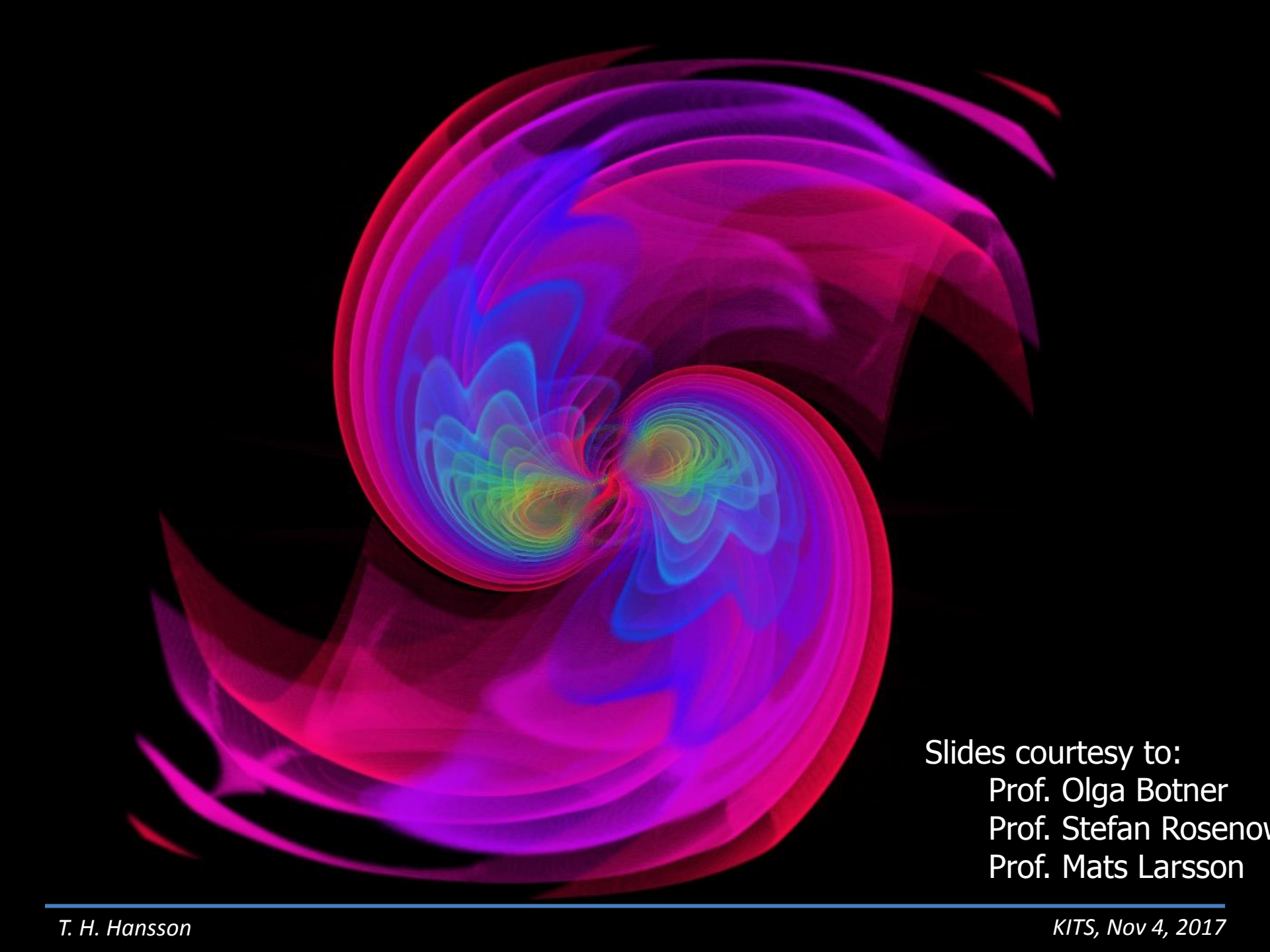
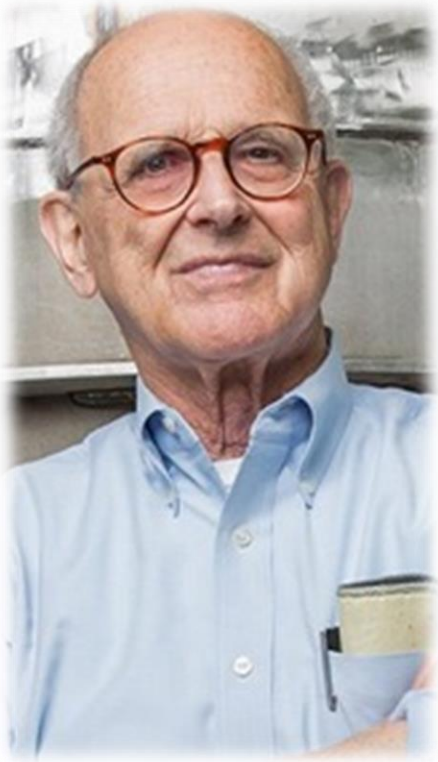


Slides courtesy to:
Prof. Olga Botner
Prof. Stefan Rosenow
Prof. Mats Larsson

2017 Nobel Prize in Physics

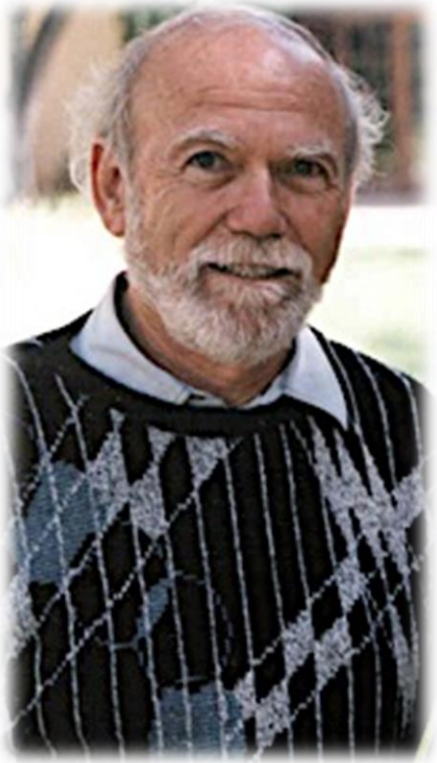
"for decisivee contributions to the LIGO detector and the observation of gravitaional waves"

with one half to



Rainer Weiss

and the other half jointly to



Barry C. Barish

Kip S. Thorne

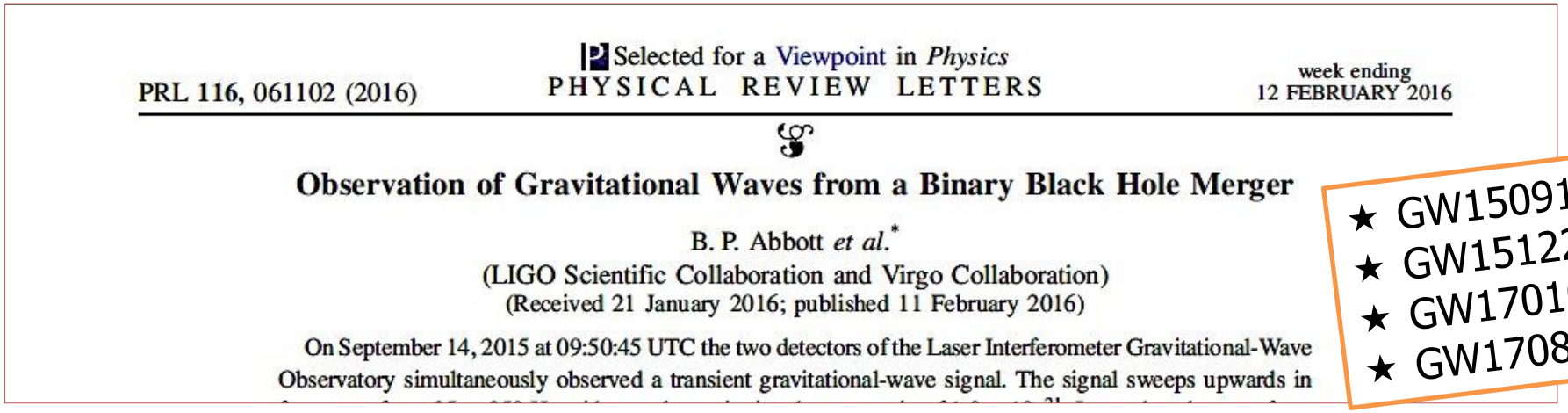
LIGO Scientific Collaboration and Virgo Collaboration

THE DISCOVERY

★ the first direct observation of a passing gravitational wave

☞ breakthrough of the century

- opens a new window to the universe
- the culmination of a long, difficult and challenging process to build a super-sensitive instrument
- opens for "hands-on" studies of the gravitational force in the "strong limit" e.g. close to black holes



Selected for a Viewpoint in *Physics*

PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

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

★ GW150914
★ GW151226
★ GW170104
★ GW170814

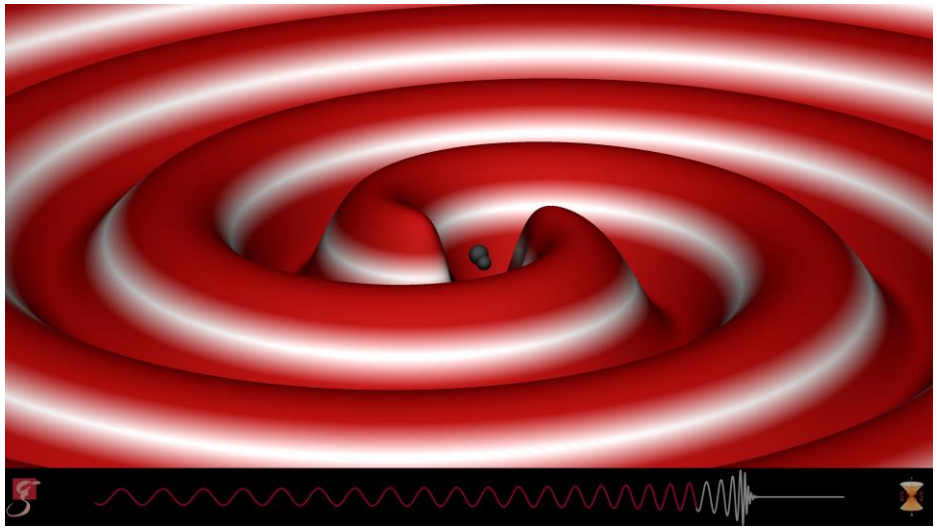
GRAVITAIONAL RADIATION

★ gravitational radiation is generated when masses accelerate

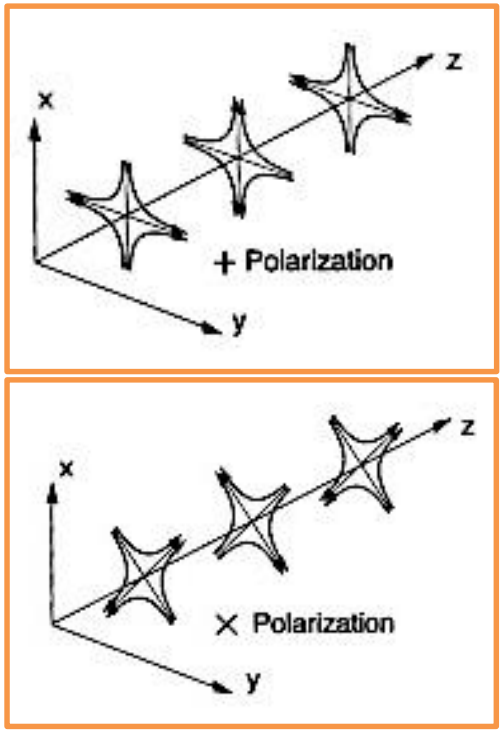
★ the space-time is deformed

★ the deformations propagate ☞ description in terms of gravitational waves that travel with the speed of light

★ space-time oscillates ☞ contracts/extends perpendicular to the direction of propagation



visualization: Haas@AEI
from A. Buananno, CERN colloquium 2017



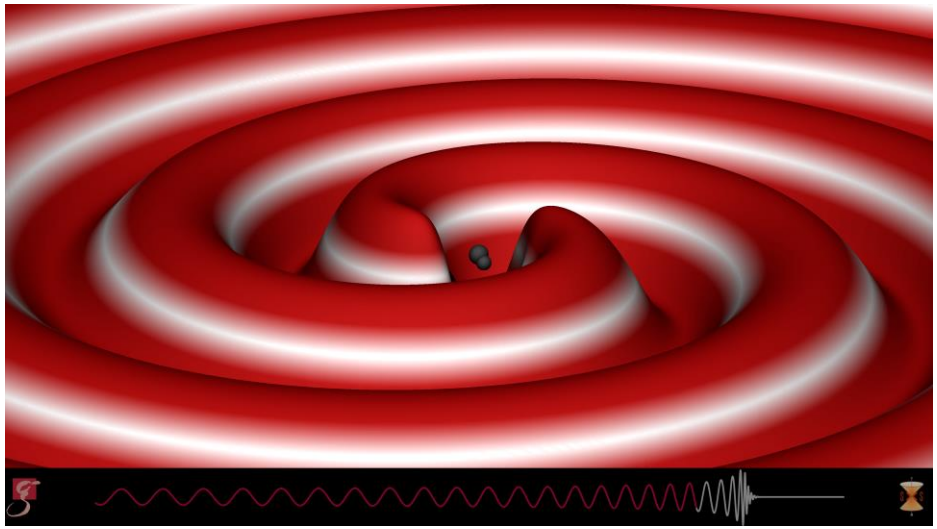
2 frihetsgrader

★ gravitational radiation is generated when masses accelerat

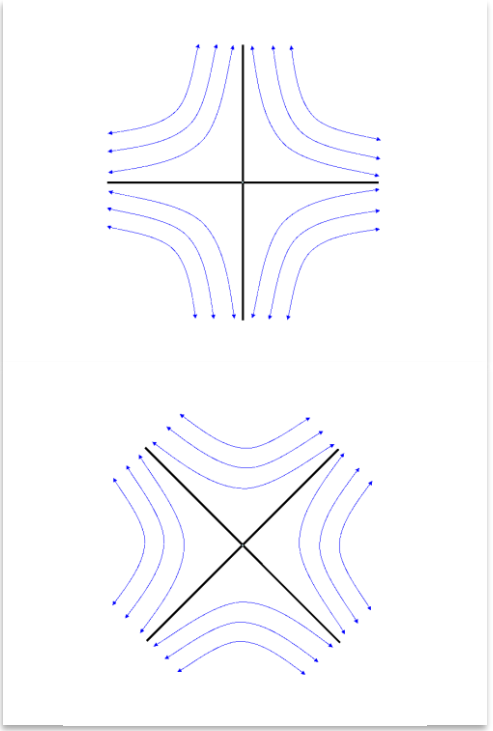
★ the space-time is deformed

★ the deformations propagate ☞ description in terms of gravitational waves that travel with the speed of light

★ space-time oscillates ☞ contracts/extends perpendicular to the direction of propagation

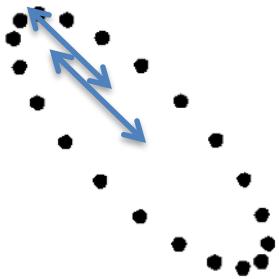


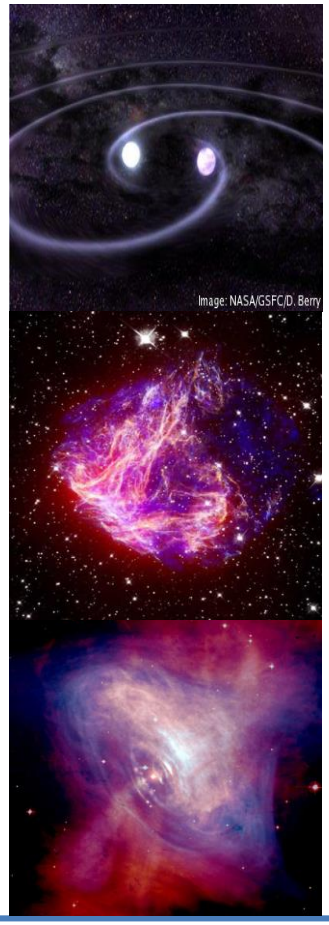
visualization: Haas@AEI
from A. Buananno, CERN colloquium 2017



★ extremely small amplitude $h \sim G/c^4 \ldots$

★ signal measured in terms of relative extension: $h = \Delta L/L$





collisions between compact objects
black holes / neutron stars

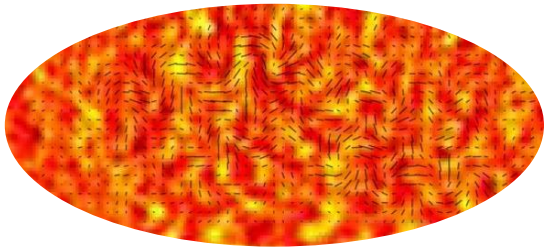
★ $h \sim 10^{-21}$

supernove
gamma ray bursts

★ $h \sim 10^{-23} - 10^{-20}$

pulsars/magnetars

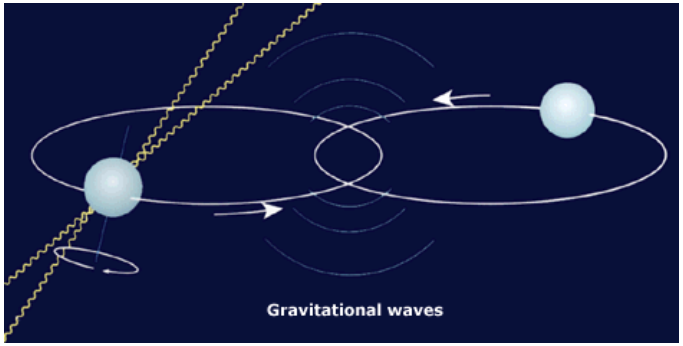
★ $h \sim 10^{-27} - 10^{-24}$



cosmic gravitational wave background

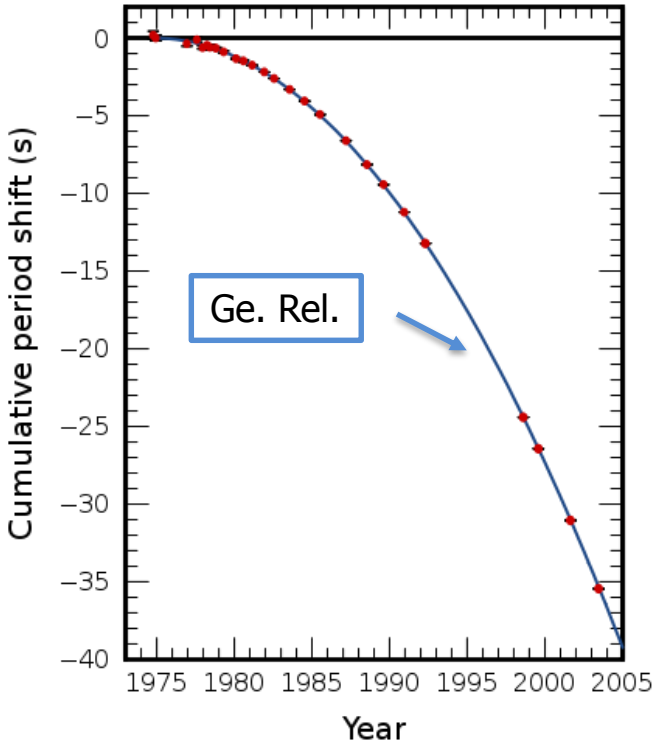
★ $h \sim 10^{-24}$??

★ Hulse and Taylor (1974) observed a dubble pulsar PSR 1913+16
★ showed that the orbit shrinks, the two stars come closer and closer
★ the effect is in accordance with general relativity and is
– a consequence of gravitational radiation!



★ Nobel Prize 1993

for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation



★ the 1957 Chapel Hill conference
  – theorists agree that gravitational radiation has detectable effects

★ Joseph Weber builds the first gravitational wave antenna in early 1960's

★ "he detects" about 1 event per day! (publ. 1969; questioned)

★ stimulated further R&D on gravitational wave detectors

  ☞ cryogeniska resonant Weberdetektors

  ☞ laser interferometrs

LIGO

Hanford

Livingston

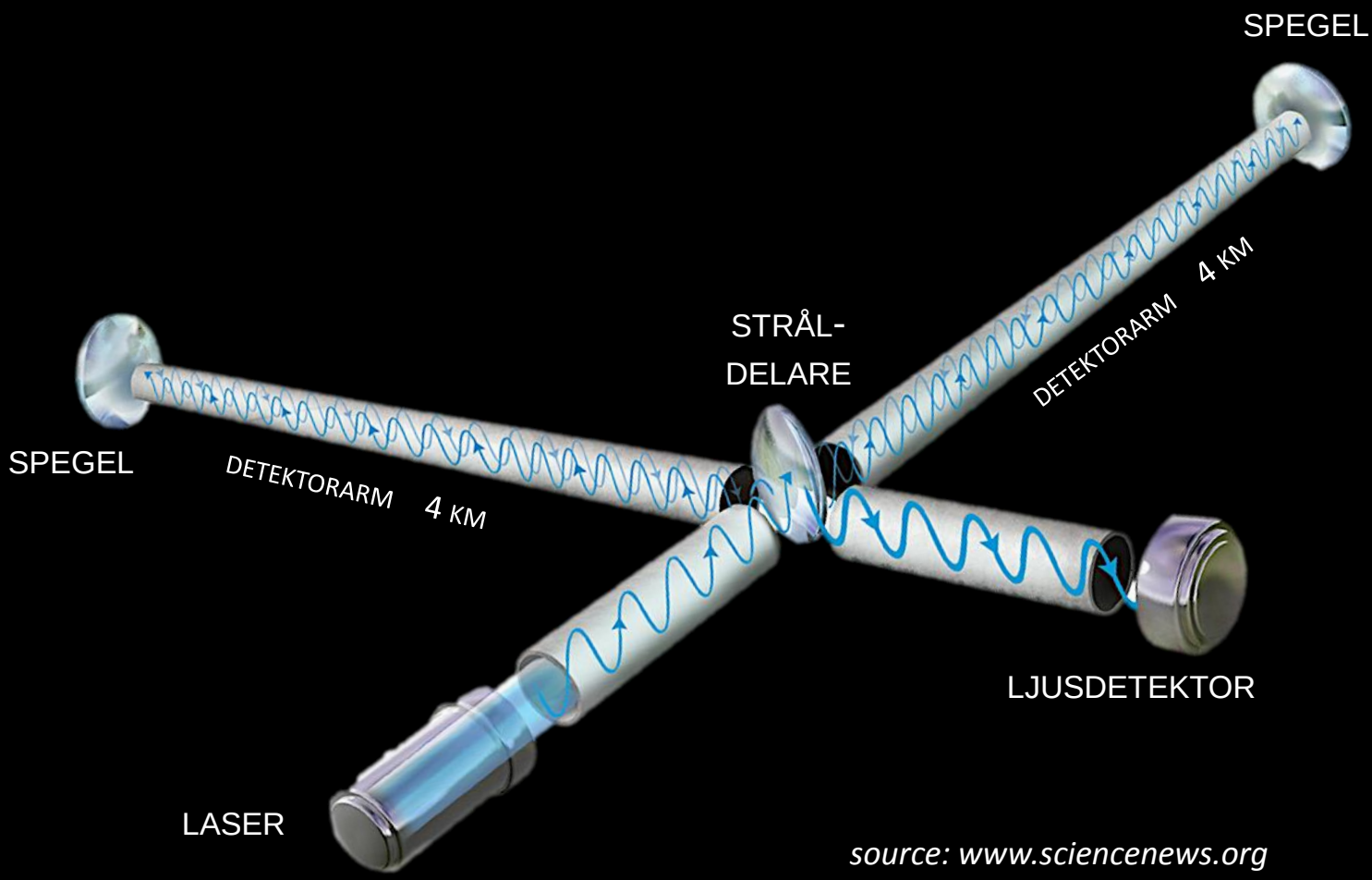
Laser Interferometer Gravitational-wave Observatory

LIGO

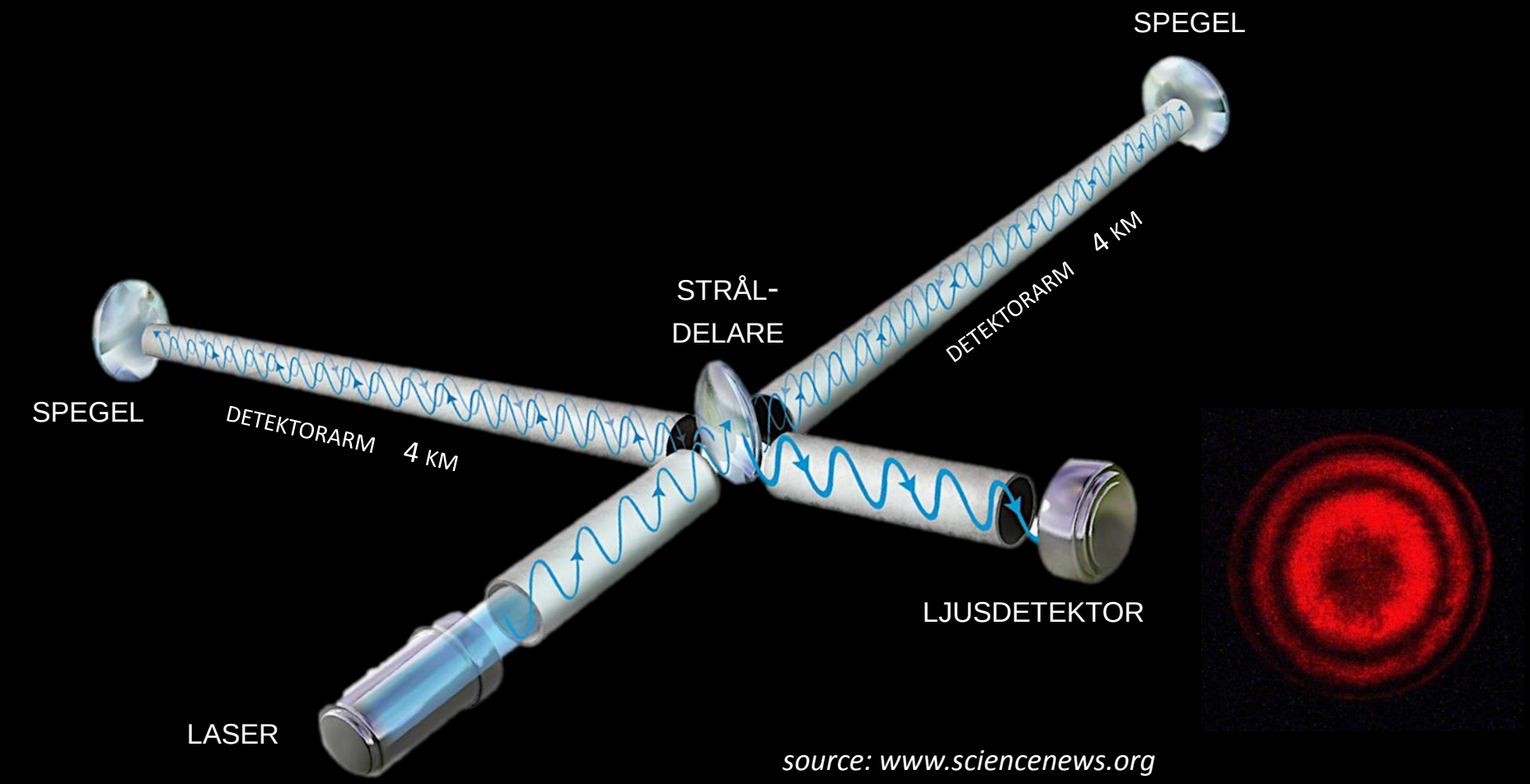
two identical laser interferometers 3002 km apart at

- Livingston, Louisiana
- Hanford, Washington

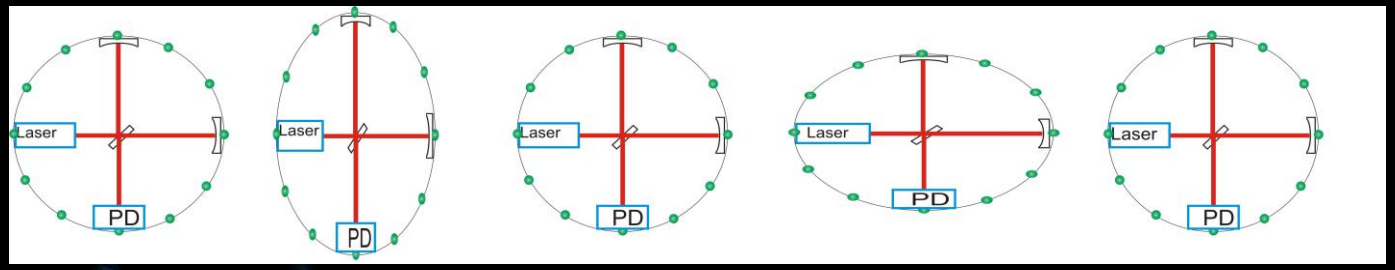
LASER INTERFEROMETER FOR GRAVITATIONAL WAVES



source: www.sciencenews.org



source: www.sciencenews.org



SPEGEL

STRÅL-
DELARE

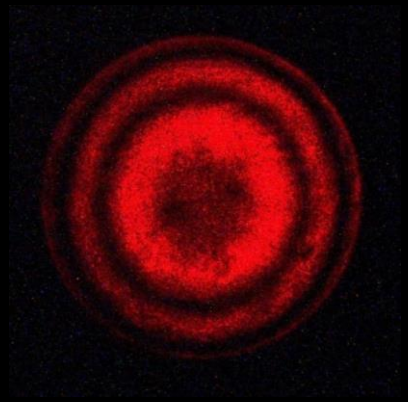
SPEGEL

DETEKTORARM 4 KM

DETEKTORARM 4 KM

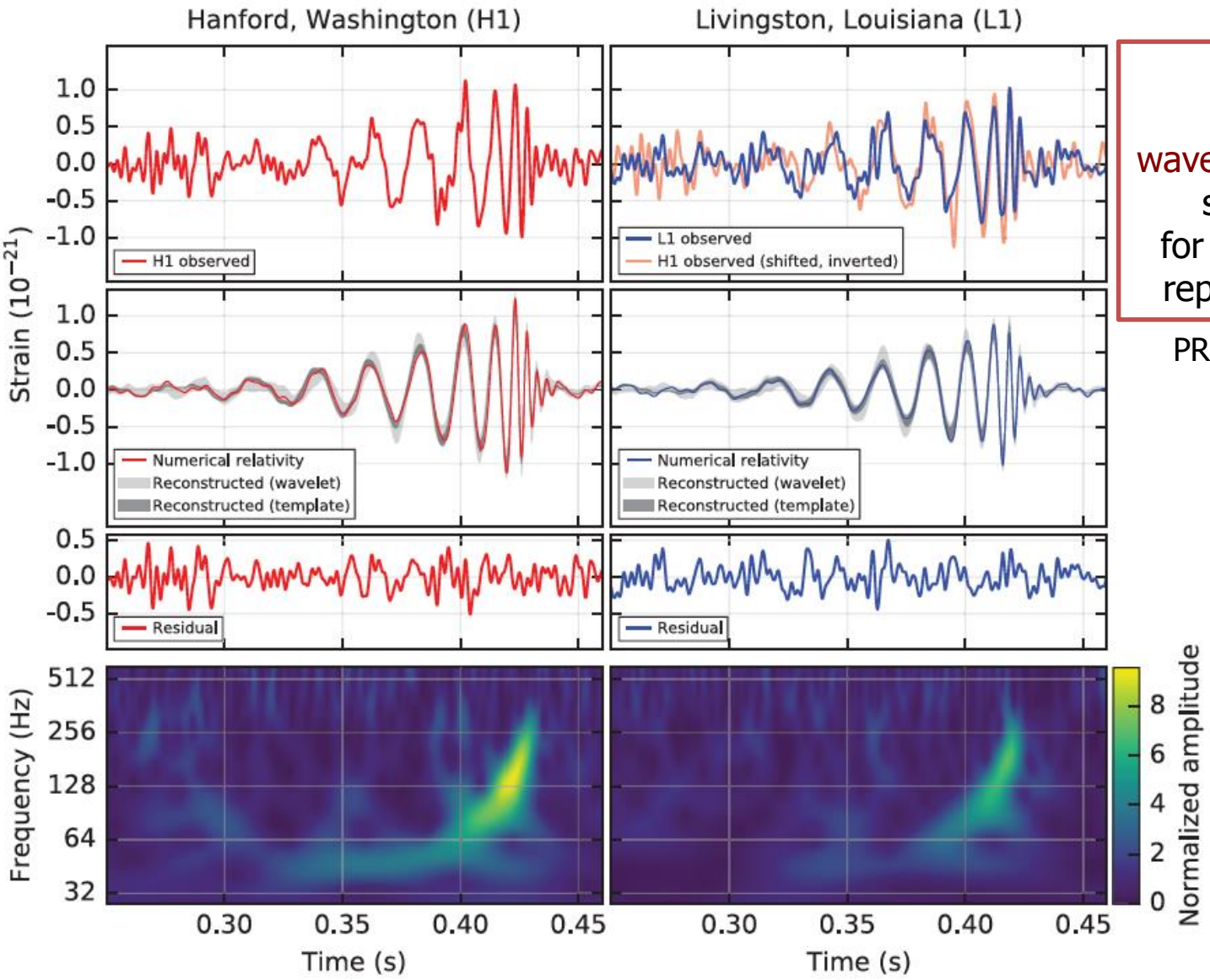
LJUSDETEKTOR

LASER



source: www.sciencenews.org

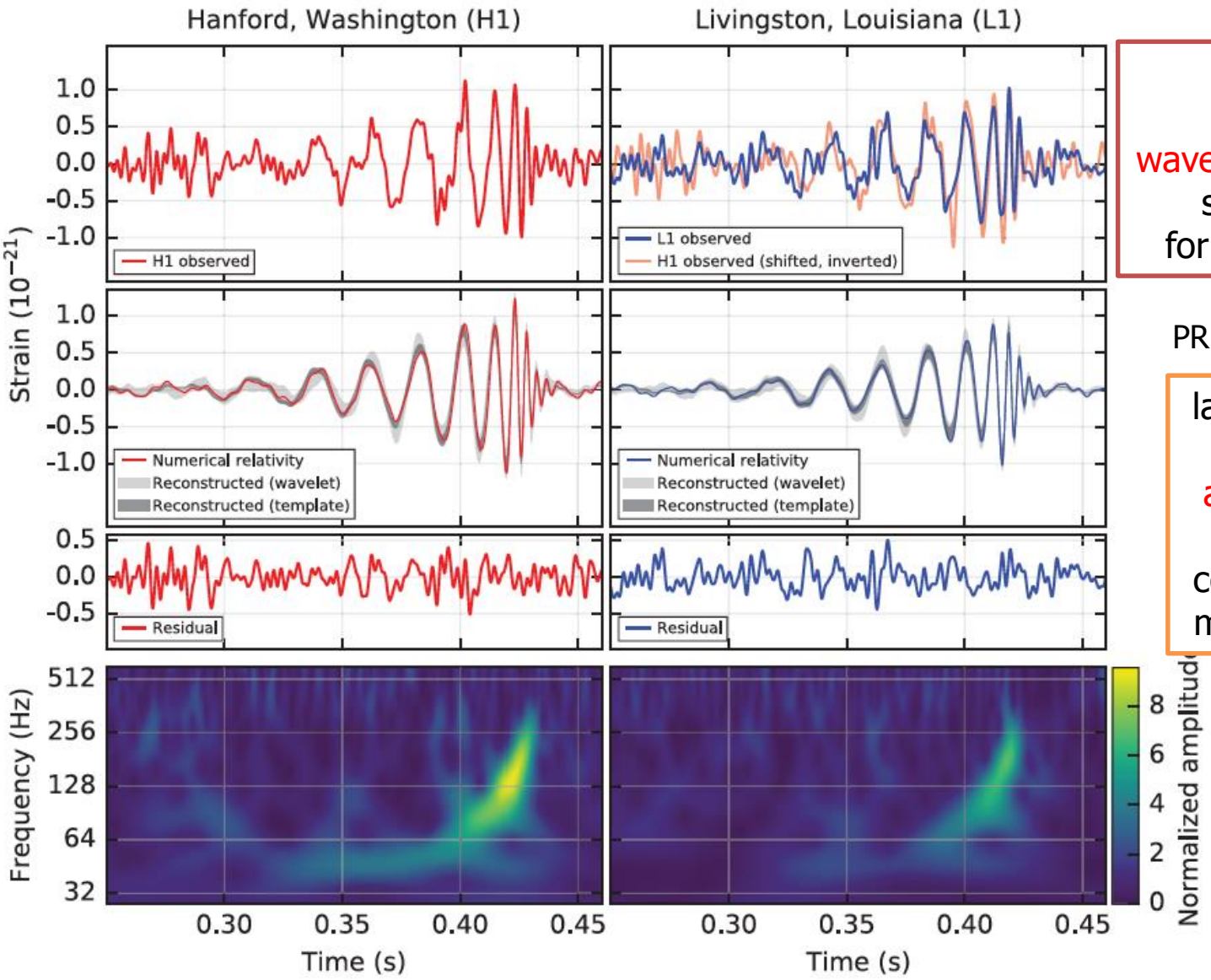
FIRST OBSERVATION GW150914 (Abbott et al., PRL 116 (2016) 061102)



DISCOVERED BY
automized,
wave shape independent
search algorithm
for generic trancients,
reported within 3 min

PRD 93 (2016) 122004

FIRSTSTA OBSERVATION GW150914 (Abbott et al., PRL 116 (2016) 061102)

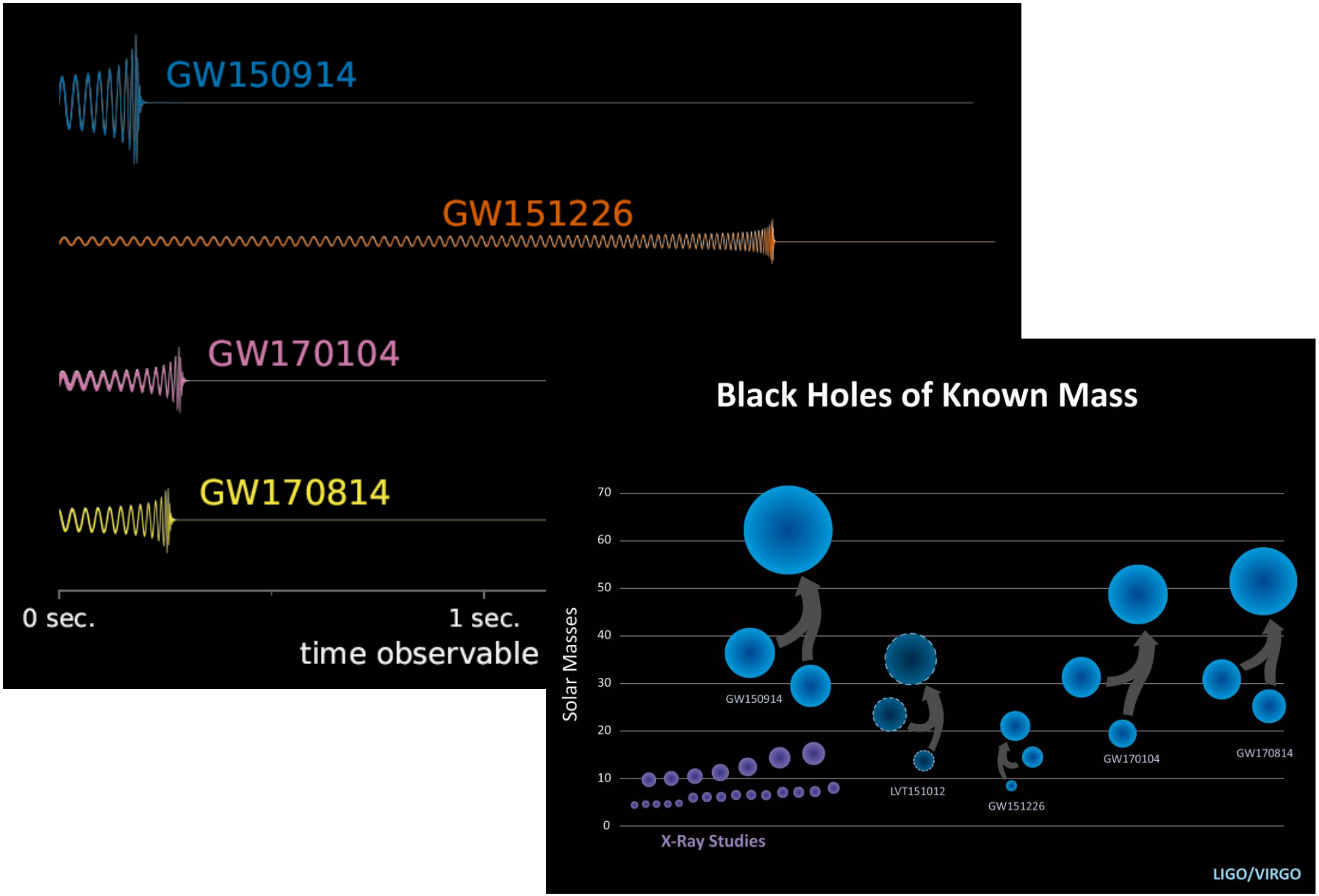


DISCOVERED BY
automized,
wave shape independent
search algorithm
for generic trancients

PRD 93 (2016) 122004

later confirmed by a
matched filter
analysis employing
wave templets
computed assuming
merging black holes

FLERA GRAVITATIONSVÅGOR



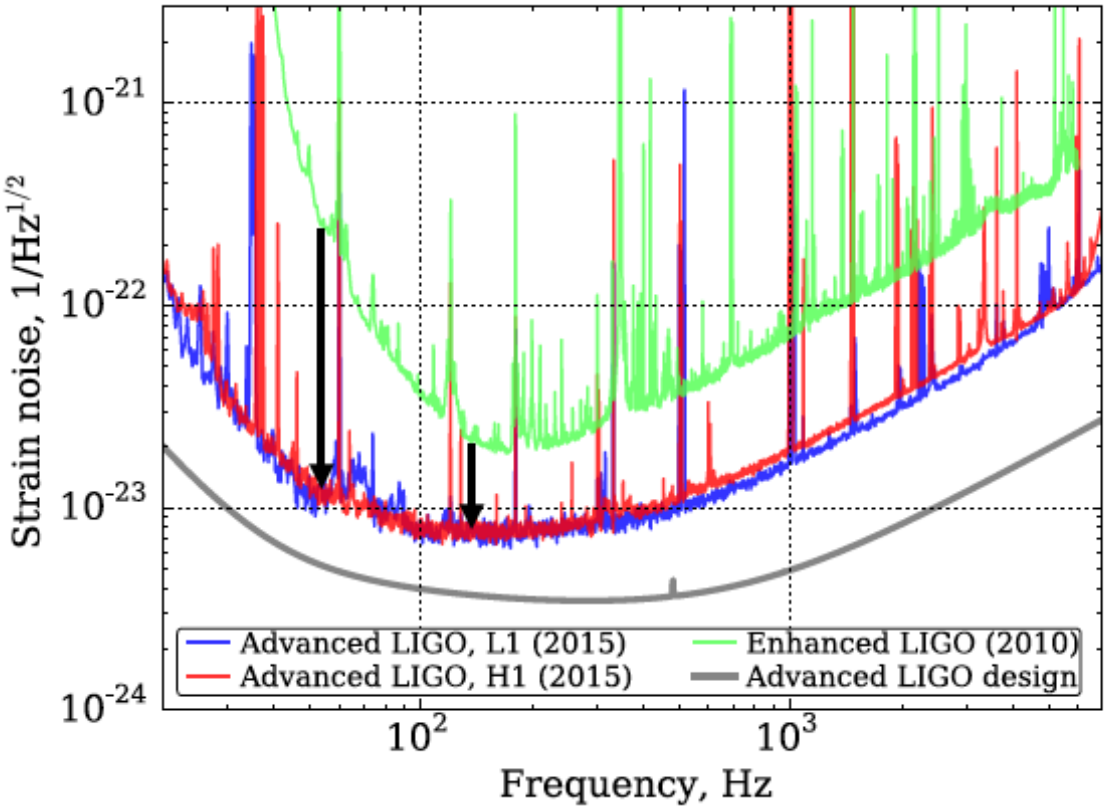
A SHORT HISTORY OF LIGO

★ Laserinterferometry for detection of gravitational waves is first mentioned in an article by Gertsenshtein and Pustovoit, USSR, 1963

★ Independently proposed by Rainer Weiss, MIT, a few years later

★ 1967 Weiss gives the first demonstration of a detector w a sensitivity only limited by by "shot noise"

★ 1972 Weiss founds LIGO identifies and evaluates about different effects that limits the sensitivity, including sesmic noice, geomagnetic storms, cosmic radiation etc.

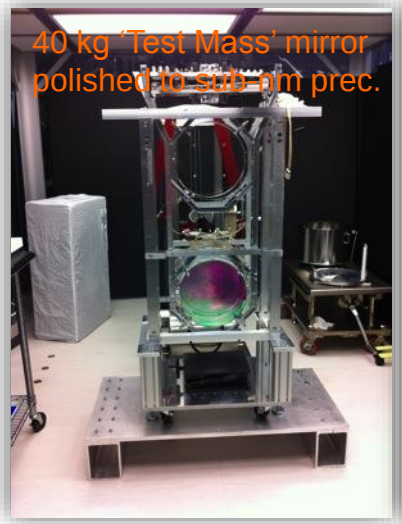


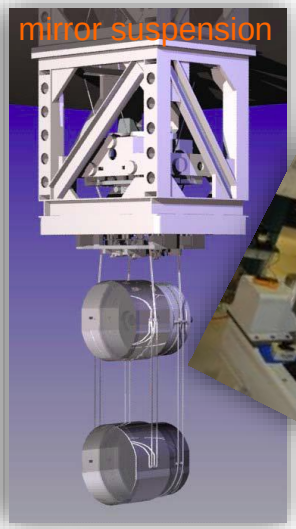
ADVANCED LIGO

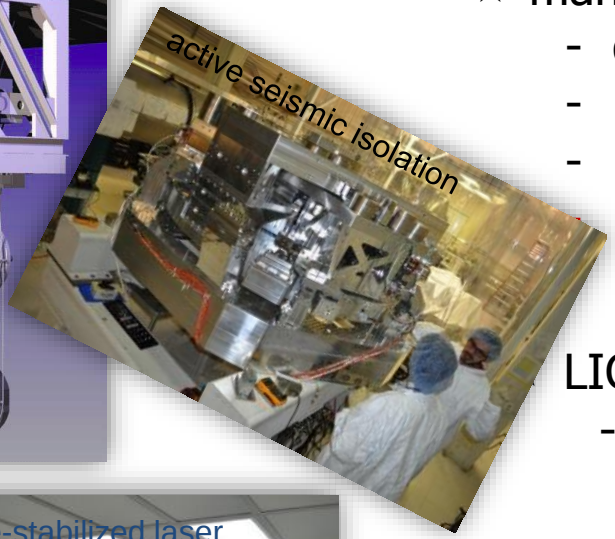
★ aLIGO – today a sensitivity of 10^{-23} at 100 Hz

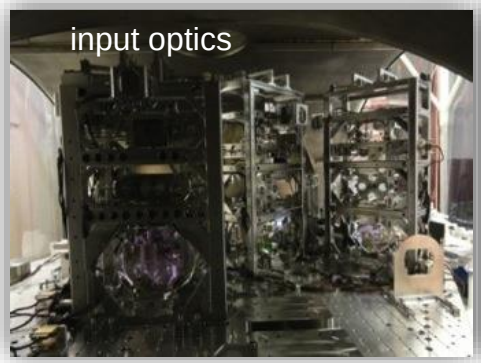
★ an enormous amount of innovation in detector technology

★ close collaboration between groups in USA, in Australia and in Europe









★ many exempels
- detector components
- mirror suspension
- calibration methods
- signal processing
- etc. etc.

LIGO collaboration
- about 1000 researchers
- 90 institutions
- 5 continents

★ continuous detector/method-development during 40 years.

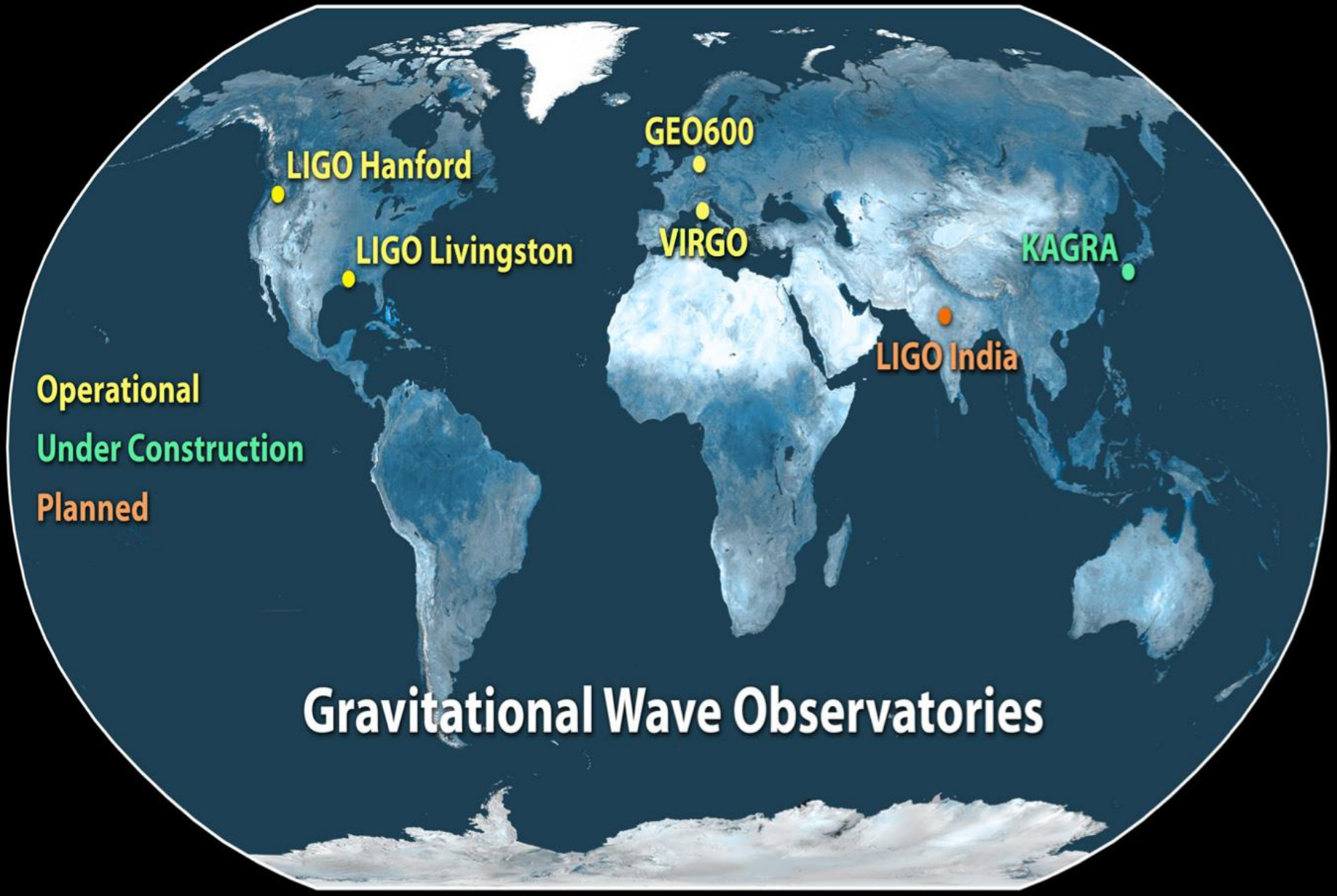
★ many crucial individual contr.

★ ~ 300 publications

ADVANCED VIRGO

6 EU countries: France, Hungary, Italy, Poland, Spain, and The Netherlands
20 labs, ~280 authors

APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay - ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest
University of Valencia


LIGO Hanford
GEO600
LIGO Livingston
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

What is new as of August 17, 2017 ?

Black holes

- only elements: space and time
- masses: > 3 $M_\odot$, in GW-detections: (7.5 - 36) $M_\odot$

⇒ **extreme spacetime**

Neutron star

- GWs produced by a *matter*-source

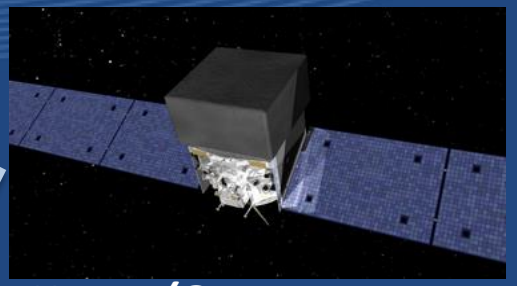
- masses: ~1.4 $M_\odot$ (< 3 $M_\odot$)
- densities: ~ 5×10^{14} g/cm^3 >> density nuclear matter
- temperatures during merger: > 10^{11} K

⇒ **extreme spacetime & *extreme matter***

Multi-messenger GW astronomy

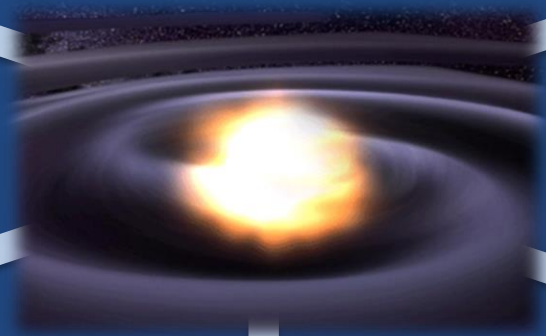
From D. Reitze CERN colloquium August 2017

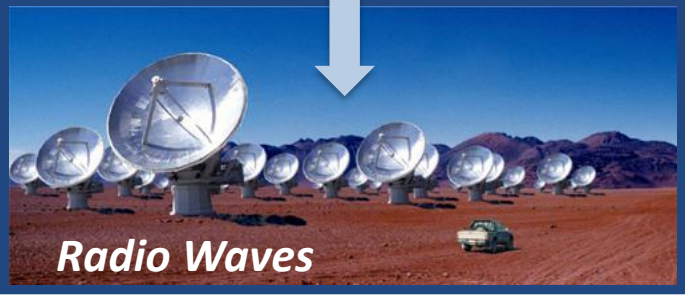
Gravitational Waves



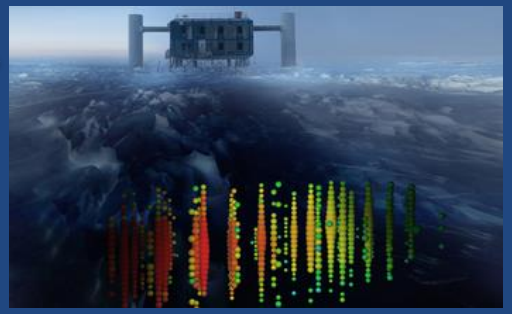
X-rays/Gamma-rays

Visible/Infrared Light

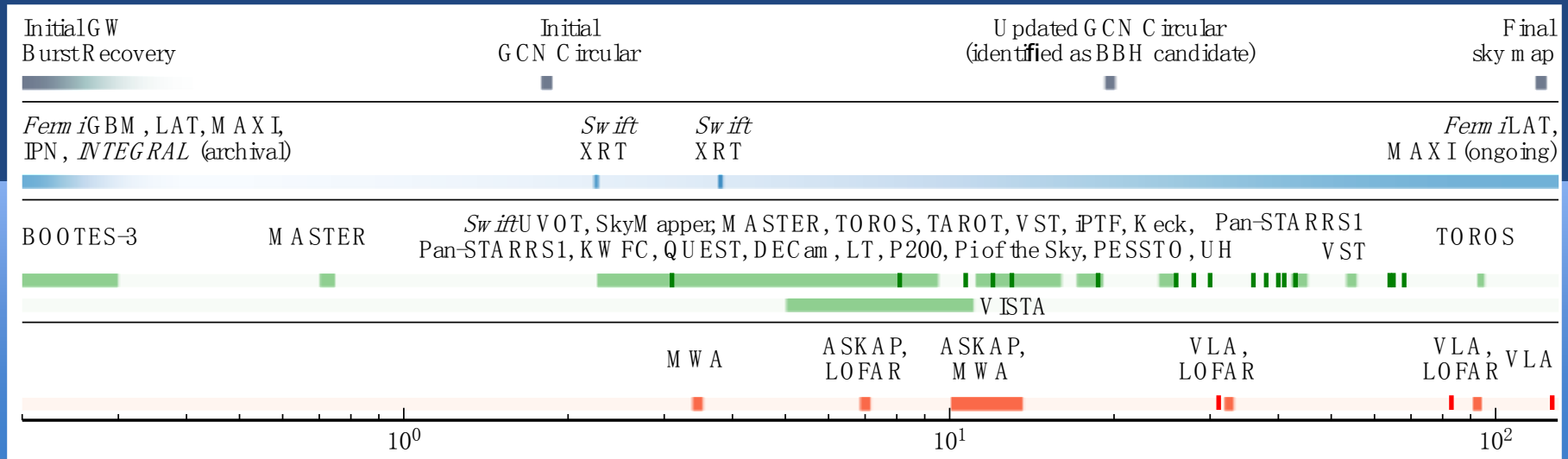




Radio Waves



Neutrinos



What have we learned from the first GW+EM multi-messenger event?

Gravitational Waves:

- "it was a neutron star neutron star merger with total mass $\approx 2.8\ M_{\odot}$"

Electromagnetic waves:

Solution of long-standing puzzles:

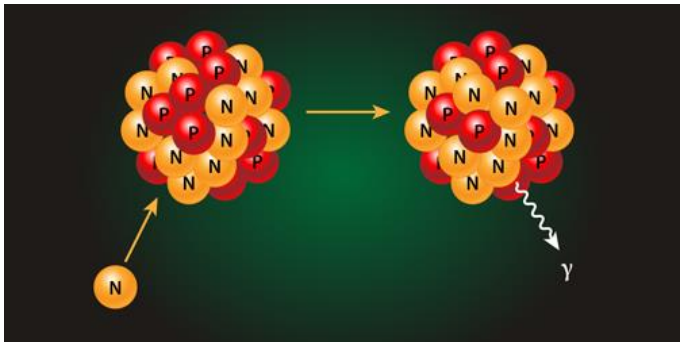
- **"neutron star mergers produce short Gamma-Ray Bursts"**
- **"neutron star mergers are a major production site of heavy elements"**

What have we learned from EM emission?

We know where it happened!

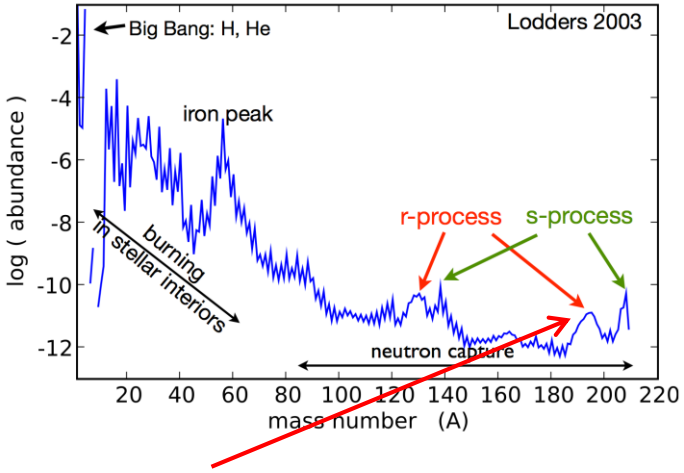
credit: LIGO/VIRGO

Nucleosynthesis via “rapid neutron capture (=r-process)”



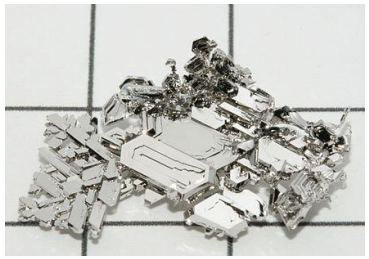
Enough matter is ejected for neutron star mergers to be *A* major/potentially *THE* major source of heavy elements in the Universe!

Examples of r-process elements

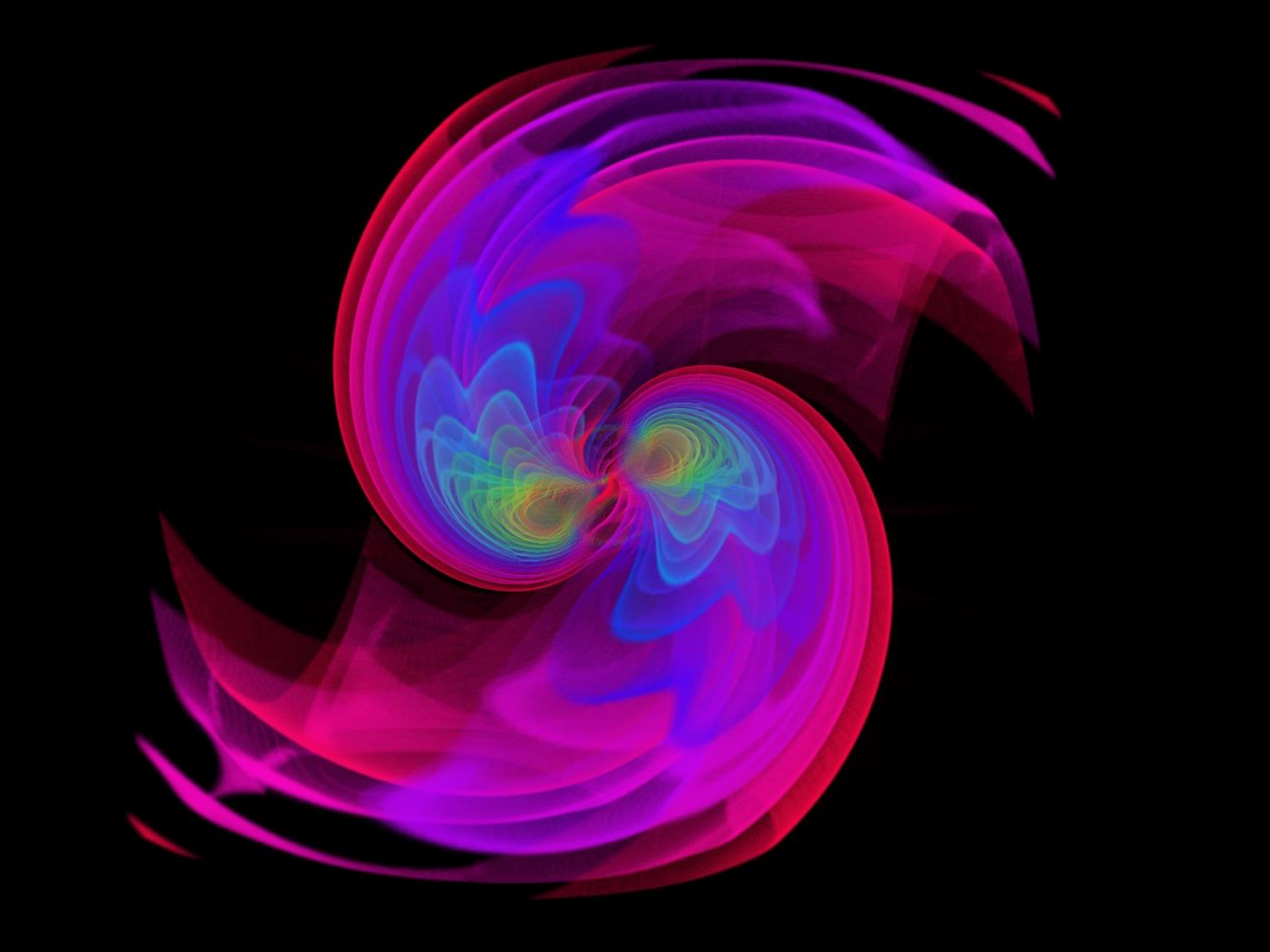


“platinum peak”

Platinum, Z= 78, A= 195



Gold, Z= 79, A= 197



Testament

Jag undertecknad Alfred Bernhard Nobel förklarar härmed efter moget betänkande min yttersta vilja i afseende i den egendom jag vid min död kan efterlemna vara följande.

- - - - -

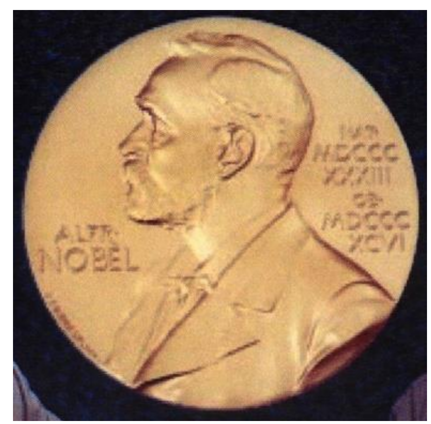
Öfver hela min återstående realiserbara förmögenhet förfogas på följande sätt: Kapitalet, af utredningsmännen realiseradt till säkra värdepapper, skall utgöra en fond hvars ränta årligen utdelas som prisbelöning åt dem som under det förlupne året hafva gjort menskligheten den största nytta. Räntan delas i fem lika delar som tillfalla: en del den som inom fysikens område har gjort den vigtigaste upptäckt eller uppfinning; en del den som har gjort den vigtigaste kemiska upptäckt eller förbättring; en del den som har gjort den vigtigaste upptäckt inom fysiologiens eller medicinens domän; en del den som inom literaturen har producerat det utmärktaste i idealisk rigtning; och en del åt den som har verkat mest eller bäst för folkens förbrödrande och afskaffande eller minskning af stående armeer samt bildande och spridande af fredskongresser. Prisen för fysik och Kemi utdelas af Svenska Vetenskapsakademien; för fysiologiska eller medicinska arbeten af Carolinska Institutet i Stockholm; för litteratur af Akademien i Stockholm samt för fredsförfäktare af ett utskott af fem personer som väljas af Norska Stortinget. Det är min uttryckliga vilja att vid prisutdelningarne intet afseende fästes vid någon slags nationalitetstillhörighet sålunda att den värdigaste erhåller priset antingen han är Skandinav eller ej.

Detta testamente är hittils det enda giltiga och upphäfver alla mina föregående testamentariska bestämmelser om sådane skulle förefinnas efter min död.

Slutligen anordnar jag såsom varande min uttryckliga önskan och vilja att efter min död pulsådrorna uppskäras och att sedan detta skett och tydliga dödstecken af kompetenta läkare intygats liket förbrännes i ett så kalladt crematorium.

Paris den 27 November 1895

Alfred Bernhard Nobel



From the will of Alfred Nobel

"The whole of my remaining realizable estate shall be dealt with in the following way: ……annually distributed in the form of prizes to those who, during the preceding year, shall have conferred the greatest benefit on mankind. …

……shall be divided into five equal parts, which shall be apportioned as follows: one part to the person who shall have made the most important discovery or *invention* within the field of physics; one part to the person who shall have made the most important chemical discovery or *improvement*; one part to the person who shall have made the most important *discovery* within the domain of physiology or medicine; one part to the person who shall have produced in the field of literature the most outstanding work in an ideal direction; ……

The prizes for physics and chemistry shall be awarded by the Swedish Academy of Sciences ….

It is my express wish that in awarding the prizes no consideration be given to the nationality of the candidates, but that the most worthy shall receive the prize, whether he be Scandinavian or not."

The Nobel Foundation

A private institution established in 1900 based on the will of Alfred Nobel. The Foundation manages the assets made available through the will for the awarding of the Nobel Prizes in Physics, Chemistry, Physiology or Medicine, Literature and Peace.

It represents the Nobel institutions externally and administers informational activities and arrangements surrounding the presentation of the Nobel Prize. The Foundation also administers Nobel symposia in the different prize areas.

- Nobel Media
- Nobel Museum
- Nobel Center

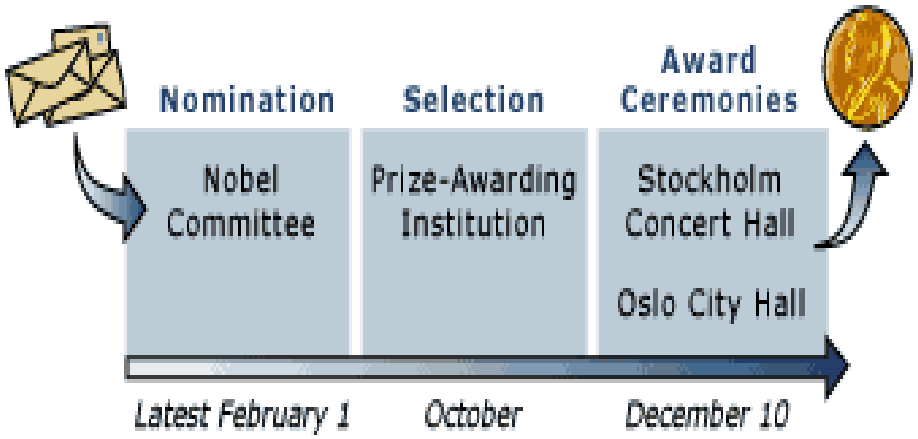
Nominations and selection of physics laureates

- Nominations to the Nobel Prize in Physics is by invitation only.
- The names of the nominees and other information about the nominations are kept secret for 50 years.
- The Nobel committee for physics sends confidential forms to institutions and persons who are competent and qualified to nominate.
- Only persons nominated a particular year can be considered for the prize that year.
- A prize cannot be awarded posthumous.

Who can nominate?

- Swedish and foreign members of the Royal Swedish Academy of Sciences
- Members of the Nobel Committee for Physics
- Nobel Laureates in Physics
- Permanent and assistant professors in the sciences of Physics at the universities and institutes of technology of Sweden, Denmark, Finland, Iceland and Norway
- Holders of corresponding chairs in at least six universities or university colleges selected by the Academy of Sciences with a view to ensuring the appropriate distribution over the different countries and their seats of learning
- Other scientists from whom the Academy may see fit to invite proposals

Timline for nomination, selection and award ceremony



In early October, the Academy selects the Nobel Laureates in Physics through a majority vote. The decision is final and without appeal. The names of the Nobel Laureates are announced immediately afterwards.

The Nobel Prize Award Ceremony takes place on 10 December in Stockholm, where the Nobel Laureates receive their Nobel Prize, which consists of a Nobel Medal and Diploma, and a document confirming the prize amount.

Example of a prize for discovery

1935

James Chadwick

”*for the discovery of the neutron*”

Example of a prize for invention

1960

Donald Arthur Glaser

”*for the invention of the bubble chamber*”

Shared prize

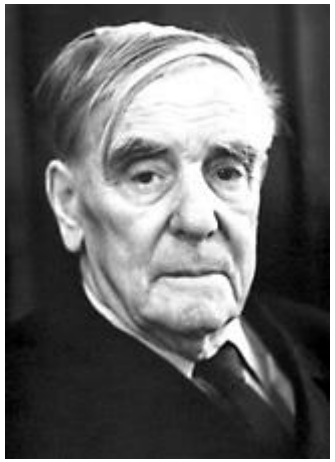
2010

Andrei Geim

Konstantin Novosëlov

” for groundbreaking experiments regarding the two-dimensional material graphene”

Divided prize, 1978



Pyotr Kapitsa

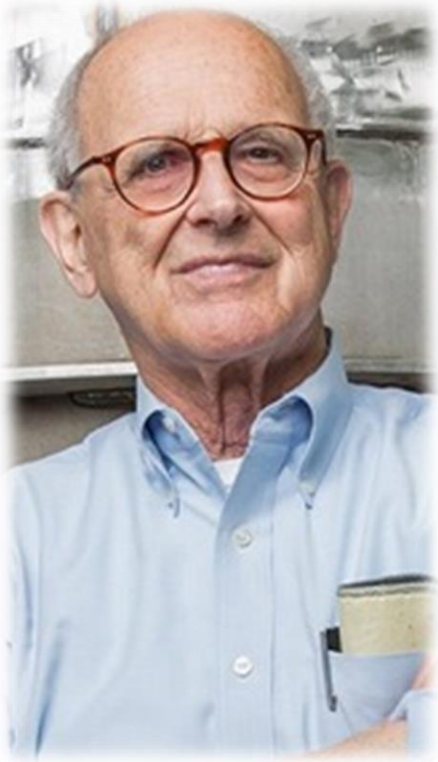
“for his basic inventions and discoveries in the area of low-temperature physics"

Arno A. Penzias and Robert W. Wilson

"for their discovery of cosmic microwave background radiation"

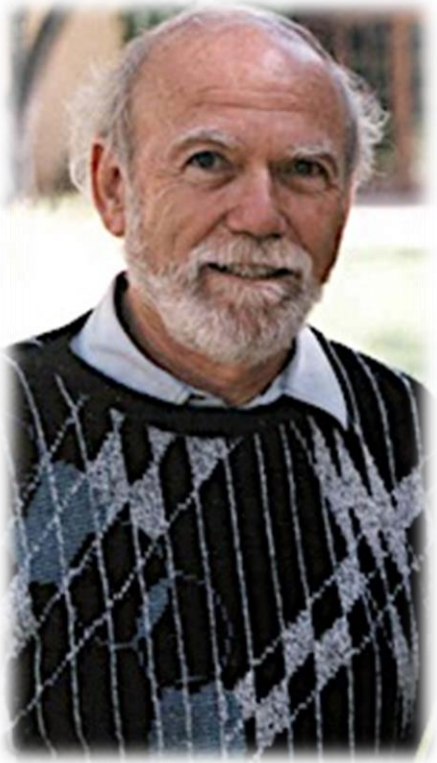
"för avgörande bidrag till LIGO-detektorn och observationen av gravitationsvågor"

med ena hälften till



Rainer Weiss

och med den andra hälften gemensamt till



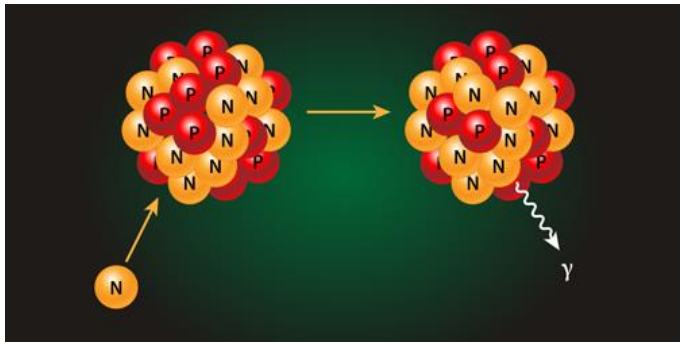
Barry C. Barish

Kip S. Thorne

LIGO Scientific Collaboration and Virgo Collaboration

We know the EM emission is powered by radioactivity from "rapid neutron capture (r-process)" nucleosynthesis!

- "rapid neutron capture":

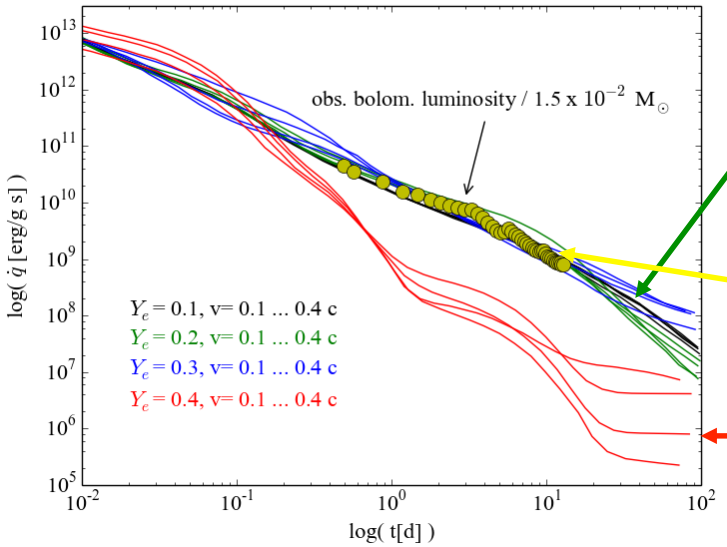


$\tau_{\text{n-capture}} \ll \tau_{\beta\text{-decay}}$

⇒ "lots of neutrons, delivered fast"

- total EM-emission decays in time as predicted by decay from r-process:

heating rate/ observed luminosity



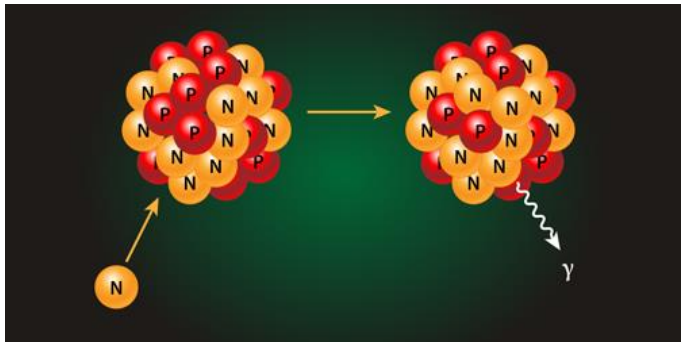
radioactive decay from r-process (electron fraction $\lesssim 0.3$) ⇒ heavy elements (A> 80)

(scaled) observed luminosity

high electron fraction (Ye= 0.4) ⇒ lighter elements (A <80)

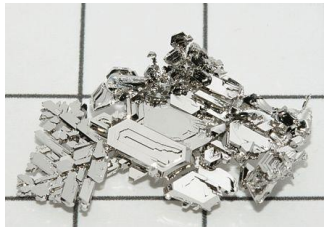
S. Rosswog et al. (2017)

Nucleosynthesis via “rapid neutron capture (=r-process)”

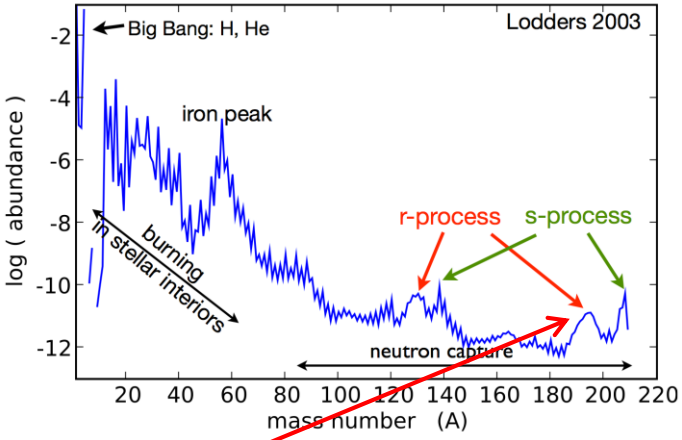


Iridium, Z= 77, A= 192

Platinum, Z= 78, A= 195



Examples of r-process elements



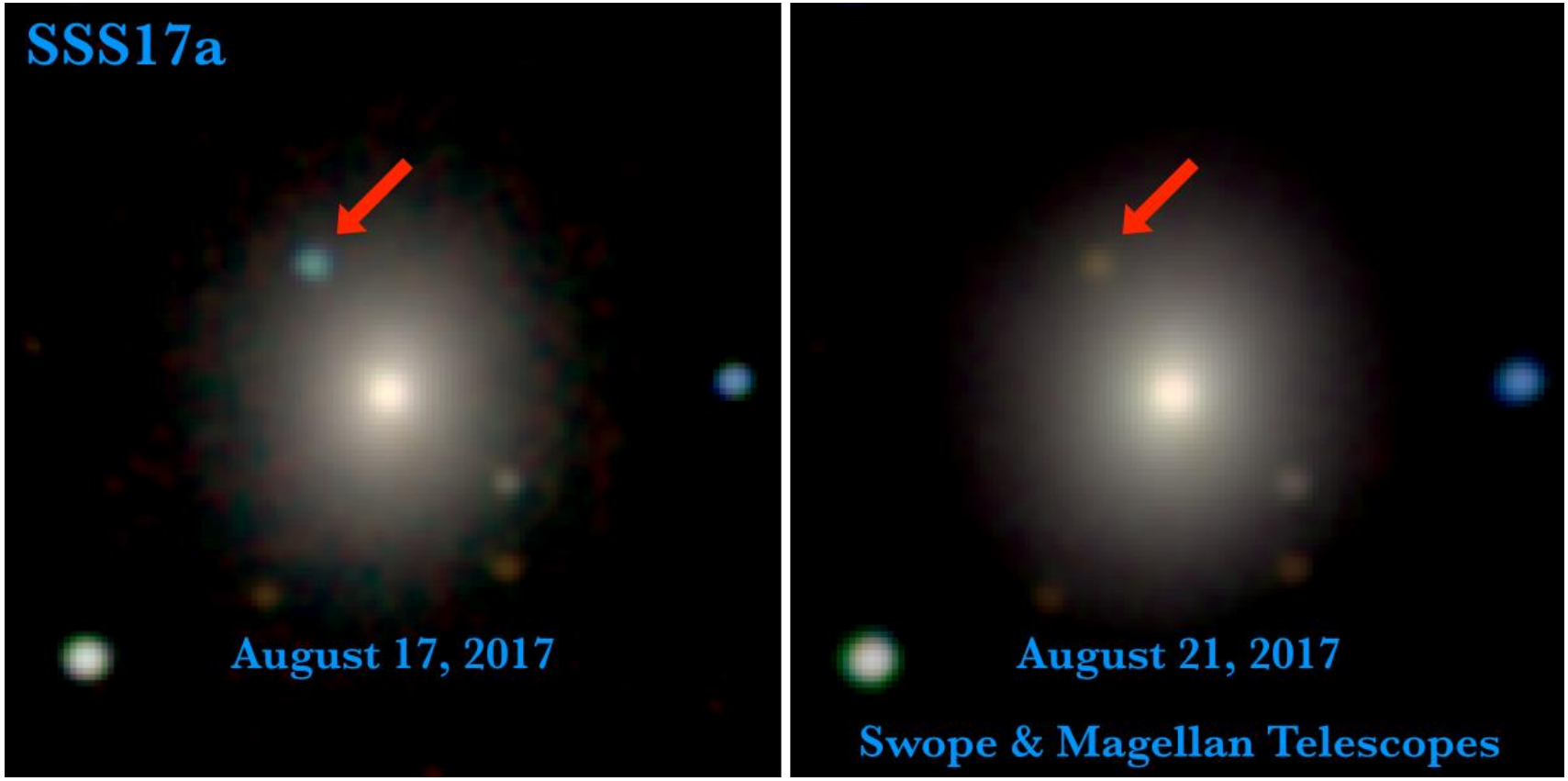
“platinum peak”

Gold, Z= 79, A= 197

Lead, Z= 82, A= 207

We know the merger produced the whole r-process range (A> 80)!

evolution of EM-flash from blue to red:



Credit: 1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

"blue":
- light r-process (80 $\lesssim$A $\lesssim$ 130)
- low opacity
- fast evolution

"red":
- heavy r-process (A $\gtrsim$130)
- high opacity
- slow evolution

Enough matter is ejected for neutron star mergers to be *A* major/ potentially *THE* major source of heavy elements in the Universe!

- the total EM-emission suggests that $\approx 0.03\ M_\odot$ were ejected in the merger

- we have event rate estimates from:
  - theoretical: stellar evolution
  - observation: short Gamma-ray bursts
  - observation: LIGO-VIRGO detection

- rate estimates differ somewhat, but are all consistent with:

$$R \times m_{ej} \times \tau_{MW} \approx \text{r-process mass in the Milky Way}$$

rate estimates

ejected mass

age Milky Way