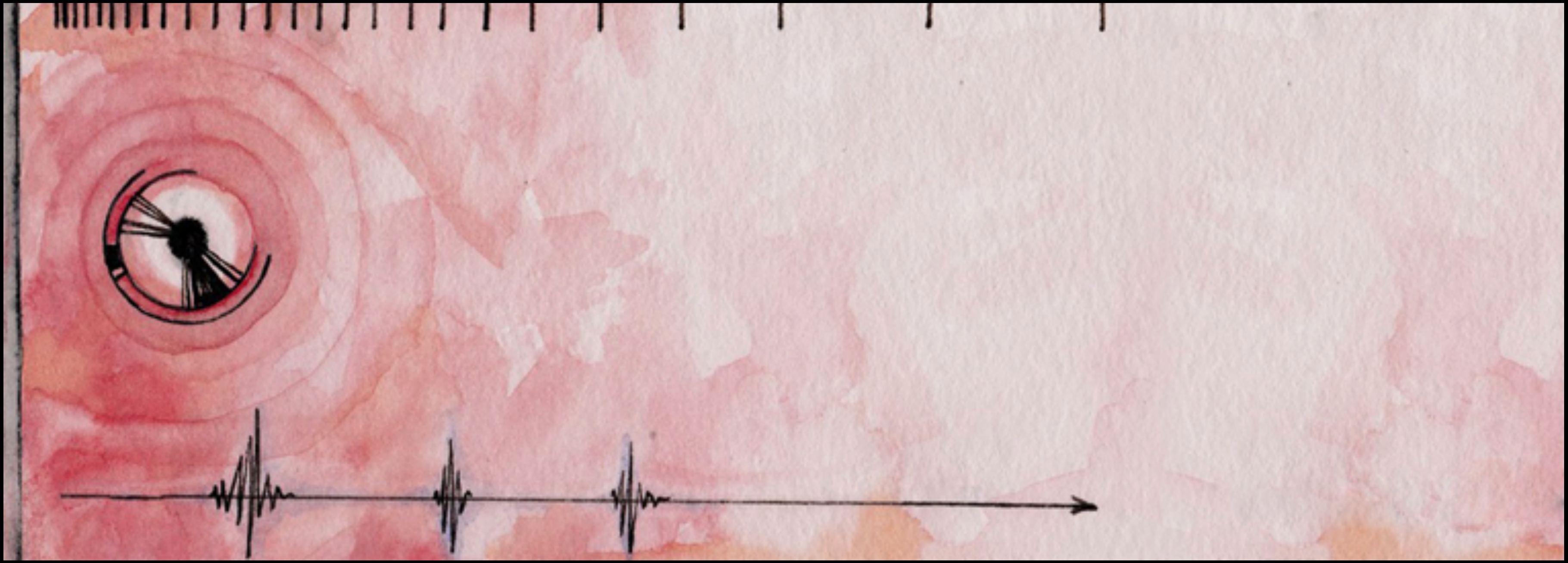


Fundamental Physics with Gravitational Waves

Thomas Hertog

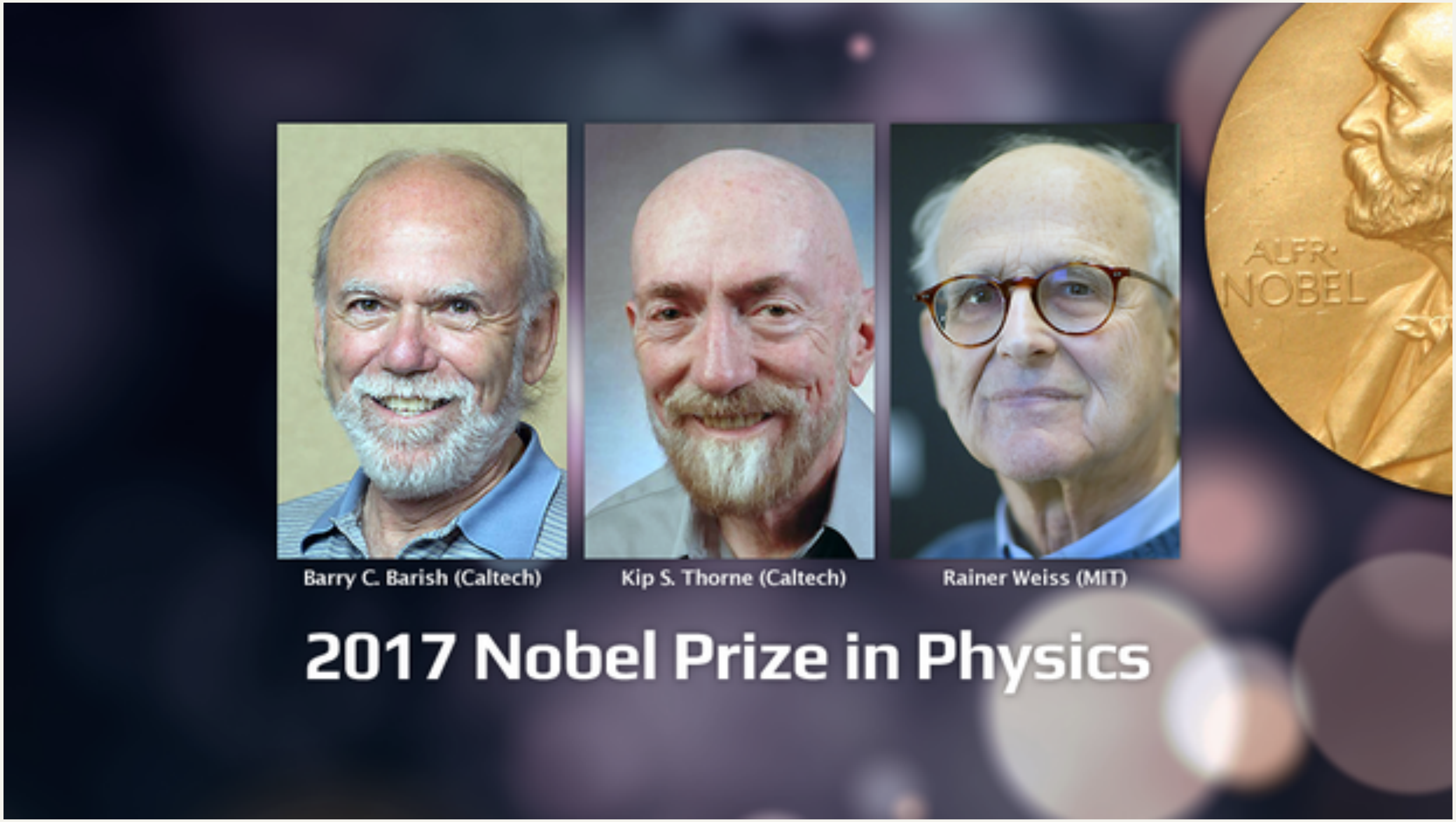
erc

Fundamental .be Interactions

Belgian Science Policy Office belspo

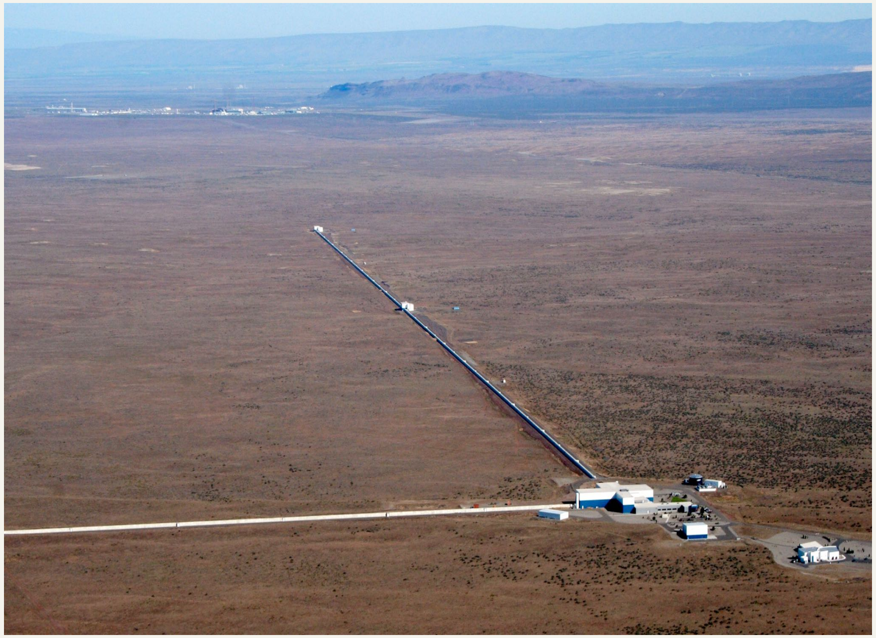
Outline

- Gravitational Waves & Fundamental Physics
- Example: plunges into Gargantua
- Prospects GW science in/for Belgium



"for decisive contributions to the LIGO detector and the observation of gravitational waves"

Laser Interferometer GW Observatory

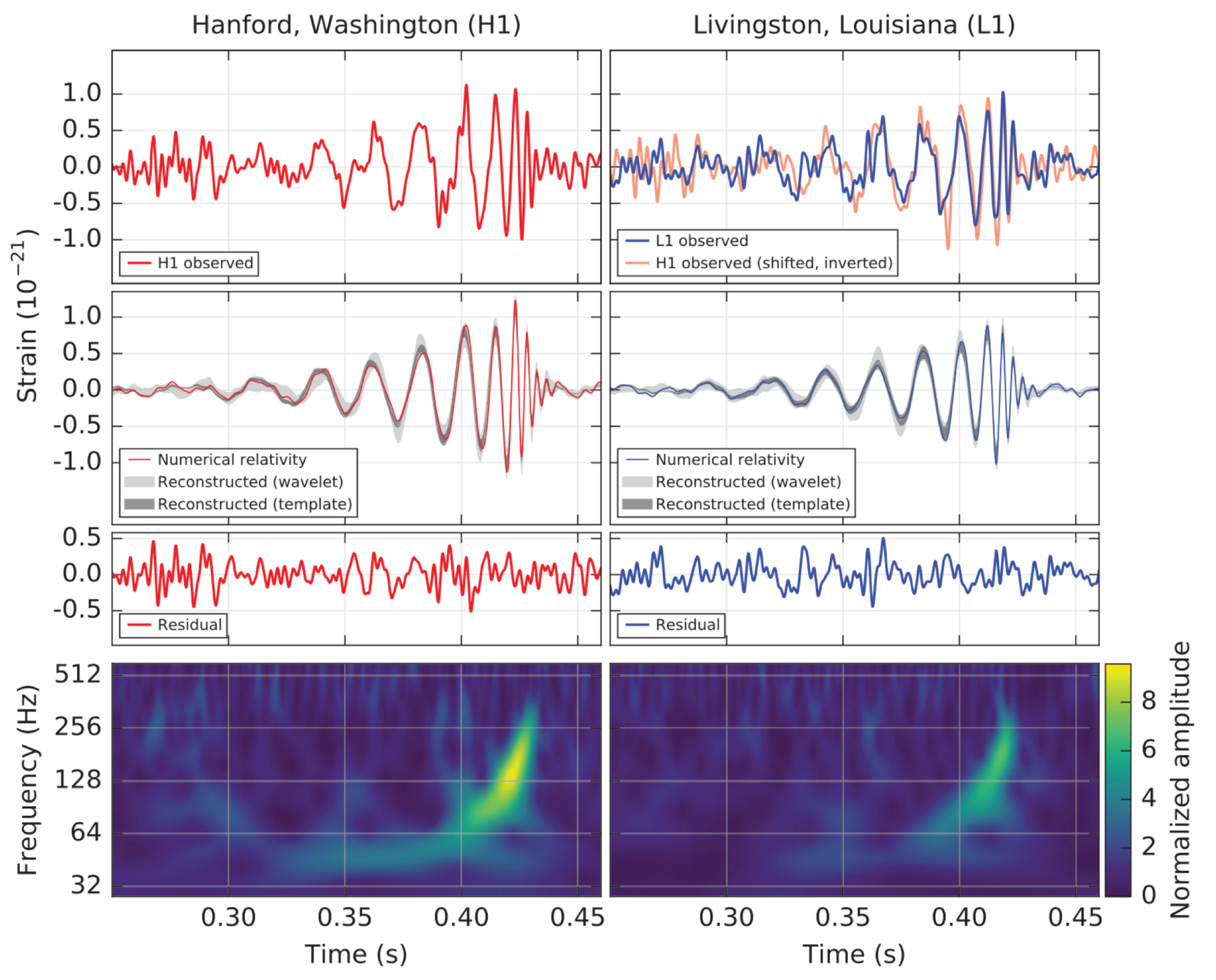


Livingston, LA

Hanford, WA

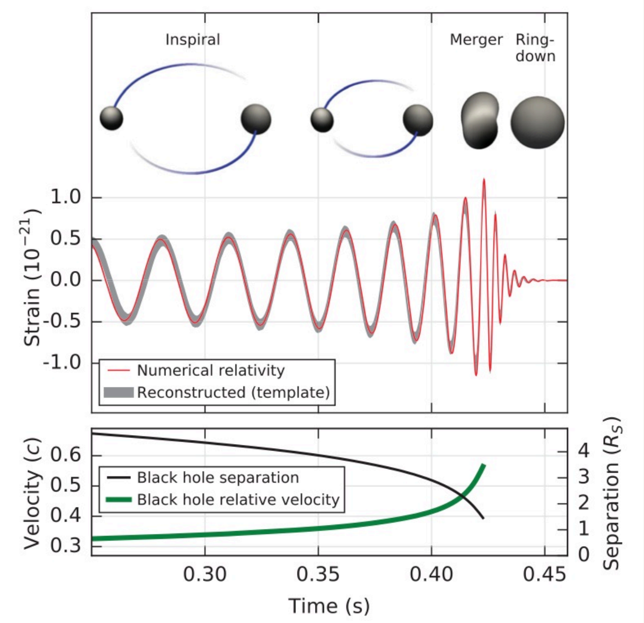
$$\frac{\delta L}{L_*} \sim 10^{-21}$$

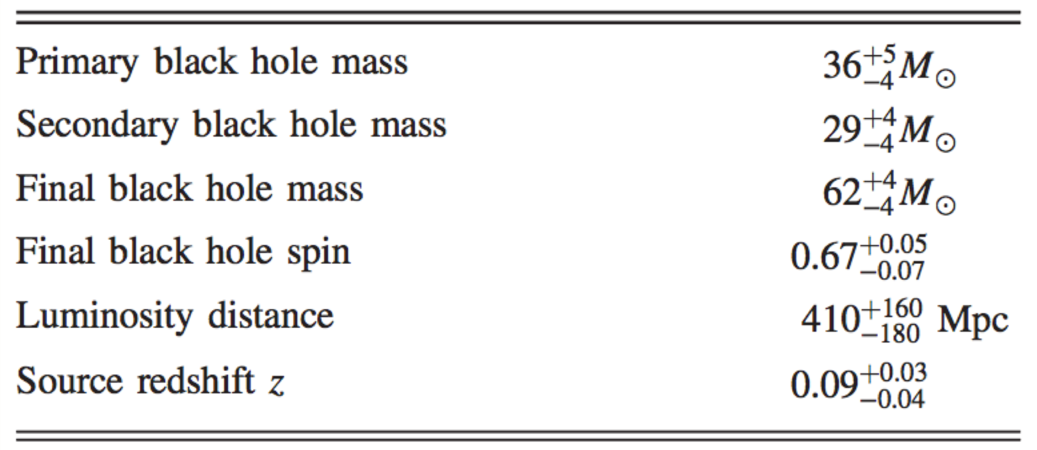
Nobel Prize Physics, 2017



[LIGO/VIRGO Collaboration, PRL 116, 2016]

A binary black hole merger



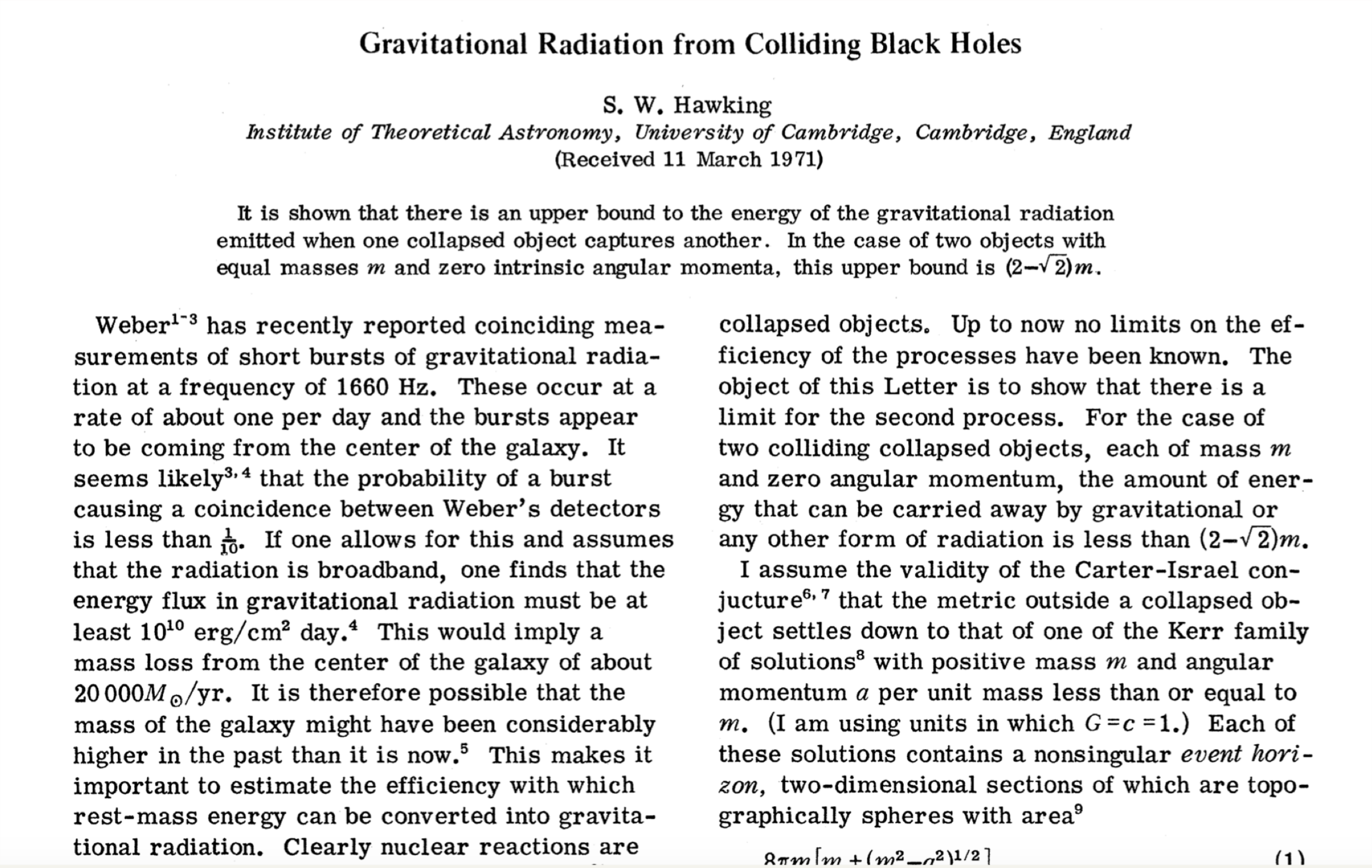


Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

$$\boxed{A_f \geq A_1 + A_2}$$

$$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5} \approx 30 \text{ M}_{\text{SUN}}$$

$$\mathcal{L}_{GW} = \frac{G}{c^5}\left(\frac{d^3Q}{dt^3}\right)^2 \sim \frac{c^5}{G}\left(\frac{v}{c}\right)^{10} \sim 10^{52}\ W$$



Gravitational Radiation from Colliding Black Holes

S. W. Hawking
Institute of Theoretical Astronomy, University of Cambridge, Cambridge, England

(Received 11 March 1971)

It is shown that there is an upper bound to the energy of the gravitational radiation emitted when one collapsed object captures another. In the case of two objects with equal masses m and zero intrinsic angular momenta, this upper bound is $(2-\sqrt{2})m$.

Weber[1-3] has recently reported coinciding measurements of short bursts of gravitational radiation at a frequency of 1660 Hz. These occur at a rate of about one per day and the bursts appear to be coming from the center of the galaxy. It seems likely[3,4] that the probability of a burst causing a coincidence between Weber's detectors is less than $\frac{1}{10}$. If one allows for this and assumes that the radiation is broadband, one finds that the energy flux in gravitational radiation must be at least 10^{10} erg/cm^2 day.[4] This would imply a mass loss from the center of the galaxy of about $20\,000 M_\odot$/yr. It is therefore possible that the mass of the galaxy might have been considerably higher in the past than it is now.[5] This makes it important to estimate the efficiency with which rest-mass energy can be converted into gravitational radiation. Clearly nuclear reactions are

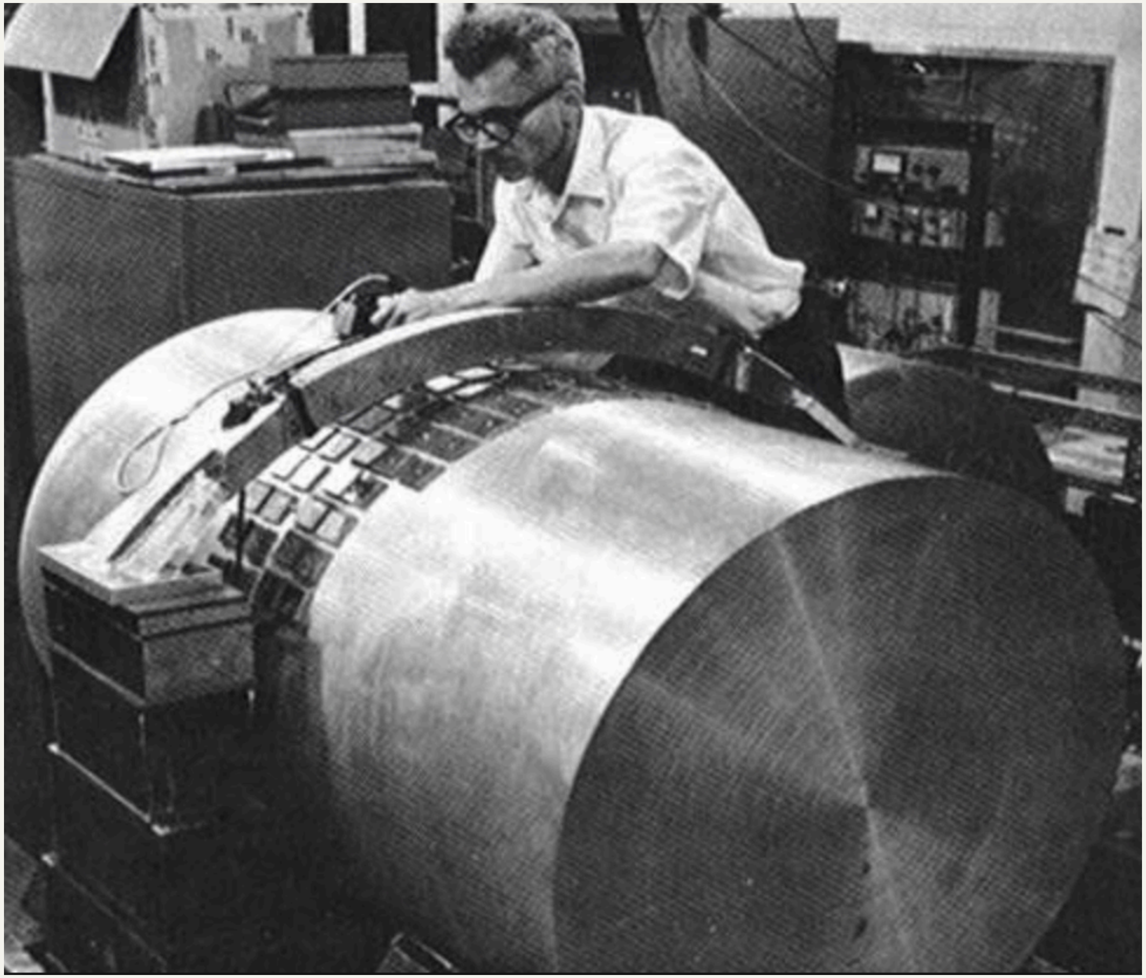
collapsed objects. Up to now no limits on the efficiency of the processes have been known. The object of this Letter is to show that there is a limit for the second process. For the case of two colliding collapsed objects, each of mass m and zero angular momentum, the amount of energy that can be carried away by gravitational or any other form of radiation is less than $(2-\sqrt{2})m$.

I assume the validity of the Carter-Israel conjucture[6,7] that the metric outside a collapsed object settles down to that of one of the Kerr family of solutions[8] with positive mass m and angular momentum a per unit mass less than or equal to m. (I am using units in which $G=c=1$.) Each of these solutions contains a nonsingular *event horizon,* two-dimensional sections of which are topographically spheres with area[9]

$$8\pi m[m+(m^2-a^2)^{1/2}] \qquad (1)$$

$$A_f \geq A_1 + A_2$$

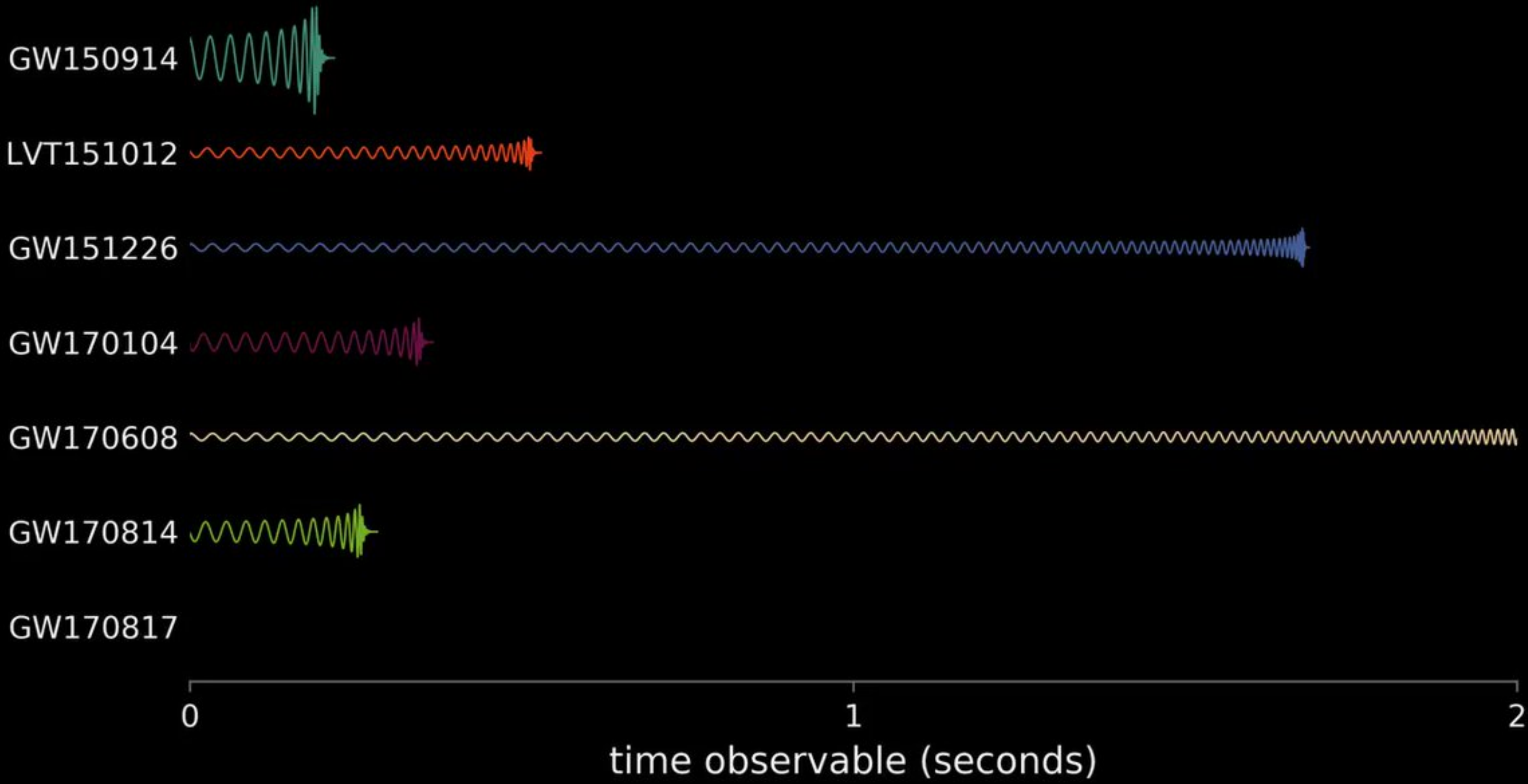
Joe Weber



Whether, in the end, he is the first to detect gravitational waves or someone else does it, hardly matters.

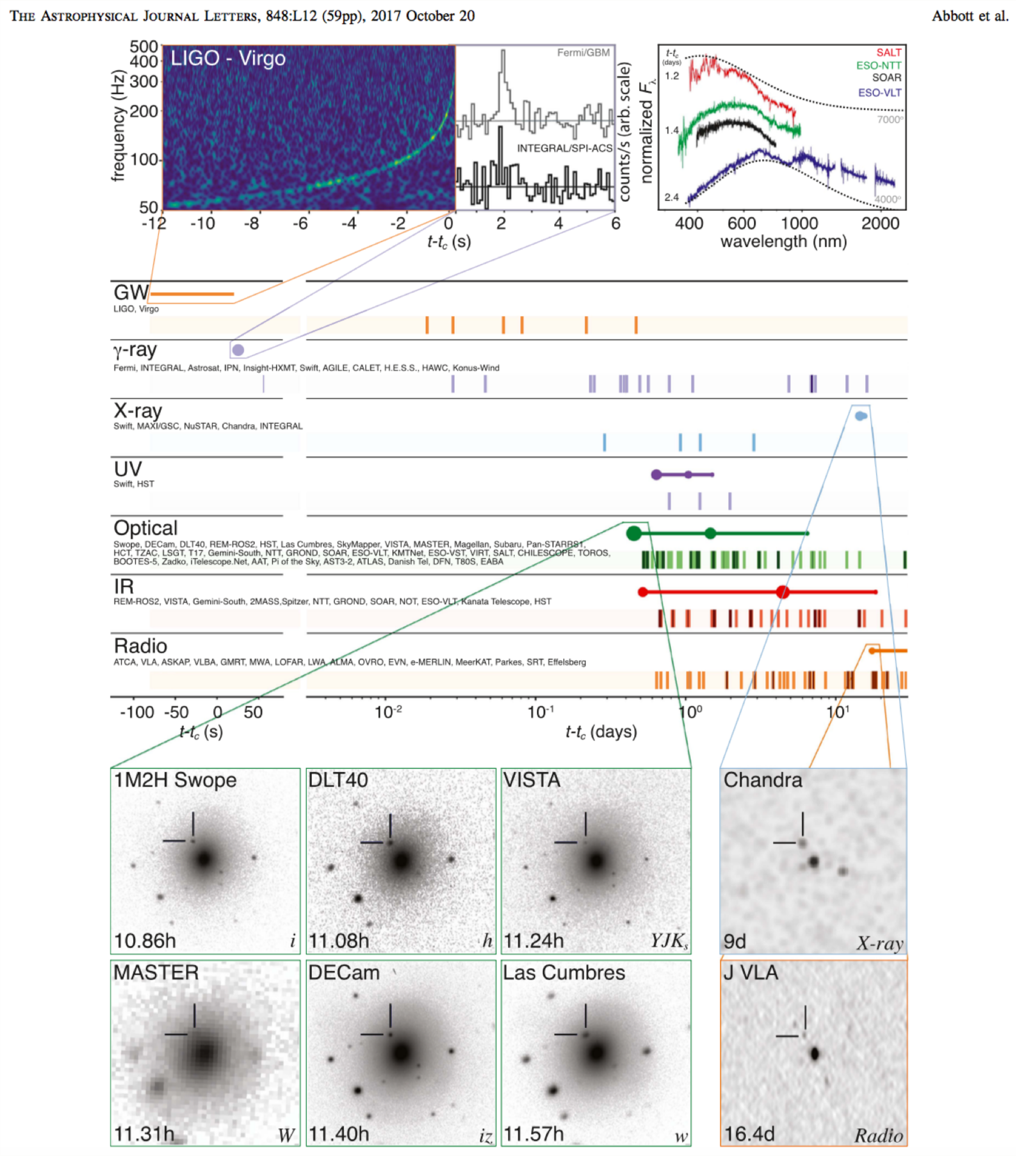
He will deserve the credit for leading the way. No one else had the courage ***to bring Einstein's equations into the lab*** *and look for gravitational waves until Weber showed that it was within the realm of the possible.*

[J. Wheeler]



LIGO/University of Oregon/Ben Farr

Binary neutron star merger


The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 Abbott et al.

[LIGO/VIRGO Collaboration, PRL 119, 2017]

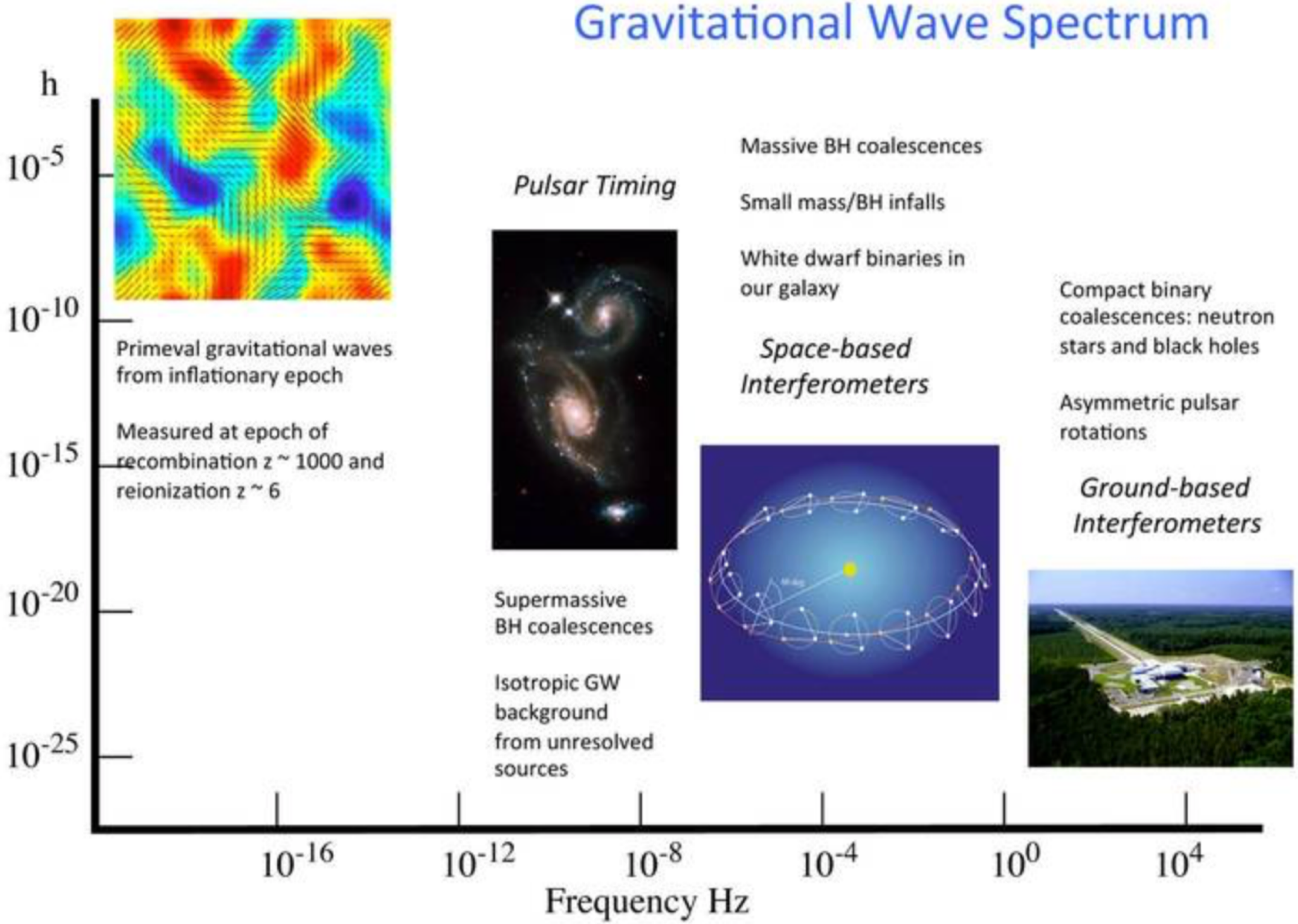
Element Origins

Merging Neutron Stars **Exploding Massive Stars** **Big Bang**
Dying Low Mass Stars **Exploding White Dwarfs** **Cosmic Ray Fission**

Based on graphic created by Jennifer Johnson

This is just the beginning..

Gravitational Wave Spectrum



Cosmic Microwave Background Polarization B Modes

Primeval gravitational waves from inflationary epoch

Measured at epoch of recombination z ~ 1000 and reionization z ~ 6

Pulsar Timing

Supermassive BH coalescences

Isotropic GW background from unresolved sources

Massive BH coalescences

Small mass/BH infalls

White dwarf binaries in our galaxy

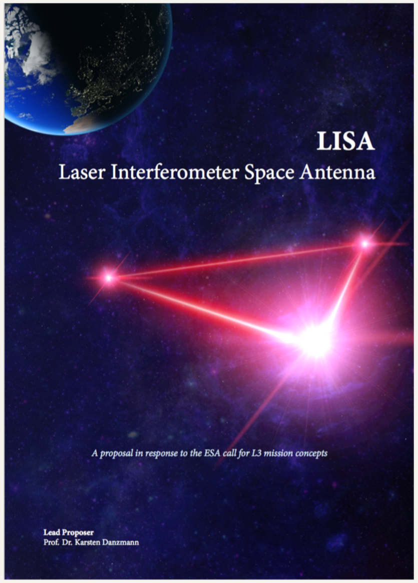
Space-based Interferometers

Compact binary coalescences: neutron stars and black holes

Asymmetric pulsar rotations

Ground-based Interferometers

Laser Interferometer Space Antenna



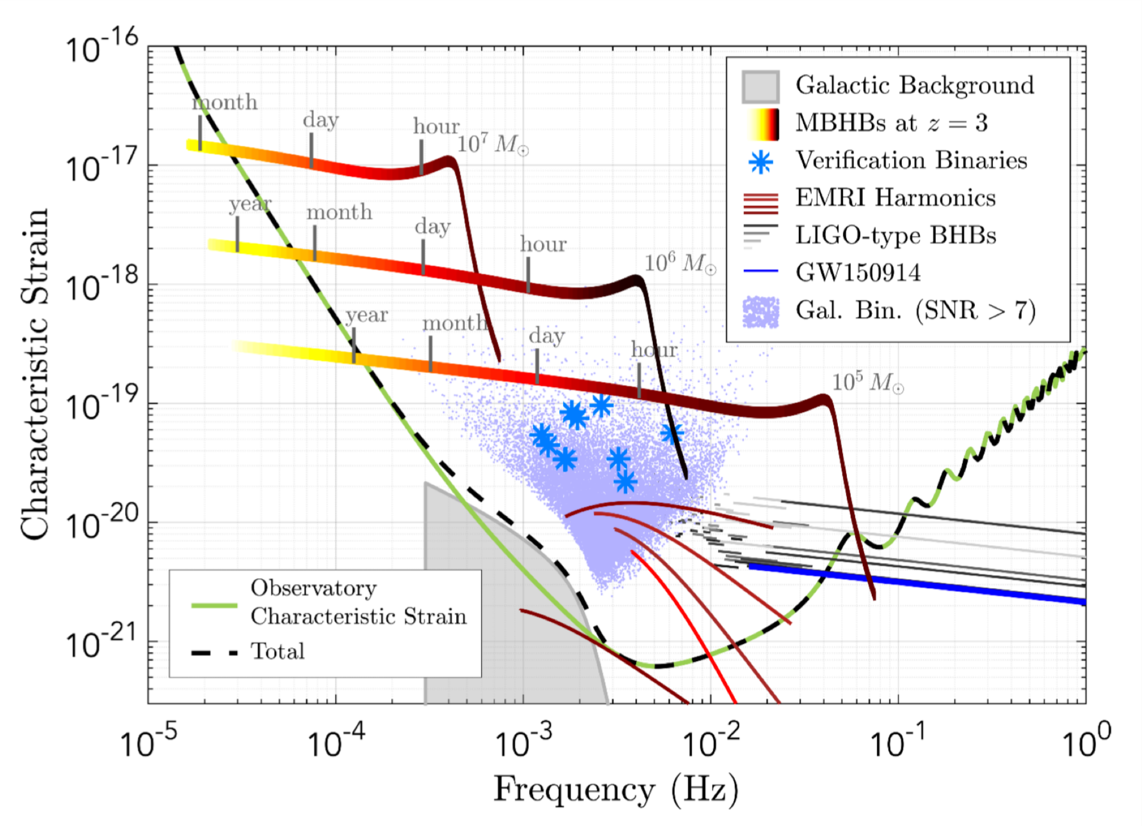
LISA

Laser Interferometer Space Antenna

A proposal in response to the ESA call for L3 mission concepts

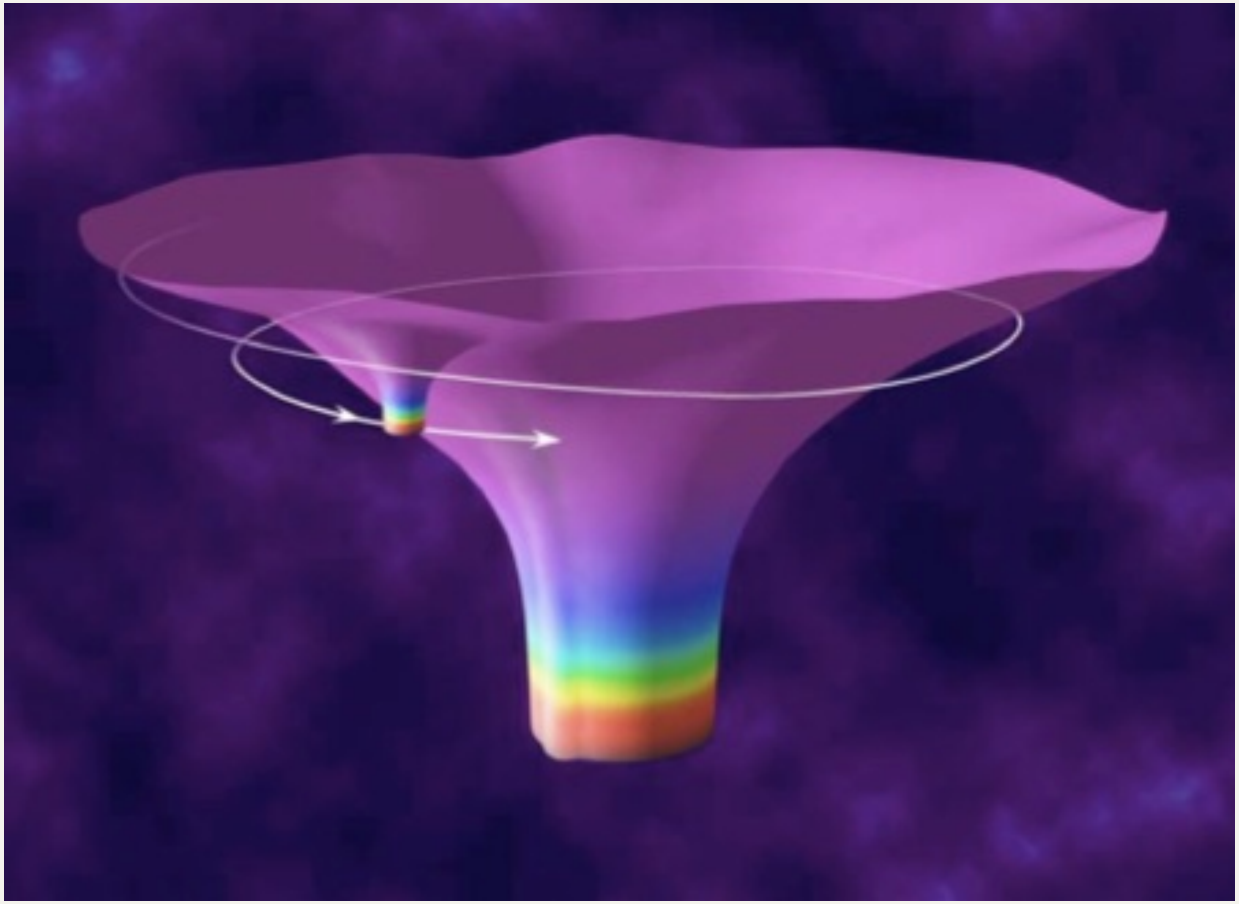
Lead Proposer

Prof. Dr. Karsten Danzmann



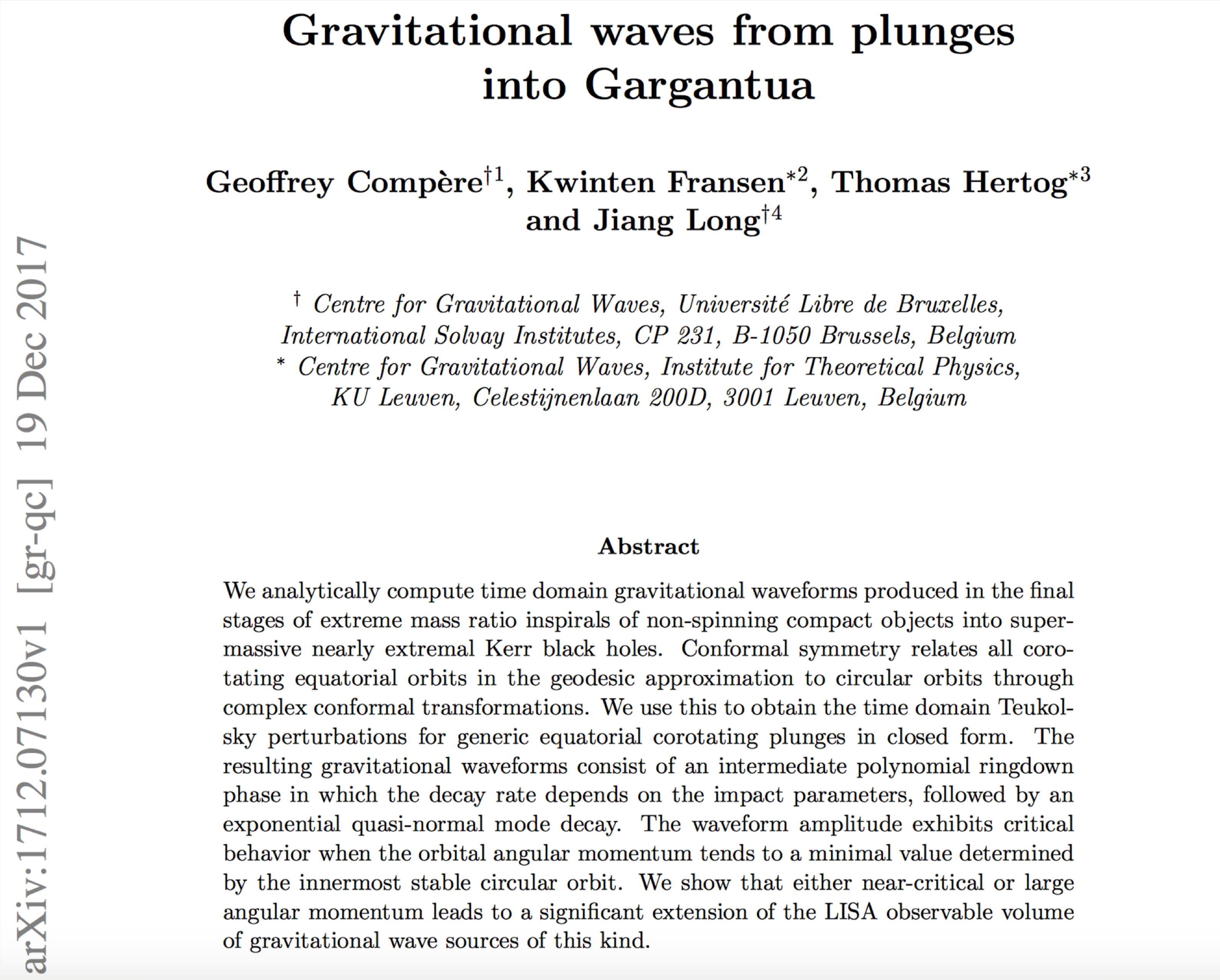
Multi-band gravitational wave astronomy

Black Hole Spectroscopy



Extreme Mass Ratio Inspirals

→ numerical challenge



Gravitational waves from plunges into Gargantua

Geoffrey Compère[†1], Kwinten Fransen[*2], Thomas Hertog[*3] and Jiang Long[†4]

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International Solvay Institutes, CP 231, B-1050 Brussels, Belgium
[*] *Centre for Gravitational Waves, Institute for Theoretical Physics,*
KU Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium

Abstract

We analytically compute time domain gravitational waveforms produced in the final stages of extreme mass ratio inspirals of non-spinning compact objects into supermassive nearly extremal Kerr black holes. Conformal symmetry relates all corotating equatorial orbits in the geodesic approximation to circular orbits through complex conformal transformations. We use this to obtain the time domain Teukolsky perturbations for generic equatorial corotating plunges in closed form. The resulting gravitational waveforms consist of an intermediate polynomial ringdown phase in which the decay rate depends on the impact parameters, followed by an exponential quasi-normal mode decay. The waveform amplitude exhibits critical behavior when the orbital angular momentum tends to a minimal value determined by the innermost stable circular orbit. We show that either near-critical or large angular momentum leads to a significant extension of the LISA observable volume of gravitational wave sources of this kind.

Near-horizon geometry

[Bardeen & Horowitz (1999)]

$$\lambda \equiv \sqrt{1 - \frac{a^2}{M^2}} \ll 1$$

Near-horizon extremal Kerr (NHEK):

$$ds^2 = 2M^2\Gamma(\theta)\left(-R^2 dT^2 + \frac{dR^2}{R^2} + d\theta^2 + \Lambda^2(\theta)(d\Phi + R dT)^2\right)$$

$$r_{ISCO} = M + 2^{1/3}\lambda^{2/3}M \longrightarrow R_{ISCO} = 2^{1/3}$$

$$r_H = M(1+\lambda)$$

Very near-horizon extremal Kerr (near-NHEK): $r \sim r_H + M \times \mathcal{O}(\lambda)$

Enhanced (conformal) symmetry *SL(2,R) x U(1)*

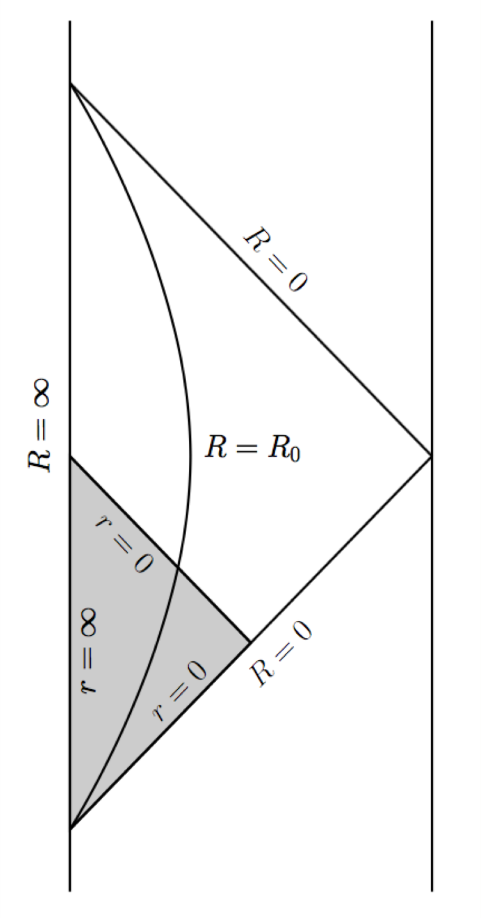
Conformal symmetry

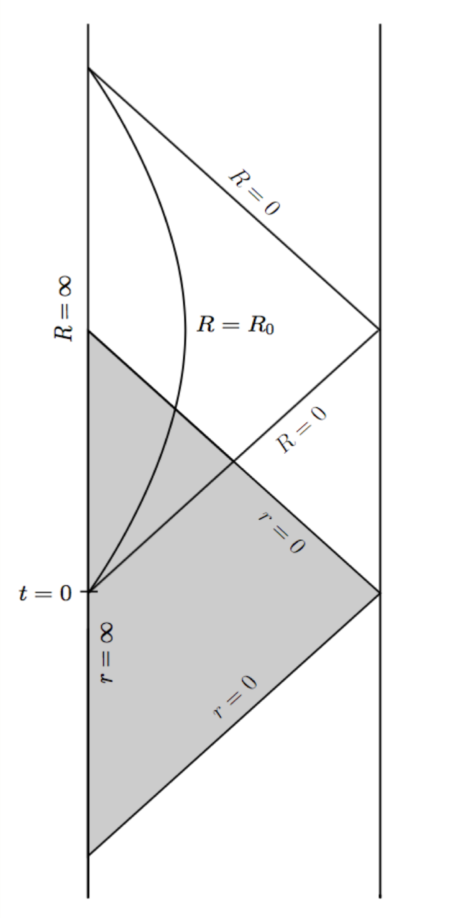
(Complex) conformal transformations relate **all equatorial orbits** to two circular seed orbits (in NHEK and near-NHEK) [Porfyriadis et al.; Hadar et al.]

Plunging in near-NHEK

↓

Circular in NHEK



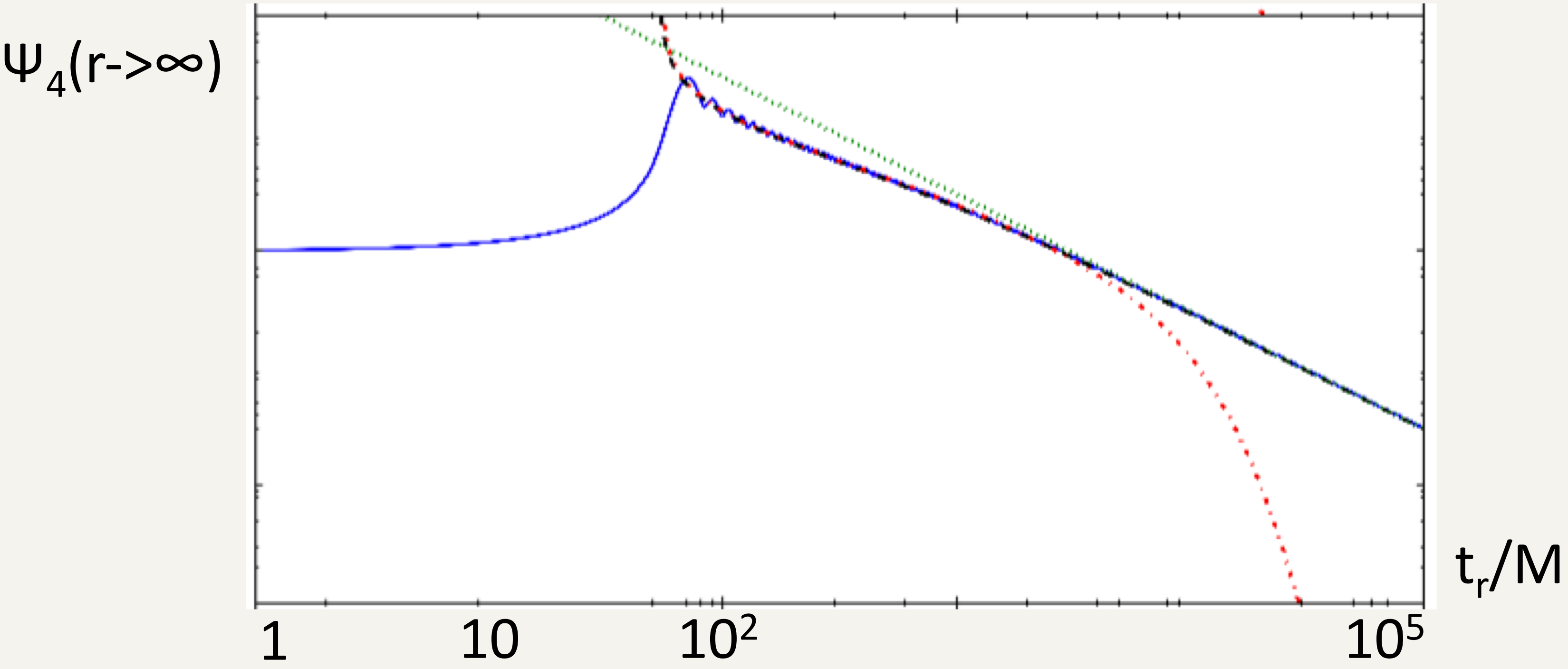


Plunging in NHEK

↓

Circular in NHEK

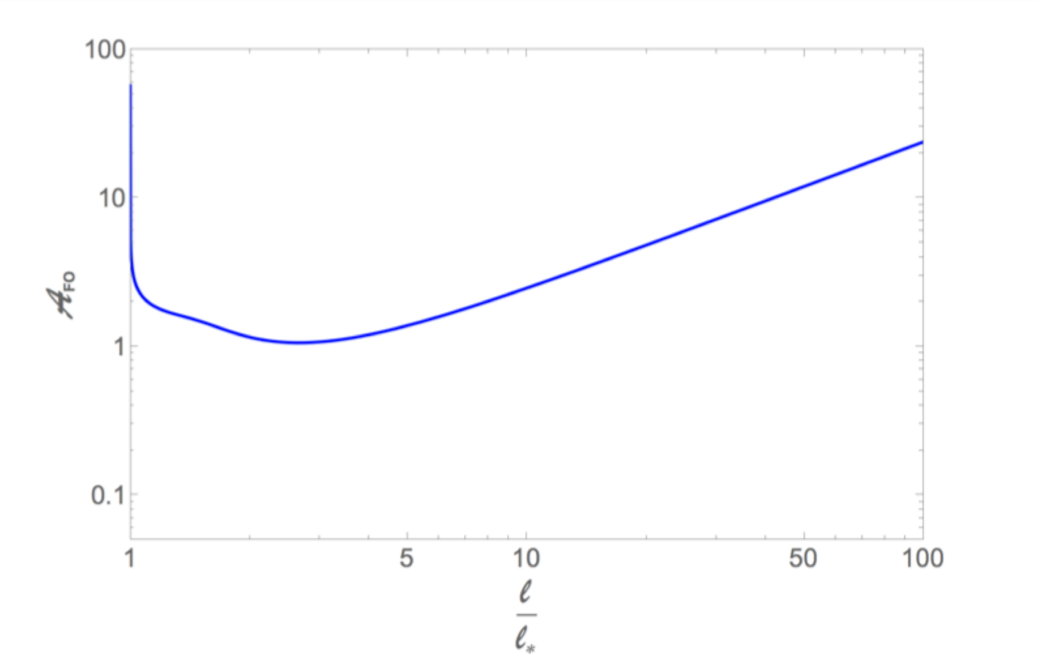
Asymptotic waveform plunge



- Zero-damped quasi-normal modes in extremal limit
- Polynomial decay, due to coherent mode stacking [Yang et al./ (2014)]
- Near-horizon behavior for $t_r > 10M$
- Transition to exponential decay as $t_r \sim M/\lambda$

Critical behavior

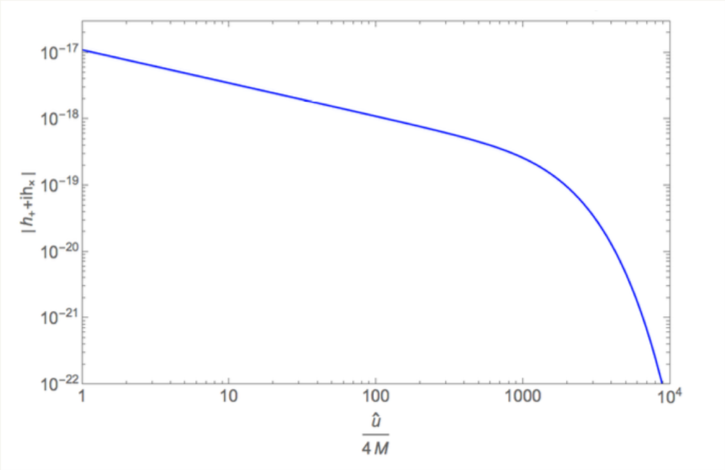
Critical angular momentum $\ell \to \ell_* = 2M/\sqrt{3}, e = 0$



$$|h_+ + ih_\times| \sim (\frac{\ell}{\ell_*} - 1)^{-\frac{1}{4}} \frac{m_0}{D} \frac{\sqrt{\lambda}}{\sqrt{\sinh \frac{\lambda \hat{u}}{2M}}}$$

LISA observations

$$SNR^2 = \frac{2}{S_h(\Omega_{ext}/\pi)} \int_{t_i}^{t_f} |h(t)|^2 dt$$



$$D_{max} \approx 0.08 \text{ Gpc} \left(\frac{M}{10^7 M_\odot}\right)^{1/2} \left(\frac{m_0}{10 M_\odot}\right) \left(\frac{\ell}{\ell_*} - 1\right)^{-\frac{1}{4}} \left(\frac{15}{\rho_{th}}\right)$$

EM observations of GRS1915+105: a/M = .98 ± 0.01 [Miller et al. (2014)]
However: Thorne bound a/M ≤ 0.998

Plunges into Gargantua

[Gralla, Hughes, Warburton (2016);
Compère, Long, TH, Fransen (2017)]

Four `smoking gun’ signatures:

- extremal frequency $f = 1/4\pi M$
- amplitude suppression $|h| \sim \lambda^{1/3}$ *or* $\lambda^{1/2}$
- polynomial ringdown $|h| \sim t_r^{-1/2}$ *or* t_r^{-1}
- critical behavior as angular momentum $l \to l_*$

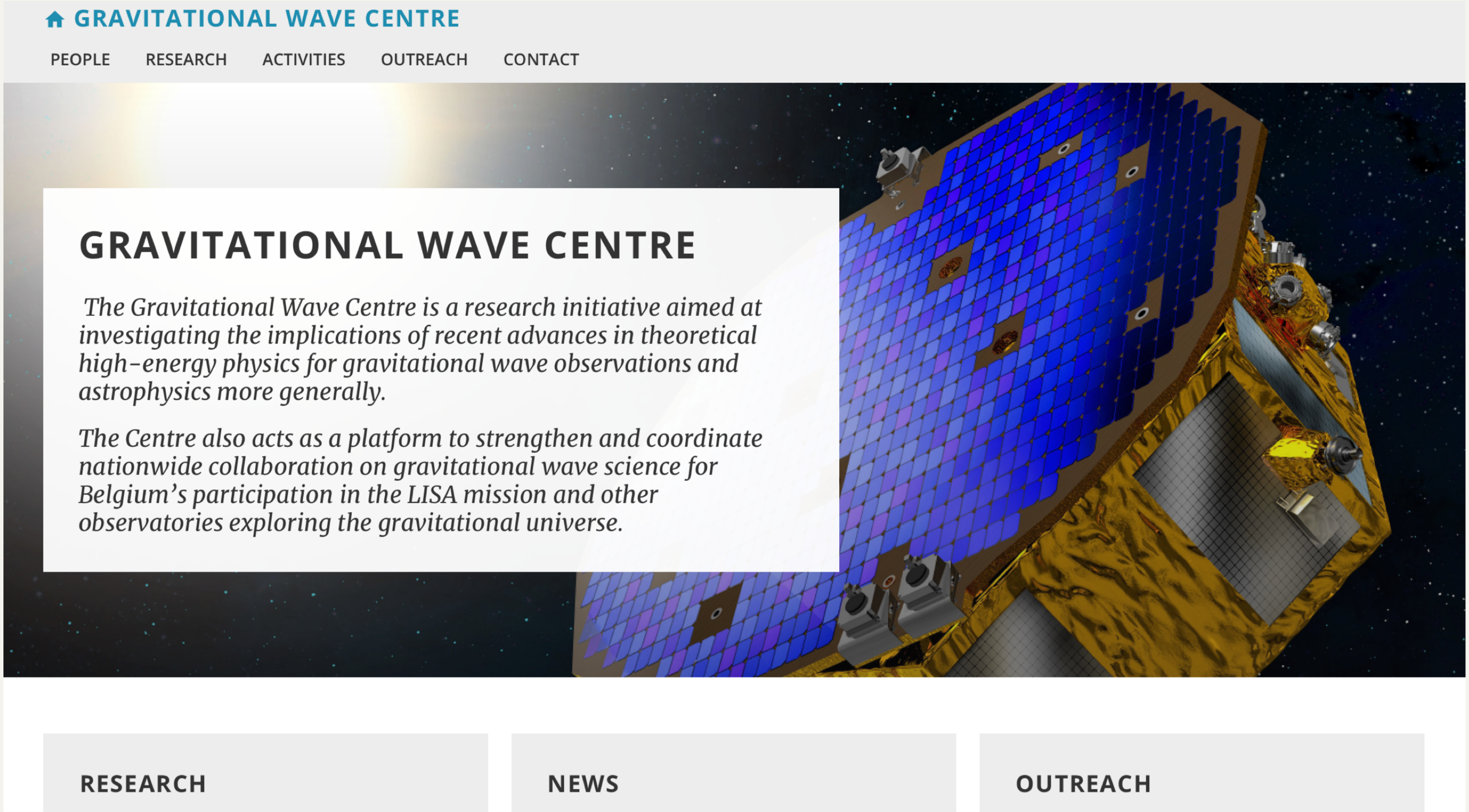
→ self-force corrections $\sim m_0/M$?

Prospects for GW science in Belgium

- Gravitational Wave Center provides science platform. Join us!
- LISA: Phase A starts April 2018. Three science working groups.

Einstein Telescope:

- 2018: set up Belgian GW exp/instr consortium
- 2019: ET ESFRI proposal
- 2021: NL-BE-DE bid?



GRAVITATIONAL WAVE CENTRE

The Gravitational Wave Centre is a research initiative aimed at investigating the implications of recent advances in theoretical high-energy physics for gravitational wave observations and astrophysics more generally.

The Centre also acts as a platform to strengthen and coordinate nationwide collaboration on gravitational wave science for Belgium's participation in the LISA mission and other observatories exploring the gravitational universe.

https://fys.kuleuven.be/gwc/