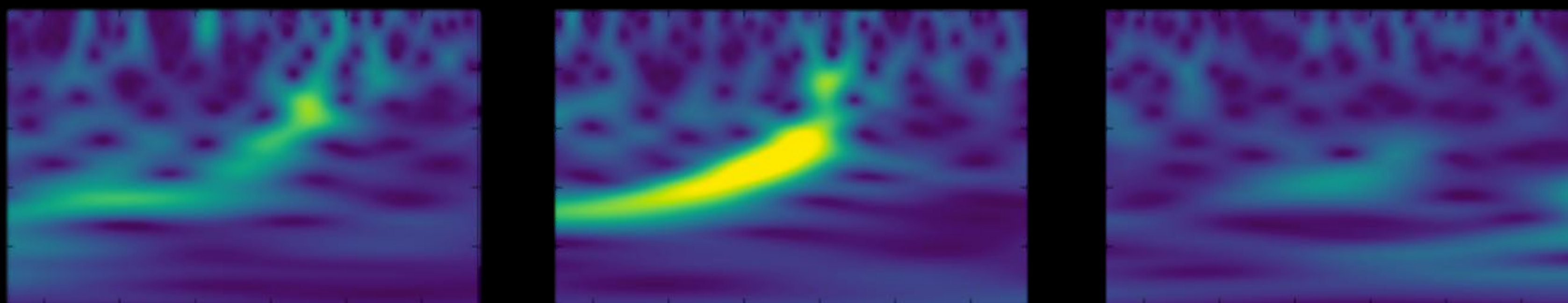
*“Rivelare le onde gravitazionali…
nessuna idea era più folle di questa”*

ADALBERTO GIAZOTTO



The Advanced Virgo observing run O2

report on the first results

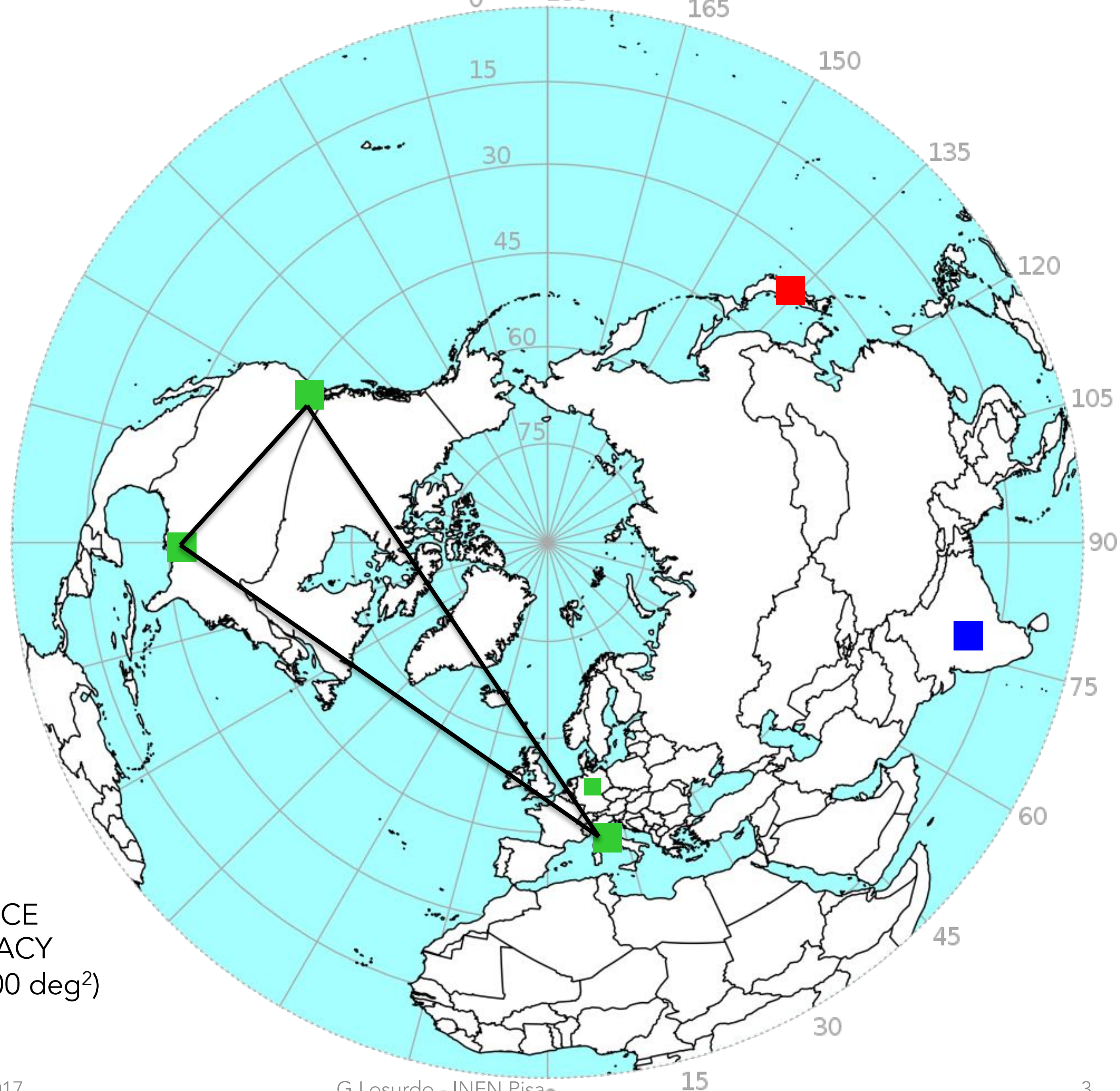
Giovanni Losurdo – INFN Pisa
presenting results of the
LSC and VIRGO Coll.

August 1st, 2017

VIRGO JOINS LIGO IN THE OBSERVATION RUN O2

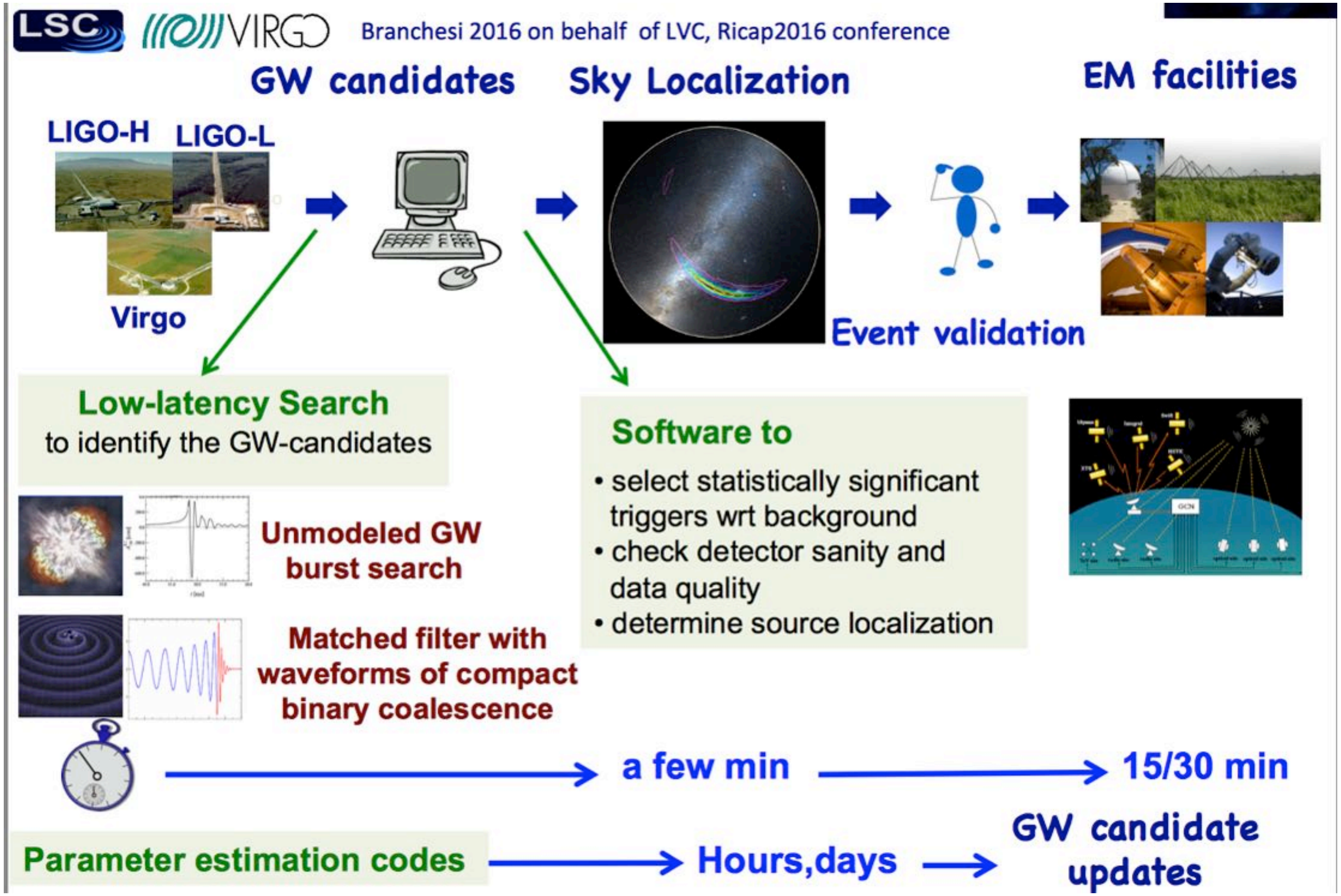
THREE 2G DETECTORS ACTING AS A "SINGLE MACHINE"

- OPERATION
- COMMISSIONING
- CONSTRUCTION
- APPROVED



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

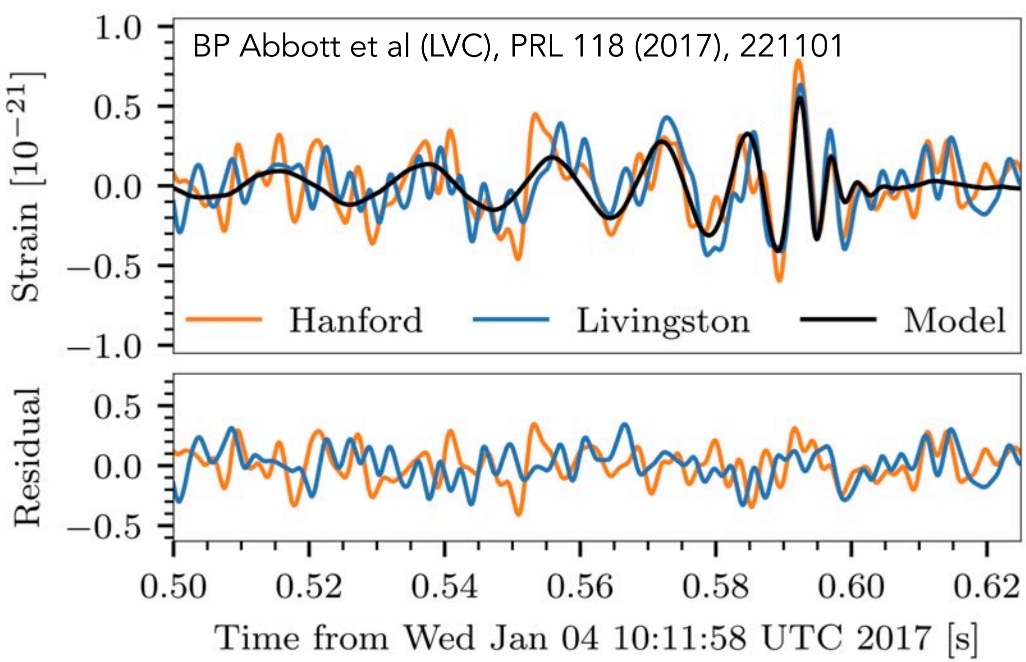
E.M. FOLLOW-UP



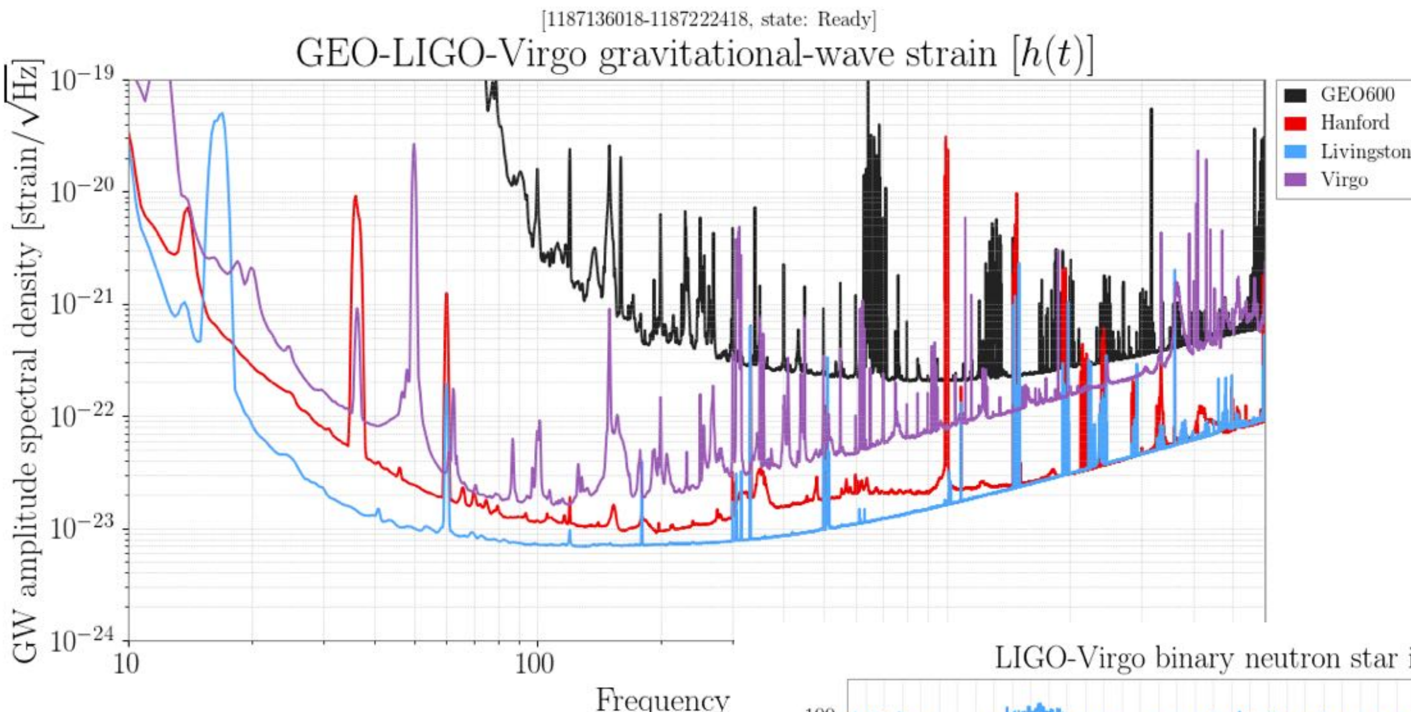
93 groups (>200 instruments) have signed the MoU with the LVC

THE O2 RUN - FACTS

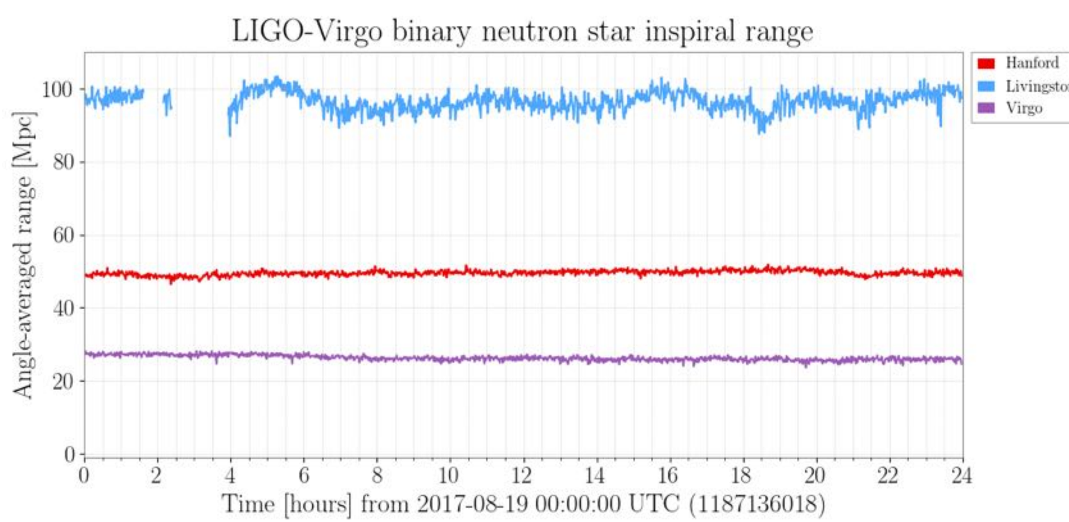
- Started on November 30, 2016
- VIRGO joined on August 1st, 2017
- The run was stopped on Aug 25th, as previously planned by LIGO
- From Aug 1st to 25th: 14.9 days of triple coincidence observation
- One event published before Aug 1st (GW170104)



NETWORK

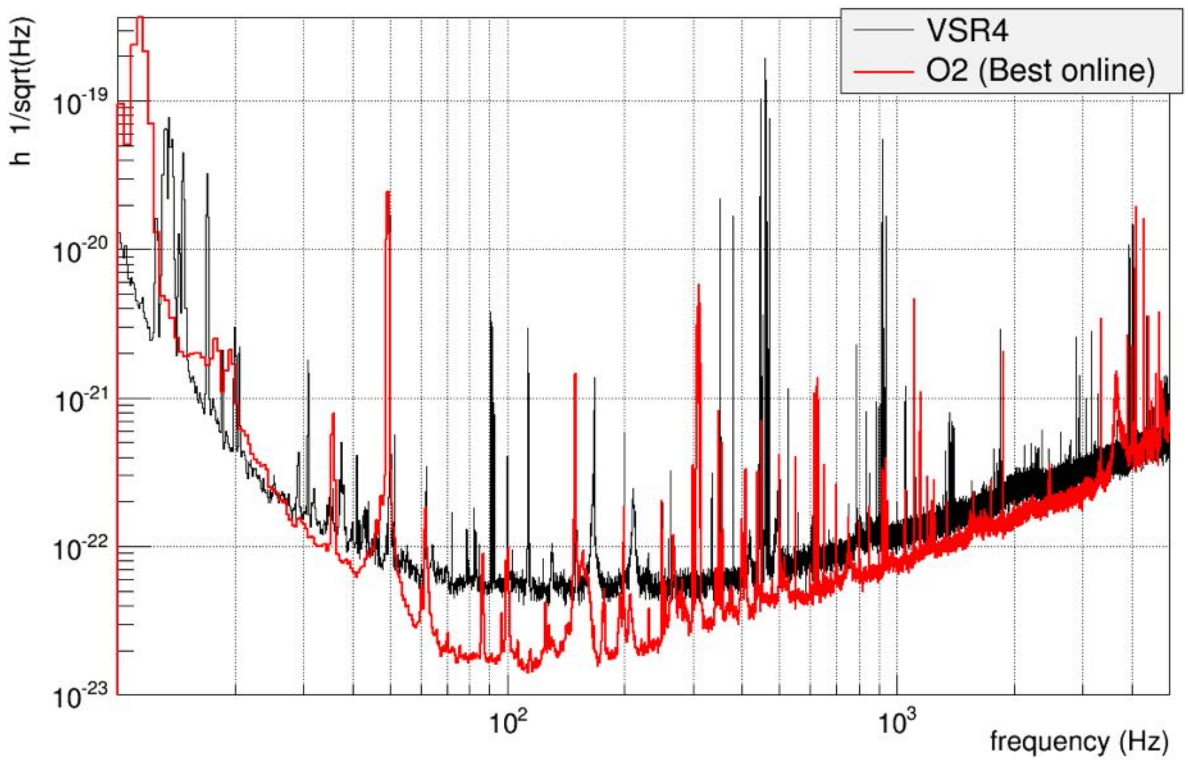


[1187136018-1187222418, state: Ready]
GEO-LIGO-Virgo gravitational-wave strain [h(t)]
GW amplitude spectral density [strain/√Hz]
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10
100
Frequency
GEO600
Hanford
Livingston
Virgo



LIGO-Virgo binary neutron star inspiral range
Angle-averaged range [Mpc]
0
20
40
60
80
100
0 2 4 6 8 10 12 14 16 18 20 22 24
Time [hours] from 2017-08-19 00:00:00 UTC (1187136018)
Hanford
Livingston
Virgo

VIRGO SENSITIVITY



- VIRGO+ (2011): BNS range of 12 Mpc
- AdV (O2): 28 Mpc, ~12x larger volume of universe reached
  - now further improved: >30 Mpc

THE COMMISSIONING RUSH

AUG '16
end of integration

DEC '16
lock at half fringe

FEB '17
1st lock at dark fringe

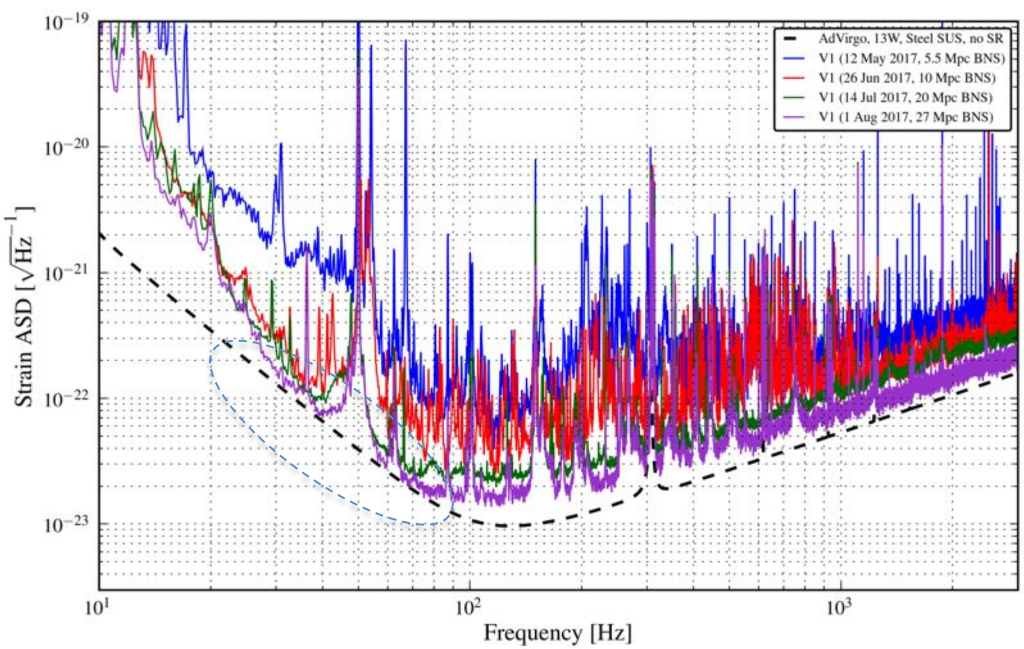
MAR '17
1st robust lock

MAY '17
1st commissioning run

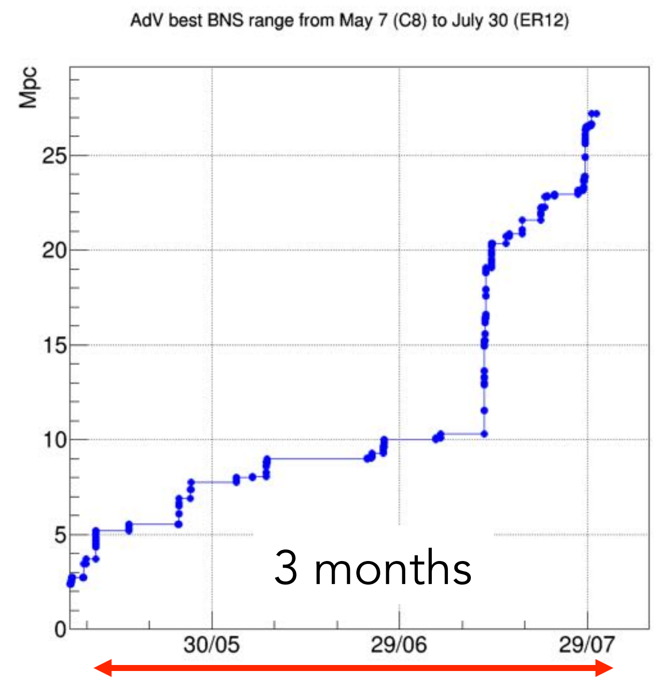
JUN '17
engineering run
with LIGO

JUL '17
20 Mpc milestone

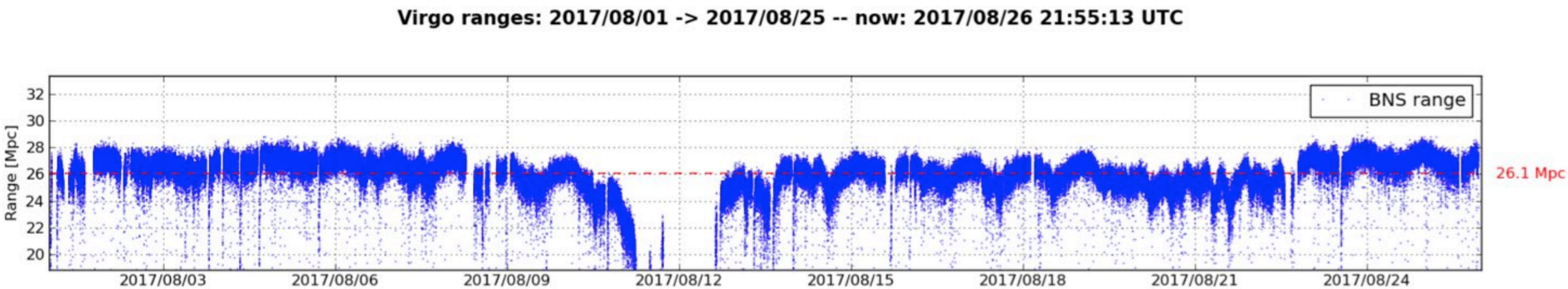
AUG 1, '17
O2 run

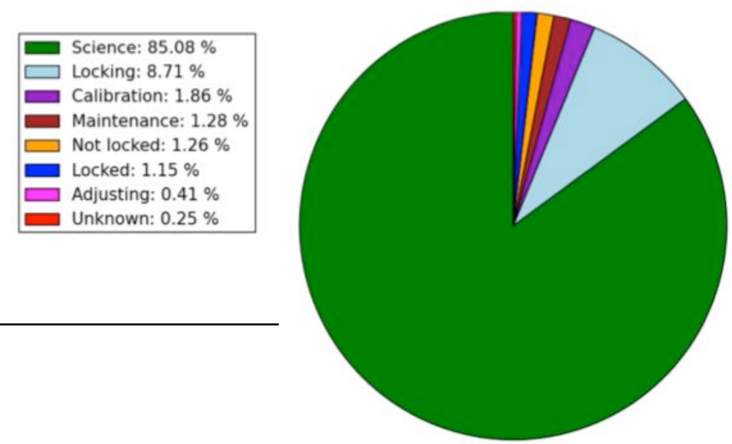


FN Pis



VIRGO IN O2





DUTY CYCLE: 85% (!!)

LONGEST LOCK STRETCH: 69 hours

HIGHEST BNS RANGE: 28.2 Mpc

AVERAGE RANGE: BNS 26 - BBH_{10} 134 - BBH_{30} 314 Mpc

Photo credit: M PERCIBALLI

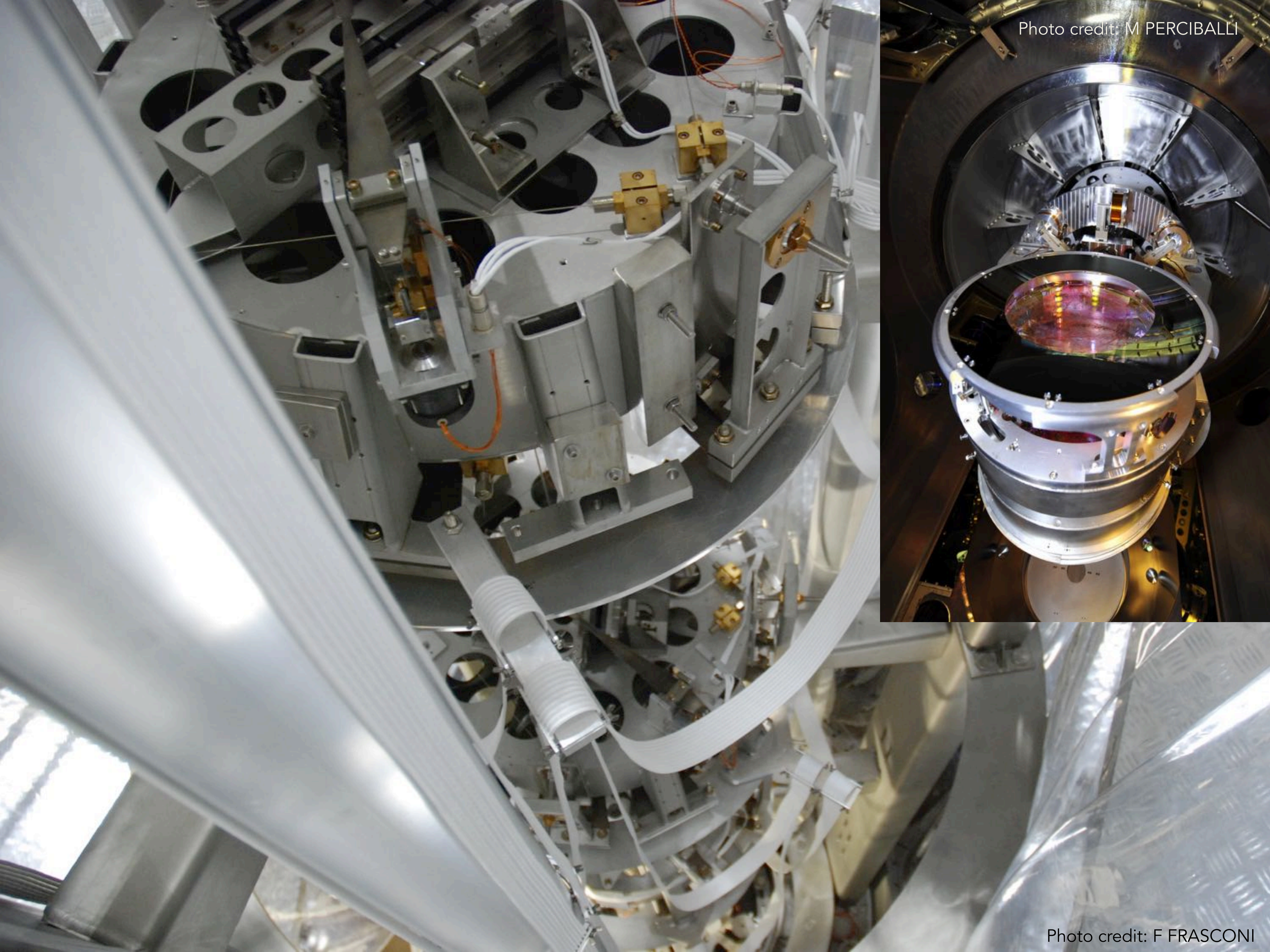


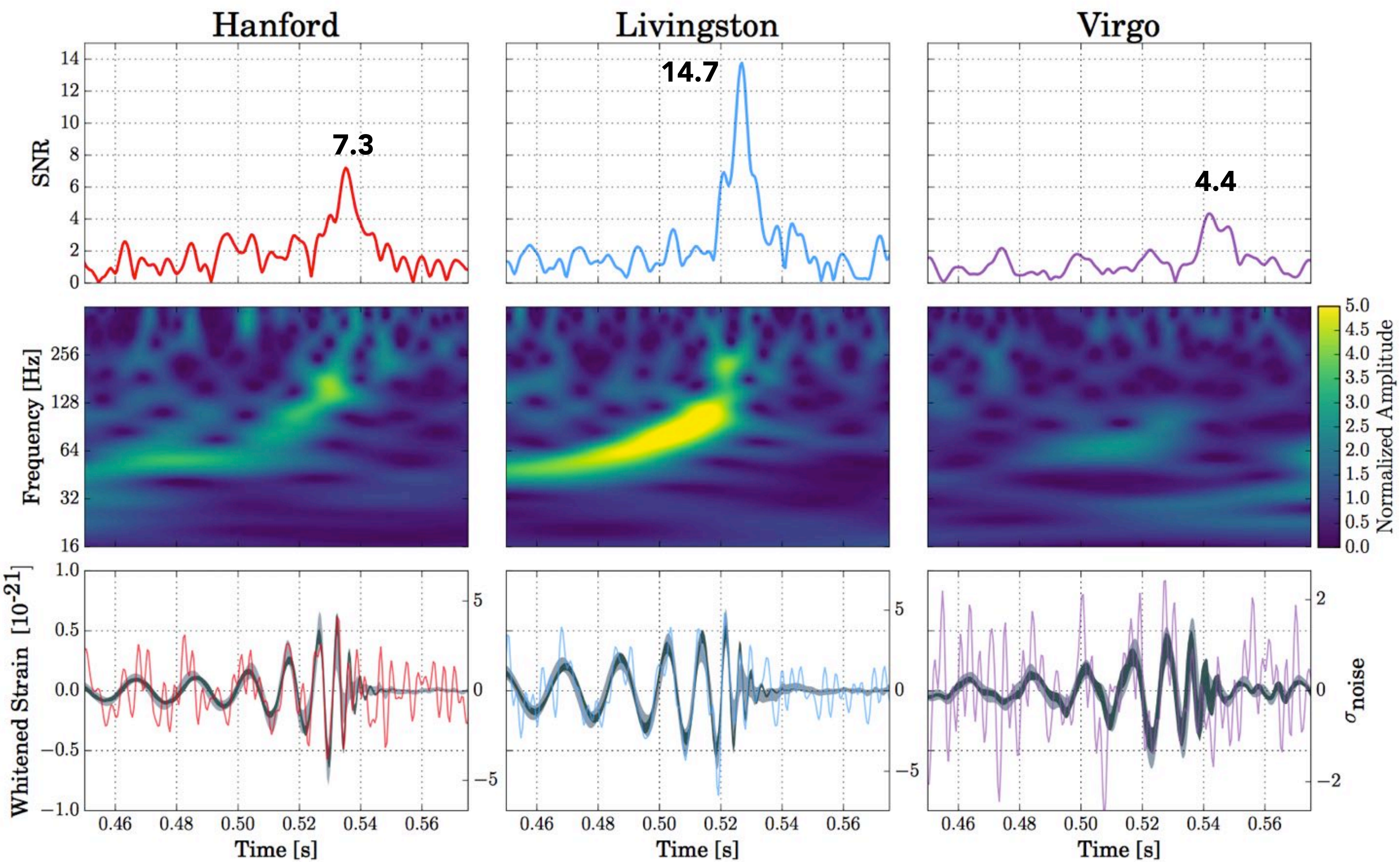
Photo credit: F FRASCONI

O2 – SCIENCE (PRELIMINARY)

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

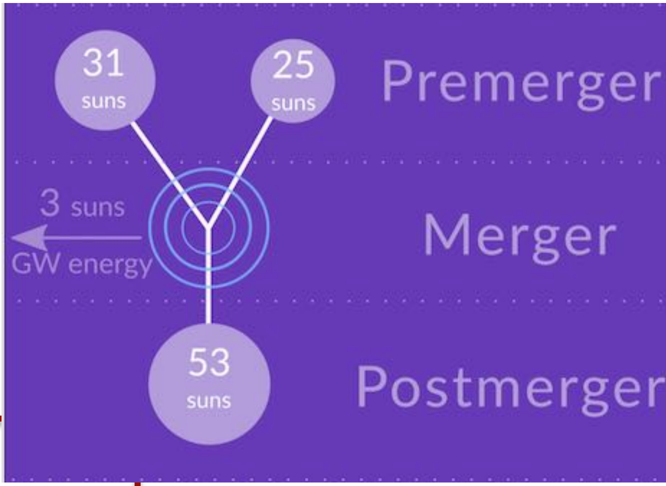
The GW hit Earth first at lat. 44.95° S, long. 72,97° W, Puerto Aysen, Chile. The signal was recorded at L1 first, then at H1 and Virgo with delays of ~8 and ~14 ms respectively



3-detector network SNR: 18.3

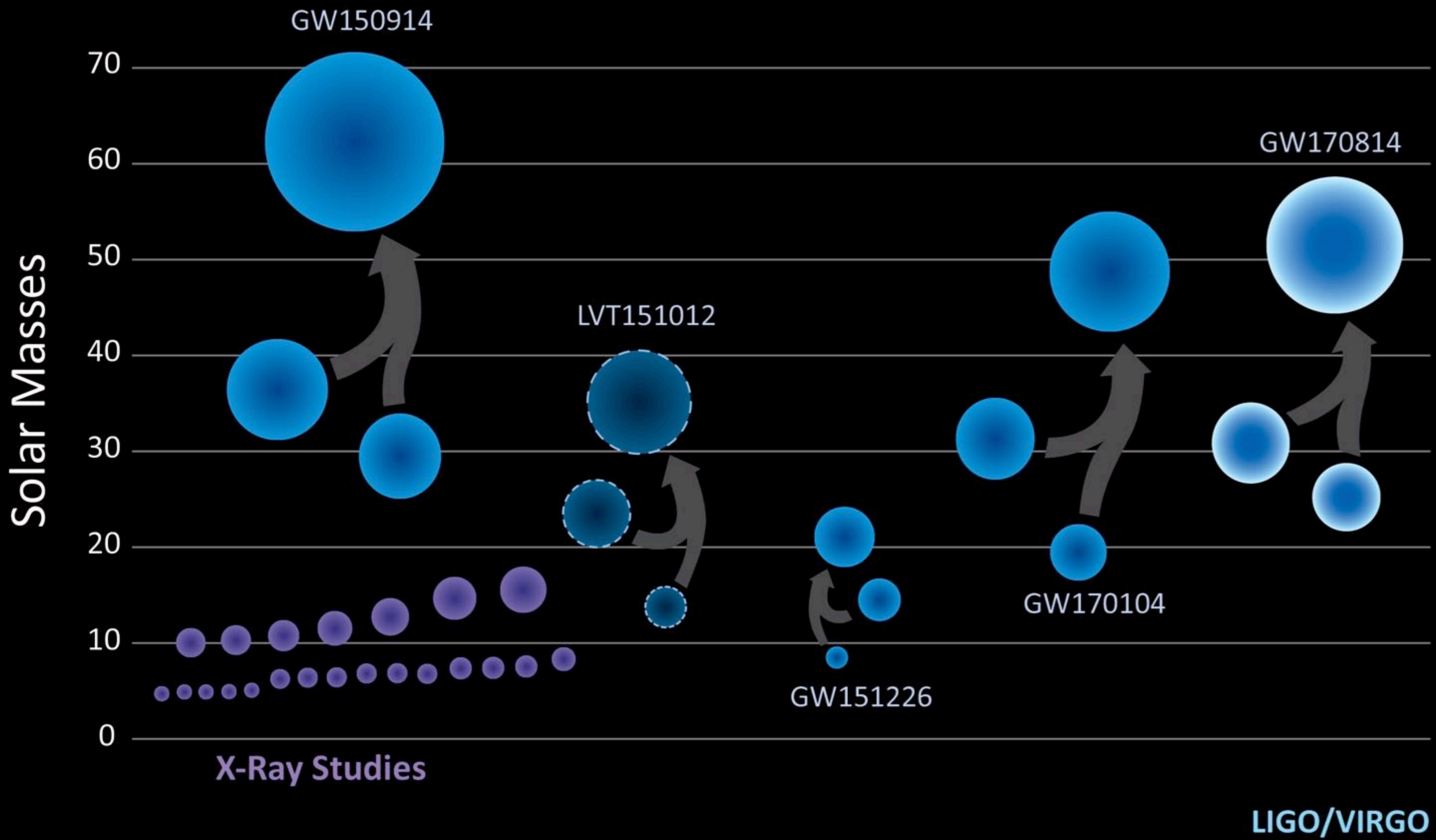
PRL, 119, 141101 (2017)

Primary black hole mass m_1	$30.5^{+5.7}_{-3.0}$ $M_\odot$
Secondary black hole mass m_2	$25.3^{+2.8}_{-4.2}$ $M_\odot$
Chirp mass $\mathcal{M}$	$24.1^{+1.4}_{-1.1}$ $M_\odot$
Total mass M	$55.9^{+3.4}_{-2.7}$ $M_\odot$
Final black hole mass M_f	$53.2^{+3.2}_{-2.5}$ $M_\odot$
Radiated energy E_{rad}	$2.7^{+0.4}_{-0.3}$ $M_\odot c^2$
Peak luminosity ℓ_{peak}	$3.7^{+0.5}_{-0.5} \times 10^{56}$ erg s^{-1}
Effective inspiral spin parameter χ_{eff}	$0.06^{+0.12}_{-0.12}$
Final black hole spin a_f	$0.70^{+0.07}_{-0.05}$
Luminosity distance D_L	540^{+130}_{-210} Mpc
Source redshift z	$0.11^{+0.03}_{-0.04}$

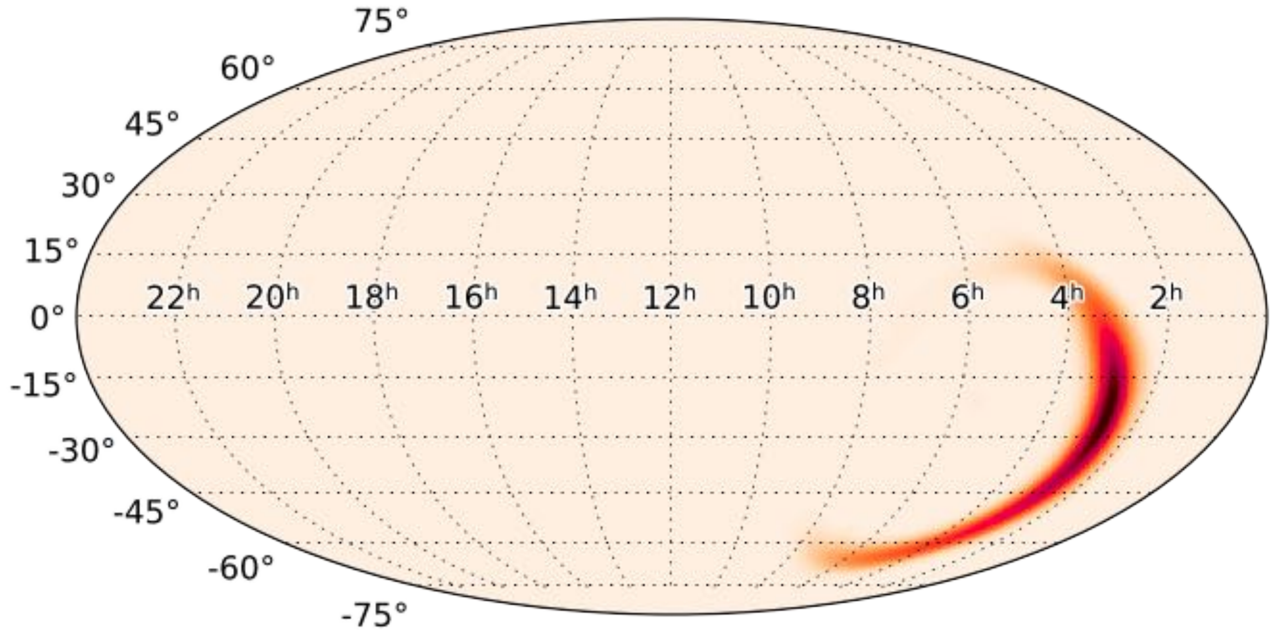


PRL, 119, 141101 (2017)

Black Holes of Known Mass

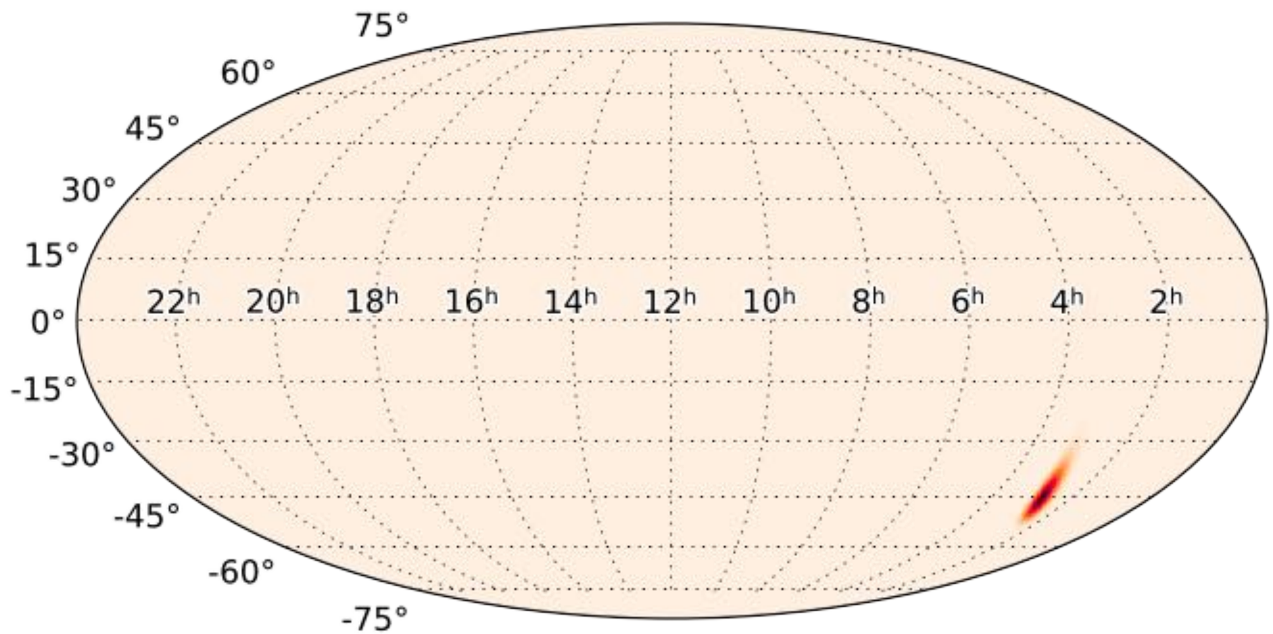


LOCALIZATION

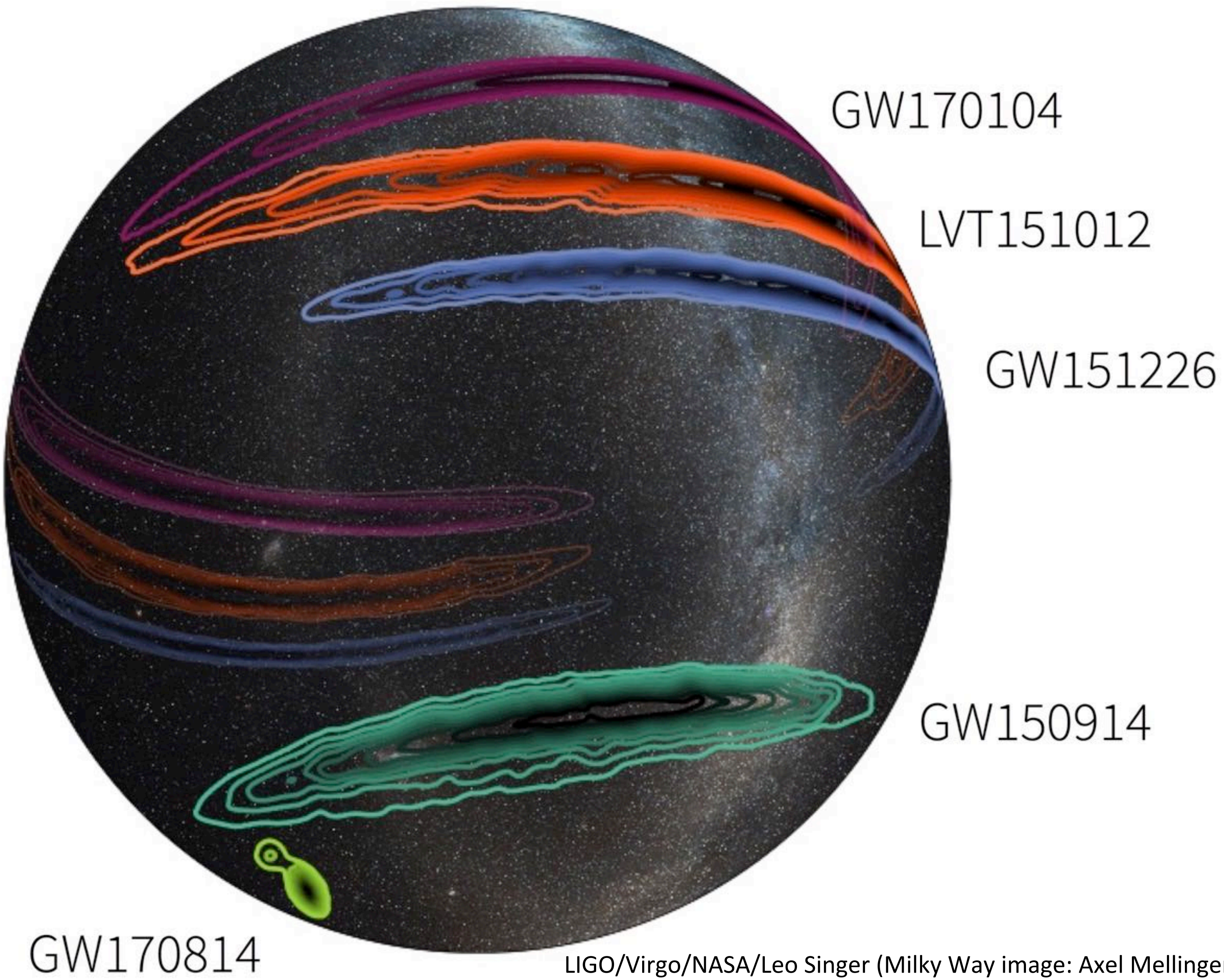


WITH THE TWO LIGOs

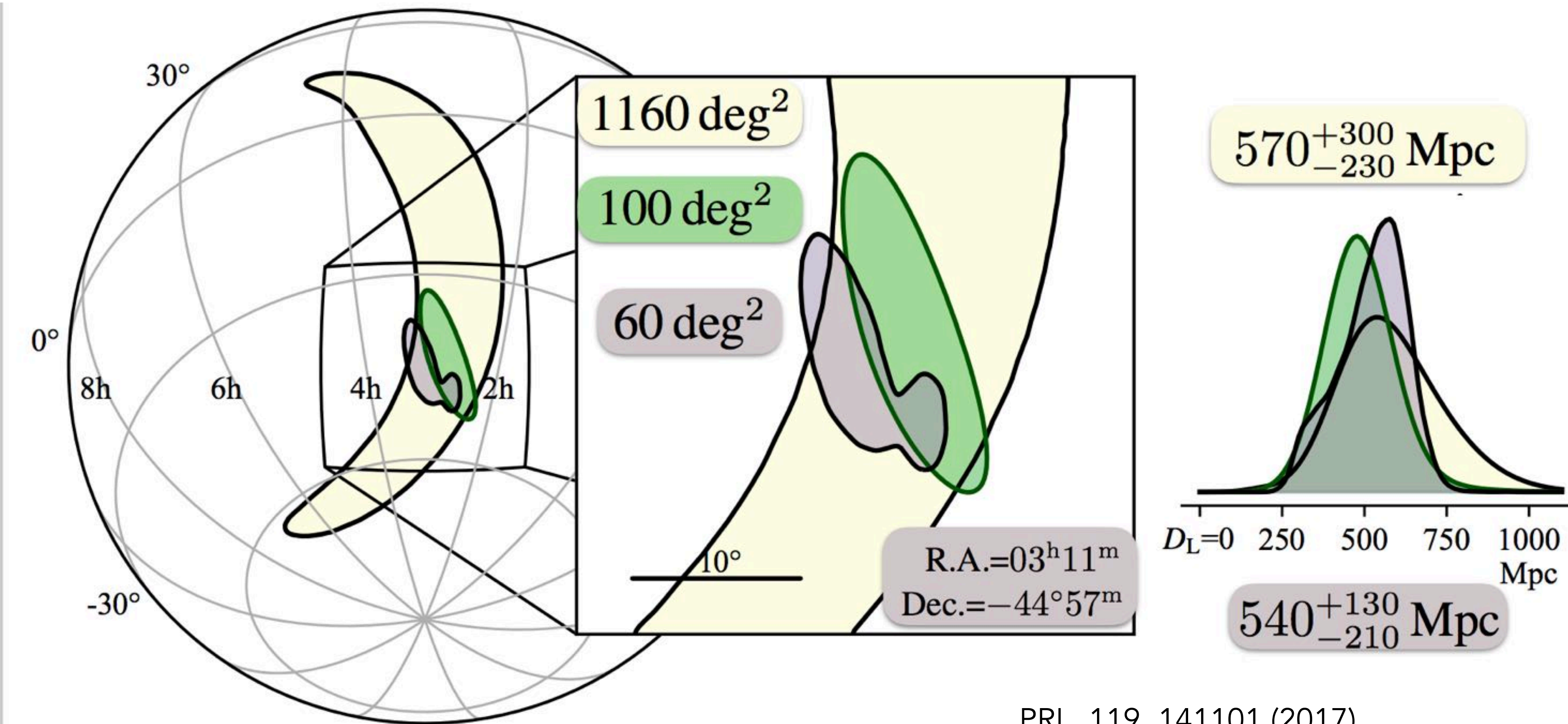
LOCALIZATION



WITH THE TWO LIGOs + VIRGO



LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)



PRL, 119, 141101 (2017)

VIRGO HELPS REDUCING:

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

THE ERA OF GW ASTRONOMY HAS FINALLY STARTED

FOLLOW UP

Follow-up observations of GW170814 were conducted by 25 facilities in neutrinos [70–72], gamma-rays [73–81], X-rays [82–85], and in optical and near-infrared [86–98]. No counterpart has been reported so far.

ν

[70] S. Countryman, GCN **21475**, 1 (2017), IceCube circular.
[71] D. Dornic, GCN **21479**, 1 (2017), ANTARES circular.
[72] J. Alvarez-Muniz, GCN **21523**, 1 (2017), Pierre Auger circular.

γ

[73] A. Pozanenko, GCN **21476**, 1 (2017), *INTEGRAL* SPI-ACS circular.
[74] F. Verrecchia, GCN **21477**, 1 (2017), *AGILE* MCAL circular.
[75] V. Savchenko, GCN **21478**, 1 (2017), *INTEGRAL* SPI-ACS and MCAL circular.
[76] D. Kocevski, GCN **21481**, 1 (2017), *Fermi* LAT circular.
[77] F. Verrecchia, GCN **21482**, 1 (2017), *AGILE* circular.
[78] A. Goldstein, GCN **21484**, 1 (2017), *Fermi* GBM circular.
[79] D. Svinkin, GCN **21500**, 1 (2017), *Konus/WIND* circular.
[80] F. Schussler, GCN **21673**, 1 (2017), H.E.S.S. circular.
[81] V. Savchenko, GCN **21695**, 1 (2017), *INTEGRAL* circular.

X

[82] A. Lien, GCN **21483**, 1 (2017), *Swift* BAT circular.
[83] S. Xiong, GCN **21486**, 1 (2017), *Insight*-HXMT circular.
[84] S. Sugita, GCN **21494**, 1 (2017), MAXI GSC circular.
[85] P. Evans, GCN **21503**, 1 (2017), *Swift* XRT circular.

visible, IR

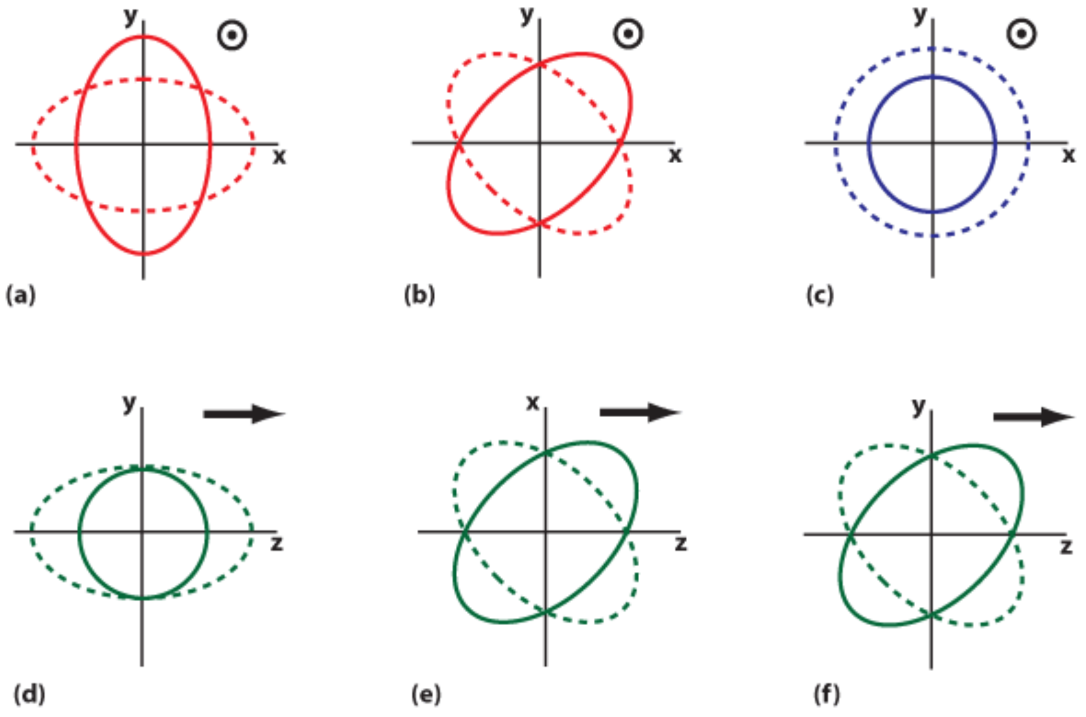
[86] S. J. Smartt, GCN **21488**, 1 (2017), Pan-STARRS circular.
[87] P. D'Avanzo, GCN **21495**, 1 (2017), REM circular.
[88] Y. Utsumi, GCN **21497**, 1 (2017), Subaru Hyper Suprime-Cam circular.
[89] G. Greco, GCN **21498**, 1 (2017), ESO-VST circular.
[90] V. Lipunov, GCN **21499**, 1 (2017), MASTER circular.
[91] C. Copperwheat, GCN **21512**, 1 (2017), Liverpool Telescope circular.
[92] G. P. Smith, GCN **21692**, 1 (2017), Gemini and VLT circular.
[93] M. Soares-Santos, GCN **21789**, 1 (2017), DECam circular.
[94] G. Hosseinzadeh, GCN **21860**, 1 (2017), LCOGT circular.
[95] S. Yang, GCN **21878**, 1 (2017), DLT40 circular.
[96] M. Im, GCN **21885**, 1 (2017), LSGT circular.
[97] D. Roberts, GCN **21888**, 1 (2017), PIRATE circular.
[98] N. Tanvir, GCN **21890**, 1 (2017), VISTA circular.

POLARIZATION

GENERAL METRIC THEORIES OF GRAVITY ALLOW UP TO 6 POLARIZATION STATES

TENSOR (SPIN 2)
GENERAL RELATIVITY

SCALAR (SPIN 0)



VECTOR (SPIN 1)

POLARIZATION

- **For the first time**, thanks to the the addition of a 3rd detector, one can probe the nature of the polarization states
- So far a preliminary and simplified investigation has been carried out, to illustrate the potential power of this new phenomenological test of gravity
  - only models with "pure" polarization states (tensor, vector or scalar) have been considered
  - a study with "mixed" states is underway
- RESULT: GR (purely tensor) is 200 and 1000 times more likely than purely vector/scalar respectively

THE PAPER

PRL **119,** 141101 (2017) PHYSICAL REVIEW LETTERS week ending 6 OCTOBER 2017

GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 23 September 2017; published 6 October 2017)

On August 14, 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 $\lesssim 1$ in 27 000 years. The signal was observed with a three-detector network matched-filter signal-to-noise ratio of 18. The inferred masses of the initial black holes are $30.5^{+5.7}_{-3.0} M_\odot$ and $25.3^{+2.8}_{-4.2} M_\odot$ (at the 90% credible level). The luminosity distance of the source is 540^{+130}_{-210} Mpc, corresponding to a redshift of $z = 0.11^{+0.03}_{-0.04}$. A network of three detectors improves the sky localization of the source, reducing the area of the 90% credible region from 1160 deg^2 using only the two LIGO detectors to 60 deg^2 using all three detectors. For the first time, we can test the nature of gravitational-wave polarizations from the antenna response of the LIGO-Virgo network, thus enabling a new class of phenomenological tests of gravity.

DOI: 10.1103/PhysRevLett.119.141101

GW170814 - SUMMARY

- FIRST EVENT SEEN BY VIRGO (4th overall)
- FIRST EVENT WITH SMALL SKY LOCALIZATION AREA, ENABLING EFFICIENT MULTI-MESSENGER OBSERVATIONS
- FIRST EVENT ALLOWING GW POLARIZATION STUDIES


G7 Ministerial Meeting on Science
Venaria Reale, Torino 27-28 September 2017
David Shoemaker
France Cordova
Valeria Fedeli
Jo van den Brand
Frederique Marion
Giovanni Losurdo

O2 SCIENCE – WHAT NEXT?

EMBARGOED

O2 SCIENCE – WHAT NEXT?

EMBARGOED

Media Advisory: Press Conference at ESO HQ Announcing Unprecedented Discovery

11 October 2017

National Science Foundation
WHERE DISCOVERIES BEGIN

Media Advisory 17-011

Scientists to discuss new developments in gravitational-wave astronomy

Scientists representing LIGO, Virgo, and some 70 observatories will reveal new details and discoveries made in the ongoing search for gravitational waves

ESO will hold a press conference on 16 October 2017 at 16:00 CEST, at its Headquarters in Garching, Germany, to present groundbreaking observations of an astronomical phenomenon that has never been witnessed before.

OCT 16, h 16

INVITO STAMPA

Comunicazione congiunta MIUR, ASI, INAF, INFN

La comunità scientifica presenta i nuovi sviluppi dell'astronomia gravitazionale e multimessaggero

SAN PIERO A GRADO, 1985

One-mile equivalent length interferometric pendulum for seismic noise reduction

A. Giazotto, D. Passuello, and A. Stefanini

I. N. F. N. Sezione di Pisa and Dipartimento di Fisica, Universitá di Pisa, Pisa, Italy

(Received 9 August 1985; accepted for publication 14 February 1986)

We describe the performances of a 100-kg, 1-m-long active pendulum provided with a reference arm to get rid of the effects of tilting of the ground. The pendulum displacement with respect to the suspension point is measured interferometrically. The phase signal, to be sent to the actuator which displaces the suspension point, is extracted from the interferometer using an analog phase follower. At 10 Hz we obtain a virtual pendulum length of 1.7 km with the reference arm locked and 1.2 km when the reference arm is free. This device can be used to reduce the seismic noise in an antenna for low-frequency gravitational wave detection.

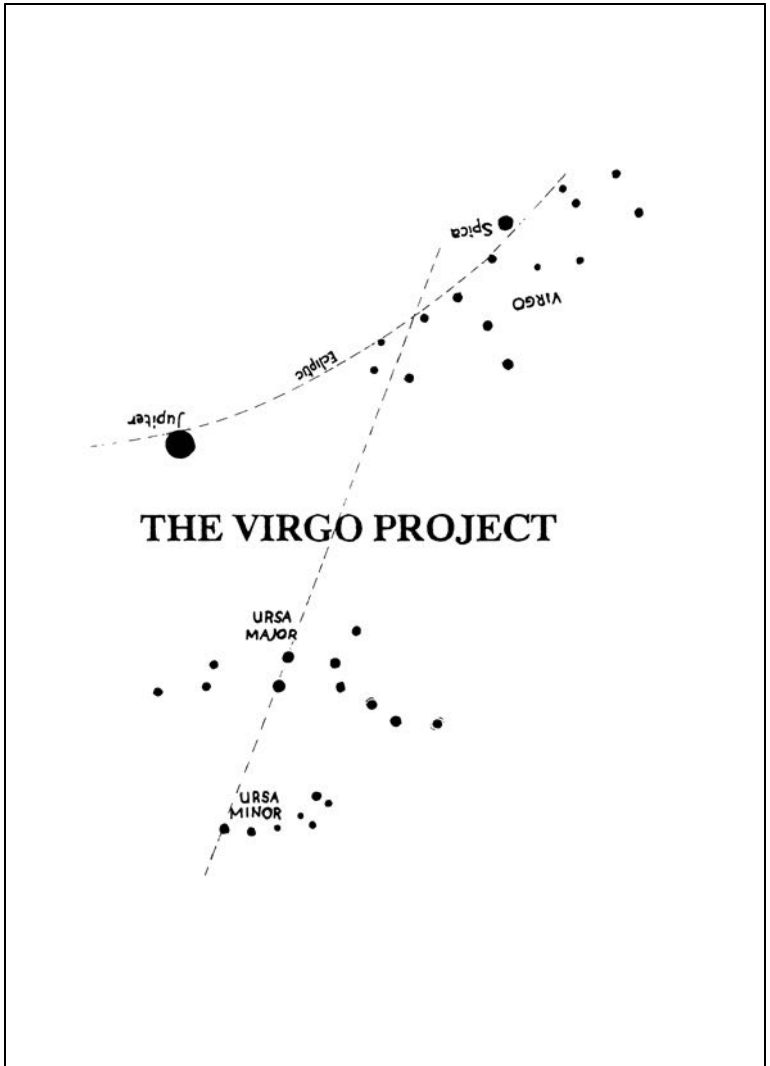
INTRODUCTION

It is well known that the length of a pendulum can be elec-

$$\psi \simeq \phi[B/(1-B)] + 0(1/B),$$

i.e., the PZT2 driving voltage is proportional to ϕ and can be

THE 1989 PROPOSAL



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

ADVANCED VIRGO

6 European countries
21 labs, ~280 authors

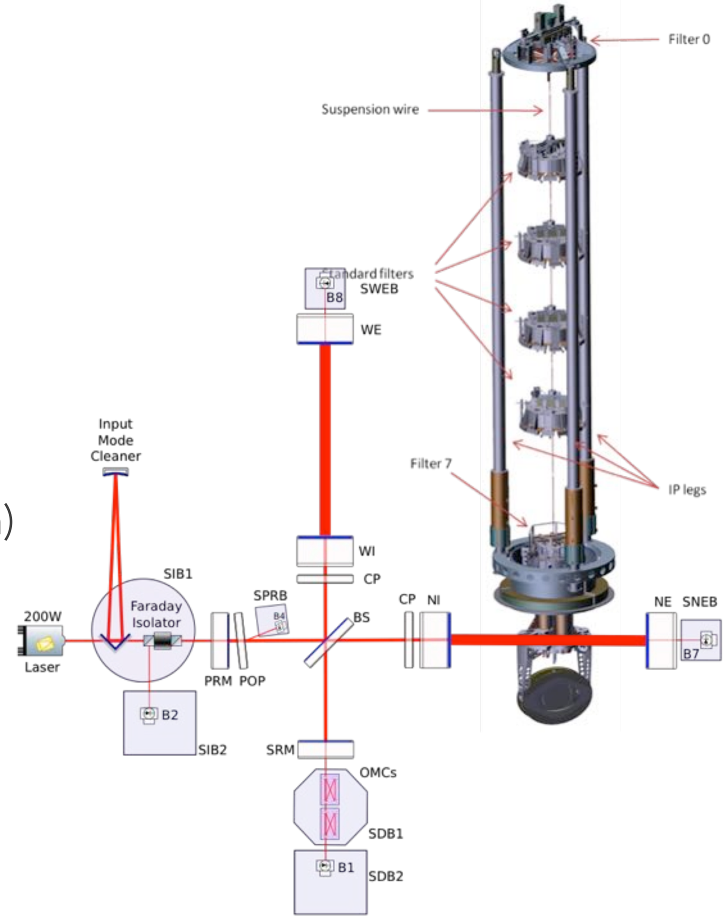
- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector
- Partecipated by France and Italy (former founders of Virgo), The Netherlands, Poland, Hungary, Spain
- Funding approved in Dec 2009 (21.8 ME + Nikhef in kind contribution)
- Project formally completed with the start of the O2 run

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

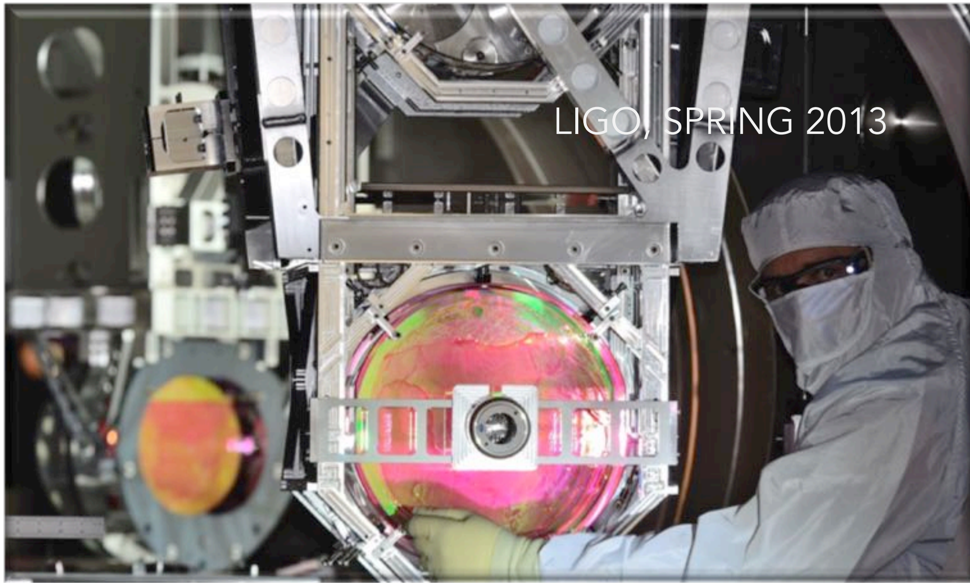
ADVANCED VIRGO

- MAIN CHANGES wrt Virgo (2017)
  - larger beam (2.5x)
  - heavier mirrors (2x)
  - higher quality optics (residual roughness <0.5 nm)
  - improved coatings (absorption <0.5 ppm, scattering <10 ppm)
  - increased arm cavity finesse (3x)
  - thermal control of aberrations
  - stray light control (baffling, photodiodes suspended in vacuum)
  - improved vacuum (1e-9 mbar instead of 1e-7)
  - improved electronics
- LATER
  - *signal recycling*
  - *200W laser*



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



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.

PRESS RELEASE

3 October 2017

The Nobel Prize in Physics 2017

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2017

with one half to

Rainer Weiss
LIGO/VIRGO Collaboration

and the other half jointly to

Barry C. Barish
LIGO/VIRGO Collaboration

and

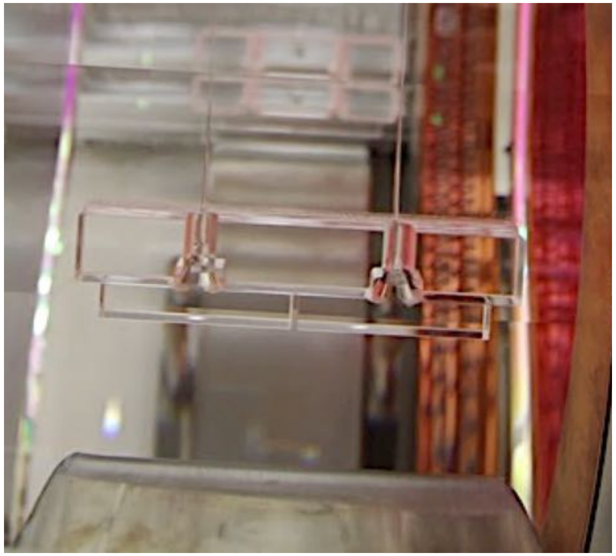
Kip S. Thorne
LIGO/VIRGO Collaboration

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

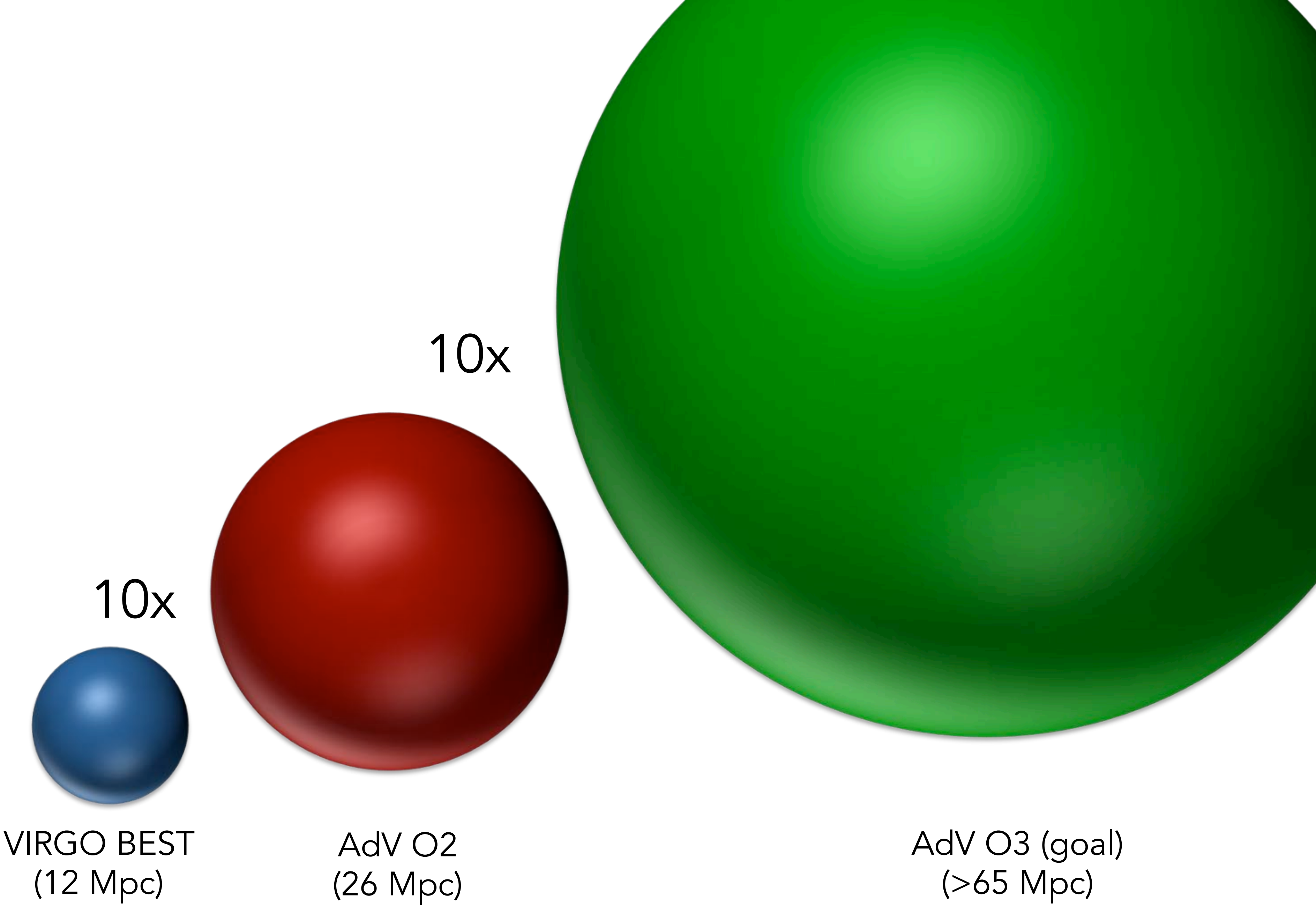
PERSPECTIVES

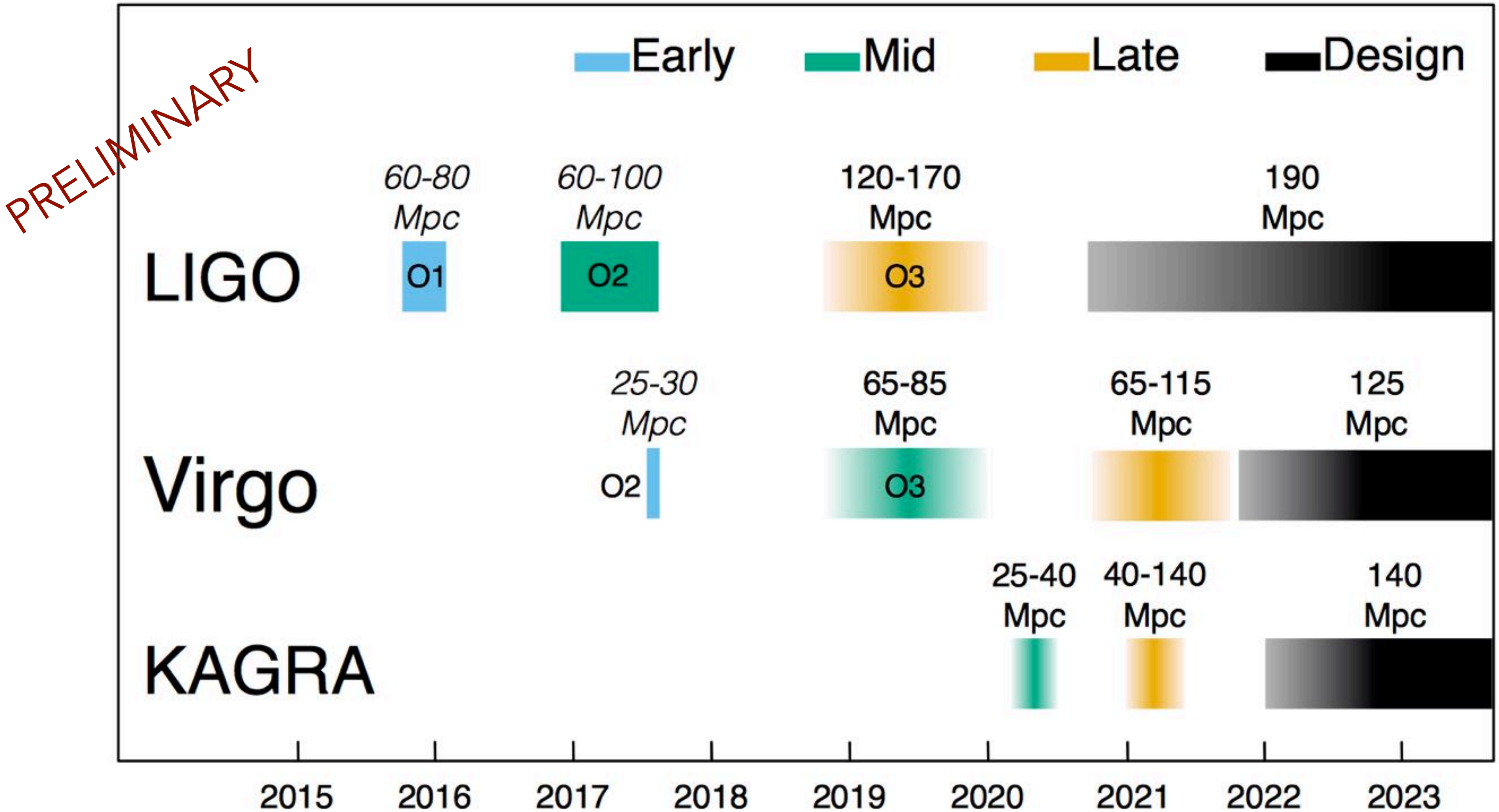
SHORT TERM: AFTER O2

- Upgrade vacuum system to kill dust contamination risk
  - get rid of scroll pumps
  - upgrade piping for big chamber inlet/outlet
- Re-install monolithic suspensions
  - fiber guards as an additional safety
- Increase laser power (now 13 W)
  - installation of the new 100W laser
- Implement squeezer provided by AEI Hannover
- Do commissioning to improve sensitivity!



TARGET BNS RANGE for O3: 65 Mpc

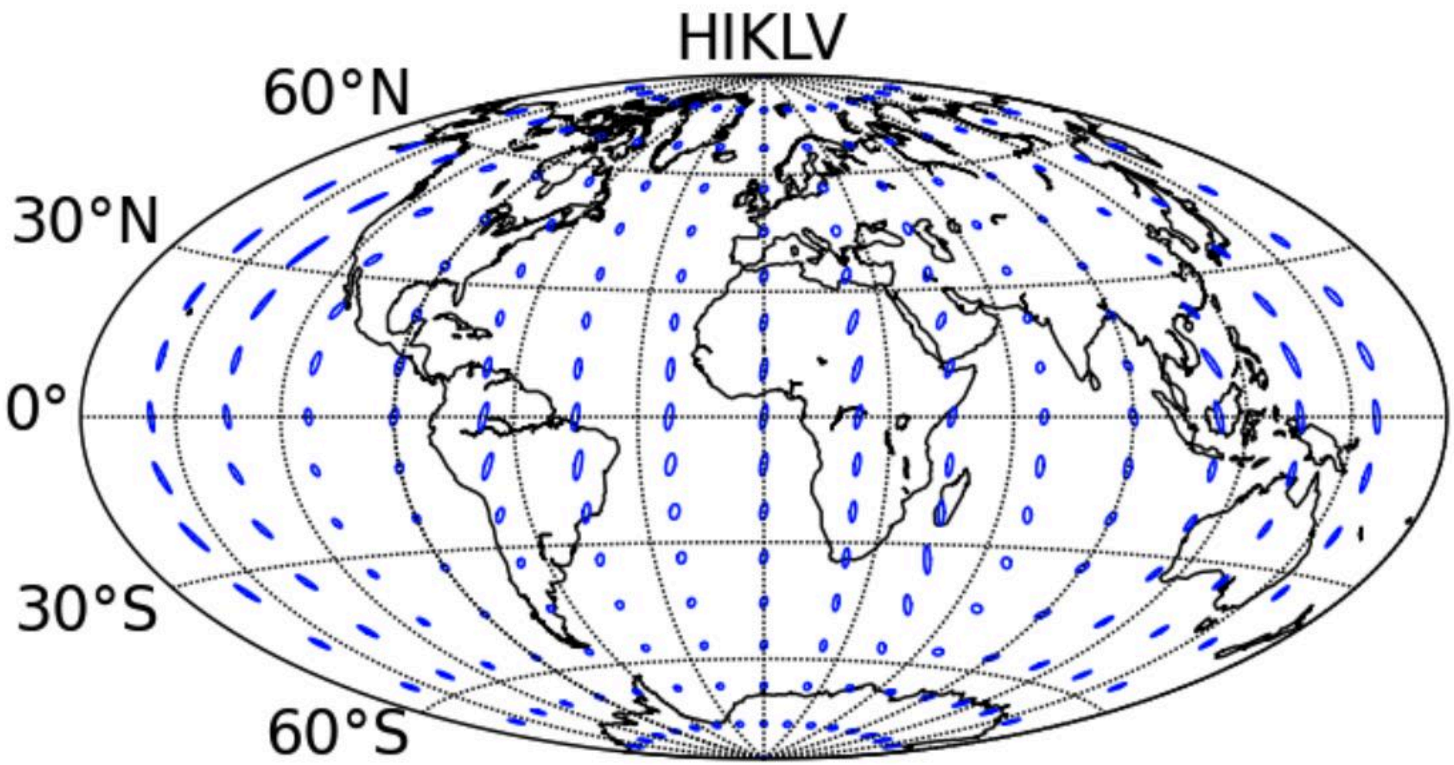

10x
10x
VIRGO BEST
(12 Mpc)
AdV O2
(26 Mpc)
AdV O3 (goal)
(>65 Mpc)



…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" (in preparation)

THE MID-TERM GOAL



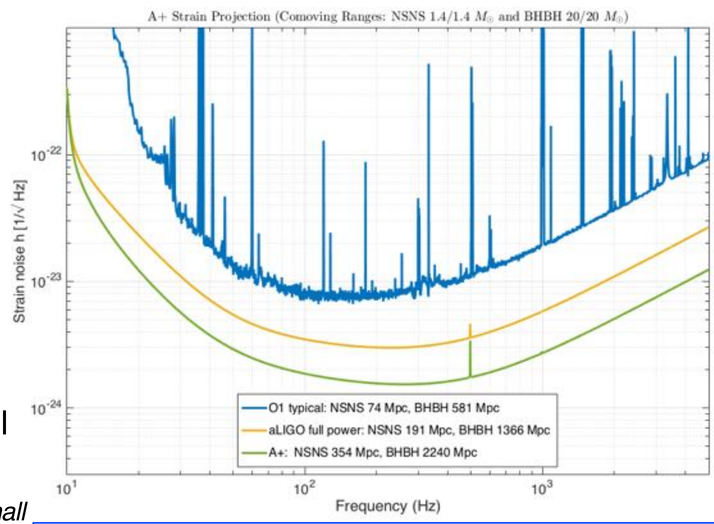
S Fairhurst, CQG 28, 2001

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

ENHANCING 2G

A+: Advanced LIGO Upgrade

- Incremental upgrade to aLIGO that leverages existing technology and infrastructure, minimal new investment and moderate risk
- Target: factor of *1.7** increase in range over aLIGO **BBH 20/20 $M_\odot$.....1.64x* **BNS 1.4/1.4 $M_\odot$... 1.85x*
  - → ~ 5X greater event rate
- Pathfinder for future 3G detector technologies
- Proposal in preparation for submittal to NSF in spring of 2018
  - Mid-scale project: Incremental cost: *a small fraction of aLIGO (2 IFOs)*
  - Follows the successful aLIGO model of in-kind partner contributions (UK, AUS,…)
  - Earliest likelihood for funding would be mid-2020, 3 year fab/install/commission



A+ key parameters: **12dB** injected squeezing
15% readout loss
100 m filter cavity (FC)
20 ppm round-trip FC loss
Coating thermal noise **0.5X** aLIGO

LIGO-G1701591-v1 ***LIGO Laboratory, LVC Mtg, CERN August 2017*** 13

SCIENTIFIC TARGET:
5x EVENT RATE
BBH at z~1

BUDGET: O(30M$)

SCHEDULE: ~2023

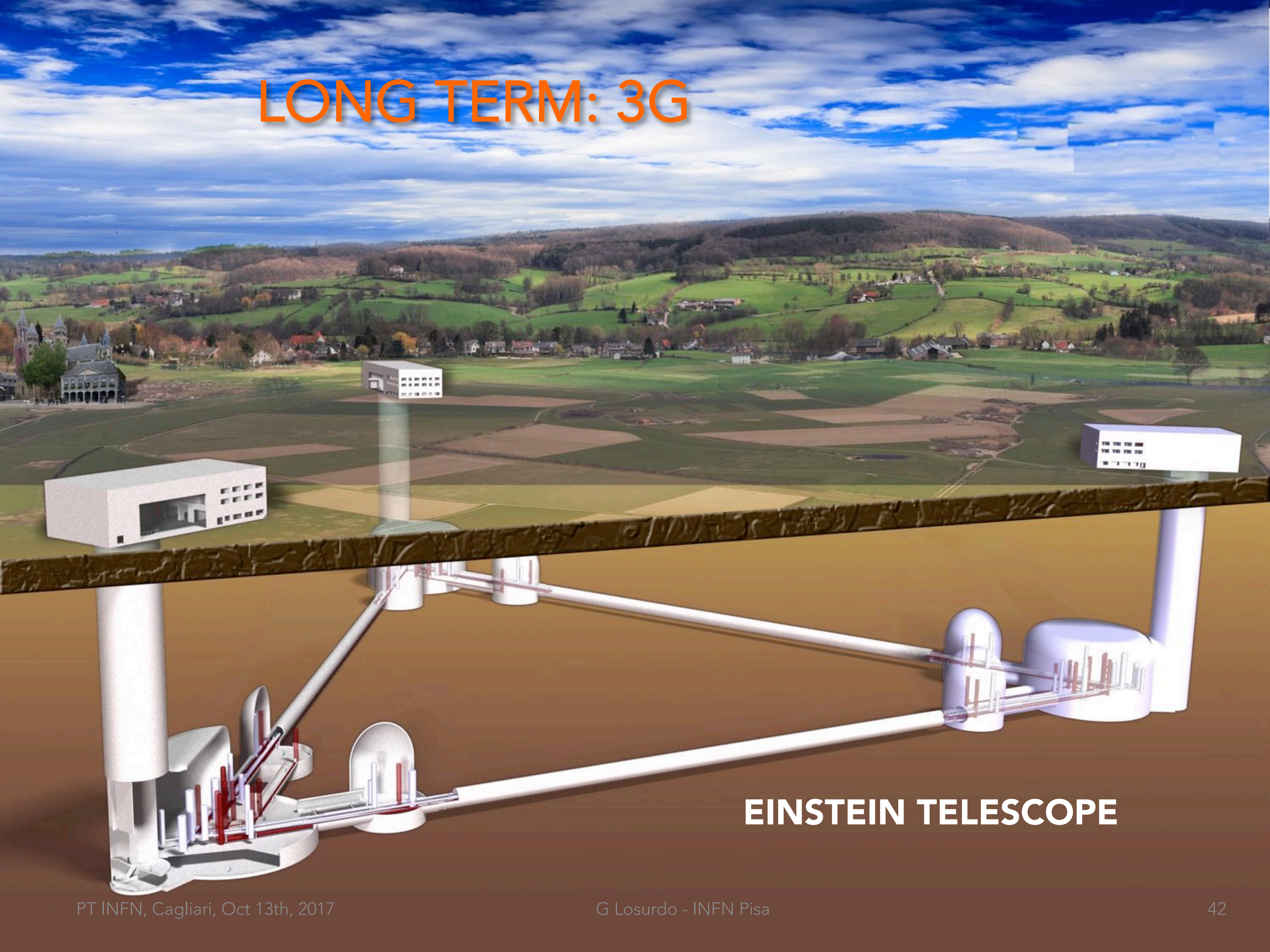
LIGO-INDIA EXPECTED ONLINE IN ~2024

VIRGO GOALS (and ISSUES)

1. Run AdV, increase the weight in the data analysis
2. Remain competitive: realize a relevant upgrade (AdV+) on the same A+ timeline
   - Limited impact: Newtonian noise subtraction, frequency dependent squeezing
   - Major impact: larger mirrors/beam, stable recycling cavities
3. Continue working for a 3G detector in Europe (E.T.)
   - A Sardinian site an option. Relations with CERN established

- Yes, there are issues and risks (R&D, resources, …)
- Definitely, the collaboration needs to grow
  - attract new groups to fully exploit the experiment potential and the science (instrument, computing, DA, e.m. follow up, theory)
- The EGO mission to be the barycentre of the EU GW research must be extended

LONG TERM: 3G



CONCLUDING REMARKS

- VIRGO HAS DETECTED GW
- VIRGO is a key player in the starting era of the multi-messenger observation of the universe: a lot of science will come out of that
- The sensitivity of the detectors will keep growing and the science outcome will get richer and richer
- VIRGO (and its community) must remain a key player in the field
  - fill the sensitivity gap with LIGO
  - prepare the detector upgrades
  - prepare for a new 3G detector

- A bright future for the GW field and the multi-messenger astronomy (i.e. astrophysics/cosmology/fundamental physics)