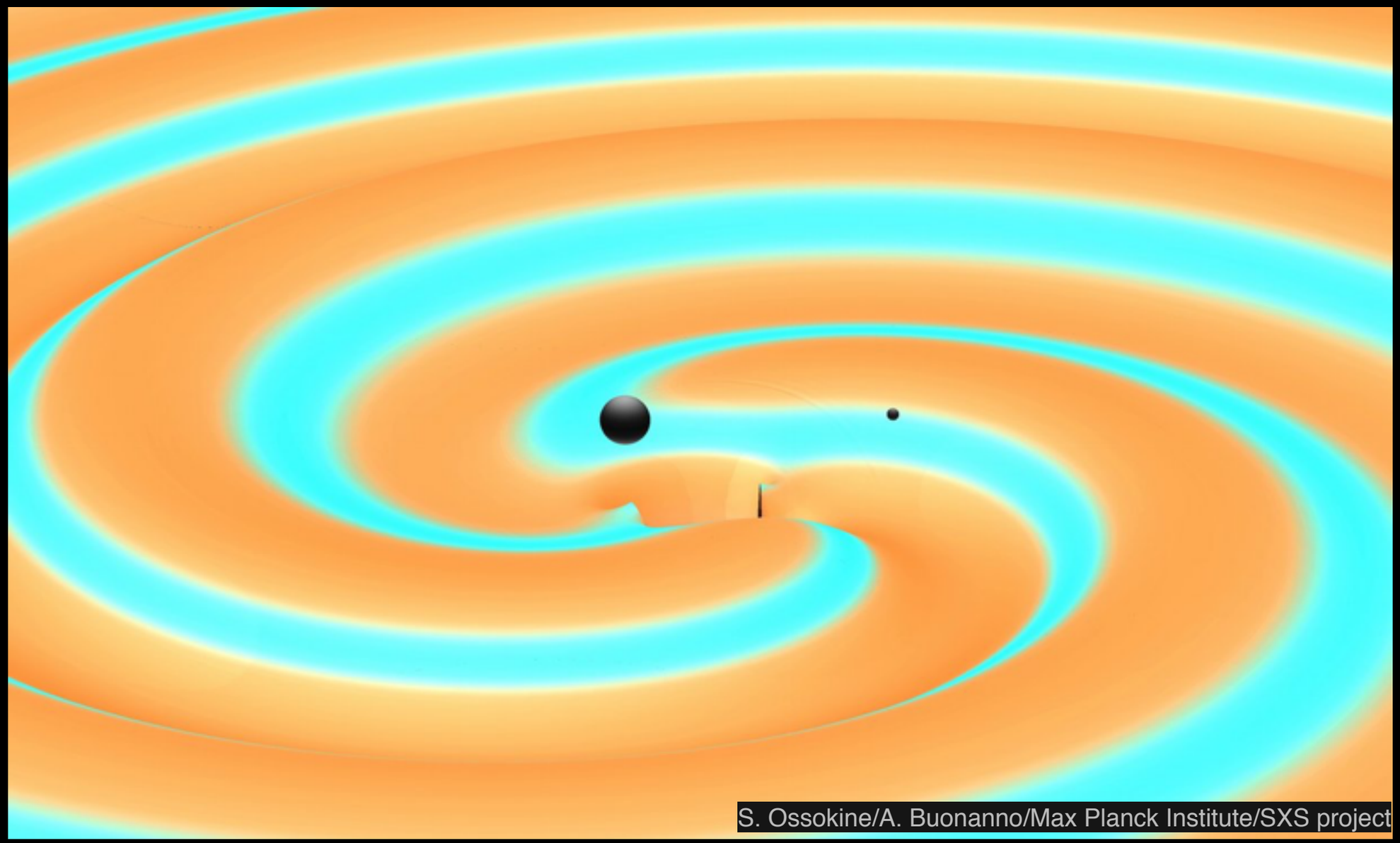
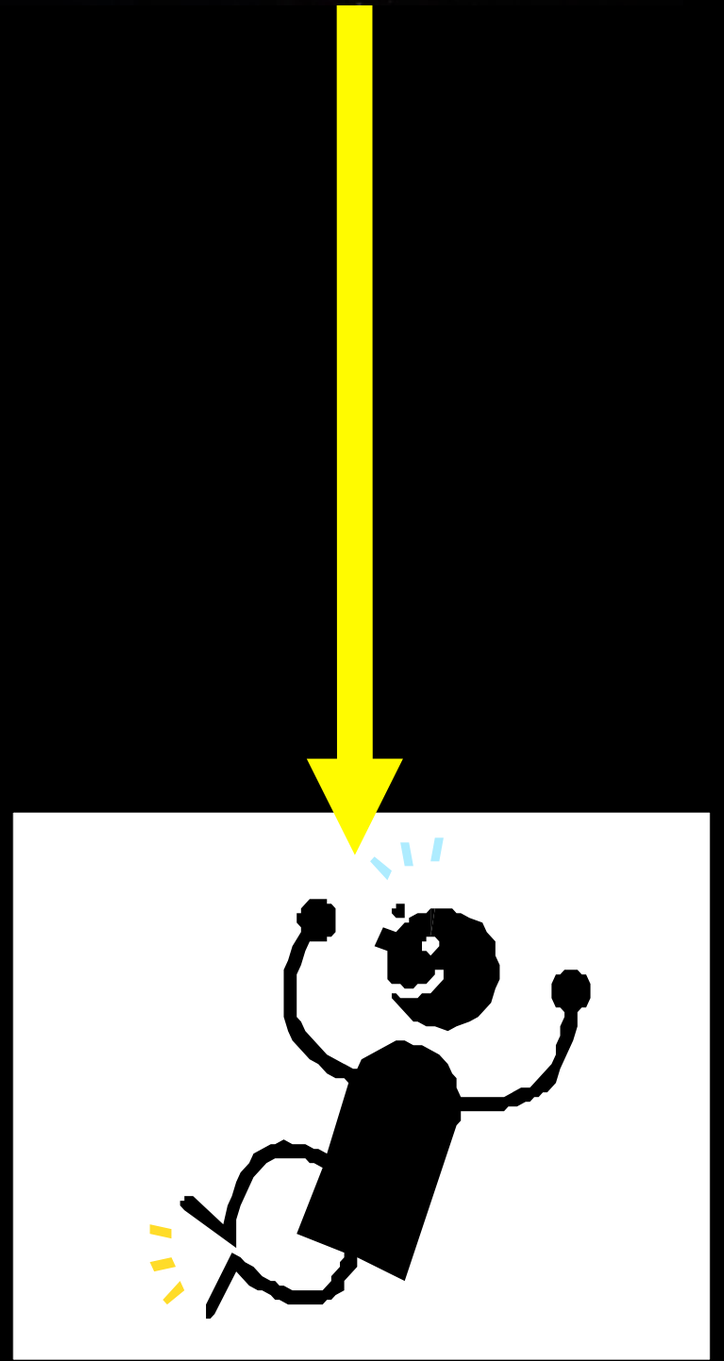
Singing binaries:
Listening to the chirps of black holes



Ilya Mandel
University of Birmingham

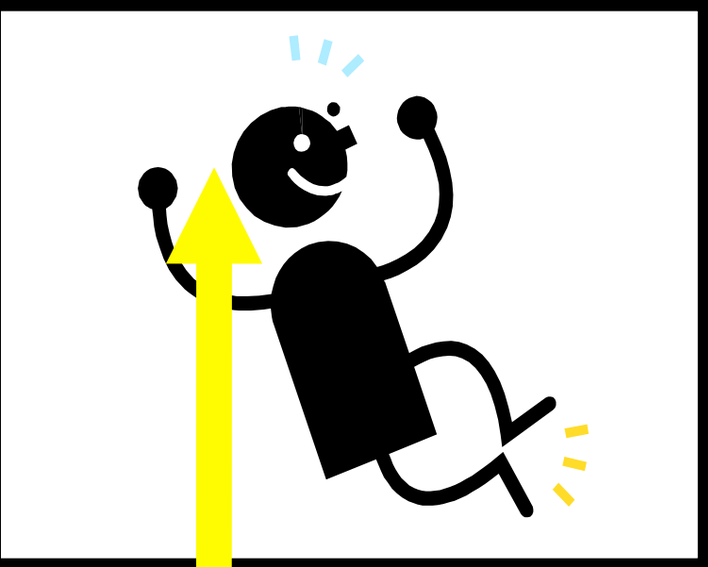
Light

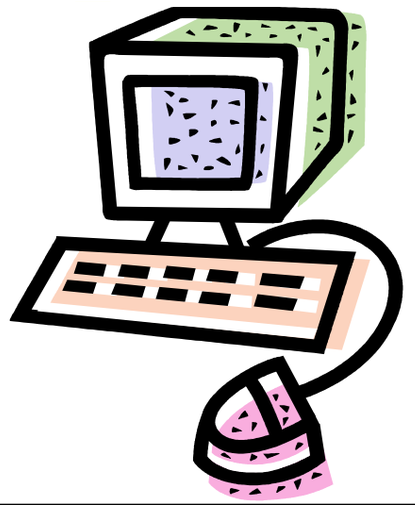
Electromagnetic Waves

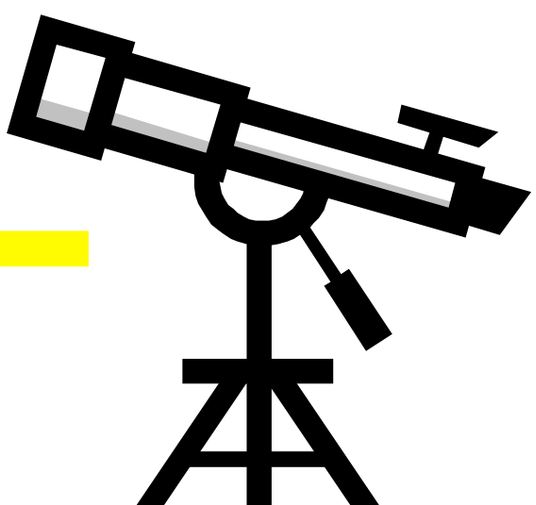


Light

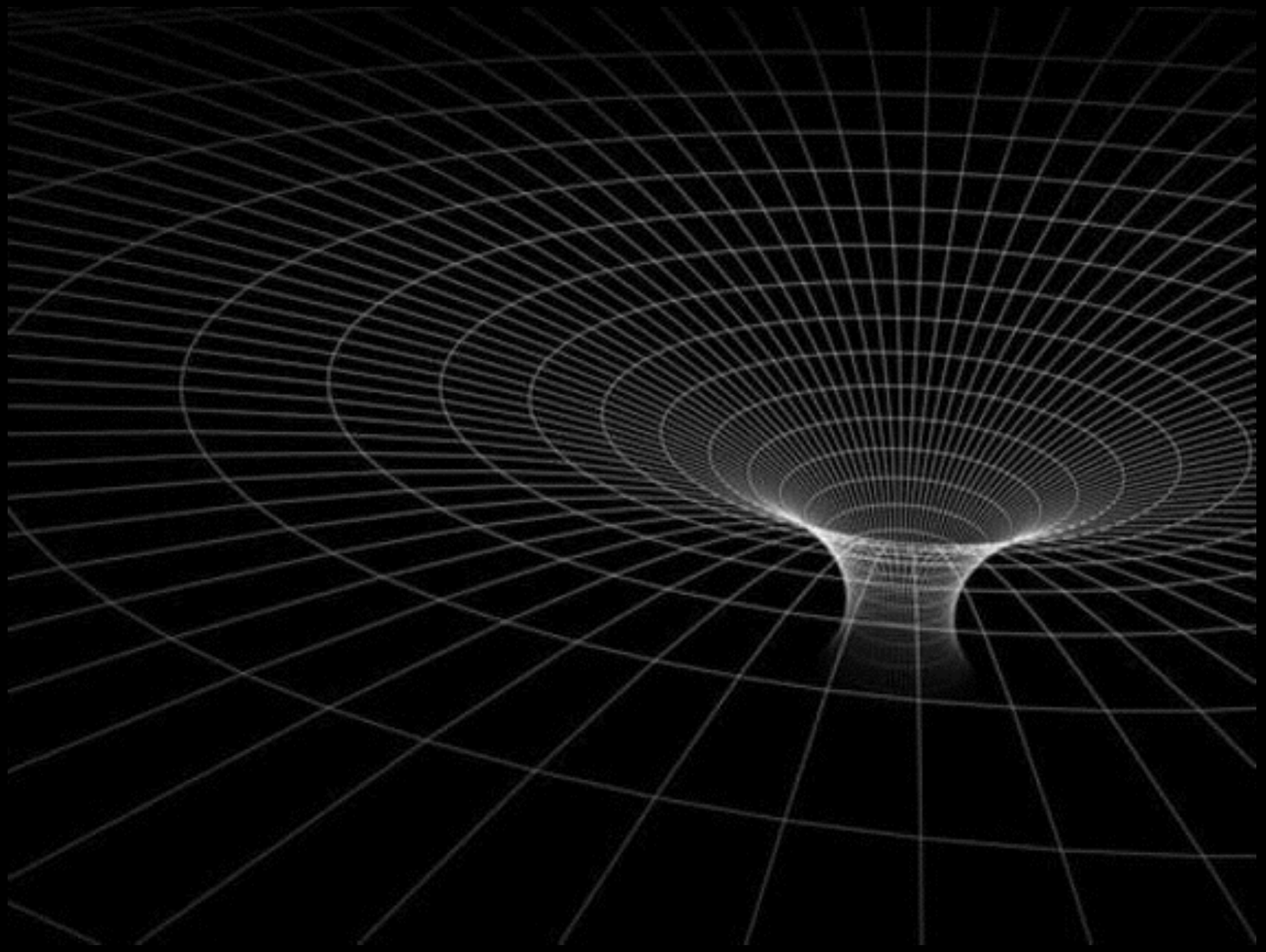
Electromagnetic Waves





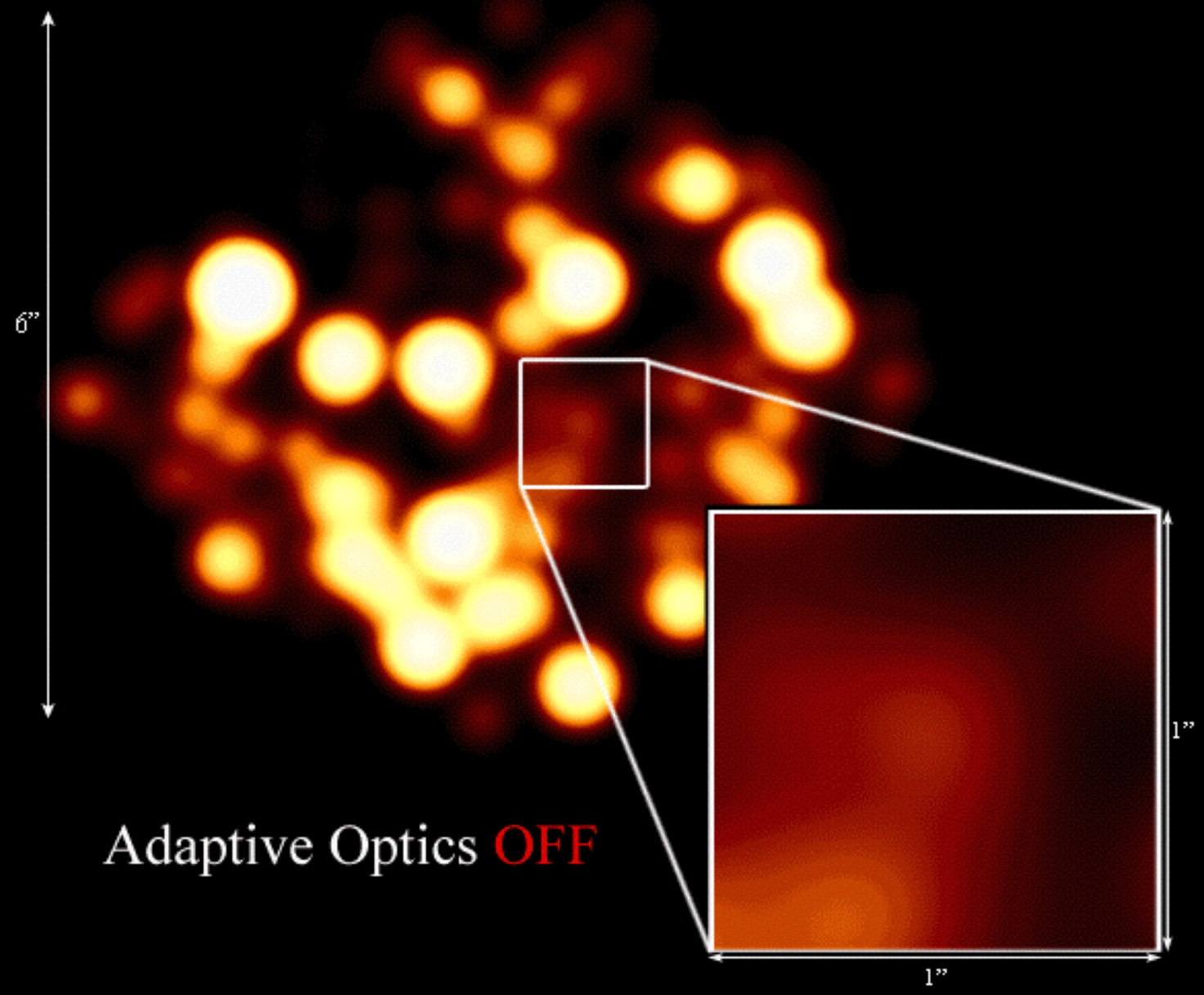


Black Holes

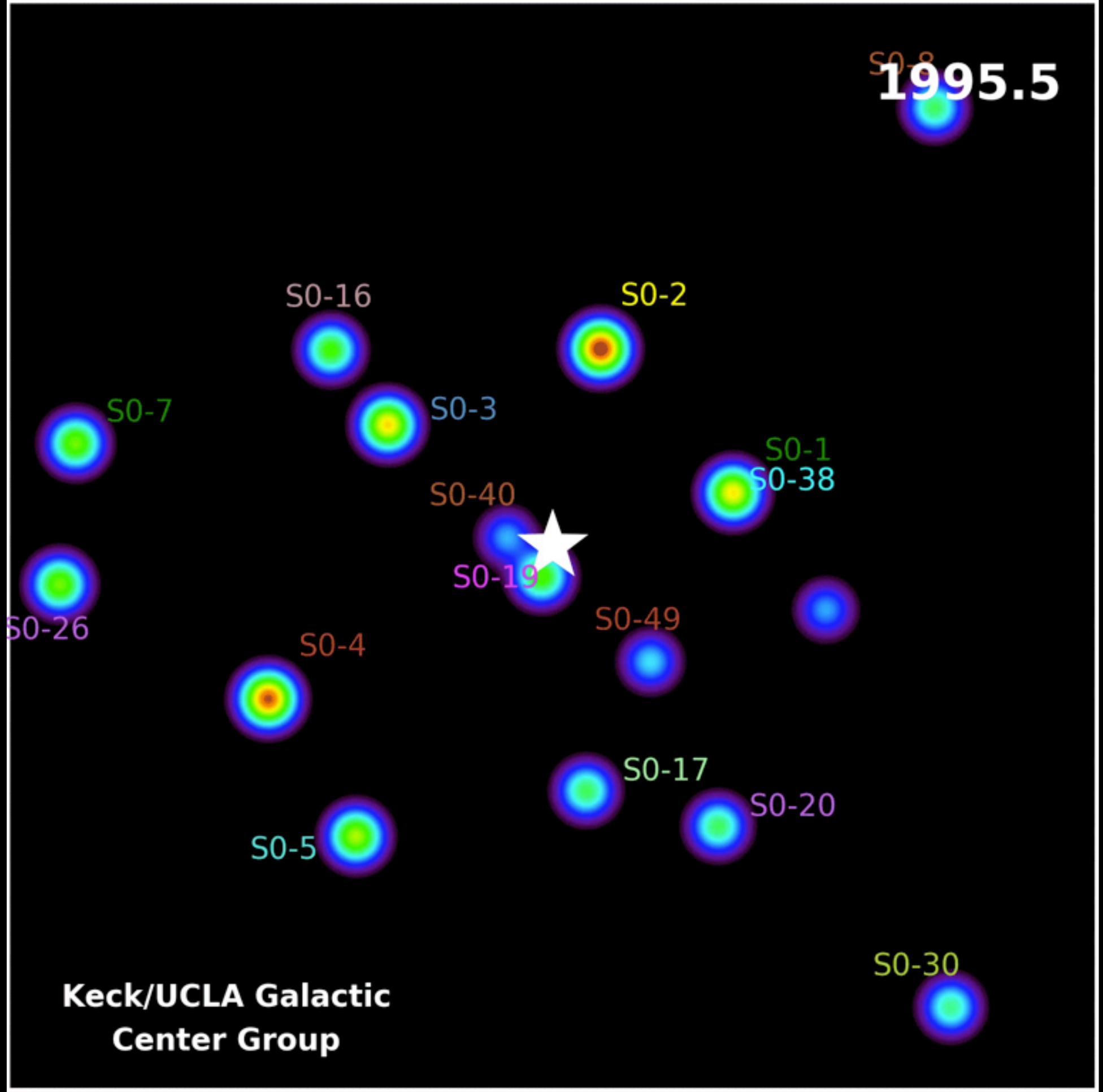


- Very dense collapsed matter
- Gravitational force so strong that not even light can escape

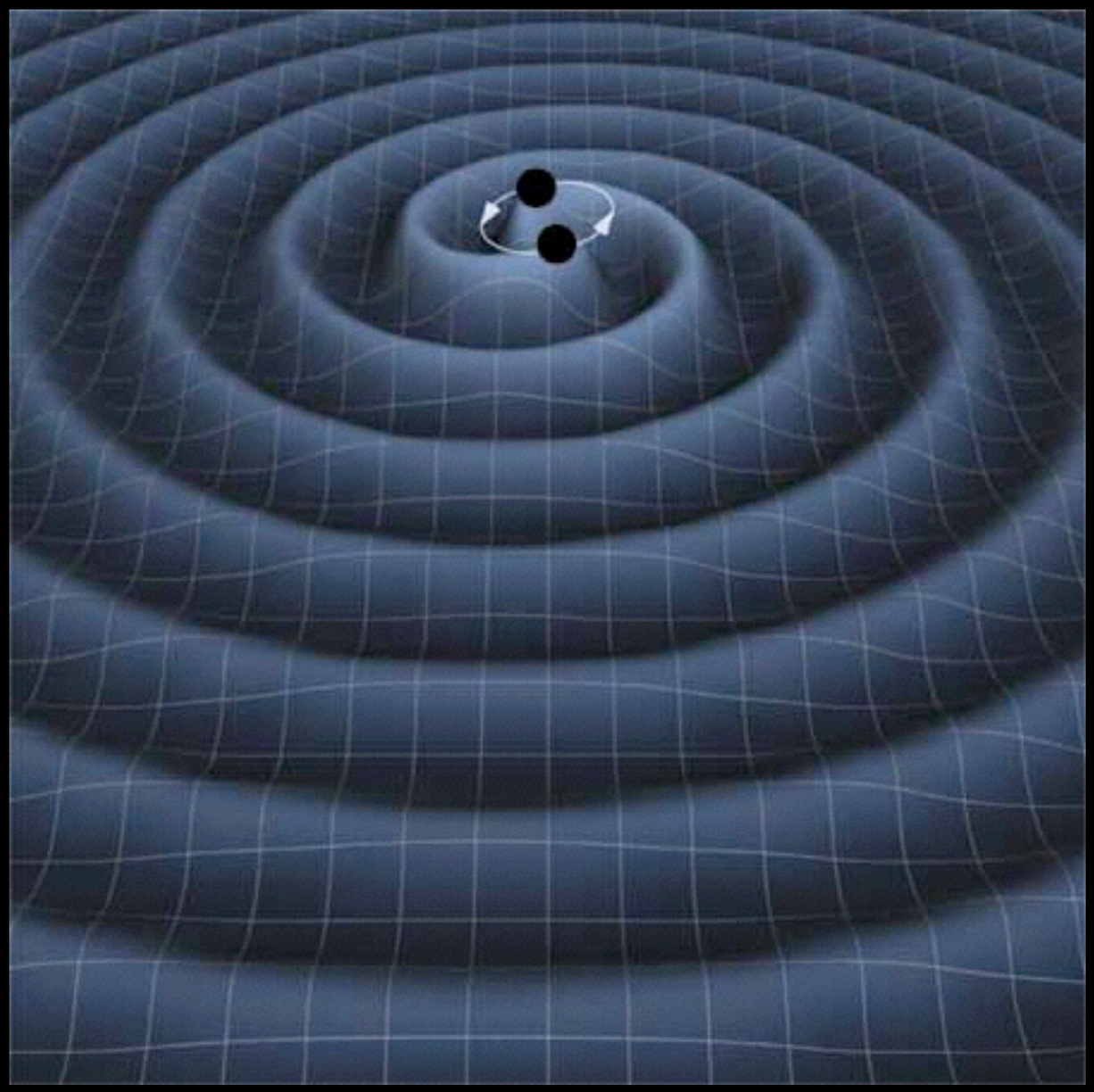
The Galactic Center at 2.2 microns



Adaptive Optics OFF

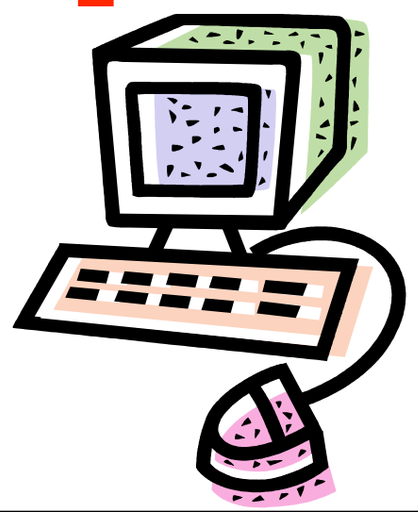

1995.5
S0-8
S0-16
S0-2
S0-7
S0-3
S0-1
S0-38
S0-40
S0-19
S0-49
S0-26
S0-4
S0-17
S0-20
S0-5
S0-30
Keck/UCLA Galactic
Center Group

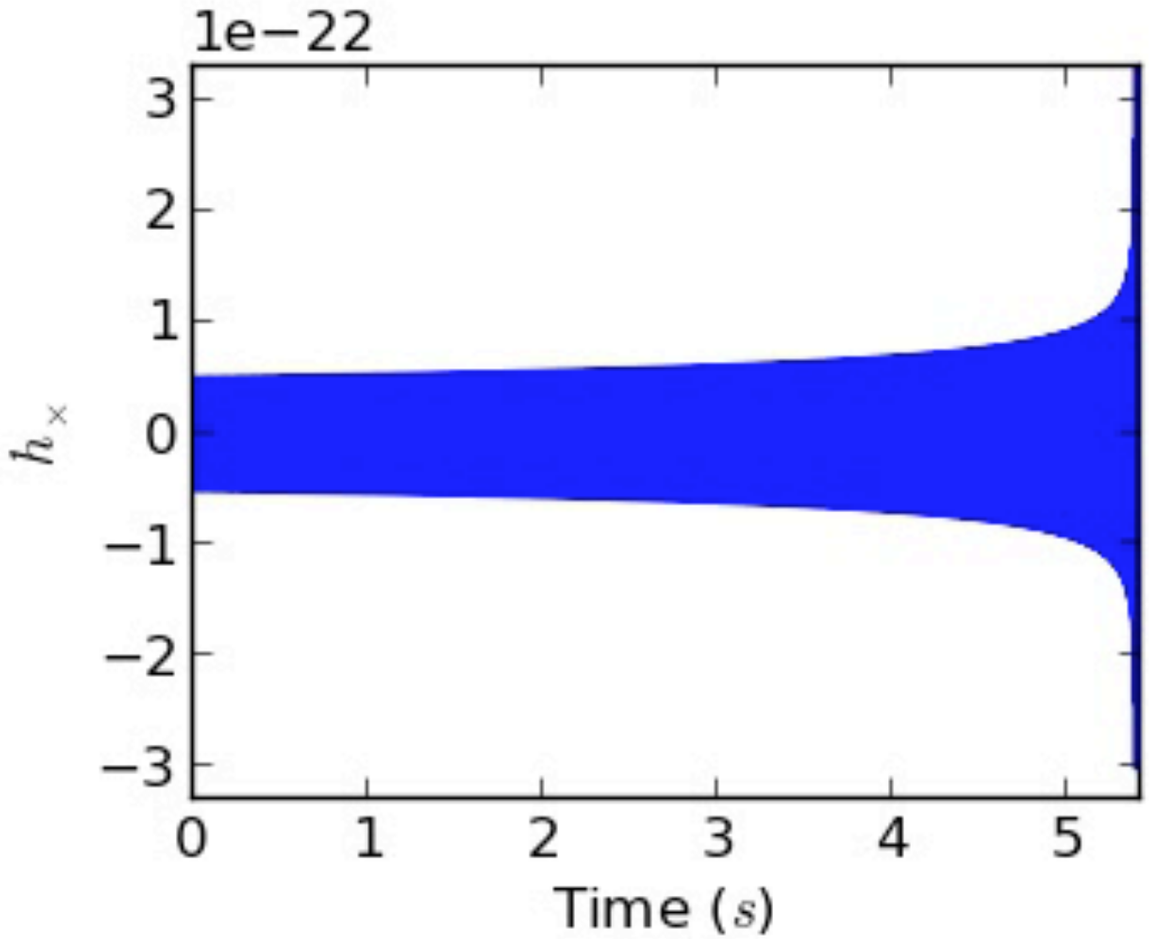
General Relativity predicts Gravitational waves

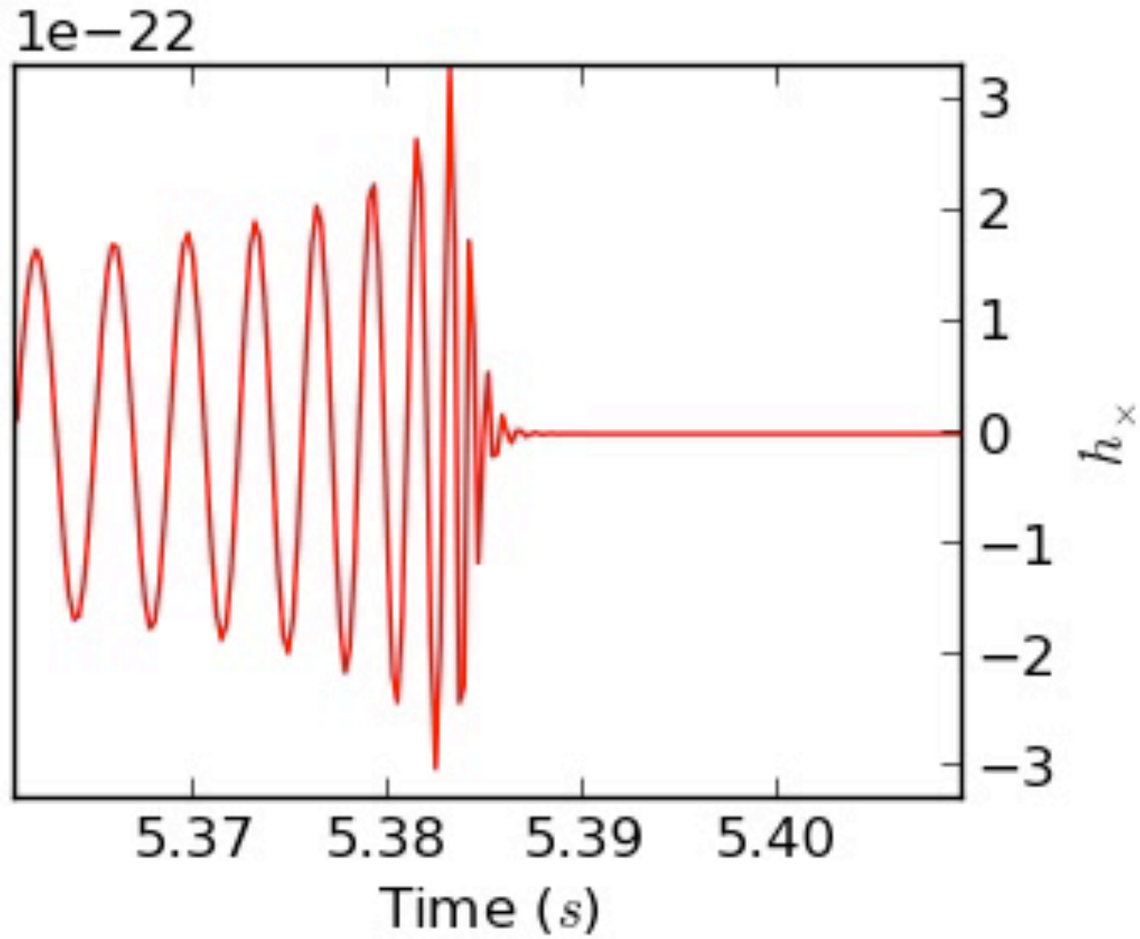


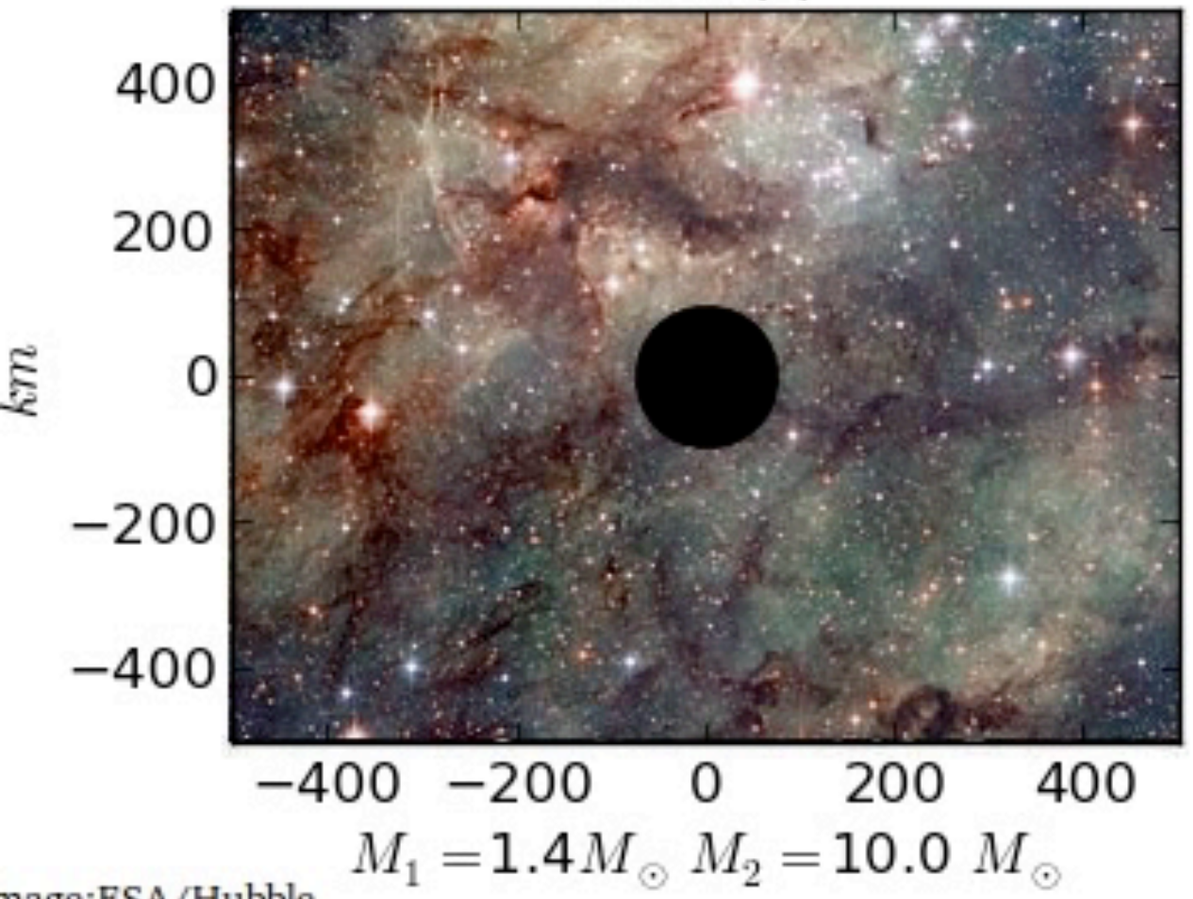
- Waves in space which spread out like ripples in a pond.
- They are produced by large fast moving concentration of mass or energy.
- Cause space to be stretched and squashed, lengths get longer and shorter.
- The specific timing and strength of the waves tell us about the object which created them.

Gravitational Waves

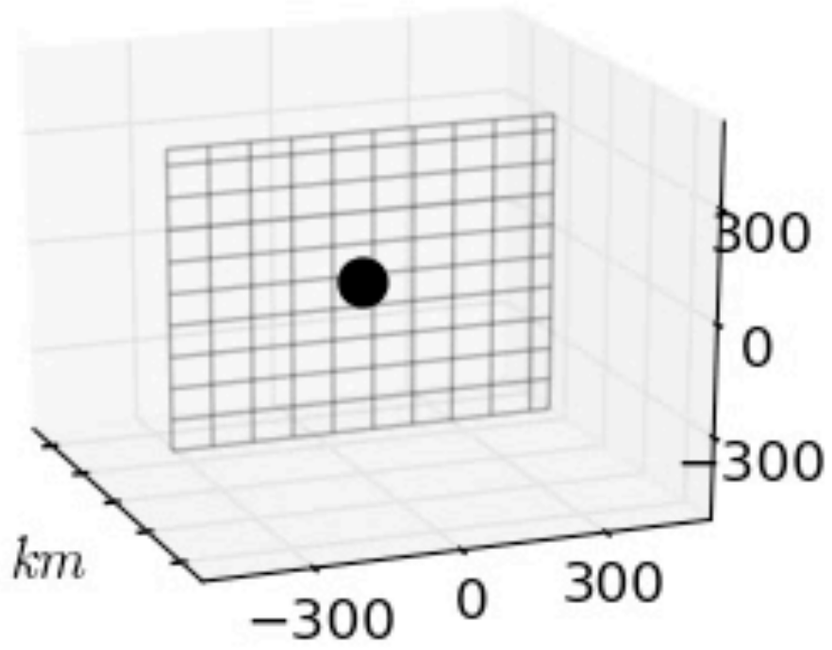




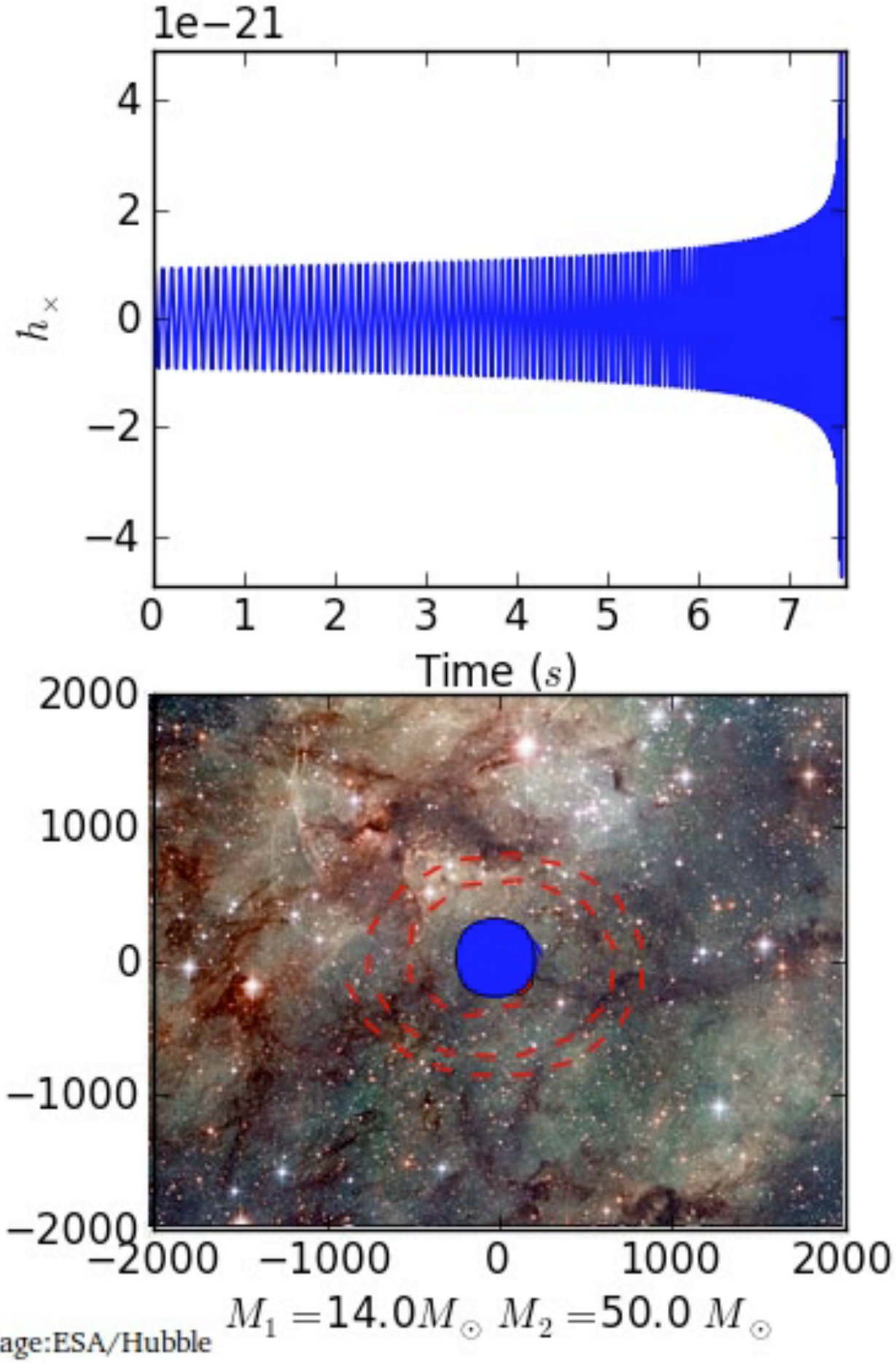


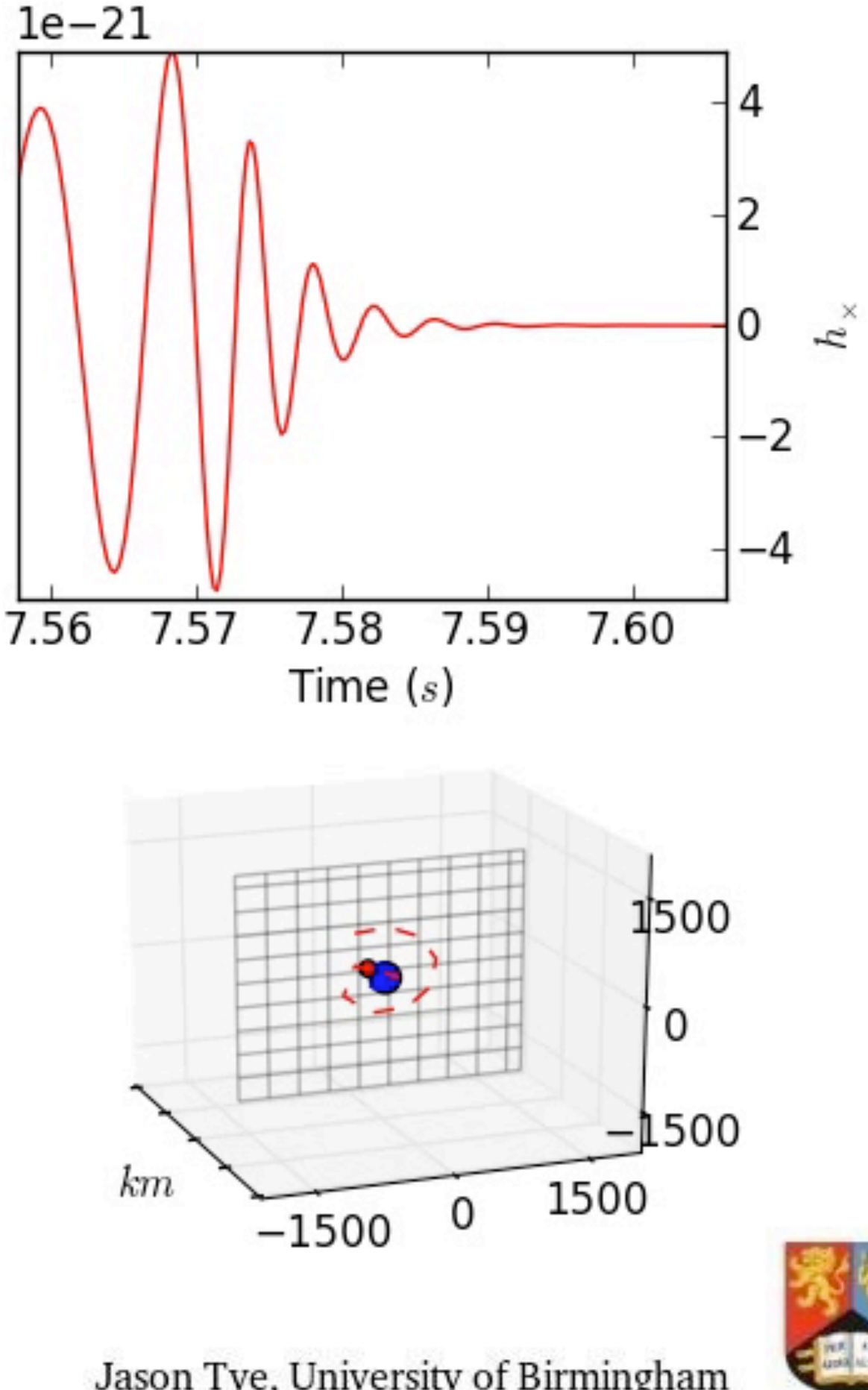


mage:ESA/Hubble



Jason Tye, University of Birmingham



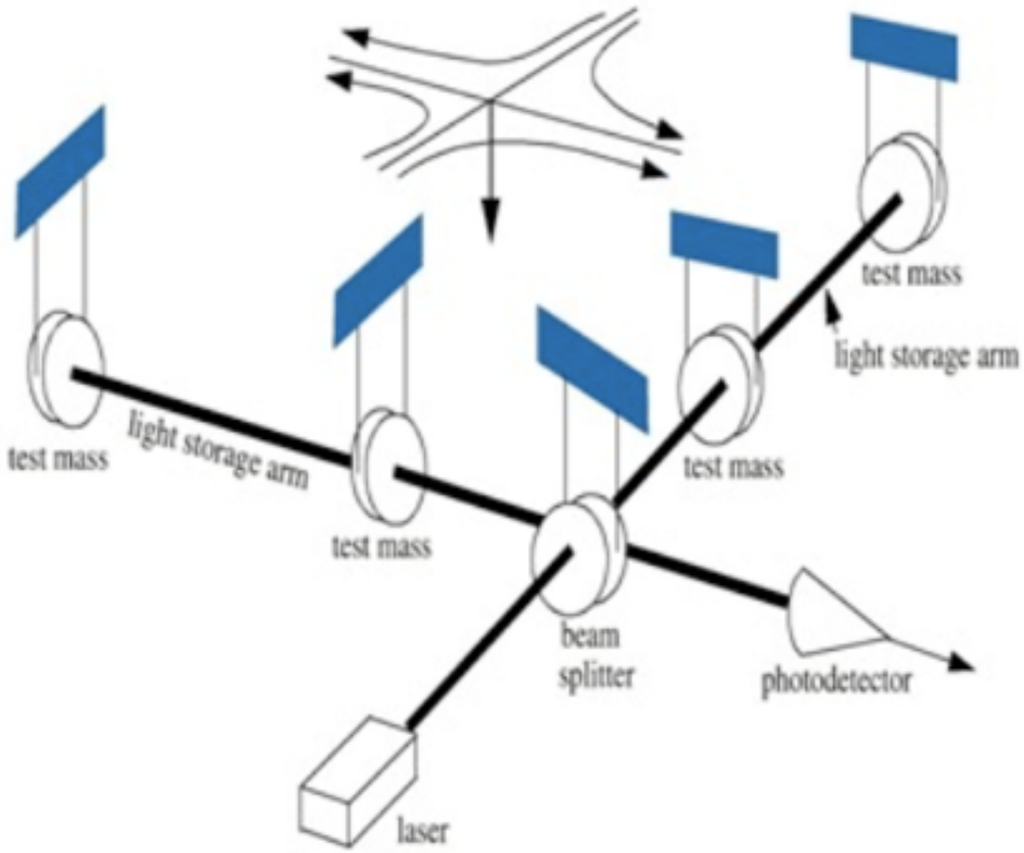


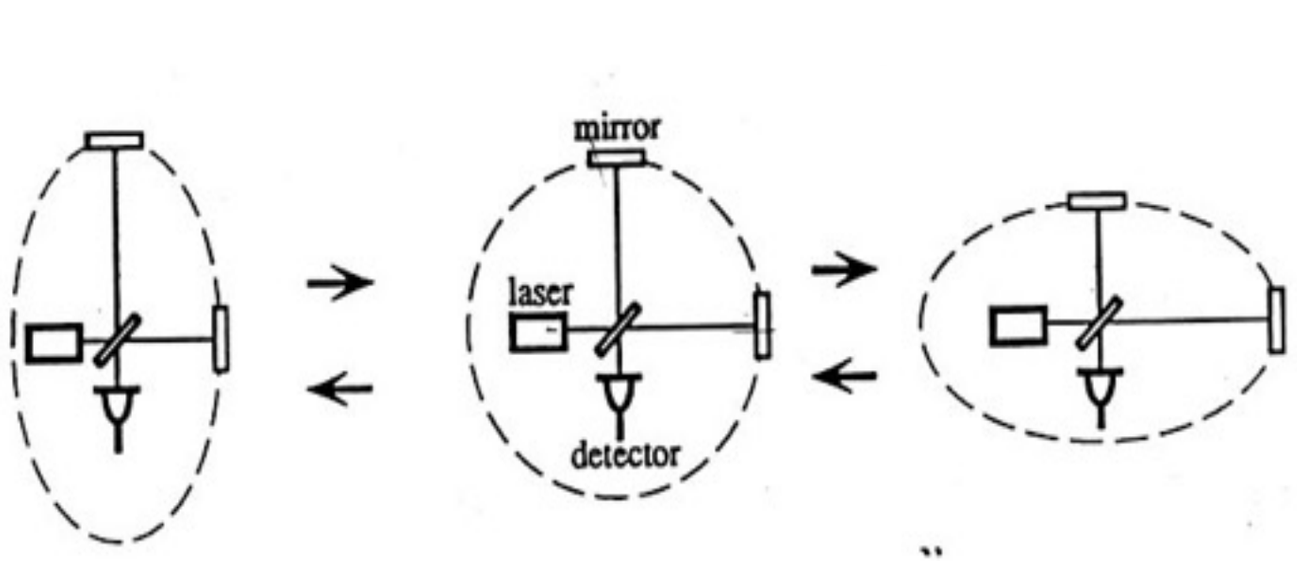
mage:ESA/Hubble

Jason Tye, University of Birmingham

Opportunity and Challenge

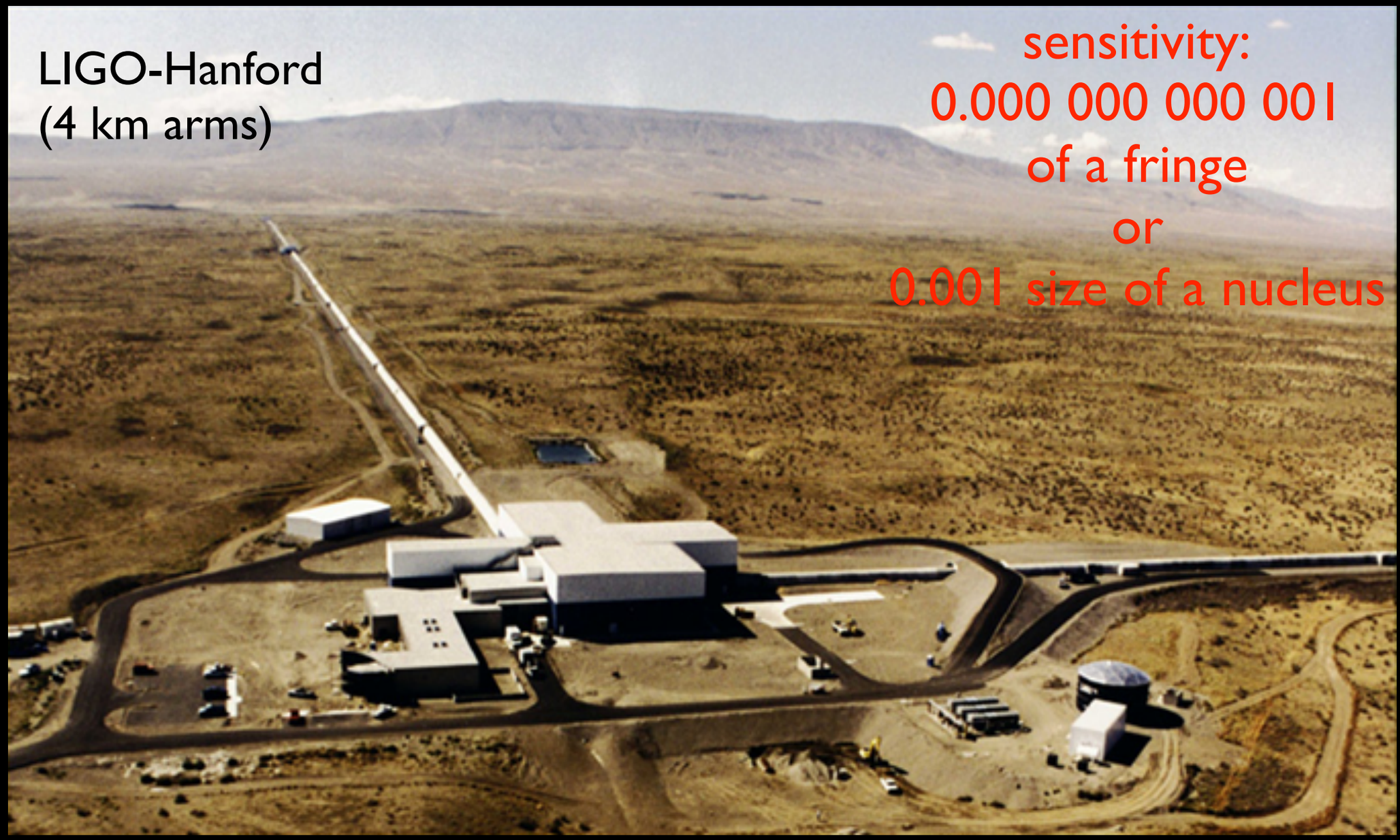
GWs carry a lot of energy, but interact weakly: can pass through everything, including detectors!





Michelson-type interferometers

GW interferometry today



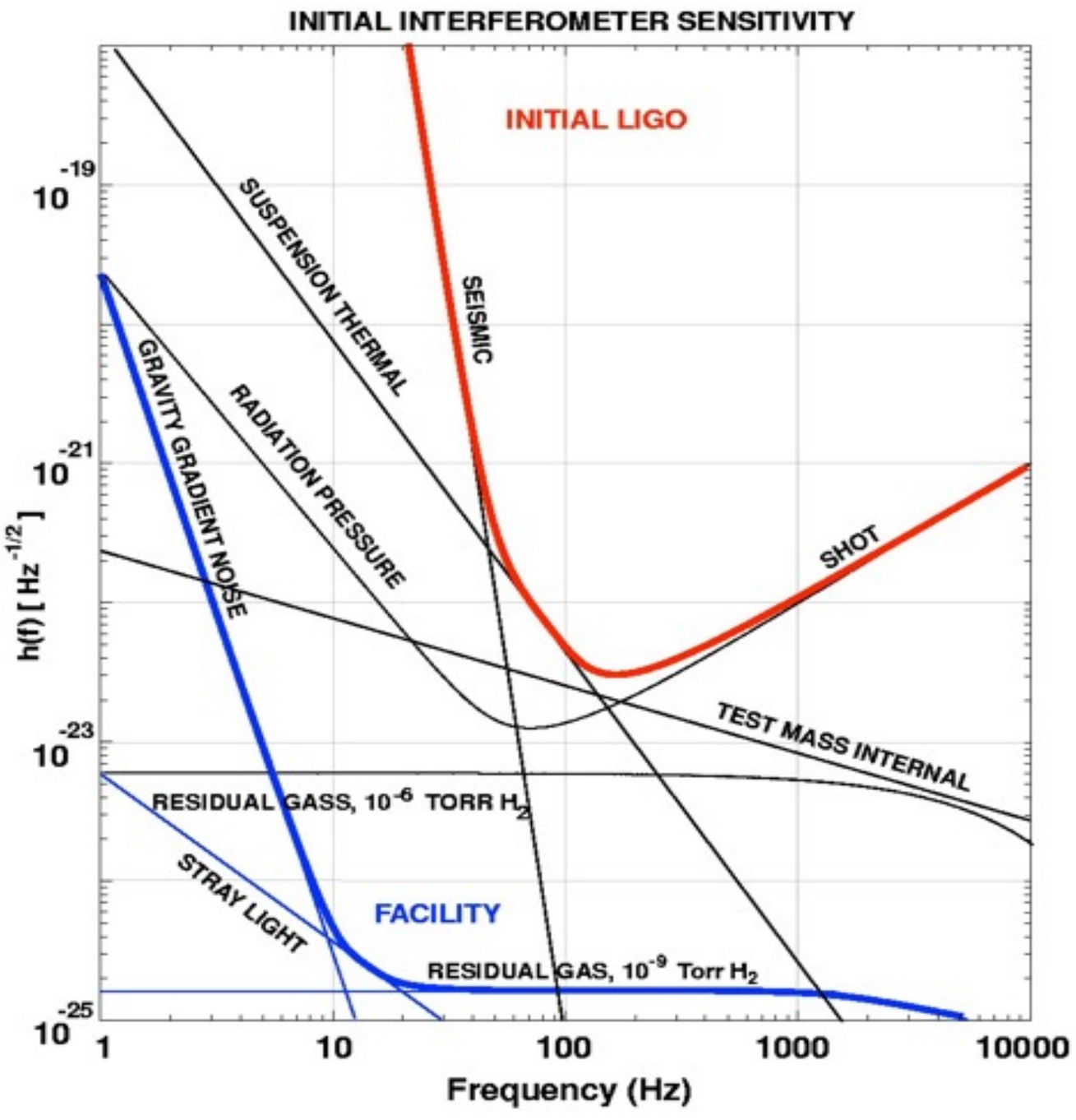
LIGO Scientific Collaboration

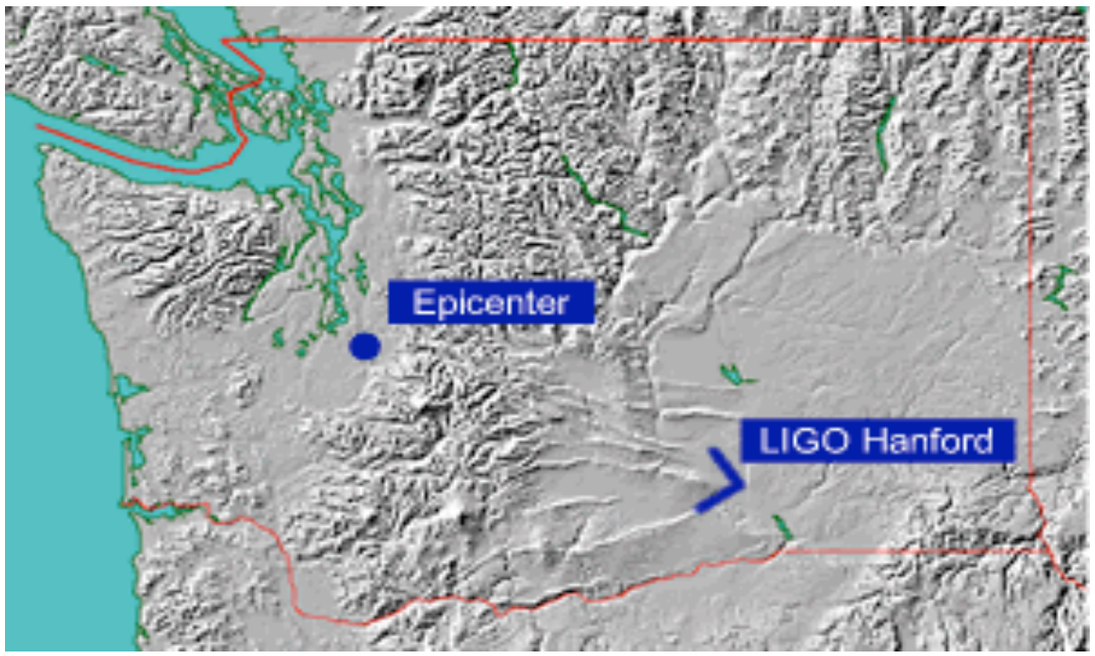
LIGO

LSC

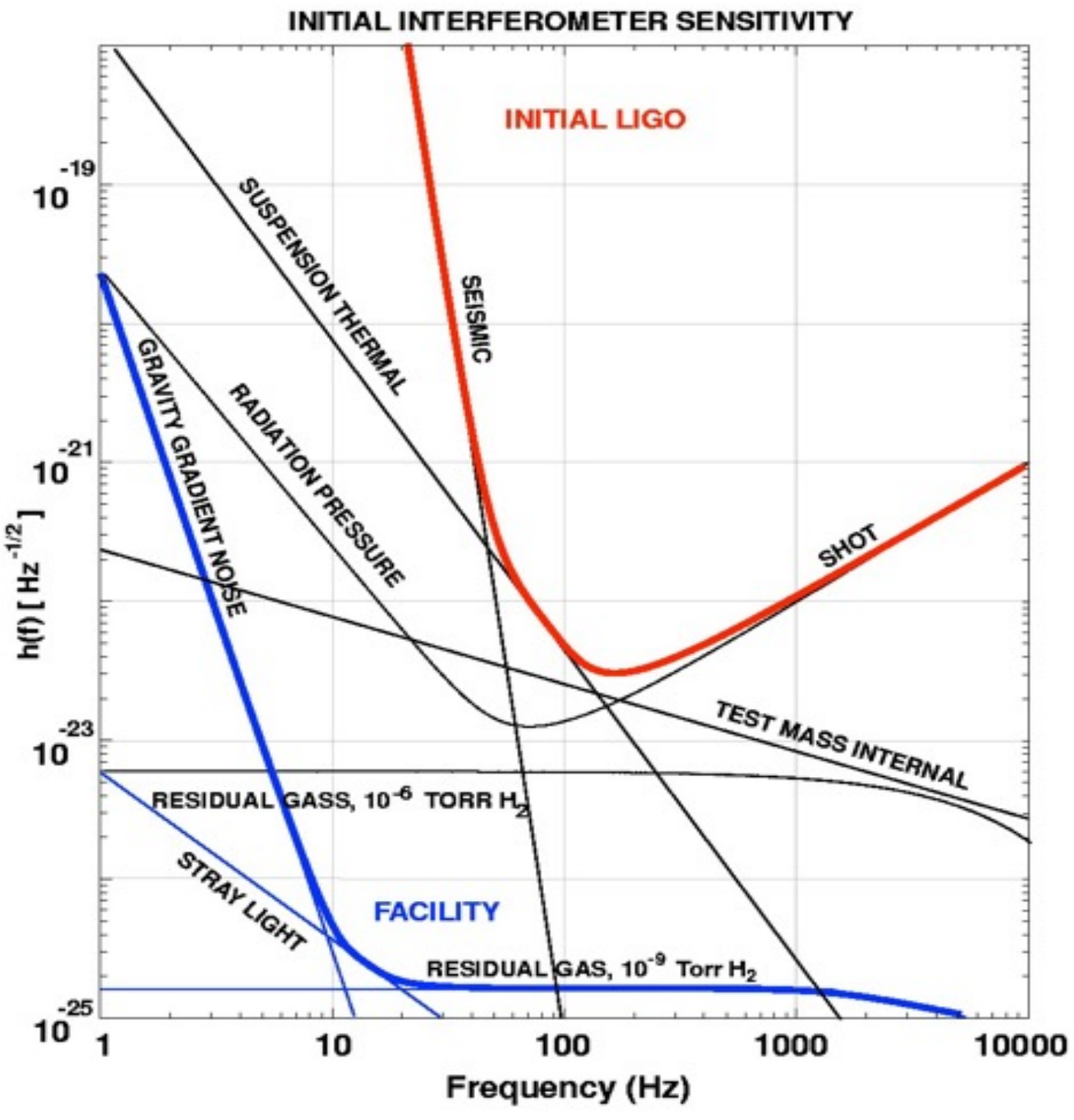
- Australian Consortium for Interferometric Gravitational Astronom
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

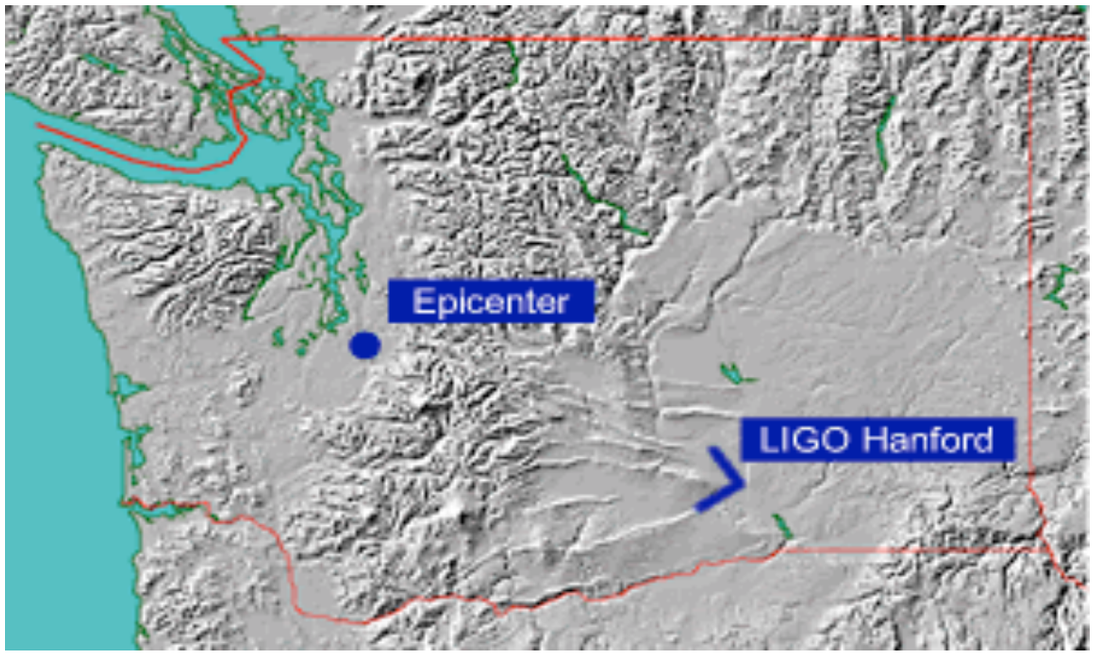
Detection Challenges





Detection Challenges





Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

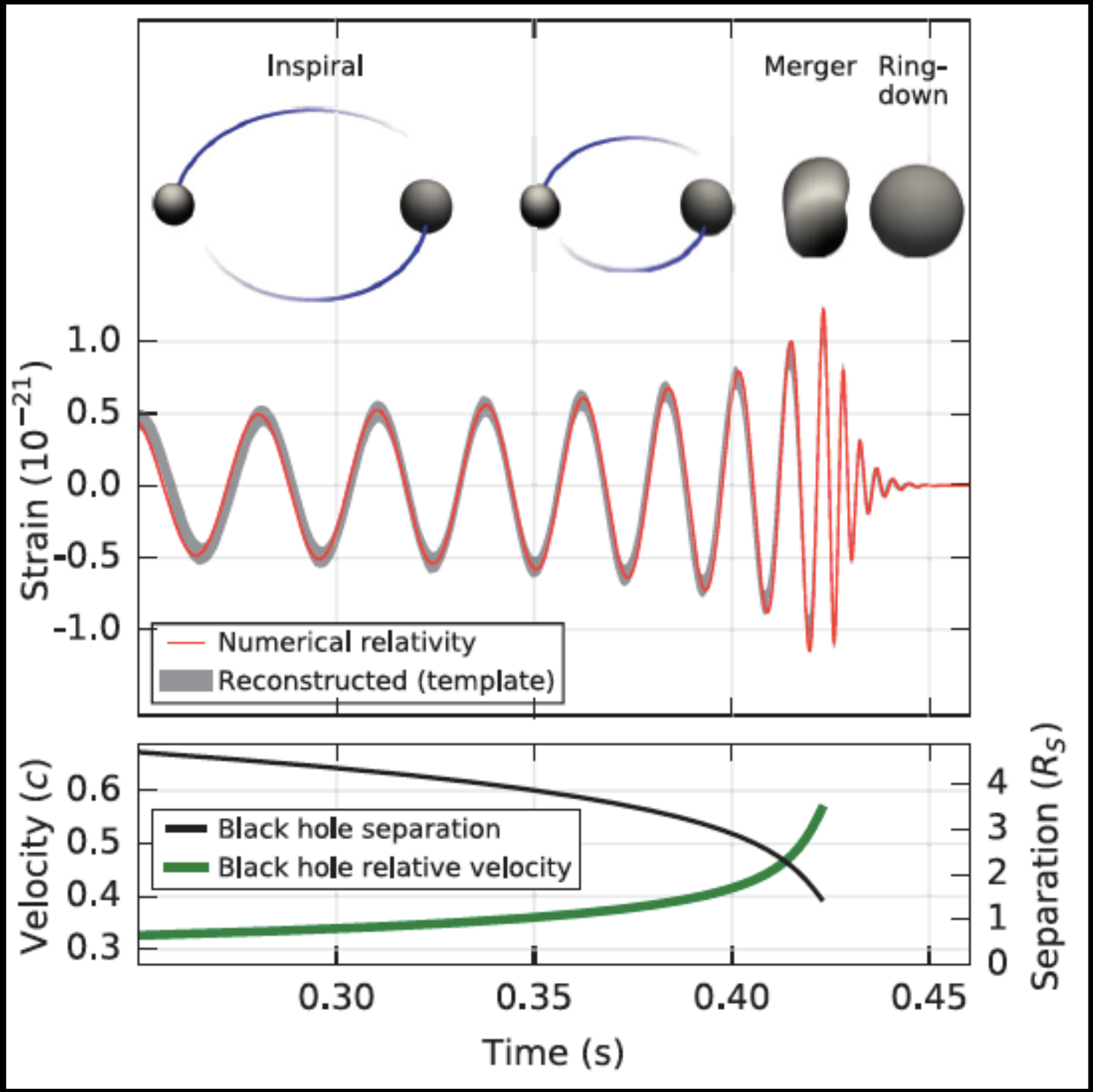
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

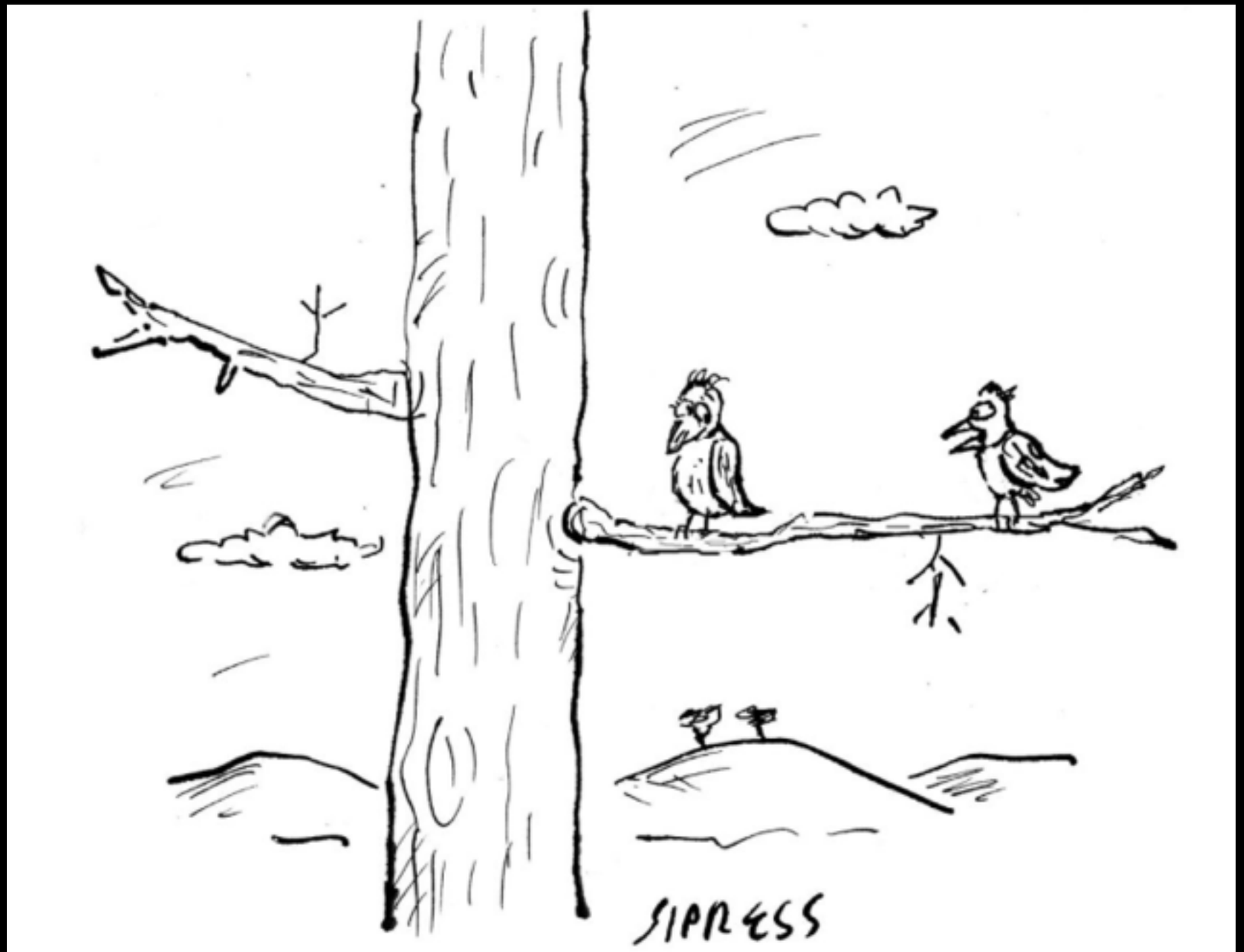
DOI: 10.1103/PhysRevLett.116.061102

R. Sturani,[121] A. L. Stuver,[6] T. Z. Summerscales,[128] L. Sun,[85] P. J. Sutton,[91] B. L. Swinkels,[34] M. J. Szczepańczyk,[97] M. Tacca,[30] D. Talukder,[59] D. B. Tanner,[5] M. Tápai,[96] S. P. Tarabrin,[8] A. Taracchini,[29] R. Taylor,[1] T. Theeg,[8] M. P. Thirugnanasambandam,[1] E. G. Thomas,[45] M. Thomas,[6] P. Thomas,[37] K. A. Thorne,[6] K. S. Thorne,[76] E. Thrane,[114] S. Tiwari,[12] V. Tiwari,[91] K. V. Tokmakov,[107] C. Tomlinson,[86] M. Tonelli,[18,19] C. V. Torres,[83,c] C. I. Torrie,[1] D. Töyrä,[45] F. Travasso,[32,33] G. Traylor,[6] D. Trifirò,[21] M. C. Tringali,[89,90] L. Trozzo,[129,19] M. Tse,[10] M. Turconi,[53] D. Tuyenbayev,[83] D. Ugolini,[130] C. S. Unnikrishnan,[99] A. L. Urban,[16] S. A. Usman,[35] H. Vahlbruch,[17] G. Vajente,[1] G. Valdes,[83] M. Vallisneri,[76] N. van Bakel,[9] M. van Beuzekom,[9] J. F. J. van den Brand,[61,9] C. Van Den Broeck,[9] D. C. Vander-Hyde,[35,22] L. van der Schaaf,[9] J. V. van Heijningen,[9] A. A. van Veggel,[36] M. Vardaro,[41,42] S. Vass,[1] M. Vasúth,[38] R. Vaulin,[10] A. Vecchio,[45] G. Vedovato,[42] J. Veitch,[45] P. J. Veitch,[104] K. Venkateswara,[131] D. Verkindt,[7] F. Vetrano,[57,58] A. Viceré,[57,58] S. Vinciguerra,[45] D. J. Vine,[50] J.-Y. Vinet,[53] S. Vitale,[10] T. Vo,[35] H. Vocca,[32,33] C. Vorvick,[37] D. Voss,[5] W. D. Vousden,[45] S. P. Vyatchanin,[49] A. R. Wade,[20] L. E. Wade,[132] M. Wade,[132] S. J. Waldman,[10] M. Walker,[2] L. Wallace,[1] S. Walsh,[16,8,29] G. Wang,[12] H. Wang,[45] M. Wang,[45] X. Wang,[70] Y. Wang,[51] H. Ward,[36] R. L. Ward,[20] J. Warner,[37] M. Was,[7] B. Weaver,[37] L.-W. Wei,[53] M. Weinert,[8] A. J. Weinstein,[1] R. Weiss,[10] T. Welborn,[6] L. Wen,[51] P. Weßels,[8] T. Westphal,[8] K. Wette,[8] J. T. Whelan,[102,8] S. E. Whitcomb,[1] D. J. White,[86] B. F. Whiting,[5] K. Wiesner,[8] C. Wilkinson,[37] P. A. Willems,[1] L. Williams,[5] R. D. Williams,[1] A. R. Williamson,[91] J. L. Willis,[133] B. Willke,[17,8] M. H. Wimmer,[8,17] L. Winkelmann,[8] W. Winkler,[8] C. C. Wipf,[1] A. G. Wiseman,[16] H. Wittel,[8,17] G. Woan,[36] J. Worden,[37] J. L. Wright,[36] G. Wu,[6] J. Yablon,[82] I. Yakushin,[6] W. Yam,[10] H. Yamamoto,[1] C. C. Yancey,[62] M. J. Yap,[20] H. Yu,[10] M. Yvert,[7] A. Zadrożny,[112] L. Zangrando,[42] M. Zanolin,[97] J.-P. Zendri,[42] M. Zevin,[82] F. Zhang,[10] L. Zhang,[1] M. Zhang,[120] Y. Zhang,[102] C. Zhao,[51] M. Zhou,[82] Z. Zhou,[82] X. J. Zhu,[51] M. E. Zucker,[1,10] S. E. Zuraw[103] and J. Zweizig[1]

(LIGO Scientific Collaboration and Virgo Collaboration)

[1]*LIGO, California Institute of Technology, Pasadena, California 91125, USA*
[2]*Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[3]*Università di Salerno, Fisciano, I-84084 Salerno, Italy*


Inspiral
Merger
Ring-down
1.0
0.5
0.0
-0.5
-1.0
Strain (10^{-21})
Numerical relativity
Reconstructed (template)
0.6
0.5
0.4
0.3
Velocity (c)
Black hole separation
Black hole relative velocity
4
3
2
1
0
Separation (R_S)
0.30
0.35
0.40
0.45
Time (s)



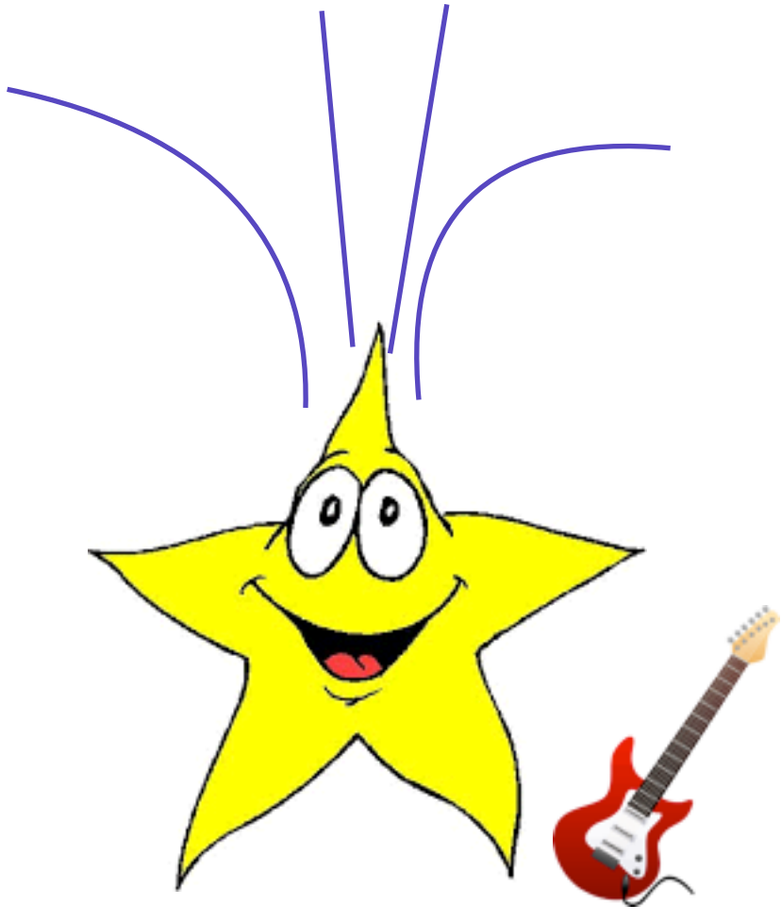
"Was that you I heard just now, or was it two black holes colliding?"

Was that you I heard just now, or was it two black holes colliding?

Stella

Estelle

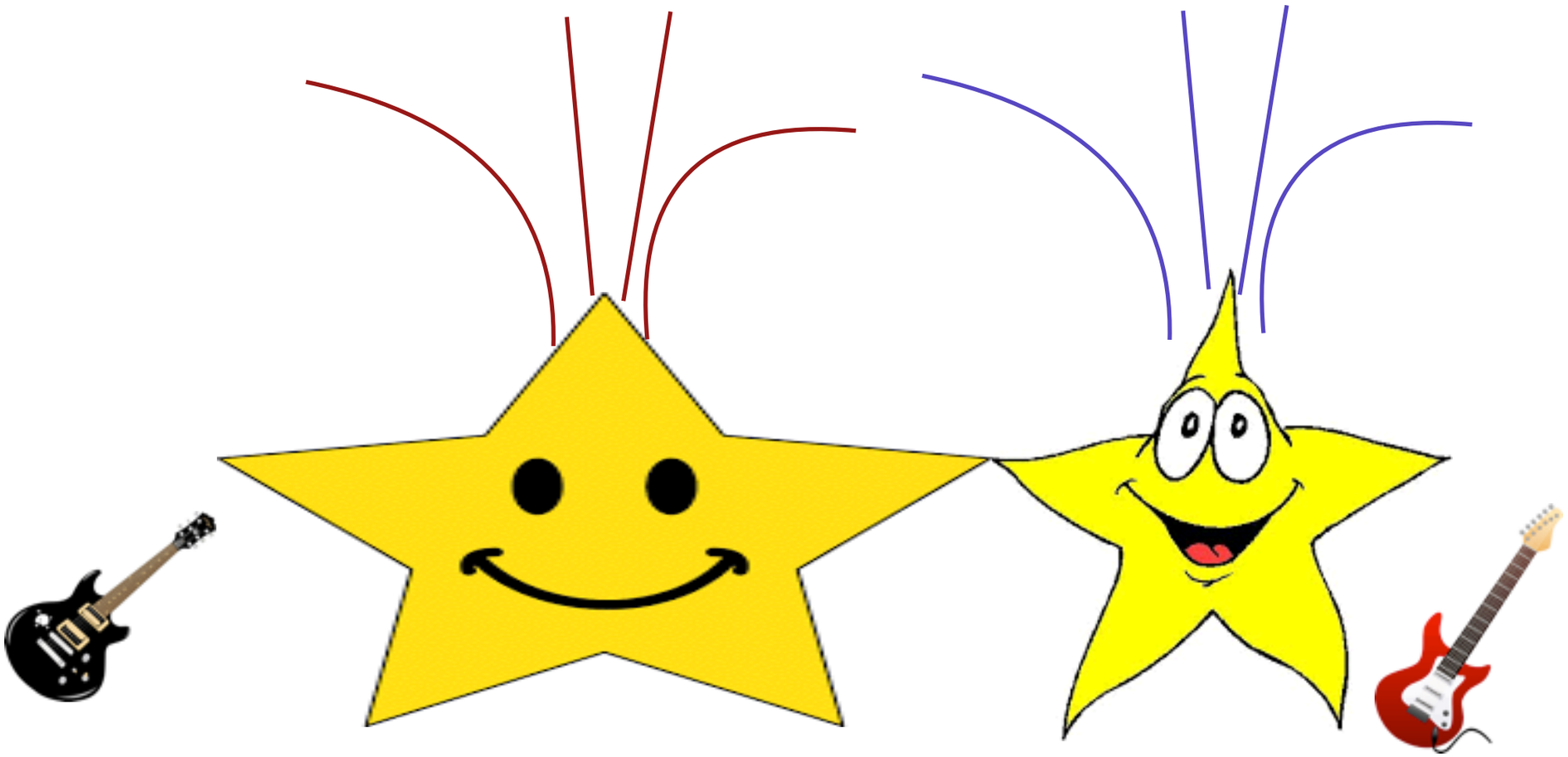
Stella



Estelle

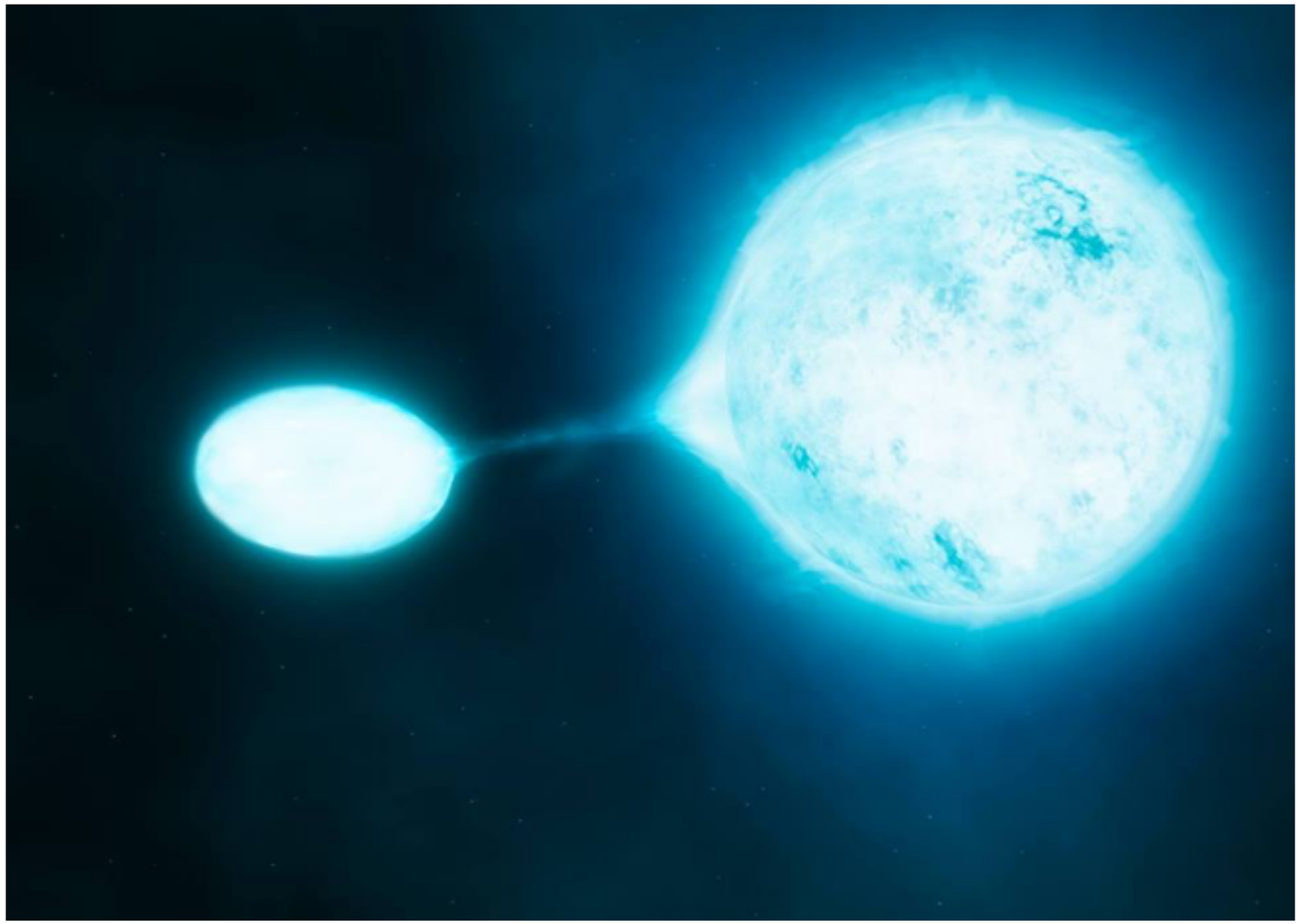
Stella

Estelle



Stella

Estelle

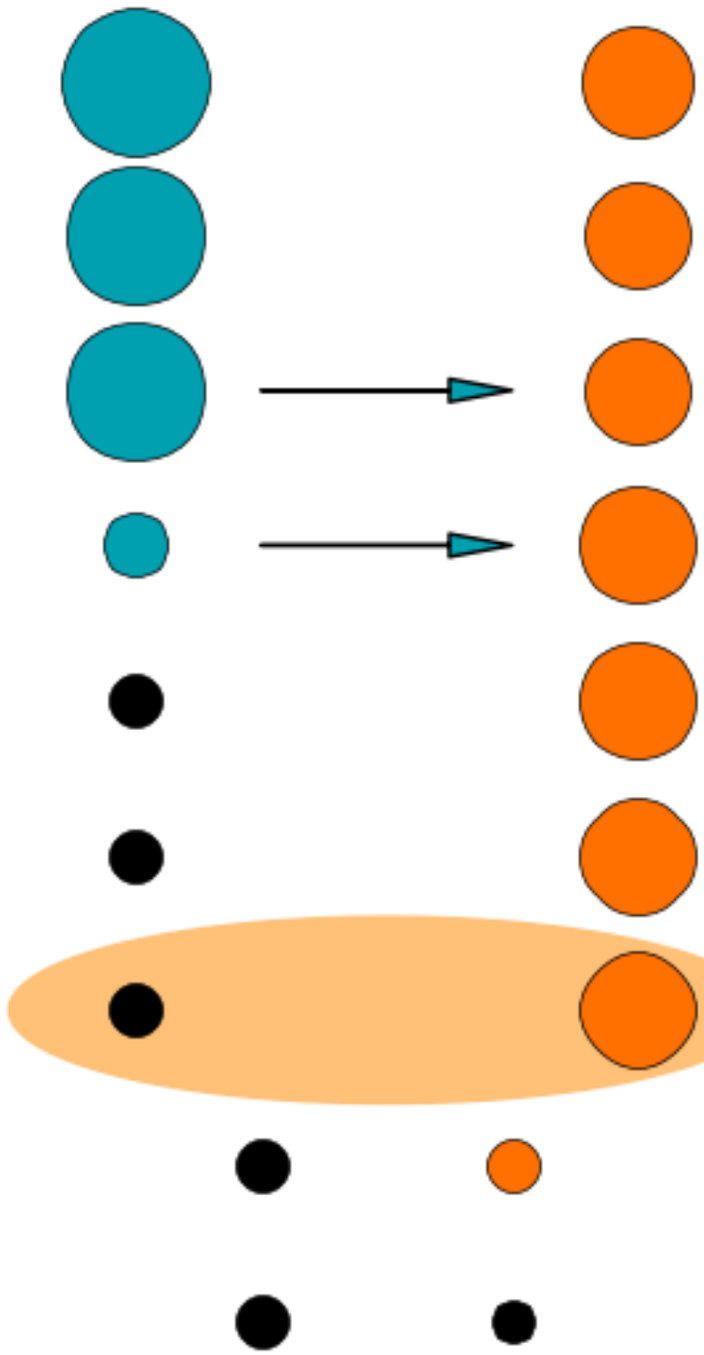


Credit: ESO Kornmesser/de Mink


Common
envelope
stelle

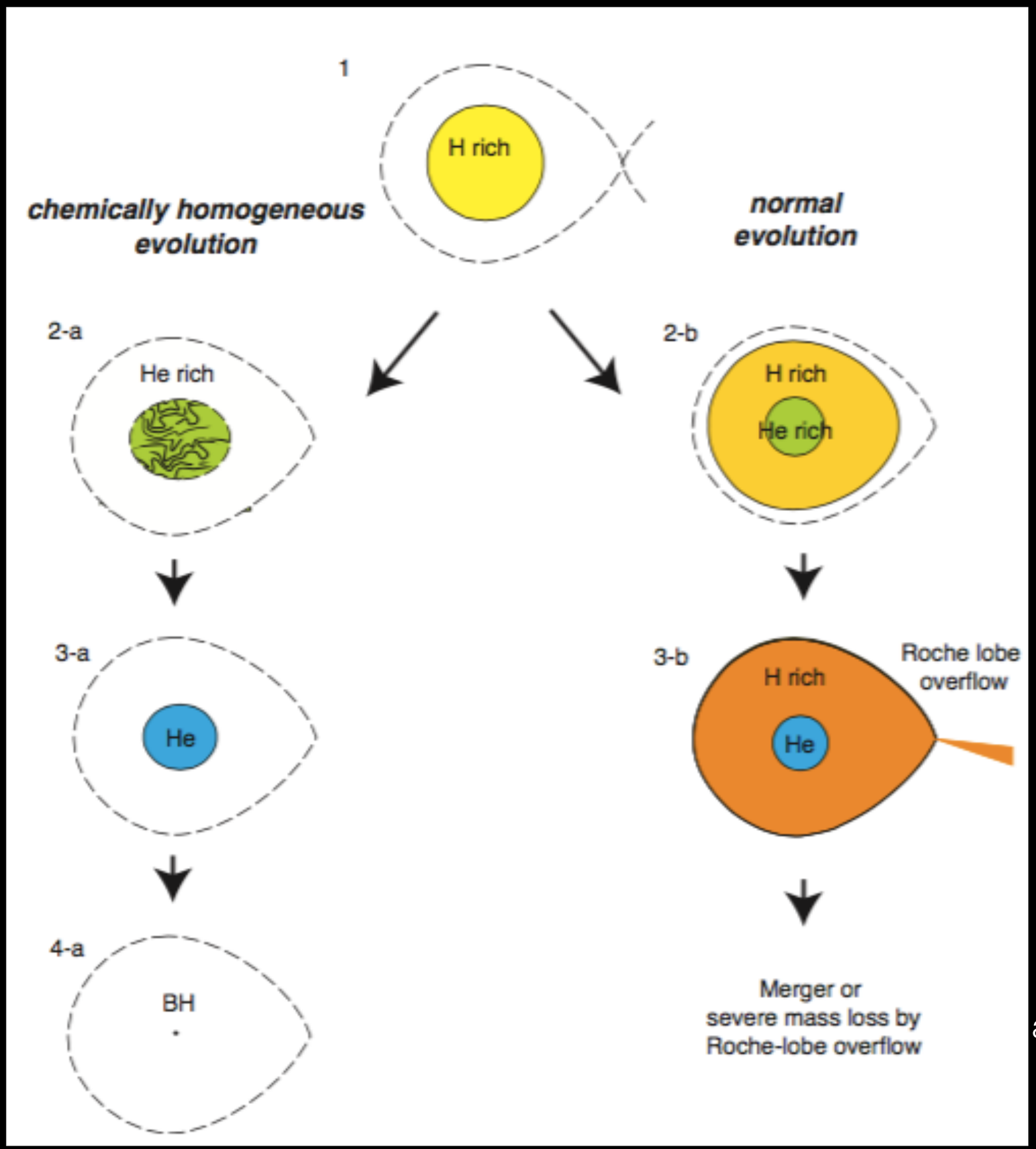
Stella

Time (Myr)	Mass 1 ($M_\odot$)		Mass 2 ($M_\odot$)		$a(R_\odot)$
0.0	MS	99.5	MS	75.8	2262.9
3.517	HG	95.2	MS	73.8	2348.5
3.5185	HG	95.0	MS	73.8	2351.1
3.5185	HeMS	43.3	MS	79.7	4031.5
3.8098	BH	34.3	MS	79.2	4372.8
4.0664	BH	34.3	HG	78.7	4391.4
4.0687	BH	34.3	CHeB	78.4	4402.3
4.0689	BH	34.3	HeMS	34.9	34.4
4.393	BH	34.3	BH	28.1	38.2



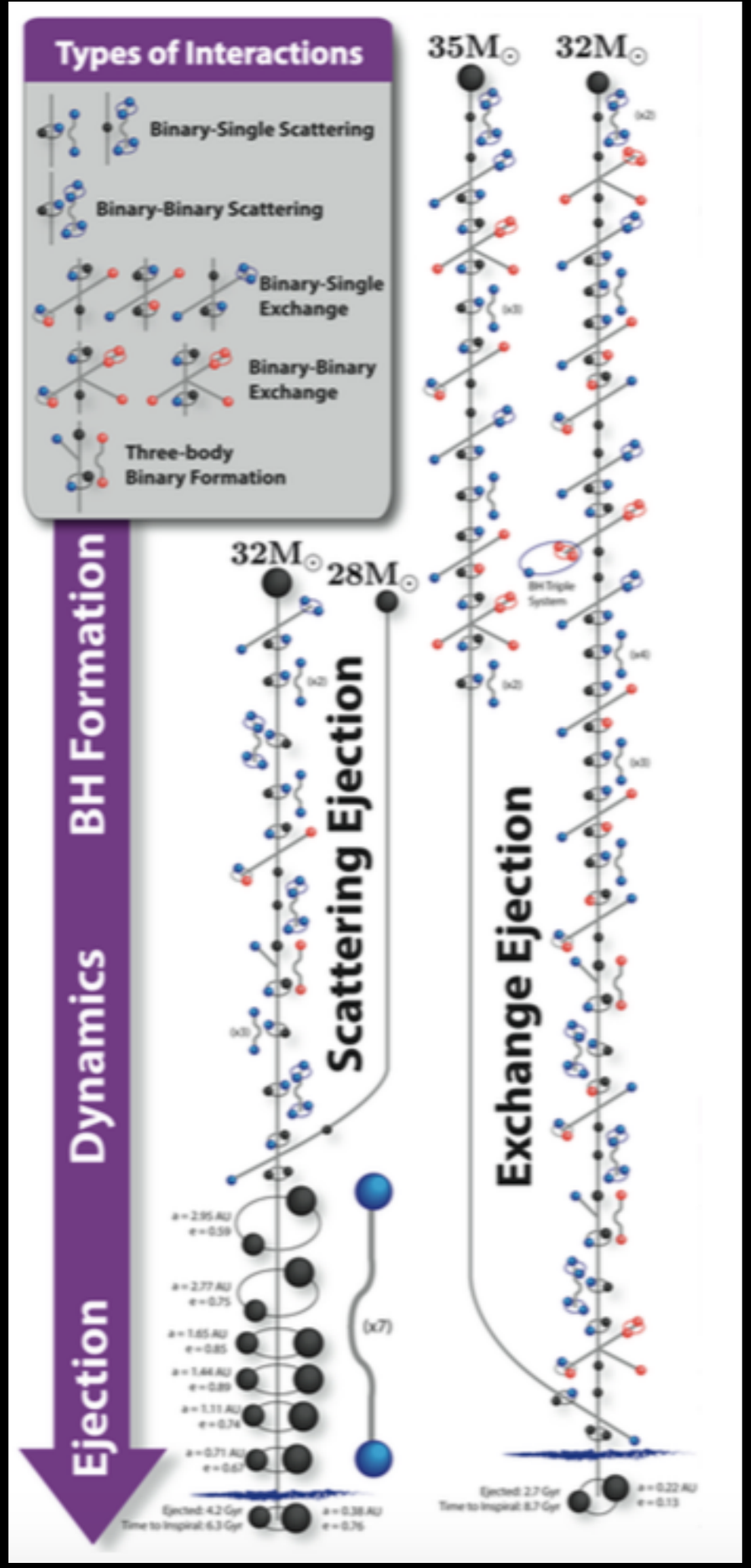
Stevenson, Vigna Gomez, Mandel, et al., 2017

see also Belczynski+, 2016; Eldridge & Stanway, 2016; Lipunov, 2016; Inayoshi+, 2016



Mandel & de Mink, arXiv:1601.00007, MNRAS

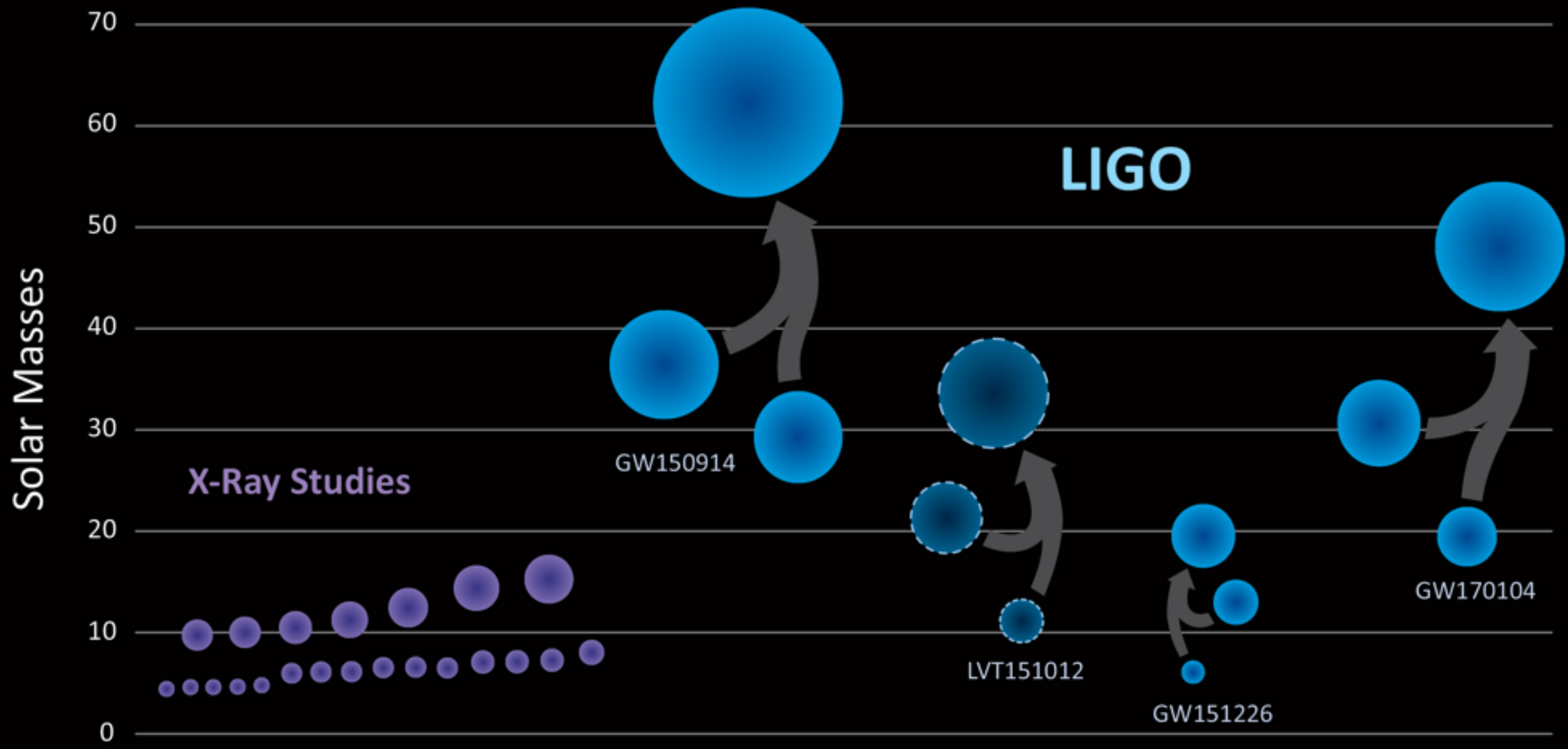
see also Marchant+, arXiv:1601.03718, A&A; de Mink & Mandel, arXiv:1603.02291, MNRAS

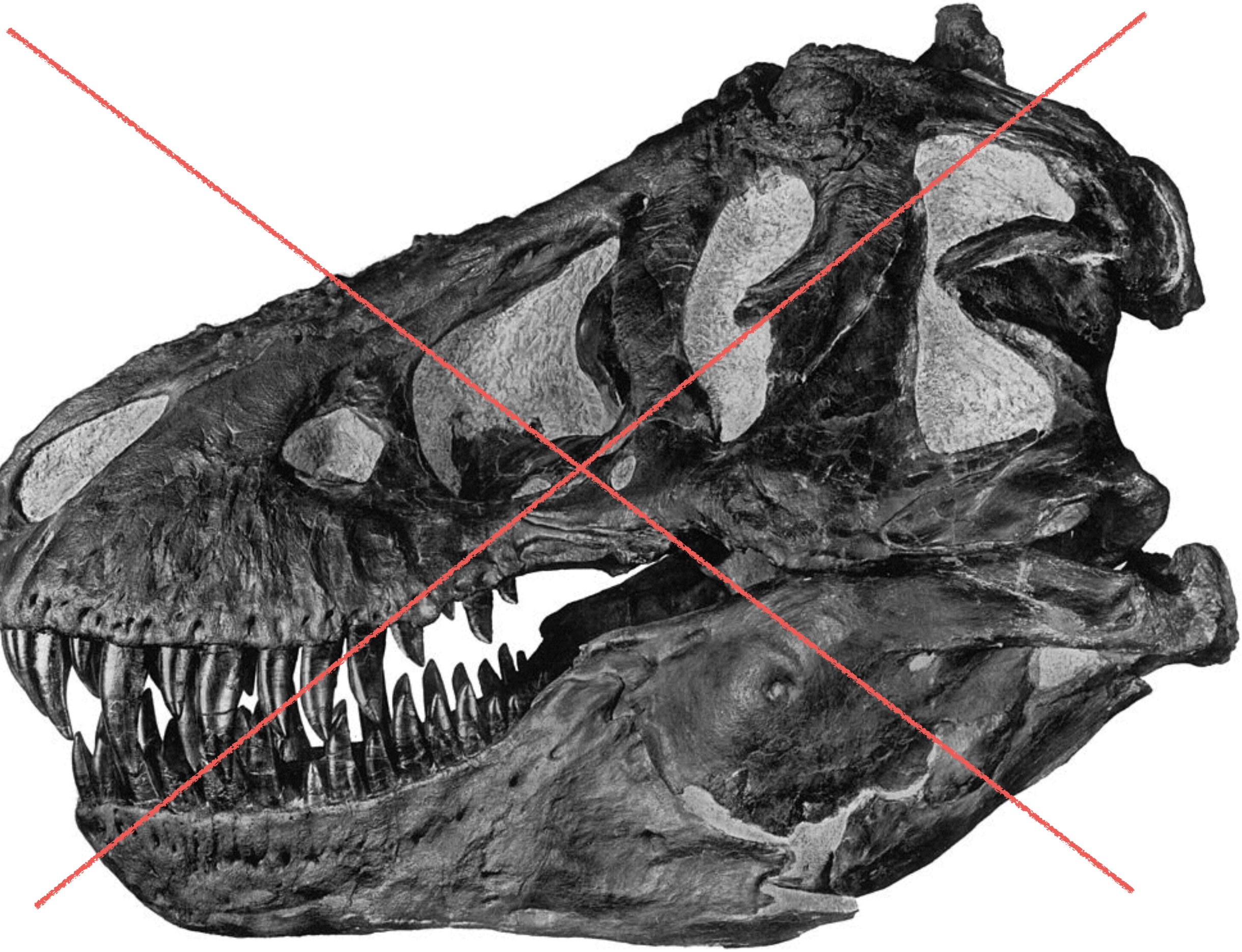


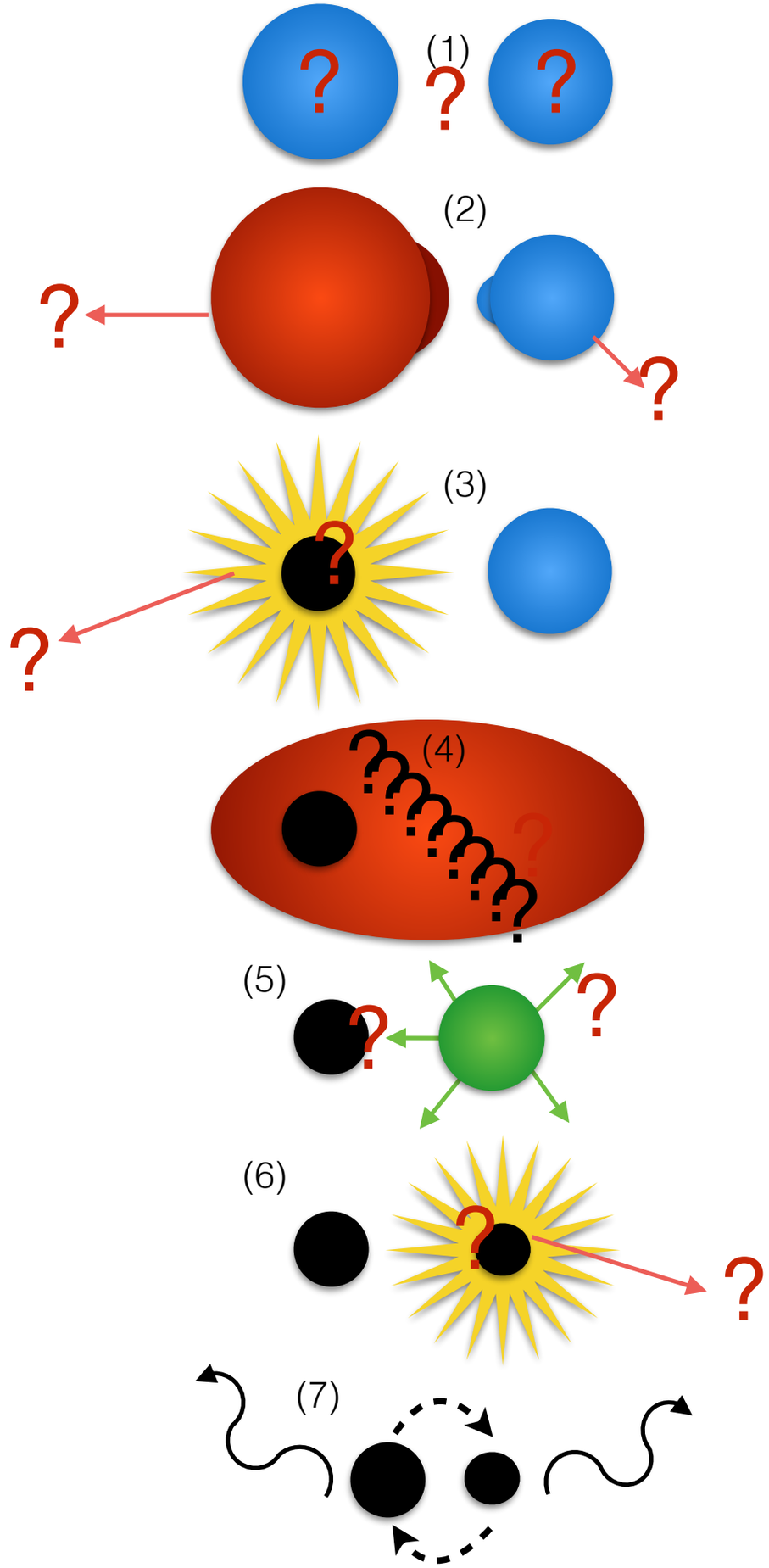
Rodriguez, Haster+, arXiv:1604.04254

see also Mapelli, arXiv:1604.03559

Black Holes of Known Mass






(1)
(2)
(3)
(4)
(5)
(6)
(7)

Whereas Stephen Hawking has such a large investment in General Relativity and Black Holes and desires an insurance policy, and whereas Kip Thorne likes to live dangerously without an insurance policy,

Therefore be it resolved that Stephen Hawking bets 1 year's subscription to "Penthouse" as against Kip Thorne's wager of a 4-year subscription to "Private Eye", that Cygnus X-1 does not contain a black hole of mass above the Chandrasekhar limit. Countersigned

Stephen Hawking June

Kip S. Thorne

A bet between Kip Thorne & Ilya Mandel

Whereas Kip Thorne is an eternal optimist,
and believes that there is a realistic chance
that the Initial LIGO/Virgo instruments could
detect a gravitational wave from a compact binary
coalescence;

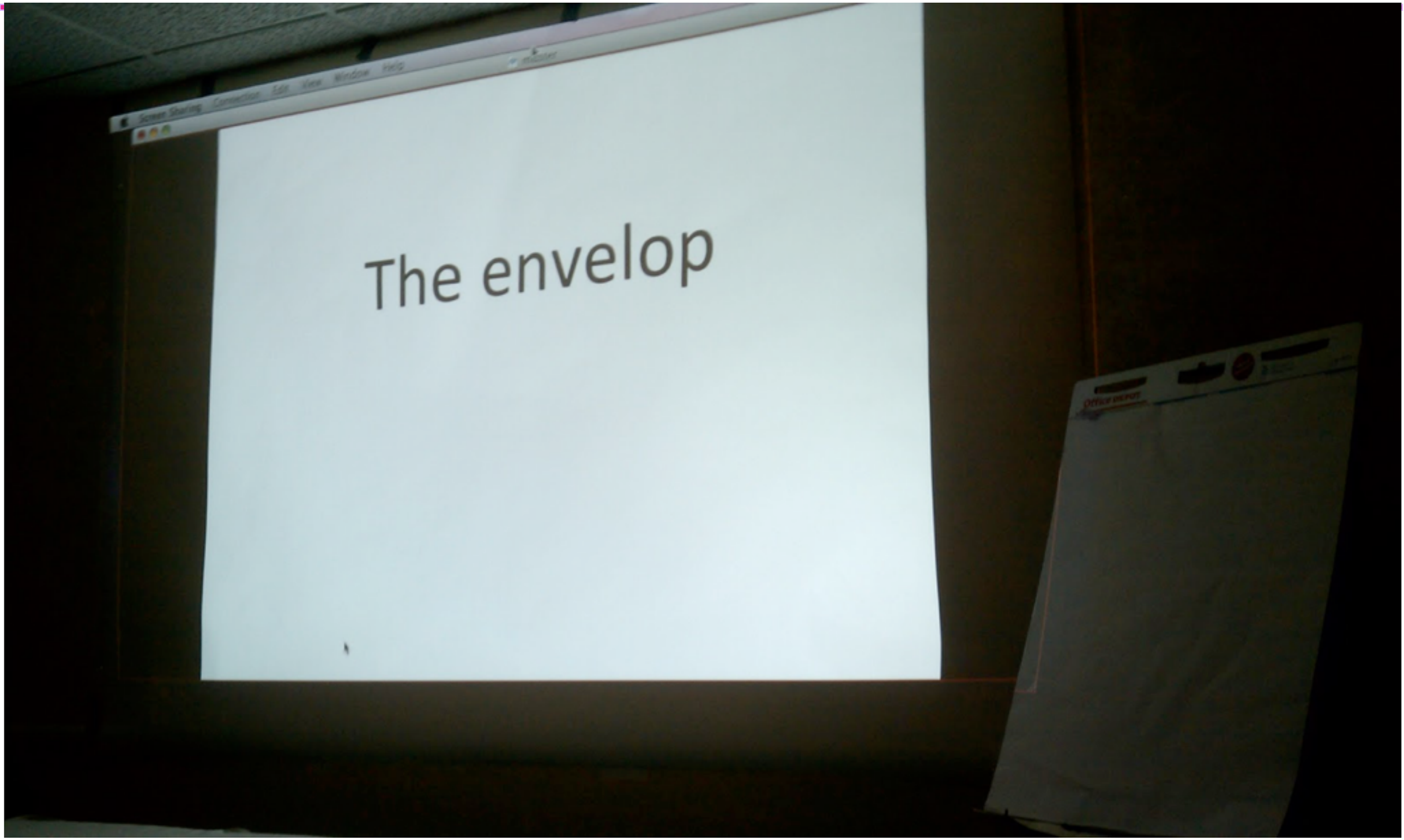
and whereas Ilya Mandel trusts the range of
predictions for binary merger rates sufficiently to
doubt this possibility; and, moreover, being a Bayesian at
heart, relies on Kip's previous betting history to infer that
betting against Kip's optimism is infinitely safer than betting
against Kip's physics;

they hereby wager, at odds of $100:$1, that GW100916
will be revealed to be a blind injection.

Signed in Arcadia, CA, on March 14, 2011:

/Kip Thorne/ /Ilya Mandel/ Witnessed by DAVID REITZE

The Big Dog



and believes that there is a realistic chance that the Initial LIGO/Virgo instruments could detect a gravitational wave from a compact binary coalescence;

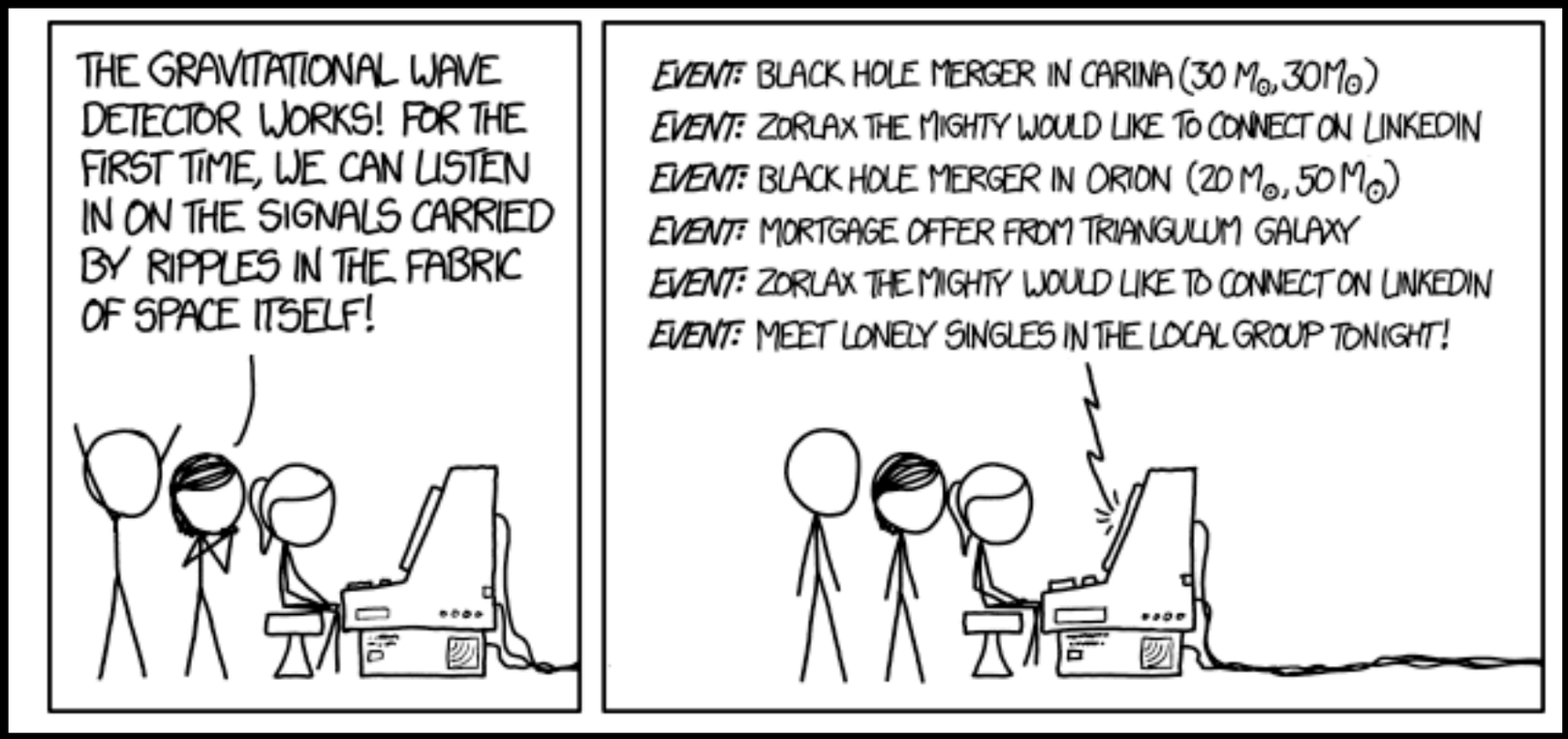
and whereas Ilya Mandel trusts the range of predictions for binary merger rates sufficiently to doubt this possibility; and, moreover, being a Bayesian at heart, relies on Kip's previous betting history to infer that betting against Kip's optimism is infinitely safer than betting against Kip's physics;

they hereby wager, at odds of $100:$1, that GW100916 will be revealed to be a blind injection.

Signed in Arcadia, CA, on March 14, 2011:

/Kip Thorne/ /Ilya Mandel/ Witnessed by DAVID REITZE

With great sadness, I hereby concede!
/Kip Thorne/


THE GRAVITATIONAL WAVE DETECTOR WORKS! FOR THE FIRST TIME, WE CAN LISTEN IN ON THE SIGNALS CARRIED BY RIPPLES IN THE FABRIC OF SPACE ITSELF!
EVENT: BLACK HOLE MERGER IN CARINA (30 $M_\odot$, 30 $M_\odot$)
EVENT: ZORLAX THE MIGHTY WOULD LIKE TO CONNECT ON LINKEDIN
EVENT: BLACK HOLE MERGER IN ORION (20 $M_\odot$, 50 $M_\odot$)
EVENT: MORTGAGE OFFER FROM TRIANGULUM GALAXY
EVENT: ZORLAX THE MIGHTY WOULD LIKE TO CONNECT ON LINKEDIN
EVENT: MEET LONELY SINGLES IN THE LOCAL GROUP TONIGHT!

GW150914: our first Binary BH merger