Title: The emergence of spacetime is governed by a quantum Mach's principle

Speakers: Lee Smolin

Collection: Quantum Spacetime in the Cosmos: From Conception to Reality

Date: May 12, 2023 - 11:45 AM

URL: https://pirsa.org/23050136

Abstract: "I describe a candidate for a fundamental physical theory called the causal theory of views. This describes a world constructed by a continual creation of events; where an event is a transition at which a small portion of the possible
becomes actual. I first recall older results which includes the emergence of space and, with space, a non-relativistic N-body quantum dynamics. I next describe recent progress on this model including, in a different limit, a formulation of a cut off quantum field theory, which we describe in terms of an S-Matrix formulation of amplitudes.

The dynamics is specified by an action principle consisting of a kinetic energy and potential energy term.
The former are based on measures of how quickly components of causal change do so with respect to averaged notions. The potential energy terms measure how much local moves alter an observer's ""view"" of the universe, as seen from their perspective.

These results show that quantum dynamics is restored in an N to infinity limit. Measurable non-linear corrections to quantum dynamics emerge to higher order in 1/sqrt{N}. "

# What do we mean when we say “…and then, Spacetime emerges..” ?

Lee Smolin
PI

work in progress, w Clelia Verde

In memory of Drucila Cornell

What do we mean when we say
"…and then, Spacetime emerges.." ?

We have a program to solve QG + QF + cosmology:

"Causal theory of views…(CTV)

Clear description of World Before Space..
And of the geometrogensis phase transition.

Within our rsmework we can state a QMach principle
That organizes how matter and space emerge correctly.
We would love more criticism, help…allies

Rob "We need a new paradigm for early universe cosmology"

Key ideas:

This new paradigm (CTV) describes physics before space emerges

- No space means no distinction between locality and non-locality

- This is the origin of quantum non-locality.
- Ie quantum non-locality. is due to non-local interactions
- left behind and frozen during th phase transition in which space emerges.

What is the physics before space? ***Relational hidden variables***

One new dof for every pair of classical dof.

New symmetry mixes them all up.. Phase transition separates and orders them.

list of classical variables becomes a matrix model.

6

***Relational hidden variables***

One new dof for every pair of classical dofs.
New Symmetry mixes them all up..

list of classical variables becomes a matrix model.

New phase transition breaks symmetry: separates diagonal and off-diagonal entries.

N diagonal dof, classical physics, $N^2$ off diagonal, hidden dof.

Heat off-diagonal def to low temperature. $T \sim 1/N$

We propose scaling as N —> infinity.

Large N limit is classical physics. These are the eigenvalues of the matrix.

1/sqrt{N} corrections are QM corrections

Higher order: non-local corrections, computable and measurable.

**_Relational hidden variables theories: Examples:_**

**_1 large general complex matrix._** (LS, 1981)
—> classical dof are N eigenvalues live in complex plane.

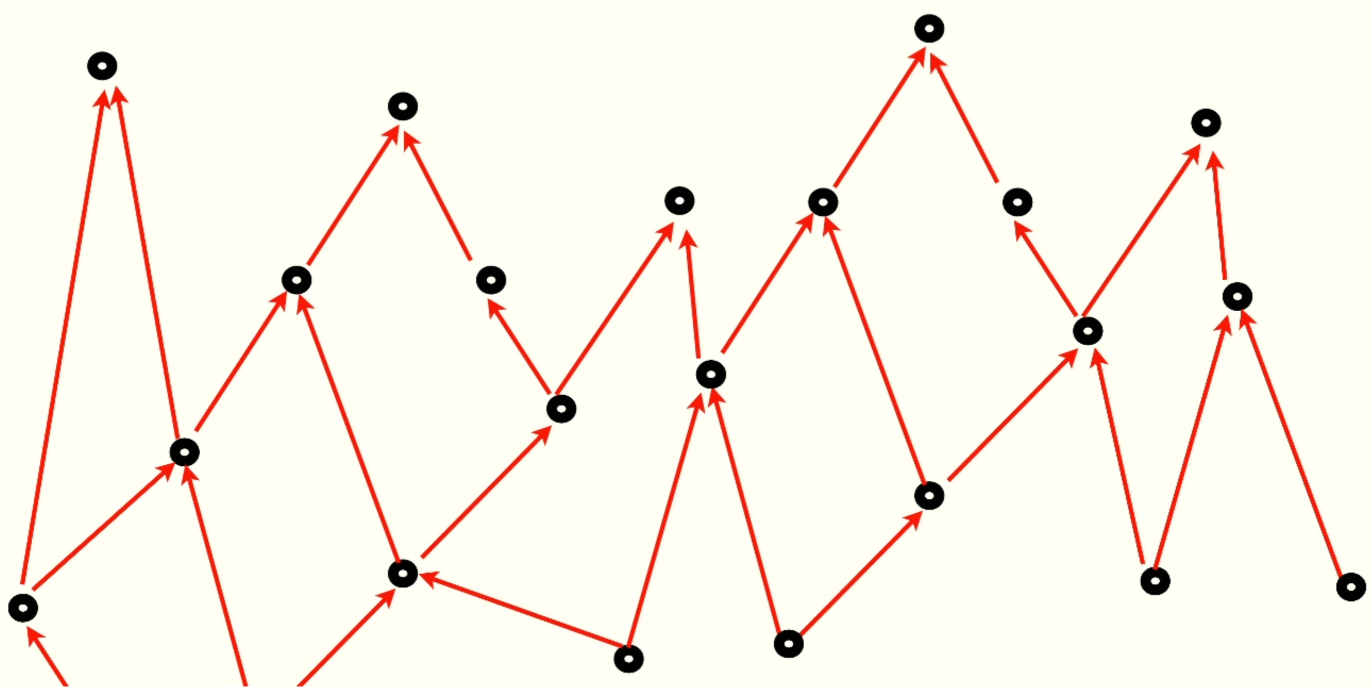
**_D large hermitian matrices_**

—> Steve Adler. ()
—> Artem. S
—> BFSS model, LS 2012
—> LQG. —>. QM. F. Markopoulou &. LS

**_Real ensemble models, l_**s. 2015

**_causal views theories_** LS. 2020

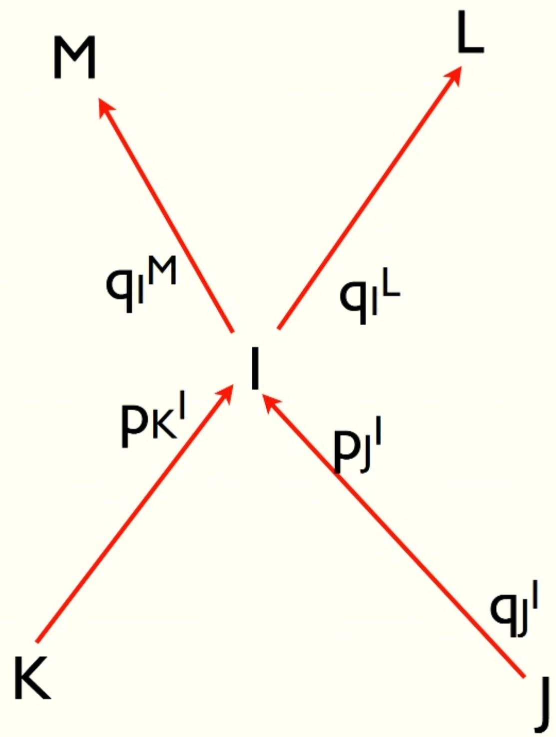
# Causal sets:



## Energetic causal sets:

Each link, connecting $E_I$ to one of its parents, $E_{j,}$ has two momenta, an incoming momenta $p_J{}^I$ and an outgoing momentum $q_I{}^J$.

The total momenta of an event $$P_a^I = \sum_J p_{aI}^J$$



## *Constraints:*

The momenta are propagated to the new event and links by three constraints:

Conservation at each event: $\mathcal{P}^I_a = \sum_K p^I_{aK} - \sum_L q^L_{aI} = 0$

Parallel transport on each edge: $\mathcal{R}^K_{aI} = p^K_{aI} - \mathcal{U}^{Kb}_{Ia} q^K_{bI} = 0$

Energy-momentum relations:

$$\mathcal{C}^I_K = \frac{1}{2}\eta^{ab} p^I_{aK} p^I_{bK} + m^2 = 0$$

$$\tilde{\mathcal{C}}^I_K = \frac{1}{2}\eta^{ab} q^I_{aK} q^I_{bK} + m^2 = 0$$

***Constraints:***

The momenta are propagated to the new event and links by three constraints:

Conservation at each event:

$$\mathcal{P}^I_a = \sum_K p^I_{aK} - \sum_L q^L_{aI} = 0$$

Parallel transport on each edge:

$$\mathcal{R}^K_{aI} = p^K_{aI} - \mathcal{U}^{Kb}_{Ia} q^K_{bI} = 0$$

Energy-momentum relations:

$$\mathcal{C}^I_K = \frac{1}{2}\eta^{ab} p^I_{aK} p^I_{bK} + m^2 = 0$$

$$\tilde{\mathcal{C}}^I_K = \frac{1}{2}\eta^{ab} q^I_{aK} q^I_{bK} + m^2 = 0$$

***No spacetime.***
***The only geometry that comes in is the metric of momentum space.***

All we need to define quantum dynamics is the amplitude law. Events have amplitudes A[i].

Probability:

$$\mathcal{P}[p_a^{in,\ I}; q_a^{out,\ I}] = \left|\mathcal{A}[p_a^{in,\ I}; q_a^{out,\ I}]\right|^2$$

The total amplitude is defined by integrating over momenta, imposing the constraints

$$\mathcal{A}[P] = \int \Pi_{(IJ)} dp_a^{IJ} dq_a^{IJ} \delta(\mathcal{C}_a^{IJ}) \delta(\mathcal{R}_I^J) \Pi_I \delta(\mathcal{P}_a^I) \Pi_I \mathcal{A}_I$$

This is the complete definition of the theory.

No hbar
No spacetime
No commutation relations
No uncertainty principle

The total amplitude is defined by integrating over momenta, imposing the constraints

$$\mathcal{A}[P] = \int \Pi_{(IJ)} dp_a^{IJ} dq_a^{IJ} \delta(\mathcal{C}_a^{IJ}) \delta(\mathcal{R}_I^J) \Pi_I \delta(\mathcal{P}_a^I) \Pi_I \mathcal{A}_I$$

We introduce lagrange multipliers to exponentiate the constraints:

$$\mathcal{A}[P] = N[\mathcal{C}] \int \Pi_{(IJ)} dp_a^{IJ} dq_a^{IJ} d\mathcal{N}_I^J d\tilde{\mathcal{M}}_I^J \Pi_I dZ_I^a \; e^{\imath S^0}$$

With an action that is pure constraints:

$$S = \sum_I z_I^a \mathcal{P}_a^I + \sum_{(I,K)} (x_K^{aI} \mathcal{R}_{aI}^K + \mathcal{N}_I^K \mathcal{C}_K^I - \tilde{\mathcal{N}}_I^K \tilde{\mathcal{C}}_K^I)$$

lagrange multipliers

Classical physics from the stationary phase approximation:

$$S = \sum_I z_I^a \mathcal{P}_a^I + \sum_{(I,K)} \left( x_K^{aI} \mathcal{R}_{aI}^K + \mathcal{N}_I^K \mathcal{C}_K^I - \tilde{\mathcal{N}}_I^K \tilde{\mathcal{C}}_K^I \right)$$

lagrange multipliers

Constraints:

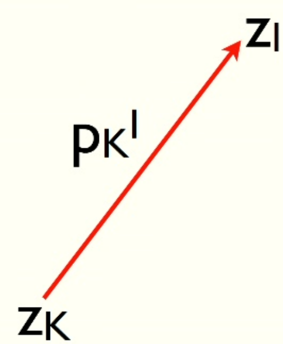
$$\mathcal{P}_a^I = \sum_K p_{aK}^I - \sum_L q_{aI}^L = 0 \qquad \mathcal{R}_{aI}^K = p_{aI}^K - \mathcal{U}_{Ia}^{Kb} q_{bI}^K = 0$$

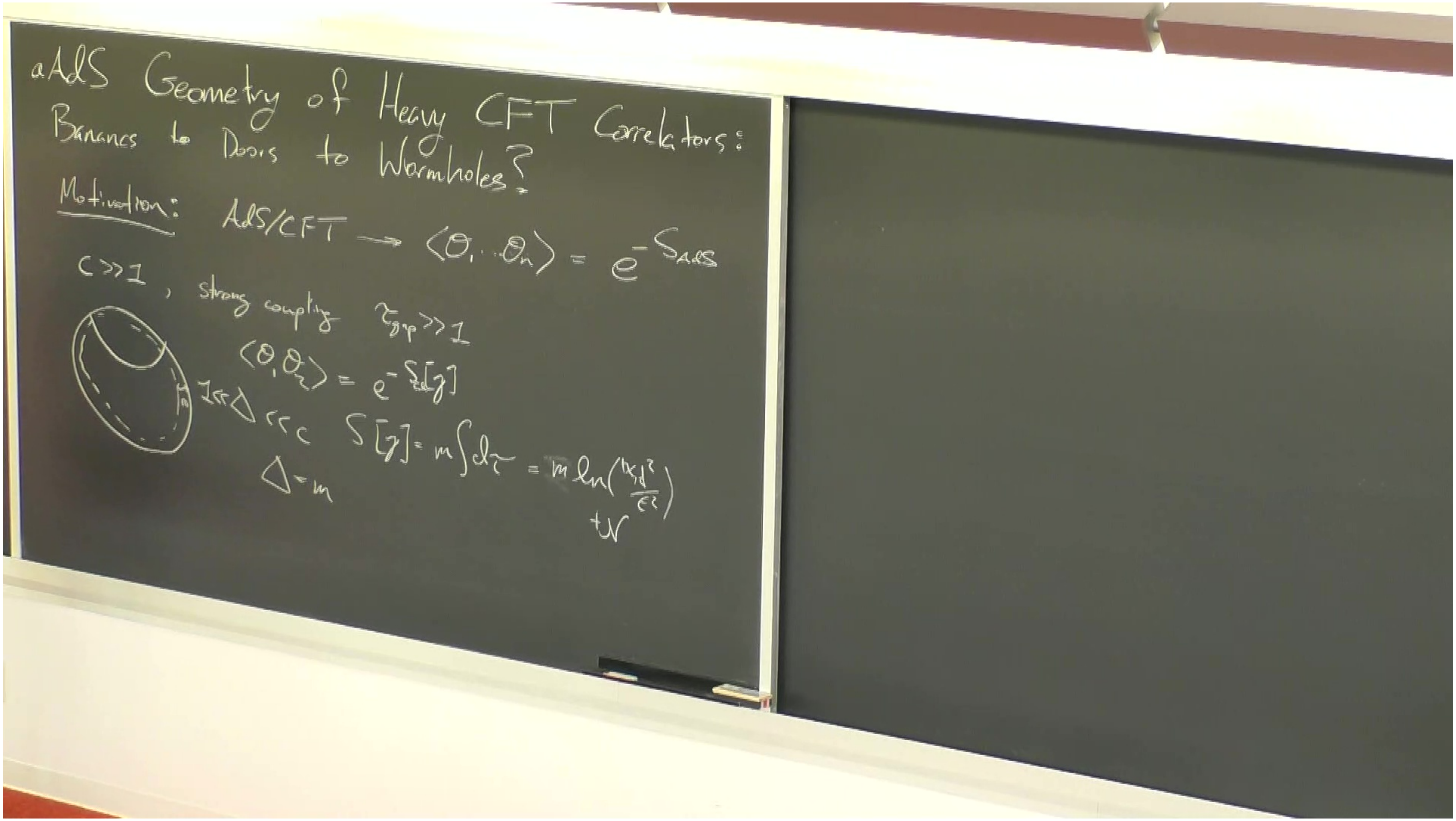
$$\mathcal{C}_K^I = \frac{1}{2} \eta^{ab} p_{aK}^I p_{bK}^I = 0 \qquad \tilde{\mathcal{C}}_K^I = \frac{1}{2} \eta^{ab} q_{aK}^I q_{bK}^I = 0$$

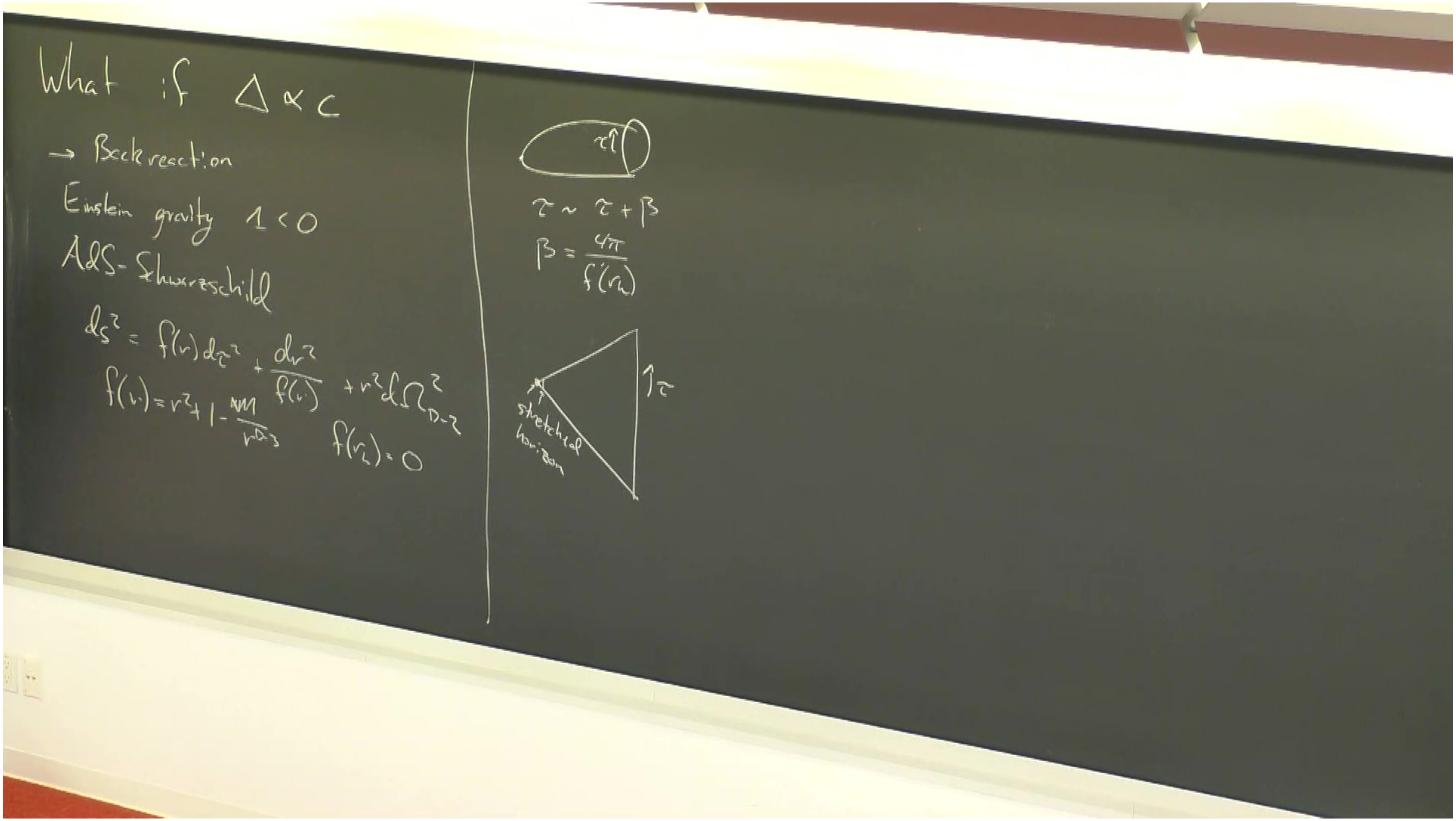
Equations of motion:

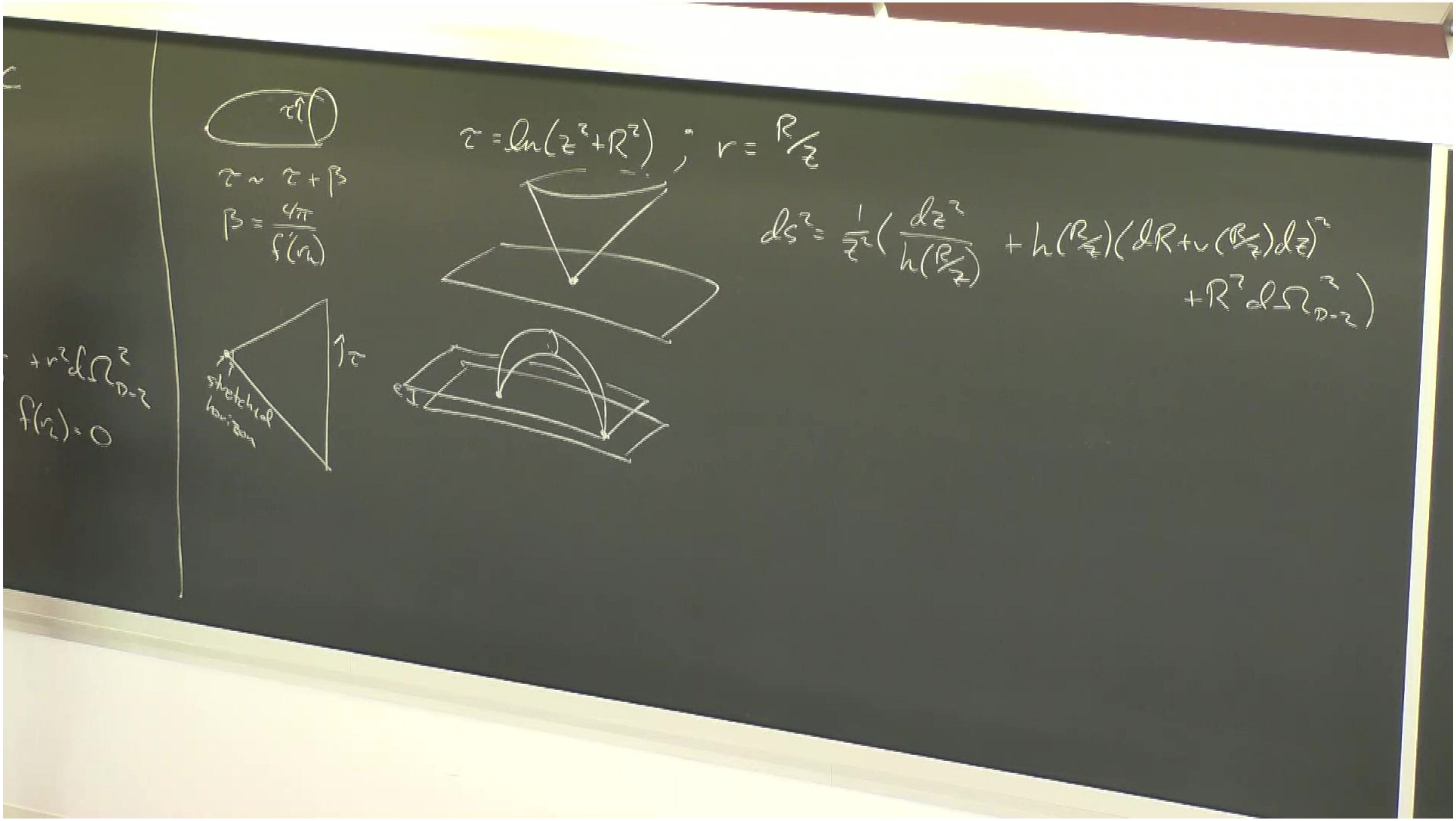
$$z_I^a - z_K^a = p_K^{aI} \mathcal{M}_I^K$$

$$\mathcal{M}_I^K = \tilde{\mathcal{N}}_I^K - \mathcal{N}_I^K$$

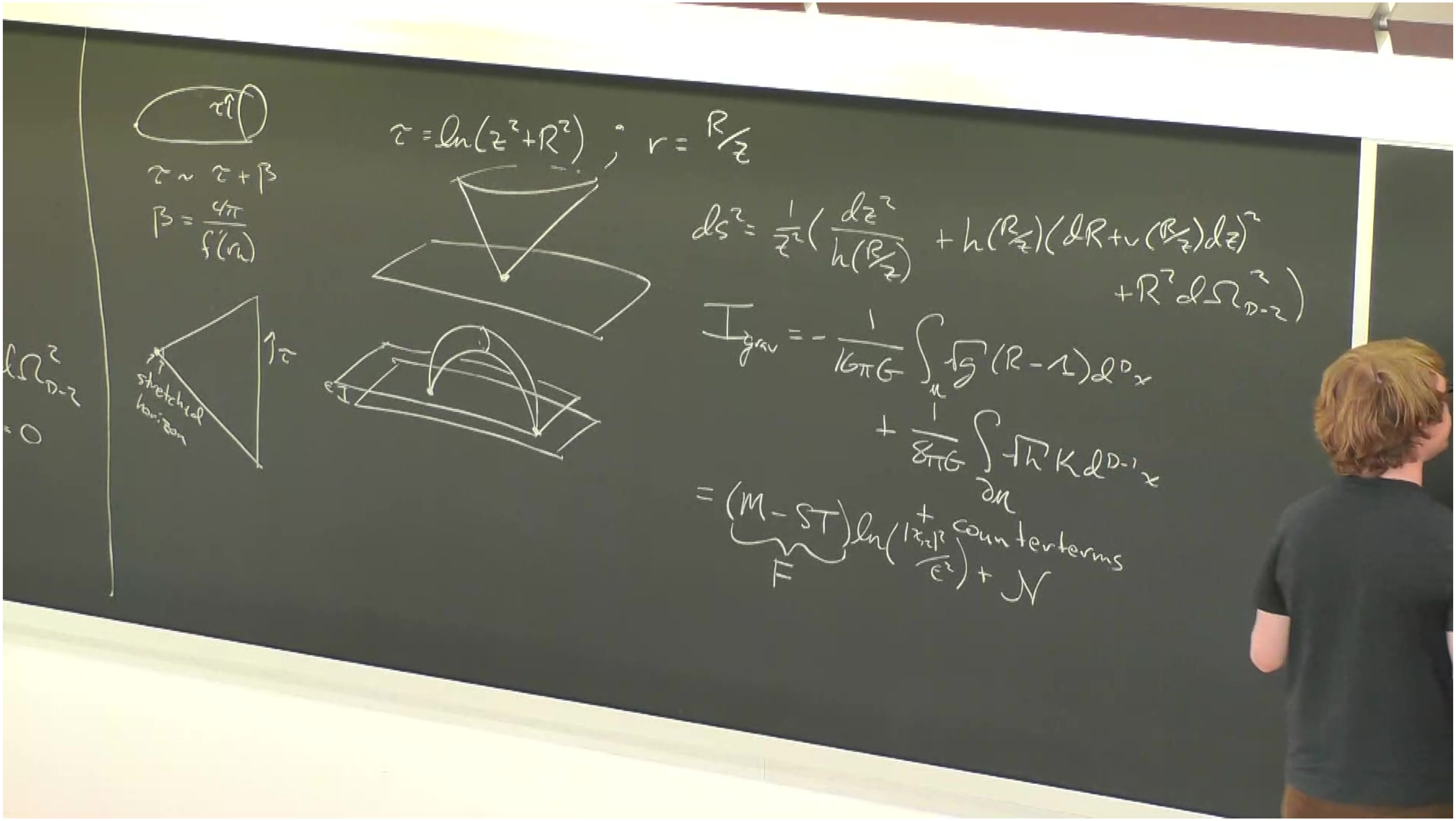



aAdS Geometry of Heavy CFT Correlators:
Bananas to Doors to Wormholes?
Motivation: AdS/CFT → ⟨O1 ... On⟩ = e^-SAdS
c>>1, strong coupling τgap>>1
⟨O1O2⟩ = e^-S[γ]
1<<Δ<<c S[γ] = m∫dτ = m ln(|x12|²/ε²) +...
Δ=m

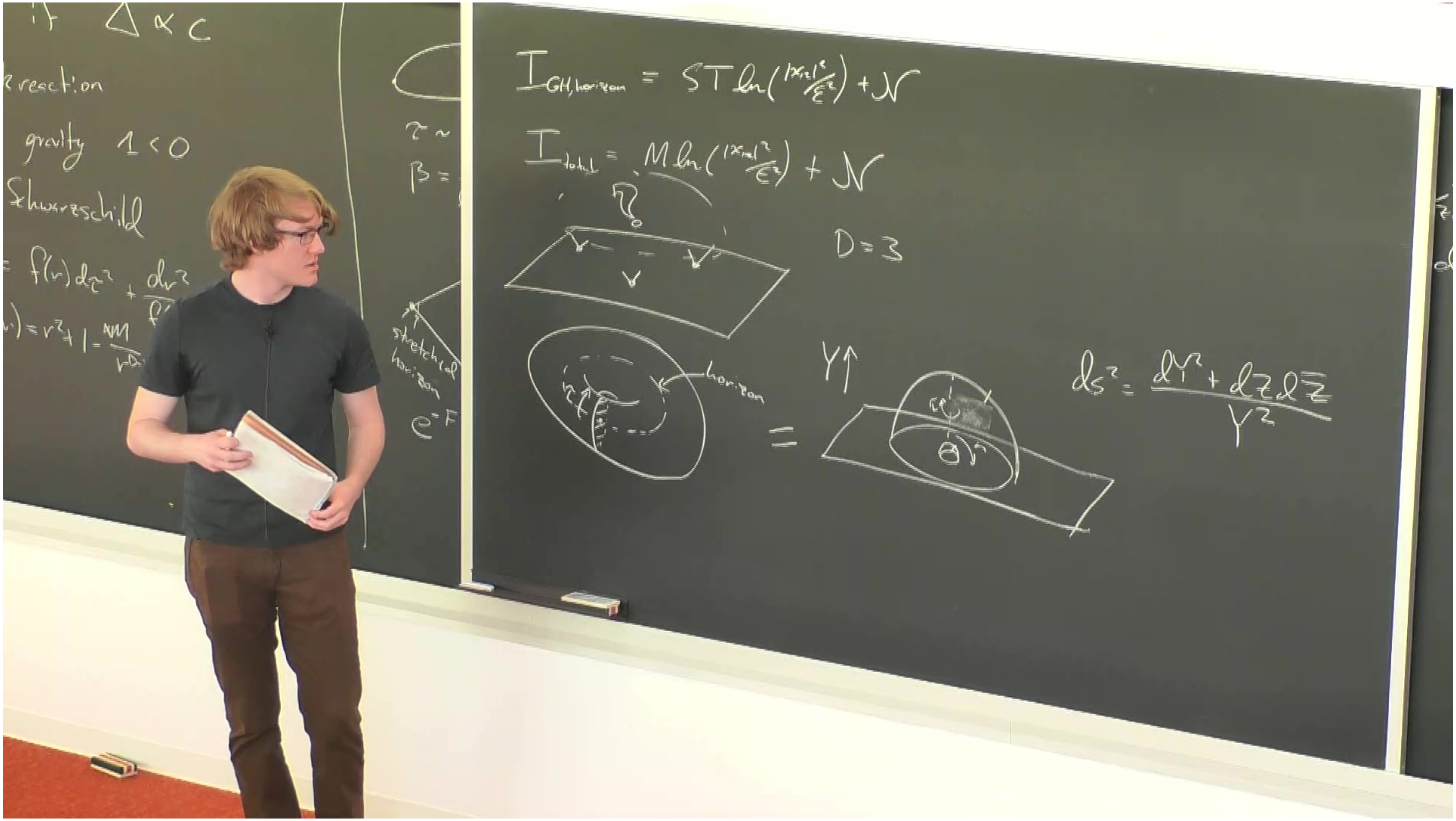

What if $\Delta \propto c$
→ Backreaction
Einstein gravity $\Lambda < 0$
AdS-Schwarzschild
$ds^2 = f(r)d\tau^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2_{D-2}$
$f(r) = r^2 + 1 - \frac{\#m}{r^{D-3}}$
$f(r_h) = 0$
$\tau$
$\tau \sim \tau + \beta$
$\beta = \frac{4\pi}{f'(r_h)}$
$\tau$
stretched horizon

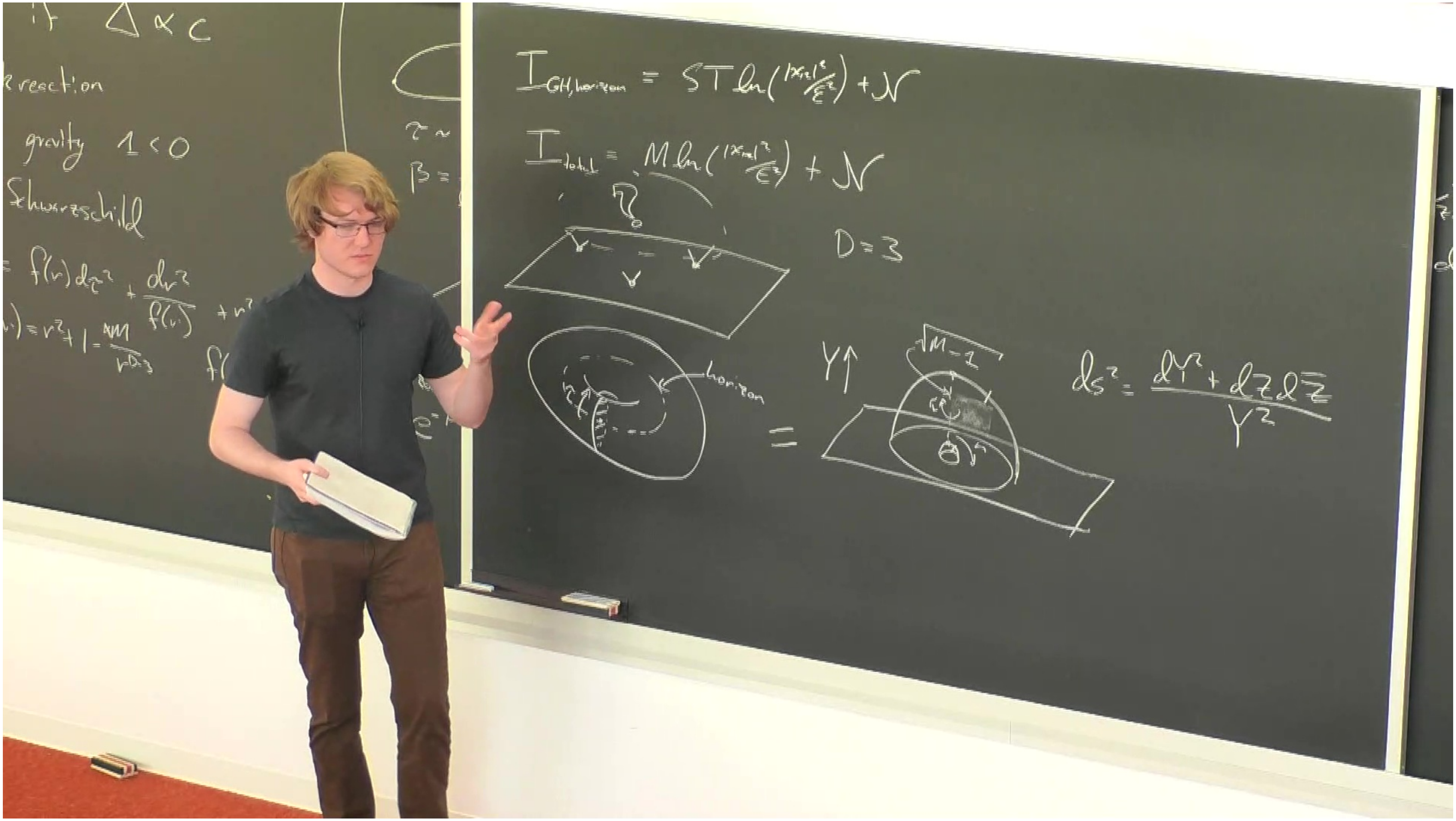


$\tau \sim \tau + \beta$
$\beta = \frac{4\pi}{f'(r_h)}$
$f(r_h) = 0$
$+ r^2 d\Omega^2_{D-2}$
stretched horizon
$\tau = \ln(z^2+R^2)$ ; $r = R/z$
$ds^2 = \frac{1}{z^2}\left( \frac{dz^2}{h(R/z)} + h(R/z)(dR + v(R/z)dz)^2 + R^2 d\Omega^2_{D-2} \right)$

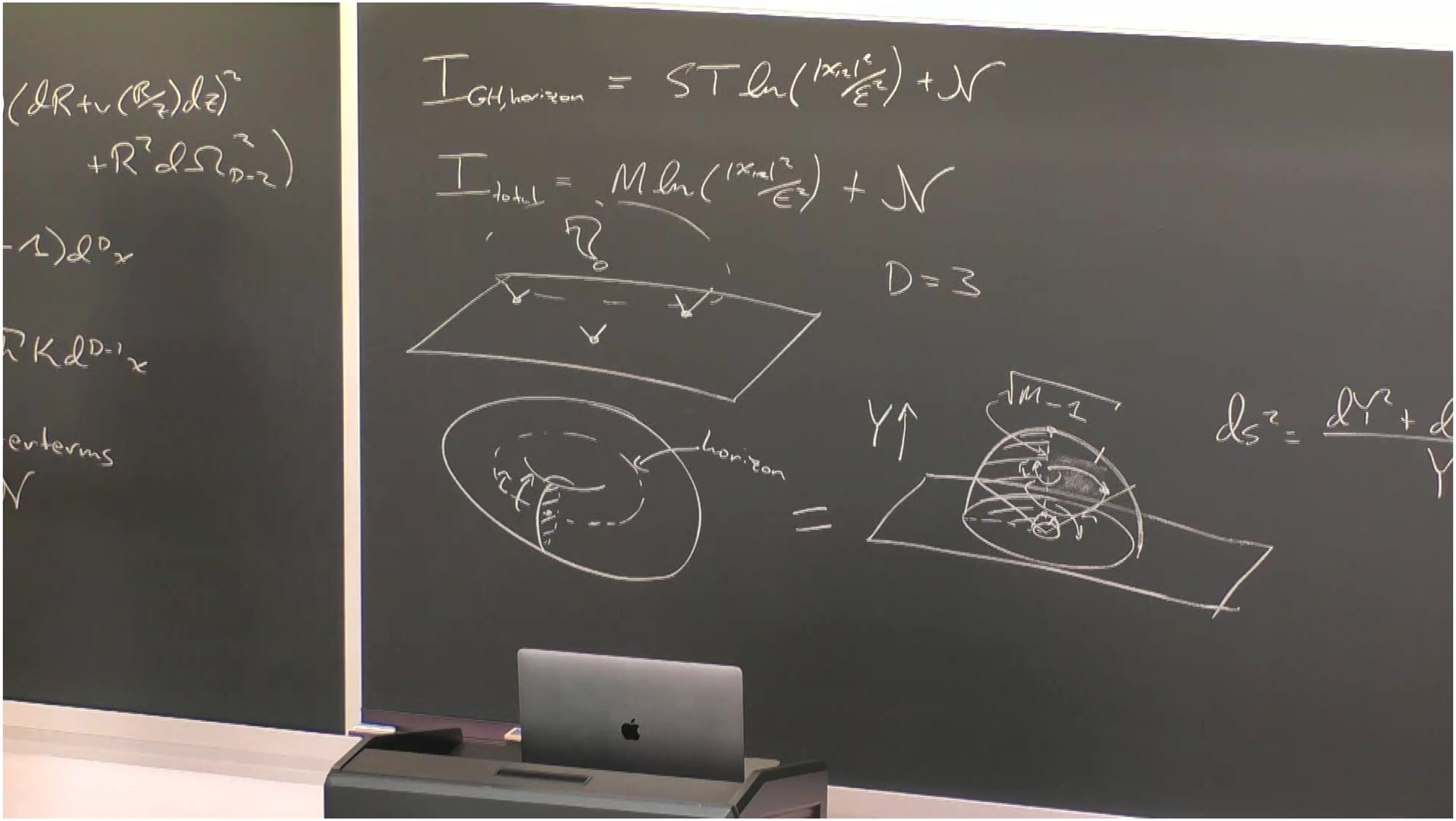


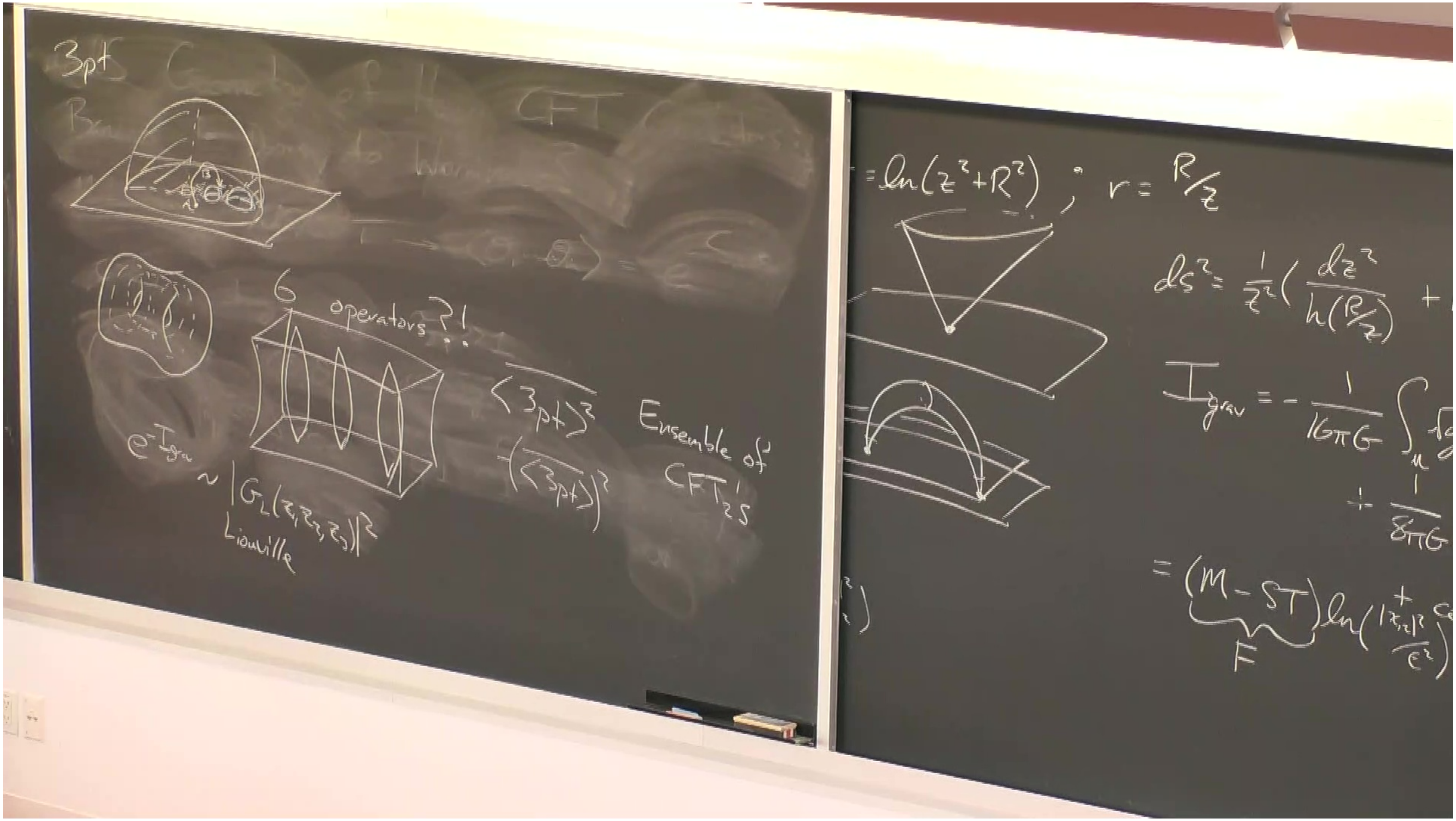
$\tau \sim \tau + \beta$
$\beta = \frac{4\pi}{f'(r_h)}$
stretched horizon
$\tau = \ln(z^2+R^2)$ ; $r = R/z$
$ds^2 = \frac{1}{z^2}\left(\frac{dz^2}{h(R/z)} + h(R/z)(dR + v(R/z)dz)^2 + R^2 d\Omega_{D-2}^2\right)$
$I_{grav} = -\frac{1}{16\pi G}\int_M \sqrt{g}(R-1)d^Dx + \frac{1}{8\pi G}\int_{\partial M}\sqrt{h}K d^{D-1}x$ + counterterms
$= (M - ST)\ln\left(\frac{|x_{12}|^2}{\epsilon^2}\right) + N$
F

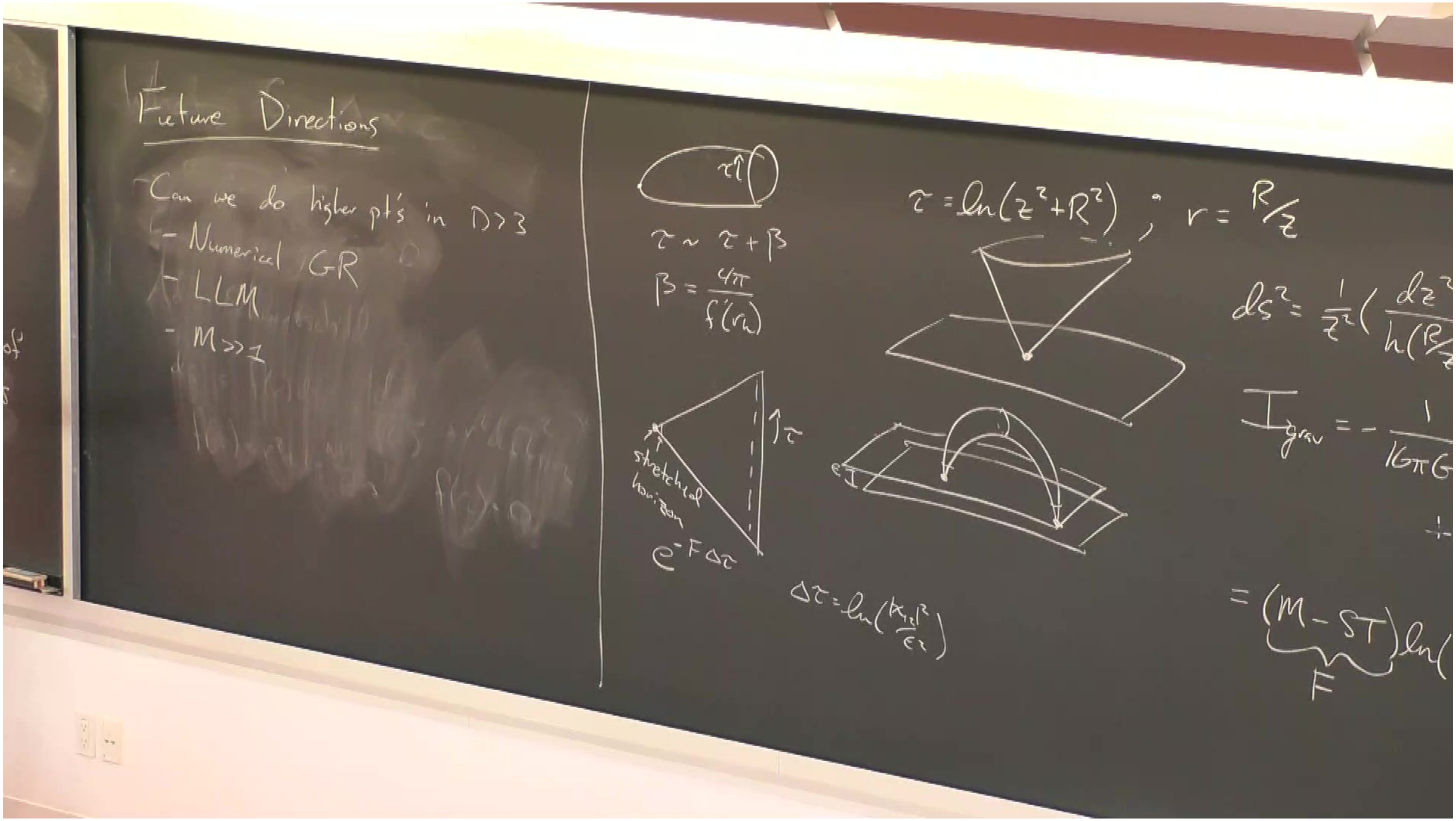

if Δ ∝ c
reaction
gravity Λ < 0
Schwarzschild
stretched horizon
I_GH,horizon = S T ln(|x12|²/ε²) + N
I_total = M ln(|x12|²/ε²) + N
D = 3
horizon
Y
ds² = (dY² + dz dz̄)/Y²

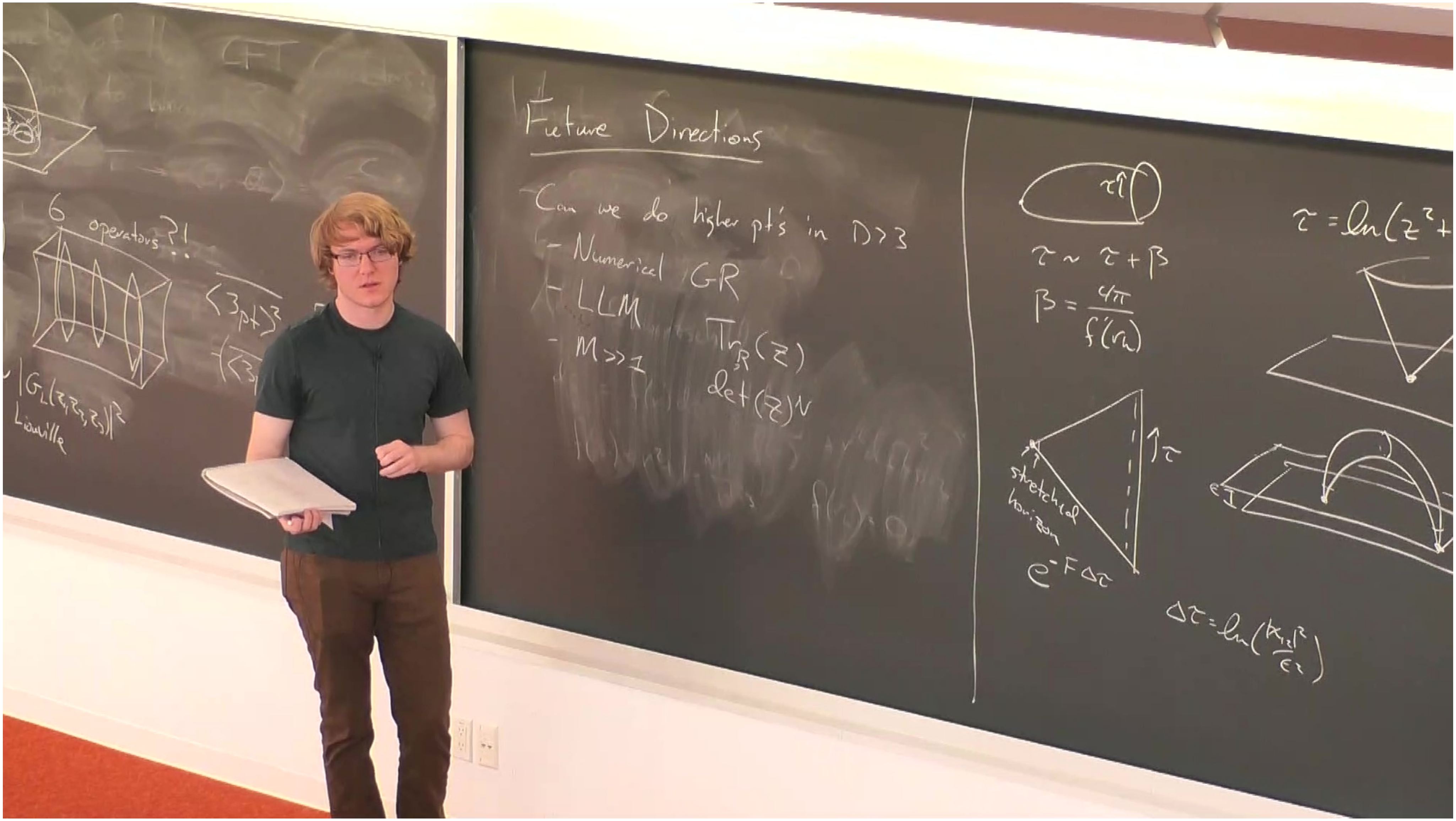


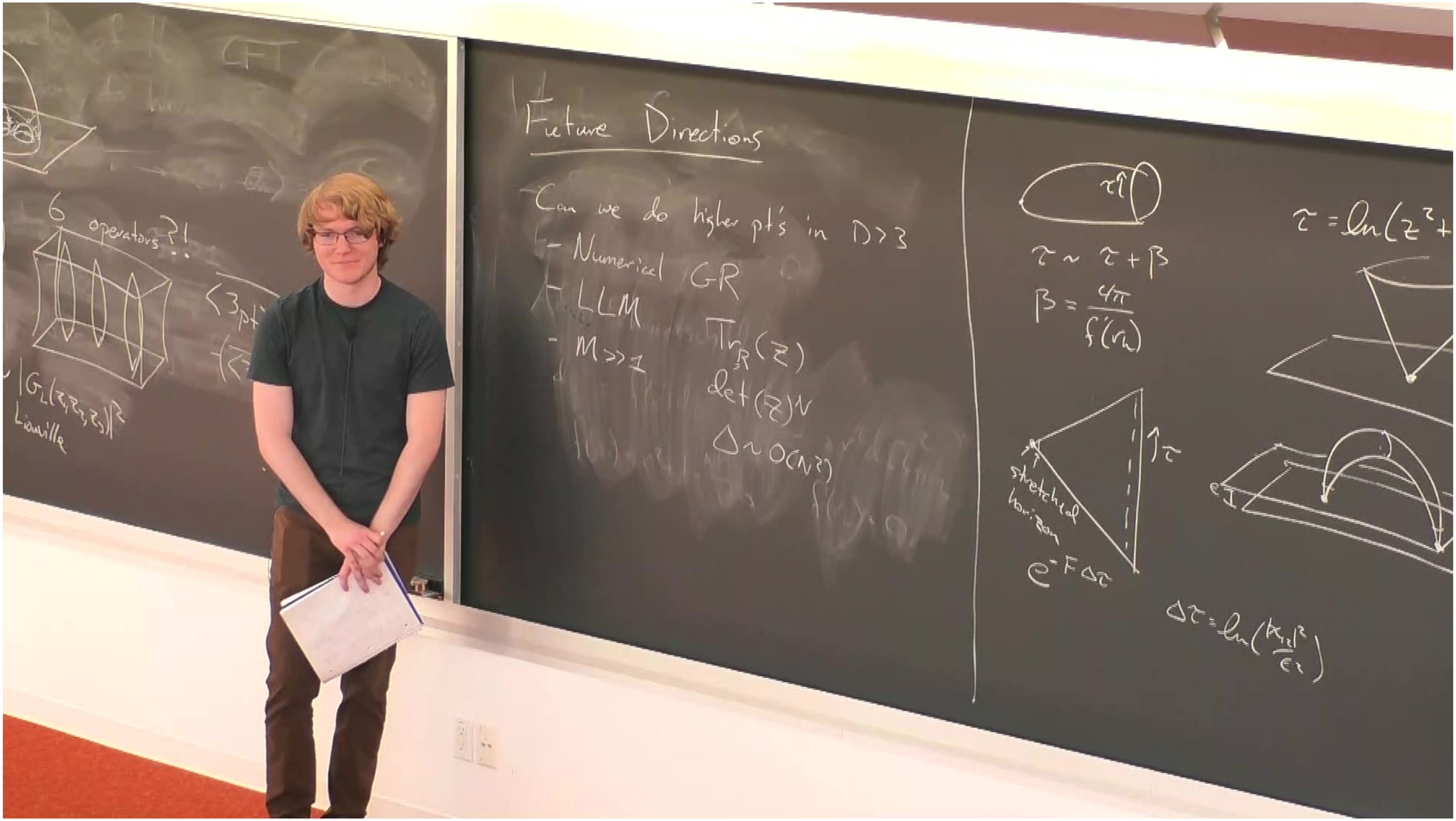
$I_{GH,horizon} = ST \ln\left(\frac{|x_{12}|^2}{\epsilon^2}\right) + \mathcal{N}$
$I_{total} = M \ln\left(\frac{|x_{12}|^2}{\epsilon^2}\right) + \mathcal{N}$
D = 3
horizon
$ds^2 = \frac{dY^2 + dz d\bar{z}}{Y^2}$
Schwarzschild


I_GH,horizon = ST ln(|x12|²/ε²) + N
I_total = M ln(|x12|²/ε²) + N
D = 3
horizon
Y
√M − 1
ds² = dY² + d
Y
+R² dΩ²_D−2)
Kd^D−1 x
erterms


3pt
CFT
6 operators ?!
$\overline{\langle 3pt \rangle^2}$
$-(\overline{\langle 3pt \rangle})^2$
Ensemble of CFT$_2$'s
$e^{-I_{grav}} \sim |G_L(z_1,z_2,z_3)|^2$
Liouville
$= \ln(z^2+R^2)$ ; $r = R/z$
$ds^2 = \frac{1}{z^2}\left(\frac{dz^2}{h(R/z)} + \right.$
$I_{grav} = -\frac{1}{16\pi G}\int_M$
$+ \frac{1}{8\pi G}$
$= (M - ST)\ln\left(\frac{|x_{12}|^2}{\epsilon^2}\right)$
F


Future Directions
- Can we do higher pt's in D>3
- Numerical GR
- LLM
- M>>1
τ ~ τ + β
β = 4π / f'(r_h)
stretched horizon
e^{-FΔτ}
Δτ = ln(|x_{12}|^2 / ε^2)
τ = ln(z^2+R^2) ; r = R/z
ds^2 = 1/z^2 ( dz^2 / h(R/z)
I_grav = - 1 / 16πG
= (M - ST) ln(
F


Future Directions
- Can we do higher pt's in D>3
- Numerical GR
- LLM
- M >> 1
Tr_R(Z)
det(Z)^N
6 operators?!
⟨3pt⟩²
Liouville
τ ~ τ + β
β = 4π / f'(r_h)
stretched horizon
e^{-FΔτ}
Δτ = ln(|x_12|² / ε²)
τ = ln(z² +


Future Directions
Can we do higher pt's in D>3
- Numerical GR
- LLM
- M >> 1
Tr_R(Z)
det(Z)^N
Δ ~ O(N²)
τ ~ τ + β
β = 4π / f'(r_h)
stretched horizon
e^-FΔτ
Δτ = ln(|x_12|²/ε²)
τ = ln(z² +
6 operators ?!
⟨3pt⟩
|G_L(z_1,z_2,z_3)|²
Liouville
CFT