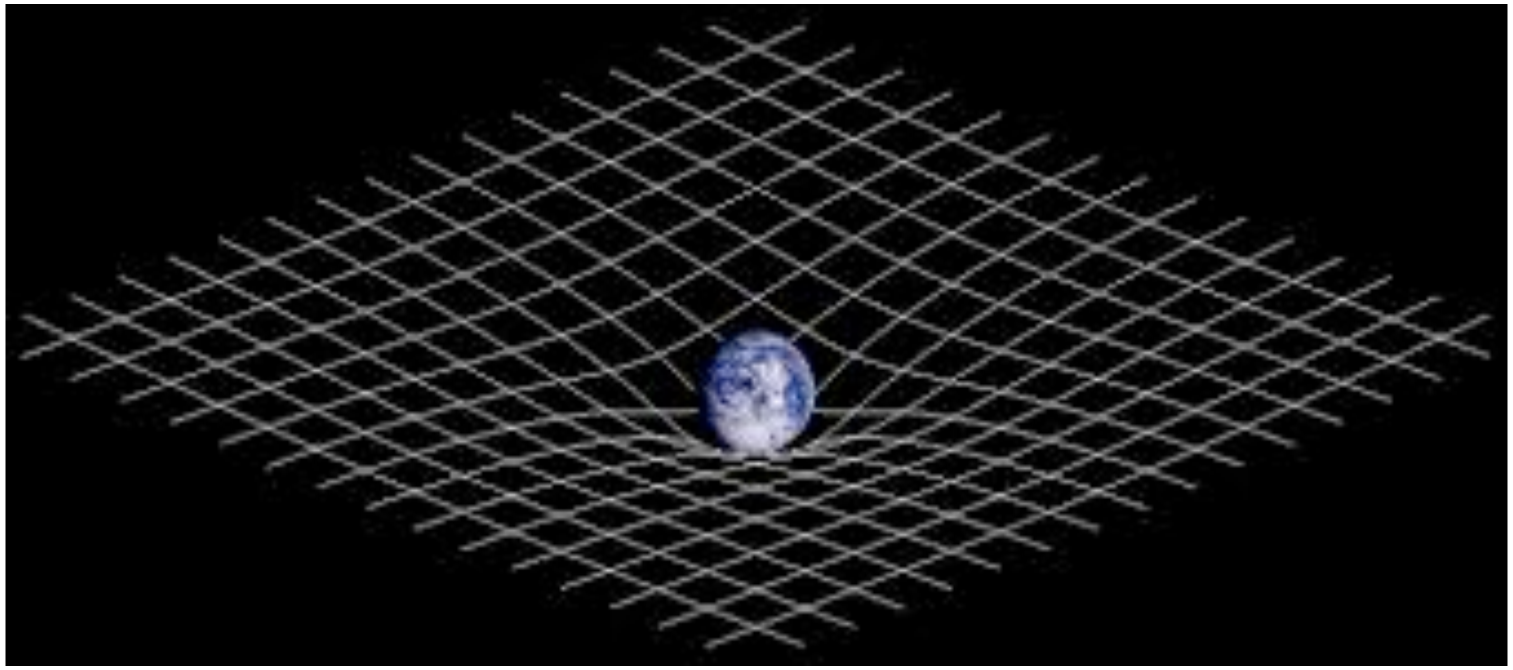
What are Black Holes?

arXiv:1812.00536

Black Holes



Large enough mass, small enough region

Gravitational Collapse

$$ds^2 = -\left(1 - \frac{r_s}{r}\right) dt^2 + \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

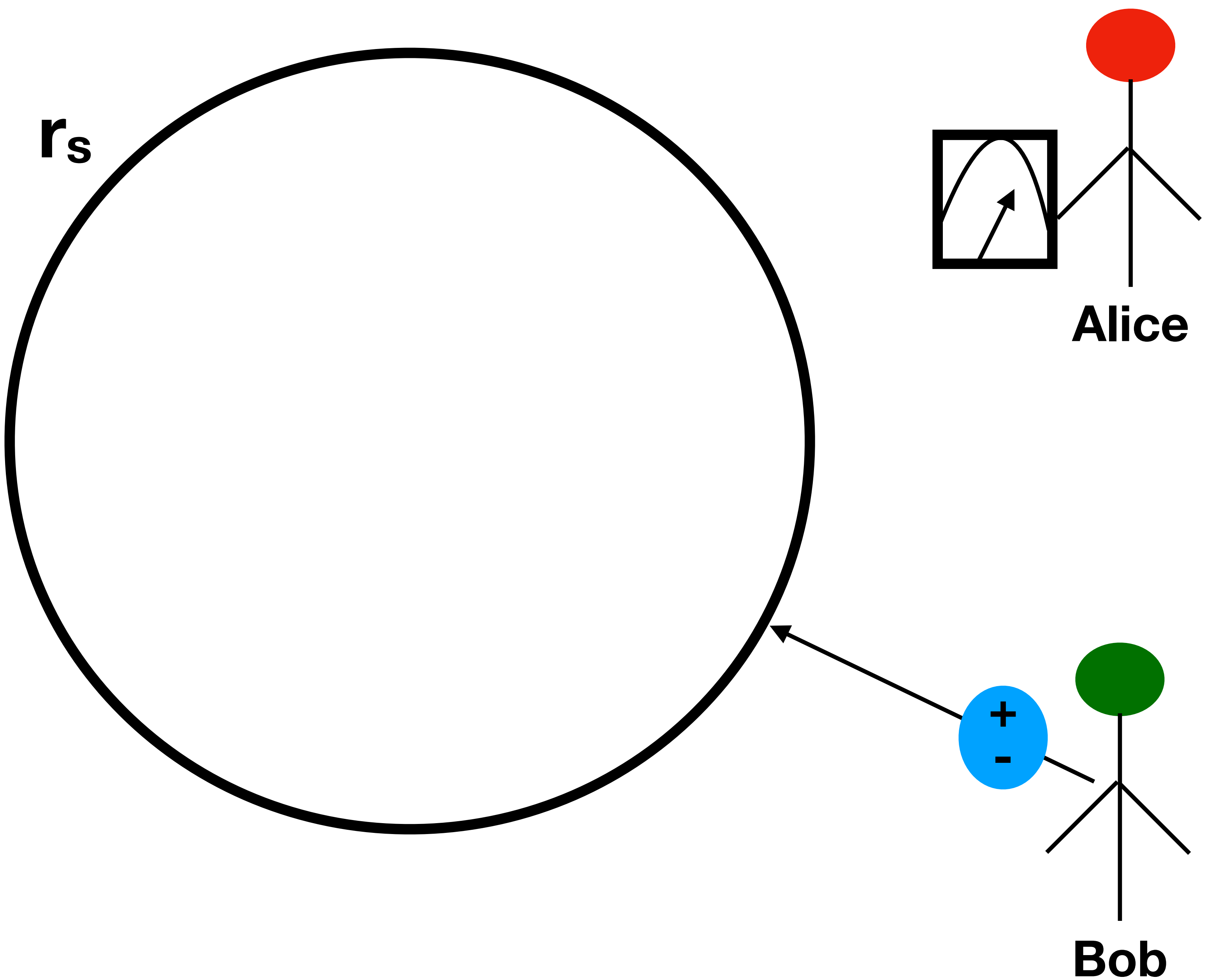
Schwarzschild Metric: Unique Spherically Symmetric Vacuum Solution

Event Horizon at r_s - “nothing” can escape

Is this a spherical cow approximation?

After all, collapsing object had multipole moments

Black Hole Moments



Alice: Outside
Bob: Falls inside

Bob: Electric dipole

Alice: Electric Field Sensor

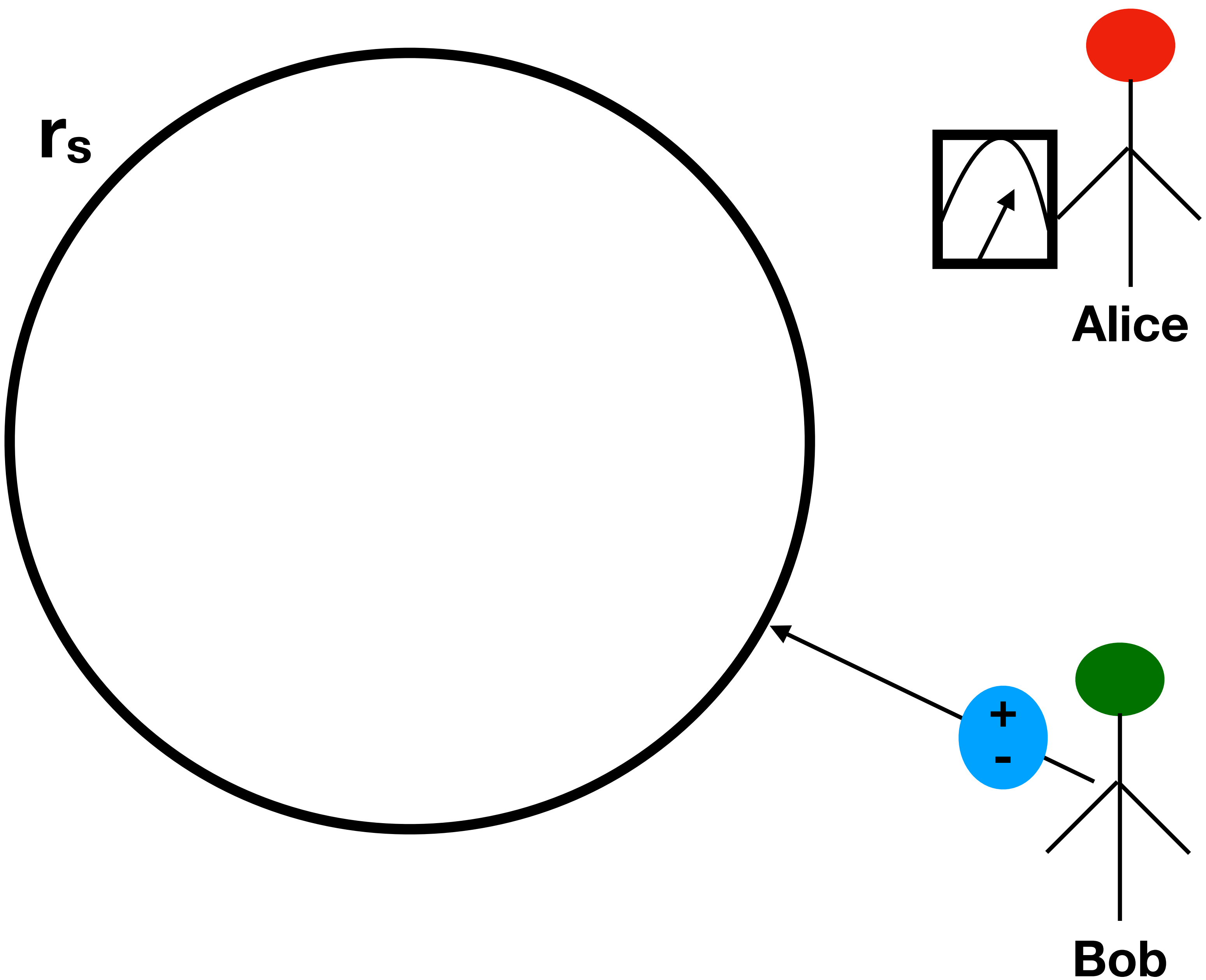
Bob communicates by flipping dipole

What happens to the dipole field when Bob crosses the horizon?

Nothing on the surface to record dipole

If dipole field visible outside, can still communicate - violates causality

No Hair



Prevent Communication

Dipole field has to vanish!

What if Bob fell with a net charge?

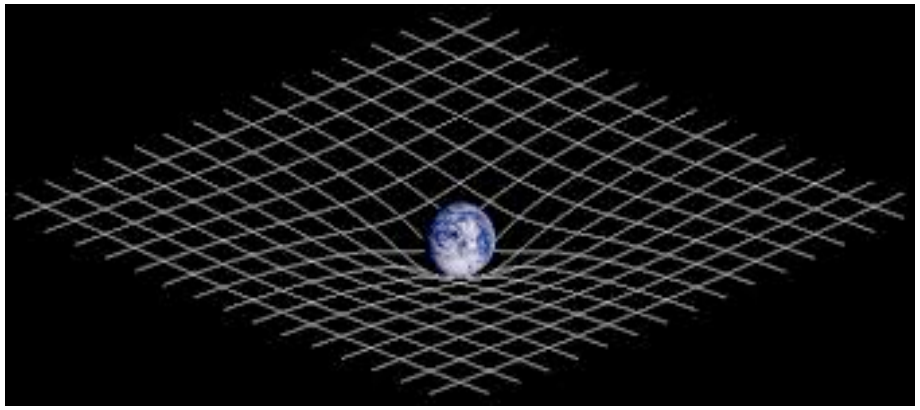
Can monopole field vanish?

Violates Gauss!

Causality + Gauss: Only monopole field is non-zero, rest zero

Metric described solely by conserved quantities.
Vast simplification - actual spherical cow!

The Event Horizon



$$ds^2 = -\left(1 - \frac{r_s}{r}\right) dt^2 + \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

What is going on at r_s?

Co-ordinate singularity at r_s.
Can show that curvature invariants are finite

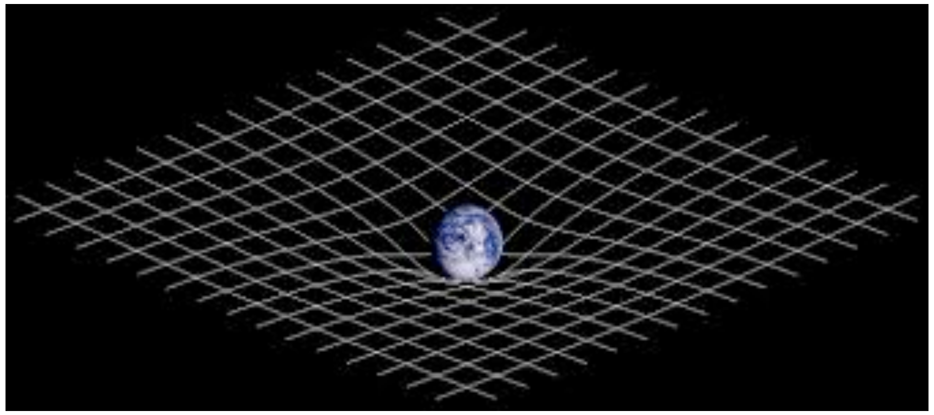
Change co-ordinates to remove singularity at r_s

What can these new co-ordinates look like?

Birkhoff: Schwarzschild is the unique time independent solution!

New co-ordinates must depend on time.
So what?

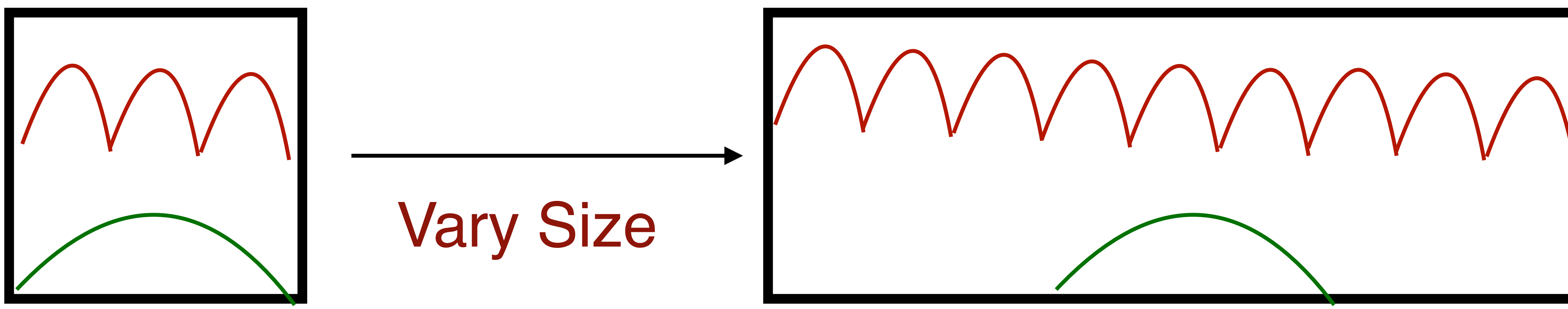
Hawking Radiation



Remove singularity at r_s - new co-ordinates must depend on time

$$ds^2 = -f(t,r)\,dt^2 + g(t,r)\,dr^2 + r^2 d\Omega^2$$

How do quantum fields behave in this time dependent geometry?

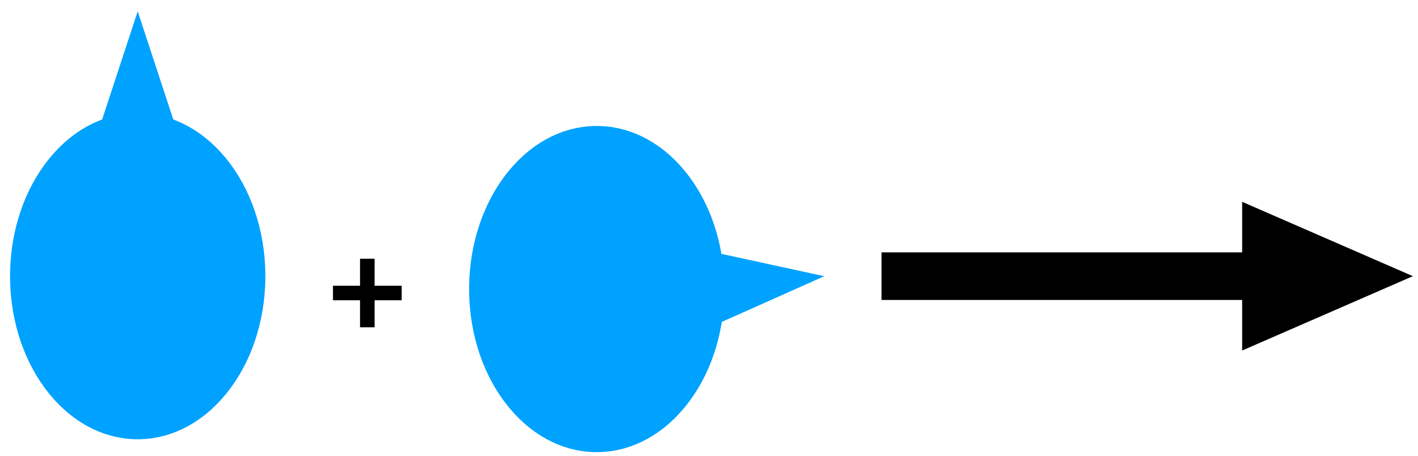


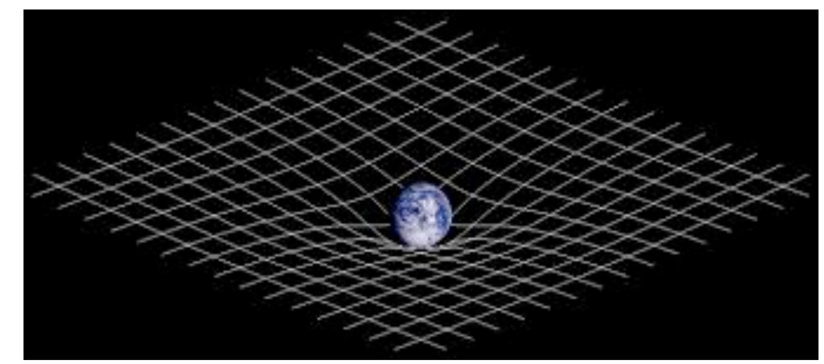
High Frequency Mode: Adiabatic Evolution. Unaffected

Low Frequency Mode: Sudden Evolution. Excited!

Horizon radiates at ~ $1/r_s$ - must lose energy and disappear!

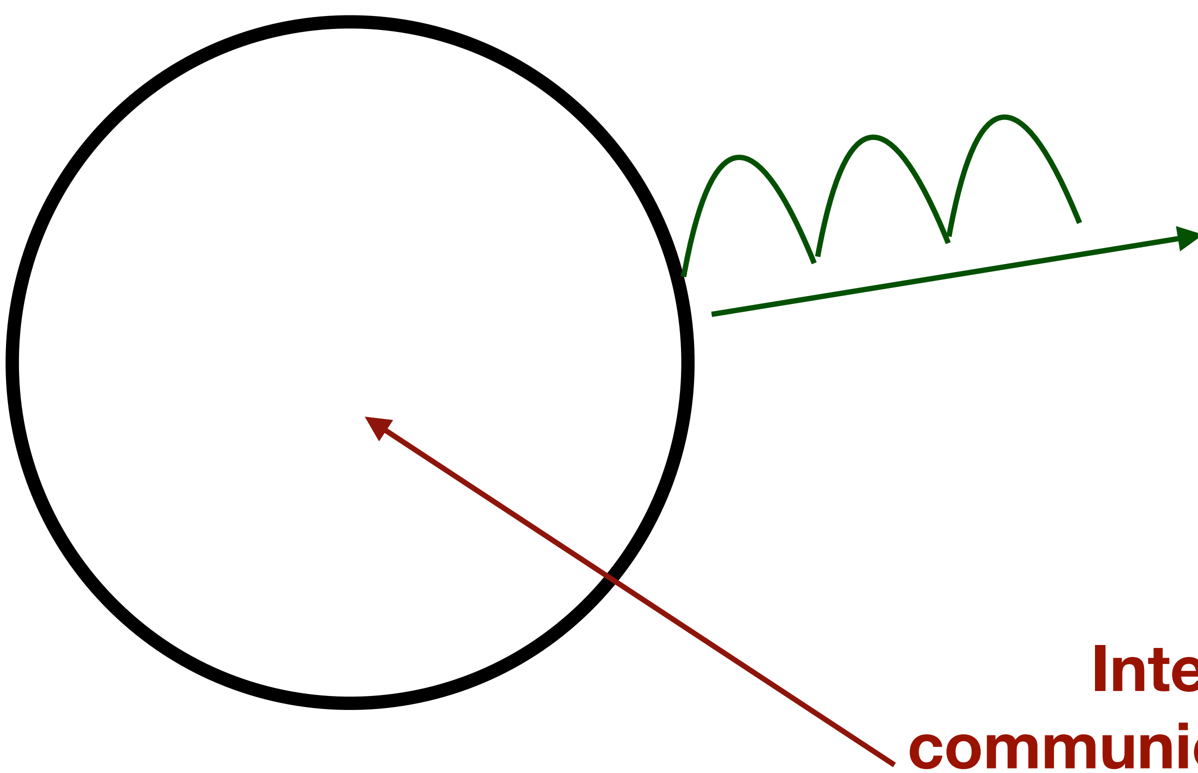
Black Hole Information Problem





Form Black Hole with number of objects with all kinds of information

Schwarzschild Solution - No hair in the exterior!



Radiation Occurs outside Horizon.

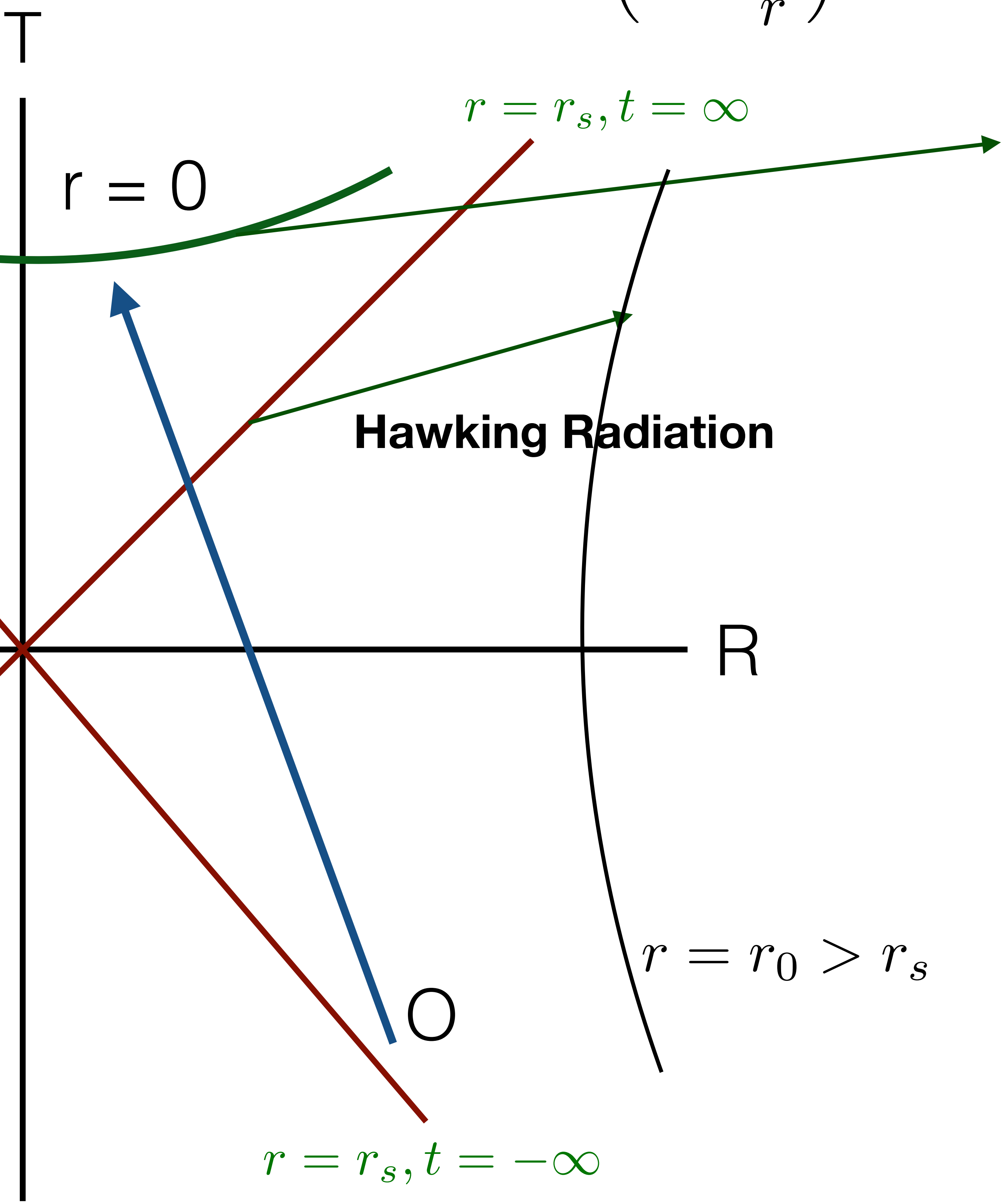
Only knows about exterior geometry

Same Final State no matter what initial state - violation of unitarity!

Interior cannot communicate with exterior

Black Hole Information Problem

$$ds^2 = -\left(1 - \frac{r_s}{r}\right) dt^2 + \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$$



Singularity is a point in the future
Cannot communicate with exterior
unless signals go "back in time"

How do we get information from the interior to the exterior?

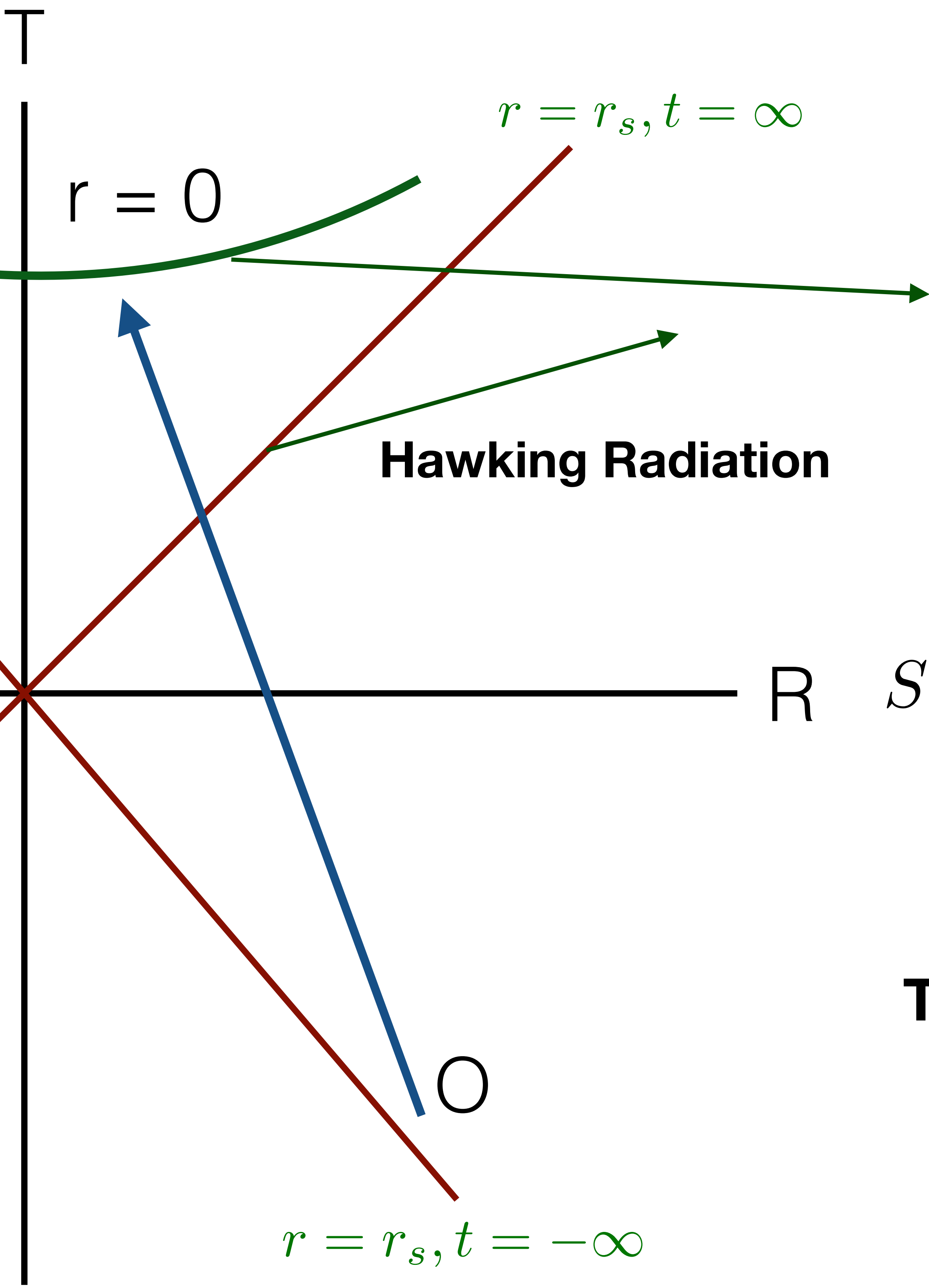
To get information out, something has to get out of the singularity

No Information Without Propagation

This violates General Relativity

Key Question: How can we sensibly violate General Relativity?

What kind of Violation?



Key Question: How can we sensibly violate General Relativity?

Need propagation from singularity to the horizon

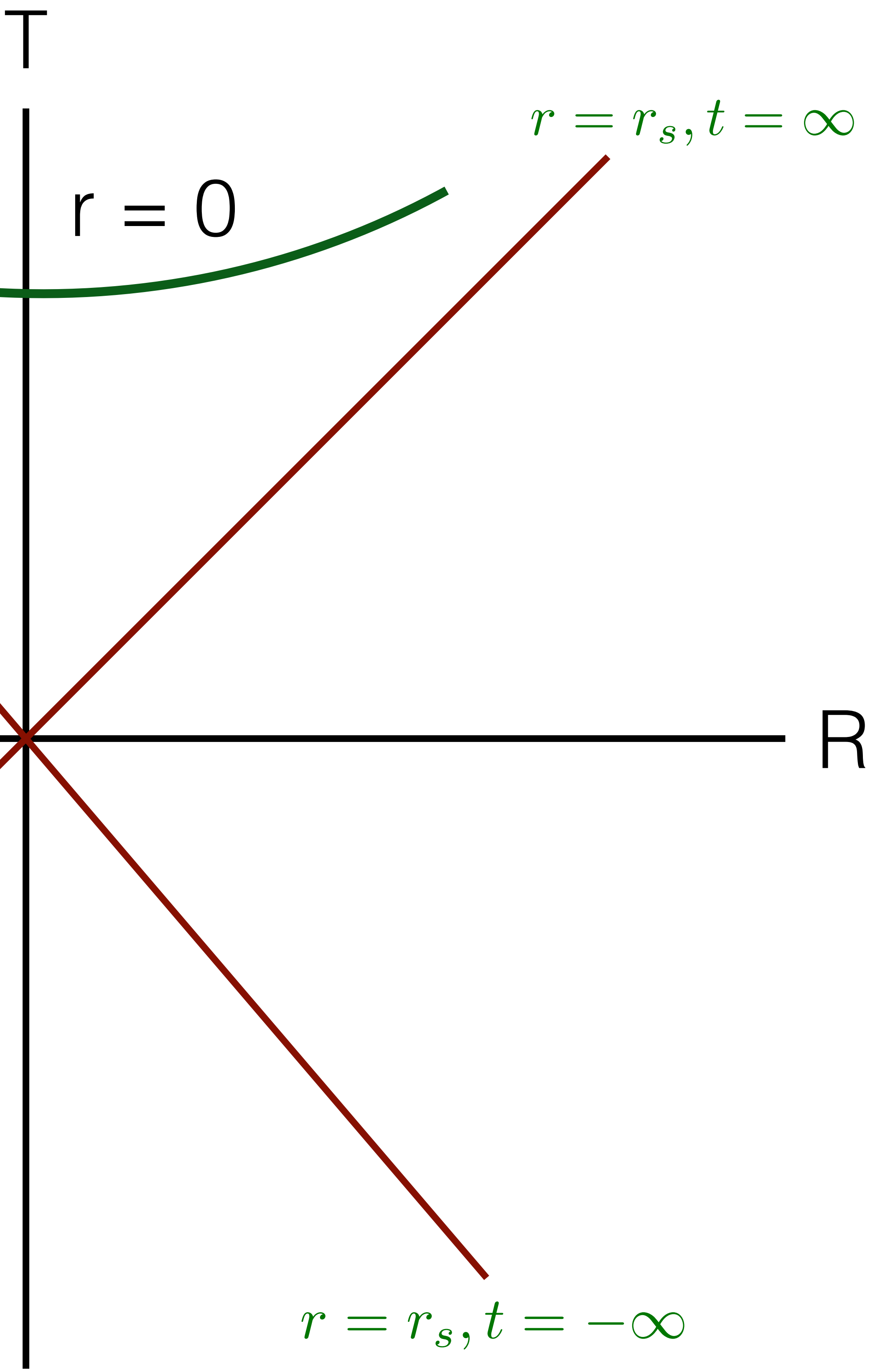
Need large correction to the metric

$$S = \int d^4x\sqrt{g}\left(g_{\mu\nu} + \frac{R_{\mu\nu}}{M_{pl}^2} + \dots\right)\partial^\mu\phi\partial^\nu\phi$$

ϕ moves as per effective metric
To change causal structure, need $R_{\mu\nu} \sim M_{pl}^2$

Not true in Schwarzschild, except at singularity. We need it to the horizon!

Objections



To change causal structure, need $R_{\mu\nu} \sim M_{pl}^2$ all the way to the horizon

Not true in Schwarzschild!

Schwarzschild should describe black hole

Co-ordinate singularity at horizon. Low curvature. $R_{\mu\nu} << M_{pl}^2$

General Relativity should hold!

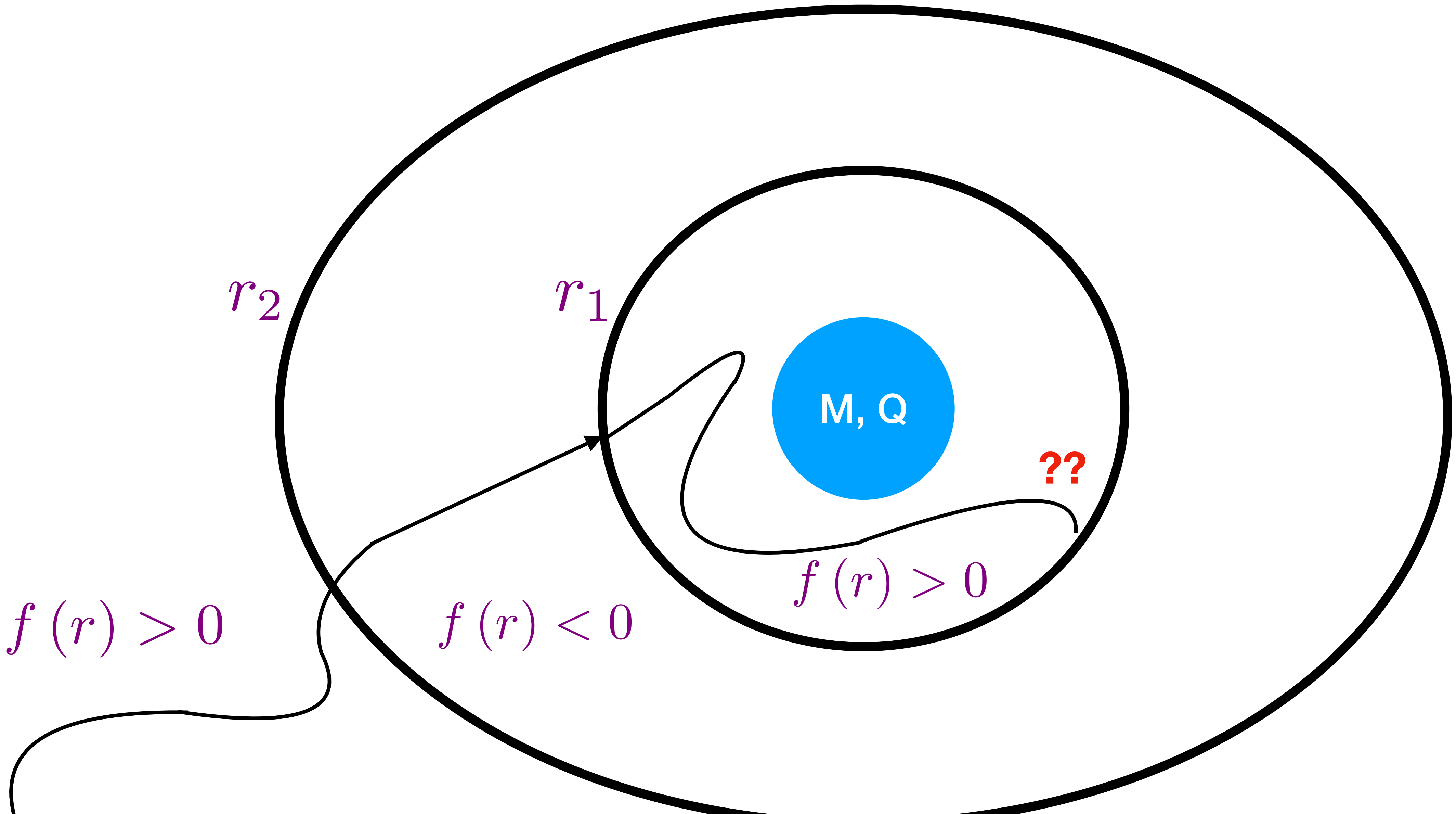
If $R \sim M_{pl}^2$, local density $\sim M_{pl}^4$ => black hole mass $M_{pl}^4 r_s^3 \sim M^3/M_{pl}^2 >> M$

Impossible?

Horizons in Reissner Nordstrom/Kerr

$$ds^2 = -f(r)\,dt^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2$$

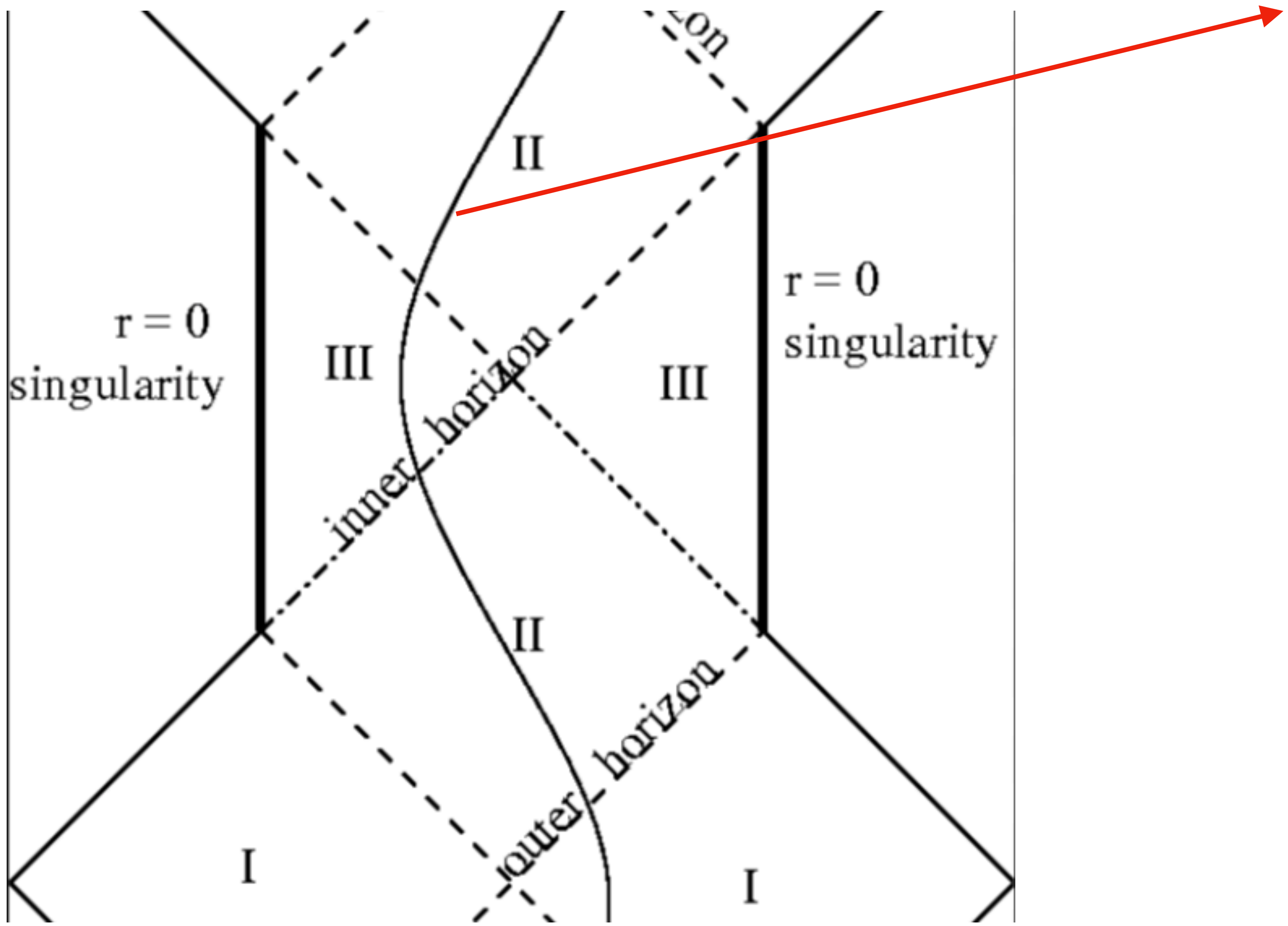
$$f(r) = \frac{(r - r_1)(r - r_2)}{r^2}$$



Cauchy Horizons in Reissner Nordstrom/Kerr

$$ds^2 = -f(r)\,dt^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2$$

$$f(r) = \frac{(r-r_1)(r-r_2)}{r^2}$$



Can only be extended into a different universe

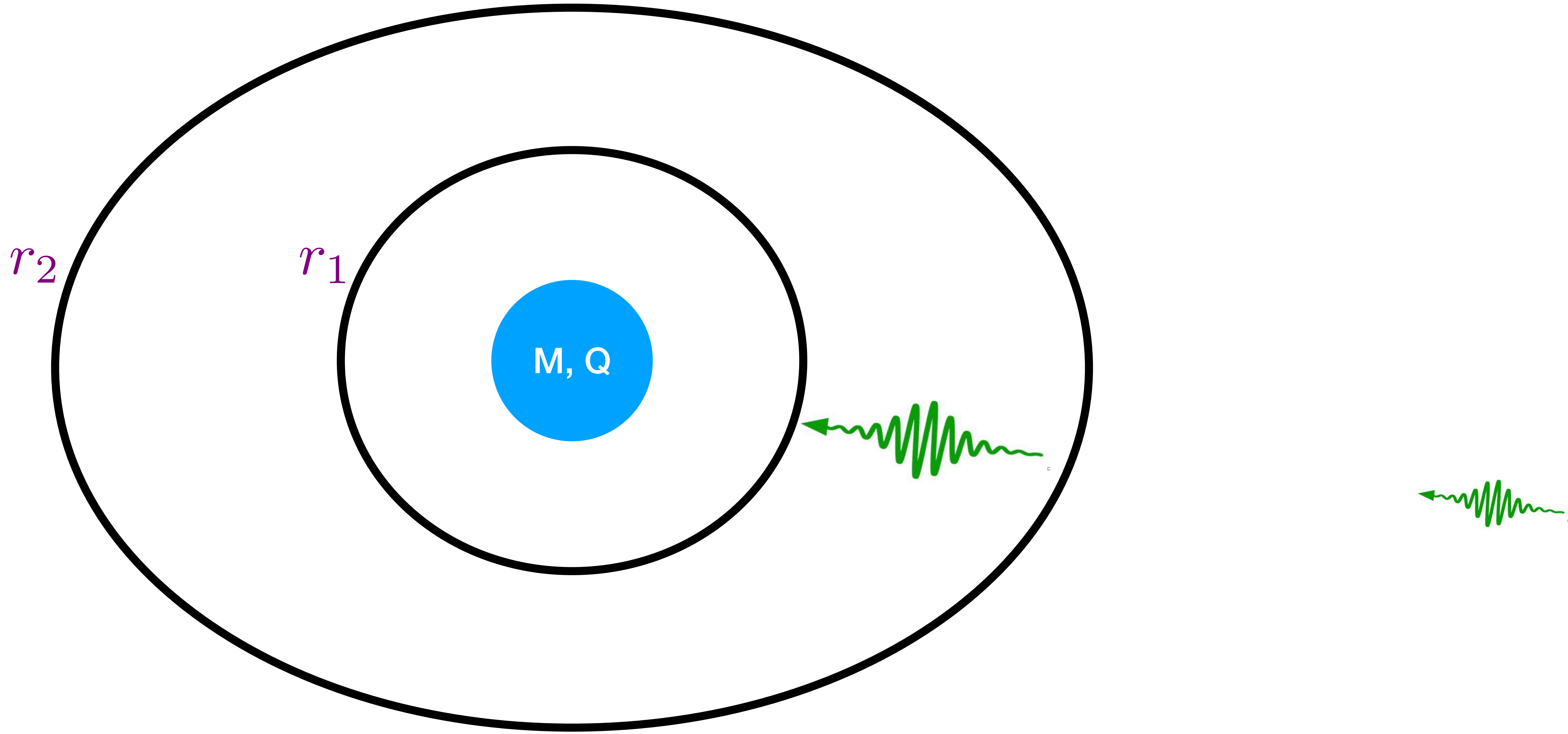
Subject to new boundary conditions, failure of predictivity

Large change to metric, no inner horizon

Static Black Hole: Singularity at inner horizon?

Fast, classical effect

Mass Inflation

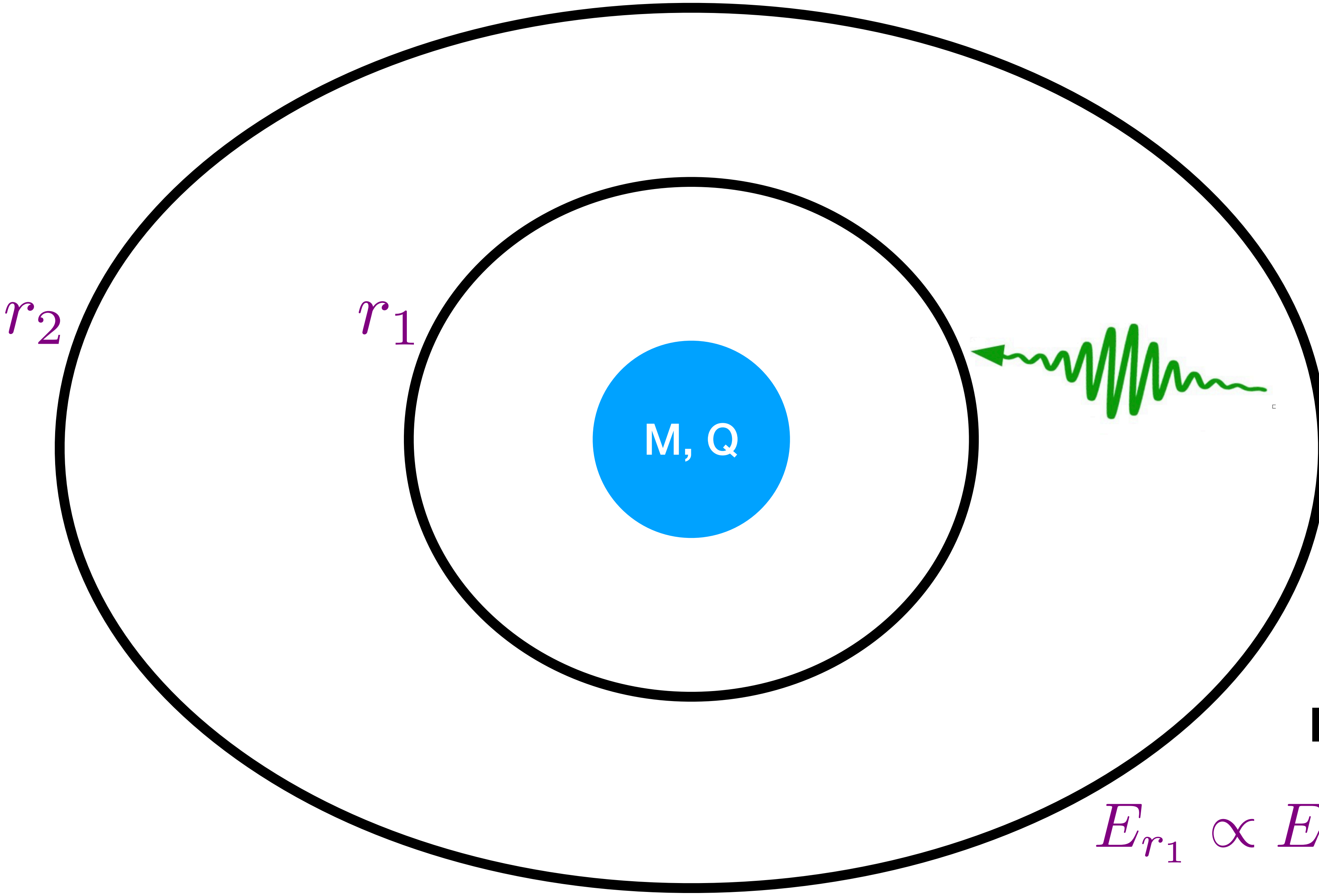


Amplification, i.e. blue-shift, of perturbations: $E_{r_1} \propto E_\infty \left(\frac{r_1}{r - r_1} \right)$

Significant local density, without changing external mass

External perturbations, really?

External Perturbations



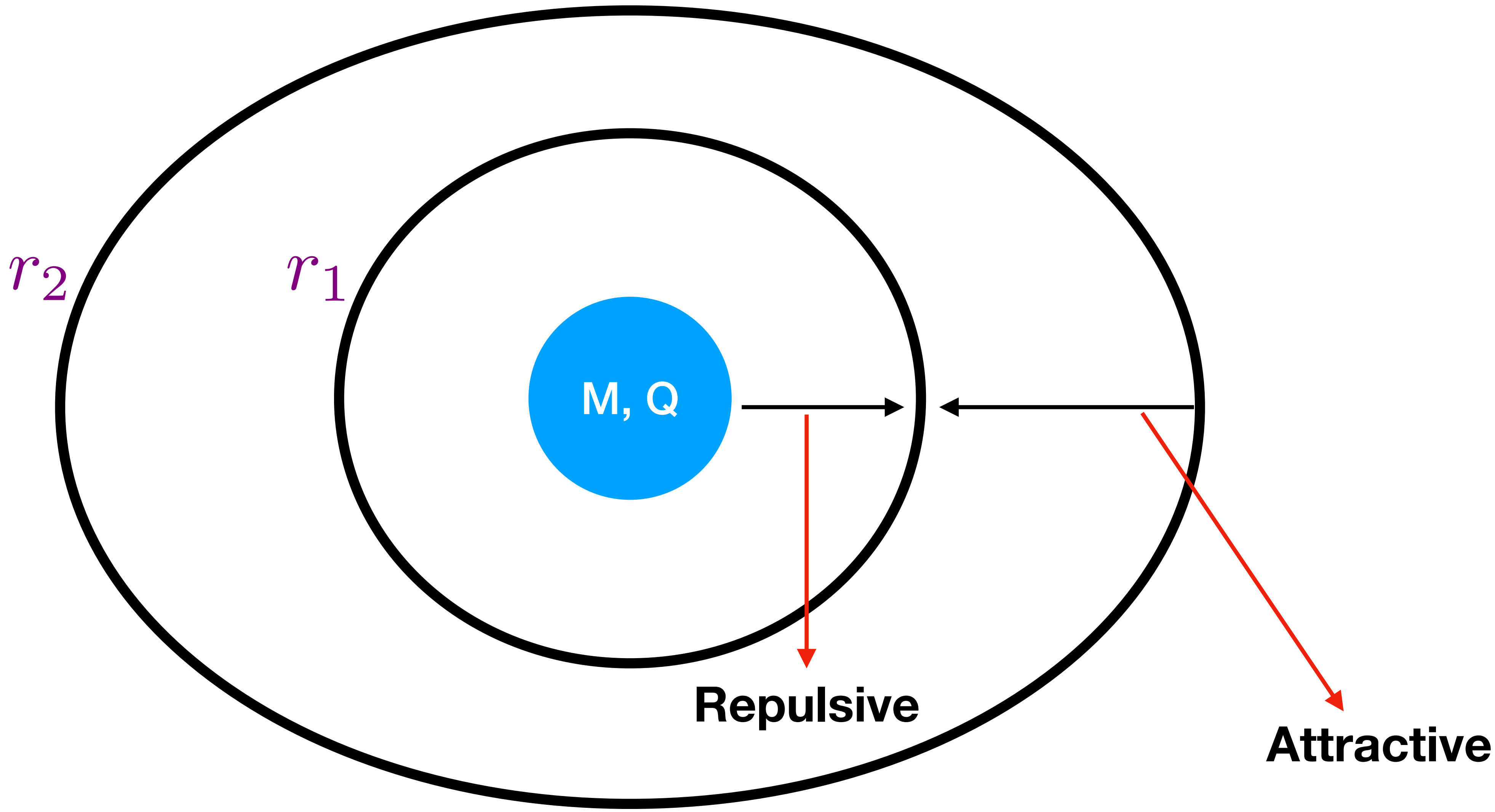
Regulate Divergence

$$E_{r_1} \propto E_\infty \left(M_{pl} r_1\right) \sim E_\infty \left(\frac{M}{M_{pl}}\right)$$

Singular Shell at r$_1$: $M_{r_1} \sim M_{pl}^3 r_1^2 \sim M \left(\frac{M}{M_{pl}}\right) \implies E_\infty \sim M$

Recent Work: Red-shift from positive Λ softens divergence

Why External?



Push mass/charge from singularity to inner horizon

Blue-shift lead to large local mass, without change to external parameters?

Final State?
Singularity/break down of General Relativity in low curvature??
Similarly overcome objections in Schwarzschild?

Outline

1. The Inner Horizon
2. The Event Horizon
3. Experimental Signatures