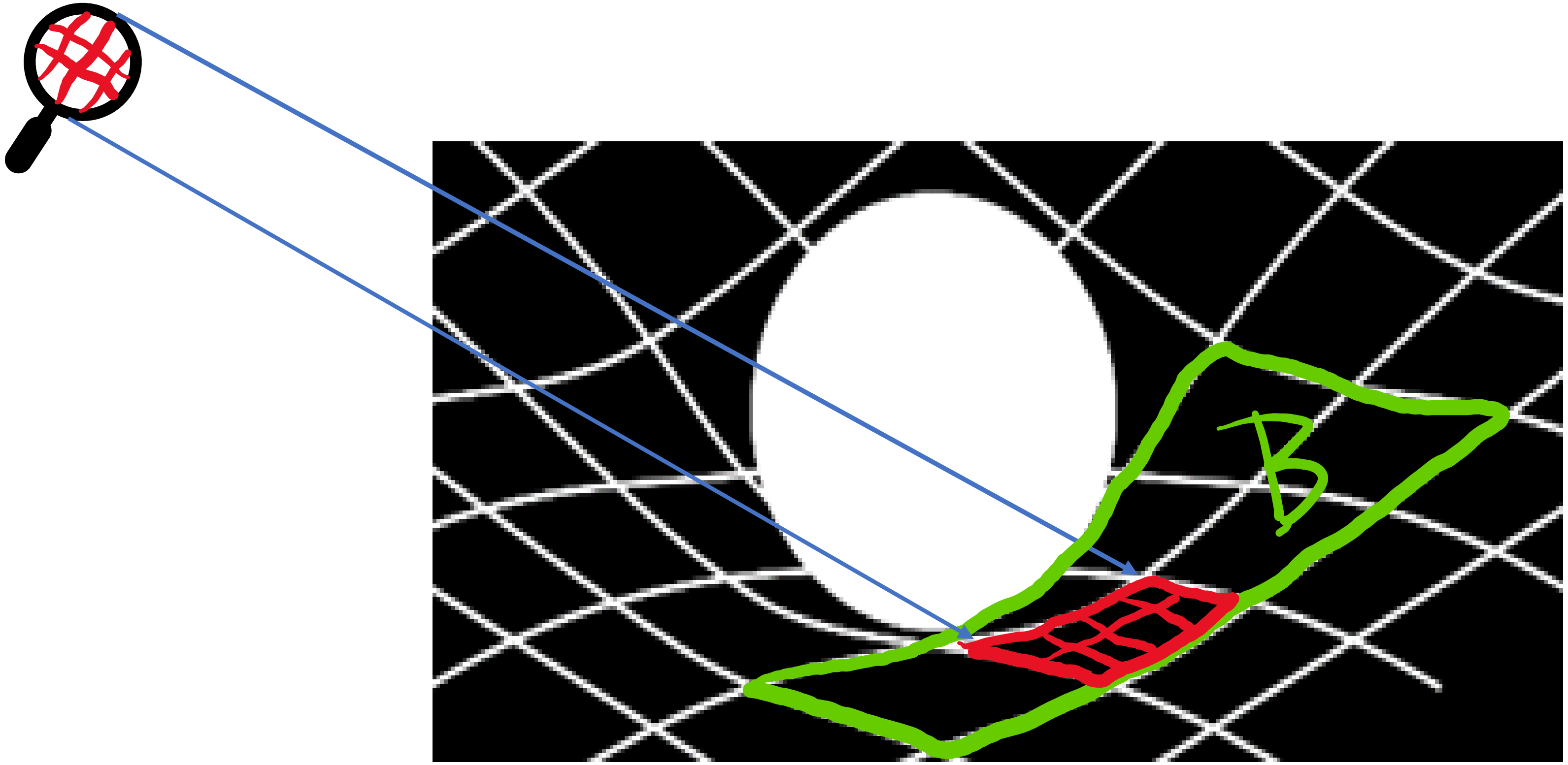
$$\rho_{out} = \mathrm{Tr}_{in}[\rho]$$

Proposal: $S_{BH} = A/G(\mu)$

(Susskind & Uglum)

Quantum mechanics is responsible even for the origin of A/l_p^2, i.e. the origin of gravity!

Quantum curse upon spacetime?



$$\underset{\text{IR}}{S_{HB}}$$ $$\overset{\text{UV}}{S_{ent}}$$

$$S_{BH} = S_{HB} + S_{ent}$$

$$= \frac{A}{l_p^2} + S_{ent}$$

$$S_{ent}^{(out)} = -\mathrm{Tr}\left[\rho_{out} \log \rho_{out}\right] = A/\epsilon^2$$

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Proposal: $S_{BH} = A/G(\mu)$

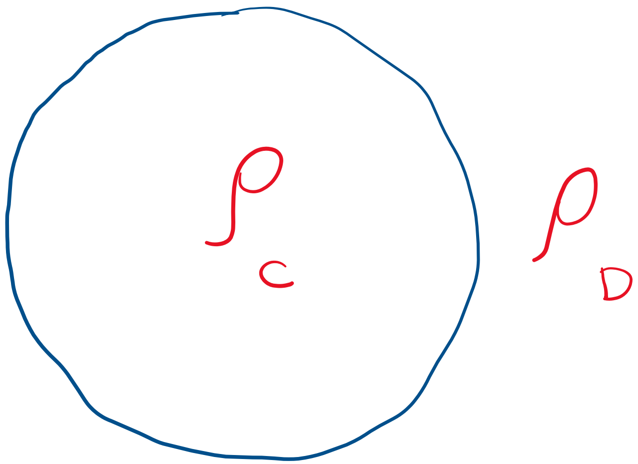
(Susskind & Uglum)

Induced gravity, Emergent Gravity ...

Quantum curse upon spacetime?

If spacetime is emergent, what is fundamental?

An Interesting approach towards emergent spacetime: info-graphs

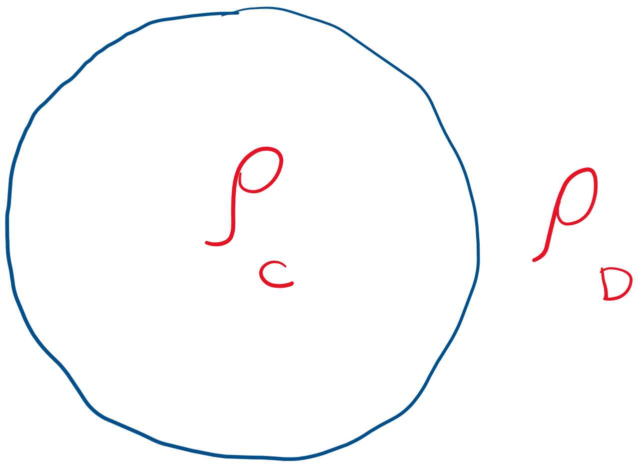


$$S^{(C)}_{ent} \overset{\text{for vacuum}}{=} \frac{\text{Area}(\partial C)}{\epsilon^2}$$

$$= -\mathrm{Tr}\left[\rho_C \log \rho_C\right]$$

$$I_{CD} \equiv S_C + S_D - S_{CD} = S_{th} - S_{ent} \geq 0$$

An Interesting approach towards emergent spacetime: info-graphs



for vacuum

$$S^{(C)}_{ent} = \frac{\text{Area}(\partial C)}{\epsilon^2}$$

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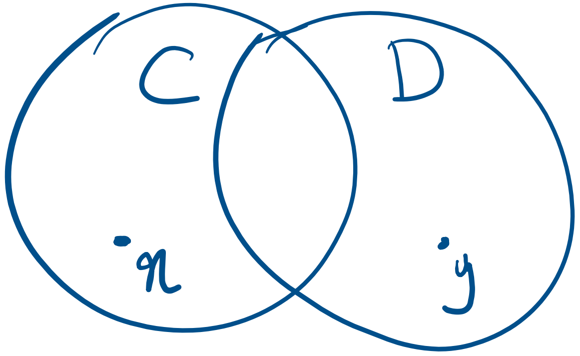
An Interesting approach towards emergent spacetime: info-graphs



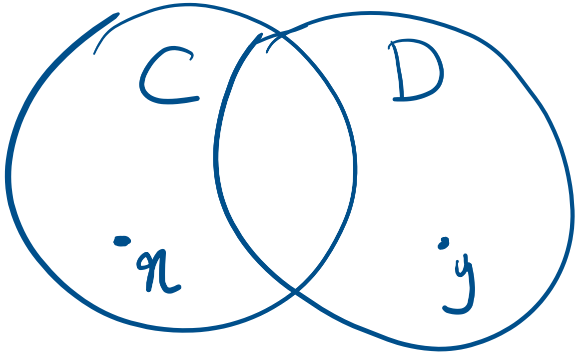
For any two $O(x)$ and $O(y)$:

$$I_{CD} \geq \frac{|\langle O(x)\, O(y) \rangle_c|^2}{2\, |O_C|^2\, |O_D|^2}$$

$$\langle O_C\, O_D \rangle_c \propto e^{-mL}$$

$$I \to 0 \Rightarrow L \to \infty$$

An Interesting approach towards emergent spacetime: info-graphs



For any two $O(x)$ and $O(y)$:

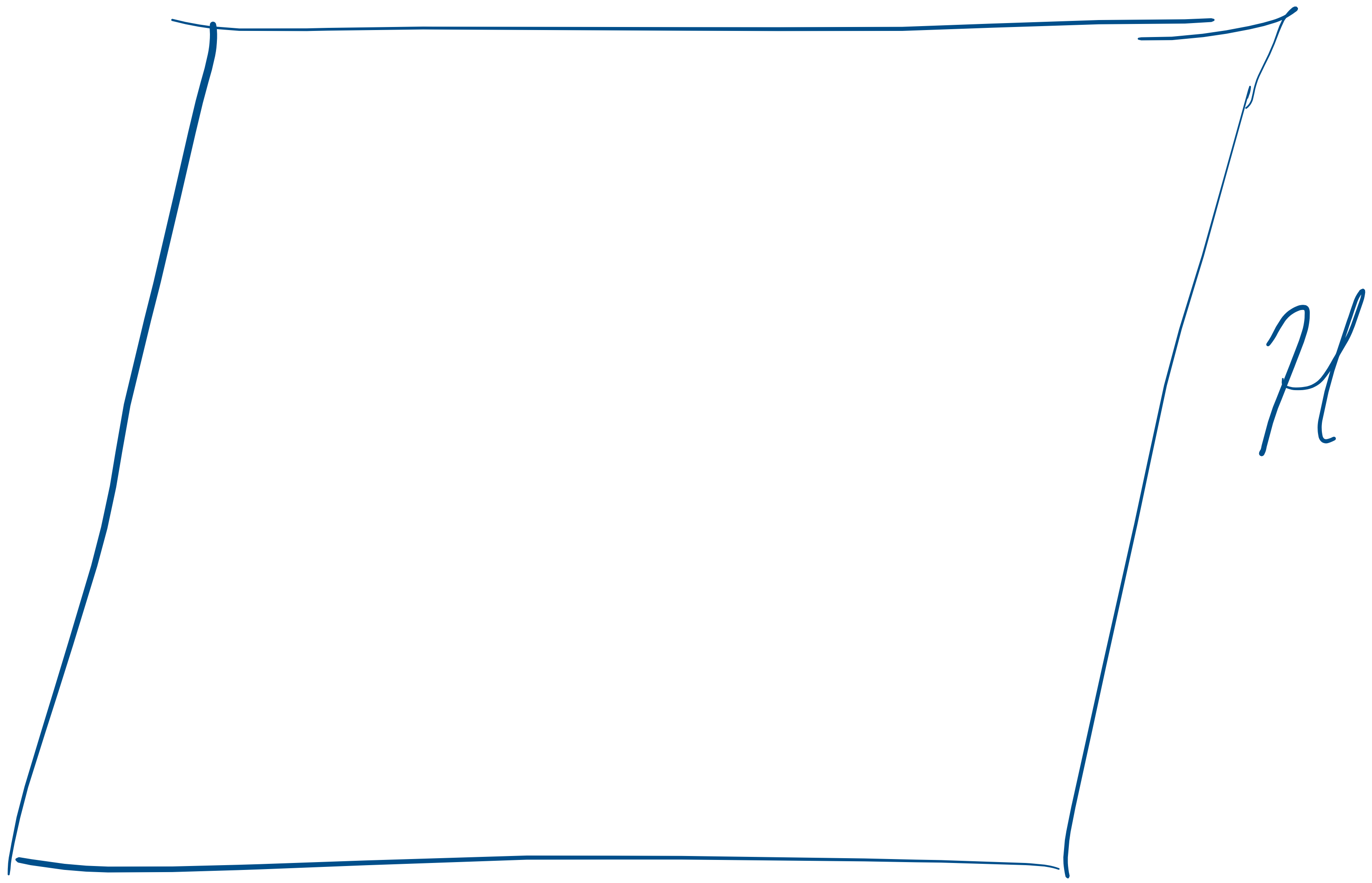
$$I_{CD} \geq \frac{|\langle O(x)\, O(y)\rangle_c|^2}{2\,|O_C|^2\,|O_D|^2}$$

Start From $\boxed{I}$ and Construct $\boxed{g_{\mu\nu}}$

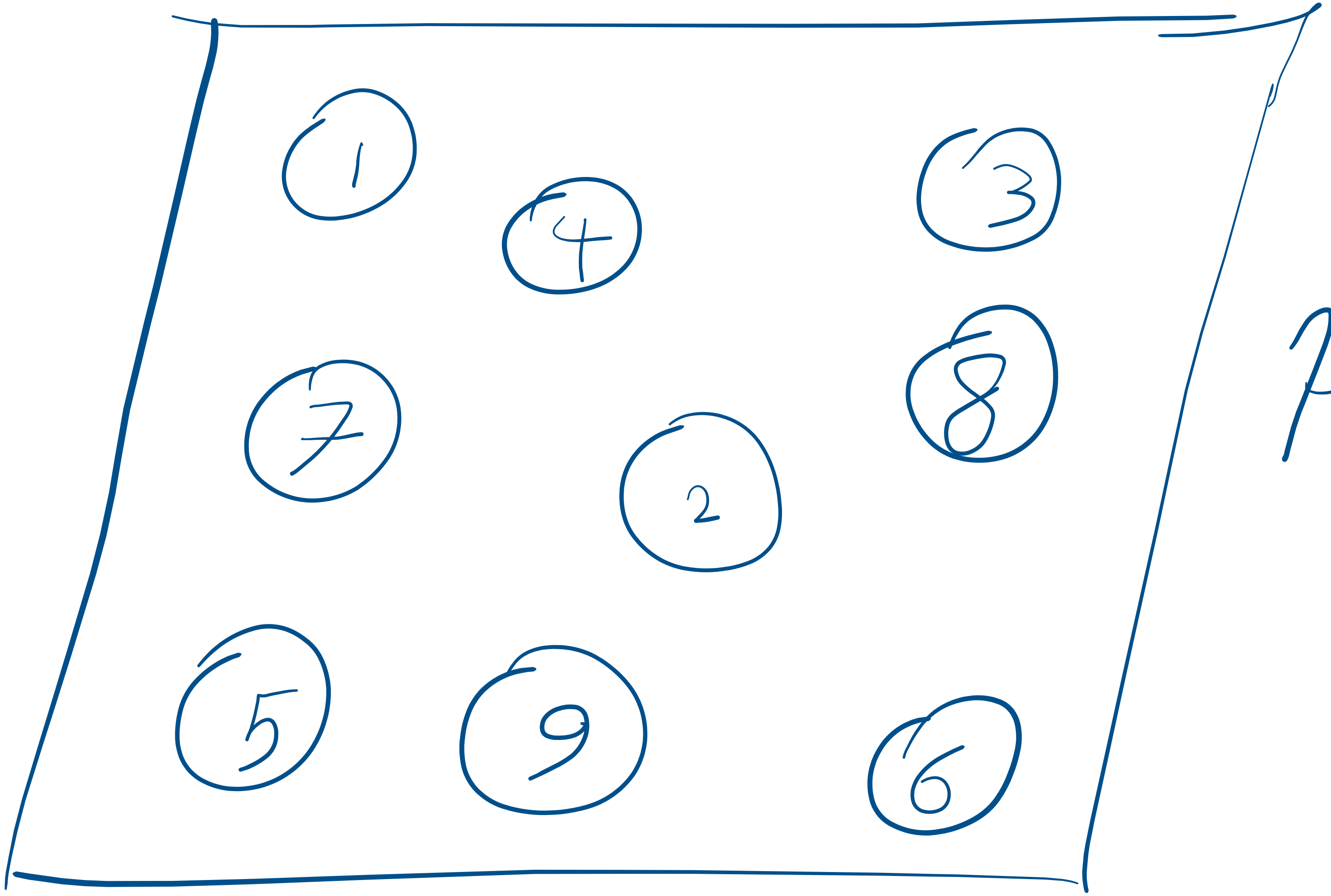
Fundamental Emergent

(Cao, Carroll, Michalakis)

An Interesting approach towards emergent spacetime: info-graphs



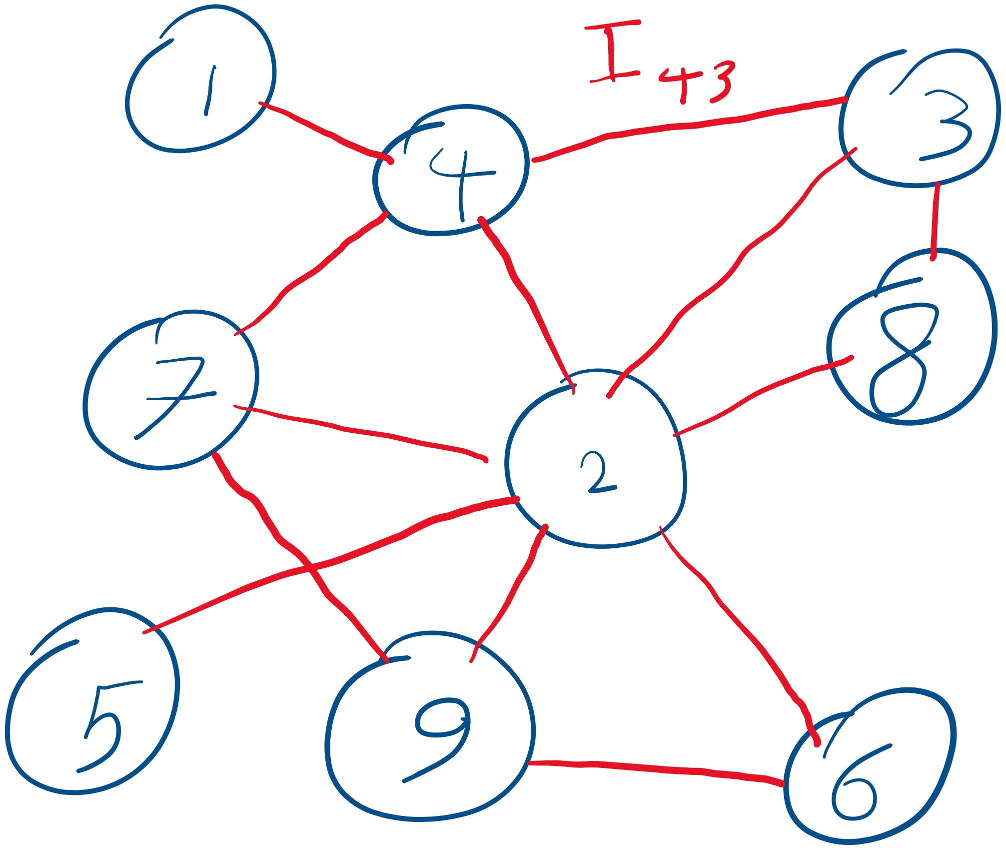
An Interesting approach towards emergent spacetime: info-graphs



$\mathcal{H}$

An Interesting approach towards emergent spacetime: info-graphs

Info_Graph

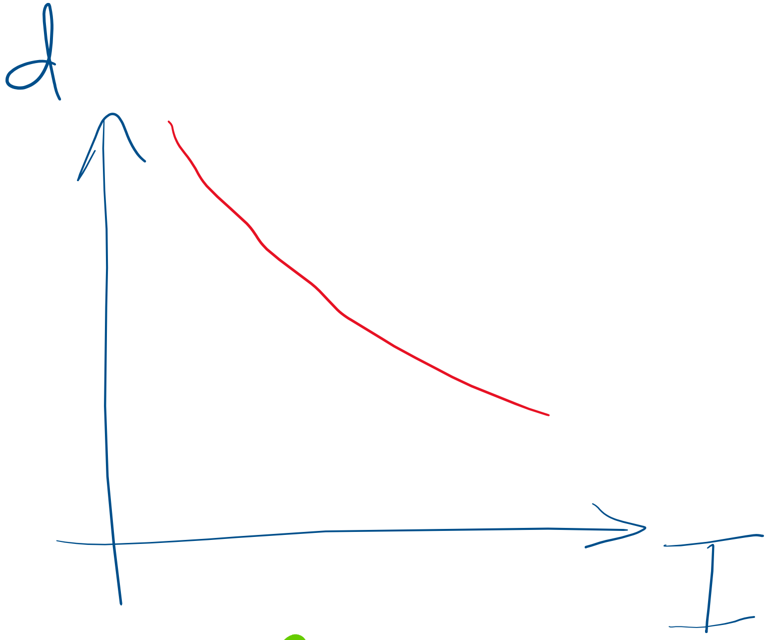


$\mathcal{H}$

An Interesting approach towards emergent spacetime: info-graphs

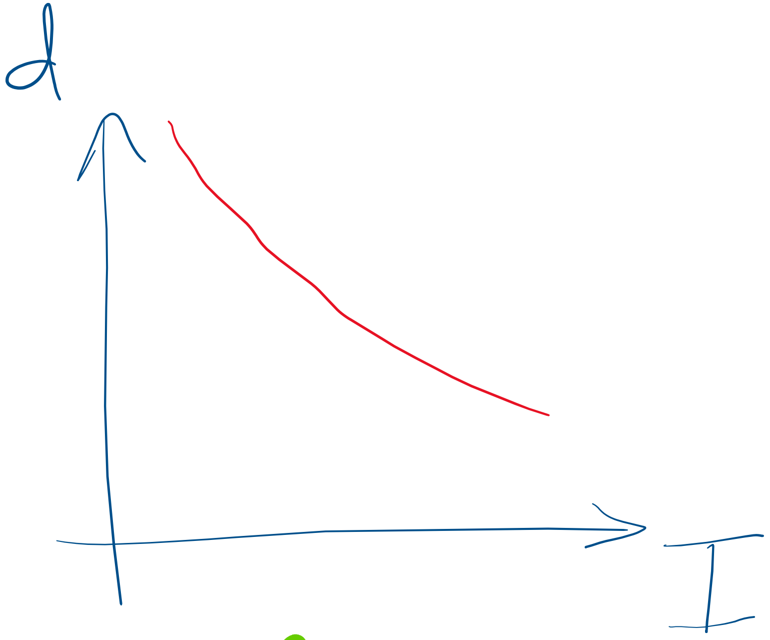
$$I_{CD} \geq \frac{|\langle O(x)\, O(y) \rangle_c|^2}{2\, |O_C|^2\, |O_D|^2}$$

An Interesting approach towards emergent spacetime: info-graphs



$$I_{CD} \geq \frac{\left|\langle O(x)\, O(y) \rangle_c\right|^2}{2\, |O_C|^2\, |O_D|^2}$$

An Interesting approach towards emergent spacetime: info-graphs



Ground state of a gapped Hamiltonian:

$$d \sim -\log(I)$$

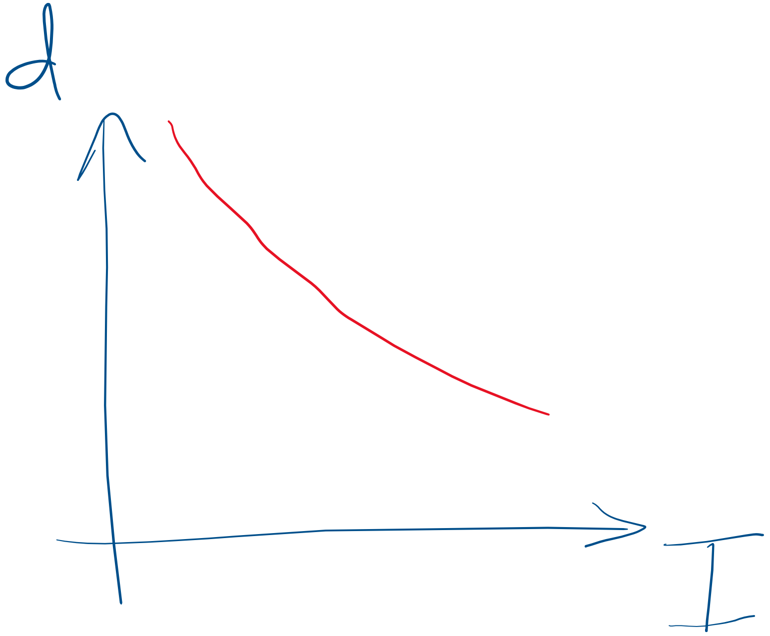
(Wolf, Verstraete, Hastings, Cirac)

(Hastings & Koma)

$$I_{CD} \geq \frac{|\langle O(x)\, O(y)\rangle_c|^2}{2\, |O_C|^2\, |O_D|^2}$$

* Normalized I

An Interesting approach towards emergent spacetime: info-graphs



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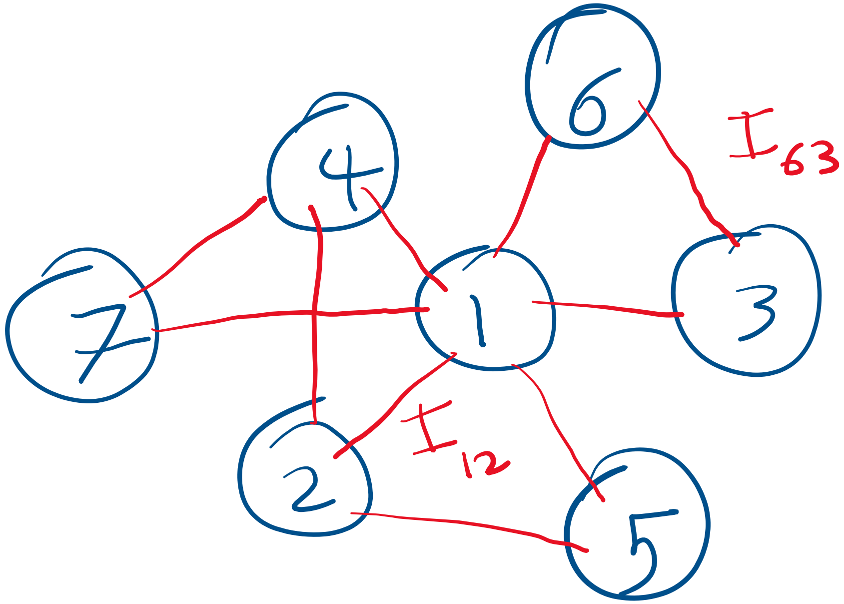

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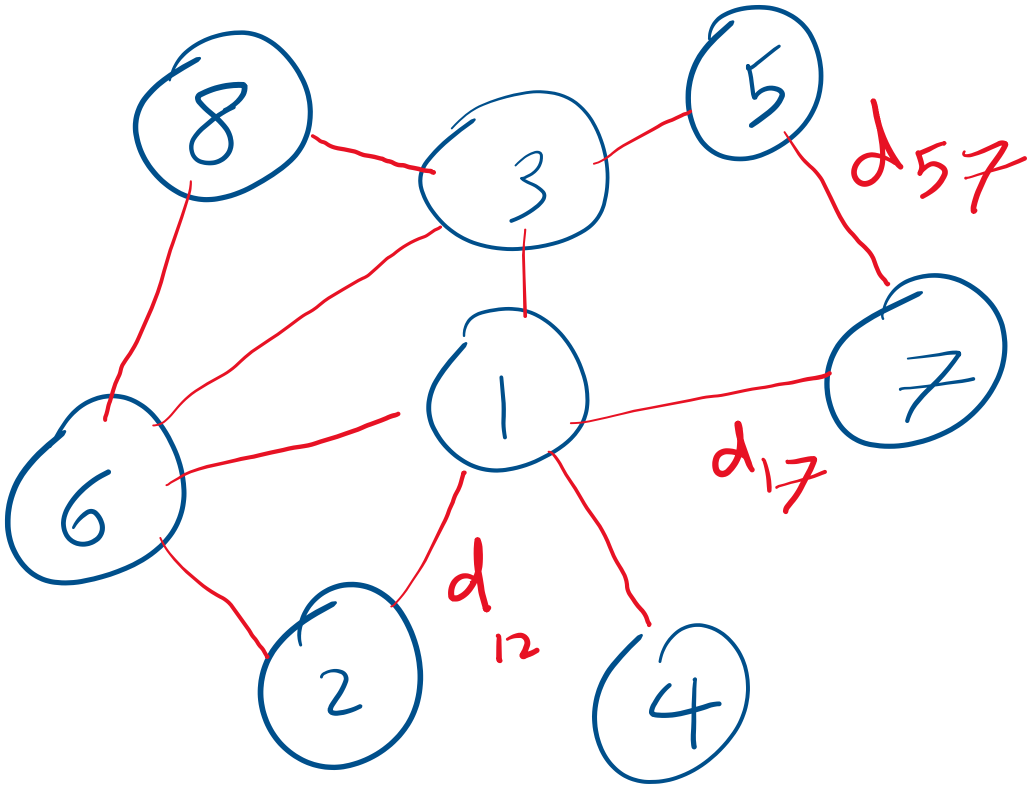
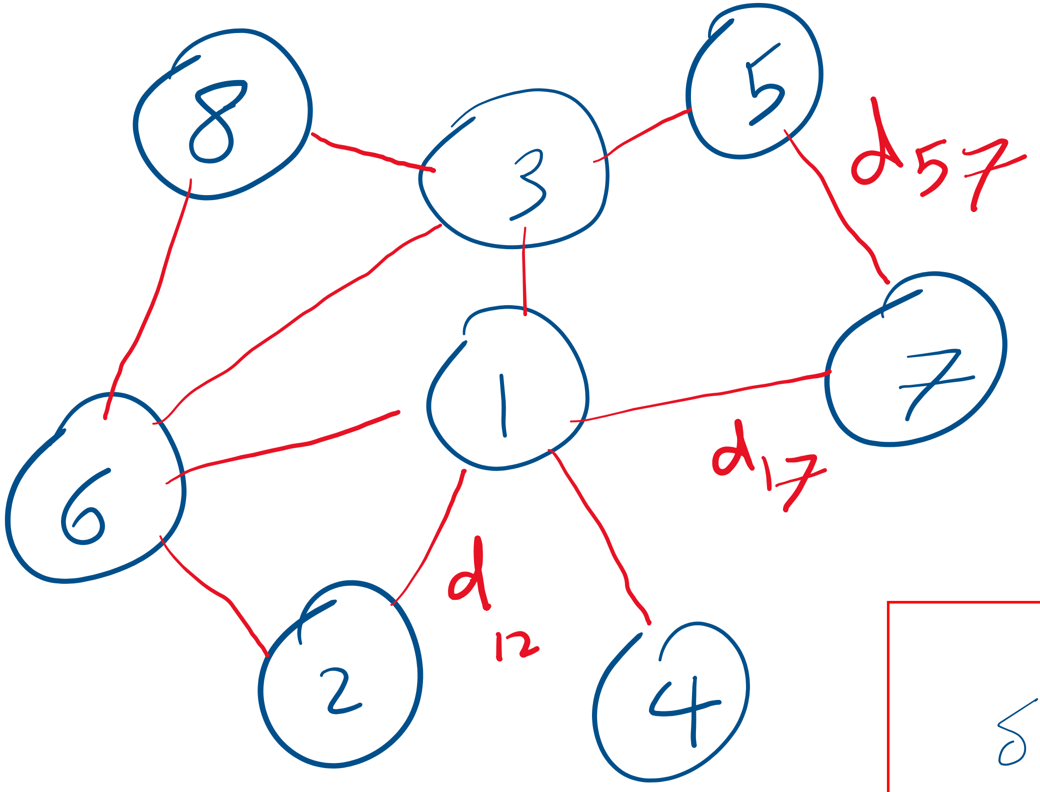
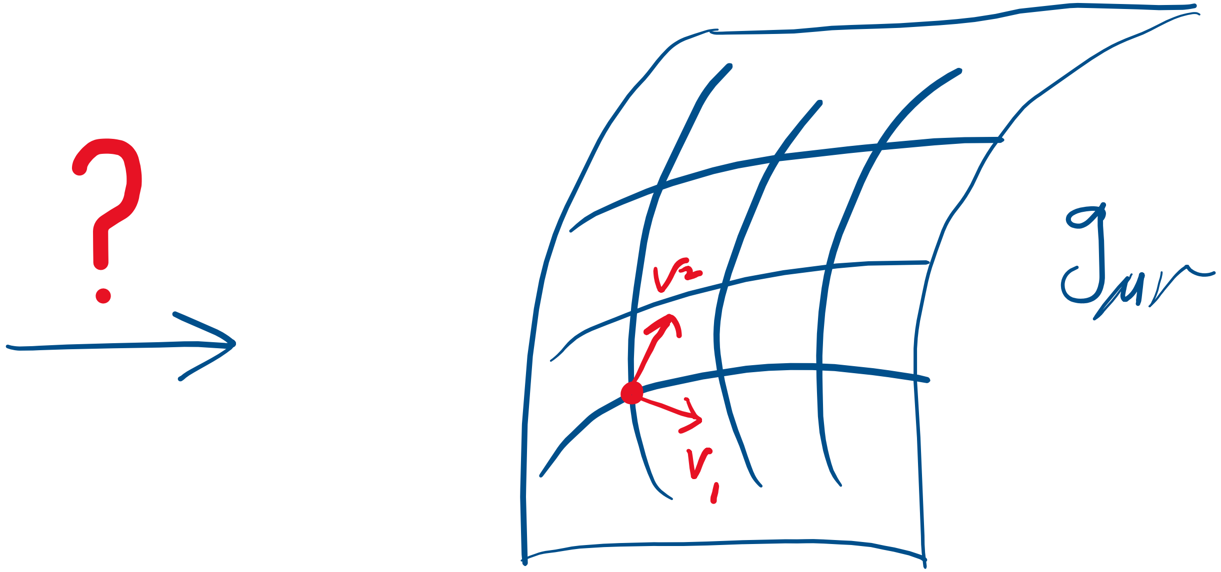
An Interesting approach towards emergent spacetime: info-graphs



This is one step further from abstract quantum mechanics to more intuitive geometric picture

An Interesting approach towards emergent spacetime: info-graphs





$$\delta\langle S\rangle = \delta\langle K\rangle \quad \longleftrightarrow \quad G_{\mu\nu} = \kappa T_{\mu\nu}$$

(Blanco, Casini, Hung, Myers) (Jacobson)

An Interesting approach towards emergent spacetime: info-graphs

- A concise summary of a new emerging theme in theoretical physics, it was just a report!
- Novelty of Info-graph: starting point is 100% quantum! We don't quantize, we classicalize!
- The only take away: MI can be extremely useful to study properties of spacetime

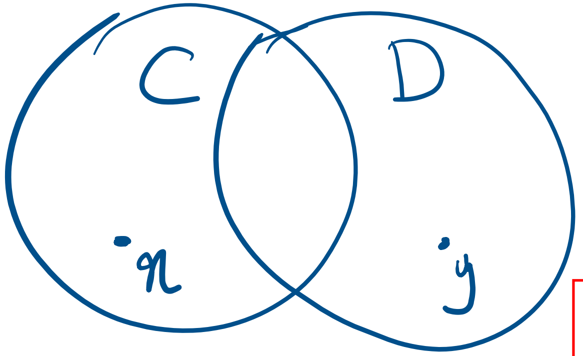
Part II

A physical constraint on info-graphs

Dynamics + $\boxed{\text{Constraints}}$

If QFT is Unitary, then <ϕ… ϕ > is constrained,
what constraint does it put on the geometry? (If any!)

A physical constraint on info-graphs



For any two $O(x)$ and $O(y)$:

Theorem:

$$\left.\begin{array}{l} I_{CD} \geq \dfrac{\left|\langle O(x)\, O(y)\rangle_c\right|^2}{2\,|O_C|^2\,|O_D|^2} \\[2em] \text{Unitarity} \end{array}\right\} \Longrightarrow I_{UV} \neq 0$$

A physical constraint on info-graphs

Callan-Symanzik equation:

$$\left[\mu\,\partial_\mu - \tfrac{1}{2}\,\eta(g(\mu))\right]\Gamma^{(n)}(p, g(\mu); \mu) = 0$$

$$\Rightarrow \quad \Gamma^{(n)} = \exp\left[\tfrac{1}{2}\int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'}\,\eta(g(\mu'))\right]\Gamma^{(n)}\Big|_{\mu=\mu_0}$$

Unitarity of QFT: $\quad \eta > 0$ and $\Gamma^{(n)} > 0$

(Casini & Huerta), (Higashijima & Itou), (Rosten)

A physical constraint on info-graphs

Unitarity:

$$\partial_\mu \langle \langle \phi_C \phi_D \rangle_c \rangle > 0$$

$$\langle \langle \phi_C \phi_D \rangle_c \rangle > 0$$

$$\downarrow$$

$$\langle \langle \phi_C \phi_D \rangle_{UV} \rangle > 0$$

A physical constraint on info-graphs

$$\left[I_{CD} \geq \frac{|\langle \phi_C \phi_D \rangle_c|^2}{2\,|\phi_C|^2\,|\phi_D|^2} \right] + \left[\text{Unitarity:} \quad \begin{array}{l} \partial_\mu \langle \phi_C \phi_D \rangle_c > 0 \\ \langle \phi_C \phi_D \rangle_c > 0 \end{array} \right]$$

$$\downarrow$$

$$\boxed{I_{UV} > 0}$$

Keep this in mind, now we investigate another interesting result

A physical constraint on info-graphs

$$I_{CD} \geq \frac{|\langle \phi_C \phi_D \rangle_c|^2}{2\,|\phi_C|^2\,|\phi_D|^2}$$

(Van Raamsdonk)

$$S \to 0 \qquad\qquad S \to 0$$

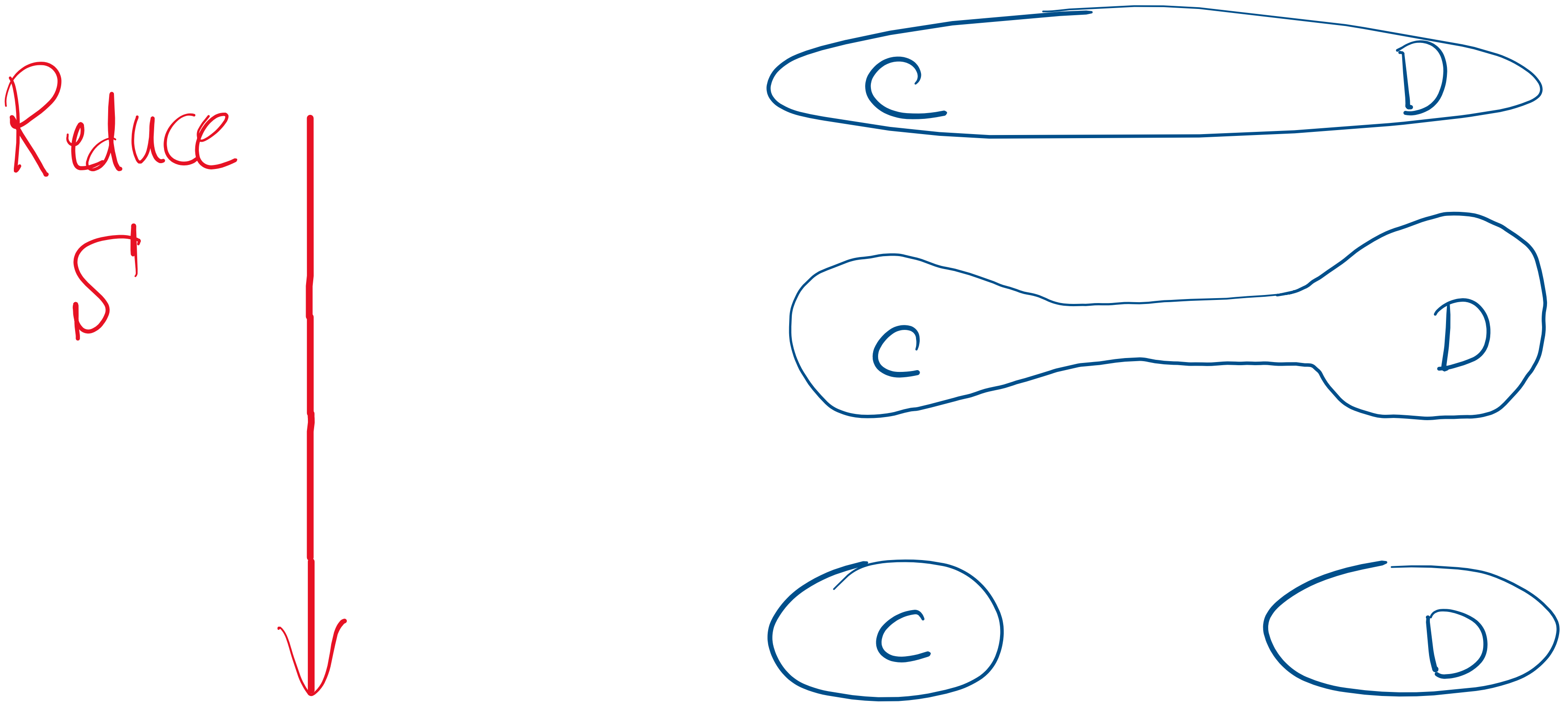
$$I \to 0,\ \langle \phi_C \phi_D \rangle \sim e^{-mL} \qquad\qquad \boxed{\text{Area} \to 0}$$

$$\boxed{L \to \infty}$$

A physical constraint on info-graphs

$$S^{\dagger}_{C} \text{ and } S^{\dagger}_{D} \to 0 \implies I_{CD} \to 0$$

(Van Raamsdonk)



A physical constraint on info-graphs

If regions C and D of spacetime are disconnected, then we have $I_{CD}=0$

(Van Raamsdonk)

This has one important consequence for the structure of spacetime: Spacetime can't be discrete!

A physical constraint on info-graphs

Assume Spacetime is a result of coarse graining a fundamentally discrete structure, i.e.

$$I_{\upsilon\nu} = 0$$

A physical constraint on info-graphs

Assume Spacetime is a result of coarse graining a fundamentally discrete structure, i.e.

$$I_{UV} = 0$$

But: $I_{UV} > 0$, Otherwise we have to discard either Unitarity or

$$I \geq \frac{\langle \phi \phi \rangle_c^2}{2 |\phi|^2 |\phi|^2}$$

A physical constraint on info-graphs

Result is true for any fundamental theory of nature (!) as long as it admits a unitary description in terms of QFT at least effectively.

If QFT survives, we have Asymptotic Safety.
If not, we probably have something like string theory.

LQG, CST, … ?!

A physical constraint on info-graphs

$$\partial_t \Pi_k = \frac{1}{2}\, \mathrm{Tr}\left[\left(\Pi^{(2)} + R_k\right) \partial_t R_k \right]$$

$$\Downarrow \; ?$$

(Pagani & Reuter)

$$\partial_t I = \beta$$

I-theorem maybe ?! …

Thank You