Gravitational waves

Advanced Virgo and Einstein Telescope

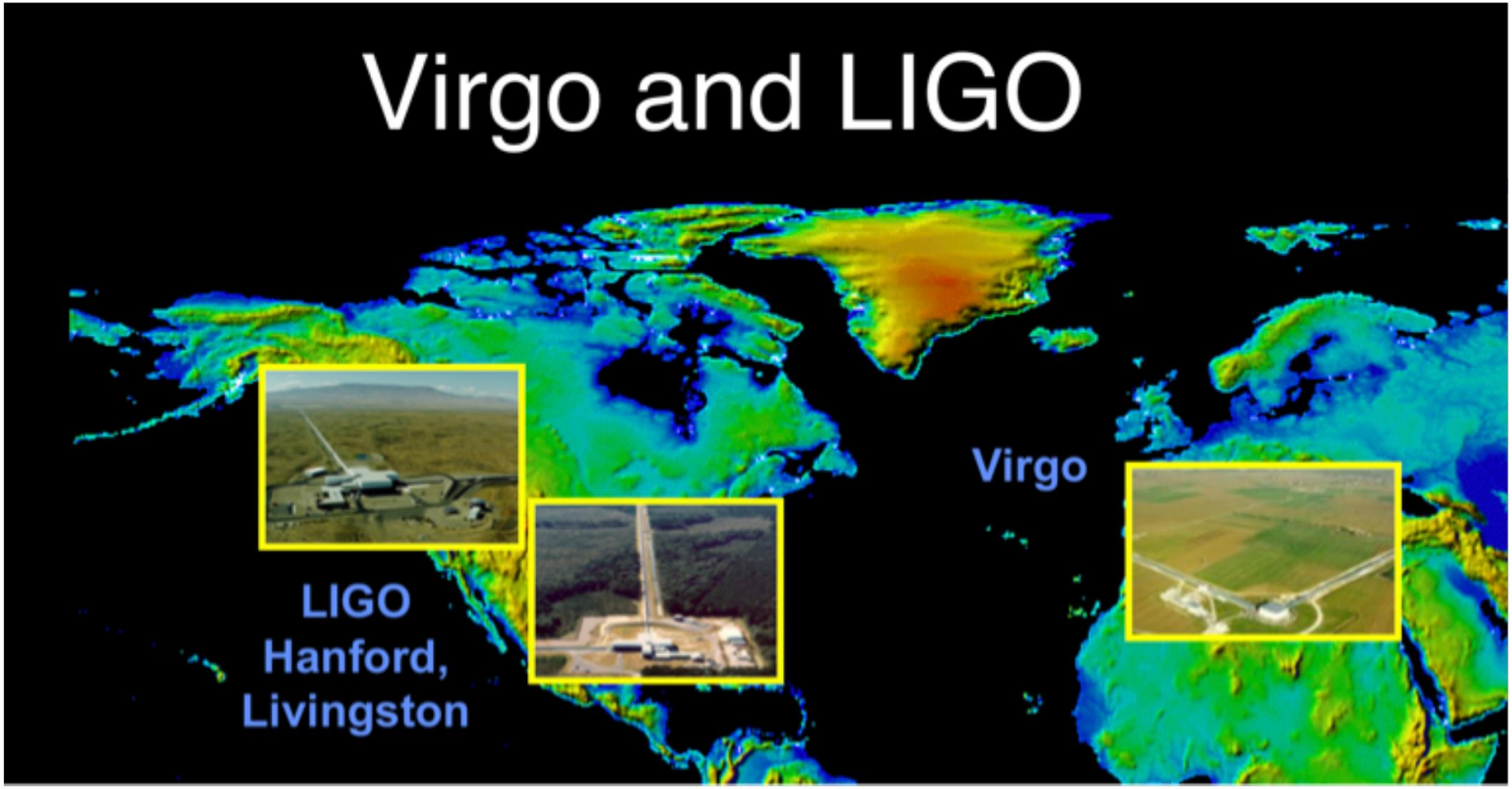
Jo van den Brand
Nikhef SAC, Amsterdam, 8 July 2019; jo@nikhef.nl

Nikhef

LIGO and Virgo

Establishing Virgo as a partner in the global GW network was a major accomplishment

LIGO and Virgo have coordinated data taking and analysis, and release joint publications
LIGO and Virgo work under an MOU already for more than a decade. KAGRA may join in 2019



Virgo Collaboration has invested in Advanced Virgo

Virgo is a European collaboration with about 400 members from about 80 institutes

Advanced Virgo (AdV) and AdV+: upgrades of the Virgo interferometric detector

Participation by scientists from France, Italy, Belgium, The Netherlands, Poland, Hungary, Spain, Germany

- Institutes in Virgo Steering Committee
  - APC Paris
  - ARTEMIS Nice
  - IFAE Barcelona
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - INFN Perugia
  - INFN Pisa
  - INFN Roma La Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - LAL Orsay – ESPCI Paris
  - LAPP Annecy
  - LKB Paris
  - LMA Lyon
  - Nikhef Amsterdam
  - POLGRAW(Poland)
  - RADBOUD Uni. Nijmegen
  - RMKI Budapest
  - UCLouvain, ULiege
  - Univ. of Barcelona
  - University of Sannio
  - Univ. of Valencia
  - University of Jena

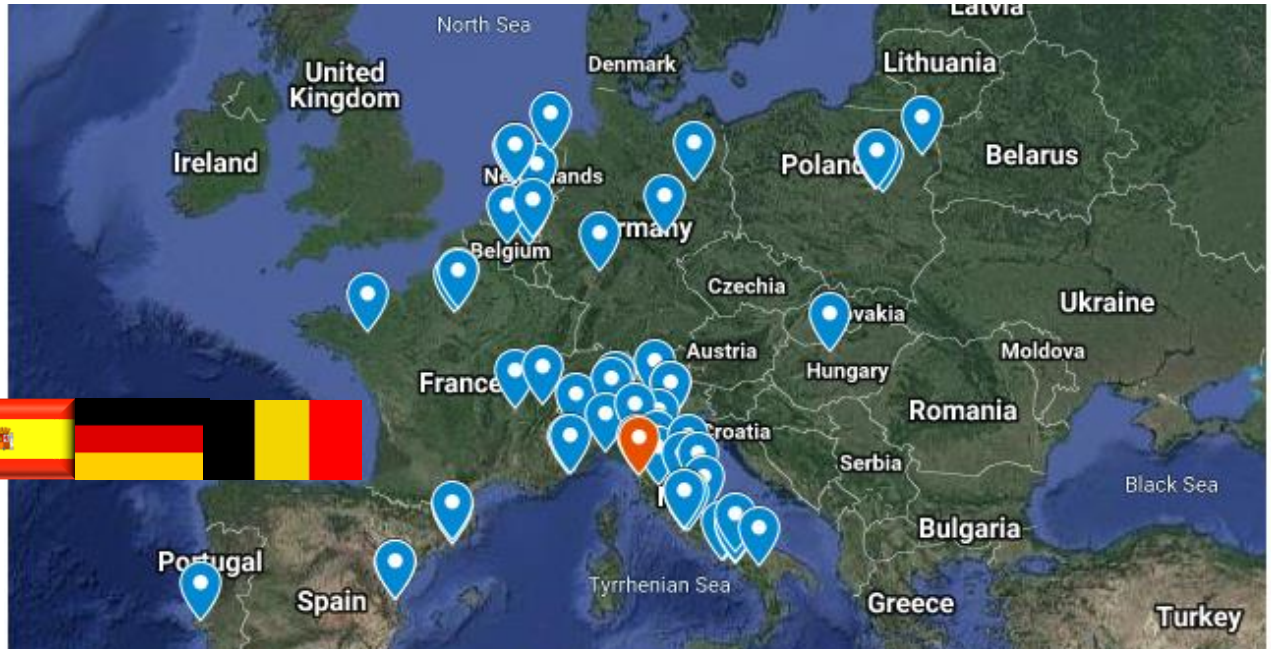
Advanced Virgo project has been formally completed on July 31, 2017

Part of the international network of 2nd generation detectors

Joined the O2 run on August 1, 2017

LIGO and Virgo running of O3

8 European countries



2018: IFAE and UBarcelona, ULiège and UCLouvain

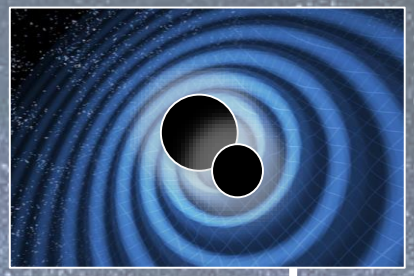
New groups strengthen Virgo in areas as Computing and Stray Light Mitigation

2019: USannio/UniSA, Jena University, Maastricht University, and request for membership by Antwerp University

Groups from UTorino, USardinia, joined Virgo indirectly

ULBrussels, UAntwerp, UGhent, UUtrecht, KULeuven, KIT, … in discussion

January 4, 2017

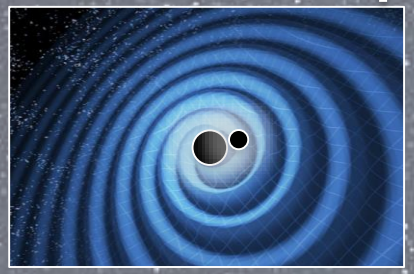


August 1, 2017

Advanced LIGO's Second Observing Run

Virgo turns on

Nov 2016	Dec 2016	Jan 2017	Feb 2017	Mar 2017	Apr 2017	May 2017	Jun 2017	Jul 2017	Aug 2017



June 6, 2017

Scientific achievements: properties of binary systems

"GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs", LIGO Virgo Collaboration, arXiv:1811.12907

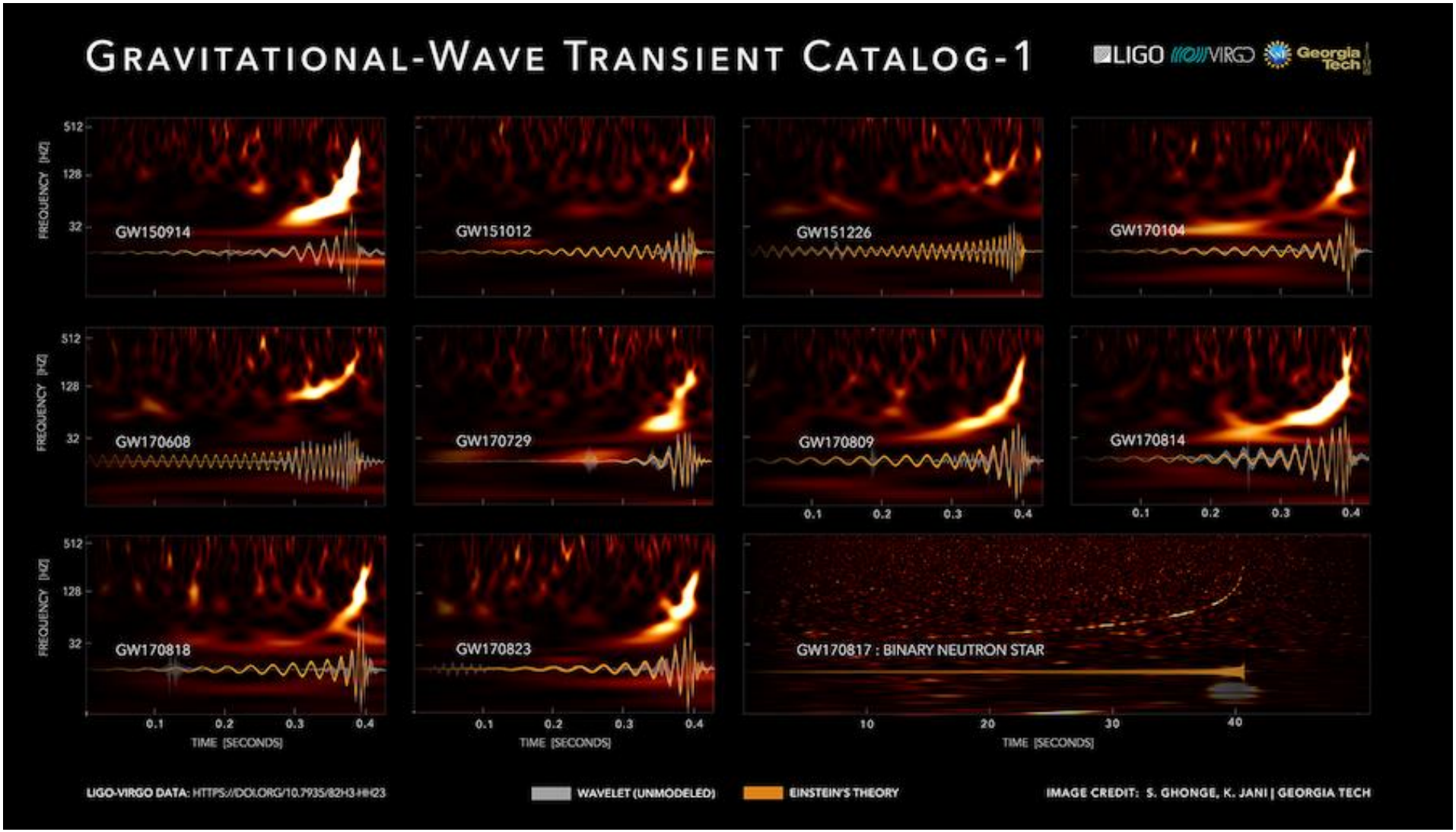


Table of O1 and O2 triggers with source properties

See arXiv:1811.12907

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_{\rm f}/M_\odot$	$a_{\rm f}$	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/({\rm erg\ s^{-1}})$	$D_{\rm L}/{\rm Mpc}$	z	$\Delta\Omega/{\rm deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	194
GW151012	$23.2^{+14.0}_{-5.4}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.2}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.7}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1491
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1075
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.4^{+5.2}_{-3.9}$	$0.66^{+0.09}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.2^{+0.7}_{-1.0}\times10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	912
GW170608	$11.2^{+5.4}_{-1.9}$	$7.5^{+1.5}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.04^{+0.19}_{-0.06}$	$17.9^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.8^{+0.1}_{-0.1}$	$3.4^{+0.5}_{-1.3}\times10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	524
GW170729	$50.7^{+16.3}_{-10.2}$	$34.4^{+8.9}_{-10.2}$	$35.8^{+6.3}_{-4.9}$	$0.37^{+0.21}_{-0.26}$	$80.3^{+14.5}_{-10.3}$	$0.81^{+0.07}_{-0.13}$	$4.9^{+1.6}_{-1.7}$	$4.2^{+0.8}_{-1.5}\times10^{56}$	2760^{+1290}_{-1350}	$0.48^{+0.18}_{-0.21}$	1069
GW170809	$35.2^{+8.3}_{-5.9}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.17}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	310
GW170814	$30.7^{+5.5}_{-2.9}$	$25.6^{+2.8}_{-4.0}$	$24.3^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.6^{+3.2}_{-2.5}$	$0.73^{+0.07}_{-0.05}$	$2.8^{+0.4}_{-0.3}$	$3.7^{+0.5}_{-0.5}\times10^{56}$	560^{+140}_{-210}	$0.12^{+0.03}_{-0.04}$	99
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1\times10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	22
GW170818	$35.5^{+7.5}_{-4.7}$	$26.9^{+4.4}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.7}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times10^{56}$	1020^{+430}_{-370}	$0.20^{+0.07}_{-0.07}$	35
GW170823	$39.5^{+10.1}_{-6.6}$	$29.4^{+6.5}_{-7.1}$	$29.3^{+4.2}_{-3.1}$	$0.08^{+0.19}_{-0.22}$	$65.6^{+9.3}_{-6.5}$	$0.71^{+0.08}_{-0.09}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9}\times10^{56}$	1860^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1780

LIGO EGO European Gravitational Observatory LSC LIGO Scientific Collaboration VIRGO

Table of O1 and O2 triggers with source properties

See arXiv:1811.12907

Virgo data contributed to Parameter Estimation of 5 events

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_{\rm f}/M_\odot$	$a_{\rm f}$	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/({\rm erg\ s^{-1}})$	$D_{\rm L}/{\rm Mpc}$	z	$\Delta\Omega/{\rm deg}^2$
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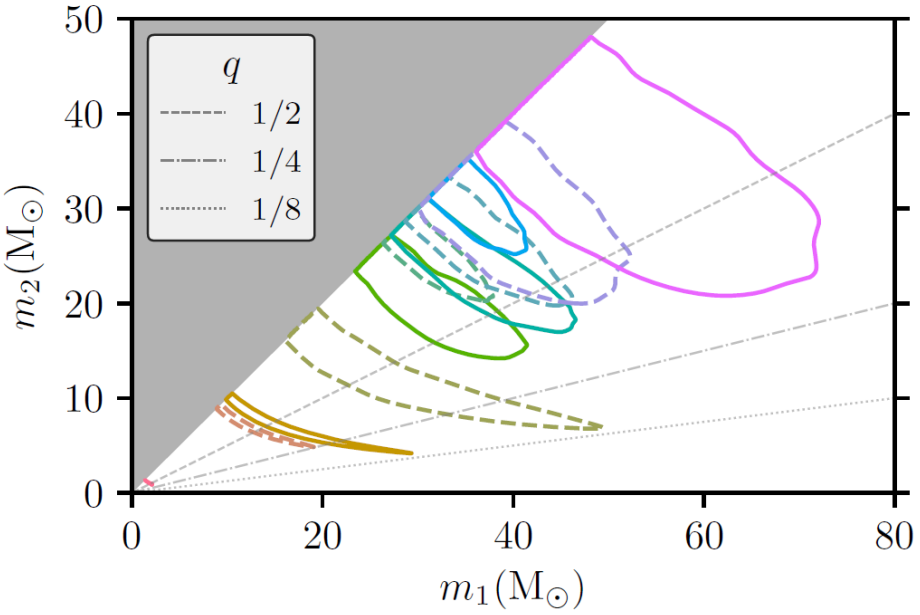
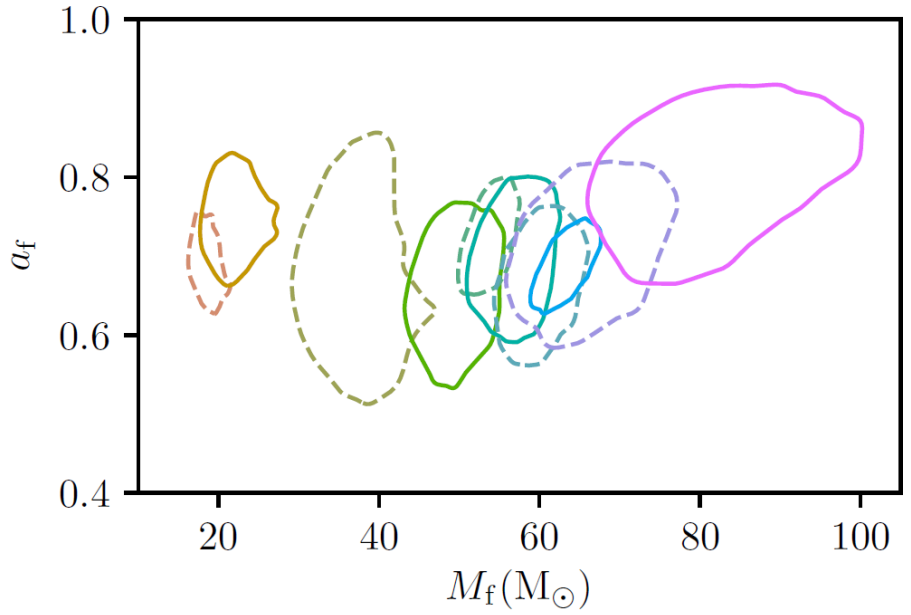
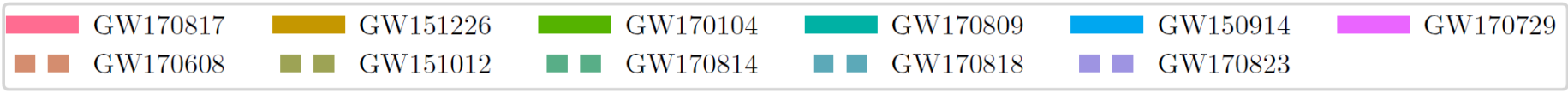
Properties of black holes

Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms







"GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs", The LIGO Virgo Collaboration, arXiv:1811.12907

Nikhef Gravitation Physics group

Good mix between instrumentation and data analysis. Instrumentation is emphasized at Nikhef and Maastricht University. Composition: 19 seniors, 7 postdocs, 12 PhD students. More to come …

Instrumentation

Alessandro Bertolini	Senior Nikhef
Bas Swinkels	Scientist Nikhef
Matteo Tacca	Scientist Nikhef
Daniela Pascucci	Postdoc Nikhef
Jo van den Brand	Professor VUAmsterdam
Henk Jan Bulten	Senior VUAmsterdam
Soumen Koley	PhD VUAmsterdam
Boris Boom	PhD VUAmsterdam
Laura van der Schaaf	PhD VUAmsterdam
Rob Walet	PhD VUAmsterdam
Stefan Hild	Professor UMaastricht
Stefan Danilishin	A. Professor UMaastricht
Jessica Steinlechner	A. Professor UMaastricht
Sebastian Steinlechner	A. Professor UMaastricht
Ayatri Singha	PhD UMaastricht
Andrei Utina	PhD UMaastricht
Frank Linde	Professor UAmsterdam

Detector R&D

Niels van Bakel	Senior Nikhef
Martin van Beuzekom	Senior Nikhef
Maria Bader	PhD VUAmsterdam
Yuefan Guo	PhD UAmsterdam

Data analysis

Sarah Caudill	Scientist Nikhef
Chris Van Den Broeck	Professor UUtrecht
Tim Dietrich	Postdoc UUtrecht
Ka Wa Tsang	PhD UUtrecht
Tsun Ho Pang (Peter)	PhD UUtrecht
Pawan Gupta	PhD UUtrecht
Anuradha Samajdar	Postdoc UUtrecht
Archisman Ghosh	Postdoc UUtrecht
Gideon Koekoek	A. Professor UMaastricht

Astrophysics

Gijs Nelemans	Professor UNijmegen
Paul Groot	Professor UNijmegen
Steven Bloemen	Senior UNijmegen

Grappa

Samaja Nissanke	Professor UAmsterdam
Tanja Hinderer	Postdoc UAmsterdam
David Nichols	Postdoc UAmsterdam
Andrew Williamson	Postdoc UAmsterdam
Geert Raaijmakers	PhD UAmsterdam

Maastricht University is partner in Nikhef

Admitted for Virgo Collaboration membership on July 4, 2019

Group is active in LIGO and has various responsibilities. For reasons of continuity there will be a 10% LSC membership (approved by LSC Council)

- S. Danilishin: LSC Quantum Noise Working Group chair
- J. Steinlechner: LSC Optics Working Group co-chair
- J. Steinlechner: LSC LAAC co-chair
- S. Hild: LSC AIC Working Group chair
- S. Hild: LSC Publications and Presentations Committee co-chair
- S. Hild: LSC Excomm member
- S. Hild: LSC technical advisor to the LIGO Oversight Committee
- G. Koekoek: Main organiser of 2018 LVC meeting in Maastricht

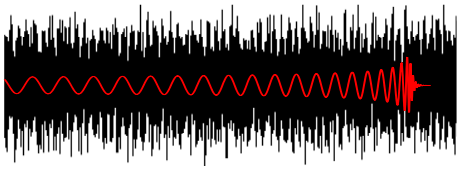
Gravitational wave science at Nikhef

Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms

Searches for binary coalescences

GstLAL is one of the main search pipelines that led to the detections in O1, O2, O3

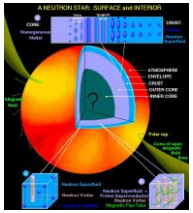
Sub-solar mass (primordial?) black holes



Inferring the structure of neutron stars

State-of-the art inspiral waveform modeling

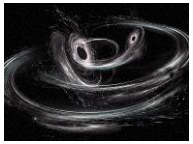
For the future: post-merger



Testing the dynamics of general relativity

Inspiral-merger-ringdown process

Gravitational wave propagation



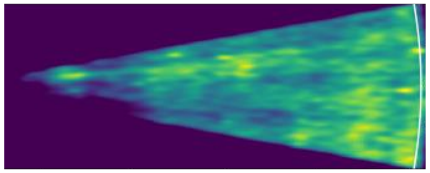
Probing the nature of massive compact objects

Testing the no-hair conjecture

Gravitational wave echoes

Cosmology

Measuring the Hubble constant with or without electromagnetic counterparts



Embedding in LIGO Virgo data analysis

Chris Van Den Broeck
Co-chair, Testing GR group
Chair of the paper writing team, "*Tests of general relativity with GW170817*"

Sarah Caudill
Co-chair, All-sky searches for compact binary coalescences
Member of the paper writing team, "*Search for sub-solar mass ultra-compact binaries in Advanced LIGO's second observing run*"

Tim Dietrich (postdoc)
Member of the paper writing team, "*Properties of the binary neutron star merger GW170817*"

Archisman Ghosh (postdoc)
Co-chair, Cosmology group
Member of the paper writing team, "*A gravitational-wave standard siren measurement of the Hubble constant*"

Anuradha Samajdar (postdoc)
Member of the paper writing team, "*Tests of general relativity with the binary black hole signals from the LIGO-Virgo catalog GWTC-1*"

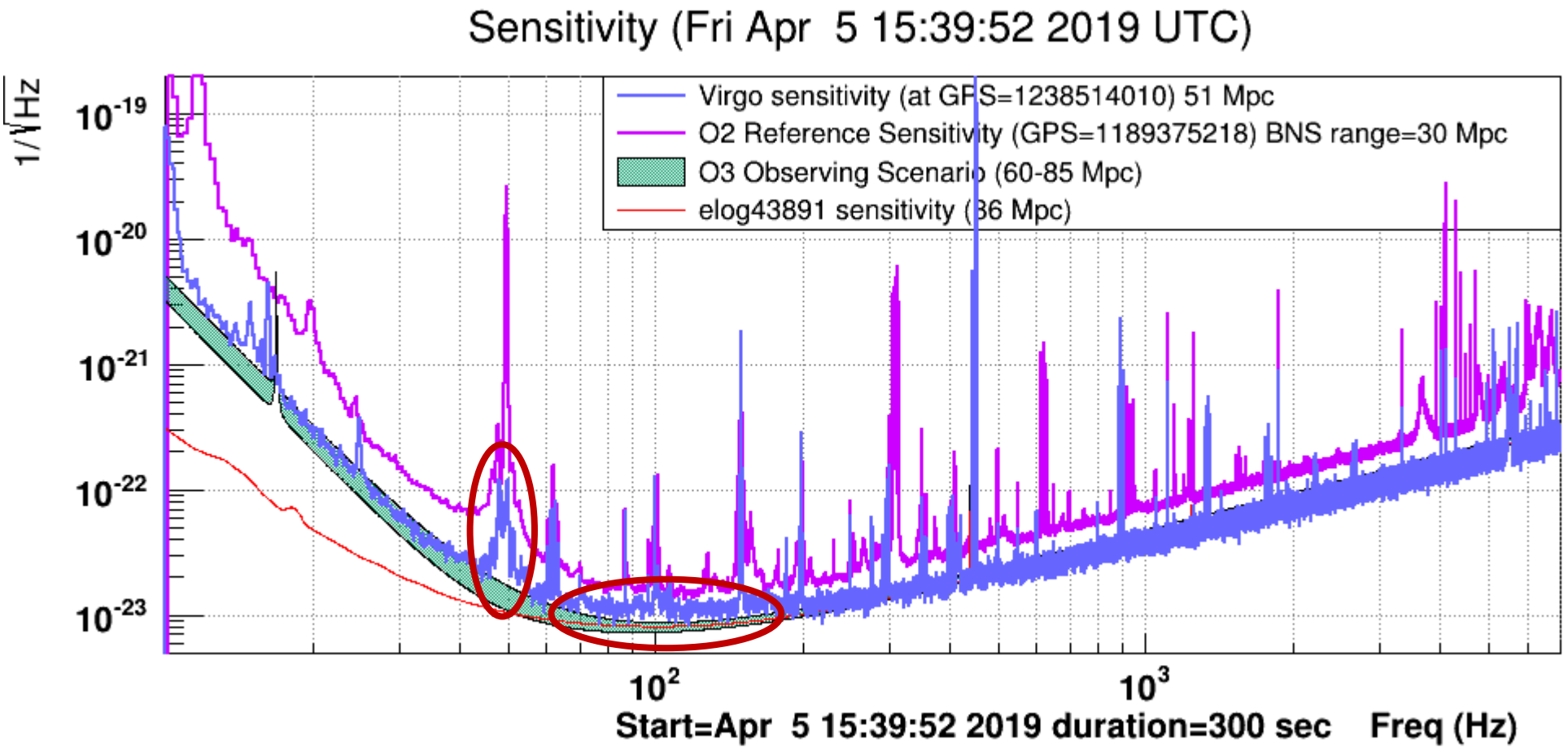
PhD students: Pawan Gupta, Peter Pang, Ka Wa Tsang

April 1, 2019: LIGO and Virgo started Observation run O3

Joining O3 is another big step for Virgo

Virgo sensitivity: typically around 50 Mpc

Significant improvement (> 90%) with respect to the average sensitivity (26 Mpc) obtained in O2. We see a flat noise contribution at mid-frequencies, and significant 50 Hz noise. Power amounts to 18 W
Efficiency around 90%



Commissioning of Virgo

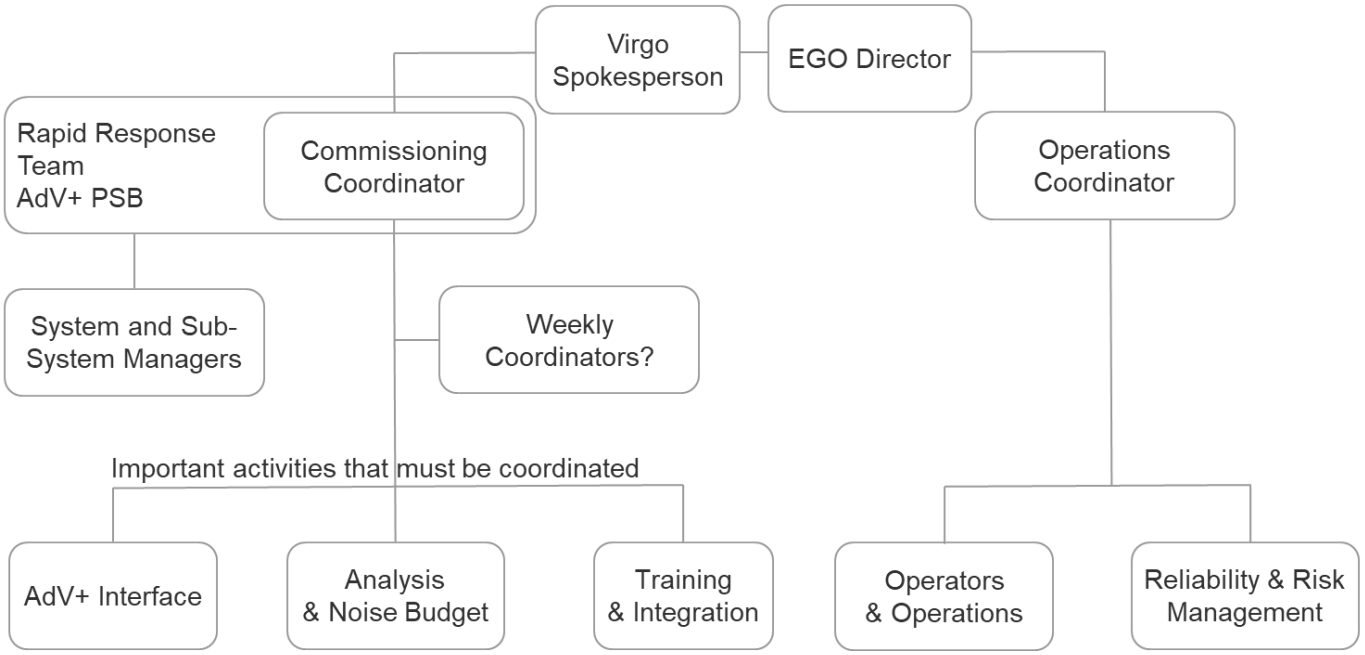
Commissioning encompasses many responsibilities. Coordinator must assemble a team and define roles and responsibilities

Main objectives of Commissioning

Identify and study current limitations: technical noise contributions at low and mid frequency

Integrate new systems to discharge mirrors, signal recycling, high power laser, squeezing, …

Commissioning and Operations



Matteo Tacca
Commissioning Coordinator

Elected:
July 4, 2019

Commissioning Coordinator must form a ROTA for Run Coordinator, be present in the Rapid Response Team, and be part of the LIGO Virgo Joint Run Planning Committee

Virgo Computing and offline Data processing

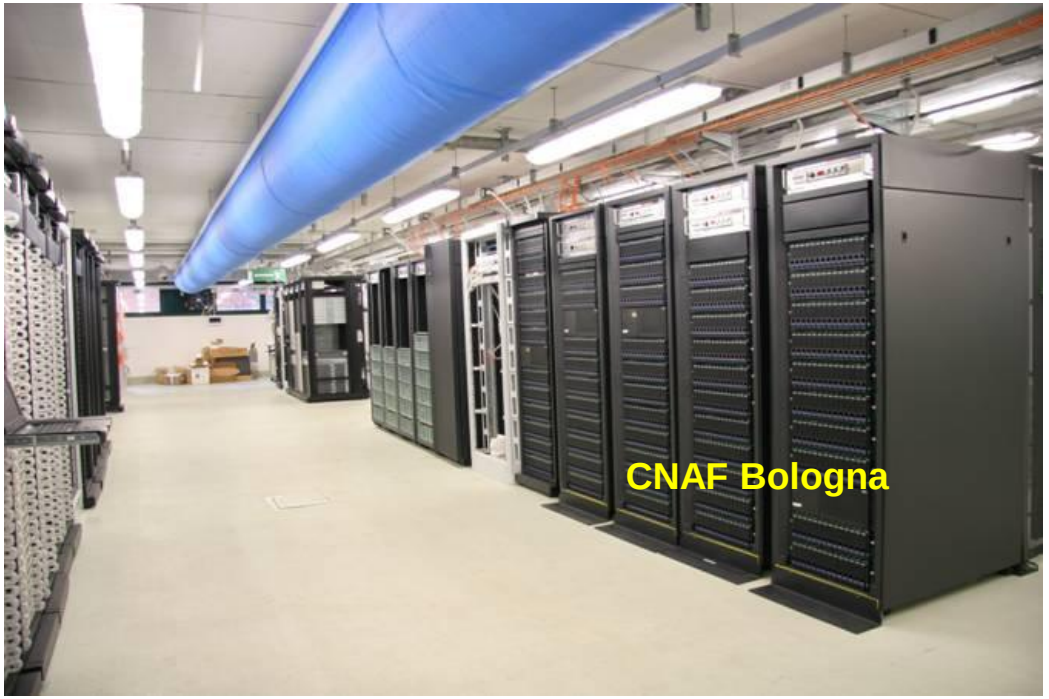
Recent developments and boundary conditions

Computing situation for LVC is a bottleneck

- Virgo is making an effort to increase its contribution to LVC computing resources for Data Analysis

Management

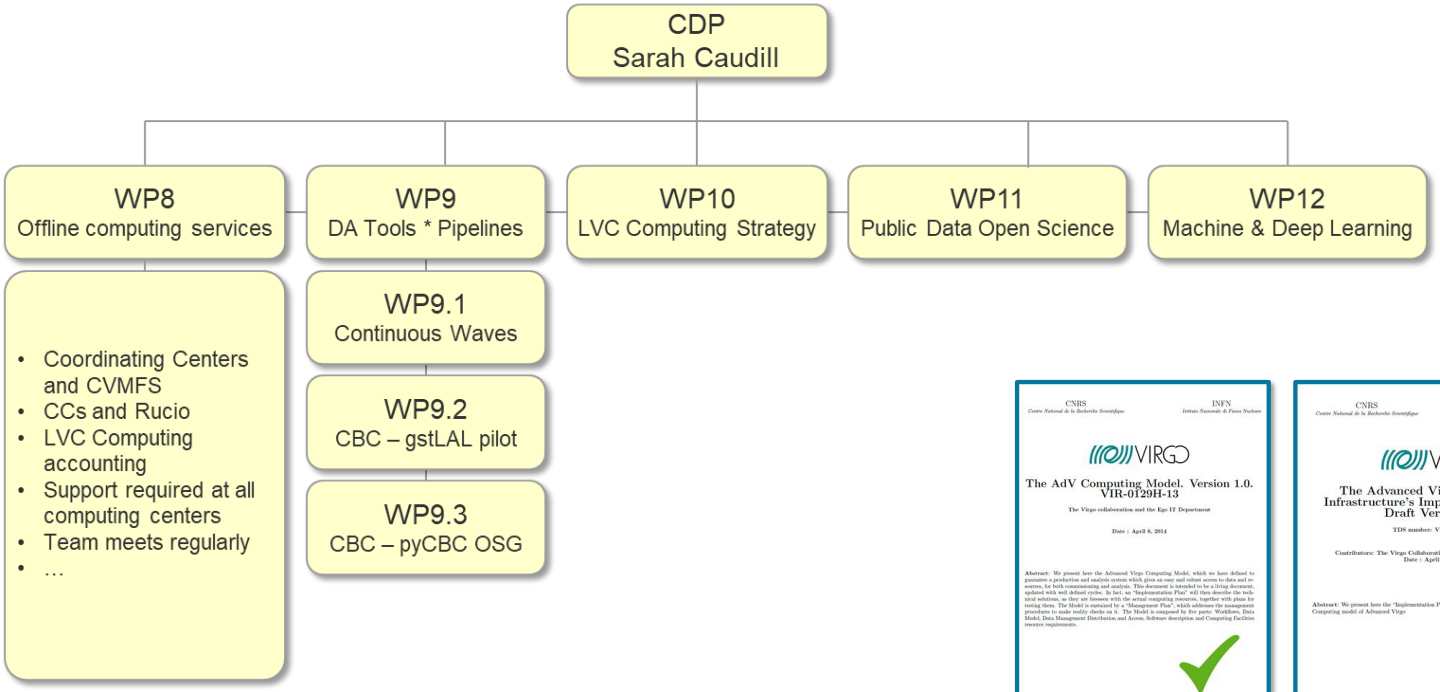
- EGO-Virgo Data Processing Infrastructure coordinator
- Virgo Computing and Data Processing Coordinator



Advanced Virgo

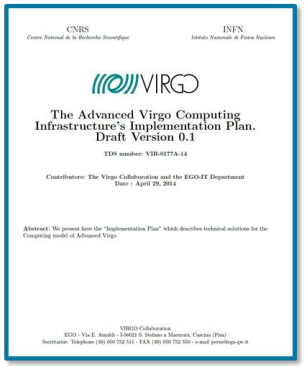
Virgo Computing and Offline Data Processing

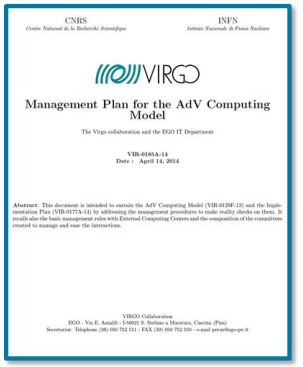
Virgo has implemented a new structure and has defined several projects



Sarah Caudill

Virgo Computing and Data Processing Coordinator





CW: Complete LV data analyses on Continuous Waves ✓

GstLAL: Allow most important CBC pipelines to run on European grid-computing resources. Start with GstLAL, but expand to other LV pipelines

LVC: I. Update VCDP Computing Model, Implementation Plan, and Management Plan (involve DA and CDP coordinators), and II. Prepare a strategy in collaboration with LSC and Computing Centers

O3 is here! See https://gracedb.ligo.org/latest/

Public alerts in the 3rd science run: already more candidate events than O1 and O2 combined

Latest — as of 8 July 2019 09:03:46 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

Search for: Superevent

Search

UID	Labels	t_start	t_0	t_end	FAR (Hz)	Created (UTC)
S190707q	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246527223.118398	1246527224.181226	1246527225.284180	5.265e-12	2019-07-07 09:33:44 UTC
S190706ai	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246487218.321541	1246487219.344727	1246487220.585938	1.901e-09	2019-07-06 22:26:57 UTC
S190701ah	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246048403.576563	1246048404.577637	1246048405.814941	1.916e-08	2019-07-01 20:33:24 UTC
S190630ag	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1245955942.175325	1245955943.179550	1245955944.183184	1.435e-13	2019-06-30 18:52:28 UTC
S190602aq	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51 UTC
S190524q	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30 UTC
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
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S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
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S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
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S190405ar	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

LIGO VIRGO LSC

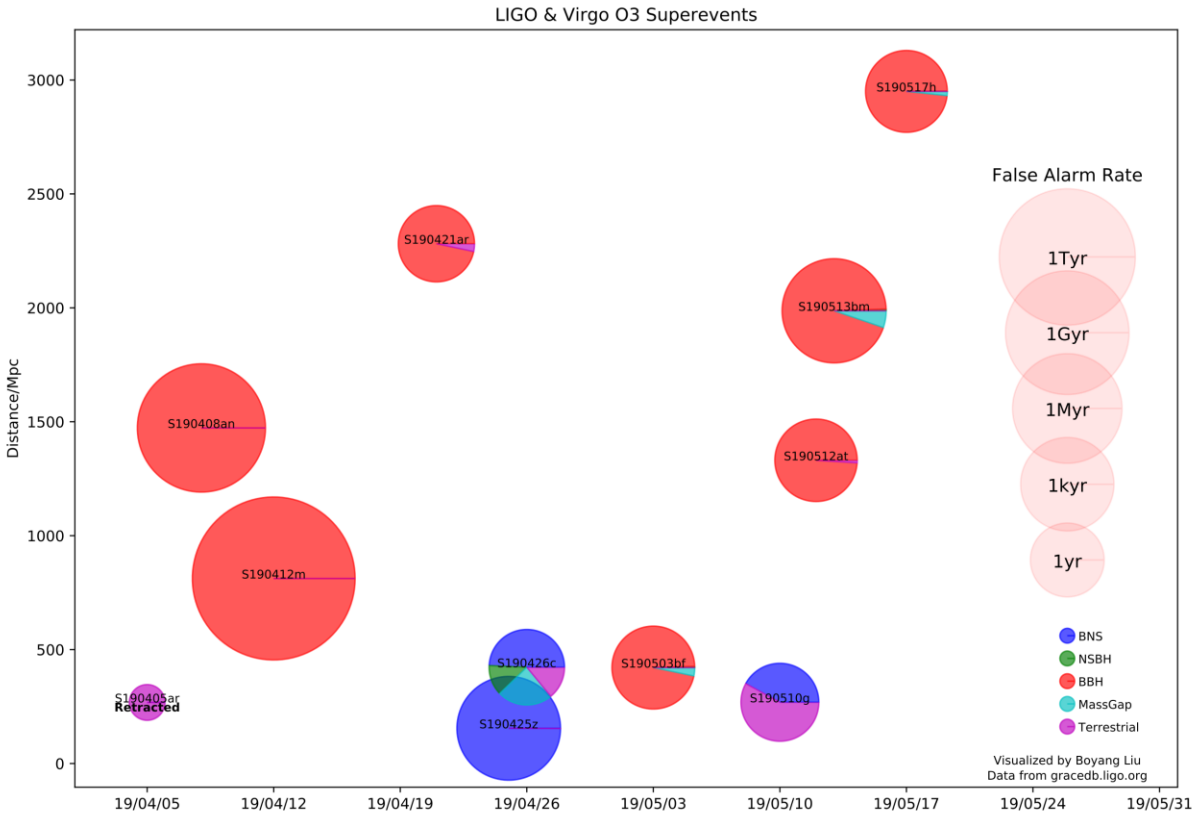
Virgo's low latency computing is working as designed. Automatic public alerts not so "automatic" (yet)

Three events were retracted by the LVC after more detailed analysis

A new **binary neutron star** event: only LIGO Livingston and Virgo were operational, thus large uncertainty in sky position. A **neutron star-black hole** event: LIGO Livingston, LIGO Hanford, and Virgo operational, but no EM counterpart found

https://en.wikipedia.org/wiki/List_of_gravitational_wave_observations

Public alerts in the 3rd science run: already more candidate events than O1 and O2 combined



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Science harvesting with the global GW detector network

Multi-messenger astronomy started: a broad community is relying of detection of gravitational waves

Fundamental physics

Access to dynamic strong field regime, new tests of General Relativity
Black hole science: inspiral, merger, ringdown, quasi-normal modes, echo's, primordial, no-hair
Black hole mimickers, Lorentz-invariance, equivalence principle, polarization, parity violation, axions

Astrophysics

First observation for binary neutron star merger, relation to sGRB
Evidence for a kilonova, explanation for creation of elements heavier than iron

Astronomy

Start of gravitational wave astronomy, population studies, formation of progenitors, remnant studies

Cosmology

Binary neutron stars can be used as standard “sirens”
Dark Matter and Dark Energy, stochastic background

Nuclear physics

Tidal interactions between neutron stars get imprinted on gravitational waves
Access to equation of state, phase transitions

LVC back with improved instruments for observation run (O3) that started in April this year

Advanced Virgo

AdV+ as the next incremental step forward in sensitivity

AdV+ is the plan to maximize Virgo's sensitivity within the constrains of the EGO site. It has the potential to increase Virgo's detection rate by up to an order of magnitude

AdV+ features

Maximize science

Secure Virgo's scientific relevance

Safeguard investments by scientists and funding agencies

Implement new innovative technologies

De-risk technologies needed for third generation observatories

Attractive for groups wanting to enter the field

Upgrade activities

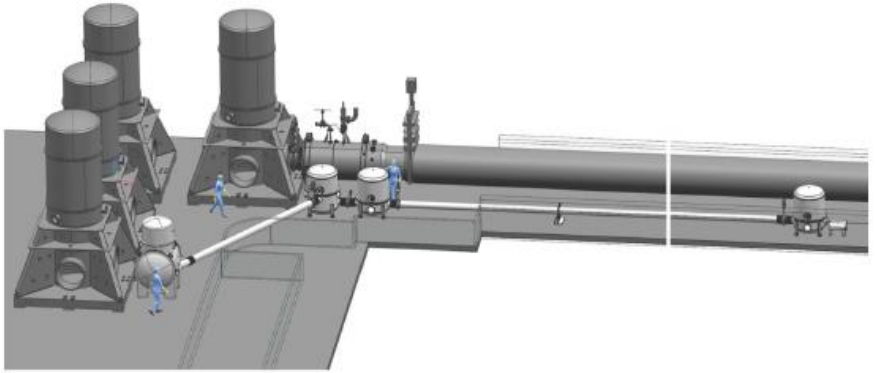
Tuned signal recycling and HPL: 120 Mpc

Frequency dependent squeezing: 150 Mpc

Newtonian noise cancellation: 160 Mpc

Larger mirrors (105 kg): 200-230 Mpc

Improved coatings: 260-300 Mpc

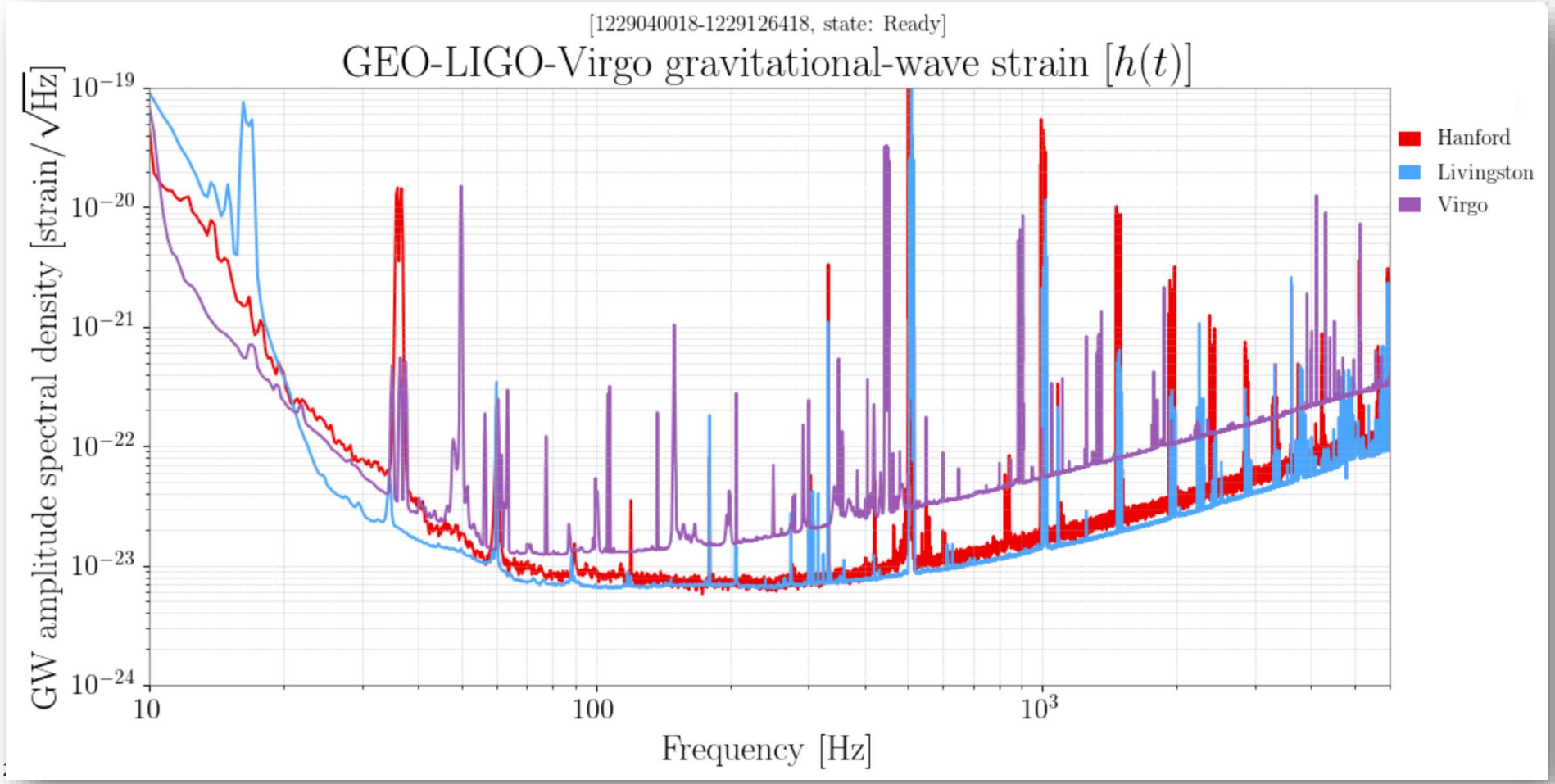


Virgo will implemented signal recycling after O3

Signal recycling will improve Virgo's sensitivity at medium to high frequency

Virgo's strain sensitivity

- Effect of no signal recycling is apparent. Also injected laser power 18 W, no squeezing, 3 km, …

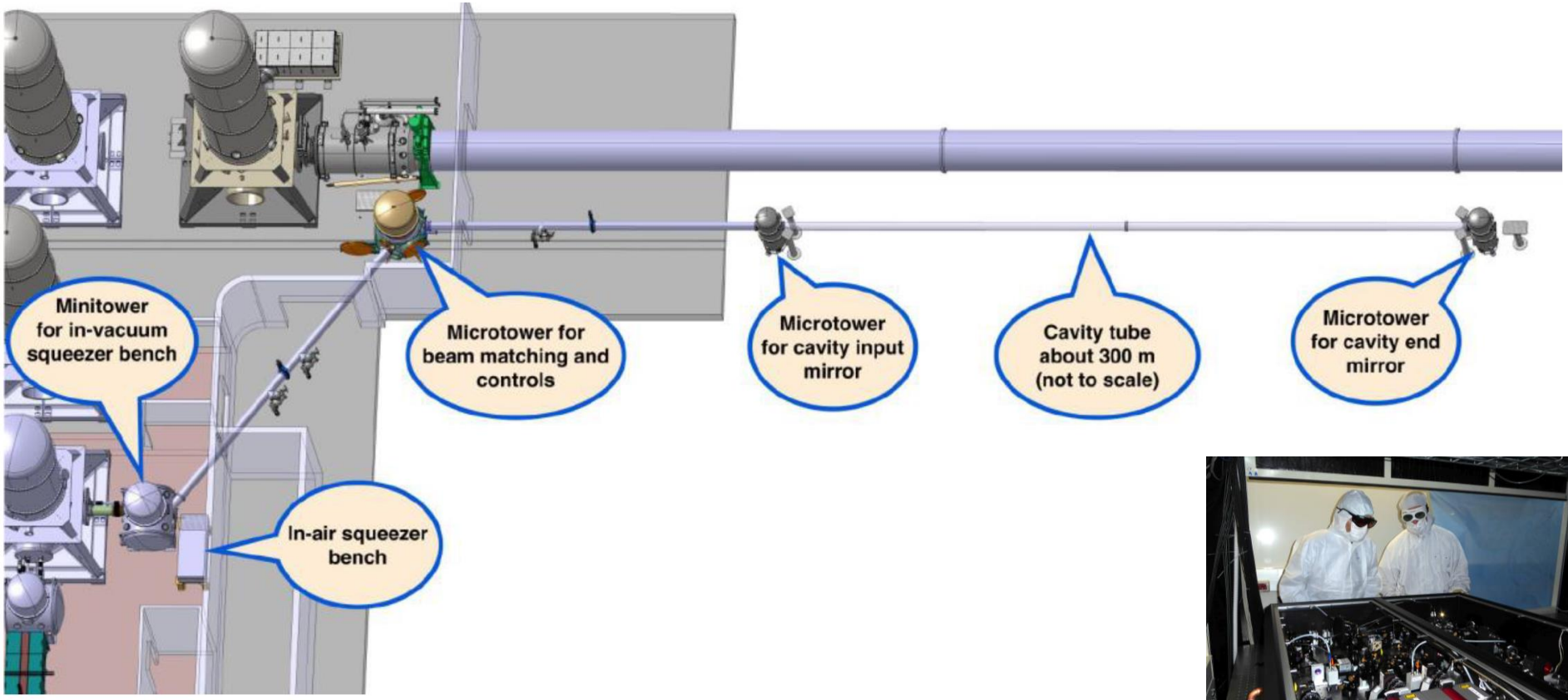


Frequency dependent squeezing

Nikhef has important responsibilities in the AdV+ upgrade project

Nikhef contributes to

a) Optical system design
b) High-finesse 300 m long filter cavity
c) Vibration isolation of in-vacuum squeezer bench and beam matching microtowers

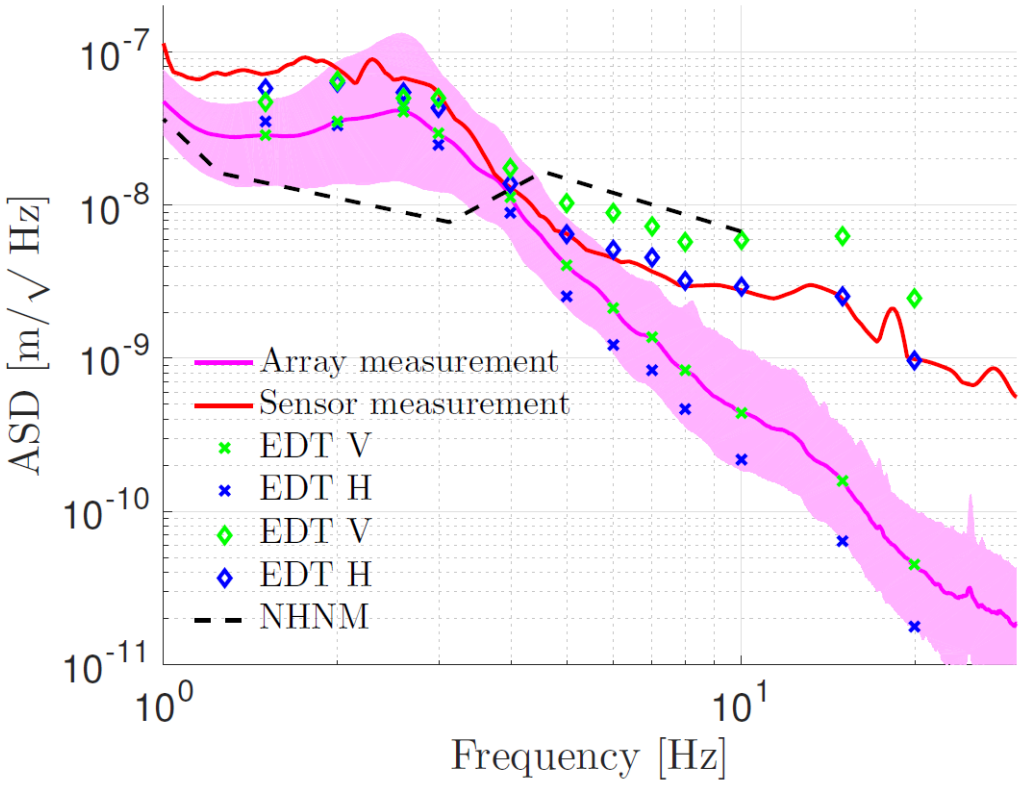


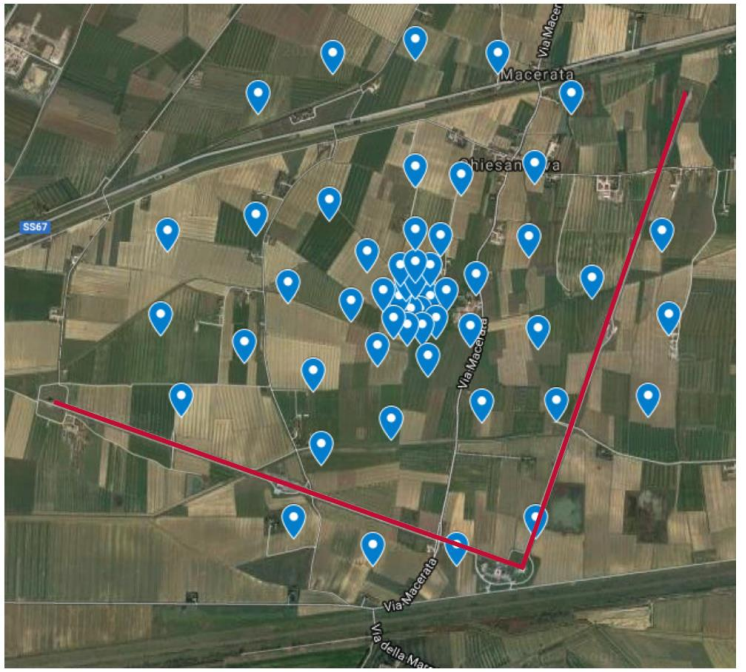
Virgo squeezer from AEI Hannover

Newtonian Noise Cancellation

Nikhef contributes arrays of seismic sensors will be used to subtract Newtonian noise in AdV+

Noise at Central Building is about an order of magnitude higher than the noise in the vicinity of Virgo



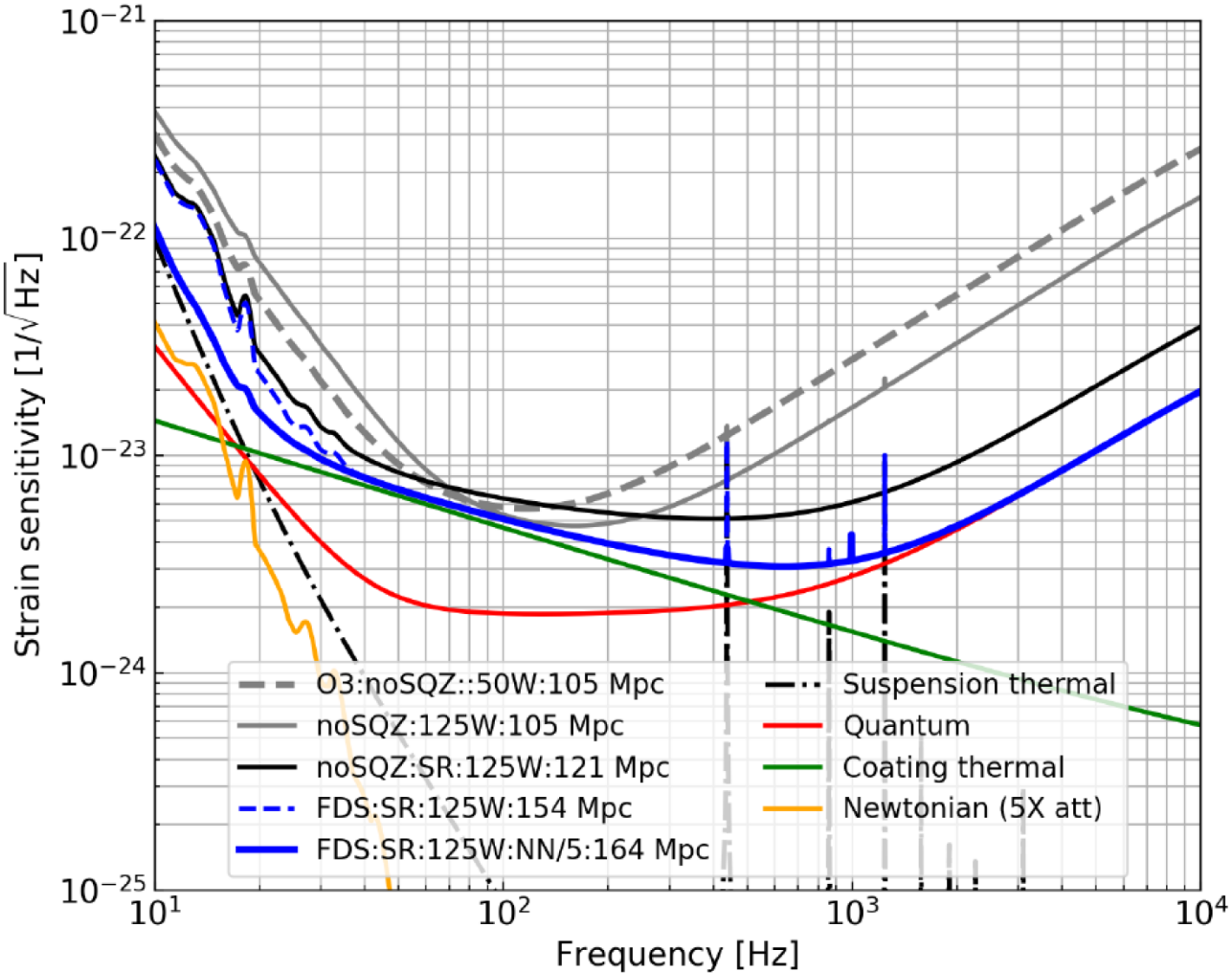


Need for emphasis on smart infrastructure for gravitational wave observatories

- Smart infrastructure design
- Newtonian noise modeling of infrastructure noise
- HVAC modification

Phase 1: reaching the thermal noise wall

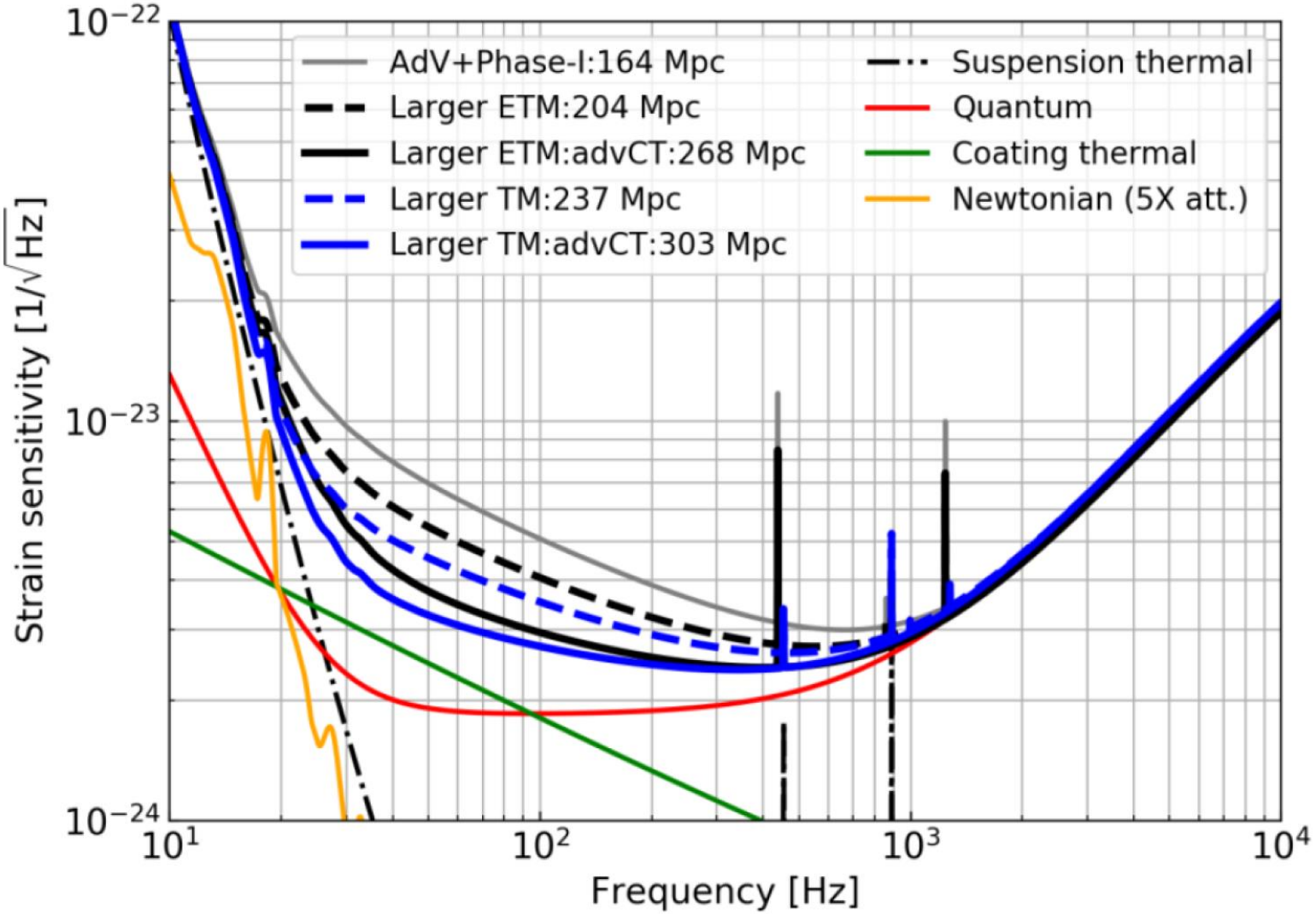
Increase laser power, implement signal recycling, frequency dependent squeezing and Newtonian noise suppression



Phase 2: pushing the thermal noise wall down

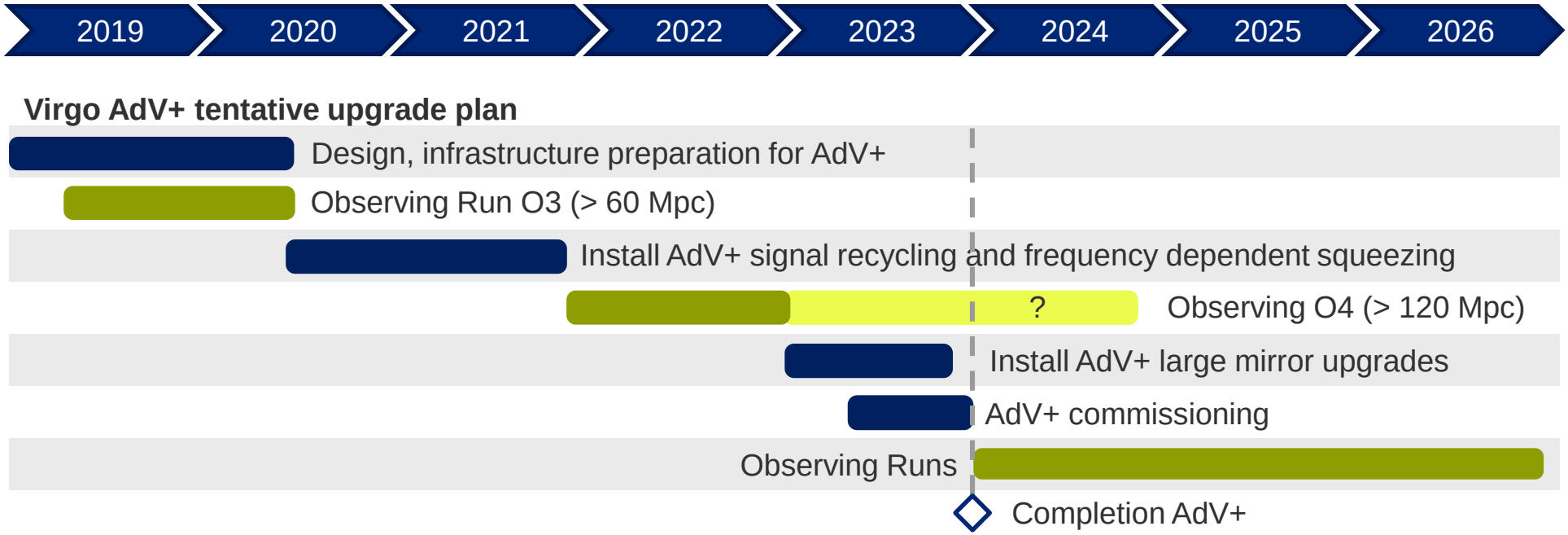
Implement larger ETMs and employ better coatings

Even better sensitivity can be obtained by replacing all mirrors, but this would be too invasive



Scheduling of science runs, AdV+ installation and commissioning

Five year plan for observational runs, commissioning and upgrades



Commissioning break in October 2019

Duration of O3: until the end of April 2020 (duration of O4 has not been decided)

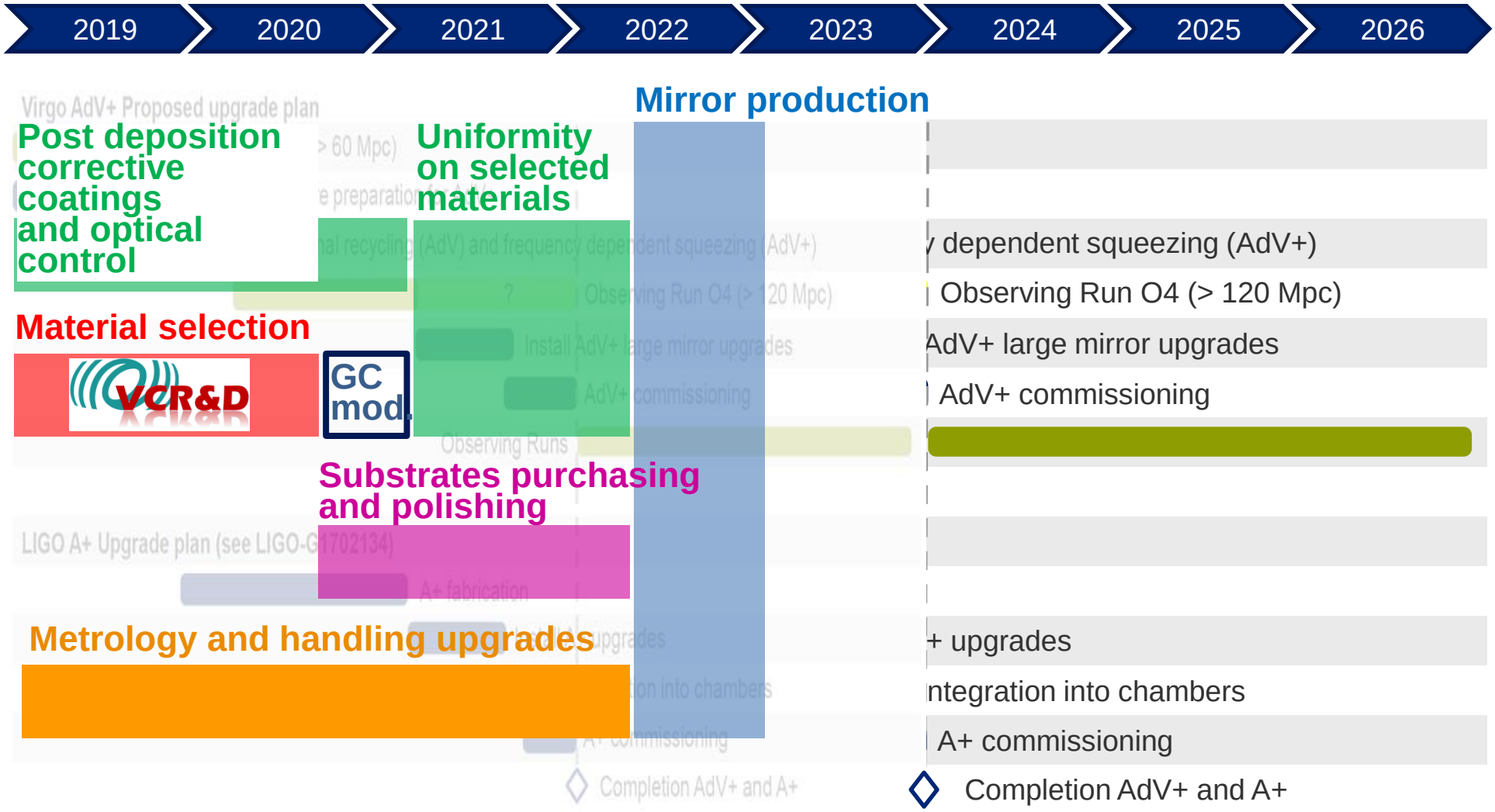
Break between O3 and O4 probably around 18 months (allow installation and commissioning)

AdV+ to be carried out in parallel with LIGO's A+ upgrade

AdV+ is part of a strategy to go from 2nd generation to Einstein Telescope

Virgo’s coating R&D and mirror production are critical

Virgo must have a credible plan for Coating R&D



Large mirrors to be installed in Phase 2, but substrates must be acquired in 2020. This has implications for the budget profile

AdV+ management structure. Nikhef contributions indicated

Project Supervisor Board
Convener: G. Gemme
EGO director
Virgo Spokesperson
Project Leader
Technical Manager
Quality responsible
Commissioning coordinator
Operations coordinator
3 Country representatives

EGO consortium

Virgo Steering Committee

Bas Swinkels

AdV+ Management Team
Project Leader: R. Flaminio
Technical Manager: H. Heitmann, System engineer: C. Olivetto
ITF: M. Was, SUM: H. Vocca, **ESC: B. Swinkels**, ENV: R. Passaquieti, QNR: J.P. Zendri

ITF
- **OSD** J. Degallaix
- **PSL** N. Christensen
- **INJ** A. Chiummo
- **SLC** L. Mir
- **DET** R. Gouaty
- **SBE** **A. Bertolini**

SUM
- **MIR** L. Pinard
- **TCS** V. Fafone
- **PAY** E. Majorana


Alessandro Bertolini

ESC
- **ISC** M. Mantovani
- **ALS** N. Leroy
- **DAQ** A. Masserot
- **CAL** L. Rolland

ENV
- **NNC** J. Harms
- **INF** A. Paoli
- **VAC** A. Pasqualetti
- **EMS** R. De Rosa

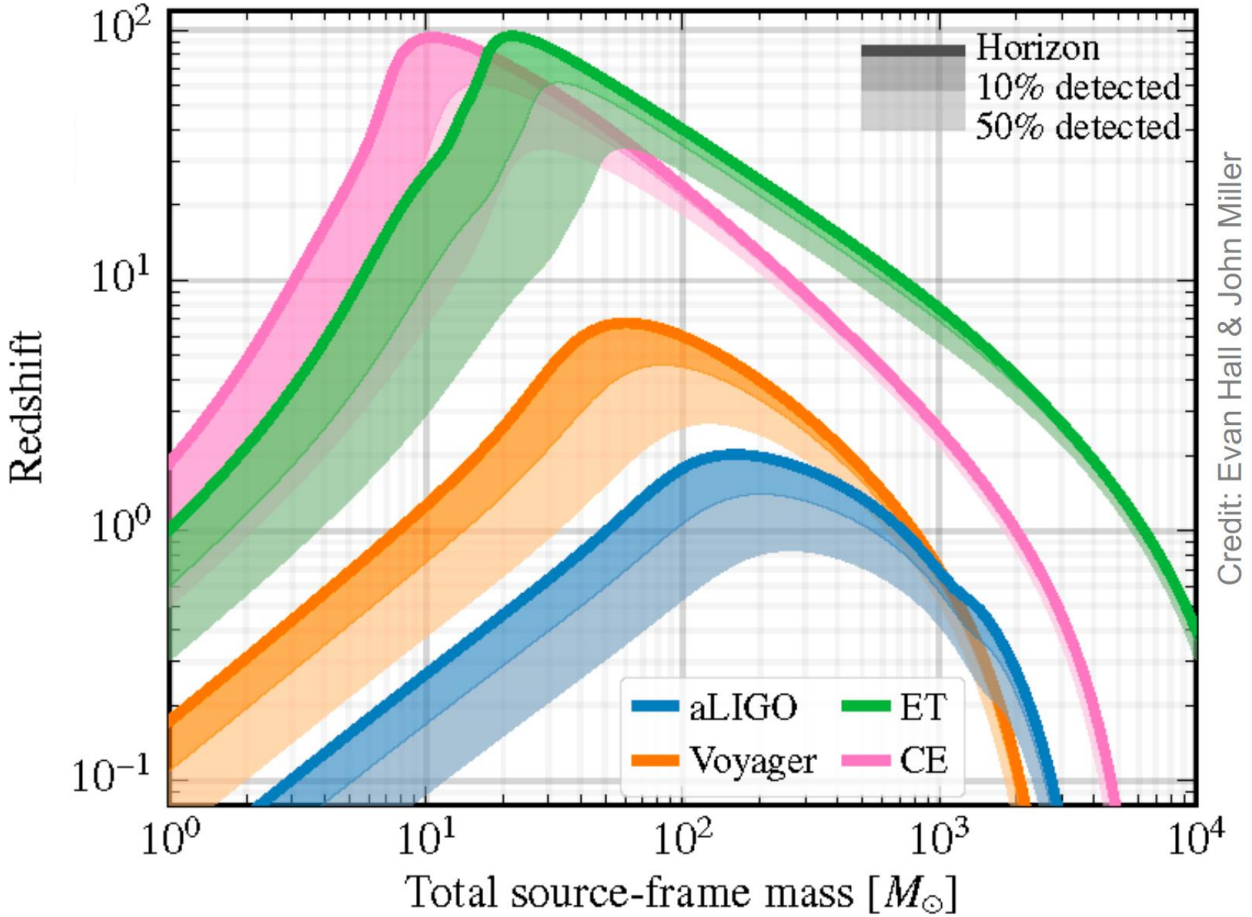
QNR
- **SGD** M. De Laurentis
- **SVS** F. Sorrentino
- **SIN** R. Bonnand
- **FLT** **M. Tacca → ?**

Einstein Telescope

ET as GW observatory with full sky coverage and high uptime

Einstein Telescope

Excellent low-f sensitivity and great discovery potential



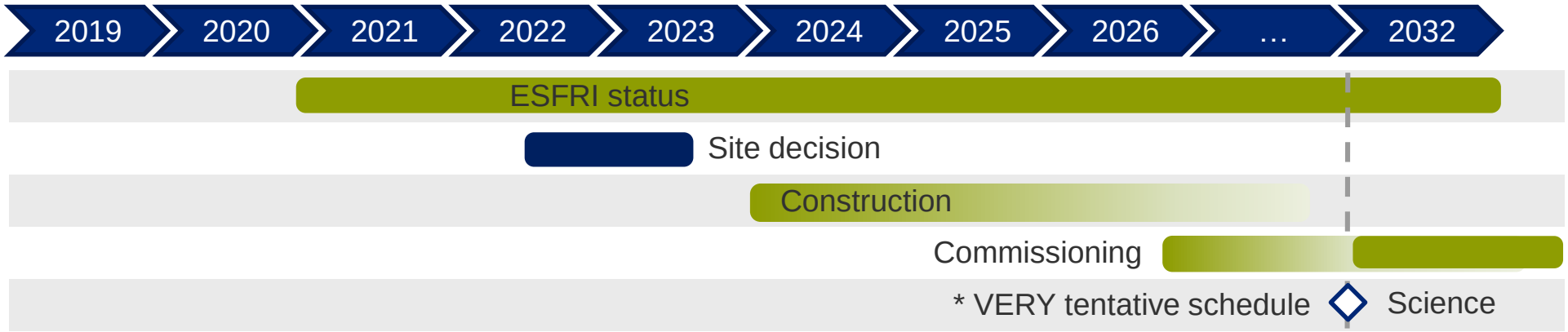
Credit: Evan Hall & John Miller

For science case, see https://www.dropbox.com/s/gihpzcue4qd92dt/science-case.pdf?dl=0

Advanced Virgo

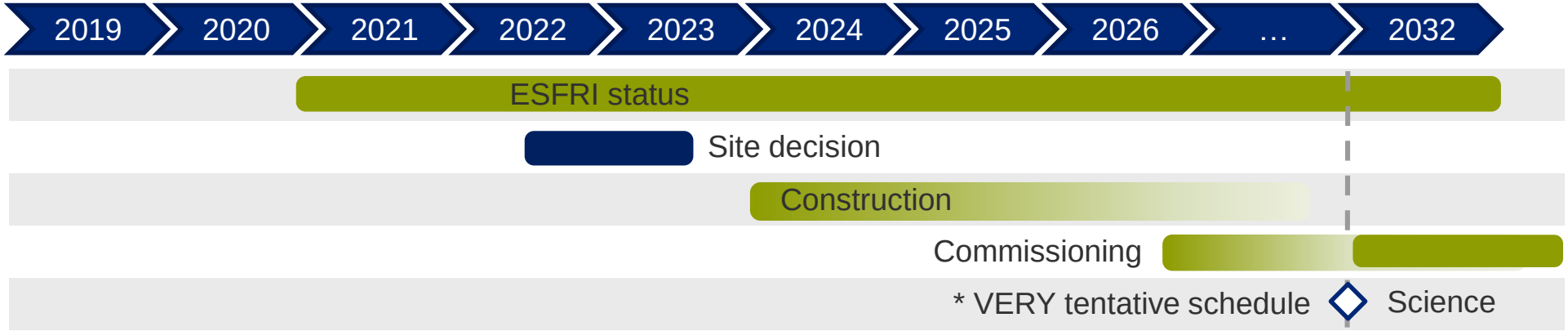
Einstein Telescope

Dreaming about a timeline?



Einstein Telescope

Dreaming about a timeline?



Reality check

TDRs, detailed cost scrutiny, realistic exploitation cost estimate, governance structure

Deadline for EU submission: April 2020

Deadline for the national submissions: January 2020

Formal support must be expressed by a consortium of governments wanting to support ET proposal

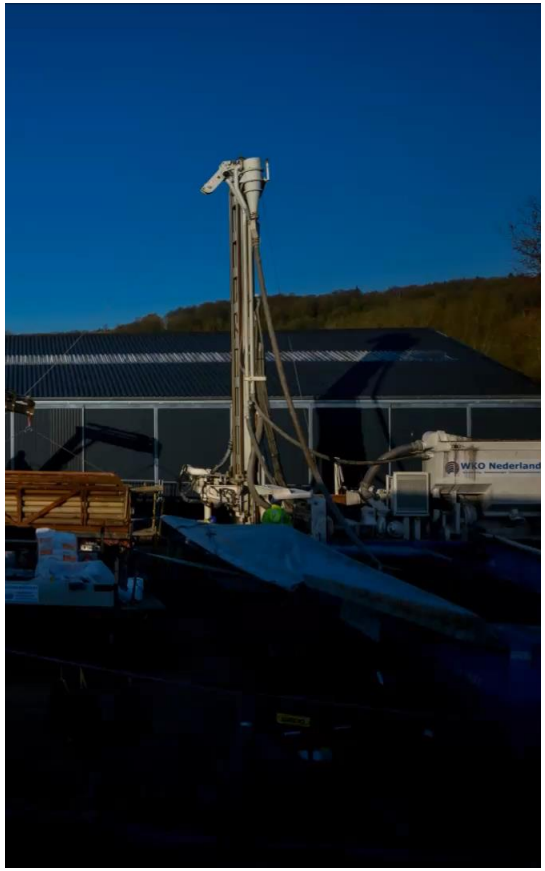
We need to organize the *global* scientific community interested in 3G (and continuously keep them informed)

For ESFRI we need to prepare a credible plan for EU funding agencies

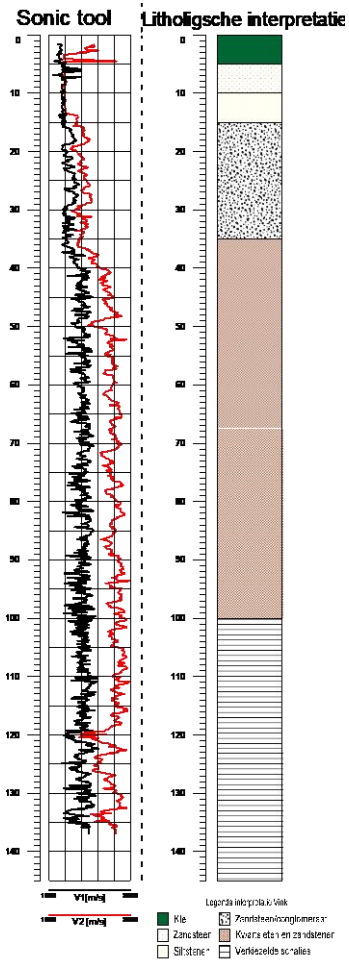
Studies of quality at potential B-G-NL site

The geology of the B-G-NL Limburg border area: hard rock with on top a layer of soft absorbing and damping soil. In addition the region is free of disturbing (human-made) seismic activities

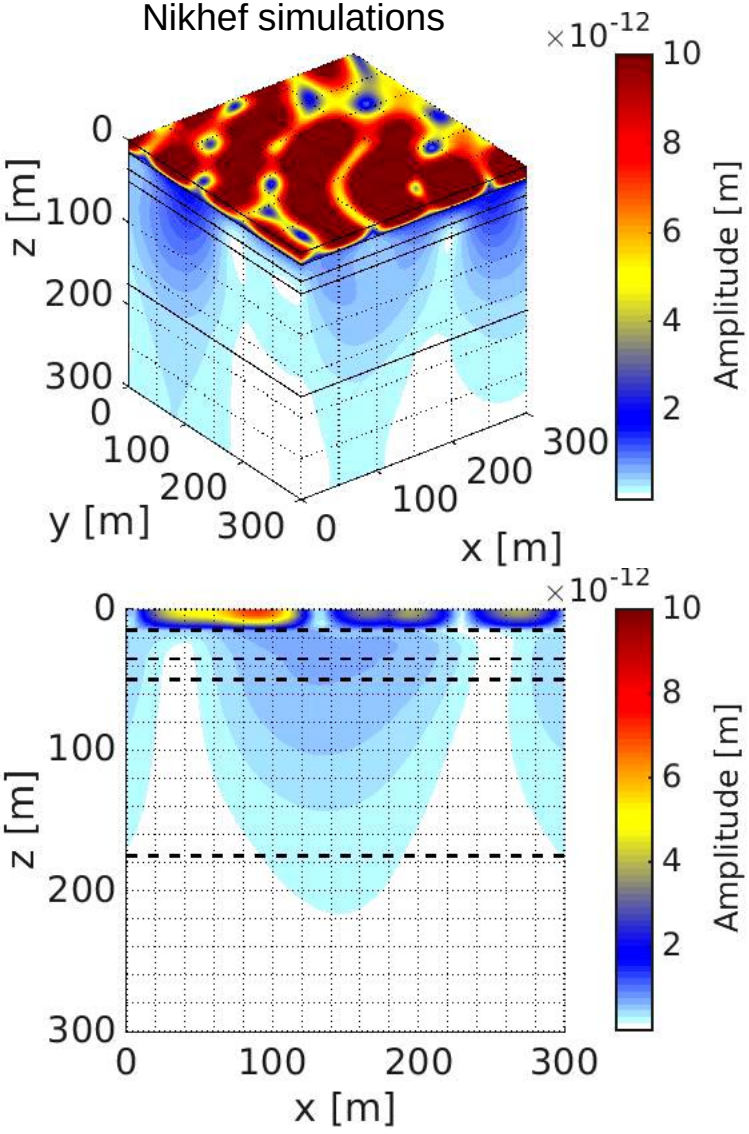
Antea borehole



Deltares research



Nikhef simulations



Geologists are actively involved in underground studies

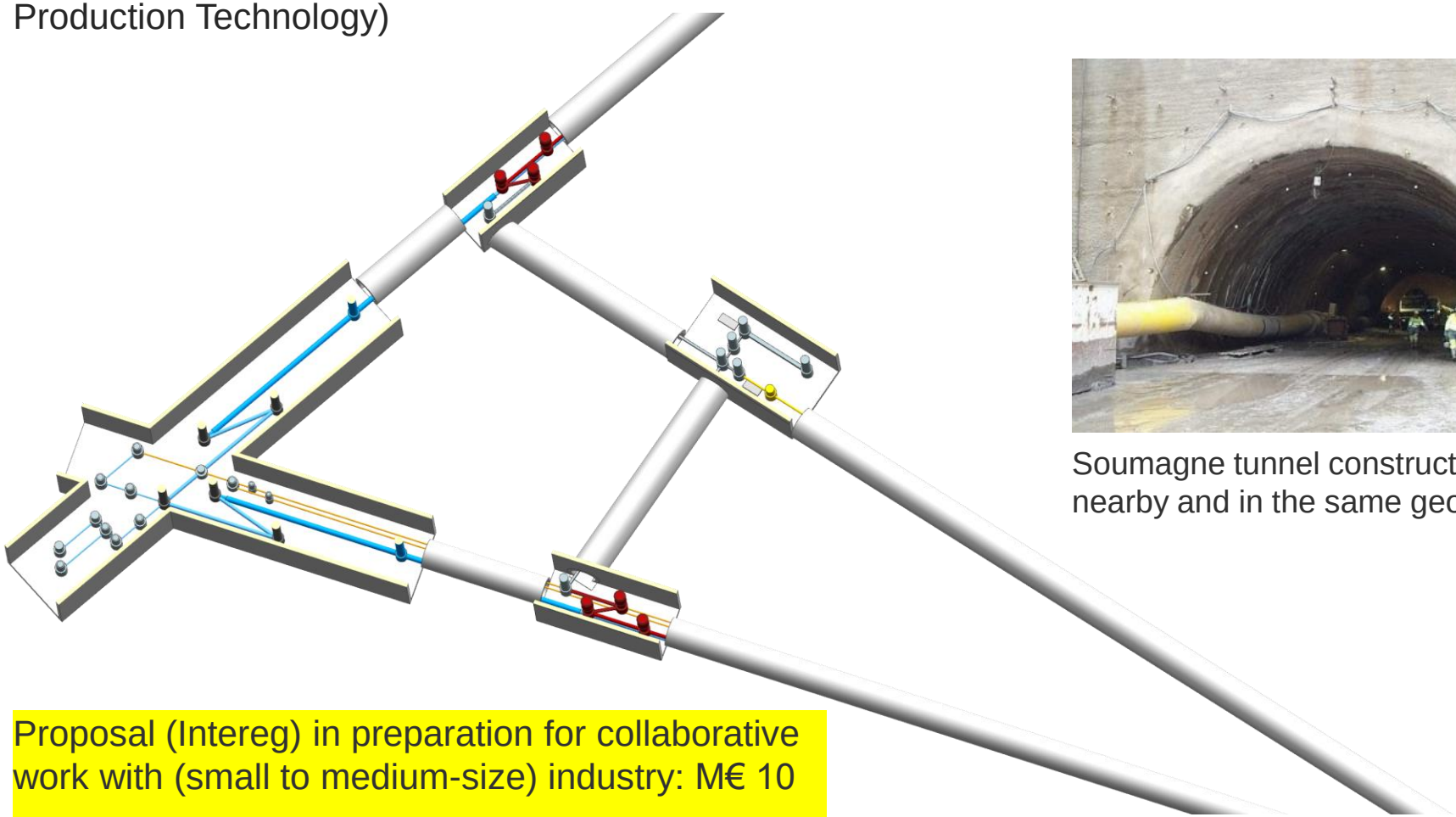
We obtained soil samples up to a depth of 140 m. Picture: Geert-Jan Vis (TNO), Jan Lutgert (EBN), Alessandro Bertolini (Nikhef). Research on samples at CITG in TU-Delft. RWTH Aachen involved

Proposal (Intereg) submitted for detailed geological studies of B-G-NL site: E-TEST M€ 14.9

ET studies on civil engineering and vacuum technology

Innovation may lead to cost reduction in main cost drivers of the project
Close collaboration with industry, e.g.

In discussion with Engineering Geology RWTH Aachen, Implenia, Fraunhofer IPT (Institute for Production Technology)



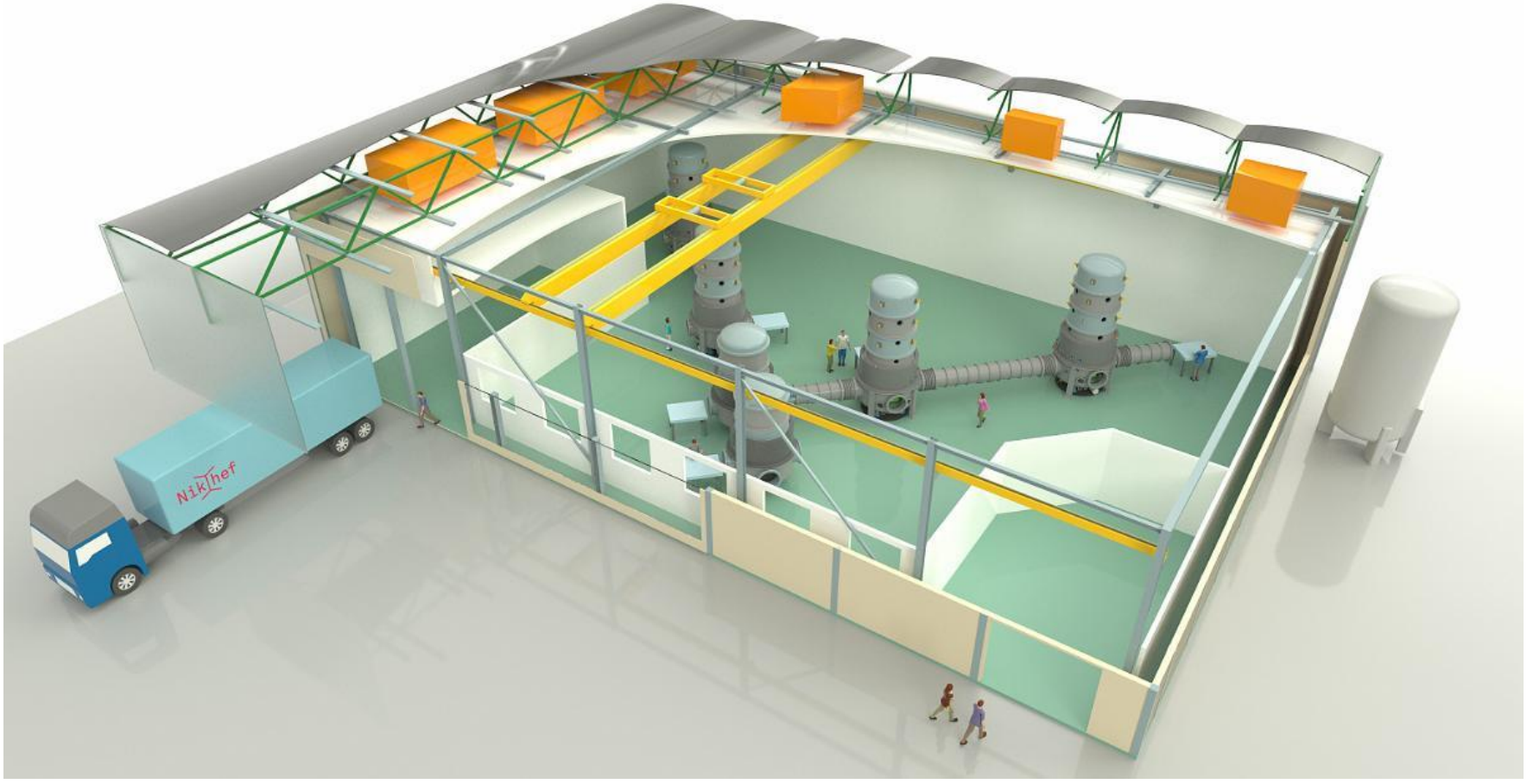
Soumagne tunnel construction was nearby and in the same geology

Proposal (Intereg) in preparation for collaborative work with (small to medium-size) industry: M€ 10

ET meets Industry in Antwerp on July 18, 2019

Funding made available for 3G R&D: B-G-NL Limburg

About M€ 14.5 for the realization of a global R&D facility. This will allow de-risking of key technologies such as large scale cryogenic test masses, sensor development, new laser technology, controls, …
Also industry will be involved. Opportunity for training on GW instrumentation



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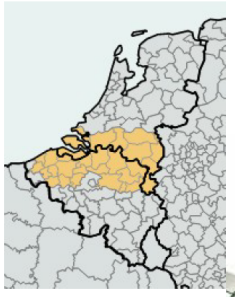
About 14.5 M€ for the realization of a global R&D facility. This will allow de-risking of key technologies such as large scale cryogenic test masses, sensor development, new laser technology, controls, … Also industry will be involved. Opportunity for training on GW instrumentation. New groups join

Funding & partners

Interreg
EUROPESE UNIE
Vlaanderen-Nederland
Europees Fonds voor Regionale Ontwikkeling



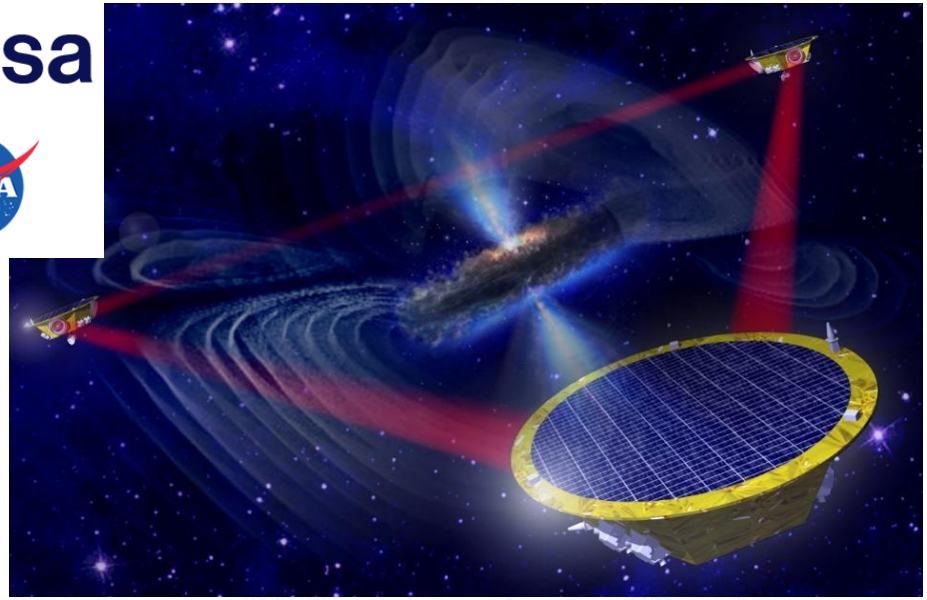
- Obtained ~14.5 MEuro funding from unconventional sources:
  - InterReg Flanders-South of NL (European fund for cross-border development)
  - Province of Limburg (NL), Dutch and Belgian national ministries
  - Matched contribution by partners
- Partners: Nikhef, universities of Antwerpen, Eindhoven, Ghent, Hasselt, Leuven, Maastrich
- Satellite partners: Aachen, Brussels, Fraunhofer, Liège, Louvain la Neuve, Twente, TNO
- Additional input from Glasgow, AEI, Perugia ...
- 100+ person-years (staff scientists and engineers) committed over the next 5 years
- New collaborators are welcome

Bright future for gravitational wave research and Nikhef is strongly committed

LIGO and Virgo are operational. KAGRA in Japan joins this year, LIGO-India under construction. ESA launches LISA in 2034. Einstein Telescope and CE CDRs financed. Strong support by APPEC

Gravitational wave research

- LIGO and Virgo operational
- KAGRA to join this year
- LIGO-India under construction (2025)
- ESA selects LISA, NASA rejoins
- Pulsar Timing Arrays, such as EPTA and SKA
- Cosmic Microwave Background radiation



Einstein Telescope and Cosmic Explorer

- CDR ET financed by EU in FP7, CE by NSF
- APPEC gives GW a prominent place in the new Roadmap and especially the realization of ET

Points of attention

- Nikhef should increase its focus on data analysis
- Increase the engagement of astro-scientists (OPA)
- Increase role in offline computing
- ET preparation for ESFRI Roadmap is a challenge


Thanks for your
attention !!