Title: Black Holes- the Harmonic Oscillators of the 21st Century

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Abstract: In the twentieth century, many problems across all of physics were solved by perturbative methods which reduced them to harmonic oscillators. Black holes are poised to play a similar role for the problems of twenty-first century physics. They are at once the simplest and most complex objects in the physical universe. They are maximally complex in that the number of possible microstates, or entropy, of a black hole is believed to saturate a universal bound. They are maximally simple in that, according to Einstein's theory, they are featureless holes in space characterized only by their mass, charge and angular momentum. This dual relation between simplicity and complexity, as expressed in black holes, has recently been successfully applied to problems in a disparate variety of physical systems. I will give an introduction to the subject intended for a general audience.

BLACK HOLES:

the Harmonic Oscillators of the 21st Century

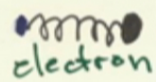
Andy Strominger
Harvard University

PERIMETER INSTITUTE COLLOQUIUM, MARCH 2014 a wide array of problems across physics were solved by mapping them to the harmonic oscillator:

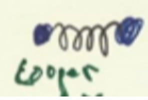
For example:

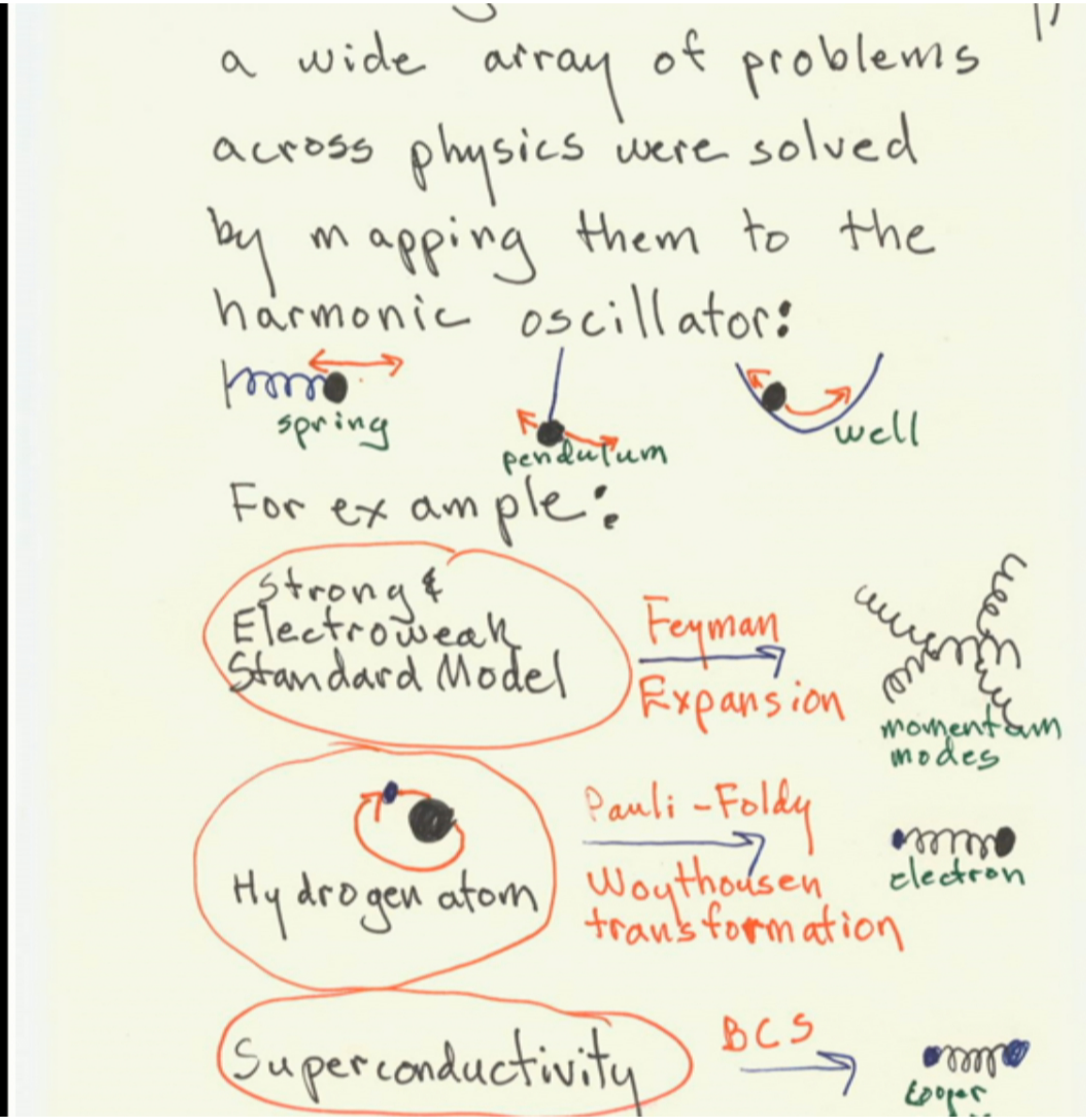
Strong & Electroweak Standard Model → Feyman Expansion

Hydrogen atom → Pauli-Foldy Wouthousen transformation



Superconductivity → BCS

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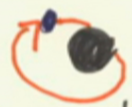

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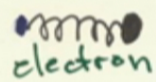

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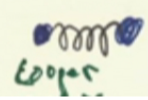
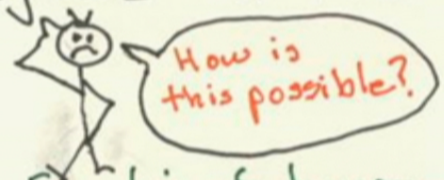


century

They are at once both the simplest and most complex objects in the physical universe.



SIMPLE

According to Einstein-Schwarzschild.. they are empty, featureless holes in space characterized only by M, Q and J.

COMPLEX

According to Bekenstein-Hawking... the number of possible microstates $e^{S_{BH}}$ saturates a universal bound $S_{BH} = \frac{1}{4}$ Area (horizon)

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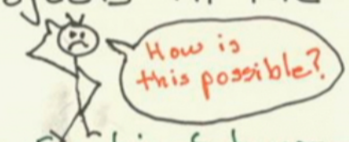

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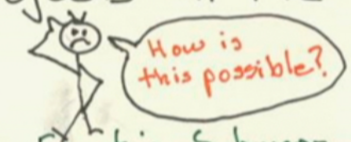

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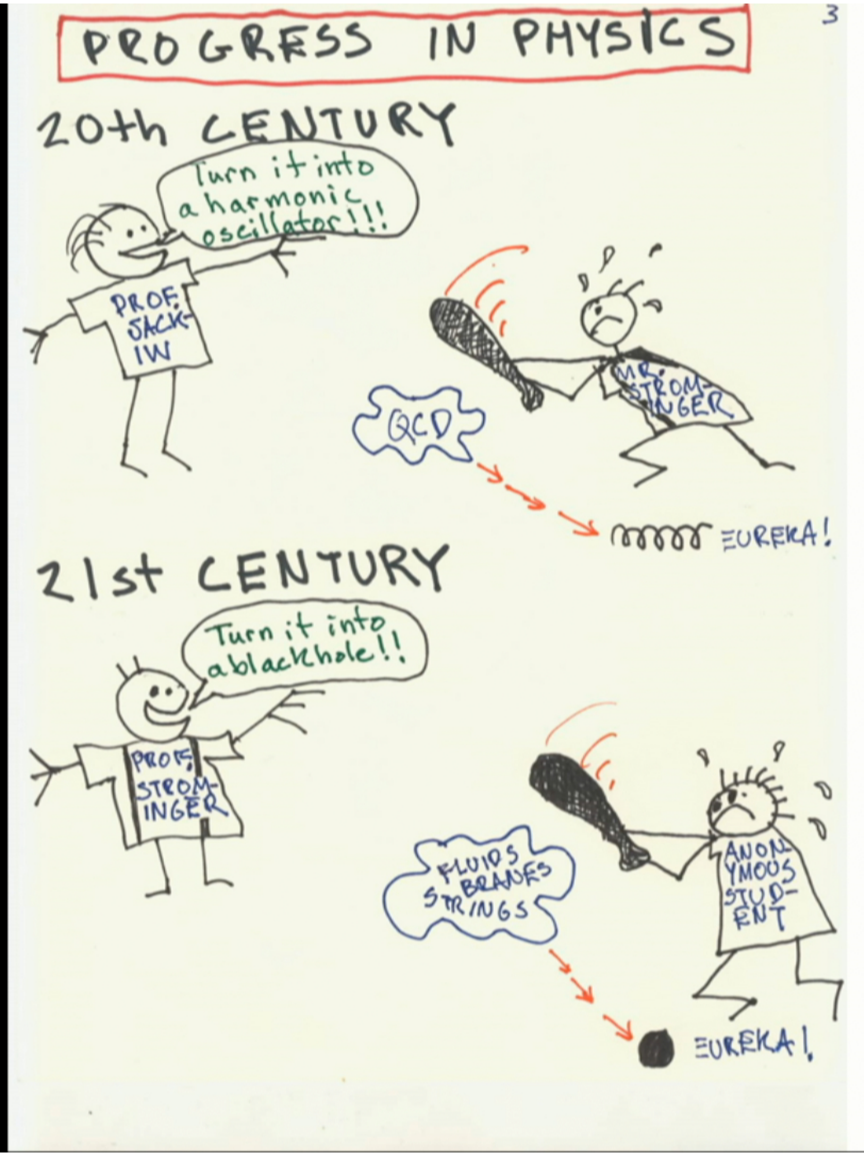

PROGRESS IN PHYSICS
3
20th CENTURY
Turn it into a harmonic oscillator!!!
PROF. SACKIW
QCD
MR. STROMINGER
EUREKA!
21st CENTURY
Turn it into a black hole!!
PROF. STROMINGER
FLUIDS BRANES STRINGS
ANONYMOUS STUDENT
EUREKA!

OUTLINE

I. Brief Bio of the Black Hole 1915- , and What We Have Learned

II. Applications

III Role of string theory

IV Current status & future prospects

Birth of the Black Hole

Nov 25, 1915
Einstein discovers the Einstein equation. Believes exact solution will never be found.

Jan 16, 1916
Exact solution announced by Einstein to Prussian academy. "It is always pleasant to have an exact solution in simple form at your disposal"
— Karl Schwarzchild

May 11 1916
Schwarzchild dies. Russian front

$$ds^2 = -\left(1 - \frac{2GM}{r}\right) dt^2 + \frac{dr^2}{\left(1 - \frac{2GM}{r}\right)} + d\theta^2 + \sin^2\theta \, d\phi^2$$

Nobody knows what it means!

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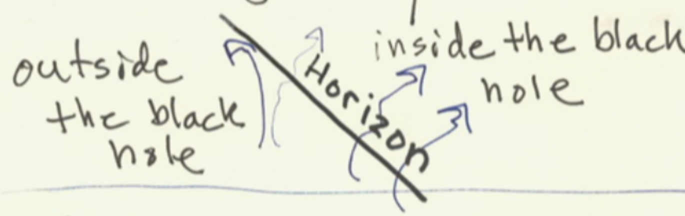
Childhood (confused)

1930's
Chandrasekhar, Oppenheimer Snyder: stars with mass $M > 3 M_{sun}$ collapse into black holes. Einstein disagrees!

1950's
Finkelstein, Kruskal: Horizon (= surface of black hole $r = 2GM$) is a one-way membrane not a singularity



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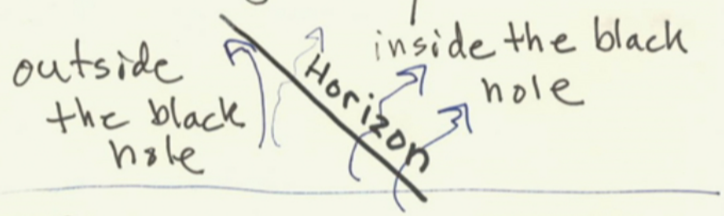

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FIRST LAW

Thermodynamics:

$$T\,dS = dE - \Phi\, dQ - \Omega\, dJ + \ldots$$

Classical Black Hole Dynamics:

$$\frac{K}{8\pi} dA = dE - \Phi\, dQ - \Omega\, dJ + \ldots$$

$K \equiv$ surface gravity
$A \equiv$ area of horizon

The first BH law is related to the "no-hair" theorem: a static BH is characterized by conserved quantities E, Q and J.

Analogy:

$$S \Leftrightarrow A$$

$$T \Leftrightarrow K$$

SECOND LAW

Thermodynamics:

$$\Delta S \geq 0$$

Classical Black Hole Dynamics:

$$\Delta A \geq 0$$

Classical black holes only grow in size.

Analogy:

$$S \Leftrightarrow A$$

Penrose Christodoulou Hawking Bardeen Carter Bekenstein . . .

The Area only increases because matter can go into, but not out of, a black hole:

As Boltzmann explained, Entropy only increases because it measures molecular disorder - hard to prove

but easy to understand. The surprise is that these are in disguise the same phemonena!

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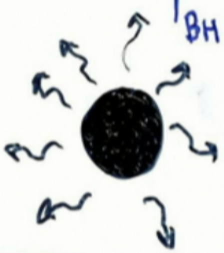
Troubled Quantum Adolescence

Hawking '74 completes the circle: Black holes radiate blackbody radiation at

$$T_{BH} = \frac{K}{2\pi}$$



Observed in the sky?

Planck Units

$\Rightarrow$ $S_{BH} = \frac{1}{4}$ Area Bekenstein-Hawking Entropy

$\Rightarrow$ Unified Laws of BHs + Thermodynamics

Generalized 1rst Law

$$T(dS_{OUT} + dS_{BH}) = dE - \Phi dQ - \Omega dJ + \ldots$$

Generalized 2nd Law

$$\Delta S_{OUT} + \Delta S_{BH} \geq 0$$

$S_{OUT} \equiv$ entropy outside the black hole

Troubled Quantum Adolescence

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Hawking '74 completes the circle: Black holes radiate blackbody radiation at

$$T_{BH} = \frac{\kappa}{2\pi}$$

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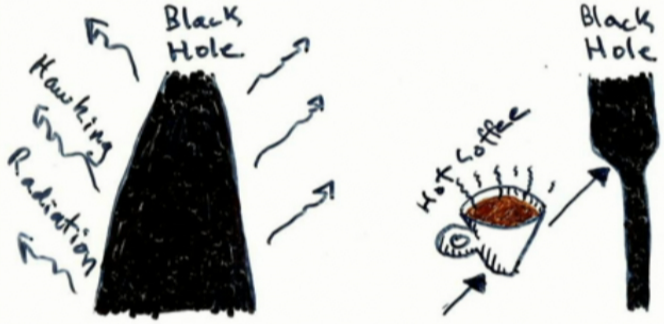

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A series of ingenious gedanken experiments has failed to find violations of the generalized 2nd law $\Delta S_{OUT} + \Delta S_{BH} \geq 0$.

$S_{BH} \sim$ ignorance about black hole interior?

Bekenstein Unruh Wald Hawking Gibbons ...

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We seek a single, unified derivation of the unified laws of BH thermodynamics: to microscopically derive those laws - as Boltzmann did for ordinary thermodynamics by counting BH microstates. ~~We need to show~~

$$S_{BH} = \frac{\text{Area}}{4 G_N \hbar} = \log[\#\text{of BH states}]$$

$$\text{STAT. MECH} = \frac{\text{GRAVITY}}{\text{QUANTUM MECH}}$$

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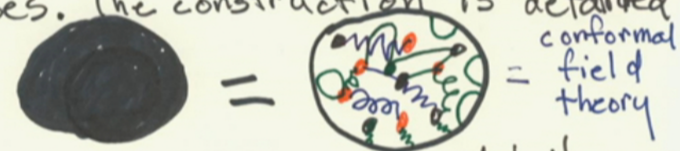

and appears to use many details of string theory. It is the first stringy example of what is now known as the AdS/CFT correspondence. Much light is shed on string theory.

TOPIC FOR A DIFFERENT LECTURE

1997

It is shown (AS) that string theory was not needed! The construction is boiled down to its key ingredients and found to apply to any consistent quantum gravity containing the black hole solutions.

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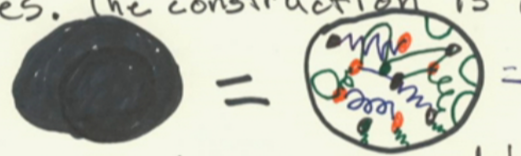

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10 years later 2008

we have obtained a statistical understanding of the thermodynamic behavior of special black holes seen in the sky without using or assuming string theory – but drawing lessons from our experience. Guica, Hartman, Song & AS

These special black holes are called extreme Kerr

the horizon rotates at (nearly) the speed of light.

An extreme 4D

Kerr  black hole

has angular momentum

$J = GM^2$,

Hawking temperature

$T_H = 0$,

and Bekenstein-Hawking entropy

$$S_{BH} = \frac{2\pi J}{\hbar}.$$

GRS 1915+105 has

$M \sim 14 M_\odot$

$$\frac{J}{GM^2} > .98$$

McClintock, Shafee, Narayan, Remillard, Davis & Li (2008)

Recently reported:

Seyfert 1.2 galaxy MCG-6-30-15 has million solar mass BH with (J/GM^2) > .989 !!! Brenneman& Reynolds

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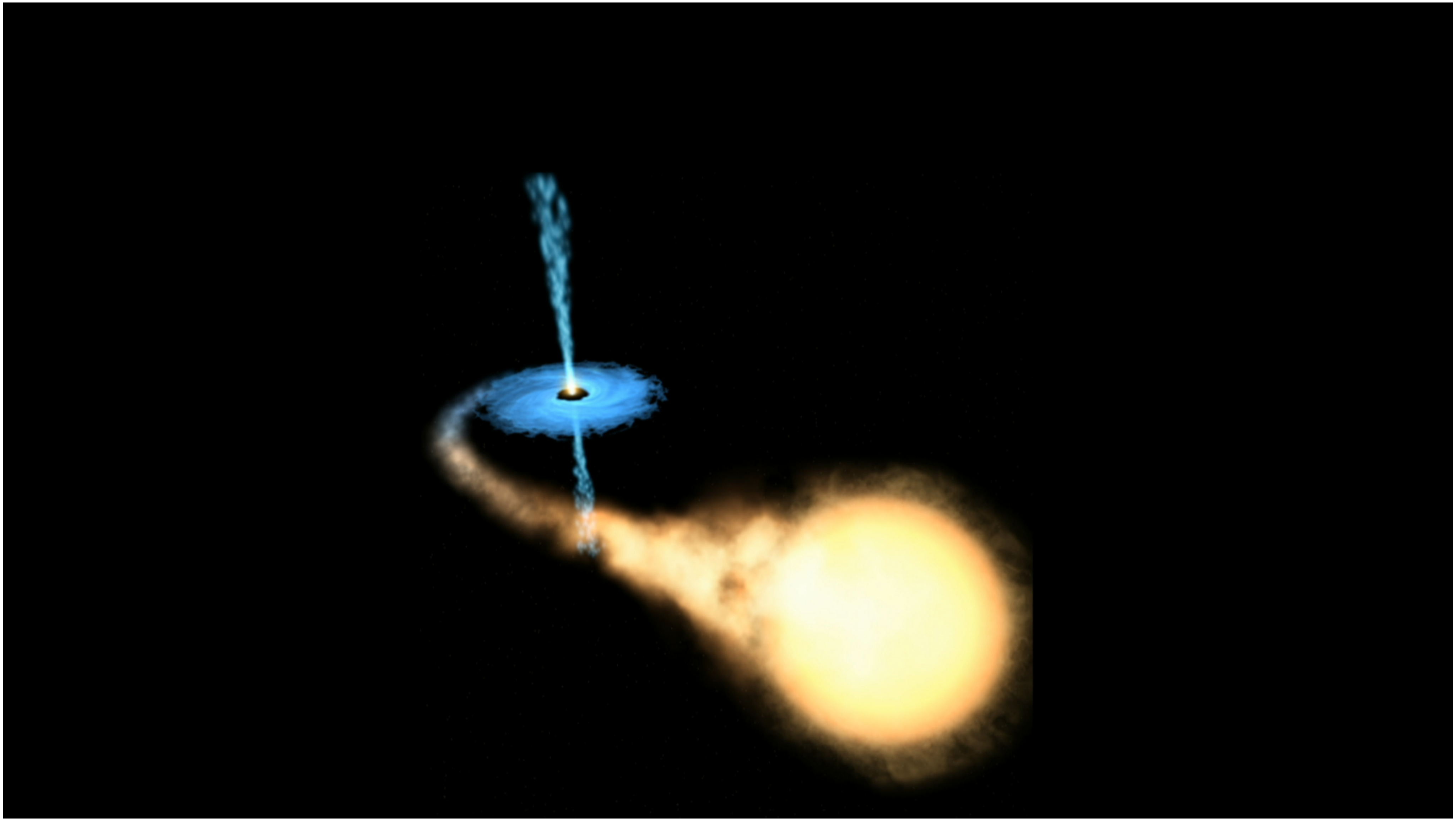

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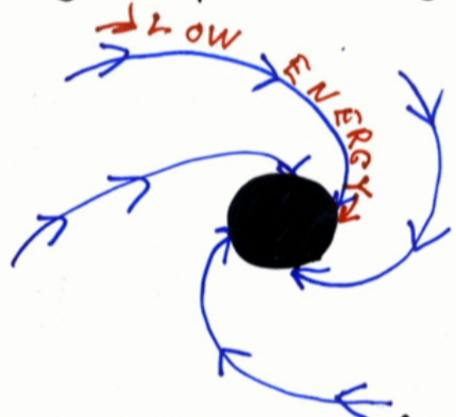
The near-horizon region of extreme Kerr

all excitations must move counterclockwise at the speed of light!

In this very-near horizon region, quantum gravitational



dynamics simplify dramatical much as is the case for e.g. dynamics of Cooper pairs in a superconductor or quantum Hall edge states at low energies. Critical behavior & powerful new symmetries — offspring of diffeomorphisms — arise in the limit.

The fixed point at the near-horizon limit is a 1+1 dimensional conformal field theory with a (ϕ, t) Virasoro algebra

$$[L_m, L_n] = (m-n) L_{m+n} + \frac{c}{12}(m^3 - m)\,\delta_{m+n}$$

and central charge

$$c = \frac{12J}{\hbar}$$

at temperature $T = \frac{1}{2\pi}$.

These facts follow simply from a careful analysis of the properties of general coordinate transformations very near the horizon.

S. A. TEUKOLSKY & W. H. PRESS
APJ 193 (1974)

is the fractional gain (or loss) of energy in a scattered wave, Starobinsky and Churilov find (in our notation)

$$Z = -\frac{k}{\epsilon}[\omega(r_+ - r_-)]^{2l+1}\left[\frac{(l-s)!\,(l+s)!}{(2l)!\,(2l+1)!!}\right]^2 \prod_{n=1}^{l}\left(1 + \frac{k^2}{4\epsilon^2 n^2}\right), \tag{6.2}$$

which shows the amplification (Z positive) in the superradiant regime ($k\omega$ negative).

For $\omega = m\omega_+$, the radial equations can be solved in terms of confluent hypergeometric functions in the special case $a = M$ (maximally rotating hole). Starobinsky and Churilov perturbed away from this solution to find solutions for Z in a neighborhood $\omega \approx m\omega_+$, but with $a = M$ exactly. Here their calculation is generalized to a neighborhood $a \approx M$.

When $a = M$, there are two distinct cases for the behavior of Z, depending on the value of

$$\delta^2 \equiv a^2m^2/M^2 - \lambda - (s + \tfrac{1}{2})^2 . \tag{6.3}$$

(Note that our definition of λ differs from that used by Starobinsky and Churilov by $-2am\omega$.) When $\delta^2 < 0$, Z passes through smoothly through zero as ω passes through $m\omega_+$. When $\delta^2 > 0$, however (which occurs for all modes with $l = m$ and for other modes with l close enough to m), Z oscillates an infinite number of times between two positive values when $\omega \to m\omega_+$ from below, while Z oscillates an infinite number of times between a negative value and -1 when $\omega \to m\omega_+$ from above. The magnitude of the oscillations is generally too small to be seen in numerical work, with one exception: for $s = l = m = 1$, $Z_{max}/Z_{min} = 1.44$. (For comparison, the value for $s = l = m = 2$ is 1.00002.) However, the numerical work of the next section shows no hint of an oscillation, even for $s = l = m = 1$ and $a = 0.99999M$. The reason for this is seen in studying the behavior of Z in the double limit $a \to M$, $\omega \to m\omega_+$.

Appendix A extends the calculation of Z to the case where

$$\alpha \equiv 1 - \omega/(m\omega_+) \ll 1 , \qquad \gamma \equiv (1 - a^2/M^2)^{1/2} \ll 1 . \tag{6.4}$$

The result is

$$\begin{aligned} Z = \sinh^2 2\pi\delta \sinh \pi\kappa \exp(2\pi\hat{\omega})/[&e^{-\pi\delta}\cosh^2 \pi(2\hat{\omega} - \delta)\cosh \pi(2\hat{\omega} + \delta + \kappa) \\ &+ e^{\pi\delta}\cosh^2 \pi(2\hat{\omega} + \delta)\cosh \pi(2\hat{\omega} - \delta + \kappa) \\ &- 2\cos\psi \cosh \pi(2\hat{\omega} + \delta)\cosh \pi(2\hat{\omega} - \delta)\cosh^{1/2} \pi(2\hat{\omega} + \delta + \kappa)\cosh^{1/2} \pi(2\hat{\omega} - \delta + \kappa)] , \end{aligned} \tag{6.5}$$

where $\kappa = ma\alpha/(\gamma M)$, $\hat{\omega} = \omega r_+$, and ψ is defined in equation (A16). The result of Starobinsky and Churilov is recovered by letting $\gamma \to 0$ ($\kappa \to \infty$). For α positive, this gives

$$Z = \sinh^2 2\pi\delta/[\cosh^2 \pi(2\hat{\omega} - \delta) + \cosh^2 \pi(2\hat{\omega} + \delta) - 2\cos\psi \cosh \pi(2\hat{\omega} - \delta)\cosh \pi(2\hat{\omega} + \delta)] , \tag{6.6}$$

where ψ = constant $- 2\delta \ln(2m^2\alpha)$. As $\alpha \to 0$, this exhibits an infinite number of oscillations between

$$Z_{max} = \cosh^2 \pi\delta/\sinh^2 2\pi\hat{\omega} \tag{6.7}$$

and

$$Z_{min} = \sinh^2 \pi\delta/\cosh^2 2\pi\hat{\omega} . \tag{6.8}$$

However, if $\alpha \to 0$ for fixed (small) γ in equation (6.5), we find $Z \to 0$ linearly with α. Thus for fixed small γ there will be a finite number of oscillations before $Z \to 0$. In the favorable case of $s = l = m = 1$, δ^2 is not positive (i.e., eq. [6.5] showing oscillations is not valid) until $a > 0.995M$. Even then, numerical evaluation of equation (6.5) shows that one must have a within 10^{-7} of M before an oscillation becomes visible. Thus for all practical purposes the oscillations can be ignored as a mathematical curiosity of the nonuniform double limit $a \to M$, $\omega \to m\omega_+$.

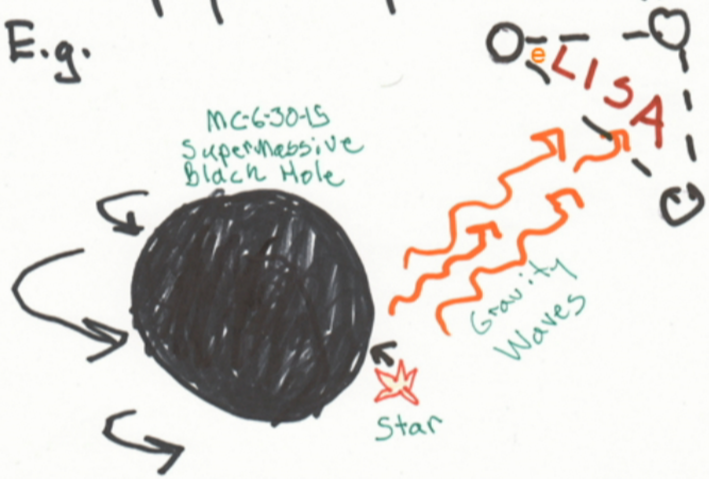
This is exactly a 2D CFT correlator at finite temperature in disguise!

VII. NUMERICAL RESULTS: WAVE ABSORPTION AND SUPERRADIANT SCATTERING

Our primary task is to calculate Z (eq. [6.1]), the fractional gain or loss of energy in a scattered wave. Z is a function of the nondimensional frequency of the wave ωM, the hole's rotation a/M, the mode numbers l and m, and of course $|s|$ which tells what perturbing field we are looking at. Using the results of the preceding sections, the calculation of Z is a straightforward: choose a form of the radial perturbation equation (§ II) which makes the inward boundary condition easy to impose and (importantly!) numerically stable against contamination with the other solution when integrated outward. At some moderate radius, say $r \sim 3M$, use the relations between the solutions (§ III) to switch to a different form of the radial equation, one which makes the ingoing wave solution stable to numerical integration out to radial infinity, and the coefficient of this wave easy to determine there. Completing the integration, use the results of § IV to read off the ingoing energy fluxes at the horizon and at

We hope to use this newly-discovered conformal symmetry to explain, organize or even predict some astrophysical phenomena.

E.g.



A. Porfyriadis & A. Strominger, 1401.3746 and to appear

many systems to consider, much data . . .

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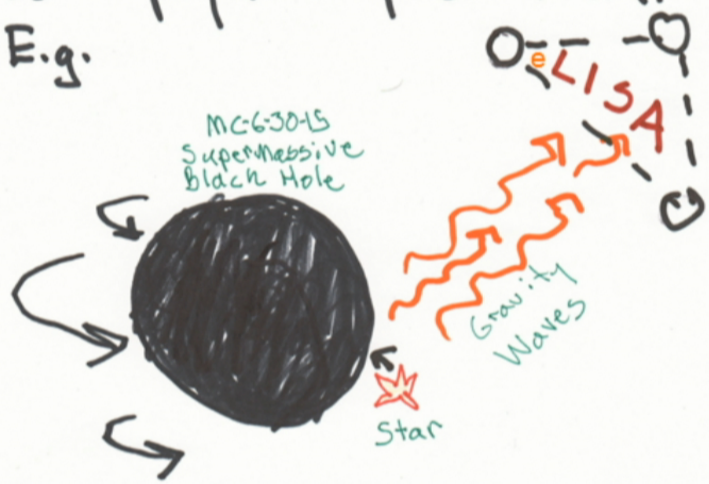

A. Porfyriadis & A. Strominger, 1401.3746 and to appear

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This is known as a

HOLOGRAPHIC DUALITY

SUMMARY

SIMPLE	⟷	COMPLEX
	⟷	
THERMODYNAMICS	⟷	STAT MECH
GRAVITY	⟷	QUANTUM FIELD THEORY
GRS 1915+105	⟷	2D CFT
BULK	⟷	BOUNDARY
HOLOGRAPHIC IMAGE	⟷	HOLOGRAPHIC PLATE

These dualities, whose quintessential realization is the macro/micro description of blackholes, are ubiquitous. They are both conceptually deep and computationally effective.* Our current understanding is very limited, yet there are already many applications....

* simplifications of this talk may be misleading!

Nuclear Physics

Long-lived states in the QCD plasma produced at the **R**elativistic **H**eavy **I**on **C**ollider in Brookhaven

are black holes!

SIMPLE ⟷ COMPLEX
BLACK HOLES ⟷ QCD PLASMA

Surprise appearance of the black hole!

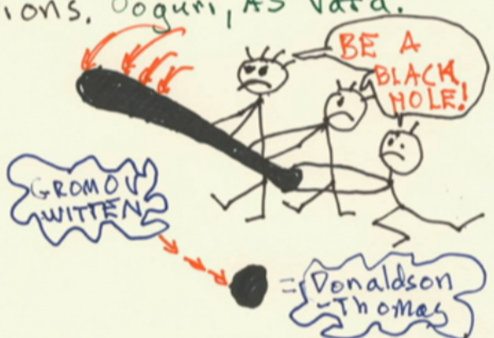
Kovtun, Son, Starinets..
Yaffe, Policastro.....
deWolfe, Gubser, Rosen, Teany

Algebraic Geometry

The Gromov-Witten invariants, which count holomorphic genus g curves in a Calabi-Yau space,

are equivalent to the

Donaldson-Thomas invariants, which count gauge field configurations. Ooguri, AS Vafa.



This equivalence can not be seen by standard algebreogeometric methods!
Many other pure math examples...
wallcrossing Moore Denef Kontsevich Soibelman....

High T_c Superconductivity

The quantum critical behavior of certain High-T_c cuprates has been mapped to the near-horizon of a black hole and then solved in a suitable approximation. This postdicted the anomalous Nernst effect, and has made further predictions awaiting experimental verification.

Hartnoll Kovtun Mueller Sachdev Herzog Son

Graphene

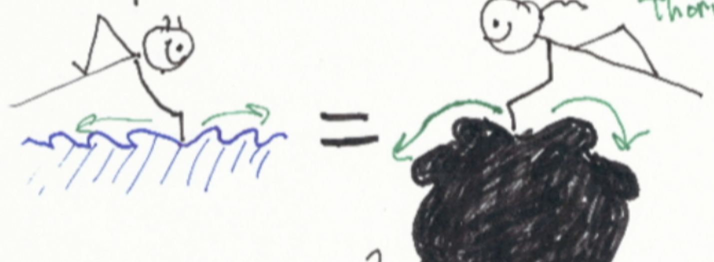
The magnetohydrodynamic electron plasma has been mapped to a black hole and a cyclotron resonance predicted.

Sachdev Kovtun Hartnoll Mueller

FLUID MECHANICS

It has been clear since the 70's that the black hole horizon closely resembles a fluid

Damour
Price
Thorne

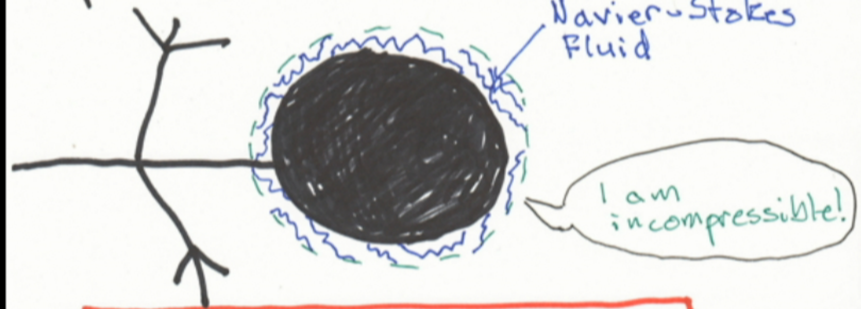


Navier Stokes $\stackrel{?}{=}$ Einstein

Recently, once again using lessons learned from string theory, good progress has been made on this problem

Battacharya Minwalla Wadia
Loganayagam Mandal Sharma Hubeny
Rangamani....

Recently this relation has been elevated to full mathematical precision Bredberg Keeler Lysov & AS



Einstein = Navier-Stokes

$$G_{ab} = 0$$

$$\Updownarrow$$

$$\dot{v}^i + v^k \partial_k v^i - \partial^2 v^i = \partial^i P$$

and Kolmogorov exponent computed with numerical GR!!! Adams Chester Liu

COSMIC CENSORSHIP ⇔ GLOBAL EXISTENCE

??? ⇔ TURBULENCE

There are more examples of surprise black hole appearances, and undoubtedly many more to come.  Before concluding, I will say a few words on the current status and fundamental role of string theory, about which there has been much public confusion.

String Theory

- Was discovered forty years ago as a highly nontrivial perturbative solution to the problem of reconciling quantum mechanics and general relativity. Later it was understood to also include matter and gauge interactions and became a promising candidate for a unified theory of all the forces and particles of nature. Over the decades it has grown into a large and highly cohesive web incorporating many ideas from disparate investigations.

In the last decade we have learned that strings are but one of many equivalent "dual" descriptions of a much larger structure still called M or string theory. 14

M/string theory has no competitors because it eats them all up.

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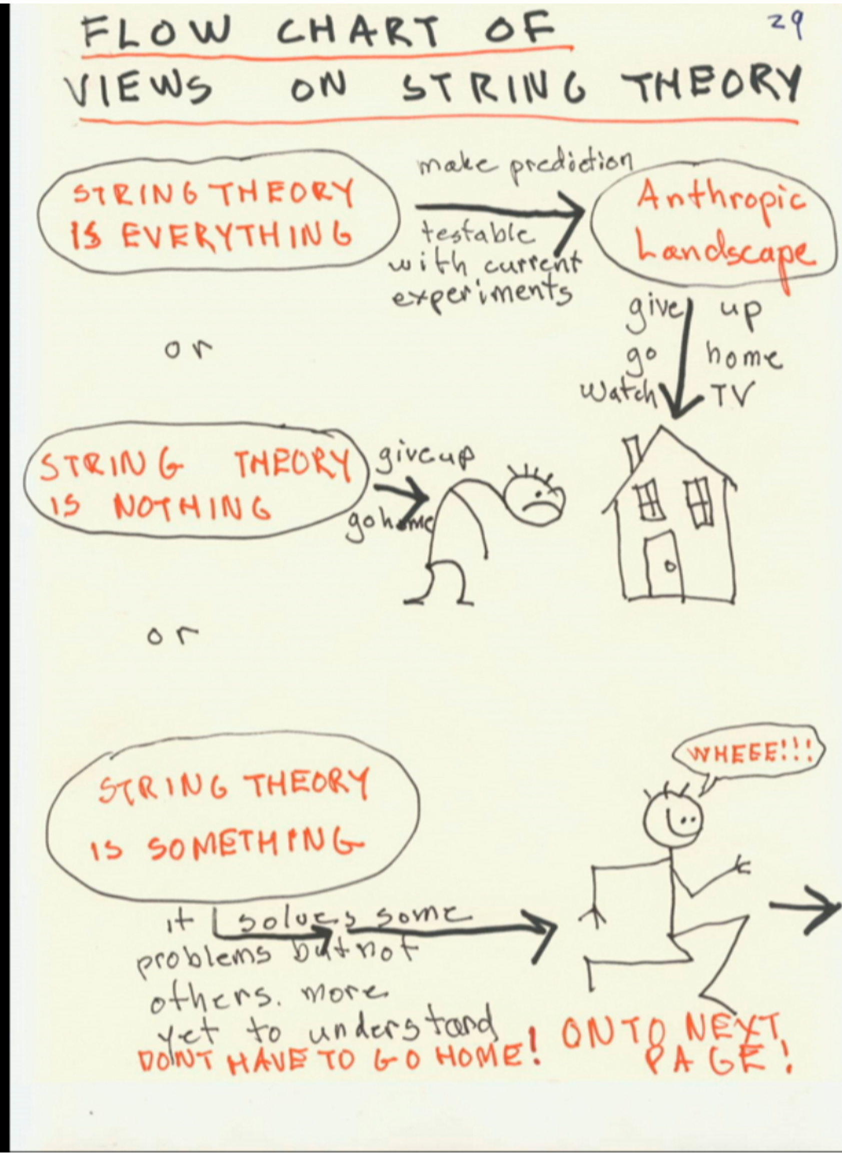
FLOW CHART OF
VIEWS ON STRING THEORY
29
STRING THEORY IS EVERYTHING
make prediction
testable with current experiments
Anthropic Landscape
give up
go home
watch TV
or
STRING THEORY IS NOTHING
give up
go home
or
STRING THEORY IS SOMETHING
it solves some problems but not others. more yet to understand
WHEEE!!!
DON'T HAVE TO GO HOME! ONTO NEXT PAGE!

STRING THEORY REPORT CARD

Issued by A. Strominger Spring Semester 2014

33

	A	B	C	D	F
Not being ruled out as theory of nature	✓				
Unambiguous testable prediction					✓
Potential for LHC signal				✓	
Solving black hole puzzles		✓			
Applications/inspirations for pure math	✓				
Applications/inspirations other areas of physics		✓			
Unification	✓				
Uniqueness				✓	
Solving the cosmological constant problem					✓
Understanding the Big Bang/Origin of Universe				✓	
Solving Pauli's renormalizability problem	✓				

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