Title: Dynamical Emergence of Universal Horizons during the formation of Black Holes

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Abstract: In many theories with fundamental preferred frame, such as Einstein-Aether or Gravitational Aether theories, K-essence, Cuscuton theory, Shape Dynamics, or (non-projectable) Horava-Lifshitz gravity, the low energy theory contains a fluid with superluminal or incompressible excitations. In this talk, I study the formation of black holes in the presence of such a fluid. In particular, I focus on the incompressible limit of the fluid (or Constant Mean Curvature foliation) in the space-time of a spherically collapsing shell within an asymptotically cosmological space-time. In this case, I show that an observer inside 3/4 of the Schwarzschild radius cannot send a signal outside, after a stage in collapse, even using signals that propagate infinitely fast in the preferred frame. This confirms the dynamical emergence of universal horizons that have been previously found in static solutions [arXiv:1110.2195, arXiv:1104.2889, arXiv:1212.1334].

Dynamical Emergence of Universal Horizons during the formation of Black Holes

Mehdi Saravani
Perimeter Institute
arXiv:1310.4143 with N. Afshordi and R. B. Mann

1-minute summary

- Light (luminal) signals cannot escape event horizon of black holes (BH). What about super-luminal signals? They probably can.
- If there were superluminal signals, would BHs be "black"? It seems the answer is still yes!

  Otherwise the classical theory would be unpredictable (naked singularity)

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- We show emergence of universal horizon in a dynamical setting.

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Outline

- Invitation: theories with superluminal excitations
- Signal propagation on a curved background
- Emergence of universal horizon in collapse of a spherical shell
- Concluding remarks

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Superluminal excitations

Example 1)

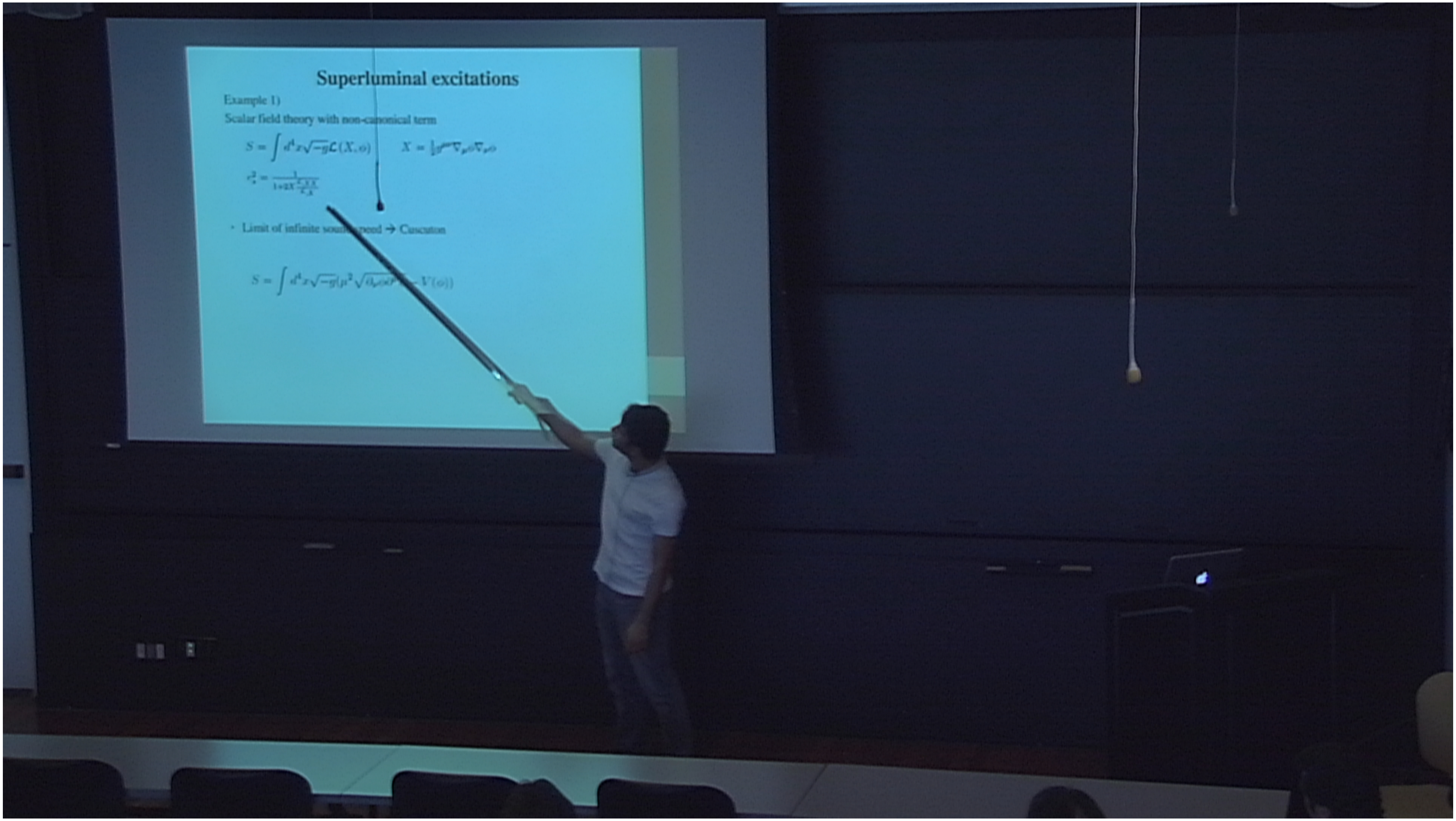
Scalar field theory with non-canonical term

$$S = \int d^4x\sqrt{-g}\mathcal{L}\left(X, \phi\right) \qquad X = \tfrac{1}{2}g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi$$

$$c_s^2 = \frac{1}{1+2X\frac{\mathcal{L}_{,XX}}{\mathcal{L}_{,X}}}$$

- Limit of infinite sound speed → Cuscuton

$$S = \int d^4x\sqrt{-g}(\mu^2\sqrt{\partial_\nu\phi\partial^\nu\phi} - V(\phi))$$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Superluminal excitations

Example 2)

Einstein-aether (EA) theories

- u is constrained to be a unit time-like vector.

$$S = -\frac{1}{16\pi G}\int \sqrt{-g}\,\left(R + K^{ab}_{mn}\nabla_a u^m \nabla_b u^n\right)\,d^4x$$

$$K^{ab}_{mn} = c_1 g^{ab} g_{mn} + c_2 \delta^a_m \delta^b_n + c_3 \delta^a_n \delta^b_m + c_4 u^a u^b g_{mn}$$

- Experimental constraints imply that aether disturbances must propagate (super)luminally.

J. W. Elliott, G. D. Moore, and H. Stoica, Constraining the new Aether: Gravitational Cerenkov radiation, [arxiv:hep-ph/0505211].

Superluminal excitations

Example 3)

Horava-Lifshitz (HL) gravity

- IR limit of HL is equivalent to EA with hypersurface orthogonal vector field.
  T. Jacobson, Extended Horava gravity and Einstein-aether theory, [arXiv:1001.4823].

- IR limit of Non-projectable HL is equivalent to Cuscuton gravity.
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- EA ⟷ (IR) Non-projectable HL ⟷ Cuscuton

  $c_2 = \lambda - 1$ $\qquad$ $\mu^2 = -V''(\phi) = \dfrac{\lambda - 1}{16\pi G_N}$

- In this limit, perturbations propagate infinitely fast.

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Signal Propagation on a Curved Background

- Consider scalar field with the following action

metric signature $(+---)$

$$S = \int d^4x \sqrt{-g}\mathcal{L}(X, \phi) \qquad X = \tfrac{1}{2} g^{\mu\nu}\nabla_\mu \phi \nabla_\nu \phi$$

- g is the metric of background spacetime.

E. Babichev et al. [arXiv:0708.0561]

- It satisfies

$$\tilde{G}^{\mu\nu}\nabla_\mu\nabla_\nu\phi + 2X\mathcal{L}_{,X\phi} - \mathcal{L}_{,\phi} = 0 \qquad \tilde{G}^{\mu\nu} = \mathcal{L}_{,X} g^{\mu\nu} + \mathcal{L}_{,XX}\nabla^\mu\phi\nabla^\nu\phi$$

- Linear perturbations π satisfy

$$\frac{1}{\sqrt{-G}}\partial_\mu\left(\sqrt{-G}G^{\mu\nu}\partial_\nu\pi\right) + M_{eff}^2\pi = 0$$

$$G^{\mu\nu} = \frac{c_s}{\mathcal{L}_{,X}^2}\tilde{G}^{\mu\nu}, \ \left(G^{-1}\right)_{\mu\nu} G^{\nu\rho} = \delta_\mu^\rho \ , \ \sqrt{-G} = \sqrt{-det\left(G^{-1}\right)_{\mu\nu}}$$

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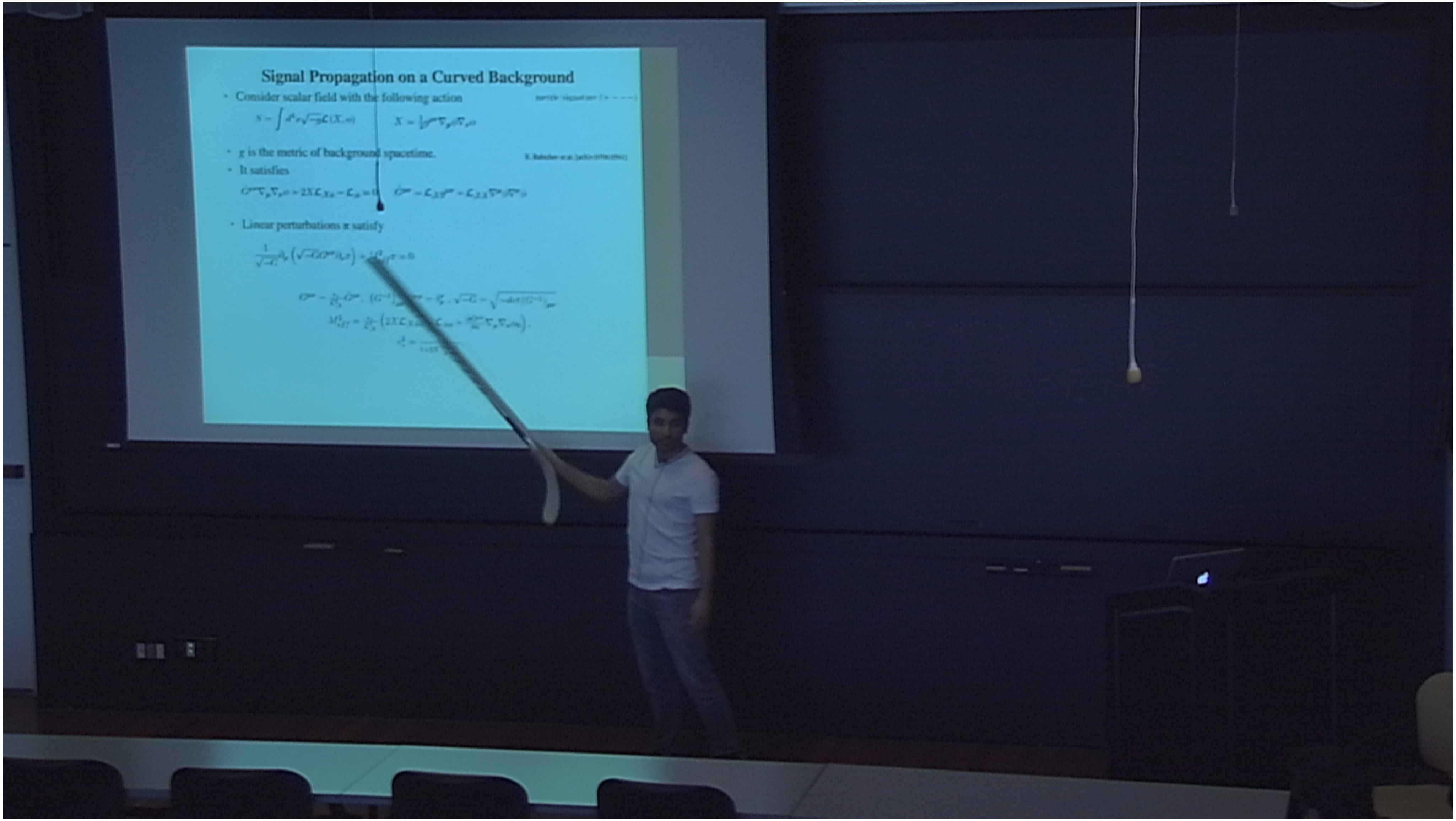
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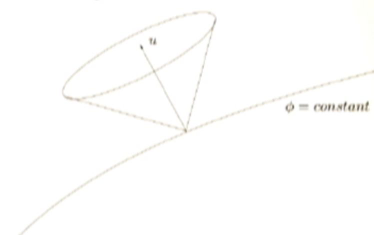
- Linear perturbations satisfy Klein-Gordon equation with effective metric *G*. As a result, propagation cone is given by the effective metric *G*.

$$\left(G^{-1}\right)_{\mu\nu} = \frac{\mathcal{L}_{,X}}{c_s}\left(g_{\mu\nu} - c_s^2 \frac{\mathcal{L}_{,XX}}{\mathcal{L}_{,X}} \nabla_\mu \phi_0 \nabla_\nu \phi_0\right)$$

- At any point, perturbations propagate inside the cone defined by vectors "*v*" that are null with respect to *G*

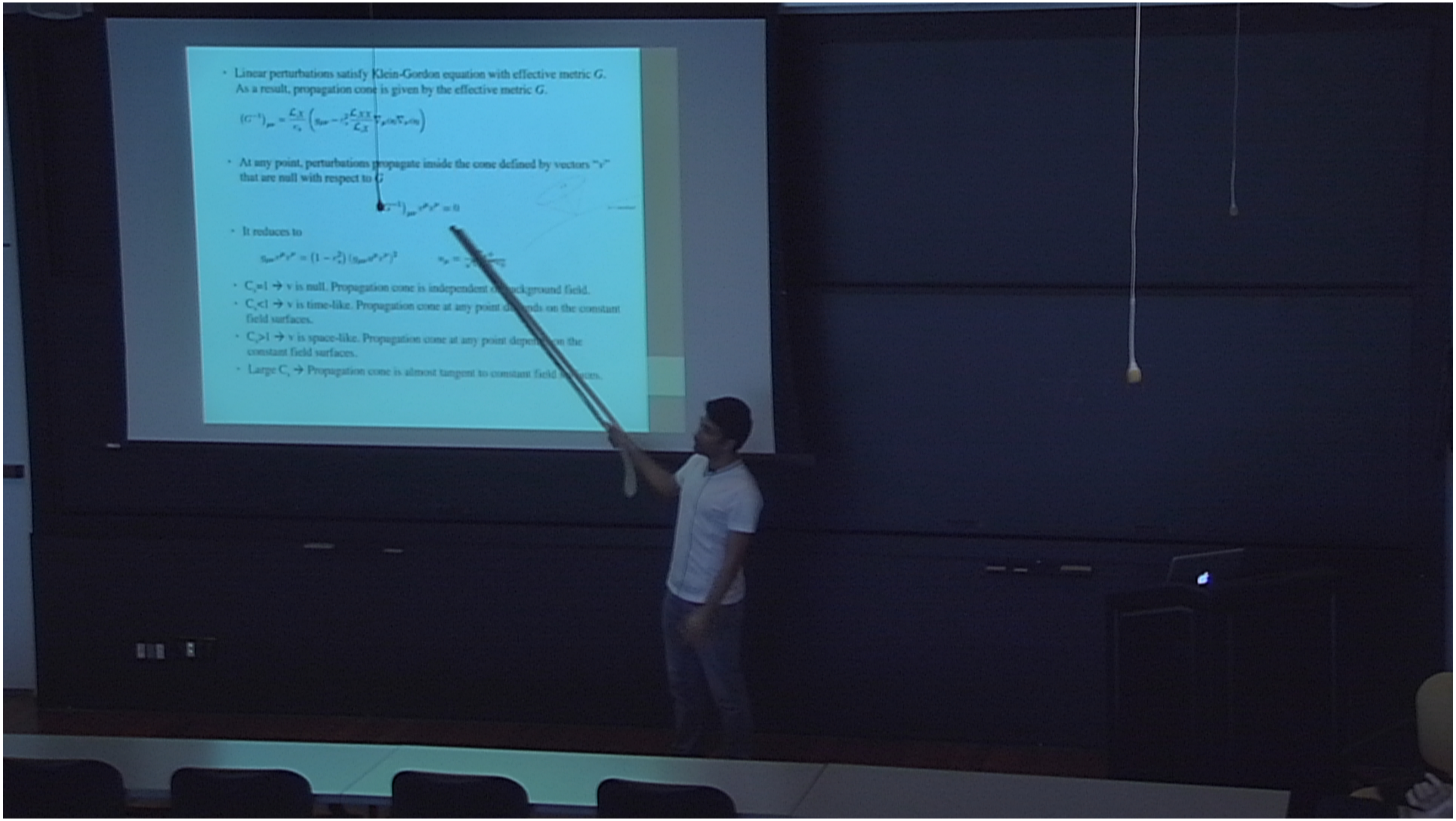


$$\left(G^{-1}\right)_{\mu\nu} v^\mu v^\nu = 0$$

- It reduces to

$$g_{\mu\nu} v^\mu v^\nu = \left(1 - c_s^2\right)\left(g_{\mu\nu} u^\mu v^\nu\right)^2 \qquad u_\mu = \frac{\nabla_\mu \phi}{\sqrt{\nabla_\alpha \phi \nabla^\alpha \phi}}$$

- C_s=1 → v is null. Propagation cone is independent of background field.
- C_s<1 → v is time-like. Propagation cone at any point depends on the constant field surfaces.
- C_s>1 → v is space-like. Propagation cone at any point depends on the constant field surfaces.
- Large C_s → Propagation cone is almost tangent to constant field surfaces.



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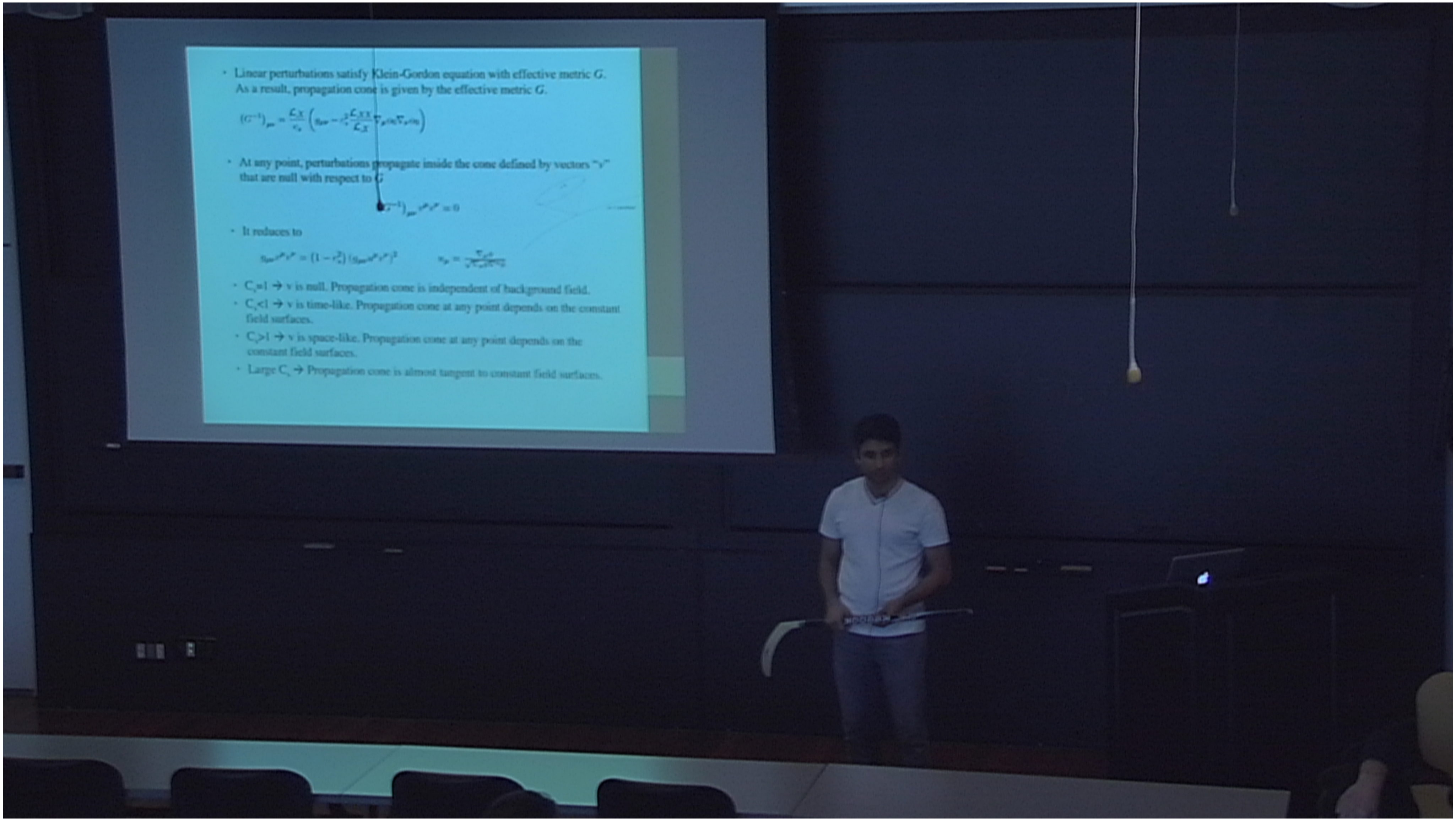

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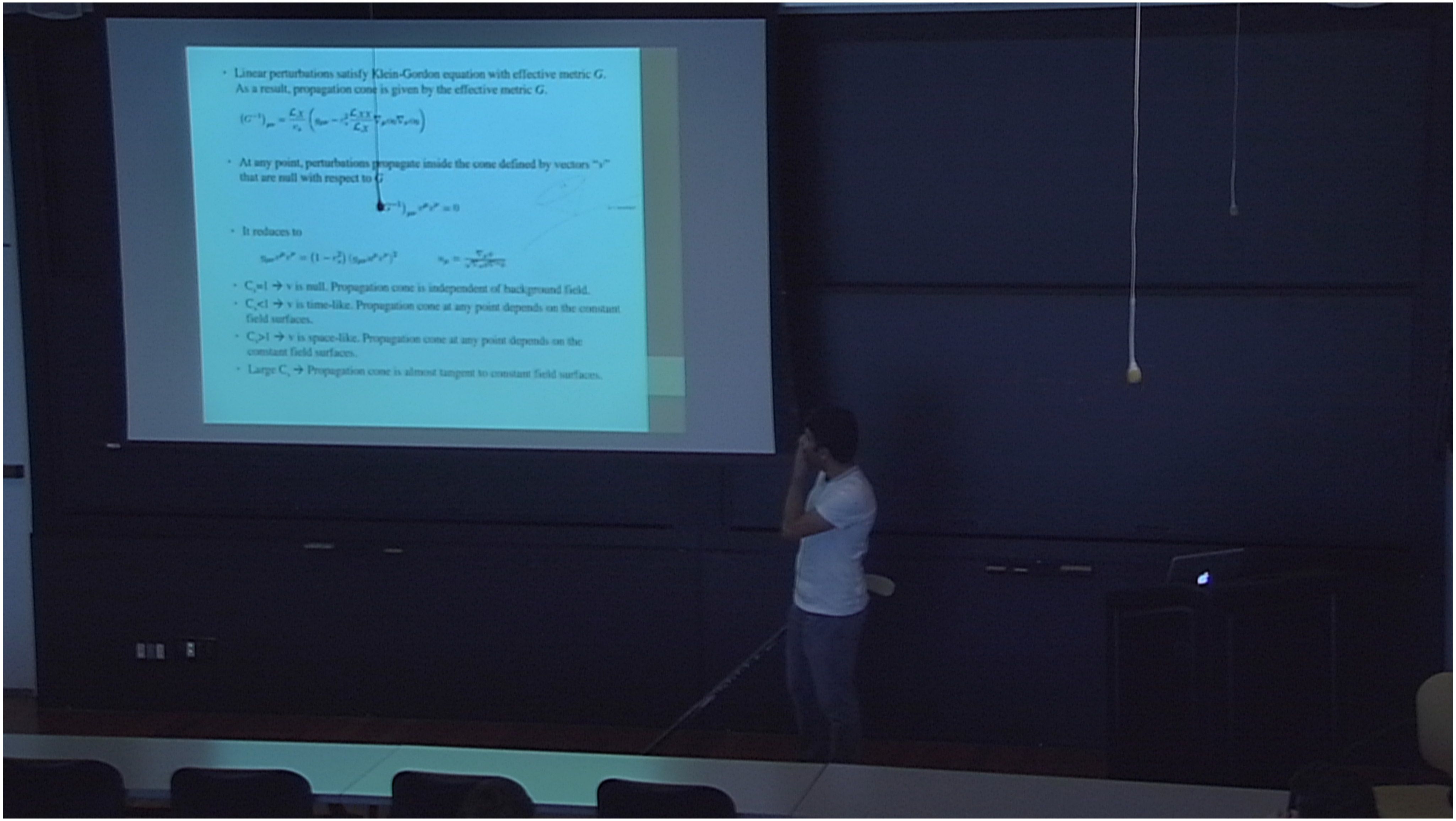
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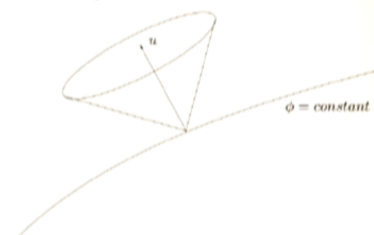

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Choosing the Lagrangian to be

$$\mathcal{L} = aX^n - V(\phi)$$

where n is very close to 1/2

$$n = \frac{1}{2}(1 + \epsilon^2)$$

up to first order in ε, we get

Background field equation → $$\frac{a\sqrt{2}}{2}\nabla_\mu u^\mu + V'(\phi) = 0 \qquad u_\mu = \frac{\nabla_\mu \phi}{\sqrt{\nabla_\alpha \phi \nabla^\alpha \phi}}$$

Propagation cone → $$u_\mu v^\mu = \epsilon$$

More on Cuscuton

- Perfect fluid with the following energy-momentum tensor

$$T_{\mu\nu} = (\rho + p)\, u_\mu u_\nu - p\, g_{\mu\nu}$$

$$\rho = V(\phi)$$
$$p = a\sqrt{X} - V(\phi)$$
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- EOM from last page $K = u^\alpha{}_{;\alpha} = -\frac{\sqrt{2}}{a} V'(\phi)$

Mean extrinsic curvature

- Constant field surfaces ⟷ Comoving surfaces ⟷ CMC (constant mean curvature) surfaces

- Ignoring backreaction (verify later), we only need to find CMC surfaces of the background spacetime.

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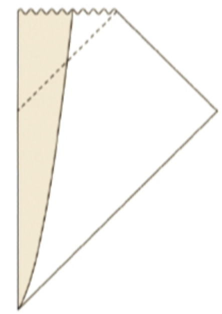
- Background spacetime: spherical thin shell collapse

$$\mathrm{I}: ds^2 = A^2(t)dt^2 - dr^2 - r^2 d\Omega^2,\ r < R(t)$$

$$\mathrm{II}: ds^2 = f(r)dt^2 - \frac{dr^2}{f(r)} - r^2 d\Omega^2,\ r > R(t)$$

$$f(r) = 1 - \frac{2M}{r}$$



- Shell at r=R(t)
- R=R(t) satisfies the geodesic equation

$$\dot{R} = -f(R)\sqrt{1 - \frac{f(R)}{e^2}} \qquad \cdot = \frac{d}{dt}$$

- A(t) is given by the continuity of the induced metric on shell surface.

$$A = f(R)\sqrt{1 + \frac{2M}{e^2 R}}$$

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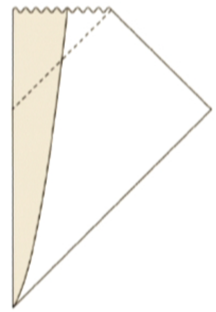

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CMC surfaces: $K = \nabla_\mu u^\mu$

- Region I

$$u_I^r = \frac{K}{3} r$$

$$u_I^t = \frac{\sqrt{(\frac{Kr}{3})^2 + 1}}{A}$$

- Region II

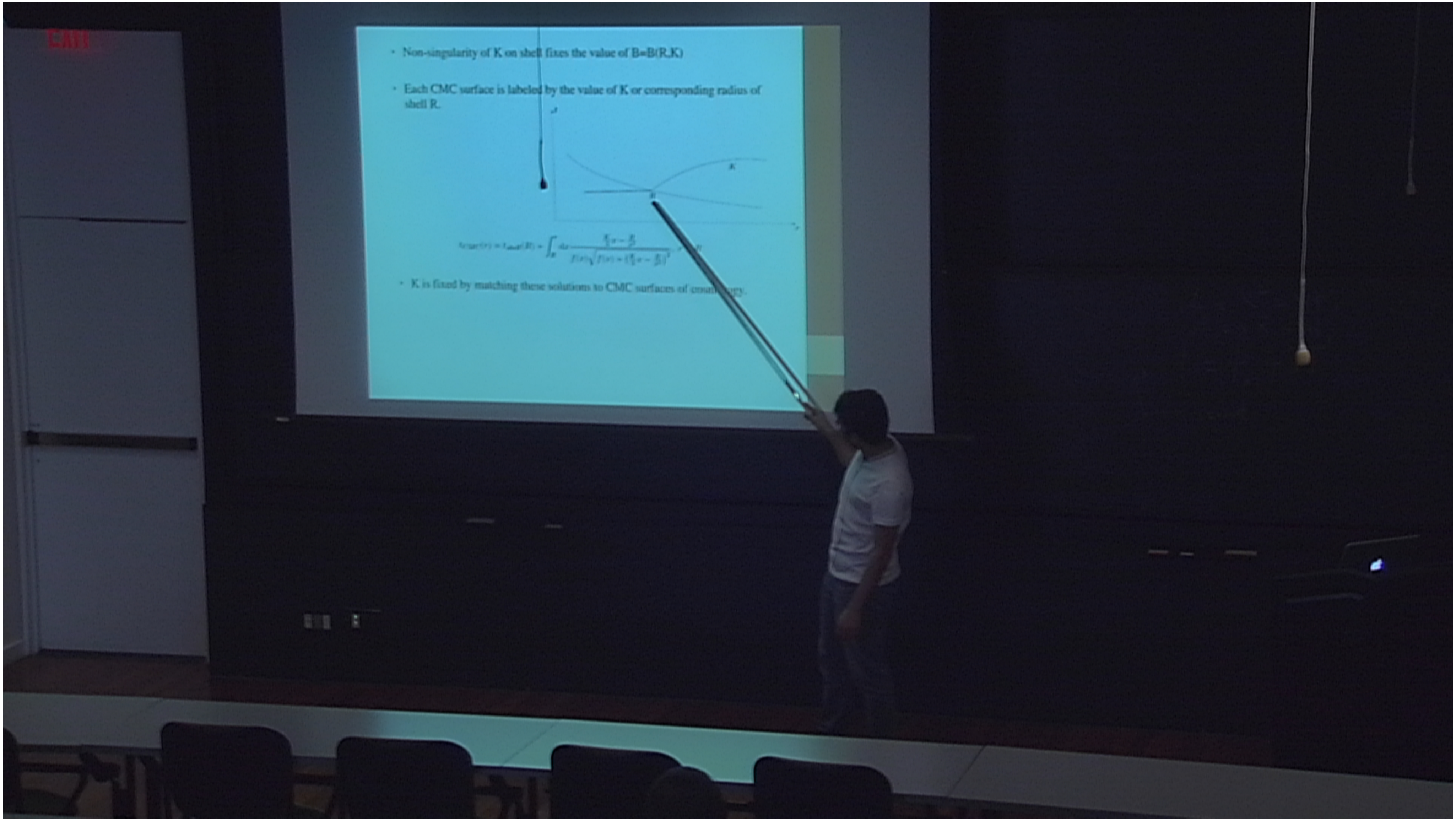
Constant of integration, fixed by matching conditions

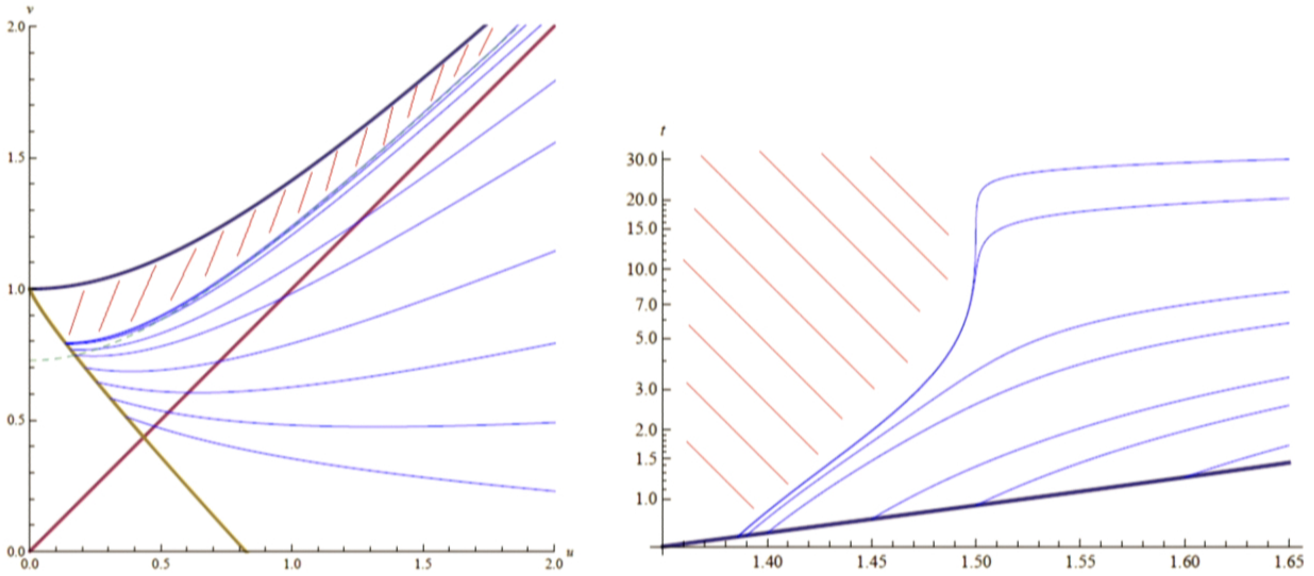
$$u_{II}^r = \frac{K}{3} r - \frac{B}{r^2}$$

$$u_{II}^t = \frac{1}{f(r)} \sqrt{(\frac{K}{3} r - \frac{B}{r^2})^2 + f(r)}$$

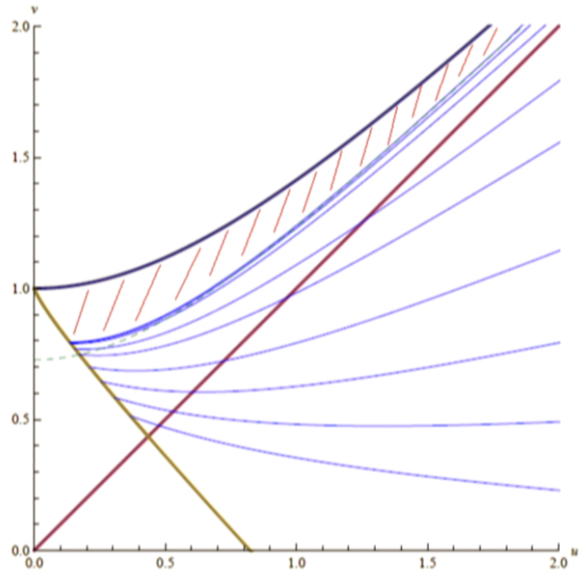
$$t_{CMC} = T(r) \qquad T'(r) = \frac{\frac{K}{3} r - \frac{B}{r^2}}{f(r)\sqrt{f(r) + \left(\frac{K}{3} r - \frac{B}{r^2}\right)^2}}$$

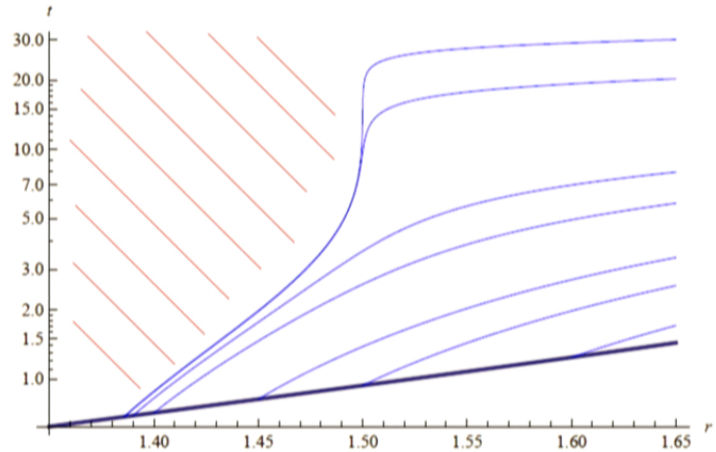
- B is constant on each surface, fixed by matching conditions.


Non-singularity of K on shell fixes the value of B=B(R,K)
Each CMC surface is labeled by the value of K or corresponding radius of shell R.
K is fixed by matching these solutions to CMC surfaces of

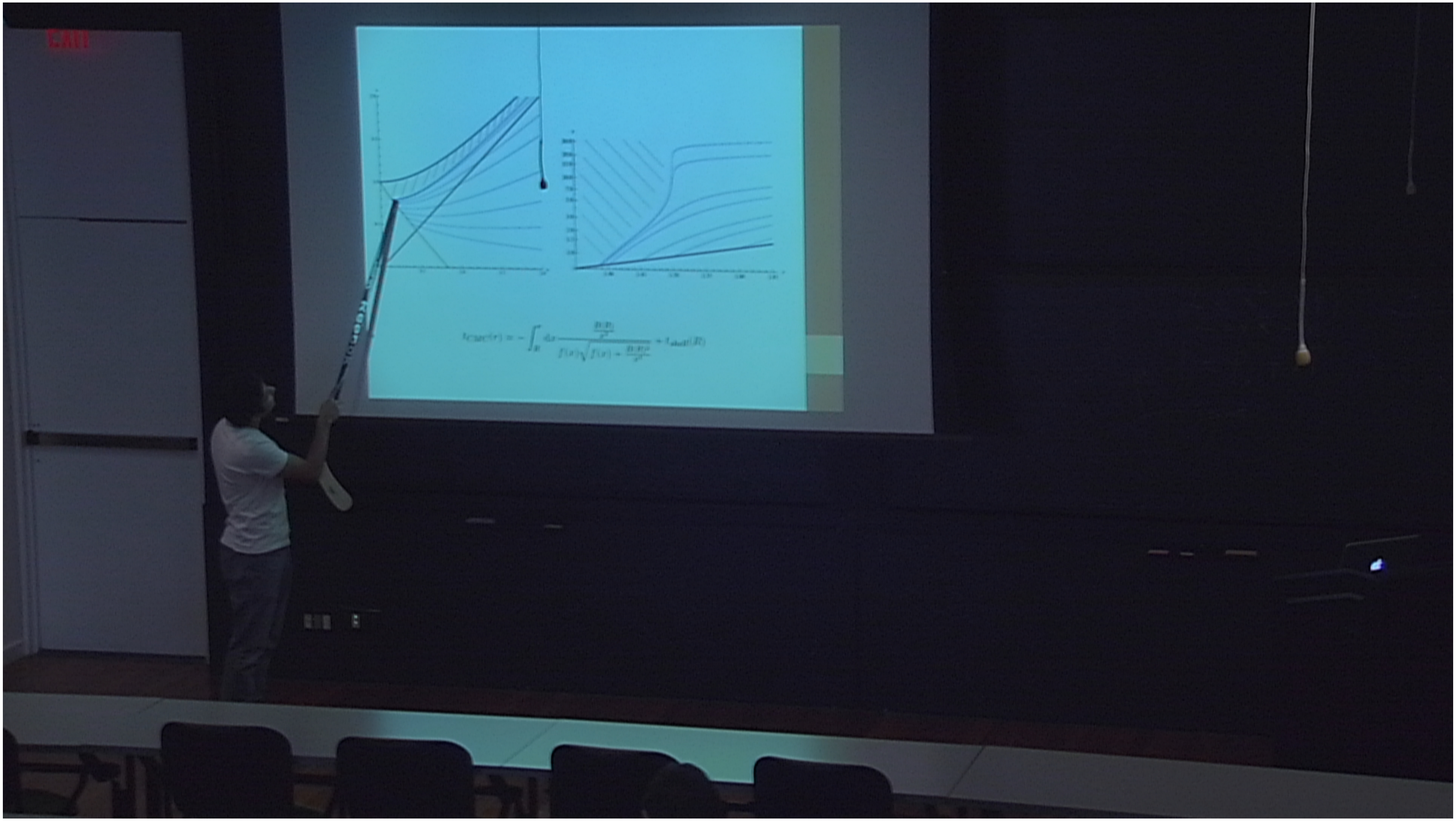


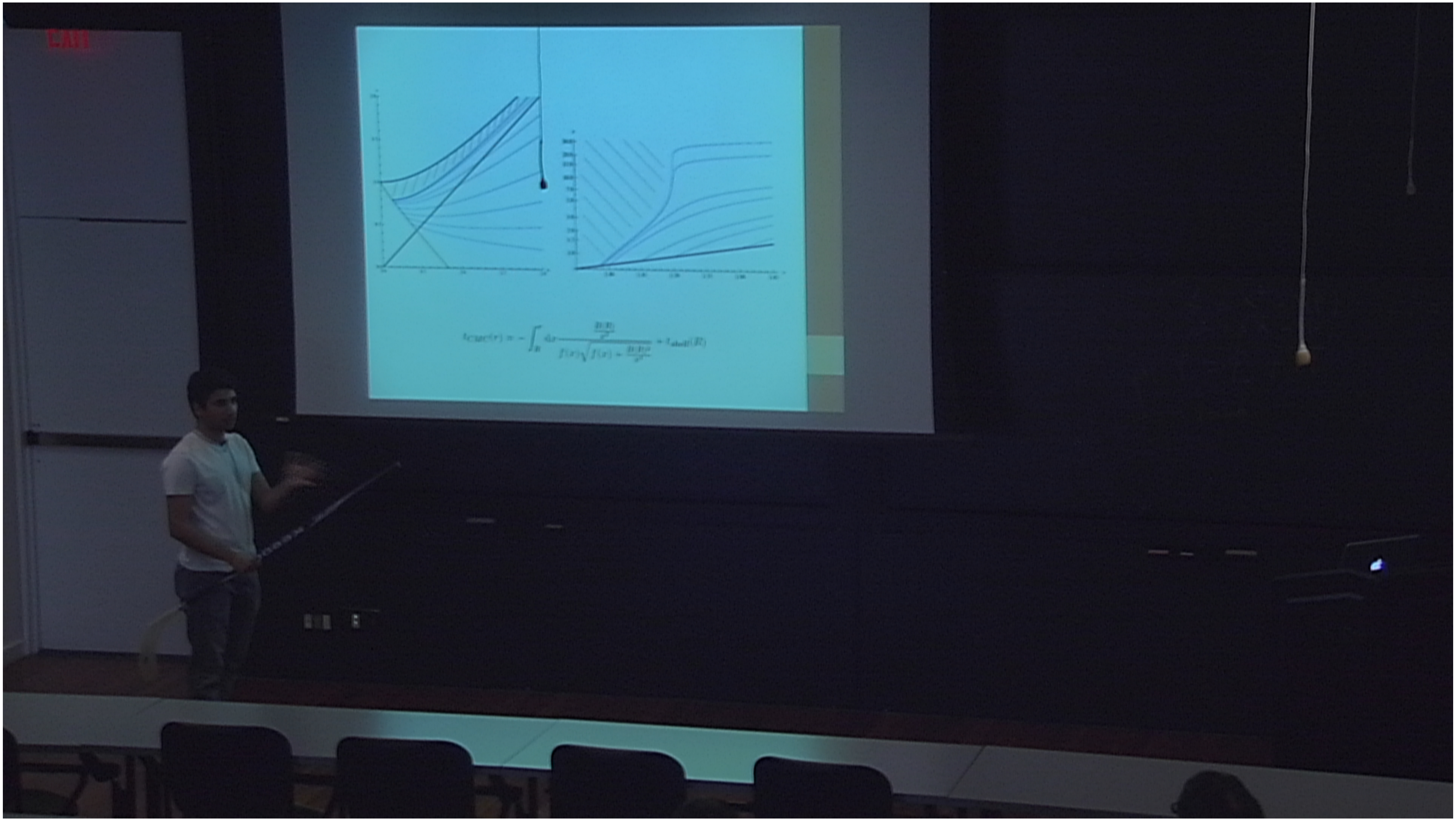
$$t_{CMC}(r) = -\int_R^r \mathrm{d}x \frac{\frac{B(R)}{x^2}}{f(x)\sqrt{f(x) + \frac{B(R)^2}{x^4}}} + t_{shell}(R)$$





$$t_{CMC}(r) = -\int_R^r \mathrm{d}x \frac{\frac{B(R)}{x^2}}{f(x)\sqrt{f(x) + \frac{B(R)^2}{x^4}}} + t_{shell}(R)$$



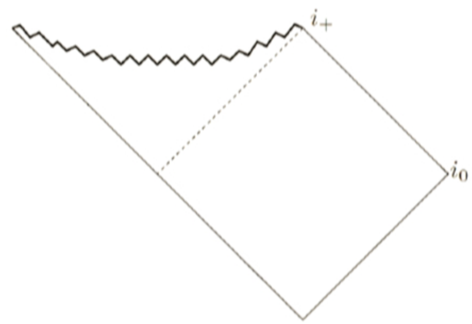


Concluding remarks

- This result is independent of the initial conditions (initial position of shell, value of e, …)
- Cuscuton's energy density and pressure remains small everywhere (suppressed by Hubble constant) → universal horizon is regular.
- Aspherical perturbations may change universal horizon to a singular surface.

D. Blas and S. Sibiryakov, Horava gravity versus thermodynamics: The Black hole case, [arXiv:1110.2195].

- We argue that this universal horizon should be considered as the future boundary of the classical space-time.

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