Galileo, 1610

ONDE GRAVITAZIONALI
oltre la scoperta

Giovanni Losurdo – INFN Pisa
Accademia Nazionale dei Lincei

GRAVITATIONAL WAVES (1916)

Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

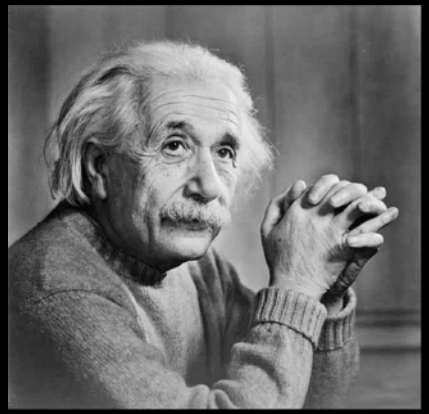
Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese all-

§ 2. Ebene Gravitationswellen.

Aus den Gleichungen (6) und (9) folgt, daß sich Gravitationsfelder stets mit der Geschwindigkeit 1, d. h. mit Lichtgeschwindigkeit, fortpflanzen. Ebene, nach der positiven x-Achse fortschreitende Gravitationswellen sind daher durch den Ansatz zu finden

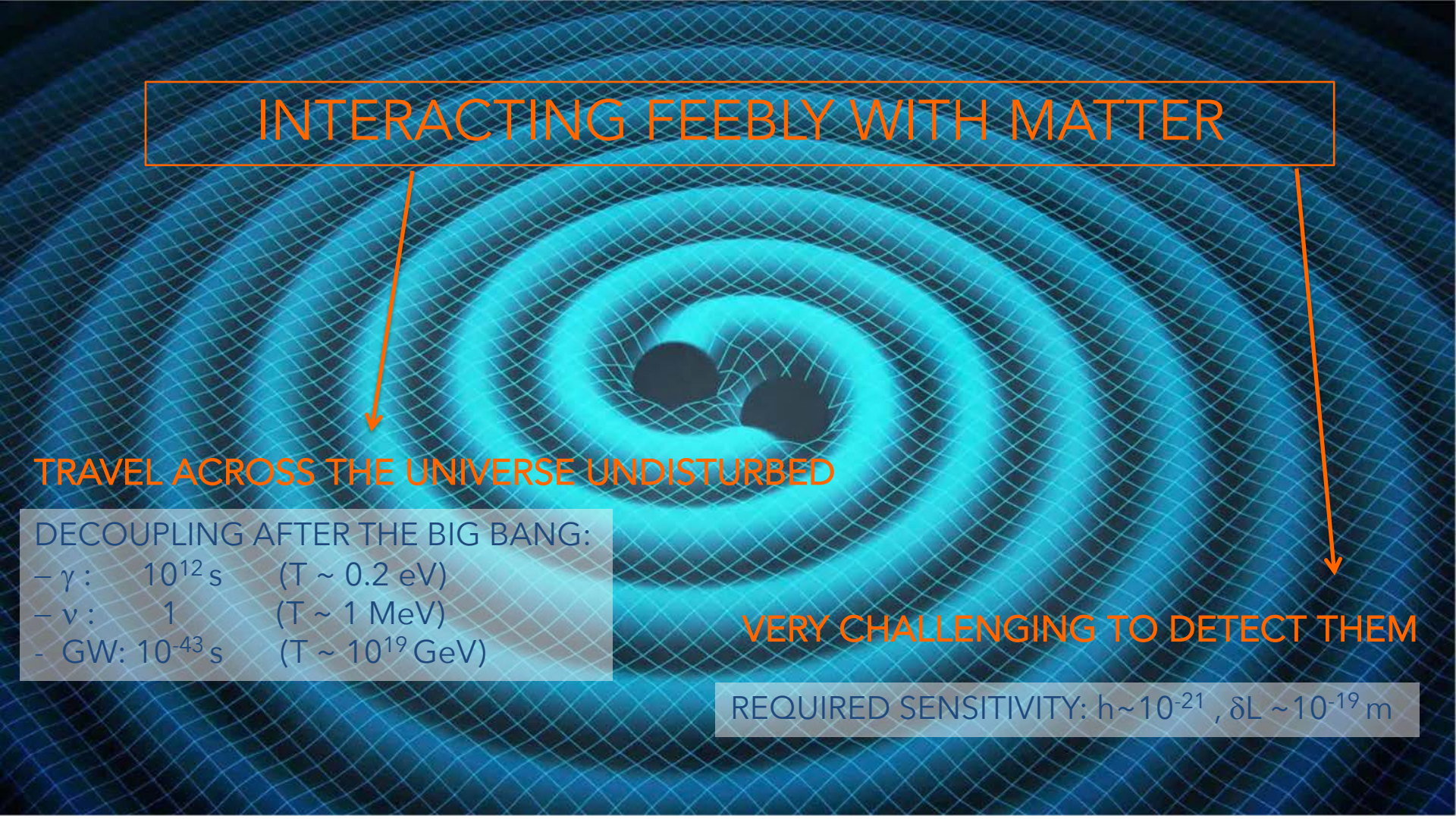
$$\gamma'_{\mu\nu} = a_{\mu\nu} f(x_1 + i x_4) = a_{\mu\nu} f(x - t). \qquad (15)$$

Nachtrag. Das seltsame Ergebnis, daß Gravitationswellen existieren sollen, welche keine Energie transportieren (Typen a, b, c), klärt sich in einfacher Weise auf. Es handelt sich nämlich dabei nicht um »reale« Wellen, sondern um »scheinbare« Wellen, die darauf beruhen, daß als Bezugssystem ein wellenartig zitterndes Koordinatensystem benutzt wird. Dies sieht man bequem in folgender Weise ein.



RIPPLES in the spacetime propagating at the speed of light

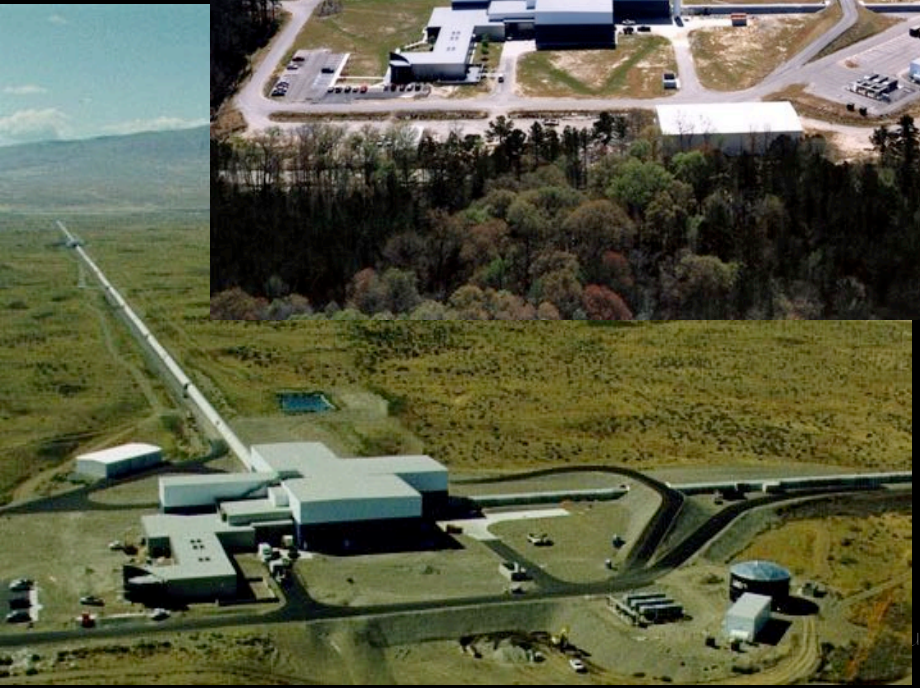
Generated by big masses moving at high speed


INTERACTING FEEBLY WITH MATTER
TRAVEL ACROSS THE UNIVERSE UNDISTURBED
DECOUPLING AFTER THE BIG BANG:
– γ : 10^{12} s (T ~ 0.2 eV)
– ν : 1 (T ~ 1 MeV)
- GW: 10^{-43} s (T ~ 10^{19} GeV)
VERY CHALLENGING TO DETECT THEM
REQUIRED SENSITIVITY: h~10^{-21} , δL ~10^{-19} m

1989


Proposal to the National Science Foundation
A
LASER INTERFEROMETER
GRAVITATIONAL-WAVE
OBSERVATORY
(LIGO)
VOLUME 1:
LIGO Science and Concepts
December 1989
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LIGO PROJECT
Jupiter
Earth
Virgo
Spica
THE VIRGO PROJECT
URSA
MAJOR
URSA
MINOR


LIGO Hanford
Virgo
LIGO Livingston



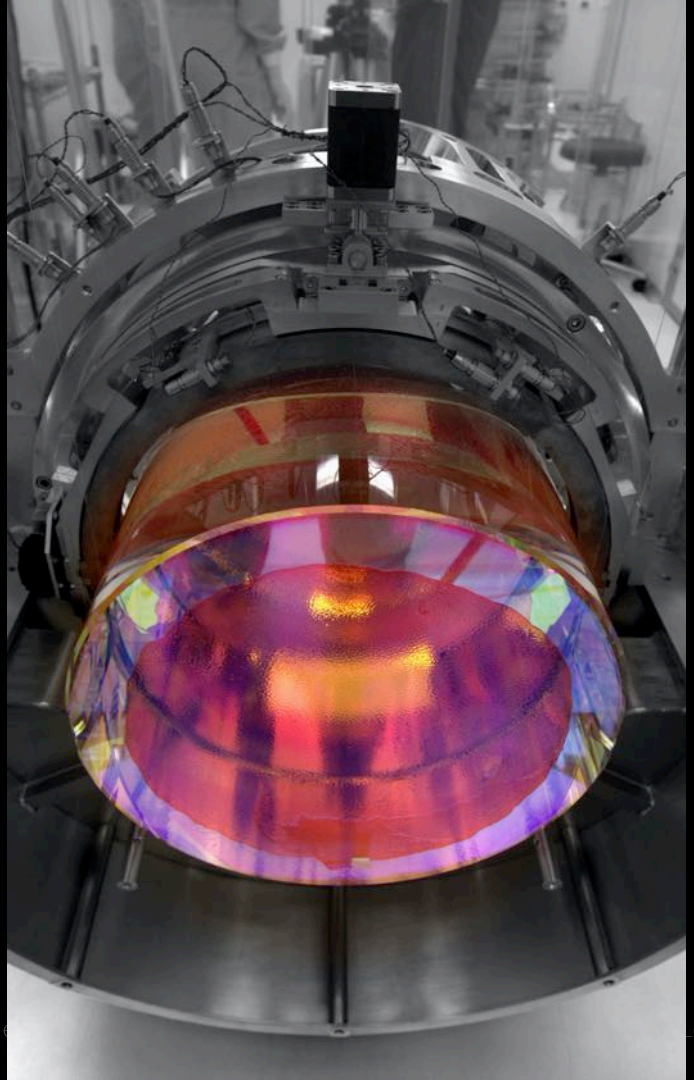
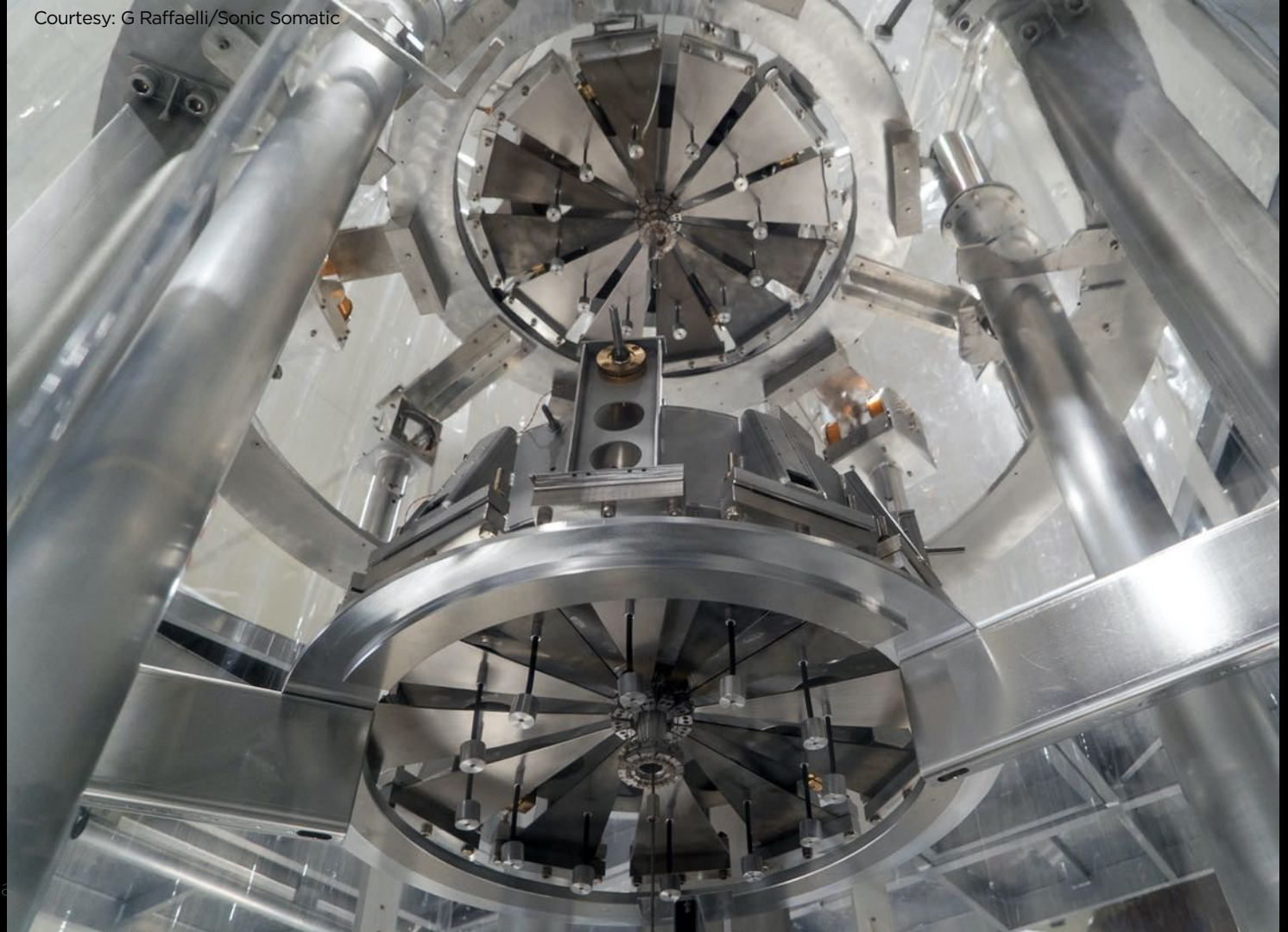
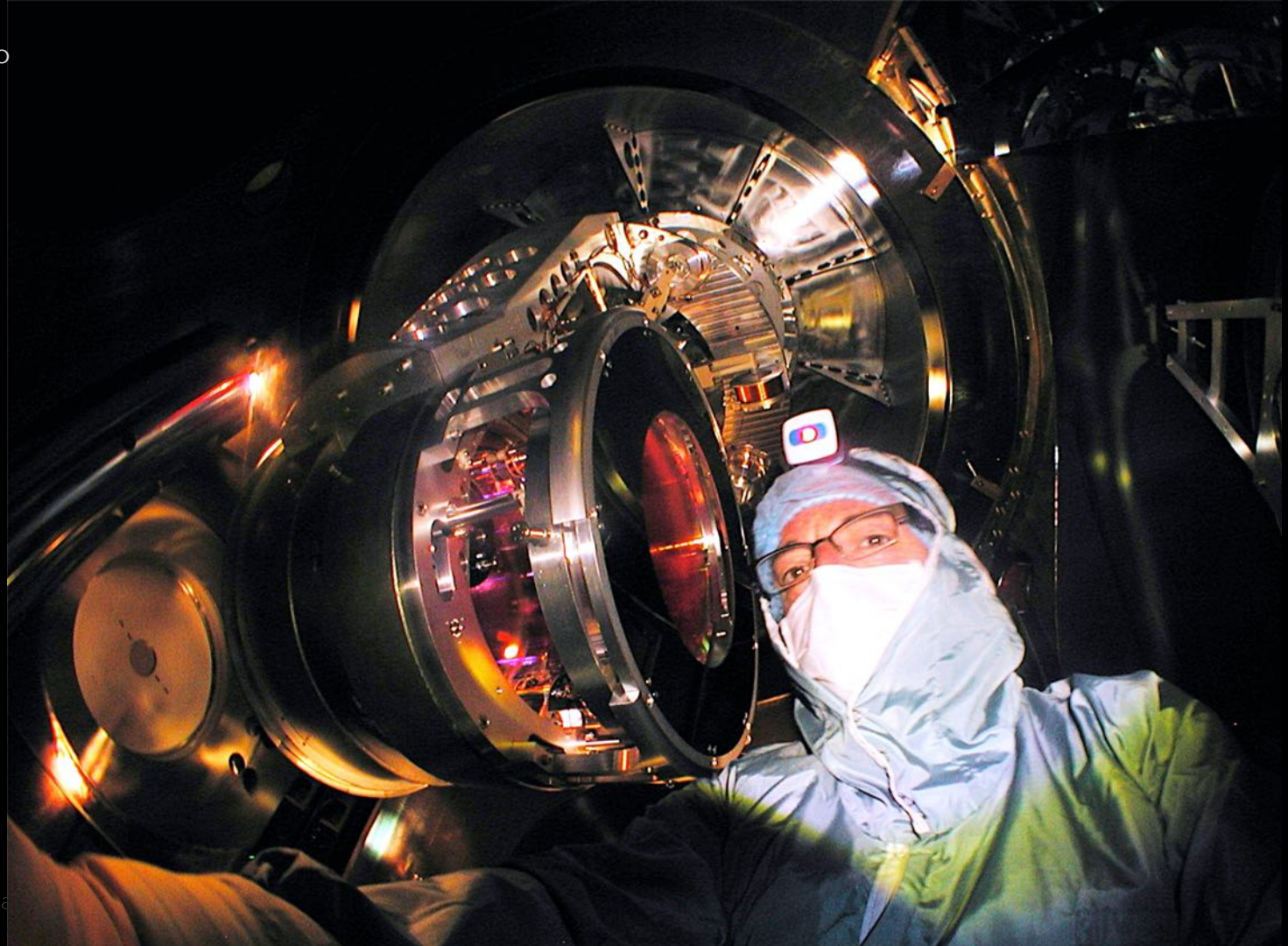


FOTO: MAURIZIO PERCIBALLI _mirror_without_first_contact_11-11-2015

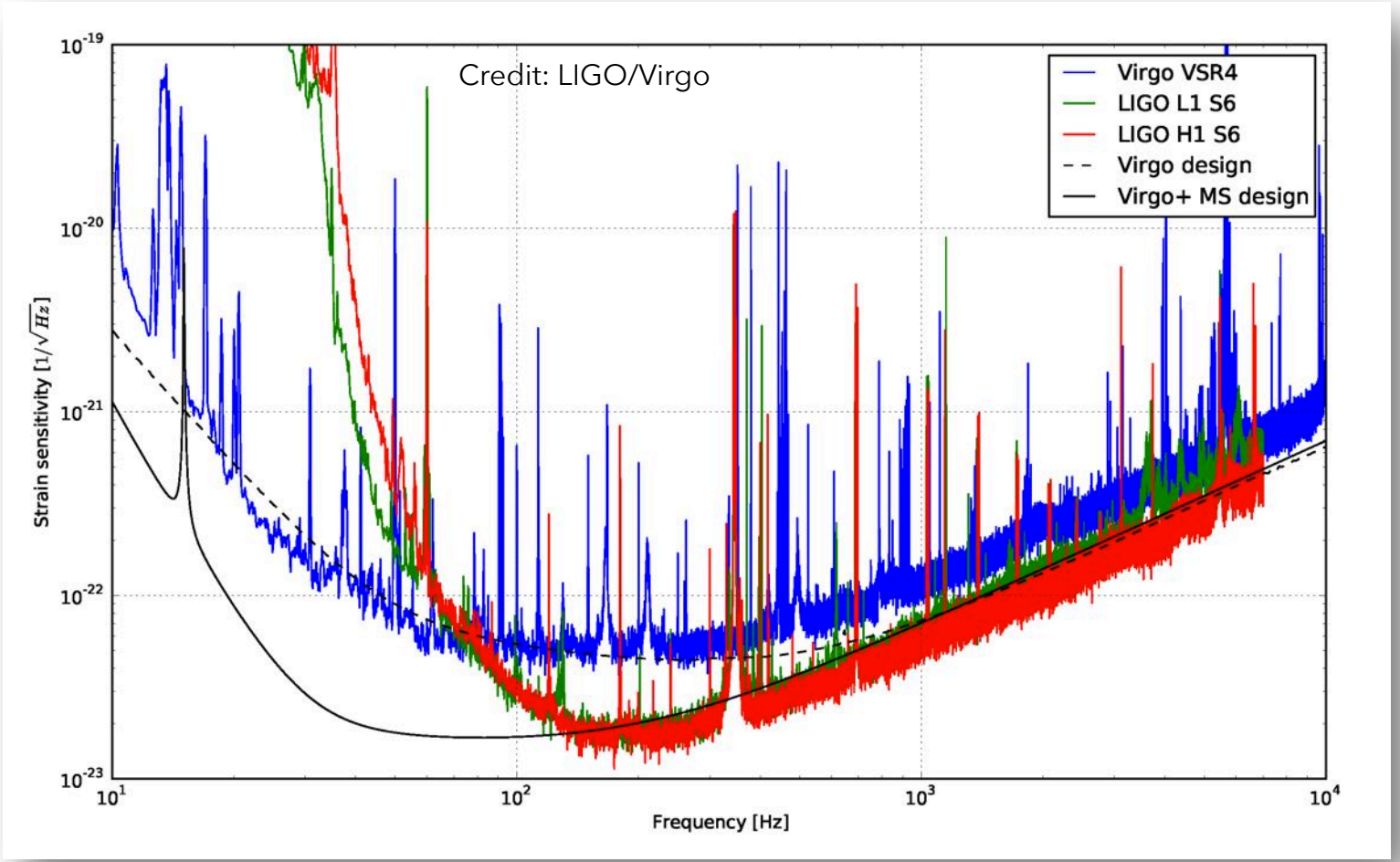


Courtesy: G Raffaelli/Sonic Somatic

Credit: Virgo

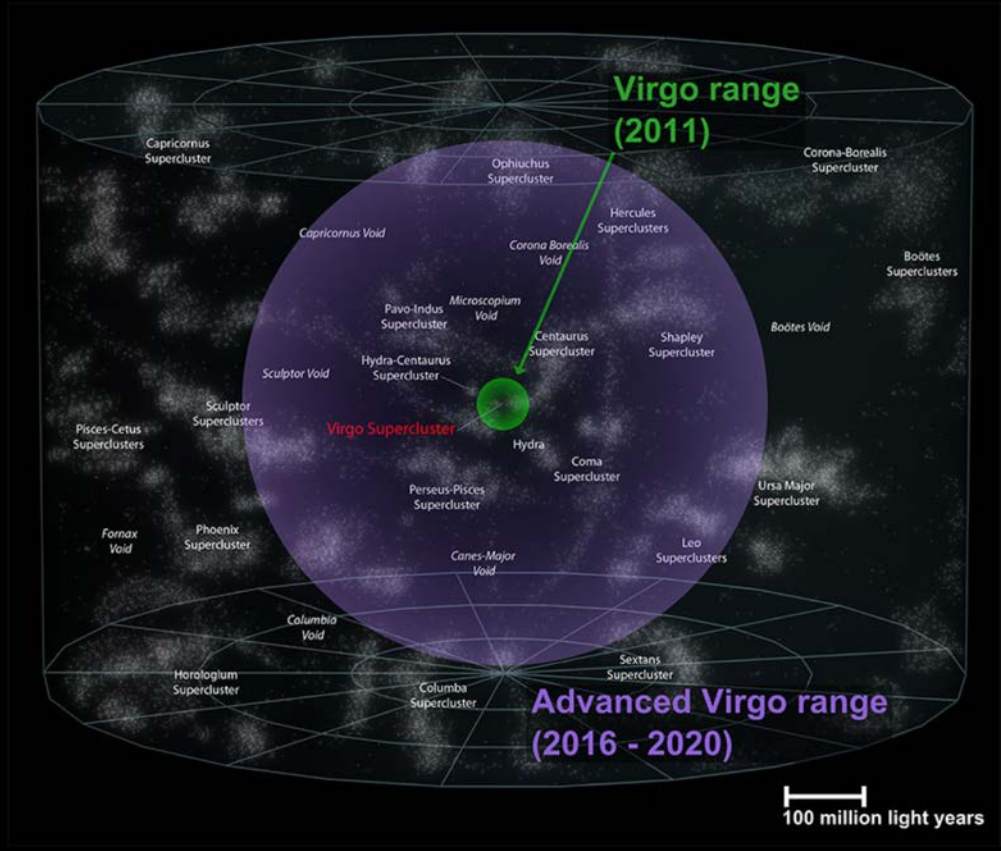


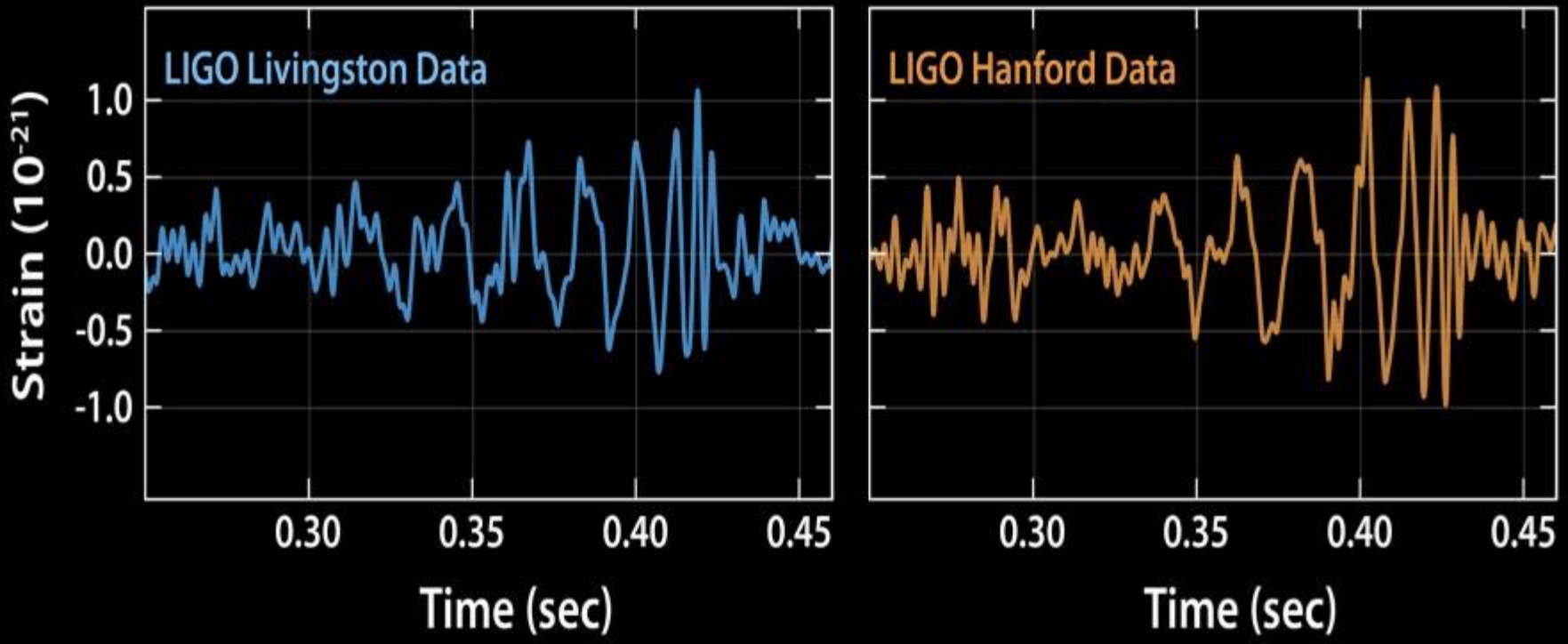
Credit: Virgo


Credit: LIGO/Virgo
Virgo VSR4
LIGO L1 S6
LIGO H1 S6
Virgo design
Virgo+ MS design
Strain sensitivity [$1/\sqrt{Hz}$]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency [Hz]

2G

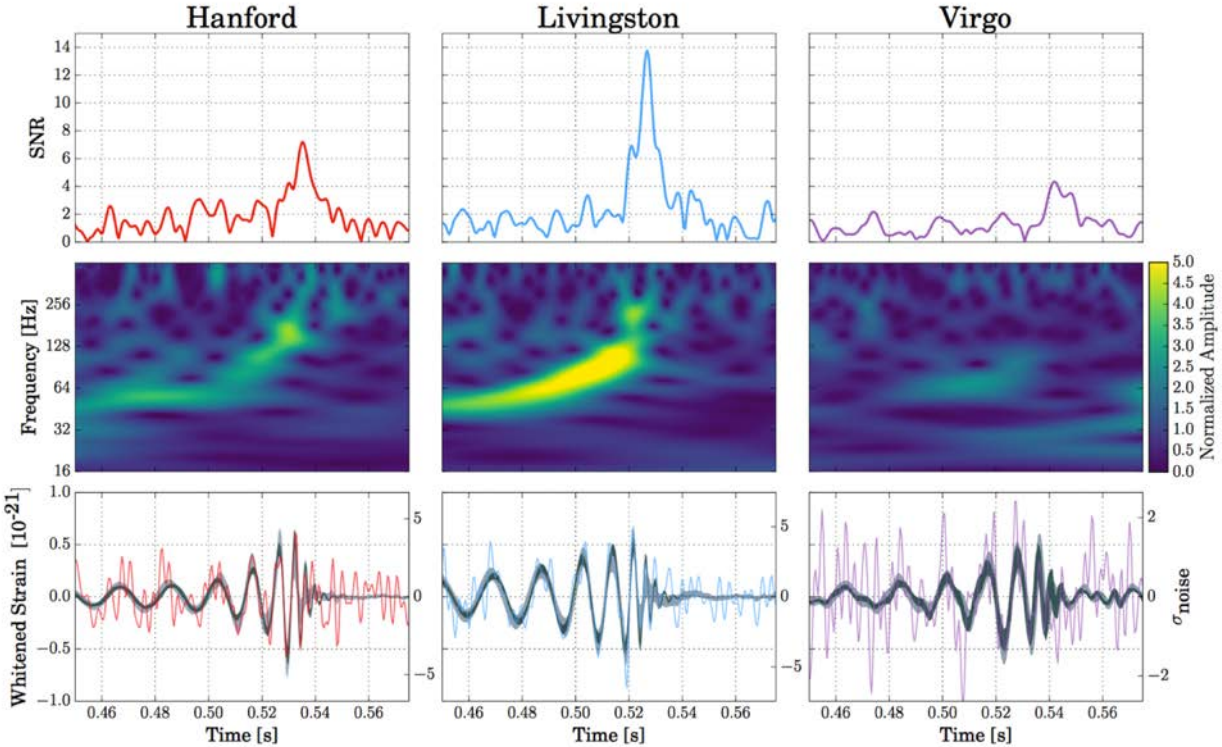
- ADVANCED LIGO
  - Funded: April 2008, >200 M$
  - Construction complete: Oct 2014
  - First data: Sept 2015
- ADVANCED VIRGO
  - Funded: Dec. 2009, 21.8 ME
  - Construction complete: Aug 2016
  - First data: Aug 2017

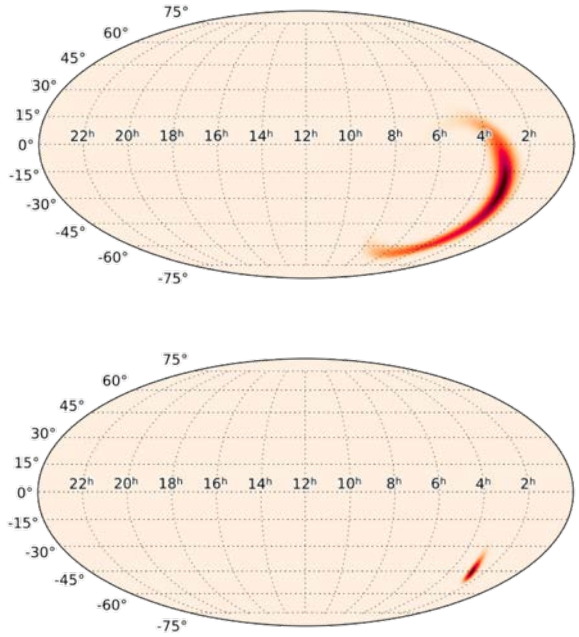



LIGO Livingston Data
LIGO Hanford Data
Strain (10-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)

AUG 14th, 2017

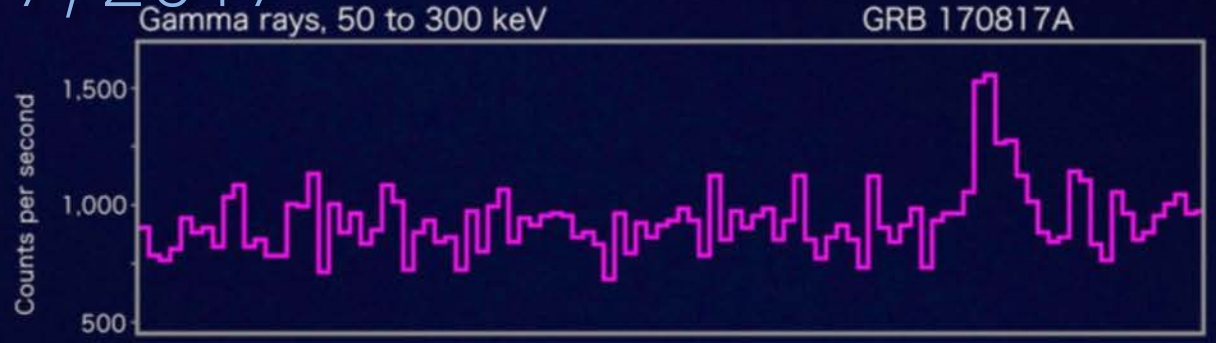
LIGO/Virgo Coll., PRL, 119, 141101 (2017)



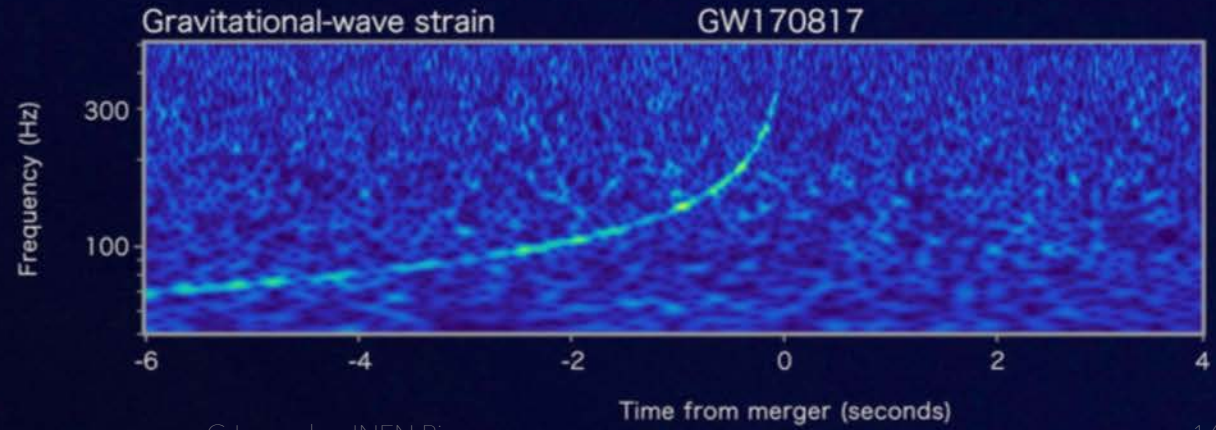


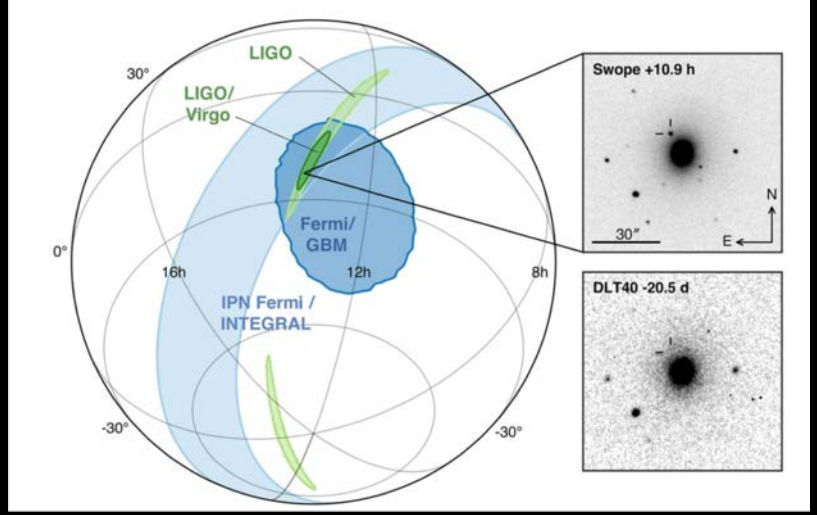
AUG 17, 2017

Fermi



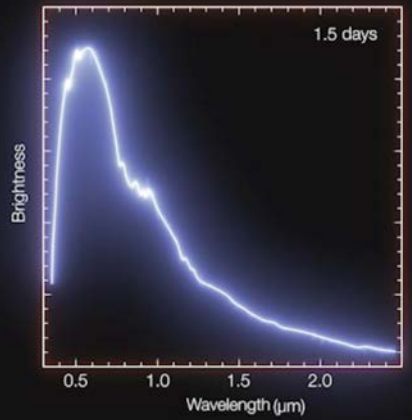
LIGO/Virgo





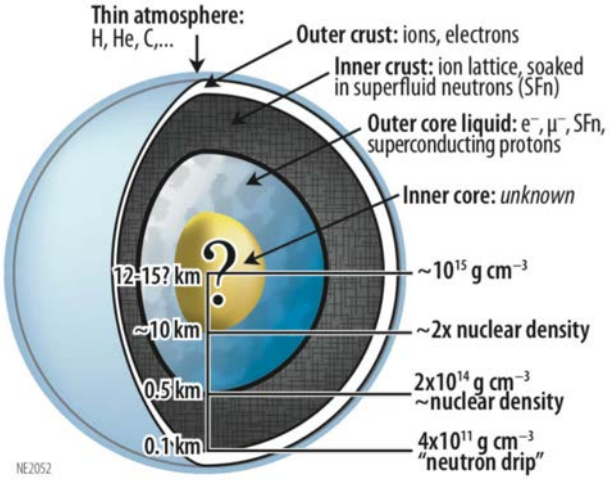
ApJL 2017 and ref. therein

ESO - VLT/X Shooter

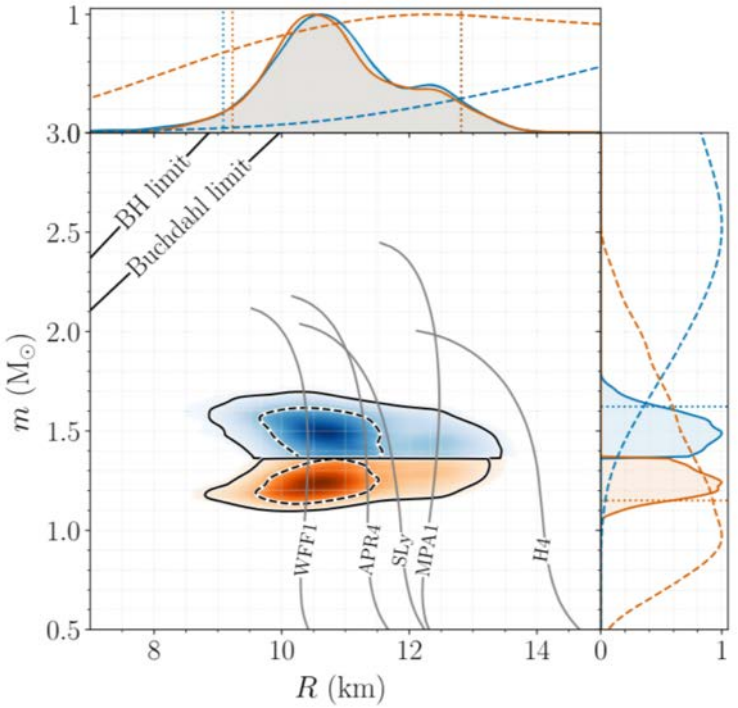


FROM NUCLEAR PHYSICS…

Image credit: NASA

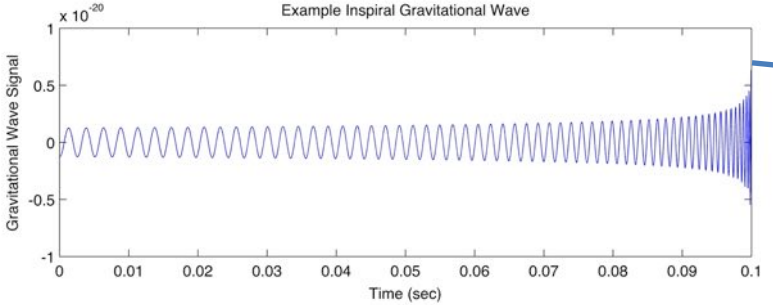


LVC, PRL 121, 161101 (2018)



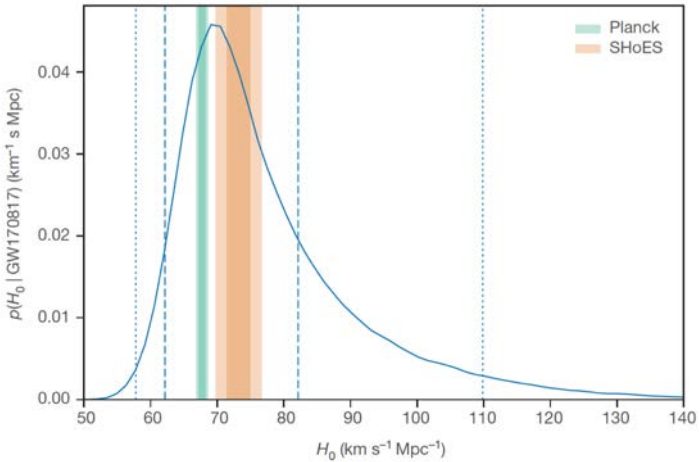
LIGO/VIRGO are measuring the NS radius/mass. Improving the accuracy (better SNR, more events) will allow to determine the EOS

…TO COSMOLOGY



$$H_0 d_L = cz$$

$$H_0 = 70^{12.0}_{-8.0}\ \mathrm{km\ s^{-1}Mpc}$$

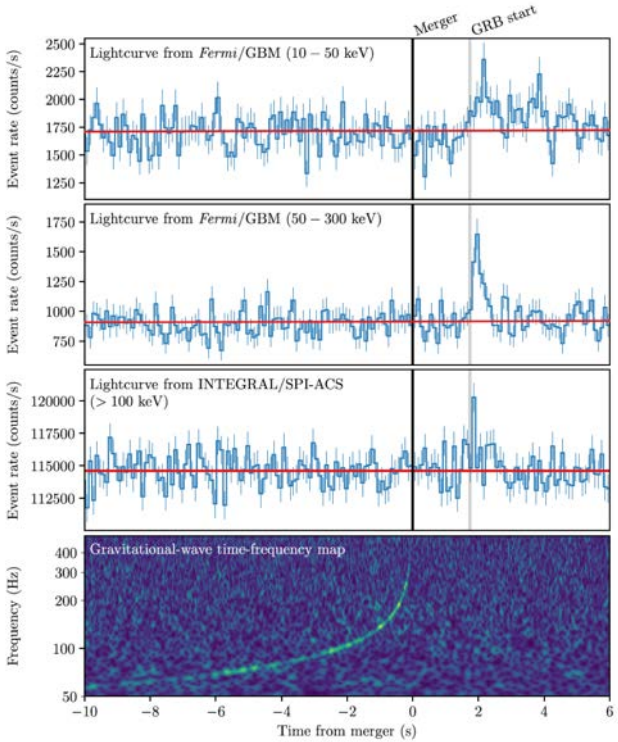


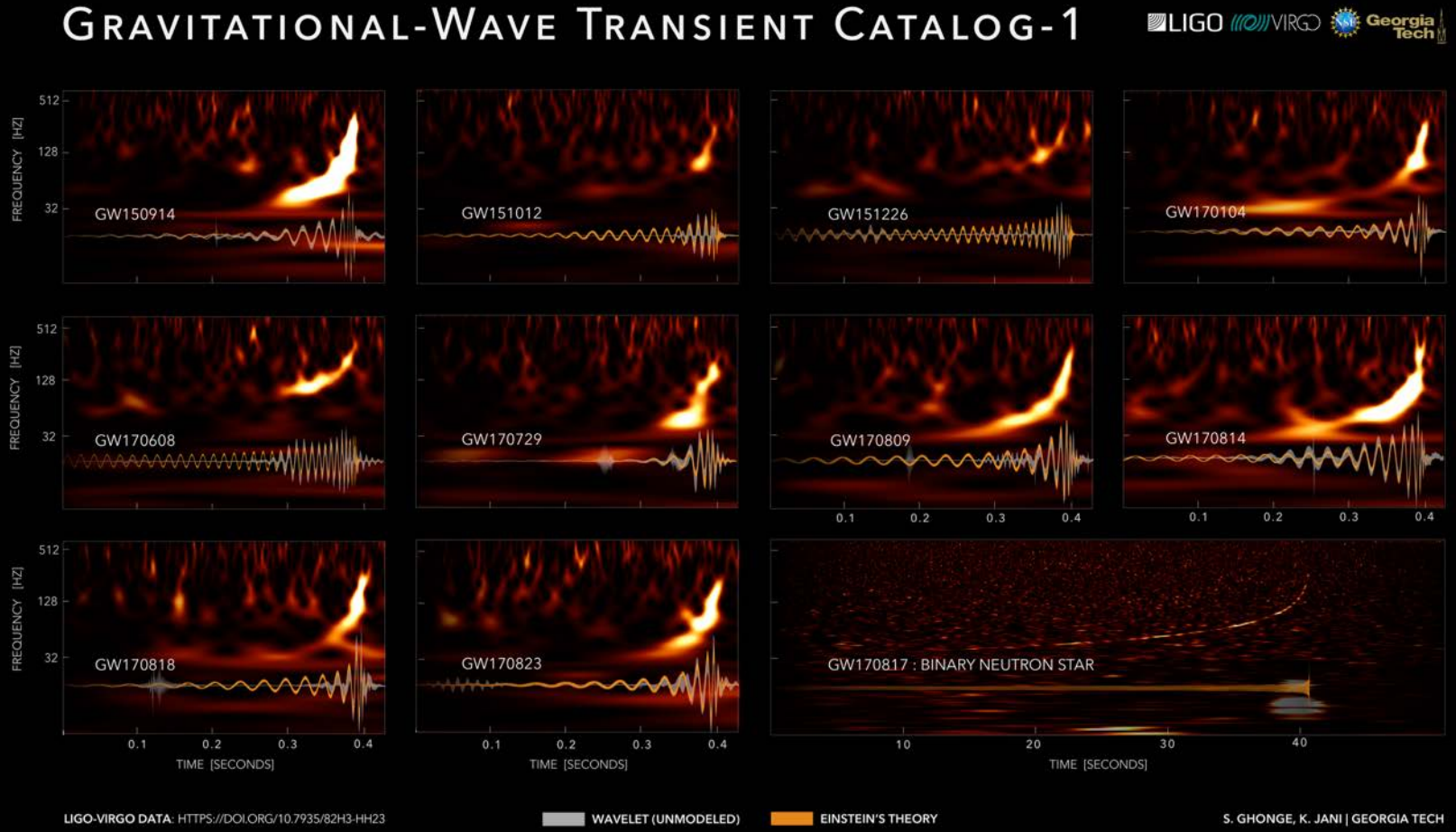
Abbott et al.,Nature, 24471 (2017)

AND FUNDAMENTAL PHYSICS

$$-3\cdot10^{-15} \leq \frac{v_{GW} - c}{c} \leq 7\cdot10^{-16}$$

Abbott et al., ApJL., 848:L13 (2017)





B. P. Abbott, et al., (LIGO Virgo Collaboration), "GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs" , PRX, 9, 031040 (2019)

O3a – Summary of public alerts

BBH

BNS

NSBH

Mass Gap

Retracted

April 2019

S	M	T	W	Th	F	S
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30				

May 2019

S	M	T	W	Th	F	S
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

June 2019

S	M	T	W	Th	F	S
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30						

July 2019

S	M	T	W	Th	F	S
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

August 2019

S	M	T	W	Th	F	S
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

September 2019

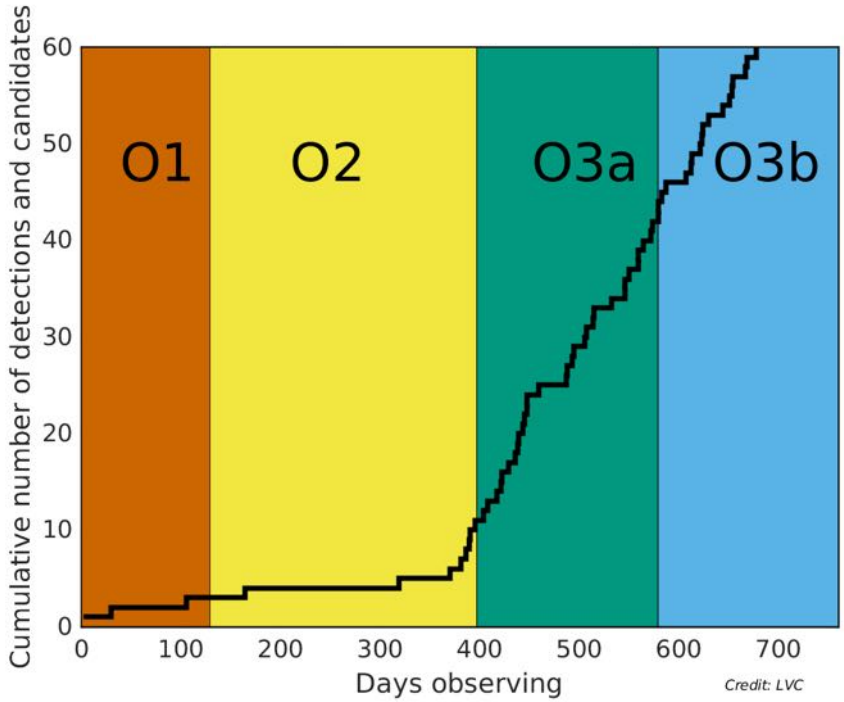
S	M	T	W	Th	F	S
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30					

Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}
O4	HLVK	8^{+42}_{-7}	2^{+94}_{-2}	68^{+81}_{-38}

https://arxiv.org/abs/1304.0670

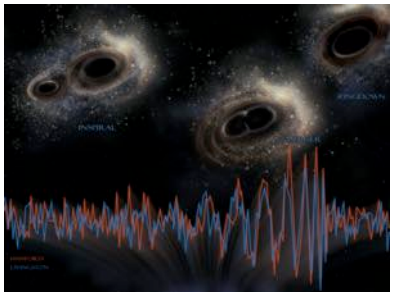
O3 ALERTS SUMMARY

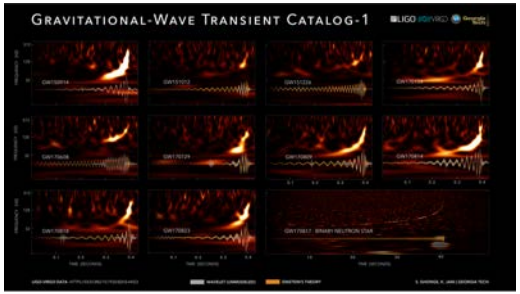
- 48 public alerts (excluding retractions) in O3 so far
- Sum of probability in each category:
  - 32 BBH
  - 6 NSBH
  - 7 BNS
  - 3 "mass gap"
- Extensive follow-up but no e.m. counterpart in O3



https://gracedb.ligo.org/latest/

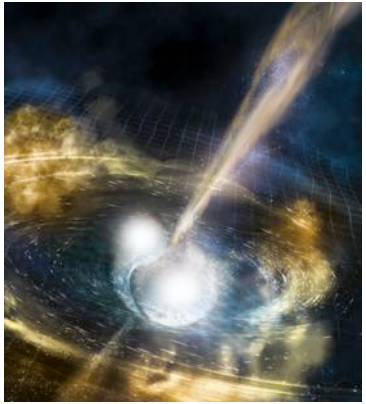
In just 4 years…

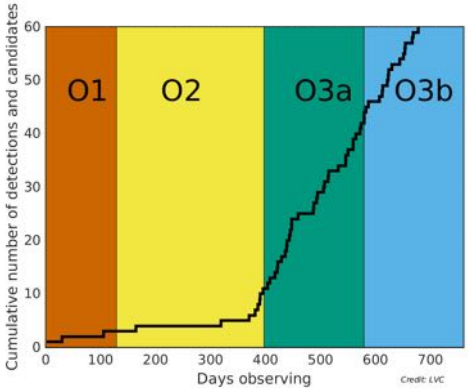




…to population studies

From discovery…





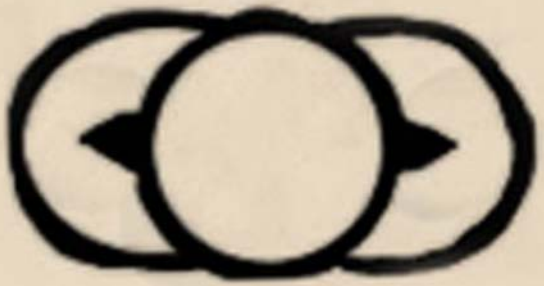
Galileo, 1610

Questo è, che Saturno, con mia grandissima ammirazione; ho osservato essere non una stella sola, ma tre insieme, le quali quasi si toccano; sono tra di loro totalmente immobili, e costituite in questa guisa: oOo

Firenze, 13 novembre 1610
Lettera a Giuliano de' Medici

Galileo, 1610

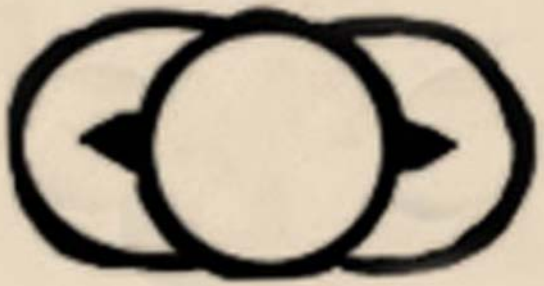
Galileo, 1616

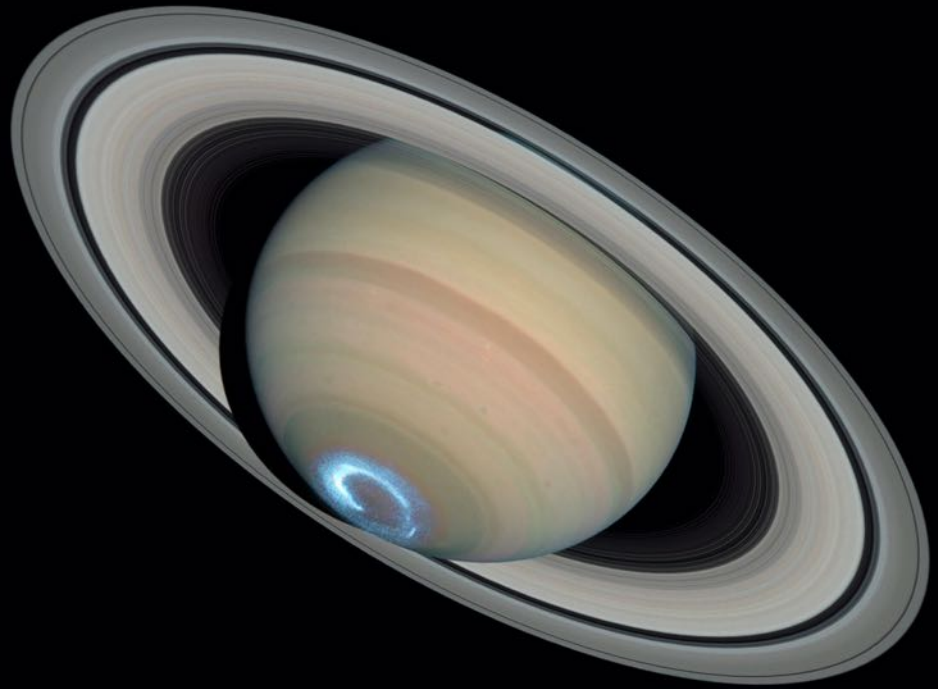


WE HAVE THE RIGHT INSTRUMENT.
NOW WE NEED TO MAKE IT BETTER AND BETTER AND BETTER…

Galileo, 1610

Galileo, 1616

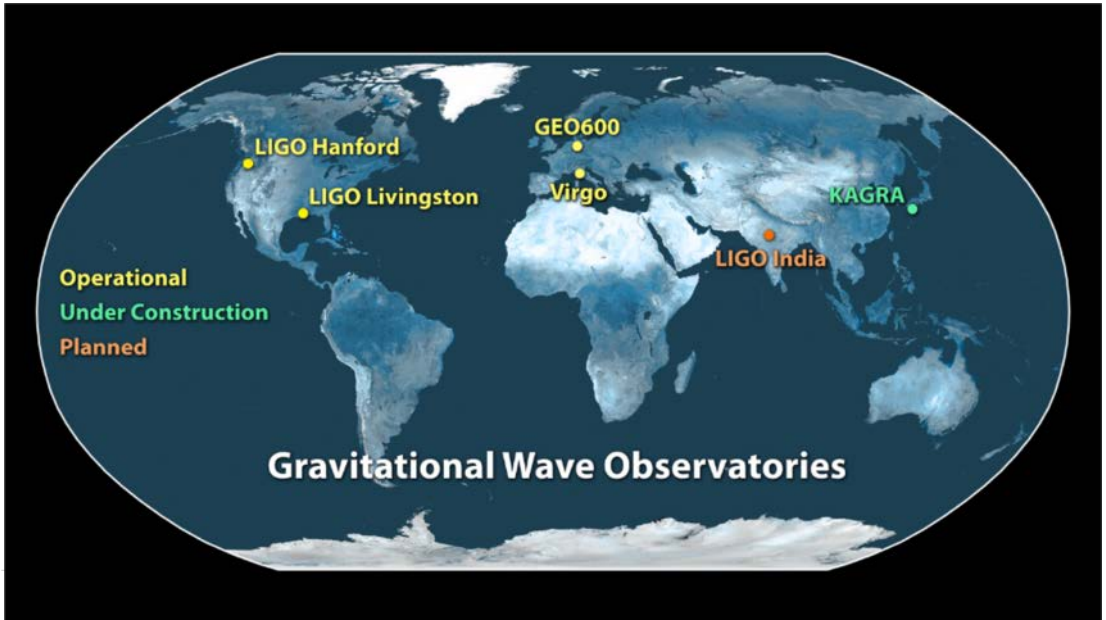


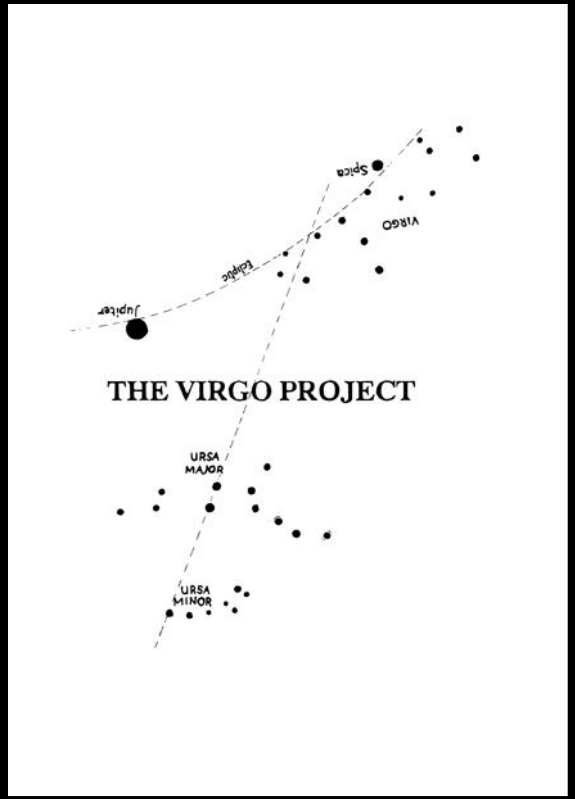


HST, 400 yrs later

MID-TERM OUTLOOK

- KAGRA to join the network in O3b
- Ligo/Virgo to be further upgraded (A+/AdV+) after O3
- Ligo India to join the network in ~2024

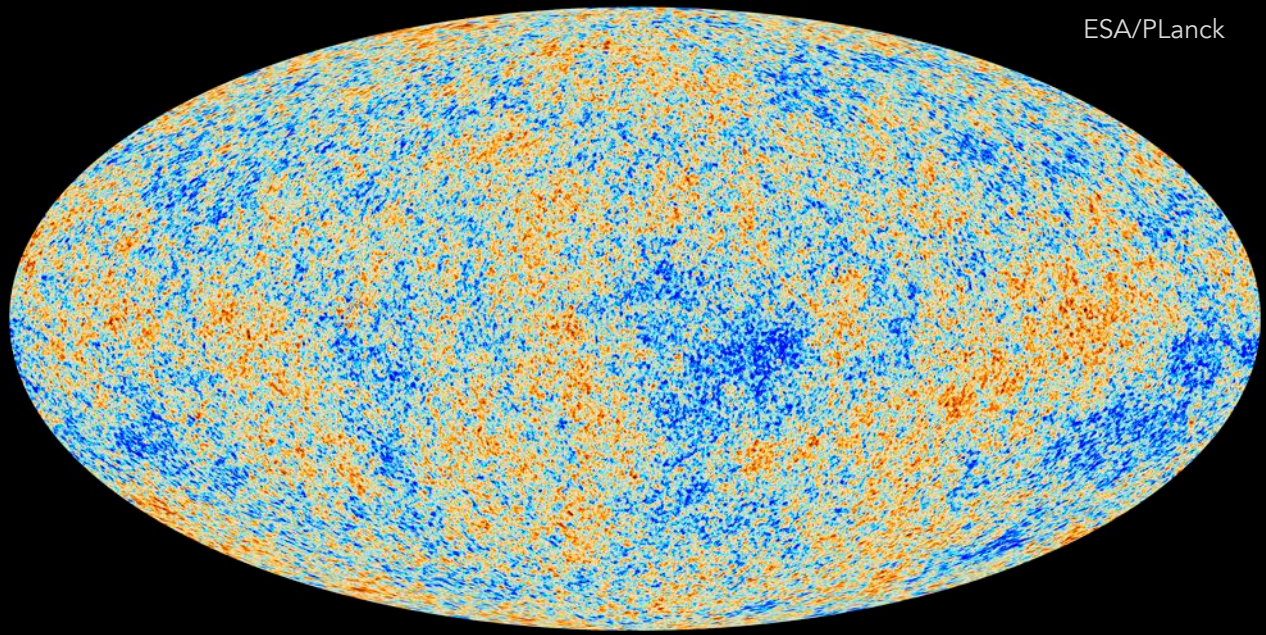




VIRGO must be considered both as an **experiment** and as a step towards a **future observatory**. (…) it also has the long term goal of **being one component of the gravitational wave detector network** which will involve other detectors in other countries, and provide data of astrophysical interest.

The group leaders from Italy, France, Germany, Scotland, and the USA have agreed to exchange all information and to collaborate on all the aspects of the construction of large interferometers in order to generate the international effort required by the birth of gravitational astronomy.

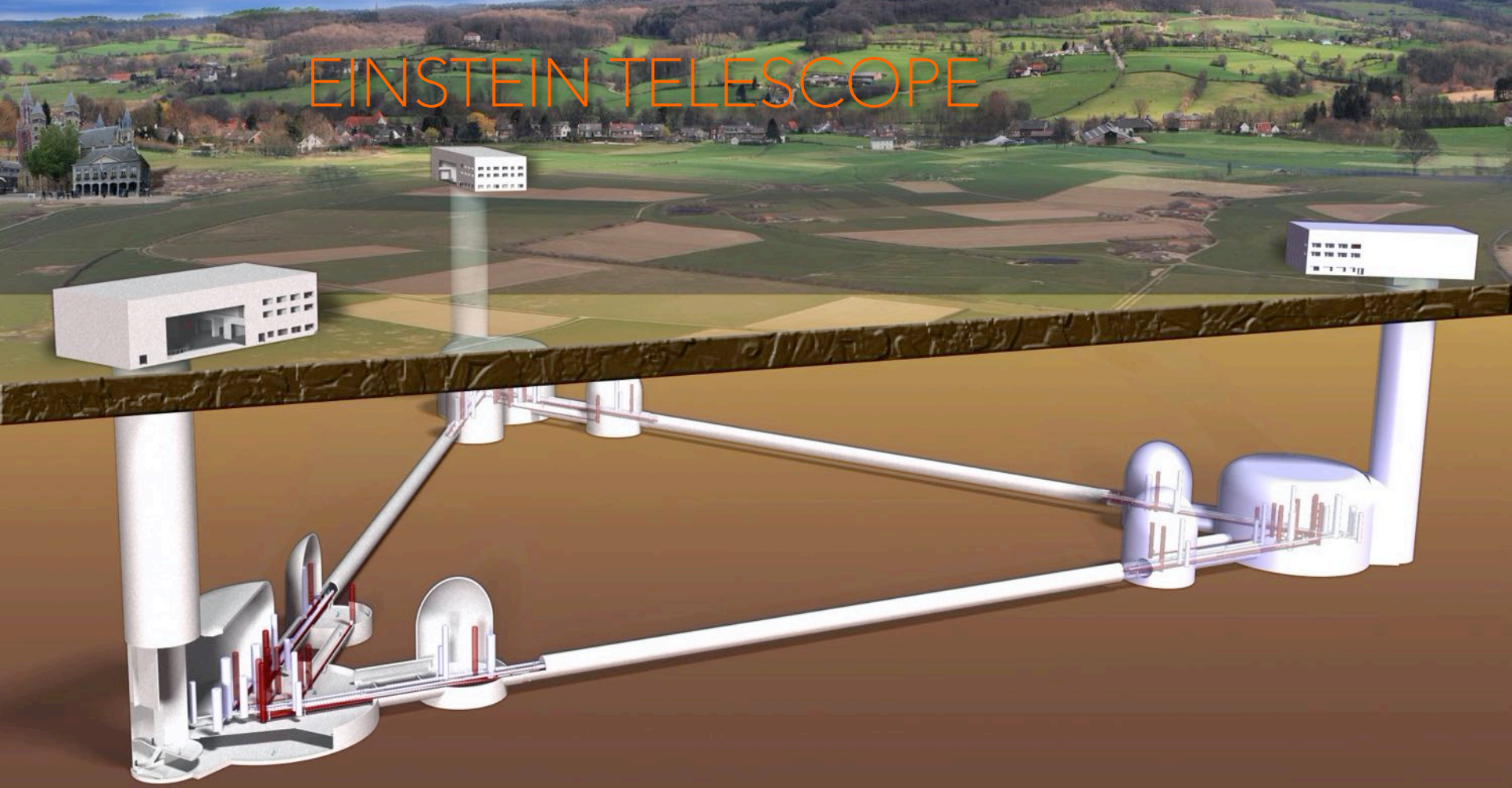
A BRILLET & A GIAZOTTO

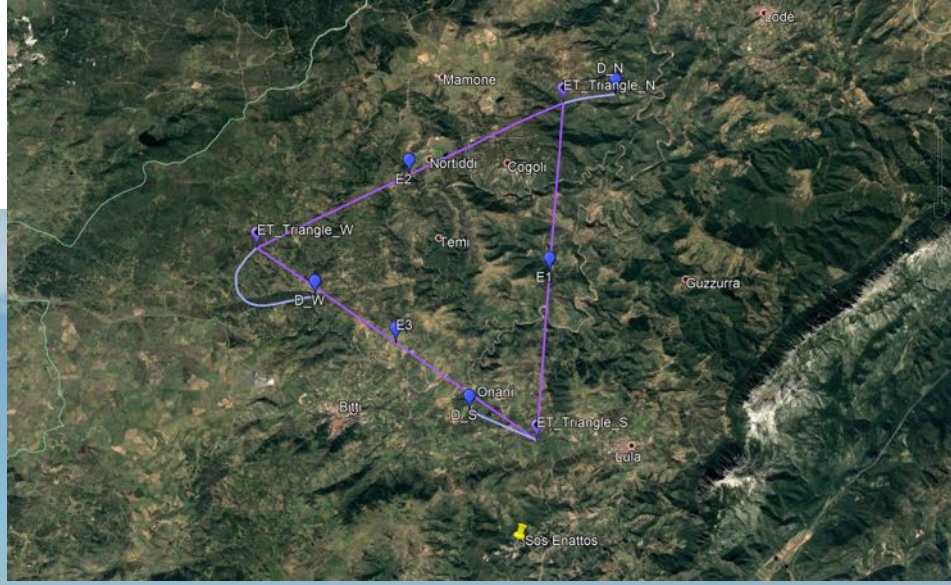


ESA/PLanck

LONG-TERM OUTLOOK

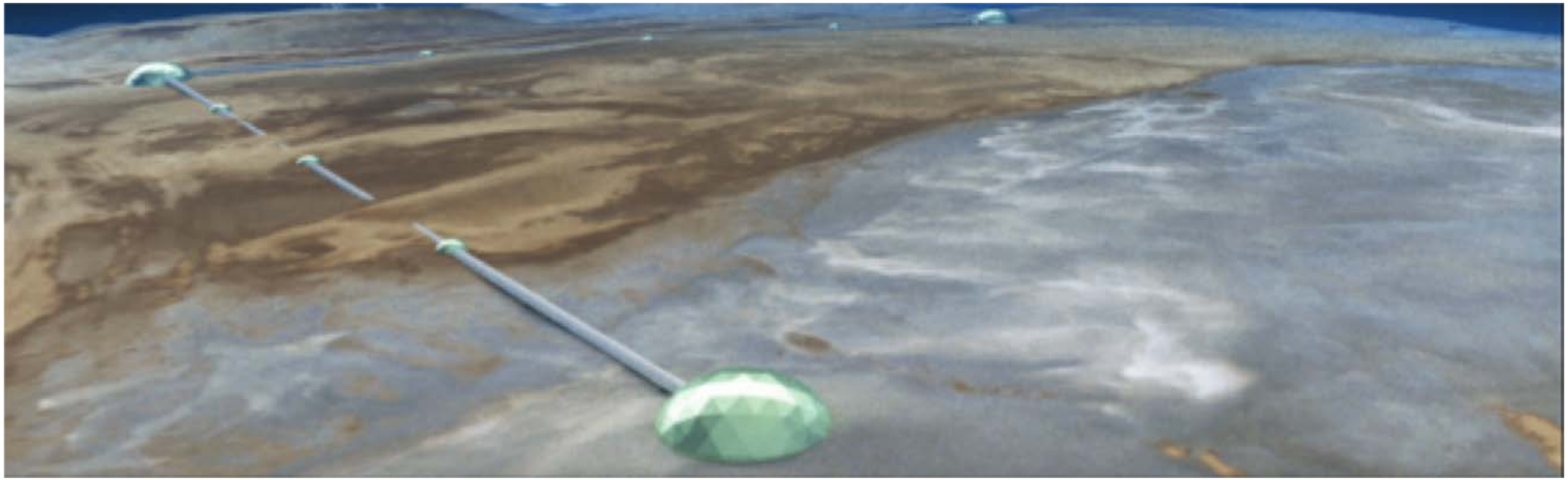
EINSTEIN TELESCOPE




Lodè
Mamone
D_N
ET_Triangle_N
E2
Nortiddi
Cogoli
ET_Triangle_W
Temi
E1
Guzzurra
D_W
E3
Onanì
Bitti
D_S
ET_Triangle_S
Lula
Sos Enattos

COSMIC EXPLORER

- 3rd generation observatory in the US
- Above ground, L shaped, 40 km
- NSF funded design study under way (www.cosmicexplorer.org)



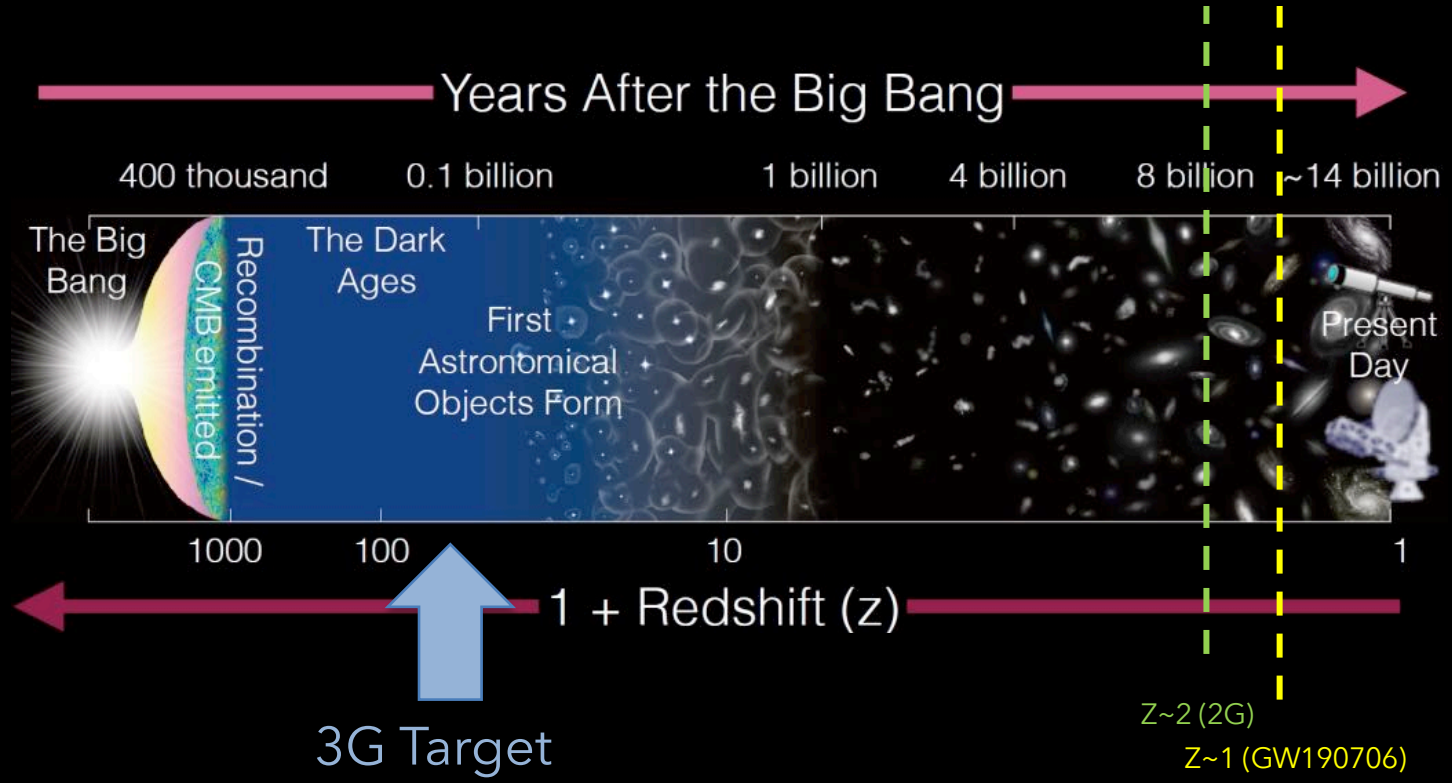
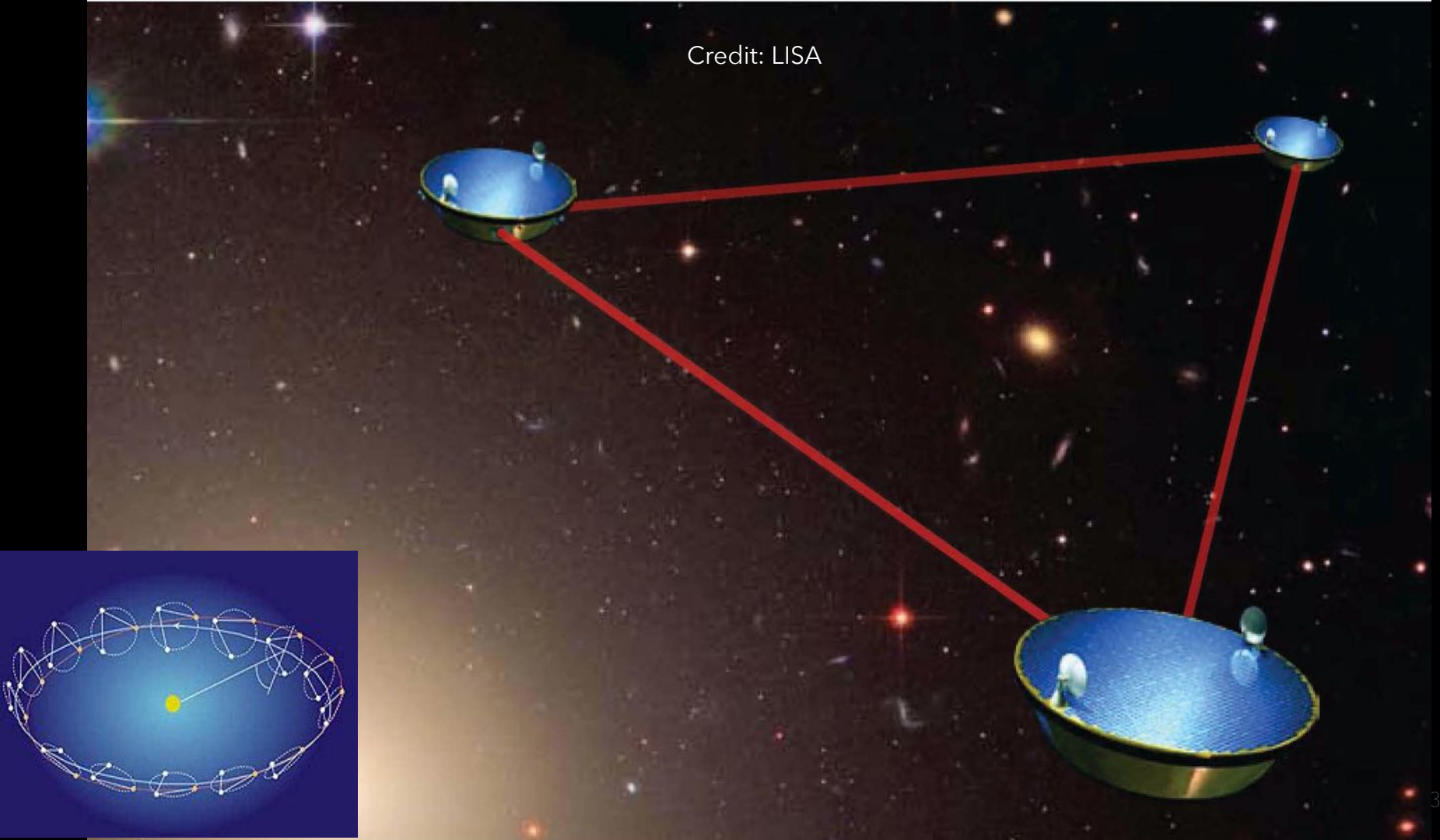


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/


Credit: LISA

Credit: INFN

"RIVELARE LE ONDE GRAVITAZIONALI.
NESSUNA IDEA E' PIU' FOLLE DI QUESTA"

A. Giazotto