Conservative Thoughts on Black Holes

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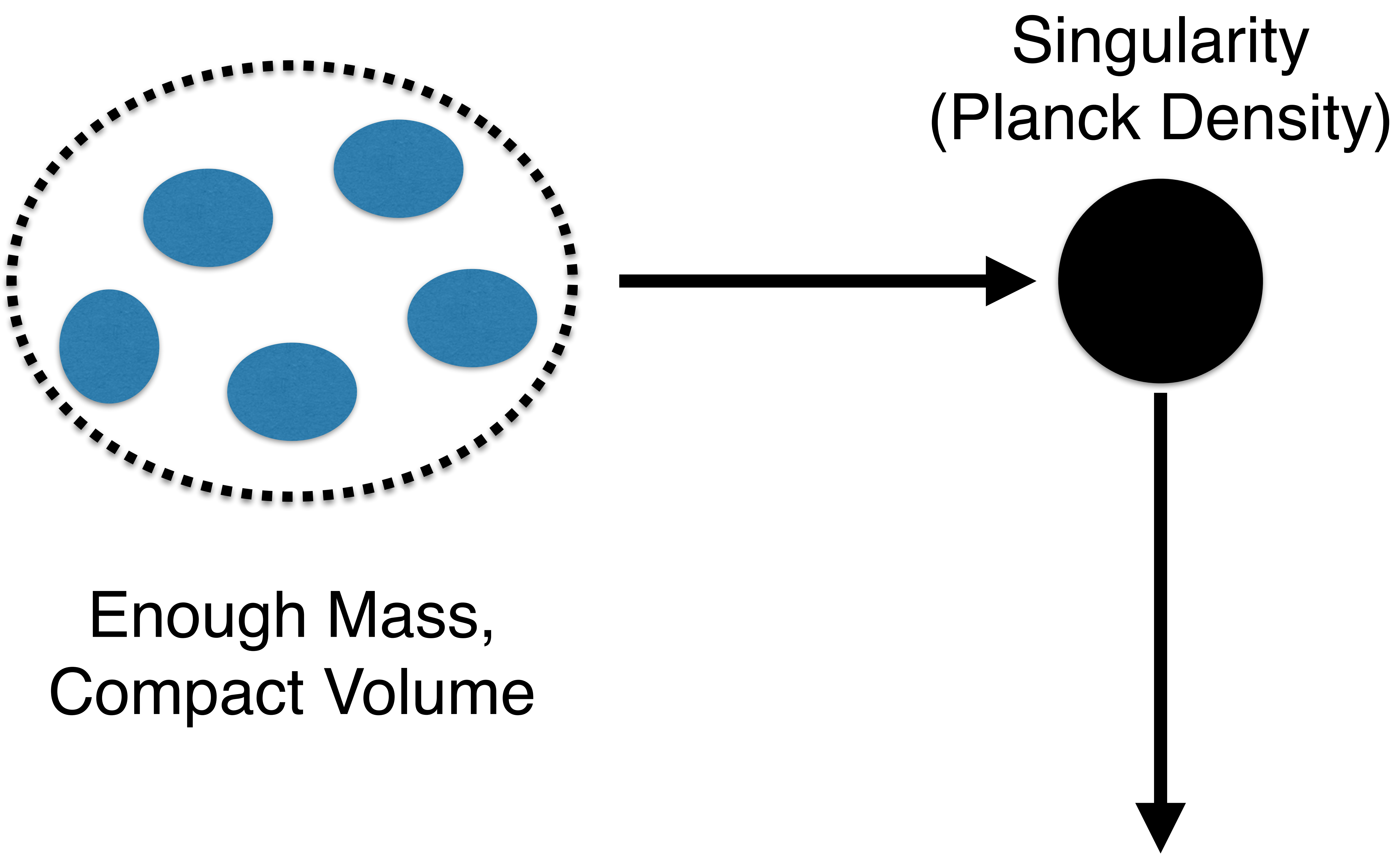
With David E. Kaplan

Black Holes

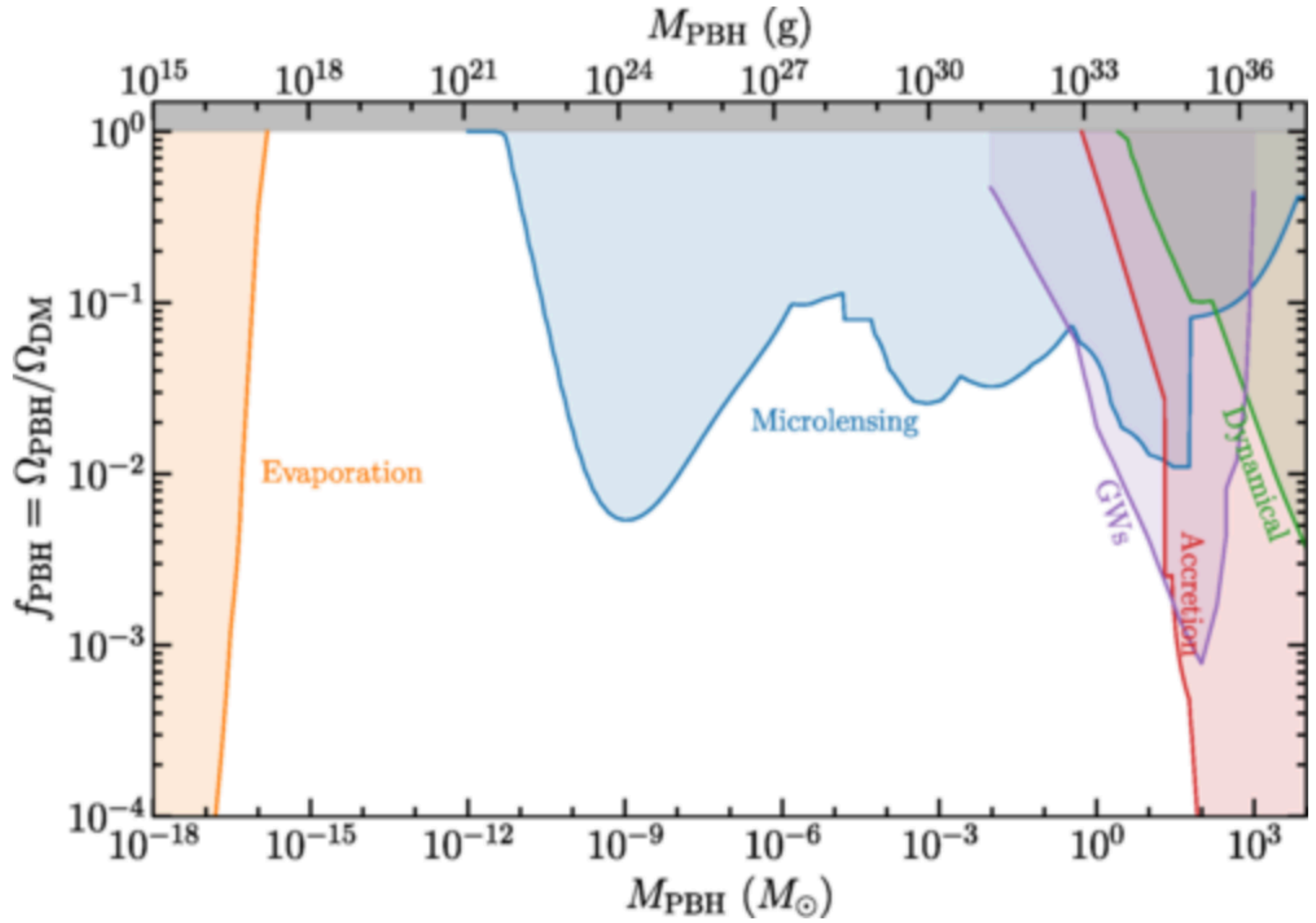


$$ds^2 = -\left(1 - \frac{r_s}{r}\right) dt^2 + \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

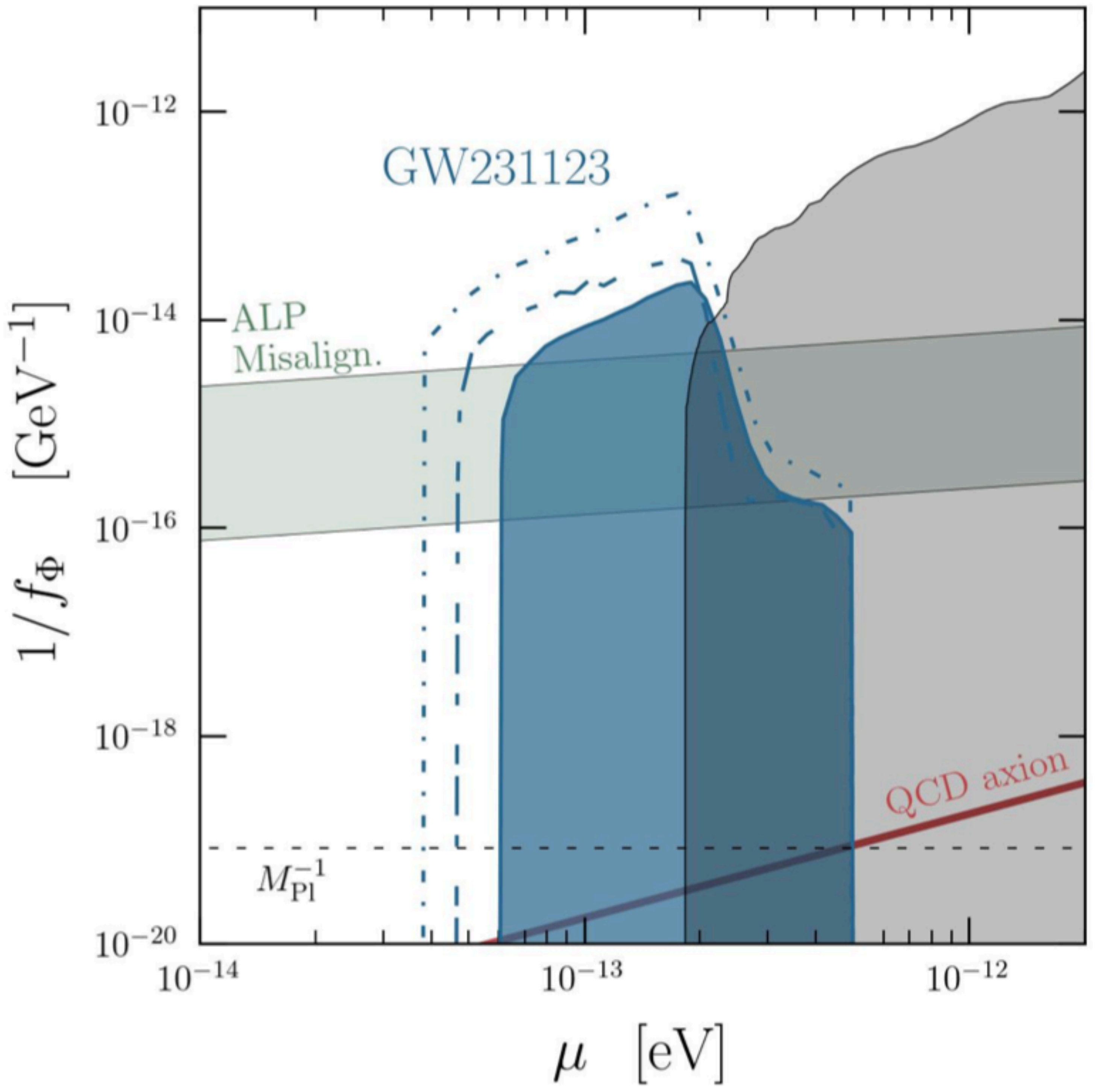
Schwarzschild Metric: Unique Spherically Symmetric Vacuum Solution

The Schwarzschild Solution

Use to place limits



Hawking Evaporation
Limit on Primordial
Black holes

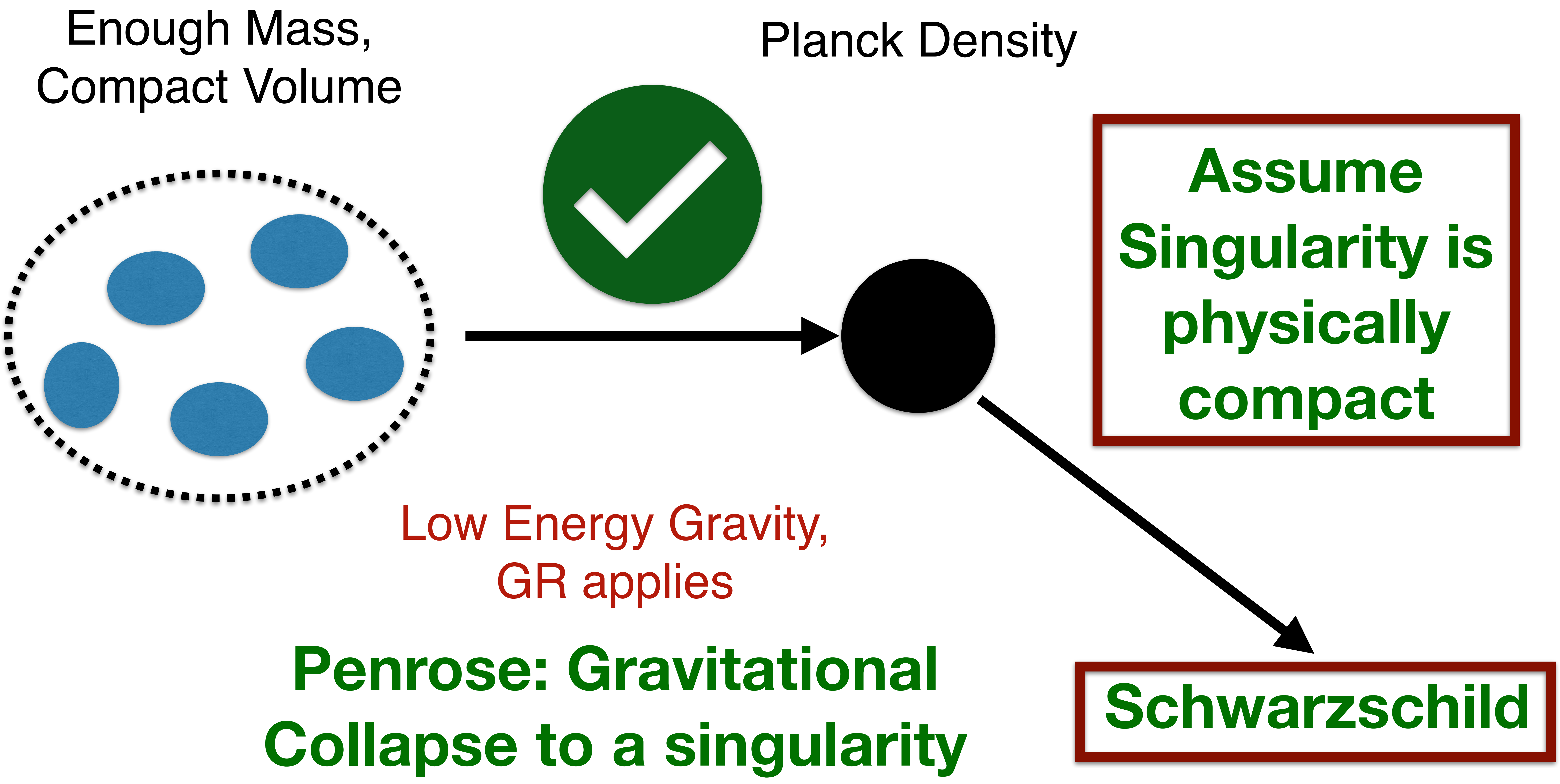


Super-radiance Limits on New
Particles without interactions

No global symmetries in quantum gravity

How robust are these conclusions?

The Schwarzschild Solution



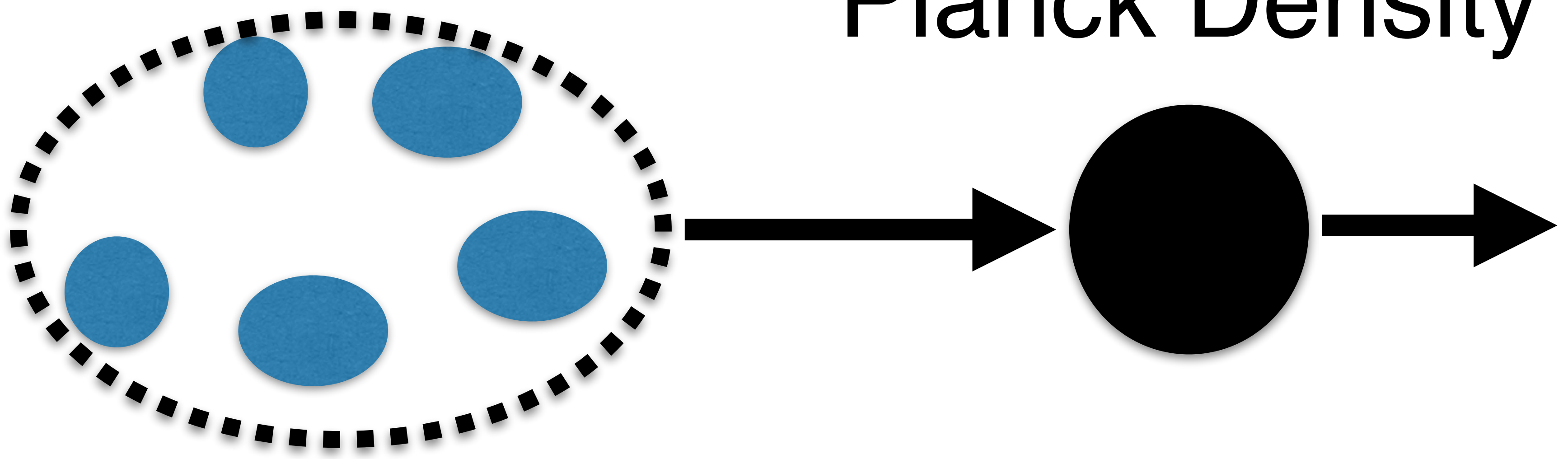
Is this the Schwarzschild solution?

Robust?

No!

Black Hole Information Problem

Planck Density



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

Breaks down at r_s

Enough Mass,
Compact Volume

Remove singularity by co-ordinate change
Interior “radial” co-ordinate becomes time-like
Exterior metric is time dependent

Hawking Evaporation - black hole disappears

Problem: Form black hole with all kinds of stuff.

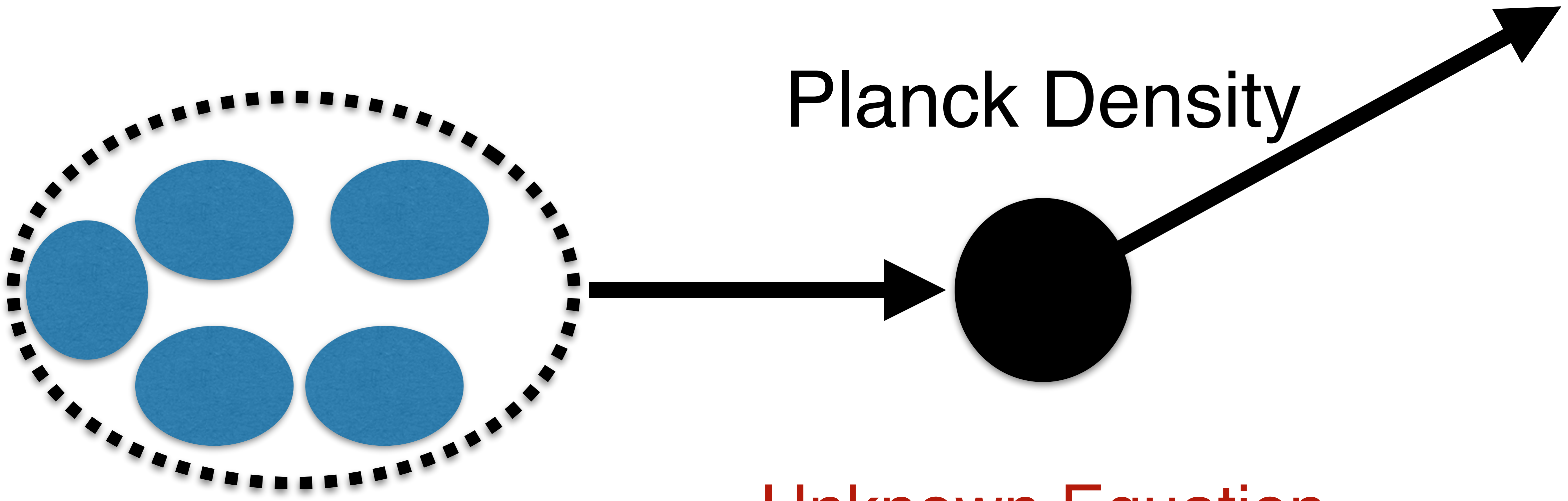
Black Hole has no hair

Radiation Occurs outside Horizon.

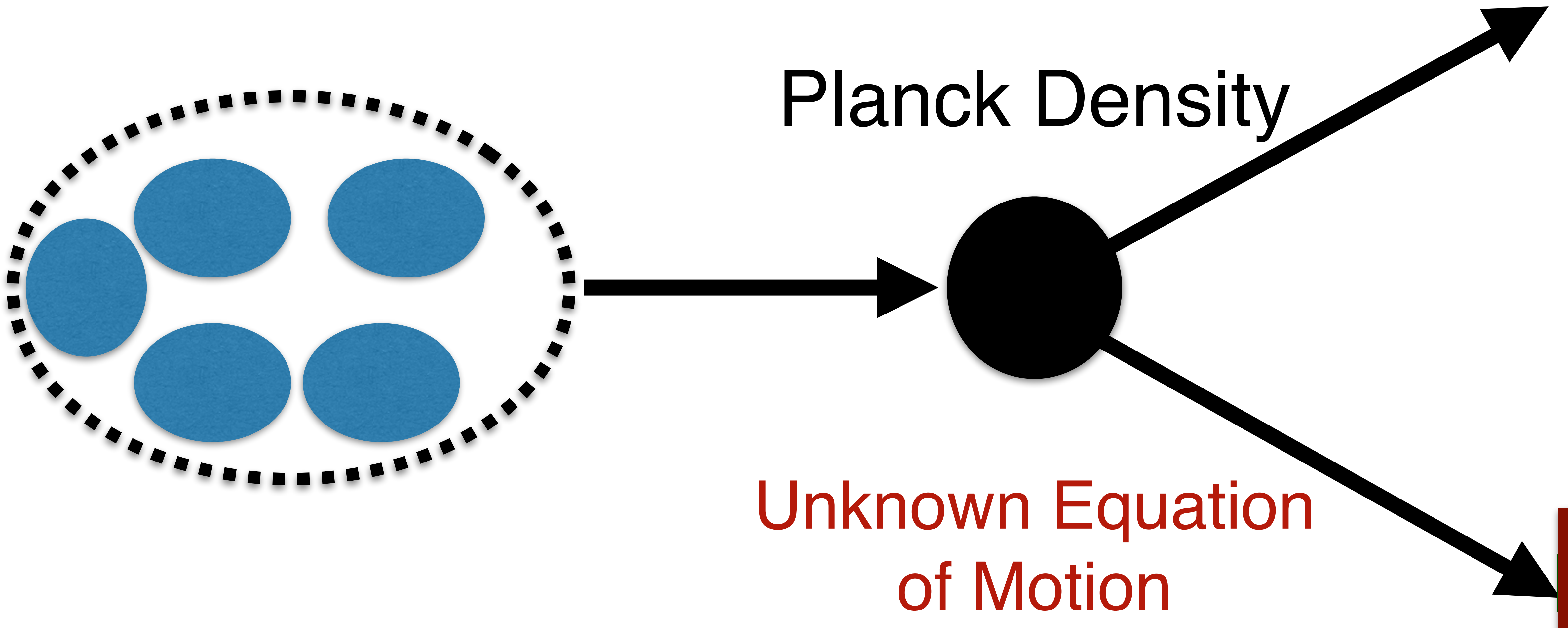
Same final state irrespective of initial state

Hawking: Belief in Schwarzschild is Problematic

The Geometry After Collapse



The Geometry After Collapse



Remains Inside Horizon
Information Problem

ER = EPR

Planck Density Object at Horizon Scale?

Observational and
Theoretical Implications

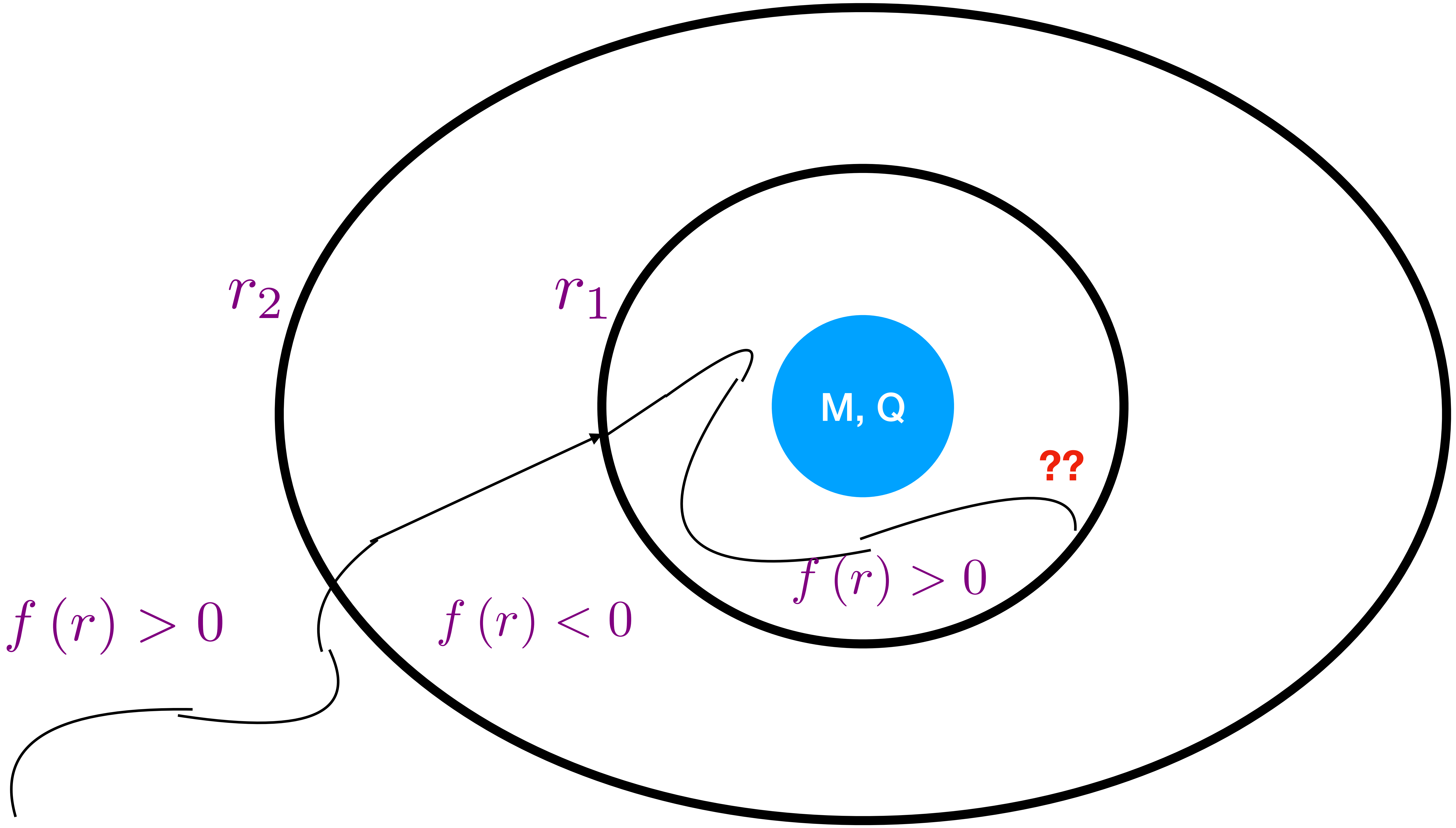
Energy Conservation?

Planck Density ~ M_{pl}^4 => black hole
mass M_{pl}^4 r_s^3 ~ M^3/M_{pl}^2 >> M

Horizons in Reissner Nordstrom/Kerr

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

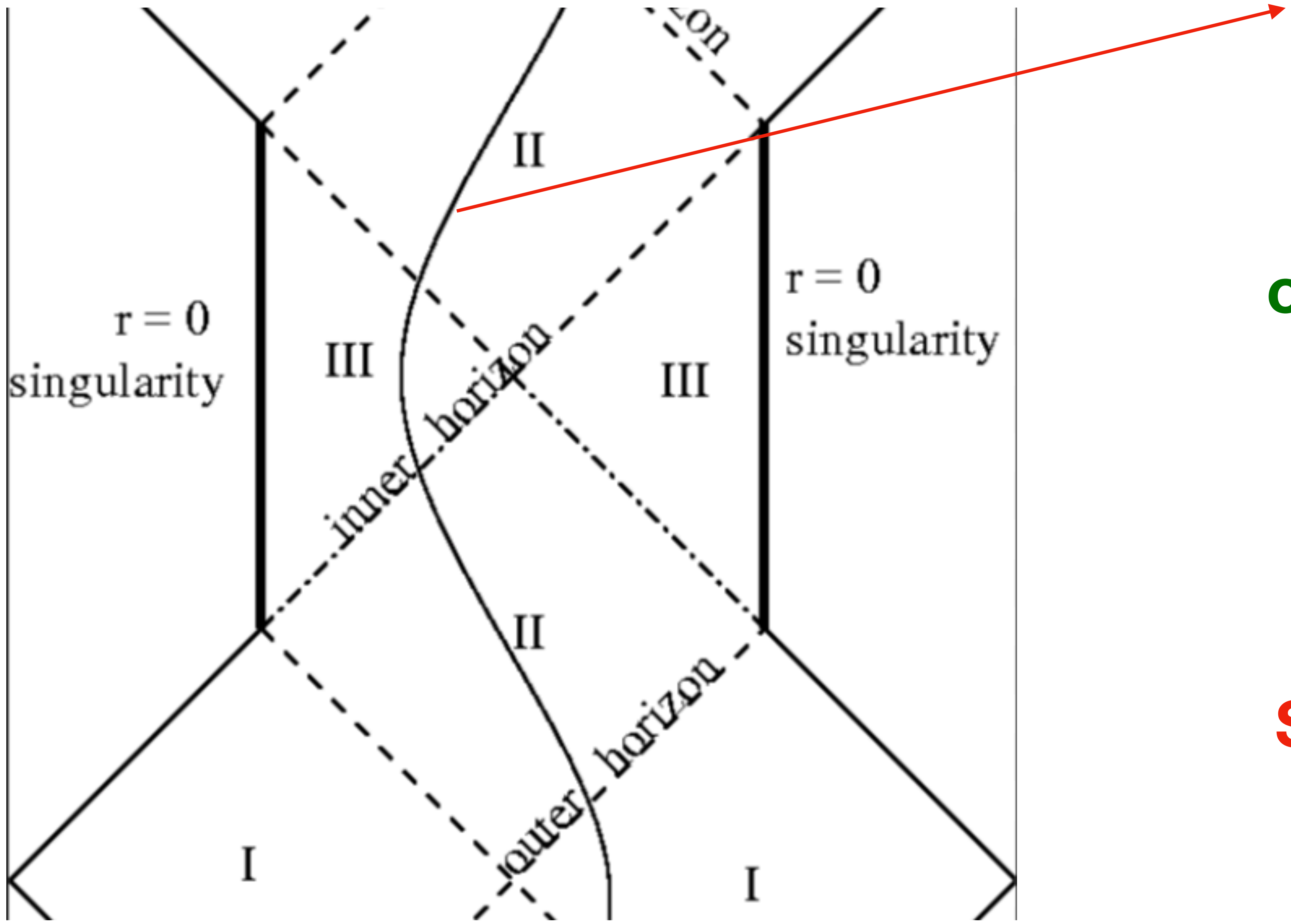
$$f(r) = \frac{(r - r_1)(r - r_2)}{r^2}$$



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

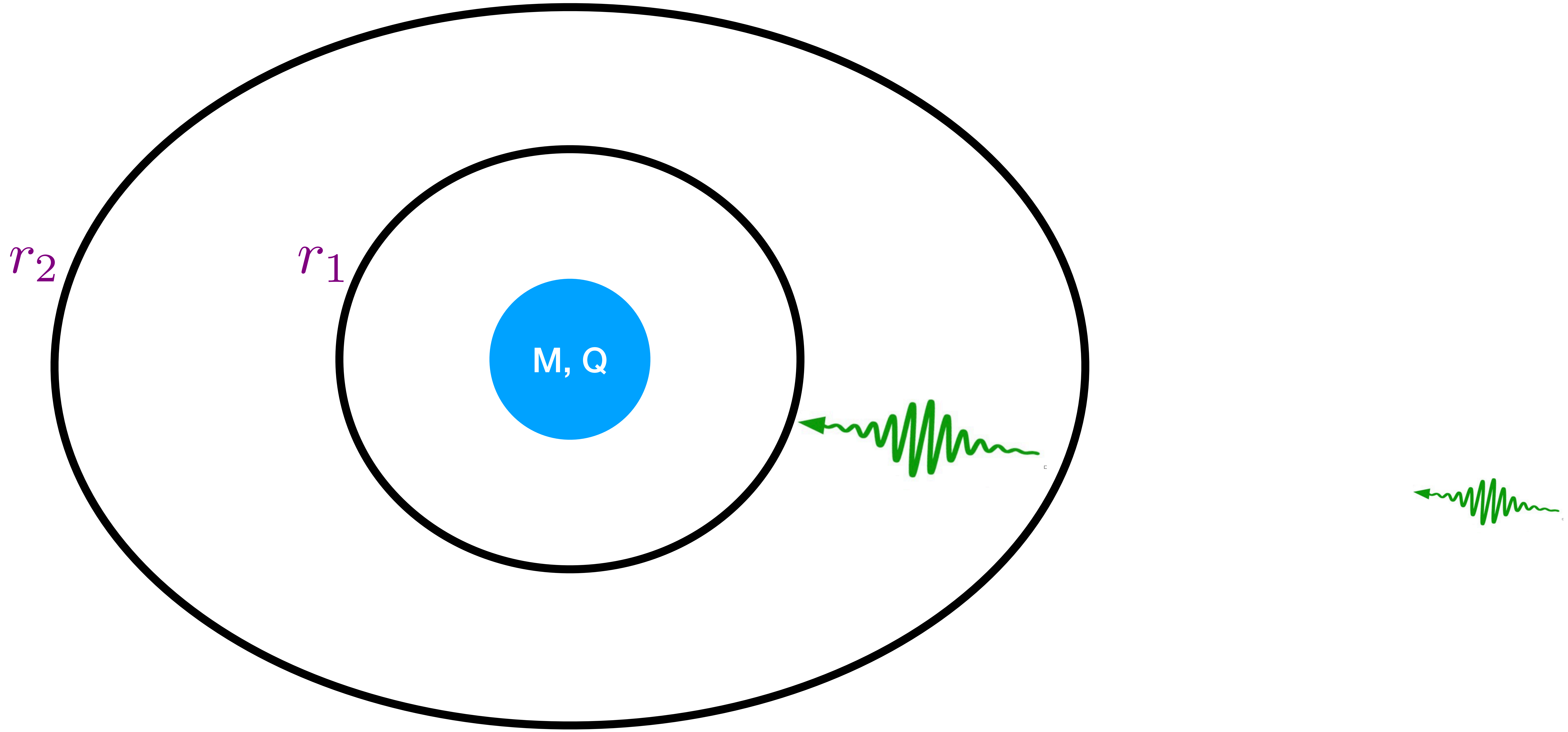
Subject to new boundary conditions, failure of predictivity

Large change to metric, no inner horizon

Static Black Hole: Singularity at inner horizon?

Fast, classical effect

Mass Inflation

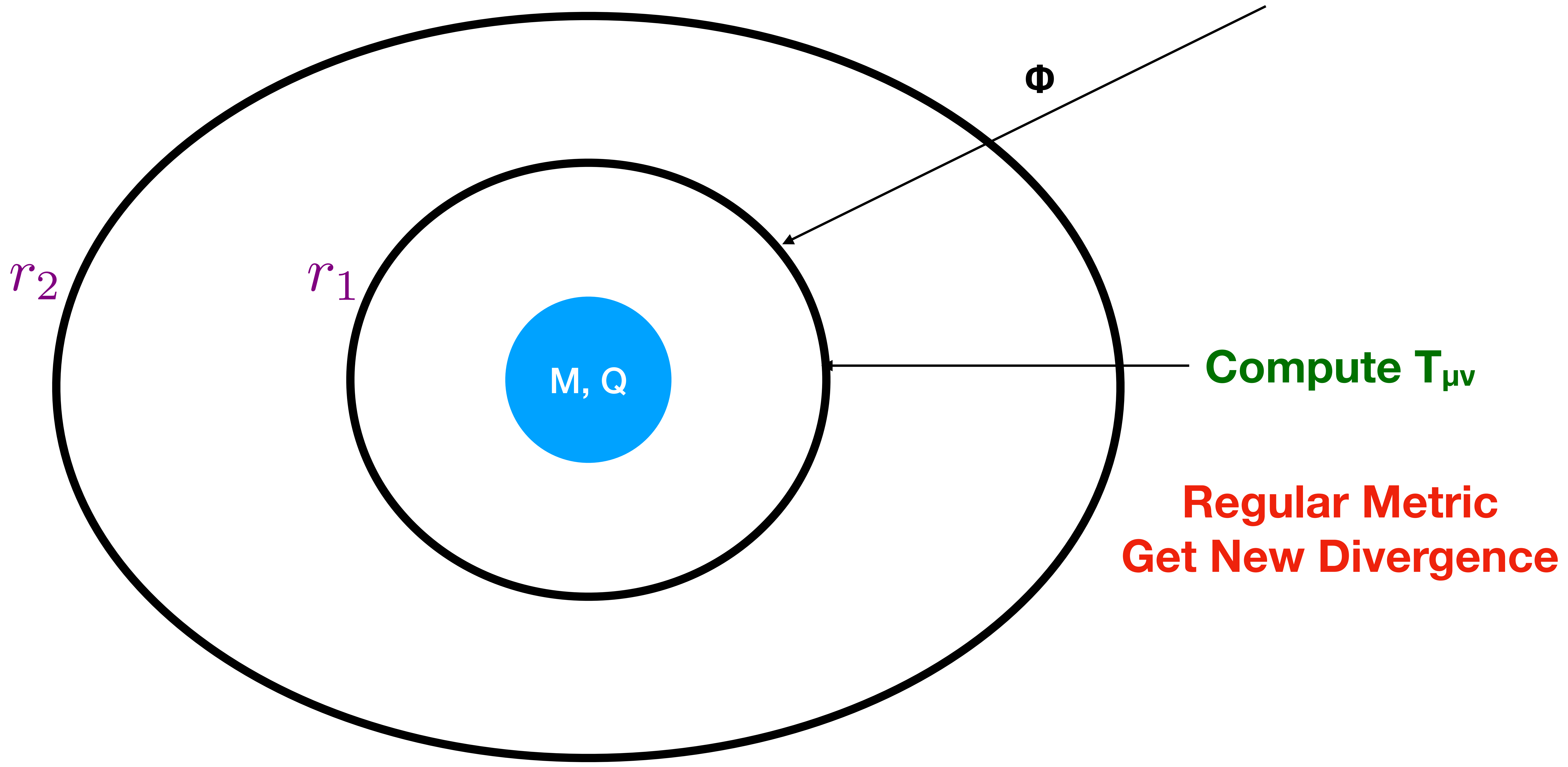


Amplification, i.e. blue-shift, of perturbations: $E_{r_1} \propto E_\infty \left(\frac{r_1}{r - r_1} \right)$

Significant local density, without changing external mass

Do we need external perturbations?

Vacuum Instability

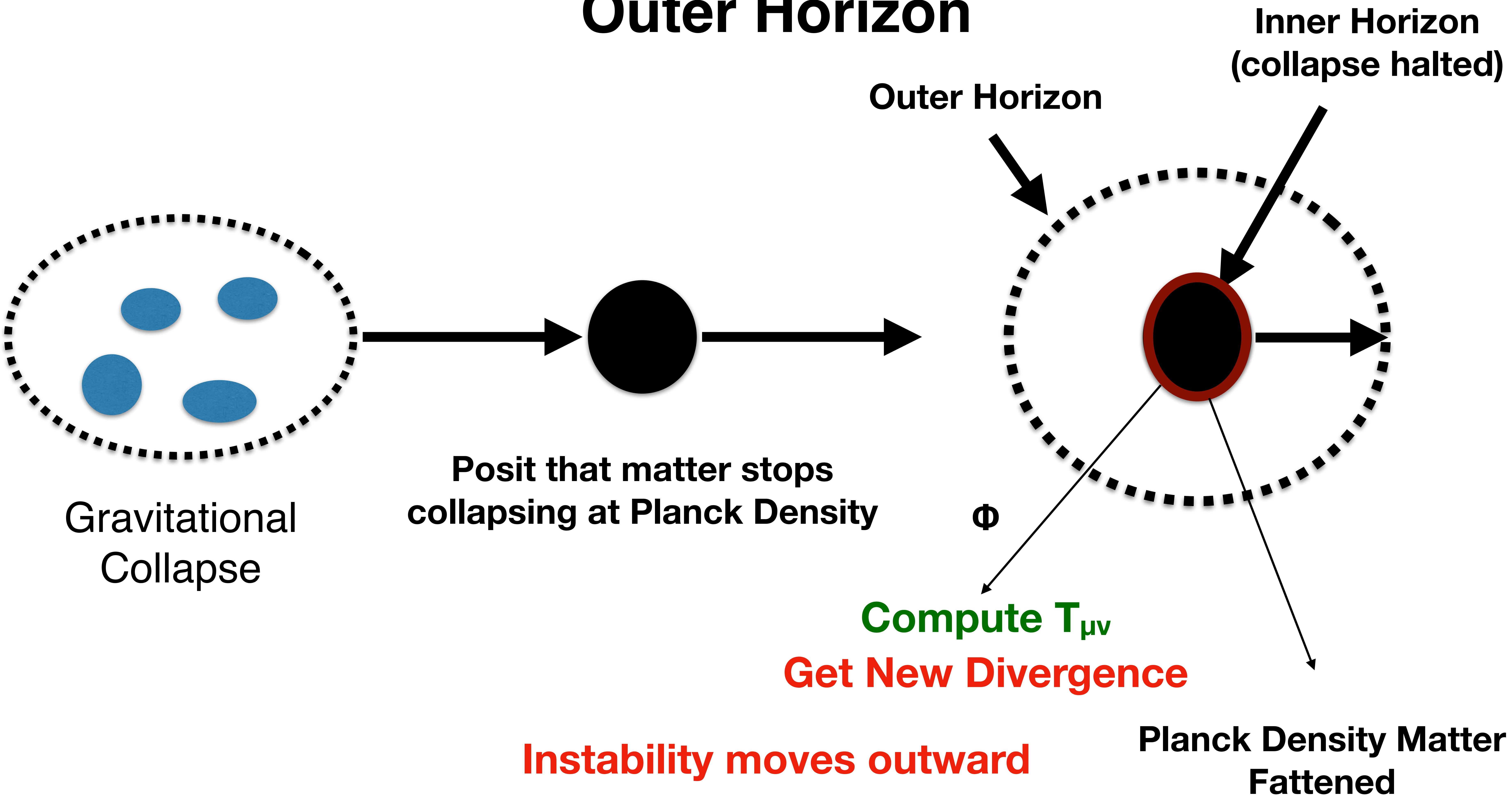


Low curvature - ought to trust General Relativity

But, massive quantum back-reaction.
Singularity at the scale of the inner-horizon

Planck density at the inner-horizon, no change to external mass

Outer Horizon



Instability moves outward

Naturally stops just outside
outer horizon

Simple hypothesis extends mass-inflation instability to outer horizon

Planck Density object at horizon scale - no change to external parameters of the black hole

Co-ordinate Singularity?

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

Breaks down at r_s

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

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

Breaks down at $r_{1,2}$

Remove singularity by co-ordinate change

Interior “radial” co-ordinate becomes time-like

How innocuous are these co-ordinate transformation?

The Laws of Nature

$$i\frac{d|\Psi\rangle}{dt} = H|\Psi\rangle$$

Quantum Field Theory Is Supreme

↓ **Coherent State |ψ>**

Classical Electromagnetism, General Relativity etc.

Quantum Field Theory and Classical General Relativity are not "co-equal". Any more so than QED and Classical Electromagnetism

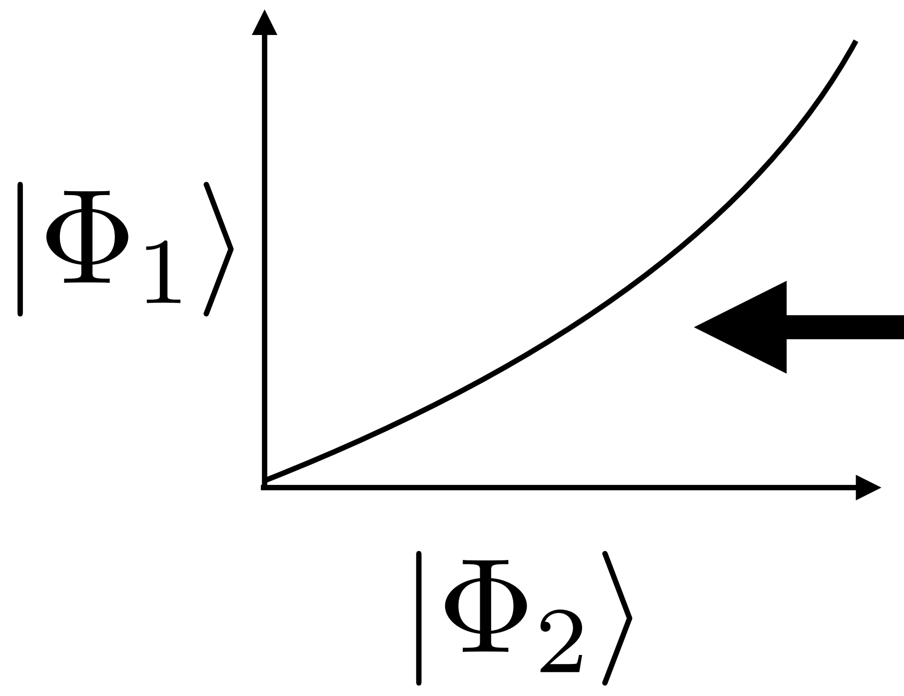
Basic Axioms should be set by Quantum Mechanics
Relativity is a symmetry of the Hamiltonian

The Laws of Nature

$$i\frac{d|\Psi\rangle}{dt} = H|\Psi\rangle$$

$|\Psi\rangle$

Spatial Manifold
Define a Hilbert space and quantum operators



Time: Evolution in Hilbert space. Characterized by a parameterization

$$|\Psi\rangle = c_1\left(t\right)|\Phi_1\rangle + c_2\left(t\right)|\Phi_2\rangle$$

Relativity

The Hamiltonian H has symmetries allowing for Lorenz invariant vacuum

When can you swap time and space?

Swapping Time and Space?

$$i\frac{d|\Psi\rangle}{dt} = H|\Psi\rangle$$

Suppose Spatial Manifold is discrete at some incredibly small scale e.g. $10^{-100000}$m

Can still do time evolution

But can no longer swap continuous time with discrete space

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

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

Co-ordinate transformations swapping t and r are super UV sensitive

Should we keep doing them in light of paradoxes?

Black Hole Geometry

Gravitational Collapse Occurs, Planck Density Object forms

No known equation of motion for this object

Does this object stay inside the horizon or not?

Opinion A

Yes

Hawking: Unstable

Set by exterior geometry

Information Problem

Solution

ER = EPR

Opinion B

No

Stop collapsing at
Planck density

Use Mass Inflation -
vacuum instability

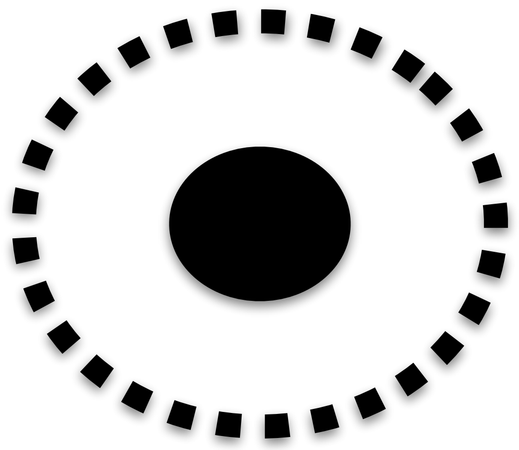
Horizon-less object

Co-ordinate transform
UV sensitive

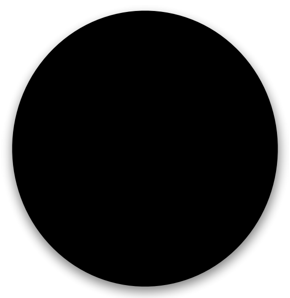
Observational
Consequences?

What do we observationally know about Black Holes?

LIGO and Event Horizon Telescope



Singularity
Inside Horizon



Horizon Scale
Singularity

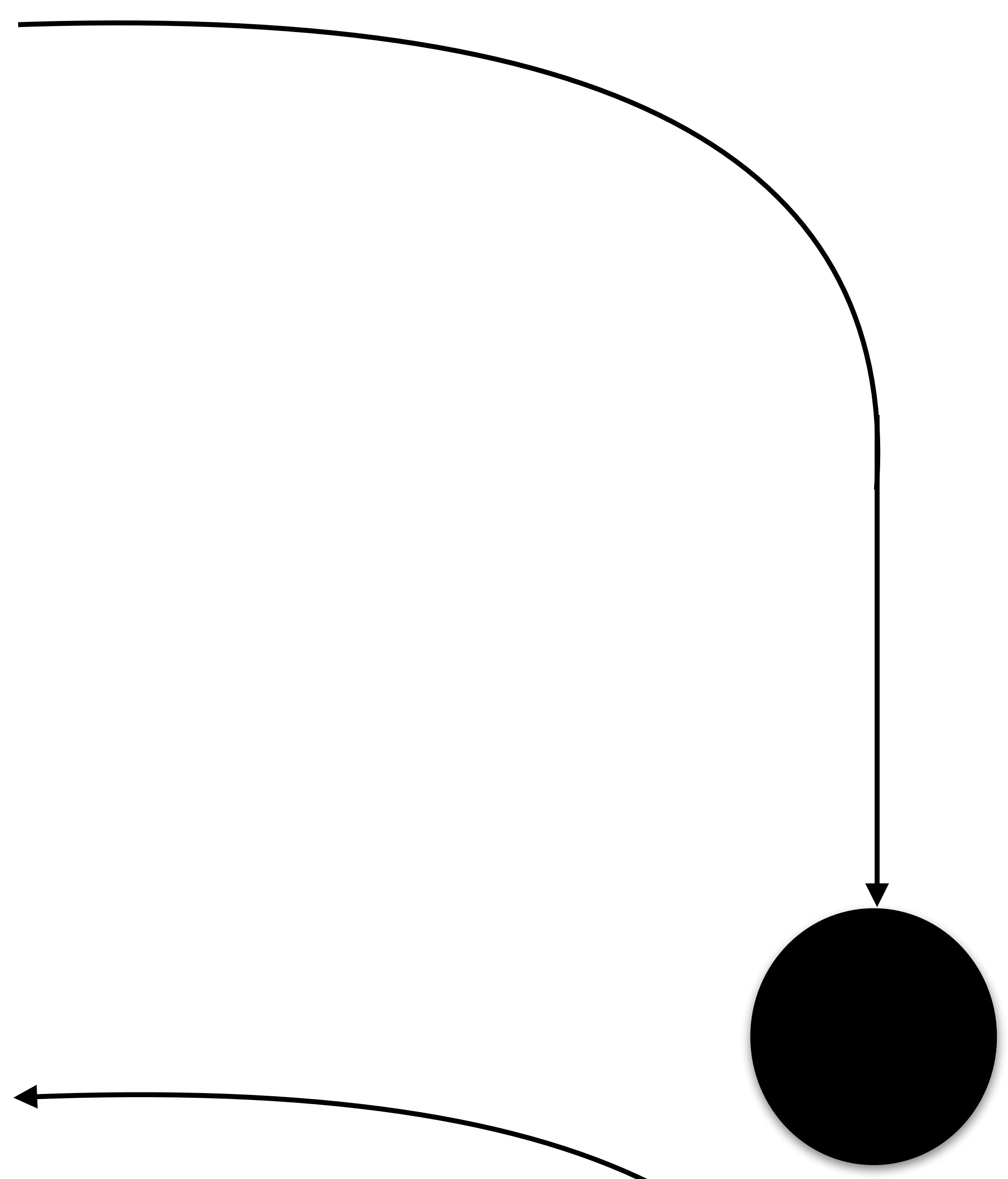
Metric for r > r_s

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

Dramatic Difference r <= r_s

How easy is it for information to get from just outside the horizon to us?

The Photon Sphere

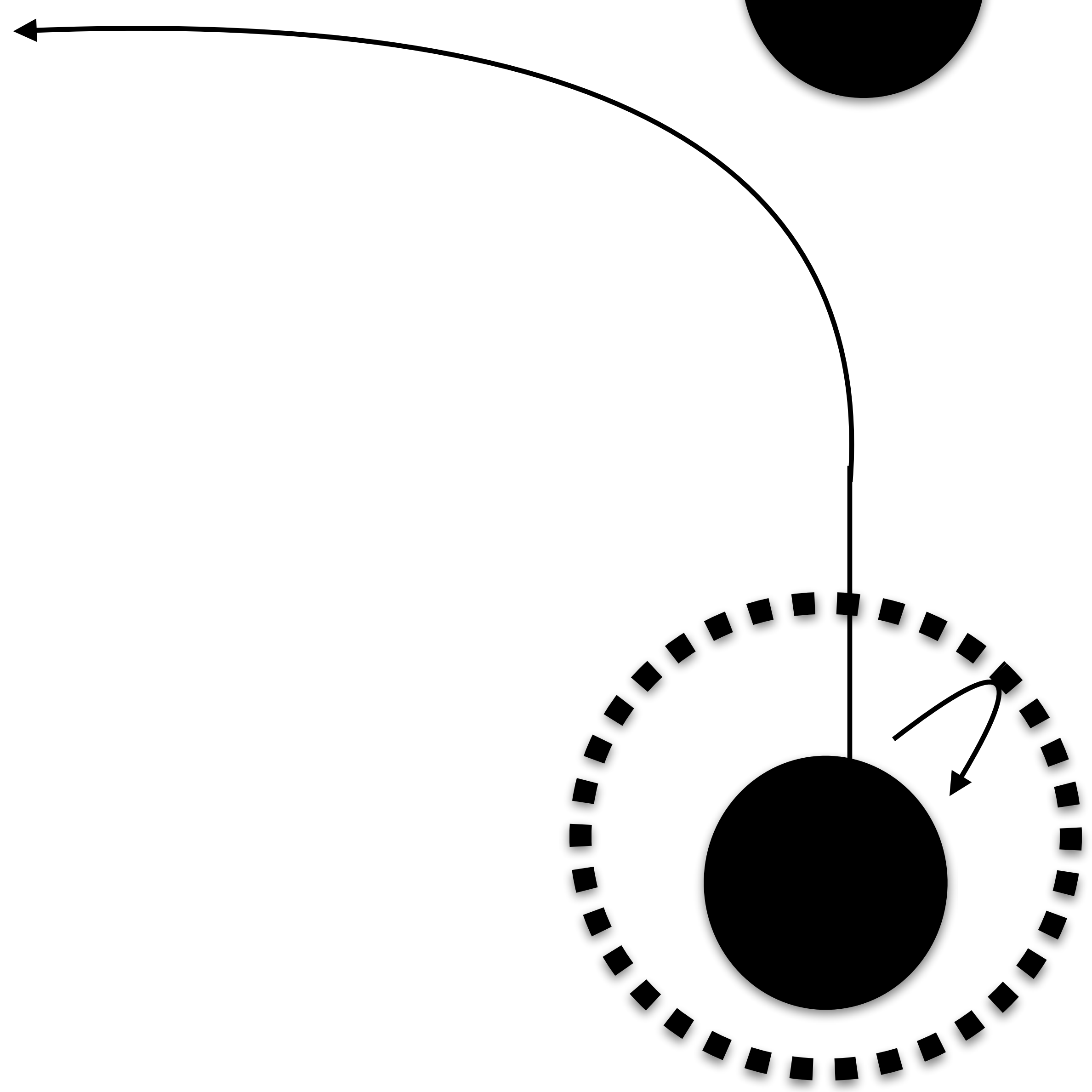


Drop particle from infinity

Radial Direction dramatically boosted

Tangential Direction not boosted

Particle hits horizon radially



Escapes only if emitted highly radially
i.e. zero angular momentum

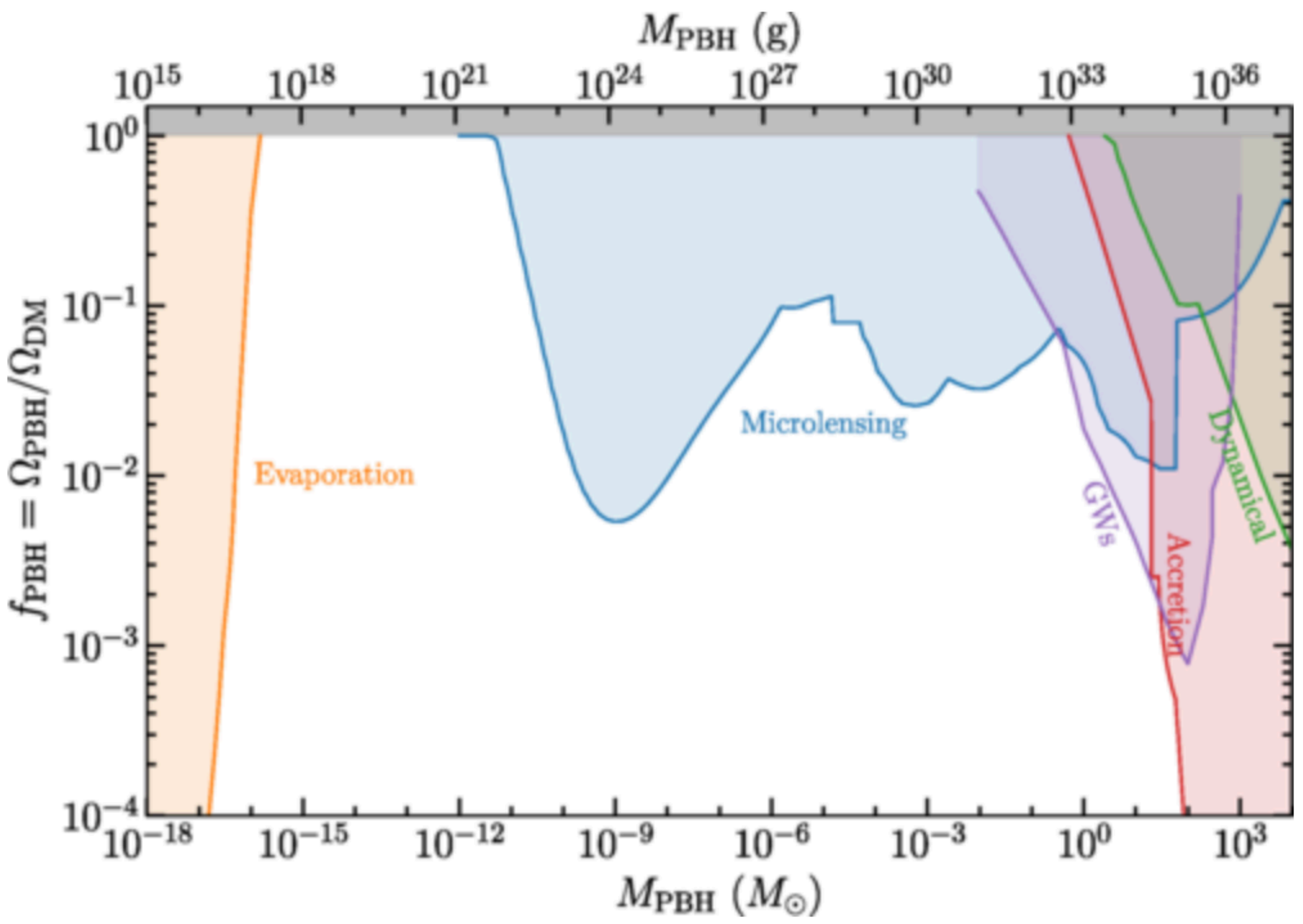
Emission with angular momentum
falls back in

Angular momentum barrier @ photon
sphere

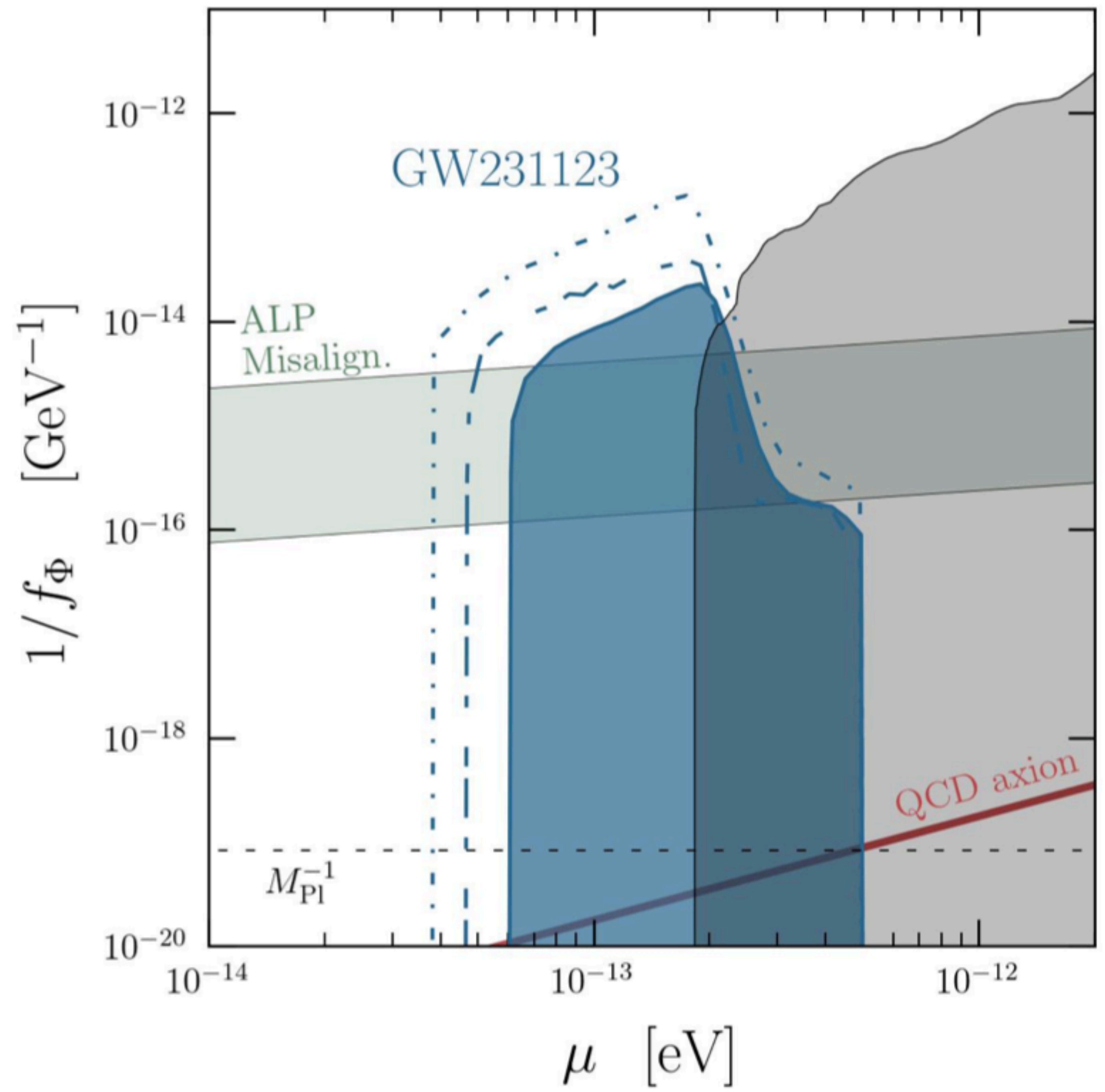
LIGO, Event Horizon Telescope: Probes Photon Sphere not Event Horizon

Black Hole Limits

Use to place limits



Hawking Evaporation Limit on Primordial Black holes



Super-radiance Limits on New Particles without interactions

Not Robust

Given photon sphere, finding "forbidden" objects may be best hope of uncovering physics of the event horizon