Black holes and exotic compact objects

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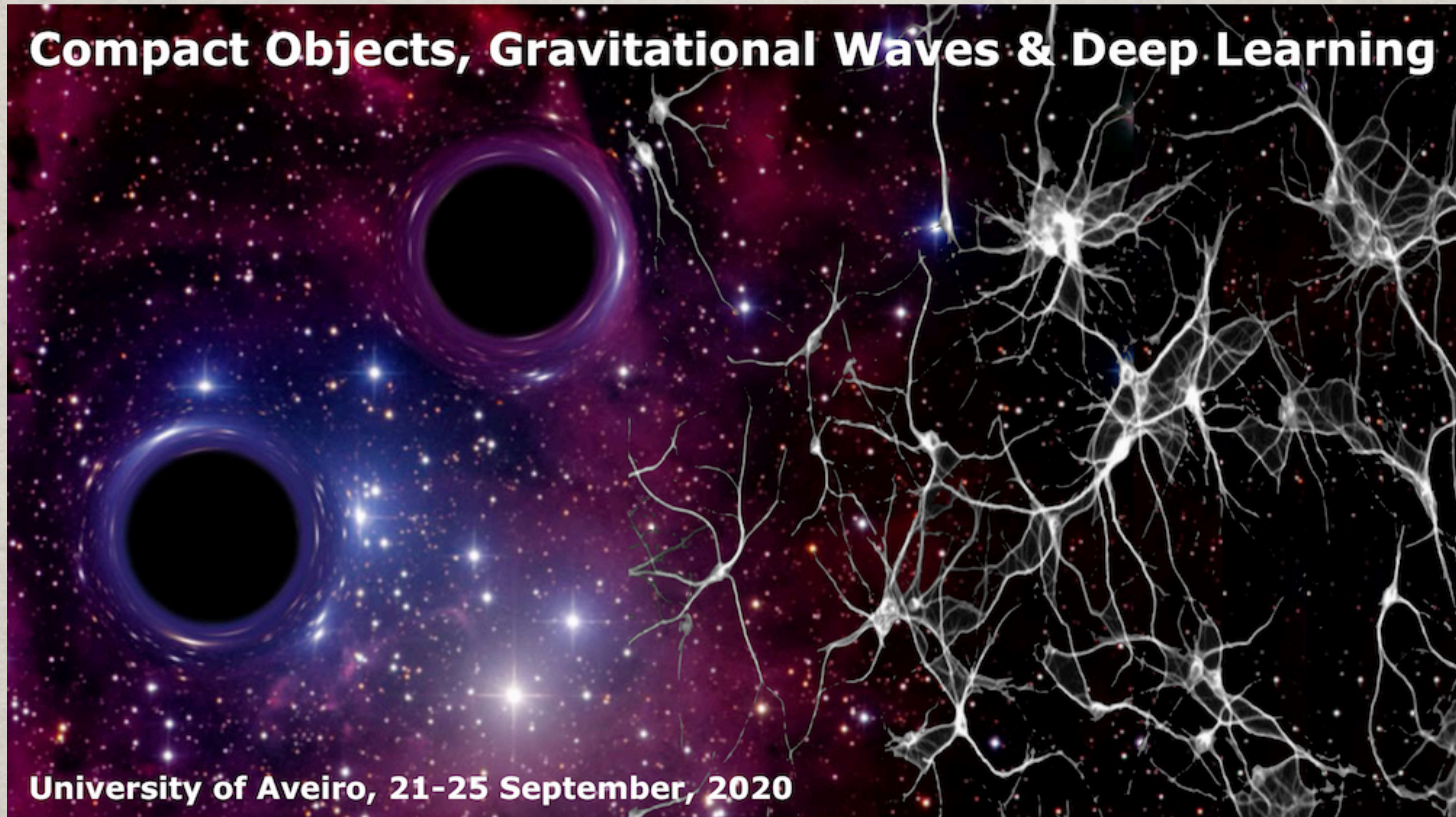


FCT Fundação para a Ciência e a Tecnologia

Grav
The Gravity group @ Aveiro University, Portugal

CIDMA

MSCA RISE

Plan of the lectures:

Lecture 1
Black holes: astrophysical evidence and a theory (brief) timeline

Lecture 2
Spherical black holes: the Schwarzschild solution

Lecture 3
Spinning black holes: the Kerr solution

Lecture 4
Exotic compact objects (ECOs): the example of bosonic stars

Lecture 5
Non-Kerr black holes

Historically,
astrophysical black hole candidates arose as radio sources (Cygnus A, 1939)
or
X-ray sources (Cygnus X-1, 1964)

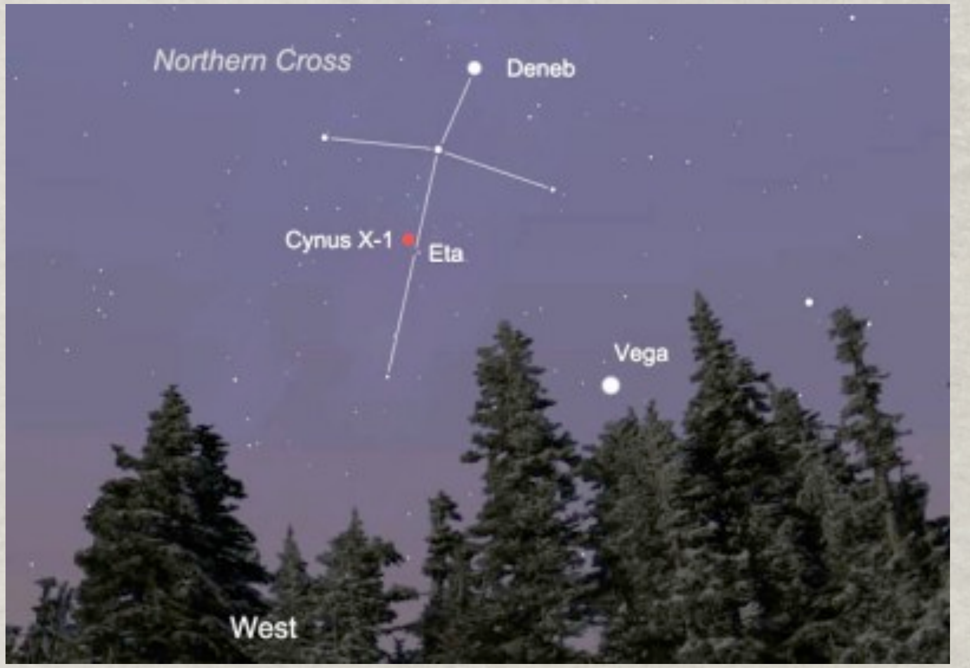
Narayan and McClintock, 1312.6698

The first (stellar mass) black hole candidate: Cygnus X-1

The first (stellar mass) black hole candidate: Cygnus X-1

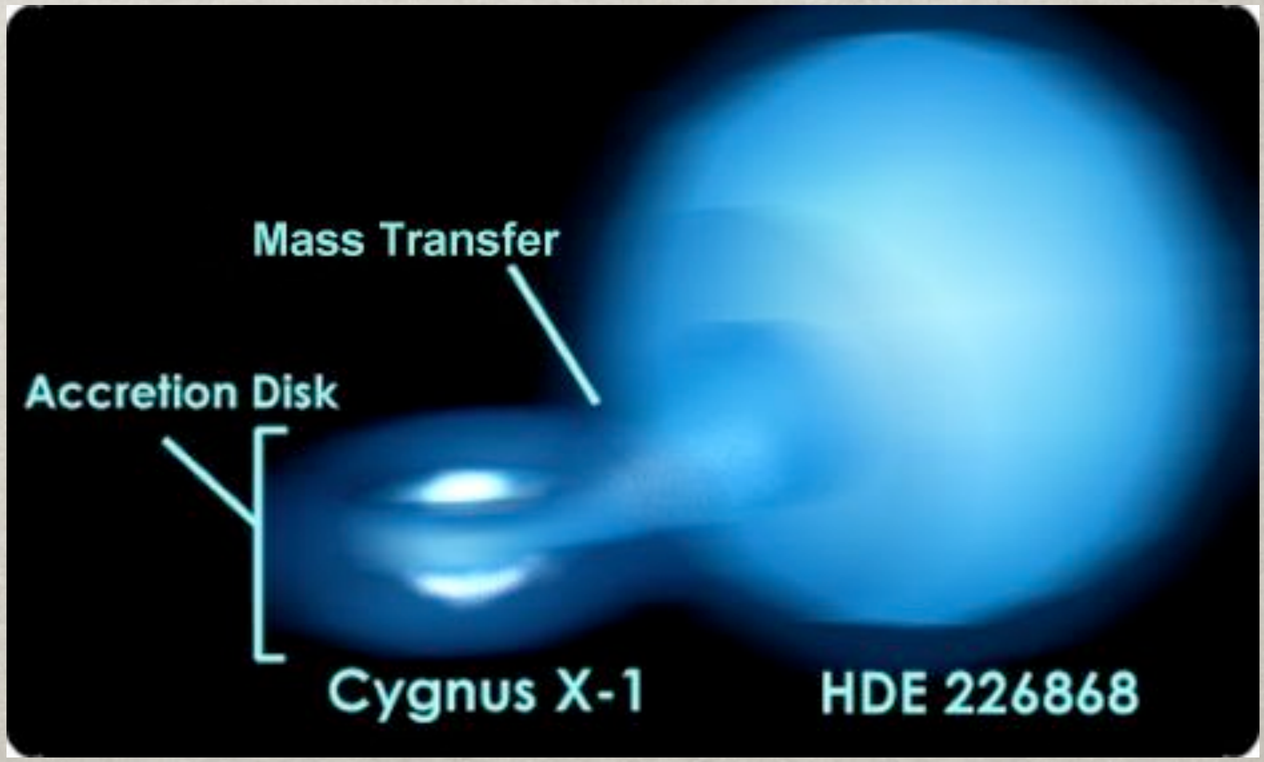
Estimated mass:
14.8 solar masses
(radius 44 kms)

Orosz, J. A. et al., The Astrophysical Journal 742 (2011) 84



Spin measurements:
Claim a>0.92 at 3 sigma level.

Gou, L. et al., Astrophysical Journal 742 (2011) 85



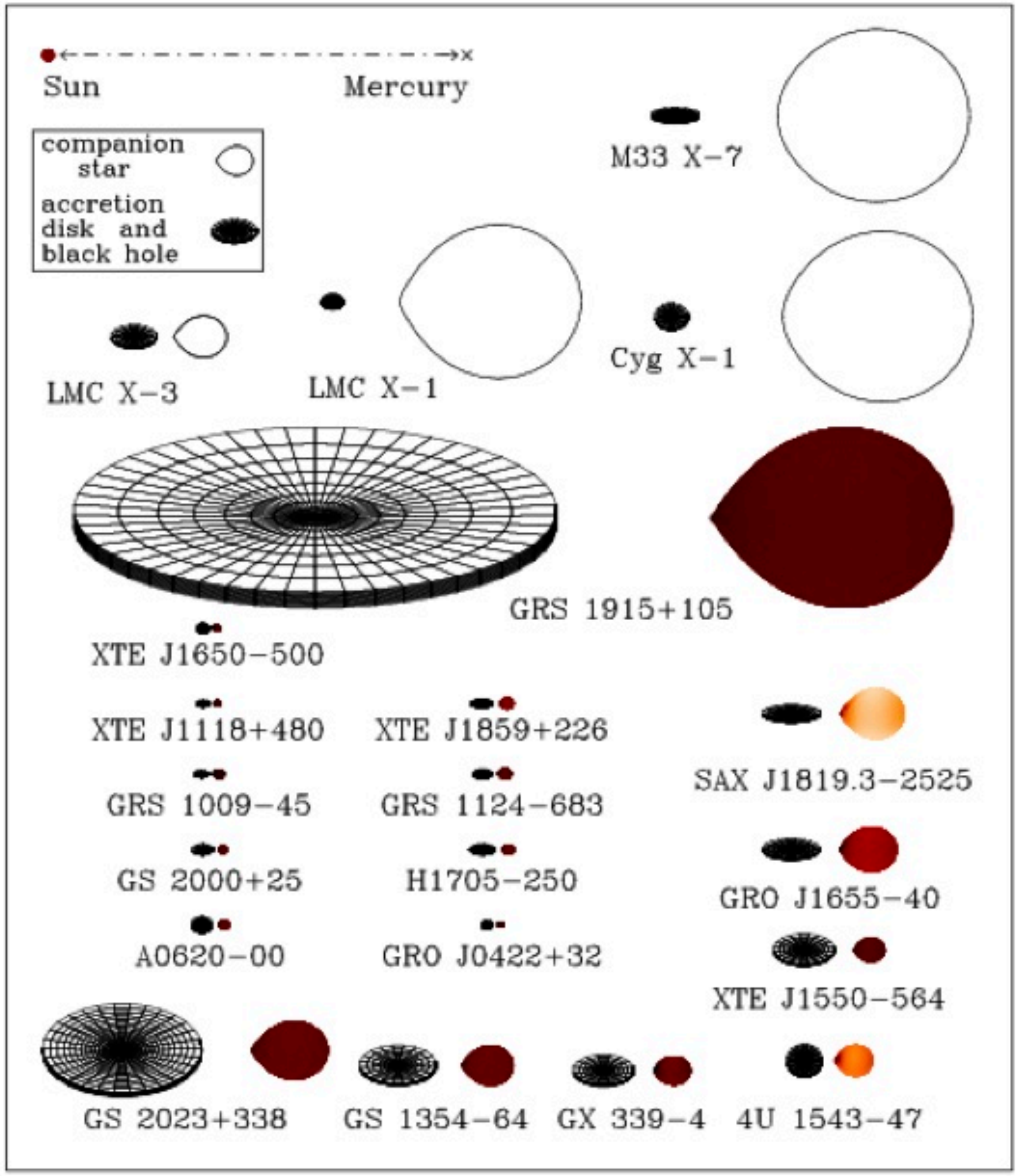
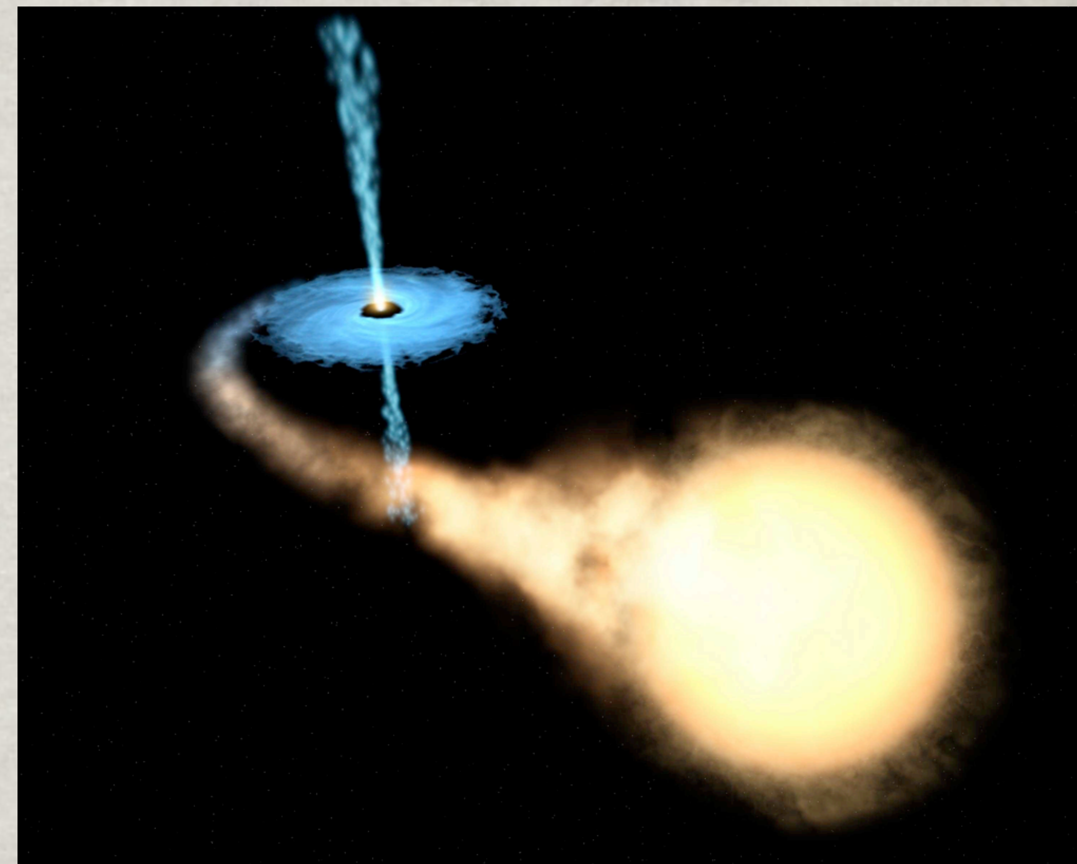


Figure 1.4 Sketches of 21 black hole binaries (see scale and legend in the upper-left corner). The tidally-distorted shapes of the companion stars are accurately rendered in Roche geometry. The black holes are located at the centers of the disks. A disk's tilt indicates the inclination angle i of the binary, where $i = 0$ corresponds to a system that is viewed face-on; e.g., $i = 21^\circ$ for 4U 1543–47 (bottom right) and $i = 75^\circ$ for M33 X–7 (top right). The size of a system is largely set by the orbital period, which ranges from 33.9 days for the giant system GRS 1915+105 to 0.2 days for tiny XTE J1118+480. Three systems hosting persistent X-ray sources — M33 X–7, LMC X–1 and Cyg X–1 — are located at the top. The other 18 systems are transient sources. (Figure courtesy of J. Orosz.)



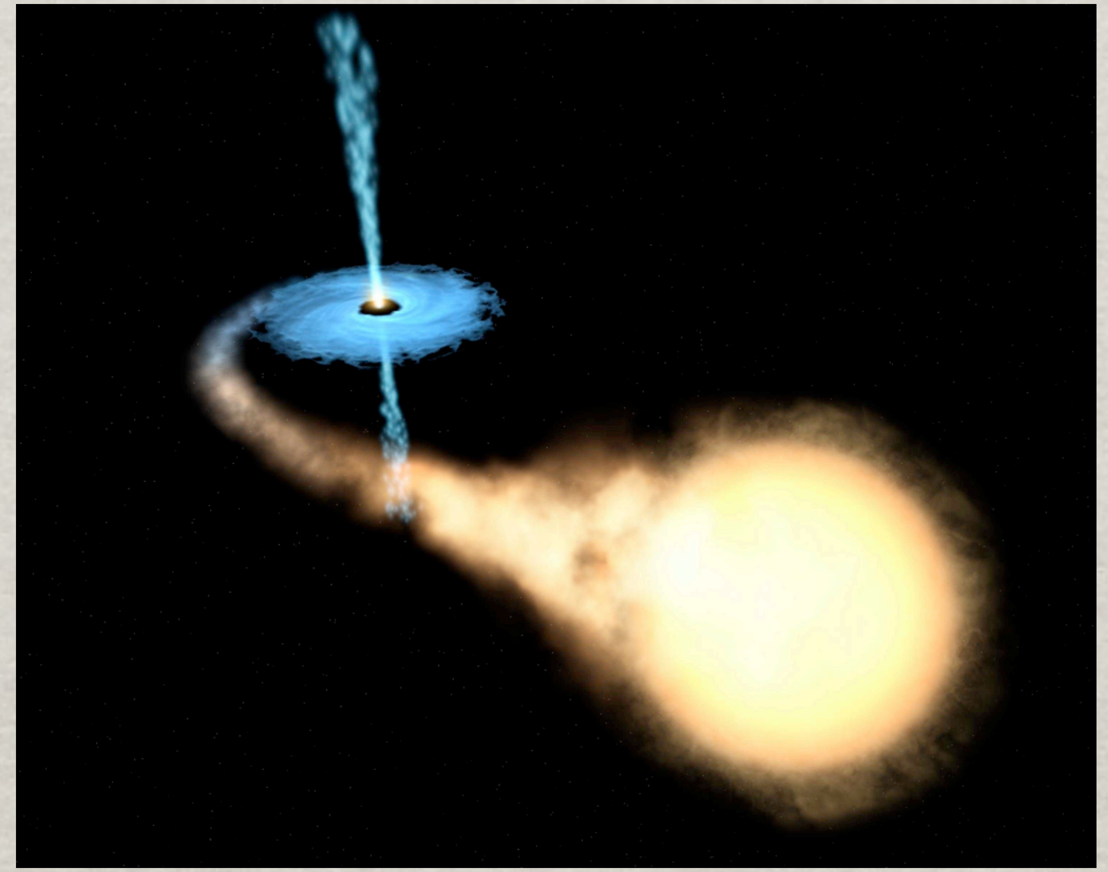
Artistic impression
of an accretion disk
around a stellar mass BH-star binary

Electromagnetic channel: X-ray band

Narayan and McClintock (2013), ArXiv:1312.6698

The iron Kα line method:

Matter accretion onto BHs provides electromagnetic signatures to infer BH properties.



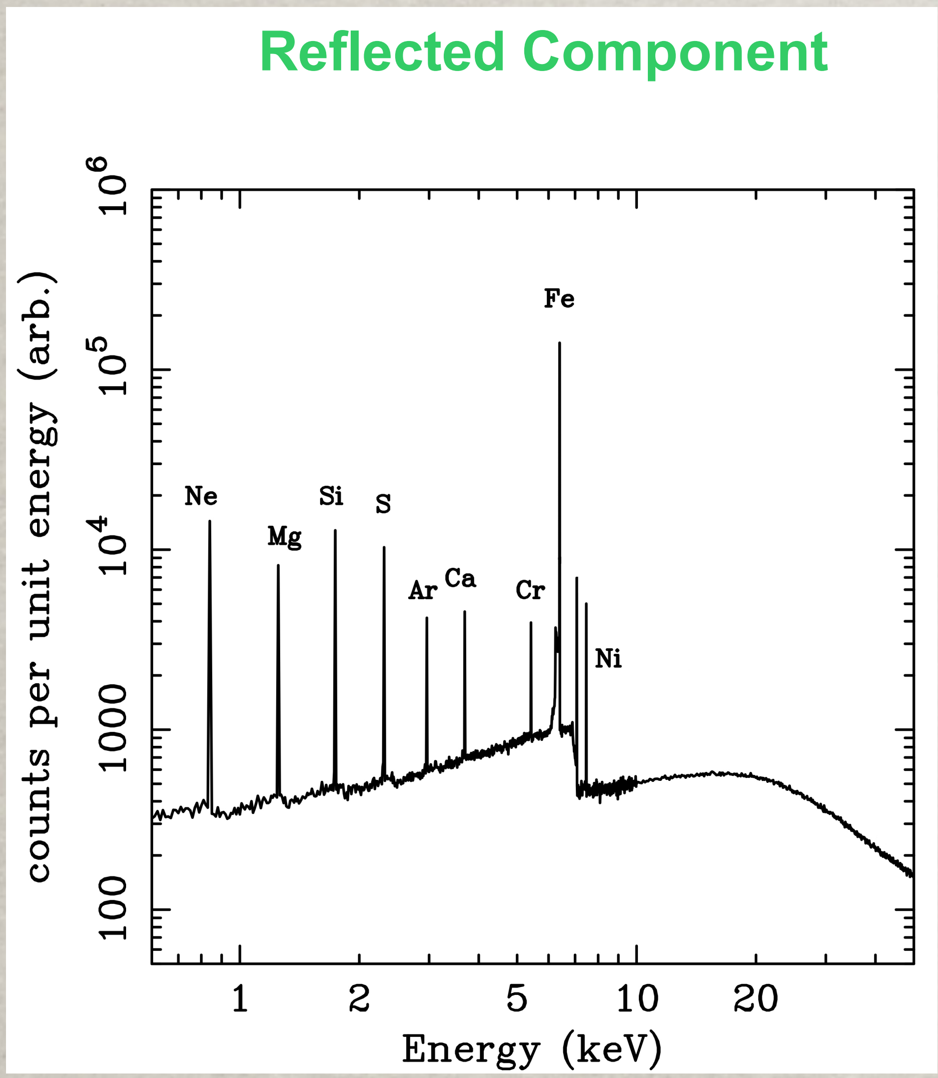
Artistic impression
of an accretion disk
around a stellar mass BH-star binary

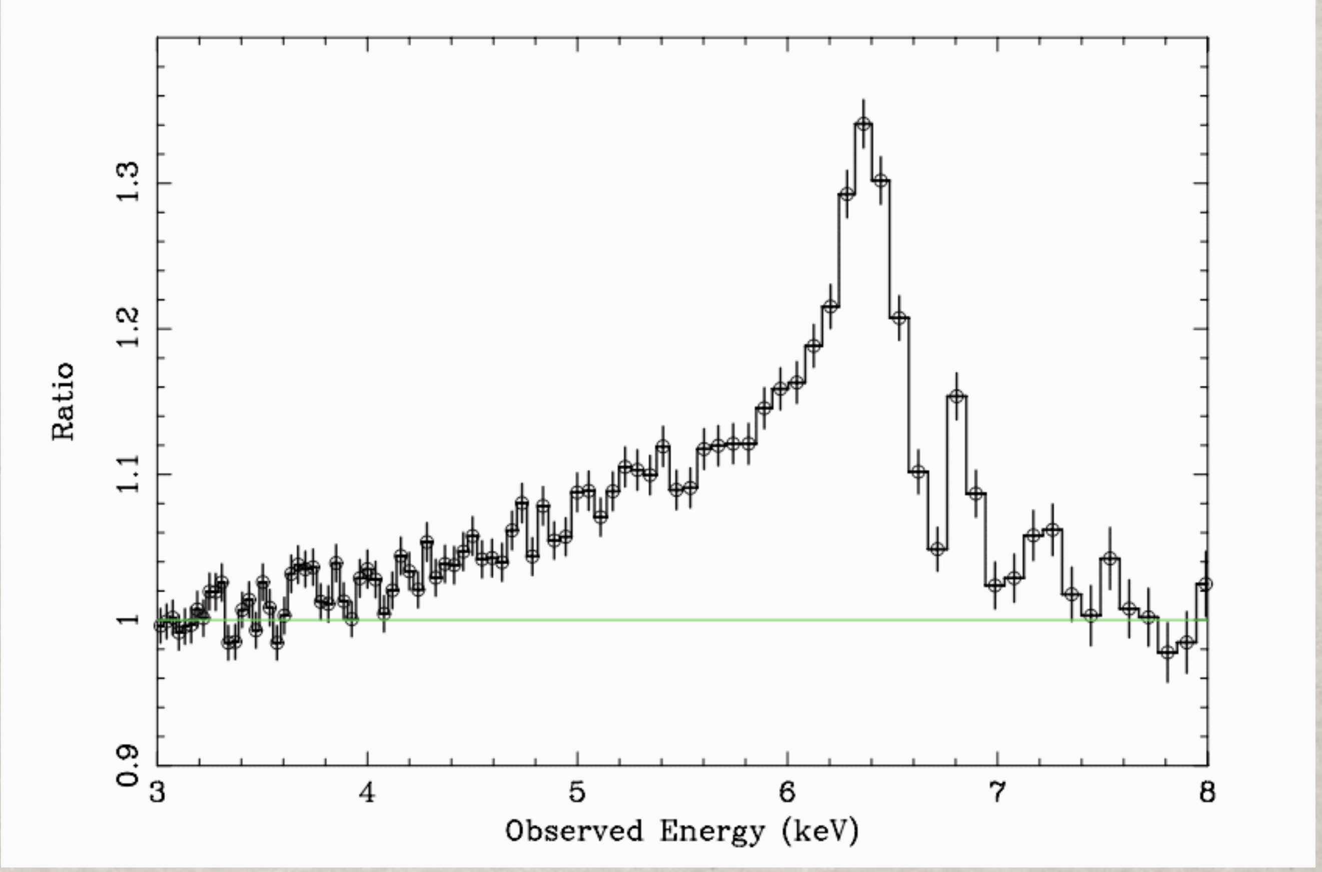
Studying the extremely broad and redshifted iron Kα line around ~ 6.4 keV, observed in X-ray binaries probes the BH geometry and constrains its parameters (iron line method), see e.g. Fabian (2012)

The iron line method:

Propagation in strong gravity makes the **locally** Dirac delta-like line...

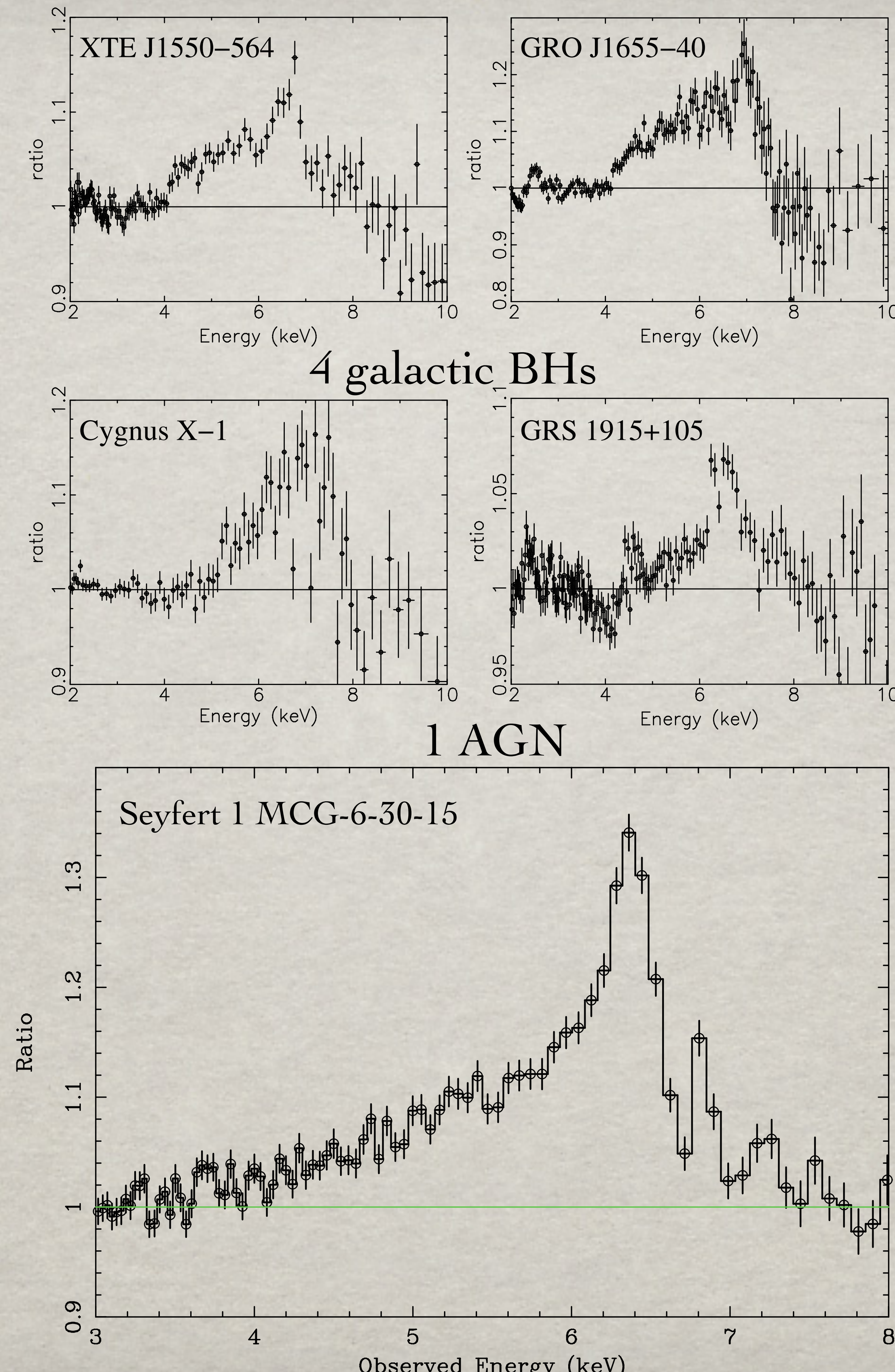
... broad and skew at the **observation** point...





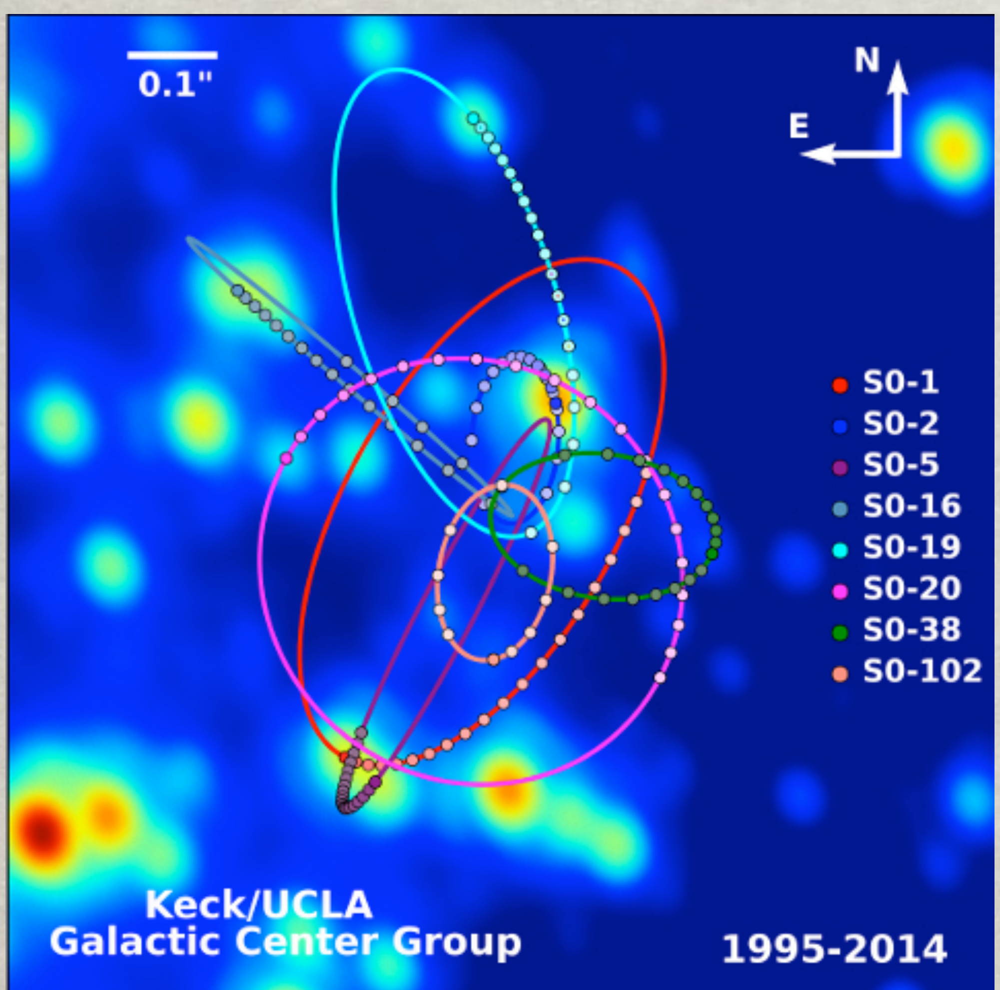
Guainazzi, Ap&SS 320 (2009) 129

And this is indeed what one sees in real data

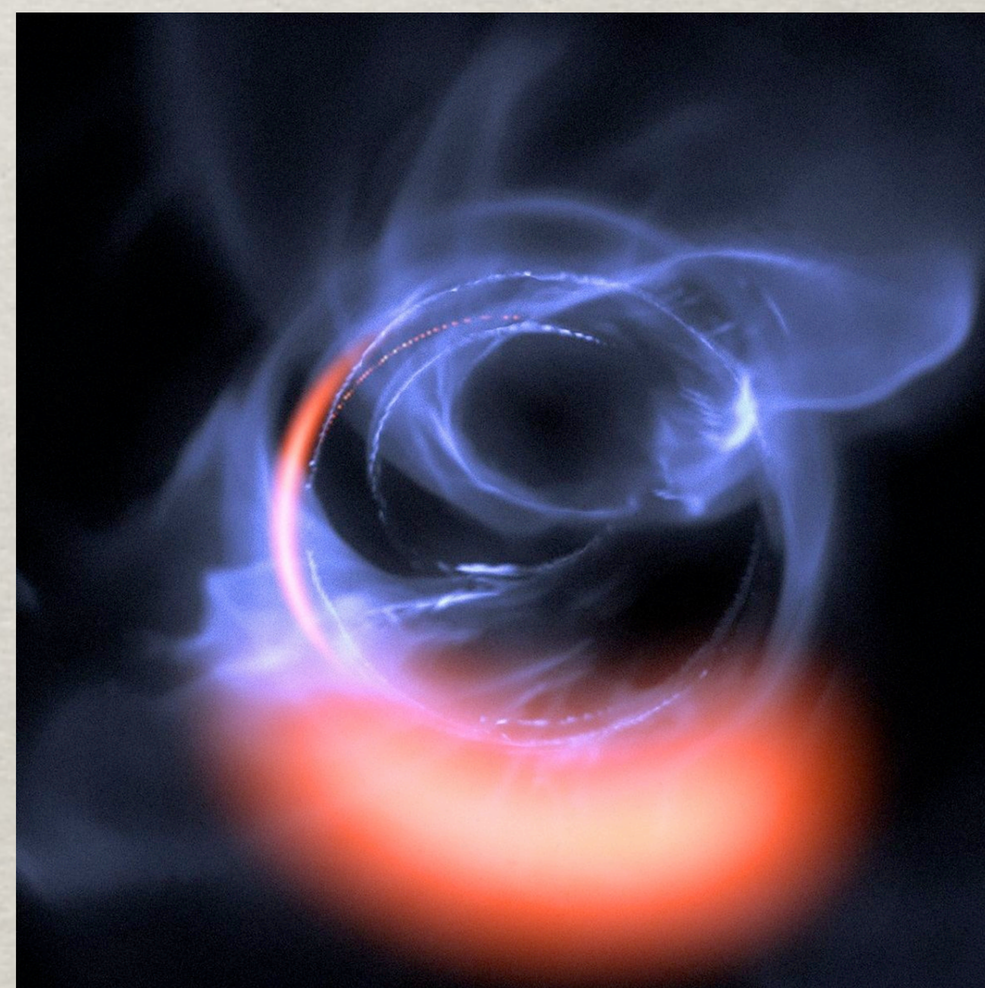


Guainazzi, Ap&SS 320 (2009) 129

Infrared observations, with adaptive optics, have provided the strongest evidence for a supermassive black hole at the centre of our galaxy



UCLA Galactic Center Group



Gravity collaboration (ESO)

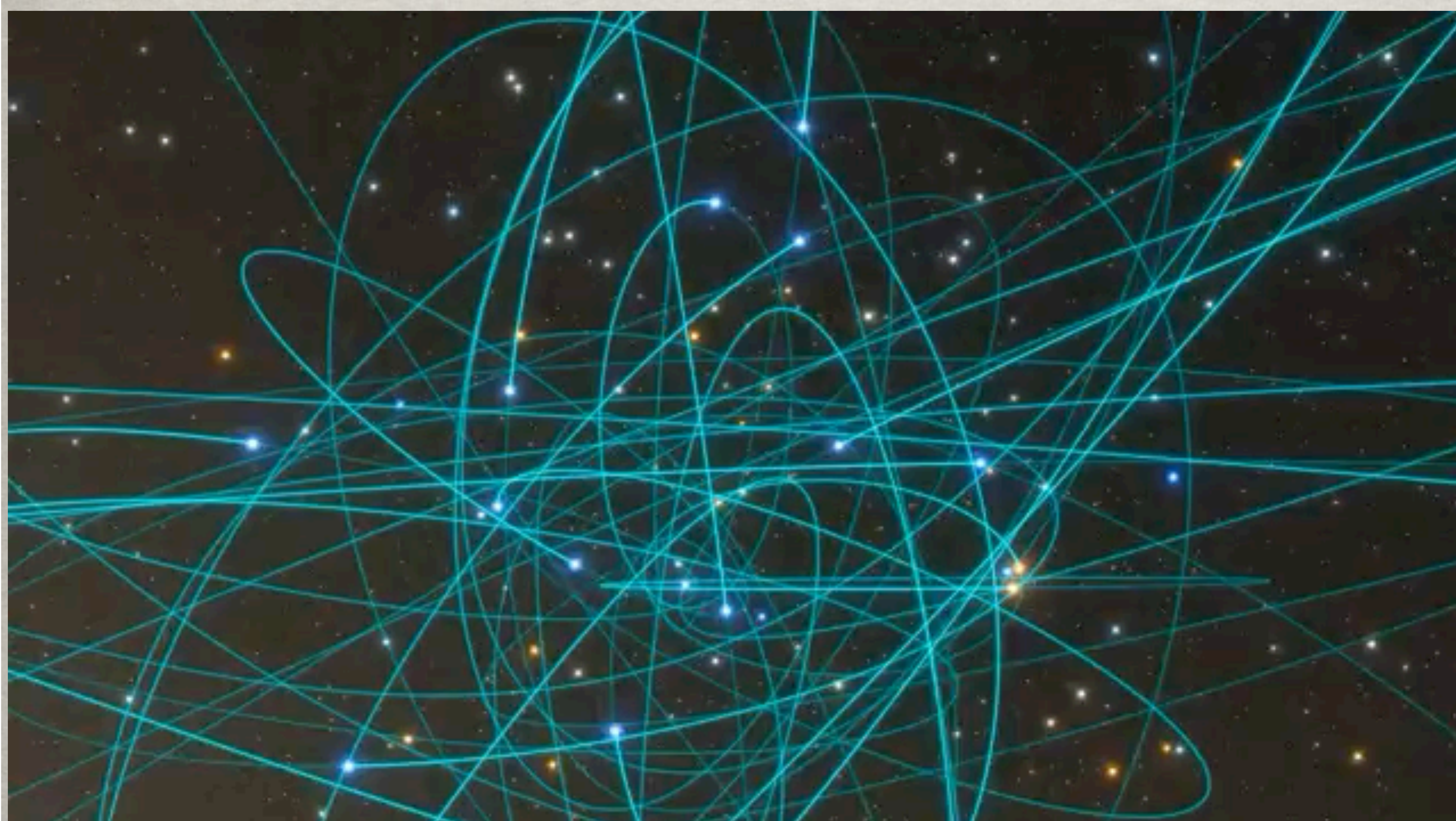
Sagittarius A*

From the motion of star S2 (say), estimated mass is 4.1 million solar masses

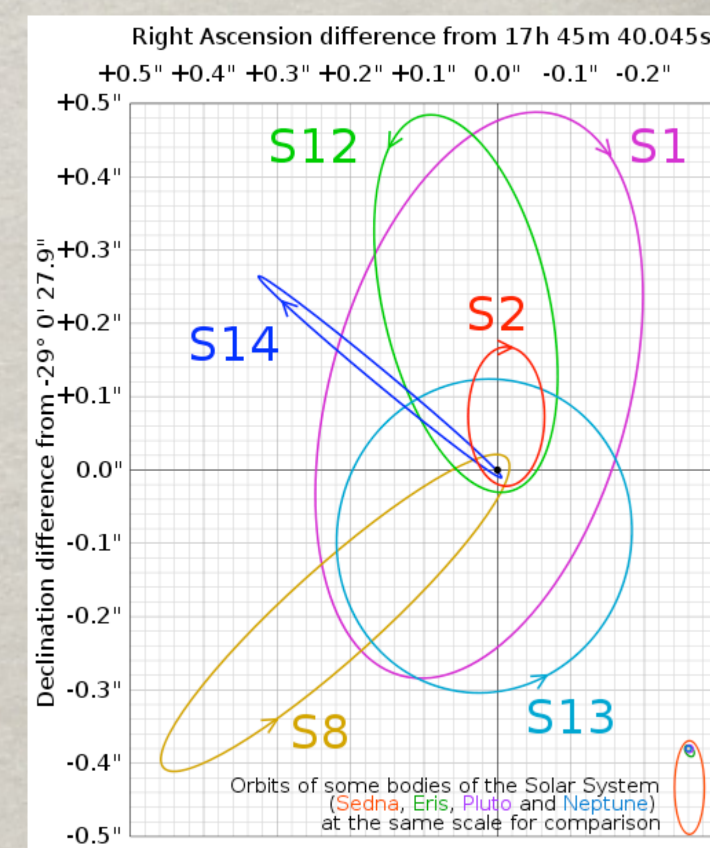
Ghez, A. M. et al., (2008) Astrophysical Journal 689 (2): 1044–1062

Estimated radius no more than 6.2 light hours

Ghez, A. M. et al., (2005) The Astrophysical Journal 620 (2): 744–757



Eisenhauer, F. et al., (2005)
The Astrophysical Journal (628): 246–259



A&A 615, L15 (2018)
https://doi.org/10.1051/0004-6361/201833718

Astronomy & Astrophysics

Letter to the Editor

Detection of the gravitational redshift in the orbit of the star S2 near the Galactic centre massive black hole[⋆]

GRAVITY Collaboration[⋆⋆]: R. Abuter[8], A. Amorim[6,14], N. Anugu[7], M. Bauböck[1], M. Benisty[5], J. P. Berger[5,8], N. Blind[10], H. Bonnet[8], W. Brandner[3], A. Buron[1], C. Collin[2], F. Chapron[2], Y. Clénet[2], V. Coudé du Foresto[2], P. T. de Zeeuw[12,1], C. Deen[1], F. Delplancke-Ströbele[8], R. Dembet[8,2], J. Dexter[1], G. Duvert[5], A. Eckart[4,11], F. Eisenhauer[1,⋆⋆⋆], G. Finger[8], N. M. Förster Schreiber[1], P. Fédou[2], P. Garcia[7,14], R. Garcia Lopez[15,3], F. Gao[1], E. Gendron[2], R. Genzel[1,13], S. Gillessen[1], P. Gordo[6,14], M. Habibi[1], X. Haubois[9], M. Haug[8], F. Haußmann[1], Th. Henning[3], S. Hippler[3], M. Horrobin[4], Z. Hubert[2,3], N. Hubin[8], A. Jimenez Rosales[1], L. Jochum[8], L. Jocou[5], A. Kaufer[9], S. Kellner[11], S. Kendrew[16,3], P. Kervella[2], Y. Kok[1], M. Kulas[3], S. Lacour[2], V. Lapeyrère[2], B. Lazareff[5], J.-B. Le Bouquin[5], P. Léna[2], M. Lippa[1], R. Lenzen[3], A. Mérand[8], E. Müler[8,3], U. Neumann[3], T. Ott[1], L. Palanca[9], T. Paumard[2], L. Pasquini[8], K. Perraut[5], G. Perrin[2], O. Pfuhl[1], P. M. Plewa[1], S. Rabien[1], A. Ramírez[9], J. Ramos[3], C. Rau[1], G. Rodríguez-Coira[2], R.-R. Rohloff[3], G. Rousset[2], J. Sanchez-Bermudez[9,3], S. Scheithauer[3], M. Schöller[8], N. Schuler[9], J. Spyromilio[8], O. Straub[2], C. Straubmeier[4], E. Sturm[1], L. J. Tacconi[1], K. R. W. Tristram[9], F. Vincent[2], S. von Fellenberg[1], I. Wank[4], I. Waisberg[1], F. Widmann[1], E. Wieprecht[1], M. Wiest[4], E. Wiezorrek[1], J. Woillez[8], S. Yazici[1,4], D. Ziegler[2], and G. Zins[9]

(Affiliations can be found after the references)

Received 26 June 2018 / Accepted 29 June 2018

ABSTRACT

The highly elliptical, 16-year-period orbit of the star S2 around the massive black hole candidate Sgr A* is a sensitive probe of the gravitational field in the Galactic centre. Near pericentre at 120 AU ≈ 1400 Schwarzschild radii, the star has an orbital speed of ≈7650 km s^{-1}, such that the first-order effects of Special and General Relativity have now become detectable with current capabilities. Over the past 26 years, we have monitored the radial velocity and motion on the sky of S2, mainly with the SINFONI and NACO adaptive optics instruments on the ESO Very Large Telescope, and since 2016 and leading up to the pericentre approach in May 2018, with the four-telescope interferometric beam-combiner instrument GRAVITY. From data up to and including pericentre, we robustly detect the combined gravitational redshift and relativistic transverse Doppler effect for S2 of $z = \Delta\lambda/\lambda \approx 200$ km s^{-1}/c with different statistical analysis methods. When parameterising the post-Newtonian contribution from these effects by a factor f, with $f = 0$ and $f = 1$ corresponding to the Newtonian and general relativistic limits, respectively, we find from posterior fitting with different weighting schemes $f = 0.90 \pm 0.09|_{stat} \pm 0.15|_{sys}$. The S2 data are inconsistent with pure Newtonian dynamics.

Key words. Galaxy: center – gravitation – black hole physics

A&A 636, L5 (2020)
https://doi.org/10.1051/0004-6361/202037813

Astronomy & Astrophysics

LETTER TO THE EDITOR

Detection of the Schwarzschild precession in the orbit of the star S2 near the Galactic centre massive black hole

GRAVITY Collaboration:* R. Abuter[8], A. Amorim[6,13], M. Bauböck[1], J. P. Berger[5,8], H. Bonnet[8], W. Brandner[3], V. Cardoso[13,15], Y. Clénet[2], P. T. de Zeeuw[11,1], J. Dexter[14,1], A. Eckart[4,10,**], F. Eisenhauer[1], N. M. Förster Schreiber[1], P. Garcia[7,13], F. Gao[1], E. Gendron[2], R. Genzel[1,12,**], S. Gillessen[1,**], M. Habibi[1], X. Haubois[9], T. Henning[3], S. Hippler[3], M. Horrobin[4], A. Jiménez-Rosales[1], L. Jochum[9], L. Jocou[5], A. Kaufer[9], P. Kervella[2], S. Lacour[2], V. Lapeyrère[2], J.-B. Le Bouquin[5], P. Léna[2], M. Nowak[17,2], T. Ott[1], T. Paumard[2], K. Perraut[5], G. Perrin[2], O. Pfuhl[8,1], G. Rodríguez-Coira[2], J. Shangguan[1], S. Scheithauer[3], J. Stadler[1], O. Straub[1], C. Straubmeier[4], E. Sturm[1], L. J. Tacconi[1], F. Vincent[2], S. von Fellenberg[1], I. Waisberg[16,1], F. Widmann[1], E. Wieprecht[1], E. Wiezorrek[1], J. Woillez[8], S. Yazici[1,4], and G. Zins[9]

(Affiliations can be found after the references)

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ABSTRACT

The star S2 orbiting the compact radio source Sgr A* is a precision probe of the gravitational field around the closest massive black hole (candidate). Over the last 2.7 decades we have monitored the star's radial velocity and motion on the sky, mainly with the SINFONI and NACO adaptive optics (AO) instruments on the ESO VLT, and since 2017, with the four-telescope interferometric beam combiner instrument GRAVITY. In this Letter we report the first detection of the General Relativity (GR) Schwarzschild Precession (SP) in S2's orbit. Owing to its highly elliptical orbit ($e = 0.88$), S2's SP is mainly a kink between the pre-and post-pericentre directions of motion $\approx\pm1$ year around pericentre passage, relative to the corresponding *Kepler* orbit. The superb 2017–2019 astrometry of GRAVITY defines the pericentre passage and outgoing direction. The incoming direction is anchored by 118 NACO-AO measurements of S2's position in the infrared reference frame, with an additional 75 direct measurements of the S2-Sgr A* separation during bright states ("flares") of Sgr A*. Our 14-parameter model fits for the distance, central mass, the position and motion of the reference frame of the AO astrometry relative to the mass, the six parameters of the orbit, as well as a dimensionless parameter f_{SP} for the SP ($f_{SP} = 0$ for Newton and 1 for GR). From data up to the end of 2019 we robustly detect the SP of S2, $\delta\phi \approx 12'$ per orbital period. From posterior fitting and MCMC Bayesian analysis with different weighting schemes and bootstrapping we find $f_{SP} = 1.10 \pm 0.19$. The S2 data are fully consistent with GR. Any extended mass inside S2's orbit cannot exceed $\approx$0.1% of the central mass. Any compact third mass inside the central arcsecond must be less than about 1000 $M_\odot$.

Key words. black hole physics – Galaxy: nucleus – gravitation – relativistic processes

A&A 618, L10 (2018)
https://doi.org/10.1051/0004-6361/201834294

Astronomy & Astrophysics

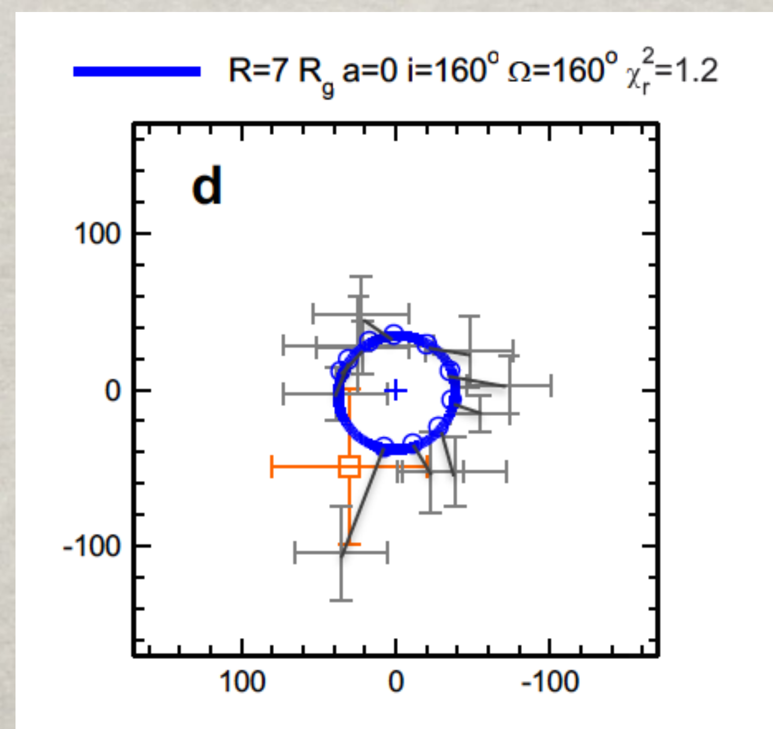
LETTER TO THE EDITOR

Detection of orbital motions near the last stable circular orbit of the massive black hole SgrA*[⋆]

GRAVITY Collaboration[⋆⋆]: R. Abuter[8], A. Amorim[6,14], M. Bauböck[1], J. P. Berger[5], H. Bonnet[8], W. Brandner[3], Y. Clénet[2], V. Coudé du Foresto[2], P. T. de Zeeuw[10,1], C. Deen[1], J. Dexter[1,⋆⋆⋆], G. Duvert[5], A. Eckart[4,13], F. Eisenhauer[1], N. M. Förster Schreiber[1], P. Garcia[7,9,14], F. Gao[1], E. Gendron[2], R. Genzel[1,11], S. Gillessen[1], P. Guajardo[9], M. Habibi[1], X. Haubois[9], Th. Henning[3], S. Hippler[3], M. Horrobin[4], A. Huber[3], A. Jiménez-Rosales[1], L. Jocou[5], P. Kervella[2], S. Lacour[2,1], V. Lapeyrère[2], B. Lazareff[5], J.-B. Le Bouquin[5], P. Léna[2], M. Lippa[1], T. Ott[1], J. Panduro [3], T. Paumard[2,⋆⋆⋆], K. Perraut[5], G. Perrin[2], O. Pfuhl[1,⋆⋆⋆], P. M. Plewa[1], S. Rabien[1], G. Rodríguez-Coira[2], G. Rousset[2], A. Sternberg[12,15], O. Straub[2], C. Straubmeier[4], E. Sturm[1], L. J. Tacconi[1], F. Vincent[2], S. von Fellenberg[1], I. Waisberg[1], F. Widmann[1], E. Wieprecht[1], E. Wiezorrek[1], J. Woillez[8], and S. Yazici[1,4]

(Affiliations can be found after the references)

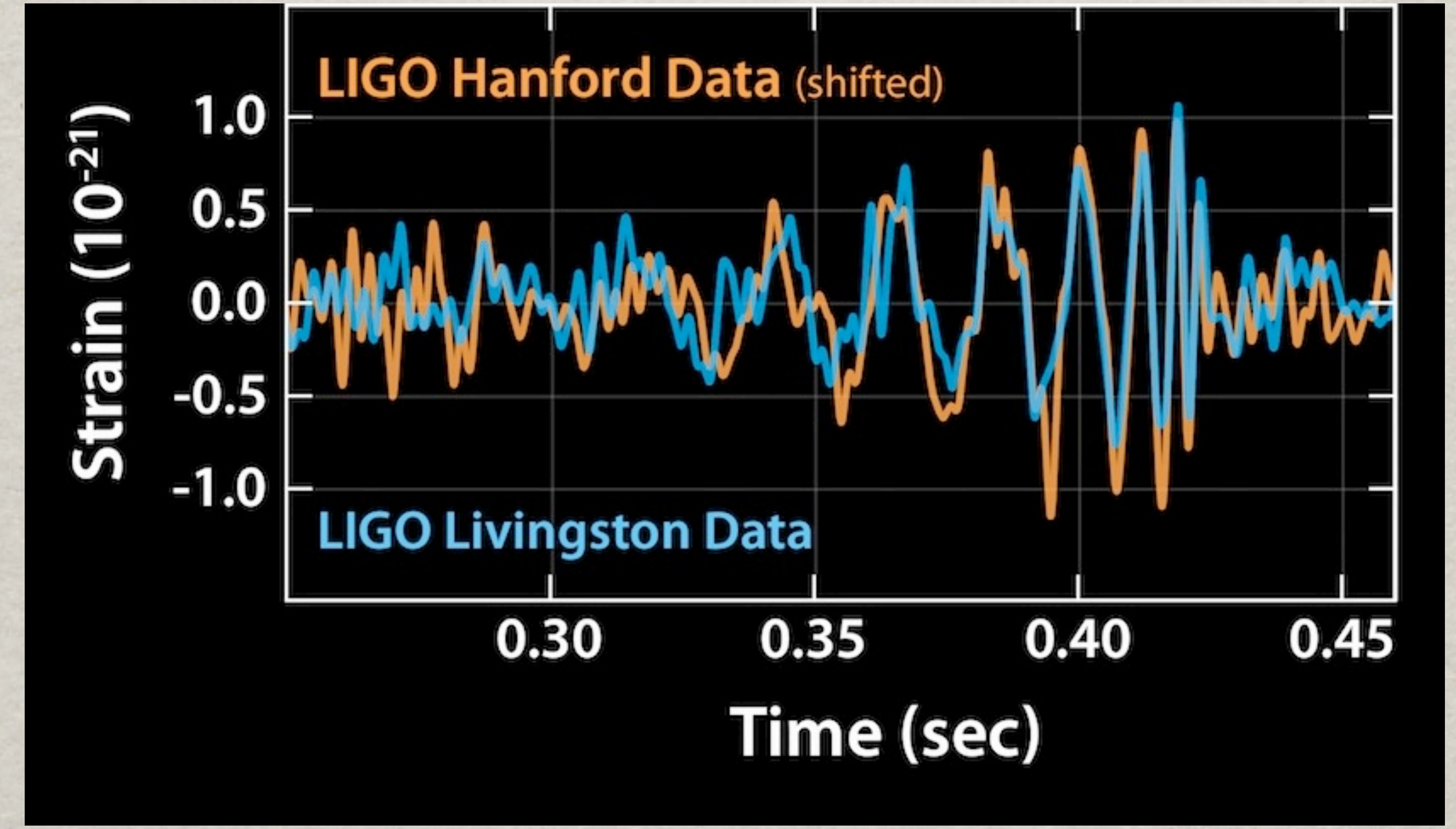
Received 21 September 2018 / Accepted 5 October 2018



Motion at r=7M
orbit of a compact "hot spot"

The spectacular detection of transient gravitational waves by the LIGO-Virgo collaboration opened a new channel of evidence for the existence of black holes

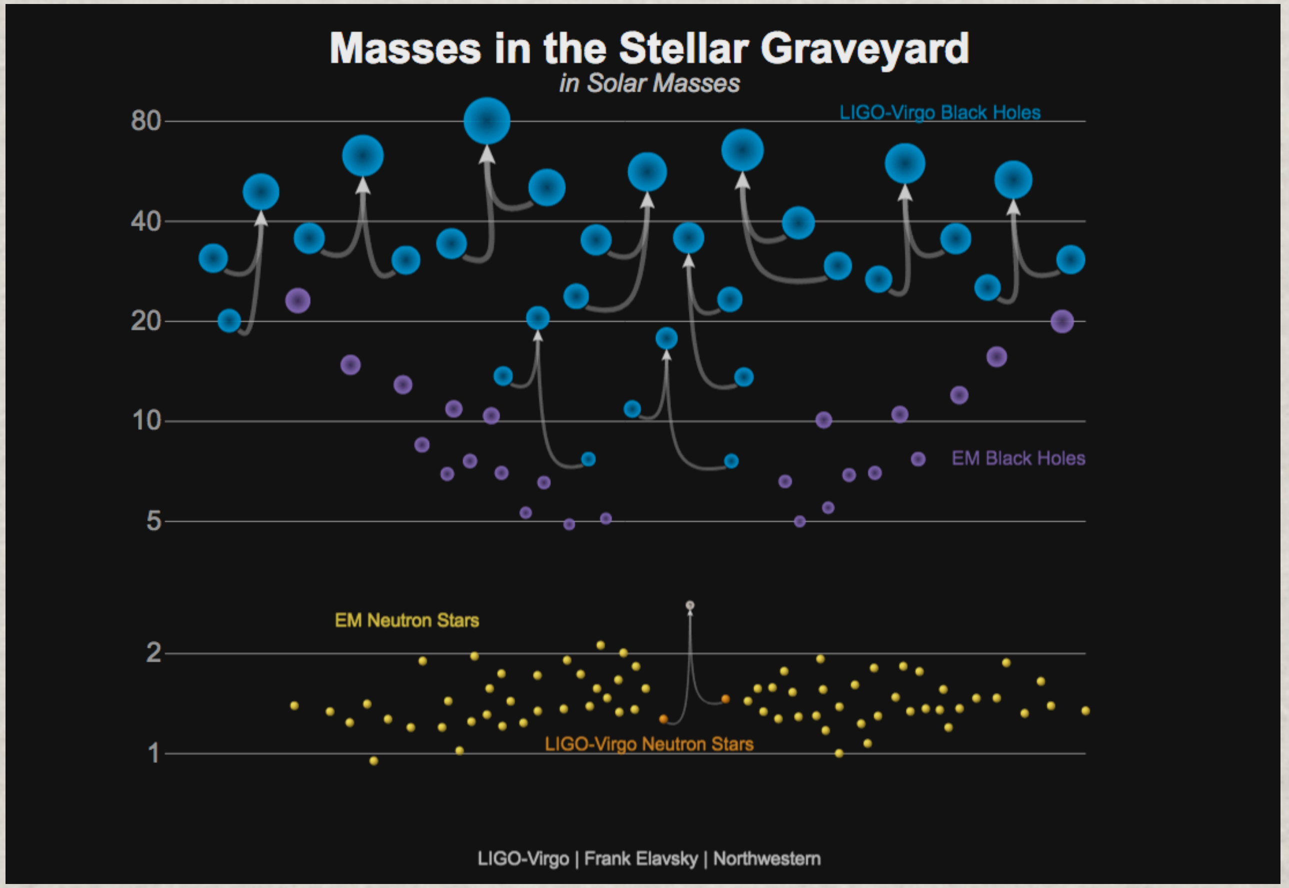
The first, epoch-making, detection



GW150914

Abbot et al., PRL 116 (2016) 061102

O1+O2 (Sep. 2015 - Aug. 2017) 11 detections



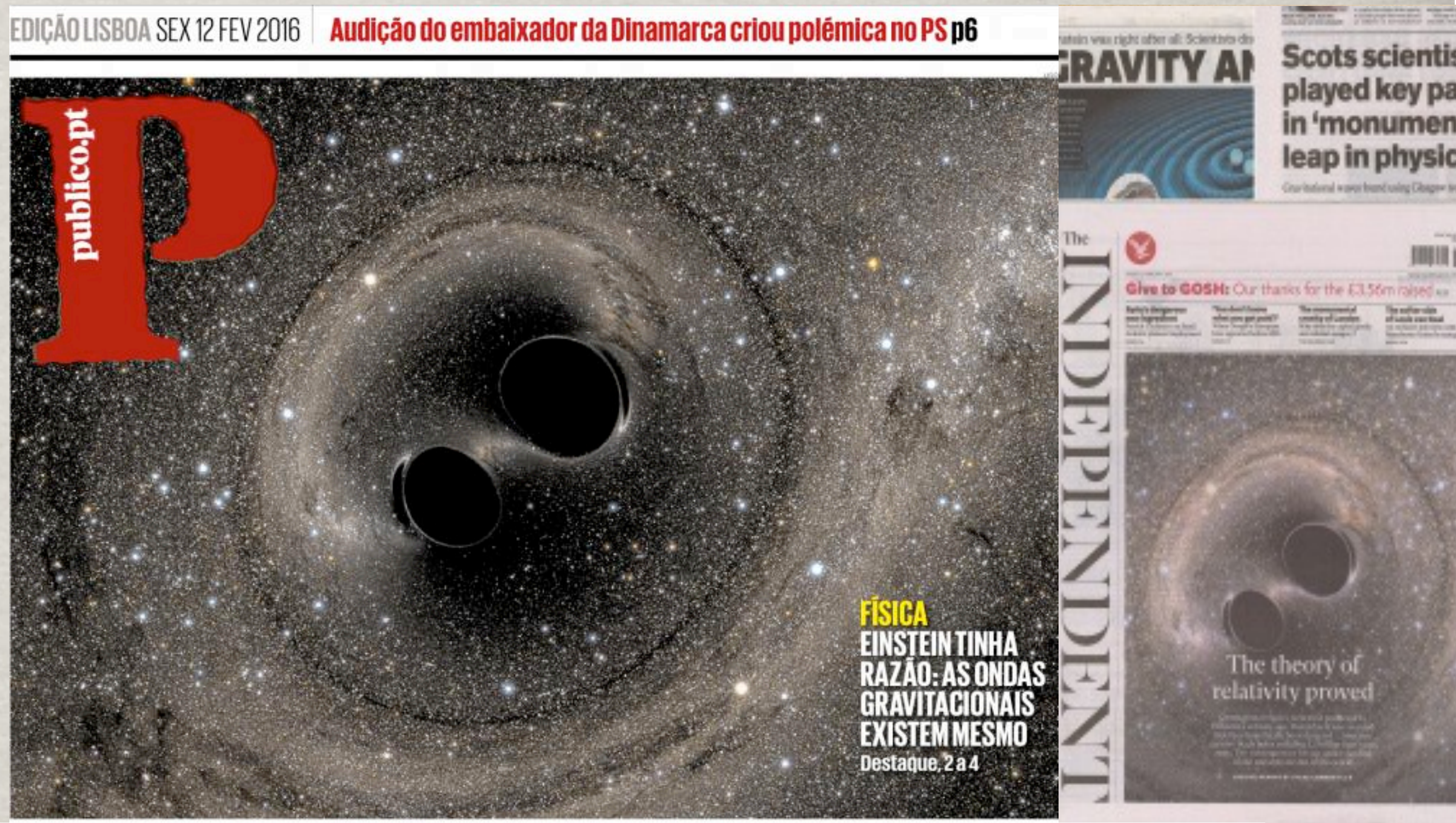
LIGO document: 30 November 2018 - https://dcc.ligo.org/public/0156/P1800307/005/o2catalog.pdf

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	χ_{eff}	$M_f/M_\odot$	a_f	$E_{rad}/(M_\odot c^2)$	$\ell_{peak}/(erg\,s^{-1})$	d_L/Mpc	z	$\Delta\Omega/deg^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	179
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

O1+O2 (Sep/15 - Aug/17) 11 detections

GW150914

- GW exist!
  Headlines worldwide
  Open GW astronomy era
- Loud, short (0.2s) event
- GR consistent
- Accessing new stellar mass
  BH population



Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	χ_{eff}	$M_f/M_\odot$	a_f	$E_{rad}/(M_\odot c^2)$	$\ell_{peak}/(\mathrm{erg\,s^{-1}})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
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GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

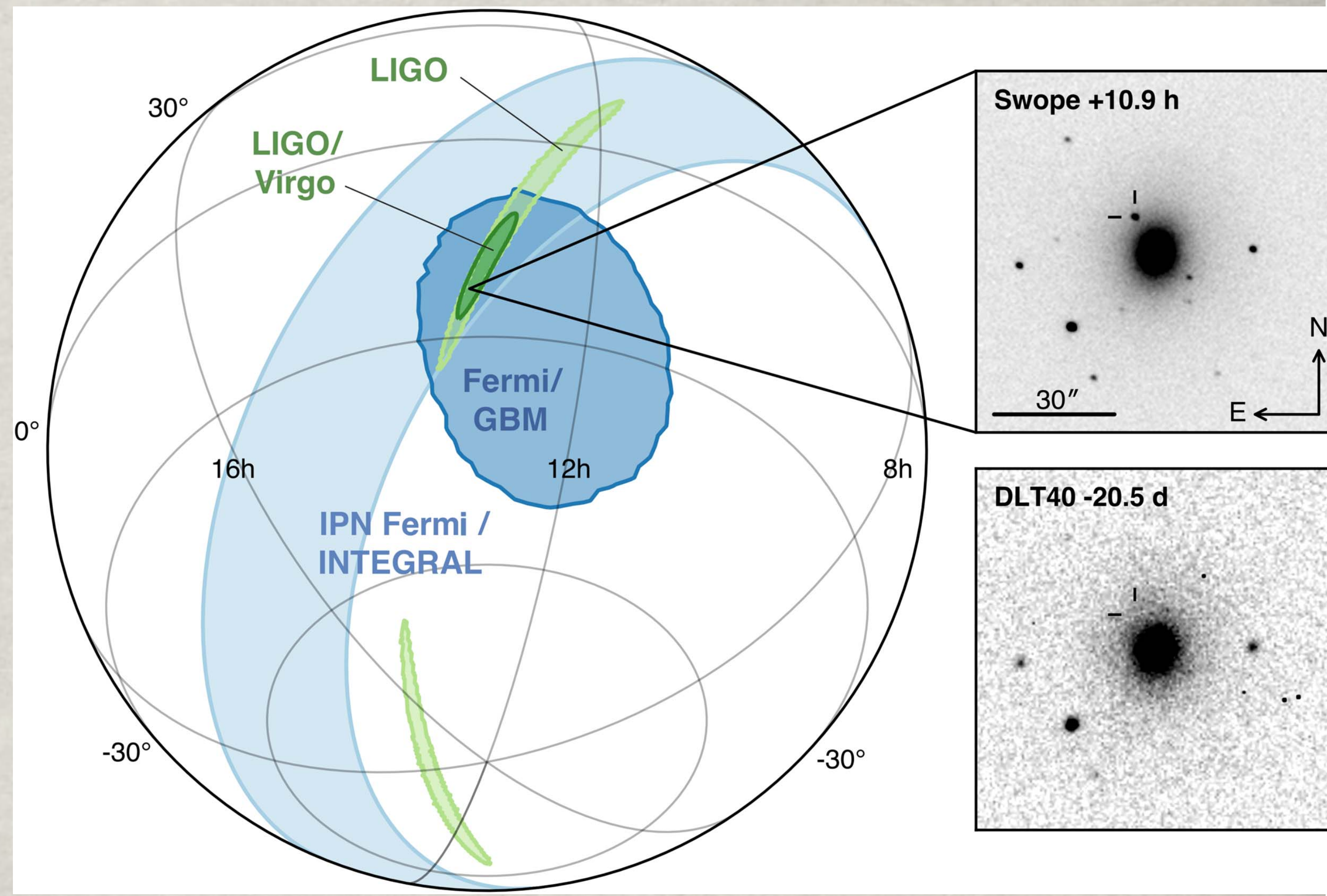
O1+O2 (Sep/15 - Aug/17) 11 detections

GW170817

- First detection of a neutron star-neutron star merger
- Multi-messanger event, with follow up across the electromagnetic spectrum
- Bound on speed of gravity: ApJL13(2017)848

$$-3 \times 10^{-15} \leqslant \frac{v_{GW} - c}{c} \leqslant +7 \times 10^{-16}$$

- Constrains classes of dark energy models
  e.g. 1710.05877, 1710.05901, 1710.06394



Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	χ_{eff}	$M_f/M_\odot$	a_f	$E_{rad}/(M_\odot c^2)$	$\ell_{peak}/(erg\,s^{-1})$	d_L/Mpc	z	$\Delta\Omega/deg^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	179
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
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GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
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GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
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O3 run (04/19-03/20): 56 candidates, 4 confirmed detections.

https://gracedb.ligo.org/superevents/public/O3/

GW190521 PRL125(2020)10, ApJLett.900(2020)L13

- Two most massive progenitors: $85^{+21}_{-14} M_\odot$, $66^{+17}_{-18} M_\odot$
- At least one in the pair instability supernova gap. Formation?
- Very short - no inspiral
- Final BH can be considered of intermediate mass: $142^{+28}_{-16} M_\odot$

GW190521 - what are the progenitors?

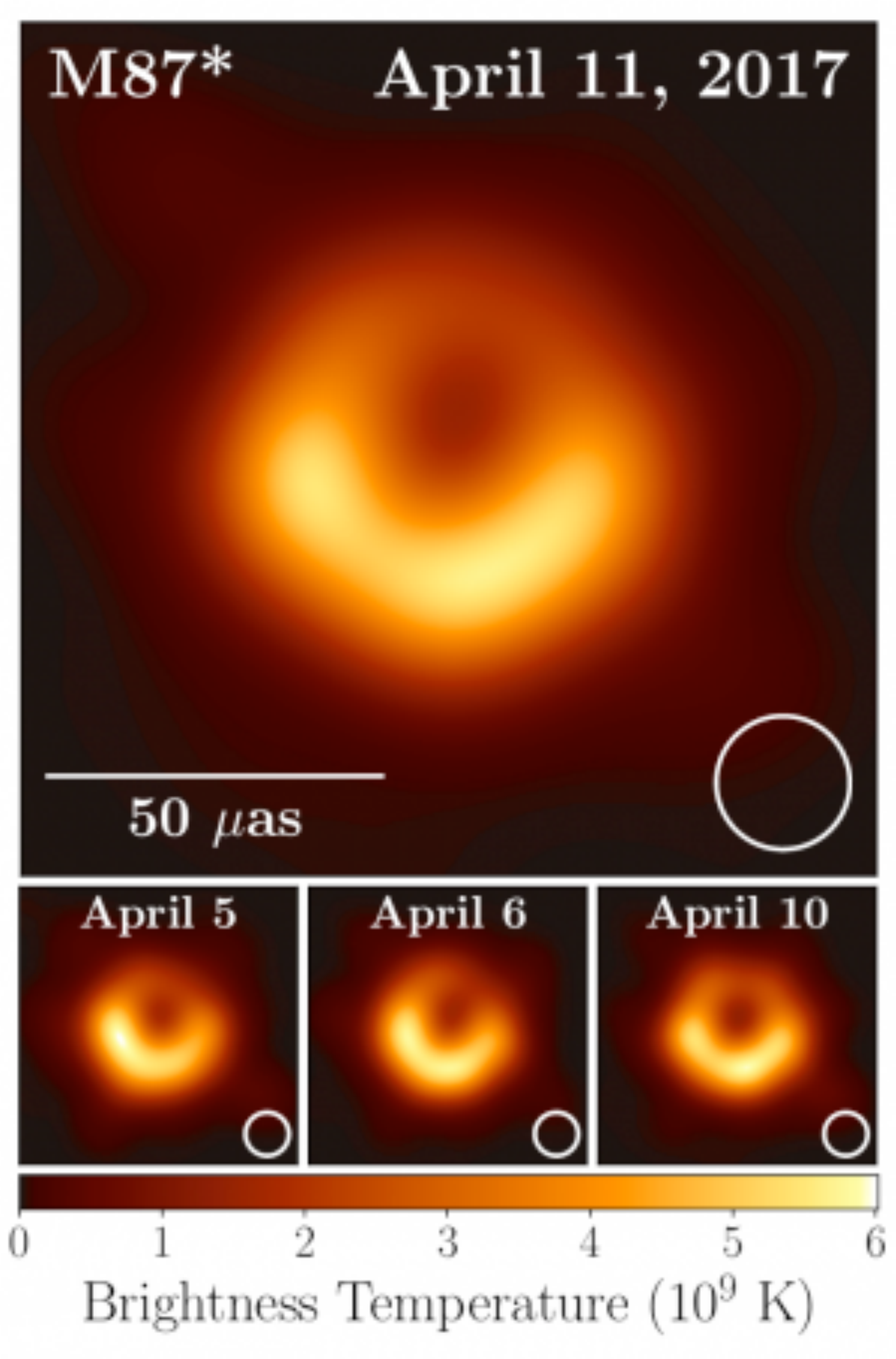
The mass gap puzzle is suggesting exploring alternative scenarios:

- are the progenitors primordial BHs ? ApJLett.900(2020)L13, arXiv:2009.01728
- is it really a BH merger (vs. core collapse or exotic objects, e.g. cosmic strings)? ApJLett.900(2020)L13
- is it evidence for new physics that allows BHs to form in the PISN gap? arXiv:2009.01213

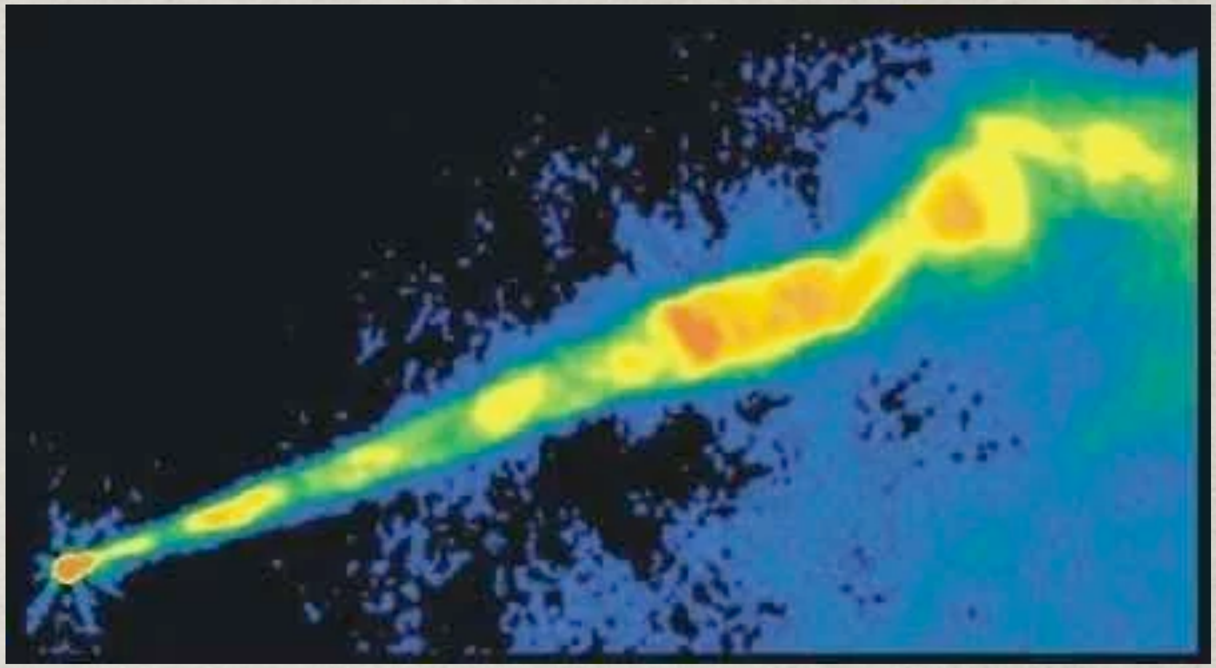
GW190521 may be evidence for new physics. If an ultra-light vector field exists in nature, with a certain mass (which is essentially fixed by the event), GW190521 can be interpreted as the collision of two exotic compact objects (non-BHs).

Moreover the a Bayesian analysis suggests this interpretation is slightly preferred to the vanilla quasi-circular BH merger used by the LVSC.
Bustillo, Sanchis-Gual, Torres-Forné, Font, Vajpeyi, Smith, C.H, Radu, Leong - arXiv:2009.05376

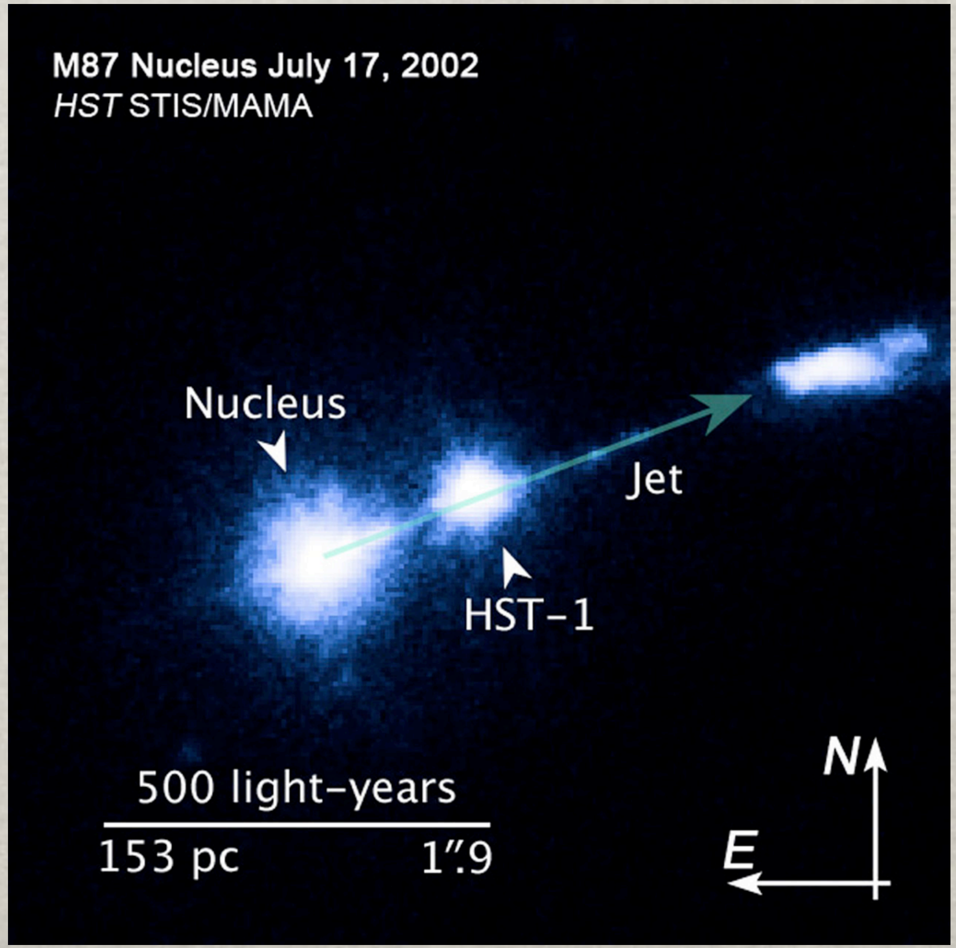
Very Large Baseline Interferometry
has also provided the first image of a black hole resolving horizon scale structure

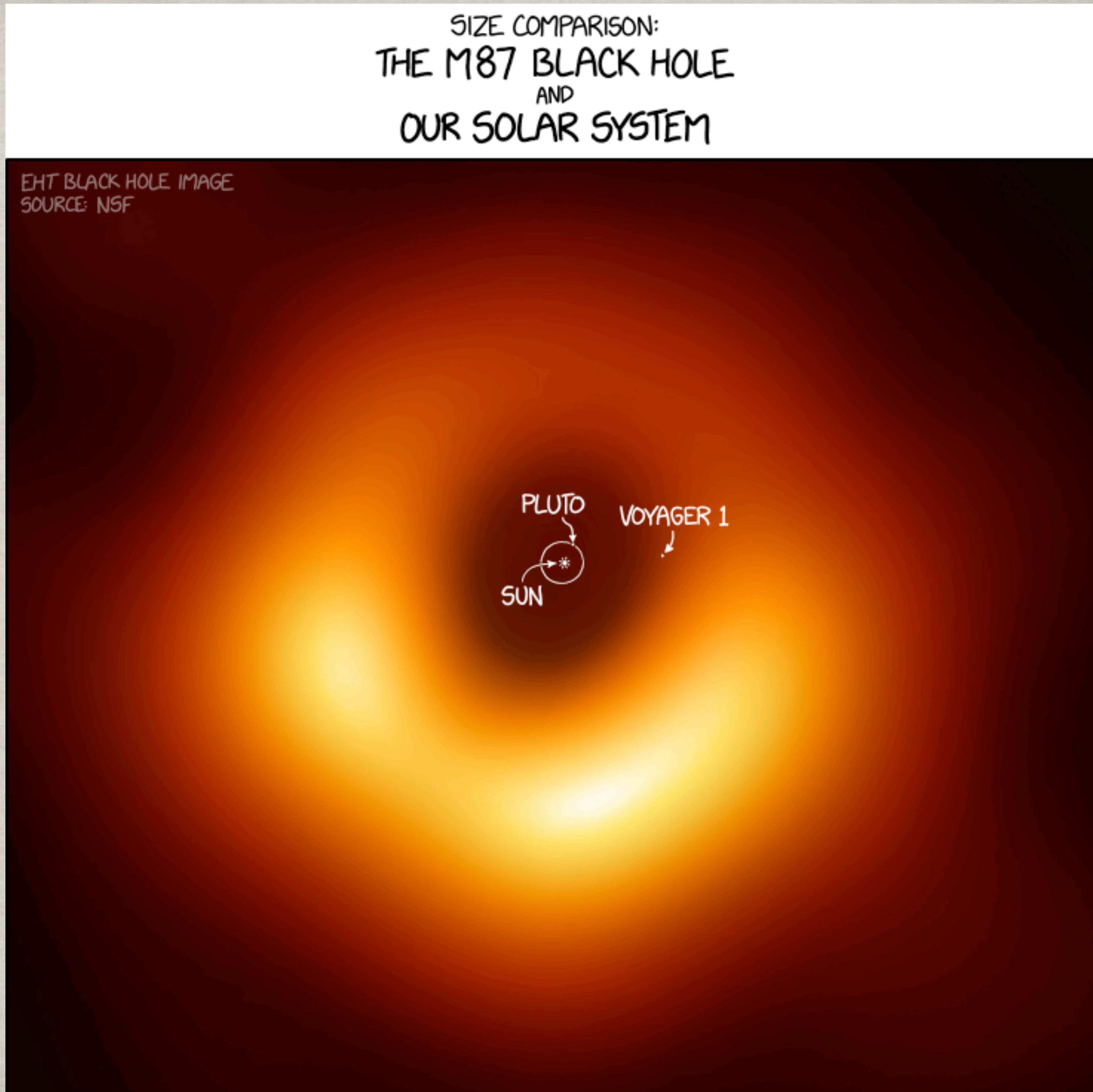


M87 supermassive
black hole imaging
by the
EHT collaboration
ApJ Lett. 875 (2019) L1



M87 supermassive black hole jet
~17° w.r.t line of sight
(radio image - Very Large Array)




SIZE COMPARISON:
THE M87 BLACK HOLE
AND
OUR SOLAR SYSTEM
EHT BLACK HOLE IMAGE
SOURCE: NSF
PLUTO
VOYAGER 1
SUN

The (near) future promises to yield observational data of unprecedented precision to test the true nature of these objects:
dawn of the precision black hole (astro)physics era

1) More accurate X-ray data (e.g. ATHENA and eXPT);

2) More accurate interferometric data (Gravity and Keck/UCLA);

3) More gravitational wave events (+ KAGRA,...);

4) Better black hole images (EHT and BlackHoleCam);

5) ...

It is therefore timely to study
both
precision phenomenology of the paradigmatic black holes
as well as of
alternatives
to the General Relativity
Kerr hypothesis
and their phenomenology

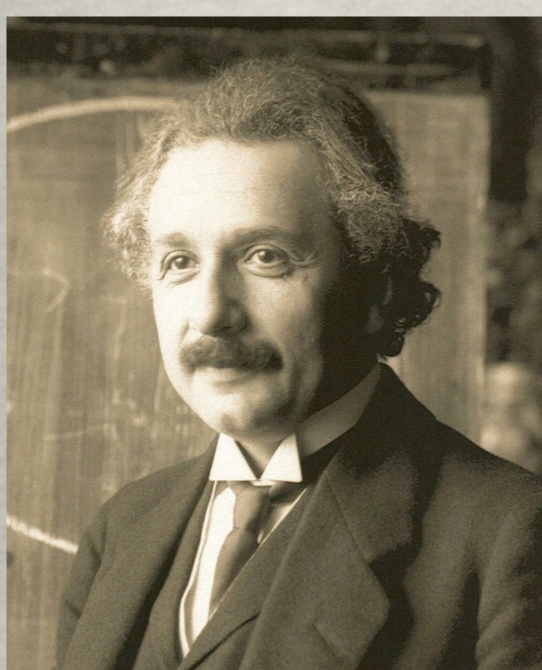
… in particular search for hints of new physics…

What is the Kerr hypothesis?

A brief timeline

1915: **Einstein's General Relativity**

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



Albert Einstein
(1879-1955)

Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten und beliebigen Substitutionen von der Determinante 1 gegenüber kovariant waren. Hierauf fand ich, daß diesen Gleichungen allgemein kovariante entsprechen, falls der Skalar des Energietensors der »Materie« verschwindet. Das Koordinatensystem war dann nach der einfachen Regel zu spezialisieren, daß $\sqrt{-g}$ zu 1 gemacht wird, wodurch die Gleichungen der Theorie eine eminente Vereinfachung erfahren.

A brief timeline

1916: **Schwarzschild's solution**

Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie.

Von K. Schwarzschild.

(Vorgelegt am 13. Januar 1916 [s. oben S. 42].)

§ 1. Hr. Einstein hat in seiner Arbeit über die Perihelbewegung des Merkur (s. Sitzungsberichte vom 18. November 1915) folgendes Problem gestellt:

Ein Punkt bewege sich gemäß der Forderung

$$\left.\begin{aligned} &\delta\int ds = 0, \\ \text{wobei} \\ &ds = \sqrt{\sum g_{\mu\nu}\, dx_\mu\, dx_\nu} \qquad \mu,\nu = 1,2,3,4 \end{aligned}\right\} \qquad (1)$$

ist, $g_{\mu\nu}$ Funktionen der Variabeln x bedeuten und bei der Variation am Anfang und Ende des Integrationswegs die Variablen x festzuhalten sind. Der Punkt bewege sich also, kurz gesagt, auf einer geodätischen Linie in der durch das Linienelement ds charakterisierten Mannigfaltigkeit.

Karl Schwarzschild (1873-1916)

Timeline

1916: **Schwarzschild's solution**

Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie.

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ist, $g_{\mu\nu}$ Funktionen der Variabeln x bedeuten und bei der Variation am Anfang und Ende des Integrationswegs die Variablen x festzuhalten sind. Der Punkt bewege sich also, kurz gesagt, auf einer geodätischen Linie in der durch das Linienelement ds charakterisierten Mannigfaltigkeit.

Physics. — "*The field of a single centre in* Einstein's *theory of gravitation, and the motion of a particle in that field.*". By J. Droste. (Communicated by Prof. H. A. Lorentz).

(Communicated in the meeting of May 27, 1916).

In two communications [1]) I explained a way for the calculation of the field of one as well as of two centres at rest, with a degree of approximation that is required to account for all observable phenomena of motion in these fields. For this I took as a starting-point the equations communicated by Einstein in 1913 [2]). Einstein has now succeeded in forming equations which are covariant for all possible transformations [3]), and by which the motion of the perihelion of Mercury is entirely explained [4]). The calculation of the field should henceforth be made from the new equations; we will make a beginning by calculating the field of a single centre at rest. We intend to calculate the field completely and not, as before, only the terms of the first and second order. After this, we investigate the

$$ds^2 = -\left(1 - \frac{2GM}{r}\right) dt^2 + \frac{dr^2}{(1 - \frac{2GM}{r})} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$c = 1$

(in the coordinates introduced by Johannes Droste, in 1916)

Finding the **Schwarzschild's solution**

key point: spherical symmetry - it is very restrictive in vacuum

$$ds^2 = -dt^2 + dr^2 + r^2 \underbrace{(d\theta^2 + \sin^2\theta \; d\phi^2)}_{d\Omega_2 \,=\, \text{line element of } S^2} \; .$$

Exercise 1.1

Show that the following vector fields are Killing vector fields of the 2-sphere and compute their algebra. Observe it is the Lie algebra of SO(3).

$$\xi_{(1)} = \sin\phi \; \partial_\theta + \cot\theta \cos\phi \; \partial_\phi \; ,$$

$$\xi_{(2)} = -\cos\phi \; \partial_\theta + \cot\theta \sin\phi \; \partial_\phi \; ,$$

$$\xi_{(3)} = -\partial_\phi \; ,$$

The most general ansatz with spherical symmetry is:

$$ds^2 = -\alpha(r,t)dt^2 + \beta(r,t)dr^2 + \gamma\sout{(r,t)dtdr} + \sout{\varepsilon(r,t)d\Omega_2}$$

$r^2 d\Omega_2$

One can use the "gauge" freedom (ability to re-define coordinates) to get rid of two of these functions. Then one can choose the parameterisation:

$$ds^2 = -e^{2A(t,r)}dt^2 + e^{2B(t,r)}dr^2 + r^2 d\Omega_2$$

This is the "ansatz". Then one computes the geometric quantities:

$$\text{Christoffel symbols}: \Gamma^{\alpha}_{\mu\nu} = \frac{1}{2}\, g^{\alpha\beta}(g_{\beta\mu,\nu} + g_{\beta\nu,\mu} - g_{\mu\nu,\beta})$$

$$\text{Riemann tensor}: R^{\alpha}{}_{\beta\mu\nu} = \Gamma^{\alpha}_{\beta\nu,\mu} - \Gamma^{\alpha}_{\beta\mu,\nu} + \Gamma^{\alpha}_{\mu\sigma}\Gamma^{\sigma}_{\beta\nu} - \Gamma^{\alpha}_{\nu\sigma}\Gamma^{\sigma}_{\beta\mu}$$

$$\text{Ricci tensor}: R_{\mu\nu} = R^{\alpha}{}_{\mu\alpha\nu}$$

$$\text{Einstein equations}: G_{\mu\nu} = 0 \overset{vacuum}{\Leftrightarrow} R_{\mu\nu} = 0$$

Exercise 1.2

Obtain, for the ansatz given before:

$$\dot{A} \equiv \frac{\partial A}{\partial t} \ , \ \dot{B} \equiv \frac{\partial B}{\partial t} \qquad\qquad A' \equiv \frac{\partial A}{\partial r} \ , \ B' \equiv \frac{\partial B}{\partial r}$$

$$\Gamma^t_{tt} = \dot{A} \ ; \ \Gamma^r_{tt} = \frac{A' e^{2A}}{e^{2B}} \ ; \ \Gamma^t_{rt} = A' \ ; \ \Gamma^r_{tr} = \dot{B} \ ;$$

$$\Gamma^t_{rr} = \frac{\dot{B} e^{2B}}{e^{2A}} \ ; \Gamma^r_{rr} = B' \ ; \Gamma^\theta_{r\theta} = \frac{1}{r} \ ; \Gamma^\phi_{r\phi} = \frac{1}{r} \ ;$$

$$\Gamma^r_{\theta\theta} = -\frac{r}{e^{2B}} \ ; \Gamma^\phi_{\theta\phi} = \frac{\cos\theta}{\sin\theta} \ ; \Gamma^r_{\phi\phi} = -\frac{r \sin^2\theta}{e^{2B}} \ ; \Gamma^\theta_{\phi\phi} = -\sin\theta\cos\theta \ ;$$

Exercise 1.2

Obtain, for the ansatz given before:

$$R^t{}_{rtr} = \frac{(-A'' - (A')^2 + A'B')e^{2A} + e^{2B}(\dot{B}^2 - \dot{A}\dot{B} + \ddot{B})}{e^{2A}} \ ;$$

$$R^t{}_{\theta t\theta} = -\frac{A'r}{e^{2B}} \ ; \ R^t{}_{\phi t\phi} = -\frac{A'r\sin^2\theta}{e^{2B}} \ ;$$

$$R^t{}_{\theta r\theta} = -\frac{\dot{B}r}{e^{2A}} \ ; \ R^t{}_{\phi r\phi} = -\frac{\dot{B}r\sin^2\theta}{e^{2A}} \ ;$$

$$R^r{}_{ttr} = \frac{(-A'' - (A')^2 + A'B')e^{2A} + e^{2B}(\dot{B}^2 - \dot{A}\dot{B} + \ddot{B})}{e^{2B}} \ ;$$

$$R^r{}_{\theta t\theta} = \frac{\dot{B}r}{e^{2B}} \ ; \ R^r{}_{\phi t\phi} = \frac{\dot{B}r\sin^2\theta}{e^{2B}} \ ;$$

$$R^r{}_{\theta r\theta} = \frac{B'r}{e^{2B}} \ ; \ R^r{}_{\phi r\phi} = \frac{B'r\sin^2\theta}{e^{2B}} \ ;$$

$$R^\theta{}_{tt\theta} = -\frac{A'e^{2A}}{re^{2B}} \ ; \ R^\theta{}_{tr\theta} = -\frac{\dot{B}}{r} \ ; \ R^\theta{}_{rt\theta} = -\frac{\dot{B}}{r} \ ;$$

$$R^\theta{}_{rr\theta} = -\frac{B'}{r} \ ; \ R^\theta{}_{\phi\theta\phi} = \frac{\sin^2\theta(e^{2B}-1)}{e^{2B}} \ ;$$

$$R^\phi{}_{tt\phi} = -\frac{A'e^{2A}}{re^{2B}} \ ; \ R^\phi{}_{tr\phi} = -\frac{\dot{B}}{r} \ ; \ R^\phi{}_{rt\phi} = -\frac{\dot{B}}{r} \ ;$$

$$R^\phi{}_{rr\phi} = -\frac{B'}{r} \ ; \ R^\phi{}_{\theta\theta\phi} = -\frac{e^{2B}-1}{e^{2B}} \ ;$$

Exercise 1.2

Obtain, for the ansatz given before:

$$R_{tt} = \frac{(-A'B'r + A''r + rA'^2 + 2A')e^{2A} + re^{2B}(\dot{A}\dot{B} - \ddot{B} - \dot{B}^2)}{re^{2B}} \ ;$$

$$R_{tr} = \frac{\dot{B}}{r} \ ;$$

$$R_{rr} = \frac{(2B' + A'B'r - A'^2r - A''r)e^{2A} + (\ddot{B}r + \dot{B}^2r - \dot{A}\dot{B}r)e^{2B}}{e^{2A}r} \ ;$$

$$R_{\theta\theta} = -\frac{1 - e^{2B} - B'r + A'r}{e^{2B}} \ ;$$

$$R_{\phi\phi} = \sin^2\theta R_{\theta\theta} \ ;$$

And the non-trivial Einstein equations:

$$i) \qquad \dot{B} = 0 \ ,$$

$$ii) \qquad 2A' + r(A'^2 + A'' - A'B') = 0 \ ,$$

$$iii) \qquad 2B' - r(A'^2 + A'' - A'B') = 0 \ ,$$

$$iv) \qquad (A' - B')r + 1 - e^{2B} = 0 \ .$$

Exercise 1.2

And the non-trivial Einstein equations:

$$
\begin{aligned}
i)& \qquad \dot{B} = 0 \ , \\
ii)& \qquad 2A' + r(A'^2 + A'' - A'B') = 0 \ , \\
iii)& \qquad 2B' - r(A'^2 + A'' - A'B') = 0 \ , \\
iv)& \qquad (A' - B')r + 1 - e^{2B} = 0 \ .
\end{aligned}
$$

Obtain the solution:

$$ds^2 = -\left(1 - \frac{C}{r}\right) \underbrace{e^{f(t)} dt^2} + \frac{dr^2}{1 - \frac{C}{r}} + r^2(d\theta^2 + \sin^2\theta \ d\phi^2) \ ,$$

redefining a new coordinate dt^2

Which is the Schwarzschild solution identifying C=2MG

Important observation:

We started with the time dependent ansatz:

$$ds^2 = -e^{2A(t,r)}dt^2 + e^{2B(t,r)}dr^2 + r^2 d\Omega_2$$

And ended with the time independent metric:

$$ds^2 = -\left(1 - \frac{2GM}{r}\right)dt^2 + \frac{dr^2}{(1 - \frac{2GM}{r})} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

The time dependence vanished!

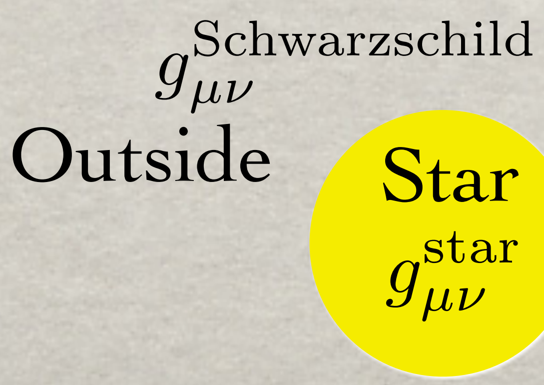
Thus, in vacuum, spherical symmetry implies staticity!
Birkhoff's theorem (1923)

G. D. Birkhoff, Relativity and Modern Physics (1923) also J. T. Jebsen, Ark. Mat. Ast. Fys. 15 (1921)

Interpretation:
In vacuum there are only purely gravitational degrees of freedom (gravitational waves) and no matter degrees of freedom. Gravitational waves do not have a dynamical spherical mode, since it is a spin 2 field.

Implication:
Outside any spherical star, if there is no matter-energy (vacuum), the metric is exactly the one of the Schwarzschild spacetime

George D. Birkhoff (1884-1944)



A brief timeline

1916,1918: **Reissner-Nordström solution**

Hans Jacob Reissner
(1874-1967)

106

4. *Über die Eigengravitation des elektrischen Feldes nach der Einsteinschen Theorie; von H. Reissner.*

Nachdem Hr. Einstein durch die Erklärung der Perihelbewegung des Merkur die Fruchtbarkeit seiner neuen kovarianten Feldgleichungen der Gravitation und damit des Postulats der allgemeinsten Relativität gezeigt und an anderer Stelle die allgemein kovariante Fassung der Maxwell-Lorentzschen Gleichungen des elektromagnetischen Feldes gegeben hat, erschien es mir als nächste Aufgabe, den Einfluß der Eigengravitation des elektrischen Feldes von Kugelsymmetrie an einem einfachen Beispiel zu untersuchen. Ich ging dabei allerdings von der Hoffnung aus, einen statischen Zusammenhalt von Elementarladungen durch deren Eigengravitation zu finden, ohne den Boden der Maxwellschen Theorie verlassen zu brauchen, konnte aber im Verlauf der Arbeit zunächst nur feststellen, daß die Einsteinsche Gravitation zwar das Feld der elektrischen Elementarladung in bestimmter, übrigens ungeheuer geringer Weise verzerrt, aber ihrem Wesen nach die gegenseitige elektrostatische Abstoßung der Ladungselemente nicht aufheben kann.

H. Reissner, Annalen der Physik, 355 (1916) 106-120

Gunnar Nordström
(1881-1923)

$$ds^2 = -\left(1 - \frac{2GM}{r} + \frac{Q^2}{r^2}\right) dt^2 + \frac{dr^2}{\left(1 - \frac{2GM}{r} + \frac{Q^2}{r^2}\right)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\ , \quad A = -\frac{Q}{r}dt$$

$4\pi\epsilon_0 = 1$

A brief timeline

1960: **Kruskal's extension**

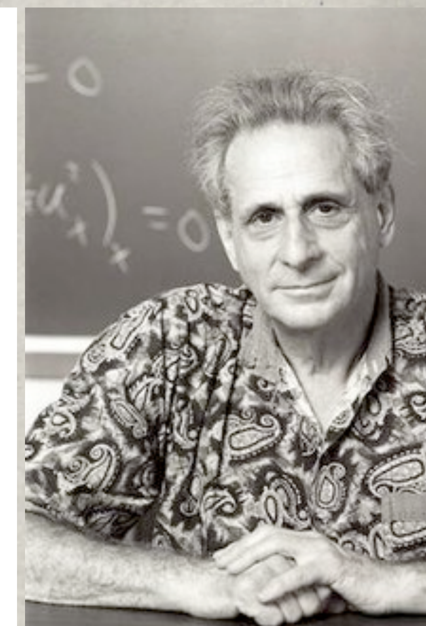
PHYSICAL REVIEW — VOLUME 119, NUMBER 5 — SEPTEMBER 1, 1960

Maximal Extension of Schwarzschild Metric*

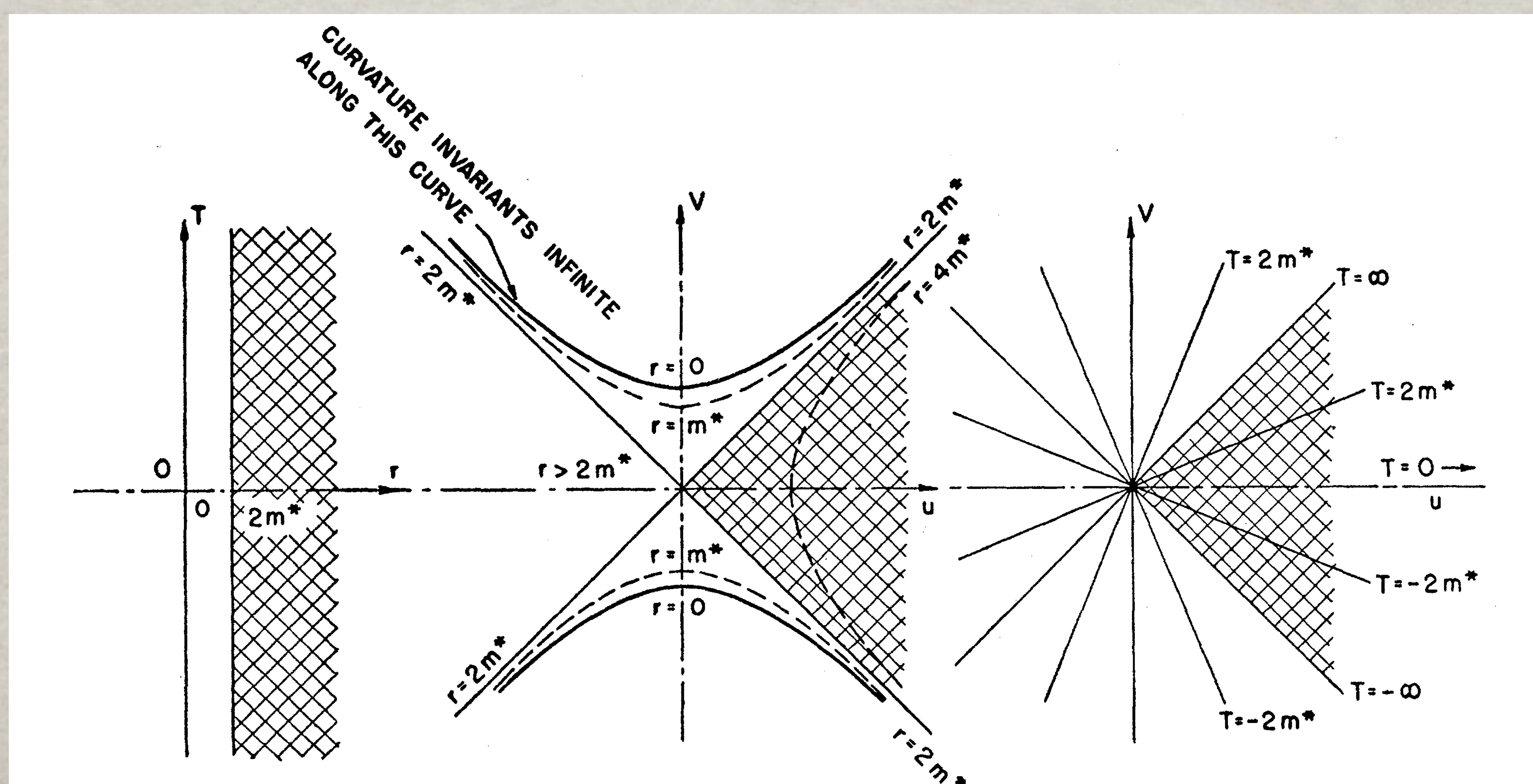
M. D. KRUSKAL†
Project Matterhorn, Princeton University, Princeton, New Jersey

(Received December 21, 1959)

There is presented a particularly simple transformation of the Schwarzschild metric into new coordinates, whereby the "spherical singularity" is removed and the maximal singularity-free extension is clearly exhibited.



Martin D. Kruskal
(1925-2006)



Independently obtained by George Szekers (1960)

A brief timeline

1963: **Kerr's solution**

Phys. Rev. Lett. 11 (1963) 237-238

GRAVITATIONAL FIELD OF A SPINNING MASS AS AN EXAMPLE OF ALGEBRAICALLY SPECIAL METRICS

Roy P. Kerr*

University of Texas, Austin, Texas and Aerospace Research Laboratories, Wright-Patterson Air Force Base, Ohio

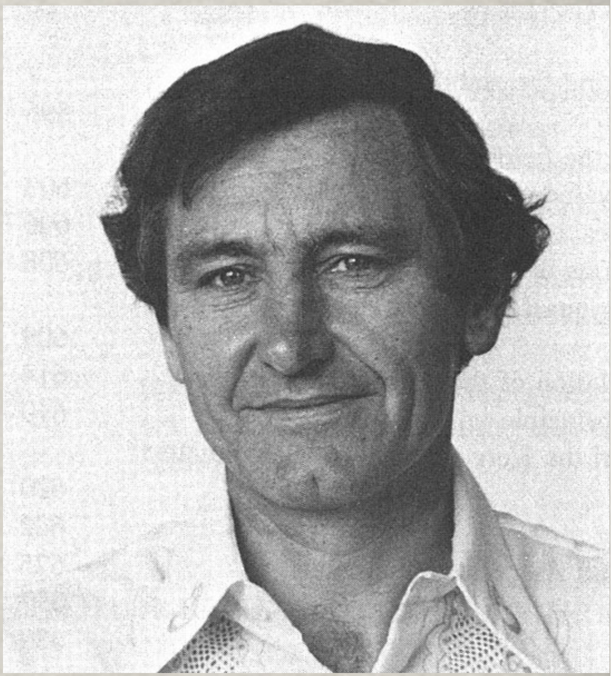
(Received 26 July 1963)

Goldberg and Sachs[1] have proved that the algebraically special solutions of Einstein's empty-space field equations are characterized by the existence of a geodesic and shear-free ray congruence, k_μ. Among these spaces are the plane-fronted waves and the Robinson-Trautman metrics[2] for which the congruence has nonvanishing divergence, but is hypersurface orthogonal.

where ζ is a complex coordinate, a dot denotes differentiation with respect to u, and the operator D is defined by

$$D = \partial/\partial\zeta - \Omega\partial/\partial u.$$

P is real, whereas Ω and m (which is defined to be $m_1 + im_2$) are complex. They are all independent of the coordinate r. Δ is defined by



Roy P. Kerr (1934-)

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

$$\Sigma = r^2 + a^2\cos^2\theta$$
$$\Delta = r^2 - 2GMr + a^2$$

(in the coordinates introduced by Robert H. Boyer and Richard W. Lindquist, in 1967, J. Math. Phys. 8 (1967) 265)

A brief timeline

1965: **Kerr-Newman solution**

JOURNAL OF MATHEMATICAL PHYSICS VOLUME 6, NUMBER 6 JUNE 1965

Metric of a Rotating, Charged Mass*

E. T. NEWMAN, E. COUCH, K. CHINNAPARED, A. EXTON, A. PRAKASH, AND R. TORRENCE
Physics Department, University of Pittsburgh, Pittsburgh, Pennsylvania
(19 June 1964)

A new solution of the Einstein–Maxwell equations is presented. This solution has certain characteristics that correspond to a rotating ring of mass and charge.

Ezra Ted Newman
(1929-)

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

$$\Sigma = r^2 + a^2\cos^2\theta$$
$$\Delta = r^2 - 2GMr + a^2 + Q^2$$

(in the coordinates introduced by Robert H. Boyer and Richard W. Lindquist, in 1967, J. Math. Phys. 8 (1967) 265)

A brief timeline

1967-68: **John Wheeler popularizes the term "black hole"**

In the fall of 1967, Vittorio Canuto, administrative head of NASA's Goddard Institute for Space Studies at 2880 Broadway in New York City, invited me to a conference to consider possible interpretations of the exciting new evidence just arriving from England on pulsars. What were these pulsars? Vibrating white dwarfs? Rotating neutron stars? What? [1] In my talk, I argued that we should consider the possibility that at the center of a pulsar is a gravitationally completely collapsed object. I remarked that one couldn't keep saying "gravitationally completely collapsed object" over and over. One needed a shorter descriptive phrase. "How about black hole?" asked someone in the audience. I had been searching for just the right term for months, mulling it over in bed, in the bathtub, in my car, wherever I had quiet moments. Suddenly this name seemed exactly right. When I gave a more formal Sigma

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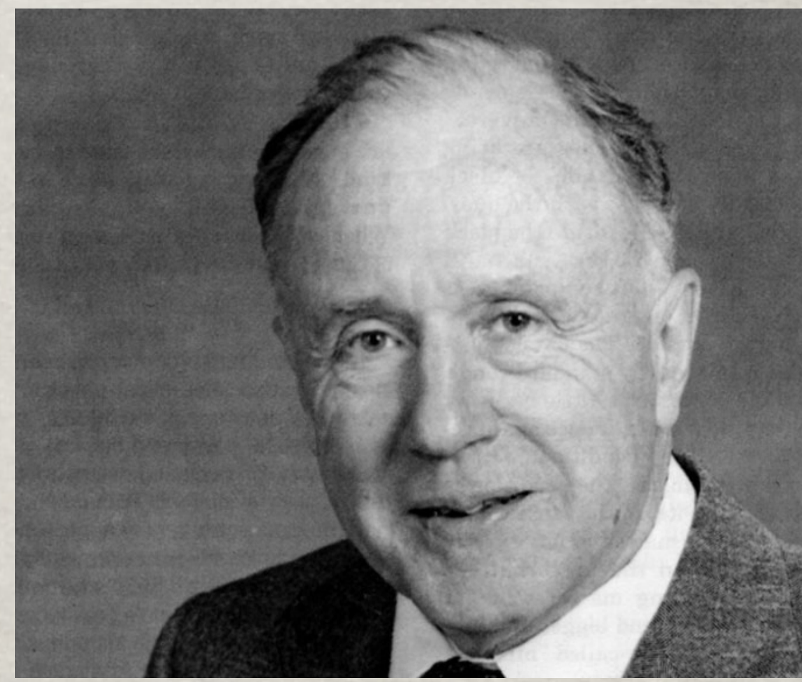
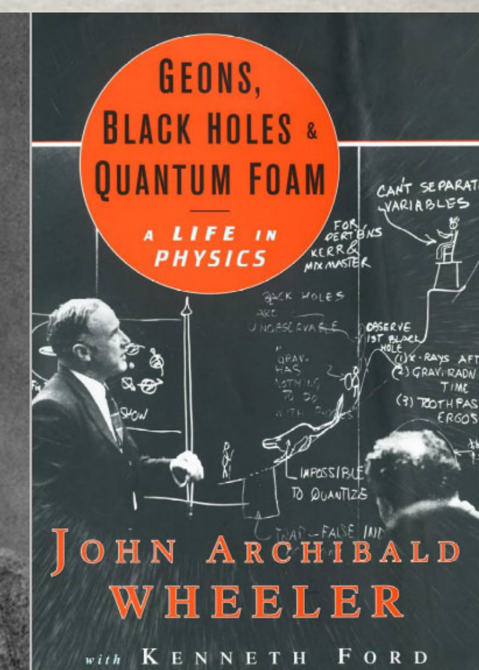
Xi—Phi Beta Kappa lecture in the West Ballroom of the New York Hilton a few weeks later, on December 29, 1967, I used the term, and then included it in the written version of the lecture published in the spring of 1968 (As it turned out, a pulsar is powered by "merely" a neutron star, not a black hole.)





John Archibald Wheeler
(1911-2008)

John Wheeler, "Geons, black holes and quantum foam", Pages 295-296

A brief timeline

1967-68: **John Wheeler popularizes the term "black hole"**

> "Well, after I used that phrase four or five times, somebody in the audience said, 'Why don't you call it a black hole?' So I adopted that."
>
> **Interview with Wheeler, 1998**

John Archibald Wheeler

Wheeler repeated this version in interviews.

M. Bartusiak, Bermuda triangles of space: How the public first met black holes,
Talk at the 27 Texas Symposium on Relativistic Astrophysics (2013)

A brief timeline

1967-68: **John Wheeler popularizes the term "black hole"**

AMERICAN SCIENTIST, *56*, 1, pp. 1–20, 1968

AMERICAN SCIENTIST

SPRING · 1968

OUR UNIVERSE: THE KNOWN AND THE UNKNOWN*

By JOHN ARCHIBALD WHEELER

WHAT KIND of a universe do we live in? A strange one, yes. But where does the strangeness mostly lie? In the seen? Or in the unseen? Shall we fix our attention on the billiard balls as they now bat about the billiard table? Or shall we ask how the game began, and how it will end?

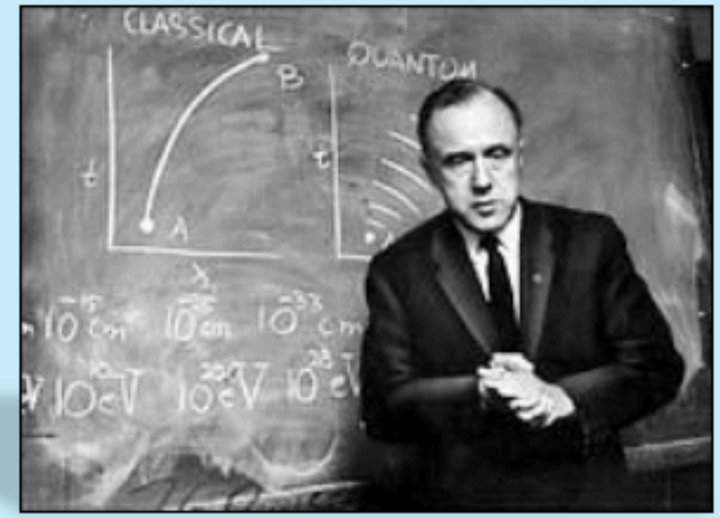
Who will not choose first to look about a little at the game? If then deeper questions come to mind, who will stop our asking them?

Our universe is incomparably more interesting than any play at billiards. The formation of new stars and the explosion of old stars and the greatest variety of events, gigantic in scale and in energy, outrival the most gorgeous fireworks explosion that anyone could imagine in his wildest dreams.

A Famous Supernova

Take up the telescope and turn it on the Crab Nebula. There was no Crab Nebula a thousand years ago. At that time astronomy was at a low level in Europe. Not so in China. There astronomers regularly swept the skies and recorded their observations. In July 1054 they reported a new star. It grew in brightness from day to day. In a few days it outshone every star in the firmament. Then it sank in brilliance, falling off in intensity from week to week. At each date the nova, or supernova as we more appropriately call it, could be compared with neighbor stars for brightness. Out of these comparisons by our Chinese colleagues of long ago one has today constructed a light curve. This light curve is similar to the light curve for supernova events which, through a powerful telescope, one sees from time to time today in far away galaxies. Only the great number of

* The Sigma Xi-Phi Beta Kappa Annual Lecture, American Association for the Advancement of Science, New York, December 29, 1967.



John Archibald Wheeler

The Black Hole

If gravitational collapse is as inescapable in a star as geometrodynamics is inescapable in the universe, then what would be the appearance of the collapsing core if it could be seen from afar without the interference of the supervening envelope? The hot core material is brilliant and at first it shines strongly into the telescope of the observer. However, by reason of its faster and faster infall it moves away from the observer more and more rapidly. The light is shifted to the red. It becomes dimmer millisecond by millisecond, and in less than a second too dark to

see. What was once the core of a star is no longer visible. The core like the Cheshire cat fades from view. One leaves behind only its grin, the other, only its gravitational attraction. Gravitational attraction, yes; light, no. No more than light do any particles emerge. Moreover, light and particles incident from outside emerge and go down the black hole only to add to its mass and increase its gravitational attraction. Has the black hole a size? In one way, yes; in another way, no. There is nothing to look at. One could of course imagine thrusting a meter stick toward the center of attraction until it "touched base." However the powerful tidal forces will tear apart that object and every other object. No conventional measurement of the dimensions is possible. Even to speak about the dimensions of the object in any conventional sense is out of the question. However a light ray can be shot at the black hole, not straight on, but directed far enough off center to one side or the other just barely to escape capture down the black hole—to emerge eventually into a faraway detector of photons. The "diameter" of the black hole as defined in this way is of the order of 10 km, the precise value depending on the mass of the core that underwent collapse. These are the long-known predictions of standard long-established theory.

Wheeler wrote the term "black hole" in a (non-technical) article in 1968...

M. Bartusiak,
Bermuda triangles of space:
How the public first met
black holes,
Talk at the
27 Texas Symposium
on Relativistic Astrophysics
(2013)

A brief timeline

1967-68: **John Wheeler popularizes the term "black hole"**

~ 1969-70

P. Kafka (Max-Planck-Institut für Physik und Astrophysik München): Discussion of Possible Sources of Gravitational Radiation.

Weber (1969) reported the detection of gravitational radiation on a high level of significance. Radiation seems to arrive in pulses of duration less than 0.4 sec. The frequency of observation was 1660 Hz. The energy arriving over the pulse in a bandwidth $\Delta\omega \approx 0.1$ was of the order of 10^4 erg cm^{-2}. Hence, if a flat spectrum is assumed up to a cut-off at or beyond the frequency of observation, the total energy per cm^2 in each pulse was $> 10^9$ ergs. A source at distance D (kiloparsecs) must have emitted

$$E > 10^{53} \times D^2 \text{ ergs.} \quad (1)$$

Whereas the observation of about one such pulse per century or even per year might be expected at the present state of knowledge, Weber's observations indicate a number of about hundred per year. This poses severe problems.

A strong pulse of gravitational radiation is expected only when a configuration of mass m comes close to its Schwarzschild radius $r_s = 2\,Gm/c^2 \approx 3\,m/m_\odot$ km, and its quadrupole and/or higher moments change rapidly. A critical surface of approximate extent r_s will exist in any relativistic theory of gravitation (cf. Trautman, 1965), also for asymmetric configurations.

The following situations are possible sources for pulses of gravitational radiation: (1) Gravitational collapse of a rotating star towards a neutron star. In this case a pulse at roughly 1 kHz, lasting about 1 sec, with a total energy of the order of 10^{53} ergs ($\lesssim 1/2\,\%$ of the stellar rest-mass energy) is expected, according to recent work at Caltech (cf. Burke and Thorne, 1969). It is due to vibrational modes excited in the collapse.

(2) Hypothetical transitions in the state of a neutron star in which asymmetric vibrations may be excited. Similar processes have been proposed as a possible cause for the sudden decrease in the period of the pulsar PSR 0833−45 between February 24th and March 3rd 1969. Such "neutron-star-quakes" might emit a gravitational pulse similar to that in case (1) but with a smaller total energy.

(3) Asymmetric collapse towards a "black hole" (as a collapsing object is called in the state where gravitational redshift and capture make all types of radiation fade away for a distant observer, and only the stationary gravitational field remains). In such events one can expect a pulse of gravitational radiation. Its duration will be roughly $\tau \gtrsim r_s/c \approx 10^{-5}\,m/m_\odot$ [sec], the high-frequency cut-off will lie near $\nu \approx \tau^{-1}$, and the total energy may nearly reach the order of $mc^2 \approx 10^{54.3}\,m/m_\odot$ [ergs].

Volume 24, Number 8 PHYSICAL REVIEW LETTERS 23 February 1970

GRAVITATIONAL COLLAPSE WITH ASYMMETRIES

V. de la Cruz
Physics Department, University of Saskatchewan, Regina, Saskatchewan, Canada

and

J. E. Chase and W. Israel
Mathematics Department, University of Alberta, Edmonton, Alberta, Canada
(Received 2 December 1969)

Two idealized collapse models, involving a magnetic dipole and a gravitational quadrupole, are analyzed, treating departures from sphericity as small perturbations. Radiative leakage (largely downwards through the Schwarzschild radius) causes externally observable asymmetries to decay to zero in an oscillatory fashion, with a period of the order of the Schwarzschild characteristic time $2Gm/c^3$. These results have significant consequences for astrophysics; they imply in particular that a "black hole" cannot be a source of synchrotron radiation.

Every static nonspherical perturbation of Schwarzschild's exterior field due to gravitational or electromagnetic sources within the stationary lightlike surface $g_{00} = 0$ becomes singular on this surface.[1-3] Stationary perturbations of Kerr's rotating solution appear to have a similar property.[4] Assuming these results to be applicable to the asymptotically stationary exterior field of a collapsing star, one is led to conjecture that all externally detectable asymmetries,[1] including magnetic fields,[2] must somehow decay, leaving behind Schwarzschild's vacuum field (or, in the case of nonvanishing angular momentum, Kerr's field) as the sole external manifestation of the collapsed object.

To examine these questions, we have carried out a dynamical analysis of two idealized collapse models, one involving a magnetic dipole, the other a gravitational quadrupole. Our results support the foregoing conjecture and reveal the decay mechanism to be a rapid radiative leakage of the asymmetric perturbing field, largely downwards through the event horizon.

We cast the Schwarzschild metric into the form $(ds^2)_{Schw} = \alpha dx dy + r^2 d\Omega^2$, where $\alpha = 1 - 1/r$, and the retarded and advanced time coordinates $-x, y$ are related to the standard Schwarzschild coordinates by $x, y = (r-1) + \ln(r-1) \mp t$. Lengths are measured in units of the Schwarzschild radius: $2m = 1$.

Both of our models can be considered as linearly perturbed variations of the following basic situation (Fig. 1). A thin, hollow spherical shell of mass $m = \frac{1}{2}$ is initially static with radius $R_0 \gg 1$; at time $t = -\frac{1}{2}x_0 = -(R_0 - 1) - \ln(R_0 - 1)$, it suddenly begins to collapse at the speed of light (history of surface $y = 0$). (This model, adopted for mathematical simplicity, is highly artificial from an astrophysicist's point of view, but does not violate any of the principles of relativity theory. Moreover, our main interest is in the asymptotic behavior of the external field as $t \to \infty$, and we do not expect this to depend too sensitively on the precise structure of the source or the initial conditions.)

In our first ("magnetic collapse") model, we suppose a static magnetic dipole of moment μ placed at the center of the shell. (It is assumed that $\mu^2 \ll 1$, which means gravitational effects of the magnetic energy density can be neglected for $r \geq 1$.) Our second ("quadrupole") model assumes a weak gravitational quadrupole of moment q superimposed on the spherical background field and caused by unevenesses in the surface density of the shell.

Since news of the onset of collapse cannot reach the interior ahead of the shell itself, the

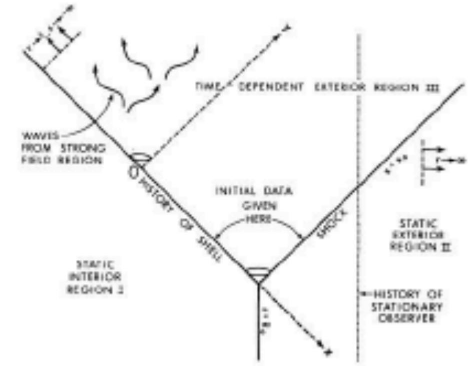


FIG. 1. Space-time diagram for collapsing shell model.

...and the scientific community started using the term

M. Bartusiak,
Bermuda triangles of space: How the public first met black holes,
Talk at the 27 Texas Symposium on Relativistic Astrophysics (2013)

A brief timeline

1967-68: **John Wheeler popularizes the term "black hole"**

But this is only the story that Wheeler decided to tell!

C. H. and J. Lemos,
arXiv:1811.06587

THE FIRST TEXAS SYMPOSIUM ON RELATIVISTIC ASTROPHYSICS

Born at poolside on a summer afternoon, the idea for a Texas-sized conference blossomed when it was realized that the newly found quasars might be relativistically significant.

Engelbert L. Schucking

Someone—I do not remember who—discovered that this is the 25th anniversary of the first Texas Symposium on Relativistic Astrophysics.[1] The discovery is the more remarkable since the conference is held every two years and the number 25 is, I believe, odd. Undoubtedly, this fact could, should and presumably will be explained by historians of science—thus I will not bother.

An interest in history awakens when the mind feebles and memory is gone. That's why I was invited to deliver this talk, which might well bear the classic title "What Little I Remember."

our reunion with Alfred's strong martinis, thought about breaking the spell of Dallas boredom.

Schild, Berkner, Robinson & Co

Schild, a Viennese Jew born in Turkey, had emigrated to England, was interned and shipped to Canada, and studied in Toronto. He became a physics professor in Pittsburgh, and, disgusted with American industry after a stint with Westinghouse, he settled in Austin. And so he became the founding father of Texas relativity. He also wrote the first paper on relativistic strings. They should inscribe his

In 1963, scientists were already using "black hole" in a scientific meeting!

A brief timeline

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ASTRONOMY

"Black Holes" in Space

The heavy densely packed dying stars that speckle space may help determine how matter behaves when enclosed in its own gravitational field—By Ann Ewing

➤ SPACE may be peppered with “black holes.”

This was suggested at the American Association for the Advancement of Science meeting in Cleveland by astronomers and physicists who are experts on what are called degenerate stars.

Degenerate stars are not Hollywood types with low morals. They are dying stars, or white dwarfs, and make up about 10% of all stars in the sky.

The faint light they emit comes from the little heat left in their last stages of life. It is not known how a star quietly declines to become a white dwarf.

Degenerate stars are made of densely packed electrons and nuclei, or cores of atoms. They are so dense that a thimbleful of their matter weighs a ton.

Some such stars are predicted in theory to have a density of one million tons per thimbleful. When this happens, the star is essentially made of neutrons and strange particles.

Modern tools, such as telescopes on an orbiting space platform, may be used to detect such black holes and to help determine how matter behaves when it is enclosed by its own gravitational field.

The light from the most famous white dwarf star, Sirius B, a companion to Sirius—which is the brightest star in the heavens visible from earth—has been captured using the 200-inch telescope atop Mt. Palomar. This was done as part of a program to study at least 20 white dwarfs.

Preliminary analysis of the light from Sirius B indicates that it has an effective temperature of 16,800 degrees Kelvin, or 30,000 degrees Fahrenheit. Its radius can be calculated from the temperature, and is only nine-thousandths that of the sun.

The star must therefore consist mainly of helium or heavier elements.

The speakers at the symposium were Drs. A. G. W. Cameron of the National Aeronautics and Space Administration's Goddard

METEOROLOGY

Weather Vans Promise Better Local Forecasts

➤ ON-THE-SPOT weather data from satellites soon will be available directly to local forecasters through the use of special vans being outfitted by the Government.

The vans receive signals through a spiral-shaped roof-top antenna and provide cloud cover pictures of the local area as “seen” by the weather satellite.

Pictures will be used by weather forecasters in the van for vast, large-scale cloud observations not now possible.

The vans, which can be transported by air or truck, are being tested at Hanscom Field, Mass., by the Air Force, the U.S. Weather Bureau and the National Aeronautics and Space Administration.

Inside weather satellites, such as Tiros and Nimbus, television transmission devices automatically take and transmit a cloud picture every three minutes during daylight. Each picture received by the vans will cover an area of about 640,000 square miles, from which the operator will be able to make his weather analysis.

In an emergency the mobile stations can be flown to any spot in the world and placed in operation in as little as two hours after landing. They can be used in military operations and for locating and tracking severe storms such as hurricanes and

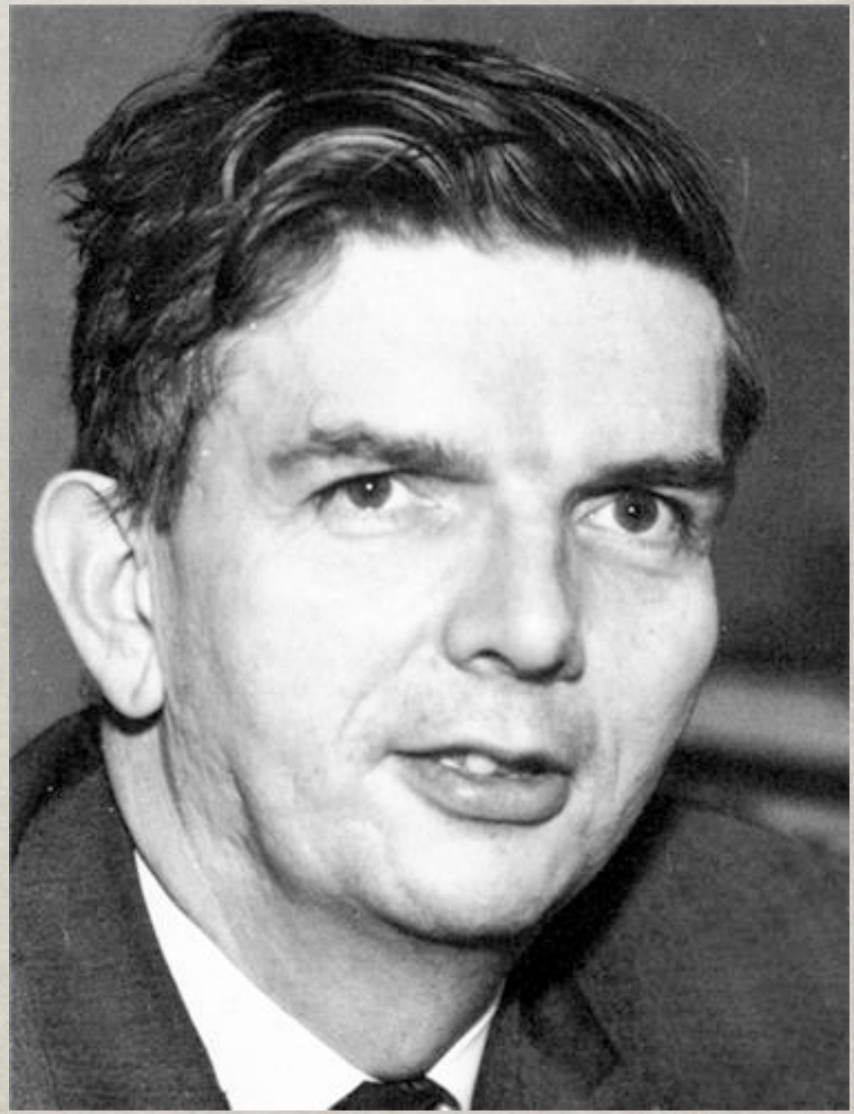
A brief timeline

1967-68: **John Wheeler popularizes the term "black hole"**

But this is only the story that Wheeler decided to tell!
C. H. and J. Lemos,
arXiv:1811.06587

In the 27th Texas symposium,
in 2013,
Hong Yee Chiu,
confirmed he used in 1963 the term
"black hole",
during the 1st Texas symposium.

He had heard it first in a colloquium,
in Princeton,
in 1961-62,
by **Robert Dicke**.



Robert Henry Dicke
(1916-1997)

A brief timeline

1967-68: **John Wheeler popularizes the term "black hole"**

But this is only the story that Wheeler decided to tell!

C. H. and J. Lemos,
arXiv:1811.06587

Black Hole of Calcutta

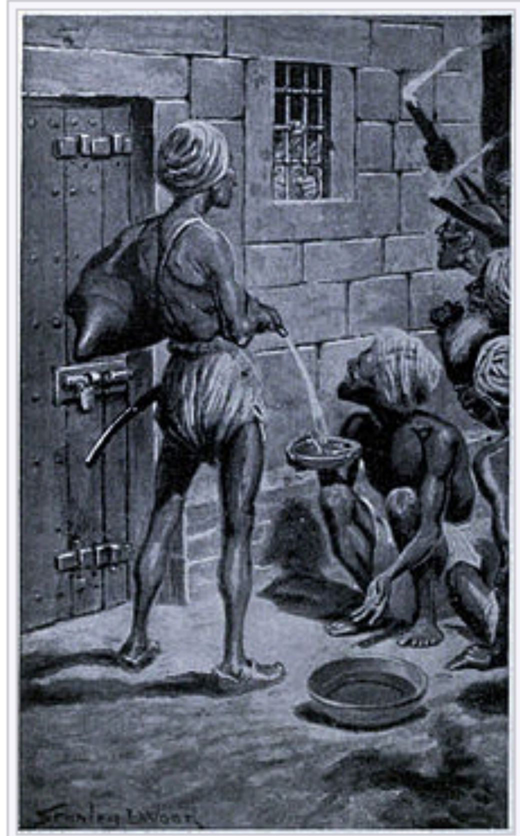
From Wikipedia, the free encyclopedia

Coordinates: 22.573357°N 88.347979°E

This article **needs additional citations for verification**. Please help improve this article by adding citations to reliable sources. Unsourced material may be challenged and removed. *(June 2017) (Learn how and when to remove this template message)*

The **Black Hole of Calcutta** was a small prison or dungeon in Fort William where troops of Siraj ud-Daulah, the Nawab of Bengal, held British prisoners of war for three days on 20 June 1756.

John Zephaniah Holwell, one of the British prisoners and an employee of the East India Company, said that, after the fall of Fort William, the surviving British soldiers, Anglo-Indian soldiers, and Indian civilians were imprisoned overnight in conditions so cramped that many people died from suffocation and heat exhaustion, and that 143 of 164 prisoners of war imprisoned there died.[1]



The Black Hole of Calcutta, 20 June 1756

Contents [hide]

1 Background
2 The Holwell account
3 Imperial aftermath
4 Monument to the victims
5 The Black Hole of Calcutta in popular culture
5.1 Literature
5.2 Television
5.3 Astronomy
6 Gallery
7 See also
8 Notes

A brief timeline

1967-68: **John Wheeler popularizes the term "black hole"**

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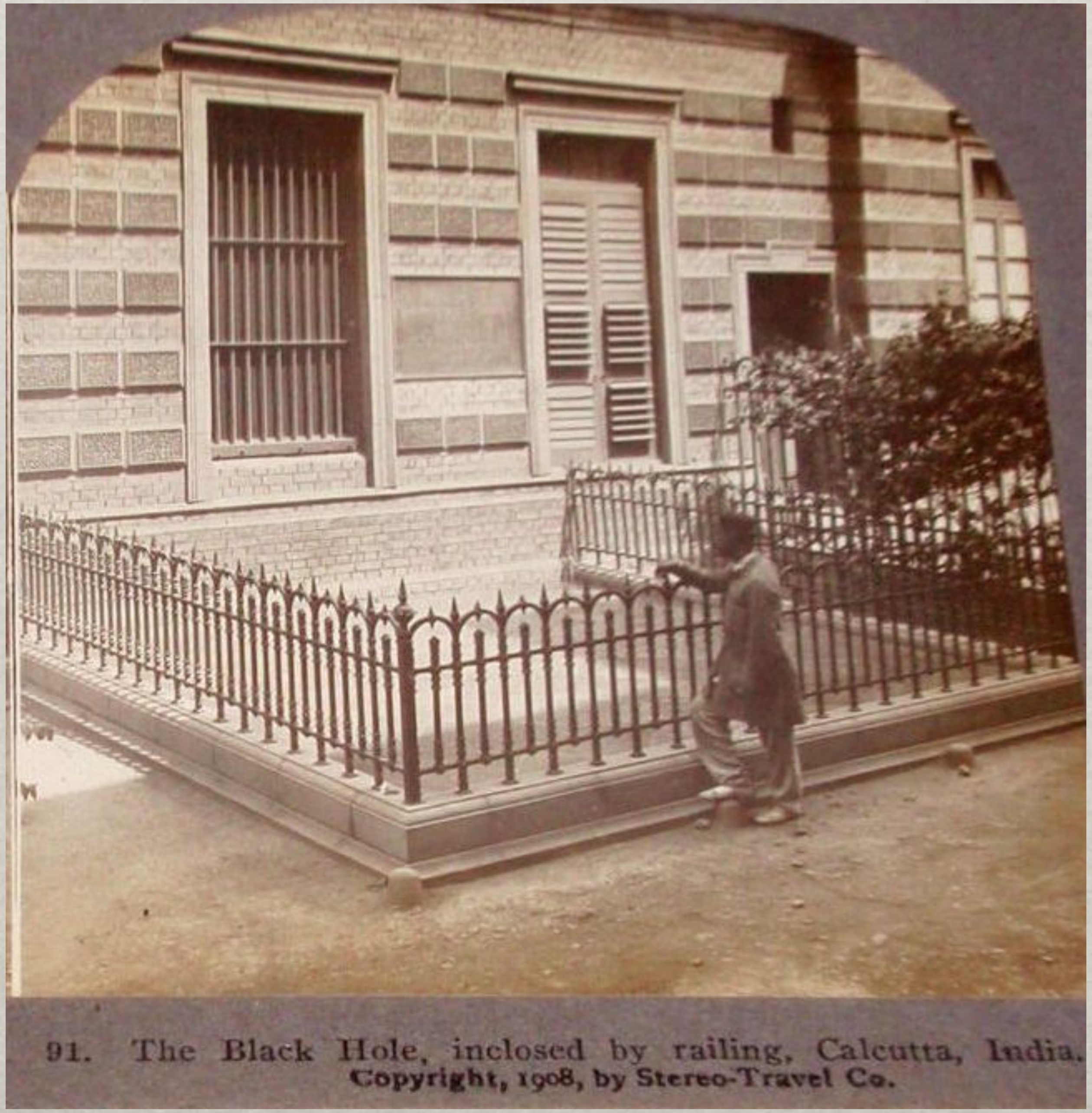

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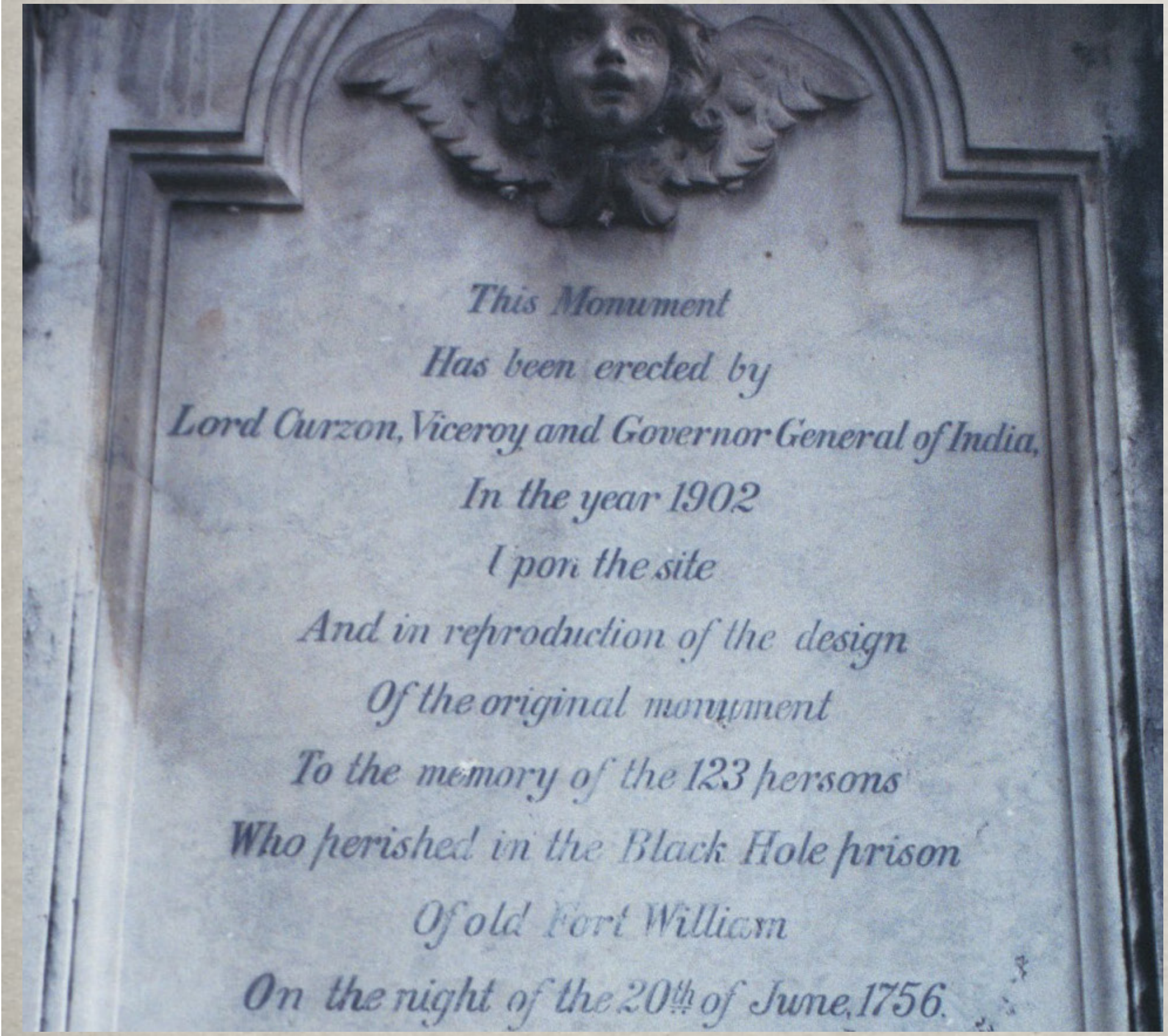

A brief timeline

1967-68: **John Wheeler popularizes the term "black hole"**

In an informal conversation, in 1996, Wheeler stated that the name "black hole" was recurrent in his conversations with Dicke, and that there were always playful smiles between the two when the name was brought up...

The black hole fifty years after: Genesis of the name

Carlos A. R. Herdeiro

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Black holes are extreme spacetime deformations where even light is imprisoned. There is an extensive astrophysical evidence for the real and abundant existence of these prisons of matter and light in the Universe. Mathematically, black holes are described by solutions of the field equations of the theory of general relativity, the first of which was published in 1916 by Karl Schwarzschild. Another highly relevant solution, representing a rotating black hole, was found by Roy Kerr in 1963. It was only much after the publication of the Schwarzschild solution, however, that the term black hole was employed to describe these objects. Who invented it? Conventional wisdom attributes the origin of the term to the prominent North American physicist John Wheeler who first adopted it in a general audience article published in 1968. This, however, is just one side of a story that begins two hundred years before in an Indian prison colloquially known as the Black Hole of Calcutta. Robert Dicke, also a distinguished physicist and colleague of Wheeler at Princeton University, aware of the prison's tragedy began, around 1960, to compare gravitationally completely collapsed stars to the black hole of Calcutta. The whole account thus suggests reconsidering who indeed coined the name black hole and commends acknowledging its definitive birth to a partnership between Wheeler and Dicke.

A brief timeline

1967: **Israel's theorem**

PHYSICAL REVIEW VOLUME 164, NUMBER 5 25 DECEMBER 1967

Event Horizons in Static Vacuum Space-Times

WERNER ISRAEL
Mathematics Department, University of Alberta, Alberta, Canada
and
Dublin Institute for Advanced Studies, Dublin, Ireland

(Received 27 April 1967)

The following theorem is established. Among all static, asymptotically flat vacuum space-times with closed simply connected equipotential surfaces g_{00}=constant, the Schwarzschild solution is the only one which has a nonsingular infinite-red-shift surface $g_{00}=0$. Thus there exists no static asymmetric perturbation of the Schwarzschild manifold due to internal sources (e.g., a quadrupole moment) which will preserve a regular event horizon. Possible implications of this result for asymmetric gravitational collapse are briefly discussed.

Werner Israel
(1931-)

Israel's theorem:
An asymptotically flat static vacuum spacetime that is non-singular on and outside an event horizon, must be isometric to the Schwarzschild spacetime.

A brief timeline

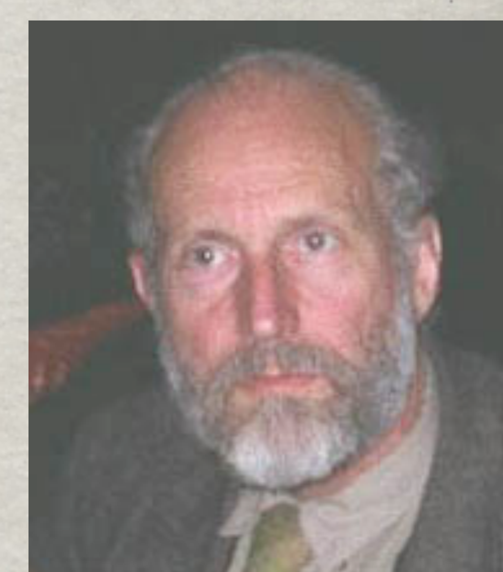
1967-....: **The electro-vacuum uniqueness theorems**

Axisymmetric Black Hole Has Only Two Degrees of Freedom

B. Carter
Institute of Theoretical Astronomy, University of Cambridge, Cambridge CB3 0EZ, England
(Received 18 December 1970)

A theorem is described which establishes the claim that in a certain canonical sense the Kerr metrics represent "the" (rather than merely "some possible") exterior fields of black holes with the corresponding mass and angular-momentum values.

Phys. Rev. Lett. 26 (1971) 331-333


Brandon Carter
(1942-)

Vacuum:

$$\mathcal{S} = \frac{1}{16\pi}\int d^4x\sqrt{-g}R$$

Kerr Kerr 1963

Uniqueness Israel 1967; Carter 1971; D.C. Robinson, Phys. Rev. Lett. 34, 905 (1975).

A brief timeline

1967-…: **The electro-vacuum uniqueness theorems**

Carter-Robinson theorem:
An asymptotically-flat stationary and axi-symmetric vacuum spacetime that is non-singular on and outside an event horizon, is a member of the two-parameter Kerr family.

The assumption of axi-symmetry was subsequently shown to be unnecessary, i.e. for black holes, stationarity ⇒ axisymmetry (via the "rigidity theorem", relating the teleologically defined "event horizon" to the local "Killing Horizon" Hawking 1972; I. Rácz and R.Wald, Class. Quant. Grav. 13 (1996) 539).

Electro-vacuum:

$$\mathcal{S} = \frac{1}{4\pi}\int d^4x\sqrt{-g}\left(\frac{R}{4} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right)$$

Kerr-Newman Newman et al. 1965

Uniqueness

W. Israel, Commun. Math. Phys. 8 (1968) 245;
D.C. Robinson, Phys. Rev. 10, 458 (1974)
(...)

Limitations: (e.g.) analyticity, assume connected event horizon, causality...

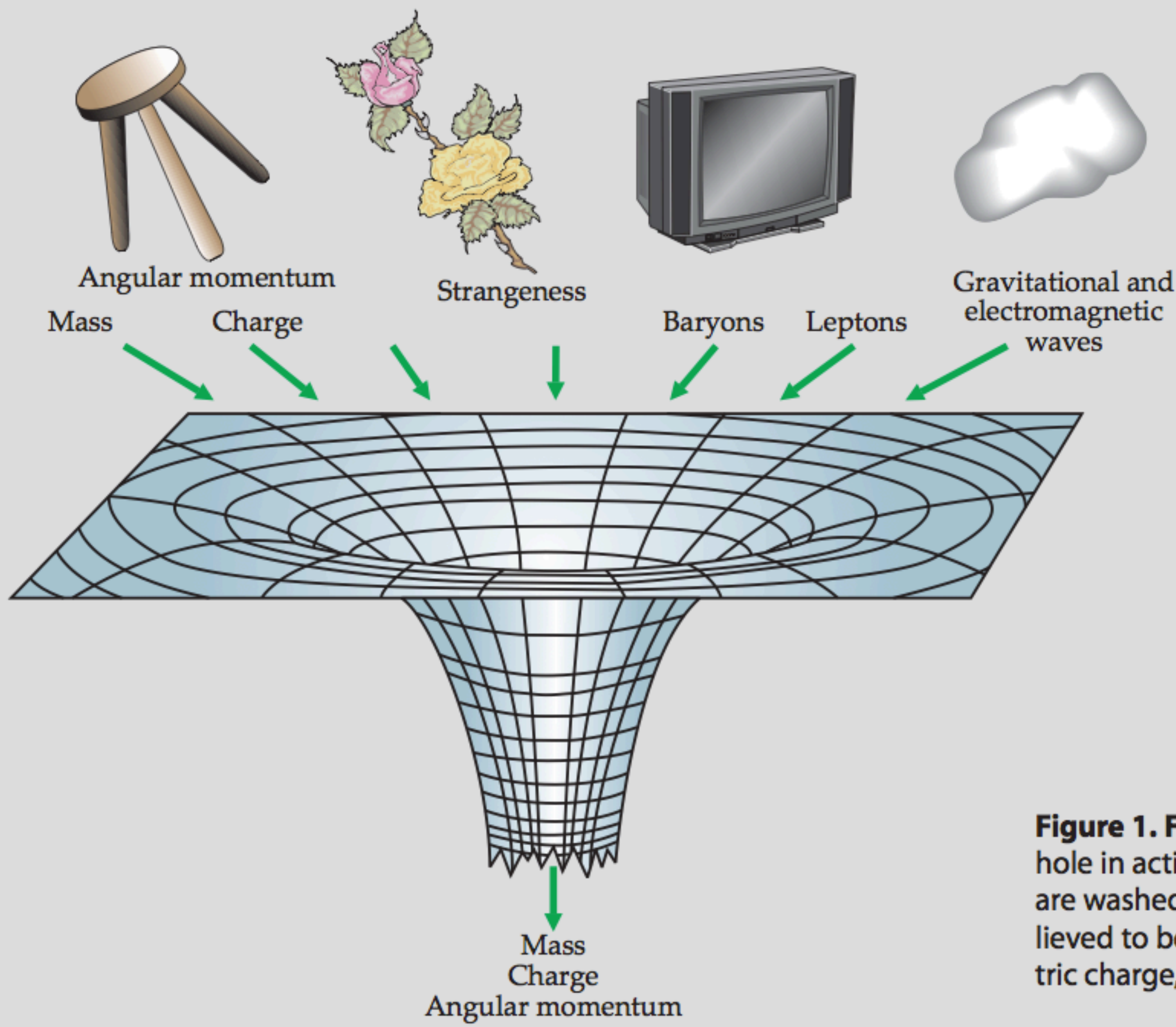
D. Robinson, in The Kerr Spacetime: Rotating Black Holes in General Relativity, edited by D. Wiltshire et al. (Cambridge University Press, Cambridge, England, 2009)

A brief timeline

1971: **Wheeler and Ruffini coin the expression "a black hole has no hair"**

The collapse leads to a black hole endowed with mass and charge and angular momentum but, so far as we can now judge, no other adjustable parameters: "A black hole has no hair." Make one black hole out of matter; another, of the same mass, angular momentum, and charge, out of antimatter. No one has ever been able to propose a workable way to tell which is which. Nor is any way known to distinguish either from a third black hole, formed by collapse of a much smaller amount of matter and then built up to the specified mass and angular momentum by firing in enough photons, or neutrinos, or gravitons. And on an equal footing is a fourth black hole, developed by collapse of a cloud of radiation altogether free from any "matter."

Electric charge is a distinguishable quantity because it carries a long-range force (conservation of flux; Gauss's law). Baryon number and strangeness carry no such long-range force. They have no Gauss's law. It is true that no attempt to observe a change in baryon number has ever succeeded. Nor has anyone ever been able to give a convincing reason to expect a direct and spontaneous violation of the principle of conservation of baryon number. In gravitational collapse, however, that principle is not directly violated; it is transcended. It is transcended because in collapse one loses the possibility of measuring baryon number, and therefore this quantity can not be well defined for a collapsed object. Similarly, strangeness is no longer conserved.

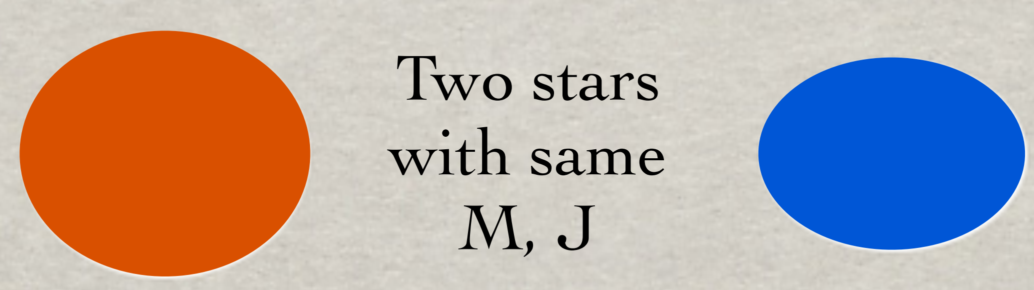


R. Ruffini and John Wheeler, "Introducing the black hole", Physics Today, January 1971, Pages 30-41

Summary:

The "no-hair" original idea (1971):
collapse leads to equilibrium black holes uniquely determined by M,J,Q - asymptotically measured quantities subject to a Gauss law and no other independent characteristics (hair)

The idea is motivated by the uniqueness theorems and indicates black holes are very special objects



Can have a different mass quadrupole, etc...

Summary:

The “no-hair” original idea (1971):
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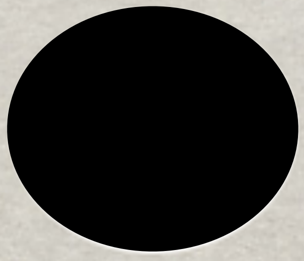
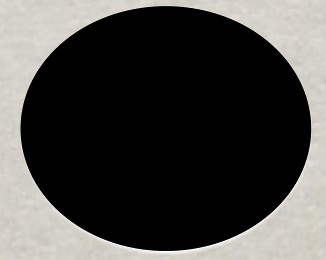


... but two
black holes
with same
M, J...



...must be exactly equal...

Elegant multipoles formula
(for the Kerr solution):

R. O. Hansen,
J. Math. Phys. 15 (1974) 46

$$M_\ell + iS_\ell = M(ia)^\ell$$

Summary:

The "no-hair" original idea (1971):
collapse leads to equilibrium black holes uniquely determined by M,J,Q -
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The idea is motivated by the uniqueness theorems
and indicates black holes are very special objects

"In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein's field equations of general relativity, discovered by the New Zealand mathematician, Roy Kerr, provides the absolutely exact representation of untold numbers of massive black holes that populate the Universe."

S. Chandrasekhar, in *Truth and Beauty* (1987)

This is the Kerr hypothesis

There was never a better time
for strong gravity research,
in particular on black holes (BHs)

Timely to address some central questions such as:

- What are the BH populations in the Universe?
- Are (all) astrophysical BHs really described by the canonical General Relativity (GR) model (the Kerr metric)?
- Can astrophysical BHs gives us hints about new physics (beyond GR or beyond Standard Model of particle physics)?
- Is there room/necessity for exotic compact objects (without an event horizon)?

Relate to other key questions in Gravitation/Cosmology:

- What is the nature of dark matter and dark energy?

Black holes and exotic compact objects

C. Herdeiro
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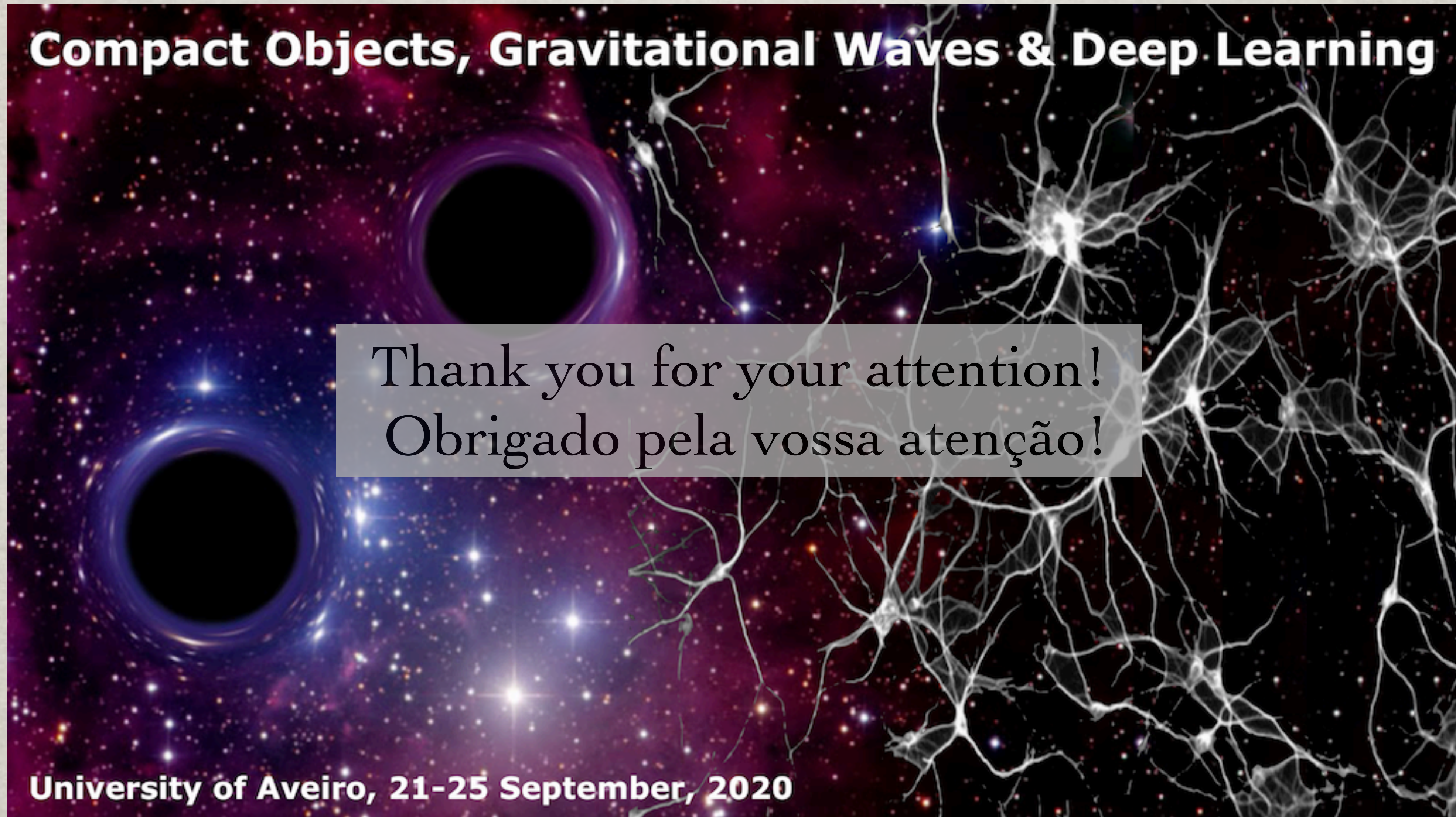

Thank you for your attention!
Obrigado pela vossa atenção!

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