BLACK HOLES

Revisit and Perspectives

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Definition

BLACK HOLES are regions from where (not even) classical light signals can escape to infinity. In asymptotically flat spacetimes $(\mathcal{M}, g)$

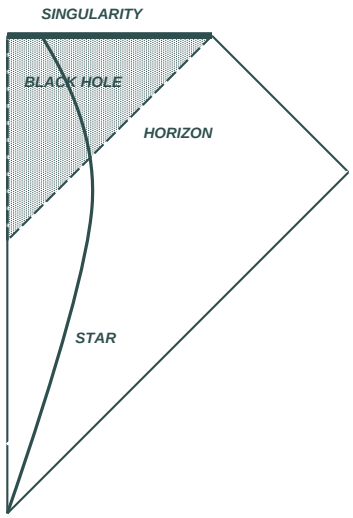
$$B \equiv \mathcal{M} - J^-(\mathcal{J}^+)$$

EVENT HORIZON is boundary of black hole

$$H \equiv \dot{J}^-(\mathcal{J}^+) \cap \mathcal{M}$$

Classical black holes must have singularity inside[a]

R. Penrose 1965



[a] Assumes Einstein Eqs. and $T_{\mu\nu}k^\mu k^\nu \geq 0$ (k^μ null) (and existence of (i) non-compact Cauchy surface $\mathcal{H}$ and (ii) trapped surface $\mathcal{T}$ in $\mathcal{M}$)

No-hair Theorems

Preliminary hints:

- Total collapse of a spherically symmetric magnetized star leads to spherically symmetric unmagnetized black hole

  V. Ginzburg 1964

- Total collapse of chargeless, spinless and almost spherically symmetric star leads to chargeless, spinless and perfectly spherically symmetric black hole

  A. Doroshkevich, I. Novikov, Ya. Zel'dovich 1964

- Total collapse of spinless star leads to spherically symmetric black hole

  W. Israel 1967

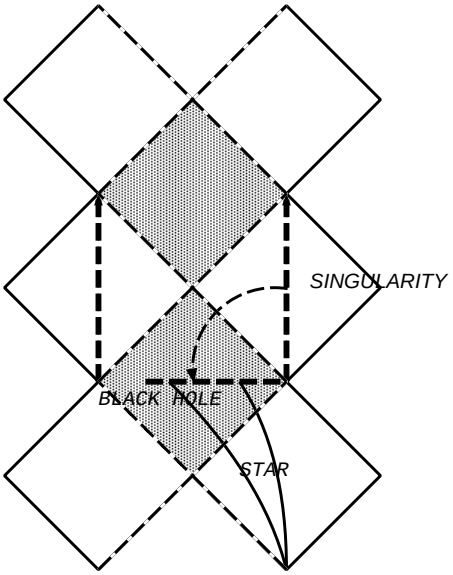
No-hair theorem:

- *Total collapse of star leads to Kerr-Newman black hole characterized by mass, charge and spin*

  B. Crater, S. Hawking, W. Israel and others

Kerr-Newman Black Holes

$$M^2 > Q^2 + J^2/M^2$$



AREA

$$A = 4\pi \left[2M^2 - Q^2 + 2M \left(M^2 - Q^2 - \frac{J^2}{M^2} \right)^{1/2} \right]$$

$$\downarrow$$

ENERGY

$$M^2 = \frac{A}{16\pi} + \frac{4\pi}{A} \left(J^2 + \frac{Q^4}{4} \right) + \frac{Q^2}{2}$$

Black Hole Mechanics

$$dM = (\mathcal{K}/8\pi)dA + \Omega dJ + \Phi dQ$$

SUPERFICIAL GRAVITY:

$$\mathcal{K} \equiv 4\pi[M^2 - Q^2 - J^2/M^2]^{1/2}/A$$

ANGULAR FREQUENCY:

$$\Omega \equiv 4\pi J/MA$$

ELECTRIC POTENTIAL:

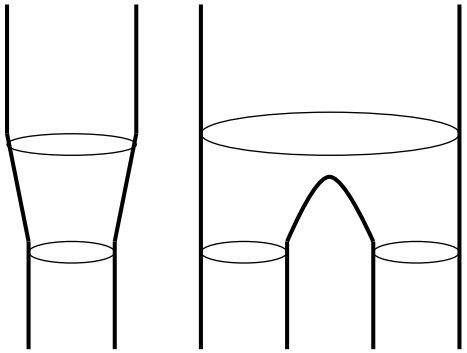
$$\Phi \equiv (4\pi Q/A)[M + (M^2 - Q^2 - J^2/M^2)^{1/2}]$$

J. Bardeen, B. Carter and S. Hawking (1973)

Increasing Area Theorem

Sum of event horizon AREAS of set of classical black holes DO NOT DECREASE with time[a]

S. Hawking 1971

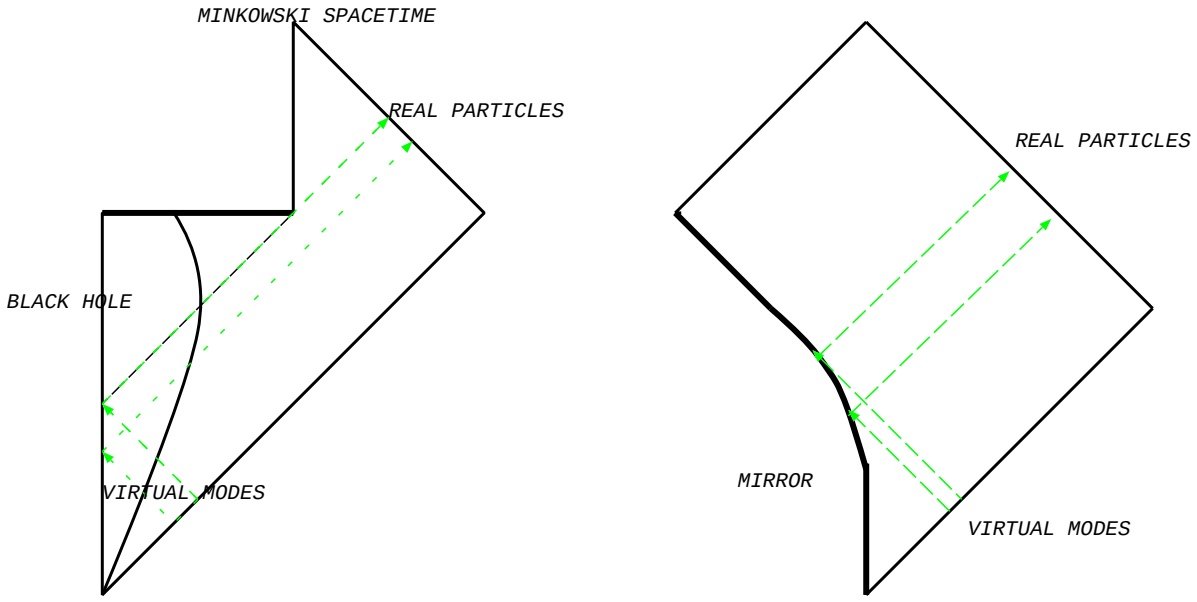


[a] Assumes Einstein Eqs. and $T_{\mu\nu}k^\mu k^\nu \geq 0$ (k^μ null) (and strongly asymptotically predictability [no naked singularities], i.e., there is a globally hyperbolic region containing $I^-(\mathcal{J}^+) \cup H$).

Hawking Radiation

BLACK HOLES formed from star collapse radiate thermally with temperature $T = \mathcal{K}/2\pi$

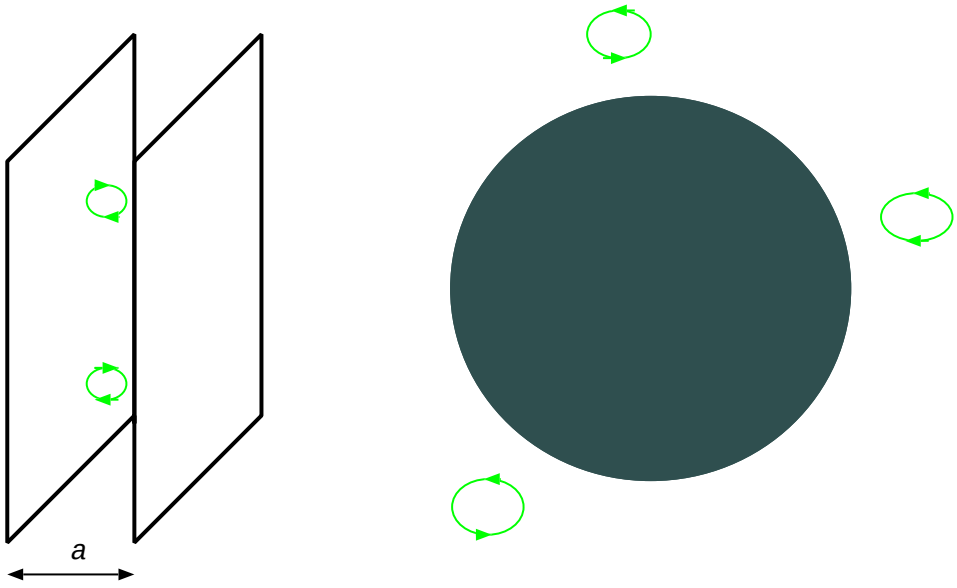
S. Hawking 1974



Circunventing Classical Theorem

QUANTUM MECHANICS ABLE TO VIOLATE

$$T_{\mu\nu}k^\mu k^\nu \geq 0 \quad (k^\mu \ \text{ null})$$



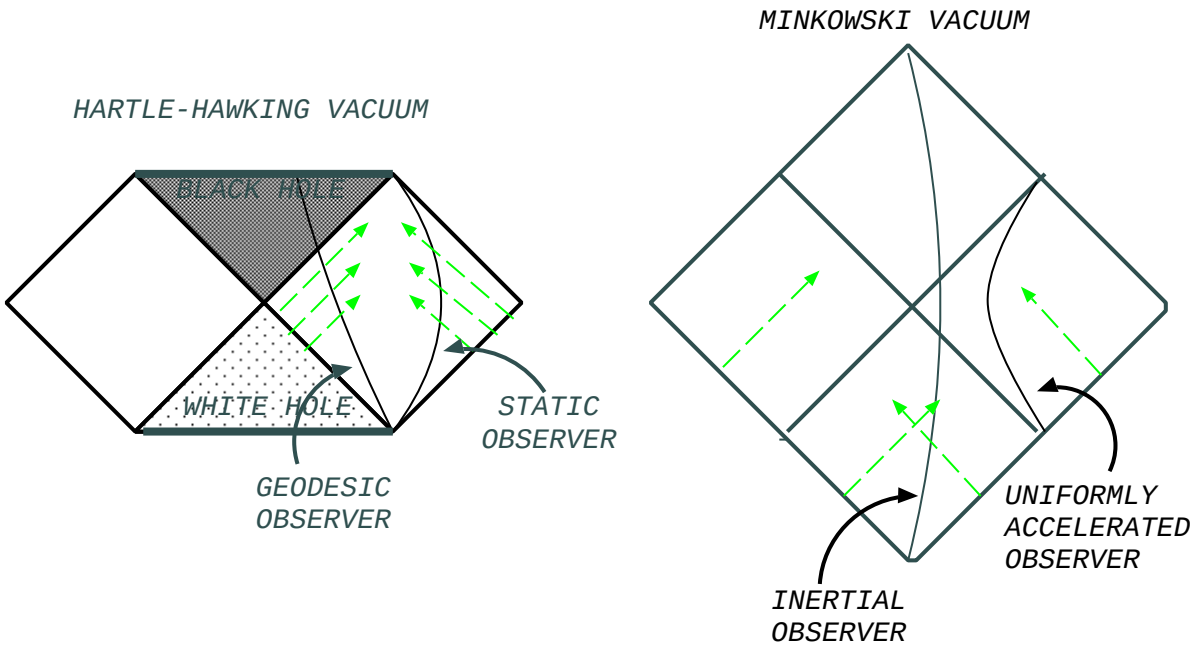
Remaining (challenging) open questions: (i) Rôle of transplanckian modes, (ii) information paradox, (iii) others...

Hawking Effect

and

Particle Concept

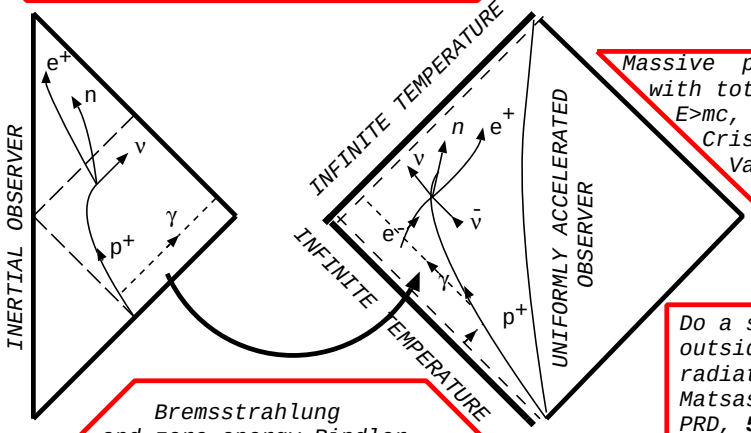
(Fulling-Davies-Unruh effect)



Remaining (challenging) open questions: None(?!)

Particle Processes around Black Holes

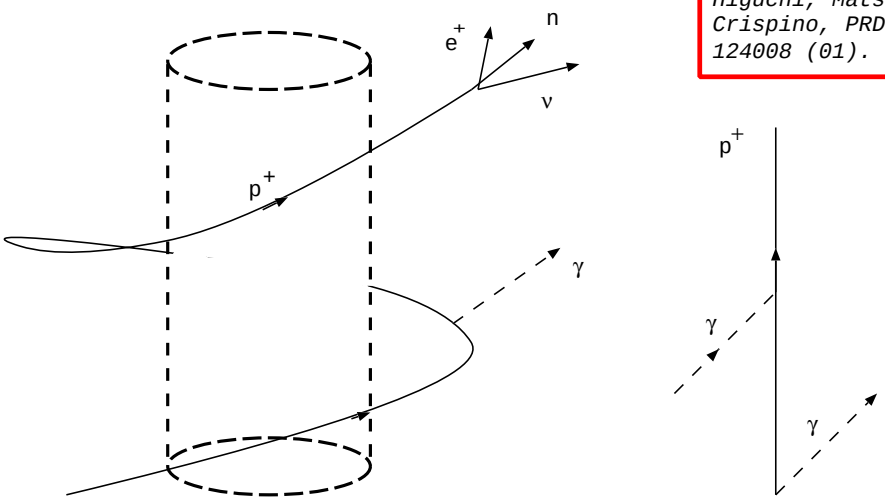
*Decay of accelerated protons and related processes: Matsas, Vanzella, PRD **59**, 094004 (99), PRD **63**, 014010 (01), PRL **87**, 151301 (01)*



Massive particles with total energy E>mc, Castineiras Crispino, Matsas Vanzella, gr-qc/ 0201093

*Bremsstrahlung and zero-energy Rindler photons: Higuchi, Matsas, Sudarsky PRD, **45** R3308 (92); **46** 3450 (92)*

*Do a static source outside a black hole radiate? Higuchi, Matsas, Sudarsky, PRD, **56**, R6071 (97), PRD, **58**, 104021 (98); Castineiras, Matsas, PRD, **62**, 064001 (00); Higuchi, Matsas, Crispino, PRD, **63**, 124008 (01).*



*Radiation emitted from a source rotating a black hole, Crispino, Higuchi, Matsas, CQG, **17**, 19 (00)*

Thermodynamics of Black Holes

$$M = E_{bh};\ \mathcal{K}/2\pi = T_{bh};\ A/4 \to S_{bh}$$

$$\downarrow$$

$$dE_{bh} = T_{bh} dS_{bh} + \Omega dJ + \Phi dQ$$

Generalized 2^{nd} Law of Thermodynamics

$$S_{\rm gen} = S + S_{bh}$$

Conjecture (J. Bekenstein 1973)

$$\Delta_t S_{\rm gen} \geq 0$$

Remaining (challenging) open questions: (i) S_{bh} from first principles(?!) (ii) $\Delta_t S_{\rm gen} \geq 0$ is really law of Nature?

"[The mystery of the quasars] allows one to suggest that the RELATIVISTS with their sophisticated work are not only magnificent cultural ornaments but MIGHT BE USEFUL TO SCIENCE"

Thomas Gold – Cornell University
First Texas Symposium (1963)

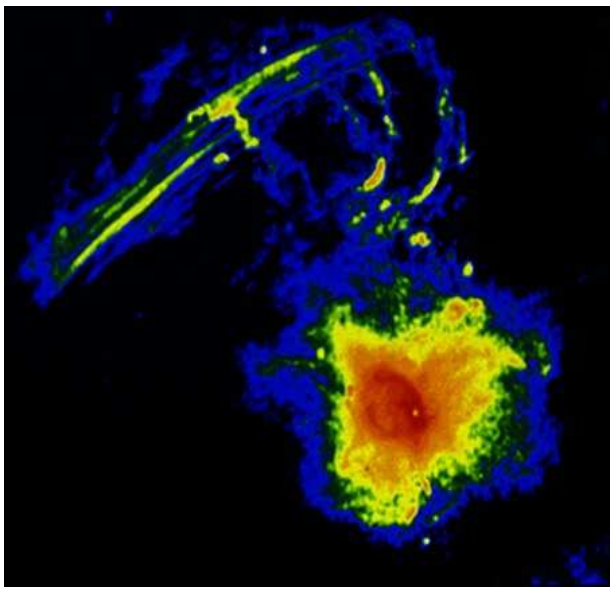
Observational Aspects

> "It could be argued that the prediction of the 'black hole' picture is simply that we will not see anything – and this is precisely consistent with observations since no 'black holes' have been seen [directly]"
>
> R. Penrose (1969)

- Indirect observation: Effects on surrounding matter (conclusions depends on validity of Einstein Eqs., etc)
- Direct observation: 'Observation' of the event horizon

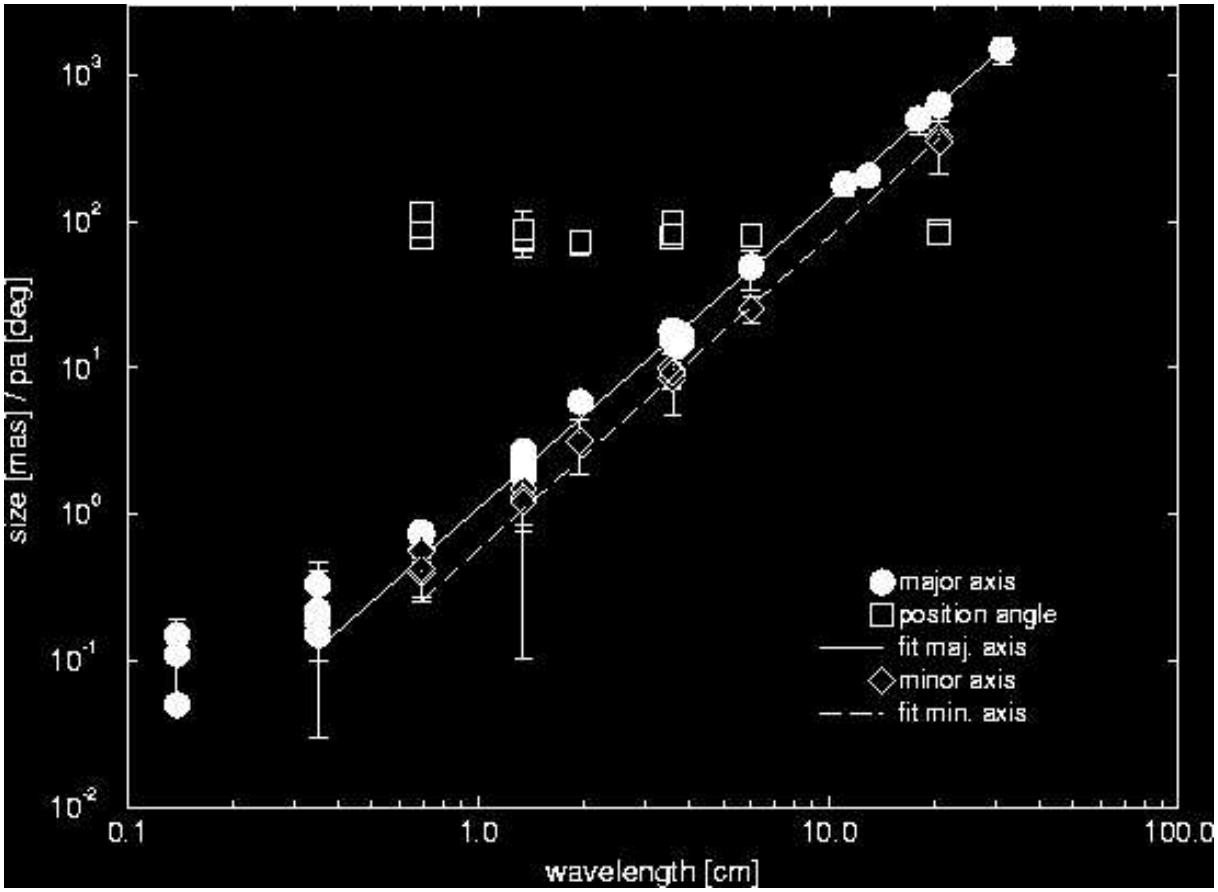
Galactic Black Holes

HUGE BLACK HOLES in GALACTIC CENTERS?



Sag A*: very (too!) bright in radio band

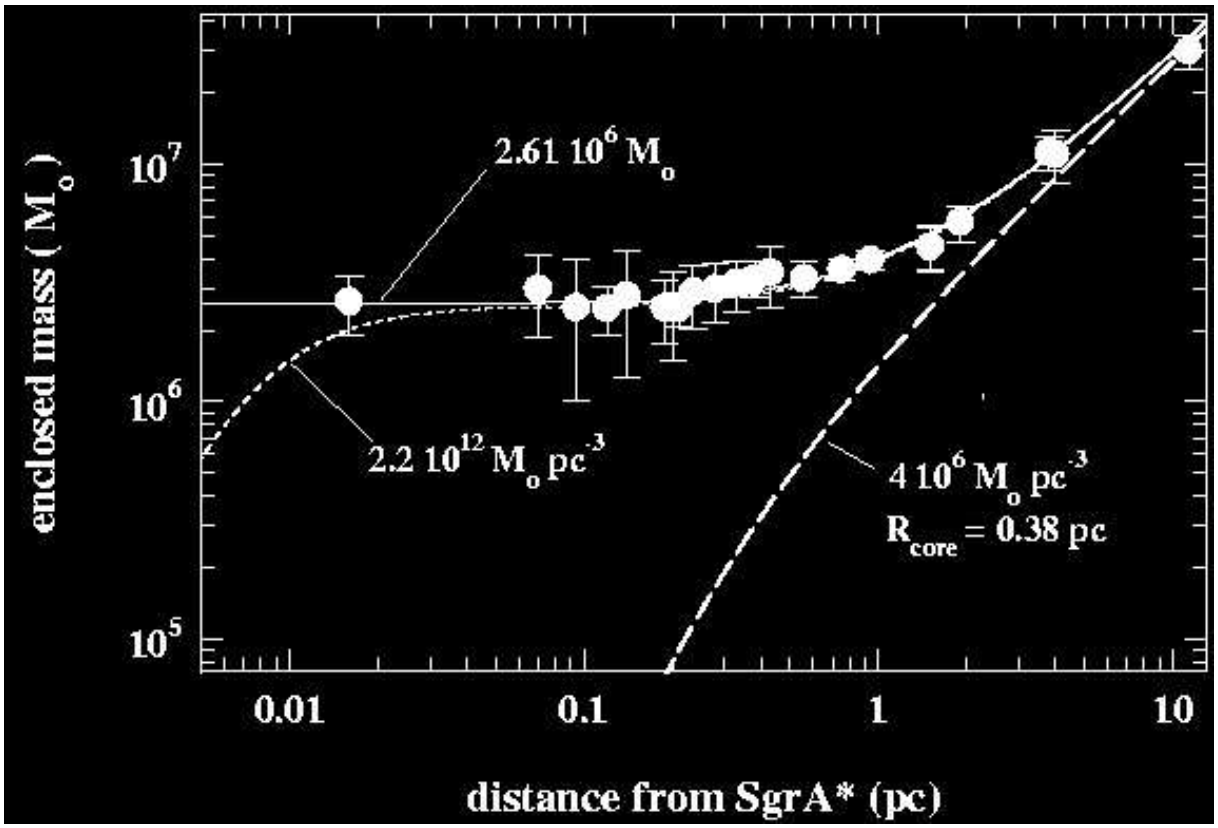
Compactness



Sag. A* size measured at different wavelengths of the observed radiation. Observations reaching about "twice" expected Schwarzschild radius.

T. Krichbaum et al

Mass Distribution

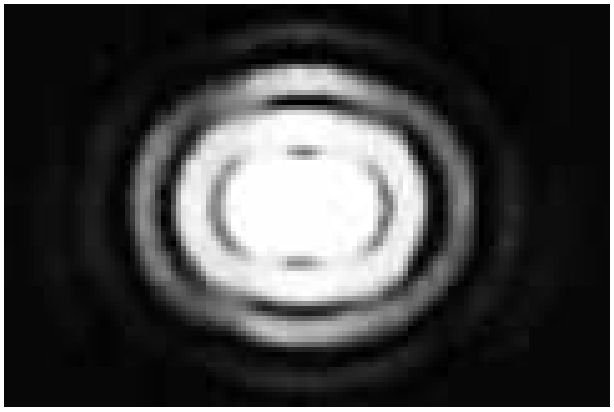


Mass enclosed within certain distance from Sag. A*.

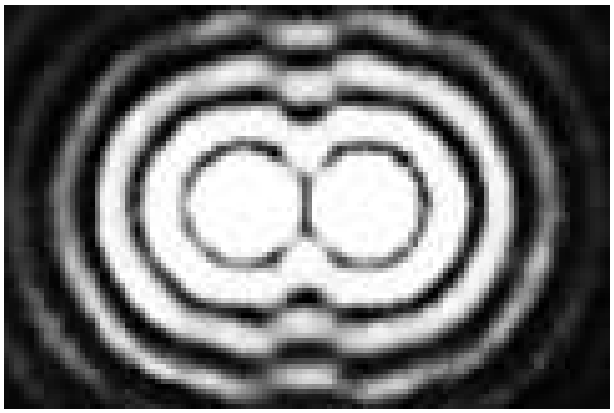
Dashed lines associated with different models

A. Eckart and R. Genzel

Black Hole × Star Cluster



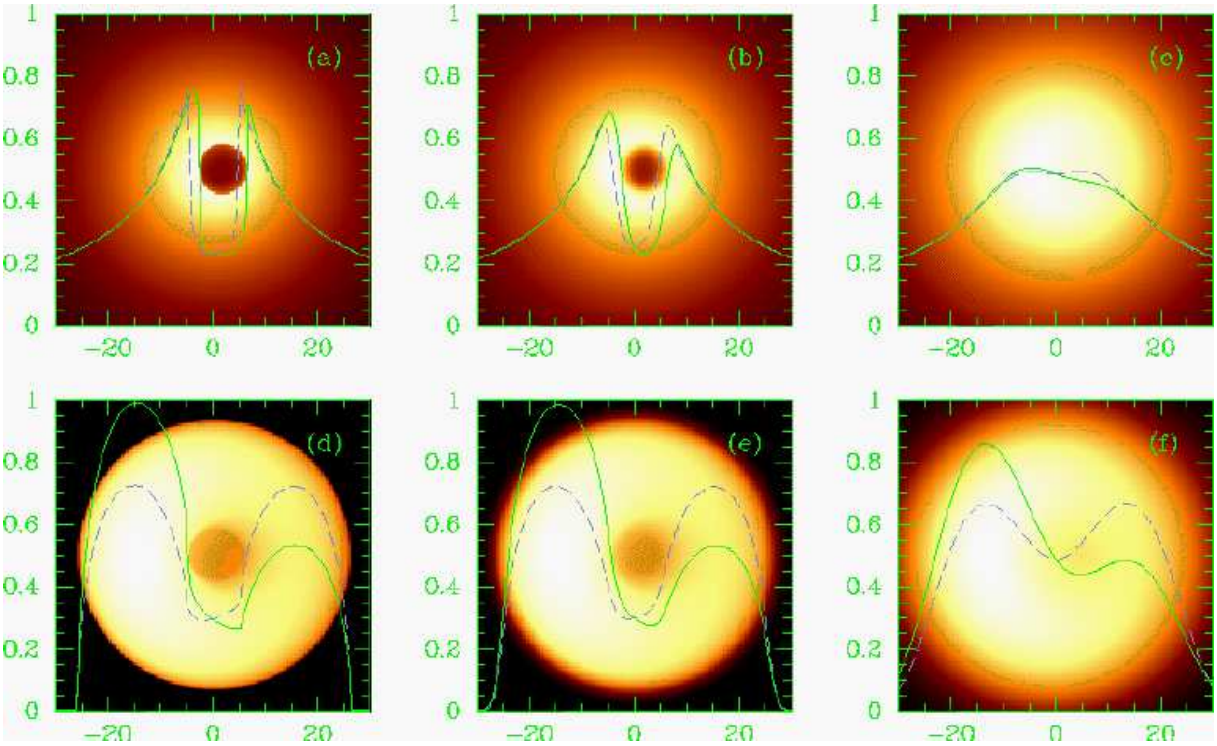
Low Resolution



High Resolution

Technical challenge: Reach better resolution

Event Horizon



THE FUTURE

left – un-blurred image;
middle – 0.6mm wavelength observation;
right – 1.3mm wavelength observation

H. Falcke, F. Melia, E. Agol

Technical challenge: Reach mm-VLBI technology.

CONCLUSIONS

- Classical Black Holes are Interesting!
- Semiclassical Black Holes are Very Interesting!