Black holes

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May 2025

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Fundamental interactions and black holes

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- Black holes prediction of our best gravity theory (general relativity)
- 1783: John Michell speculated about $v_{\text{escape}} > c$
- 1916: Schwarzschild published first black hole solution of GR
- 1967: term "black hole" (BH) popularized by John Wheeler
- 1971: Cygnus X-1 first widely accepted BH detection
- 1973: Bekenstein–Hawking entropy $S \sim \frac{A}{4}$
- 1992-2008: discovery of supermassive BH in center of Milky Way
- 1993-1997: holographic principle ('t Hooft, Susskind, Maldacena)
- 2016: LIGO discovers gravitational waves from BH merger

Humanity starts gravitational wave astronomy

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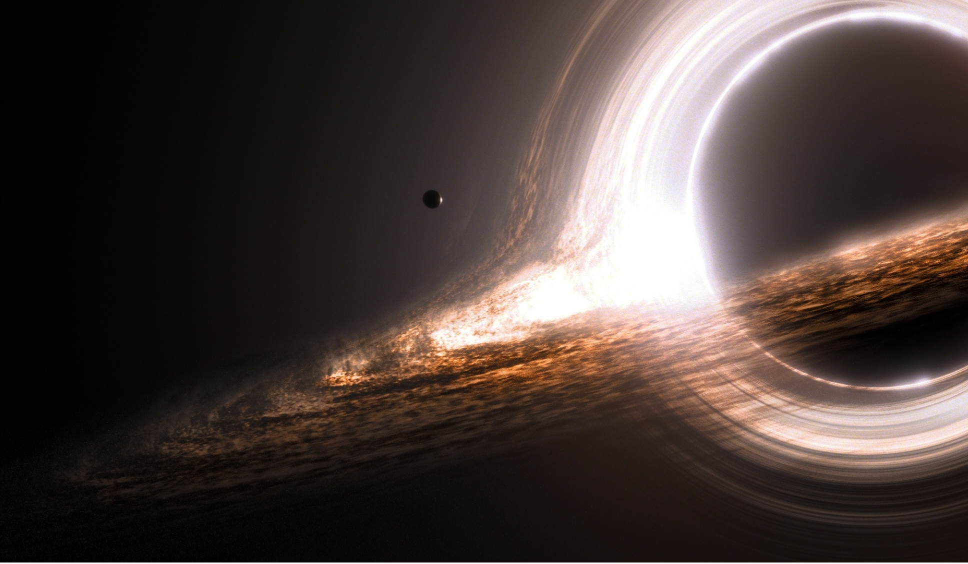
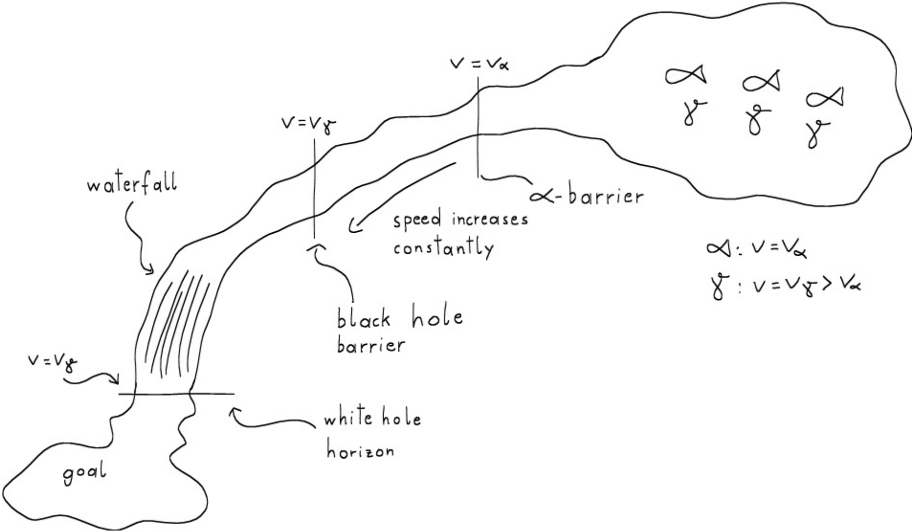
- 2016: LIGO discovers gravitational waves from BH merger
- 2019: Event Horizon Telescope publishes first image of BH shadow
- 2020: First black hole-neutron star merger
- 2026: to be discovered!

shadow of black hole M87 (distance: $5.3 \cdot 10^7$ ly, mass: $6.5 \cdot 10^9 M_\odot$)
photo released April 2019 by Event Horizon Telescope (EHT)



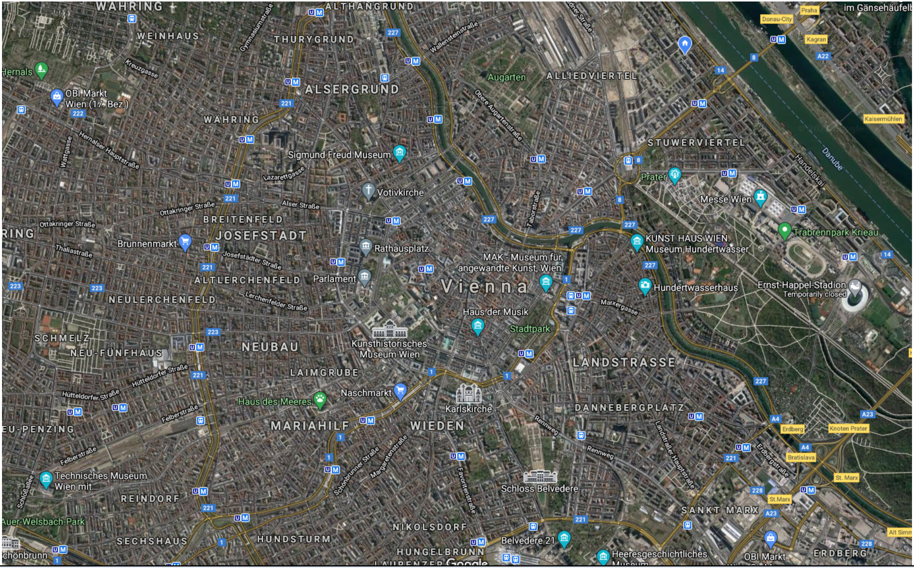
black hole simulation "Gargantua" for movie *Interstellar*
https://arxiv.org/pdf/1502.03808

Fishy analogy



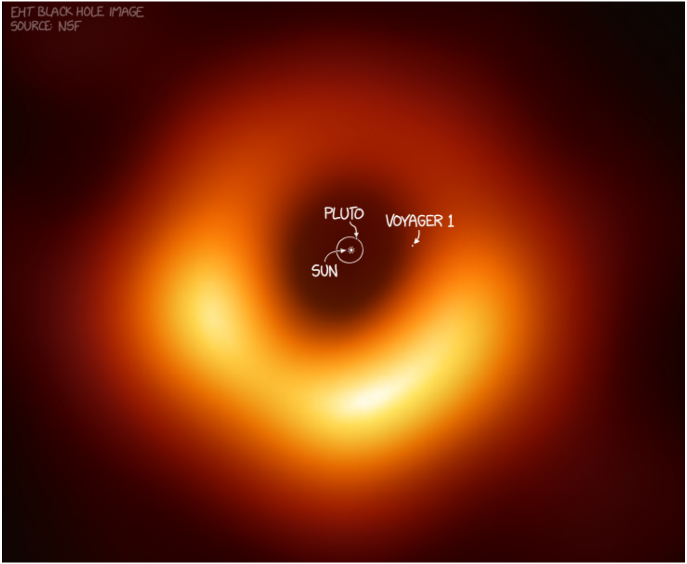
How large is a black hole? (a couple of kilometer)

stellar black holes: about the size of downtown Vienna

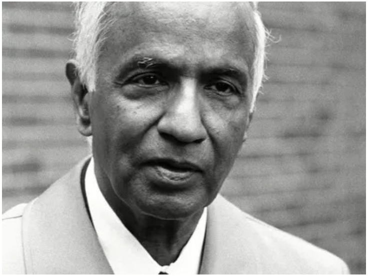


How large is a black hole? (several billion kilometer)

galactic black holes: about the size of our solar system



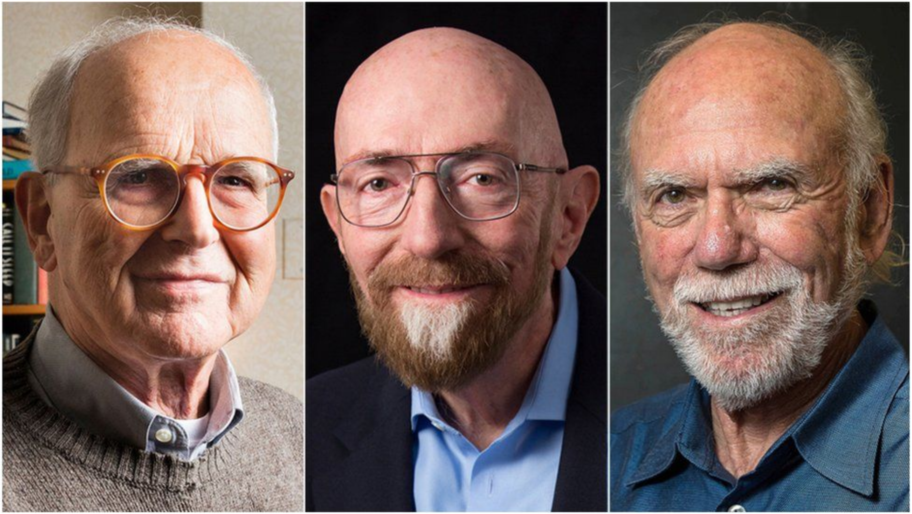
Physics nobel prize 1983



Subrahmanyan Chandrasekhar

star evolution (including gravitational collapse to black hole)

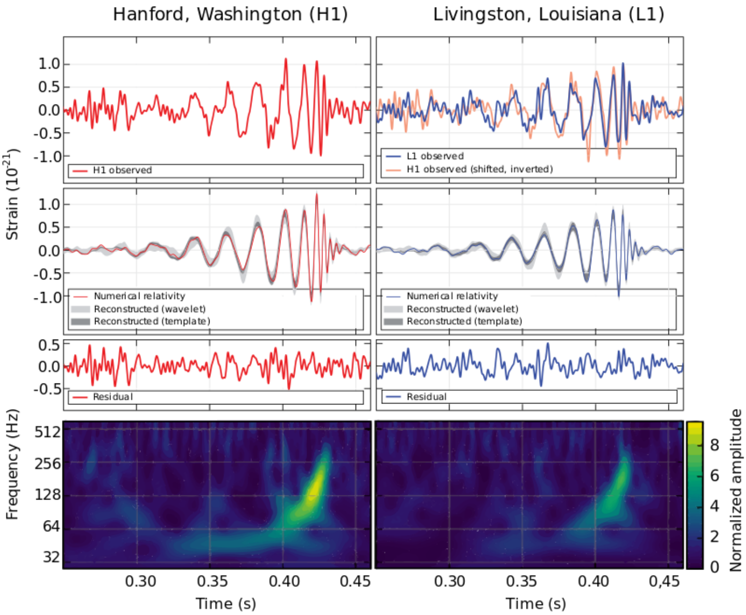
Physics nobel prize 2017



Rainer Weiss   Kip Thorne   Barry Barish

Detection of gravitational waves from black hole merger

Physics nobel prize 2017 (LIGO Experiment)



Physics nobel prize 2020

Roger Penrose

Andrea Ghez

Reinhard Genzel

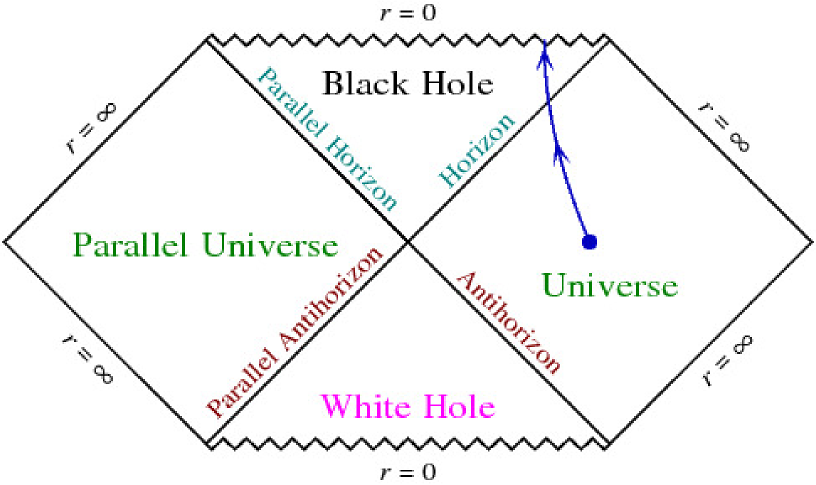
Black hole theory

Observation of black hole in center of Milky Way

Physics nobel prize 2020

Roger Penrose:

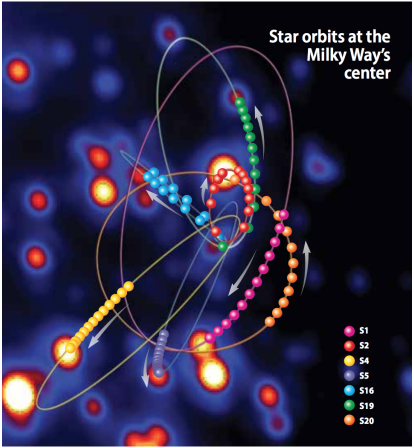
Made infinity finite & showed black holes robust GR prediction

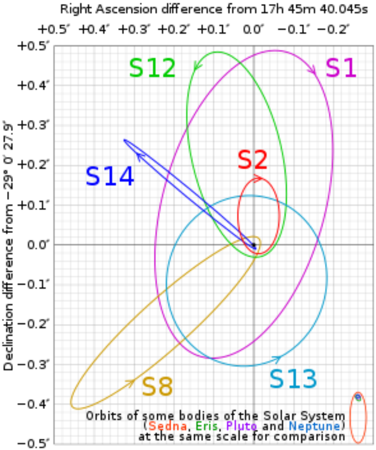


Physics nobel prize 2020

Andrea Ghez und Reinhard Genzel:

Detected supermassive black hole in center of Milky Way





How to detect black holes?

Experimental Evidence for Black Holes (BH):

- Stellar BH: gravitational collapse Chandrasekhar 1930
- Stellar BH: accretion disk Bolton, Webster, Murdin 1972

  Objects whose mass exceeds critical, $M > 3M_{\odot}$ (2006):

System	$P_{\rm orb}$ [days]	$f(M)$ [$M_{\odot}$]	Donor Spect. Type	Classification	$M_{\rm x}$ † [$M_{\odot}$]
GRS 1915+105[a]	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	,,	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
LMC X-1	4.229	0.14 ± 0.05	07 III	,,	> 4
XTE J1819-254	2.816	3.13 ± 0.13	B9 III	IMXB/Transient	7.1 ± 0.3
GRO J1655-40	2.620	2.73 ± 0.09	F3/5 IV	,,	6.3 ± 0.3
BW Cir[b]	2.545	5.74 ± 0.29	G5 IV	LMXB/Transient	> 7.8
GX 339-4	1.754	5.8 ± 0.5	–	,,	
LMC X-3	1.704	2.3 ± 0.3	B3 V	HMXB/Persistent	7.6 ± 1.3
XTE J1550-564	1.542	6.86 ± 0.71	G8/K8 IV	LMXB/Transient	9.6 ± 1.2
4U 1543-475	1.125	0.25 ± 0.01	A2 V	IMXB/Transient	9.4 ± 1.0
H1705-250	0.520	4.86 ± 0.13	K3/7 V	LMXB/Transient	6 ± 2
GS 1124-684	0.433	3.01 ± 0.15	K3/5 V	,,	7.0 ± 0.6
XTE J1859+226[c]	0.382	7.4 ± 1.1	–	,,	
GS2000+250	0.345	5.01 ± 0.12	K3/7 V	,,	7.5 ± 0.3
A0620-003	0.325	2.72 ± 0.06	K4 V	,,	11 ± 2
XTE J1650-500	0.321	2.73 ± 0.56	K4 V	,,	
GRS 1009-45	0.283	3.17 ± 0.12	K7/M0 V	,,	5.2 ± 0.6
GRO J0422+32	0.212	1.19 ± 0.02	M2 V	,,	4 ± 1
XTE J1118+480	0.171	6.3 ± 0.2	K5/M0 V	,,	6.8 ± 0.4

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Experimental Evidence for Black Holes (BH):

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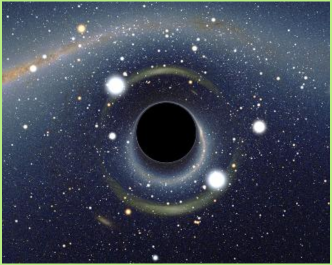
- Stellar BH: accretion disk Bolton, Webster, Murdin 1972
- Stellar BH merger: gravitational wave production LIGO '16
- Supermassive BH: Kepler orbits Ghez et al '08; Gilessen et al '09
- Supermassive BH: Shadow EHT '19
- Intermediate BH: little evidence $(100 - 10^6 M_\odot)$ GW190521
- Primordial BH: no evidence from cosmology
- Particle generated BH: no evidence from LHC

> - overwhelming evidence for stellar and supermassive BH
> - confirmed mass ranges: $3 - 142 M_\odot$ and $10^6 - 10^{10} M_\odot$
> - BH could exist in principle for all masses $> 10^{-5} g$

Why are BHs interesting for quantum gravity?

BH have apparently paradoxical properties

BH: simplest object in Universe



All properties determined by

- Mass M
- Spin J
- Charge Q

Black hole $\sim$ elementary particle

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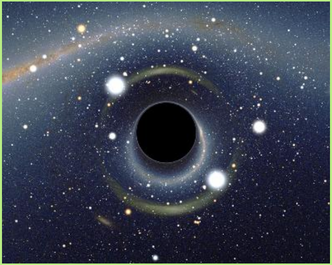

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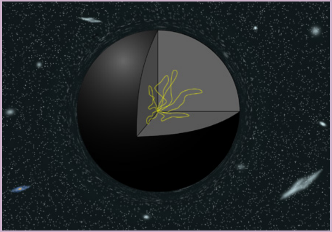

Quantum mechanics:

- BHs radiate
- BHs have entropy S_{BH}
- BHs behave holographically

Bekenstein–Hawking:

$$S_{\text{BH}} = \frac{A}{4}$$

Entropy comparison

Entropy of ideal gas:

$$S \sim V \sim L^d$$

V: volume; L: length; d: number of spatial dimensions

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BH entropy:

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A: area

BH = "black hole" or "Bekenstein–Hawking"

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Observe: area in 3d $\sim$ volume in 2d

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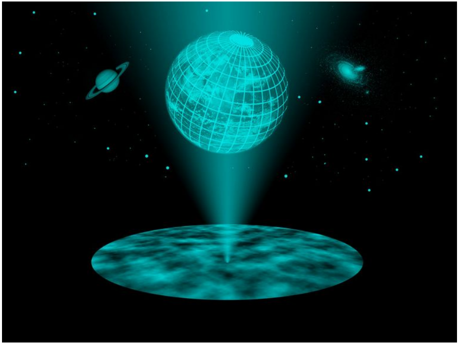
Daring idea by 't Hooft and Susskind in 1990ies:

Holographic Principle:

Theory with gravity in $d+1$ dimensions equivalent to theory without gravity in d dimensions

Consequences of holographic principle



One of the most fruitful ideas of contemporary physics:

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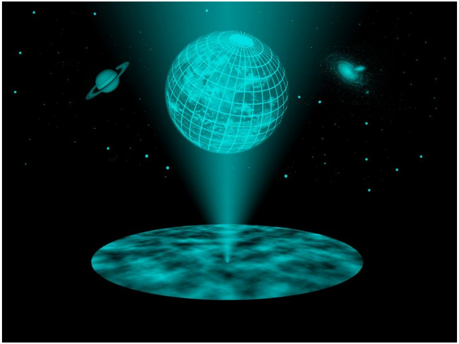
Consequences of holographic principle



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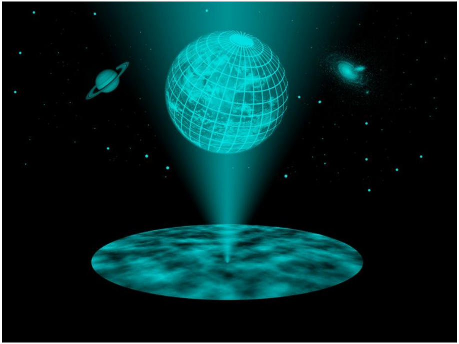

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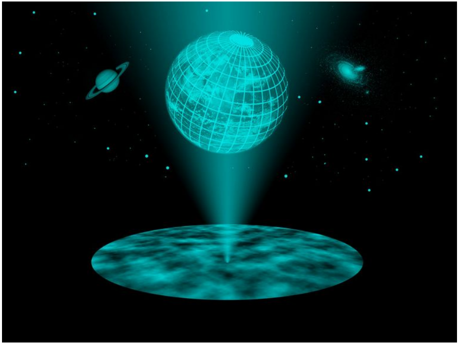

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- can describe same physical situation using two different formulations in different dimensions
- formulation in higher dimension is theory with gravity
- formulation in lower dimension is theory without gravity

Amusing, but so what?

...and why are there $> 20,000$ research papers on this?

- numerous applications

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heavy ion collisions at LHC, neutron stars, cold atoms, viscous hydrodynamics, holographic superconductors, strange metals, ...

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microscopic understanding of black holes, information paradox, black hole evaporation, quantum information aspects of black holes, ...

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Open key questions:

- How general is the holographic principle?
- Does it work in our Universe?
- If yes, how, and if no, when does it work?

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If you want to learn about black holes at TU Wien, here are some options:

- lecture "Black Holes I", WS25/26

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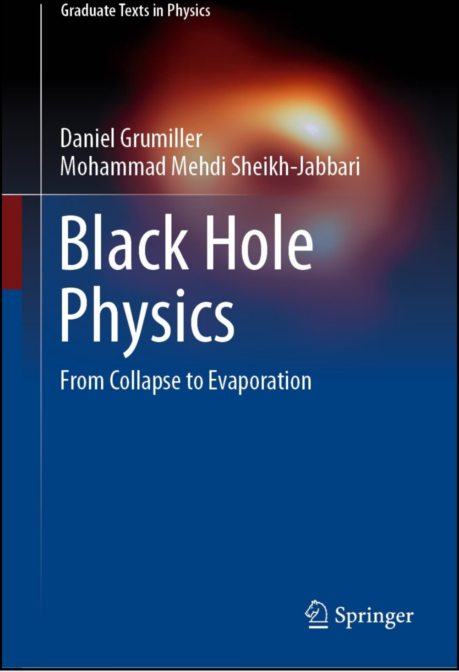
Near future: new professor in theoretical high energy physics — additional opportunities for students!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Mohammad Mehdi Sheikh-Jabbari
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