Title: Whatâ€™s the Matter with Black Holes? Gravitational Condensate Stars & New Horizons in the LIGO Era

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Abstract: <p>Conventional equations of state suggest that in complete gravitational collapse a singular state of matter with infinite density could be reached finally to a black hole, the characteristic feature of which is its apparent horizon, where light rays are first trapped. The loss of information to the outside world this implies gives rise to serious difficulties with well-established principles of quantum mechanics and statistical physics.</p>

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<p>The formation of a gravitational vacuum condensate star with a p=âˆ’Ï• interior solves these problems and remarkably, actually follows from Schwarzschild's second paper over a century ago. The surface tension of the condensate star surface is the difference of equal and opposite surface gravities between the exterior and interior Schwarzschild solutions. The First Law is then recognized as a purely mechanical classical relation at zero temperature and zero entropy. The Schwarzschild time of such a non-singular gravitational condensate star is a global time, fully consistent with unitary time evolution in quantum theory.</p>

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<p>The advent of BH imaging by the EHT and Gravitational Wave Astronomy with LIGO should allow for observational tests of the gravastar hypothesis, particularly in the discrete surface modes of oscillation and GW resonances or â€œechoes,â€• which may be observable by advanced LIGO and successor GW detectors.</p>

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

Gravitational Condensate Stars & New Horizons in the LIGO Era

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w. P. O. Mazur, Class. Quant. Grav. 32, 215024 (2015)

Review: Acta Phys. Pol. B 41, 2031 (2010)

Outline

- Classical Black Holes in General Relativity
- Black Holes & Quantum Mechanics: The Paradoxes
  - Temperature & the 'Trans-Planckian Problem'
  - Entropy & the Second Law of Thermodynamics
  - Negative Heat Capacity & the 'Information Paradox'
- Solution inherent in Schwarzschild's Interior Soln. (1916)
  - Constant $p = -\rho$ vacuum interior—no singularity, Zero Entropy
  - Surface gravity is surface tension
- Gravitational Vacuum Condensate Stars
  - Macroscopic Effect of Standard Model Physics
  - Dynamical Vacuum = gravitational Bose-Einstein Condensate
- Astrophysical Tests of Gravastars
  - Gravitational Wave Spectroscopy
  - VLBI Imaging with Event Horizon Telescope

Classical Black Holes

Schwarzschild Metric (1916)

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

$$-g_{tt} = f(r) = 1 - \frac{2GM}{r} = h(r) = g^{rr}$$

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 $h = 0$

And iff $T_{\mu\nu} = 0$ on the horizon

Mathematical Black Holes

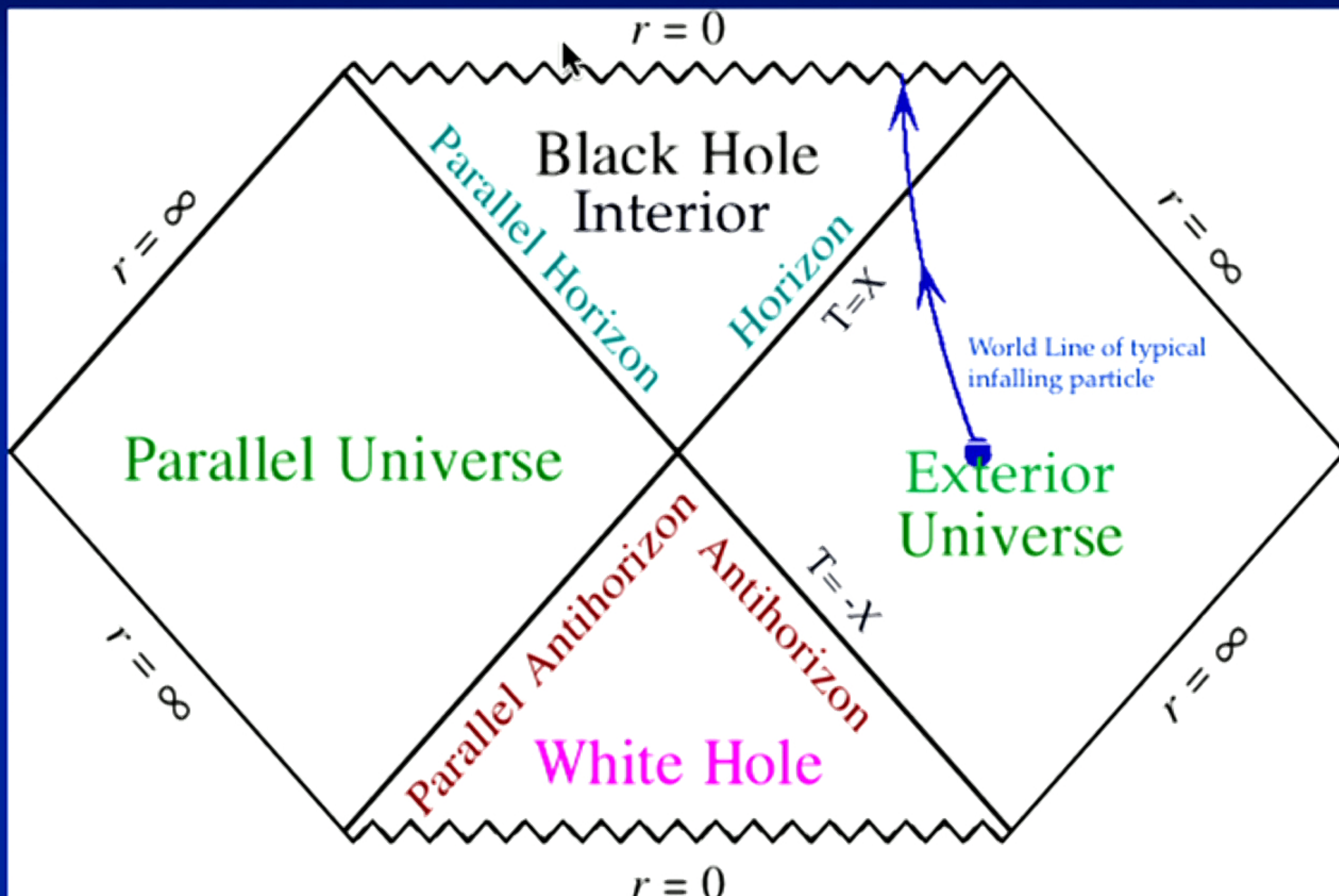
- Classical Matter reaches the Horizon in Finite Proper Time
- The Local Riemann Tensor Field Strength
  & its Contractions remain Finite at $r=2GM$
- Kruskal-Szekeres Coordinates (1960) $(G/c^2 = 1)$

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

- Future/Past Horizon at $r = 2GM$ is $T = \pm X$ Regular
- Kruskal coordinates analytically continue inside $r < 2GM$
  all the way to $r = 0$ singularity
- Involves complex analytic continuation of coordinates

Schwarzschild Maximal Analytic Extension

Carter-Penrose Conformal Diagram



Rotating Black Holes

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

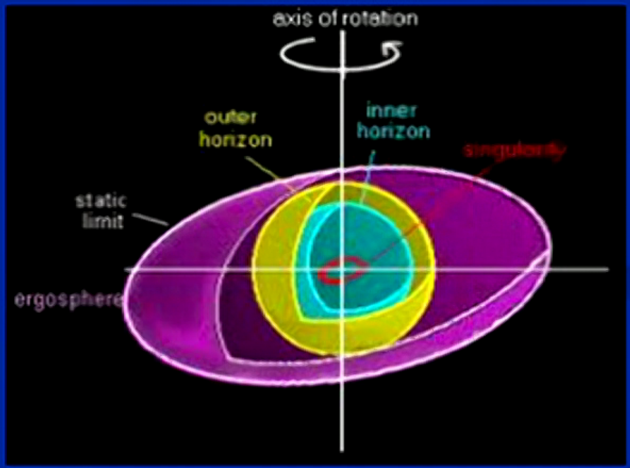
Roy Kerr, circa 1975

In 1963, Roy Kerr gave an exact (analytic) solution for a rotating black hole.

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

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

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

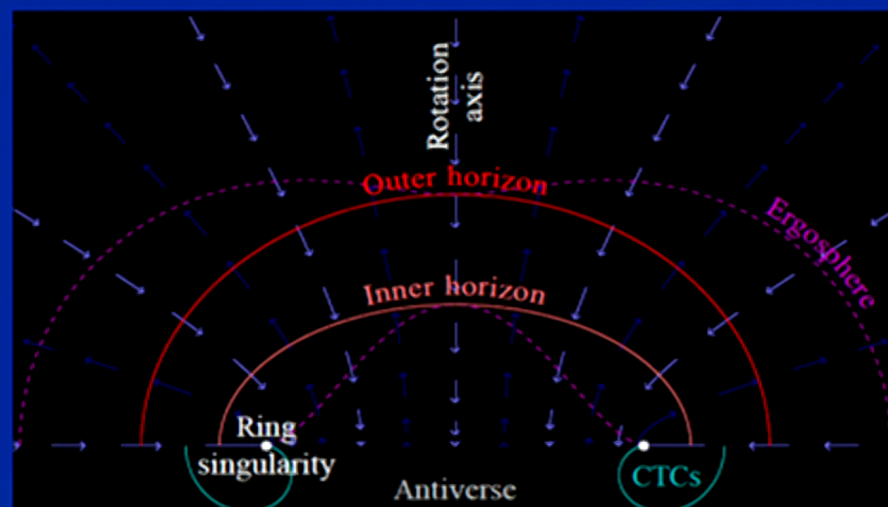


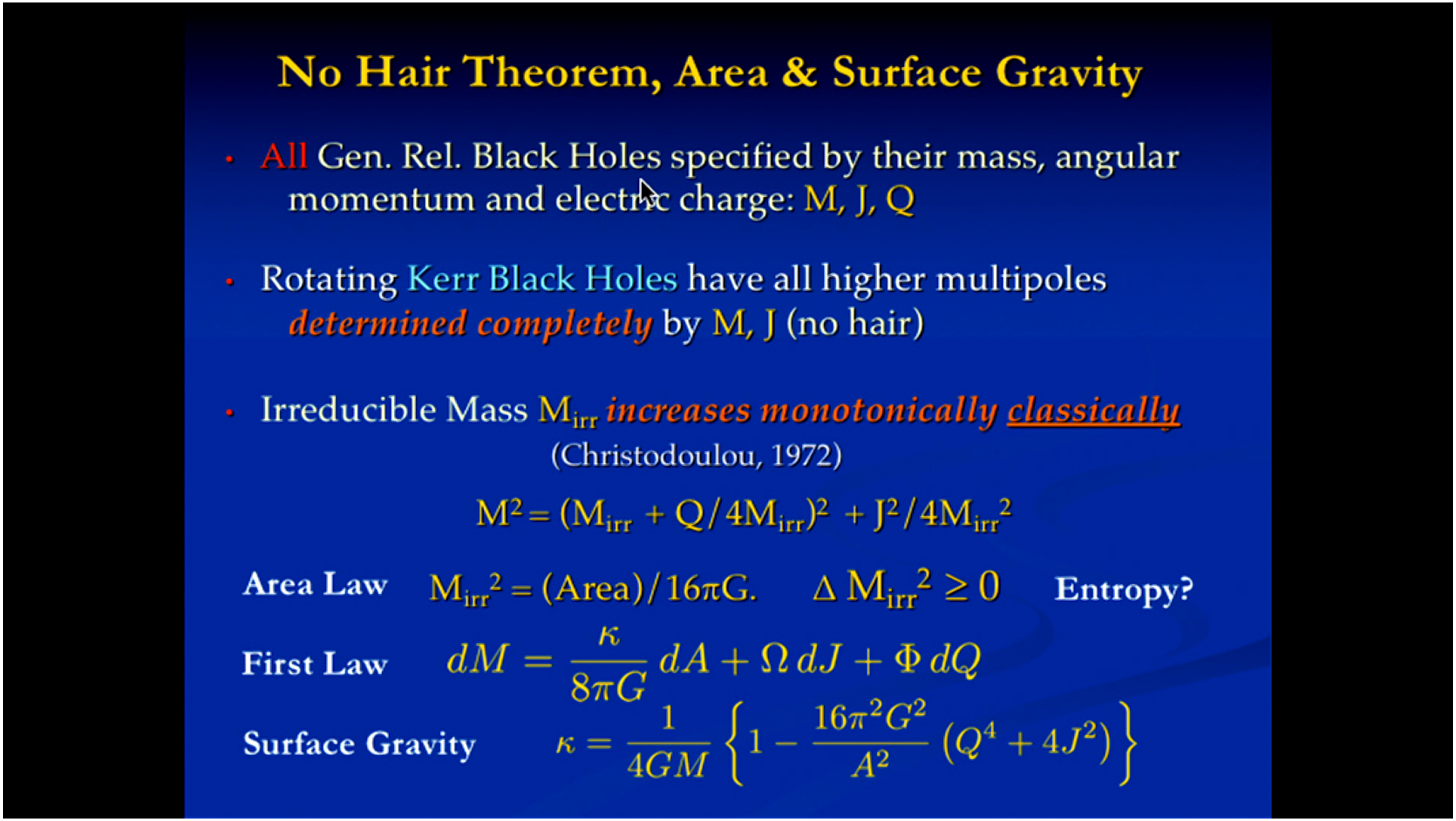
Mathematical Kerr Black Hole Interiors

- More singularities
- More universes
- Closed Timelike Curves:

(say hello to your greatgrandparents)

More unphysical interior, even classically




No Hair Theorem, Area & Surface Gravity
All Gen. Rel. 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)
$M^2 = (M_{irr} + Q/4M_{irr})^2 + J^2/4M_{irr}^2$
Area Law $M_{irr}^2 = (\text{Area})/16\pi G.$ $\Delta M_{irr}^2 \geq 0$ Entropy?
First Law $dM = \frac{\kappa}{8\pi G} dA + \Omega\, dJ + \Phi\, dQ$
Surface Gravity $\kappa = \frac{1}{4GM}\left\{1 - \frac{16\pi^2 G^2}{A^2}(Q^4 + 4J^2)\right\}$

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 disappears into the black hole, what happens to its entropy? (Only **M, J, Q** remain)

- Is horizon area **A** (which always increases) a kind of "entropy"?

  To get units of entropy need to divide **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 $\mathbf{S_{BH} = \gamma\, k_B\, A/\ell_{Pl}^2}$ with $\gamma \sim O(1)$
- Hawking (1974) then argued black holes emit thermal radiation at

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

The **classical** relation $dE = \kappa\, dA/8\pi G$ is then **thermal/quantum**

$dE = T_H\, dS_{BH}$ & fixes $\gamma = \frac{1}{4}$: multiply & divide by $\hbar$ k_B

But a few problems still remained…

No Hair Theorem, Area & Surface Gravity

- All Gen. Rel. 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)

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

- $\hbar$ cancels out of $dE = T_H\, dS_{BH}$: Quantum or Classical?
- T_H requires trans-Planckian frequencies at the horizon
- In the classical limit $T_H \to 0$ **(cold)** but $S_{BH} \to \infty$ (?)
- $S_{BH} \propto A$ is non-extensive and **HUGE**
- $E \propto T^{-1}$ implies <u>negative</u> heat capacity: $\langle (H-E)^2 \rangle < 0$ (?)

  $\frac{dE}{dT} << 0$ $\Rightarrow$ highly <u>unstable</u>

  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: $\mathbf{S = k_B \ln W}$ **?**

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S = k log W
LVDWIG
BOLTZMANN
1844 – 1906
HENRIETTE
BOLTZMANN
ARTHUR
BOLTZMANN
LVDWIG
BOLTZMANN

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 $$S \sim k_B\,(M/M_{Pl})^{3/2}$$ ← *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

Horizon in Quantum Theory

- Infinite Blueshift Surface

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

No problem classically, but in quantum theory,

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

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

Singular coordinate transformations need not be harmless (e.g. Vortices)

- Large local energies must be felt by the gravitational field
- Trans-Planckian energies in conflict with semi-classical fixed background metric approximation
- Large local energy densities/stresses are generic near the horizon

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

Geometry may be changed near $r = 2GM$ **Non-local effect of the state**

Quantum Backreaction may be very large there

Black 'Holes'… or Not

Black Holes believed 'inevitable' in General Relativity but

- Difficulties reconciling Black Holes with Quantum Mechanics
  - Hawking Temperature & the 'Trans-Planckian Problem'
  - Entropy & the Second Law of Thermodynamics
  - Negative Heat Capacity & the 'Information Paradox'
- Singularity Theorems assume Trapped Surface & Energy Conditions: Strong Energy Condition

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

Violated by Quantum Fields, e.g. by Casimir Effect & Hadron 'Bag', Cosmological Dark Energy, Inflation V(φ):

Negative Pressure $p_i = -\rho < 0$ Effective **Repulsion**

Bose-Einstein Condensation

- Bose-Einstein statistics imply any number of particles can occupy the same single particle state.
- At high enough densities and/or low enough temperatures a finite fraction of all the particles are in the lowest energy (ground) state.
- This tendency of bosons to condense takes place in the absence of interactions or even with (not too strong) repulsive interactions. Attractive interactions make it all the more favorable.
- Bose-Einstein Condensation is a generic macroscopic quantum phenomenon, observed in Superfluids, ^4He (even ^3He by fermion pairing), Superconductors, and Atomic Gases, ^{87}Rb.
- Relativistic Quantum Field Theory exhibits a similar phenomenon in Spontaneous Symmetry Breaking, in both the strong and electroweak interactions $\langle \bar{q}q \rangle \neq 0 \quad \langle \Phi \rangle \neq 0$.

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,
  $$p_V = -\rho_V = -V(\phi) \quad \text{as in inflation}$$
- 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 **dynamical**

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

Gravitational Vacuum Condensate Star Proposed (2001)

Today: Realization in Schwarzschild Soln II (1916)

Static, Spherical Symmetry

- **2 Metric Fns.**

$$f(r),\ h(r) \equiv 1 - \frac{2Gm(r)}{r}$$ ← **Misner-Sharp Mass**

- **3 Stress Tensor Fns.**

$$T^{\mu}{}_{\nu} = \begin{pmatrix} -\rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p_\perp & 0 \\ 0 & 0 & 0 & p_\perp \end{pmatrix}$$

- **2 Einstein Eqs.**

$$\frac{dm}{dr} = 4\pi\, r^2 \rho \qquad \frac{h}{2f}\frac{df}{dr} = \frac{Gm}{r^2} + 4\pi G p r$$

- **1 Conservation Eq.**

$$\nabla_\mu T^{\mu}{}_{r} = \frac{dp}{dr} + \frac{\rho + p}{2f}\frac{df}{dr} + \frac{2\,(p - p_\perp)}{r} = 0$$

Buchdahl Bound (1959)

Assuming classical Einstein eqs. &

- Static Killing time: $$K^\mu \frac{\partial}{\partial x^\mu} = \frac{\partial}{\partial t}$$
- Spherical Symmetry:

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

- Isotropic Pressure: $$p_i = p(r)$$
- Positive Monotonically Decreasing Density: $$\frac{d\rho}{dr} \leq 0$$
- Metric Continuity at Surface of Star r=R
- Then $$R > \tfrac{9}{8} R_s = \tfrac{9}{4}\, GM$$

or the pressure must diverge in the Interior
before horizon is reached Critical case: $\rho' = 0$

Importance of Buchdahl Bound

Schwarzschild Interior

- Constant Density $m(r) = \frac{4\pi}{3}\rho r^3 = \frac{M}{R^3} r^3$

$$\rho' = 0 \qquad h(r) = 1 - H^2 r^2$$

Saturates Buchdahl Bound

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

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

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

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

$$f(r) = D^2/4 \qquad h(r) = 1 - R_s r^2/R^3$$

Buchdahl Bound (1959)

Assuming classical Einstein eqs. &

- Static Killing time: $$K^\mu \frac{\partial}{\partial x^\mu} = \frac{\partial}{\partial t}$$
- Spherical Symmetry:

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Critical case: $\rho' = 0$

Importance of Buchdahl Bound

- Under **Adiabatic Compression** Something Happens
  Inside the star–
- Before a Black Hole Event Horizon is Formed
- Bound is Saturated by Schwarzschild Interior Soln. (1916)
- Constant Density $\rho(r) = \bar{\rho} \equiv \frac{3M}{4\pi R^3}$
- Solve for Pressure *p(r)*:

$$p(r) + \bar{\rho} = 2\,\bar{\rho}\,\frac{\sqrt{1 - R_s/R}}{D}$$

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

$$f(r) = D^2/4 \quad h(r) = 1 - R_s r^2/R^3$$

Schwarzschild Interior

- **Constant Density** $m(r) = \frac{4\pi}{3}\bar{\rho} r^3 = \frac{M}{R^3} r^3$

  $\rho' = 0$

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

  Saturates

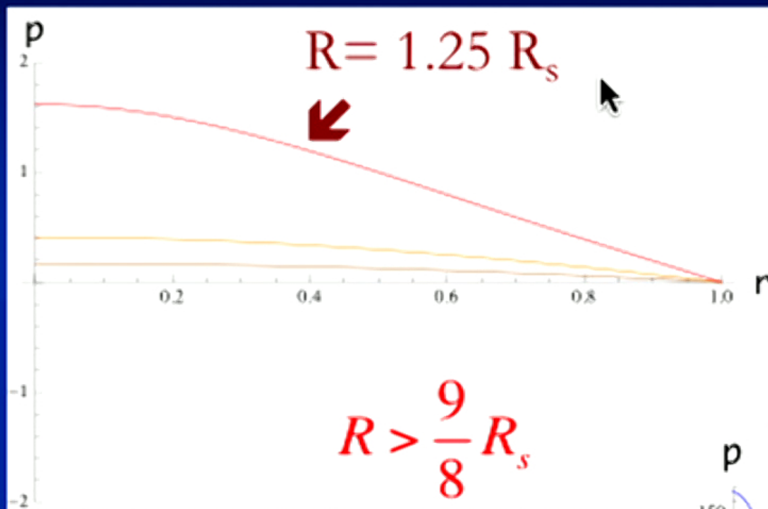
  Buchdahl Bound $H^2 = \frac{8\pi G}{3}\bar{\rho} = \frac{2GM}{R^3}$

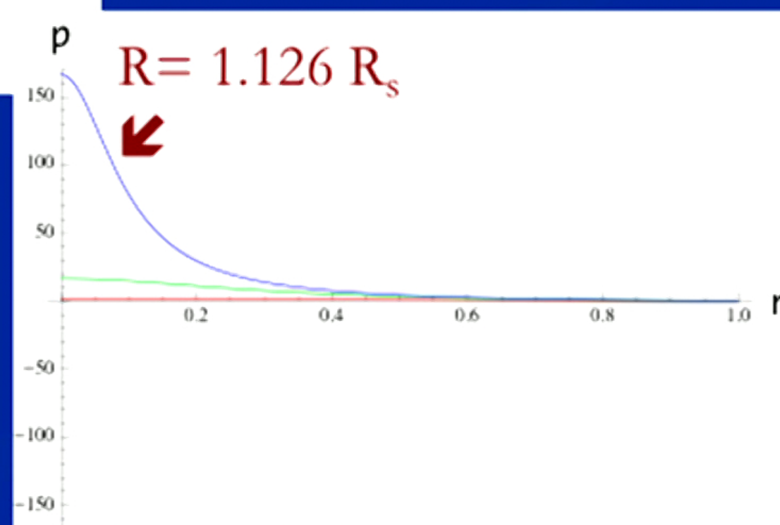
- **Pressure** $p(r) = \bar{\rho}\left[\frac{\sqrt{1 - H^2 r^2} - \sqrt{1 - H^2 R^2}}{3\sqrt{1 - H^2 R^2} - \sqrt{1 - H^2 r^2}}\right]$

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

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

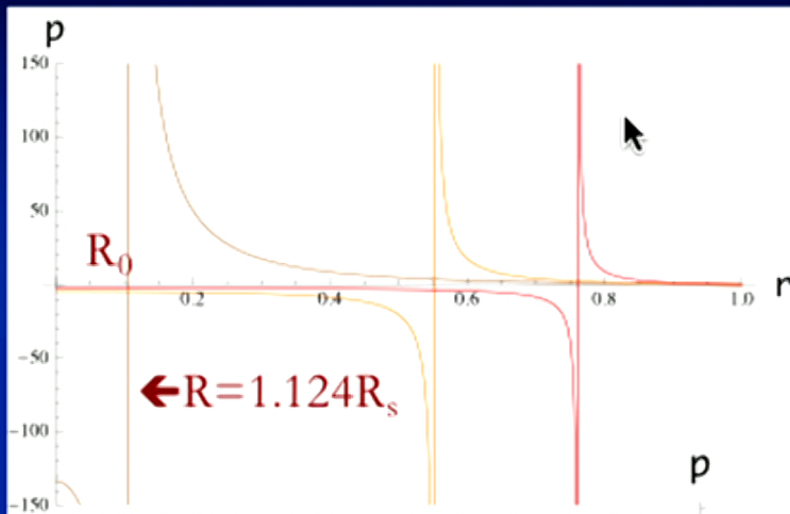
Interior Pressure





As R → 9/8 R_s from above
central pressure diverges

Interior Pressure

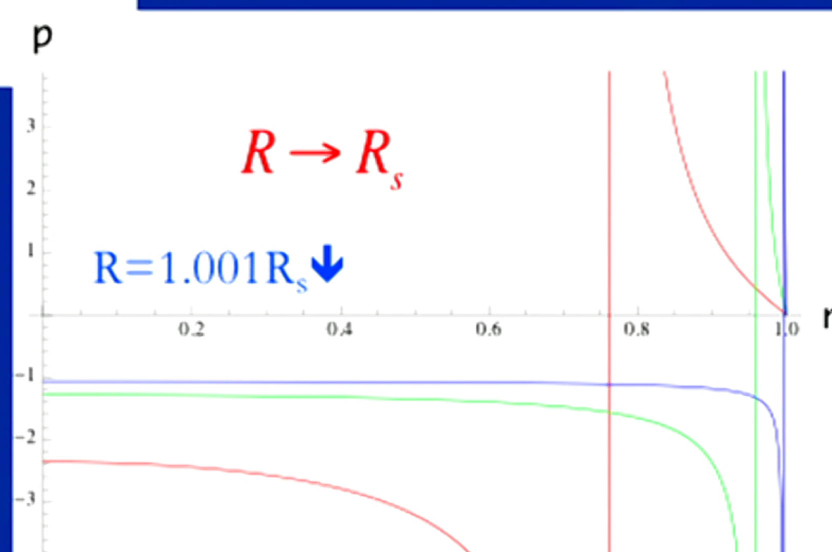


$$R < \frac{9}{8} R_s$$

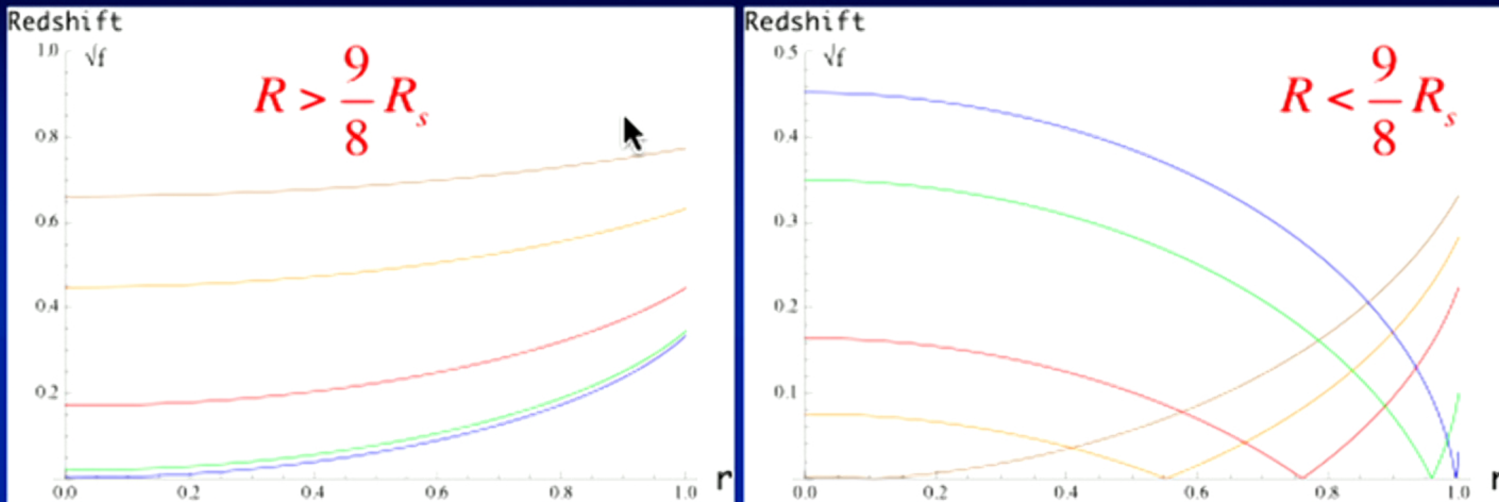
Negative Pressure soln. opens up for $R < R_0$

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



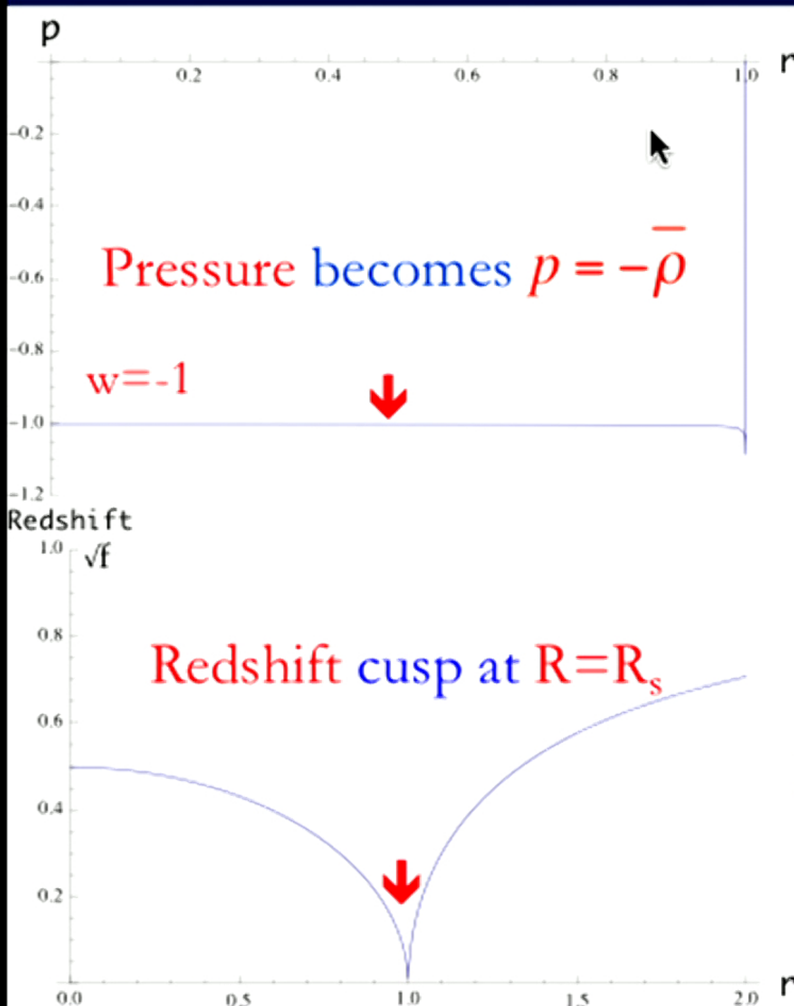
$f(r) = \frac{1}{4} D^2 \geq 0$ Non-negative (no horizon)

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

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)

Komar Mass-Energy Flux (1959-62)

$$\frac{1}{G}\frac{d}{dr}\left(r^2\kappa\right) = 4\pi\sqrt{\frac{f}{h}}\,r^2\left(\rho + p + 2p_\perp\right)$$

$$\kappa(r) = \frac{1}{2}\sqrt{\frac{h}{f}}\,\frac{df}{dr} \to \frac{GM}{r^2}$$ Surface Gravity

Total Mass: Compare Gauss' Law

$$M = 4\pi\int_0^{R_s} dr\,\sqrt{\frac{f}{h}}\,r^2\left(\rho + p + 2p_\perp\right)$$

Transverse Pressure

Cusp in Redshift produces Transverse Pressure

$$r\frac{d}{dr}\left[(p+\bar{\rho})f^{\frac{1}{2}}\right] = 2\,(p_\perp - p)f^{\frac{1}{2}}$$

Localized at $r = R_0$

$$8\pi\sqrt{\frac{f}{h}}\;r^2\,(p_\perp - p) = \frac{8\pi}{3}\,\bar{\rho}\,{R_0}^3\,\delta(r-R_0)$$

Integrable Surface Energy

$$E_s = \frac{8\pi}{3}\,\bar{\rho}\,{R_0}^3 = 2M\left(\frac{R_0}{R}\right)^3 \to 2M$$

$$M = E_v + E_s$$

Surface Tension

Discontinuity in Surface Gravities

$$\kappa_{\pm} \equiv \lim_{r \to R_0^{\pm}} \kappa(r) = \pm \frac{4\pi G}{3} \bar{\rho}\, R_0$$

$$\Delta\kappa \equiv \kappa_{+} - \kappa_{-} = \frac{R_s R_0}{R^3} \to \frac{1}{R_s}$$

is (redshifted) surface tension

$$\tau_s = \frac{E_s}{2A} = \frac{\Delta\kappa}{8\pi G} \to \frac{1}{8\pi G R_s} > 0$$

Interior is not analytic continuation of exterior

First Law

Classical Mechanical Conservation of Energy

$$dM = dE_v + \tau_s \, dA$$

Gibbs Relation

$$p + \rho = s\,T + \mu\,N = 0$$

Schw. Interior Soln. in $R \rightarrow R_s$ Limit describes a **Zero Entropy/Zero Temperature Condensate**

Discontinuity in κ implies non-analytic behavior

No horizon, Truly Static, **t** is a Global Time

Surface Area is Surface Area not Entropy
Surface Gravity is Surface Tension not Temperature

Rindler-like $\mathcal{C}^1$ Coordinates

$$ds^2 = -\frac{\xi^2}{4R_s^2}\,dt^2 + q^2(\xi)\,d\xi^2 + r^2(\xi)\,d\Omega^2$$

$$q(\xi) = \begin{cases} \dfrac{R_s}{r} = \left(1 - \dfrac{\xi^2}{R_s^2}\right)^{-\frac{1}{2}} & -R_s < \xi \leq 0 \\[2ex] \dfrac{r^2}{R_s^2} = \left(1 - \dfrac{\xi^2}{4R_s^2}\right)^{-2} & 0 \leq \xi < 2R_s \end{cases}$$

Surface is at $\xi = 0$ $\quad \xi^2 \geq 0 \quad$ ξ remains real

Generalizes Israel Jcn. Condition to Null Boundary

Faithful to Einstein Equivalence Principle as originally conceived for real coordinate transformations

Surface Oscillations

$$dM = dE_v + \tau_s \, dA$$

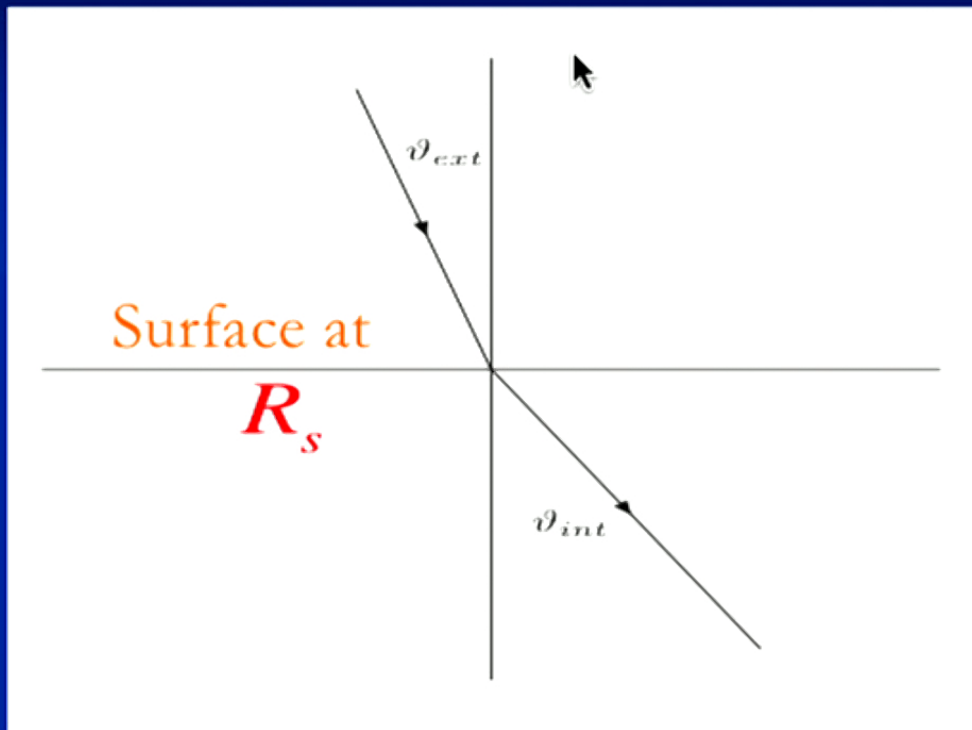
- Energy Minimized by minimizing A for fixed Volume
- Surface Tension acts as a restoring force
- Surface Oscillations are **Stable**
- Surface Normal Modes are **Discrete**
- Characteristic Frequency

$$\omega \sim \frac{c}{4\pi R_s} = 8.1 \left(\frac{M_\odot}{M}\right) \text{kHz}$$

- **Discrete Gravitational Wave Spectrum**
- Striking Signature for LIGO/VIRGO if

$$M \sim 10^{1-2} M_\odot$$

Refraction of Null Rays at Surface



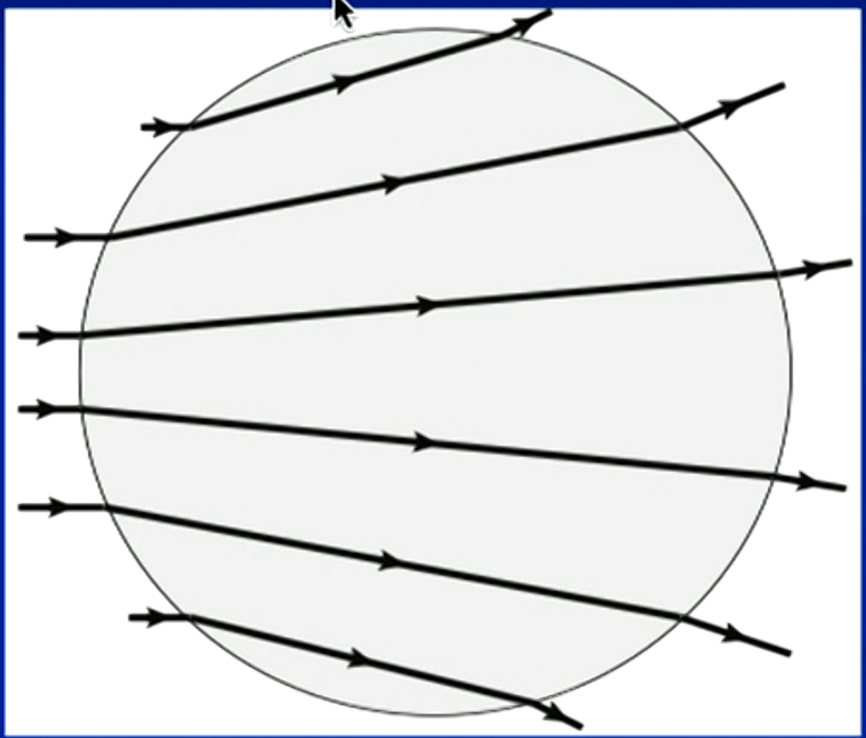
Solve
Geodesic Eq.
➔ Snell's Law
$n < 1$

Impact
Parameter
b

$$\sin\vartheta_{ext}\sqrt{1+\frac{4R_s^2}{b^2}} = \sin\vartheta_{int}\sqrt{1+\frac{R_s^2}{b^2}}$$

Defocusing of Null Rays

No Horizon ➔ Light Rays Penetrate Interior



Different Imaging from a Black Hole

Summary of Interior Schwarzschild

- Buchdahl Bound ➔ Under Adiabatic Compression Interior Pressure Divergence Develops **before** Event Horizon Forms for any EoS $R > \frac{9}{8} R_s = \frac{9}{4} GM$
- Constant Density Interior Schwarzschild Solution **Saturates Bound** & shows the generic behavior:
- Infinite Redshift at the Central Pressure Divergence
- But gives **Integrable Komar Energy**
- Implies Formation of a **δ-fn.** Surface & **Surface Tension** (Transverse Pressure)
- A Non-Singular (de Sitter $p = -\rho$) Interior

Remarks

- Non-Analyticity Characteristic of a Phase Boundary
  Freezing of Time ➔ Critical Slowing Down
  $$-g_{tt} = -K_\mu K^\mu = f(r) = c_{eff}^2 \geq 0$$
- K_μ is everywhere timelike: Hamiltonian exists & is Hermitian w. proper b.c. at 0 and ∞
- Stationary State boundary conditions: No Hawking Flux
- Significant Backreaction when $f(r) \geq \epsilon \sim \frac{L_{pl}}{R_s}$
- Occurs at Physical Length $\ell \sim \frac{\Delta r}{\sqrt{h(r)}} \sim \sqrt{L_{pl} R_s}$
- Time delay $\sim R_s \ln(\varepsilon)$
- Regulated by finite ε

Gravitational Condensate Stars

- Area term is Classical **Mechanical Surface Energy** **not Entropy**
- QM, Unitarity ✓ **No 'Information Paradox'**
- **Condensate Star negative pressure** already realized/
  inherent in Classical General Relativity
  in Schwarzschild Interior Solution (1916)
- **Cold** Coherent **Final State** of Gravitational Collapse
- Dynamical Vacuum Condensate Energy
- Regulated Finite Thickness Boundary layer
- Full Non-Singular Soln. Requires Quantum
  Effective Theory of the Conformal Anomaly

Gravitational Wave Resonances "Echoes"

- Different b. c. on surface from BH Horizon
- Transmission (with time delay) through surface
- Use Regge-Wheeler radial coordinate

$$dr^* = \frac{dr}{\sqrt{fh}}$$

- Scalar Wave or Grav. Wave Eq. gives

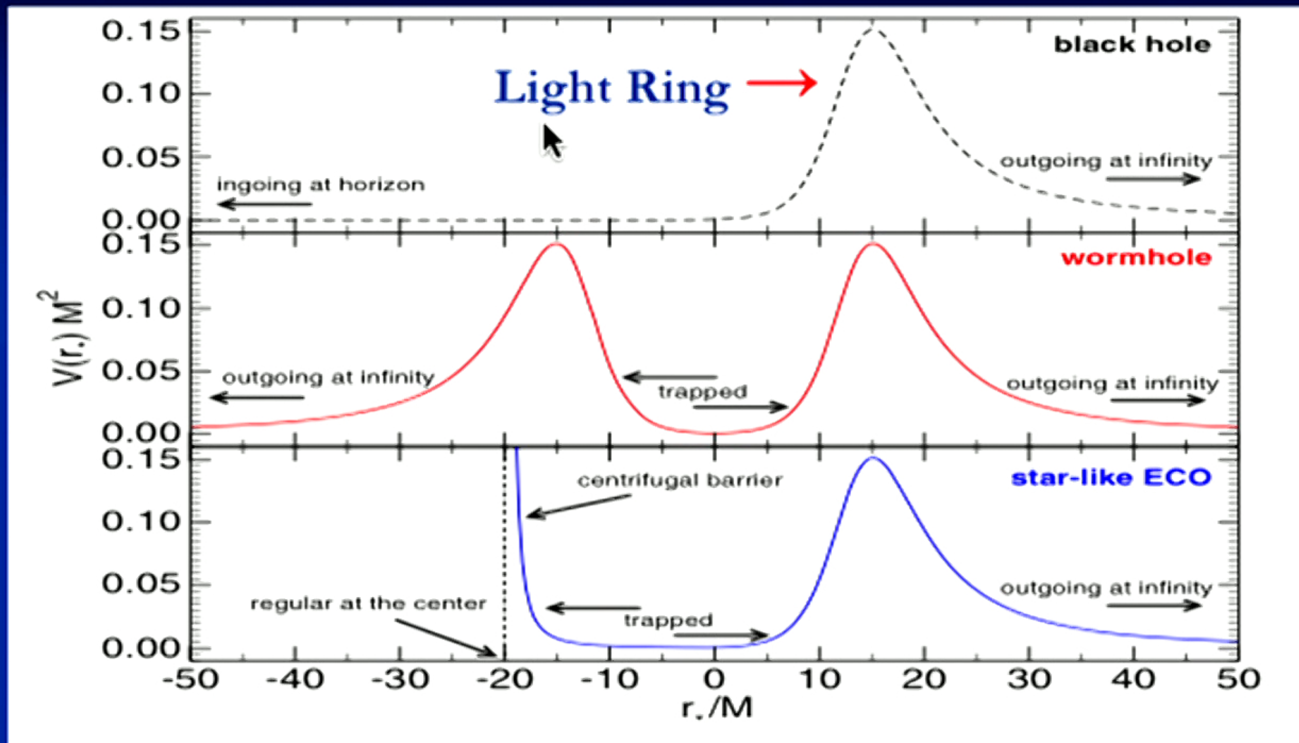
$$\left(-\frac{d^2}{dr^{*\,2}} + V_\ell\right)\phi_{\omega\ell} = \omega^2\phi_{\omega\ell}$$

- Resonant reflection from de Sitter interior barrier: 'Echo'

$$V_\ell = \left(1 - \frac{2M}{r}\right)\left(\frac{\ell(\ell+1)}{r^2} + m^2 + \frac{2M}{r^3}\right) \qquad r > 2M$$

$$V_\ell = \frac{1}{4}\left(1 - H^2r^2\right)\left(\frac{\ell(\ell+1)}{r^2} + m^2 - 2H^2\right) \qquad r < H^{-1} = 2M$$

GW 'Echoes' from the Interior



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

Probes Planck scale physics if shell thickness

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

GW Echoes from ECOs

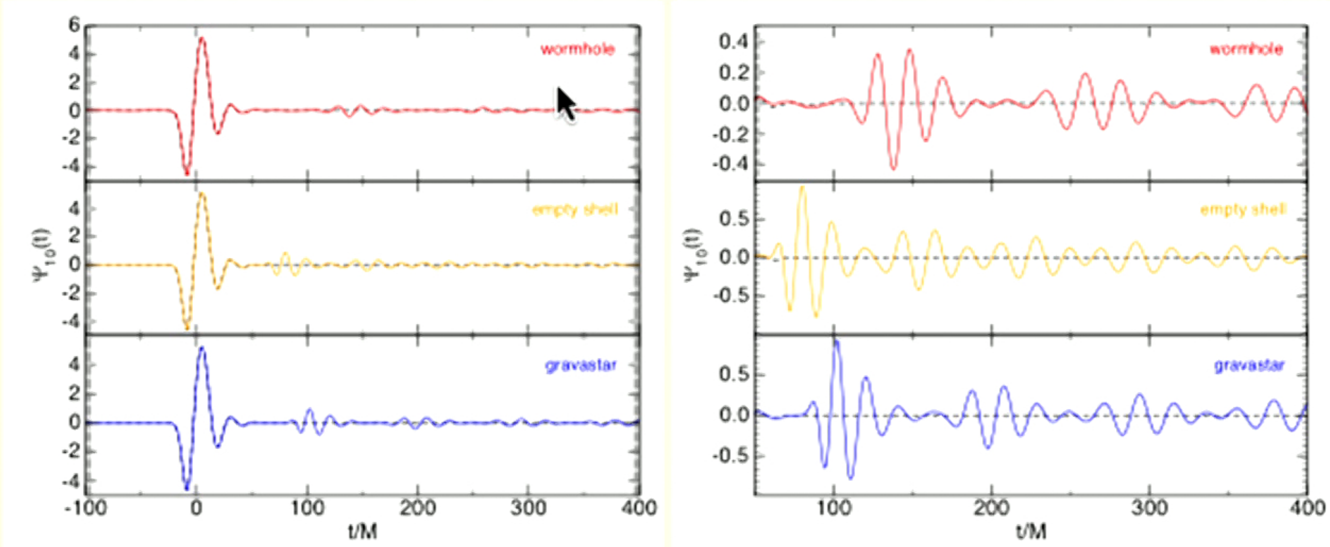


FIG. 2. Left: A dipolar ($l = 1, m = 0$) scalar wavepacket scattered off a Schwarzschild BH and off different ECOs with $\ell = 10^{-6}M$ ($r_0 = 2.000001M$). The right panel shows the late-time behavior of the waveform. The result for a wormhole, a gravastar, and a simple empty shell of matter are qualitatively 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 an horizon

Have GW Echoes been seen by LIGO?

"…tentative evidence for Planck-scale structure near black hole horizons at false detection probability of 1% (corresponding to 2.5σ significance level)."

J. Abedi et. al. **Phys. Rev. D96 (2017) 082004**

Independent analysis by LIGO:

"…reduced statistical significance… ~ 1.5σ

"consistent with noise"

J. Westerweck, et. al. **Phys. Rev. D97 (2018) 124037**

Perimeter Conference, Nov. 8-10, 2017

https://www.perimeterinstitute.ca/conferences/quantum-black-holes-sky **Bottom Line: Not ruled out, only more data will tell**

More data Black Hole Spectroscopy arXiv:1805.00293 is coming

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 expected thermal radiation, there must be no surface.

<u>This argument does not apply to gravastars since:</u>

- **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)**

New Horizons in Gravity

Gravastars as Astrophysical Objects

- Cold, Dark, Compact, Arbitrary M, J
- Accrete Matter just like a black hole
- But matter does not disappear down a 'hole'
- Relativistic Surface Layer can re-emit radiation
- Can support Electric Currents, Large Magnetic Fields
- Possibly more efficient central engine for Gamma Ray Bursters, Jets, UHE Cosmic Rays
- Formation should be a violent phase transition converting gravitational energy and baryons into HE leptons and entropy
- Interior could be completely non-singular **dynamical condensate**
- **Dark Energy = Condensate** -- **Finite Size effect** of boundary conditions at the horizon ➔ Implications for Cosmology

- <u>Gravitational Condensate Stars</u> resolve all 'black hole' paradoxes
- **<u>Discrete</u> Grav. Wave Signatures of Surface Modes**
- **Imaging** mm/sub-mm by Event Horizon Telescope

Much to be done