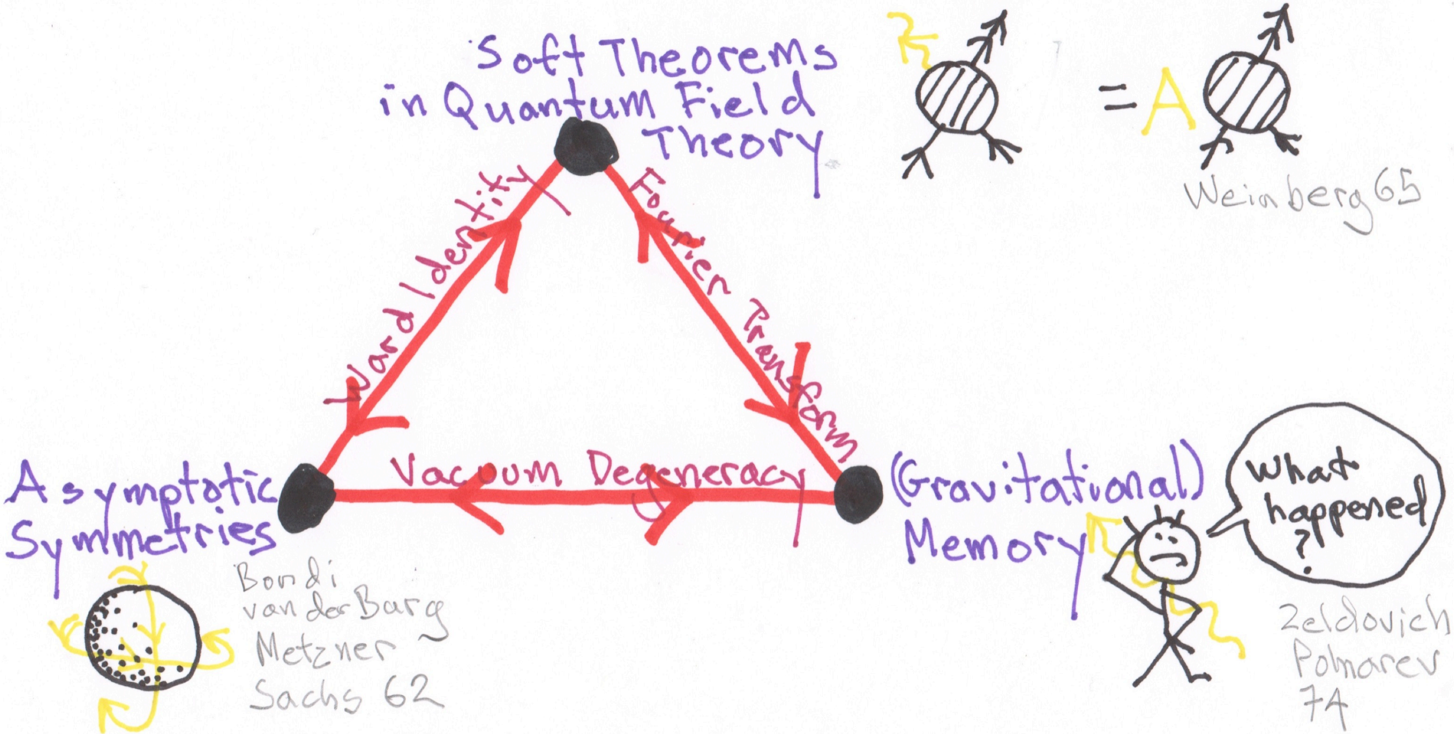
Soft Hair on Black Holes Part I

Strings 2016, Beijing

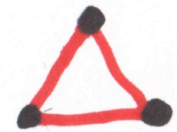
Andy Strominger, Harvard

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.

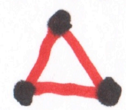
Outline

I. Describe basics of  &

∞ of conservation laws in QED, YM, gravity.

He, Dumitrescu, Kapec, Lysov, Mitra, Pasterski, Pate, Porfyriadis, Zhiboedov & AS 2013-2016

II. Review BH information paradox Hawking 75

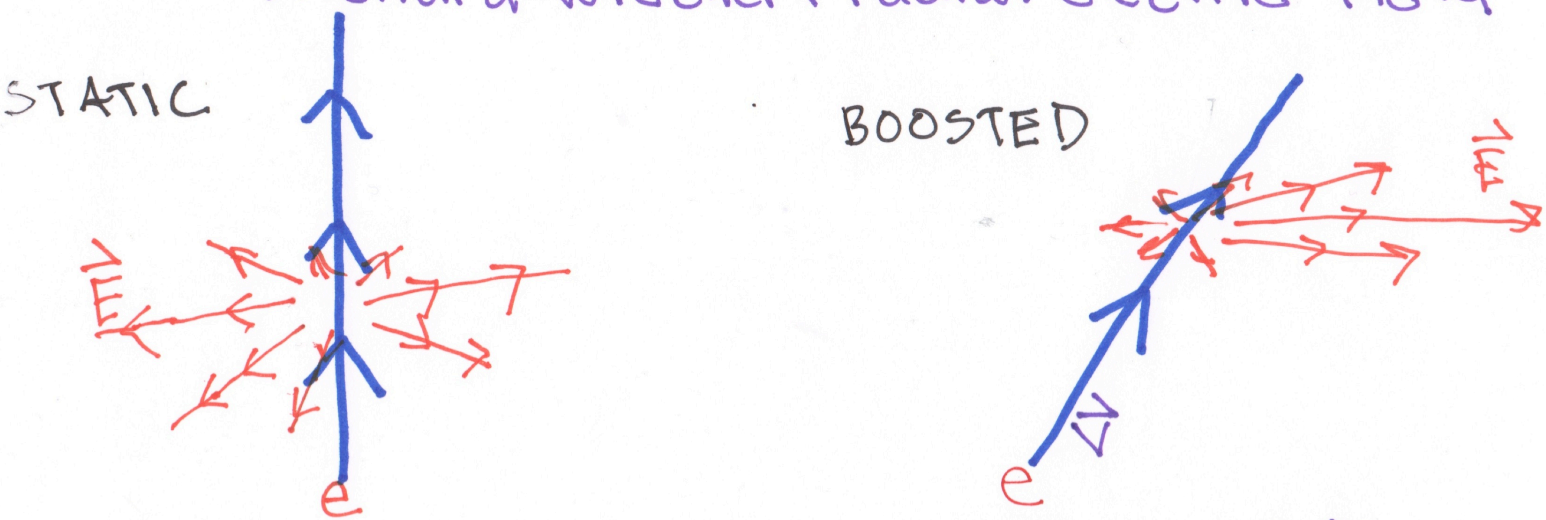
and why  ⇒ flaw in argument

"Soft quantum" hair Hawking, Perry AS next talk by Perry

III Conclude

∞ of conserved charges in E&M

Lienard-Wiechert radial electric field

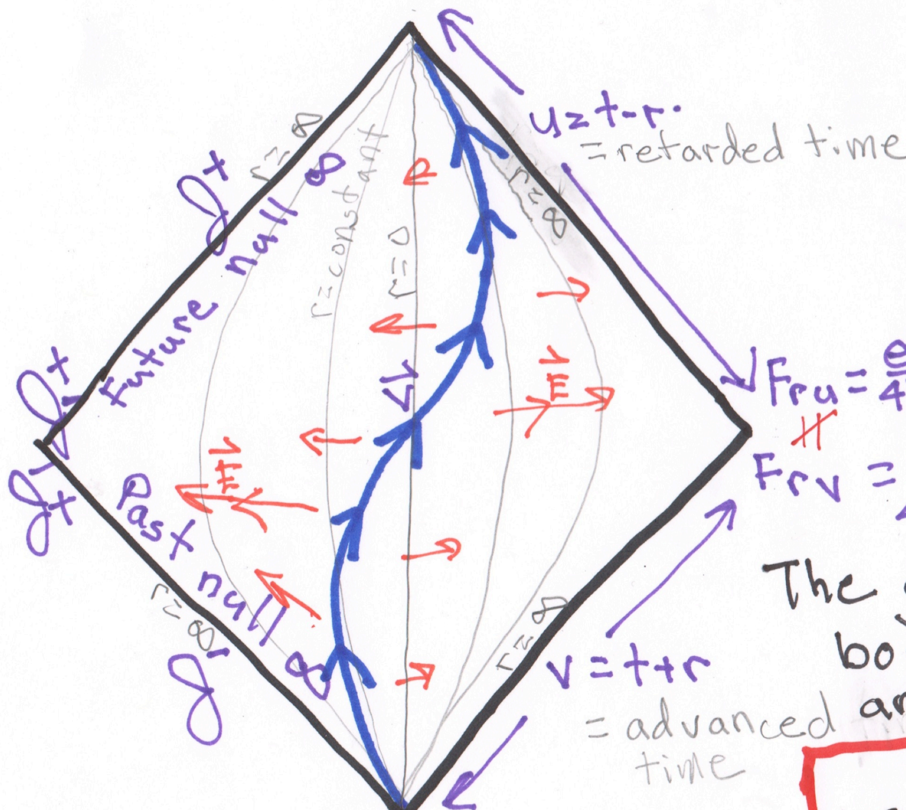


$$F_{rt} = \frac{e}{4\pi r^2}$$

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

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:

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

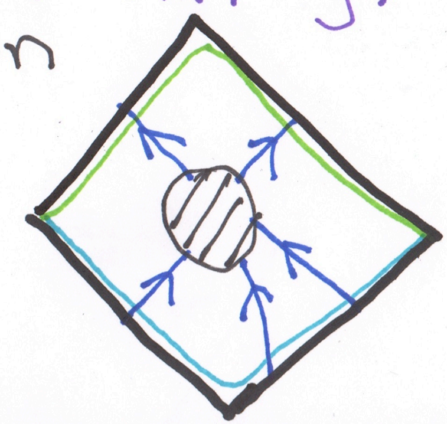
$A = 1, 2$ angle on sphere; antipodal angle on sphere

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 hep-th 1505.05346
Kapec, Pate, AS hep-th 1506.02906

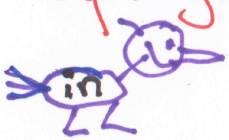
But what are the conservation laws when $\partial_A \varepsilon(\theta^A) \neq 0$???

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 $\quad |out\rangle = S|in\rangle$

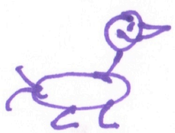
↖ S-matrix

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 <u>any</u> pair $|in\rangle, |out\rangle$ and <u>any</u> 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

$\lim_{\omega \to 0}$  $= A(e_K \ldots)$ 

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 $\Rightarrow Q^+_\varepsilon = Q^-_\varepsilon$

Conservation Laws → Symmetries

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

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 $|0\rangle$

$\exists\ \infty$ 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 $g_{00}(\Theta^A)\big|_{\mathscr{I}^+_-} = g_{00}(\tilde{\Theta}^A)\big|_{\mathscr{I}^-_+}$

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 HLC 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

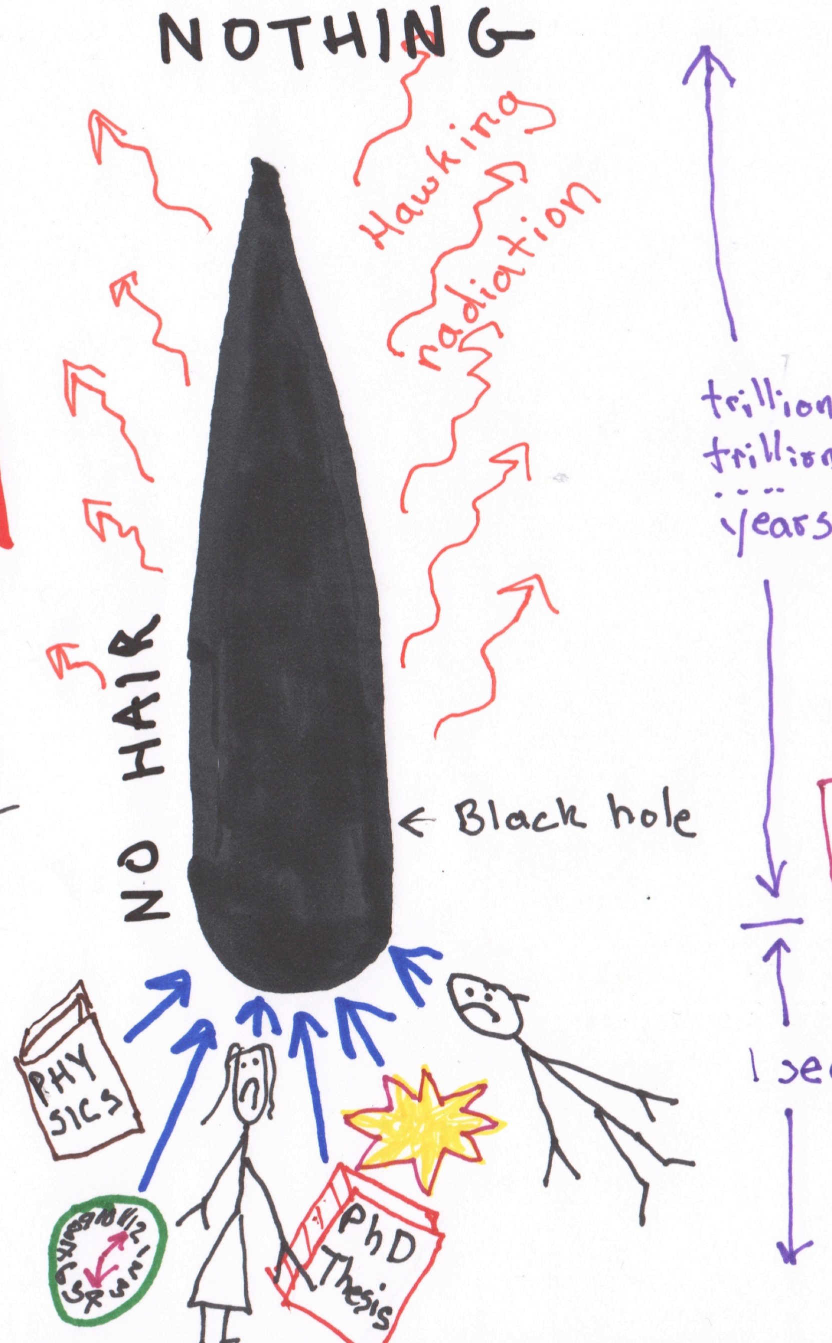
Oddly, though technically more complex, gravity was understood earlier than Maxwell theory!

THE BLACK HOLE INFORMATION PARADOX

Hawking 1975

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

~~DETERM~~INISM



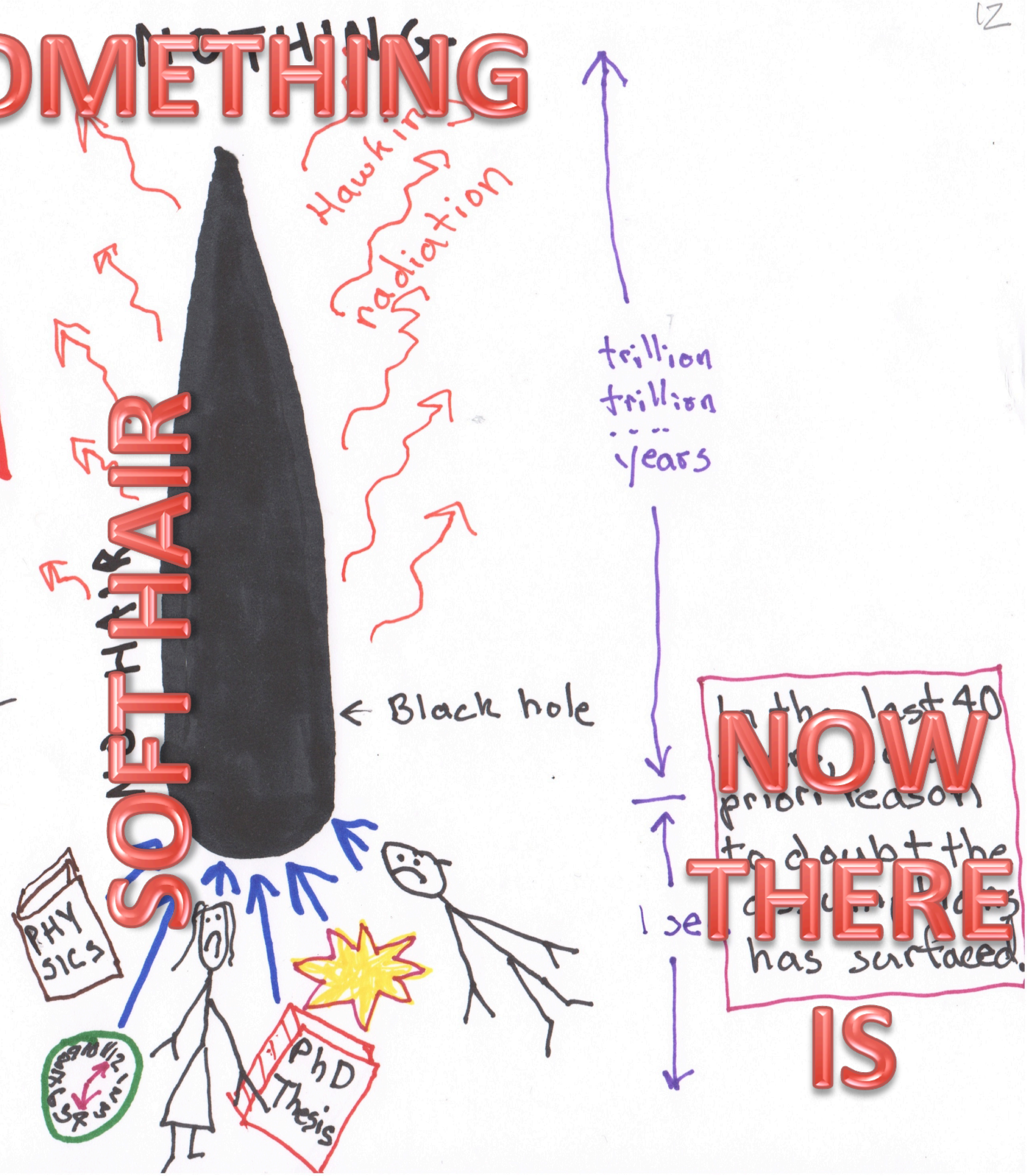
In the last 40 years, no a priori reason to doubt the assumptions has surfaced.

THE BLACK HOLE INFORMATION PARADOX

Hawking 1975

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

~~DETERMINISM~~



Conclusions

I. Recent developments in IR gravity have uncovered a flaw underlying the information loss argument.

II. We have not resolved the information paradox.

III. The nature of the flaw suggests concrete new avenues of investigation, as you will now hear from Malcolm!


THANK YOU!