

QUANTUM BLACK HOLES AS HOLOGRAMS

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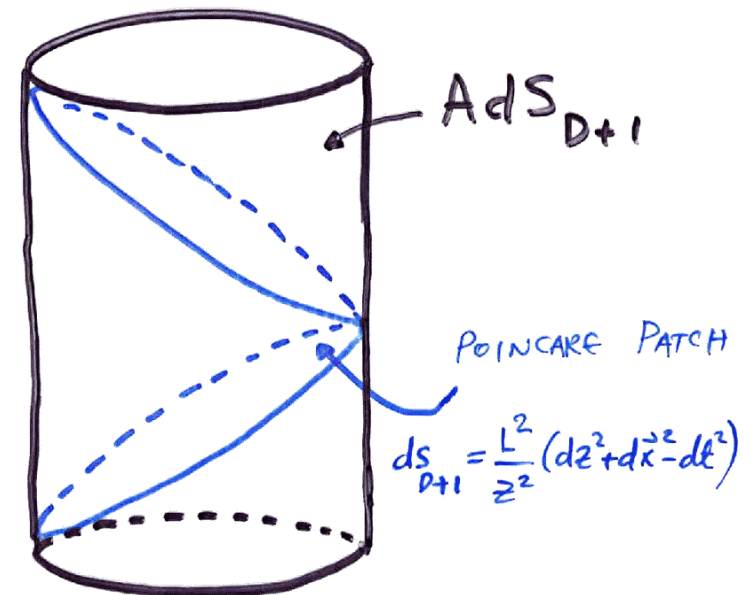
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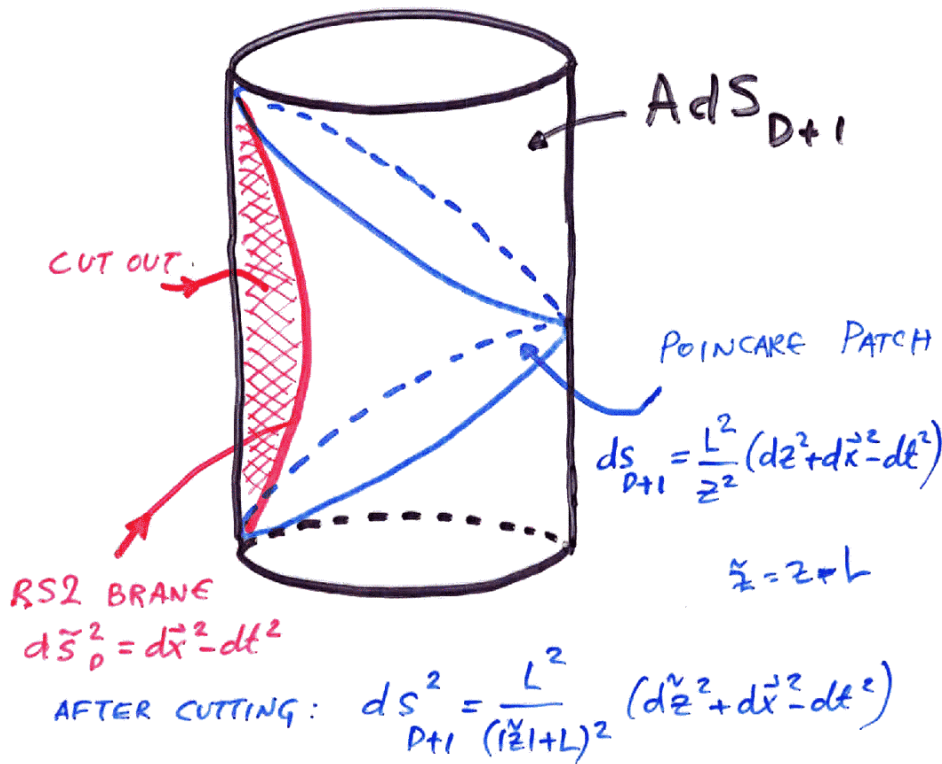
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FOLLOW THE AdS/CFT FRAMEWORK - AS
CLOSELY AS POSSIBLE - GEOMETRICALLY:



RS2

FOLLOW THE AdS/CFT FRAMEWORK - AS CLOSELY AS POSSIBLE - GEOMETRICALLY:



RANDALL & SUNDRUM

DUAL INTERPRETATION

BEFORE CUTTING: AdS/CFT MALDACENA

CLASSICAL WEAK SUPERGRAVITY IN AdS_{D+1} IS DUAL TO QUANTUM SYM_N IN M_D IN THE STRONG COUPLING REGIME TO LEADING ORDER IN 1/N

CLASSICAL BULK CONFIGURATIONS ENCODE QUANTUM EFFECTS TRUNCATED TO PLANAR DIAGRAMS

AFTER CUTTING: AdS/CFT @ CUTOFF μ_{UV} + D-DIM GRAVITY (+ LOCALIZED GAUGE THEORY...)

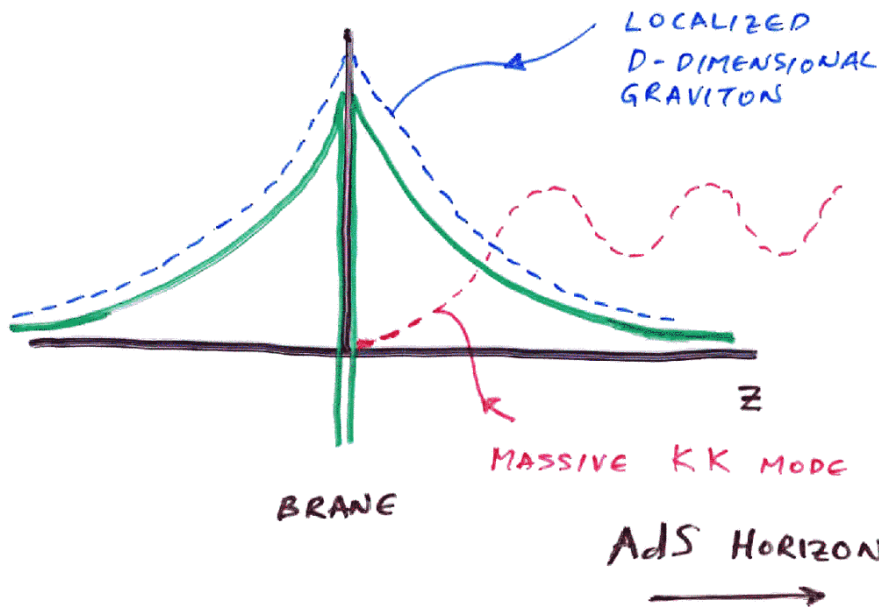
PUT IN μ_{UV} ~ $\frac{\hbar}{L_{\text{ADS}}}$ & INTEGRATE OUT CFT ABOVE IT

PUT IN D-DIM GRAVITY: M_D^{D-2} ≈ M_{D+1}^{D-1} L_{ADS}

PUT IN δ-FUNCTION MATTER

MALDACENA
WITTEN
GUBSER
VERLINDE
ARKANI-HAMED ET AL ...

CUTOFF CFT DEFINED BY THE BULK DUAL: SMALL FLUCTUATIONS OF BULK FIELDS IN THE VOLCANO



MASSIVE KK MODE \simeq CFT STATE AT ENERGY $\sim m$

$g_{\text{BRANE-CFT}} \sim mL$

TUNNELING SUPPRESSION
RANDALL & SUNDRUM;
 DIMOPOULOS, KACHRU, DE LUZENCE,
 SILVERSTEIN

LINEARIZED GRAVITY

$$V(r) = -\frac{G_4 M}{r} \left(1 + \frac{2}{3} \frac{L^2}{r^2} + \dots\right) \quad r \gg L$$

RANDALL & SUNDRUM;
 GUBSER, GIDDINGS, KATZ, RANDALL;
 DUFF & LIU;

WHAT ABOUT BLACK HOLES?

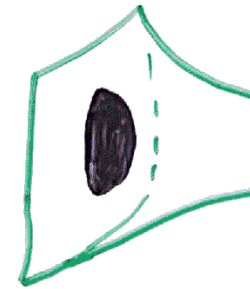
EXPECT:

\exists D-DIMENSIONAL DYNAMICAL GRAVITY
 ($D > 3$) \rightarrow THERE MUST EXIST
 D-DIMENSIONAL BLACK HOLES

THEY SHOULD BE LOCALIZED TO THE BRANE
 BECAUSE STRINGS IN AdS DIVERGE ON THE
 POINCARÉ HORIZON IN THE BULK

CHAMBLIN, HAWKING & REALL

"PANCAKES"



IN $D=3$ ~~\exists~~ DYNAMICAL GRAVITON \rightarrow IN
 ASYMPTOTICALLY FLAT SPACE ~~\exists~~ BLACK HOLES!

DESER, JACKIW & 'T HOOFT

FROM THE BULK VIEWPOINT ...

COMPLETE FAILURE !?

- * IN $D > 3$ CASES TO DATE NO-ONE HAS FOUND ANY EXACT LOCALIZED BLACK HOLE SOLUTIONS!

TO MAKE THINGS EVEN WORSE, THERE IS A "THEOREM" STATING THAT A COLLAPSE "ON THE BRANE" WILL NOT PRODUCE A STATIC SPHERICALLY SYMMETRIC BLACK HOLE

BRUNI, GERMANI & MARTENS

- * IN $D=3$ CASES EXACT STATIC BLACK HOLES IN ASYMPTOTICALLY FLAT SPACE, LOCALIZED ON THE BRANE, WERE FOUND!

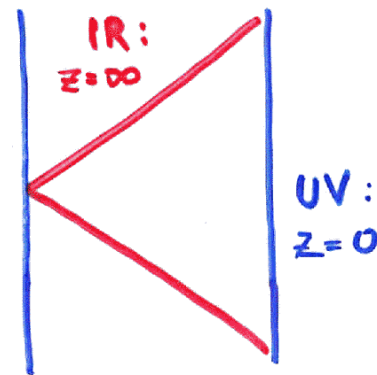
EMPARAN, HOROWITZ & MYERS

IS THIS COMPLETELY THE OPPOSITE TO WHAT SHOULD BE EXPECTED?!

... MUCH CONFUSION IN THE LITERATURE ...

QM TO THE RESCUE

RESOLUTION: OUR EXPECTATIONS WERE UNREALISTIC SINCE WE IGNORED QUANTUM MECHANICS



z^{-1} = ENERGY SCALE

CLASSICAL GRAVITY
IN ADS BULK \Leftrightarrow

DUAL CFT TO
LEADING $1/N$ ORDER
(PLANAR DIAGRAMS)

WE SHOULD READJUST OUR EXPECTATIONS TO INCLUDE QUANTUM MECHANICAL BACKREACTION: $T_{\mu\nu} \rightarrow T_{\mu\nu}^{\text{CLASSICAL}} + \langle T_{\mu\nu} \rangle$

IN PARTICULAR: IN THE GRAVITATIONAL SECTOR OF THE DUAL THEORY:

EINSTEIN'S EQS IN D-DIM THEORY

$$G_{\mu\nu} = 8\pi G_D \langle T_{\mu\nu} \rangle$$

CHECK ?

EINSTEIN'S EQS "ON THE BRANE" IN AdS₅

$$G_{\mu\nu} = 8\pi G_4 T_{\mu\nu} + G_5^2 \mathcal{O}(T_{\mu\nu}^2)$$

SHIROMIZU, MAEDA & SASAKI

DICTIONARY:

$$G_4 \sim \frac{1}{L} G_5 \quad M_D = \frac{\hbar}{l_D}$$

$$\# \text{ OF CFT DOFS: } g_* \sim N^2 \sim \left(\frac{L}{l_5}\right)^3 \sim \left(\frac{L}{l_4}\right)^2 \sim \left(\frac{M_4}{M_{\text{UV}}}\right)^2$$

* NOTE: IN CLASSICAL 4D THEORY

$$G_4 = \frac{l_4}{M_4}$$

(l_4 AND M_4 SEPARATELY DO NOT MAKE SENSE)

$$\begin{aligned} * \quad G_5^2 &= G_4 \frac{G_5^2}{G_4} = G_4 L^2 G_4 \\ &\equiv \hbar \left(\frac{L}{l_4}\right)^2 G_4 \equiv \hbar g_* G_4 ! \end{aligned}$$

∴

$$G_{\mu\nu} = 8\pi G_4 T_{\mu\nu} \left(1 + \hbar g_* \mathcal{O}(T_{\mu\nu}) + \dots\right)$$

" \mathcal{O}^2 " TERMS ARE NOTHING BUT THE QUANTUM CORRECTIONS WHICH MAY BE LARGE BECAUSE $g_* \gg 1$!

de HARO, SKENDERIS, SOLODUKHIN
MARCH-RUSSELL & HEBECKER
IDA & SHIROMIZU
HAWKING, HERTOG, REALL

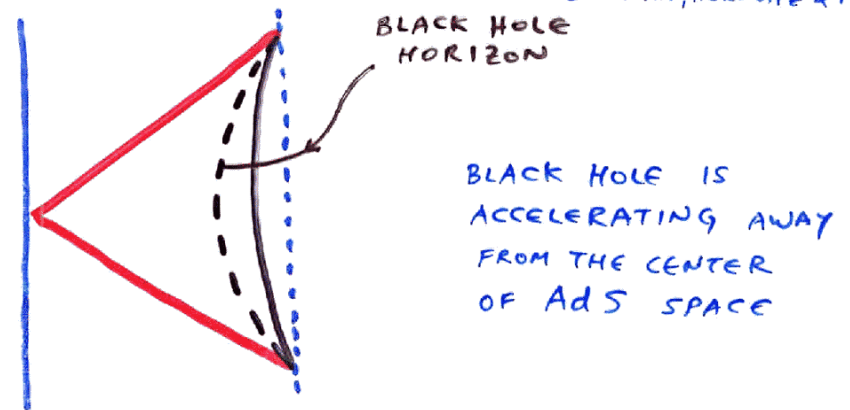
CONJECTURE:

BLACK HOLES WHICH SOLVE CLASSICAL BULK EQUATIONS WITH BRANE BOUNDARY CONDITIONS CORRESPOND TO QUANTUM-CORRECTED BLACK HOLE SOLUTIONS IN THE DUAL CFT+GRAVITY THEORY

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T. TANAKA

BLACK HOLES IN D=3

THE EXACT SOLUTION IN THE BULK IS THE C-METRIC IN AdS_4 CUT-OFF BY ASYMPTOTICALLY FLAT RS^2 BRANE
EMPARAN, HOROWITZ & MYERS



METRIC INDUCED ON THE BRANE:

$$ds^2 = - \left(1 - \frac{r_0}{r}\right) dt^2 + \frac{dr^2}{1 - \frac{r_0}{r}} + r^2 d\varphi^2$$

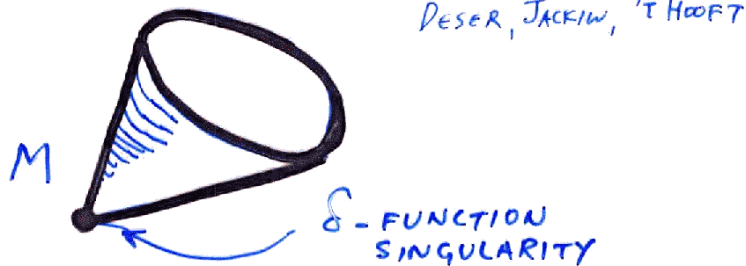
$\Delta\varphi < 2\pi$

EQUATORIAL SECTION OF 4D SCHWARZSCHILD WITH CONICAL DEFICIT ANGLE $\delta = 8\pi \frac{M}{M_3}$

r_0 : HORIZON = $f(M)$
(complicated function...)

THIS MUST BE INTERPRETED AS ARISING COMPLETELY FROM QUANTUM CORRECTIONS SINCE THERE ARE NO CLASSICAL BH'S!

INDEED: TAKE A LUMP OF CFT WITH MASS M AND IGNORE QUANTUM CORRECTIONS - IN $D=3$ IT PRODUCES THE CONICAL GEOMETRY:



BUT NOW: SINCE THE BACKGROUND GEOMETRY IS A CONE, CAN COMPUTE THE QUANTUM CORRECTIONS TO $T_{\mu\nu}$ - CASIMIR ENERGY!

FOR A WEAKLY COUPLED CFT WITH g_* DOF'S

$$\langle T^{\mu}_{\nu} \rangle = \frac{g_* \alpha(M)}{r^3} (1, 1, -2)$$

SOORADEEP & SAHNI

NOW PLUG BACK INTO THE EINSTEIN'S EQUATIONS AND SOLVE ANEW;

LO AND BEHOLD!

$$ds^2 = -\left(1 - \frac{r_0}{r}\right) dt^2 + \frac{dr^2}{1 - \frac{r_0}{r}} + r^2 d\psi^2$$

H. SOLENG, 1993
SAME AS EHM

$$r_0 = \hbar g_* \frac{\alpha(M)}{M_3}$$

$$M \ll M_3 \quad r_0 \sim \hbar g_* \frac{M}{M_3^2}$$

$$M \lesssim \frac{M_3}{4} \quad r_0 \sim \frac{\hbar g_*}{M_3} \frac{1}{\left(1 - 4\frac{M}{M_3}\right)^3} \rightarrow \infty$$

UP TO $O(1)$ COEFFICIENTS THE SAME RESULT IS OBTAINED BOTH FROM THE BULK AND FROM THE SCALINGS IN THE DUAL CFT+GRAVITY THEORY

QUANTUM CORRECTIONS DRESS UP THE NAKED SINGULARITY!

THE GREATER g_* , THE BETTER ...

NOTE: IN '93 SOLENG CONSIDERED A CONFORMALLY COUPLED SCALAR IN 2+1 - A PROTOTYPE WEAKLY COUPLED CFT WITH SMALL # OF DEGREES OF FREEDOM...

IN THIS CASE $r_0 \approx \hbar \frac{\alpha(M)}{M_3}$ AND FOR $M \ll M_3$, $r_0 \sim \hbar \frac{M}{M_3^2}$ WHICH MAKES $R_{\mu\nu} R^{\mu\nu} \gg M_3^4$ OUTSIDE OF THE HORIZON - BACKGROUND EINSTEIN'S EQS **COMPLETELY UNRELIABLE**

SOLENG HAS CONSEQUENTLY DISMISSED THE QUANTUM CORRECTIONS AS A COSMIC CENSOR

BUT THAT IS NOT TRUE: EVEN FOR $g_* \sim 1$ SOLUTIONS WITH $M \rightarrow M_3$ REMAIN CENSORED AS $R_{\mu\nu} R^{\mu\nu} < M_3^4$ OUTSIDE OF r_0

$g_* \gg 1$ MAKES THE QUANTUM CORRECTIONS BETTER BEHAVED BY LOWERING THE ENTROPY PER CHANNEL (AND SO, THE TEMPERATURE) ...

RESOLVING THE MYSTERY OF THE MISSING 4D BLACK HOLE

- * IN 4D, \exists DYNAMICAL GRAVITY $\Rightarrow \exists$ BLACK HOLE: SCHWARZSCHILD SOLN (LARGE HOLE: $r_H > L \rightarrow$ CFT+GRAVITY VALID!)
- * BUT: IN ASYMPTOTICALLY AdS SPACE IN THE BULK, THERE'S NO BRANE-LOCALIZED STATIC SPHERICALLY SYMMETRIC BH SOLNS?

DUAL CFT+GRAVITY:

IF BULK AdS IN THE IR (REGULAR HORIZON) THE CFT IS CONFORMAL IN THE IR AND THERE IS NO MASS GAP!

SO ANY BLACK HOLE, HOWEVER HEAVY AND COLD ($T_{BH} \propto \frac{M_4^2}{M_{BH}}$) CAN EMIT THERMAL CFT STATES WHICH ARE ACCESSIBLE TO IT IN THE DEEP IR!

By AdS/CFT, BULK SOLUTIONS AUTOMATICALLY ACCOUNT FOR THIS!

BULK SOLUTIONS TAKE THIS AUTOMATICALLY INTO ACCOUNT: THUS THEY DESCRIBE BLACK HOLE **CORRECTED** BY THE BACKREACTION FROM THE CFT HAWKING RADIATION!

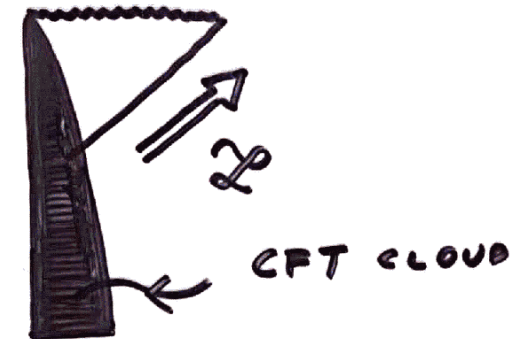
ESCAPING HAWKING RADIATION

⇓

$$\frac{dM_{\text{BH}}}{dt} < 0$$

∴ BLACK HOLE MUST BE TIME-DEPENDENT!

CHECK: CONSIDER A COLLAPSING DUST OF CFT AND MATCH IT ON AN EXTERIOR SOLUTION WITH OUTGOING FLUX OF RADIATION:



INTERIOR: FRW À LA OPPENHEIMER-SNYDER

$$\frac{\dot{R}^2}{R^2} + \frac{1}{R^2} = \frac{M}{R^3} + k g_* \frac{M^2}{R^6 M_{\text{pl}}^2} \quad \text{Shiomi et al, Brunet et al}$$

EXTERIOR: FAR FIELD REGION OUTGOING VAIDYA

$$ds^2 = -\left(1 - \frac{2M}{r}\right) du^2 + 2du dr + r^2 d\Omega_2$$

MATCHING: FLUX OF RADIATION $T_{uv} = \frac{\mathcal{L}}{r^2} \hat{u} \hat{v}$

$$\mathcal{L} = \frac{L^2}{G_4 (G_4 M)^2} = \frac{k g_*}{(G_4 M)^2}$$

THERMAL HAWKING FLUX OF g_* FLAVORS!

* MATCHING SOLUTIONS REQUIRES THAT THEY SATISFY THE CONSISTENCY CHECK: THE CONFORMAL ANOMALY MUST BE CONSISTENT WITH THE ASYMPTOTIC AdS GEOMETRY:

$$G^M_M = O(1) \frac{1}{2} g_* G_4 \left(R^{M\nu} R_{M\nu} - \frac{R^2}{3} \right)$$

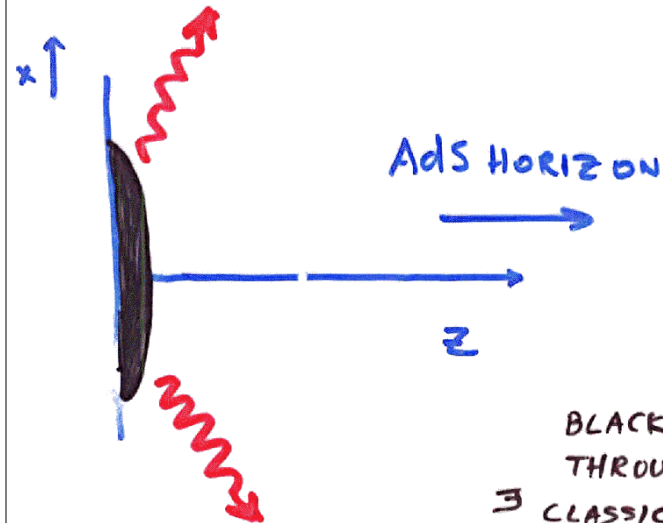
THIS IS JUST THE SHIROMIZU ET AL EQS AFTER PERTURBATIVE REARRANGEMENTS

* "NO-GO" THM OF BRUNI, GERMANI & MAARTENS EASY TO UNDERSTAND: CFT QUANTUM EFFECTS WOULD REQUIRE A STATIC EXTERIOR SOLUTION WITH $G^M_M \propto R_{\mu\nu\lambda\sigma} R^{\mu\nu\lambda\sigma} \rightarrow$ INCONSISTENT WITH THE CFT ANOMALY! SO TO MATCH THE ANOMALIES IN & OUT ONE NEEDS TIME DEPENDENCE

BUT THIS IS OF COURSE JUST A NATURAL CONSEQUENCE OF QUANTUM CORRECTIONS RATHER THAN A FUNDAMENTAL OBSTRUCTION

THE CLASSICAL APPEARANCE OF THE "NO-GO" THM FROM THE BULK POINT OF VIEW IS A MISCONCEPTION...

HAWKING RADIATION AS A HOLOGRAM?



BLACK HOLE ACCELERATES THROUGH THE BULK:
 ⇒ CLASSICAL BREHMSSTRAHLUNG

CLASSICAL BREHMSSTRAHLUNG \simeq HAWKING EMISSION!?

* FREQUENCY:

$$\omega^2 \sim \frac{1}{\lambda^2} \sim G_D \rho_D \sim \frac{M}{M_5^3 V} \sim \frac{M}{M_5^3 L (G_4 M)^3} \sim \frac{1}{(G_4 M)^2} \sim T_H^2 !$$

PRECISELY HAWKING TEMPERATURE

BUT WHY? NO FULL PICTURE YET...

PHENOMENOLOGY

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WITHOUT BLACK HOLES RS_2 APPEARS TO BE CONSISTENT AS LONG AS L IS ALLOWED BY TABLE-TOP EXPERIMENTS

EÖT-WASH: $L \lesssim 100 \mu\text{m}$

$$g_* \sim \left(\frac{L}{l_p}\right)^2 \sim 10^{60}!$$

SUCH A LARGE # OF HIDDEN SECTOR DOF'S MAY REMAIN INVISIBLE DUE TO THEIR EXTREMELY WEAK COUPLINGS

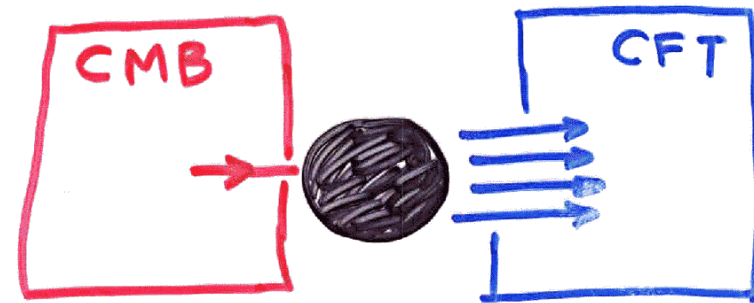
THIS MAY EVEN BE OK WITH COSMOLOGY IF THE LAST REHEATING STAGE WAS STRONGLY INTO THE SM: CFT MUST BE COLDER THAN CMB BY $\gtrsim 10^{15}$:

$$T_{\text{CFT}} \lesssim 10^{-15} \text{ K}$$

HEBECKER & MARSH-RUSSELL

HOWEVER: BLACK HOLES ARE SENSITIVE TO SO MANY NEW DOF'S: THEY EVAPORATE MUCH MORE QUICKLY!

THERMODYNAMIC PICTURE:



BLACK HOLE MASS CHANGES:

- * UP, BY ACCRETION (MOSTLY CMB)
- * DOWN, BY HAWKING EMISSION (MOSTLY CFT)

MASS BALANCE:

α - GRAY BODY FACTOR
 $\sim \text{few} \times 10^{-5}$

$$\dot{M} = -\alpha g_* T^4 A + T_{\text{CMB}}^4 A$$

EVAPORATION

ACCRETION

CARRIED AWAY BY HAWKING

WITH $T \sim \frac{M_4^2}{M}$, WE SEE THAT FOR

$$M T_{\text{CMB}} < g_*^{\frac{1}{4}} M_4^2$$

ACCRETION IS NEGLIGIBLE; FOR
 A SOLAR MASS BH, $M_{\odot} \sim 10^{57} \text{ GeV}$,
 THIS IS TRUE FOR CMB BELOW

$$T_{\text{CMB}} \sim \text{MeV}$$

THUS: IF $L \sim 0.1 \text{ mm}$, A
 LARGE BLACK HOLE WOULD BE
 MOSTLY RADIATING FOR ALMOST
 ALL OF ITS LIFE!

IGNORING THE ACCRETION
 TERMS AND USING $A \sim \frac{M^2}{M_4^2}$
 AND $\alpha \sim 10^{-5}$, WE GET
 THE BH LIFETIME:

$$\tau \sim \frac{10^5}{g_*} \frac{M^3}{M_4^4}$$

FAMILIAR FORMULA, EXCEPT THAT
 NOW $g_* \gg 1$!

REQUIRING THAT A FEW M_{\odot} BH LIVES
AT LEAST 10^9 YEARS (X-RAY BINARIES)
GIVES

$$g_* \lesssim 10^{52}$$

OR THEREFORE, $g_* \sim \left(\frac{L}{\ell_4}\right)^2$

$$L \lesssim 0.1 \mu\text{m}$$

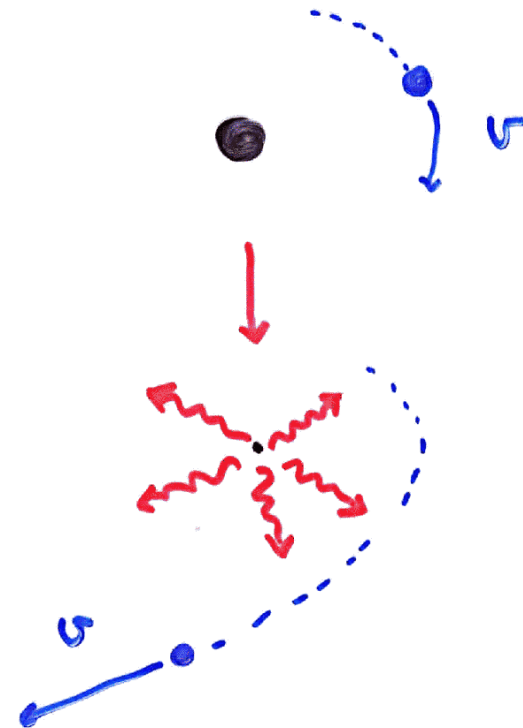
STRONGER THAN TABLETOPS & COSMOLOGY!

IF 0.1-0.5 M_{\odot} MACHOS ARE BH'S
THEY MUST BE PRIMORDIAL: BOUND GETS
DOWN TO:

$$L \lesssim \text{few nm}$$

IMPROVEMENT OVER EÖT-WASH BY 10^5 !

JUST FOR FUN: A POSSIBLE DETECTION?
SUPPOSE L IS CLOSE TO ITS UPPER BOUND;
CONSIDER A BINARY WITH A BH



GRAVITATIONAL SLINGSHOT: LOOK
FOR PLANETS MOVING WITH
UNREASONABLY HIGH SPEED!

CONCLUSION

- * A NEW ANGLE ON BH'S FROM THE AdS/CFT POINT OF VIEW



- * EXPLICIT EXAMPLES IN 2+1 WHICH CONFIRM THE CONJECTURE
 SPINOFF: QUANTUM CENSORSHIP EVEN IN WEAK COUPLING !!!

- * DIRECTIONS TO PURSUE:

- LUMINOSITY FROM THE BULK?
- EVOLUTION FROM THE BULK?
 (VACUA: HARTLE-HAWKING, UNRUH, BOULWARE...)
- THERMALITY?
- KARCH-RANDALL?
- CHARGED BHs?
- ...