

Beyond Schwarzschild: quantum implications for black holes

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Karl Schwarzschild Meeting 2015
FIAS

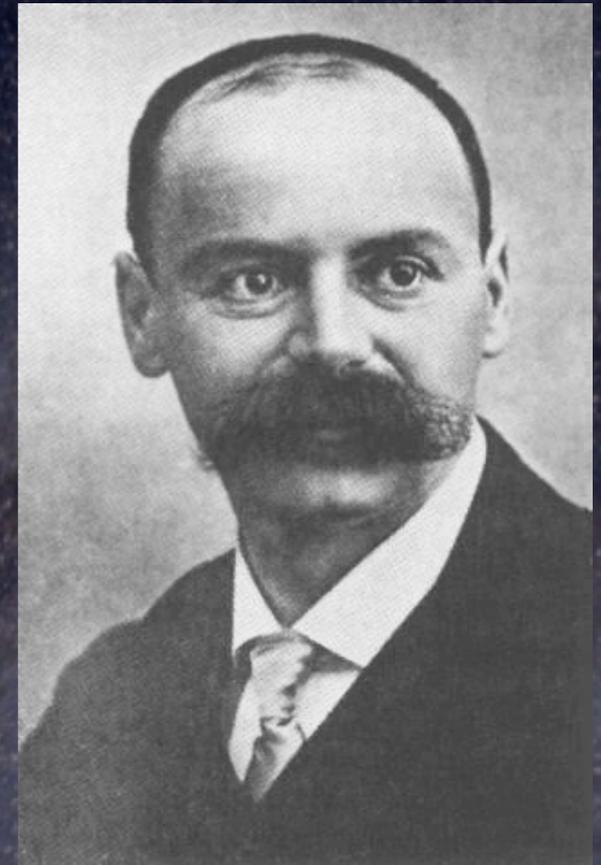


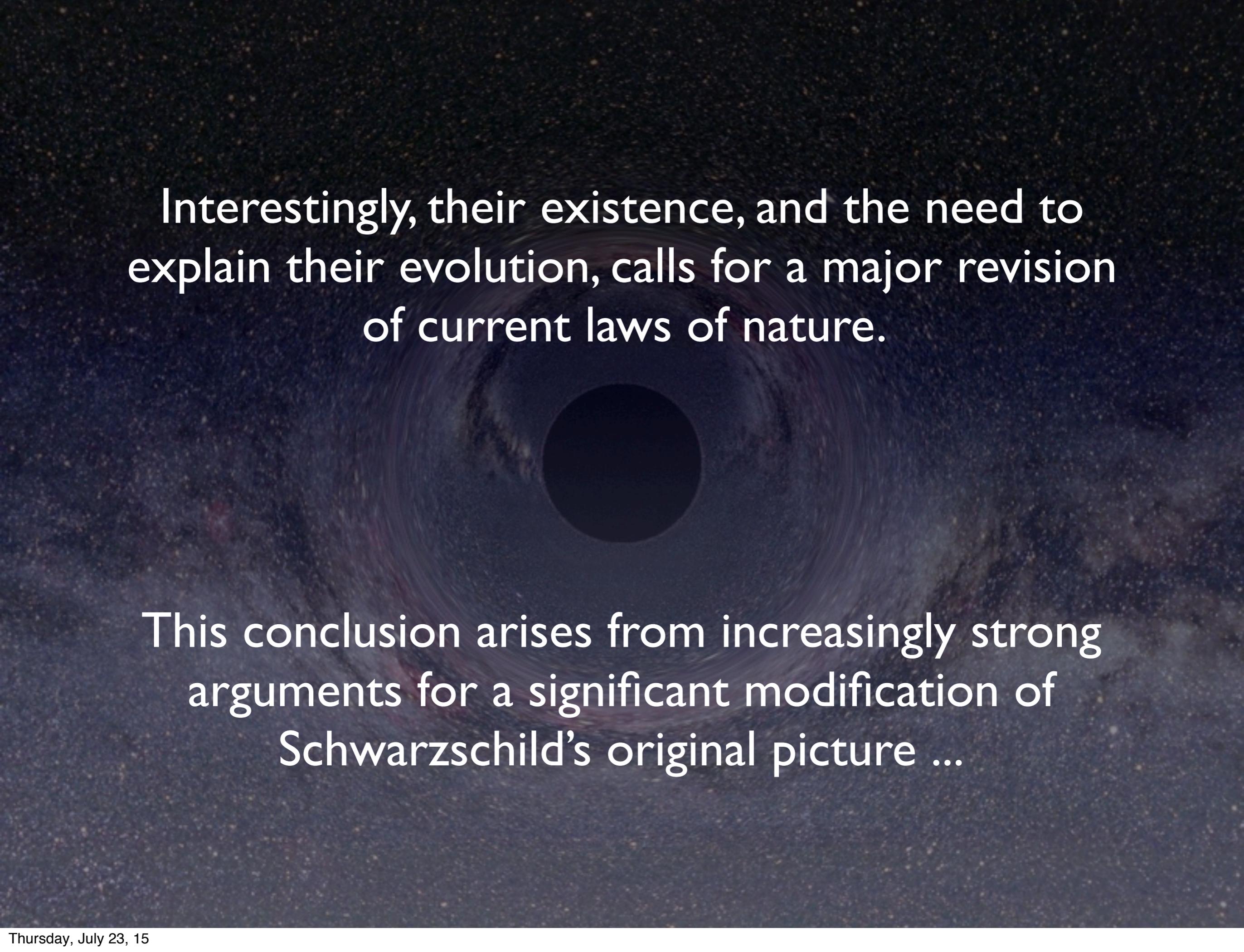
Black holes are the most profoundly mysterious objects in nature.

While the BH concept first originated w/ Michell (1783) and Laplace (1796), Schwarzschild first placed them in our current understanding of gravity:

1916: Schwarzschild solution

$$ds^2 = (1 - \alpha/R) dt^2 - \frac{dR^2}{1 - \alpha/R} - R^2 (d\vartheta^2 + \sin^2 \vartheta d\phi^2), \quad R = (r^3 + \alpha^3)^{1/3}. \quad (14)$$



A black hole with a glowing accretion disk against a starry background. The black hole is a dark, circular void in the center, surrounded by a bright, multi-colored ring of gas and dust. The background is a deep blue and purple space filled with numerous small, distant stars.

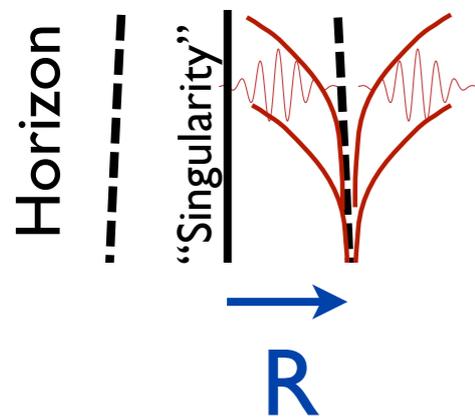
Interestingly, their existence, and the need to explain their evolution, calls for a major revision of current laws of nature.

This conclusion arises from increasingly strong arguments for a significant modification of Schwarzschild's original picture ...

A first crucial update: Hawking 1974

Include quantum effects;

Black hole



$$\omega \sim \frac{1}{R}$$

$$\frac{dM}{dt} \sim -\frac{1}{R^2}$$

Black holes evaporate

This is based on physics we know and love ...

Semiclassical spacetime + local QFT

... but yields a fundamental conflict

- Entanglement between BH and environment grows: monotonic
- If BH disappears, unitarity violated

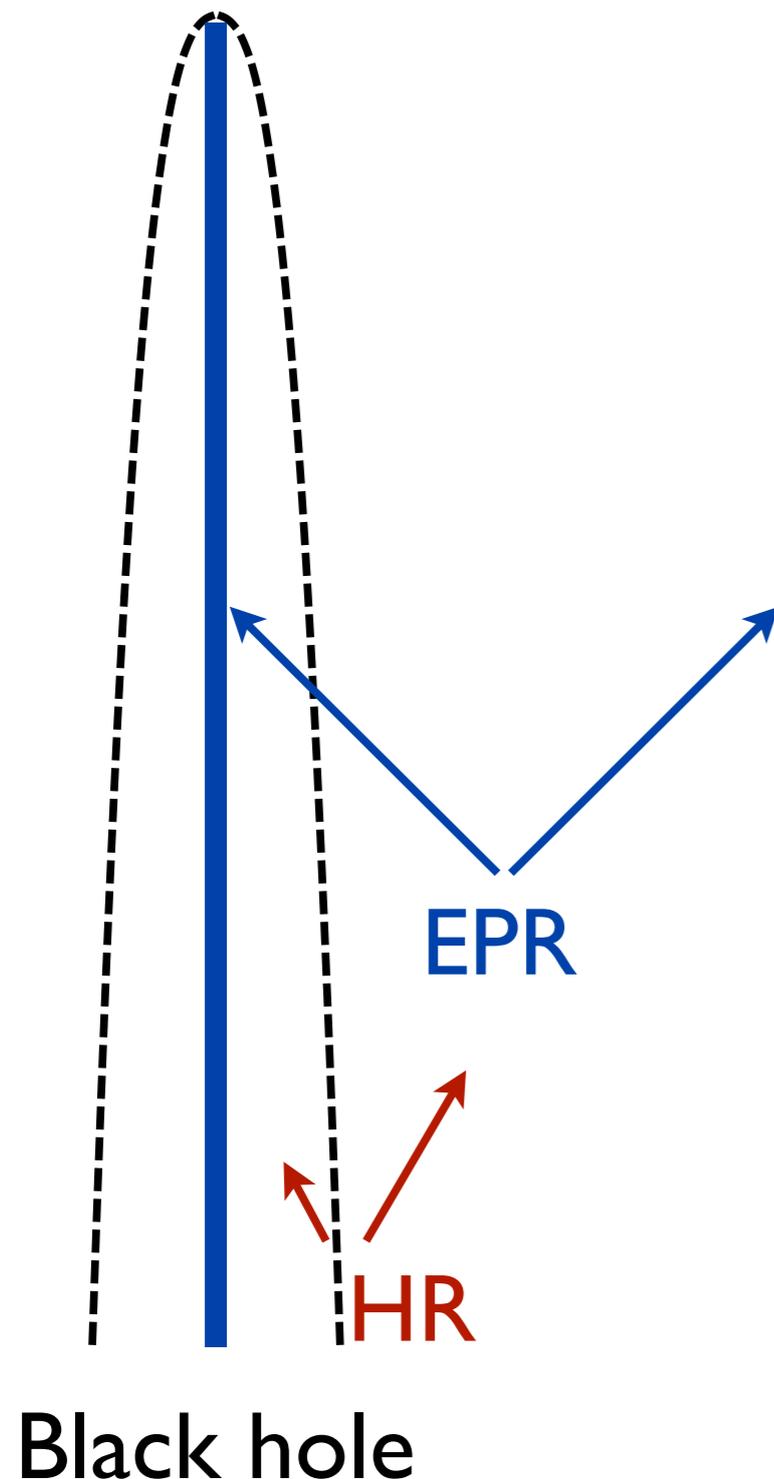
Failure of quantum mechanics

Conflict among basic principles:

Principles of relativity

Principles of quantum mechanics

Principles of locality



Apparently one or more of these principles
must be modified.

A goal:

Find more basic physics that:

- Matches LQFT in “ordinary circumstances”
E.g. doesn't violate locality, etc.
- Saves quantum mechanics
- Minimally disrupts semiclassical picture

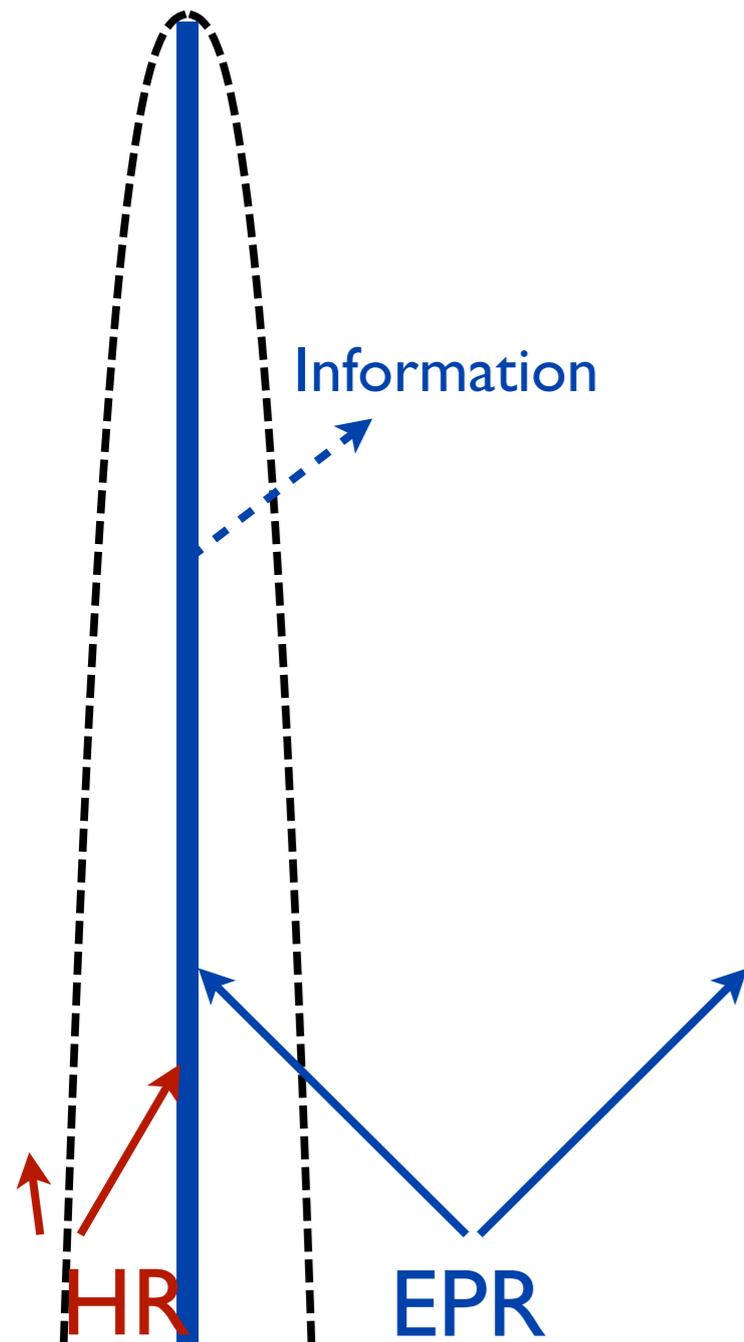
*correspondence
principle*

The need to unitarize BH evolution is a crucial constraint

What is required?

In order to

- 1) approximately maintain spacetime,
- 2) save unitarity/QM:



Black hole

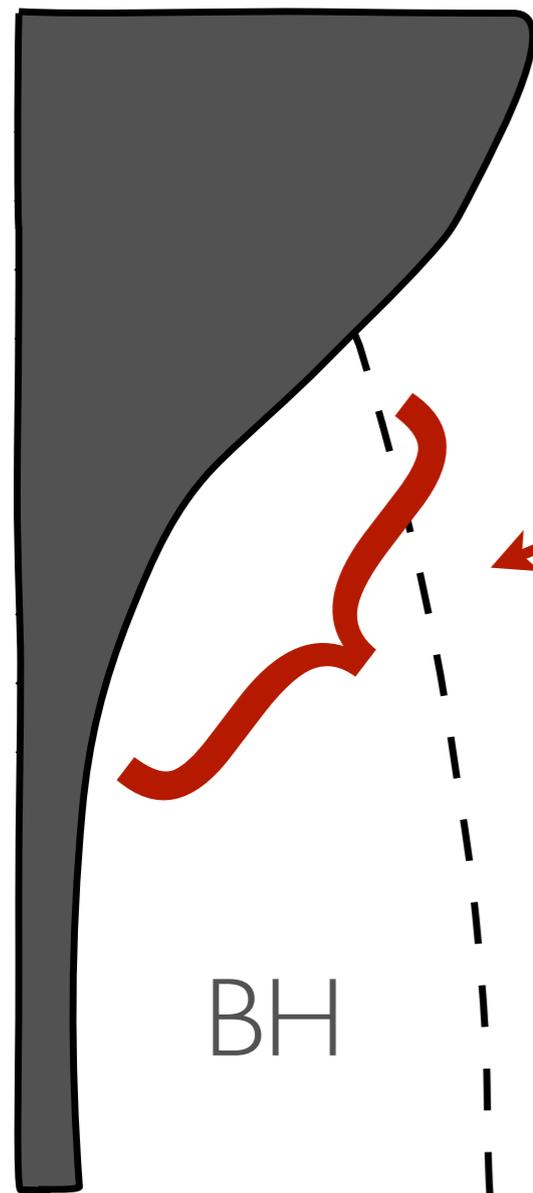
Need to transfer q. information
(entanglement) from BH to
environment.

LQFT doesn't do this (*locality*)

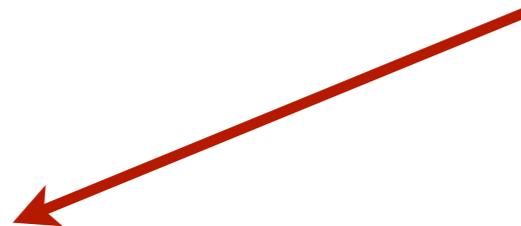
How is SCST + LQFT modified?

A first proposal for nonlocal transfer: hep-th/9203059

Massive Remnant



Nonlocal information transfer



Subsequent incarnations:

Fuzzballs

Firewalls (if $R_{rem} = R$)

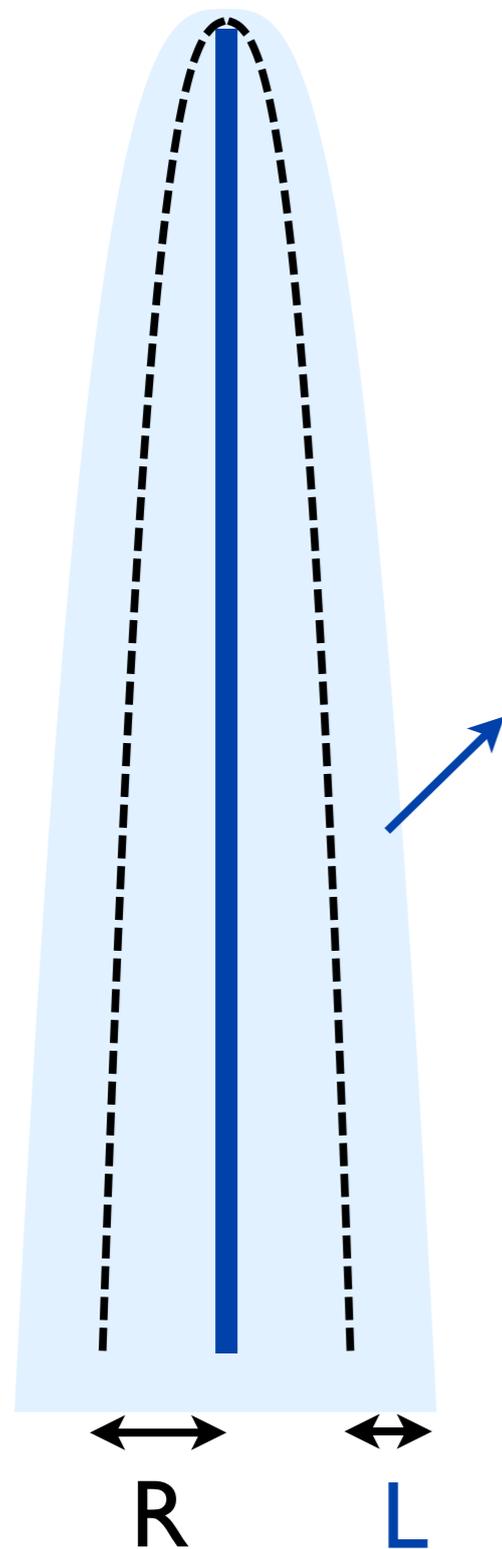
Planck stars

The problems with such massive remnant alternatives:

- They represent a violent breakdown of semiclassical spacetime
(not minimal disruption)
- They “artificially” introduce new short-scale (“hard”) physics to resolve a long-distance problem

Is there a less violent alternative?

Proposal: Nonviolent nonlocality -- basic picture



Characteristics:

1) Information transfer from “internal” DOF to BH exterior.

Locality w.r.t. SC geom forbids: “nonlocal”

2) Relevant scales

$$L \gg l_{Pl} \quad \text{e.g.} \quad L \sim R^p, \quad p > 0$$

(characterizes horizon separation, wavelengths)

“Soft,” or nonviolent

(see e.g. arXiv:0911.3395, 1108.2015, 1201.1037, 1211.7070; Dodelson/Silverstein?)

Another way to state:

Complementarity/AMPS postulates

[hep-th/9306069;
1207.3123]

- I) Unitary QM / S-matrix
- II) Semiclassical field eqns outside stretched horizon
- III) BH is Q. system with # states given by S_{BH}
- IV) Free-faller sees nothing unusual crossing horizon

Violate postulate II

specifically: info transfer allowed, over characteristic scale L

How does this arise from a fundamental theory?

Don't yet have complete picture.

Dovetails w/understanding: *locality not sharp in QG*

(See, e.g., hep-th/010323, hep-th/0604072, 1503.08207)

Maybe comes out of AdS/CFT, somehow.
(If/when we understand what AdS/CFT tells us.)

Or: BH as *key guide* to principles? (cf: atom/QM)

A possible approach:

If “small” corrections near BH: can model as
modification to LQFT?

[arXiv:1211.7070,
1302.2613,1310.5700]

Can begin to test:

What sharp constraints?
(firewall, or more radical, necessary?)

What do we have to give up?
(we know something!)

Are there observational consequences?

Let's avoid double standards:

Objection: no fundamental theory, or complete model

E.g. "I can find problem X in your model. Therefore, there must be a firewall."

Well, one doesn't have a fundamental theory or complete model of firewalls either, and if people started to write them down I expect there would be various serious objections.

So: can we infer reasonable physical behavior by making more detailed models,

Or is there a sharp argument against such models on reliable physical grounds?

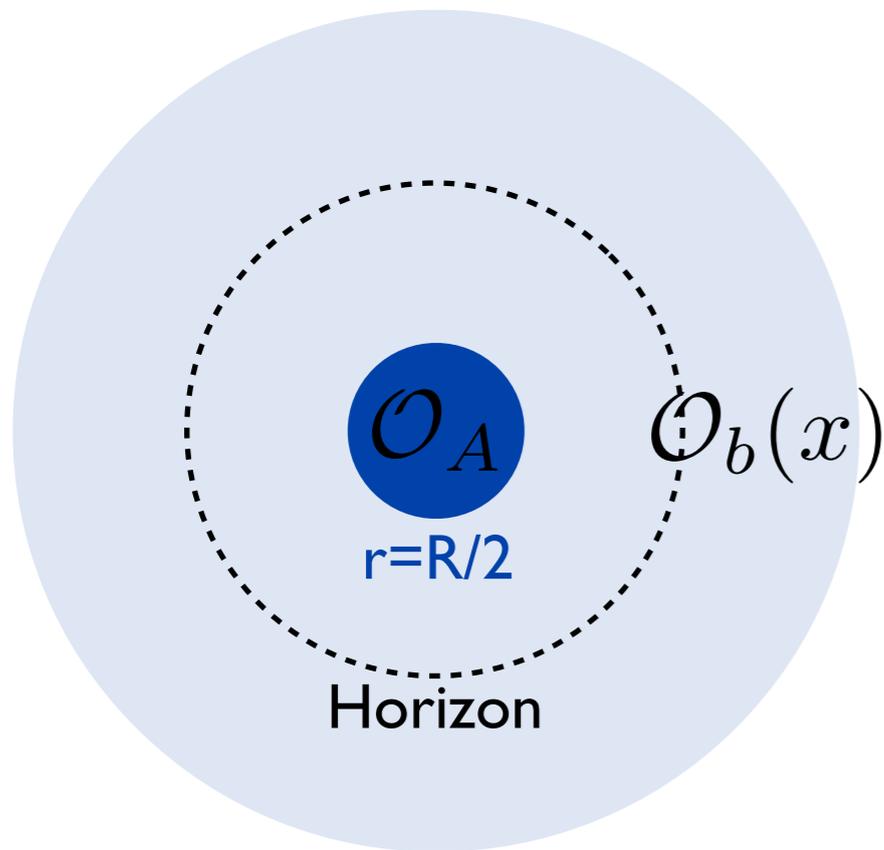
Put differently: since the unitarity crisis tells us we have to give up something, assess: what could it plausibly be?

Phenomenological *models* (not yet theories)

Assume SCST, LQFT, +corrections, for $r > R/2$

$$\int dt \Delta H \sim -\Delta S \sim \sum_{Ab} \int_{r > R/2} dV_4 \mathcal{O}_A G_{Ab}(x) \mathcal{O}_b(x)$$

\uparrow acts on " $\mathcal{H}_{r < R/2}$ " \uparrow acts on " $\mathcal{H}_{r > R/2}$ "
 coupling functions



Simple examples:

[arXiv:1302.2613,
1310.5700, 1401.5804]

$$\int dV_4 J(x) \Phi(x)$$

$$\int dV_4 J^{\mu\nu}(x) T_{\mu\nu}(x)$$

J's: quantum
sources;
~classical

These interactions transfer information (entanglement) from BH to its atmosphere; it then escapes.

A challenge:

Generically, unless disrupt Hawking process, these yield

$$\frac{dE}{dt} > \frac{dE}{dt} \Big|_{\text{Hawk}}$$

[arXiv:1201.1037,
1205.4732, 1211.7070]

So $S_{bh} < S_{BH}$ by detailed balance

[arXiv:1211.7070, AMPSS,
1308.3488]

So, we face a choice:

- 1) Make peace w/ $S_{bh} < S_{BH}$?
- 2) Find special evolution w/ Hawking flux (or, no go)
- 3) Firewall, or more radical ...

$$S_{bh} < S_{BH} ?$$

Do we **know** BH density of states $\sim e^{S_{BH}}$?

Alternative: S_{BH} characterizes semiclassical near-horizon geometry (which we know doesn't give exact physics - extreme case FW)

Any incontrovertible evidence for S_{BH} ?

- 1) BTZ/Cardy formula 2+1 special; assumes AdS=CFT
- 2) Strominger/Vafa weak coupling; \sim BPS
- 3) Hanada et al ?

These are strongly suggestive.

Are they incontrovertible?

If $S_{bh} = S_{BH}$ did imply firewalls, would we believe it?

\therefore perhaps $S_{bh} < S_{BH}$ consistent.

[arXiv:1308.3488]

But this is a little inelegant; people are uncomfortable giving up such a simple story

An apparent alternative, with intriguing features:

$$\int dV_4 \cancel{J^{\mu\nu}}(x) T_{\mu\nu}(x)$$

$G^{\mu\nu}(x)$

I.e. *effective* description: BH state-dependent metric fluctuations

(think of as \sim inaccuracy of classical geometry)

universality \sim gravity

(helps address mining)

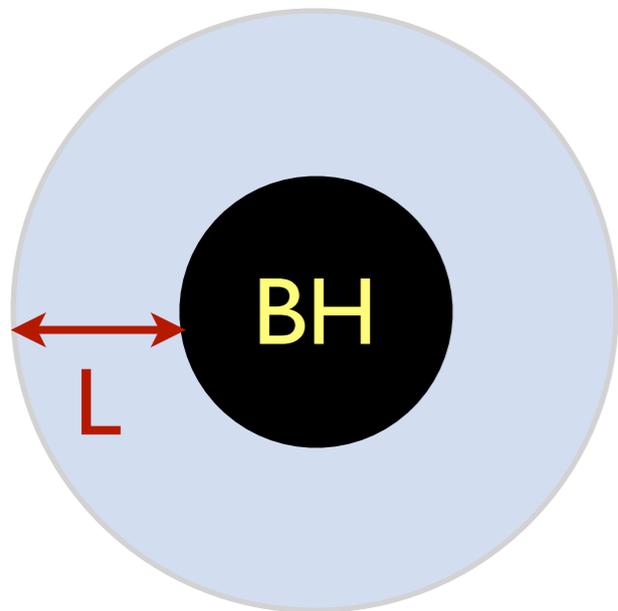
These can “modulate” Hawking radiation; possibility of small (vanishing?) increase of energy flux.

[arXiv:1401.5804]

2d model: $\delta P_-(x^-) = \int dx^- \langle \delta T_{--} \rangle_G = 0$

to linear order in G

How large are these effective fluctuations?



Constraint: $\frac{dS_{\text{vN}}}{dt} \sim -\frac{1}{R}$

Suppose (e.g.) $L \sim 1/\omega \sim R$

\Rightarrow e.g. $\langle I | G^{\mu\nu}(x) | J \rangle \sim e^{-i\omega v + ikr} f_L(r)$

\uparrow
 $\mathcal{O}(1)$

\uparrow
restricts to
 $r \lesssim R + L$

\therefore **Strong, soft** effective metric fluctuations

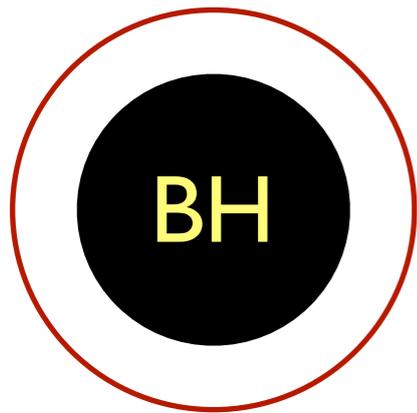
A new firewall alternative (significant mods. to HR...)

[arXiv:1401.5804]

(Some superficial similarity to Dvali/Gomez; though strong interacting, closer to Schwarzschild; not just weak graviton “gas”)

An opportunity:

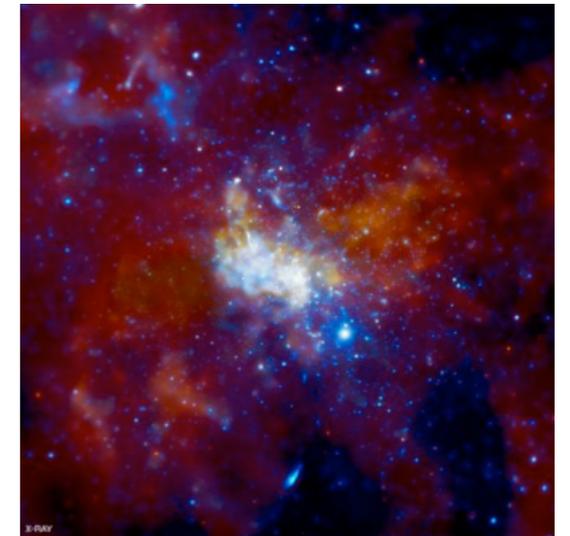
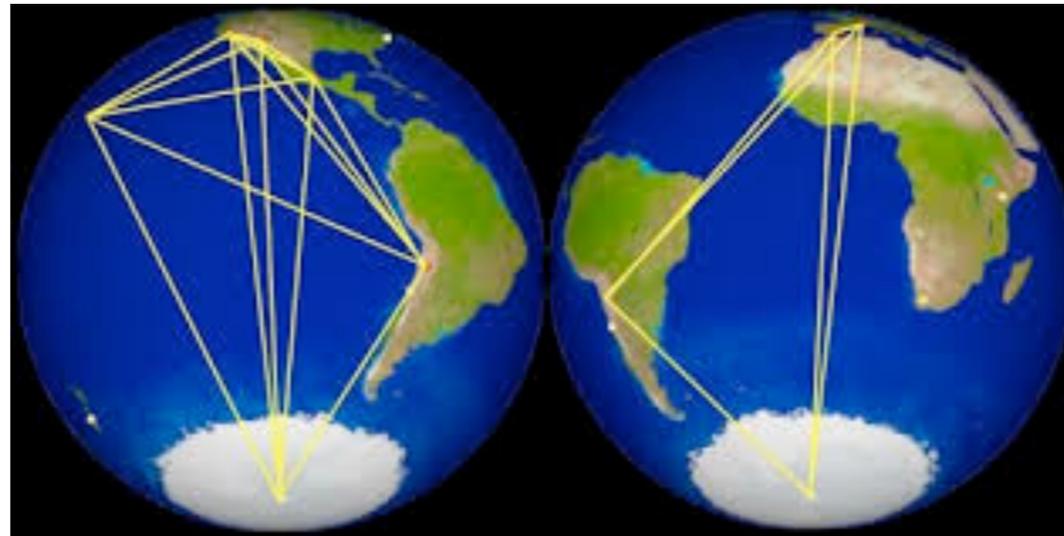
arXiv:1406.7001



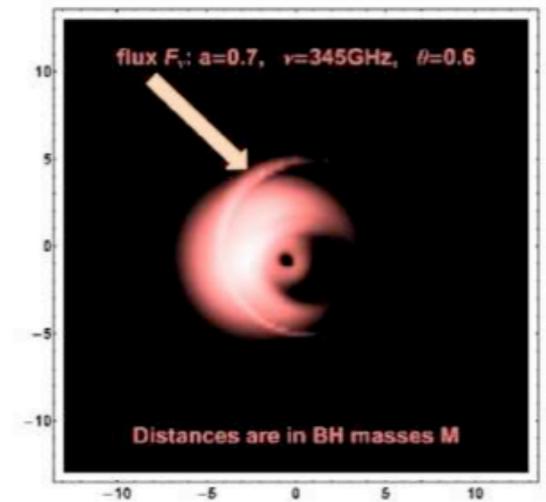
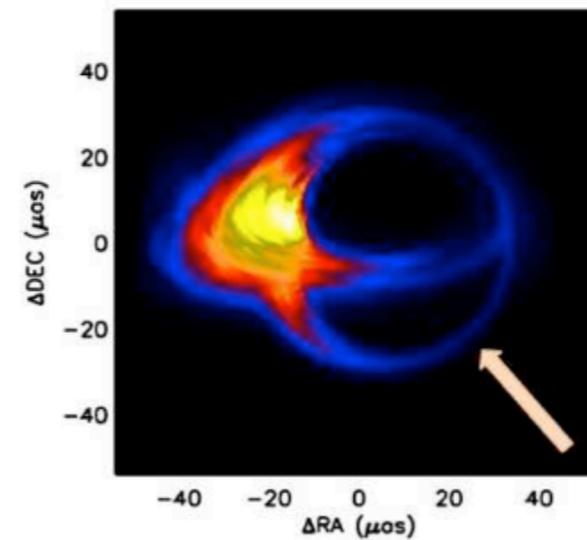
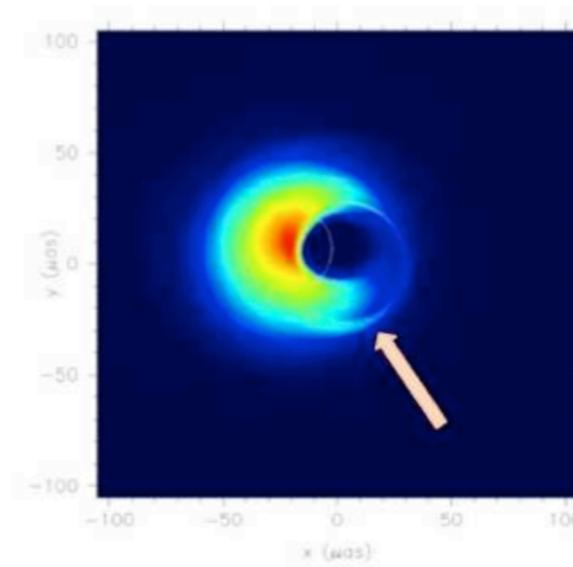
$$r=3R/2$$

(Schwarzschild)

Event horizon telescope:



Sgr A*



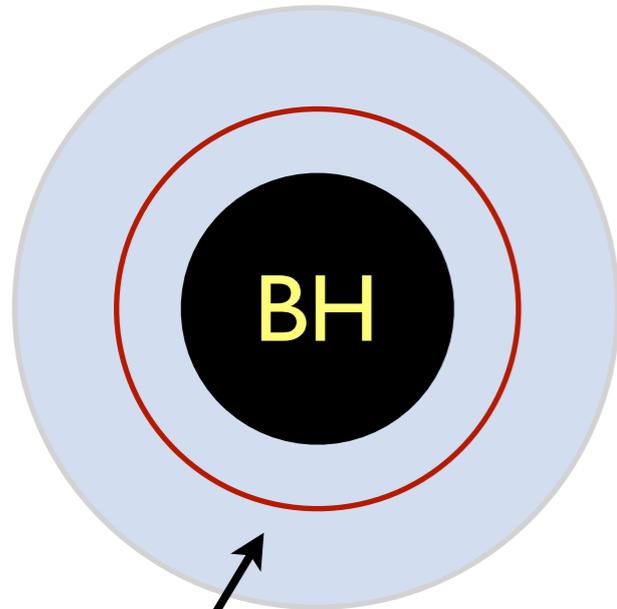
Psaltis/Johannsen

BH shadow, **photon ring**

(see talk by S. Britzen)

An opportunity:

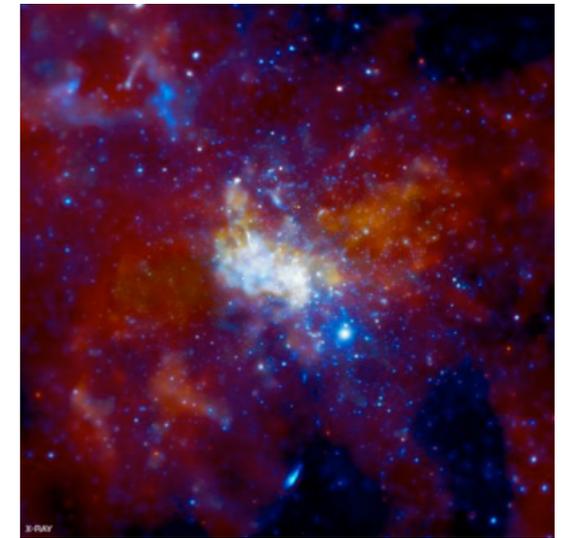
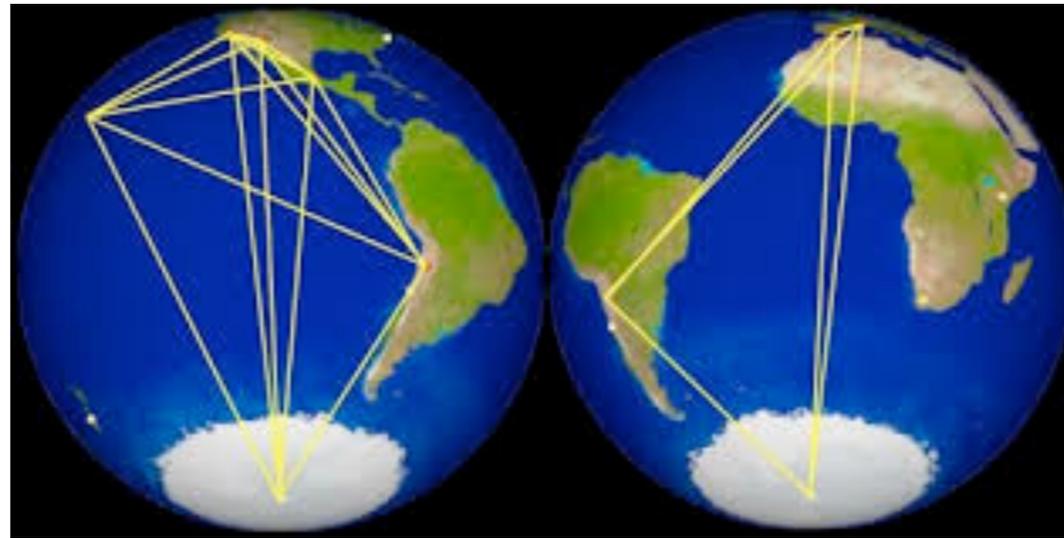
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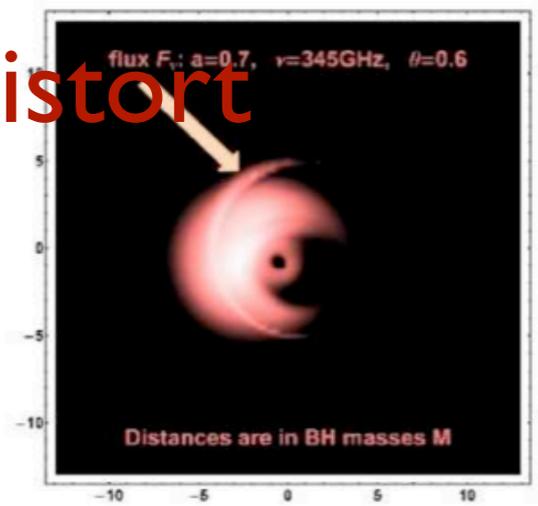
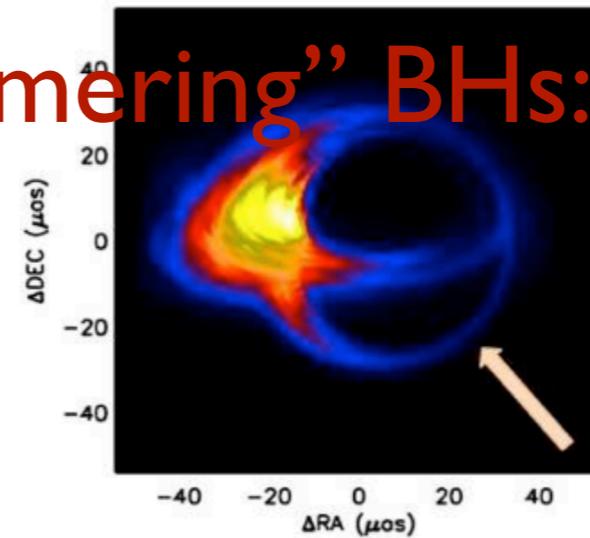
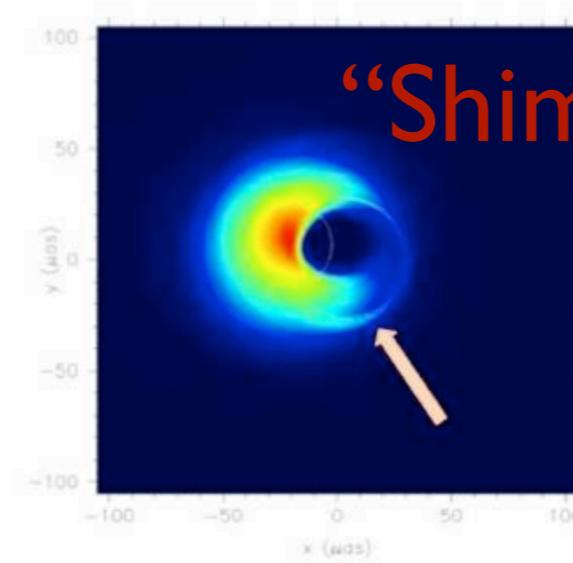
$$r = 3R/2$$

(Schwarzschild)

Event horizon telescope:



Sgr A*



“Shimmering” BHs: distort

SBG/Psaltis, WIP

Theoretical uncertainty:

$$t_{qn} \sim t_{Fast Sc} \sim R \log R \sim 8 \text{ hr}$$

$$t_{1/2} \sim R^3 \sim 10^{74} t_{\text{Universe}}$$

} bounds

If due to inaccuracy of geometrical description, $R \ln R$ reasonable

Summary:

BHs have led us to a “Unitarity crisis;” represents a conflict among fundamental principles ... **something has to give**

“NVNL” proposes “soft” information transfer to the “atmosphere” of a BH; **violates macro. SC locality**

[hep-th/9203059]

Typical models give $S_{bh} < S_{BH}$; $S_{bh} = S_{BH}$ requires significant modifications of Hawking radiation

Effective metric fluctuations: a natural, universal alternative

Necessary info transfer: **strong, soft** fluctuations; big departure from Schwarzschild’s solution!

These present observational opportunity as we image BHs (**EHT, etc.**)