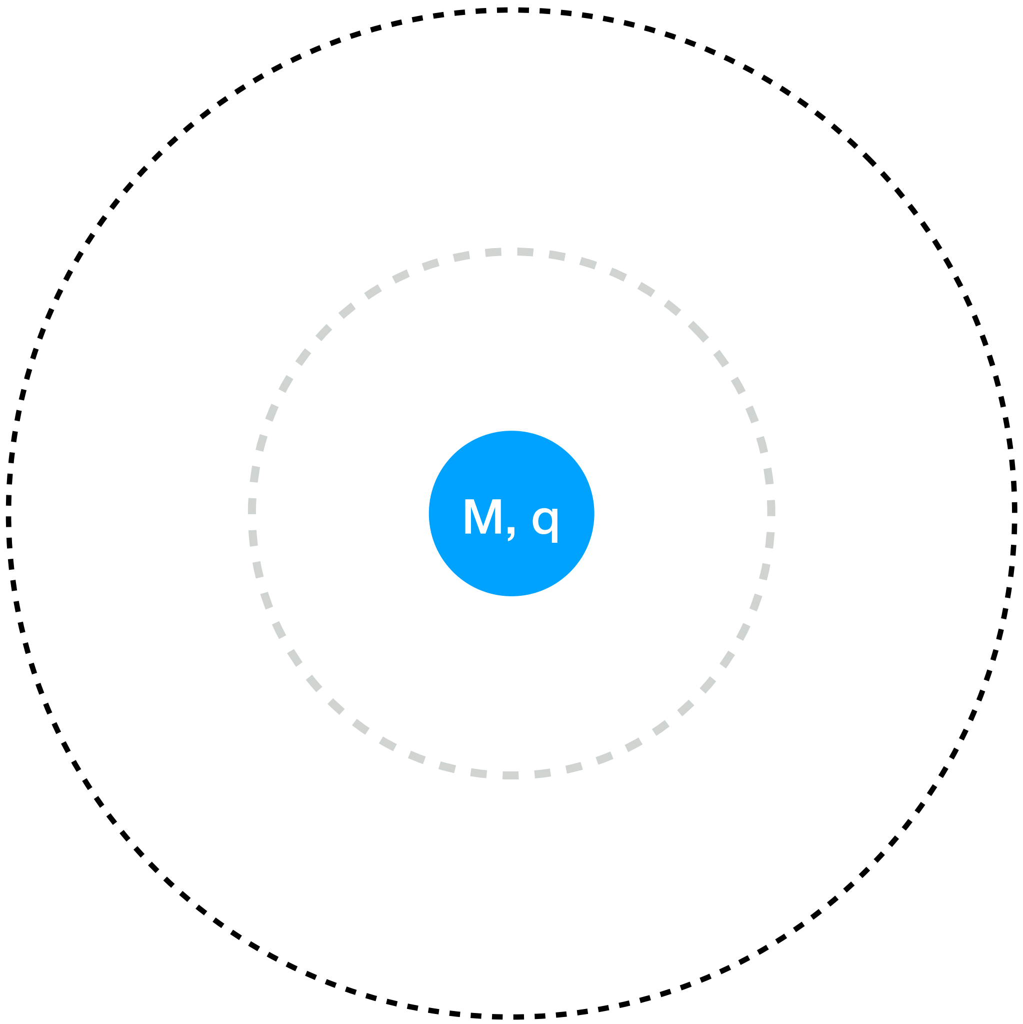
Firewalls in General Relativity

with Surjeet Rajendran

arXiv:1812.00536

Black Holes and Unitarity in GR

Classically, what falls into a black hole (past the horizon), cannot get out.

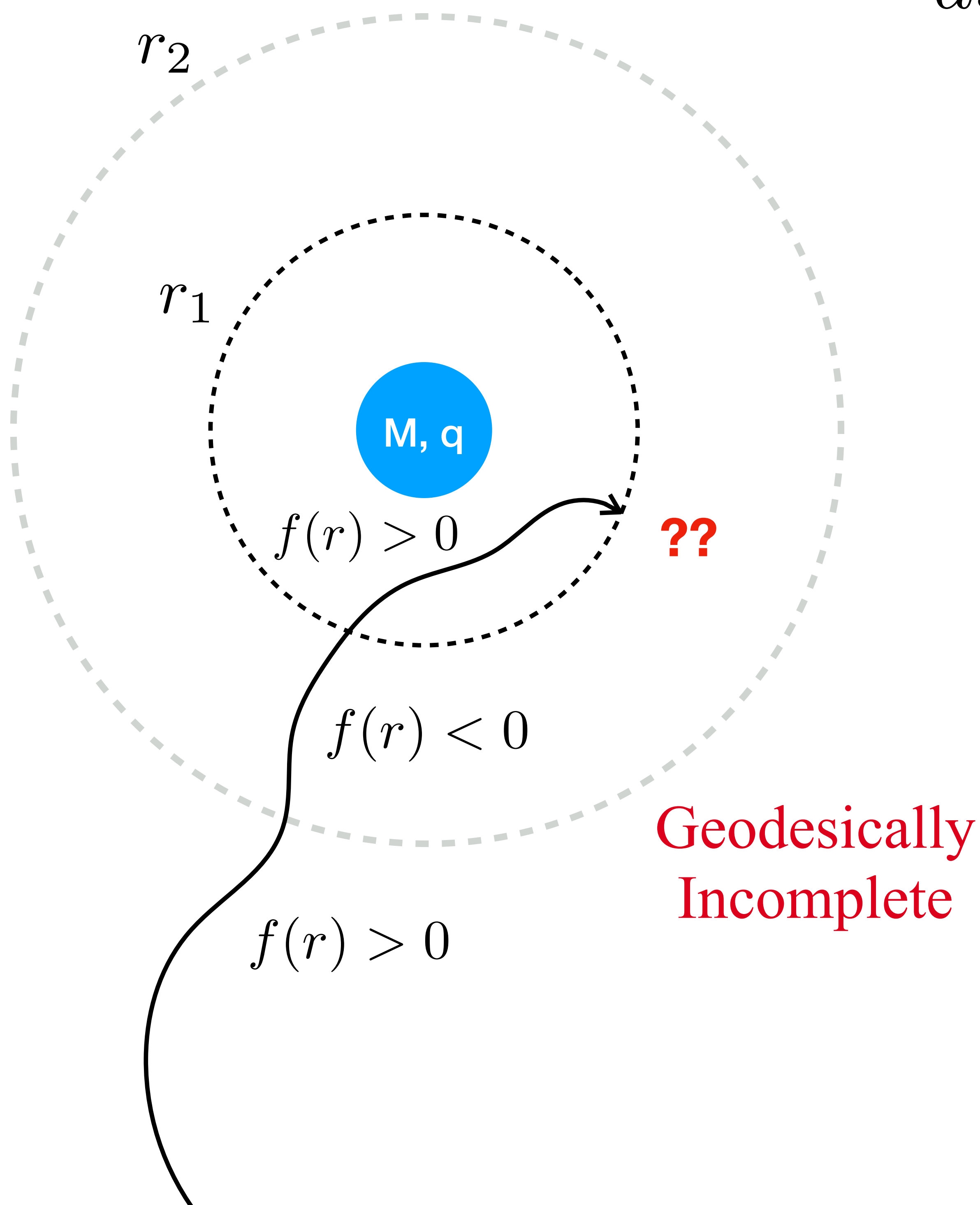


QM fluctuations near the horizon generate radiation that leaves the black hole:
—It has a temperature
—It has entropy proportional to area
—It shrinks

If the black hole shrinks to zero…
—How is unitary evolution maintained?
—Where is the entropy stored?
—Is GR violated??

Cauchy Horizons in Charged Bus

Charged (and spinning) black holes have a second (inner) horizon



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

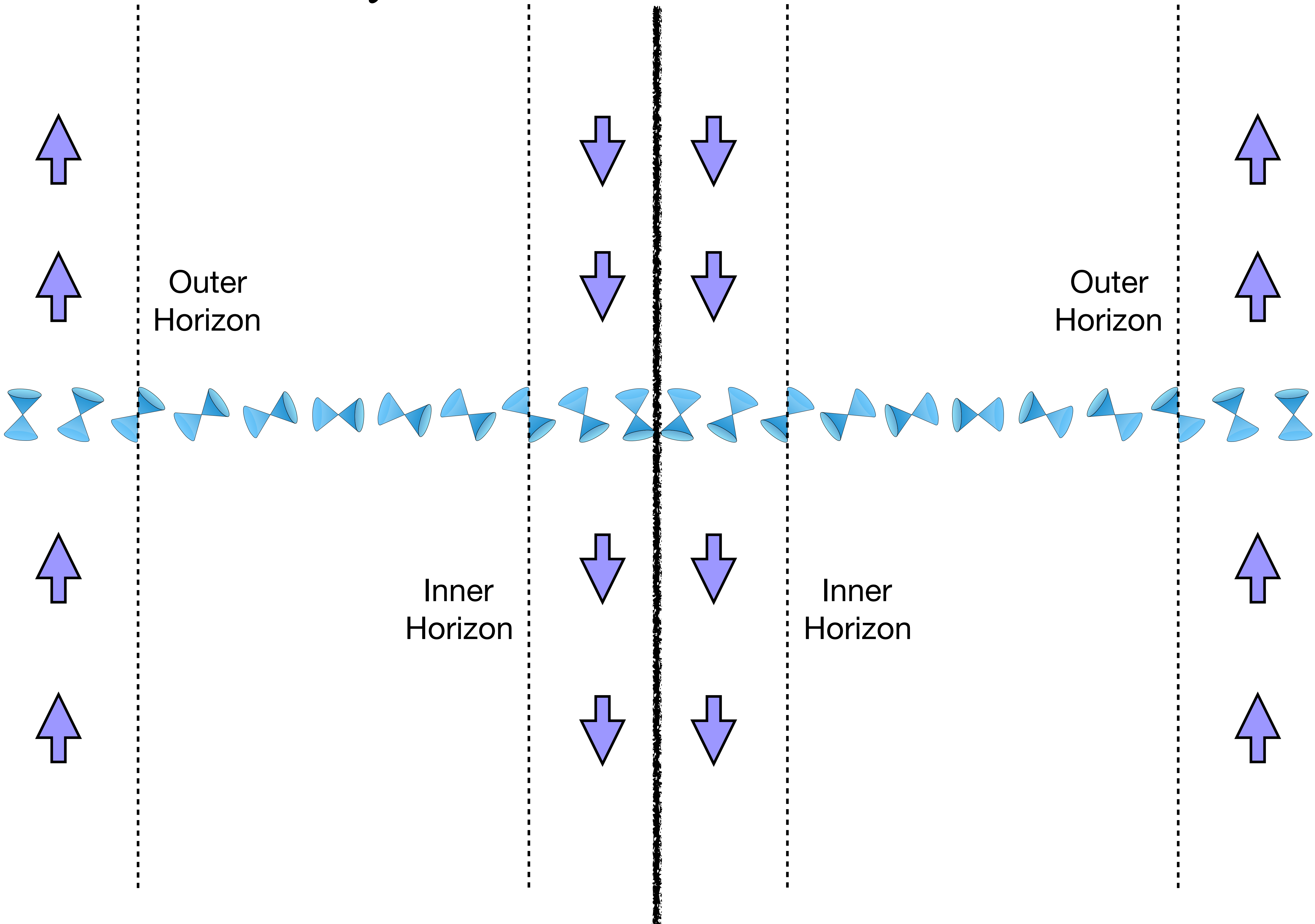
$$f(r) = \frac{(r - r_1)(r - r_2)}{r^2}$$

$$r_{2/1} = GM \pm \sqrt{(GM)^2 - GQ^2}$$

The r coordinate first becomes time-like inside r_1 and then space-like inside r_2. Can avoid singularity.

(Note: a dozen protons can produce an inner horizon in an otherwise uncharged BH)

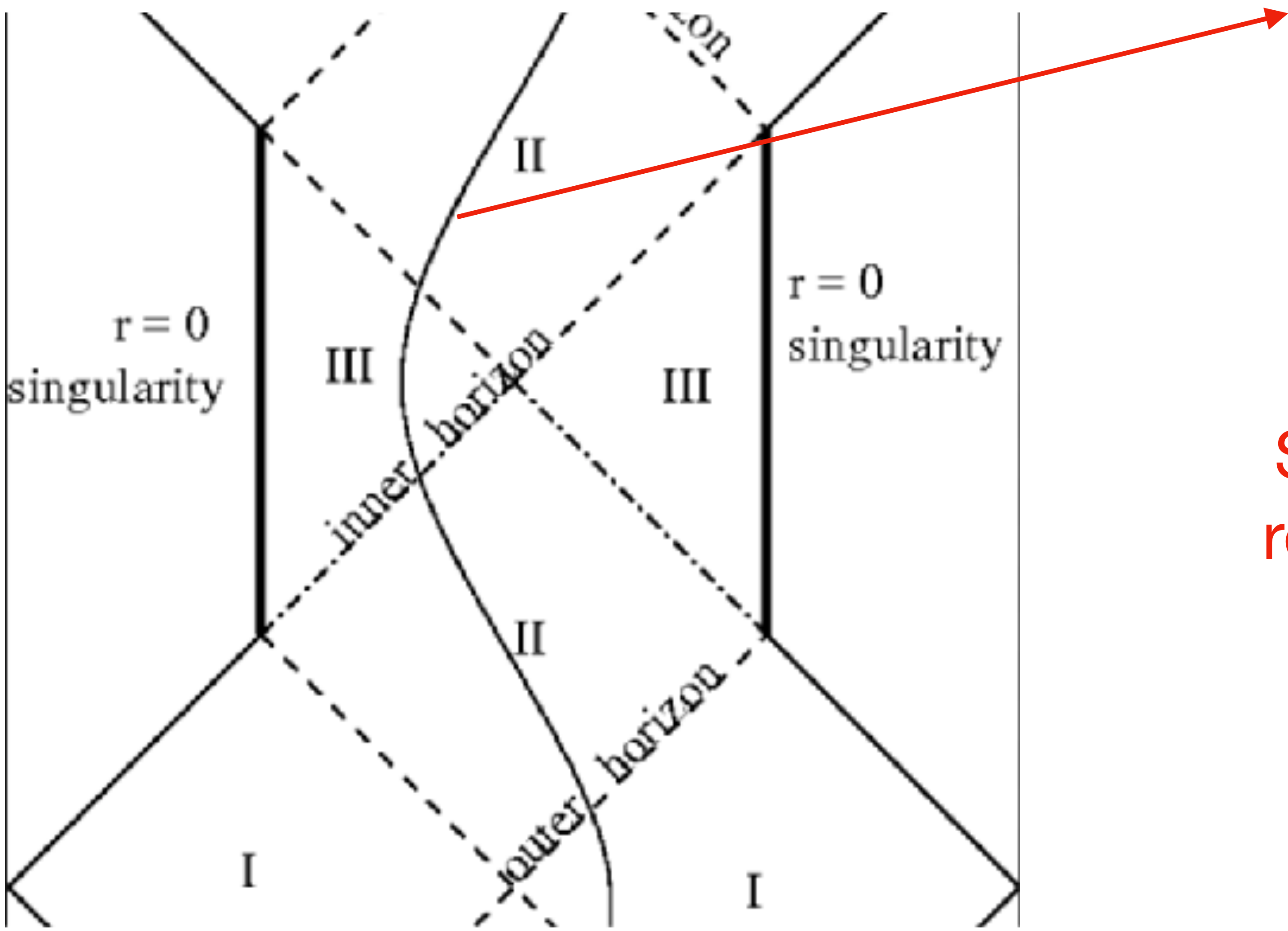
Cauchy Horizons in Reissner-Nordstrom



Cauchy Horizons in Reissner-Nordstrom

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

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



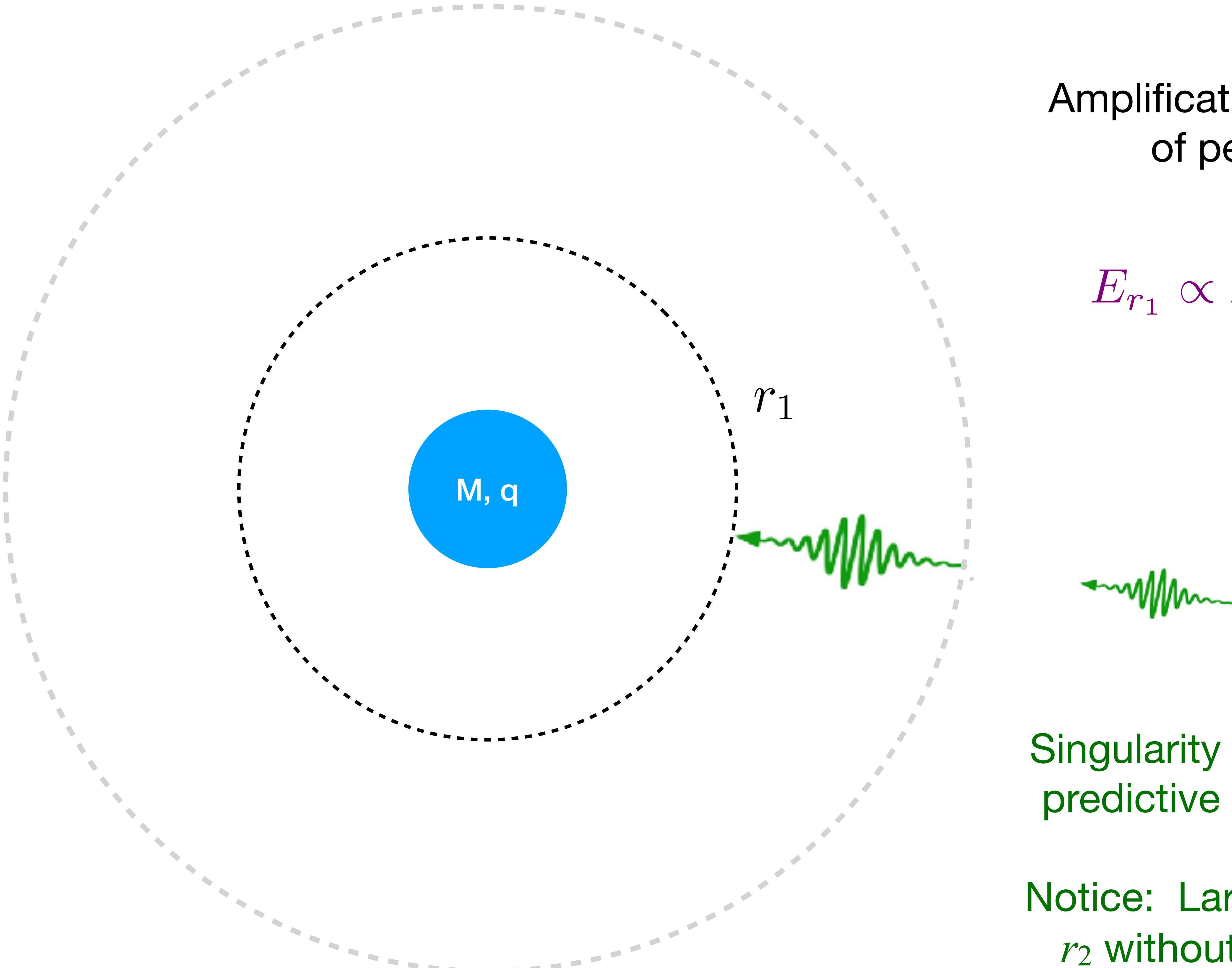
Can only be extended into a different universe

Subject to new boundary conditions, failure of predictivity

Sensible (non-eternal) black hole requires a large change to metric, no inner horizon

Static Black Hole: Singularity at inner horizon?

Mass Inflation



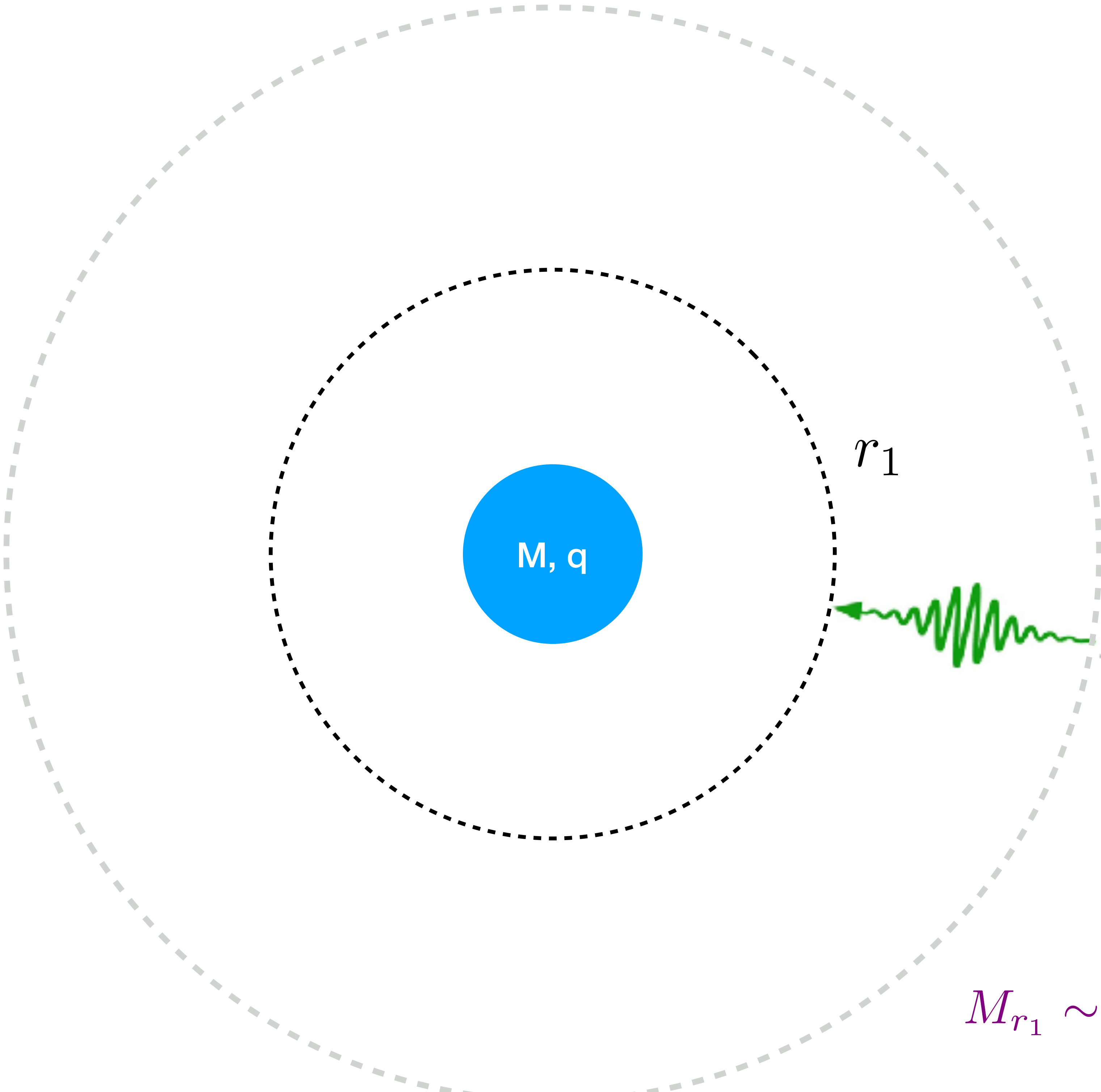
Amplification, i.e. blue-shift, of perturbations:

$$E_{r_1} \propto E_\infty \left(\frac{r_1}{r - r_1} \right)$$

Singularity can be source of non-predictive mathematical results.

Notice: Large (divergent) mass at r_2 without big change to ADM mass.

External Perturbations



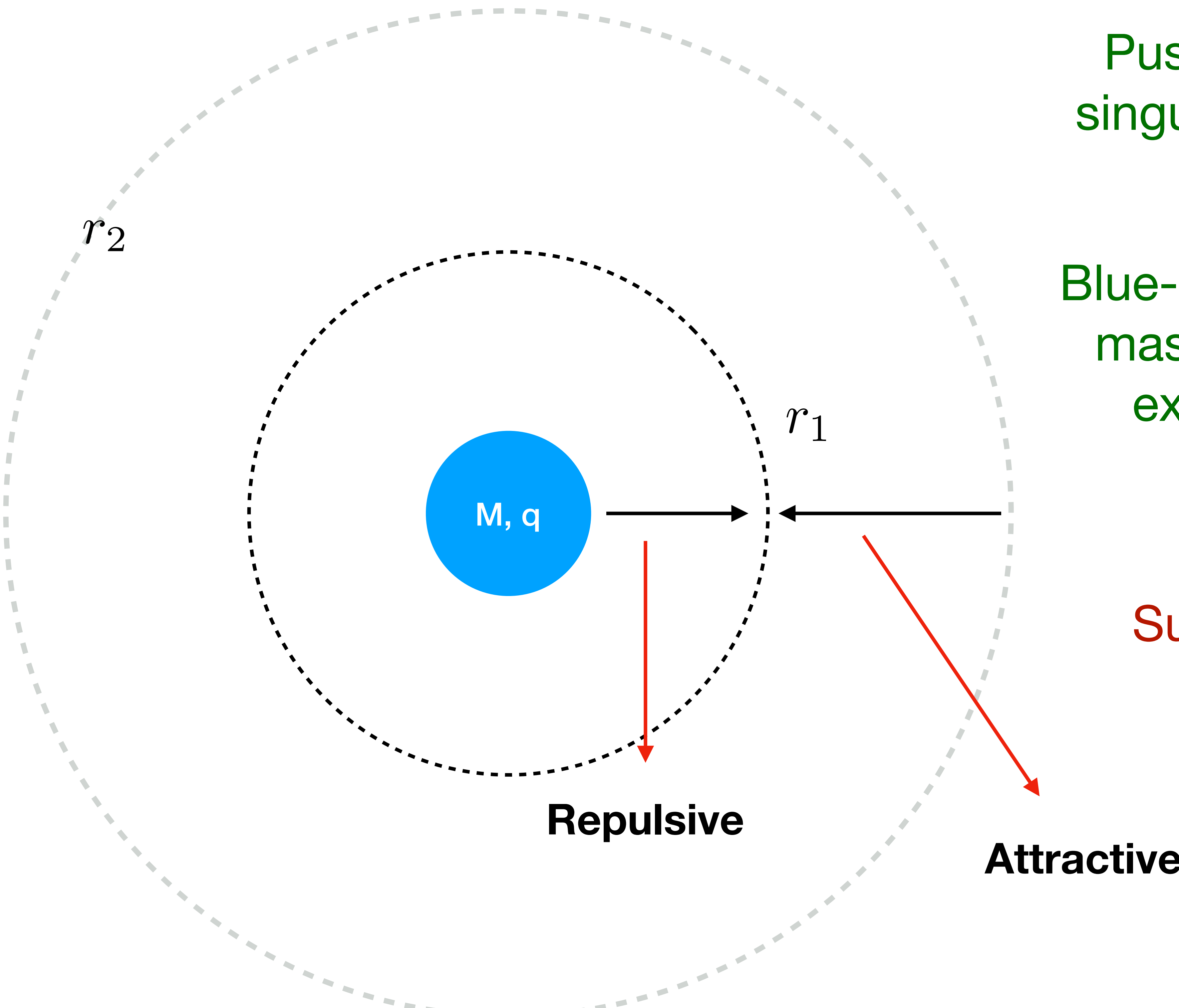
Regulate Divergence

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

Planckian Shell at r_1:

$$M_{r_1} \sim M_{pl}^3 r_1^2 \sim M \left(\frac{M}{M_{pl}}\right) \implies E_\infty \sim M$$

Matter is gravitationally attracted to this surface



Push mass/charge from singularity to inner horizon

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

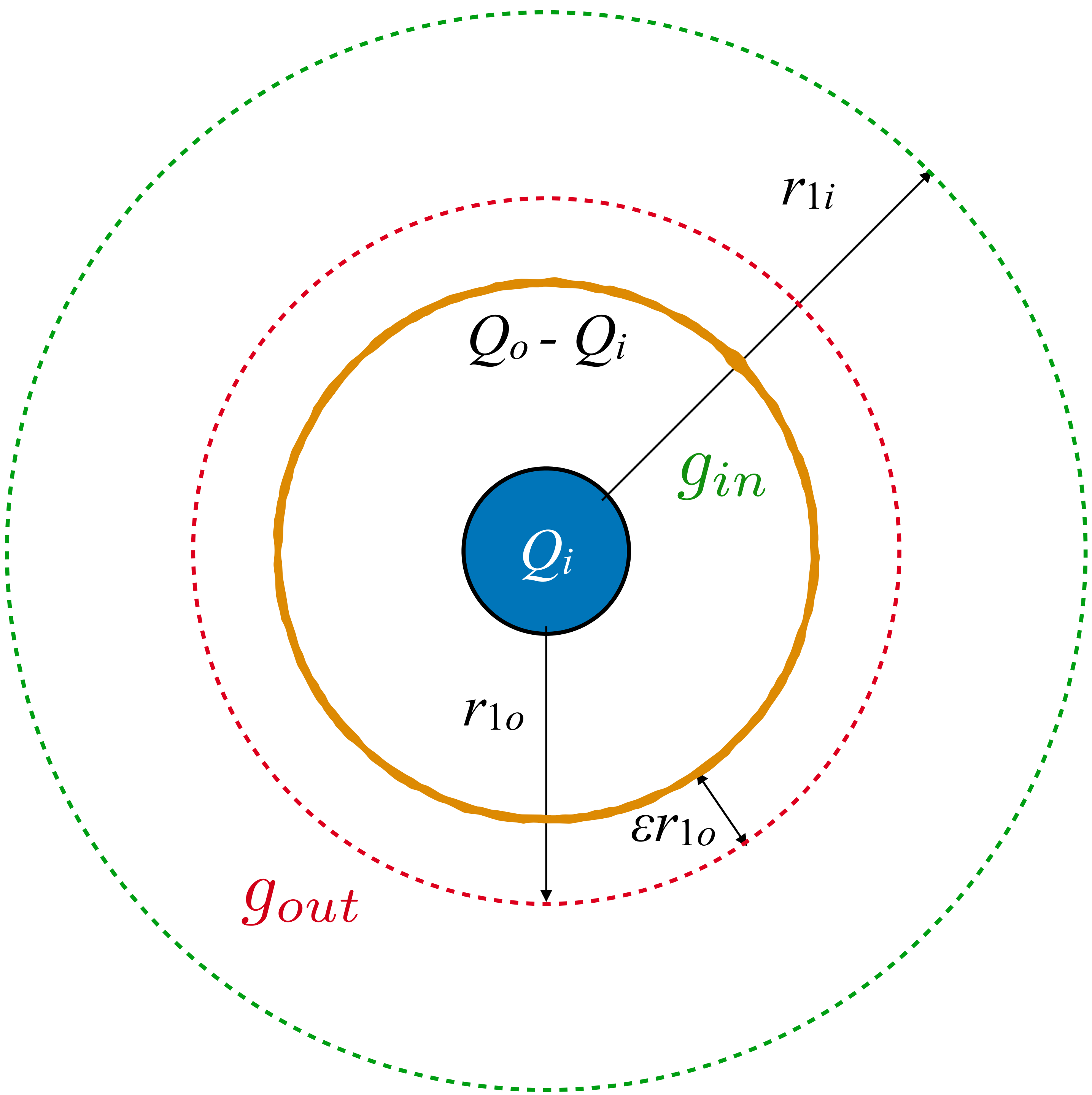
Suggests this interior never forms

Outline

1. Inner Horizons: Charged Black Holes
2. Outer Horizons: Neutral/Charged Black Holes
3. Weird Solutions
4. Formation and other speculation

The Inner Horizon of Reissner-Nördstrom

Reissner-Nordstrom Metric



g_{out} : required external RN metric

Place thin shell just within inner horizon

Can this shell be singular?

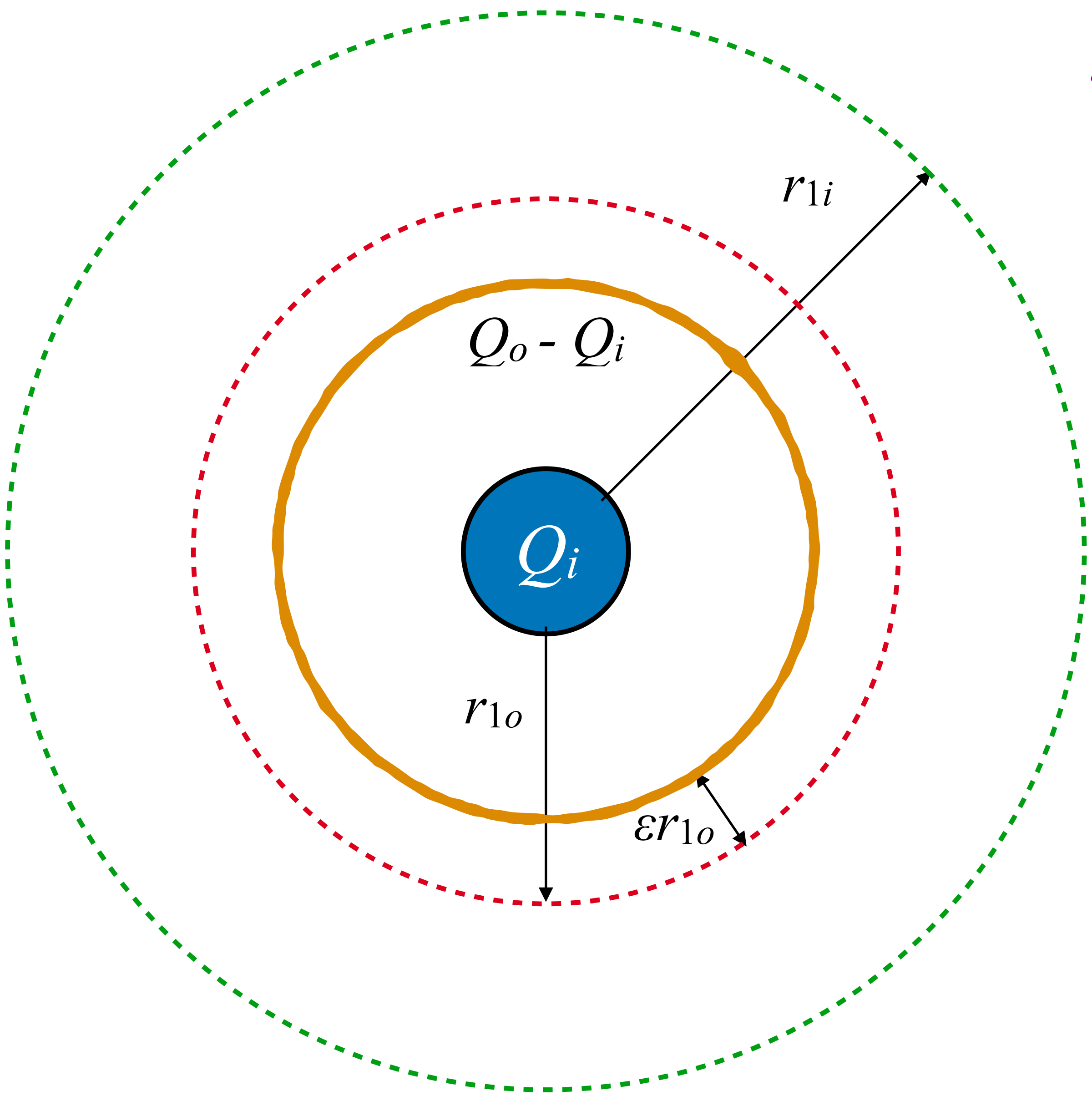
g_{in}: internal RN metric,
Free internal parameters

Use junction conditions to match

Match possible with positive mass?
Reasonable matter?

Reissner-Nordstrom Metric

Pick global (t, r, θ, φ) to cover entire space-time



$$g_{in} = -C^2 \Delta_i(r)\, dt^2 + \frac{dr^2}{\Delta_i(r)} + r^2 d\Omega^2$$

$$g_{out} = -\Delta_o(r)\, dt^2 + \frac{dr^2}{\Delta_o(r)} + r^2 d\Omega^2$$

$$\Delta_i = \frac{(r - r_{1i})(r - r_{2i})}{r^2} \qquad \Delta_o = \frac{(r - r_{1o})(r - r_{2o})}{r^2}$$

Match @ $r = r_0 < r_{1o}$

What are r_{1i}, r_{2i} for singular shell as $r_0 \to r_{1o}$? Charge on this shell?

Reissner-Nordstrom Metric

$$r_0 = r_{1o}\left(1 - \epsilon\right) \qquad \epsilon \to 0$$

$$\rho \to \frac{M_{pl}^2}{4\pi r_{1o}^2}\sqrt{\left(r_{1i} - r_{1o}\right)\left(r_{2i} - r_{1o}\right)}$$

$$p = \frac{M_{pl}^2}{16\pi r_{1o}}\left(-\sqrt{\frac{r_{2o} - r_{1o}}{\epsilon r_{1o}}} + \ldots\right)$$

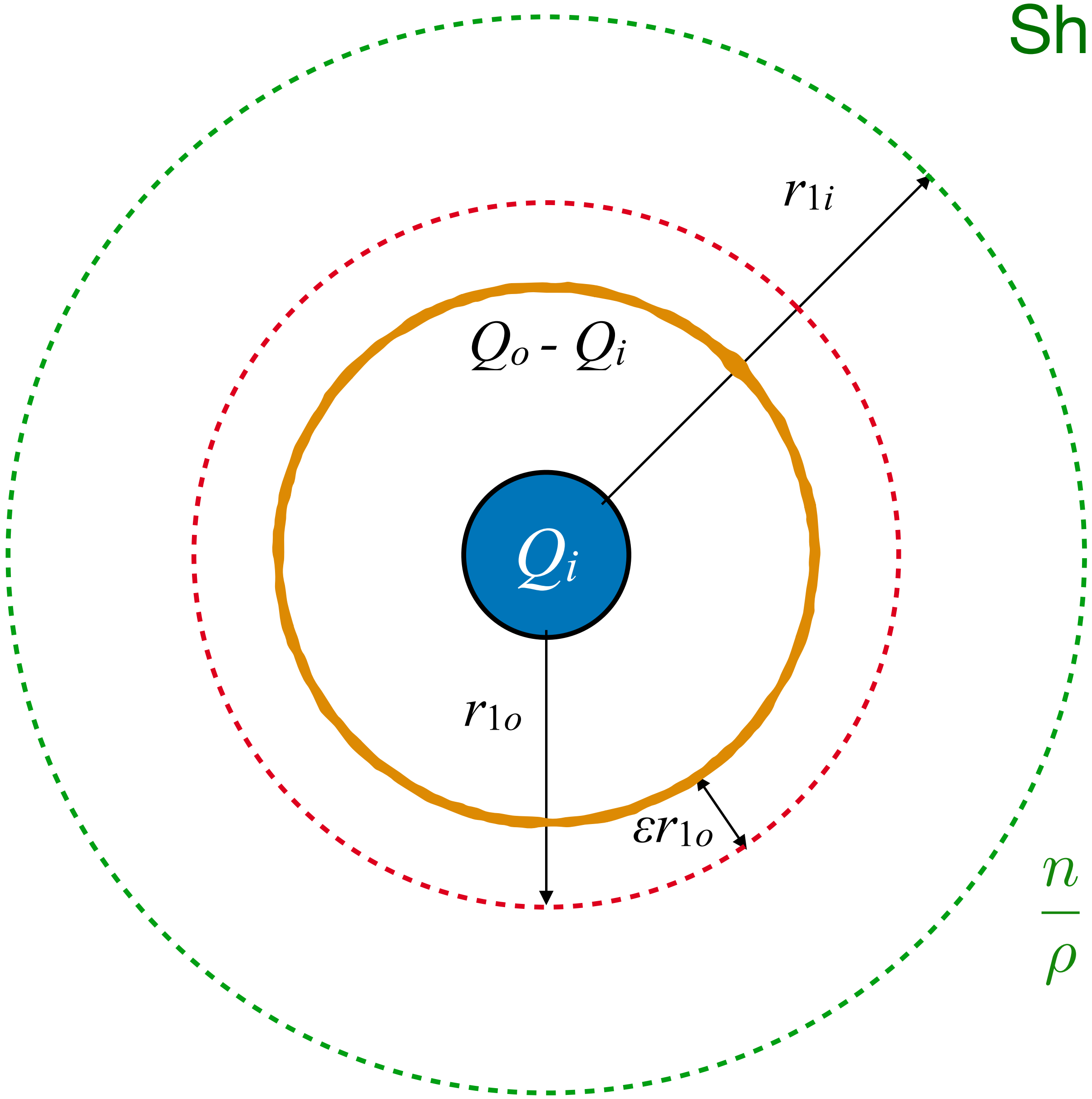
Place shell at a physical distance ~ $1/M_{pl}$ from r_{1o}

$$\epsilon \sim \left(r_{2o} - r_{1o}\right) / \left(M_{pl}^2 r_{1o}^3\right) \qquad \Longrightarrow \; p \sim -M_{pl}^3$$

By choosing: $r_{1i},\, r_{2i} \sim M_{pl} r_{1o}^2 \qquad \Longrightarrow \; \rho \sim M_{pl}^3$

Characteristics?

Shell Characteristics



Shell at a physical distance ~ $1/M_{pl}$ from r_{1o}

$$r_{1i}, r_{2i} \sim M_{pl} r_{1o}^2$$

$$Q = M_{pl} \sqrt{\frac{r_{1i} r_{2i}}{\alpha}}$$

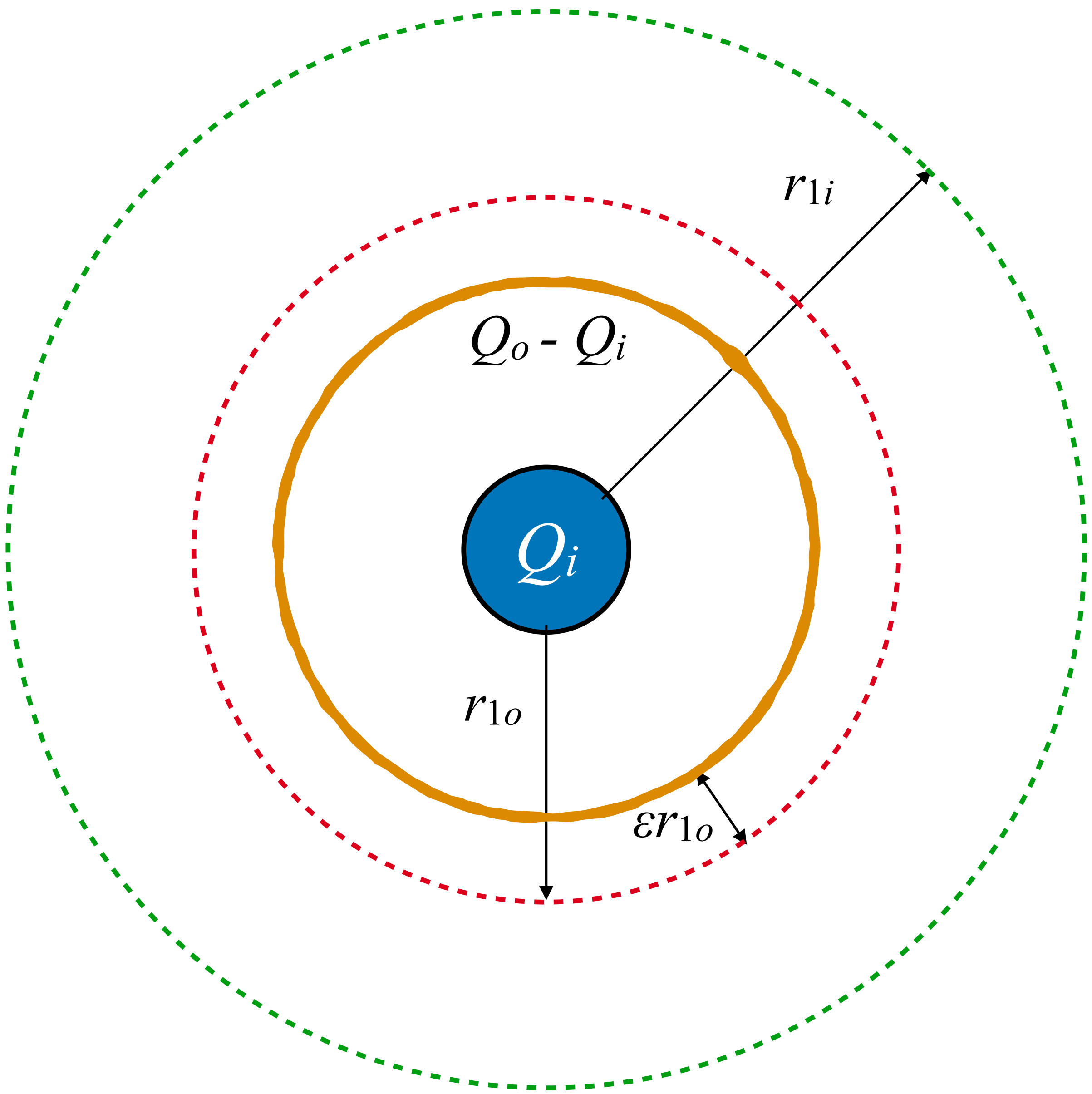
$$\frac{n}{\rho} = \frac{M_{pl} Q}{4\pi \rho r_{1o}^2} \sim \sqrt{\frac{r_{1i} r_{2i}}{(r_{1i} - r_{1o})(r_{1i} - r_{1o})\,\alpha}} \gtrapprox 1$$

Can this shell exist by itself, without inner singularity?

No static solutions where shell has given mass, charge and surface area, with interior being Minkowski and RN exterior - binding energy of singularity necessary

Do not know microphysics of shell - cannot analyze stability

Reissner-Nordstrom Metric



Shell at a physical distance ~ $1/M_{pl}$ from r_{1o}

$$r_{1i}, r_{2i} \sim M_{pl} r_{1o}^2$$

With this choice of parameters, can show that the physical distance from r_{1o} to $r = 0$ is ~ $1/M_{pl}$!

The volume of the interior becomes proportional to the *area* of the horizon!

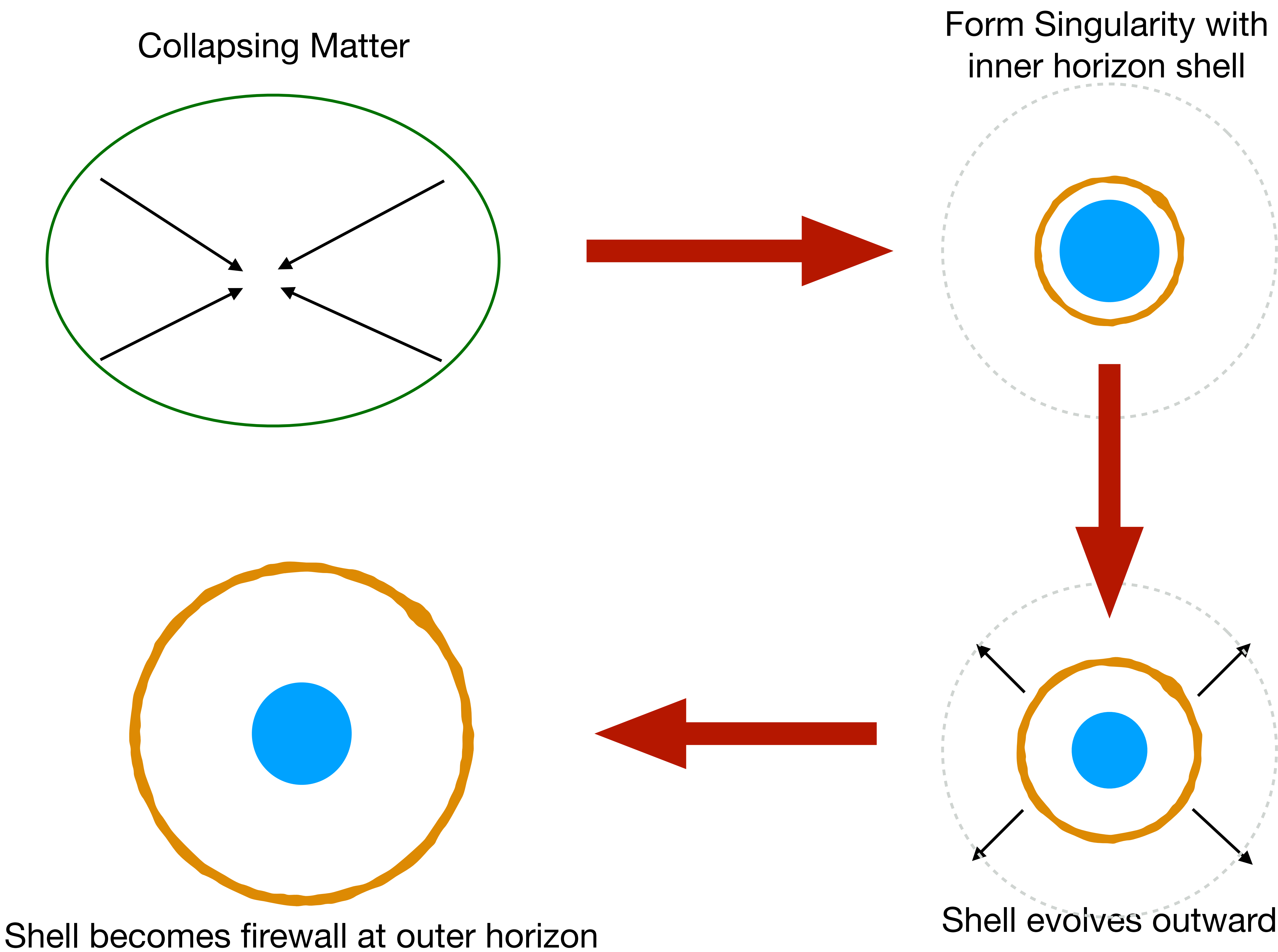
Complete breakdown of General Relativity at inner horizon:

$$R_{\mu\nu\lambda\sigma} R^{\mu\nu\lambda\sigma} \gtrapprox M_{pl}^4 \text{ for } r \lessapprox r_{1o}$$

Trust as a limit of non-singular solutions

Perhaps such a shell could live at the outer horizon?

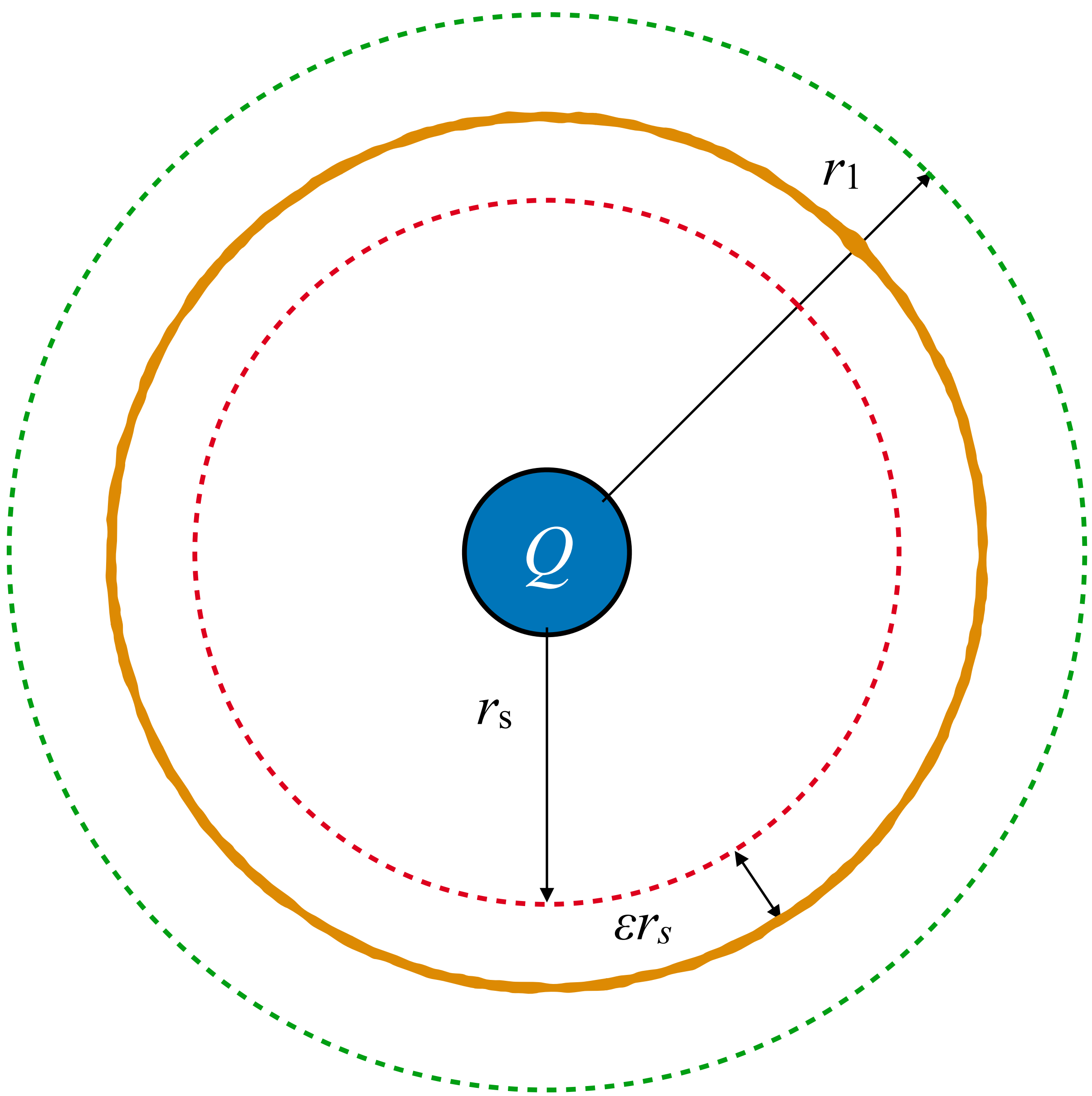
Firewall Formation



Event Horizon of Schwarzschild

(Or Reissner-Nordstrom)

The Schwarzschild Metric



g_{out} : required external Schwarzschild metric

Place thin shell just outside event horizon

Can this shell be Planckian?

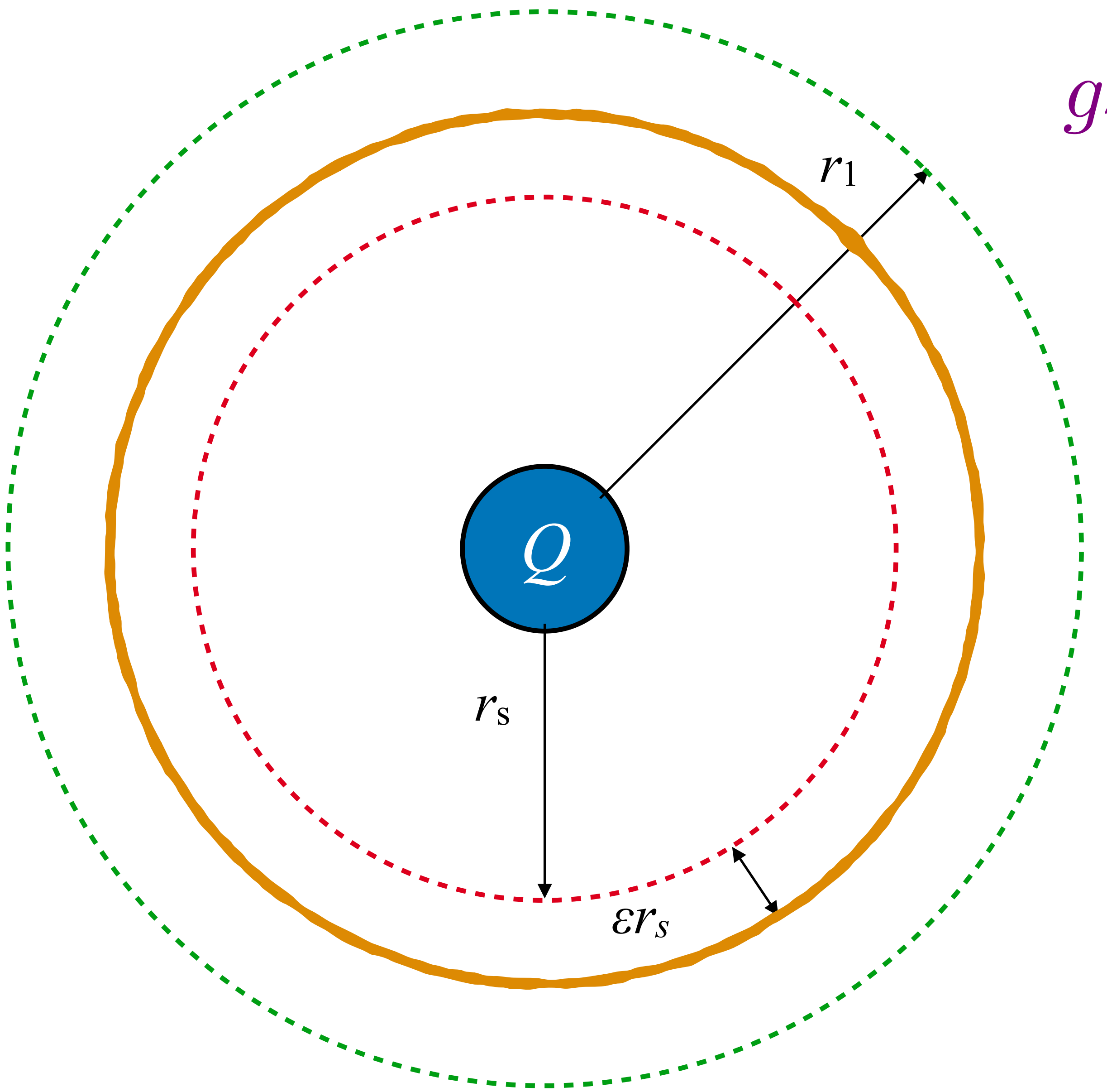
g_{in}: internal RN metric,
Free internal parameters

Use junction conditions to match

Match possible with positive mass?
Reasonable matter?

The Schwarzschild Metric

Pick global (t, r, θ, φ) to cover entire space-time



$$g_{in} = -C^2 f_i(r)\, dt^2 + \frac{dr^2}{f_i(r)} + r^2 d\Omega^2$$

$$g_{out} = -f_o(r)\, dt^2 + \frac{dr^2}{f_o(r)} + r^2 d\Omega^2$$

$$f_i = \frac{(r - r_1)(r - r_2)}{r^2} \qquad f_o = \frac{(r - r_s)}{r}$$

Match @ $r = r_0 > r_s$

What are r_1, r_2 for Planckian shell as r_0 -> r_s? Charge on this shell?

Schwarzschild Metric

$$r_0 = r_s\,(1+\epsilon) \qquad \epsilon \to 0$$

$$\rho \to \frac{M_{pl}^2}{4\pi r_s^2}\sqrt{(r_1 - r_s)\,(r_2 - r_s)}$$

$$p = \frac{M_{pl}^2}{16\pi r_s\sqrt{\epsilon}} + \ldots$$

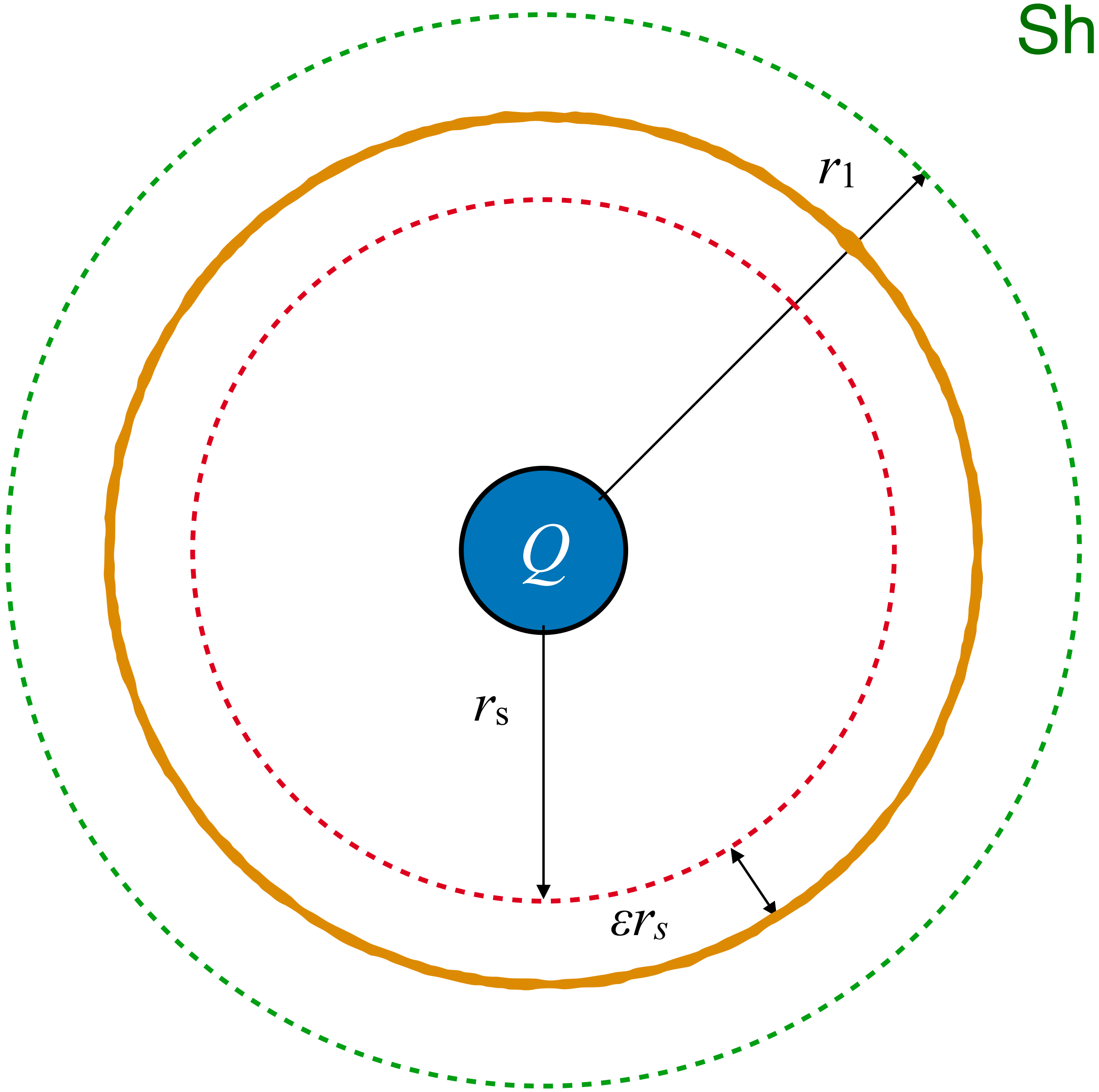
Place shell at a physical distance ~ $1/M_{pl}$ from r_s

$$\epsilon \sim \frac{1}{\left(M_{pl} r_s\right)^2} \qquad \Longrightarrow \quad p \sim M_{pl}^3$$

By choosing: $r_1,\, r_2 \sim M_{pl} r_s^2 \qquad \Longrightarrow \quad \rho \sim M_{pl}^3$

Characteristics very similar to that of the shell needed for Reissner-Nordstrom outer horizon

"Black Hole" Entropy



Shell at a physical distance ~ $1/M_{pl}$ from r_s

$$r_1,\, r_2 \sim M_{pl} r_s^2$$

Again, can show that the physical distance from r_{1o} to $r = 0$ is ~ $1/M_{pl}$! Inner volume grows at area!

Simple singular/Planckian object
Entropy should scale like area

$$R_{\mu\nu\lambda\sigma} R^{\mu\nu\lambda\sigma} \gtrapprox M_{pl}^4 \text{ for } r \lessapprox r_s$$

New kind of naked singularity

Firewall Formation

Many naked singularity solutions in General Relativity
(extremal RN/Kerr, fuzzballs, gravastars…)

A sufficiently large, low density cloud of matter can collapse to a black hole.
How can this collapsing matter evolve to the required solution?

Key Distinction: Singular Shell not subject to General Relativity

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

EP Preserving

Lorentz Preserving, EP violating

Higher Order Corrections => new effective metric
Causal, GR violating evolution of shell possible

Firewall Stability

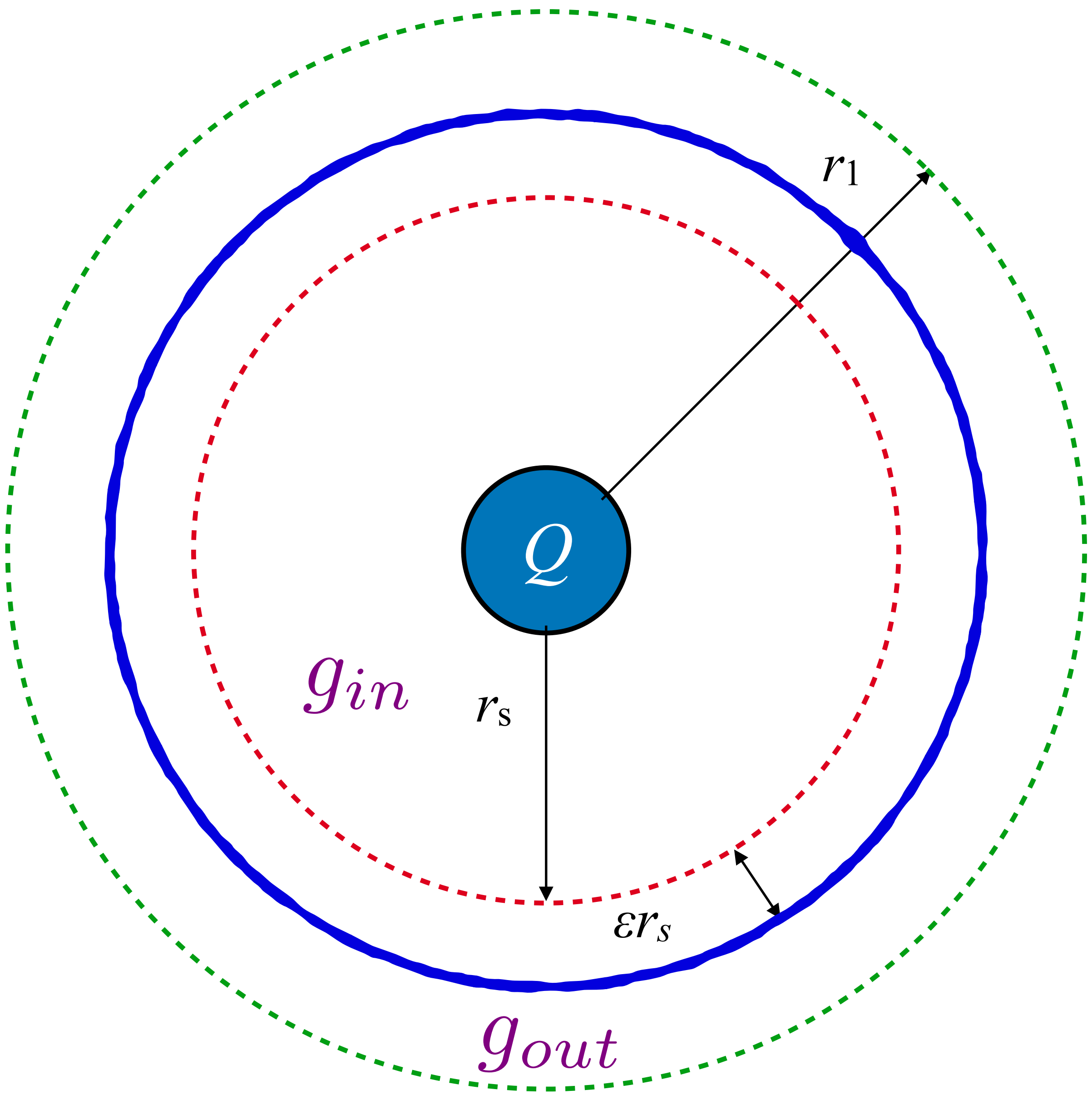
In progress…
“with” Emanuele Berti, Caio Macedo, Ryan McManus

Monopole fluctuations stable for range of equations of state.

Other modes being checked (non-trivial due to long-range interactions).

Negative Mass Schwarzschild

Negative Mass Schwarzschild



Solutions involve delicate cancellation of large positive masses and negative binding energy

Do not know microphysics of shell or core singularity

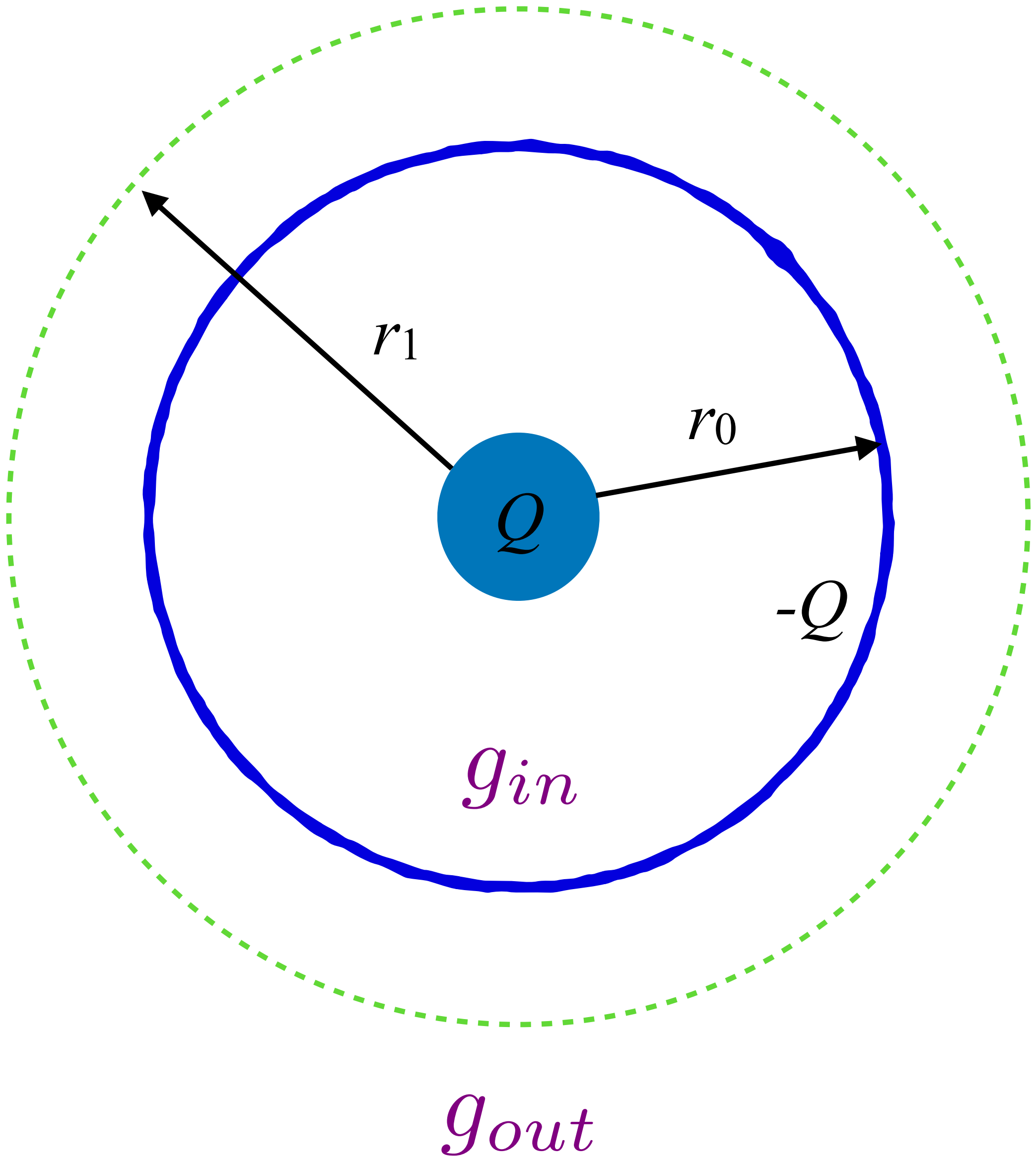
Could we cancel the positive mass too much, leading to negative mass solutions?

Difference between objects needed for positive mass and negative mass solutions?

Potential restriction on the UV?

Negative Mass Schwarzschild

Pick global (t, r, θ, φ) to cover entire space-time



$$g_{in} = -C^2 f_i(r)\, dt^2 + \frac{dr^2}{f_i(r)} + r^2 d\Omega^2$$

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

$$g_{out} = -f_o(r)\, dt^2 + \frac{dr^2}{f_o(r)} + r^2 d\Omega^2$$

$$f_o = \frac{(r + r_s)}{r}$$

Key Difference: r_s simply a parameter. Match at any possible r_0

Parameters needed to get $\rho \sim |p| \sim M_{pl}{}^3$

Negative Mass Schwarzschild

$$p = \frac{M_{pl}^2}{16\pi r_0^2}\left(r_s\gamma_o + (r_1 + r_2)\,\gamma_i + 2r_0\,(\gamma_o - \gamma_i)\right)$$

$$\gamma_o = \sqrt{\frac{r_0}{r_0 + r_s}} \qquad \gamma_i = \sqrt{\frac{r_0^2}{(r_1 - r_0)\,(r_2 - r_0)}}$$

No natural horizons in the base geometry - non-singular pressure

Pick r_s, r_0, r_2, r_1 to get M_{pl}^3 pressure

1. $r_0 < 1/M_{pl}$ → GR breaks well outside shell
2. $r_2 >> r_1$ → Different Branch UV restriction?
3. $r_2 \sim r_1$, $r_s \sim M_{pl}^2\, r_0^3$ → Can't avoid

Negative Mass Schwarzschild

$$r_2 \sim r_1,\ r_s \sim M_{pl}^2\ r_0^3$$

Can get solutions with $\rho \sim M_{pl}^3$, $p \sim M_{pl}^3$

BUT

UV theory gives shell with specific equation of state

e.g., pick $p = \rho/4$

With $r_2 \sim r_1$, what do we need to construct positive mass vs negative mass Schwarzschild?

Test for GR Breakdown: $R_{\mu\nu\lambda\sigma} R^{\mu\nu\lambda\sigma} > M_{pl}^4$

Positive Mass	Negative Mass
$r < r_s$	$r > r_0$

Not parametric, but strict numerical

What does this mean?

Restrictions on UV e.g. $r_2 \sim r_1$, $p \sim \rho/4$ help avoid negative mass solutions while preserving desired solutions

Of course, cannot collapse normal matter to get negative mass solution

Spontaneous Vacuum Decay

Γ = |Matrix Element|^2 x (phase space)

Exponentially Suppressed

Non Compact Lorentz Group

∞

No Lorentz invariant regulation possible

How much should we trust Lorentz?
Simple Regulator: Finite universe

Experimental Signatures

Savas Dimopoulos, Peter Graham, Roni Harnik and Surjeet Rajendran

(in progress)

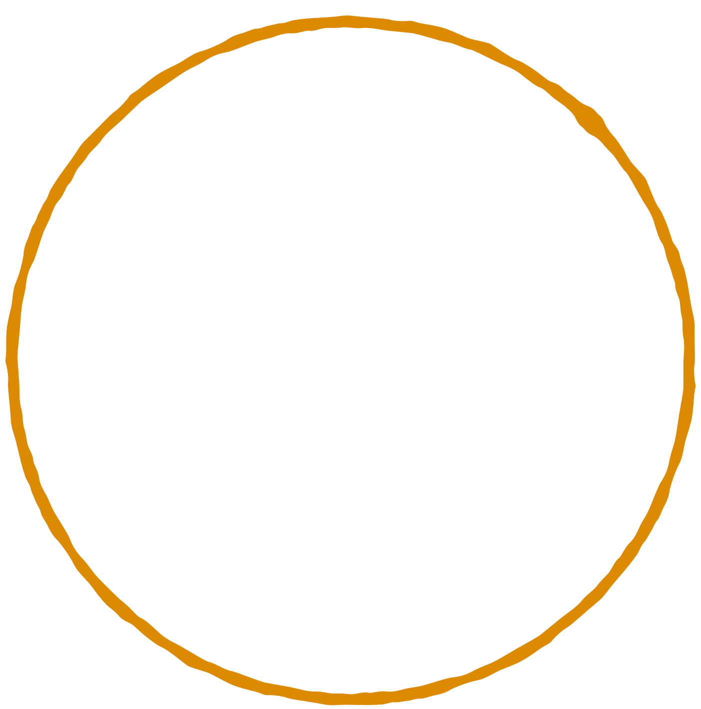
Signatures of Firewalls

Caveat: Formation time unclear

Instant Formation in the inner horizon of Reissner Nordstrom. But not visible outside

For outer horizon, could wait a Page time, but no reason not to expect instant formation

Naked Singularity



Deviations from No Hair Theorem (GR & EM)
Event Horizon Telescope?

Ringdown of Quasi-Normal Modes set by Firewall physics
Testable in Black Hole Mergers @ LIGO?

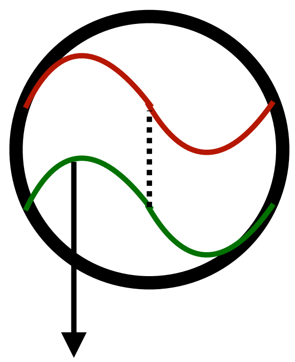
Reflectivity of the horizon to EM and GW
LIGO? Radio?

Wild Speculation

Light States?

Binding energy cancels large positive energies

Known Example in Particle Physics: Composite Axion



Fermions at energy F

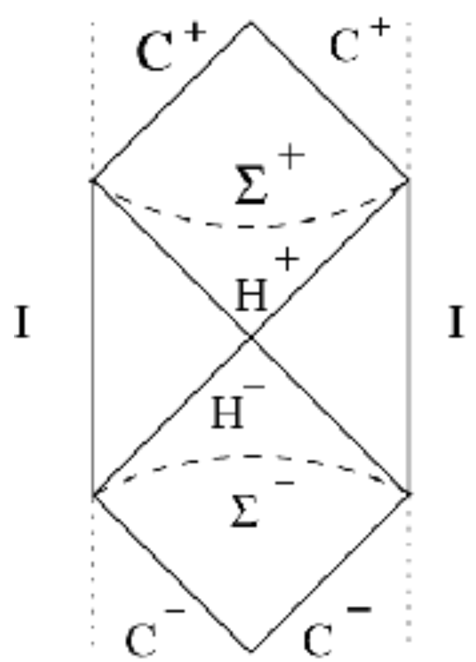
Break global symmetry through confinement at high scale F.

Get massless goldstone boson

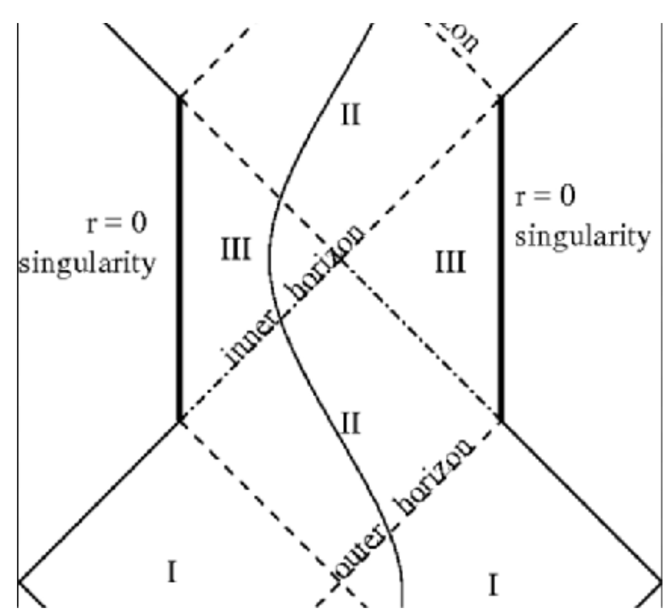
Light State ensured by symmetry

No symmetry reason for cancellation in firewall solutions

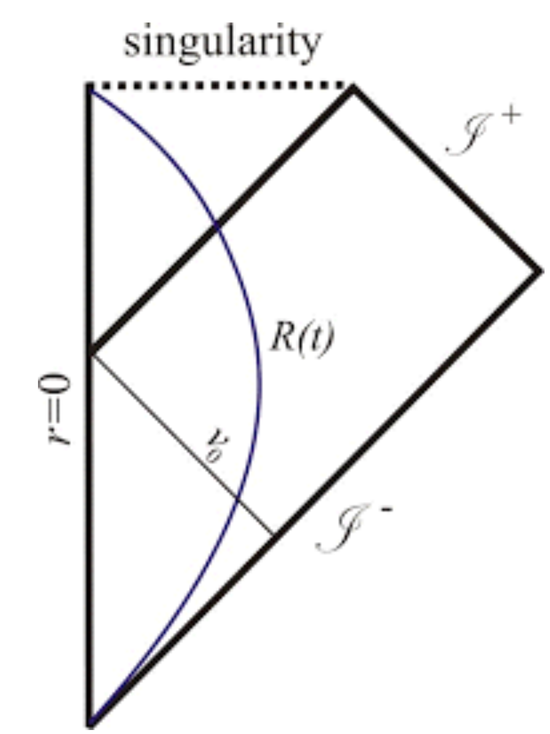
New principle tied to Causality?



Vacuum Energy Regulation in Rotating BTZ



Inner Horizons of RN/Kerr



Event Horizon of Schwarzschild

Particle Physics Implications

Firewall/Naked Singularity solution could mean that Black Holes do not actually evaporate

Global Symmetries may actually be preserved under quantum gravity

Weakens/changes limits on new physics based on black hole evaporation (primordial black hole dark matter, LHC limits on extra-dimensions, superradiance limits on axions)

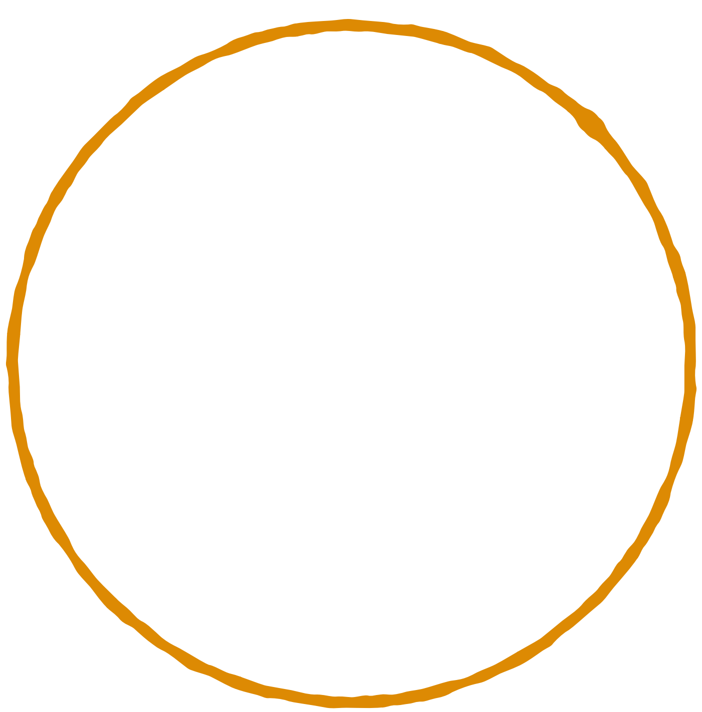
Gauge theory analog of firewall solutions?
New light states in the gauge theory?
New Solutions to the Hierarchy Problem?

Summary

These metrics represent **new spherically symmetric solutions** in General Relativity + matter

Inner (Cauchy) horizons of black holes with even tiny bits of charge or spin are unstable and suggest **new interior solutions are required**.
These **firewalls** present a potential solution as a limit of GR.

Planck-density firewalls have the possibility of **emerging from the singularity**.



The outer horizons of all black holes could evolve to the firewall solution in with volume ~ r_s^2/M_{pl} (for any BH). D.O.F. live at surface and suggest **correct state counting / entropy**.

Black holes can **source hair**, and signals include tests of the geometry, consistency checks of spinning BHs, ring-down after BH collisions,…