What's the (Quantum) Matter with Black Holes?

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Regular Black Holes: Towards a New Paradigm of Gravitational Collapse
C. Bambi ed., Springer Nature 2023

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w. P. O. Mazur: Proc. Natl. Acad. Sci. 101, 9545 (2004)

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Outline

- Classical Black Holes in General Relativity
- Problems Reconciling Black Holes, Quantum Mechanics, & Statistical Physics
    - Entropy & the Second Law of Thermodynamics
    - Temperature & the 'Trans-Planckian Problem'
    - Negative Heat Capacity & the 'Information Paradox'
- Solution Inherent in GR from Schwarzschild Interior Soln. (1916)
- Effective Theory of Low Energy Gravity
    - New Scalar Degree of Freedom from Anomaly
    - Conformal Phase Transition
    - Near Horizon Boundary Layer
- Gravitational Vacuum Condensate Stars
- Gravitational Wave Observations and Tests

Classical Black Holes

Schwarzschild Metric (1916)

$$ds^2 = -dt^2 \boxed{f(r)} + \frac{dr^2}{\boxed{h(r)}} + r^2 \left(d\theta^2 + \sin^2\theta \, d\phi^2\right)$$

$$f(r) = 1 - \frac{2GM}{r} = h(r)$$

Classical Singularities:

- $r = 0$: Infinite Tidal Forces, Breakdown of Gen. Rel.
- $r \equiv R_S = 2GM \quad (c = 1)$: Event Horizon, Infinite Blueshift, Change of sign of f, h

Trapping of light inside the horizon is what makes a black hole

BLACK

The $r = R_S$ singularity is purely kinematic, removable by a coordinate transformation

iff $\hbar = 0$

Horizon: Escape Velocity is Speed of Light

Mathematical Black Holes

- Classical Matter reaches the Horizon in Finite Proper Time
- The Local Riemann Tensor Field Strength

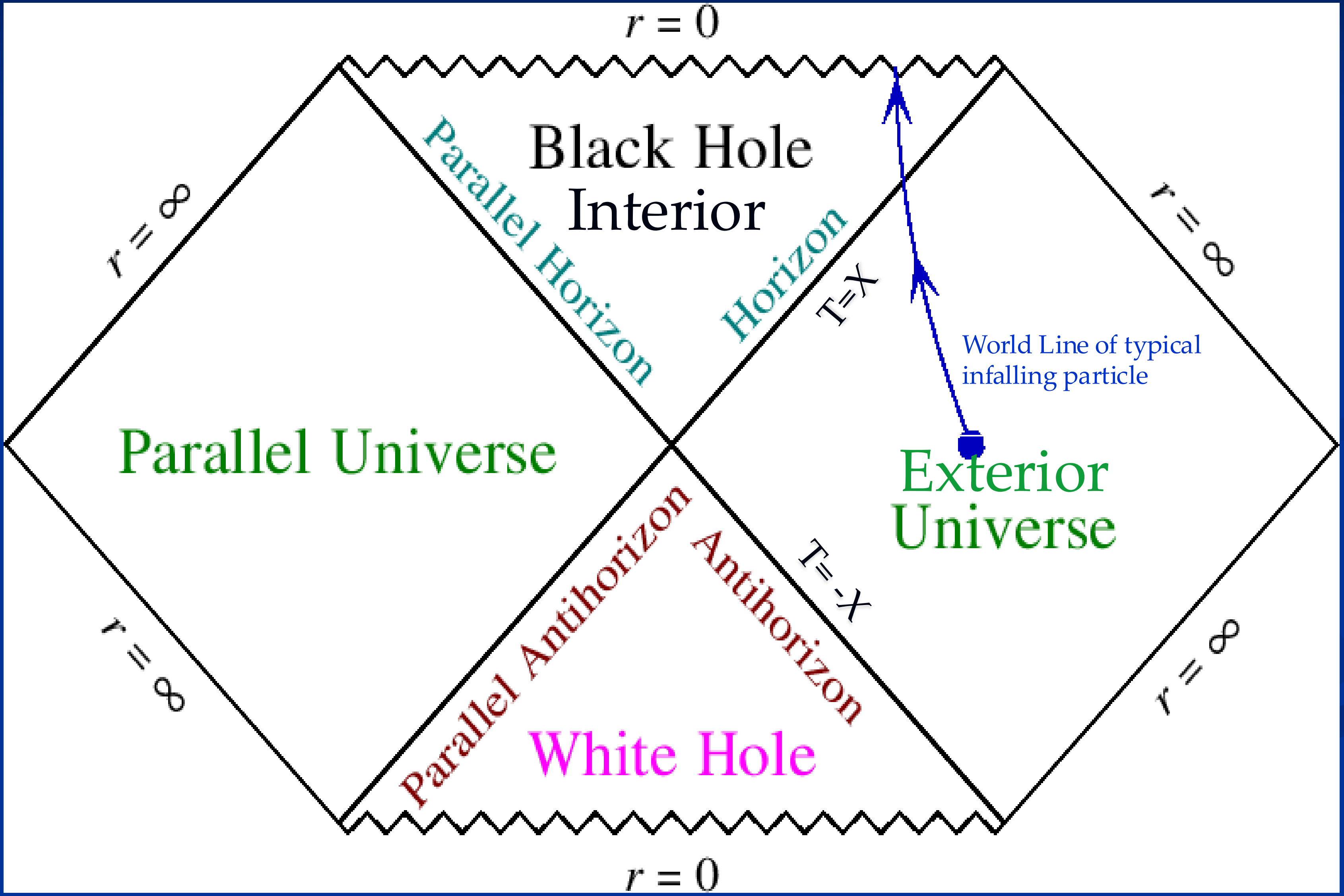
  & its Contractions remain Finite at $r=2GM/c^2$
- Kruskal-Szekeres Coordinates (1960) ($G/c^2 = 1$)

$$ds^2 = (32M^3/r)\, e^{-r/2M} (-dT^2 + dX^2) + r^2\, d\Omega^2$$

- Same geometry in different coordinates outside Horizon
- Future/Past Horizon at $r = 2GM/c^2$ is $T = \pm X$ Regular
- It is possible to use Kruskal coordinates to analytically continue inside $r < 2GM/c^2$ all the way to $r = 0$ singularity
- Necessarily involves complex continuation of coordinates

Schwarzschild Maximal Analytic Extension

Carter-Penrose Conformal Diagram



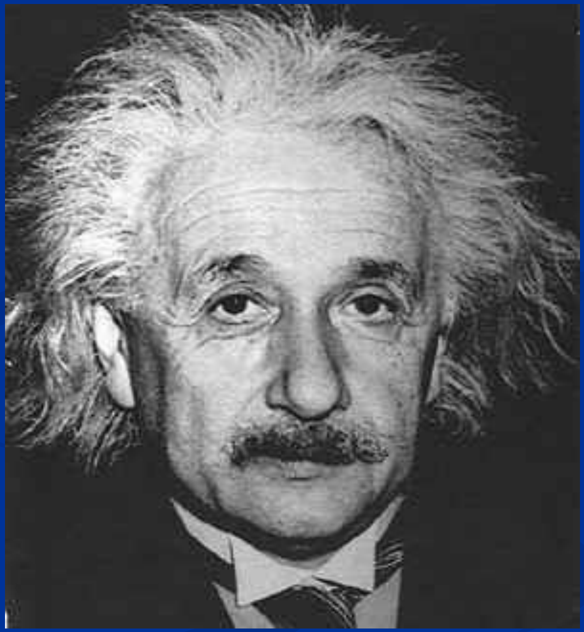
Mathematical Black Hole Interiors

Mathematics is fine, but what *really* happens when one reaches the Event Horizon and inside it?

"There arises the question whether it is possible to build up a field containing such singularities with the help of actual gravitating masses, or whether such regions with vanishing g_{44} do not exist in cases which have physical reality."

--- A. Einstein (1939)

(Same year as Oppenheimer-Snyder)

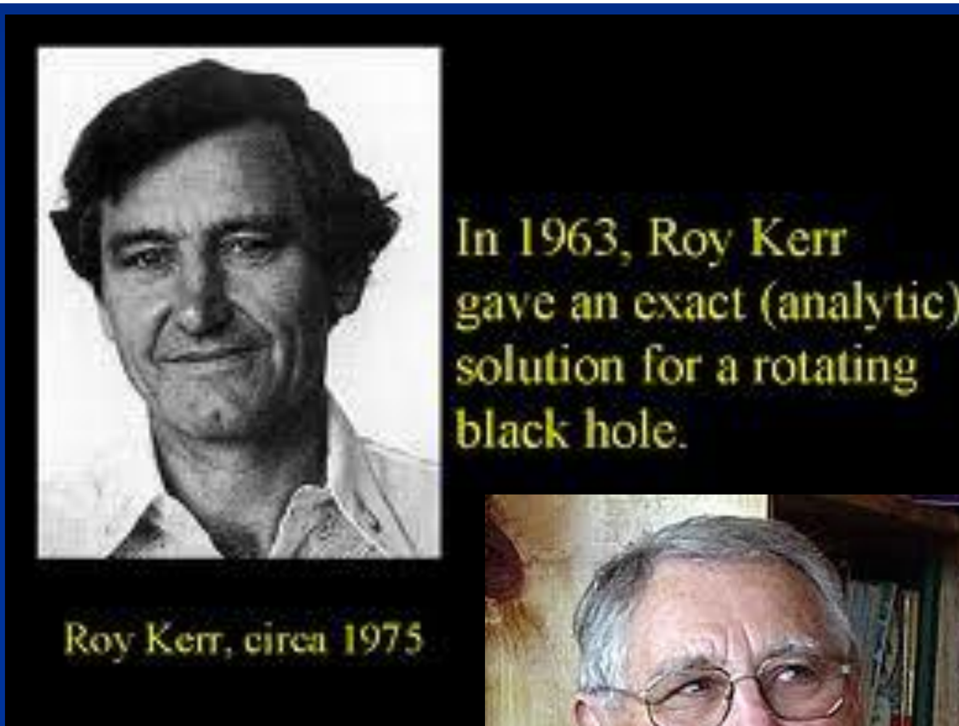


- Schwarzschild soln. also has a true spacetime singularity at r=0

A Single Spacetime Point with the mass of a million suns?

Rotating Black Holes

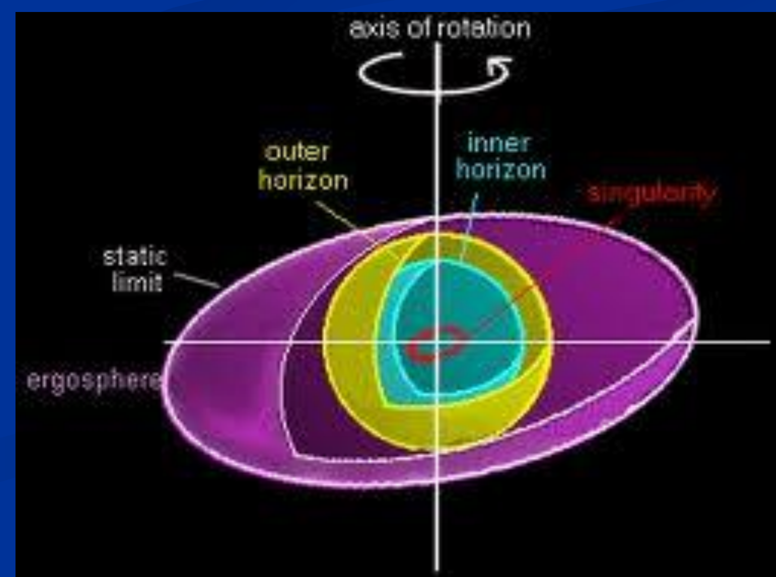
$$ds^2 = -\frac{\Delta}{\rho^2}\left(dt - a\sin^2\theta d\phi\right)^2 + \frac{\sin^2\theta}{\rho^2}\left[(r^2+a^2)d\phi - a dt\right]^2 + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2$$



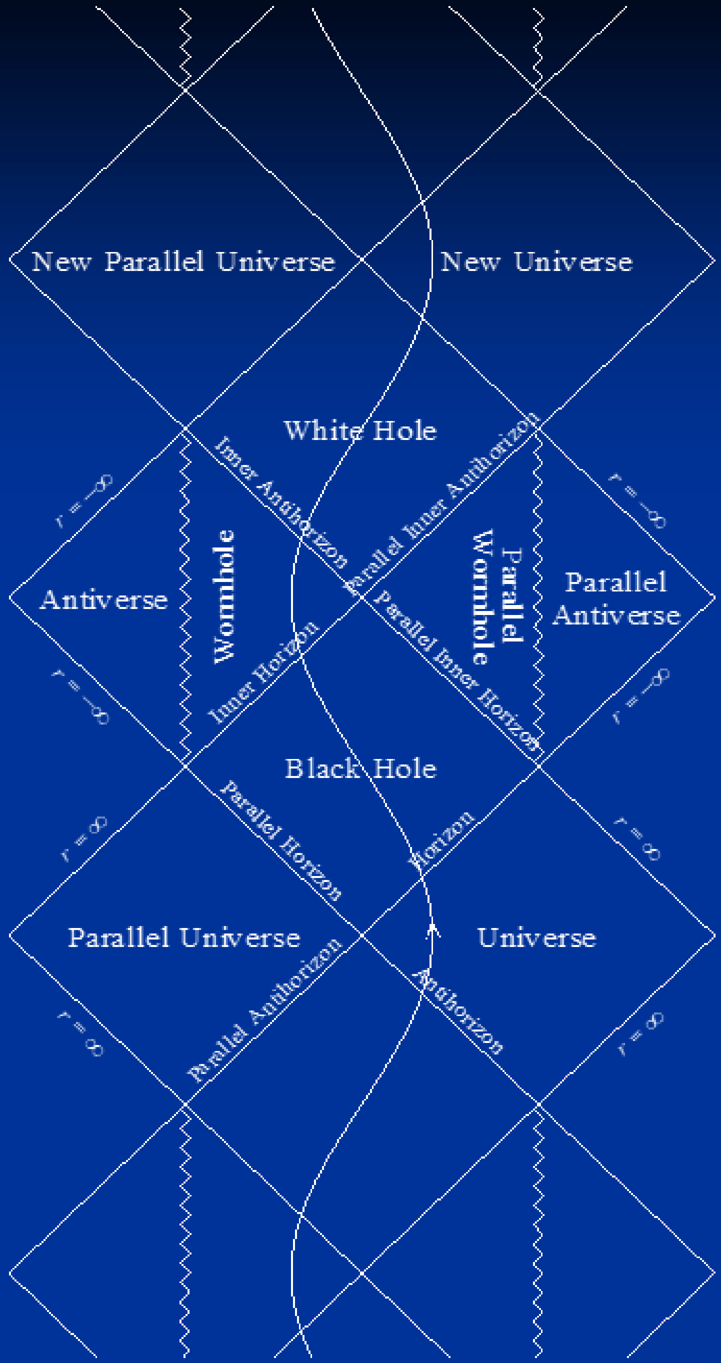
$$\rho^2 \equiv r^2 + a^2\cos^2\theta$$

$$\Delta \equiv r^2 - 2GMr + a^2$$

$$a \equiv \frac{J}{M}$$



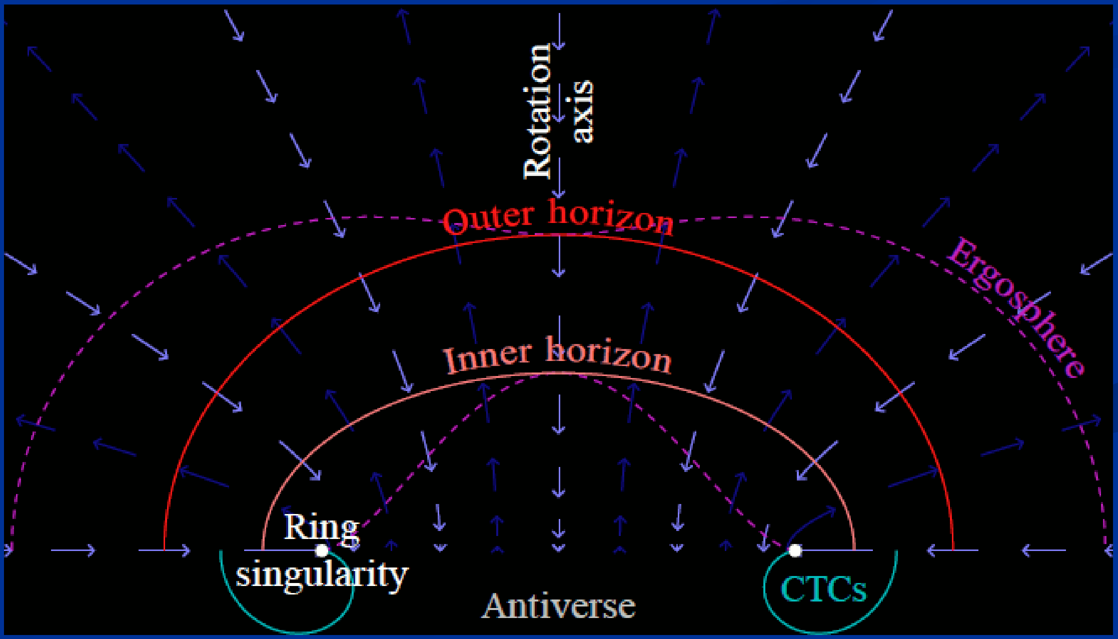
Mathematical Kerr Black Hole Interiors



- More singularities
- More universes!
- Closed Timelike Curves:

(say hello to your greatgrandparents)

More unphysical



Irreducible Mass and 'No Hair' Theorem

- All Black Holes specified by their mass, angular momentum and electric charge: M, J, Q
- Rotating Kerr Black Holes have all higher multipoles ***determined completely*** by M, J (no "hair")
- Irreducible Mass M_{irr} ***increases monotonically classically*** (Christodoulou, 1972)

$$M^2 = (M_{irr} + Q/4M_{irr})^2 + J^2/4M_{irr}^2$$

$$M_{irr}^2 = (\text{Area})/16\pi G$$

$$\Delta M_{irr}^2 \geq 0$$

Black Holes and Entropy

- A fixed classical solution usually has no entropy :
  (What is the "entropy" of the Coulomb potential $\Phi = Q/r$?)
  … But if matter/radiation disappears into the black hole,
  what happens to its entropy? (Only M, J, Q remain)
- Maybe M_{irr}^2 (which always increases) is a kind of "entropy"?
  To get units of entropy need to divide Area, A by $(\text{length})^2$
  … But there is no fixed length scale in classical Gen. Rel.
- Planck length $\ell_{Pl}^2 = \hbar G/c^3$ involves $\hbar$
- Bekenstein suggested $S_{BH} = \gamma\, k_B\, A/l_{Pl}^2$ with $\gamma \sim O(1)$
- Hawking (1974) argued black holes emit thermal radiation at

$$T_H = \frac{\hbar c^3}{8\pi G k_B M}$$

Apparently then the first law, $dE = T_H\, dS_{BH}$ fixes $\gamma = 1/4$

Great ! But …

Statistical Entropy of a Relativistic Star

- $S = k_B \ln W(E)$ (microcanonical) is equivalent to

$$S = - k_B \, Tr\,(\rho \ln \rho)$$

- Maximized by canonical thermal distribution

Eg. Blackbody Radiation $E \sim V\, T^4$, $S \sim V\, T^3$

$$S \sim V^{1/4} E^{3/4} \sim R^{3/4} E^{3/4}$$

For a fully collapsed relativistic star $E = M$, $R \sim 2GM$,

so $\boxed{S \sim k_B\, (M/M_{Pl})^{3/2}}$ ← *note 3/2 power*

$S_{BH} \sim M^2$ is a factor $(M/M_{Pl})^{1/2}$ larger or 10^{19} for $M = M_{\odot}$

- There is *no way* to get $S_{BH} \sim M^2$ by any standard statistical thermodynamic counting of states

What's the (Quantum) Matter with Black Holes?

- $\hbar$ cancels out of $dE = T_H \, dS_{BH}$: Quantum or Classical?
- In the classical limit $T_H \to 0$ **(cold)** but $S_{BH} \to \infty$ (?)
- $S_{BH} \propto A$ is non-extensive and **HUGE**
- How does a huge entropy get associated with the horizon if there is 'nothing' there?
- $E \propto T^{-1}$ implies negative heat capacity: $\langle (H-E)^2 \rangle < 0$ (?)

  $$\frac{dE}{dT} << 0 \quad \Rightarrow \quad \text{unstable}$$

  Equilibrium Thermodynamics cannot be applied (?)
- Information Paradox: Where does the information go? (Pure states $\to$ Mixed States? Unitarity ?)
- What is the microstate statistical interpretation of S_{BH} ? Boltzmann asks: $\mathbf{S = k_B \ln W}$ **?**


S = k. log W
LVDWIG
BOLTZMANN
1844 – 1906
Dr PHIL PAULA
BOLTZMANN
1891 – 1977
ARTHUR
BOLTZMANN
LVDWIG
BOLTZMANN
HENRIETTE
BOLTZMANN

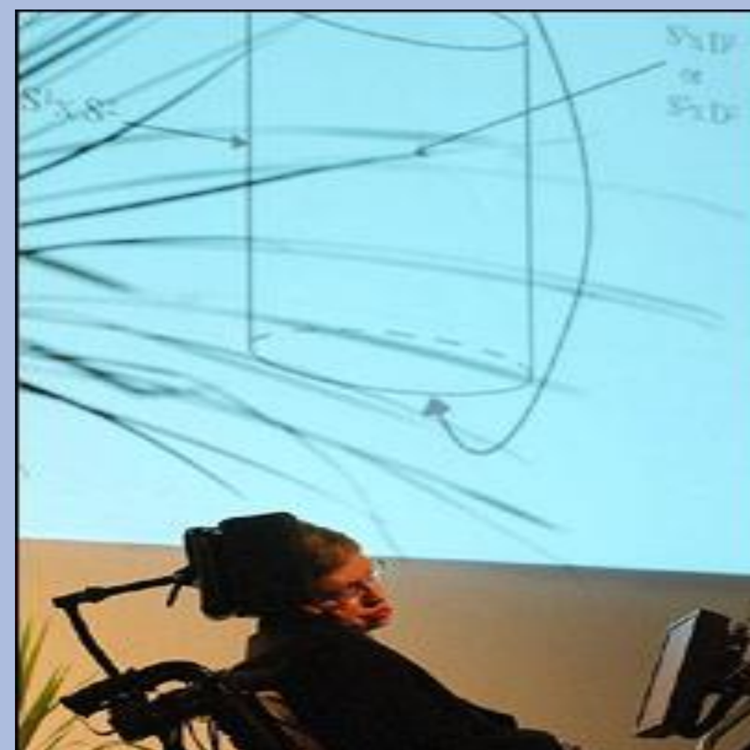
BBC NEWS UK EDITION

Thursday, 15 July, 2004, 17:08 GMT 18:08 UK

Hawking backs down on black holes

Stephen Hawking says he was wrong about a key argument he put forward 30 years ago on the behaviour of black holes.

The world-famous physicist addresses an international conference on Wednesday to revise his claim that black holes destroy everything that falls into them.



Stephen Hawking: 'There are no black holes'

Notion of an 'event horizon', from which nothing can escape, is incompatible with quantum theory, physicist claims. Zeeya Merali NATURE 24 January 2014

Horizon in Quantum Theory

- Infinite Blueshift Surface

$$\omega_{local} = \omega_\infty \, (1 - 2GM/r)^{-1/2}$$

No problem classically, but in quantum theory,

$$E_{local} = \hbar\omega_{local} = \hbar\omega_\infty \, (1 - 2GM/r)^{-1/2} \rightarrow \infty$$

$\hbar \rightarrow 0$ and $r \rightarrow 2GM$ limits do not commute ($\Rightarrow$ non-analyticity)

Singular coordinate transformations $\rightarrow$ new physics

- Energies becoming trans-Planckian should call into doubt the semi-classical fixed metric approximation
- Large local energies must be felt by the gravitational field
- Large local energy densities/stresses are generic near the horizon

$$\langle T_a^{\ b} \rangle \sim \hbar\omega_{local}^{\ 4} \sim \hbar M^{-4} (1 - 2GM/r)^{-2}$$

The geometry does not remain unchanged down to $r = 2GM$

Quantum Vacuum Polarization Effects are important on horizon

Quantum Effects Are Non-Local

- Isn't the horizon 'just a coordinate artifact,' that can be transformed away ('symmetry transformation'?
- But the coordinate transformation is itself **singular**
- ***Singular*** coordinate/gauge transformations need not be harmless and can contain new physics

E.g. from U(1) QED: Vortices in Superfluids/BECs

$$\oint_{\mathbb{S}^1} A_\lambda dx^\lambda = \oint A \overset{A=d\theta}{=} \int d\theta = 2\pi$$ is gauge invariant

Aharonov-Bohm Effect also "Pure Gauge" = no Local $F_{\mu\nu}$ Field

Quantum Effects are Non-Local

(e.g. Entanglement)

DO NOT REQUIRE LARGE CURVATURES

Black 'Holes'… or Not
Singularity Theorems

Black Holes 'inevitable' in Gen. Rel. if

- Trapped Surface forms
- Energy Conditions hold

- **Weak** Energy Condition (Penrose 1965)

$$\rho + p_i \geq 0 \qquad i = 1, 2, 3$$

Violated by Quantum Fields, e.g. by Casimir Effect

- **Strong** Energy Condition (Hawking-Penrose 1970)

$$\rho + \sum_{i=1}^{3} p_i \geq 0$$

Violated by Hadronic 'Bag', Cosmological Dark Energy,

Inflation V(φ): $p_i = -\rho < 0$

Negative Pressure → Defocusing → Effective **Repulsion**

Gravitational Vacuum Condensates

- Gravity is a theory of spin-2 bosons
- Its interactions are attractive
- The interactions become strong near $r = R_s$
- Energy of any scalar order parameter must couple to gravity with the vacuum eq. of state,
$$p_V = -\rho_V = -V(\phi)$$
- Relativistic Entropy Density s is (for $\mu = 0$),
$$Ts = p + \rho = 0 \text{ if } p = -\rho$$
- Zero entropy density for a single macroscopic quantum state, $k_B \ln \Omega = 0$ for $\Omega = 1$
- This eq. of state violates the energy condition, $\rho + 3p \geq 0$ (if $\rho_V > 0$) needed to prove the classical singularity theorems
- Dark Energy acts as a repulsive core

A GBEC phase transition can stabilize a high density, compact cold stellar remnant to further gravitational collapse

Gravitational Vacuum Condensate Star Proposed (2001)

It is Realized in Schwarzschild Soln.II (1916)

Schwarzschild Interior Solution

- Constant Density

$$\rho' = 0$$

Saturates

Buchdahl Bound

$$h(r) = 1 - H^2 r^2$$

$$H^2 = \frac{8\pi G}{3}\bar{\rho} = \frac{2GM}{R^3}$$

- Pressure $$p(r) = \bar{\rho}\left[\frac{\sqrt{1-H^2r^2} - \sqrt{1-H^2R^2}}{3\sqrt{1-H^2R^2} - \sqrt{1-H^2r^2}}\right]$$

- Diverges at $$\boxed{R_0 = 3R\sqrt{1 - \frac{8}{9}\frac{R}{R_s}}}$$ iff $$\boxed{R < \frac{9}{8}R_s = \frac{9}{4}GM}$$

- Pressure becomes negative for $0 < r < R_0$

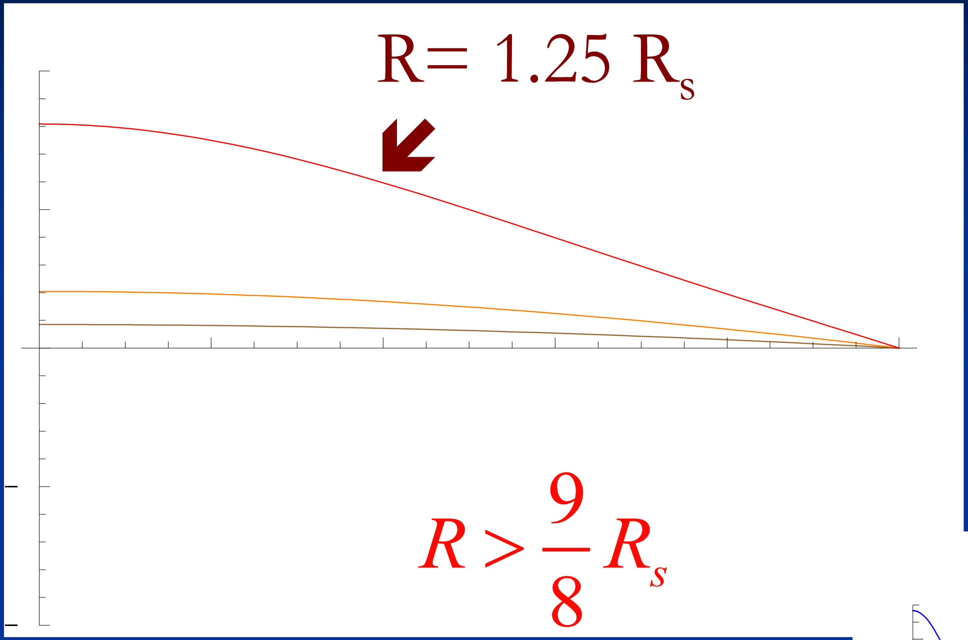
- $$f(r) = \tfrac{1}{4}\left[3\sqrt{1-H^2R^2} - \sqrt{1-H^2r^2}\right]^2$$

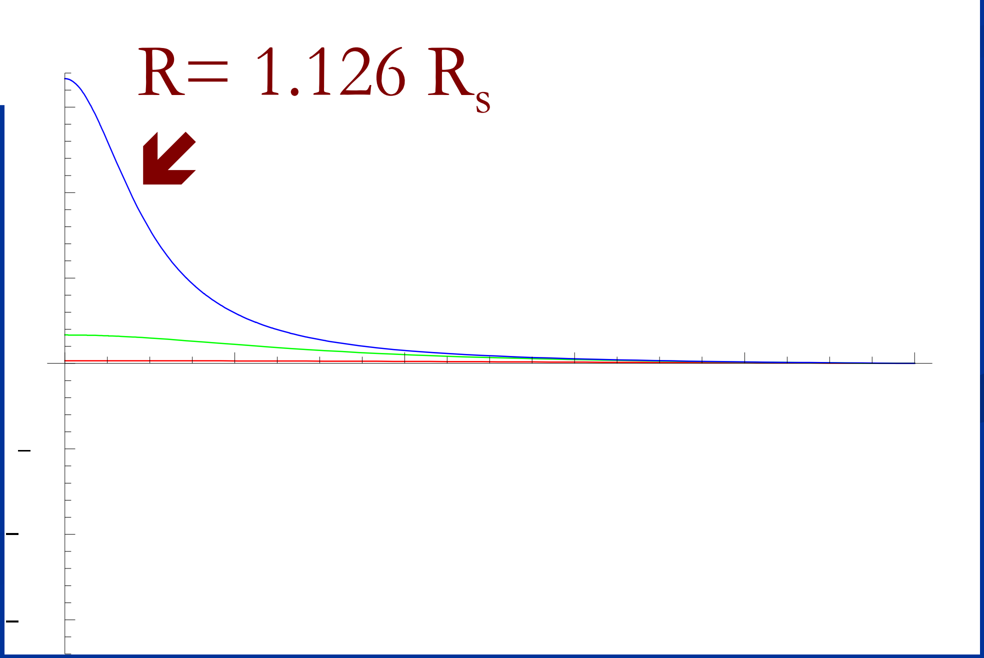
Vanishes at same R_0

Never Negative

- If $\boxed{R = R_S = R_0\,, \quad H^2R^2 = 1 \Longrightarrow p = -\bar{\rho}}$ **= constant (de Sitter)**

Interior Pressure

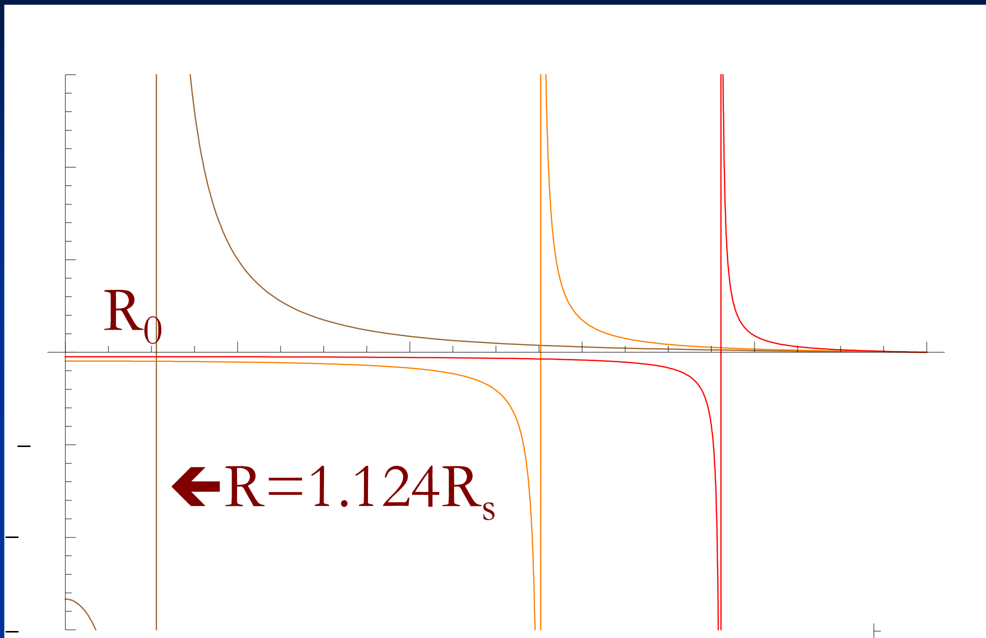




As R → 9/8 R_s from above

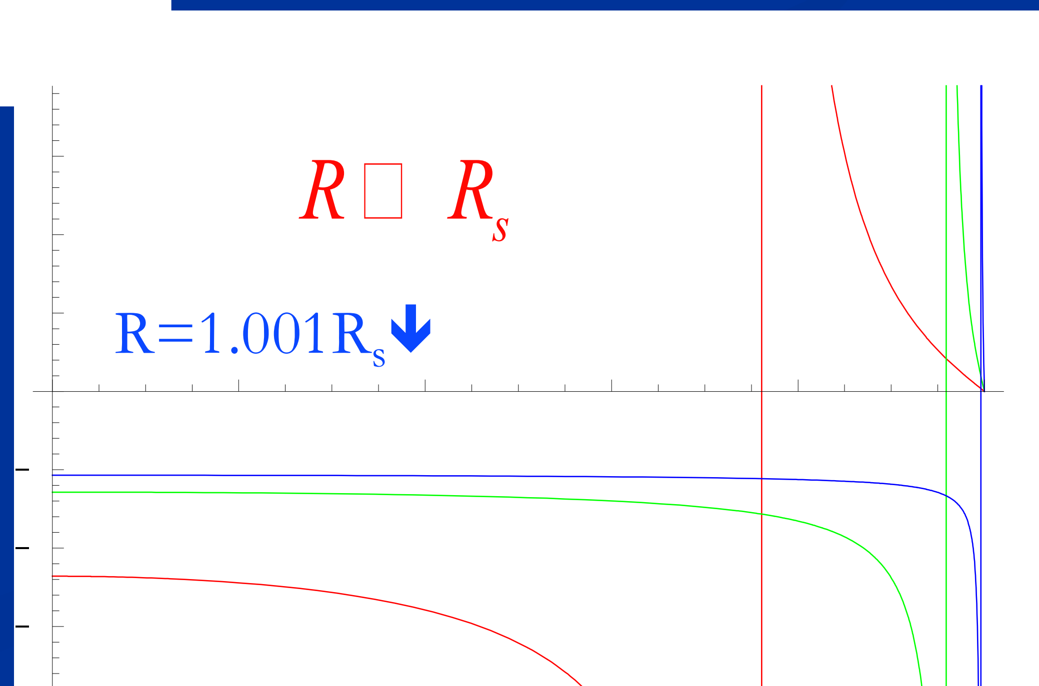
central pressure diverges

Interior Pressure



$$R < \frac{9}{8} R_s$$

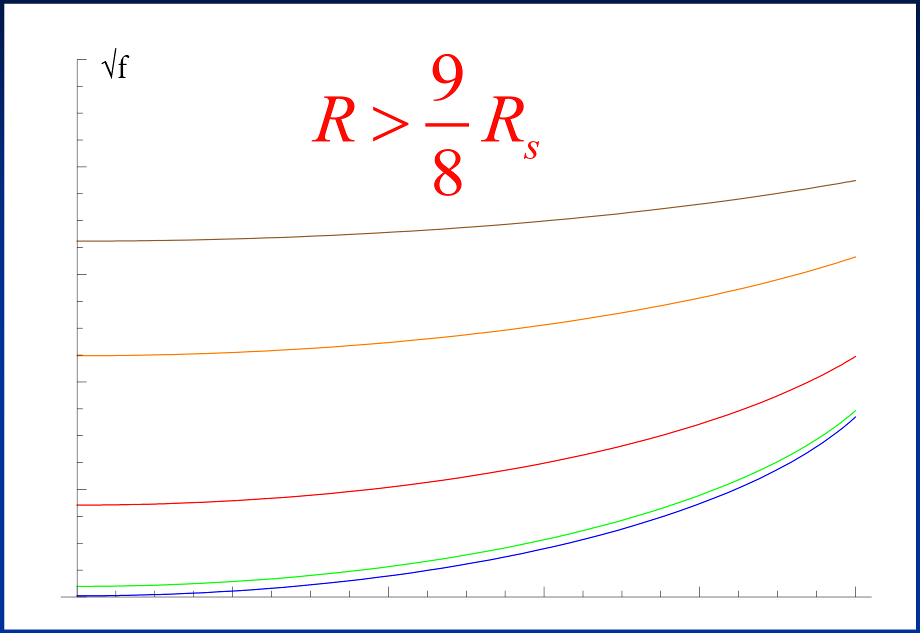
Negative Pressure soln. opens up for $R < R_0$

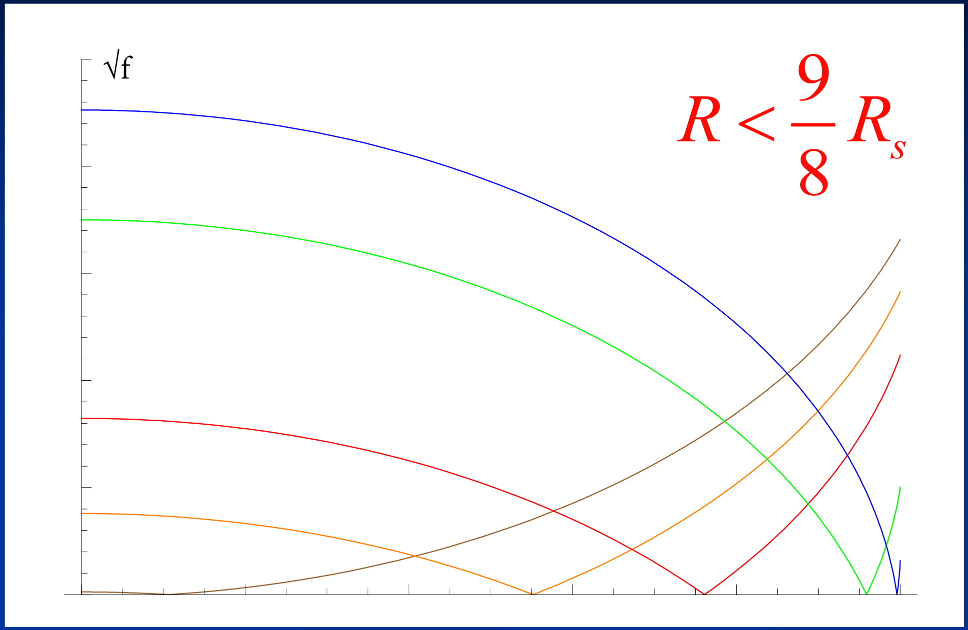


As $R \to R_s$ from above $R_0 \to R_s$ from below and negative pressure region fills entire interior with

$p = -\rho$, $w=-1$

Interior Redshift





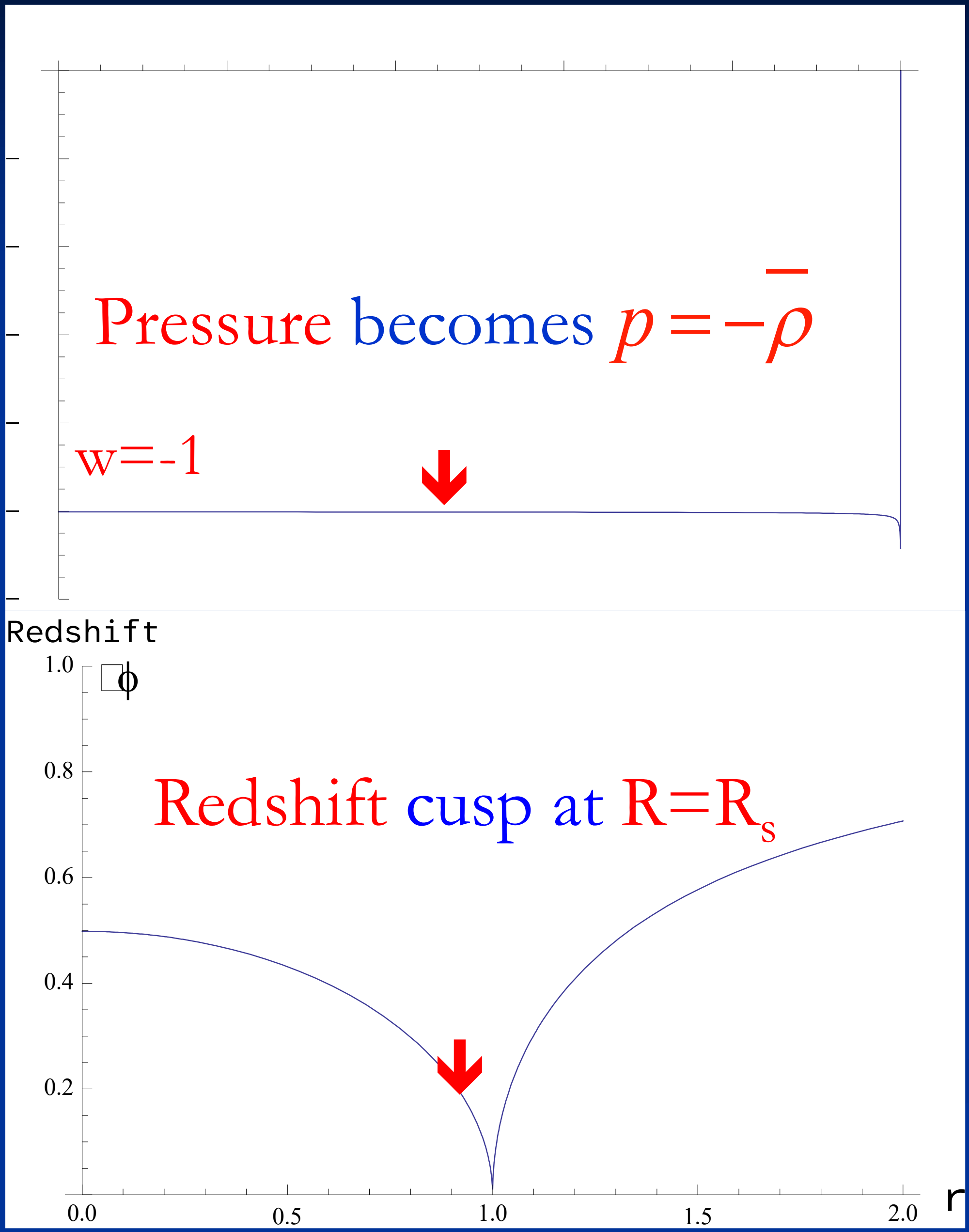
$f(r) = \frac{1}{4} D^2 \geq 0$ Non-negative (no horizon)

$$D \equiv 3\sqrt{1 - R_s/R} - \sqrt{1 - R_s r^2/R^3}$$

vanishes at same radius $R_0 = 3R\sqrt{1 - \frac{8}{9}\frac{R}{R_s}}$ where p diverges

Redshift $\sqrt{f(r)} = \frac{1}{2}|D|$ has cusp-like behavior

$R=R_s$ Limit is Grav. Condensate Star (2001)



No divergence in p

$$p = -\bar{\rho}$$

$$h(r) = 1 - H^2 r^2$$

$$f(r) = \frac{1}{4}\, h(r)$$

$$H = 1/R_s$$

but non-analytic cusp

Discontinuity (classically)

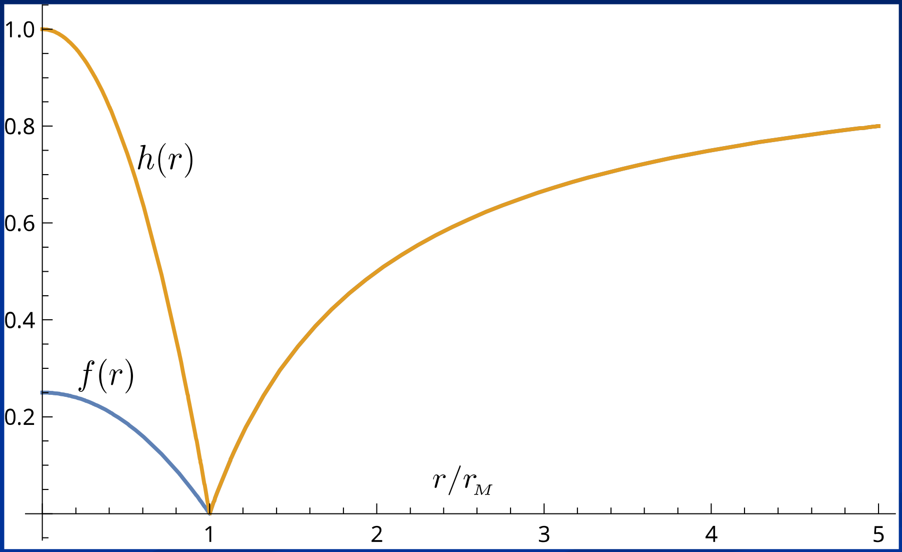
Interior is de Sitter space in (modified) static coordinates

(Time runs slower inside)

The Classical Gravastar:
Schwarzschild Star in Horizon Limit $R=R_s \equiv r_M$

$$f(r) = \begin{cases} \frac{1}{4}\left(1 - \frac{r^2}{r_M^2}\right), & 0 \le r \le r_M \\ 1 - \frac{r_M}{r}, & r \ge r_M \end{cases}$$

$$h(r) = \begin{cases} 1 - \frac{r^2}{r_M^2}, & 0 \le r \le r_M \\ 1 - \frac{r_M}{r}, & r \ge r_M \end{cases}$$



- Interior is static patch of de Sitter space with $\Lambda_{\text{eff}} = \frac{3}{r_M^2}$
- Exterior is Schwarzschild with $r_M \equiv R_s = \frac{2GM}{c^2}$
- Requires Vacuum Energy to change abruptly at $r = r_M$

Discontinuity in derivatives is a surface tension of a physical surface

Surface Replaces the BH Horizon

Step Function Discontinuity in Surface Gravity

$$\kappa(r) = \frac{1}{2}\sqrt{\frac{h}{f}}\frac{df}{dr} \to \begin{cases} \kappa_- = -\dfrac{1}{2r_M}, & r \to r_M^- \quad \text{Outward Force} \\ \kappa_+ = +\dfrac{1}{2r_M}, & r \to r_M^+ \quad \text{Inward Force} \end{cases}$$

$$\Delta\kappa = \kappa_+ - \kappa_- = \frac{1}{r_M} \qquad \tau_S = \frac{\Delta\kappa}{8\pi G} > 0$$ is positive surface tension

Surface Stress Tensor $^{(\Sigma)}T^A{}_B\sqrt{\frac{f}{h}} = \tau_S\,\delta(r - r_M)\,\delta^A{}_B\,, \qquad A, B = \theta, \phi$

Interior is non-singular, not analytic continuation of exterior

$dE_S = \tau_S\, dA_H$ Zero Temperature, No BH Entropy

Class. Quan. Grav. 32, 215024 (2015)

Challenge: Derive this result in EFT of Gravity


NewScientist
GRAVASTARS
ARE THEY THE
NEW BLACK HOLES,
AND COULD OUR UNIVERSE
EXIST INSIDE ONE?

Gravitational Vacuum Condensate Stars

- Area term is Classical **Mechanical Surface Energy** **not Entropy**
- QM, Unitarity ✓ **No 'Information Paradox'**
- **Condensate Star negative pressure** already inherent in Classical General Relativity in Schwarzschild Interior Solution (1916)
- **Cold** Coherent **Final State** of Gravitational Collapse

  But a Fully Satisfactory Theory Requires
  - Dynamical Vacuum Condensate
  - Quantum Effective Theory
  - Finite Thickness Boundary layer

EFT of Gravity

- **EFT** = Expansion of Effective Action in *Local* Invariants with increasing dimension determined by Symmetry
- Based on **Decoupling** of Short Distance from Long Distance Physics
- **In modern terms, GR is an EFT (2nd order eqs.) with metric d.o.f.**
- **But must identify all low energy relevant degrees of freedom**
  - **Std. Model Stress Tensor is Quantum**

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \langle T_{\mu\nu} \rangle$$

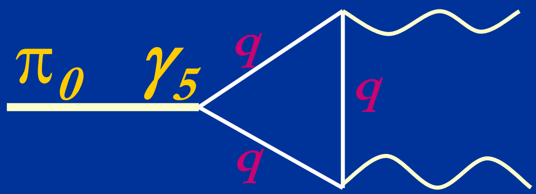
  - Massless Quantum Fields do not decouple
  - And conformal Symmetry is Anomalous: Trace Anomaly in $\langle T^{\mu}{}_{\mu} \rangle$
- **As in chiral case *IR*** Relevant & Low Energy/**Macroscopic** Effects

Effective Scalar Degree of Freedom in **Low Energy** Gravity

Chiral Anomaly in QCD EFT

Anomaly Matching of **UV** (QCD) ↔ ***IR*** (pion EFT)

- Anomaly calculated in **UV** theory -- QCD with massless quarks
- But Low Energy $\pi_0 \to 2\gamma$ rate is dominated by the anomaly



$$\partial_\mu j^{\mu 5} = e^2 N_c F_{\mu\nu} \tilde{F}^{\mu\nu} / 16\pi^2$$

topological density

- Measured decay rate verifies $N_c = 3$, fractional charges in QCD
- An *IR* window into the **UV** theory
- ***No Local*** action in original QCD/QED matter/gauge fields
- ***But IR Relevant Local Operator/Action*** in terms of mesons

Low Energy EFT of QCD must include the WZ effective action of the chiral anomaly & its collective meson mode(s)

Conformal Anomaly Effective Action

- Trace/Conformal Anomaly of Massless QFT (CFT)

$$\langle \hat{T}^{\mu}{}_{\mu} \rangle \equiv \frac{\mathcal{A}}{\sqrt{-g}} = a\left(E - \tfrac{2}{3}\,\Box R\right) + b\,C^2 + \sum_i \beta_i\,\mathcal{L}_i$$

$$E = R_{\alpha\beta\gamma\lambda}R^{\alpha\beta\gamma\lambda} - 4R_{\alpha\beta}R^{\alpha\beta} + R^2$$

$$C^2 = R_{\alpha\beta\gamma\lambda}R^{\alpha\beta\gamma\lambda} - 2R_{\alpha\beta}R^{\alpha\beta} + \tfrac{1}{3}R^2$$

$$a = -\frac{\hbar}{(4\pi)^2}\,\frac{1}{360}\left(N_S + 11N_F + 62N_V\right)$$

$$b = \frac{\hbar}{(4\pi)^2}\,\frac{1}{120}\left(N_S + 6N_F + 12N_V\right)$$

- Intrinsically Non-Local Quantum Effect but Local Covariant Effective Action

$$S_{\mathcal{A}}[g;\varphi] = -\frac{a}{2}\int d^4x\sqrt{-g}\left\{\left(\Box\varphi\right)^2 - 2\left(R^{\mu\nu} - \tfrac{1}{3}Rg^{\mu\nu}\right)(\partial_\mu\varphi)(\partial_\nu\varphi)\right\}$$

$$+\frac{1}{2}\int d^4x\,\mathcal{A}\,\varphi$$ ← Linear Coupling to Total Anomaly

- **New Dynamical Scalar** in Conformal Sector: **<u>'Conformalon'</u>**

$$\Delta_4\varphi \equiv \nabla_\mu\left(\nabla^\mu\nabla^\nu + 2R^{\mu\nu} - \tfrac{2}{3}Rg^{\mu\nu}\right)\nabla_\nu\varphi = \frac{1}{2a}\frac{\mathcal{A}}{\sqrt{-g}}$$

IR Relevant Term in the Action

The effective action for the trace anomaly scales logarithmically with distance, is a relevant operator and hence should be included in the low energy EFT of macroscopic gravity —
Compare chiral anomaly in meson EFT of QCD

Not given purely in terms of Local Curvature

$$S_{\rm eff}[g;\varphi] \supset S_{\rm EH}[g] + S_{\mathcal{A}}[g;\varphi]$$

This is a non-trivial low energy modification of classical General Relativity from QFT

A scalar-tensor EFT but very different from e.g. Brans-Dicke
Consistent with all laboratory expts./solar system observations

Anomaly Stress Tensor in Schwarzschild Space

General static spherically symmetric solution for $\varphi(r)$ in Schwarzschild

$$\frac{d\varphi_S}{dr} = \frac{c_S\, r_M}{r(r-r_M)} - \left(1+\frac{b}{a}\right)\left\{\frac{2}{3r_M}\left(\frac{r}{r_M}+1+\frac{r_M}{r}\right)\ln\left(1-\frac{r_M}{r}\right)+\frac{2}{3r_M}+\frac{1}{r}\right\}$$

c_S is a state dependent integration constant

Generic divergence on horizon

$$(T^\mu{}_\nu)_{\mathcal{A}} \to \frac{c_S^2}{2r_M^2}\,\frac{a}{(r-r_M)^2}\begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & \frac{1}{3} & 0 & 0 \\ 0 & 0 & \frac{1}{3} & 0 \\ 0 & 0 & 0 & \frac{1}{3} \end{pmatrix} \to \infty \qquad \text{as} \qquad r \to r_M = \frac{2GM}{c^2}$$

for any M, no matter how large, & no matter how small the local curvature

Result of Extreme Blue Shift $\omega_{\mathrm{loc}}(r) = \dfrac{\omega_\infty}{\sqrt{f(r)}}$

Conformal Behavior $\langle T^\mu{}_\nu\rangle \to \hbar\omega_{\mathrm{loc}}^4 \propto \dfrac{\hbar}{M^4 f^2(r)}$

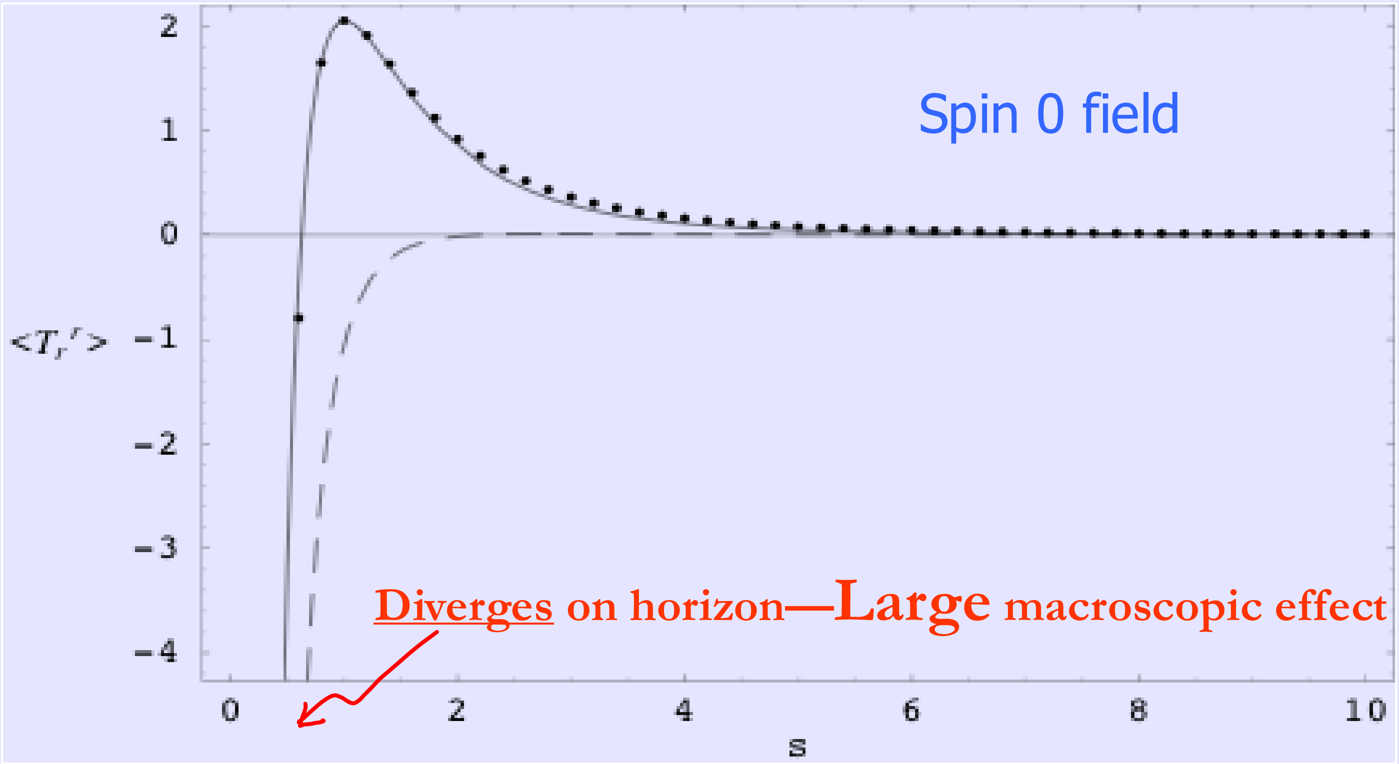
Large Effect on geometry in near horizon region

Stress-Energy Tensor in Boulware Vacuum – Radial Component

Dots – Direct Numerical Evaluation of <$T_a^{\ b}$> (Jensen et. al. 1992)

Solid – Stress Tensor from the Auxiliary Fields of the Anomaly (E.M & R. Vaulin 2006)

Dashed – Page, Brown and Ottewill approximation (1982-1986)



Quantum Effective Theory

Needs to have 2 main elements

- Quantum Conformal Anomaly Important Effects Near Macroscopic (Apparent) Horizons

  Analogous to Axial Anomaly in QCD

- Allow Vacuum Energy to Change

  (Quantum Phase Transition)

Note: QCD also provides $p = -\rho$ Vacuum Energy in Bag Constant (Gluon Condensate)

$$\bar{\rho} = \frac{3M}{4\pi R^3} = 10.5\,\frac{\text{GeV}}{\text{fm}^3}\left(\frac{M_\odot}{M}\right)^2 \leftrightarrow B = 75\,\frac{\text{MeV}}{\text{fm}^3}$$

Vacuum Energy as a 4-Form Gauge Field

Four-Form Field Strength (matched to D=4 dimensions)

$$F = \frac{1}{4!}\, F_{\alpha\beta\gamma\lambda}\, dx^\alpha \wedge dx^\beta \wedge dx^\gamma \wedge dx^\lambda$$

Hodge Dual is a Scalar—only one 'electric' component

$$\tilde{F} \equiv \star F = \frac{1}{4!}\, \varepsilon_{\alpha\beta\gamma\lambda} F^{\alpha\beta\gamma\lambda} = F^{txyz}$$

If F is <u>Exact</u>: F = dA there is a Three-Form Gauge Potential A

$$F_{\alpha\beta\gamma\lambda} = 4\, \nabla_{[\alpha} A_{\beta\gamma\lambda]} \qquad A = \frac{1}{3!} A_{\alpha\beta\gamma}\, dx^\alpha \wedge dx^\beta \wedge dx^\gamma$$

with a 'Maxwell' Action

$$S_F = -\frac{1}{2\varkappa^4} \int F \wedge \star F = -\frac{1}{48\varkappa^4} \int d^4x \sqrt{-g}\, F_{\alpha\beta\gamma\lambda} F^{\alpha\beta\gamma\lambda}$$

'Maxwell' Eqs.: With no source this 1 component is **constant**

$$\frac{1}{\varkappa^4} \nabla_\lambda F^{\alpha\beta\gamma\lambda} = J^{\alpha\beta\gamma} = 0 \qquad \partial_\lambda \tilde{F} = 0 \quad \Rightarrow \quad F = const.$$

Natural Solution of Naturalness Problem

Stress Tensor for F

$$T_F^{\mu\nu} = \frac{2}{\sqrt{-g}}\frac{\delta S_F}{\delta g_{\mu\nu}} = -\frac{1}{2\varkappa^4} g^{\mu\nu}\,\tilde{F}^{\,2}$$

Equivalent to an Effective Cosmological Constant

$$\Lambda_{\rm eff} = \frac{4\pi G}{\varkappa^4}\tilde{F}^2 \geq 0$$

But Integration Constant set by **Classical** Boundary Condition in Flat Space

$$T_F^{00}\Big|_{\rm flat} = \frac{1}{2\varkappa^4}\,\tilde{F}^{\,2} \quad \Rightarrow \quad \tilde{F} = 0$$

Absolute Minimum of Energy, Stable Ground State

Required by Consistency with Einstein's eqs. in Flat Space limit

$$\left[R_{\mu\nu} - \frac{R}{2}g_{\mu\nu}\right]_{\rm flat} = 0 = -\Lambda_{\rm eff}\Big|_{\rm flat}\,\eta_{\mu\nu}$$

No Infinite or **UV** Sensitive Zero Point Energy, No Fine Tuning

$\varkappa$ Coupling still **arbitrary**

EFT of Gravity: QFT + GR

1) QFT Conformal Anomaly contributes to Macroscopic Gravity

- Additional scalar conformalon φ degree of freedom in EFT of Low Energy Gravity + GR
- IR Relevant and Important on BH Horizon

2) Λ replaced by a 4-form gauge field ***F*** & free integration constant

- Λ_{eff} vanishes *identically* in flat space
- Decoupled from UV divergences or Planck scale physics
- Eliminates Λ 'Naturalness' Problem

Conformal anomaly of light fermions near horizon generates coupling of ***F*** to φ and implies activation of torsion

$\Rightarrow$ A Theory of Dynamical Vacuum Energy

Λ_{eff} can change rapidly at the BH horizon

Consequences of EFT for 'non-Black Holes' a.k.a. gravastars

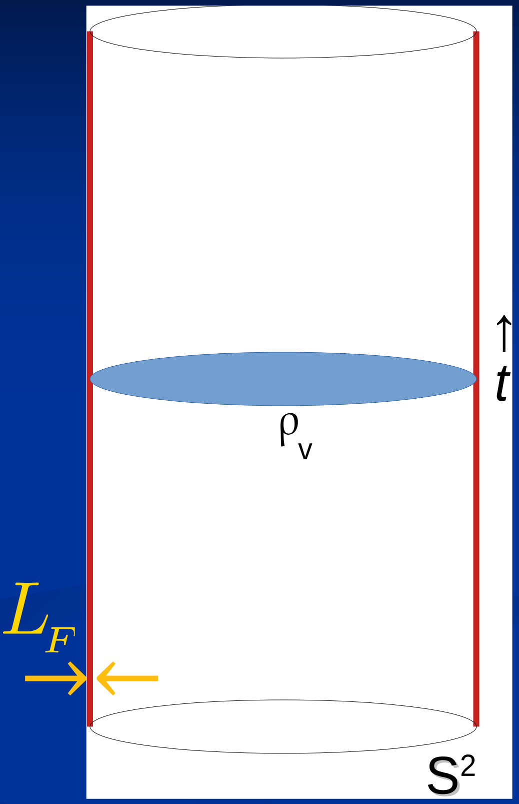
Gravastar Boundary Layer

Current Source for F activated at the lightest ν mass scale

at r coordinate distance from horizon

$$\hbar\omega_{\rm loc}(r) = \frac{\hbar c}{4\pi r_M}\left(1 - \frac{r_M}{r}\right)^{-\frac{1}{2}} \geq m_\nu c^2$$

$$|r - r_M| \leq \Delta r_F = \frac{L_F^2}{4 r_M}$$



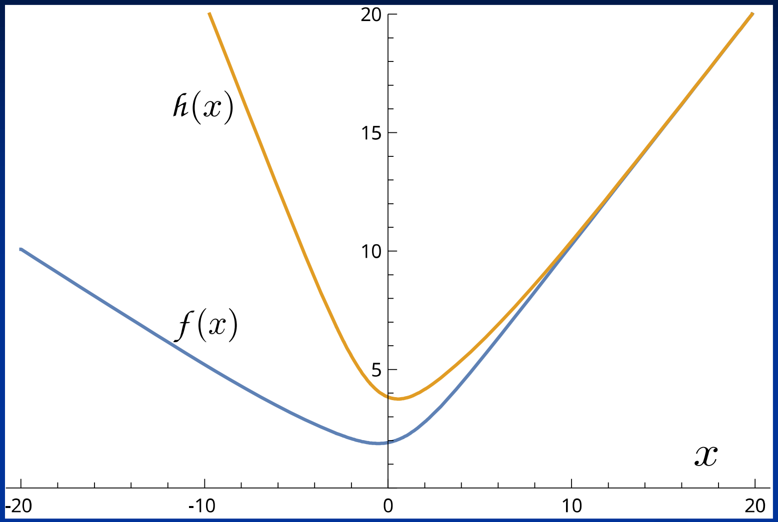
Allows Vacuum Energy to change in thin boundary layer of physical width ~ 1 μm at r_M

$$L_F = \int_{r_M}^{r_M + \Delta r_F} dr \left(1 - \frac{r_M}{r}\right)^{-\frac{1}{2}} = \frac{\hbar}{2\pi m_\nu c} \simeq 7.85 \times 10^{-5} \left(\frac{0.04\text{eV}}{m_\nu c^2}\right) \text{cm}$$

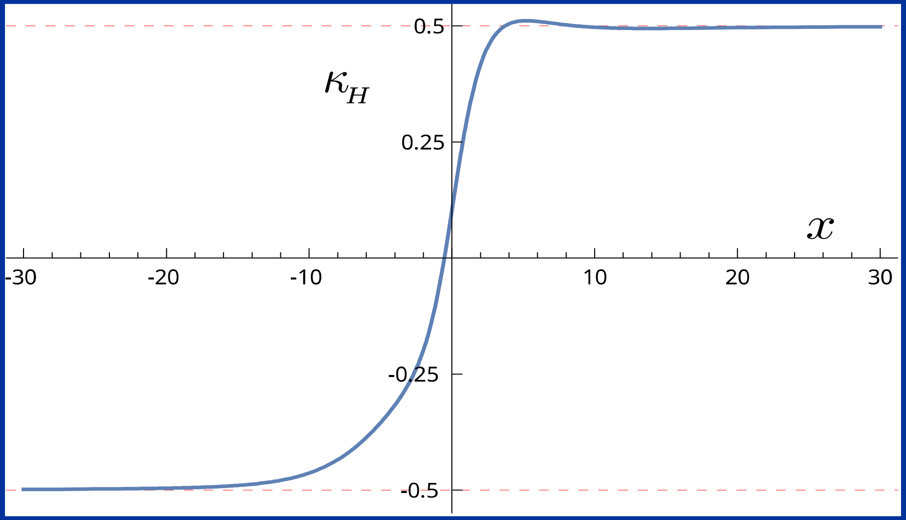
$L_F \gg L_{\rm Planck}$ Low Energy EFT remains applicable

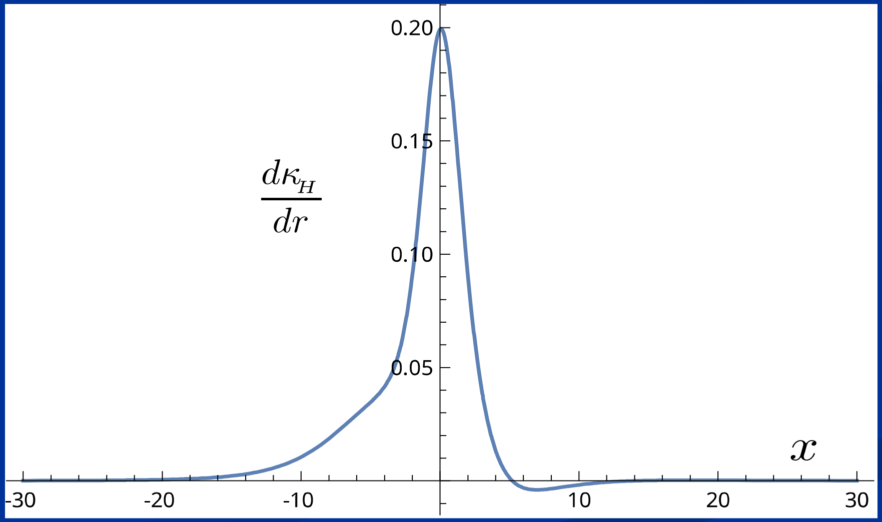
Gravastar Boundary Layer

Metric function cusp is regularized and made smooth within the quantum boundary layer



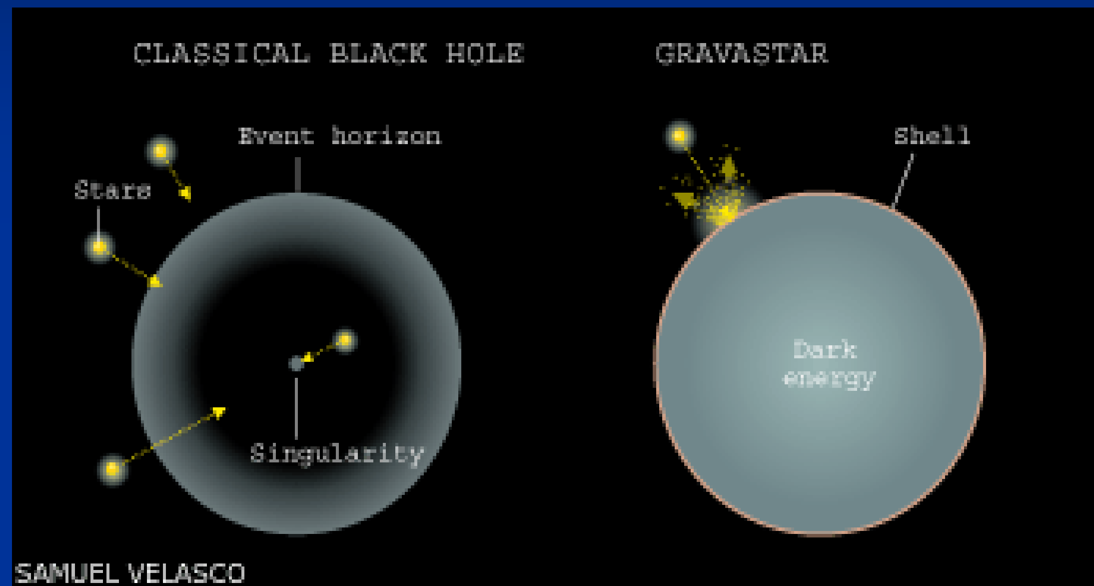
Surface Gravity Step Function becomes continuous





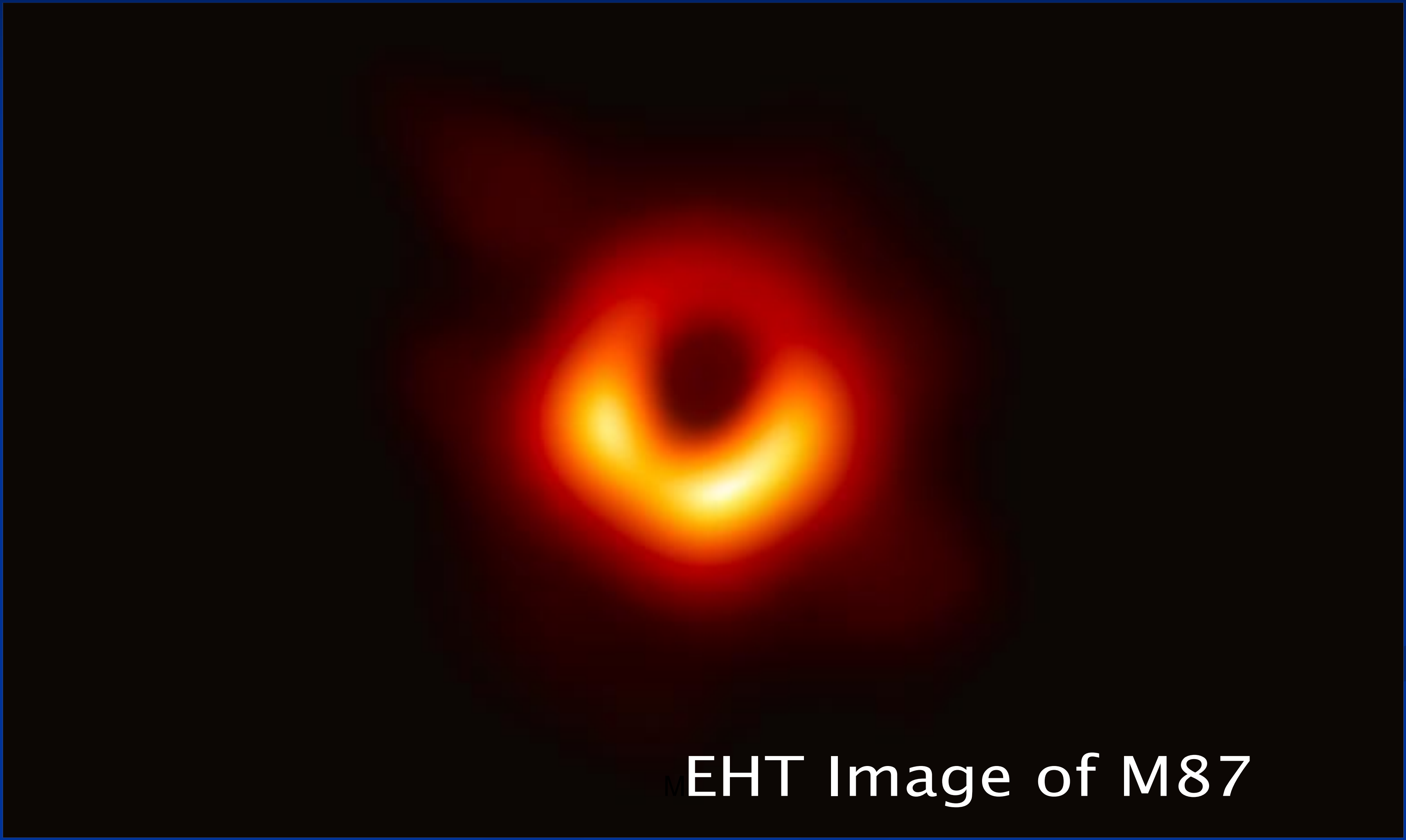
EFT with Massless Fermions provides Lagrangian framework for the rapid but continuous change in Vacuum Energy at r_M

Gravitational Vacuum Condensate Stars (Gravastars) vs. Black Holes



- Both **Echoes** and **Discrete Surface Modes—LIGO** searches
- **Very Thin Surface Layer very close to would-be horizon is consistent with EHT observation of M87 & LIGO**

Have we ‘seen’ a ‘Black Hole?’



Evidence for Event Horizon?

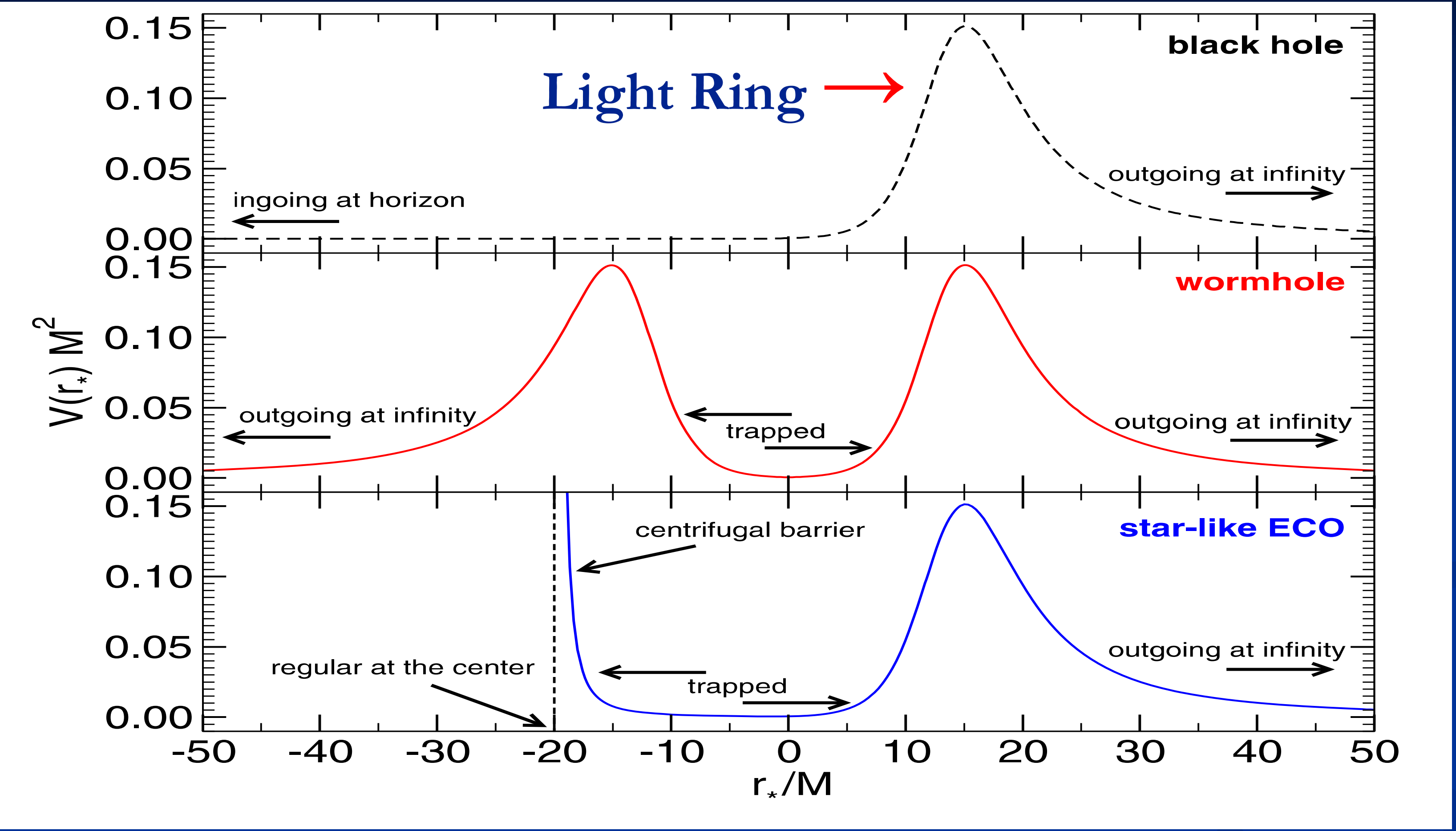
One Line of Argument:

Accretion onto compact objects (e.g. white dwarfs, NS's) results in formation of a boundary layer in which the inflow is thermalized & re-radiated. If one knows the mass accretion rate and sees no thermal radiation, there must be no surface.

This argument does not apply to gravastars since:

- **Gravastar surface is not nuclear matter supporting a photosphere like a NS as assumed**
- **Adiabatic accretion flow can be absorbed--like a BH**
- **Equilibration time scale viewed from infinity is very long**
- **Deeply red-shifted surface radiation cannot easily escape**
- **Total re-emission expected to be very small (Black body viewed through a pinhole)**

GW 'Echoes' from the Interior



Time Delay of Reflected Signal $\sim GM \ln\left(GM/\Delta r\right)$

Probes Planck scale physics if shell thickness

$$\Delta r \simeq L_{Pl} \simeq 2 \times 10^{-33}\,\mathrm{cm}$$

One way to test what's inside: GW Echoes

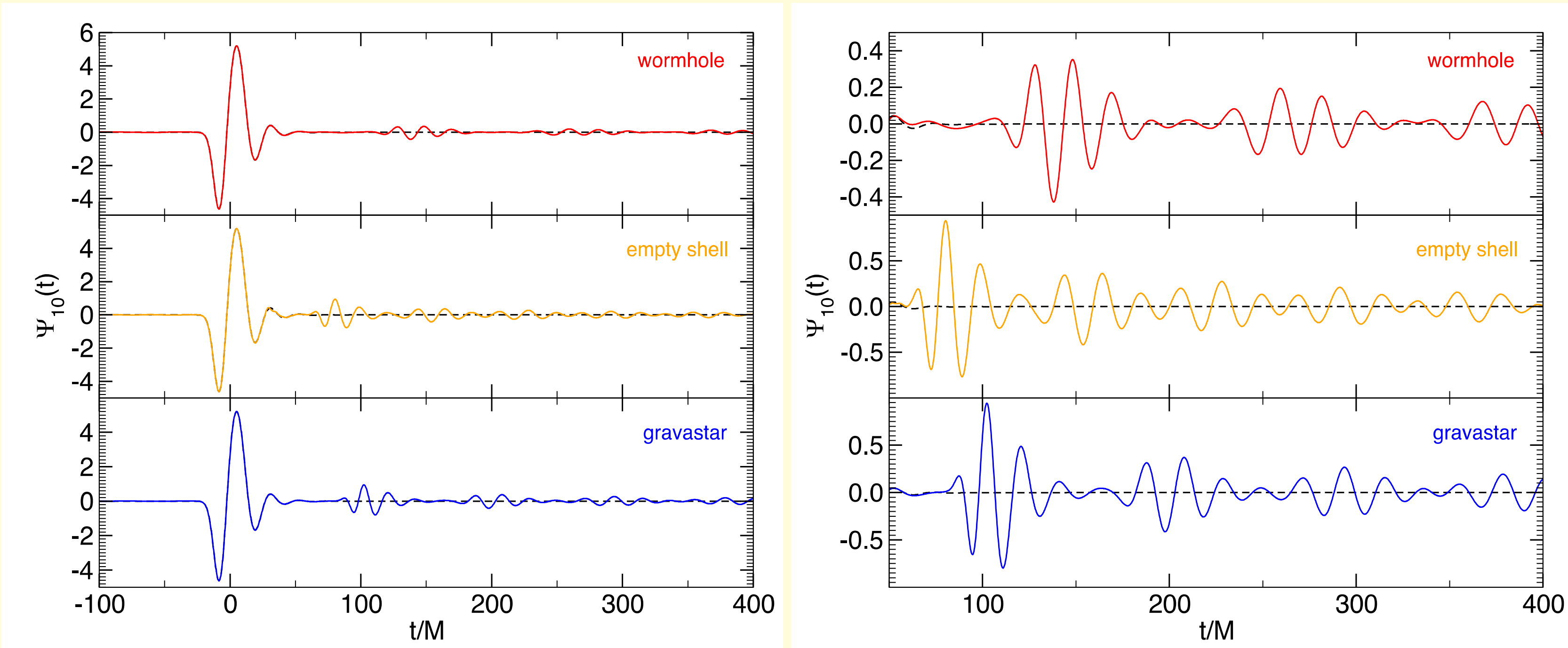


FIG. 2. Left: A dipolar ($l = 1, m = 0$) scalar wavepacket scattered off a Schwarzschild BH and off different ECOs with $\ell = 10^{-6}M$ ($r_0 = 2.000001M$). The right panel shows the late-time behavior of the waveform. The result for a wormhole, a gravastar, and a simple empty shell of matter are qualitatively similar and display a series of "echoes" which are modulated in amplitude and distorted in frequency. For this compactness, the delay time in Eq. (6) reads $\Delta t \approx 110M$ for wormholes, $\Delta t \approx 82M$ for gravastars, and $\Delta t \approx 55M$ for empty shells, respectively.

From V. Cardoso et. al. **Phys.Rev. D94 (2016) 084031**

Primary LIGO GW Ringdown signal is from Light Ring—

<u>not</u> a test of the existence of horizon

Gravitational Vacuum Condensate Stars Summary

- Area term is Classical Surface Energy **not Entropy**
- Positive Surface Tension **not Temperature**
- **Condensate Star negative pressure** already realized/inherent in Classical GR in Schwarzschild Interior Solution (1916)
- Full Non-Singular Soln. Requires Quantum EFT with the Conformal Anomaly
- Dynamical Vacuum Condensate Energy
- Regulated Finite Thickness Boundary layer
- 4-Form gauge field is the gravitational condensate (classical coherent field) changing abruptly on 3-dim. world tube
- Proposed **Cold** Quantum Final State of Gravitational Collapse
- QM, Unitarity **No 'Information Paradox'**
- Full EFT makes possible quantitative predictions for GWs

New Horizons in GR: Quantum Black 'Holes'

- Classical Black Holes have unphysical interiors
- The tension between General Relativity and Quantum Mechanics & Statistical Physics in BHs leads to a 'Crisis in Physics' similar to c. 1900
- Quantum Effects are computable & relevant at Macroscopic Distances & at Event Horizons
- Quantum Effective Theory of Gravity predicts a Quantum Phase Transition at the Event Horizon of a Black 'Hole'
- Interior is a non-singular Dark Energy Condensate (GBEC)

Gravitational Condensate Stars resolve all 'black hole' paradoxes ⇒ **GW** predictions of gravastars

General Relativity & Quantum Theory Reconciled