Black Holes

in

String Theory

Outline

1) Review current ideas about B.H. in string theory

2) Two misconceptions

3) New results on B.H. in AdS

4) A surprise

Black p-branes

Solutions to 10D or 11D SUGRA
with extended horizons

Can carry RR charge

$$Q = \int {}^{*}F_{p+2}$$

Simplest solutions had

- maximal symmetry
- two parameters $M \geq Q$
- extremal limit $M = Q$

Generalizations:

1) Angular momentum
2) Multiple charges
3) Traveling waves

String theory includes fundamental sources called D-branes (Polchinski)

$$\left.\frac{\text{charge}}{\text{mass}}\right|_{\text{D-brane}} = \left.\frac{\text{charge}}{\text{mass}}\right|_{\substack{\text{extreme}\\\text{black}\\\text{p-brane}}}$$

Low energy excitations of N // D-branes ($gN \ll 1$)

described by $U(N)$ gauge theory

$\Downarrow$

Have possibility of counting quantum states of B.H. for first time

For three branes ($p=3$)

$gN \ll 1$: Count # of states of 3+1 Yang-Mills at temp. T

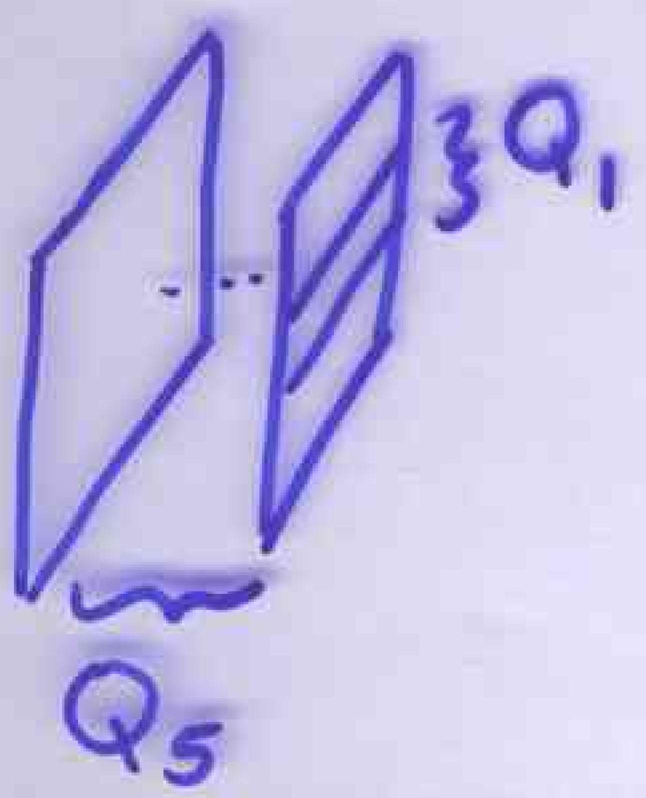
$gN \gg 1$: Compute Bekenstein-Hawking entropy of black three brane at same temperature

Find: $\boxed{S_{BH} = \frac{3}{4} S_{YM}}$

(Gubser, Klebanov, Peet; Strominger)

For 5-branes + 1-branes

Suppose four dim are compactified on small T^4



$g^2 Q_1 Q_5 \ll 1$: Get 1+1 dim conformal field theory

$g^2 Q_1 Q_5 \gg 1$: Get black string in six dim.

Find: $\boxed{S_{BH} = S_{CFT}}$

(Strominger, Vafa)

Why does this work?

For special case where $P = E$ (excite only rt. moving modes) there is unbroken susy. Black string remains extremal. Can count BPS states.

But entropy agrees even when $P = 0$, when $J \neq 0$ ...

Spectrum of Hawking radiation also agrees

And Maldacena said:

$$\mathrm{AdS} \equiv \mathrm{CFT}$$

i.e. the CFT describes the near horizon geometry

How does this explain agreement?

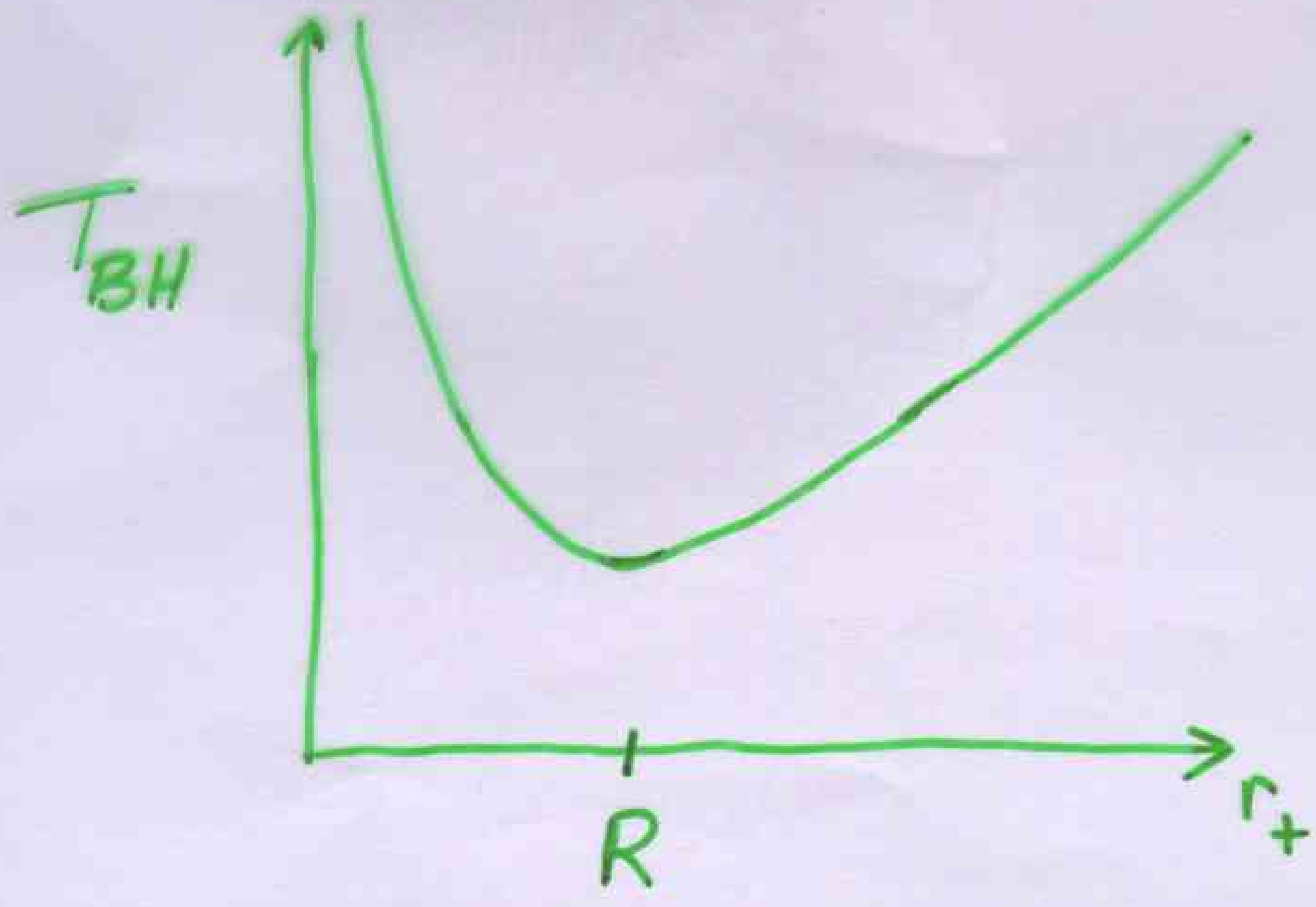
For near extremal solns, near horizon geometry is BH in AdS

For AdS_3, get BTZ black hole. Locally has constant curvature $\Rightarrow$ no string corrections

The formation of a large BH in AdS corresponds to the gauge theory evolution of a very special high energy state into a typical (approx. thermal) state.

The formation and evaporation of small BH's in AdS is described by unitary evolution in gauge theory

Misconception 1: Small B.H.



B.H. with $r_+ \ll R$ have negative specific heat $\Rightarrow$ they will evaporate

But these B.H. can still have more entropy than same energy in radiation

At fixed energy, small B.H. will evaporate slightly & come into equil. with Hawking radiation unless

$$\frac{r_+}{R} < \frac{1}{N^{2/17}} \qquad \text{(in 10D)}$$

These stable small B.H. are described by <u>typical</u> states in gauge theory.

Misconception 2:

Scale - radius duality

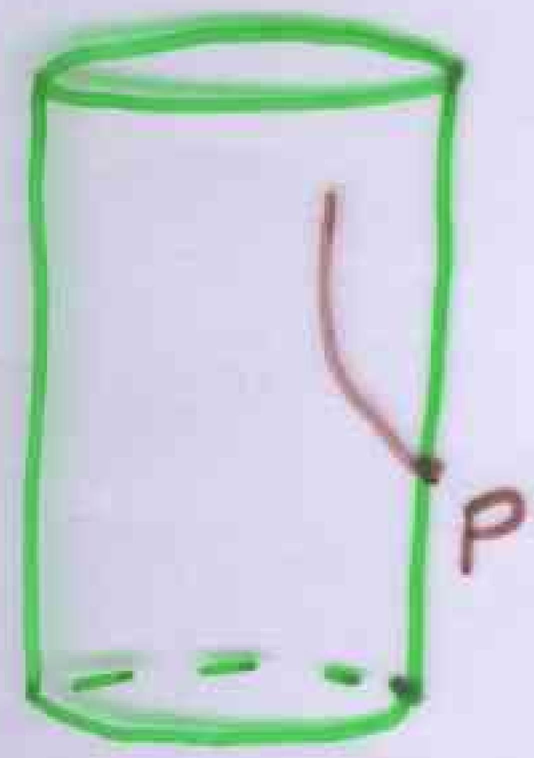
scale size in SYM $\longleftrightarrow$ radial position in AdS

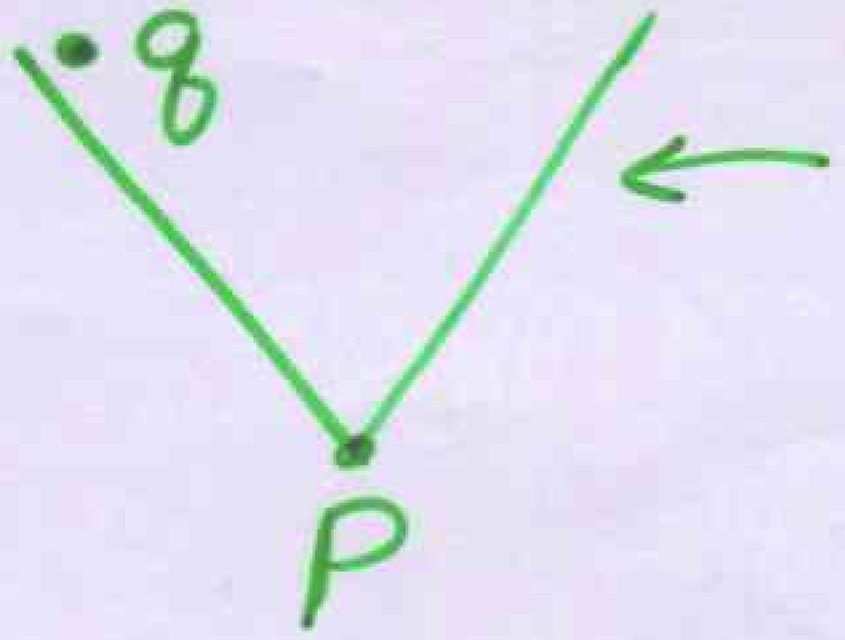
Simple example (Itzhaki, G.H.)

A radial null particle is described by $\langle T_{\mu\nu} \rangle$ in SYM concentrated on light cone.

What if particle changes its orbit inside AdS?

Ans: $\langle T_{\mu\nu} \rangle$ continues to grow with speed of light even if particle stops at radius r





Causality $\Rightarrow$ field at q depends only on particle near p - <u>Not</u> what happens inside

Quasinormal Modes

(Hubeny, G.H.)

A field in AdS has normal modes with discrete real frequencies.

A field in Schwarz. AdS has "quasinormal" modes with discrete complex frequencies

$$\phi = \psi(r)\, Y(\text{angles})\, e^{-i\omega t}$$

$$\text{Im } \omega < 0$$

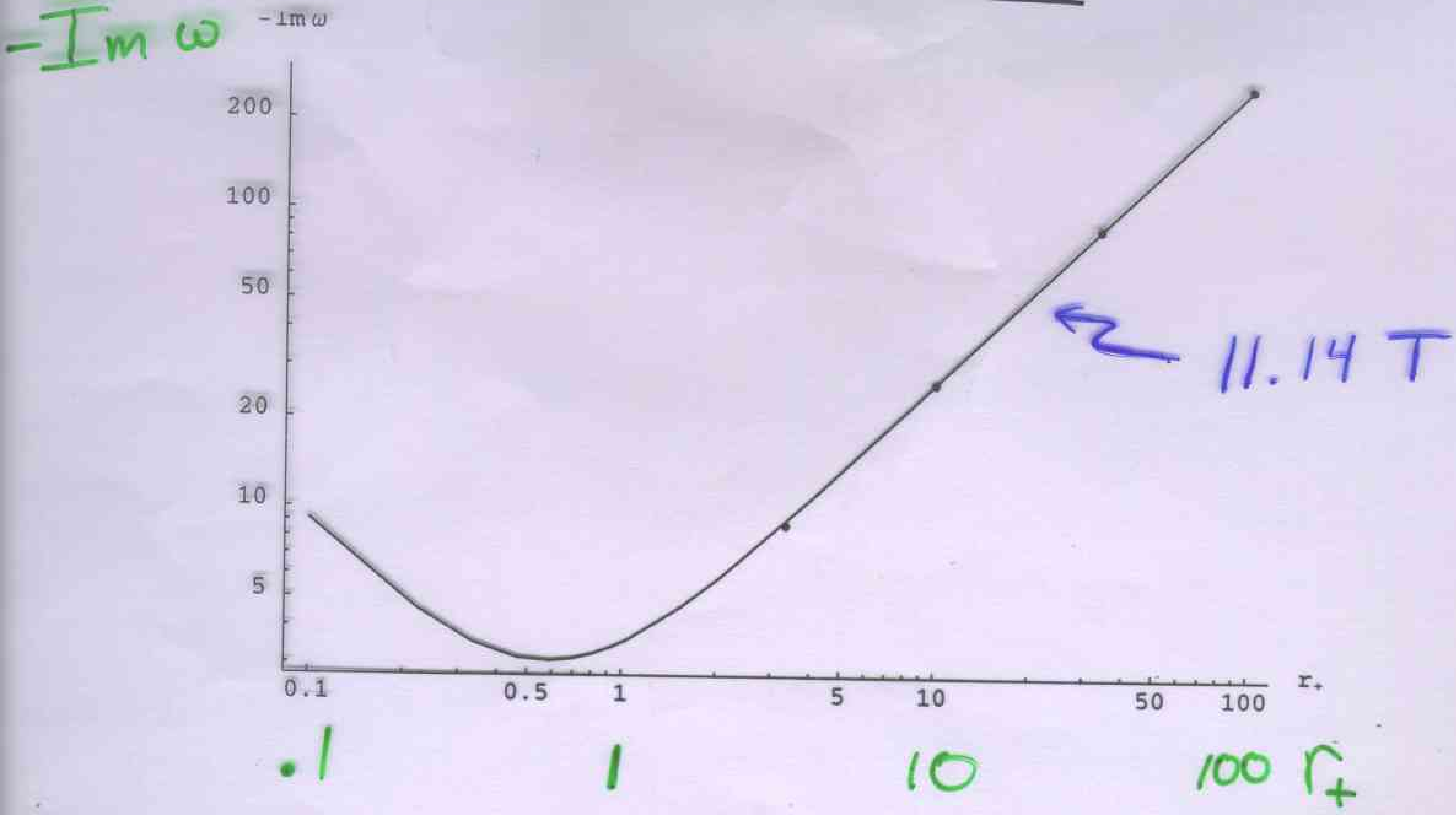
Lowest mode gives decay of the field

$\equiv$ decay of $\langle \mathcal{O} \rangle$ in CFT

For large BH, this yields timescale to return to thermal equilibrium in CFT

Timescale is universal: independent of initial perturbation.

BH in AdS$_4$


-Im ω
-Im ω
200
100
50
20
10
5
0.1
0.5
1
5
10
50
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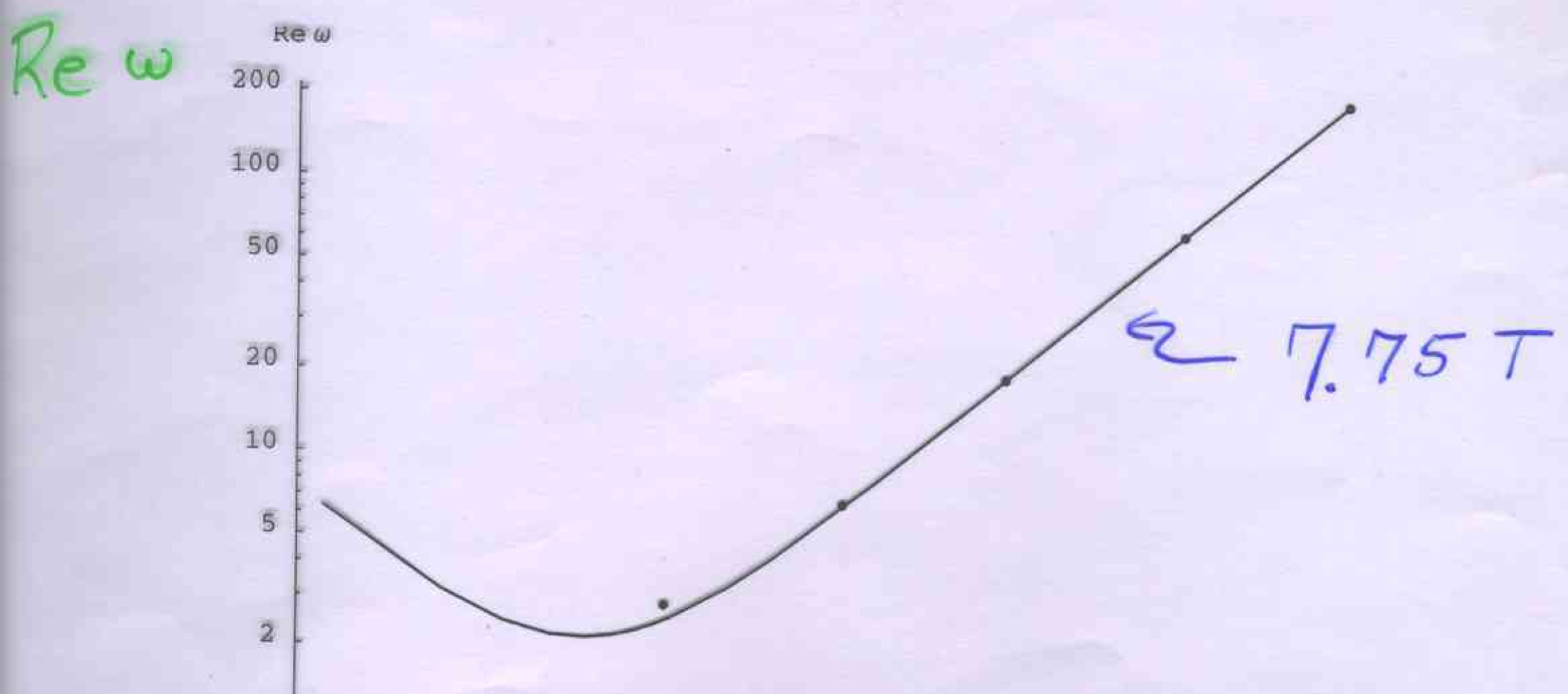
r+
11.14 T
.1
1
10
100 r+


Re ω
Re ω
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100
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10
5
2
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r+
7.75 T
.1
1
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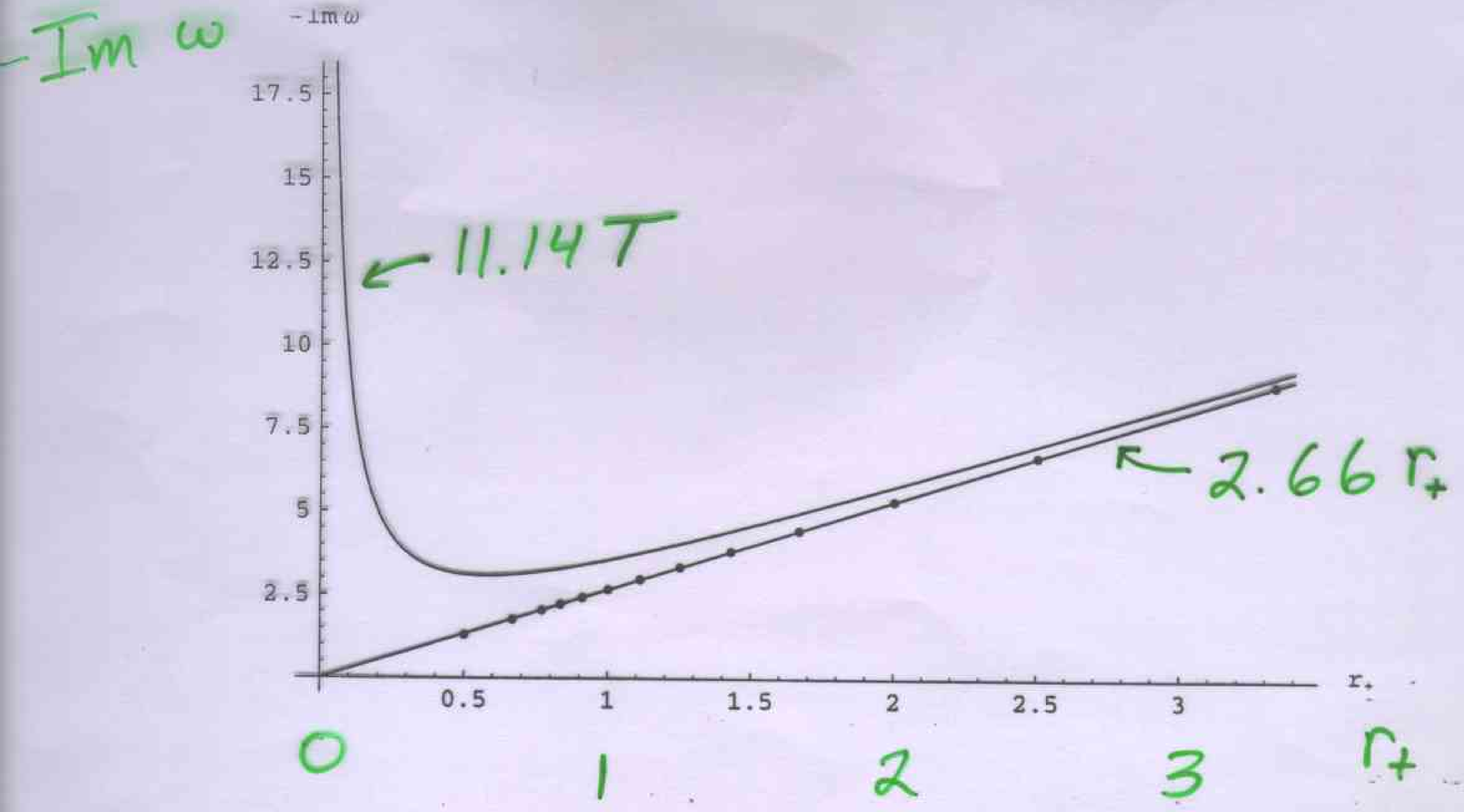
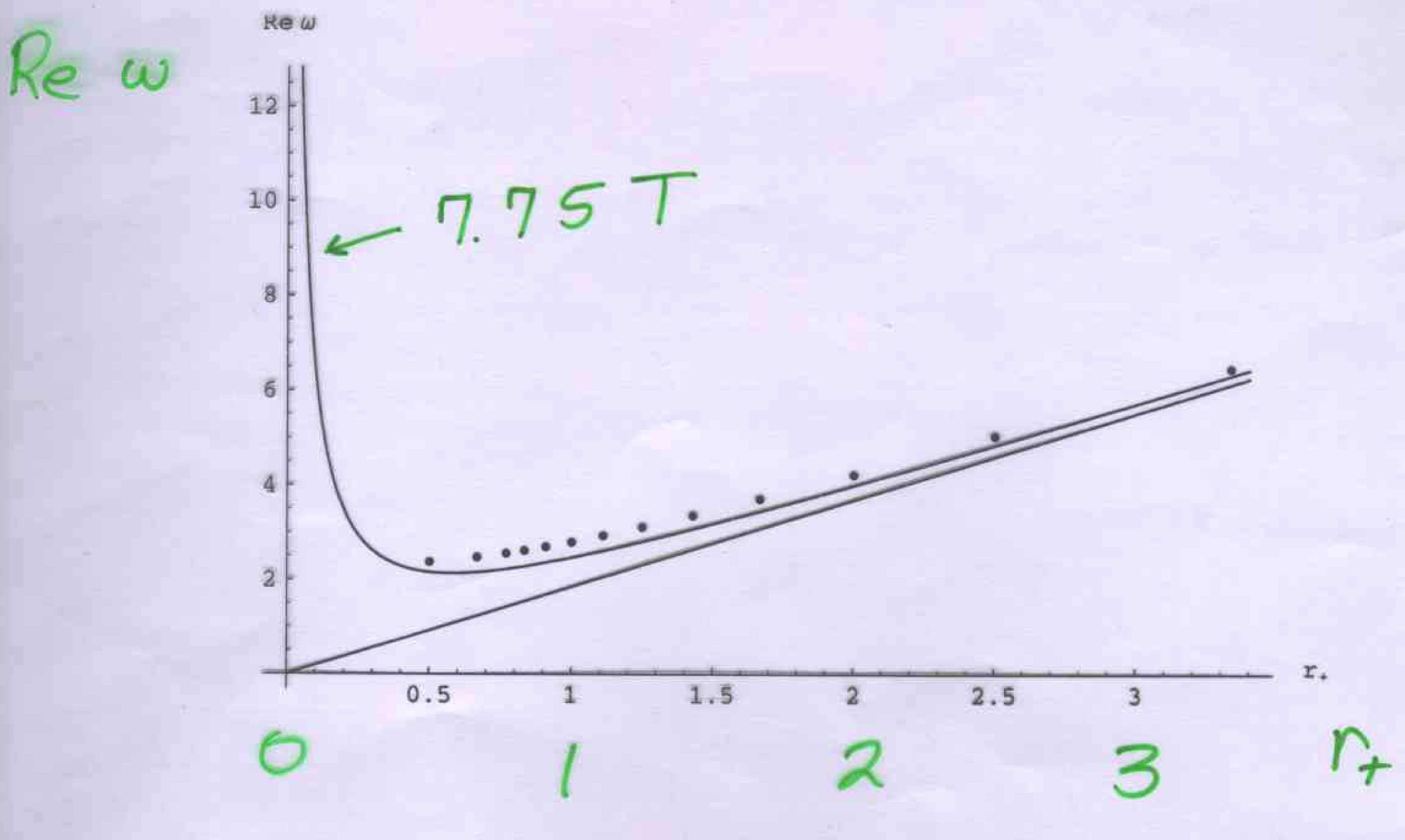
r+

BH in AdS_4



-Im ω
-Im ω
17.5
15
12.5
10
7.5
5
2.5
0.5
1
1.5
2
2.5
3
r+
11.14 T
2.66 r+
0
1
2
3
r+



Re ω
Re ω
12
10
8
6
4
2
0.5
1
1.5
2
2.5
3
r+
7.75 T
0
1
2
3
r+

BH Critical Phenomena

Gravitational collapse of S.S. scalar field can either disperse or form BH

Near transition point

$$M_{BH} \sim |p - p_*|^{\gamma}$$

(Choptuik)

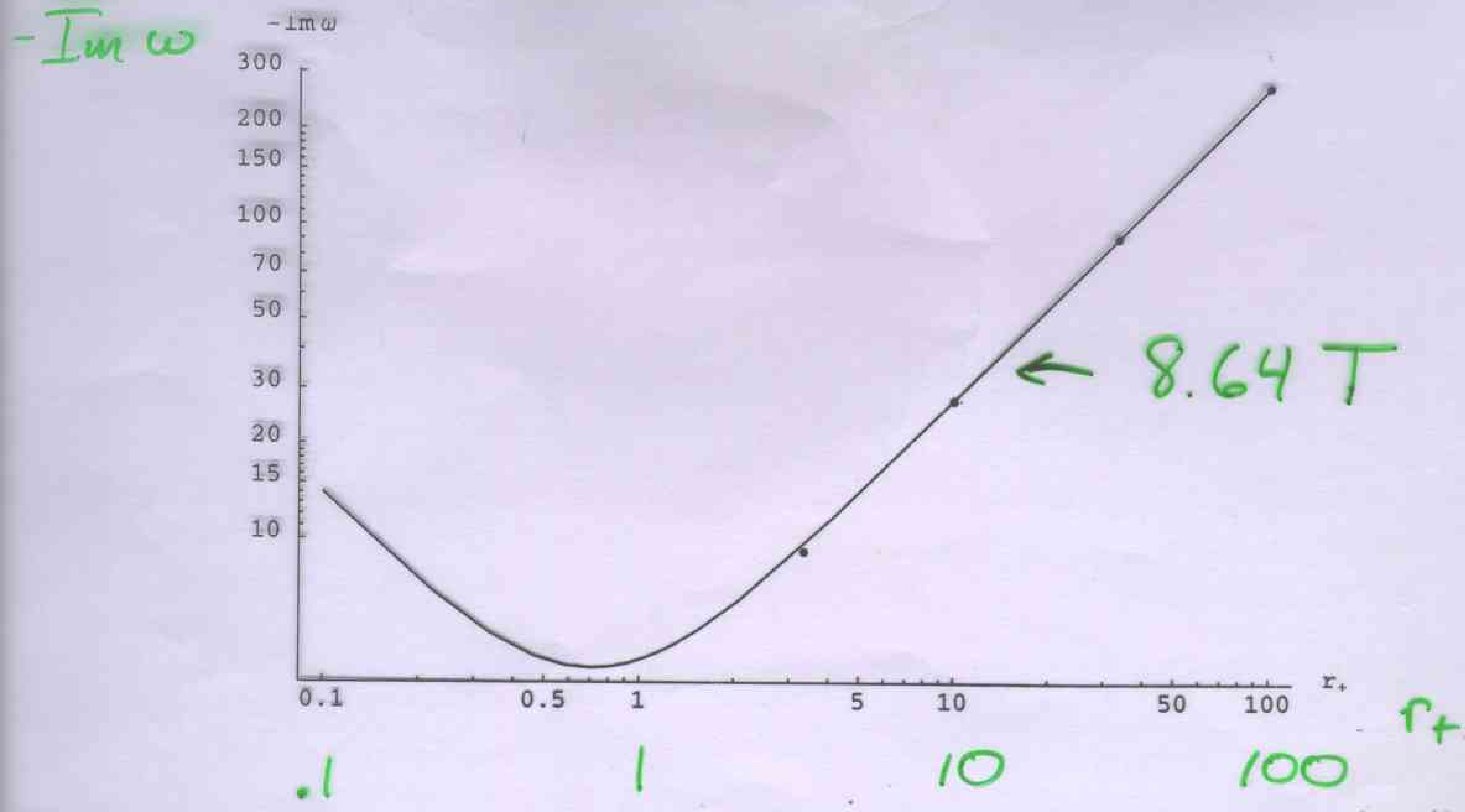
$$\gamma \approx .374$$

Soln with $p = p_*$ has one unstable mode $\sim e^{+\lambda\tau}$ with

$$\lambda = 1/\gamma \approx 2.67$$

agrees with slope of $\mathrm{Im}\,\omega$

BH in AdS_5


-Im ω
-Im ω
300
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0.1
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5
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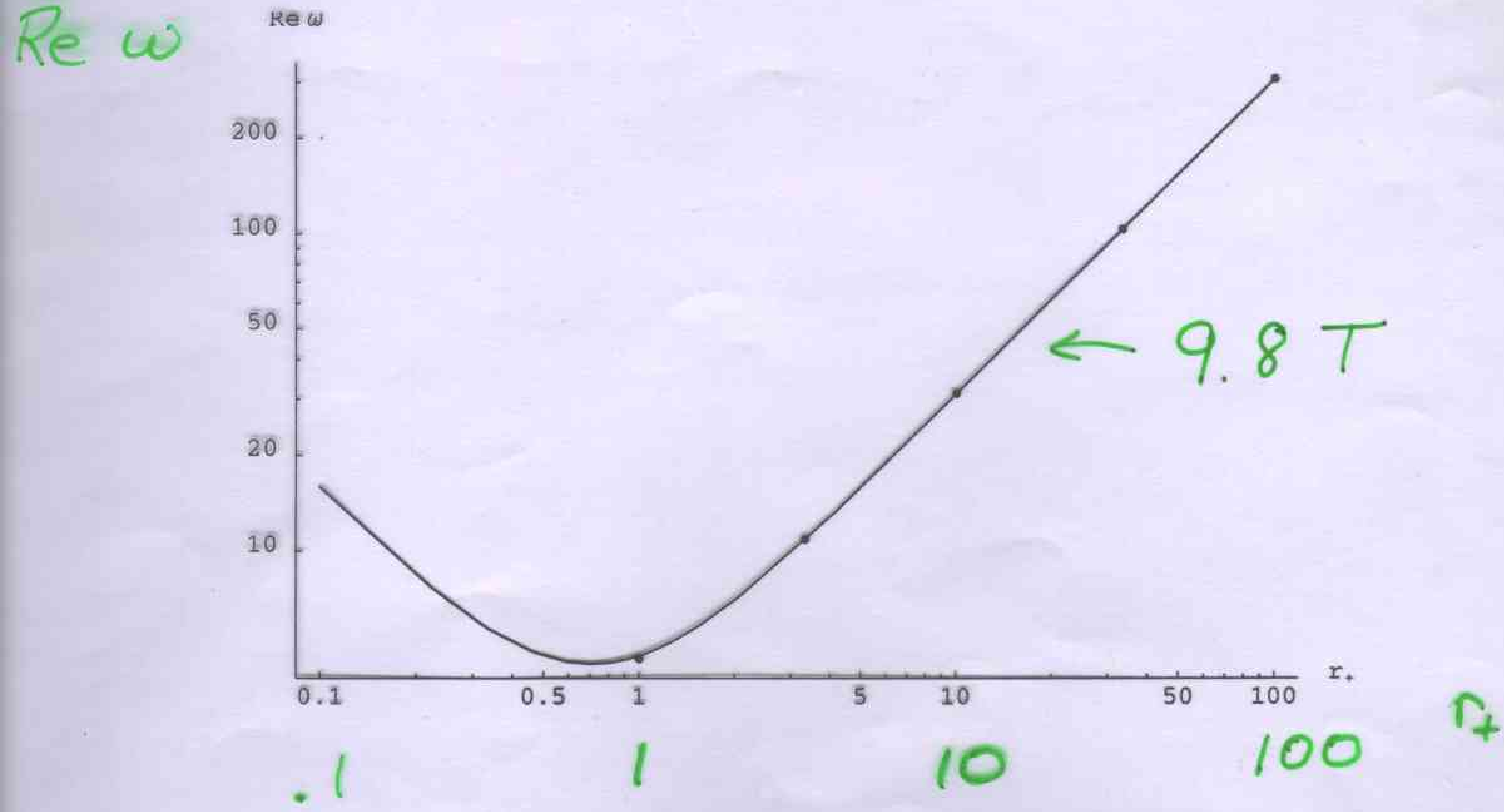
100
r₊
← 8.64 T
r₊
.1
1
10
100


Re ω
Re ω
200
100
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20
10
0.1
0.5
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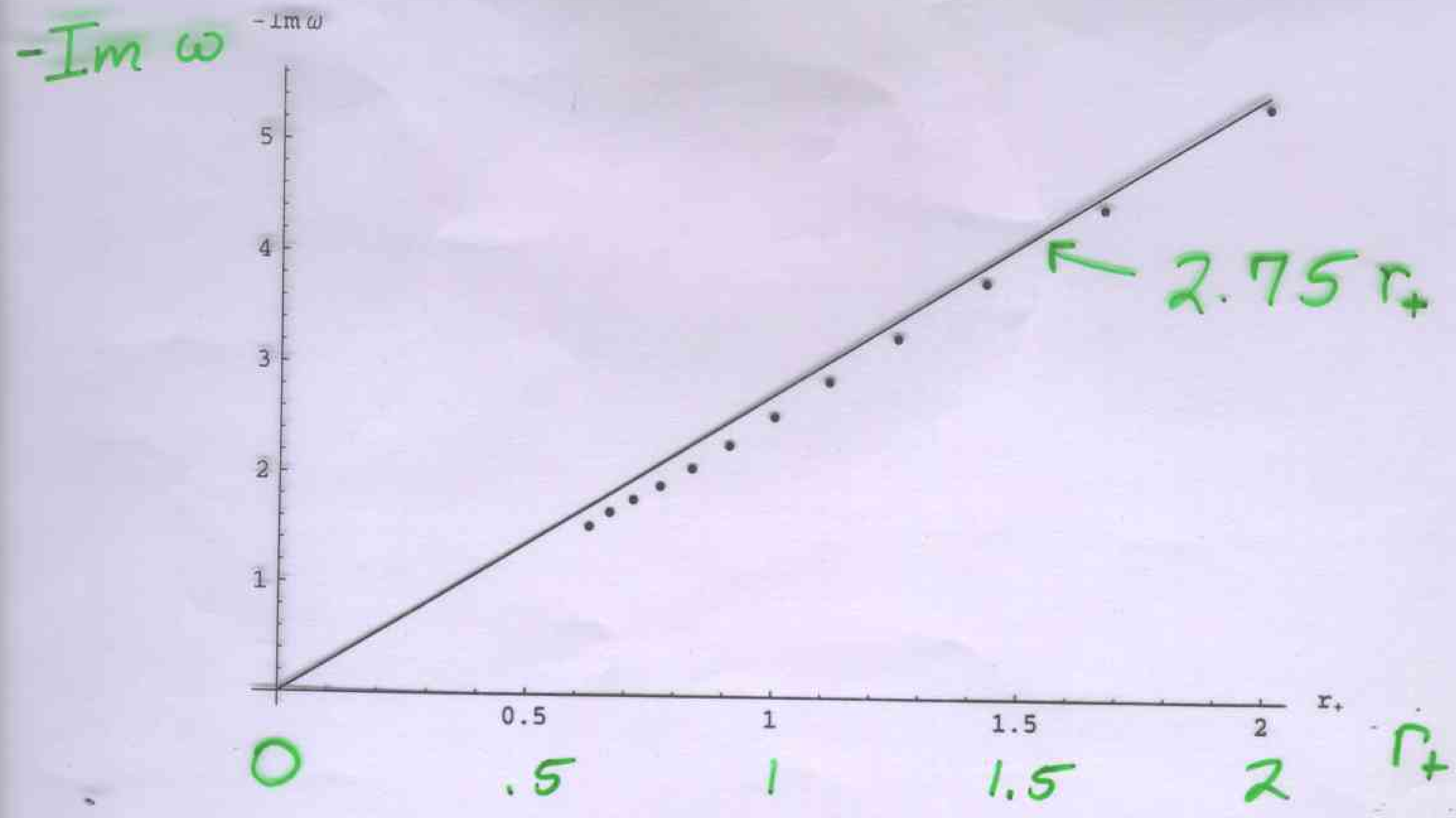
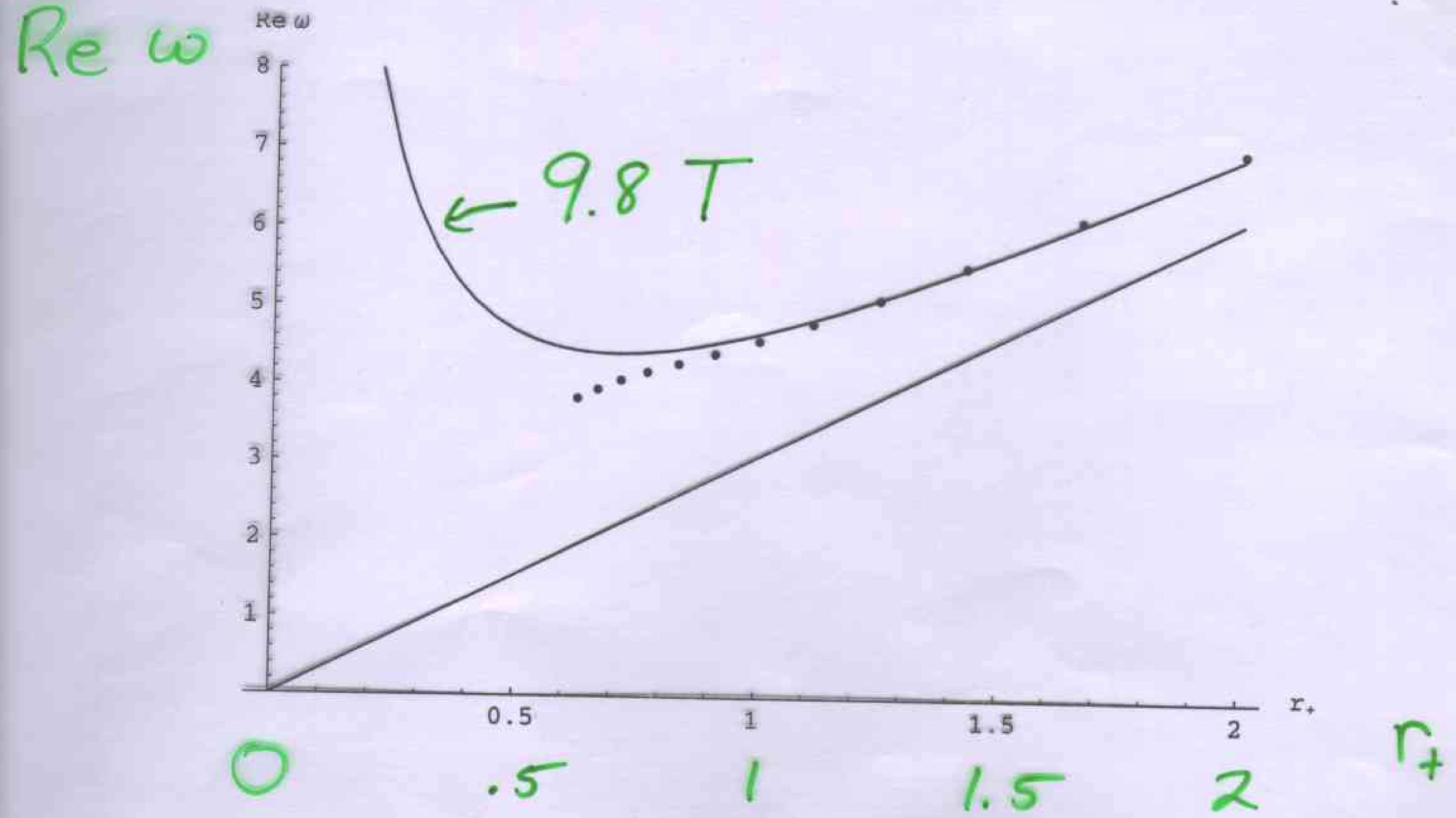
5
10
50
100
r₊
← 9.8 T
r₊
.1
1
10
100

BH in AdS_5



-Im ω
- Im ω
5
4
3
2
1
0.5
1
1.5
2
r+
2.75 r+
0
.5
1
1.5
2
r+



Re ω
Re ω
8
7
6
5
4
3
2
1
9.8 T
0.5
1
1.5
2
r+
0
.5
1
1.5
2
r+

Three Wishes

1) Explanation of 3/4 factor in 3-brane entropy

2) Exact calculation of entropy for Schwarzschild

3) Understand how old information loss arguments break down

Challenge for the new millennium

We need a <u>spacetime reconstruction theorem</u> to recover spacetime from dual CFT. This will finally explain why

$$A_{BH} = 4 G \hbar S$$