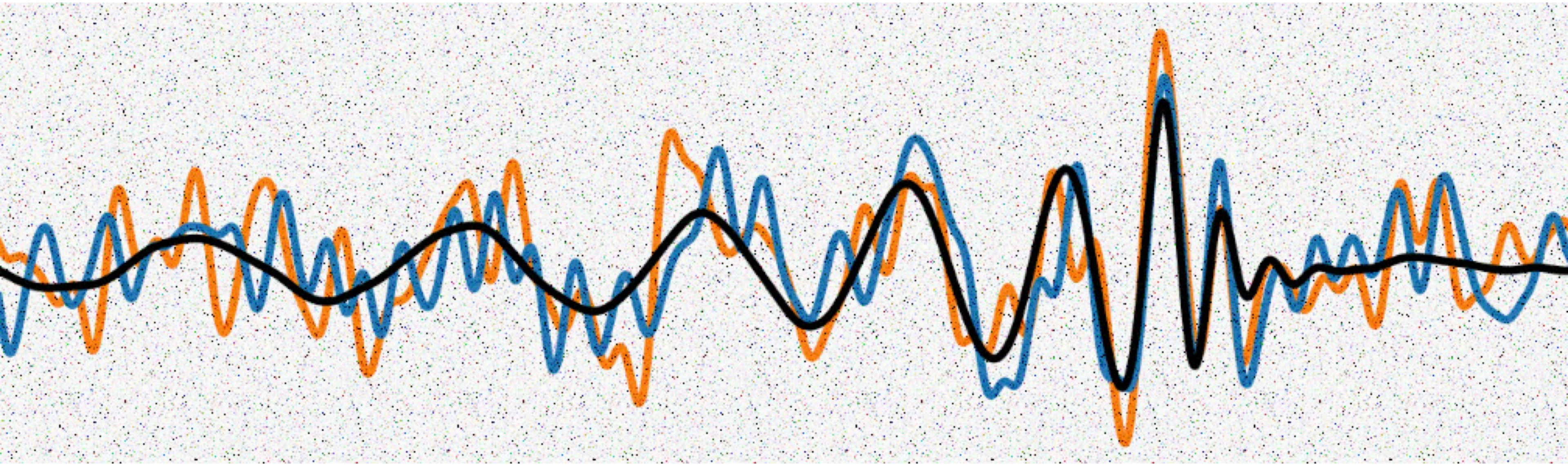
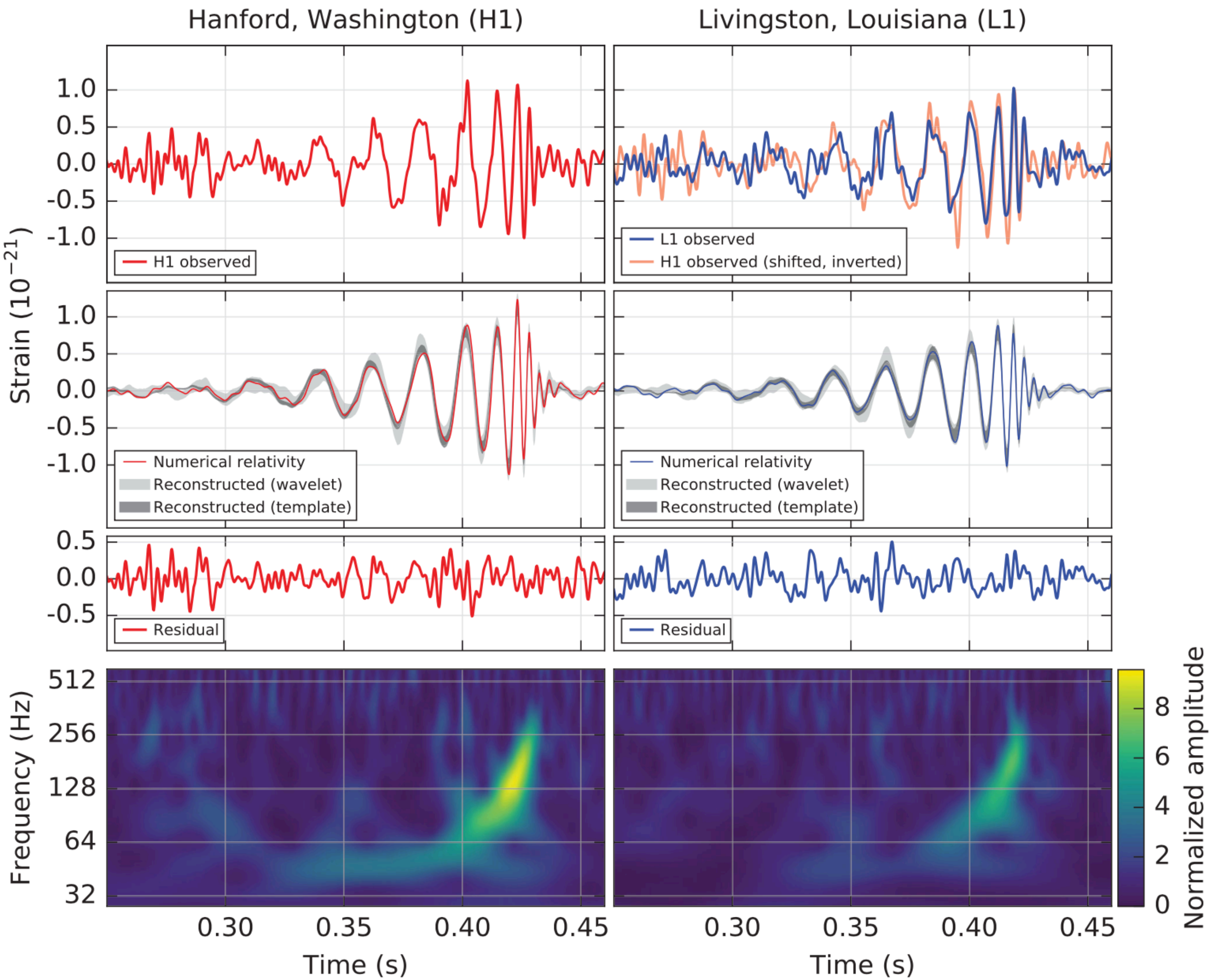
The second Observing Run (O2):
detectors, results so far, perspectives



Giovanni Losurdo – INFN Pisa

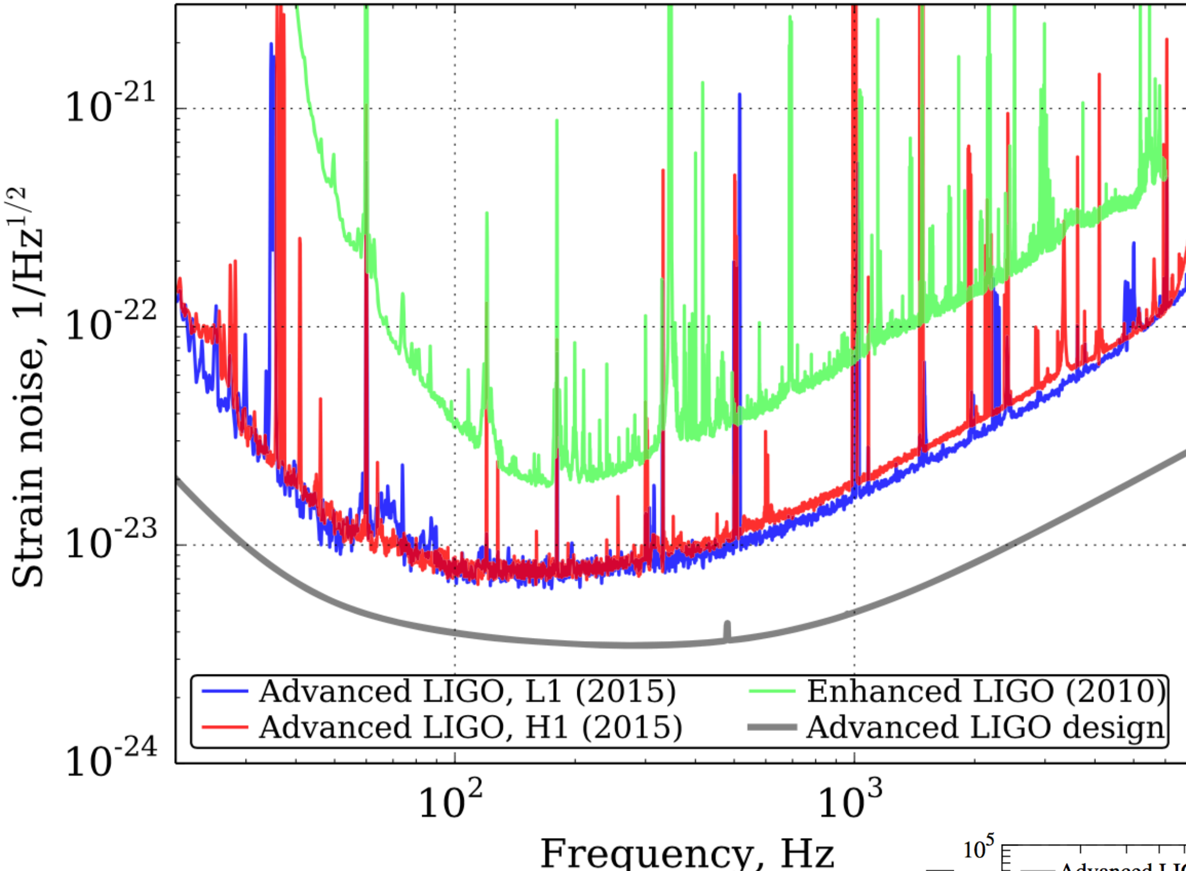
on behalf of the

LIGO Scientific Collaboration and Virgo Collaboration



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

THE ADVANCED DETECTORS ERA STARTED ON SEPT 14TH 2015, WITH THE FIRST EVER DETECTION OF GW BY THE TWO LIGO INTERFEROMETERS

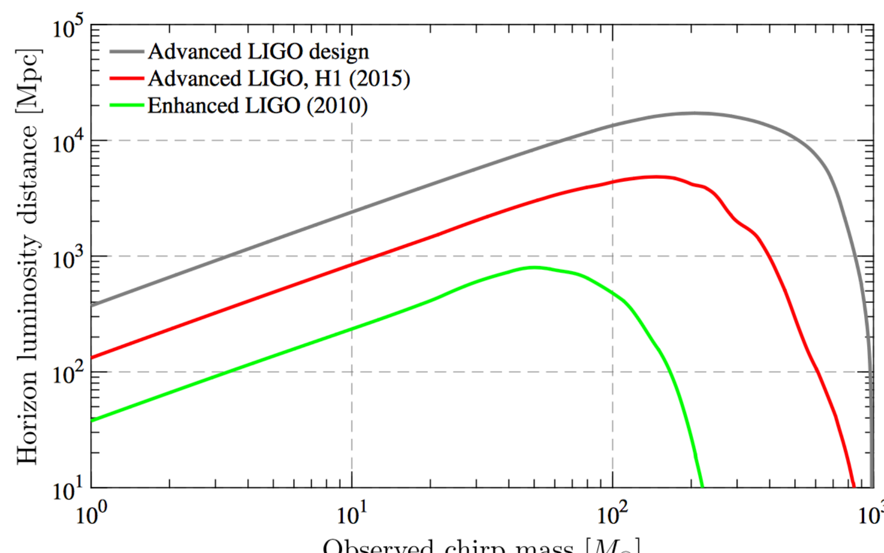


iLIGO best (2010)

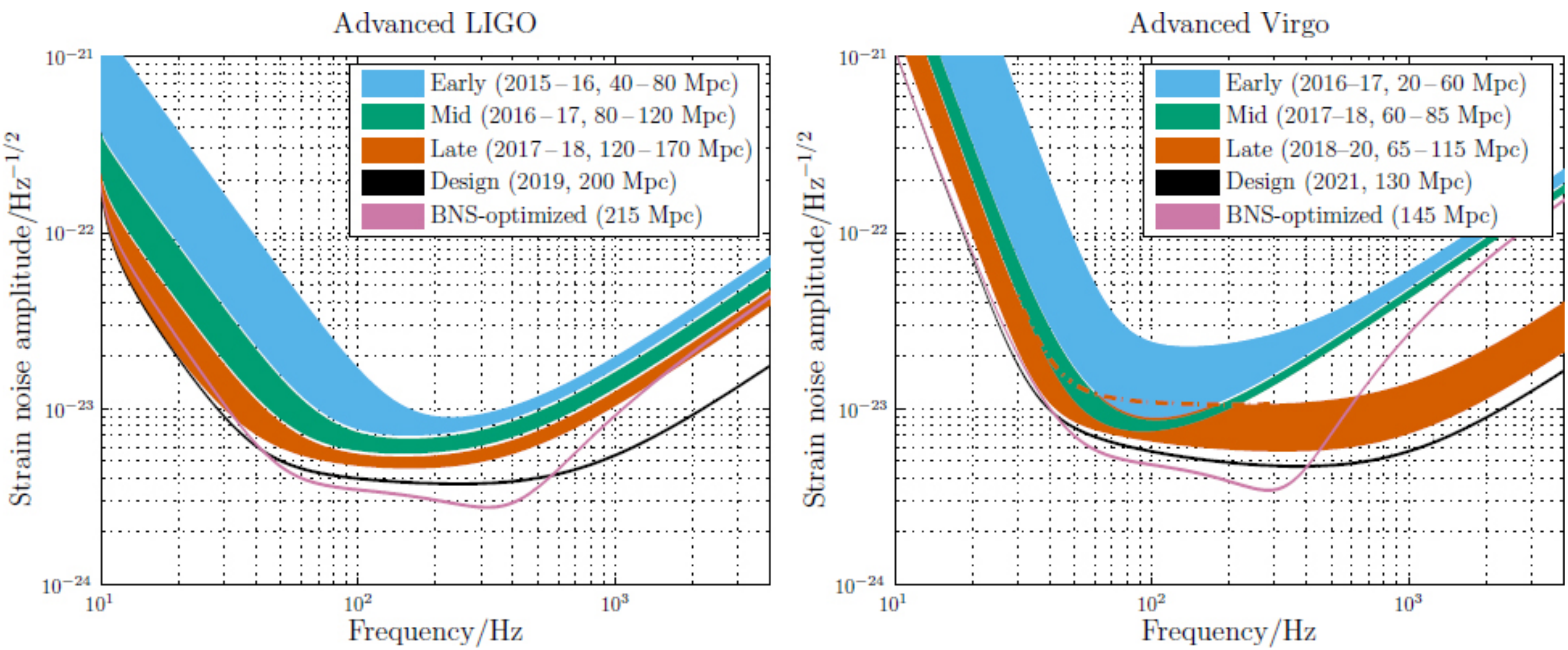
aLIGO O1 (2015)

aLIGO design

from D Martynov et al, PRD 93 (2016), 112004



ENVISAGED PROGRESS



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

LIGO and VIRGO have envisaged that a few years would be necessary to reach the design sensitivities, interleaving data taking and commissioning periods

WHY DOES DATA TAKING STOP?

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

1 day of data at a range of 80 Mpc is equivalent to 64 days at 20 Mpc
1 day of data at a range of 100 Mpc is equivalent to 2 days at 80 Mpc

it's good to observe for a long time,
it's even better to improve the sensitivity further

for this reason science runs are stopped and time is dedicated
to commissioning in order to further
increase the volume of observable universe (d^3)
and improve the machine stability (T)

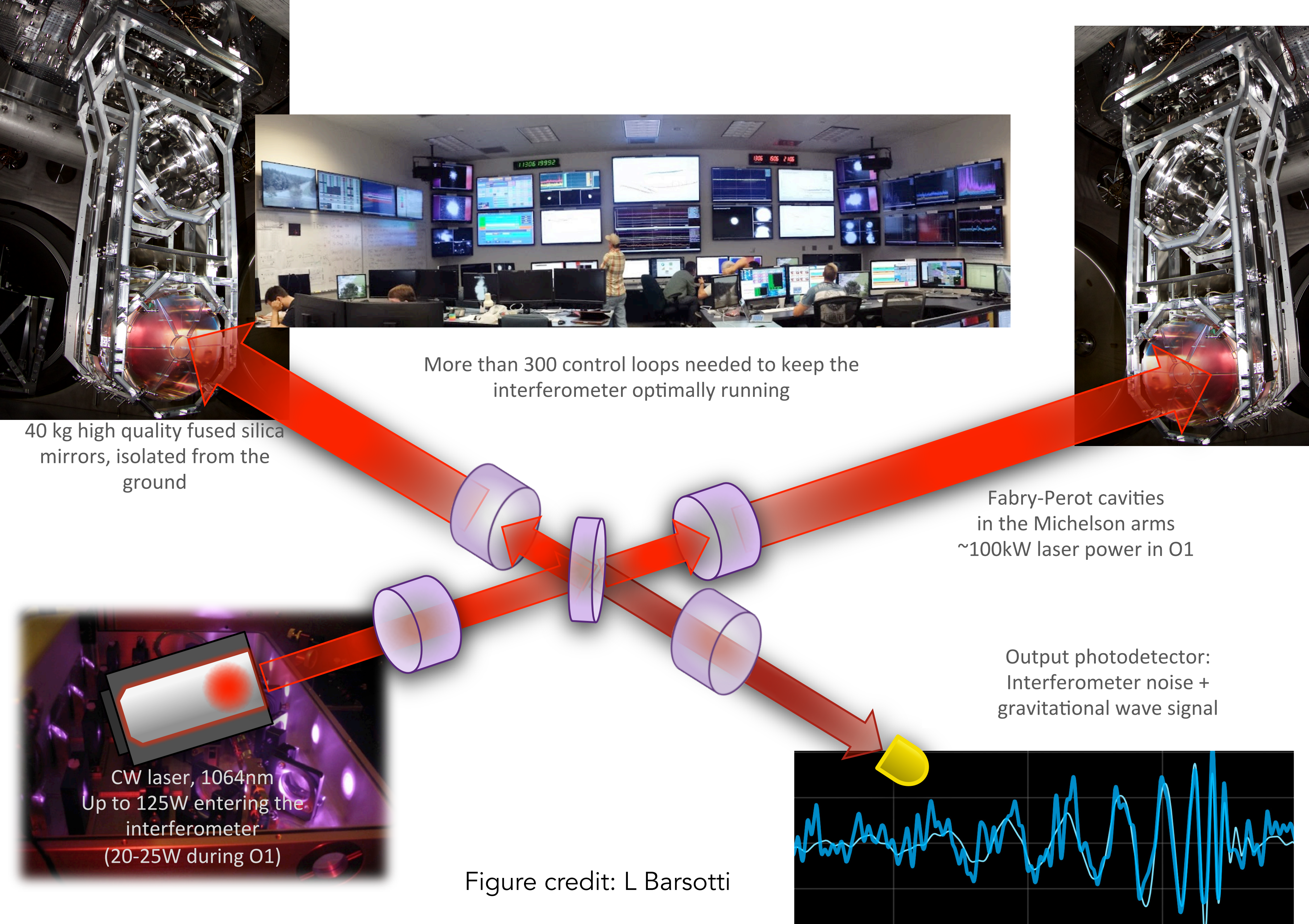
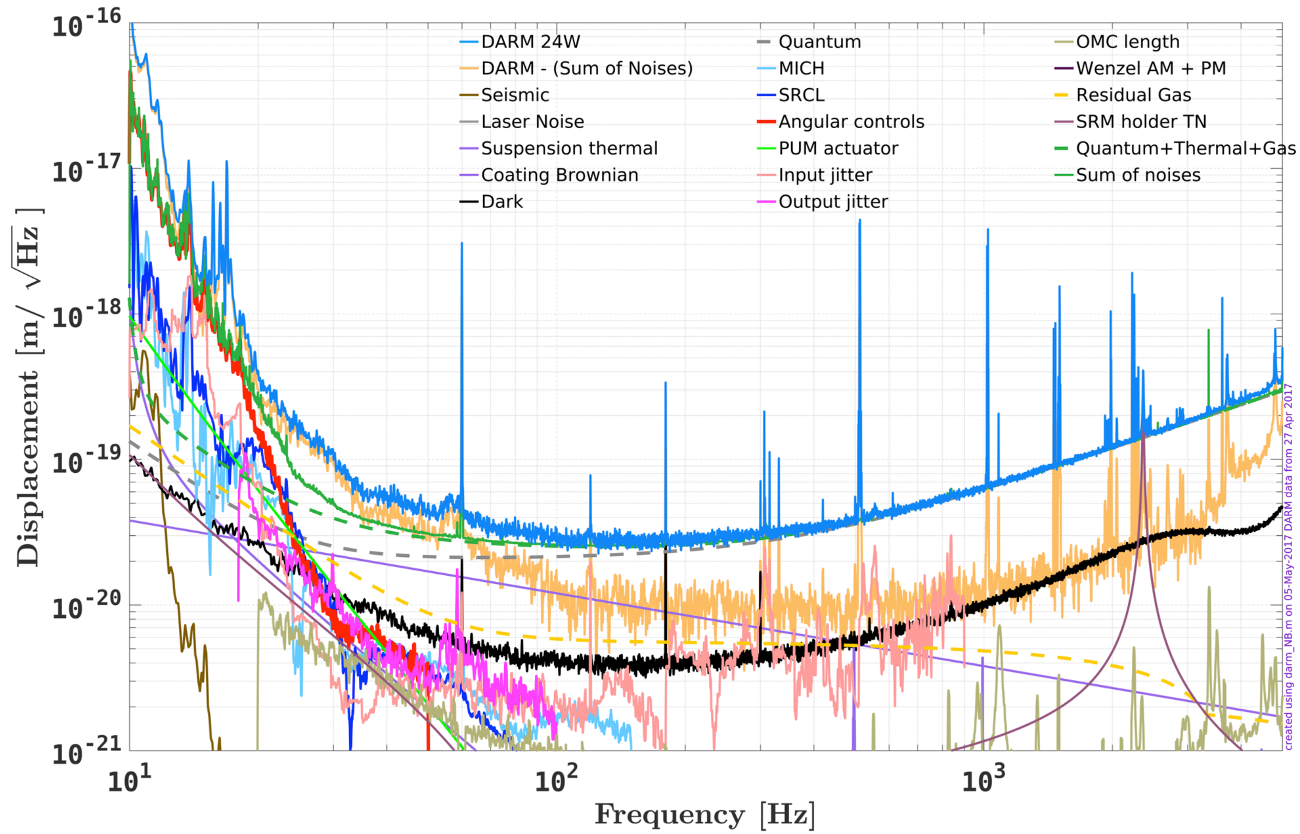


Figure credit: L Barsotti

COMMISSIONING

CHALLENGING (SOMETIMES HEROIC) EFFORT TO IDENTIFY, MODEL, TACKLE **MANY** NOISE SOURCES

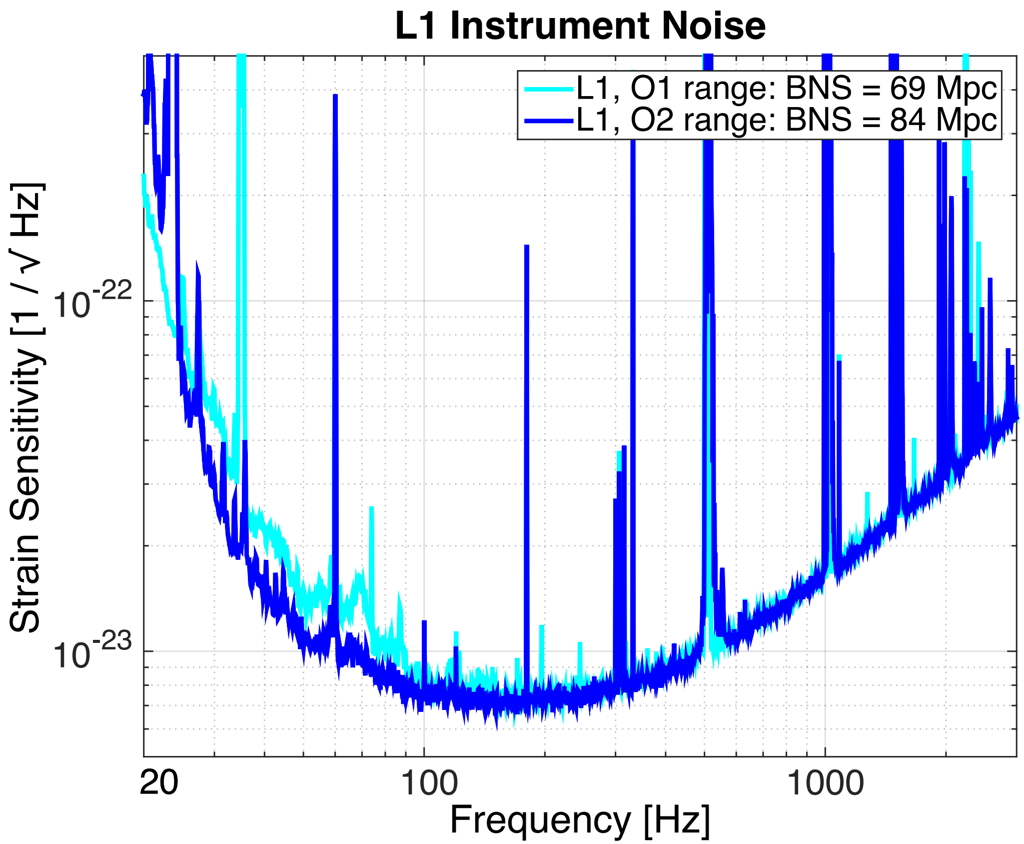


from LLO e-log entry 33552

FROM O1 to O2

- 10 months (January – October 2016) of work on both Livingston and Hanford detectors to reduce detector noise, improve duty cycle and data quality
- Main activities:
  - H1: laser power increase
    - Required commissioning of high power laser and improvements in interferometer control
  - L1: mitigation of scattered light noise, interferometer robustness
    - Required hardware changes inside the vacuum chambers
- Transition into engineering run in November 2016

L1

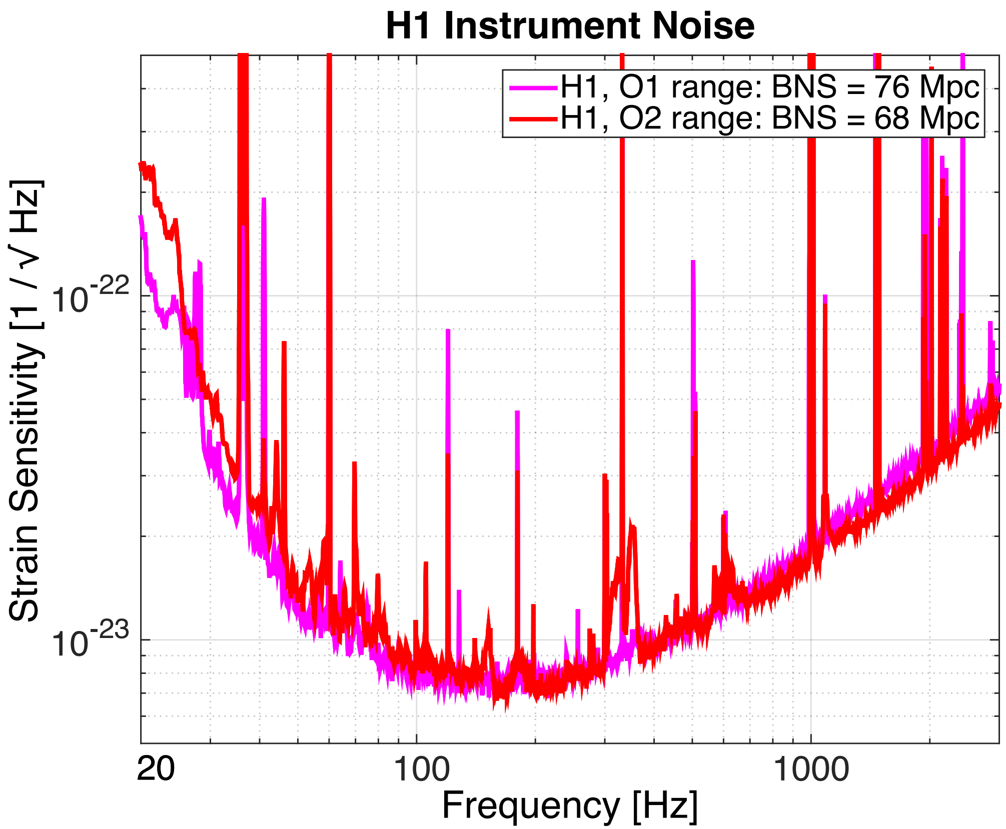


LIGO G-1602060

Improvement at low frequency mostly due to mitigated scatter light noise

Significant average range improvement (+20%)

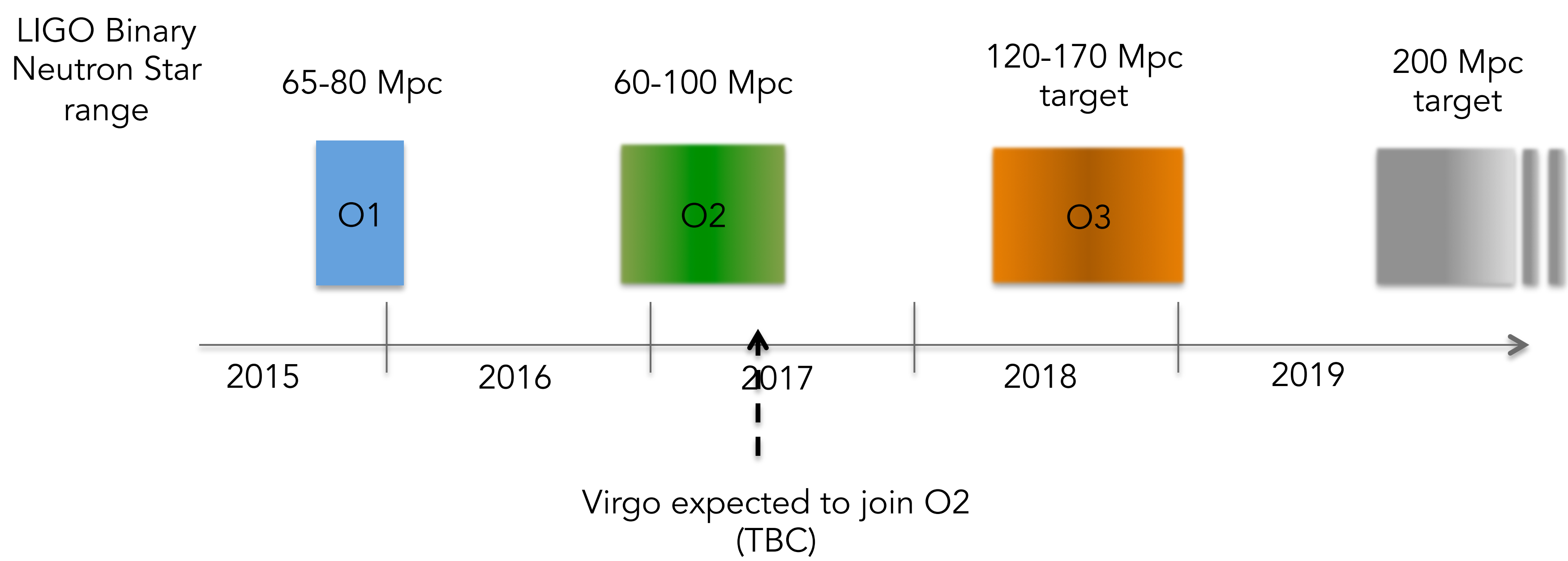
H1



LIGO G-1602060

Noise improvement at high frequency due to 30% higher power

Average range slightly worse than O1 (by 10%): higher power → larger jitter noise at low frequency


LIGO Binary Neutron Star range
65-80 Mpc
60-100 Mpc
120-170 Mpc target
200 Mpc target
O1
O2
O3
2015
2016
2017
2018
2019
Virgo expected to join O2 (TBC)

MEANWHILE AT VIRGO…

- Advanced Virgo in vacuum for the first time in August 2016
  - preliminary commissioning could start
- November 2016: vacuum broken in the NE tower to install a baffle
  - NE suspension (last fused silica fibers in place) failed during venting
  - key event allowing identification of the issue (contamination from scroll pumps)
- Commissioning restarted
  - first lock on at half fringe on Dec 30
  - first lock on dark fringe in February
  - first 1-hr lock in March

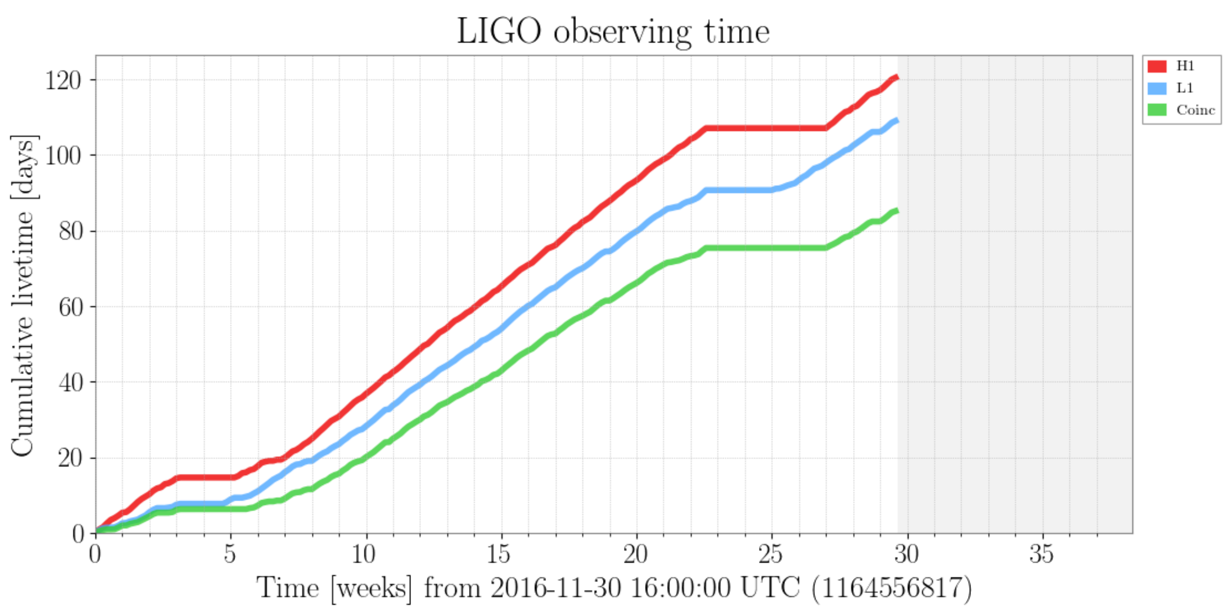
ABOUT MONOLITHIC SUSPENSIONS

- Detector integration troubled by repeated breakage of fused silica fibers when test masses suspended in vacuum
- Lead to decision of suspending them with steel wires in order not to stop commissioning progress
  - Achievable BNS inspiral range limited to ~50 Mpc
- Extensive/intense research in parallel to understand the cause
- Eventually found: dust particle generated by scroll pumps and blown towards the fibers during a venting of the vacuum chamber
- Risk mitigation action plan ready, to be implemented after O2
  - upgrade of the vacuum system: scroll pumps replacement, modifications of the venting piping
  - installation of "fiber guards"
- Test masses to be suspended again with fused silica fibers after O2

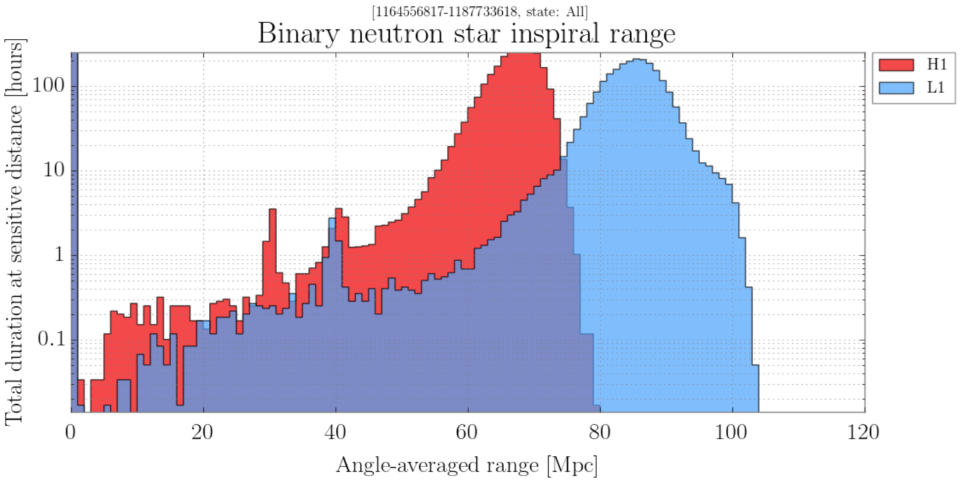
- Talk by F Travasso (MON, Suspension session)

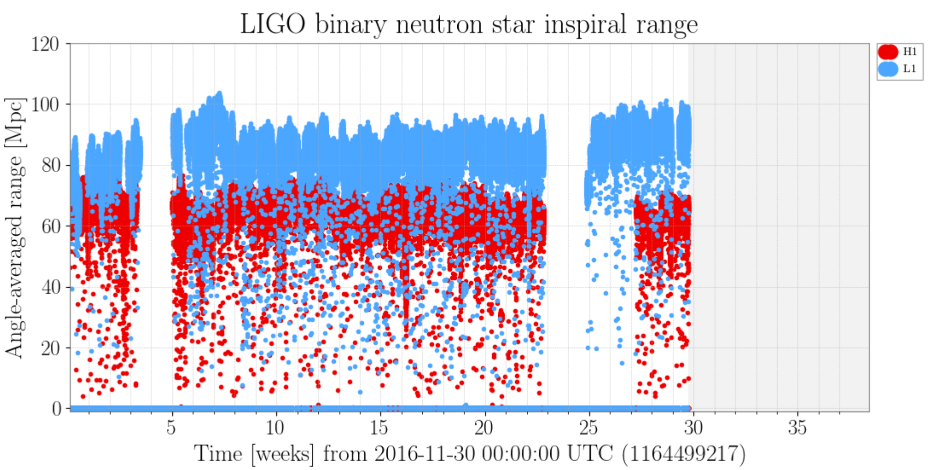
THE O2 RUN - FACTS

- Started on November 30, 2016
- ~75 days of Hanford-Livingston coincident science data have been collected so far
  - two breaks (holiday season, May vent/commissioning)
- ~45% of runtime has been coincident data (50% without recent vent downtime)



- Average reach of the LIGO network for binary merger events:
  - 70 Mpc for 1.4+1.4 Msun
  - 300 Mpc for 10+10 Msun
  - 700 Mpc for 30+30 Msun
  - Relative variations in time of the order of 10%





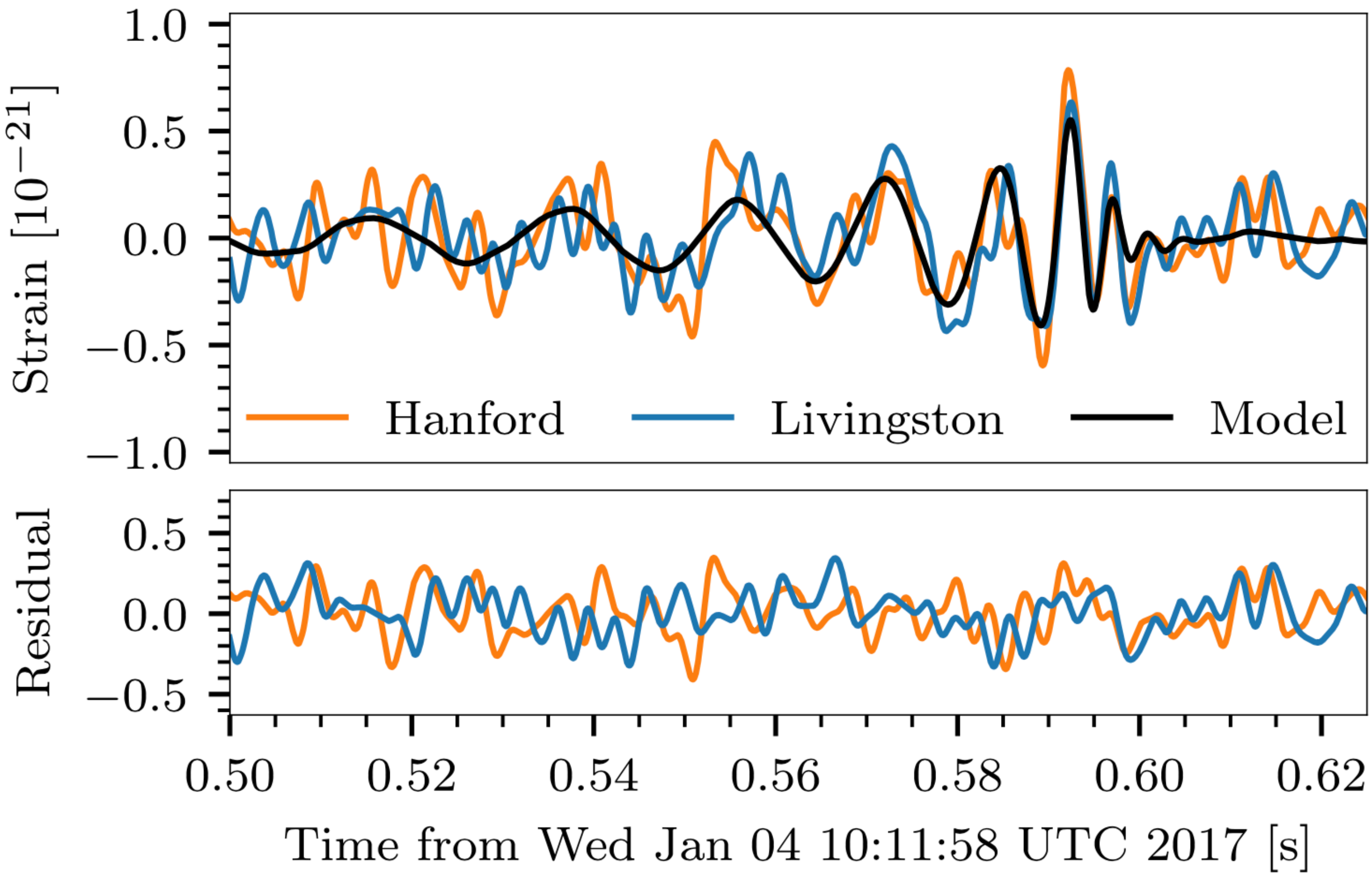
- More on the LIGO commissioning and on the current understanding of the noise in the talk by K Kawabe later this morning

O2- TRIGGERS

Prior to the May commissioning break, 7 triggers, identified by online analysis using a loose false-alarm-rate threshold of one per month, have been identified and shared with astronomers who have signed memoranda of understanding with LIGO and Virgo for electromagnetic follow-up. A thorough investigation of the data and offline analysis are in progress; results will be shared when available.

GW170104

BP Abbott et al (LVC), PRL 118 (2016), 221101



PRL **118,** 221101 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

B. P. Abbott *et al.**
(LIGO Scientific and Virgo Collaboration)

(Received 9 May 2017; published 1 June 2017)

We describe the observation of GW170104, a gravitational-wave signal produced by the coalescence of a pair of stellar-mass black holes. The signal was measured on January 4, 2017 at 10:11:58.6 UTC by the twin advanced detectors of the Laser Interferometer Gravitational-Wave Observatory during their second observing run, with a network signal-to-noise ratio of 13 and a false alarm rate less than 1 in 70 000 years. The inferred component black hole masses are $31.2^{+8.4}_{-6.0} M_\odot$ and $19.4^{+5.3}_{-5.9} M_\odot$ (at the 90% credible level). The black hole spins are best constrained through measurement of the effective inspiral spin parameter, a mass-weighted combination of the spin components perpendicular to the orbital plane, $\chi_{\rm eff} = -0.12^{+0.21}_{-0.30}$. This result implies that spin configurations with both component spins positively aligned with the orbital angular momentum are disfavored. The source luminosity distance is 880^{+450}_{-390} Mpc corresponding to a redshift of $z = 0.18^{+0.08}_{-0.07}$. We constrain the magnitude of modifications to the gravitational-wave dispersion relation and perform null tests of general relativity. Assuming that gravitons are dispersed in vacuum like massive particles, we bound the graviton mass to $m_g \leq 7.7 \times 10^{-23}\ \mathrm{eV}/c^2$. In all cases, we find that GW170104 is consistent with general relativity.

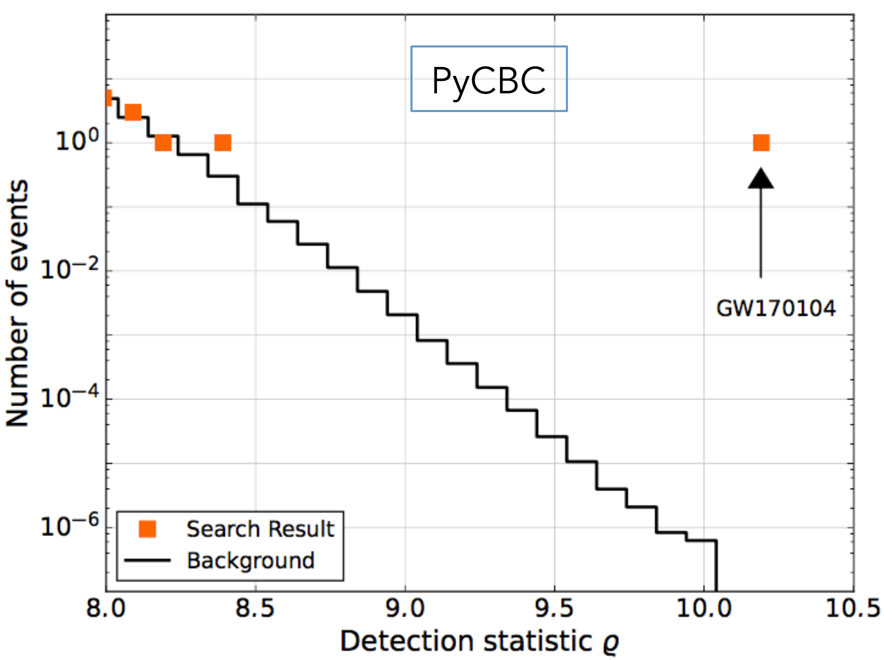
DOI: 10.1103/PhysRevLett.118.221101

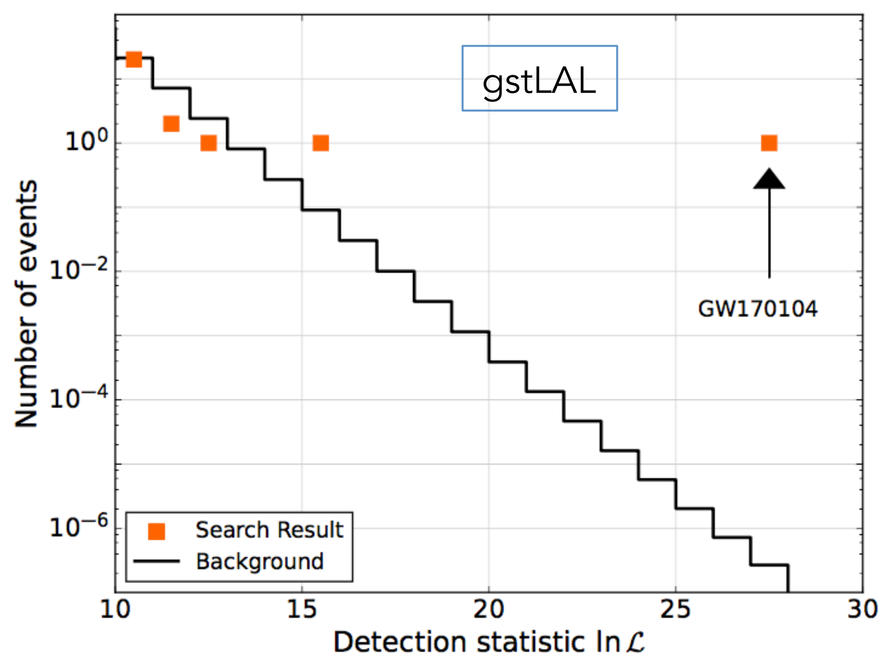
JAN 4TH, 2017: FIRST O2 DETECTION. PUBLISHED ON PRL, JUN 2ND

GW170104: SIGNIFICANCE

- SNR ~ 13
- FAR ~ 1/70000 yrs
- Two independent analyses

BP Abbott et al (LVC), PRL 118 (2016), 221101





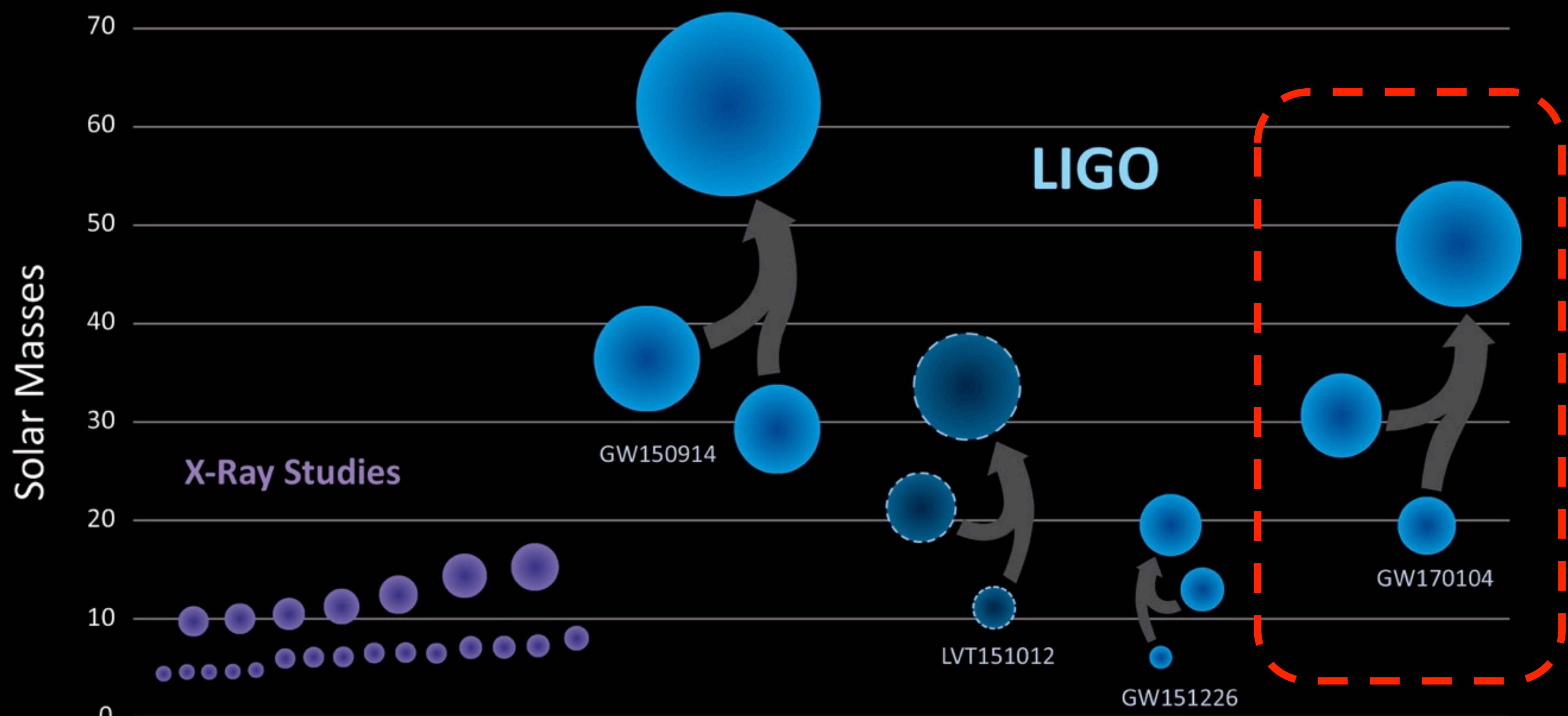
GW170104: PARAMETERS

Primary black hole mass m_1	$31.2^{+8.4}_{-6.0} M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy E_{rad}	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity ℓ_{peak}	$3.1^{+0.7}_{-1.3} \times 10^{56} \mathrm{erg\,s}^{-1}$
Effective inspiral spin parameter χ_{eff}	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

BP Abbott et al (LVC), PRL 118 (2016), 221101

Black Holes of Known Mass

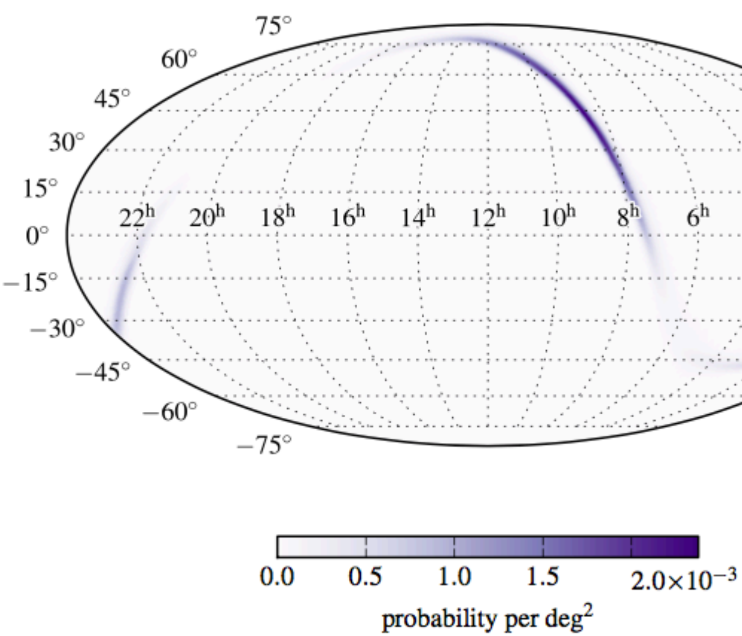
Image credit: LIGO/Caltech/Sonoma State (Aurore Simonnet)

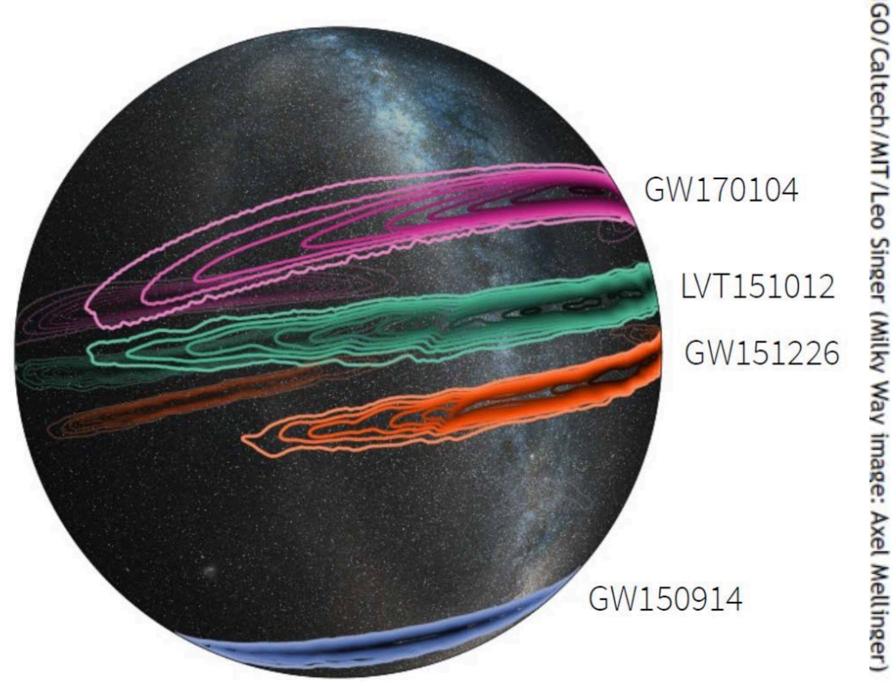


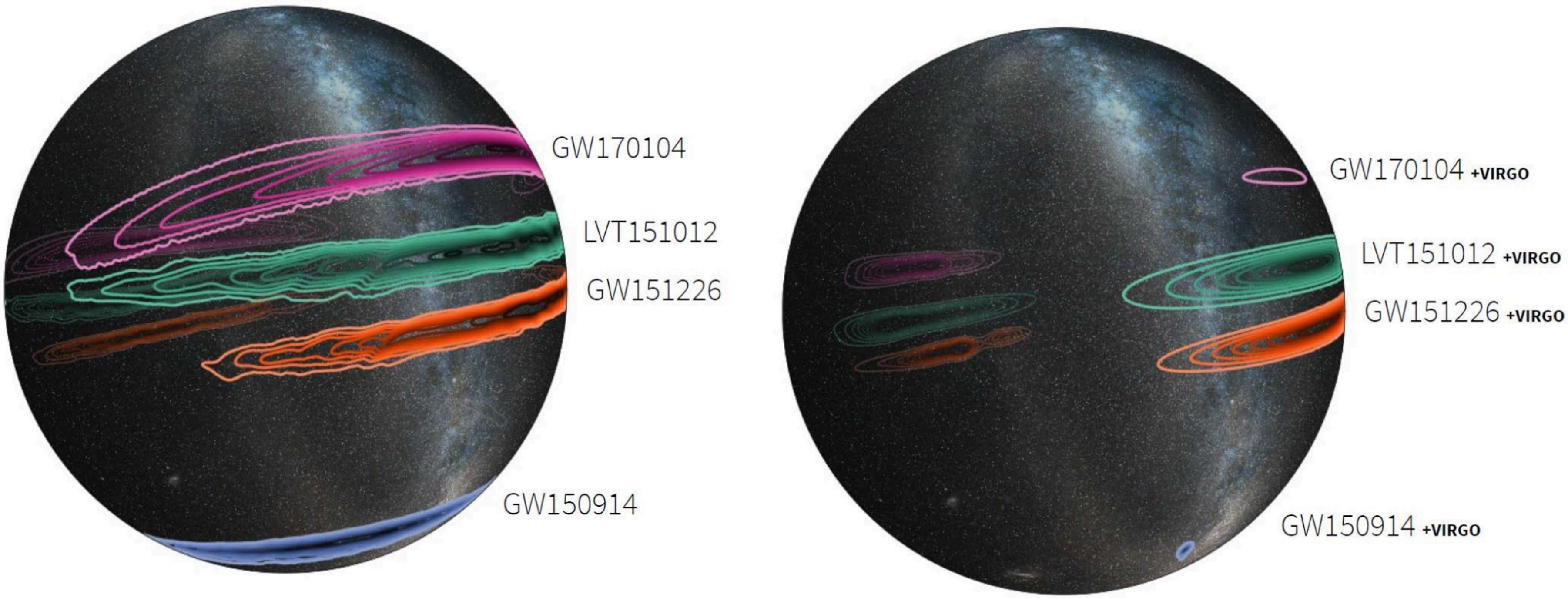
MORE ON GW170104 AND ITA IMPLICATIONS FOR ASTROPHYSICS AND GR TESTS IN THE TALKS BY C VAN DEN BROECK (THU) AND M MAPELLI (FRI)

GW170104: EM FOLLOW UP

- Localization: within an area of ~1200 deg^2
- About 30 groups and 50 instruments involved
- 70 GCN sent (https://gcn.gsfc.nasa.gov/other/G268556.gcn3)
  - no interesting counterpart found



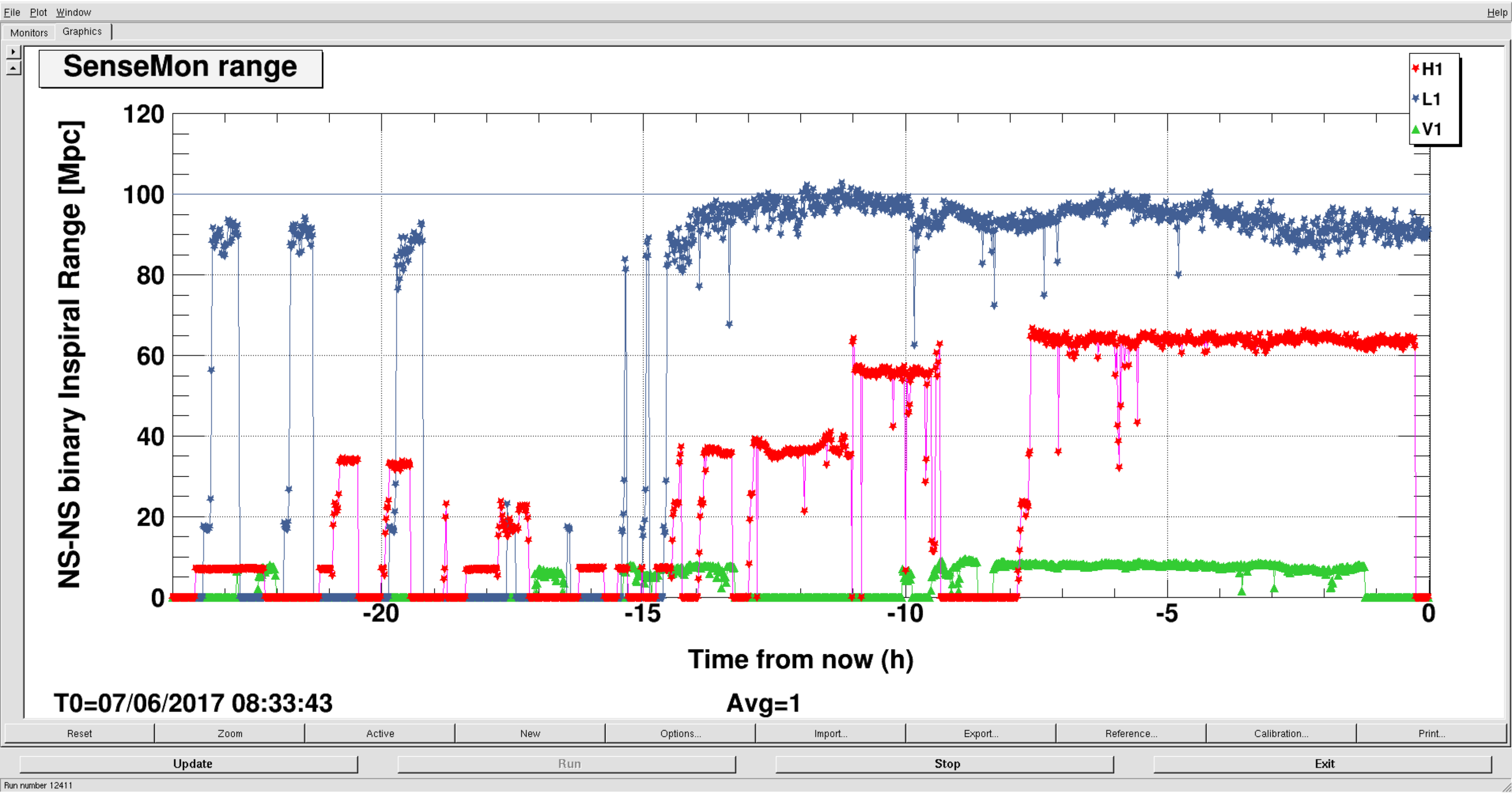




3-D projection of the Milky Way onto a transparent globe shows the probable locations of confirmed detections GW150914 (blue), GW151226 (orange) and GW170104 (pink), and the candidate LVT151012 (green). The outer contour for each represents the 90 percent confidence region while the innermost contour is the 10 percent region. Image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)

TOWARDS THE NETWORK

June 7: 3 advanced detectors locked together for the first time



A FEW DAYS LATER VIRGO JOINED ER11

Daniel Williams
@daniel_williams

Segui

It's my last day at @LIGOLA, but it's a big day for #gravitationalwaves. As of today we have three running interferometers @ego_virgo+@LIGO!

Traduci dalla lingua originale: inglese

LHO	OK+Intent	3:56
LLO	OK+Intent	14:48
Virgo	Science	1:33

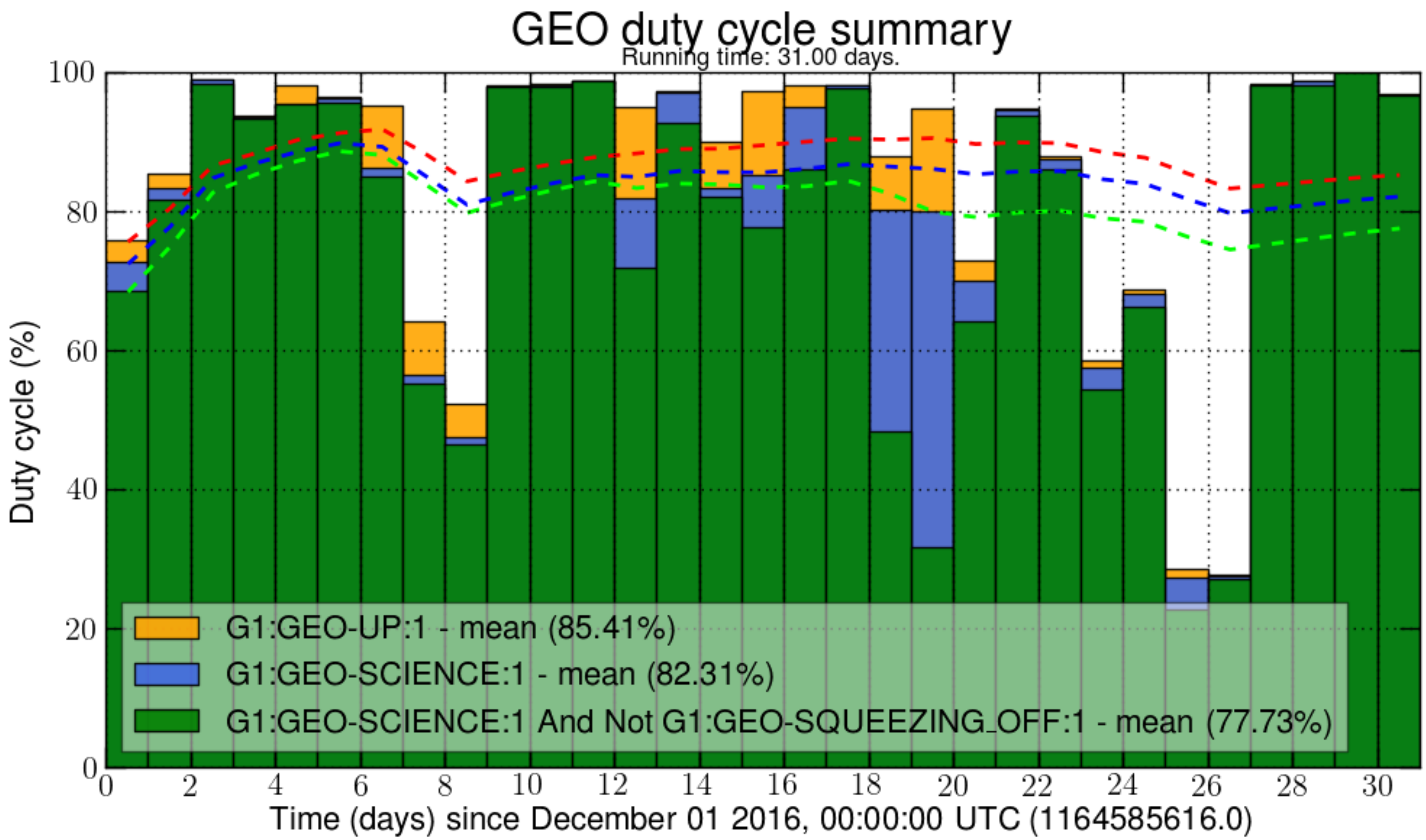
Retweet 25 Mi piace 34

07:36 - 16 giu 2017

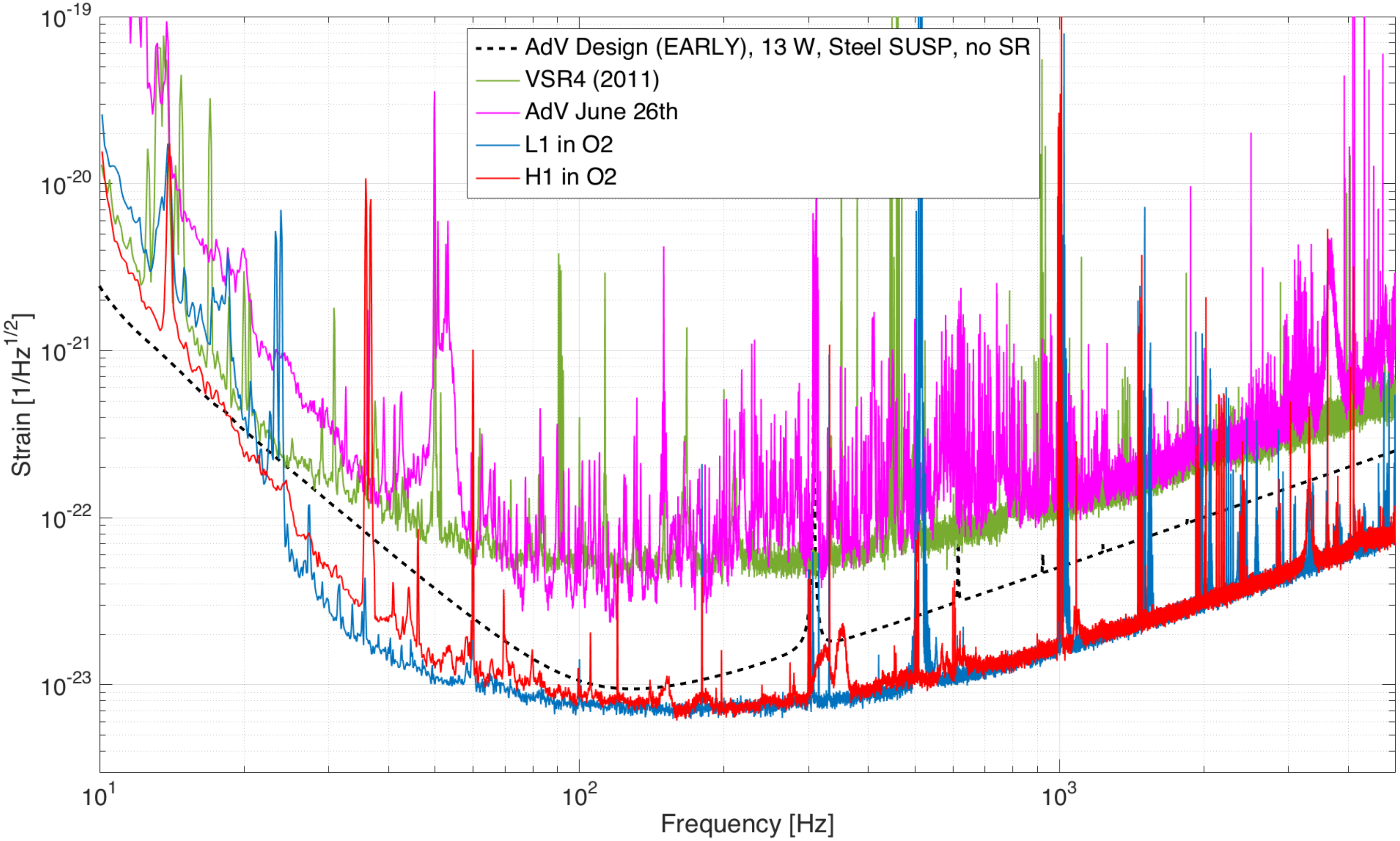
1 25 34

GEO DURING O2

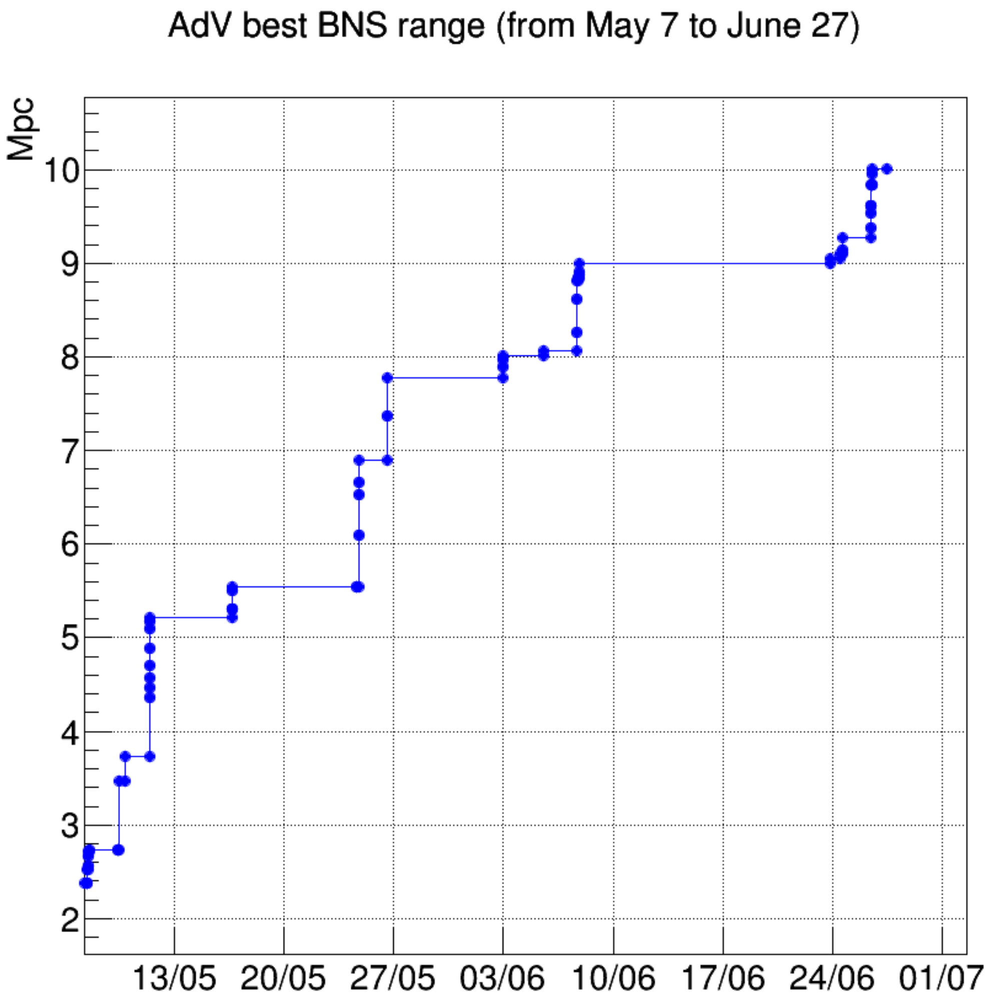
ASTROWATCH AT HIGH DUTY CYCLE (~80%)



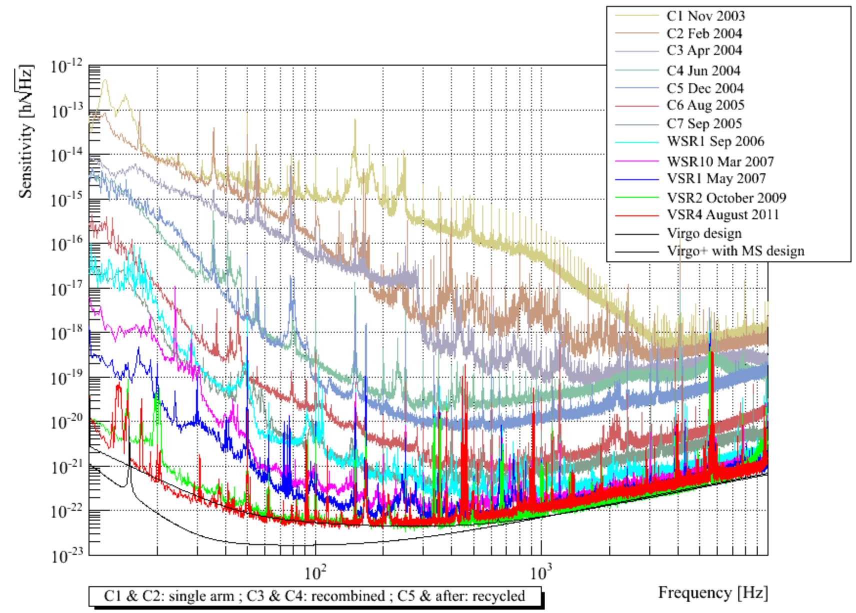
VIRGO PROGRESS



VIRGO PROGRESS

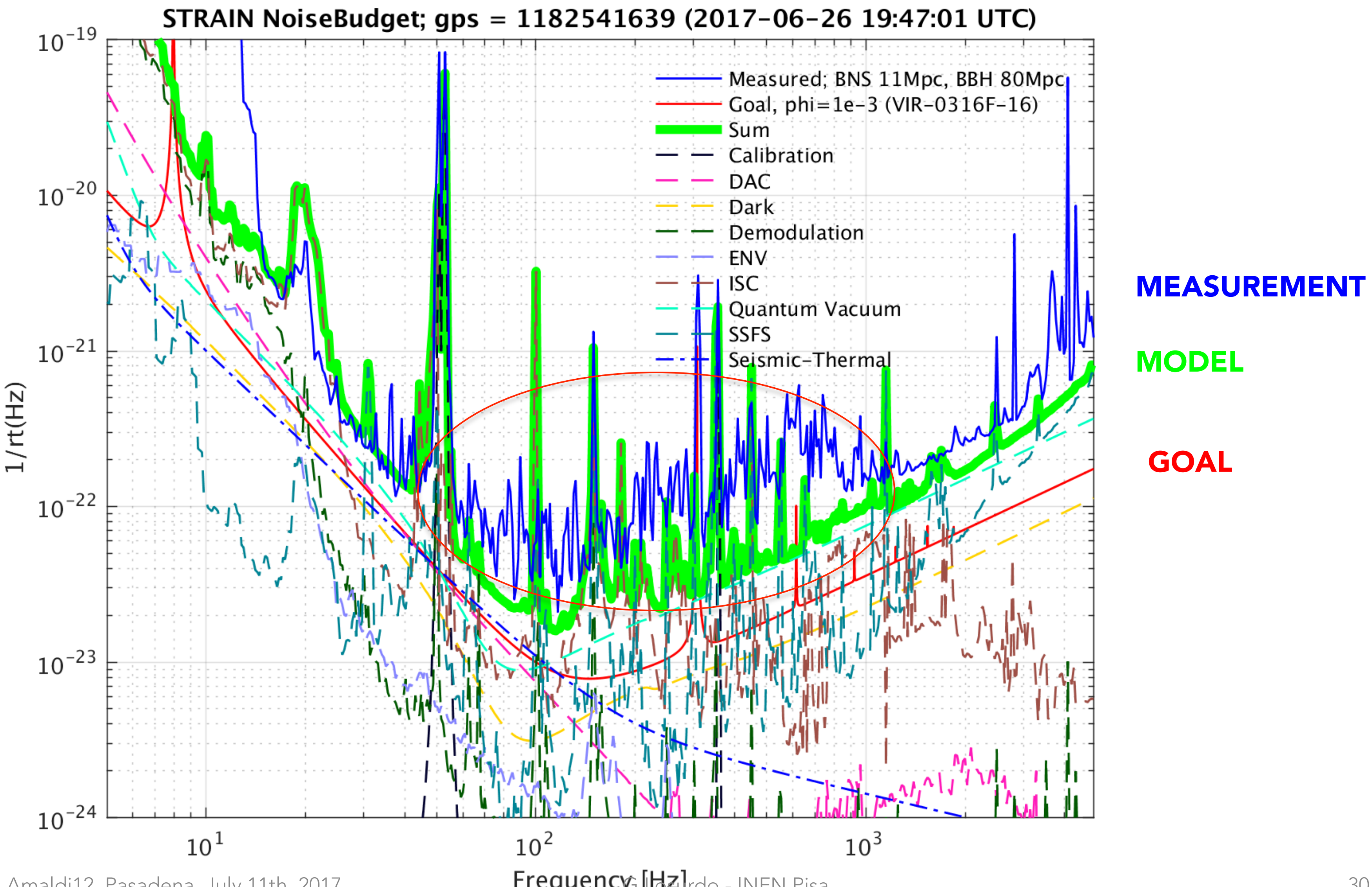


INITIAL VIRGO EVOLUTION (2003-2011)



IN ~3 MONTHS ACHIEVED WHAT VIRGO DID IN ~5 YEARS
(from 1st lock of the power recycled Virgo to ~10 Mpc)

ADVANCED VIRGO NOISE

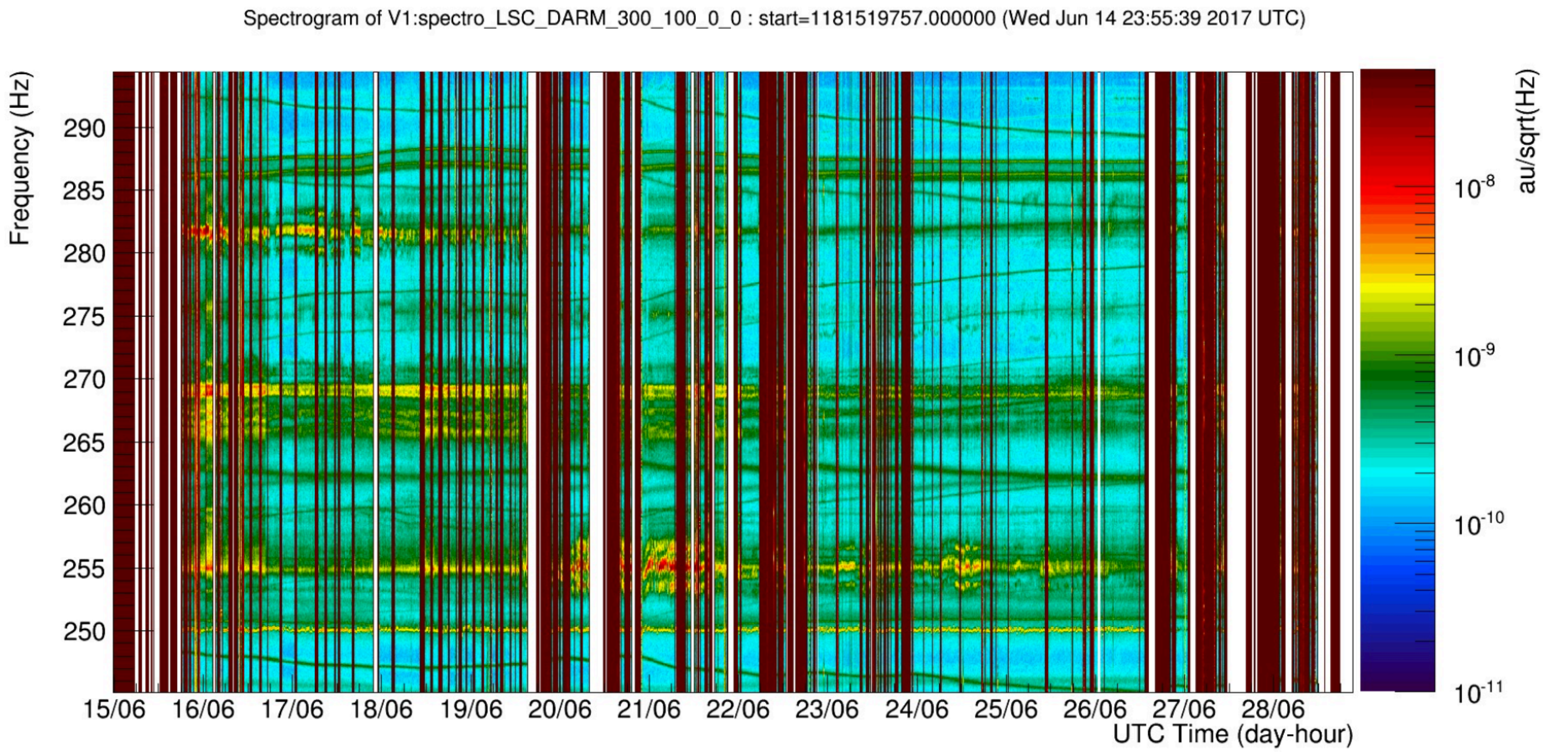


ADVANCED VIRGO COMMISSIONING

- Thermal compensation not used so far, but "central heating" prepared to improve the stability of the power recycling cavity
- "Mystery" broadband noise in the 100 Hz-1 kHz range, plus a forest of lines
- Extensive detector characterization and noise hunting activity in progress
  - quantify origin and impact of scattered light, define mitigation strategies
  - tracking the origin of many peaks in the spectrum

Output mode matching telescope illuminated by stray light

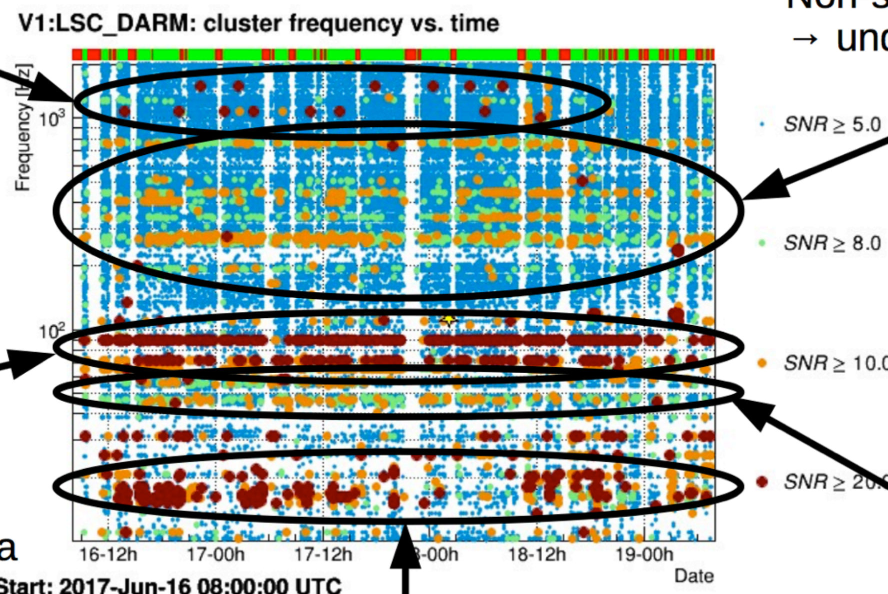
- Spectral noise in the detector is under investigation → mitigation
  - switch-off tests
  - correlation of moving lines with auxiliary signals (temperature, ...)



- Transient noise in the detector is under investigation → mitigation

Frequency stabilization control loop instabilities
→ Fixed

Non-statioanry spectral lines
→ under investigation



Missing one cycle in control loops
→ subtracted in calibrated data

Noise coupling at 50 Hz (mains power)
→ under investigation

Scattered light glitches
(detection bench)

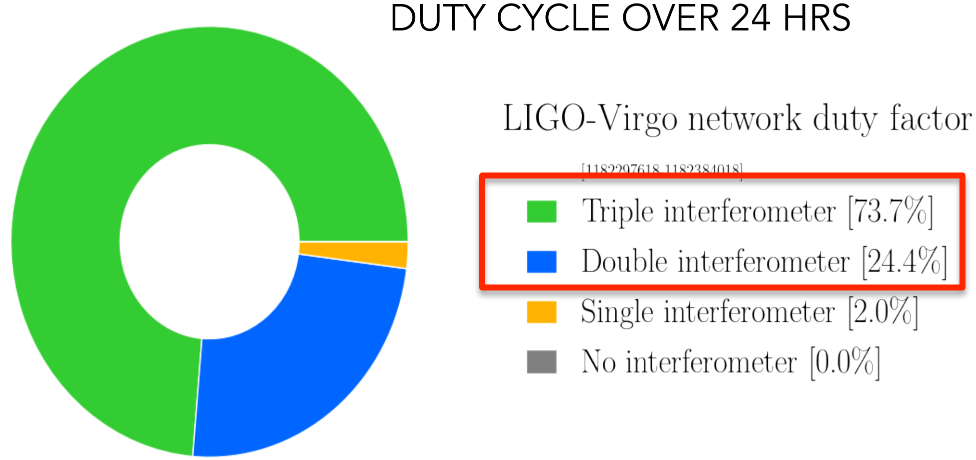
WHEN TO JOIN O2?

- Virgo targets a sensitivity in excess of 20 Mpc
  - about twice the current BNS range
- Several important commissioning actions are planned for the next weeks, and these likely will lead to an improvement of our sensitivity.
- Virgo is in close and continuous discussion with LIGO through our Joint Run Planning Committee

TOWARDS A 3-DETECTOR NETWORK

- LIGO and Virgo are preparing for EM alerts using 3 interferometers
- ER11 was the first chance to make tests
  - Virgo joined ER11 for two weekends
- Virgo has put in place a Rapid Response Team to cover the different aspects of an alert: operator on shift + experts on detector, calibration, detchar
- A full end-to-end test with 3 interferometers event (low FAR) has been used to check that all needed information to take decisions were in place

DUTY CYCLE OVER 24 HRS

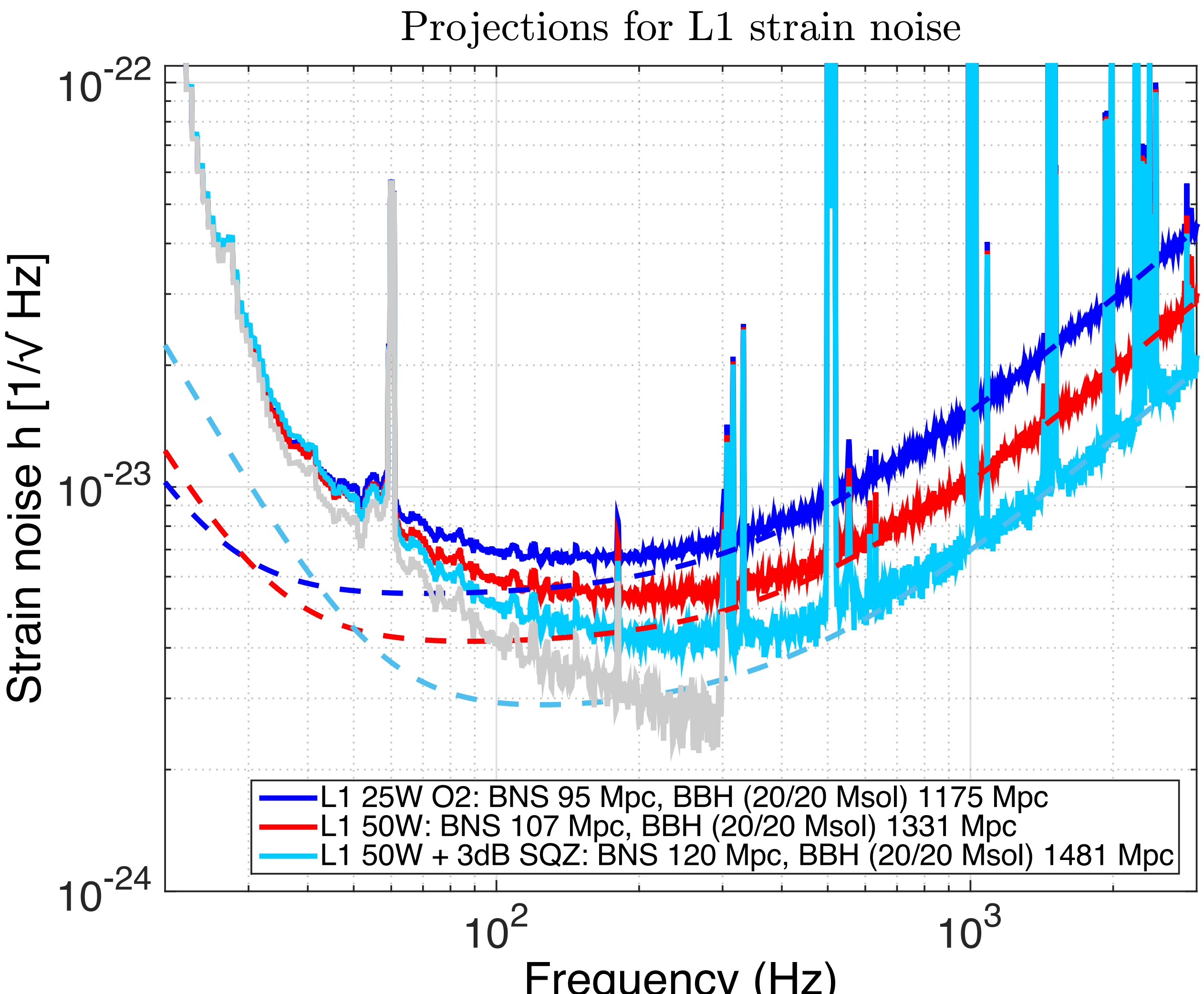


98.1%

AFTER O2 - LIGO

- Stop data taking on Aug 25th, for ~1 year
- Goal: substantial improvement of the sensitivity
- Planned activities:
  - further scattered light mitigation at both sites
  - input power increase at both sites
  - injection of squeezed light

AFTER O2 - LIGO



x2 Higher power

x2 Higher power + squeezing

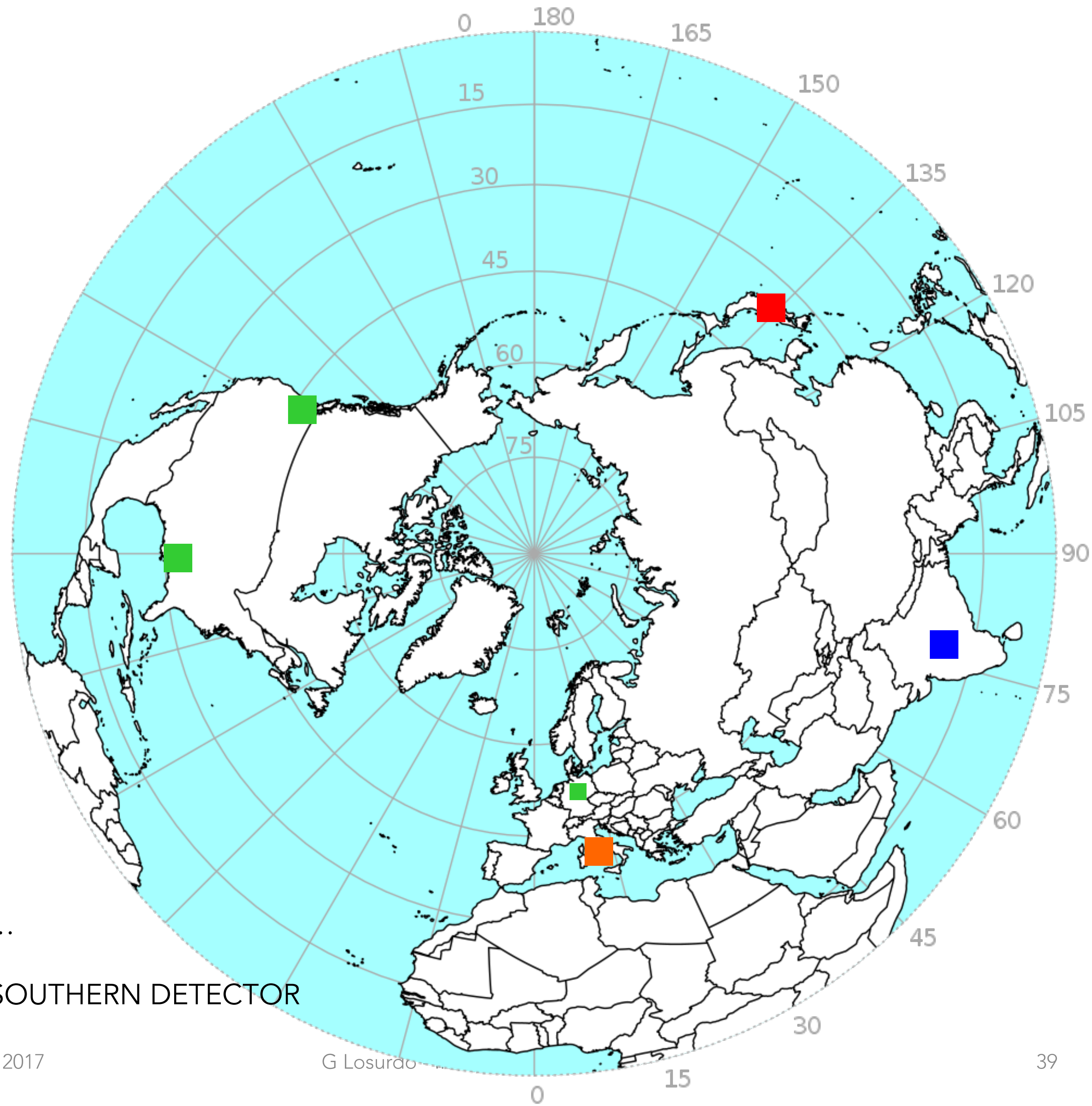
No further reduction of low frequency noise assumed in this plot

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
- Increase laser power (now 13 W)
- Implement squeezer provided bi AEI Hannover
- Do commissioning to improve sensitivity!

~5 months

- Installation of SR mirror not planned for this time frame



■ OPERATION

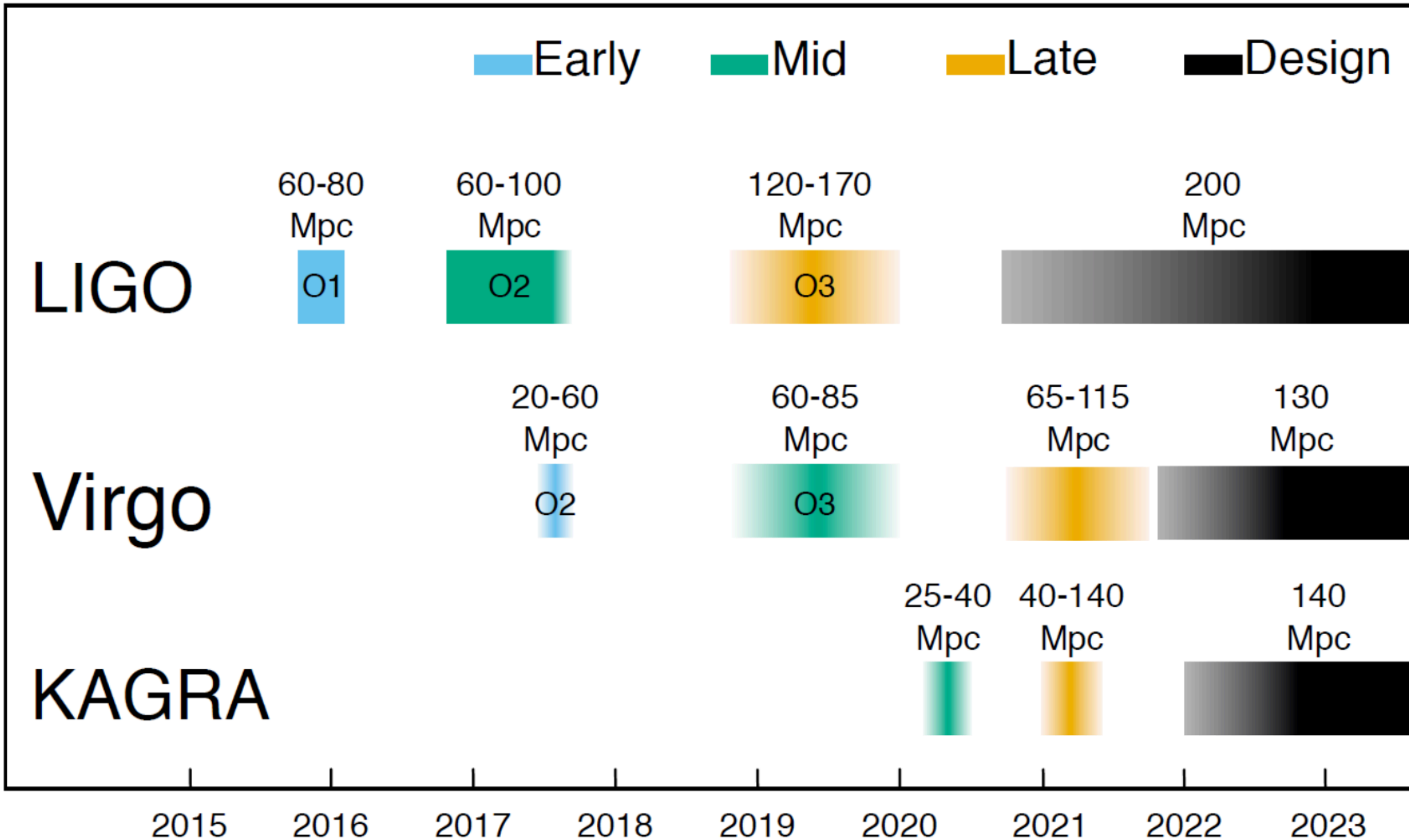
■ COMMISSIONING

■ CONSTRUCTION

■ APPROVED

ALL DETECTORS IN THE NORTHERN EMISPHERE…

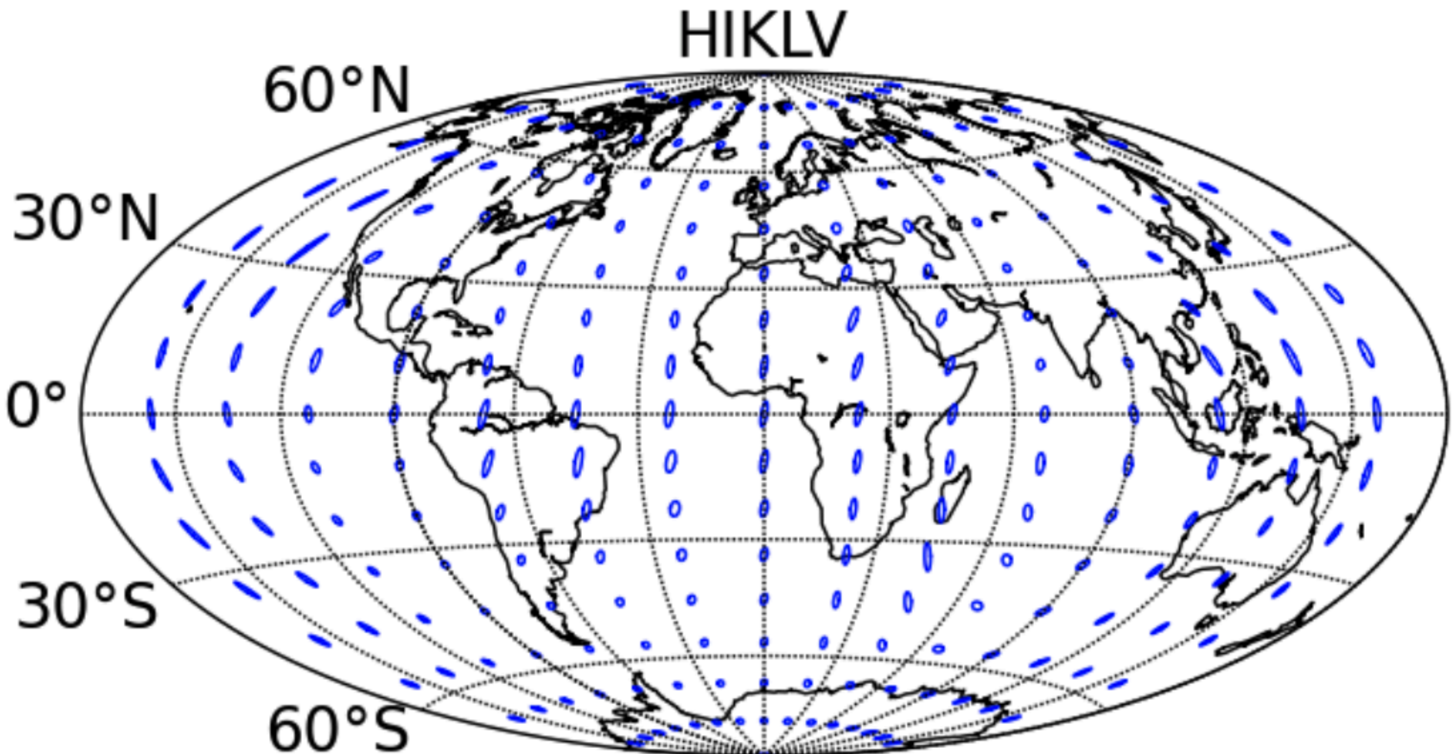
TIME TO PLAN/FUND A SOUTHERN DETECTOR



…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



Credit: S Fairhurst

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

SUMMARY

- O2 run in progress, one event published so far (GW170104)
- Virgo in stable operation and continuing commissioning to improve sensitivity and join O2
- First tests of 3-ITF operation successfully done