

Title: Lessons from Thermodynamics with Lambda

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Collection: Everpresent Lambda: Theory Meets Observations

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BH TDS WITH Λ

1) MOTIVATION

$$ds^2 = -f dt^2 + \frac{dr^2}{f} + r^2 d\Omega^2$$

$$f = 1 - \frac{2M}{r} + \frac{Q^2}{r^2}$$

SCALING (EULER'S) ARGUMENT

$$T = \frac{\rho}{4\pi}, \quad S = \frac{A}{4} = \pi r_+^2$$
$$\Phi = \frac{Q}{r_+}$$

$$\boxed{\begin{aligned} dM &= T dS + \Phi dQ \\ M &= 2TS + \Phi Q \end{aligned}}$$

1ST

SMARR

SCALING (EULER'S) ARGUMENT

$$\Pi = \alpha \Pi S + \phi Q$$

SMARR

$$M = \Pi(S, Q)$$

$$\Rightarrow (\dim M) M = (\dim S) \frac{\partial M}{\partial S} S + (\dim Q) \frac{\partial M}{\partial Q} Q$$

SCALING (EULER'S) ARGUMENT

$$M = 2TS + \Phi Q$$

SMARR

$$M = M(S, Q)$$

$$\Rightarrow (\underbrace{\dim M}_1) M = (\underbrace{\dim S}_2) \underbrace{\frac{\partial M}{\partial S}}_T S + (\underbrace{\dim Q}_1) \underbrace{\frac{\partial M}{\partial Q}}_\Phi Q$$

• AdS:

$$f = 1 - \frac{2M}{r} + \frac{Q^2}{r^2} + \frac{r^2}{l^2}$$

$$dM = TdS + \Phi dQ$$

$$M \neq 2TS + \Phi Q$$

SCALING (EULER'S) ARGUMENT

$$M = 2TS + \Phi Q$$

SMARR

$$M = M(S, Q)$$

$$\Rightarrow (\underbrace{\dim M}_1) M = (\underbrace{\dim S}_2) \underbrace{\frac{\partial M}{\partial S}}_T S + (\underbrace{\dim Q}_1) \underbrace{\frac{\partial M}{\partial Q}}_\Phi Q$$

• AdS:

$$f = 1 - \frac{2M}{r} + \frac{Q^2}{r^2} + \frac{r^2}{\ell^2}$$

$$G_{ab} + \Lambda g_{ab} = 8\pi T_{ab}$$

" $-8\pi((g+p)_{\mu\nu} + p g_{\mu\nu})$

$$dM = TdS + \Phi dQ$$

$$M \propto 2TS + \Phi Q$$

$$\Rightarrow P = -\frac{\Lambda}{8\pi} = \frac{3}{8\pi\ell^2}$$

KASTOR & RAY & TRISEREN - 2003

$$dM = TdS + \phi dQ + VdP$$

$$M = 2TS + \phi Q - 2PV$$

KASTOR & RAJ & TRADKEM - 2009

$$dM = TdS + \phi dQ + VdP$$

$$M = 2TS + \phi Q - 2PV$$

MI: YOU NEED TO VARY Δ
SO THAT SMARR IS CONSISTENT
WITH 1ST LAW.

KASTOR & RAY & TRIDIKEN - 2009

$$dM = TdS + \phi dQ + VdP$$

$$M = 2TS + \phi Q - 2PV$$

M1: YOU NEED TO VARY Λ
SO THAT SMARR IS CONSISTENT
WITH 1ST LAW.

M2:

$$V = \frac{\partial M}{\partial P}$$

$$V = \frac{4}{3}\pi r^3$$

KASTOR & RAJ & TRIDIBEN - 2009

$$dM = TdS + \phi dQ + VdP$$
$$M = 2TS + \phi Q - 2PV$$

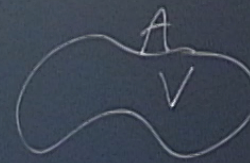
M1: YOU NEED TO VARY Λ
SO THAT SMARR IS CONSISTENT
WITH 1ST LAW.

M2:

$$V = \frac{\partial M}{\partial P}$$

$$V = \frac{4}{3}\pi \Lambda^3$$

BH VOLUME



$$\frac{V^{1/3}}{A^{1/2}} = R \geq 1$$

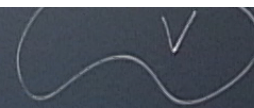
$V_4 \rightarrow \Lambda$... CANONICAL

$V_3 - \Lambda$... TD CONJUGATE

M1: YOU NEED TO VARY Λ
SO THAT SMARR IS CONSISTENT
WITH 1ST LAW.

$V_4 \rightarrow \Lambda$... CANONICAL

$V_3 = \Lambda$... TD CONJUGATE



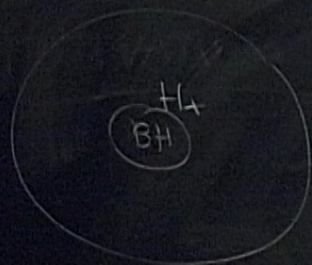
$$\frac{V^{1/3}}{A^{1/2}} = R \geq 1$$

M3:

$$M = U + PV$$

↑
ENTHALPY

2) COSMOLOGICAL SETTING (ds)



$$\ominus dM = T_+ dS_+ + V_+ dP$$

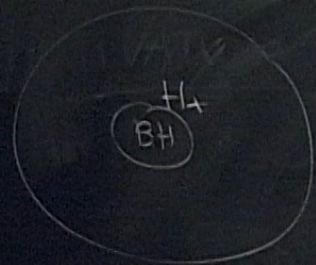
$$\oplus dM = -T_c dS_c + V_c dP$$

↑
POSITIVE TEMP.

$$0 = -T_c dS_c + V_c dP - V_+ dP - T_+ dS_+$$

$$(V_c - V_+) dP = T_c dS_c + T_+ dS_+$$

2) COSMOLOGICAL SETTING (ds)



$$\ominus dM = T_+ dS_+ + V_+ dP$$

$$\oplus dM = -T_c dS_c + V_c dP$$

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POSITIVE TEMP.

$$0 = -T_c dS_c + V_c dP - V_+ dP - T_+ dS_+$$

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TRASCHEH ... 1905?

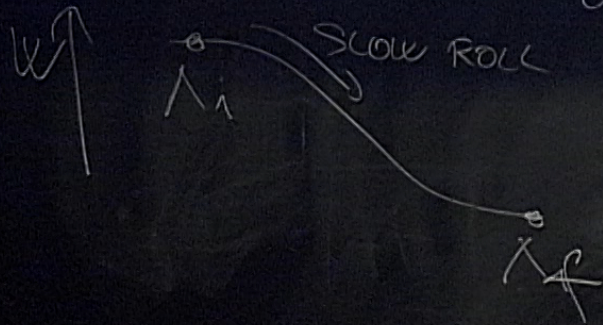
$$0 = -T_- dS_- + V_- dP - V_+ dP - T_+ dS_+$$

$$\boxed{(V_- - V_+) dP = T_- dS_- + T_+ dS_+}$$

TRASCHEIN ... 1905?

V... OBSERVABLE UNIVERSE

DYNAMICAL SETTING

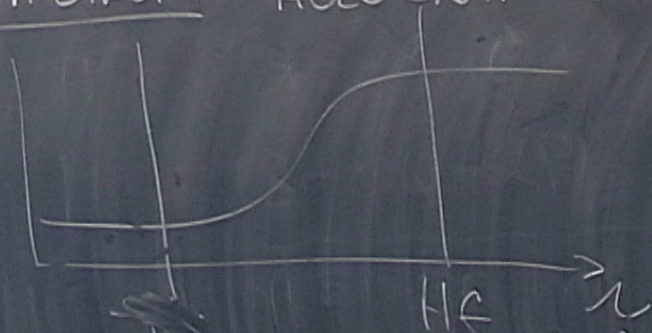


$$\mathcal{L} = R + |\nabla\phi|^2 + W(\phi)$$

$$1707.06586$$

$$f = 1 - \frac{2M(\pi)}{\Lambda} - \frac{\Lambda^2}{Q^2(\pi)}$$

SIMILARLY: HOLOGRAPHIC RG FLOWS



Λ (TEITELBOIM-1985)

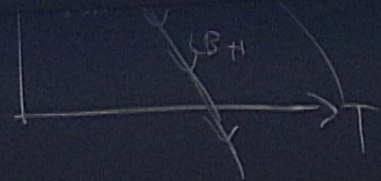
A - 3-FORM

$F = dA$ - 4-FORM

$$\mathcal{L} = R + F_{\alpha\beta\gamma\delta} F^{\alpha\beta\gamma\delta}$$

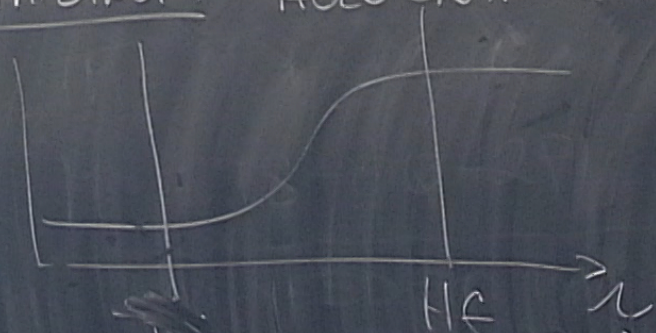
$$F = \text{CONST } e$$

$$\Lambda$$



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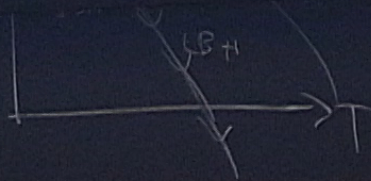
SIMILARLY: HOLOGRAPHIC RG FLOWS



Λ (TEITELBOIM-1985)

A - 3-FORM

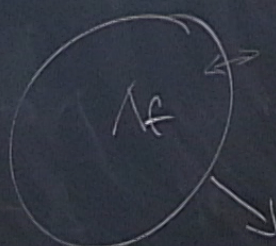
$F = dA$ - 4-FORM



$$\mathcal{L} = R + F \wedge \star F$$

$$F = \text{CONST } \varrho$$

$$\Lambda$$



Λ_i

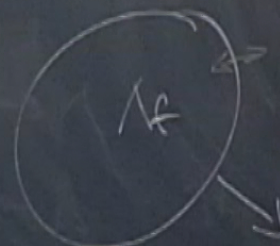
$$\Lambda_f < \Lambda_i$$

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Λ (TEITZELBOIM-1985)

$A \dots$ - 3-FORM

$F = dA \dots$ 4-FORM



$$\Lambda_f < \Lambda_i$$

COMPACTIFICATION: THEORY IN 4d FROM HIGHER-DIM. THEORY BY COMPACT.

$$\Lambda = \frac{3}{8\pi l^2 G_4}$$

$$G_4 = \frac{G_{4+n}}{\text{VOL}(K_n)} \text{ CAN BE TIME DEP.}$$

TORSION APPROACH - 1905, 10380

$$S \propto \int \epsilon_{abcd} \left(\underbrace{\ell^a_{12} \ell^b_{12}}_{\text{G-B TERM}} R^{cd}(\omega) - \underbrace{\frac{\Delta}{6} \ell^a_{12} \ell^b_{12} \ell^c_{12} \ell^d_{12}}_{\text{G-B TERM}} - \frac{3}{2\Delta} R^{ab} \wedge R^{cd} \right)$$

$$\frac{\delta \ell}{\delta \ell}: R^{ab} = \frac{\Delta}{3} \ell^a_{12} \ell^b_{12} \quad DR^{ab} = 0$$

$$\frac{\delta \omega}{\delta \omega}: T^a = -\frac{d\Delta}{\Delta} \ell^a_{12} \nabla_a (G^{ab} + \Lambda g^{ab}) = 0$$

$$\frac{\delta \Lambda}{\delta \Lambda}: 0 = 0 \quad \checkmark$$

• TORSION APPROACH - 1905, 10380