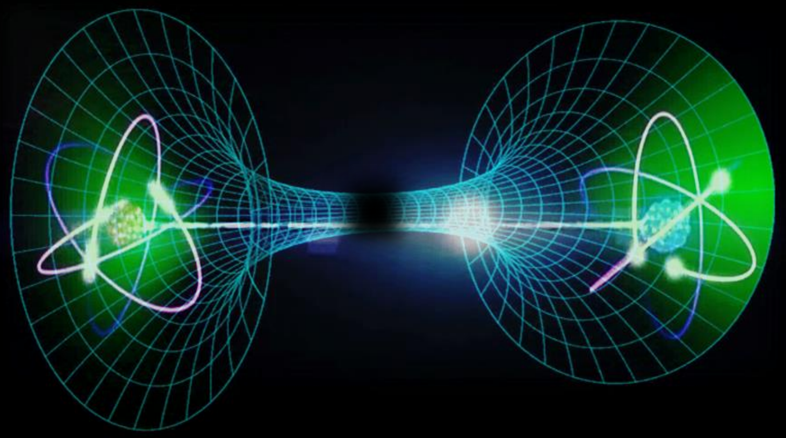

Tearing Down Spacetime with Quantum Disentanglement

ROBERTO EMPARAN ICREA+ICCUB

GC2024 YITP KYOTO

1 FEBRUARY 2024

WITH JAVIER M. MAGÁN

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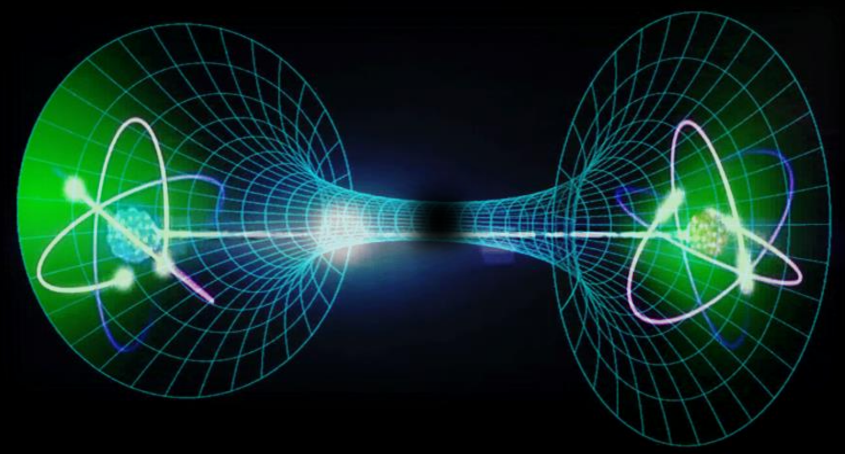


Entanglement: the quintessential quantum property

Spacetime: the quintessential classical entity

Holography connects them

Quantum entanglement is classicalized as geometry Ryu+Takayanagi

Classical spacetime built up from quantum entanglement

Quantum disentangling should disassemble holographic spacetime

But apparently it does not

Disentangled state retains large holographic entanglement entropy

Spacetime from Entanglement

EINSTEIN VS EINSTEIN

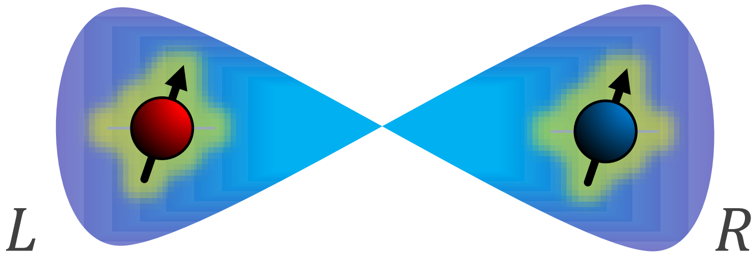
EPR pair

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_L \, |0\rangle_R + |1\rangle_L \, |1\rangle_R\right)$$

EPR, Bell

Maximally entangled

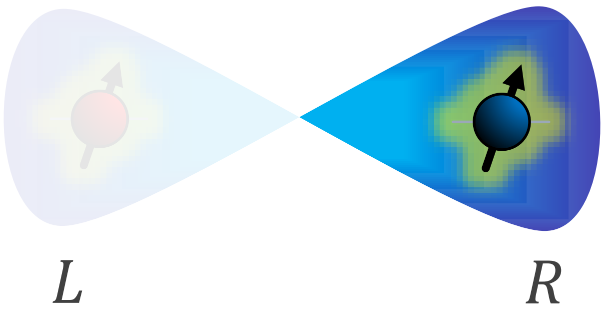
Correlation,
no communication



entangled up in blue

Entanglement entropy

Trace over (ie ignore) Left



$$\rho_R = \mathrm{Tr}_L \, |\Psi\rangle\langle\Psi|$$

$$S_{\mathrm{vonNeumann}} = -\mathrm{Tr}\, \rho_R \log \rho_R = \log 2$$

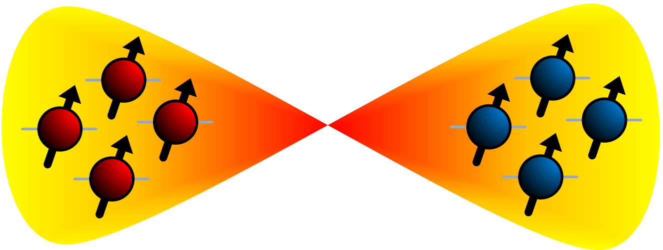
Many EPR pairs

ThermoField Double

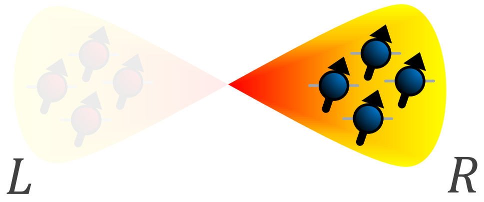
$$|\mathrm{TFD}\rangle = \frac{1}{\sqrt{Z}} \sum_i e^{-E_i/2T} |i\rangle_L |i\rangle_R$$

T: entangling temperature

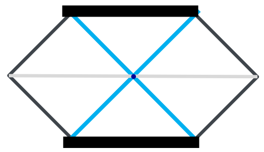
Fully entangled



Entanglement entropy = Thermal entropy of R



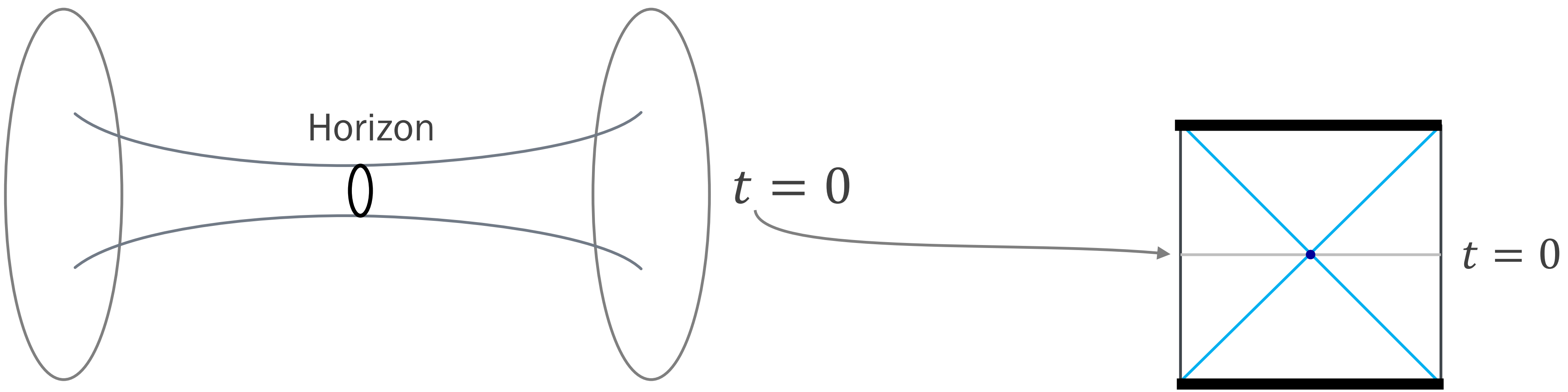
Black Hole ER Bridge



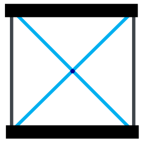
Einstein-Rosen (ER) bridge

Connection,

no communication



Black Hole Bridge ⇔ ThermoField Double



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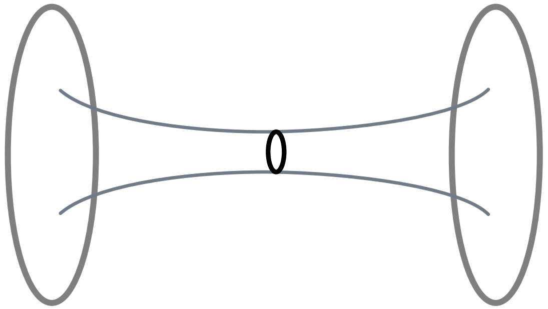
$$|\mathrm{TFD}\rangle = \frac{1}{\sqrt{Z}} \sum_i e^{-E_i/2T} |i\rangle_L |i\rangle_R$$



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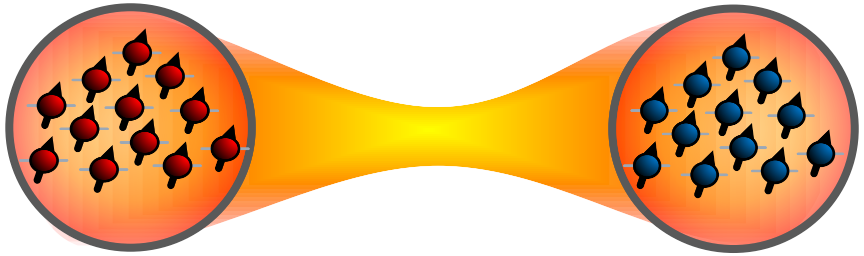
ER=EPR



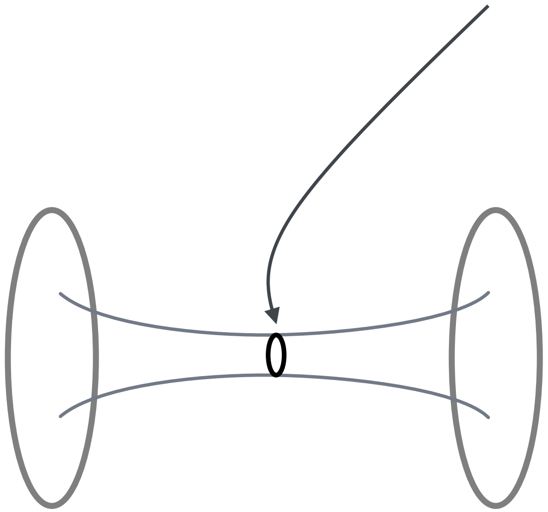
Correlation but no communication

Maldacena+Susskind

Bridge is **geometrization** of huge **entanglement**

Area = Entanglement entropy

$$S = \frac{A}{4G\hbar}$$



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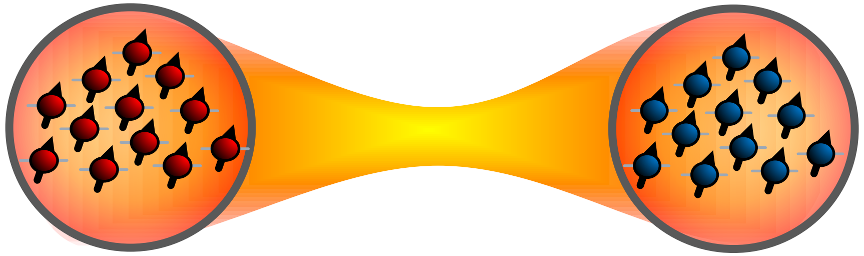
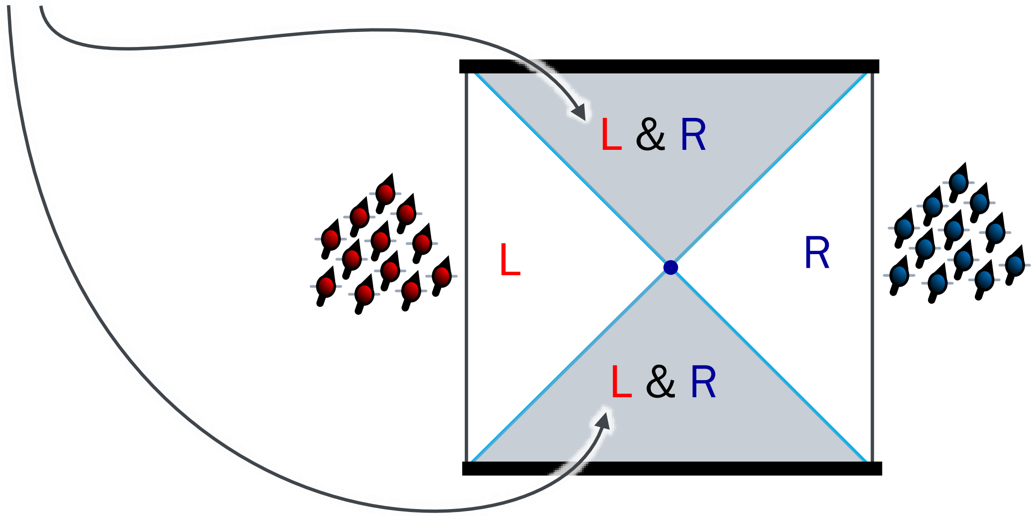


Ryu+Takayanagi

Building up Spacetime

- **Fundamental** degrees of freedom are **quantum & non-geometric**
- Localized **at the asymptotic boundary**

Spacetime born out of **entanglement**



van Raamsdonk

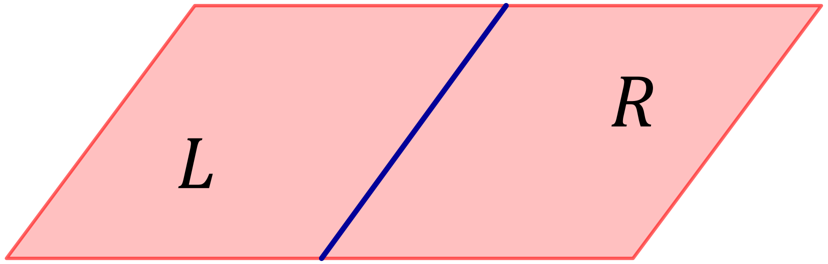
Puzzle

Entangled vacuum

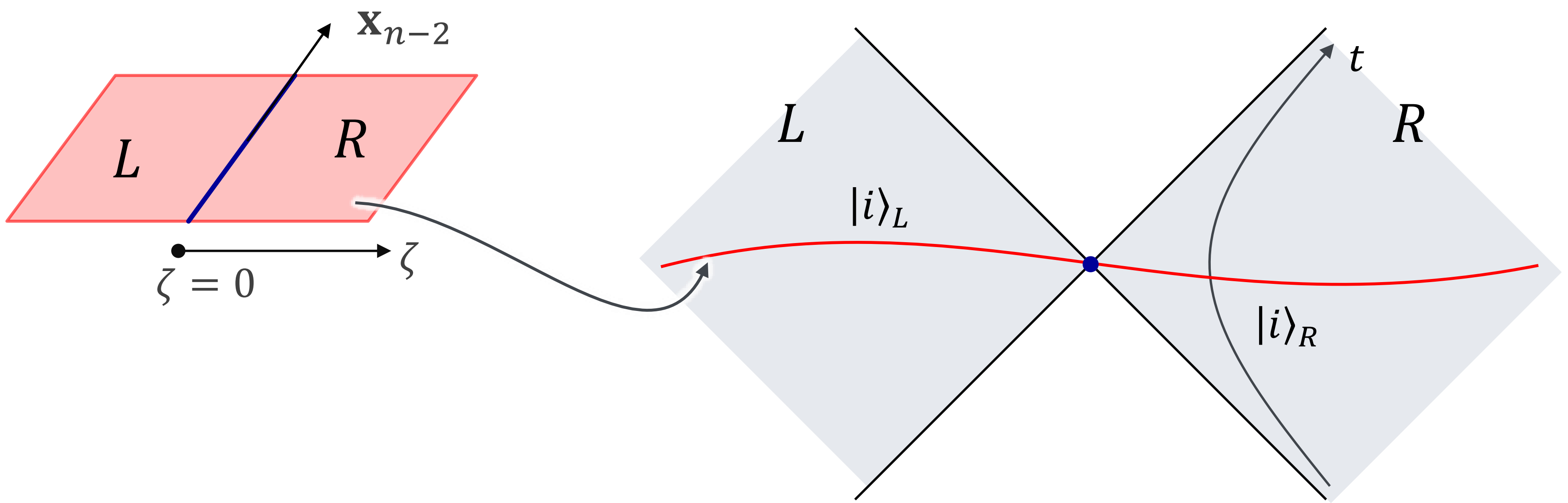
QFT vacuum is fully entangled

$$|0\rangle_M = \frac{1}{\sqrt{Z}} \sum_i e^{-\pi E_i} |i\rangle_L |i\rangle_R$$

$$\mathcal{H} = \mathcal{H}_L \otimes \mathcal{H}_R$$



Unruh 1976

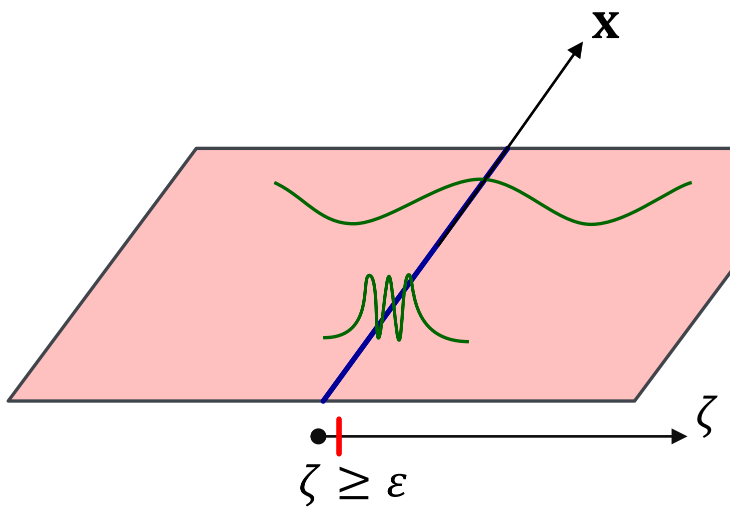


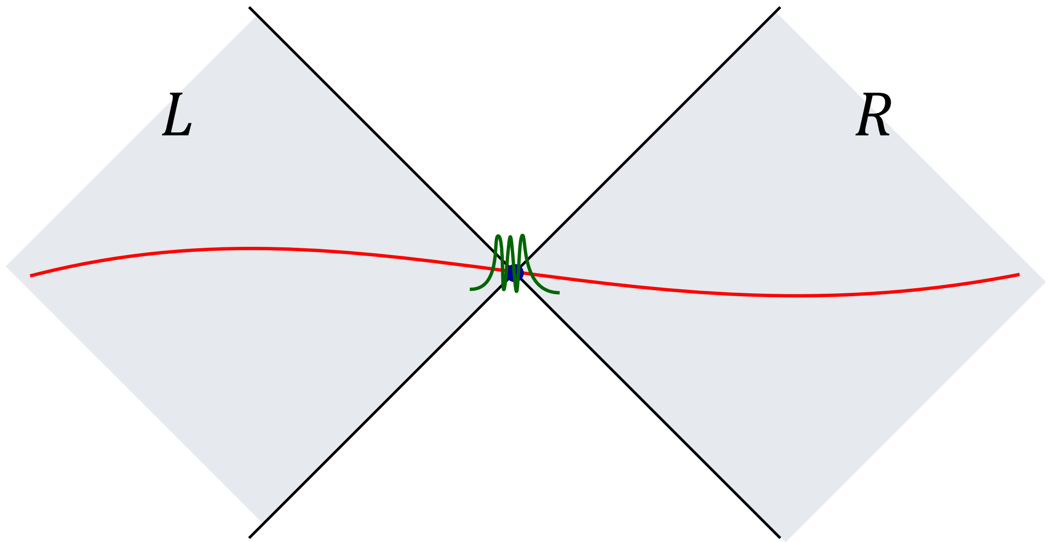
Rindler spacetime

$$|0\rangle_M = \frac{1}{\sqrt{Z}} \sum_i e^{-\pi E_i} |i\rangle_L |i\rangle_R$$ Thermofield double state

$T = \beta^{-1} = \frac{1}{2\pi}$: entanglement (modular) temperature of vacuum

Unruh 1976





Entanglement entropy diverges

$$S = \frac{A_{\mathbf{x}}}{\varepsilon^{n-2}}\, s$$

cutoff-dependent but **non-zero**

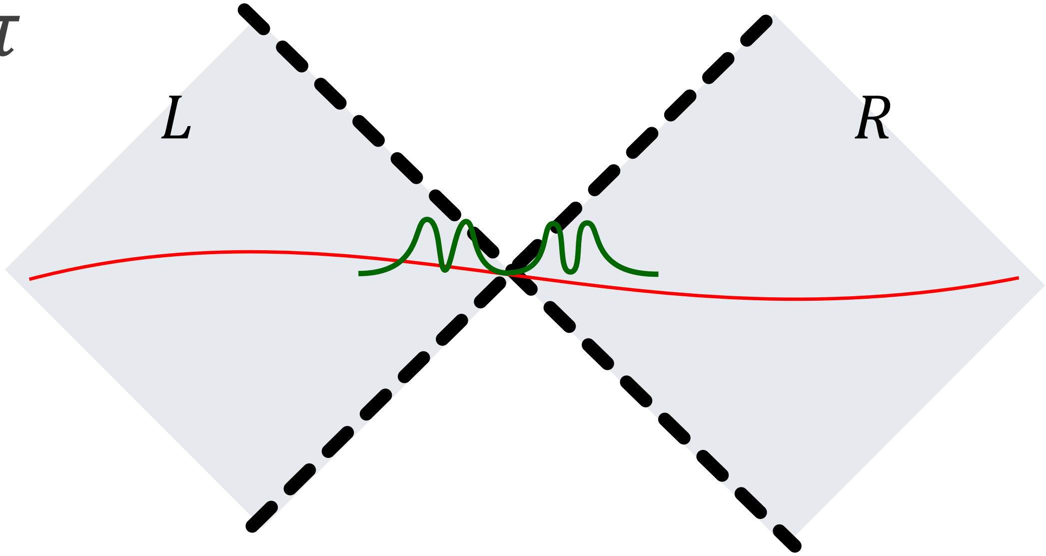
Sorkin et al 1986
Srednicki 1993

Disentangling the wedges

Boulware states

$$|\Psi_\beta\rangle = \frac{1}{\sqrt{Z}} \sum_i e^{-\beta E_i/2} |i\rangle_L |i\rangle_R$$

$\beta > 2\pi$



Firewall states

$S(\beta) < S(2\pi)$: disentanglement

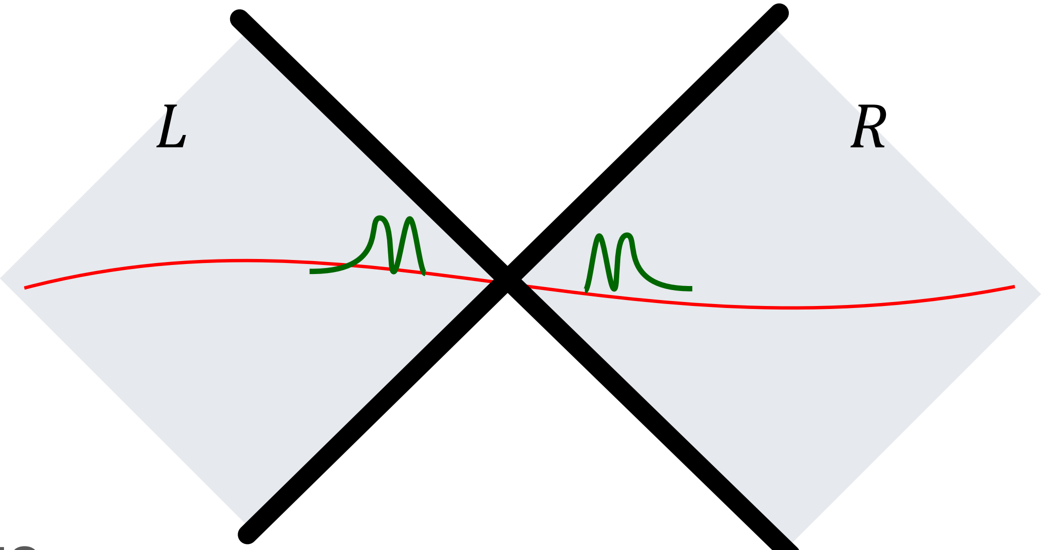
The puzzle

Boulware vacuum $\beta \to \infty$

$\left|\Psi_{\beta\to\infty}\right\rangle \to |0\rangle_L |0\rangle_R$ unentangled

but holographic calculation
of CFT in Rindler gives

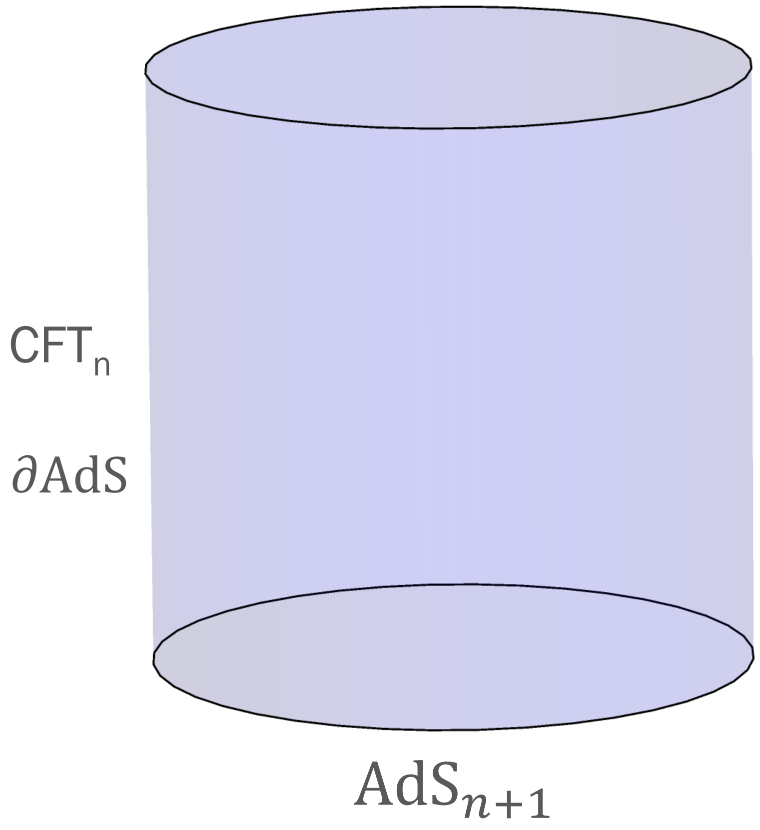
$S(\beta \to \infty) \neq 0$ unentangled?



Holographic Rindler CFT

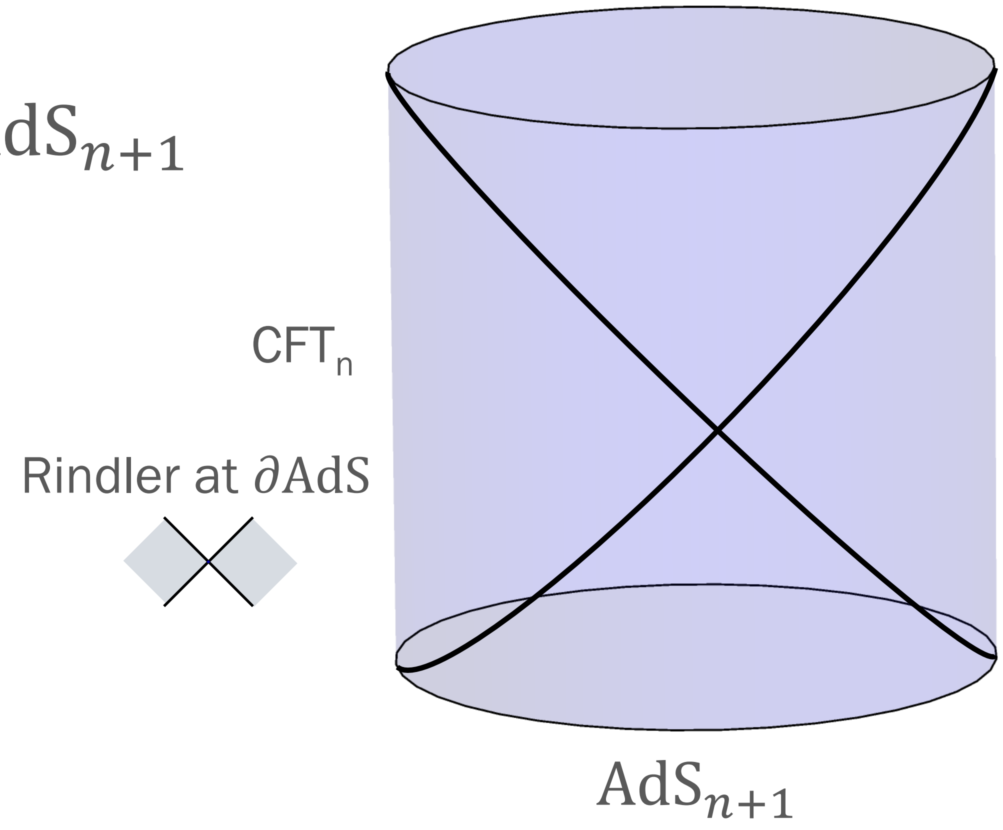
AdS/CFT

Gravity in $\mathrm{Ad}S_{n+1}$ ≡ CFT_n on the spacetime at $\partial\mathrm{Ad}S$

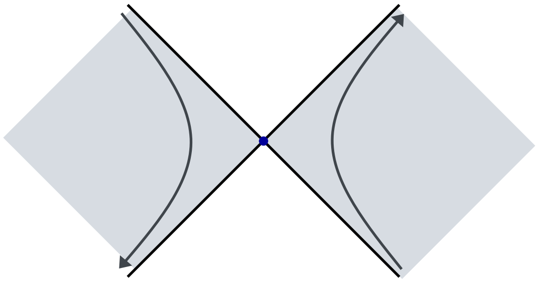
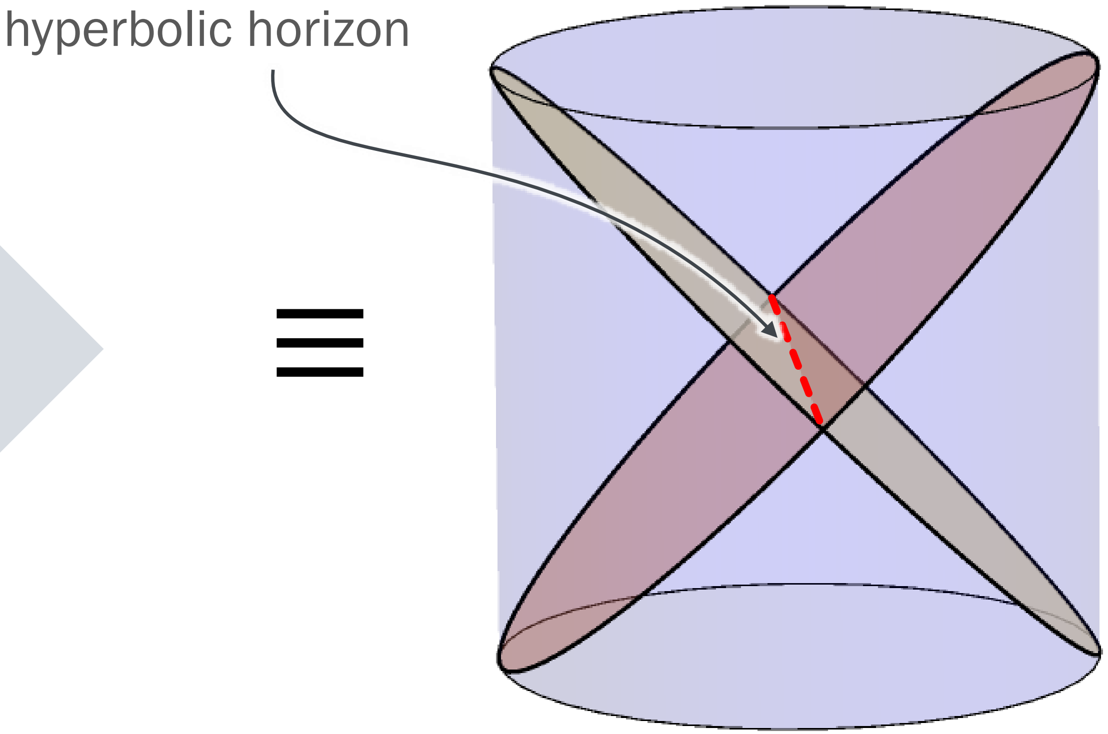


AdS/CFT

CFT_n in Rindler $\equiv$ Gravity in Rindler-AdS_{n+1}



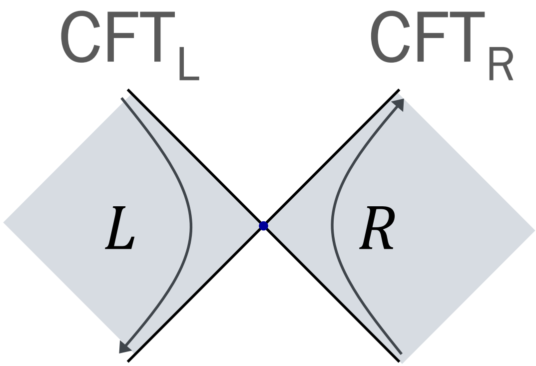
Rindler-AdS ⇔ CFT in Rindler

CFT in  ≡ 

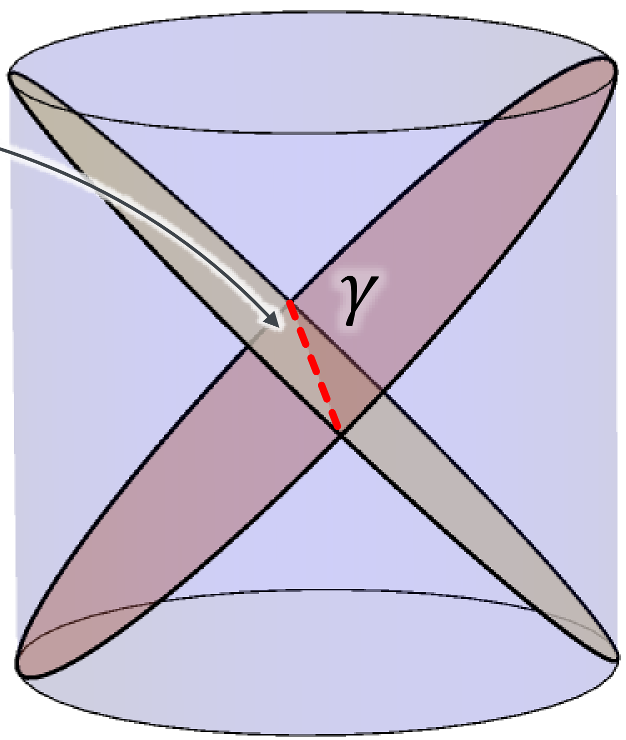
$$\partial(\text{Rindler AdS}_{n+1}) = \text{Rindler}_n$$

Holographic Entanglement Entropy

Ryu+Takayanagi
Casini+Huerta+Myers

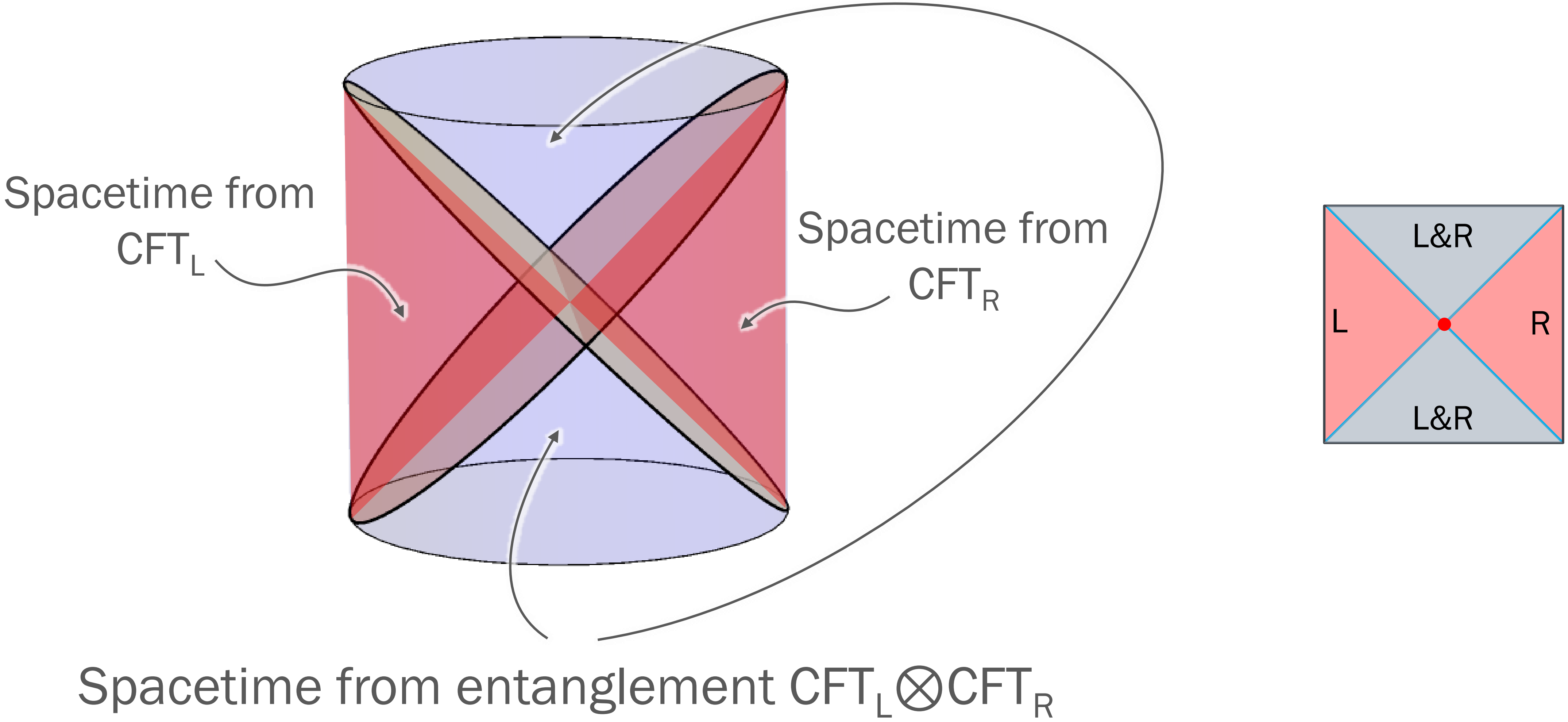


$\equiv$



$$S = \frac{\text{Area}(\gamma)}{4G\hbar}$$

= entropy of hyperbolic horizon

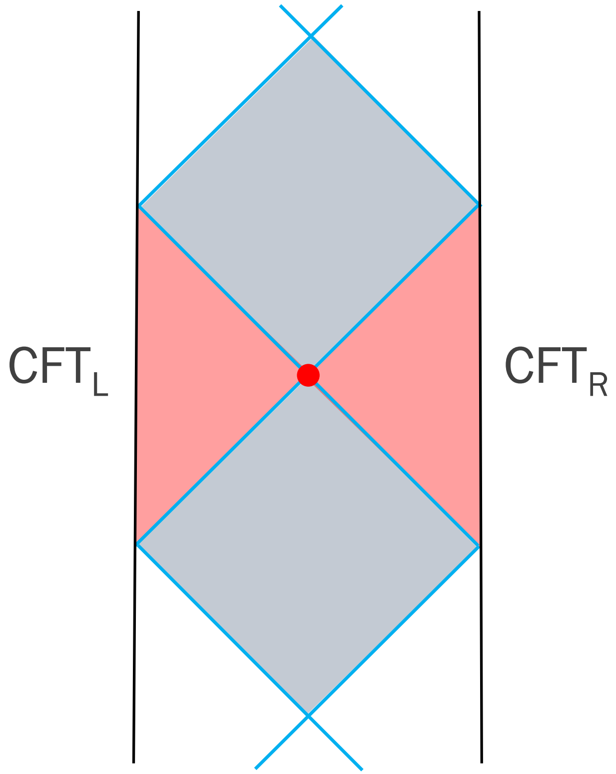

Spacetime from
CFT$_L$
Spacetime from
CFT$_R$
Spacetime from entanglement CFT$_L \otimes$CFT$_R$
L&R
L
R
L&R

Rindler CFT ≡ Hyperbolic AdS

$\mathrm{CFT_L} \otimes \mathrm{CFT_R}$

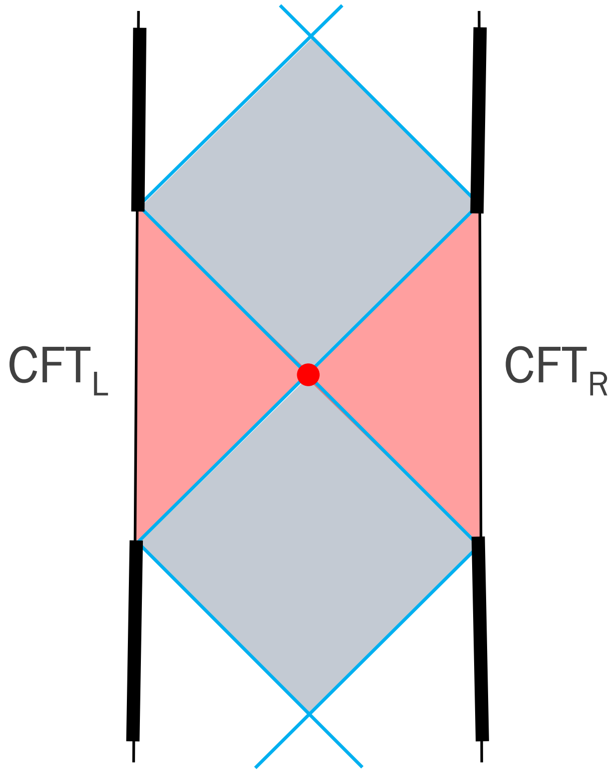
$$|0\rangle_M = \frac{1}{\sqrt{Z}} \sum_i e^{-\pi E_i} |i\rangle_L |i\rangle_R \qquad \equiv$$

$$T = \frac{1}{2\pi}$$



Disentangled Rindler CFT ≡ Hyperbolic AdS *black hole*

$$|\Psi_\beta\rangle = \frac{1}{\sqrt{Z}}\sum_i e^{-E_i/2T}|i\rangle_L|i\rangle_R \qquad \equiv$$



$$0 \leq T < \frac{1}{2\pi}$$

RE 1999
Czech et al 2012

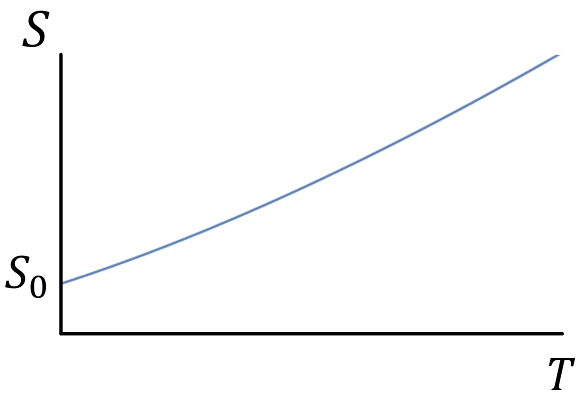
Boulware vacuum ≡ <u>Extremal</u> hyperbolic black hole $T = 0$

$$\left|\Psi_{\beta\to\infty}\right\rangle = |0\rangle_L |0\rangle_R$$

$$S(T \to 0) \neq 0$$

Extremal black hole → Unentangled state

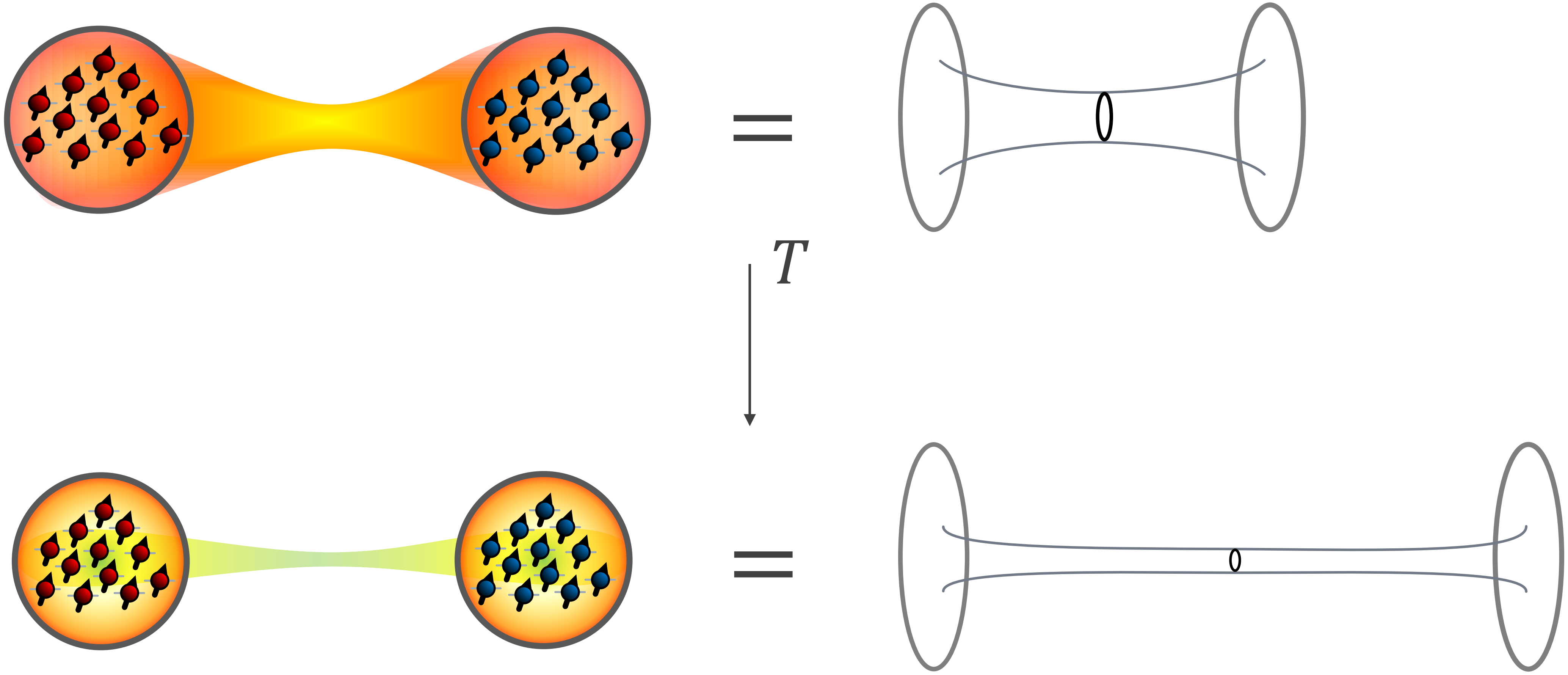
non-zero area → non-zero entanglement entropy



Entangled bridges

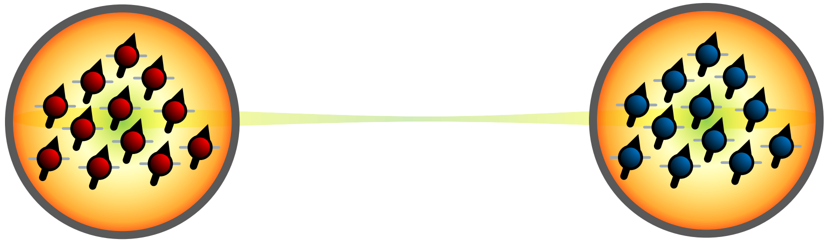
$$\sum_i e^{-E_i/2T}|i\rangle_L|i\rangle_R$$

T = entangling temperature

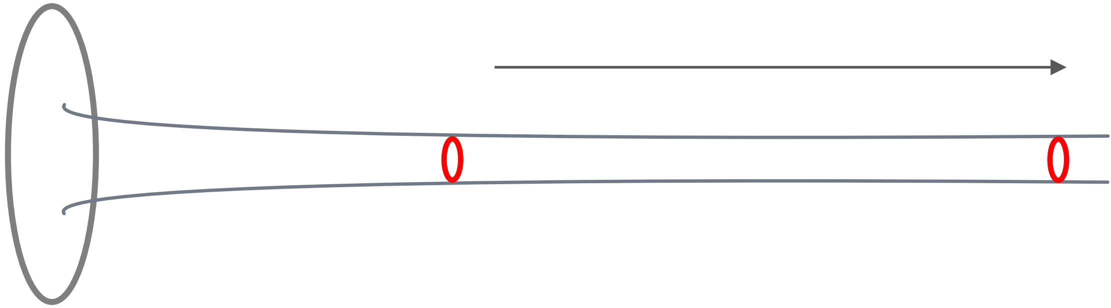


Disentangled bridges?

$$T \to 0$$



$$= $$



$L_{\text{bridge}} \sim \frac{1}{T} \sim$ 1/correlation $\longrightarrow \infty$ ☺

$A_{\text{bridge}} \sim$ entanglement entropy $\longrightarrow S_0 \neq 0$ ☹

Quantum throat dynamics

EXTREME BRIDGE DEMOLITION

Entropy of extremal black holes has long been puzzling

Large degeneracy of ground state: non-generic (unless susy-protected)

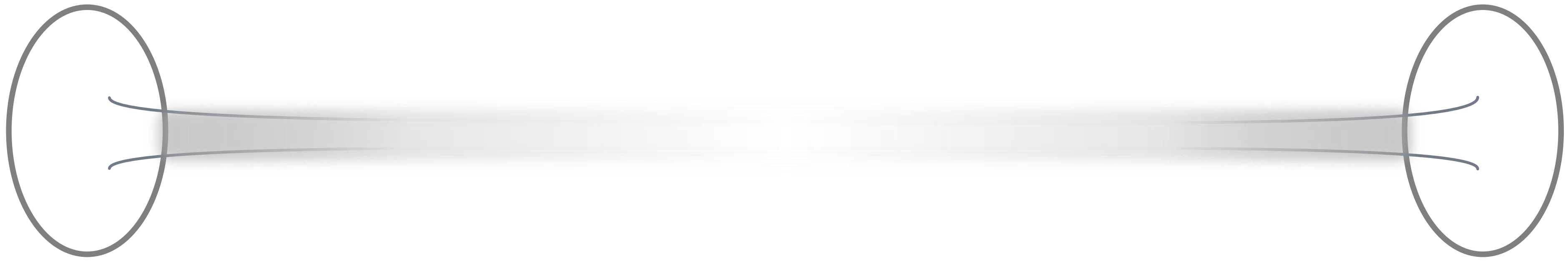
3rd Law of Thermo?

(Nernst theorem)

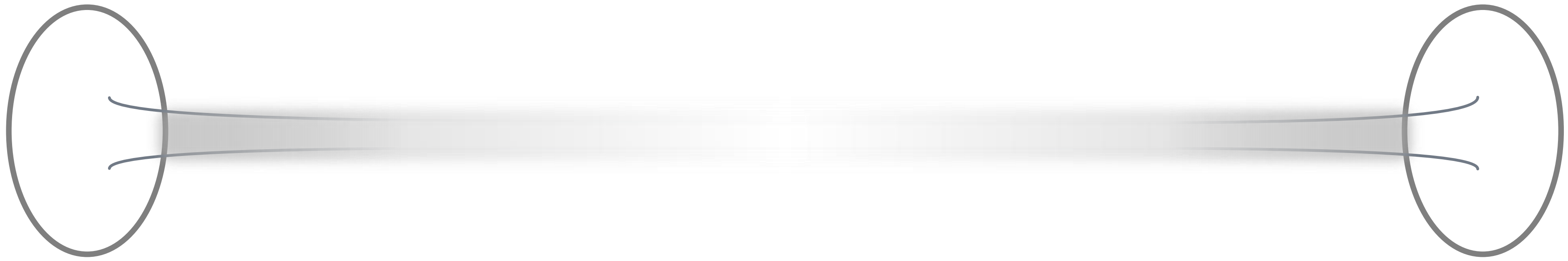
Quantum effects important at low temperatures

Quantum fluctuations of long throats

Quantum gravity in low curvature geometry



Entropy $\neq$ Area



Quantum Near extremality (w/out susy)

Charged Reissner-Nordstrom black holes — Iliesiu+Turiaci

Rotating Kerr & BTZ black holes — Ghosh+Maxfield+Turiaci, Rakic+Rangamani+Turiaci, Kapec+Sheta+Strominger+Toldo

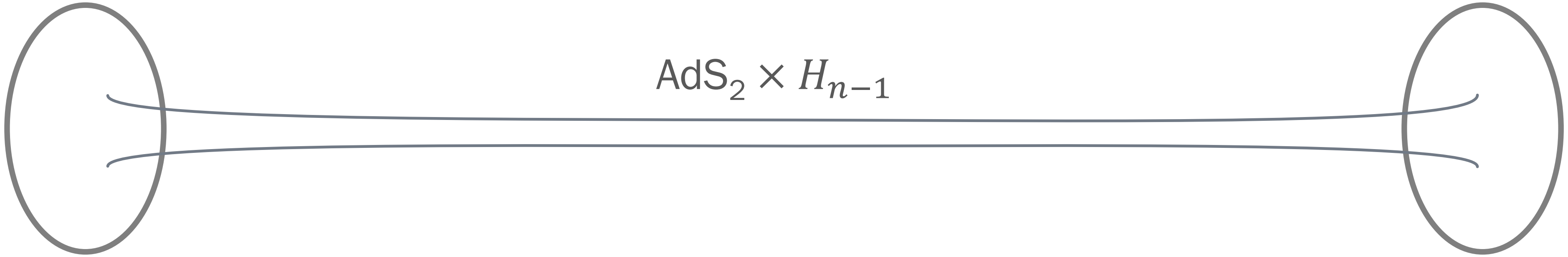
Hyperbolic AdS black holes — RE+Magán

Quantum Throat

- Euclidean gravitational path integral around saddle-point: near-extremal black hole

$$Z(T) = e^{-I_{\mathrm{bh}}(T)} \times \det(\mathrm{Q})^{-1/2}$$

- Find dominant quantum fluctuations at low T
- Dynamics of throat: 2D dilaton gravity (JT gravity)



Quantum Throat

Maldacena+Stanford+Yang
Stanford+Witten
Mertens+Turiaci+Verlinde

- Dynamics of throat → 1D theory (Schwarzian) of fluctuations of throat mouth

$$I_{\text{mouth}} = -\frac{1}{M_b}\int_0^\beta du\, \text{Sch}(\tau, u)$$

Quantum Throat

Maldacena+Stanford+Yang
Stanford+Witten
Mertens+Turiaci+Verlinde

- Dynamics of throat → 1D theory (Schwarzian) of fluctuations of throat mouth
- Strongly coupled at low $T < M_b$: Large quantum fluctuations of geometry
- Can be quantized – one-loop exact

$$I_{\text{mouth}} = -\frac{1}{M_b}\int_0^\beta du\,\text{Sch}(\tau,u)$$

Quantum corrections to BH entropy

$$S = \frac{A_H}{4G\hbar} + c \log A_H$$

scale of quantum fluctuations

Small quantum correction

Quantum corrections to *near-extremal* BH entropy

$$S = \frac{A_H}{4G\hbar} + c_T \log T + c_A \log A_H$$

two scales of quantum fluctuations

Iliesiu+Murthy+Turiaci
Banerjee+Saha+Srinivasan

Quantum log T

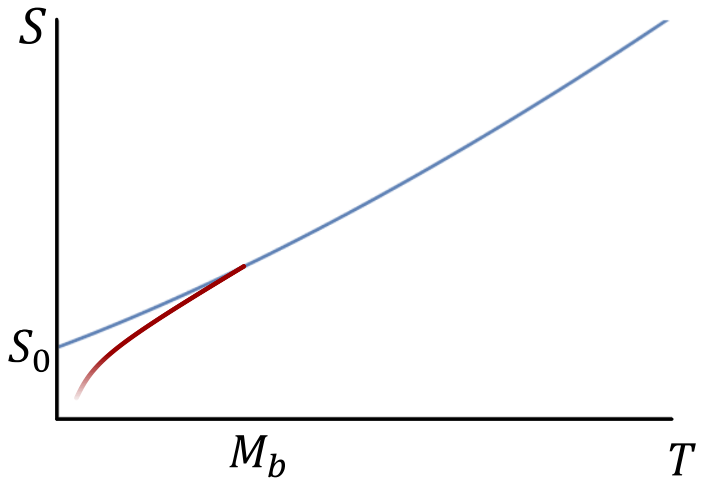
$$S = \frac{A_H}{4G\hbar} + c_T \log T + c_A \log A_H$$

negative and not small at low T

Rindler entanglement entropy at low temperature

$$S(T) = S_0 + 4\pi^2 \frac{T}{M_b} - \frac{3}{2}\left|\log \frac{T}{M_b}\right| + \cdots$$

semiclassical $A_H/4G\hbar$ quantum fluctuations of throat



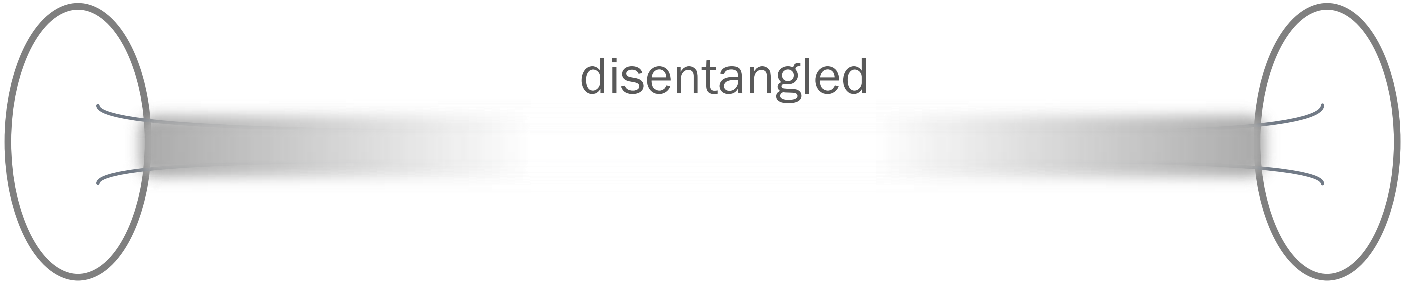
Gravitational partition function

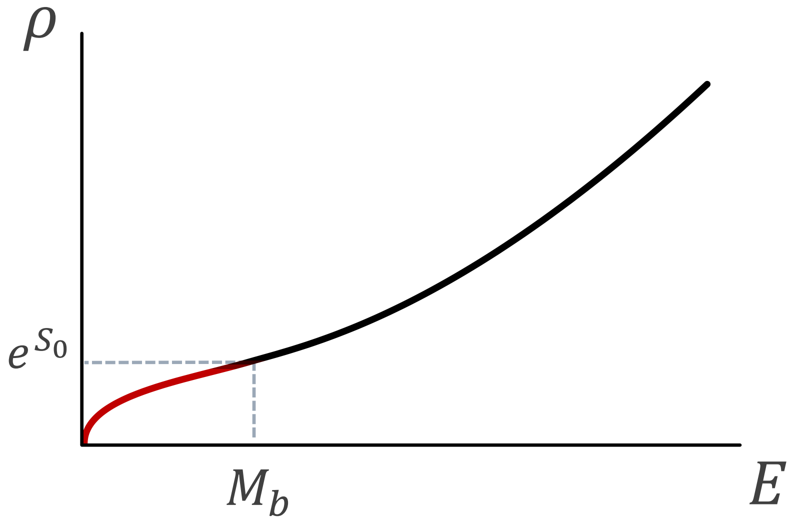
$$Z(T) = e^{S_0 + 2\pi^2 \frac{T}{M_b}} \left(\frac{T}{M_b}\right)^{3/2}$$

quantum

Density of entangled states at low energies

$$\rho(E) = e^{S_0} \sinh\left(2\pi\sqrt{2E/M_b}\right)$$



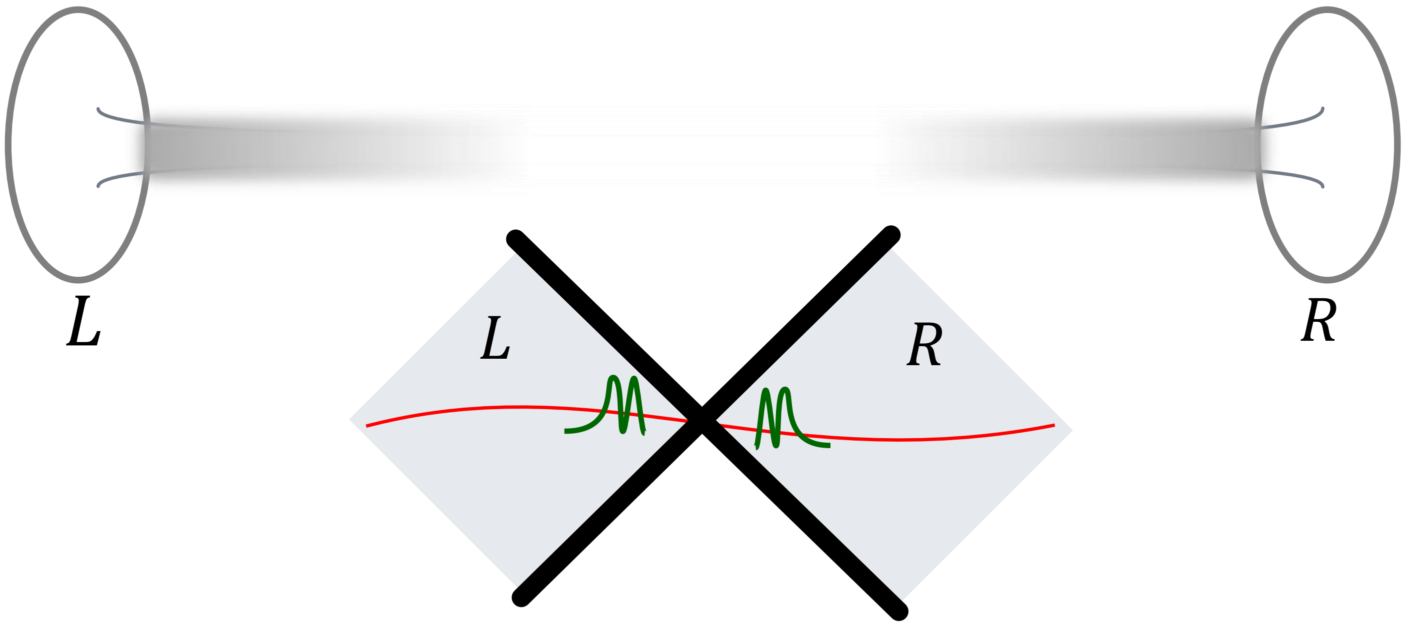


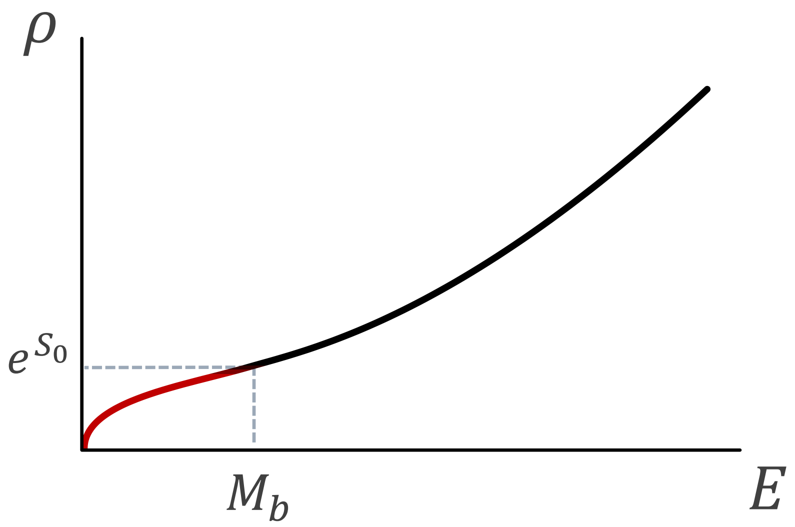
Entanglement not given by the area

not classicalized as geometry

Disentangled holographic Boulware vacuum

$$|\Psi_{E\to 0}\rangle \to |0\rangle_L |0\rangle_R$$

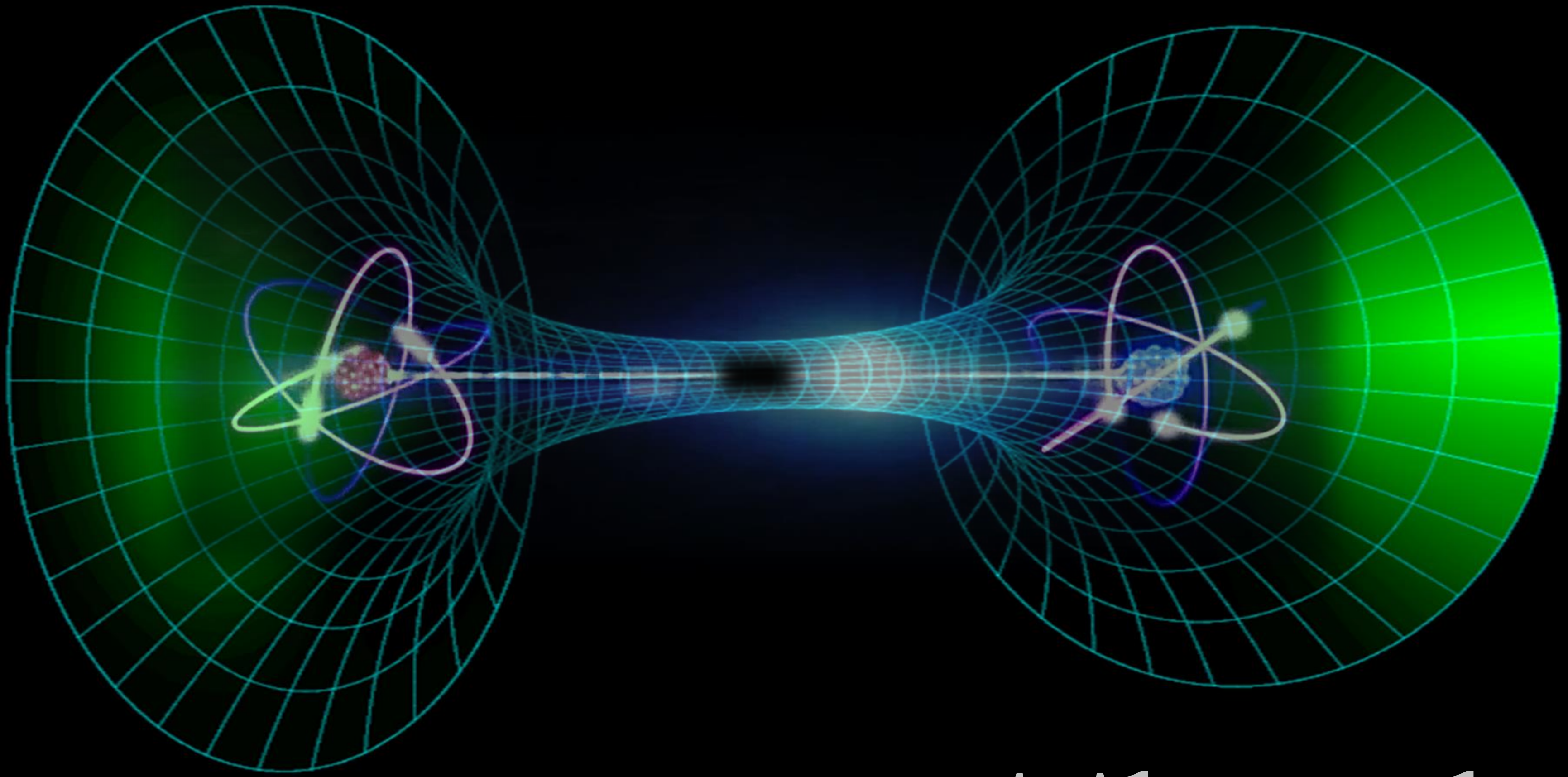




Puzzle solved ✓

Outlook

- Controlled strong quantum gravity in a large, weakly curved geometry
- Infrared Quantum Gravity fluctuations demolish geometric bridges – no Planck-scale curvatures
- Spacetime becomes quantum fuzz, untangles apart
- Gradually assemble large spacetime from random matrices?



Thank you

Outlook

> "O time, thou must untangle this, not I.
> It is too hard a knot for me t'untie."
>
> W. S.

- Controlled strong quantum gravity in a large, weakly curved geometry
- Infrared Quantum Gravity fluctuations demolish geometric bridges – no Planck-scale curvatures
- Spacetime becomes quantum fuzz, untangles apart
- Gradually assemble large spacetime from random matrices?

Backup material

Rindler-AdS

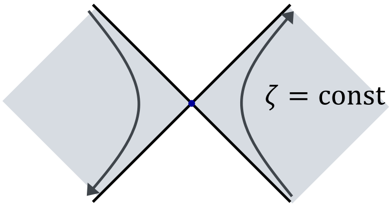
hyperboloid H_{n-1}

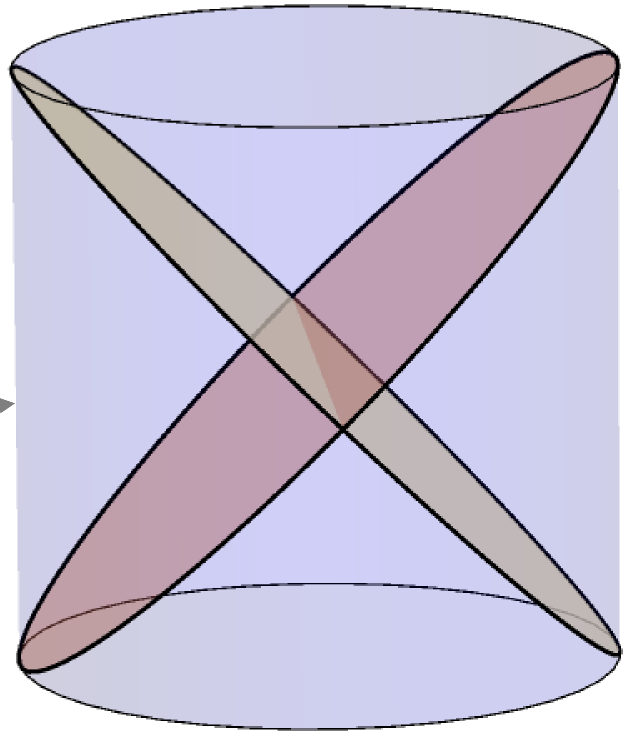
$$ds^2 = -\left(r^2 - \ell^2\right)dt^2 + \frac{\ell^2 dr^2}{r^2 - \ell^2} + r^2\,\overbrace{\frac{d\zeta^2 + d\mathbf{x}^2}{\zeta^2}}$$

$$= \frac{r^2}{\zeta^2}\left[-\left(1 - \frac{\ell^2}{r^2}\right)\zeta^2 dt^2 + d\zeta^2 + d\mathbf{x}^2\right] + \frac{\ell^2}{r^2}\frac{dr^2}{1 - \frac{\ell^2}{r^2}}$$

$r \to \infty$

$$ds^2\Big|_{\partial\mathrm{AdS}} = -\zeta^2 dt^2 + d\zeta^2 + d\mathbf{x}^2$$





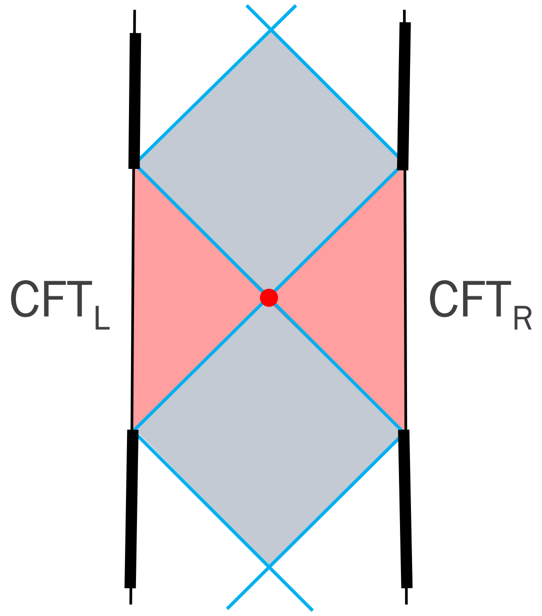
$\partial(\text{Rindler AdS}_{n+1}) = \text{Rindler}_n$

Disentangled Rindler CFT = Hyperbolic AdS *black hole*

$$|\Psi_\beta\rangle = \frac{1}{\sqrt{Z}}\sum_i e^{-\beta E_i/2}|i\rangle_L|i\rangle_R \qquad 0 \le T < \frac{1}{2\pi}$$

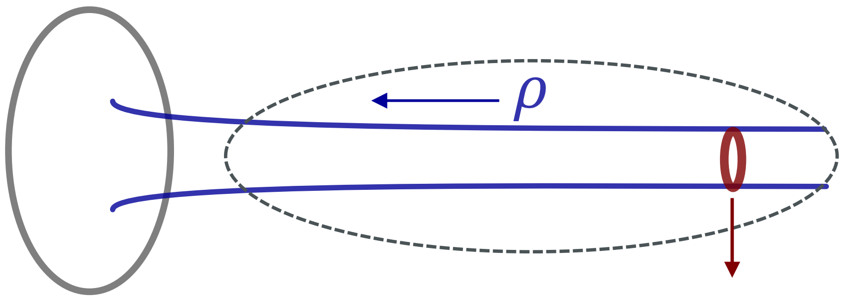
$$ds^2 = \frac{r^2}{\zeta^2}\underbrace{[-f(r)\zeta^2 dt^2 + d\zeta^2 + d\mathbf{x}^2]}_{\text{Rindler @bdry}} + \frac{\ell^2}{r^2}\frac{dr^2}{f(r)}$$

$$f(r) = 1 - \frac{\mu}{r^n} - \frac{\ell^2}{r^2}$$



RE 1999
Czech et al 2012

Throat geometry



near-extremality & near throat

$\rho, \rho_+ \ll r_0$

$r_h = r_0 + \rho_+ \qquad r = r_0 + \rho$

$$ds^2 = \underbrace{-(\rho^2 - \rho_+^2)dt^2 + \frac{d\rho^2}{\rho^2 - \rho_+^2}}_{\mathrm{AdS}_2} + r_0^2 \underbrace{\frac{d\zeta^2 + d\boldsymbol{x}^2}{\zeta^2}}_{H_2}$$

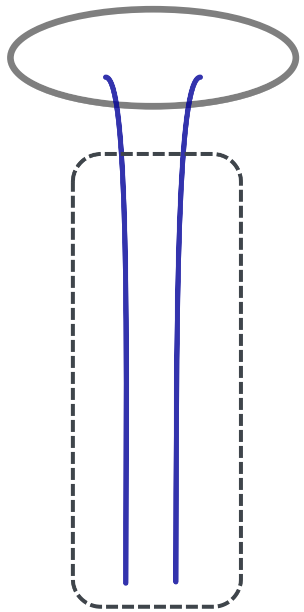
Throat reduction → 2-dim dilaton gravity

Throat $= \mathrm{AdS}_2 \times H_2$

$$ds^2 = \Phi^{-1/2} g^{(2)}_{\mu\nu} dx^\mu dx^\nu + r_0^2 \Phi\, dH_2$$

$$\Phi = \Phi_0 + \phi(\rho)$$

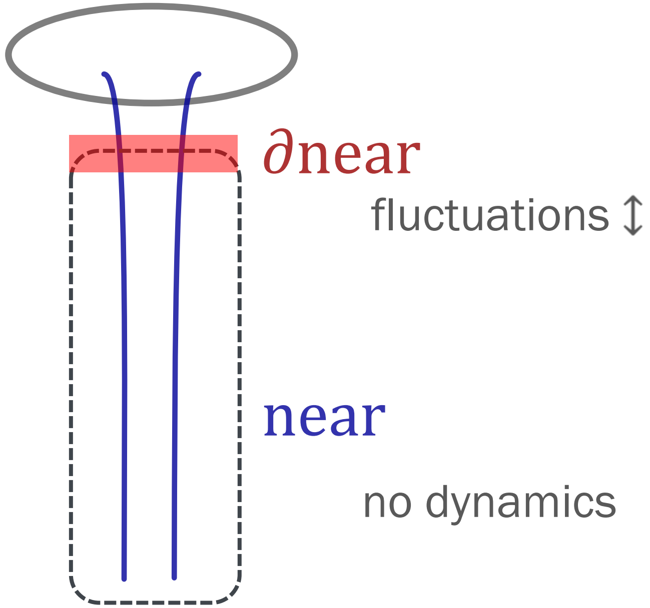
$$g^{(2)}_{\mu\nu}\,,\ \Phi$$



Throat reduction → 2-dim JT gravity

$$I = -\frac{1}{2}\int_{\mathbf{near}} d^2x\,\sqrt{g}\left[\phi_0 R + \phi\left(R + \frac{2}{L_2^2}\right)\right]$$

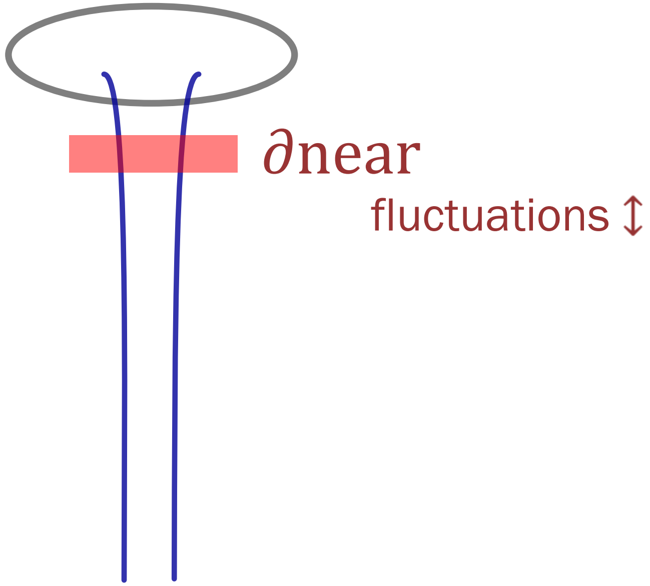
$$-\int_{\partial\mathbf{near}} dx\,\sqrt{h}\left[\phi_0 K + \frac{1}{\epsilon\, M_b}\left(K - \frac{1}{L_2}\right)\right]$$



Throat reduction → 2-dim JT gravity

$$I = -\frac{1}{2}\int_{\mathbf{near}} d^2x\,\sqrt{g}\left[\phi_0 R + \phi\left(R + \frac{2}{L_2^2}\right)\right]$$

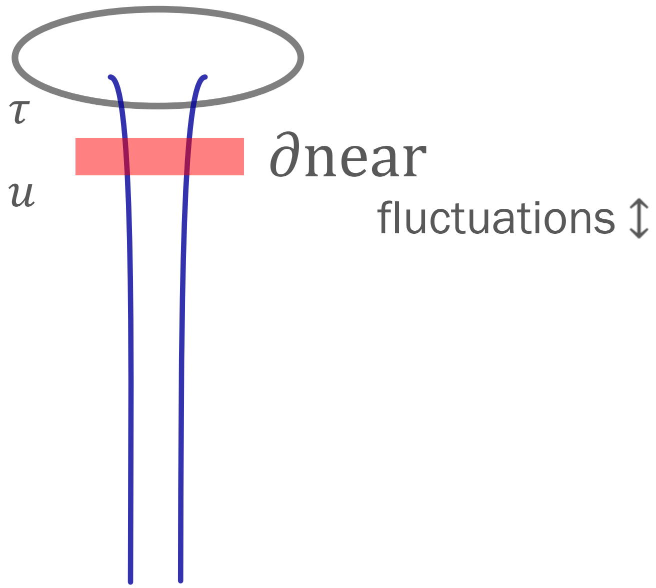
$$-\int_{\mathbf{\partial near}} dx\,\sqrt{h}\left[\phi_0 K + \frac{1}{\epsilon\, M_b}\left(K - \frac{1}{L_2}\right)\right]$$



Maldacena+Stanford+Yang,
Stanford+Witten,
Mertens+Turiaci+Verlinde, Yang,...

2-dim JT gravity ⟶ 1-dim Schwarzian theory

$$I = \beta E_0 - S_0 - \frac{1}{M_b}\int_0^\beta du\,\mathrm{Sch}(\tau, u)$$



fluctuations in height of mouth

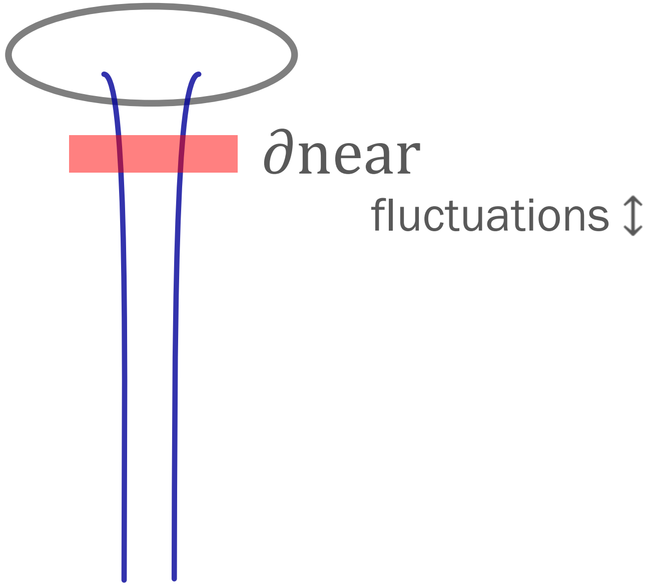
matching of near and far time

Maldacena+Stanford+Yang,
Stanford+Witten,
Mertens+Turiaci+Verlinde, Yang,...

1-dim Schwarzian theory

$$I = \beta E_0 - S_0 - \frac{1}{M_b}\int_0^\beta du\,\mathrm{Sch}(\tau, u)$$

Can be exactly quantized

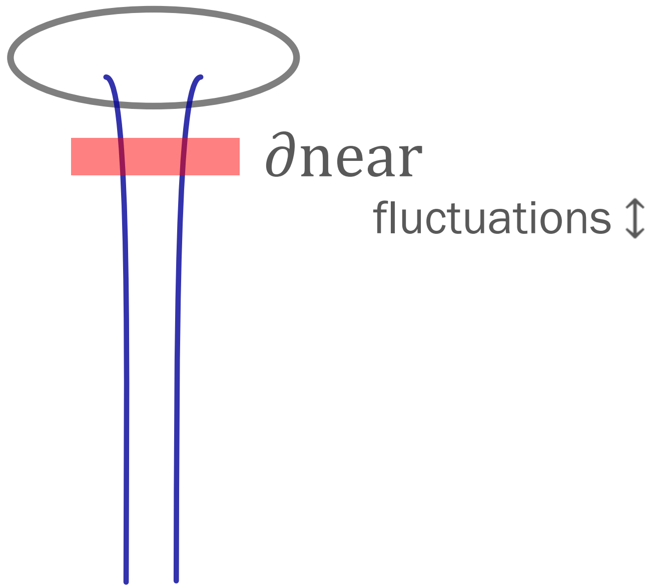


Quantum Gravity of throat

$$I = \beta E_0 - S_0 - \frac{1}{M_b}\int_0^{\beta} du\, \mathrm{Sch}(\tau, u)$$

↓

Quantum fluctuations of large geometry



Quantum Throat

Maldacena+Stanford+Yang,
Stanford+Witten,
Mertens+Turiaci+Verlinde, Yang,...

Gravitational partition function at small T

$$Z(T) = \underbrace{e^{S_0 + 2\pi^2 \frac{T}{M_b}}}_{\text{semiclassical Gibbons-Hawking}} \underbrace{\left(\frac{T}{M_b}\right)^{3/2}}_{\text{quantum fluctuations of throat}}$$