Firewalls in General Relativity

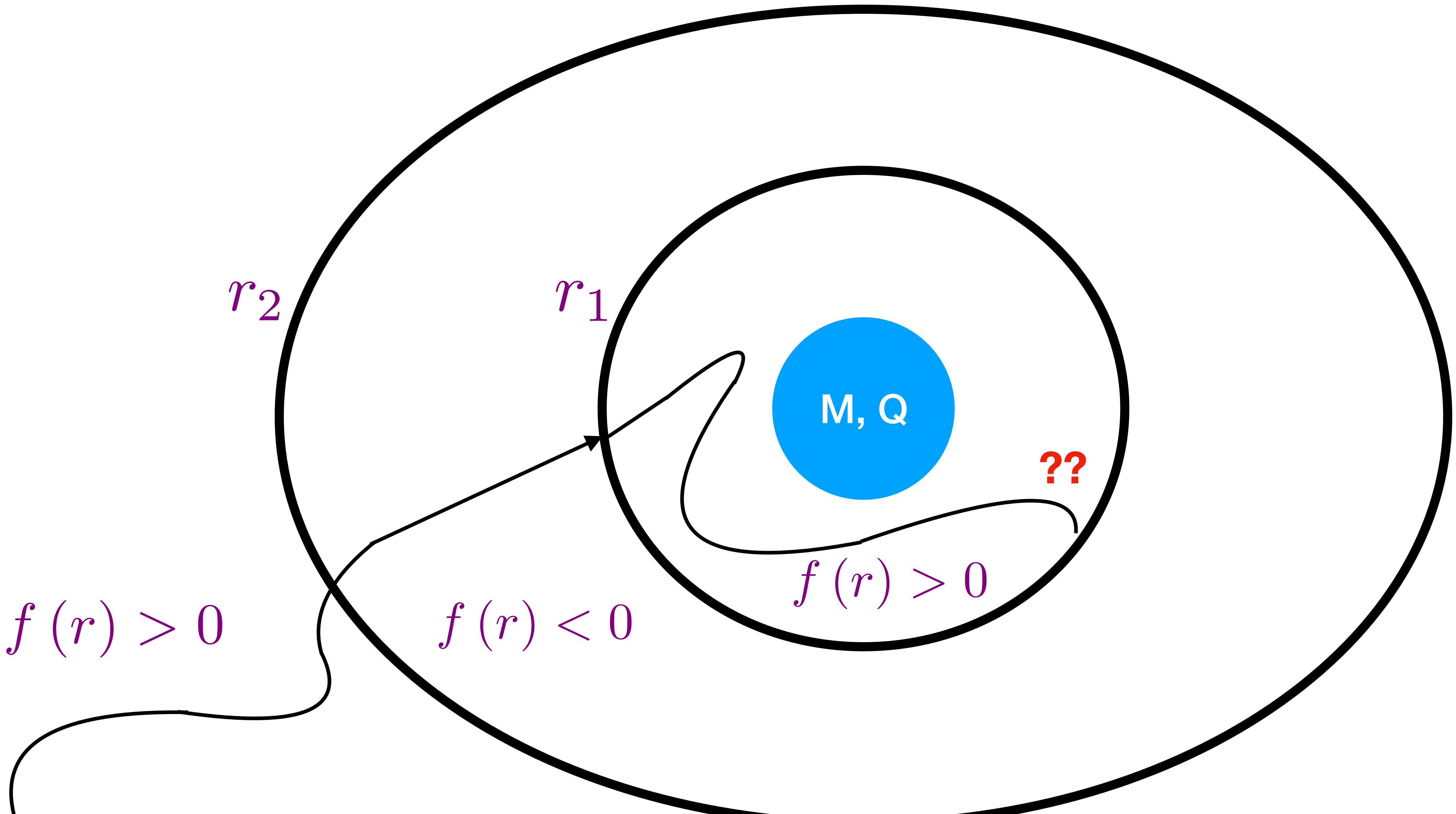
with David *E.* Kaplan

arXiv:1812.00536

Cauchy Horizons in Reissner Nordstrom/Kerr

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

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



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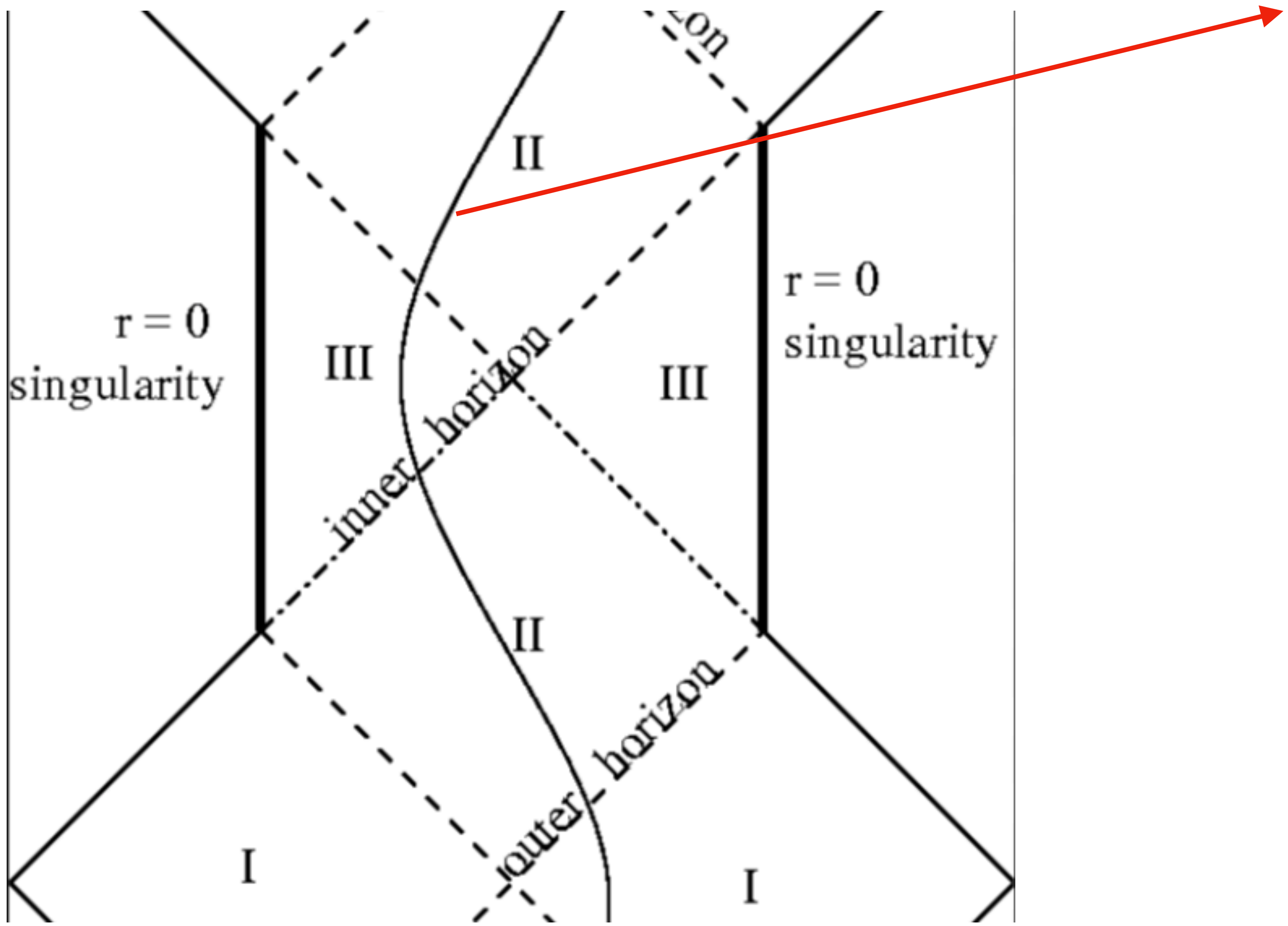


Can only be extended into a different universe

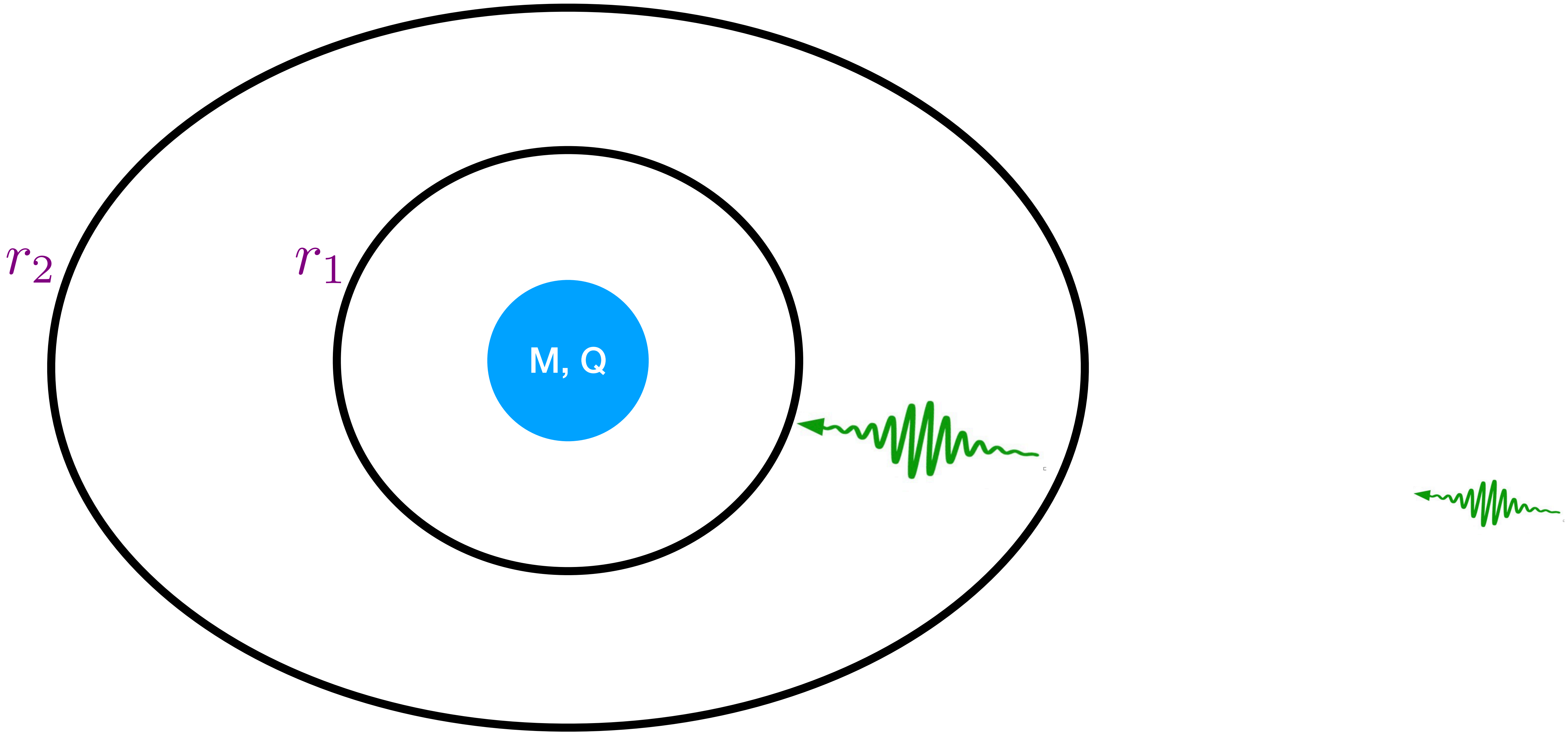
Subject to new boundary conditions, failure of predictivity

Large change to metric, no inner horizon

Static Black Hole: Singularity at inner horizon?

Fast, classical effect

Mass Inflation

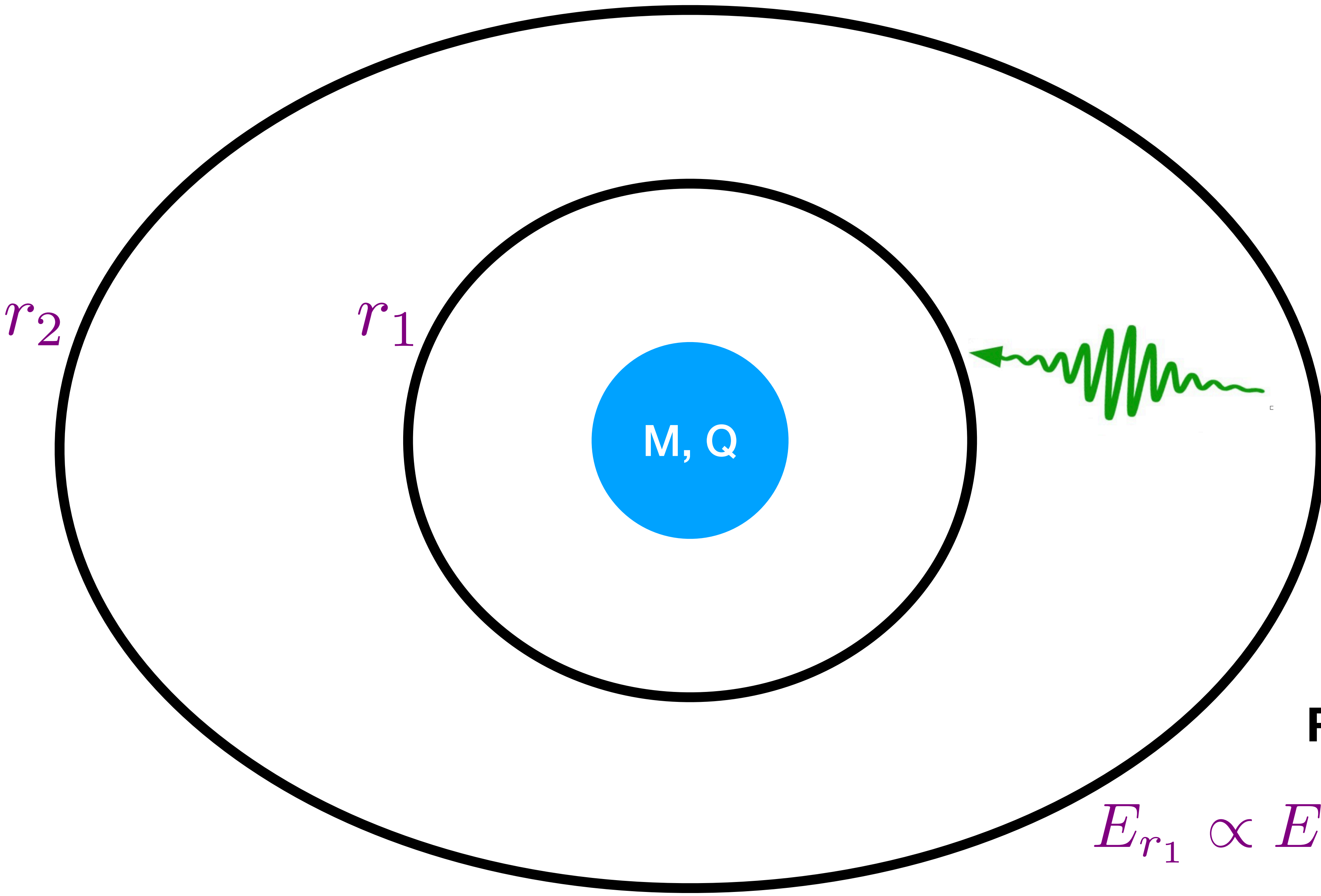


Amplification, i.e. blue-shift, of perturbations: $E_{r_1} \propto E_\infty \left(\frac{r_1}{r - r_1} \right)$

Significant local density, without changing external mass

External perturbations, really?

External Perturbations



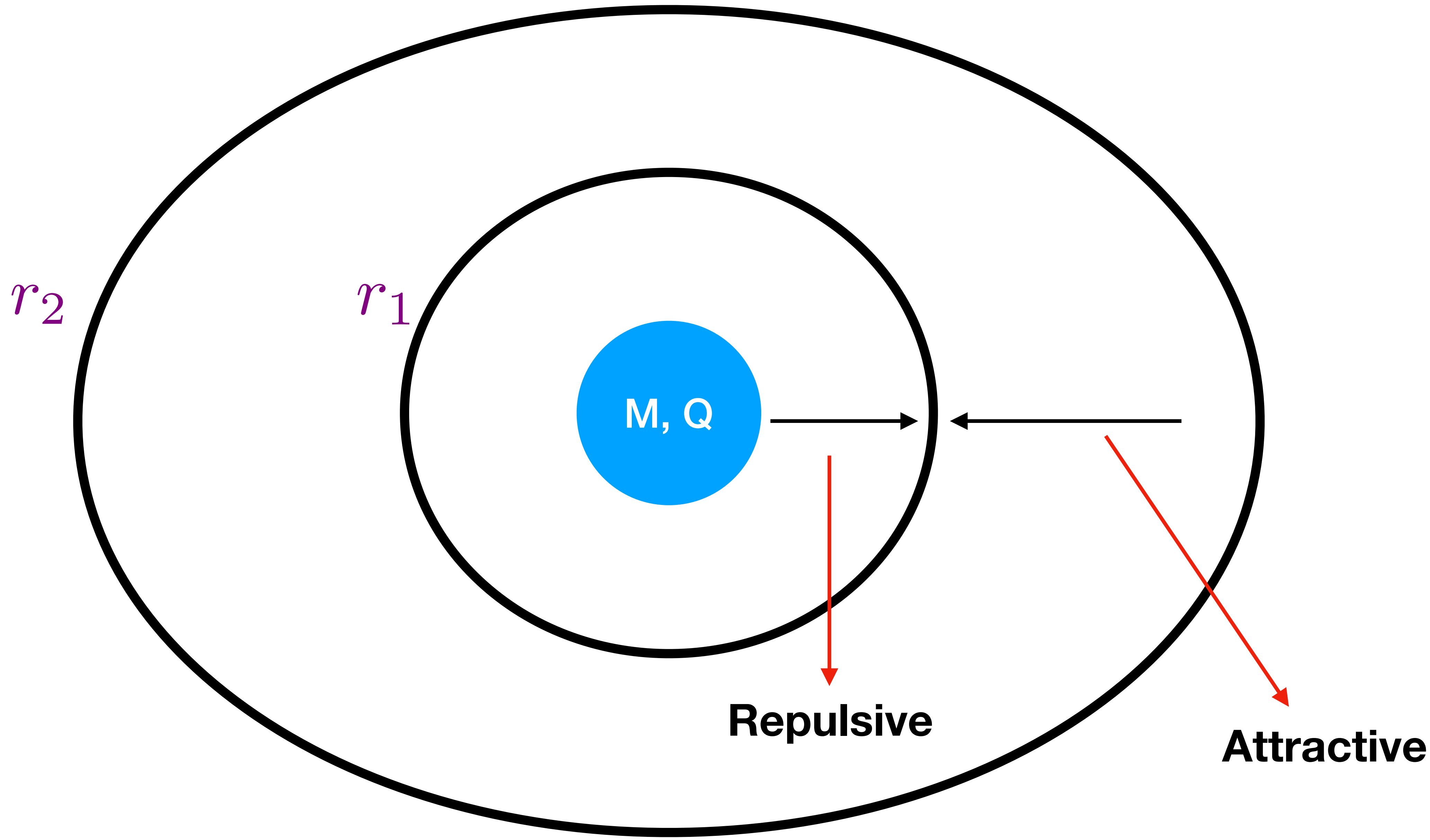
Regulate Divergence

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

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?

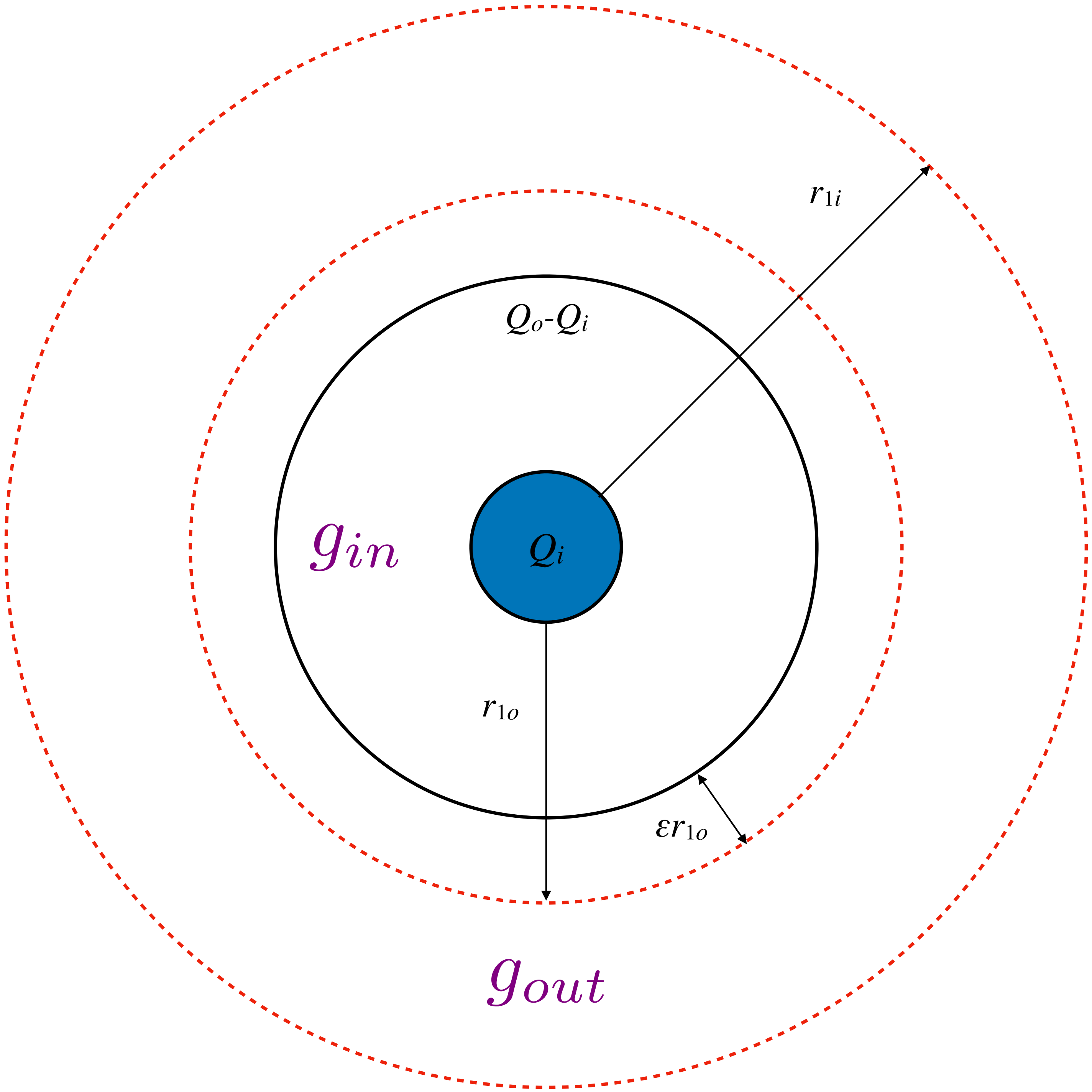
Singularities in low curvature??

Outline

1. Known Knowns
2. Known Unknowns
3. Unknown Unknowns
4. Unknown Knowns?

The Inner Horizon of Reissner Nordstrom

Reissner Nordstrom Metric



g_{out} : required external RN metric

Place thin shell just within inner horizon

Can this shell be singular?

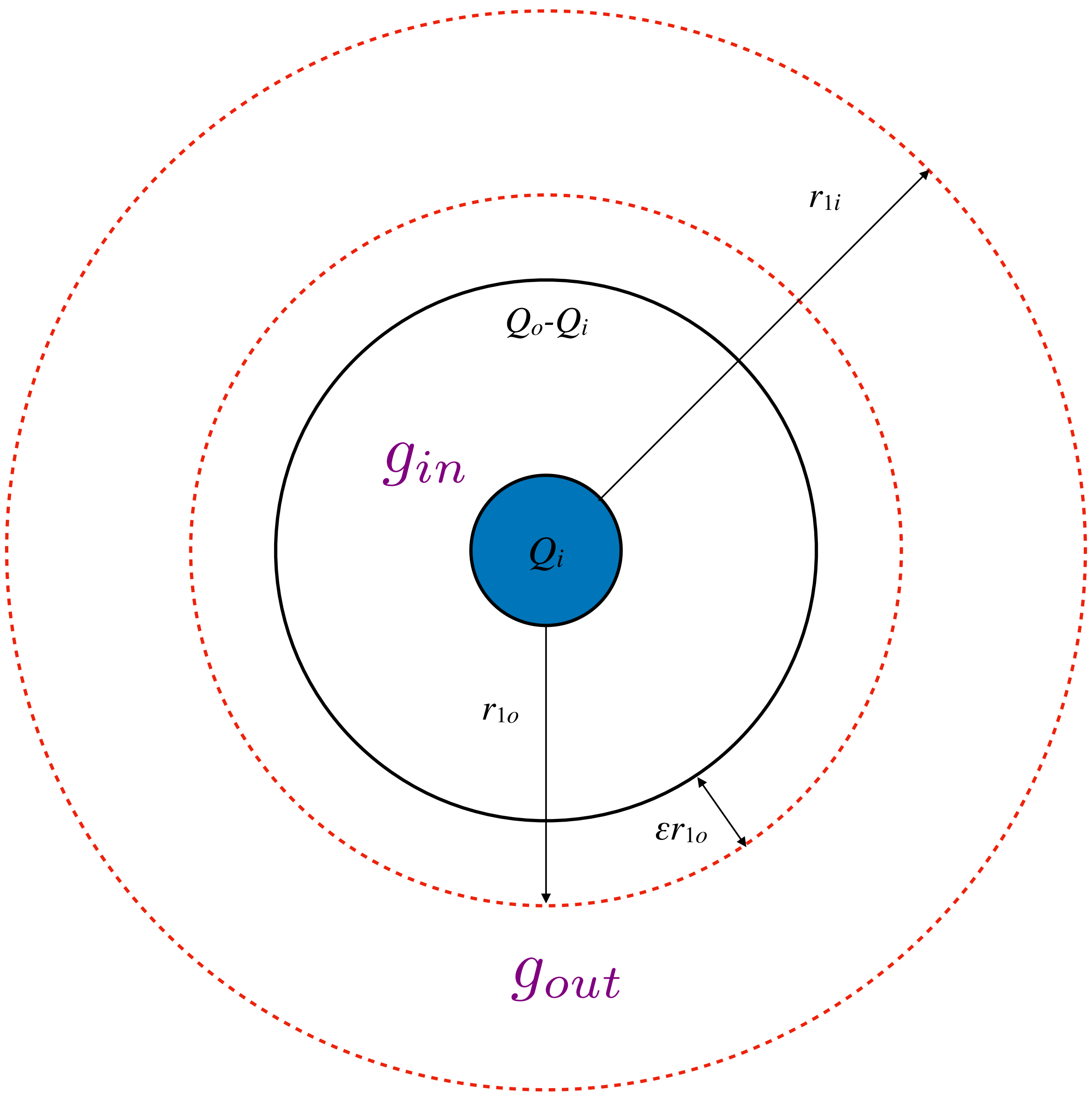
g_{in}: internal RN metric,
Free internal parameters

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



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

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

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

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

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

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

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

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

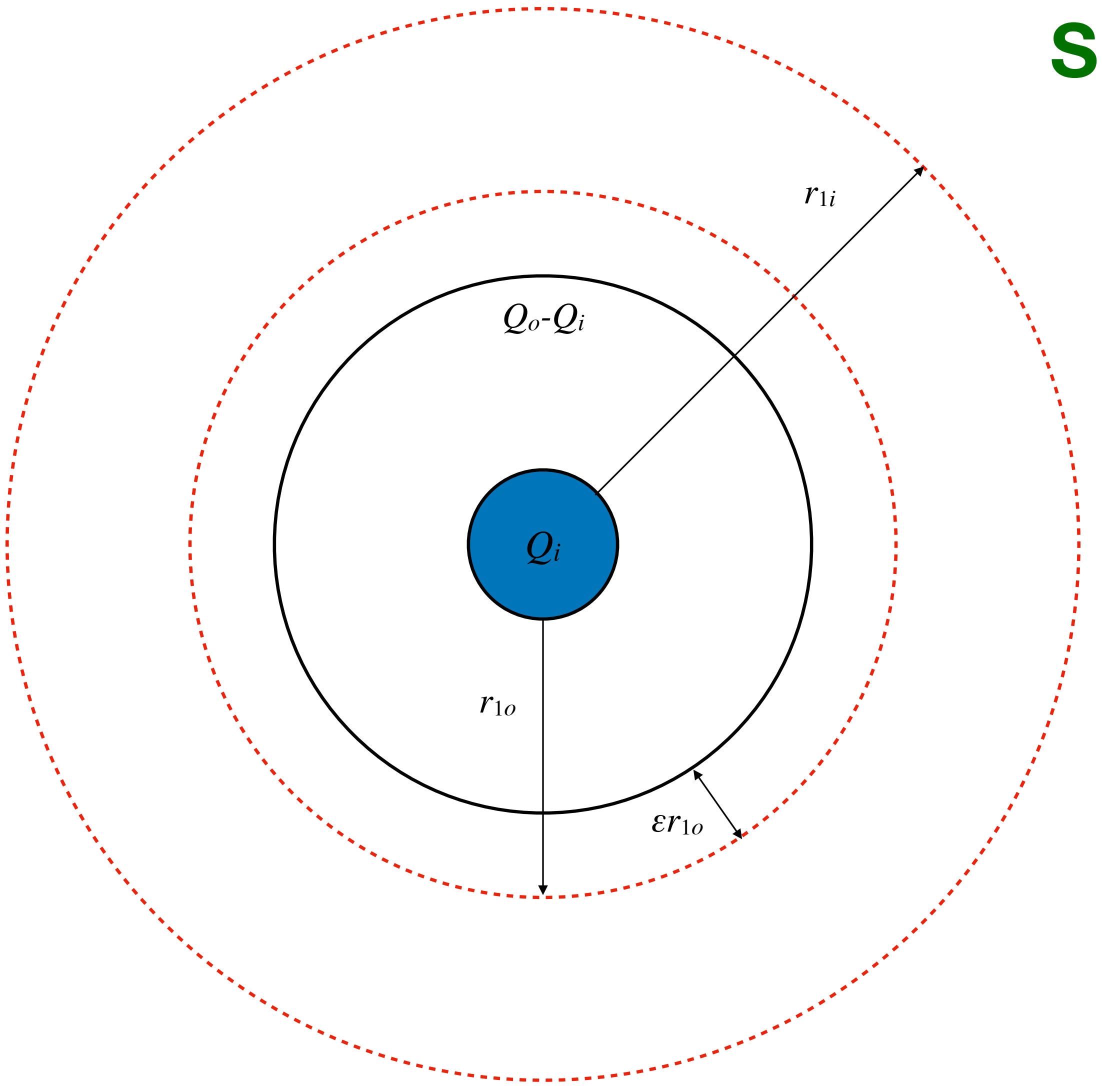
Place shell at a physical distance ~ 1/M_{pl} from r_{1o}

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

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

Characteristics?

Reissner Nordstrom Metric



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

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

Physical distance from r_{1o} to r = 0 is ~ $1/M_{pl}$

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

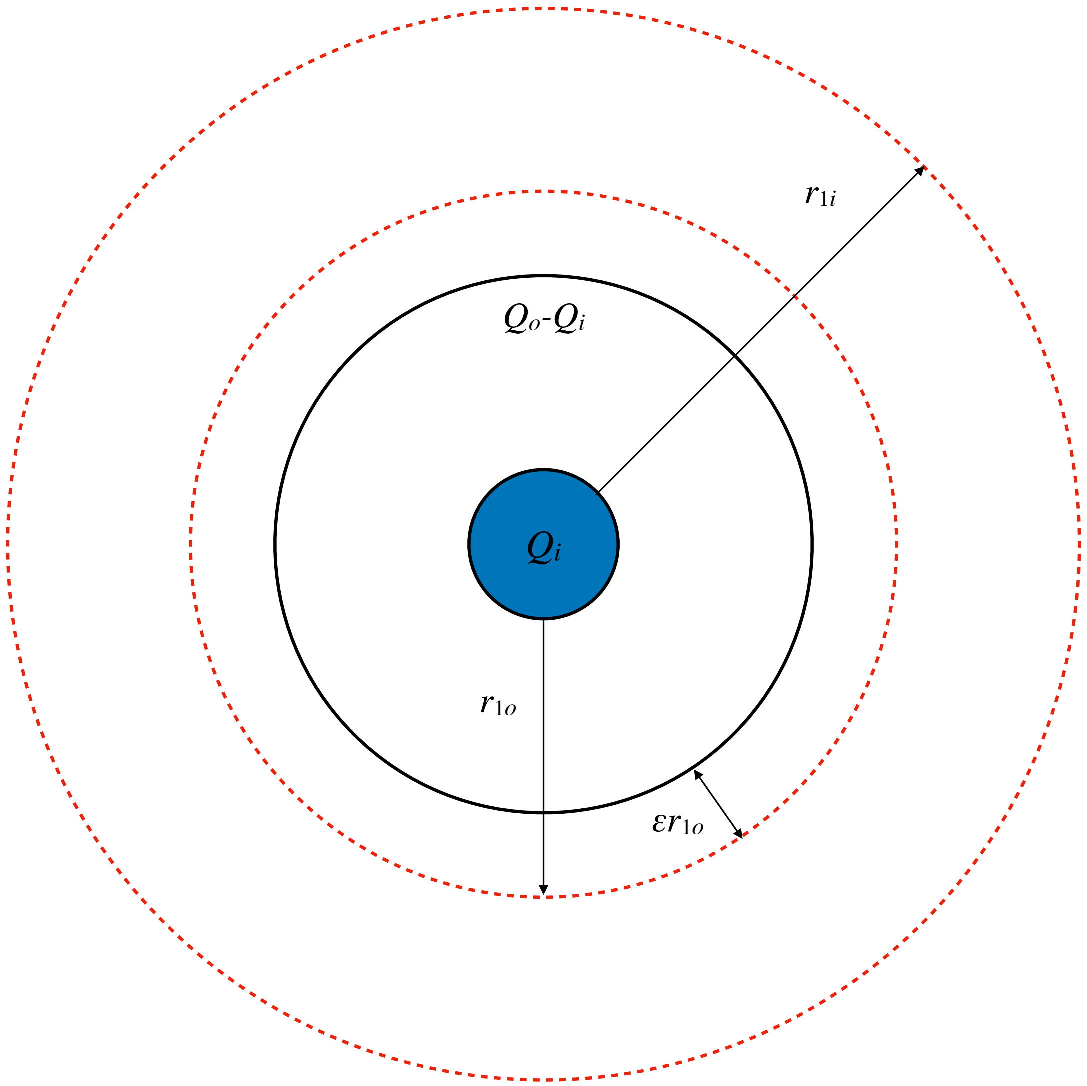
Complete breakdown of General Relativity at inner horizon

Trust as a limit of non-singular solutions

Shell and singularity have large positive mass ~ M (M/M_{pl}), with ADM mass M

Not due to external perturbations - but internal singular dynamics

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?

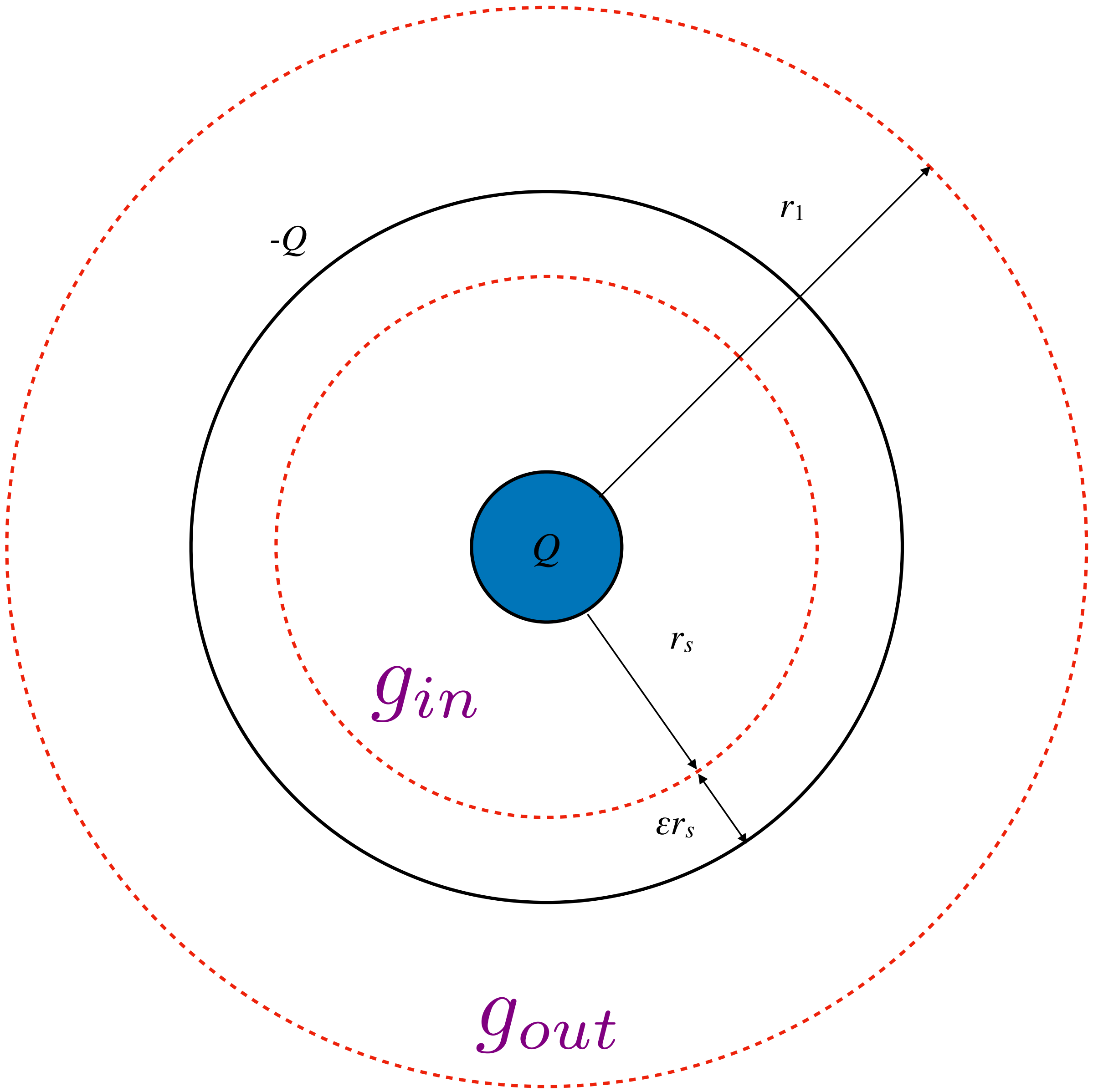
No static solutions where shell has given mass, charge and surface area, with interior being Minkowski and RN exterior - binding energy of singularity necessary

Do not know microphysics of shell - cannot analyze stability

Event Horizon of Schwarzschild

(also applicable to outer horizon of Reissner Nordstrom)

The Schwarzschild Metric



g_{out} : required external Schwarzschild metric

Place thin shell just outside event horizon

Can this shell be singular?

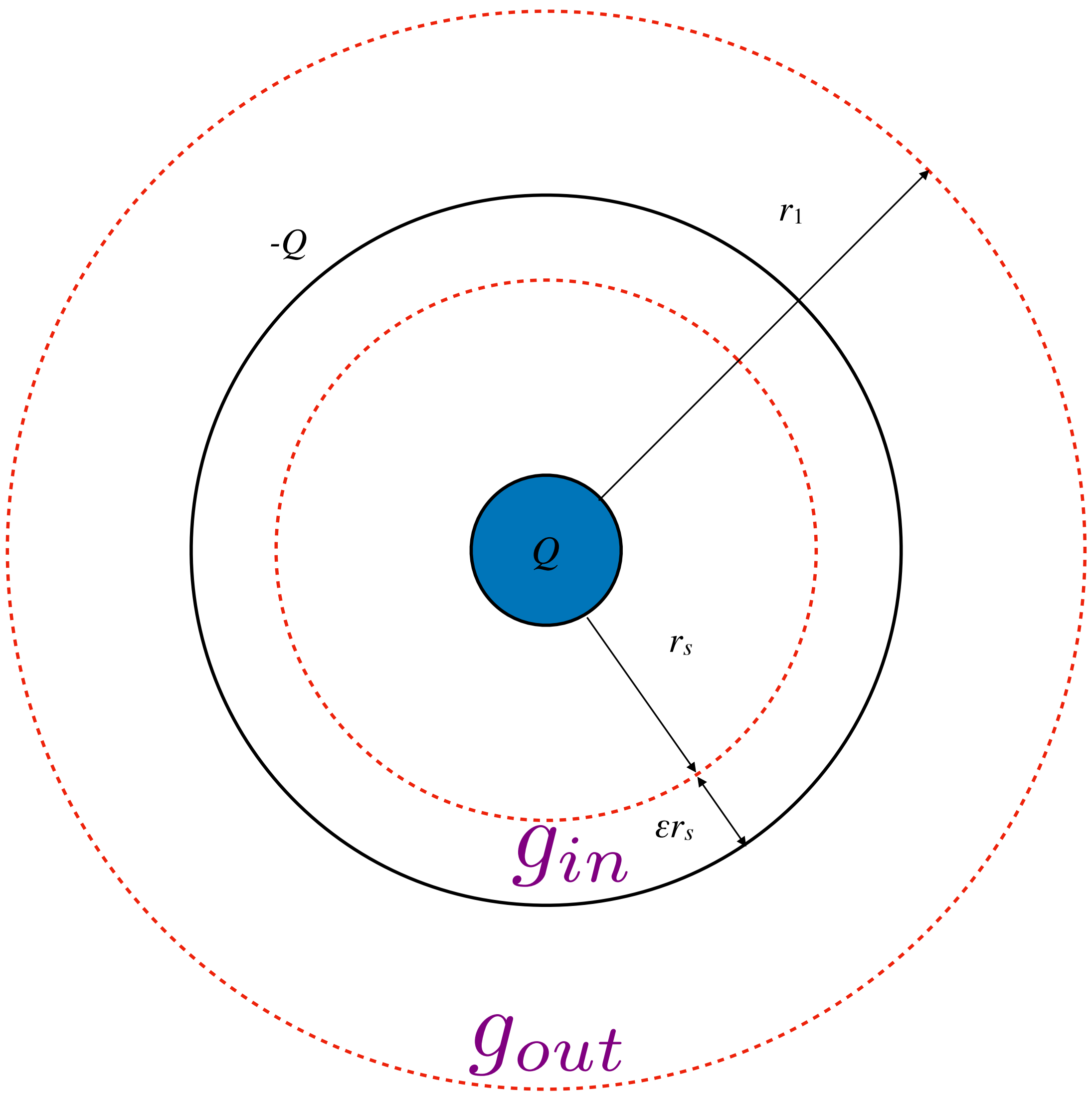
g_{in}: internal RN metric,
Free internal parameters

Use junction conditions to match

Match possible with positive mass?
Reasonable matter?

Schwarzschild Metric

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



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

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

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

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

Match @ $r = r_0 > r_s$

What are r_1, r_2 for singular shell as $r_0 \to r_s$? Charge on this shell?

Schwarzschild Metric

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

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

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

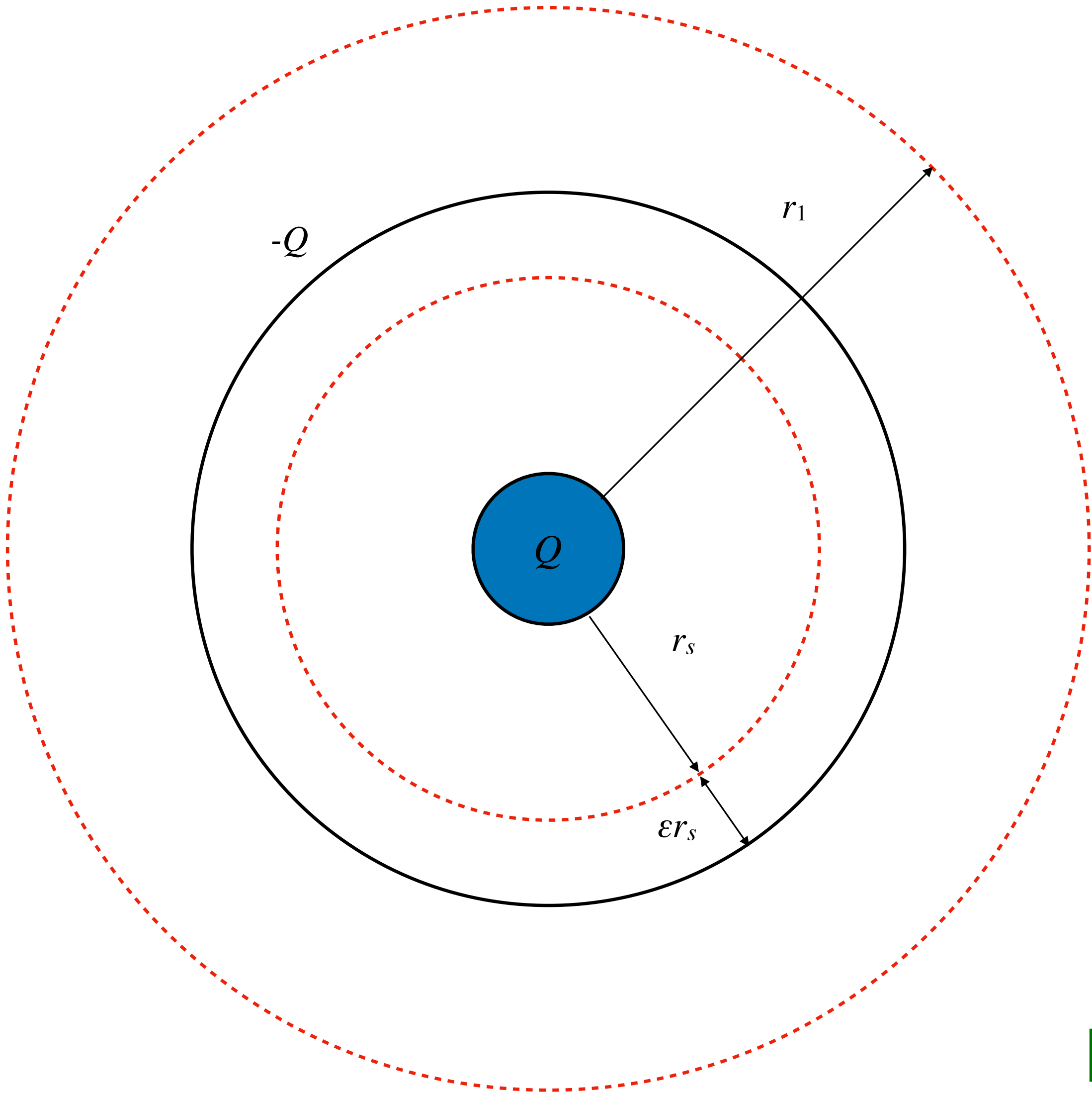
Place shell at a physical distance ~ $1/M_{pl}$ from r_s

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

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

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

Black Hole Entropy



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

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

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

Physical distance from r_s to $r = 0$ is ~ $1/M_{pl}$

Not much space inside horizon
Simple singular object, complex shell?
Entropy would scale like area

New kind of naked singularity

Formation

Firewall Formation

Many naked singularity solutions in General Relativity (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

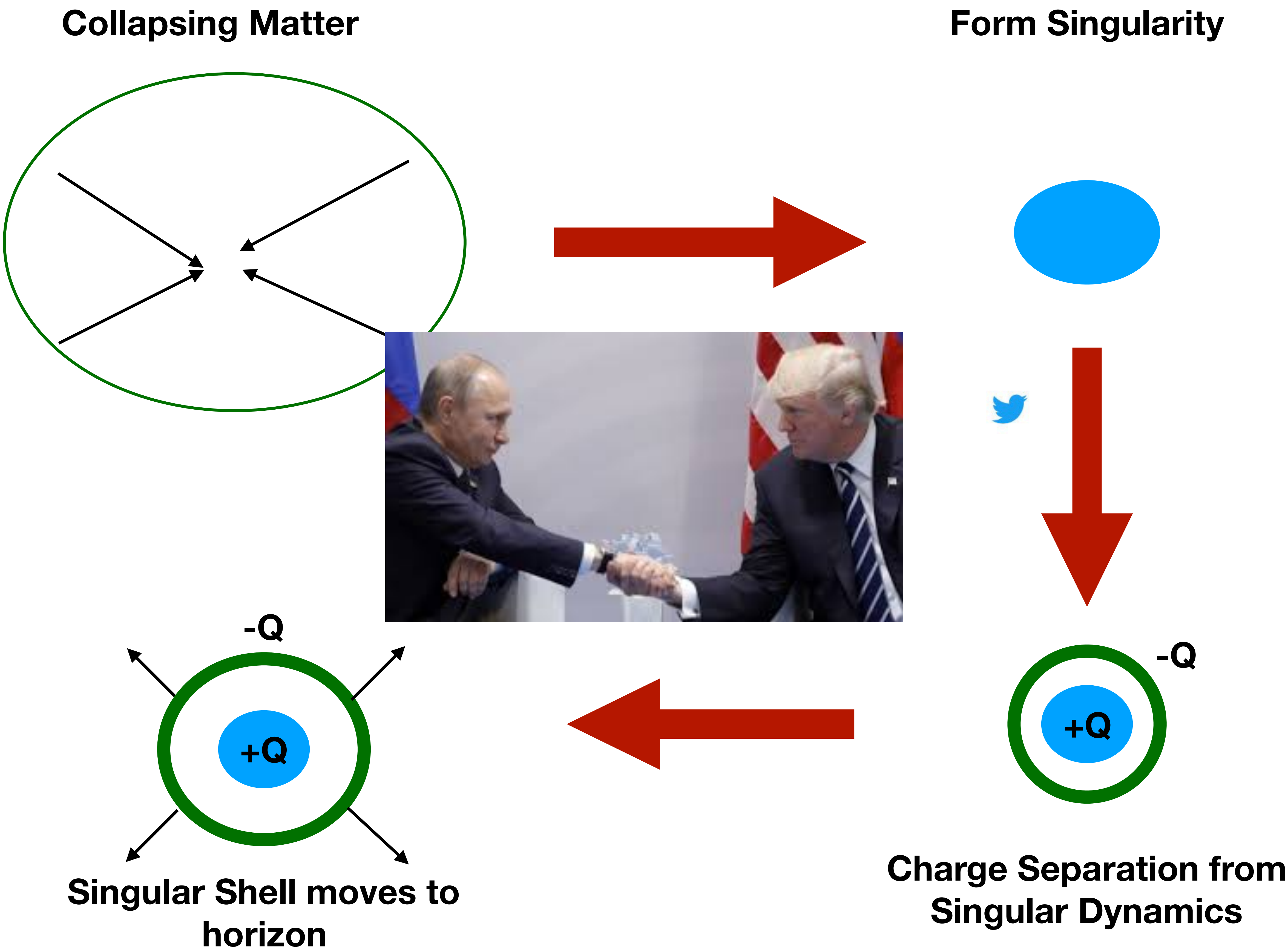
$$S = \int d^4x \sqrt{g} \left(g_{\mu\nu} + \frac{R_{\mu\nu}}{M_{pl}^2} + \ldots \right) \partial^\mu \phi \partial^\nu \phi$$

EP Preserving

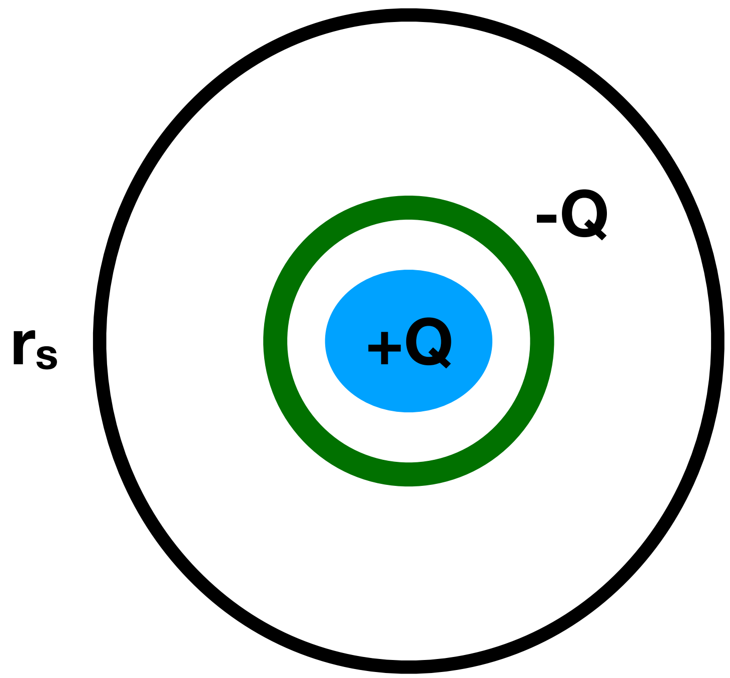
Lorentz Preserving, EP violating

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

Firewall Formation



Ultra-Violet Requirements

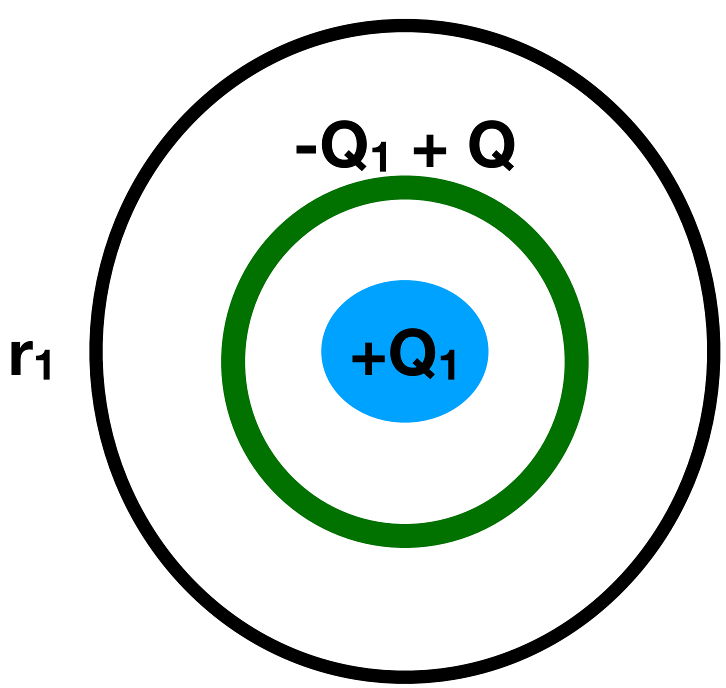


Allow singular evolution along space-like path

Cancellation of internal mass and binding energy

Cancellation Plausible due to solution in GR

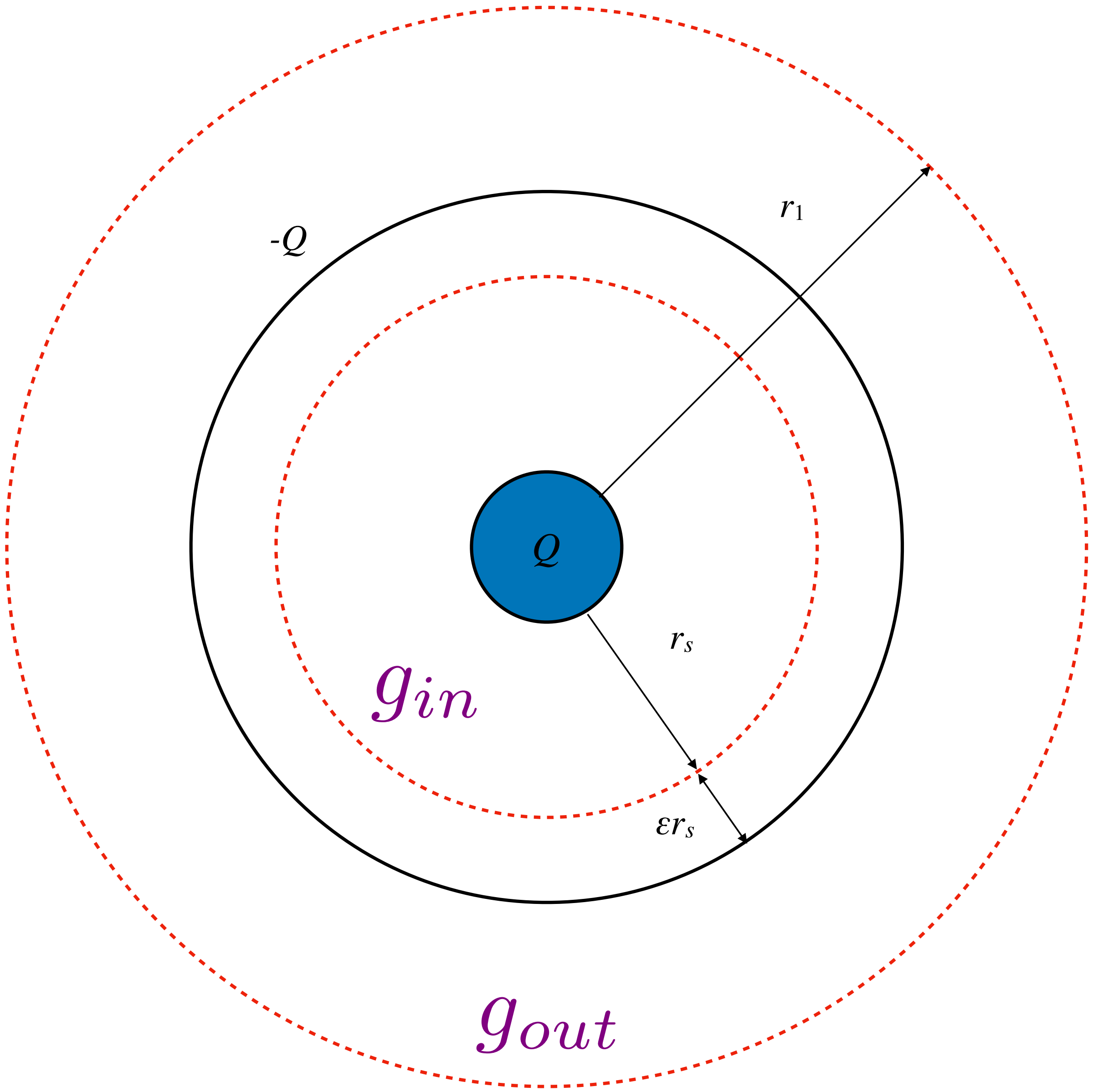
Similar Cancellation must occur in interior of Reissner Nordstrom



In Reissner Nordstrom, shell evolution along time-like path

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

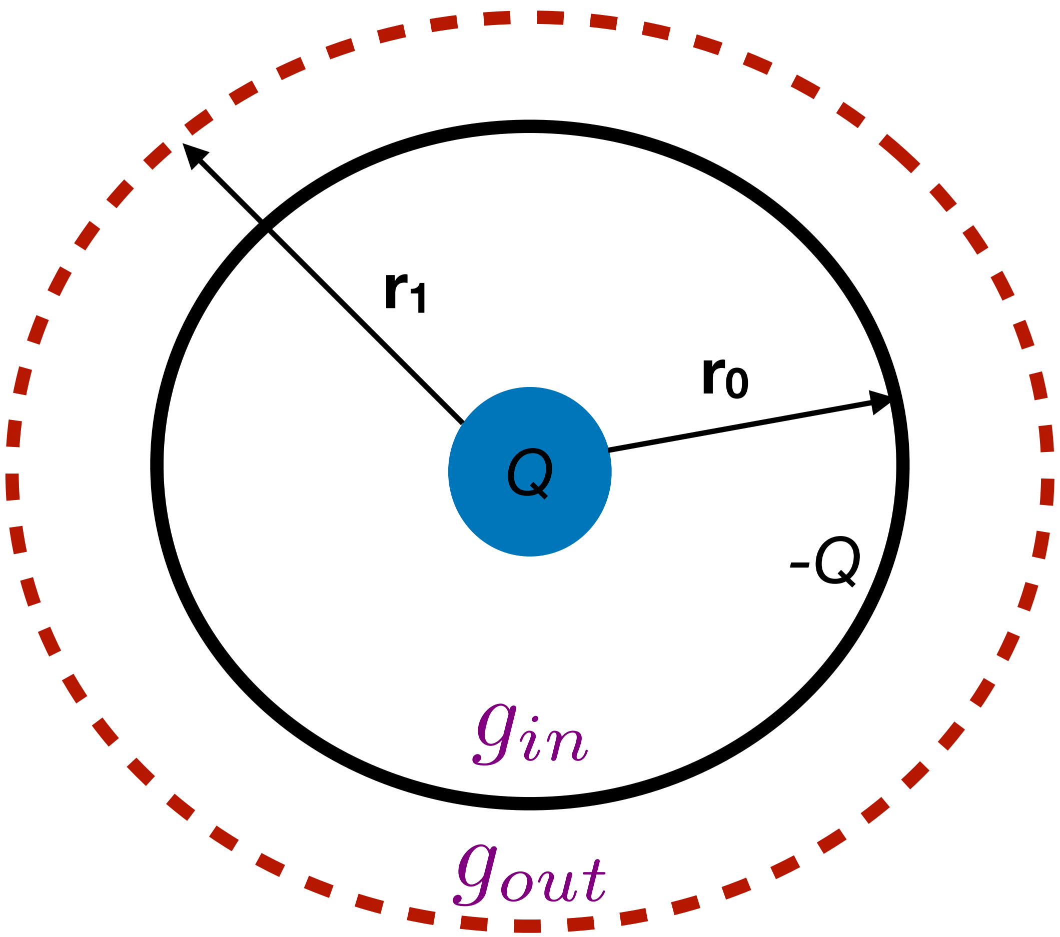
Could we cancel the positive mass too much, leading to negative mass solutions?

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



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

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

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

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

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

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

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. $r_2 \sim r_1$, $r_s \sim M_{pl}^2 r_0^3$ → **Bad**

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 $p = (1/4)\,\rho$

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

How Problematic?

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

with Savas Dimopoulos, Peter Graham, Roni Harnik and David *E.* Kaplan

(in progress)

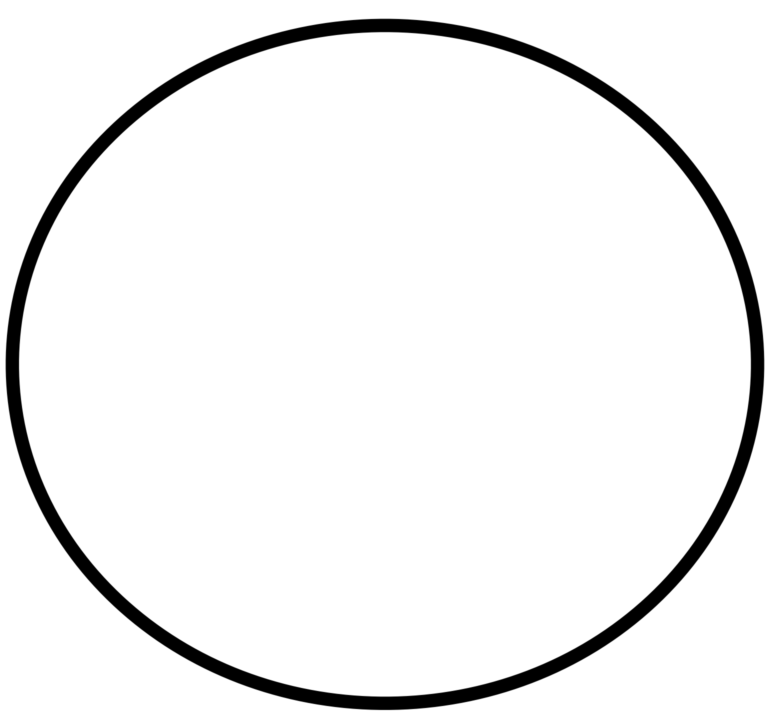
Signatures of Firewalls

Caveat: Formation time unclear

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

For Schwarzschild, could wait till 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?

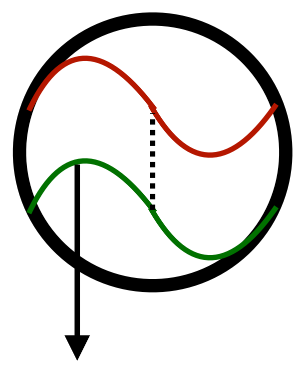
Reflectivity of the horizon to EM and GW
LIGO? Radio?

Moral Turpitude

Light States?

Binding energy cancels large positive energies

Known Example in Particle Physics: Composite Axion



Fermions at energy F

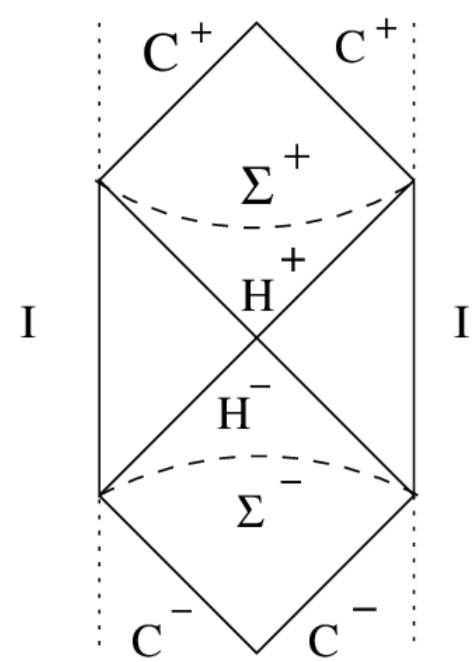
Break global symmetry through confinement at high scale F.

Get massless goldstone boson

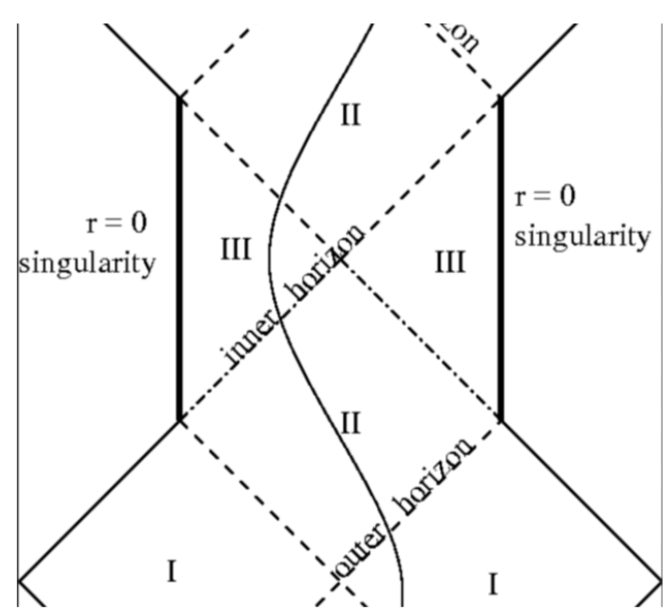
Light State ensured by symmetry

No symmetry reason for cancellation in firewall solutions

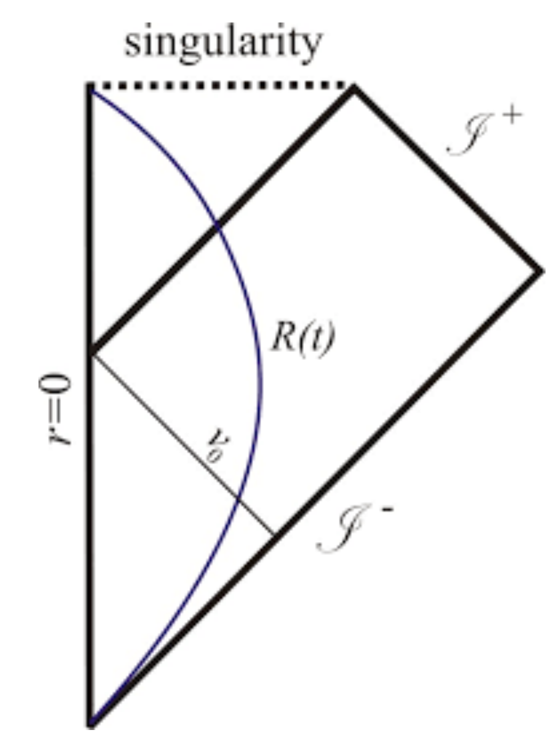
New principle tied to Causality?



Vacuum Energy Regulation in Rotating BTZ



Inner Horizons of RN/Kerr



Event Horizon of Schwarzschild

Particle Physics Implications

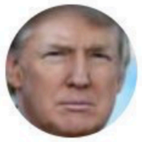
Firewall/Naked Singularity solution could mean that Black Holes do not actually evaporate

Global Symmetries may actually be preserved under quantum gravity

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

Black hole hair could destroy super radiant growth of light fields

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



Donald J. Trump
@realDonaldTrump

Even black holes need firewalls…..

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