Soft Hair on Black Holes

NORDITA, August 2016

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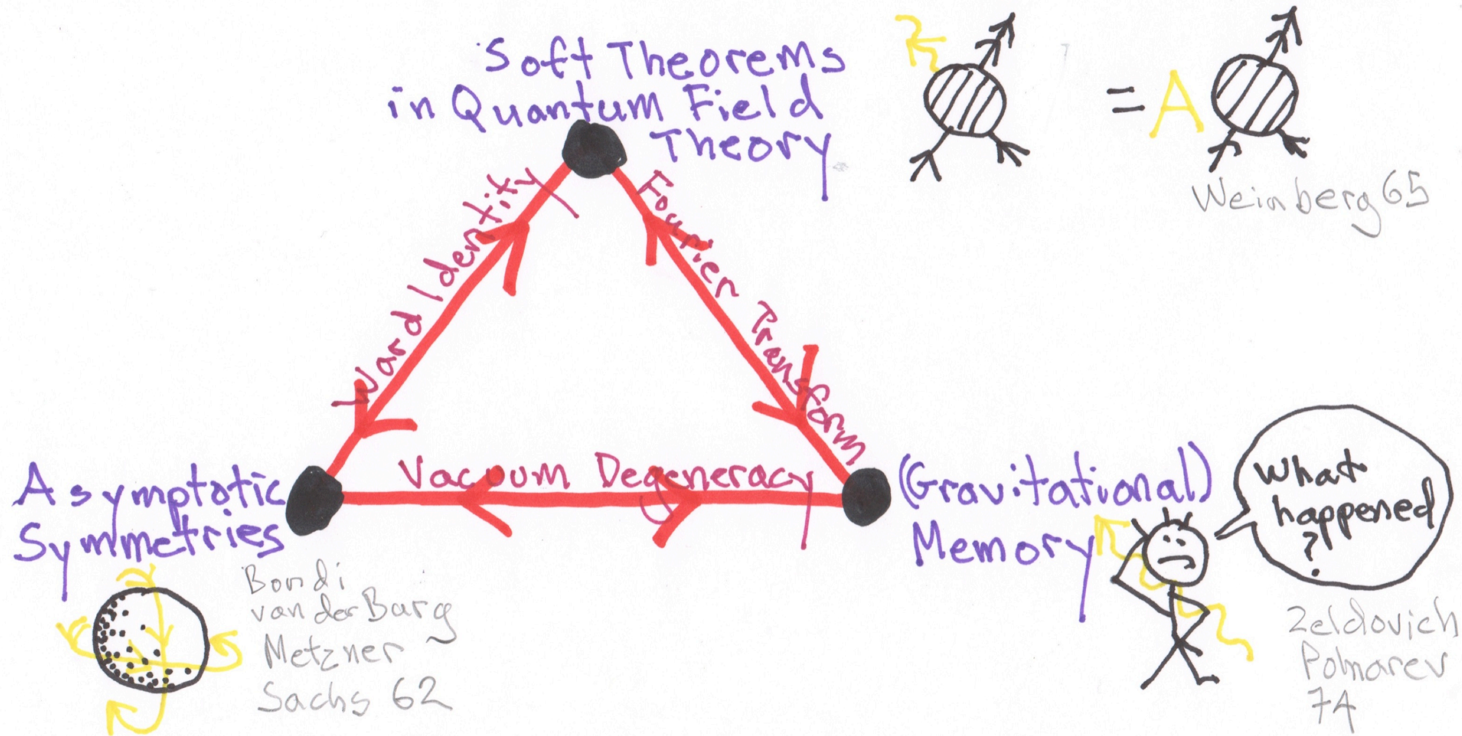
Over the last 3 years, an exact mathematical equivalence has been discovered of 3 previously disparate phenomena, each studied for half a century:



This has led to surprising new insights into the low-energy structure of gravitational & electromagnetic theories. It also has profound implications for black hole information, the focus of this lecture.

OUTLINE

I. Describe some basics of the $\triangle$, and the consequent ∞ of conservation laws in all theories with gravity or electromagnetism.
He, Dumitrescu, Kapec, Lysov, Mitra, Pasterski, Pate, Porfyriadis, Zhiboedov, AS 2013-2015

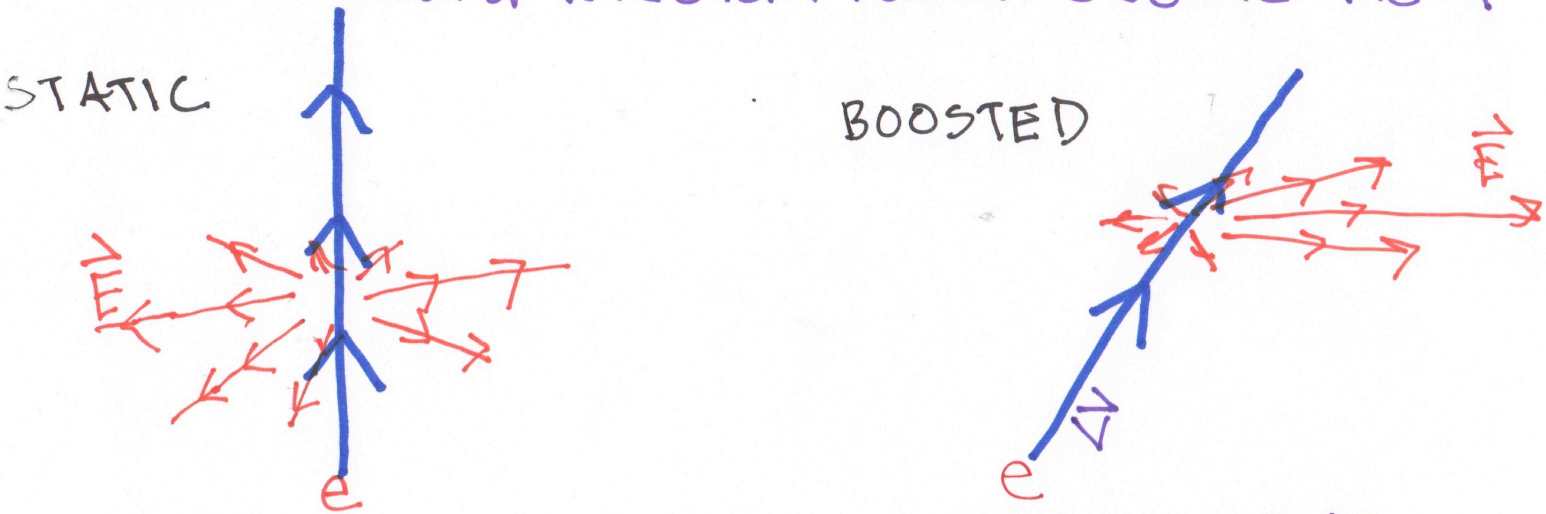
II. Review the black hole information paradox
Hawking 75

III. Describe implications of $\triangle$ for paradox
Pasterski, Zhiboedov, AS 2014, and the existence of 'soft quantum hair' on black holes
Hawking, Perry, AS 2016

IV Conclude

∞ of conserved charges in E&M

Lienard-Wiechert radial electric field

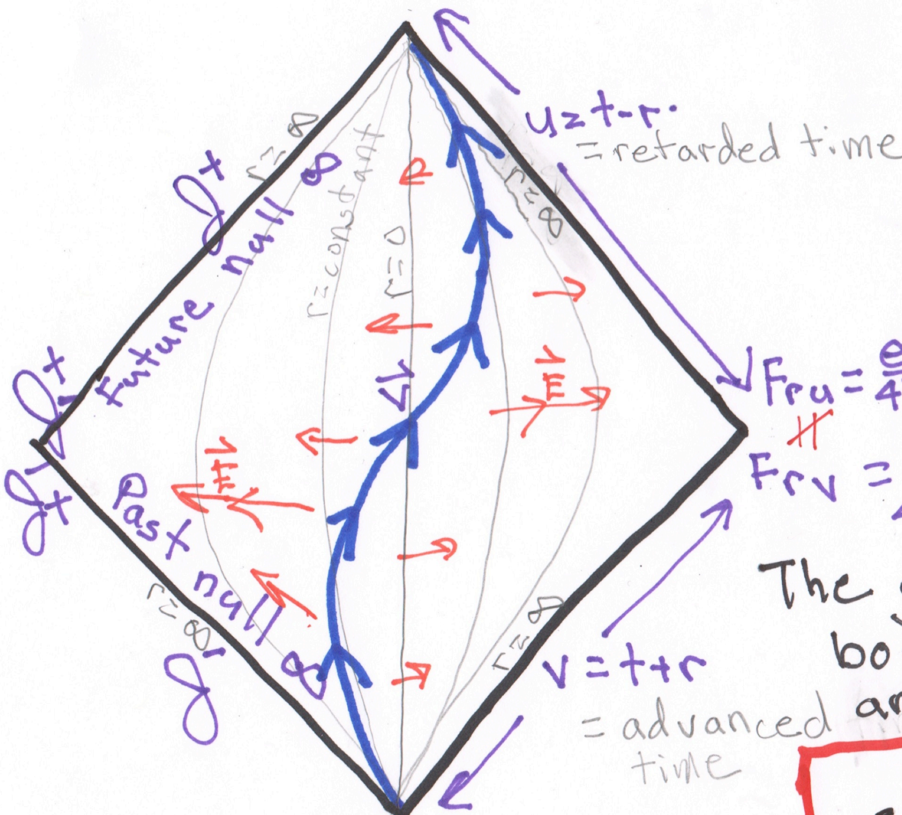


$$F_{rt} = \frac{e}{4\pi r^2}$$

$$F_{rt} = \frac{e\sqrt{1-v^2}\,(r^2 - t\,\vec{x}\cdot\vec{v})}{4\pi r\left[(1-v^2)(t-\vec{x}\cdot\vec{v})^2 - t^2 + r^2\right]^{3/2}}$$

The BOOSTED field is not single-valued near spatial ∞. We need to understand this carefully.

Penrose diagram for a moving charge in Minkowski space



$$F_{ru} = \frac{e}{4\pi}\frac{(1-v^2)}{(r-\vec{v}\cdot\vec{x})^2}$$

$\neq$

$$F_{rv} = \frac{e}{4\pi}\frac{(1-v^2)}{(r+\vec{v}\cdot\vec{x})^2}$$

different sign

The general Lorentz-invariant boundary condition is antipodal:

$$r^2 F_{ru}(\theta^A)\Big|_{\mathscr{I}^+_-} = r^2 F_{rv}(\tilde{\theta}^A)\Big|_{\mathscr{I}^-_+}$$

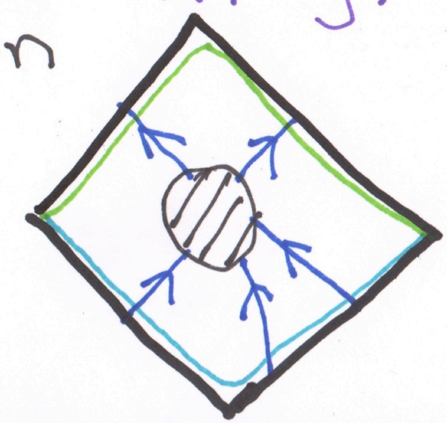
$A=1,2$ angle on sphere; antipodal angle on sphere

This implies an ∞ of 'antipodal' conservation laws

$$Q^+_\varepsilon \equiv \int_{\mathcal{I}^+_-} d^2\Omega\, r^2 F_{ru}\, \varepsilon(\theta^A)$$

$$= Q^-_\varepsilon \equiv \int_{\mathcal{I}^-_+} d^2\Omega\, r^2 F_{rv}\, \varepsilon(\theta^A)$$

where $\varepsilon(\theta^A)\big|_{\mathcal{I}^+_-} = \varepsilon(\tilde{\theta}^A)\big|_{\mathcal{I}^-_+}$ is any function on the sphere. For the special case $\varepsilon = 1$ using Gauss's law $\nabla^\mu F_{\mu\nu} = j^M_\nu$ this is global charge conservation



$$\sum_k e^{in}_k = \sum_k e^{out}_k$$

AS hep-th 1308.0589
He, Mitra Porfyriadis AS hep-th 1407.3789
Campiglia & Laddha hepth 1505.05346
Kapec Pate AS hep-th 1506.02906

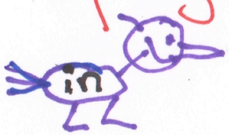
But what are the conservation laws when $\partial_A \varepsilon(\theta^A) \neq 0$???

Integrating by parts and using Gauss's law, the conservation laws are

$$\sum_K \varepsilon(\theta^A_K) e^{in}_K +$$  $$= \sum_K \varepsilon(\theta^A_K) e^{out}_K +$$ 

incoming charges weighted by angle

strange duck



$$= \int d^2\Omega \int_{-\infty}^{a} dv\, \partial_A \varepsilon\, F^A{}_v =$$ soft photon w/ polarization $\partial_A \varepsilon$

soft = zero-energy

At the classical level, this cons. law equates the sum of a zero mode of the incoming EM field and a moment of the incoming charge distribution to its antipodal outgoing counterpart.

Quantum Conservation Laws

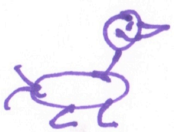
In QM $|out\rangle = S|in\rangle$
↖ S-matrix

He Mitra Porfyriadis
Kapec Pate Campiglia
Laddha AS

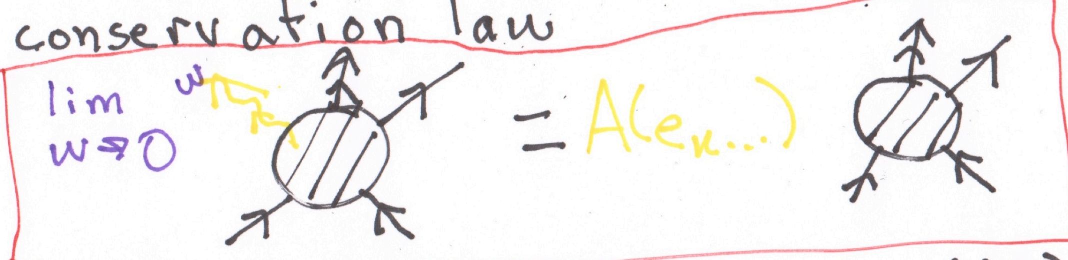
the ∞ of conservation laws are

$$\langle out| Q^+_\varepsilon S - S Q^-_\varepsilon |in\rangle = 0$$

for any pair $|in\rangle$, $|out\rangle$ and any ε.

 $= \lim_{\omega \to 0} \int d^2\Omega \int_{-\infty}^{\infty} dv\, e^{i\omega v} \partial_A \varepsilon F^A{}_v$ creates/annihilates soft photons.

Bizzare conservation law



but it was discovered long ago Low (58) Weinberg (65)
and = SOFT PHOTON THEOREM all EM theories e.g. QED
Con reverse logic: soft photon theorem ⇒ $Q^+_\varepsilon = Q^-_\varepsilon$

Conservation Laws → Symmetries

$$[Q^+_\varepsilon, A_B]_{\mathcal{J}^+} = i\partial_B \varepsilon$$

are "large gauge transformations" that go to angle-dependent constants at null infinity. They act non-trivially on physical states & can be measured via the electromagnetic memory effect: EM analog of well-known gravitational memory effect.

Bieri, Garfinkle gr-qc 1307.5098
Pasterski hep-th 1505.00716
Susskind hep-th 1507.02584

∞ Vacuum Degeneracy

$$H|0\rangle = 0 \qquad H Q^{+}_{\varepsilon}|0\rangle = 0$$

$$\langle 0| Q^{+}_{\varepsilon}|0\rangle = 0$$

$$\Rightarrow Q^{+}_{\varepsilon}|0\rangle \neq |0\rangle$$

= an additional soft photon on $|0\rangle$

∃ ∞ many degenerate vacua w/ different angular momenta: quantum vacuum has 'soft hair'

Large gauge symmetries are spontaneously broken.

SOFT PHOTON = NAMBU-GOLDSTONE BOSON

Ditto for gravity!!!

I. 'Newtonian potential' in GR obeys $g_{00}(\Theta^A)\big|_{\mathcal{I}^+_-} = g_{00}(\tilde{\Theta}^A)\big|_{\mathcal{I}^-_+}$

II. $\exists$ ∞ of conserved 'supertranslation charges' generalizing the total mass $Q_f^+ = Q_f^-$ $f = f(\Theta^A)$
& creating 'soft gravitons'
AS hep-th 1312.2229

III. Quantum conservation law = Weinberg's 1965 soft graviton theorem He Mitra Lysov AS hep-th 1401.7026

IV. Symmetry = Bondi, van der Burg, Metzner Sachs 1962 BMS supertranslations

V. ∞-degenerate vacua measured via Zeldovich-Polnarev 1974 'gravitational memory effect' Zhiboedov AS hep-th 1411.5745

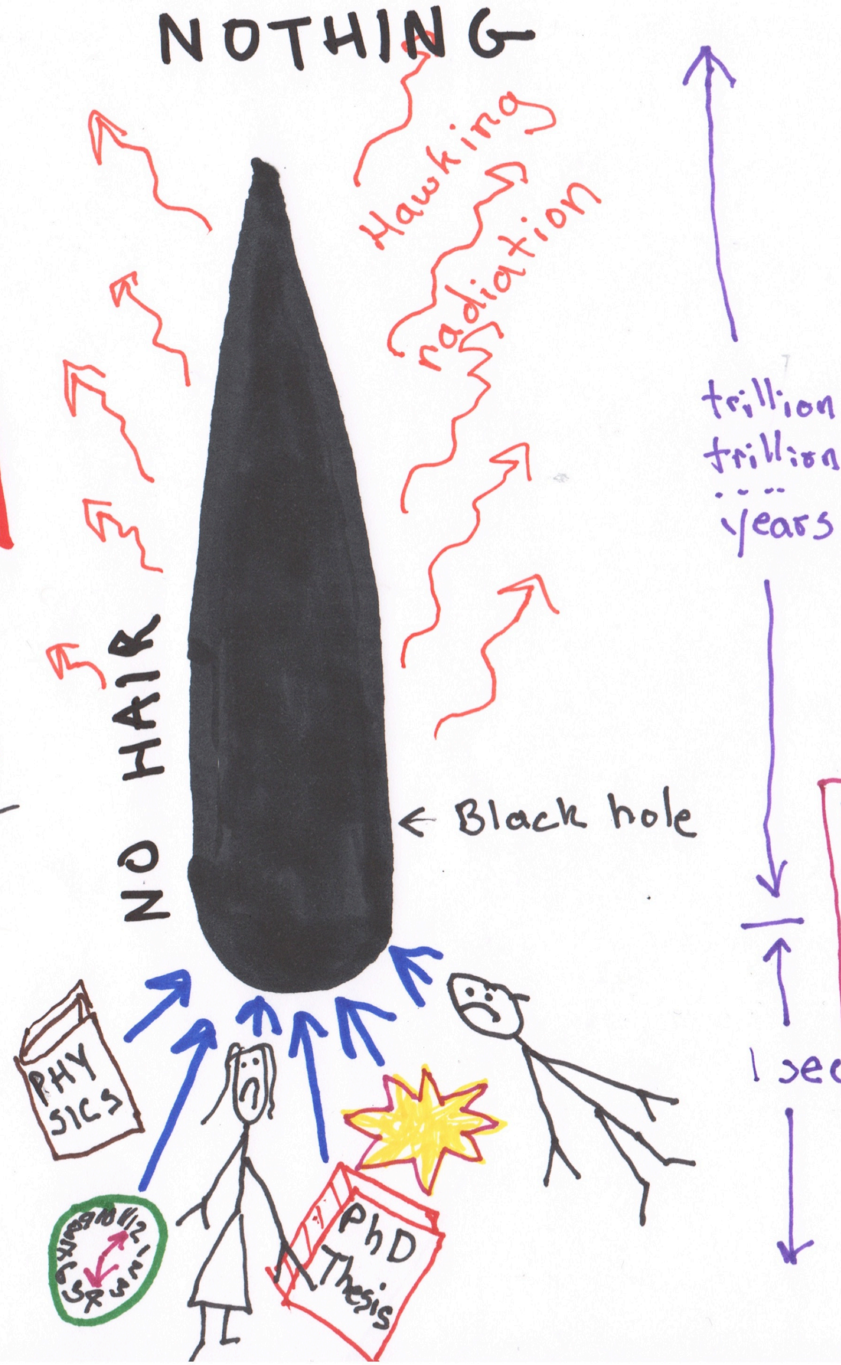
Oddly, though technically more complex, gravity was understood earlier than Maxwell theory!

THE BLACK HOLE INFORMATION PARADOX

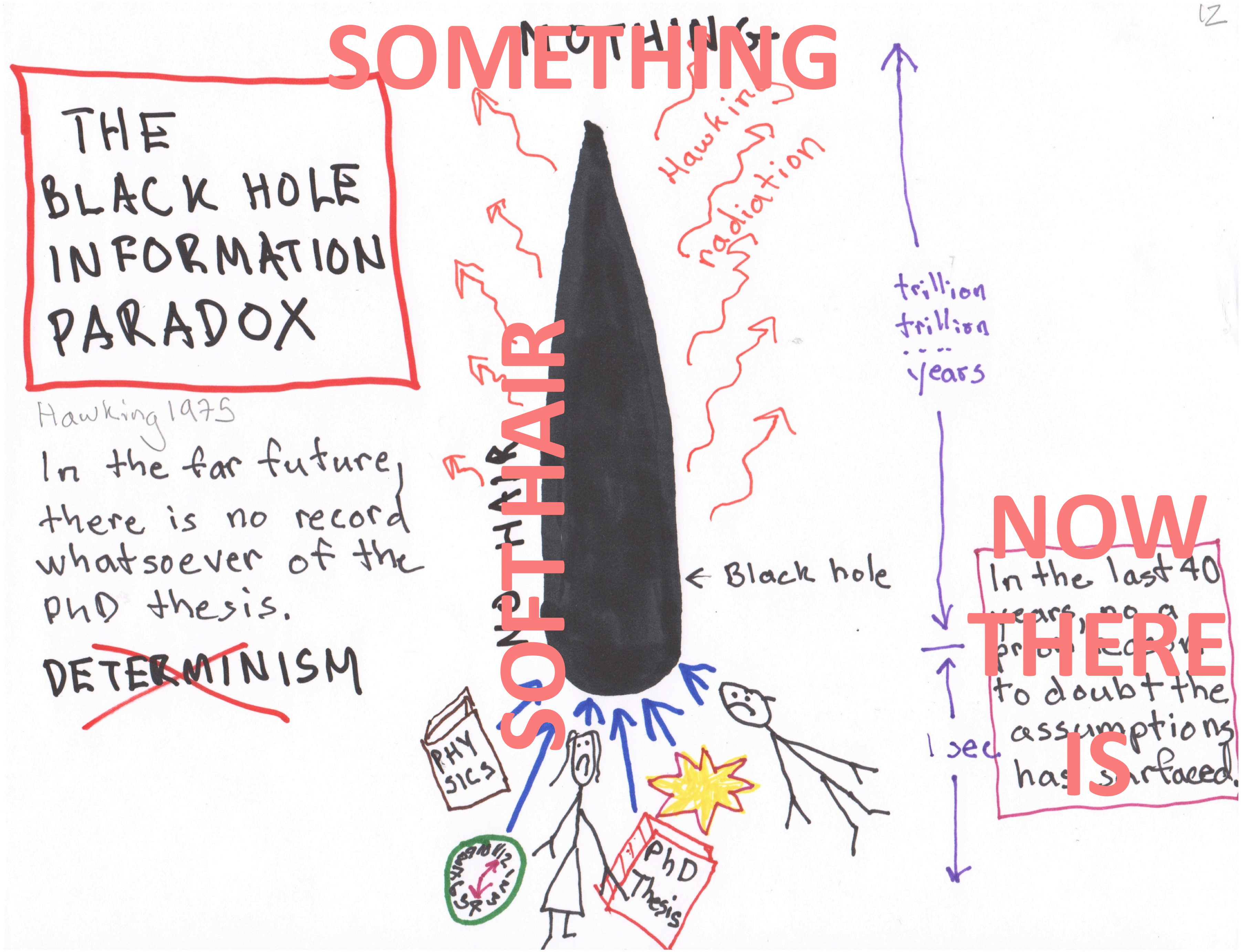
Hawking 1975

In the far future, there is no record whatsoever of the PhD thesis.

~~DETER~~MINISM



In the last 40 years, no a priori reason to doubt the assumptions has surfaced.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SOMETHING
NOTHING
THE BLACK HOLE INFORMATION PARADOX
Hawking 1975
In the far future, there is no record whatsoever of the PhD thesis.
DETERMINISM
Hawking radiation
trillion trillion .... years
SOFT HAIR
Black hole
1 sec
NOW THERE IS
In the last 40
to doubt the assumptions has surfaced.
PHYSICS
PhD Thesis

SUMMARY SO FAR

1. We have found a flaw in the assumptions underlying the information loss argument.

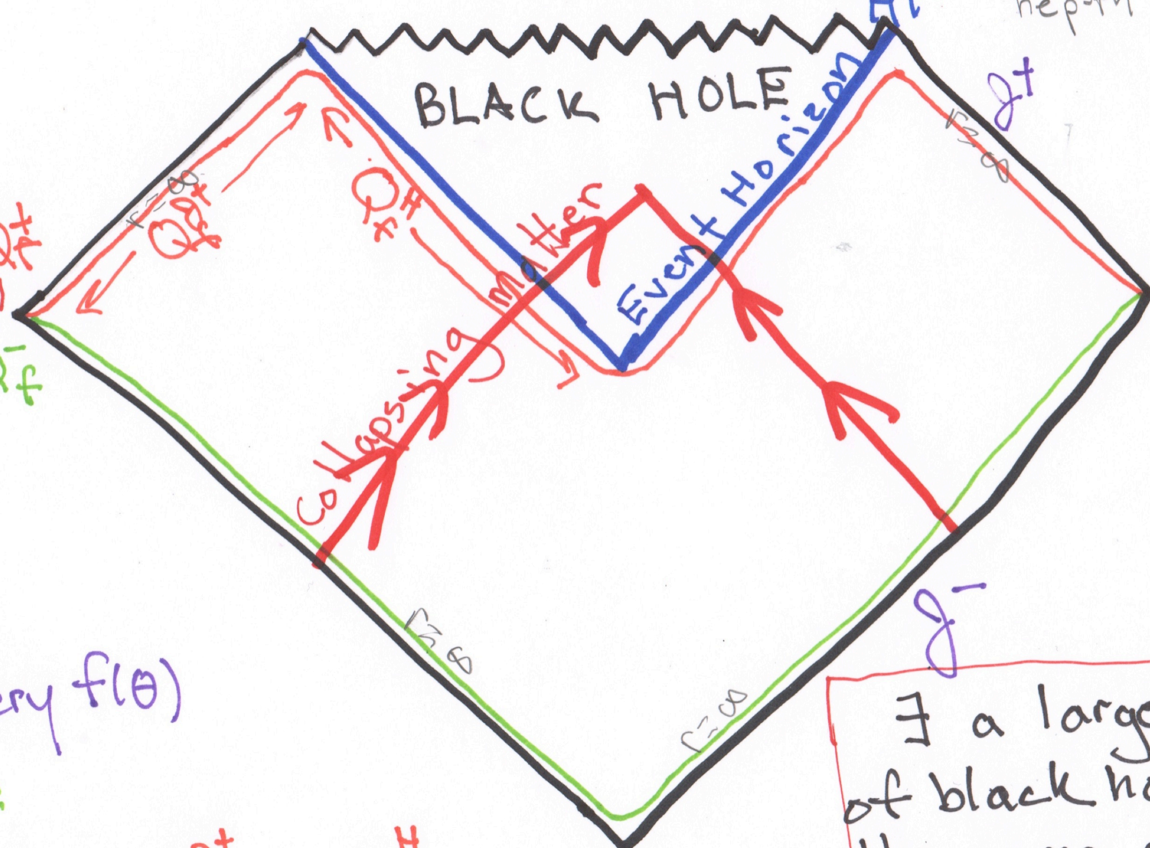
2. We have not resolved the information paradox.

3. The nature of the flaw suggests concrete new avenues of investigation.

onward....

SOFT HAIR ON BLACK HOLES

Hawking, Perry AS
hep-th 1601.00921



for every $f(\theta)$

Q_f^-

$= Q_f^+ = Q_f^{\mathcal{J}^+} + Q_f^H$

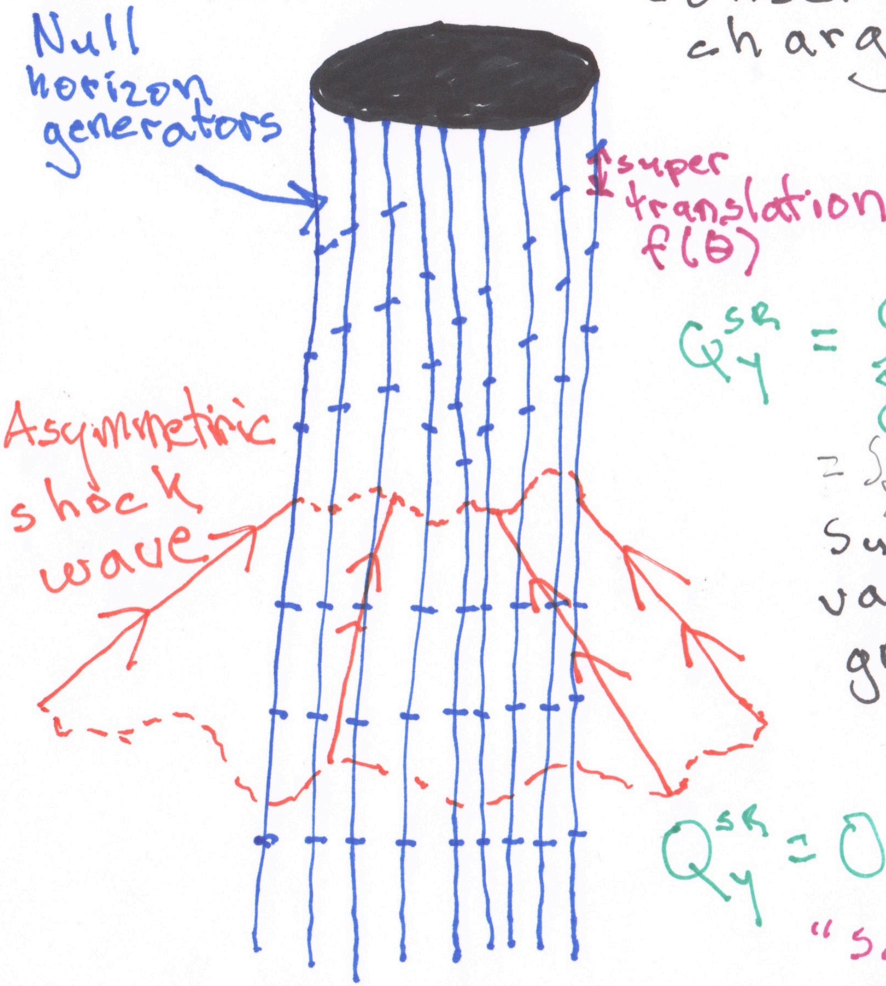
creates soft graviton on $\mathcal{J}^+$

creates soft graviton on the horizon,
= pixel in the hologram at H^+

∃ a large degeneracy of black holes with the same mass but different numbers of soft gravitons = soft hair

Supertranslated black holes are **classically** distinguishable via conserved **superrotation** charges.

No-~~hair~~ theorem



$$Q^{SR}_Y = \int_{\mathcal{I}^+_-} d^2\Omega \, m_B Y^A \partial_A f \neq 0$$

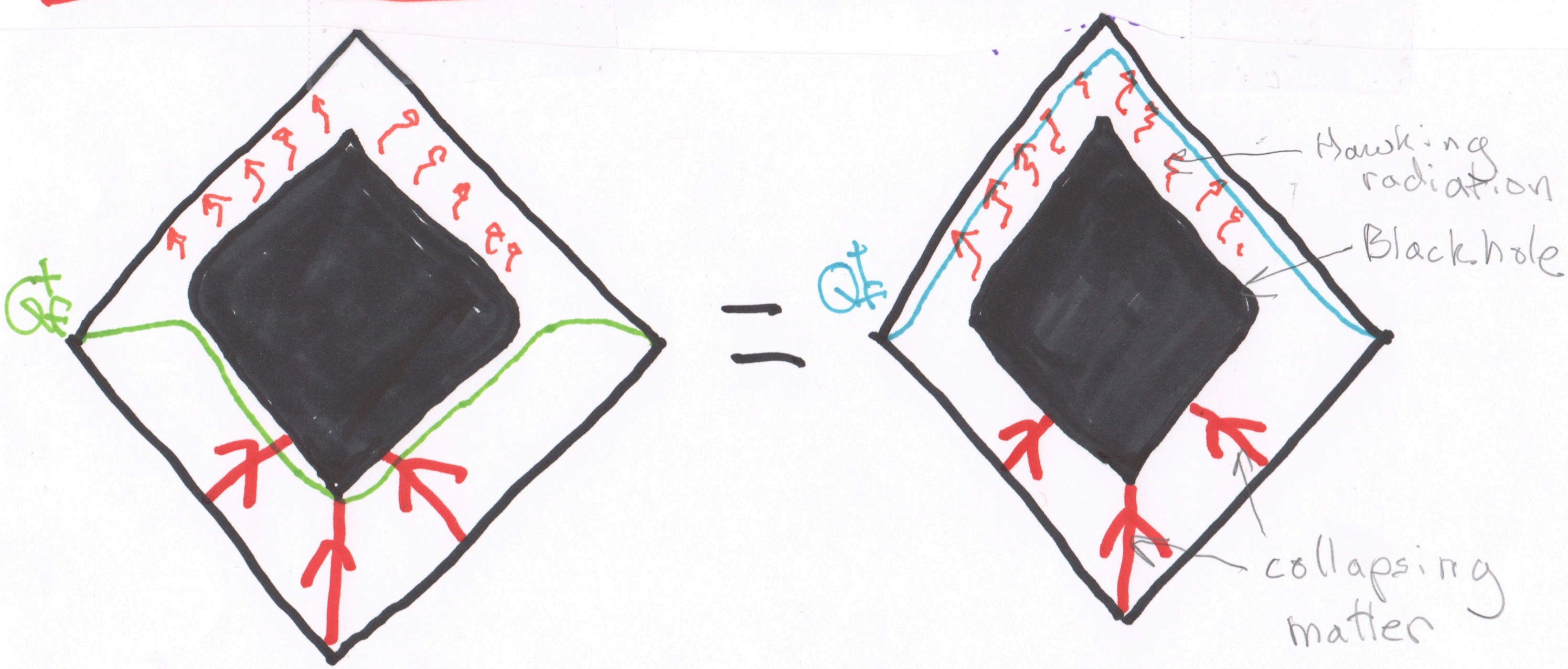
$= \int_{\mathcal{I}^+} d^2\Omega \, Y^A N_A \leftarrow$ angular momentum aspect

Supertranslation charges vanish because the group is abelian.

$$Q^{SR}_Y = 0$$

Hawking, Perry AS "Supertranslation Hair on Black Holes" to appear

Does this affect quantum black hole formation/evaporation?



If $|\psi_{in}\rangle \to |\psi_{out}\rangle$

then $Q^+_f|\psi_{in}\rangle \to Q^+_f|\psi_{out}\rangle$,

thereby distinguishing deterministically the out-states from BHs with or without soft hair

in other words... **Yes!**

Concluding Comment

Black holes carry quantum hair in the form of soft gravitons (or photons) arising from supertranslations. These comprise some of the pixels in the hologram at the boundary H^+ of the horizon. We think it unlikely they are all the pixels or store all the information. However more symmetries (e.g. superrotations) ⇒ more pixels. Whether or not a complete picture of black hole information can be obtained in this manner is a concrete & interesting challenge for future research.


THANK YOU!