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

Quantum Effects near Black Hole Horizons & the Non-Singular Endpoint of Gravitational Collapse

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

w. R. Vaulin, *Phys. Rev. D* 74, 064004 (2006)

w. P. Anderson & R. Vaulin, *Phys. Rev. D* 76, 024018 (2007)

Review Article: w. I. Antoniadis & Mazur, *N. Jour. Phys.* 9, 11 (2007)

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

w. M. Chandra, G.M. Manca & E. Sorkin, (2013) to appear

Outline

- Classical Black Holes in General Relativity
- The Problems reconciling Black Holes with Quantum Mechanics
  - Entropy & the Second Law of Thermodynamics
  - Temperature & the 'Trans-Planckian Problem'
  - Negative Heat Capacity & the 'Information Paradox'
  - Update on Recent 'Firewall' Controversies
- Effective Theory of Low Energy Gravity
  - New Scalar Degrees of Freedom
  - Conformal Phase Transition
  - Near Horizon Boundary Layer
- Gravitational Vacuum Condensate Stars
- Astrophysical Observations and Tests

Gravitational Collapse -- Why Black Holes?

- Gravitational force is weak but it is cumulative
  Nothing can shield it
- If matter is sufficiently compressed it heats up and produces nuclear reactions becoming a star
- But nuclear fusion of H to He is eventually exhausted, and after burning through heavier elements, collapse must resume
- For some stars this leads to white dwarf status -- cool and dim, held up by their electrons' quantum degeneracy pressure
- Often the collapse is catastrophic and results in a supernova
- The central object left behind if not too massive can be a neutron star -- held up by neutrons' quantum degeneracy pressure
- But if $M > 3\text{-}4\ M_{sun}$ there is no known matter eq. of state stiff enough to stop further collapse -- Gravity wins in the end

Classical Black Holes

Schwarzschild Metric (1916)

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

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

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

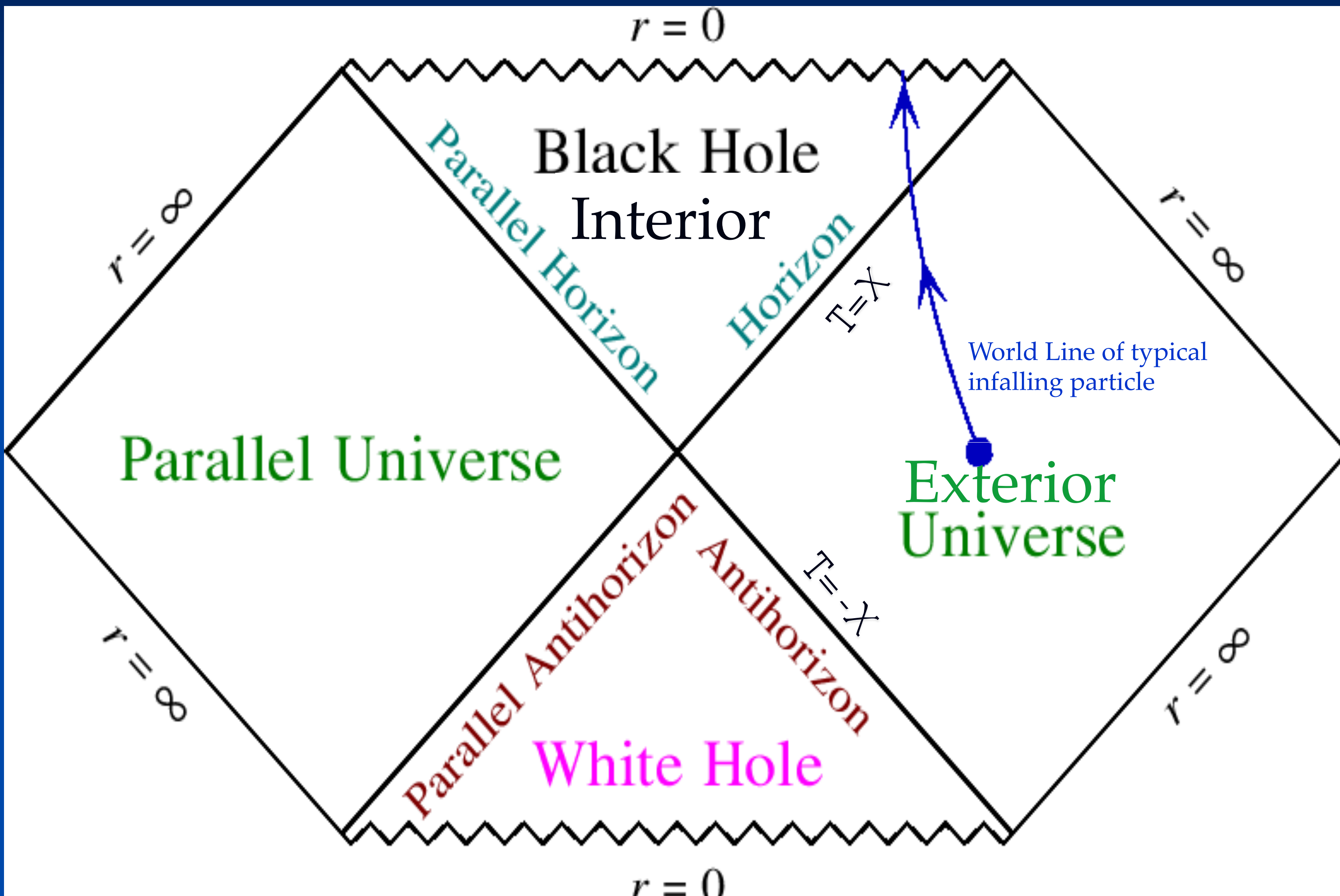
  & its Contractions remain Finite at $r=2GM/c^2$
- Kruskal-Szekeres Coordinates (1960) $(G/c^2 = 1)$

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

- 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



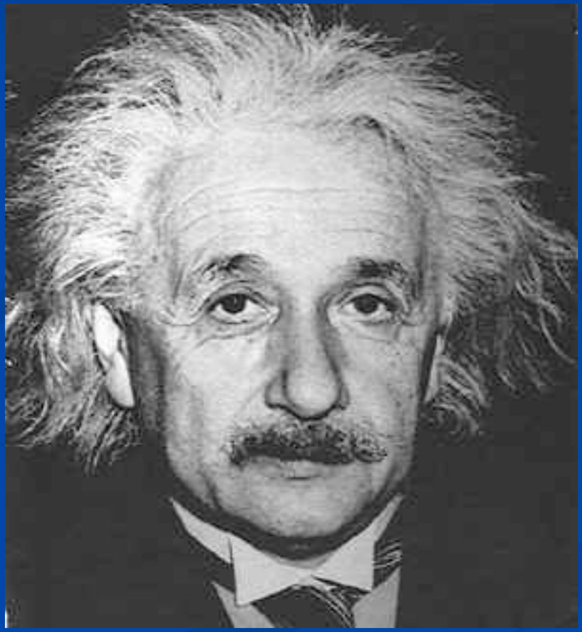
Mathematical Black Hole Interiors

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)

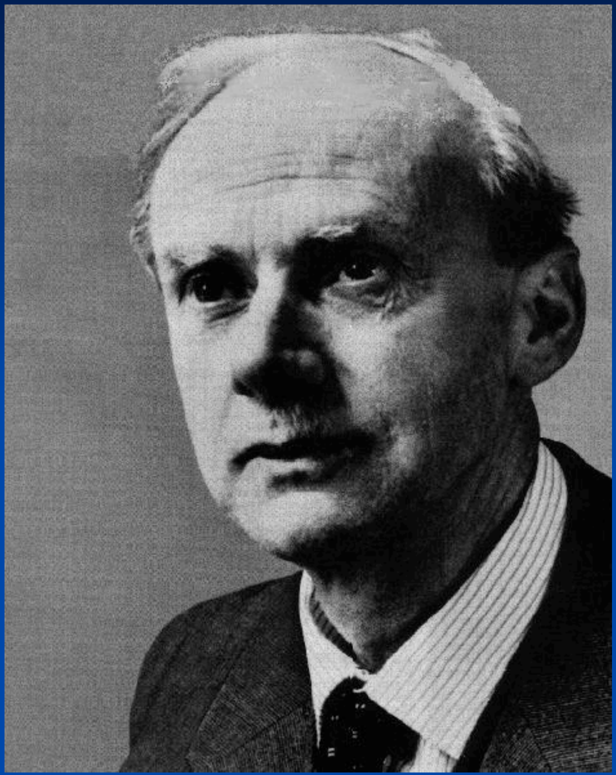
(Same year as Oppenheimer-Snyder)



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

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

Mathematical Black Hole Interiors



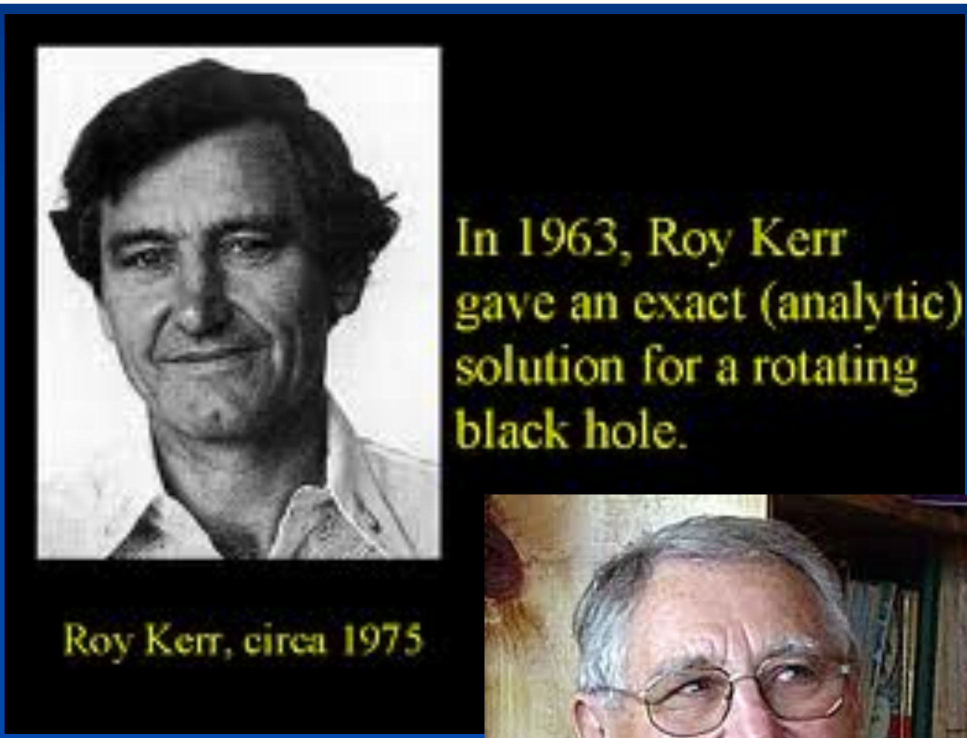
"The mathematicians can go beyond the Schwarzschild radius, and get inside, but I would maintain that this region is not physical space, because to send a signal inside and get it out again would take an infinite time. So I feel that the space inside the Schwarzschild radius must belong to a different universe, and should not be taken into account in any physical theory."

--- P. A. M. Dirac (1962)

- Schwarzschild soln. is time *reversible* (white holes & black holes)
  But Classical Matter falls into a black hole *irreversibly*
  Where does it go? What happens to the matter's entropy?
  What is inside a 'black hole'?
-

Rotating Black Holes

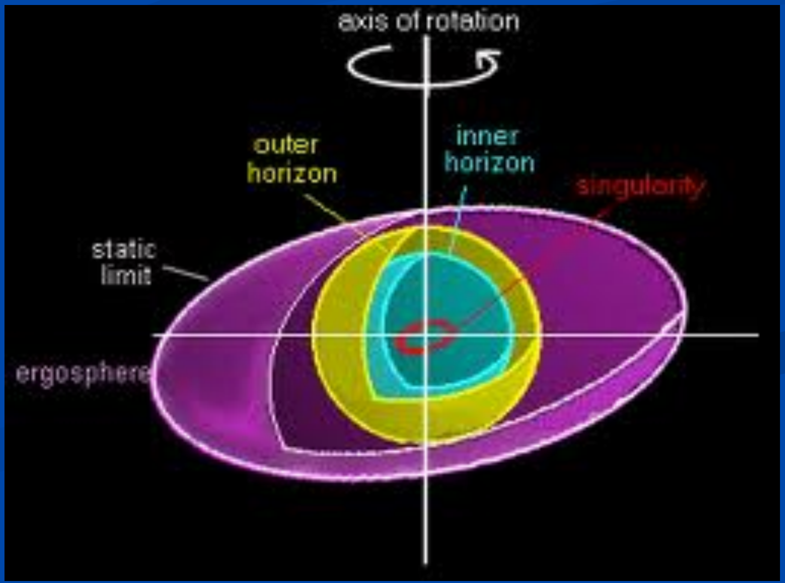
$$ds^2 = -\frac{\Delta}{\rho^2}\left(dt - a\sin^2\theta d\phi\right)^2 + \frac{\sin^2\theta}{\rho^2}\left[(r^2+a^2)d\phi - a dt\right]^2 + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2$$



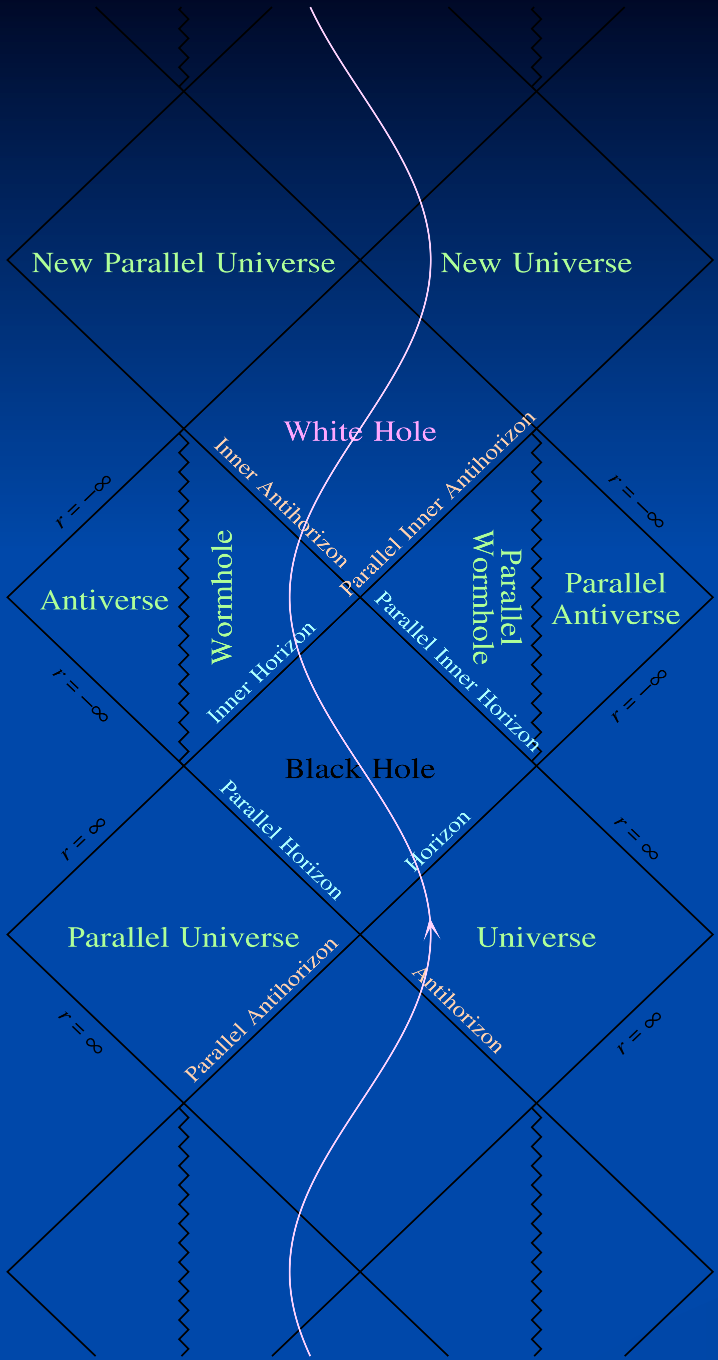
$$\rho^2 \equiv r^2 + a^2\cos^2\theta$$

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

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



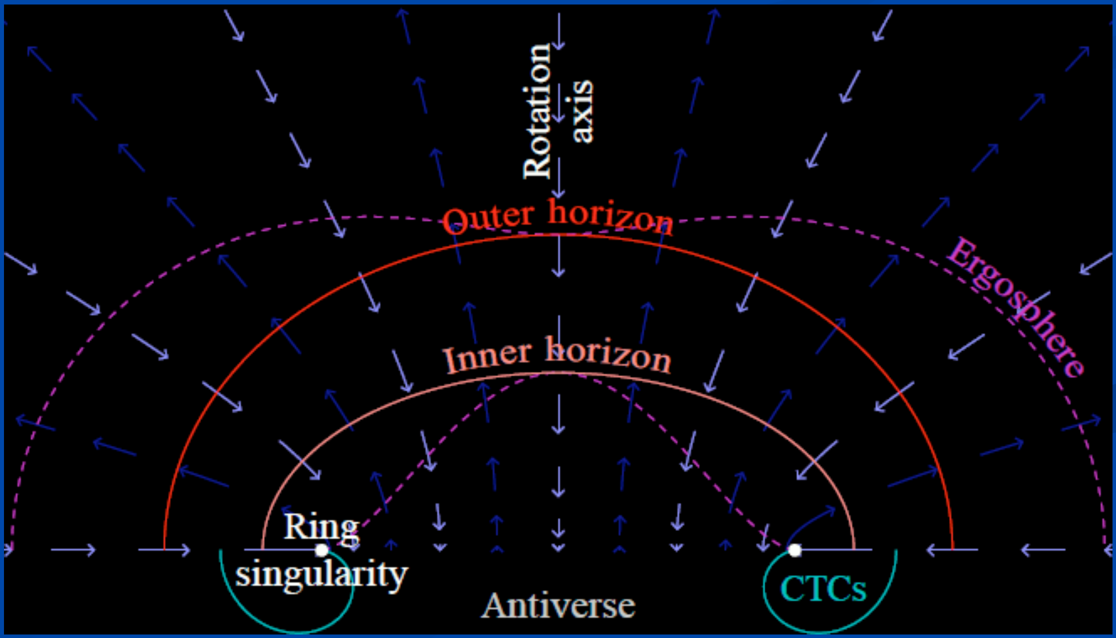
Mathematical Kerr Black Hole Interiors



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

(say hello to your greatgrandparents)

More unphysical



Irreducible Mass and 'No Hair' Theorem

- All 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)

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

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

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

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 …

A few problems remained …

- Hawking Temperature requires trans-Planckian frequencies
- $S_{BH} \propto A$ is *non-extensive* and *HUGE !*
- In the classical limit $T_H \to 0$ (cold) but $S_{BH} \to \infty$ (? !)
- $E \propto T^{-1}$ implies negative heat capacity

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

Equilibrium Thermodynamics cannot be applied

- Information Paradox: Where does the information go?

  (Pure states → Mixed States? Unitarity ?)
- What is the statistical interpretation of S_{BH} ?

  Boltzmann asks: **$S = k_B \ln W$** ??


S = k log W
LVDWIG
BOLTZMANN
1844 – 1906
HENRIETTE
BOLTZMANN
DR PHIL PAULA
BOLTZMANN
GEB. CHIARI
1891 – 1977
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 $$\boxed{S \sim k_B\,(M/M_{Pl})^{3/2}}$$ ← *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

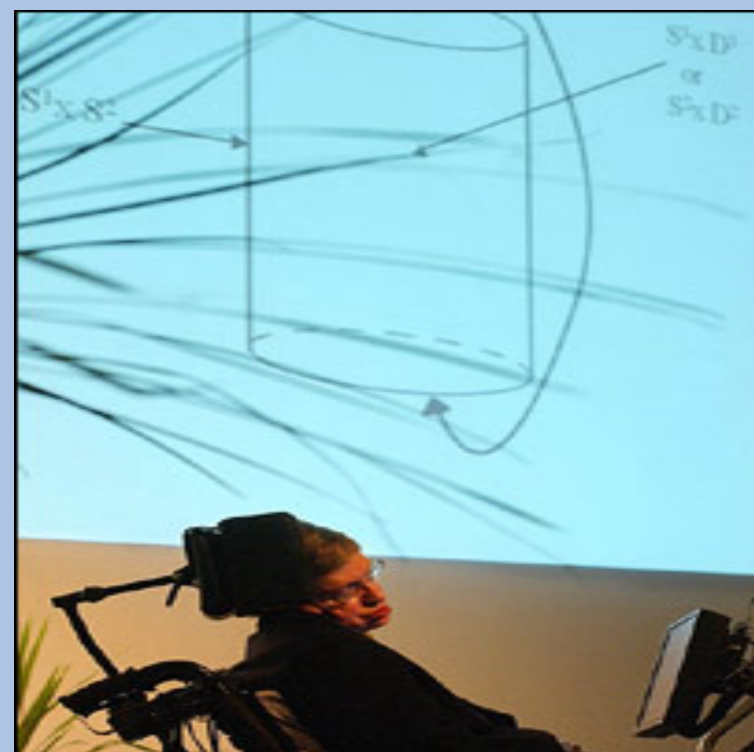
BBC NEWS UK EDITION

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.



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 $\rightarrow$ new physics (e.g. vortices)

- 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

Latest Report from the Front of ‘Black Hole Wars’

~60 ‘Firewall’ papers in last year arguing about **mutual inconsistency** of:

- Hawking radiation is in a pure state (QM: unitarity)
- information carried by radiation in low-energy EFT
- Nothing happens at the horizon to infalling observer

“Proof” by contradiction, many assumptions but still doesn’t tell you what actually happens c.f. (Aug. ‘13) http://online.kitp.ucsb.edu/online/fuzzorfire_m13/

NATURE | NEWS FEATURE

Astrophysics: Fire in the hole!

Will an astronaut who falls into a black hole be crushed or burned to a crisp?

Zeeya Merali

03 April 2013   Corrected: 05 April 2013

ANDY POTTS

Crisis in Foundations of Physics ?!

Desperate conditions
demand desperate
measures ?!

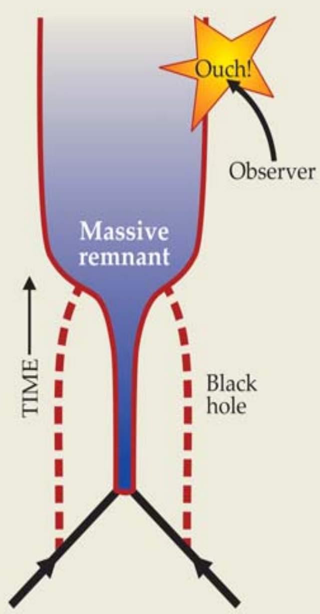
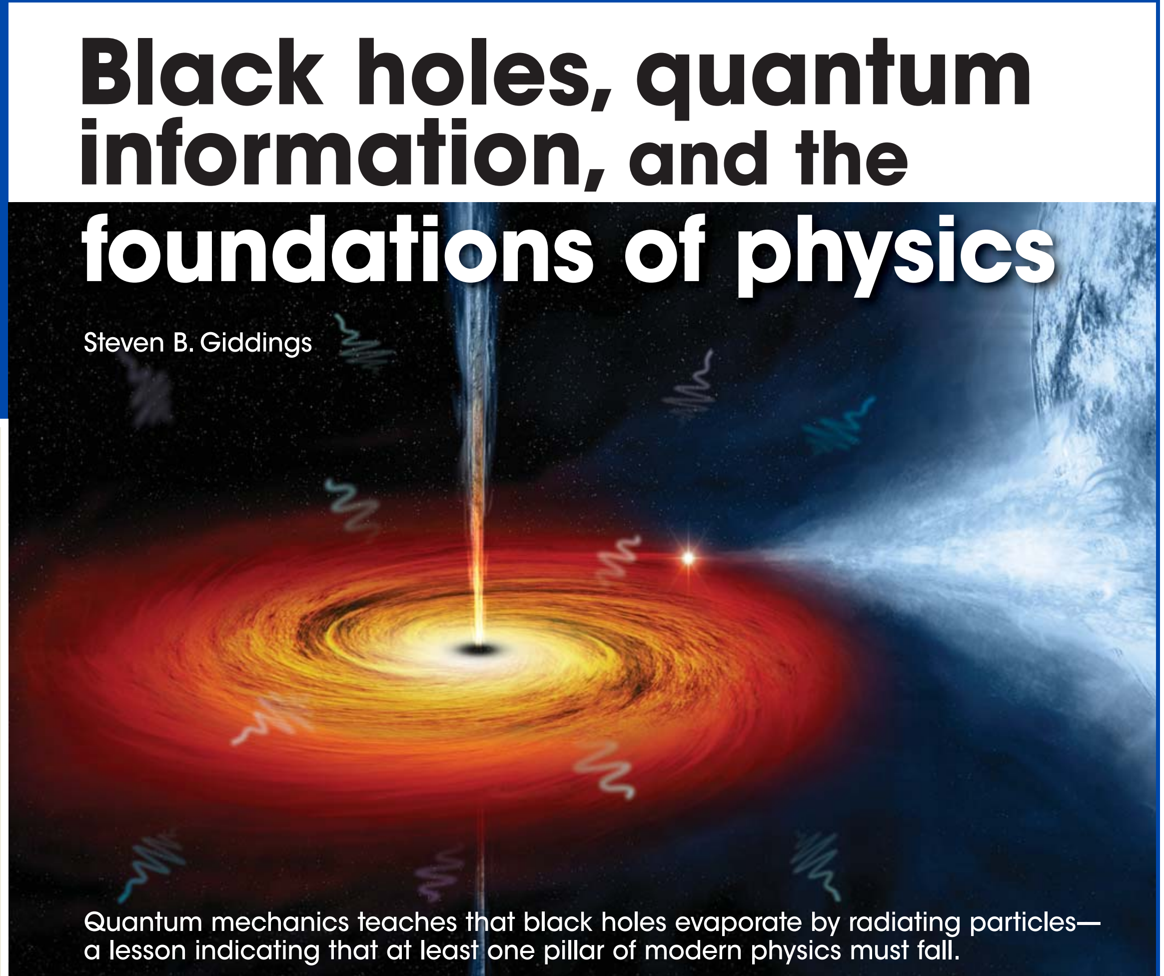


Figure 4. Massive-remnant scenarios are nonlocal. In these models, a black hole transitions to a massive object whose surface lies outside, or possibly at, the location of what would be the horizon (dashed lines on either side of the origin). In this illustration, the black hole is formed from the collision of two particles (black lines). To reach the horizon, the surface must propagate faster than the speed of light, which violates the locality of quantum field theory. An infalling observer encounters the remnant surface at a high velocity—compare falling into a neutron star—and, barring a miracle, experiences strong disruption. Variants of this general scenario include so-called fuzzballs and firewalls.



Black holes, quantum information, and the foundations of physics

Steven B. Giddings

Quantum mechanics teaches that black holes evaporate by radiating particles—a lesson indicating that at least one pillar of modern physics must fall.

Faster than Light Propagation ?

Equivalence Principles

- Weak Equivalence Principle (WEP):
  Equality of inertial and gravitational mass, recognized already by Galileo and Newton. *All bodies fall in a gravitational field with the same acceleration regardless of their mass or internal structure.*

- Einstein Equivalence Principle (EEP): Einstein added:
  The outcome of any local non-gravitational experiment in a freely falling frame is independent of the velocity of the frame and its location in spacetime.

- Strong Equivalence Principle (SEP): Extends the EEP to include **all** experiments: The outcome of any local experiment (gravitational or not) in a freely falling frame is independent of the velocity of the frame **and its location** in spacetime.
  Too Strong? How do local sources, QM influence the expt.?

Strong Equivalence Principle
(Strict Locality of All Physics)

vs.

Quantum Correlations
(Non-locality of Entanglement, EPR, Macroscopic Coherence)

- QM is about matter waves not point particles.
- Waves satisfy wave eqs. whose solns. depend upon boundary conditions.
- Macroscopic Quantum Cohererence, BEC, Cooper pairing in Superconductors, Bohm-Aharonov Effect, Entanglement are not strictly local because of this.
- Local Casimir 'vacuum' stresses depend on boundary conditions (but $G = 0$ causes no problems).
- Strict locality (SEP) cannot be maintained when both $\hbar \neq 0$ and $G \neq 0$.

The ‘crisis’ is caused by assuming ‘nothing happens’ at the black hole horizon - tacitly assuming SEP.
The quantum ‘vacuum’ is not featureless ‘nothing.’

Effective Field Theory & Quantum Anomalies

- Expansion of Effective Action in *Local* Invariants assumes

  Decoupling of Short Distance from Long Distance Modes
- But *Massless* Modes do not decouple
- Chiral, Conformal Symmetries are *Anomalous*
- Special Non-local Additions to Local EFT
- *IR* Sensitivity to *UV* degrees of freedom
- Macroscopic Effects of Short Distance (high energy) physics
- Conformal Symmetry & its Breaking controlled by the

  Conformal Trace Anomaly

Constructing the EFT of Gravity

- Assume *Equivalence Principle* (Symmetry)
- Metric Order Parameter Field g_{ab}
- Only two strictly *relevant* operators (R, Λ)
- Einstein's General Relativity is an EFT
- But EFT = General Relativity **+** Quantum Corrections
- Semi-classical Einstein Eqs. $(k << M_{pl})$:

$$G_{ab} + \Lambda\, g_{ab} = 8\pi\, G \langle T_{ab} \rangle$$

- But there is also a quantum (trace) anomaly:

$$\langle T_a^{\ a} \rangle = b\, F + b' \left(E - \tfrac{2}{3} \Box R\right) + b'' \Box R$$

- *New* (marginally) relevant operator(s) *needed*

Effective Action for the Trace Anomaly
Local Auxiliary Field Form

$$S_{anom} = \frac{b}{2}\int d^4x\sqrt{-g}\left[-2\varphi\Delta_4\psi + F\,\varphi + \left(E - \frac{2}{3}\Box R\right)\psi\right]$$
$$+\frac{b'}{2}\int d^4x\sqrt{-g}\left[-\varphi\Delta_4\varphi + \left(E - \frac{2}{3}\Box R\right)\varphi\right]$$

- Two New Scalar Auxiliary Degrees of Freedom
- Variation of the action with respect to φ, ψ -- the auxiliary fields -- leads to the equations of motion,

$$\Delta_4\varphi = \frac{1}{2}\left(E - \frac{2}{3}\Box R\right) \qquad \Delta_4\psi = \frac{1}{2}F$$

$$\Delta_4 = \Box^2 + 2R^{ab}\nabla_a\nabla_b - \frac{2}{3}R\Box + \frac{1}{3}(\nabla^a R)\nabla_a$$

Why is this Quantum effect relevant for Black Hole Horizons?
Stress Tensor of the Anomaly

Variation of the Effective Action with respect to the metric gives stress-energy tensor

$$T_{\mu\nu}(g_{\mu\nu}, \varphi, \psi) = -\frac{2}{\sqrt{-g}} \frac{\delta S_{anom}}{\delta g_{\mu\nu}}$$

- Quantum Vacuum Polarization in Terms of (Semi-) Classical Auxiliary potentials
- φ, ψ are new scalar degrees of freedom in low energy gravity which depen upon the global topology of spacetimes and its boundaries, horizons

Schwarzschild Spacetime (again)

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

$$\varphi = \sigma = \ln\sqrt{f} = \frac{1}{2}\ln\left(1 - \frac{2M}{r}\right) \rightarrow \infty$$

solves homogeneous $\Delta_4\varphi = 0$

Timelike Killing field (Non-local Invariant)

$$\xi^a = (1, 0, 0, 0) \quad e^\sigma = (-\xi_a\xi^a)^{\frac{1}{2}} = f^{\frac{1}{2}}$$

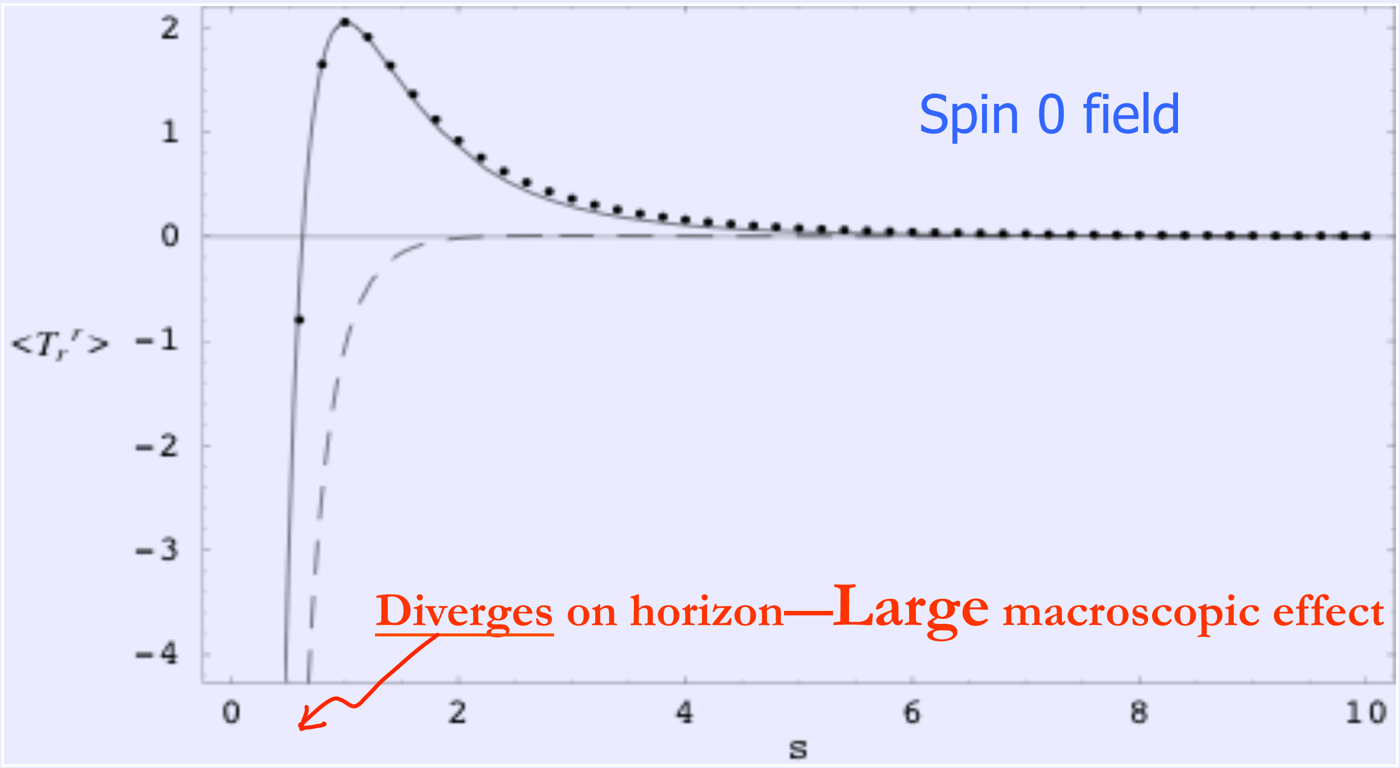
Energy density scales like $e^{-4\sigma} = f^{-2}$

Auxiliary Scalar Potentials give Geometric (Coordinate Invariant) Meaning to Stress Tensor becoming Large on Horizon

Does not violate WEP, General Covariance.

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)



IR Relevant Term in the Action

The effective action for the trace anomaly scales logarithmically with distance and therefore should be included in the low energy macroscopic EFT description of gravity—

Not given in terms of Local Curvature

This is a non-trivial modification of classical General Relativity from quantum effects

$$S_{Gravity}[g,\varphi,\psi] = S_{H-E}[g] + S_{Anom}[g,\varphi,\psi]$$

Fluctuations of new scalar degrees of freedom can generate a Quantum Phase Transition in Gravity

Quantum Effects Near $r = R_S$

- Huge Vacuum Stresses for generic b. c. at horizon:

$$\langle T^t_t \rangle \sim \langle T^r_r \rangle \sim \left(1 - \frac{2GM}{r}\right)^{-n}, \; n = \begin{cases} 1 & \text{Unruh} \\ 2 & \text{Boulware} \end{cases}$$

- Gravitational effects of quantum matter become strong near $r = R_S$ and affect the geometry.
- Strong attractive self-interactions $\Rightarrow$ Condensation.
- If Quantum Correlations $\langle T^b_a(x)\, T^d_c(y) \ldots \rangle$ also grow when $x, y, \ldots$ approach the horizon $\Rightarrow$ Highly Entangled Quantum State.
- Possibility of Quantum Phase Transition to BEC-like phase near $r = R_S$.
- Critical region where Sound Speed = Light Speed:

$$c_S^2 = \frac{dp}{d\rho} = c^2$$

  Any Additional Increase in Pressure would violate Causality: Onset of Superluminal Modes is the Signature of a Relativistic Phase Transition.
- A Critical Surface Layer with $p = \rho$ is Necessary for Joining $p = -\rho$ Interior with Vacuum Exterior.

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 $\langle \bar{q} q \rangle \neq 0 \quad \langle \Phi \rangle \neq 0$.

A Macroscopic Quantum Effect

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 $\mu = 0$),
$Ts = p + \rho = 0$ 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

The Quantum Final State of Gravitational Collapse

$$R_a^{\ b} - \tfrac{1}{2} R\, \delta_a^{\ b} = 8\pi G\, T_a^{\ b}$$

- $1 - \frac{d(r\,h)}{dr} = 8\pi G\, \rho\, r^2$
- $\frac{r\,h}{f}\frac{df}{dr} + h - 1 = 8\pi G\, p\, r^2$
- $\frac{dp}{dr} + \frac{p+\rho}{2f}\frac{df}{dr} = 0 \qquad (\nabla_b T_r^{\ b} = 0)$

Other components follow by differentiating these

Define $h \equiv 1 - \frac{2Gm(r)}{r}$

Then $\frac{dm}{dr} = 4\pi\, \rho\, r^2$ and

$$\frac{dp}{dr} = -\frac{G(\rho+p)(m+4\pi p r^3)}{r\,(r-2Gm)} \qquad \text{(TOV eq.)}$$

Eqs. become closed when eq. of state is given:

$$p = \kappa\, \rho$$

with $\kappa = \begin{cases} -1, & r < r_1 \\ +1, & r_1 < r < r_2 \end{cases}$

$$p = \rho = 0\,, \quad r_2 < r$$

A Simple Model
2001-2004

The EFT and Stress Tensor of the Trace Anomaly can be used to solve the matching problem in the quantum phase boundary layer

(a mean field approximation for the auxiliary fields)

- I. Interior (Vacuum Condensate) de Sitter:
  $f(r) = Ch(r) = C\left(1 - H_0^2\, r^2\right)\,,$
  $\rho_V = -p_V = \frac{3H_0^2}{8\pi G}$
- III. Exterior (Vacuum) Schwarzschild:

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

  C, H_0 and M are (so far) arbitrary parameters
- II. Only Non-Vacuum Region:
  Thin shell with $p = \rho \rightarrow pf = const.$
  Let $w \equiv 8\pi G p r^2$ so the other two eqs. are

  - $\frac{dr}{r} = \frac{dh}{1-w-h} \simeq \frac{dh}{1-w}$
  - $\frac{dh}{h} = -\frac{1-w-h}{1+w-3h}\frac{dw}{w} \simeq -\frac{1-w}{1+w}\frac{dw}{w}$

  If region II shell is **thin**,$i.e.$ exists only near
  $r \simeq R_s \simeq H_0^{-1}$, then $h \ll 1$ in region II
  and h can be neglected on r.h.s. of •
  Elementary Integration gives then

  $h \simeq \epsilon\,\frac{(1+w)^2}{w} \ll 1 \rightarrow \epsilon \ll 1$, integ. const.

  $$r \simeq r_1\left[1 - \epsilon\ln\left(\frac{w}{w_1}\right) + \epsilon\left(\frac{1}{w} - \frac{1}{w_1}\right)\right]$$

Integration of final (conservation) eq. gives

$$f(r) = \left(\frac{r}{r_1}\right)^2 \left(\frac{w_1}{w}\right) f(r_1) \simeq \left(\frac{w_1}{w}\right) f(r_1)$$

A consistent soln. matching at r_1 and r_2 is obtained if w is $\mathcal{O}(1)$ but $\Delta w \equiv w_2 - w_1 = \mathcal{O}(\epsilon)$. Then

$$r \simeq r_1 \simeq H_0^{-1} \simeq R_s \simeq r_2$$

barely changes in region II with

$$\Delta r \equiv r_2 - r_1 = \mathcal{O}(\epsilon^2)$$

and both f and h are of order ϵ in region II but nowhere vanishing. This means that the soln. has a globally defined time and **NO** event horizon. The physical meaning of $\epsilon \ll 1$ is that $\epsilon^{-\frac{1}{2}}$ is the order of the very large but finite redshift a photon emitted at the shell experiences in escaping to infinity.

The proper thickness of the shell is

$$\ell = \int_{r_1}^{r_2} dr h^{-\frac{1}{2}} \simeq R_s \epsilon^{\frac{1}{2}} \int_{w_1}^{w_2} dw\, w^{-\frac{3}{2}}$$

which is $\quad \mathcal{O}(\epsilon^{\frac{3}{2}} R_s) \ll R_s$

Likewise the energy in the thin shell of region II is

$$E_{II} = 4\pi \int_{r_1}^{r_2} \rho r^2 dr = \epsilon\, M \int_{w_1}^{w_2} dw$$

which is $\mathcal{O}(\epsilon M) \sim M_{pl} \ll M$

However, the entropy all resides in the shell since

$$p = \rho = \frac{a^2}{8\pi G}\left(\frac{k_B T}{\hbar}\right)^2$$

$$s = \frac{p+\rho}{T} = k_B \frac{a}{4\pi G \hbar} \frac{\sqrt{w}}{r}$$

$$S_{II} = 4\pi \int_{r_1}^{r_2} \frac{s r^2 dr}{\sqrt{h}} \simeq k_B \frac{a R_s^2}{\hbar G} \sqrt{\epsilon} \int_{w_1}^{w_2} \frac{dw}{w}$$

which is of order

$$a k_B \frac{M\ell}{\hbar} \sim S_{BH}\sqrt{\epsilon} \ll S_{BH} = 4\pi k_B \frac{GM^2}{\hbar}$$

and **very** much smaller than S_{BH}.

Eg. If $a \sim 1,\ \ell \sim \sqrt{L_{pl} R_s},\ M \sim M_\circ,$

$$S \simeq 10^{57} k_B \sim S_\circ \simeq 10^{58} k_B \ll S_{BH} \simeq 10^{77} k_B$$

Modest Entropy $\propto M^{3/2}$ consistent with
Standard Thermodynamics & Quantum Unitarity

Main Features of New Soln.

- Vacuum Schwarzschild Exterior
- de Sitter (GBEC) Interior, No Singularity
- $\Lambda > 0$ Casimir Energy due to b.c.
- GBEC similar to Gluon Condensate in Bag Model of Hadrons
- Thin Shell of $p = \rho$, No Event Horizon
- Global Time, Unitarity, No Hawking Radiation
- Modest Entropy, No Information Paradox
- Maximizes Entropy, Completely Stable
- No Planckian Pressures or Densities
- Hydrodynamic Einstein Eqs. Valid Everywhere except at r_1, r_2 Stationary Shock Fronts
- Interior de Sitter also a Cosmological Soln.

Analog to BEC quantum transition near the classical horizon

Gravitational Vacuum Condensate Stars

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
- Gravitational Wave Signatures
- Dark Energy as Condensate Core -- Finite Size Casimir effect of boundary conditions at the horizon

Observations are Coming

- High resolution sub-mm **Very Large Baseline Imaging** (VLBI) will zero in on event horizon of black hole (or gravastar surface) in the center of our galaxy
- Maxima of X-ray Continuum Thermal Spectra from Accretion Disk can determine the location of the **Innermost Stable Circular Orbits** (ISCO's) of candidate black holes
- X-Ray Fe Line Spectra Doppler Shifts will allow measurement of velocities and **test rotating Kerr black hole solution no-hair theorem** in external geometry
- **Gravitational Waves** expected first detection by Advanced LIGO II will observe inspiral and black hole merger events
- Millisec. Pulsar Timing Arrays may even detect **GW's** first
- Possibility of detection of **scalar 'breathing' mode** polarization from scalar φ waves

Next few years will be an exciting period

Testing the Exterior Kerr Solution

Violations of No Hair Theorem

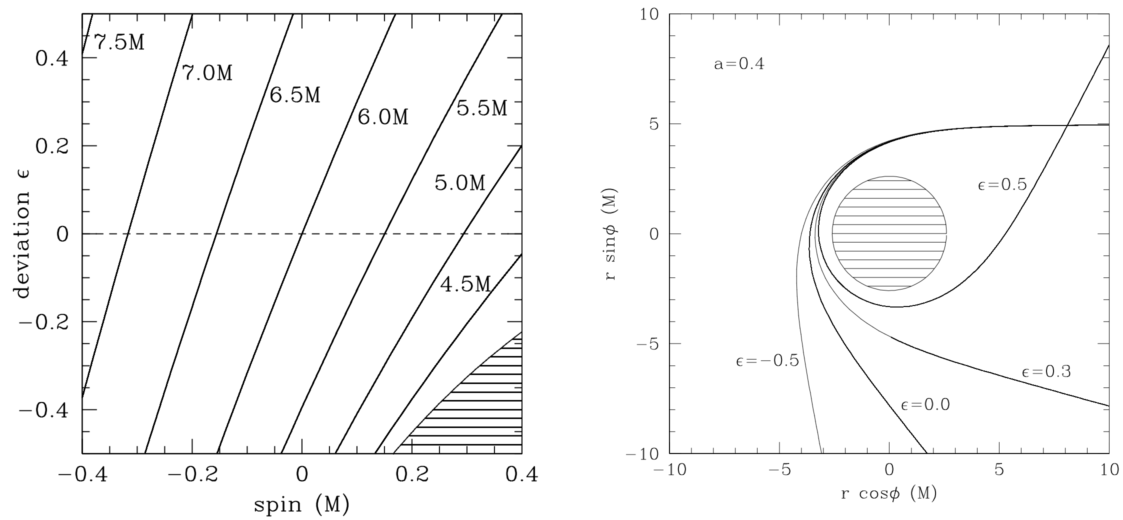


Figure 7. The dependence of *(Left)* the radius of the innermost stable circular orbit around a black hole and of *(Right)* the trajectories of photons on the black-hole spin a and on the parameter ϵ that measures the degree of violation of the no-hair theorem (Johannsen & Psaltis 2010a, 2010c).

Innermost Stable Circular Orbit (ISCO) and Image of the Ring of Light depend upon the Quadrupole Deviation $q = -(a^2 + \epsilon)$

VLBI Imaging of Galactic SMBH's

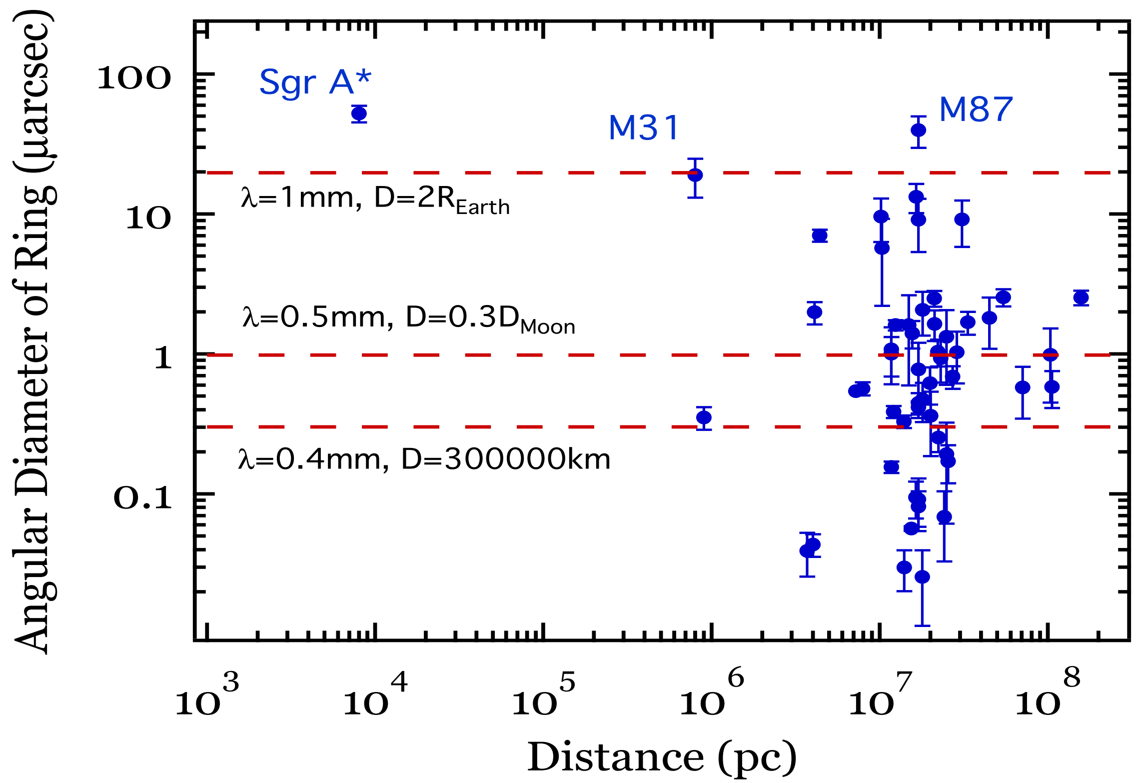
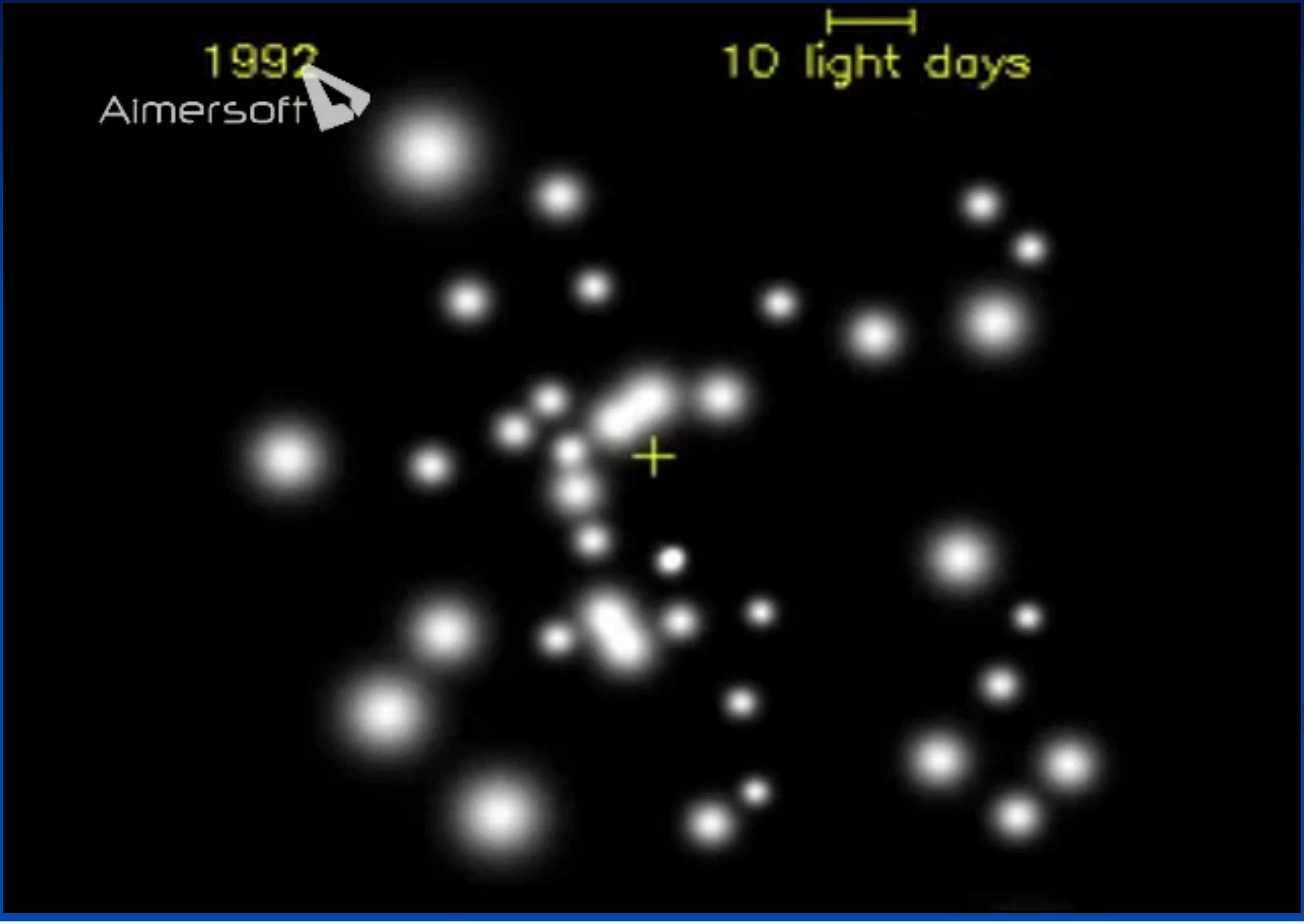


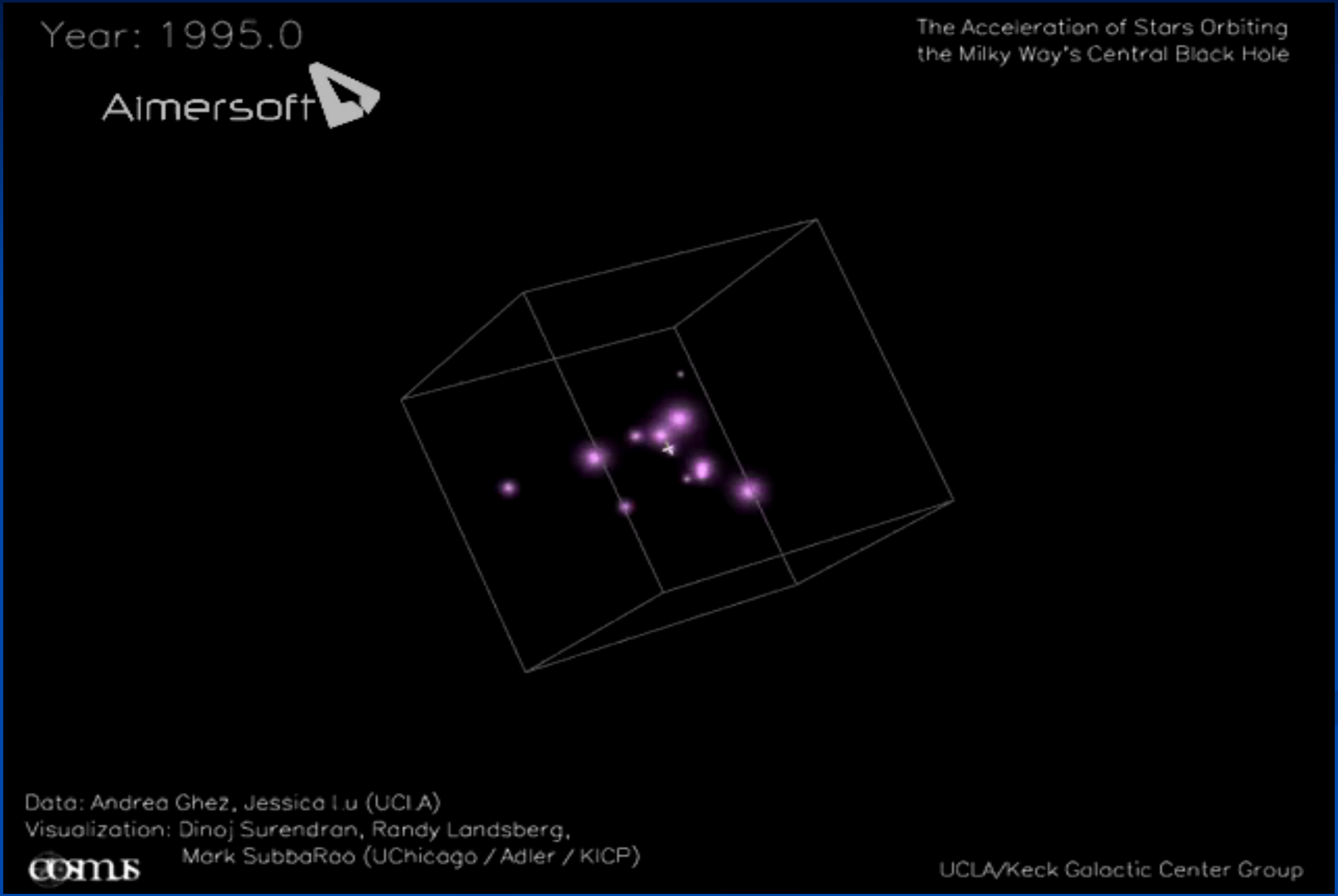
FIG. 4.— Angular diameters and distances of several supermassive black holes. Sgr A* has the largest angular diameter, closely followed by M87 due to its high mass, making these sources ideal targets for VLBI imaging. Data taken from Gültekin et al. (2009).

Supermassive 'black holes' (10^6 to 10^{11} $M_\odot$) are at the centers of (nearly) all large galaxies

The Center of our Milky Way Galaxy: Sgr A*



Orbits of Stars around Sgr A*



New Horizons in Quantum 'Black Holes'

- Classical Black Holes already have some unphysical features
- The tension between General Relativity and both Quantum Mechanics and Statistical Physics in Black Holes leads

  to a 'Crisis in Physics'
- The most suspect assumption is the SEP which is violated by Quantum Fields in Black Hole Curved Spacetimes
- Quantum Vacuum (Casimir) Effects are computable & relevant at Macroscopic Distances & near Event Horizons
- New scalar degrees of freedom in the EFT of Gravity are required in the Standard Model by the Conformal Anomaly
- Their fluctuations induce a **Quantum Phase Transition** at the would-be 'Black Hole' horizon

- Interior could be completely non-singular condensate
- Gravitational Condensate Stars resolve all 'black hole' paradoxes/ 'crisis'
- Astrophysics of gravastars & 'no-hair' testable by mm VLBI, X-rays, ISCO's, GW's in this decade (Sgr A*--gas cloud in collision this year)
- Science that 'Matters': Far-reaching implications for eventual unification of quantum matter with gravity