The Advanced Virgo observing run O2

report on the first results

Giovanni Losurdo – INFN Pisa

on behalf of the

LSC and VIRGO Coll.

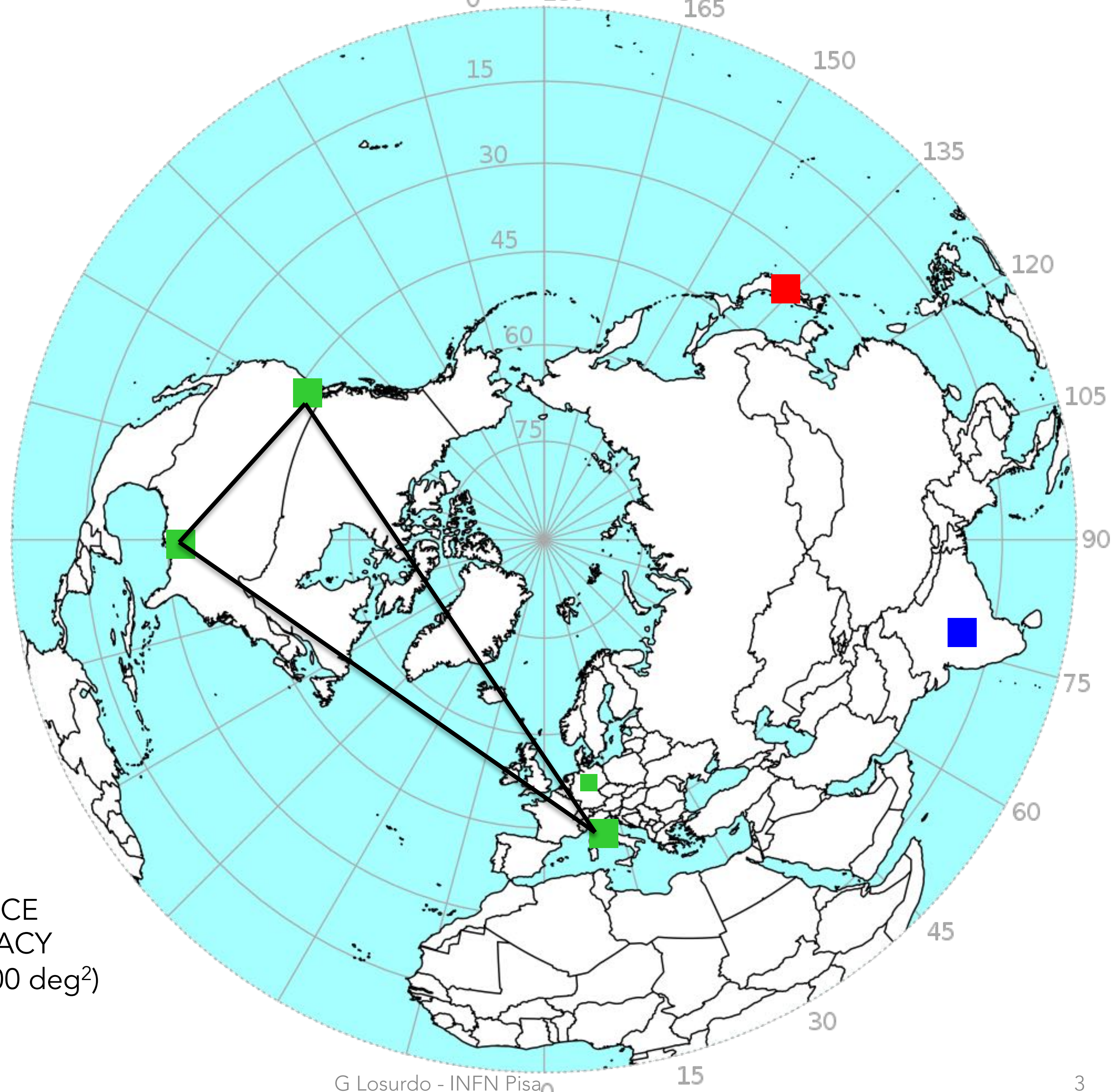
August 1st, 2017

…and then there were three…

VIRGO JOINS LIGO IN THE OBSERVATION RUN O2

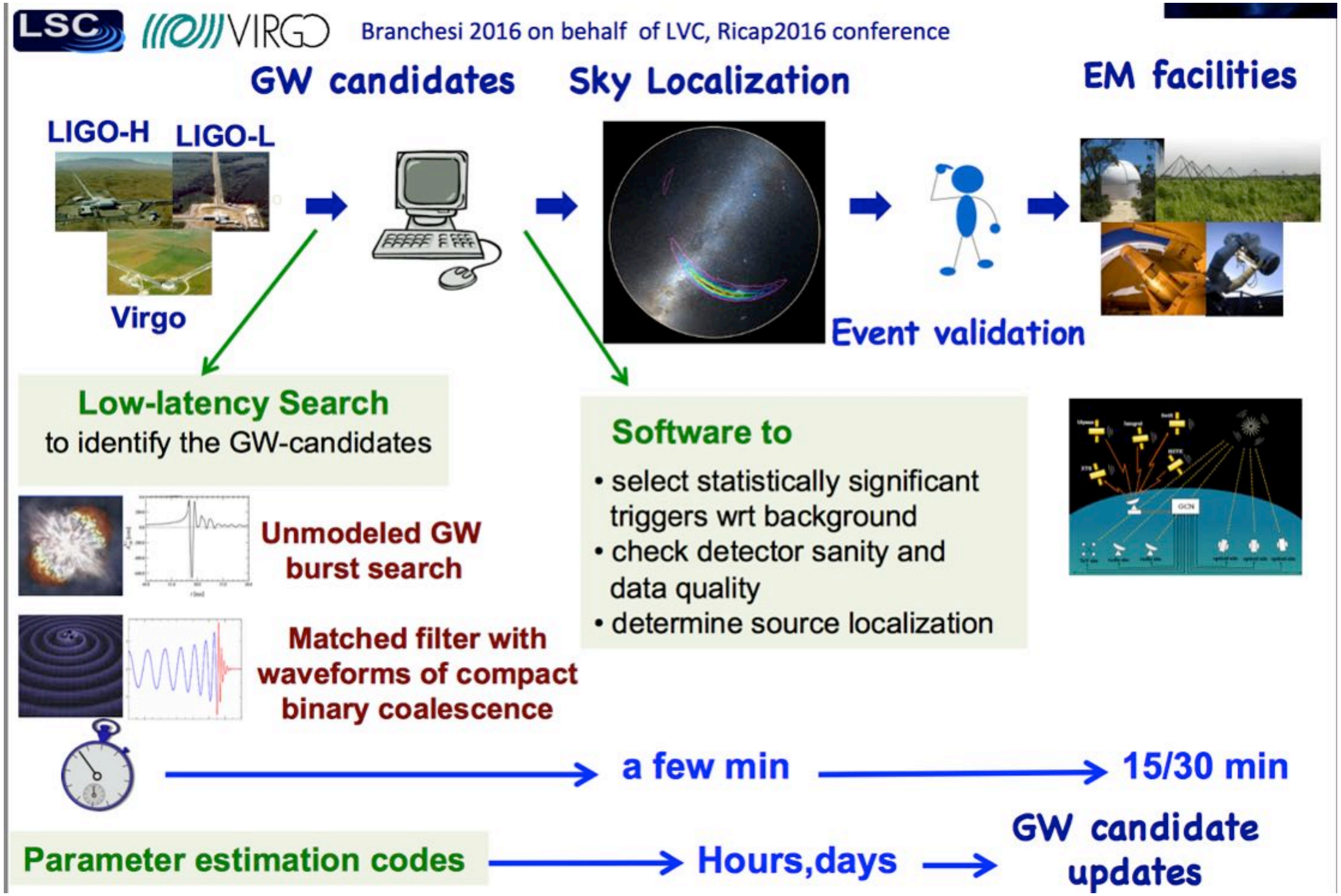
THREE 2G DETECTORS ACTING AS A “SINGLE MACHINE”

- OPERATION
- COMMISSIONING
- CONSTRUCTION
- APPROVED



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

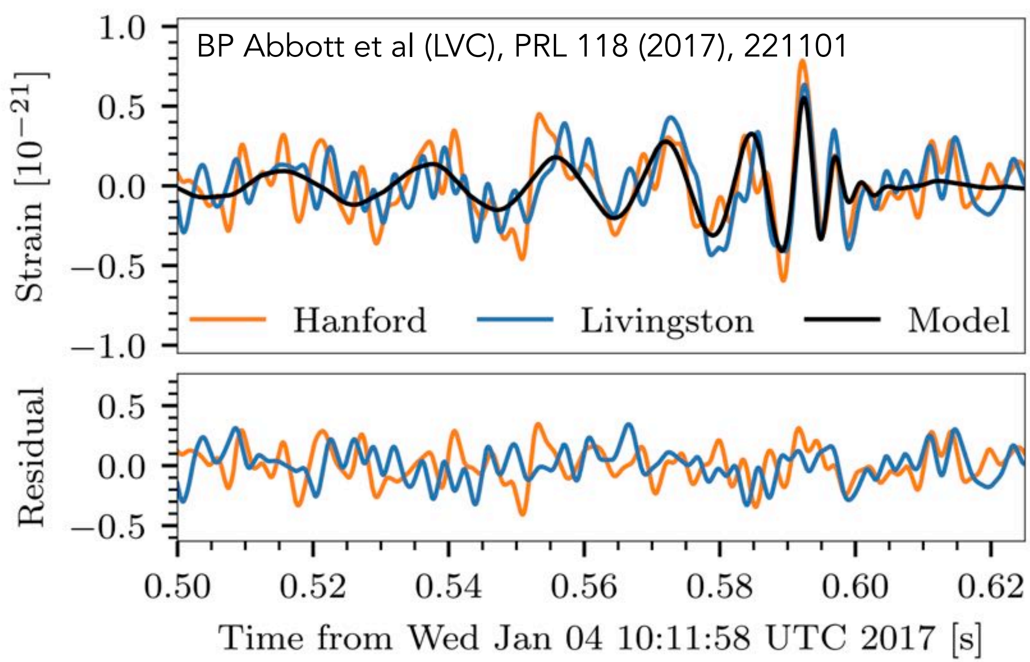
E.M. FOLLOW-UP



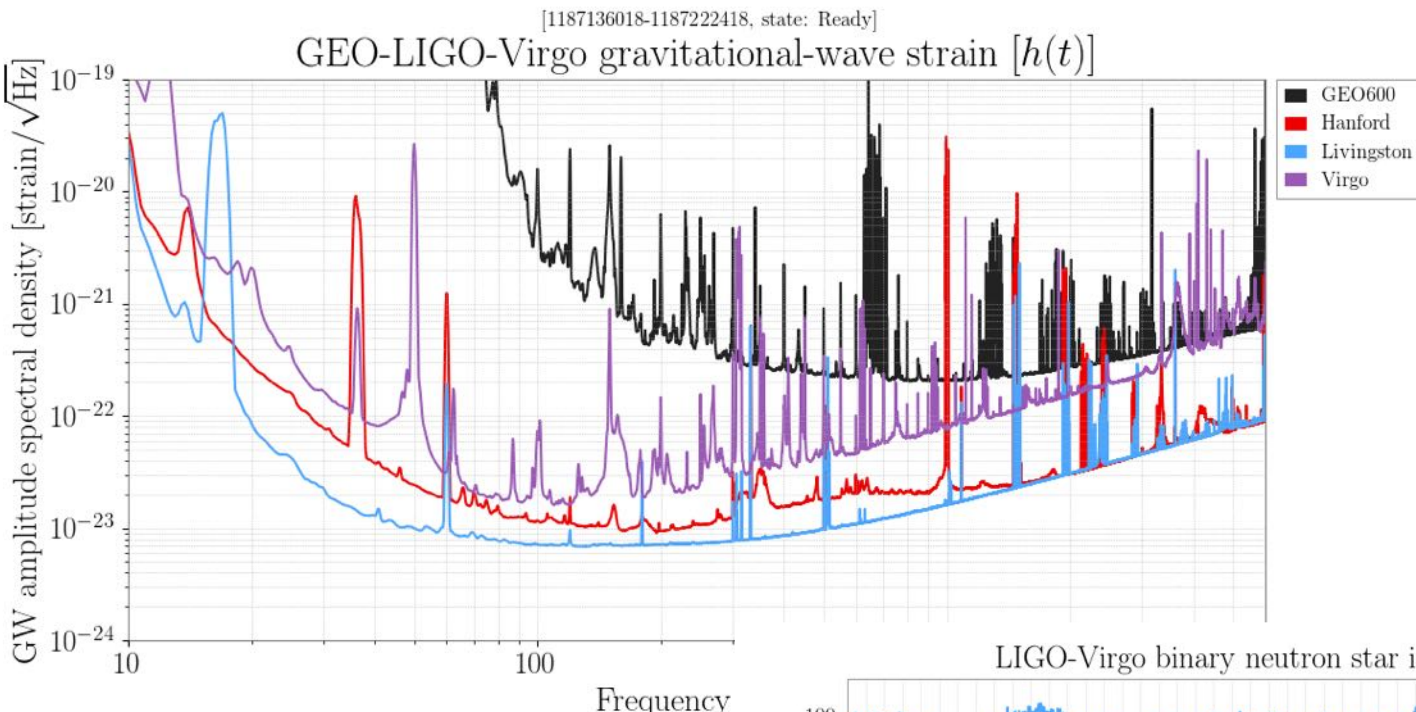
93 groups (>200 instruments) have signed the MoU with the LVC

THE O2 RUN - FACTS

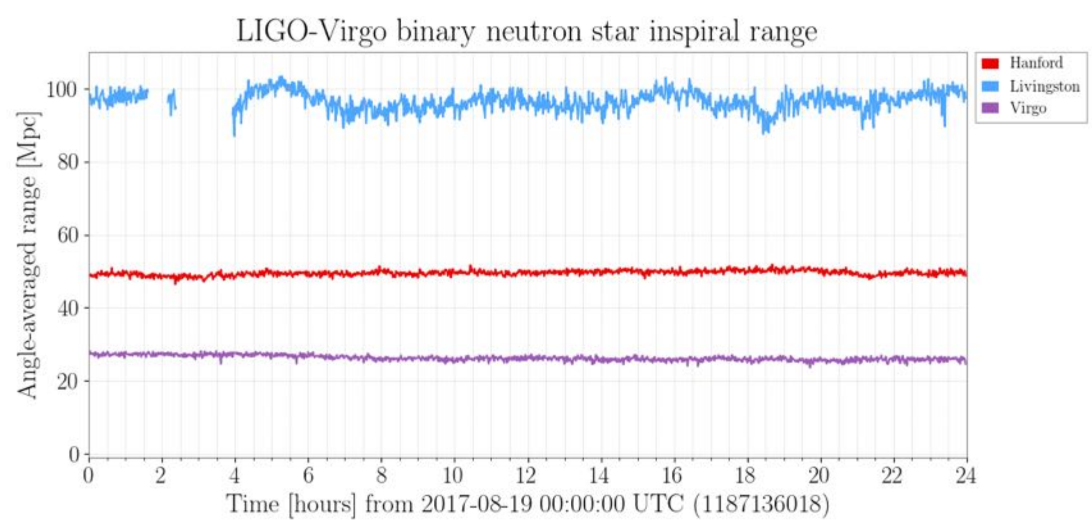
- Started on November 30, 2016
- VIRGO joined on August 1st, 2017
- The run was stopped on Aug 25th, as previously planned by LIGO
- From Aug 1st to 25th: 14.9 days of triple coincidence observation
- One event published before Aug 1st (GW170104)



NETWORK

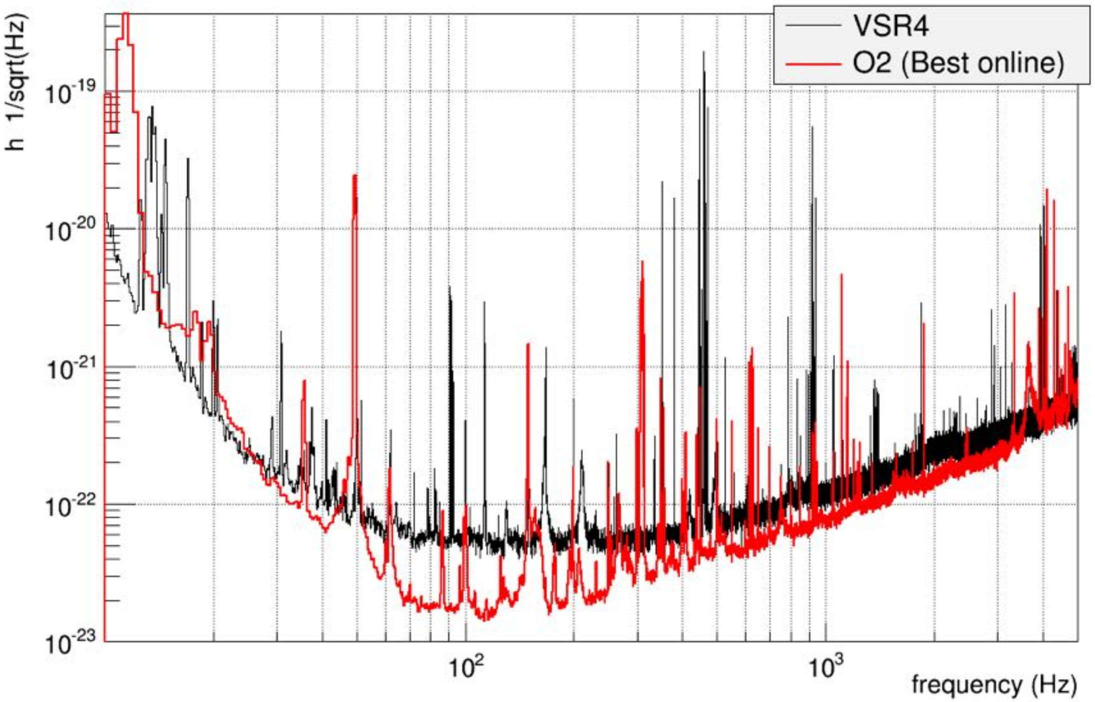


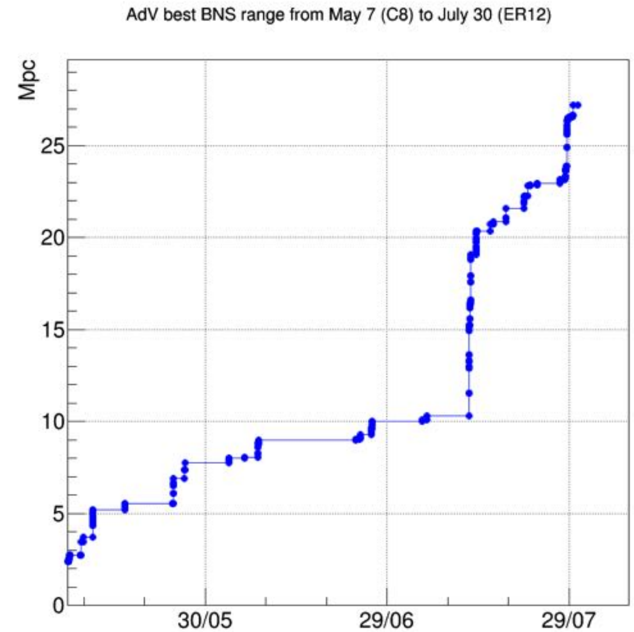
[1187136018-1187222418, state: Ready]
GEO-LIGO-Virgo gravitational-wave strain $[h(t)]$
GW amplitude spectral density [strain/$\sqrt{\text{Hz}}$]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10
100
Frequency
GEO600
Hanford
Livingston
Virgo

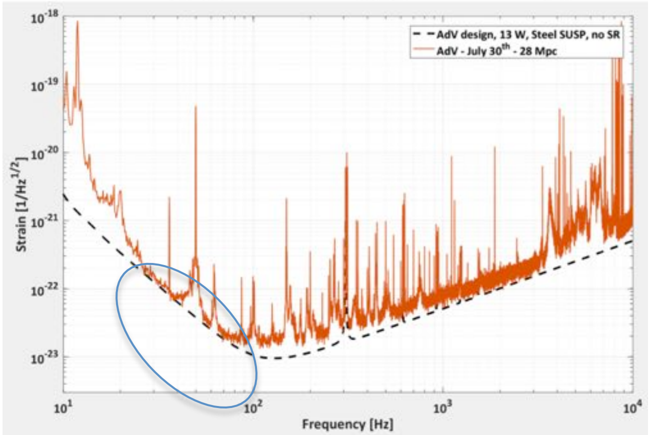


LIGO-Virgo binary neutron star inspiral range
Angle-averaged range [Mpc]
100
80
60
40
20
0
0 2 4 6 8 10 12 14 16 18 20 22 24
Time [hours] from 2017-08-19 00:00:00 UTC (1187136018)
Hanford
Livingston
Virgo

SENSITIVITY

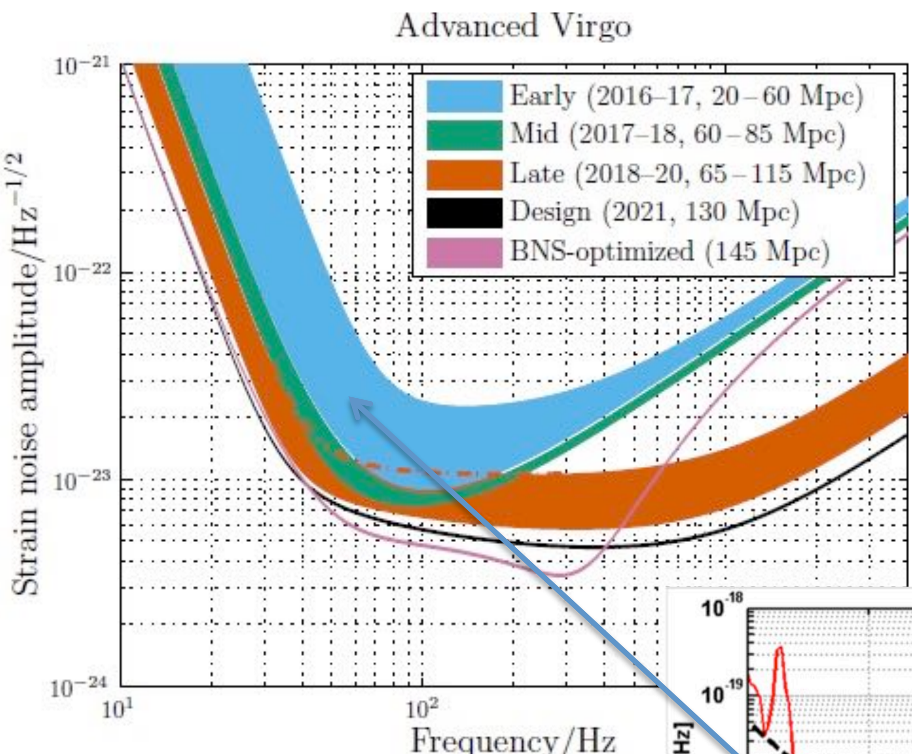






- VIRGO+ (2011): BNS range of 12 Mpc
- AdV (O2): 28 Mpc, ~12x larger volume of universe reached
  - now further improved: >30 Mpc
- Limited by steel wires thermal noise in the low frequency range

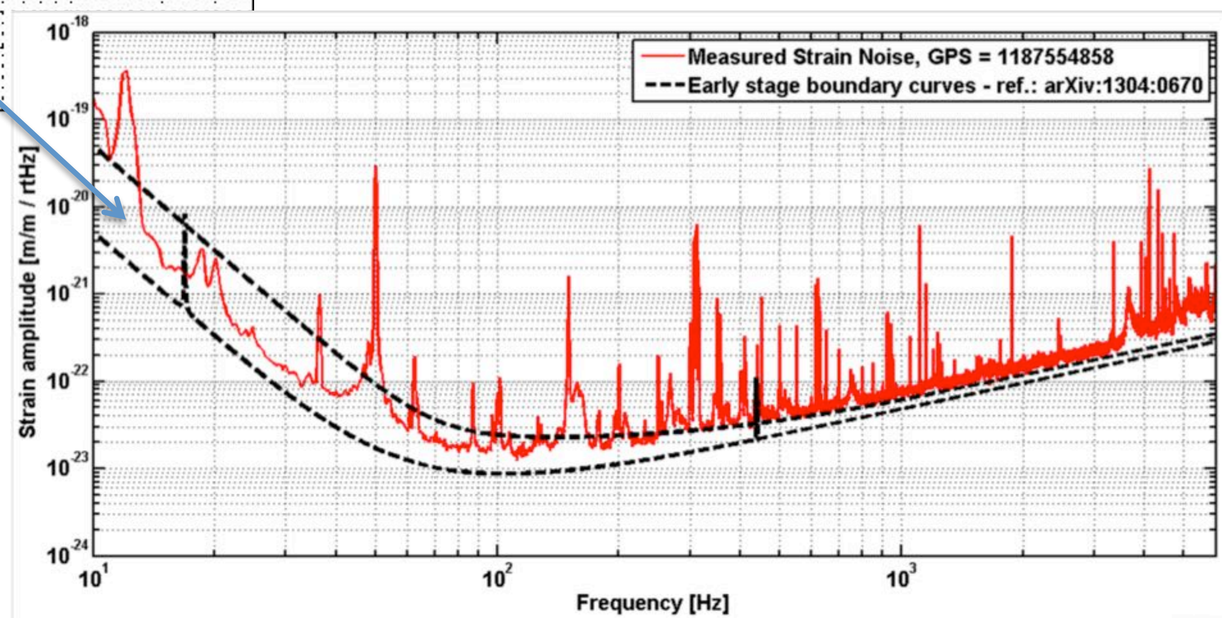
SENSITIVITY

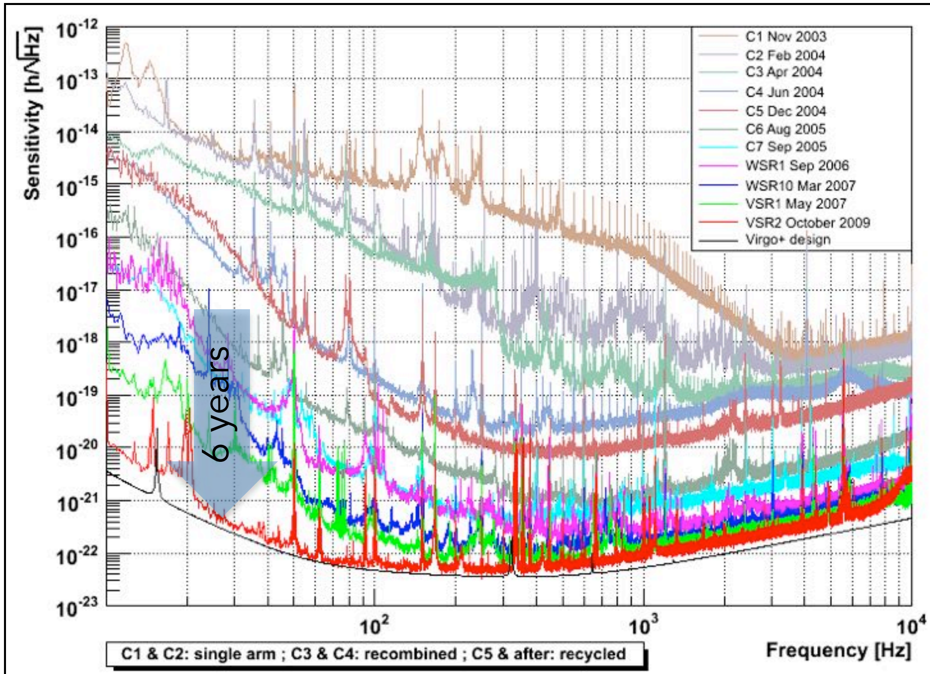


FROM THE 2013 "OBSERVING SCENARIO"

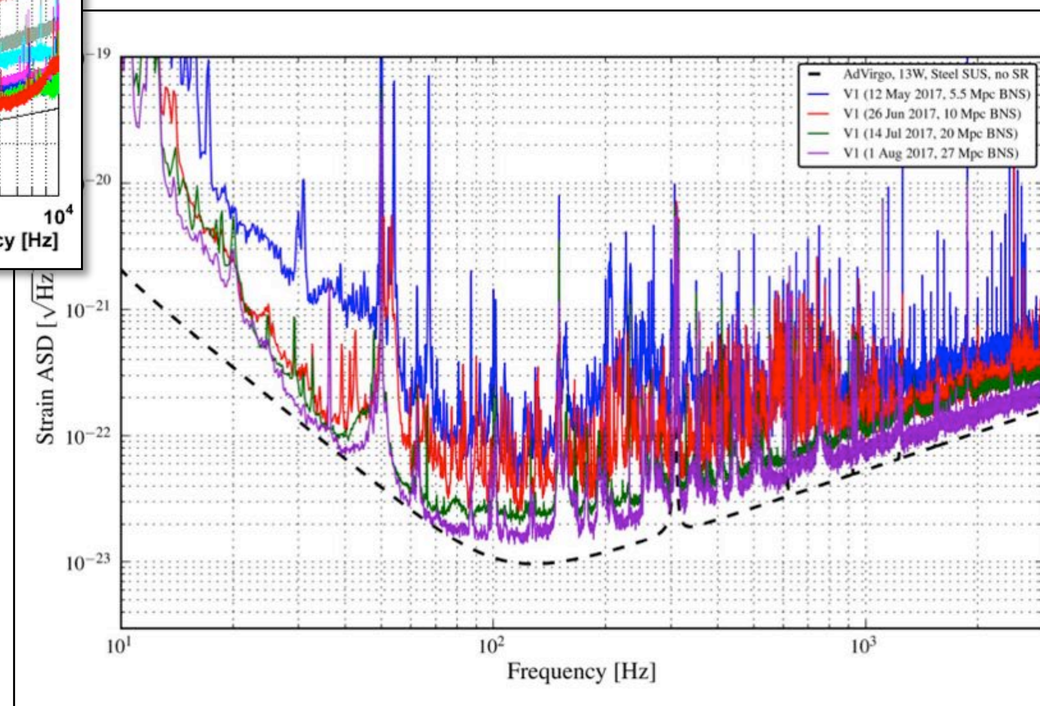
Abbott BP et al. (LSC-Virgo), arXiv:1304:0670

THE EARLY SENSITIVITY TARGET HAS BEEN MET



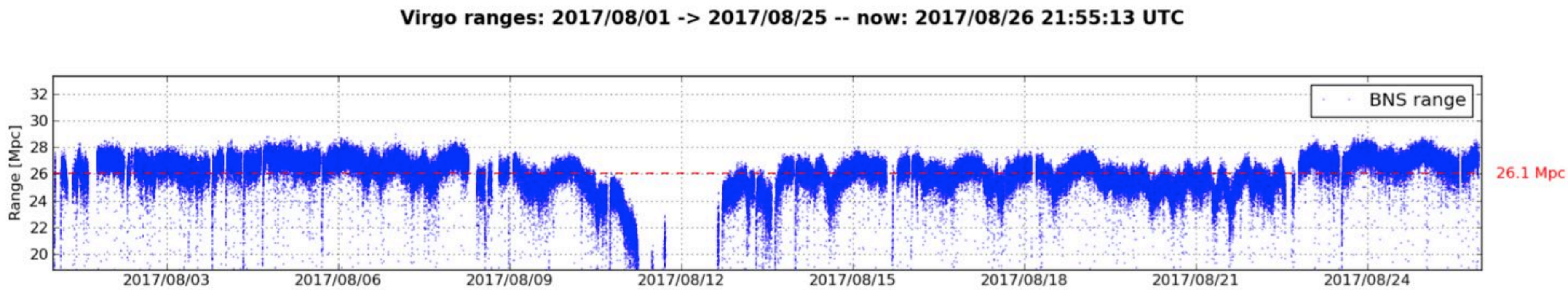


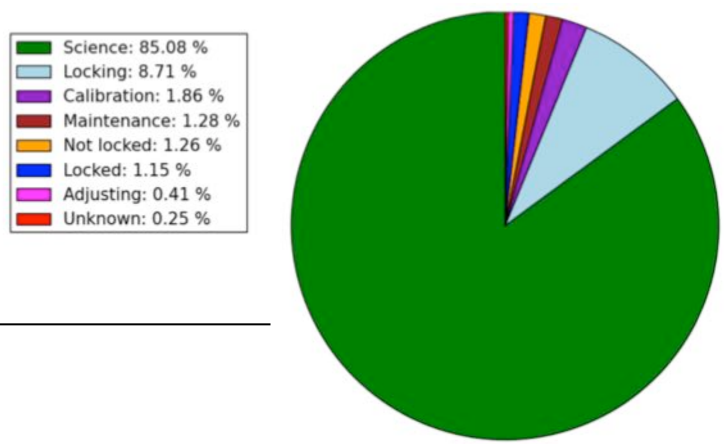
ADVANCED VIRGO: 5 MTS FROM FULL LOCK (MARCH 2017) TO **27 Mpc** BNS RANGE



VIRGO: 6 YRS (72 MTS) FROM FULL LOCK (2005) TO **12 Mpc** BNS RANGE

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

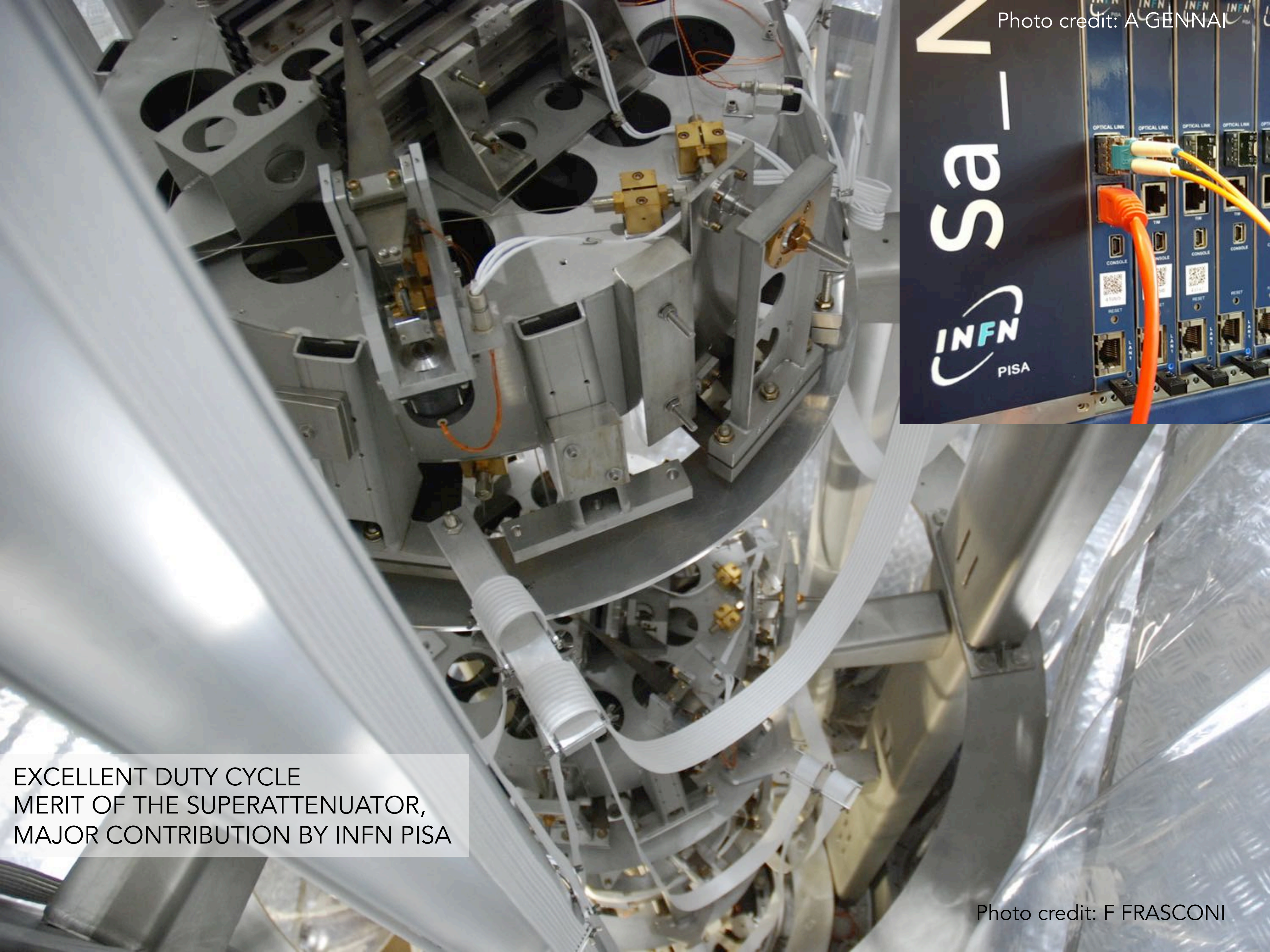
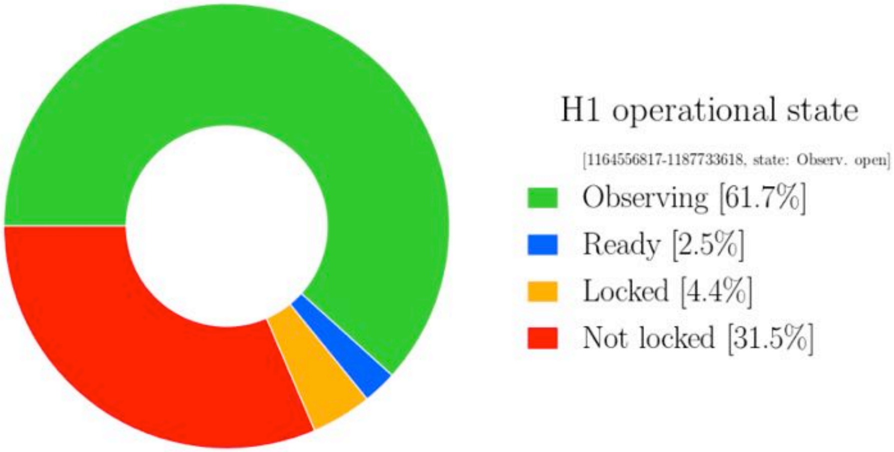


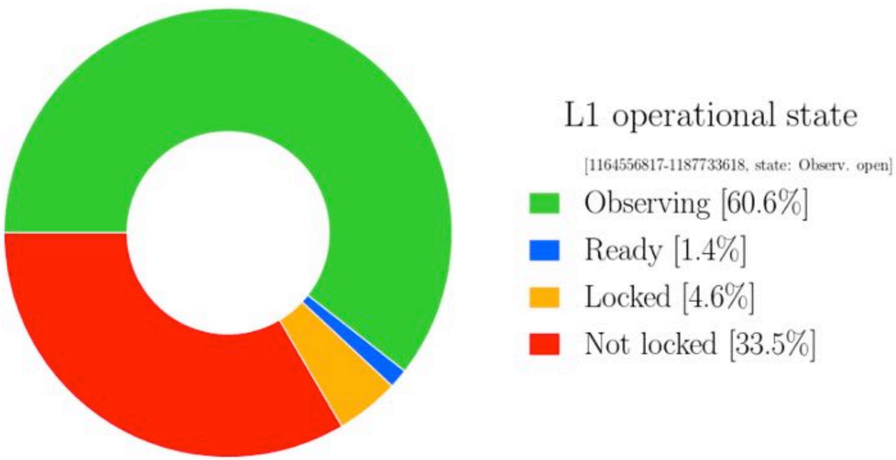
Photo credit: A GENNAI

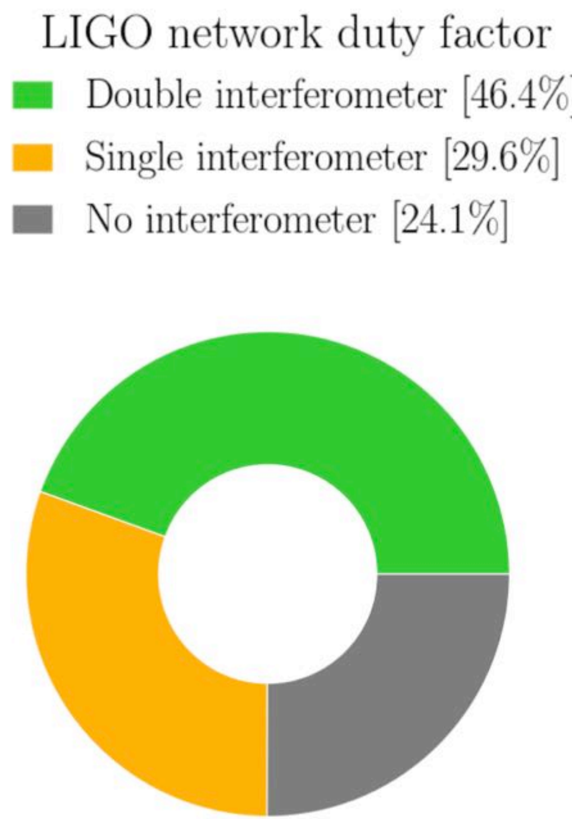
EXCELLENT DUTY CYCLE
MERIT OF THE SUPERATTENUATOR,
MAJOR CONTRIBUTION BY INFN PISA

Photo credit: F FRASCONI

O2 Status: Uptime
(as of 25 August 2017)



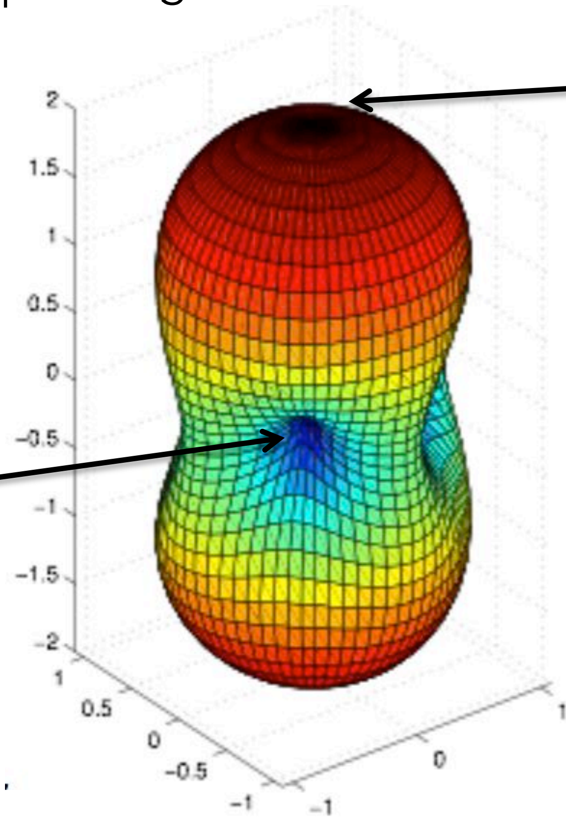




ANTENNA PATTERN

The “INSPIRAL RANGE” is averaged over the antenna response to source direction and polarization
BNS RANGE = 28 Mpc → sight distance between 0 and ~ 63 Mpc
BBH_{30} RANGE = 314 Mpc → sight distance between 0 and ~ 700 Mpc

314 x 2.24 ~ 700 Mpc



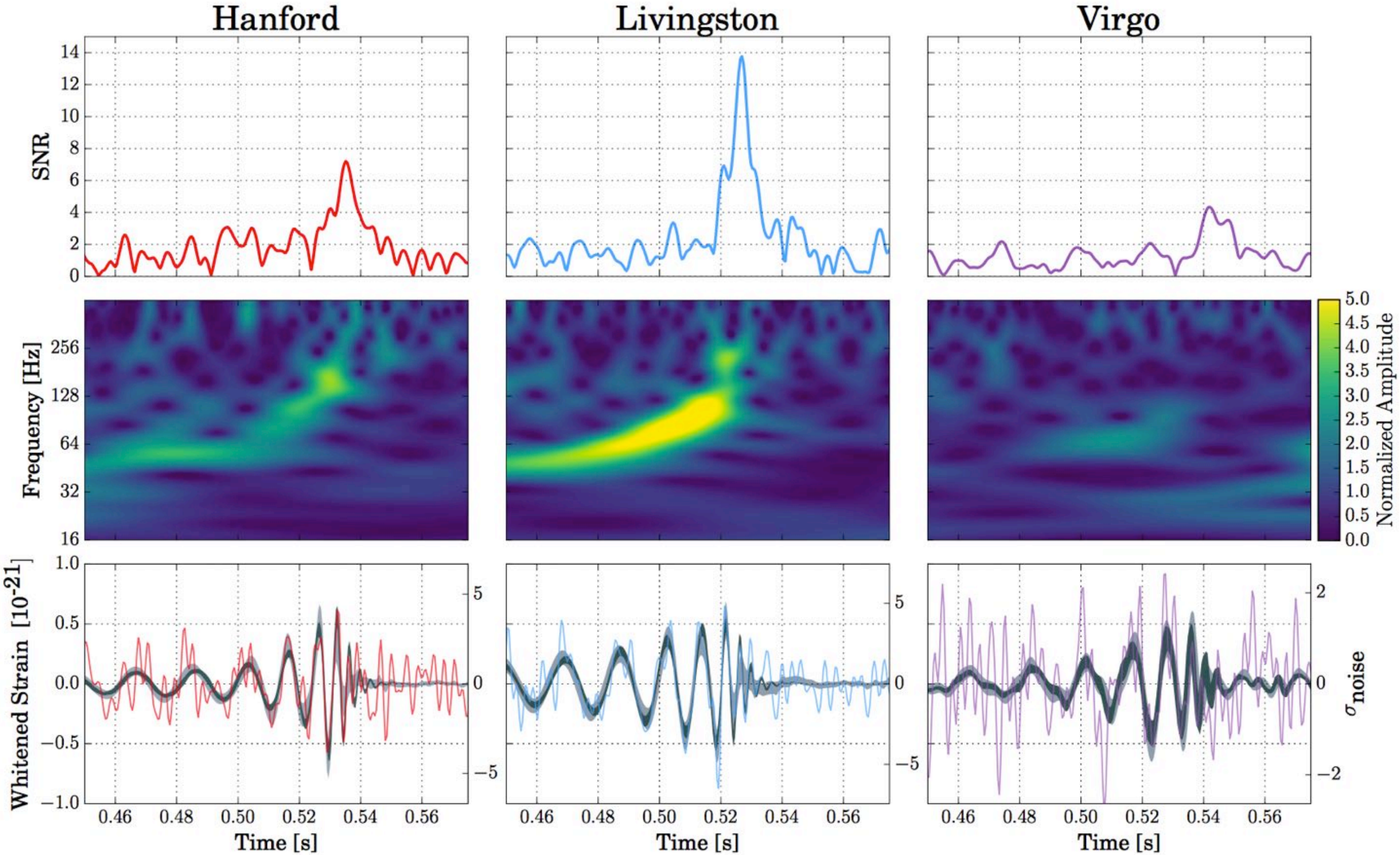
~0 Mpc

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

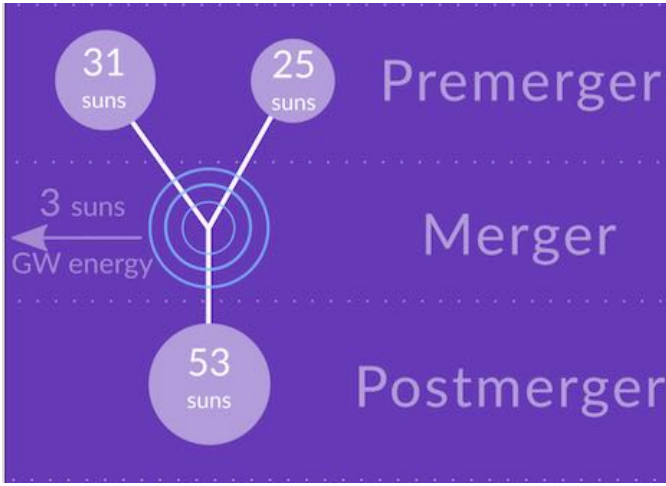
The GW hit Earth first at lat. 44.95° S, long. 72,97° W, Puerto Aysen, Chile. The signal was recorded at L1 first, then at H1 and Virgo with delays of ~8 and ~14 ms respectively



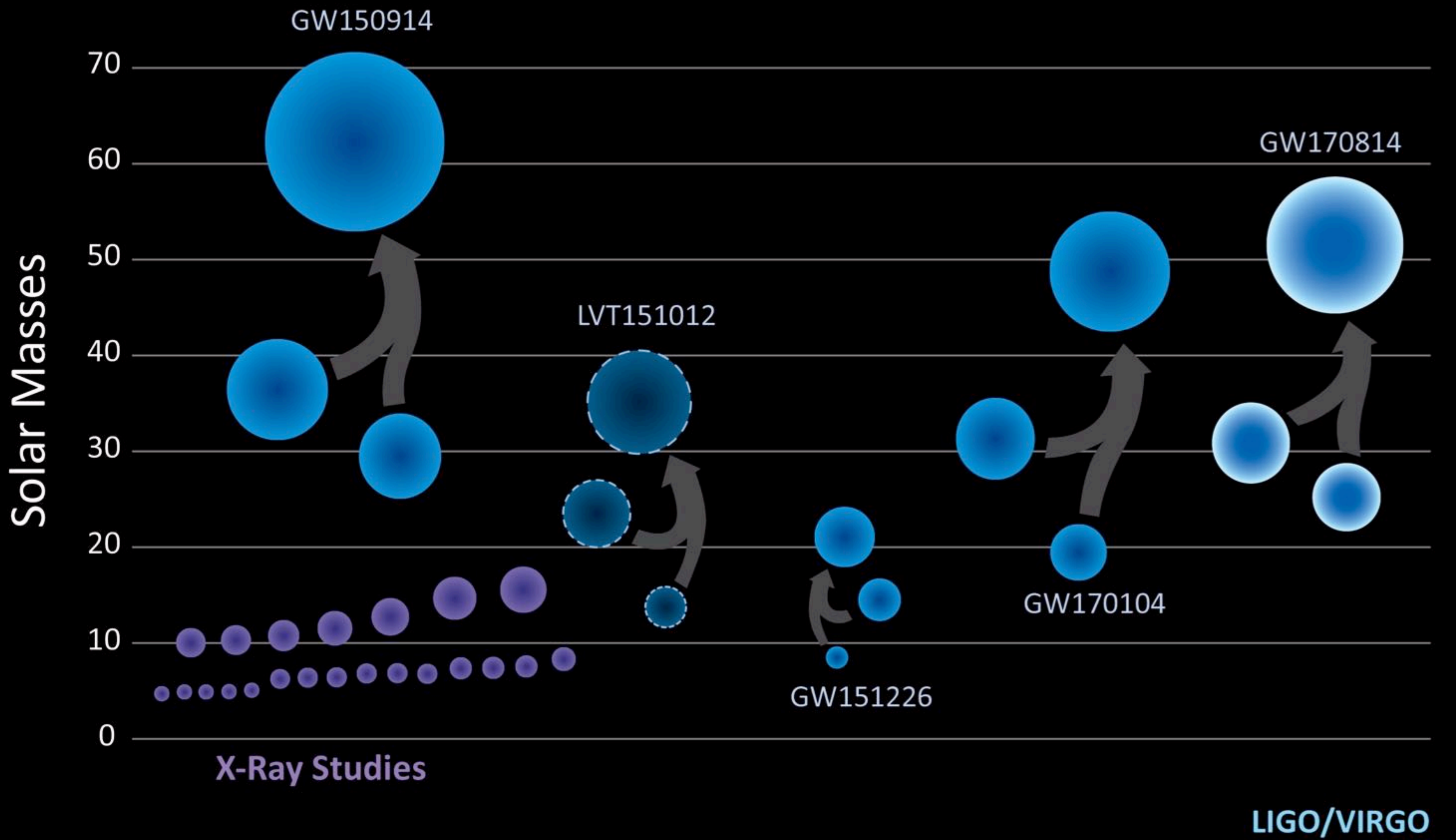
3-detector network SNR: 18.3


beam
splitter
mode-cleaner

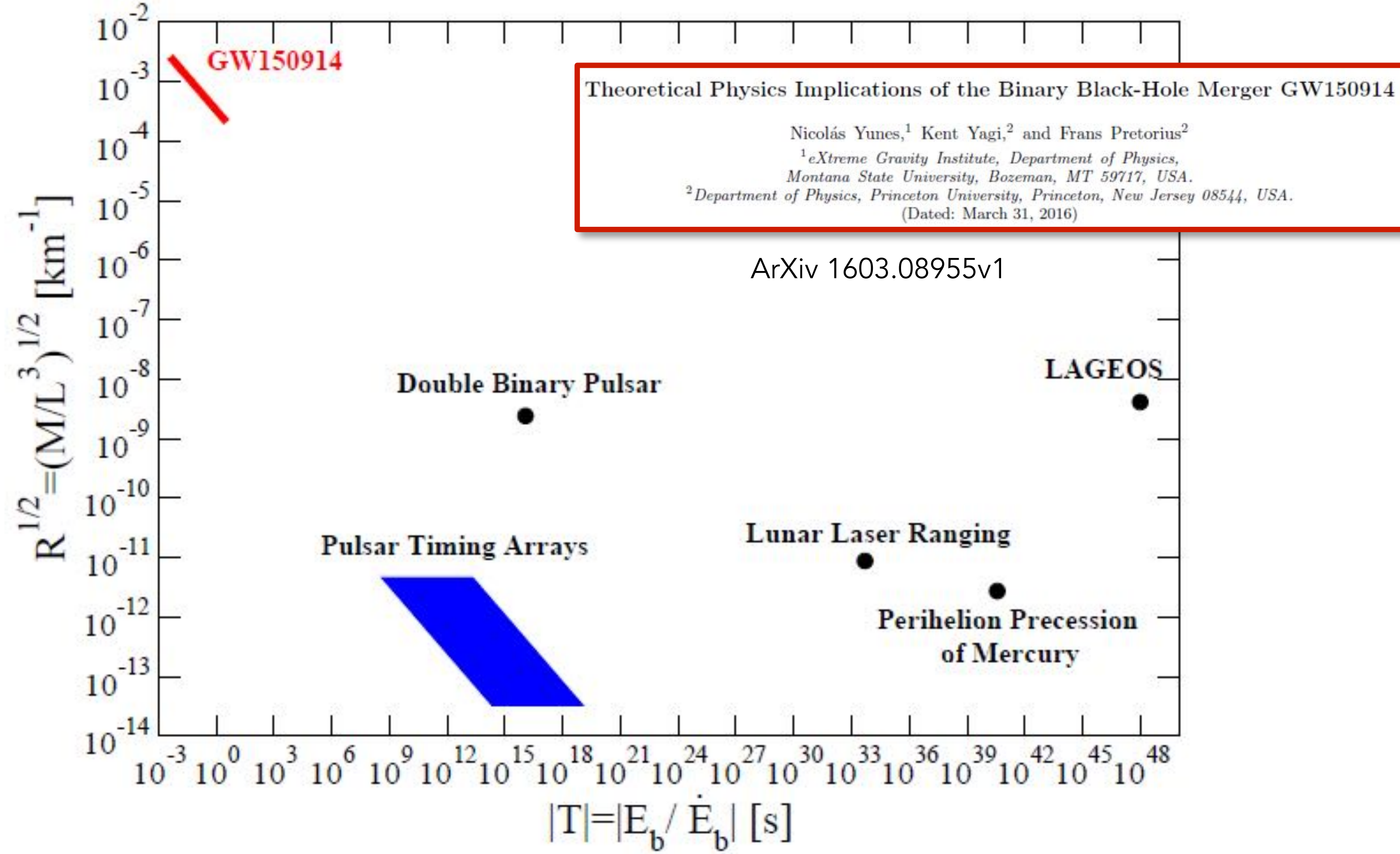
Primary black hole mass m_1	$30.5^{+5.7}_{-3.0}\,\mathrm{M}_\odot$
Secondary black hole mass m_2	$25.3^{+2.8}_{-4.2}\,\mathrm{M}_\odot$
Chirp mass $\mathcal{M}$	$24.1^{+1.4}_{-1.1}\,\mathrm{M}_\odot$
Total mass M	$55.9^{+3.4}_{-2.7}\,\mathrm{M}_\odot$
Final black hole mass M_f	$53.2^{+3.2}_{-2.5}\,\mathrm{M}_\odot$
Radiated energy E_rad	$2.7^{+0.4}_{-0.3}\,\mathrm{M}_\odot\mathrm{c}^2$
Peak luminosity ℓ_peak	$3.7^{+0.5}_{-0.5}\times 10^{56}\,\mathrm{erg\,s^{-1}}$
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	$540^{+130}_{-210}\,\mathrm{Mpc}$
Source redshift z	$0.11^{+0.03}_{-0.04}$



Black Holes of Known Mass

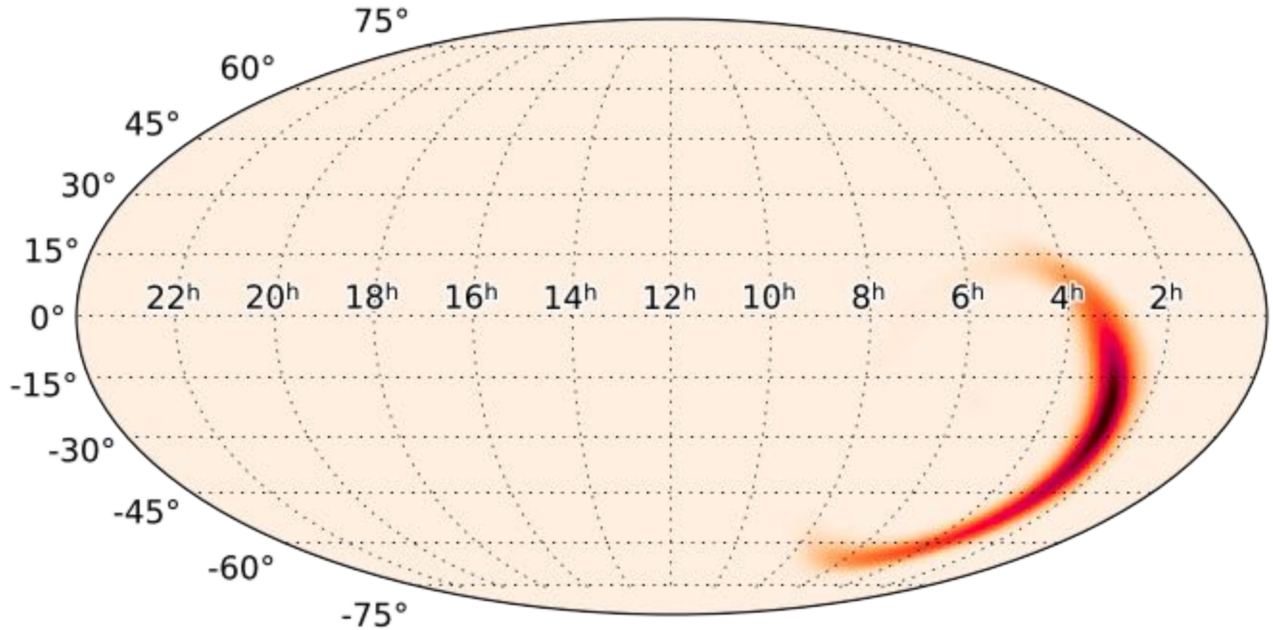


GRAVITY IN STRONG-FIELD REGIME

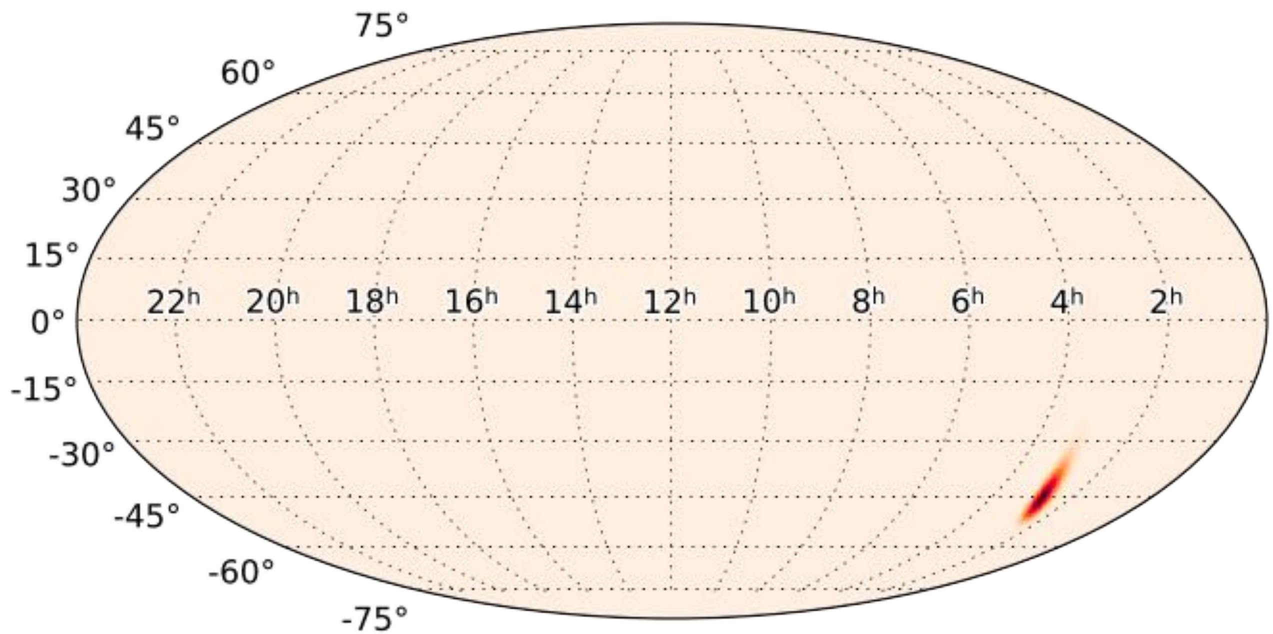


ArXiv 1603.08955v1

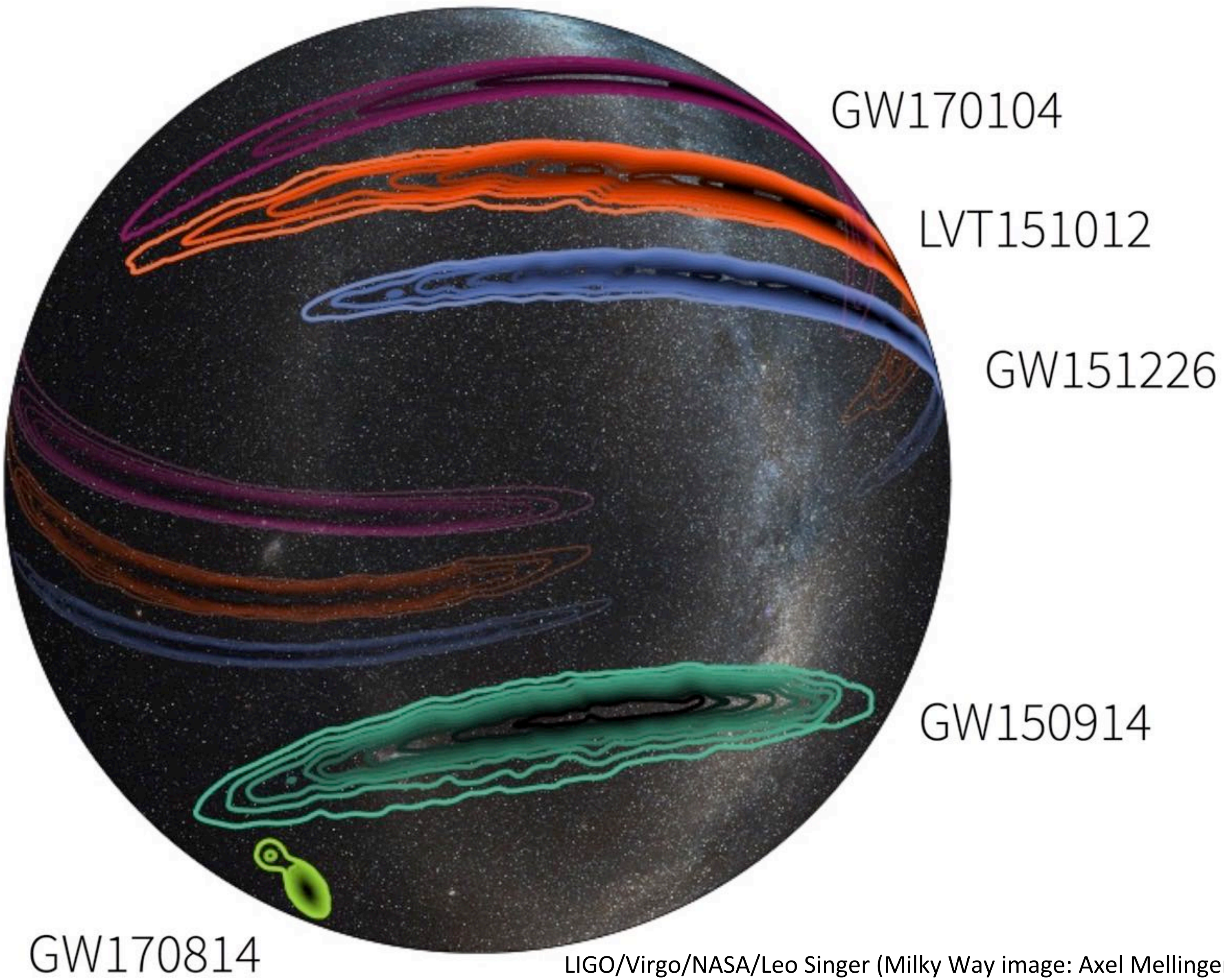
LOCALIZATION



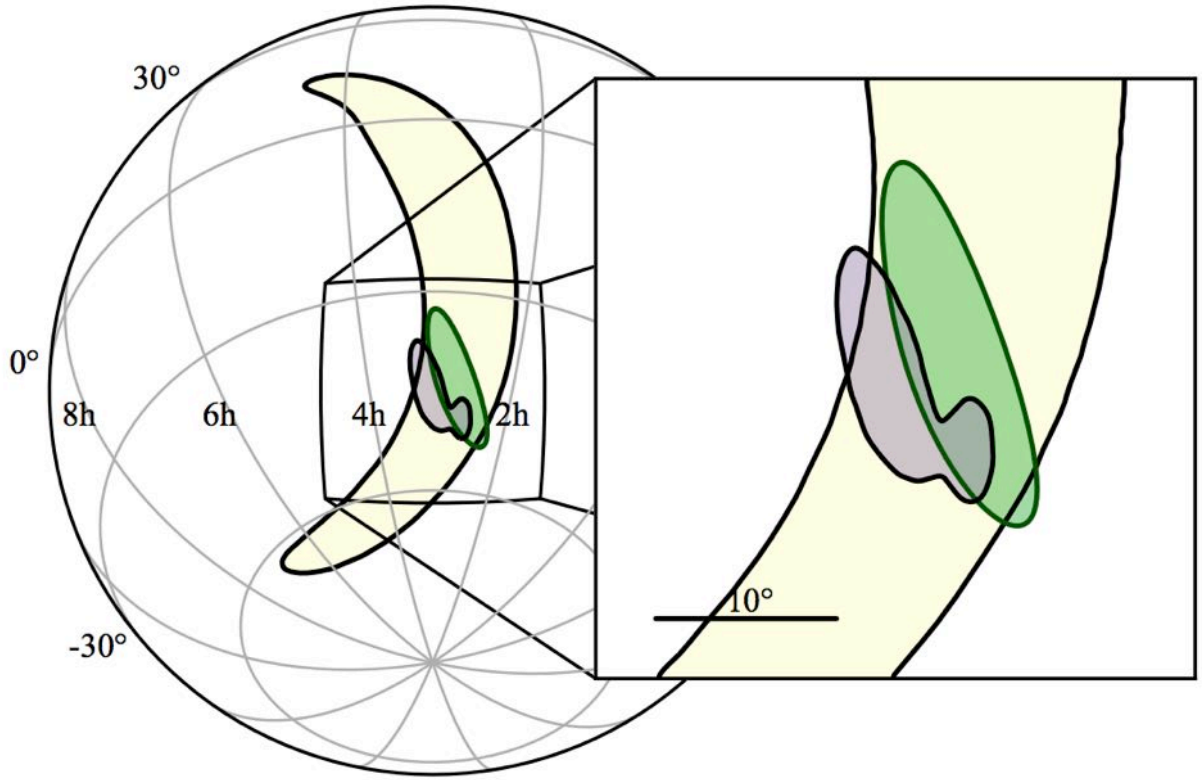
WITH THE TWO LIGOs



WITH THE TWO LIGOs + VIRGO



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



SOURCE SKY LOCALIZATION AREA, 90% C.L.

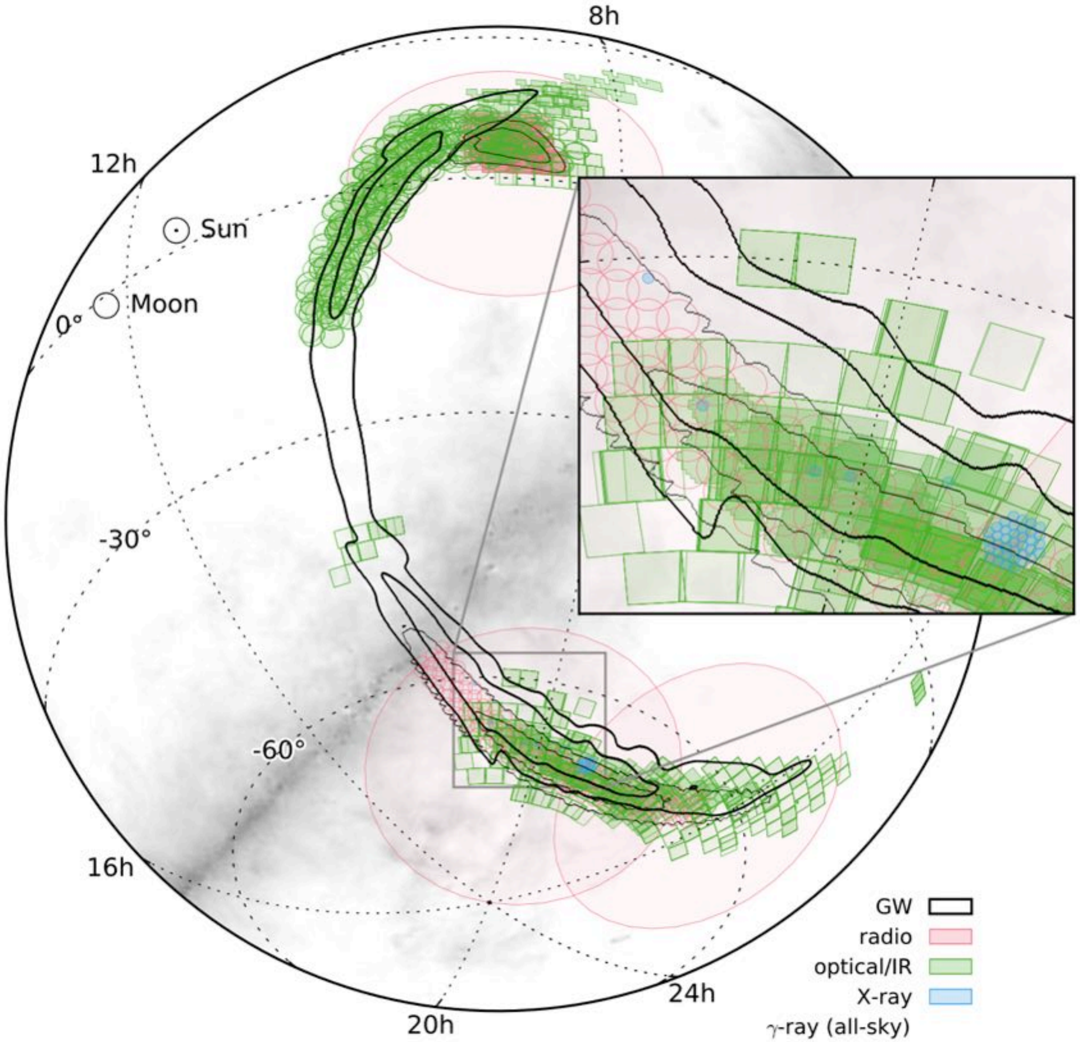
LIGO ONLY: 1160 deg^2

WITH VIRGO: 60 deg^2

THE ERA OF GW ASTRONOMY HAS FINALLY STARTED

SKY LOCALIZATION AND FOLLOW UP FOR GW150914

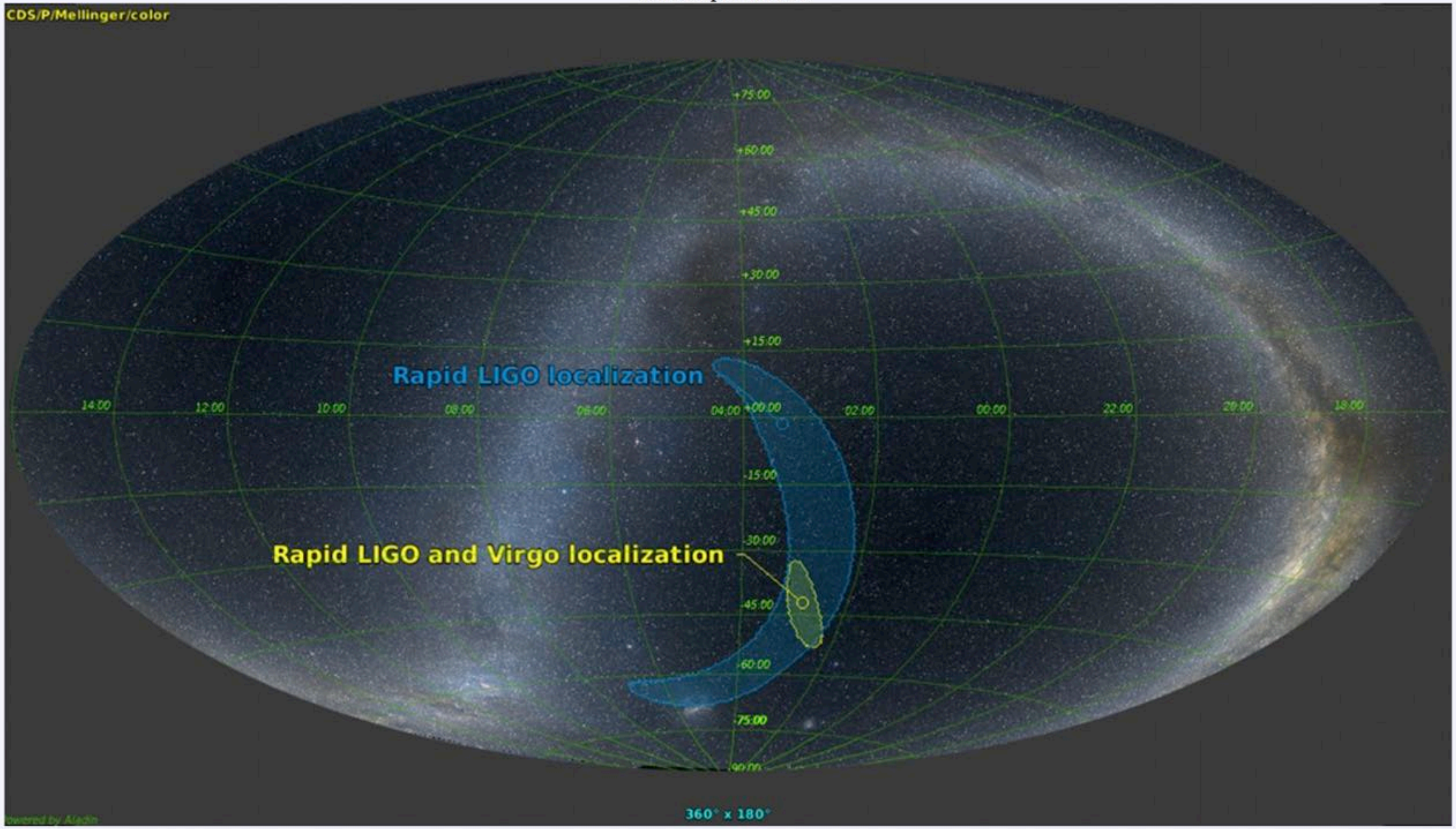
Abbott et al. (LIGO/VIRGO), APJL, 826:L13 (2016)



Astronomy Picture of the Day

Discover the cosmos! Each day a different image or photograph of our fascinating universe is featured, along with a brief explanation written by a professional astronomer.

2017 September 28



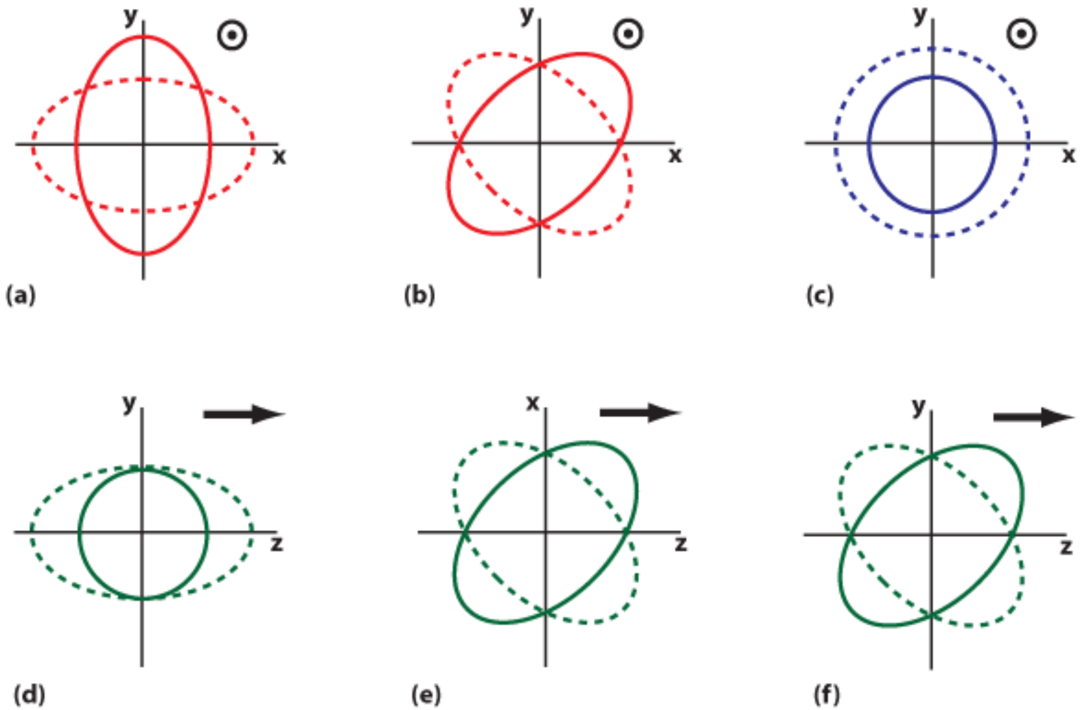
LIGO-Virgo GW170814 Skymap
Illustration Credit: LIGO- Virgo Collaboration - Optical Sky Data: A. Mellinger

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

GW170814 : A three-detector observation of gravitational waves from a binary black hole coalescence

The LIGO Scientific Collaboration and The Virgo Collaboration

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.

APPROVED BY PRL ON SEPT 25th. IN PRESS

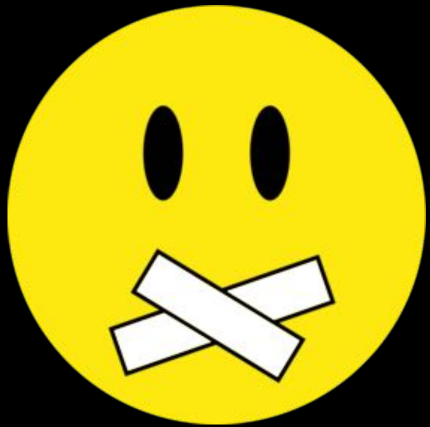
GW170814 - SUMMARY

- FIRST EVENT SEEN BY VIRGO (4^{th} 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



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)

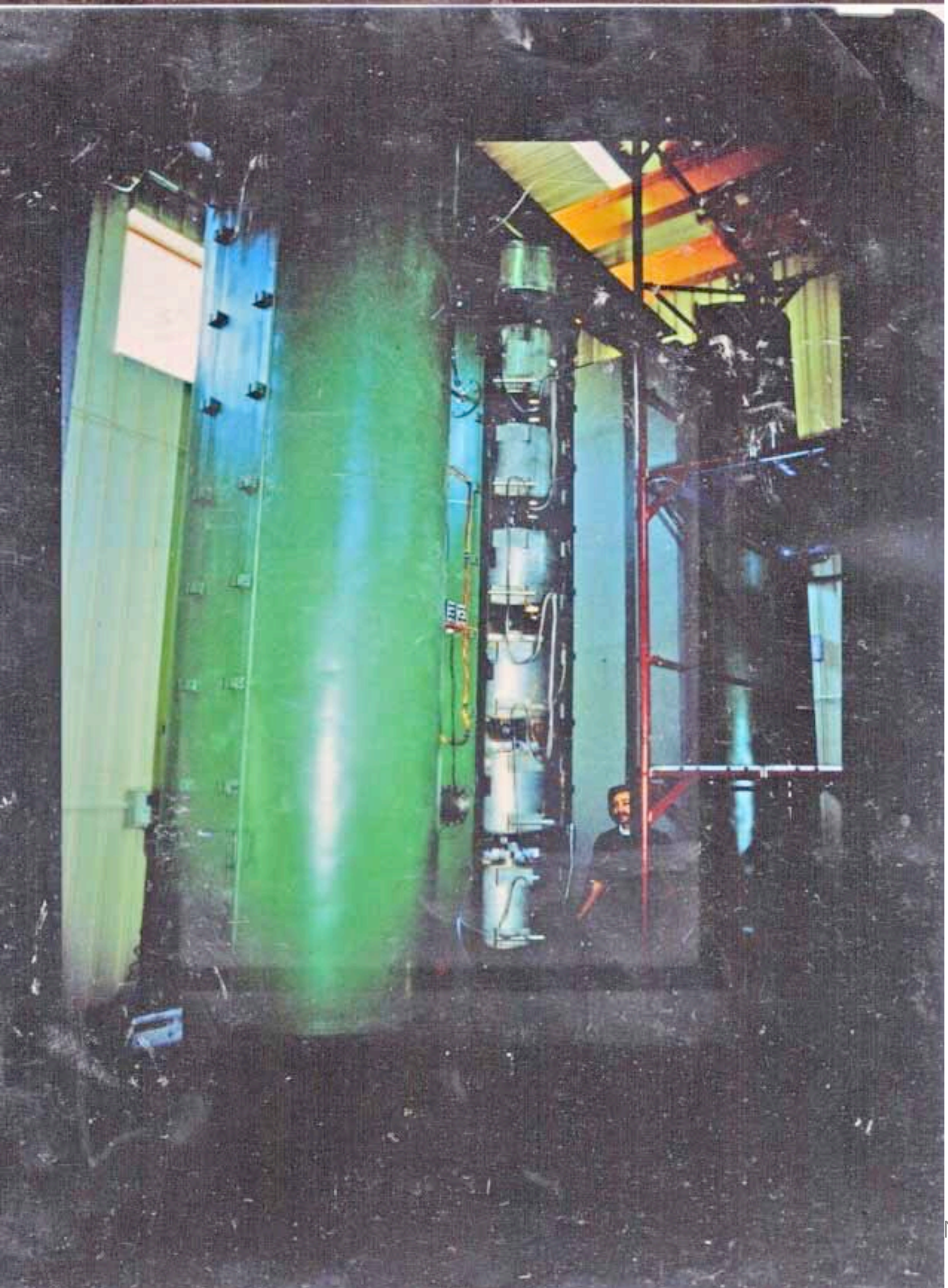
We describe the performances of a 100-kg, 1-m-long active pendulum provided with a reference arm to get rid of the effects of tilting of the ground. The pendulum displacement with respect to the suspension point is measured interferometrically. The phase signal, to be sent to the actuator which displaces 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

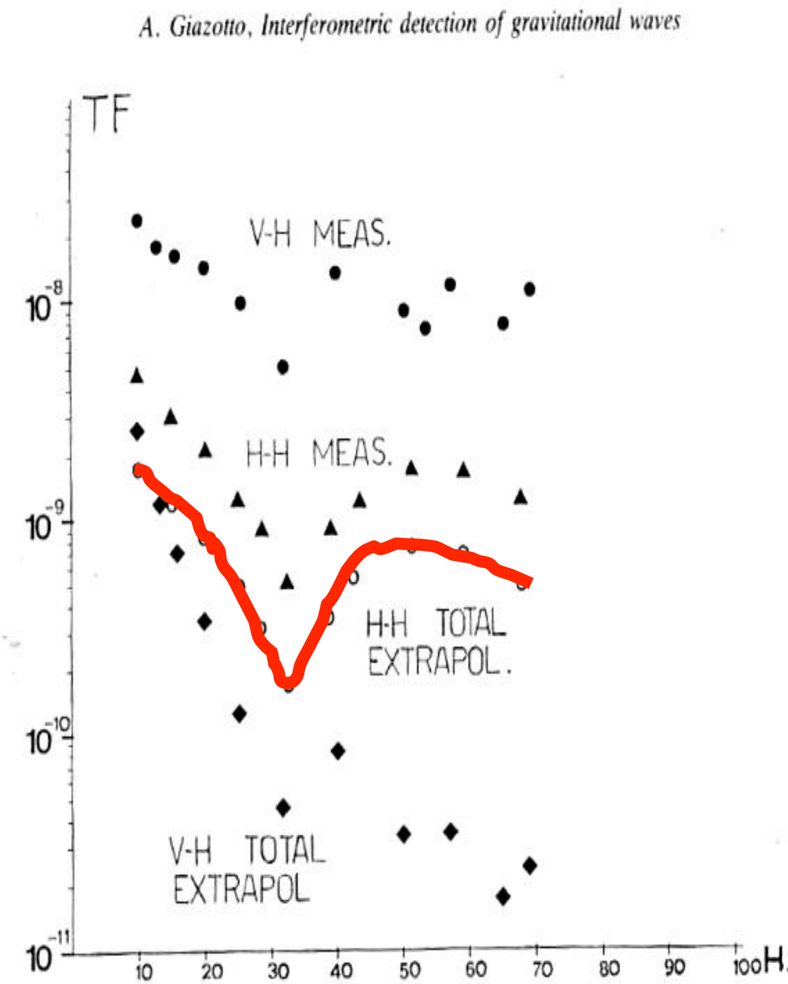
It is well known that the length of a pendulum can be elec-

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

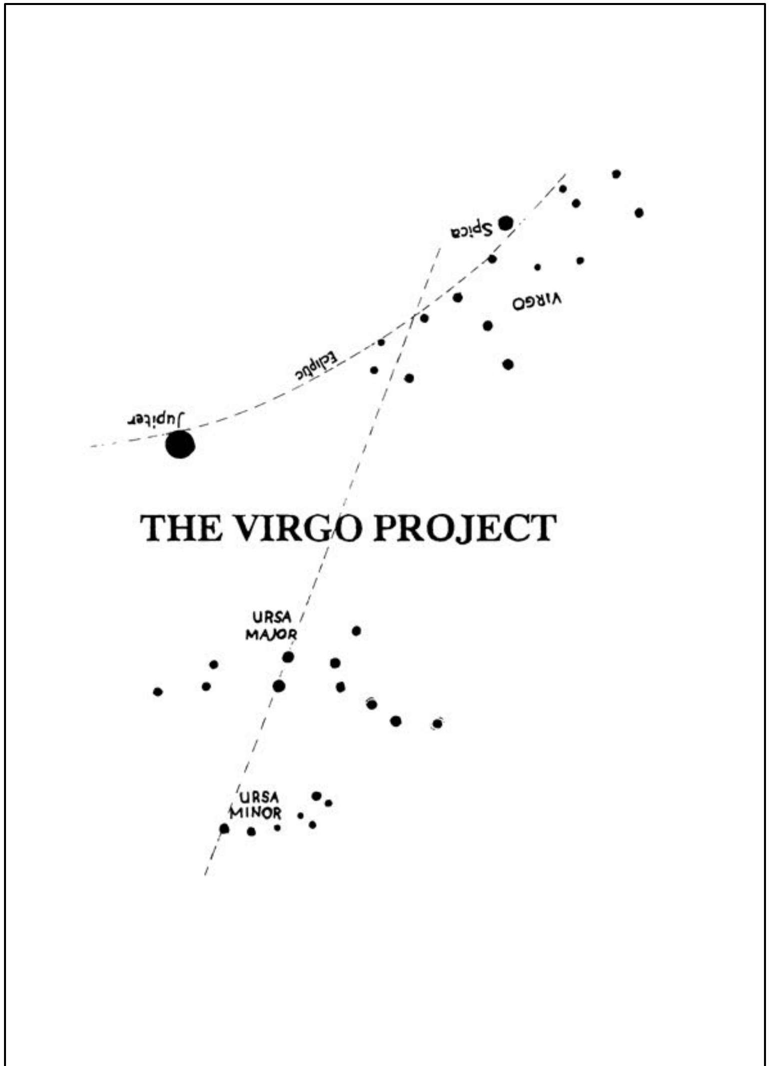
i.e., the PZT2 driving voltage is proportional to ϕ and can be



SAN PIERO A GRADO, 1987



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

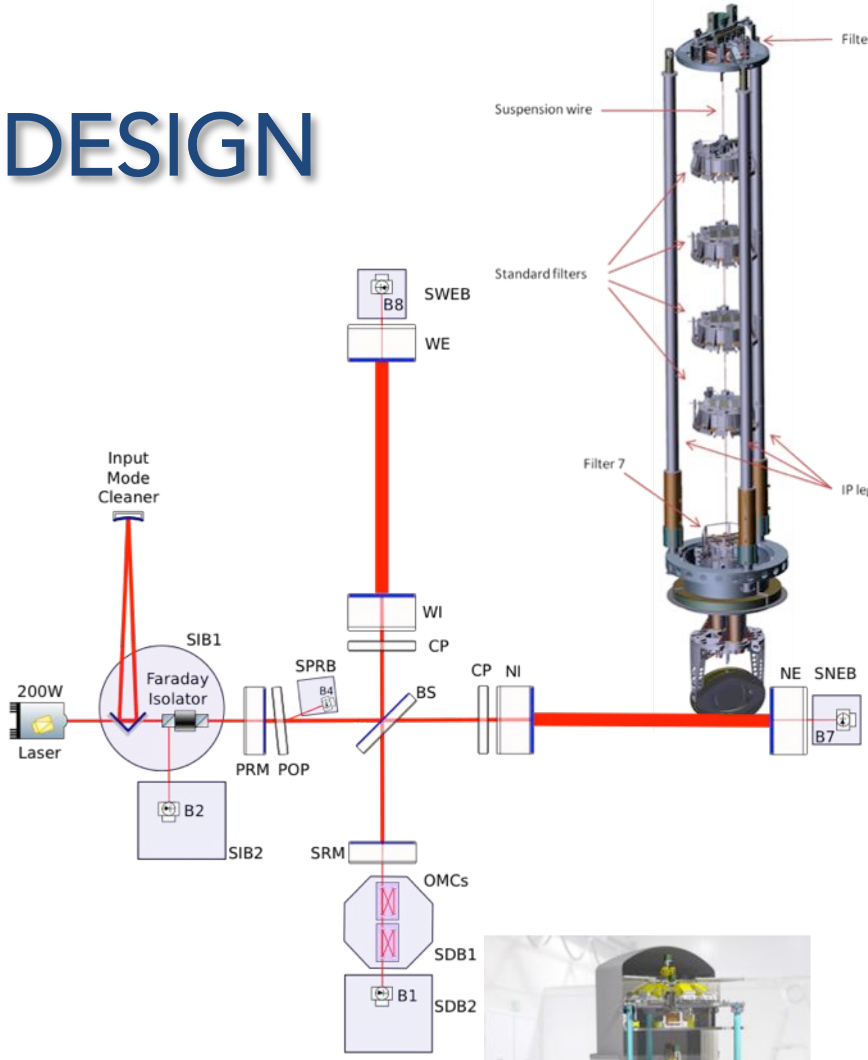
6 European countries
21 labs, ~280 authors

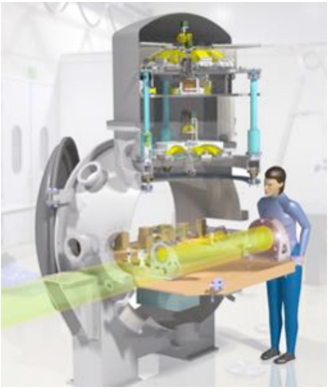
- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector
- Partecipated by France and Italy (former founders of Virgo), The Netherlands, Poland, Hungary, Spain
- Funding approved in Dec 2009 (21.8 ME + Nikhef in kind contribution)
- Project formally completed with the start of the O2 run

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

ADV DETECTOR DESIGN

- 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)
- LATER
  - *200W laser*
  - *signal recycling*





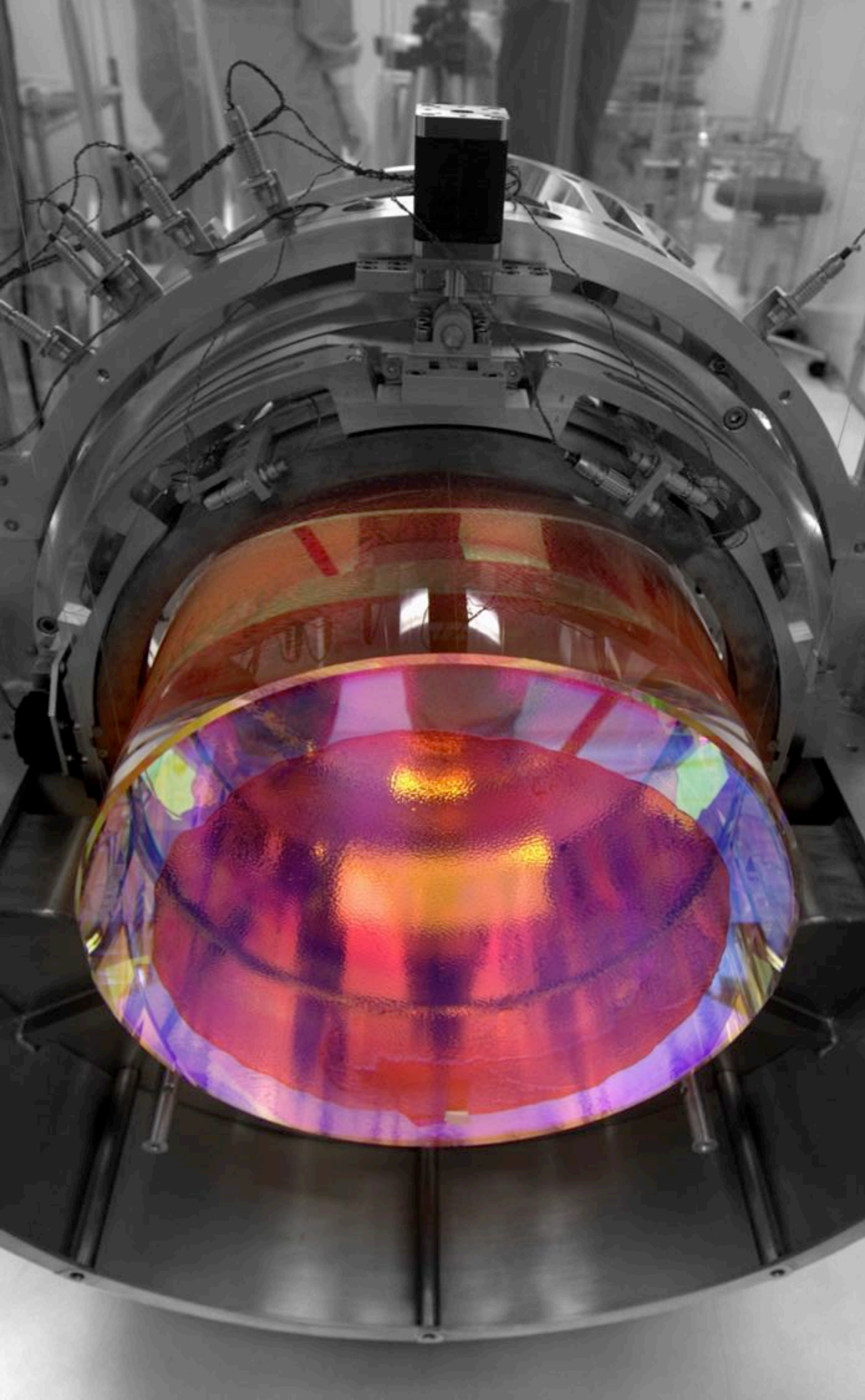
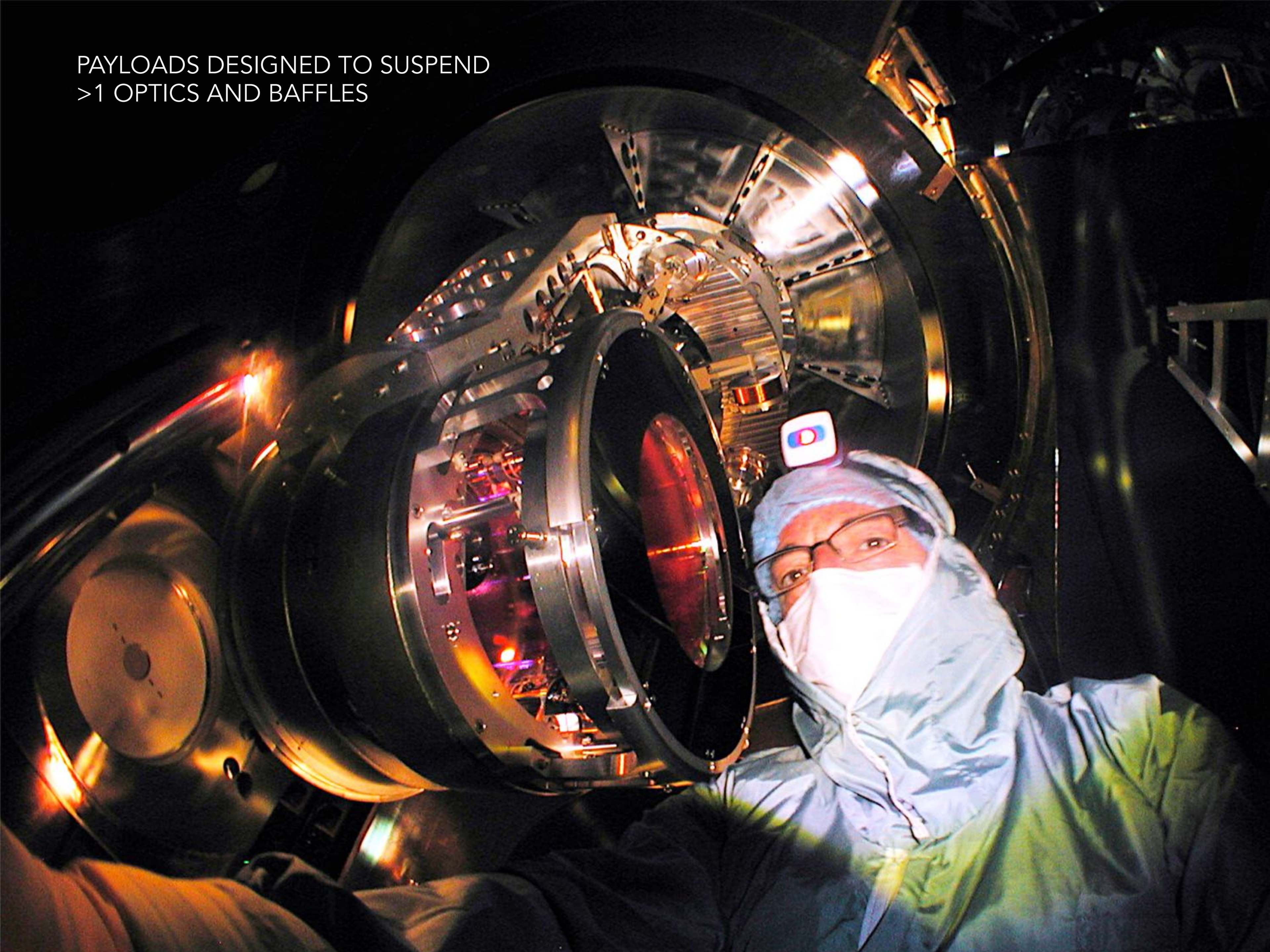
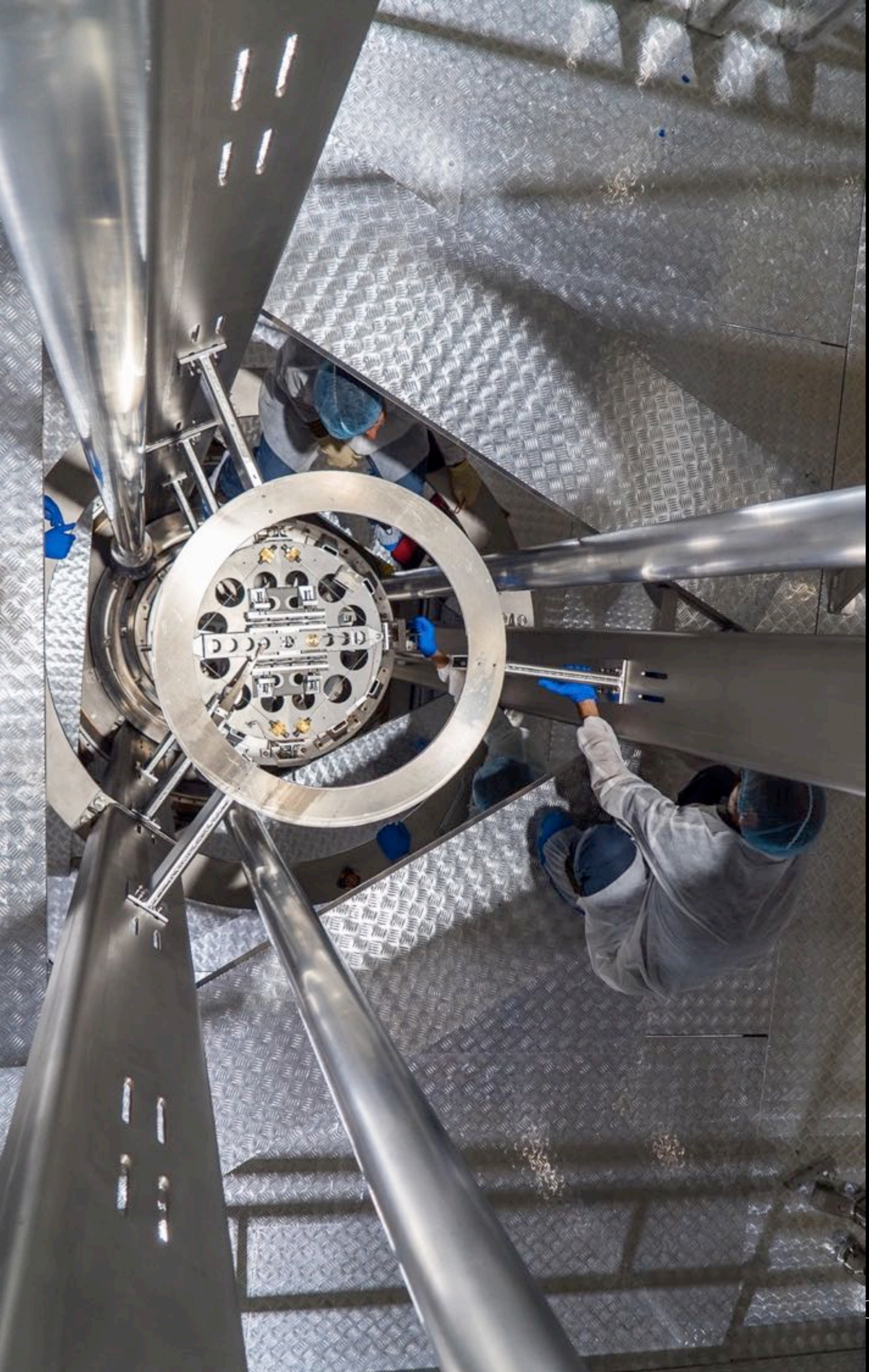
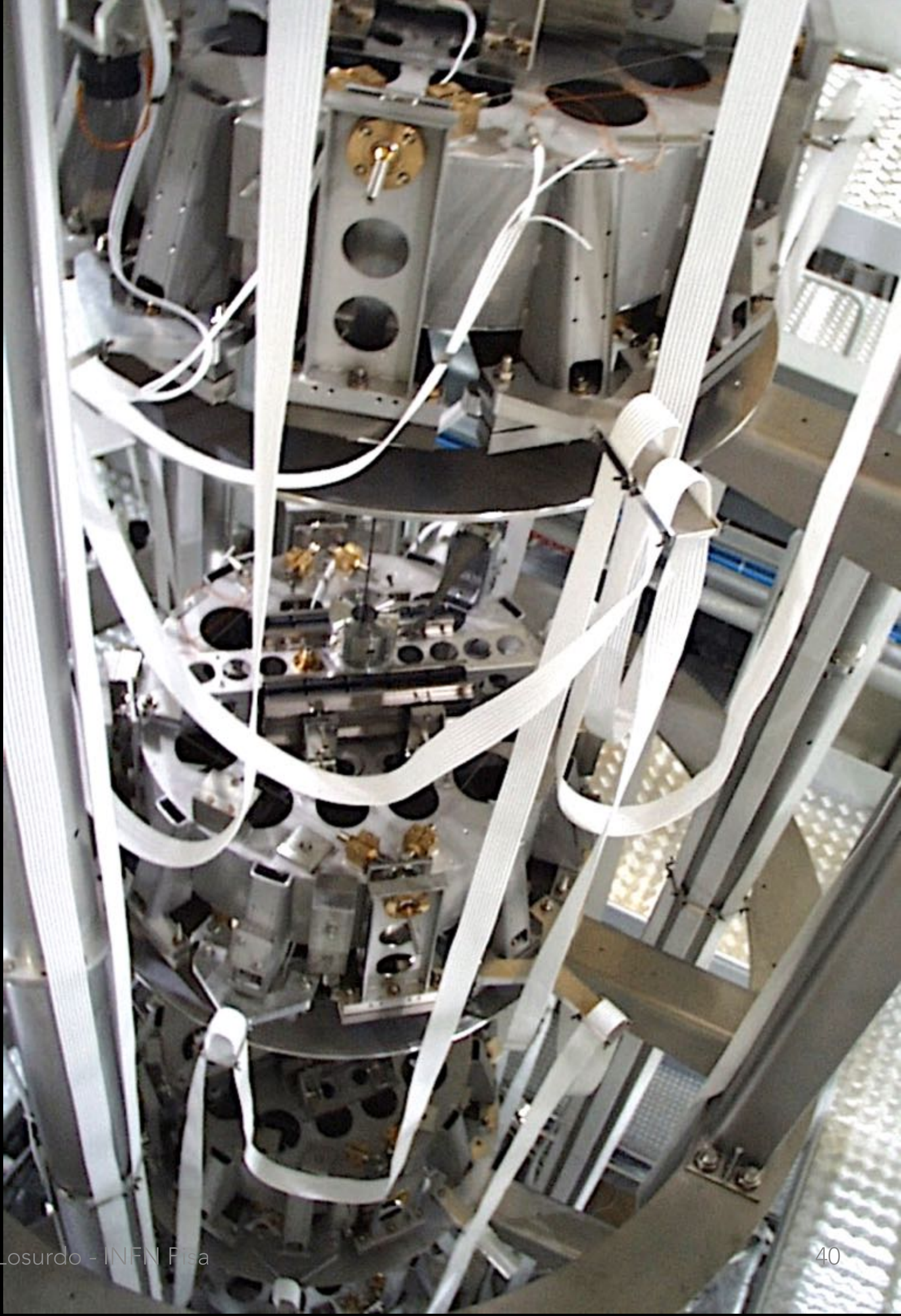


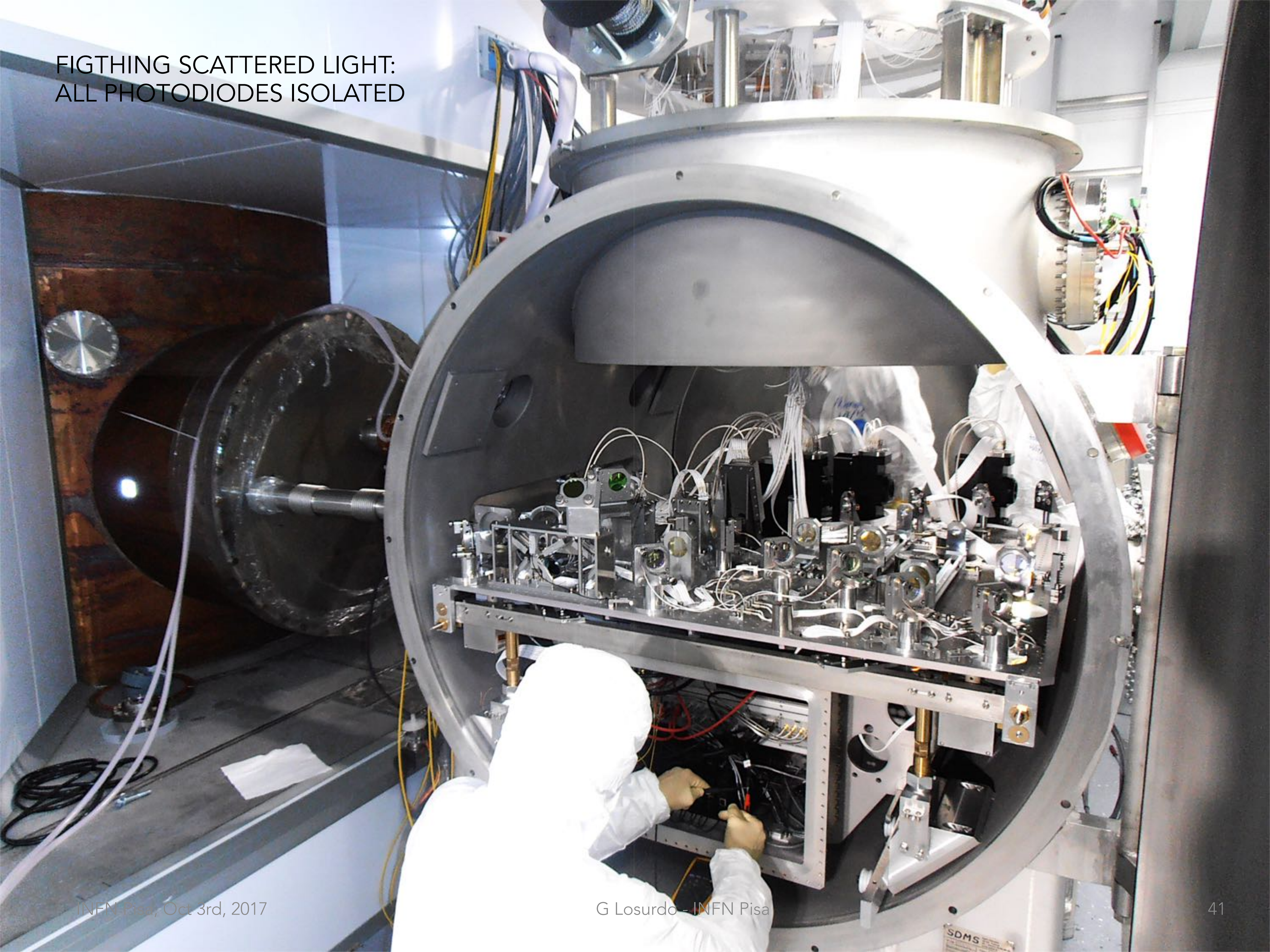

FOTO: MAURIZIO PERCIBALLI_mirror_without_first_contact_11-11-2015


PAYLOADS DESIGNED TO SUSPEND
>1 OPTICS AND BAFFLES

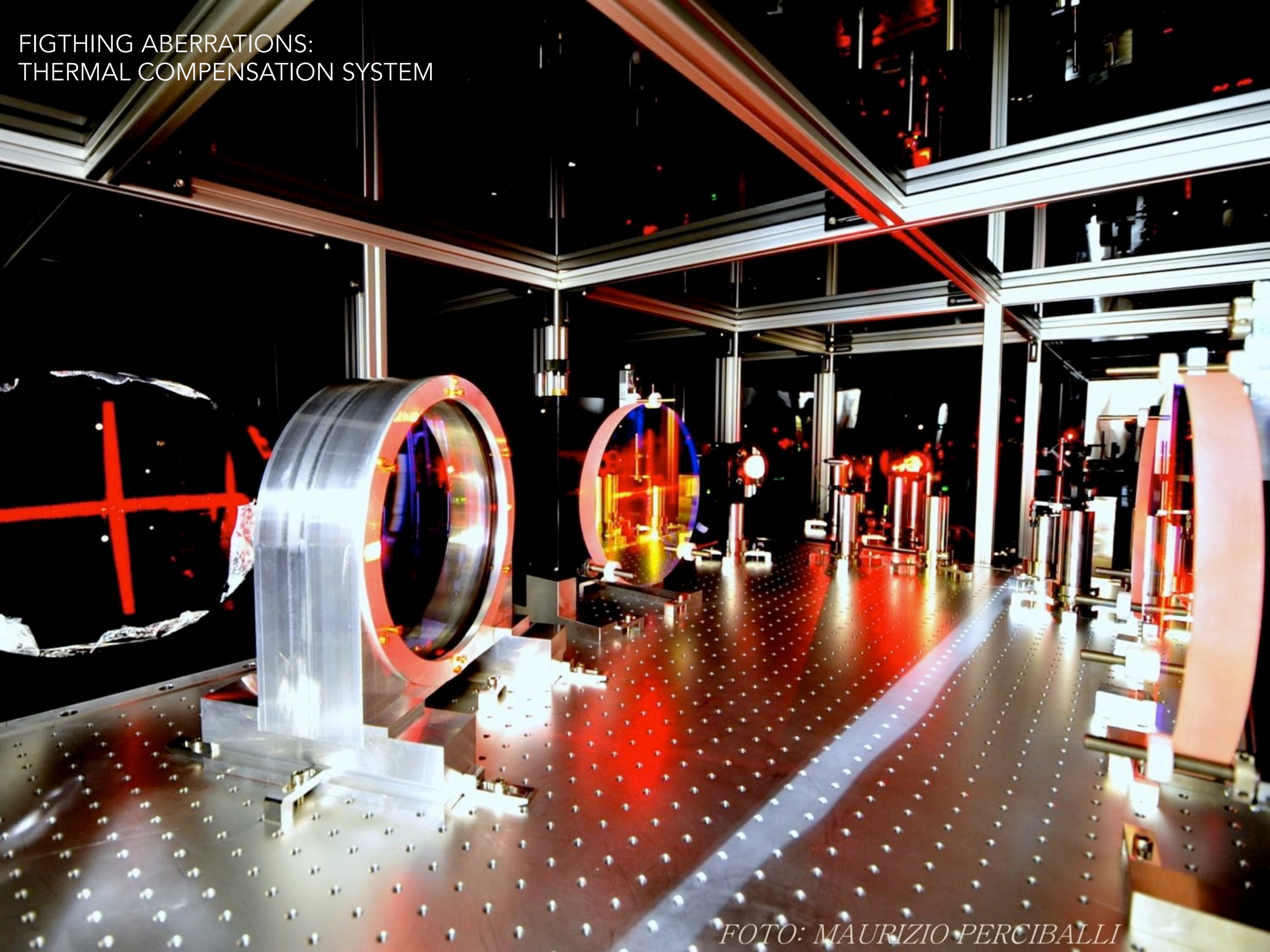




FIGTHING SCATTERED LIGHT: ALL PHOTODIODES ISOLATED



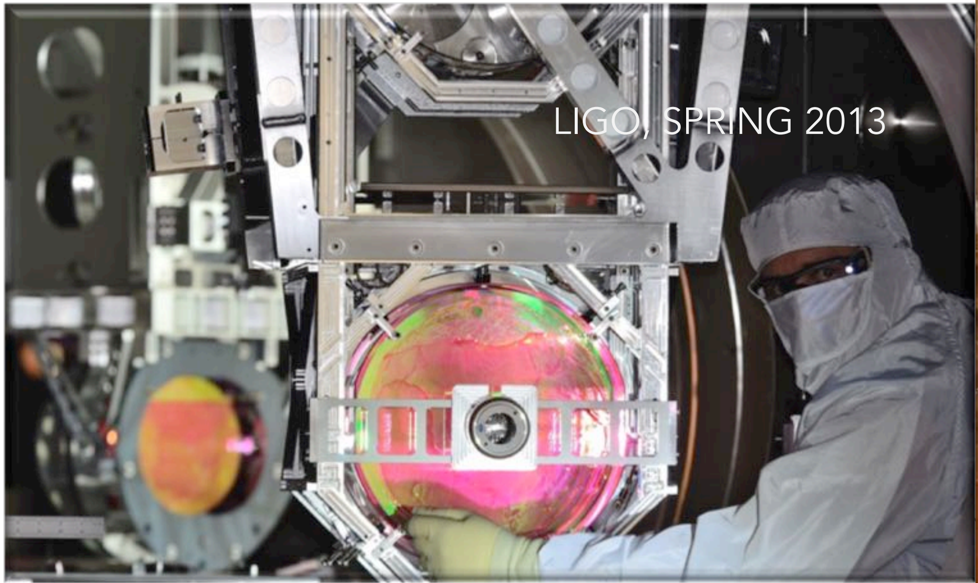
FIGTHING ABERRATIONS:
THERMAL COMPENSATION SYSTEM



IMPROVING THE VACUUM LEVEL: CRYOLINKS

ADV HISTORY

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



AdV vs aLIGO TIMELINES

	AdV	aLIGO*
Date of approval	Dec 2009	Apr 2008
End of integration	Aug 2016	Oct 2014 (LHO)
First stable lock	Mar 2017	Feb 2015 (LHO)
Start of science run	Aug 2017	Sep 2015

~6.5 yrs

~7.5 yrs

*LIGO data from **LIGO-L1400164-v3**

COMPARED TIMELINES

	LIGO	VIRGO	Δ (yrs)
Proposal	1989	1989	0
Funding	1992	1994	-2
End of construction	1999	2003	-4
2G upgrade approval	4/2008	12/2009	-2
Start of data taking	9/2015	8/2017	-2
First GW event	9/2015	8/2017	-2
First 3G 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
MAX CBC RANGE (BNS)	200 Mpc	140 Mpc
BUDGET	205(A) M$ + 16(B) (D/UK/AUS)	21.8(C) M€ + 2(B) (NL)
FUNDING APPROVED	Apr 2008	Dec 2009
CONSTRUCTION END(D)	Jul 2014	May 2016
1^{st} PROJECT REVIEW	2003	2008
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 in other labs)
(F) EGO R&D calls 2003 and 2007
(G) CSN2 funding 2005-2010 (data from Fulvio Ricci)

PERSPECTIVES

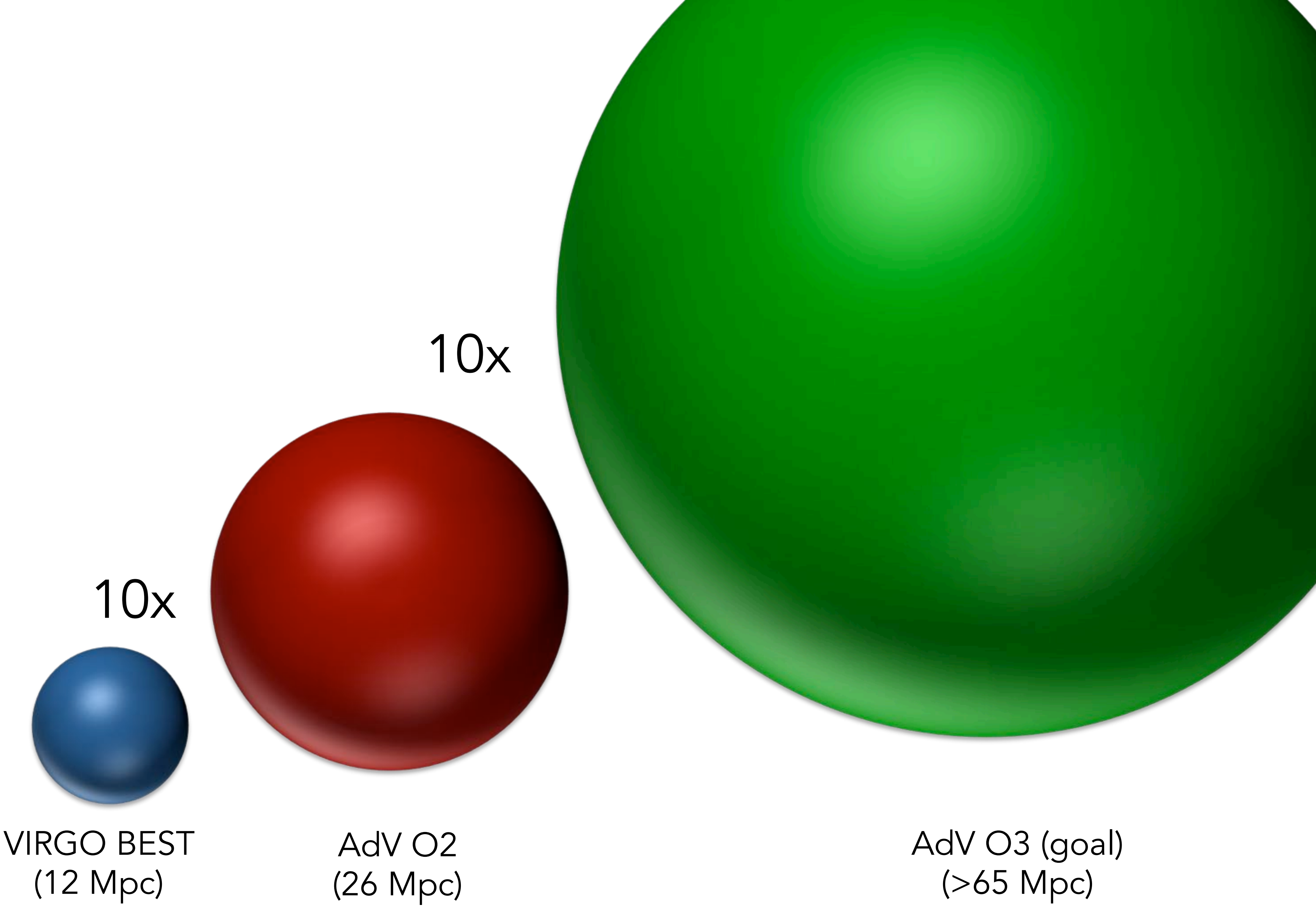
AFTER O2 - VIRGO

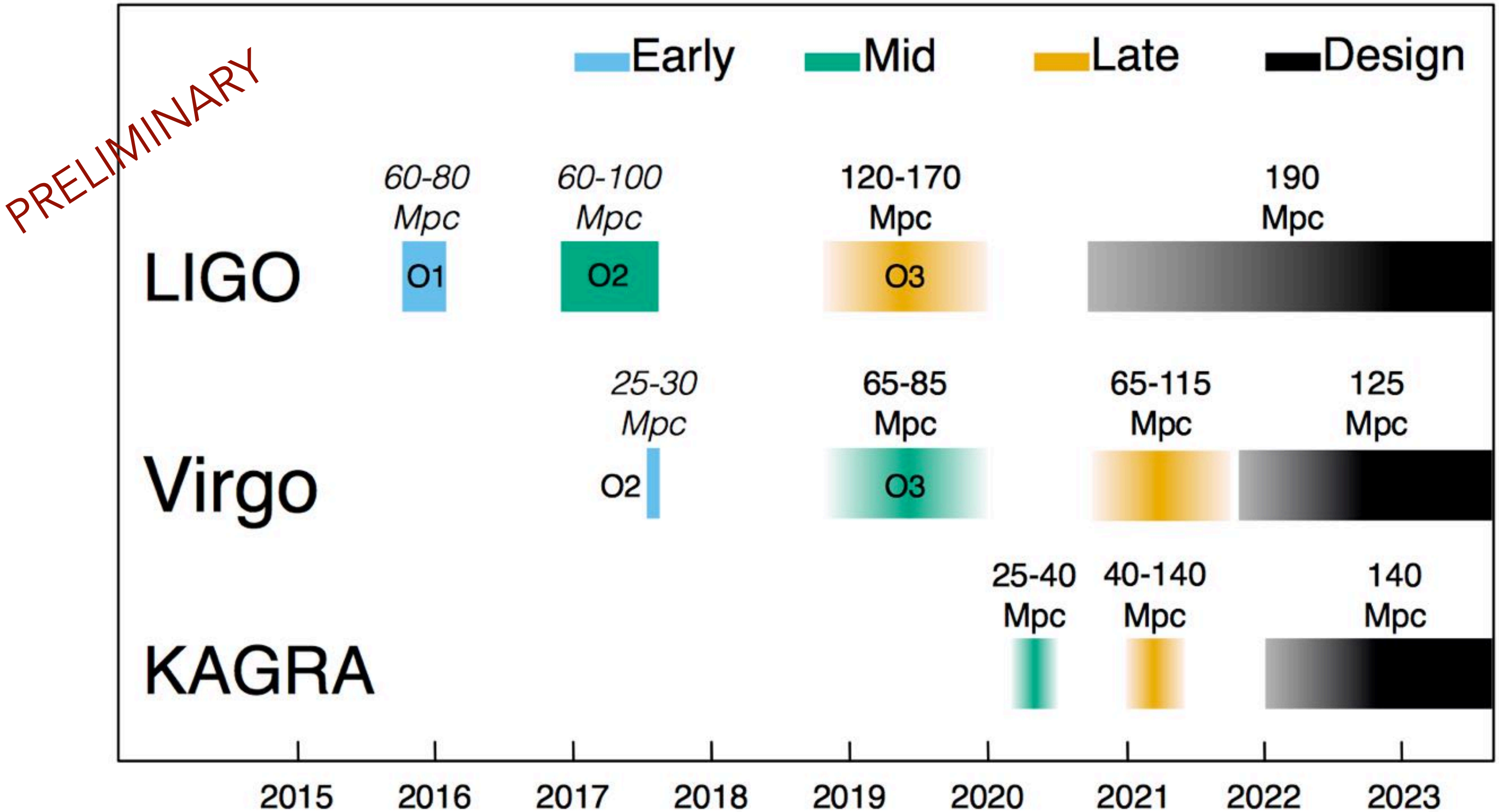
- Upgrade vacuum system to kill dust contamination risk
  - get rid of scroll pumps
  - upgrade piping for big chamber inlet/outlet
- Re-install monolithic suspensions
  - fiber guards will protect the fibers as an additional safety

~5 months

- Increase laser power (now 13 W)
  - decision on the installation of the new 100W laser
- Implement squeezer provided by AEI Hannover
- Do commissioning to improve sensitivity!

- Target BNS range for O3: 65-85 Mpc (a factor ~10 in volume wrt to O2, a factor ~100 wrt to the best Virgo)

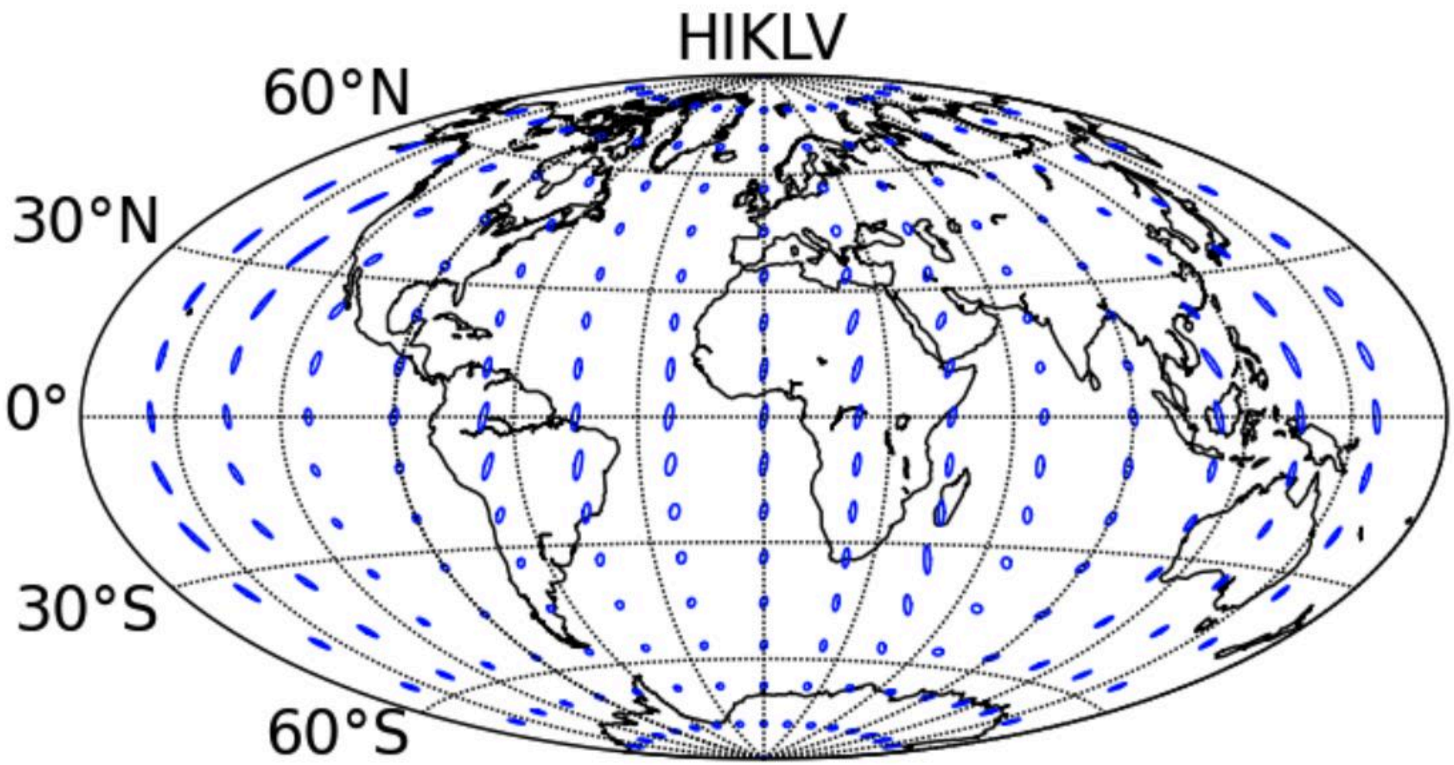

10x
10x
VIRGO BEST
(12 Mpc)
AdV O2
(26 Mpc)
AdV O3 (goal)
(>65 Mpc)



…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

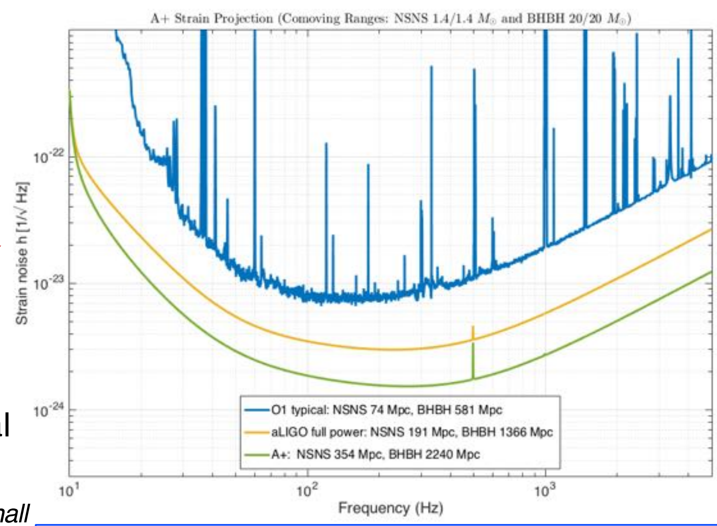
LONGER TERM

- Phase 1 (now-2021): achieve AdV target sensitivity
- **Phase 2 (2021-25): upgrade AdV to reach the infrastructure limits**
  - AdV vision document, VIR-0136B-16
- Phase 3 (>2025): preparing for a new infrastructure

CONTEXT

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

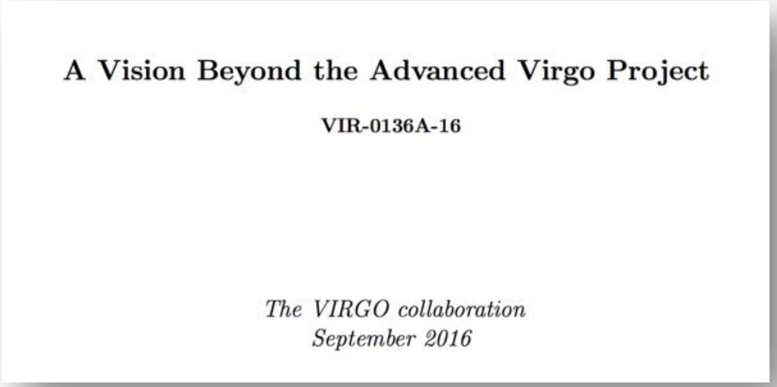
BUDGET: O(30M$)

SCHEDULE: ~2023

LIGO-INDIA EXPECTED ONLINE IN ~2024

VIRGO PLANS

- Remain competitive: realize a relevant upgrade (AdV+) on the same A+ timeline



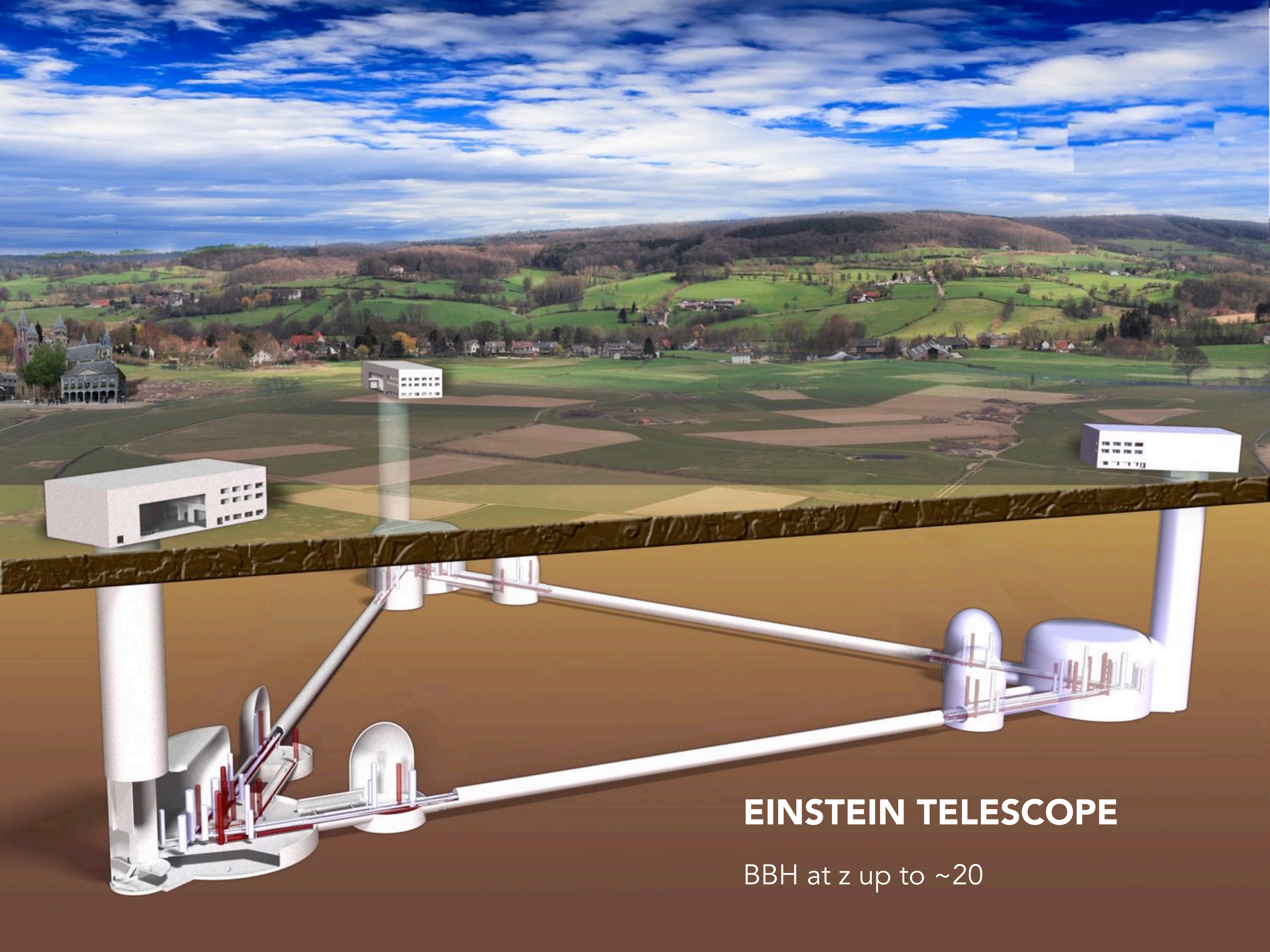
A Vision Beyond the Advanced Virgo Project

VIR-0136A-16

The VIRGO collaboration
September 2016

- Continue working for a 3G detector in Europe (E.T.)

- 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, DA, e.m. follow up, theory)


EINSTEIN TELESCOPE
BBH at z up to ~20

3G SCIENCE CASE

CREDIT: B SATHYAPRAKASH

- *extremes of physics*
  - structure and dynamics of neutron stars
  - physics of extreme gravity and quantum geometry
- *black holes through cosmic history*
  - formation, evolution and growth of black holes and their properties
- *explosive phenomena*
  - gamma ray bursts, gravitational collapse and supernovae

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)