Gravitational Waves - Ripples in Spacetime from Colliding Black Holes

Dr. Brian Lantz
for the LIGO Scientific Collaboration &
the Virgo Collaboration
KLA-Tencor, May 2, 2017

black hole image courtesy of LISA,
http://lisa.jpl.nasa.gov

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LIGO

LSC

LIGO Scientific Collaboration

Trinity University
University of Maryland 1856
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Whitman College
American University Washington, DC
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
University of Sheffield
University of Strathclyde
University of the West of Scotland UWS
College of William & Mary
Texas Tech University
清華大學 Tsinghua University
R·I·T
Stanford University
Max Planck Institute for Gravitational Physics Albert Einstein Institute
Michigan
PAH
Università degli Studi del Sannio
CITA | ICAT Canadian Institute for Theoretical Astrophysics L'institut Canadien d'astrophysique théorique
Université Libre de Bruxelles
Massachusetts Institute of Technology
NASA Goddard Space Flight Center
ICTP SAIFR
The University of Western Australia
ACU
West Virginia University
Monash University
Southern University Agricultural & Mechanical College
University of Cambridge
The University of Chicago
Montana State University
The University of Mississippi
The University of Adelaide Australia
Columbia University in the City of New York
Caltech
University of Minnesota
University of Birmingham
The University of Melbourne
University of Oregon
GEO 600
University of Szeged
UIB Universitat de les Illes Balears
UTRGV
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Lomonosov Moscow State University
Carleton College
Eötvös Loránd University
University of Washington
University of Wisconsin–Milwaukee
Universität Hamburg
Syracuse University
Cardiff University Prifysgol Caerdydd
National Tsing Hua University
Northwestern
Monash University
INPE
UF University of Florida
Georgia Institute of Technology
Korean Gravitational-Wave Group
LSU Louisiana State University
ACIGA
University of Southampton
Charles Sturt University
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
PennState
Hobart and William Smith Colleges
Science & Technology Facilities Council Rutherford Appleton Laboratory

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Science & Technology Facilities Council Rutherford Appleton Laboratory

LIGO National Science Foundation + International partners

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International Network

map from http://www.nationsonline.org/maps/political_world_map3000.jpg

Sept. 14, 2015

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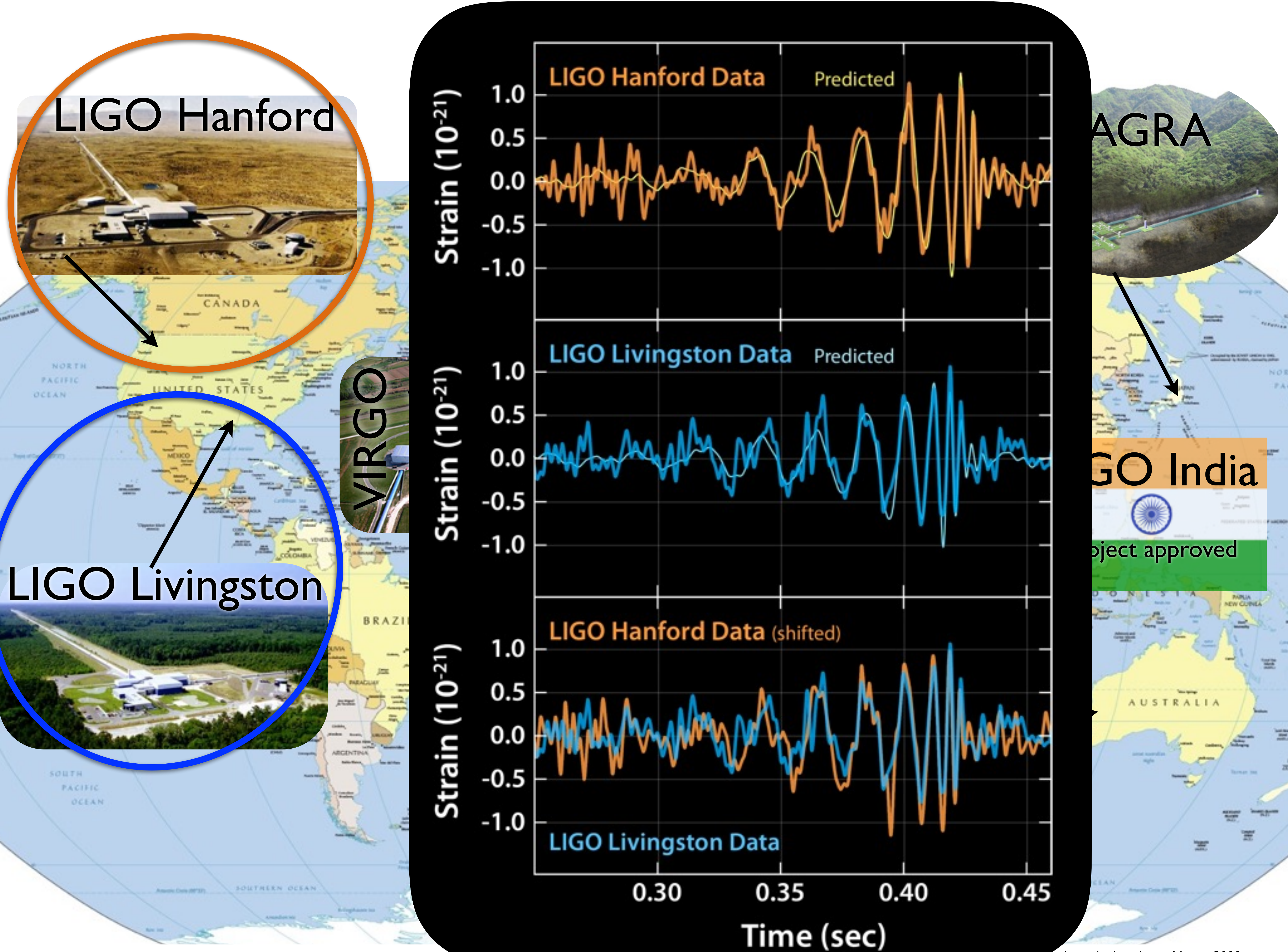

e.org/maps/political_world_map3000.jpg

two black holes merging

http://mediaassets.caltech.edu/gwave

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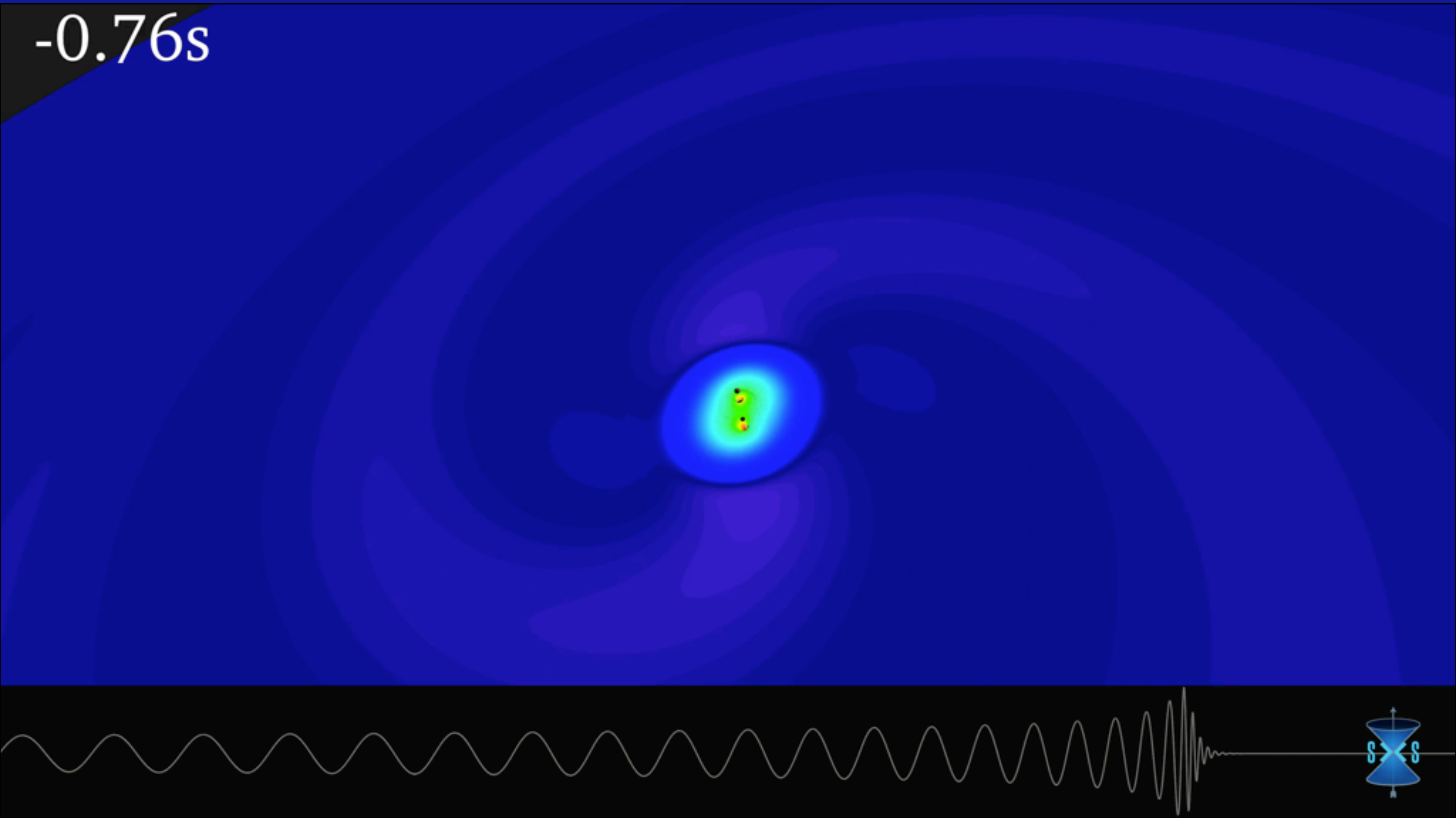
Simulation of the event



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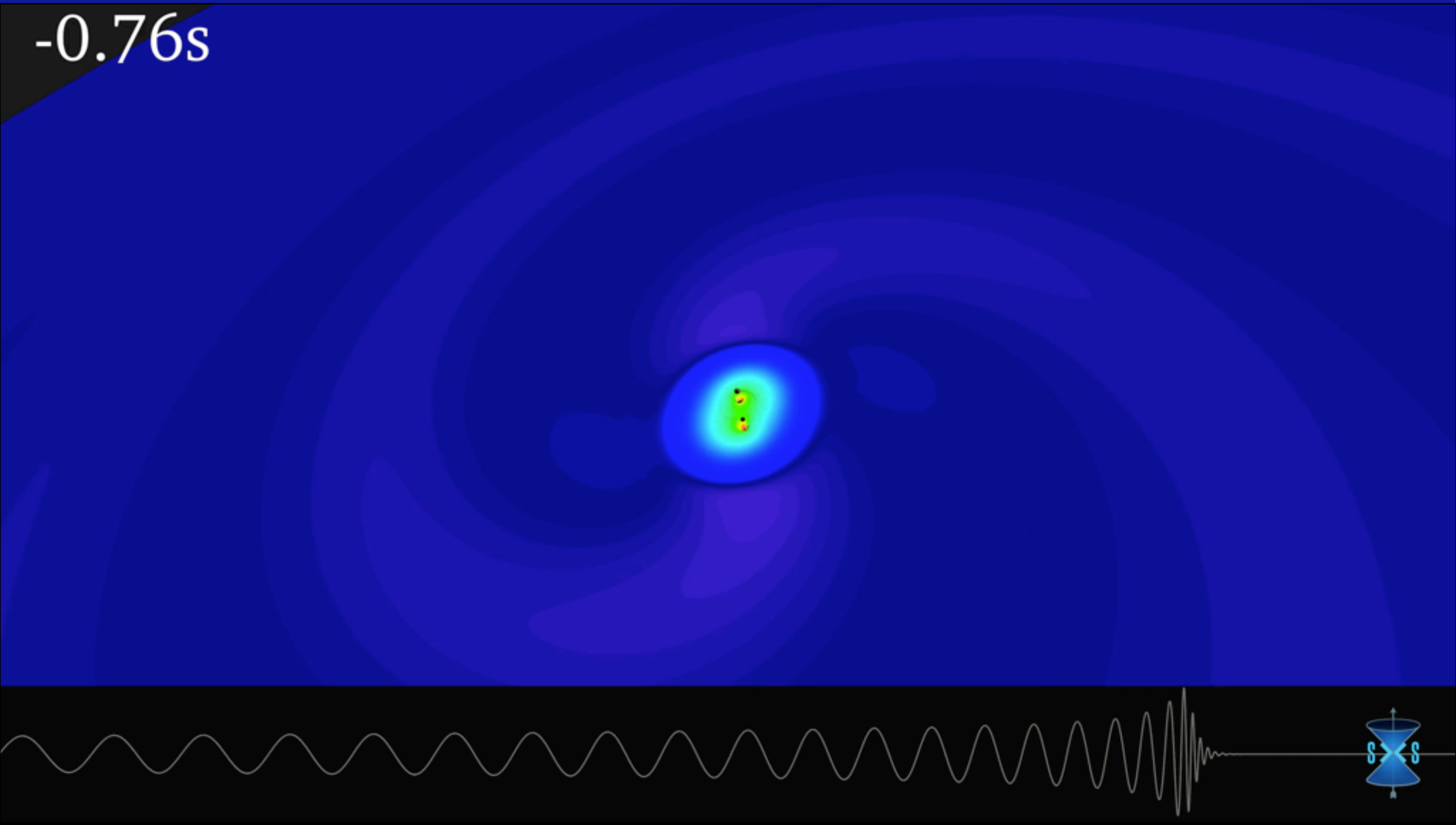

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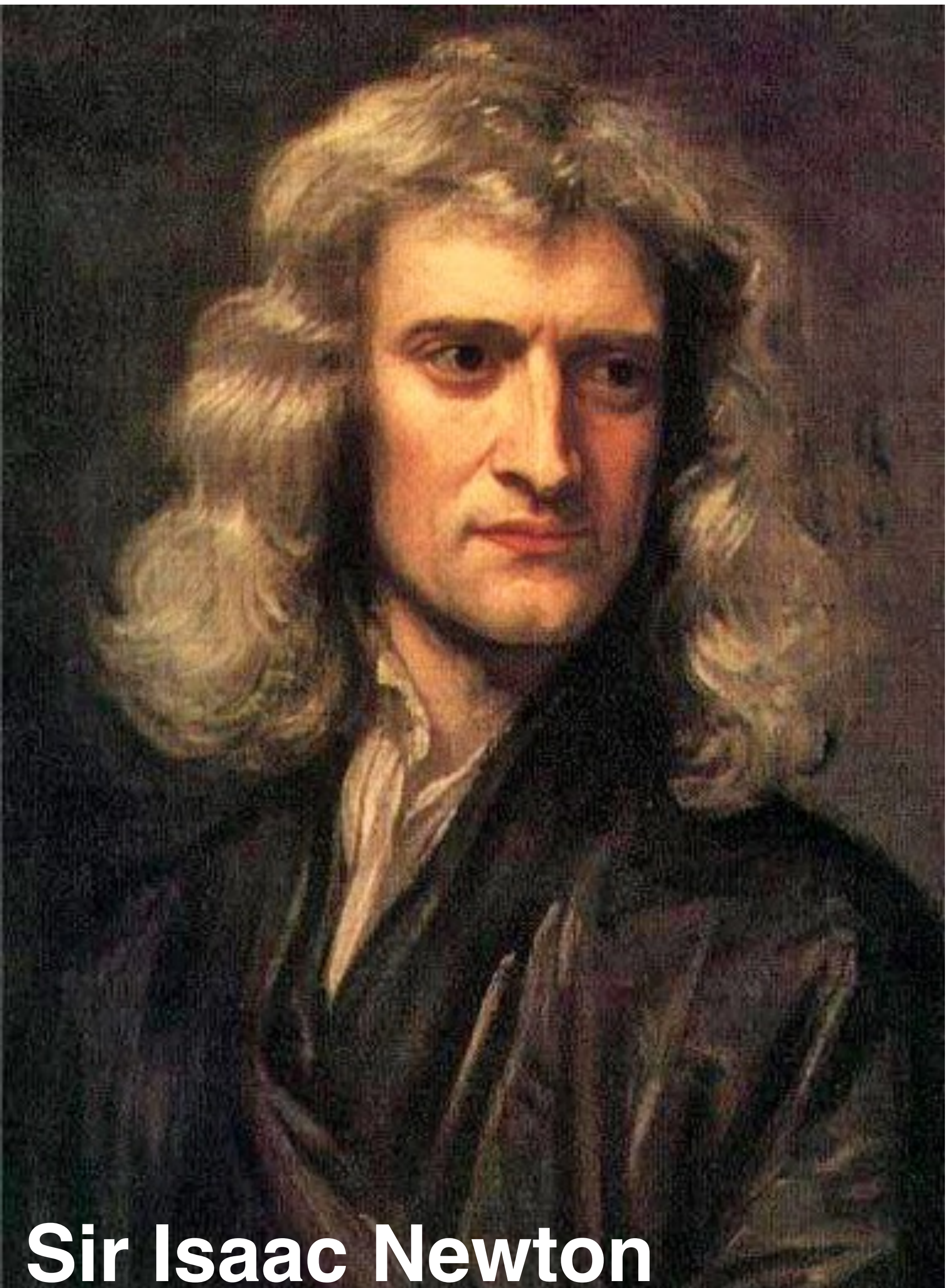
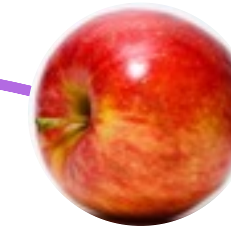
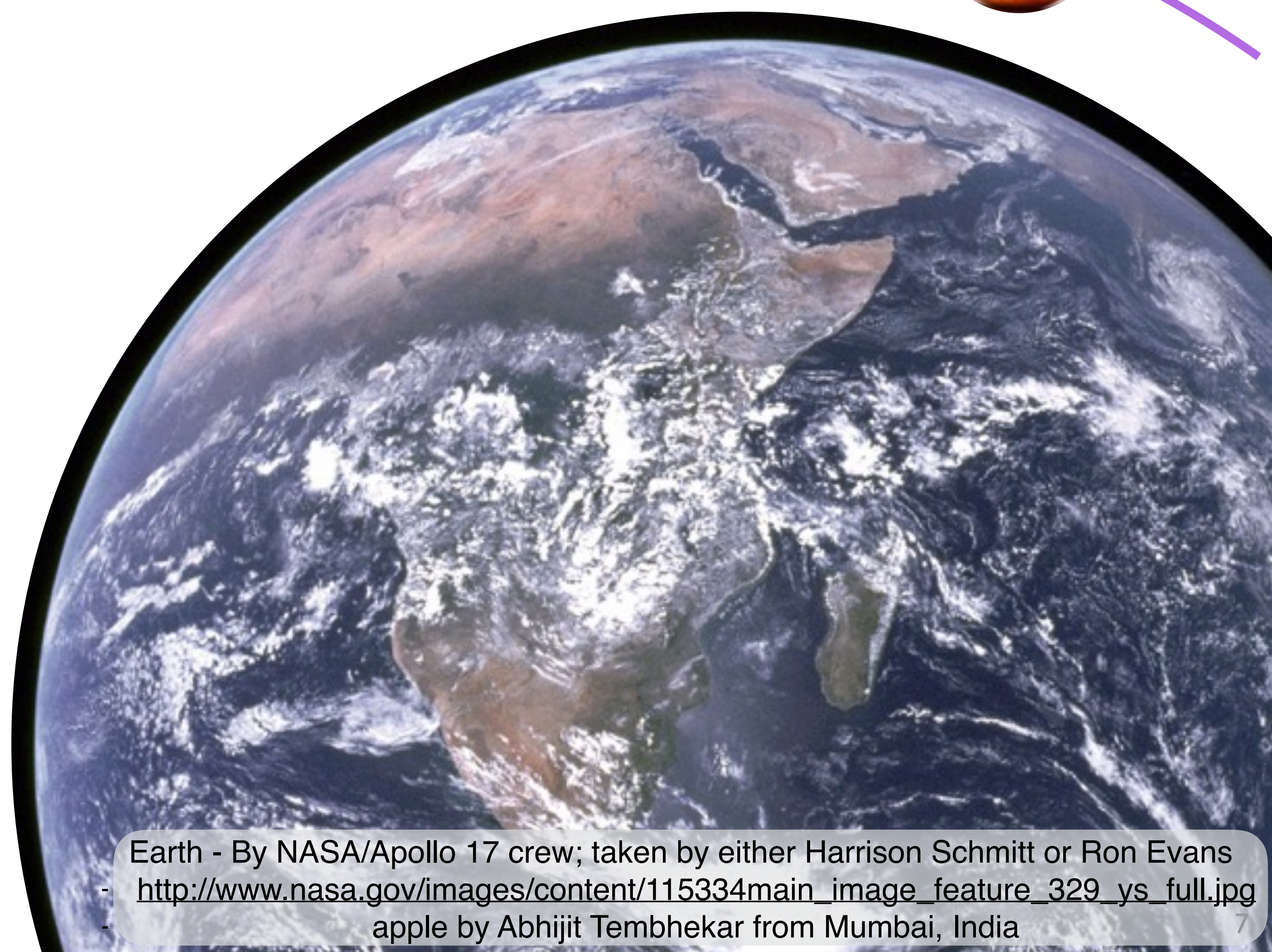
What is a Gravitational Wave?



$$F = \frac{G m_1 m_2}{r^2}$$

Implies immediate action at a distance





By Sir Godfrey Kneller
- http://www.newton.cam.ac.uk/art/portrait.html

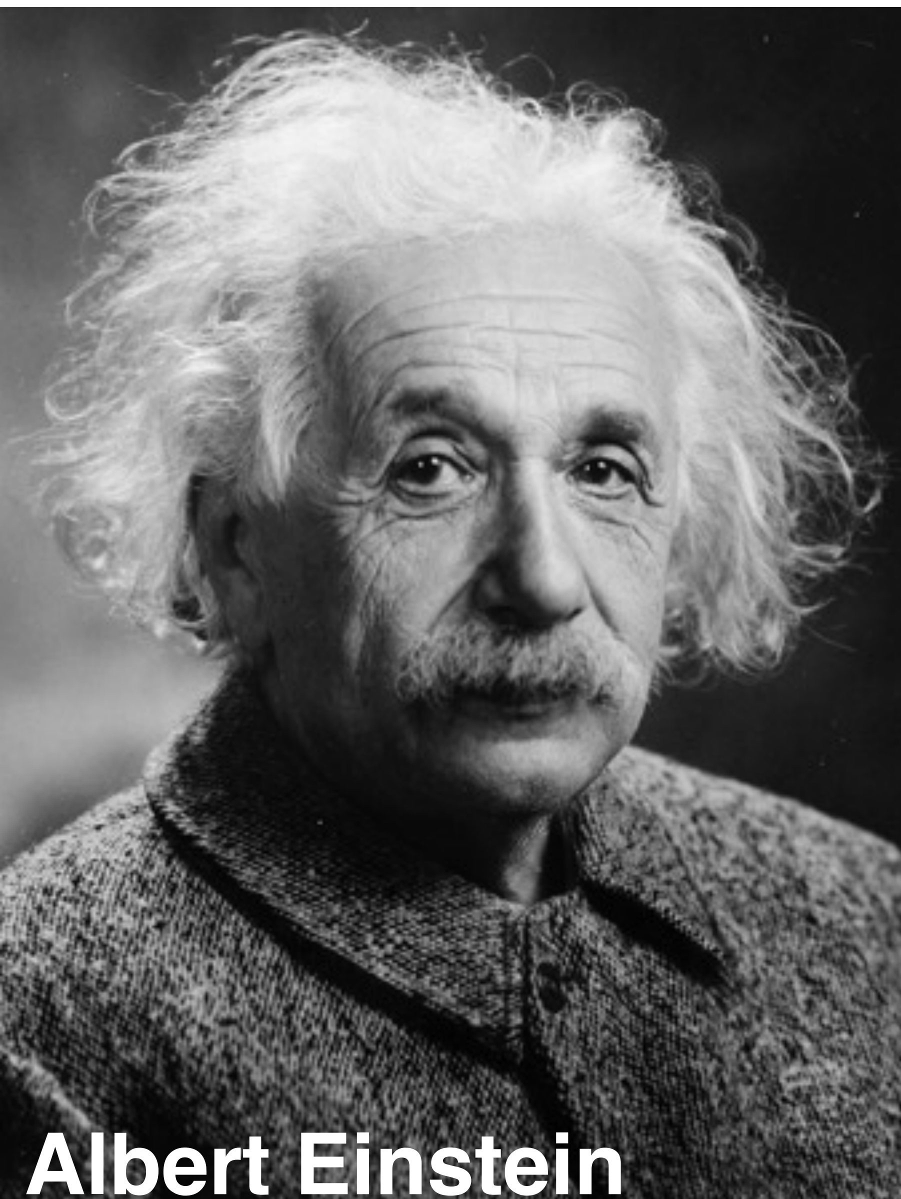
Earth - By NASA/Apollo 17 crew; taken by either Harrison Schmitt or Ron Evans
- http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
- apple by Abhijit Tembhekar from Mumbai, India

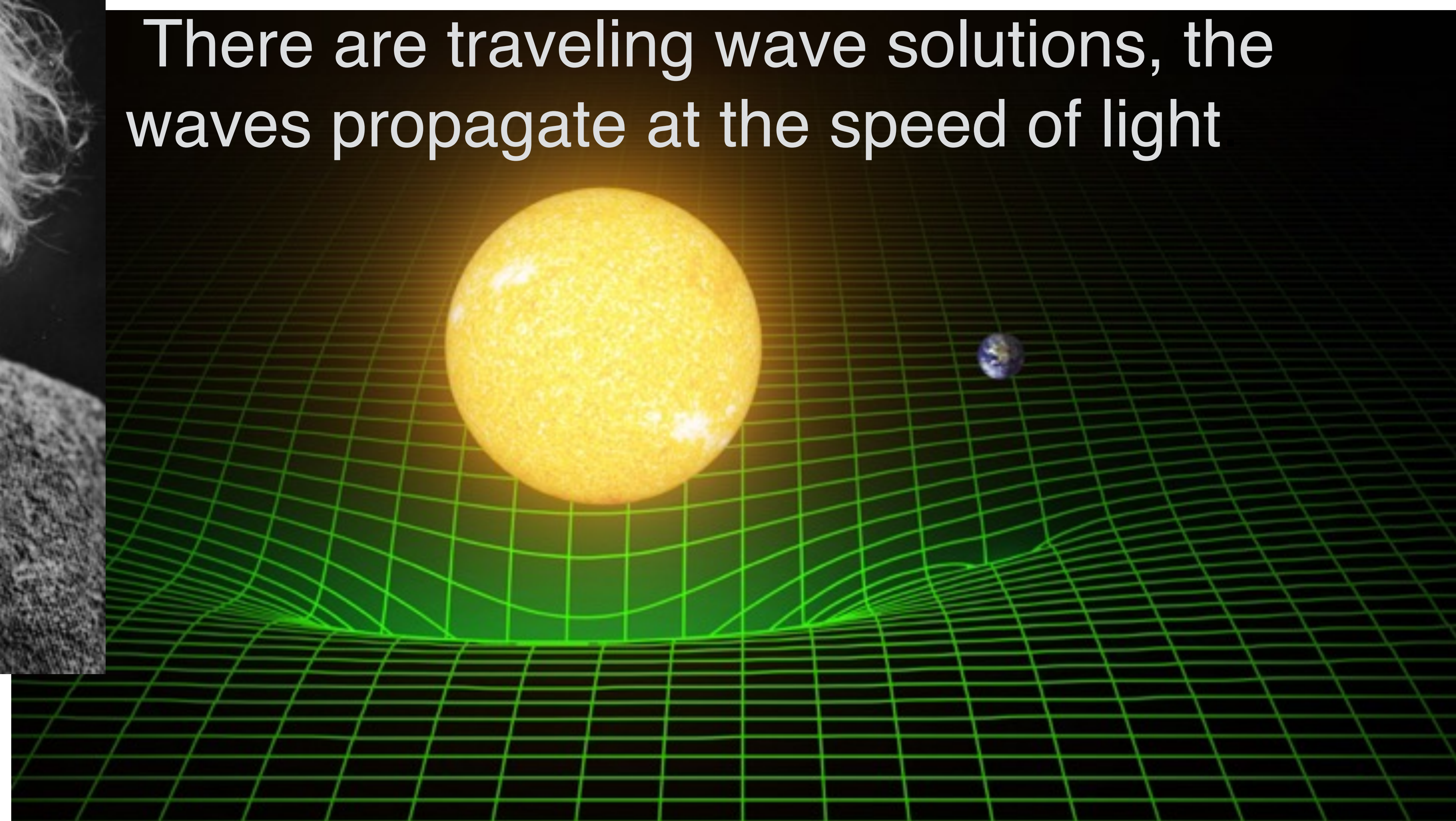
What is a Gravitational Wave?

Predicted by Einstein in 1916 as part of GR.

“Spacetime tells matter how to move,
matter tells spacetime how to curve”

- J. A. Wheeler





Photograph by Orren Jack Turner,
Library of Congress digital ID cph.3b46036.

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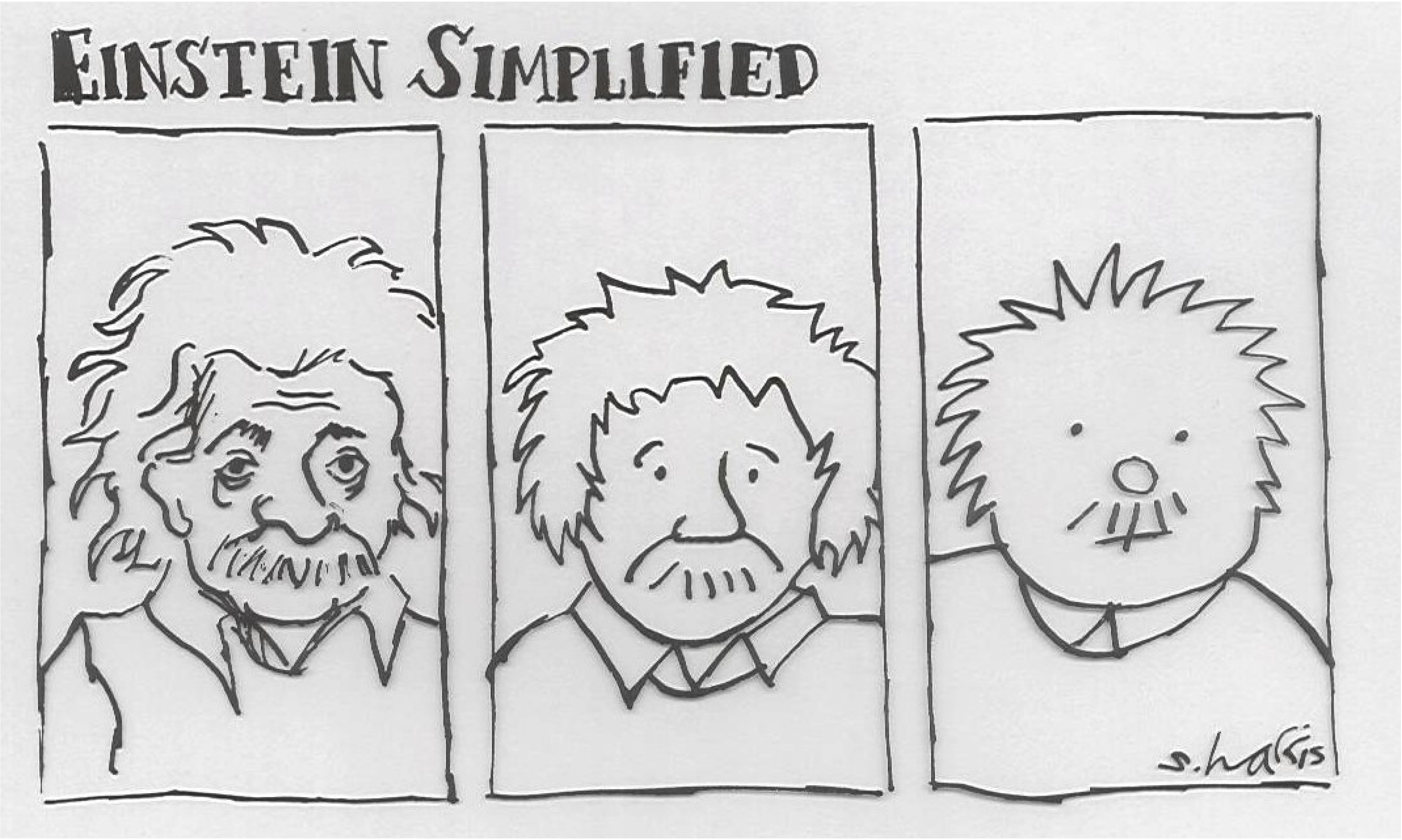
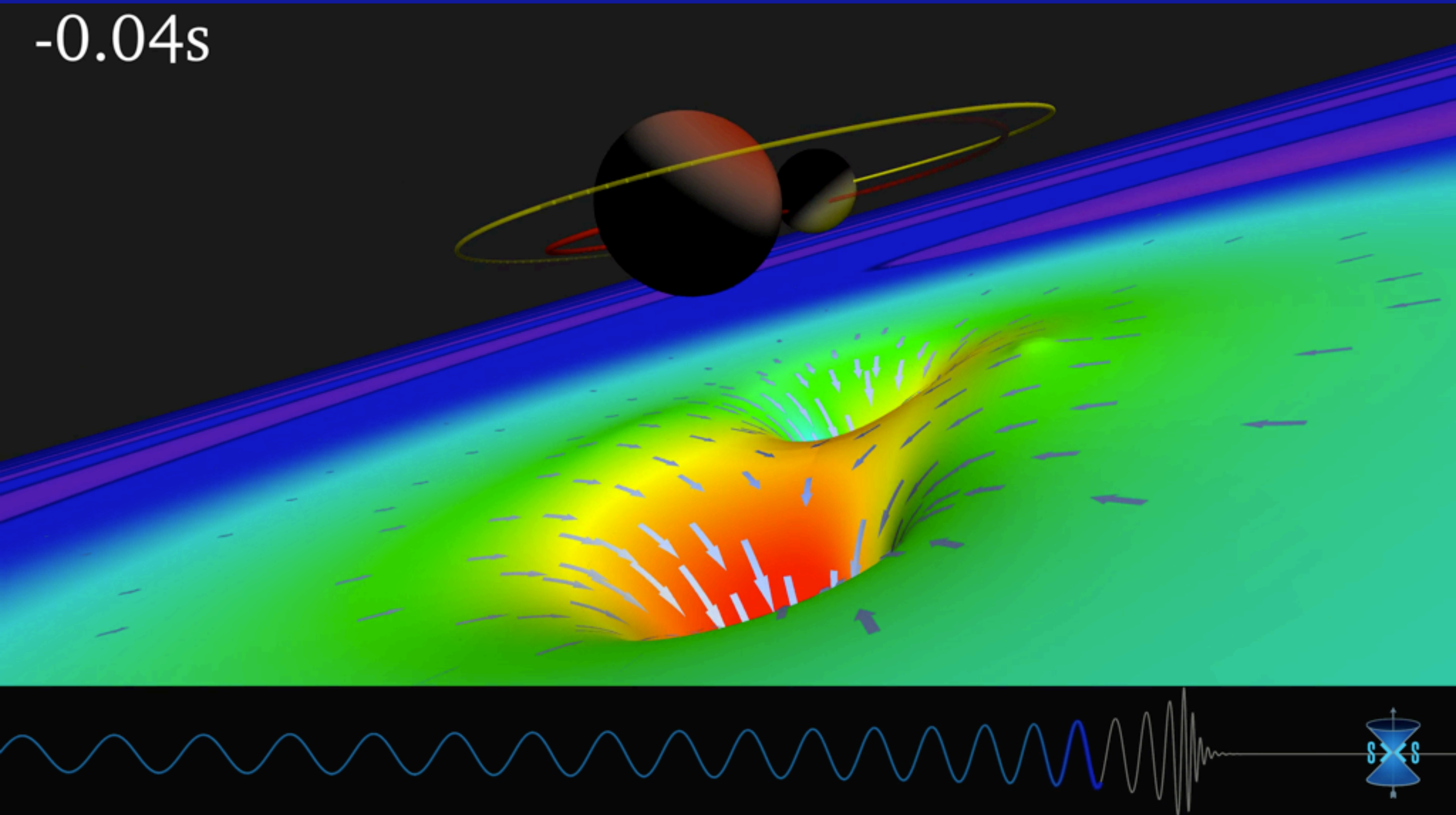


Sydney Harris

Simulation of the event



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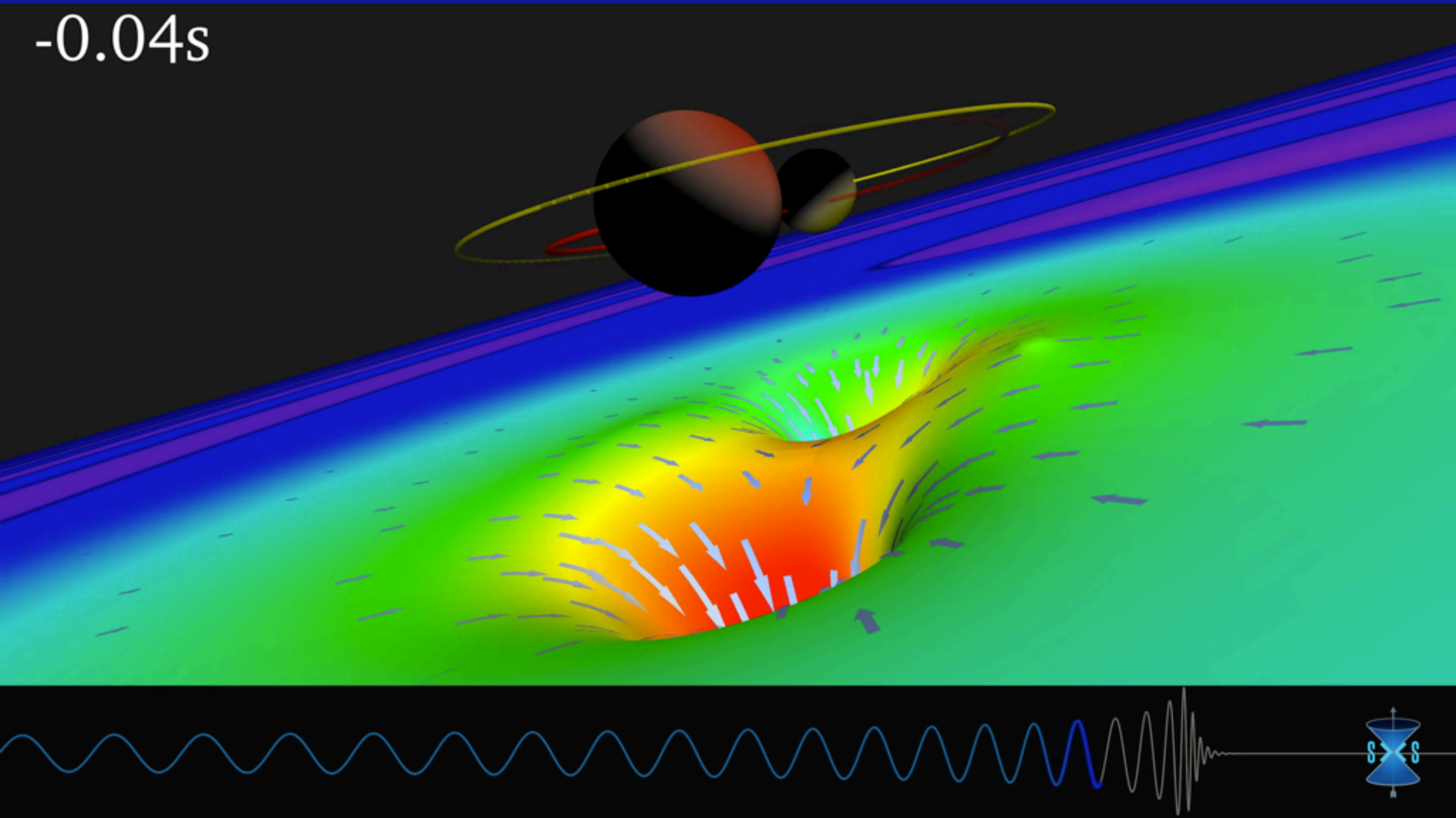
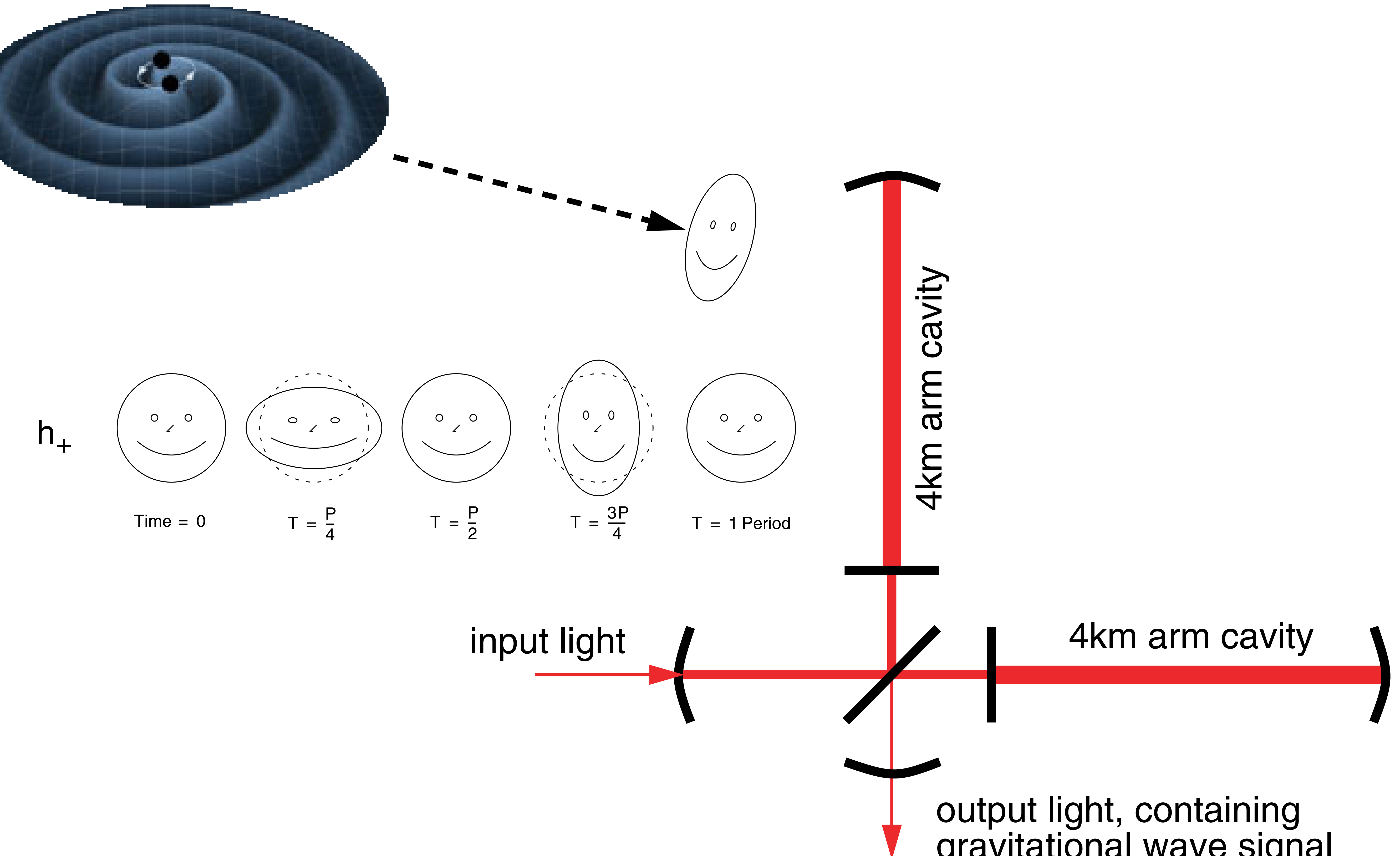


The LIGO concept



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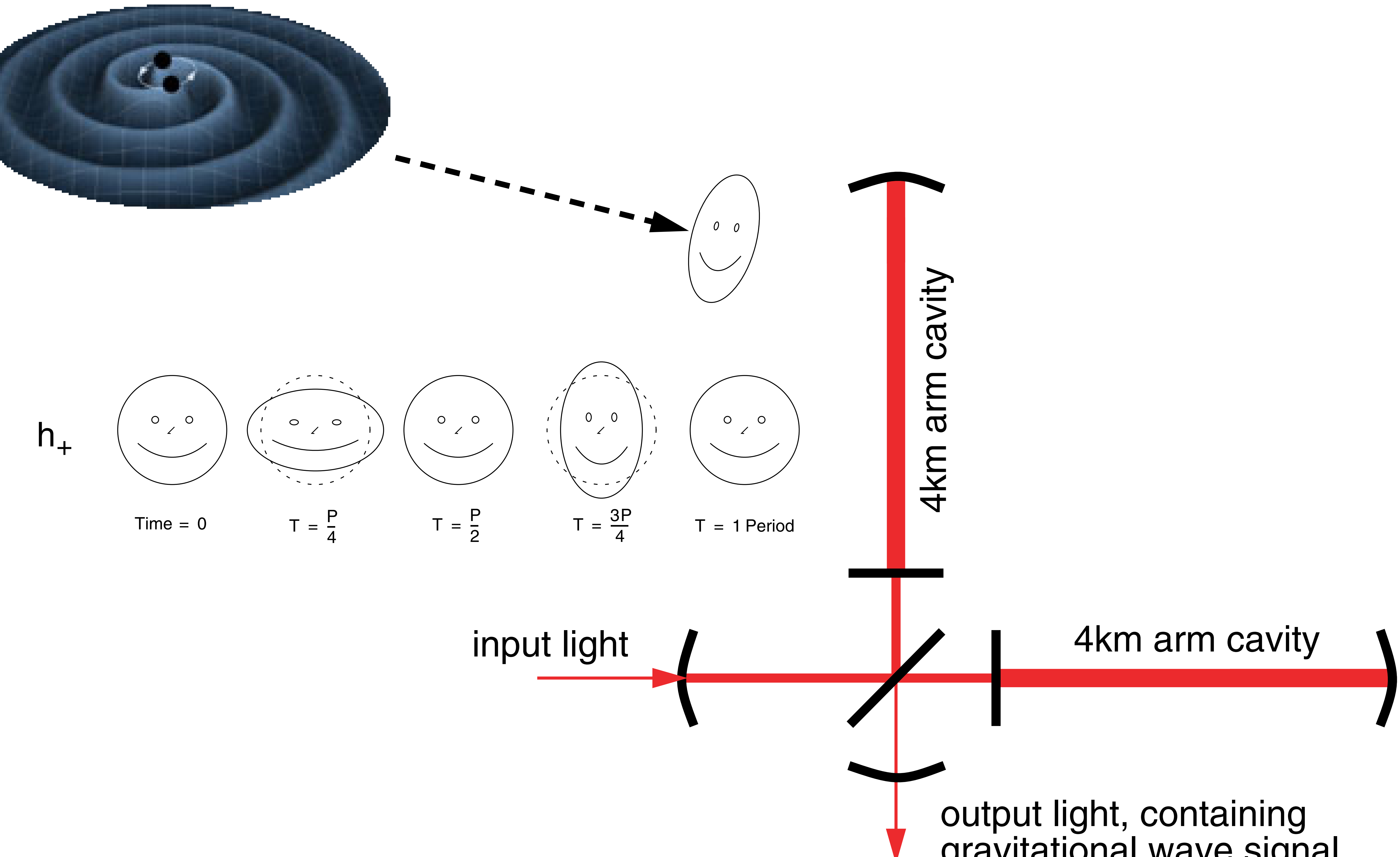

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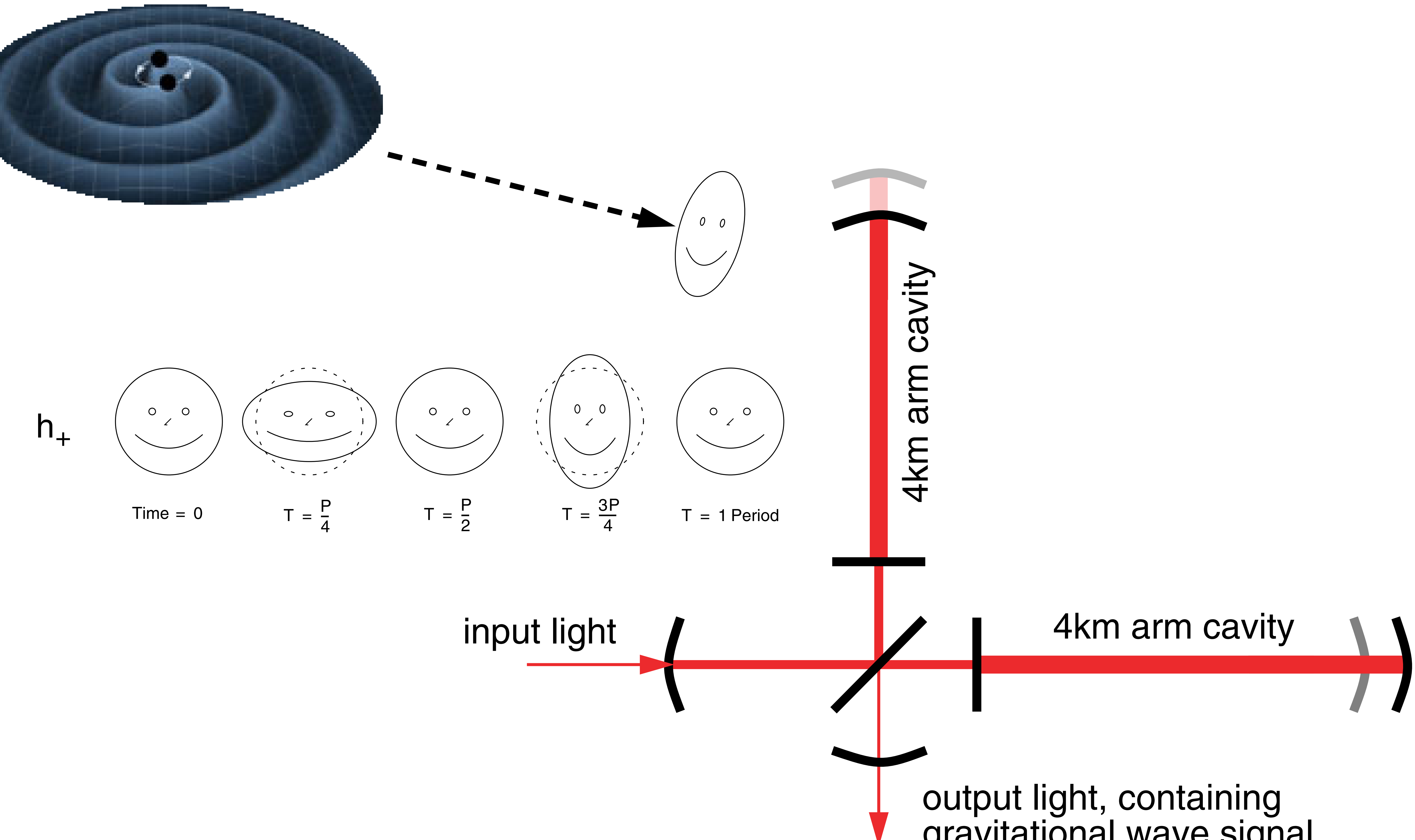

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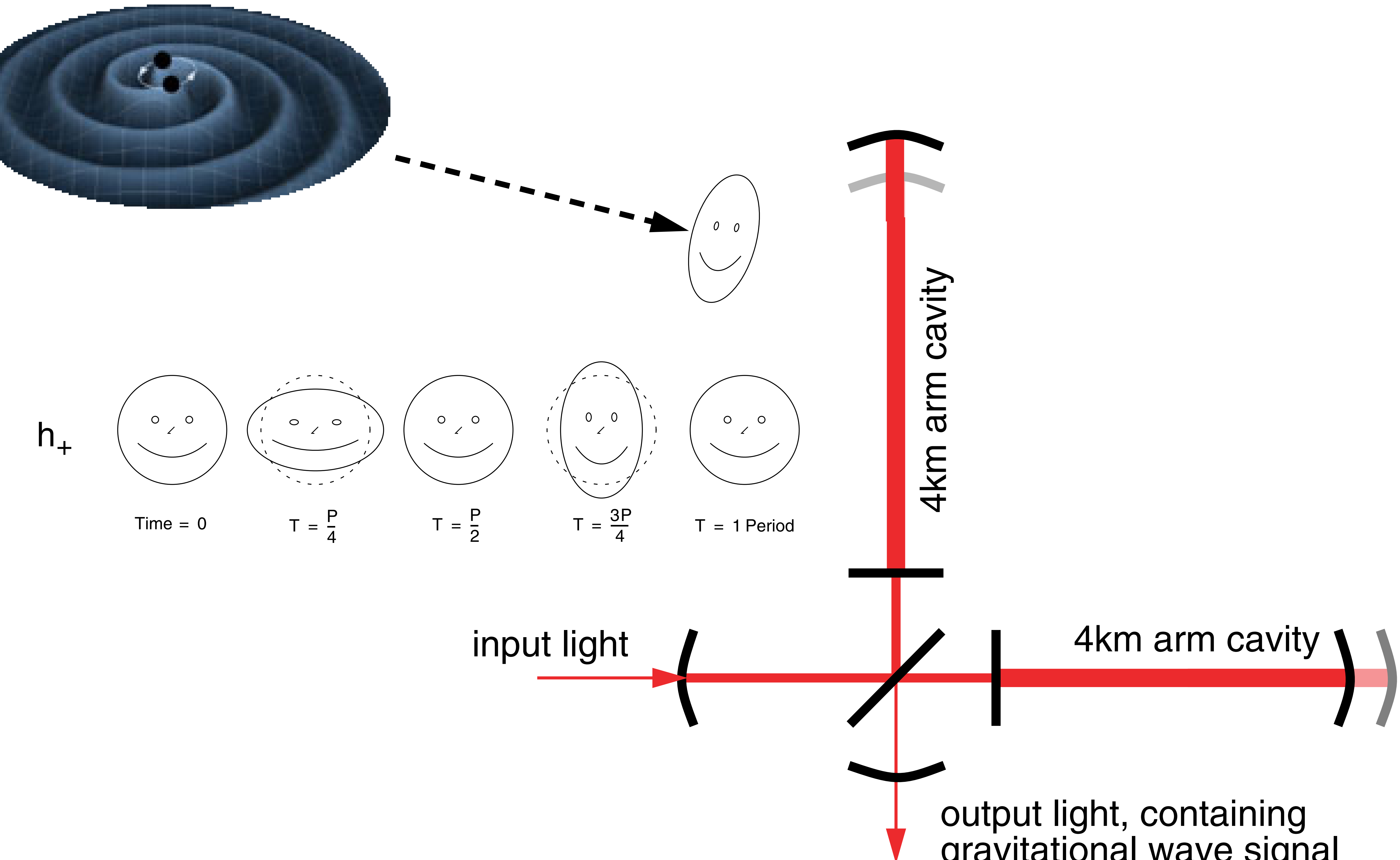

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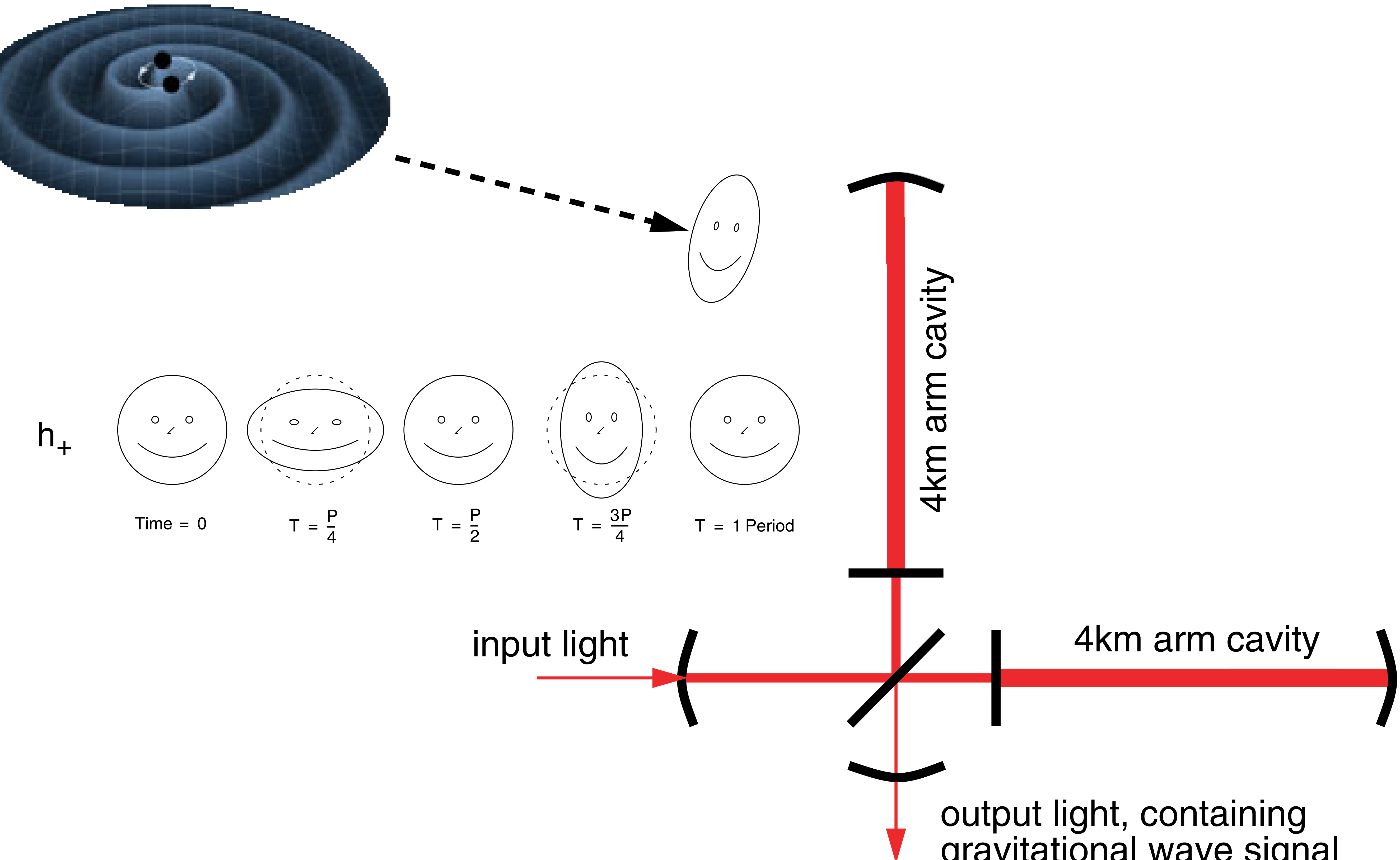


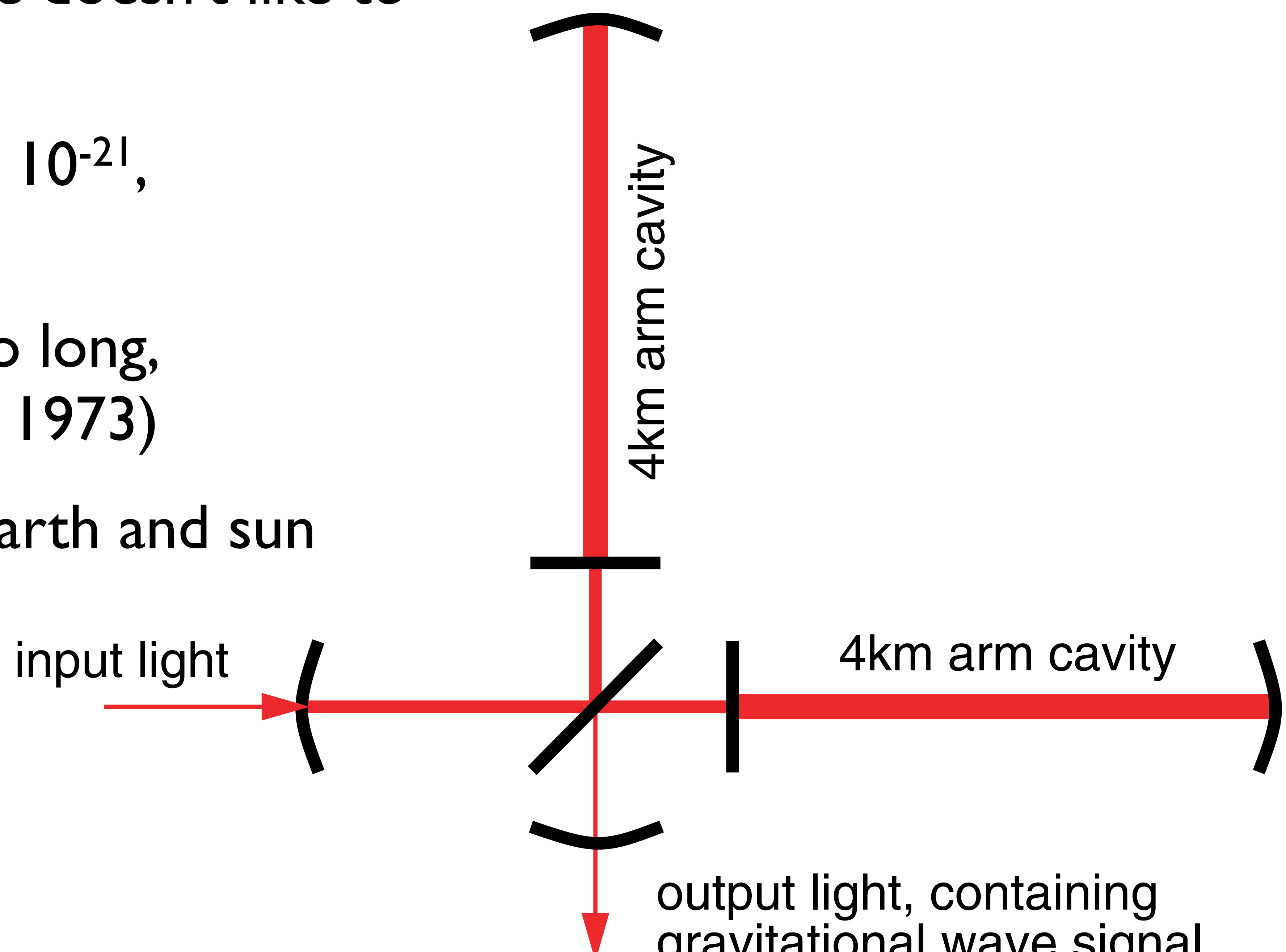
The LIGO concept
why it is nearly impossible

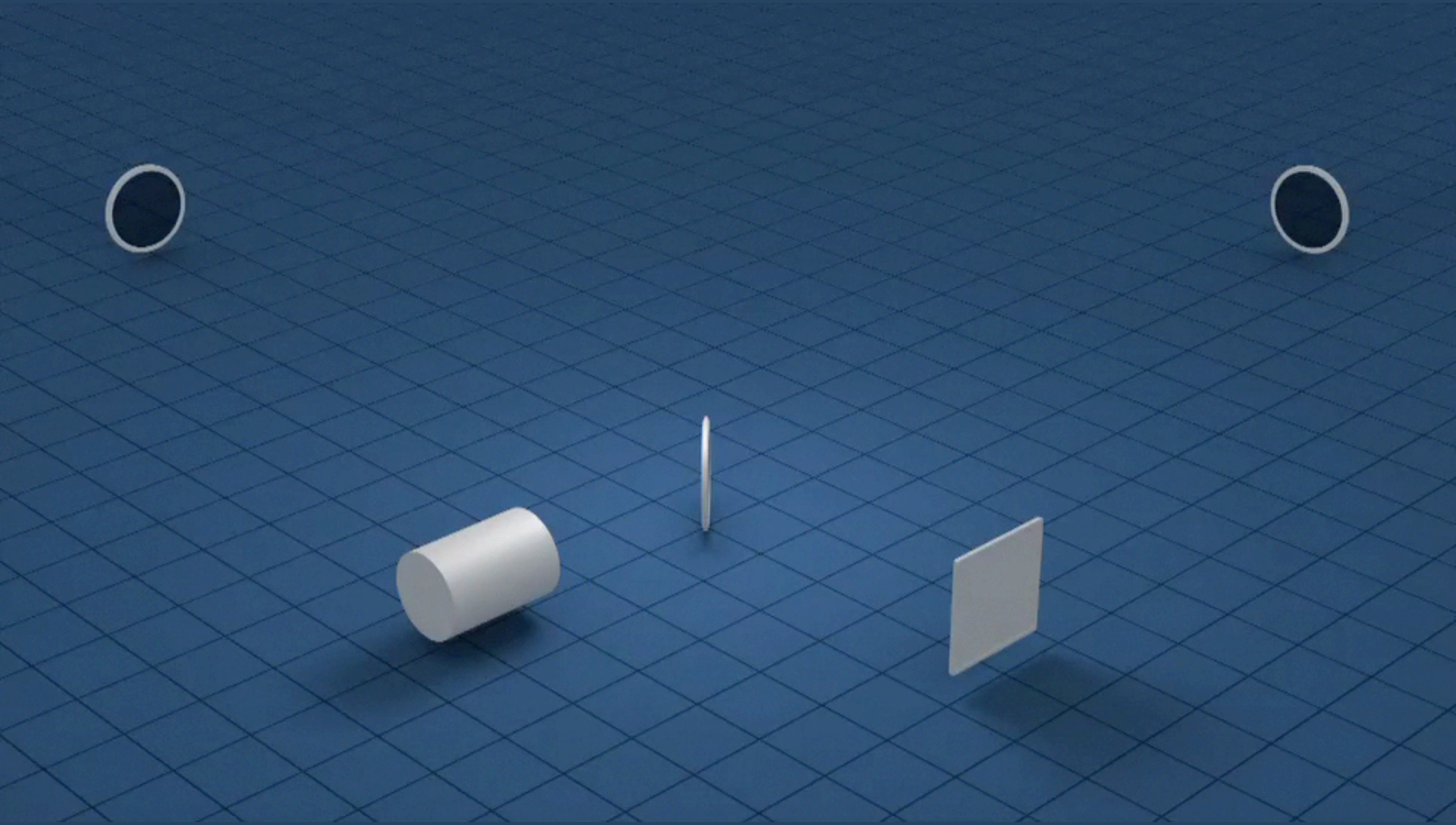
Gravitational waves are hard to measure because space doesn't like to stretch.

Our signal strain (h) = 10^{-21},
dL = $4*10^{-18}$ meters

(that's why it's taken so long,
Einstein 1916, Weiss 1973)

1 atom between the earth and sun





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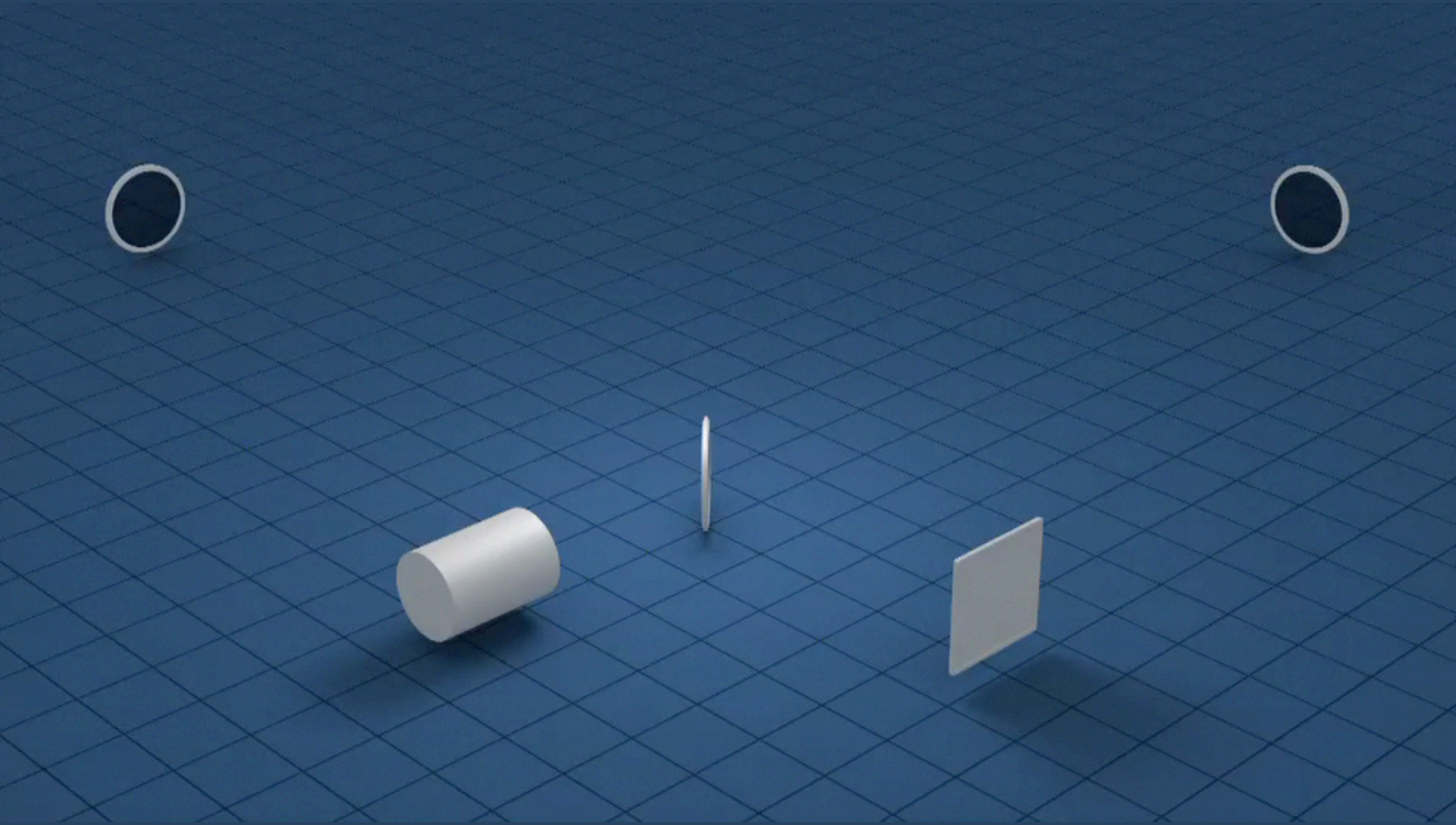

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The LIGO concept

Gravitational waves are hard to measure because space doesn't like to stretch.

Our signal strain (h) = 10^{-21},
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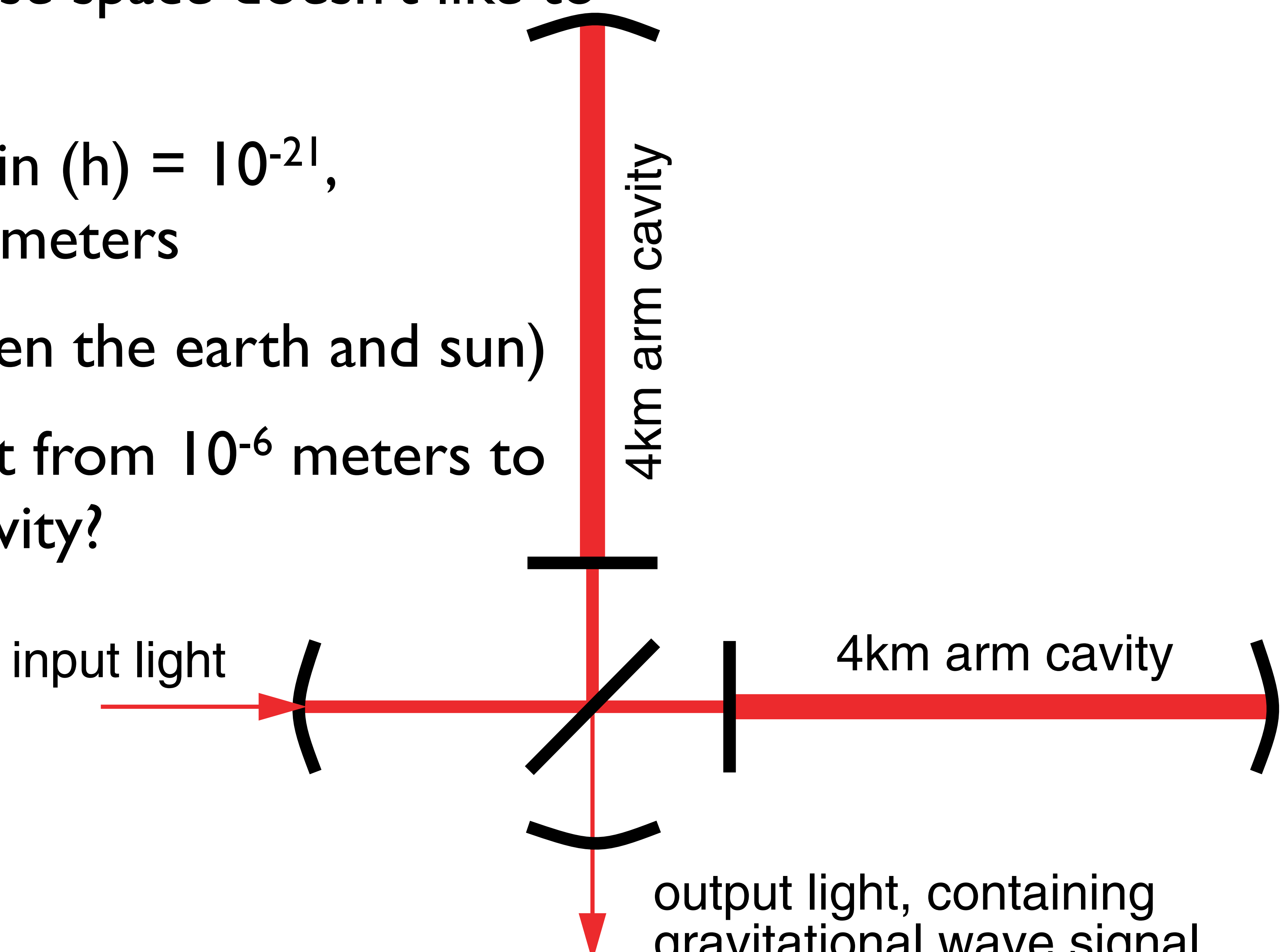
(1 atom between the earth and sun)

How do we get from 10^{-6} meters to LIGO sensitivity?



The LIGO concept

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Our signal strain (h) = 10^{-21}
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(1 atom between the earth

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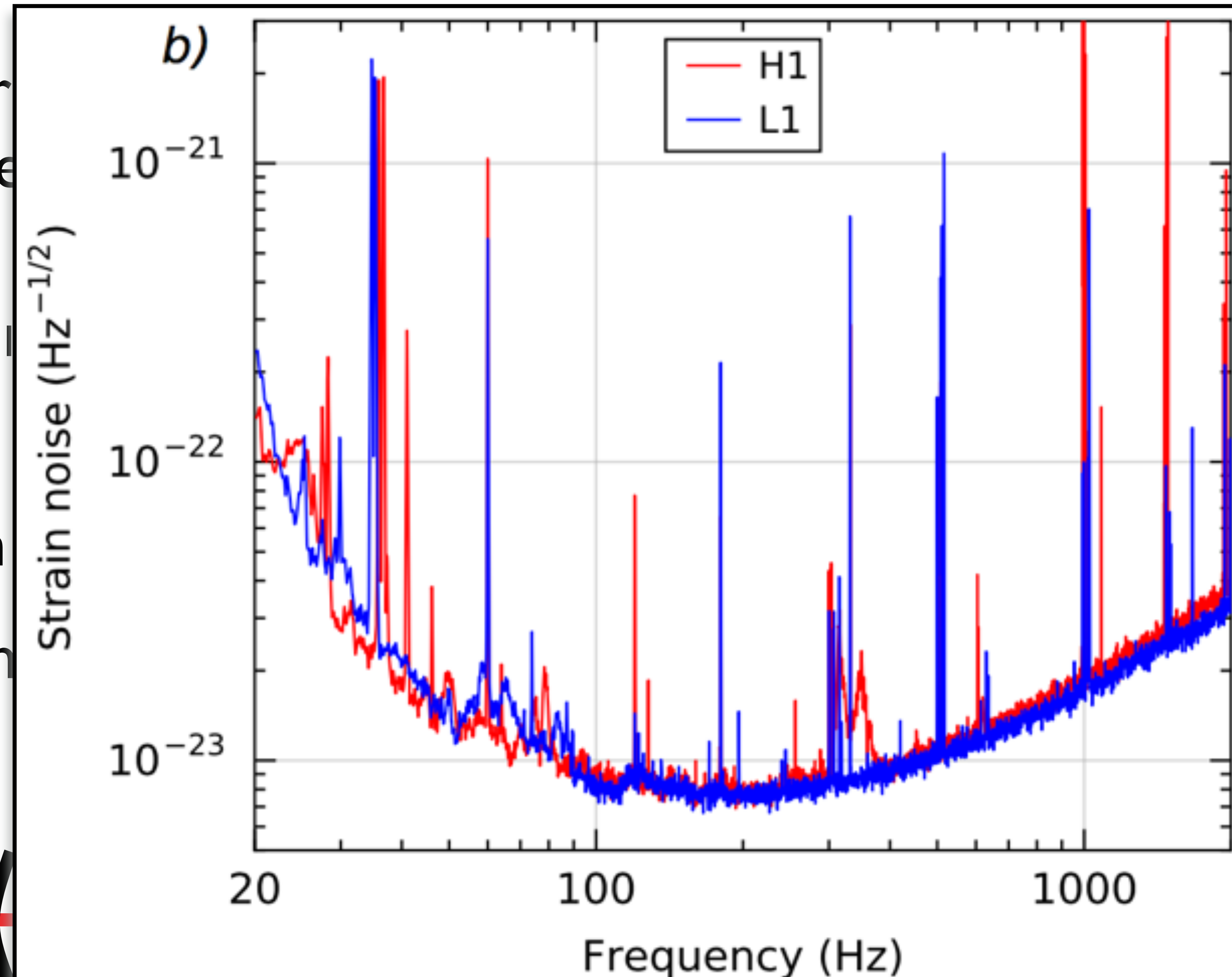
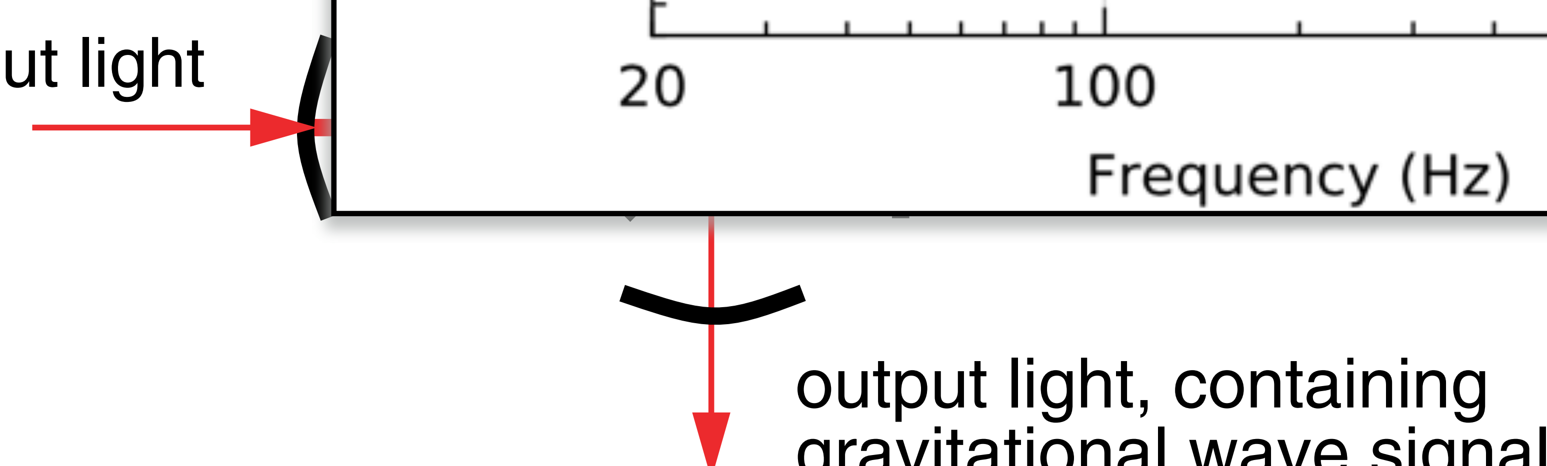


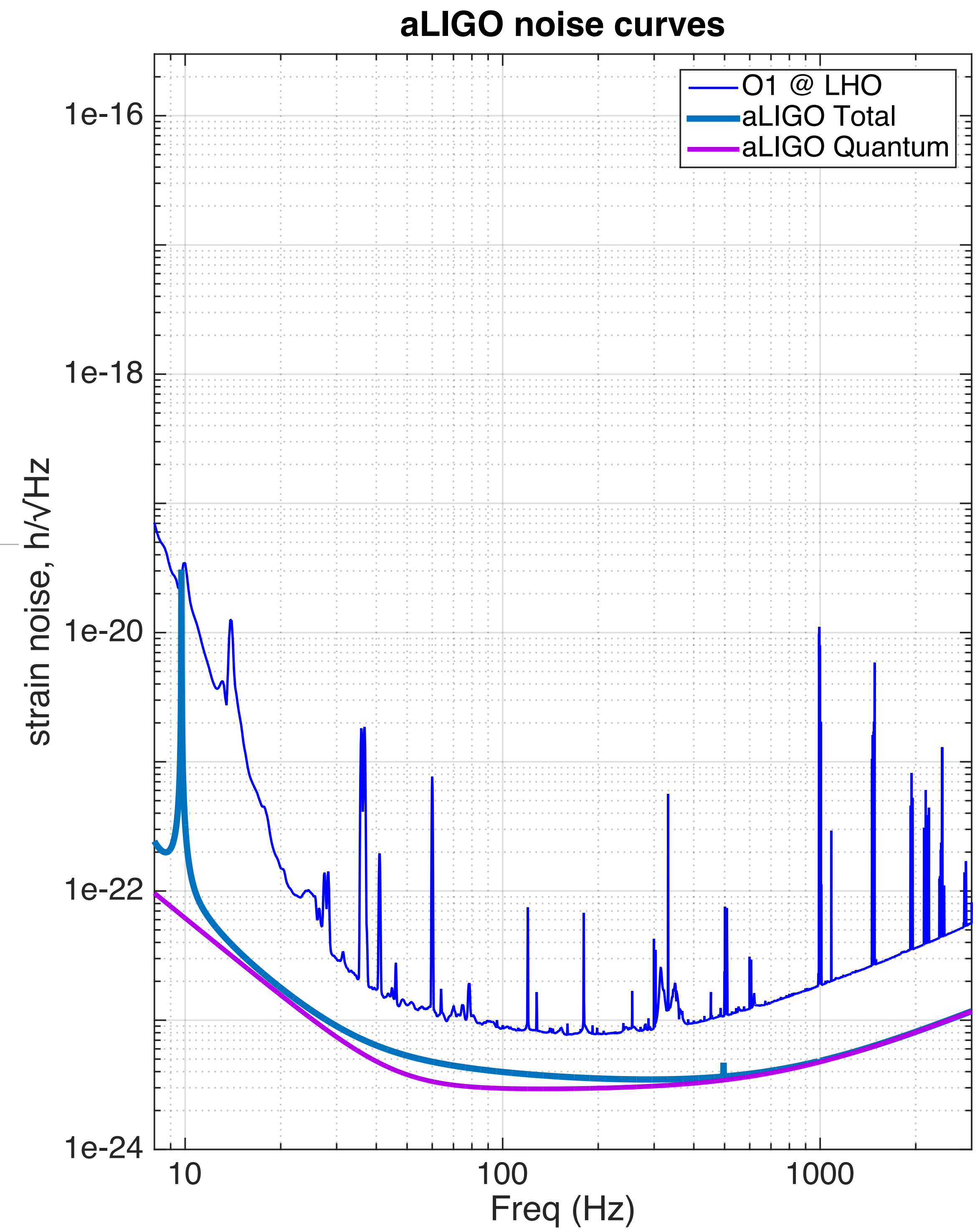


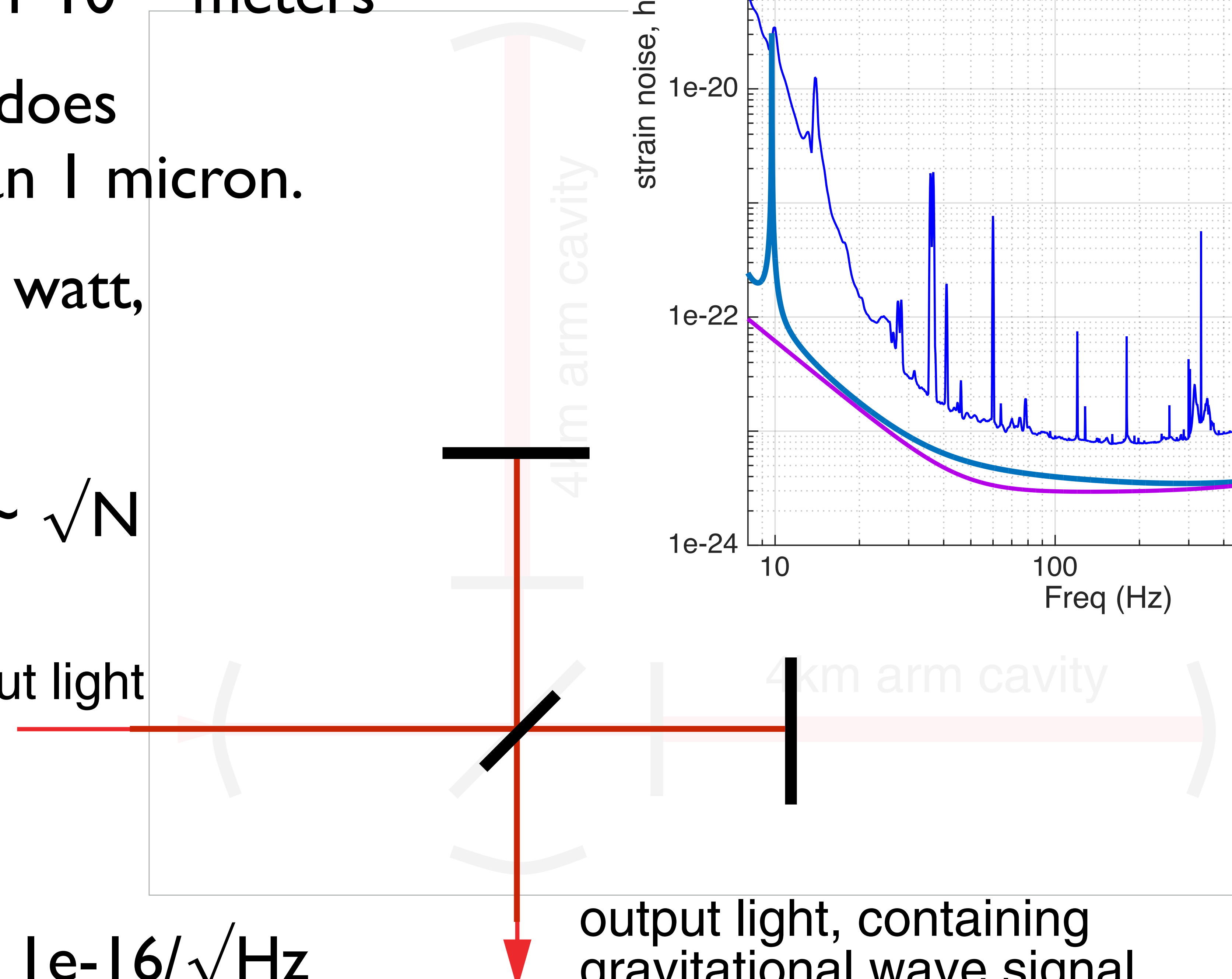
From 1 micron to aLIGO

From 10^{-6} meters to a signal of (h) = 10^{-21}, dL = $4*10^{-18}$ meters

Simple Michelson does Much Better than 1 micron.

L = 1 meter, P = 1 watt, count photons, if you expect N, quantum error ~ $\sqrt{N}$





dL/L = h (noise) = 1e-16/$\sqrt{\text{Hz}}$

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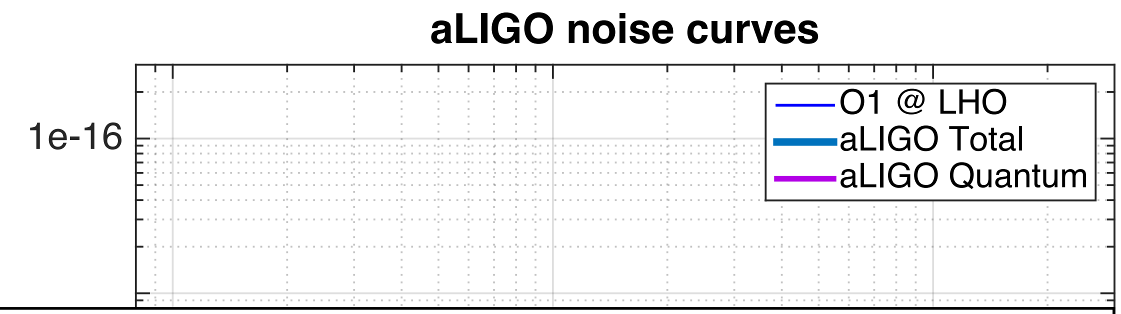

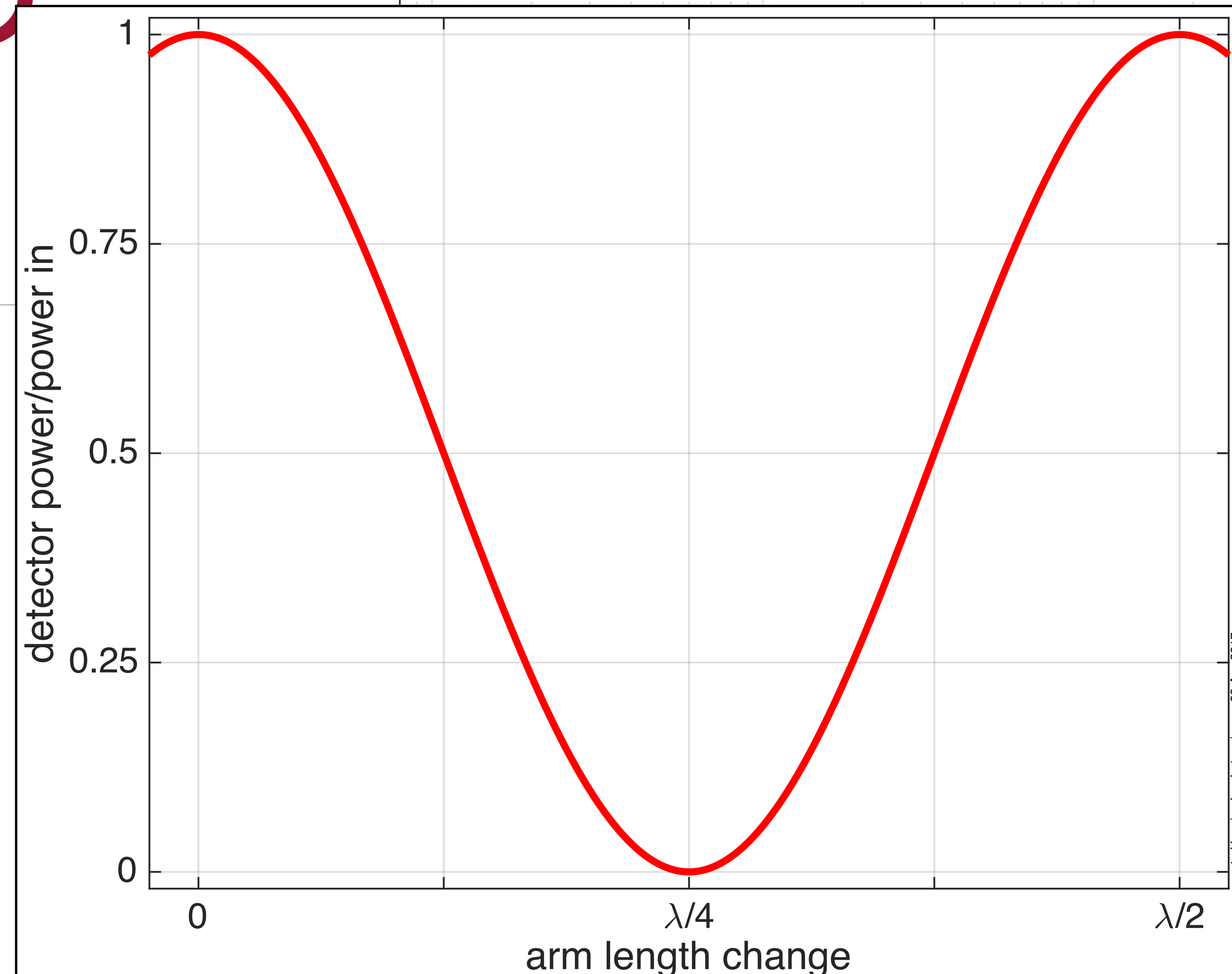

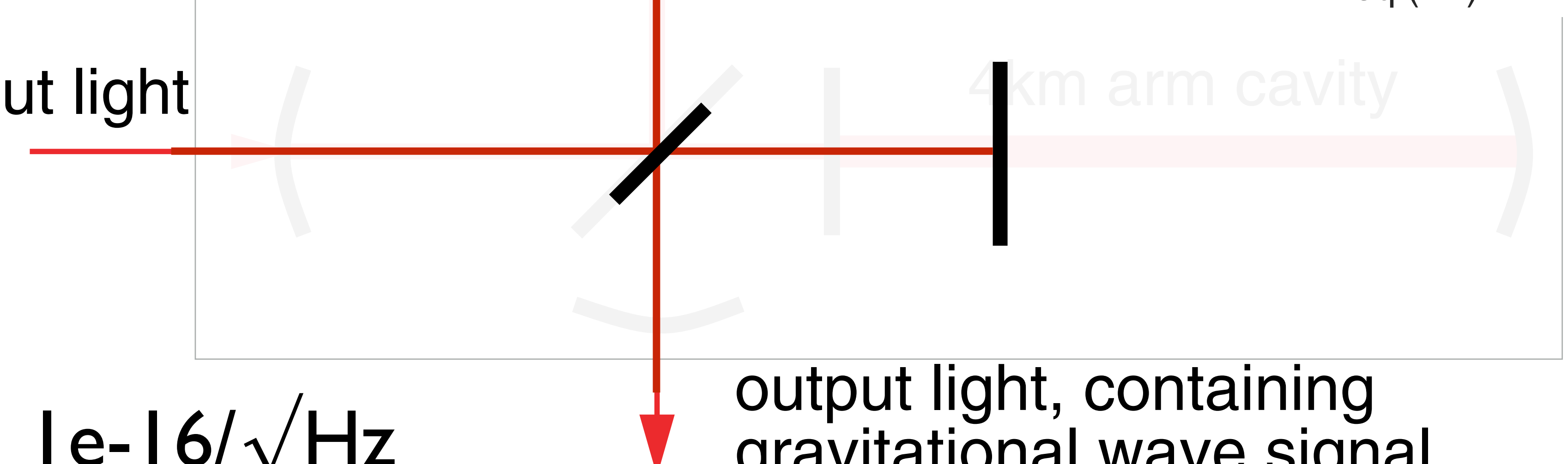

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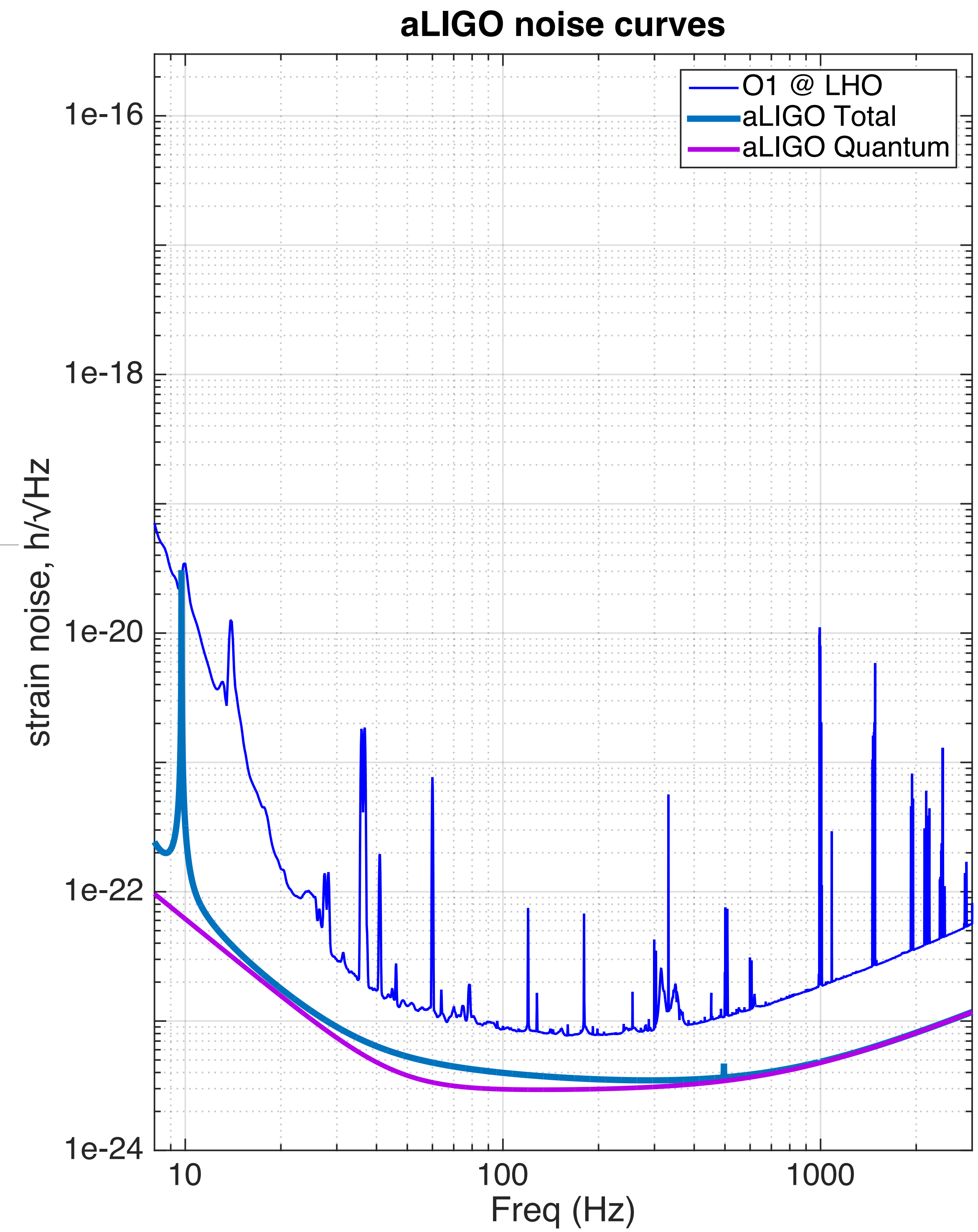

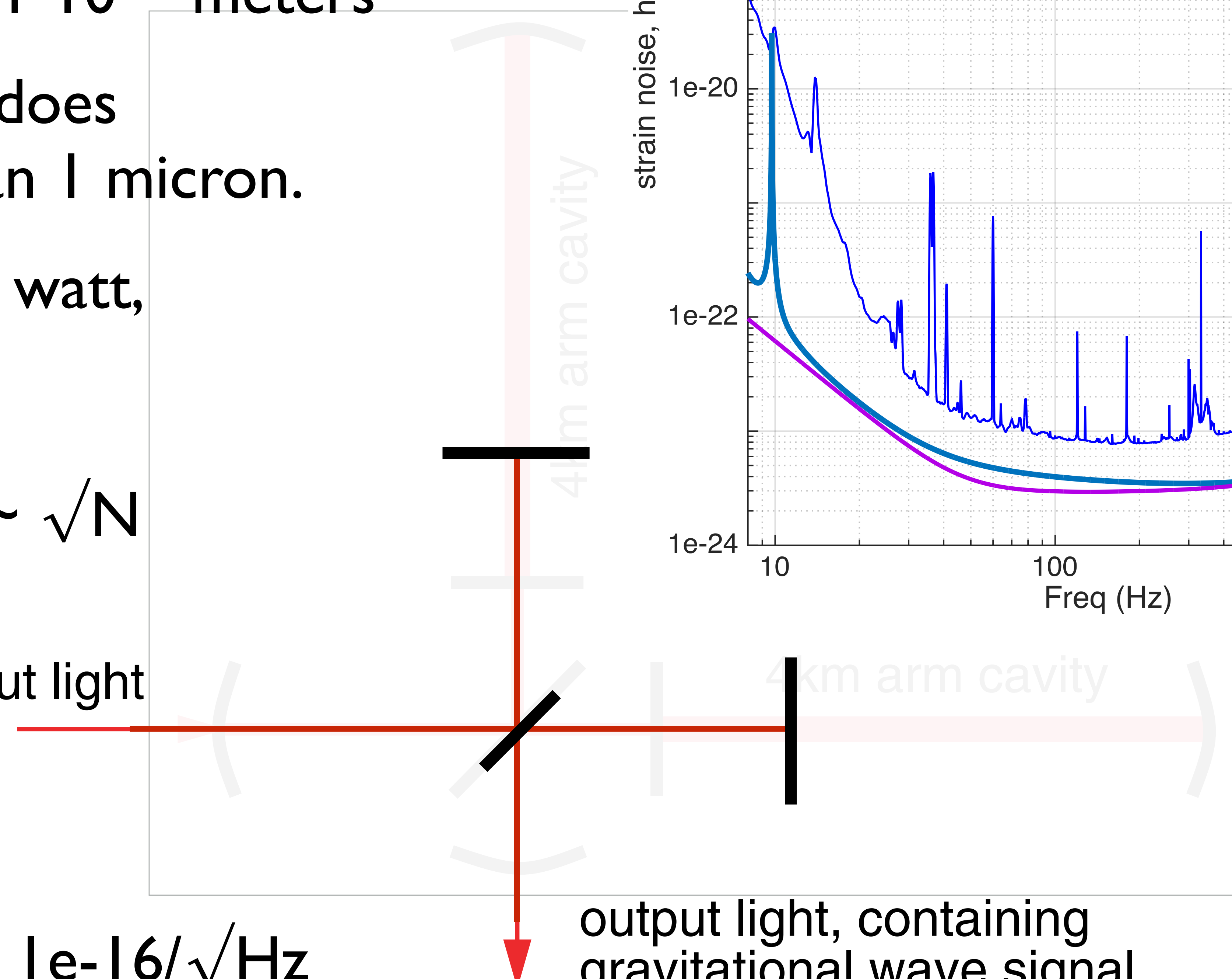

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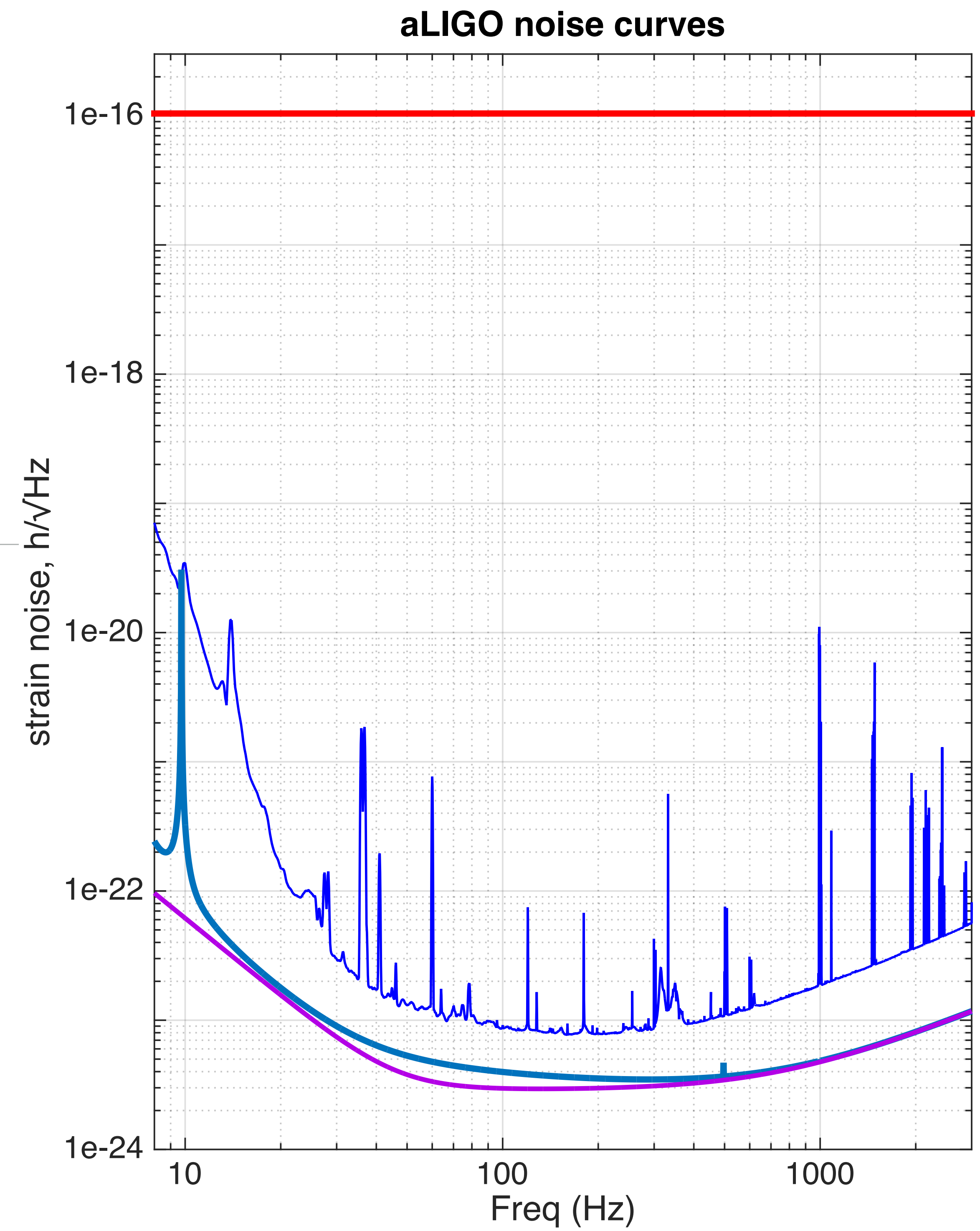
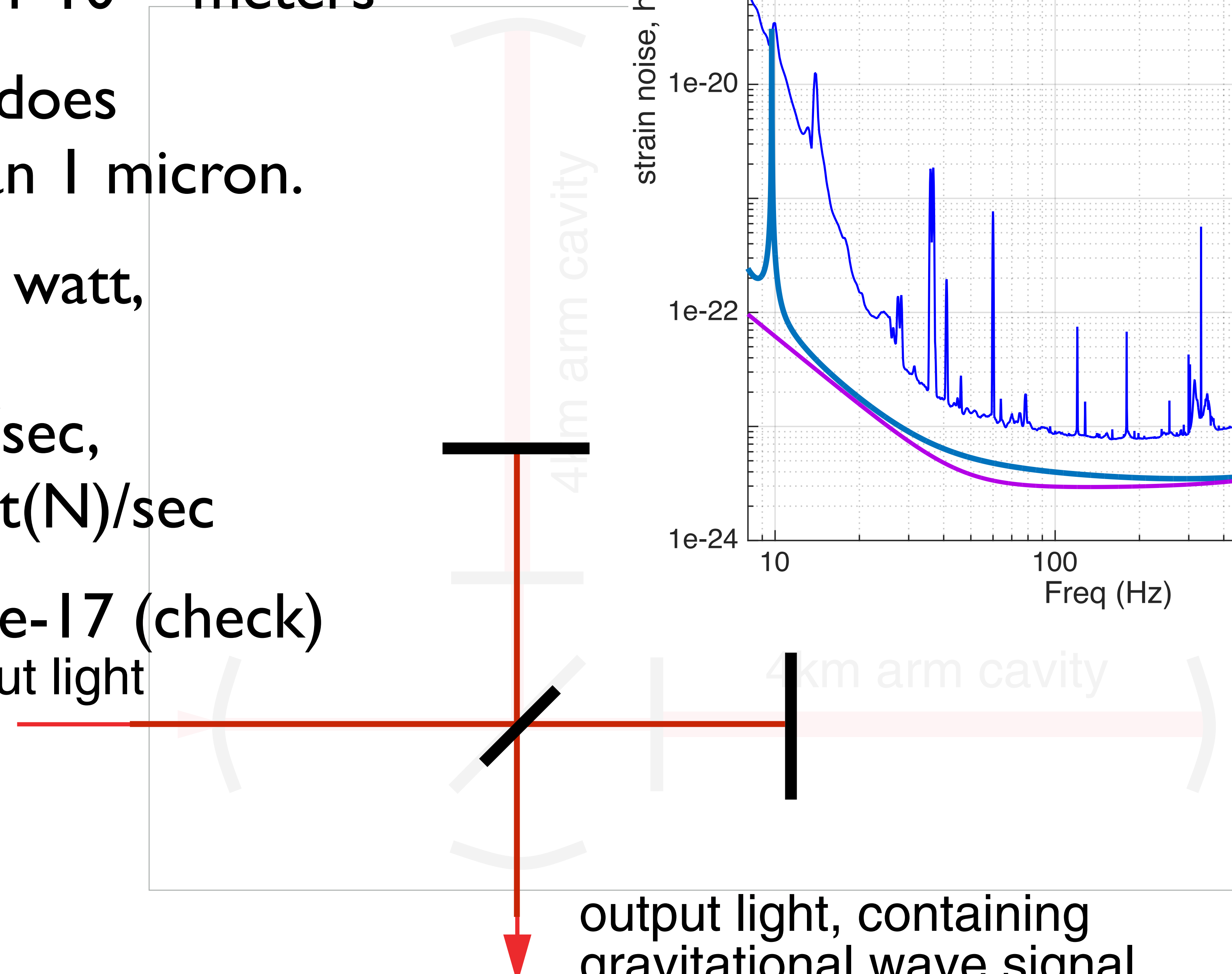
Simple Michelson does
Much Better than 1 micron.

L = 1 meter, P = 1 watt,
count photons,
if you expect N/sec,
QM error is sqrt(N)/sec

dL = h (noise) = 5e-17 (check)



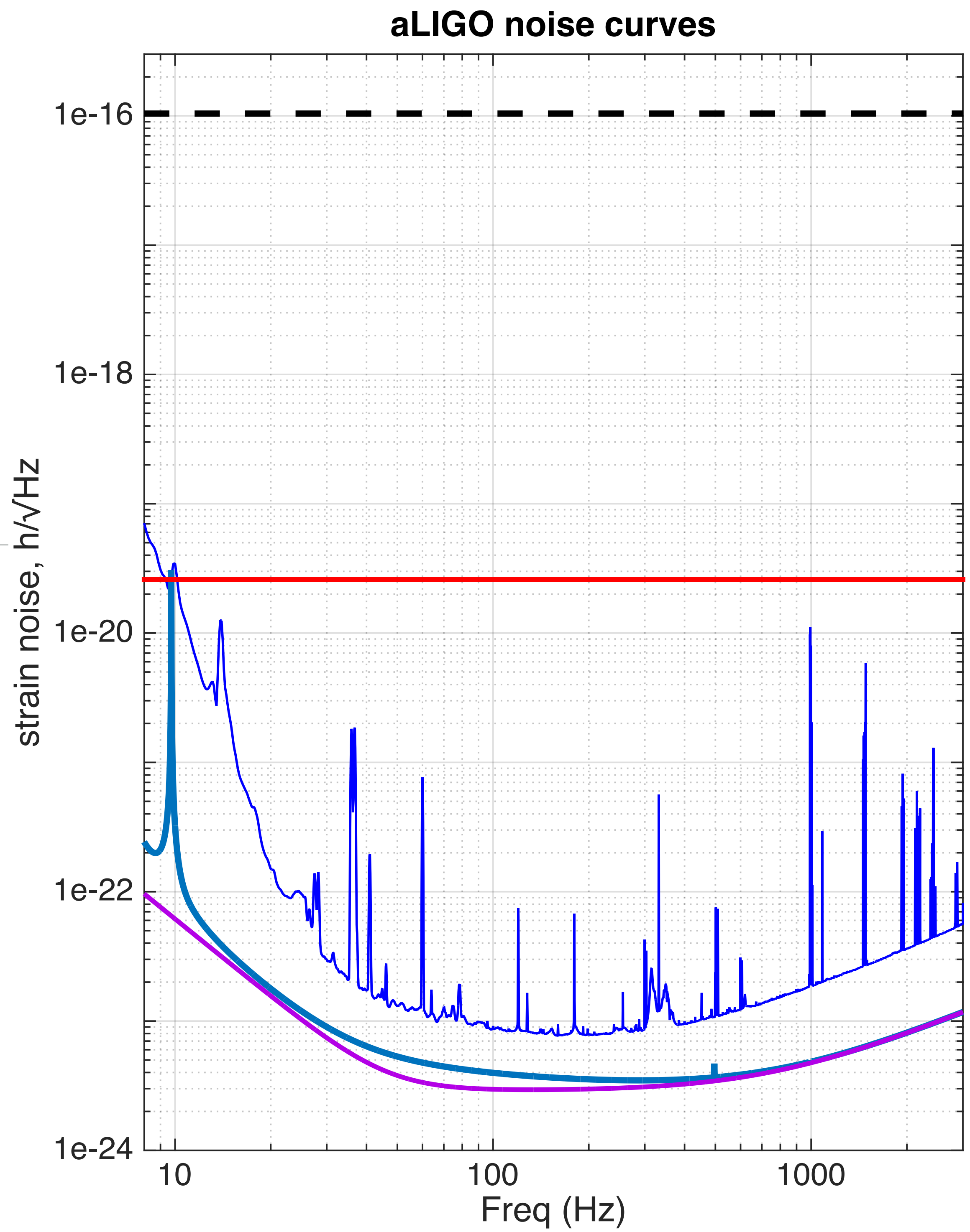


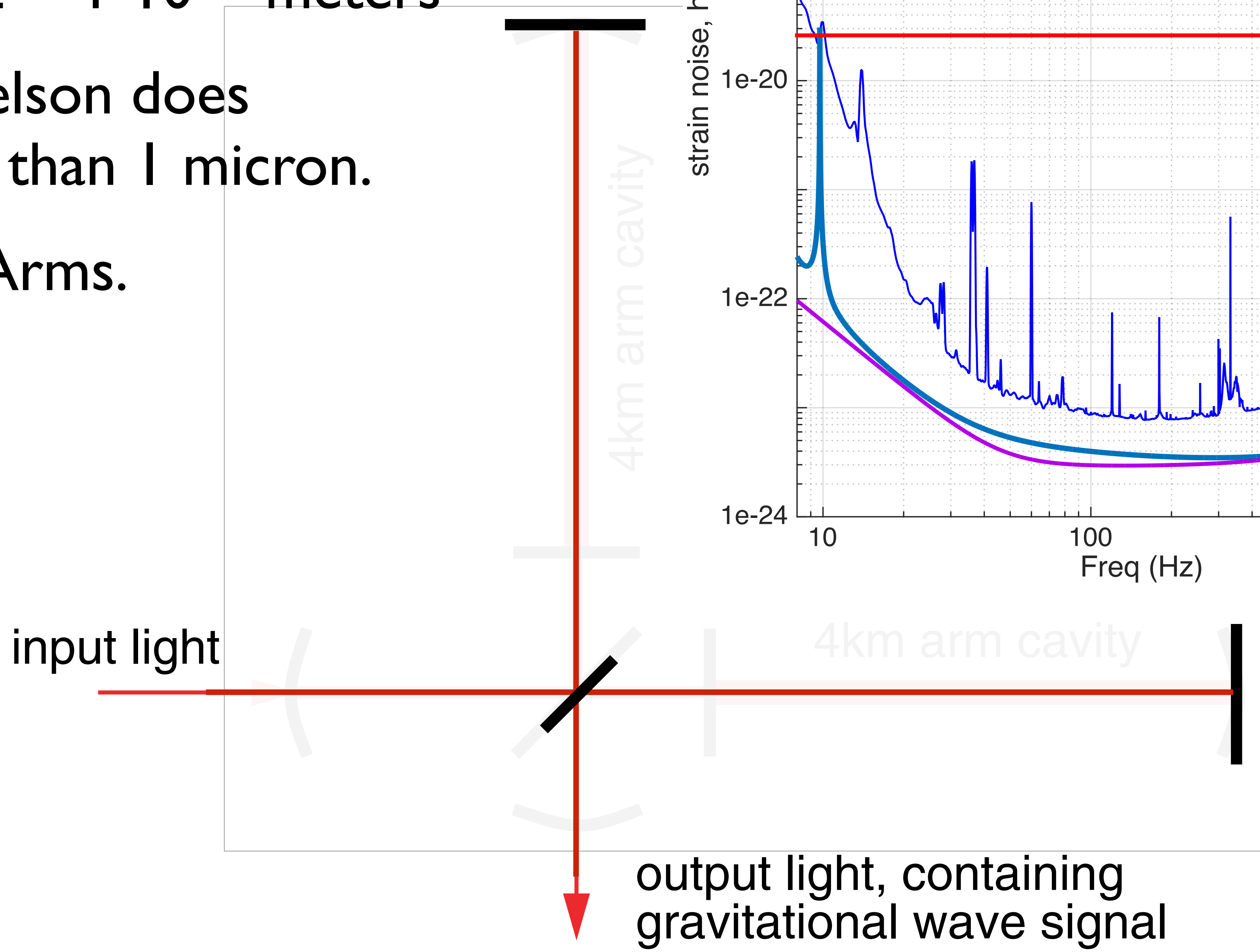
From 1 micron to aLIGO

From 10^{-6} meters to a signal of (h) = 10^{-21}, dL = $4*10^{-18}$ meters

1. Simple Michelson does Much Better than 1 micron.

2. Really Long Arms.





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From 10^{-6} meters to a signal of (h) = 10^{-21}, dL = $4*10^{-18}$ meters

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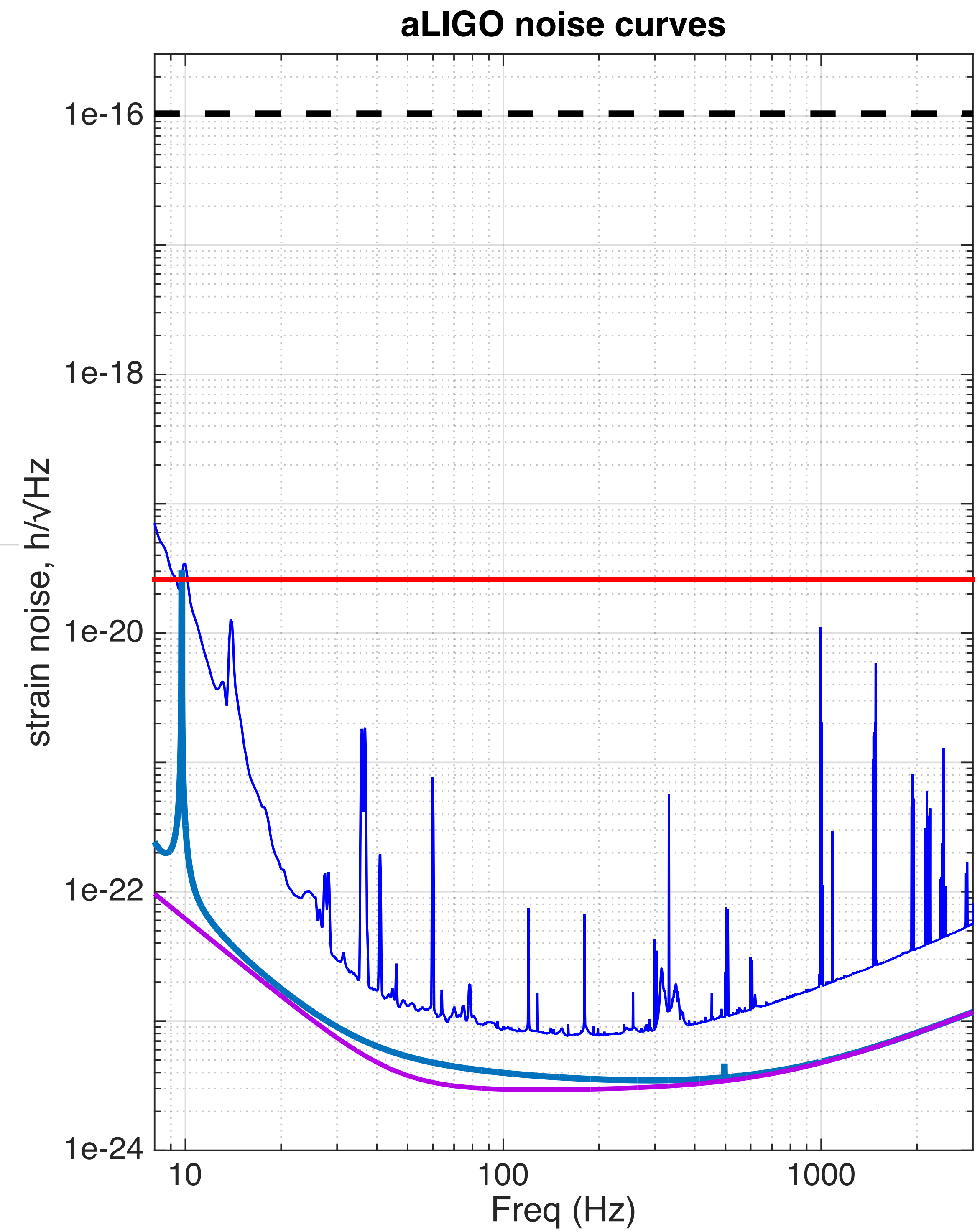
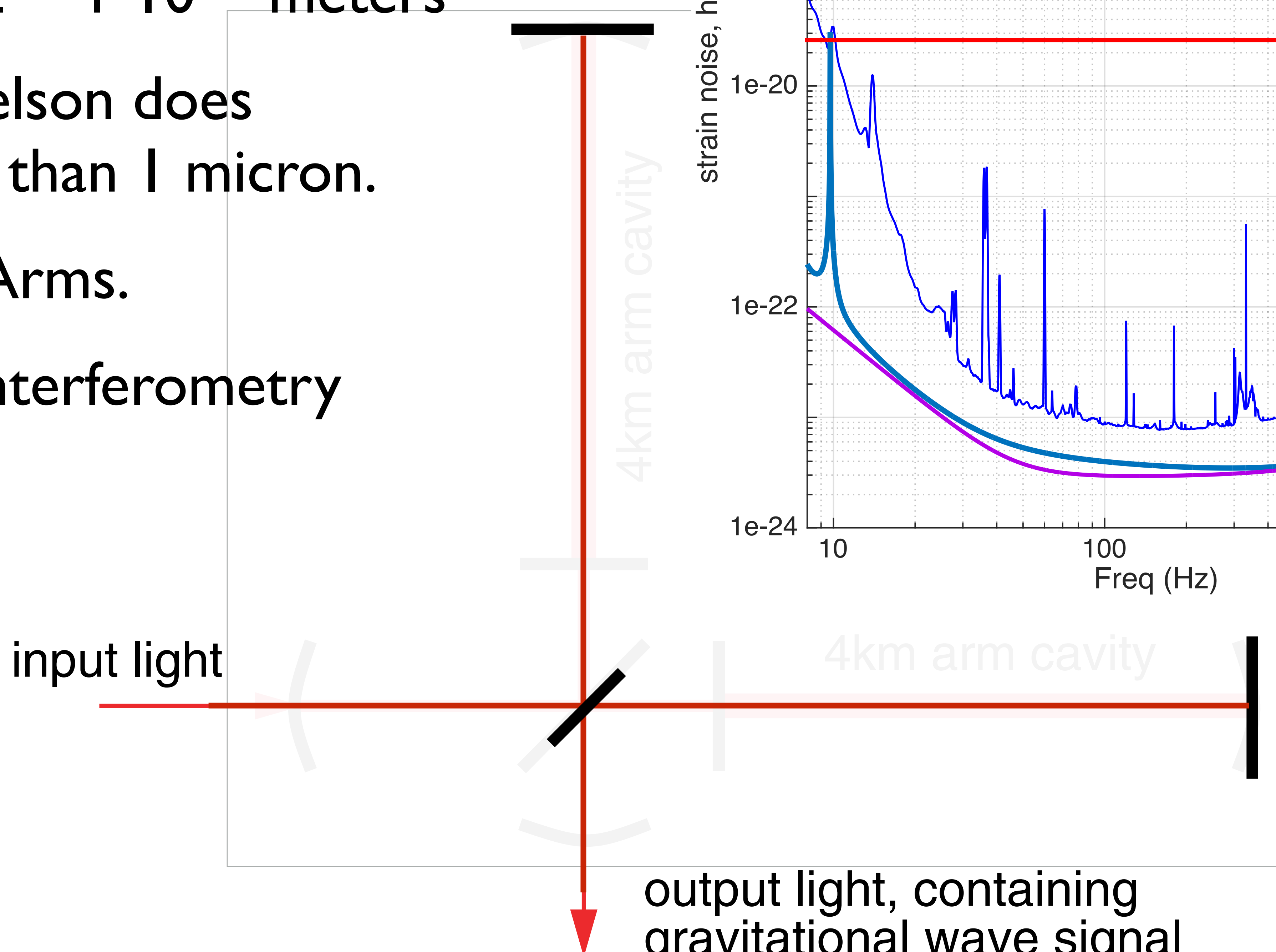
3. Interesting Interferometry





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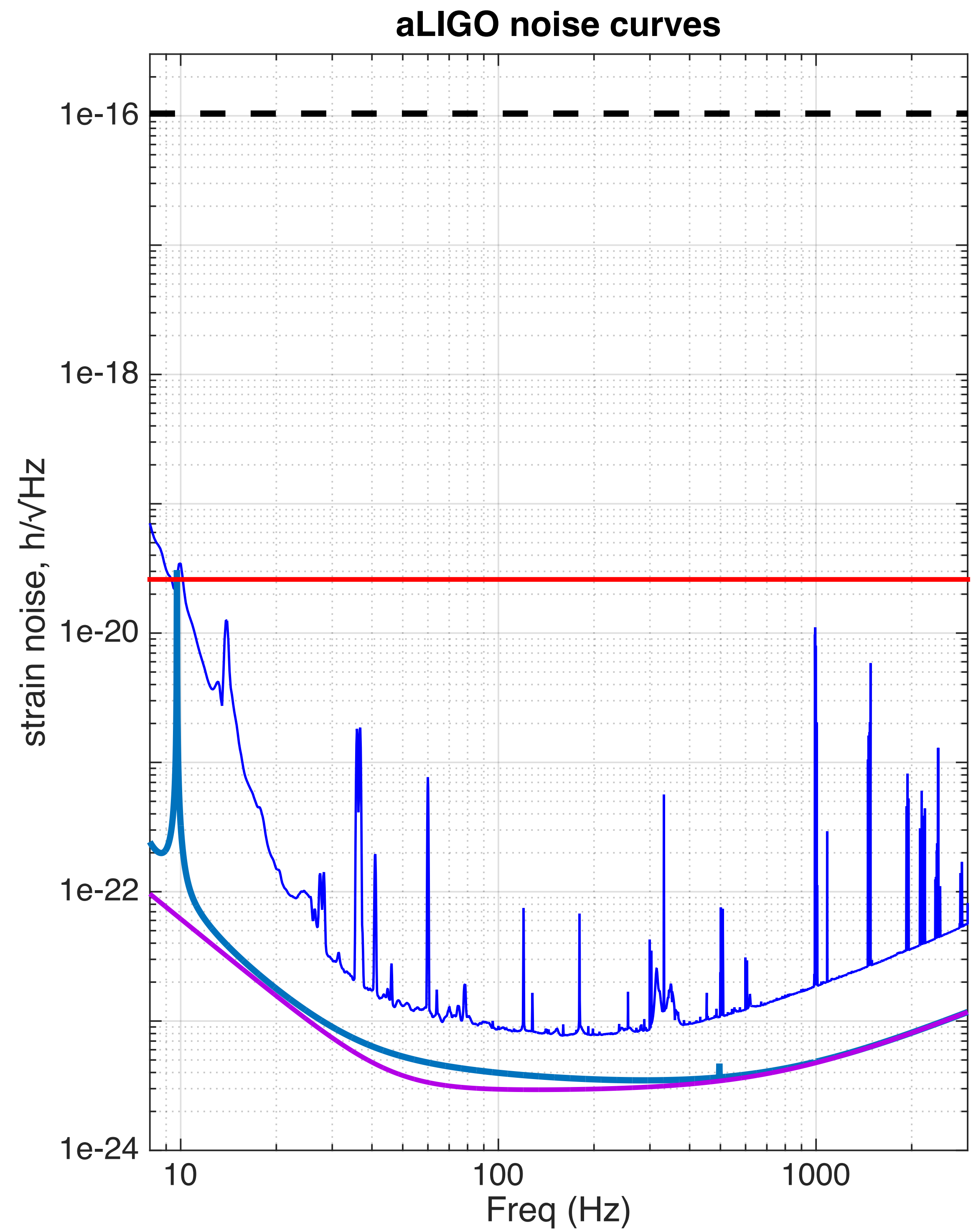

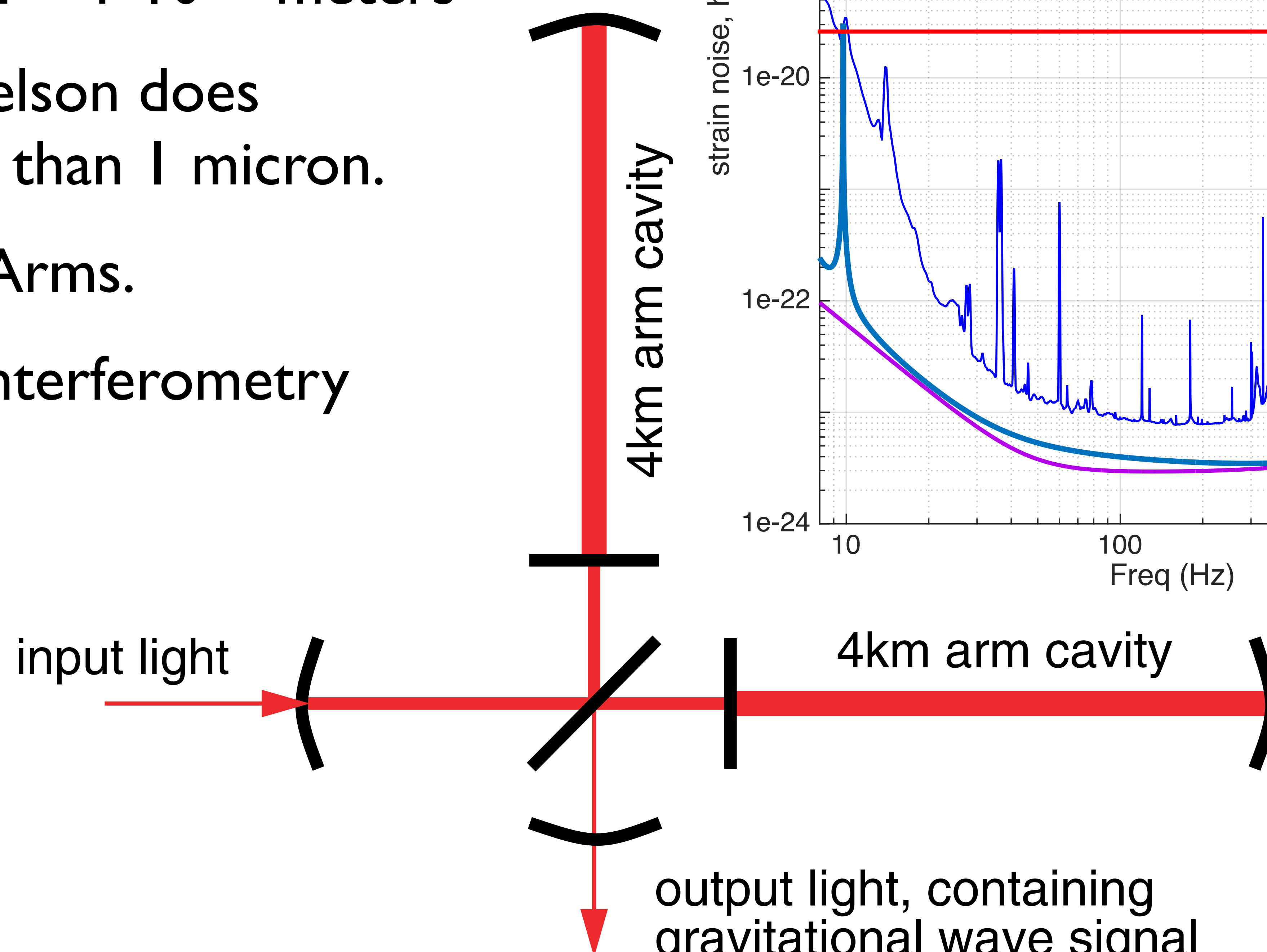

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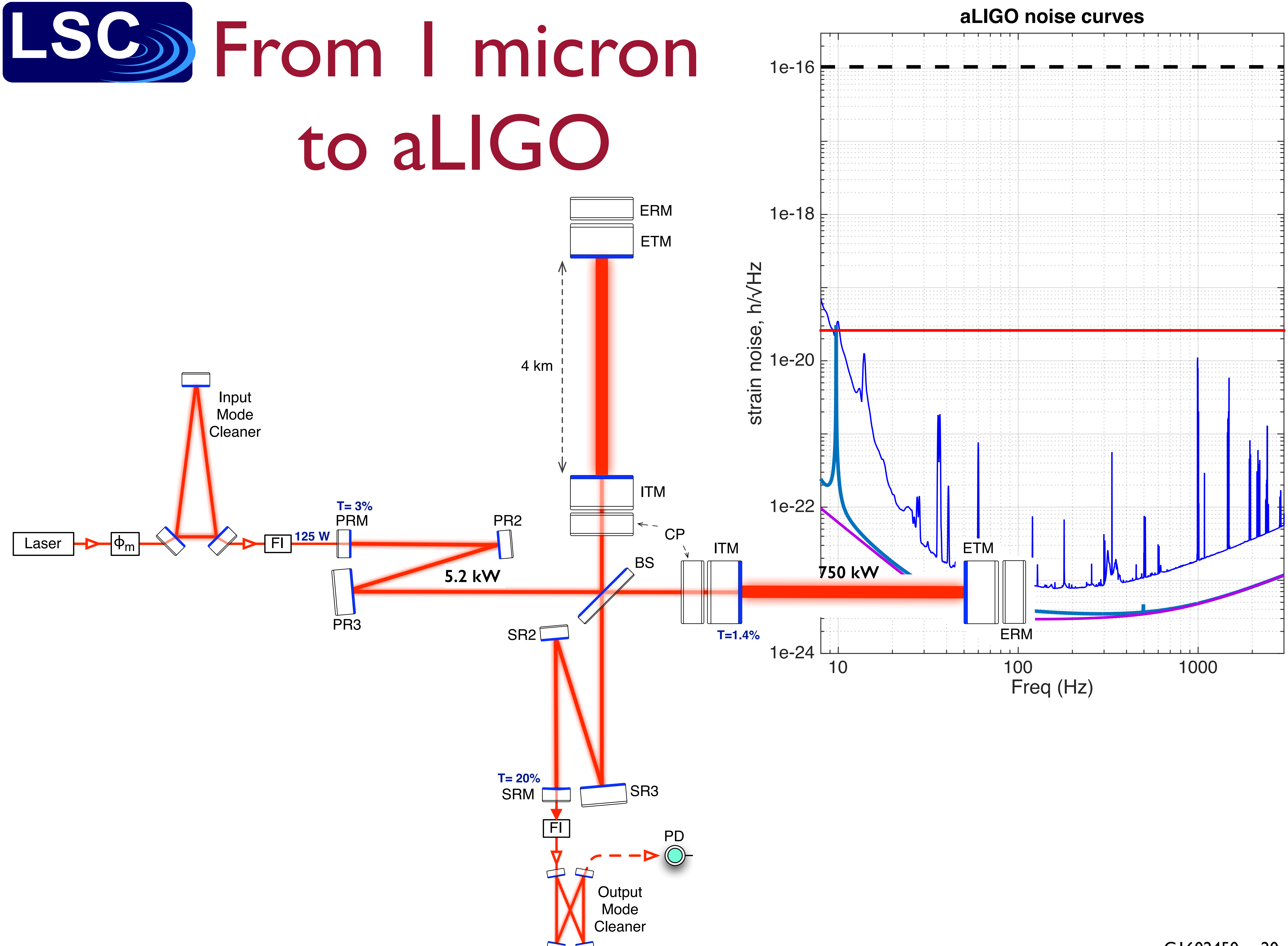

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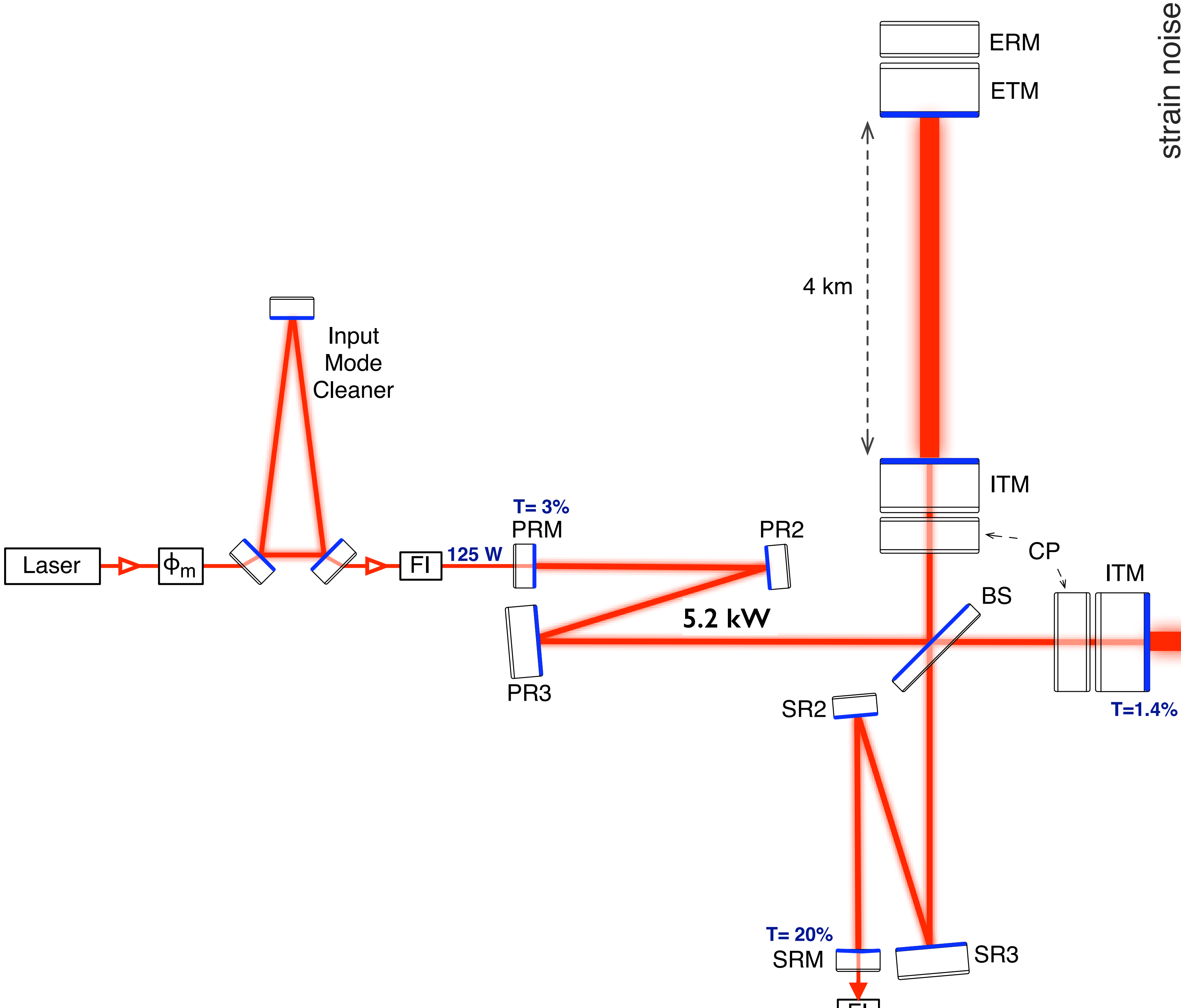
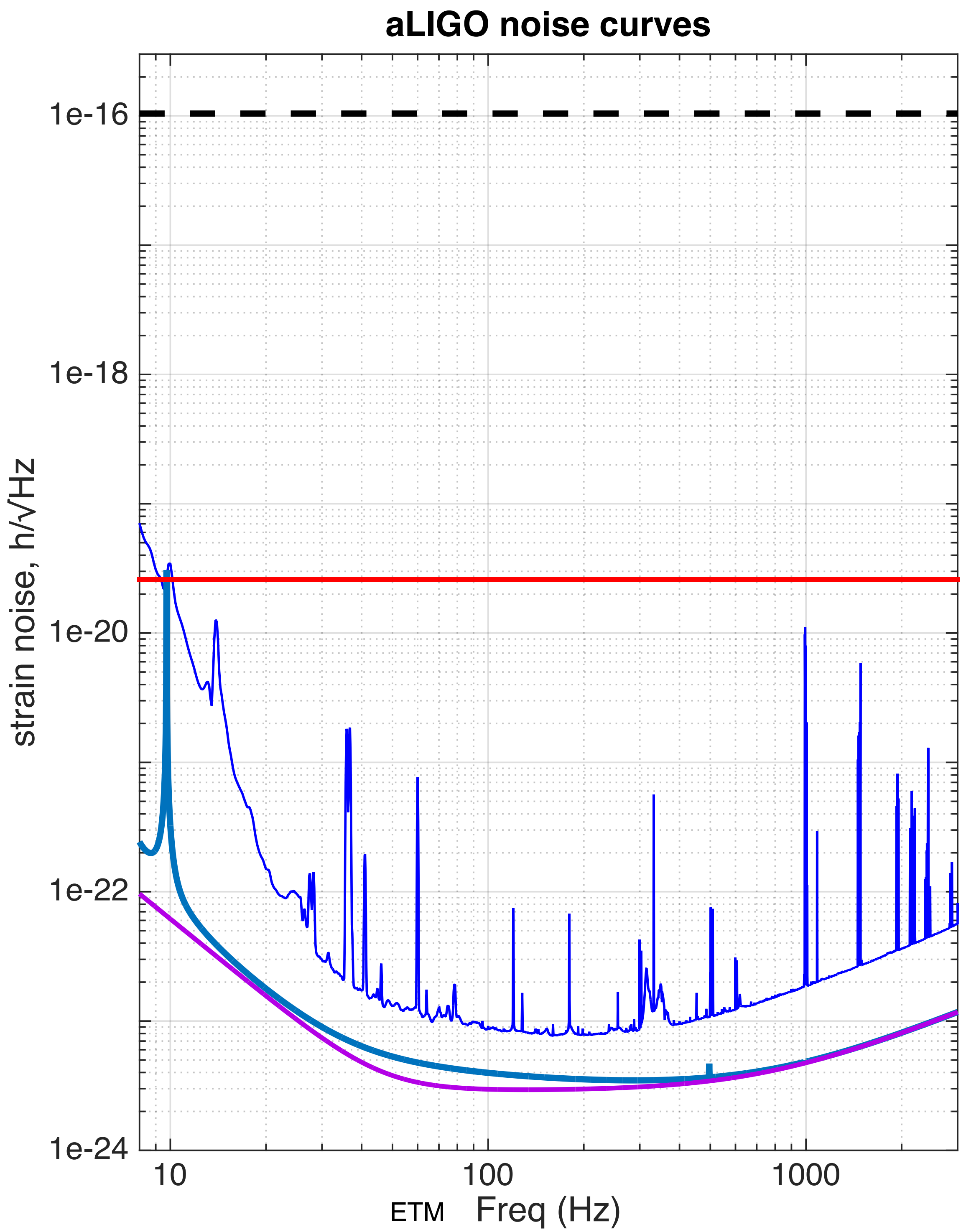
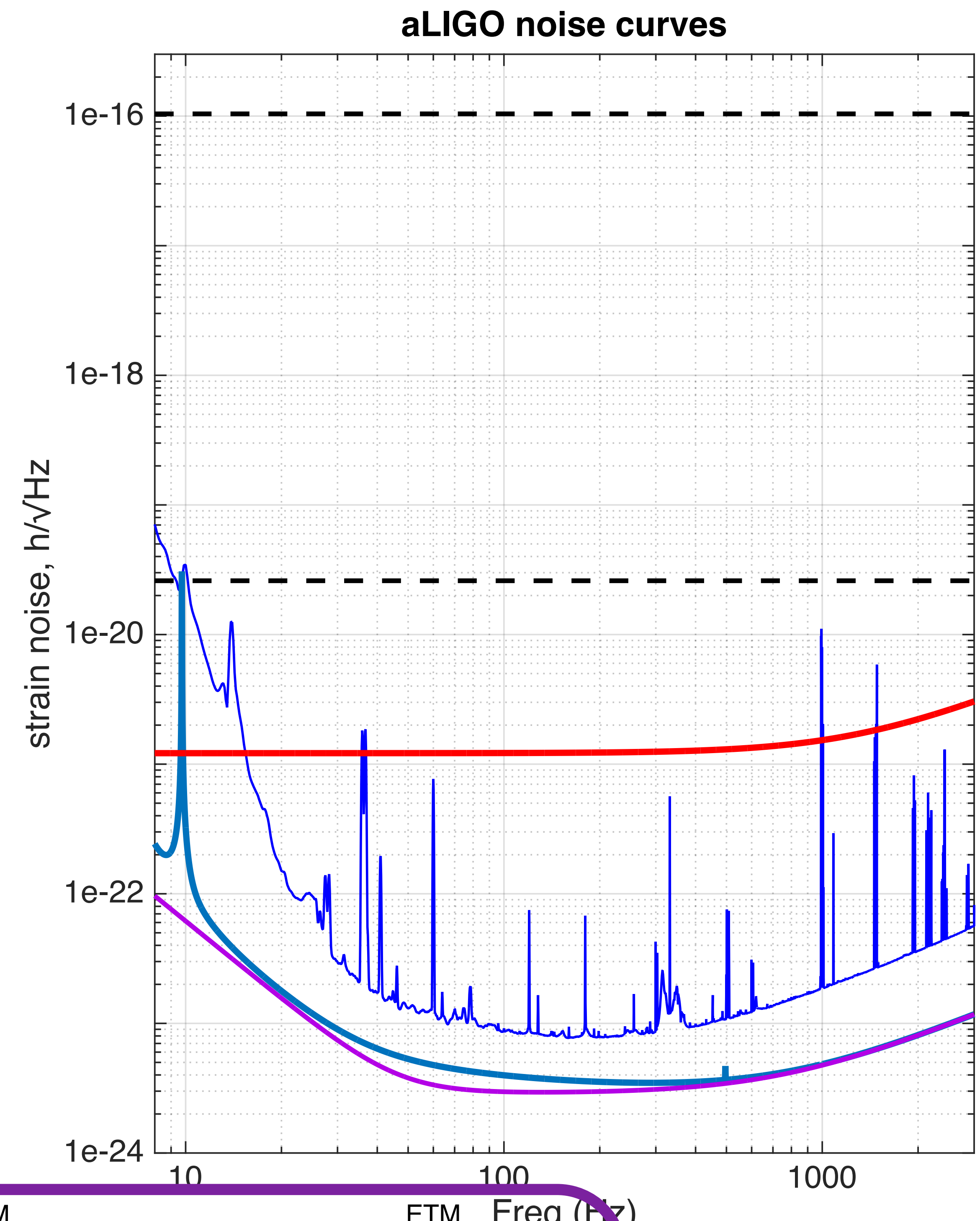
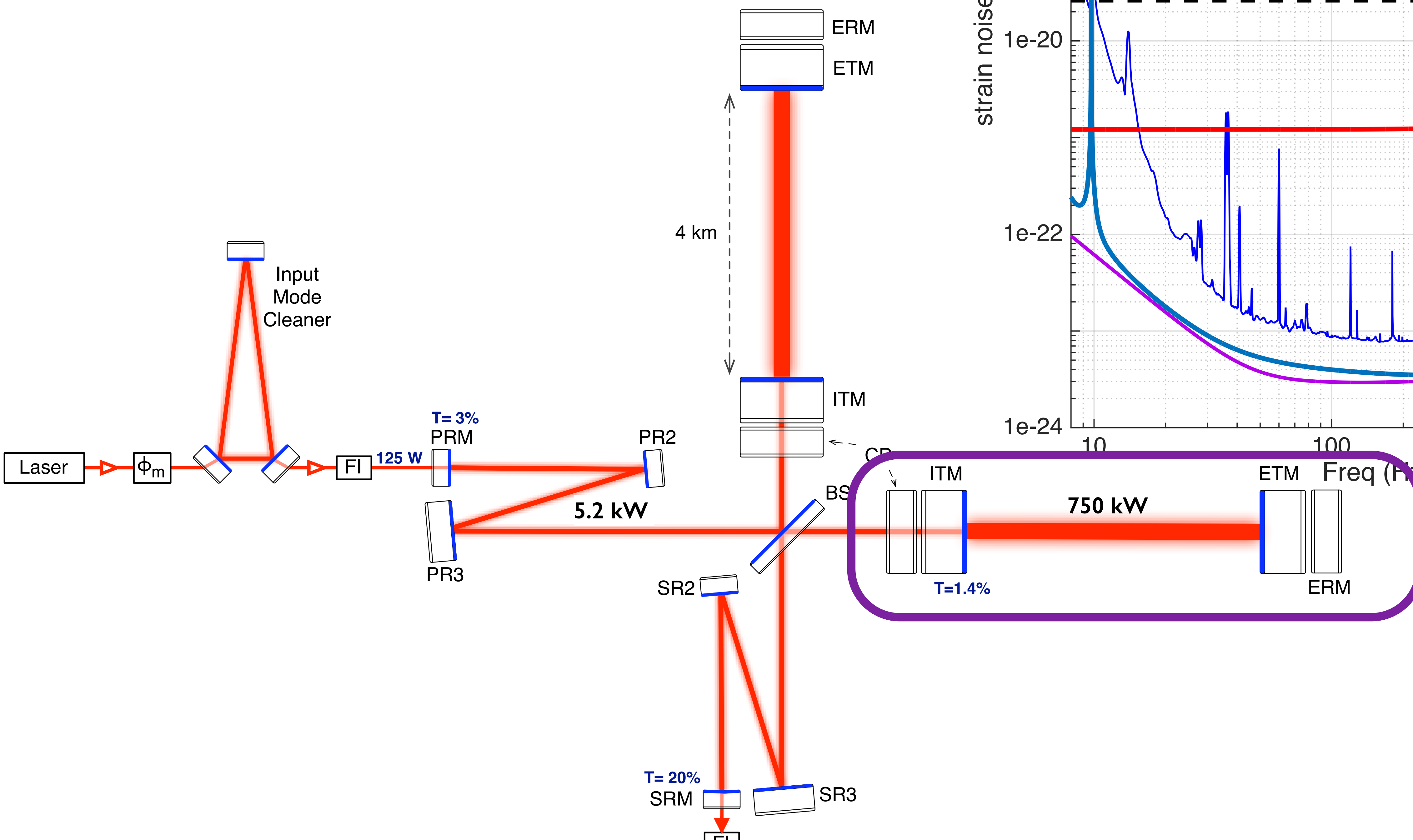




Interferometry

3. Interesting Interferometry
(measure length change accurately)
 - Fabry-Perot arm cavities





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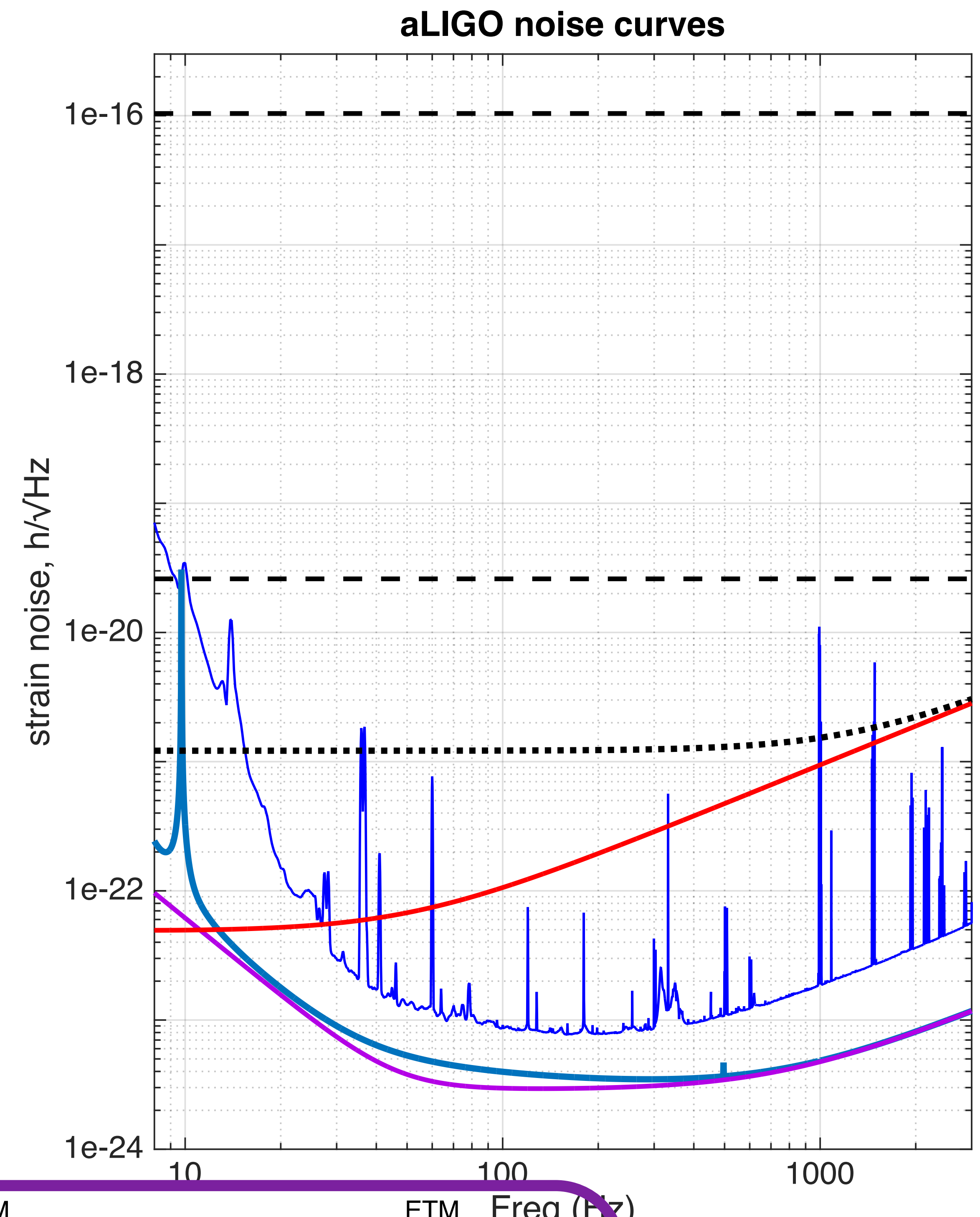

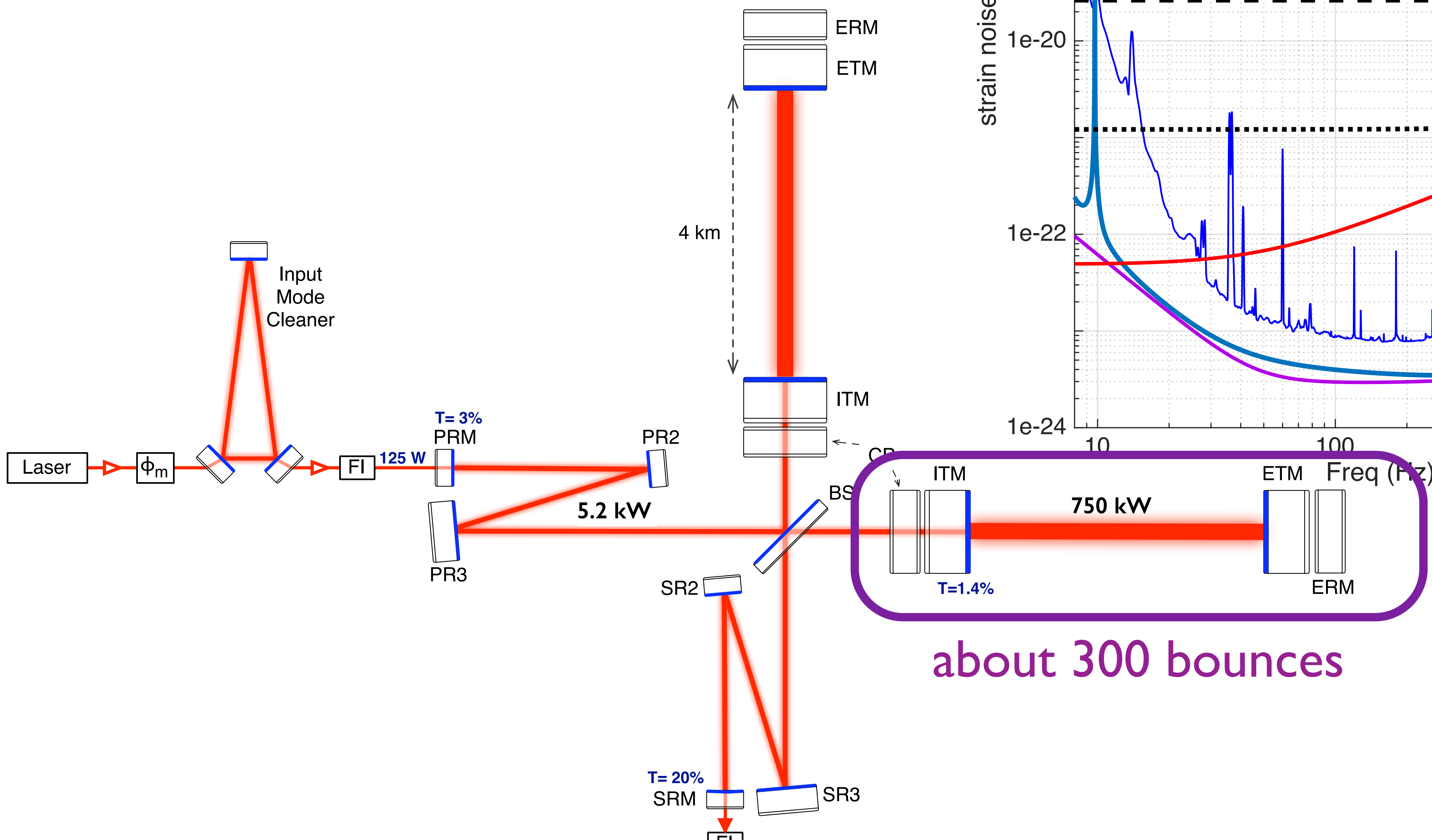

about 300 bounces

Interferometry

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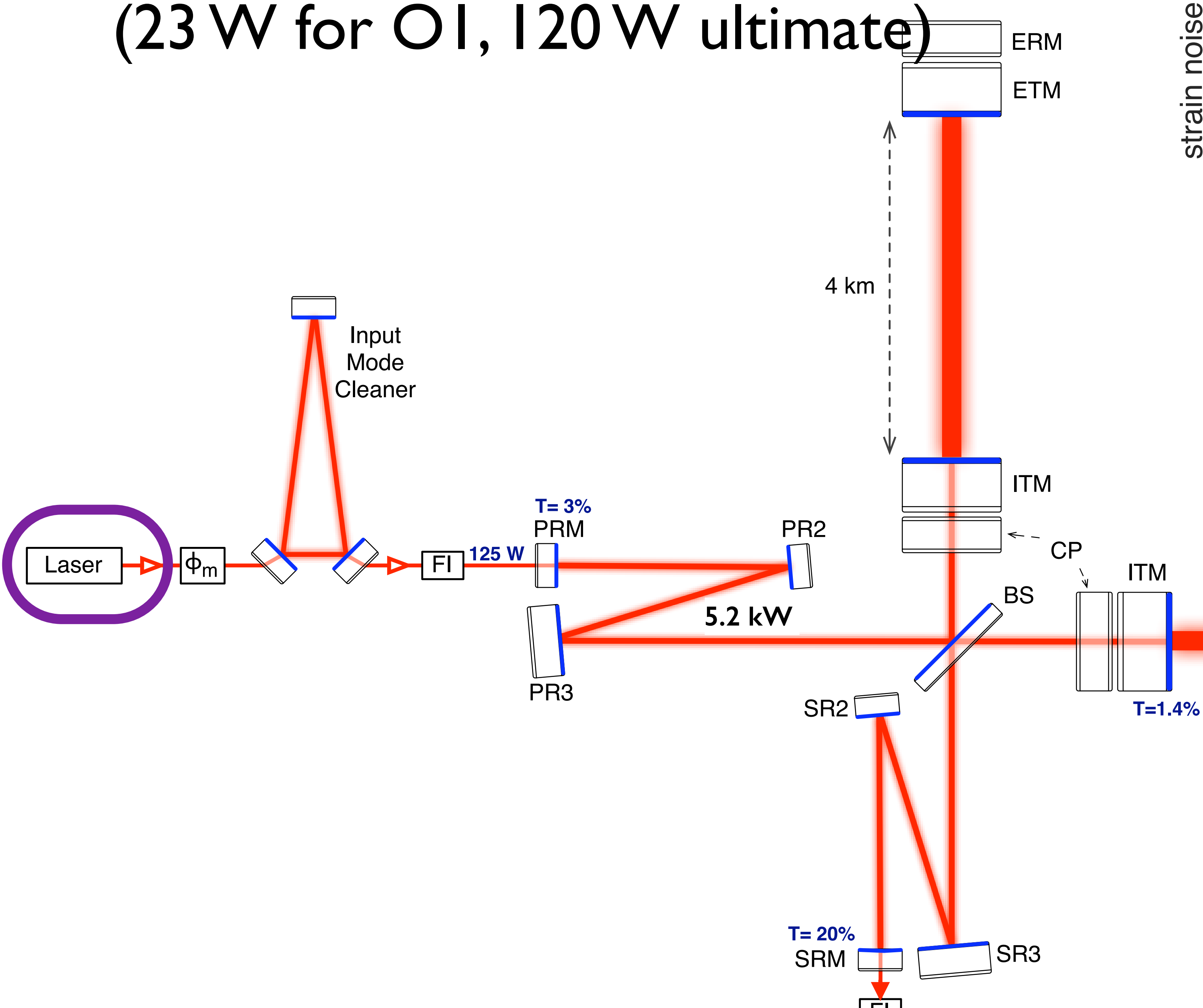
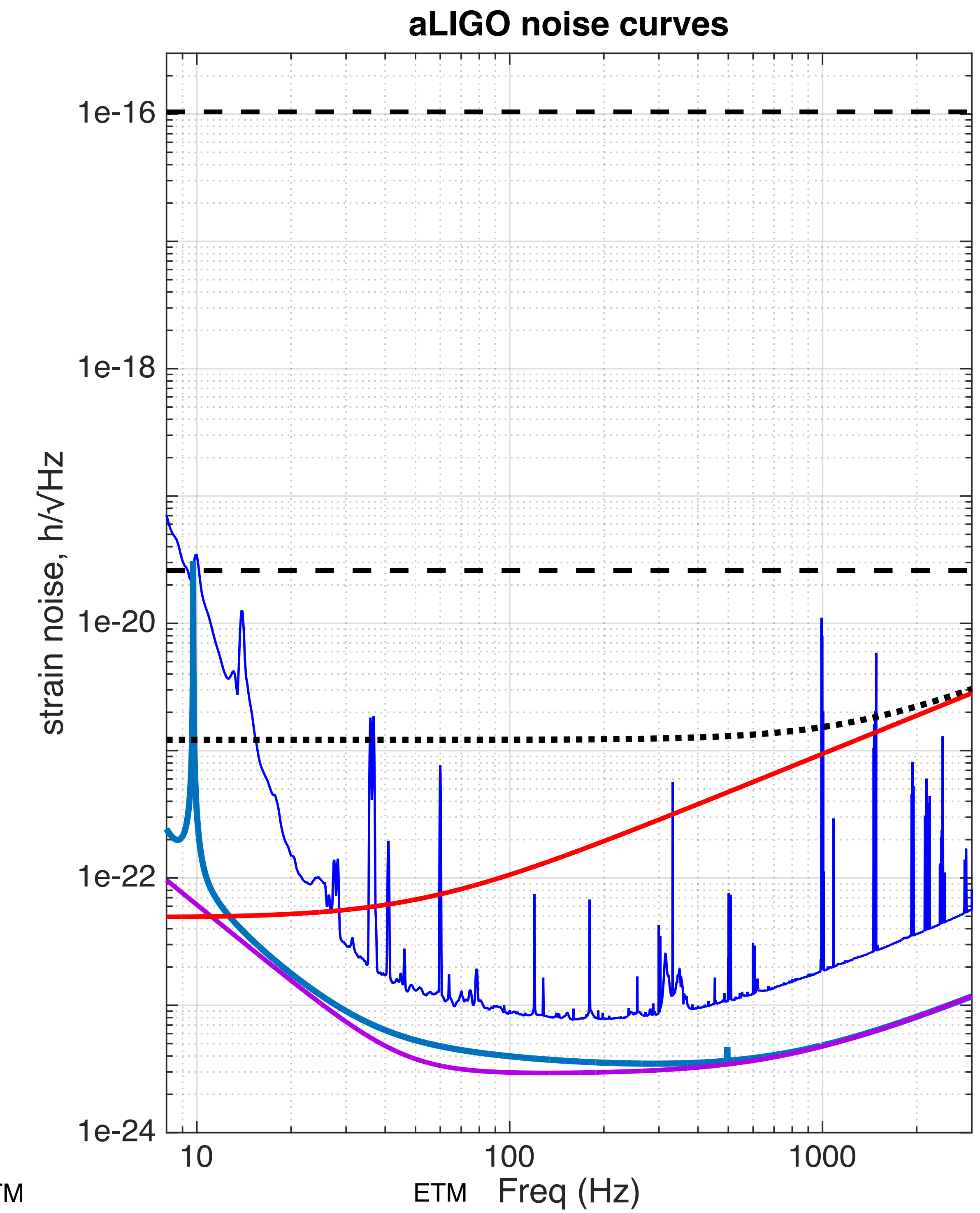
- More Power
  (23 W for O1, 120 W ultimate)





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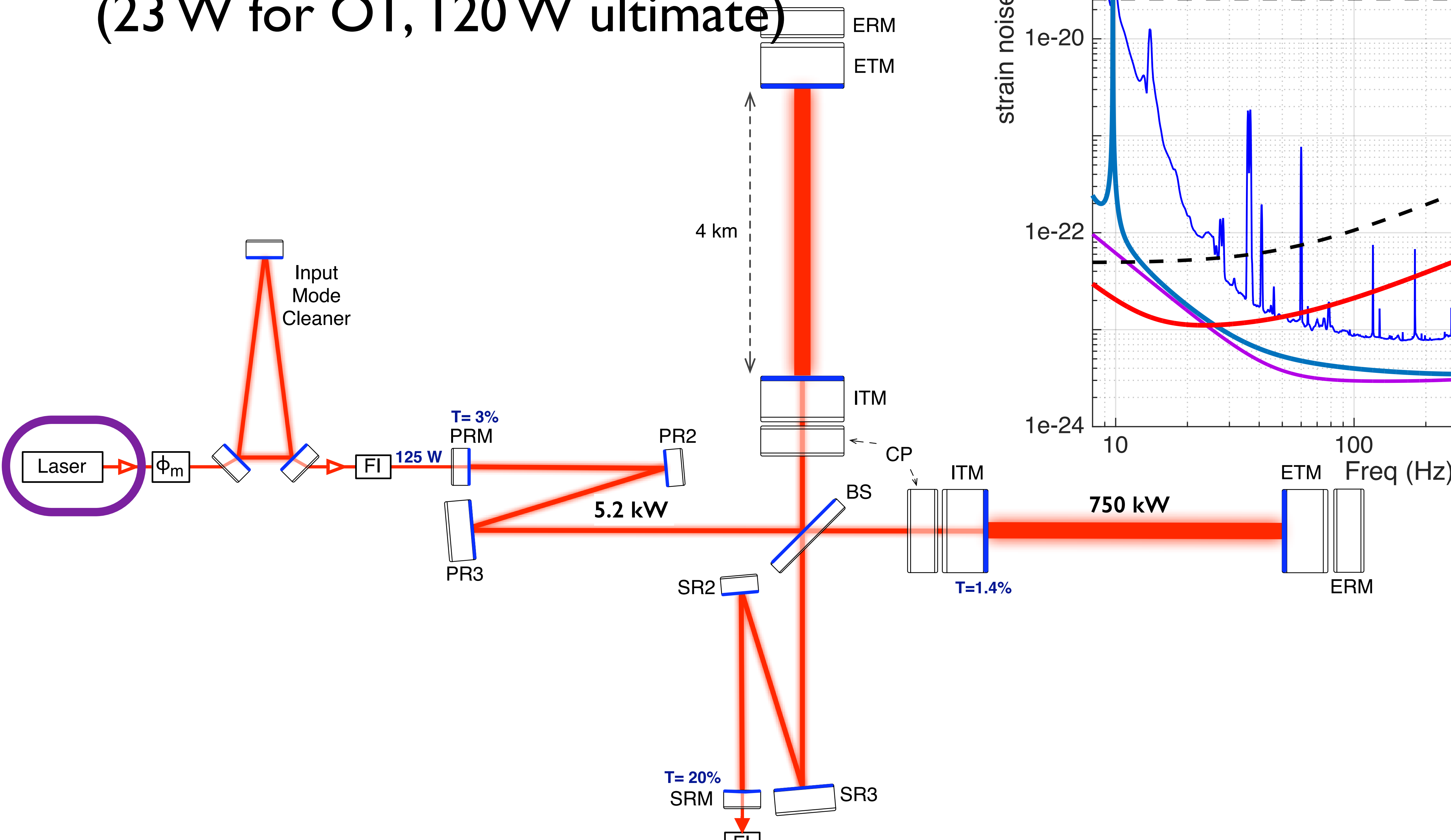
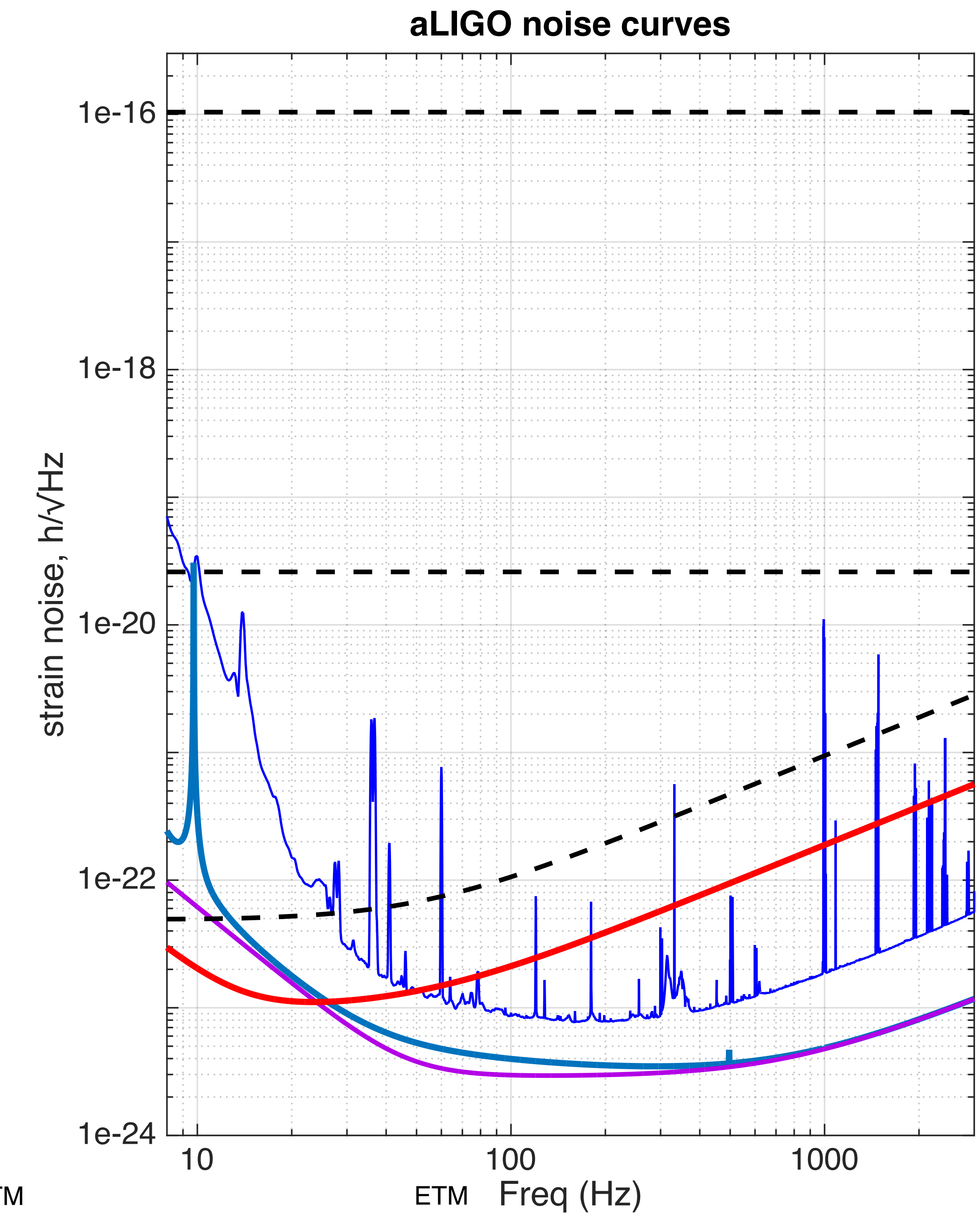
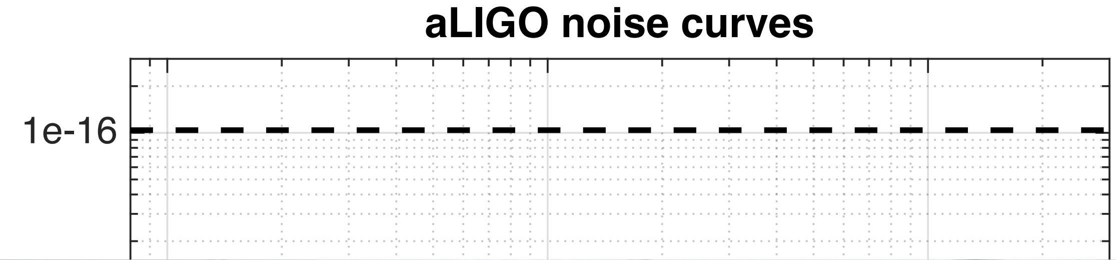
- More Power
  (23 W for O1, 120 W ultimate)

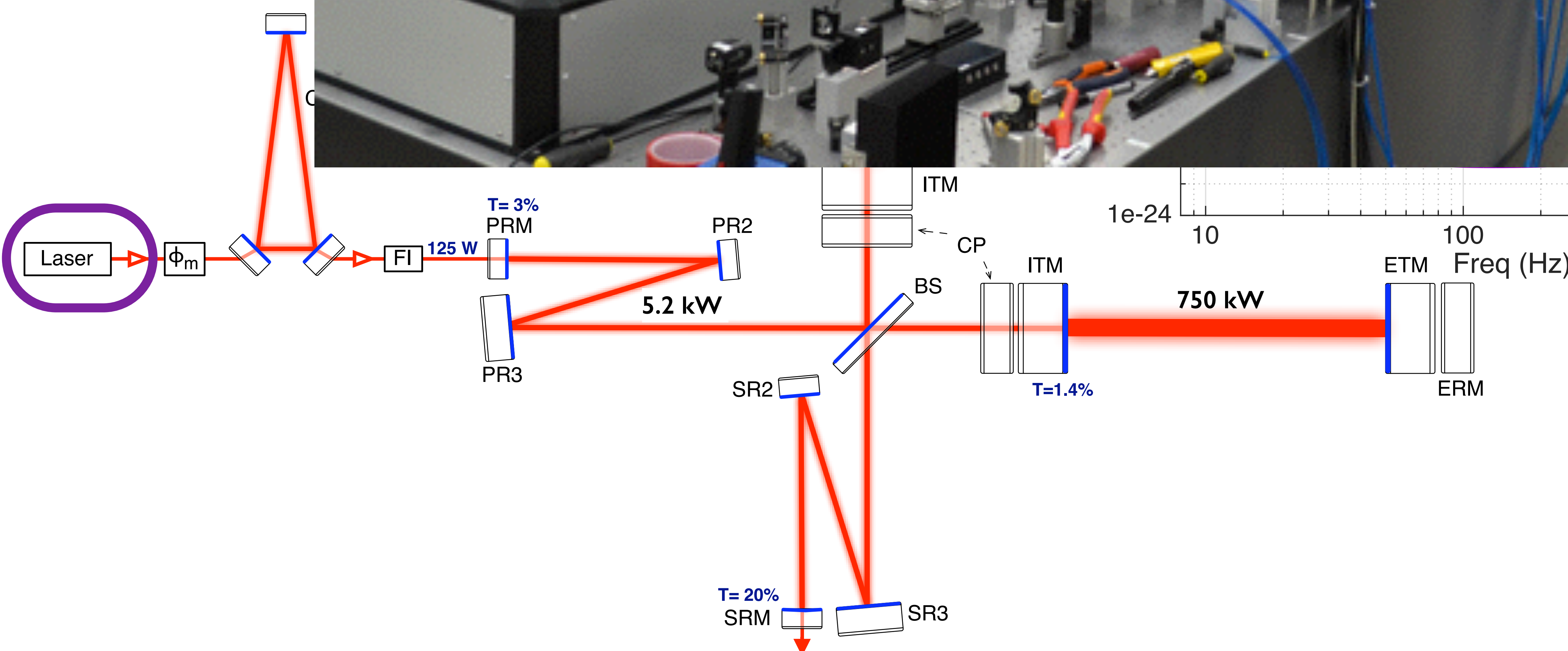




Interferometry

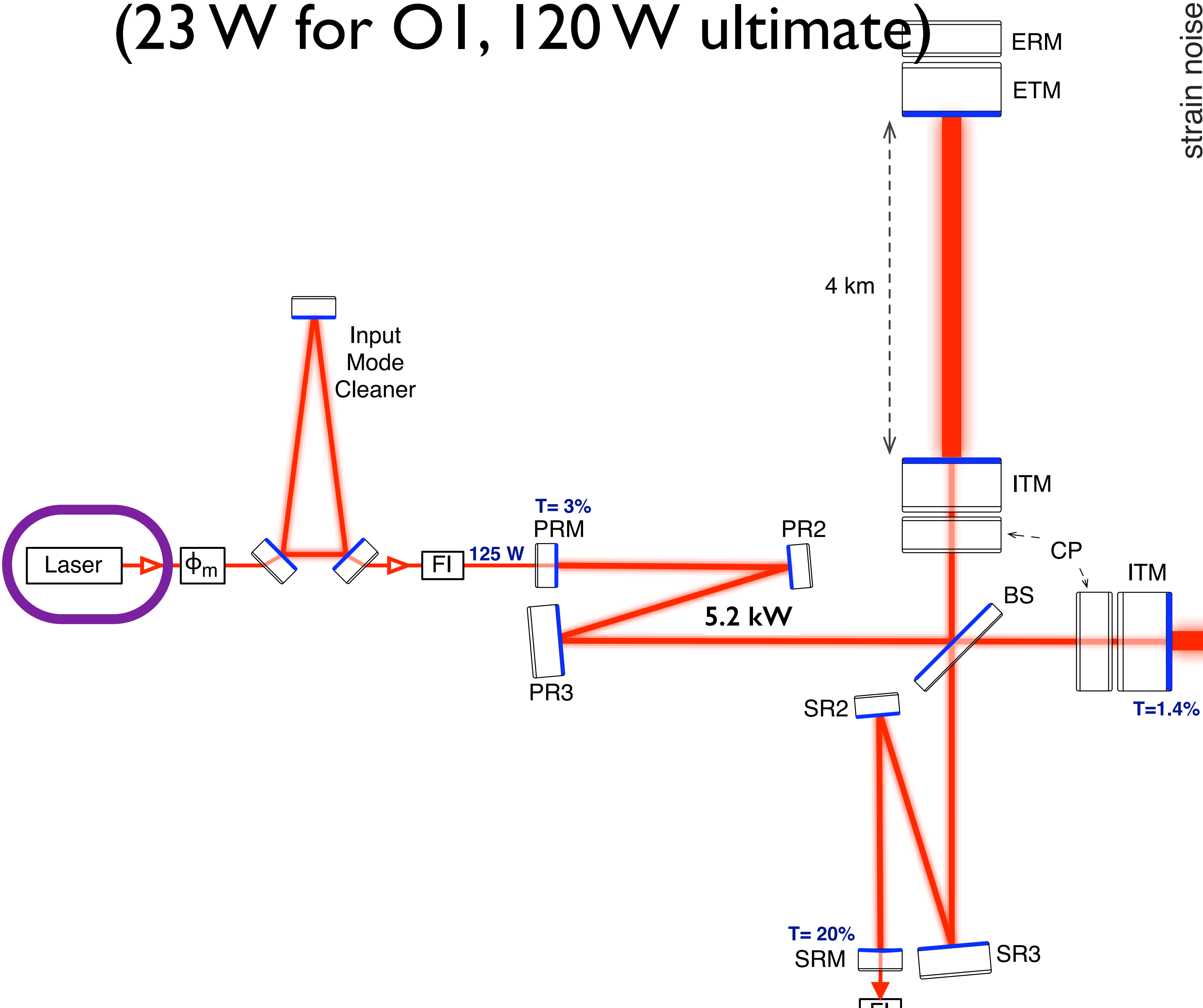
3. Interesti
(measure le
- Fabry-Pe
- More Po
(23 W fo

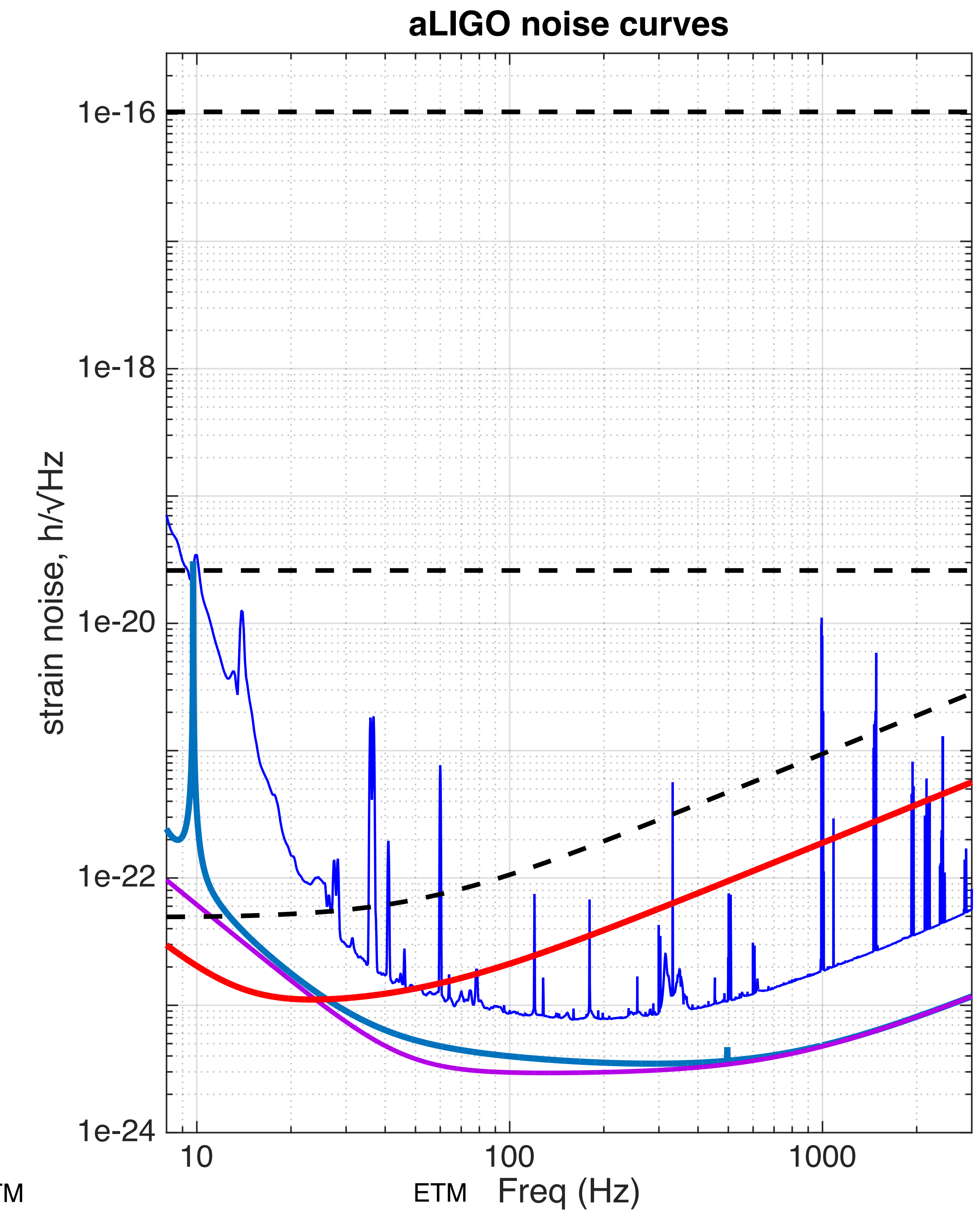




Interferometry

3. Interesting Interferometry
(measure length change accurately)
- Fabry-Perot arm cavities
- More Power
  (23 W for O1, 120 W ultimate)

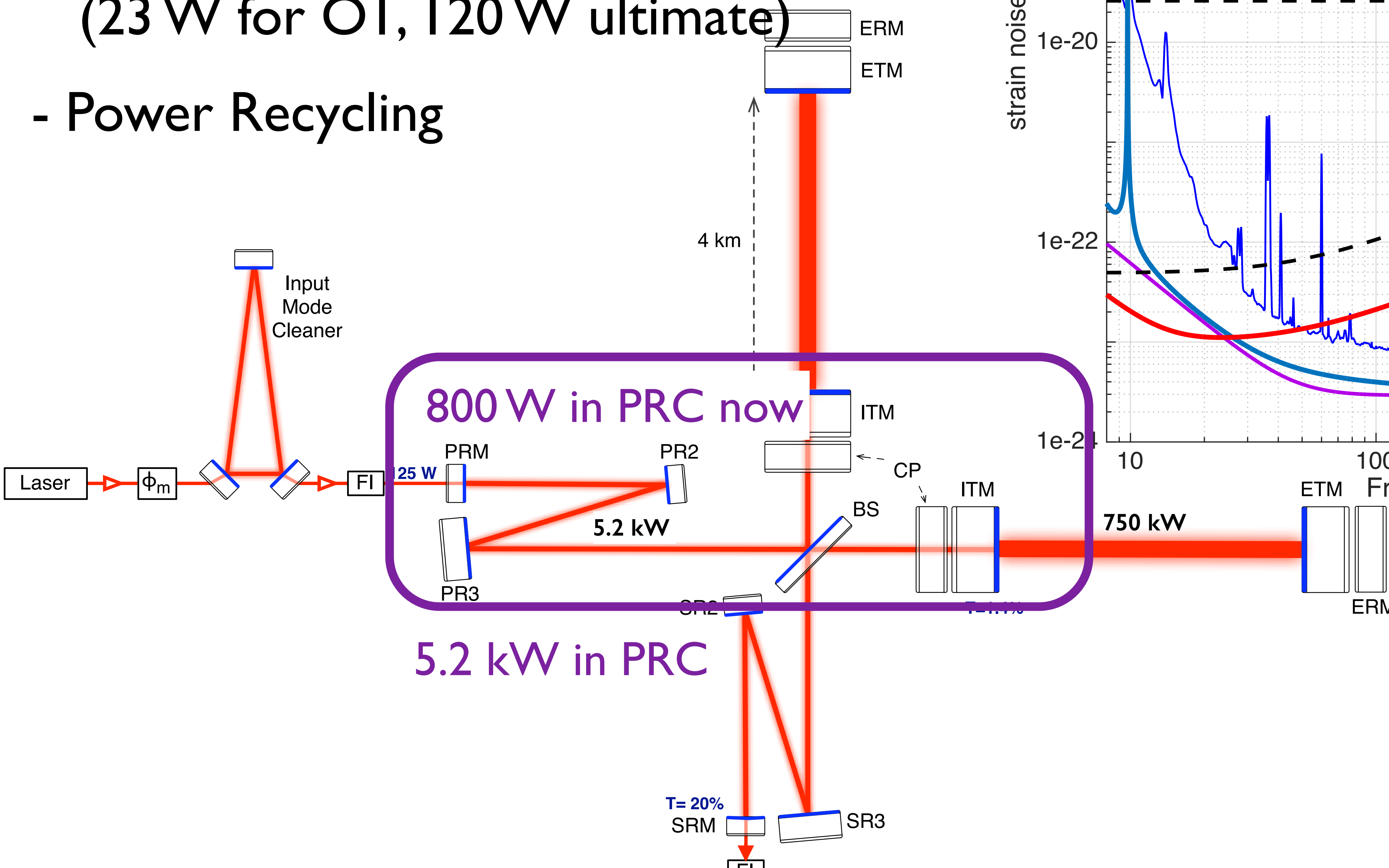


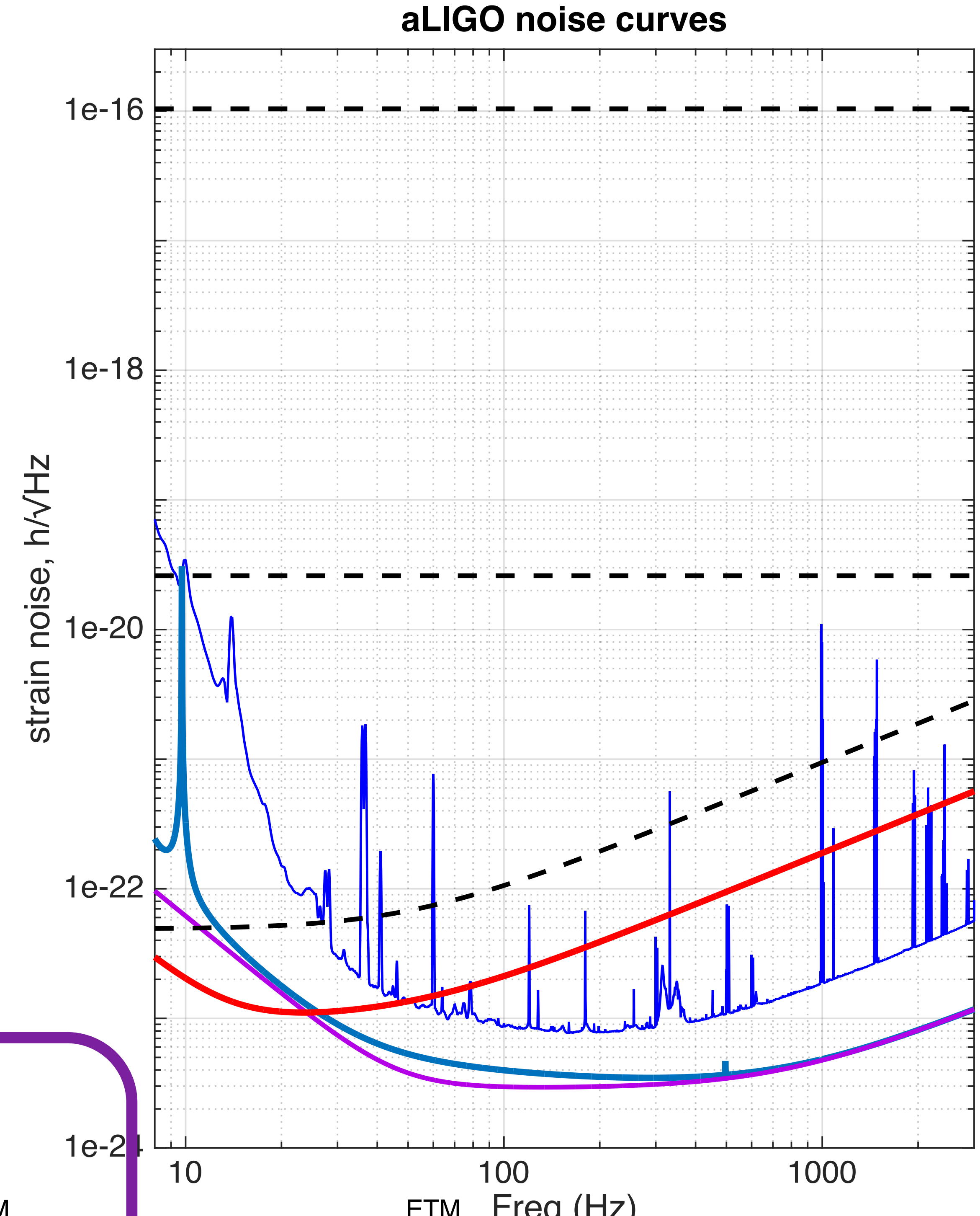


LSC Interferometry

3. Interesting Interferometry
(measure length change accurately)
- Fabry-Perot arm cavities
- More Power
  (23 W for O1, 120 W ultimate)

- Power Recycling





Interferometry

3. Interesting Interferometry
(measure length change accurately)
- Fabry-Perot arm cavities
- More Power
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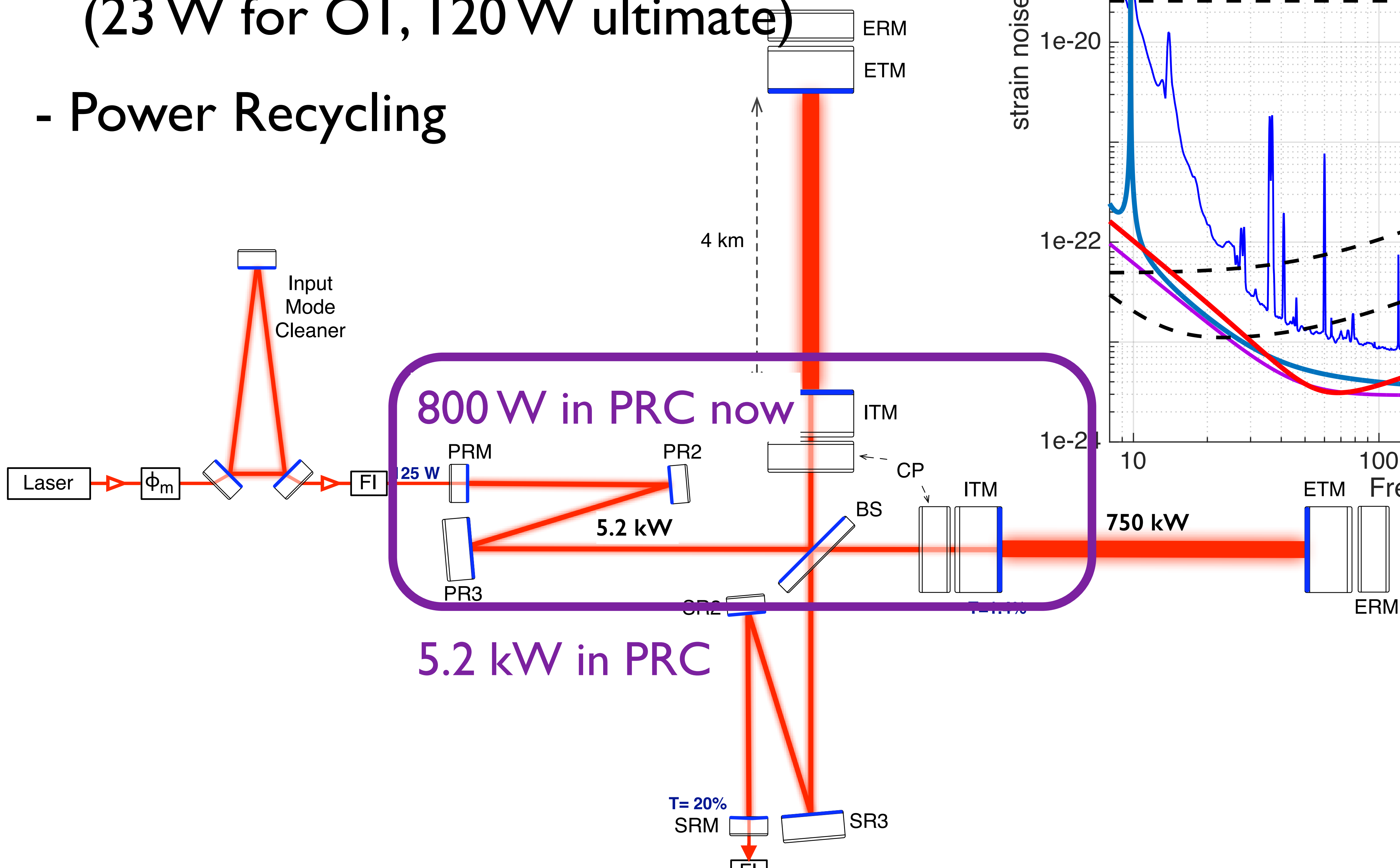
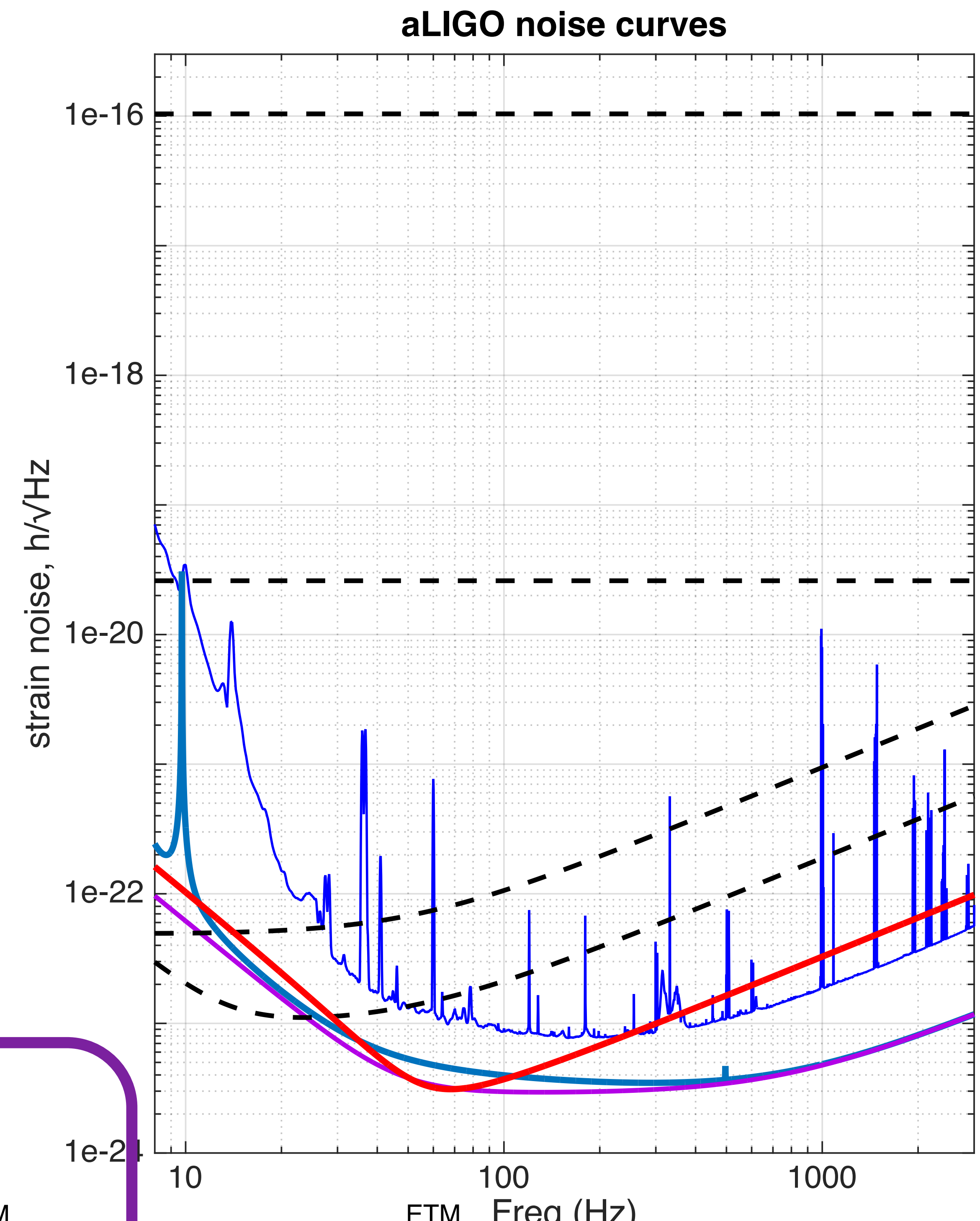
- Power Recycling



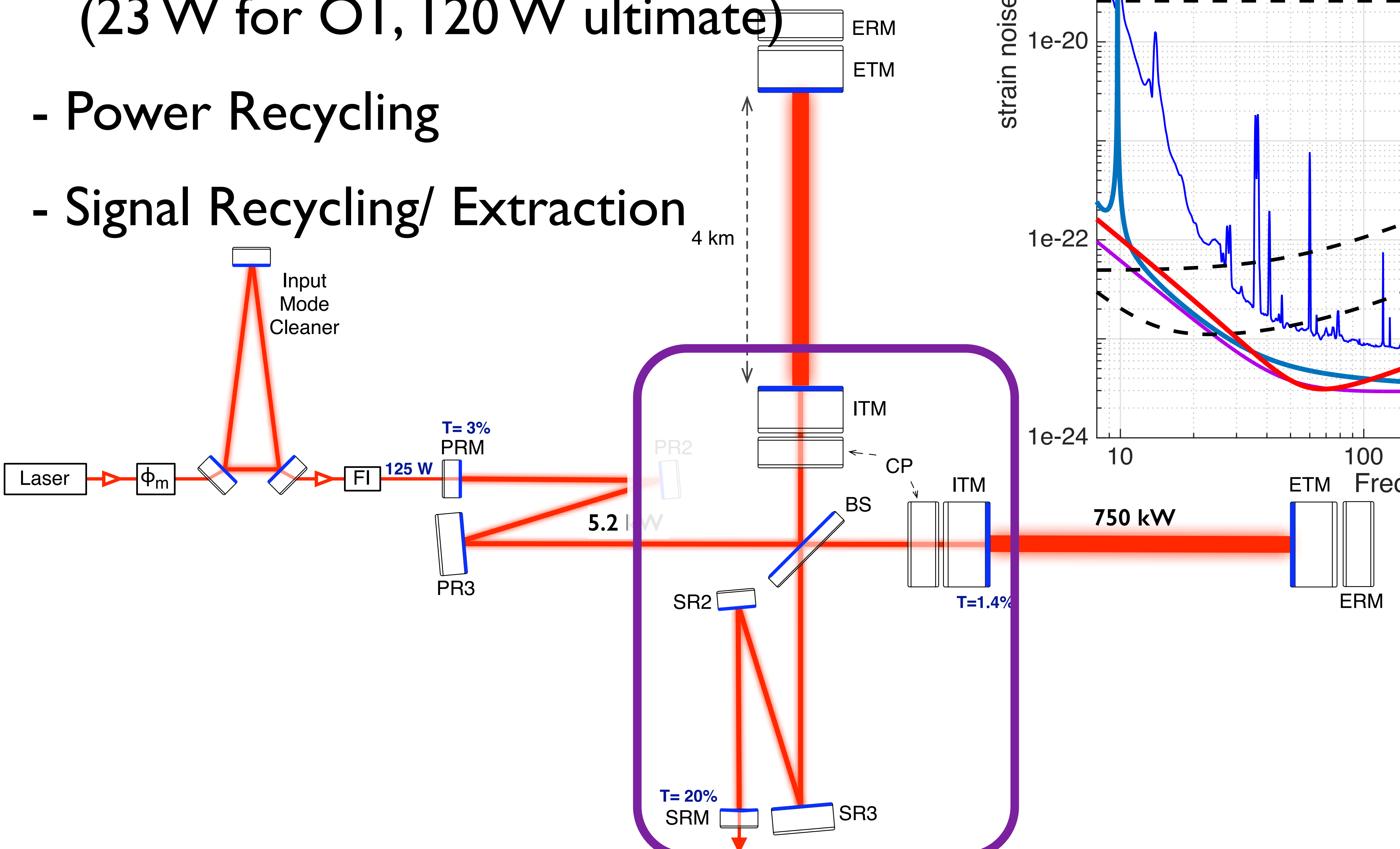


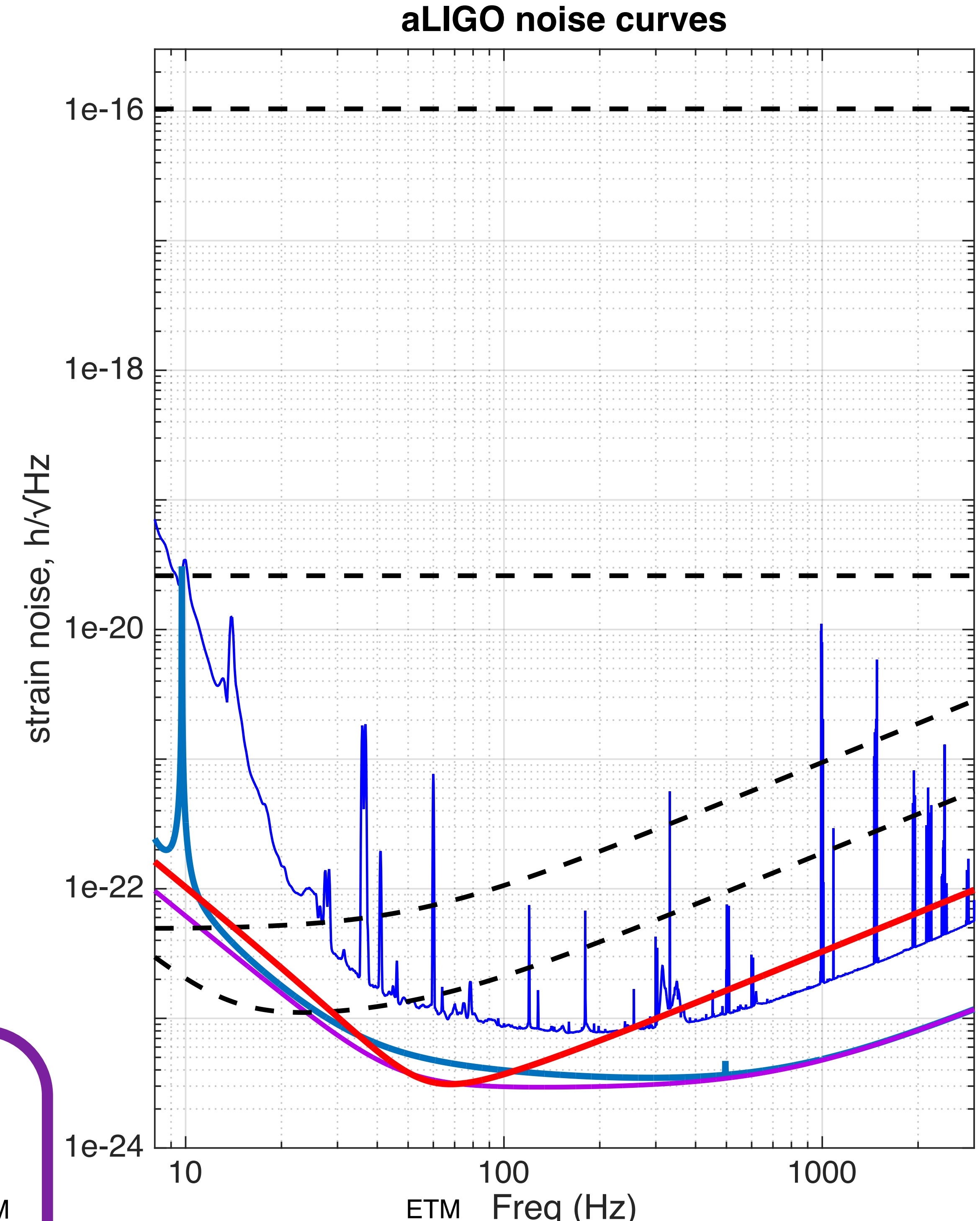
Interferometry

3. Interesting Interferometry
(measure length change accurately)
- Fabry-Perot arm cavities
- More Power
  (23 W for O1, 120 W ultimate)

- Power Recycling

- Signal Recycling/ Extraction



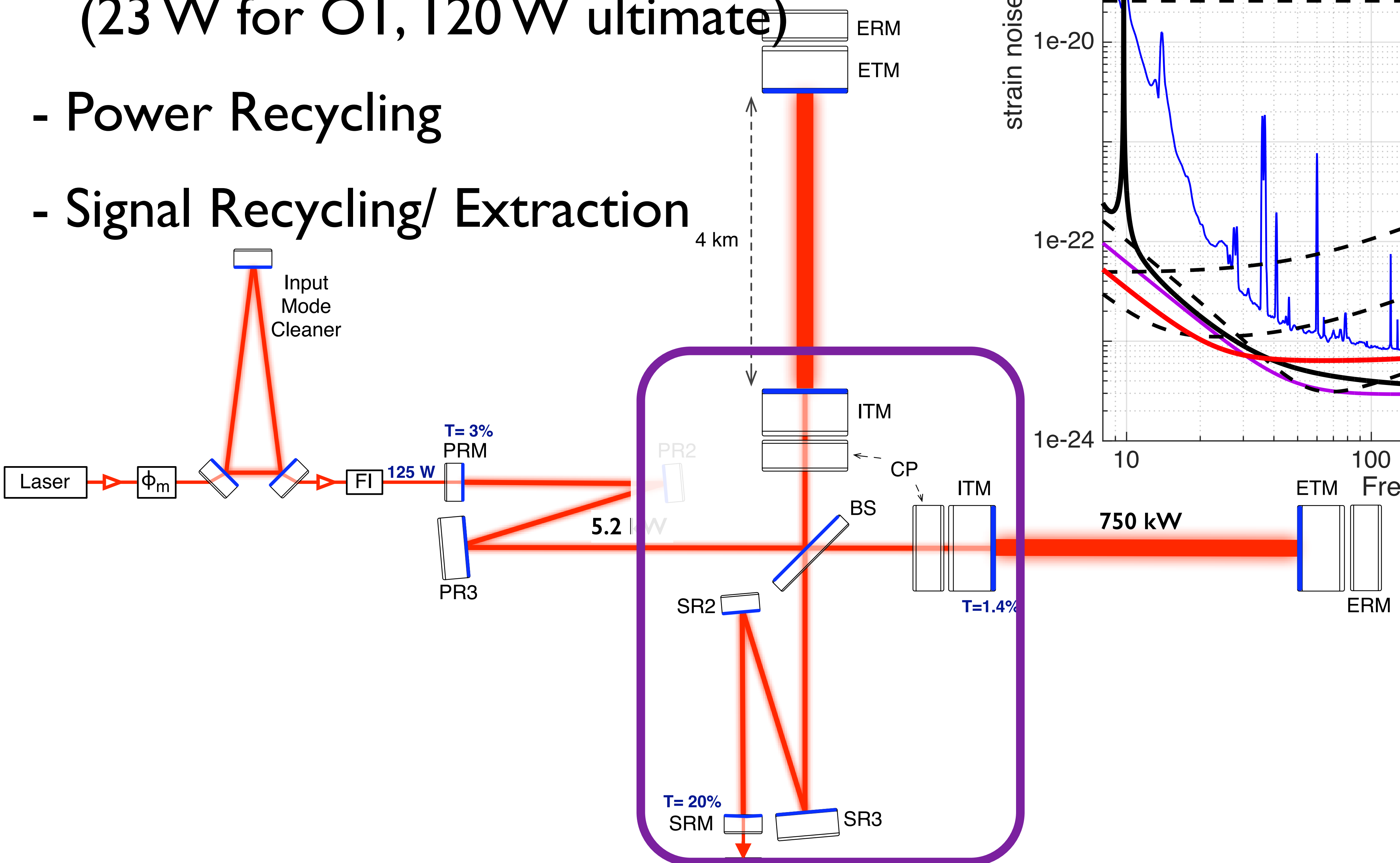


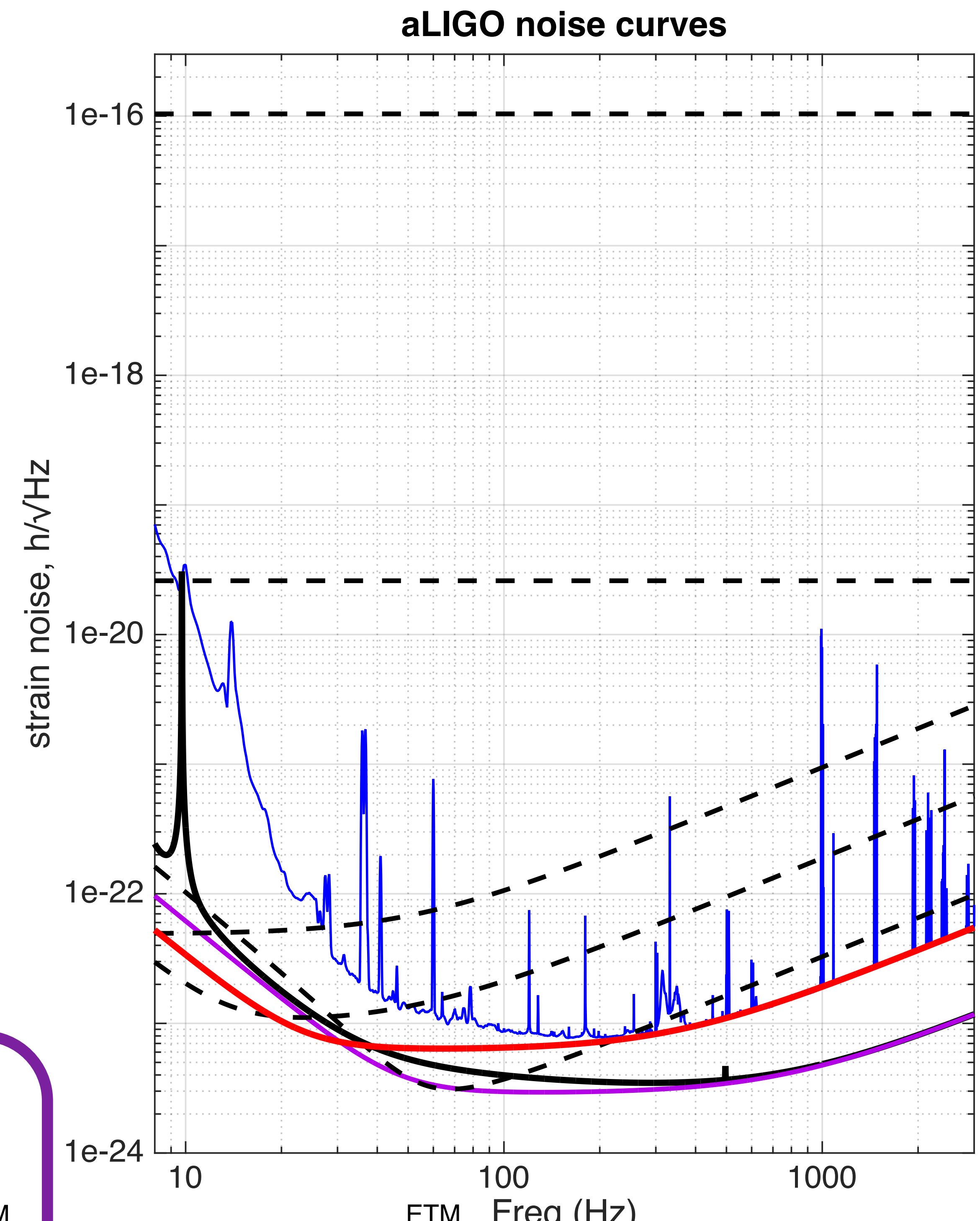
Interferometry

3. Interesting Interferometry
(measure length change accurately)
- Fabry-Perot arm cavities
- More Power
  (23 W for O1, 120 W ultimate)

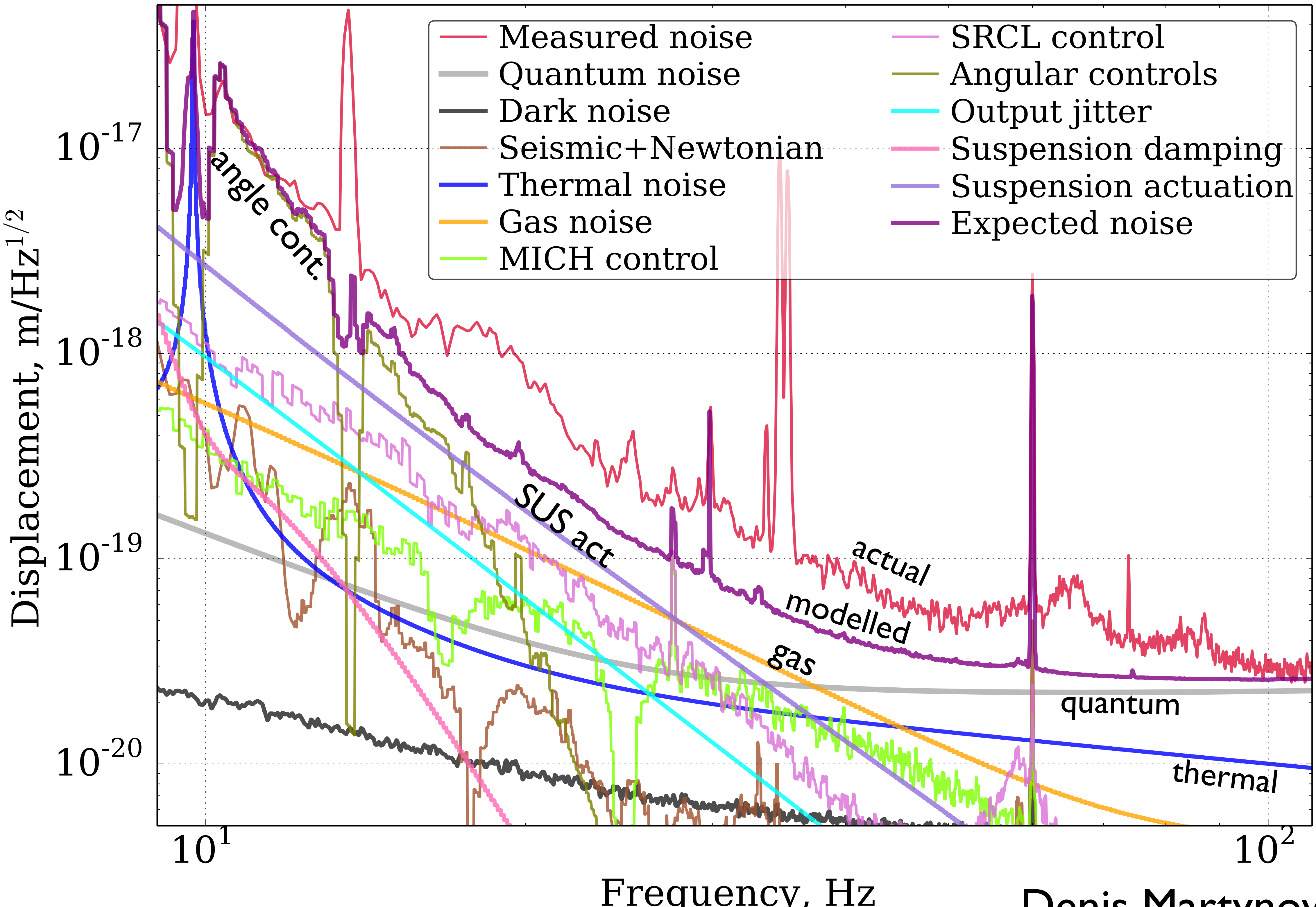
- Power Recycling

- Signal Recycling/ Extraction





Noise at 10-100 Hz

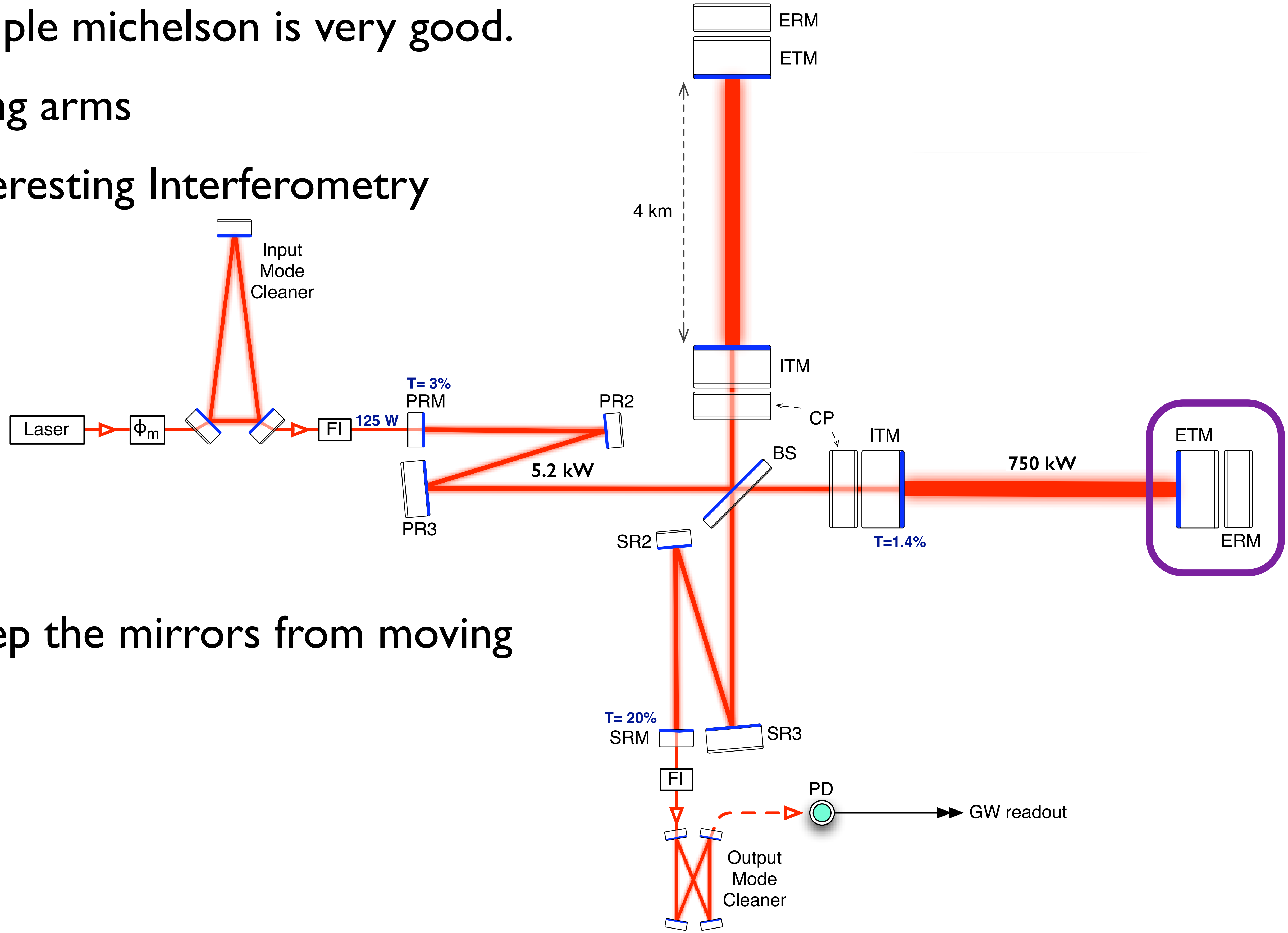


Denis Martynov, et. al.

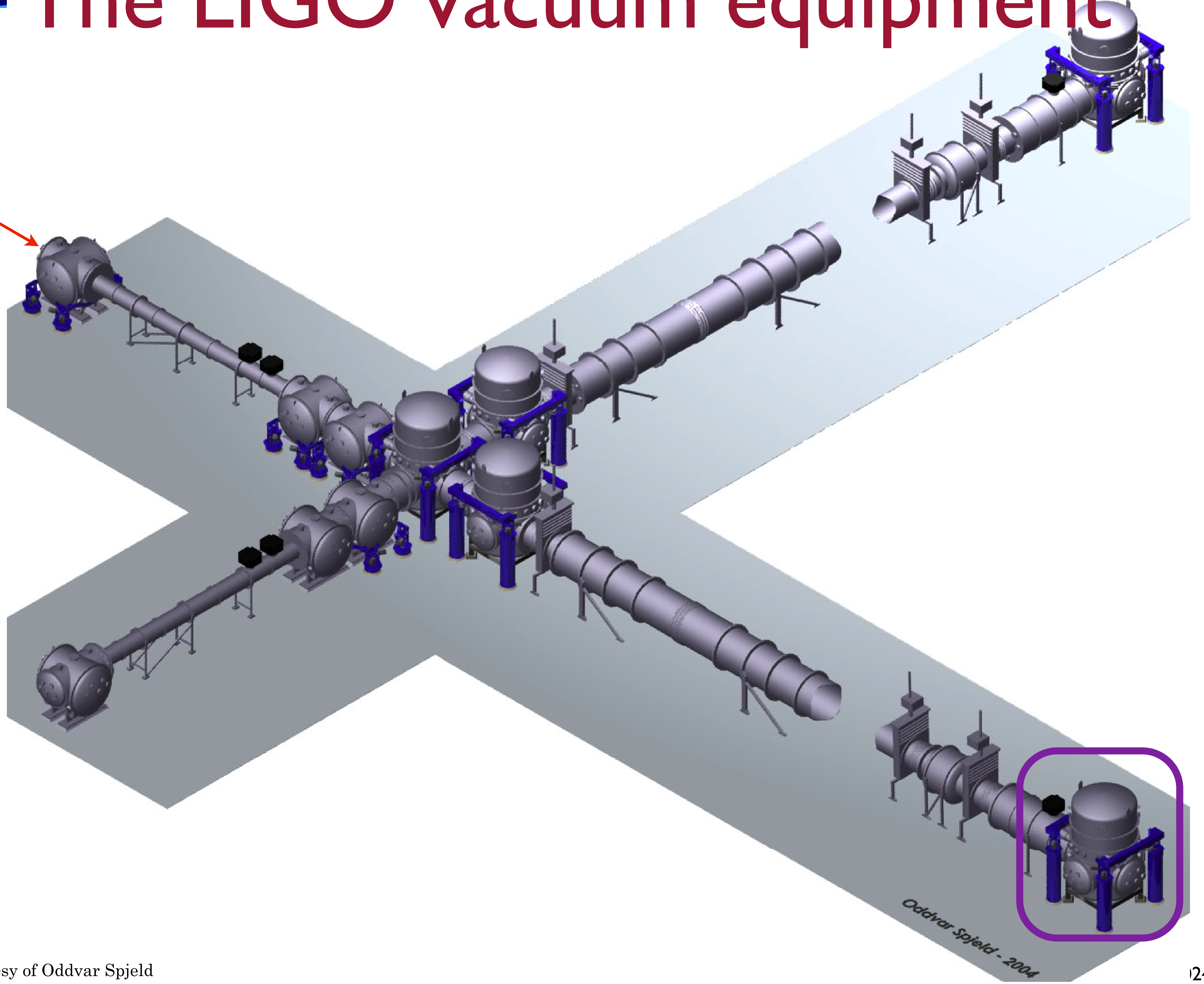
(a) LIGO Livingston Observatory

Mirror control

1. Simple michelson is very good.
2. Long arms
3. Interesting Interferometry
4. Keep the mirrors from moving

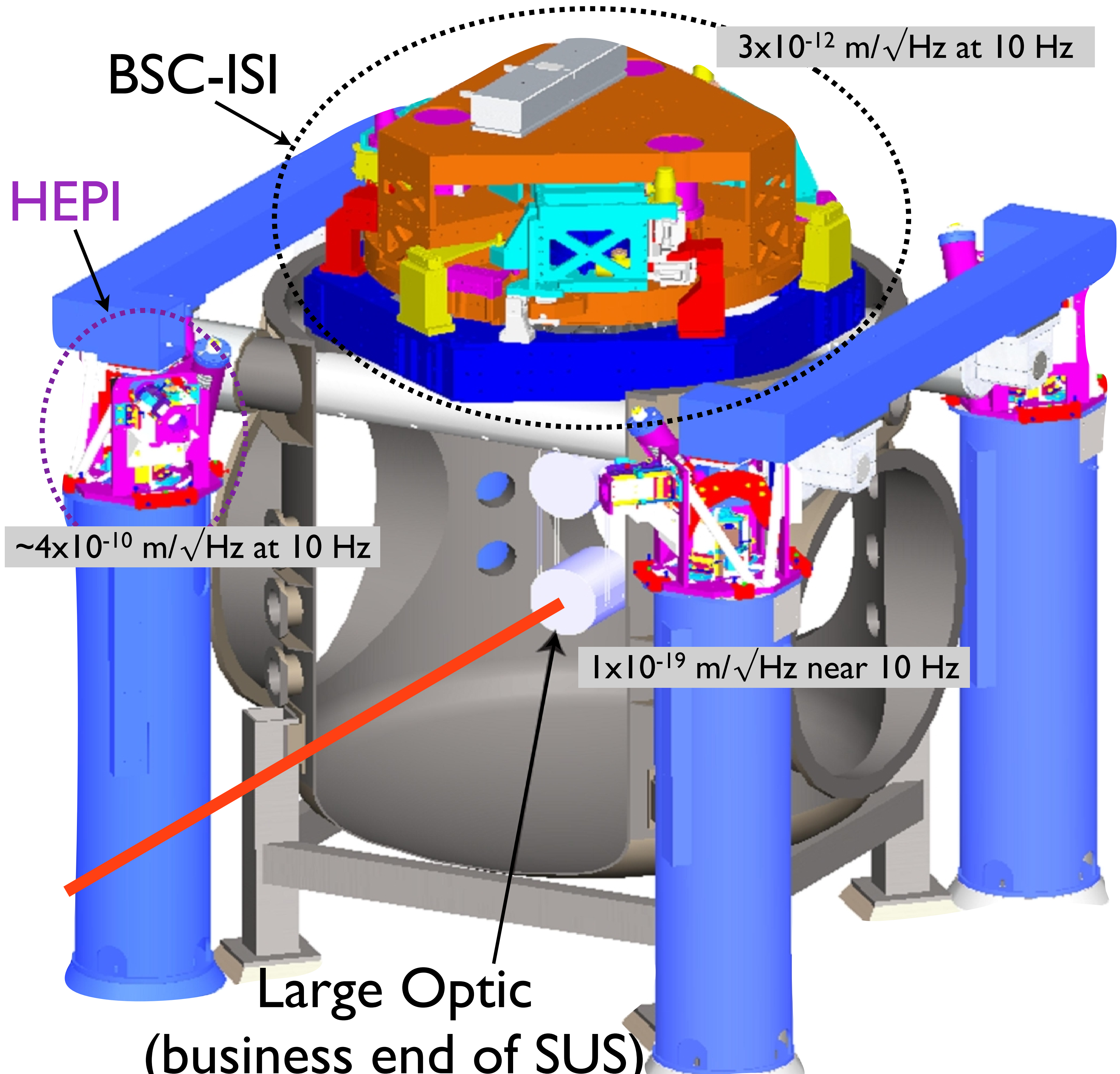


The LIGO vacuum equipment

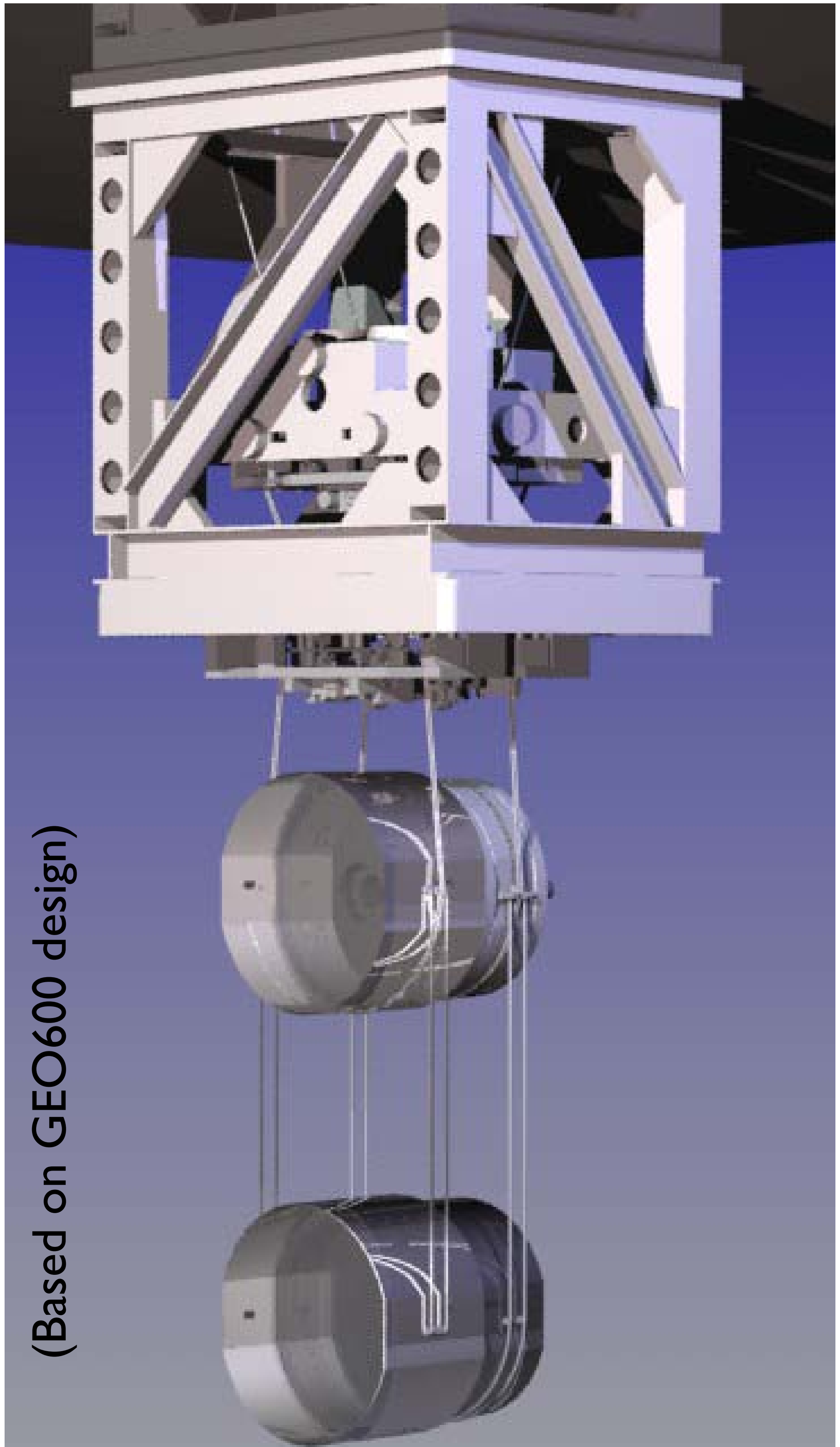


drawing courtesy of Oddvar Spjeld

Overall Isolation of Test Masses

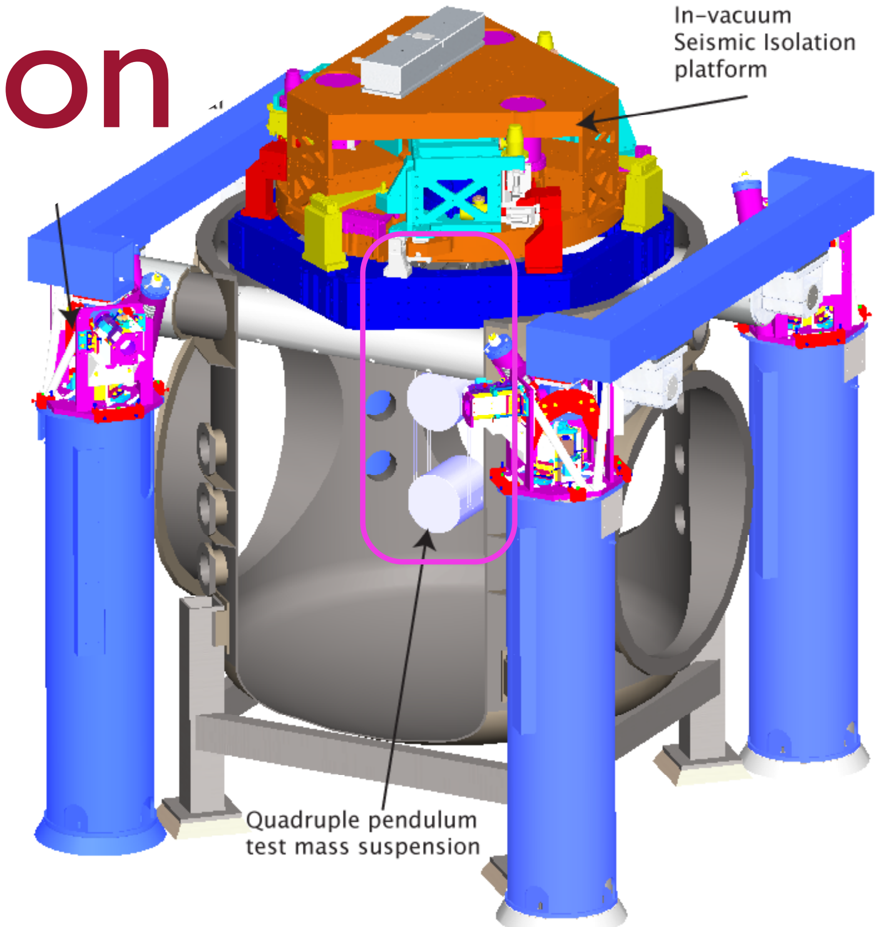


Pendulum Suspension

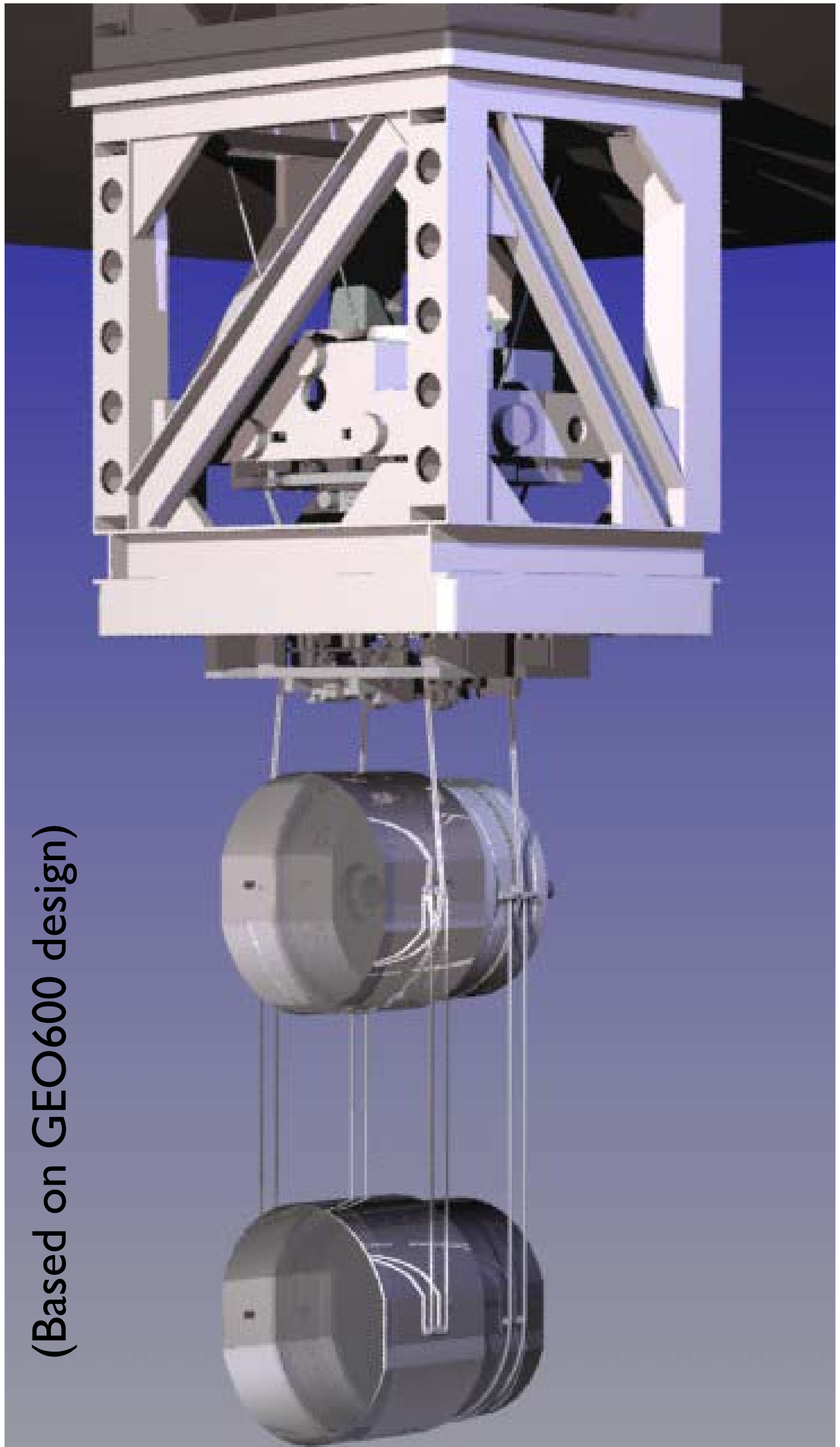


LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

Suspended as a
4 stage pendulum



Pendulum Suspension

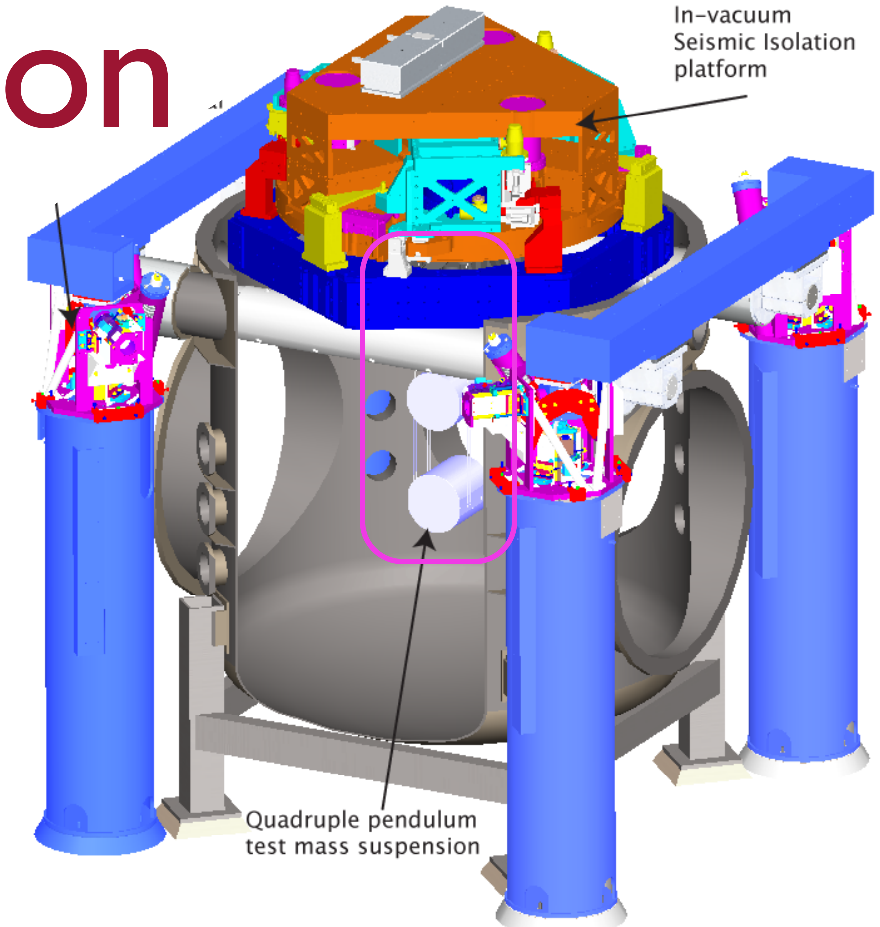


LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

Suspended as a
4 stage pendulum

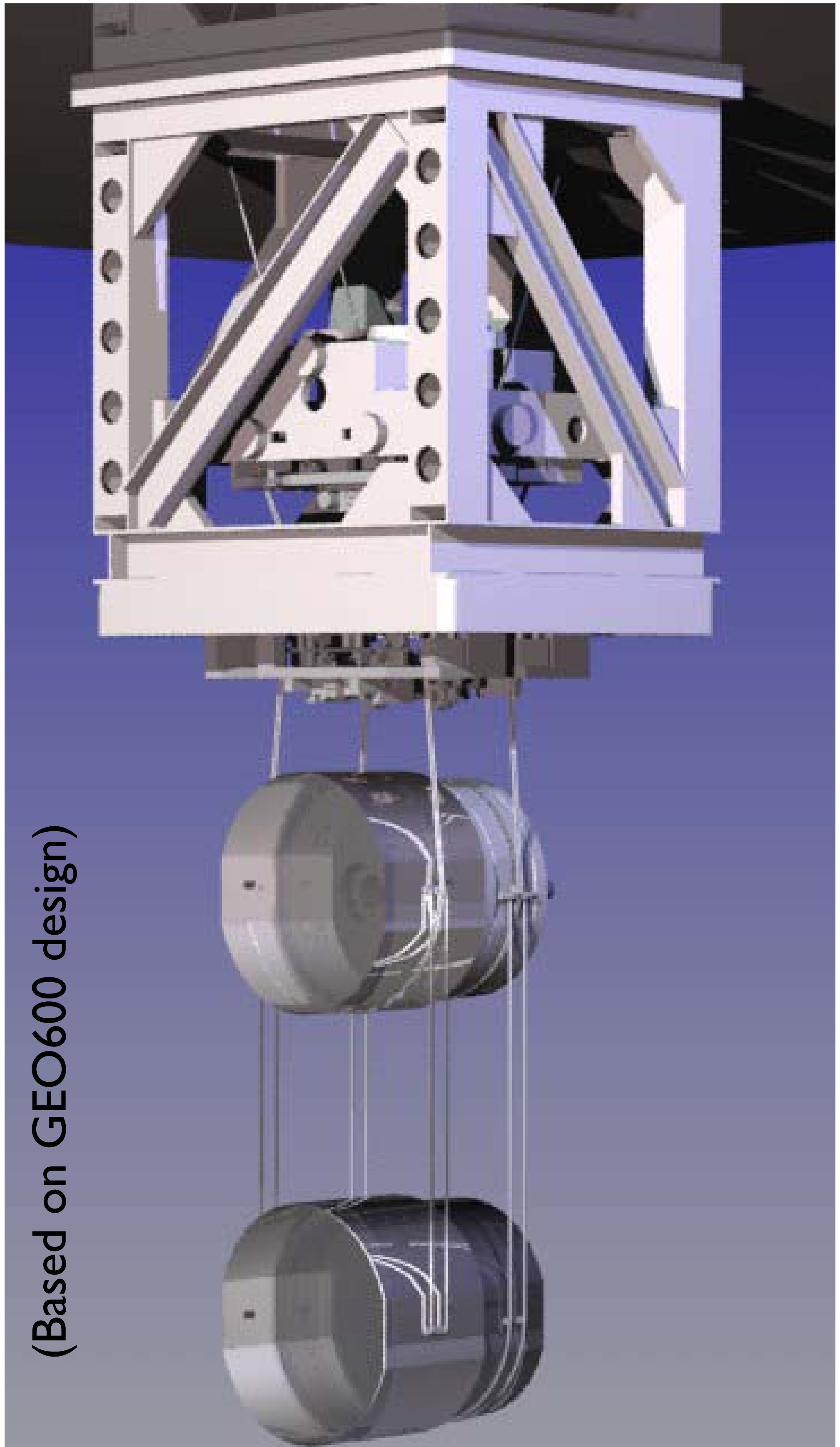
Best coatings available

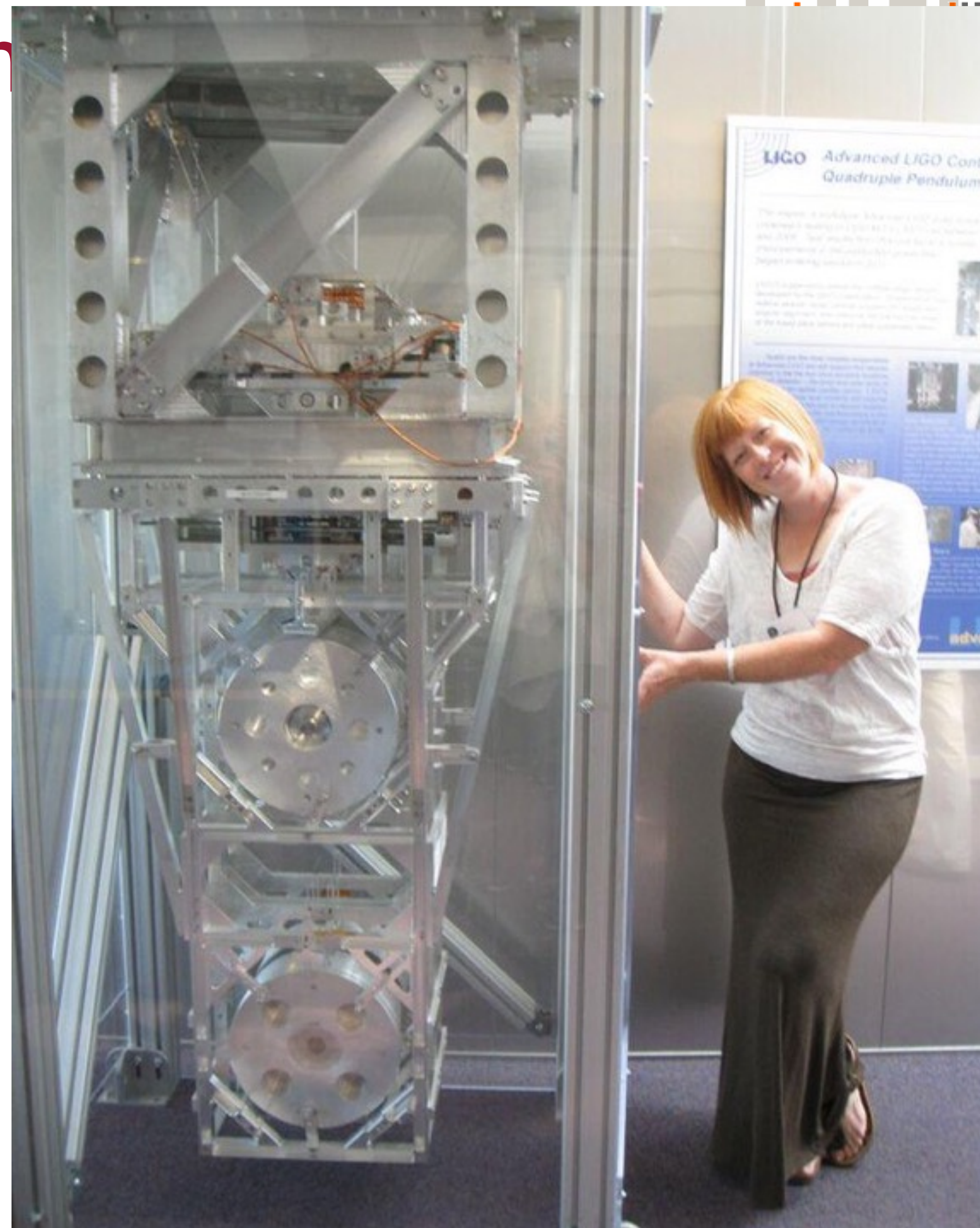
Motion at 10 Hz set by
thermal driven vibration

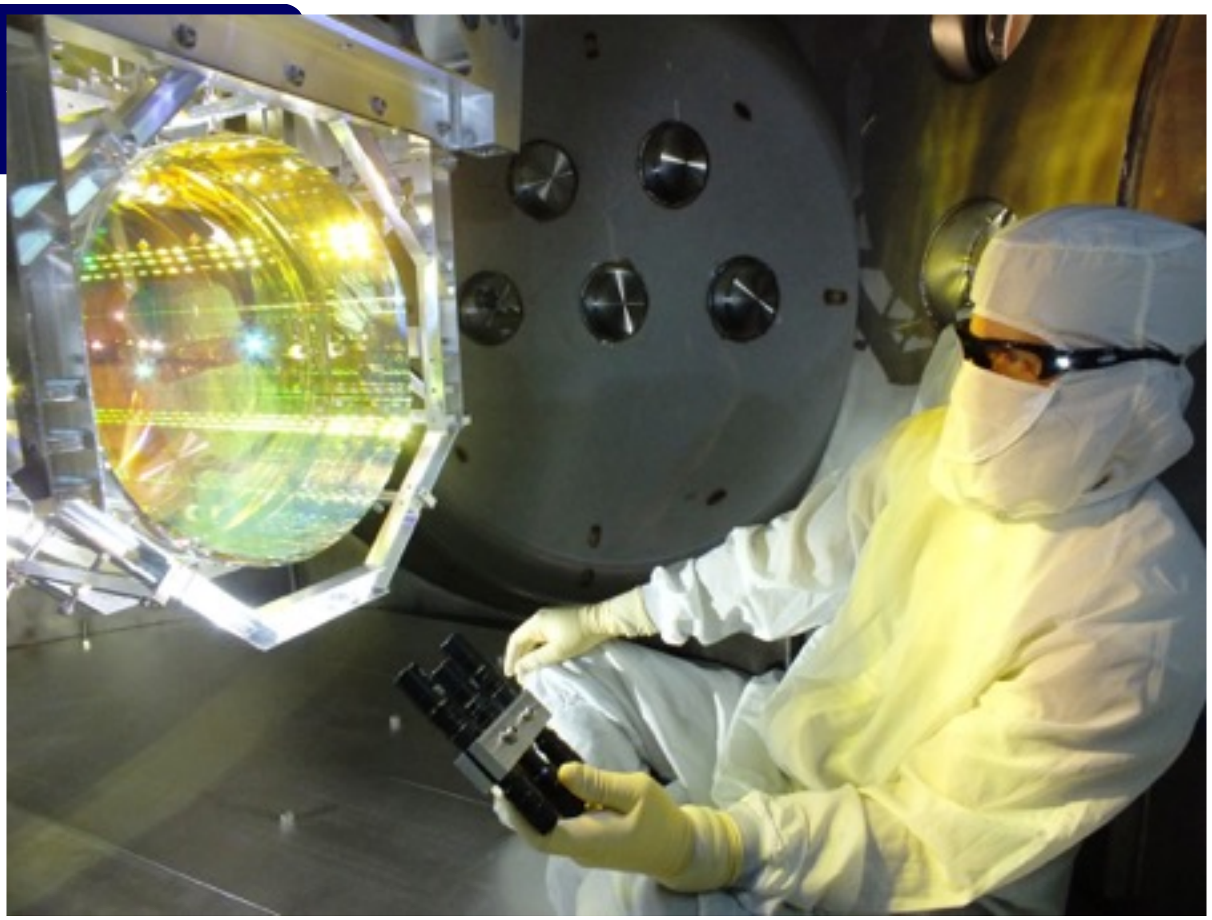


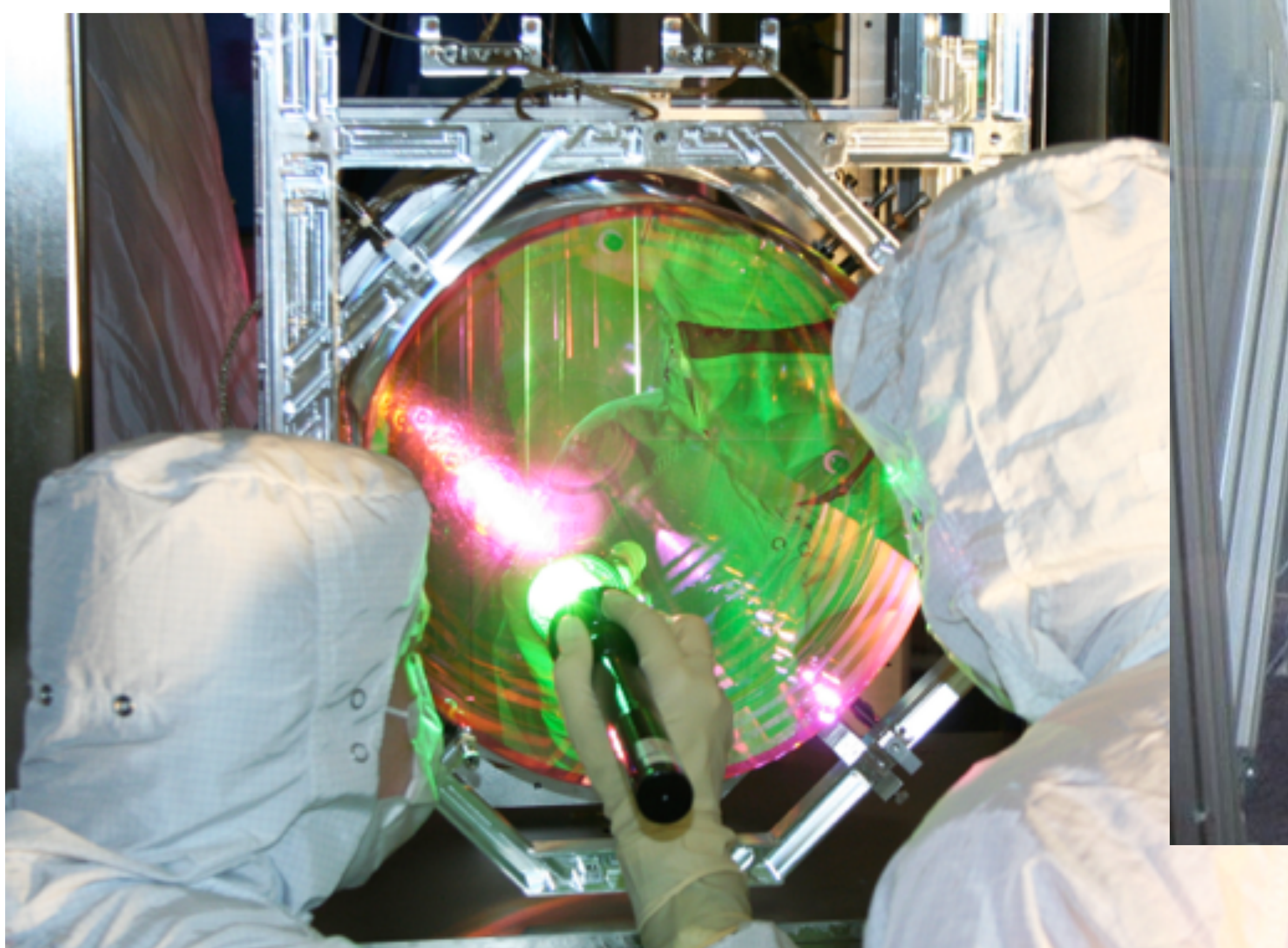
silicate bonding creates a monolithic final stage

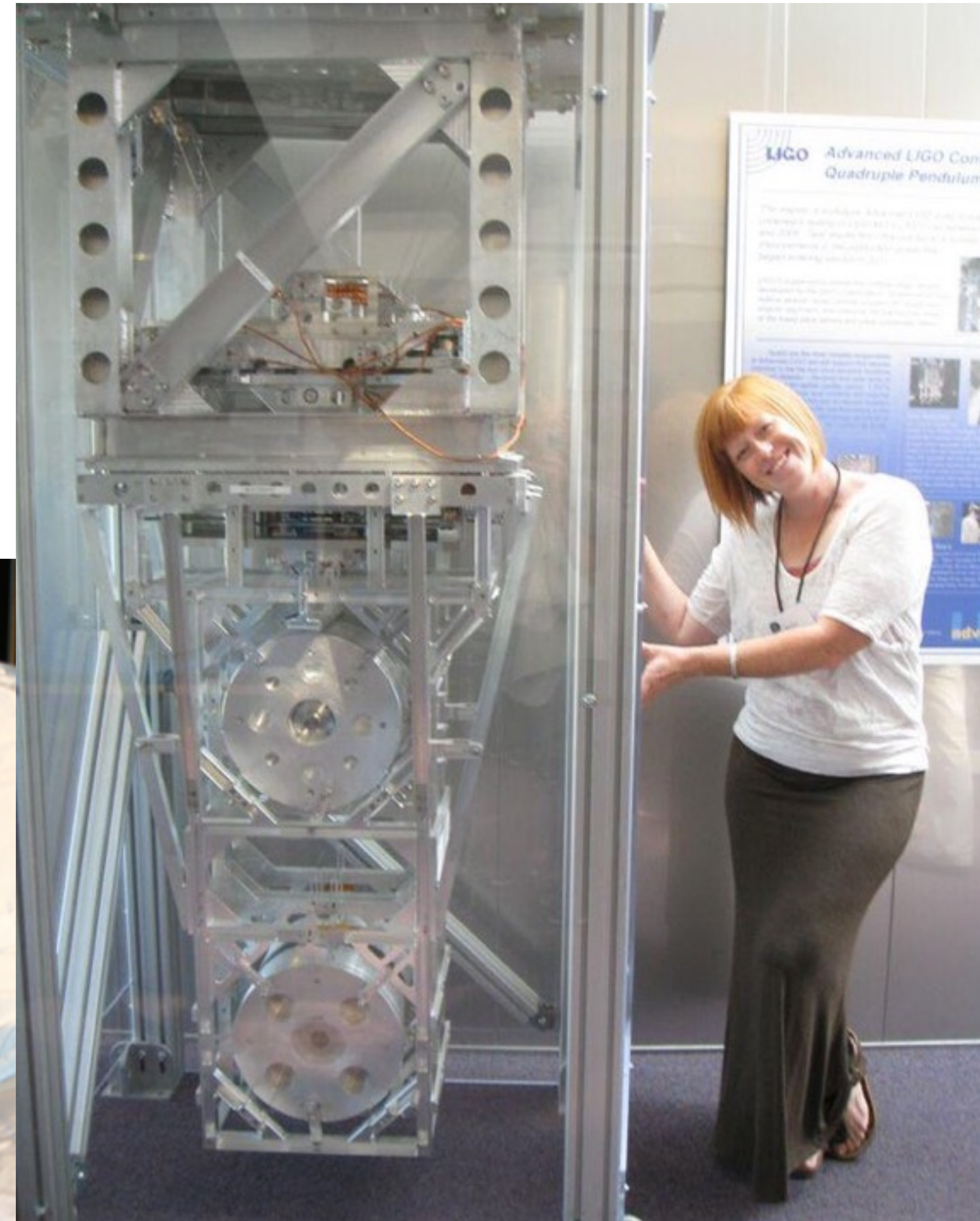
Pendulun



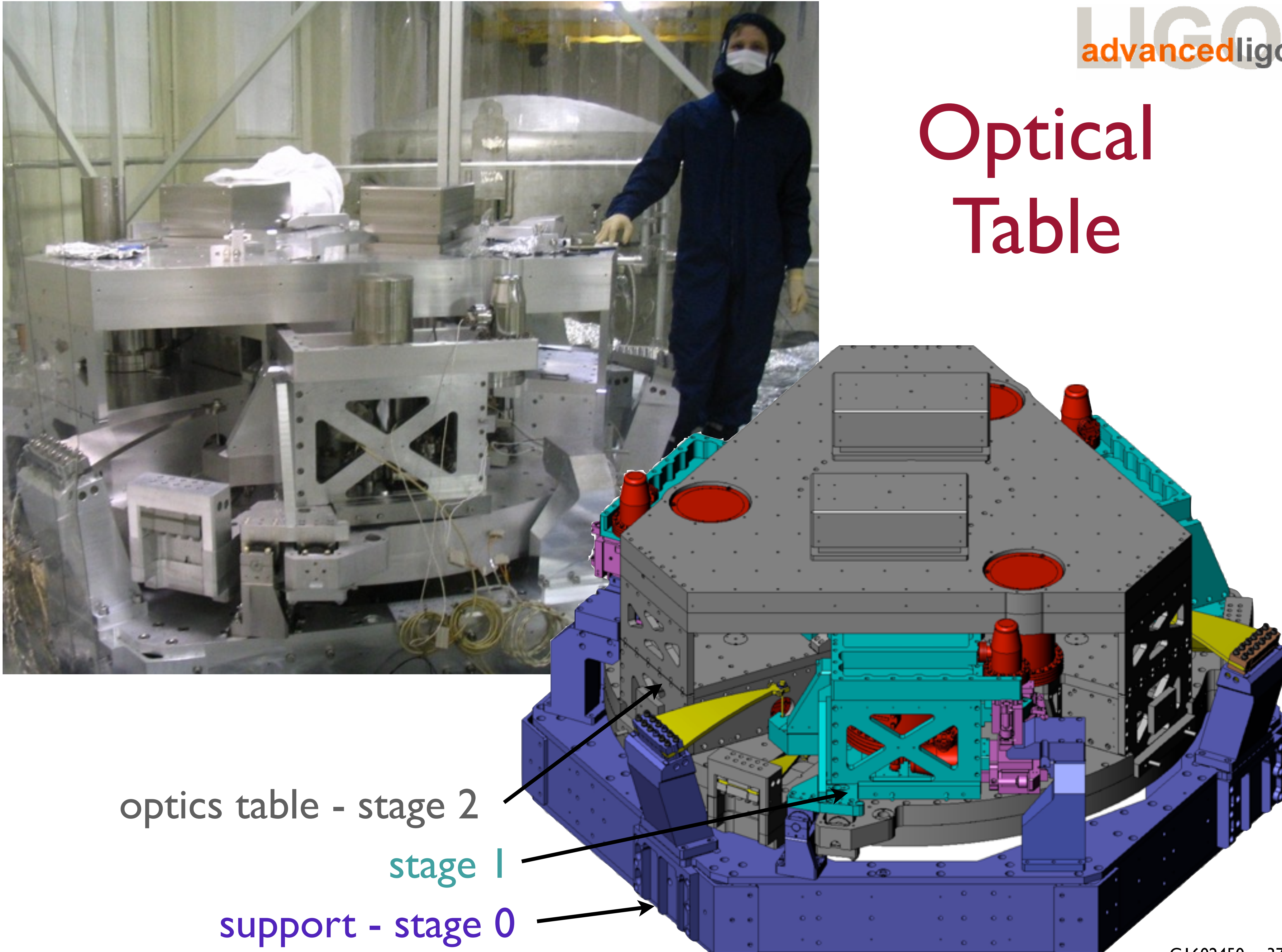


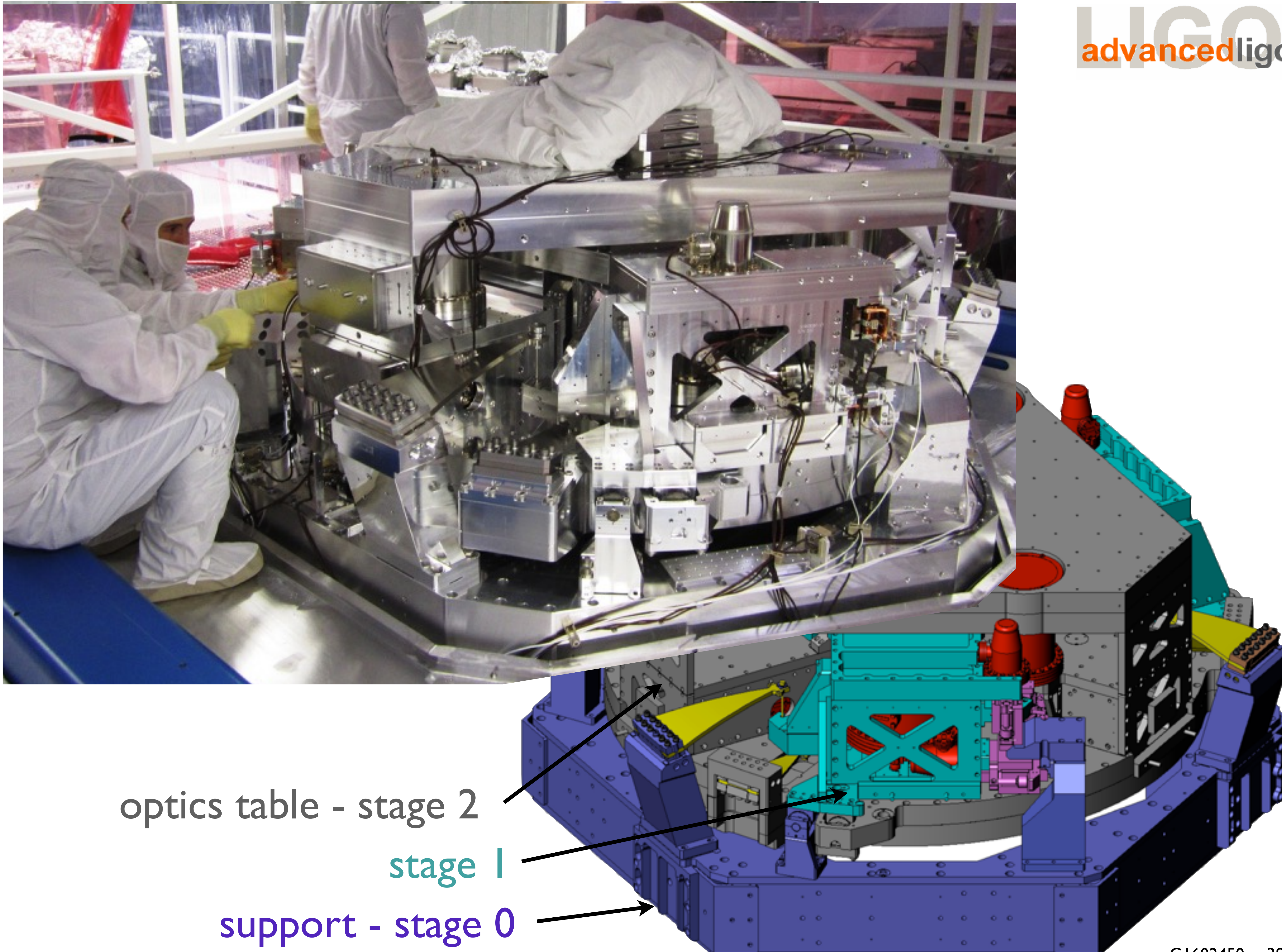




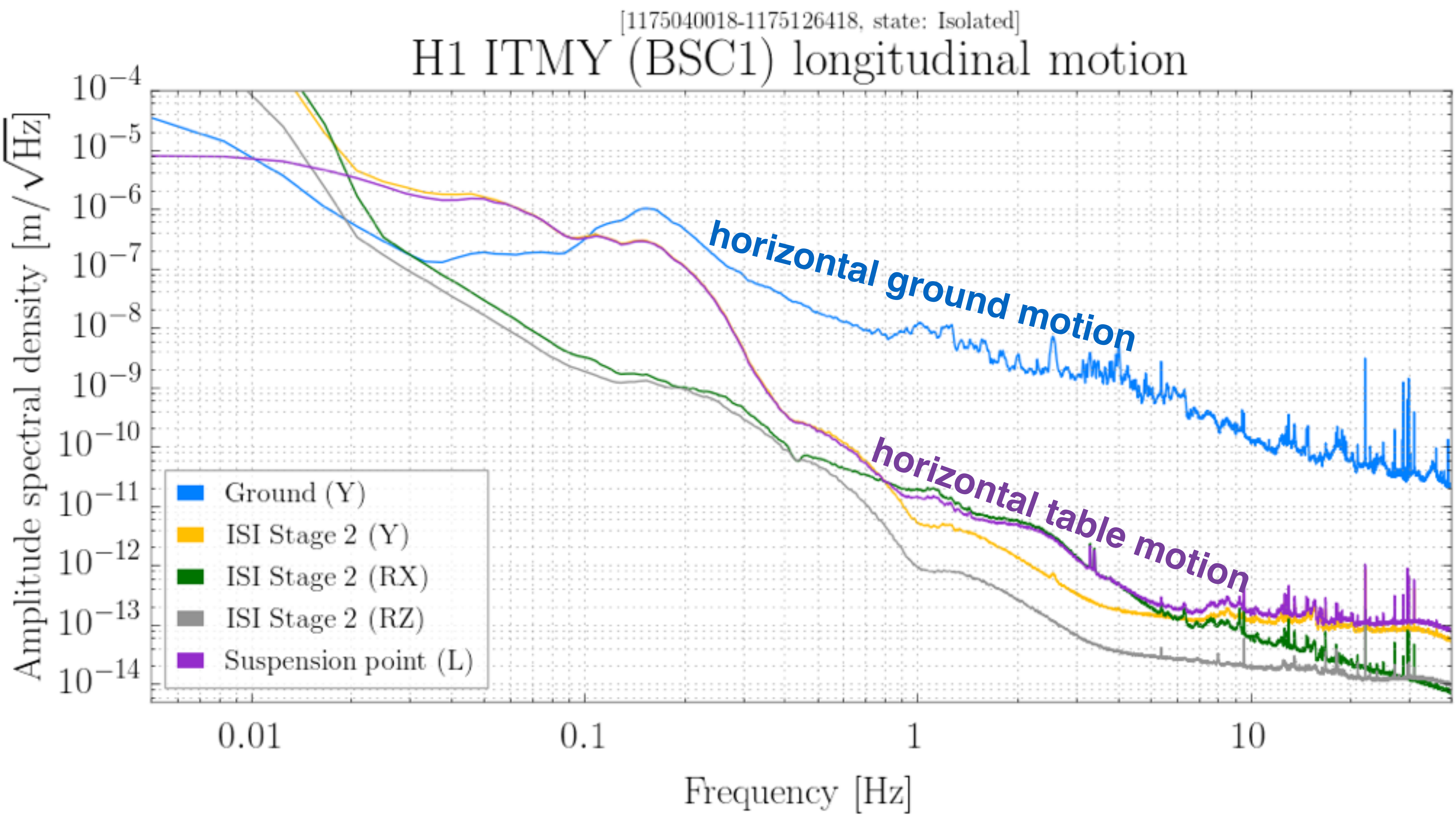

LIGO
Quadruple Pendulum

Optical Table



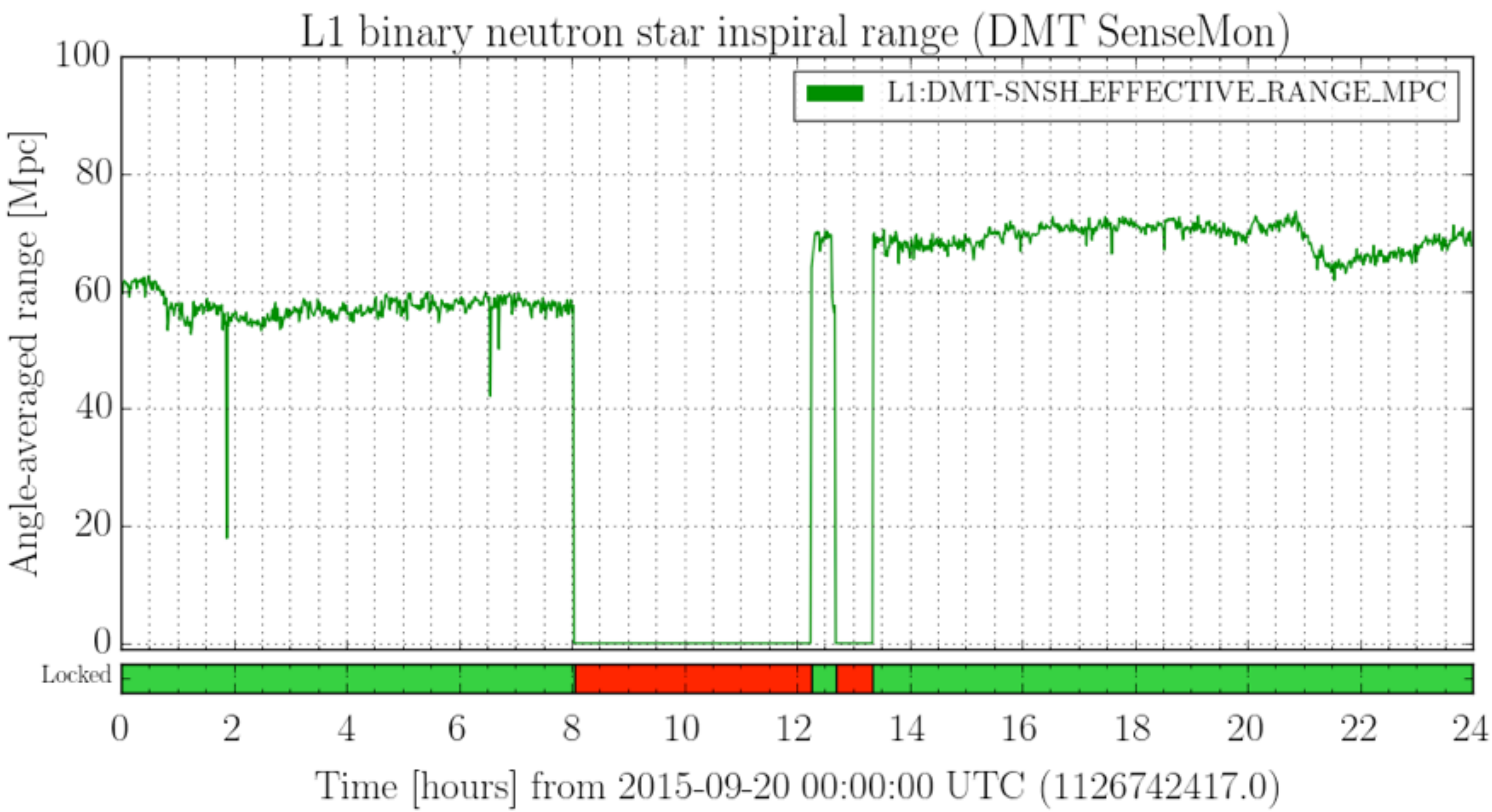

optics table - stage 2
stage 1
support - stage 0

motion of the optical table

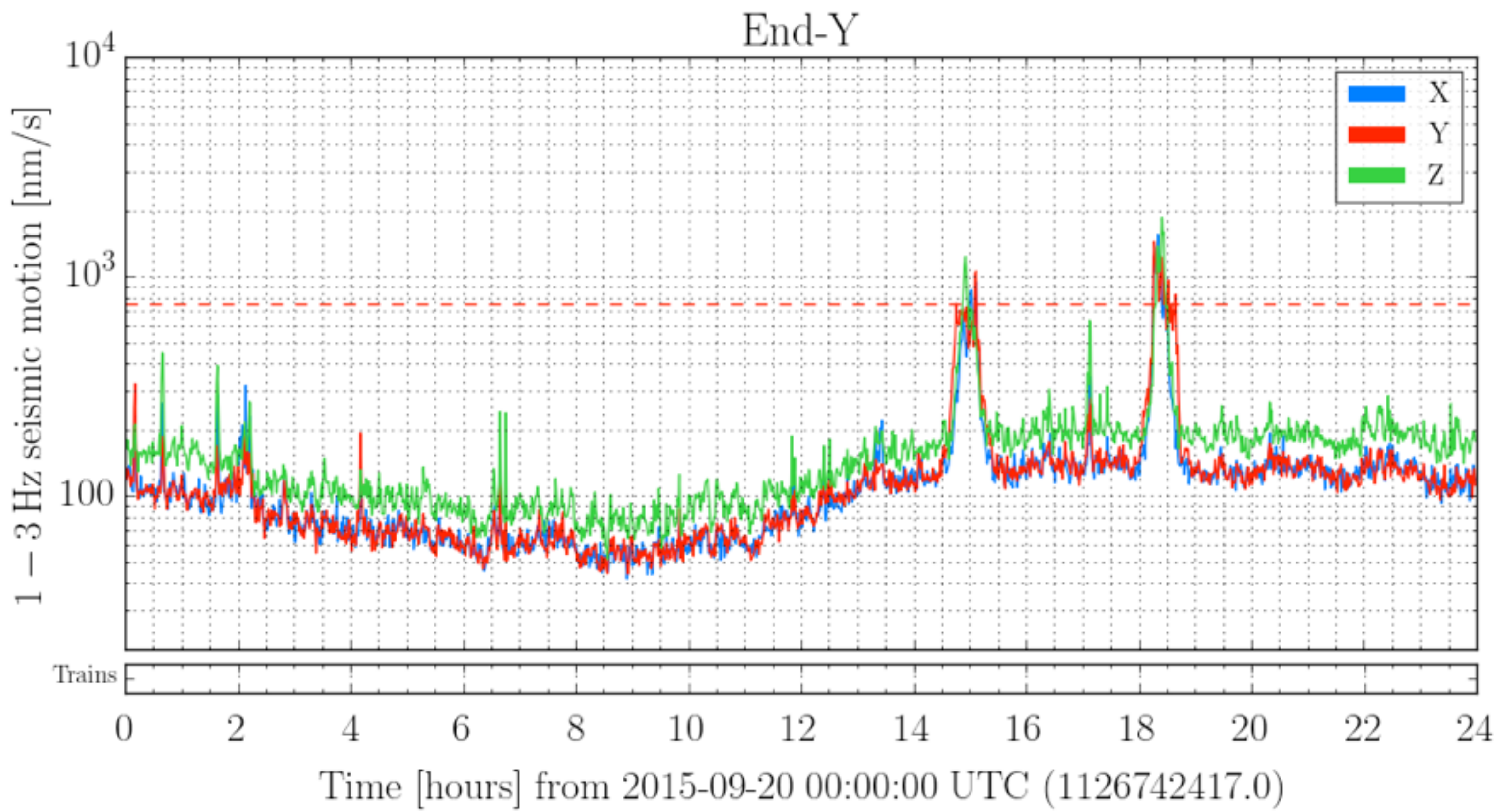


April 6, 2017, DetChar page

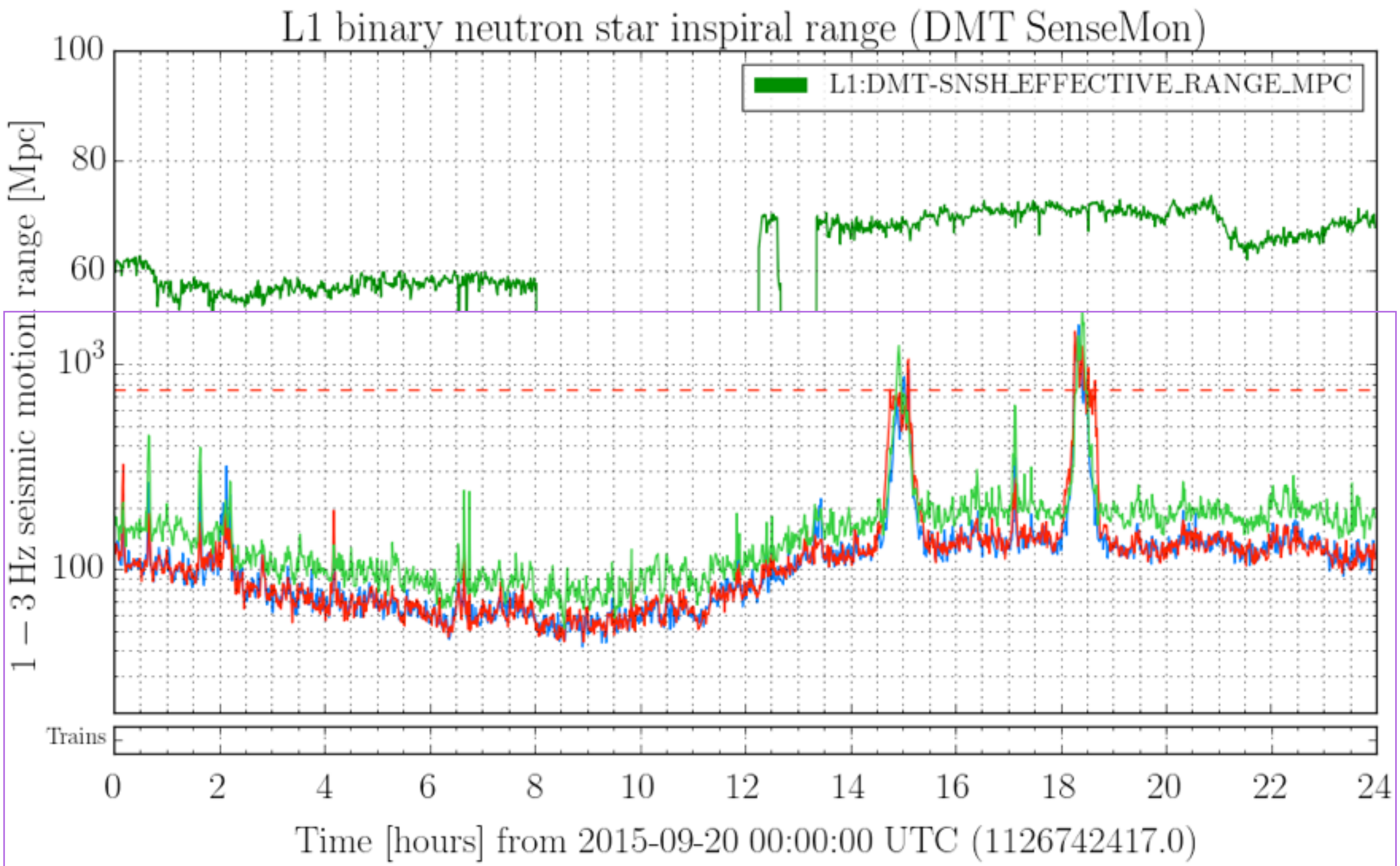
Real impact of isolation, alignment & control



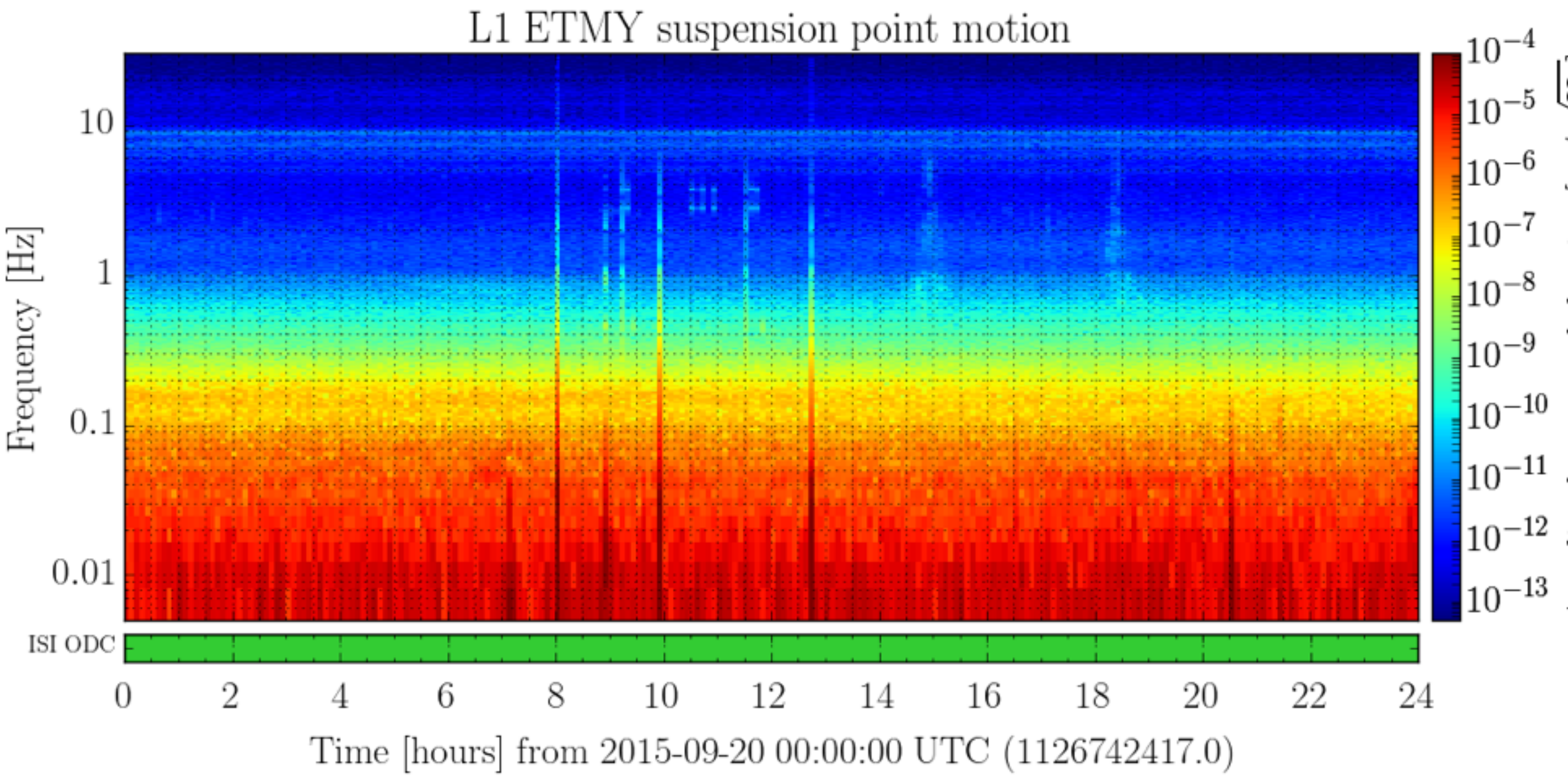
but there was a train…



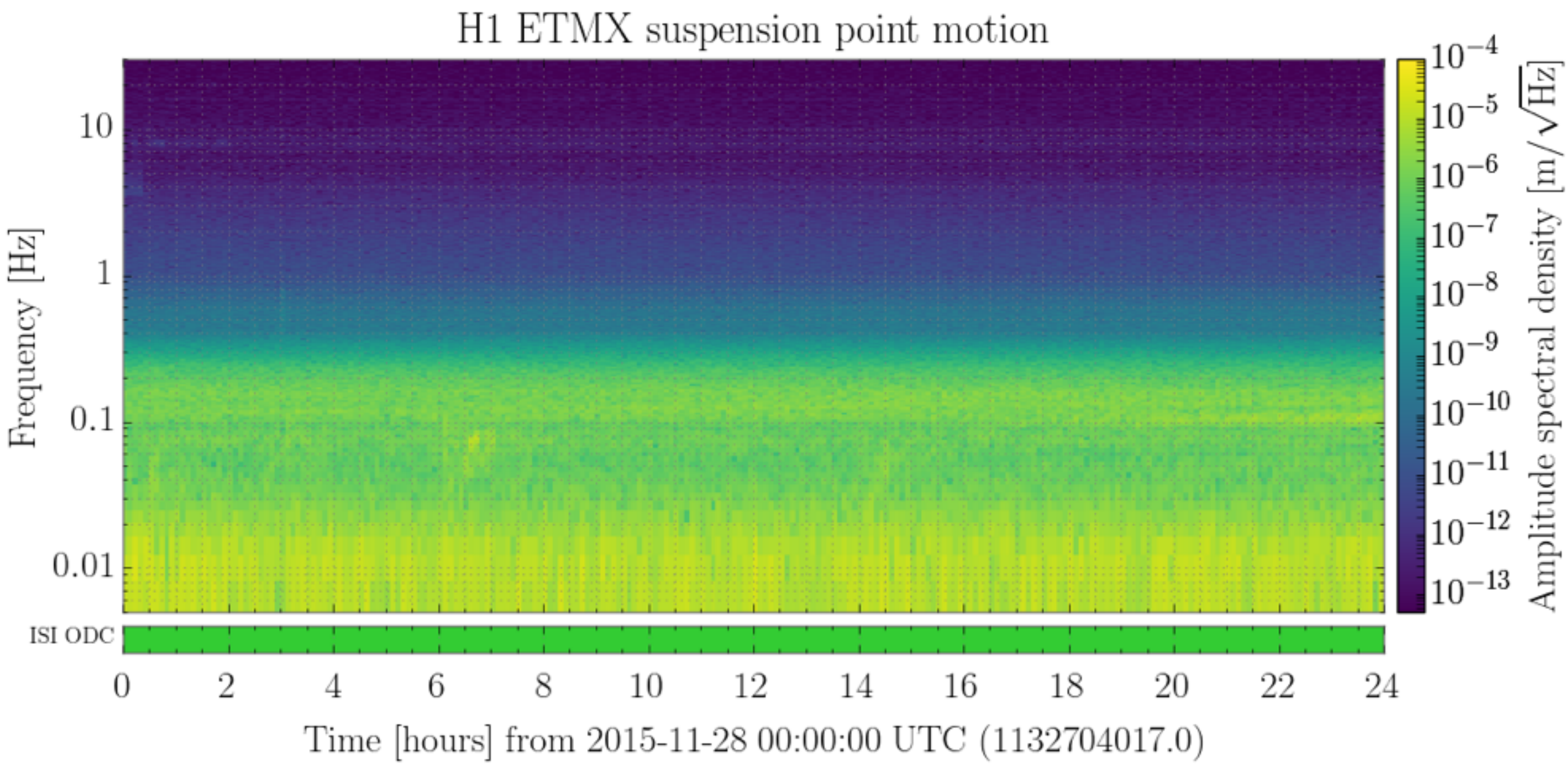
Real impact of isolation, alignment & control



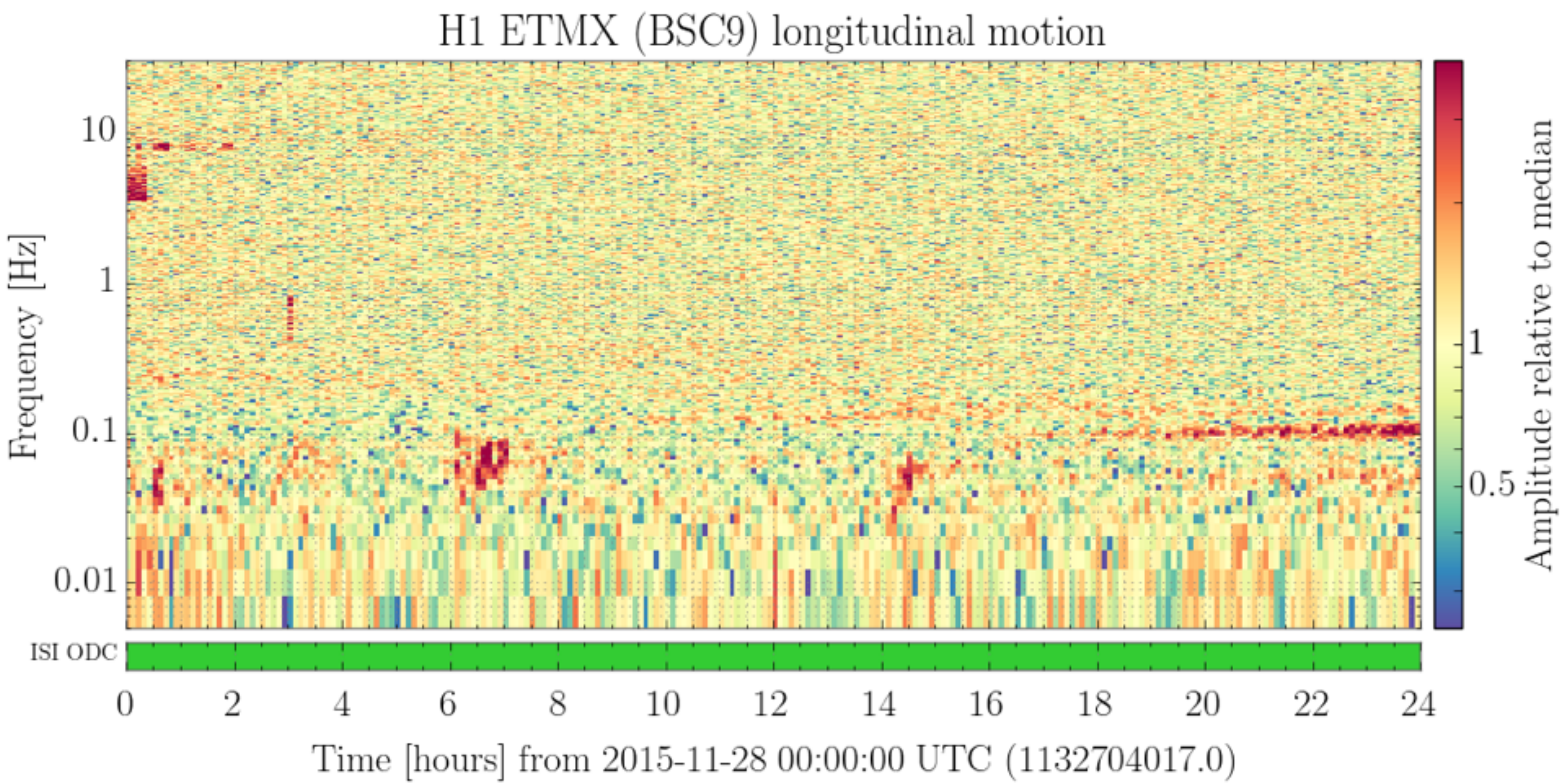
‘Environmental’ sensors



This is what we strive for

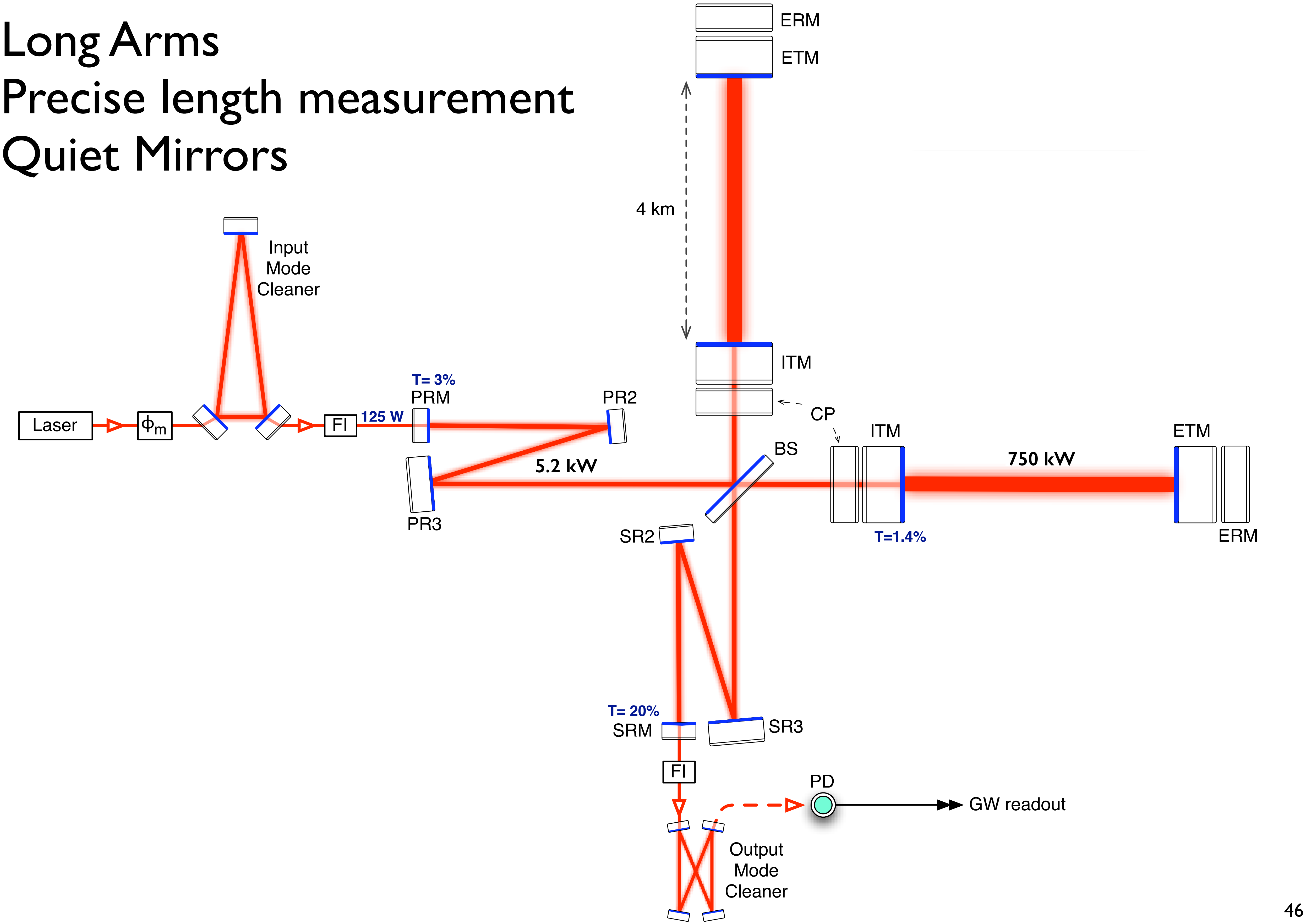


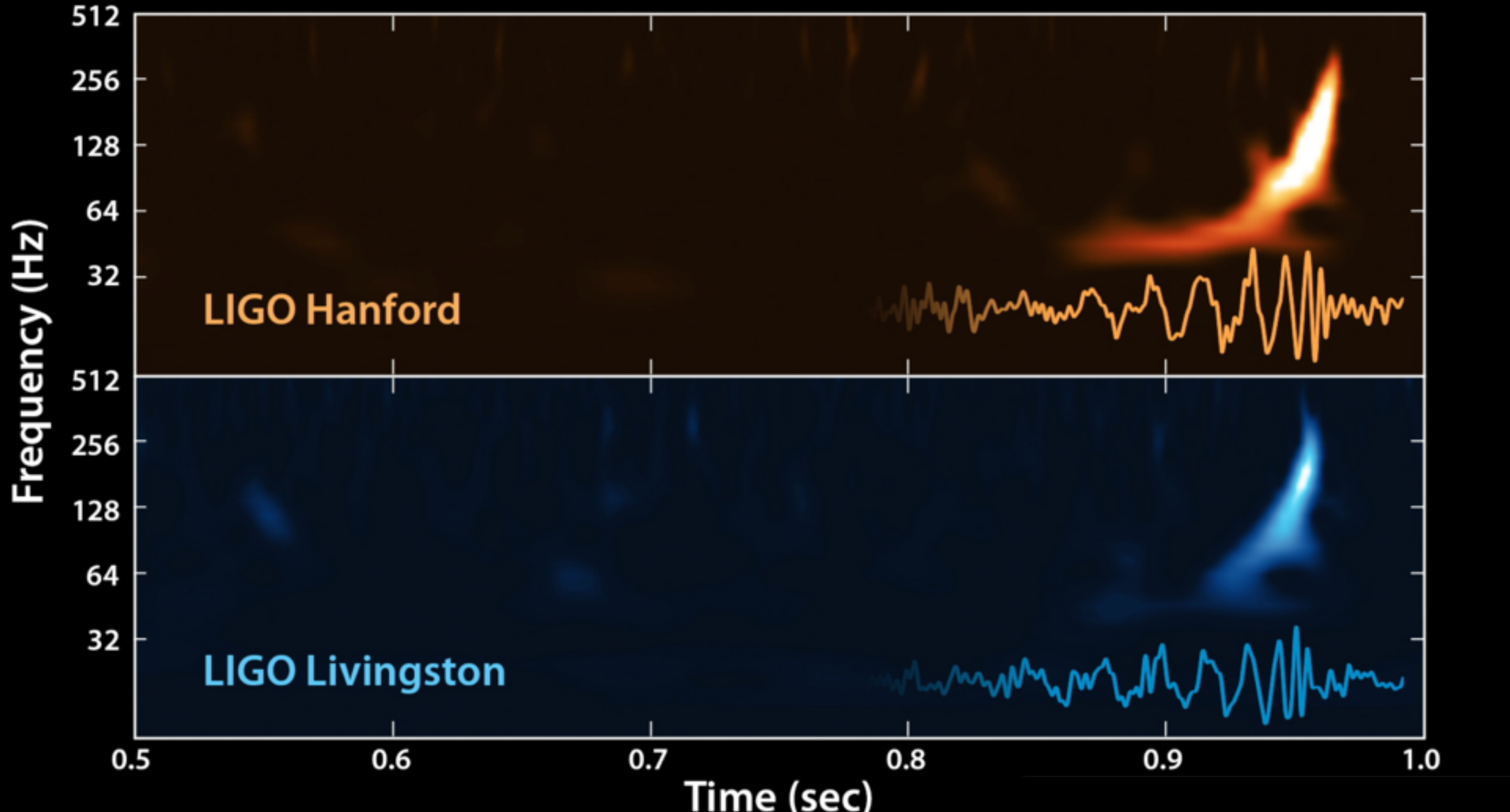
Glitch monitoring



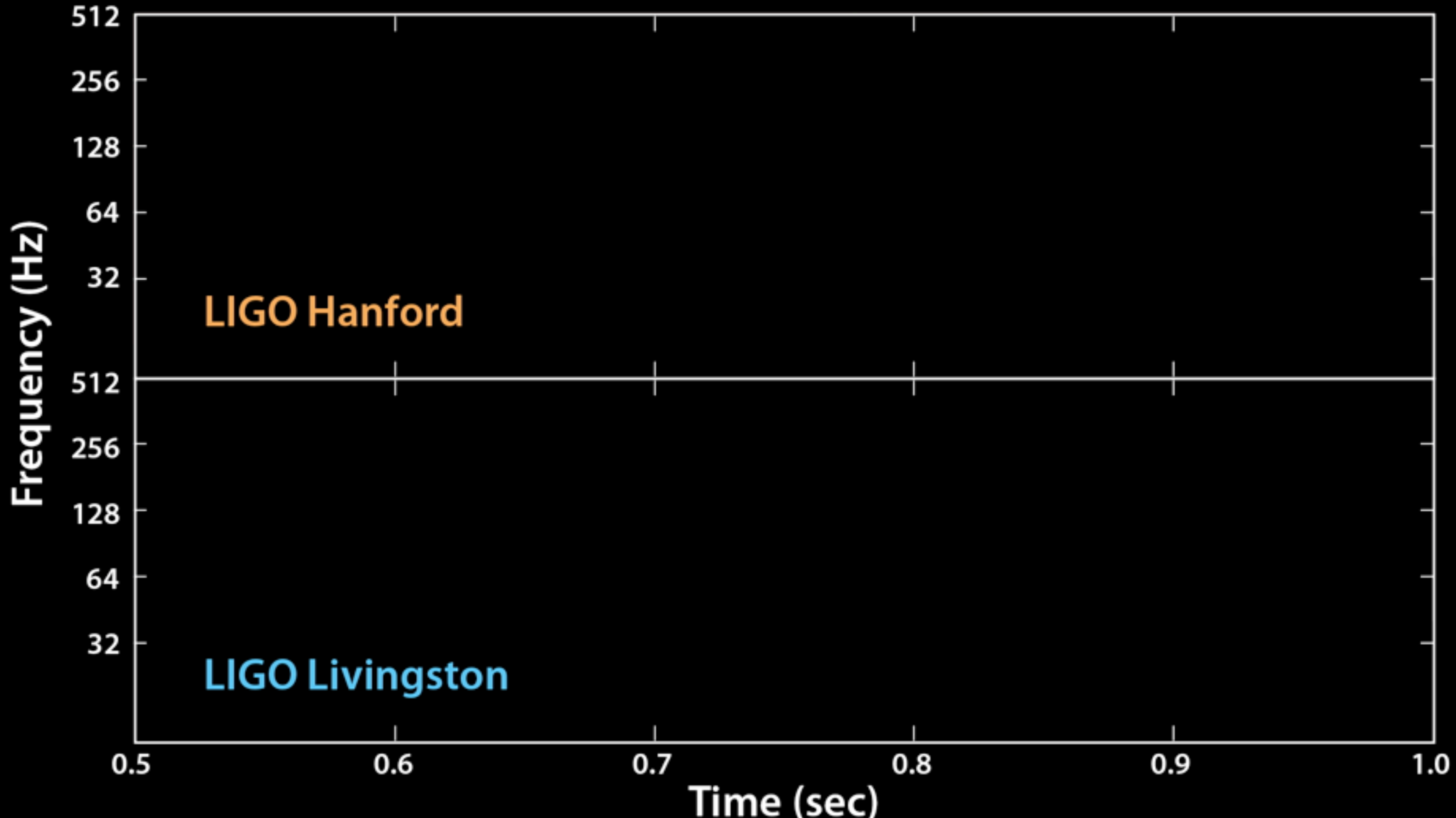
Now we are ready…

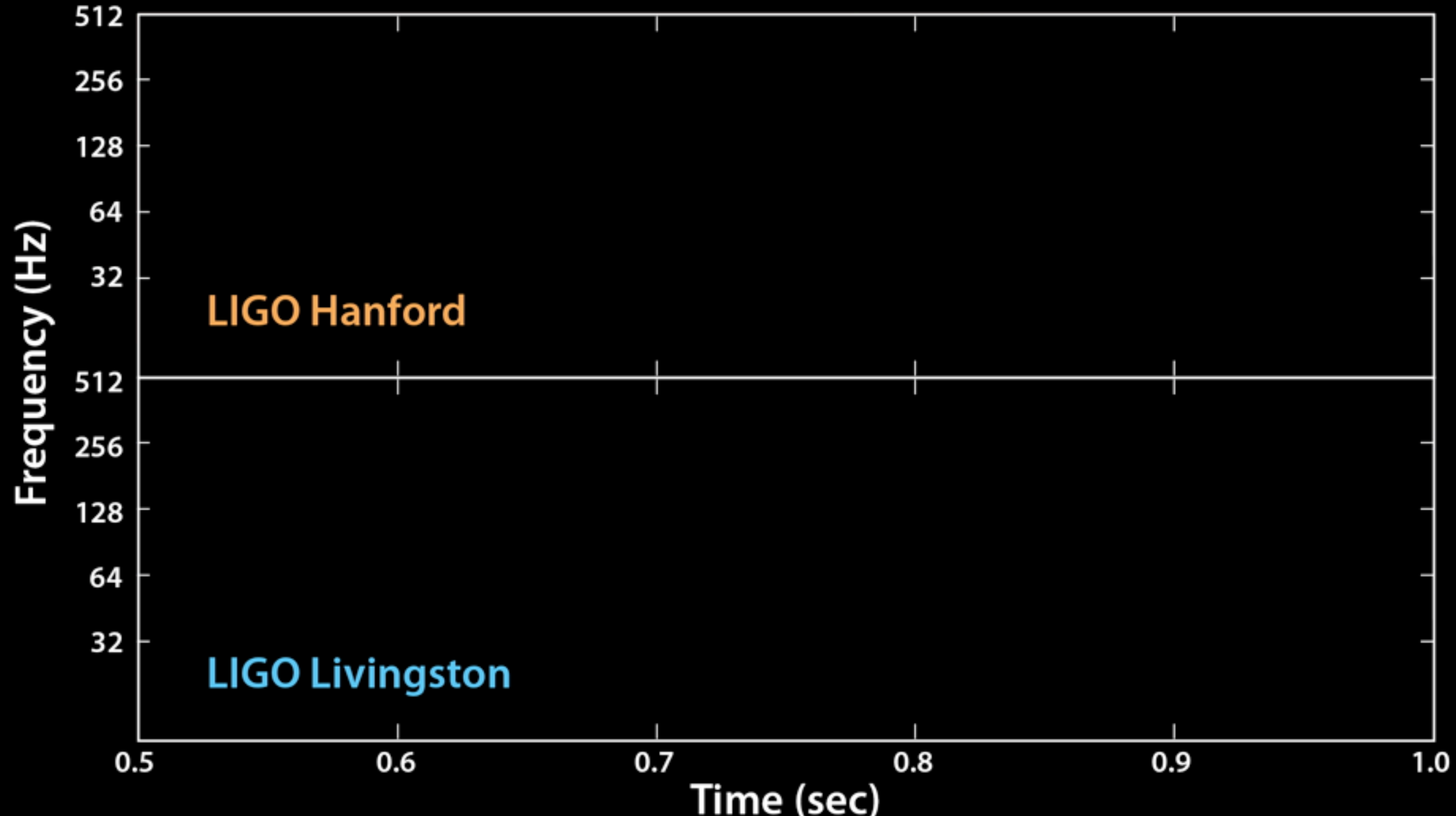
1) Long Arms
2) Precise length measurement
3) Quiet Mirrors





http://mediaassets.caltech.edu/gwave


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


512
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LIGO Hanford
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0.5
0.6
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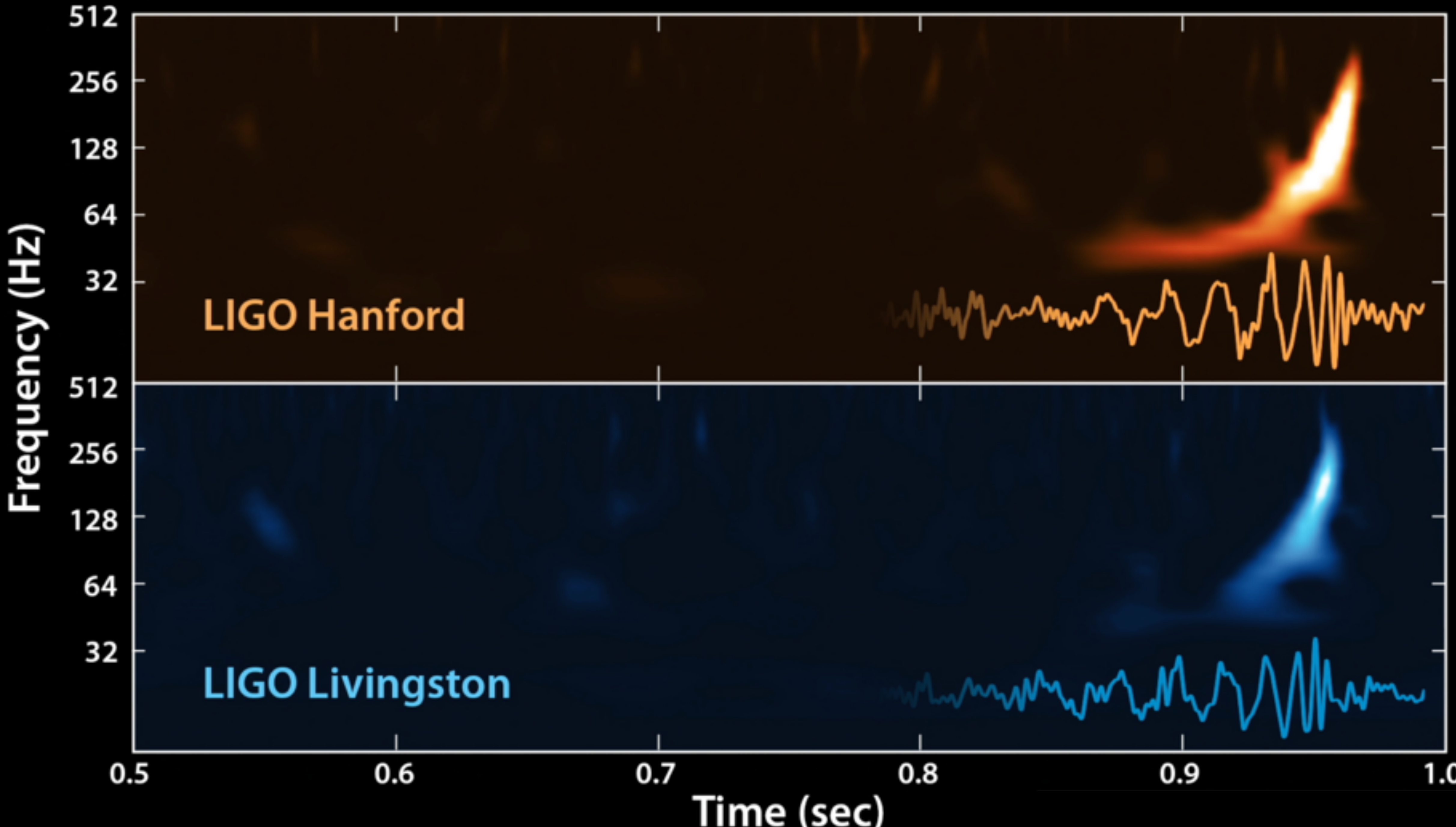
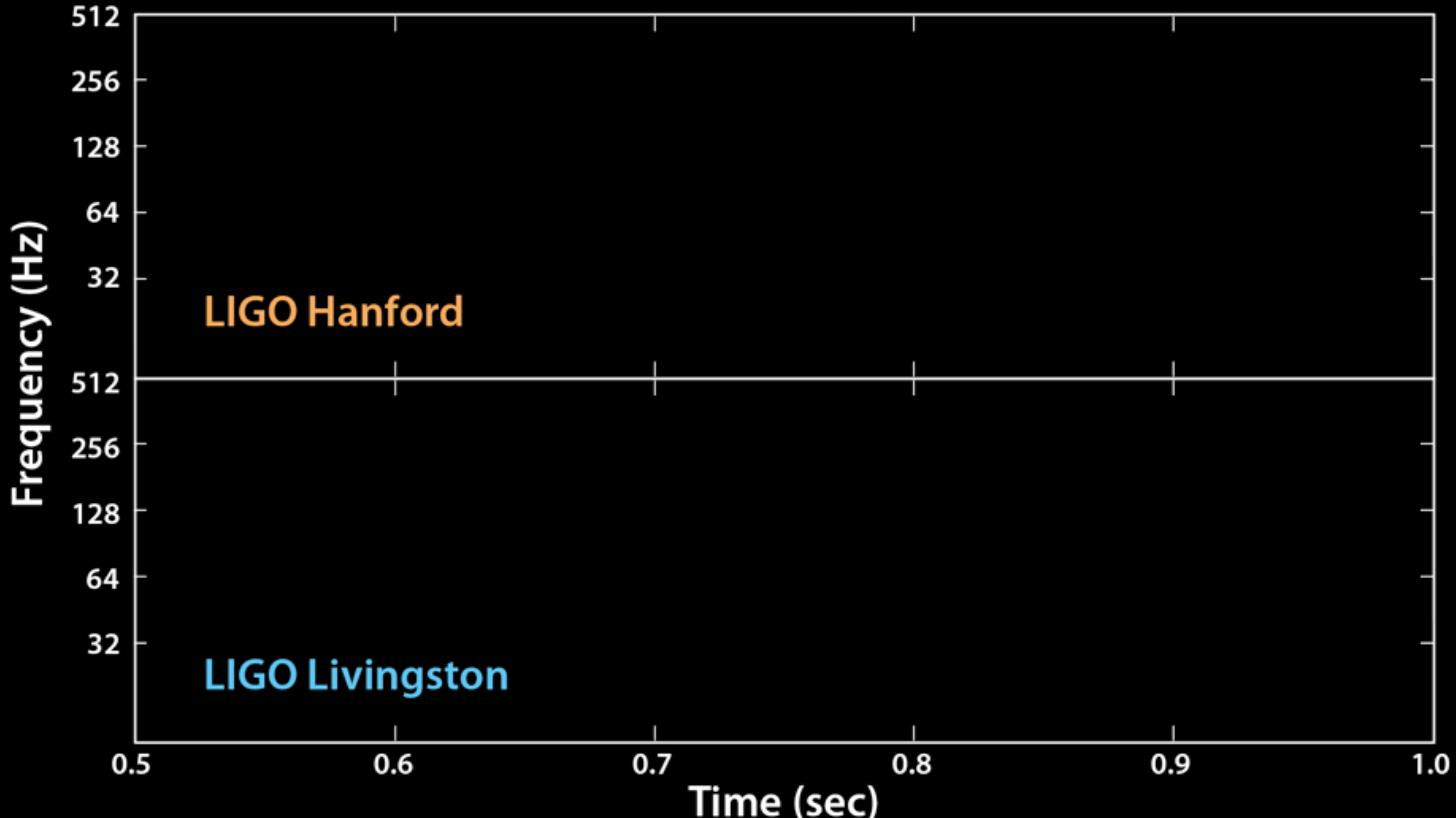
1.0
Time (sec)

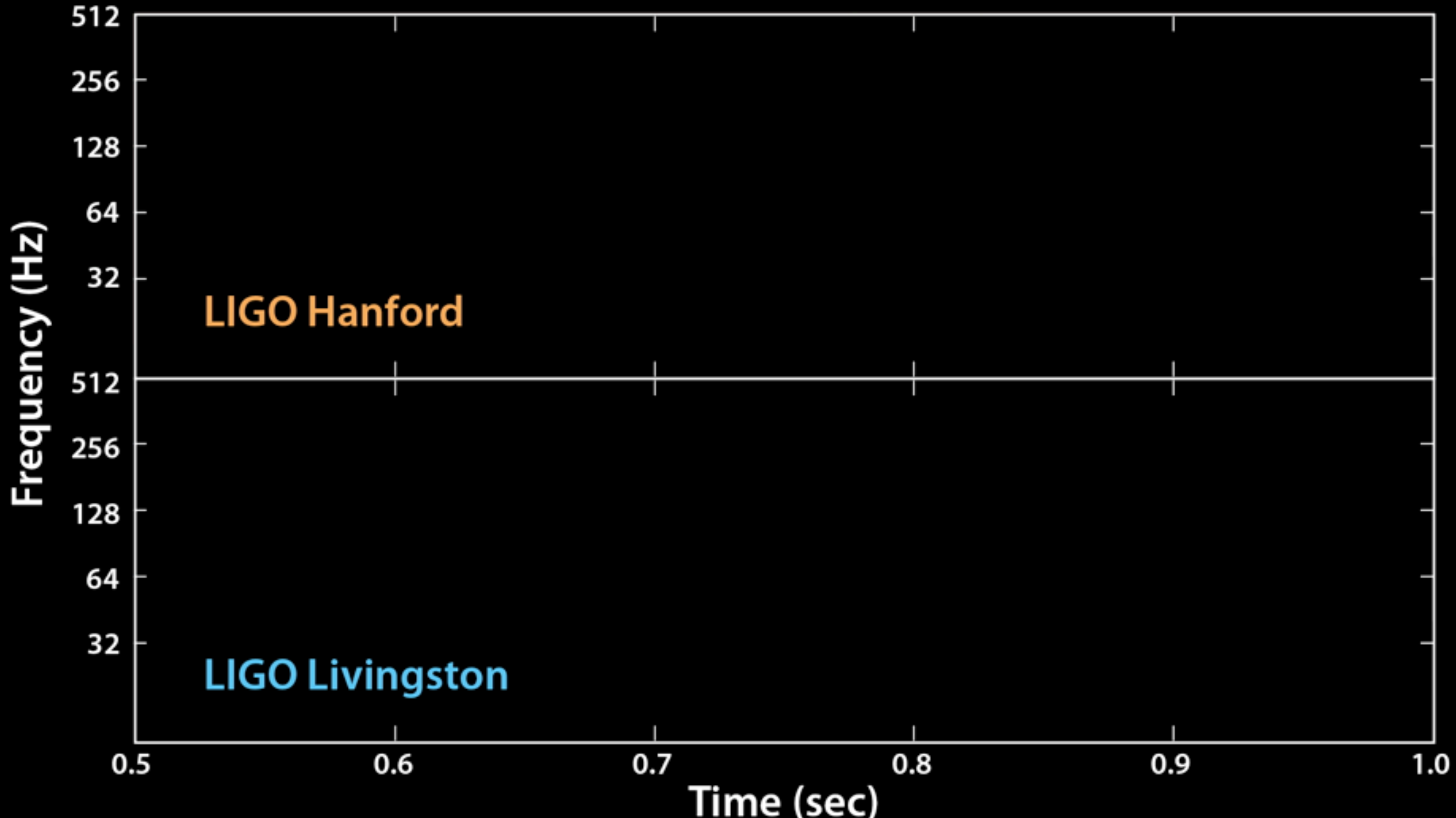


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

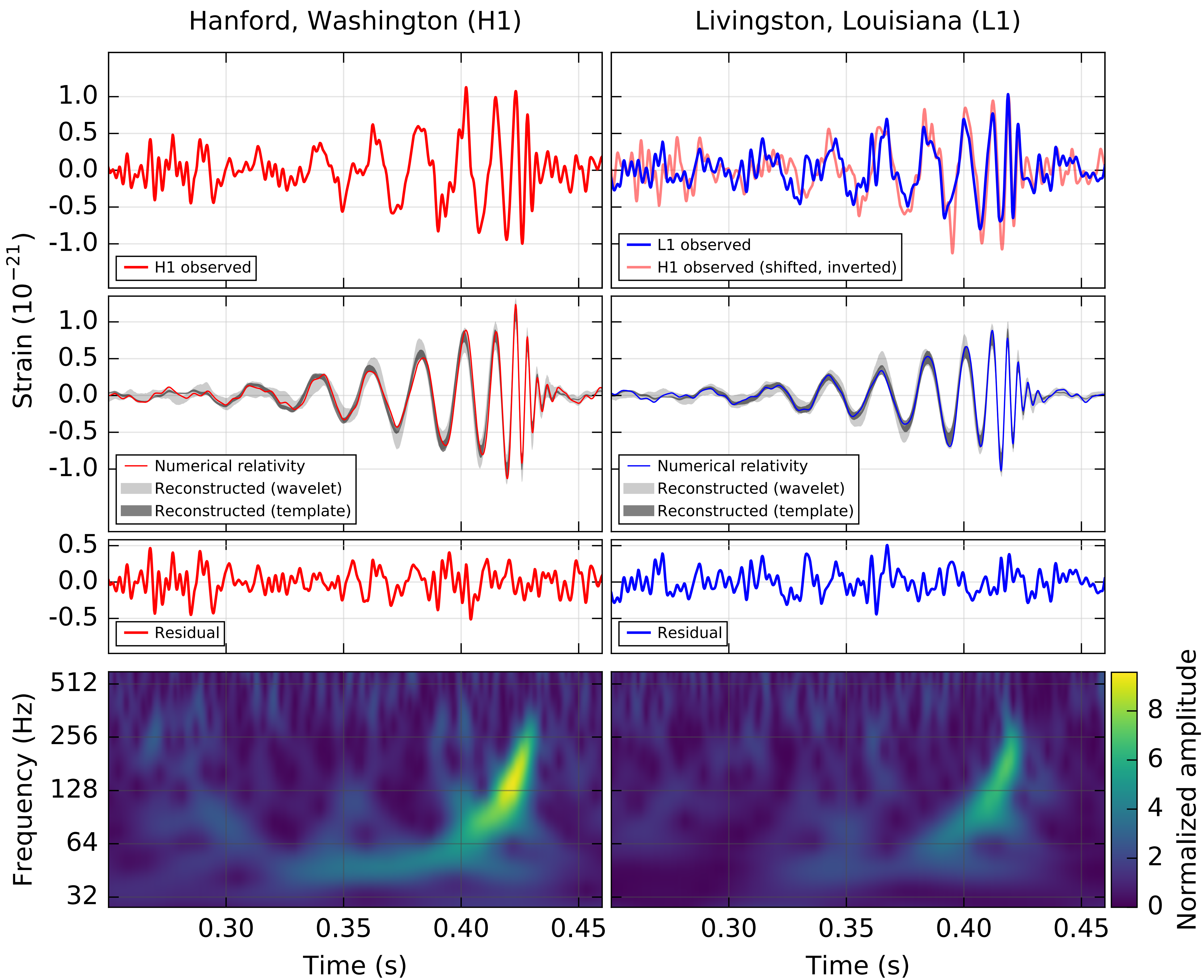
The sound of black holes colliding



The sound of black holes colliding



First signal - Sept 14, 2015



http://dx.doi.org/10.1103/PhysRevLett.116.061102

Best fit with Numerical Relativity

Initial Masses:

29 (+4/-4) & 36 (+5/-4) M_{sun}

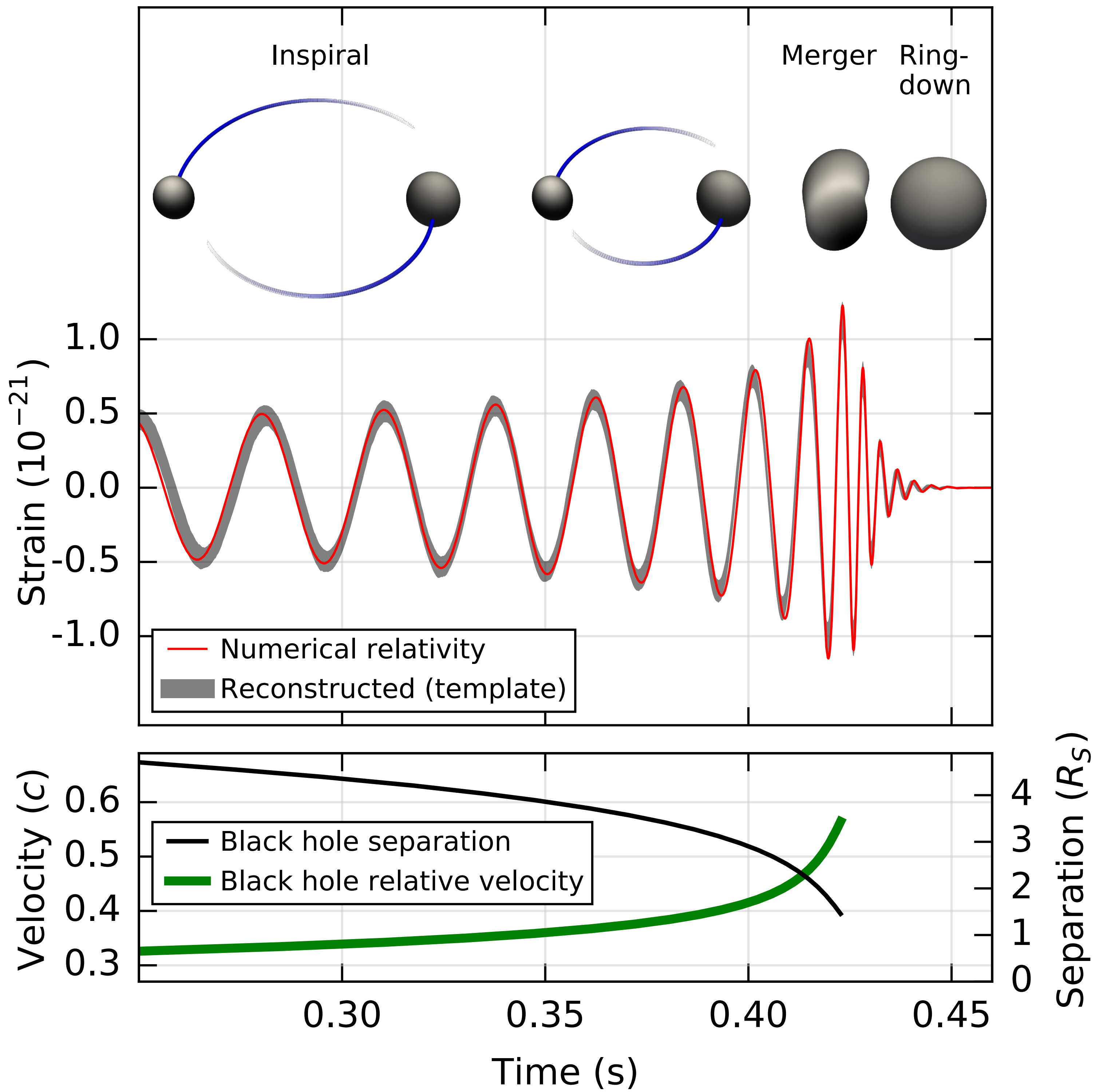
Final Mass:

62 (+4/-4) M_{sun}

Distance

410 (+160/-180) MPc

(1.3 Billion light years)



http://dx.doi.org/10.1103/PhysRevLett.116.061102

Best fit with Numerical Relativity

Initial Masses:

29 (+4/-4) & 36 (+5/-4) M_{sun}

Final Mass:

62 (+4/-4) M_{sun}

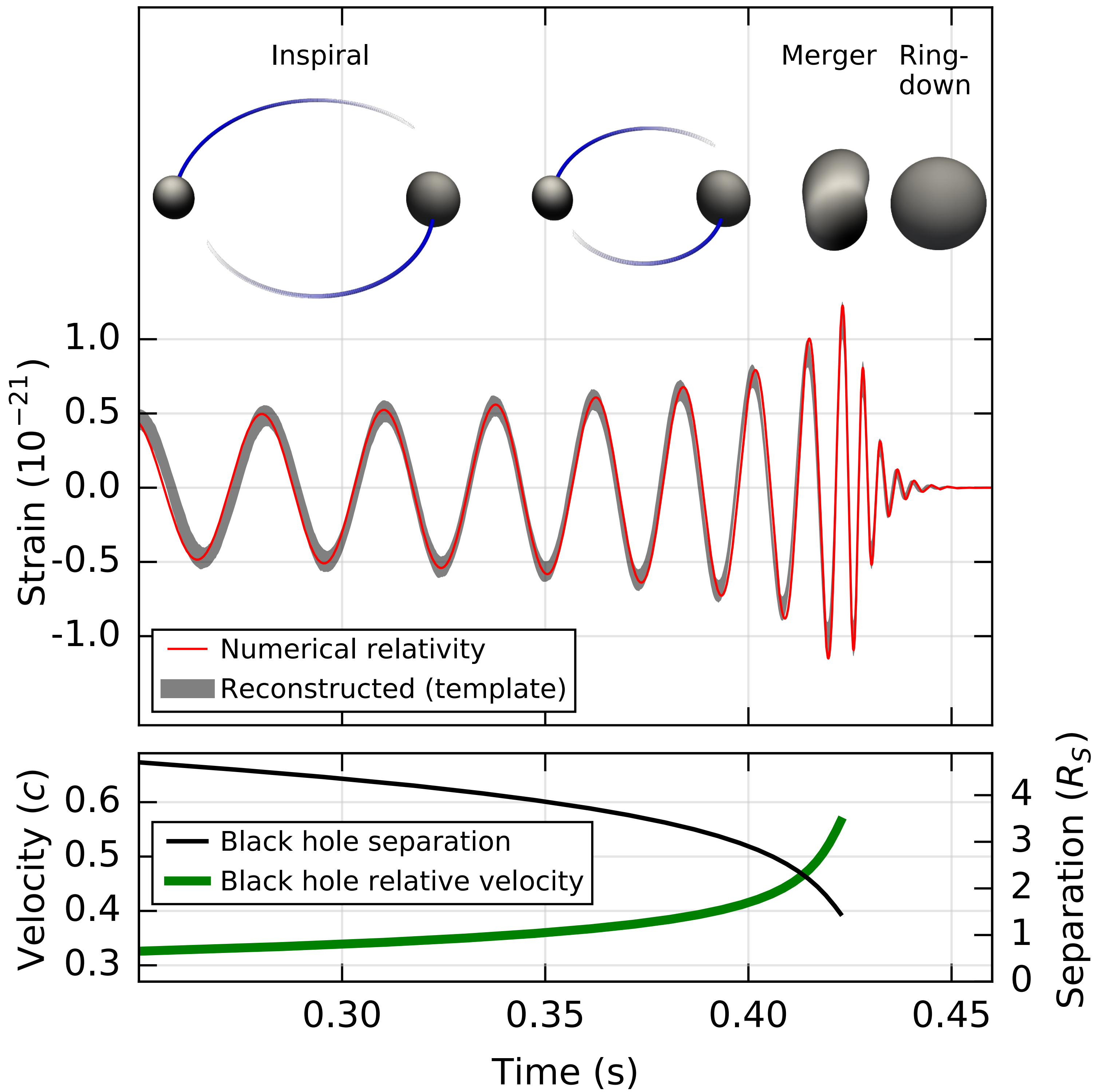
Energy radiated

3 (+0.5/-0.5) $M_{sun}\ c^2$

Distance

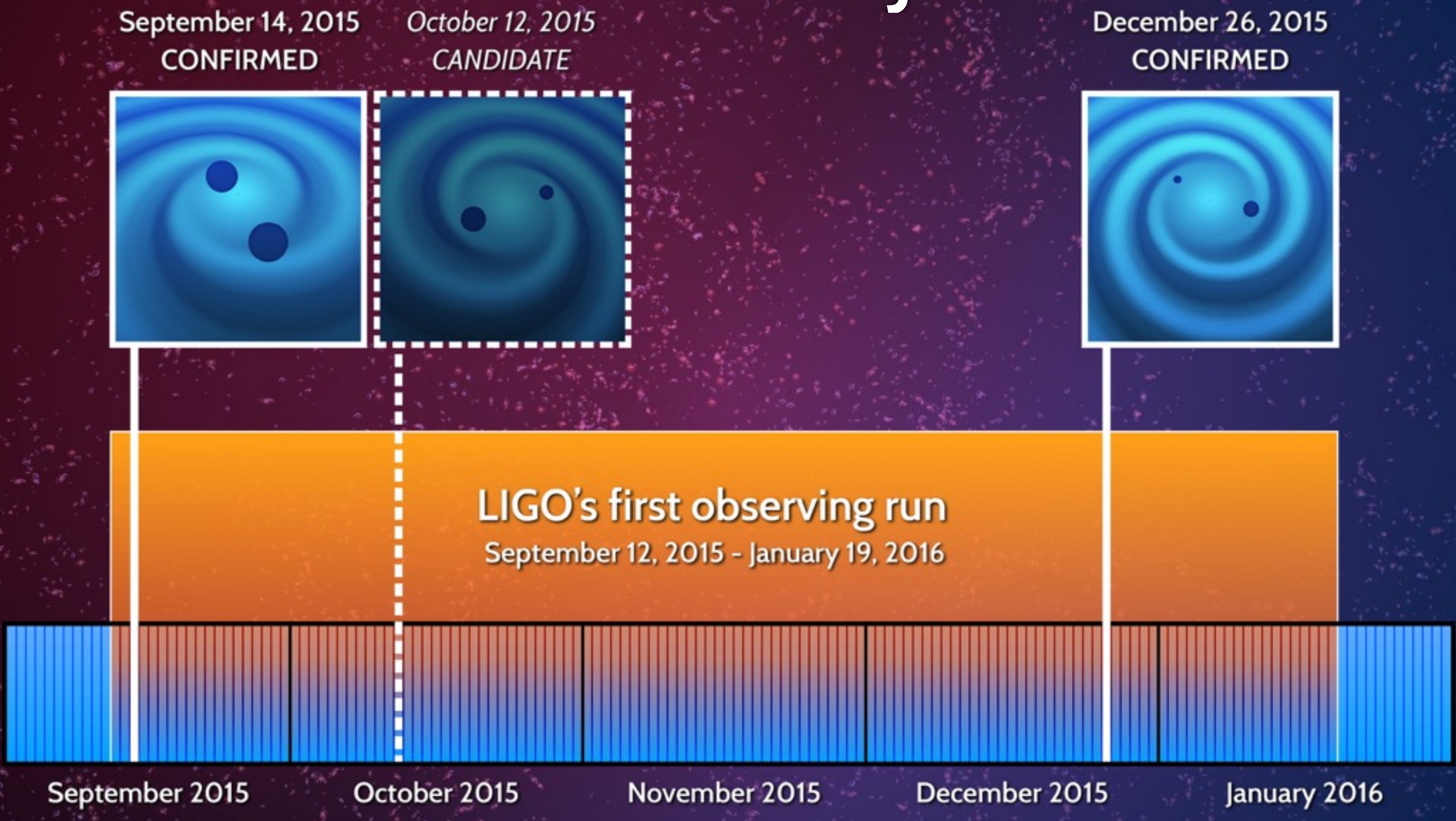
410 (+160/-180) MPc

(1.3 Billion light years)

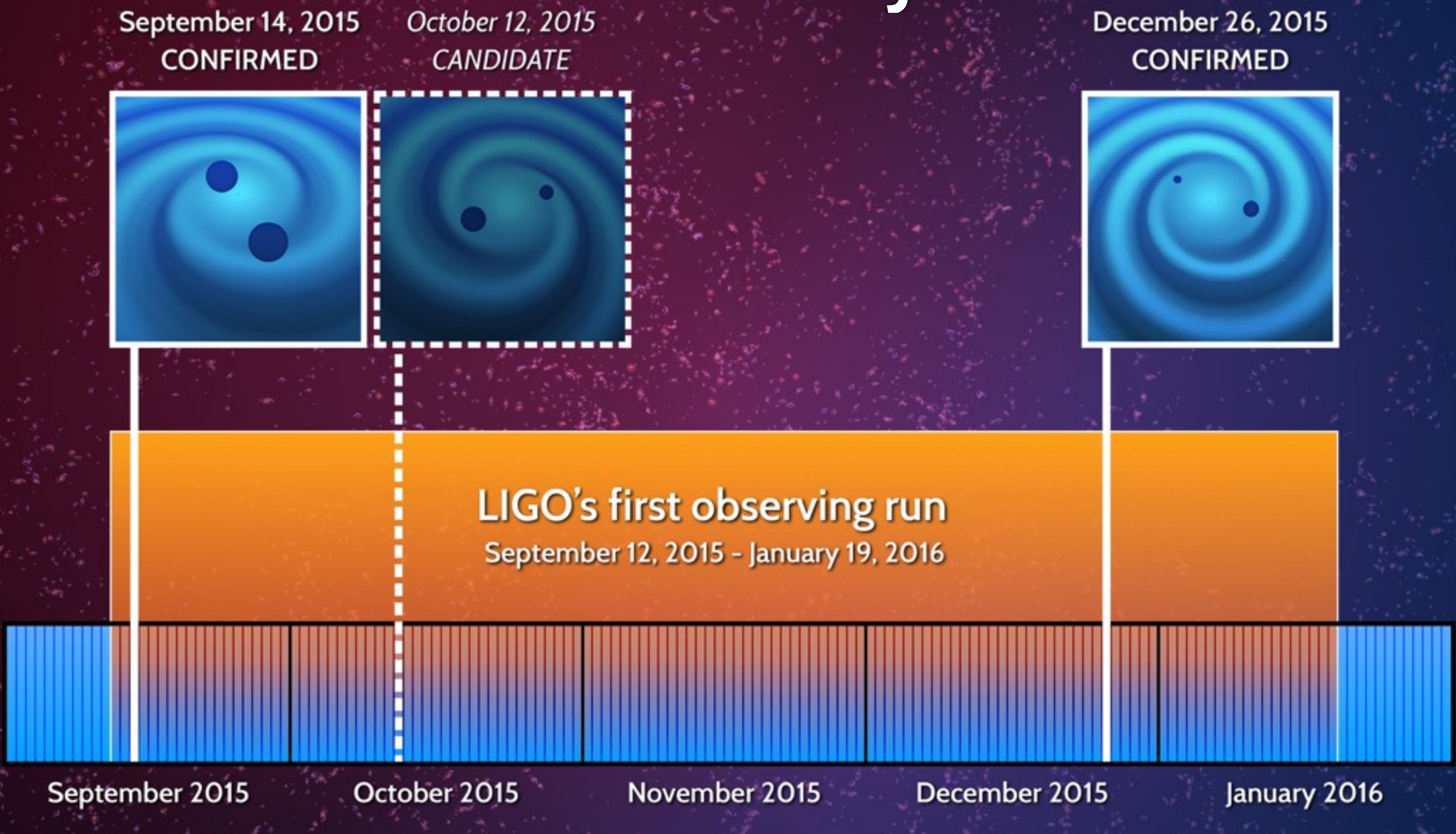


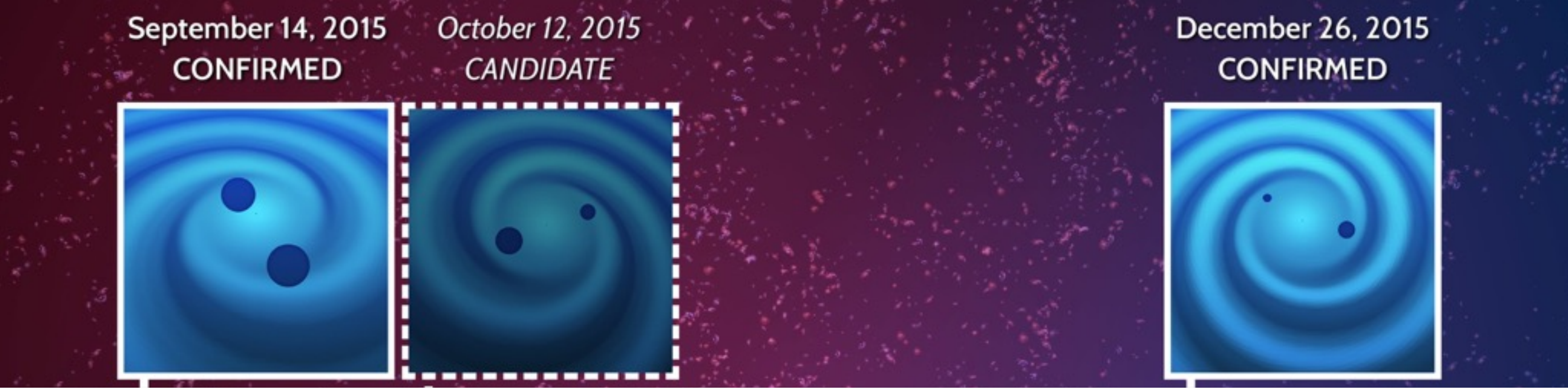
http://dx.doi.org/10.1103/PhysRevLett.116.061102

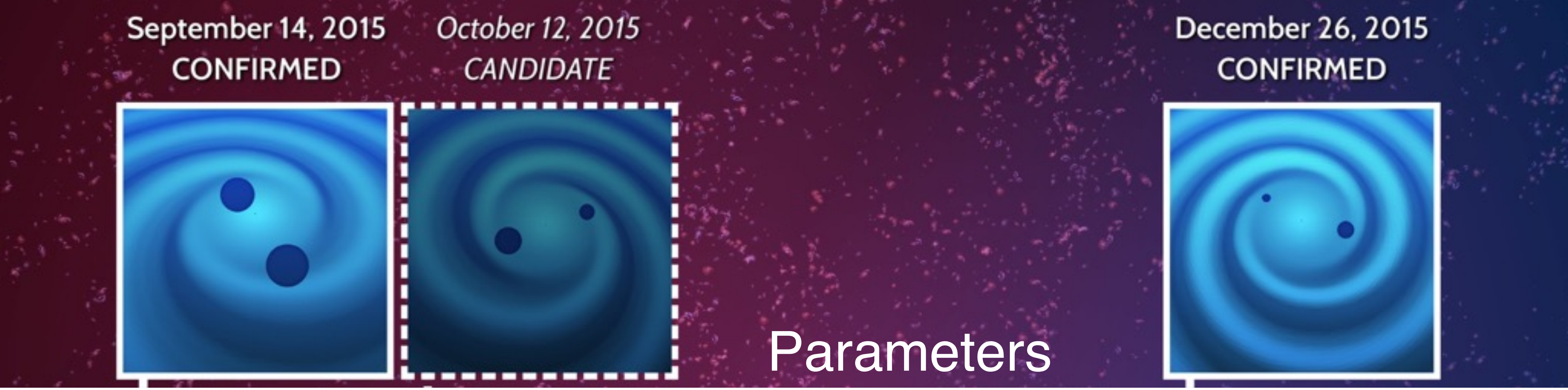
2nd detection announced on June 15



2nd detection announced on June 15



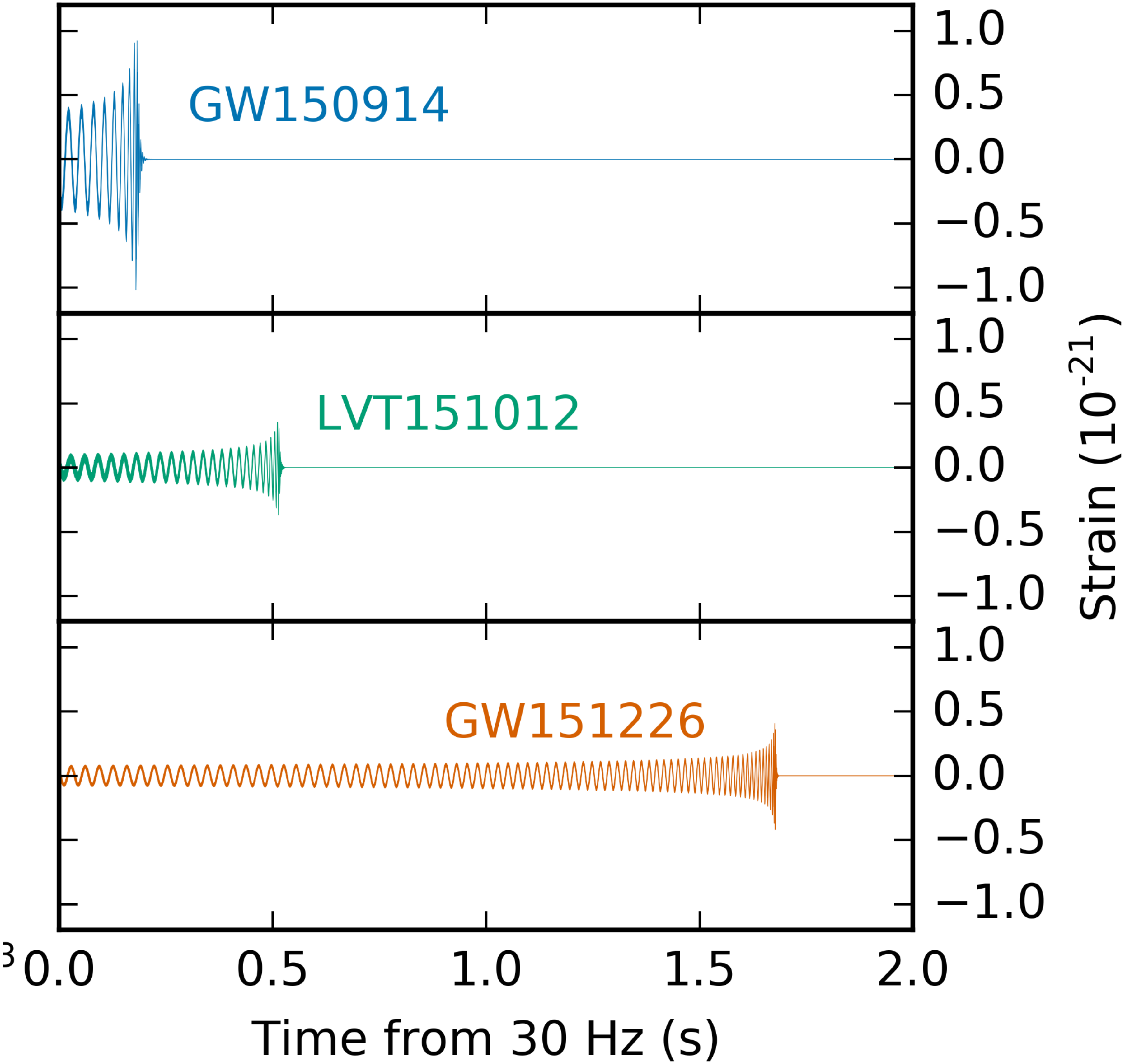

September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED



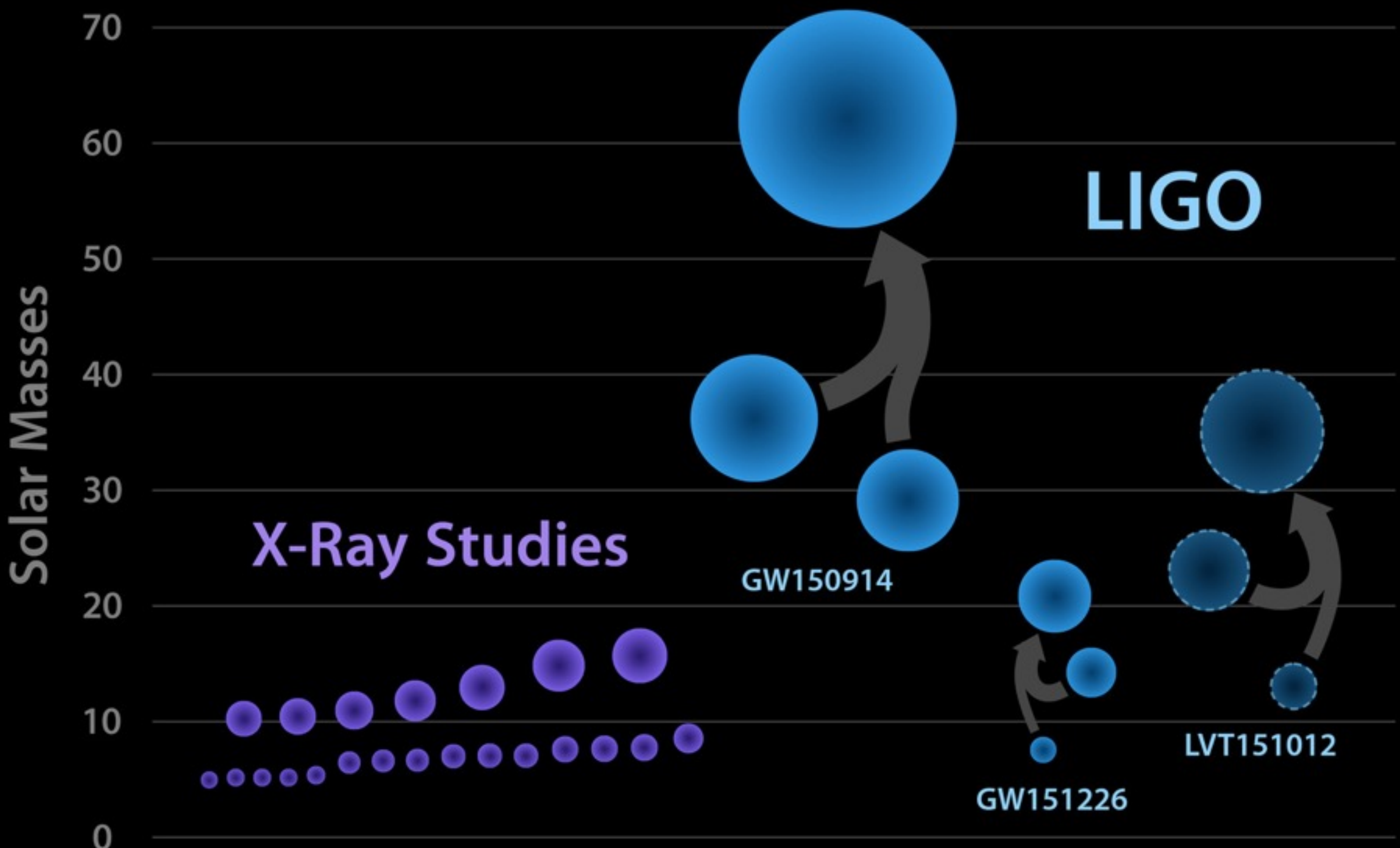
Parameters

First Detection	Maybe?	*Importance*	Second Detection
$> 5.3\ \sigma$	$1.7\ \sigma$	***Significance***	$> 5.3\ \sigma$
$29^{+4}_{-4}\ /36^{+5}_{-4}\ M_\odot$	$23^{+18}_{-6}\ /13^{+4}_{-5}\ M_\odot$	***Original masses***	$14^{+8}_{-4}\ /7.5^{+2}_{-2}\ M_\odot$
$62^{+4}_{-4}\ M_\odot$	$35^{+14}_{-4}\ M_\odot$	***Final mass***	$21^{+6}_{-2}\ M_\odot$
$3.0^{+0.5}_{-0.5}\ M_\odot c^2$	$1.5^{+0.3}_{-0.4}\ M_\odot c^2$	***energy radiated***	$1.0^{+0.1}_{-0.2}\ M_\odot c^2$
1.3 billion light years	3.3 GLy	***distance***	1.4 GLy
420^{+150}_{-180} MPc	1000^{+500}_{-500} MPc		440^{+180}_{-190} MPc

Comparison signals

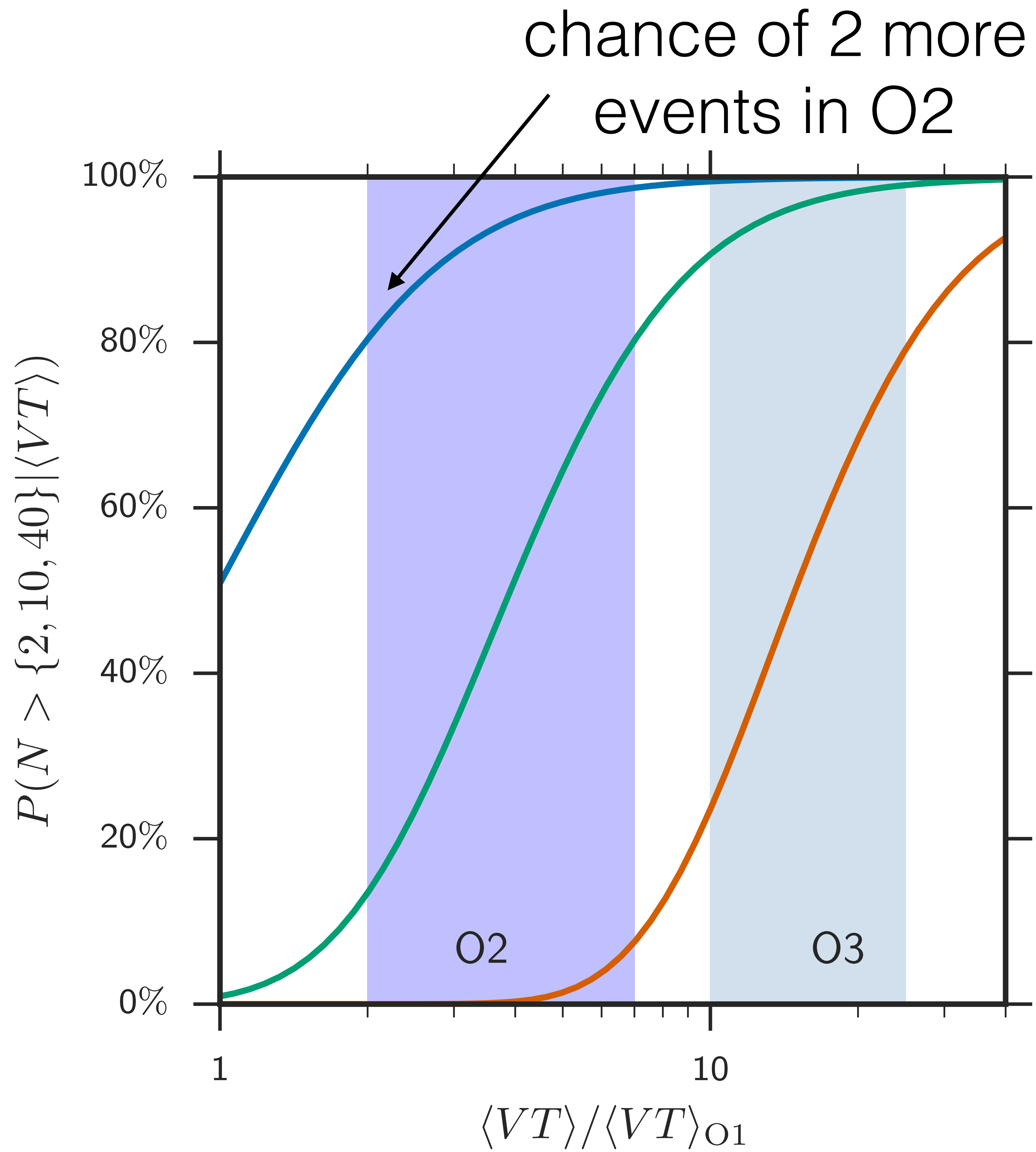


Black Holes of Known Mass

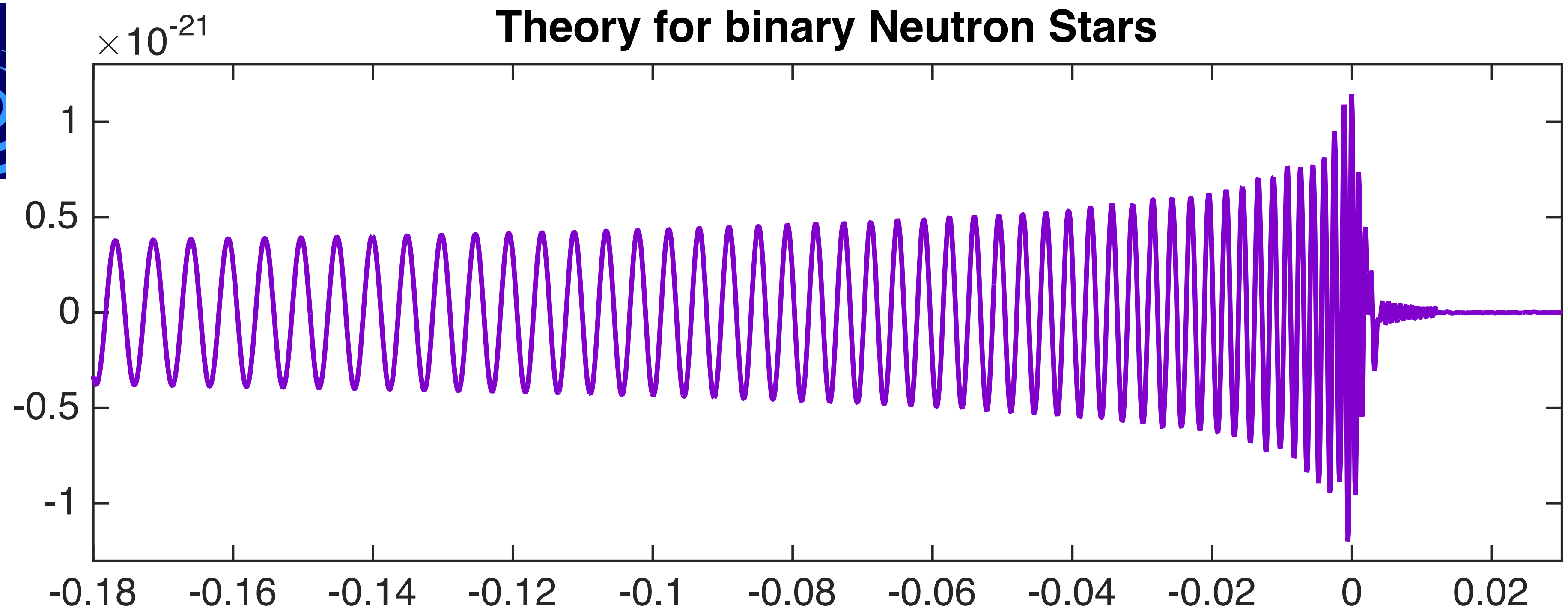


What is next?

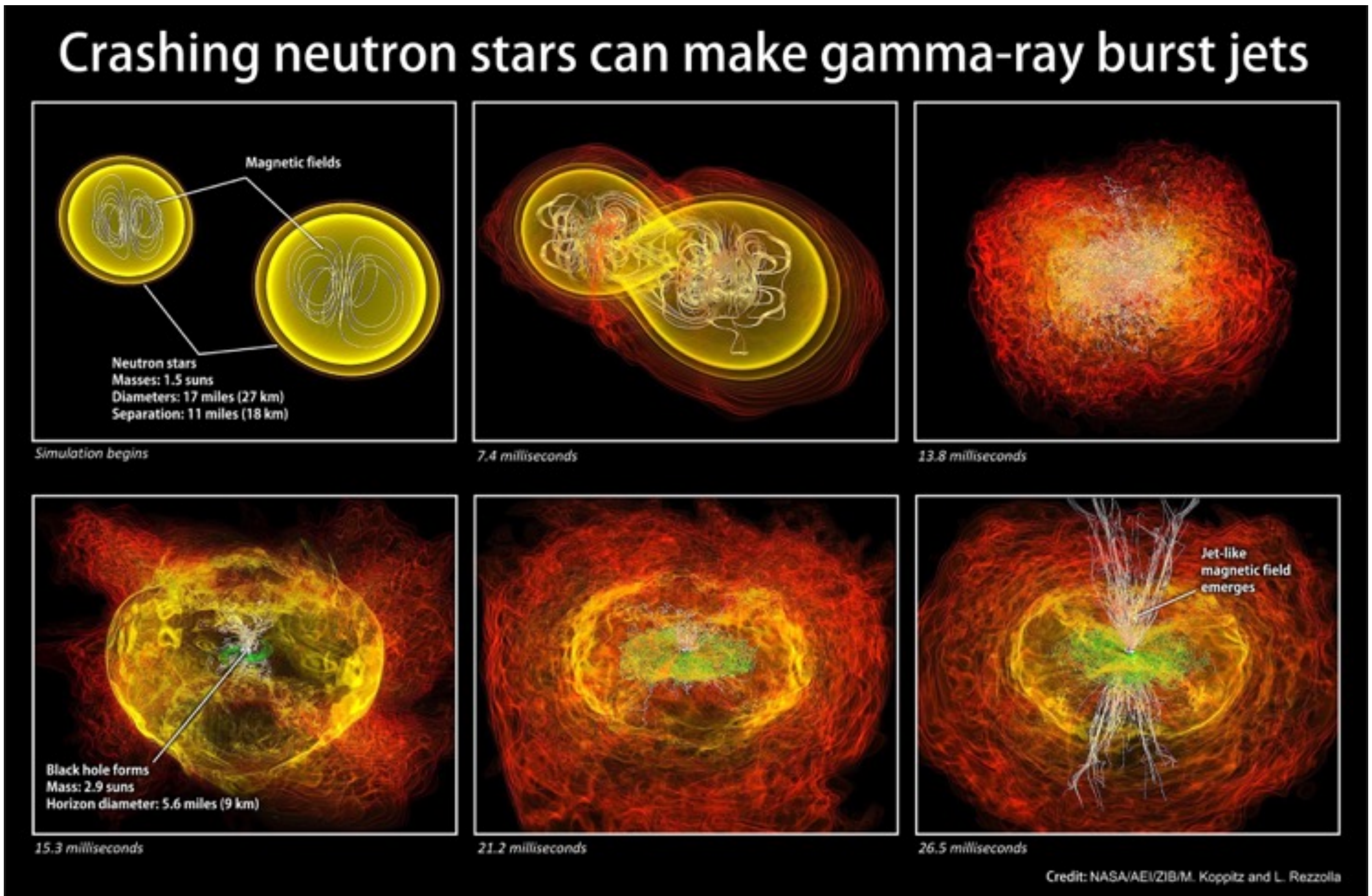
- Observing run #2 started Nov. 30 runs ~ 6 months
- Slightly better performance
- VIRGO plans to join in ~April
- Hope to see several more black holes
- O3 will probably start in early 2018…
- Looking for other sources



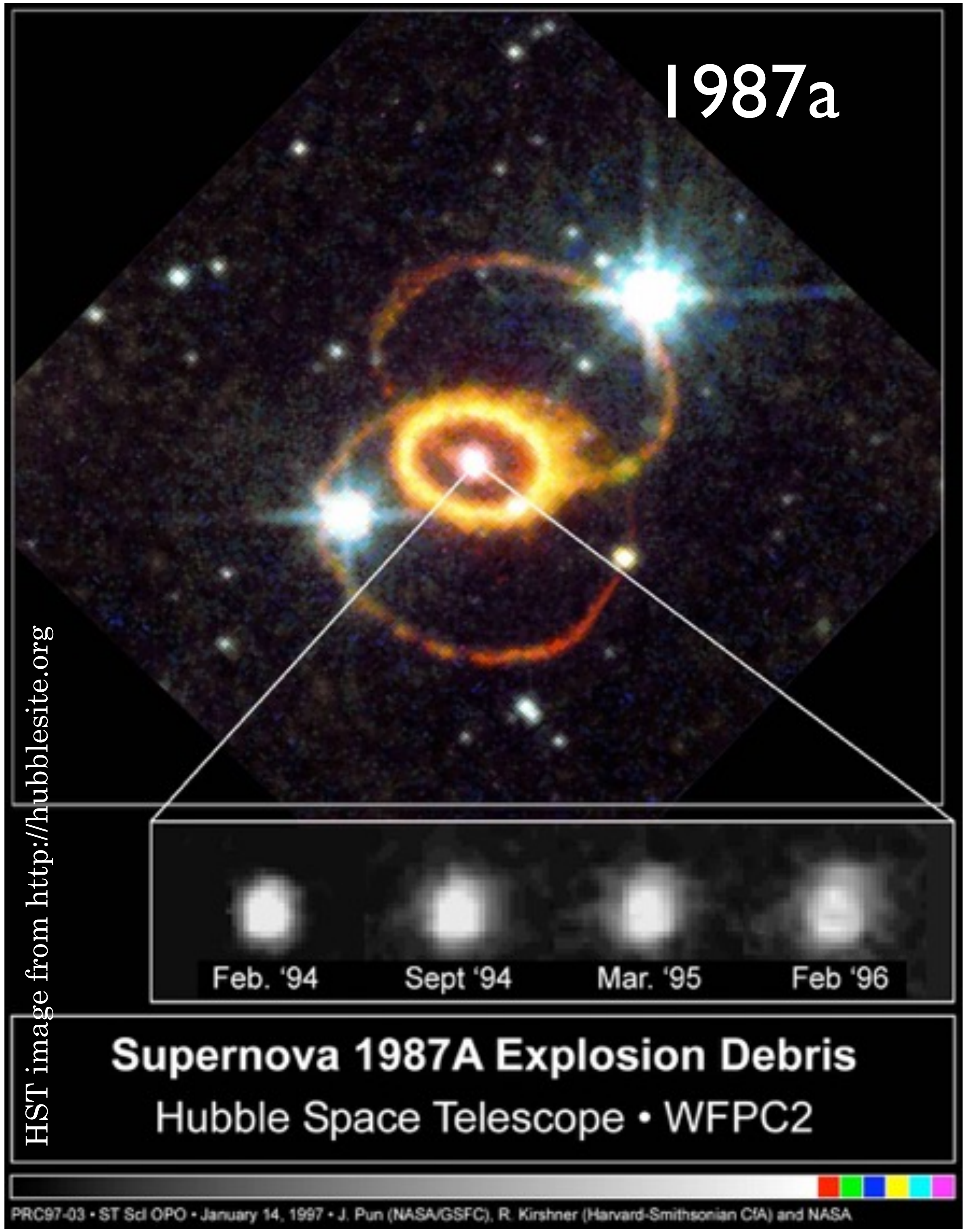
Theory for binary Neutron Stars



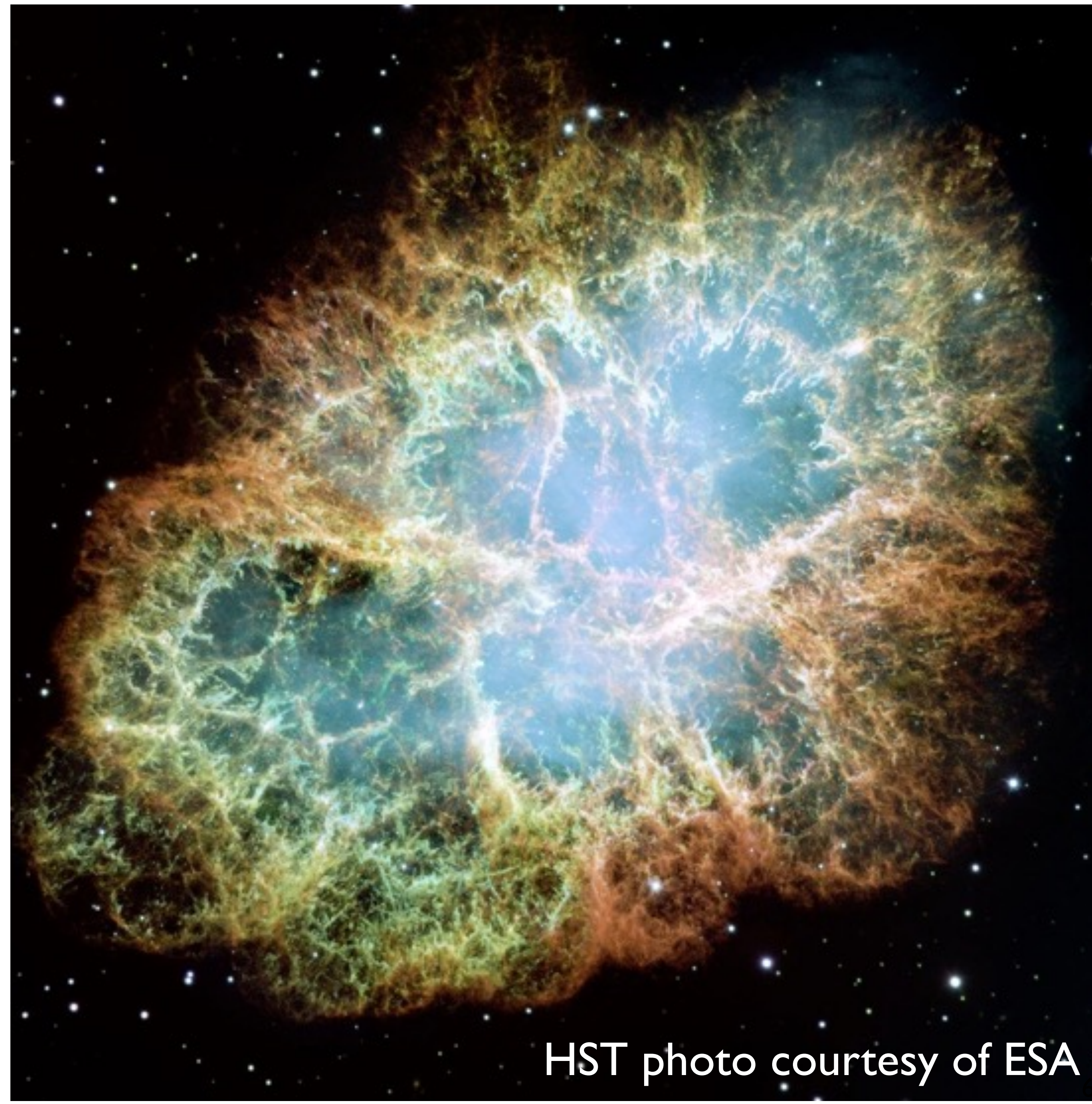
Crashing neutron stars can make gamma-ray burst jets



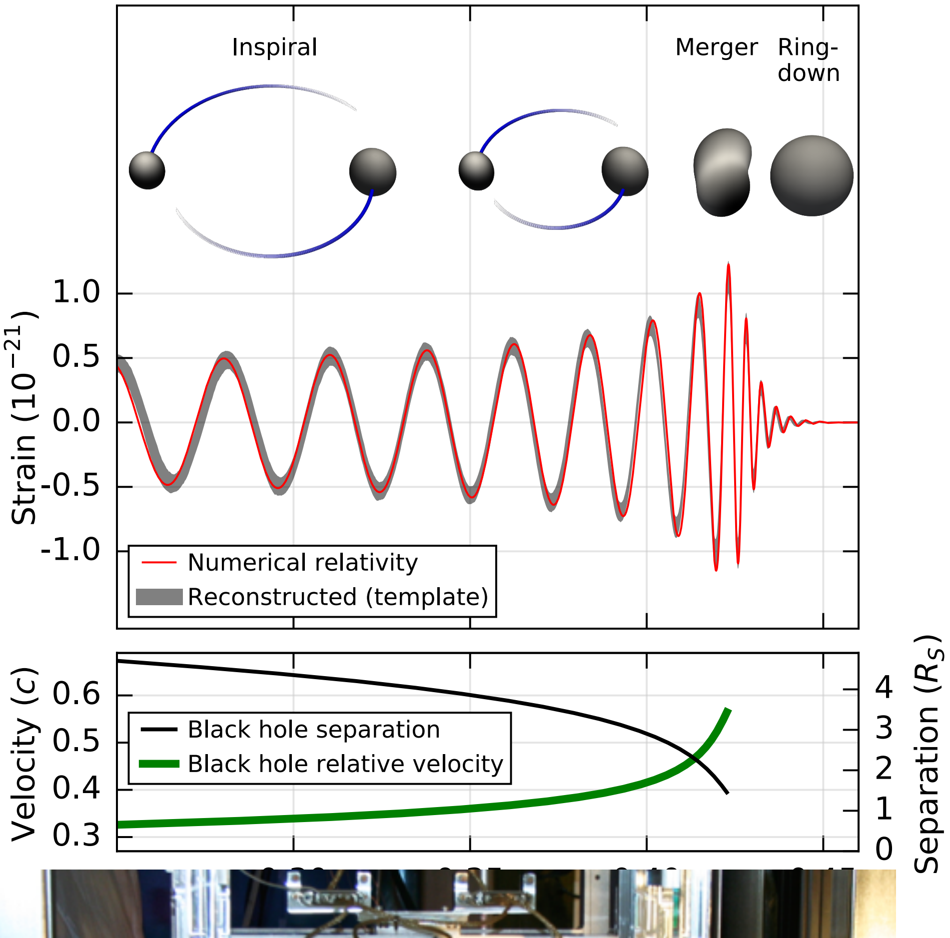
Supernovas and remnants

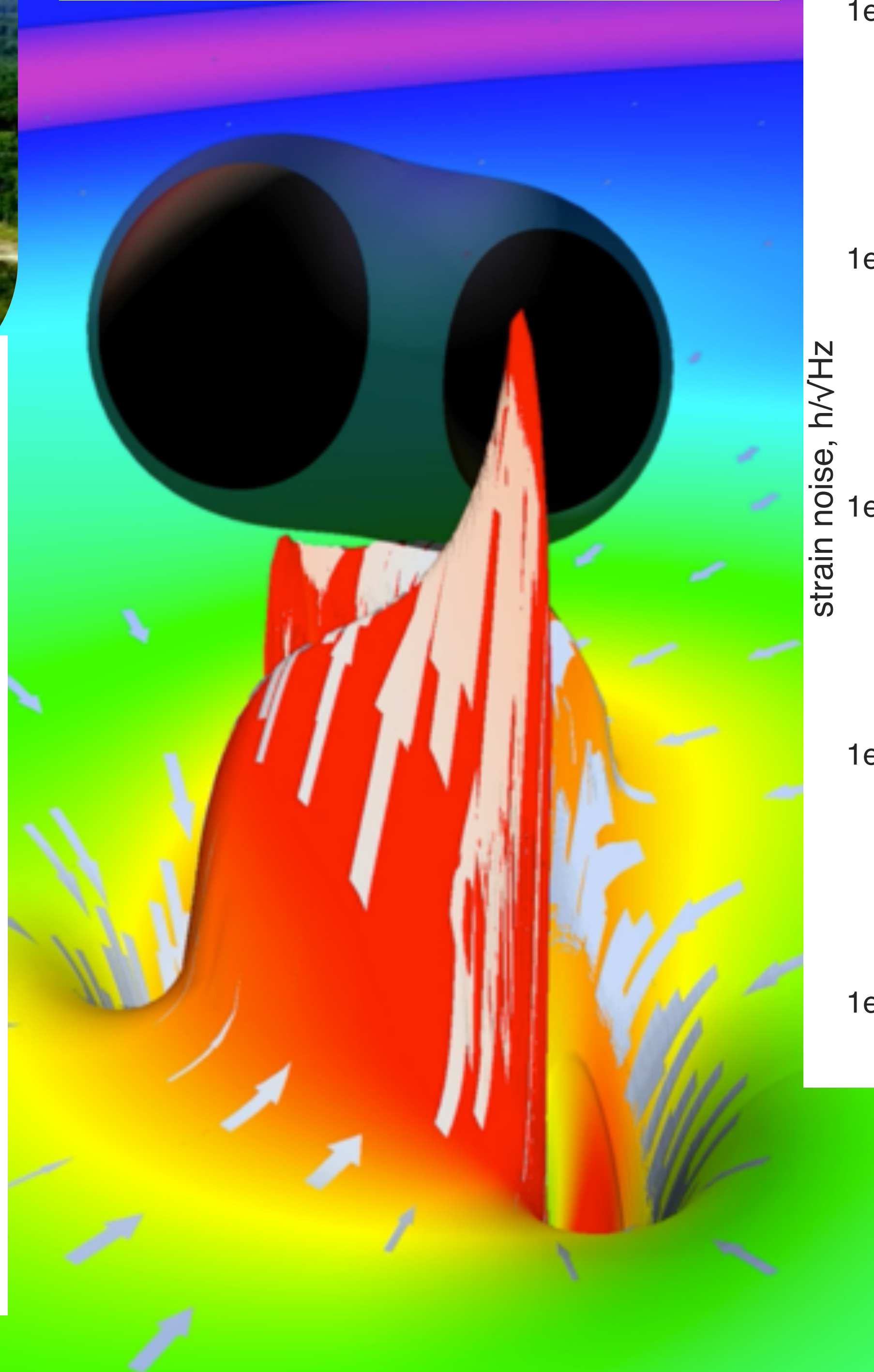


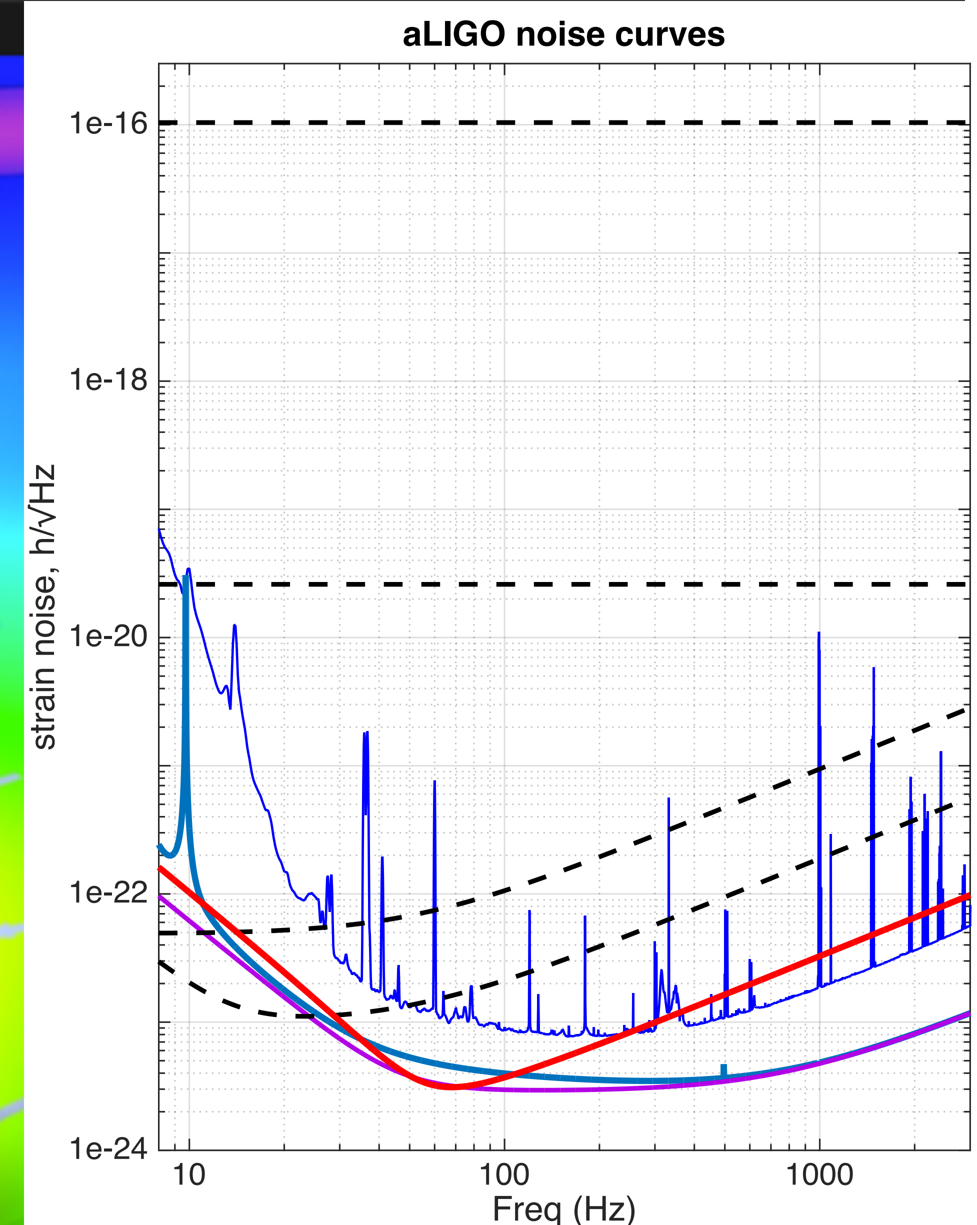
Crab Nebula, supernova in 1054, now a spinning neutron star

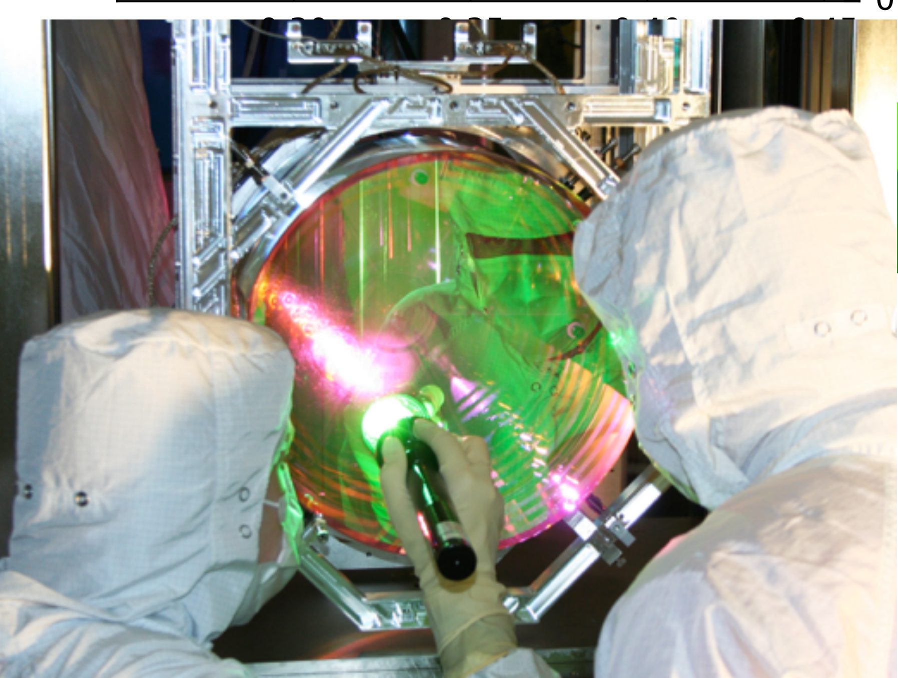


http://papers.ligo.org







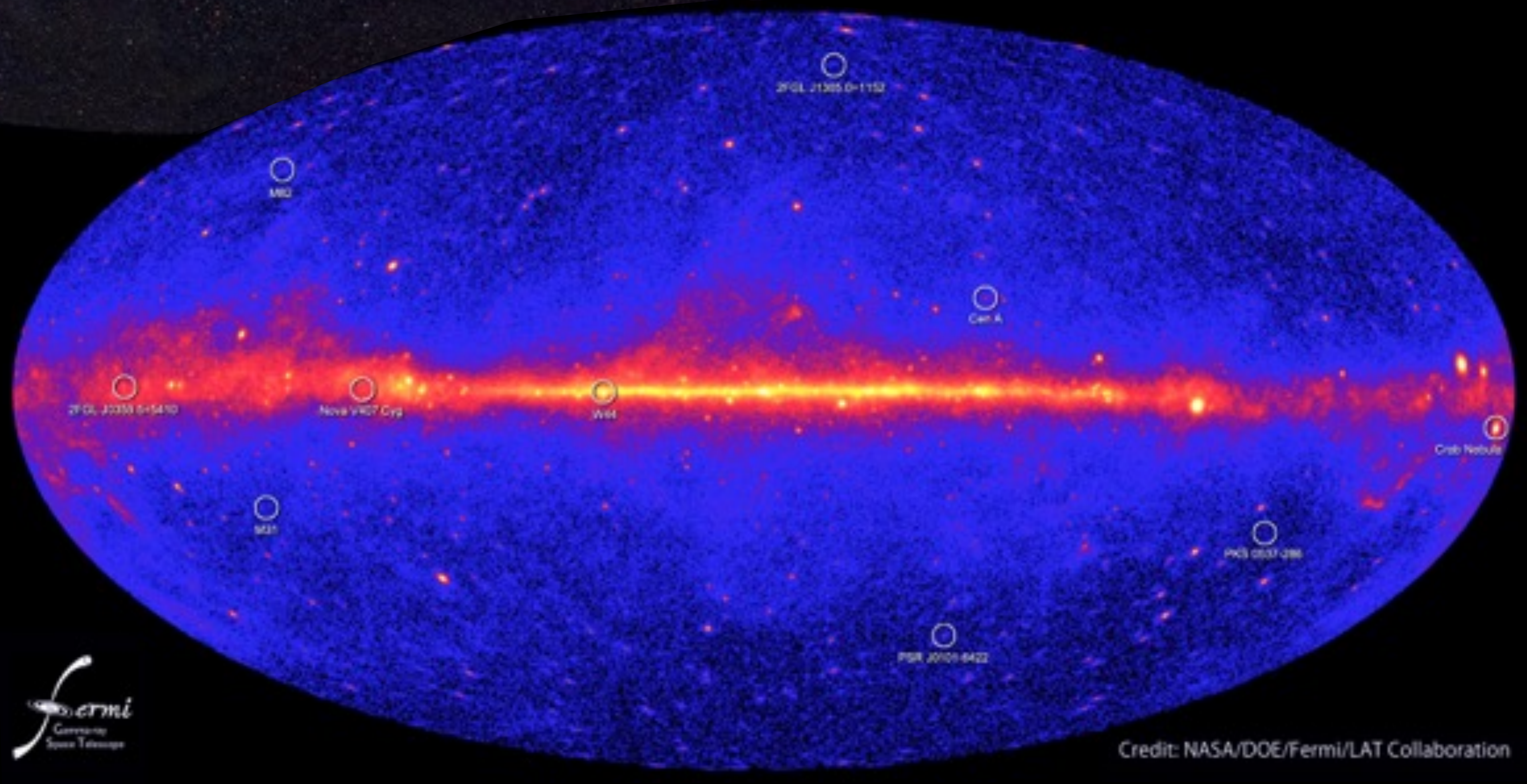


extra slides

new ways to see the sky

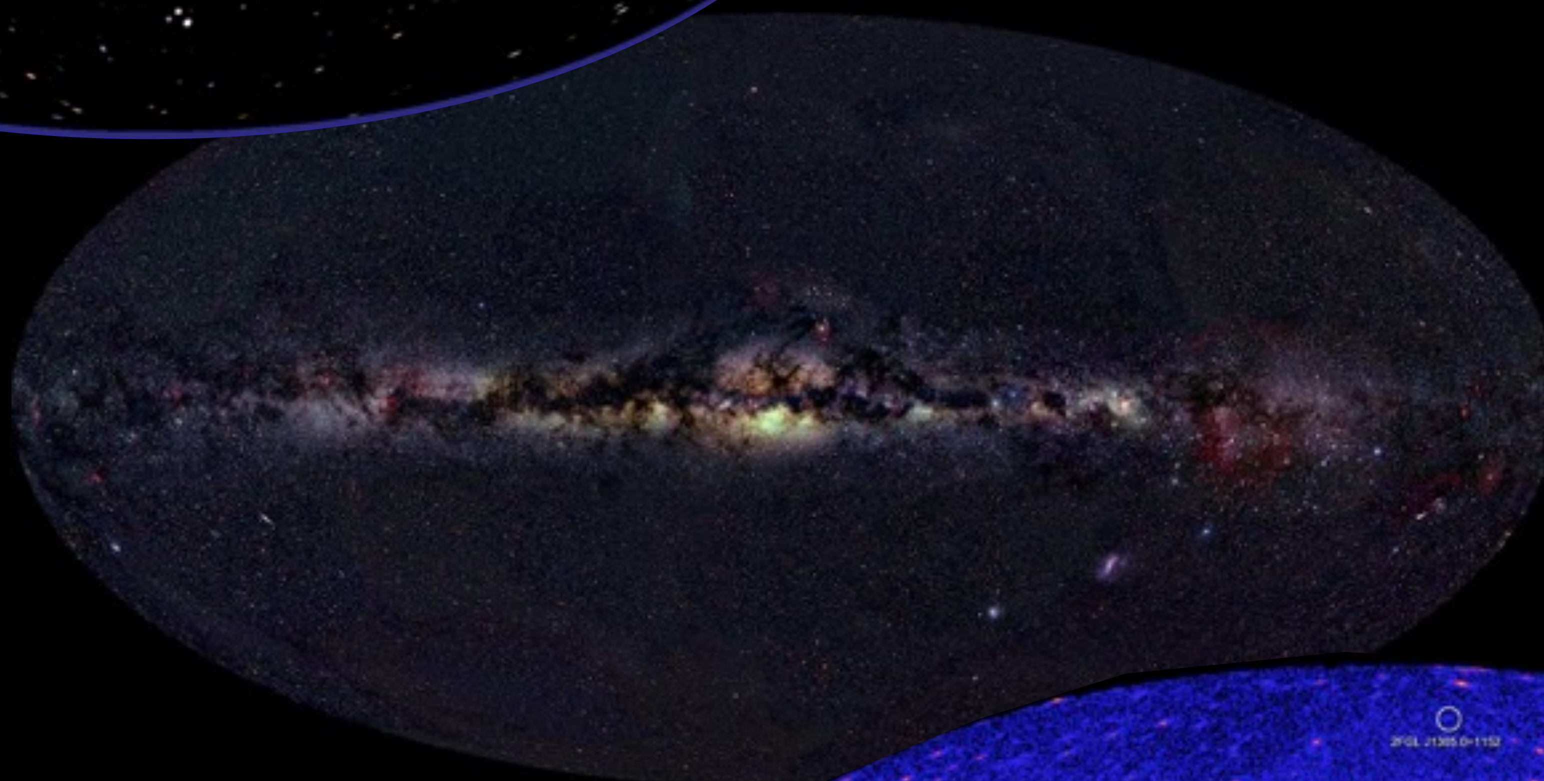
new ways to see the sky

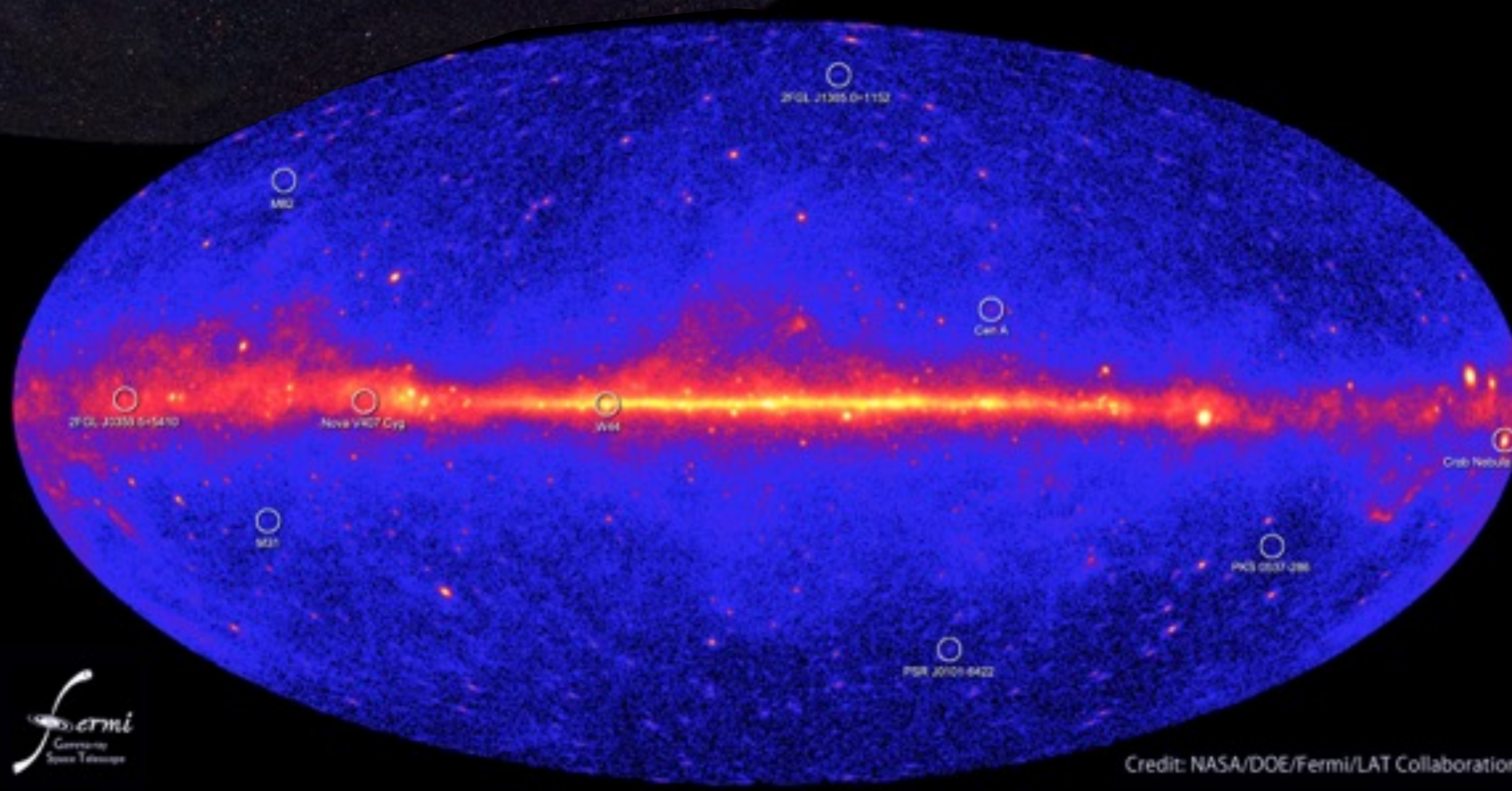
new ways to see the sky

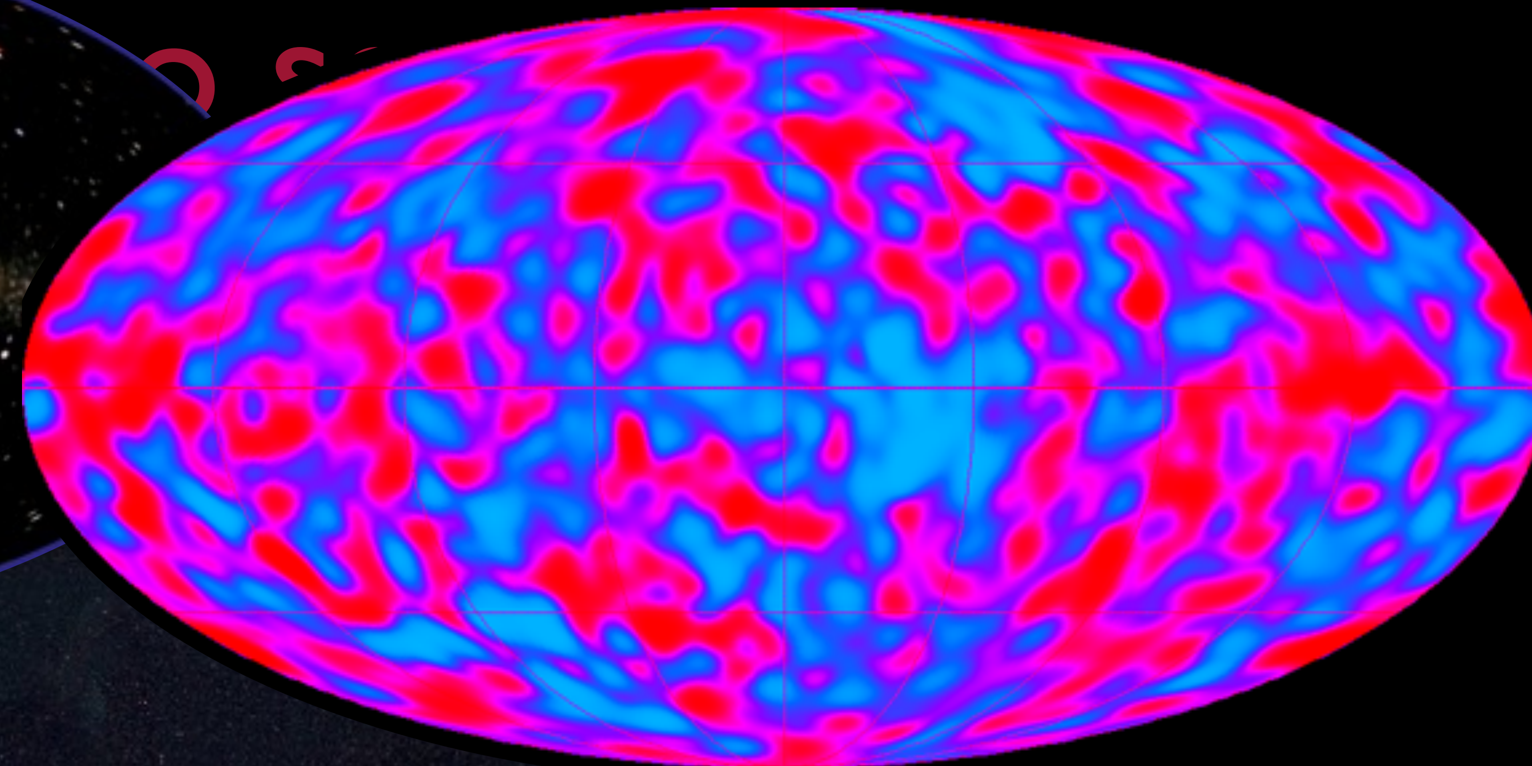
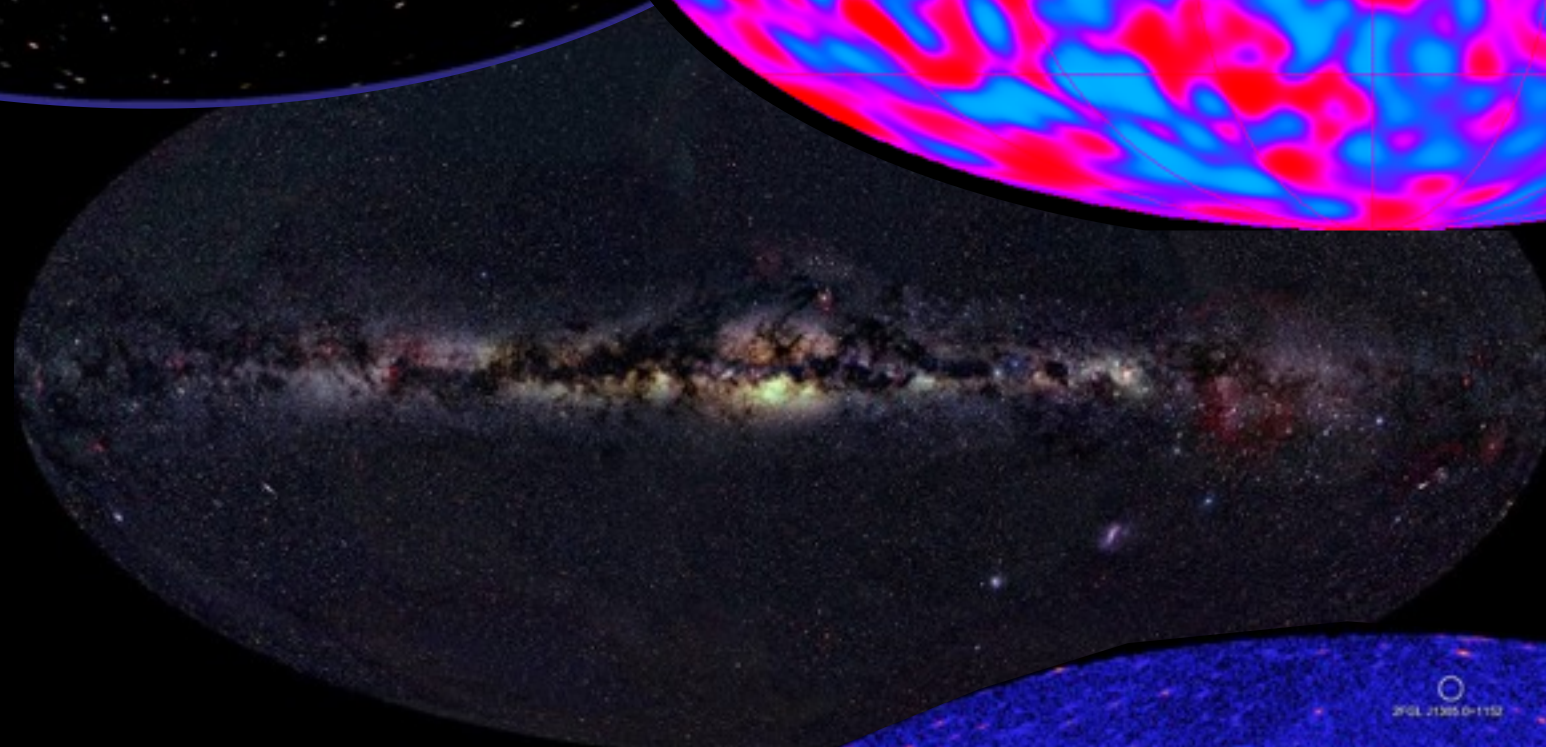


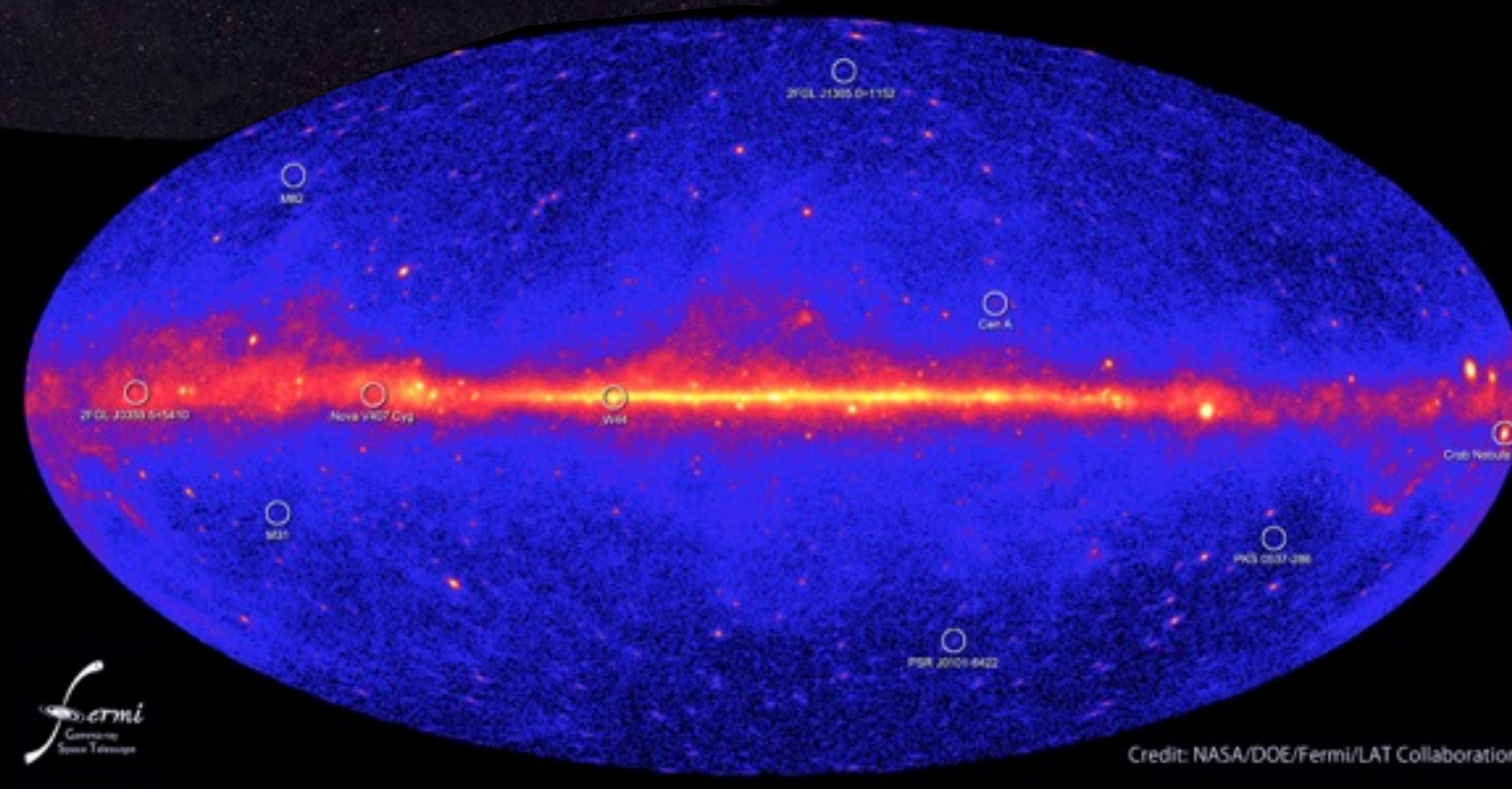
o see the sky

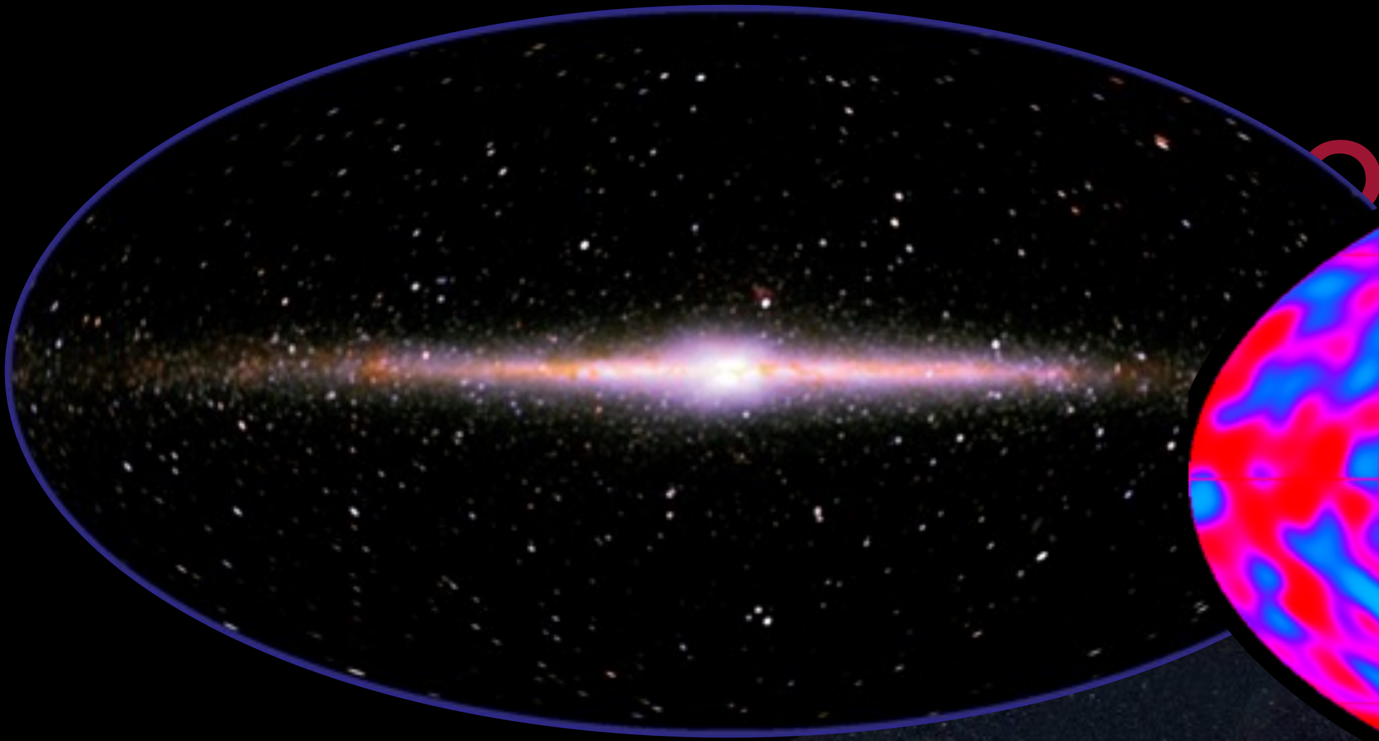
ep Sky

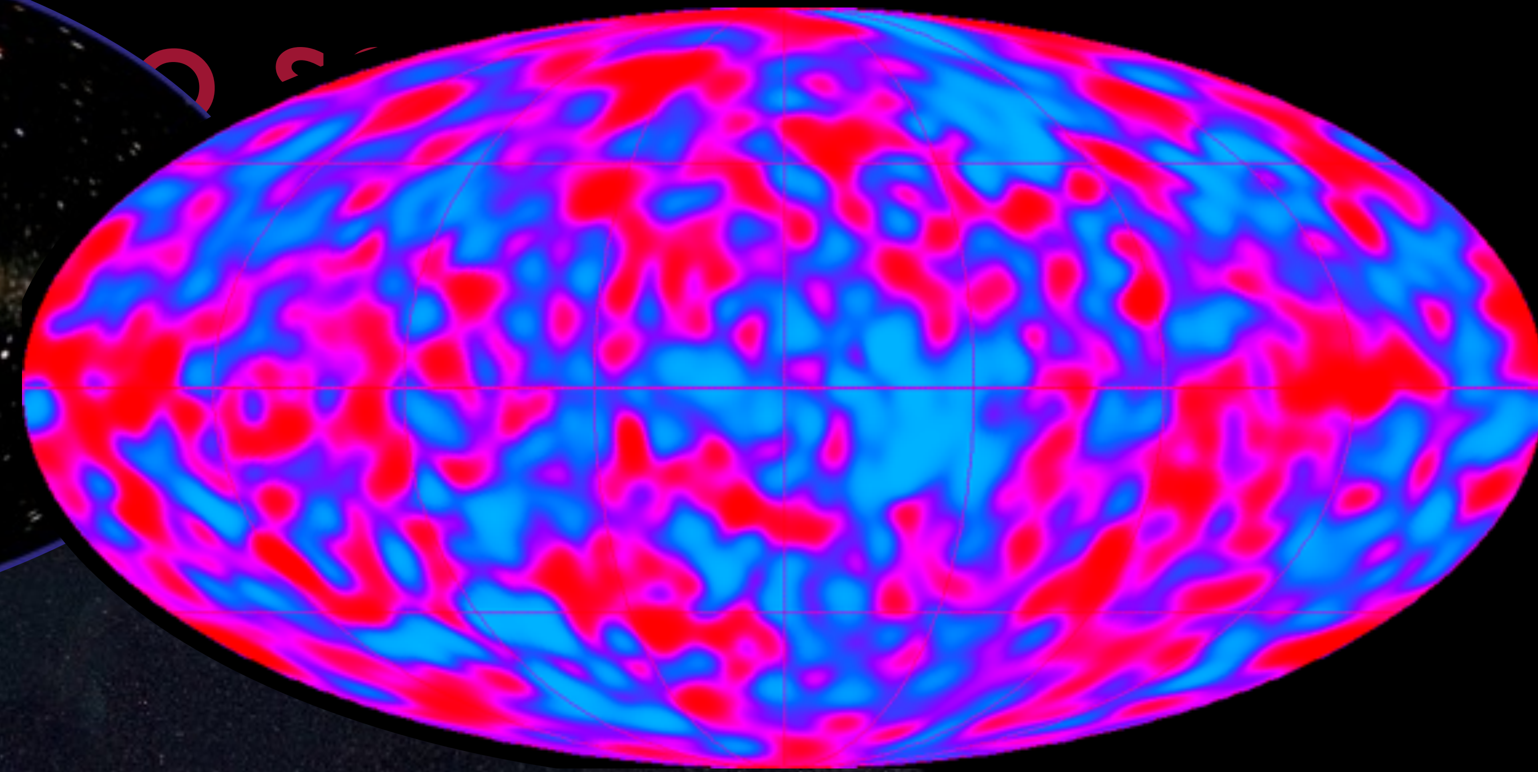




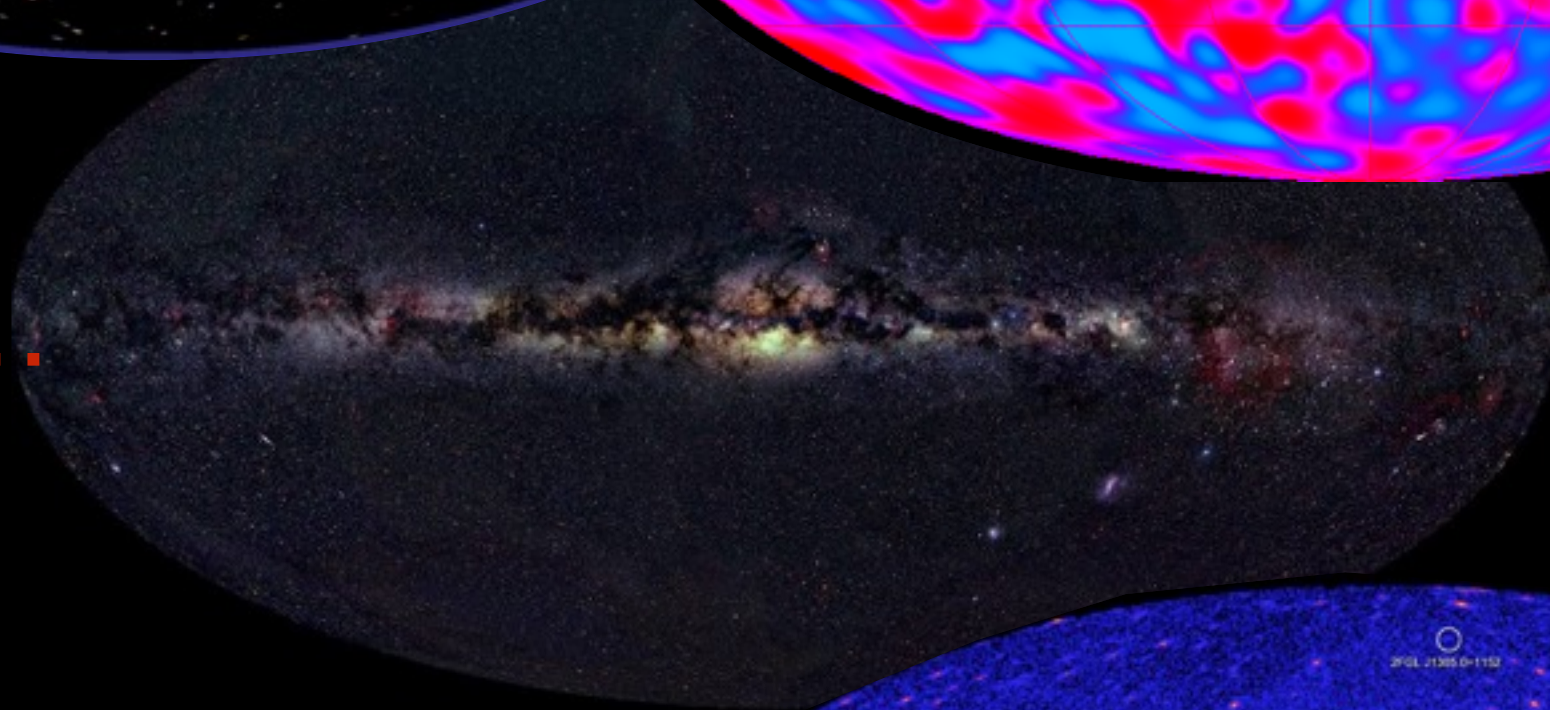




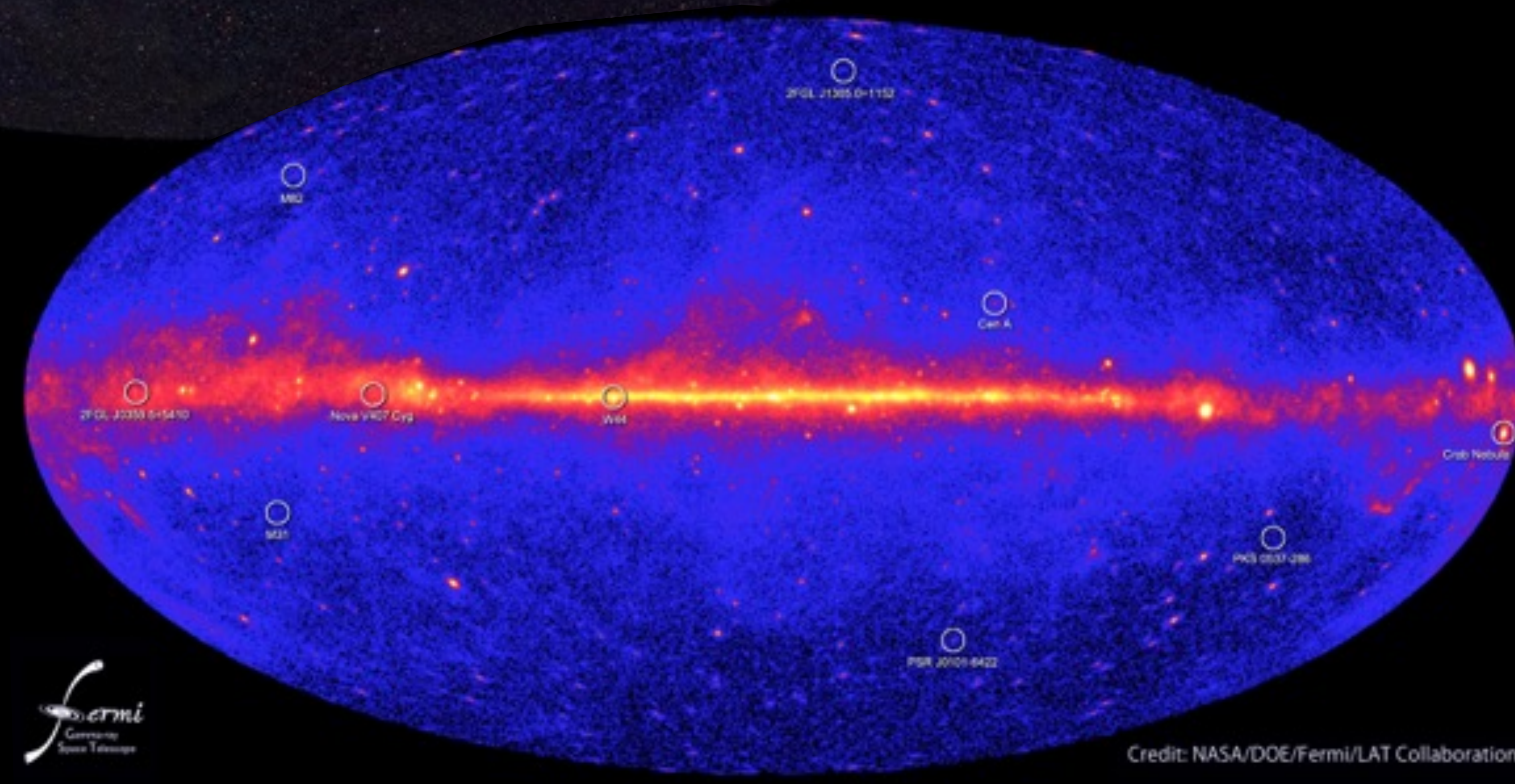

M82
Cen A
Nova V407 Cyg
Crab Nebula
M31
Credit: NASA/DOE/Fermi/LAT Collaboration

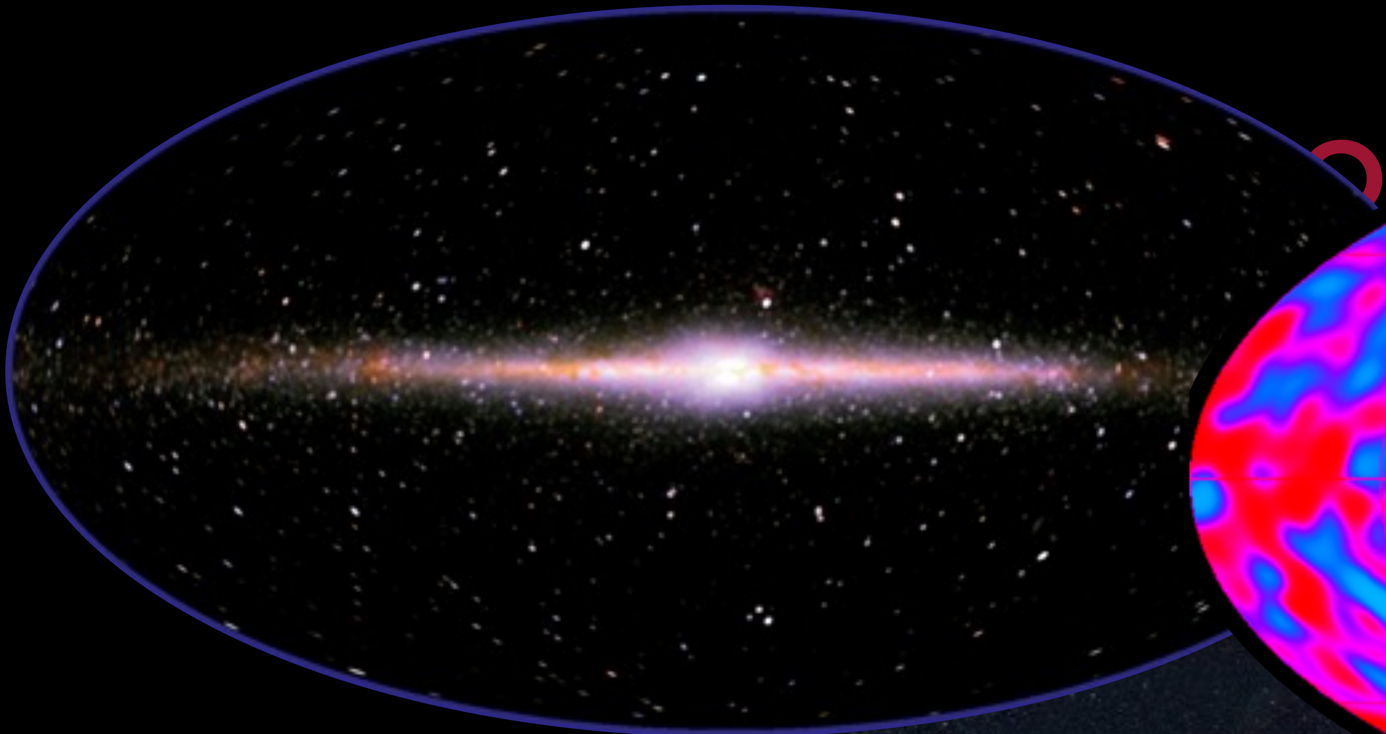


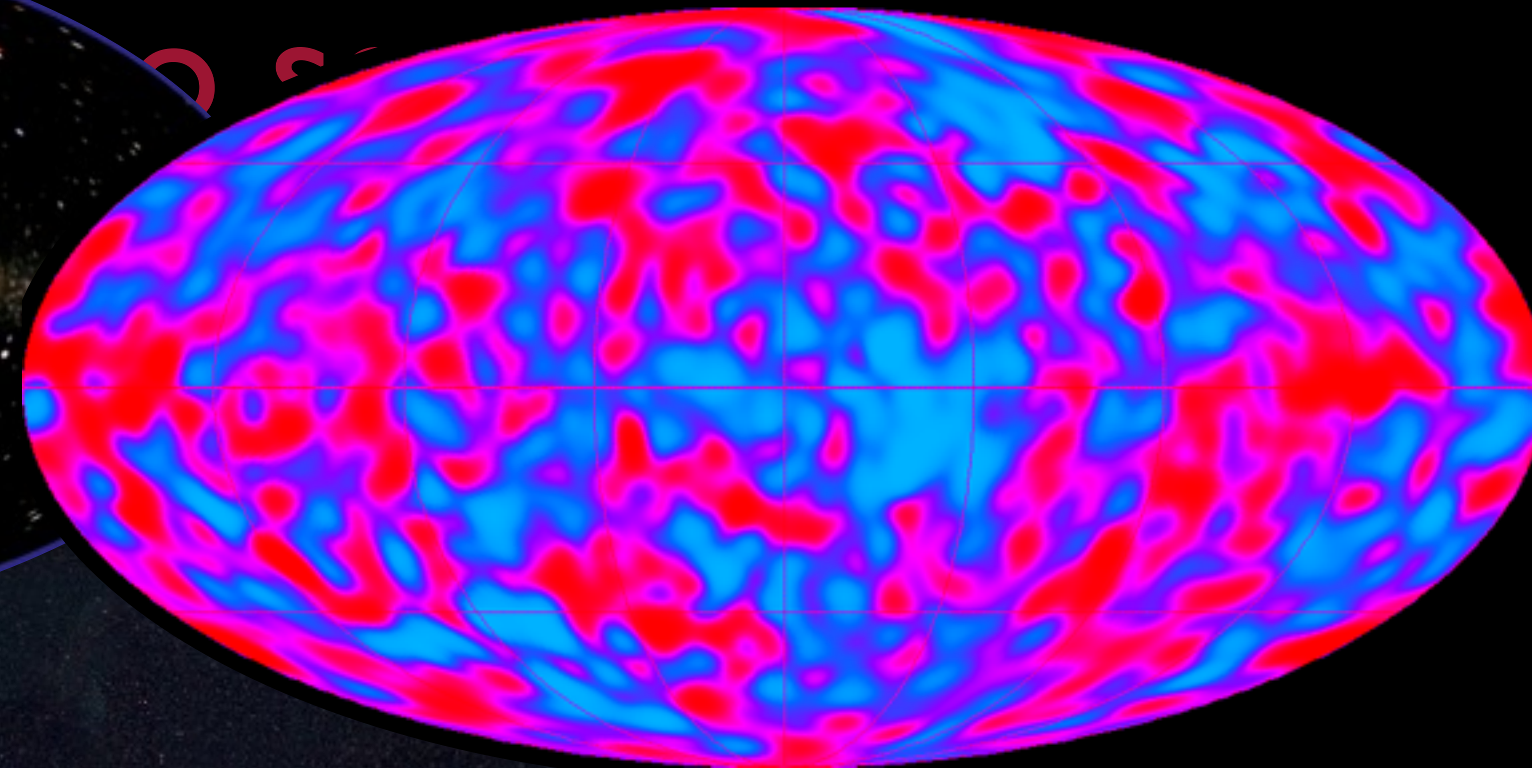


And Now…

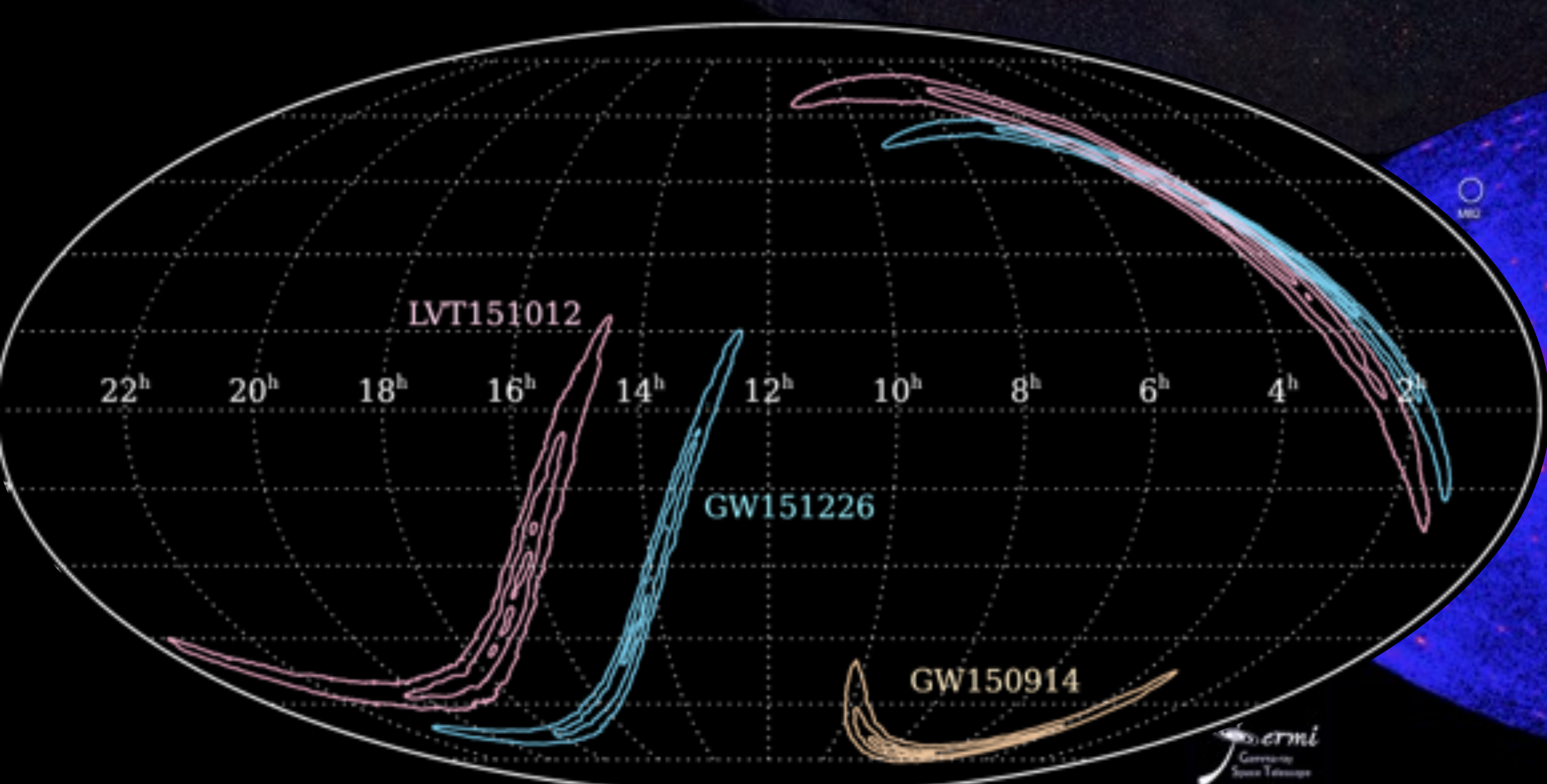


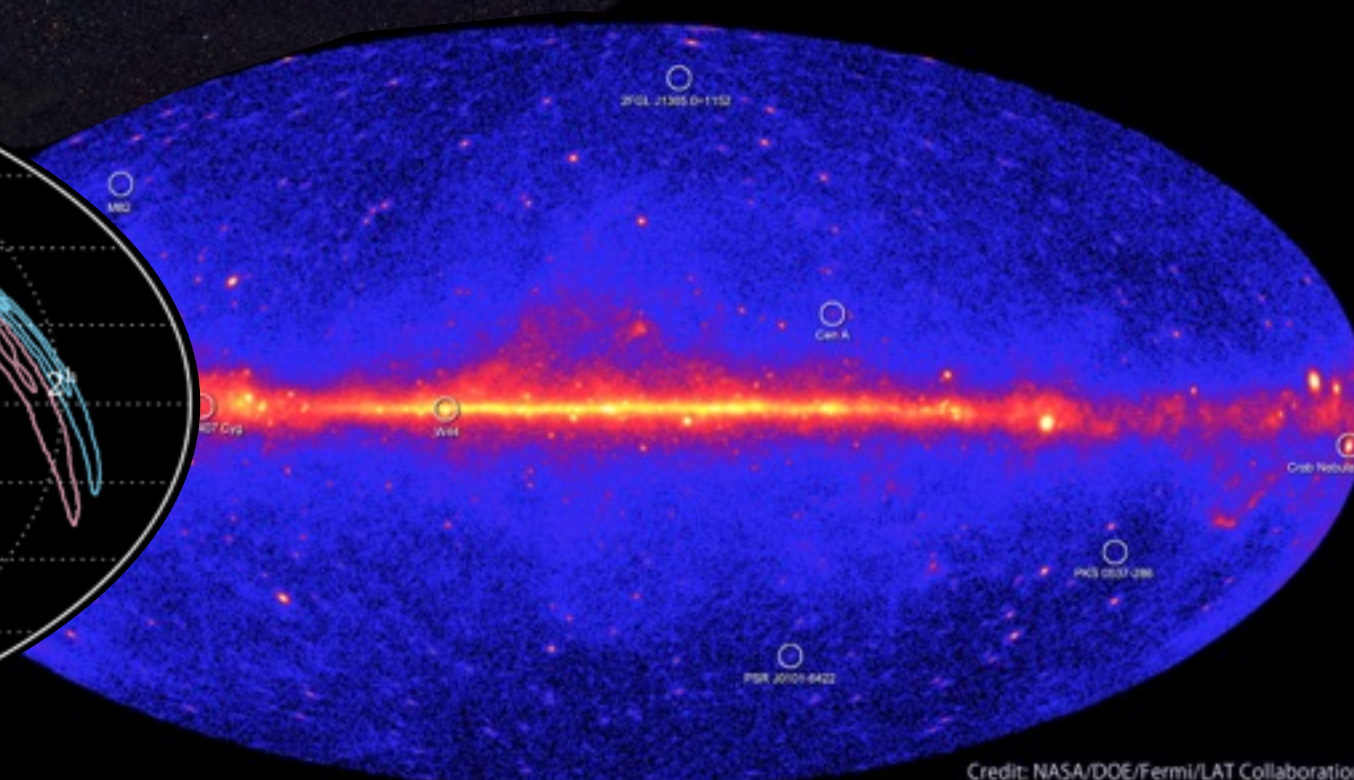


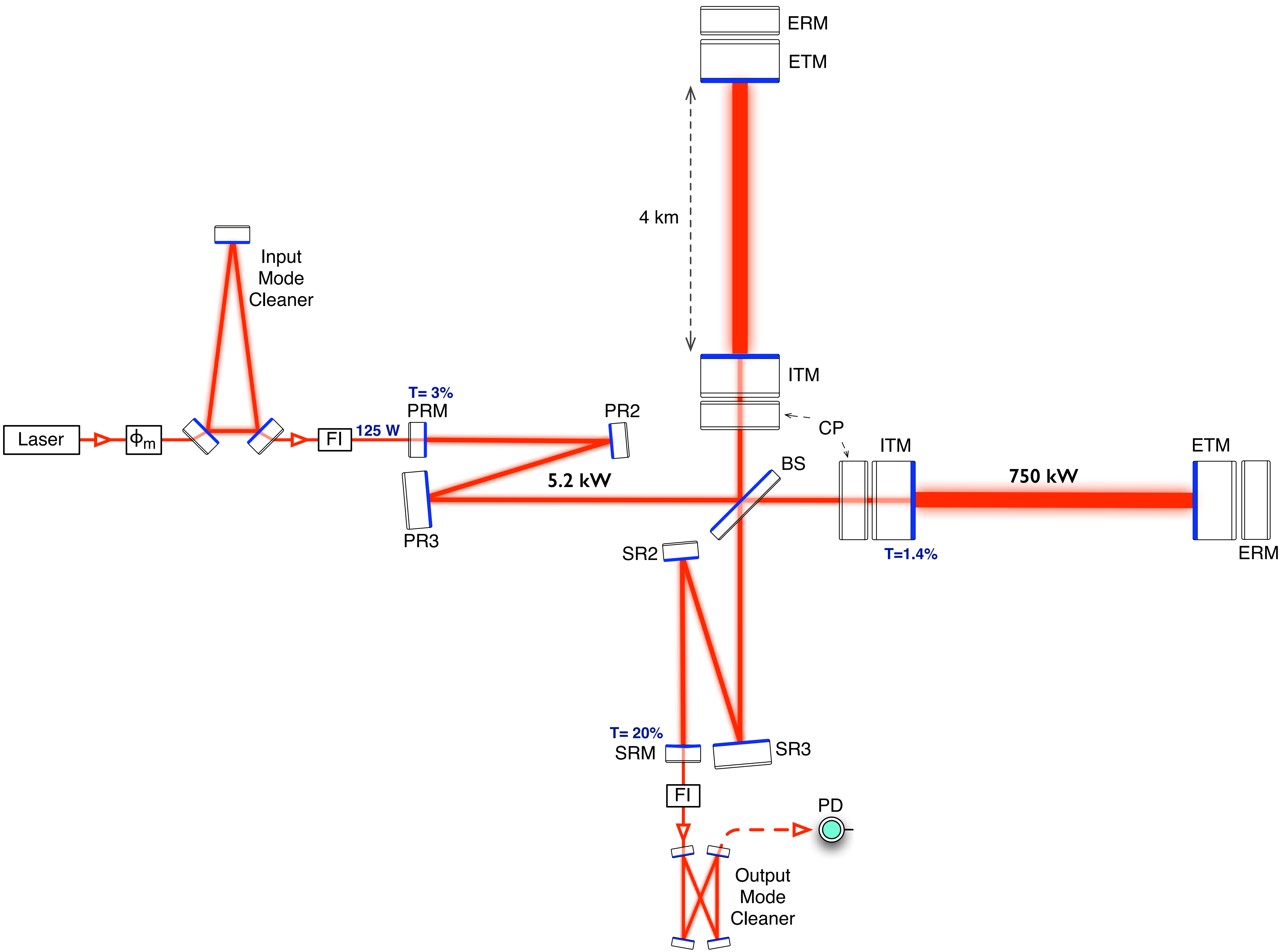




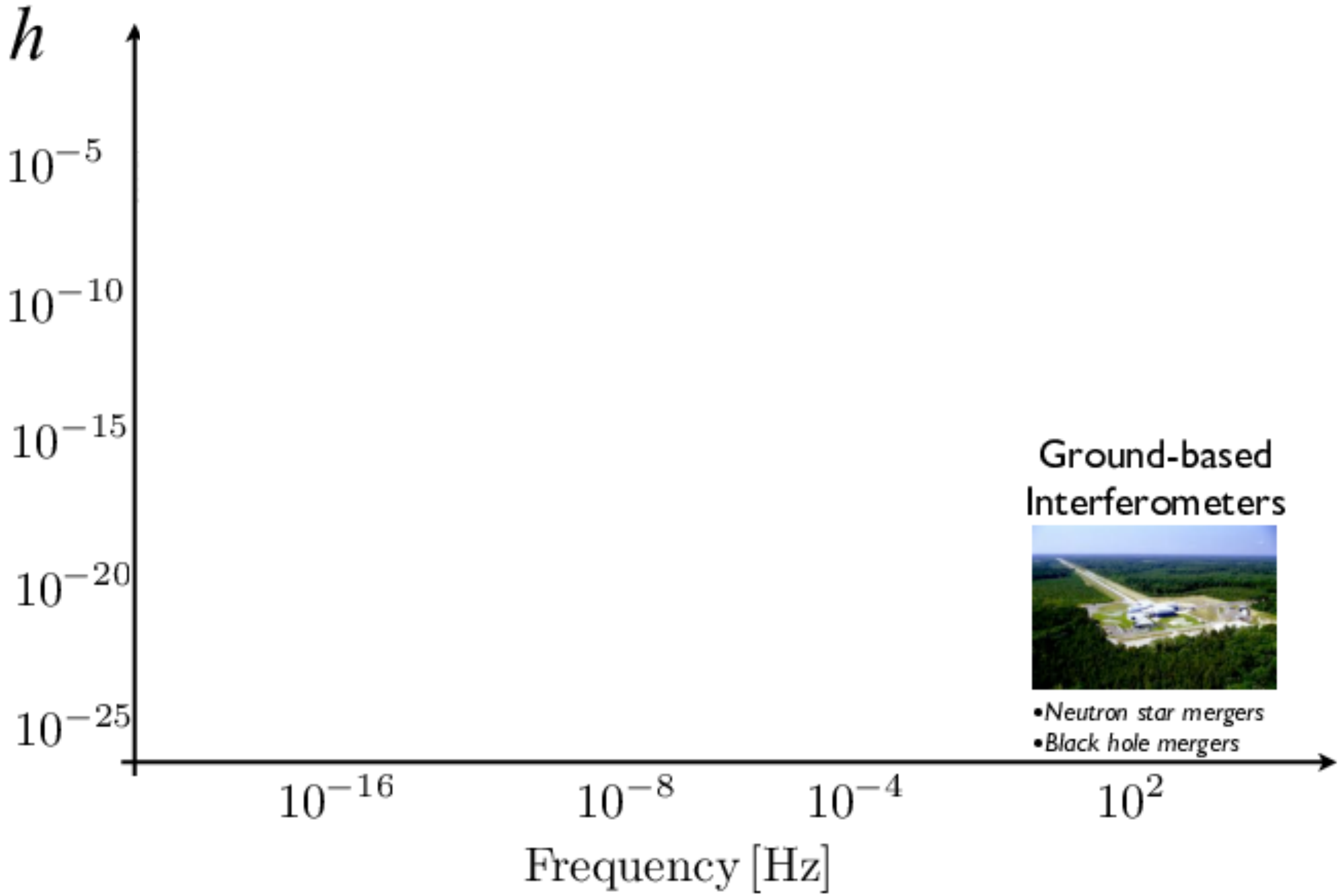
And Now…


LVT151012
GW151226
GW150914
22^h 20^h 18^h 16^h 14^h 12^h 10^h 8^h 6^h 4^h 2^h

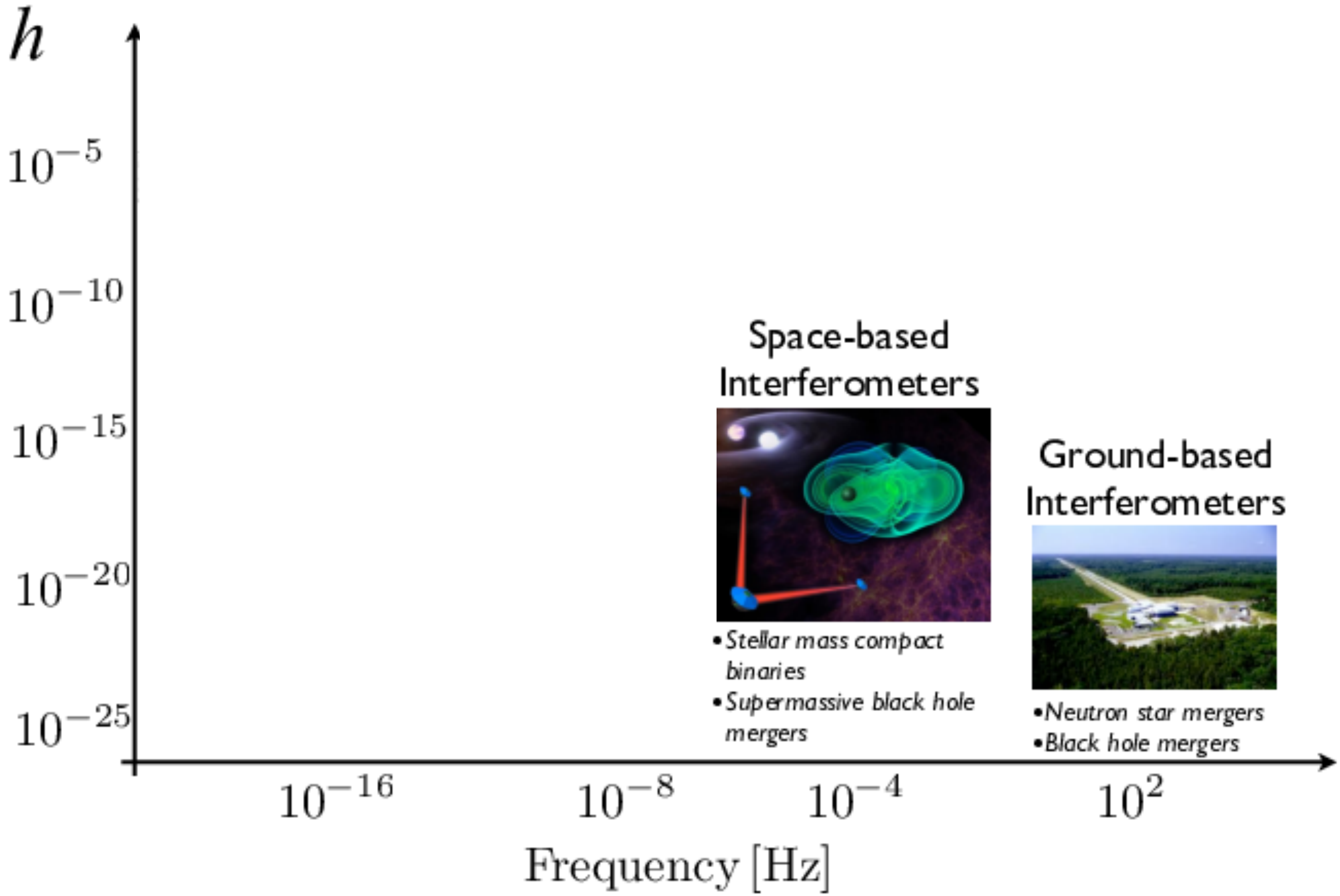

Cen A
Crab Nebula
Credit: NASA/DOE/Fermi/LAT Collaboration


ERM
ETM
4 km
Input
Mode
Cleaner
ITM
CP
T= 3%
PRM
PR2
Laser
ϕm
FI
125 W
5.2 kW
BS
ITM
750 kW
ETM
PR3
SR2
T=1.4%
ERM
T= 20%
SRM
SR3
FI
PD
Output
Mode
Cleaner

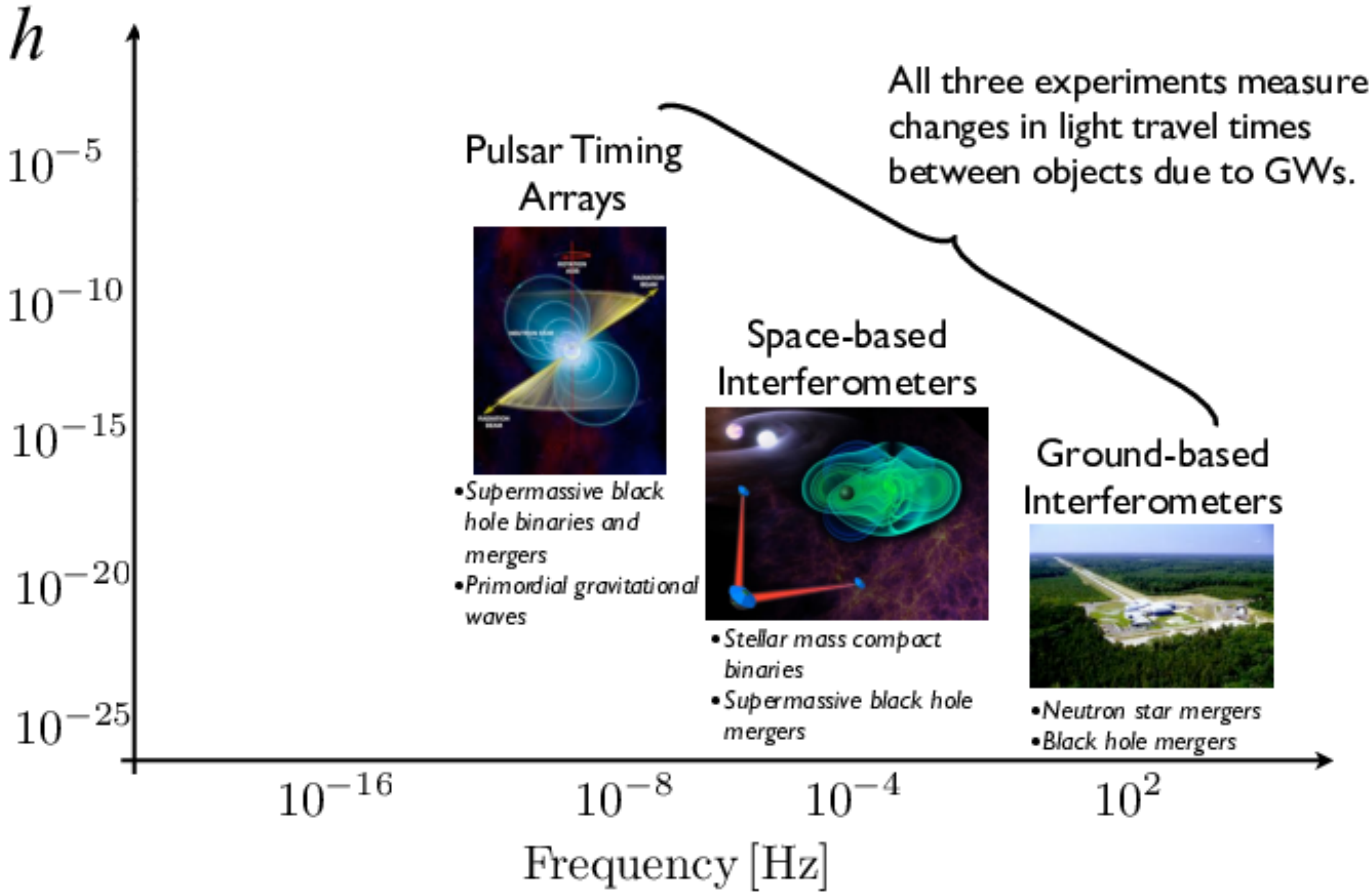
The spectrum of gravitational wave astronomy



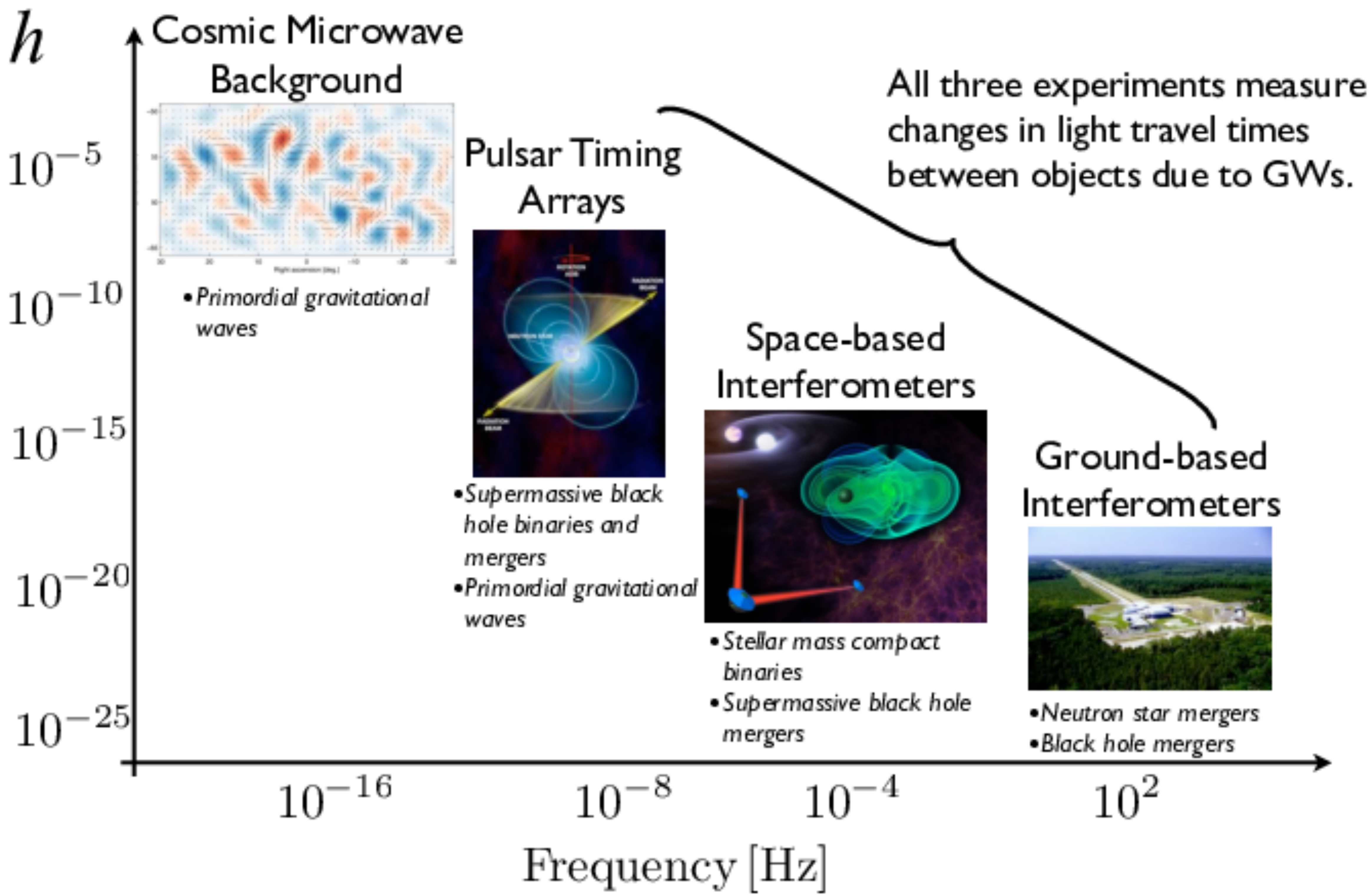
The spectrum of gravitational wave astronomy



The spectrum of gravitational wave astronomy

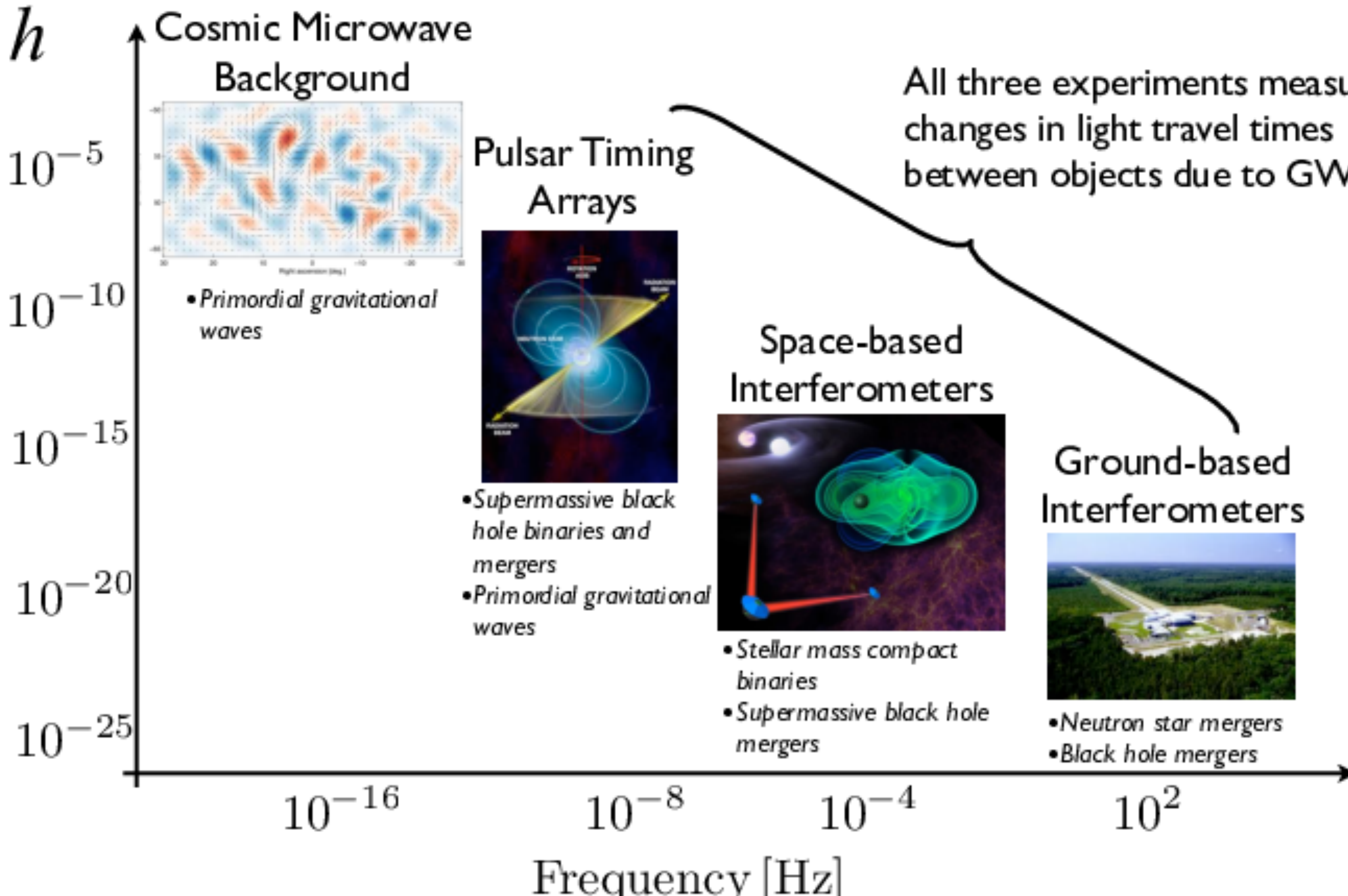


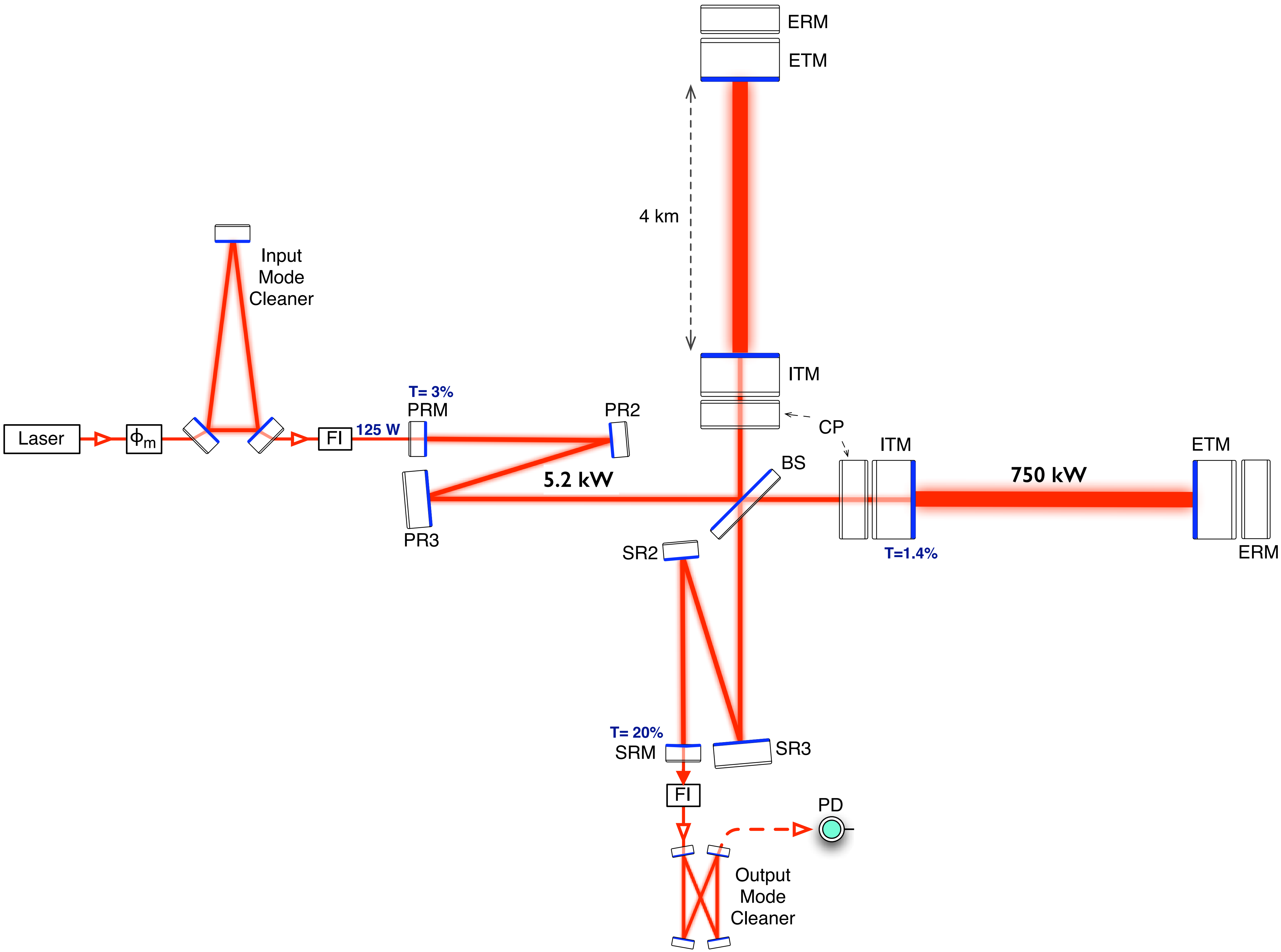
The spectrum of gravitational wave astronomy



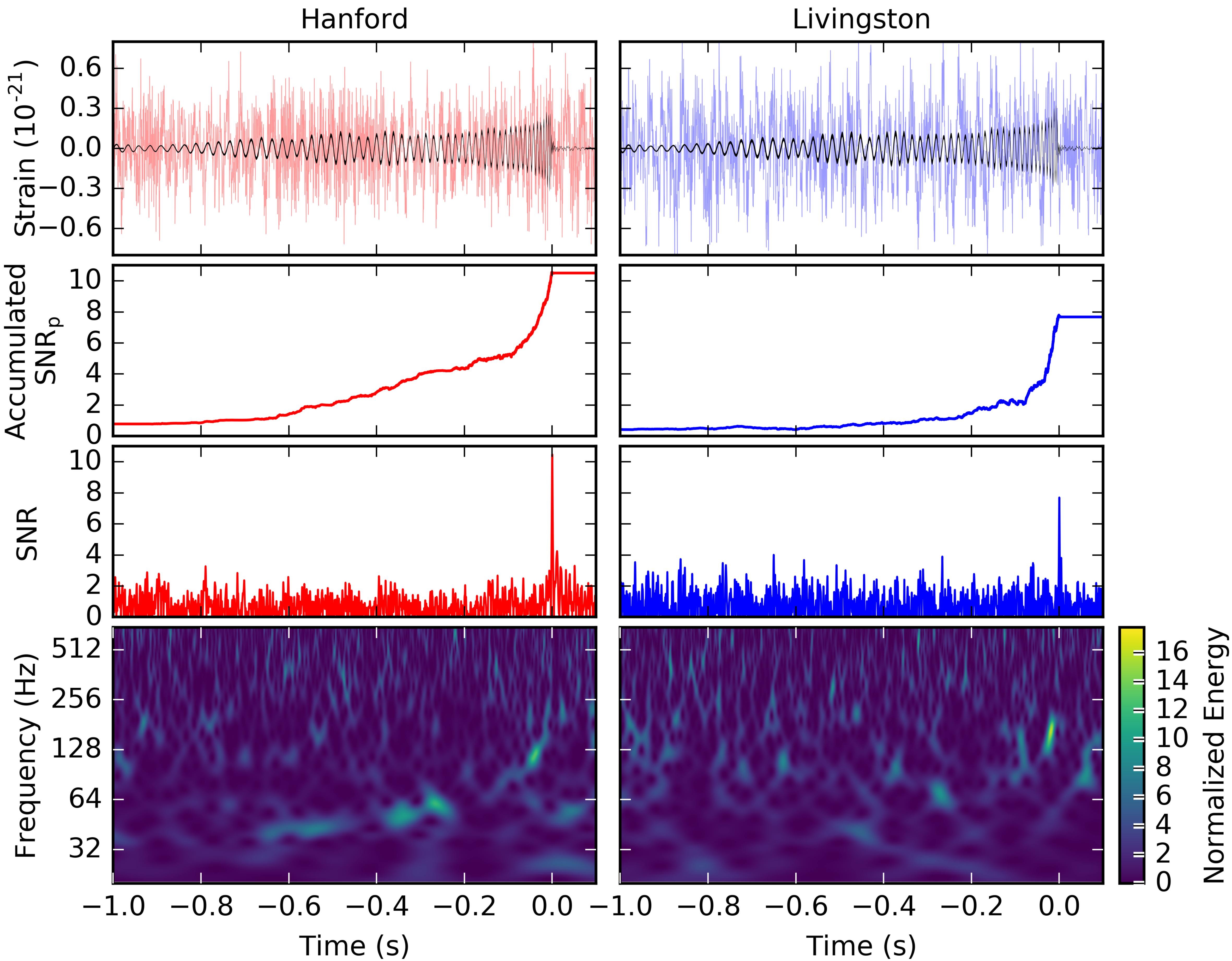
NANOGrav

The spectrum of gravitational wave astronomy



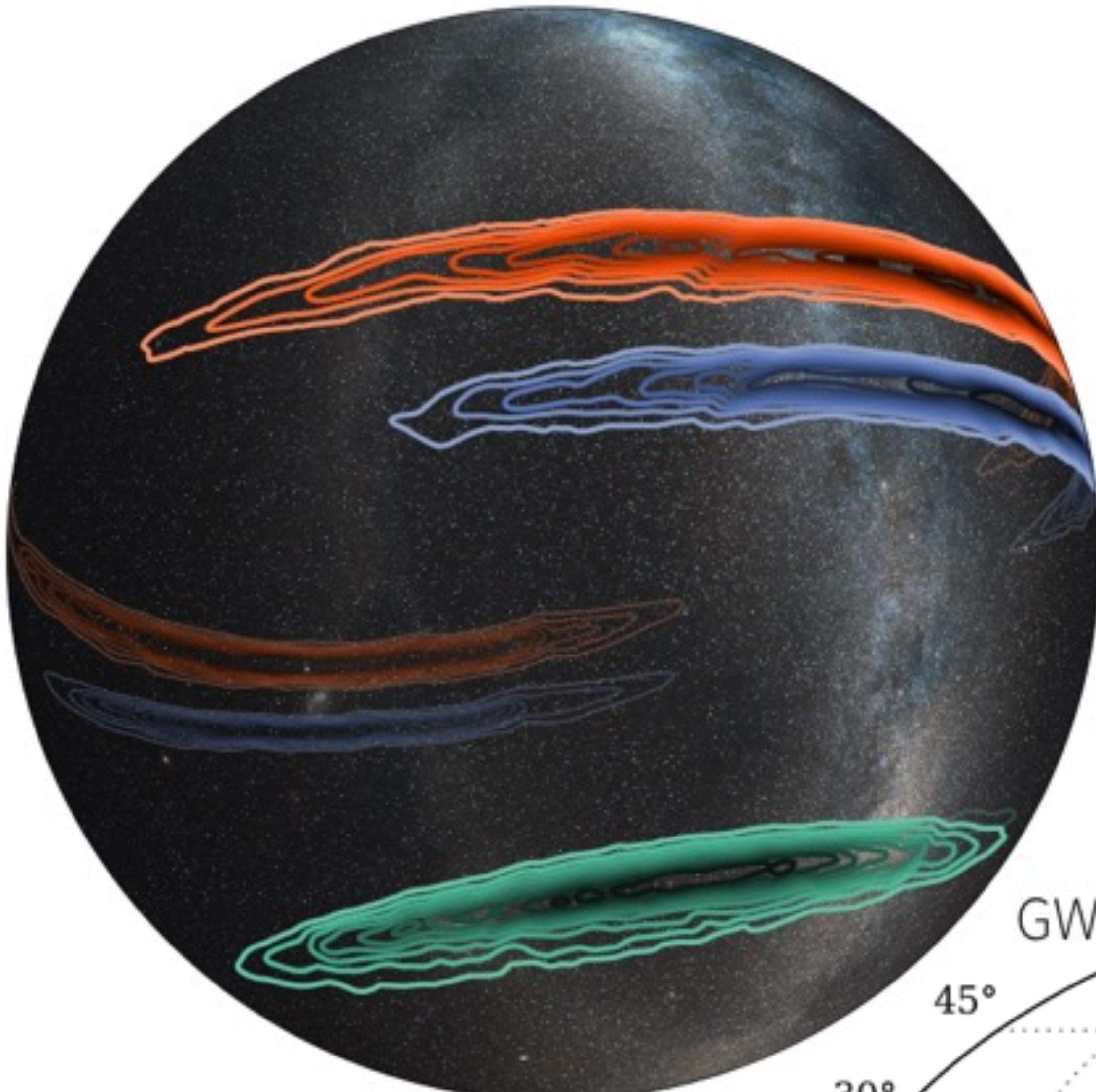

ERM
ETM
4 km
ITM
CP
Input
Mode
Cleaner
T= 3%
PRM
PR2
Laser
ϕ_m
FI
125 W
5.2 kW
BS
ITM
ETM
750 kW
PR3
SR2
T=1.4%
ERM
T= 20%
SRM
SR3
FI
PD
Output
Mode
Cleaner

Time series GW151226

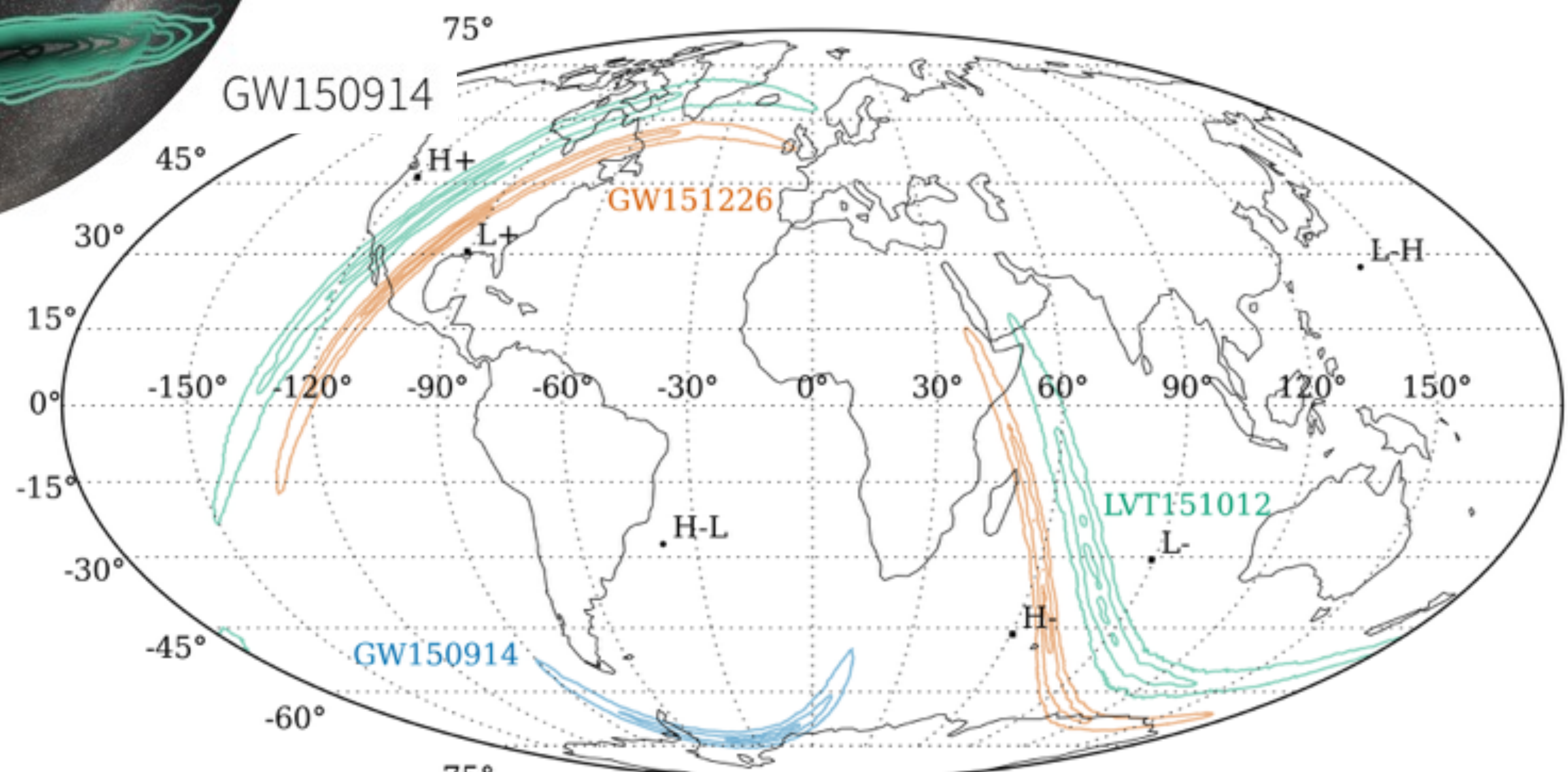


http://link.aps.org/doi/10.1103/PhysRevLett.116.241103

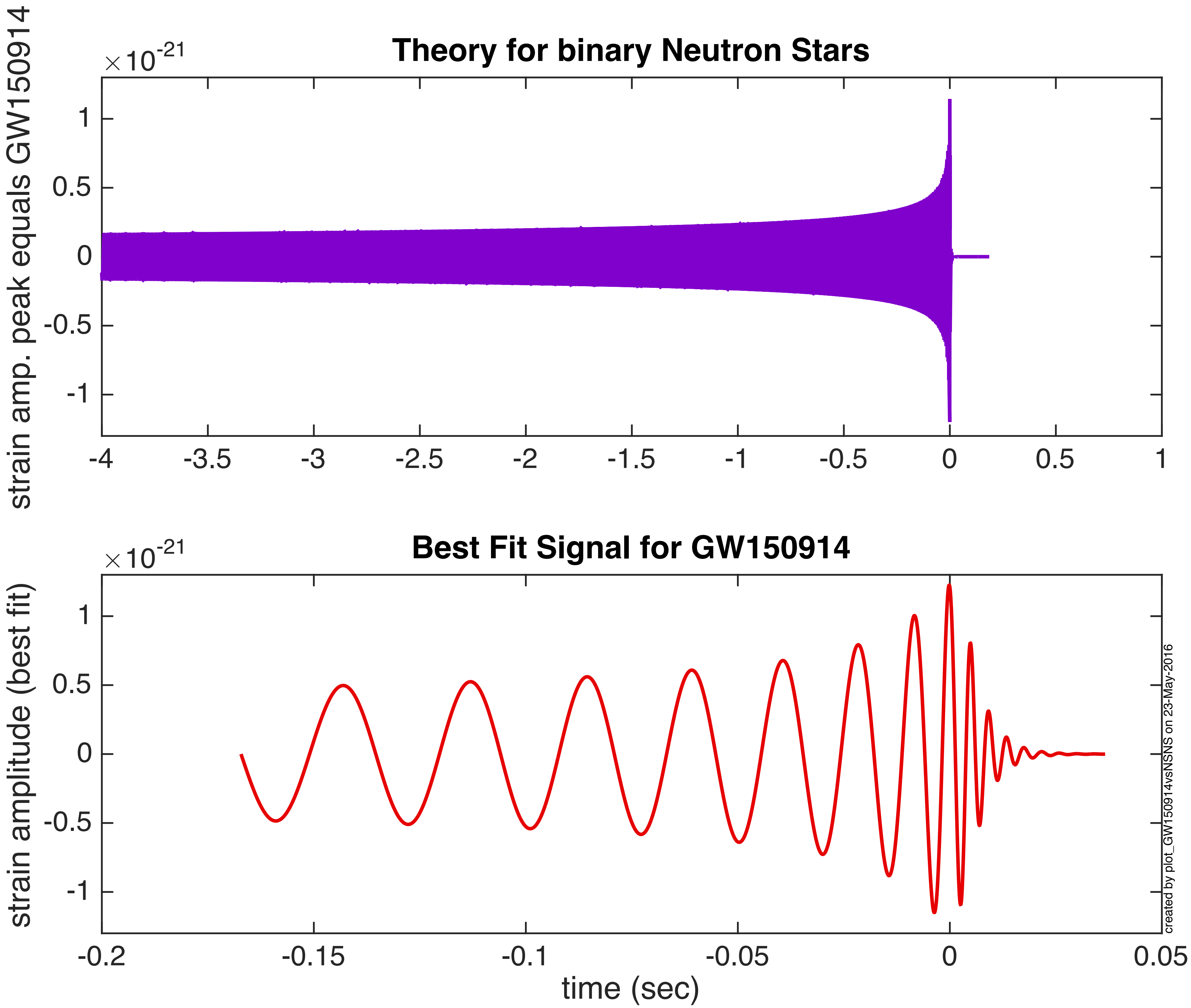
Where did that signal come from?

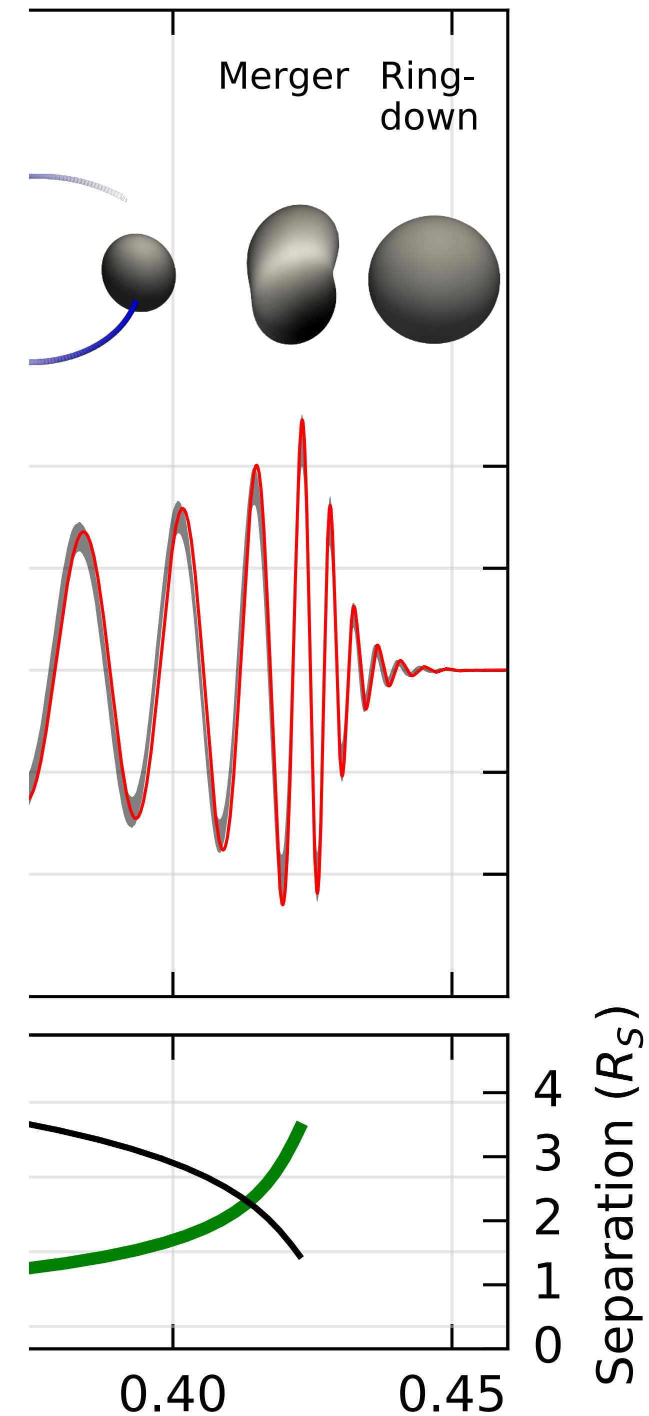


It's hard to say…



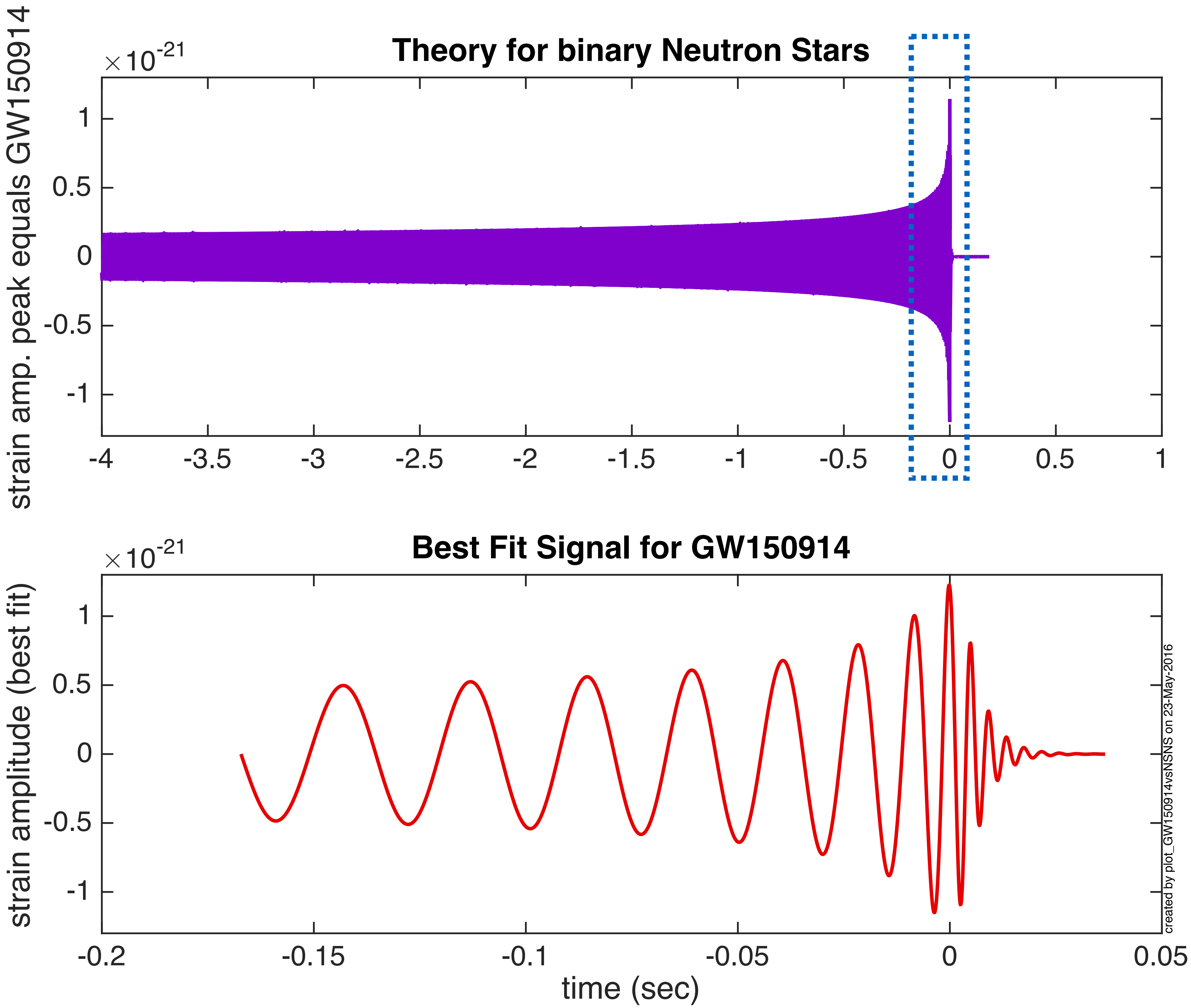
Best fit with Numerical Relativity

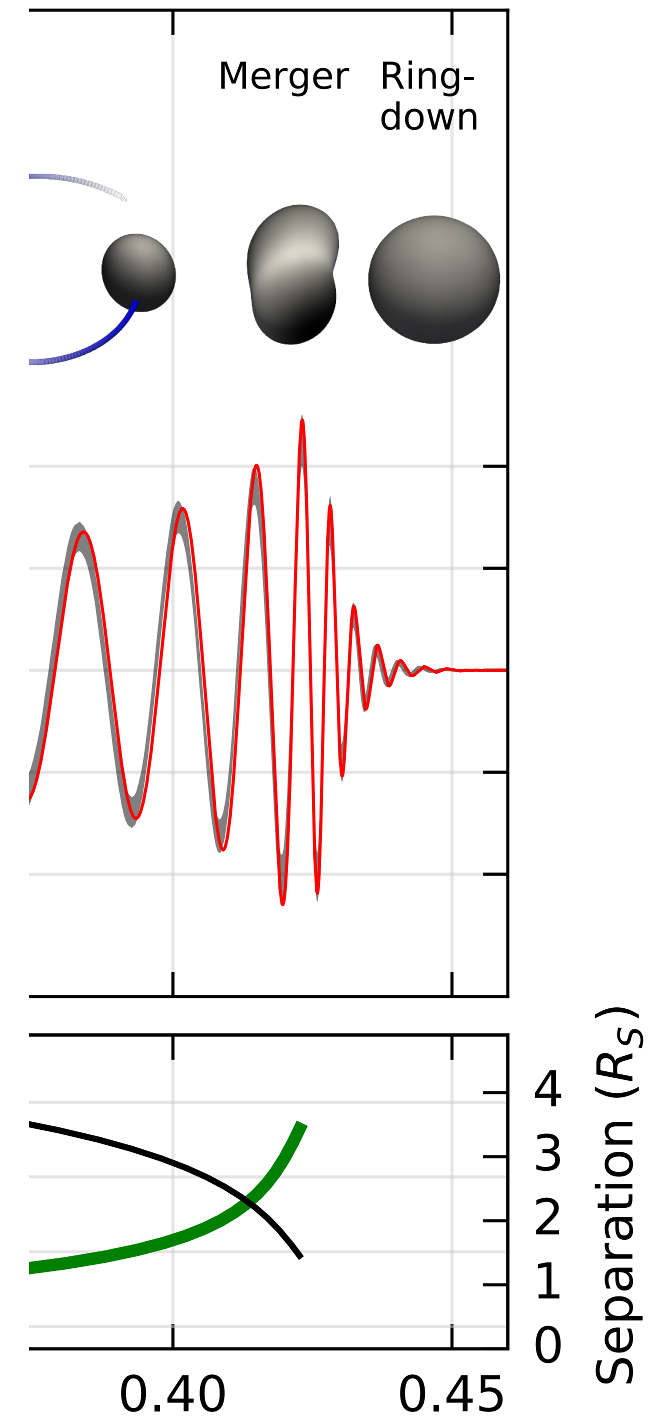




NS/NS waveform from http://web.mit.edu/sahughes/www/sounds.html

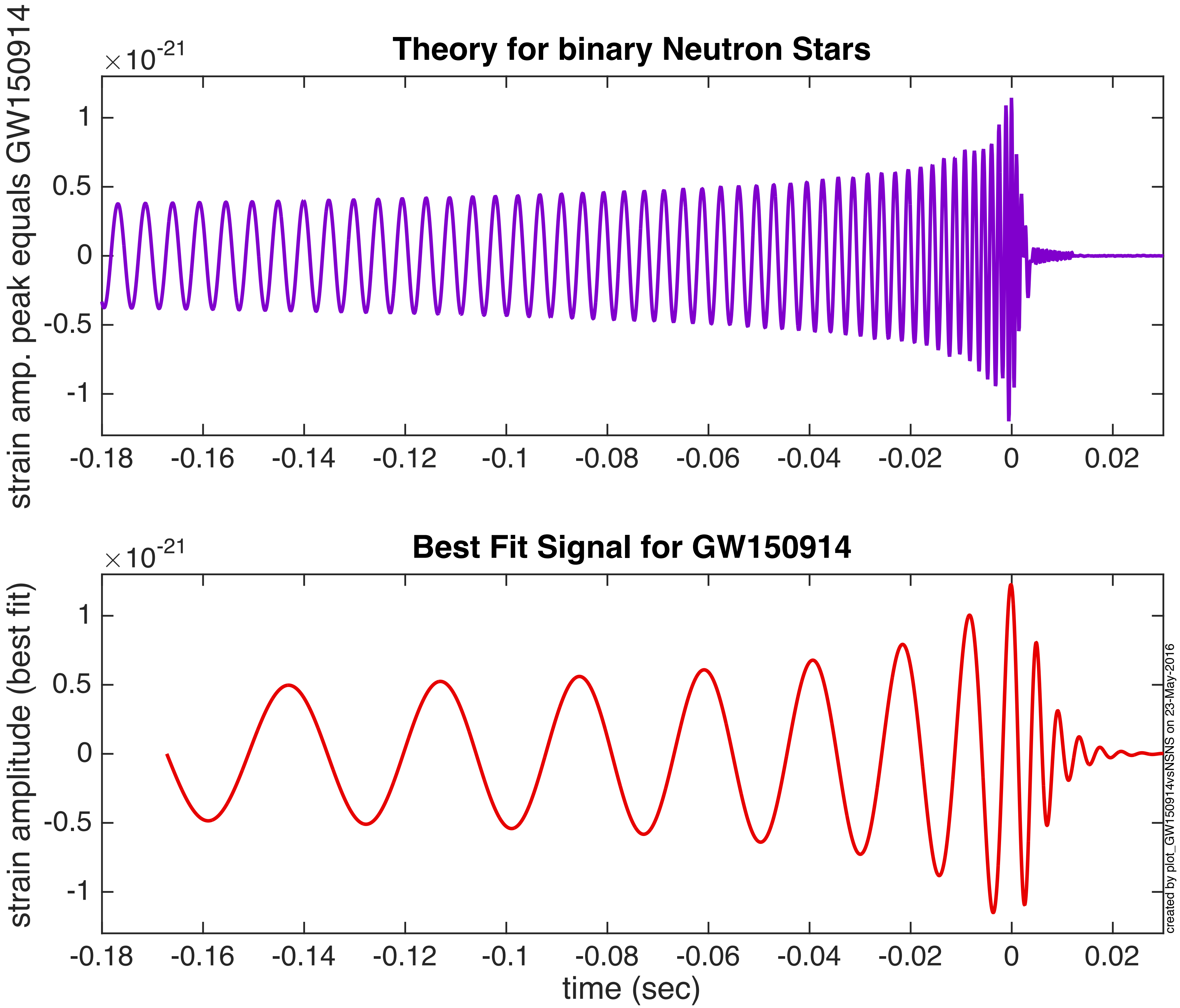
Best fit with Numerical Relativity

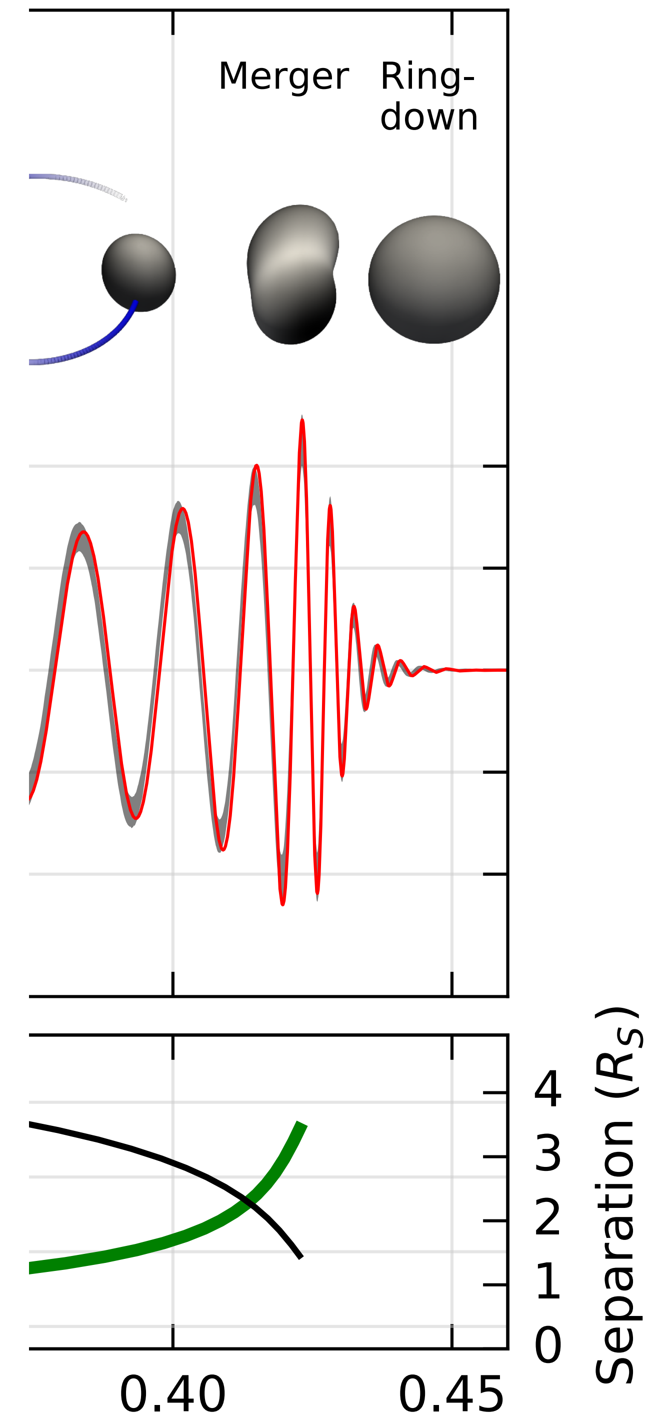




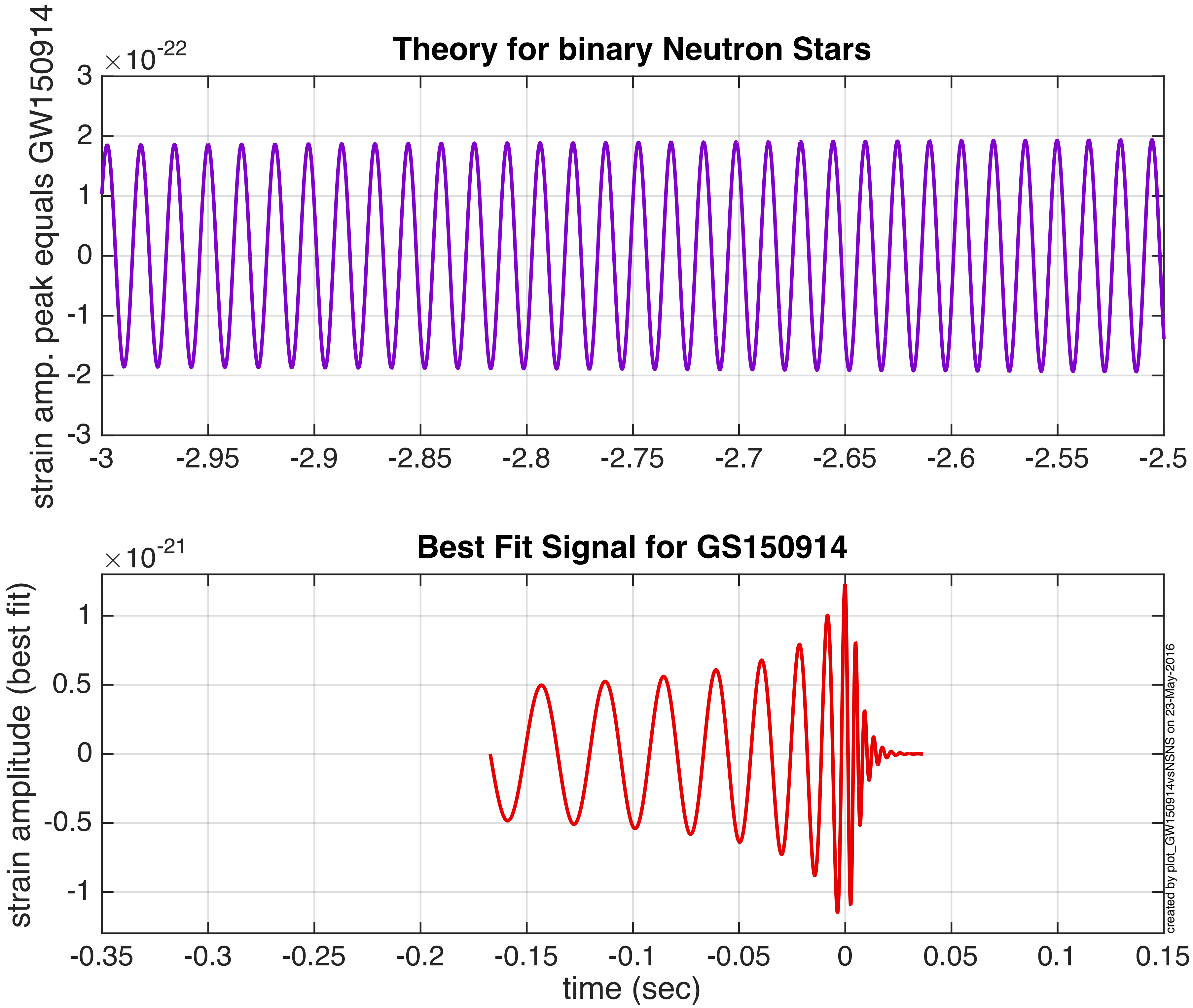
NS/NS waveform from http://web.mit.edu/sahughes/www/sounds.html

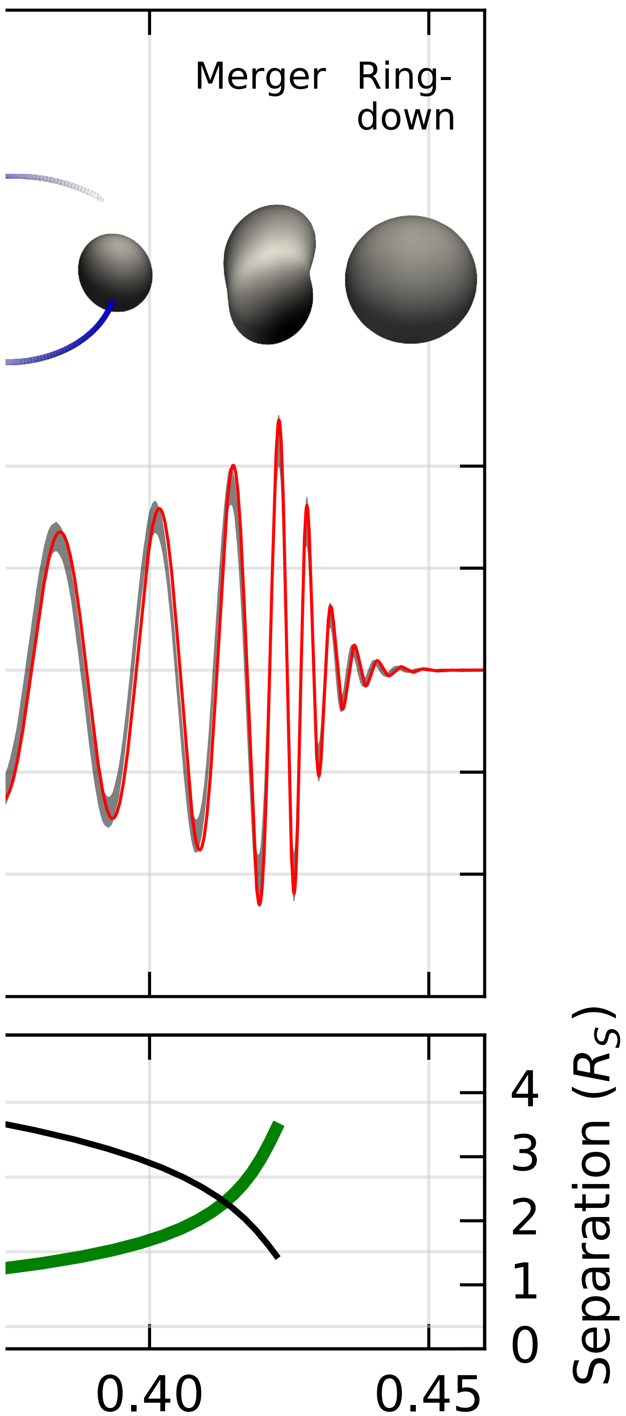
Best fit with Numerical Relativity





Best fit with Numerical Relativity





Best fit with Numerical Relativity

Initial Masses:

29 (+4/-4) & 36 (+5/-4) M_{sun}

Final Mass:

62 (+4/-4) M_{sun}

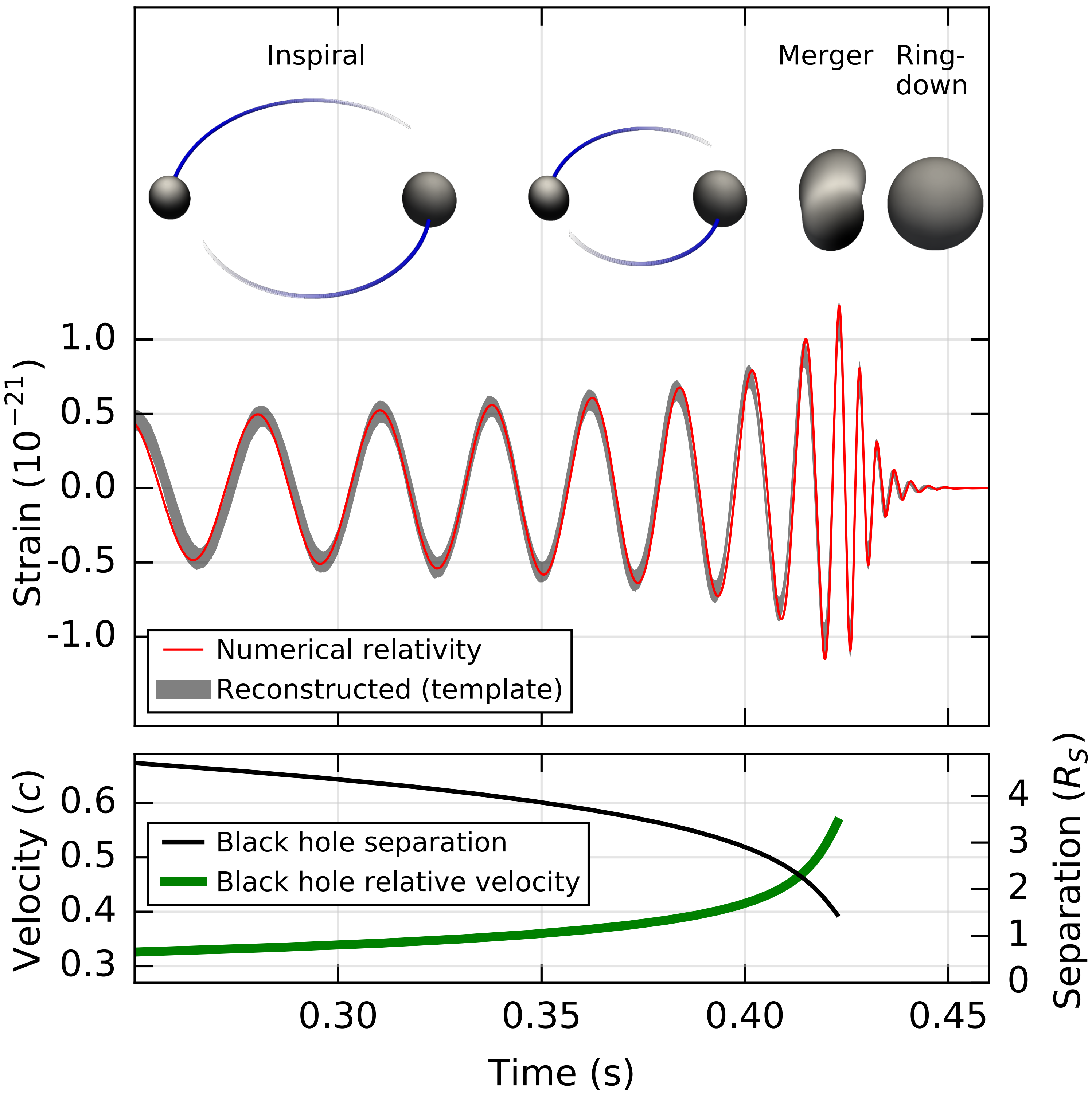
Distance

1.3 Billion light years

(410 (+160/-180) MPc)

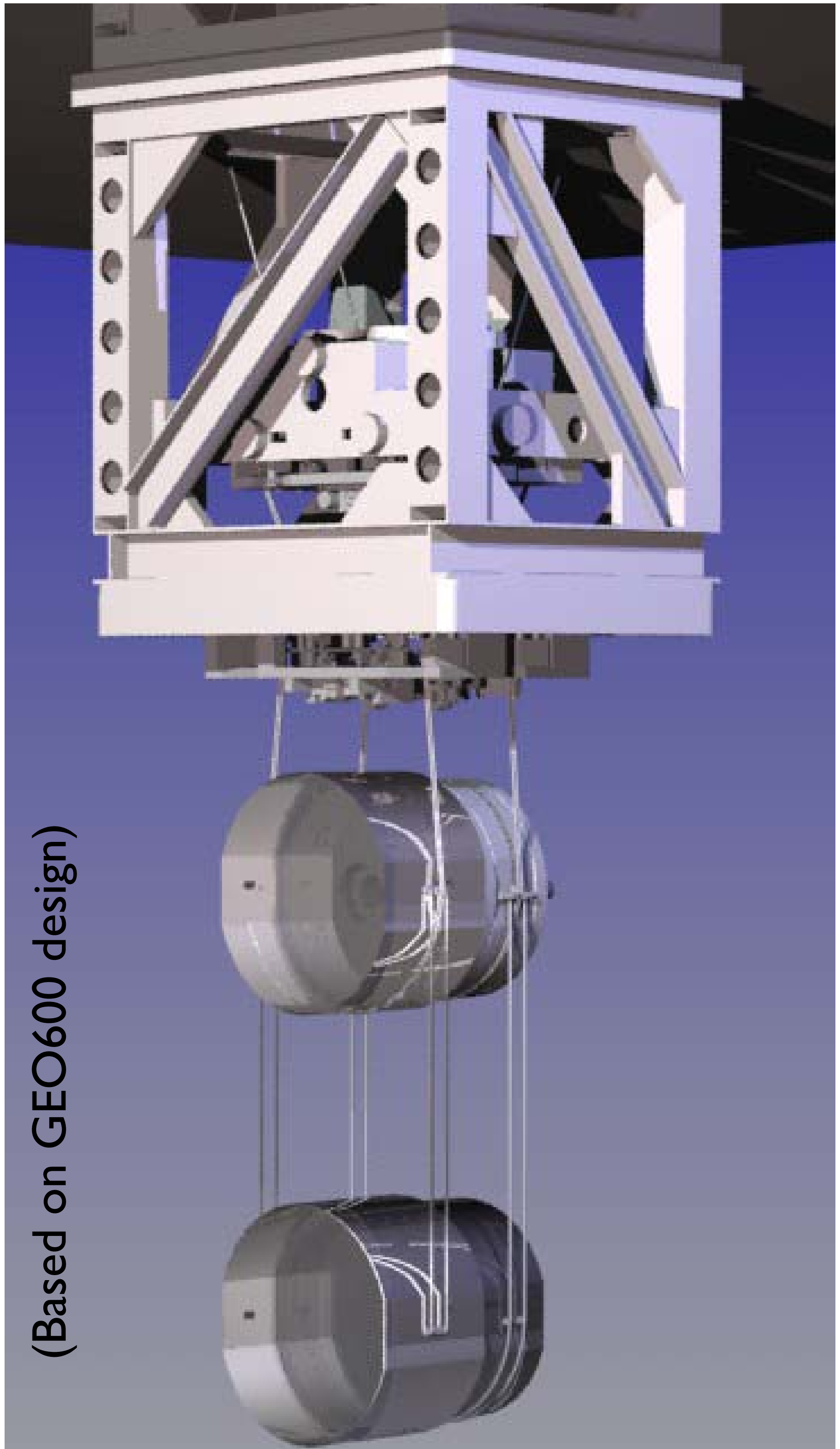
Energy radiated

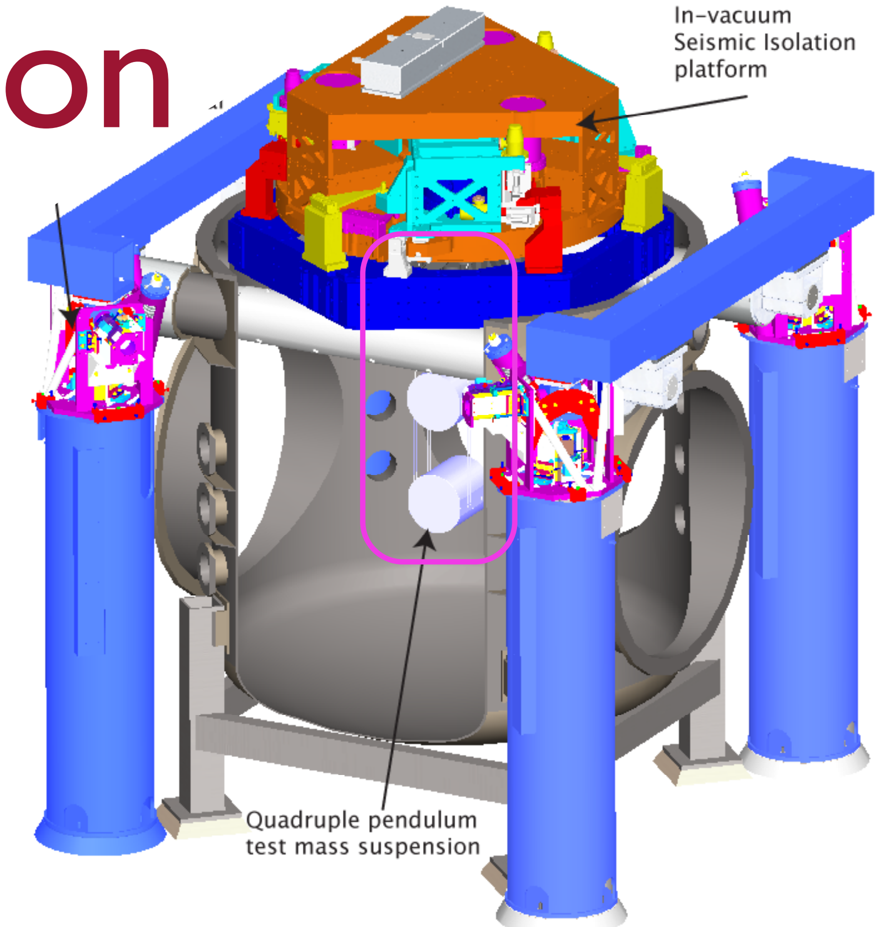
3 (+0.5/-0.5) M_{sun} c^2



http://dx.doi.org/10.1103/PhysRevLett.116.061102

Pendulum Suspension





LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

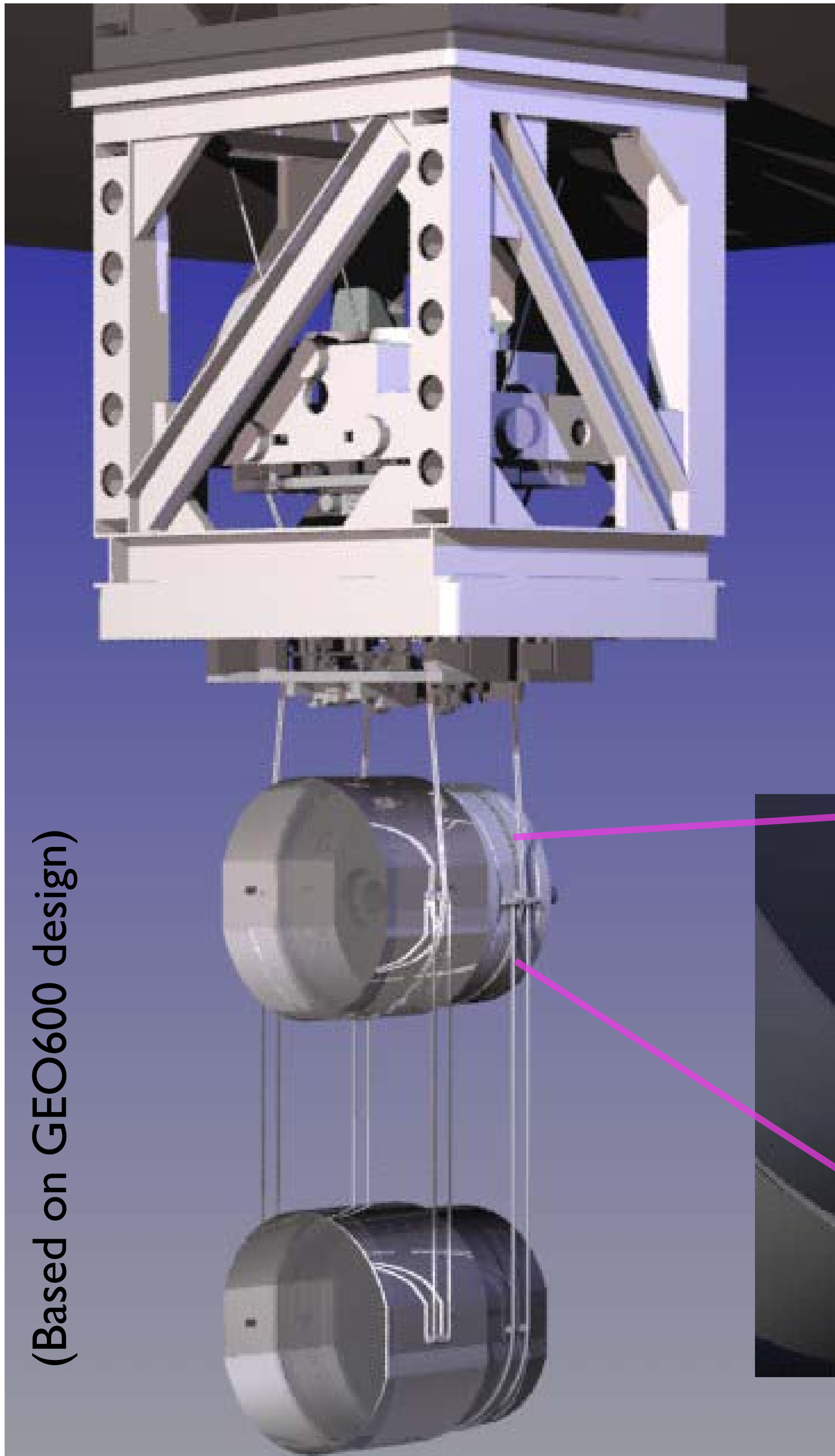
Suspended as a
4 stage pendulum

Best coatings available

Motion at 10 Hz set by
thermal driven vibration

silicate bonding creates a monolithic final stage

Pendulum Suspension



LIGO Mirrors:
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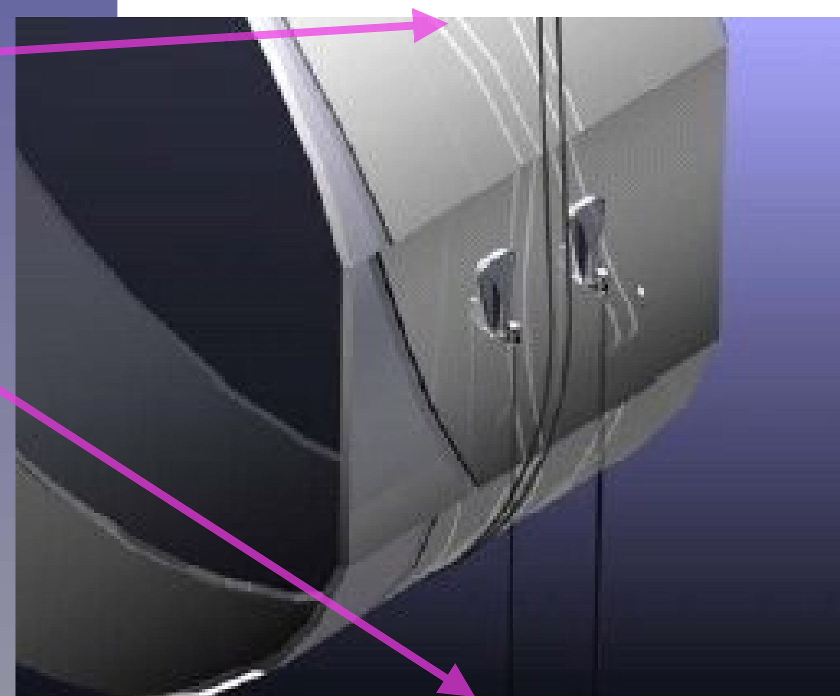
40 kg mass
34 cm diameter
20 cm thick

Suspended as a
4 stage pendulum

Best coatings available



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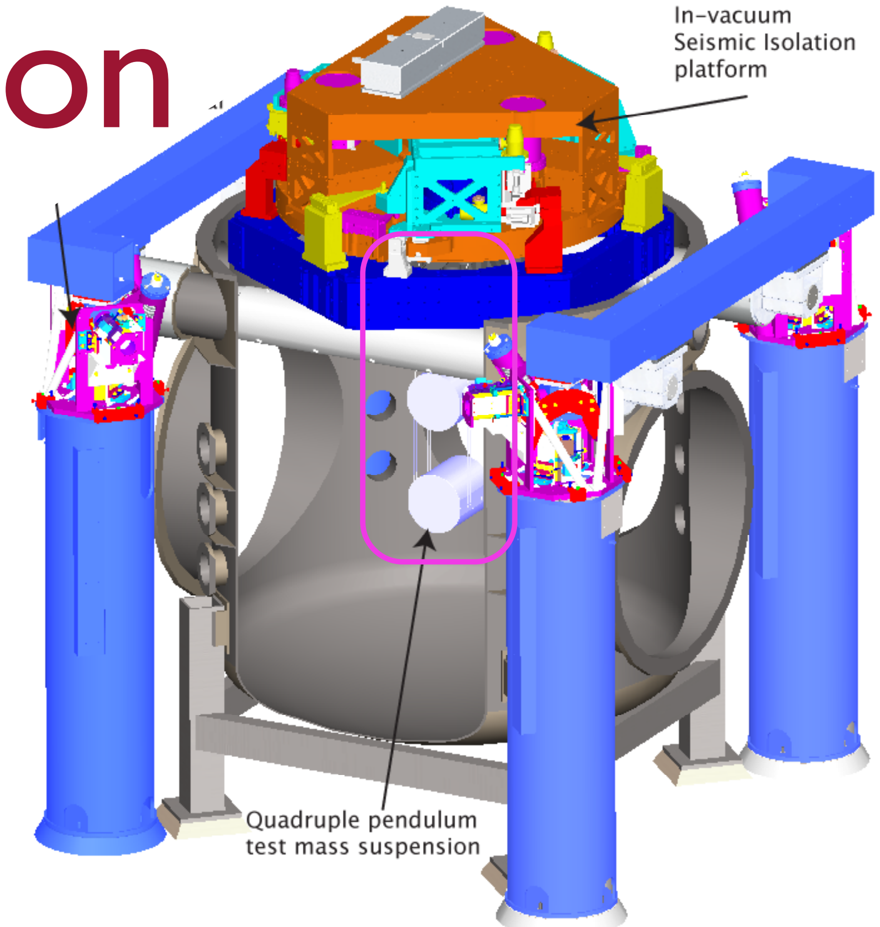
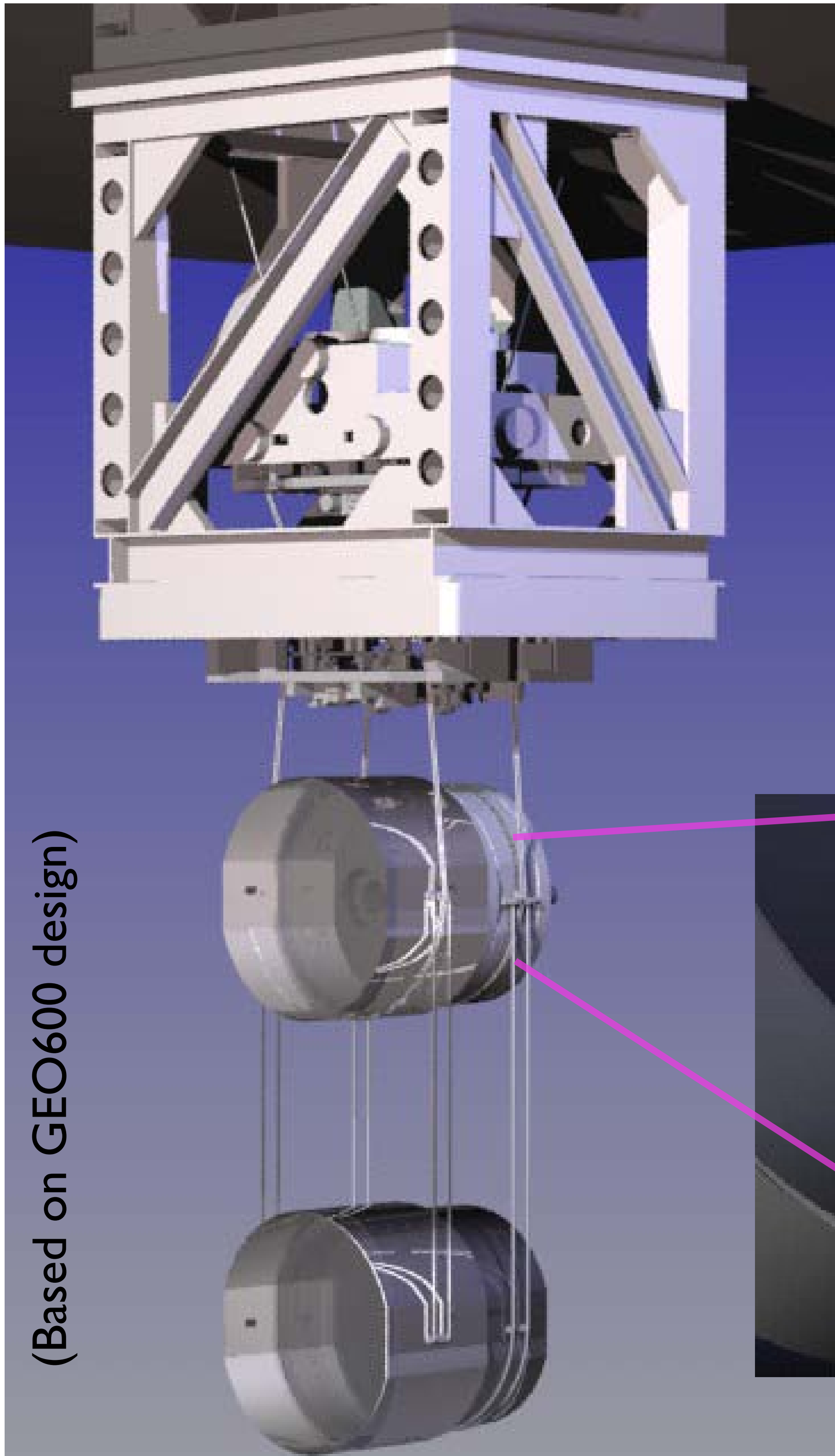


silicate bonding creates a monolithic final stage

Pendulum Suspension



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Suspended as a
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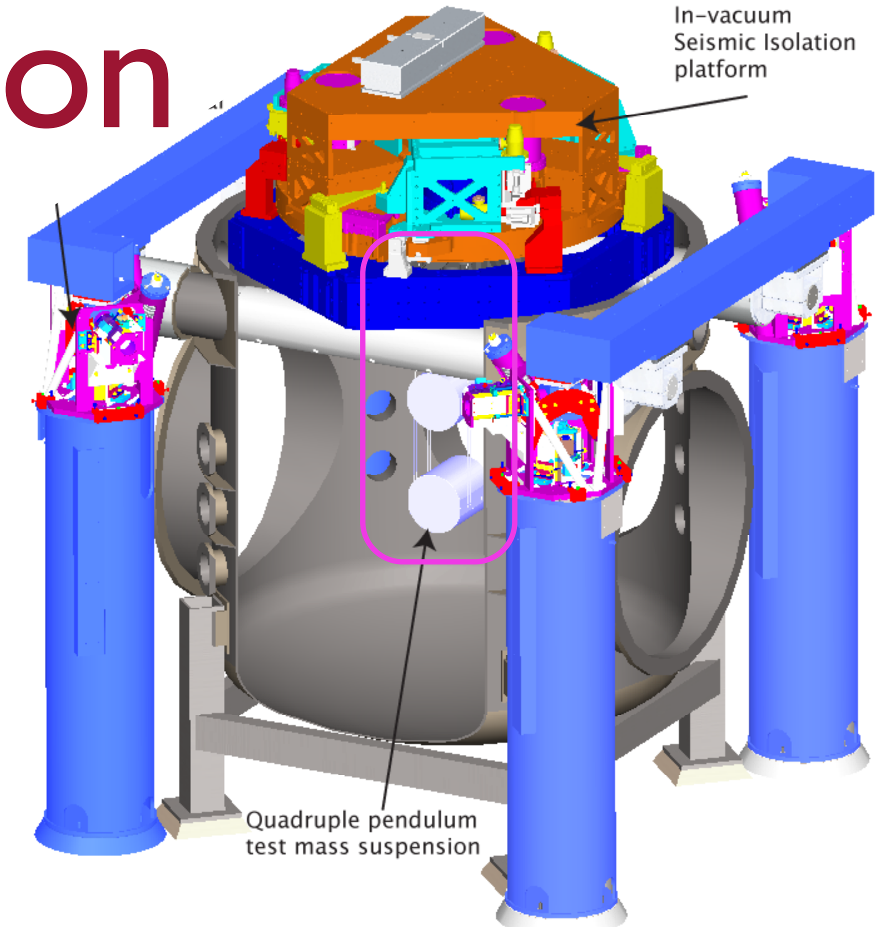
Best coatings available



silicate bonding creates a monolithic final stage

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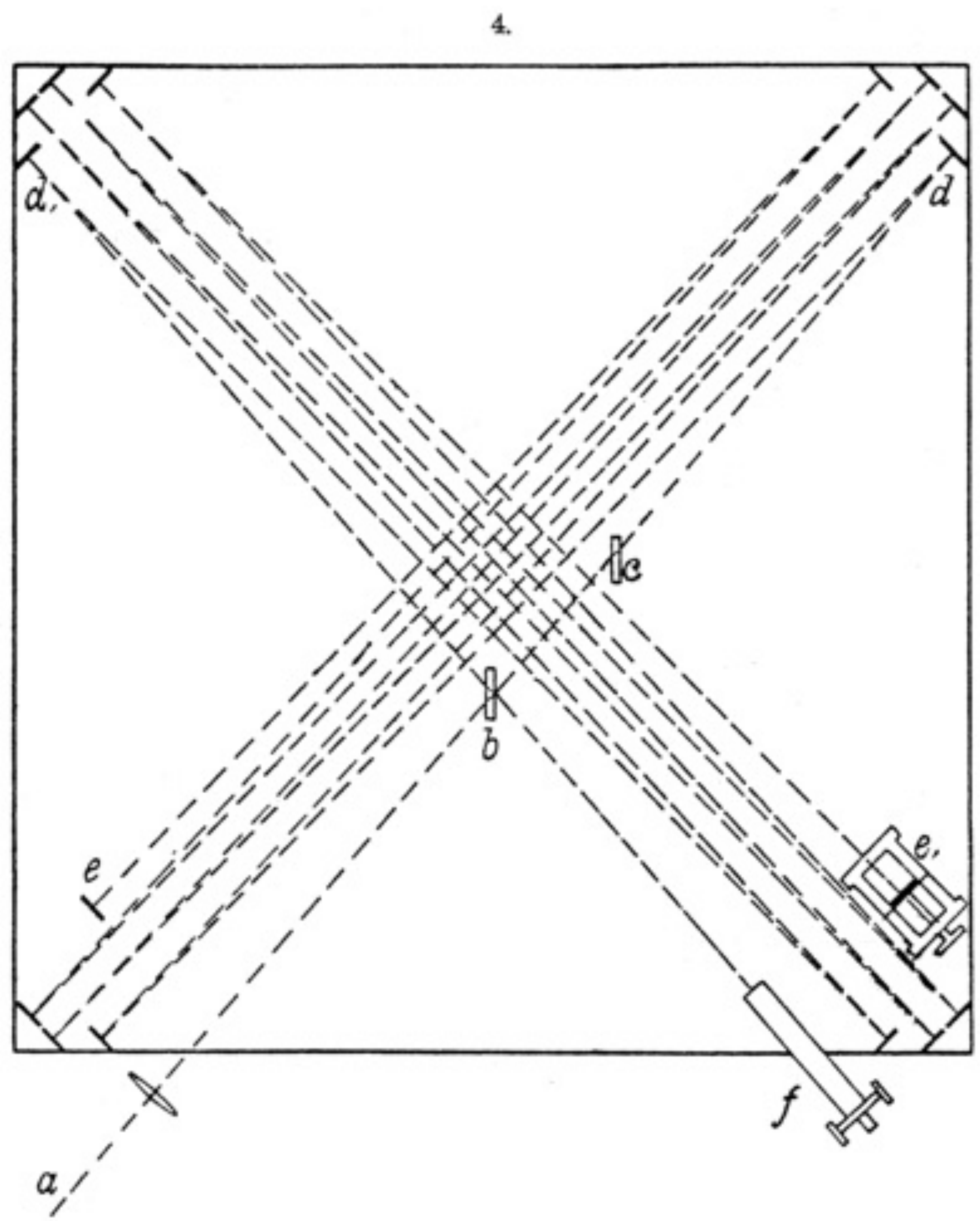
Mittleman,[10] A. Moggi,[19] M. Mohan,[34] S. R. P. Mohapatra,[10] M. Montani,[57,58] B. C. Moore,[88] C. J. Moore,[122] D. Moraru,[37] G. Moreno,[37] S. R. Morriss,[83] K. Mossavi,[8] B. Mours,[7] C. M. Mow-Lowry,[45] C. L. Mueller,[5] G. Mueller,[5] A. W. Muir,[91] Arunava Mukherjee,[15] D. Mukherjee,[16] S. Mukherjee,[83] N. Mukund,[14] A. Mullavey,[6] J. Munch,[104] D. J. Murphy,[39] P. G. Murray,[36] A. Mytidis,[5] I. Nardecchia,[25,13] L. Naticchioni,[79,28] R. K. Nayak,[123] V. Necula,[5] K. Nedkova,[103] G. Nelemans,[52,9] M. Neri,[46,47] A. Neunzert,[98] G. Newton,[36] T. T. Nguyen,[20] A. B. Nielsen,[8] S. Nissanke,[52,9] A. Nitz,[8] F. Nocera,[34] D. Nolting,[6] M. E. N. Normandin,[83] L. K. Nuttall,[35] J. Oberling,[37] E. Ochsner,[16] J. O'Dell,[100] E. Oelker,[10] G. H. Ogin,[124] J. J. Oh,[125] S. H. Oh,[125] F. Ohme,[91] M. Oliver,[66] P. Oppermann,[8] Richard J. Oram,[6] B. O'Reilly,[6] R. O'Shaughnessy,[102] C. D. Ott,[76] D. J. Ottaway,[104] R. S. Ottens,[5] H. Overmier,[6] B. J. Owen,[71] A. Pai,[108] S. A. Pai,[48] J. R. Palamos,[59] O. Palashov,[109] C. Palomba,[28] A. Pal-Singh,[27] H. Pan,[73] Y. Pan,[62] C. Pankow,[82] F. Pannarale,[91] B. C. Pant,[48] F. Paoletti,[34,19] A. Paoli,[34] M. A. Papa,[29,16,8] H. R. Paris,[40] W. Parker,[6] D. Pascucci,[36] A. Pasqualetti,[34] R. Passaquieti,[18,19] D. Passuello,[19] B. Patricelli,[18,19] Z. Patrick,[40] B. L. Pearlstone,[36] M. Pedraza,[1] R. Pedurand,[65] L. Pekowsky,[35] A. Pele,[6] S. Penn,[126] A. Perreca,[1] H. P. Pfeiffer,[69,29] M. Phelps,[36] O. Piccinni,[79,28] M. Pichot,[53] M. Pickenpack,[8] F. Piergiovanni,[57,58]

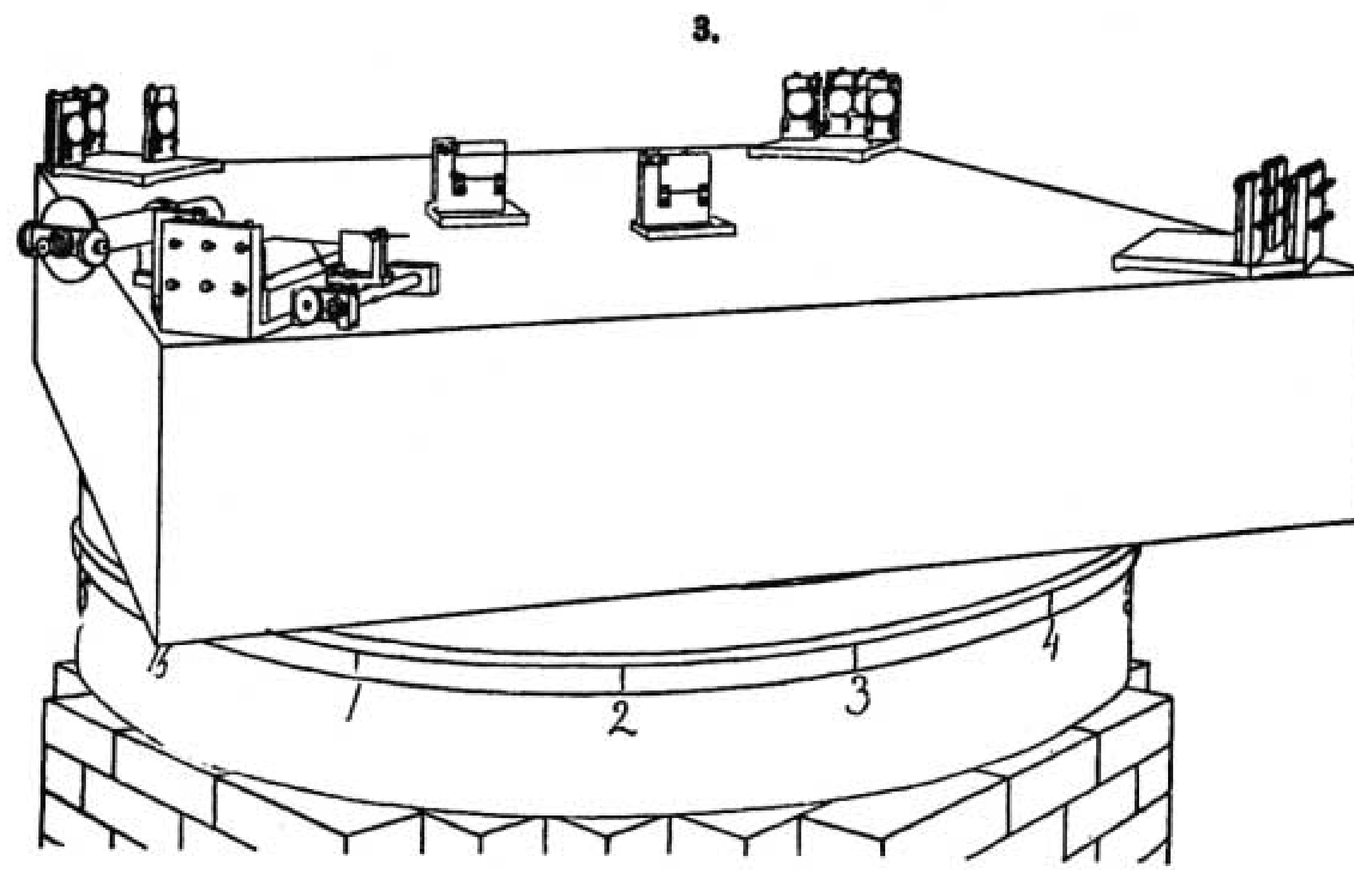
Michelson's Interferometer!

1887 experiment to measure "luminiferous ether" with an interferometer



Michelson's Interferometer!

1887 experiment to measure "luminiferous ether" with an interferometer



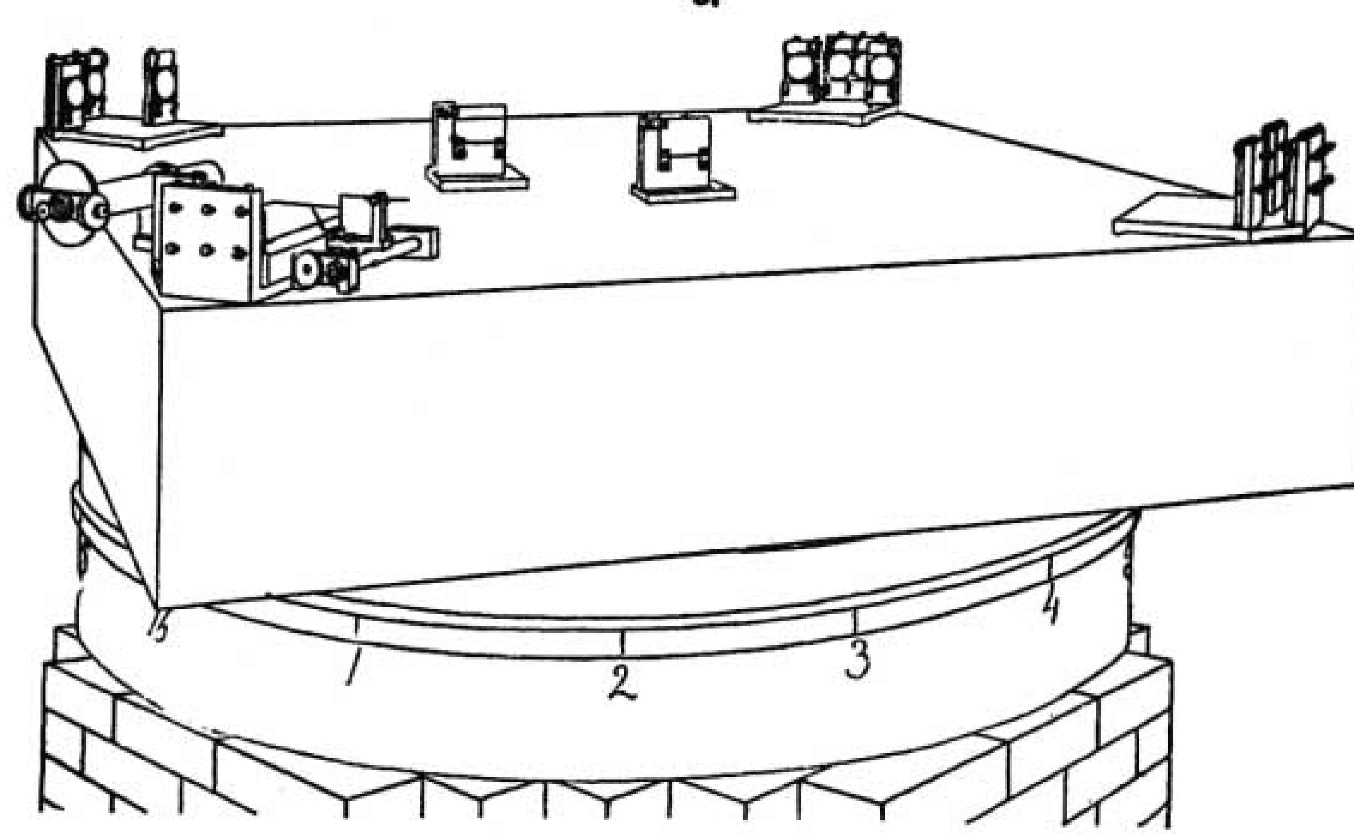
Am. Jour. Sci. - Third Series, Vol. 34, No. 203, Nov. 1887. pg 333-345

Michelson's Interferometer!

1887 experiment to measure "luminiferous ether" with an interferometer

In the first experiment one of the principal difficulties encountered was that of revolving the apparatus without producing distortion; and another was its extreme sensitiveness to vibration. This was so great that it was impossible to see the interference fringes except at brief intervals when working in the city, even at two o'clock in the morning.

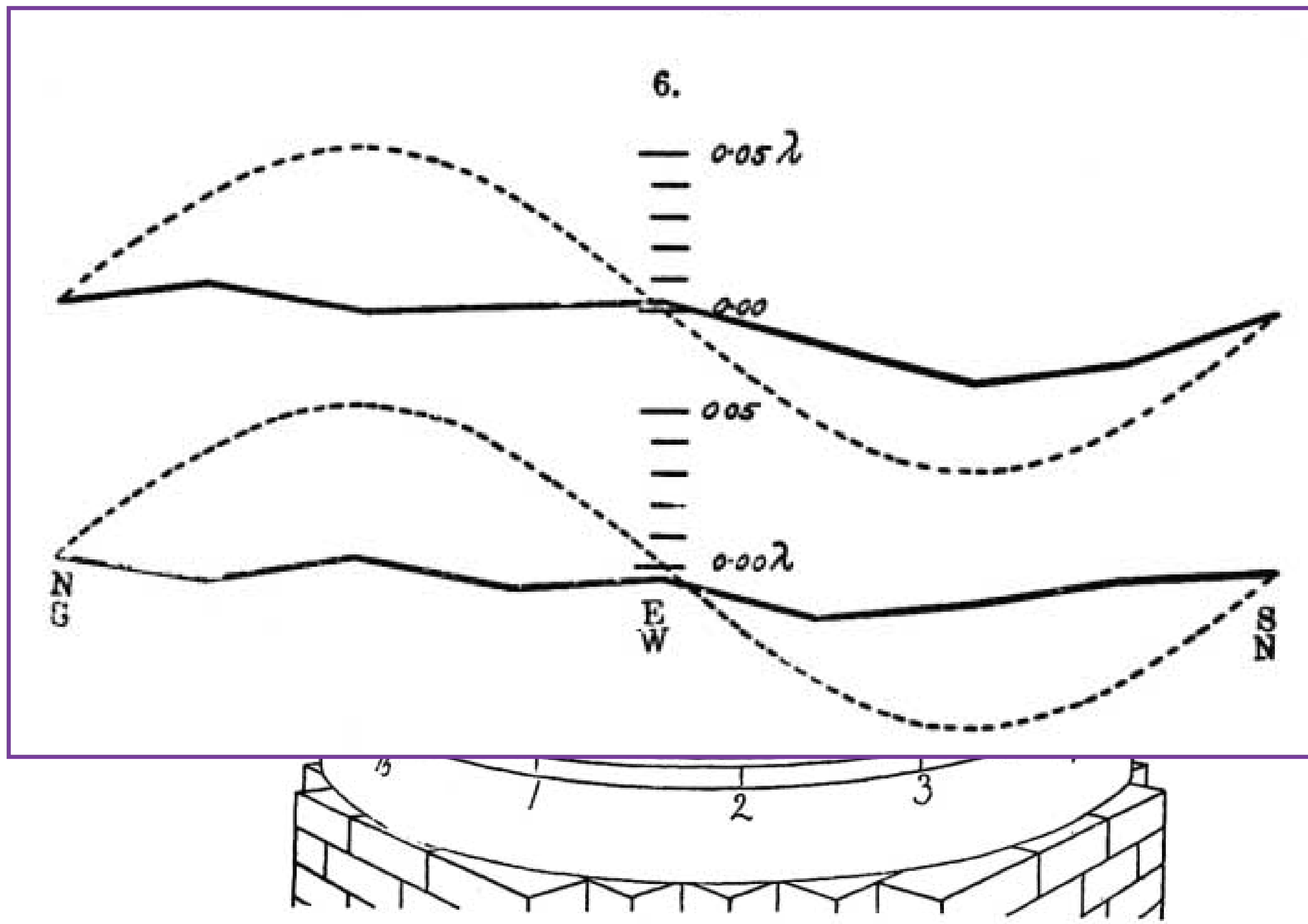
3.



Am. Jour. Sci. - Third Series, Vol. 34, No. 203, Nov. 1887. pg 333-345

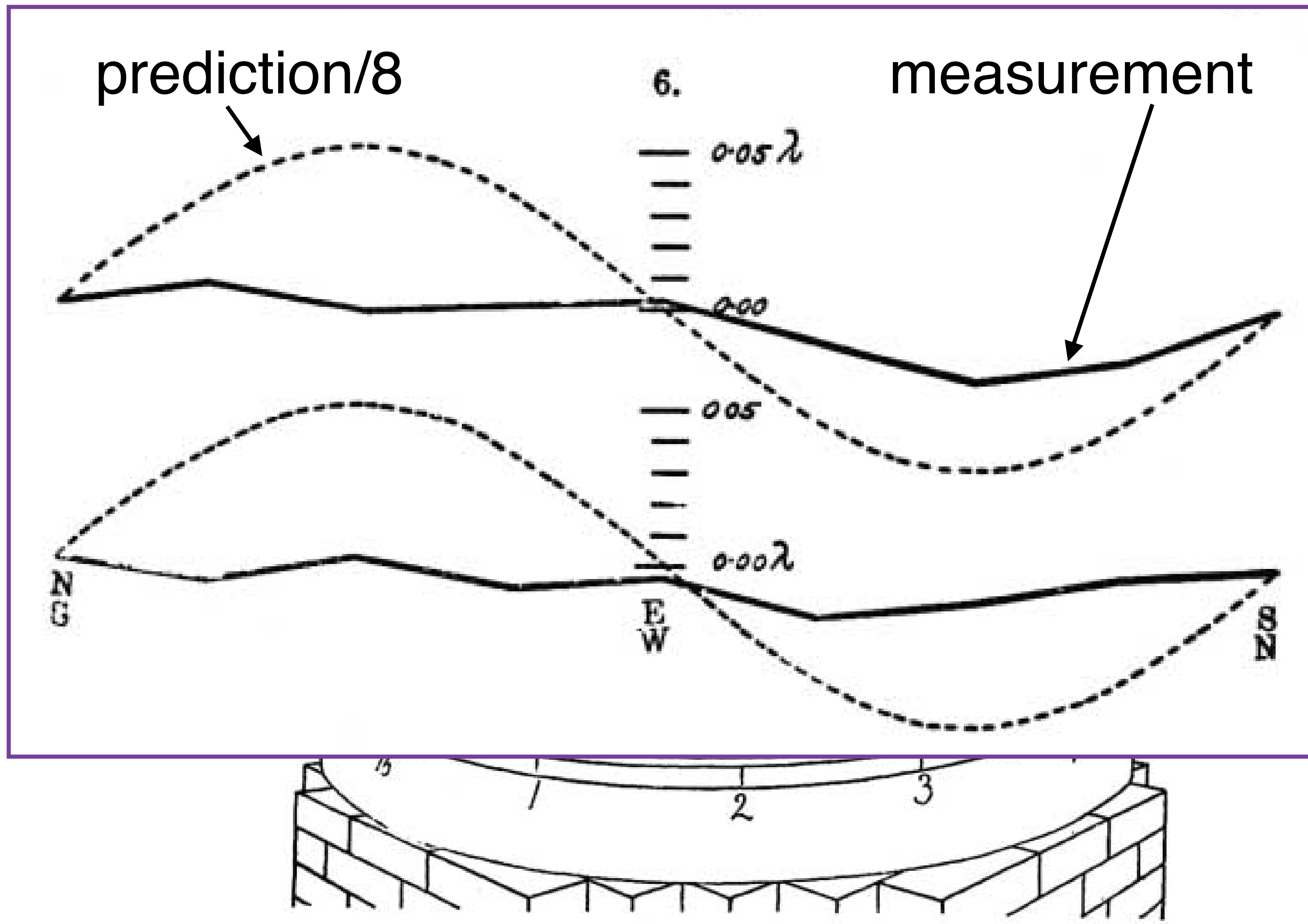
Michelson's Interferometer!

1887 experiment to measure "luminiferous ether" with an interferometer



Michelson's Interferometer!

1887 experiment to measure
"luminiferous ether" with an interferometer



Am. Jour. Sci. - Third Series, Vol. 34, No. 203, Nov. 1887. pg 333-345

story outline:
prep the detector -
it goes boop
look at time trace of signal -
discuss params, firsts
character of BBH vs BNS
move to astronomy
show time line
discuss second event,
show time, match filters
describe O2/ O3
other

notes:

>> r1 = 2 * G * Ms /c^2

r1 = 2.9644e+03 (3 km)

>> r30 = 2 * G * 30 * Ms /c^2

r30 = 8.8933e+04 (89 km): 2*r30 = 188 km

(SF center, santa rosa to hollister)

r70 = 2 * G * 70 * Ms /c^2

r70 = 2.0751e+05

monterey to fresno ~ 180 km

1.5 * r65 = 290 km

SF to Reno = 295 km

monterey to lake tahoe = 310 km

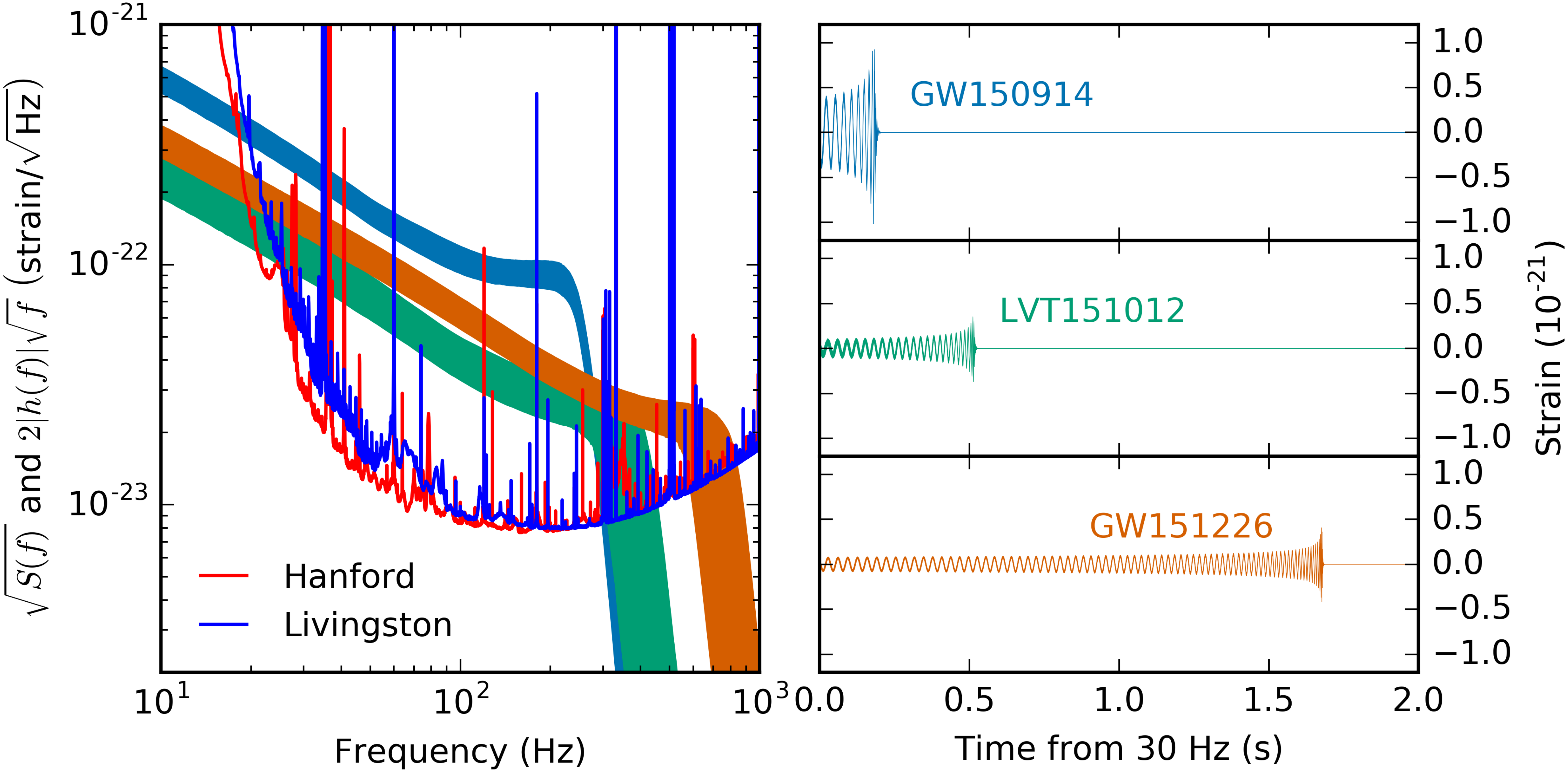
1/75 Hz = 13.3 msec. (in traffic)

d = 410 * 3.086e22 = 1.2653e+25 meters

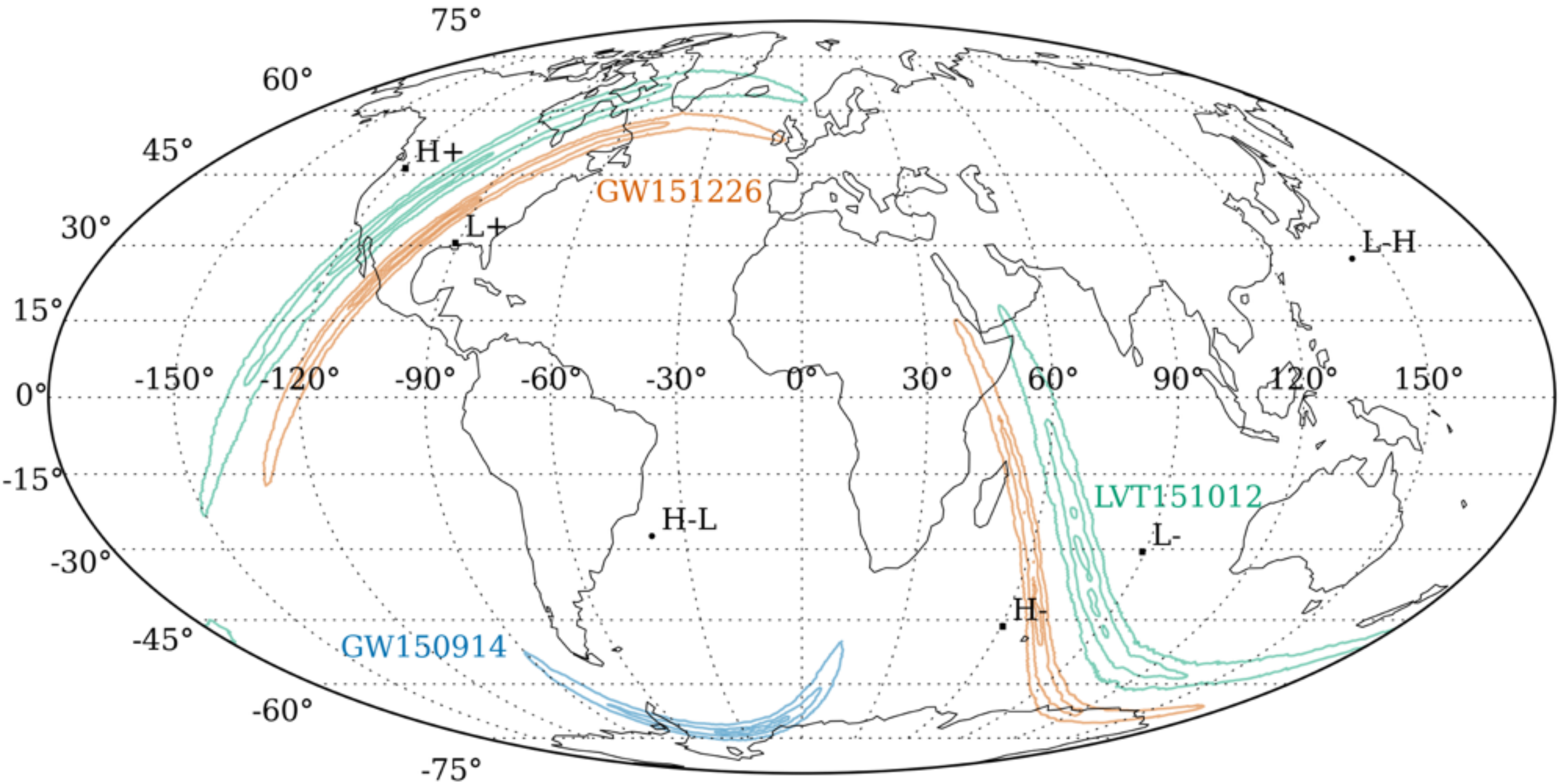
1e-3/1e-21 = 1e18; 1.27e25 /1e18 =1.27e7 12,000 km

diam of earth = 13.7 K km

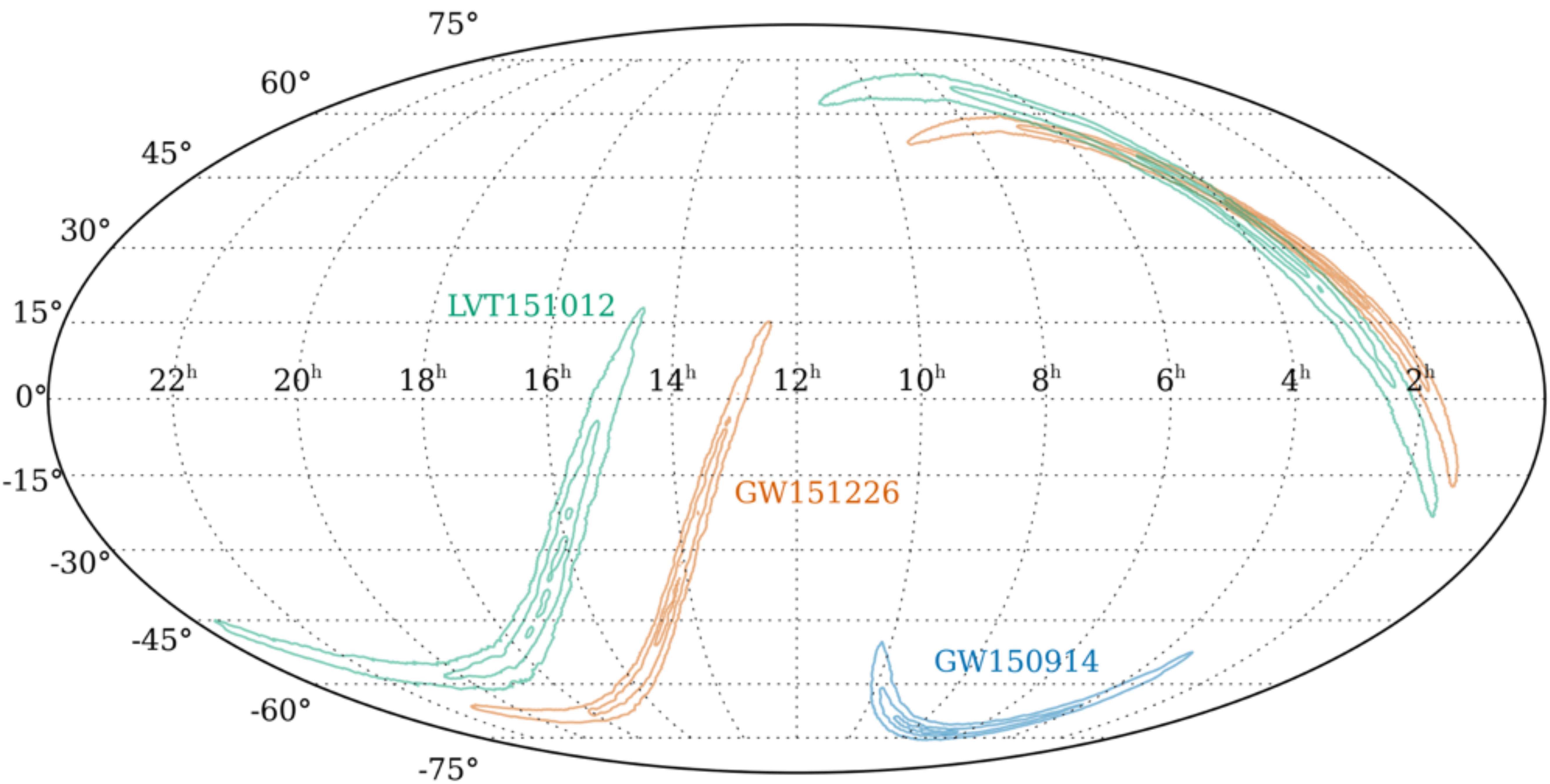
SF to Reno = 295 km

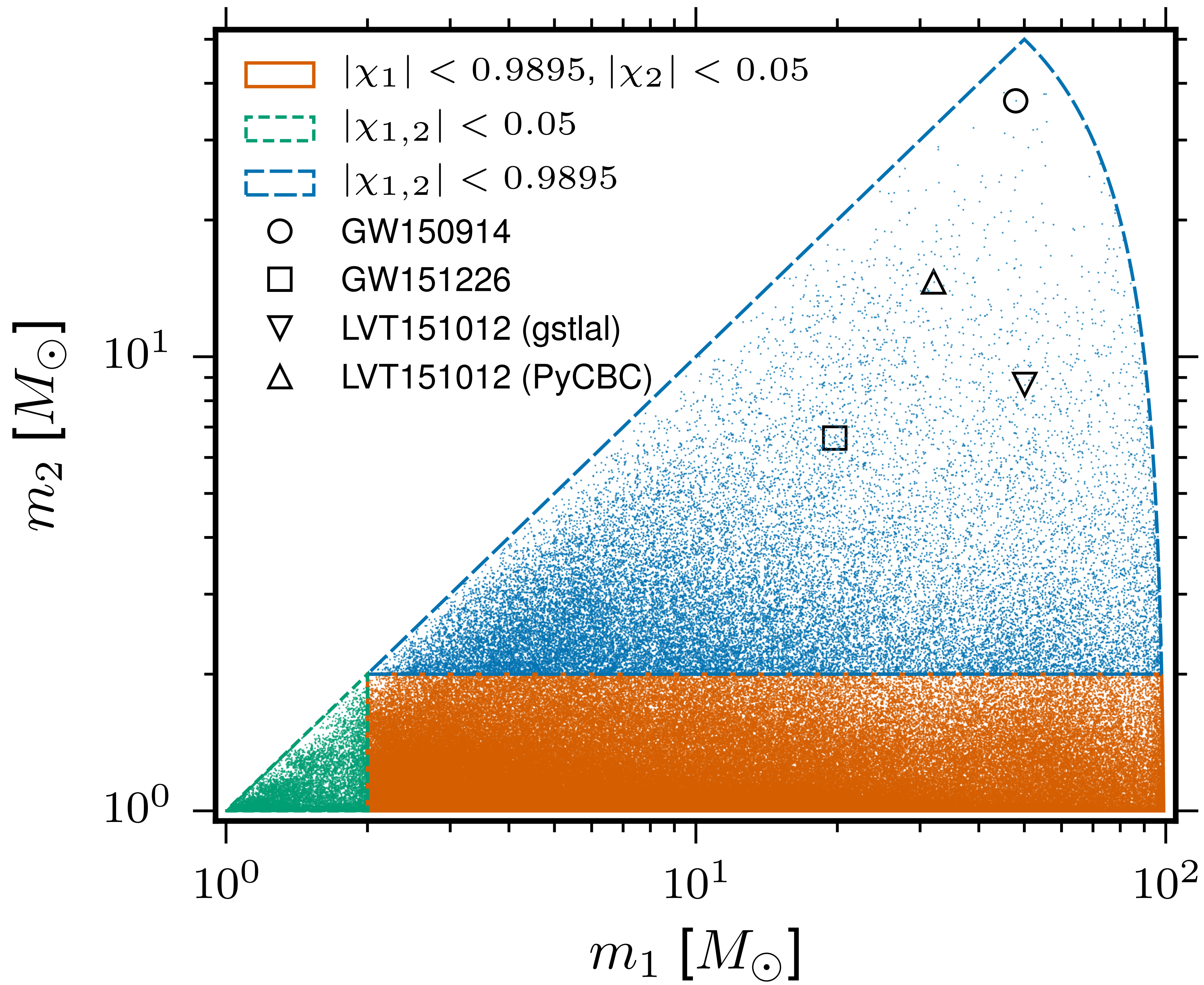


$\sqrt{S(f)}$ and $2|h(f)|\sqrt{f}$ (strain/$\sqrt{\text{Hz}}$)
10^{-21}
10^{-22}
10^{-23}
Hanford
Livingston
10^1
10^2
10^3
Frequency (Hz)
GW150914
LVT151012
GW151226
1.0
0.5
0.0
−0.5
−1.0
Strain (10^{-21})
0.0
0.5
1.0
1.5
2.0
Time from 30 Hz (s)



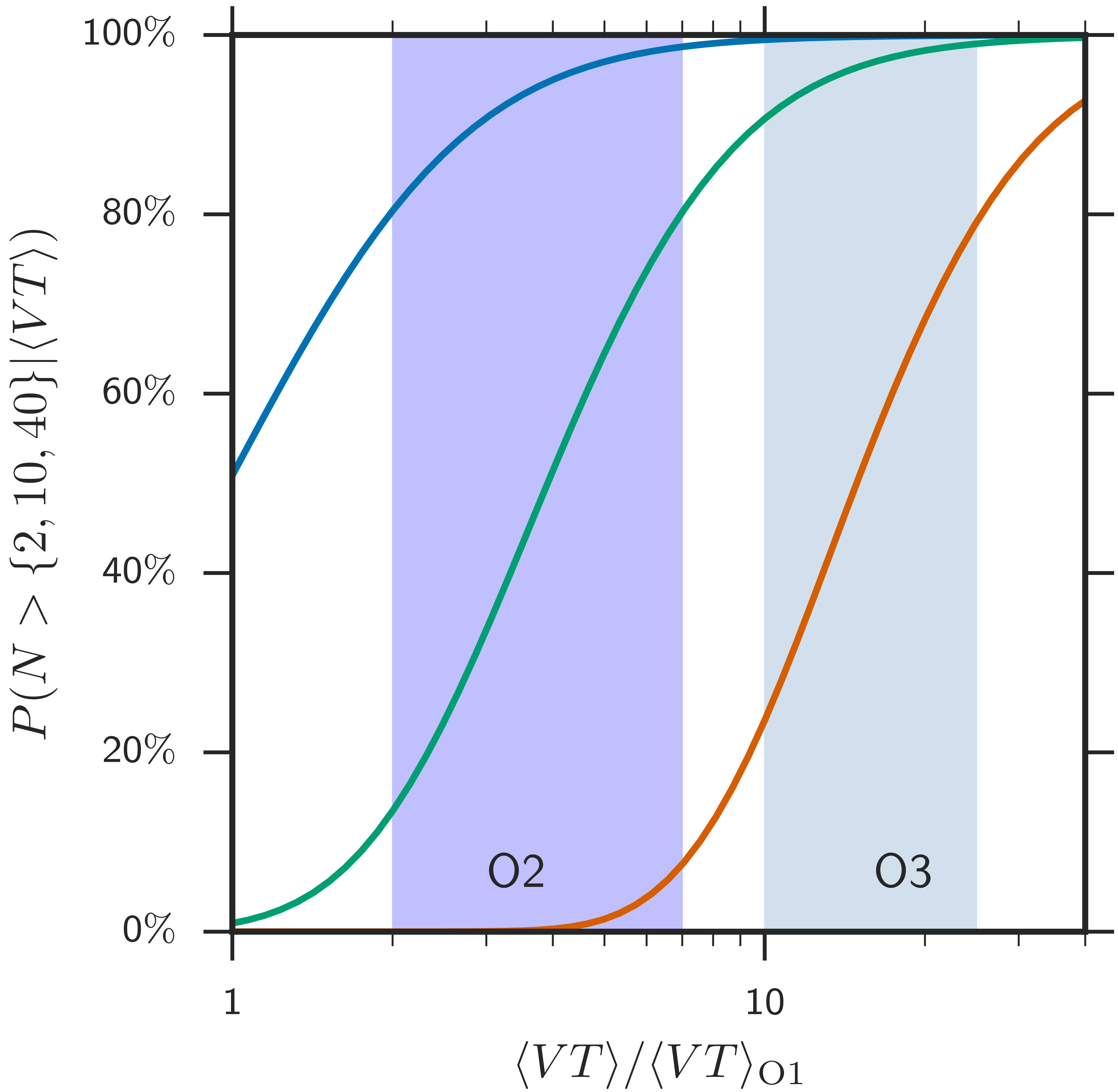
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
H+
L+
L-H
H-L
L-
H-
GW151226
LVT151012
GW150914


75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
22h
20h
18h
16h
14h
12h
10h
8h
6h
4h
2h
LVT151012
GW151226
GW150914

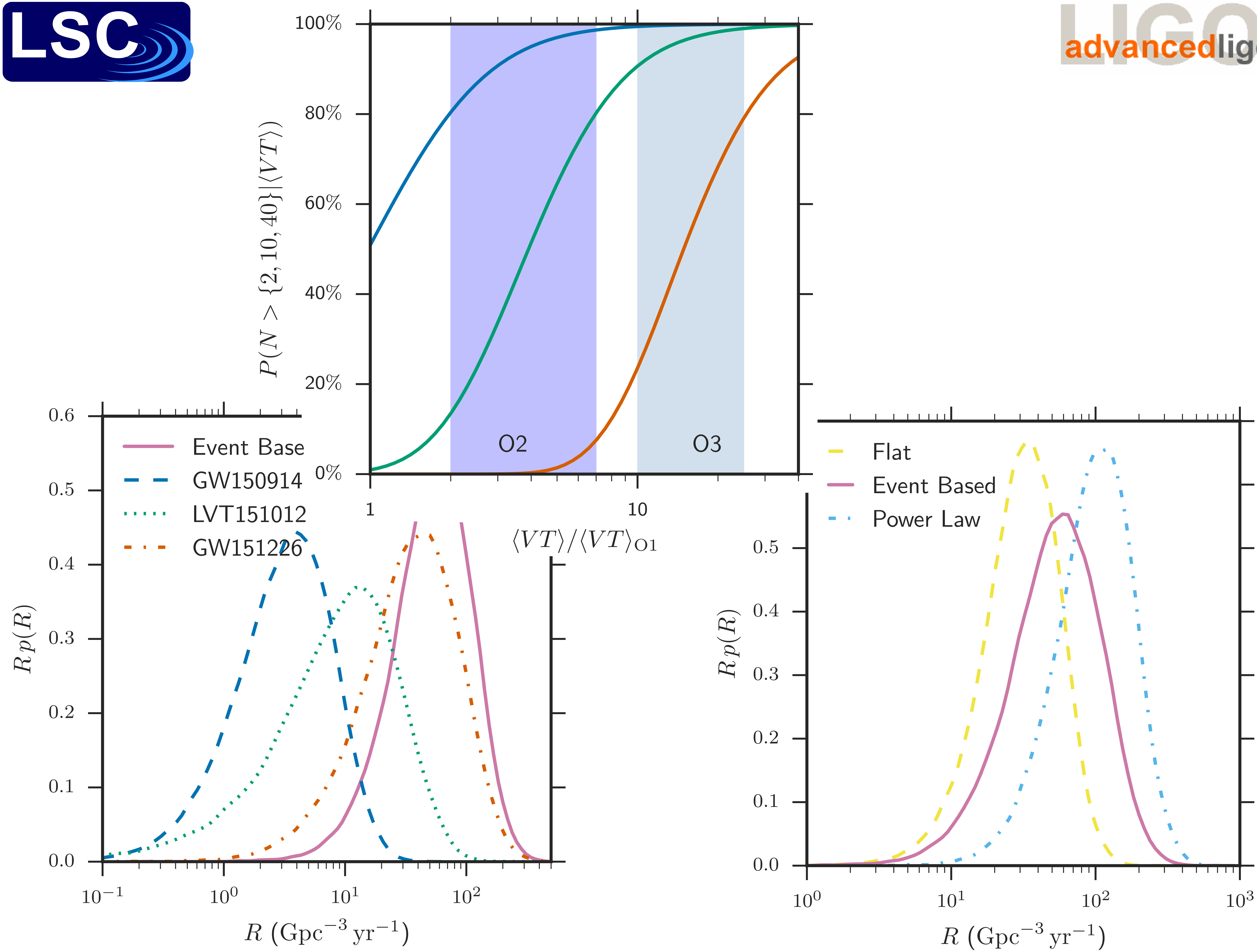


$|\chi_1| < 0.9895, |\chi_2| < 0.05$
$|\chi_{1,2}| < 0.05$
$|\chi_{1,2}| < 0.9895$
GW150914
GW151226
LVT151012 (gstlal)
LVT151012 (PyCBC)
10^1
10^0
$m_2\ [M_\odot]$
10^0
10^1
10^2
$m_1\ [M_\odot]$

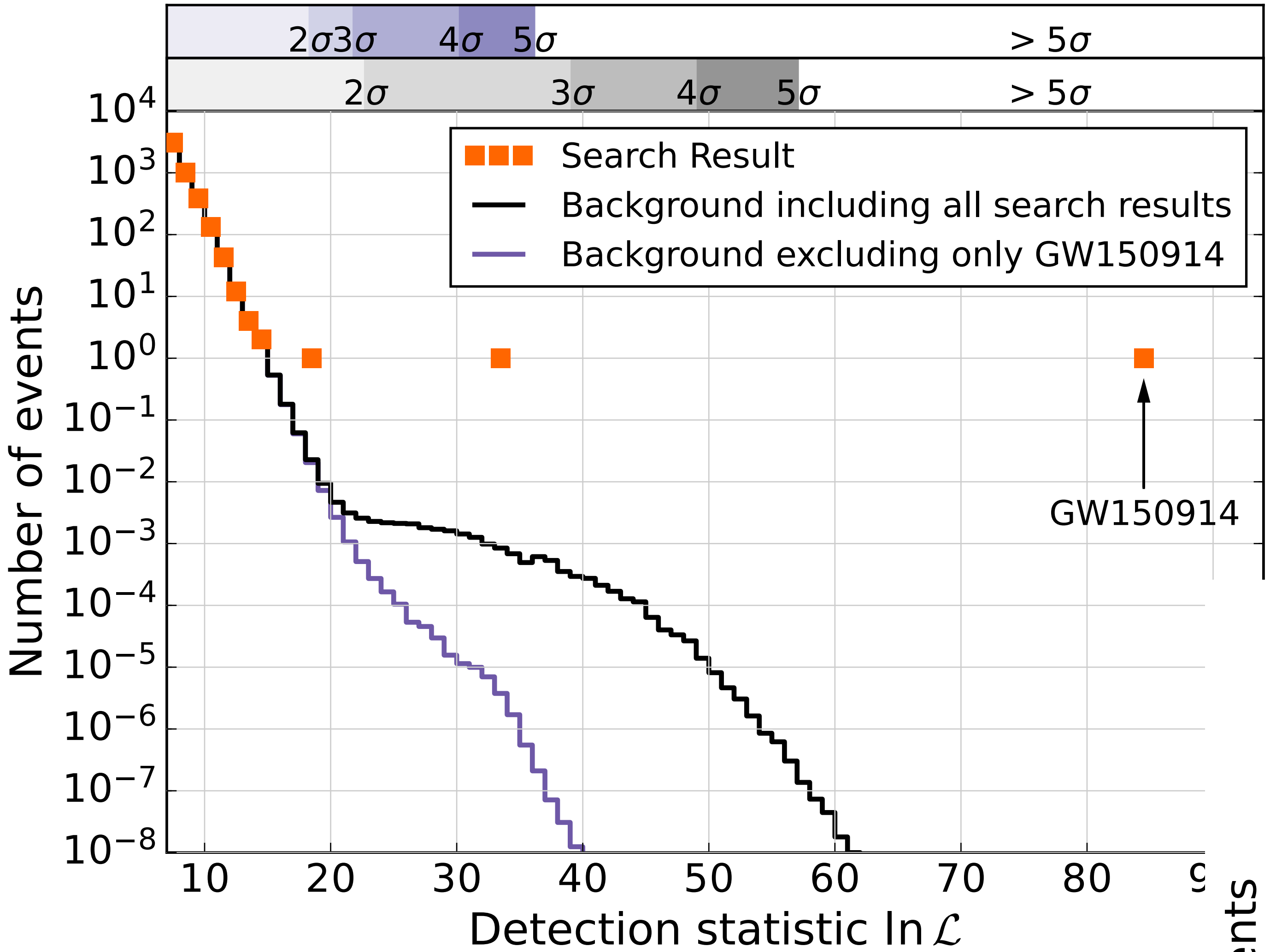
rates



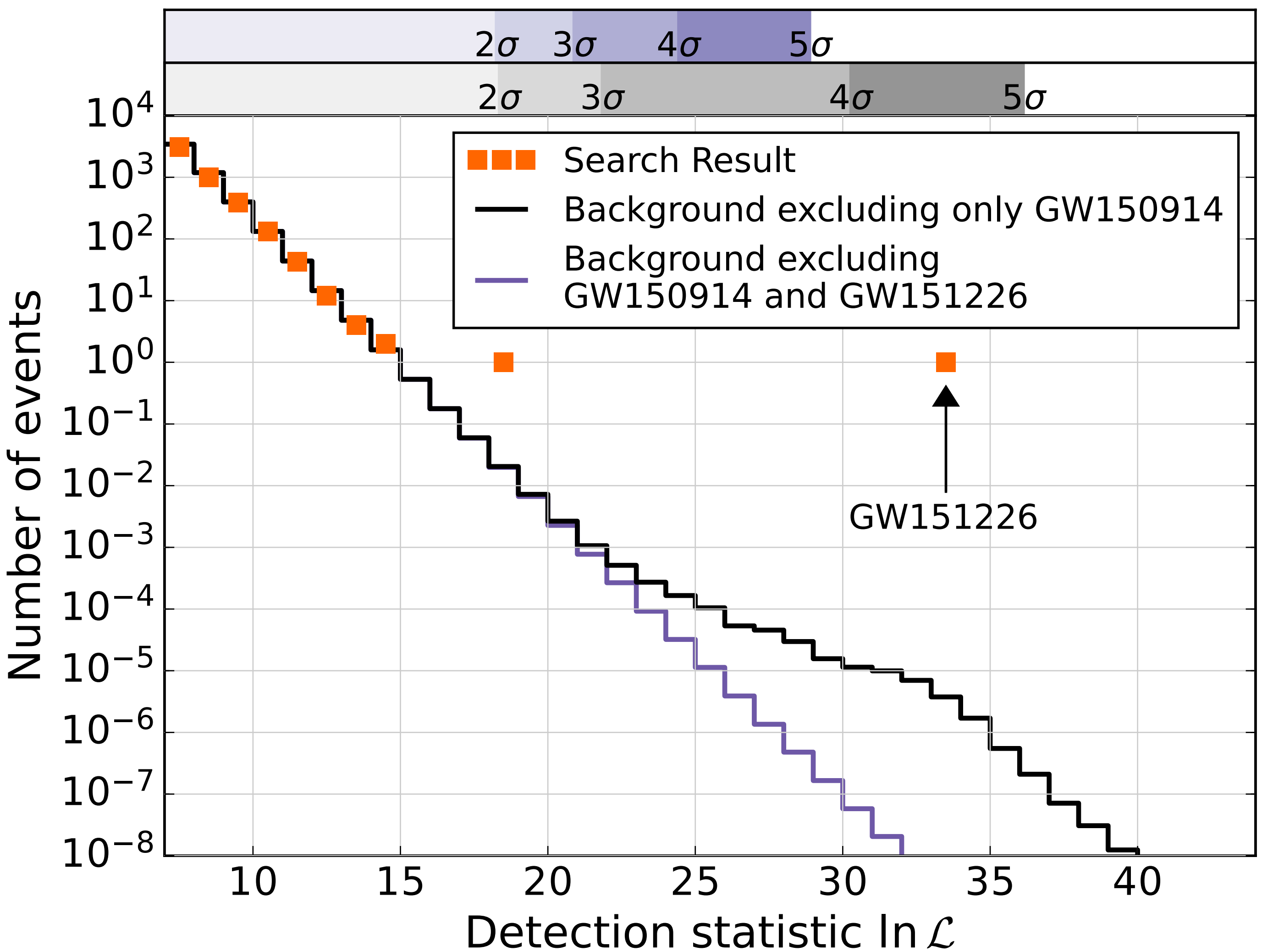
100%
80%
60%
40%
20%
0%
$P(N > \{2, 10, 40\} | \langle VT \rangle)$
O2
O3
1
10
$\langle VT \rangle / \langle VT \rangle_{\mathrm{O1}}$



100%
80%
60%
40%
20%
0%
$P(N > \{2, 10, 40\} | \langle VT \rangle)$
O2
O3
1
10
$\langle VT \rangle / \langle VT \rangle_{O1}$
Event Base
GW150914
LVT151012
GW151226
0.0
0.1
0.2
0.3
0.4
0.5
0.6
$R\,p(R)$
10^{-1}
10^{0}
10^{1}
10^{2}
R (Gpc^{-3} yr^{-1})
Flat
Event Based
Power Law
0.0
0.1
0.2
0.3
0.4
0.5
$R\,p(R)$
10^{0}
10^{1}
10^{2}
10^{3}
R (Gpc^{-3} yr^{-1})



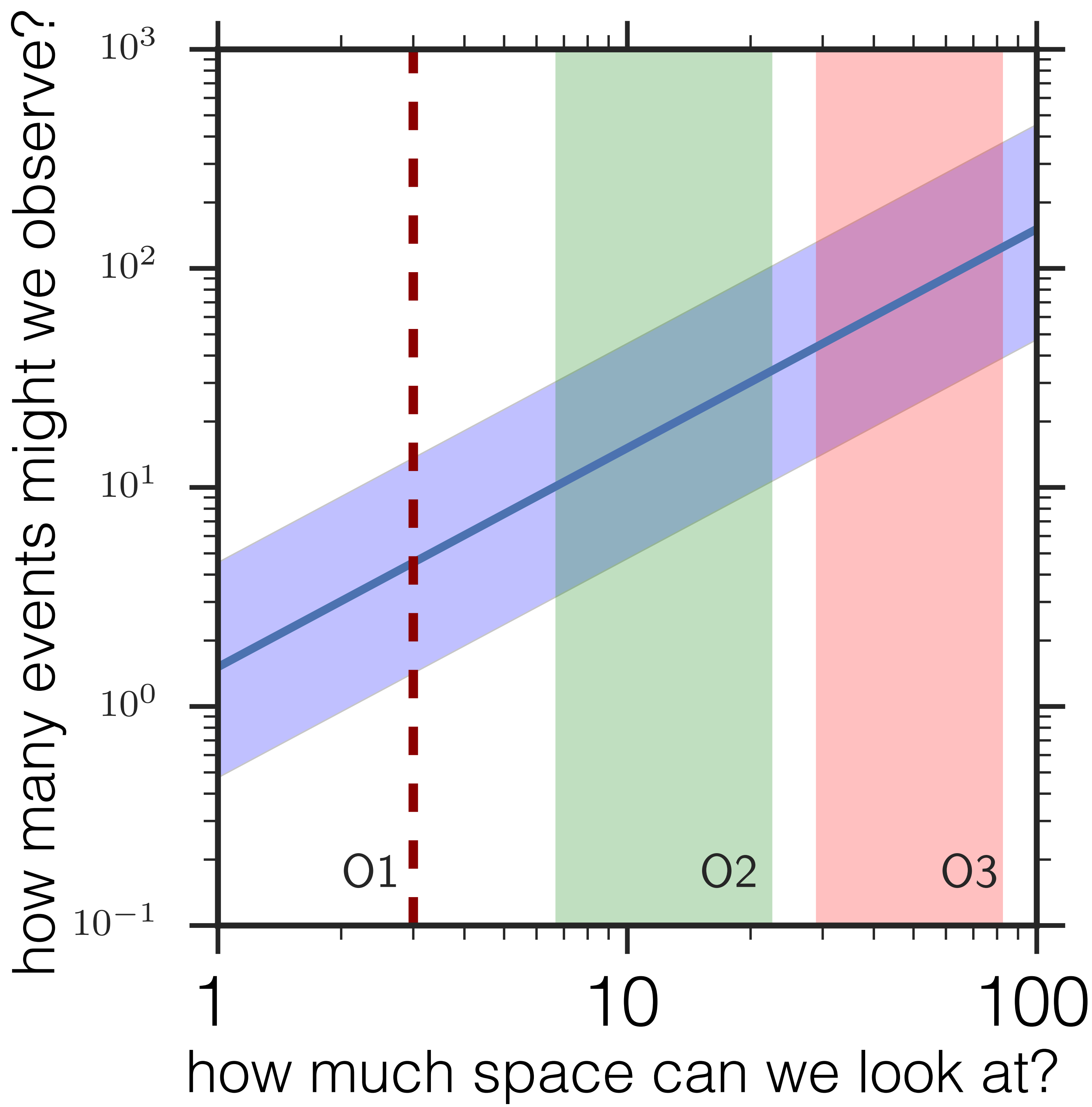
2σ 3σ 4σ 5σ > 5σ
2σ 3σ 4σ 5σ > 5σ
Search Result
Background including all search results
Background excluding only GW150914
GW150914
Number of events
Detection statistic ln $\mathcal{L}$



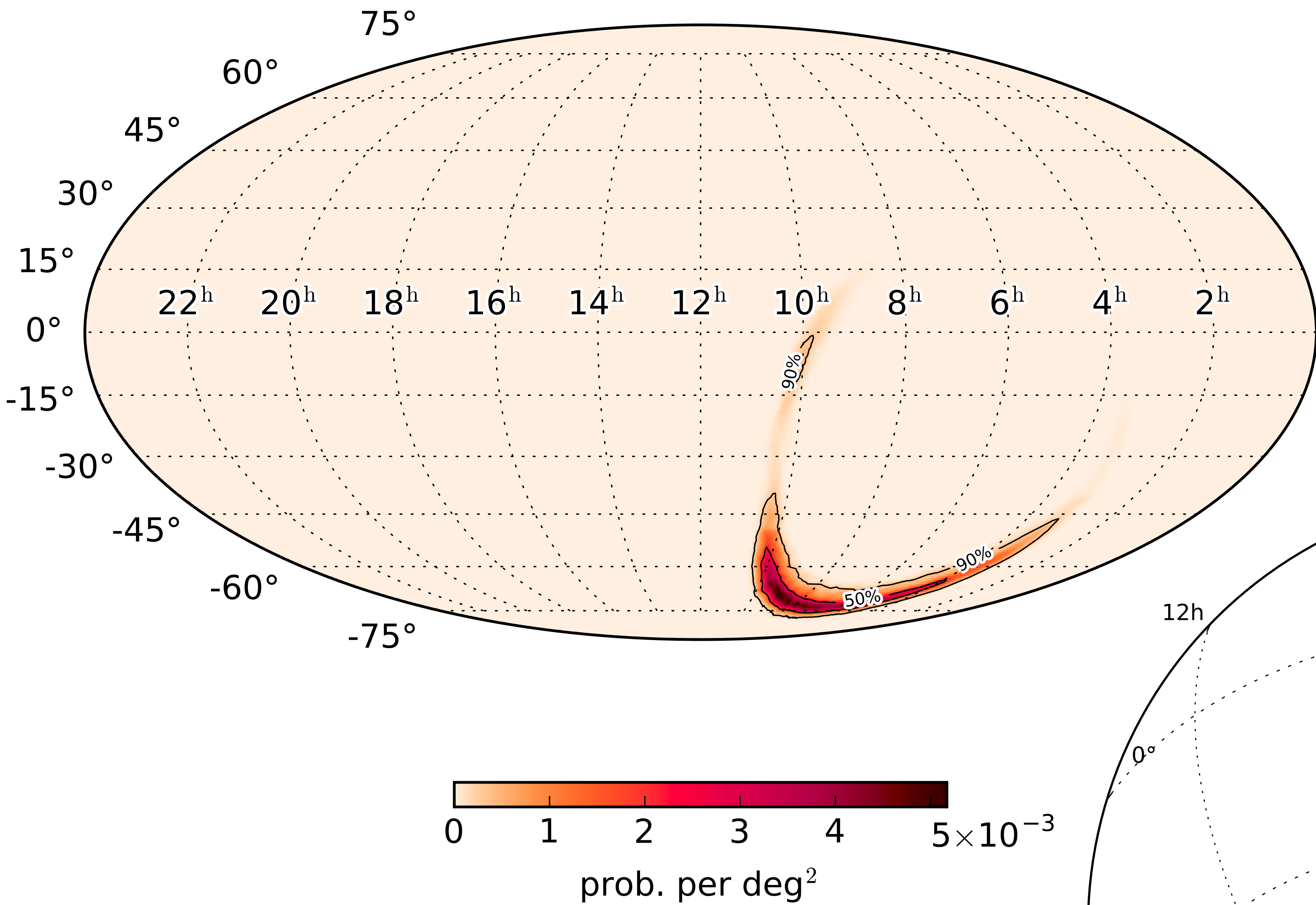
2σ 3σ 4σ 5σ
2σ 3σ 4σ 5σ
Search Result
Background excluding only GW150914
Background excluding GW150914 and GW151226
GW151226
Number of events
Detection statistic ln $\mathcal{L}$

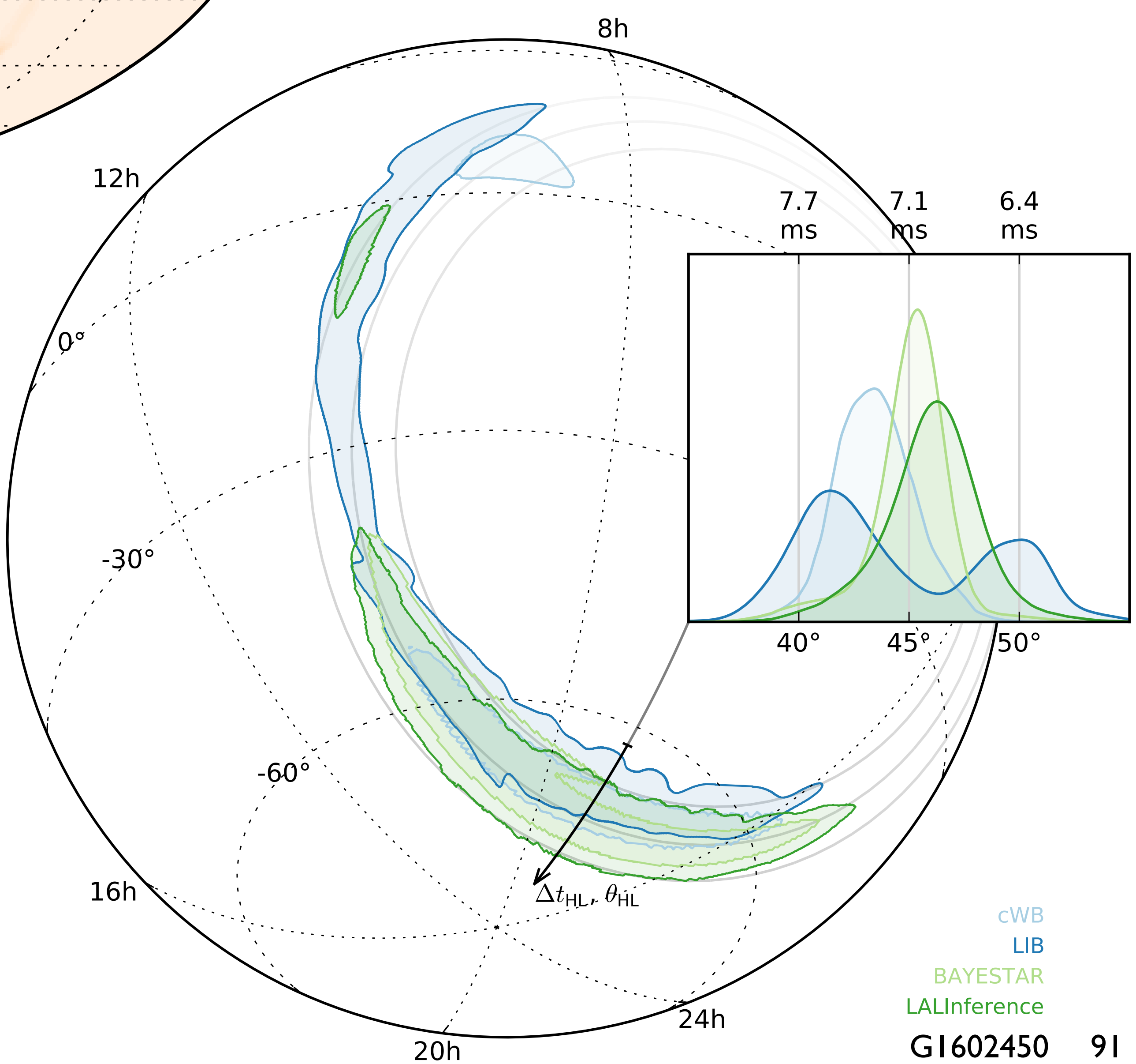
The End/ The Beginning…

How many black hole collisions can we see?

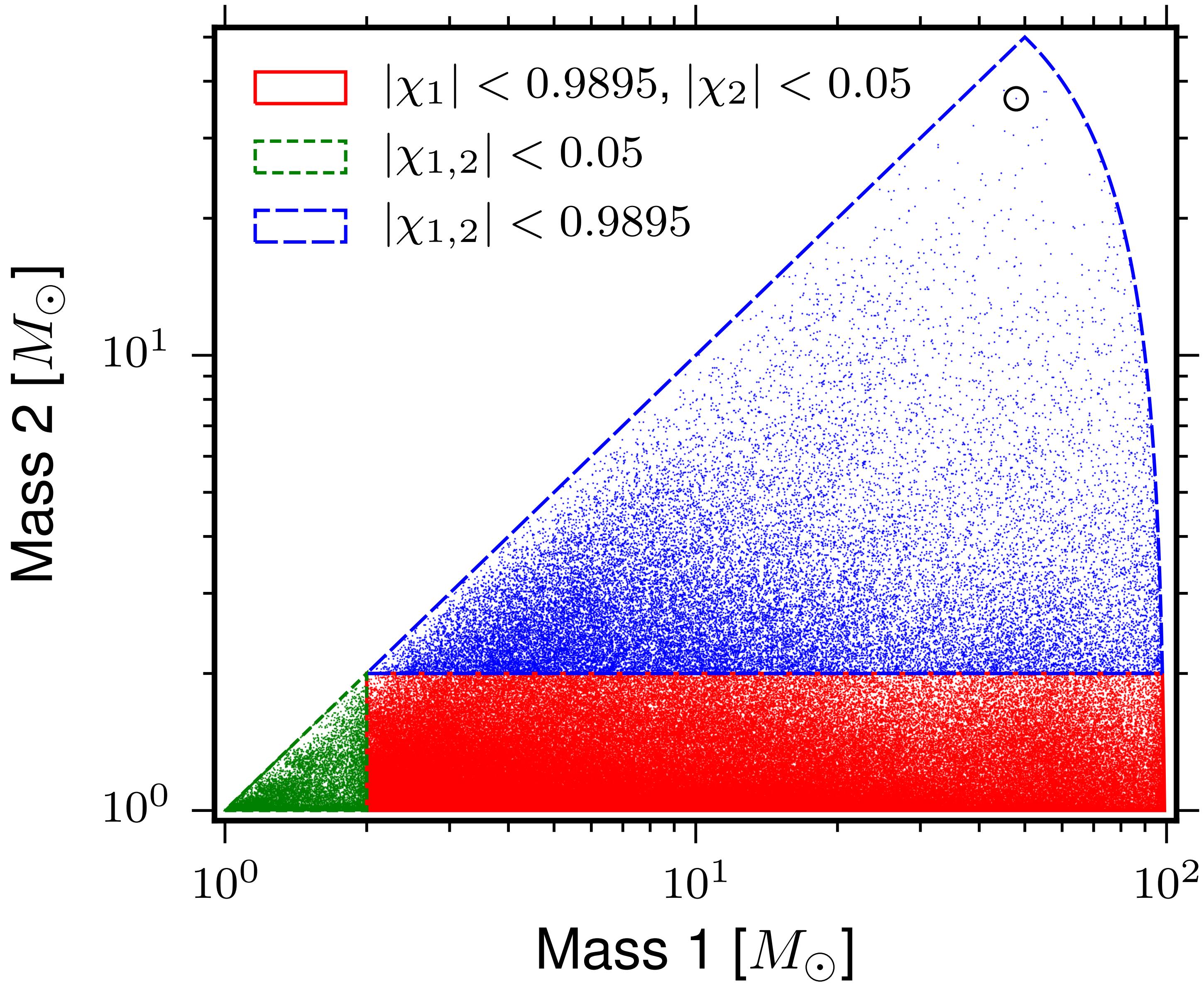


Where was it?


75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
22h 20h 18h 16h 14h 12h 10h 8h 6h 4h 2h
90%
90%
50%
0 1 2 3 4 5×10−3
prob. per deg2


8h
12h
0°
-30°
-60°
16h
20h
24h
7.7 ms
7.1 ms
6.4 ms
40°
45°
50°
ΔtHL, θHL
cWB
LIB
BAYESTAR
LALInference

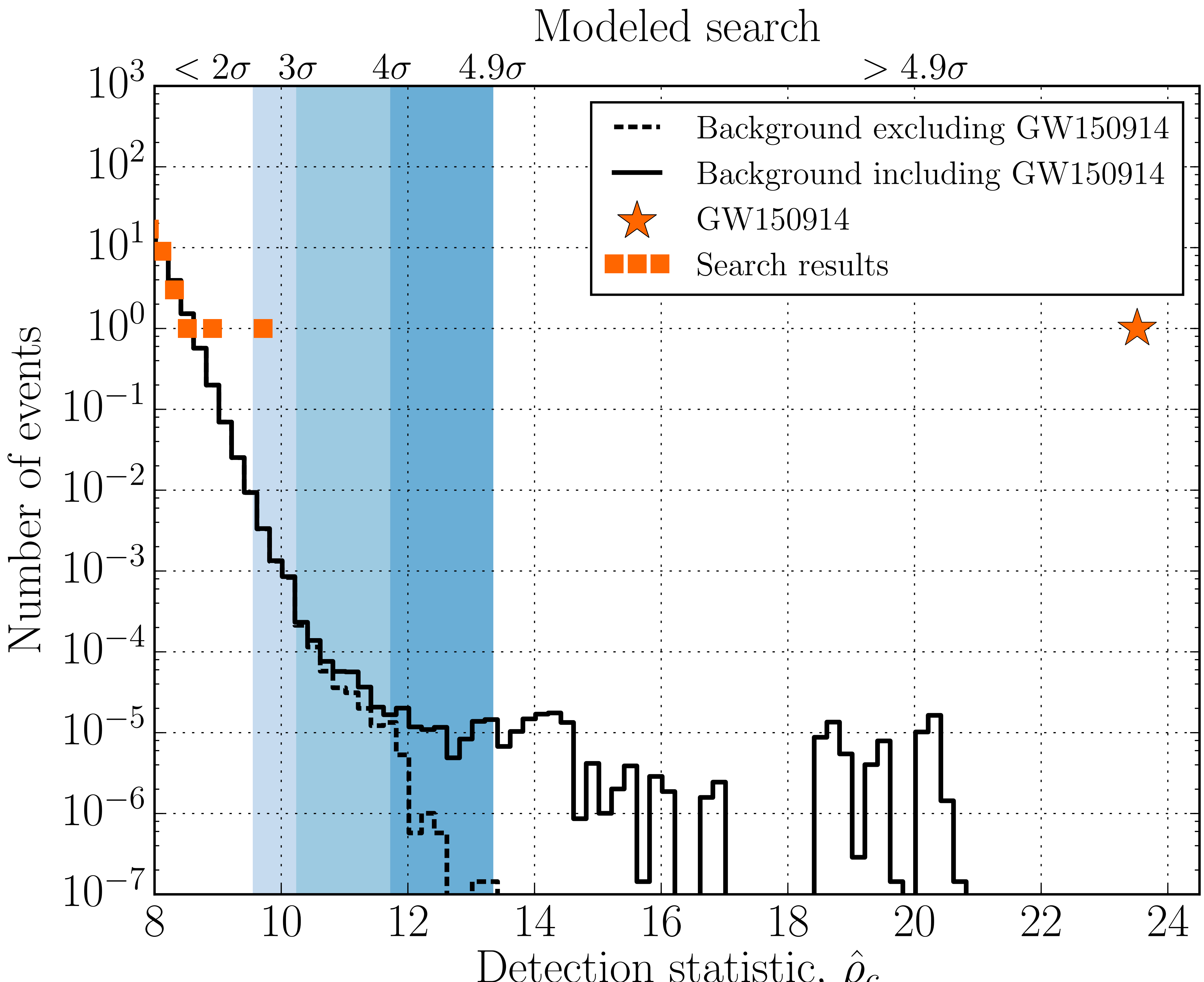
CBC template bank

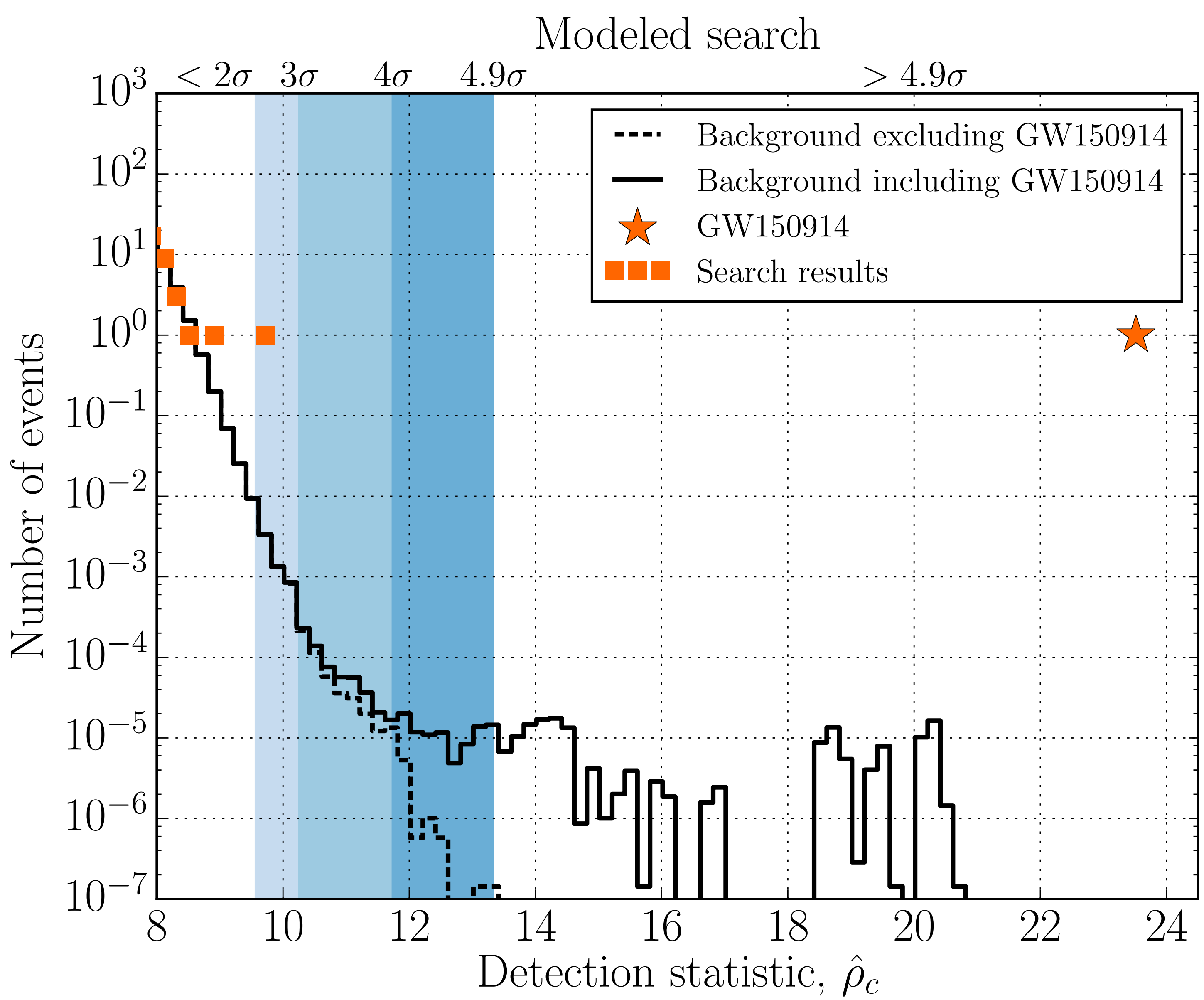


(just at the edge…)

FIG. 1. The four-dimensional search parameter space covered by the template bank shown projected into the component-mass plane, using the convention $m_1 > m_2$. The lines bound mass regions with different limits on the dimensionless aligned-spin parameters χ_1 and χ_2. Each point indicates the position of a template in the bank. The circle highlights the template that best matches GW150914. This

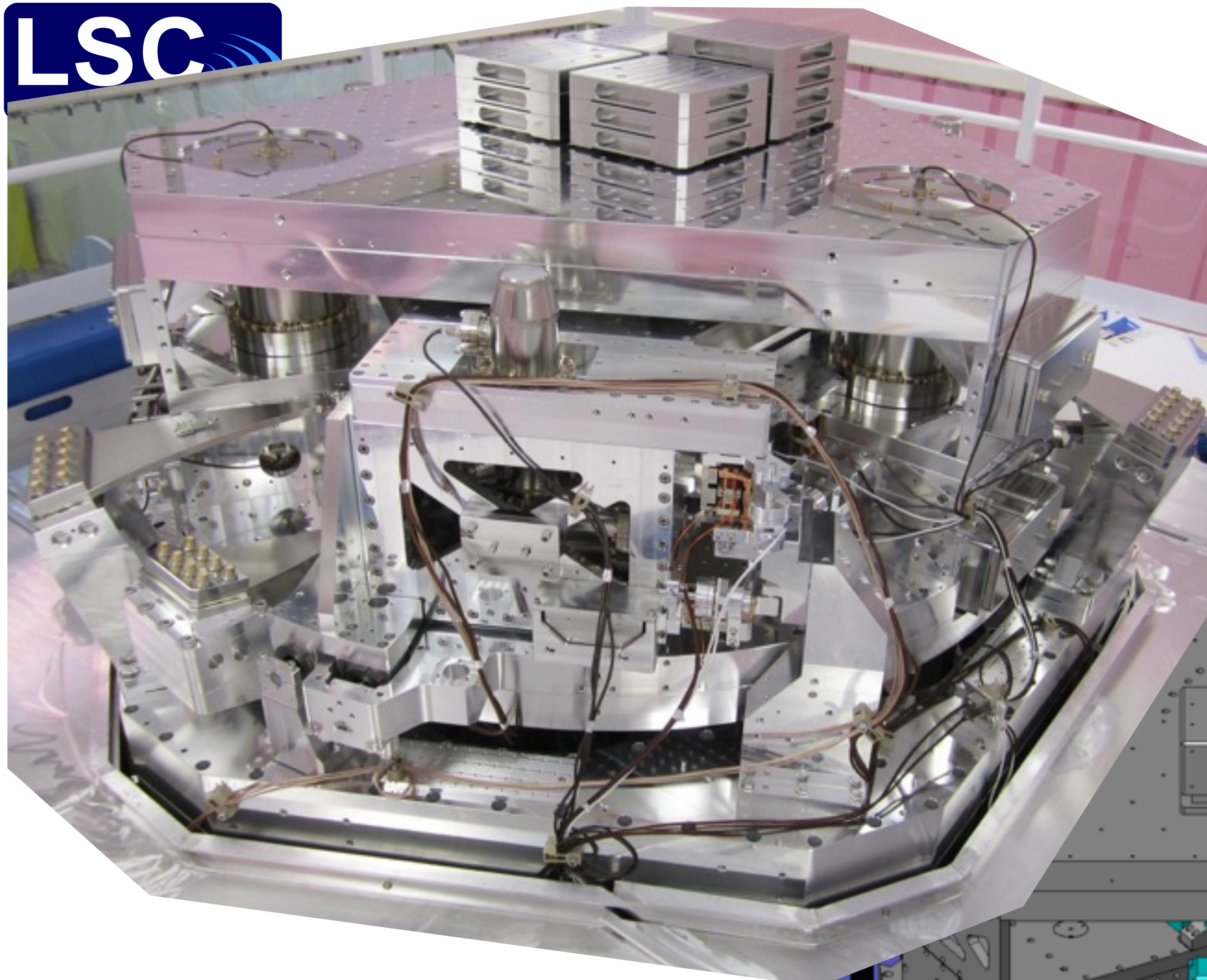
Detection statistic

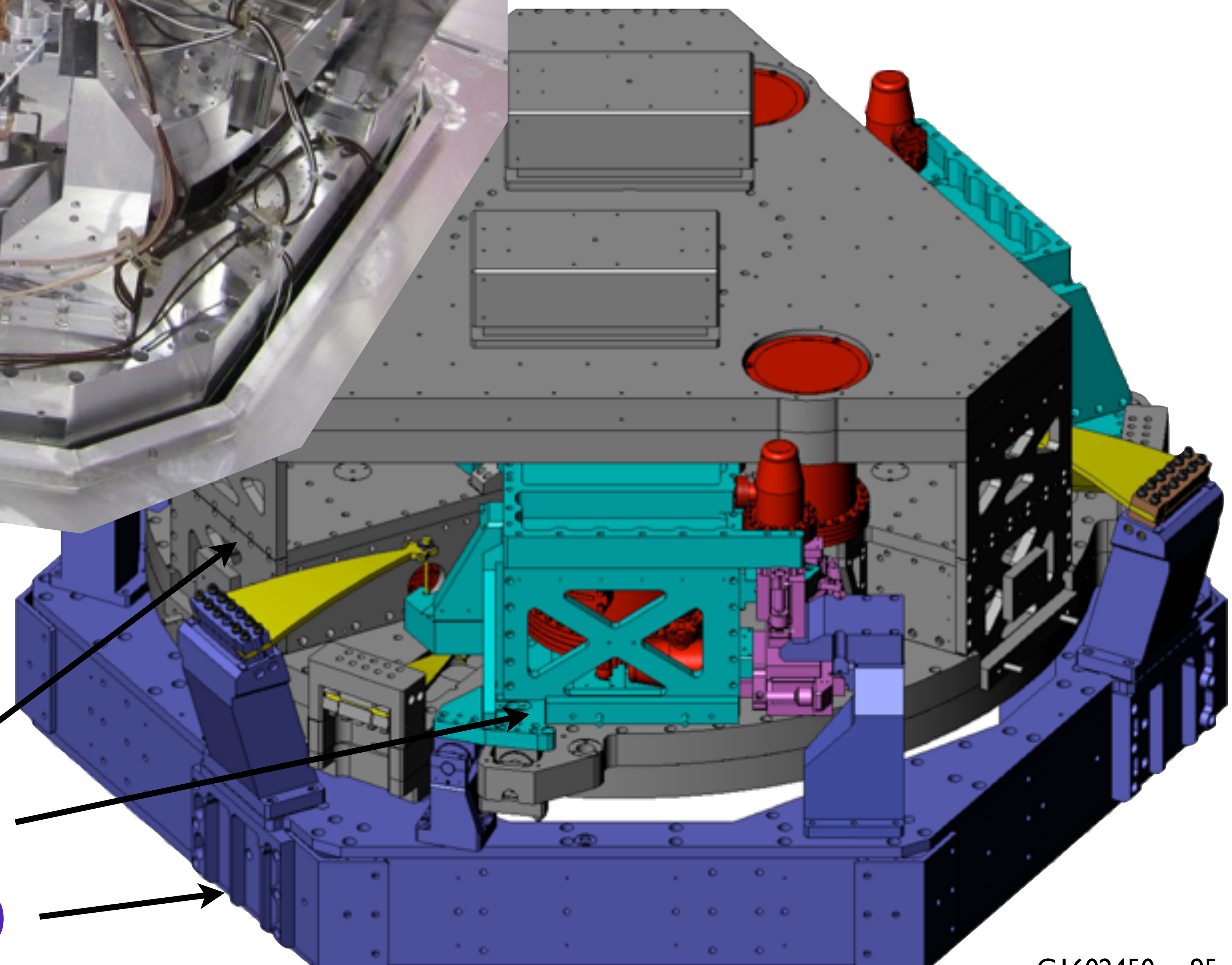




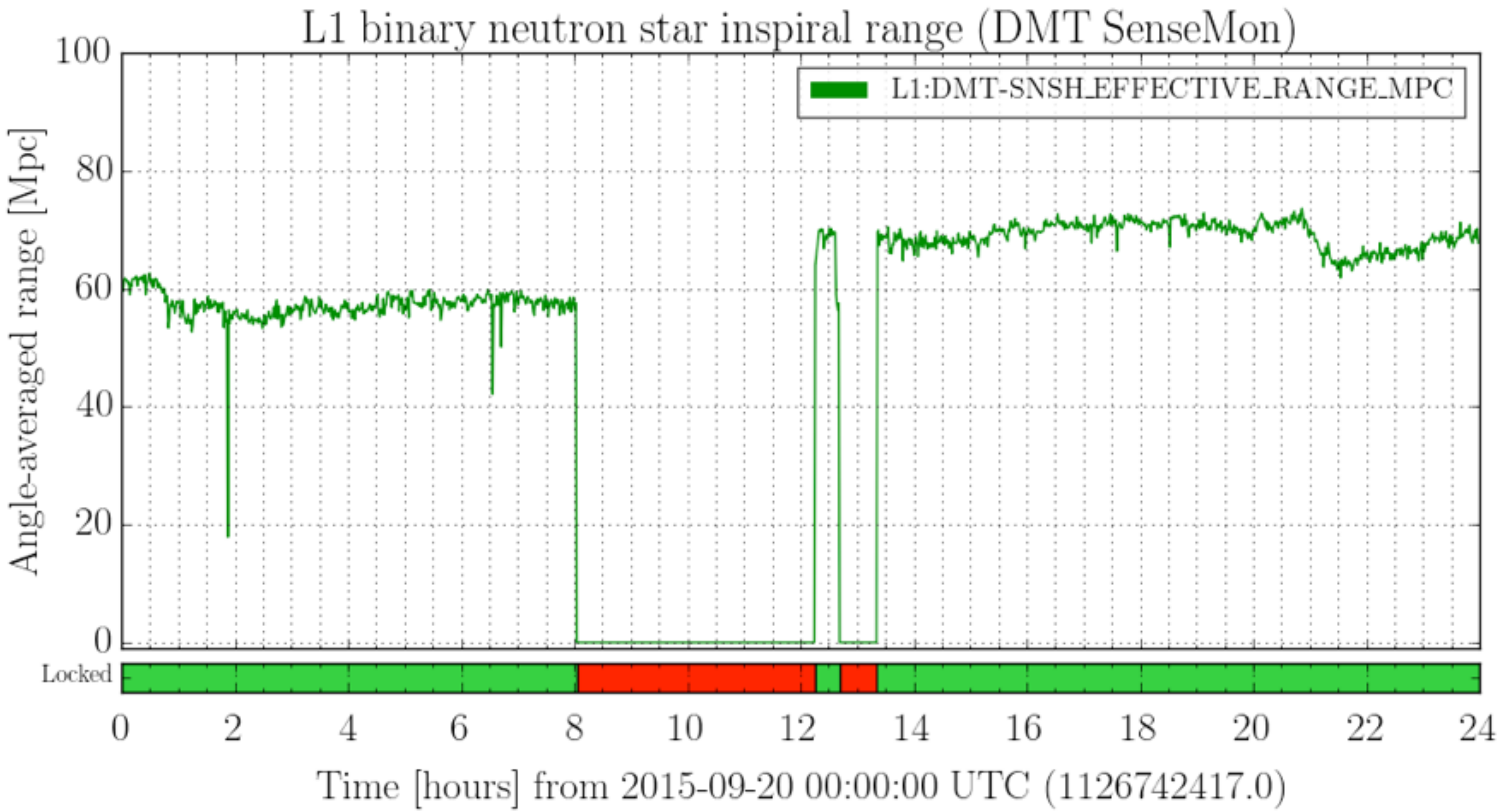
Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	$\chi_{\rm eff}$	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5 \times 10^{-6}$	$< 2 \times 10^{-7}$ ($> 5.1\,\sigma$)	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.06^{+0.17}_{-0.18}$	410^{+160}_{-180}
LVT151012	12 October 2015 09:54:43	0.44	0.02 ($2.1\,\sigma$)	15^{+1}_{-1}	23^{+18}_{-5}	13^{+4}_{-5}	$0.0^{+0.3}_{-0.2}$	1100^{+500}_{-500}

BSC-ISI

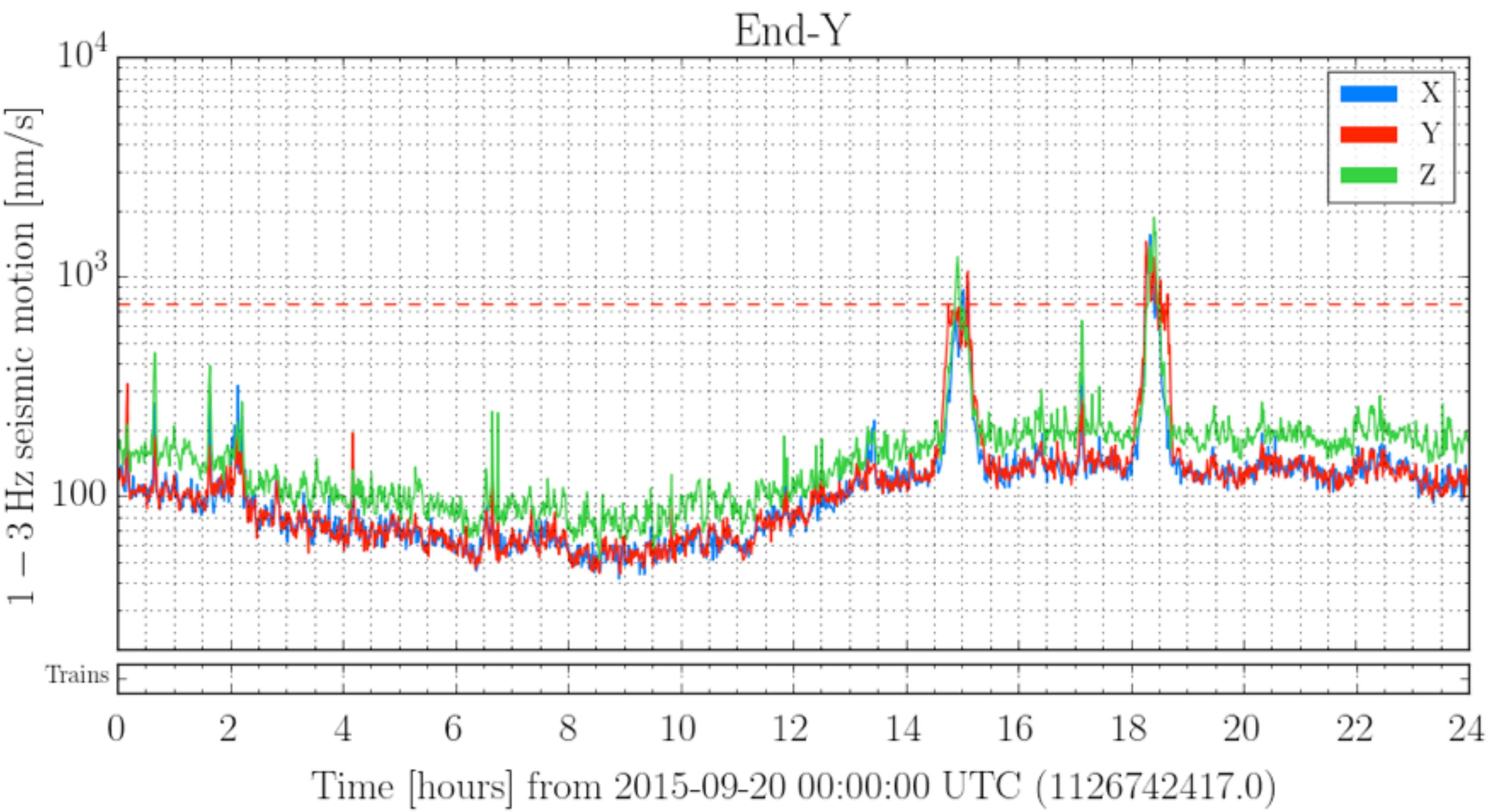




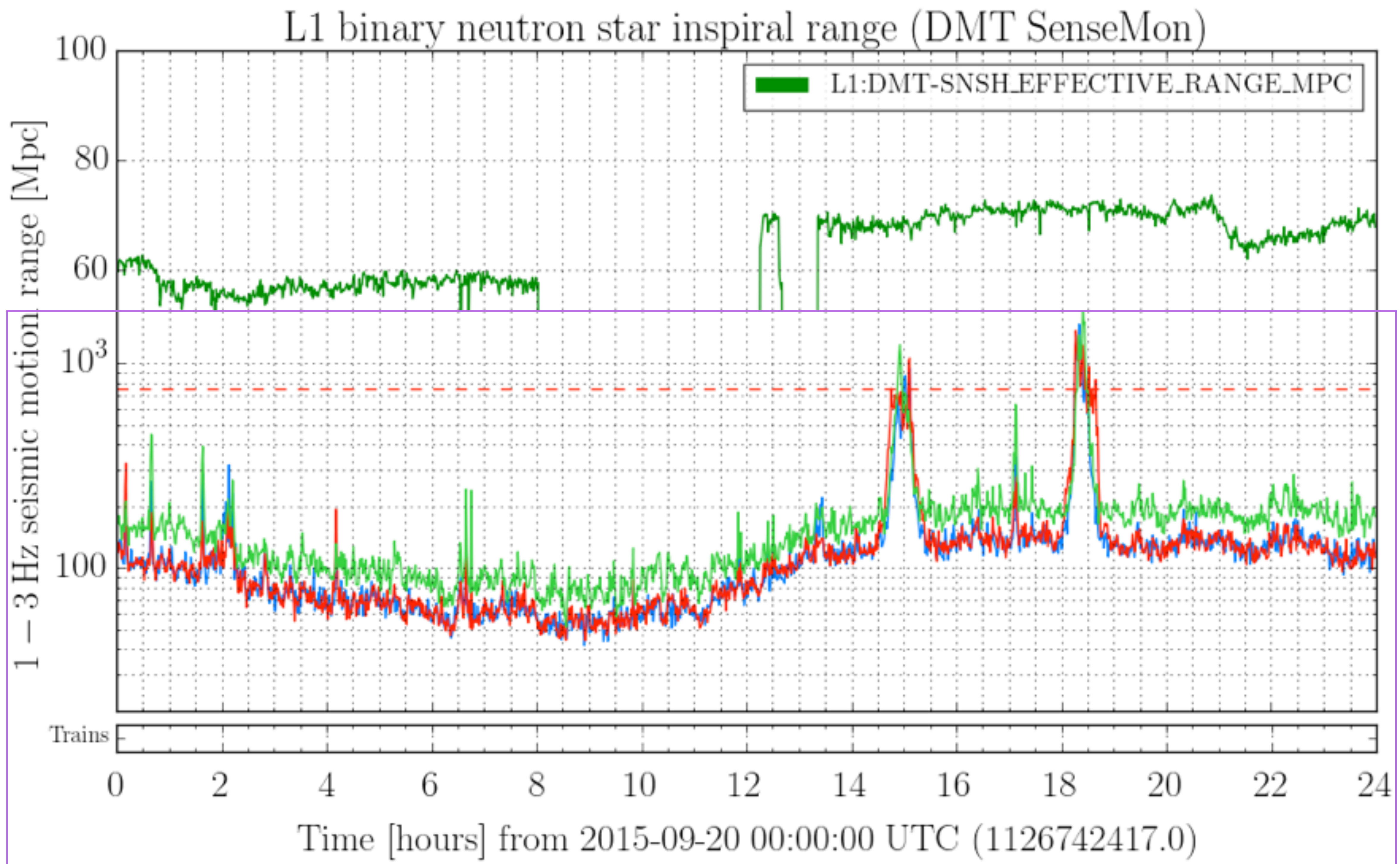
Real impact of



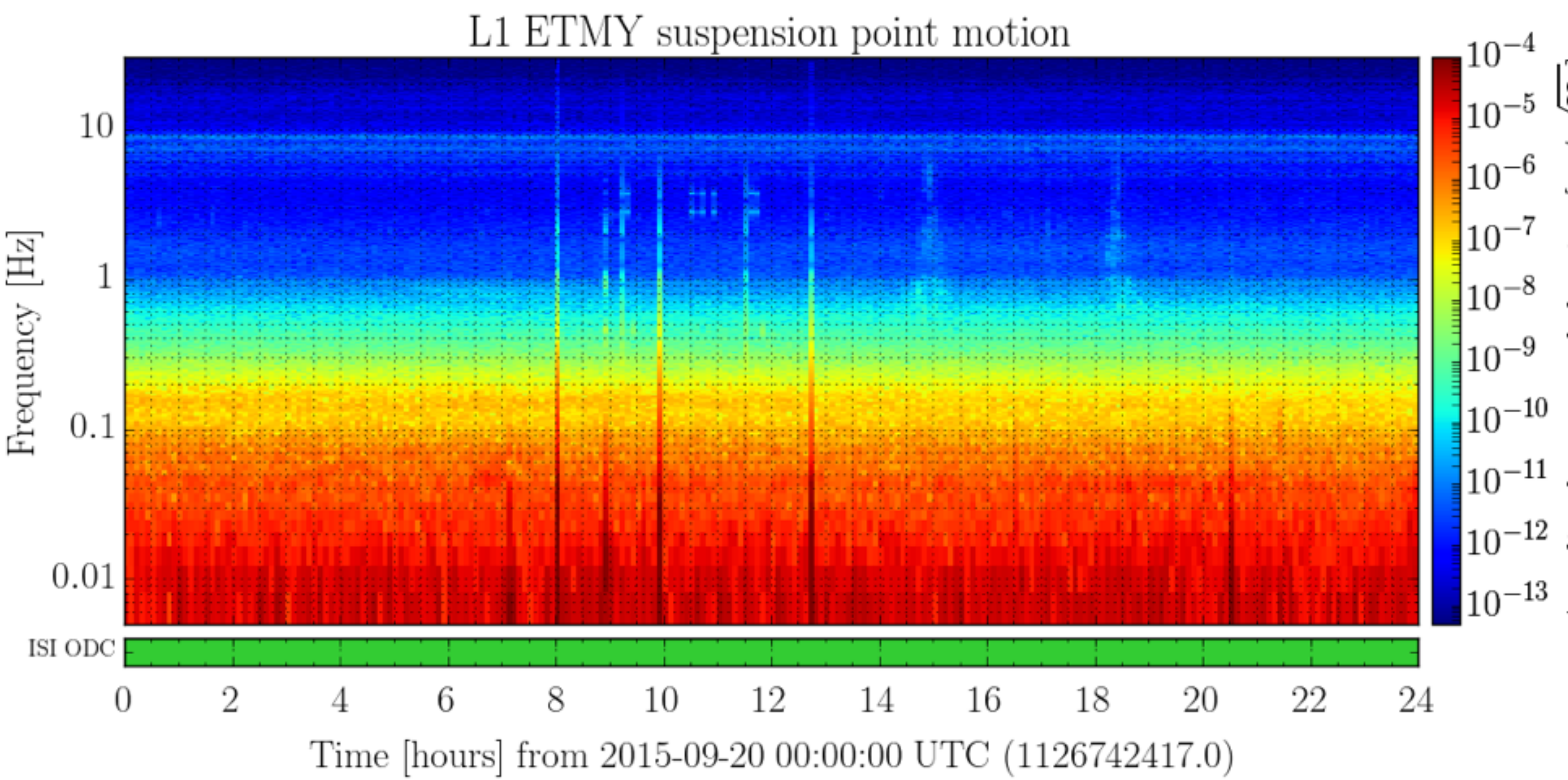
but there was a train…



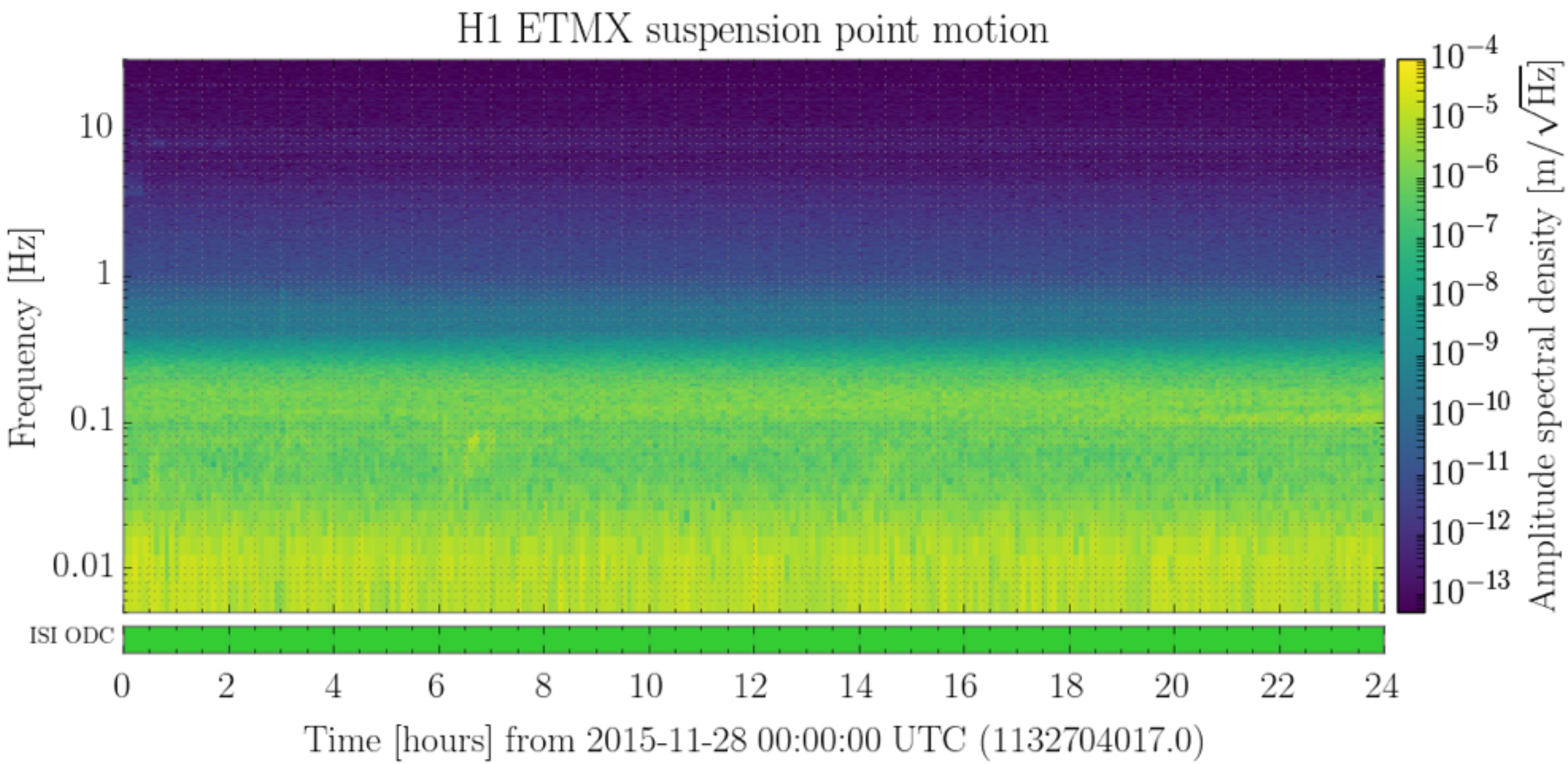
Real impact of



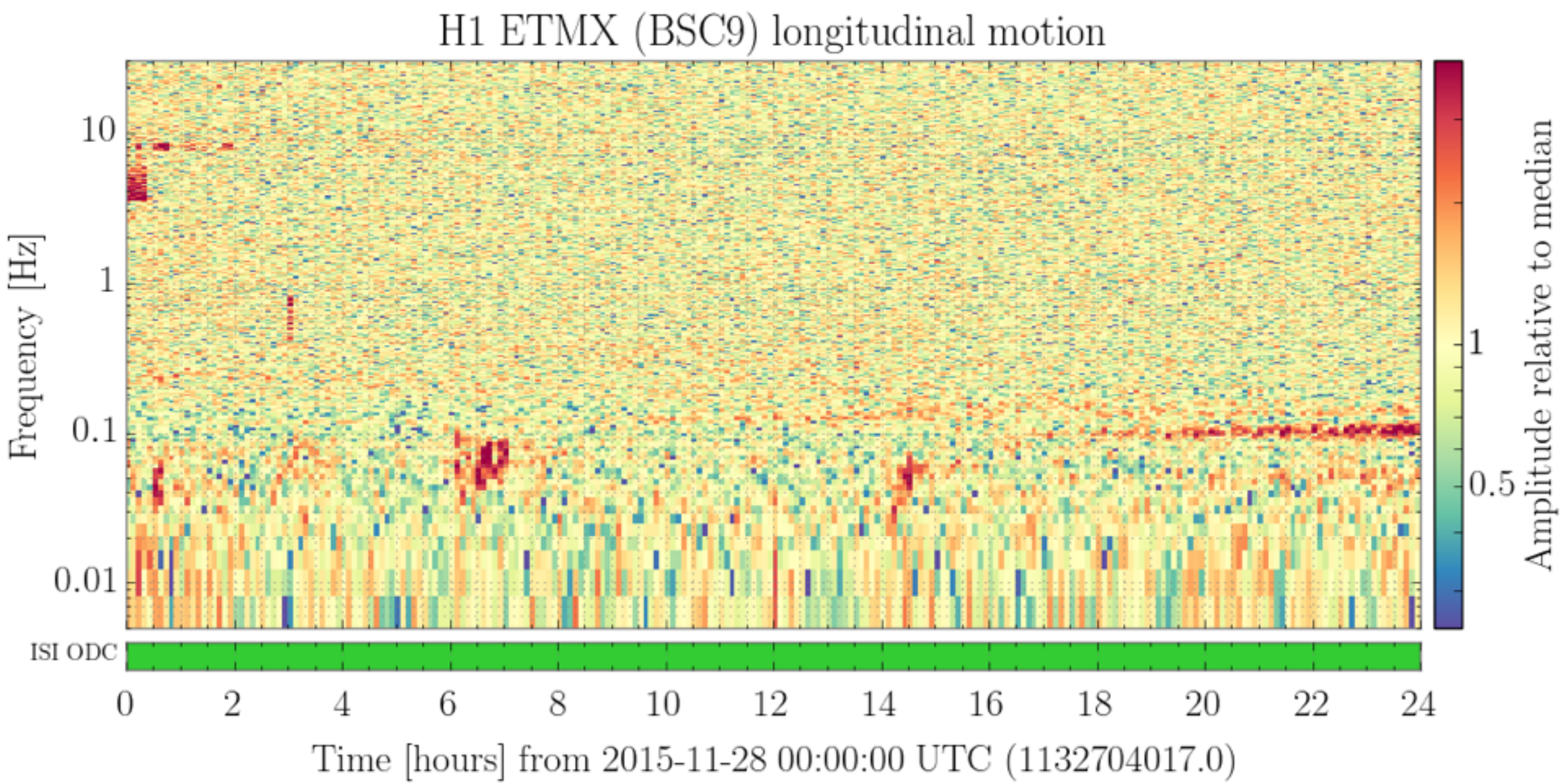
‘Environmental’ sensors



This is what we strive for

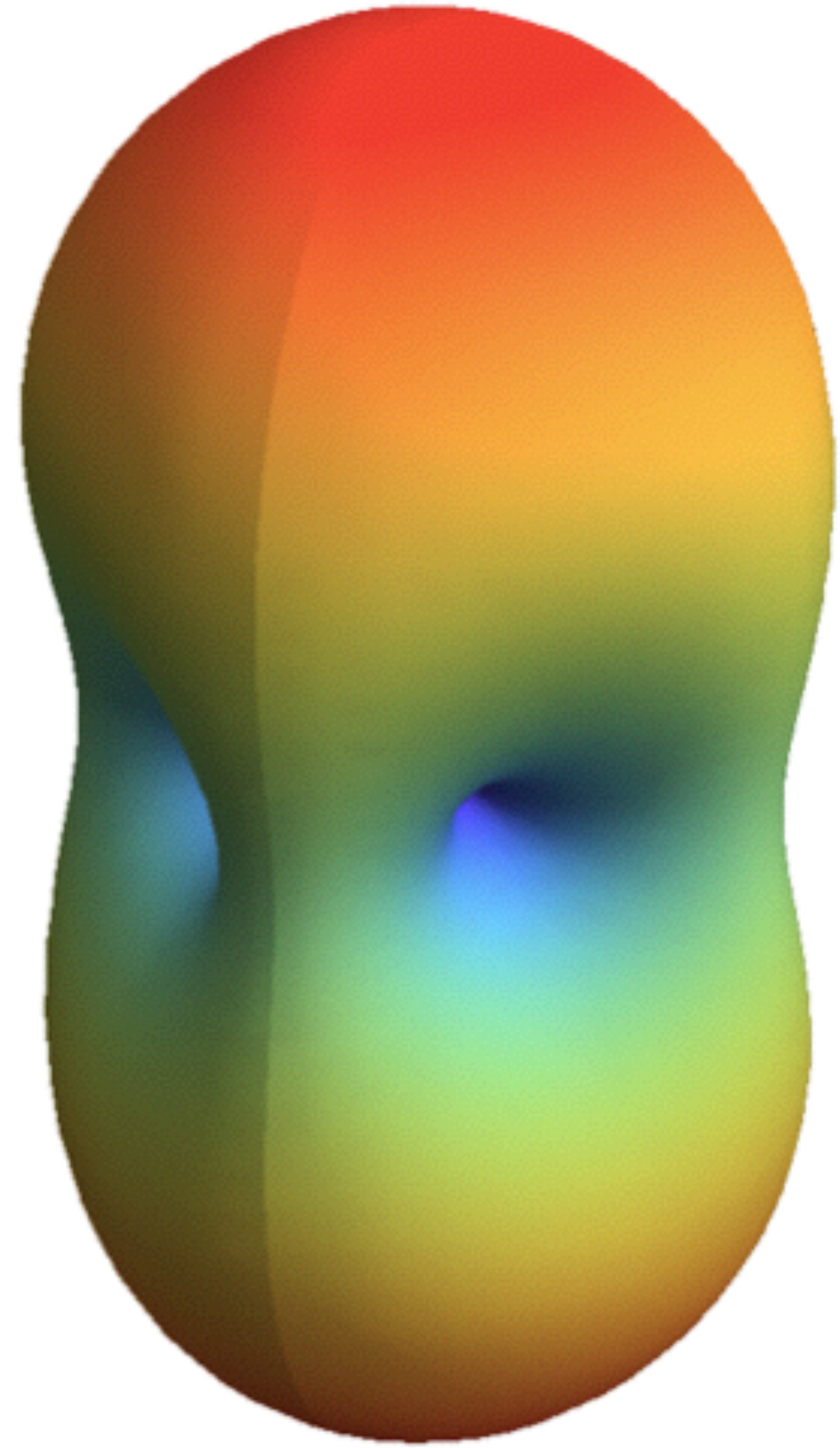


Glitch monitoring



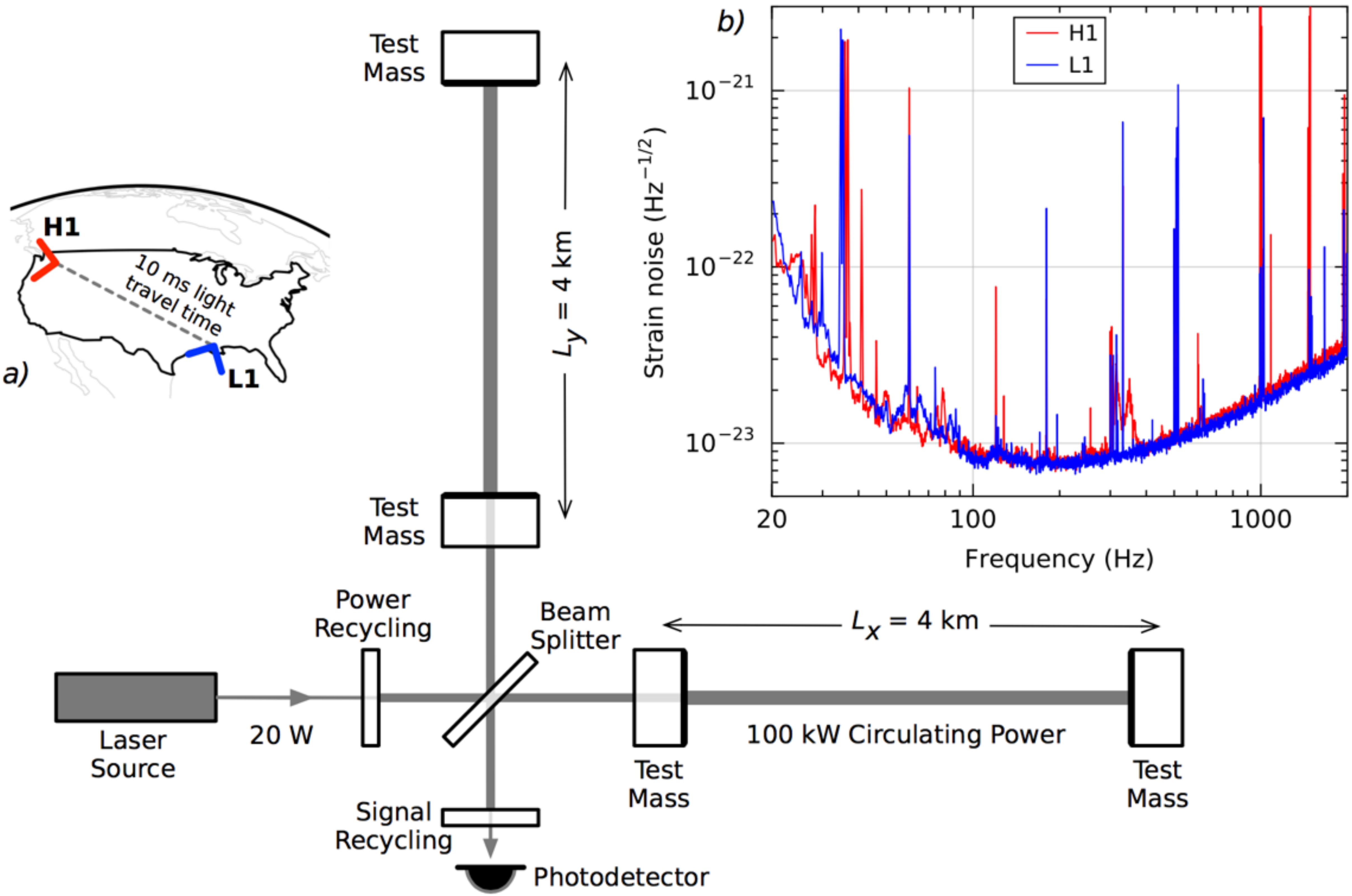
Interferometer's Antenna Pattern LIGO is not an Imaging Detector

- Antenna pattern for aLIGO, for an optimally polarized wave.
- LIGO is more like a microphone than a telescope.
- i.e. We measure the amplitude of a wave coming from pretty much any direction.
- Good for first detections, but not so good for finding the source.



From R. Adhikari, P1200121.

Detector



a)
H1
10 ms light travel time
L1
Test Mass
Test Mass
$L_y = 4$ km
Power Recycling
Beam Splitter
$L_x = 4$ km
Laser Source
20 W
Test Mass
Test Mass
100 kW Circulating Power
Signal Recycling
Photodetector
b)
H1
L1
Strain noise ($Hz^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
20
100
1000
Frequency (Hz)