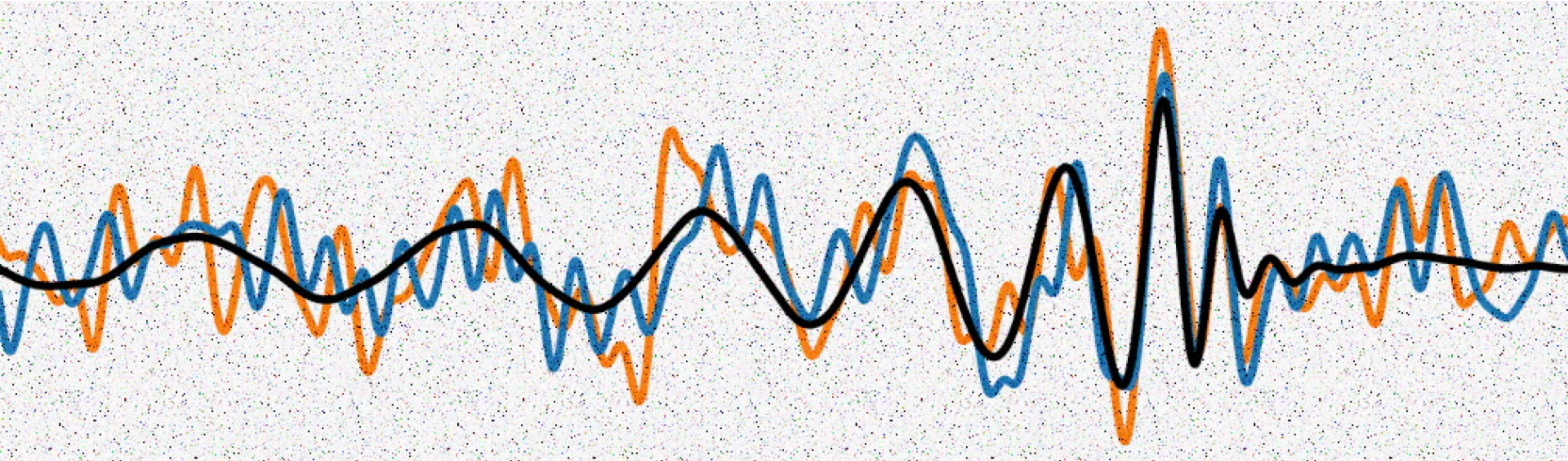
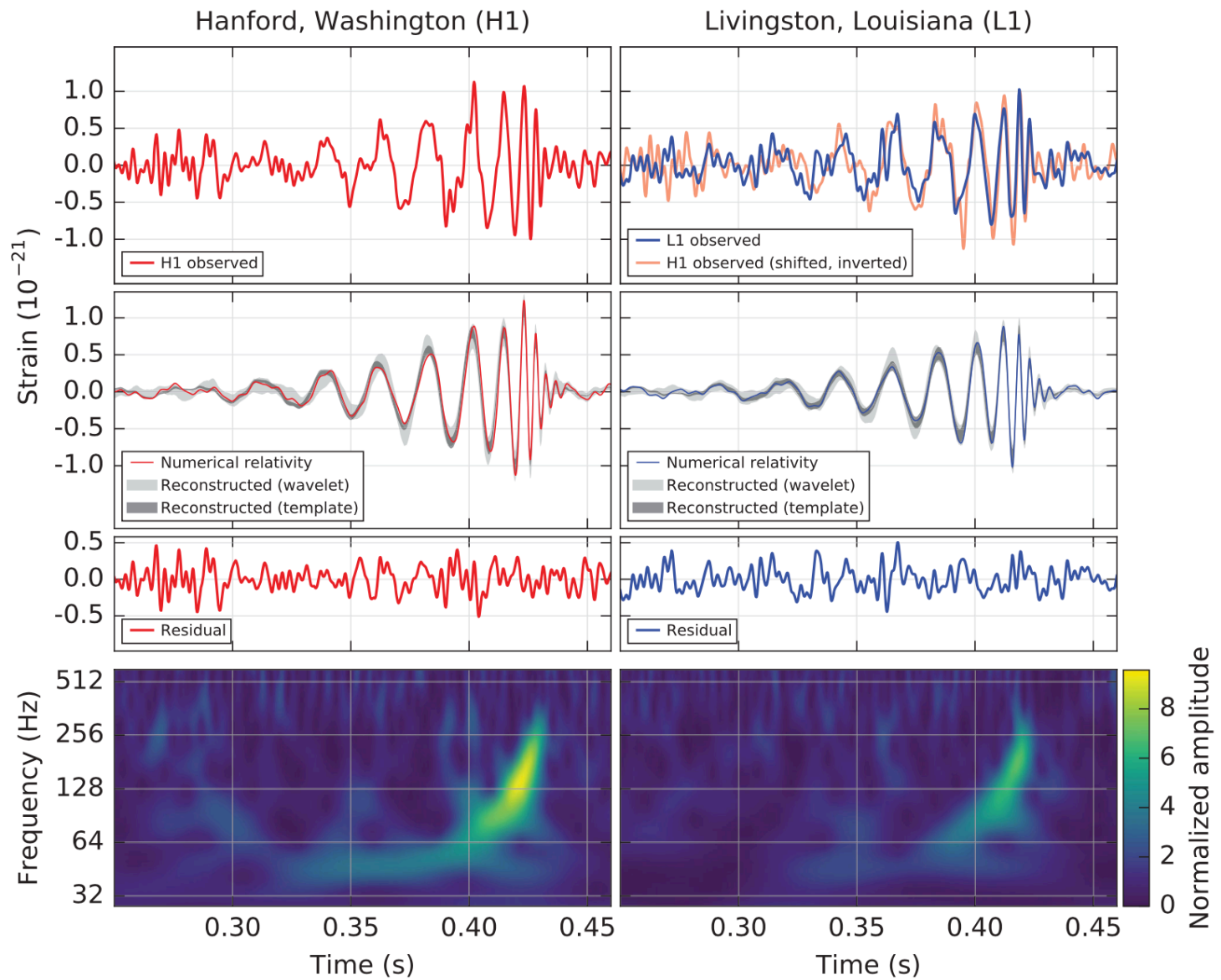


The second Observing Run (O2): detectors, results so far, perspectives

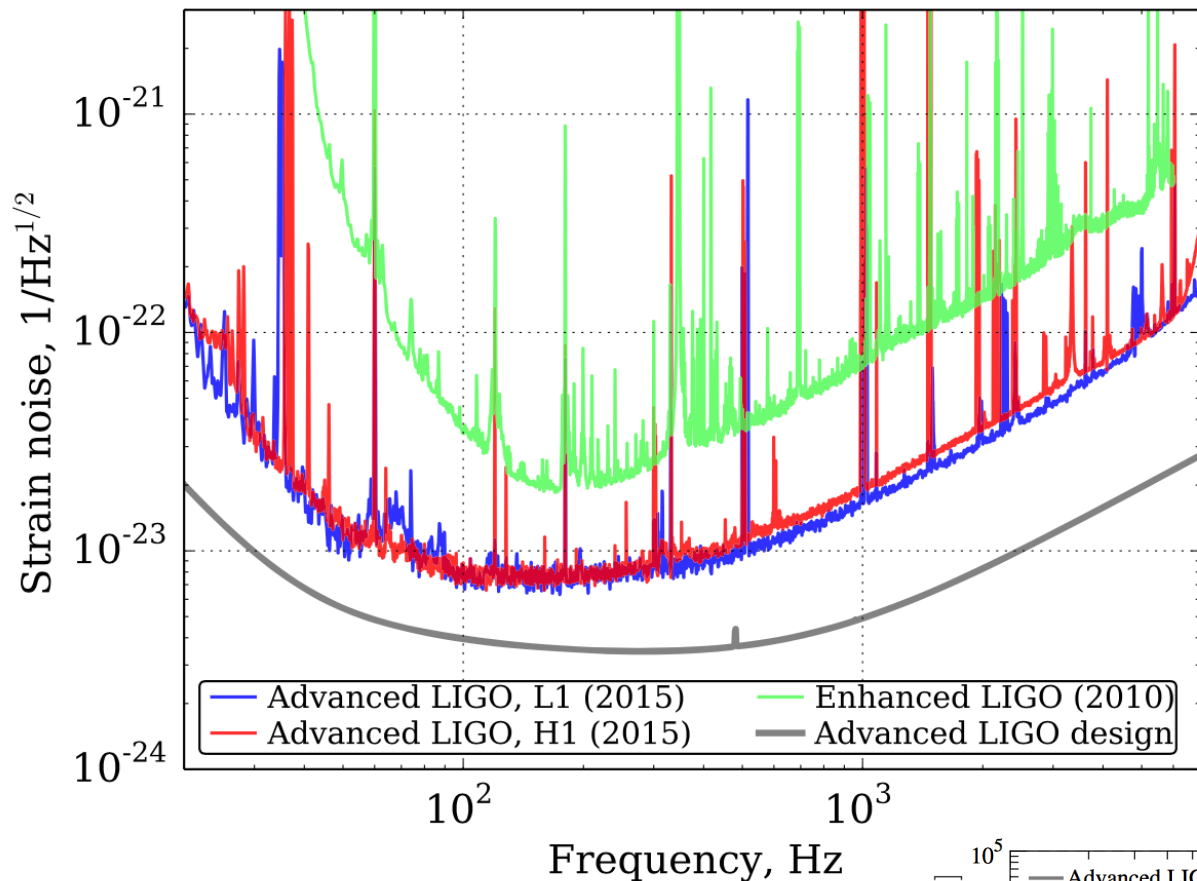


Giovanni Losurdo – INFN Pisa

on behalf of the
LIGO Scientific Collaboration and Virgo Collaboration



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

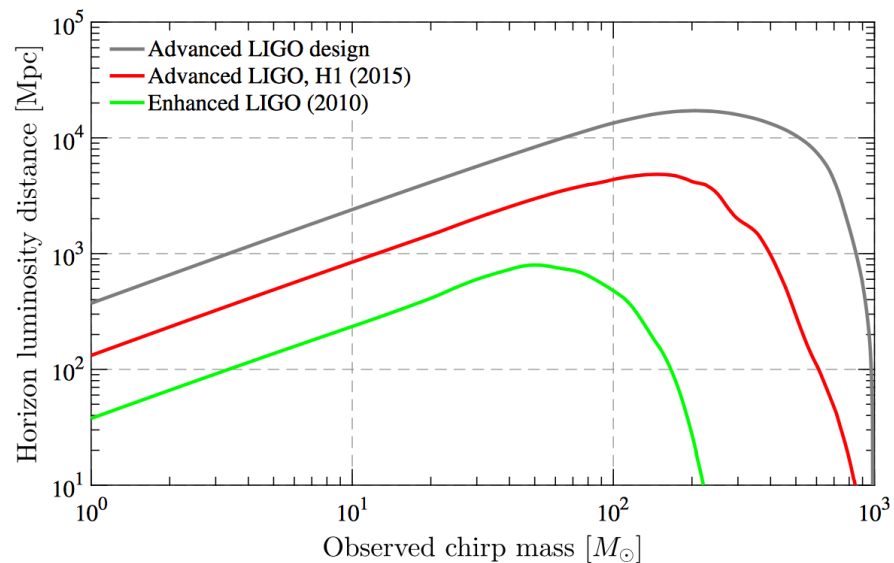


iLIGO best (2010)

aLIGO O1 (2015)

aLIGO design

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



WHY DOES DATA TAKING STOP?

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

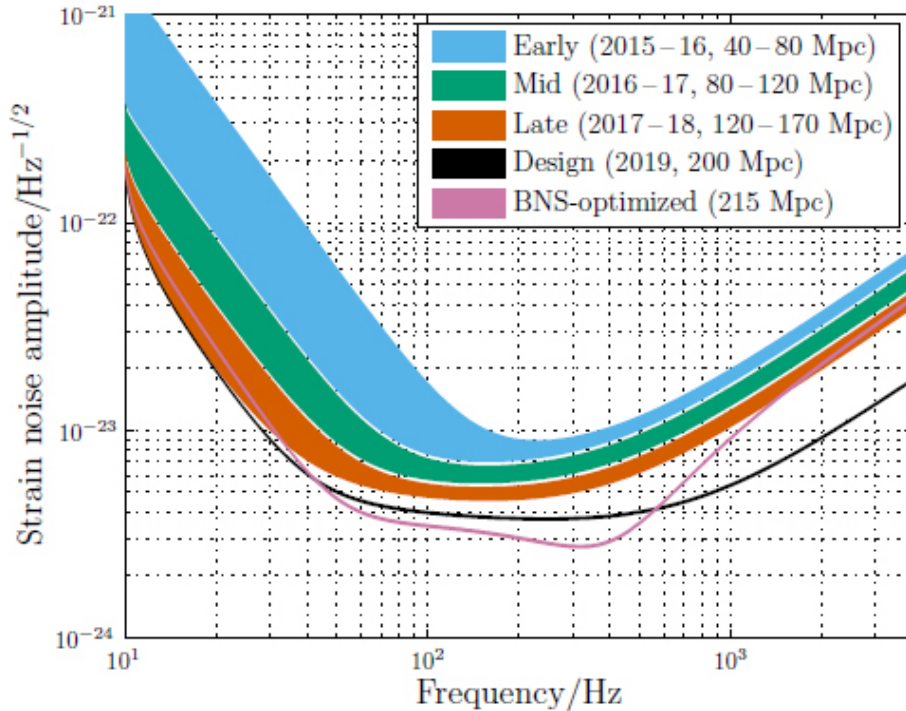
1 day of data at a range of 80 Mpc is equivalent to 64 days at 20 Mpc
1 day of data at a range of 100 Mpc is equivalent to 2 days at 80 Mpc

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

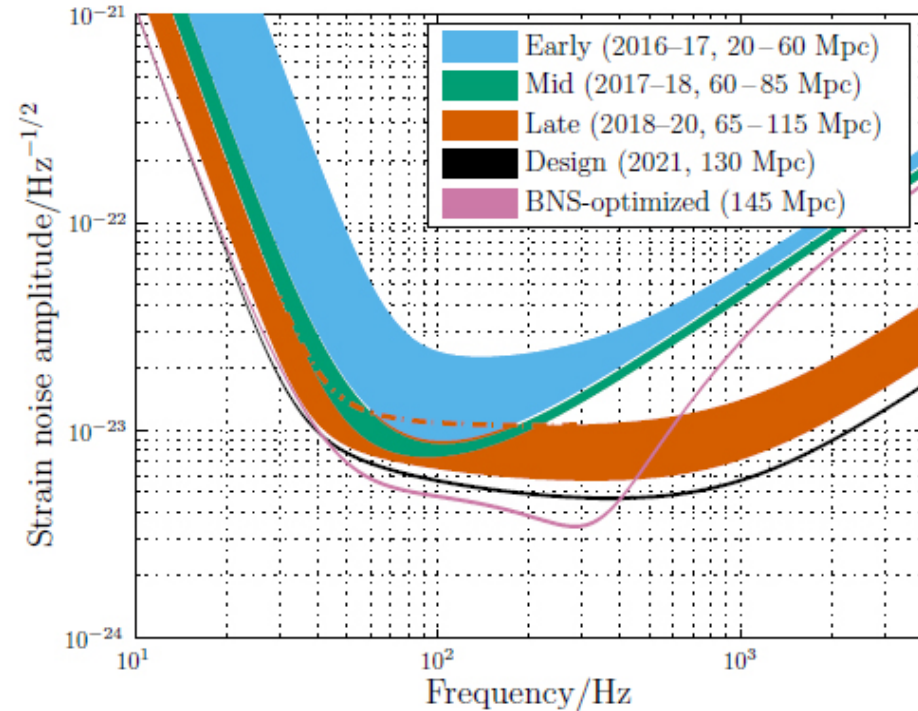
for this reason science runs are stopped and time is dedicated
to commissioning in order to further
increase the volume of observable universe (d^3)
and improve the machine stability (T)

ENVISAGED PROGRESS

Advanced LIGO

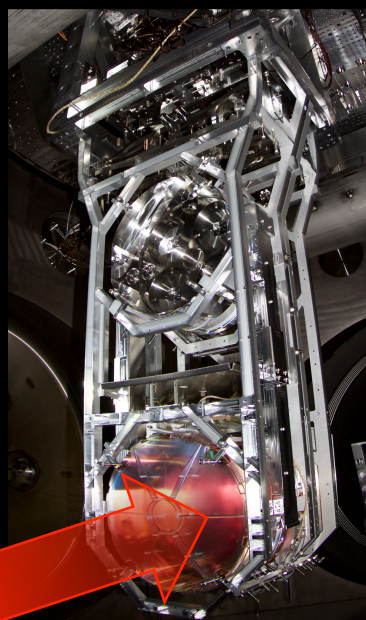
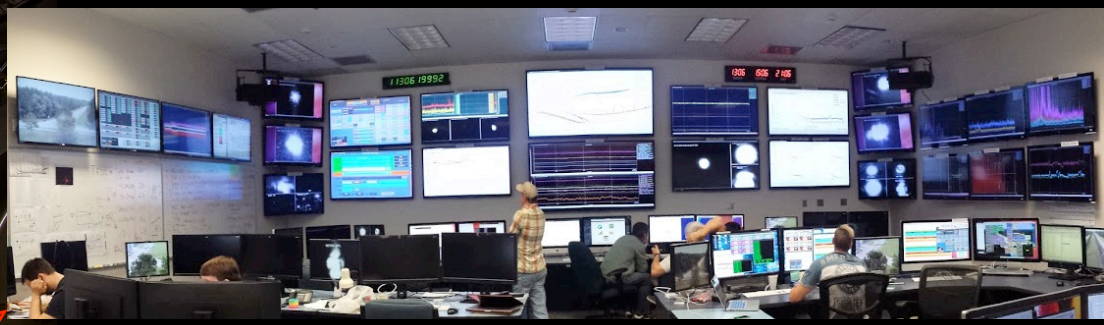
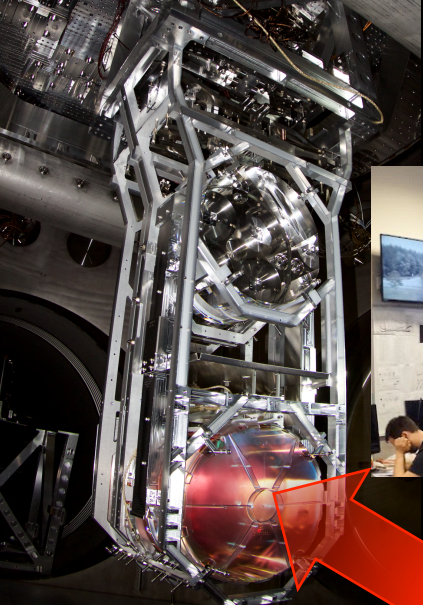


Advanced Virgo



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

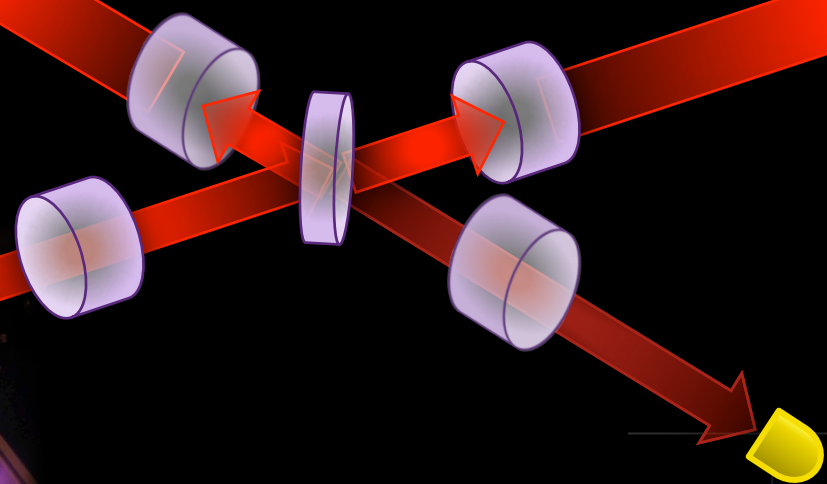
LIGO and VIRGO have envisaged that a few years would be necessary to reach the design sensitivities, interleaving data taking and commissioning periods



More than 300 control loops needed to keep the interferometer optimally running

40 kg high quality fused silica mirrors, isolated from the ground

Fabry-Perot cavities in the Michelson arms
~100kW laser power in O1



Output photodetector:
Interferometer noise + gravitational wave signal

CW laser, 1064nm
Up to 125W entering the interferometer
(20-25W during O1)

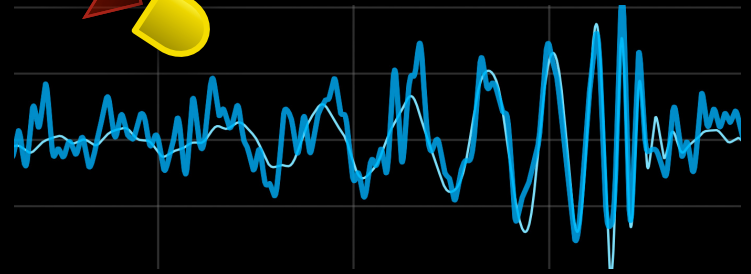
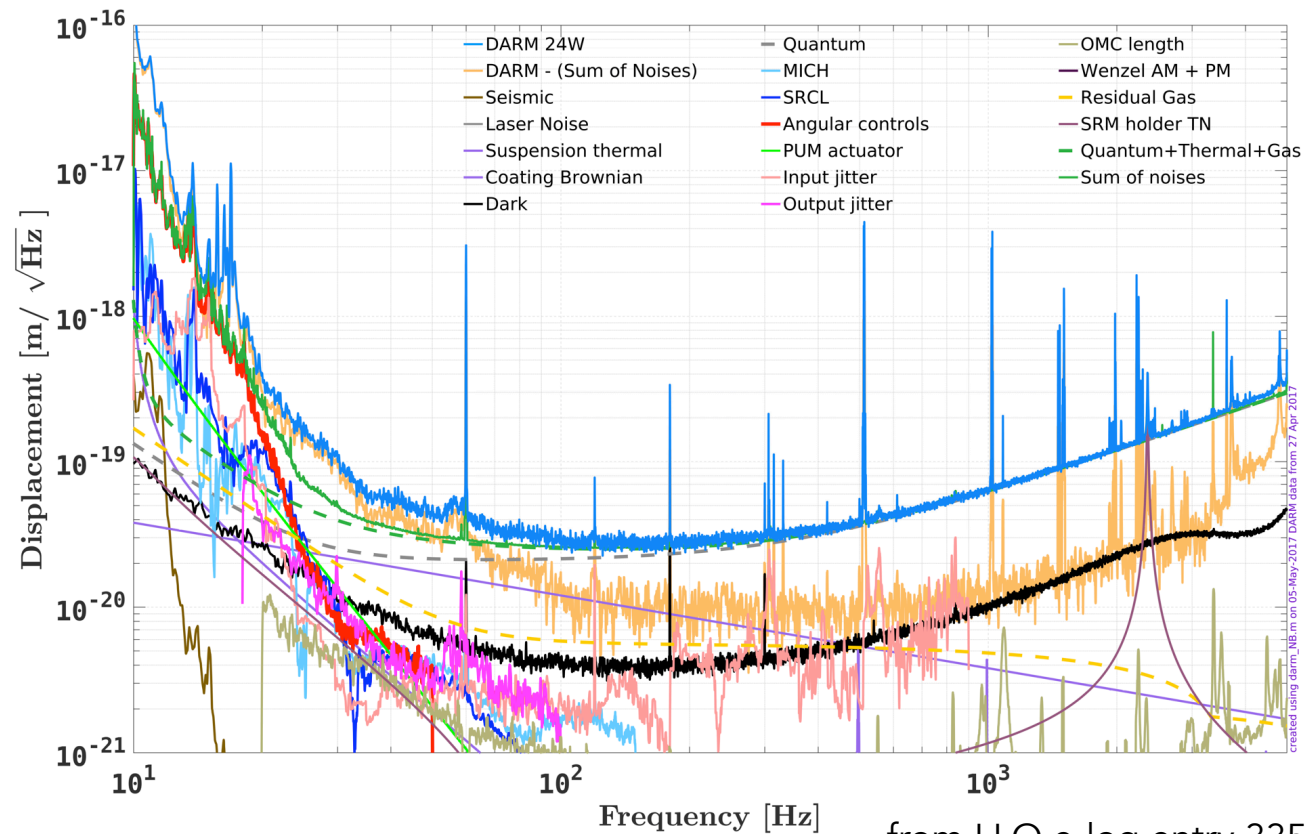


Figure credit: L Barsotti

COMMISSIONING

CHALLENGING (SOMETIMES HEROIC) EFFORT TO IDENTIFY, MODEL, TACKLE **MANY** NOISE SOURCES AND IMPROVE THE DETECTOR ROBUSTNESS AND THE QUALITY OF THE DATA

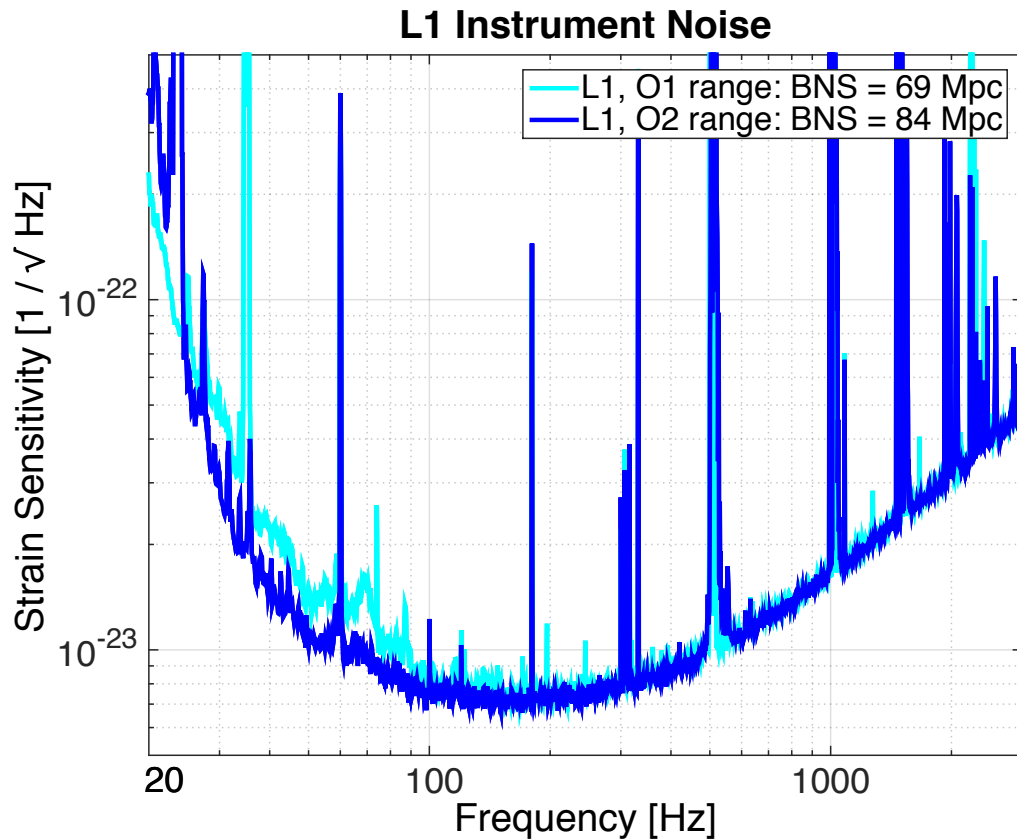


FROM O1 TO O2

- ❑ 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, work on interferometer robustness
 - required hardware changes in the vacuum chambers
- ❑ Transition into engineering run in November 2016

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

L1



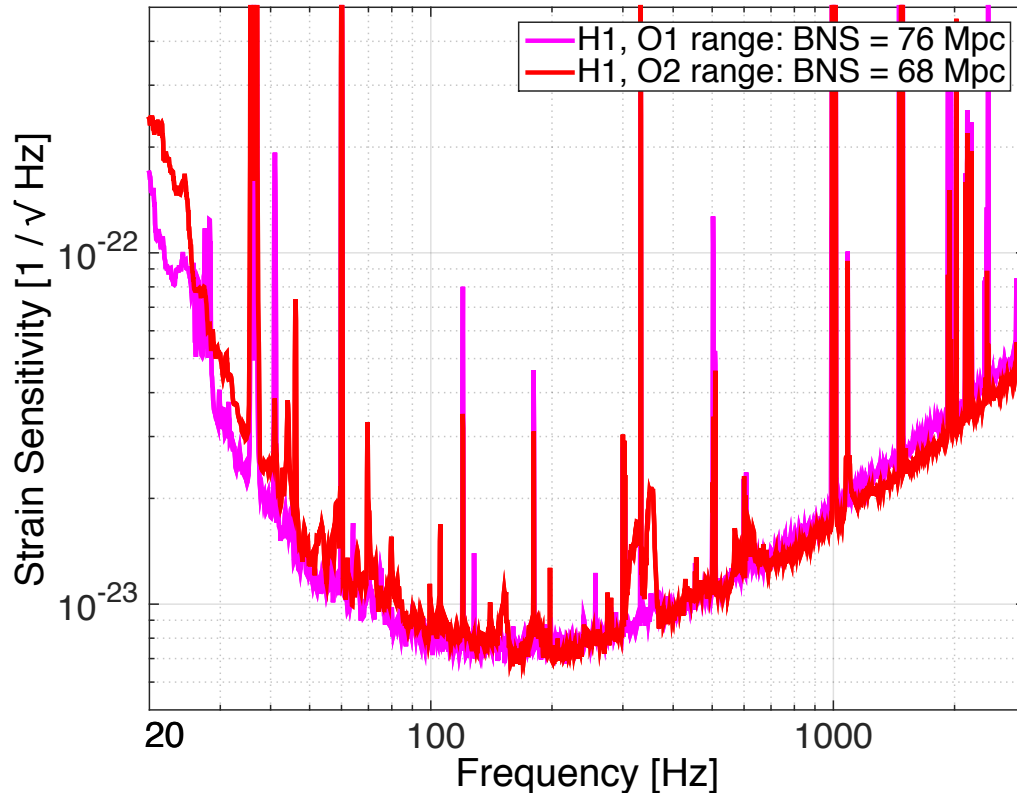
LIGO G-1602060

Improvement at low frequency mostly due to mitigated scatter light noise

Significant average range improvement (+20%)

H1

H1 Instrument Noise



LIGO G-1602060

Noise improvement at high frequency due to 30% higher power

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

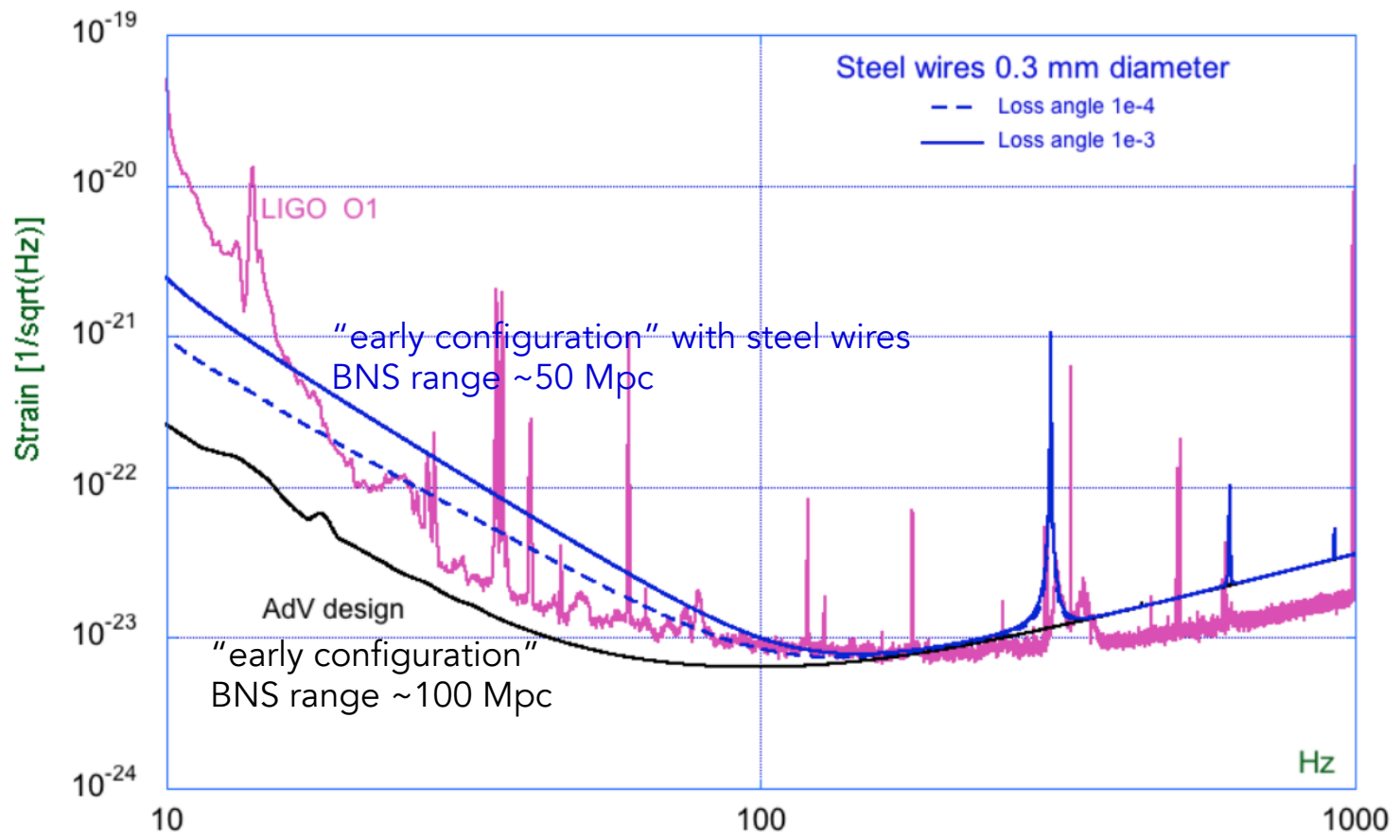
VIRGO DURING O2

- ❑ 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
- ❑ Advanced Virgo dedication ceremony on Feb 20

ABOUT MONOLITHIC SUSPENSIONS

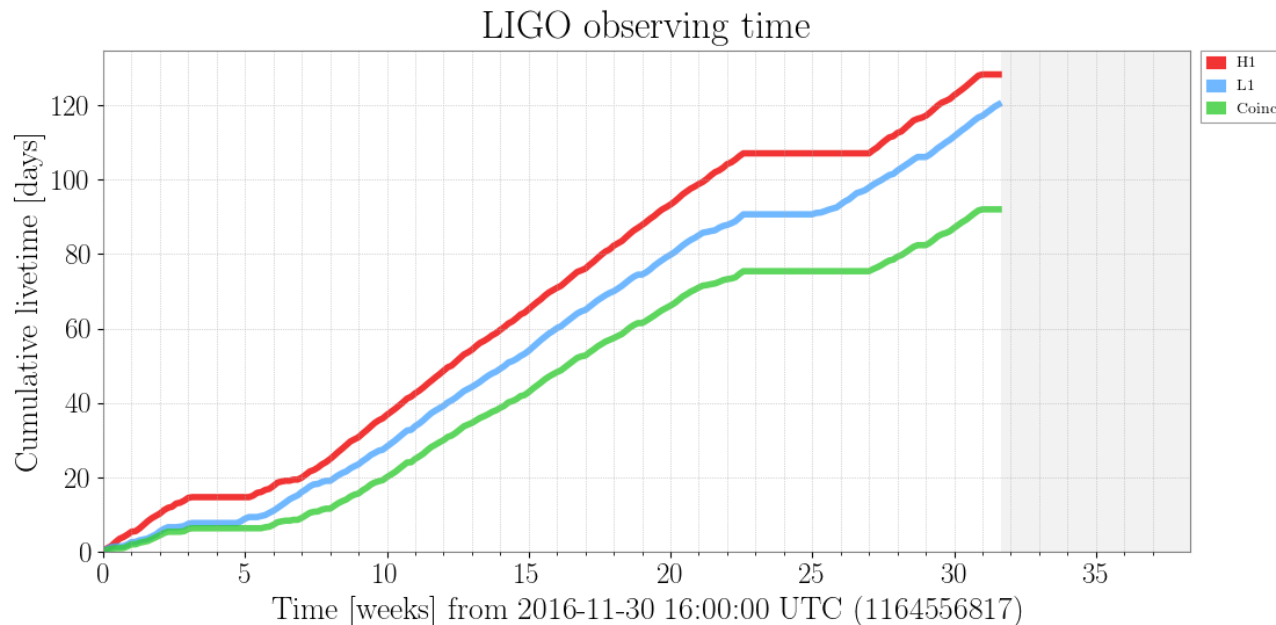
- ❑ Detector integration troubled by repeated breakage of fused silica fibers when test masses suspended in vacuum
- ❑ Lead to decision of suspending them with steel wires in order not to stop commissioning progress
 - Achievable BNS inspiral range limited to ~ 50 Mpc
- ❑ Extensive/intense research in parallel to understand the cause
- ❑ Eventually culprit 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

- ❑ Talks by F Travasso and L Naticchioni (MON, Suspension session)



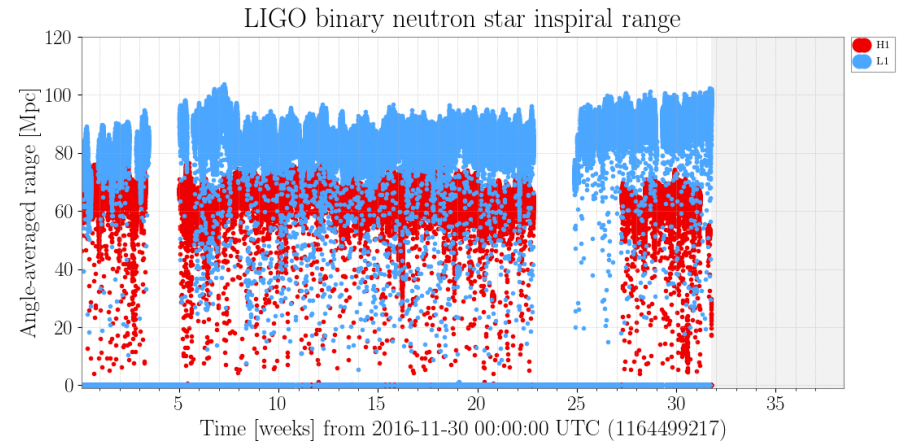
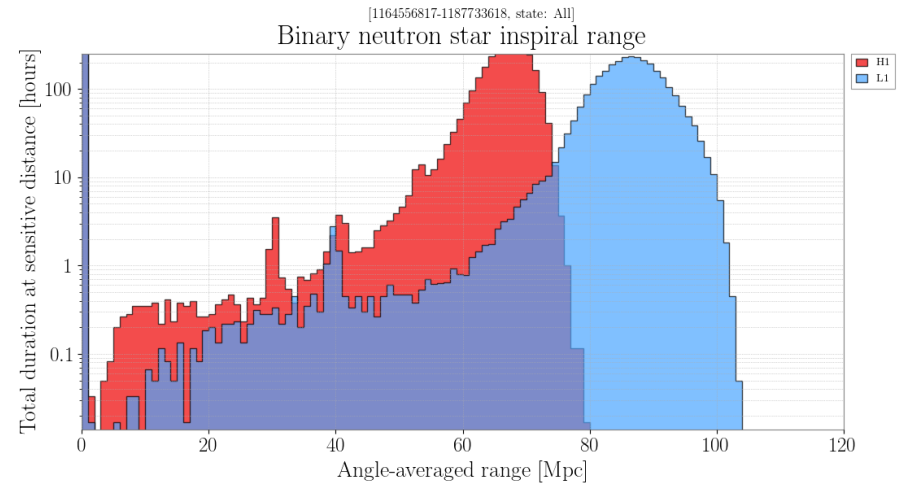
THE O2 RUN - FACTS

- ❑ Started on November 30, 2016
- ❑ ~90 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)

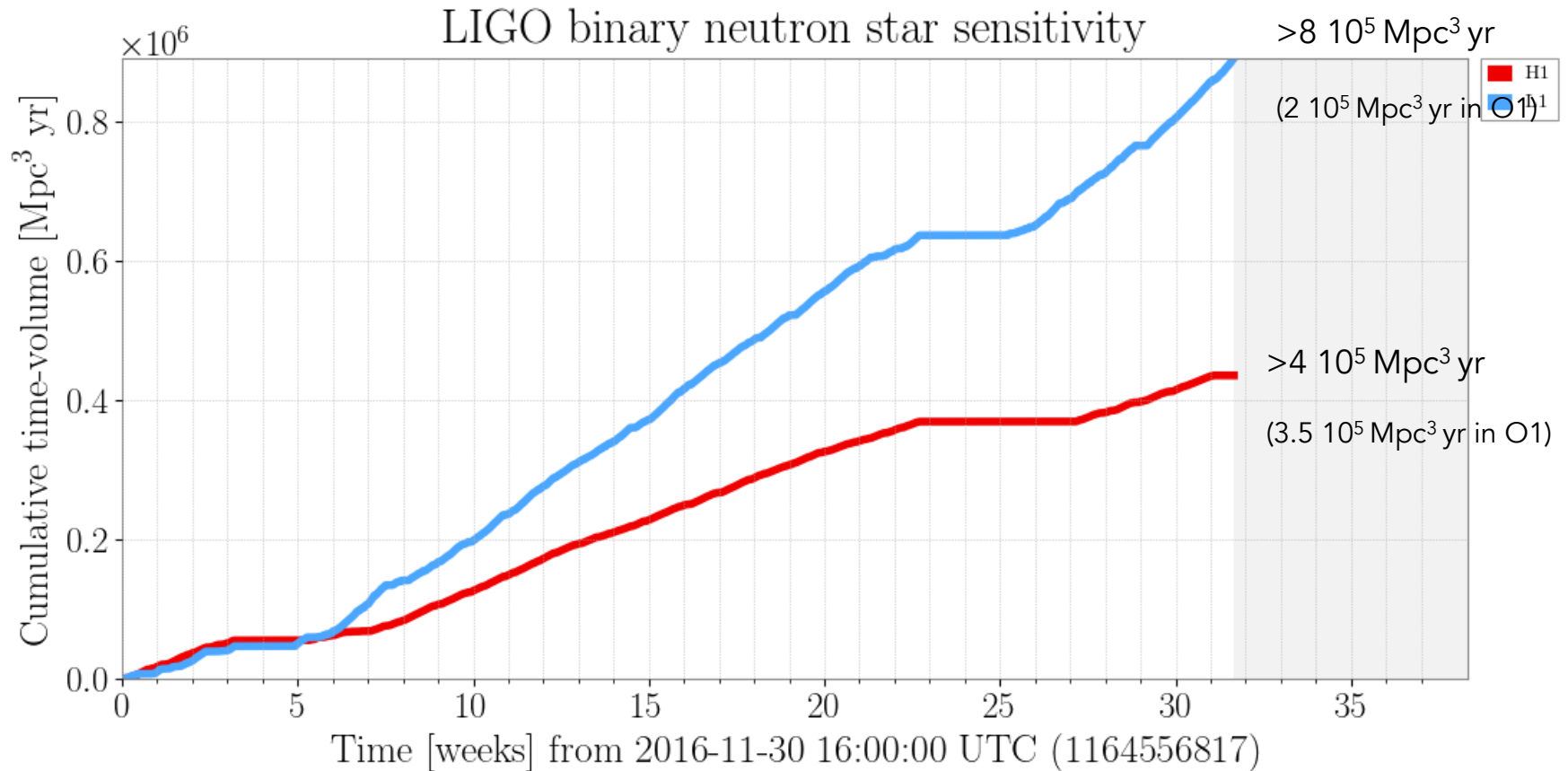


- Average reach of the LIGO network for binary merger events:
 - 70 Mpc for 1.4+1.4 Msun
 - 300 Mpc for 10+10 Msun
 - 700 Mpc for 30+30 Msun

- Relative variations in time of the order of 10%



O2: CUMULATIVE TIME×VOLUME



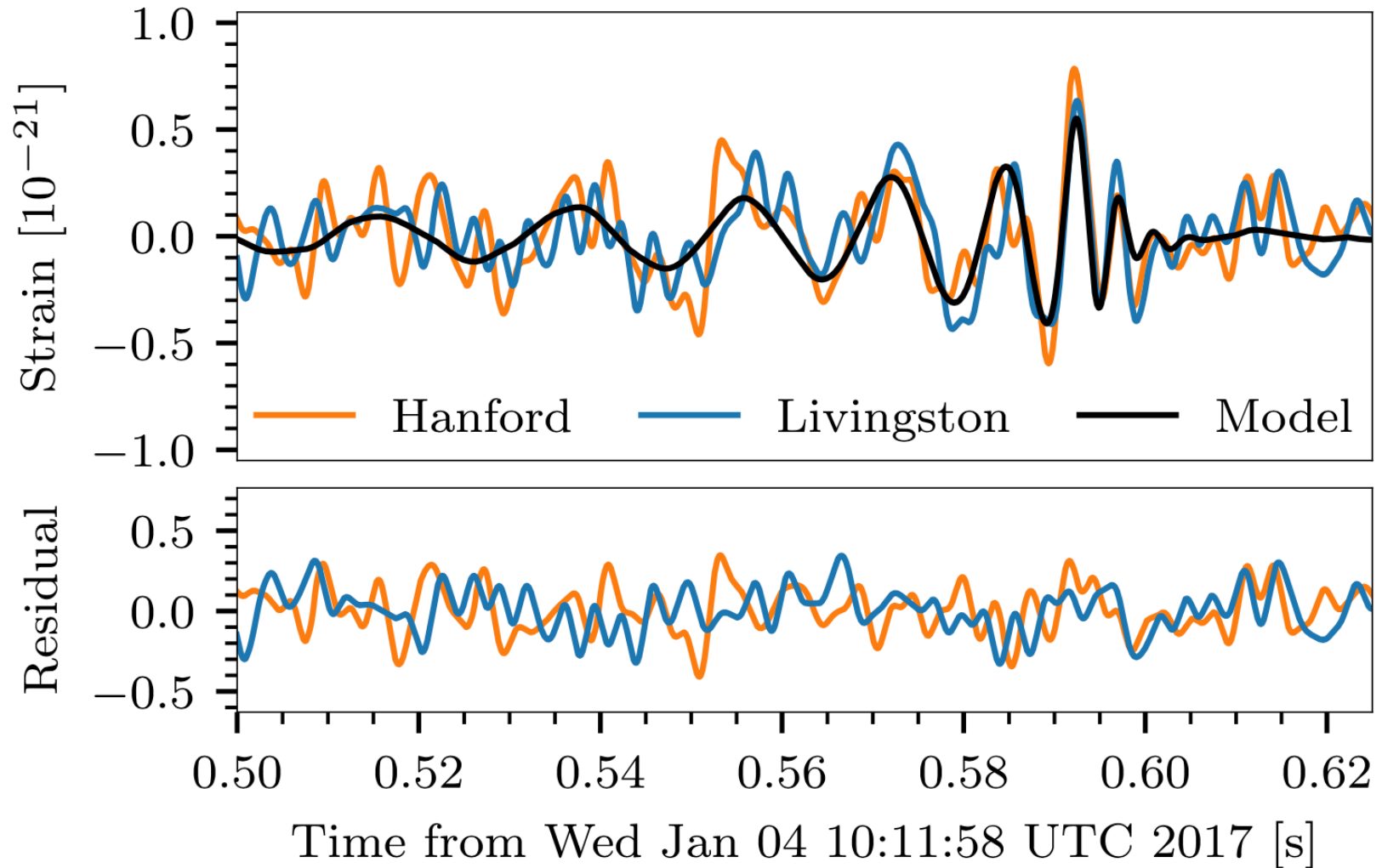
EACH DETECTOR HAS NOW ACQUIRED A CUMULATIVE T×V LARGER THAN O1

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 (2017), 221101





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 $31.2_{-6.0}^{+8.4}M_{\odot}$ and $19.4_{-5.9}^{+5.3}M_{\odot}$ (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, $\chi_{\text{eff}} = -0.12_{-0.30}^{+0.21}$. 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_{-390}^{+450} Mpc corresponding to a redshift of $z = 0.18_{-0.07}^{+0.08}$. 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 $m_g \leq 7.7 \times 10^{-23}$ eV/ c^2 . In all cases, we find that GW170104 is consistent with general relativity.

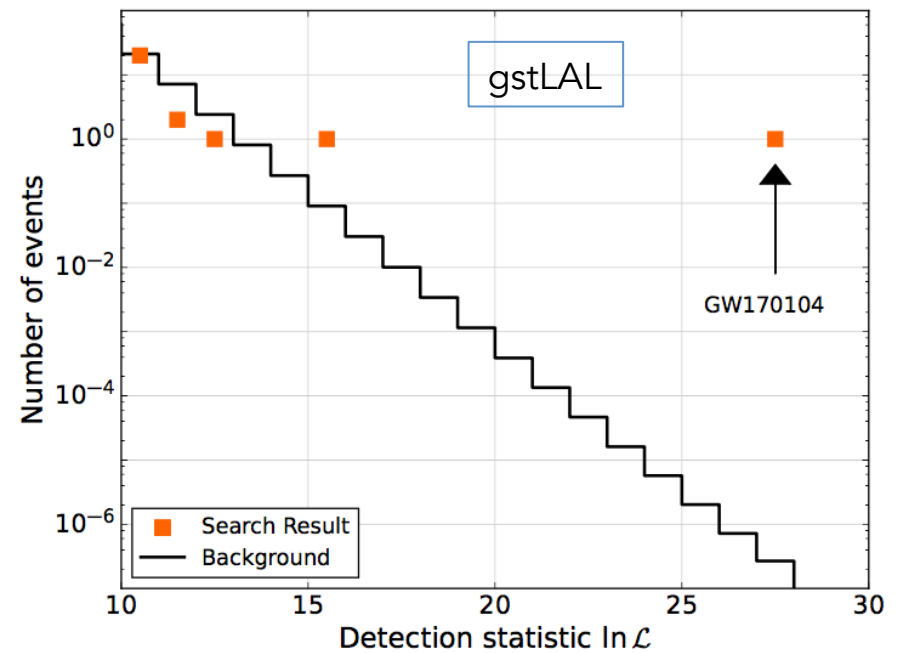
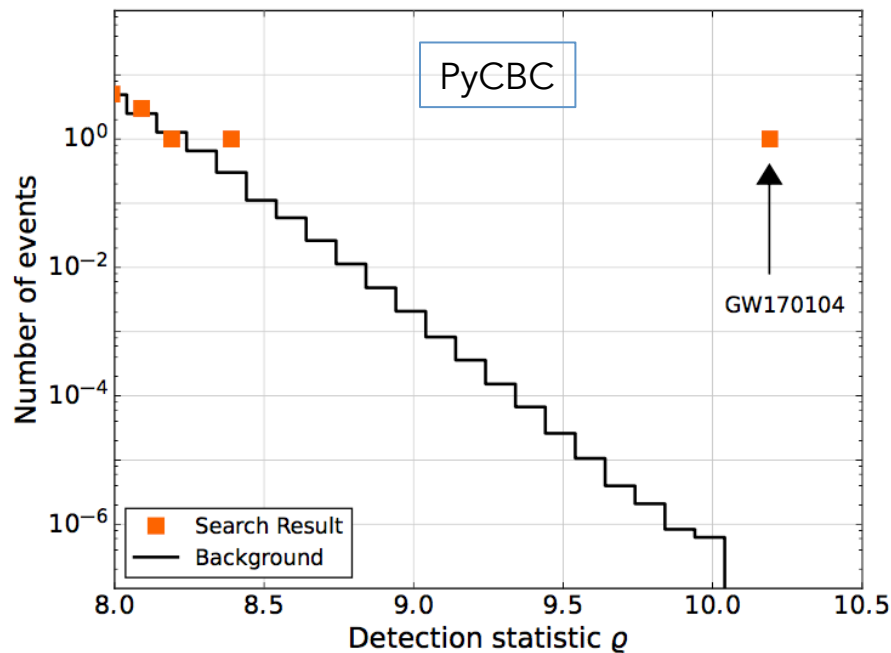
DOI: [10.1103/PhysRevLett.118.221101](https://doi.org/10.1103/PhysRevLett.118.221101)

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

GW170104: SIGNIFICANCE

- ❑ SNR ~ 13
- ❑ FAR $\sim 1/70000$ yrs
- ❑ Two independent analyses

BP Abbott et al (LVC), PRL 118 (2017), 221101

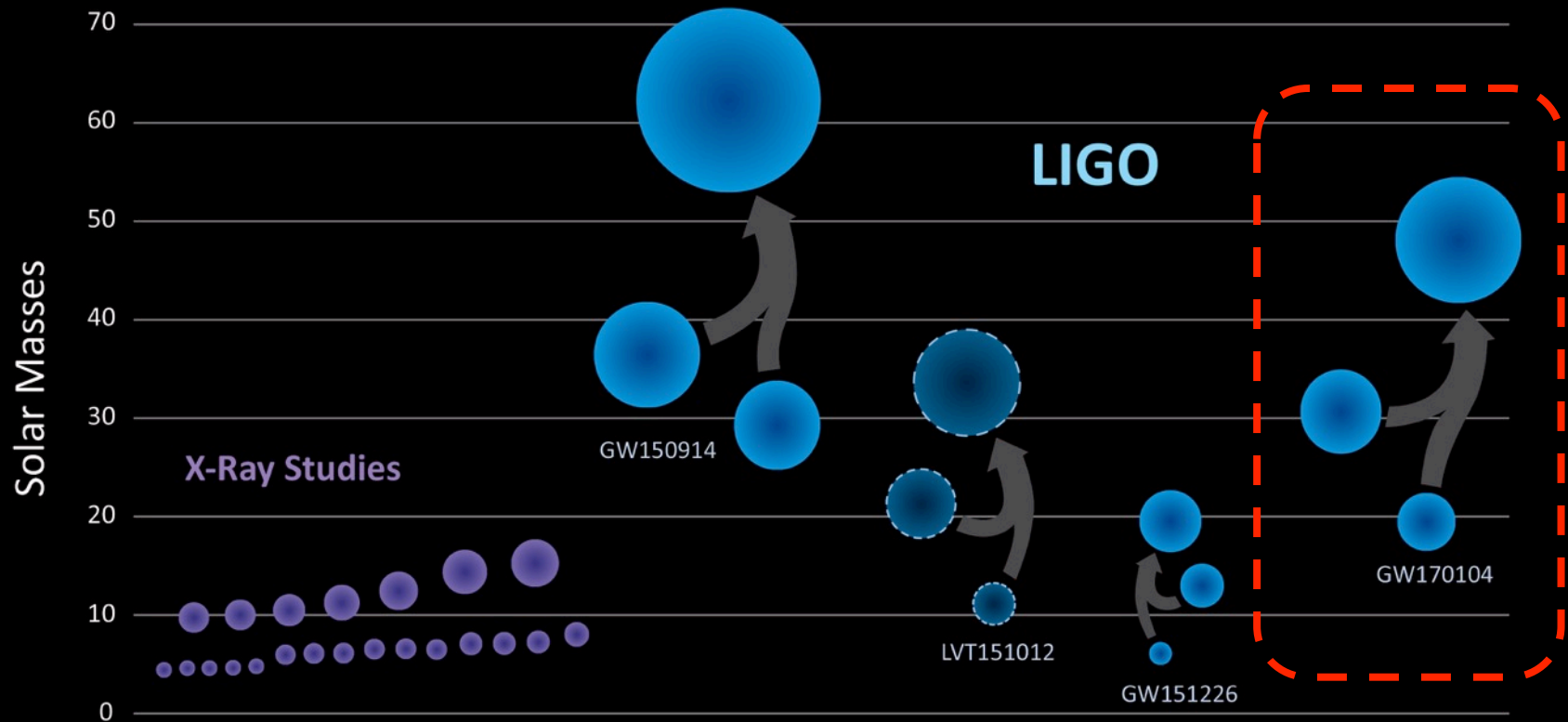


GW170104: PARAMETERS

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}	$3.1^{+0.7}_{-1.3} \times 10^{56} \text{erg s}^{-1}$
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	$880^{+450}_{-390} \text{Mpc}$
Source redshift z	$0.18^{+0.08}_{-0.07}$

Black Holes of Known Mass

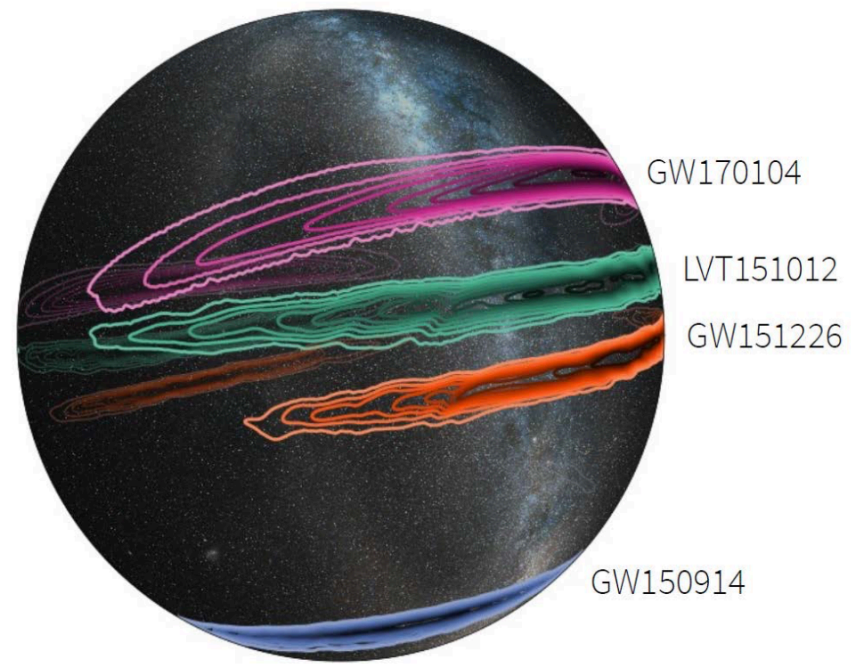
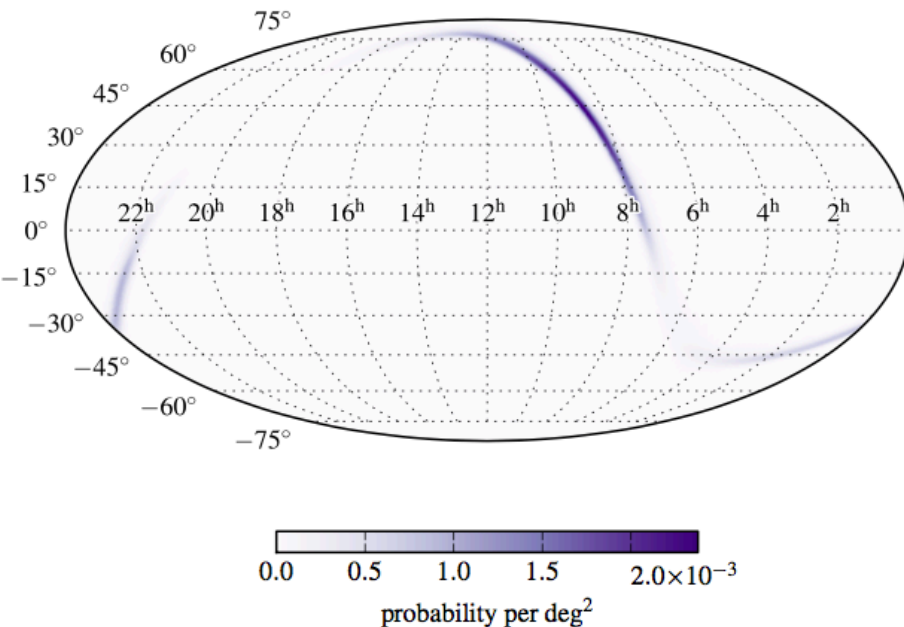
Image credit: LIGO/Caltech/Sonoma State (Aurore Simonnet)



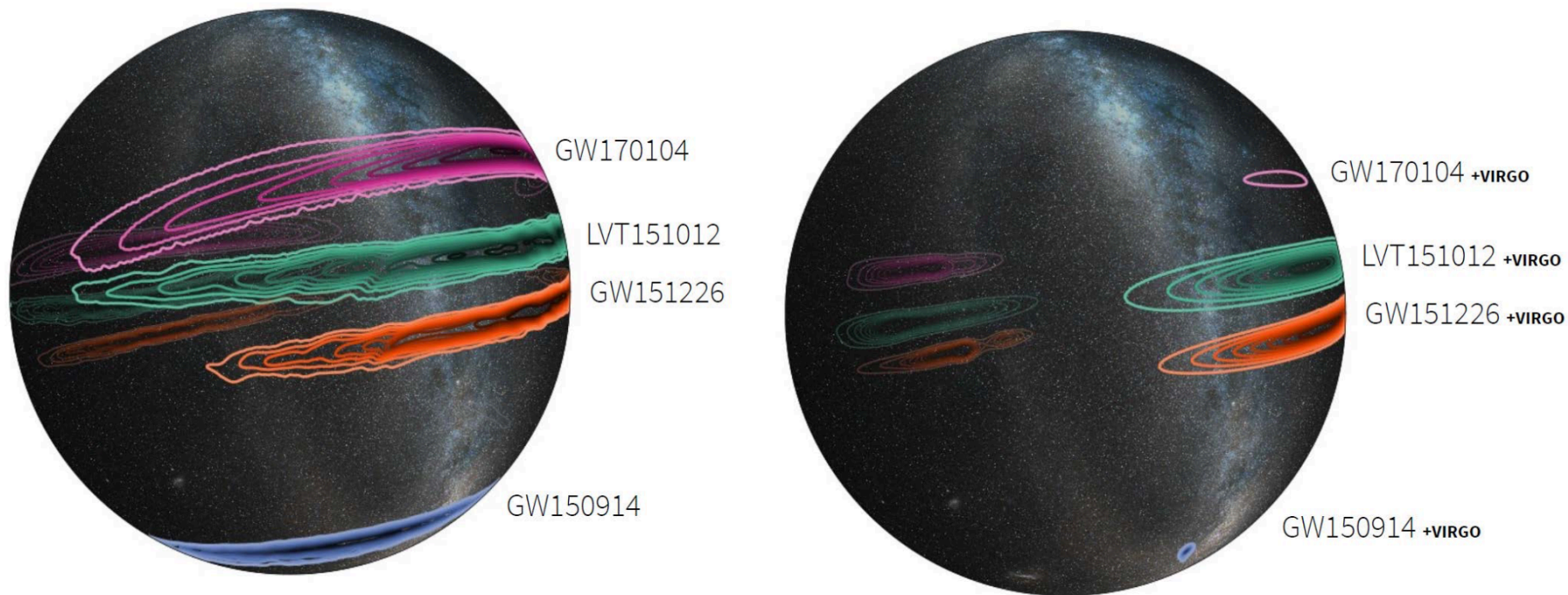
MORE ON GW170104 AND ITS IMPLICATIONS FOR ASTROPHYSICS AND GR TESTS IN THE TALKS BY C VAN DEN BROECK (THU) AND M MAPELLI (FRI)

GW170104: EM FOLLOW UP

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



UGO/Cattech/MIT/Leo Singer (Milky Way image: Axel Mellinger)



3-D projection of the Milky Way onto a transparent globe shows the probable locations of confirmed detections GW150914 (blue), GW15226 (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 HAS 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

<u>LHO</u>	OK+Intent	3:56
<u>LLO</u>	OK+Intent	14:48
<u>Virgo</u>	Science	1:33

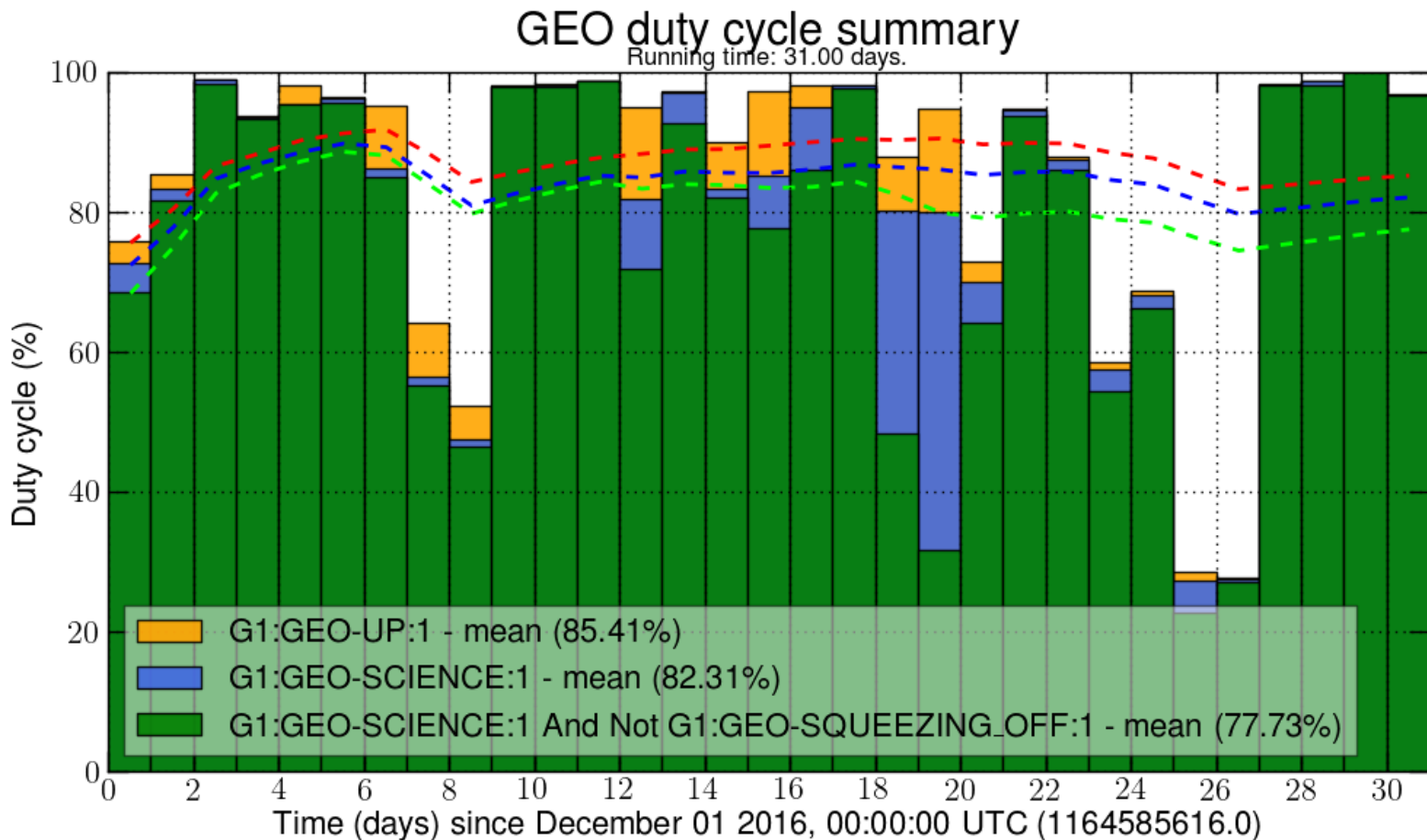
Retweet 25 Mi piace 34

07:36 - 16 giu 2017

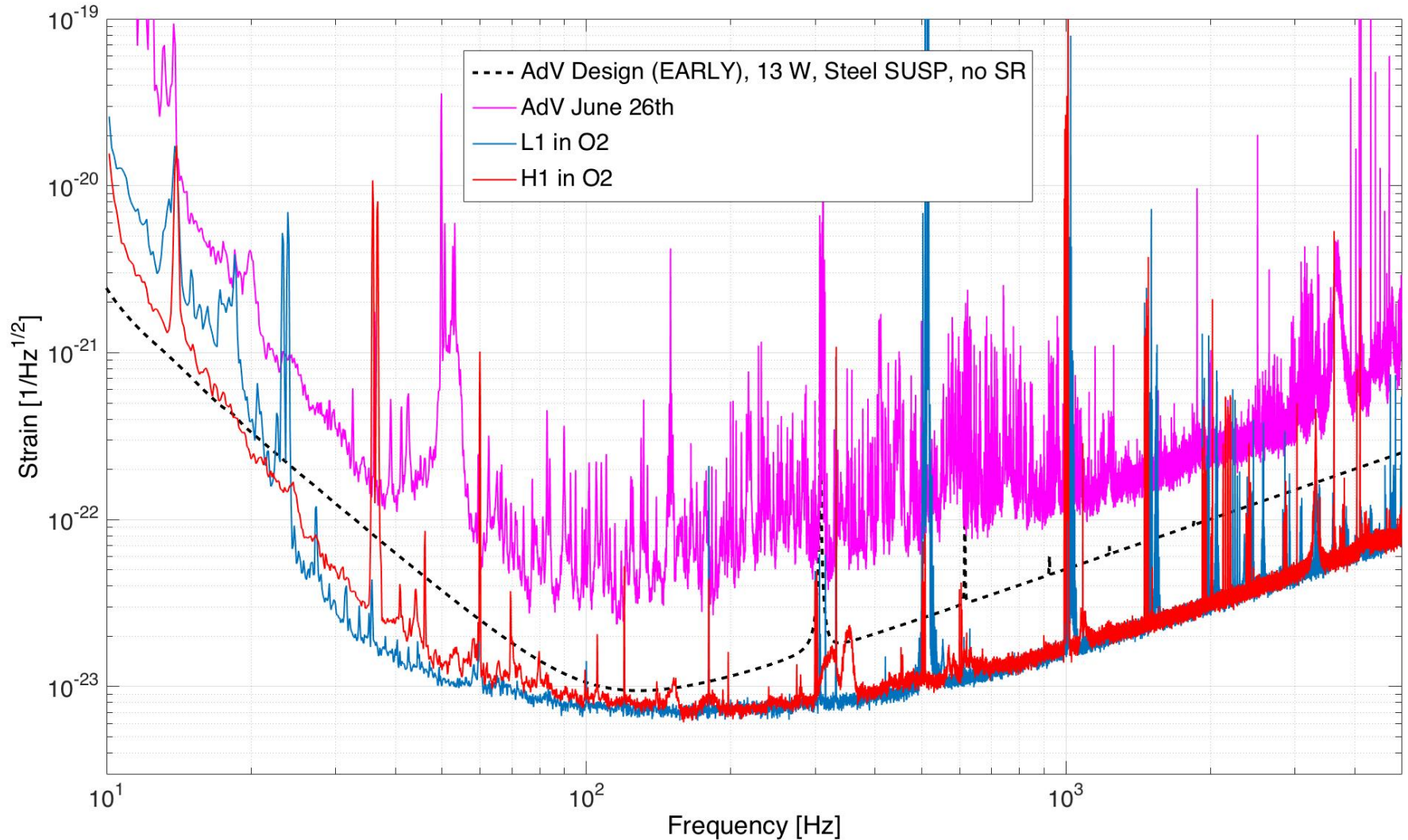
1 25 34

GEO DURING O2

ASTROWATCH AT HIGH DUTY CYCLE (~80%)

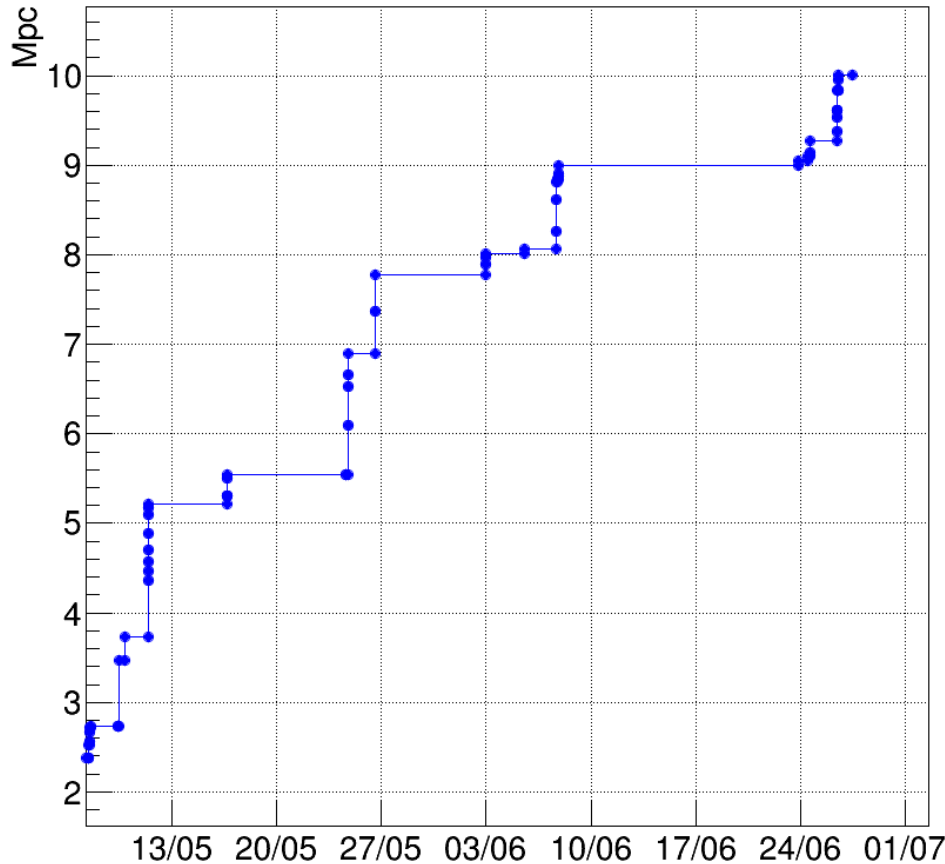


ADVANCED VIRGO STATUS

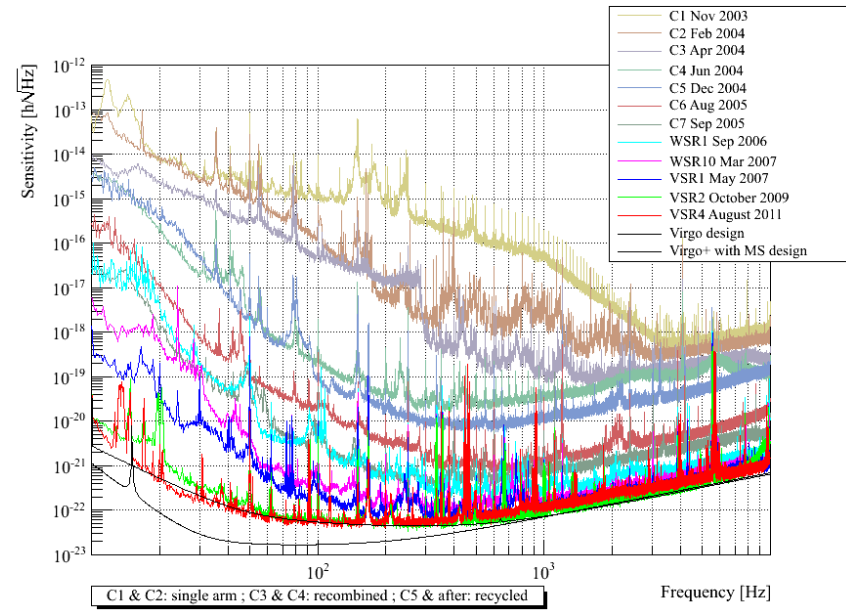


ADVANCED VIRGO STATUS

AdV best BNS range (from May 7 to June 27)

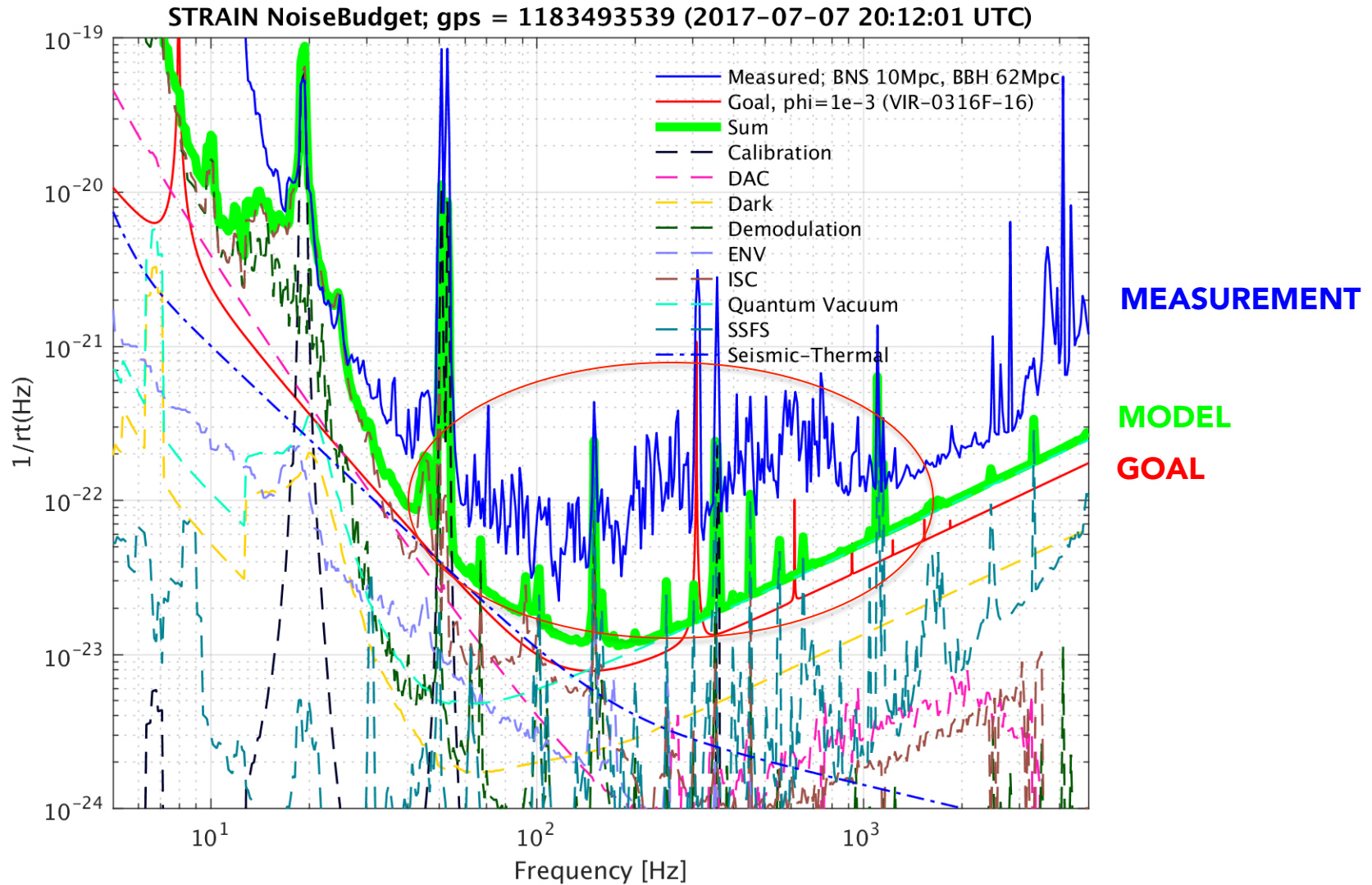


IN ~3 MONTHS ACHIEVED WHAT VIRGO DID IN ~5 YEARS
(from 1st lock of the power recycled Virgo to ~10 Mpc)



INITIAL VIRGO EVOLUTION (2003-2011)

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 noise hunting and detchar activity in progress
 - quantify origin and impact of scattered light, define mitigation strategies
 - tracking the origin of many peaks in the spectrum

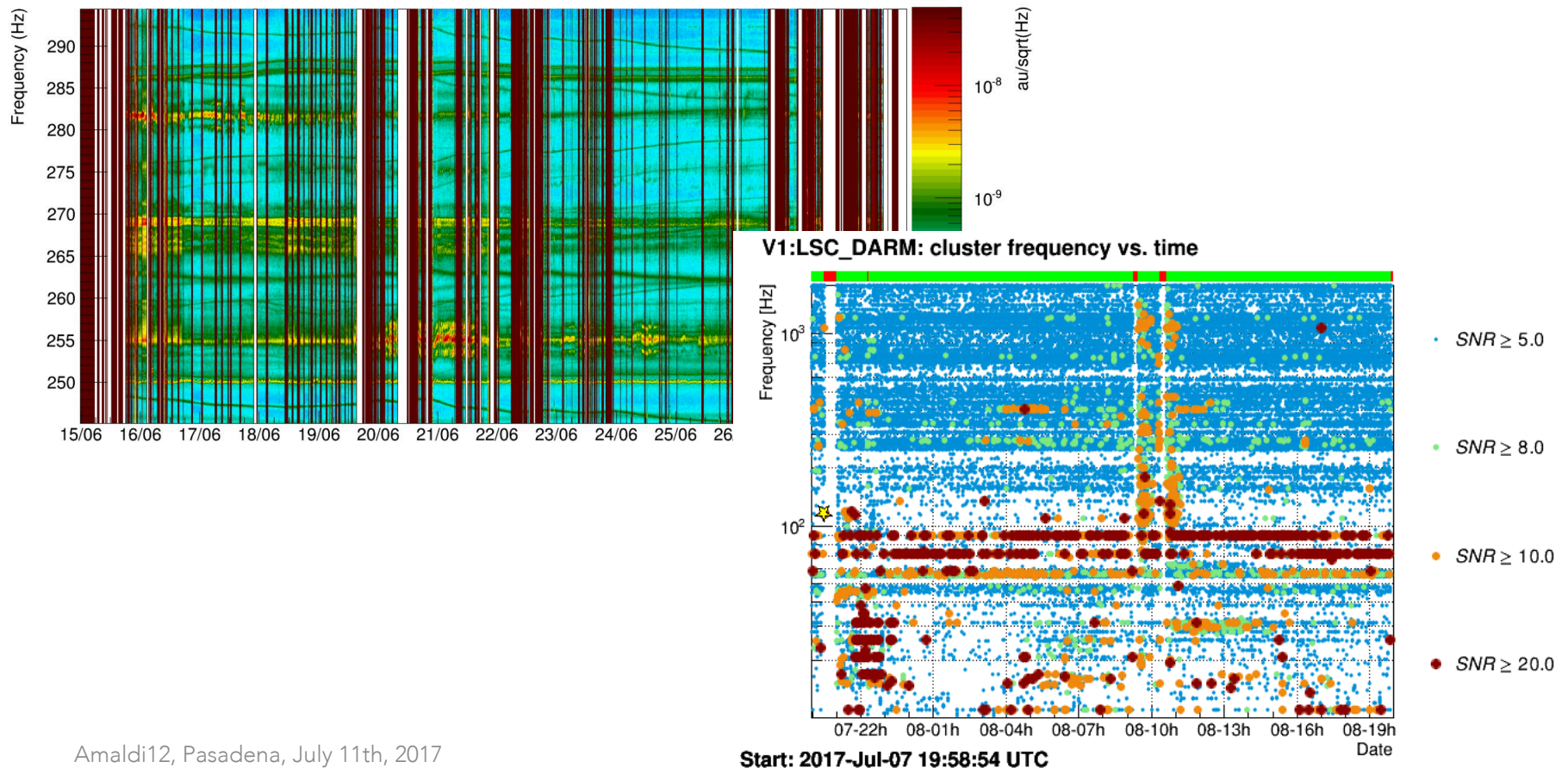


Output mode matching telescope illuminated by stray light

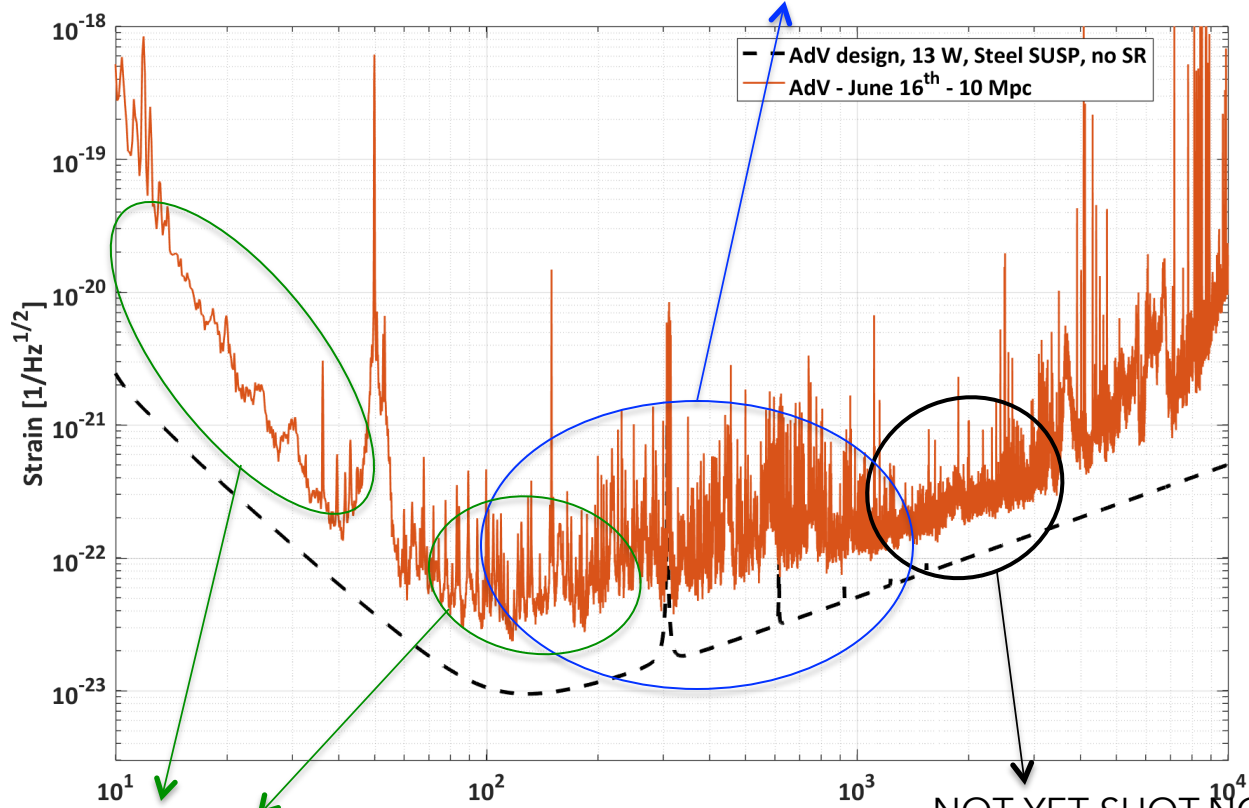
DETECTOR CHARACTERIZATION

- Crucial in helping to investigate and mitigate spectral and transient noise in the detector

Spectrogram of V1:spectro_LSC_DARM_300_100_0_0 : start=1181519757.000000 (Wed Jun 14 23:55:39 2017 UTC)



“FOREST” OF LINES, MANY MOVING IN FREQUENCY WITH TEMPERATURE + UNDERLYING BACKGROUND



IDENTIFIED SOURCE OF SCATTERED LIGHT
REQUIRES A NEW IN-VACUUM BAFFLE
(~1 WEEK OF DOWNTIME)

NOT YET SHOT-NOISE LIMITED

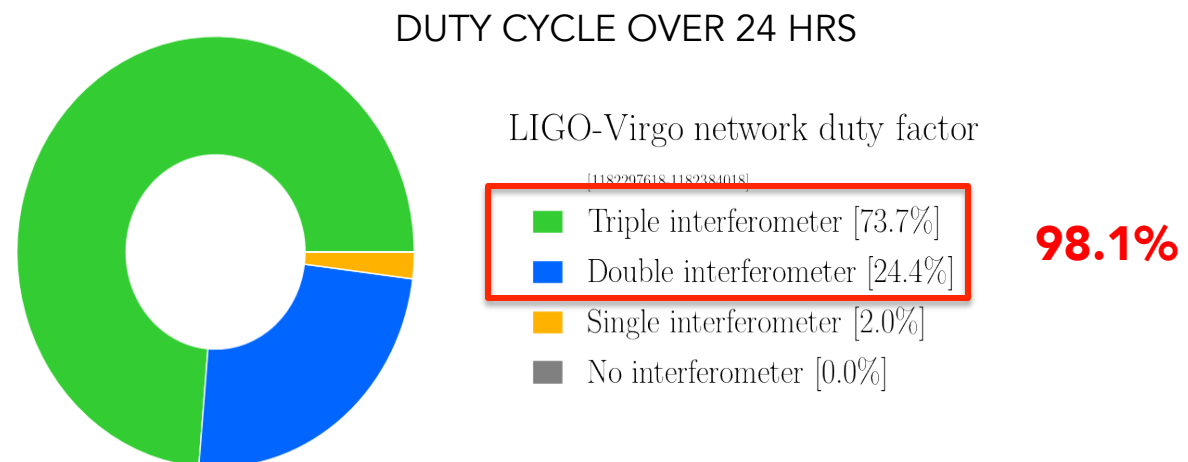
- electronic noise?
- frequency noise due to finesse asymmetry?

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
 - two vacuum chambers will be opened soon to mitigate scattered light
- ❑ Virgo is in close and continuous discussion with LIGO through our Joint Run Planning Committee

TOWARDS A 3-DETECTOR NETWORK

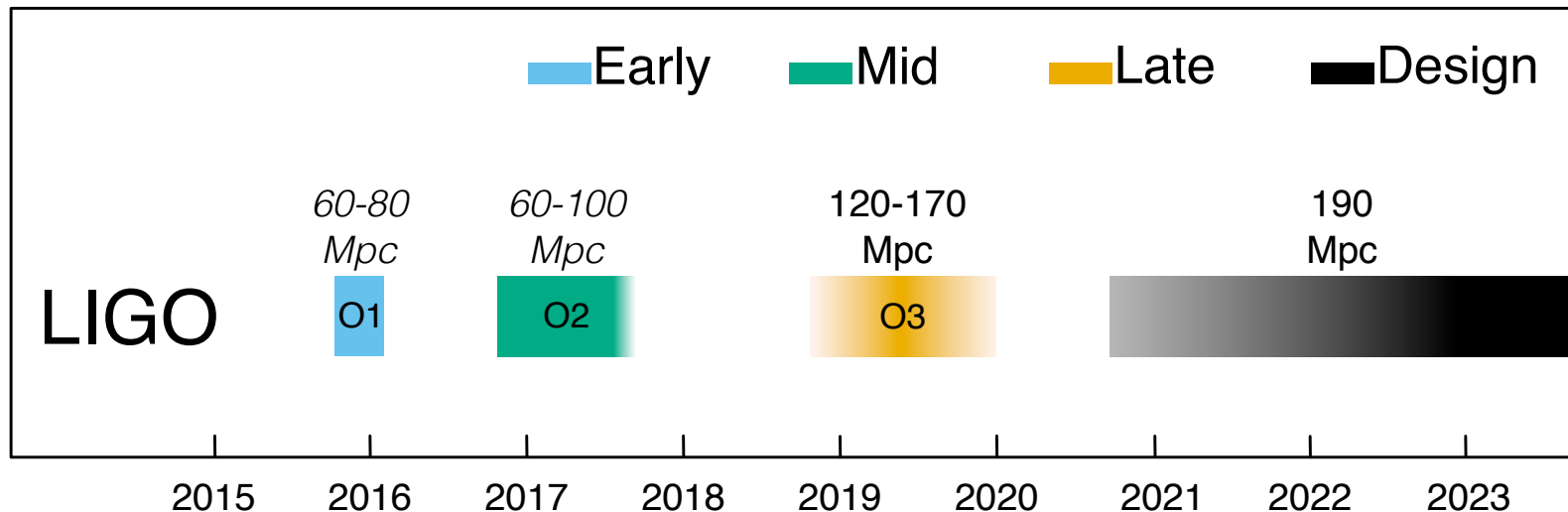
- ❑ LIGO and Virgo are preparing for EM alerts using 3 interferometers
- ❑ ER11 was the first chance to make tests
 - Virgo joined ER11 for two weekends
- ❑ Virgo has put in place a Rapid Response Team to cover the different aspects of an alert: operator on shift + experts on detector, calibration, detector characterization
- ❑ 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



AFTER O2 - LIGO

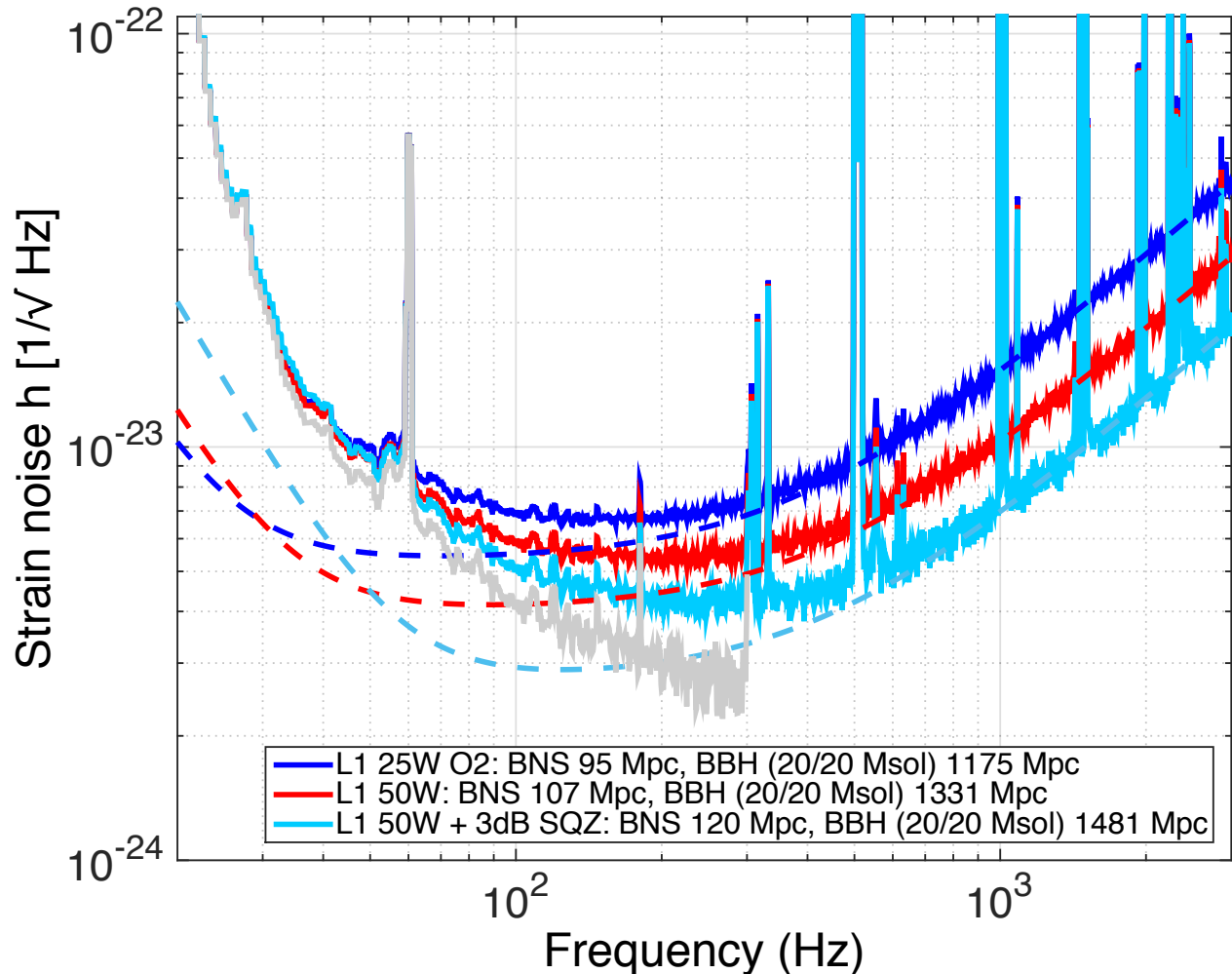
- Stop data taking on Aug 25th, for ~1 year
- Goal: substantial improvement of the sensitivity
- Planned activities:
 - further scattered light mitigation at both sites
 - input power increase at both sites
 - injection of squeezed light

from LIGO G-1700895



AFTER O2 - LIGO

Projections for L1 strain noise



x2 Higher power

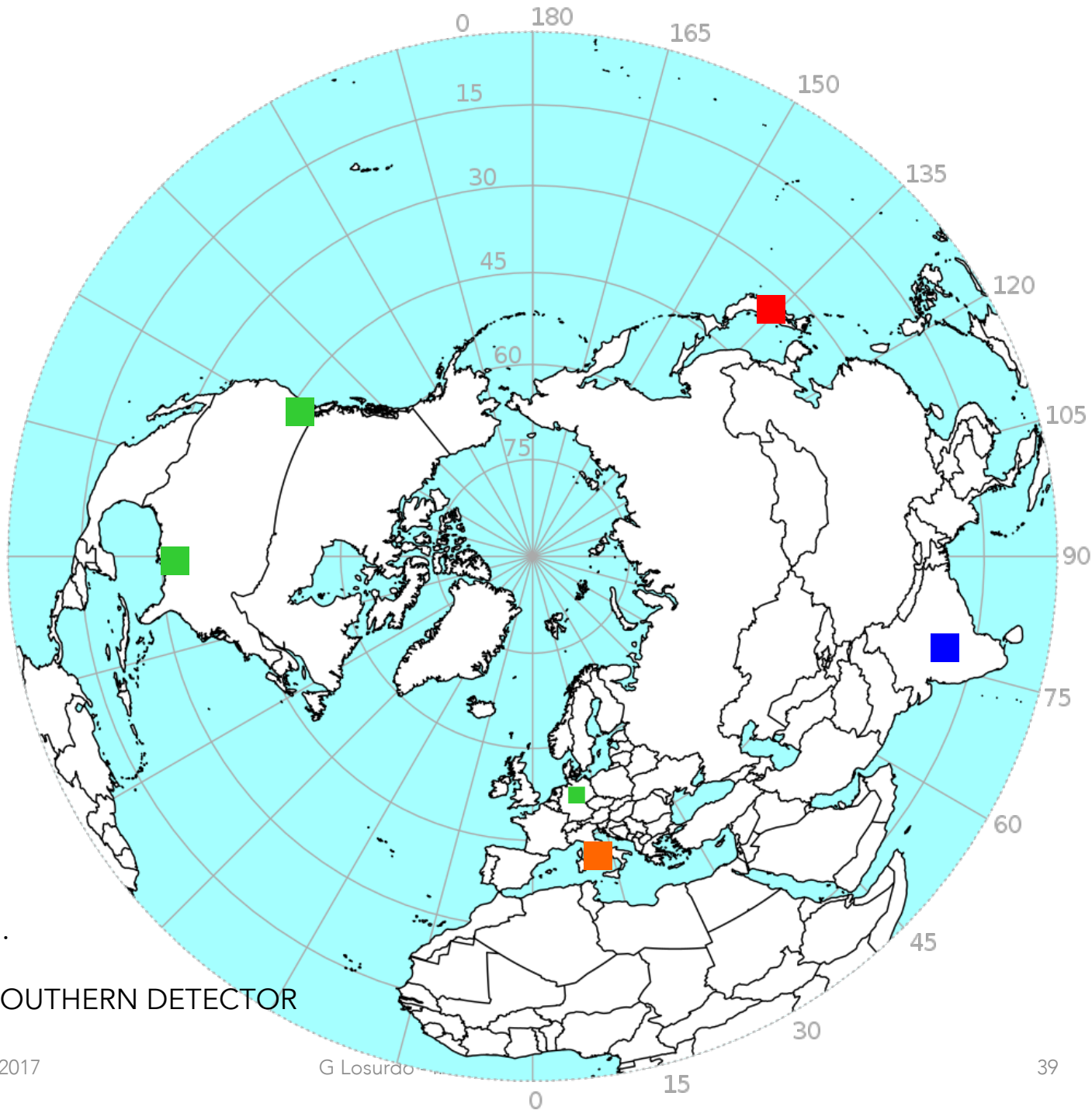
x2 Higher power
+ squeezing

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)
 - decision on the installation of the new 100W laser
 - ❑ Implement squeezer provided by AEI Hannover
 - ❑ Do commissioning to improve sensitivity!
- } ~5 months
- ❑ Installation of SR mirror not planned for this time frame

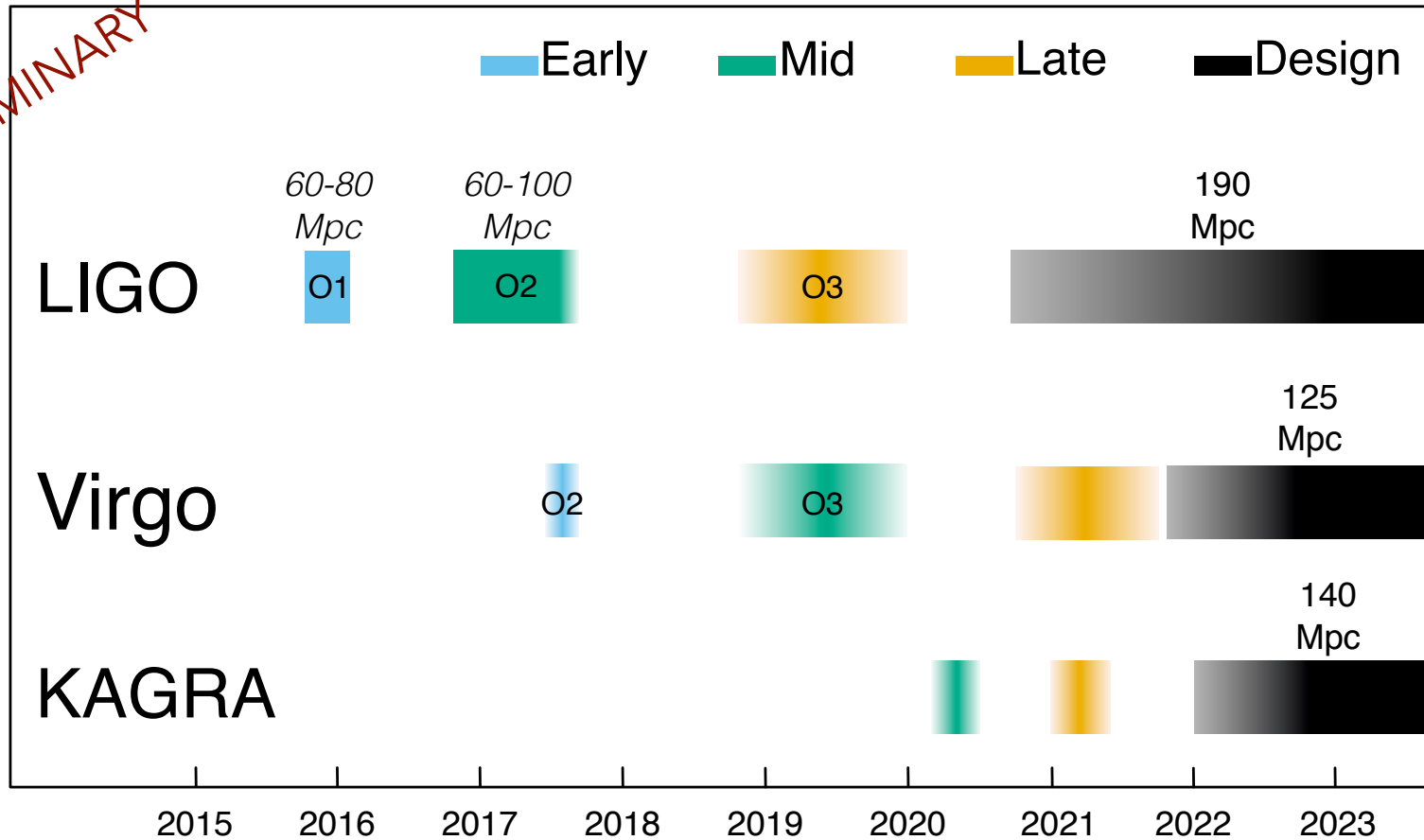
- OPERATION
- COMMISSIONING
- CONSTRUCTION
- APPROVED



ALL DETECTORS IN THE
NORTHERN EMISPHERE...

TIME TO PLAN/FUND A SOUTHERN DETECTOR

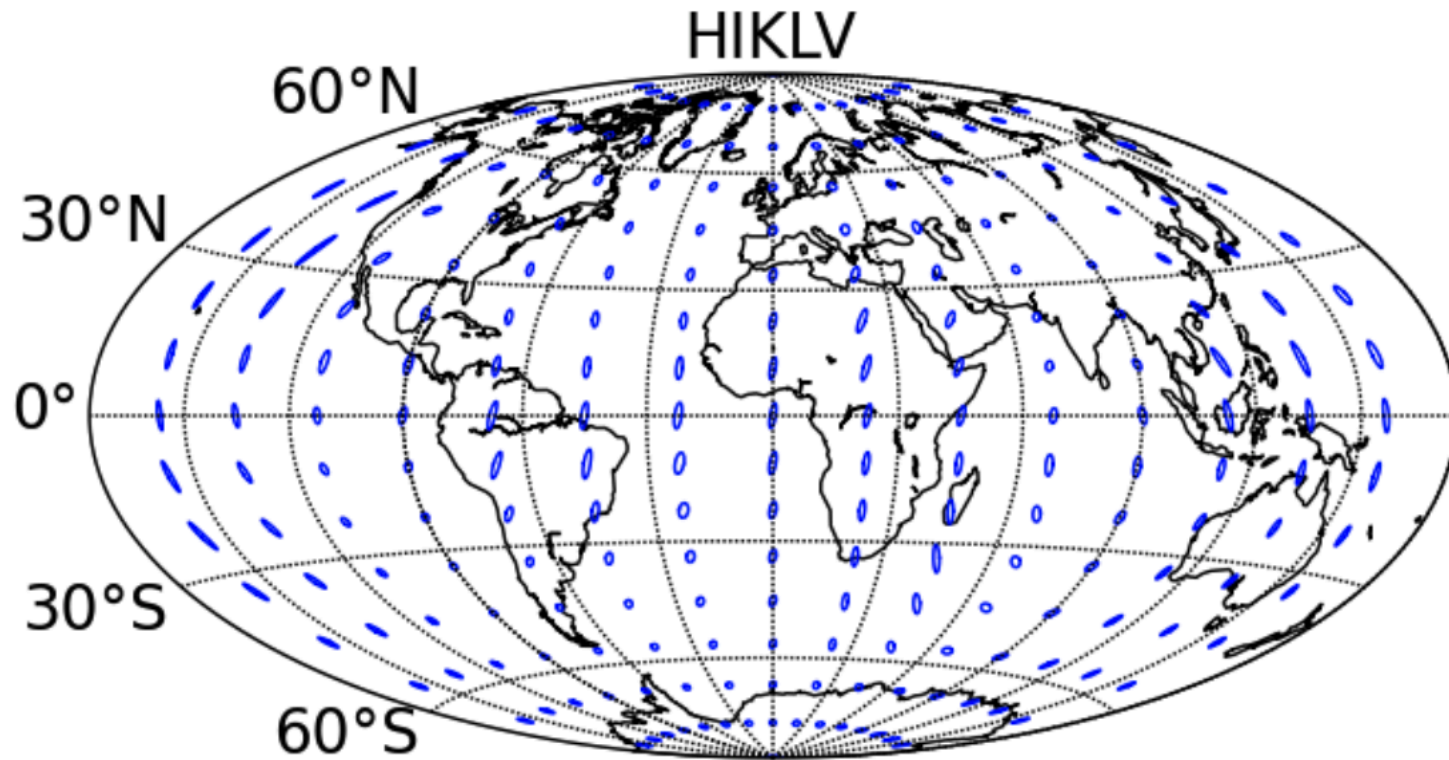
PRELIMINARY



...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

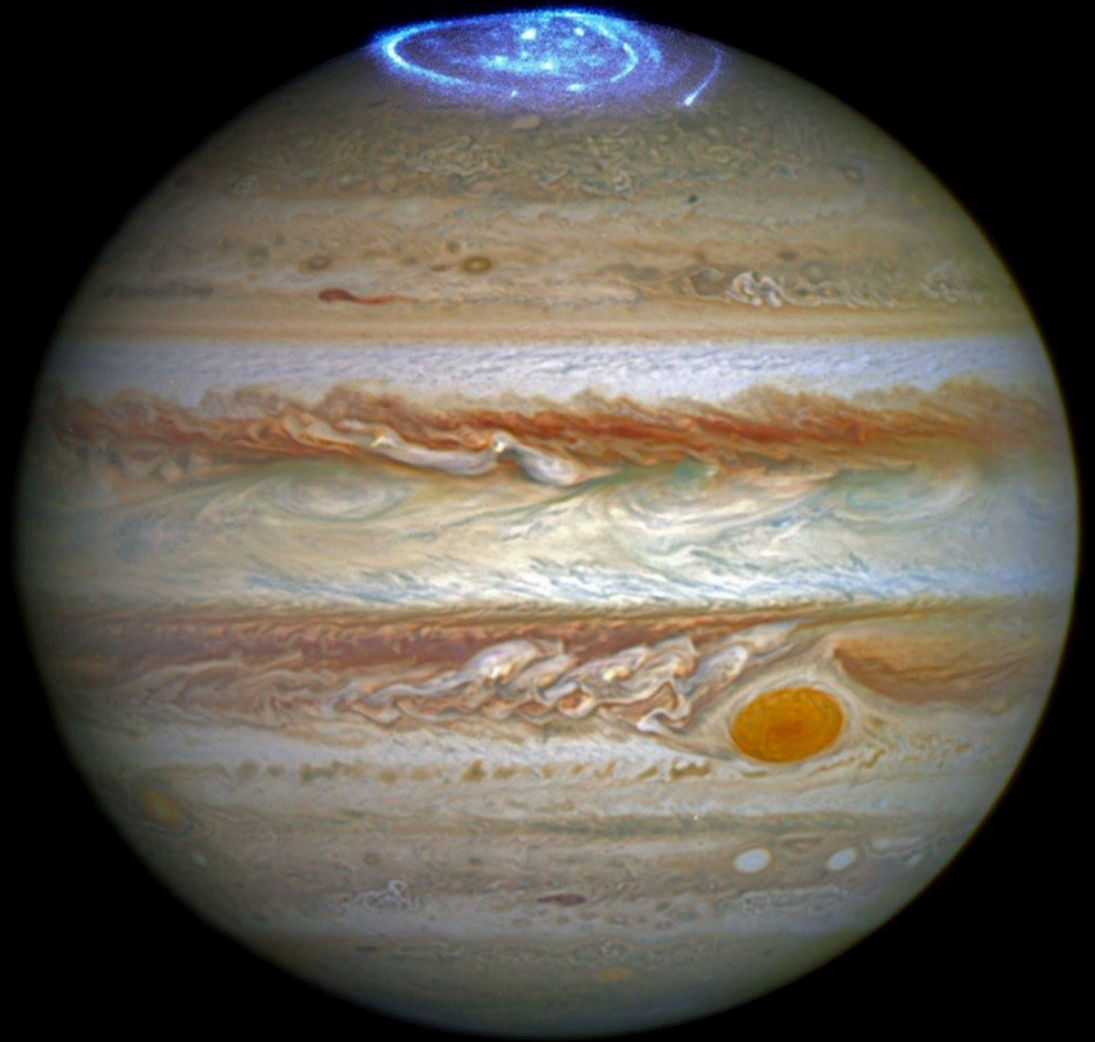
Localization capabilities of the 2G network
at mid 2020s:
>60% of the sources localized within 10 deg²



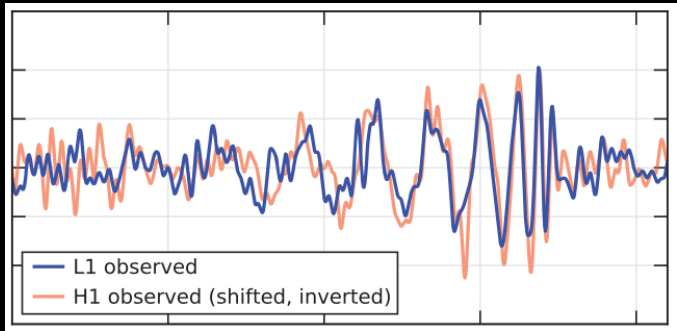
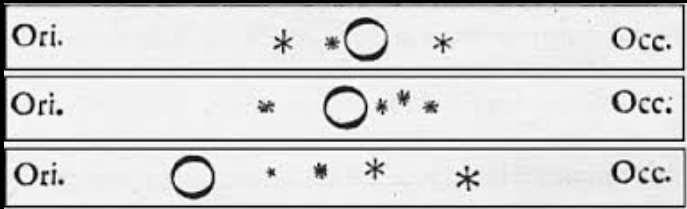
400 YEARS

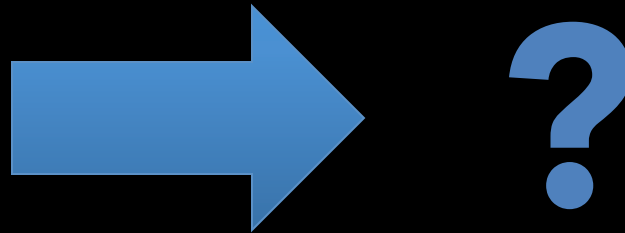
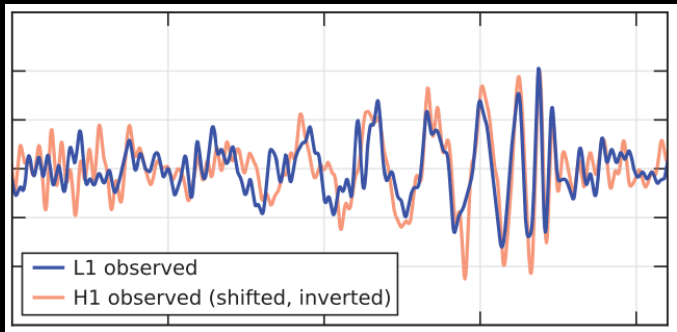
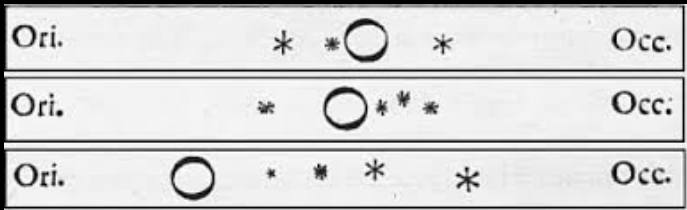
Ori.	*	*	○	*		Occ.
Ori.	*	○	*	*	*	Occ.
Ori.	○	*	*	*	*	Occ.

Ori.	*	*	○	*	Occ.
Ori.	*	○	*	*	Occ.
Ori.	○	*	*	*	Occ.



Credit: NASA/Hubble





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
- ❑ A world-wide network of 5 km-scale detectors expected to be in operation in the mid 2020s...

...a major step forward in the path towards a multi-messenger astronomy with GW