Title: The entanglement interpretation of black hole entropy

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Abstract: We show that the entropy resulting from the counting of microstates of non extremal black holes using field theory duals of string theories can be interpreted as arising from entanglement. The conditions for making such an interpretation consistent are discussed. First, we interpret the entropy (and thermodynamics) of spacetimes with non degenerate, bifurcating Killing horizons as arising from entanglement. We use a path integral method to define the Hartle-Hawking vacuum state in such spacetimes and discuss explicitly its entangled nature and its relation to the geometry. If string theory on such spacetimes has a field theory dual, then, in the low-energy, weak coupling limit, the field theory state that is dual to the Hartle-Hawking state is a thermofield double state. This allows the comparison of the entanglement entropy with the entropy of the field theory dual, and thus, with the Bekenstein-Hawking entropy of the black hole. As an example, we discuss in detail the case of the five dimensional anti-de Sitter, black hole spacetime.

Entanglement interpretation of BH entropy

Ram Brustein

אוניברסיטת בן-גוריון

R.B., M. Einhorn, A. Yarom, hep-th/0508217

Series of papers with Amos Yarom, BGU (also David Oaknin)

français

english

What does BH entropy count?

- What is entanglement entropy ?
- ❖ How is it related to BH entropy ?
- ❖ How to evaluate entanglement entropy ?

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  - ❖ How to evaluate entanglement entropy ?
- How does string theory evaluate BH entropy ?
  - ❖ How are the two methods related ?

The idea

- Thermodynamics of space-times with a causal boundary is due to the lack of information about the inaccessible region

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What's new ?

- ➢ Extension of PI methods to more space-times (BHs,dS)
- ➢ Application to FT/Gravity duals

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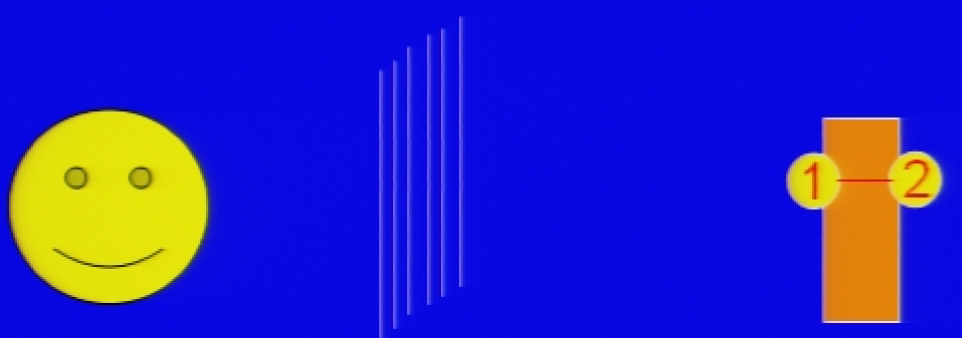

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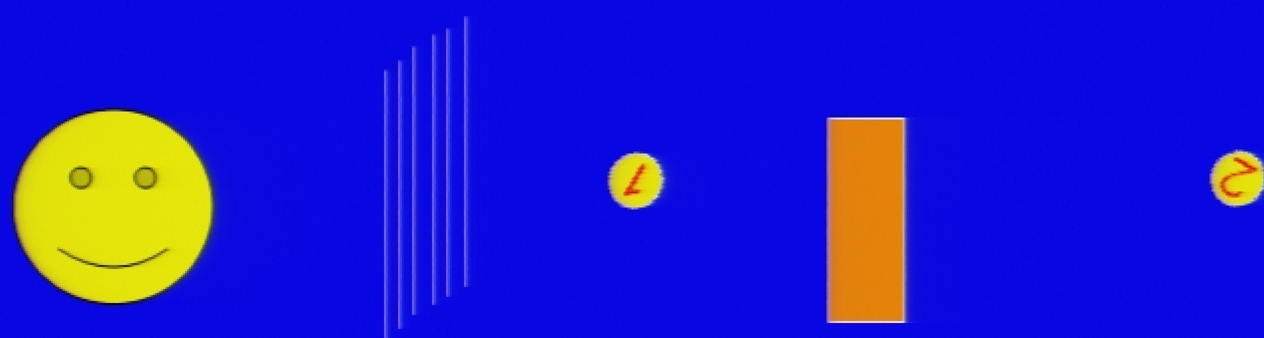

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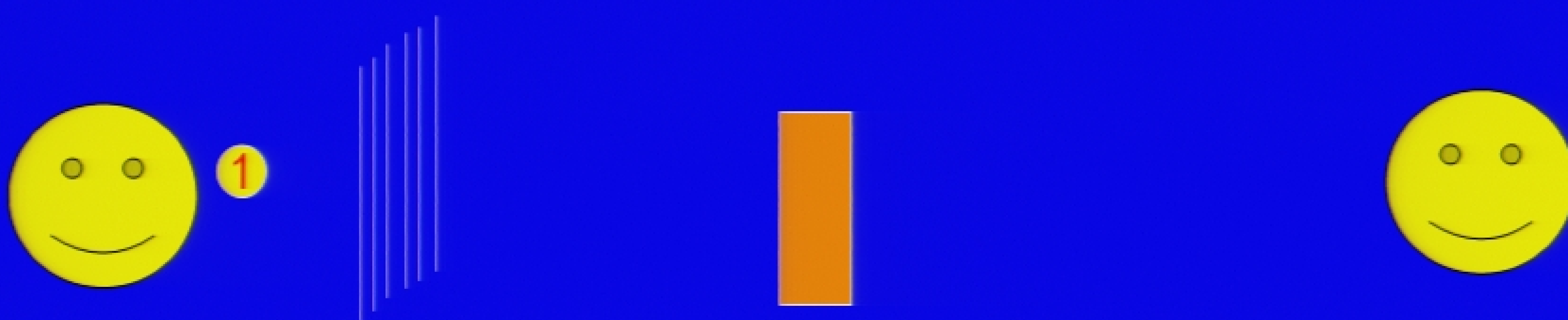

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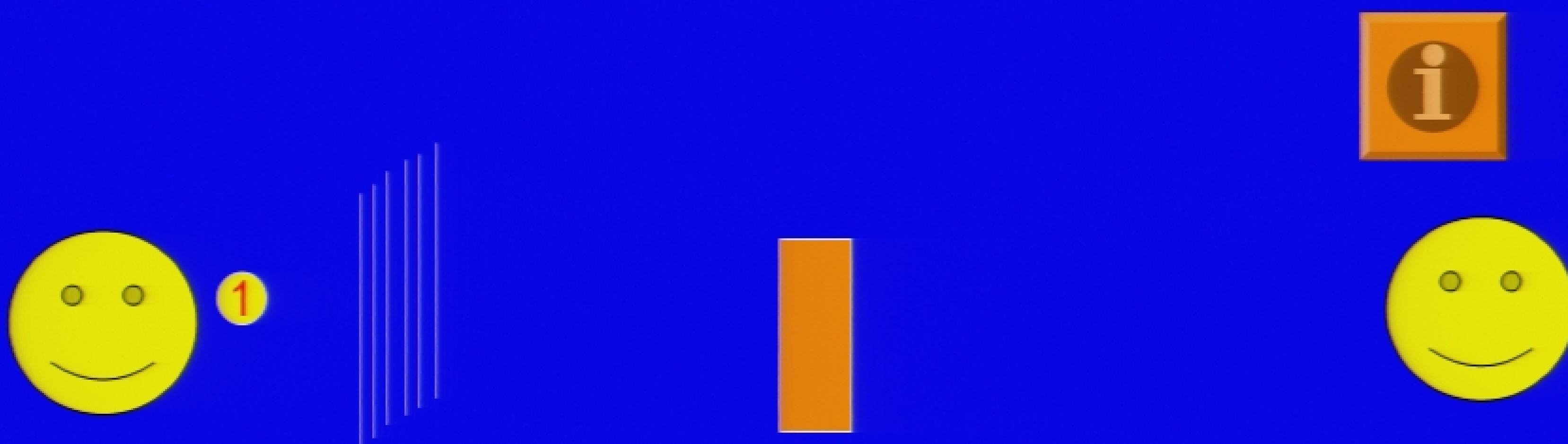

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If : thermal & time translation invariance then TFD:

$$H_{in} = -H_{out} \quad \& \quad |\psi\rangle = \frac{1}{\sqrt{Z}}\sum_i e^{-\frac{\beta}{2}E_i}|E_i\rangle|E_i\rangle$$

purification

Entanglement in space-time

$$ds^2 = -f(r)d\tau^2 + dr^2/f(r) + q(r)dx_\perp^2$$

Examples: Minkowski, de Sitter, Schwarzschild, non-rotating BTZ BH, can be extended to rotating, charged, non-extremal BHs

“Kruskal” extension

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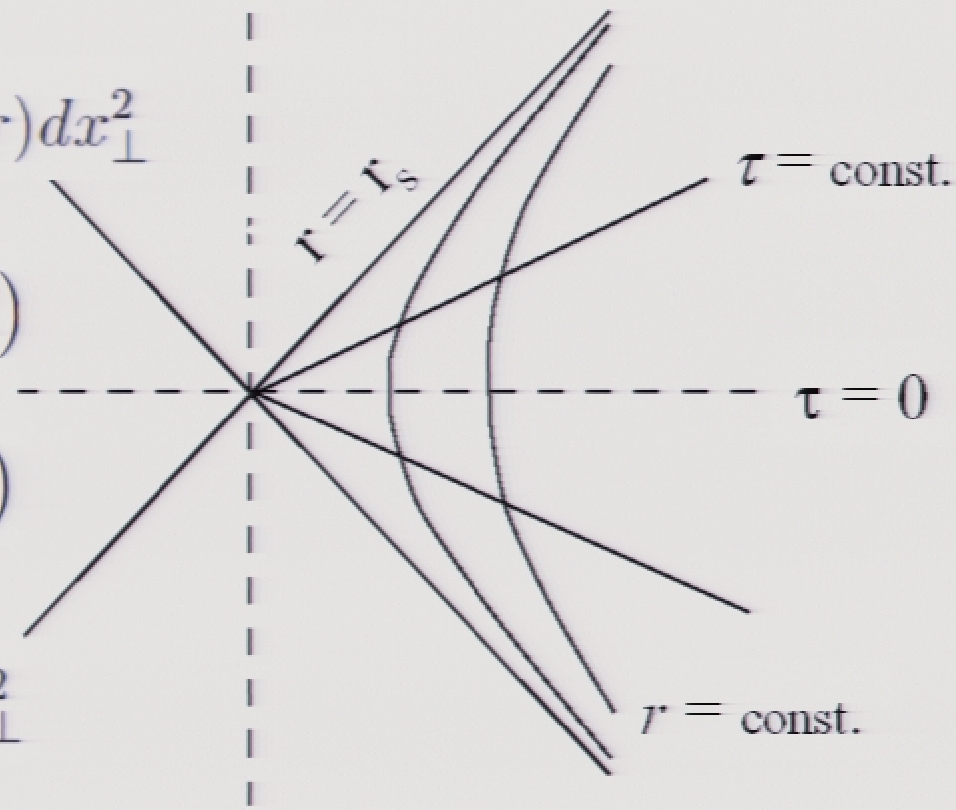

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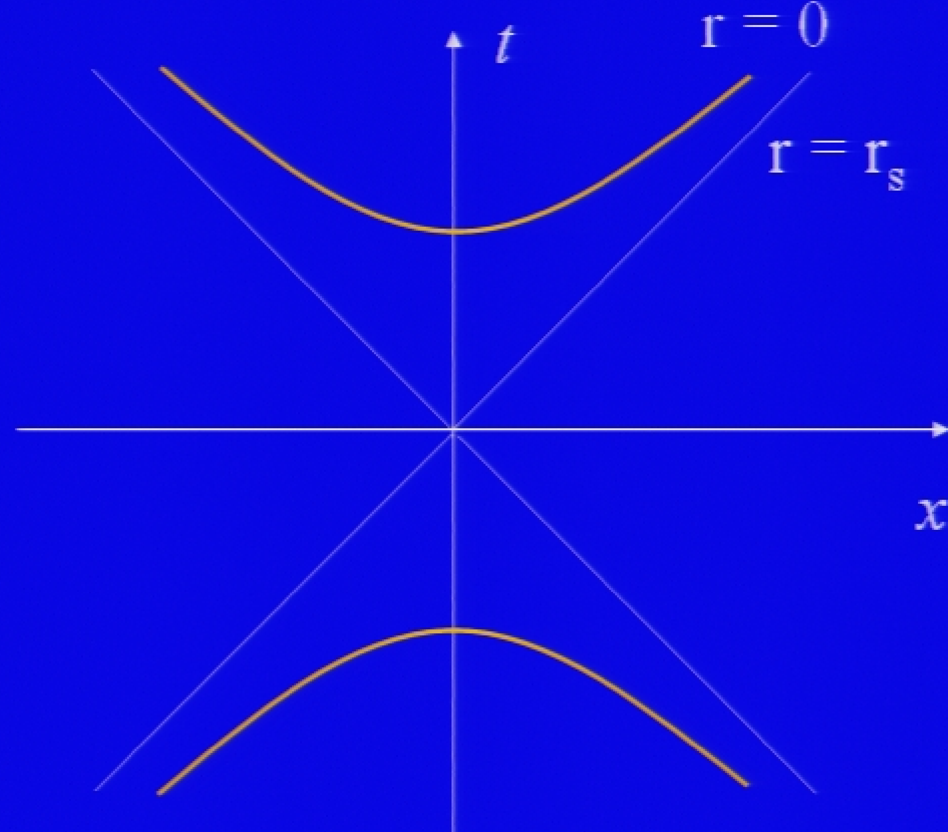

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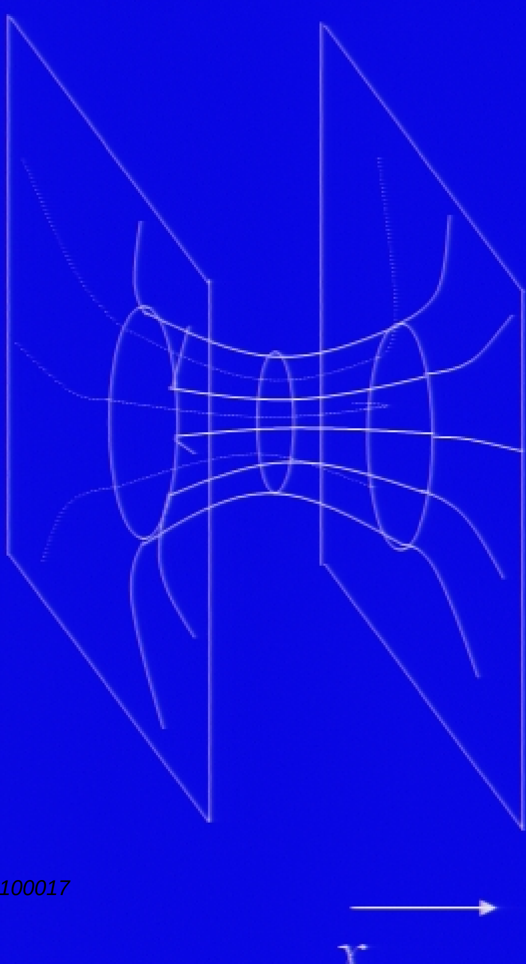

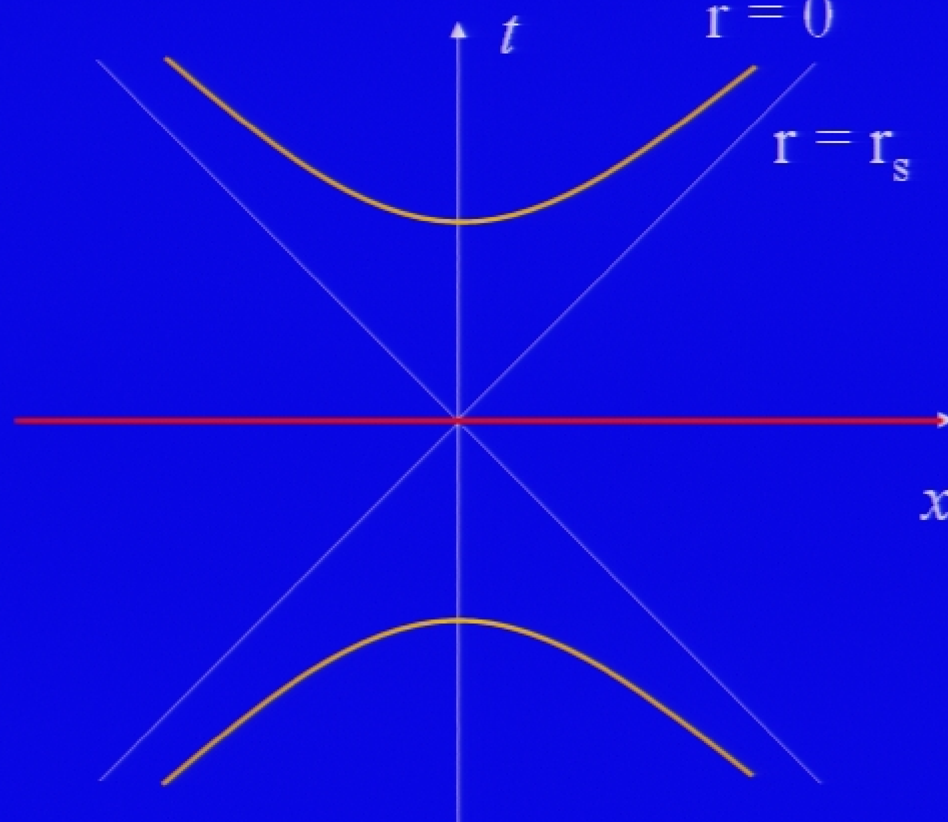

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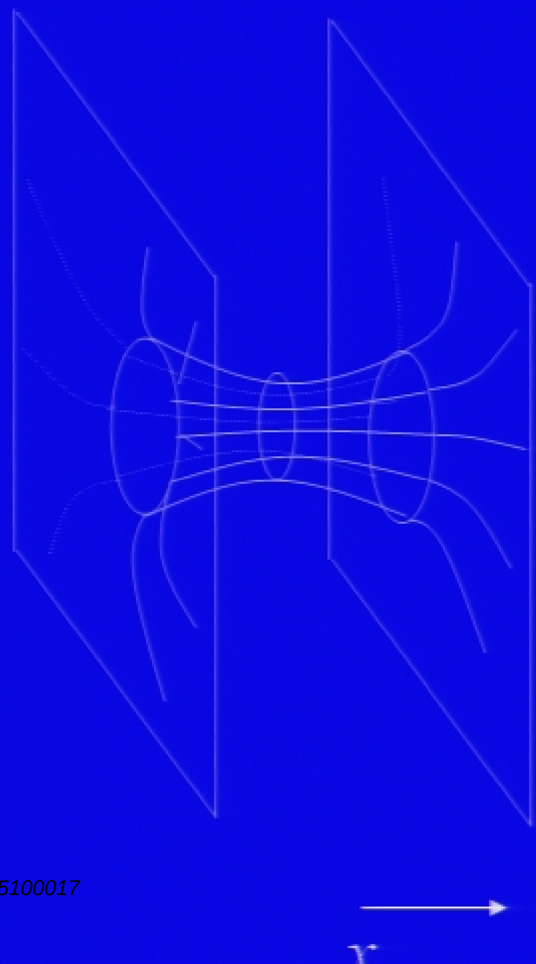

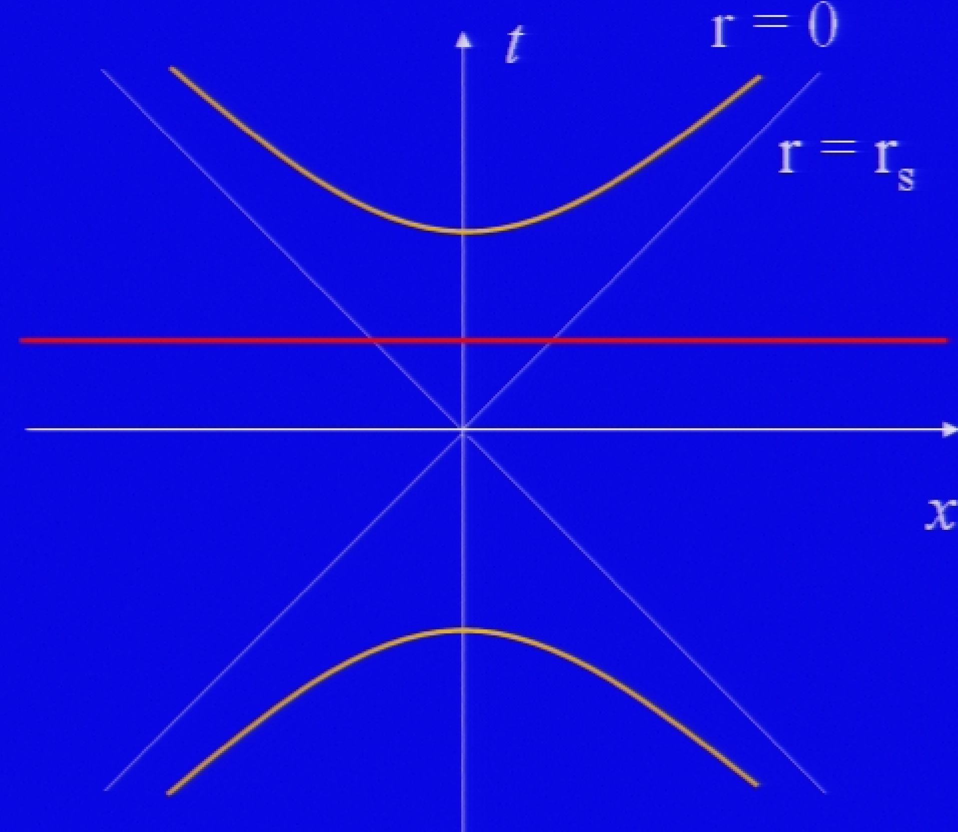

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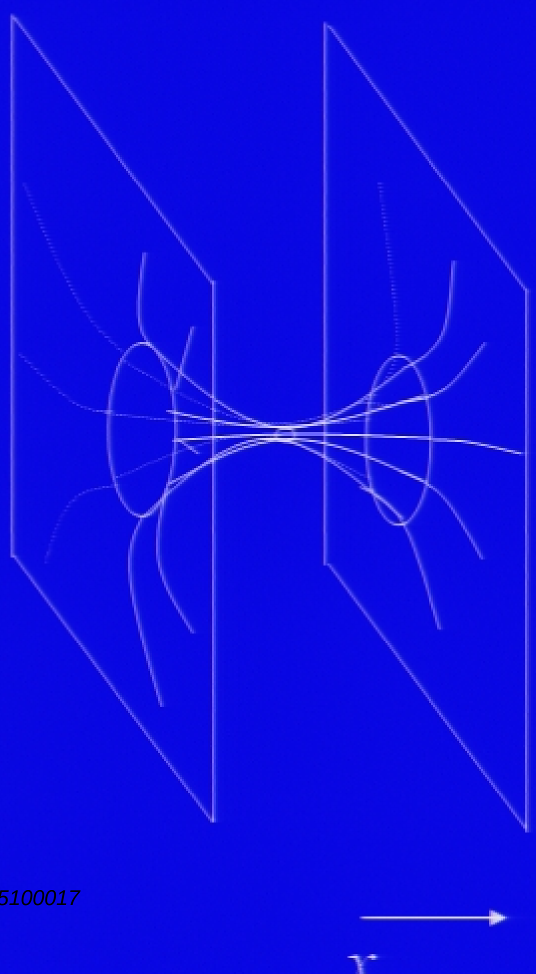

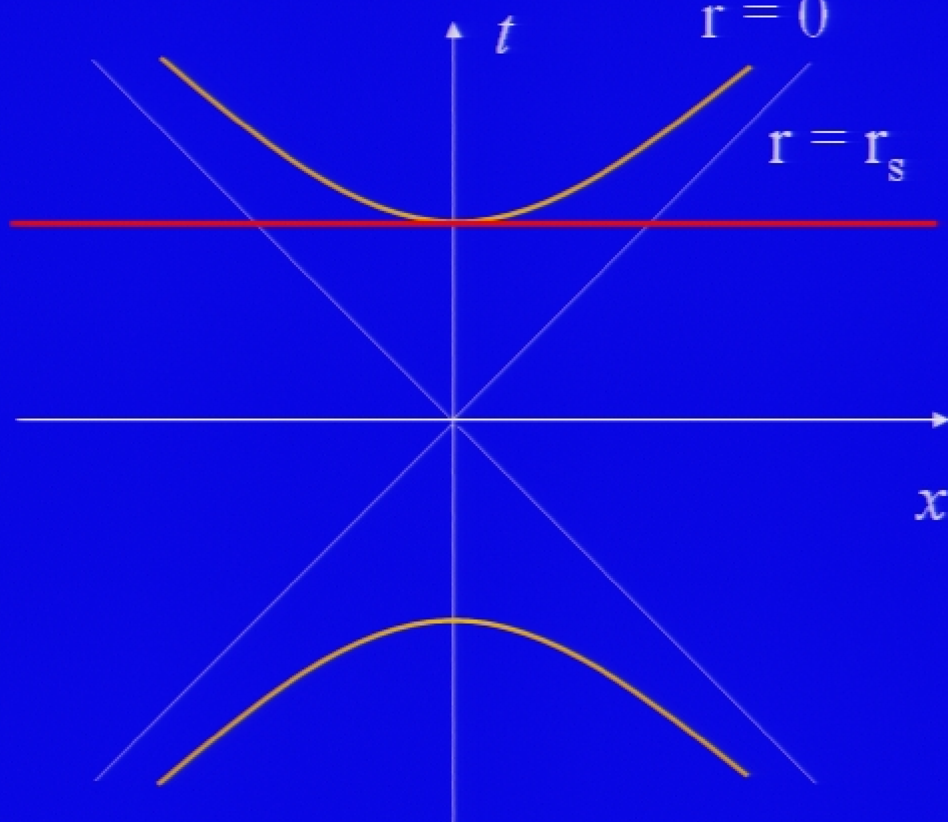

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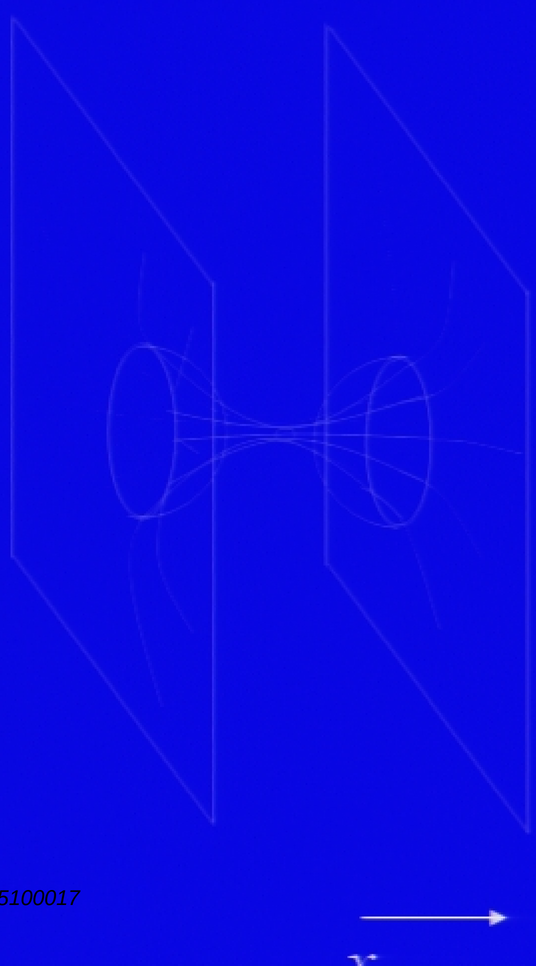

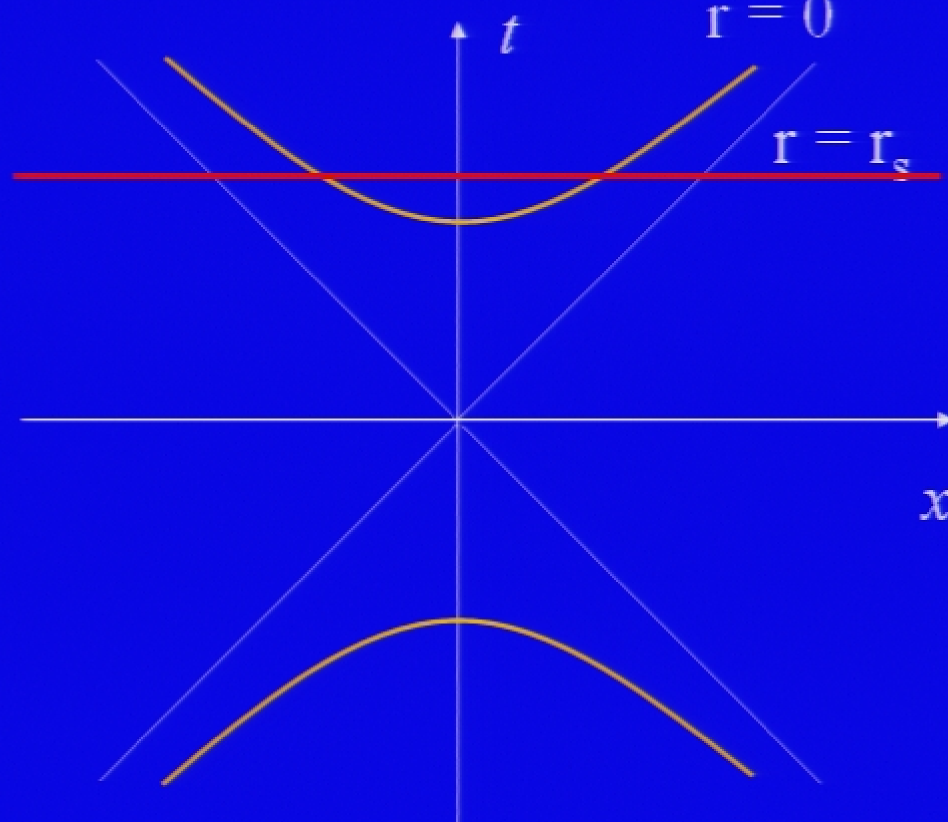

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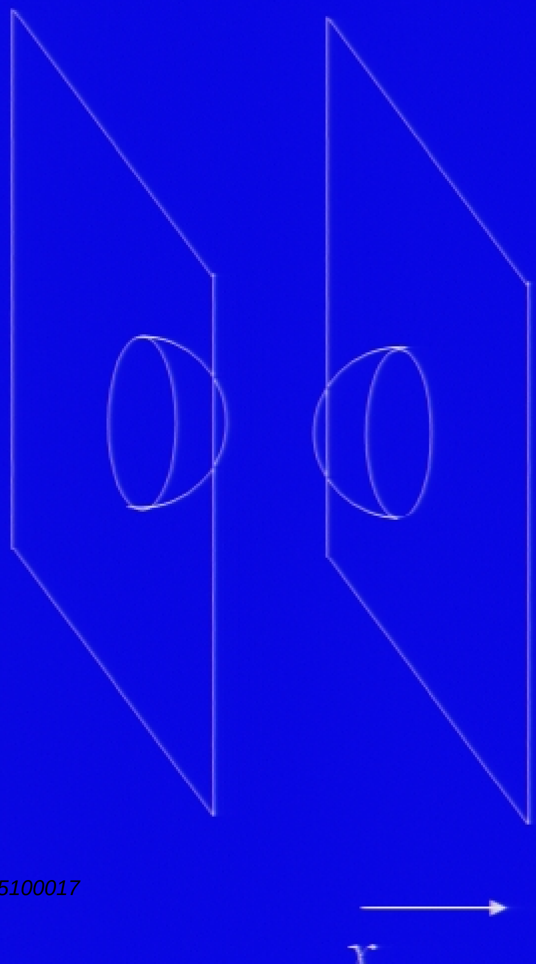
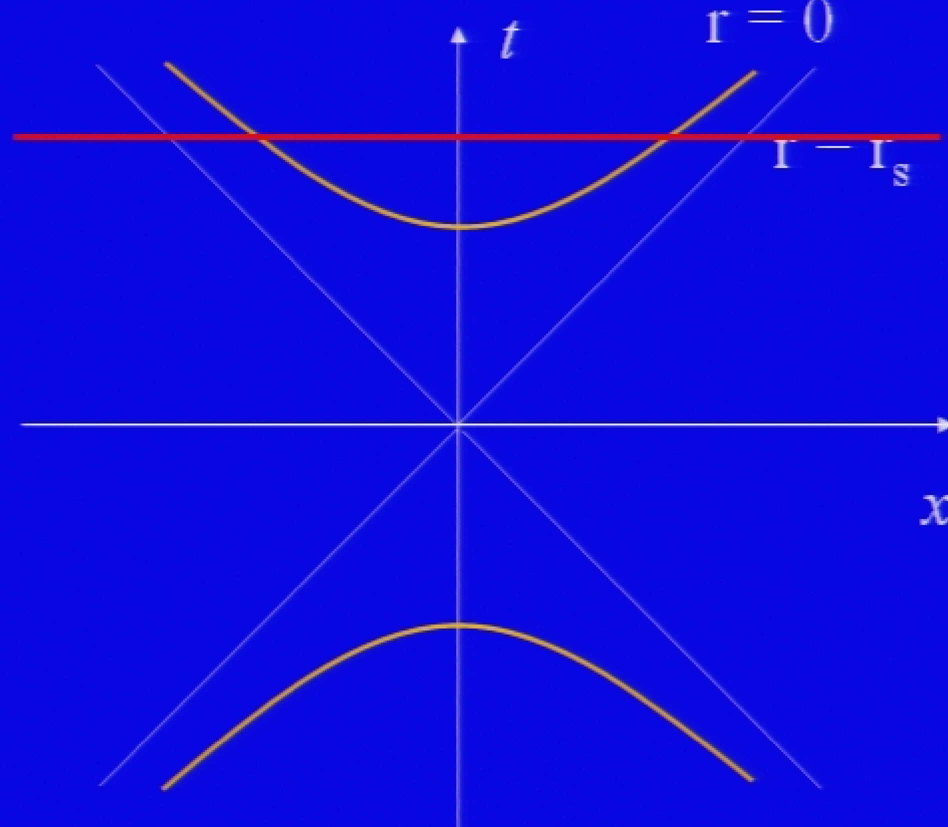
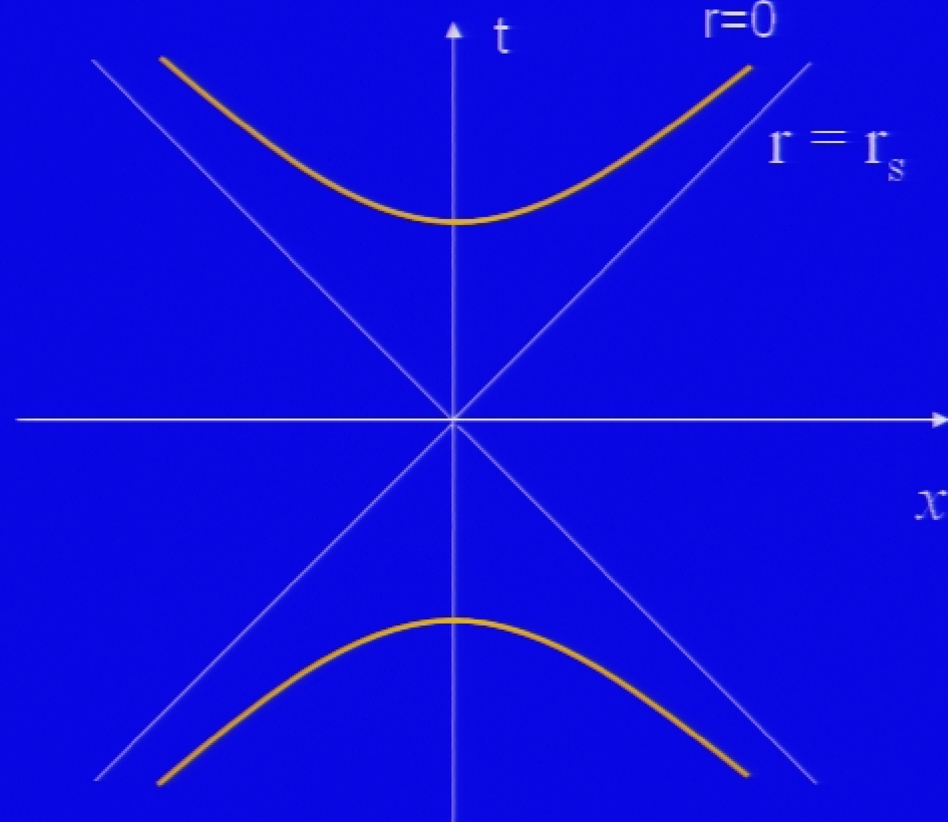




The vacuum state



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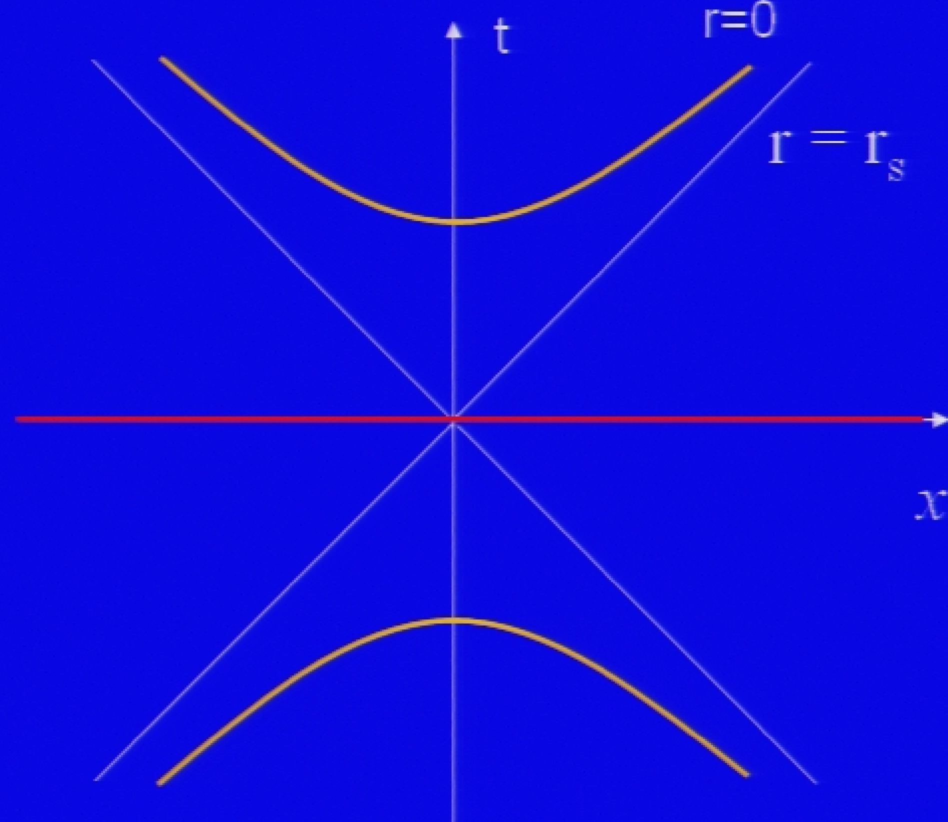

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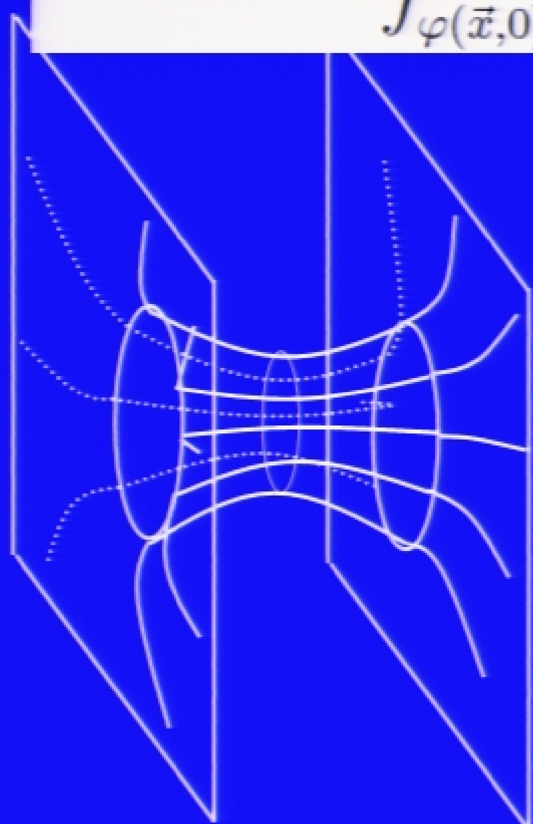
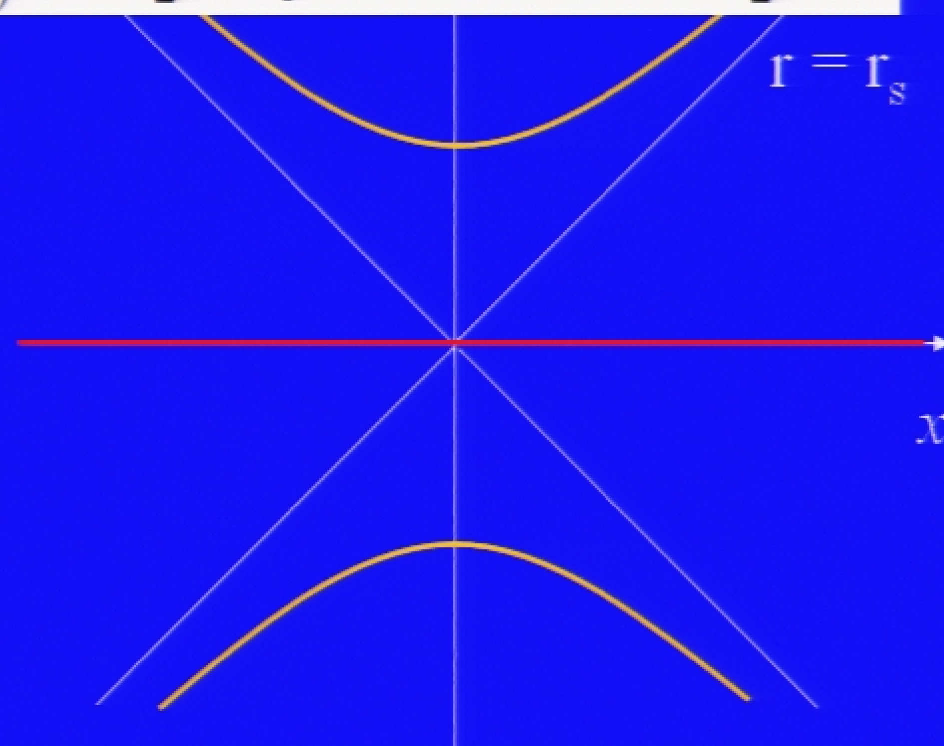
$$|0\rangle$$

$$\langle 0|\psi(\vec{x})\rangle = \int_{\varphi(\vec{x},0)=\psi(\vec{x})} \exp\left[-\int_0^\infty \ldots \int \mathcal{L} d^d x d\tau\right] D\varphi$$





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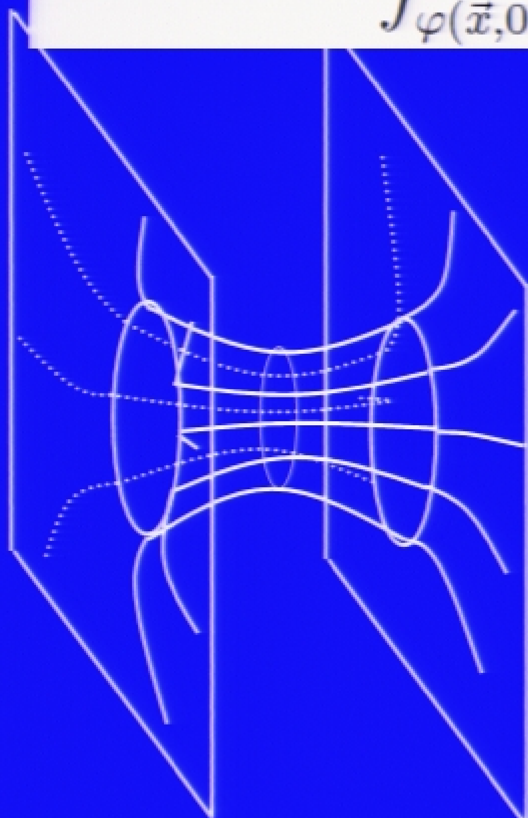

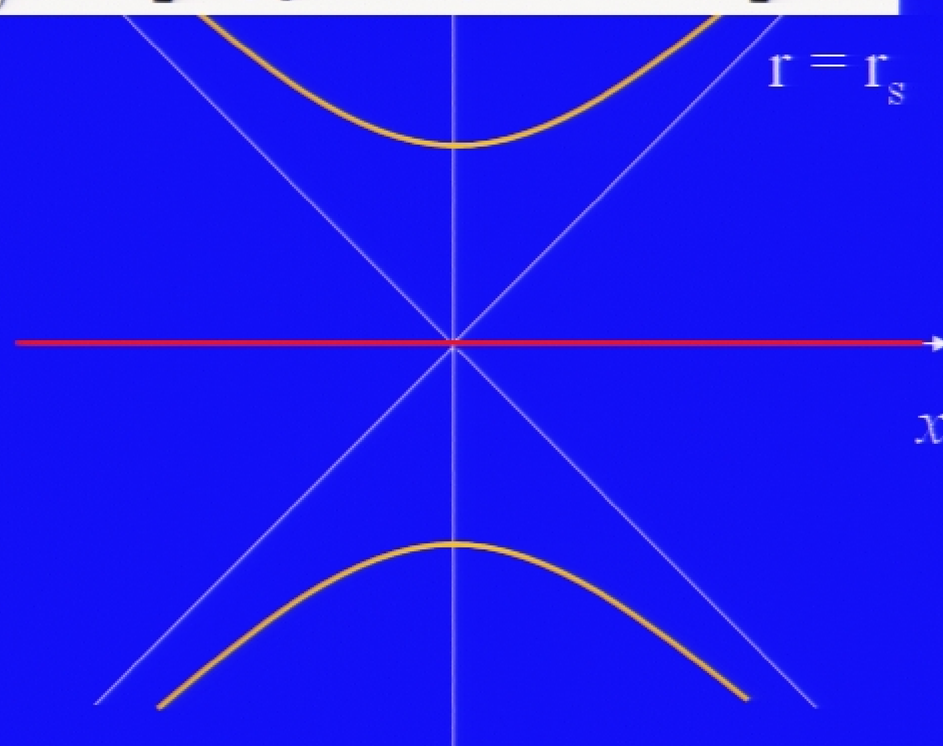

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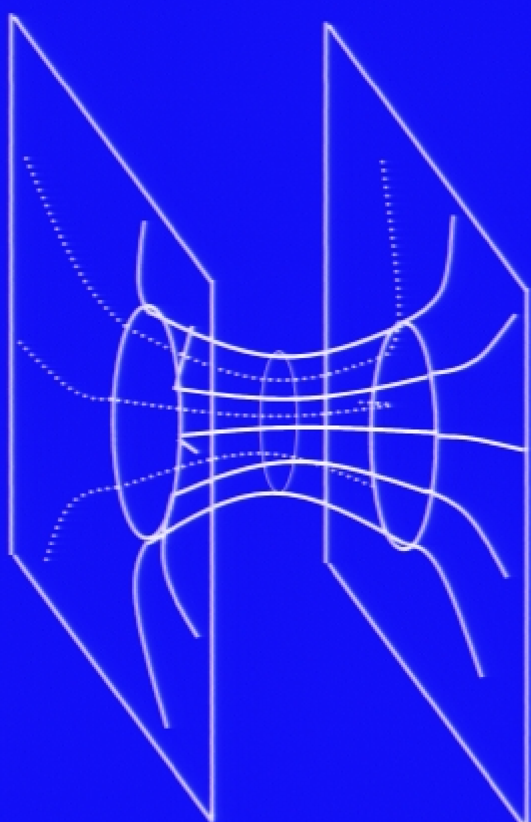

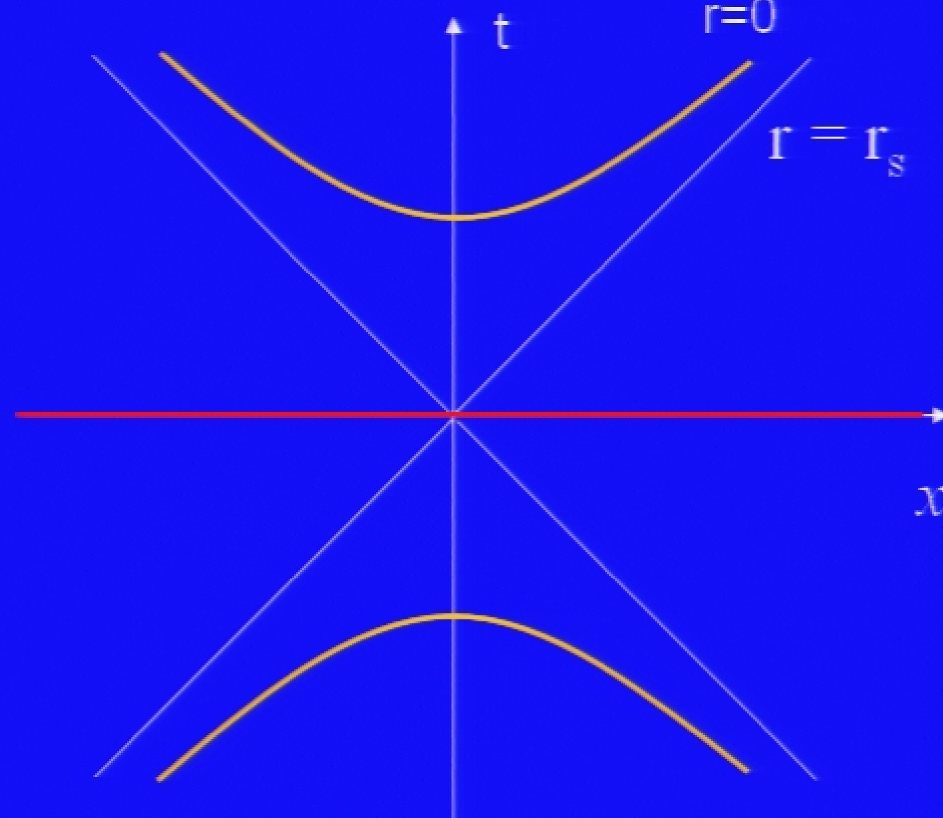

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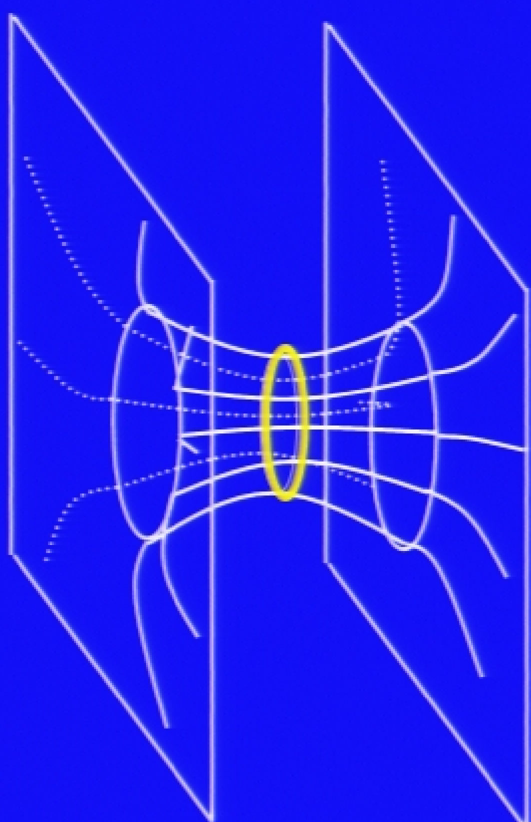

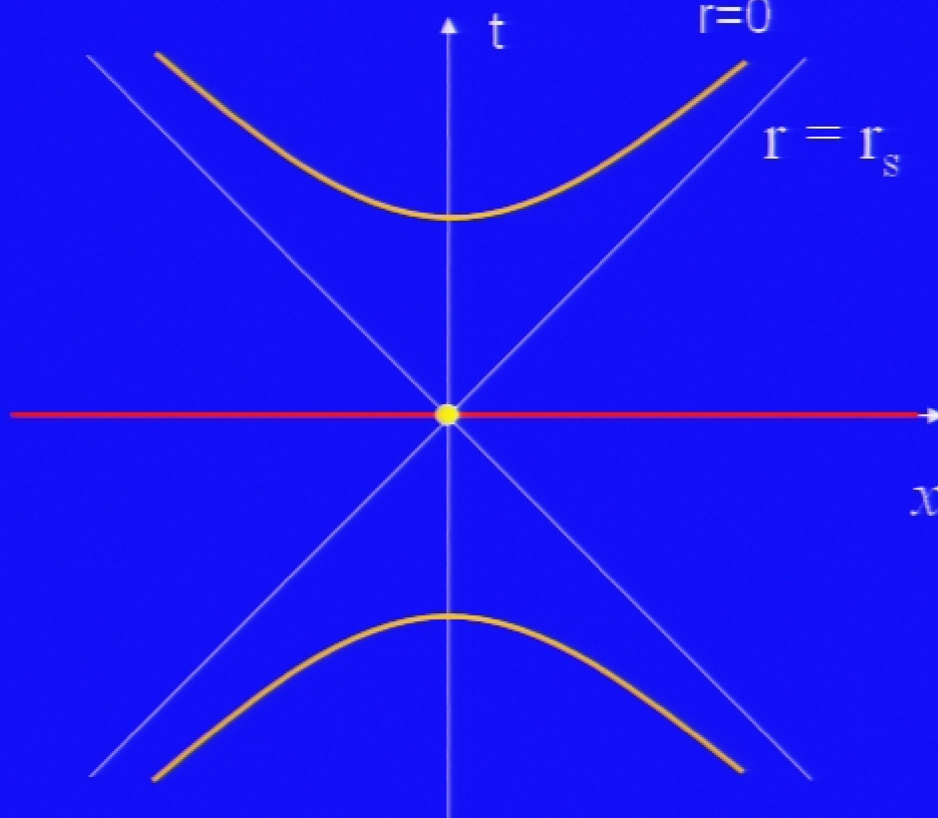

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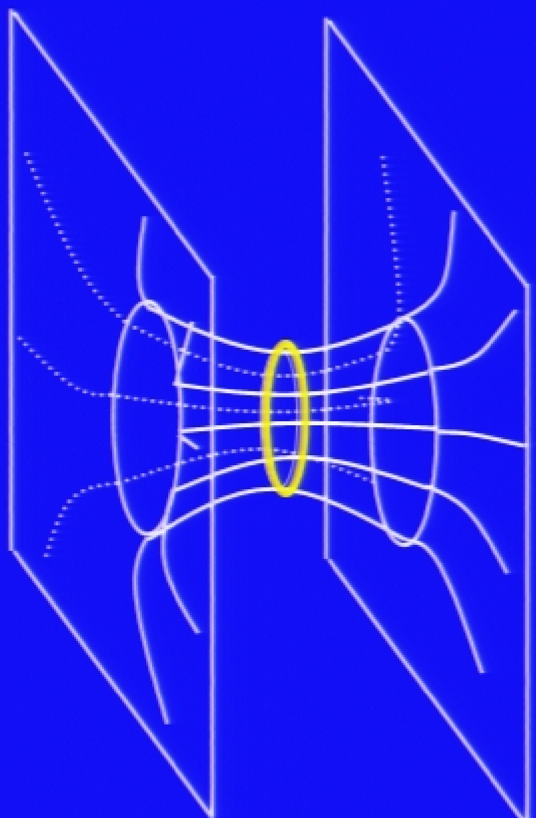

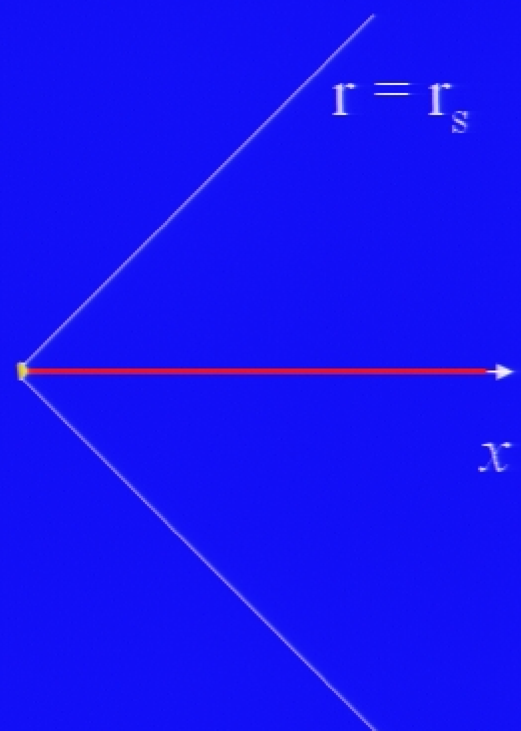

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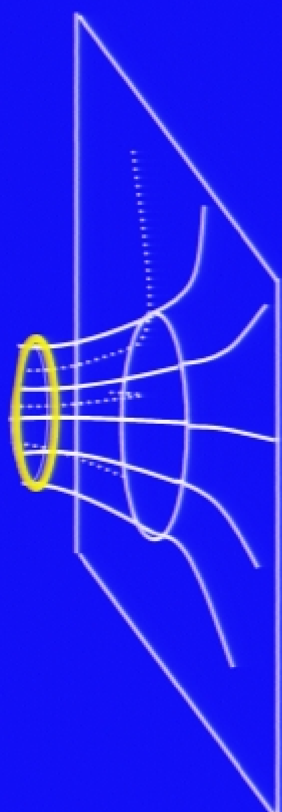

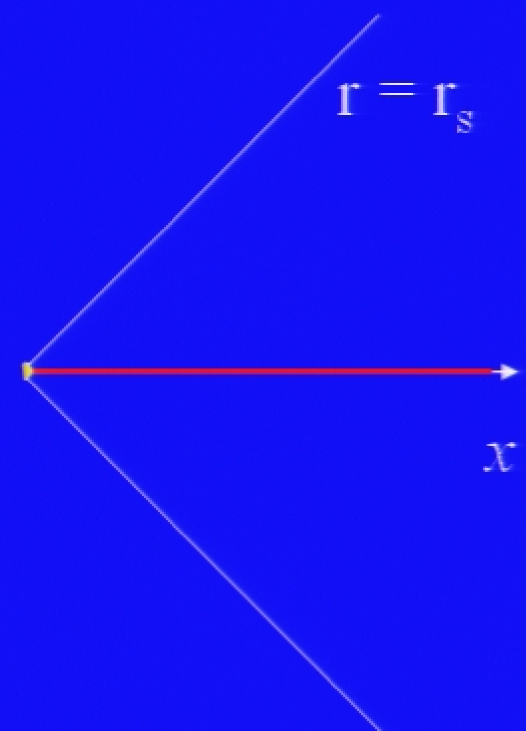

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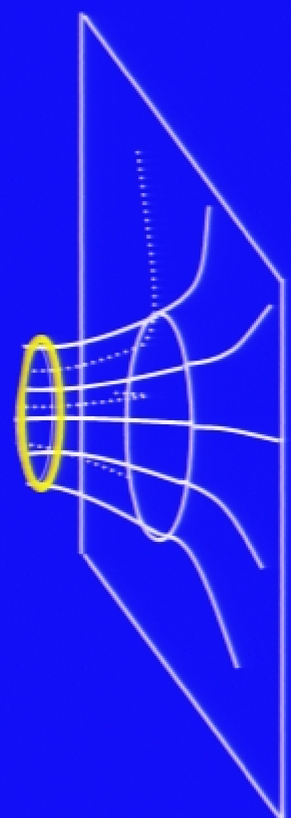

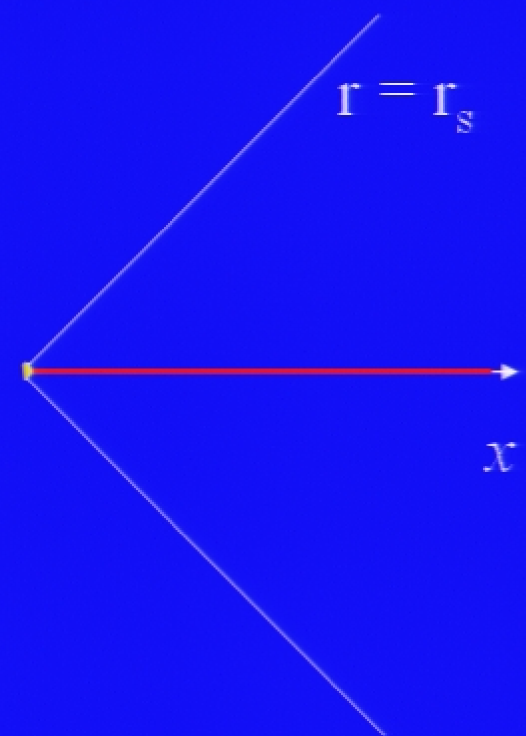

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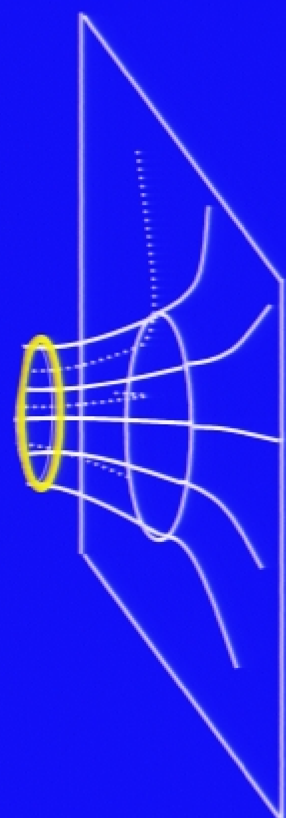

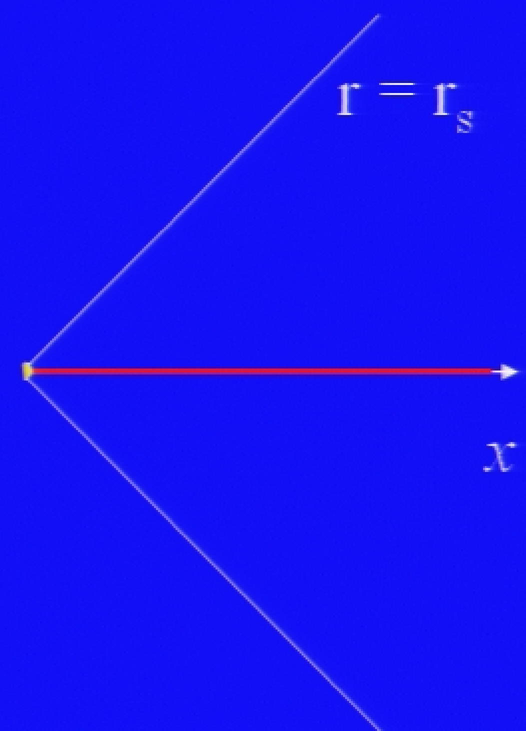

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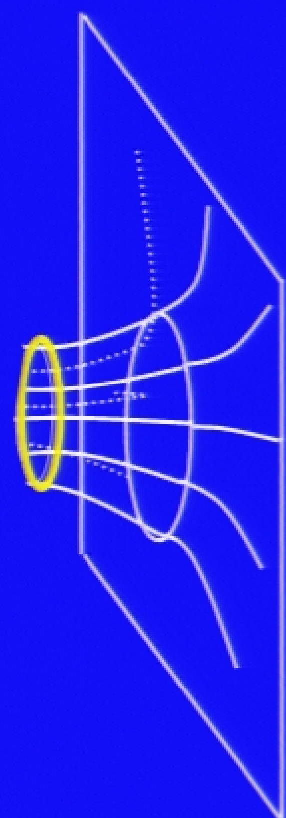
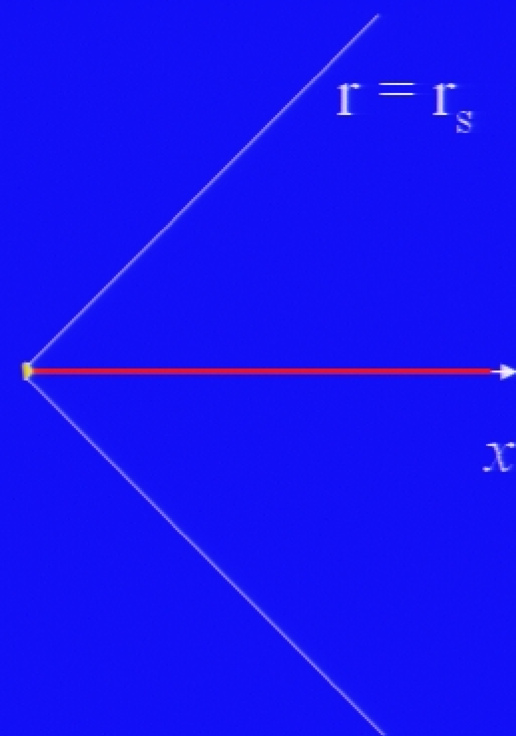
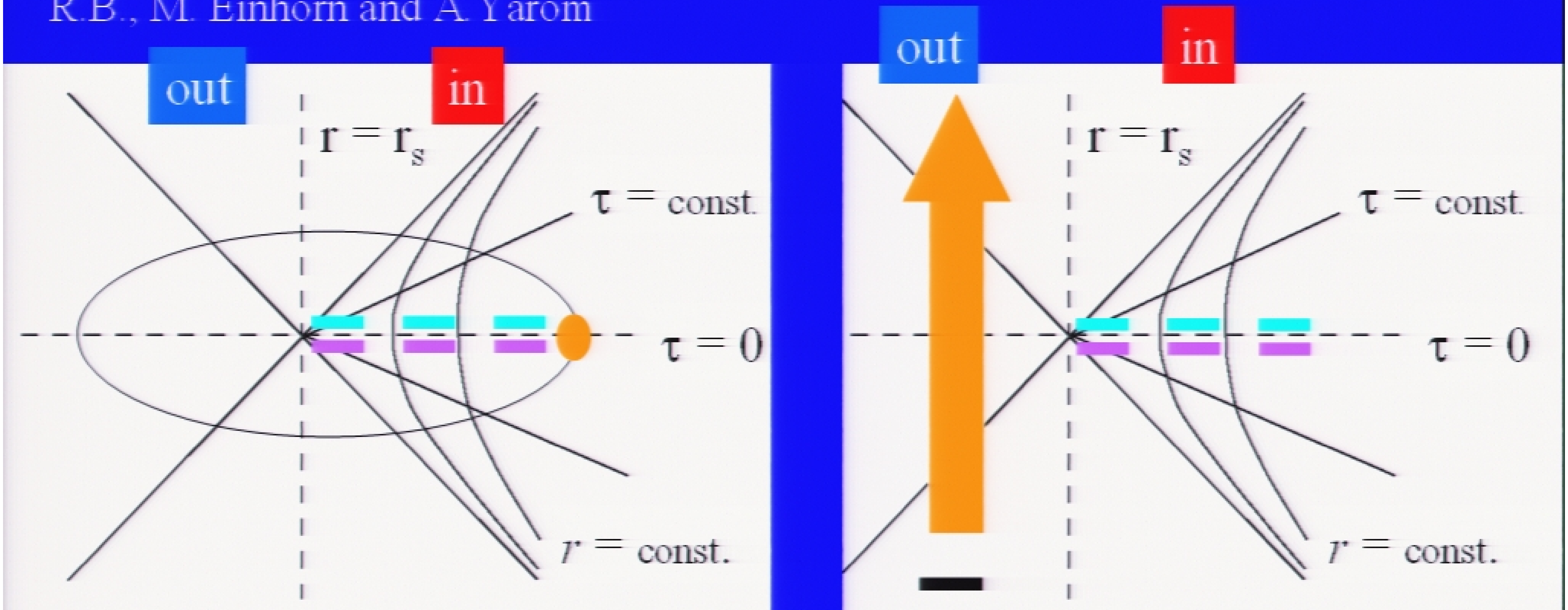




Two ways of calculating ρ_{in}

R.B., M. Einhorn and A Yarom



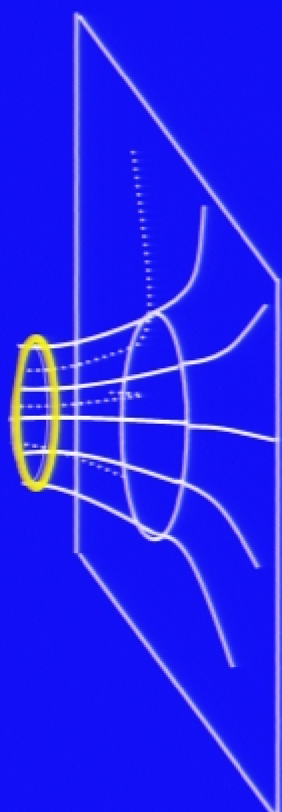
Construct the HH vacuum: the invariant regular state

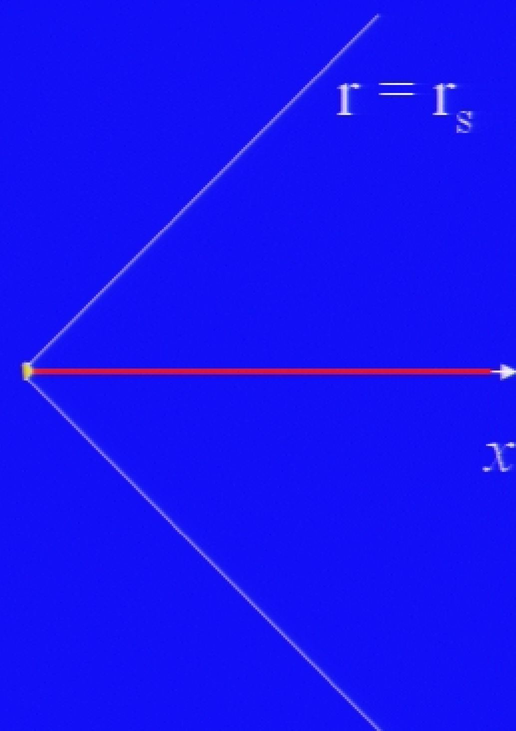
Kabat & Strassler (flat space)
Jacobson

The vacuum state

$$|0\rangle \rightarrow \rho_{out} = Tr_{in}|0\rangle\langle 0|$$

$$S_{out} = Tr\rho_{out}\ln\rho_{out} = S_{in} = Tr\rho_{in}\ln\rho_{in}$$





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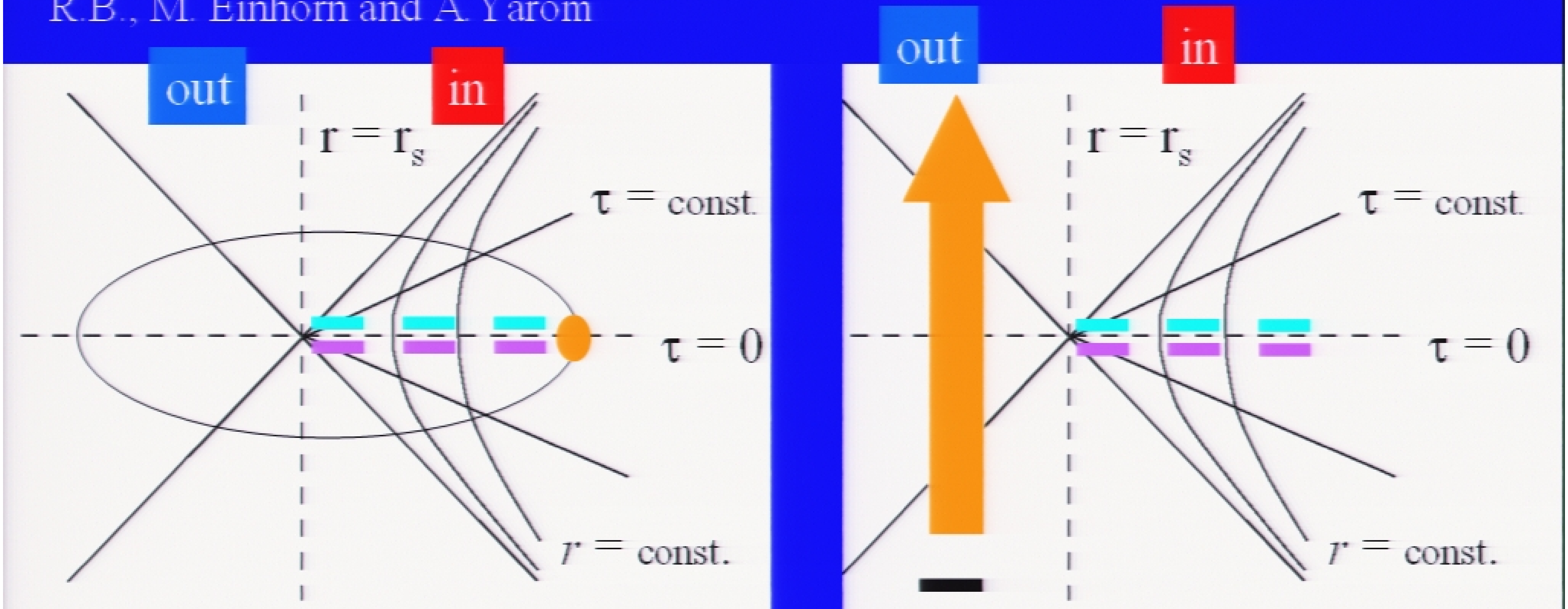

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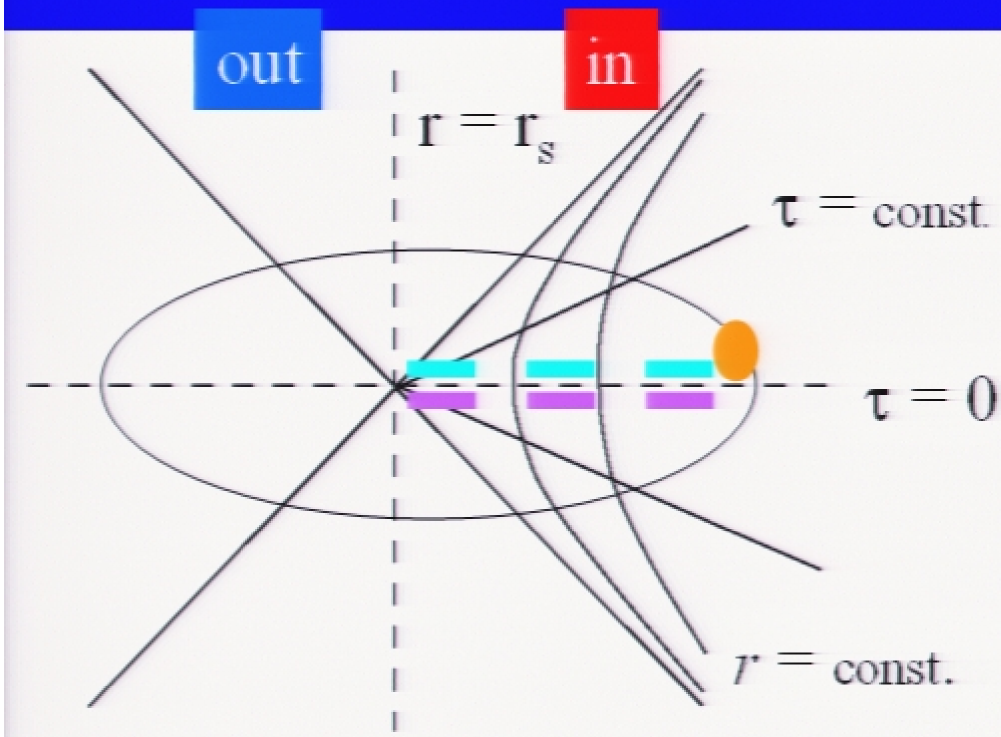

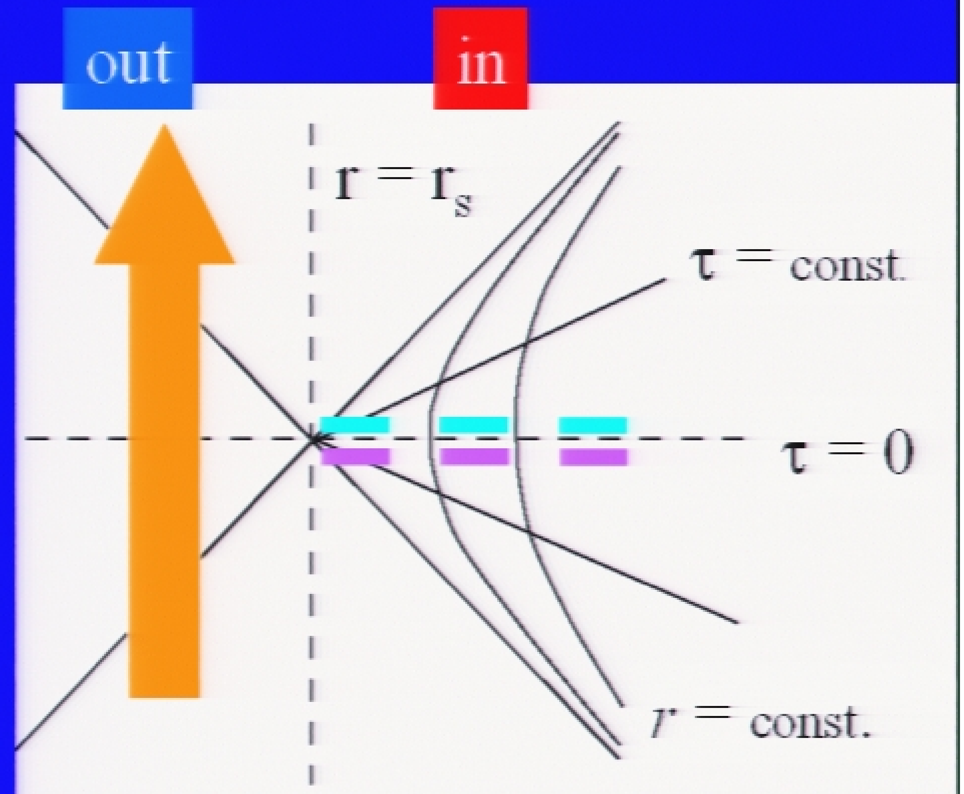

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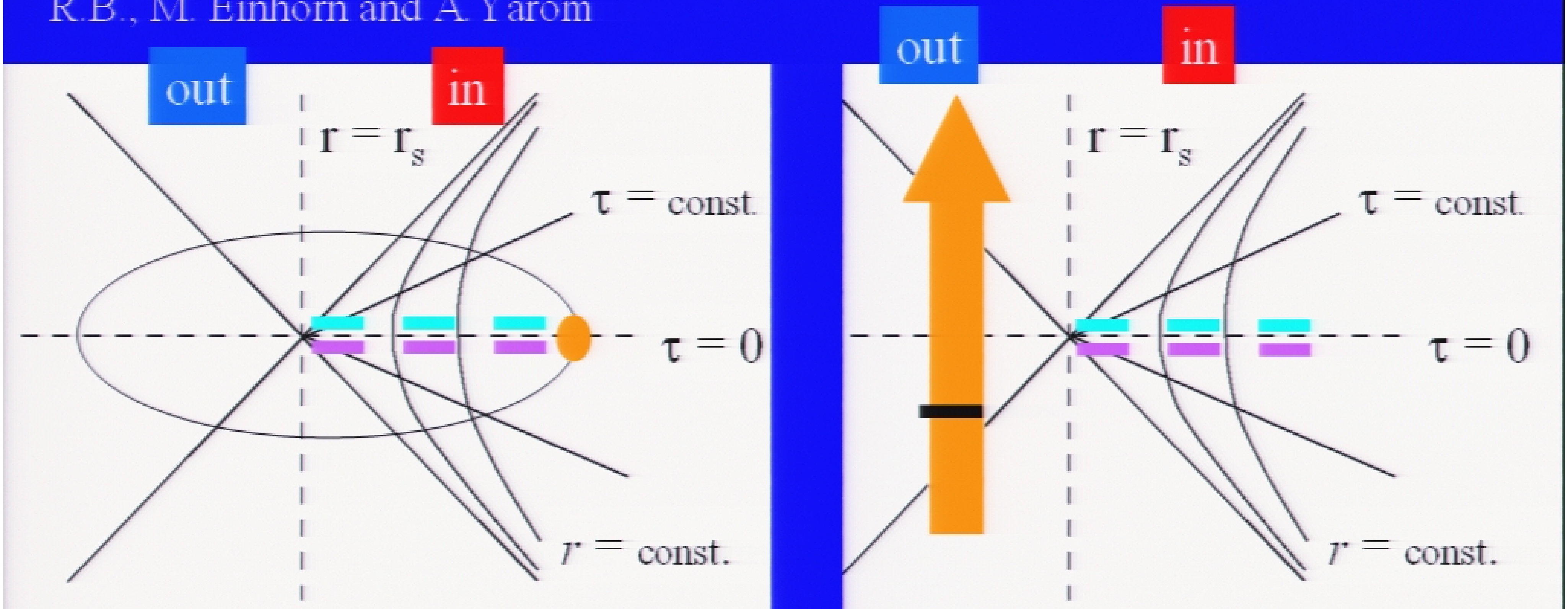

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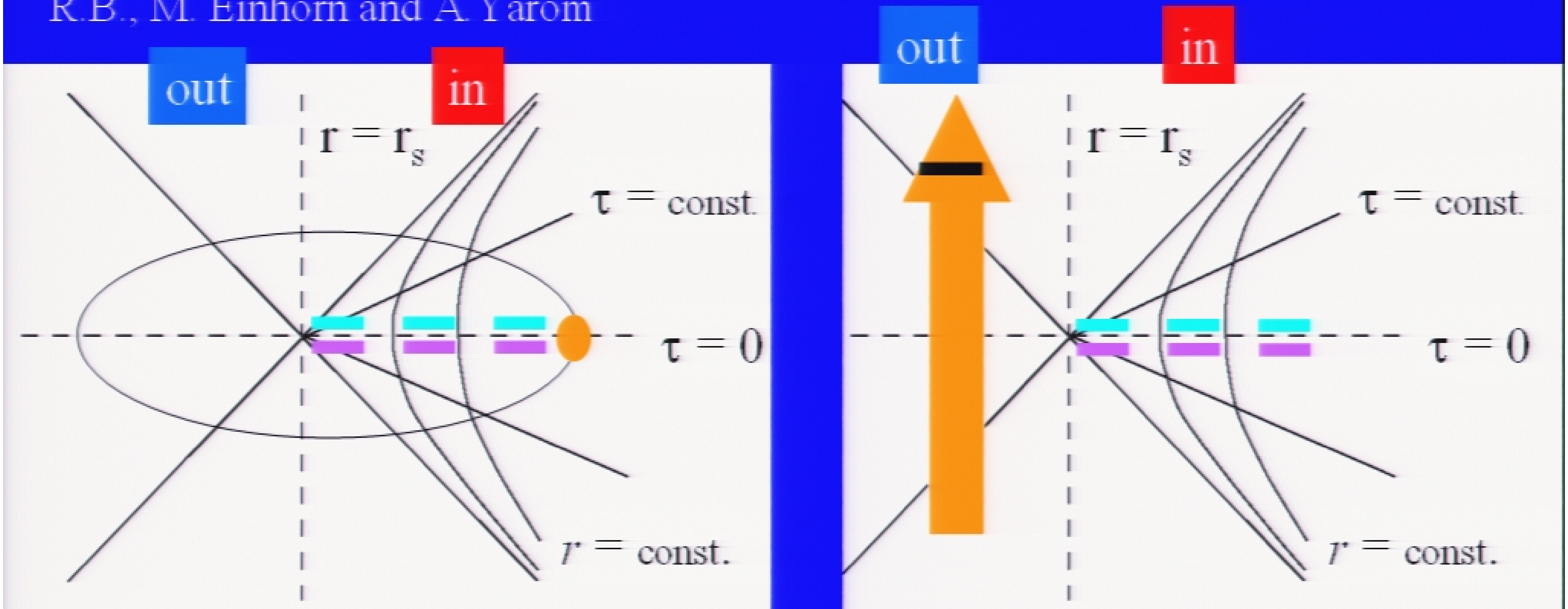

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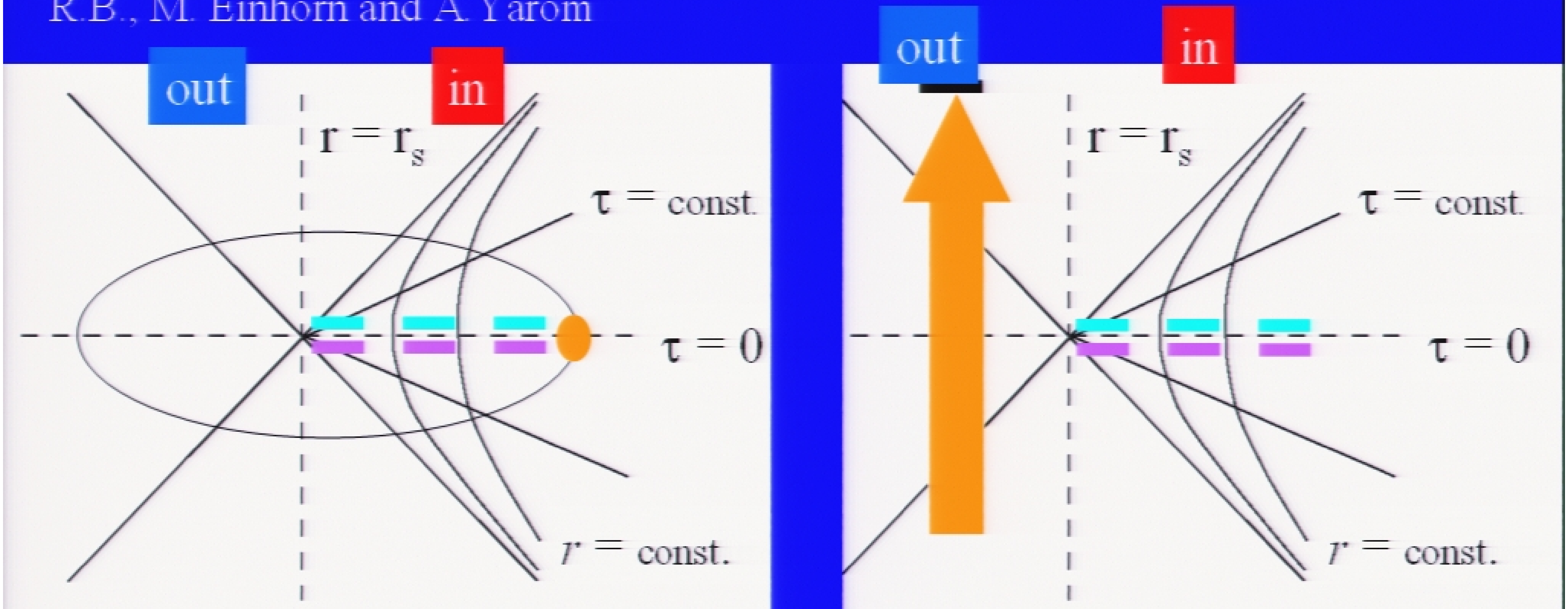

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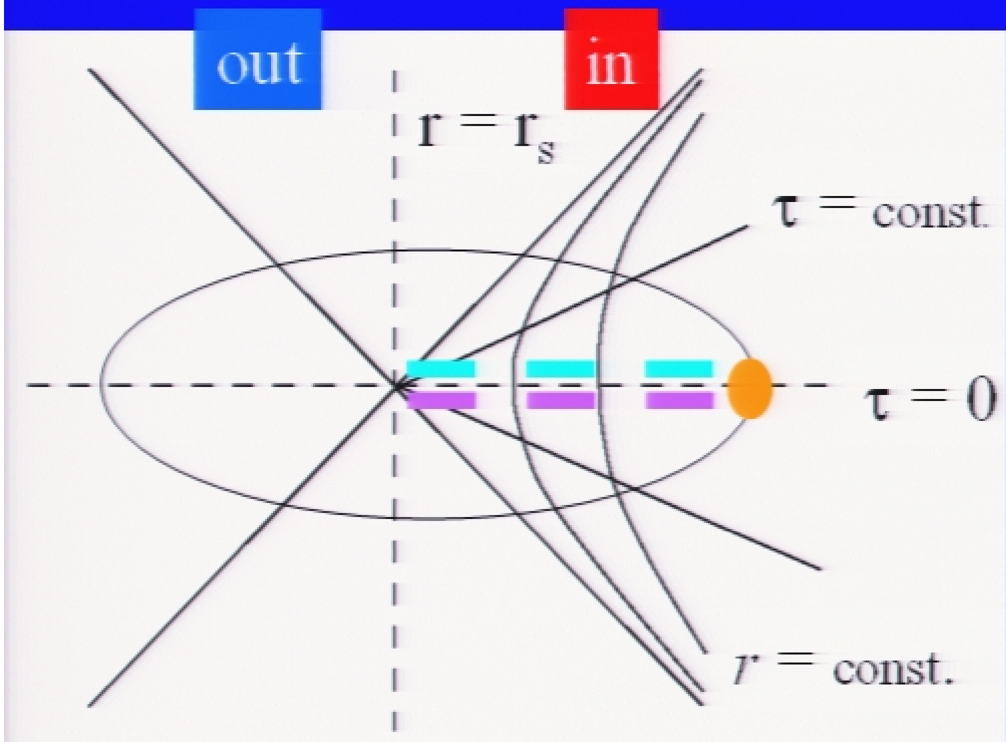

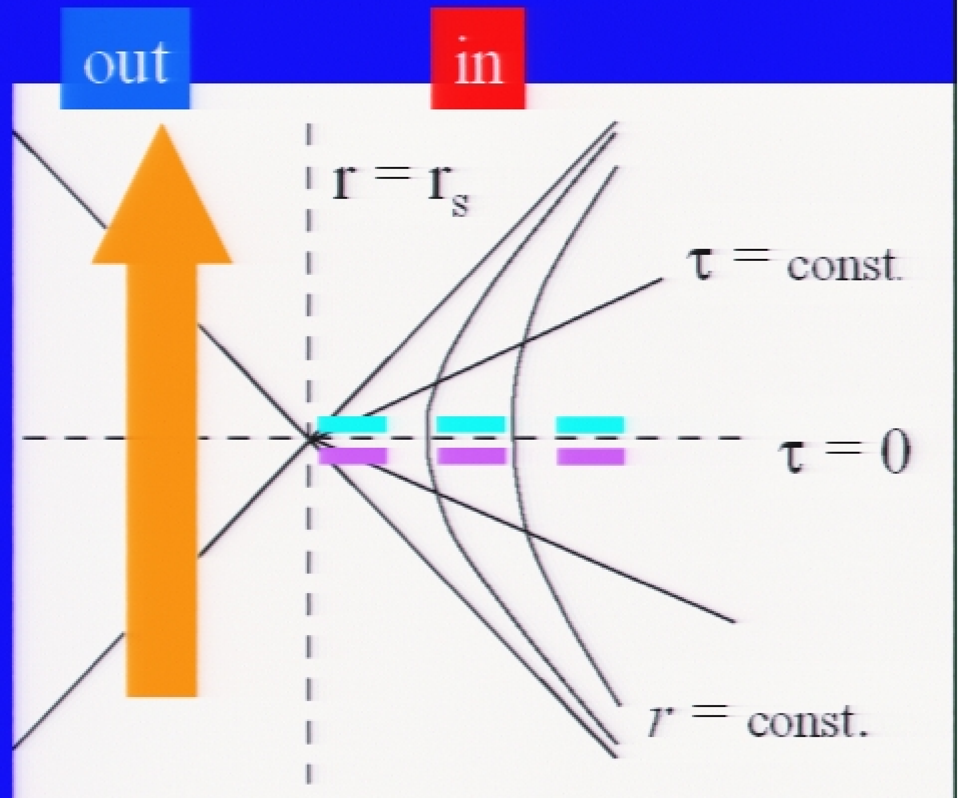

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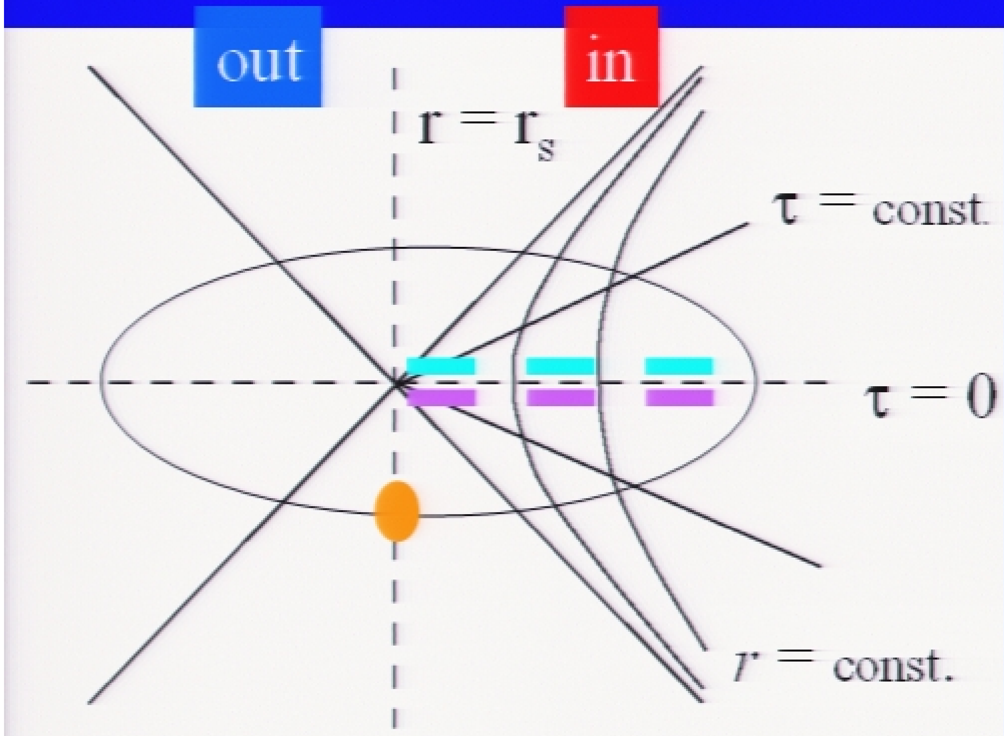

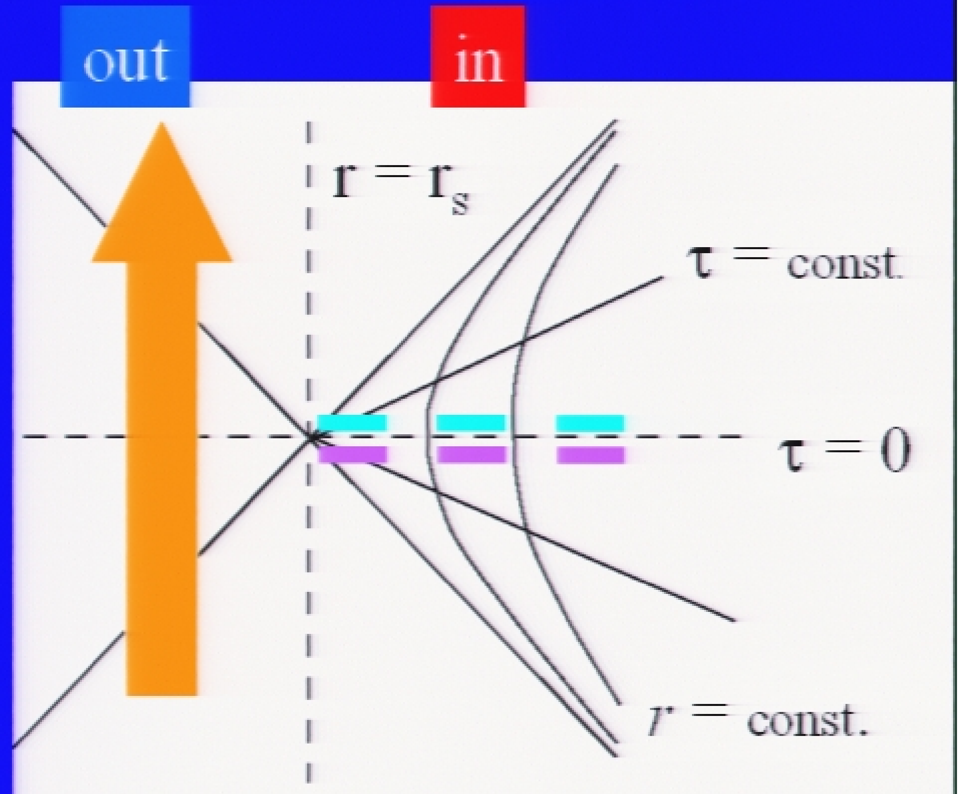

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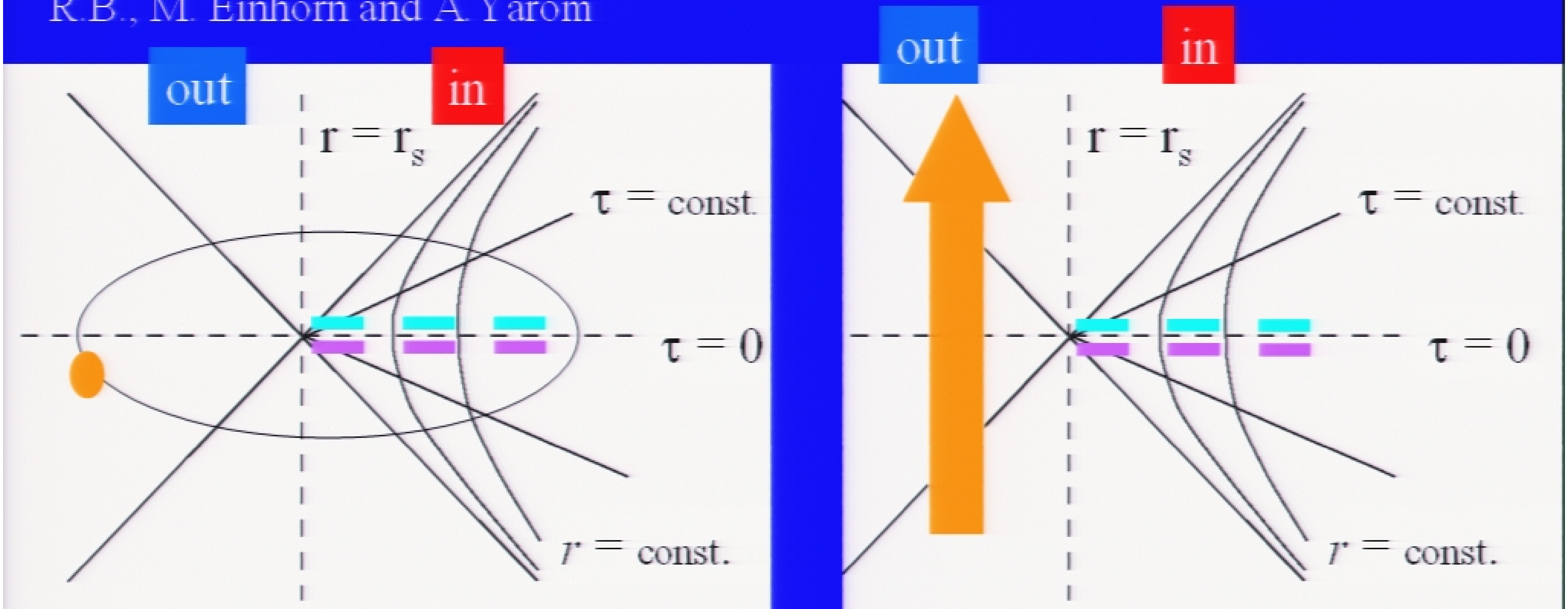

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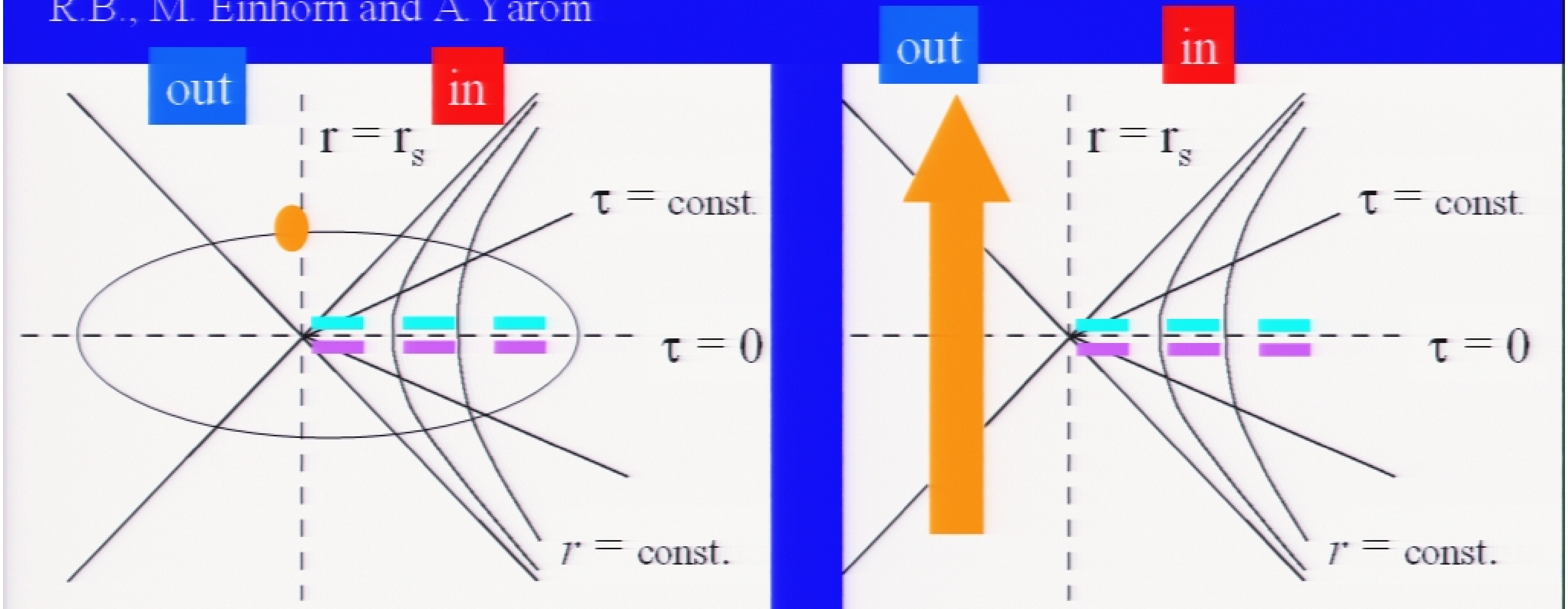

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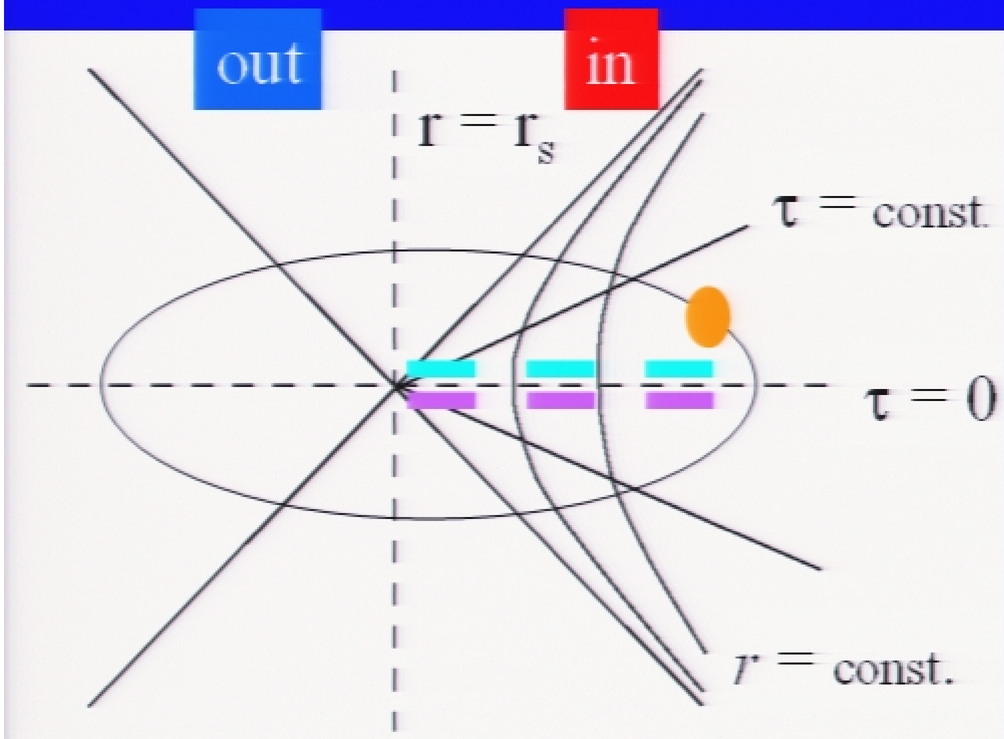

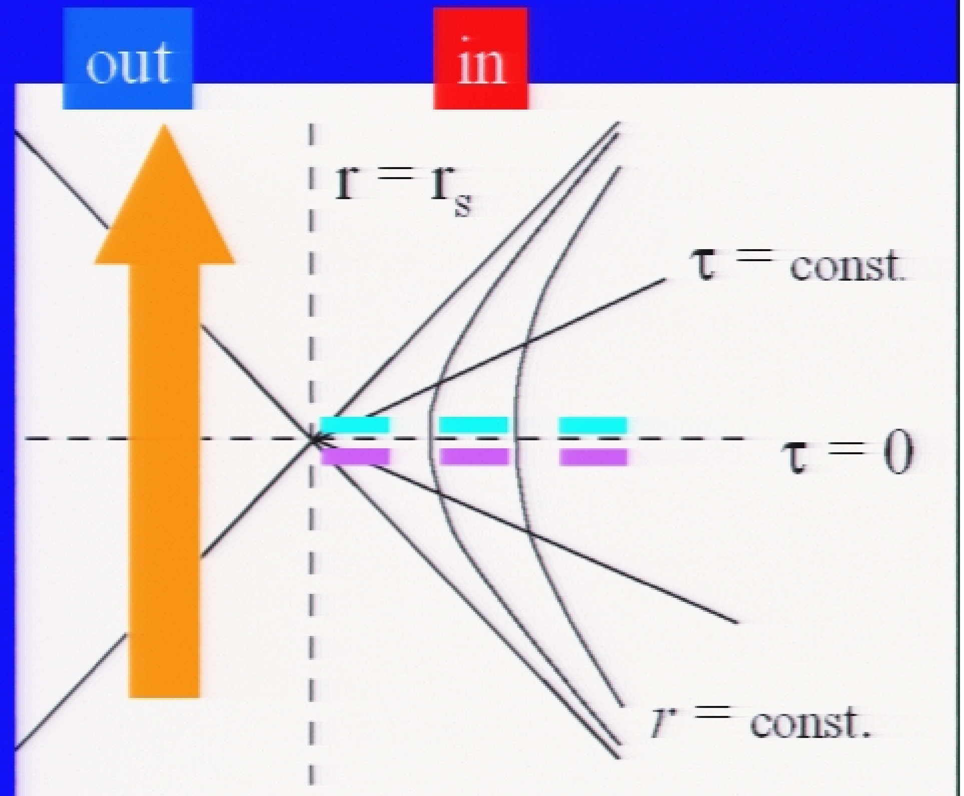

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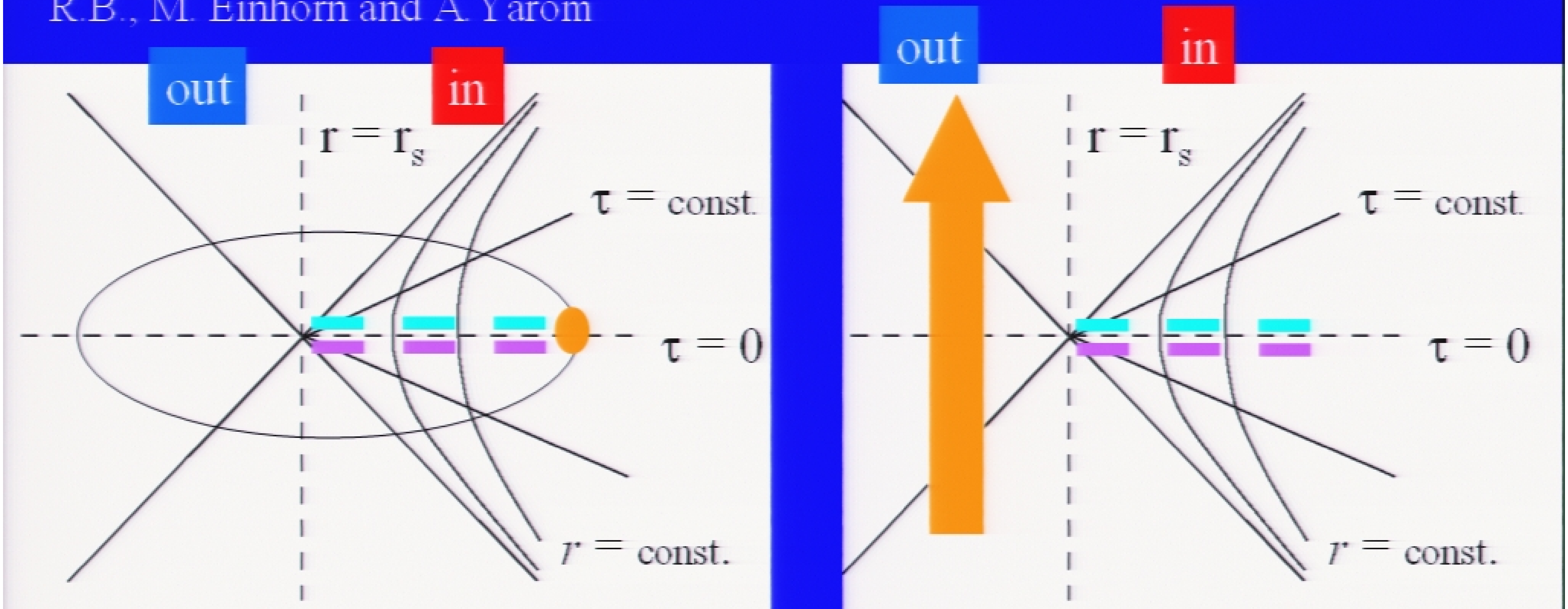

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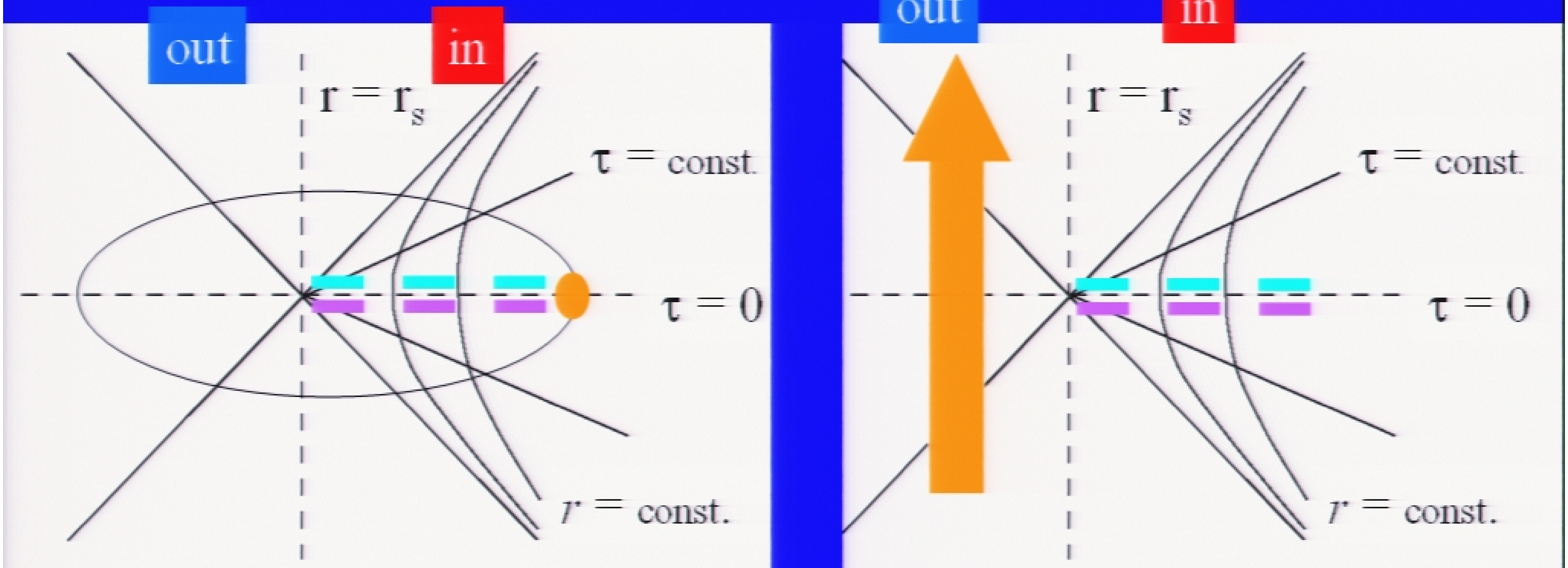

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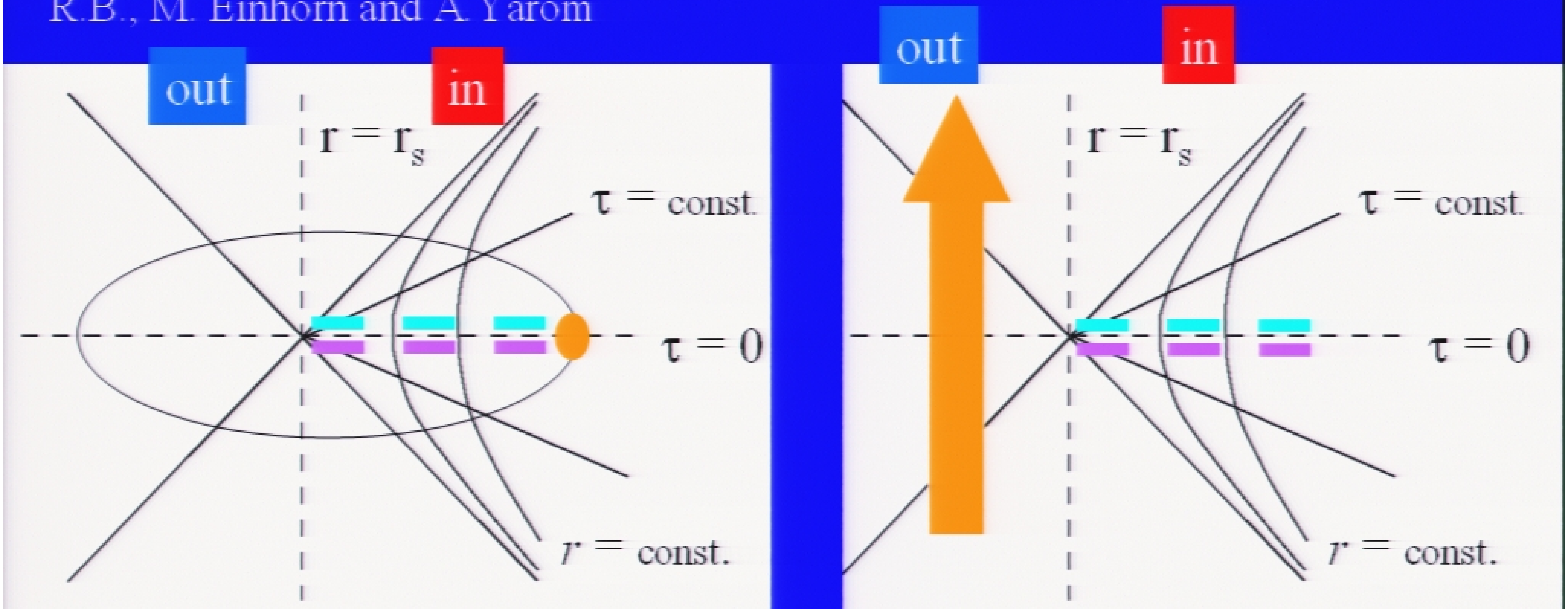

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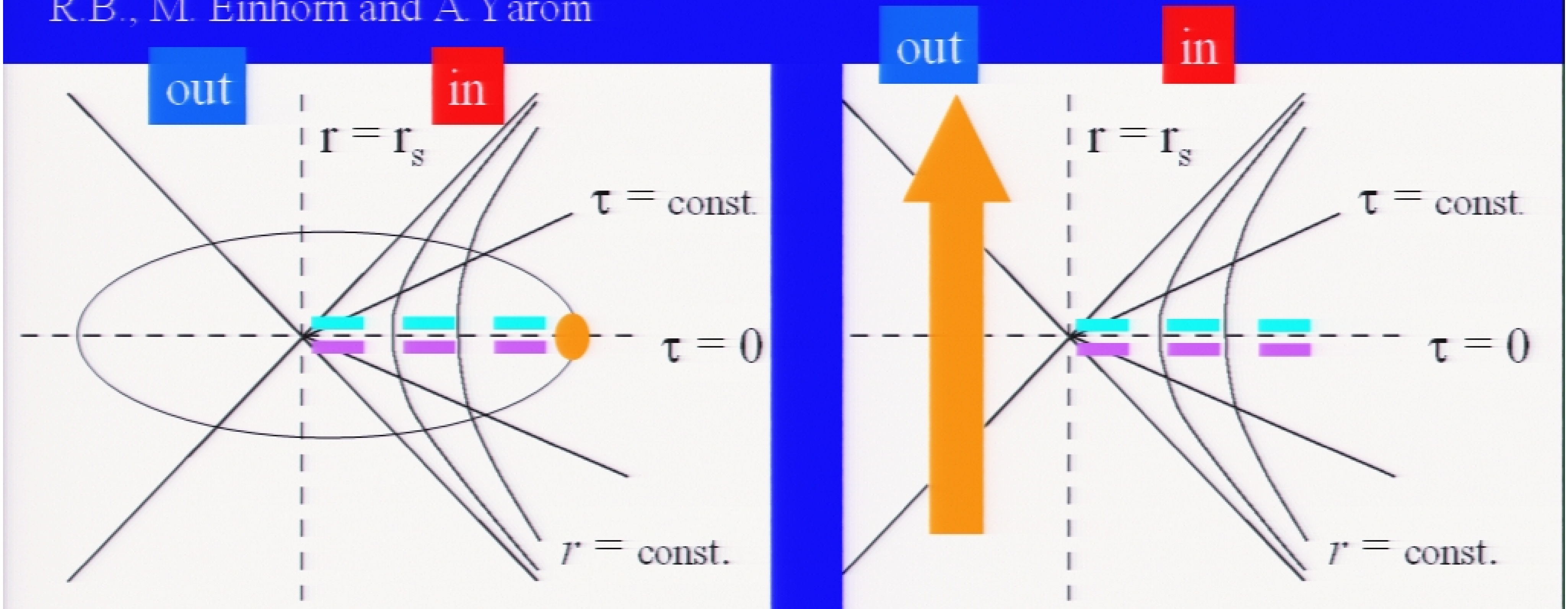

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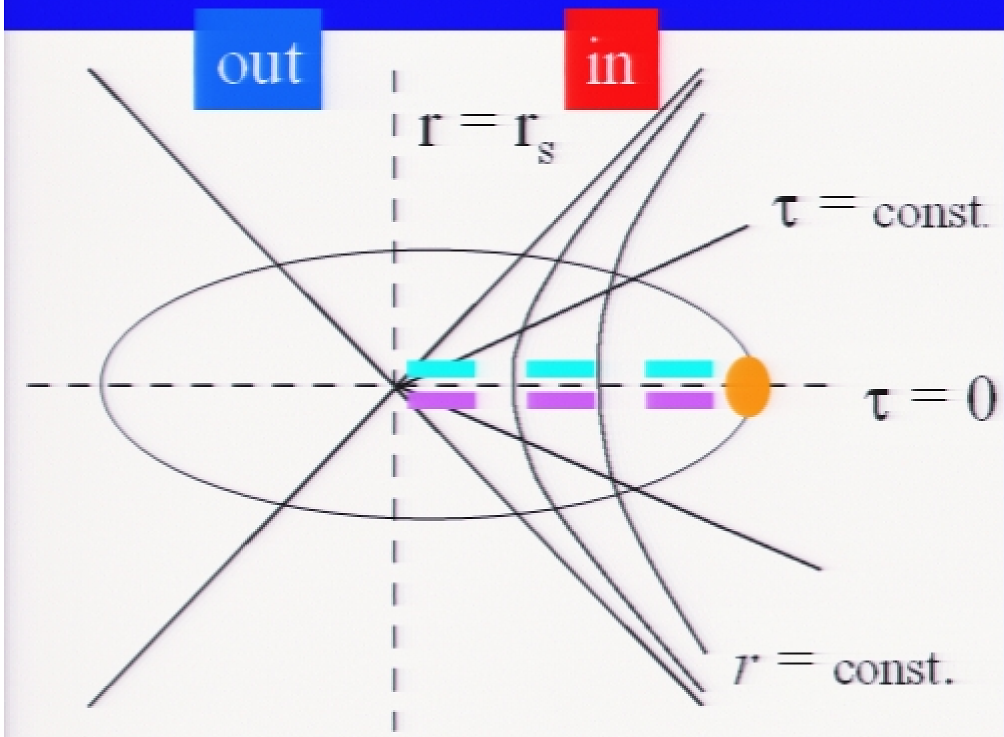

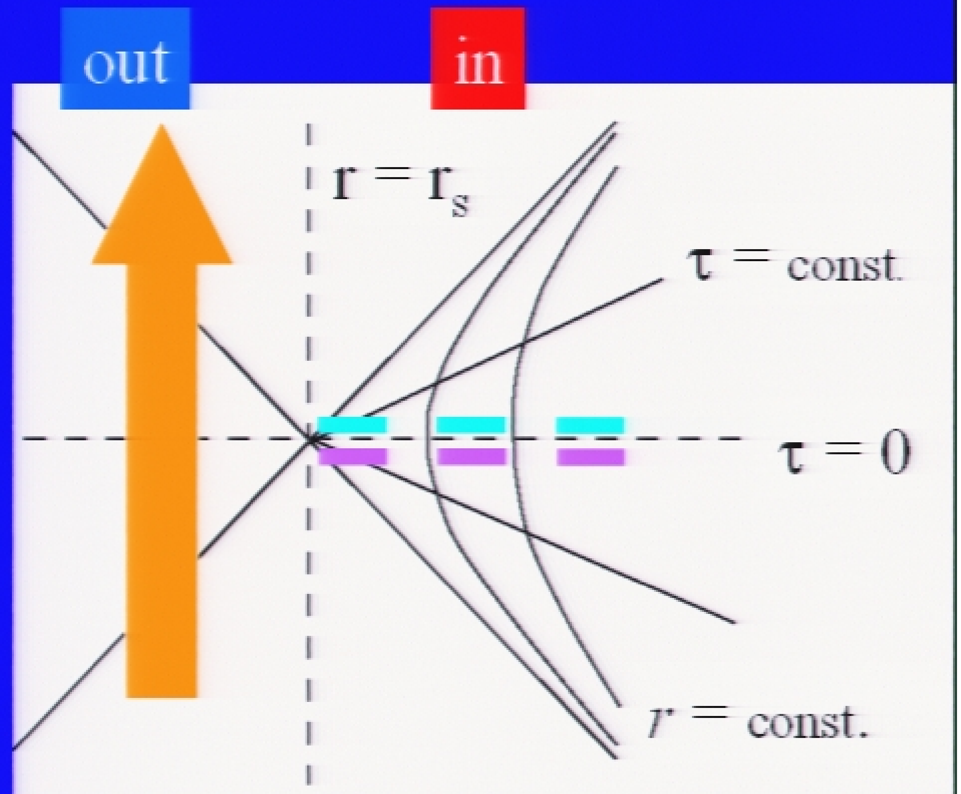

Construct the HH vacuum: the invariant regular state

Kabat & Strassler (flat space)
Jacobson

Results*:

* Method works for more general cases

$$\langle \psi'_{in} | \rho_{in} | \psi''_{in} \rangle = \int_{\varphi(r,\vec{x}_\perp,0)=\begin{cases} r>r_S,\tau=0^- & \psi'_{in}(r,\vec{x}_\perp) \\ r>r_S,\tau=0^+ & \psi''_{in}(r,\vec{x}_\perp) \end{cases}} D\varphi \exp\left[-\int_{-\infty}^{+\infty} d\tau dr dx_\perp^{d-1} L \right]$$

$$\langle \psi'_{in} | e^{-\beta_0 H_{eff}} | \psi''_{in} \rangle = \int_{\begin{cases} \varphi(\vec{x},0)=\psi'_{in}(x,x_\perp) \\ \varphi(\vec{x},\beta_0)=\psi''_{in}(x,x_\perp) \end{cases}} D\varphi |\Omega| |g|^{1/4} \exp\left[-\int_0^{\beta_0} d\eta d\xi dx_\perp^{d-1} L \right]$$

$$\Omega = \frac{1}{\sqrt{g_{00}^E}}$$

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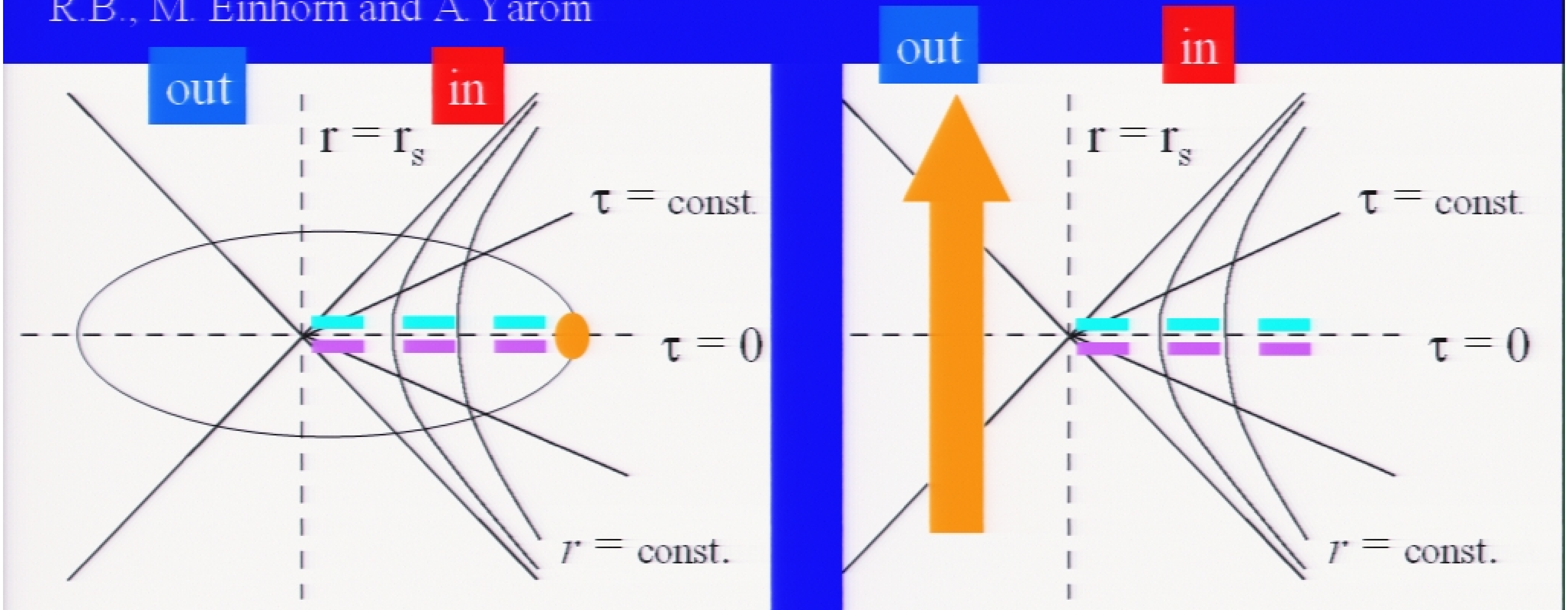

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If

1. The boundary conditions are the same
2. The actions are equal
3. The measures are equal

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$$\rho_{in} = e^{-\beta_0 H_{eff}}$$

H_{eff} – generator of (Im t) time translations

Entanglement entropy

$$S_{in} = -Tr\left(\rho_{in} \ln \rho_{in}\right)$$

$$T = \frac{f'(r_s)}{4\pi}$$

de Alwis & Ohta

$$S = \frac{q(r_s)^{\frac{d-1}{2}}(d+1)\Gamma\left(\frac{d+1}{2}\right)\zeta(d+1)}{2^{2d-1}\pi^{\frac{3d+1}{2}}(d-1)}\delta^{-(d-1)}\int d\vec{x}_{\perp}$$

δ – proper length short distance cutoff

S is divergent

Naïve origin:

divergence of the optical volume near the horizon

More later …*not* brick wall

Two ways of calculating ρ_{in}

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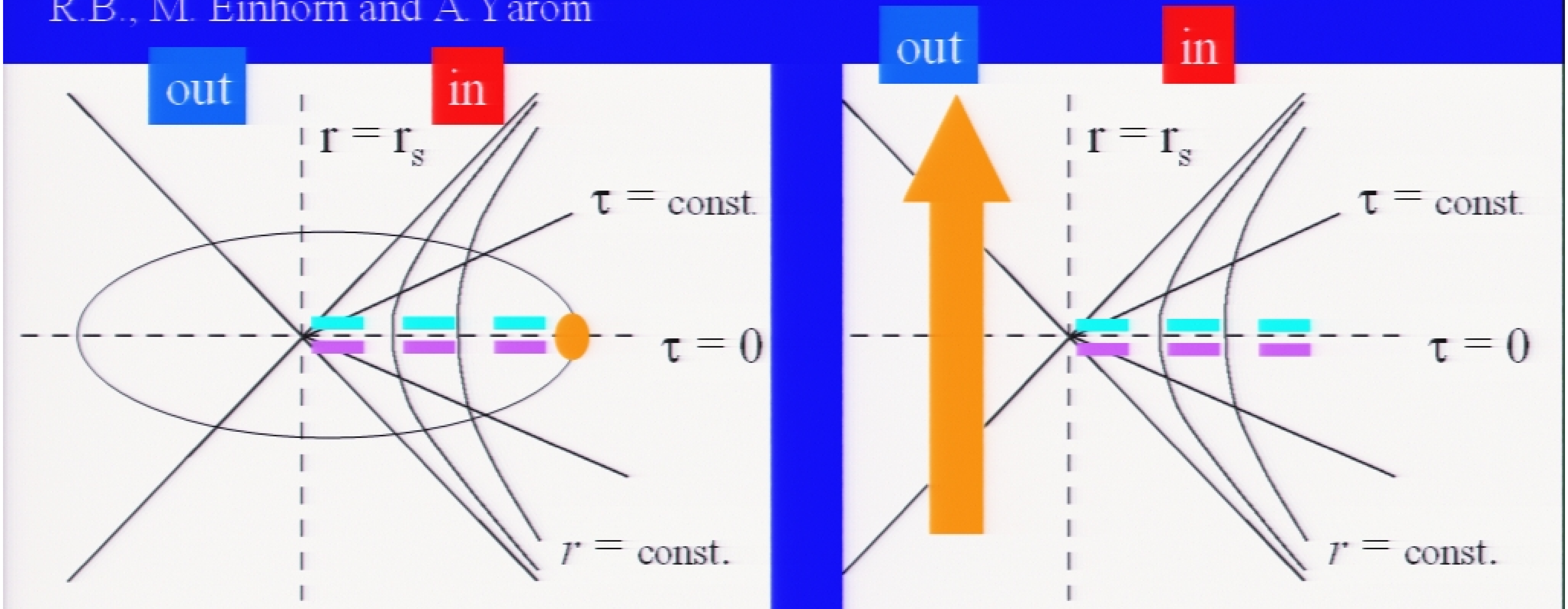

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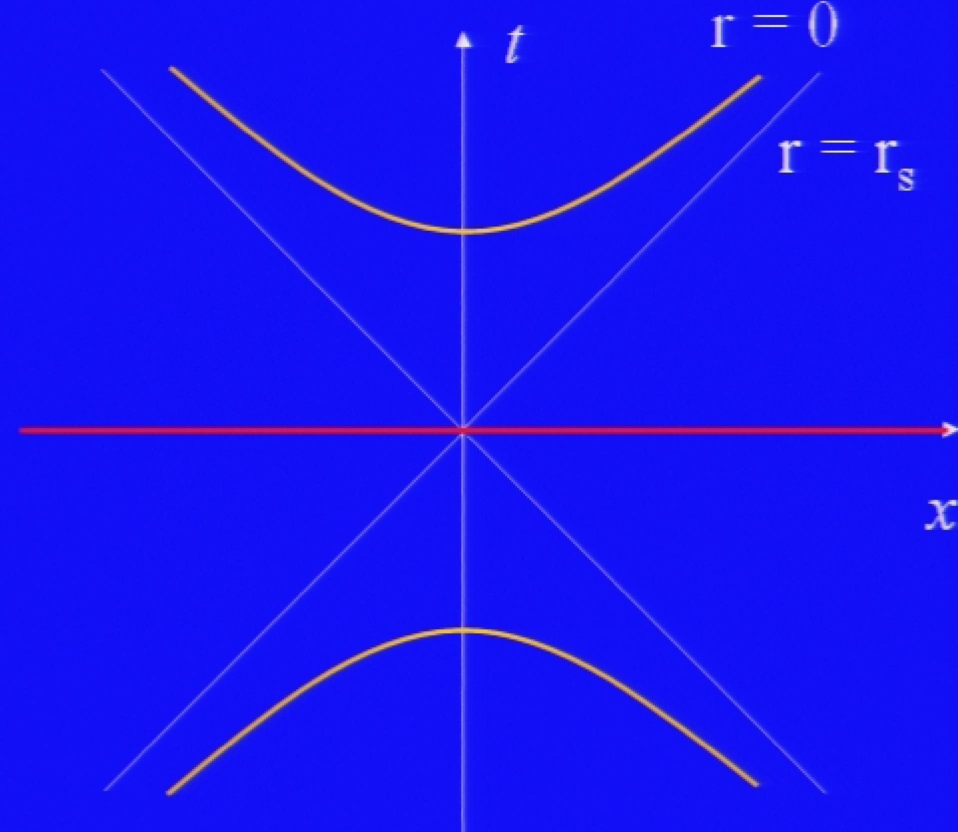
"Kruskal" extension

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + q(r)d\Omega^2$$

$$ds^2 = h(r)(-dt^2 + dx^2) + q(r)d\Omega^2$$

$$x = \sqrt{g(r)}Cosh(\tau / a)$$

$$t = \sqrt{g(r)}Sinh(\tau / a)$$

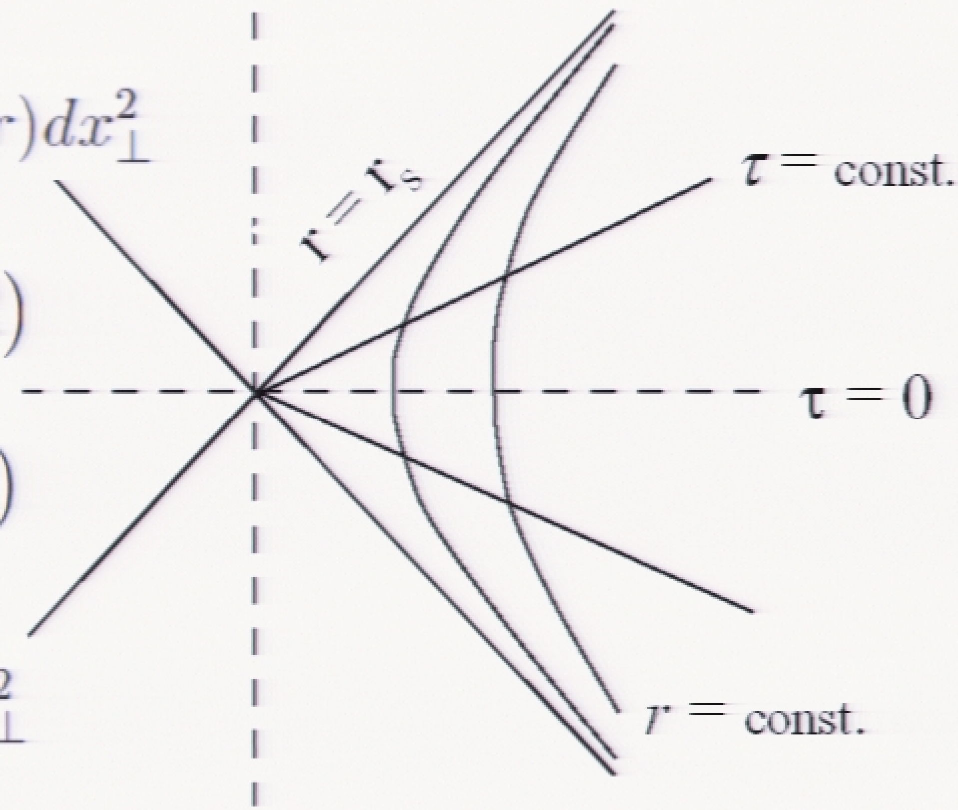


“Kruskal” extension

$$ds^2 = -f(r)d\tau^2 + dr^2/f(r) + q(r)dx_\perp^2$$

$$x = \sqrt{g(r)}\cosh(\tau f'(r_s)/2)$$

$$t = \sqrt{g(r)}\sinh(\tau f'(r_s)/2)$$

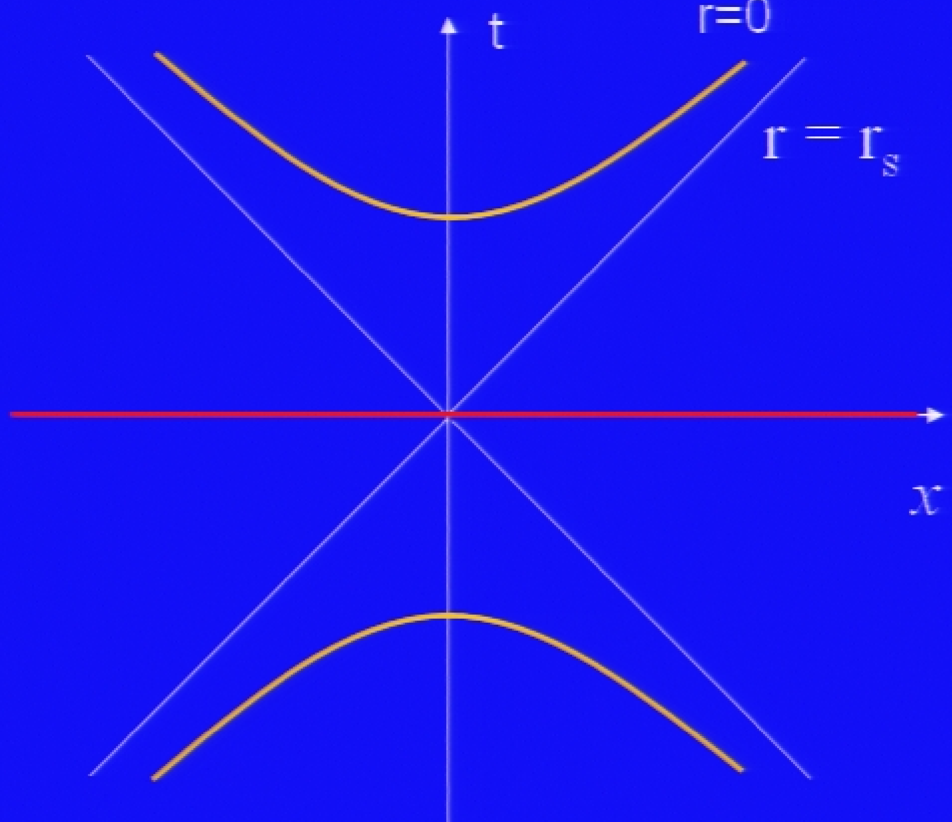


$$ds^2 = h(r)(-dt^2 + dx^2) + q(r)dx_\perp^2$$

$$h(r) = \frac{1}{\xi_0} f(r) e^{-f'(r_s)\int^r \frac{dr'}{f(r')}}$$

Examples: Minkowski, de Sitter, Schwarzschild, non-rotating BTZ BH, can be extended to rotating, charged, non-extremal BHs

The vacuum state



How to relate them?

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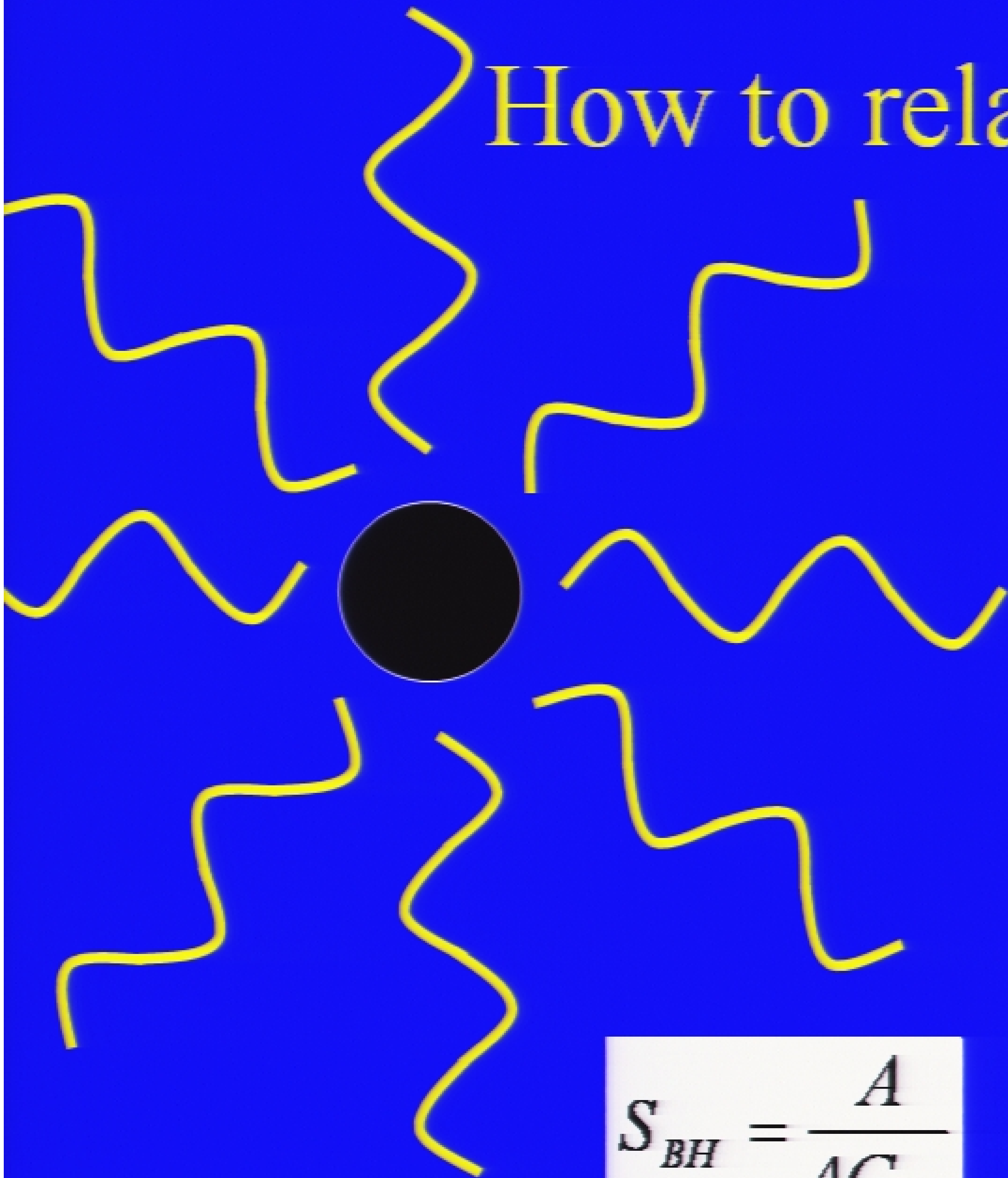
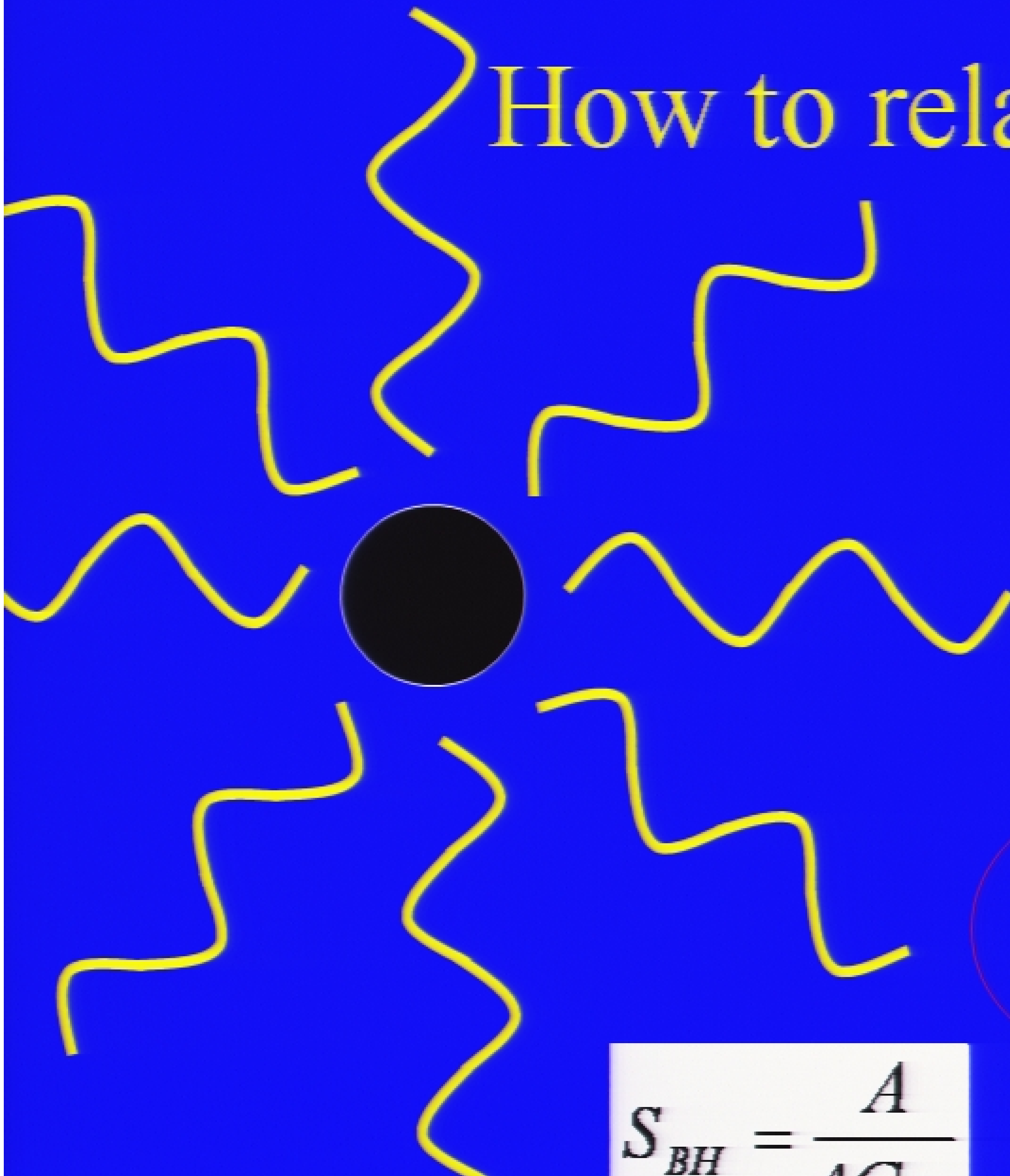


$$S_{BH} = \frac{A}{4G_N}$$

How to relate them?



$$S_{BH} = \frac{A}{4G_N}$$

$$S_{BH} \propto N \frac{A}{\delta^{(d-1)}}$$

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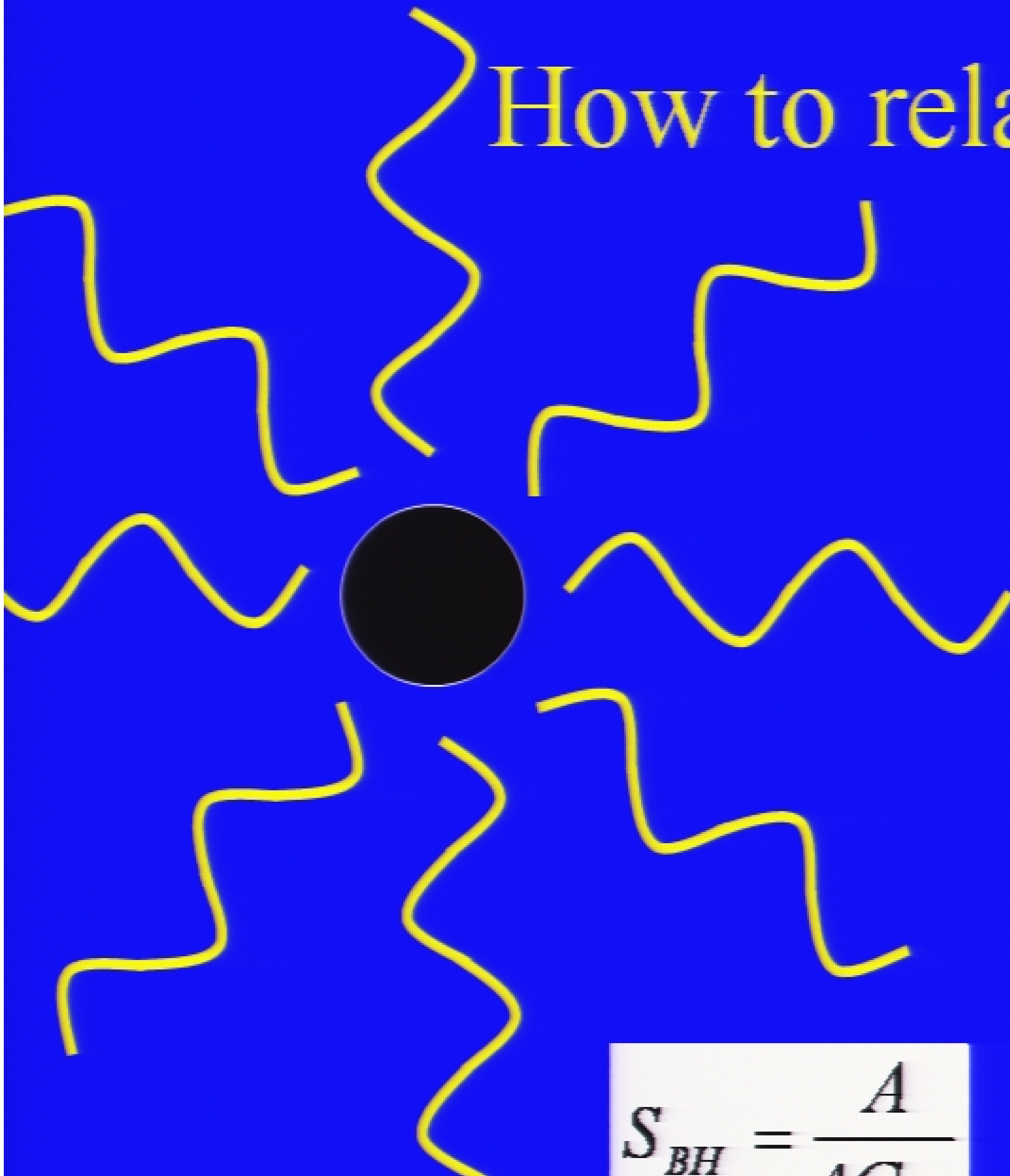

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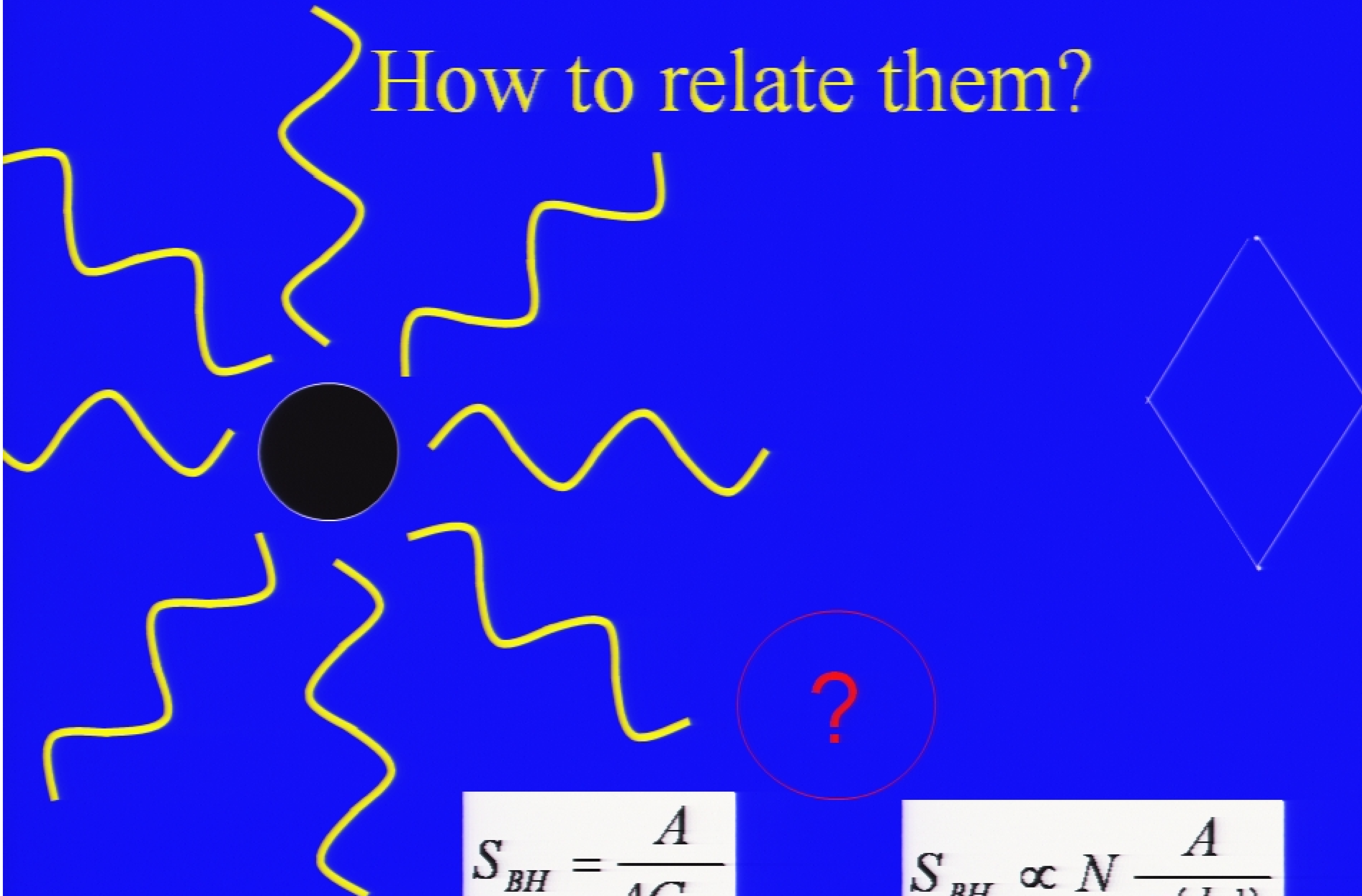

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BH entropy in string theory

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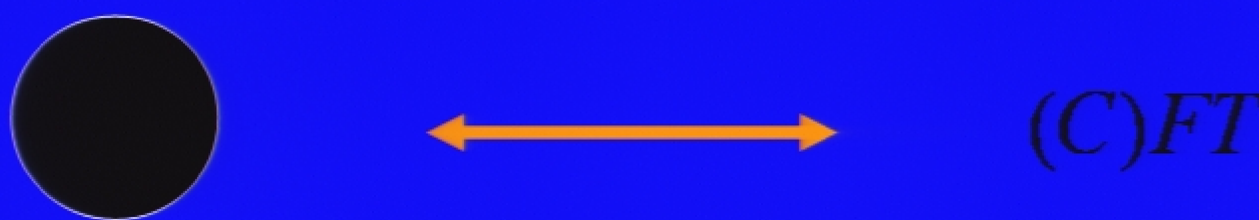


BH entropy in string theory

↔ *(C)FT*

$$T_{BH} = T_{FT}$$

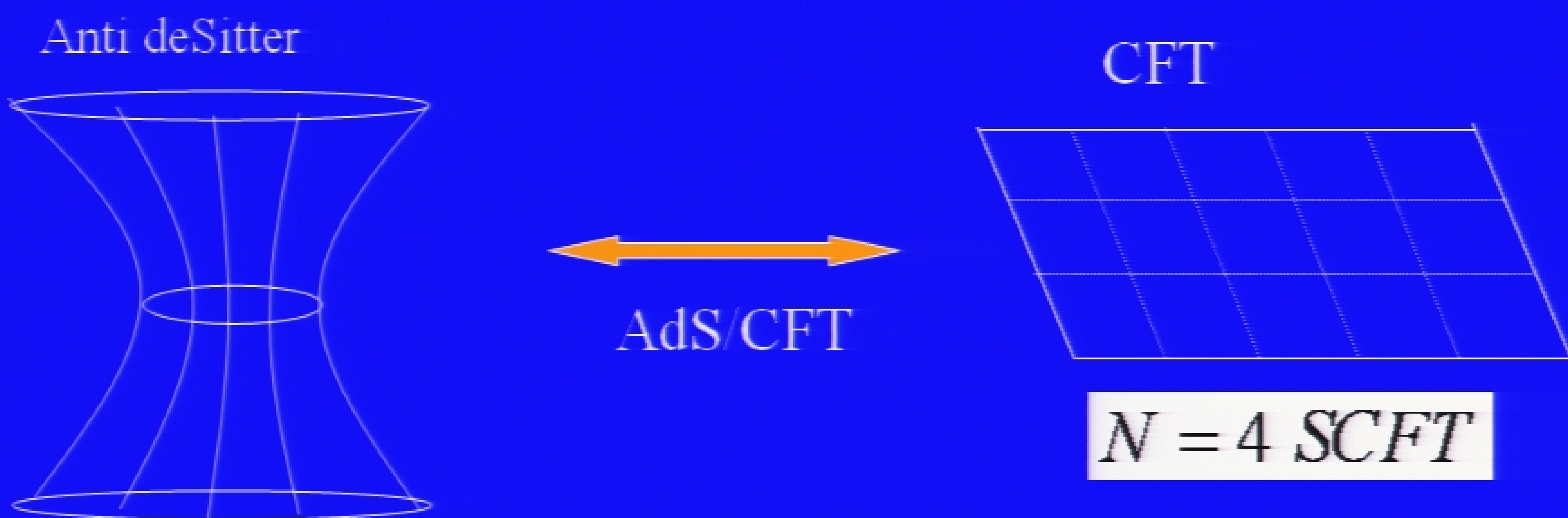
$$S_{BH} = S_{FT}(T_{BH})$$

AdS BH Entropy

Gubser, Klebanov, Peet

AdS BH Entropy

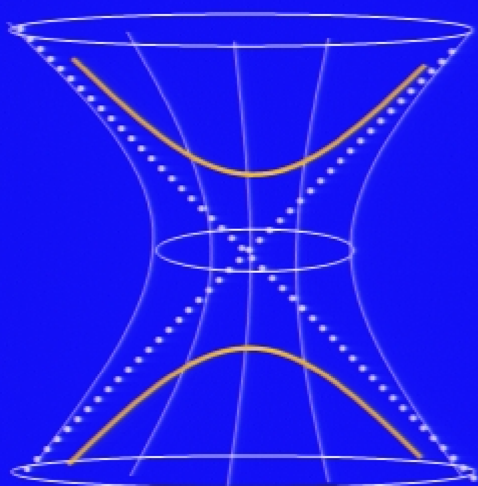
Gubser, Klebanov, Peet



AdS BH Entropy

Gubser, Klebanov, Peet

Anti deSitter +BH



AdS BH Entropy

Gubser, Klebanov, Peet

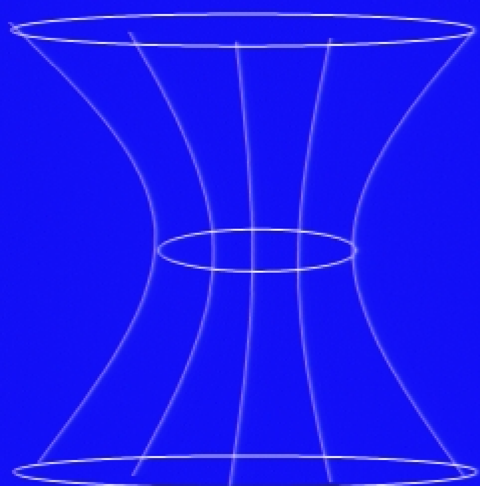
Anti deSitter +BH

AdS/CFT

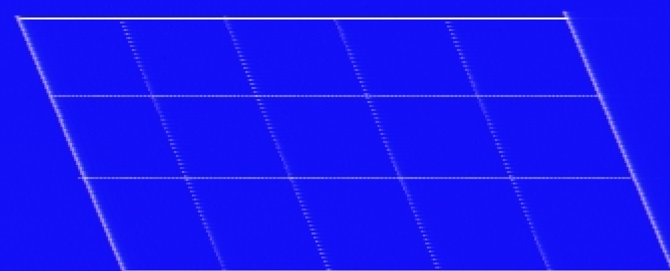
AdS BH Entropy

Gubser, Klebanov, Peet

Anti deSitter



CFT



AdS/CFT

$N = 4\ SCFT$

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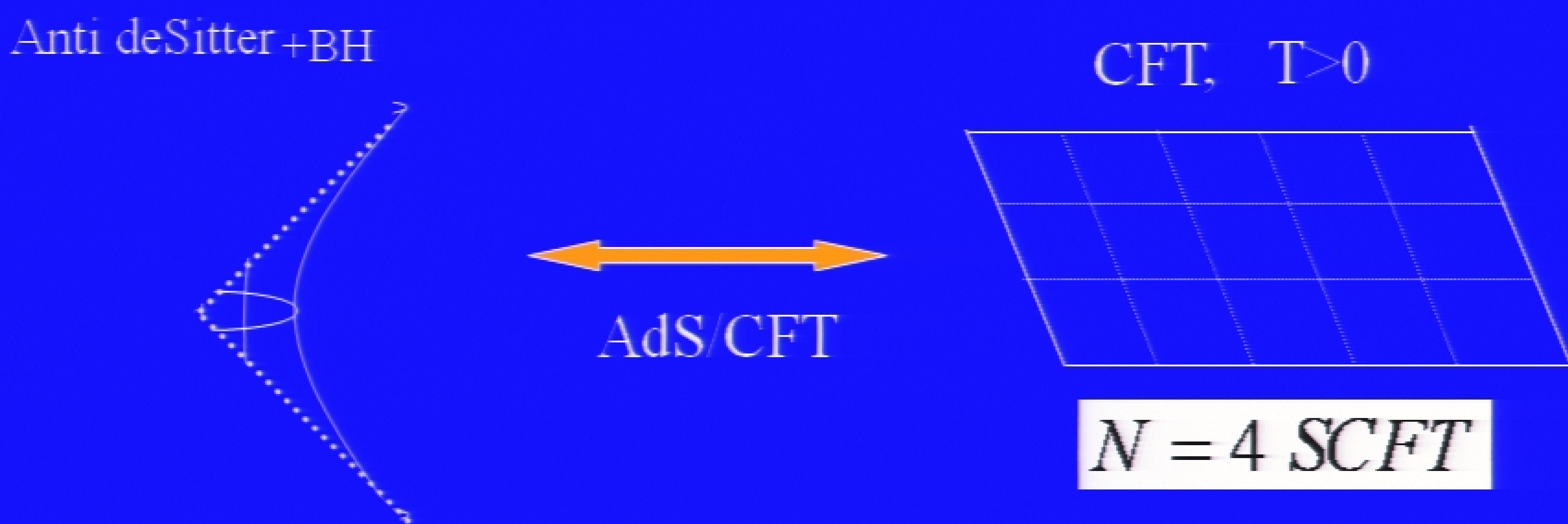

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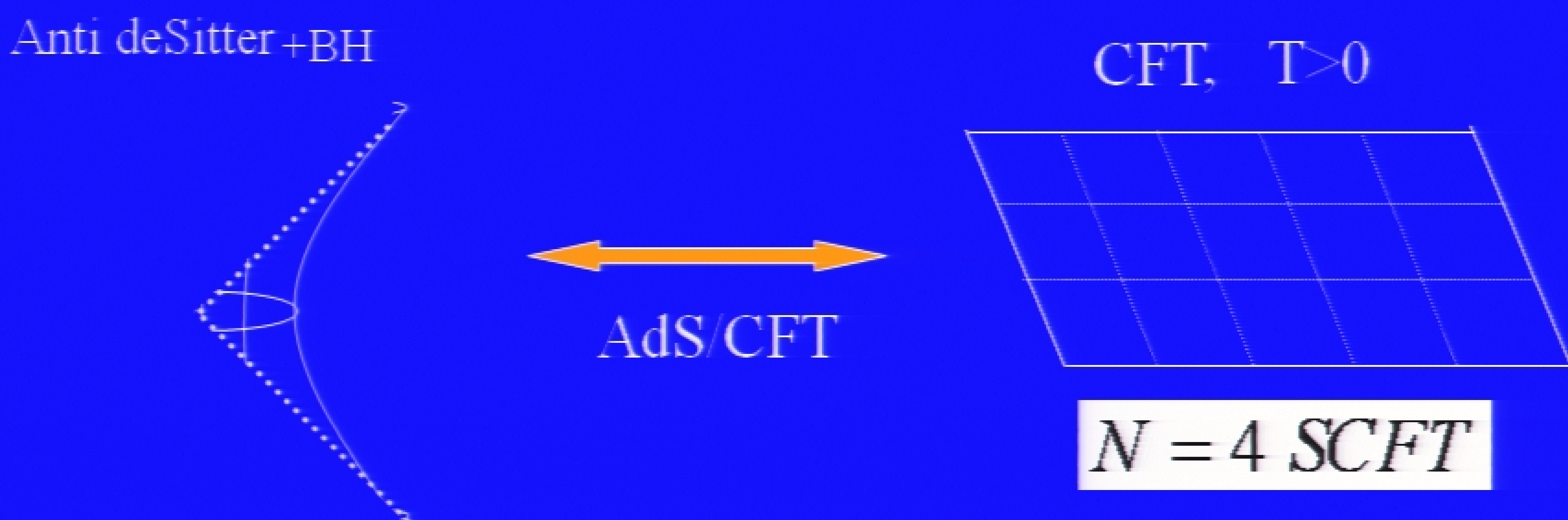

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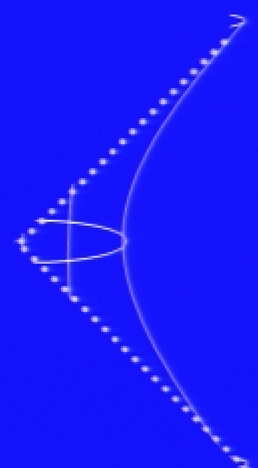
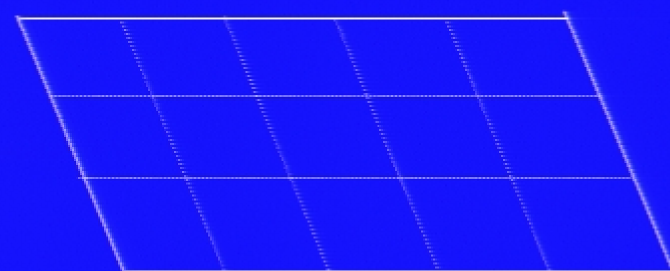
Gubser, Klebanov, Peet

Anti deSitter+BH



AdS/CFT

CFT, T>0



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S_{BH}=A/4

S=A/3

$R^4 = \lambda_{YM}$

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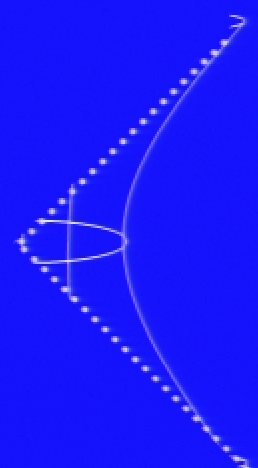

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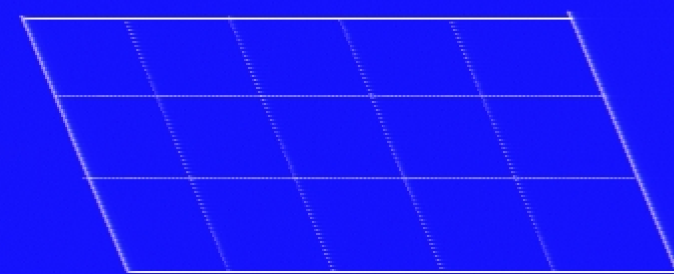
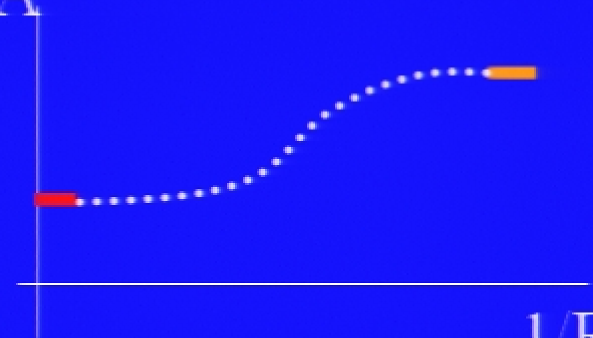


AdS/CFT

$N=4$ *SCFT*



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Semiclassical gravity:

$R >> l_s$

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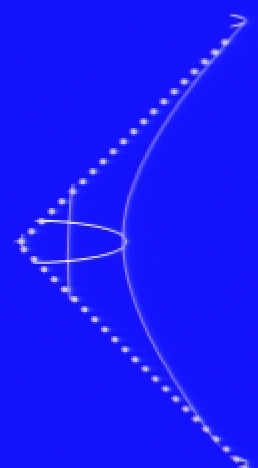
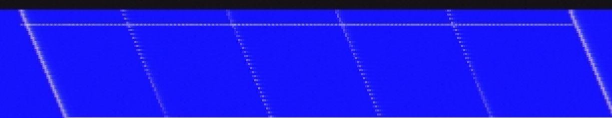


What is entanglement entropy? ✓
What is entanglement entropy of BH's ✓
How does string theory evaluate BH entropy? ✓
How are the two methods related to each other ?



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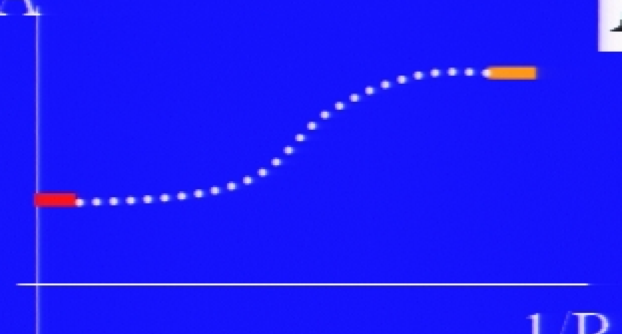

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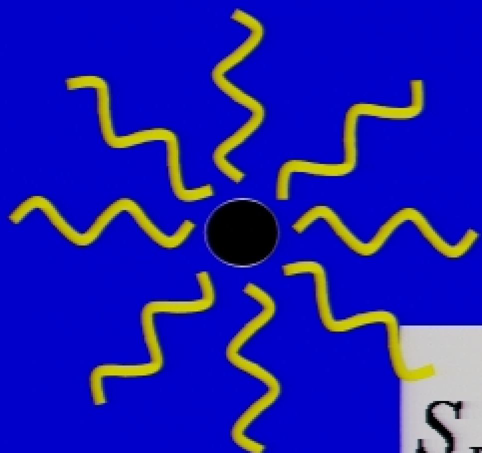

$$S_{BH} = \frac{A}{4G_N}$$

$$S_{BH\,ent.} \propto N \frac{A}{\delta^{(d-1)}}$$

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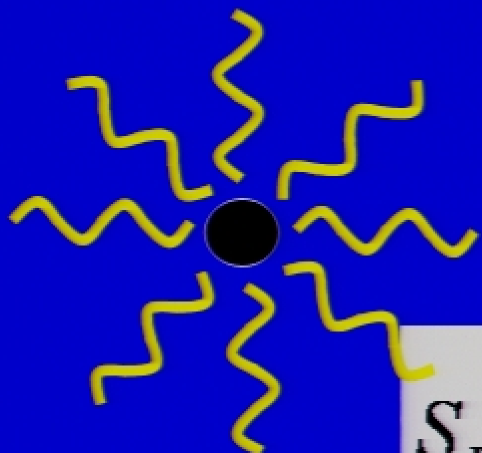

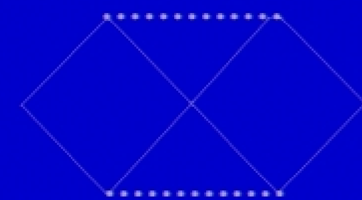

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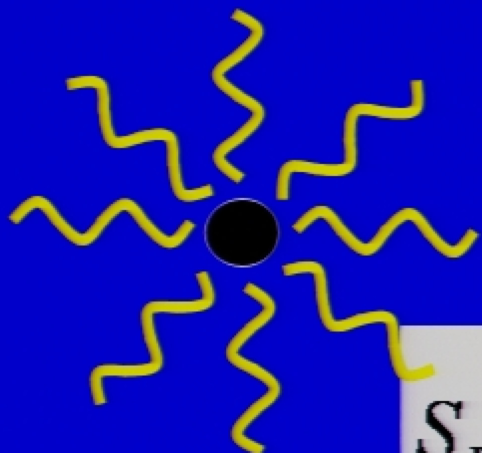

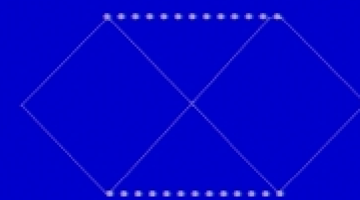

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$$\|$$

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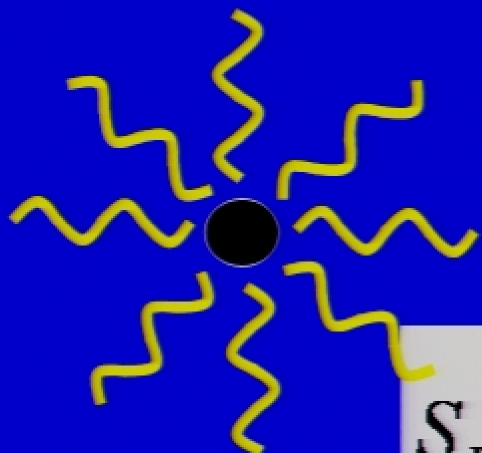

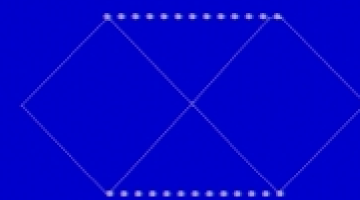

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$\|$

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?

Entanglement & FT/Gravity duality

R.B., M. Einhorn and A. Yarom

Extension of Maldacena's "eternal BHs in AdS"

- $Z_{string}(X) = Z_{FT}(M)$
- Hilbert spaces isomorphic

$$\mathbf{H}_W \simeq \widetilde{\mathbf{H}}_W$$

- $Z_{string}(X_W) = Z_{FT}(M_W)$
- Hilbert spaces isomorphic

$$\mathbf{H} \simeq \widetilde{\mathbf{H}}$$

Assume:

if one side of the duality is in a thermal state so is the other

(Periodic time on one side is mapped to periodic time on the other side)

$X \longleftrightarrow M$ $\qquad$ $X_W \longleftrightarrow M_W$

Entanglement & FT/Gravity duality

$X \longleftrightarrow M$ $\qquad$ $X_W \longleftrightarrow M_W$

$g_s \rightarrow 0, \alpha' \rightarrow 0$

- $Z_{string}(X) \sim e^{-I_{SUGRA}}$
- Some limit in the FT (In AdS/CFT $N \rightarrow \infty$, $\lambda_{YM} \rightarrow \infty$)

The duality holds in the limit

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$$\tilde{H} = \tilde{H}_W \otimes \tilde{H}_W \quad \leftarrow \quad H = H_W \otimes H_W$$

- Bulk
  - Thermal state

$$\rho_R = \mathrm{Tr}_L |0\rangle\langle 0|$$

$$e^{-I(X)} \xrightarrow[Tr]{} e^{-I(X_W)}$$

- Bulk
  - Thermal state

$$\rho_R = \mathrm{Tr}_L |0\rangle\langle 0|$$

$$e^{-I(X)} \xrightarrow[Tr]{} e^{-I(X_W)}$$

- Boundary
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$$\tilde{\rho}_W = \frac{1}{\tilde{Z}} \sum_i e^{-\beta \tilde{E}_i} |\tilde{E}_i\rangle\langle \tilde{E}_i|$$

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$$\widetilde{\rho}_W = \frac{1}{\widetilde{Z}} \sum_i e^{-\beta \widetilde{E}_i} |\widetilde{E}_i\rangle\langle \widetilde{E}_i|$$

$$Z_{FT}(M) = e^{-I(X)} \xrightarrow[Tr]{} e^{-I(X_W)} = Z_{FT}(M_W)$$

$g_s \to 0,\ \alpha' \to 0$

$$\sum_i \langle \psi_{Li} | 0 \rangle \langle 0 | \psi_{Li} \rangle \cong \sum_i \langle \widetilde{\psi}_{Li} | \widetilde{0} \rangle \langle \widetilde{0} | \widetilde{\psi}_{Li} \rangle$$

$$\rho_W = \mathrm{Tr}_L |0\rangle\langle 0| \cong \mathrm{Tr}_L |\widetilde{0}\rangle\langle\widetilde{0}|$$

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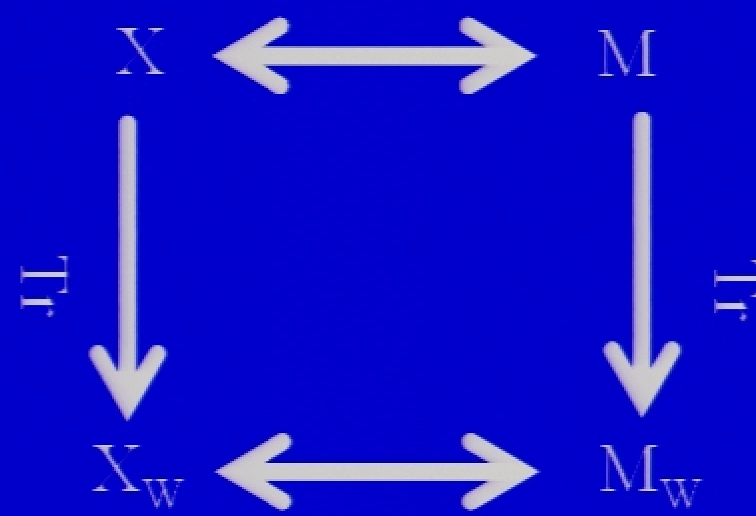

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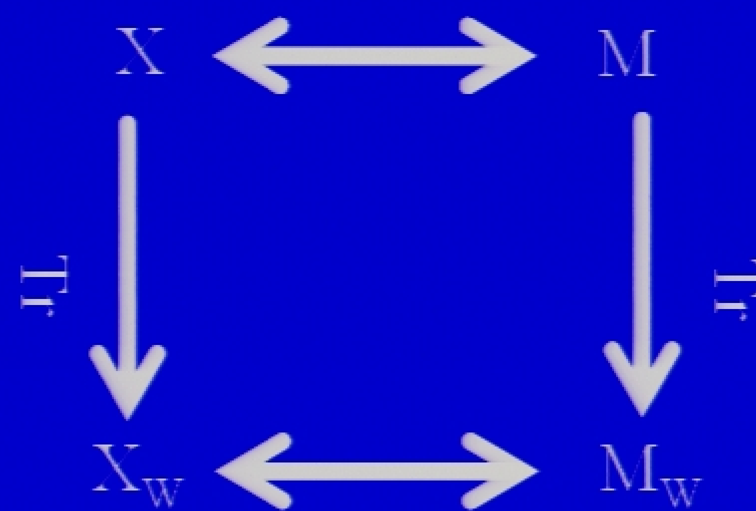
$|\widetilde{0}\rangle$ is TFD on $\widetilde{\mathbf{H}}_W \otimes \widetilde{\mathbf{H}}_W$



If the trace on each side gives a thermal state with the same temp. then the state is a TFD

Entanglement & FT/Gravity duality

A chain of equalities

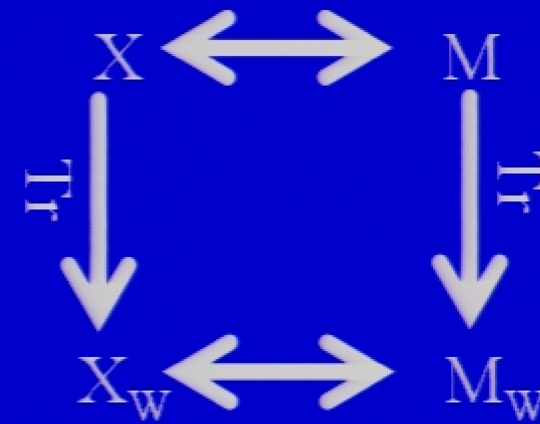
Entanglement & FT/Gravity duality

A chain of equalities

1. $S_{\text{entanglement, gravity}} = S_{\text{entanglement, FT}}$

2. $S_{\text{entanglement, FT}} = S_{\text{thermal,FT}}\ ;\ T > 0$

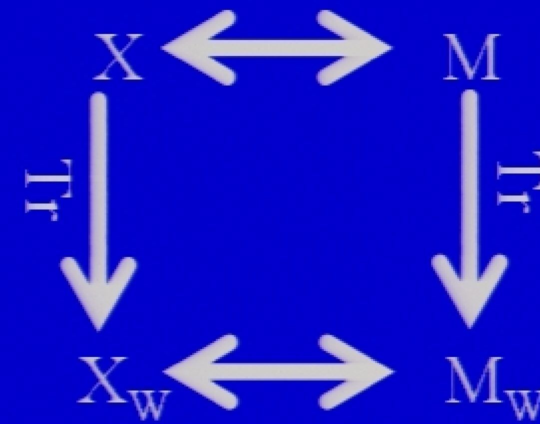
Interpretation



$g_s \to 0, \alpha' \to 0$

$$S(M_W) = \frac{A}{4G_N} \quad \to \quad S(X_W) = \frac{A}{4G_N}$$

Interpretation



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$$S(M_W) = \frac{A}{4G_N} \rightarrow S(X_W) = \frac{A}{4G_N}$$

BH entropy is due (entirely) to entanglement

$S(M_W)$ is due to entanglement ➔

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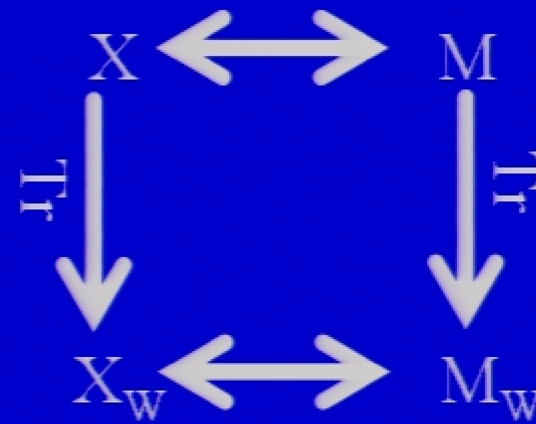

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<u>BH entropy is due (entirely) to entanglement</u>

$S(M_W)$ is due to entanglement $\rightarrow$

$S(X_W)$ is due to entanglement

Both entropies diverge in the limit $G_N \rightarrow 0$

Use FT to define and compare at finite G_N

Eternal AdS-BH (5D)

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$$ds^2 = -\left(\frac{r^2}{R^2} - \frac{b^4 R^2}{r^2}\right) dt^2 + \left(\frac{r^2}{R^2} - \frac{b^4 R^2}{r^2}\right)^{-1} dr^2 + \frac{r^2}{R^2}\left(dx_1^2 + dx_2^2 + dx_3^2\right)$$

$$r_s \simeq bR$$

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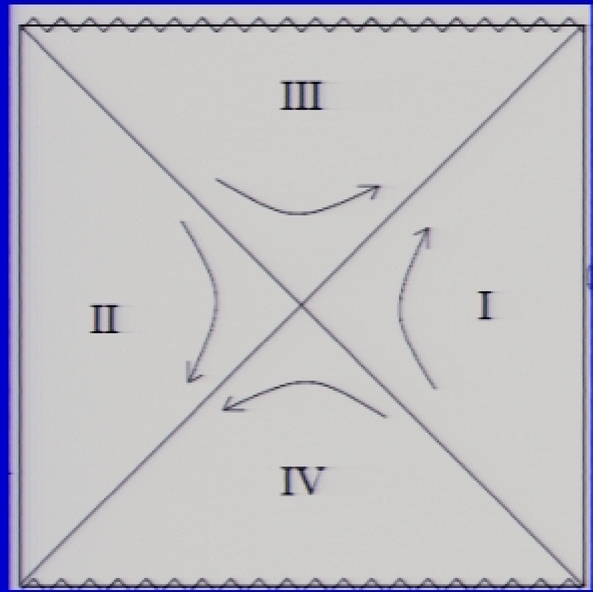
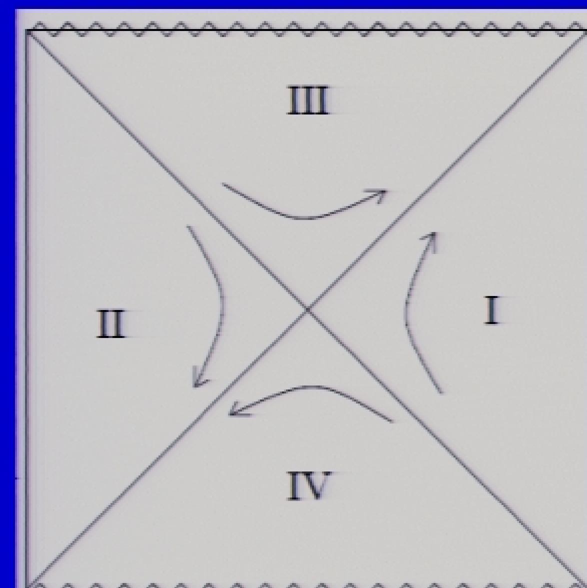


Eternal AdS-BH (5D)

Entanglement entropy is the entropy in a canonical ensemble of the FT.

$$S_{BH} = \frac{A}{4G_5} = \frac{1}{4}\frac{CR^5 A}{\alpha'^4 g_s^2}$$

$$S_{ENT} = NA\delta^{-3}$$



Number of fields

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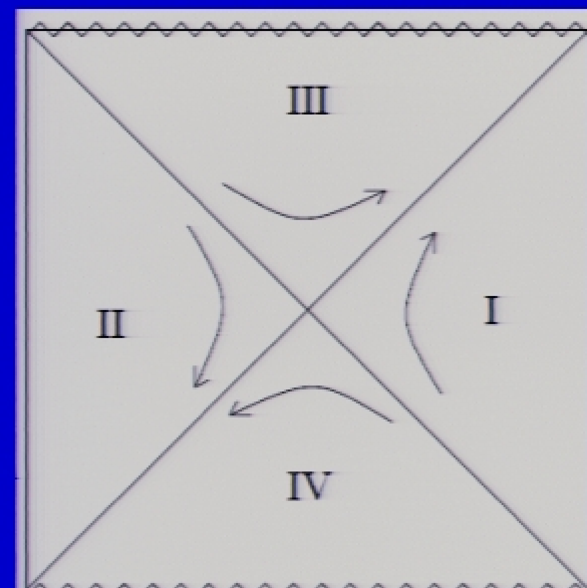
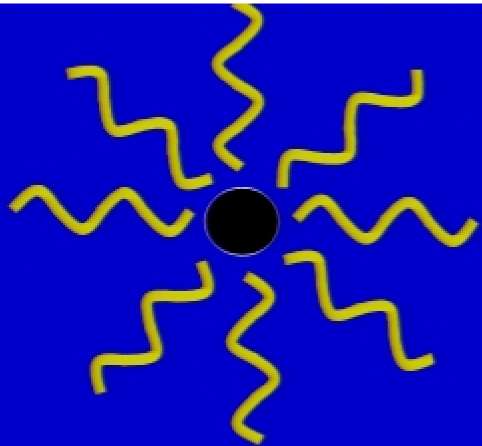
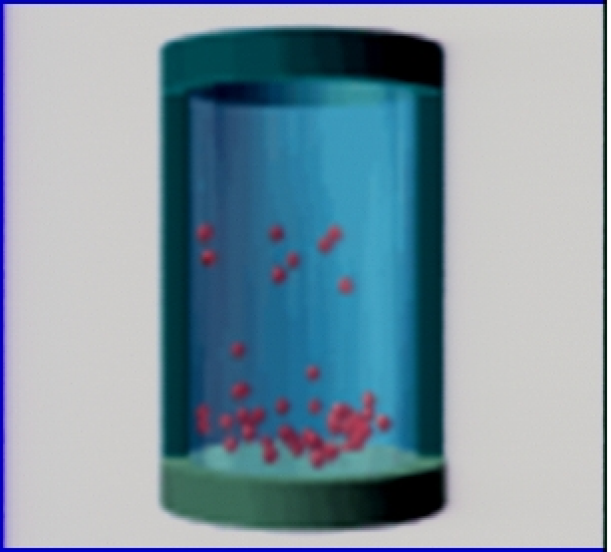


At the moment cannot compute the bulk regulator in terms of the boundary regulator ➔ free constant





$$S_{ENT} = C\ N \frac{A}{\delta^3}$$

$$S_{ENT} = S_{BH} = \frac{A}{4G_N^{(5)}}$$

$$G_N^{(5)} = \frac{l_s^{\,8} g_s^{\,2}}{R^5}$$

$$g_s \to 0$$
$$l_s \to 0$$

$$\Rightarrow G_N^{(5)} \to 0$$

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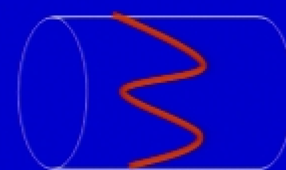

KK modes

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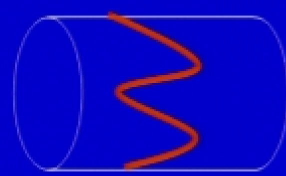

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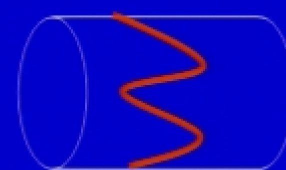

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$$\frac{1}{G_N^{(5)}} = \frac{R^5}{l_s^{\,8} g_s^{\,2}}$$

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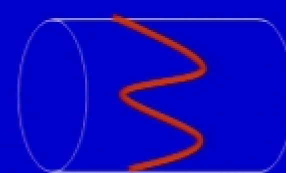

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- Expect a softer, finite expression in string theory
- To calculate need correlation functions in the coincidence limit, or a physical renormalization

Extensions, Consequences

1. Rotating and charged BHs, RB, Einhorn, Yarom
2. Extremal BHs (on FT side): Marolf and Yarom, TBP
3. Information paradox : RB, Einhorn, Yarom, in progress
4. Gibbons-Hawking, Wald vs. entanglement
   RB+Hadad, in progress

Summary

1. Method of calculating ρ in a wedge
2. FT/Gravity duality: The dual state to the global HH vacuum is a TFD
3. BH Entropy can be interpreted as entanglement entropy (not a correction!)
4. UV sensitivity

Extensions, Consequences

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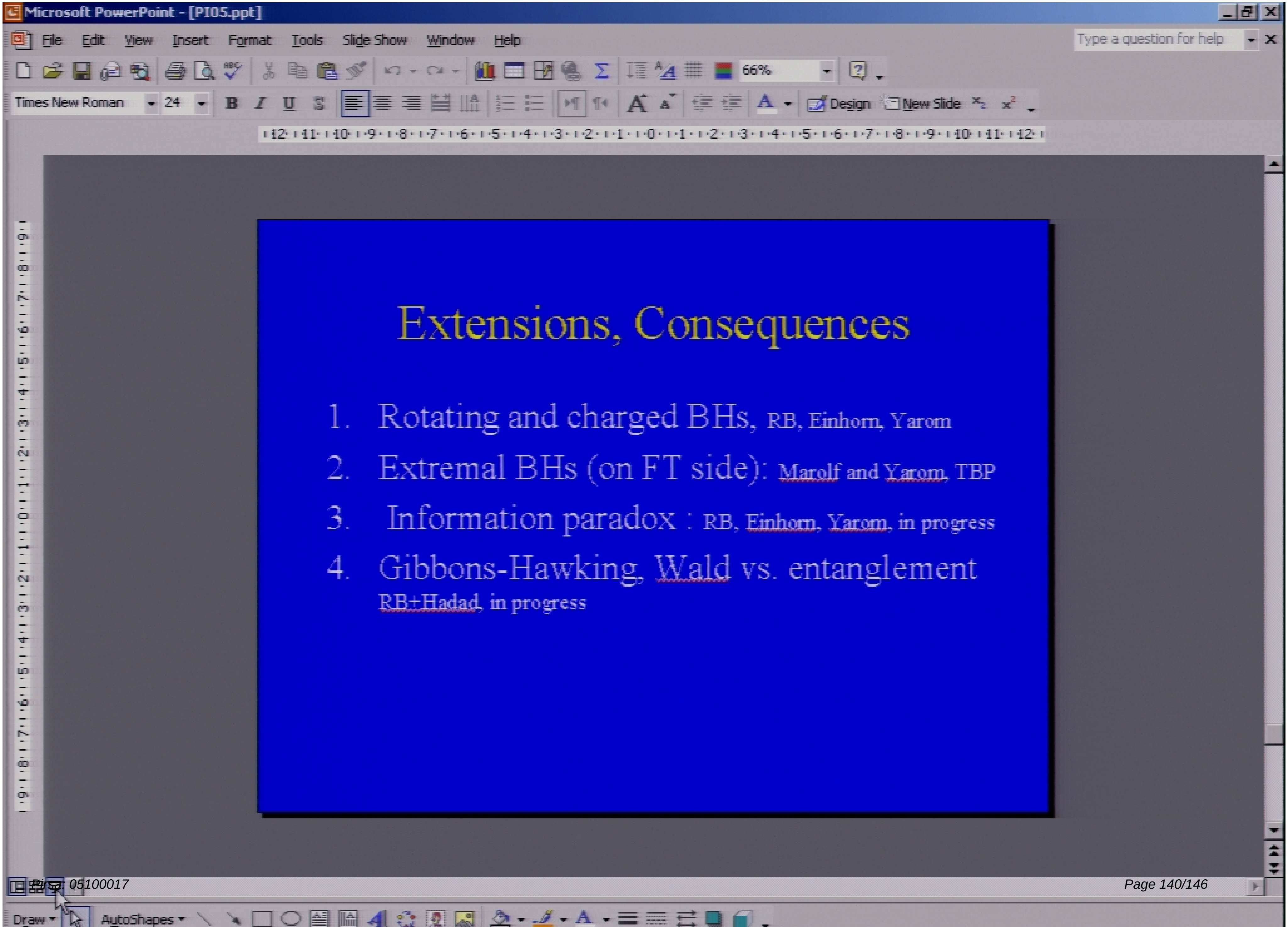
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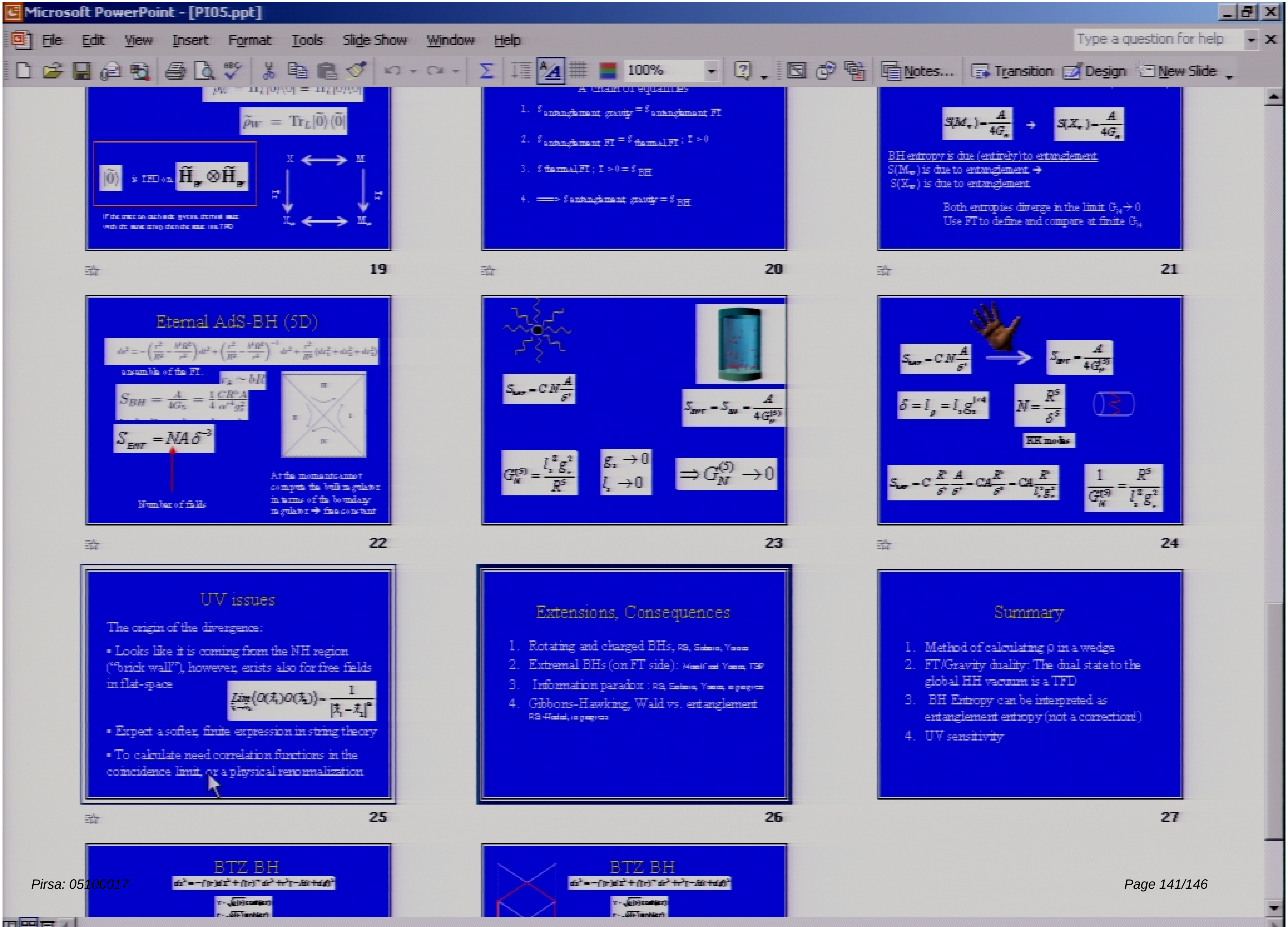
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BH entropy is due (entirely) to entanglement
Both entropies diverge in the limit
Use FT to define and compare at finite
19
20
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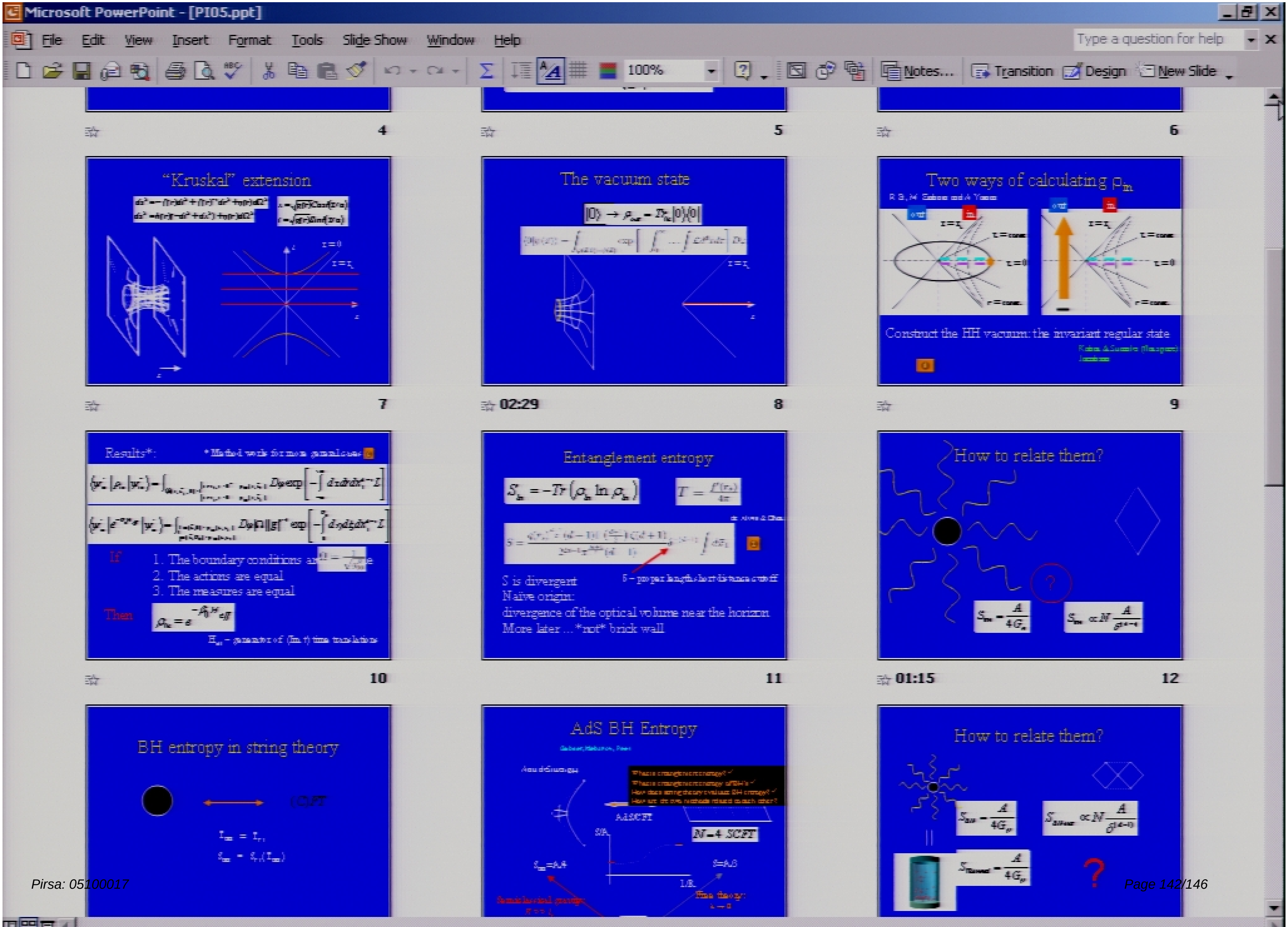
Eternal AdS-BH (5D)
Number of fields
22
23
KK modes
24
UV issues
The origin of the divergence:
• Looks like it is coming from the NH region ("brick wall"), however, exists also for free fields in flat-space
• Expect a softer, finite expression in string theory
• To calculate need correlation functions in the coincidence limit, or a physical renormalization
25
Extensions, Consequences
1. Rotating and charged BHs,
2. Extremal BHs (on FT side):
3. Information paradox
4. Gibbons-Hawking, Wald vs. entanglement
26
Summary
1. Method of calculating ρ in a wedge
2. FT/Gravity duality: The dual state to the global HH vacuum is a TFD
3. BH Entropy can be interpreted as entanglement entropy (not a correction!)
4. UV sensitivity
27
BTZ BH
BTZ BH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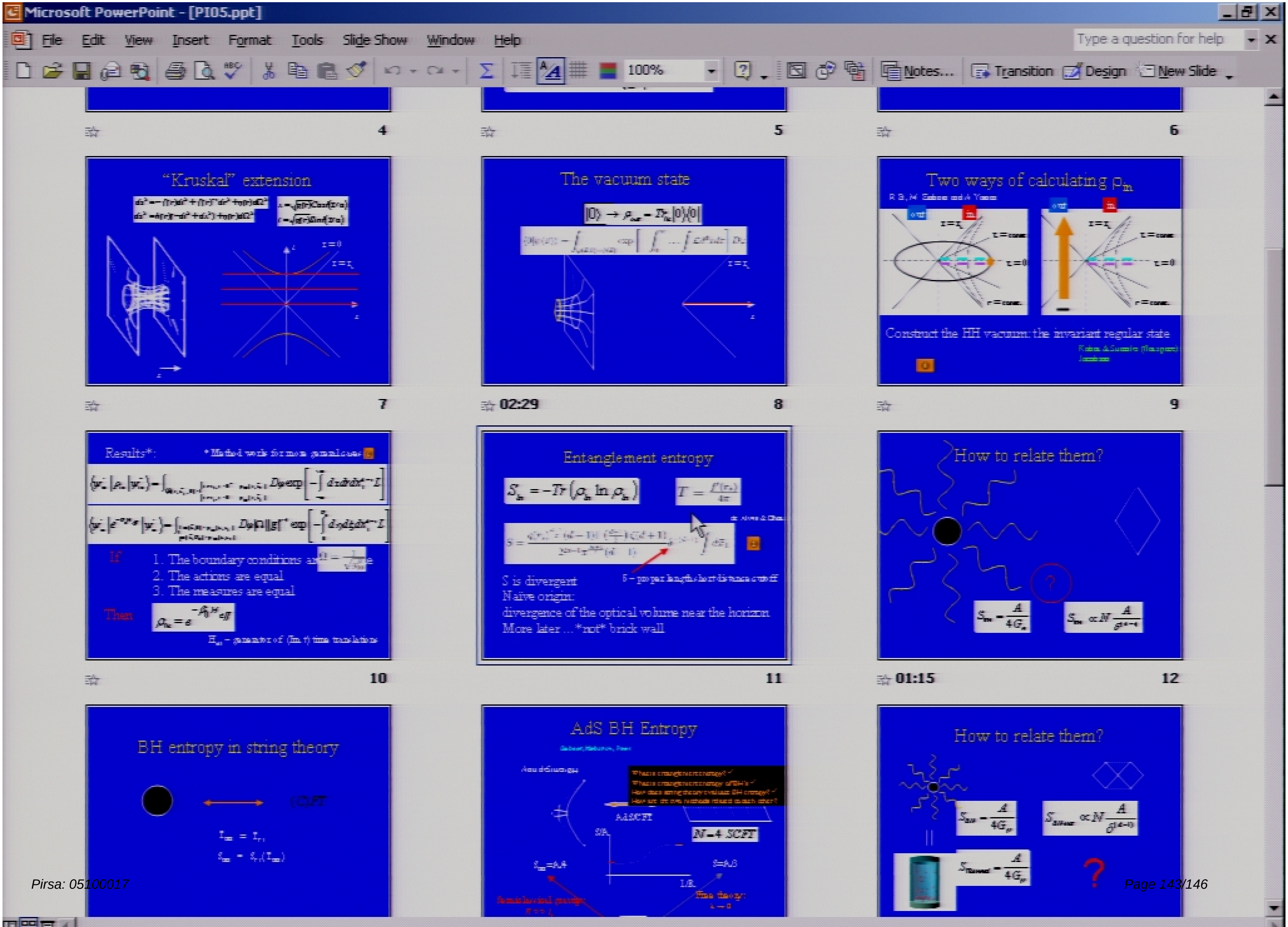
"Kruskal" extension
The vacuum state
Two ways of calculating ρ_{in}
Construct the HH vacuum: the invariant regular state
7
02:29
8
9
Results*:
If
1. The boundary conditions are
2. The actions are equal
3. The measures are equal
Then
Entanglement entropy
S is divergent
Naive origin:
divergence of the optical volume near the horizon
More later ... *not* brick wall
How to relate them?
10
11
01:15
12
BH entropy in string theory
AdS BH Entropy
AdS/CFT
N=4 SCFT
How to relate them?



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Entanglement entropy
$S_{in} = -Tr(\rho_{in} \ln \rho_{in})$
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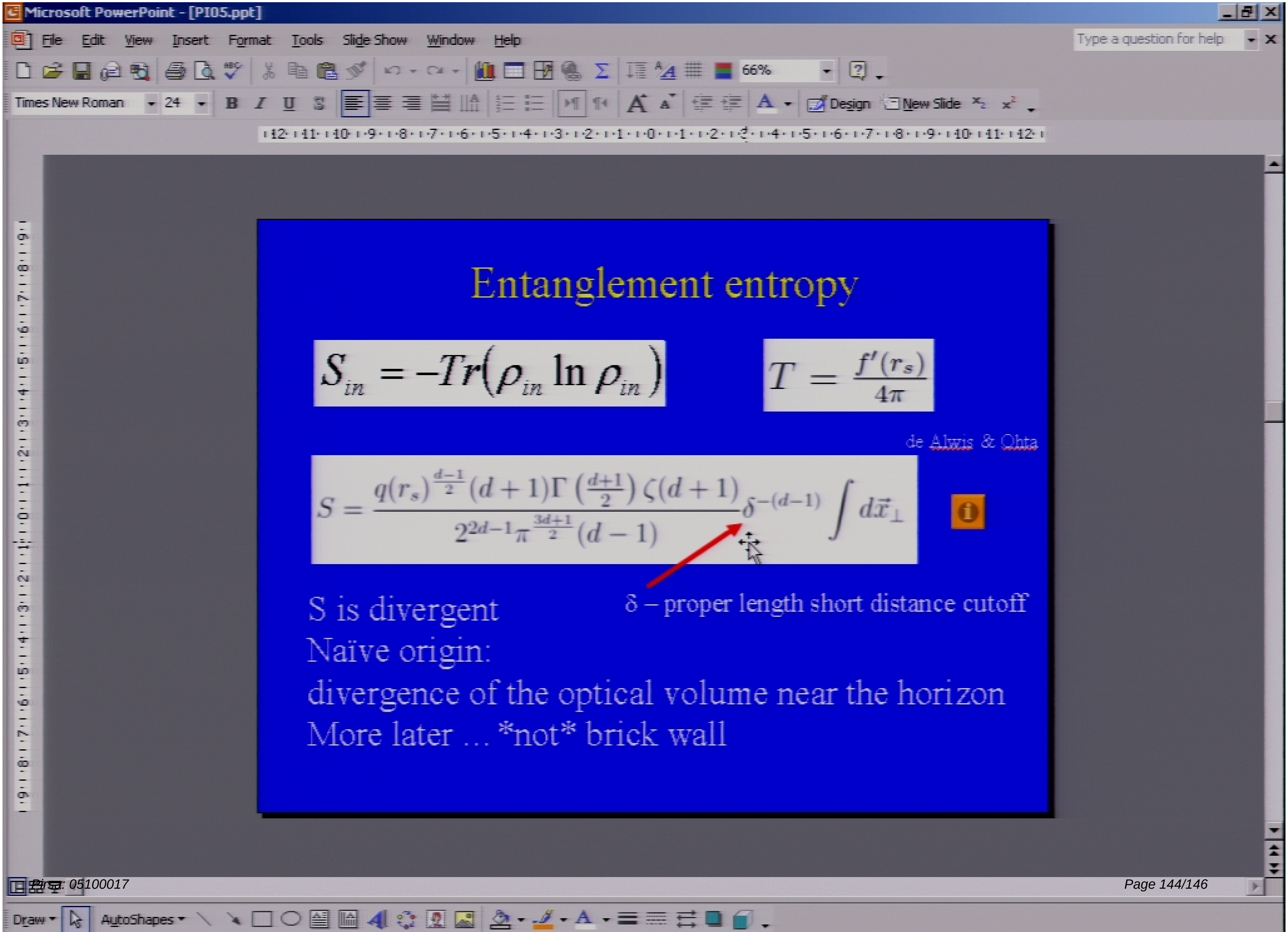
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Entanglement entropy
$S_{in} = -Tr(\rho_{in} \ln \rho_{in})$
$T = \frac{f'(r_s)}{4\pi}$
de Alwis & Ohta
$S = \frac{q(r_s)^{\frac{d-1}{2}}(d+1)\Gamma\left(\frac{d+1}{2}\right)\zeta(d+1)}{2^{2d-1}\pi^{\frac{3d+1}{2}}(d-1)}\delta^{-(d-1)}\int d\vec{x}_\perp$
δ – proper length short distance cutoff
S is divergent
Naïve origin:
divergence of the optical volume near the horizon
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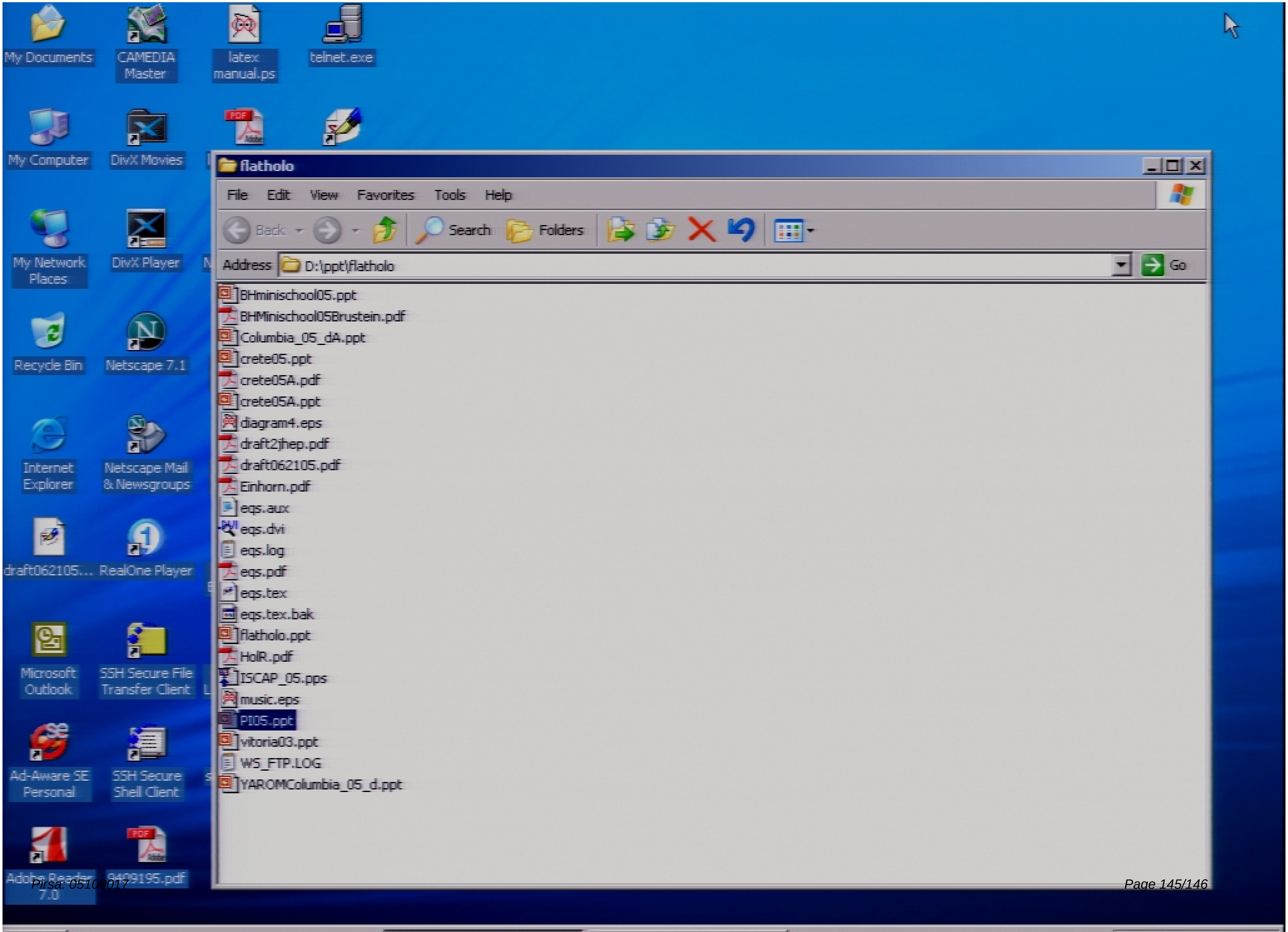
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Microsoft Outlook
SSH Secure File Transfer Client
Ad-Aware SE Personal
SSH Secure Shell Client
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Entanglement entropy

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$$T = \frac{f'(r_s)}{4\pi}$$

de Alwis & Ohta

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