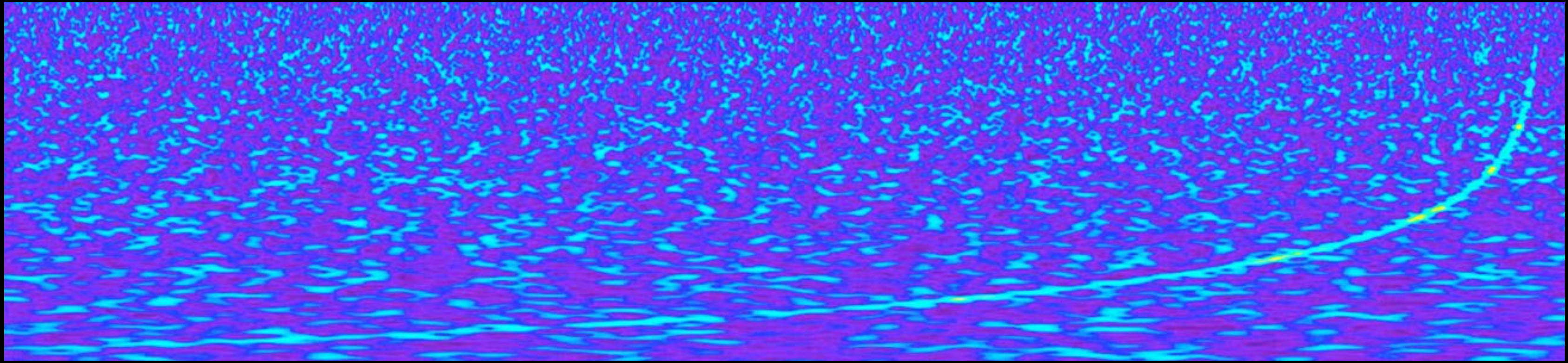
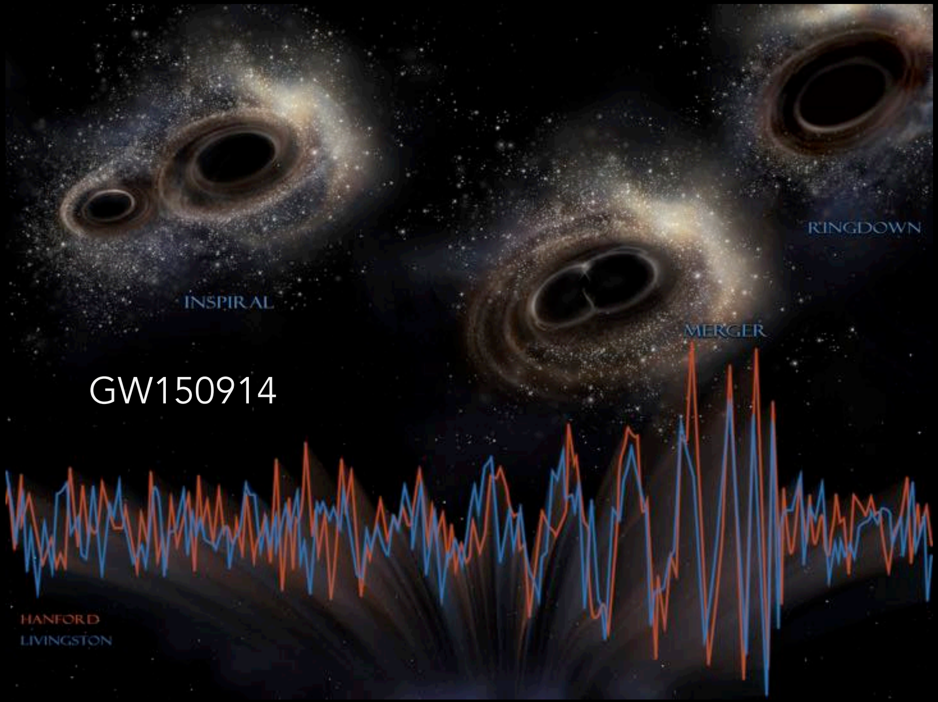
gravitational waves

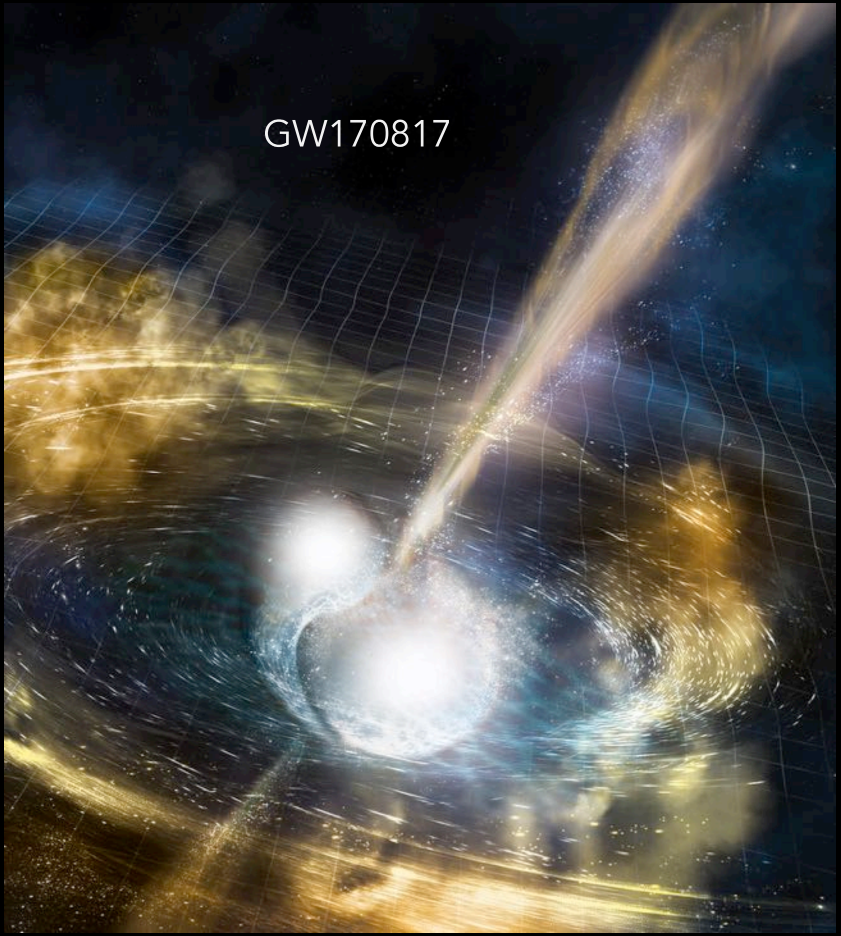


Giovanni Losurdo –

THE GREAT GIG IN THE SKY

TWO GROUND-BREAKING DISCOVERIES
A NEW ERA IN THE OBSERVATION OF THE UNIVERSE





Grandi cose per verità in questo breve trattato propongo all'osservazione e alla contemplazione di quanti studiano la natura. Grandi, dico, e per l'eccellenza della materia stessa, e per la novità non mai udita nei secoli, e infine per lo strumento mediante il quale queste cose stesse si sono palesate al nostro senso.

In the present small treatise I set forth some matters of great interest for all observers of natural phenomena to look at and consider. They are of great interest, I think, both from their intrinsic excellence, and from their absolute novelty, and also on account of the instrument by the aid of which they have been presented to my apprehension. .

GALILEO GALILEI, *SIDEREUS NUNCIUS*, 1610

1989

Proposal to the National Science Foundation

A
LASER INTERFEROMETER
GRAVITATIONAL-WAVE
OBSERVATORY
(LIGO)

VOLUME 1:
LIGO Science and Concepts

December 1989

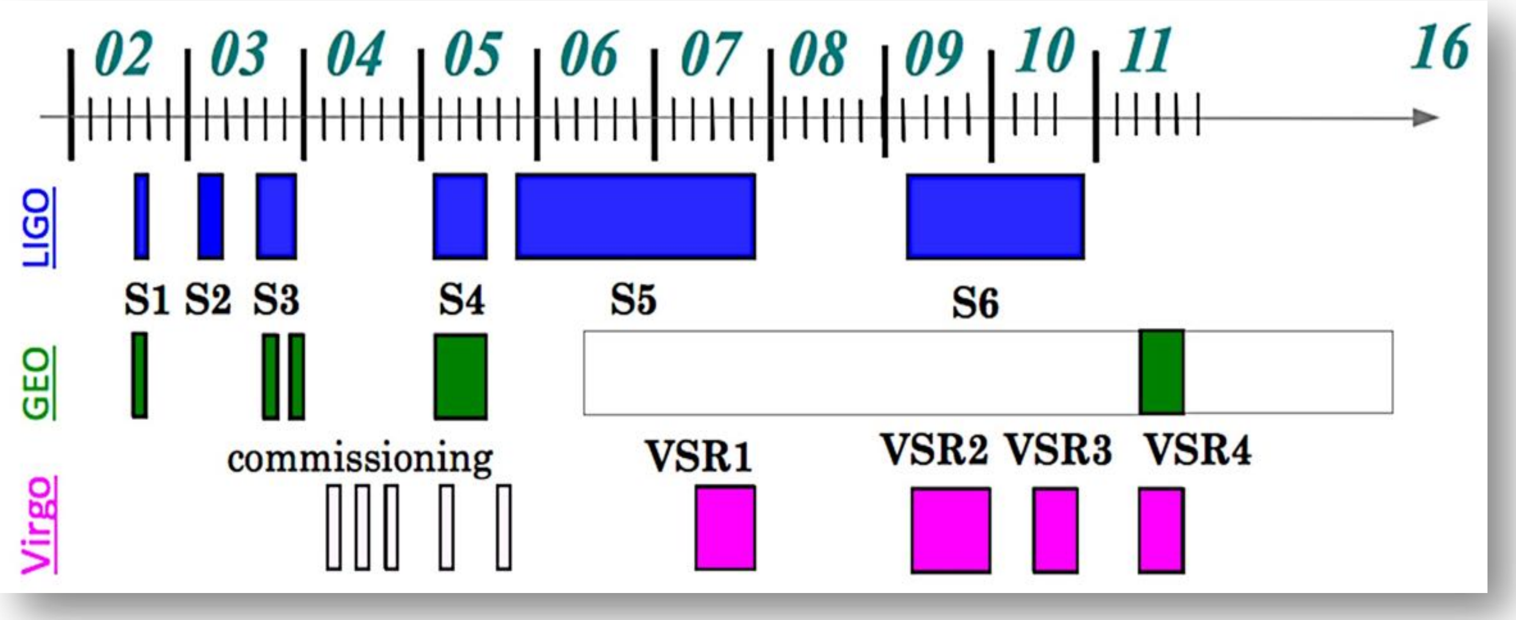
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LIGO PROJECT

THE VIRGO PROJECT

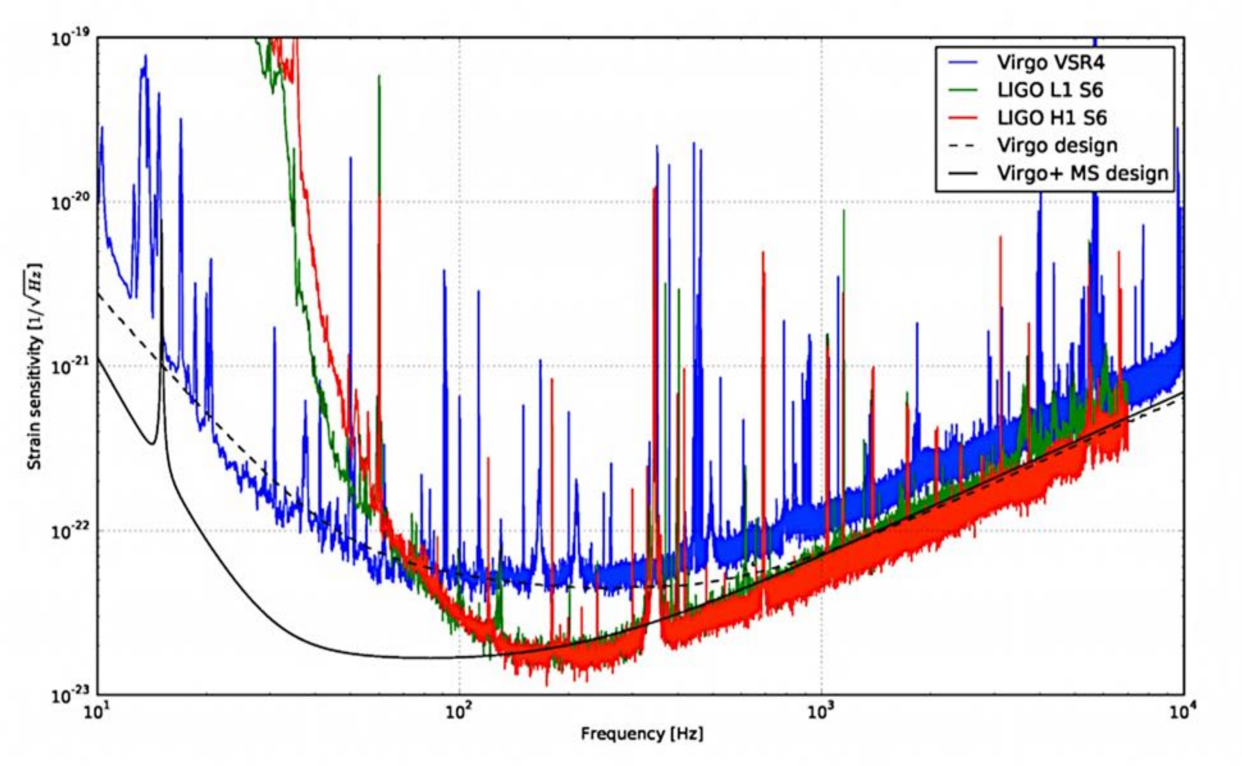
1st GENERATION DETECTORS

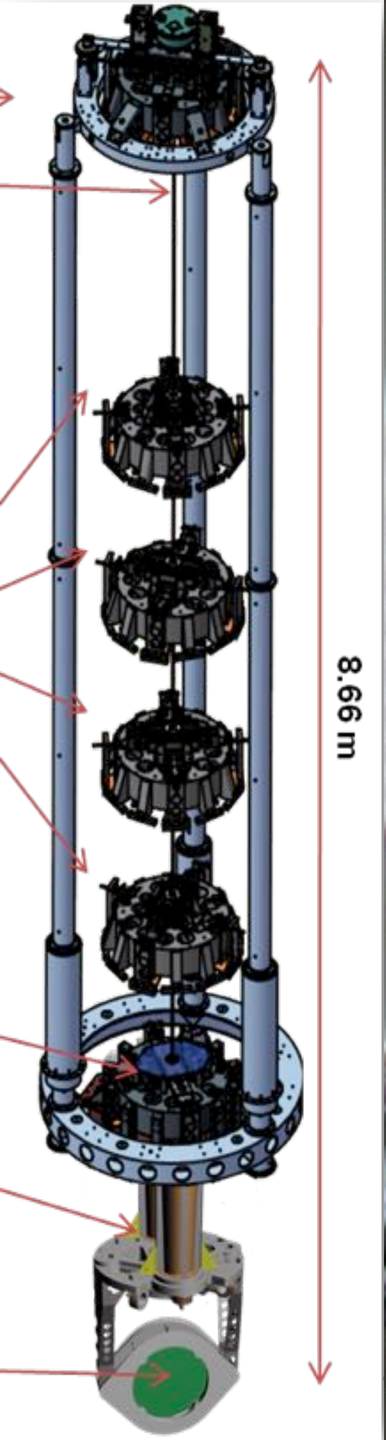
- The interferometers of the 1t generation (LIGO, Virgo, GEO600) have run in the 1st decade of 2000's
- No detection but a rich legacy invested on 2nd generation detectors

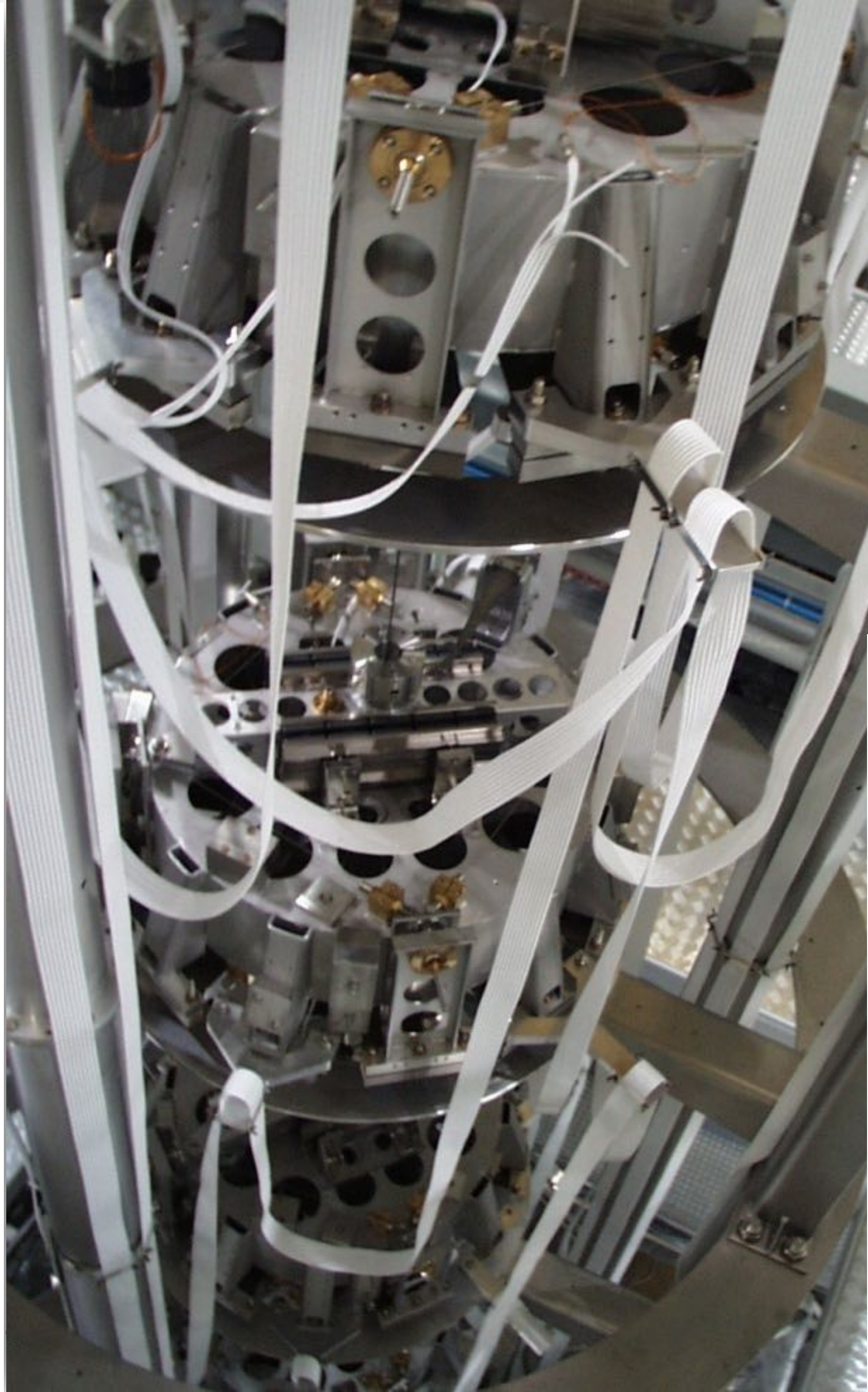


2009-11: DESIGN SENSITIVITY

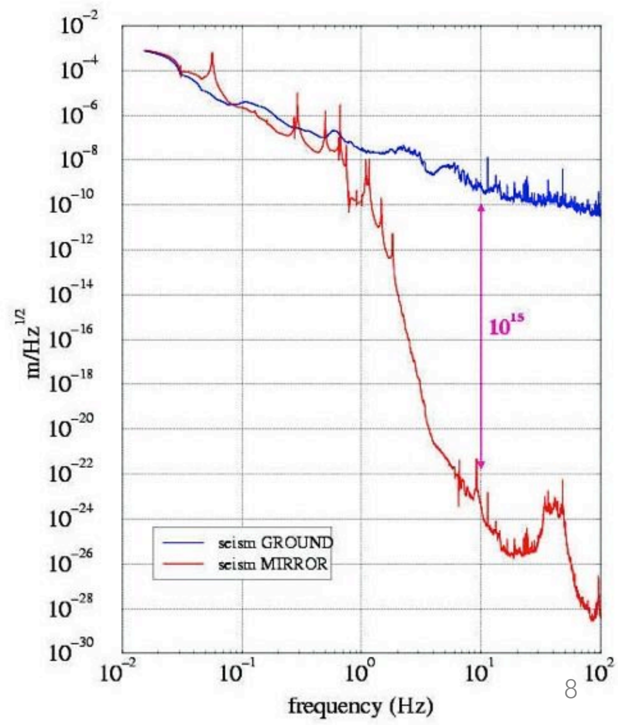
- The 1st generation design sensitivities have been approached closely (and somewhere exceeded upon detector upgrades)
- Excellent duty cycle (~80%): reliable instruments!



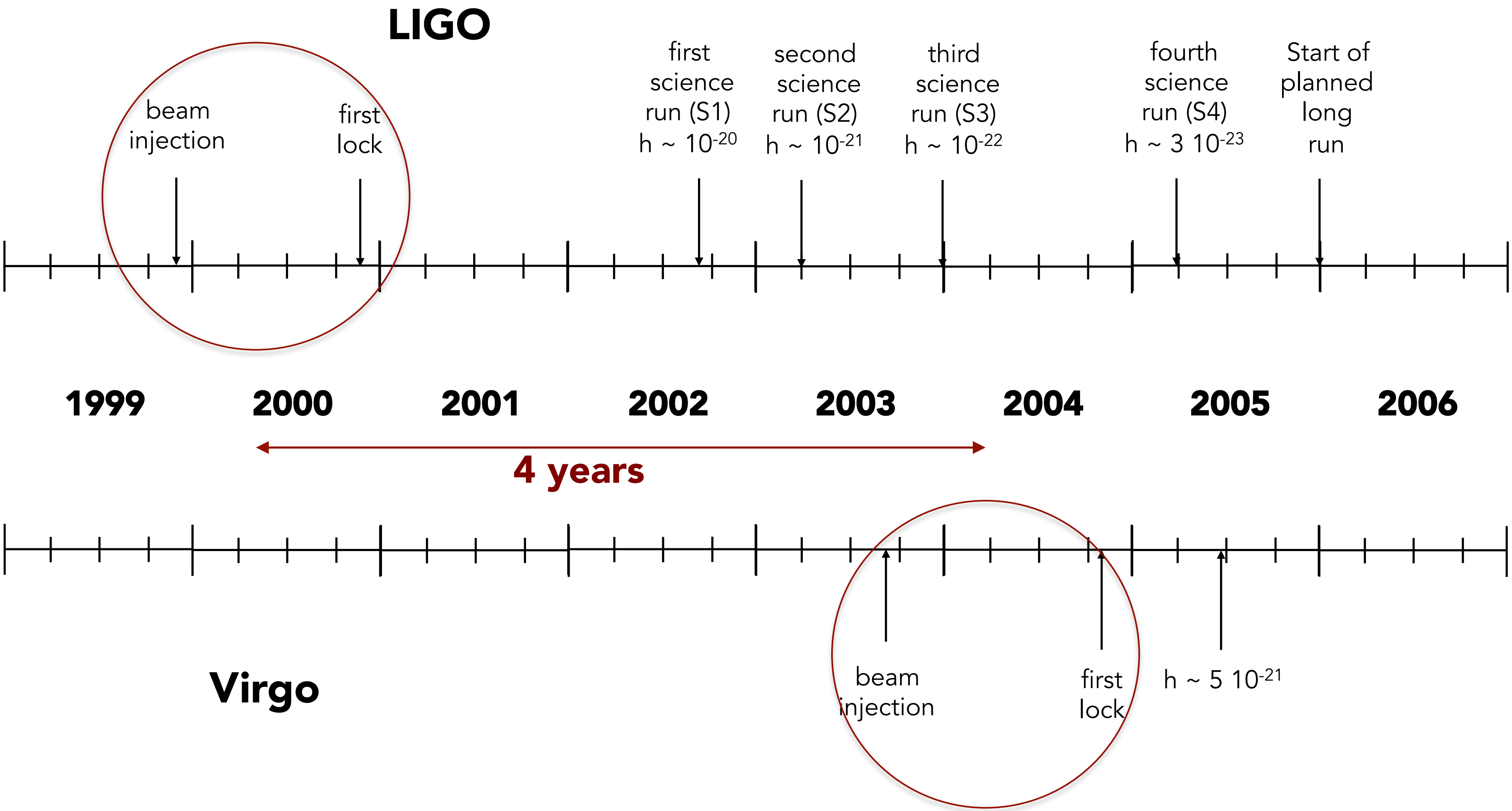

8.66 m



A Giazotto


m/Hz^1/2
frequency (Hz)
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-16
10^-18
10^-20
10^-22
10^-24
10^-26
10^-28
10^-30
10^-2
10^-1
10^0
10^1
10^2
10^15
seism GROUND
seism MIRROR

Virgo vs LIGO timelines



LIGO

beam injection

first lock

first science run (S1) h ~ 10^{-20}

second science run (S2) h ~ 10^{-21}

third science run (S3) h ~ 10^{-22}

fourth science run (S4) h ~ $3\ 10^{-23}$

Start of planned long run

1999 2000 2001 2002 2003 2004 2005 2006

4 years

Virgo

beam injection

first lock

h ~ $5\ 10^{-21}$

ADVANCED LIGO

- Proposal to NSF: 2003. Project start: April 2008
- Funding: $205 M$ from NSF, in-kind contribution from D/UK/AUS
- Two detectors installed, third interferometer to be shipped to India
- Construction completed: Jul 2014
- First run started on Sep 2015

ADVANCED VIRGO

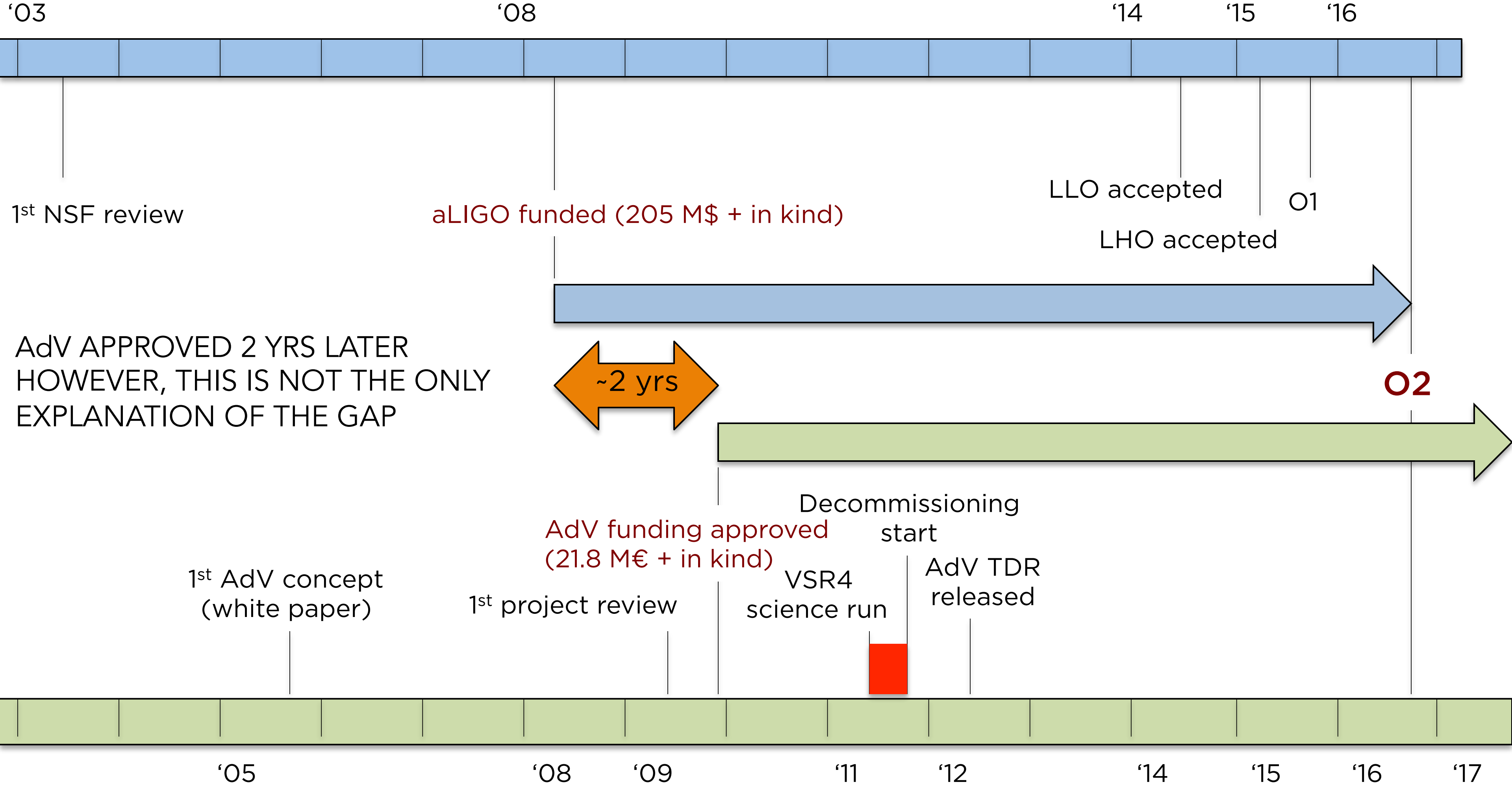
6 European countries
21 labs, ~280 authors

- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector
- Partecipated by France and Italy (former founders of Virgo), The Netherlands, Poland, Hungary, Spain
- Funding approved in Dec 2009 (21.8 ME + Nikhef in kind contribution)
- Project formally completed with the start of the O2 run (Aug 1st, 2017)

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 Padova
INFN TIFPA Trento
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW
RADBOUD Uni. Nijmegen
RMKI Budapest
University of Valencia

…and more have just joined: GSSI, Milano Bicocca, Torino, UniSalerno

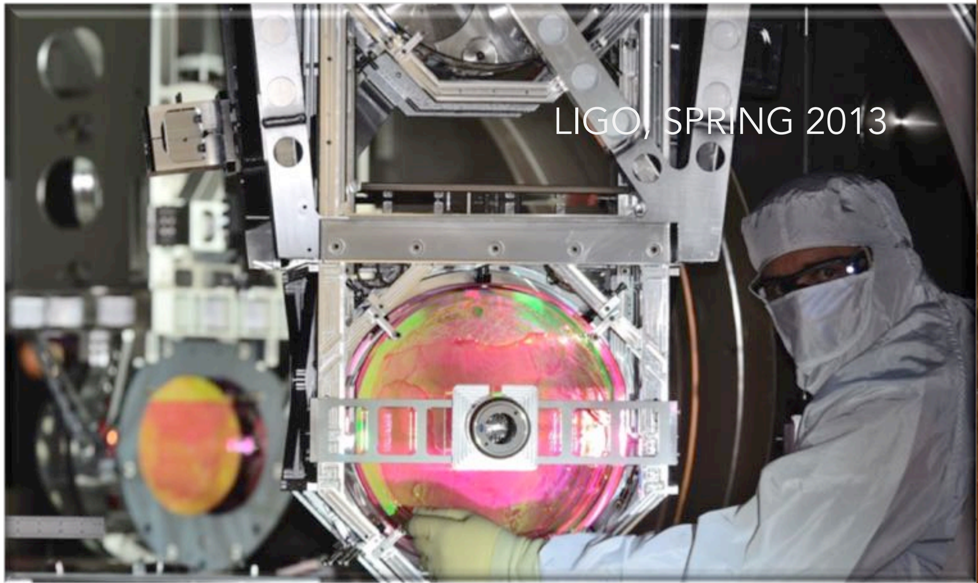
Advanced LIGO vs VIRGO TIMELINES



AdV APPROVED 2 YRS LATER
HOWEVER, THIS IS NOT THE ONLY
EXPLANATION OF THE GAP

ADV TIMELINE

- Approved in Dec 2009 (~2 yrs after Advanced LIGO)
- Last Virgo run: summer 2011
- TDR released in Apr 2012
- Construction completed: Aug 2016
- First full and stable lock: Mar 2017



LIGO, SPRING 2013

VIRGO MAIN HALL, SPRING 2013

COMPARED TIMELINES

	LIGO	VIRGO	Δ (yrs)
1G proposal	1989	1989	0
1G approval	1992	1994	-2
1G End of construction	1999	2003	-4
2G 1st project review	2003	2008	-5
2G upgrade approval	4/2008	12/2009	-2
2G end of integration	10/2014	8/2016	-2
2G start of data taking	9/2015	8/2017	-2
First GW event	9/2015	8/2017	-2
3G first design	N.A.	2011 (EU)	N.A.

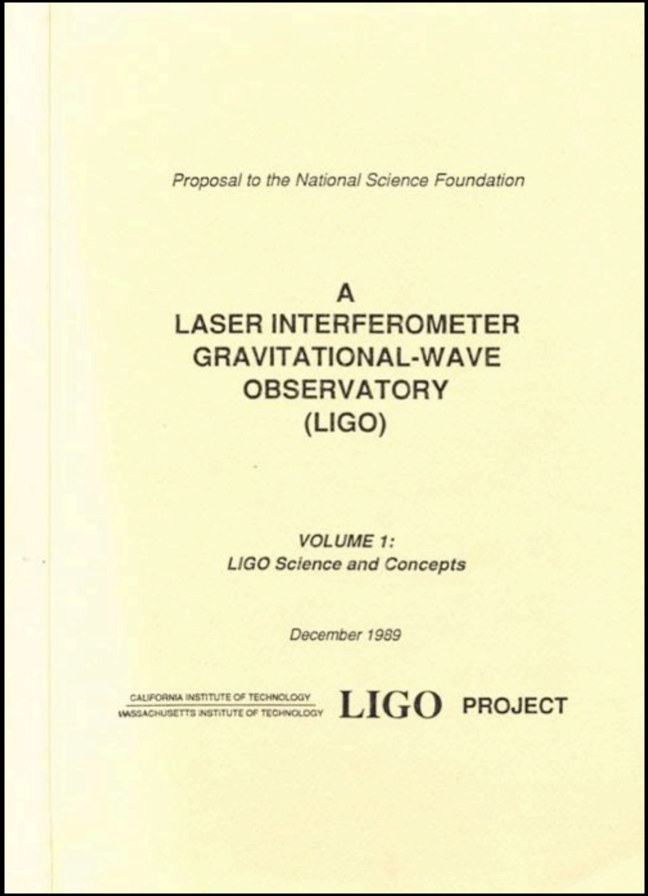
A WIDER COMPARISON

SNAPSHOT at the time of the TDR (2012)

	Advanced LIGO	Advanced Virgo
# DETECTORS	2+1	1
LENGTH	4 km	3 km
MAX CBC RANGE (BNS)	200 Mpc	140 Mpc
BUDGET	205(A) M\$ + 16(B) (D/UK/AUS)	21.8(C) M€ + 2(B) (NL)
1st PROJECT REVIEW	2003	2008
FUNDING APPROVED	Apr 2008	Dec 2009
MEMBERS	~900	~200
COUNTRIES	17	5
LABS	82	19
R&D INVESTMENTS	~60(E) M\$	~2(F)+1.5(G) M€

(A) Includes money for people ("half stuff, half staff")
(B) In kind contribution
(C) Only for investments
(D) Expected according to the latest planning
(E) Personal communication from D Shoemaker. LIGO lab R&D (+2-3 M\$/yr from other sources)
(F) EGO R&D calls 2003 and 2007
(G) CSN2 funding 2005-2010 (data by Fulvio Ricci)

1989



Proposal to the National Science Foundation

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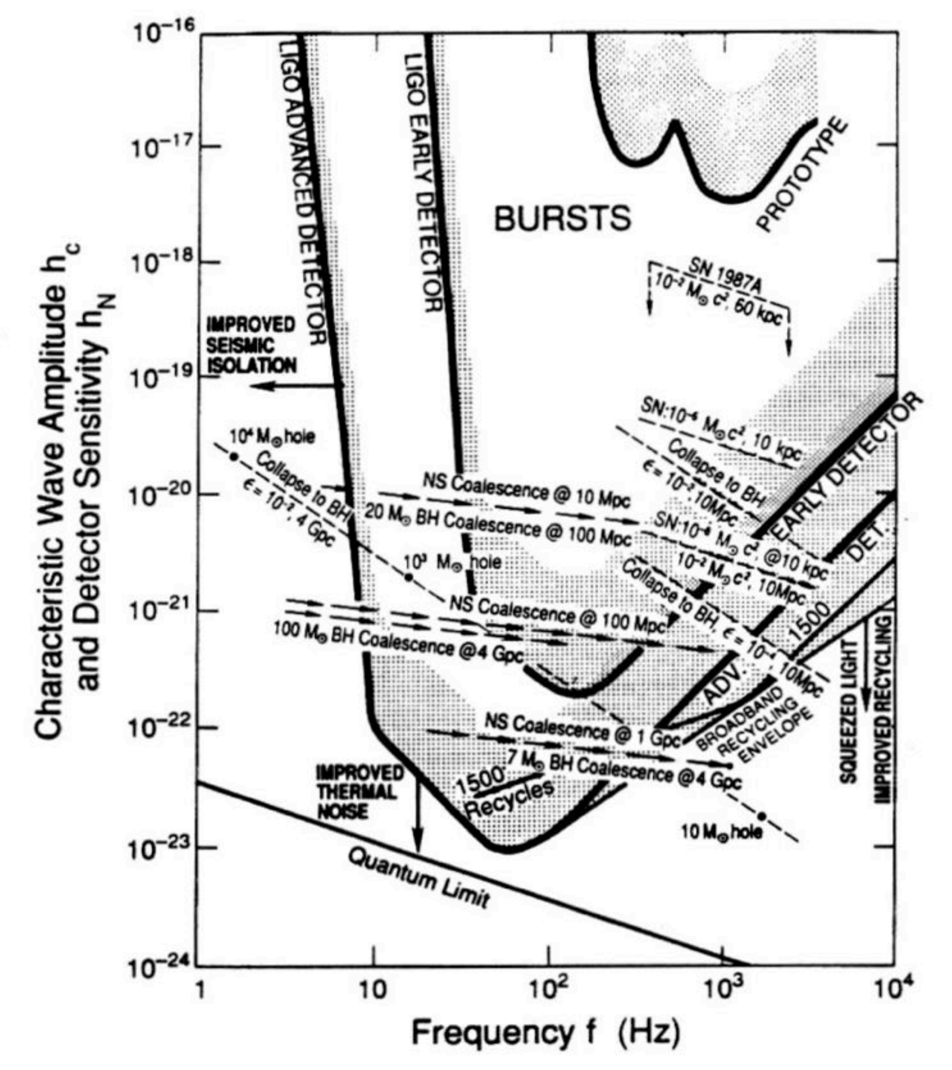
LIGO PROJECT



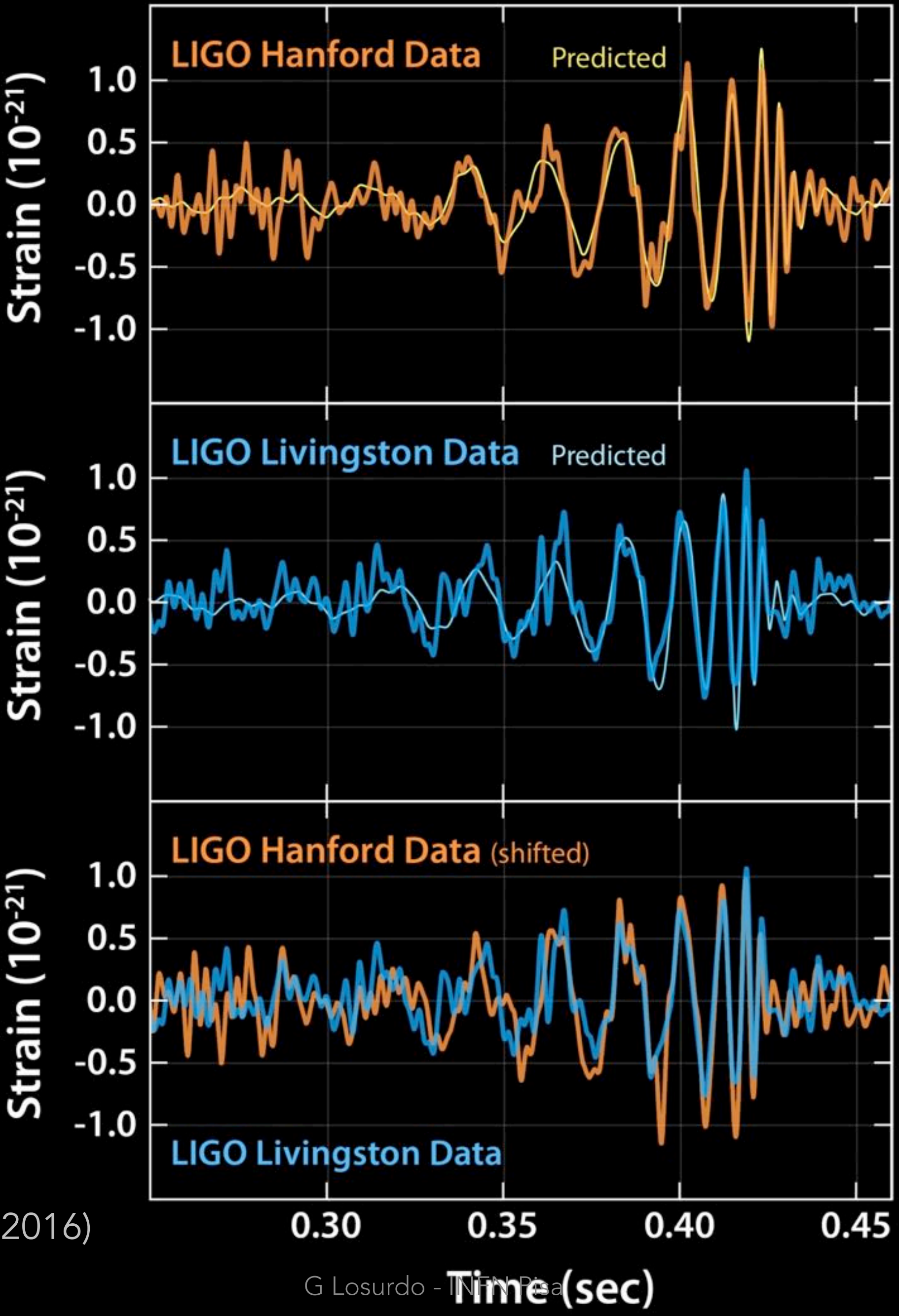
THE CONCEPT OF AN "ADVANCED" DETECTOR IS ALREADY IN THE LIGO PROPOSAL TO NSF

This set the framework for substantial R&D funding

Credit: I. Nardecchia

OBSERVATIONS

GW150914



Abbott et al., PRL, 116, 061102 (2016)

GW150914: MANY “firsts”

- First direct detection of gravitational waves (100 years after Einstein's prediction)
- First direct observation of black holes
- First observation of the largest known stellar mass BH (>25 $M_\odot$)
- First observation of a binary black hole (BBH) system,
- First observation of a BBH merger
- First tests of general relativity in strong field (extreme) conditions

- AND: the ground based interferometers proved to be the right instruments!

Black Holes of Known Mass

MORE BBH DETECTED AFTER GW150914:
A DIFFERENT POPULATION IS SHOWING UP

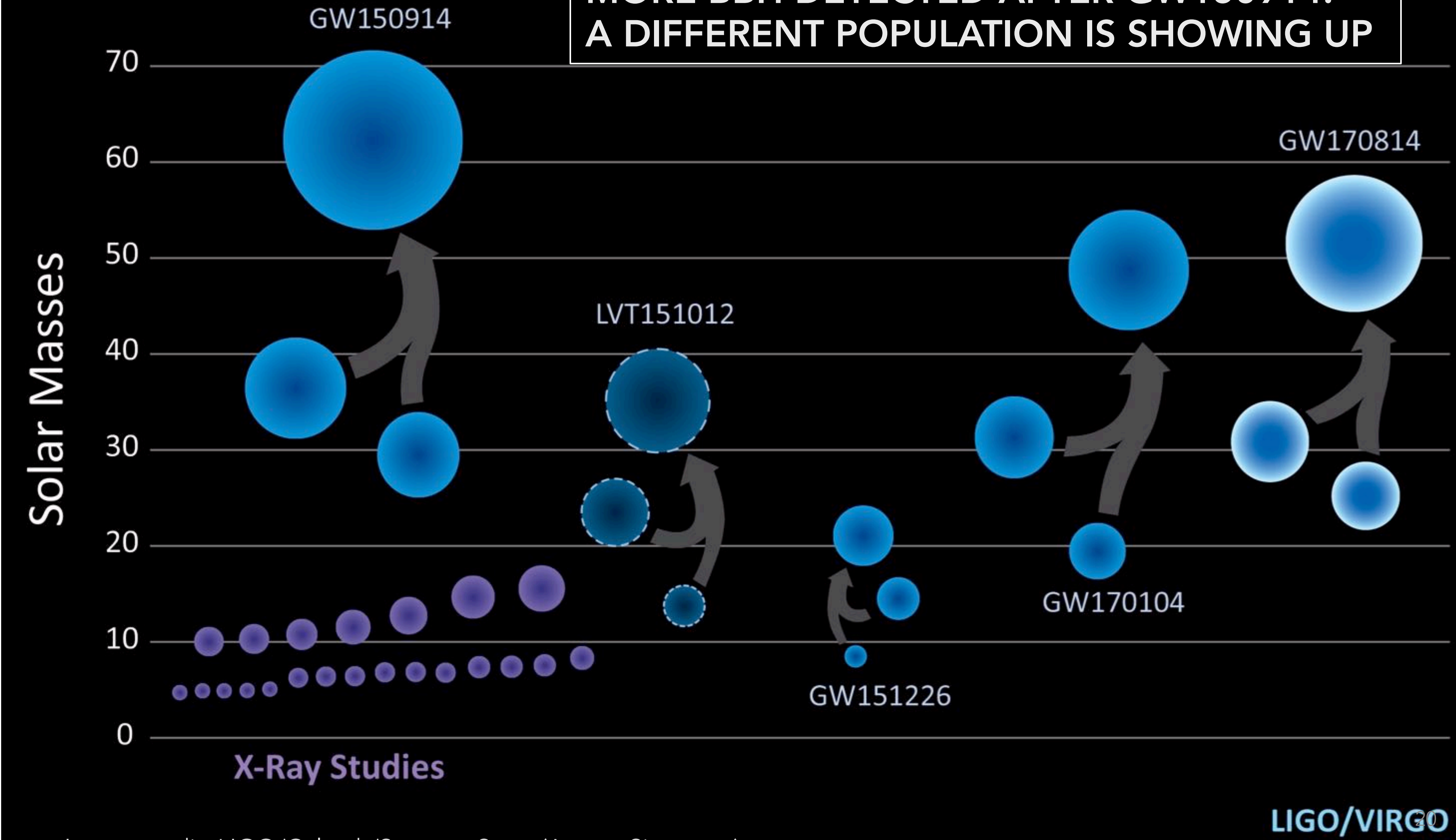


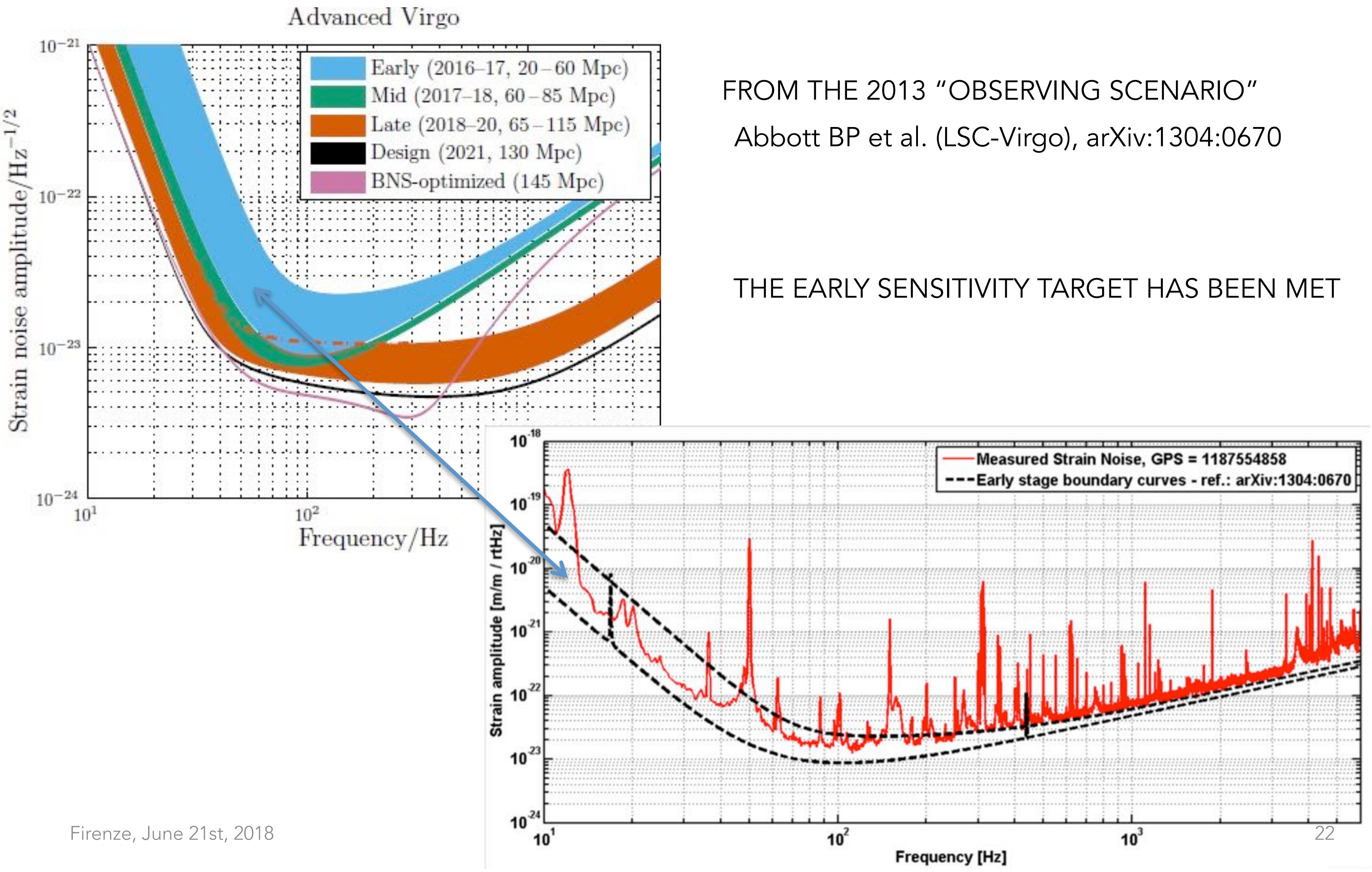
Image credit: LIGO/Caltech/Sonoma State (Aurore Simonnet)

August 1st, 2017

VIRGO JOINS LIGO IN THE OBSERVATION RUN O2

THREE 2G DETECTORS ACTING AS A “SINGLE MACHINE”

SENSITIVITY

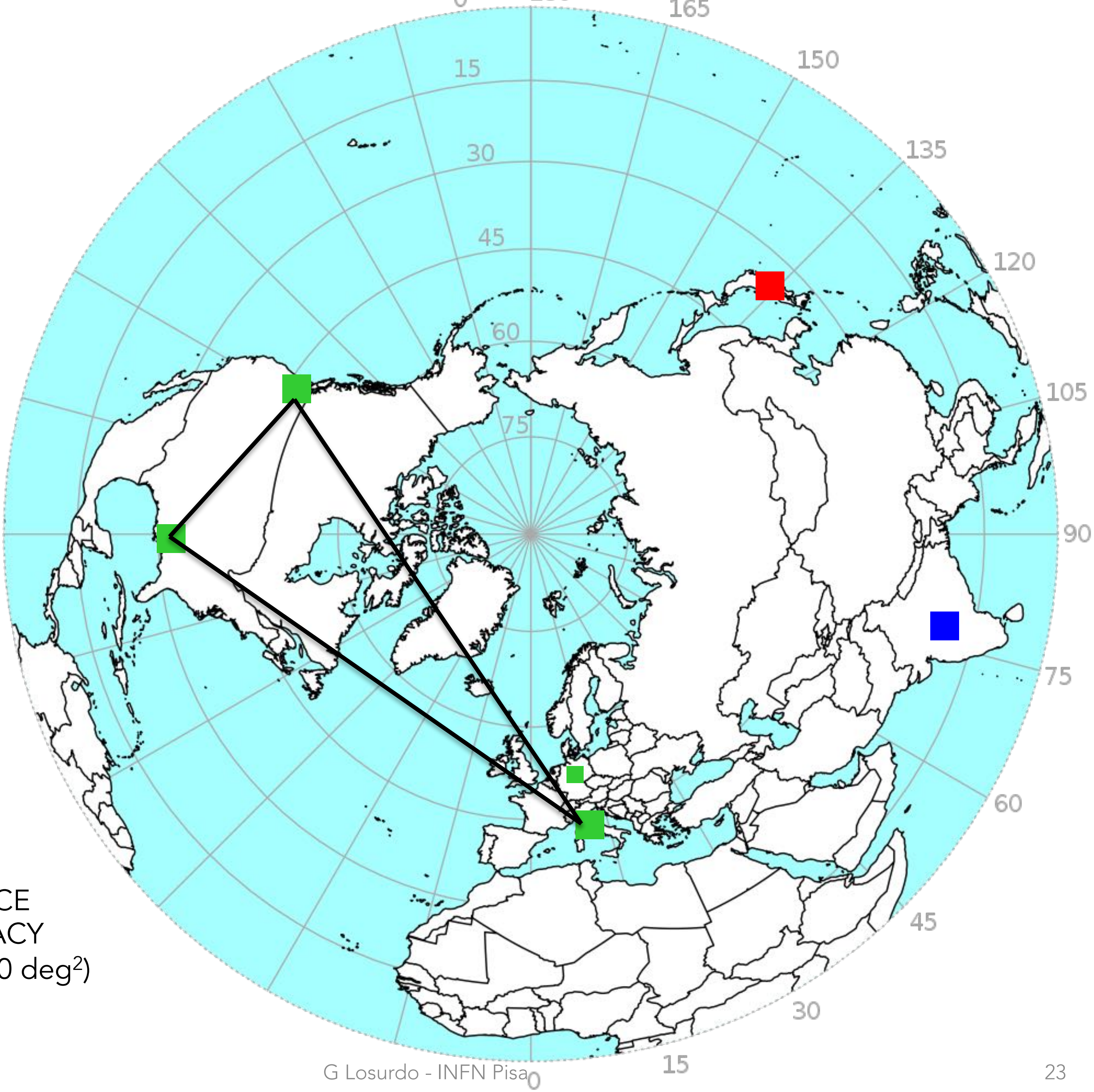


FROM THE 2013 "OBSERVING SCENARIO"

Abbott BP et al. (LSC-Virgo), arXiv:1304:0670

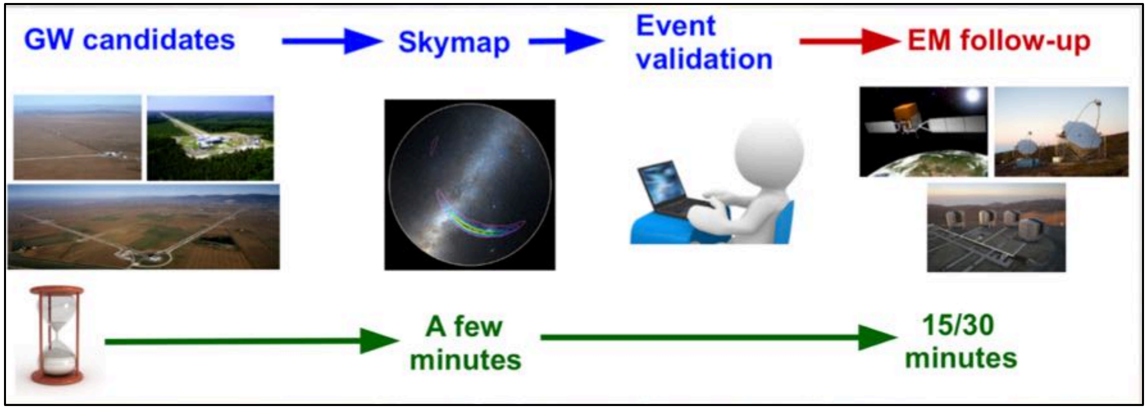
THE EARLY SENSITIVITY TARGET HAS BEEN MET

- 🟩 OPERATION
- 🟧 COMMISSIONING
- 🟥 CONSTRUCTION
- 🟦 APPROVED



WITH VIRGO THE SOURCE LOCALIZATION ACCURACY IMPROVES FROM O(1000 deg^2) to 10s-100s deg^2

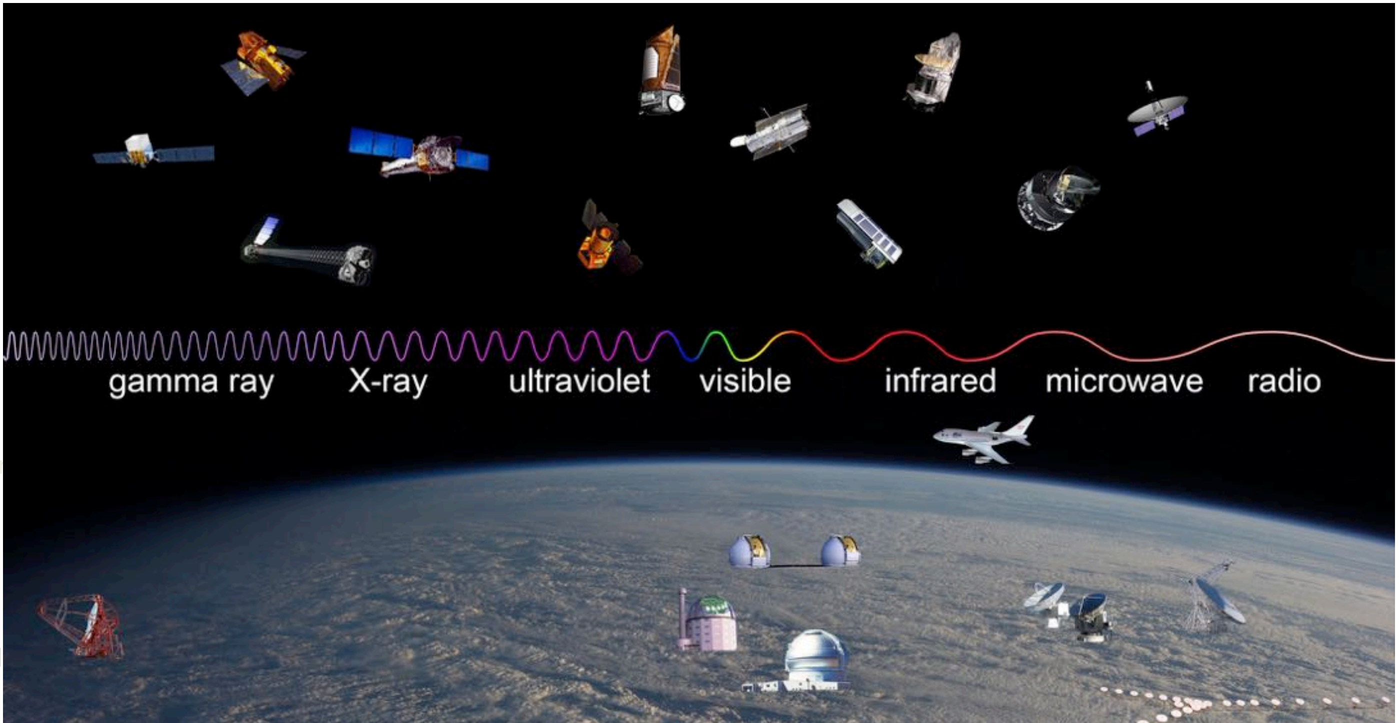
MULTI-MESSENGER NETWORK



GW candidates → Skymap → Event validation → EM follow-up

A few minutes → 15/30 minutes

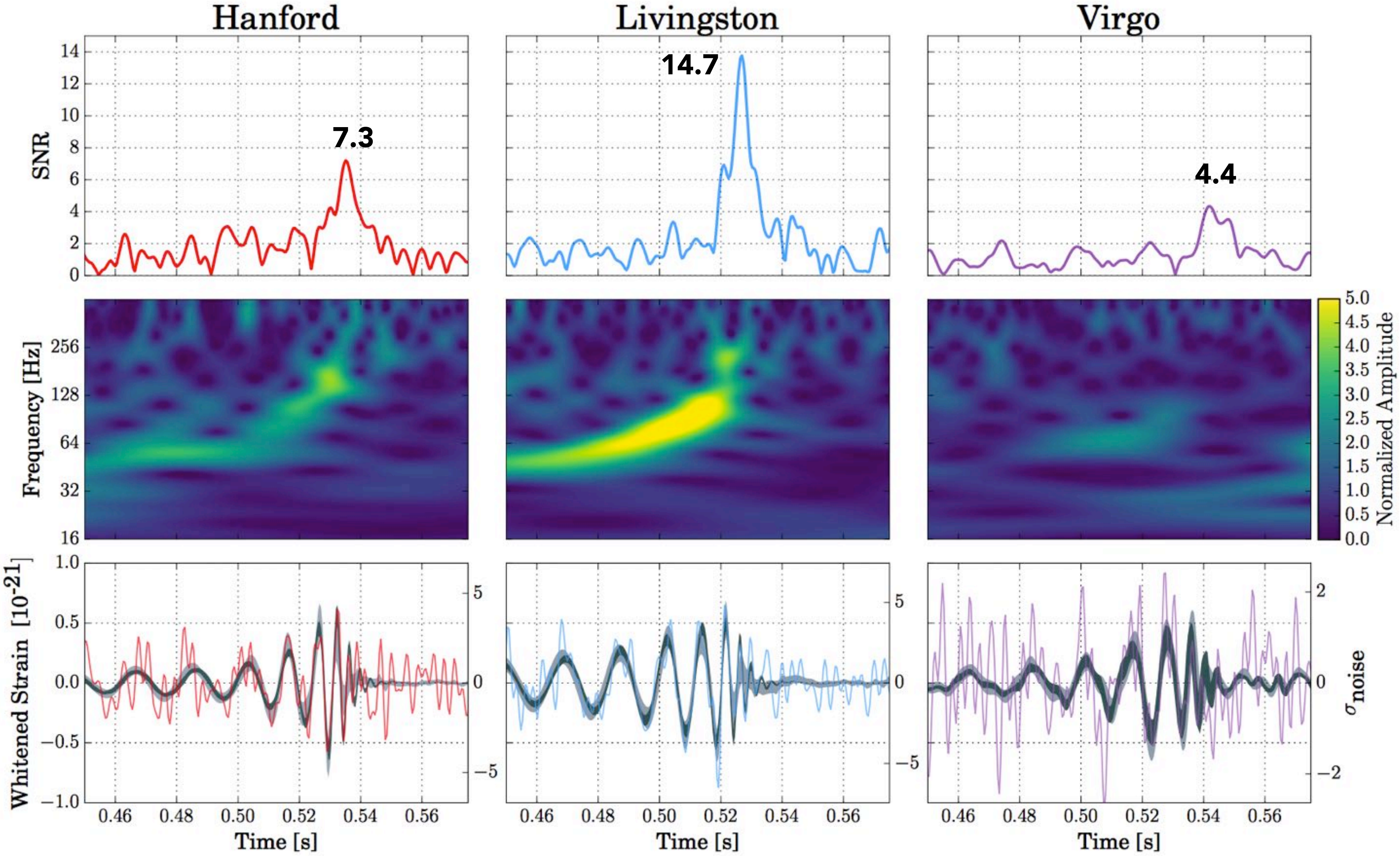
93 groups (>200 instruments) have signed the MoU with the LVC



August 14th, 2017

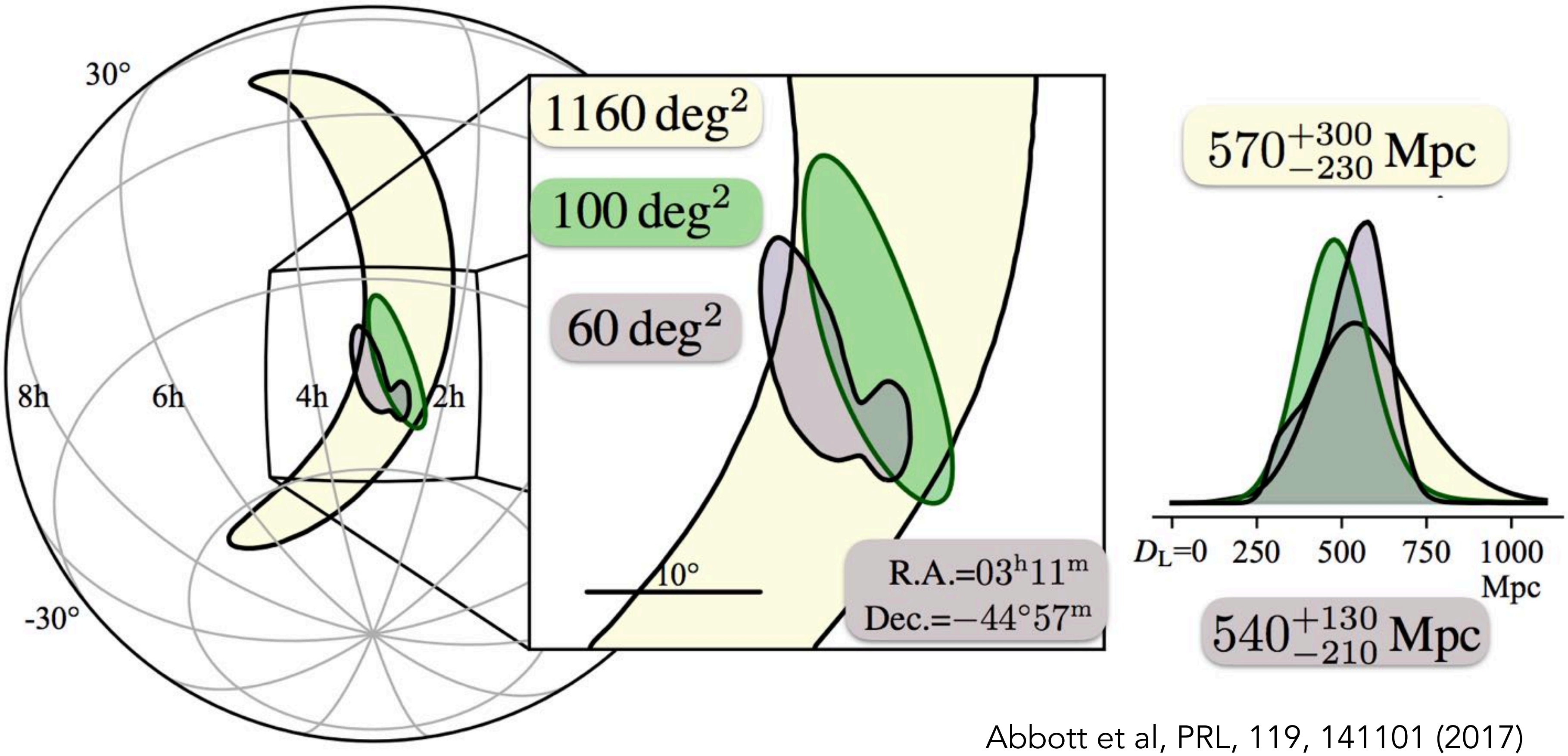
At 10:30:43 UTC, the Advanced Virgo detector and the two Advanced LIGO detectors coherently observed a transient gravitational-wave signal produced by the coalescence of two stellar mass black holes, with a false-alarm-rate of <~ 1 in 27 000 years

The GW hit Earth first at lat. 44.95° S, long. 72,97° W, Puerto Aysen, Chile. The signal was recorded at L1 first, then at H1 and Virgo with delays of ~8 and ~14 ms respectively



PRL, 119, 141101 (2017)

3-detector network SNR: 18.3



Abbott et al, PRL, 119, 141101 (2017)

VIRGO HELPS REDUCING:

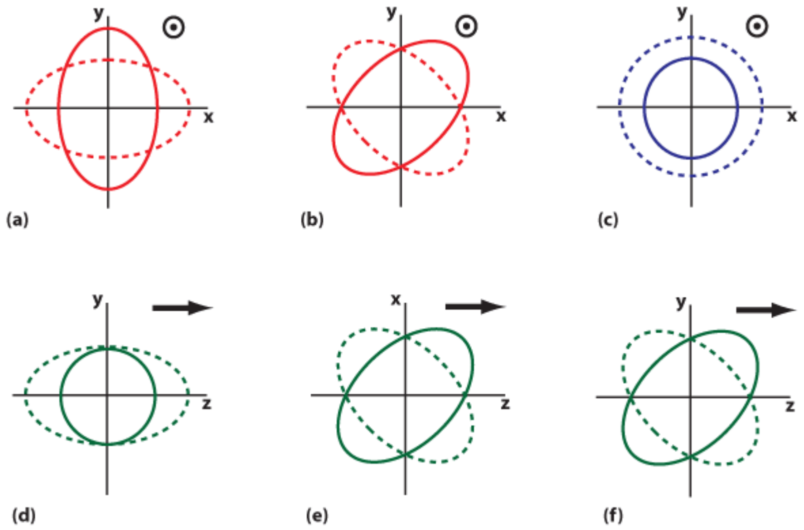
ERROR IN SKY AREA:	20x
ERROR IN DISTANCE:	1.5x
ERROR BOX ON THE SKY: (from 70 to 2 Mpc^3)	30x

POLARIZATION

- **For the first time**, thanks to the the addition of a 3rd detector, one can probe the nature of the polarization states
- PRELIMINARY ANALYSIS: GR (purely tensor) is 200 and 1000 times more likely than purely vector/scalar respectively

TENSOR (SPIN 2)
GENERAL RELATIVITY

SCALAR (SPIN 0)



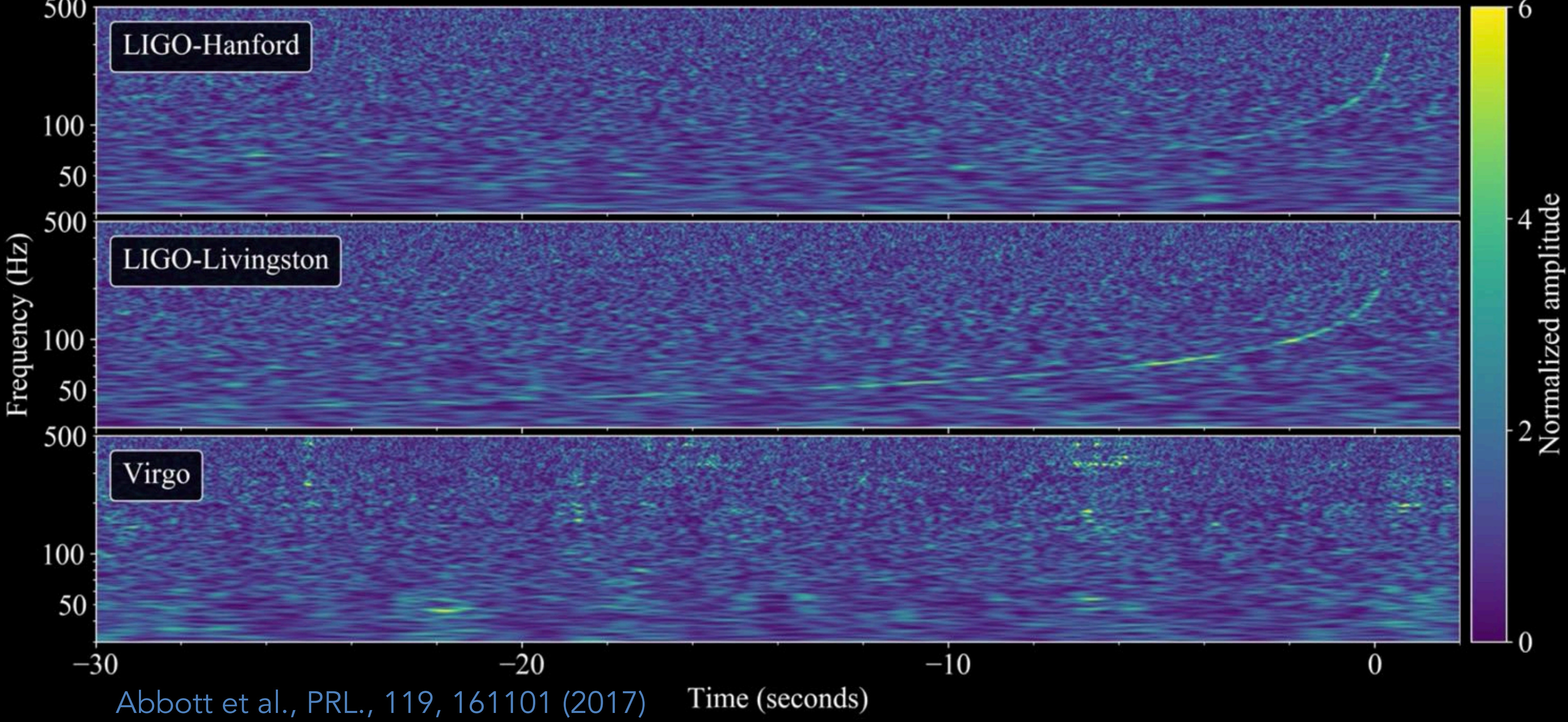
VECTOR (SPIN 1)

Abbott et al., PRL, 119, 141101 (2017)

AUGUST 17th, 2017

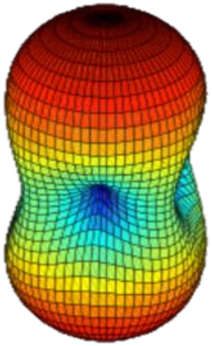
IT…

Aug 17th 2017 at 12:41 UTC Advanced LIGO-Virgo detected a binary neutron star inspiral

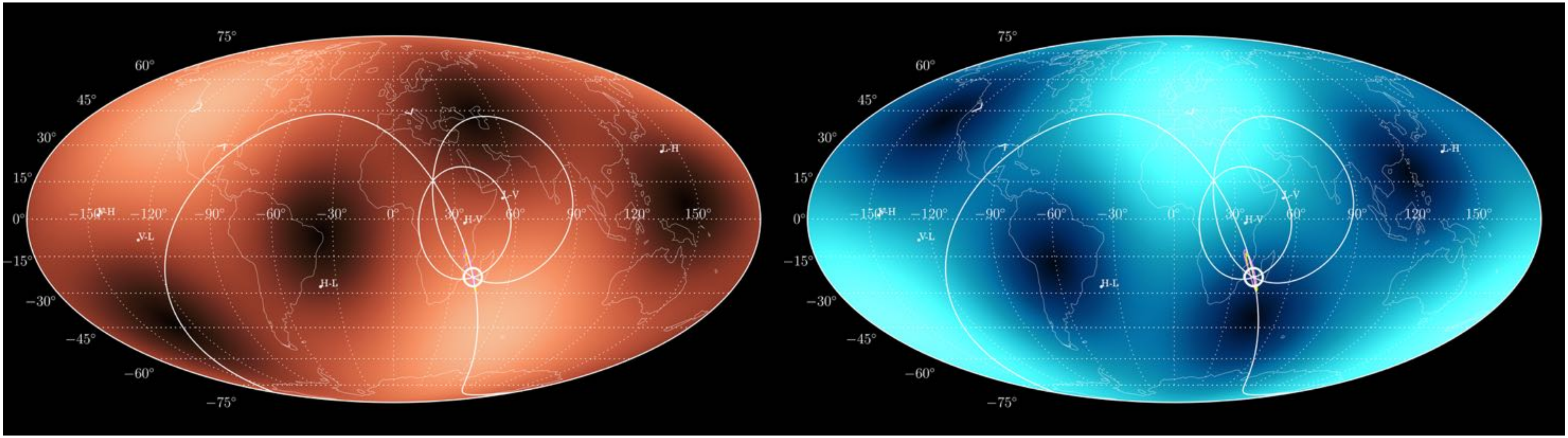


Abbott et al., PRL., 119, 161101 (2017)

GW170817

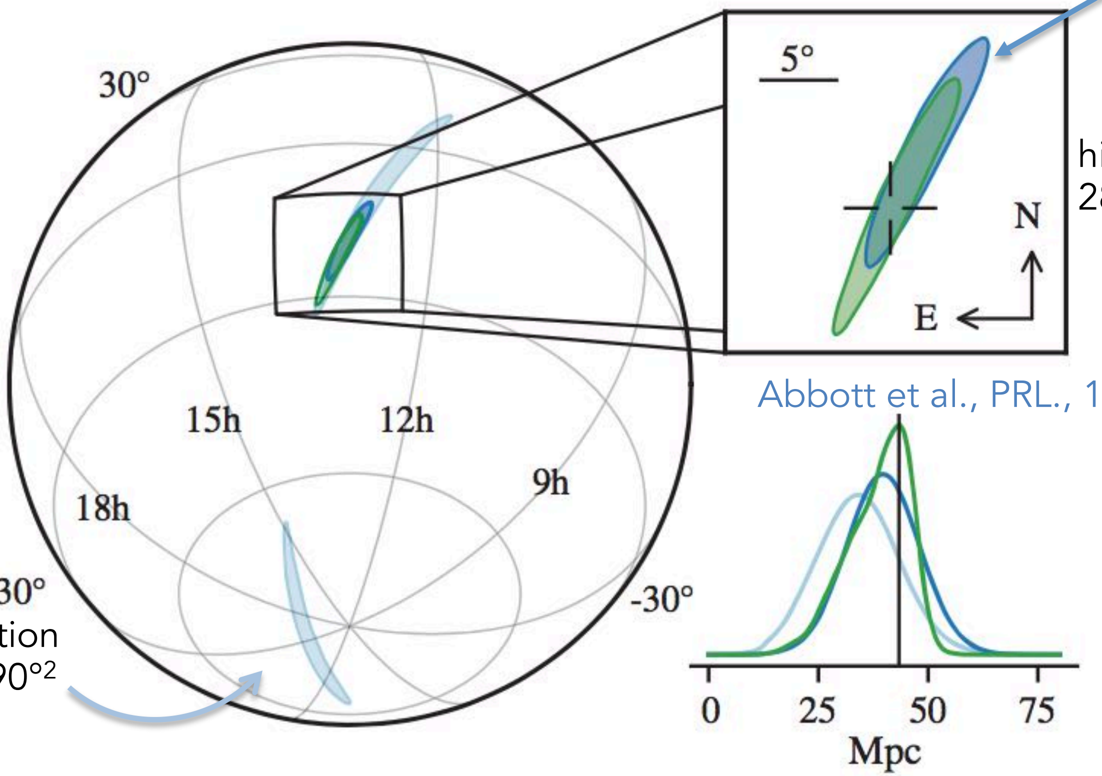


- Network SNR: 32.4: loudest signal so far
- FAR < 1/80000 yr: highly significant event
- Duration ~100 s: longest signal so far
- Small signal in Virgo: source close to blind spot. Quite important for localization



GW170817

- Early sky maps accurate to ~31°^{2}
- Final sky maps: localization within 28°^{2} (90% probability): vital for subsequent EM follow-up
- Initial alert: 27′ after detection



rapid localization with LIGO-Virgo: 31°^{2}

high-latency follow-up: 28°^{2}, 380 Mpc^3

rapid localization with LIGO: 190°^{2}

Abbott et al., PRL., 119, 161101 (2017)

GW170817

$\mathcal{M}_c = (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$

- Chirp mass measured over ~3000 cycles:

$$\mathcal{M}_c^{\rm det} = 1.1977^{+0.0008}_{-0.0003}\ M_\odot$$

- Total mass:

$$2.73 < M_{\rm Total} < 3.29\ \mathrm{M}_\odot$$

- Constraint on the two masses:

$$0.86 < m_i < 2.26\ \mathrm{M}_\odot$$

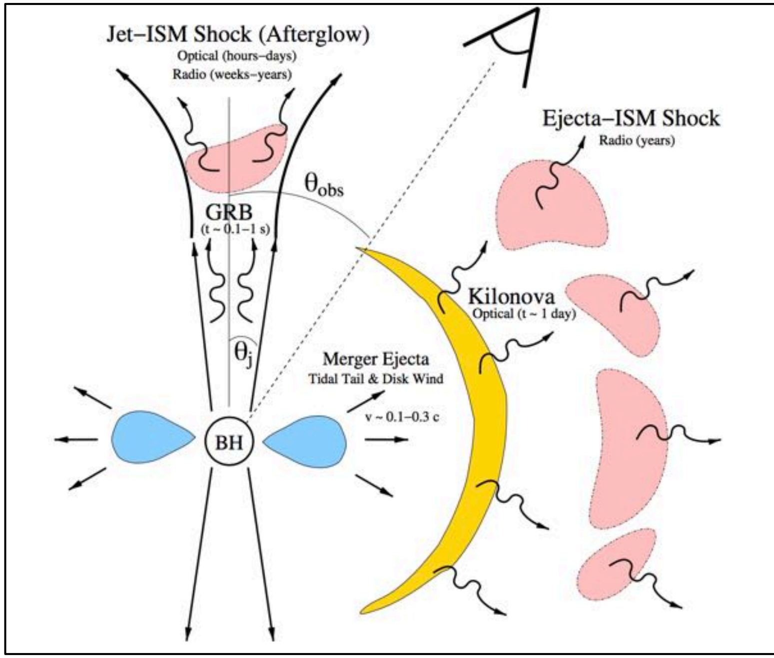
- Luminosity distance:

$$D_L = 40^{+8}_{-14}\ \mathrm{Mpc}$$

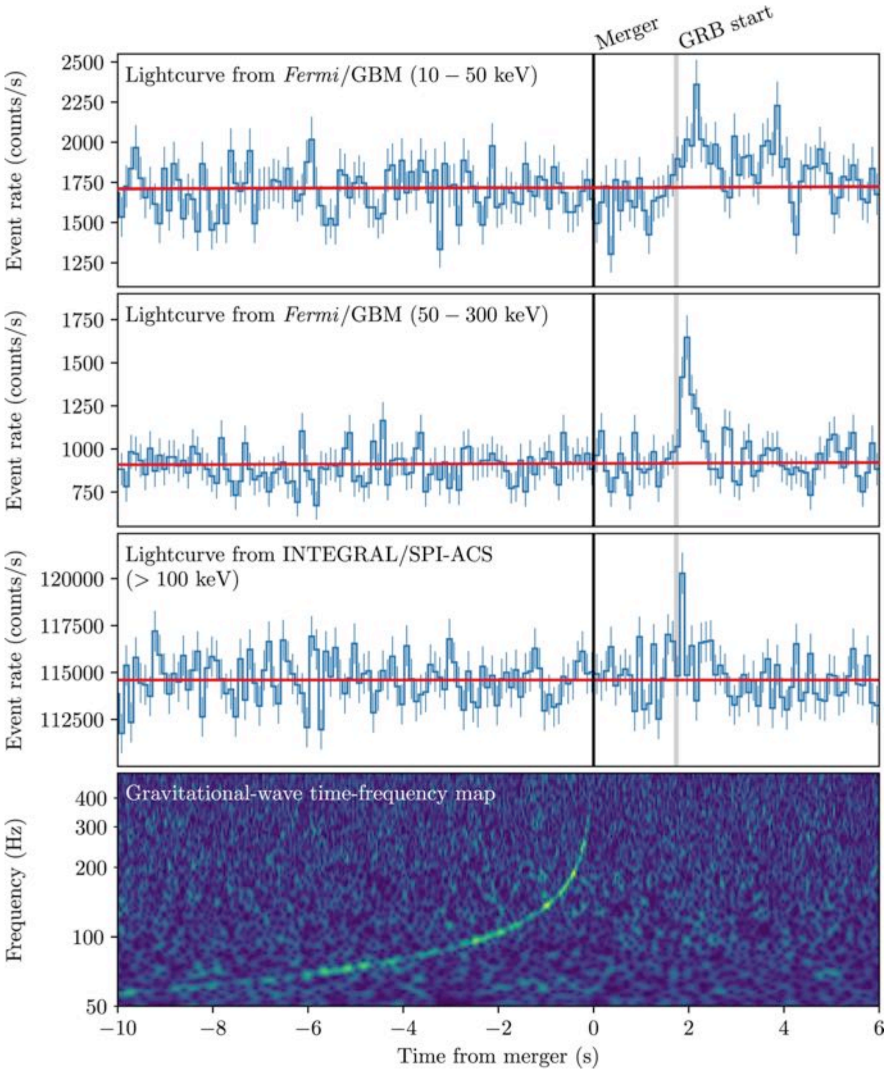
EXPECTED COUNTERPARTS

- Short GRB
  - prompt γ-ray emission (t>2 s)
  - multi-wavelength afterglow (X, optical, radio. Timescale: mins to months)
- Kilonova
  - Isotropic thermal emission produced by radioactive decay of rapid nucleon capture elements (r-process) synthesized in the merger ejecta
  - Term first introduced by Metzger et al (2010), but mechanism known since 1998 (Li & Paczynski)

Metzger & Berger, 2012



OBSERVATIONS



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

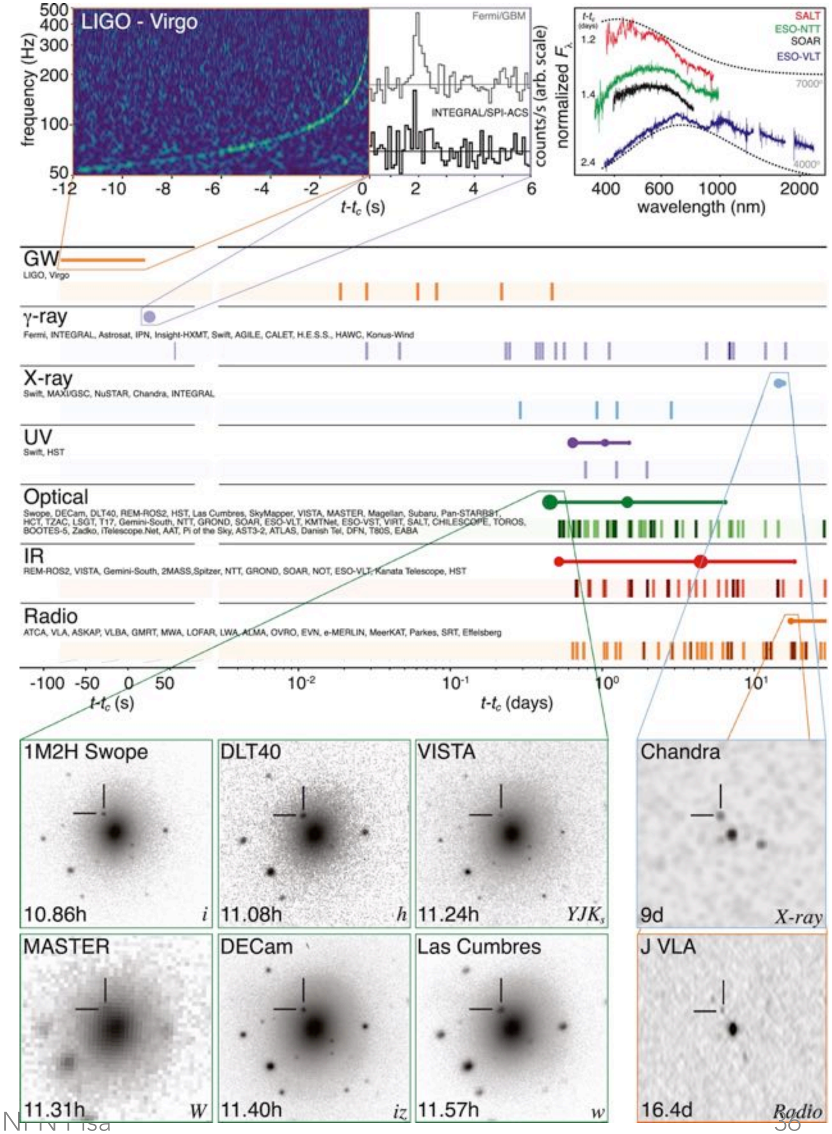
A GRB event, 1.7 sec after…

First direct evidence that BNS mergers are progenitors of sGRB

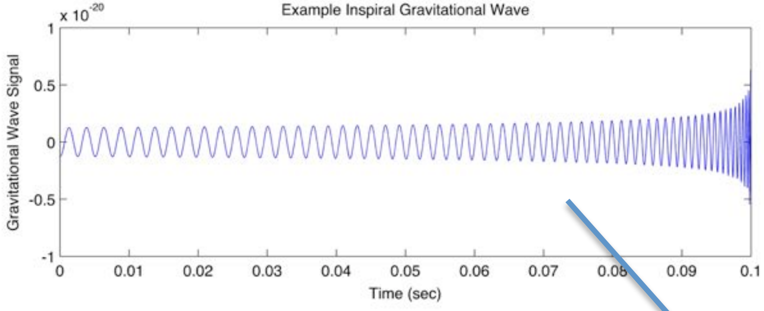
OBSERVATIONS

- Optical counterpart found in host galaxy NGC4993
- Optical/infrared/UV counterpart has been detected
  - first spectroscopic identification of a kilonova
- X-ray and a radio counterparts have been identified
  - Off-axis afterglow? Cocoon emission?

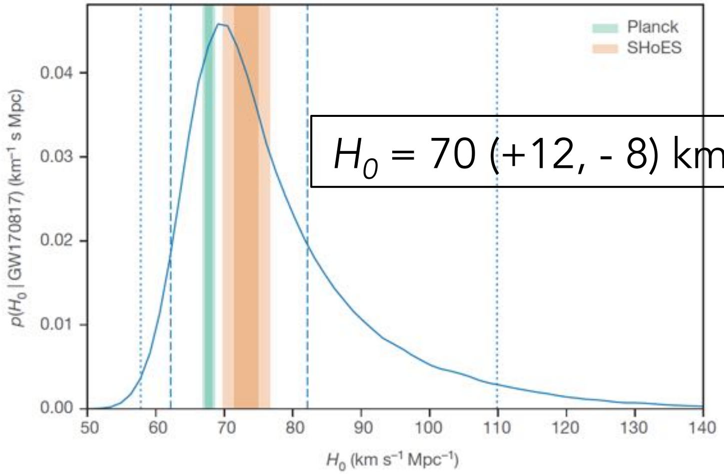
Abbott et al., ApJL., 848:L12 (2017)



MEASURING H_0

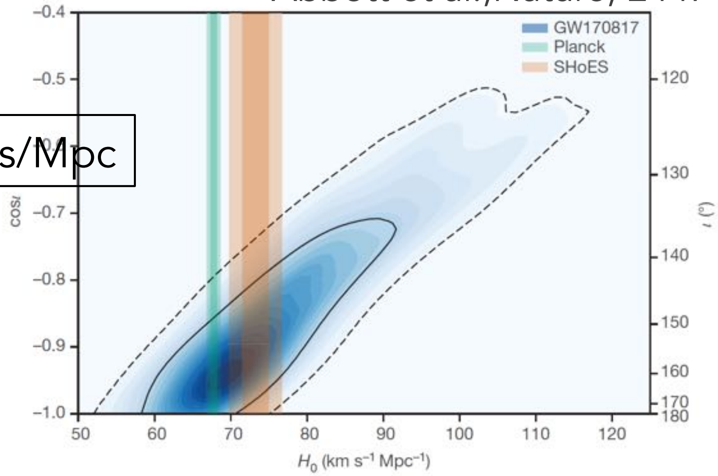


$$H_0 \, d_L = c \, z$$



H_0 = 70 (+12, - 8) km/s/Mpc

Abbott et al.,Nature, 24471 (2017)



With a few tens of events a measurement with 1% accuracy will be possible (Del Pozzo, PRD, 2012)

THE SPEED OF GRAVITY

- ❑ GW170817 provides a stringent test of the speed of gravitational waves

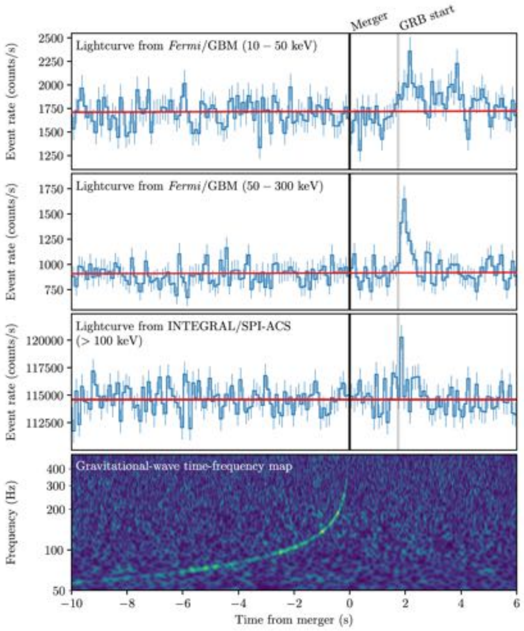
$$\frac{v_{GW} - c}{c} \approx \frac{c\Delta t}{D}$$

- ❑ $\Delta t = 1.7 \pm 0.5$ s over ~130 Myrs

$$-3 \cdot 10^{-15} \leq \frac{v_{GW} - c}{c} \leq 7 \cdot 10^{-16}$$

Assuming D=26 Mpc

Assuming sGRB emitted
10 s after GW

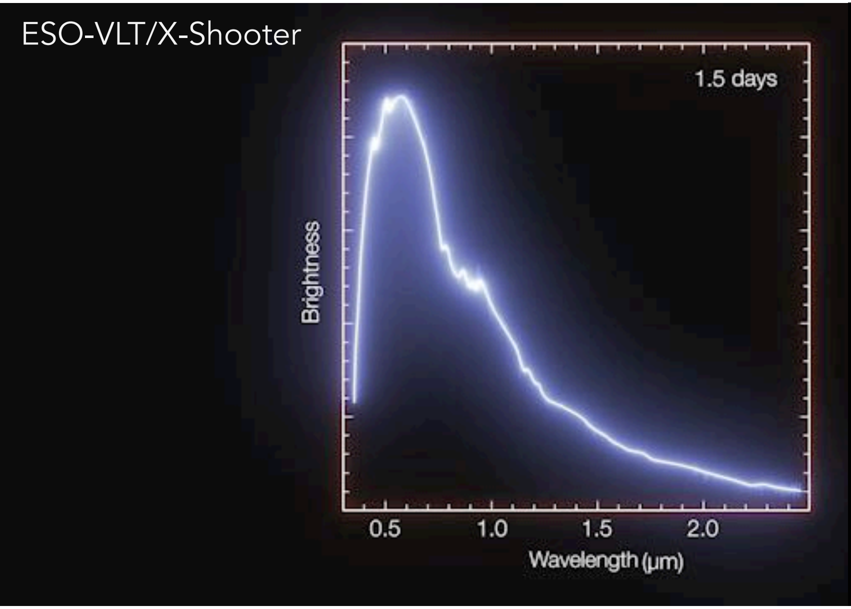


Abbott et al., ApJL., 848:L13 (2017)

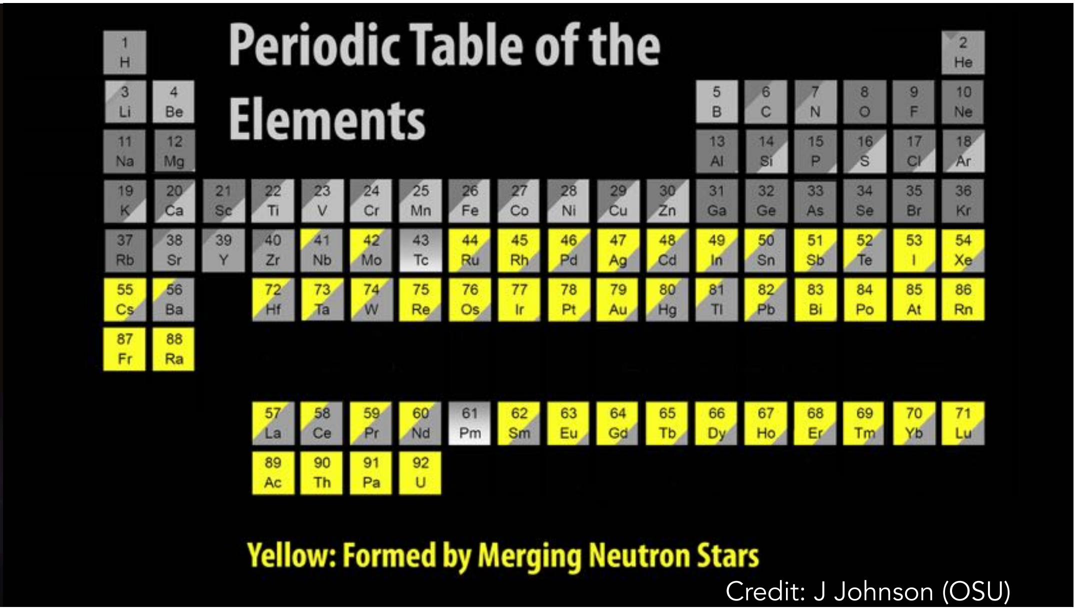
KILONOVA

- Electromagnetic follow-up of GW170817 provides strong evidence for kilonova model
- Spectra taken over 2 week period across all electromagnetic bands consistent with kilonova models

e.g. Pian et al, Nature, 2017

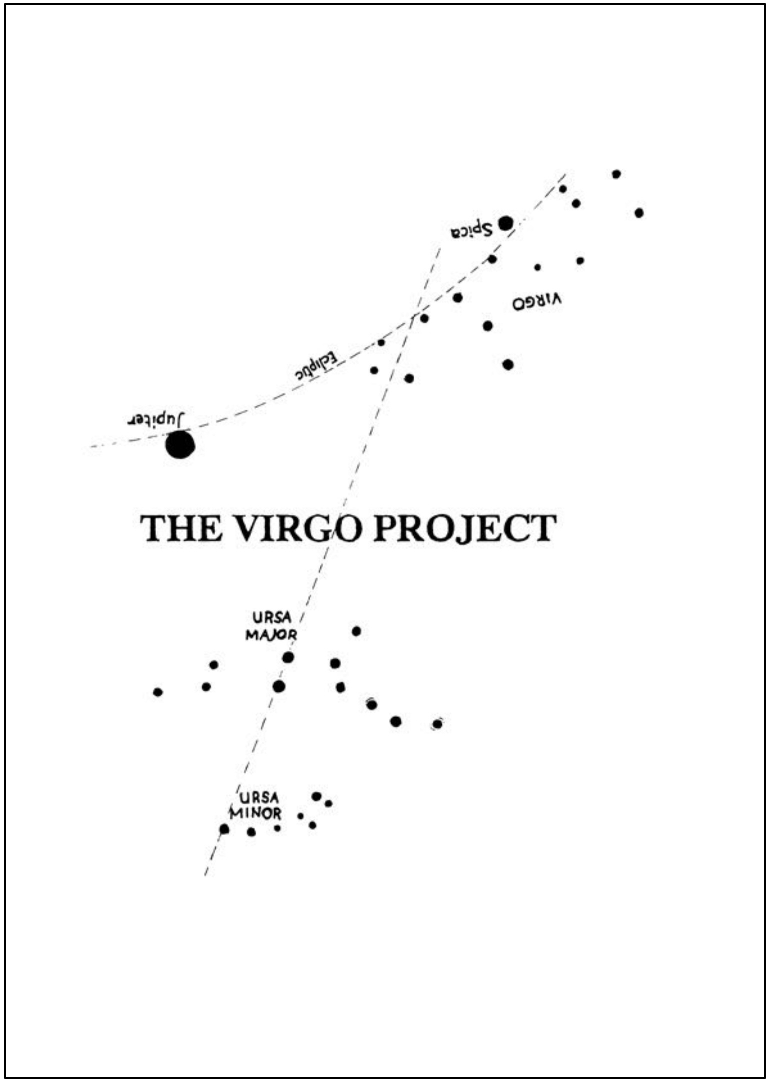


ESO-VLT/X-Shooter



Credit: J Johnson (OSU)

1989

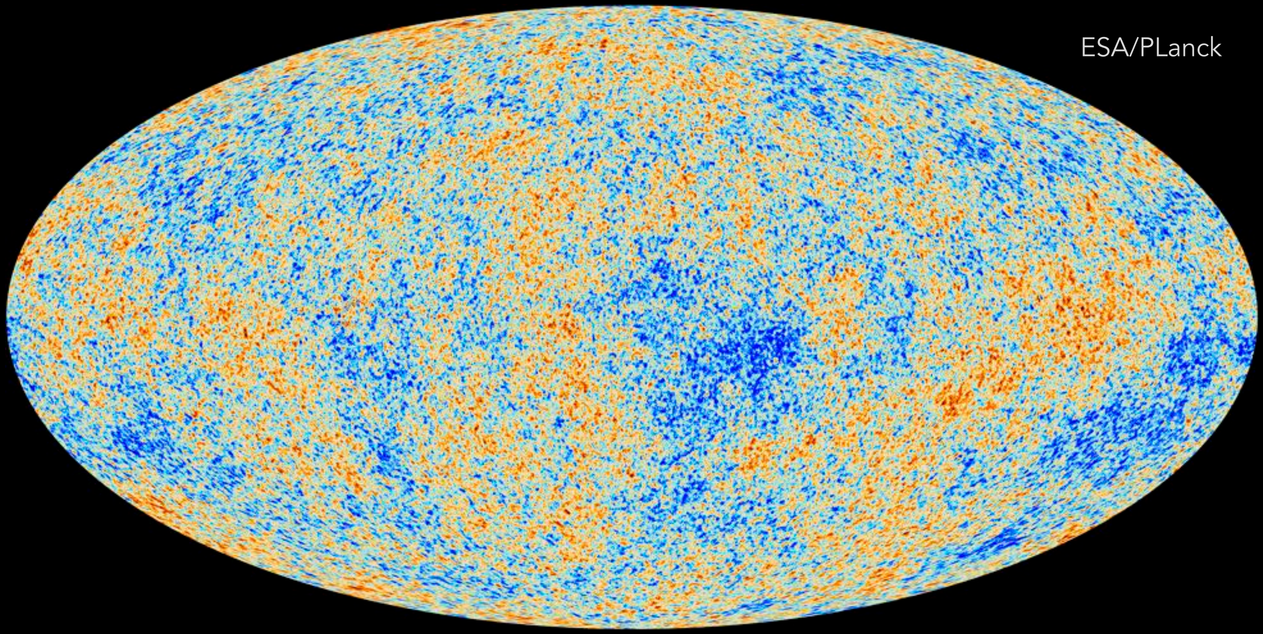


THE VIRGO PROJECT

VIRGO must be considered both as an experiment and as a step towards a future observatory. The immediate goal of the VIRGO experiment is to realize, or to participate in, the first detection of gravitational radiation, but it also has the long term goal of being one component of the gravitational wave detectors network which will involve other detectors in other countries, and provide data of astrophysical interest. These goals imply a collaboration with the other groups having similar projects, without excluding some competition.

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

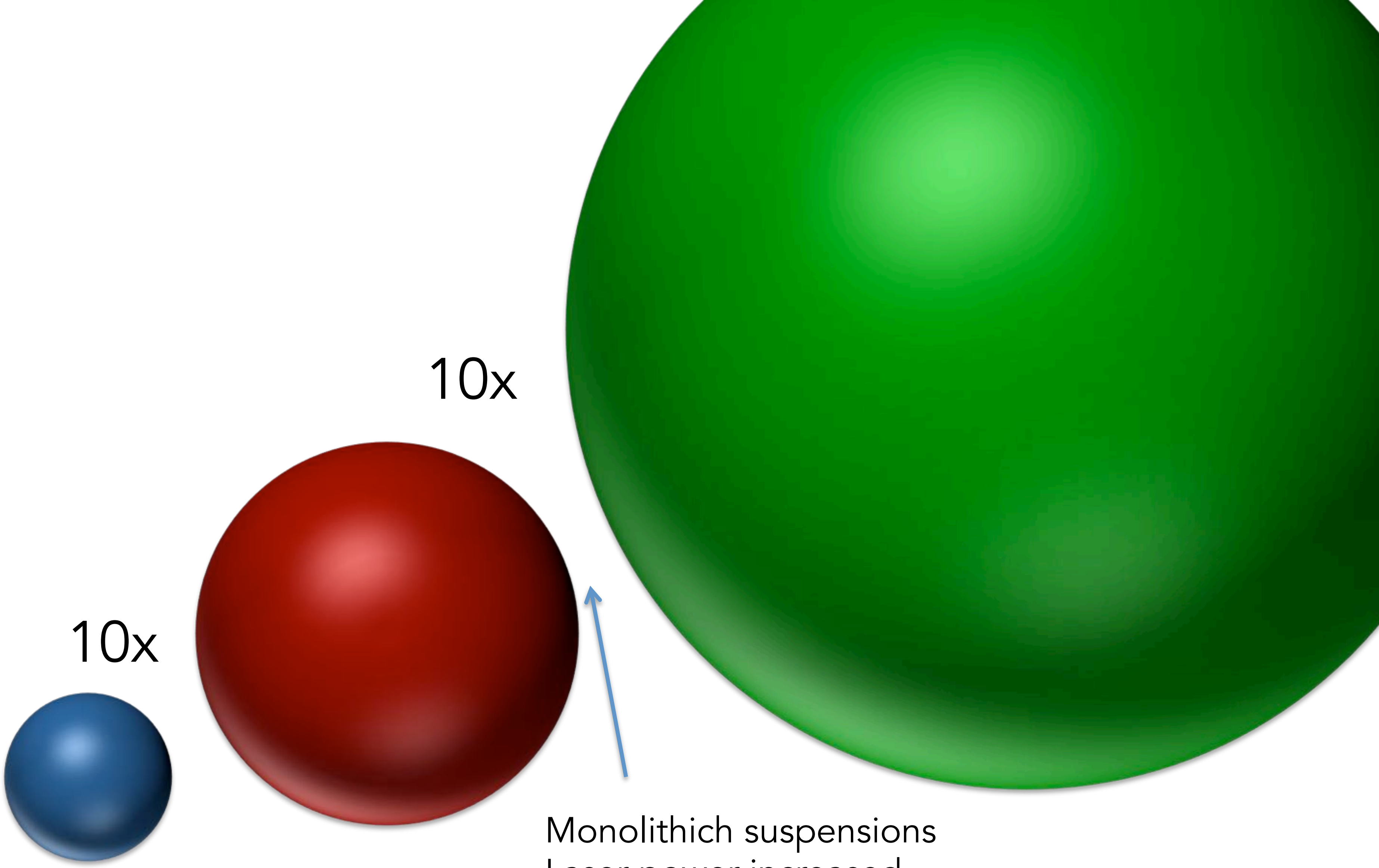
PERSPECTIVES

THE CASE FOR BETTER DETECTORS

$$\# \text{ EVENTS} \propto d^3\ T$$

1 day of data at a range of 80 Mpc (Advanced LIGO in O1)
is equivalent to 64 days at 20 Mpc (LIGO, 2009)

Observing for a long time is good,
improving the sensitivity further is better.



10x

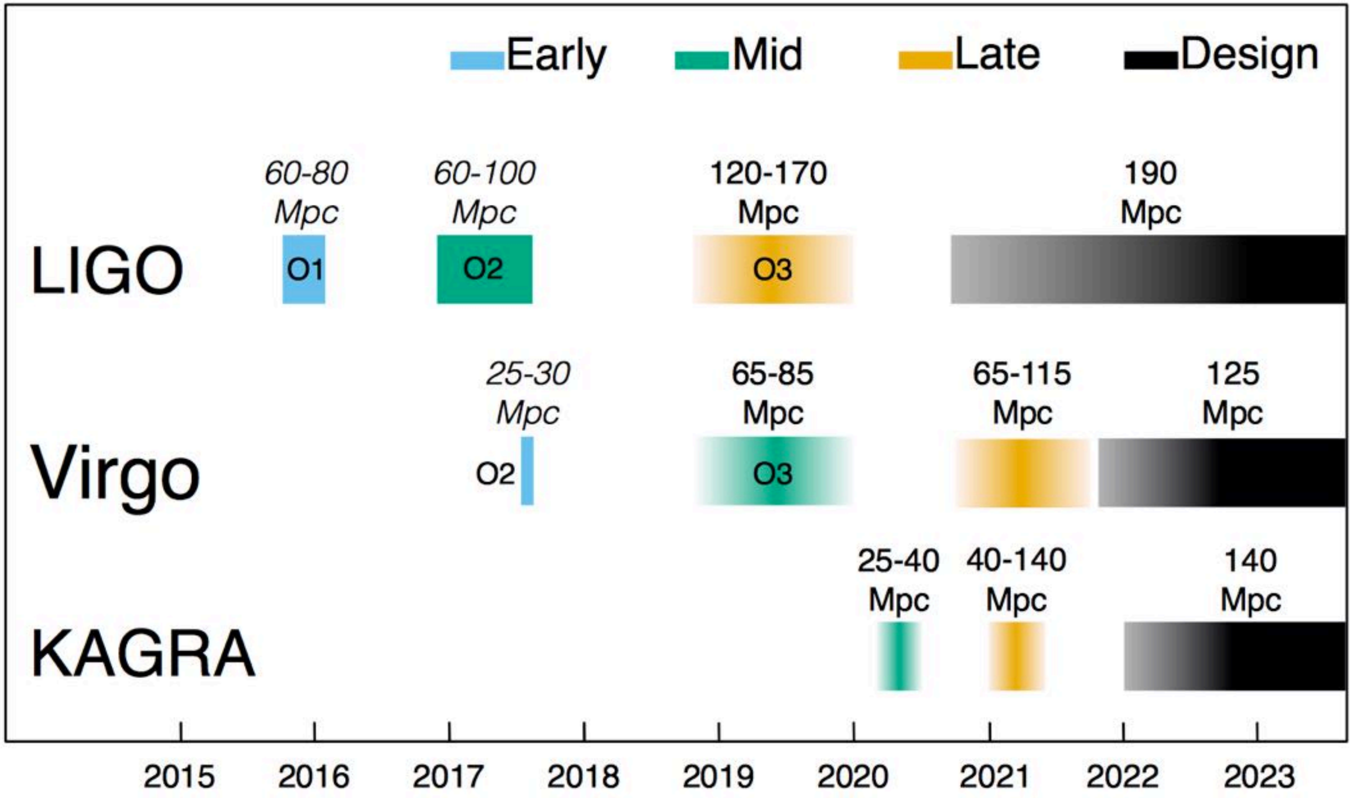
10x

Monolithich suspensions
Laser power increased
Squeezer

VIRGO BEST
(12 Mpc)

AdV O2
(26 Mpc)

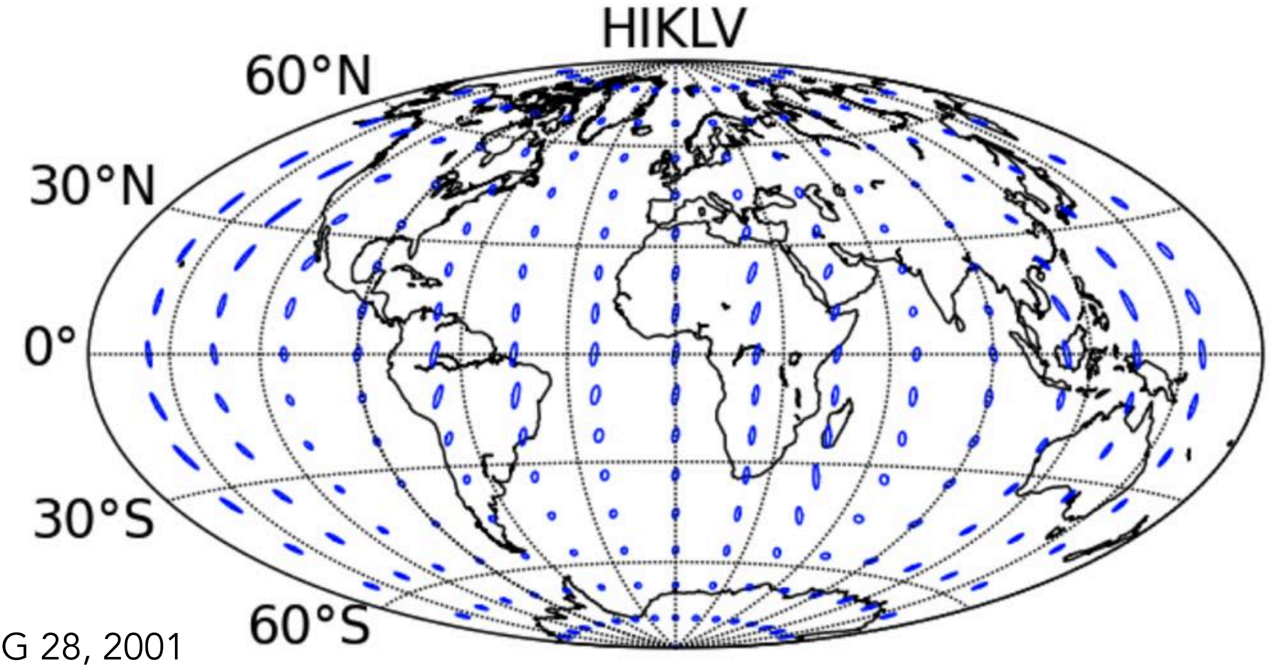
AdV O3 (goal)
(>65 Mpc)



…and LIGO India plans to come on line with Advanced LIGO sensitivity – with any upgrades incorporated – in 2024

B.P. Abbott et al. "Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA" – ArXiv 1304.0670 (2017)

THE MID-TERM GOAL



S Fairhurst, CQG 28, 2001

KAGRA (2019) and LIGO-India (2024) will expand the network.
LIGO and Virgo expected to be upgraded to 2.5G (2023)

Localization capabilities of the 2G network at mid 2020s:
>60% of the sources localized within 10 deg^2

WHAT NEXT?

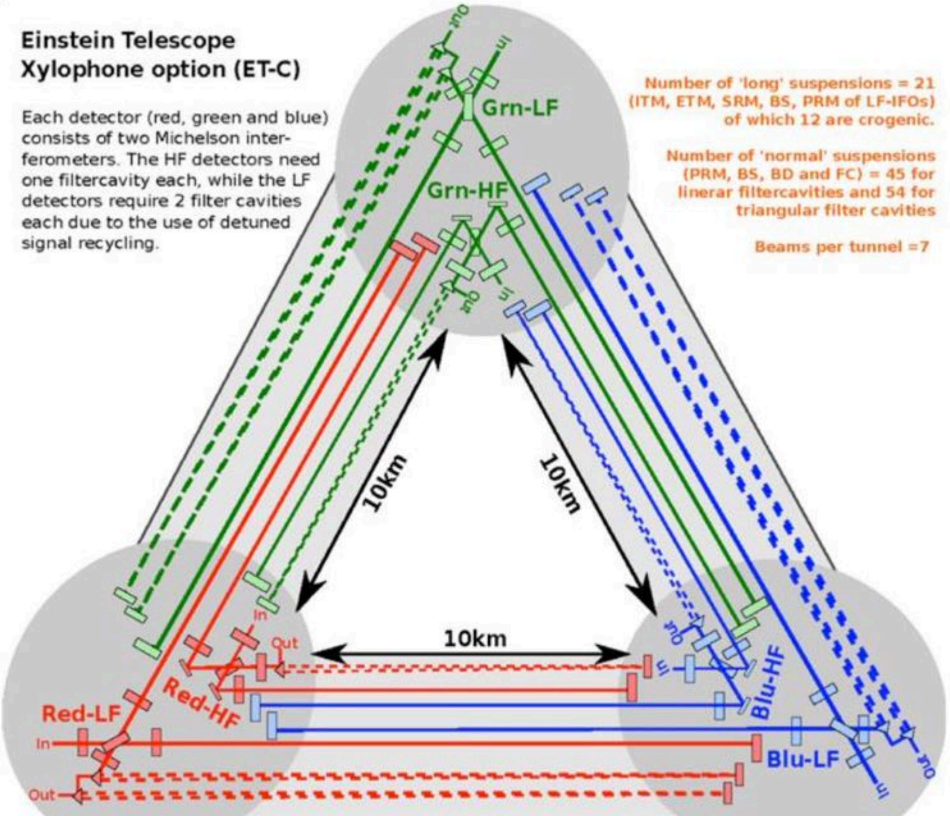
- **2.5 G:** a set of upgrades capable of enhancing the sensitivities of the current detectors (event rate 5-10x)
  - Timeline:~2023
  - A+ at LIGO, AdV+ at Virgo
- **3 G:** new infrastructures/detectors capable of reaching the early universe. One order of magnitude gained in sensitivity wrt 2G
  - Timeline: ~2030
  - Cost > 1 Geuros

1. Einstein Telescope: European project for a nested assembly of 6 co-located interferometers, 10 km long
   - underground
   - bandwidth extended to 1 Hz
   - cryogenics
2. Cosmic Explorer: US project for a 40 km interferometer

AdV+

- ❑ Set of upgrades for AdV, aimed to approach the “infrastructure limit”, split in two phases
- ❑ Phase 1: BNS range up to 160 Mpc
  - frequency dependent squeezing
  - newtonian noise cancellation
- ❑ Phase 2: BNS range up to 260 (300) Mpc
  - new, larger mirrors
  - factor 3 of coating thermal noise reduction

EINSTEIN TELESCOPE



Einstein Telescope
Xylophone option (ET-C)

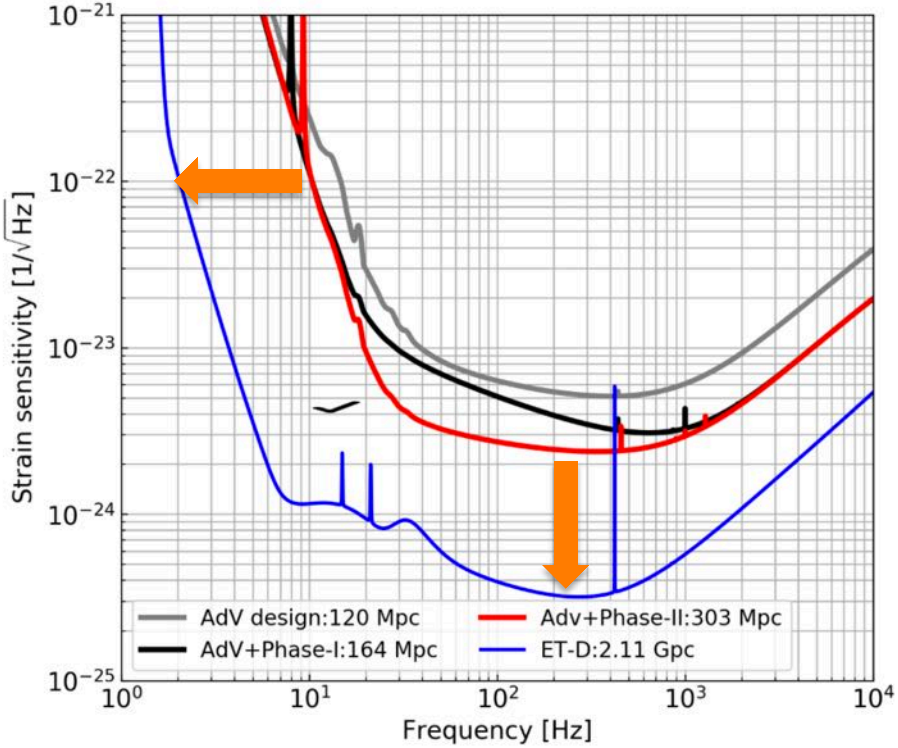
Each detector (red, green and blue) consists of two Michelson interferometers. The HF detectors need one filtercavity each, while the LF detectors require 2 filter cavities each due to the use of detuned signal recycling.

Number of 'long' suspensions = 21 (ITM, ETM, SRM, BS, PRM of LF-IFOs) of which 12 are crogenic.

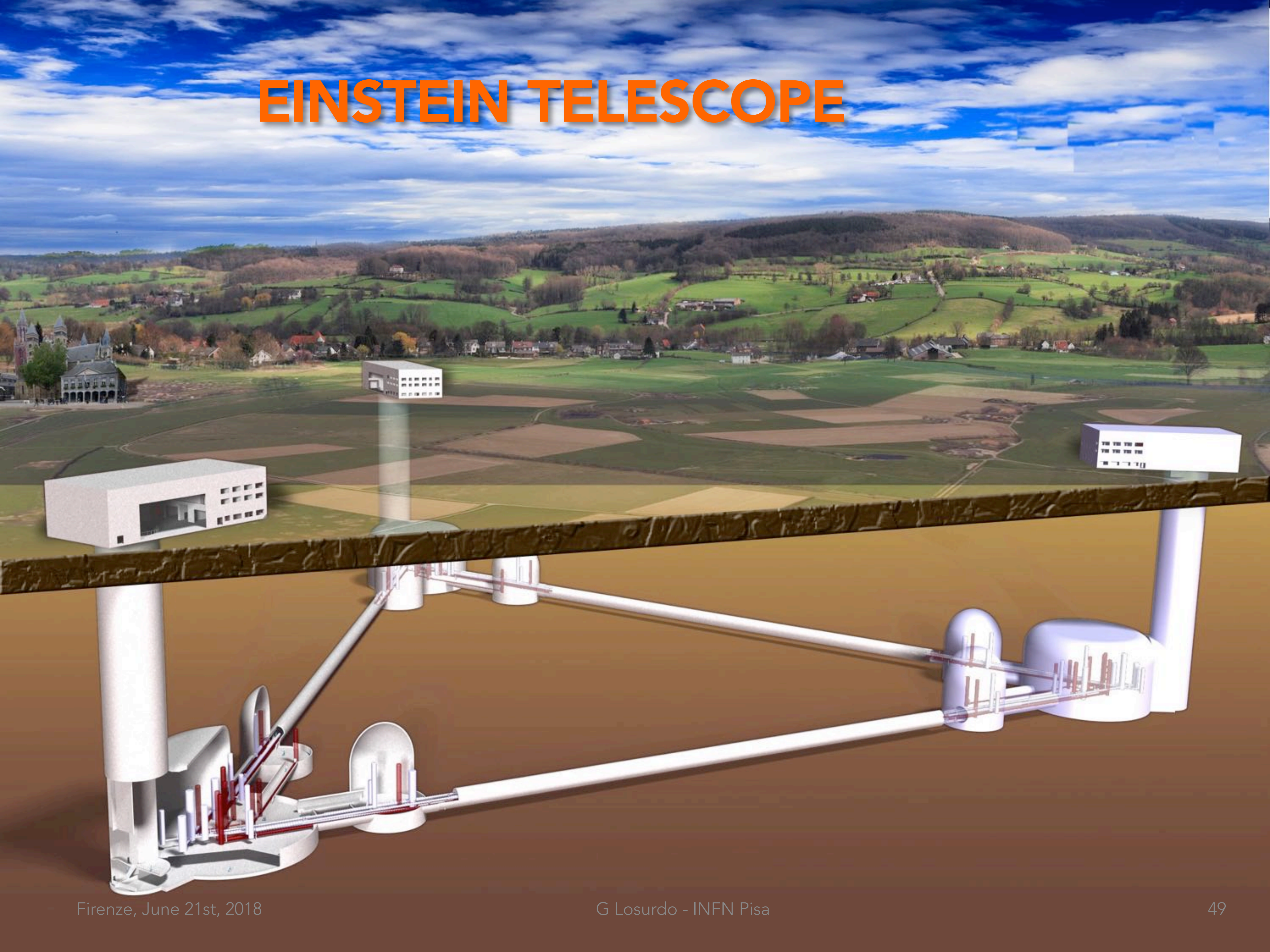
Number of 'normal' suspensions (PRM, BS, BD and FC) = 45 for linear filtercavities and 54 for triangular filter cavities

Beams per tunnel =7

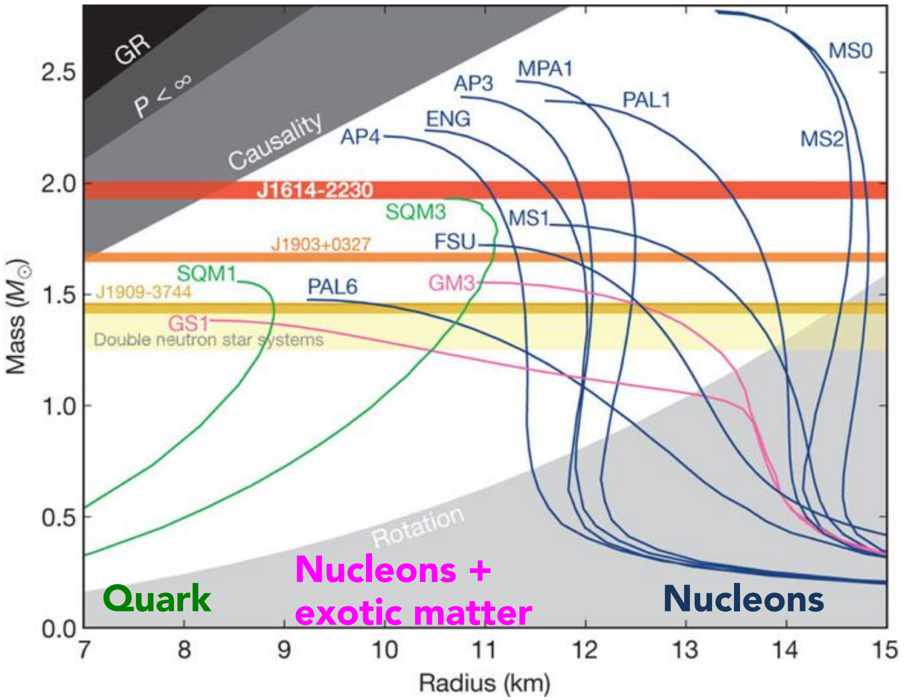
ET Design Study, 2011



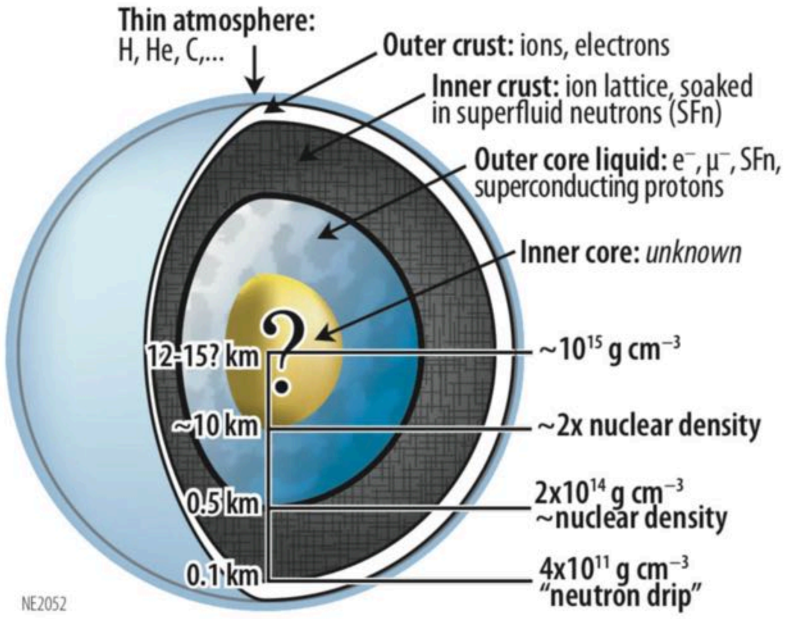
EINSTEIN TELESCOPE



EXTREME MATTER



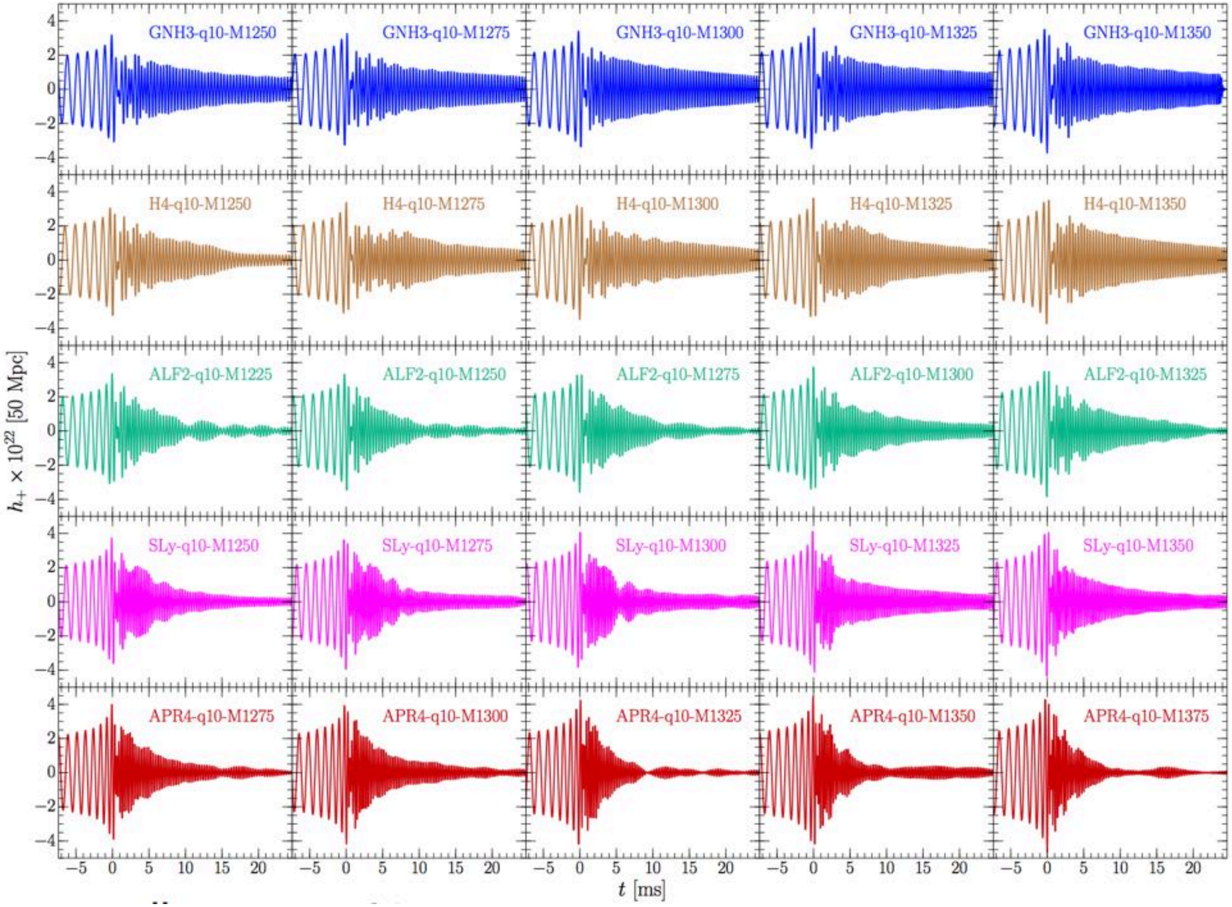
DEMOREST+, 2010



INTERNAL STRUCTURE AND COMPOSITION OF NS (LARGELY UNKNOWN) ENCODED IN THE EQUATION OF STATE

EXTREME MATTER

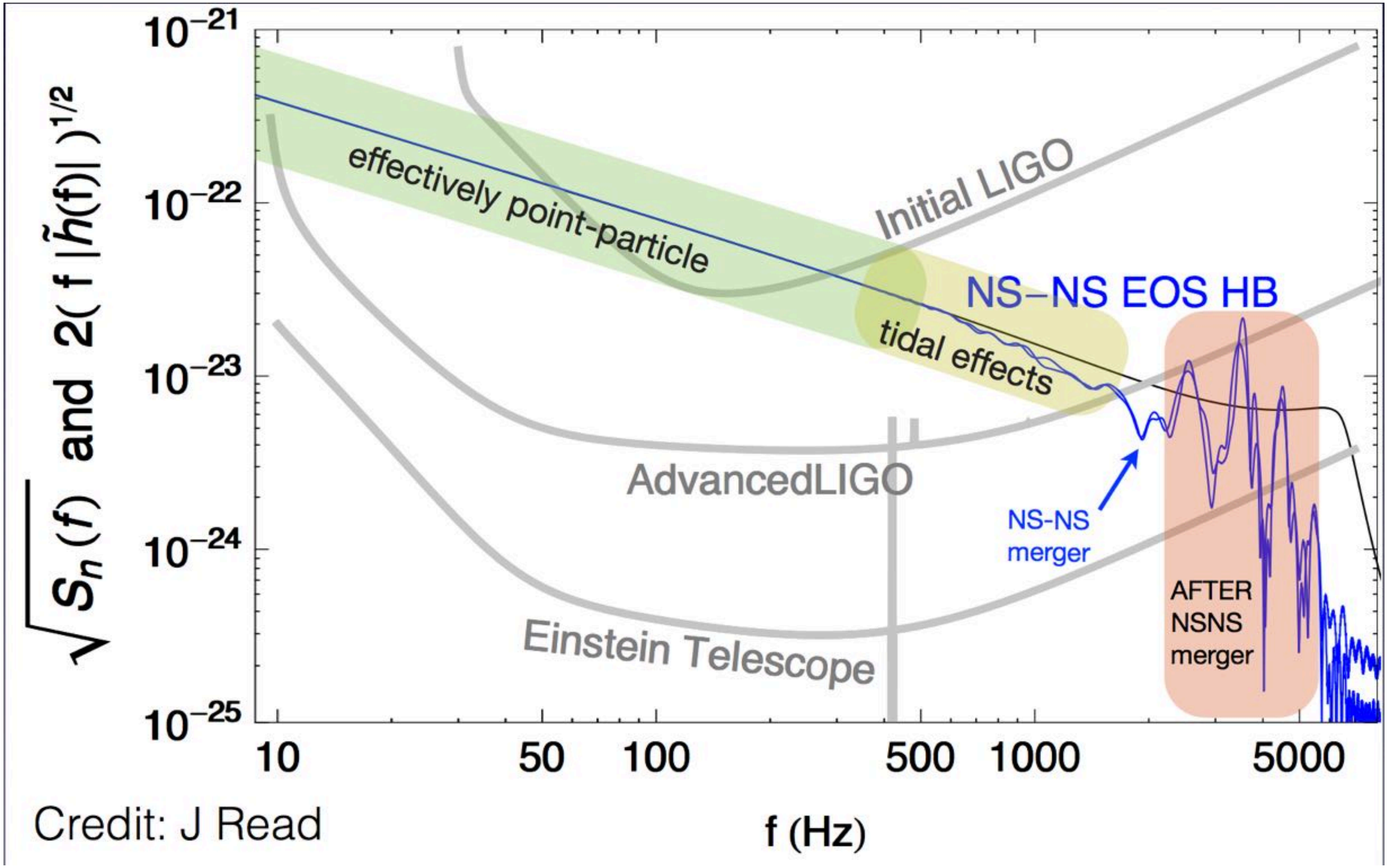
WE ARE ABLE TO COMPUTE THE WAVEFORMS FOR THE VARIOUS EOS



Takami, Rezzolla, Baiotti (2014)

EXTREME MATTER

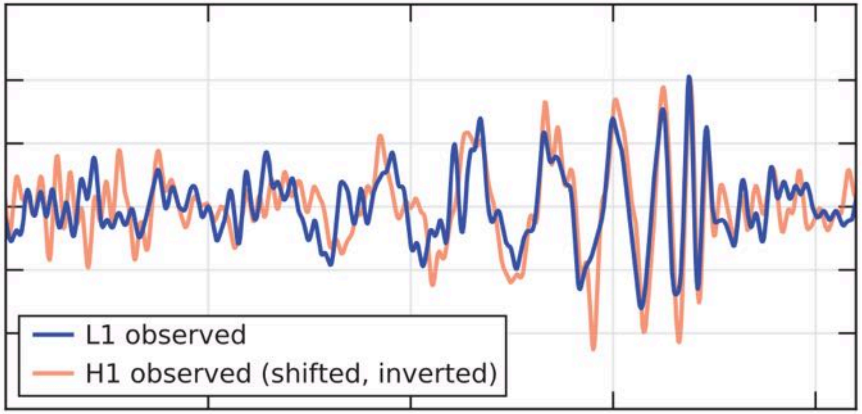
A 3G DETECTOR IS NEEDED TO MEASURE WHICH EOS IS THE RIGHT ONE



Credit: J Read

EXTREME GRAVITY

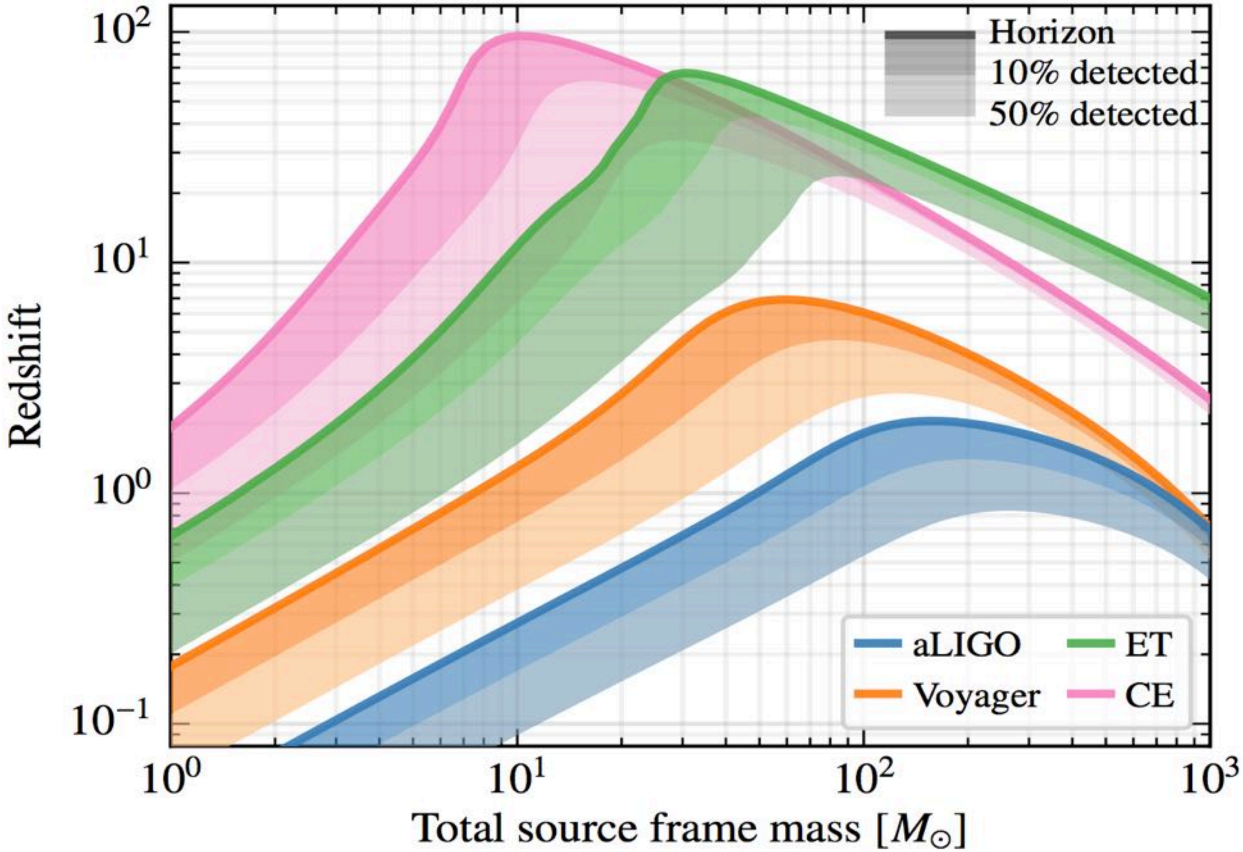
- ❑ Precision tests of alternative theories
  - polarizations
  - graviton mass
  - Lorentz invariance
- ❑ Exotic compact objects
- ❑ BH QNM



Detector	GW150914 SNR	QNM SNR
O1	25	7
Advanced LIGO	80	20
LIGO-India ALIGO+ (2024)	250	80
ET (2030)	800	200
Cosmic Explorer (2034)	2400	800

EXTREME UNIVERSE

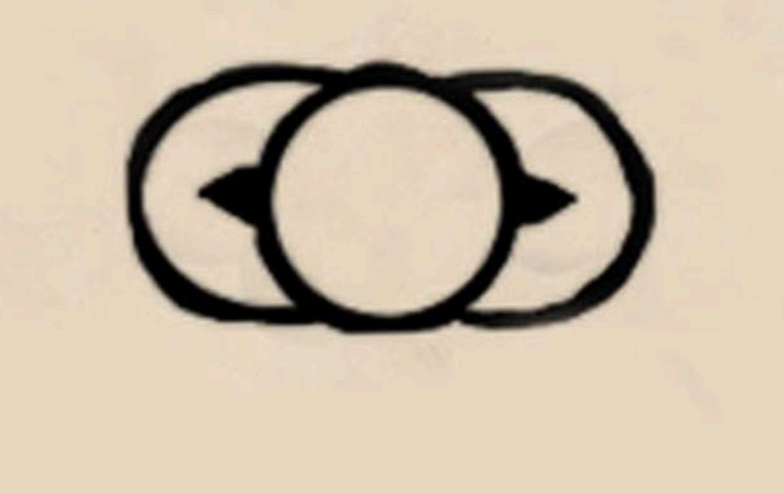
- Hubble parameter
- Stochastic background

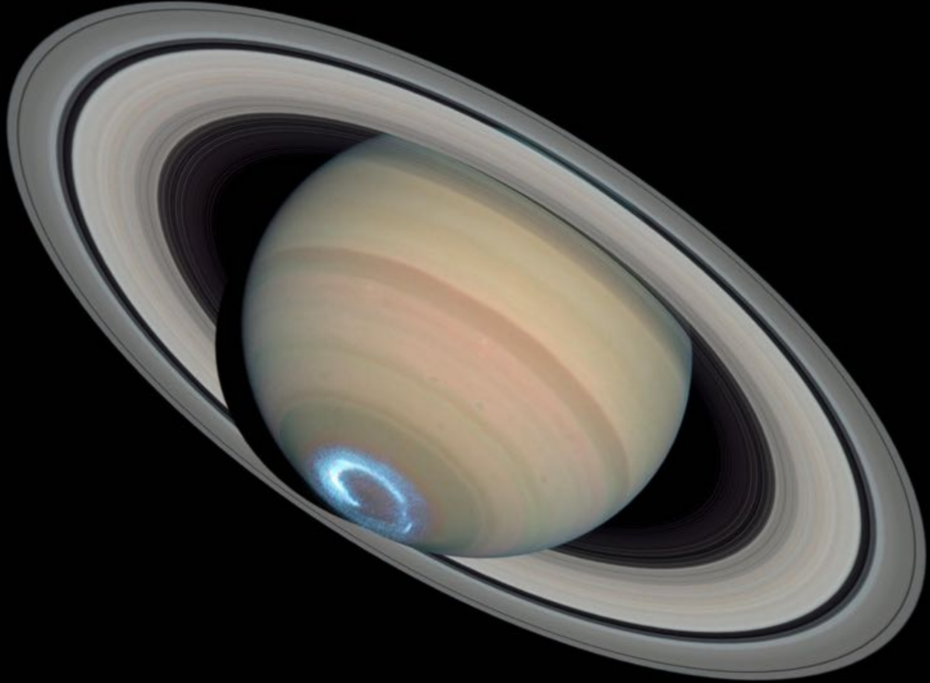


WE HAVE THE RIGHT INSTRUMENT.
NOW WE NEED TO MAKE IT BETTER AND BETTER AND BETTER…

Galileo, 1610

Galileo, 1616

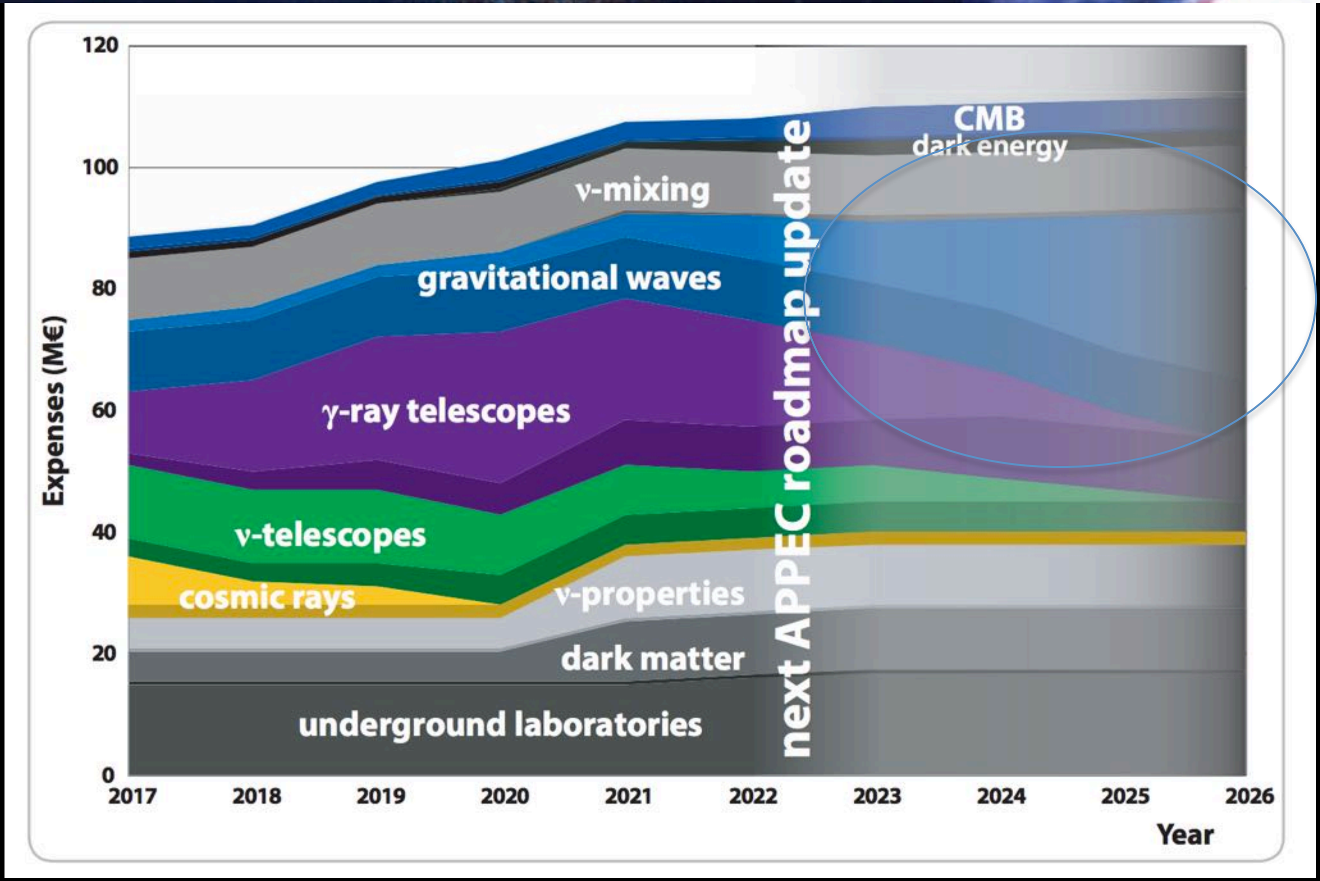




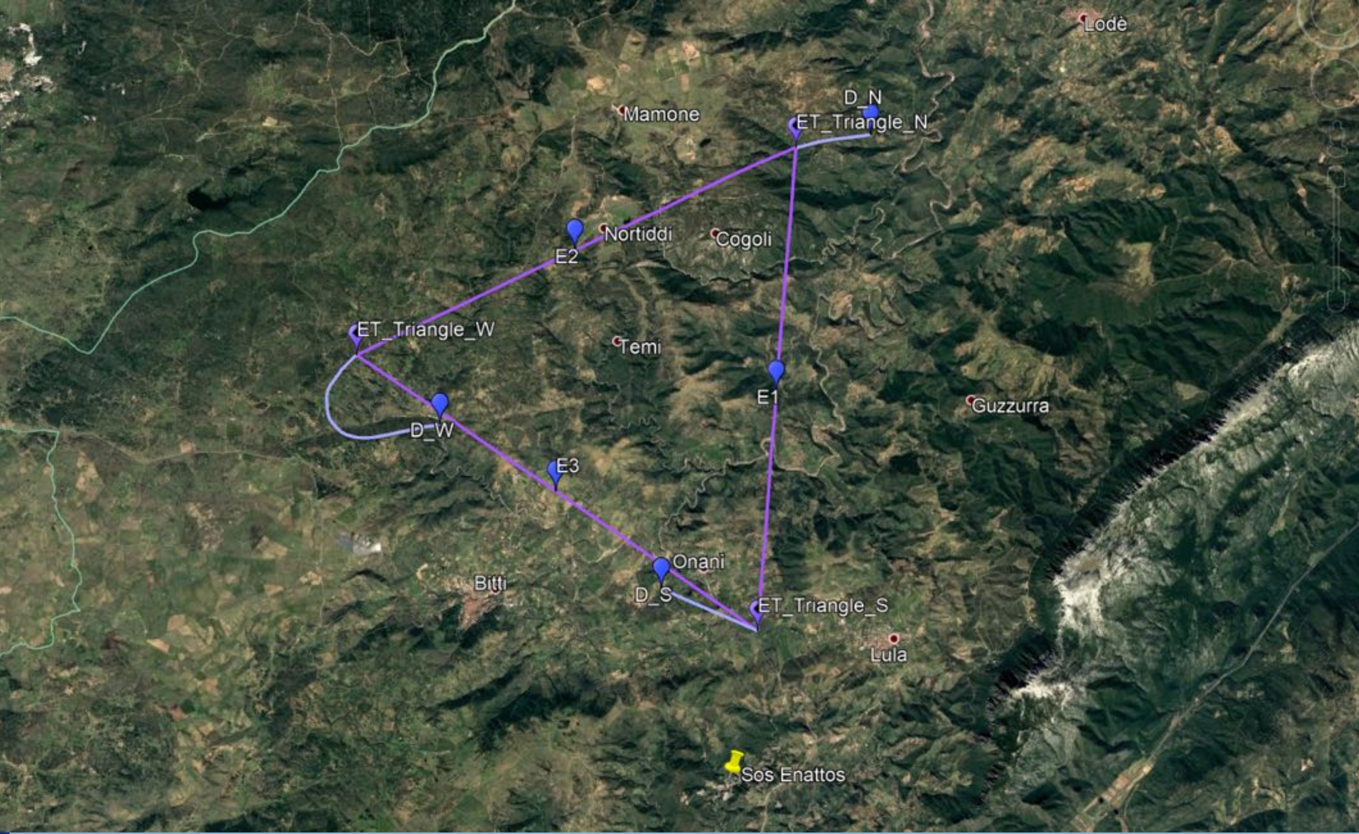
HST, 400 yrs later

APPEC

European Astroparticle Physics Strategy 2017-2026



ET: the big investment for the next decade

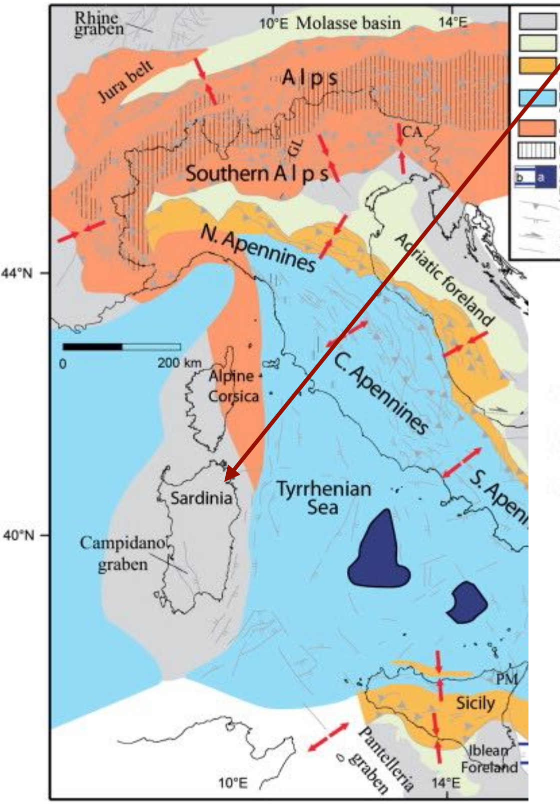


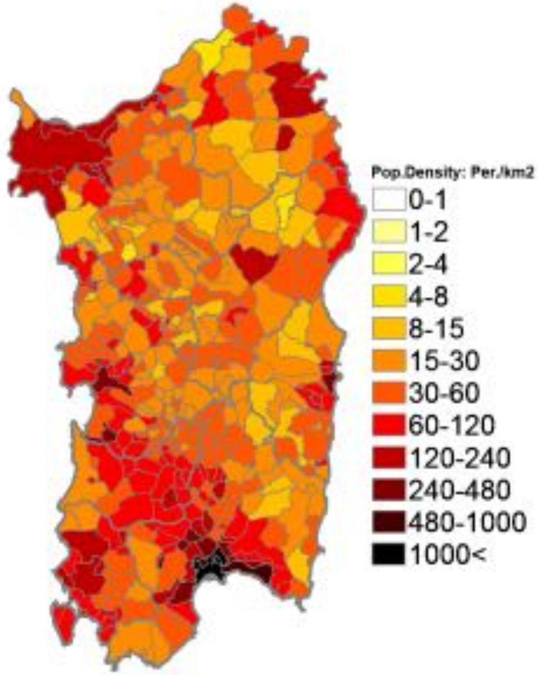
More at the ET Symposium, EGO, April 19-20

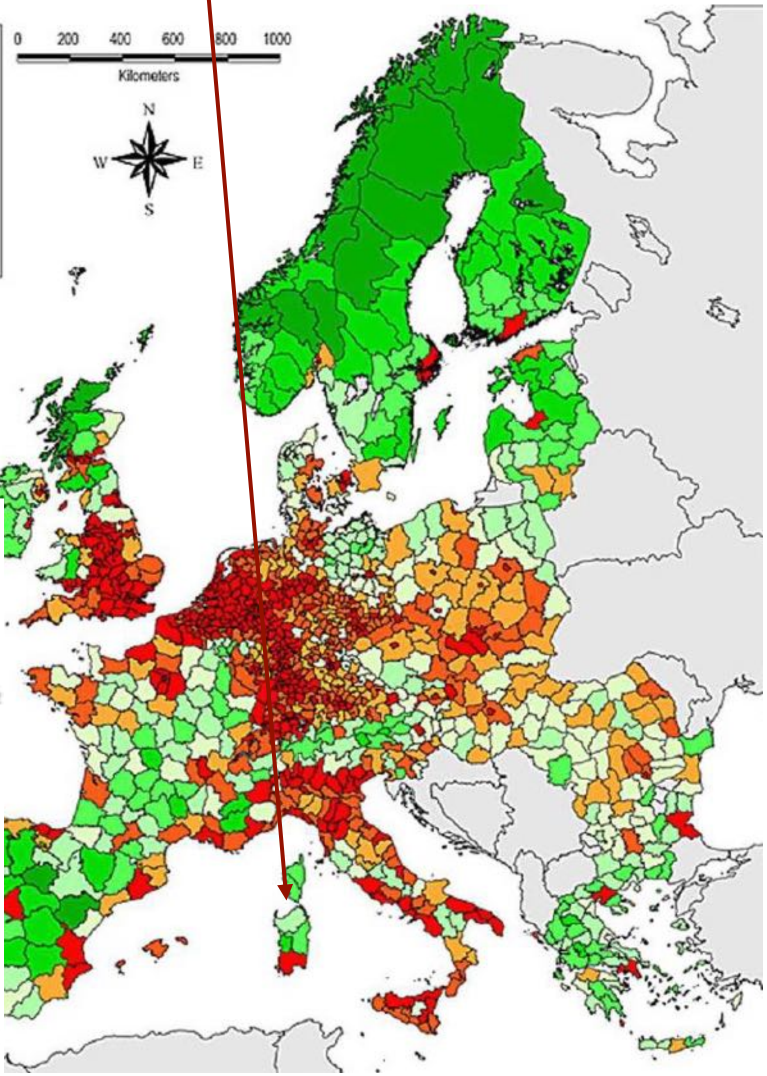
AREA ASSETS

One of the least populated areas in EU

Ancient rocks, European continental landmass: <u>seismically quiet</u>







ITALY GOVERNMENT SUPPORT

17 Meuros for AdV+, ET R&D and support of the Sos Enattos candidature

ONDE GRAVITAZIONALI: MIUR, INFN E UNISS CANDIDANO LA REGIONE SARDEGNA A OSPITARE IL FUTURO OSSERVATORIO INTERNAZIONALE

Pubblicato: 22 Febbraio 2018

COMUNICATO CONGIUNTO MIUR/INFN/REGIONE SARDEGNA/UNISS_Il Ministero dell'Istruzione, dell'Università e della Ricerca sosterrà la candidatura della Regione Sardegna a ospitare un Centro europeo per l'Osservatorio delle onde gravitazionali nella miniera di Sos Enattos a Lula. Il MIUR, la Regione, l'Istituto Nazionale di Fisica Nucleare e l'Università di Sassari hanno firmato un Protocollo d'intesa finalizzato a mettere in atto ogni iniziativa utile a favorire l'insediamento della infrastruttura Einstein Telescope nell'Isola, anche con lo scopo di entrare nella lista delle infrastrutture di ricerca riconosciute a livello europeo. Il progetto era stato presentato lo scorso 7 febbraio a Roma alla ministra Valeria Fedeli dal presidente della Regione Francesco Pigliaru e dall'assessore della Programmazione

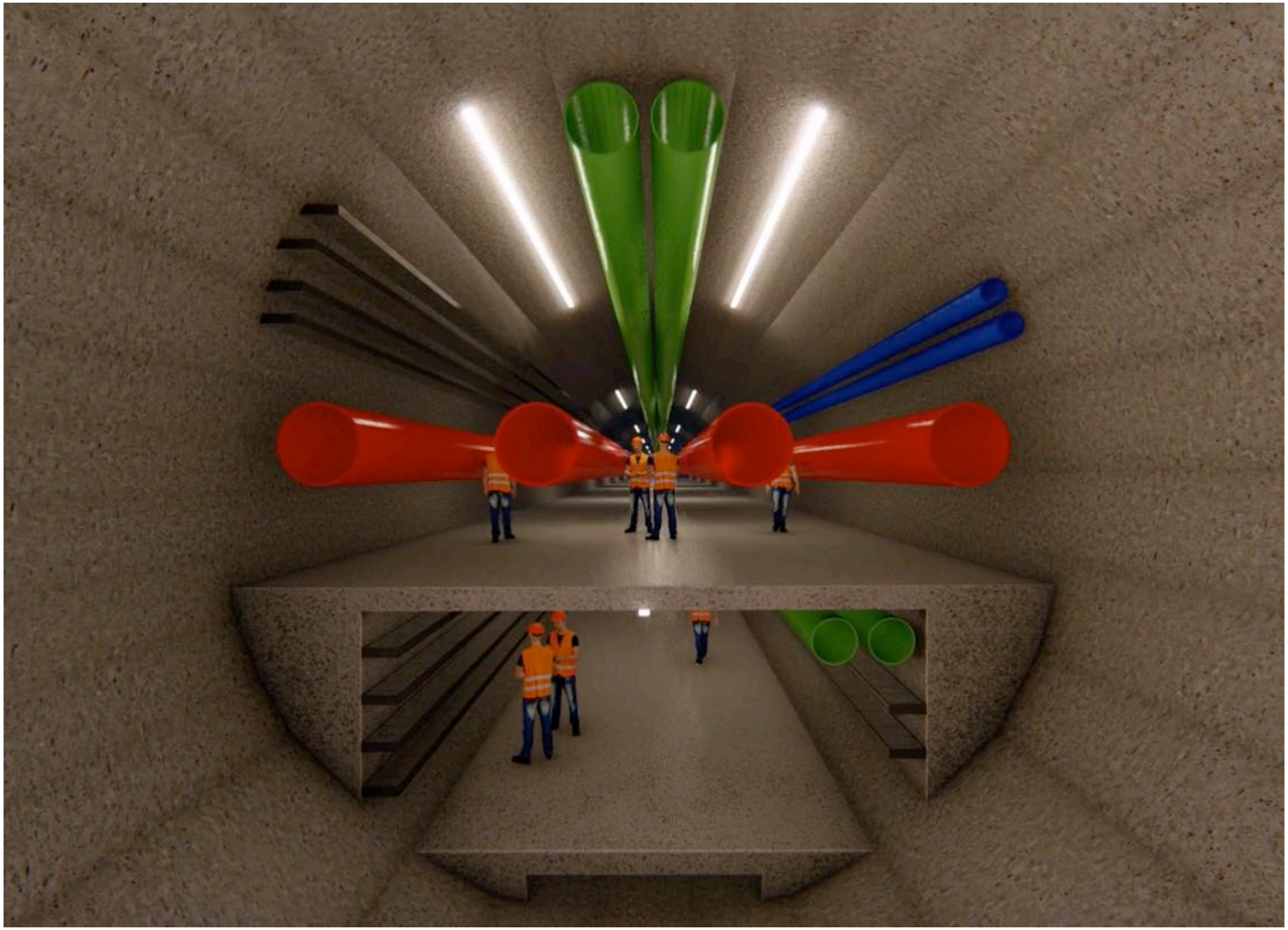
Ministero dell'Istruzione dell'Università e della Ricerca

REGIONE AUTÒNOMA DE SARDIGNA
REGIONE AUTONOMA DELLA SARDEGNA

INFN
Istituto Nazionale di Fisica Nucleare

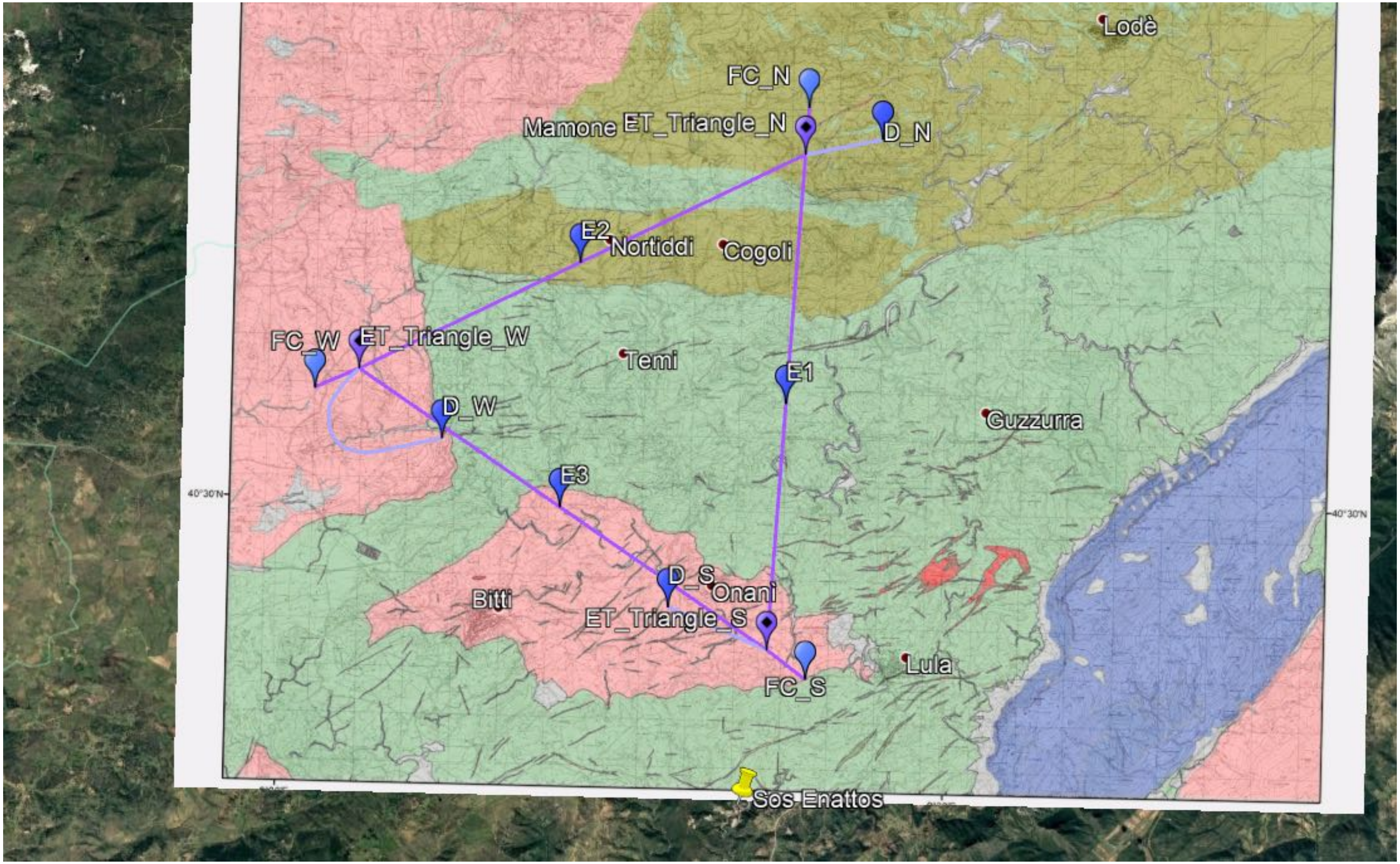
uniss
UNIVERSITÀ DEGLI STUDI DI SASSARI

TUNNEL - $\oslash_{in}$ 10m



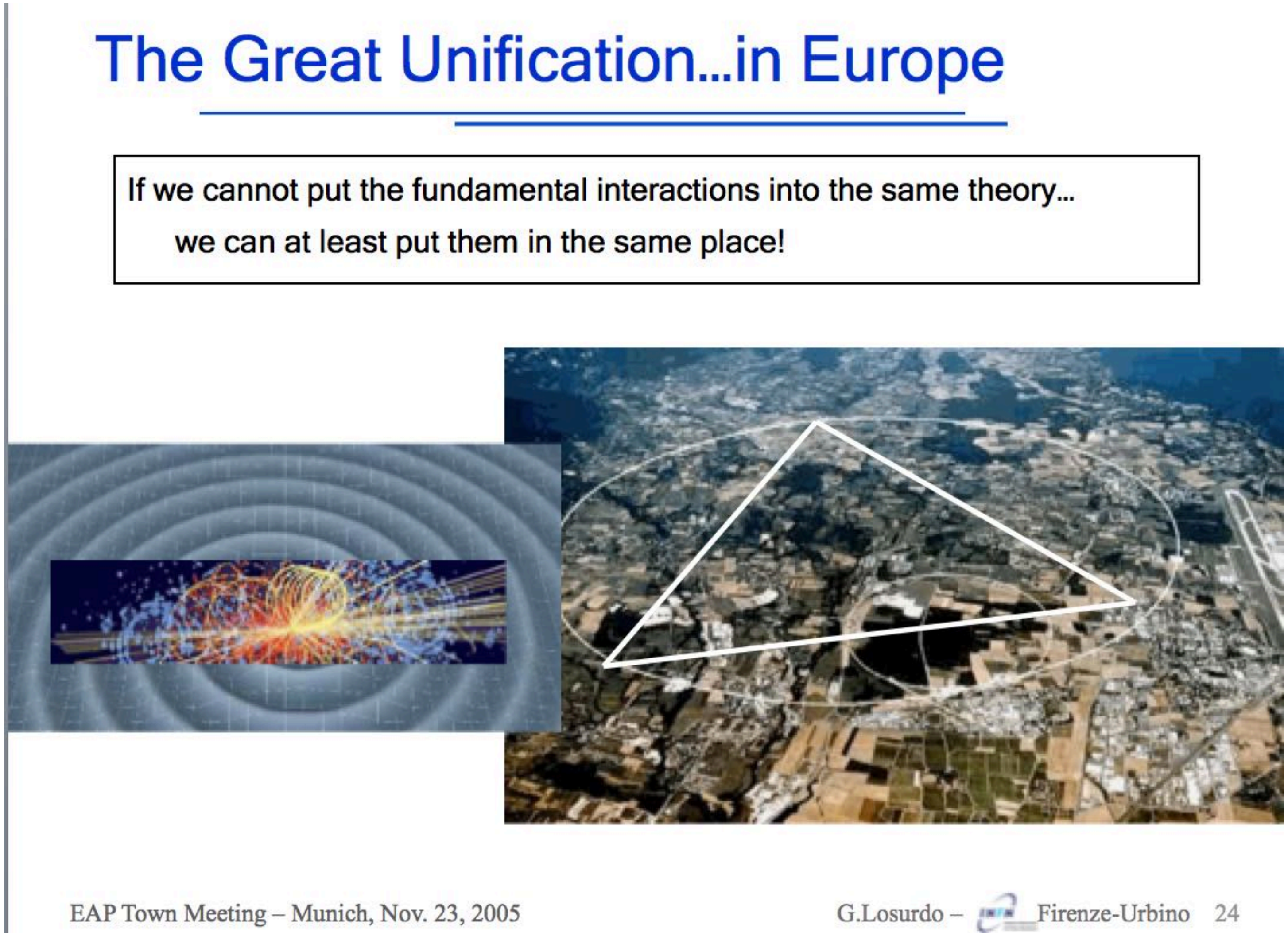
CORNER CAVERN

LOCATION - TRIANGLE



CERN

NOT THE BEST SITE FOR ET BUT….



The Great Unification…in Europe

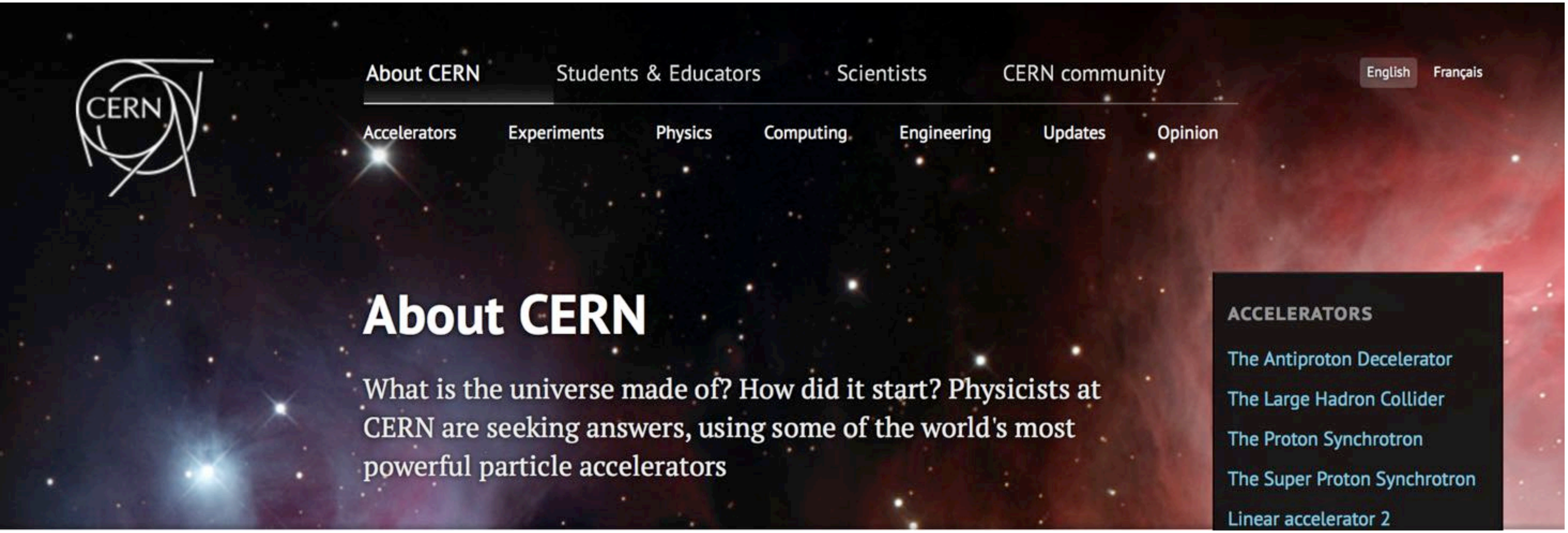
If we cannot put the fundamental interactions into the same theory…
we can at least put them in the same place!

EAP Town Meeting – Munich, Nov. 23, 2005

G.Losurdo – Firenze-Urbino 24

THE POSSIBLE ROLE OF CERN

- The GW community looks at CERN as a model to many extents
- We have a lot to learn from CERN:
  - Model of governance
  - Management of big projects
  - Technology: underground infrastructure, vacuum, cryogenics



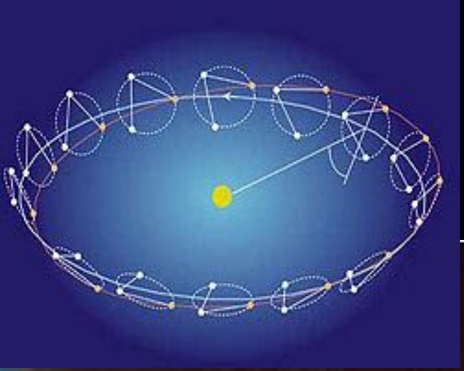
About CERN

What is the universe made of? How did it start? Physicists at CERN are seeking answers, using some of the world's most powerful particle accelerators

GF Giudice, CERN 9/2017

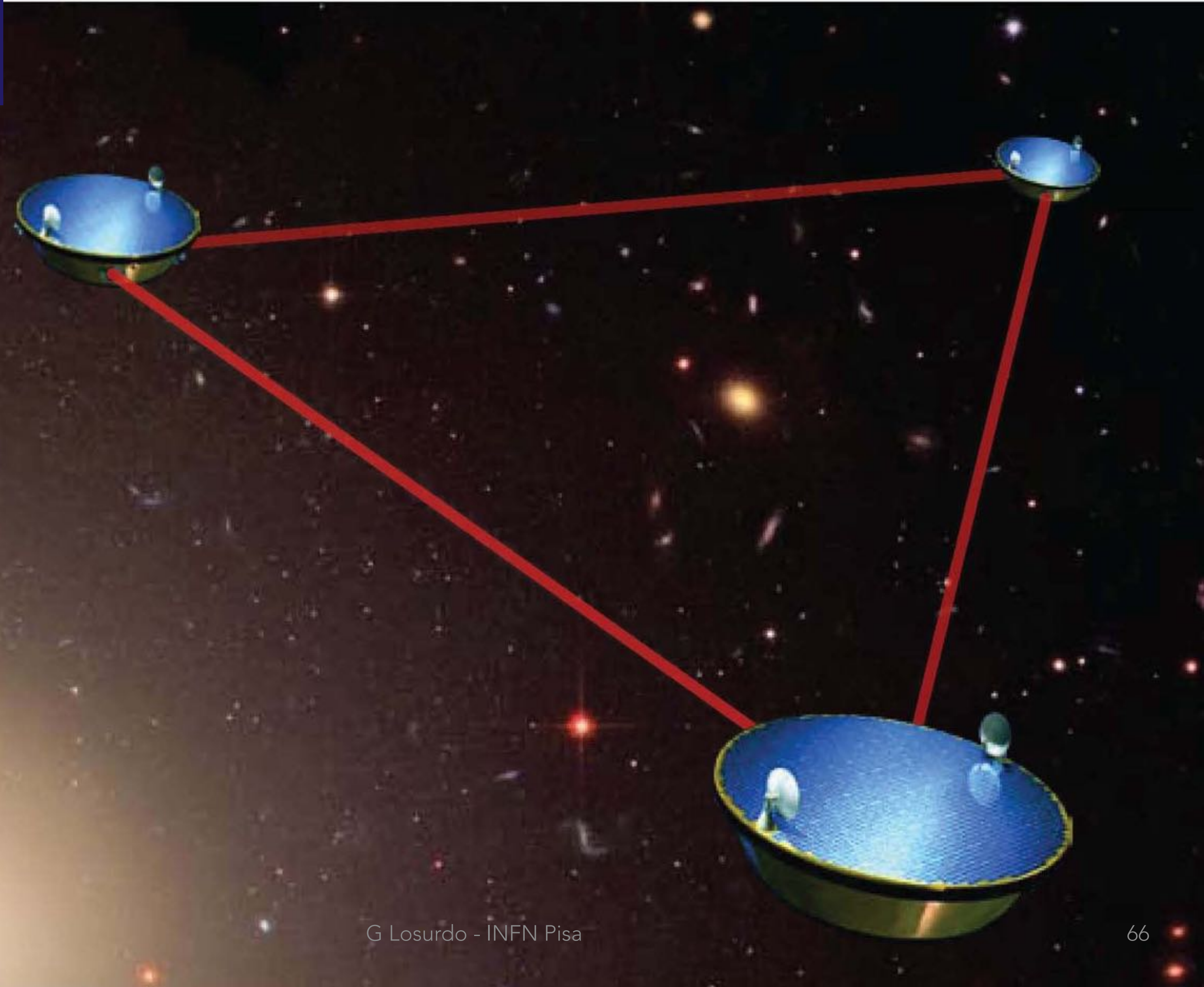
- GW physics is awesome
- Our sciences have much in common
- More than ever, particle physics needs exchange with other sciences
- GW physics has much to offer to particle physics and CERN

(tests of GR, search for ECOs, primordial BH as DM, early-universe phase transitions, cosmological stochastic bkgrd, search for light particles through superradiance, QCD in extreme conditions, ...)



LISA

credit: LISA/ESA



Enrico ha contribuito in modo tangibile ai progressi di EGO/Virgo con la sua partecipazione costante alle riunioni del Consiglio di EGO. Preciso ed acuto nei suoi interventi, capace di esercitare il suo toscano spirito critico senza condizionamenti di parte o interessi di sorta, ha operato lucidamente in modo costruttivo verso il successo del progetto. Sono rimasto sempre colpito da come Enrico potesse essere pragmatico restando comunque rigorosamente fedele ai principi. Grazie Enrico!!!

Federico Ferrini
Direttore EGO 2011-2017