Gravitational Waves: Ripples in Space-Time from Colliding Black Holes and Neutron Stars

Brian Lantz, June 2019
for the LSC, Virgo, &
~2500 astronomers!

LIGO Scientific Collaboration

LIGO

LSC

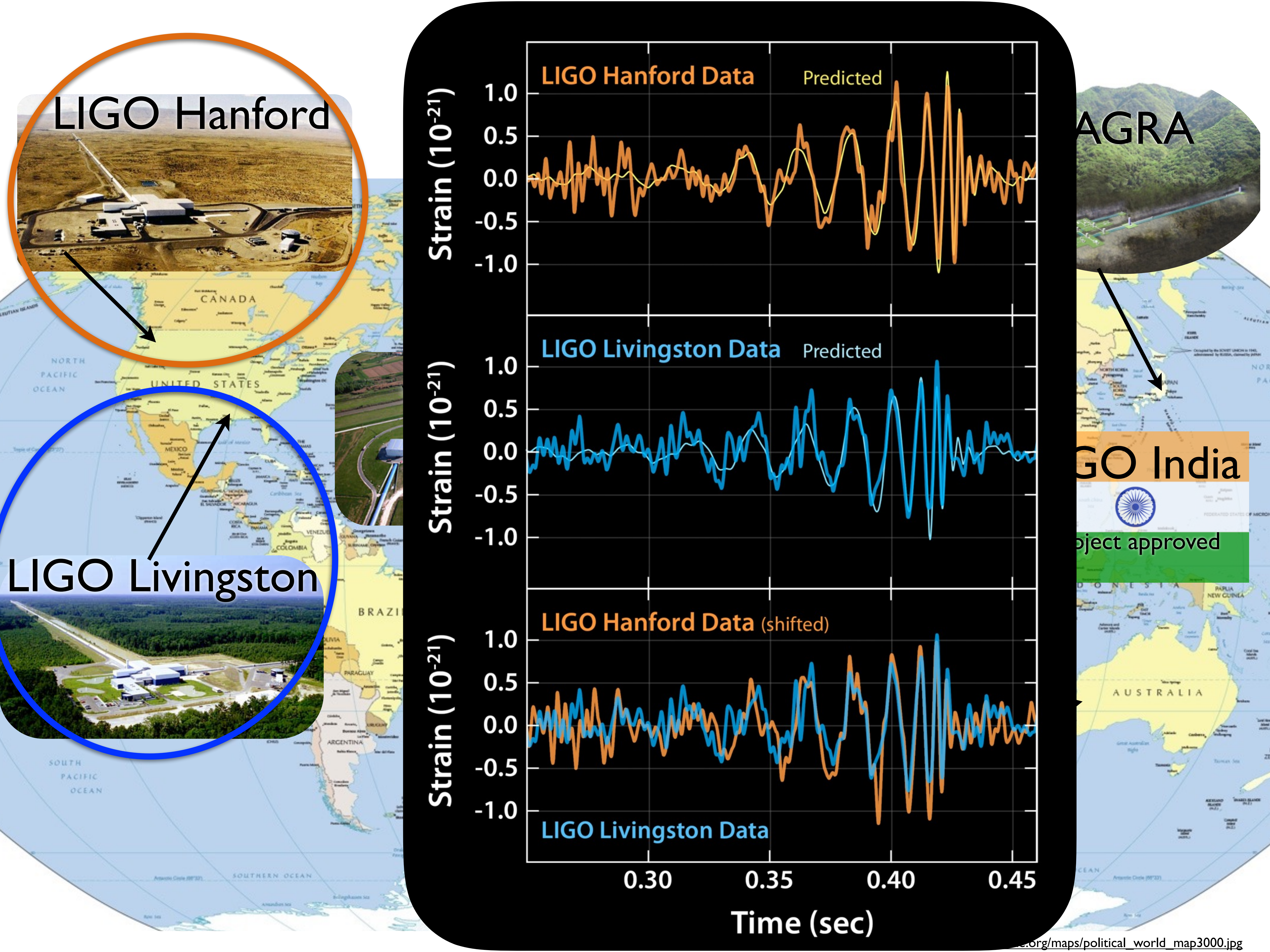
Caltech
American University
Andrews University
Washington State University
California State University Fullerton
PennState
Southern University and Agricultural & Mechanical College
Massachusetts Institute of Technology
Leland Stanford Junior University
The University Of Sheffield.
University of Maryland
indigo
Texas Tech University
Hillsdale College
Montclair State University
清華大学 Tsinghua University
Université de Montréal
Monash University
Universitat de les Illes Balears
International Institute of Physics
Cal State LA
Bellevue College
Montana State University
University of Cambridge
University of Southampton
Polytechnique Montréal
The University of Adelaide Australia
NCSA
W Bothell
Michigan
University of Wisconsin Milwaukee
Trinity University
Australian National University
University of the West of Scotland UWS
University of Strathclyde
University of Glasgow
Columbia University in the City of New York
Lomonosov Moscow State University
Syracuse University
OzGrav
The University of Western Australia
R·I·T
Cardiff University Prifysgol Caerdydd
Sonoma State University
University of Minnesota
RRCAT
NASA
The University of Chicago
IIT Hyderabad
University of Washington
Università degli Studi del Sannio
LSU Louisiana State University
Colorado State University
Charles Sturt University
Marshall Space Flight Center
Chennai Mathematical Institute
東京大学 The University of Tokyo
ACIGA
ICTS International Centre for Theoretical Sciences, Tata Institute of Fundamental Research
University of Birmingham
Georgia Institute of Technology
Korean Gravitational-Wave Group
The University of Melbourne
Embry-Riddle Aeronautical University
Northwestern
University of Florida
Universität Hamburg, Der Forschung | Der Lehre | Der Bildung
Whitman College
tifr
IUCAA
UTRGV
University and Institute of Advanced Research, The Puri Foundation for Education in India
Swinburne University of Technology
The University of Mississippi
INPE
GEO 600
Max Planck Institute for Gravitational Physics, Albert Einstein Institute
Leibniz Universität Hannover
University of Zurich
IISER Thiruvananthapuram
CITA ICAT
King's College London
IISER Kolkata
NASA Goddard Space Flight Center

International Network

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

Sept. 14, 2015

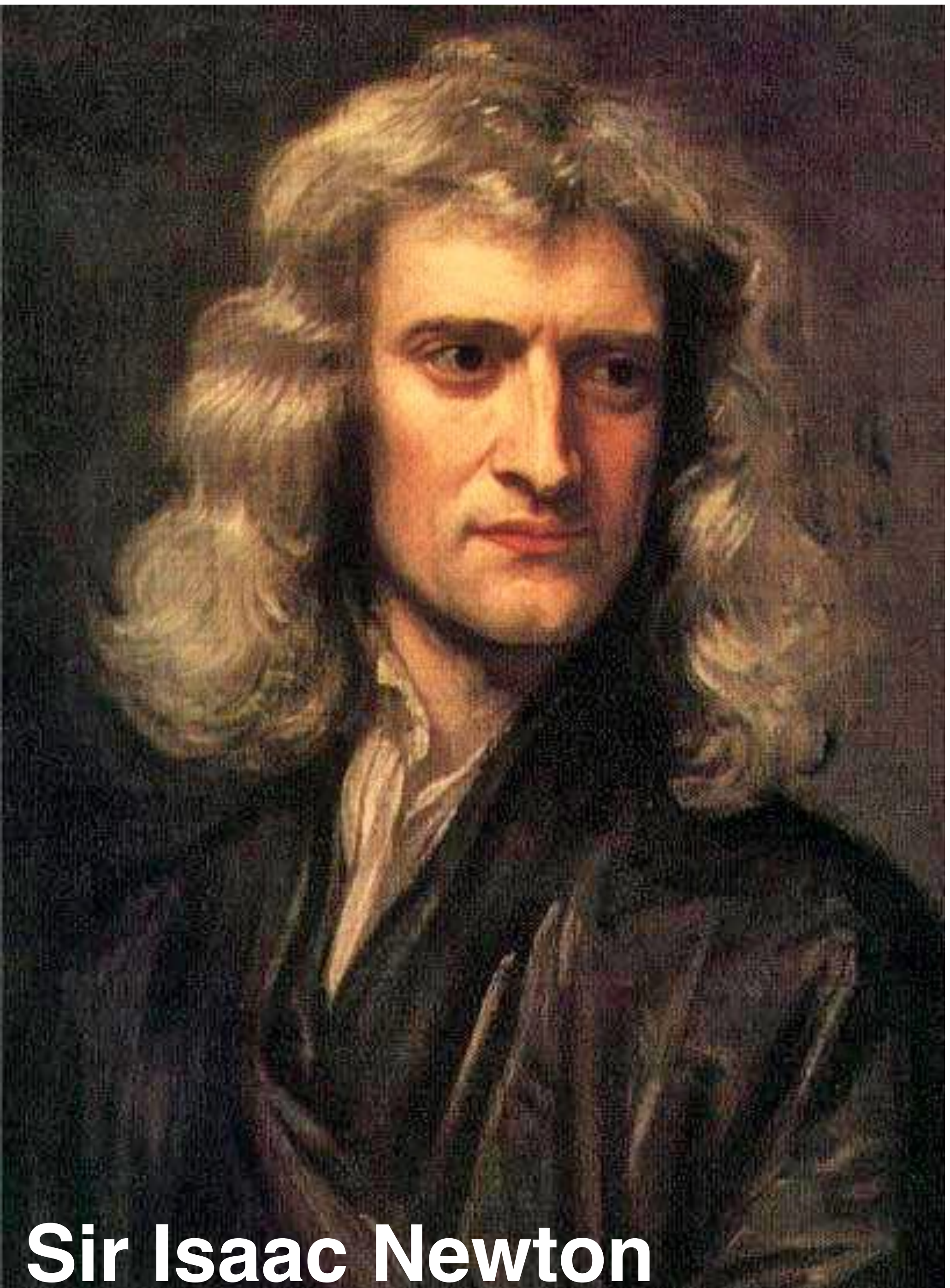
map from http://www.nationsonline.org/maps/political_world_map3000.jpg


LIGO Hanford
LIGO Livingston
AGRA
GO India
oject approved
LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
CANADA
UNITED STATES
NORTH PACIFIC OCEAN
MEXICO
SOUTH PACIFIC OCEAN
SOUTHERN OCEAN
AUSTRALIA
e.org/maps/political_world_map3000.jpg

Oct. 3, 2017

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

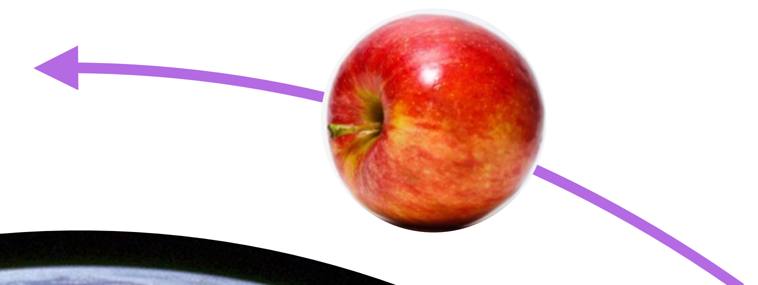
What is a Gravitational Wave?

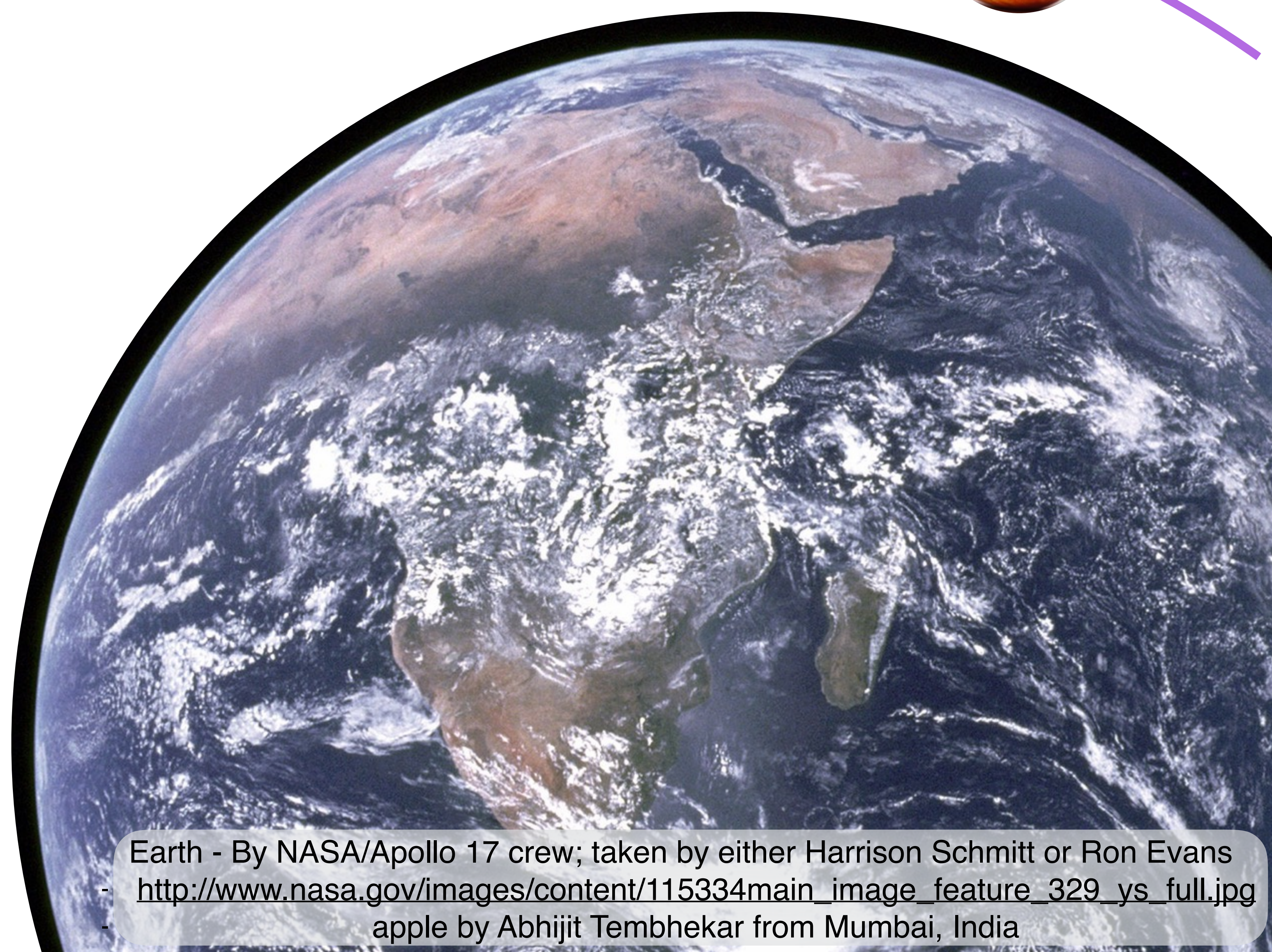


By Sir Godfrey Kneller
- http://www.newton.cam.ac.uk/art/portrait.html

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

Implies immediate action at a distance





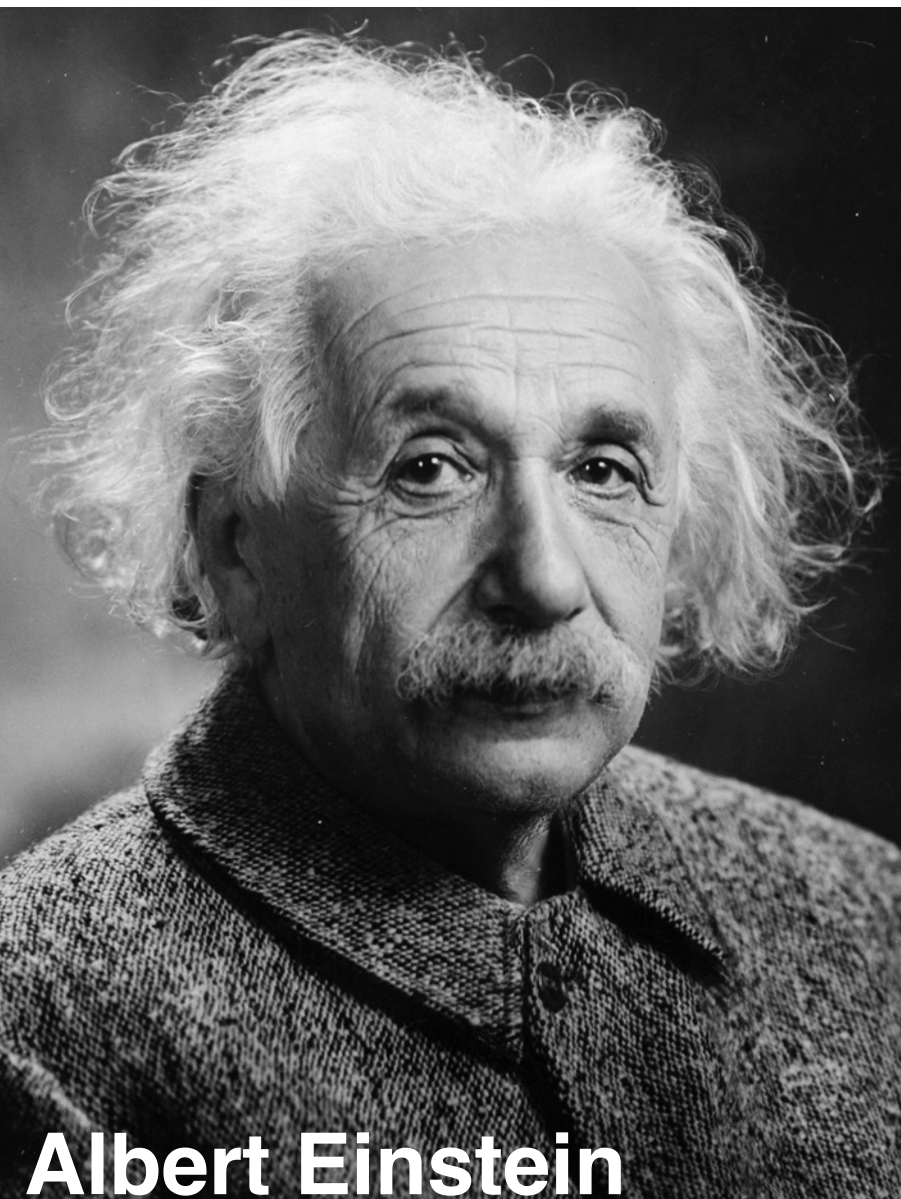
Earth - By NASA/Apollo 17 crew; taken by either Harrison Schmitt or Ron Evans
- http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
- apple by Abhijit Tembhekar from Mumbai, India

What is a Gravitational Wave?

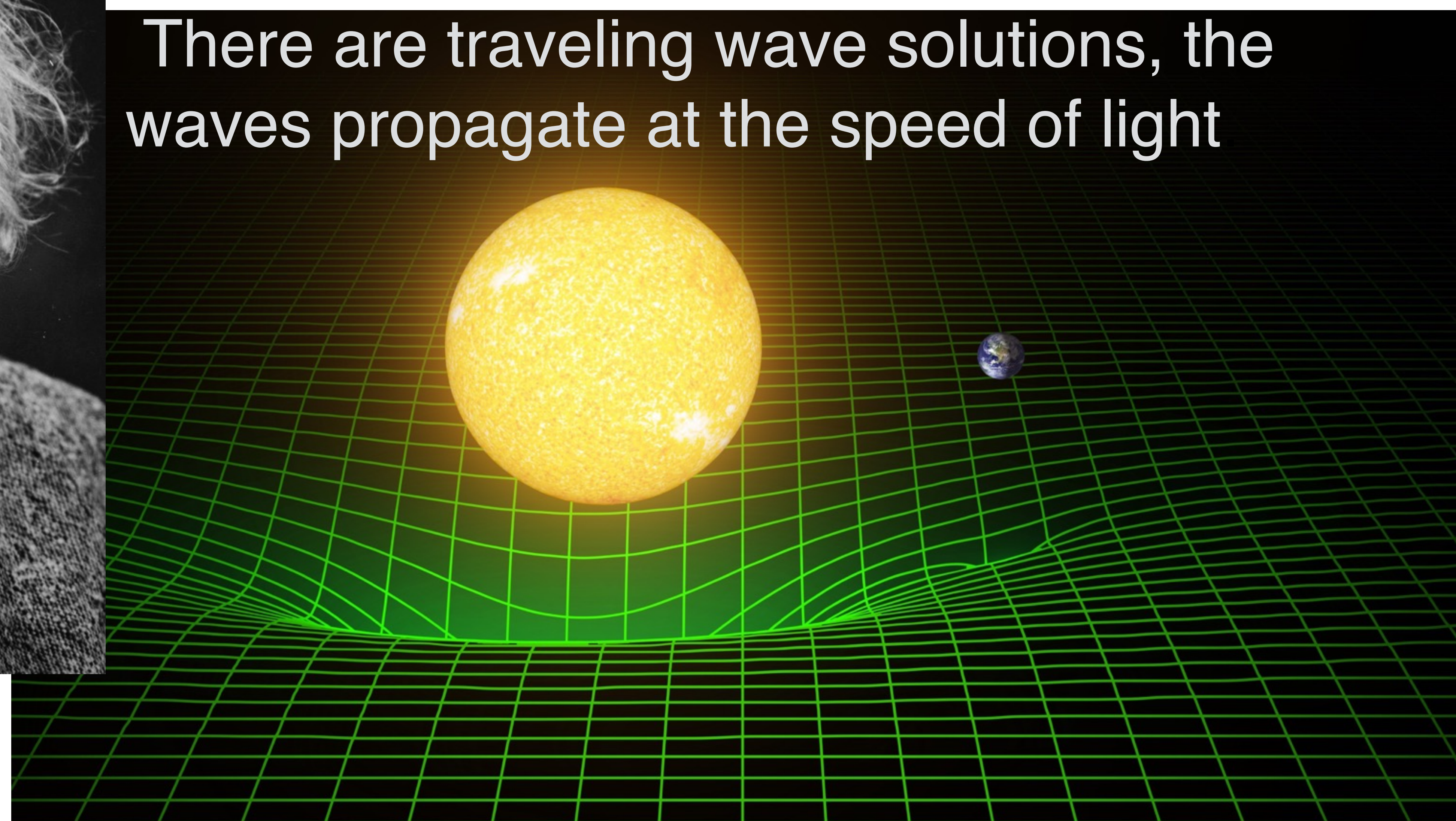
Predicted by Einstein in 1916 as part of GR.

"Spacetime tells matter how to move,
matter tells spacetime how to curve"

- J. A. Wheeler

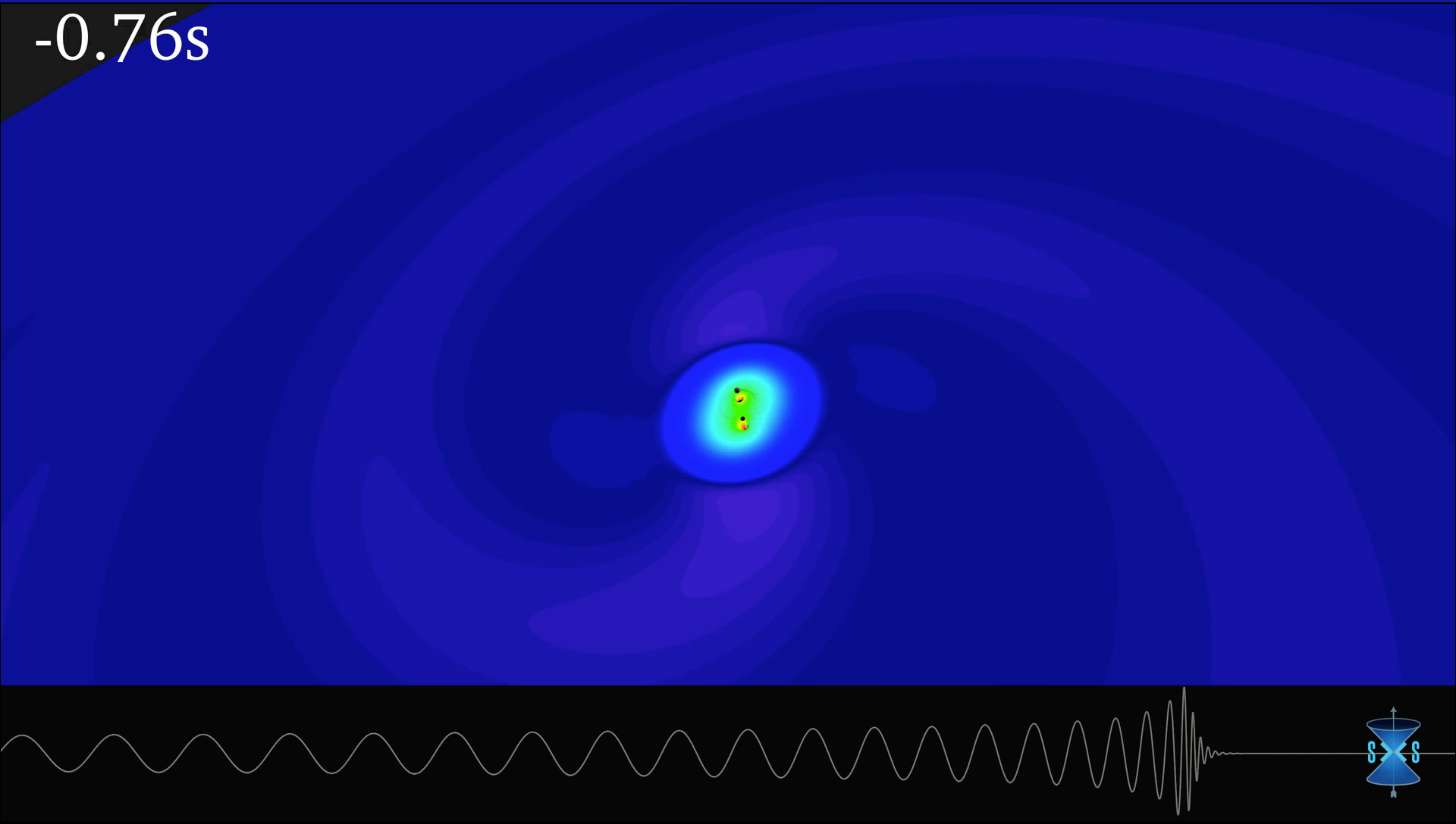


There are traveling wave solutions, the waves propagate at the speed of light



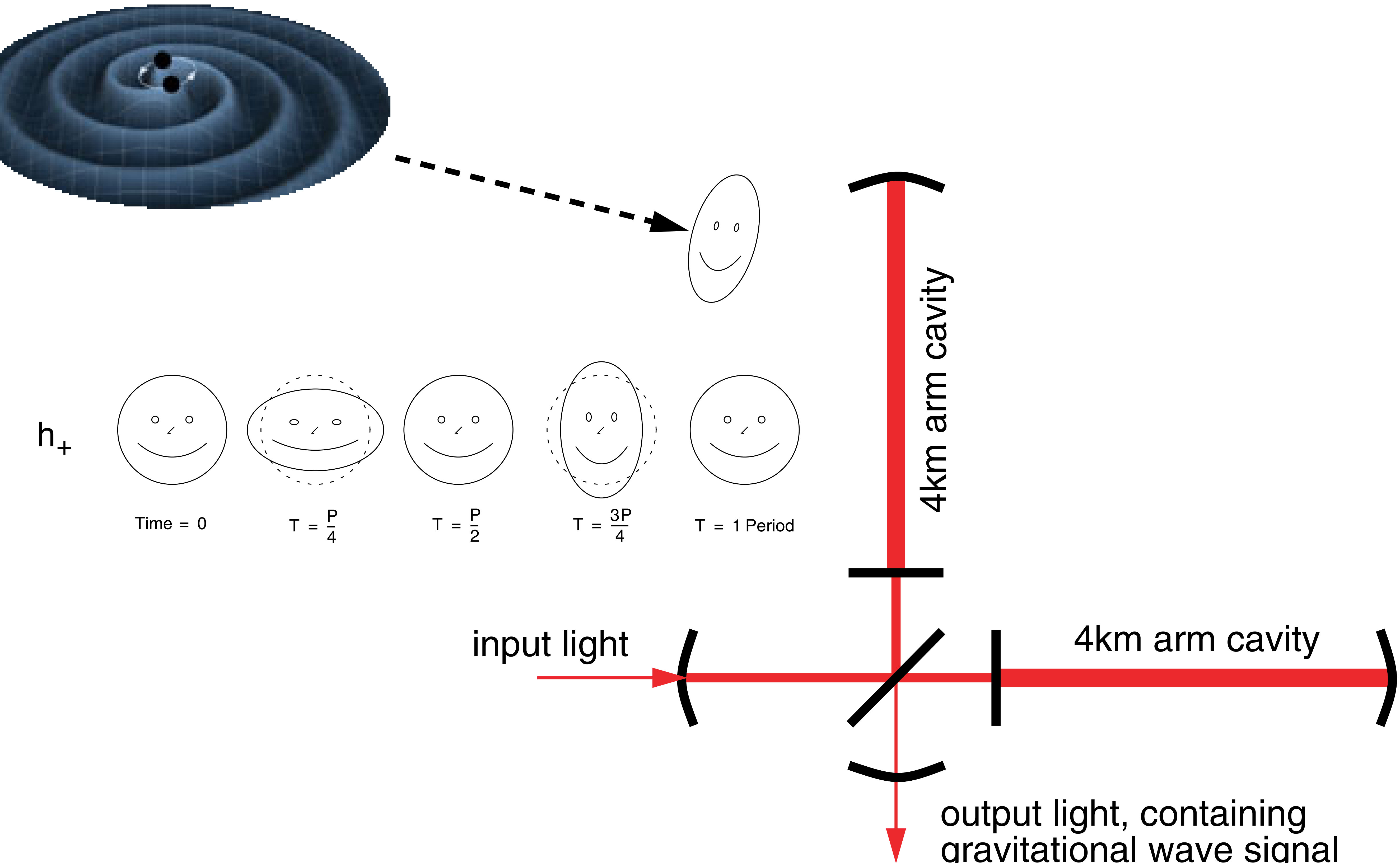
Photograph by Orren Jack Turner,
Library of Congress digital ID cph.3b46036.

Simulation of the event



http://mediaassets.caltech.edu/gwave

The LIGO concept



The LIGO concept

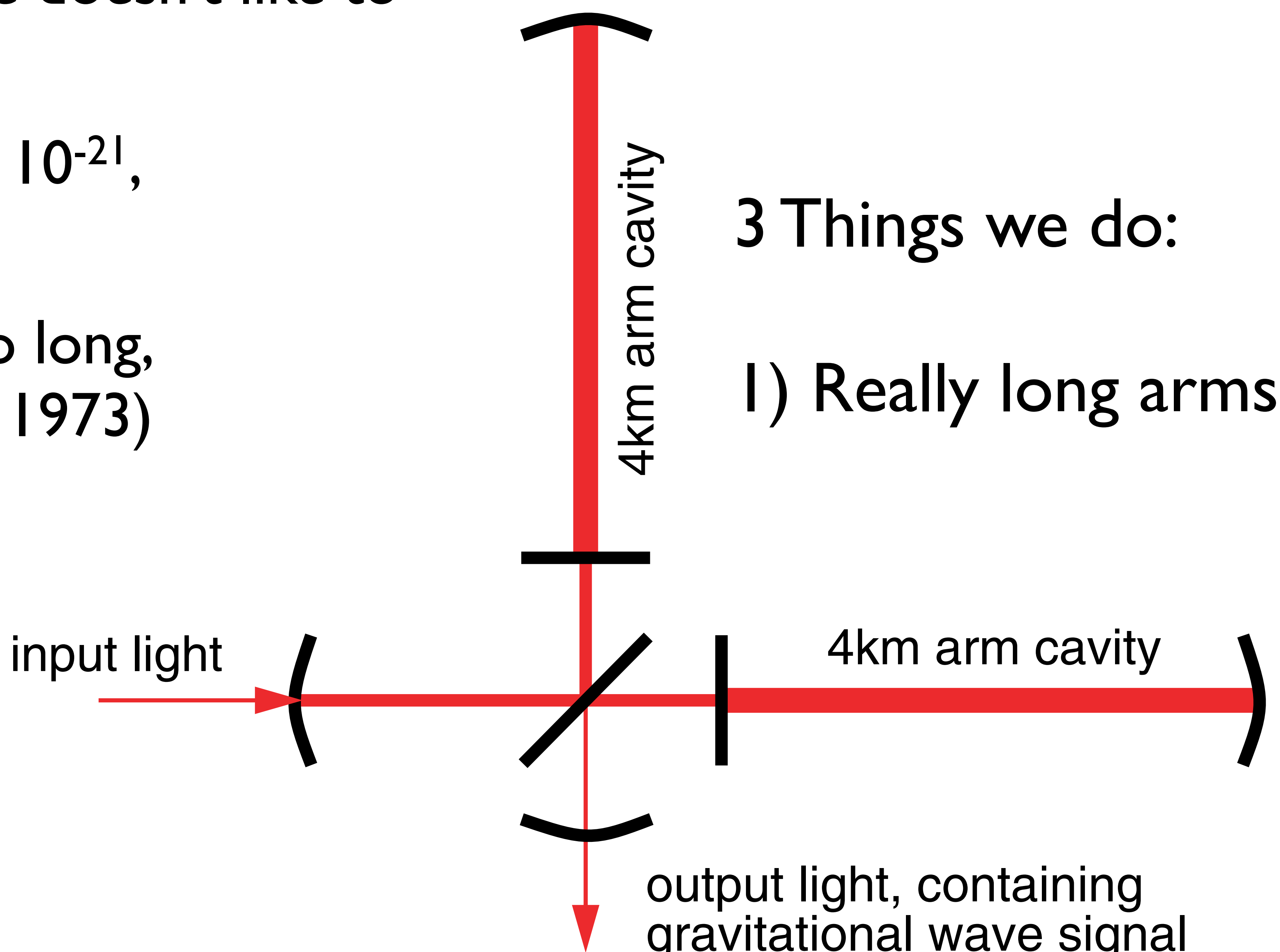
Gravitational waves are hard to measure because space doesn't like to stretch.

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

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

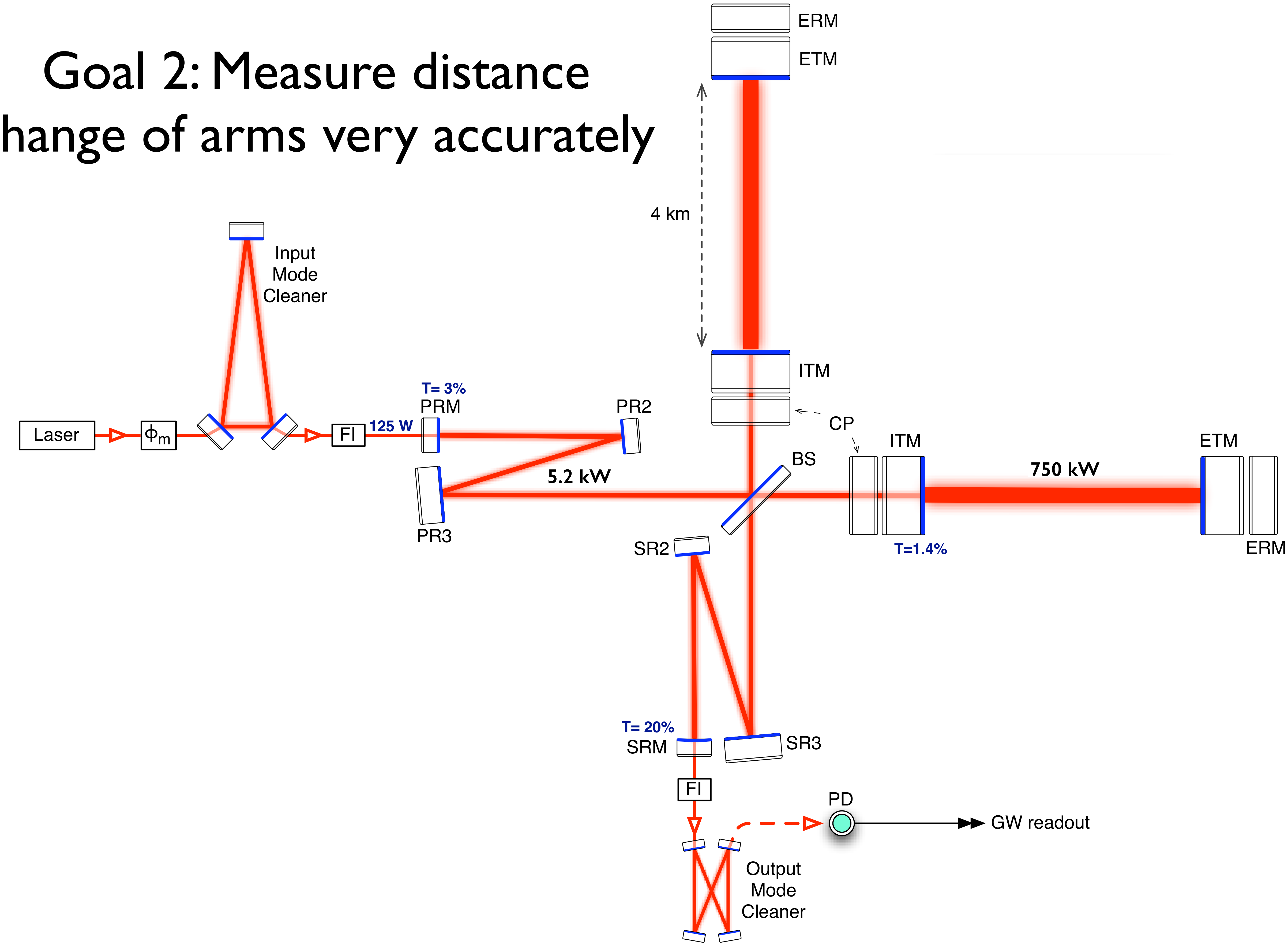
3 Things we do:

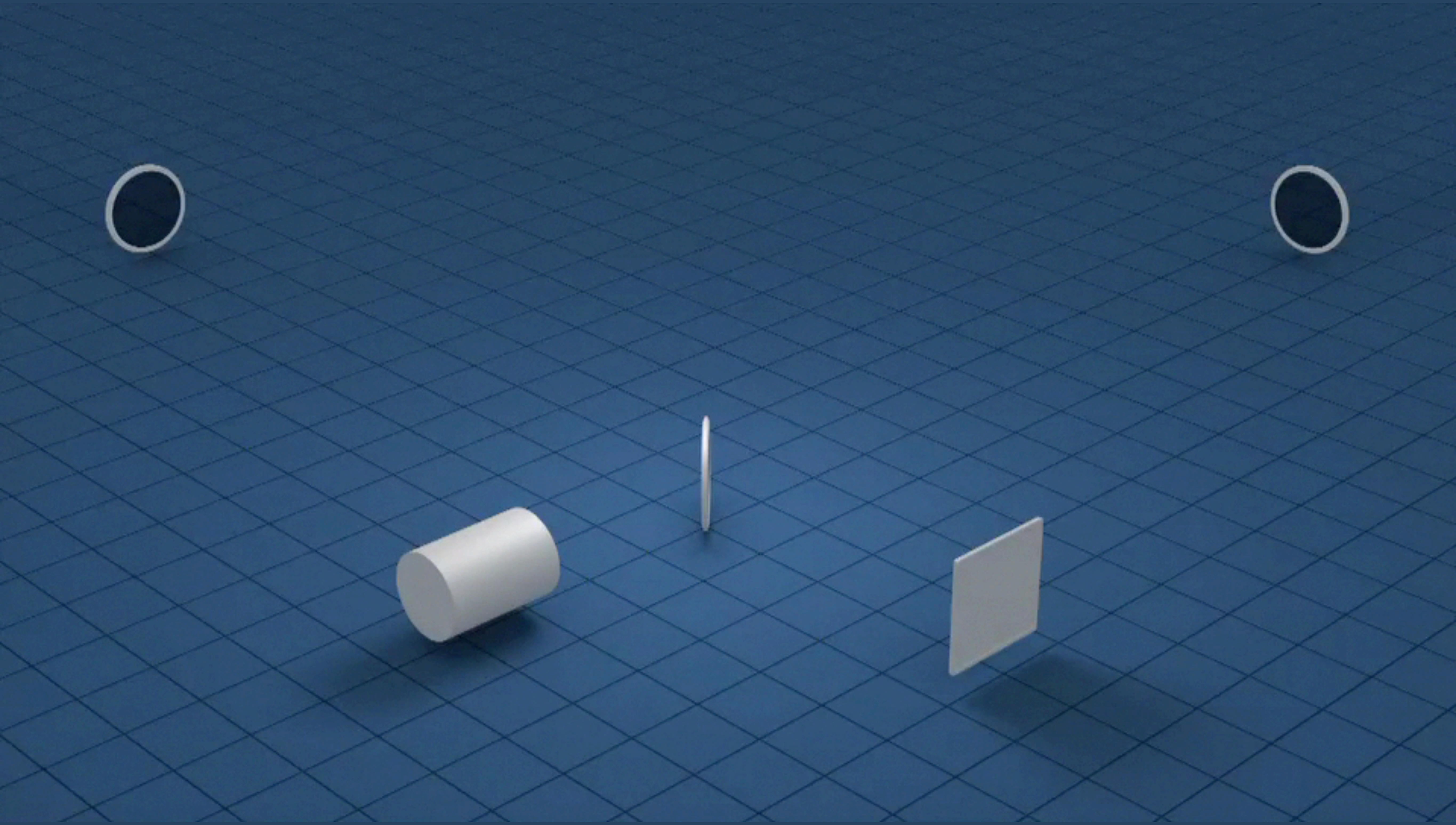
1) Really long arms.



Layout of the interferometer

Goal 2: Measure distance change of arms very accurately

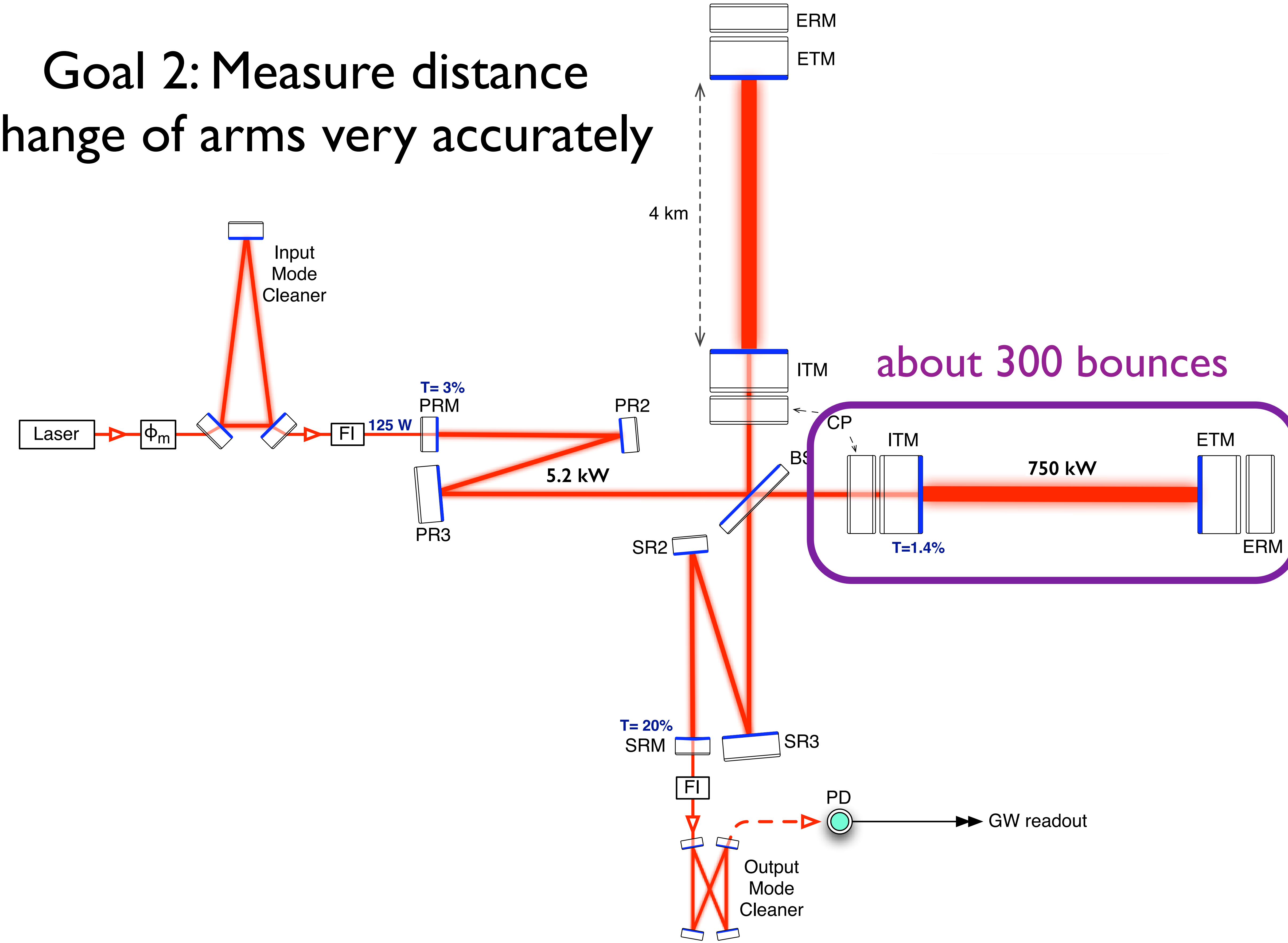




http://mediaassets.caltech.edu/gwave

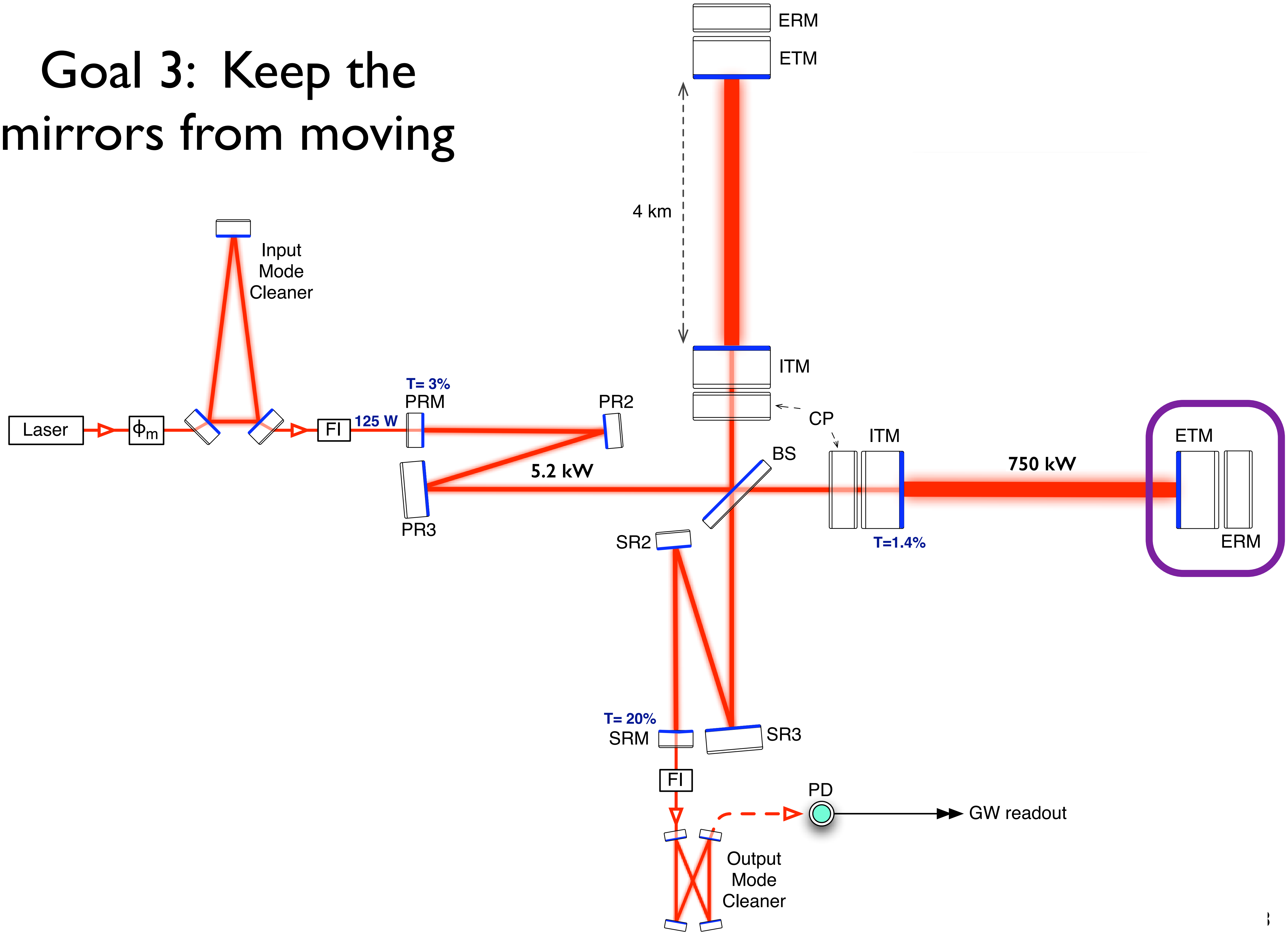
Fabry-Perot arms

Goal 2: Measure distance change of arms very accurately

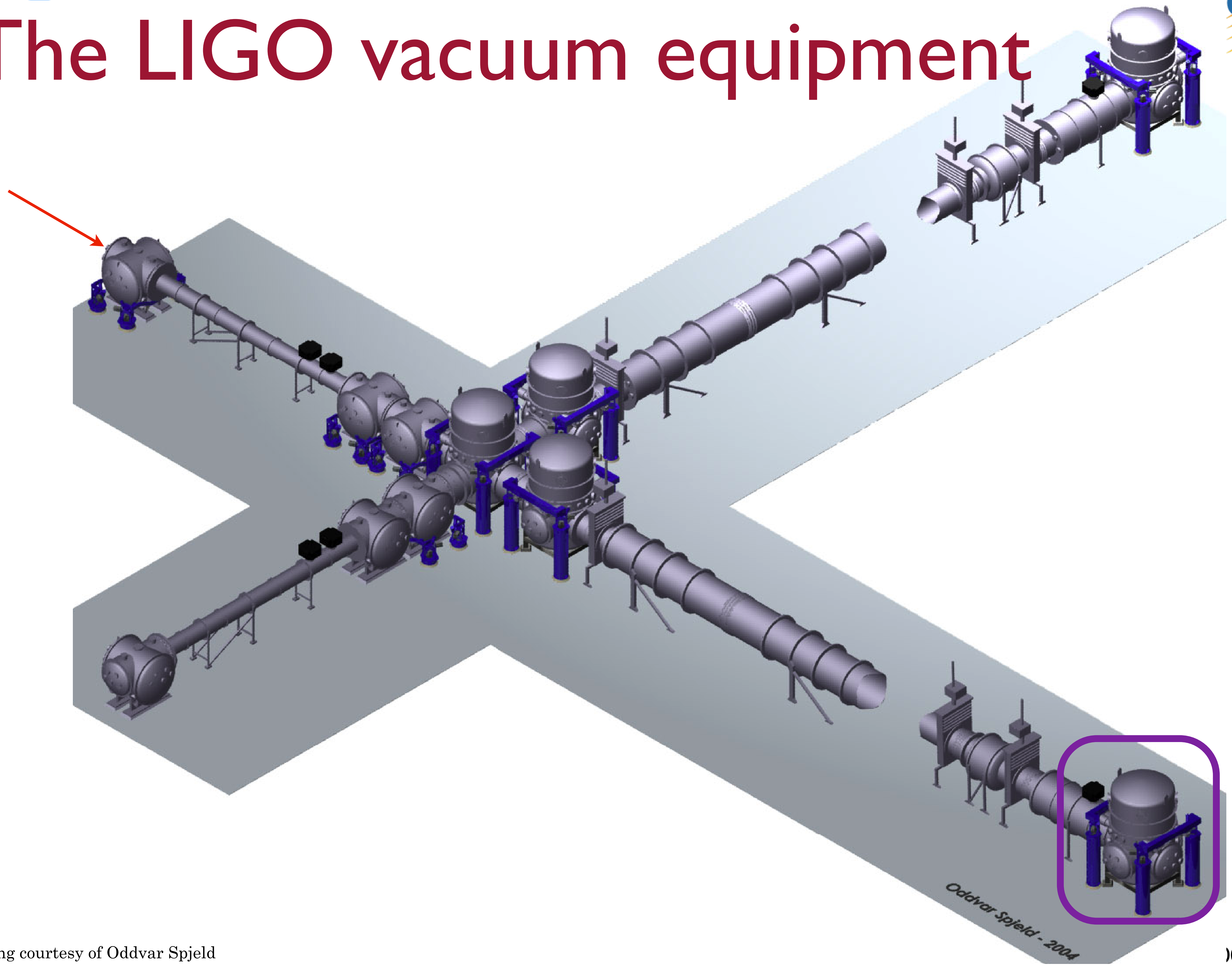


Layout of the interferometer

Goal 3: Keep the mirrors from moving

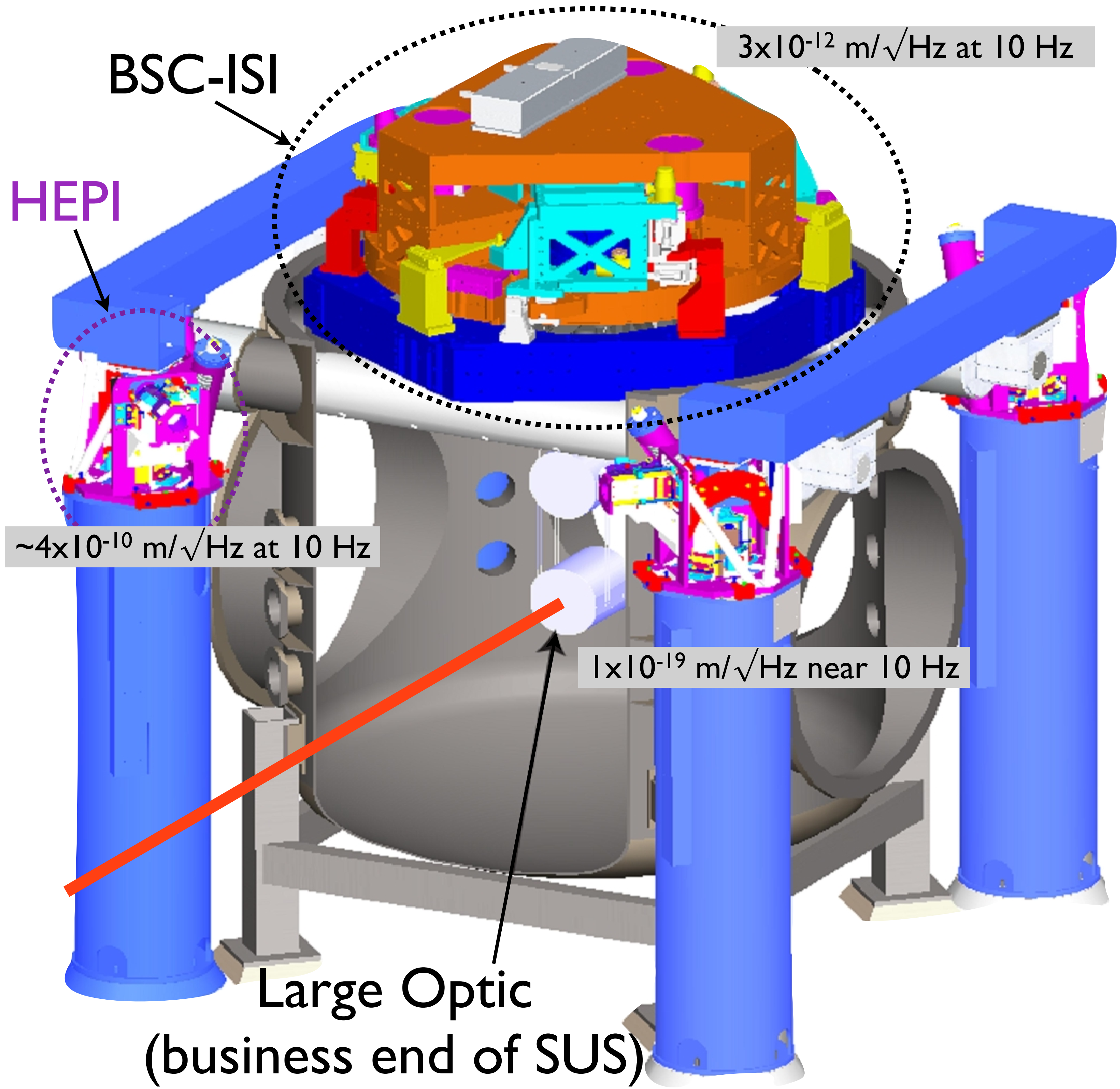


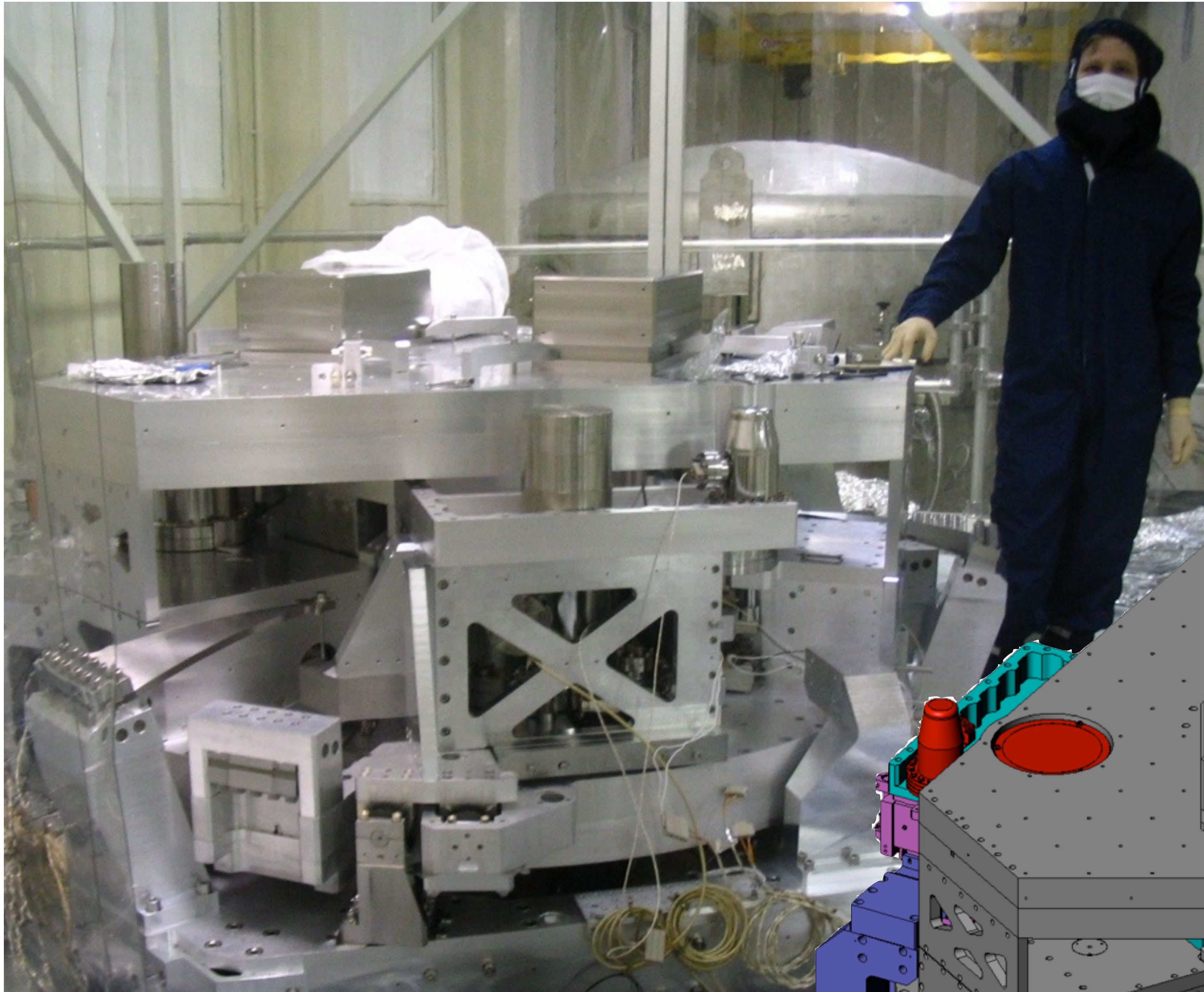
The LIGO vacuum equipment

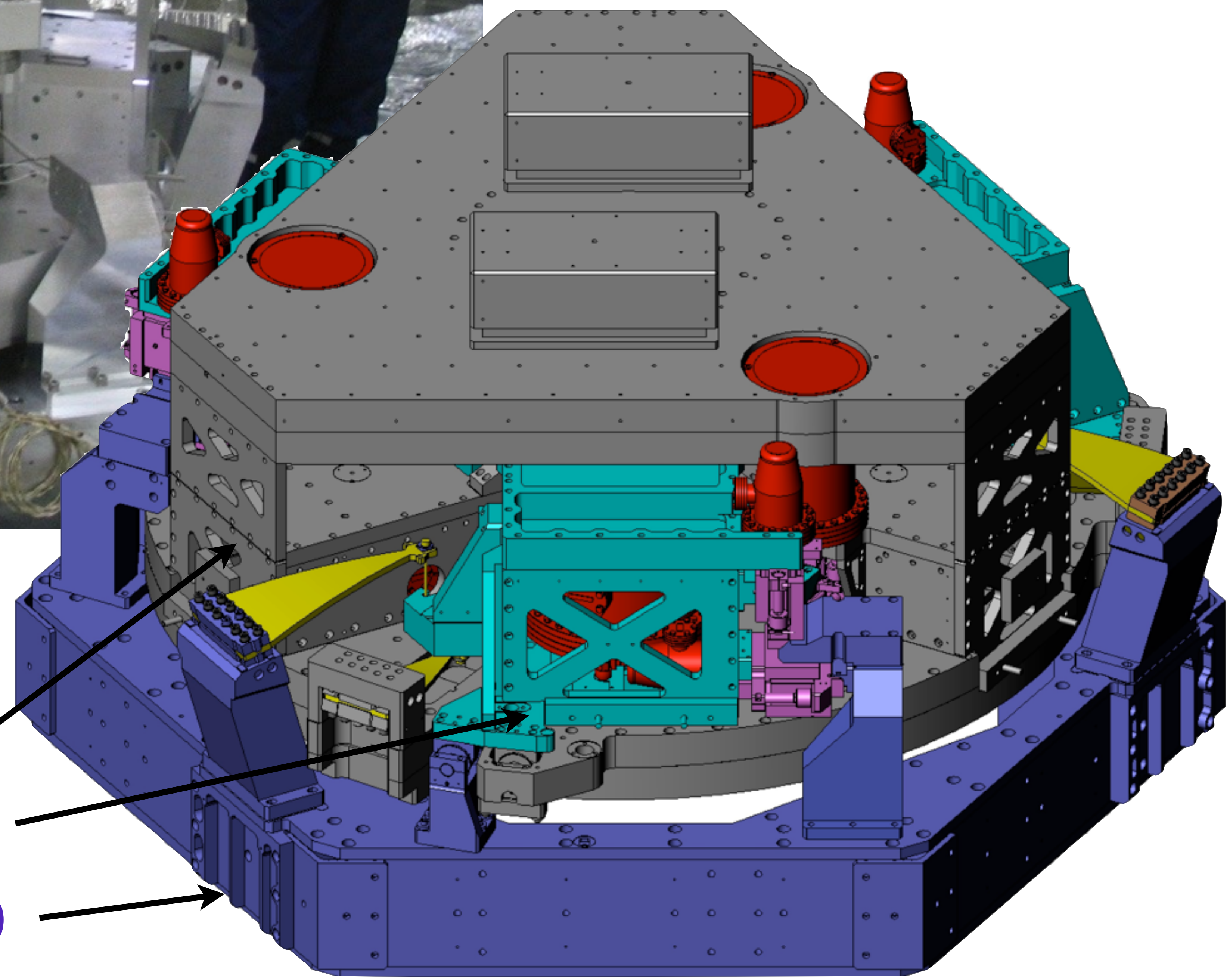


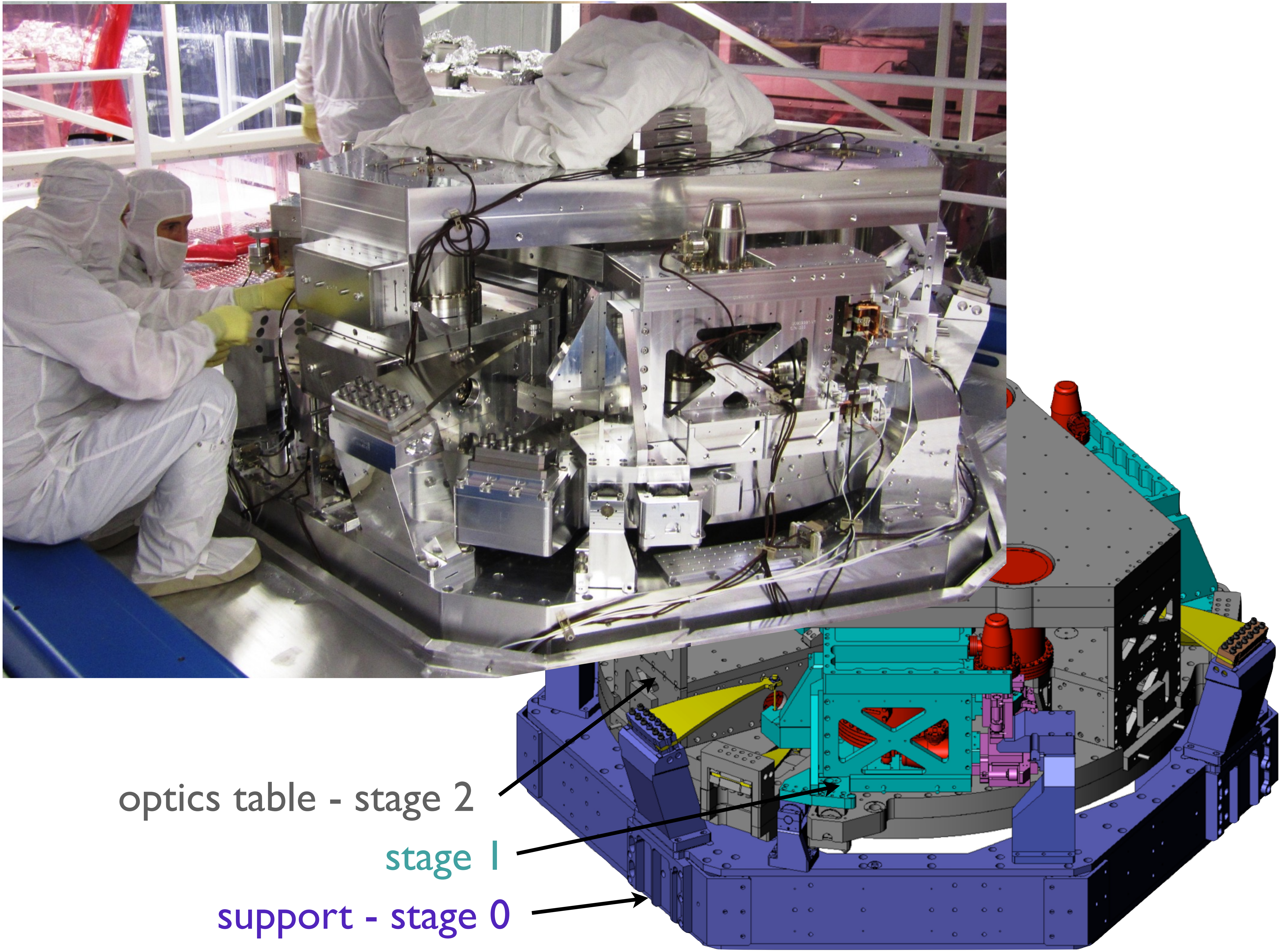
drawing courtesy of Oddvar Spjeld

Isolation of the Mirrors

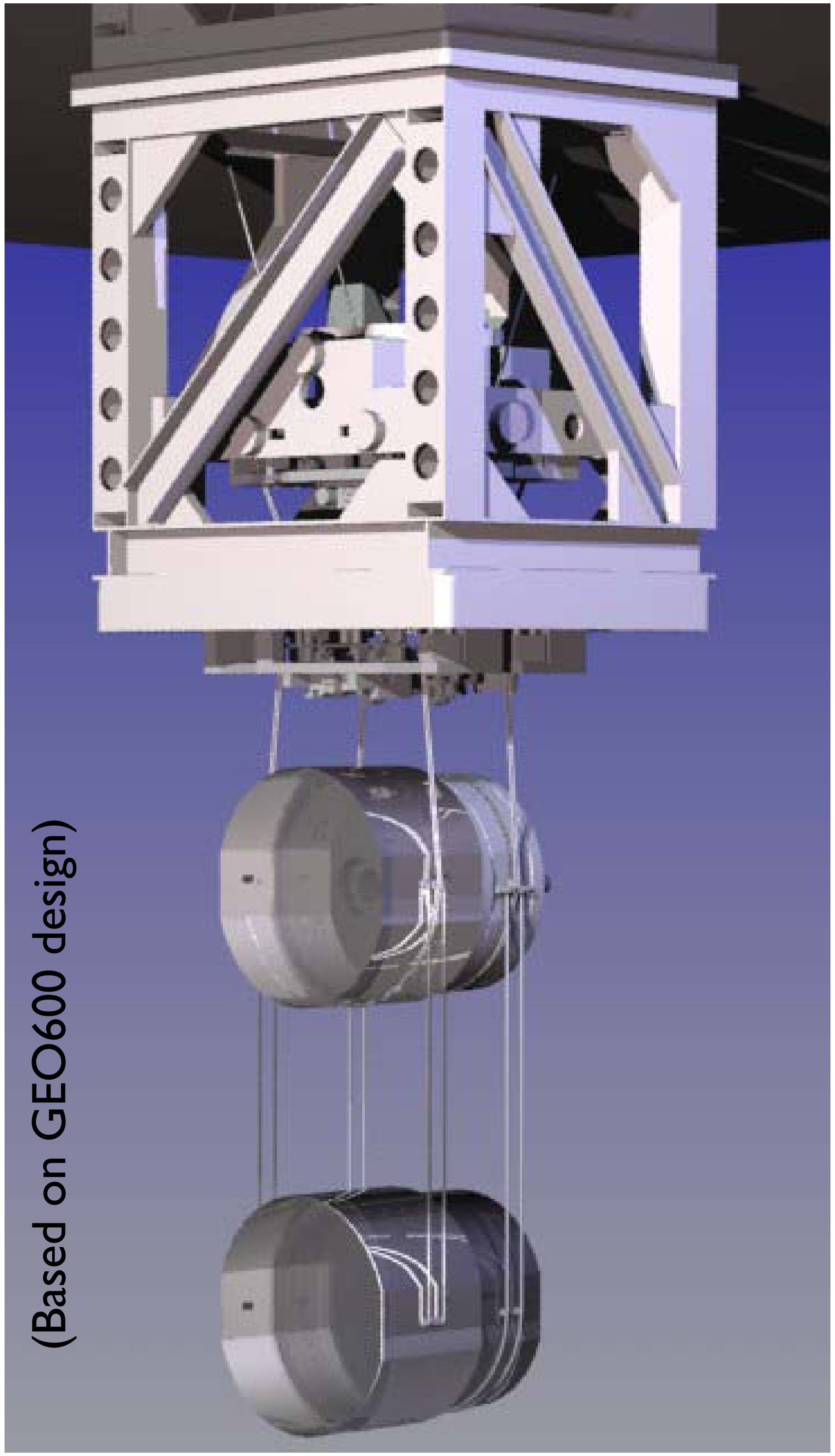





optics table - stage 2
stage 1
support - stage 0


optics table - stage 2
stage 1
support - stage 0

Pendulum Suspension

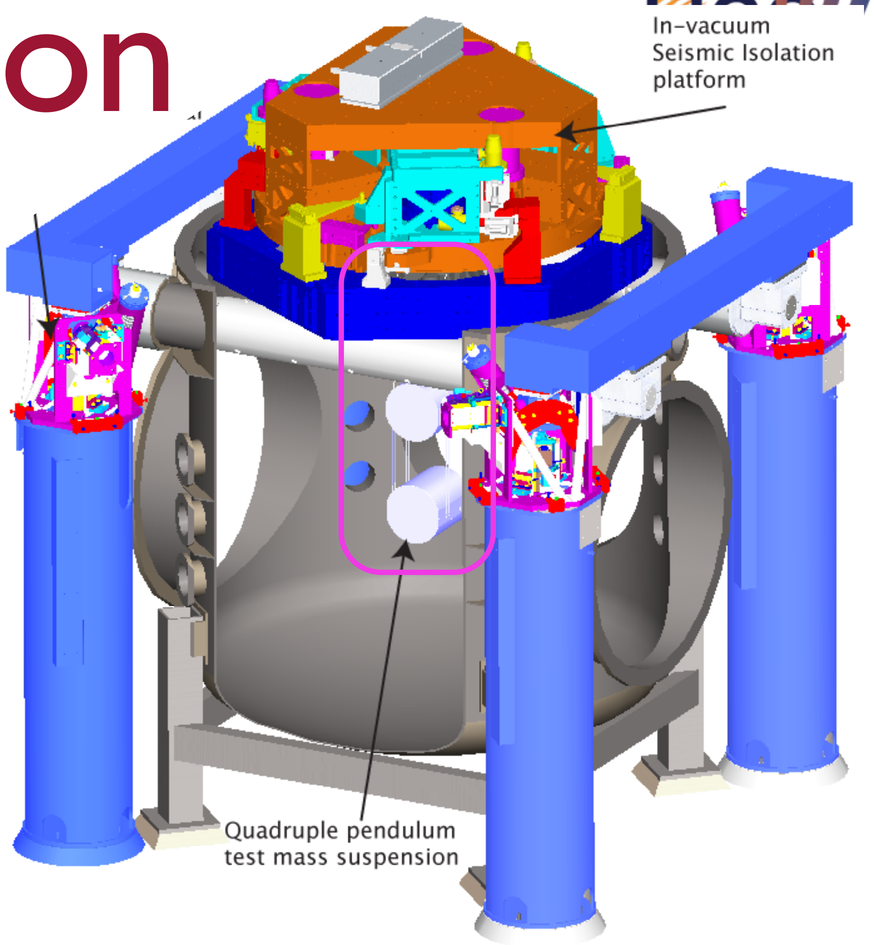


LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

Suspended as a
4 stage pendulum

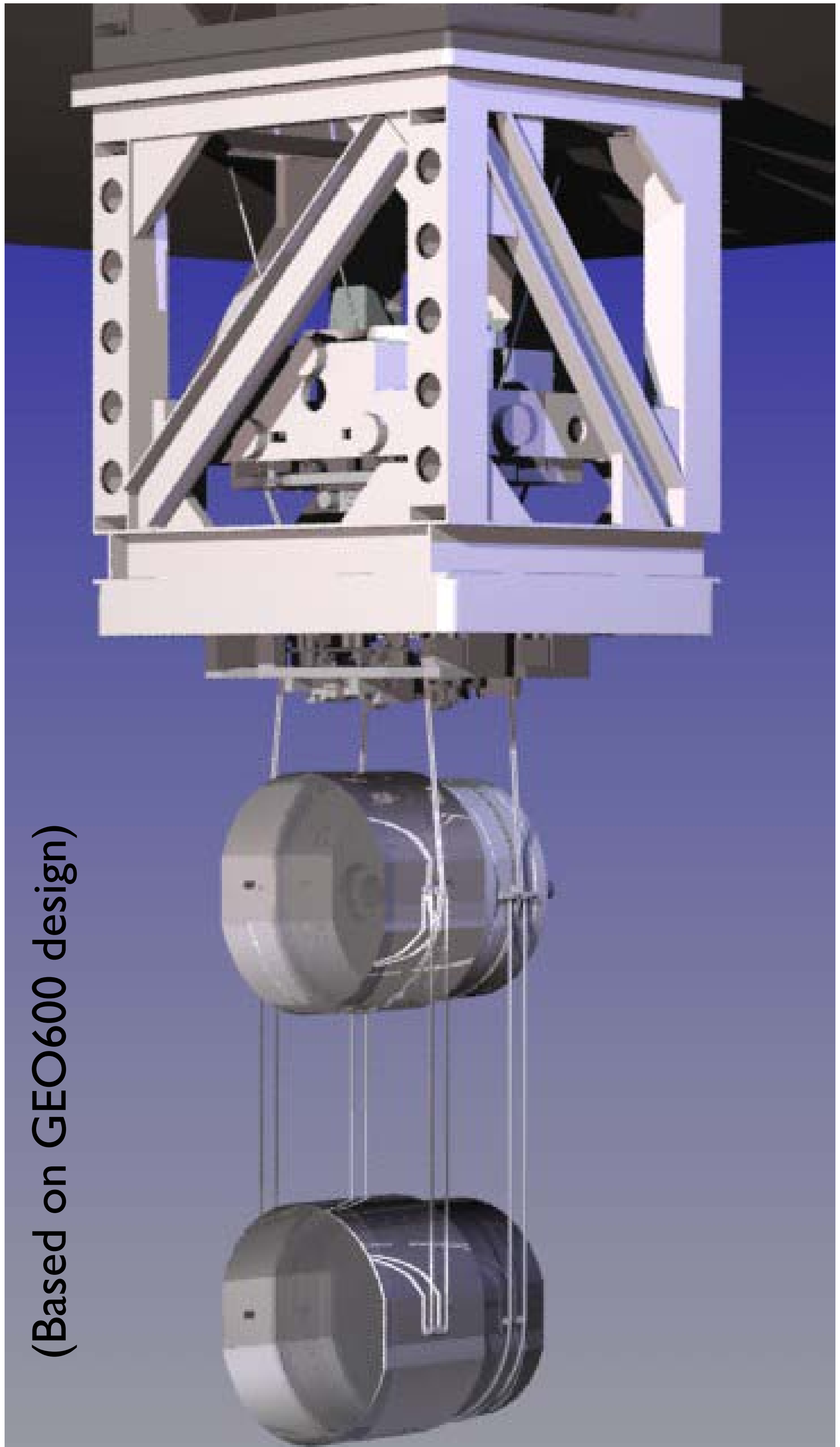
Best coatings available

Motion at 10 Hz set by
thermal driven vibration

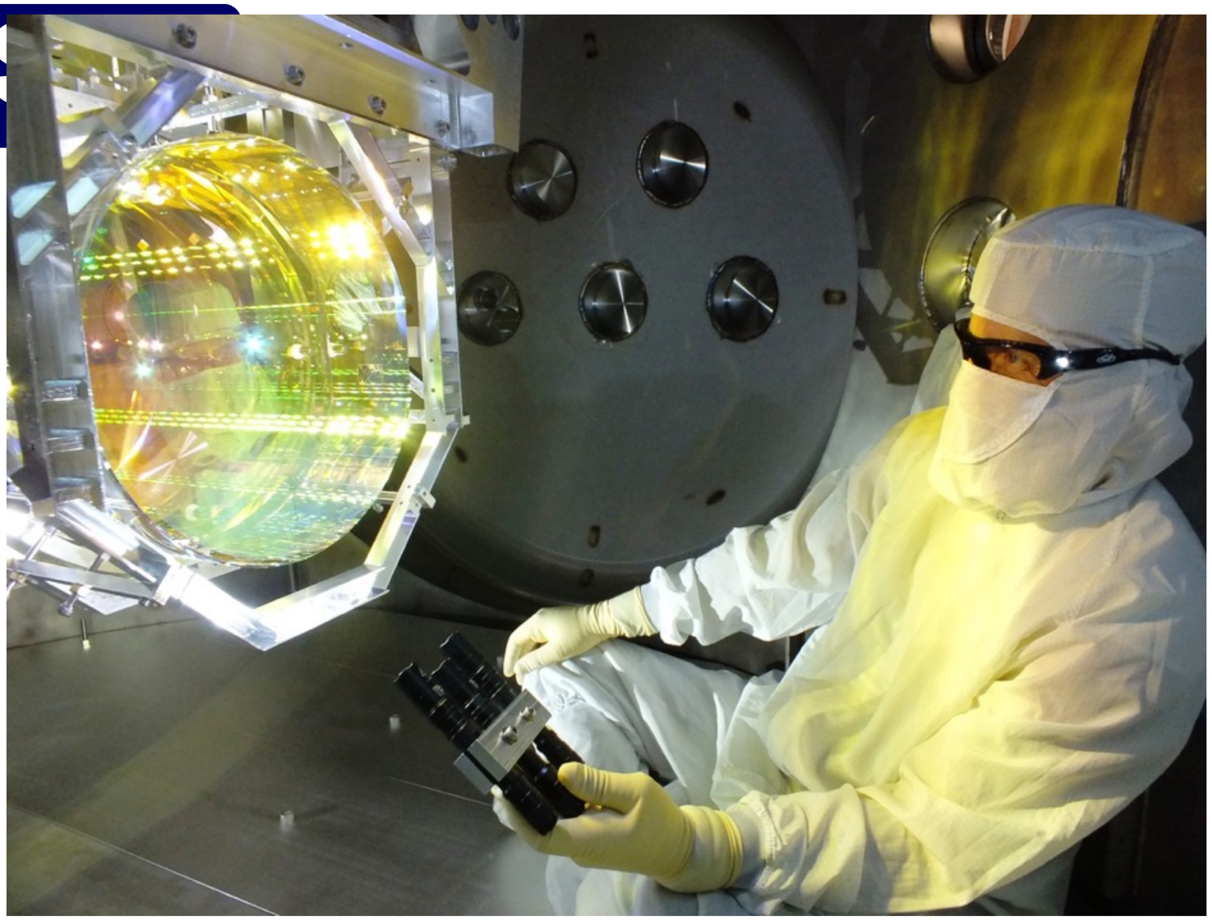


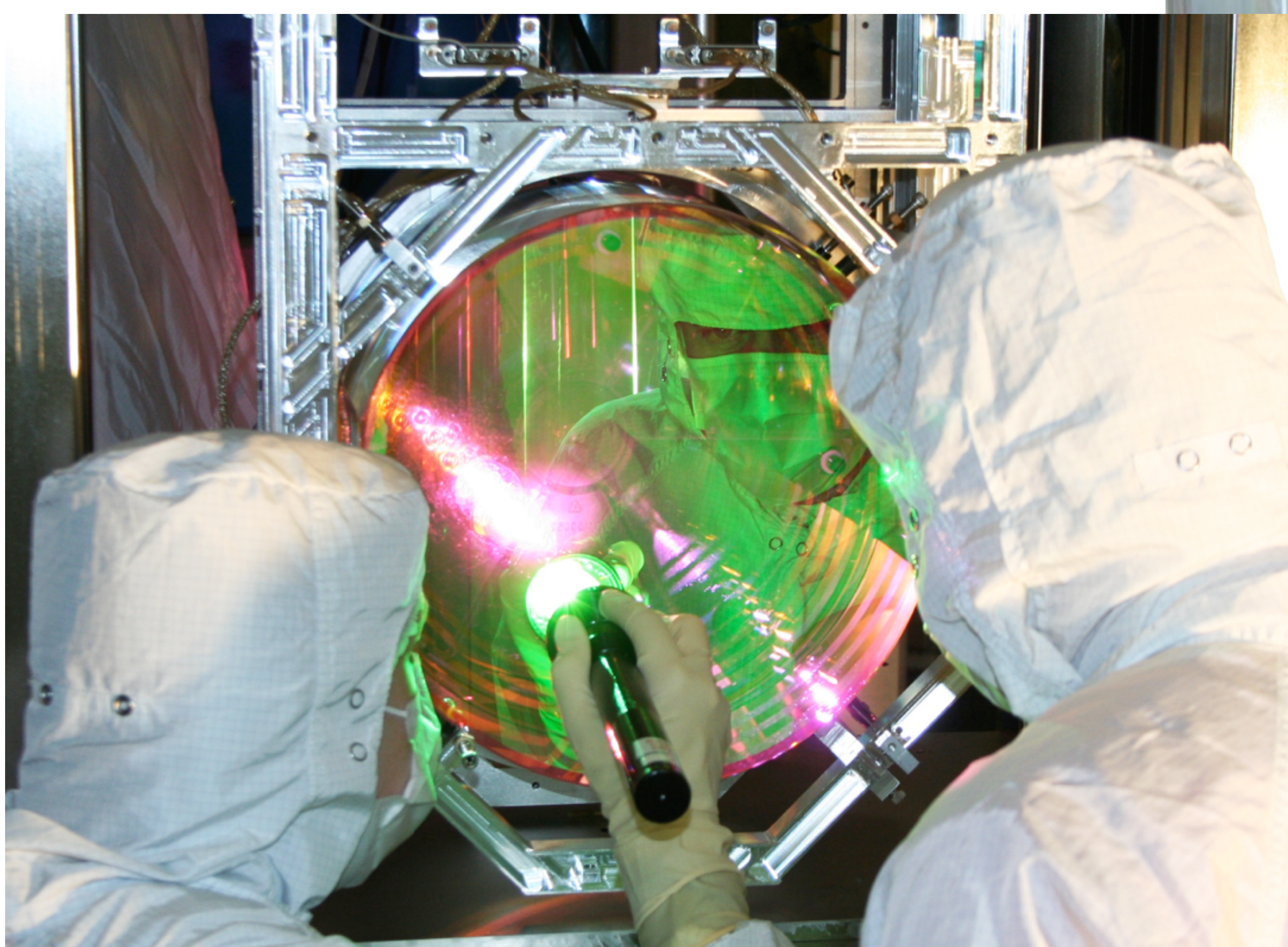
silicate bonding creates a monolithic final stage

Pendulu



Mirror picts

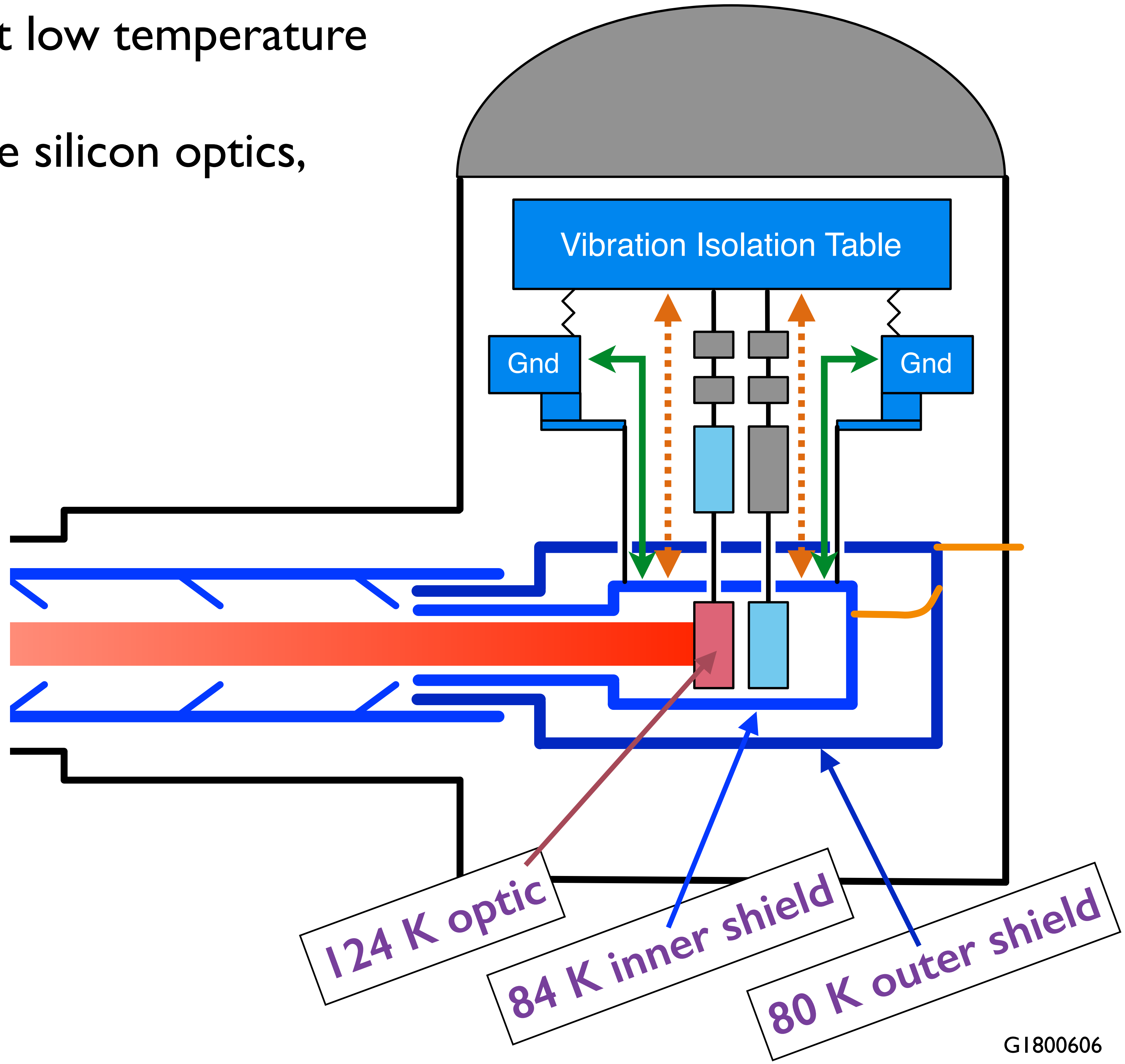




Next Generation Tech.

Silicon optics working at low temperature

- New lasers,
- new suspensions, large silicon optics,
- new coatings,



G1800606

Next Generation Tech.

Silicon optics working at low temperature

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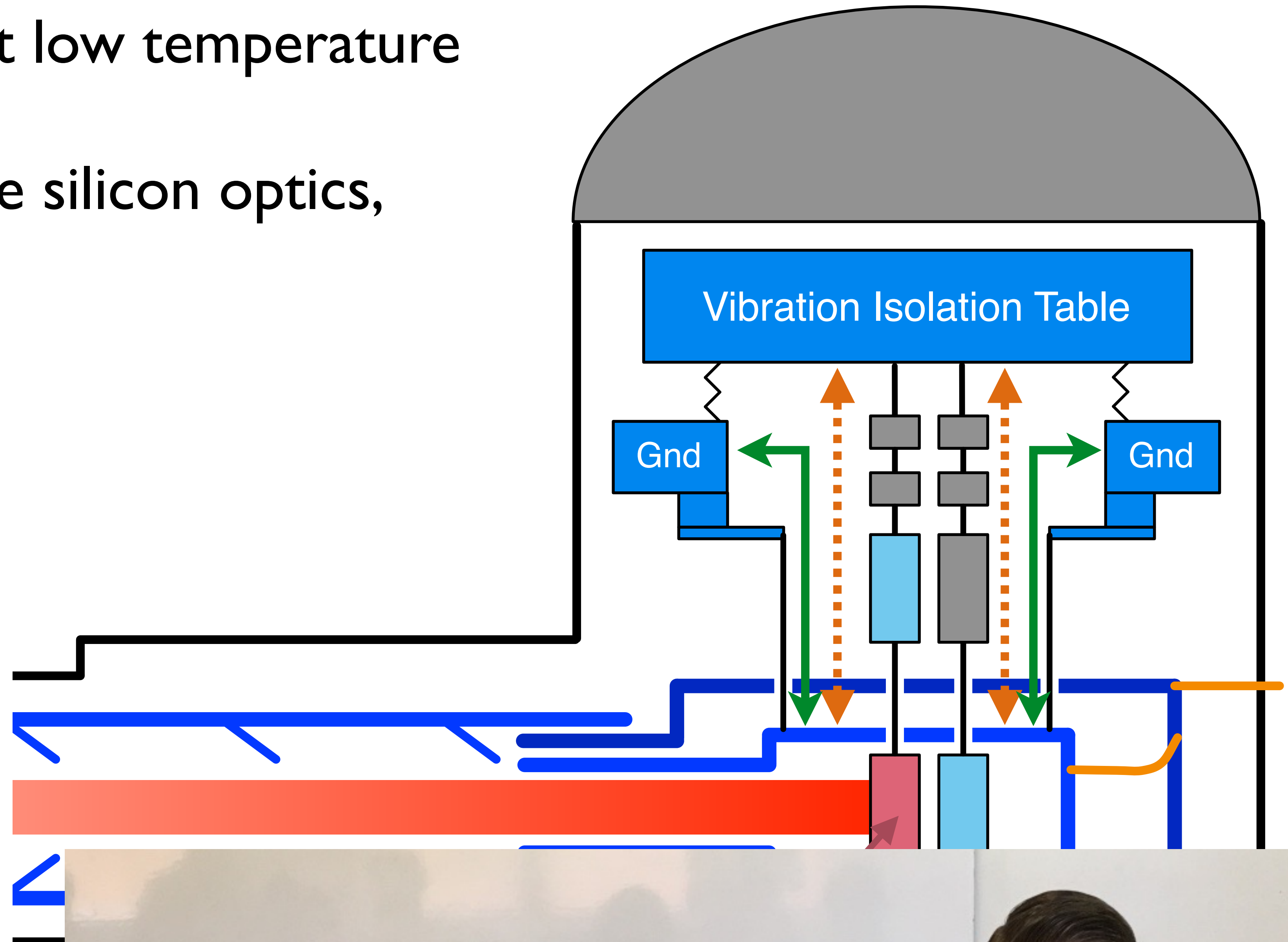
- new coatings,



Next Generation Tech.

Silicon optics working at low temperature

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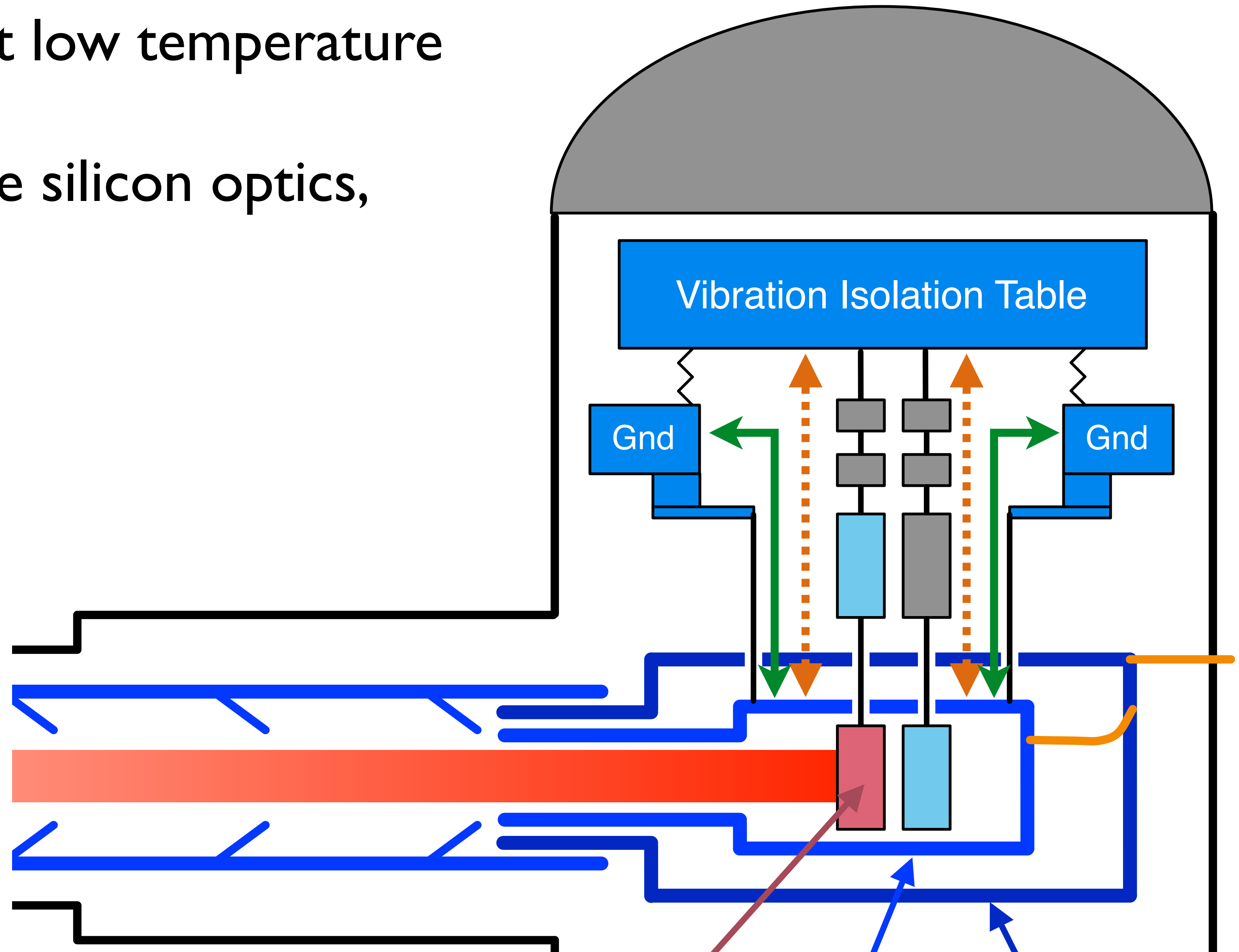
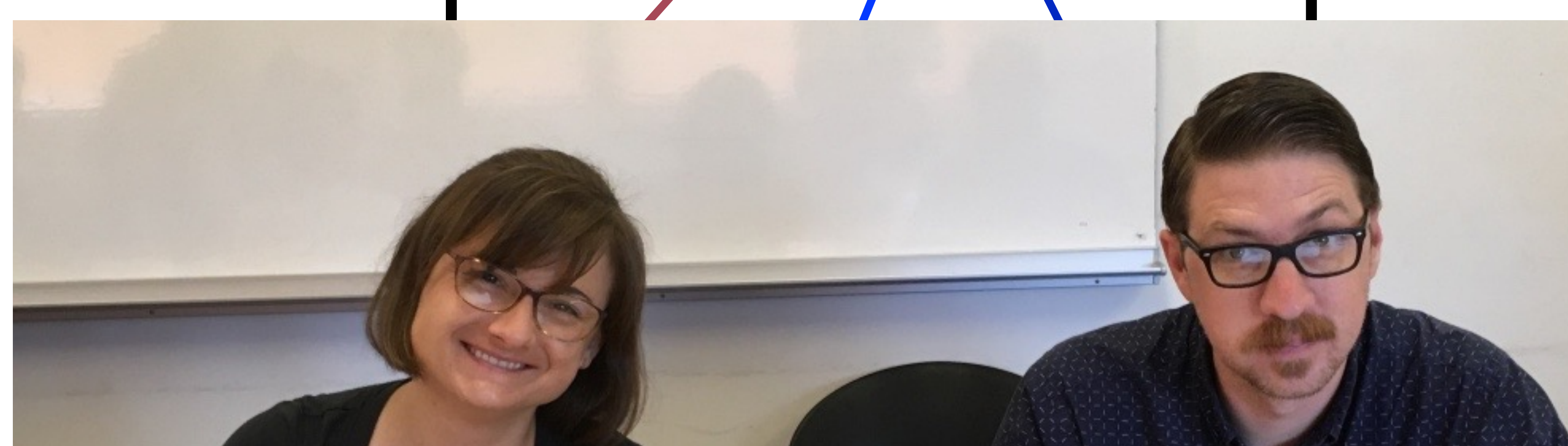


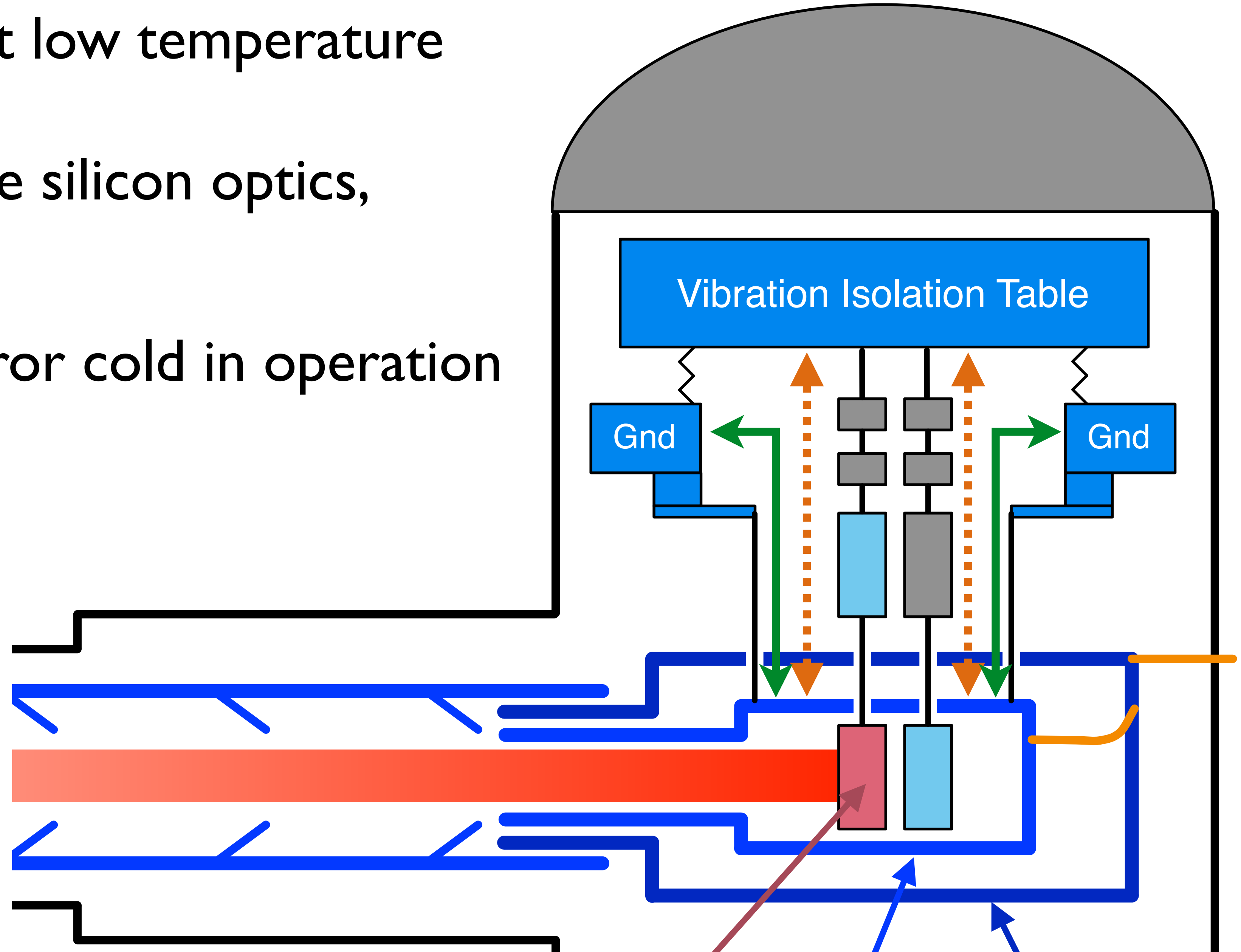


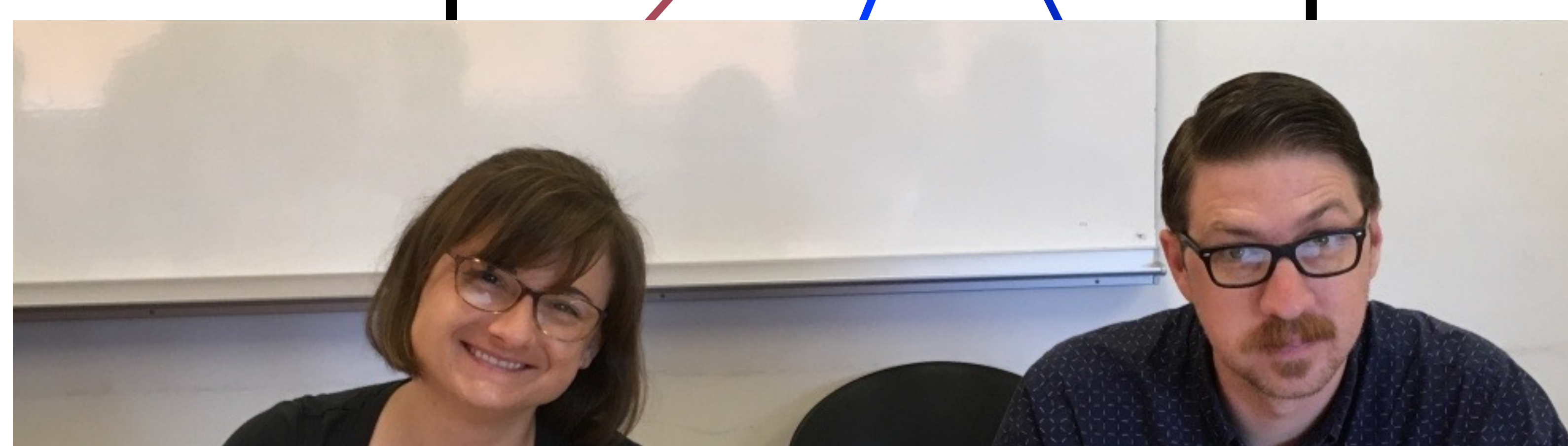
Next Generation Tech.

Silicon optics working at low temperature

- New lasers,
- new suspensions, large silicon optics,
- new coatings,

- tech. to keep the mirror cold in operation





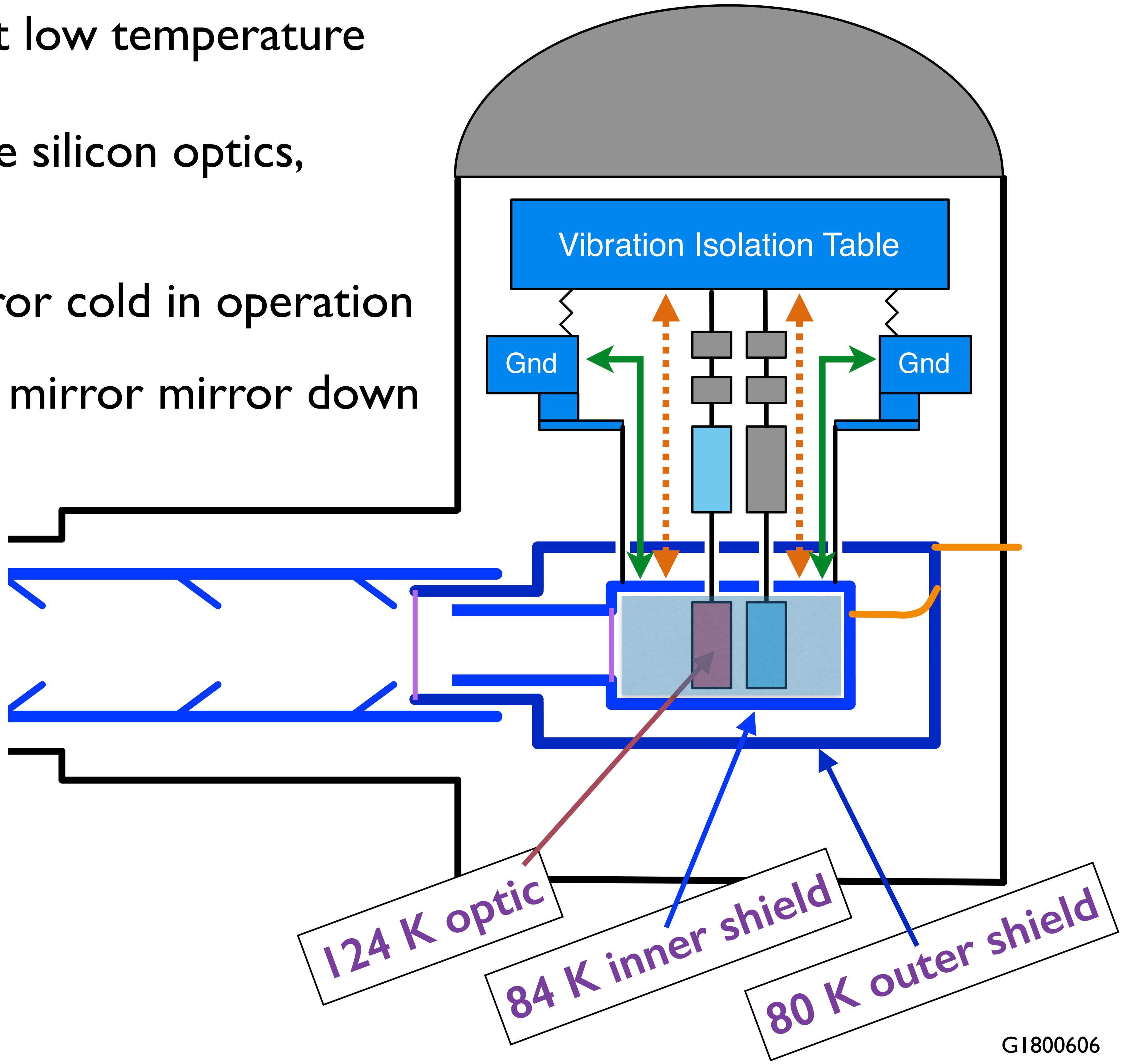
Next Generation Tech.

Silicon optics working at low temperature

- New lasers,
- new suspensions, large silicon optics,
- new coatings,

- tech. to keep the mirror cold in operation

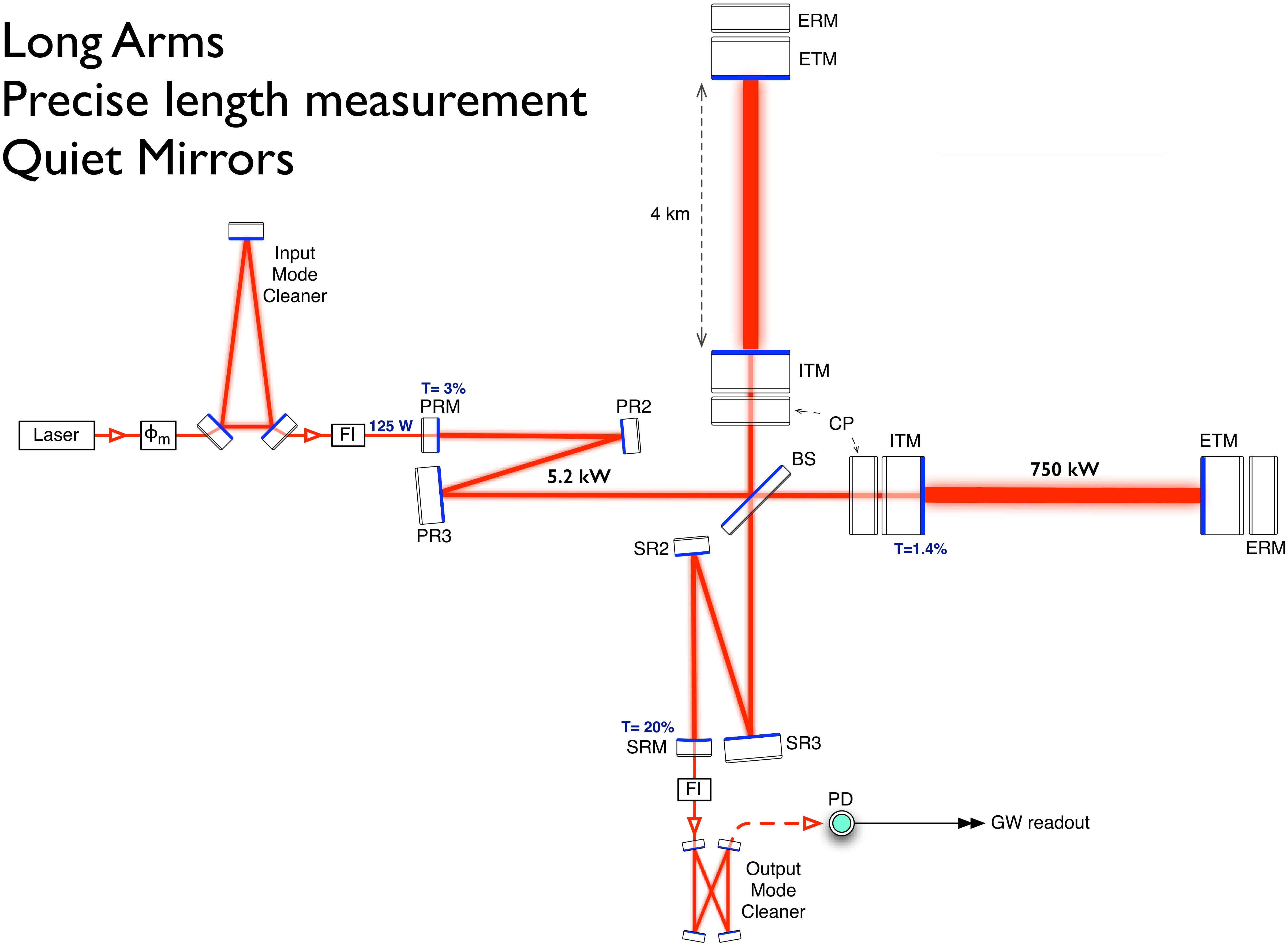
- tech. to help cool the mirror mirror down



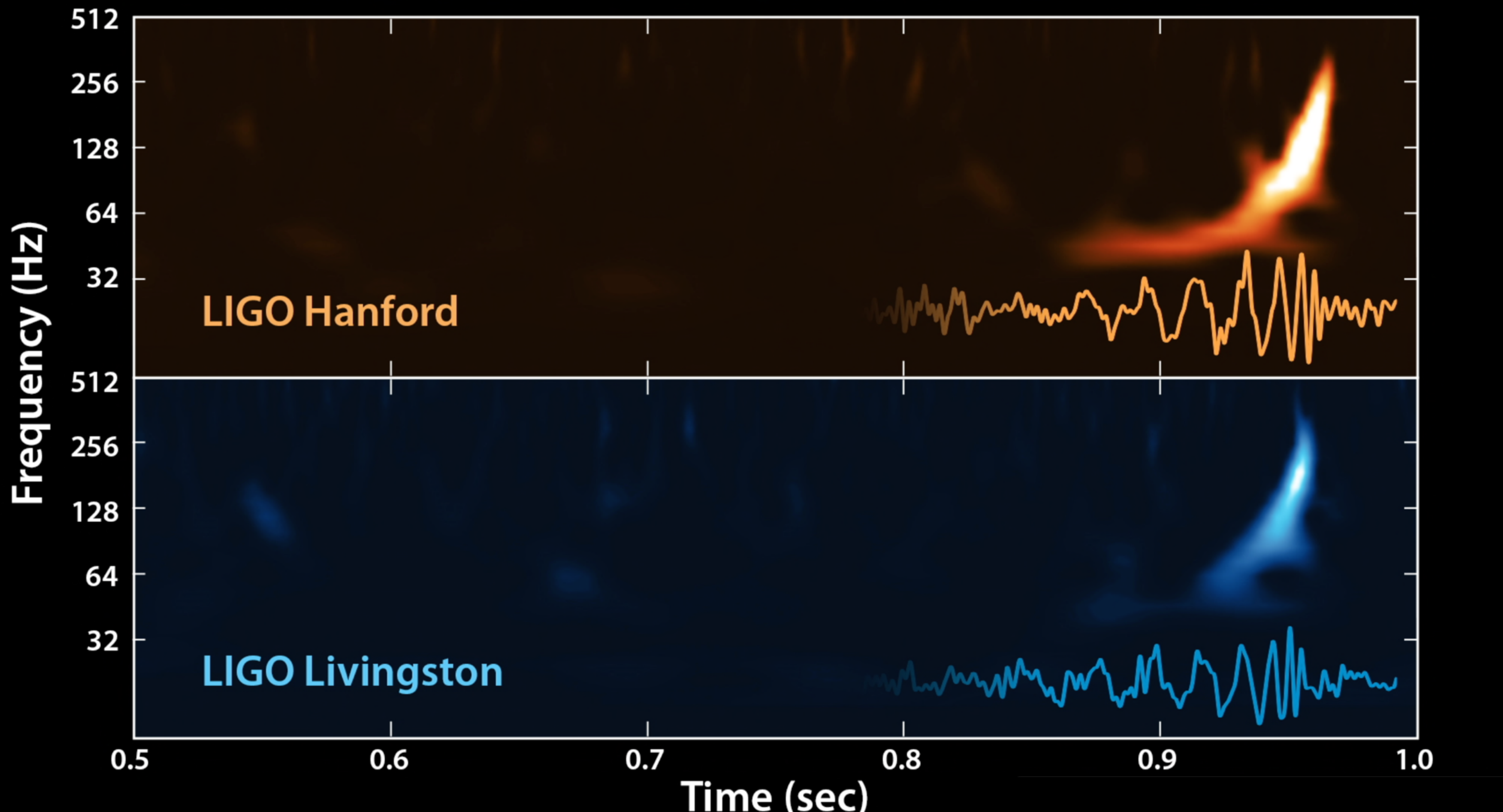
G1800606

Now we are ready…

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

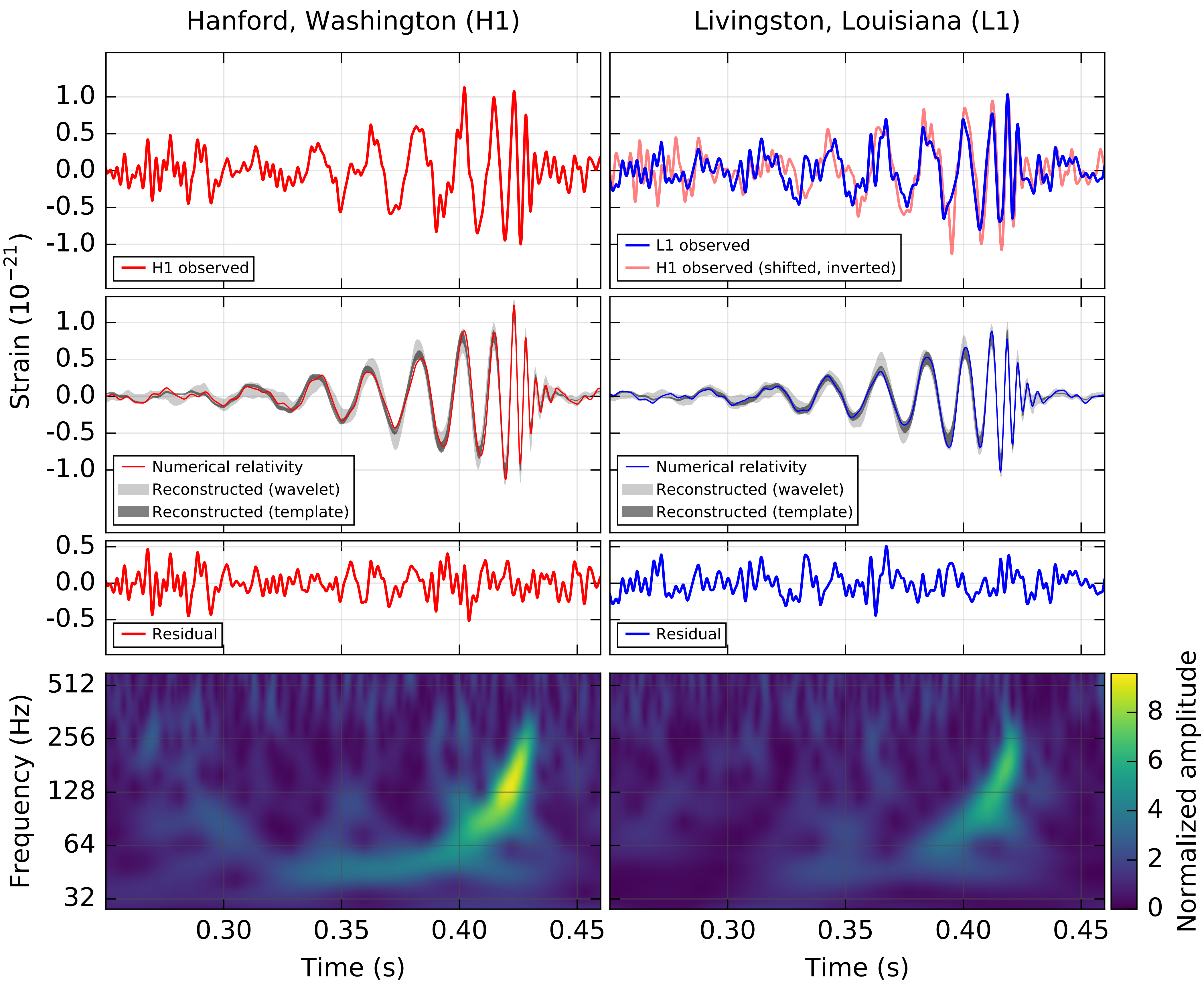


The sound of black holes colliding



http://mediaassets.caltech.edu/gwave

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}

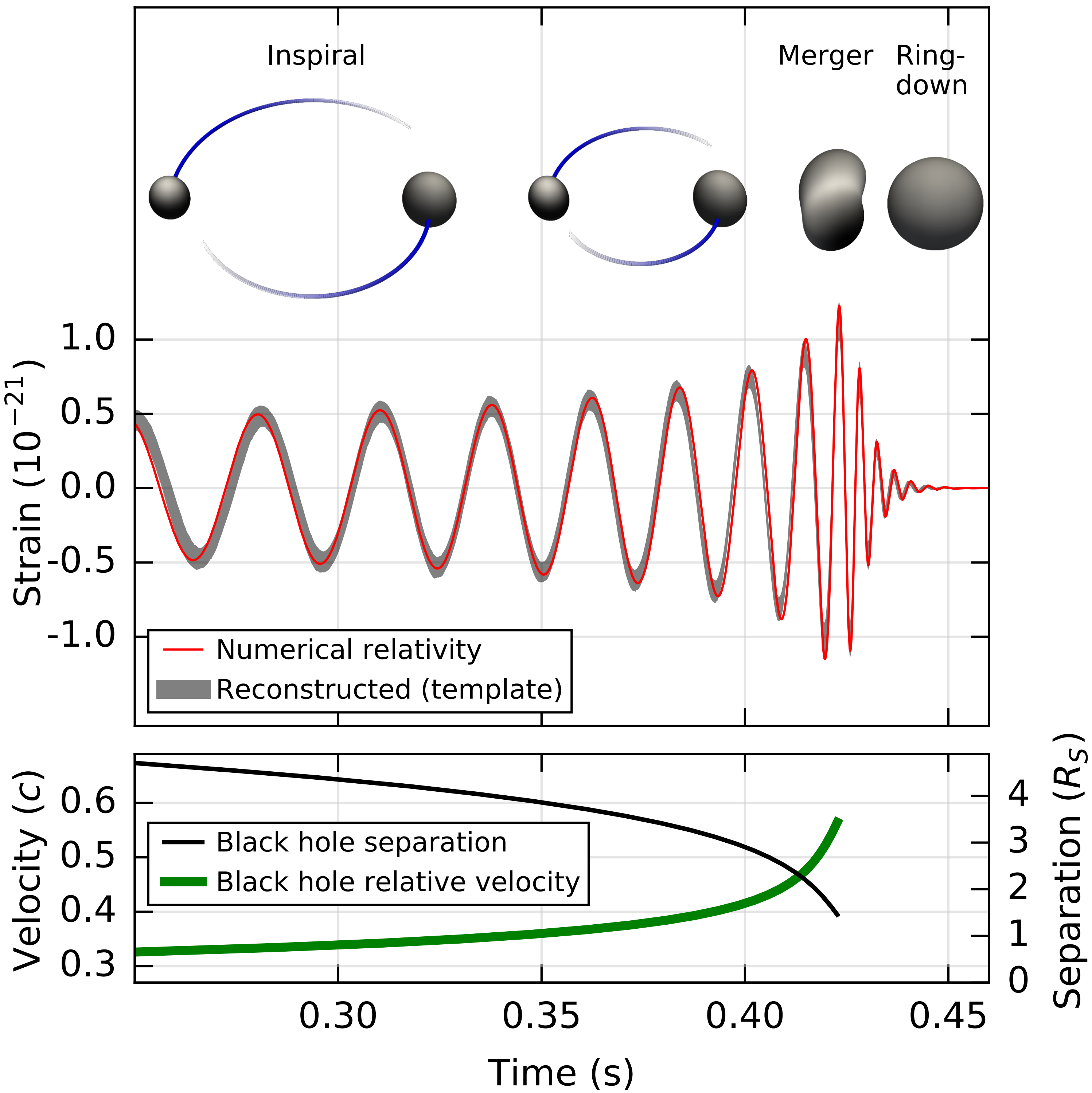
Final Mass:

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

Distance

420 (+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}

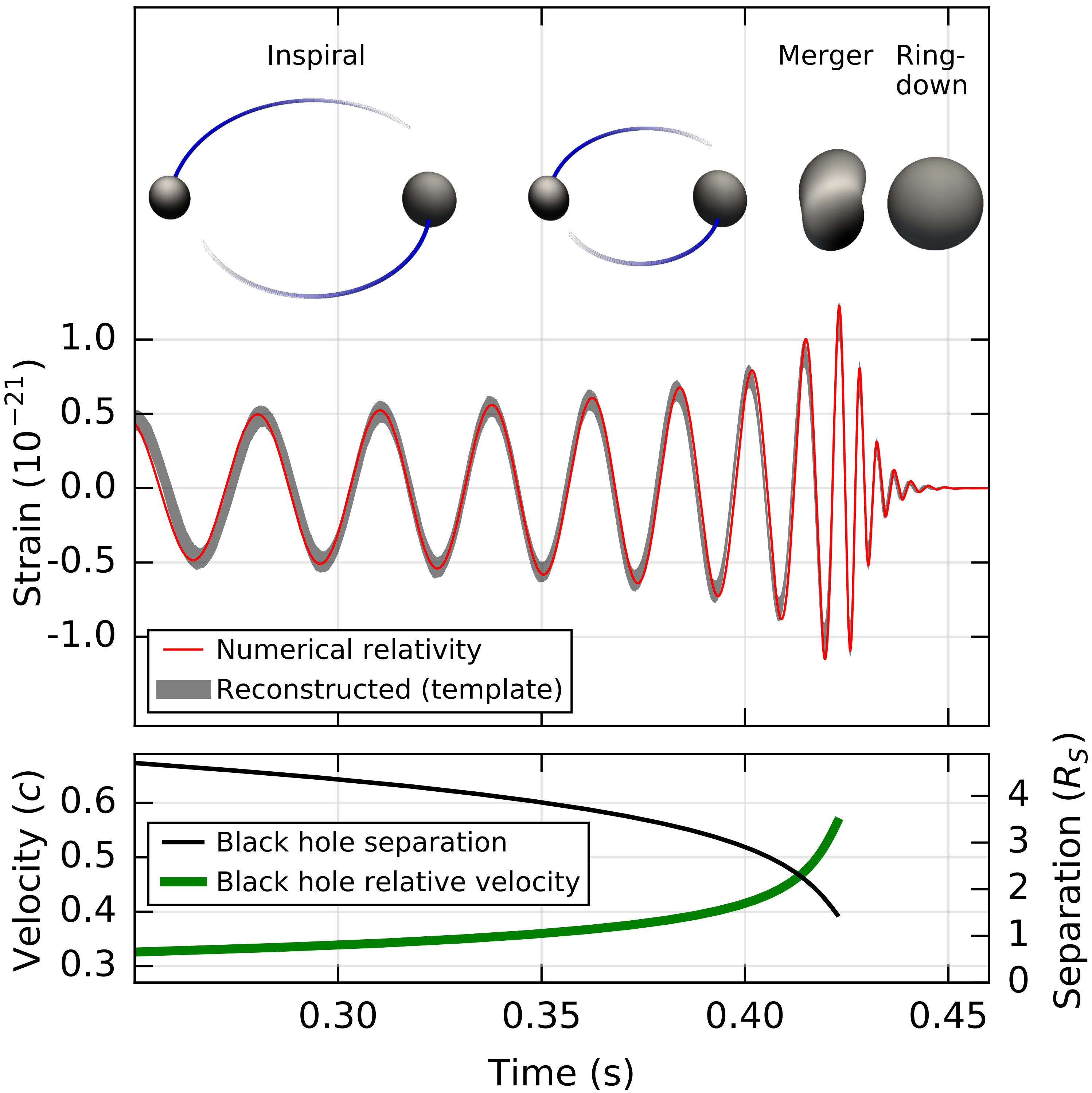
Energy radiated

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

Distance

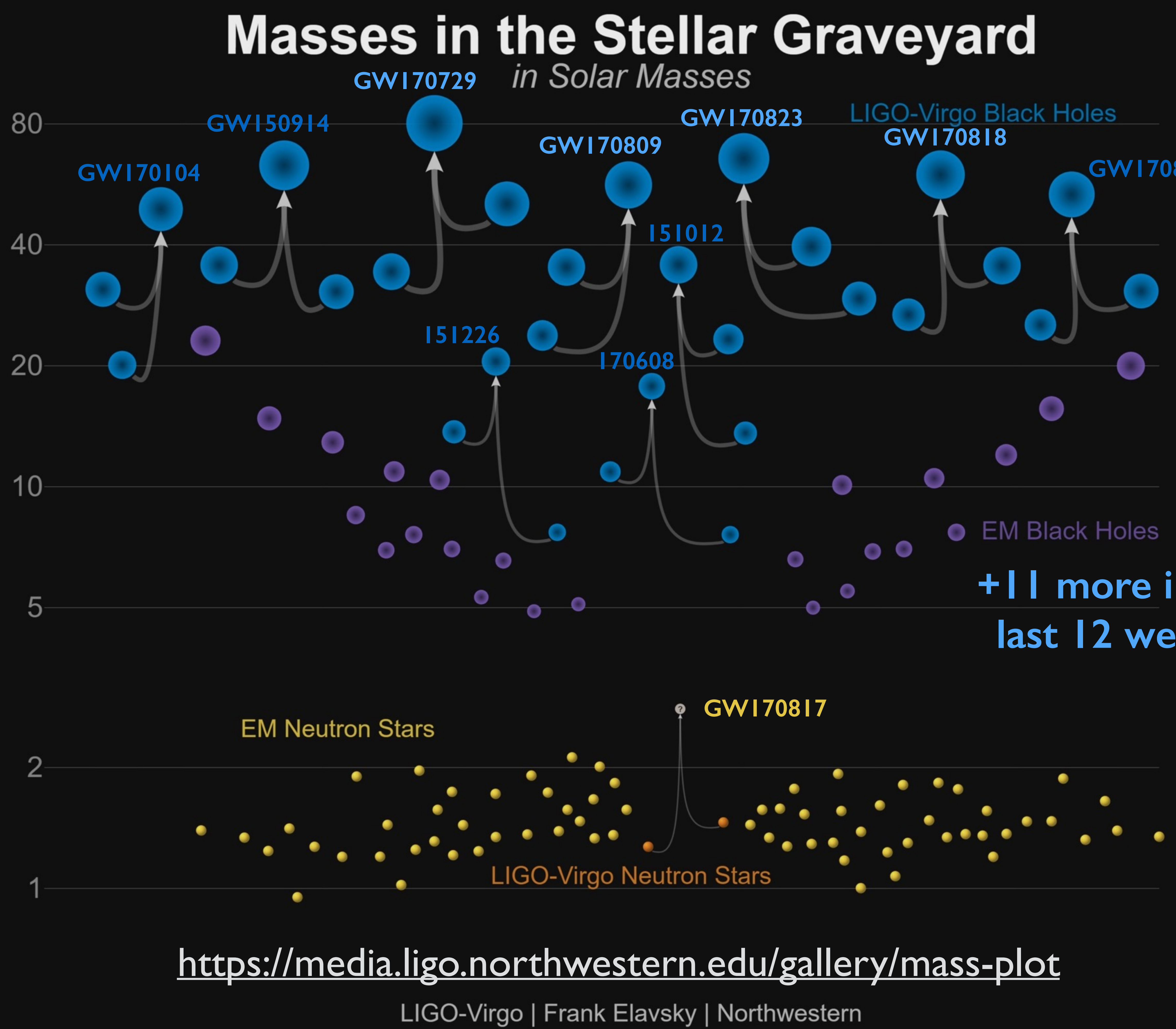
420 (+160/-180) MPc

(1.3 Billion light years)



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

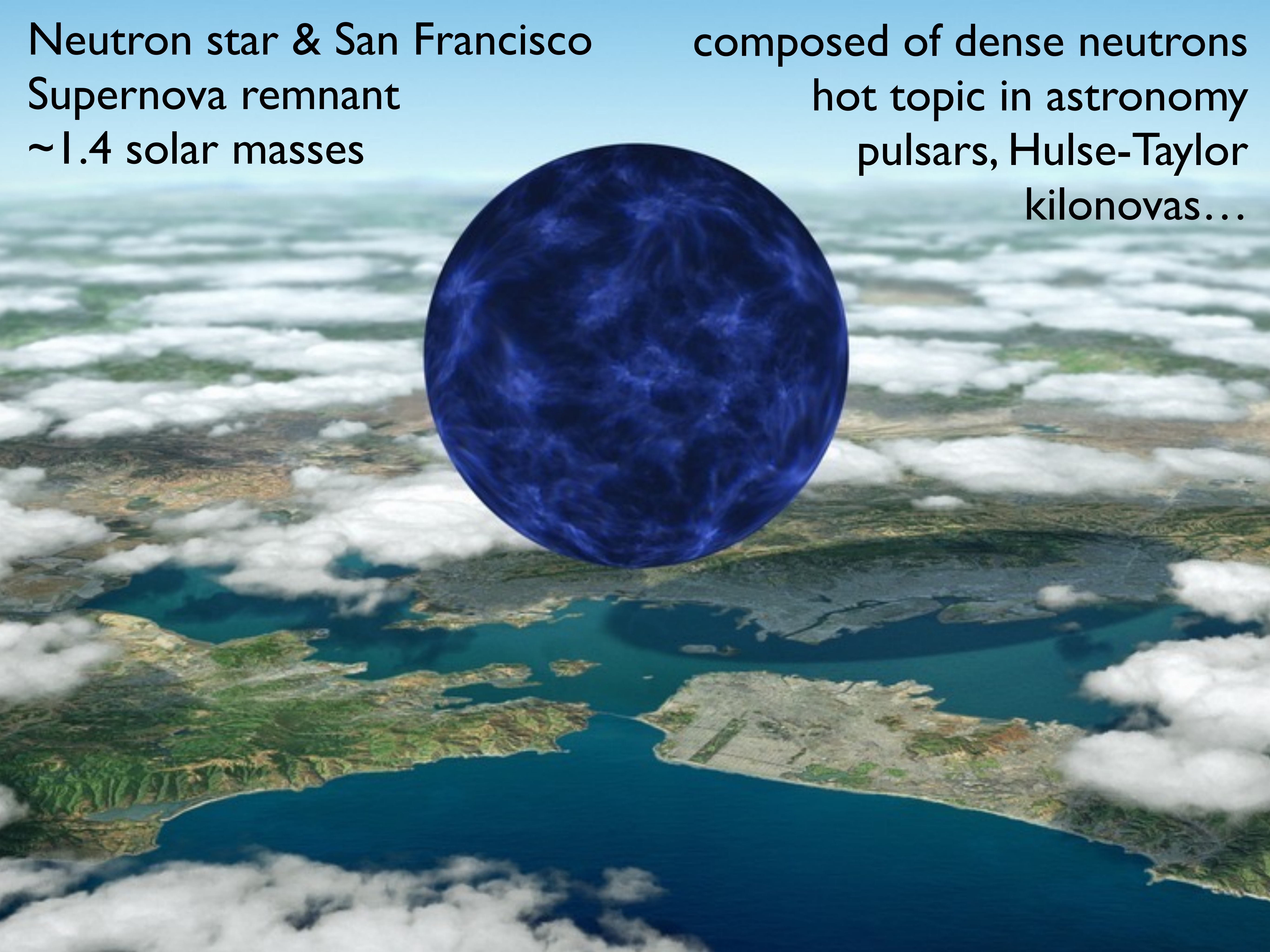
Lots of astrophysics



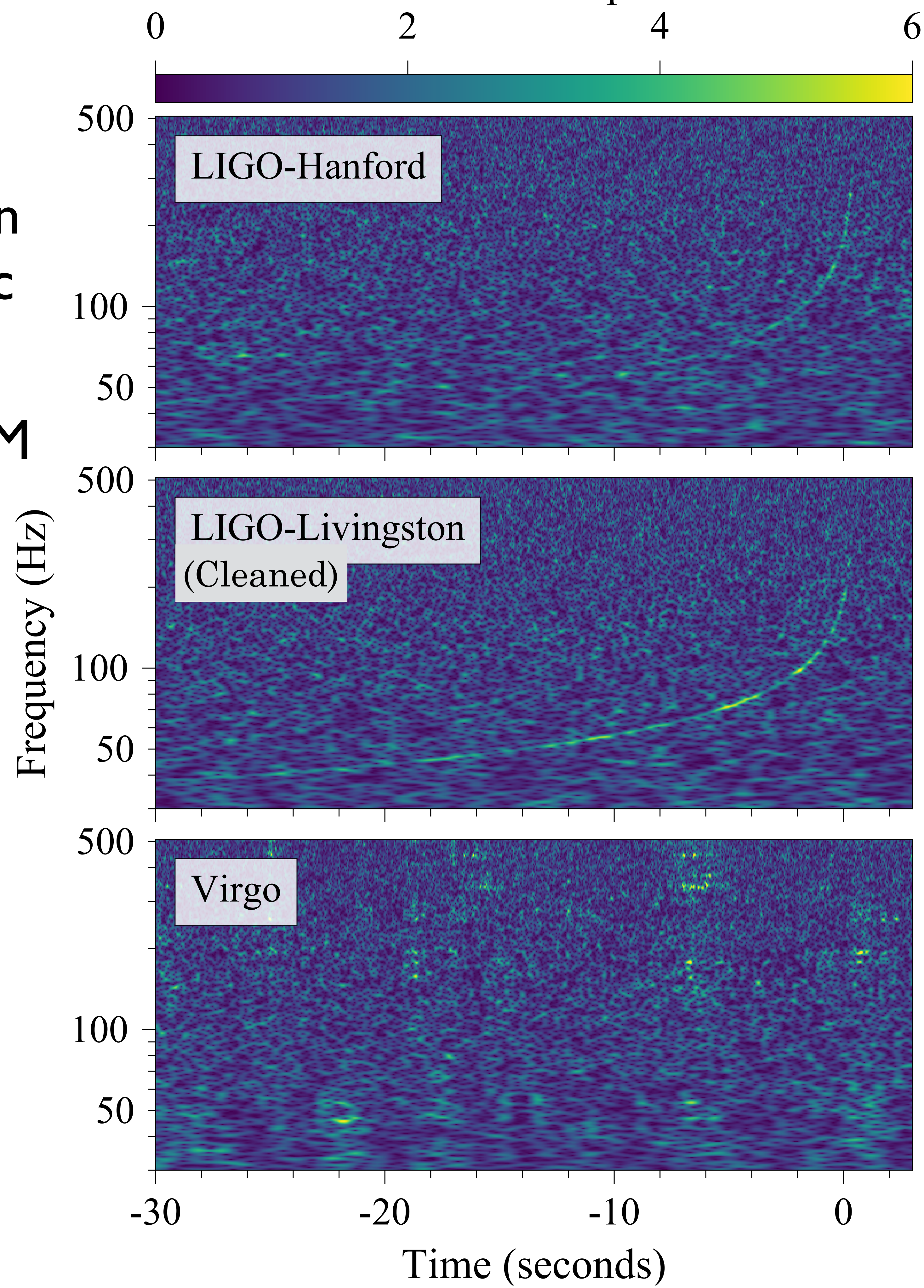
But no light…

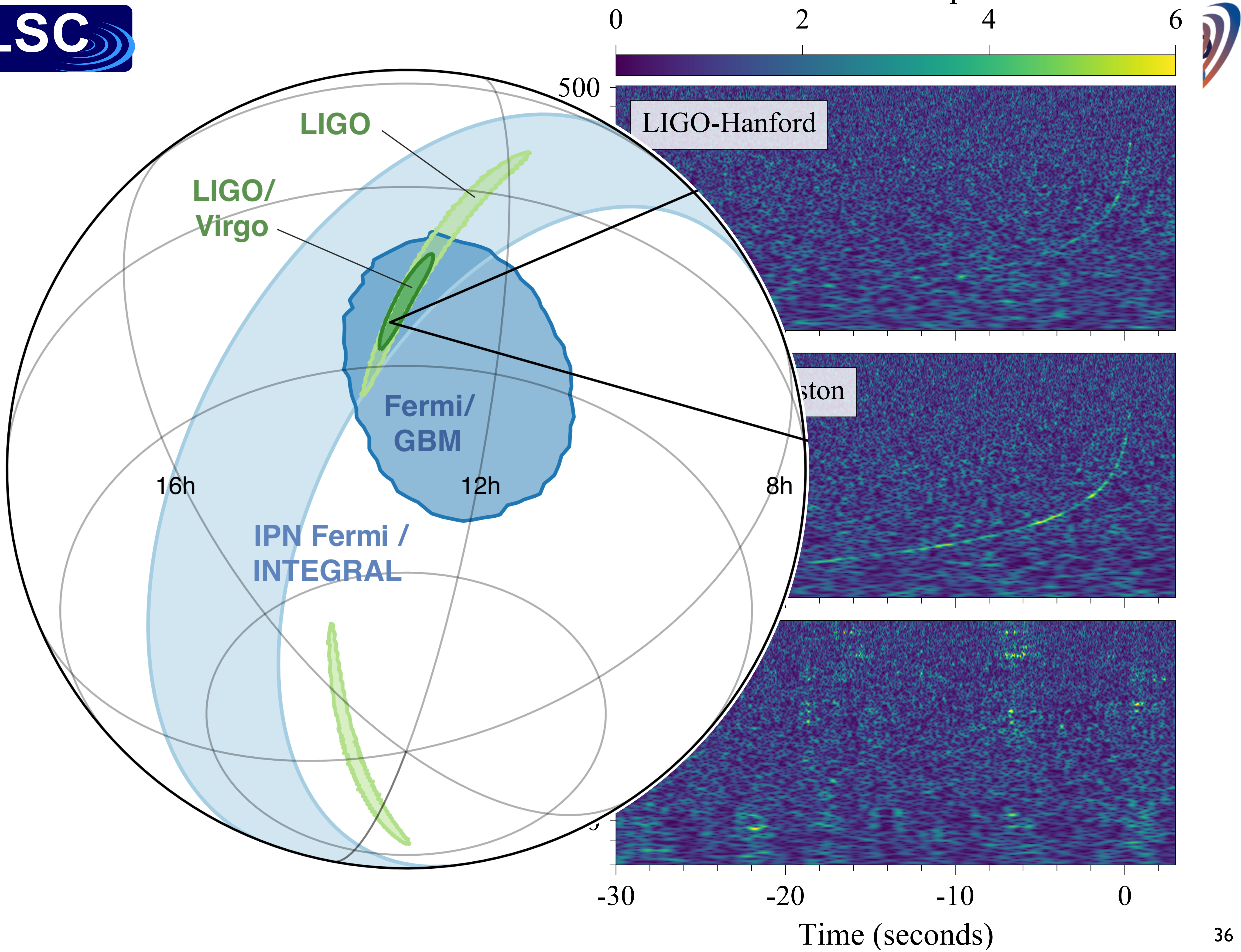
+11 more in the last 12 weeks!

https://media.ligo.northwestern.edu/gallery/mass-plot

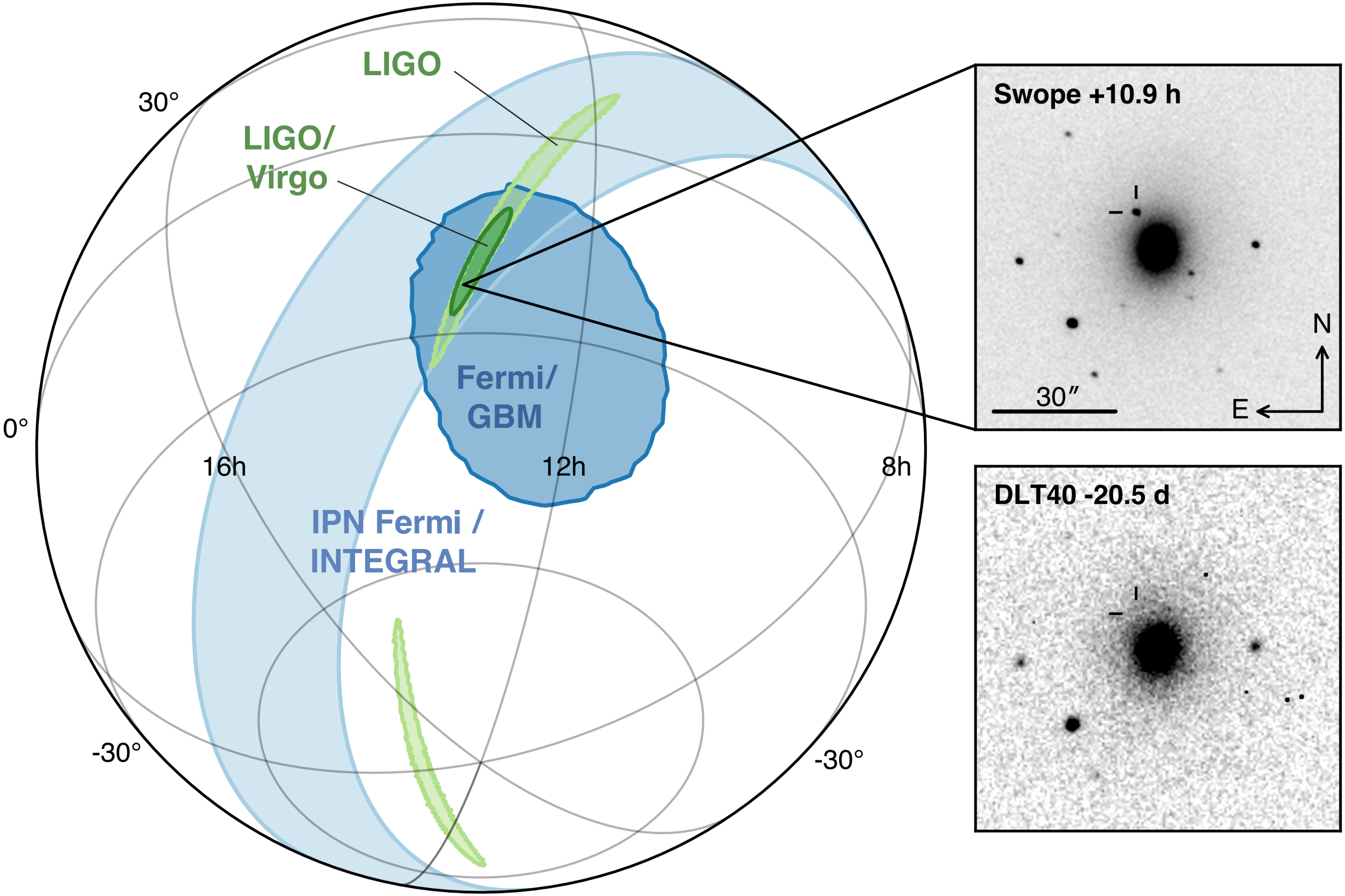

Neutron star & San Francisco
Supernova remnant
~1.4 solar masses
composed of dense neutrons
hot topic in astronomy
pulsars, Hulse-Taylor
kilonovas…

- LIGO software finds trigger in LHO data - 5:41:04 am Pacific time, August 17.
- LIGO realizes that Fermi GBM has triggered on event 1.7 seconds after GW merger.
- Thus, BNS mergers cause short gamma-ray bursts.
- Finally solving a mystery uncovered by Vela-4 in 1967. (as predicted by many).
- Forcing a best match to Virgo (~in the blind spot, so SNR is only 2!)



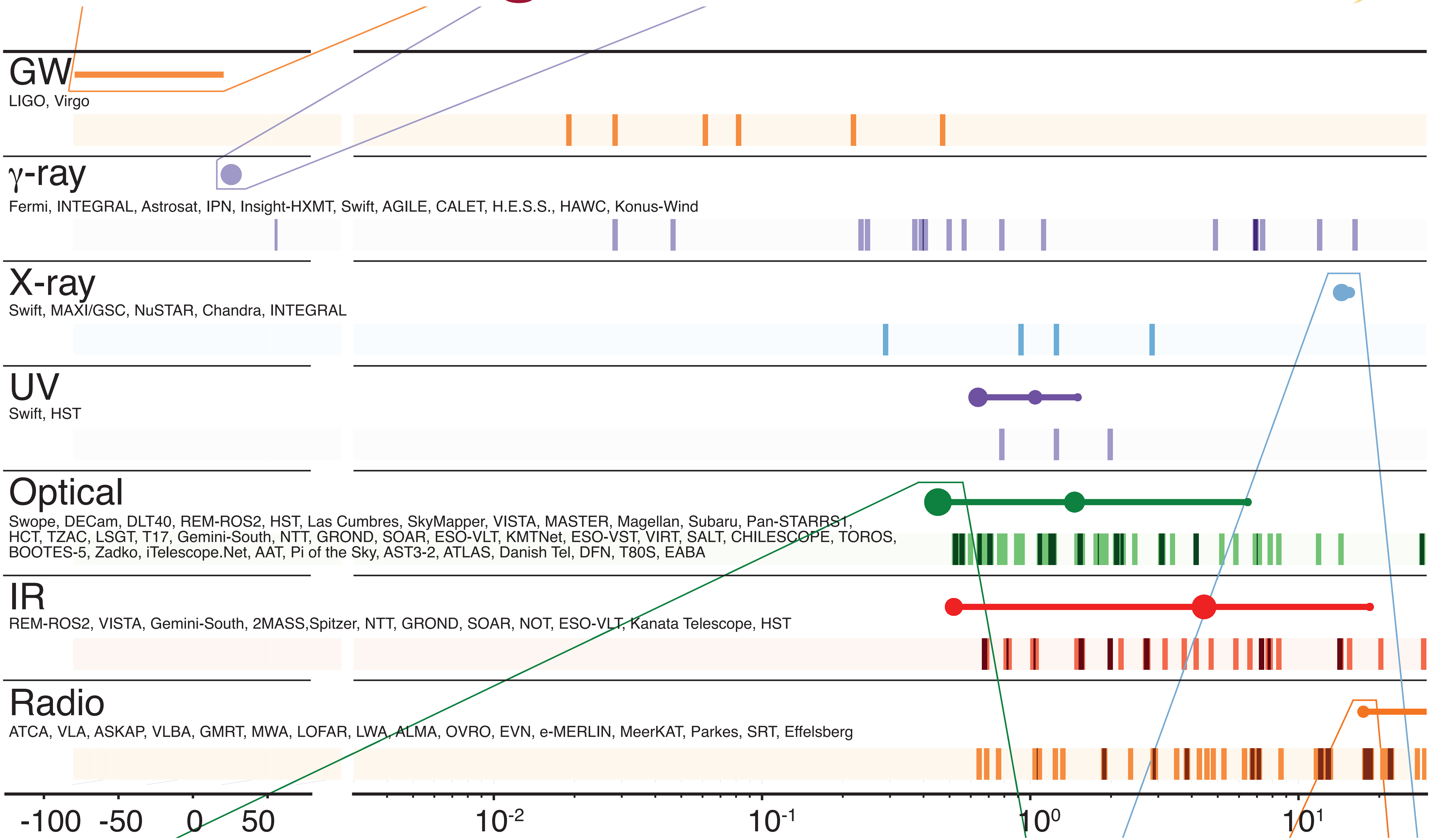

LIGO
LIGO/
Virgo
Fermi/
GBM
IPN Fermi /
INTEGRAL
16h
12h
8h
0
2
4
6
500
LIGO-Hanford
ston
-30
-20
-10
0
Time (seconds)

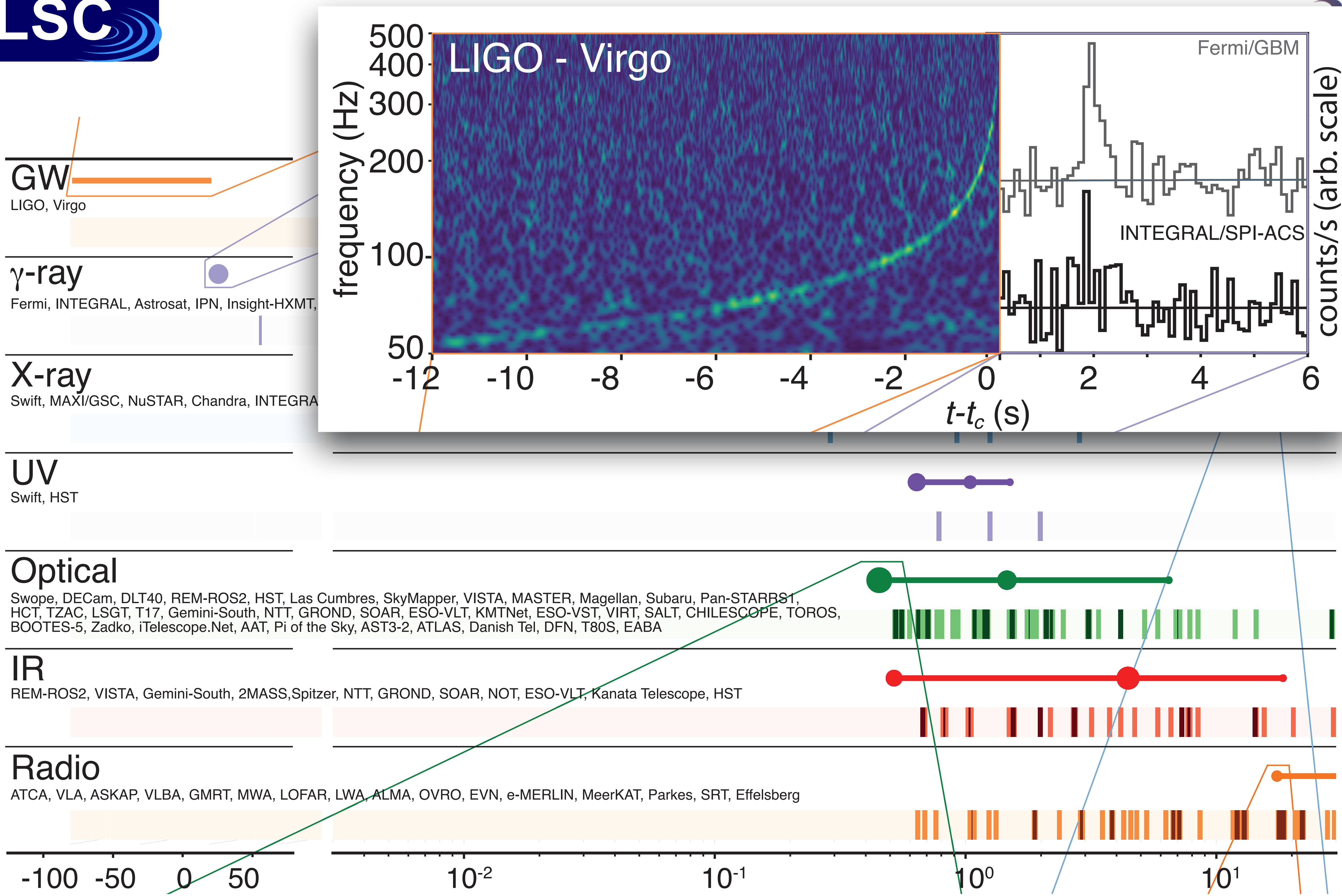
GW + GRB + Kilonova

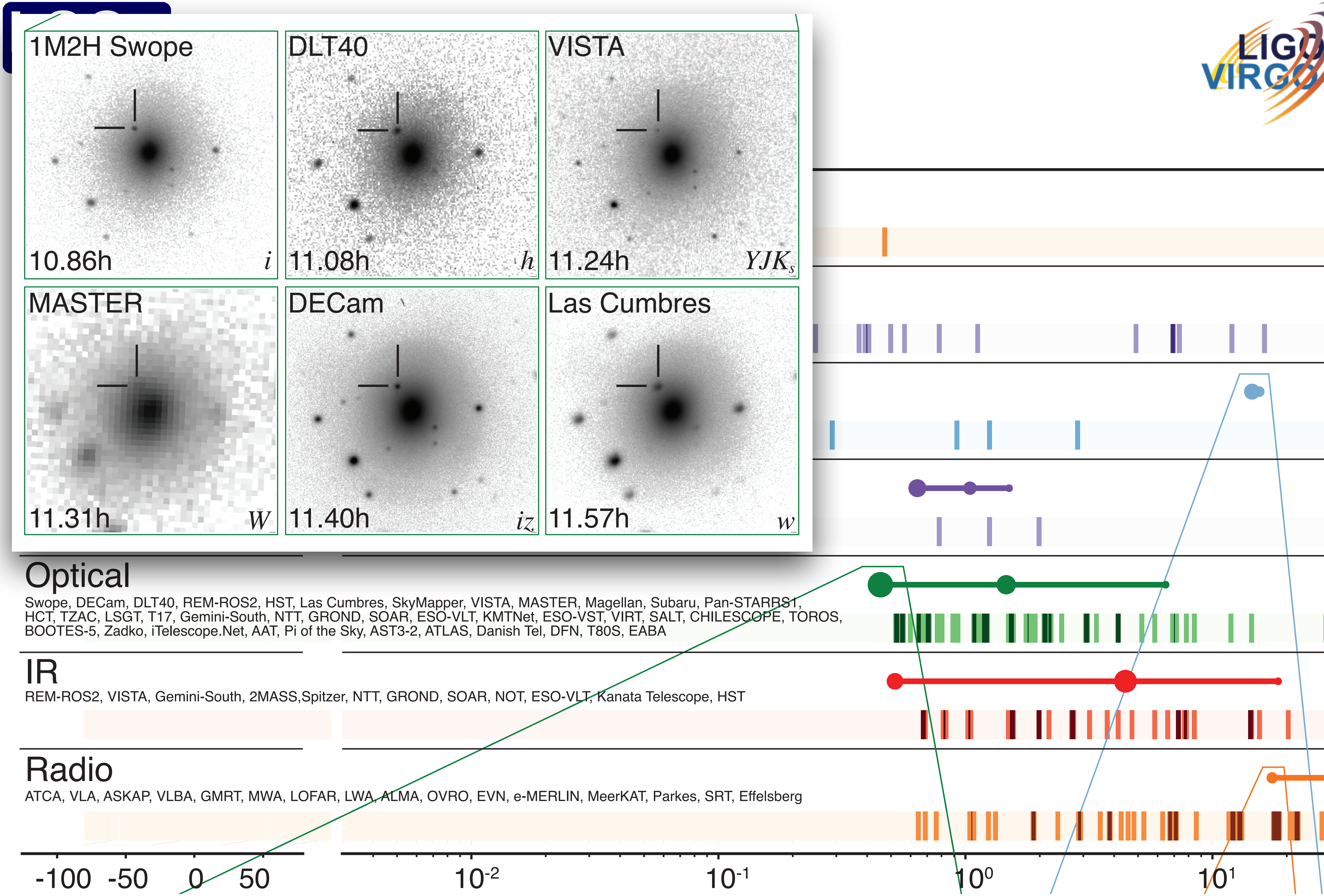


There is matter, and we can watch it

Amazing measurement set




LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12
-10
-8
-6
-4
-2
0
2
4
6
t-t_c (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT,
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRA
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1,
HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS,
BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
10^-2
10^-1
10^0
10^1


1M2H Swope
10.86h
i
DLT40
11.08h
h
VISTA
11.24h
YJKs
MASTER
11.31h
W
DECam
11.40h
iz
Las Cumbres
11.57h
w
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
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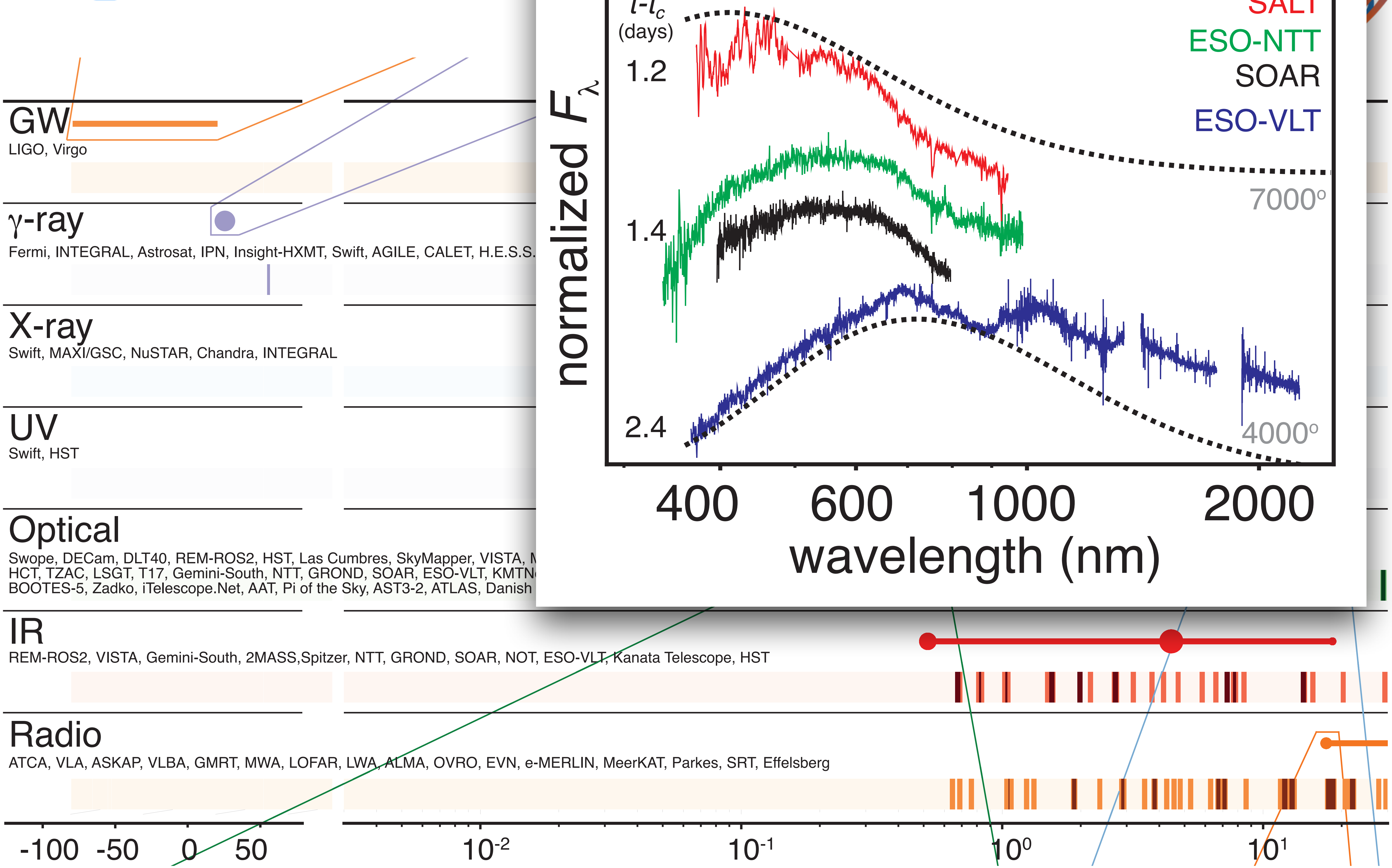
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100 -50 0 50
10^{-2}
10^{-1}
10^{0}
10^{1}


GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S.
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
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IR
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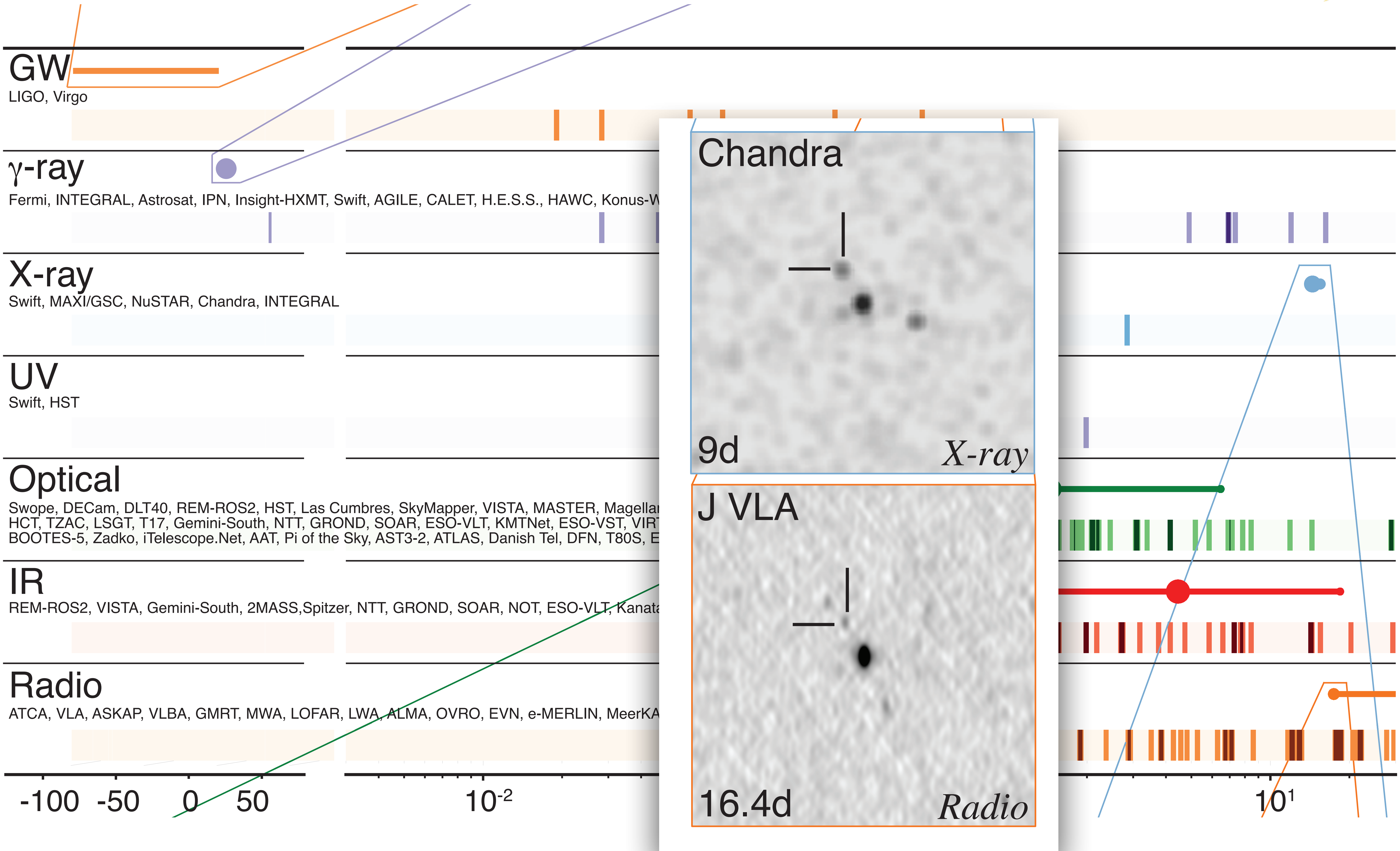
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100 -50 0 50
10^{-2}
10^{-1}
10^{0}
10^{1}
$t-t_c$ (days)
1.2
1.4
2.4
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
normalized F_λ
400
600
1000
2000
wavelength (nm)


GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-W
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan
HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIR
BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, E
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKA
-100
-50
0
50
10^{-2}
10^{1}
Chandra
9d
X-ray
J VLA
16.4d
Radio

Many things learned

- These events do happen!
- These events happen (330 - 4500) times / $GPc^3 Yr$[1]
- They follow an evolution similar to kilonova predictions
- They constrain the 'stiffness' or Equation of State of neutron stars
- You can get an estimate for the Hubble constant
- Many papers out now, many more expected
- Triumph of Multi-messenger astronomy
  distance, (H0/ angle), jet size, adiabatic glow vs. jet beam

Many questions remain,

- How common are kilonovas?
- Can they accurately predict the abundance of heavy elements?
- This event was ~1000x less bright than other gamma-ray bursts with known distance - observer effect?
- What's going on with the jets?
- Did it merge into a big neutron star or a small black hole?
- Did it collapse to a BH later?
  Is that why the x-rays were late to the party?
- What's the equation of state?
- Can we learn more about the Hubble constant?

http://papers.ligo.org