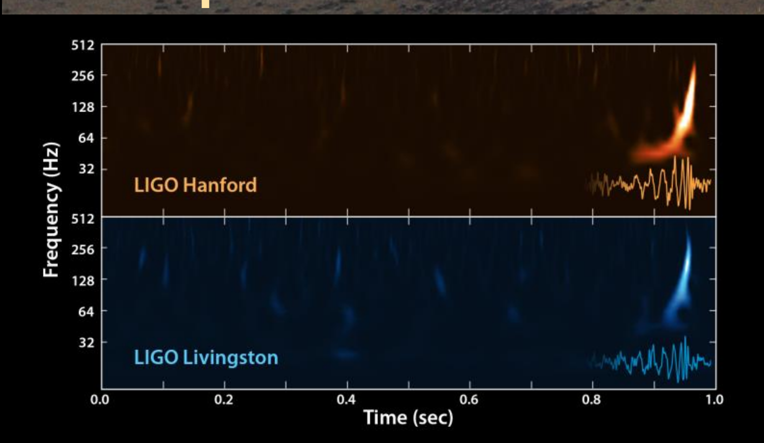
Gravitational-Wave Astronomy
The next steps

Sept 14 2015



LIGO-Gxxxxxxx

NCTS Annual Theory Meeting
Hsinchu, Taiwan
Dec 06 2016
Stefan Ballmer

The wave's field

Wave propagation

- "Ripples in Space-Time"

Amplitude:

dL/L = h

- Measureable effect:
  - Stretches/contracts distances perpendicular to propagation

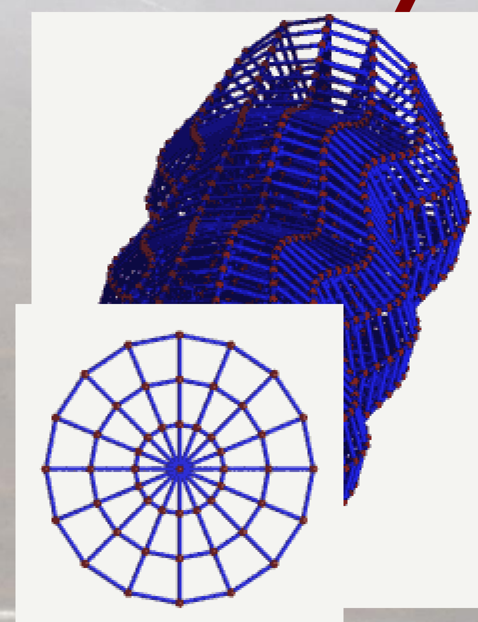
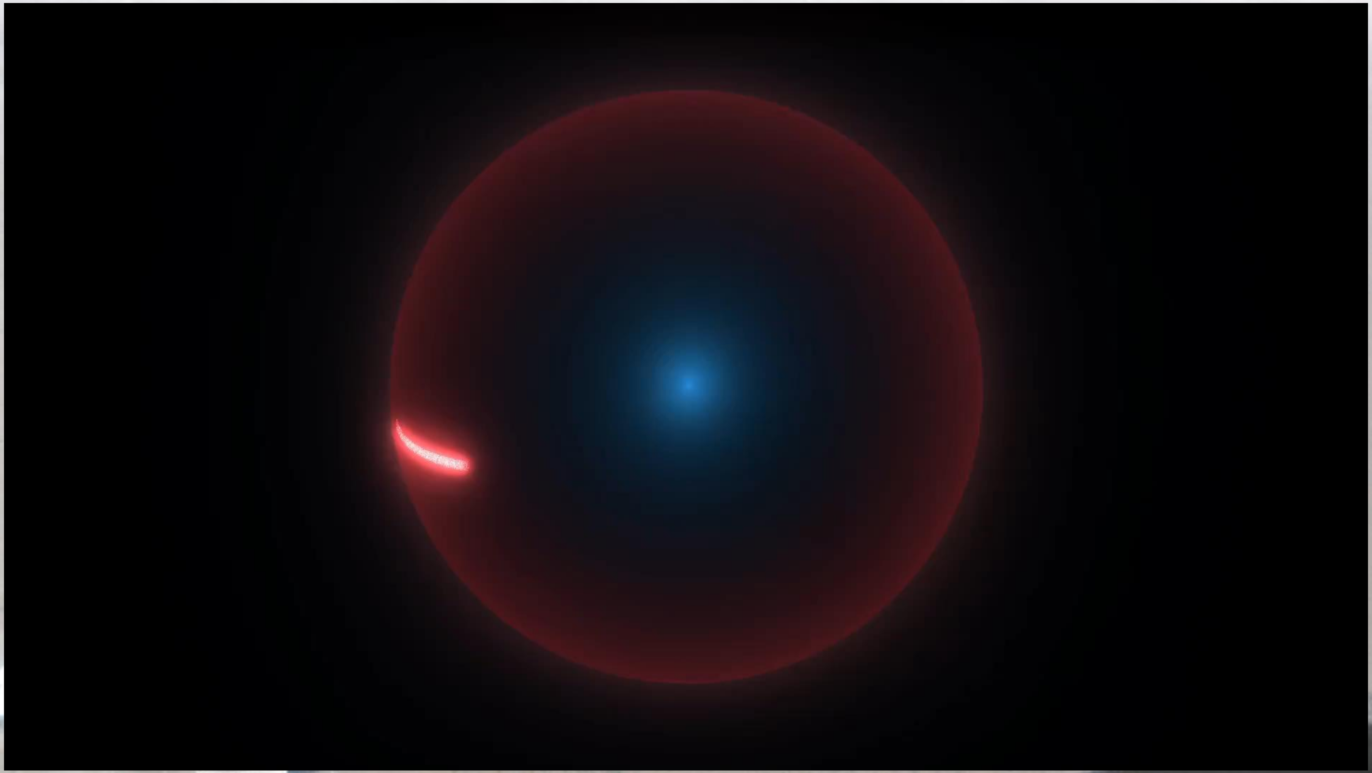


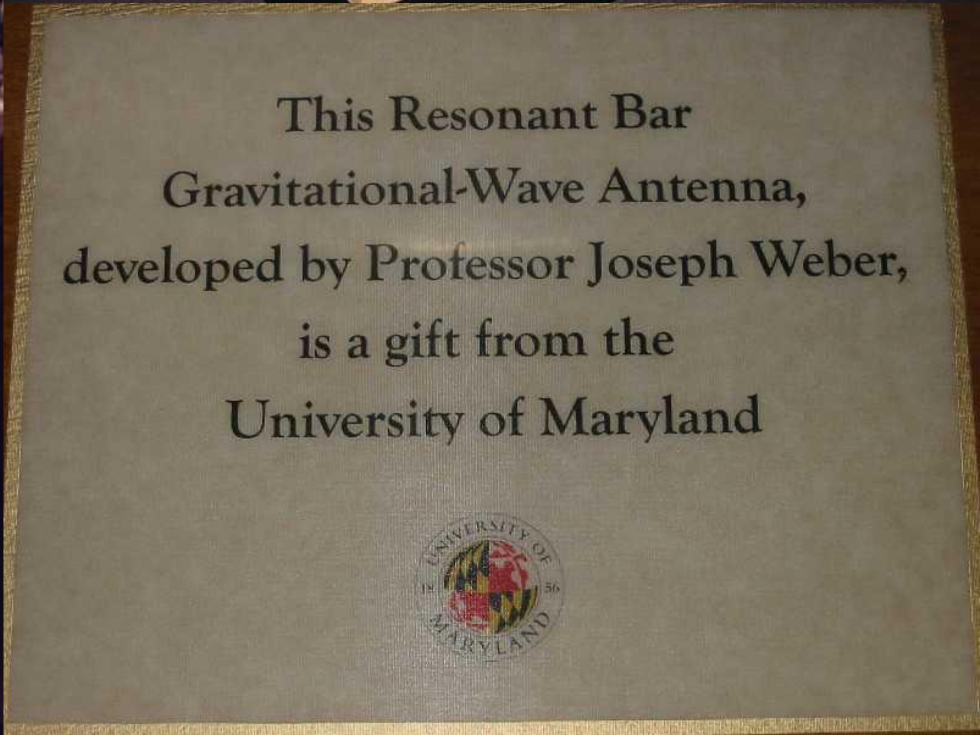
Image credit: Markus Pössel, *Einstein Online* **Vol. 02** (2006), 1008

The weakness of Gravity!

For the 4 km arms of LIGO, a typical strain:

- A fraction of a proton!



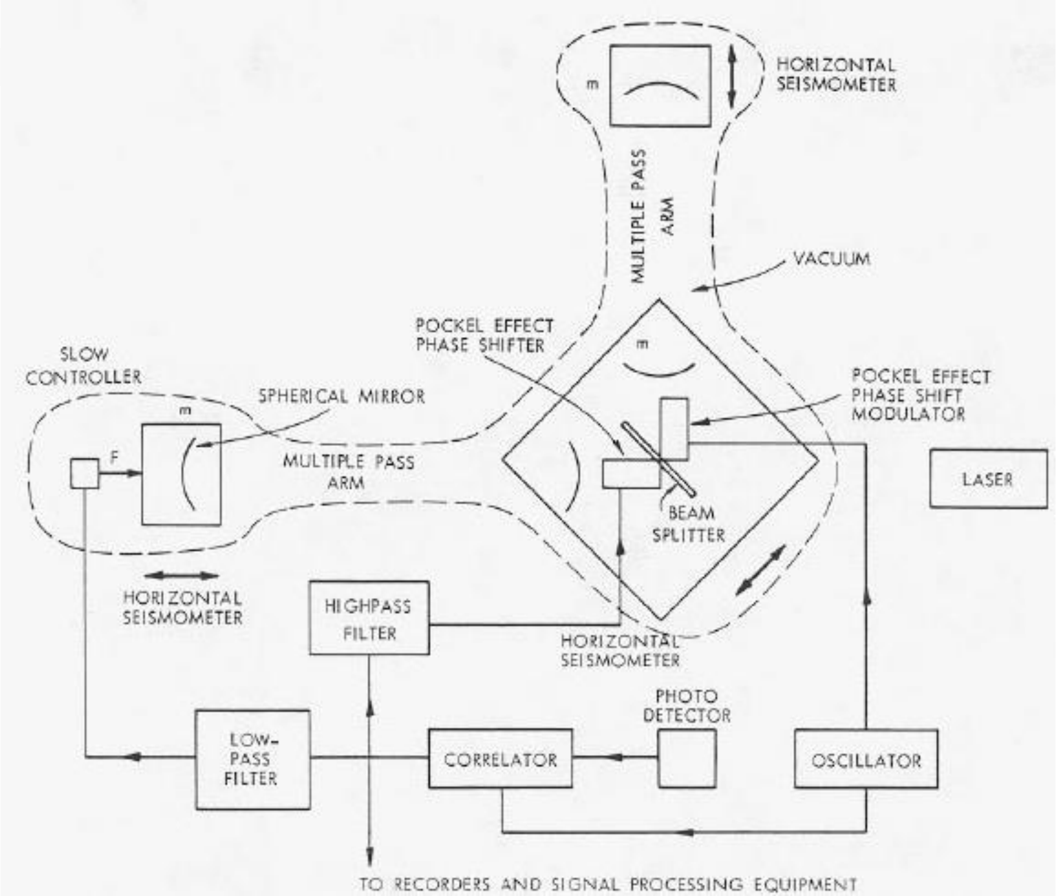


1960s and ‘70s:
First gravitational wave detectors
By Joseph Webber

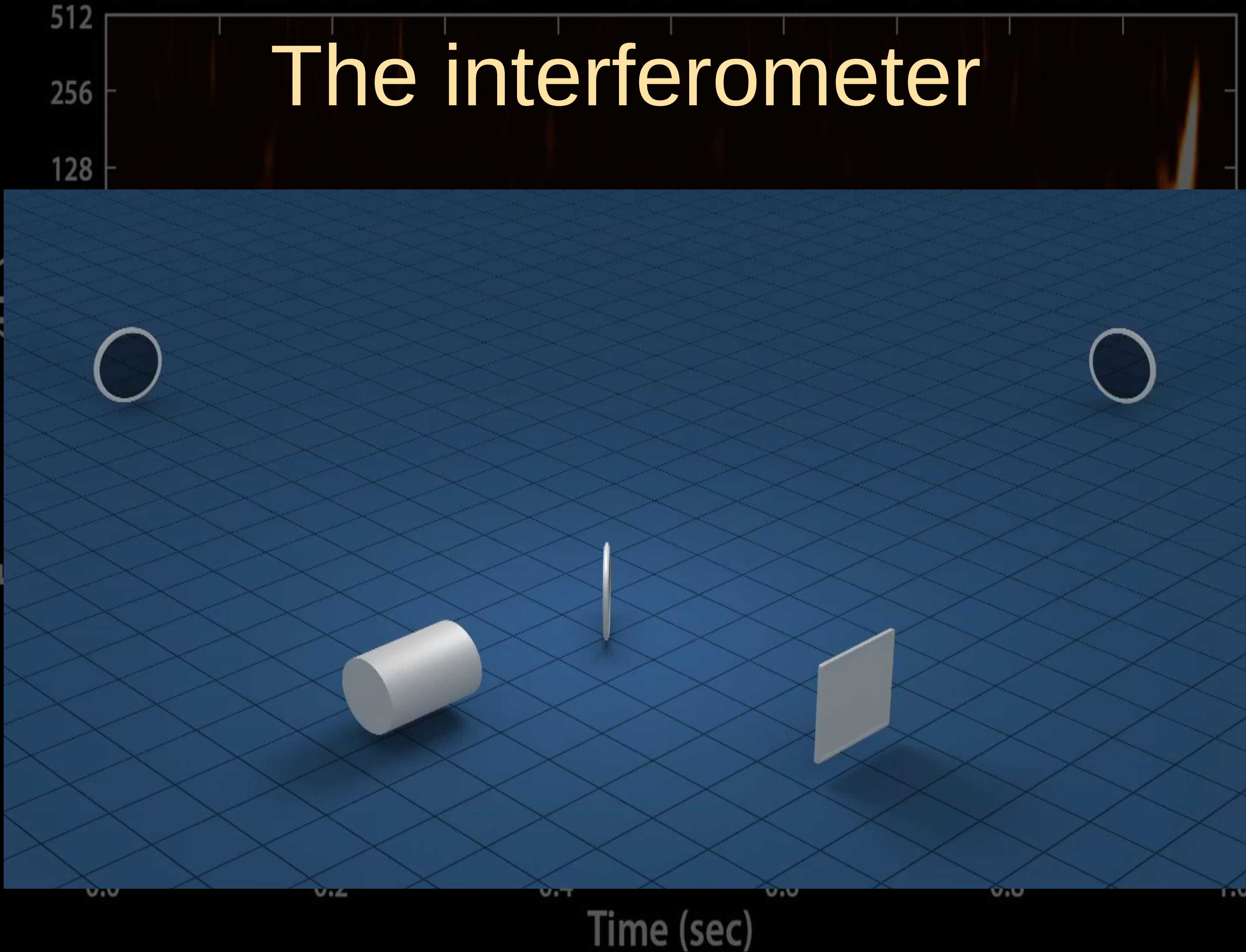
1972: Gravitational Wave Antenna

- Electromagnetically coupled broad-band gravitational wave antenna, R.Weiss, MIT

- Use a laser to compare the length of the interferometer arms!



The interferometer

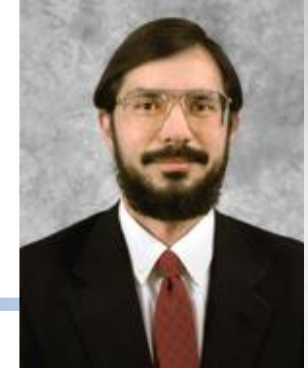


MIT Research Laboratory of Electronics Quarterly Progress Report 1972

The discovery of the pulsars may have uncovered sources of gravitational radiation which have extremely well-known frequencies and angular positions. The fastest known pulsar is NP 0532, in the Crab Nebula, which rotates at 30.2 Hz. The gravitational flux incident on the Earth from NP 0532 at multiples of 30.2 Hz can be 10^{-6} erg/cm^2/s at most. This is

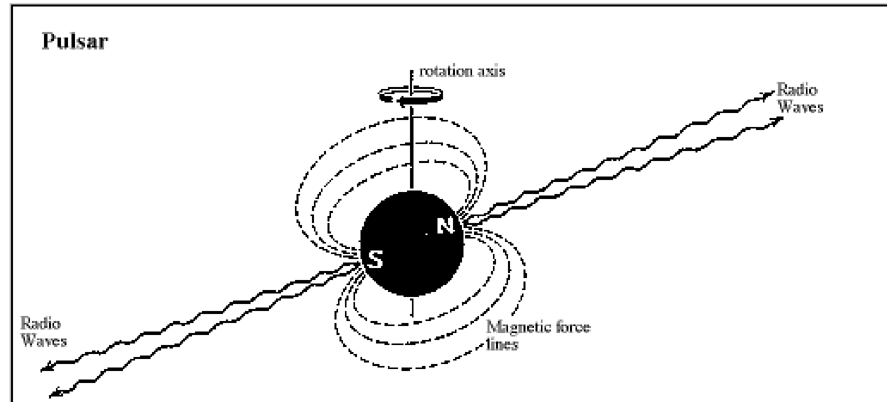
The antenna arms can be made as large as is consistent with the condition that the travel time of light in the arm is less than one-half the period of the gravitational wave that is to be detected. This points out the principal feature of electromagnetically coupled antennas relative to acoustically coupled ones such as bars; that an electromagnetic antenna can be longer than this acoustic counterpart in the ratio of the speed of light to the speed of sound in materials, a factor of 10^5. Since it is not the strain but rather the differential displacement that is measured in these gravitational antennas, the proposed antenna can offer a distinct advantage in sensitivity relative to bars in detecting both broadband and single-frequency gravitational radiation. A significant improvement in thermal noise can also be realized.

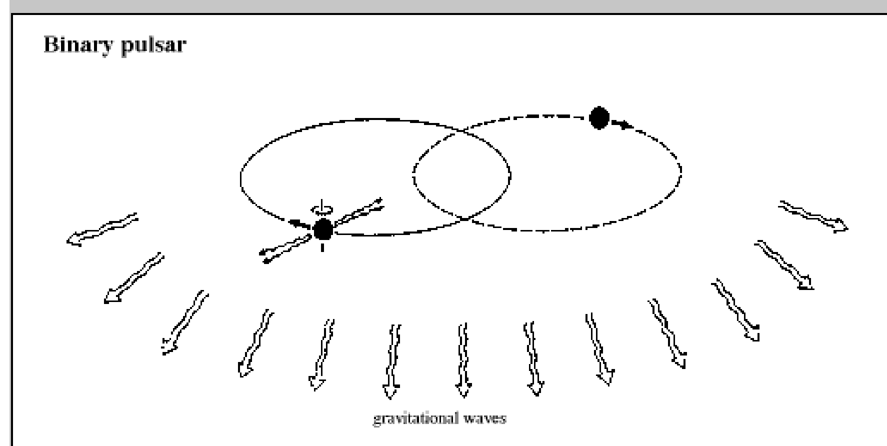
Relativistic Binary Pulsar B1913+16




R. A. Hulse J. H. Taylor

- First binary Pulsar
  - Spinning neutron star with radio beacon
- Discovered in 1974
- Loses energy by radiating gravitational waves
- Standard source for GW observatories





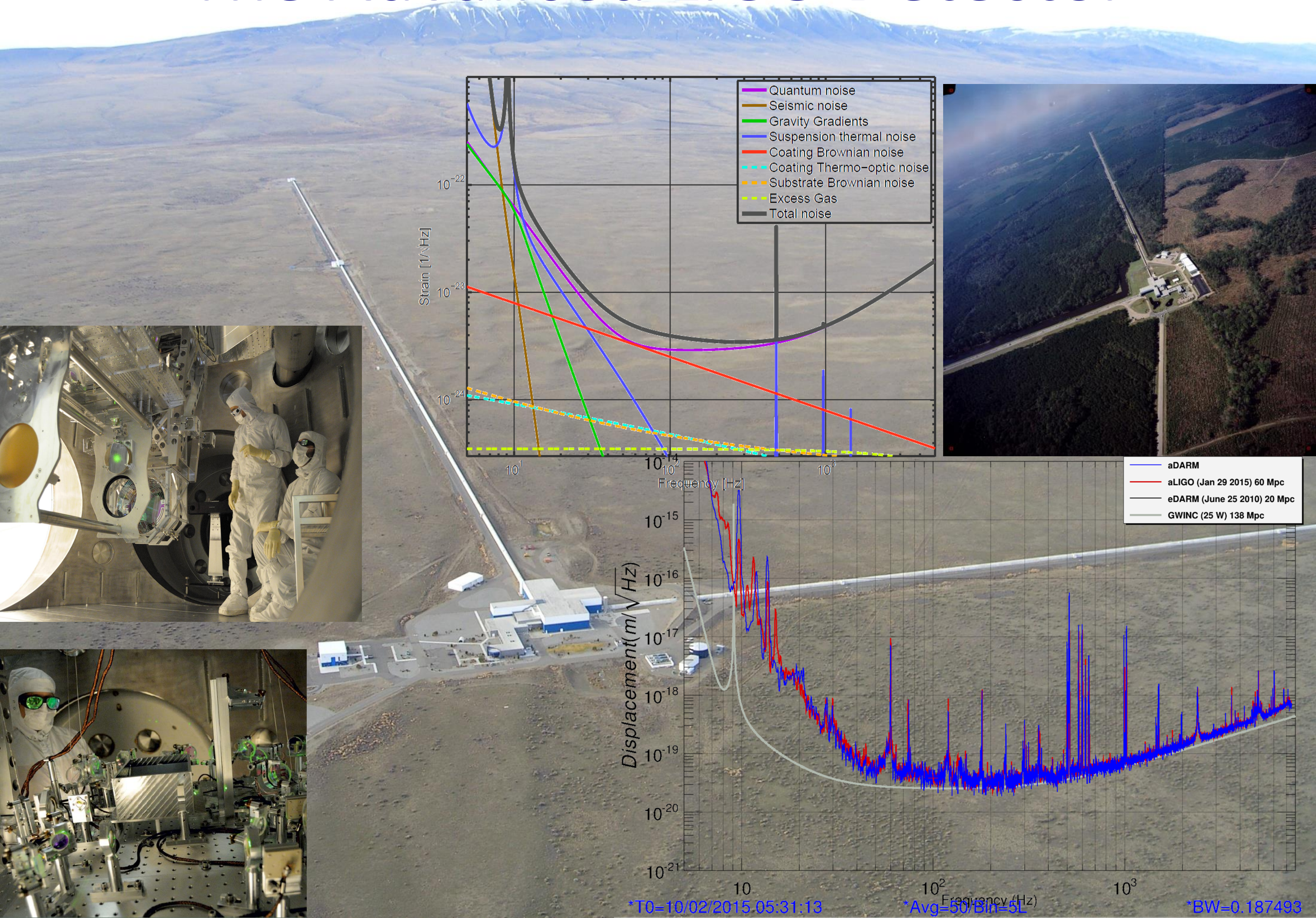
KUNGL. VETENSKAPSAKADEMIEN THE ROYAL SWEDISH ACADEMY OF SCIENCES 1993

LIGO: NSF Funding in 1990; Design sensitivity 2005

LIGO Livingston Observatory

LIGO Hanford Observatory

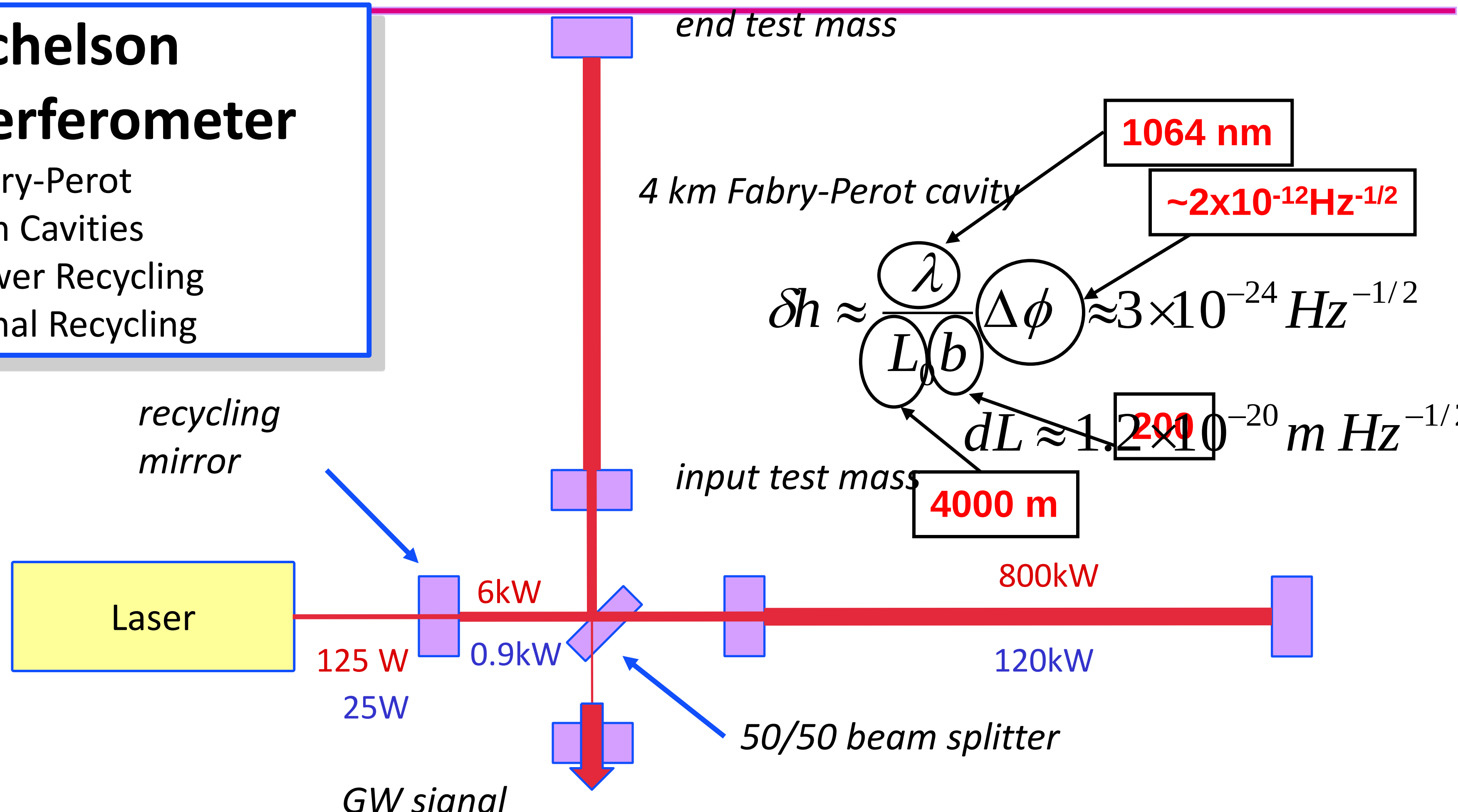
The Advanced LIGO Detector



Interferometer Sensitivity: Quantum noise

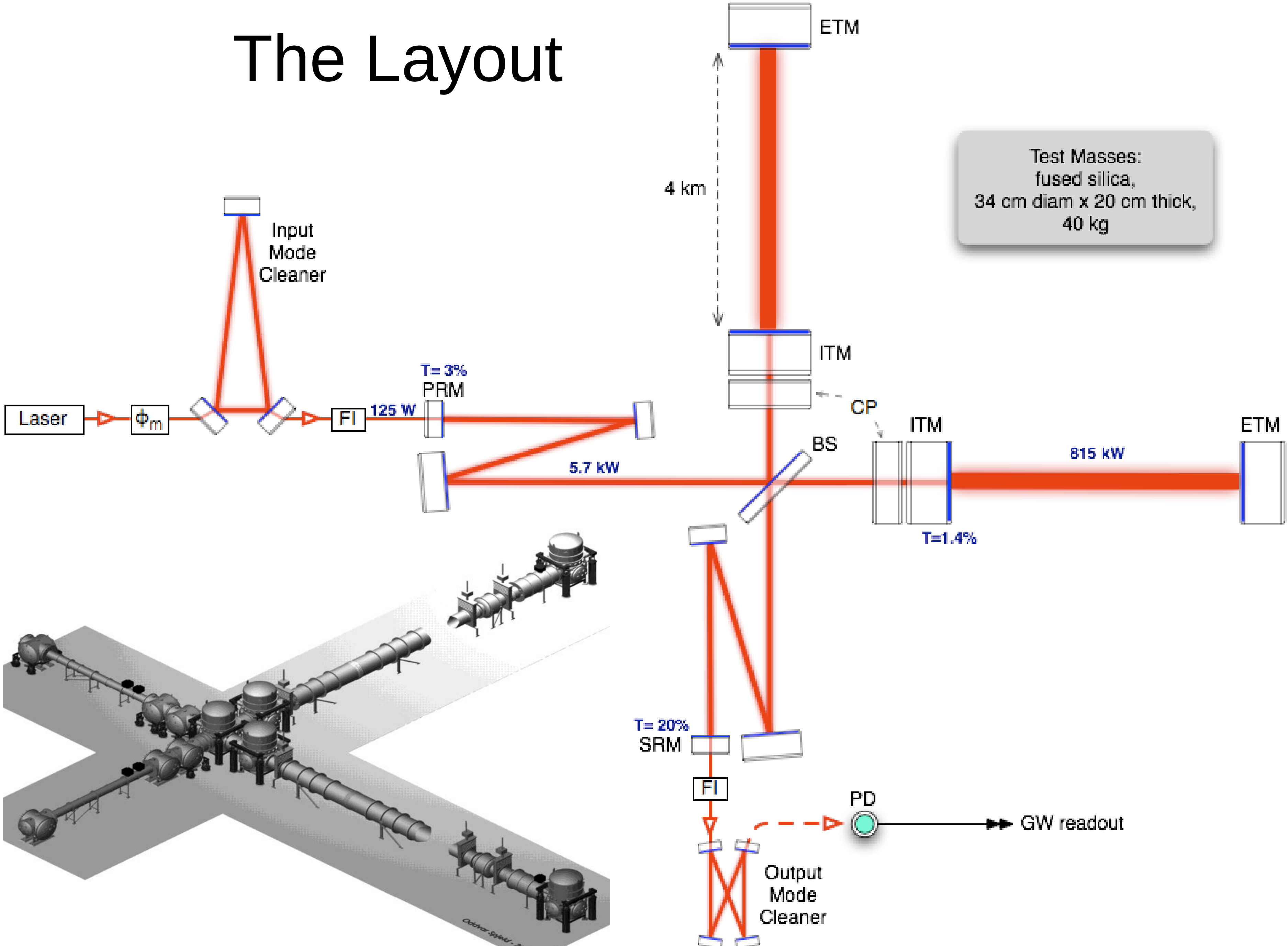
Michelson Interferometer

+ Fabry-Perot Arm Cavities
+ Power Recycling
+ Signal Recycling



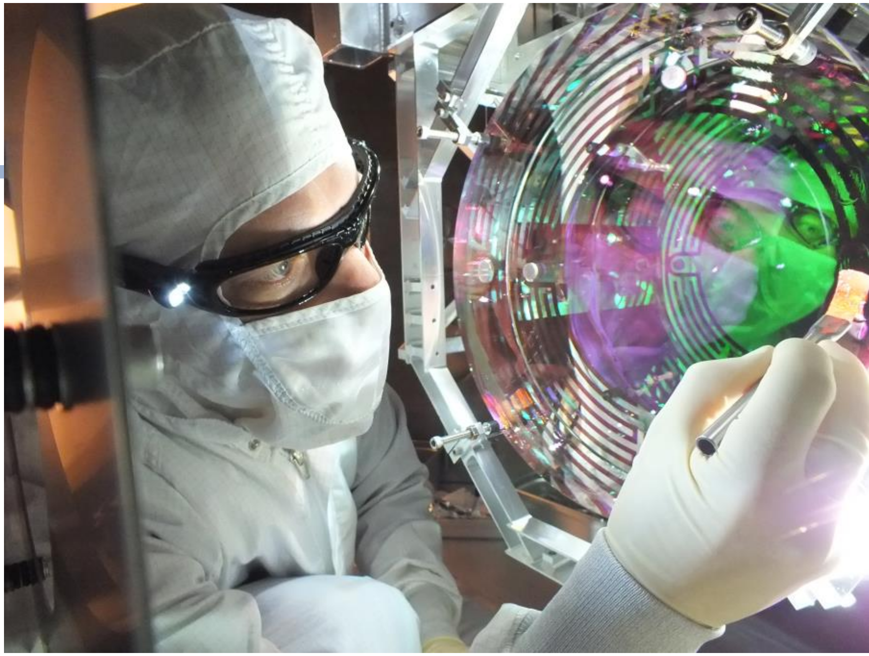
(Numbers: Red: for aLIGO design)
(Blue: for aLIGO O-1 run)

The Layout


ETM
4 km
Test Masses:
fused silica,
34 cm diam x 20 cm thick,
40 kg
Input
Mode
Cleaner
T= 3%
PRM
ITM
CP
Laser
Φ_m
FI
125 W
5.7 kW
BS
ITM
ETM
815 kW
T=1.4%
T= 20%
SRM
FI
PD
GW readout
Output
Mode
Cleaner

The Advanced LIGO Detectors

The Test Masses



Reduce to photon pressure noise

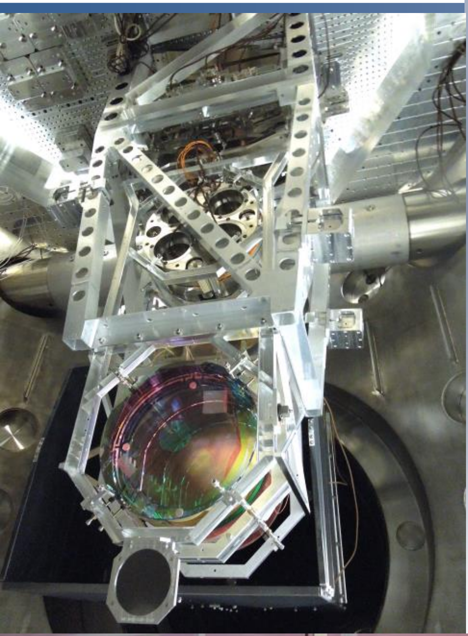
- -large!

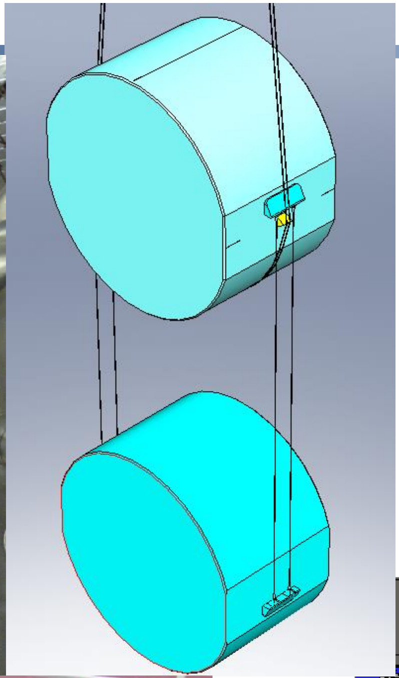
Reduce Brownian noise

- Lower Mechanical Loss
- Large surface area

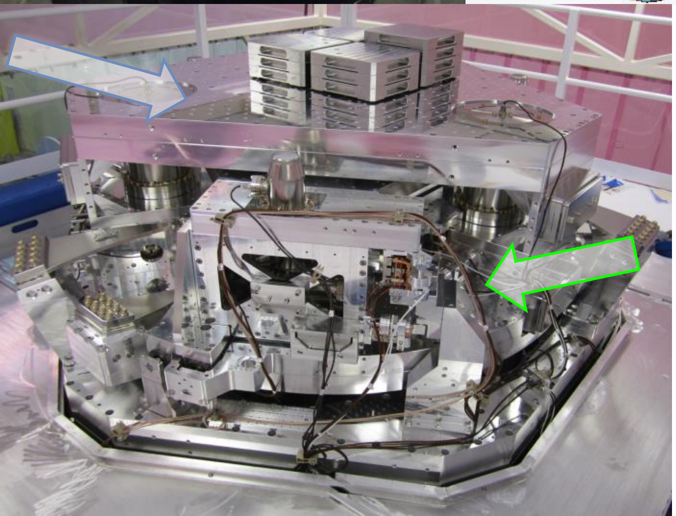
Diameter	**34 cm**
Thickness	**20 cm**
Mass	**40 kg**
1/e Beam Size	**6.2 cm**

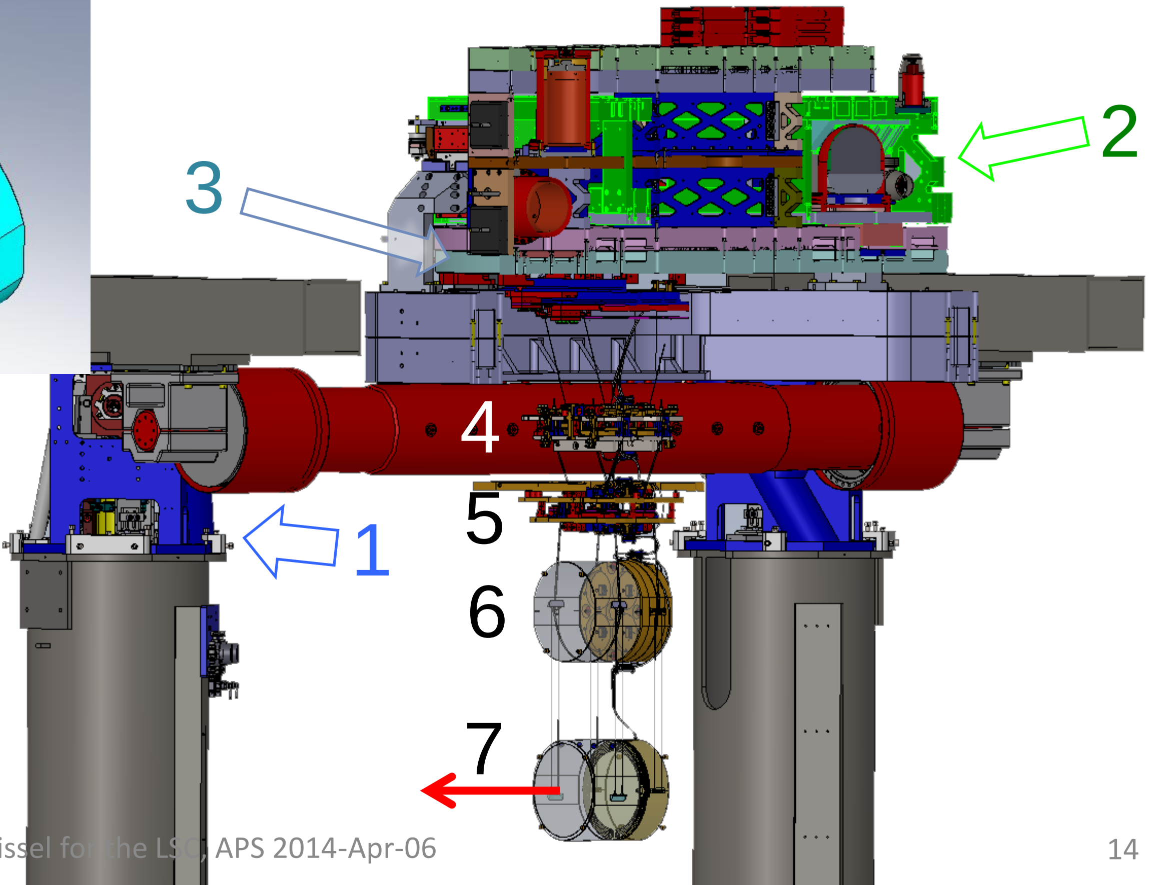
The Advanced LIGO Detectors
Seismic Isolation





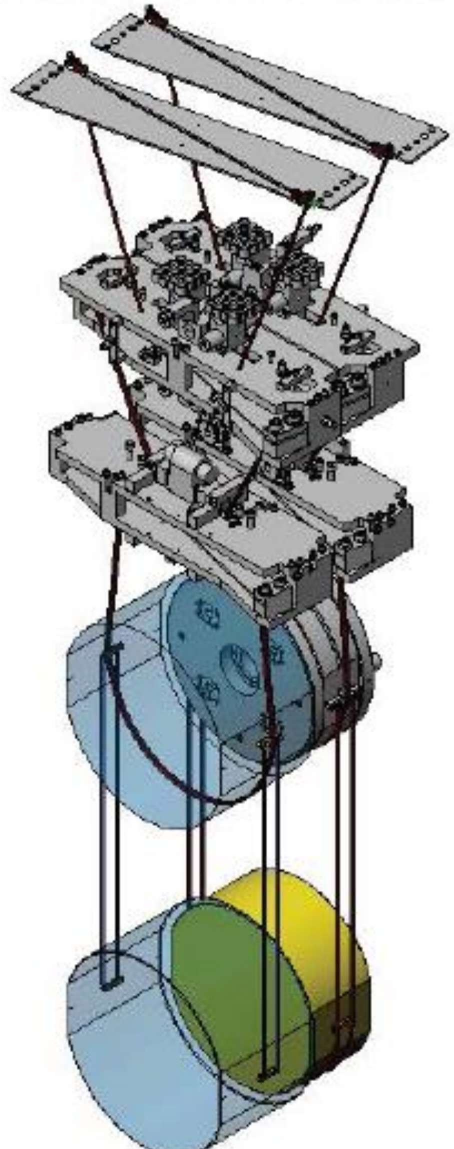
Last two stages are monolithic to improve Brownian noise



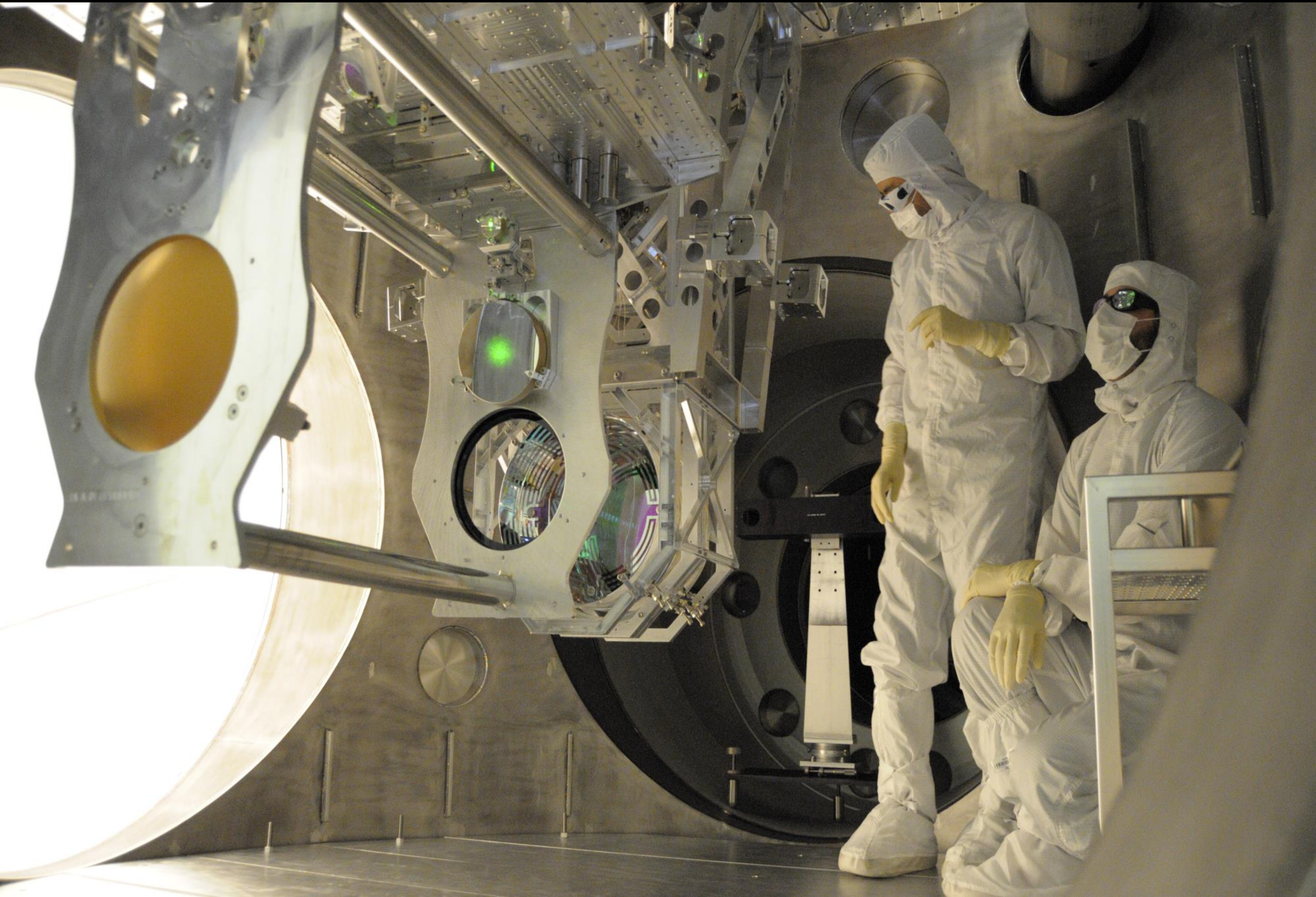


Test Mass Quadruple Pendulum Suspension

- Test masses are suspended with fused silica fibers (d=400 um) to minimize thermal noise
- Main chain recoils against the quiet reaction chain. Magnet-coil actuators on top stages, electro-static on the test mass.
- Laser welded
- Measured violin mode Q-factors ~10^9 (f_{violin}~500 Hz)



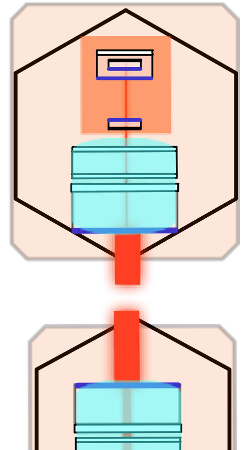
End Test Mass, and Trans Mon Telescope

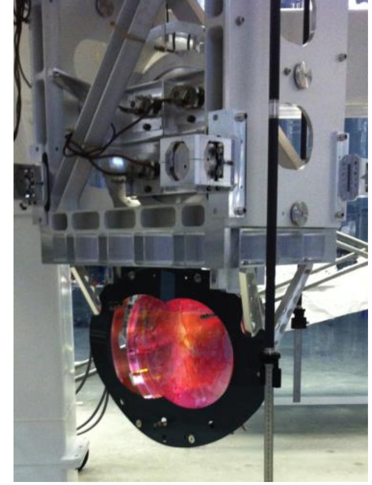


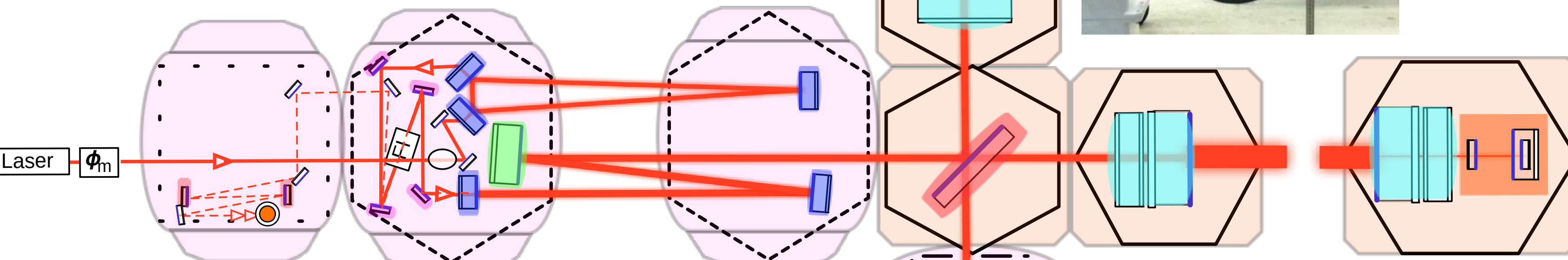
The Advanced LIGO Detectors
Seismic Isolation

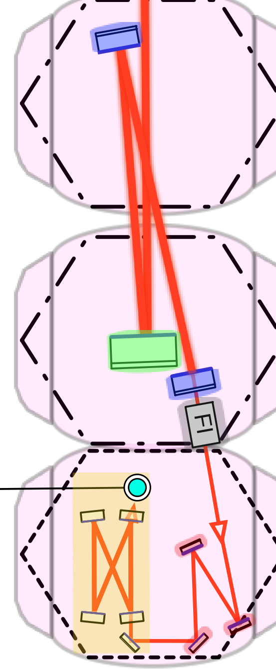
Test Masses are not the only thing that needs isolation…

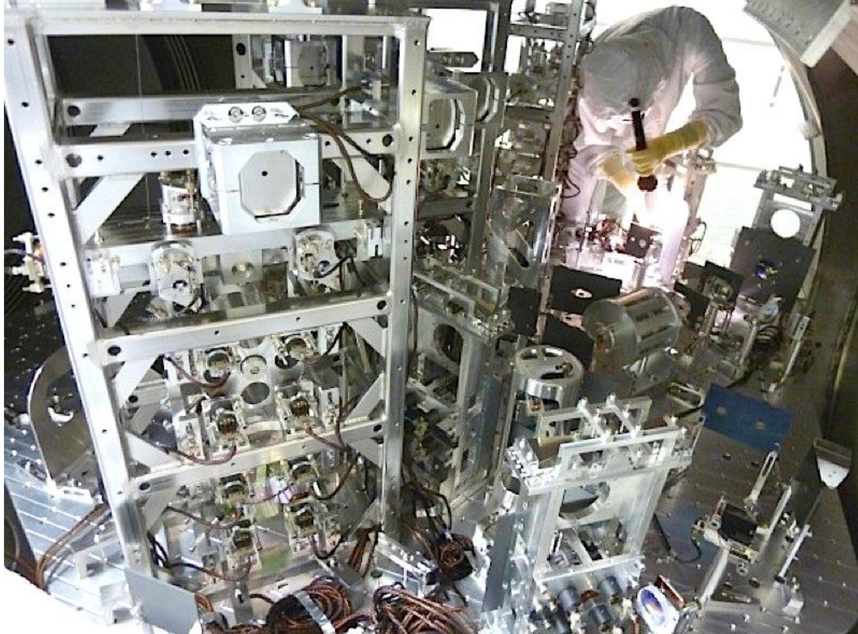
Interferometer is a zoo of seismic isolation!

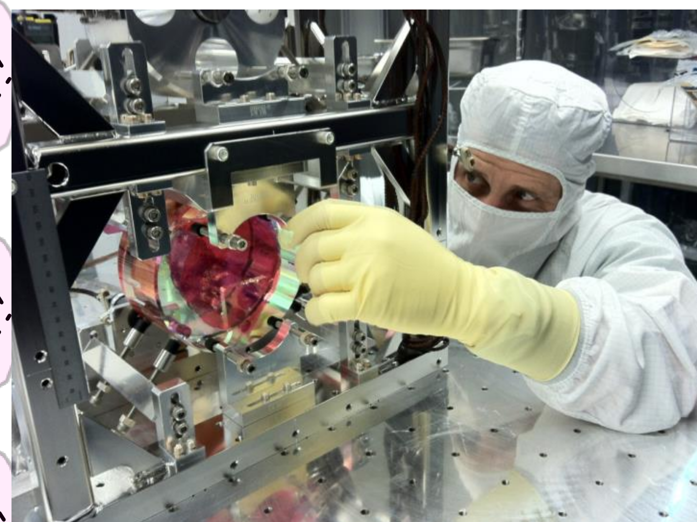




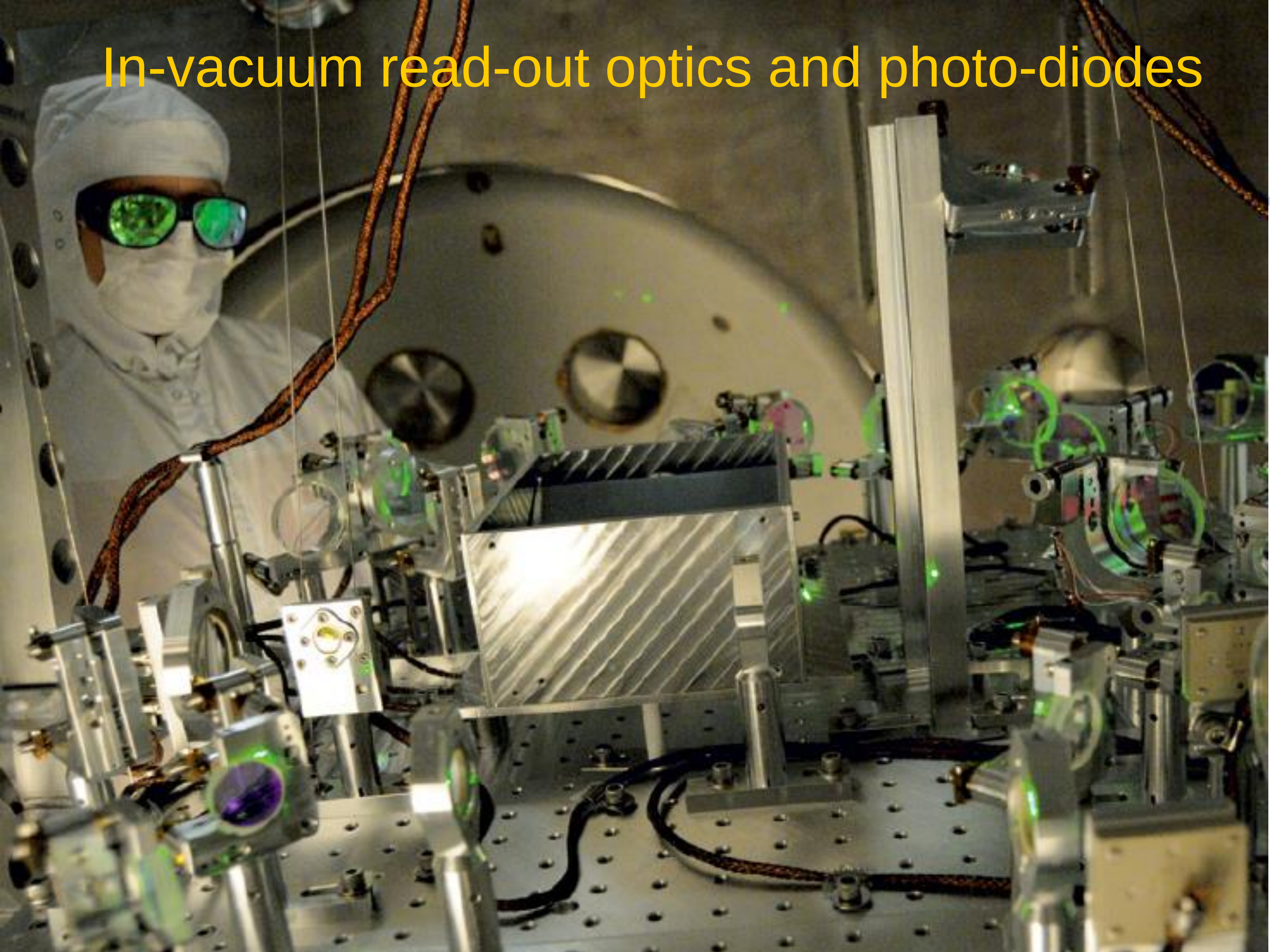




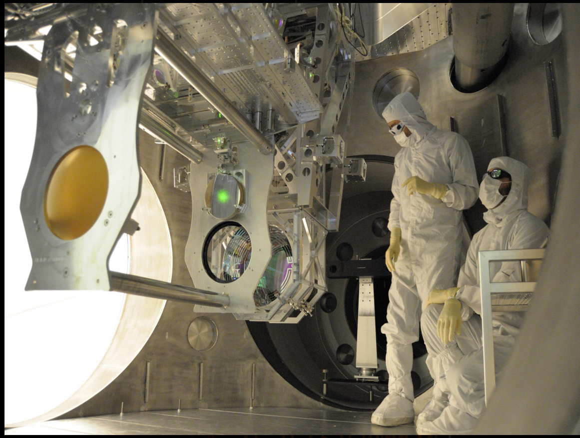




In-vacuum read-out optics and photo-diodes

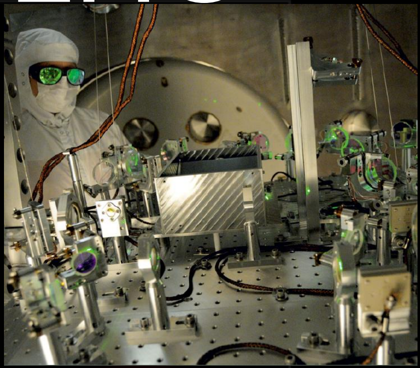


Advanced LIGO Timeline LHO

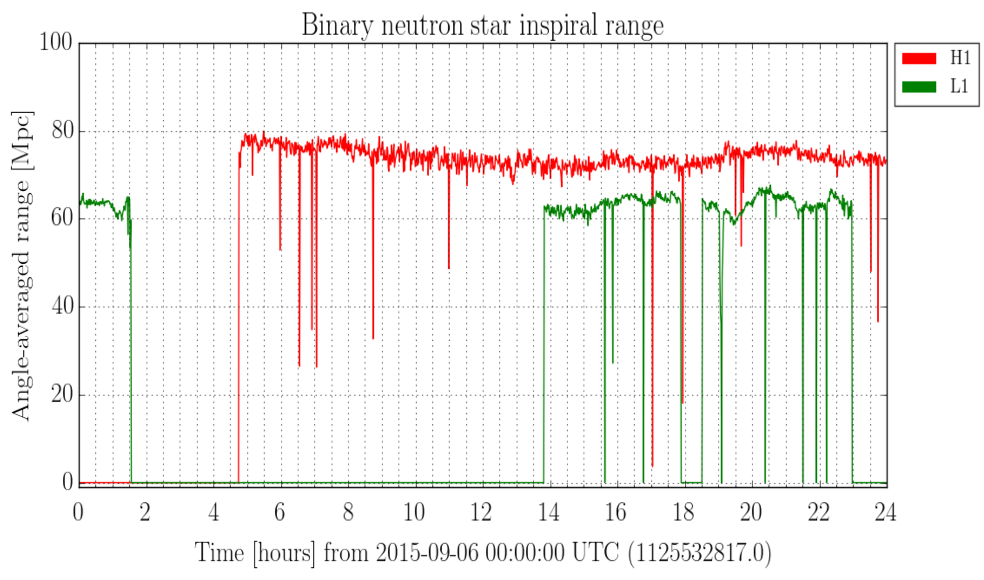


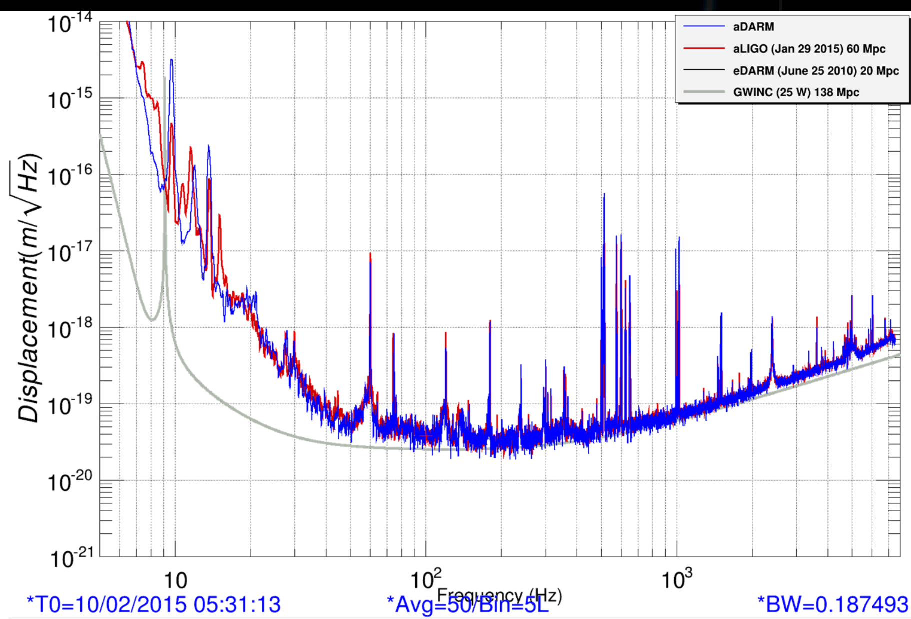
- Summer 2012: One Arm Test
  - Static alignment < 0.5 μrad
- Summer 2013: Half-Interferometer (Y)
  - Control arm length by < 1e-10 meter…
    … and move it!
- Fall 2014: Half-Interferometer (X&Y)
  Central Interferometer locked
  - Angular control with up to 10Hz bandwidth
- 04 February 2015: 1st Full Lock
  - Intra-cavity power 10'000 x input power

Advanced LIGO Timeline LHO



- Summer 2015:
  - Full Interferometer Angular Control < 0.1 µrad
  - Noise commissioning, NS/NS sky-average range:
    - ~20 Mpc by Feb; 57 Mpc by May
    - 80 Mpc by September, 8e-24 meter / rtHz peak sensitivity





Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave

H1 ISC Link

evan.hall@LIGO.ORG - posted 02:14, Monday 14 September 2015 (21489) → Sept. 14, 2015, 9:14 UTC log time

HAM6 power measurements in full lock

Stefan, Evan

We spent some time today trying to estimate the amount of carrier power (00 or otherwise) in HAM6 in full lock. Stefan had previously estimated about 270 mW of non-45-MHz light entering HAM6, based on AS_C calibration. This seemed high to us, since we should expect < 150 mW of carrier: 25 mW or so of 00 carrier (based on the DCPD sum), and 110 mW or so of other carrier (23 W input power × 0.88 input chain throughput × 37 W/W recycling gain × 150 ppm contrast defect, taken at low power).

[Does Dan have updated numbers for the contrast defect (and the 9 MHz AS port content) based on new 23 W modescans???]

According to Dan, there is a factor-of-two error in Stefan's AS_C calibration, which would bring the estimated carrier power down to 135 mW [but this is problematic; see below]. Since one can never have too many calibrations of the same diode, I'm going to use $60{\times}10^3$ ct/W for the calibration [referred to watts of power entering HAM6], based on 1638.4 ct/V (ADC) × 0.78 A/W (responsivity) × 2 V/V (single/differential conversion) × $10^{36/20}$ V/V (whitening) × 370 ppm (optical throughput to AS_C).

We did a few different measurements.

DARM offset sweep

We locked the IFO on RF at 23 W, locked the OMC (with dither on), and swept the DARM offset by a few tens of picometers (positive and negative). From these data it should be possible to compute a calibrated curve of current versus DARM offset, as Dan has done previously at lower power. But even without that, we can already infer $2700(640){\times}10^3$ ct on AS_C for 39.5(6) mA on the DCPD sum [= 68(16) ct/mA]. Assuming an AS_C calibration of $60{\times}10^3$ ct/W, and noting that the amount of photocurrent at zero DARM offset is small (< 1 mA), this suggests that for 20 mA of DCPD sum we have 23 mW of carrier from the arms entering HAM6. This seems unphysically low, since we already expect 26 mW of carrier based on a DCPD responsivity of 0.75 A/W. **Either way, something about the numbers in HAM6 doesn't hang together,** which is a conclusion that Koji and Dan already came to based on single-bounce power budgeting.

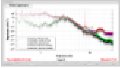
I believe we expect **at least 30 mW** coming into HAM6 under normal operation, since we expect at least 14 % readout losses, not including the quantum efficiencies of the photodiodes or anything upstream of the OFI. [31 mW × (1 − 0.14) × 0.75 A/W = 20 mA.]

[For this measurement, we notched out the 332 Hz pcal line in the EX drive, so it is visible in the DCPDs. So this can be used to estimate the optical gain at each DARM offset.]

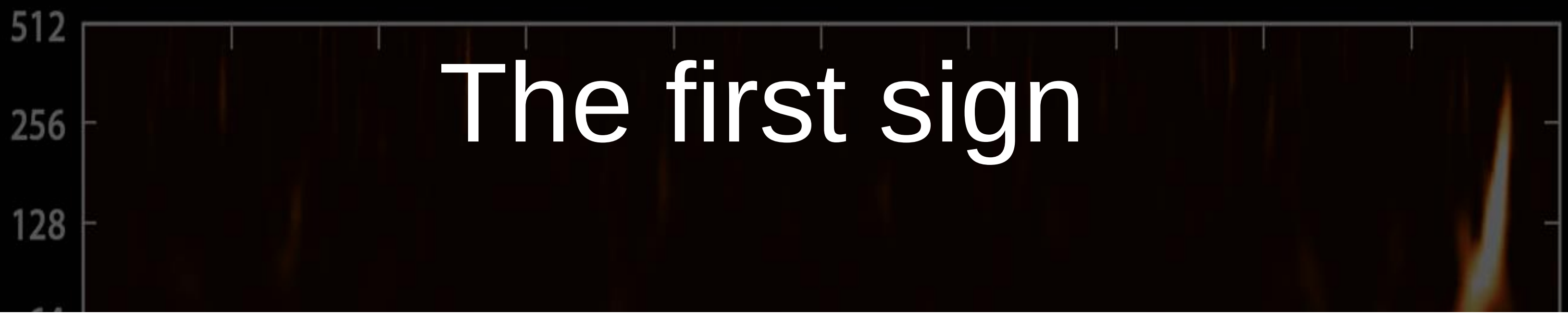
DCPDs vs AS_C vs OMC REFL

As a second test, we modulated DCPD sum at 8 Hz by driving OMC-READOUT_X0 while watching AS_C and OMC_REFL (we again opened the beam diverter for this). First, from the quiescent spectra alone we could already calibrate the PDs against each other; the calibrations are roughly 70 ct/mA for AS_C sum / DCPD sum and 2 ct/ct for AS_C sum / OMC REFL A sum. With AS_C and OMC REFL A calibrated (attachment), the strength of the line in OMC REFL A appears with a factor of 0.012 relative to the line in AS_C, suggesting that >98% of the modulated DARM light is coupled into the OMC.

Images attached to this report



The first sign



Marco Drago September 14, 2015 at 6:55 AM

To: burst@sympa.ligo.org Cc: cbc@ligo.org Binaries Group, The LIGO Data Analysis Software Working Group, Calibration, dac@sympa.ligo.org, and 4 more...

Reply-To: cbc@ligo.org

[CBC] Very interesting event on ER8

MD

Hi all,
cWB has put on gracedb a very interesting event in the last hour.
https://gracedb.ligo.org/events/view/G184098

This is the CED:
https://ldas-jobs.ligo.caltech.edu/~waveburst/online/ER8_LH_ONLINE/JOBS/112625/1126259540-1126259600/OUTPUT_CED/ced_1126259420_180_1126259540-1126259600_slag0_lag0_1_job1/L1H1_1126259461.750_1126259461.750/

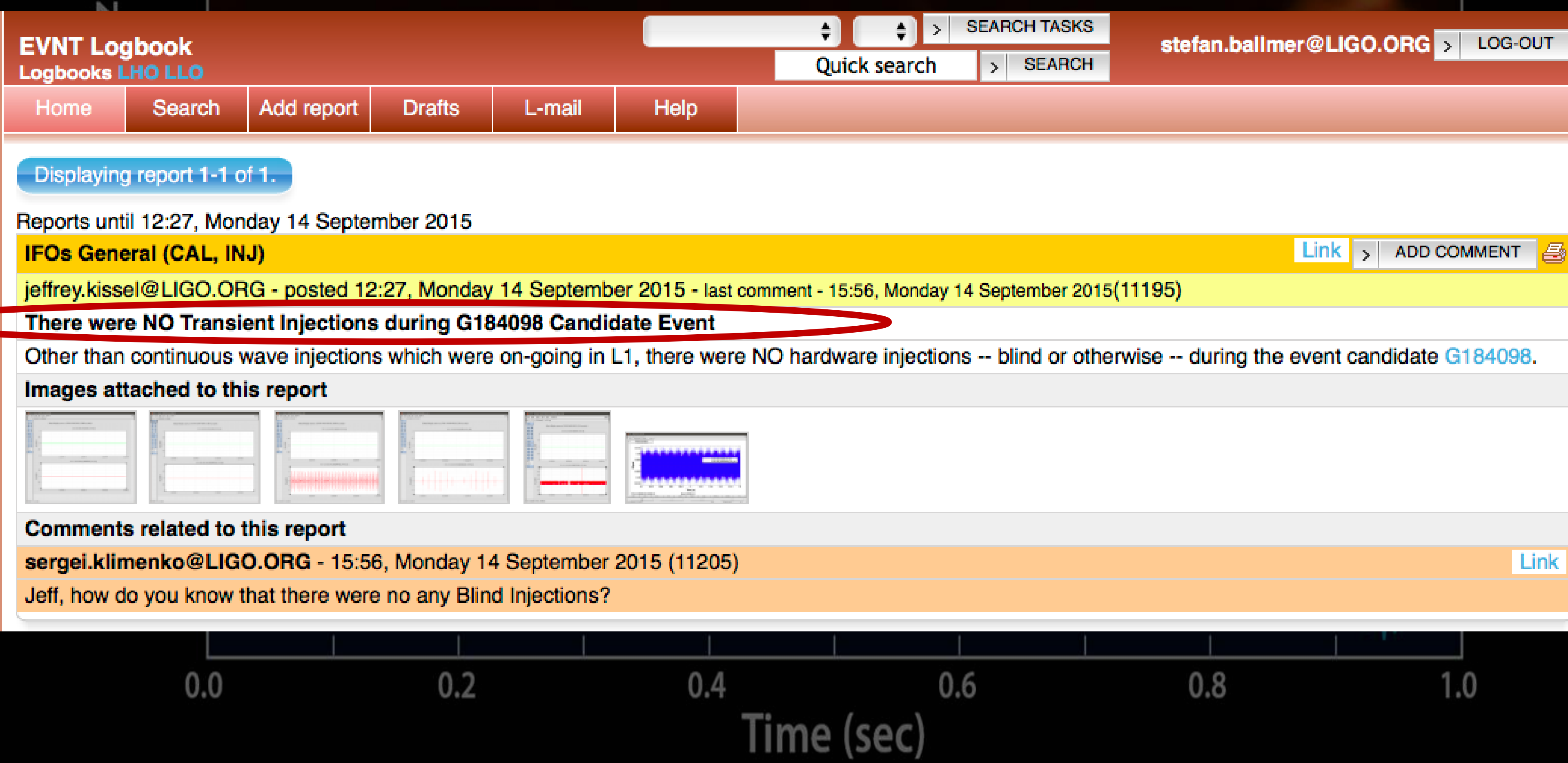
Qscan made by Andy:
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/L1_1126259462.3910/
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/H1_1126259462.3910/

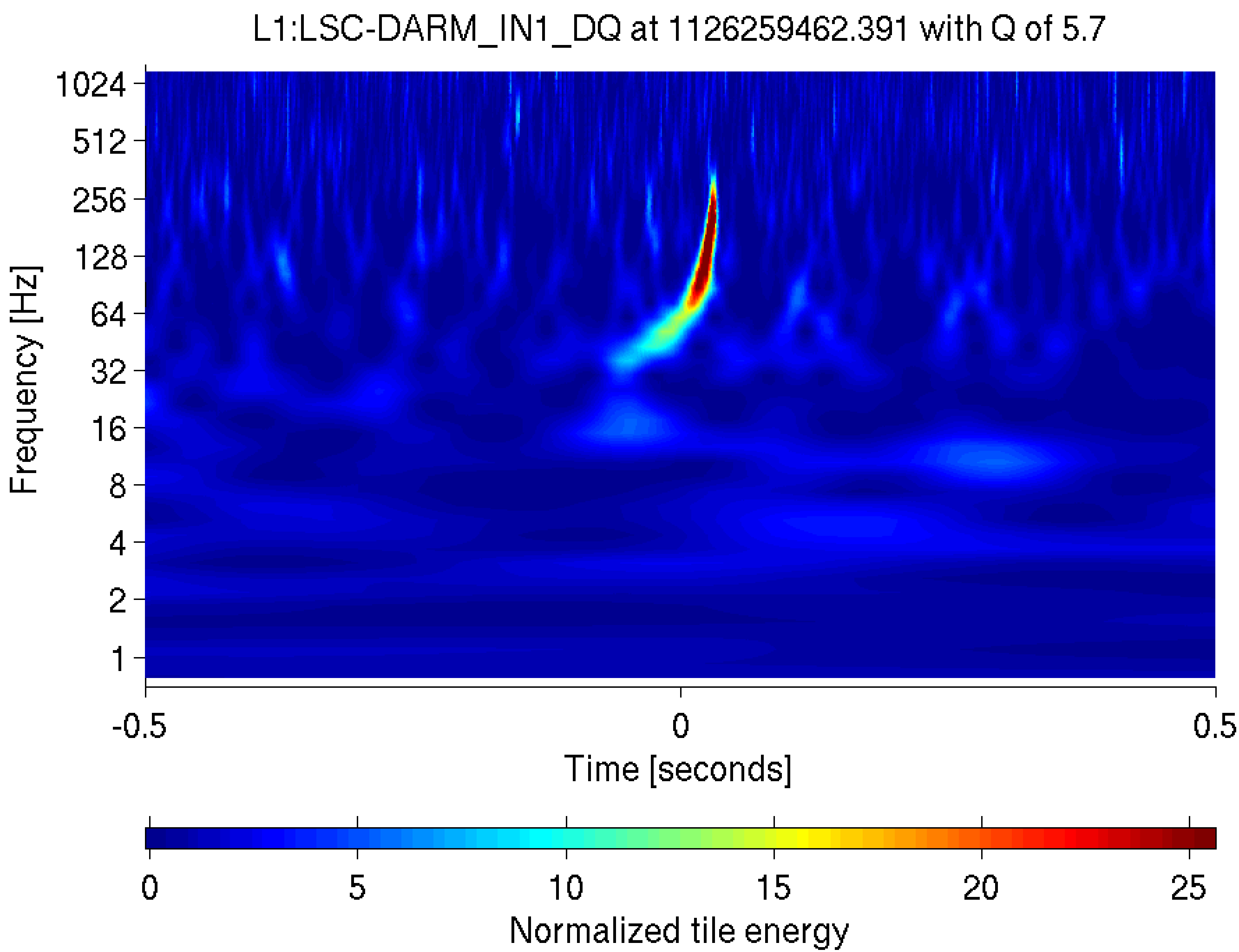
It is not flag as an hardware injection, as we understand after some fast investigation. Someone can confirm that is not an hardware injection?

Marco

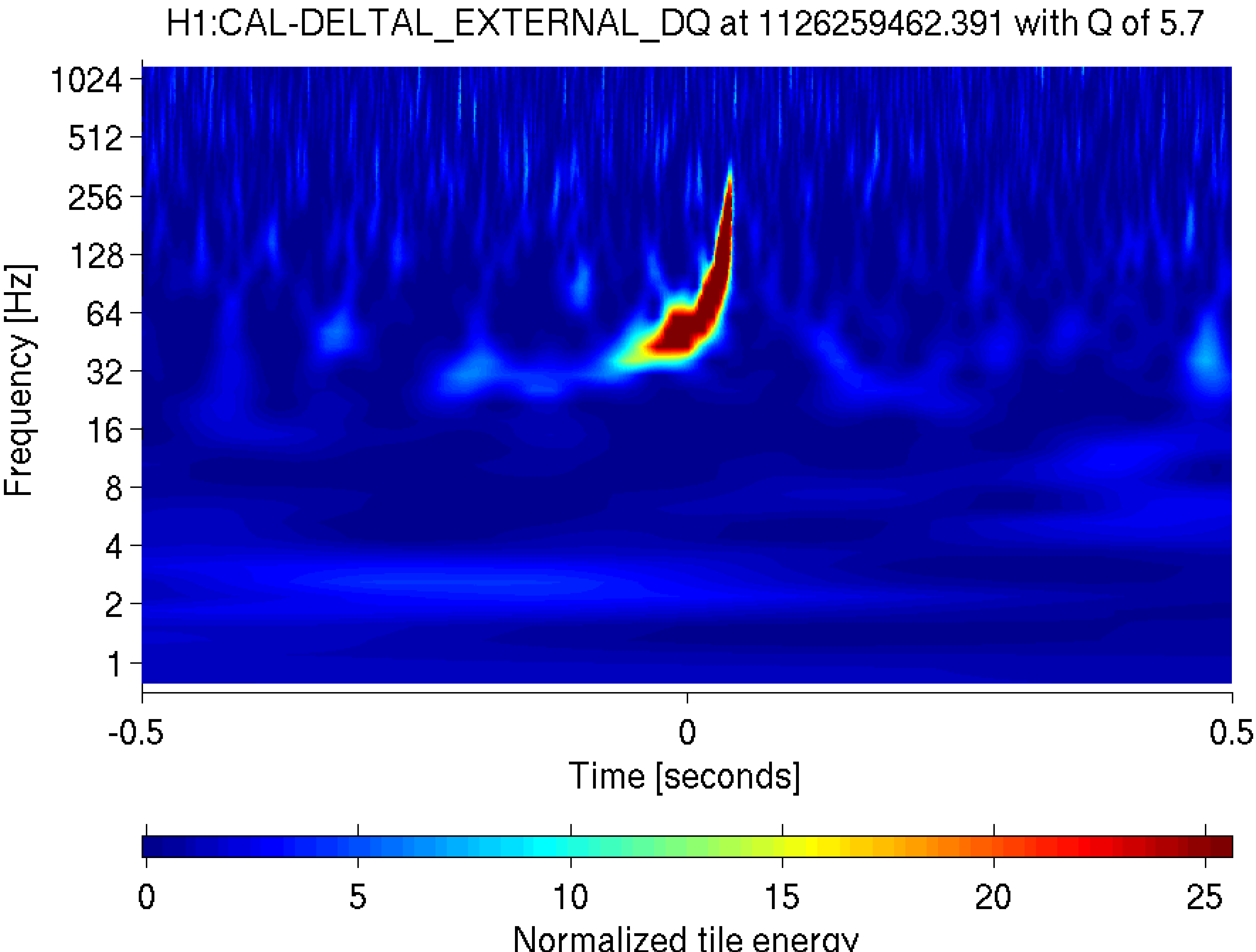
Time (sec)

The morning after, in the control room

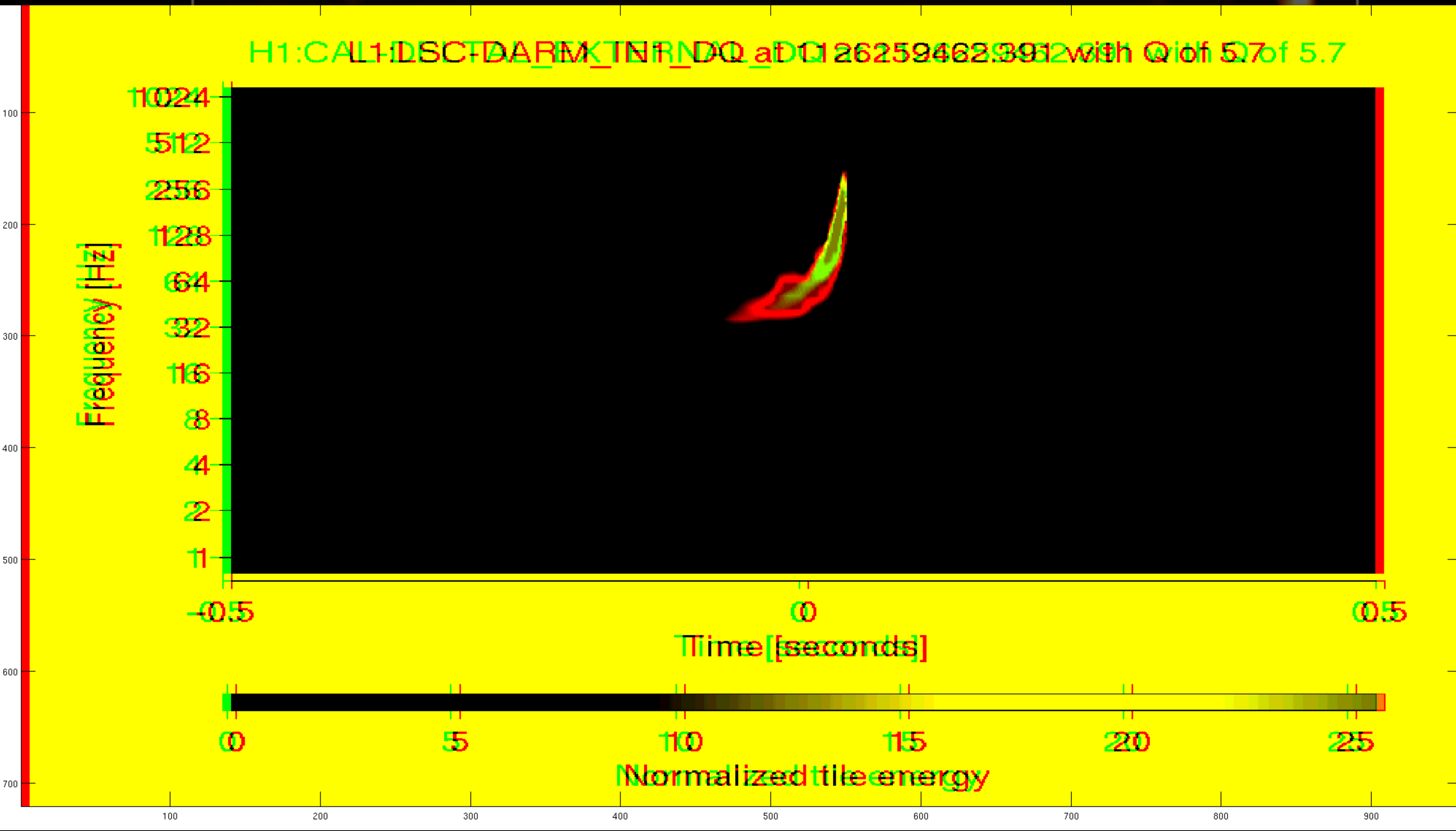




L1:LSC-DARM_IN1_DQ at 1126259462.391 with Q of 5.7
Frequency [Hz]
1024
512
256
128
64
32
16
8
4
2
1
-0.5
0
0.5
Time [seconds]
0
5
10
15
20
25
Normalized tile energy

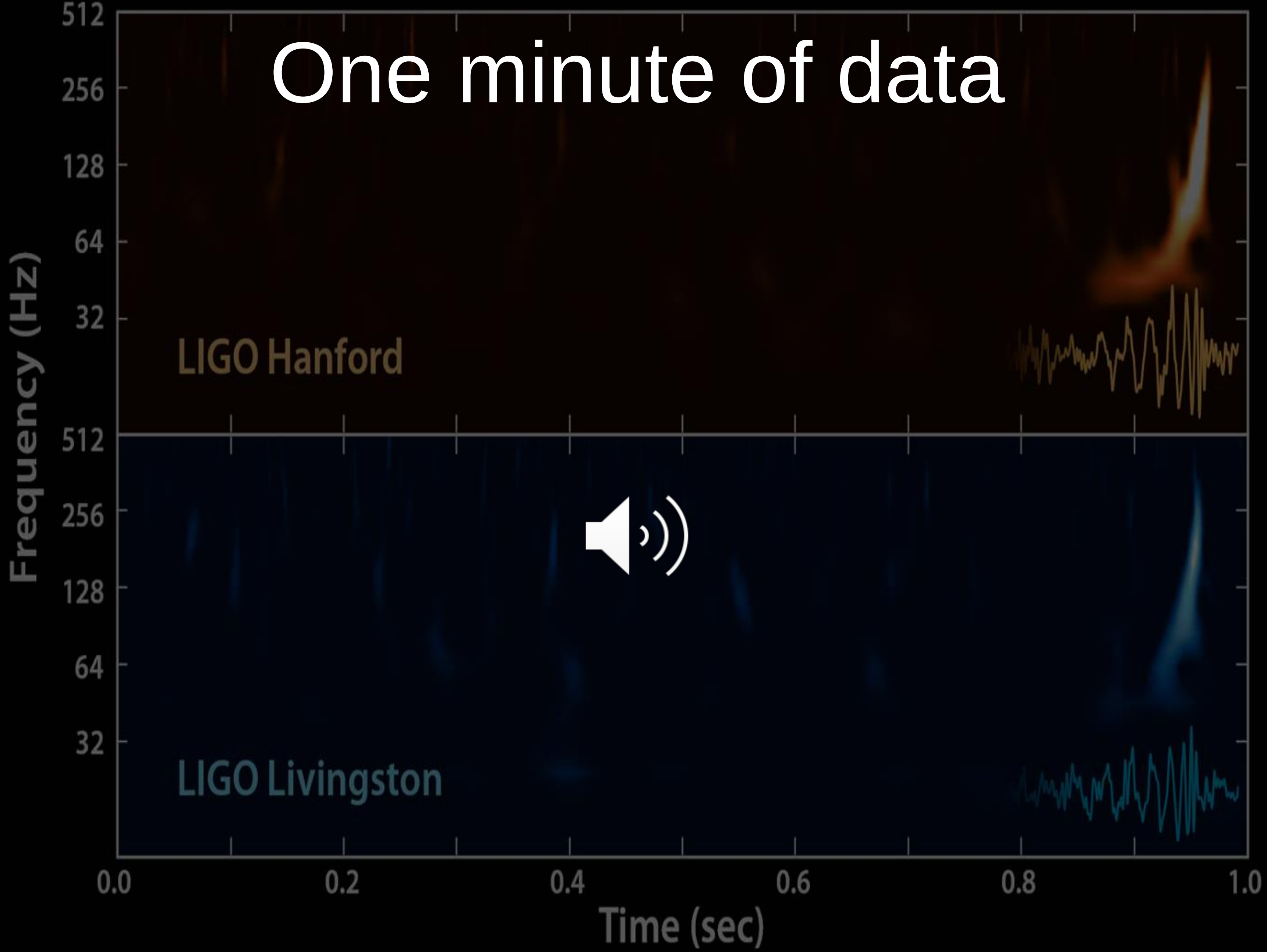

H1:CAL-DELTAL_EXTERNAL_DQ at 1126259462.391 with Q of 5.7
1024
512
256
128
64
32
16
8
4
2
1
Frequency [Hz]
-0.5
0
0.5
Time [seconds]
0
5
10
15
20
25
Normalized tile energy

posted 22:48, Monday 14 September 2015 UTC

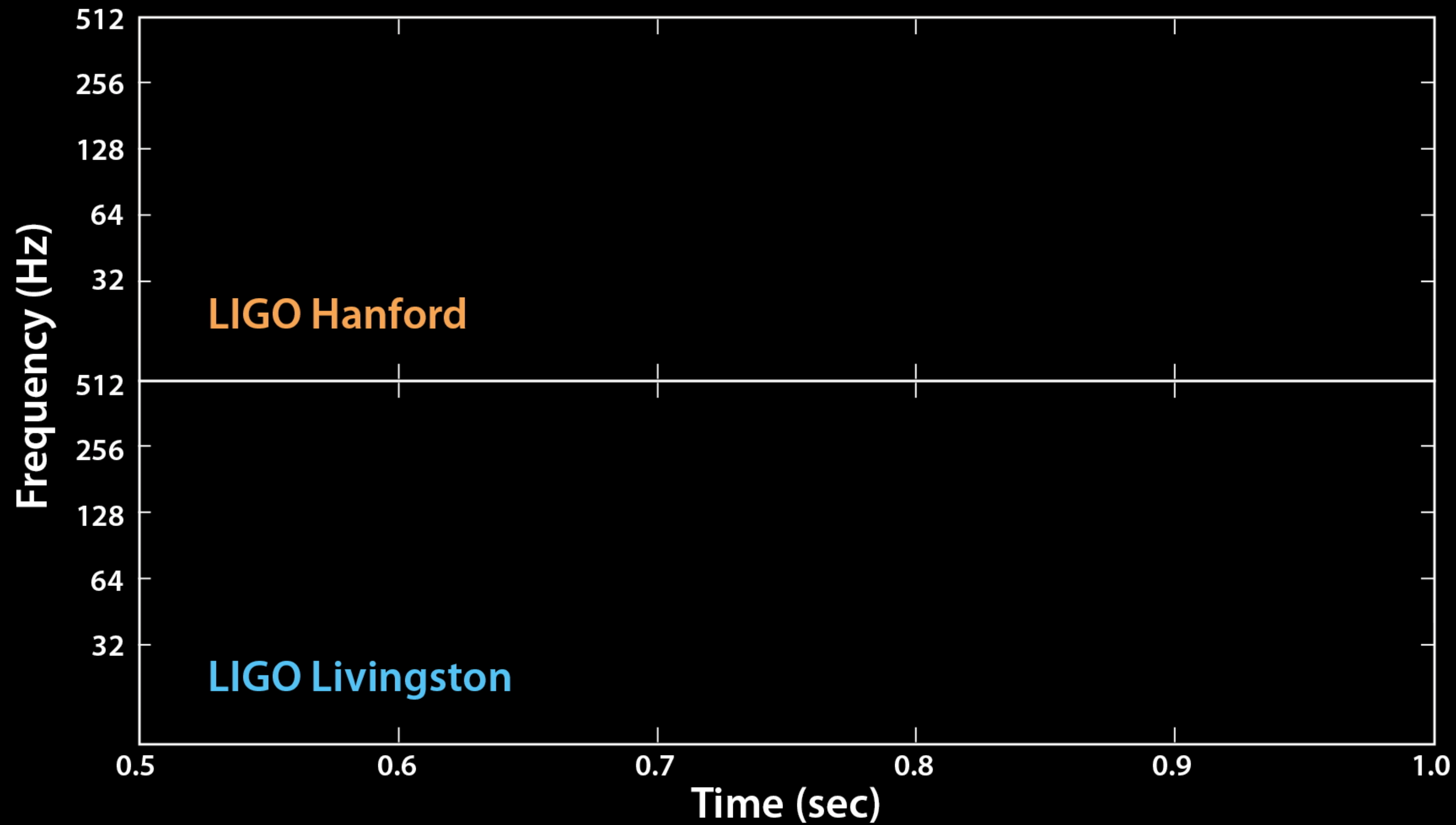



Later that week,
somewhere in Maine

One minute of data



Sped Up & Spectrogram



How do we know it's a binary black hole?

PHY 785: Theory of Relativity I, Spring 2015

Problem Set 9

Distribution: Tue April 14, 2015; Due: **Thu April 23, 2015**

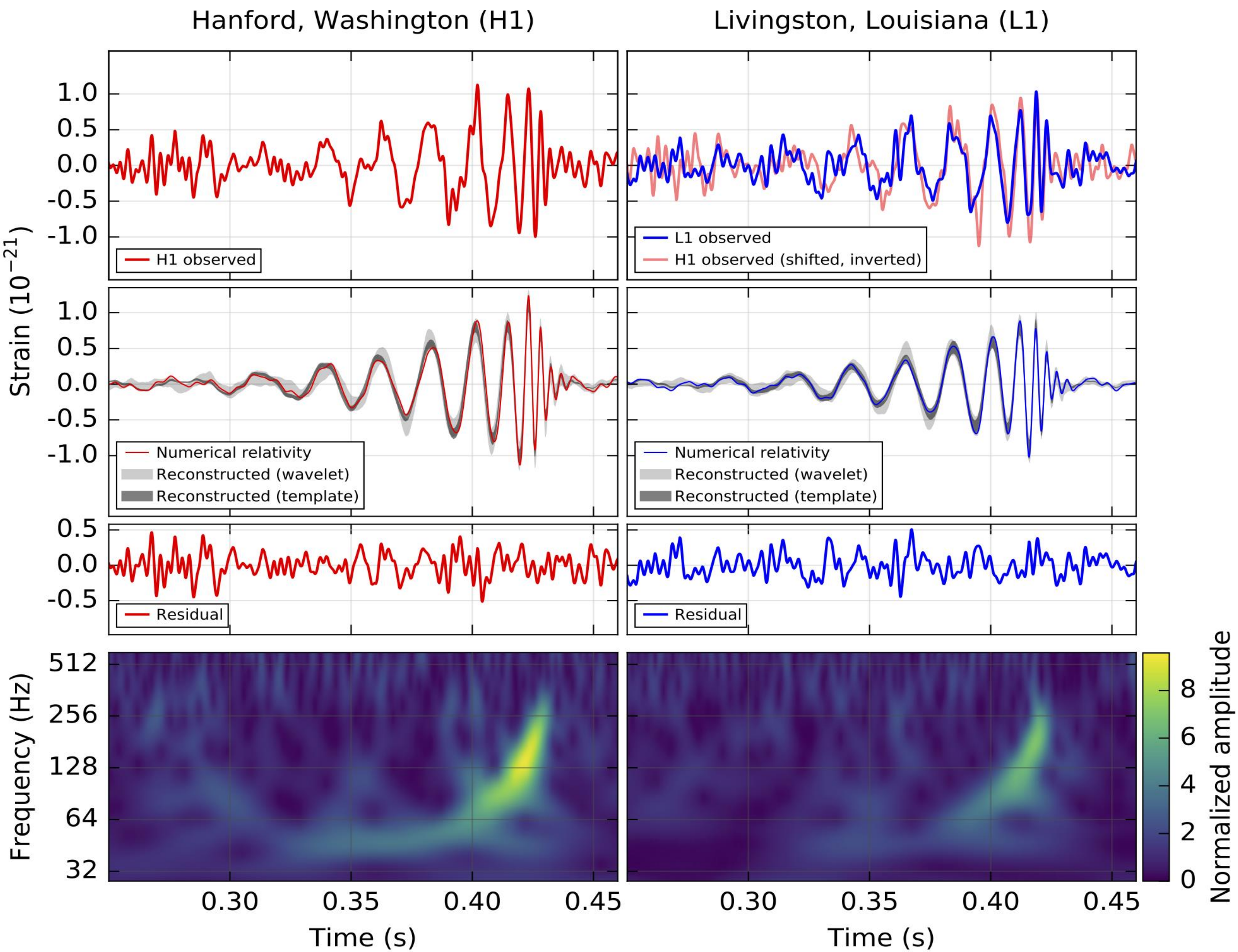
Wave form of a compact binary inspiral

Time to merger: $\tau_0 = 3.0 \text{ sec} \left(\frac{100 \text{ Hz}}{f_{\rm gw}}\right)^{\frac{8}{3}} \left(\frac{M_{\rm sun}}{M_{\rm chirp}}\right)^{\frac{5}{3}}$

$$M_{\rm chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

From directly fitting the data: $M_{\rm chirp} \sim 30\ M_{\rm sun}$. → $M_{\rm tot} >\sim 70\ M_{\rm sun}$

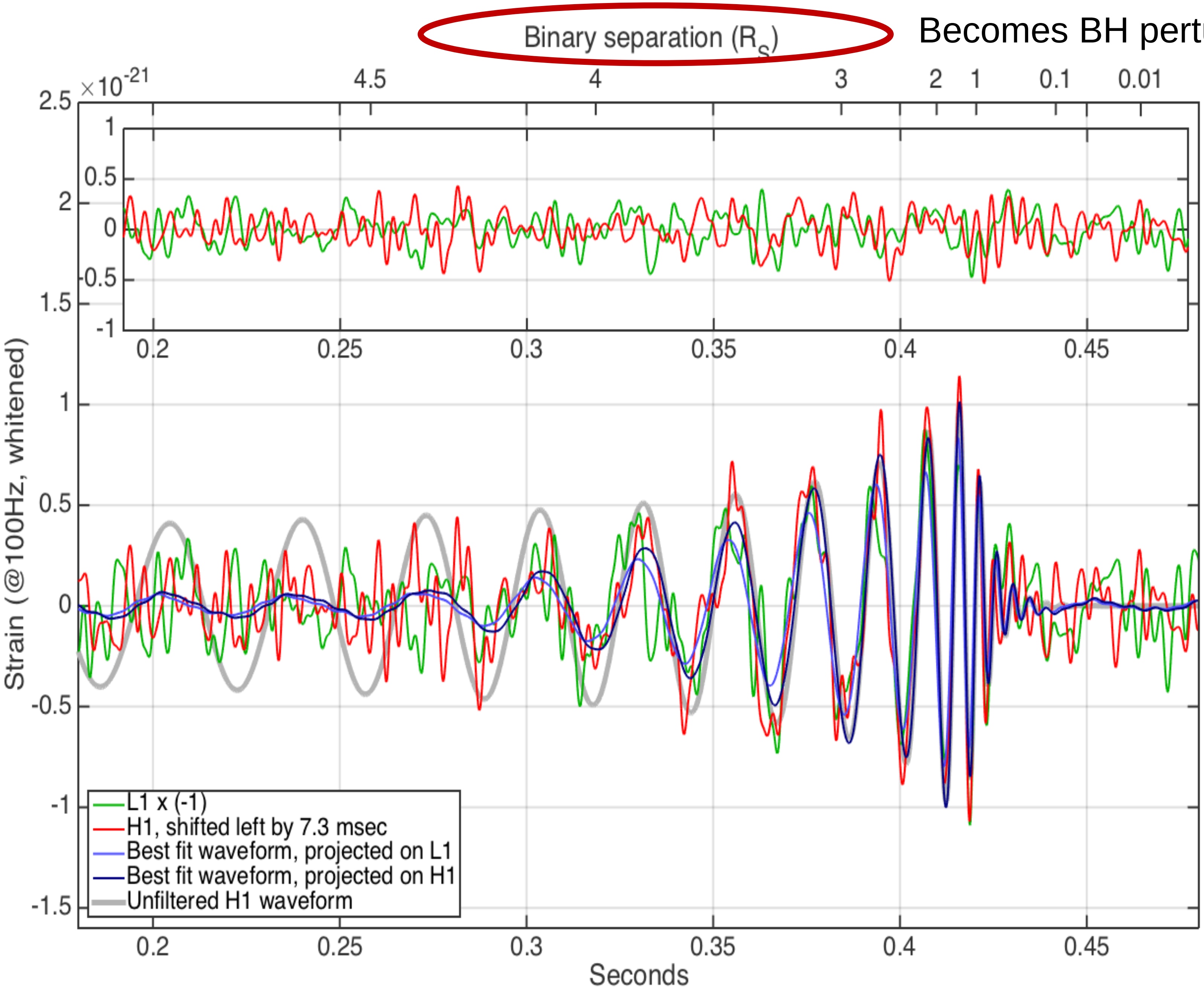
An extreme mass ratio (NS/BH) would merge at a lower frequency.



Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
Normalized amplitude
8
6
4
2
0
0.30
0.35
0.40
0.45
Time (s)

Defined through quadrupole moment

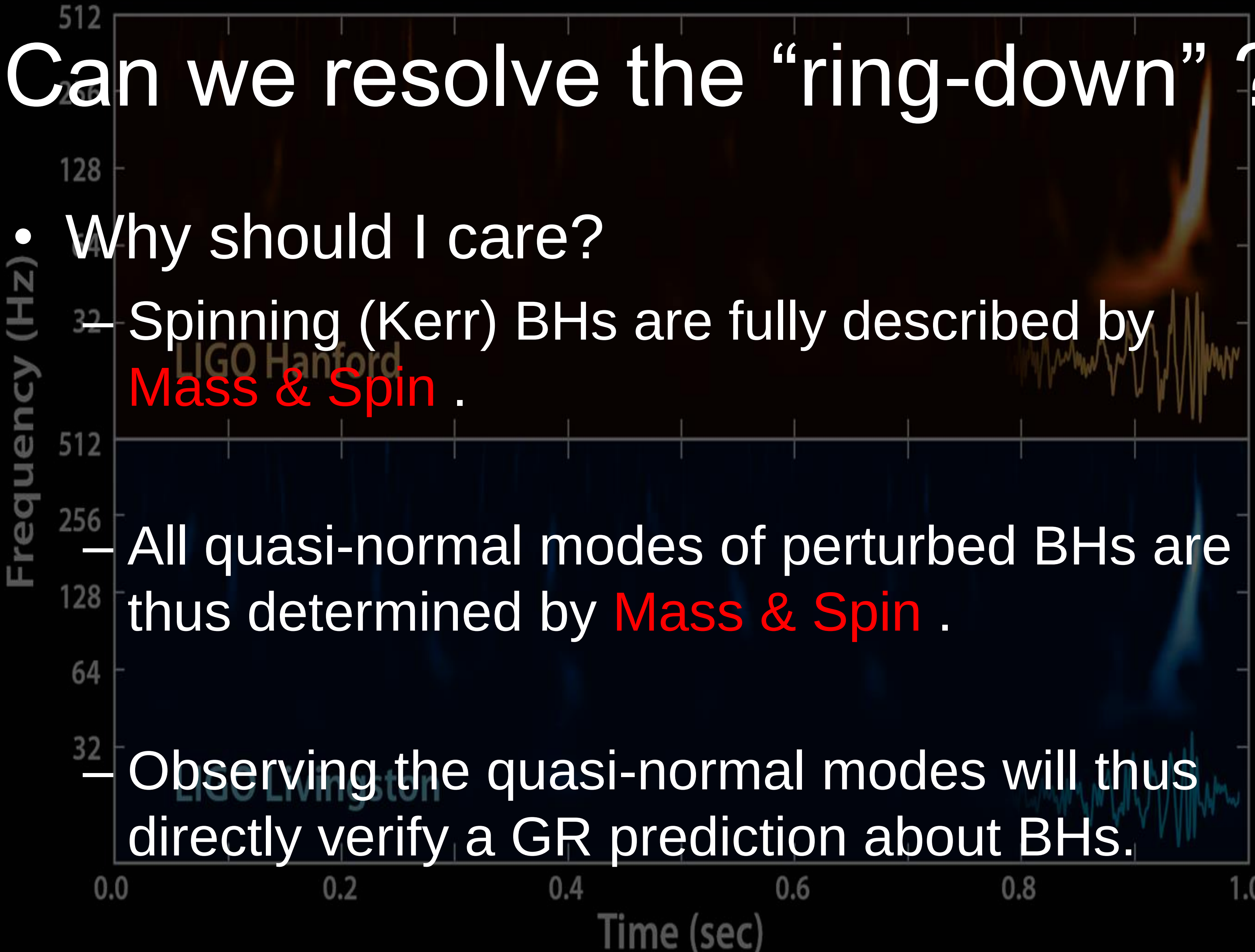
Becomes BH perturbation



Swetha Bhagwat

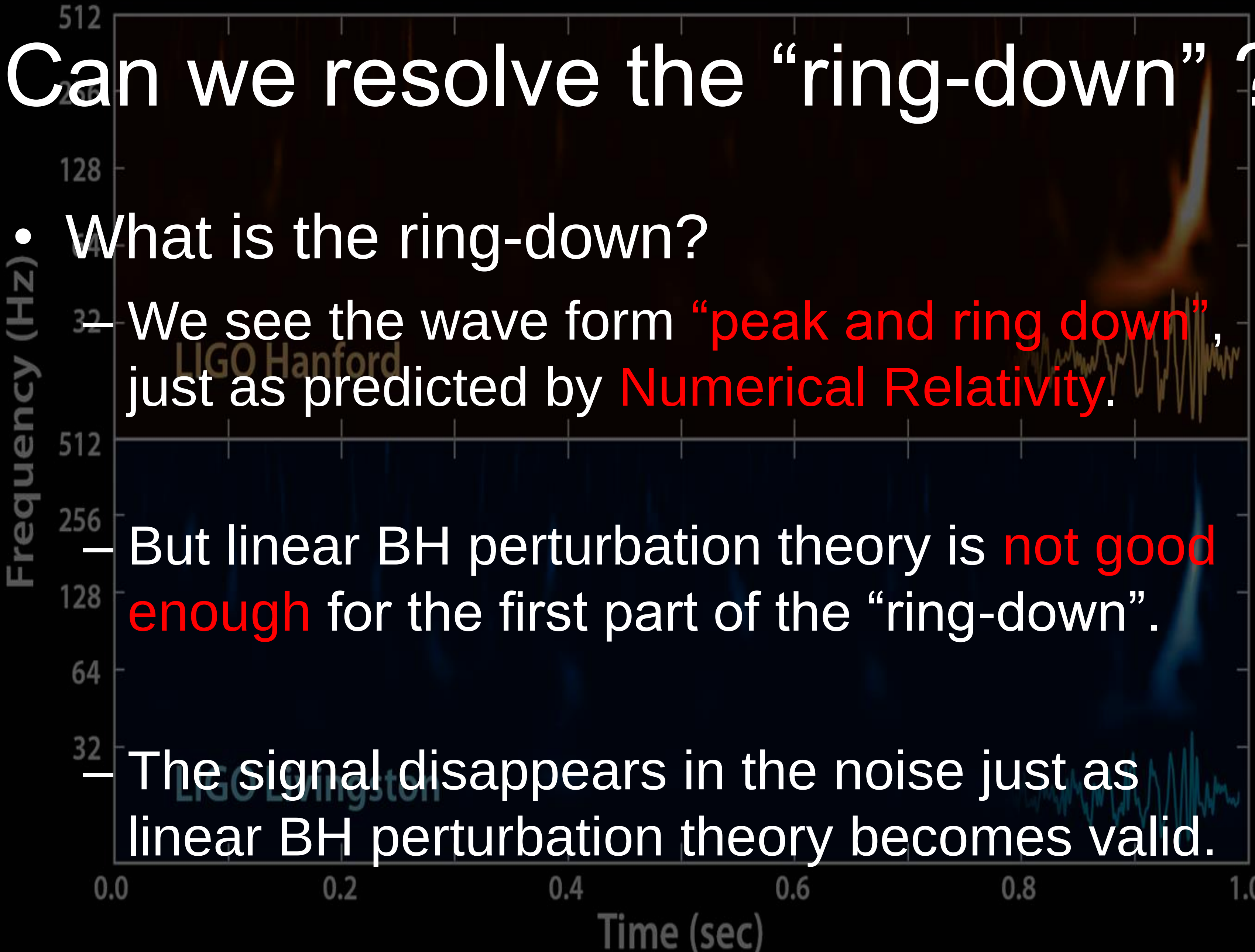
Can we resolve the “ring-down” ?

- Why should I care?
  - Spinning (Kerr) BHs are fully described by Mass & Spin .
  - All quasi-normal modes of perturbed BHs are thus determined by Mass & Spin .
  - Observing the quasi-normal modes will thus directly verify a GR prediction about BHs.



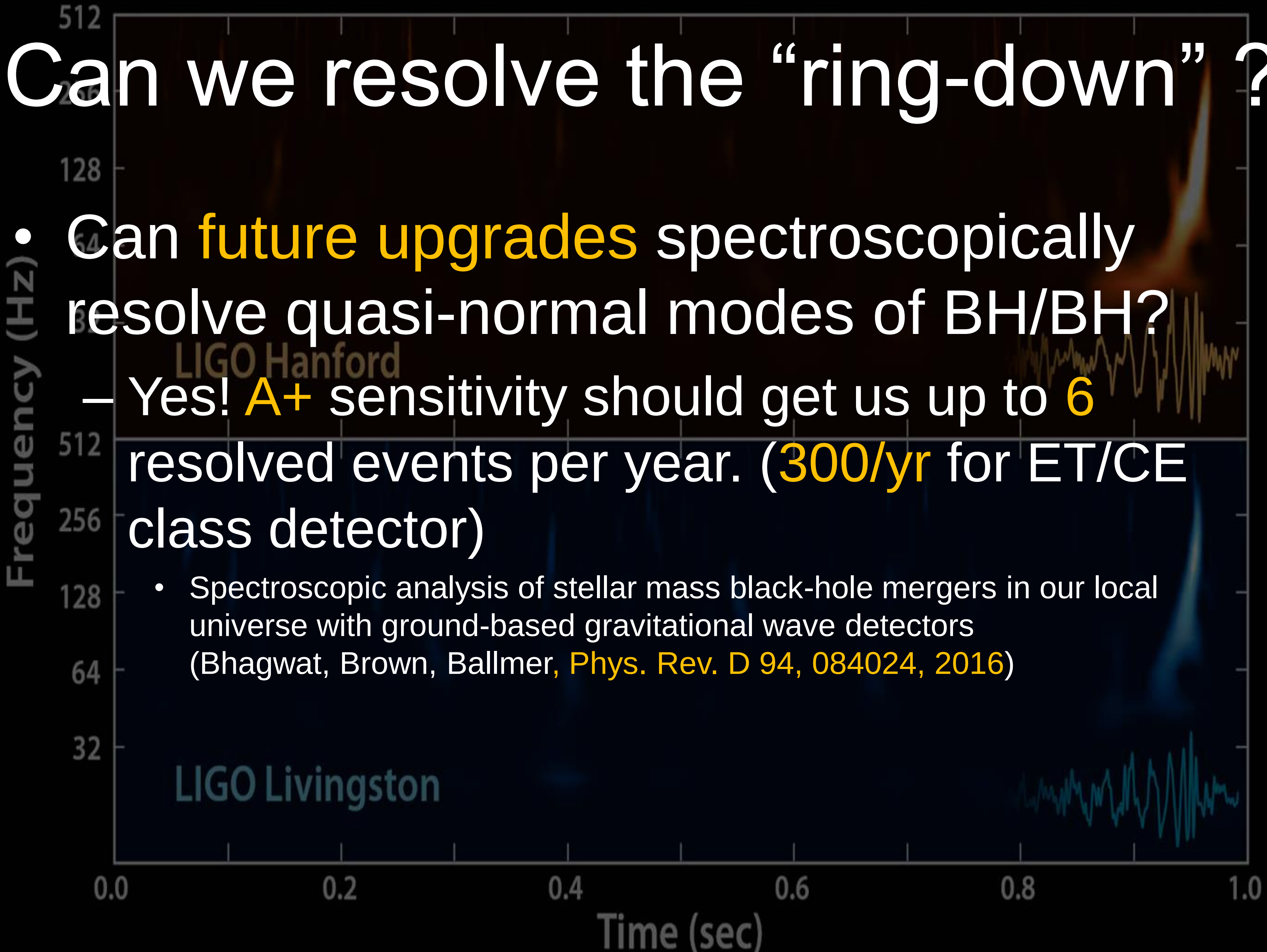
Can we resolve the “ring-down” ?

- What is the ring-down?
  - We see the wave form “peak and ring down”, just as predicted by Numerical Relativity.
  - But linear BH perturbation theory is not good enough for the first part of the “ring-down”.
  - The signal disappears in the noise just as linear BH perturbation theory becomes valid.

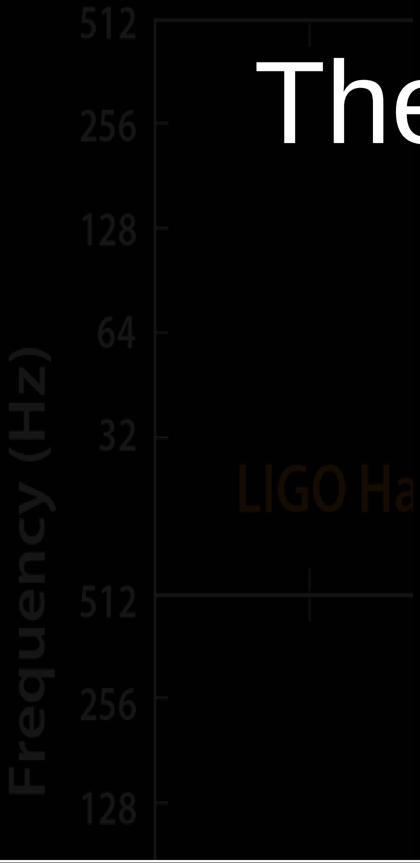


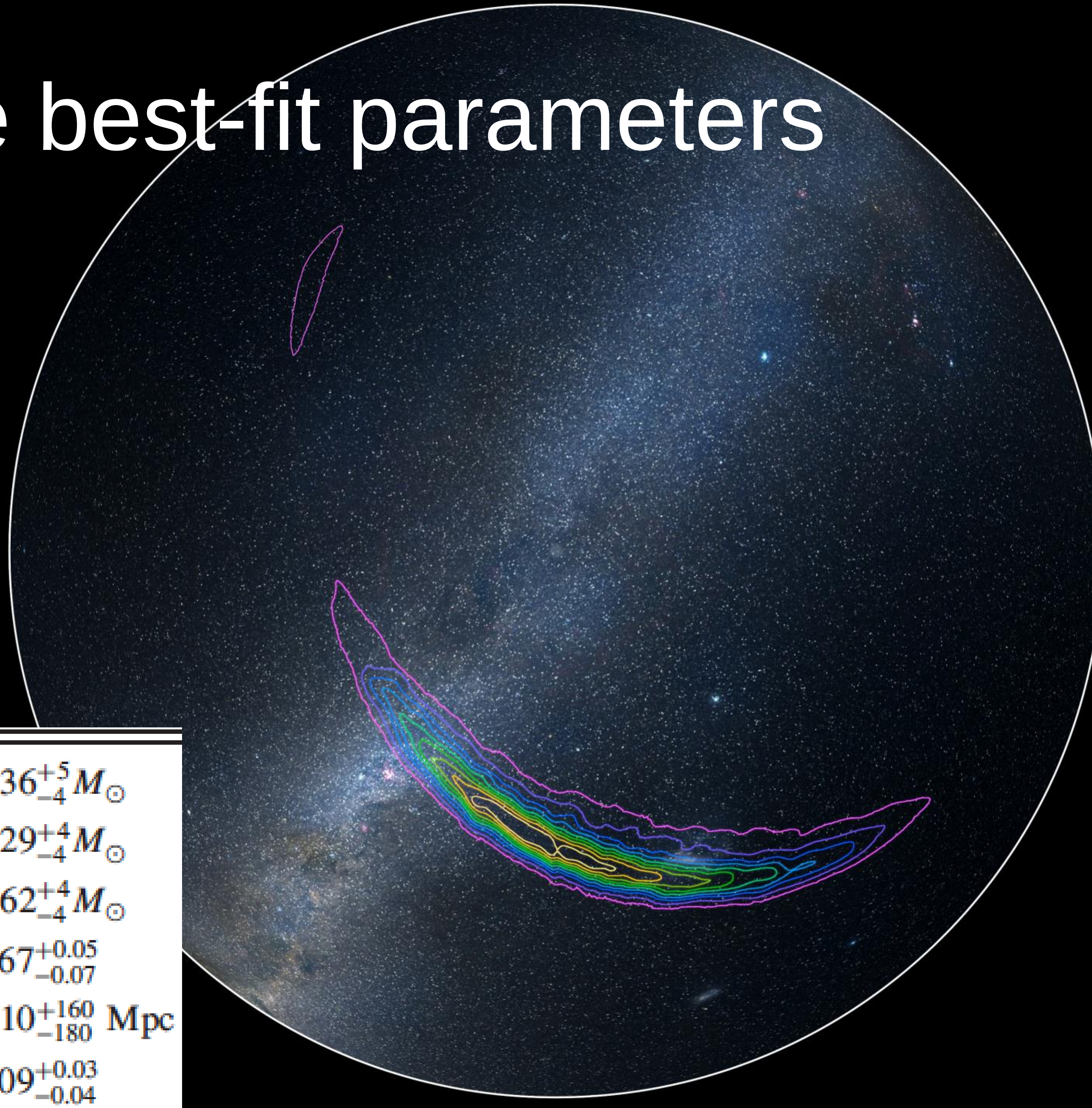
Can we resolve the “ring-down” ?

- Can future upgrades spectroscopically resolve quasi-normal modes of BH/BH?
  - Yes! A+ sensitivity should get us up to 6 resolved events per year. (300/yr for ET/CE class detector)
    - Spectroscopic analysis of stellar mass black-hole mergers in our local universe with ground-based gravitational wave detectors (Bhagwat, Brown, Ballmer, Phys. Rev. D 94, 084024, 2016)



The best-fit parameters

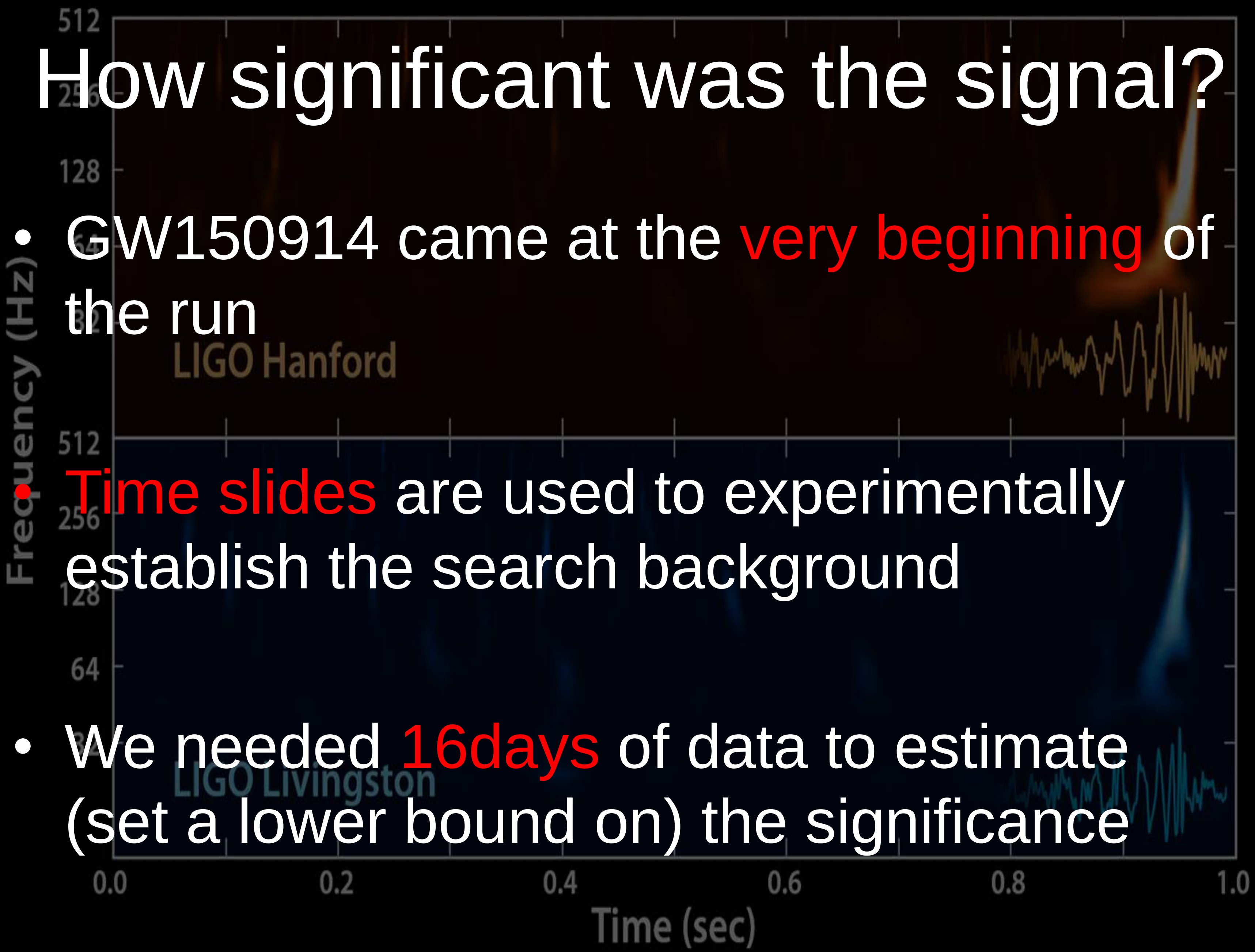


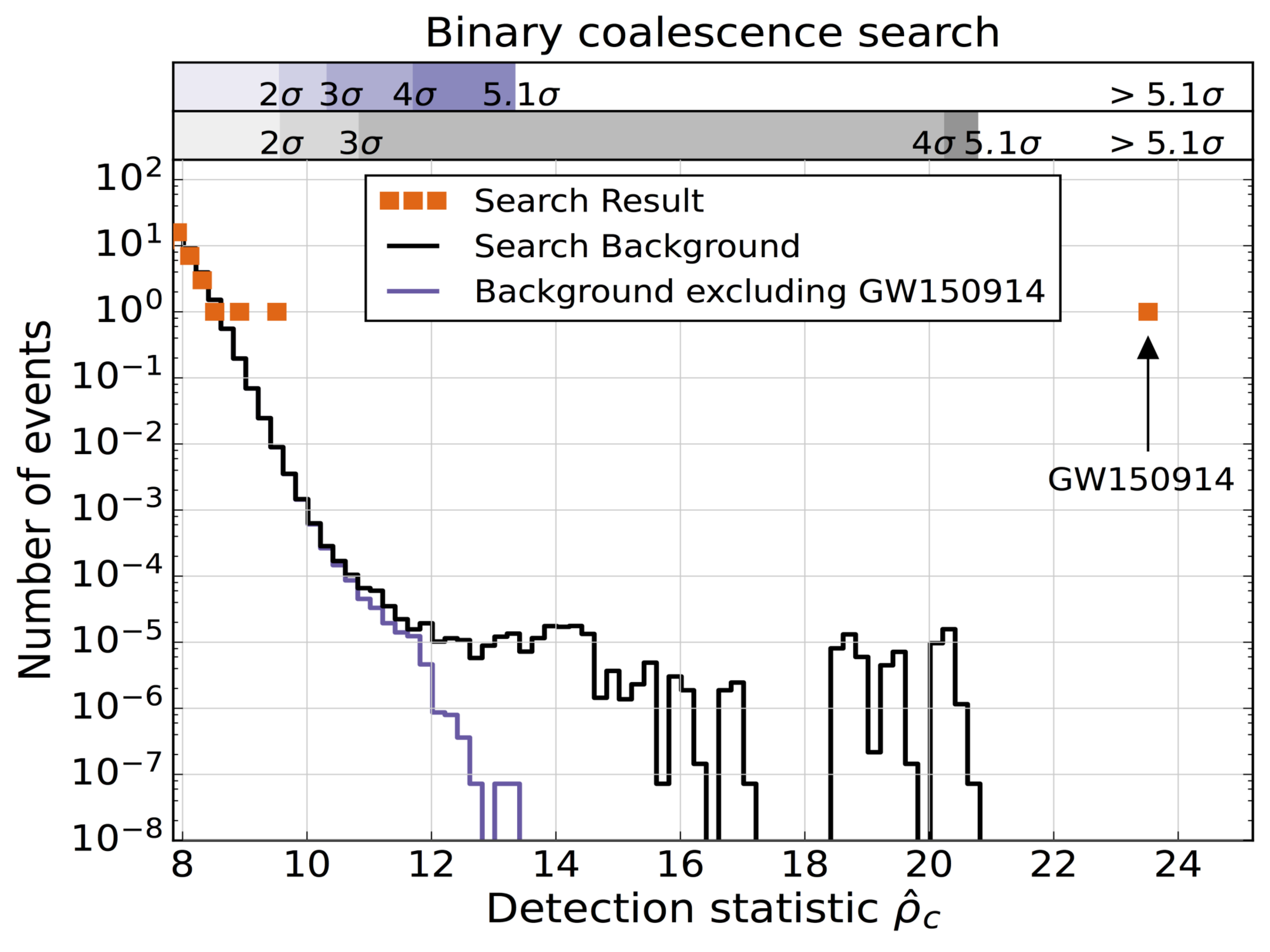


Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

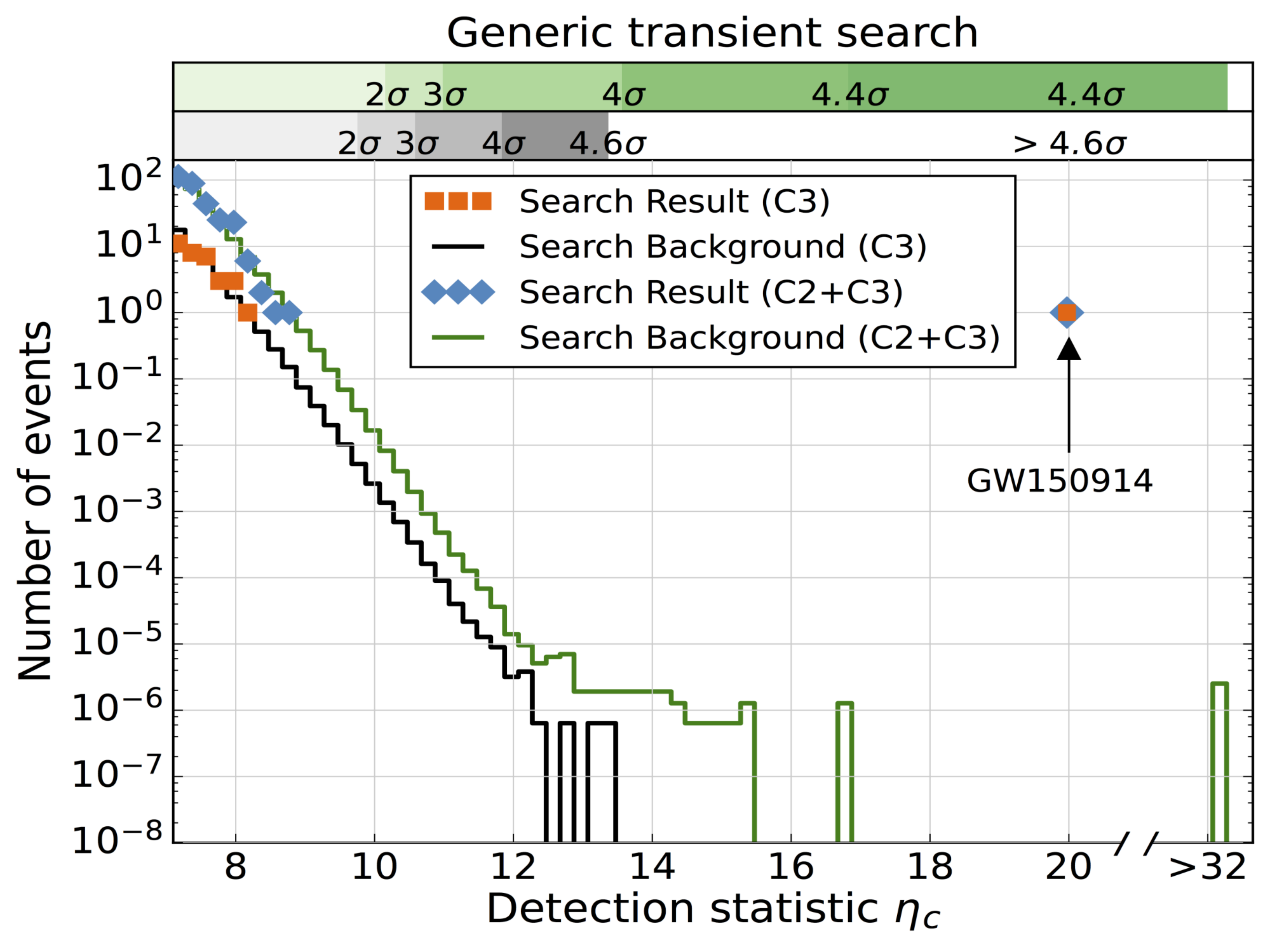
How significant was the signal?

- GW150914 came at the very beginning of the run
- Time slides are used to experimentally establish the search background
- We needed 16days of data to estimate (set a lower bound on) the significance



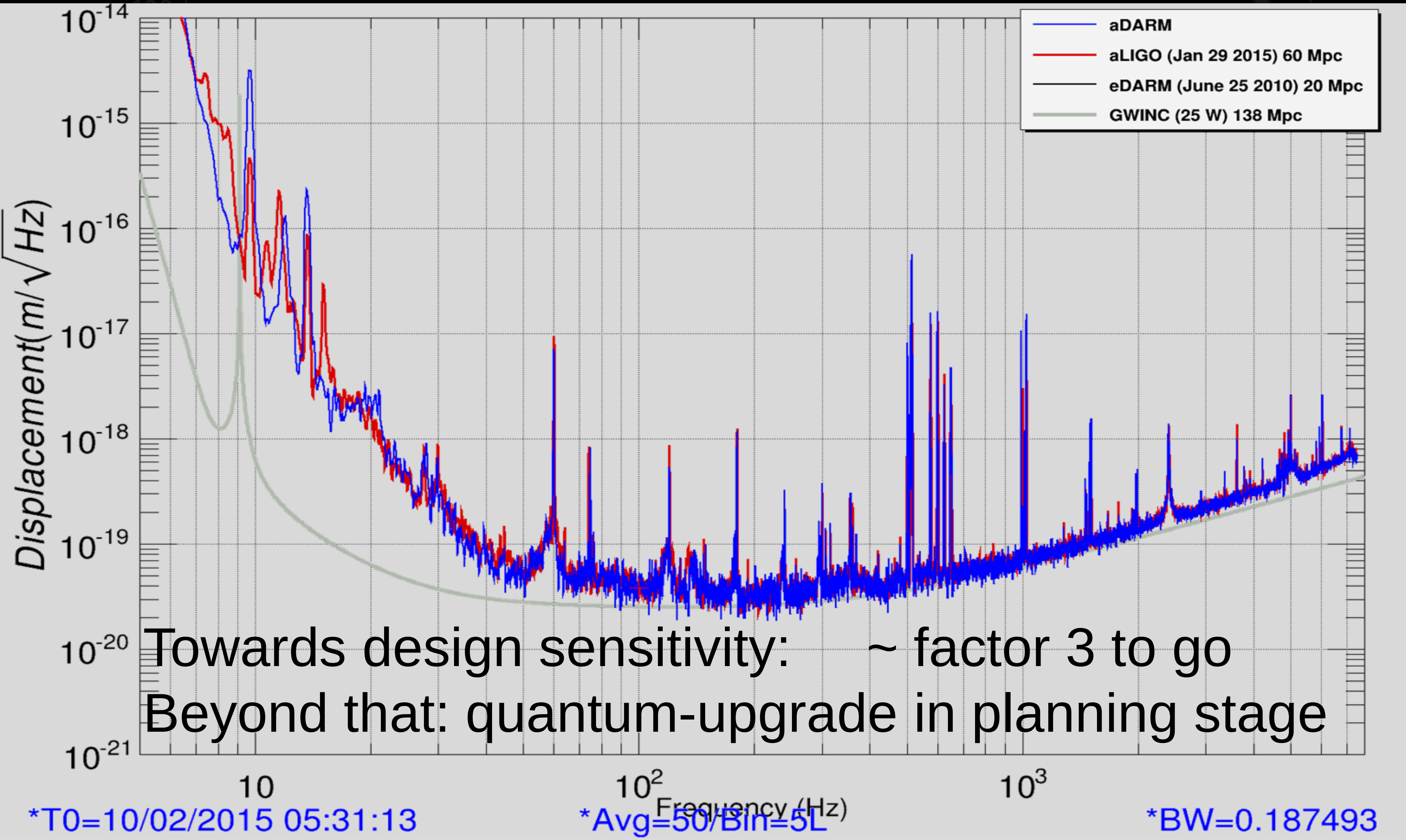


Binary coalescence search
2σ 3σ 4σ 5.1σ
> 5.1σ
2σ 3σ
4σ 5.1σ
> 5.1σ
Search Result
Search Background
Background excluding GW150914
GW150914
Number of events
Detection statistic $\hat{\rho}_c$
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
8
10
12
14
16
18
20
22
24



Generic transient search
2σ 3σ 4σ 4.4σ 4.4σ
2σ 3σ 4σ 4.6σ > 4.6σ
Search Result (C3)
Search Background (C3)
Search Result (C2+C3)
Search Background (C2+C3)
GW150914
Number of events
Detection statistic ηc
10^2 10^1 10^0 10^−1 10^−2 10^−3 10^−4 10^−5 10^−6 10^−7 10^−8
8 10 12 14 16 18 20 >32

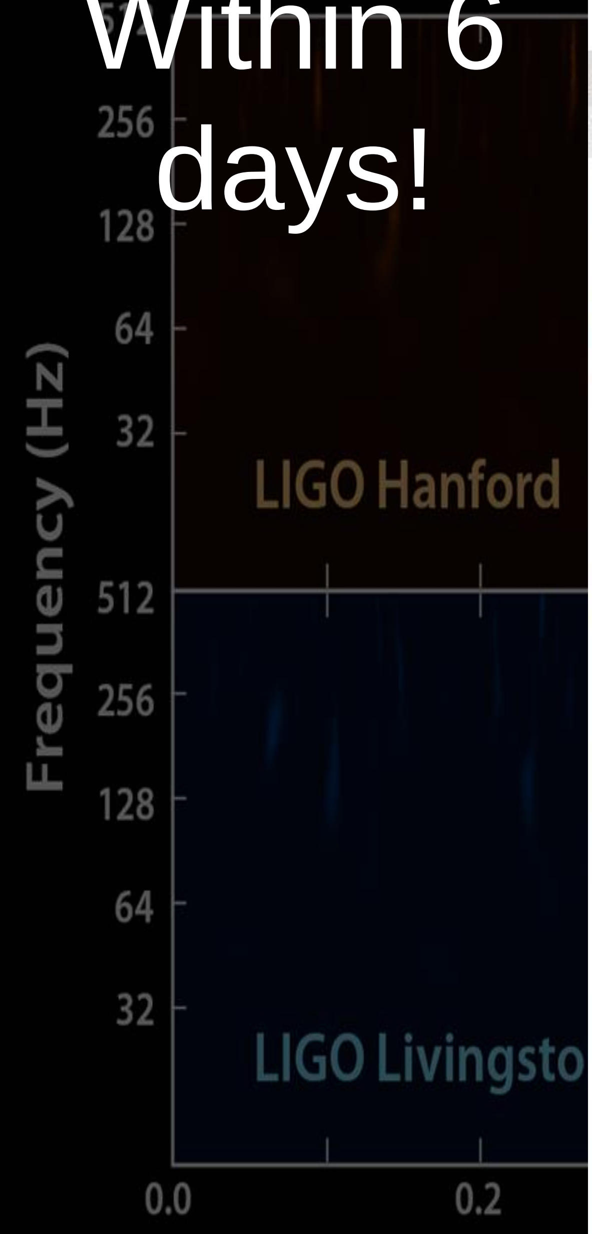
Next steps Advanced LIGO



Towards design sensitivity: ~ factor 3 to go

Beyond that: quantum-upgrade in planning stage

Within 6 days!



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SCI-TECH » SCIENCE

NEW DELHI, February 17, 2016

Updated: February 18, 2016 01:49 IST

Union Cabinet clears LIGO-India gravitational wave observatory

JACOB KOSHY

COMMENT · PRINT · T T

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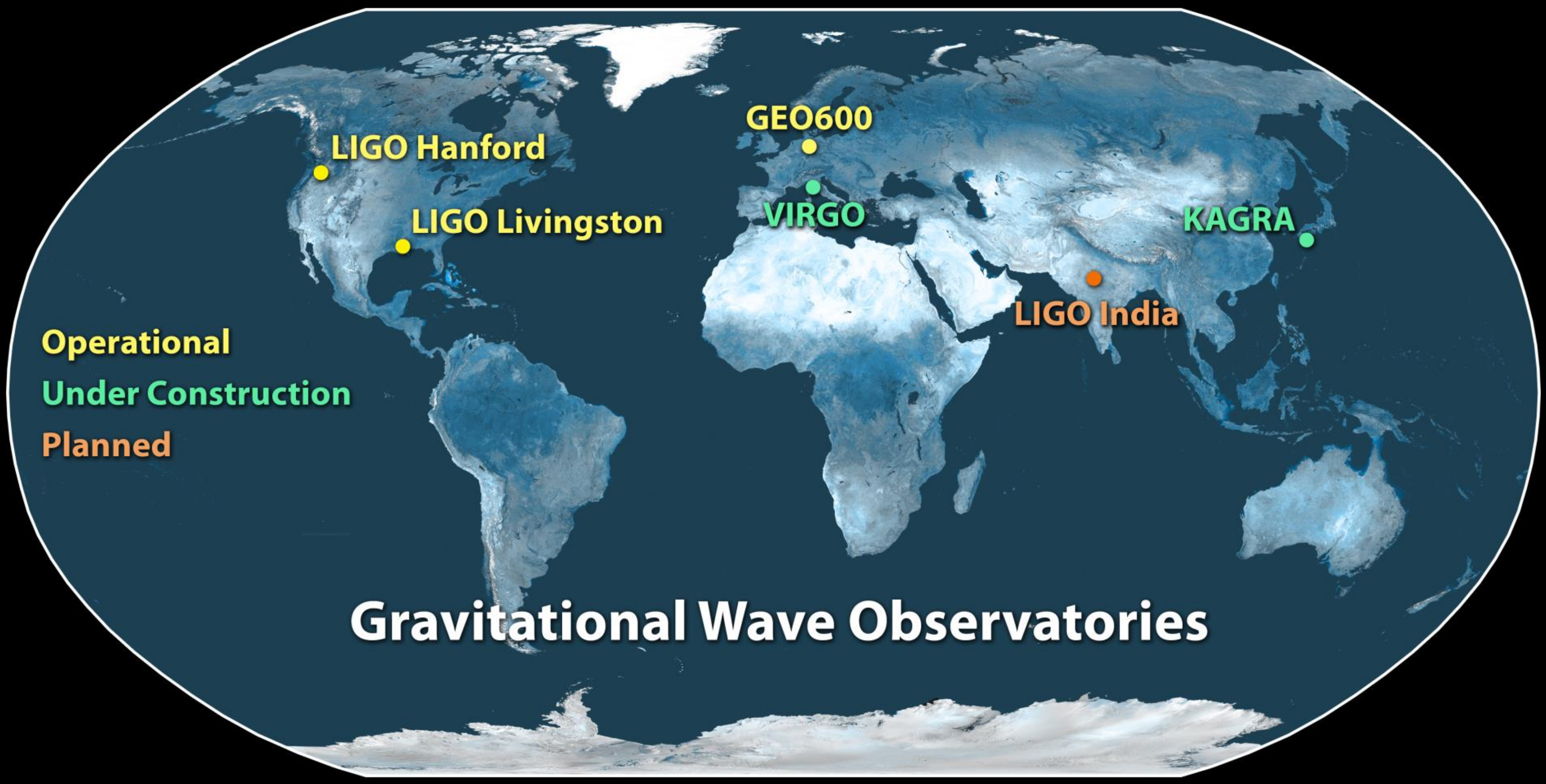
NSF Signs LIGO-India MOU

Secretary of India Department of Atomic Energy Sekhar Basu

NSF Director France A. Córdova

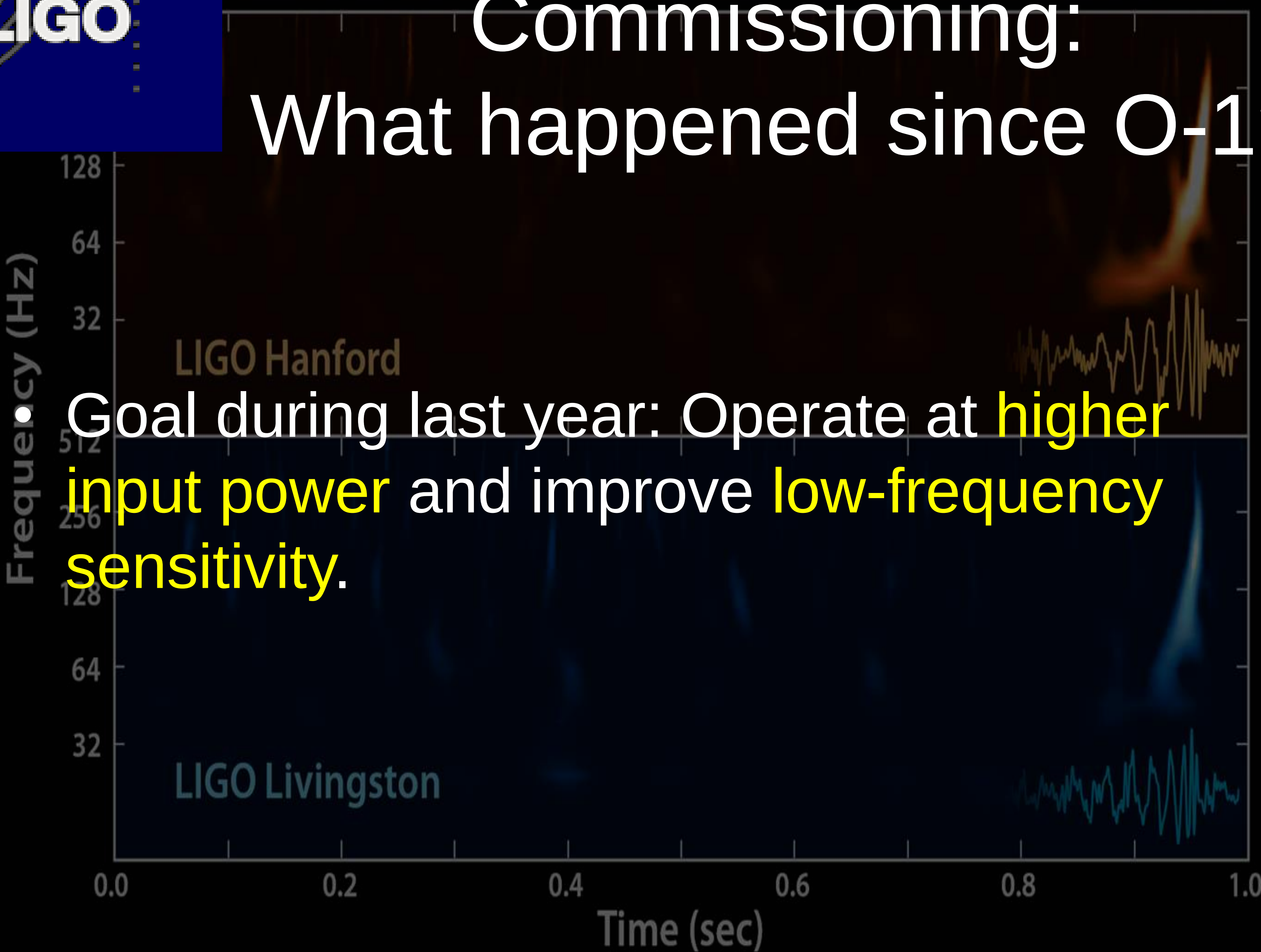
March 31, 2016

Future Detectors



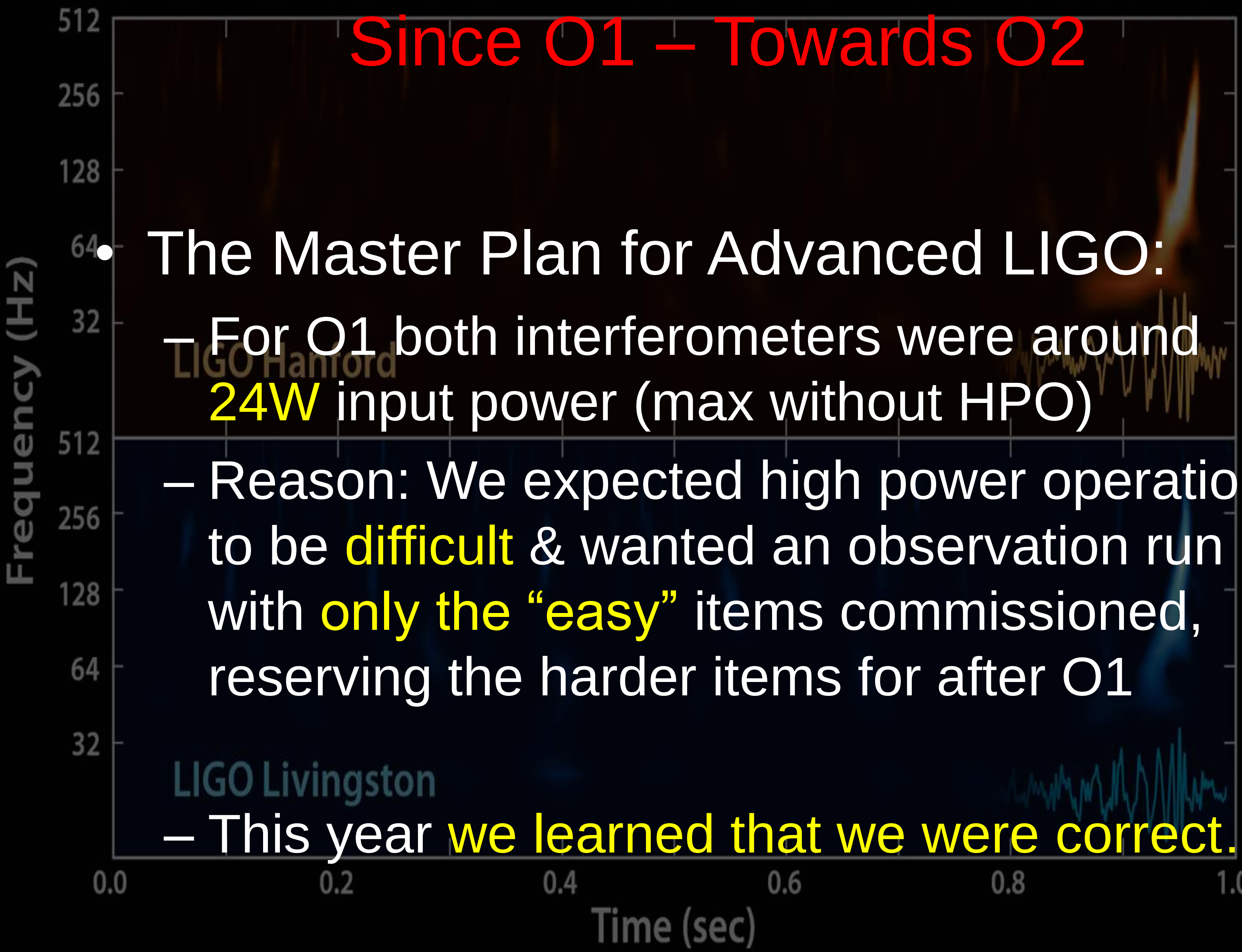
Commissioning:
What happened since O-1?

- Goal during last year: Operate at higher input power and improve low-frequency sensitivity.

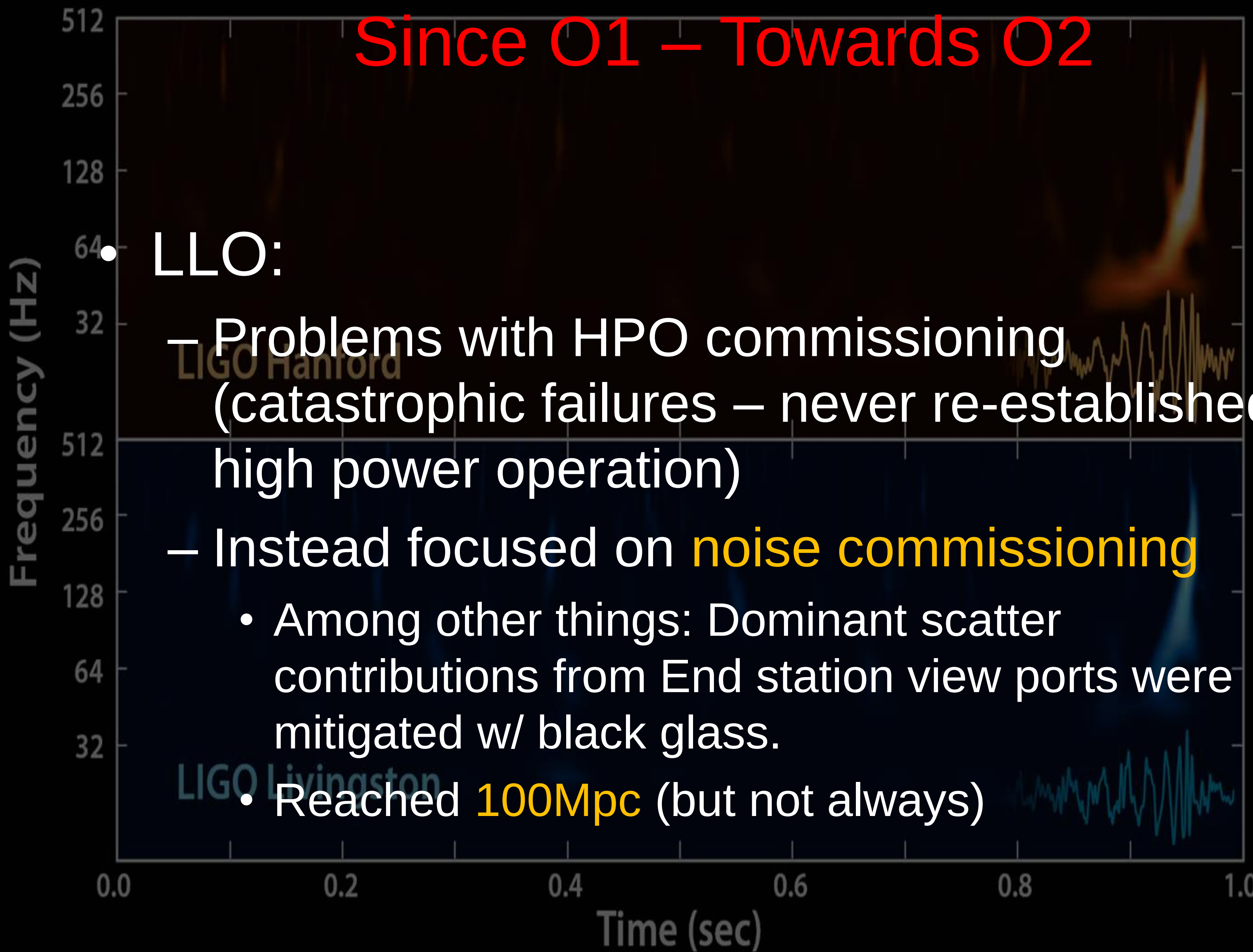


Since O1 – Towards O2

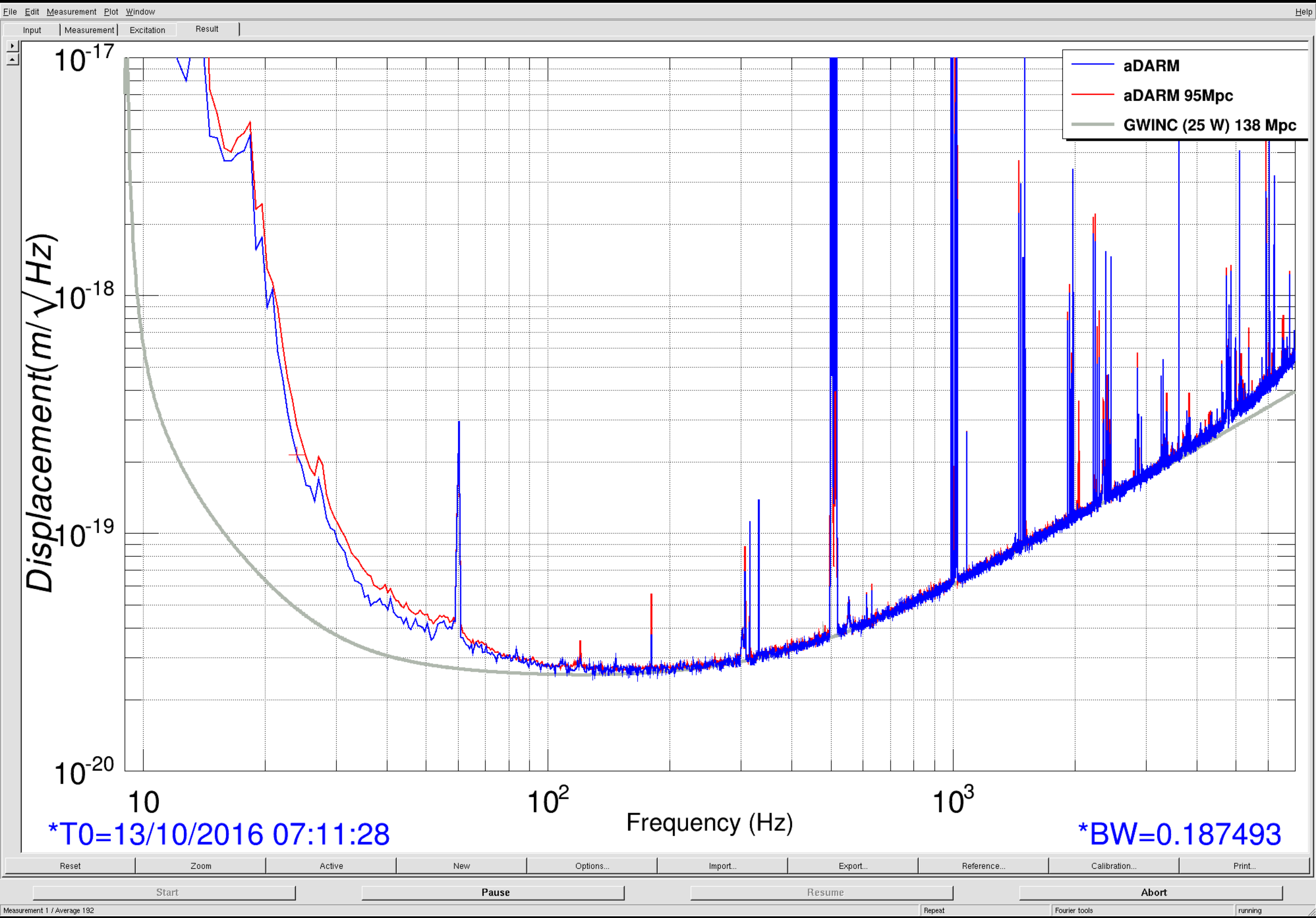
- The Master Plan for Advanced LIGO:
  - For O1 both interferometers were around 24W input power (max without HPO)
  - Reason: We expected high power operation to be difficult & wanted an observation run with only the “easy” items commissioned, reserving the harder items for after O1
  - This year we learned that we were correct…



Since O1 – Towards O2

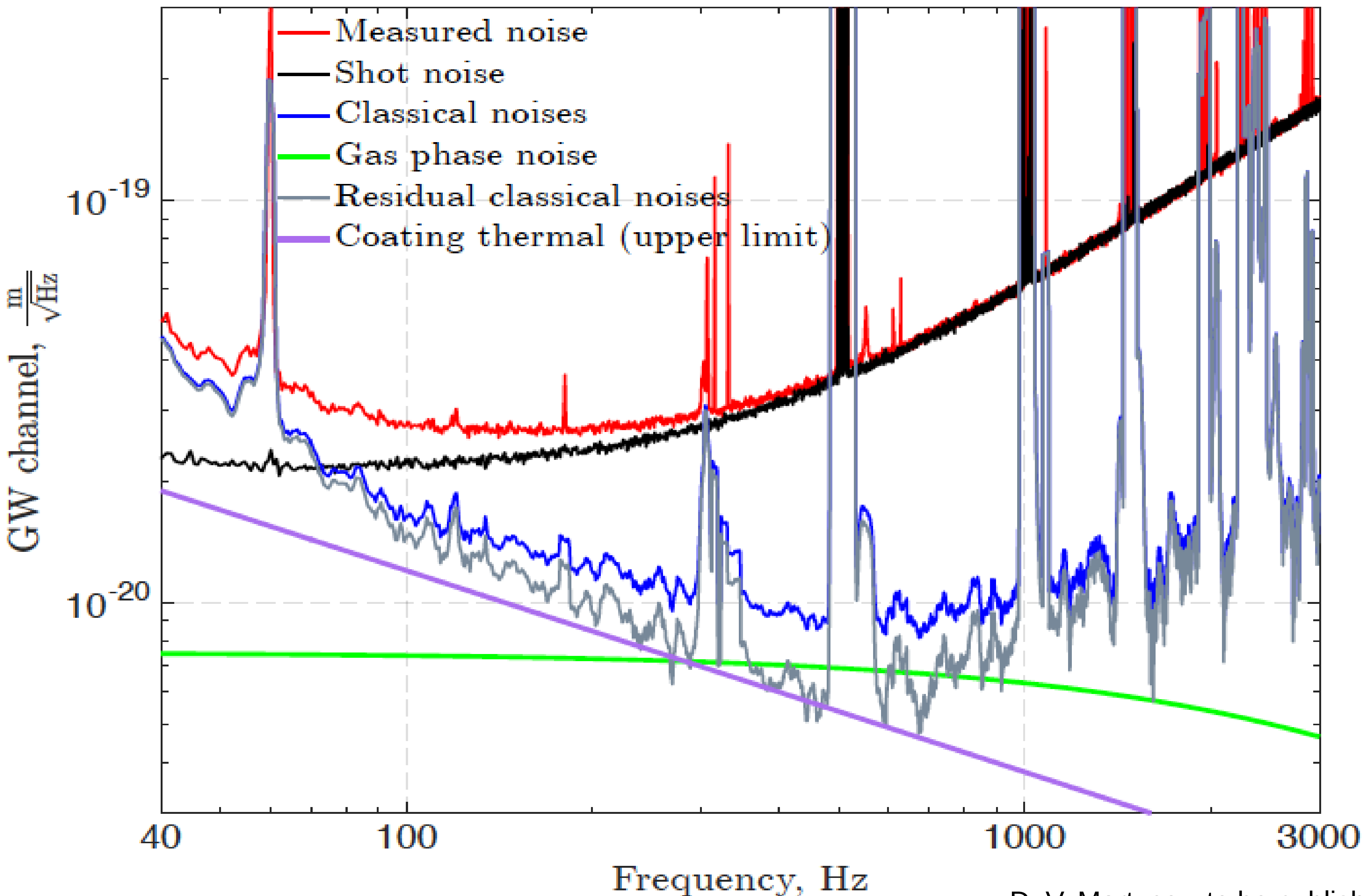


- LLO:
  - Problems with HPO commissioning (catastrophic failures – never re-established high power operation)
  - Instead focused on noise commissioning
    - Among other things: Dominant scatter contributions from End station view ports were mitigated w/ black glass.
    - Reached 100Mpc (but not always)



File Edit Measurement Plot Window
Help
Input
Measurement
Excitation
Result
aDARM
aDARM 95Mpc
GWINC (25 W) 138 Mpc
Displacement(m/√Hz)
10^-17
10^-18
10^-19
10^-20
10
10^2
10^3
Frequency (Hz)
*T0=13/10/2016 07:11:28
*BW=0.187493
Reset
Zoom
Active
New
Options...
Import...
Export...
Reference...
Calibration...
Print...
Start
Pause
Resume
Abort
Measurement 1 / Average 192
Repeat
Fourier tools
running

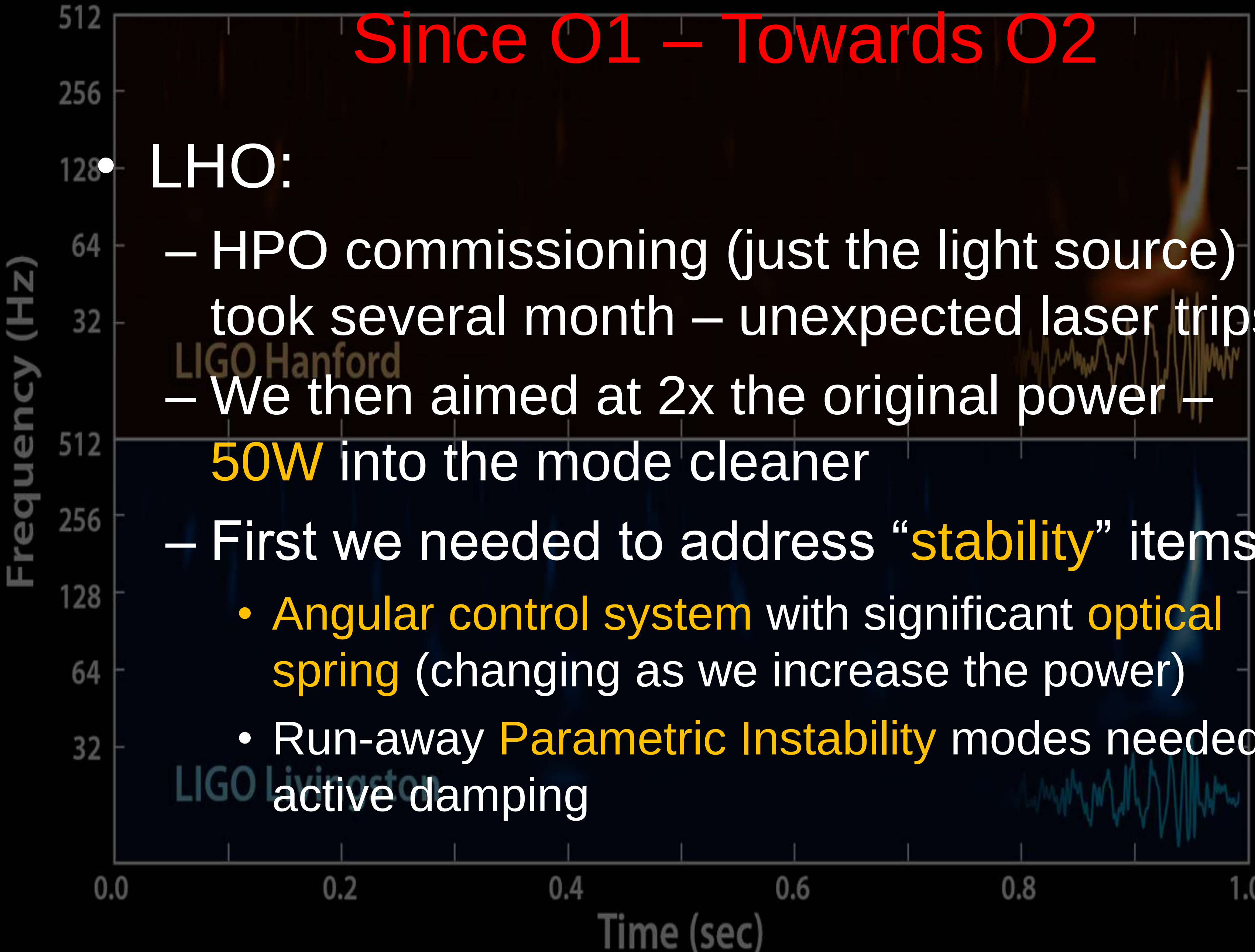
Classical noise below shot noise



D. V. Martynov, to be published

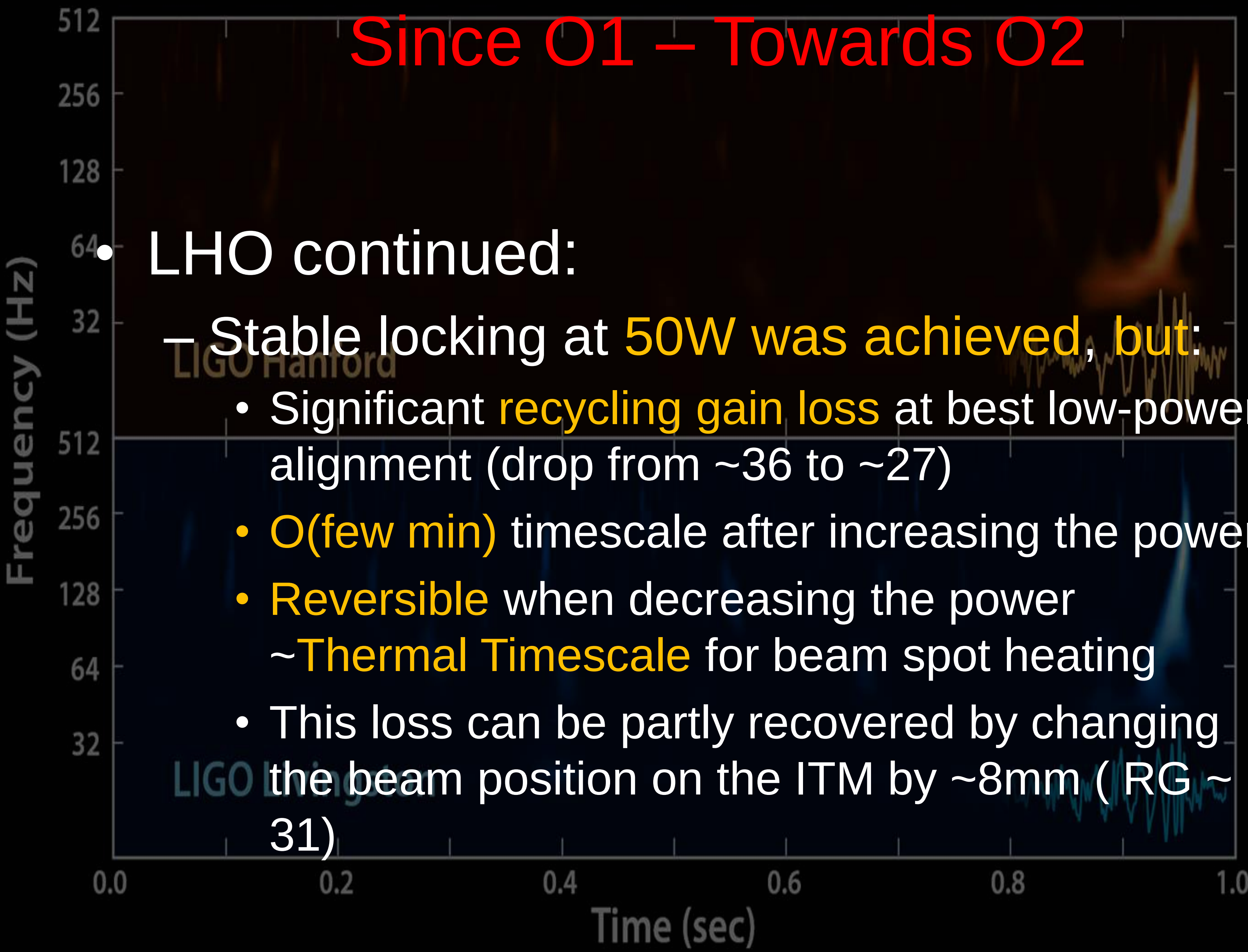
Since O1 – Towards O2

- LHO:
  - HPO commissioning (just the light source) took several month – unexpected laser trips
  - We then aimed at 2x the original power – 50W into the mode cleaner
  - First we needed to address “stability” items:
    - Angular control system with significant optical spring (changing as we increase the power)
    - Run-away Parametric Instability modes needed active damping



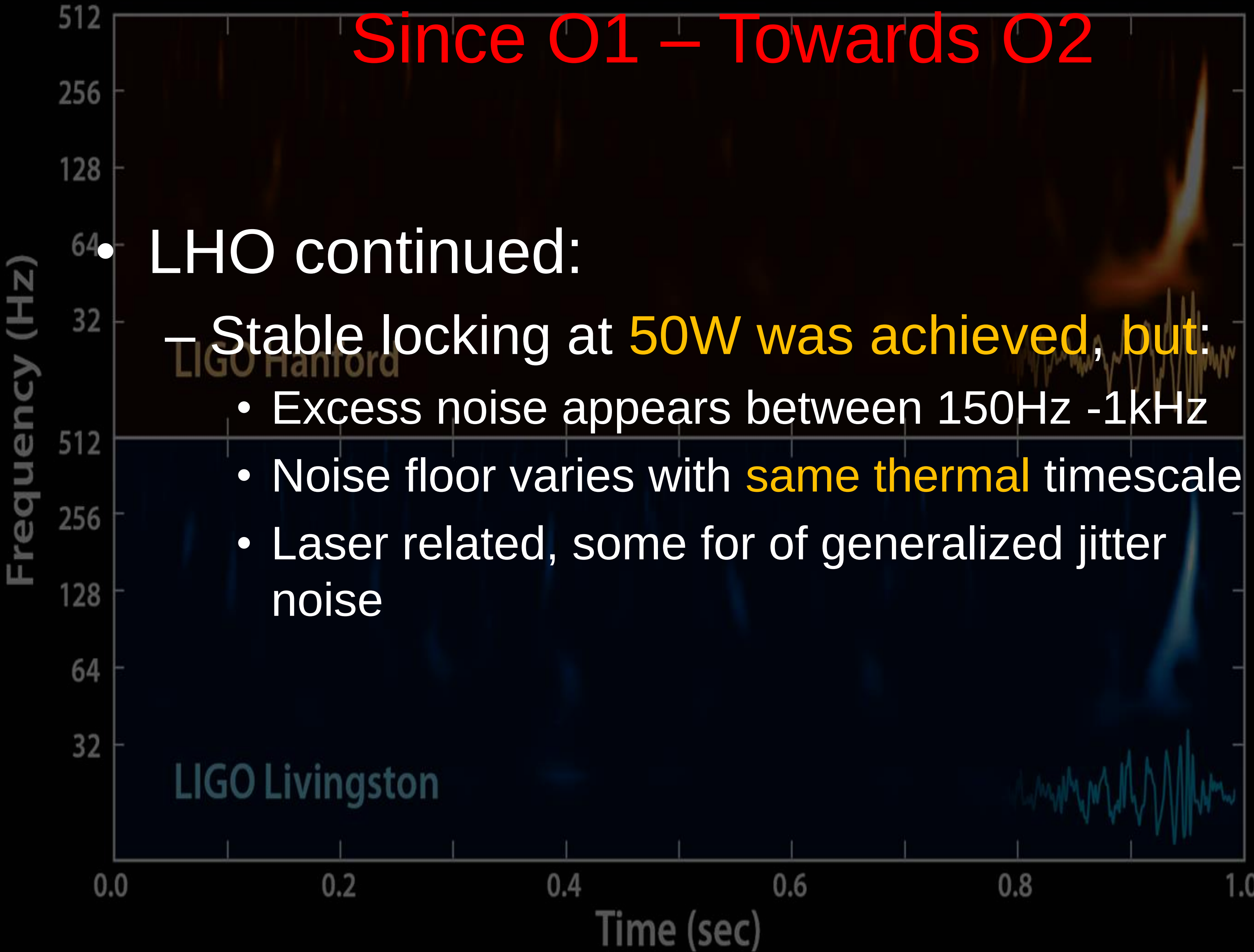
Since O1 – Towards O2

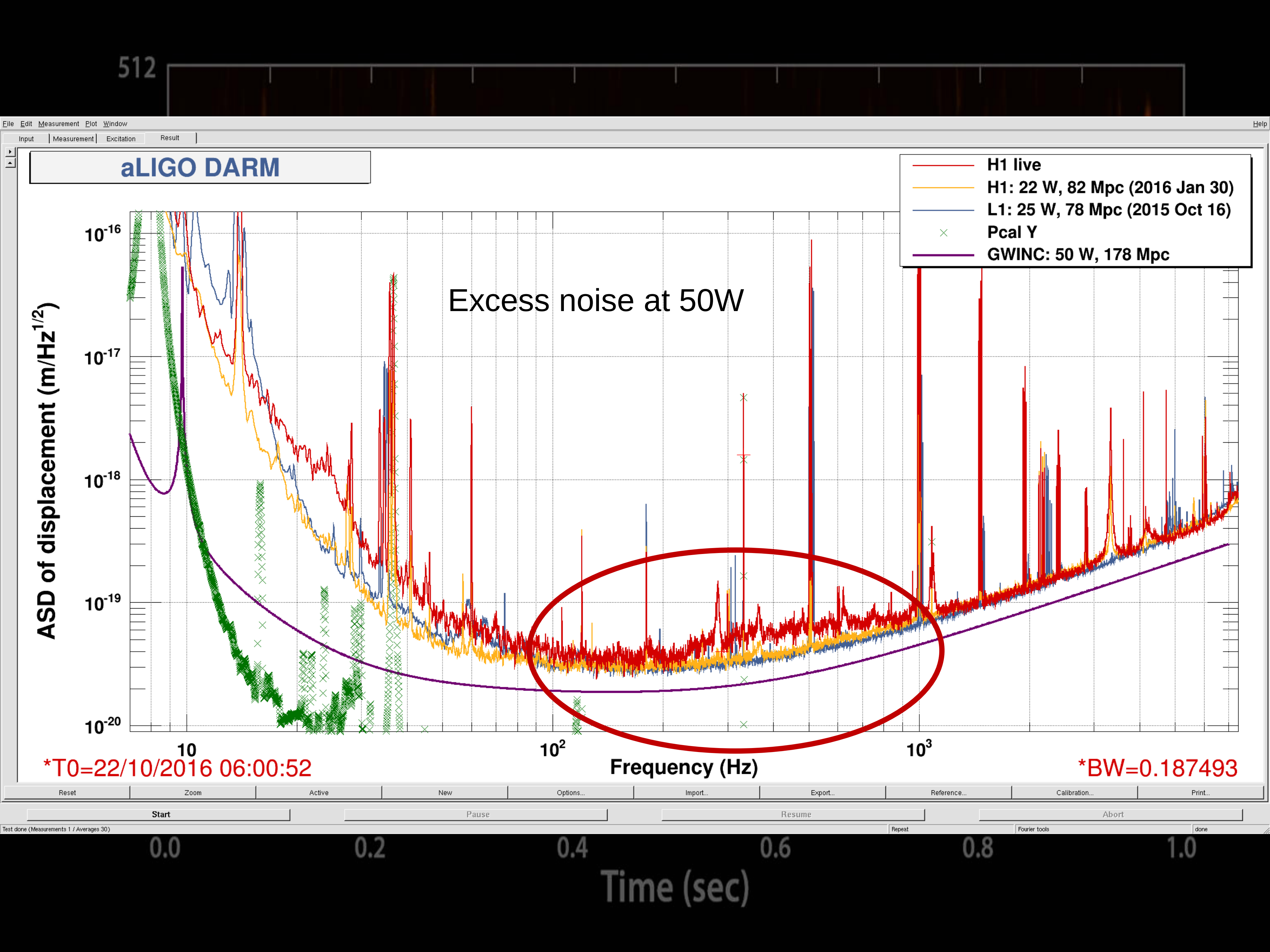
- LHO continued:
  - Stable locking at 50W was achieved, but:
    - Significant recycling gain loss at best low-power alignment (drop from ~36 to ~27)
    - O(few min) timescale after increasing the power
    - Reversible when decreasing the power ~Thermal Timescale for beam spot heating
    - This loss can be partly recovered by changing the beam position on the ITM by ~8mm (RG ~ 31)



Since O1 – Towards O2

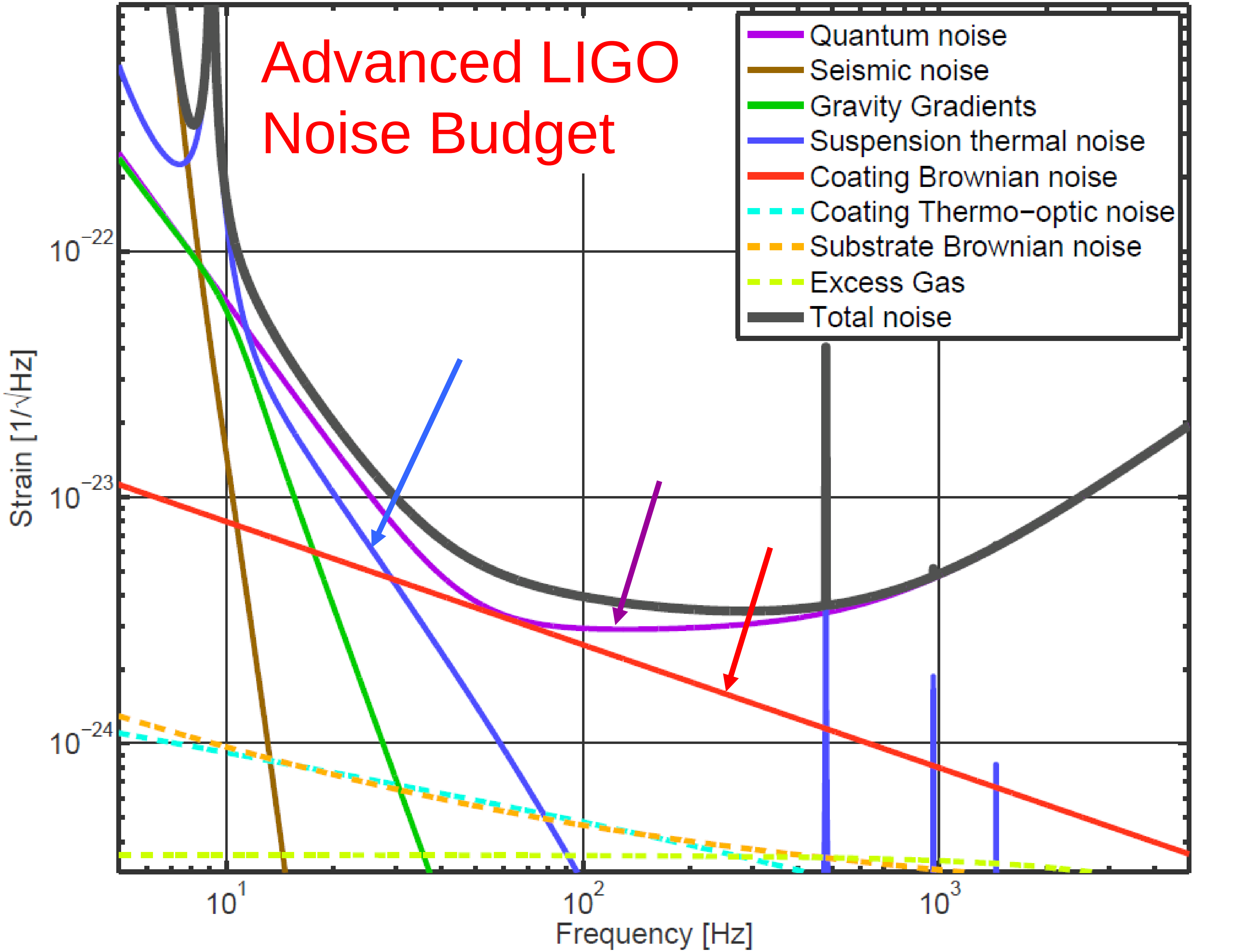
- LHO continued:
  - Stable locking at 50W was achieved, but:
    - Excess noise appears between 150Hz -1kHz
    - Noise floor varies with same thermal timescale
    - Laser related, some for of generalized jitter noise




aLIGO DARM
H1 live
H1: 22 W, 82 Mpc (2016 Jan 30)
L1: 25 W, 78 Mpc (2015 Oct 16)
Pcal Y
GWINC: 50 W, 178 Mpc
Excess noise at 50W
ASD of displacement (m/Hz^1/2)
10^-16
10^-17
10^-18
10^-19
10^-20
10
10^2
10^3
Frequency (Hz)
*T0=22/10/2016 06:00:52
*BW=0.187493
Time (sec)
0.0
0.2
0.4
0.6
0.8
1.0
512

What next?

- O2 run ongoing, we should observe additional BBH mergers.
- Can we go beyond the sensitivity of these initial observatories?


Advanced LIGO
Noise Budget
Quantum noise
Seismic noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo−optic noise
Substrate Brownian noise
Excess Gas
Total noise
Strain [1/√Hz]
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
Frequency [Hz]

What 10x the Sensitivity would give us

- **Stellar Evolution at High Red-Shift: Black Holes from the first stars (Population III)**
  - Reach $z>\sim10$
  - Moderate GW luminosity distance precision

- **Checking GR in extreme regime / NS EoS**
  - High Signal-to-Noise needed

MIT Research Laboratory of Electronics Quarterly Progress Report 1972

The antenna arms can be made as large as is consistent with the condition that the travel time of light in the arm is less than one-half the period of the gravitational wave that is to be detected. This points out the principal feature of electromagnetically coupled antennas

- Given the detector technology we installed in Advanced LIGO…

- What would limit the arm length? (without any new technology)

Scaling Up GW Detectors

- Nothing… 10x longer is technologically feasible

Biggest advantage:
Coating Brownian Thermal Nosie
becomes irrelevant (strain~$L^{-1.5}$)

Stefan W. Ballmer†
Department of Physics, Syracuse University, NY 13244, USA

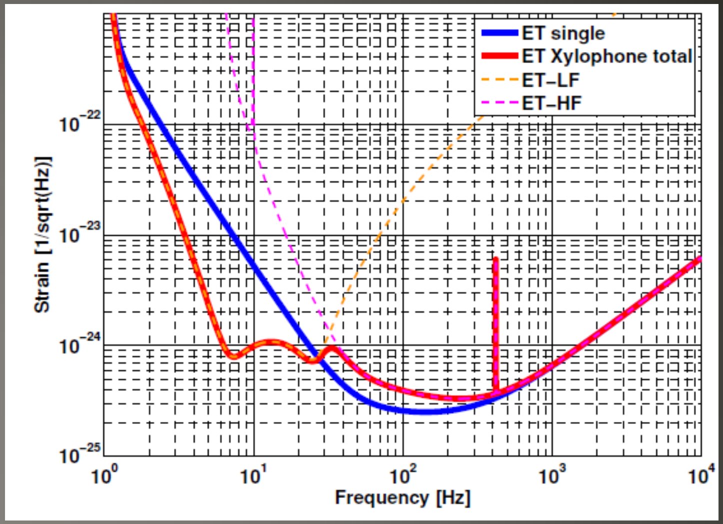
Lisa Barsotti, Nergis Mavalvala, and Matthew Evans
Massachusetts Institute of Technology, Cambridge, MA 02139, USA

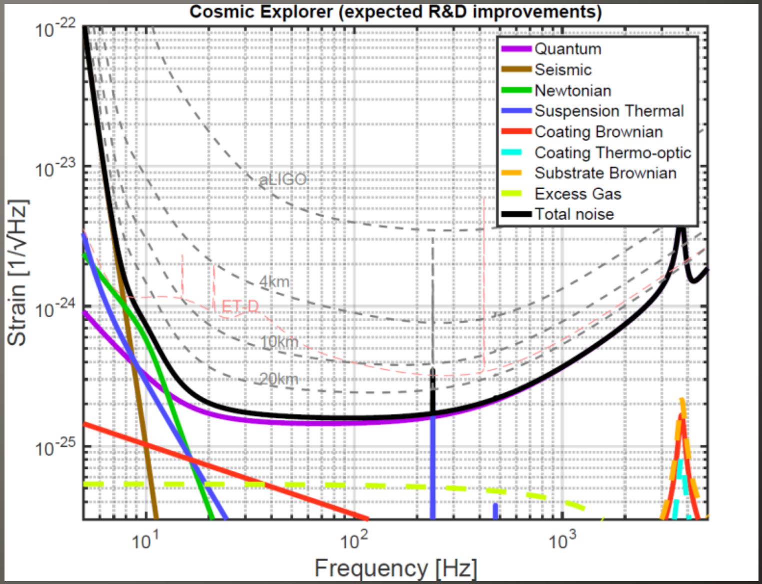
(Dated: January 10, 2015)

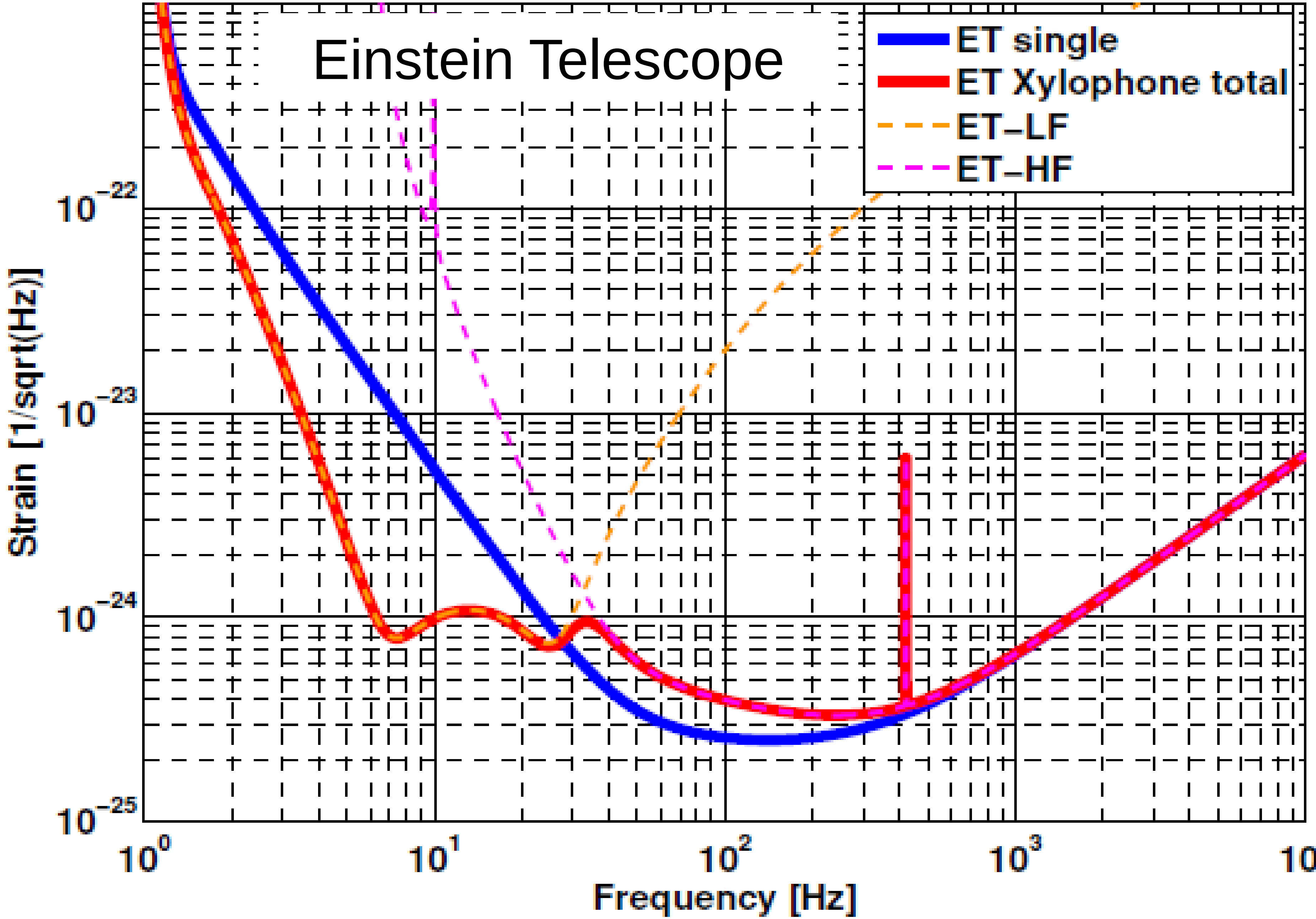
Phys. Rev. D 91, 082001

3^{rd} Generation Concepts

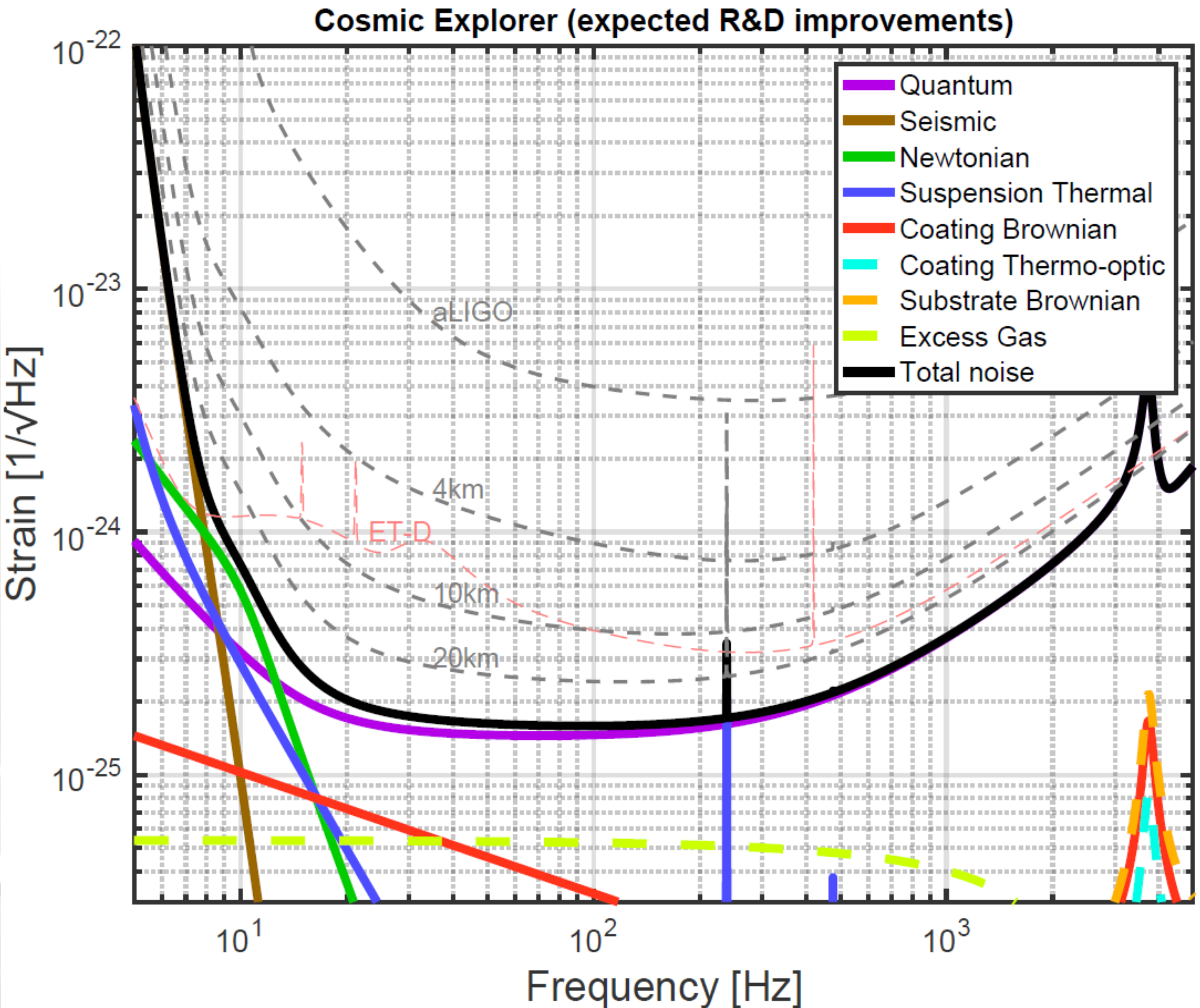
	CE	CE pess	ET-D (HF)	ET-D (LF)
L_{arm}	40 km	40 km	10 km	10 km
P_{arm}	2 MW	1.4 MW	3 MW	18 kW
λ	1550 nm	1064 nm	1064 nm	1550 nm
r_{sqz}	3	3	3	3
m_{TM}	320 kg	320 kg	200 kg	200 kg
r_{beam}	14 cm	12 cm	9 cm	7 cm (LG_{33})
T	123 K	290 K	290 K	10 K
ϕ_{eff}	5×10^{-5}	1.2×10^{-4}	1.2×10^{-4}	1.3×10^{-4}



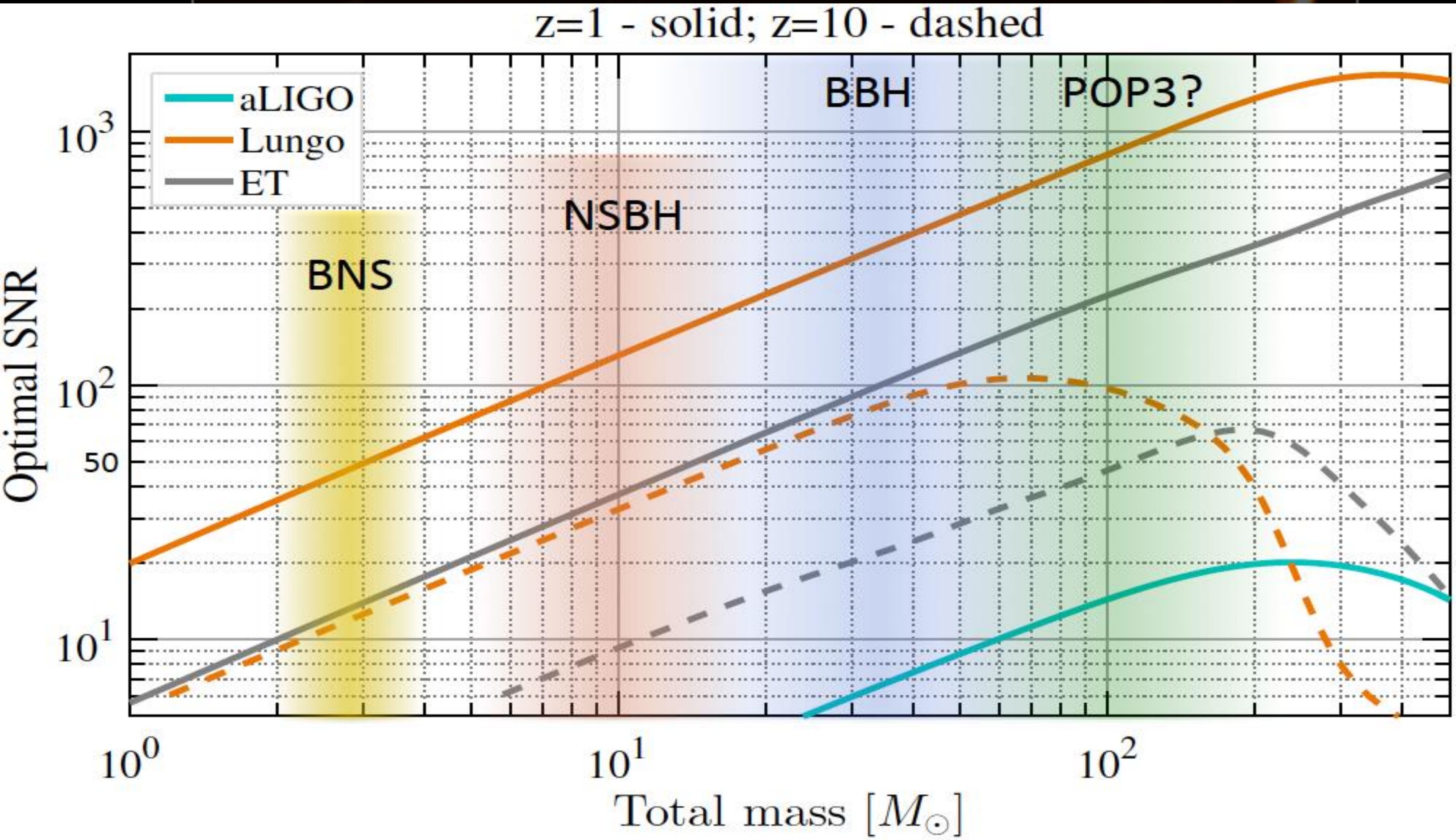



Einstein Telescope
ET single
ET Xylophone total
ET−LF
ET−HF
Strain [1/sqrt(Hz)]
Frequency [Hz]
10^−22
10^−23
10^−24
10^−25
10^0
10^1
10^2
10^3

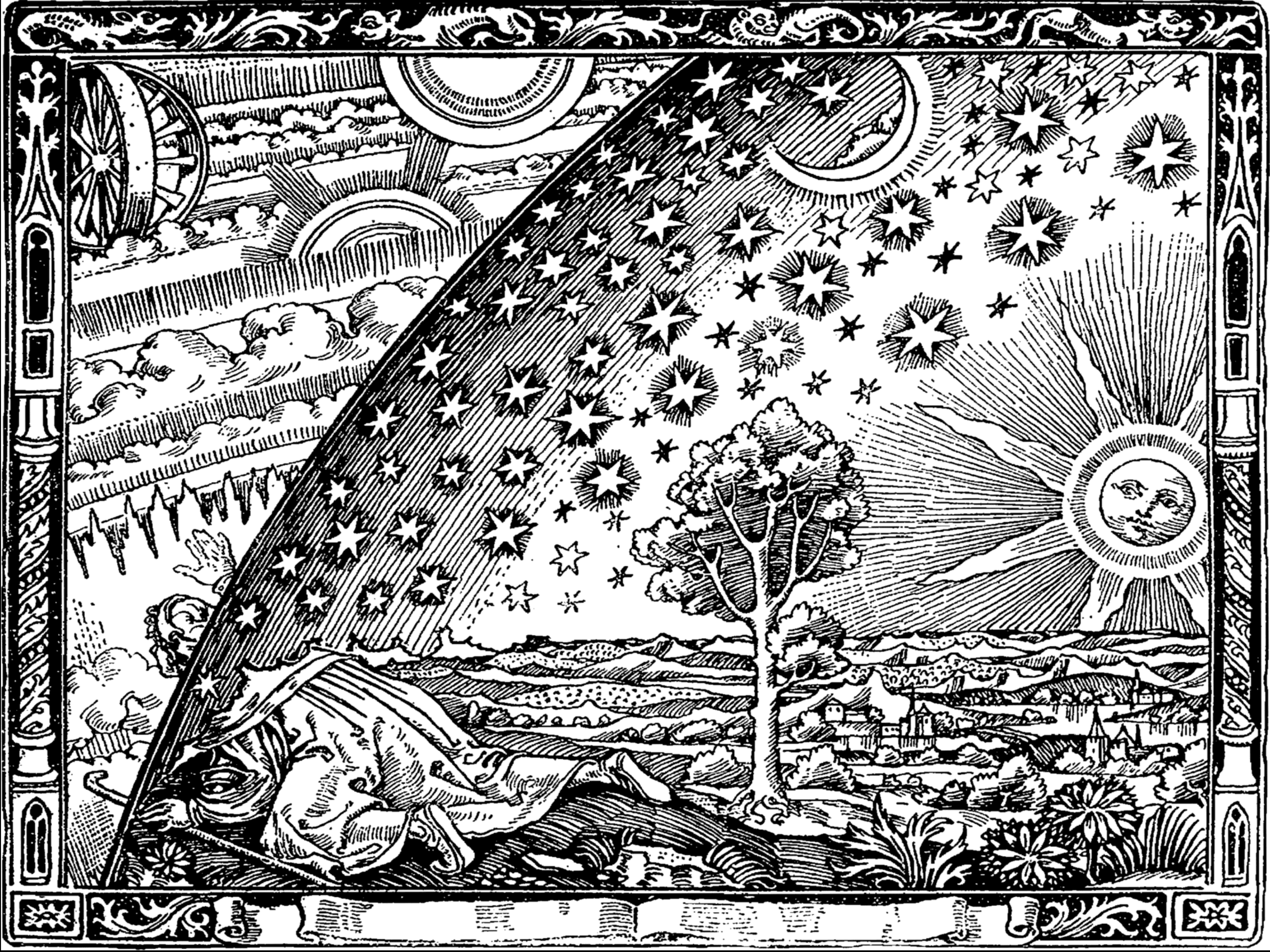
Cosmic Explorer expected scale matched to previous slide



The Future: New Observatories



Future
Global Detector Array



LIGO Scientific Collaboration

LIGO

LSC

Trinity University

University of Maryland 1856

Andrews University

Washington State University

California State University Fullerton

indigo

ANU The Australian National University

Texas Tech University

R·I·T

ICTP SAIFR

Montana State University

Sonoma State University

University of the West of Scotland UWS

Montclair State University

Tsinghua University

American University Washington, DC

University of Strathclyde

Michigan

University of Glasgow

Whitman College

LSU

CITA–ICAT

Goddard Space Flight Center

ACU

UTB TSC

University of Cambridge

The University of Western Australia

California Institute of Technology 1891

University of Minnesota

The University of Mississippi

The University of Adelaide Australia

The University of Melbourne

Massachusetts Institute of Technology

Southern University Agricultural & Mechanical College

Embry-Riddle Aeronautical University

University of Washington

GEO 600

Universitat de les Illes Balears

Northwestern University 1851

Syracuse University Founded AD 1870

Cardiff University

Charles Sturt University

UF University of Florida

Georgia Tech

University of Wisconsin UW Milwaukee

Universität Hamburg

ACIGA

University of Southampton

Korean Gravitational-Wave Group

University of Rochester

Leibniz Universität Hannover

Penn State 1855

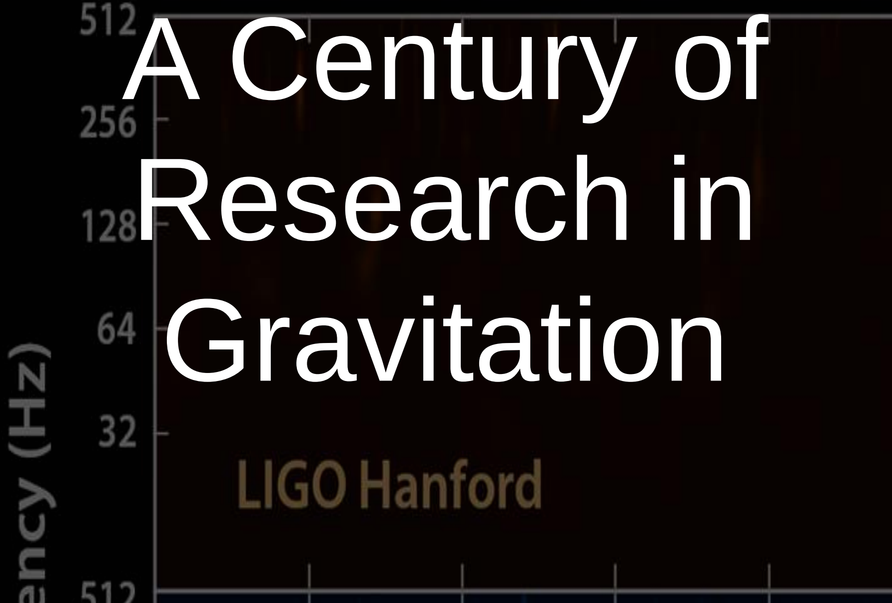
Hobart and William Smith Colleges

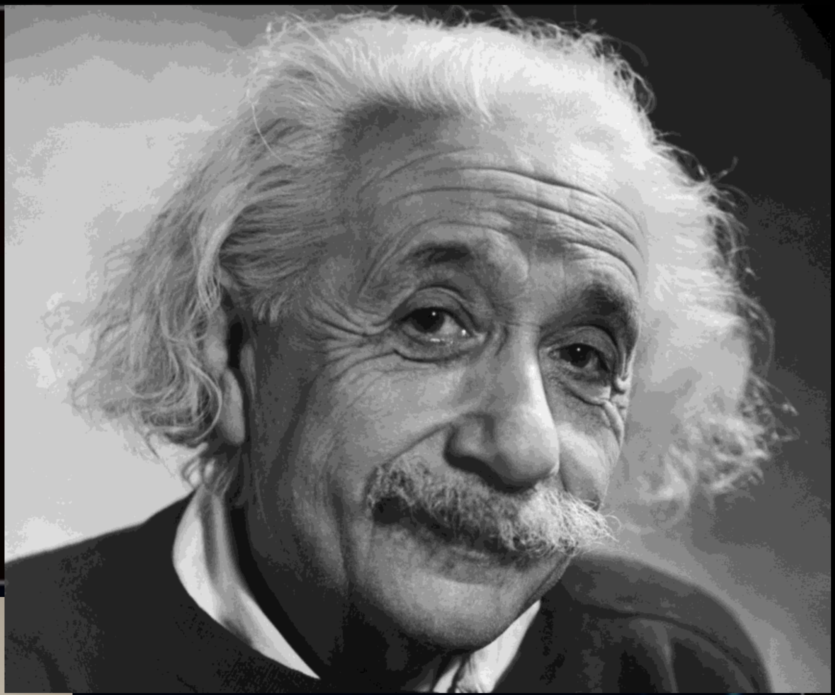
Science & Technology Facilities Council Rutherford Appleton Laboratory

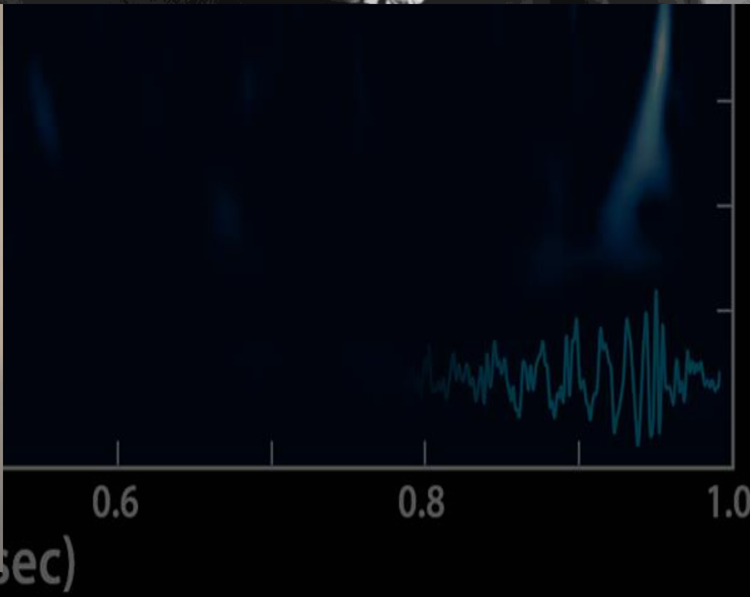
LIGO HANFORD OBSERVATORY

LIGO LIVINGSTON OBSERVATORY STAFF

A Century of Research in Gravitation







Conclusion

- The observation of GW150914 marks a historic turning point, opening up Gravitational Wave Astronomy at the centennial of their prediction.
- Technology available for both short and long-term upgrades
- Detectors that can sustain Gravitational-Wave Astrophysics for the rest of the 21st century are feasible.


Thank you!