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

Brian Lantz, Nov. 2017
for the LSC, Virgo, &
~2500 astronomers!

LIGO

LSC

LIGO Scientific Collaboration

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LIGO India

project approved

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

Sept. 14, 2015

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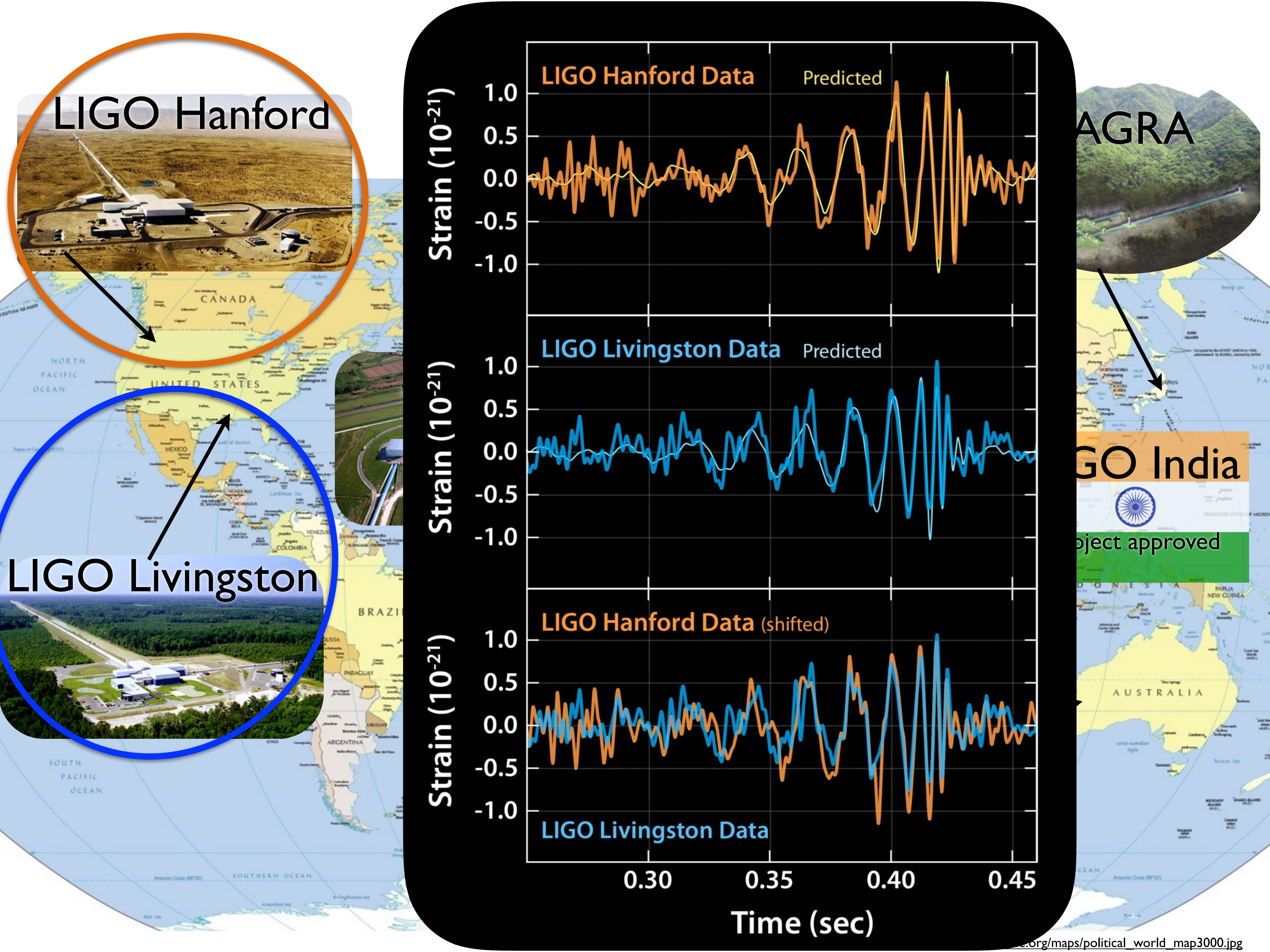

e.org/maps/political_world_map3000.jpg

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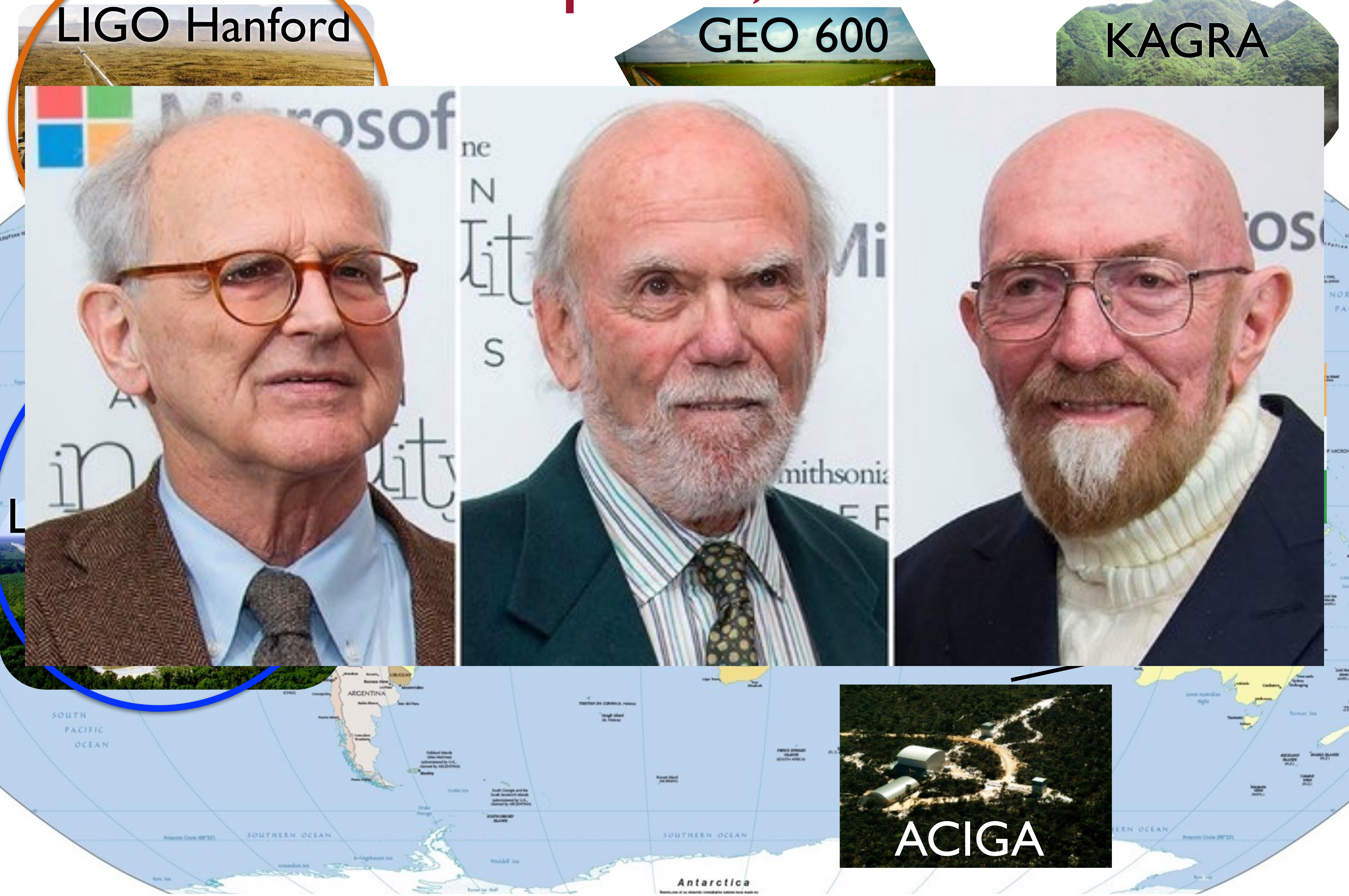

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Aug. 17, 2017

two black holes merging

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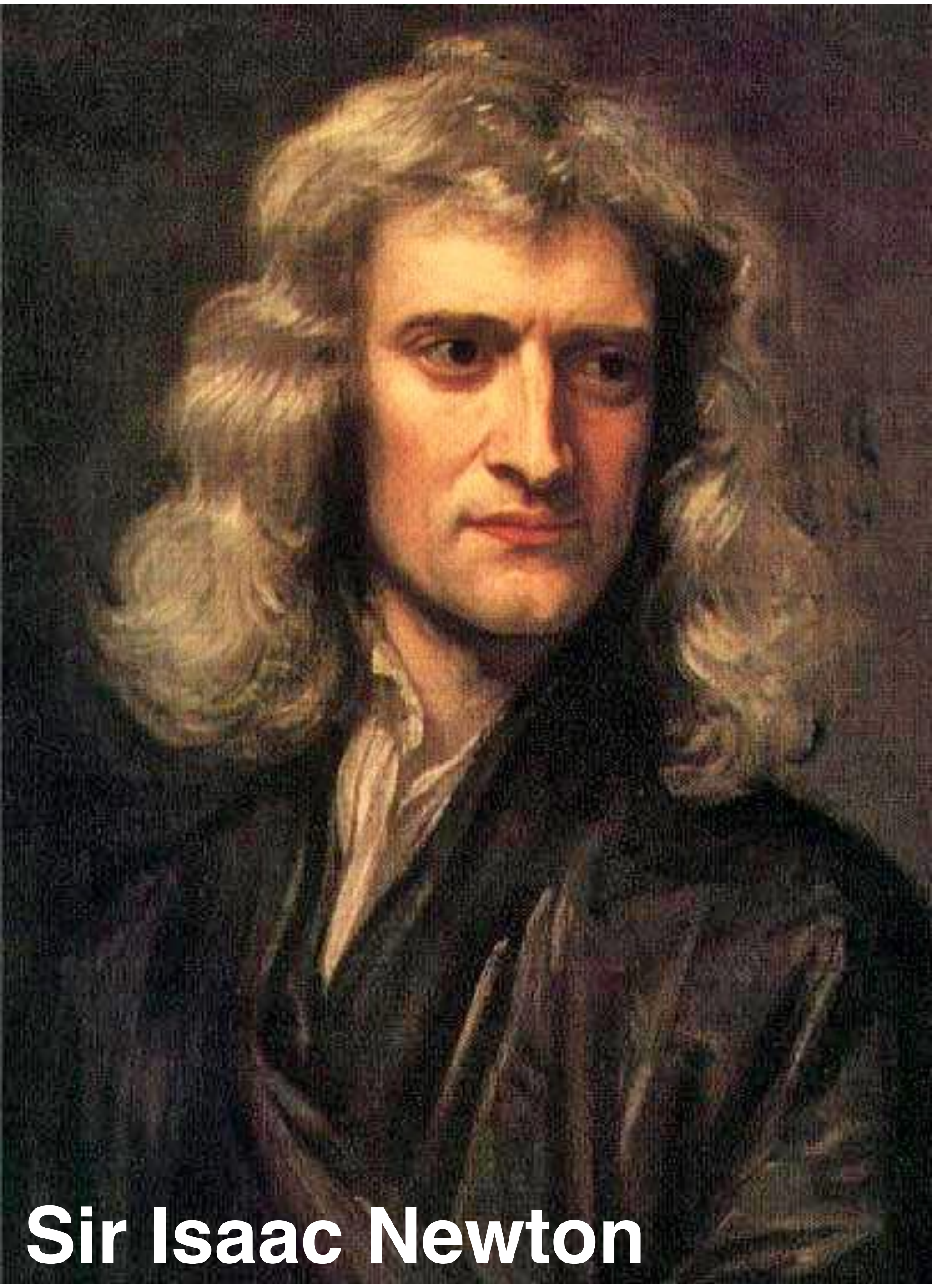
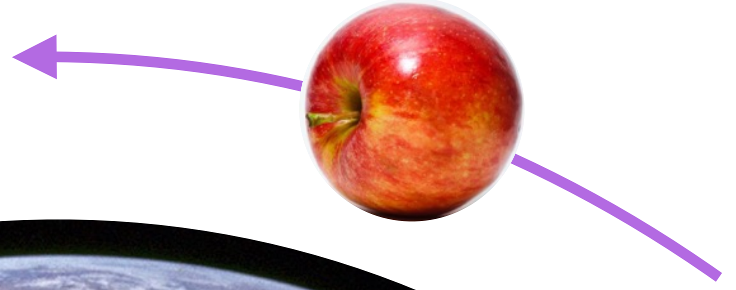
What is a Gravitational Wave?



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

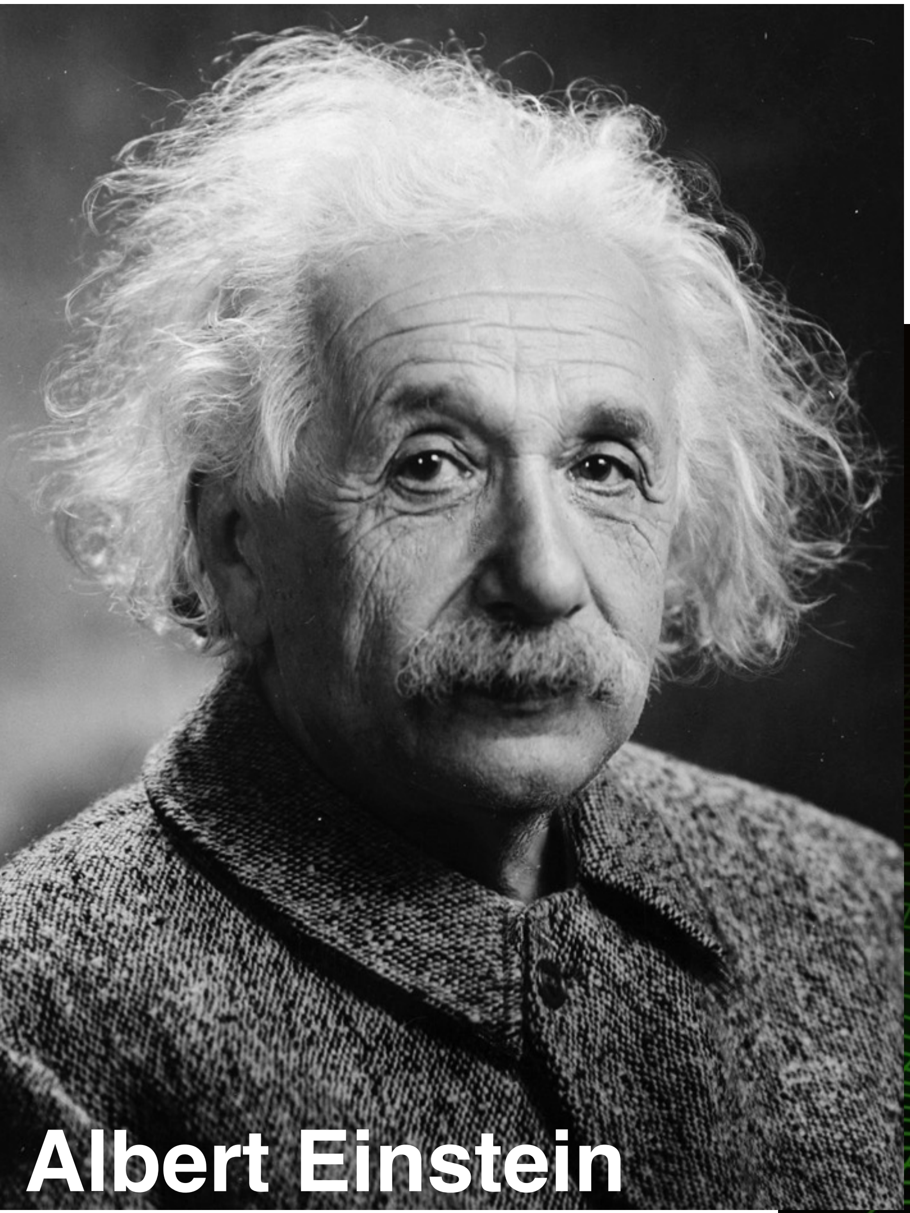


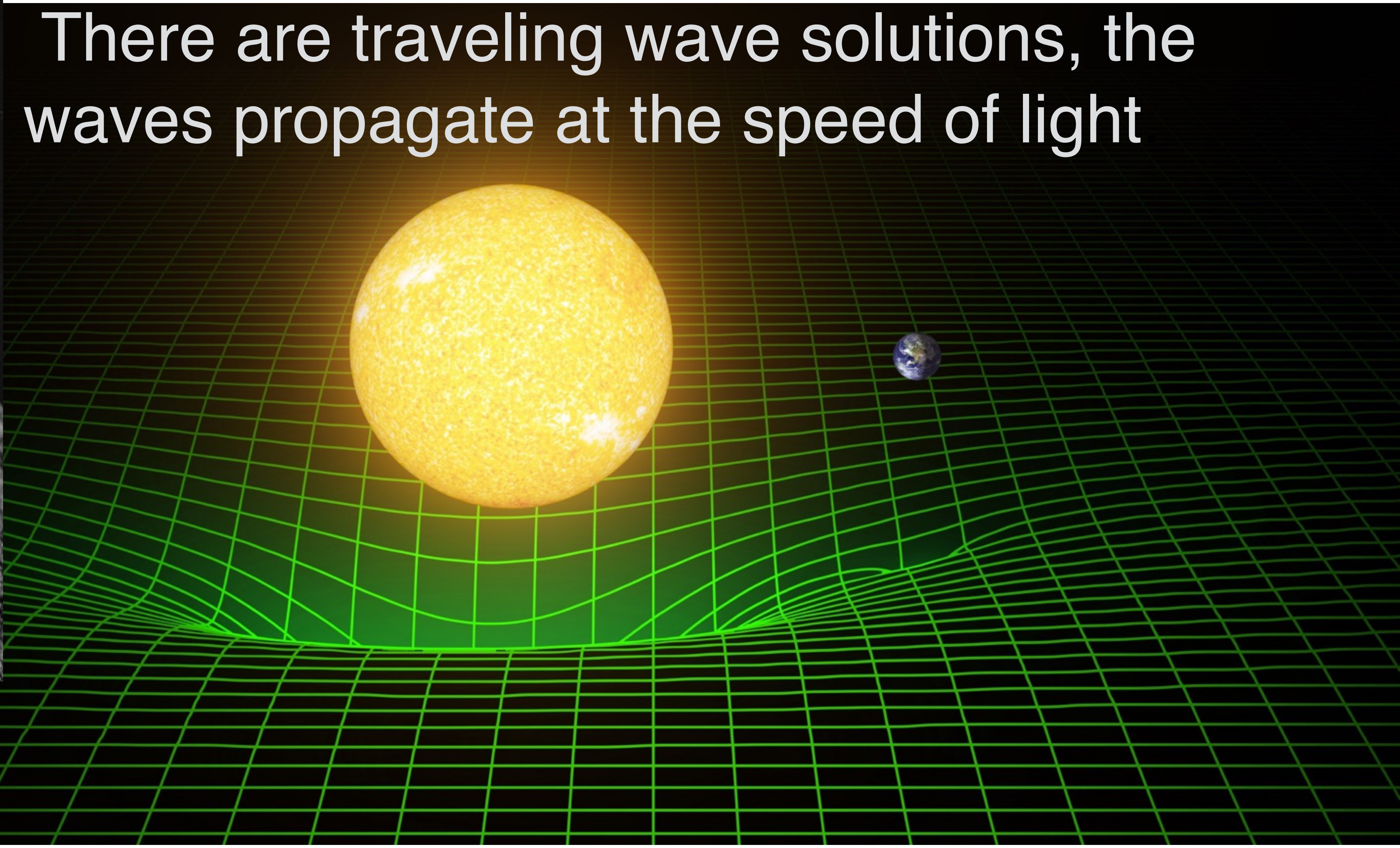
Earth - By NASA/Apollo 17 crew; taken by either Harrison Schmitt or Ron Evans
- http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
- apple by Abhijit Tembhekar from Mumbai, India

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

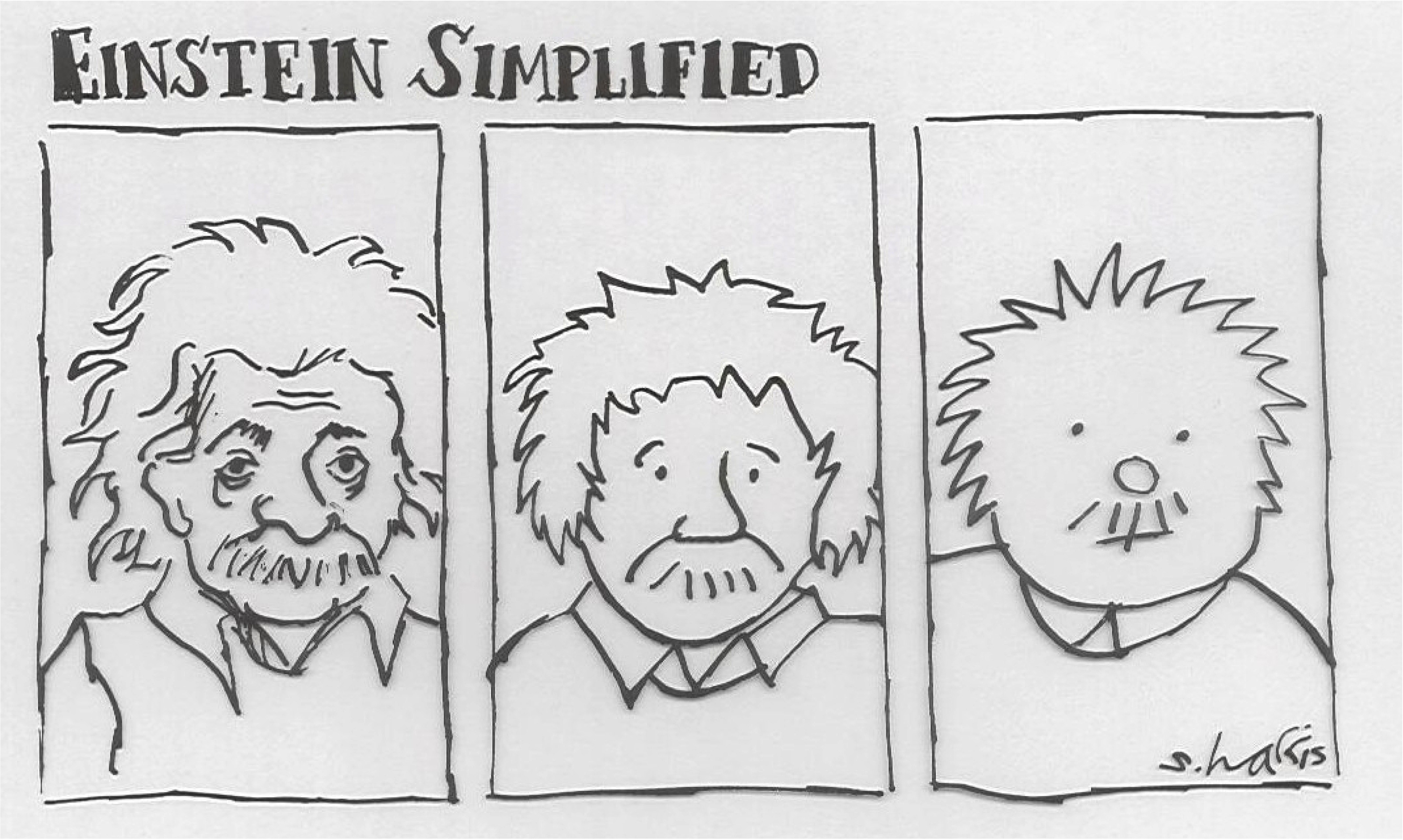




There are traveling wave solutions, the waves propagate at the speed of light

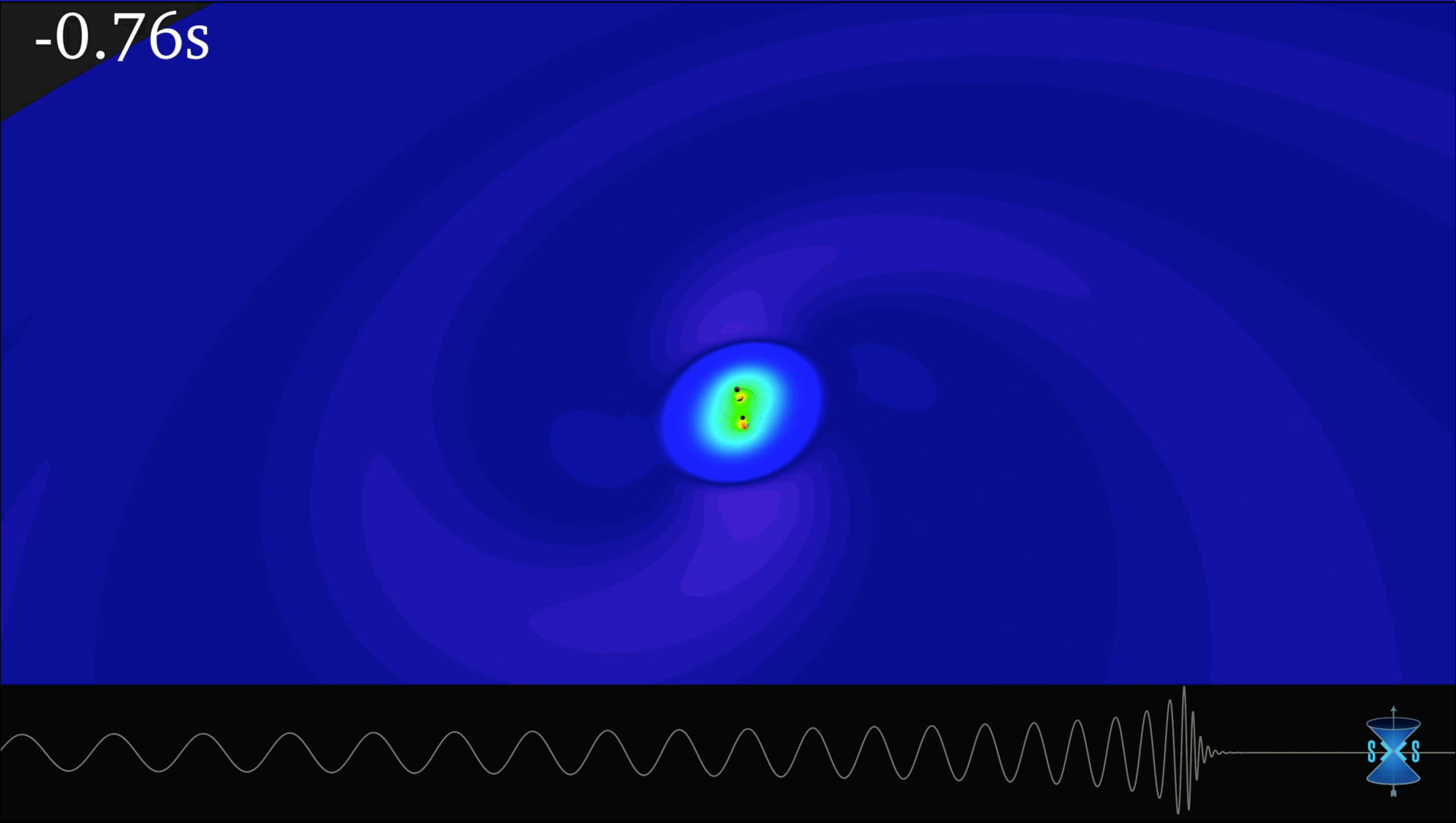
Photograph by Orren Jack Turner,
Library of Congress digital ID cph.3b46036.

What is a Gravitational Wave?



Sydney Harris

Simulation of the event



http://mediaassets.caltech.edu/gwave

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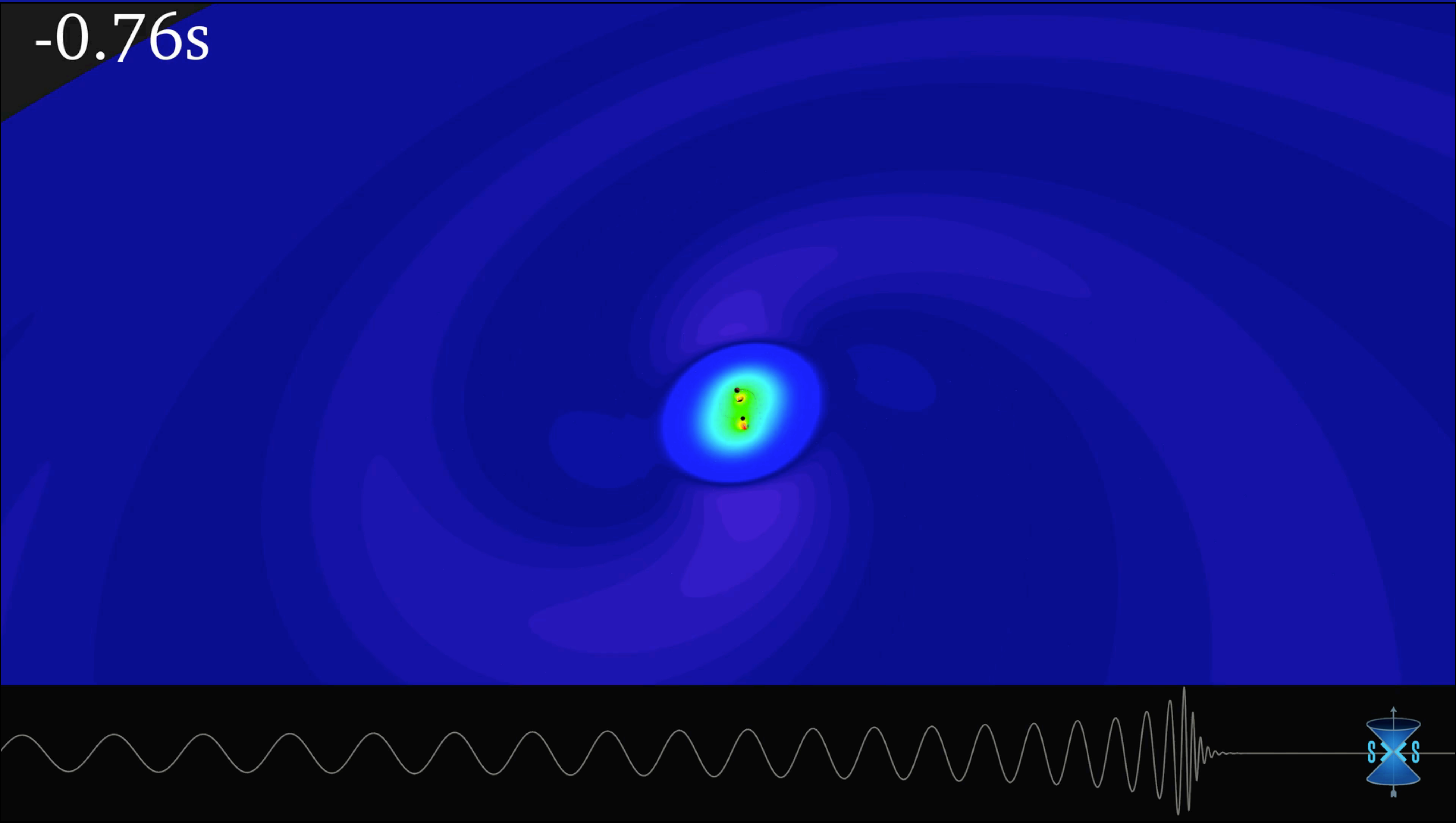

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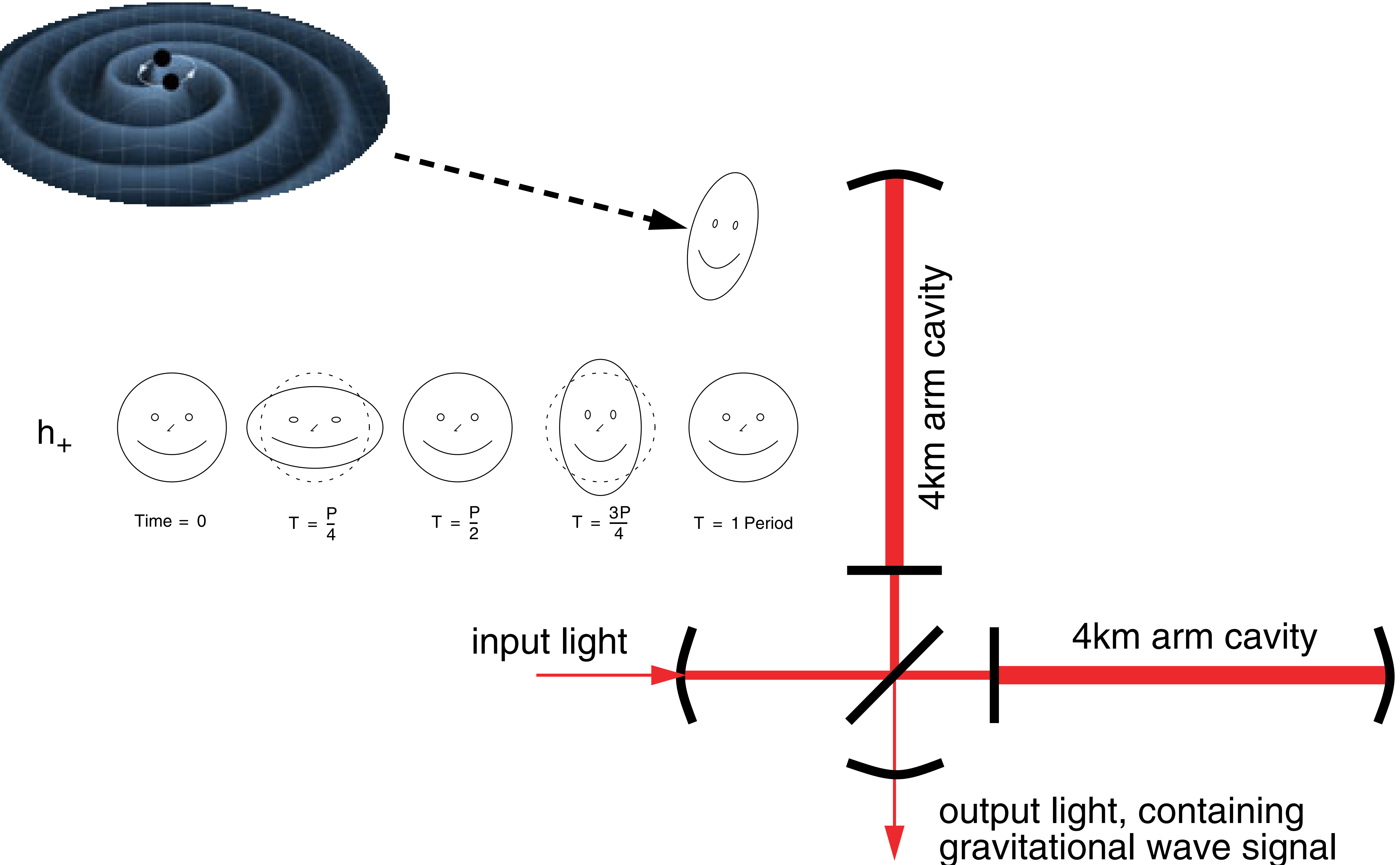
The LIGO concept



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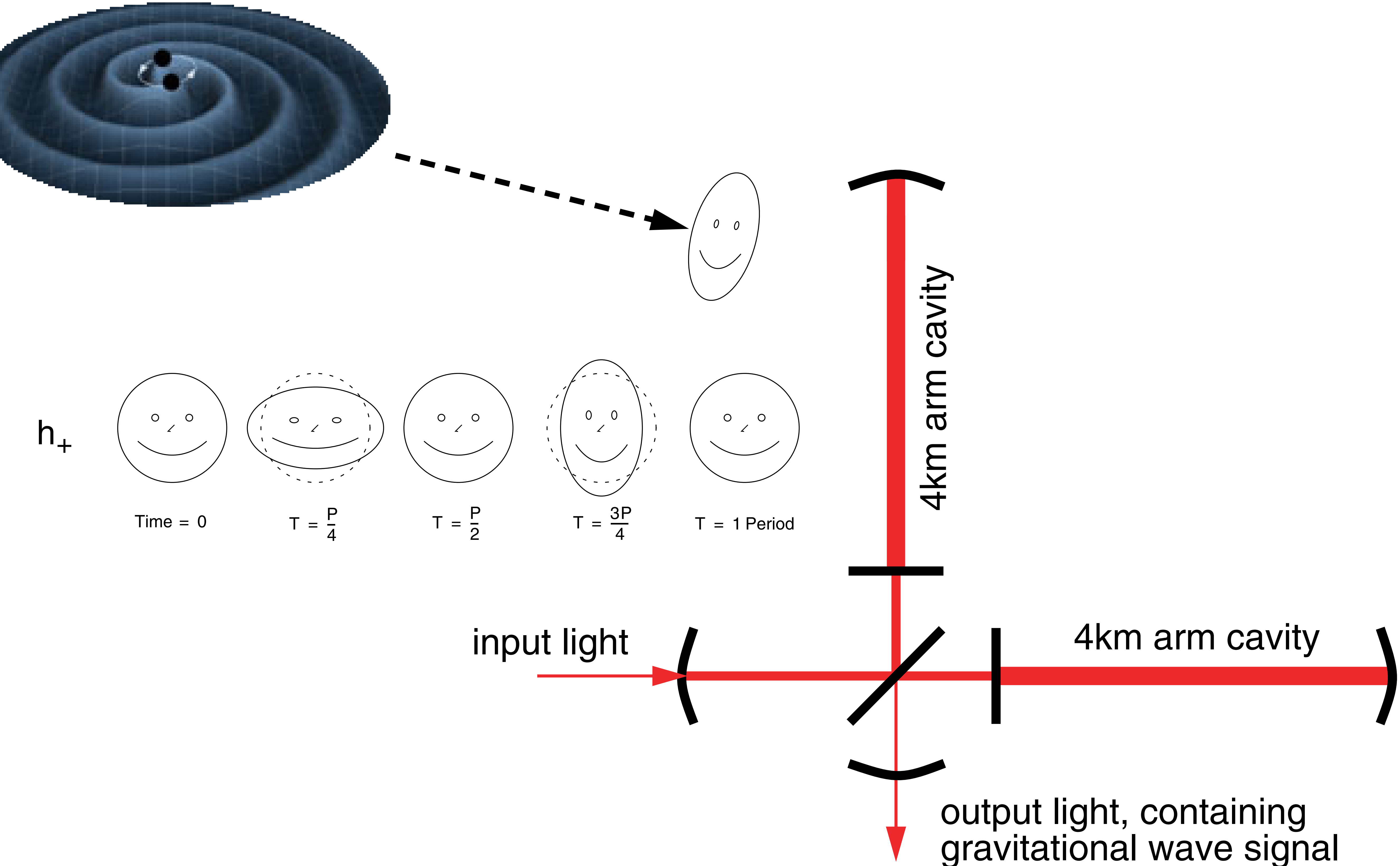

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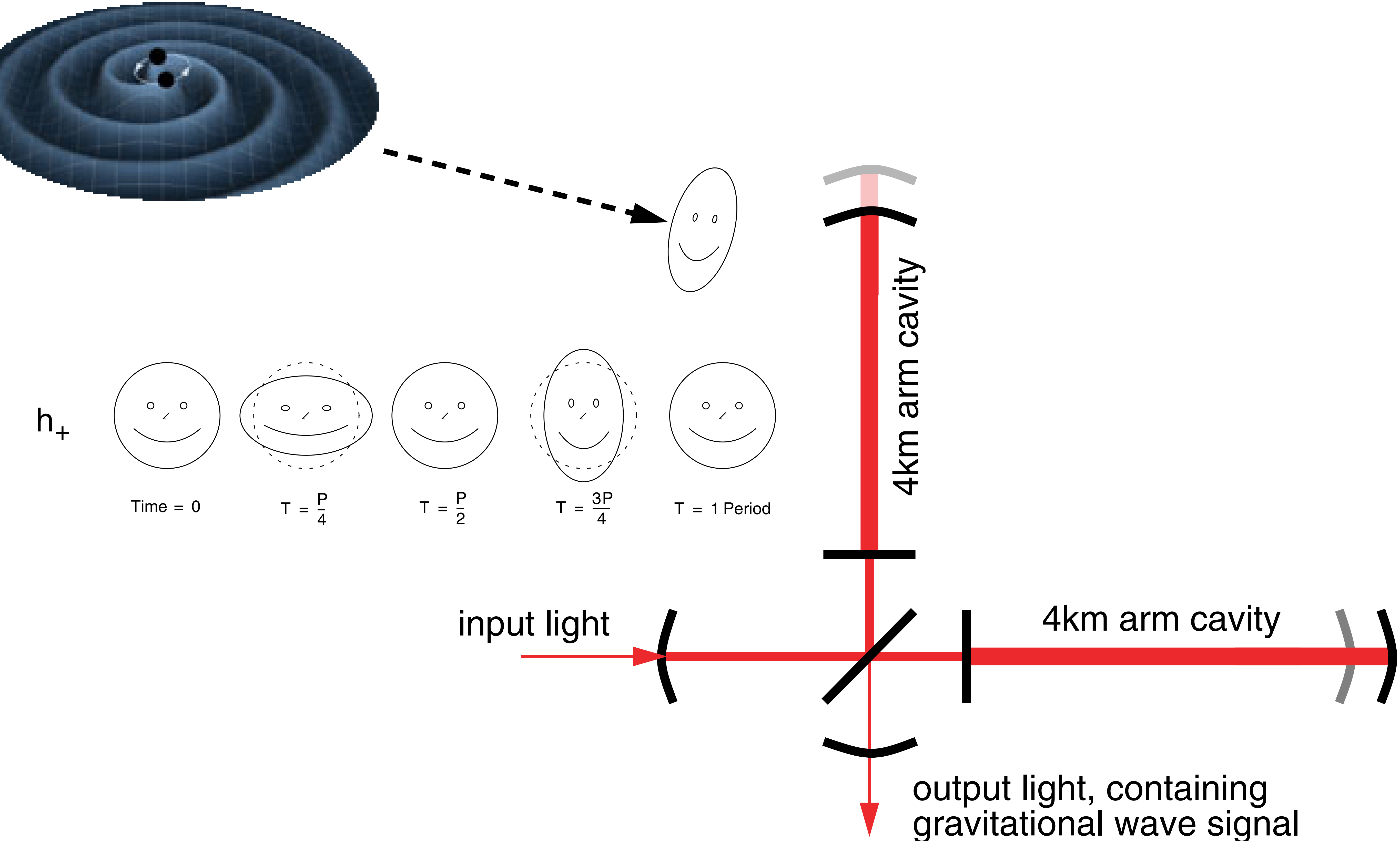


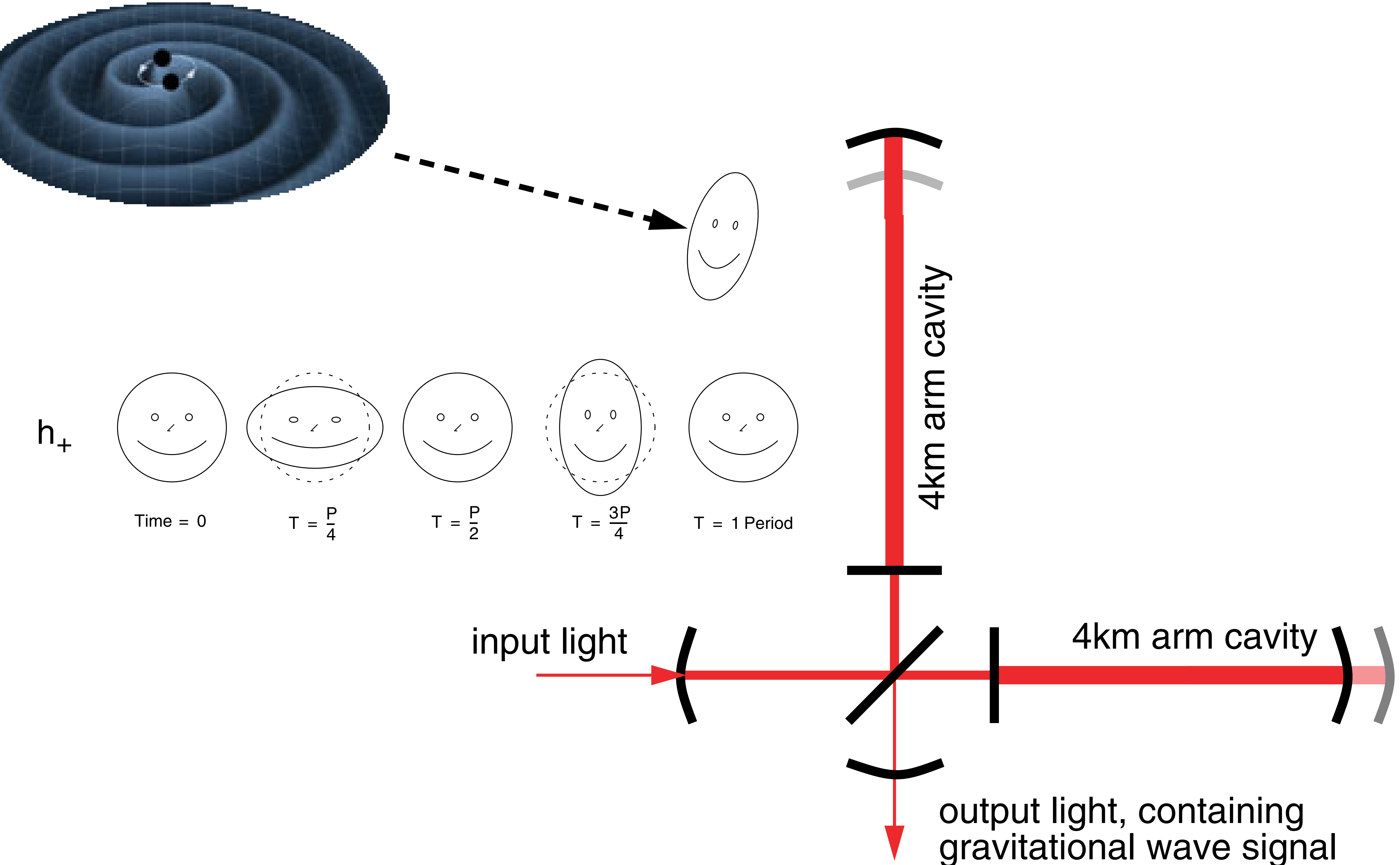
4km arm cavity

input light

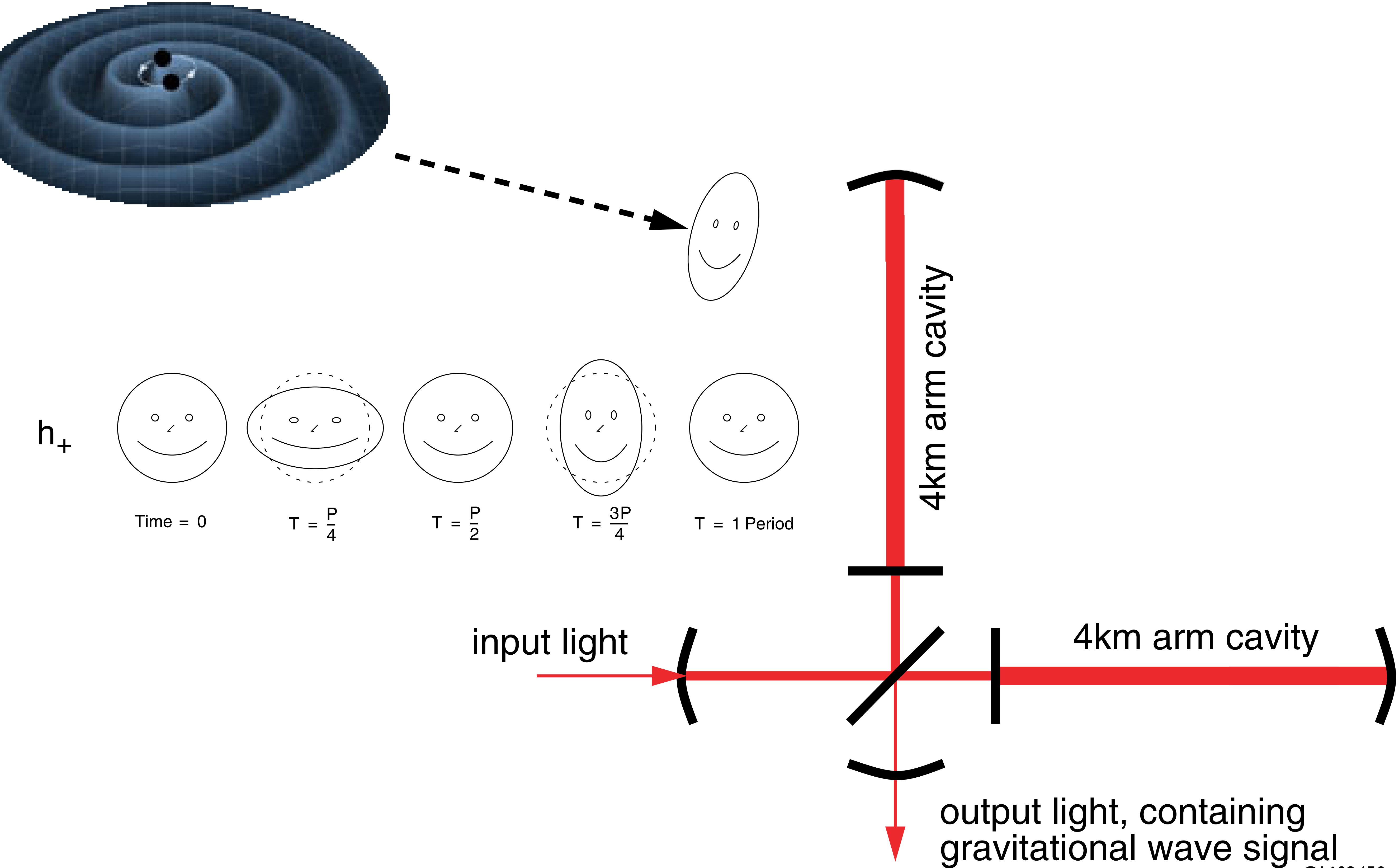
4km arm cavity

output light, containing
gravitational wave signal

The LIGO concept



The LIGO concept



h_+

Time = 0

$T = \frac{P}{4}$

$T = \frac{P}{2}$

$T = \frac{3P}{4}$

T = 1 Period

4km arm cavity

4km arm cavity

input light

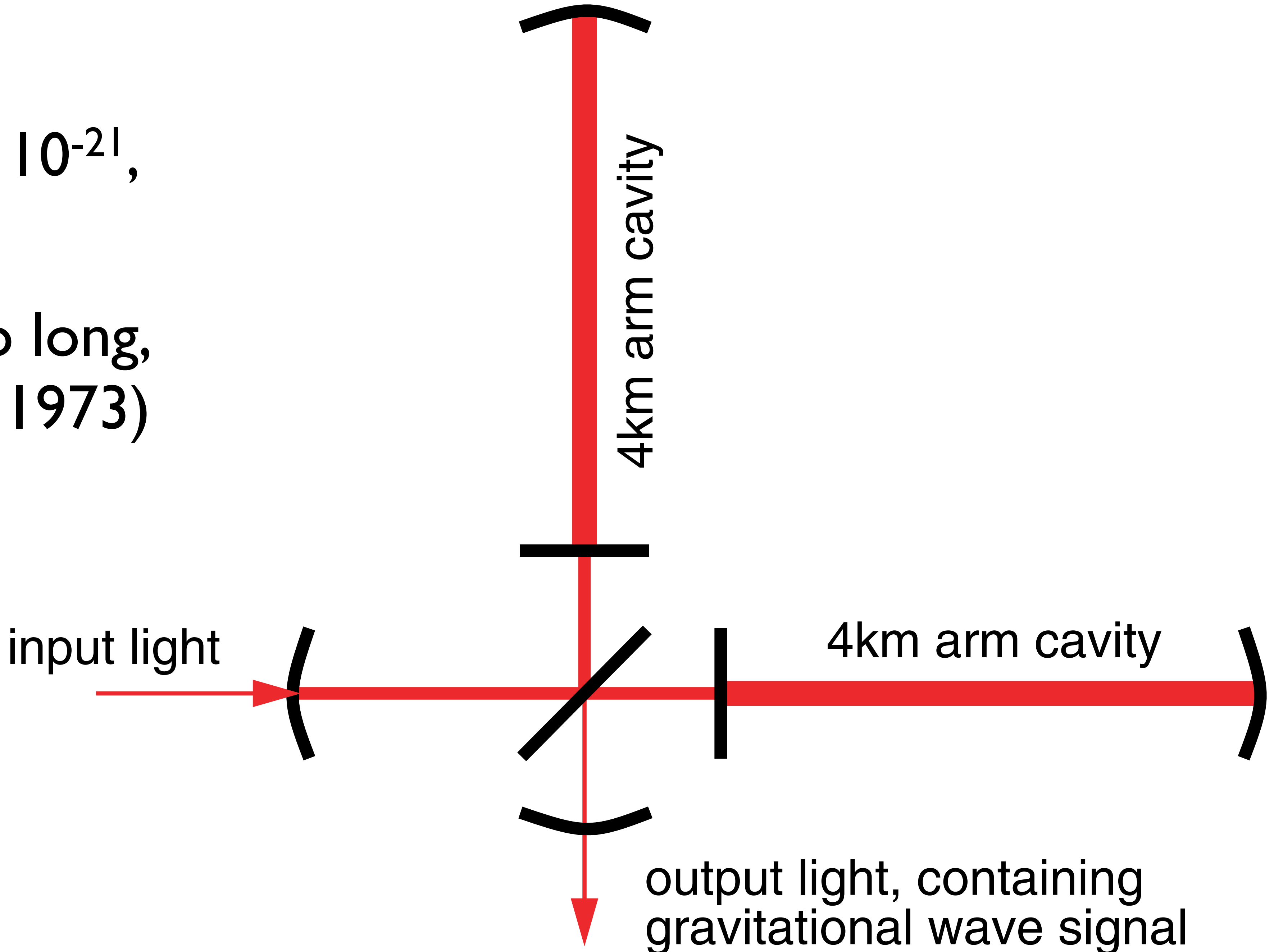
output light, containing
gravitational wave signal

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)



4km arm cavity

input light

4km arm cavity

output light, containing gravitational wave signal

The LIGO concept

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

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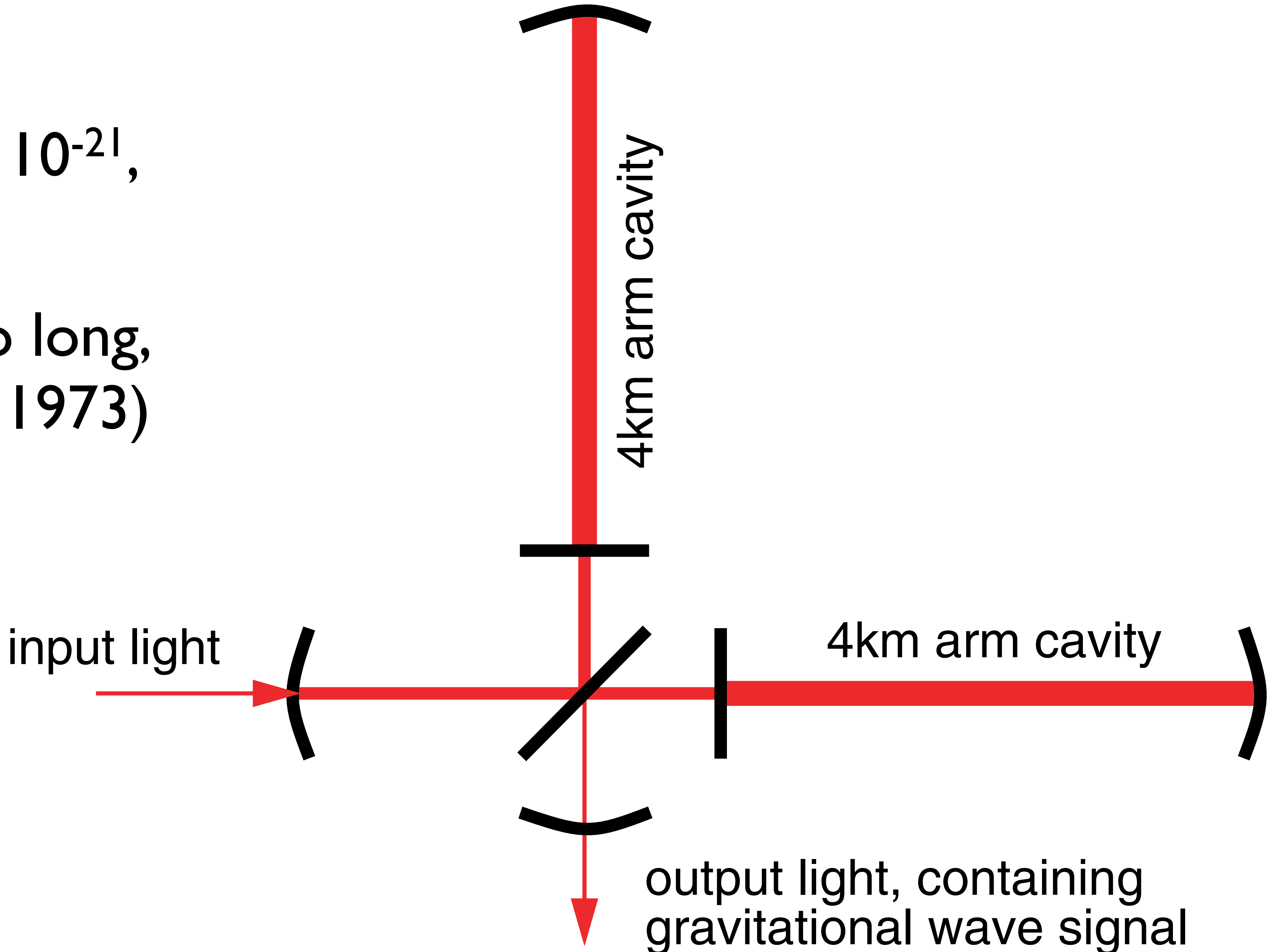

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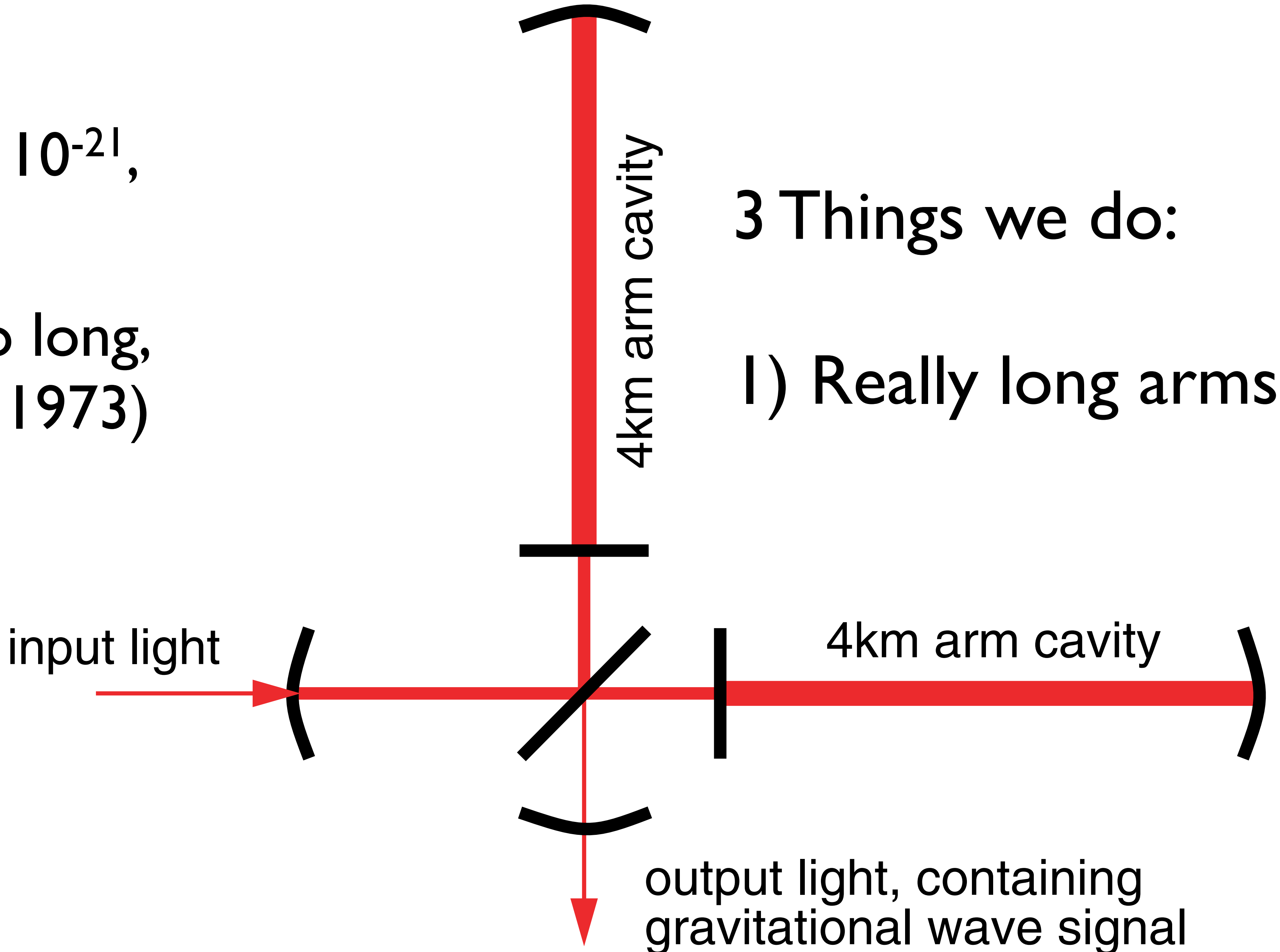
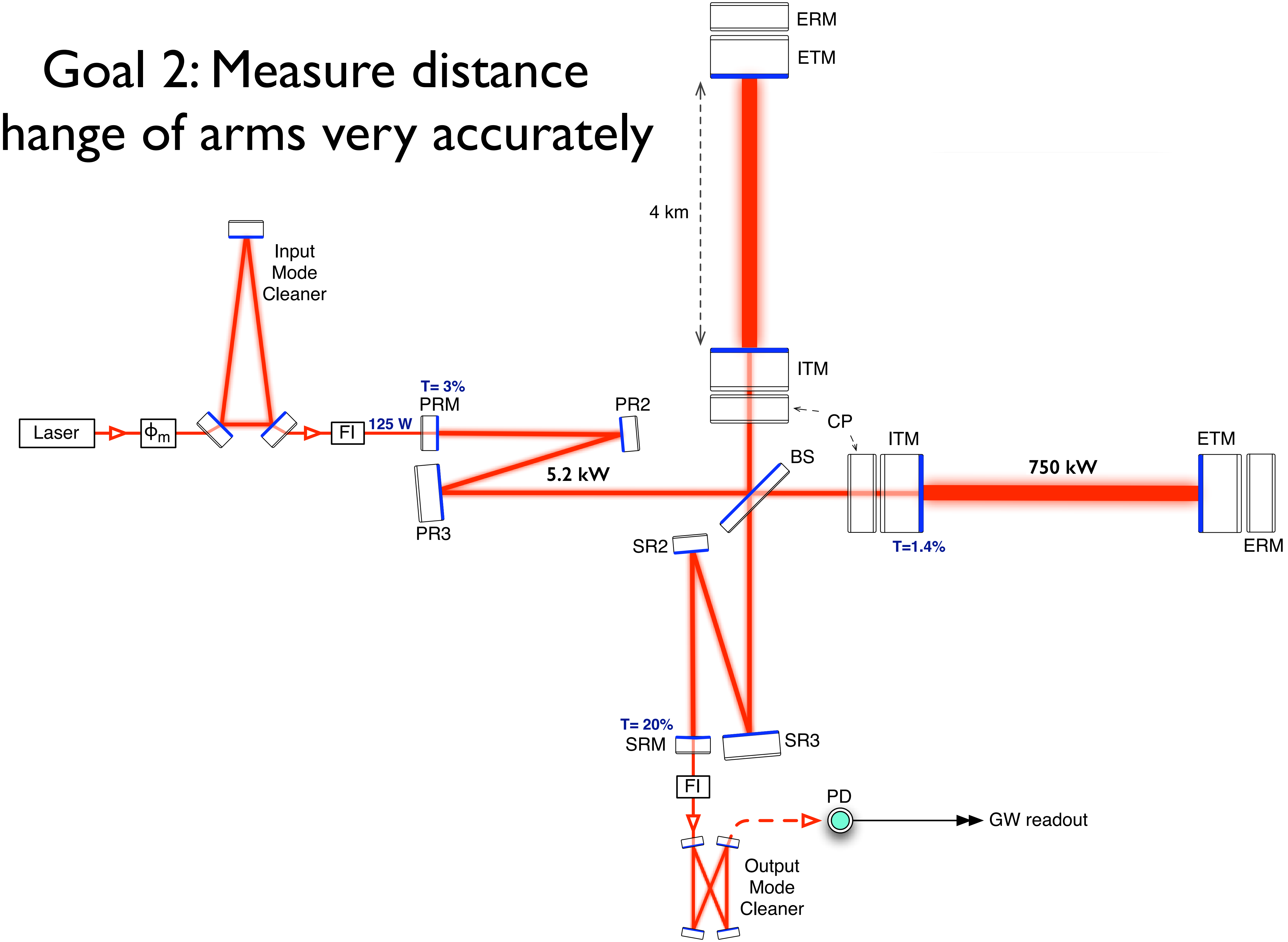


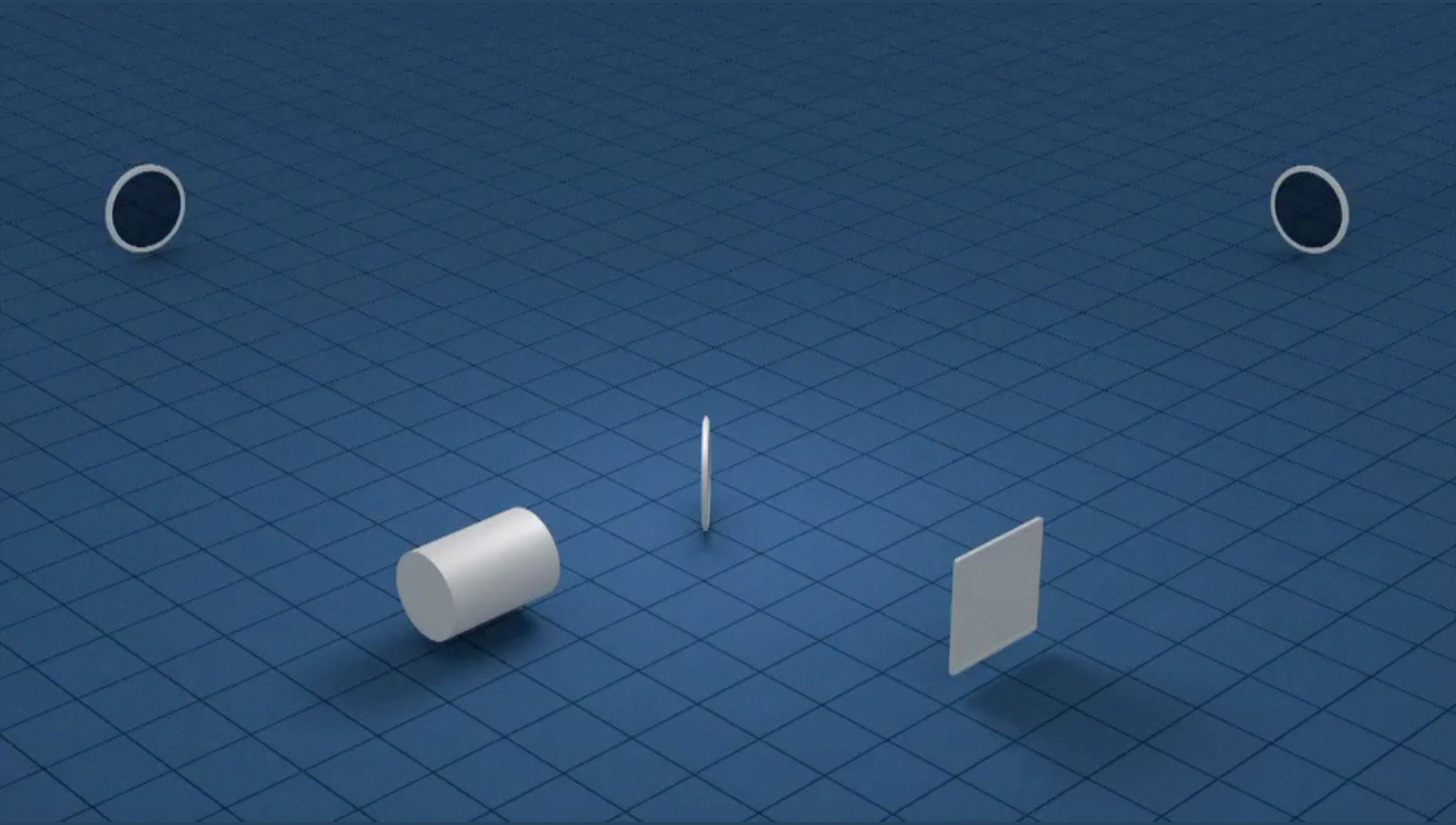
3 Things we do:

1) Really long arms.

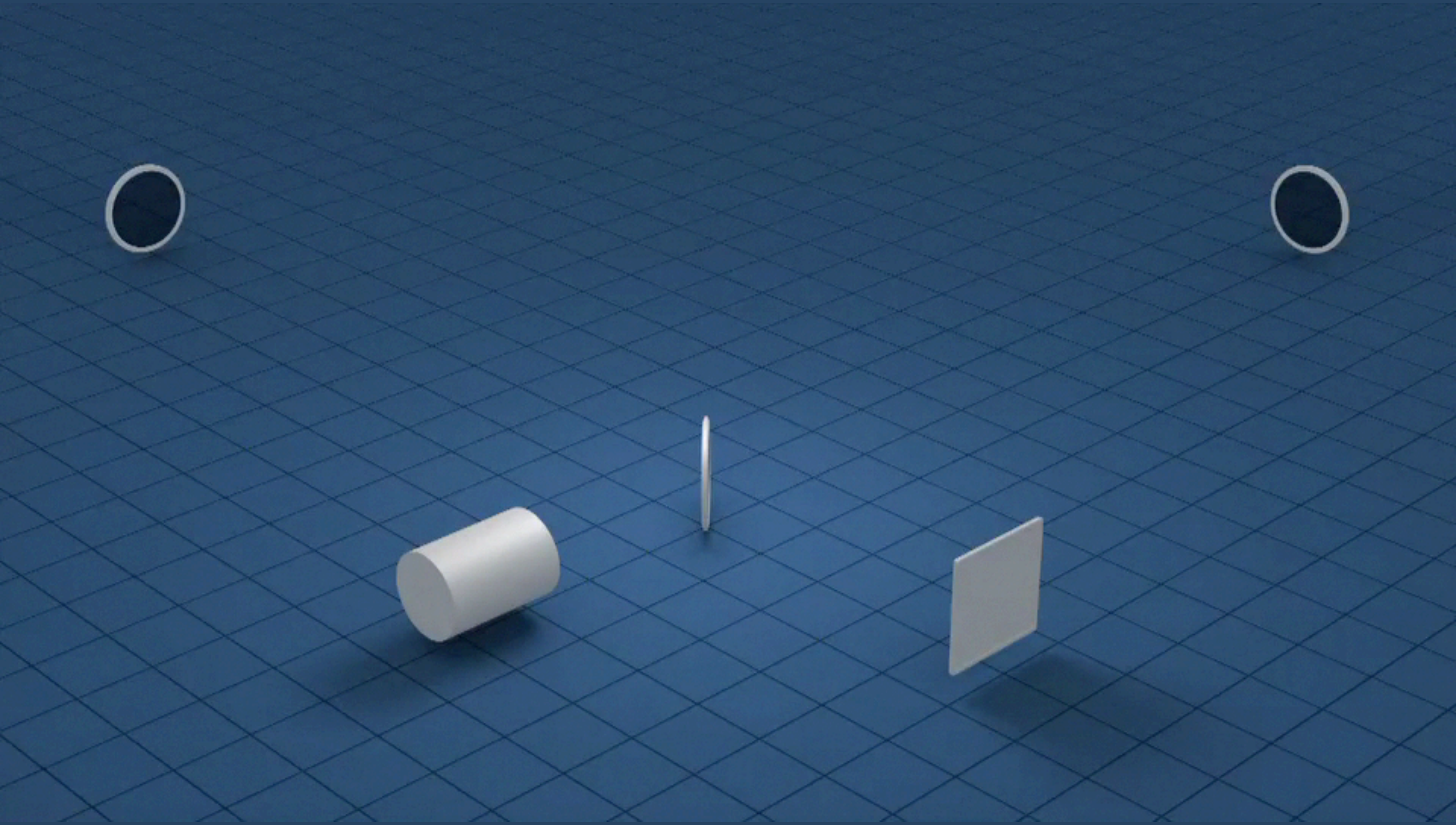
Layout of the interferometer

Goal 2: Measure distance change of arms very accurately





http://mediaassets.caltech.edu/gwave



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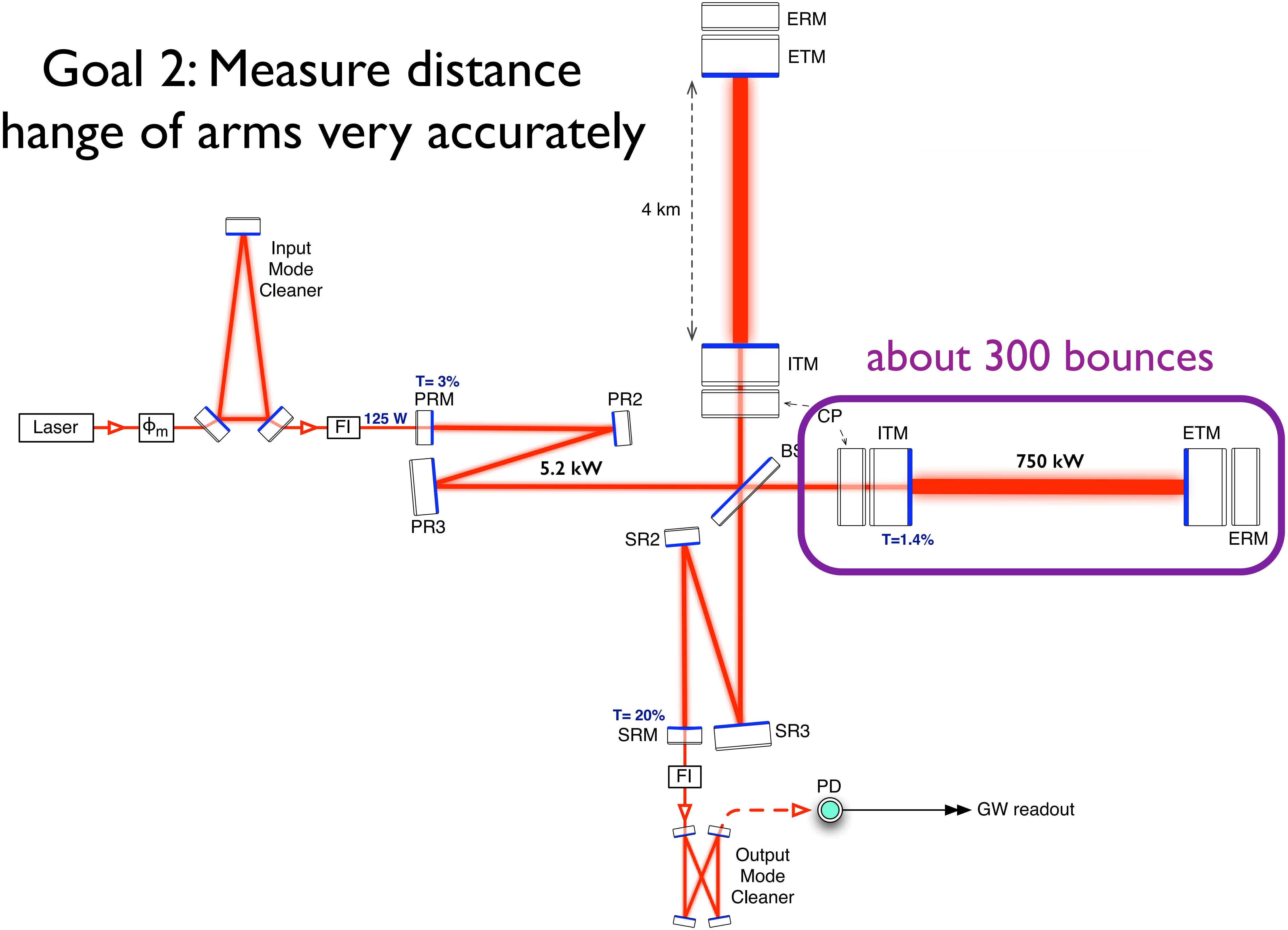
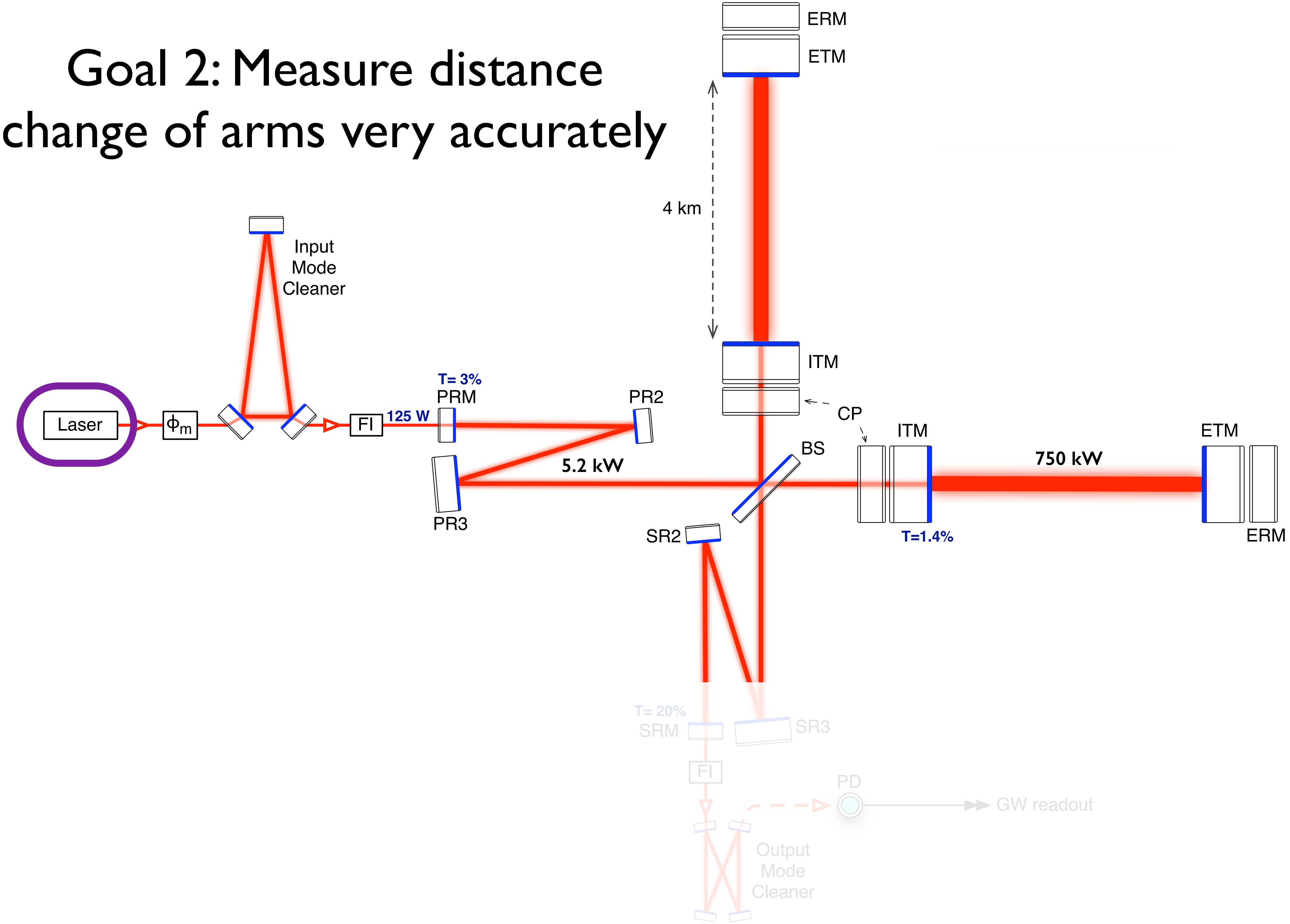
Fabry-Perot arms

Goal 2: Measure distance change of arms very accurately



Power

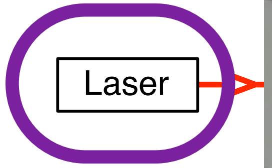
Goal 2: Measure distance change of arms very accurately

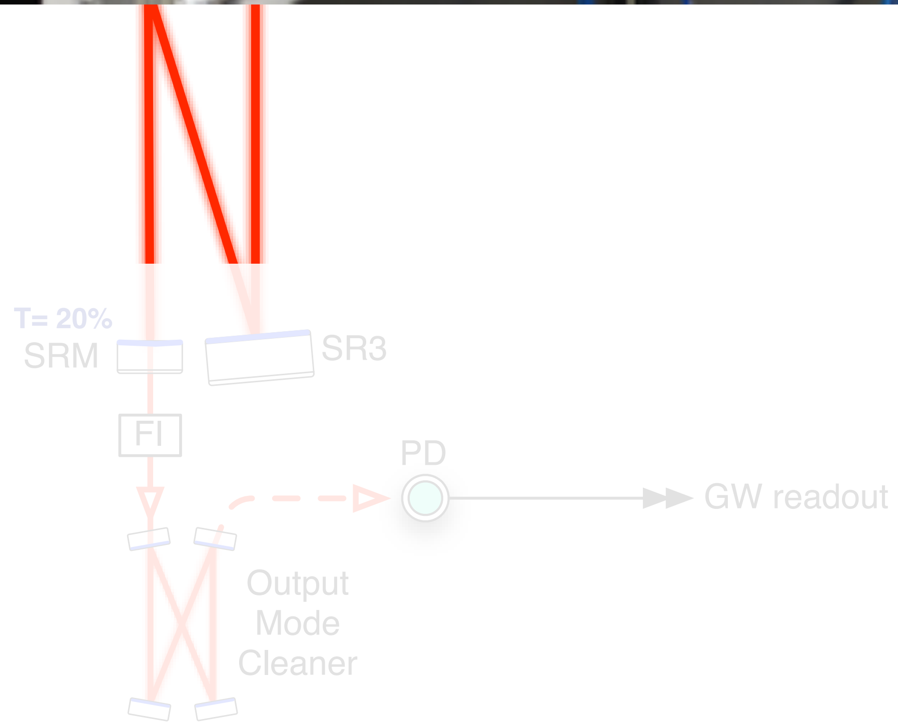


Power

Goa

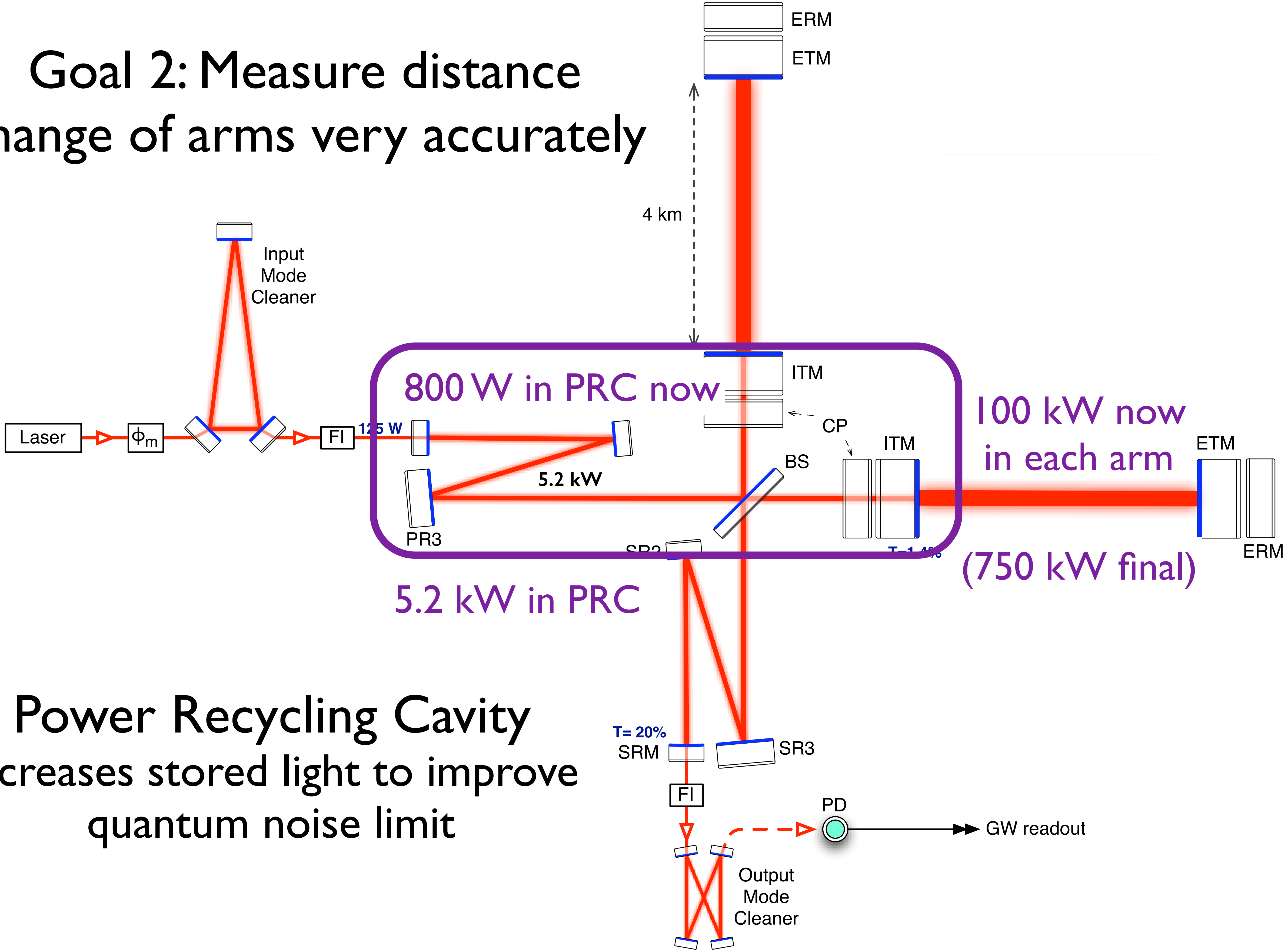
change





Power recycling

Goal 2: Measure distance change of arms very accurately



800 W in PRC now

100 kW now in each arm

(750 kW final)

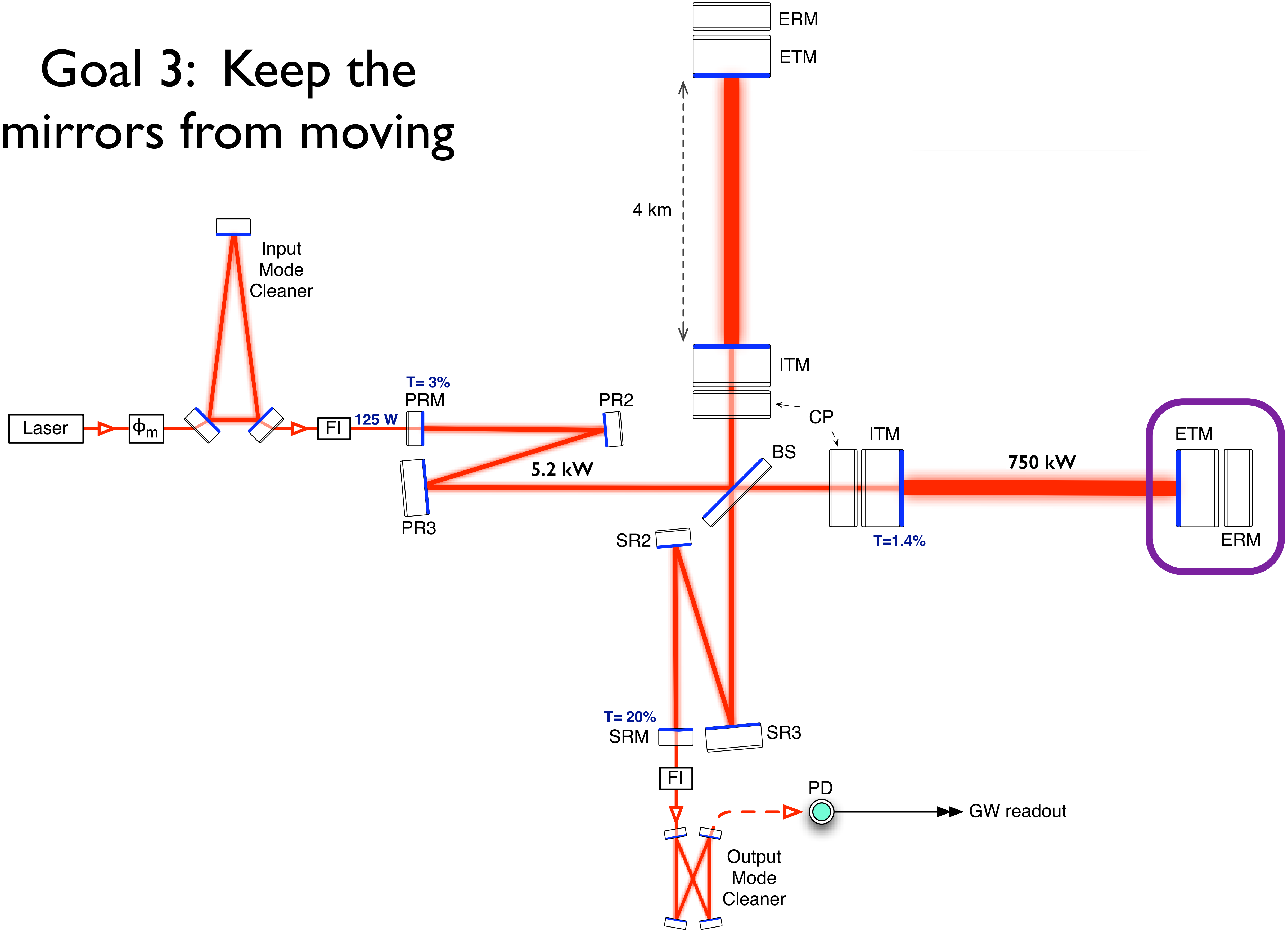
5.2 kW in PRC

Power Recycling Cavity

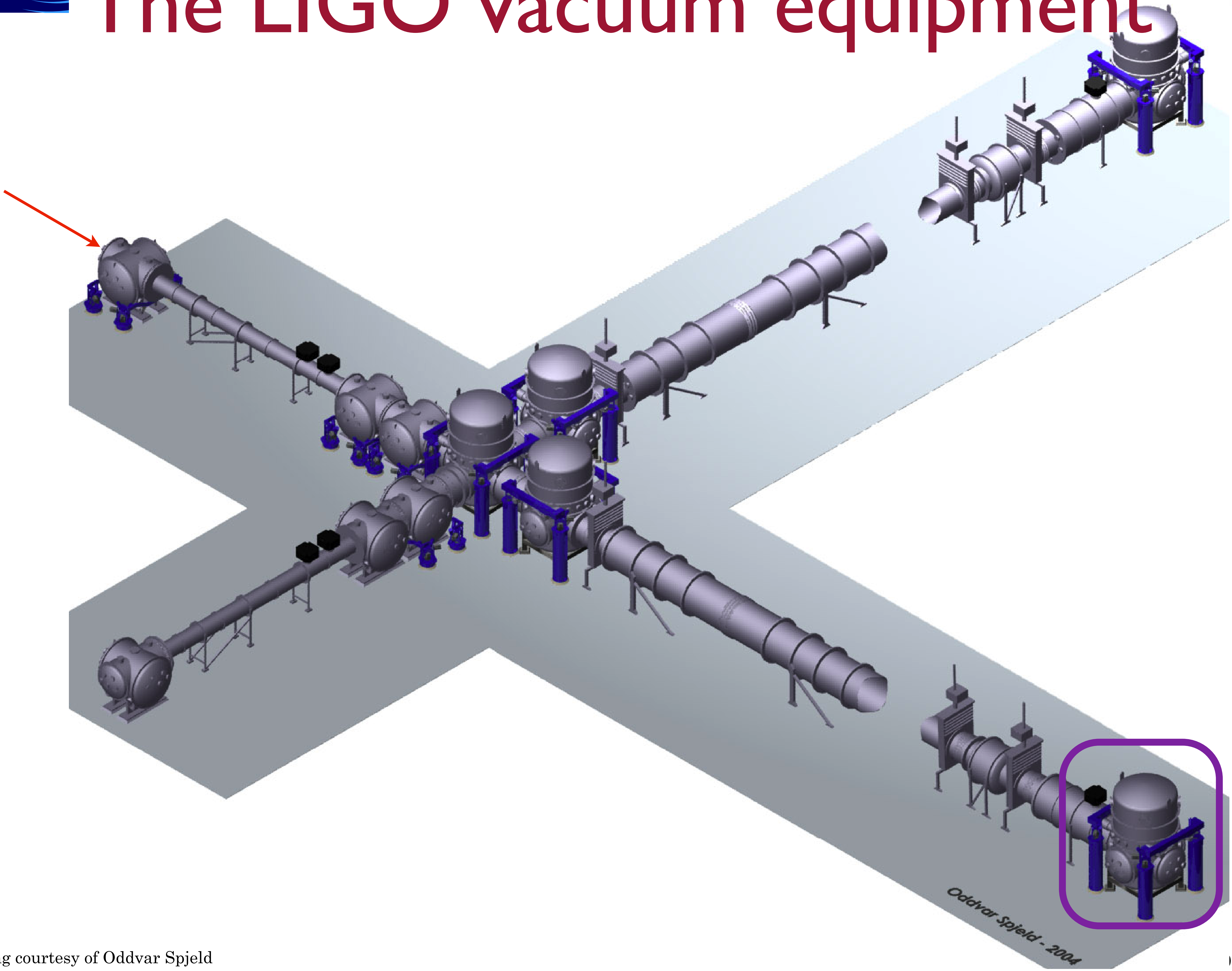
increases stored light to improve quantum noise limit

Layout of the interferometer

Goal 3: Keep the mirrors from moving

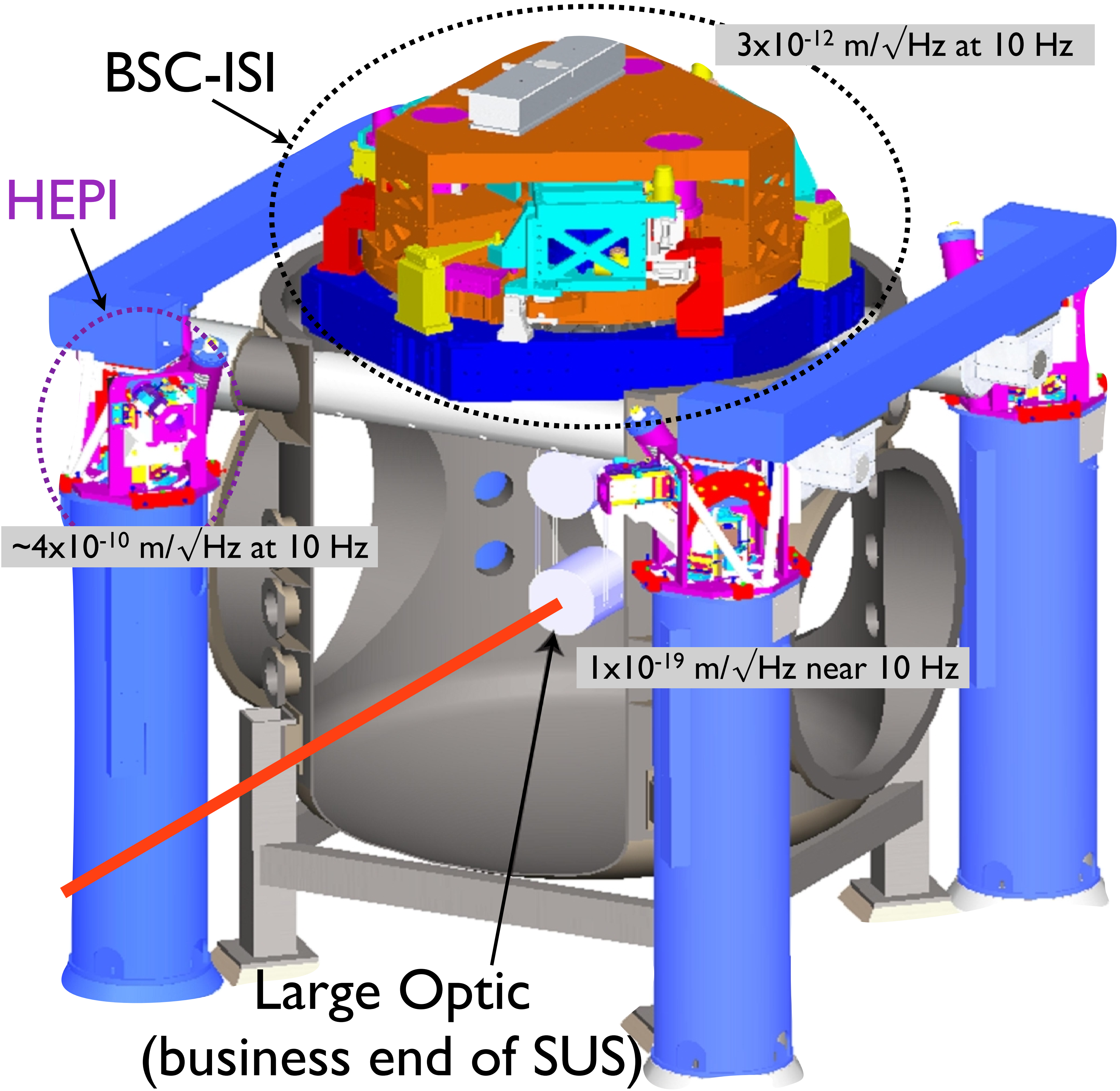


The LIGO vacuum equipment

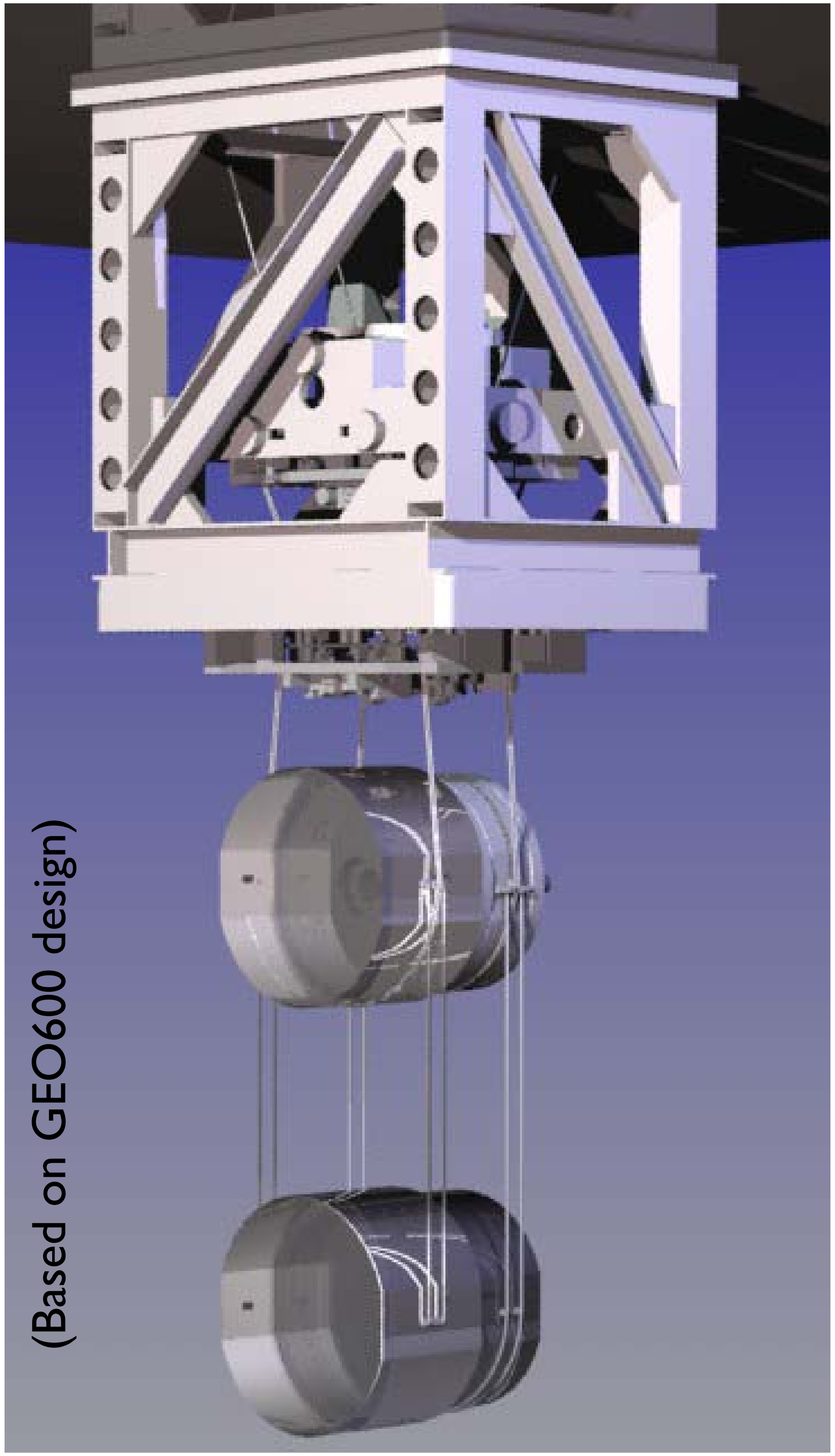


drawing courtesy of Oddvar Spjeld

Overall Isolation of Test Masses

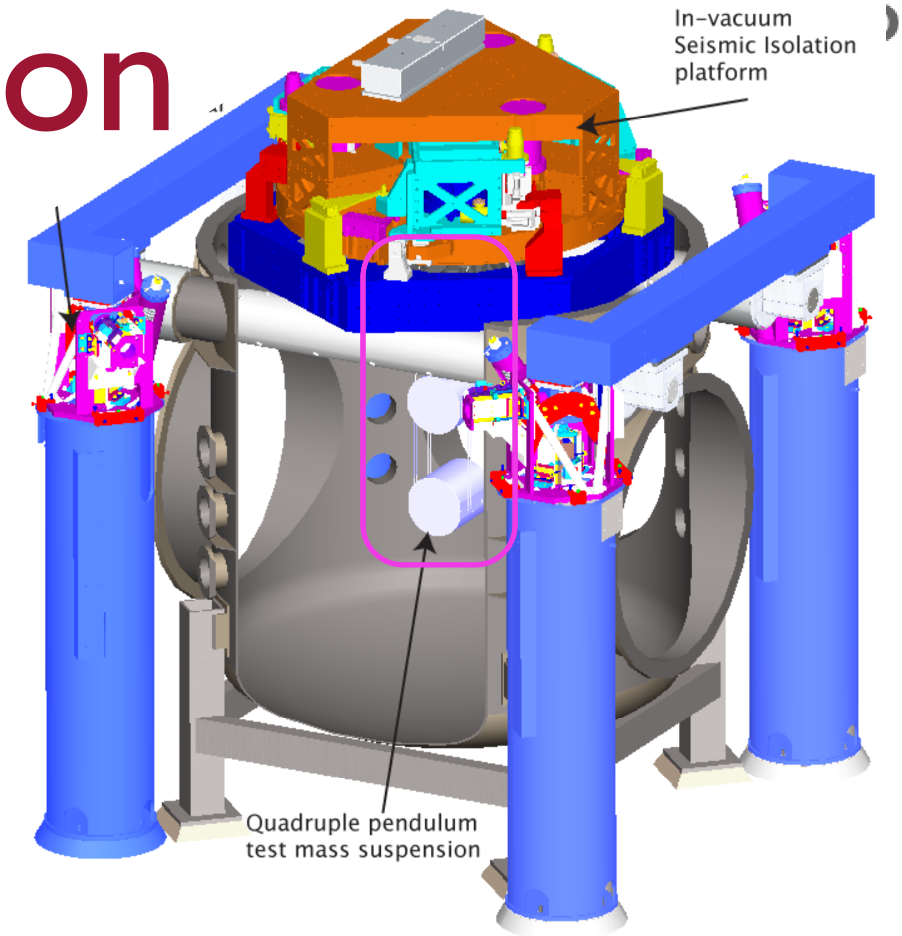


Pendulum Suspension

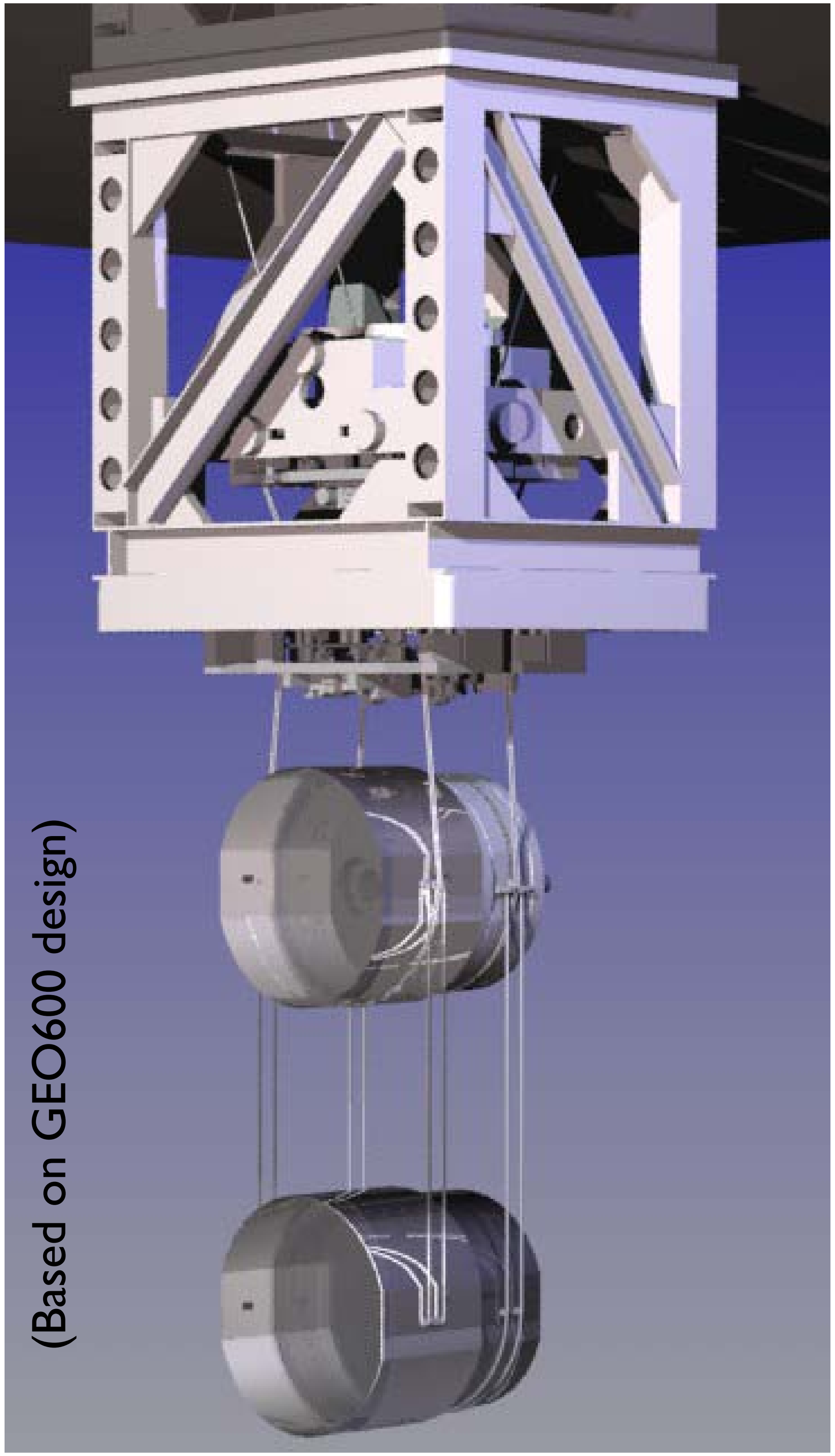


LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

Suspended as a
4 stage pendulum



Pendulum Suspension

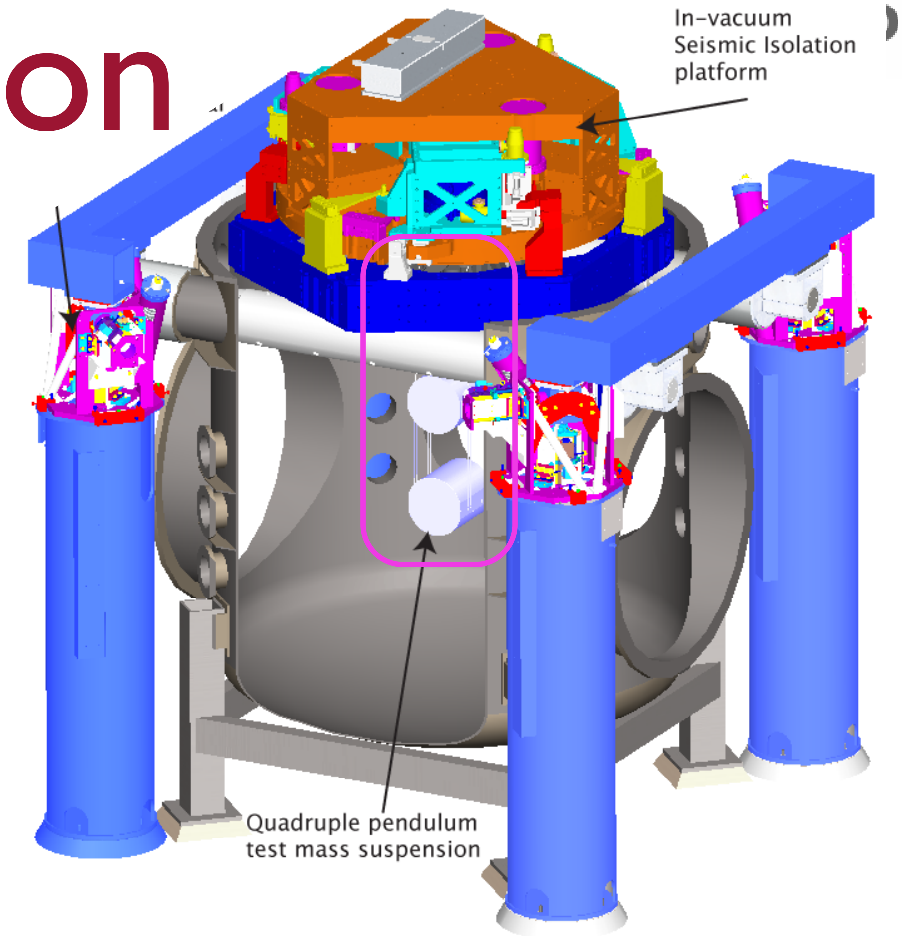


LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

Suspended as a
4 stage pendulum

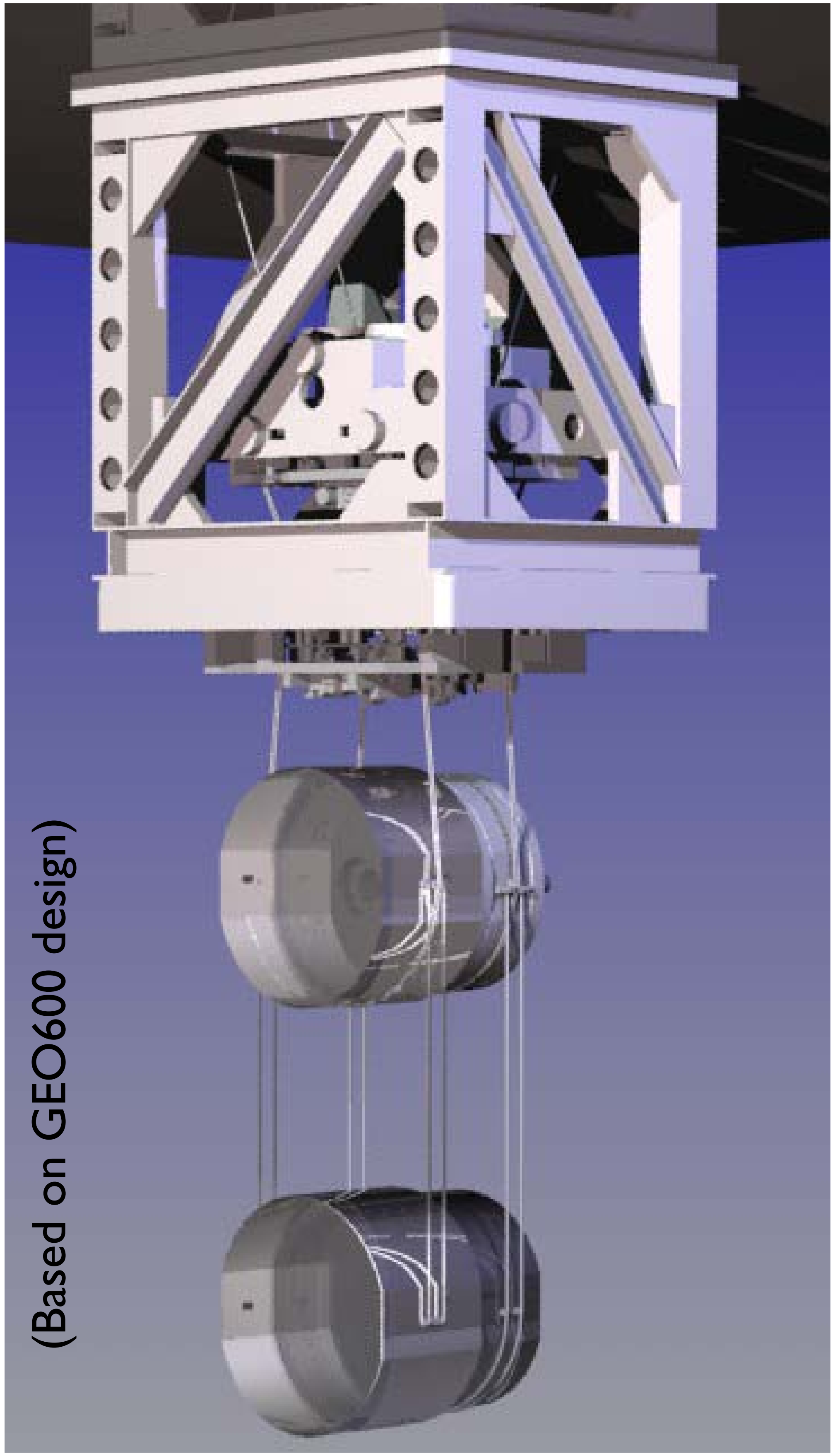
Best coatings available

Motion at 10 Hz set by
thermal driven vibration

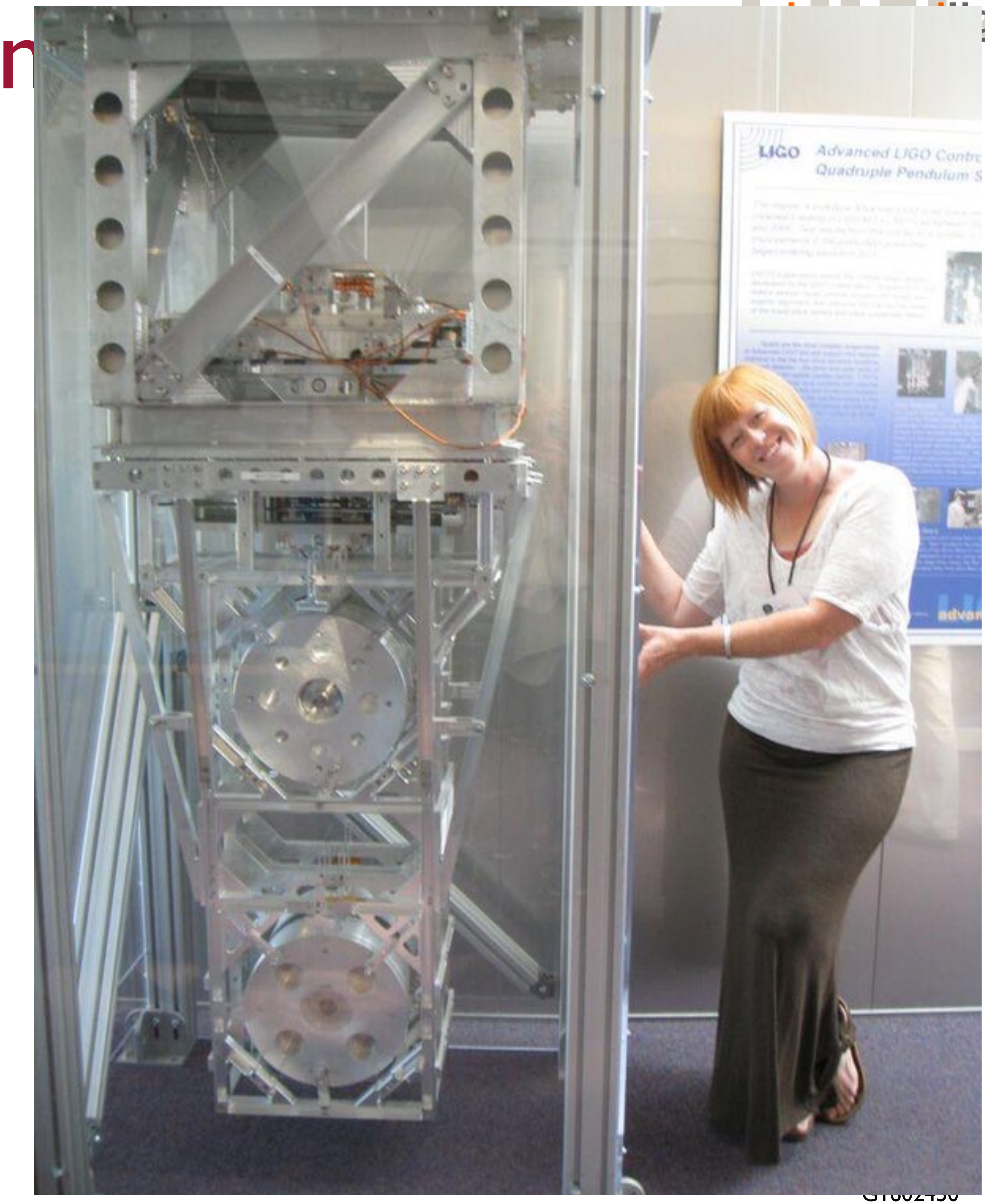


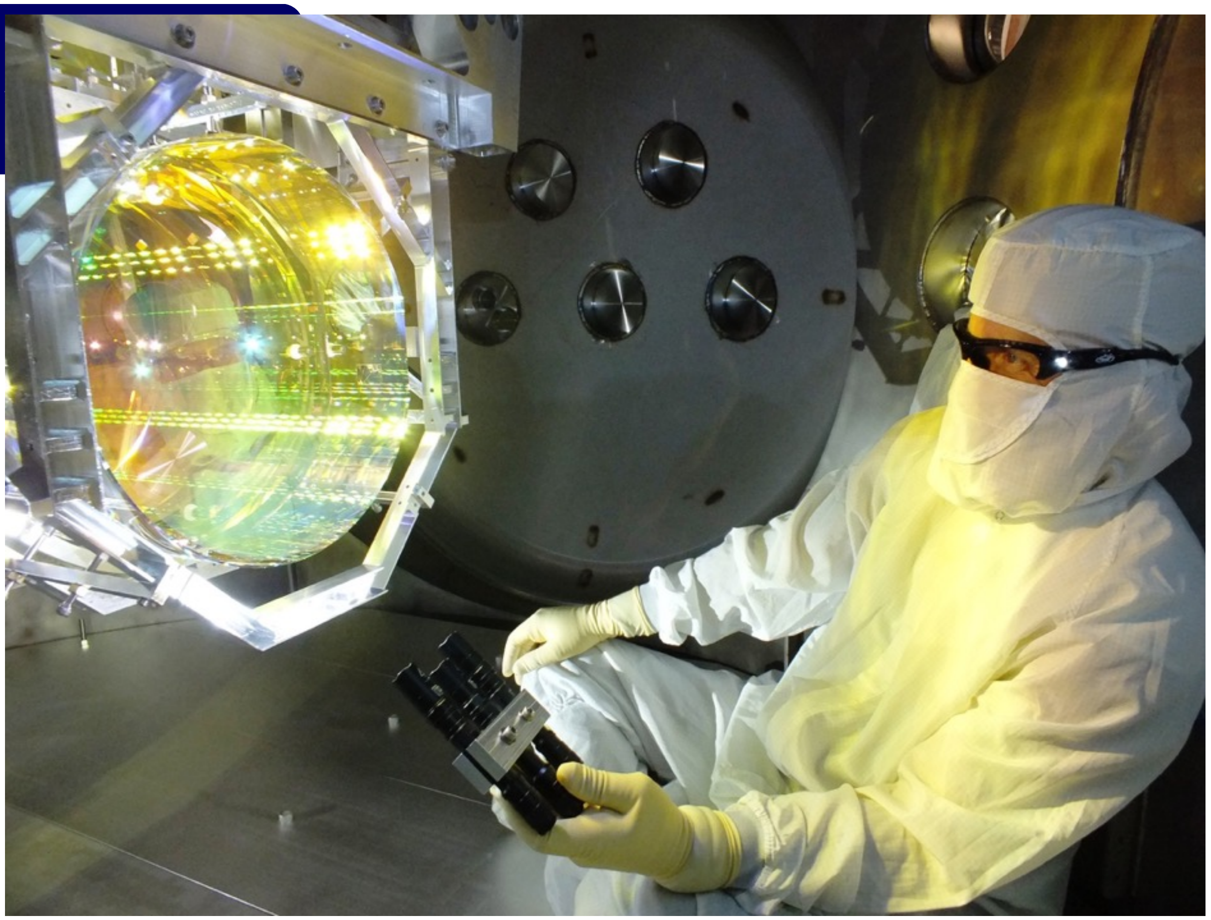
silicate bonding creates a monolithic final stage

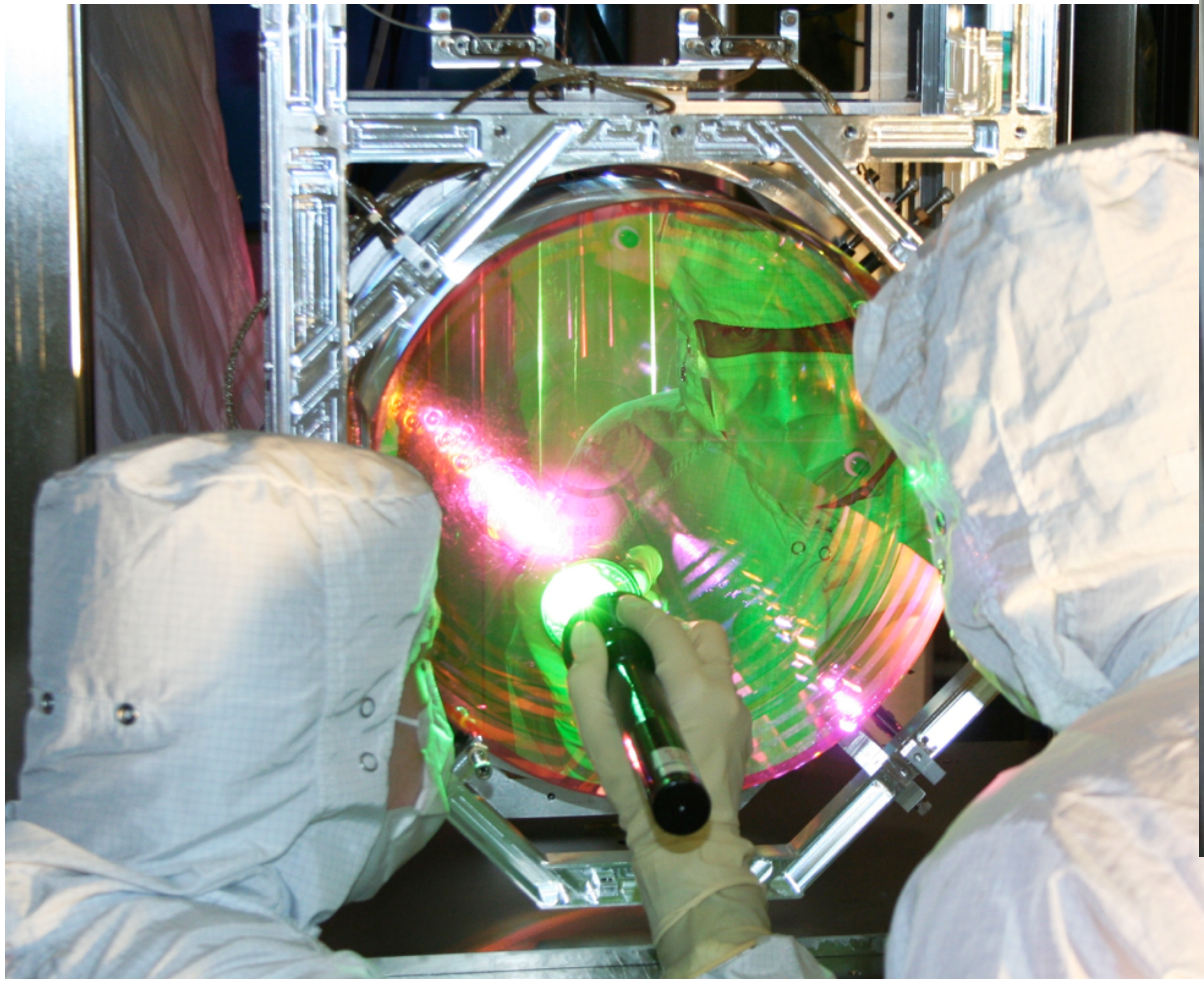
Pendulun

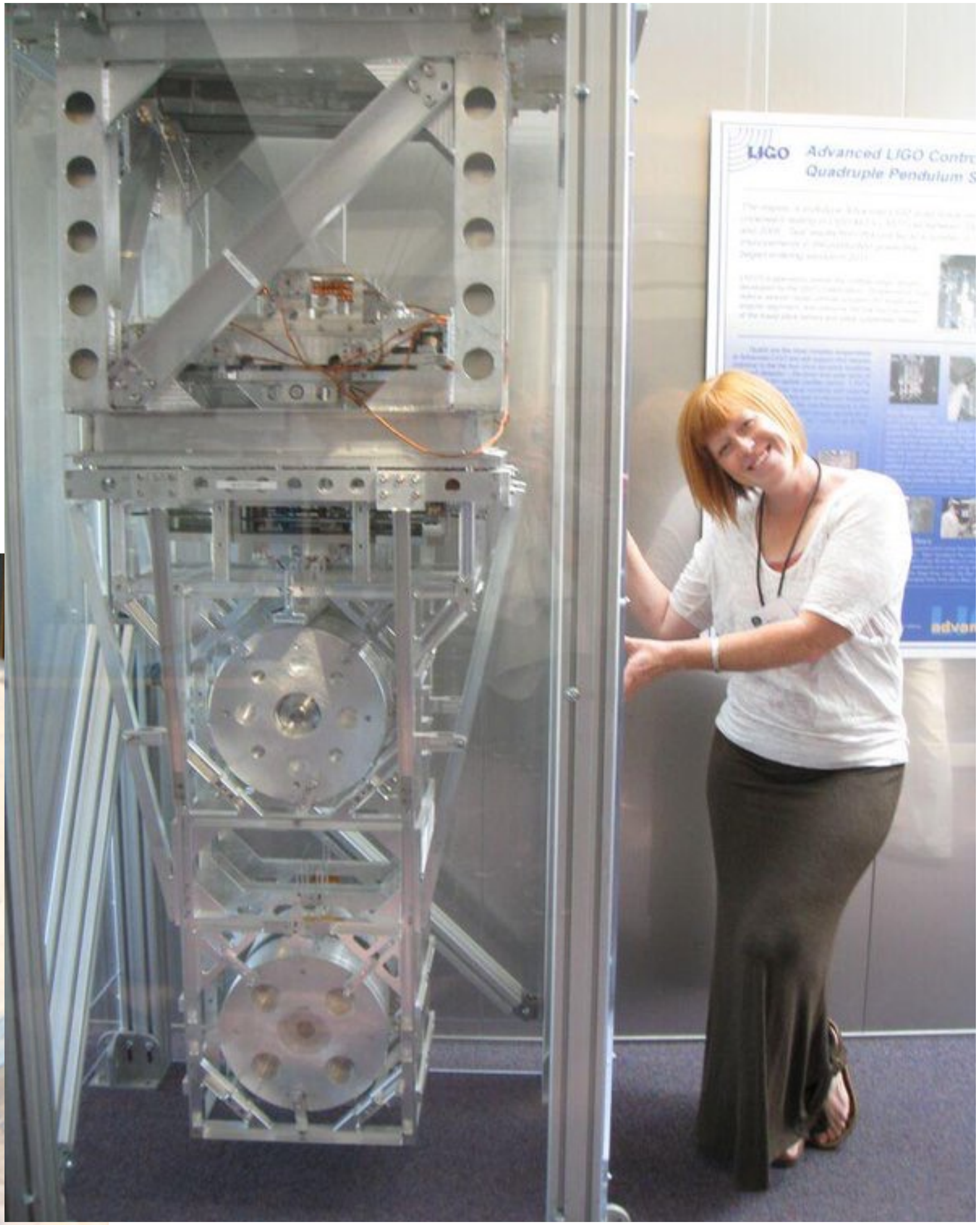


(Based on GEO600 design)

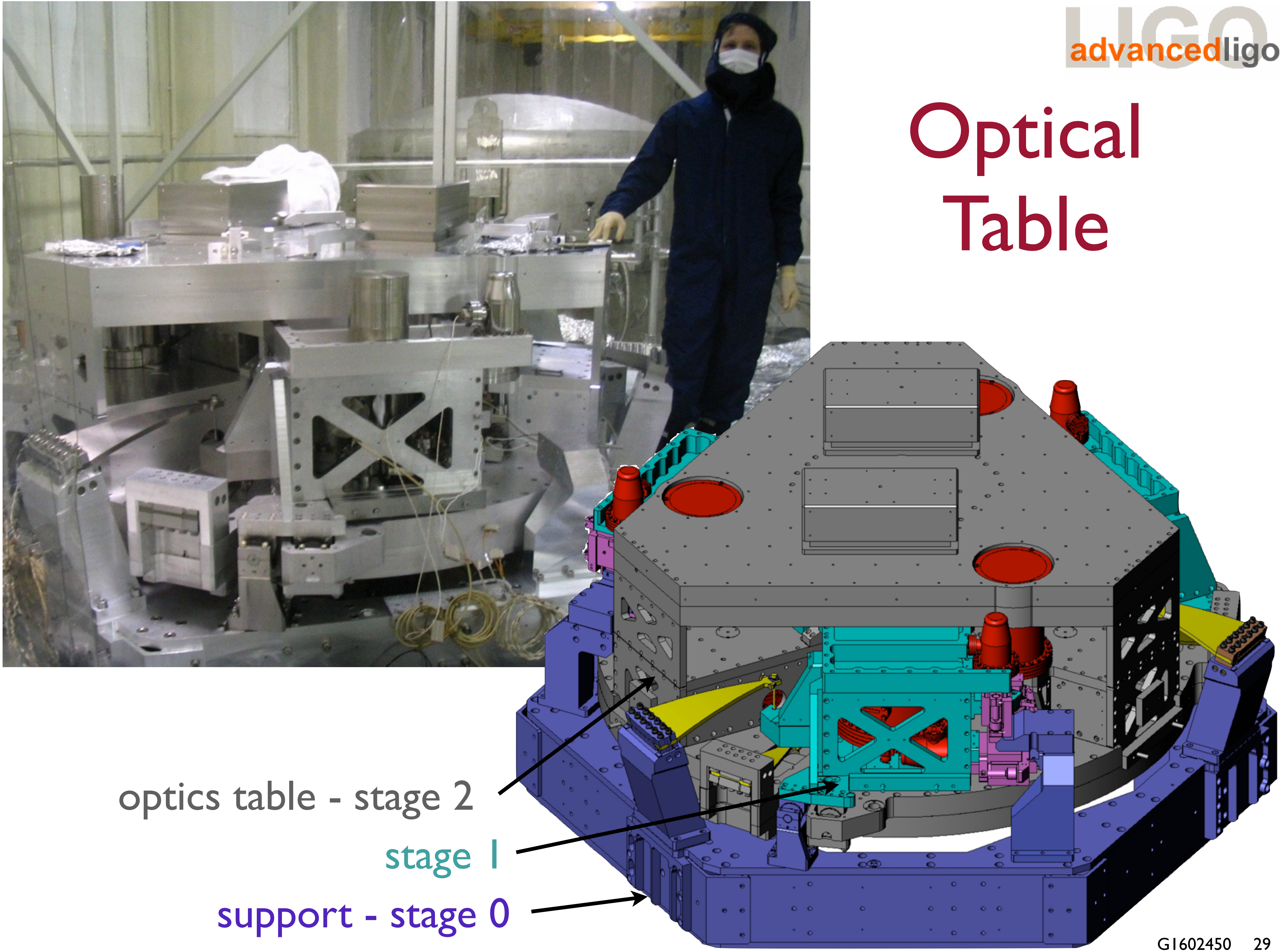







LIGO
Advanced LIGO Contr
Quadruple Pendulum S

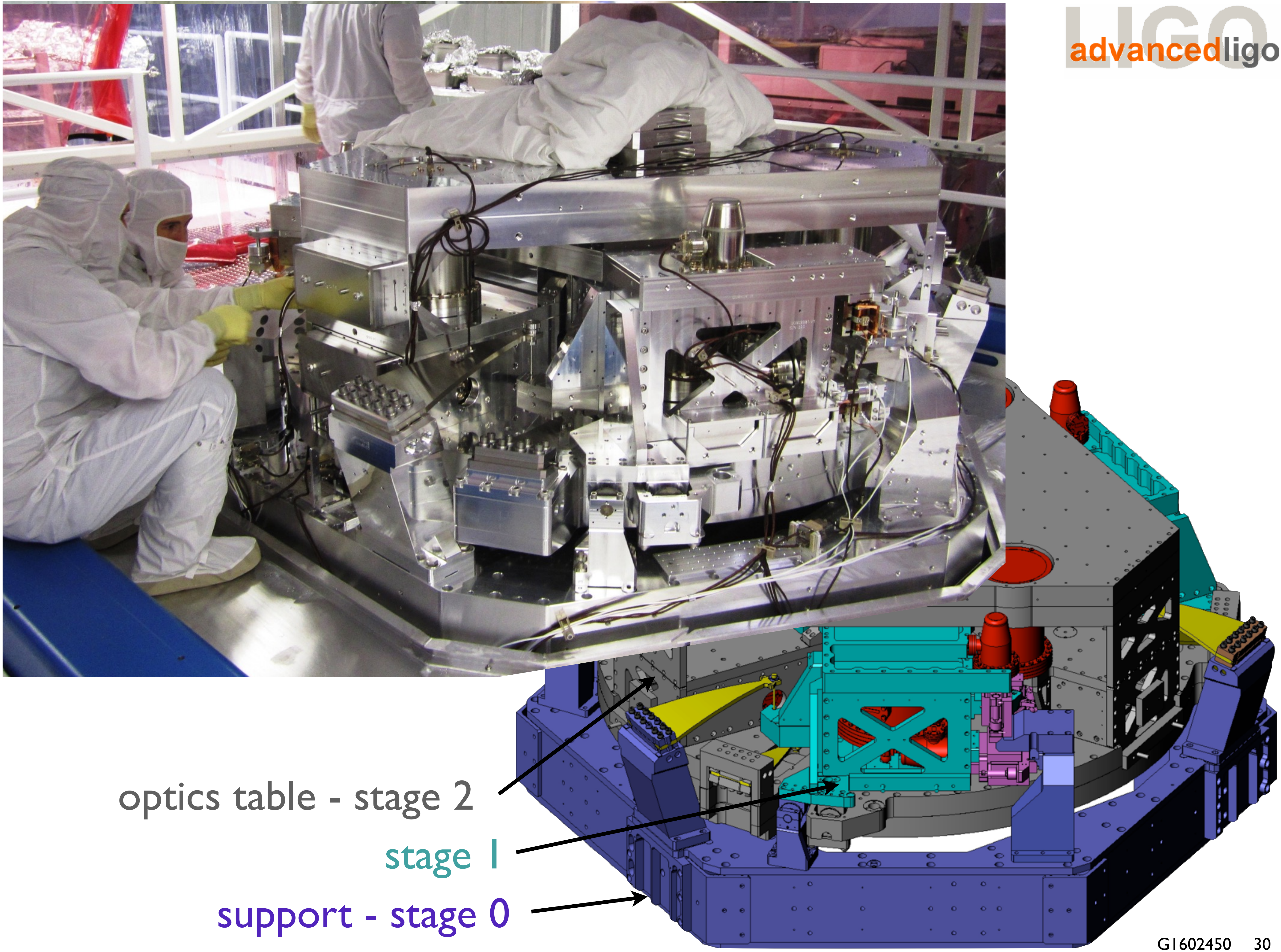
Optical Table



optics table - stage 2

stage 1

support - stage 0



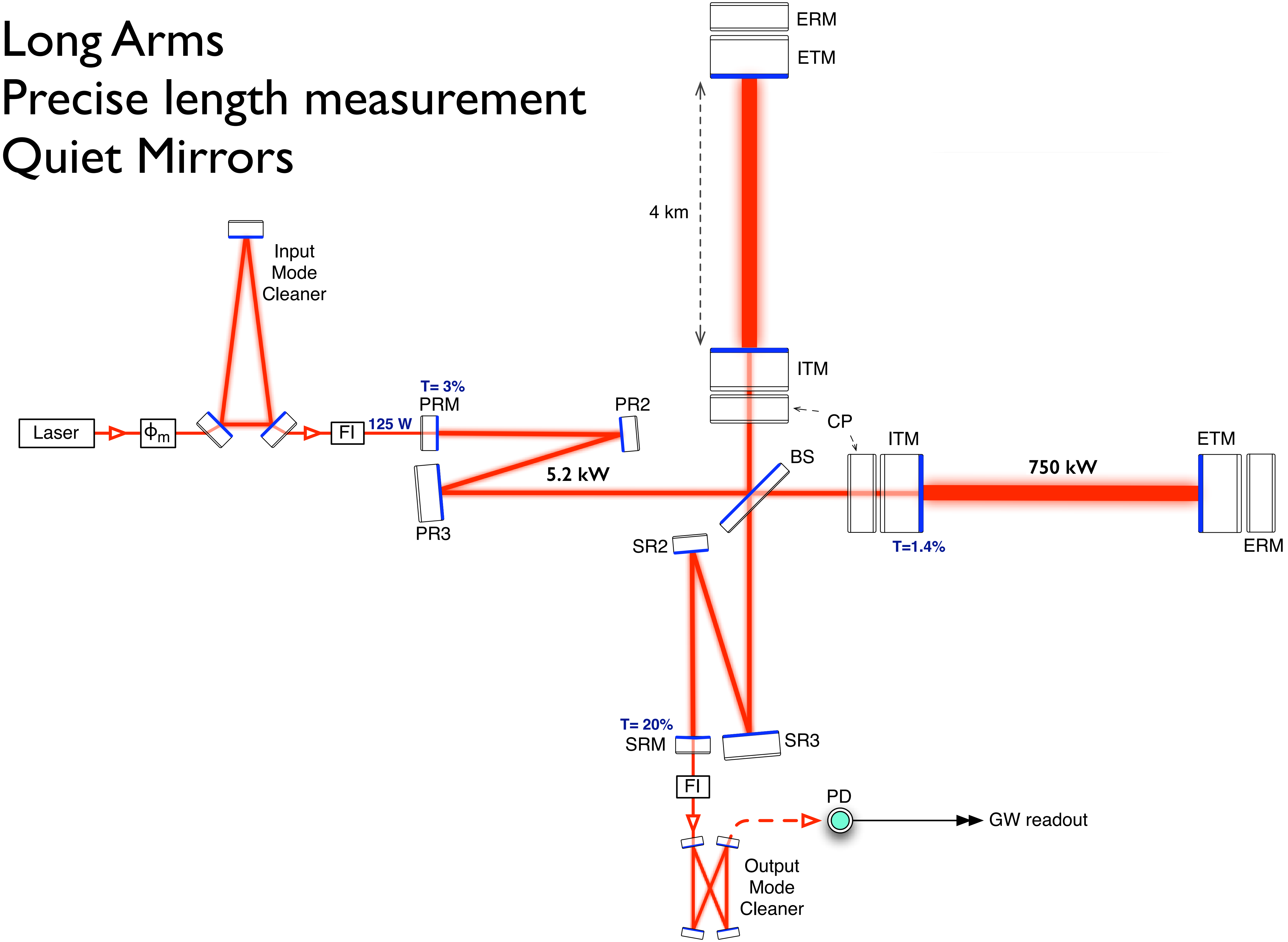
optics table - stage 2

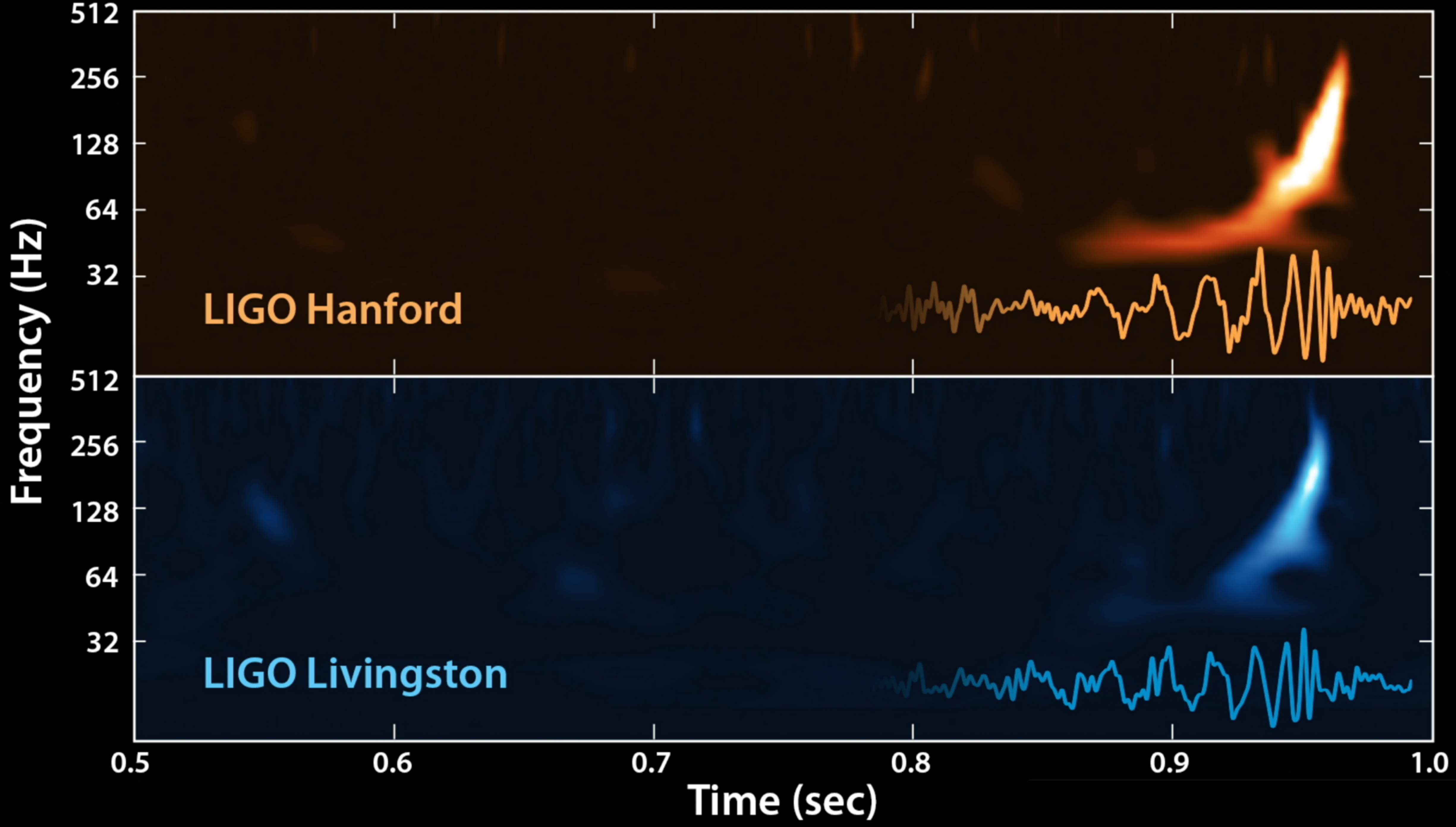
stage 1

support - stage 0

Now we are ready…

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





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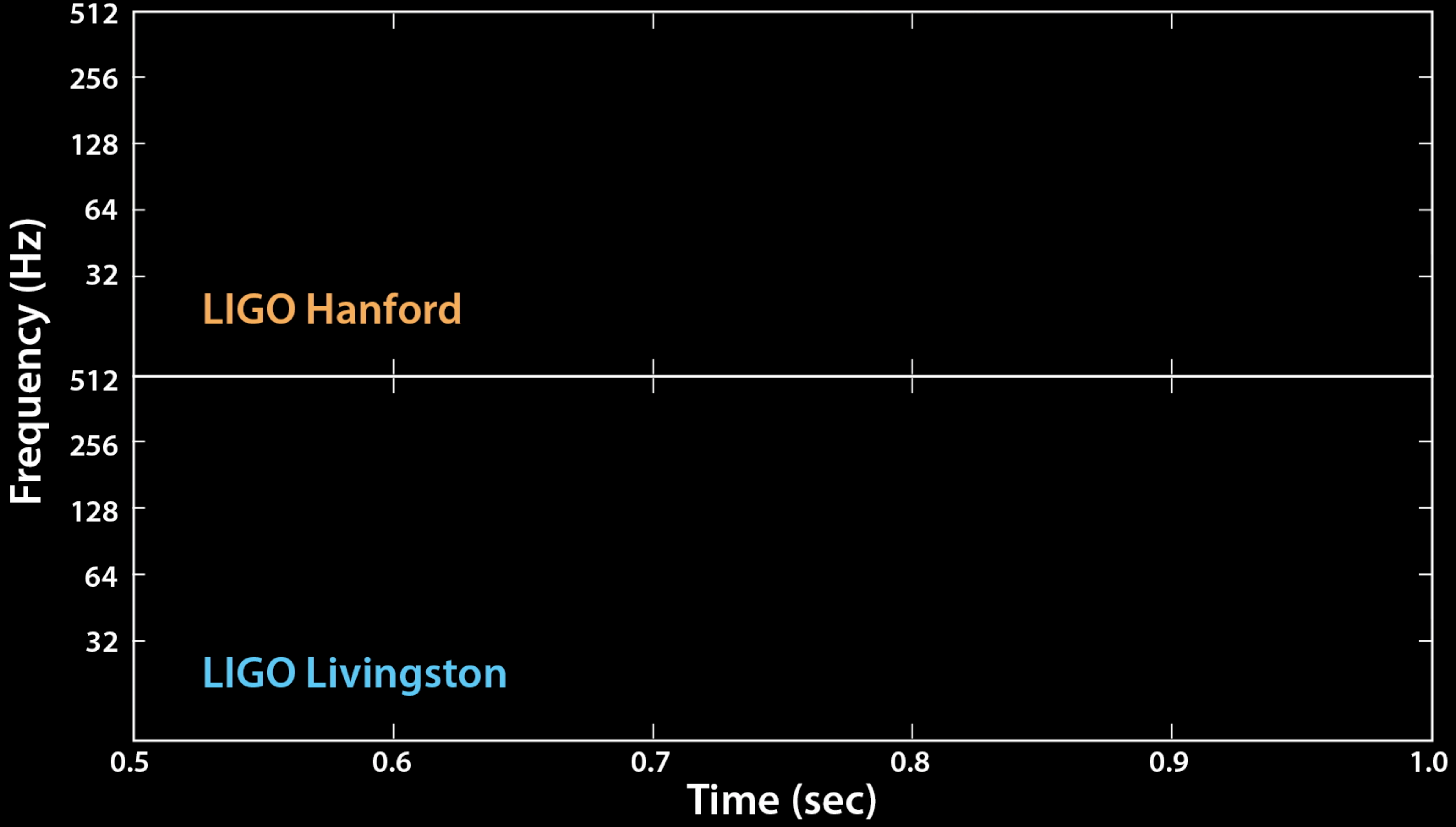
LIGO Hanford
LIGO Livingston
Frequency (Hz)
512
256
128
64
32
512
256
128
64
32
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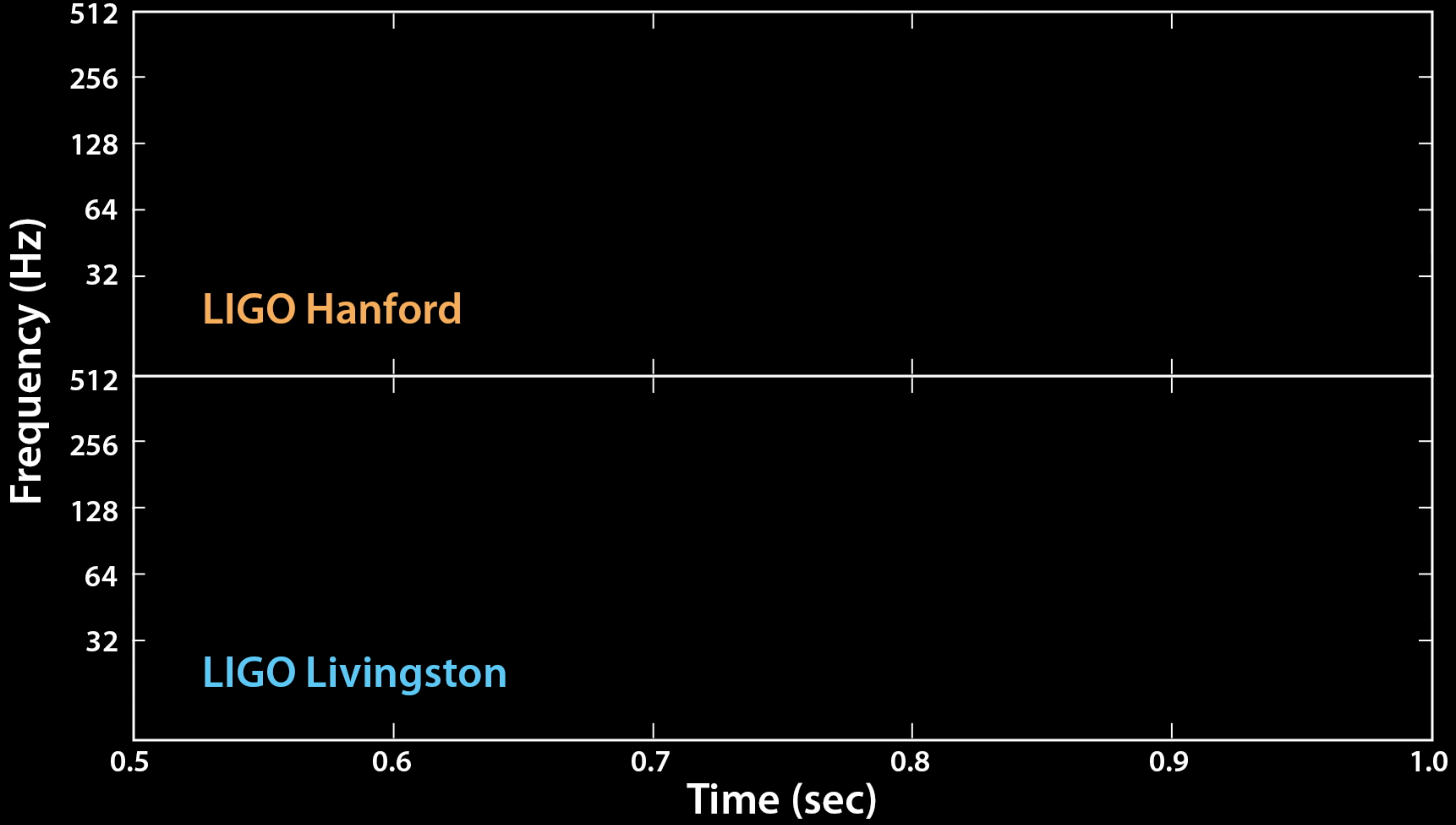
0.6
0.7
0.8
0.9
1.0
Time (sec)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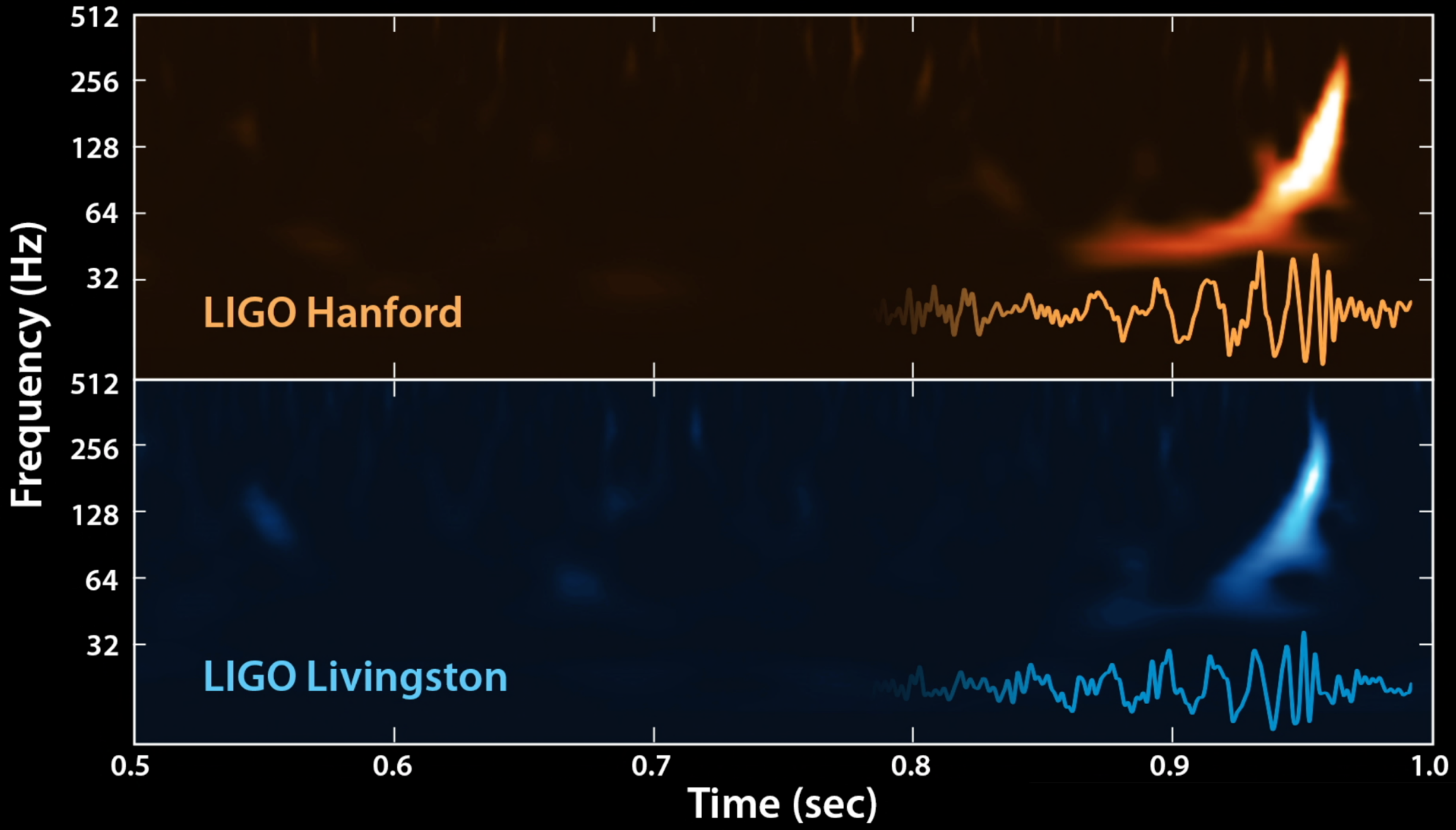
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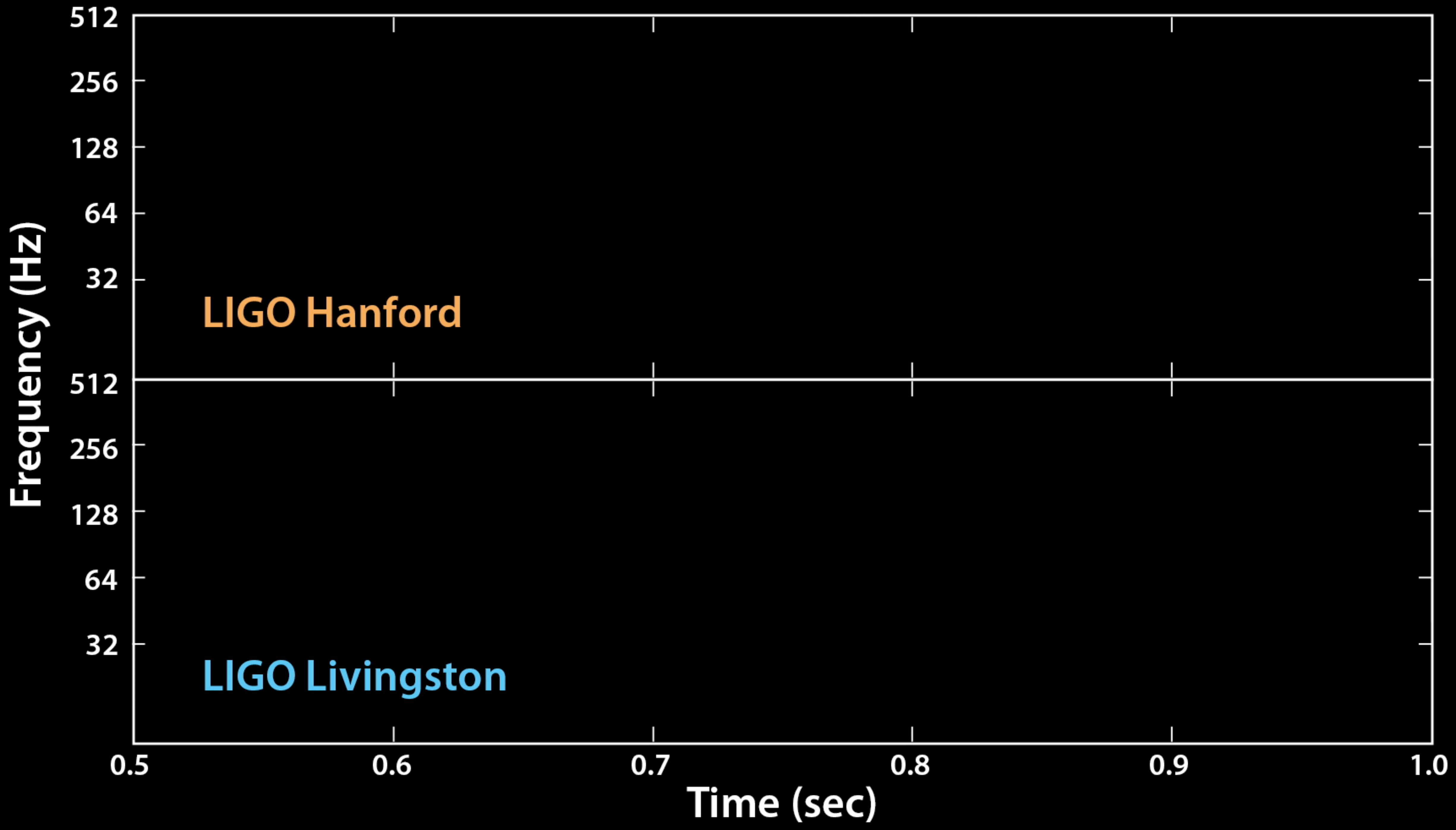
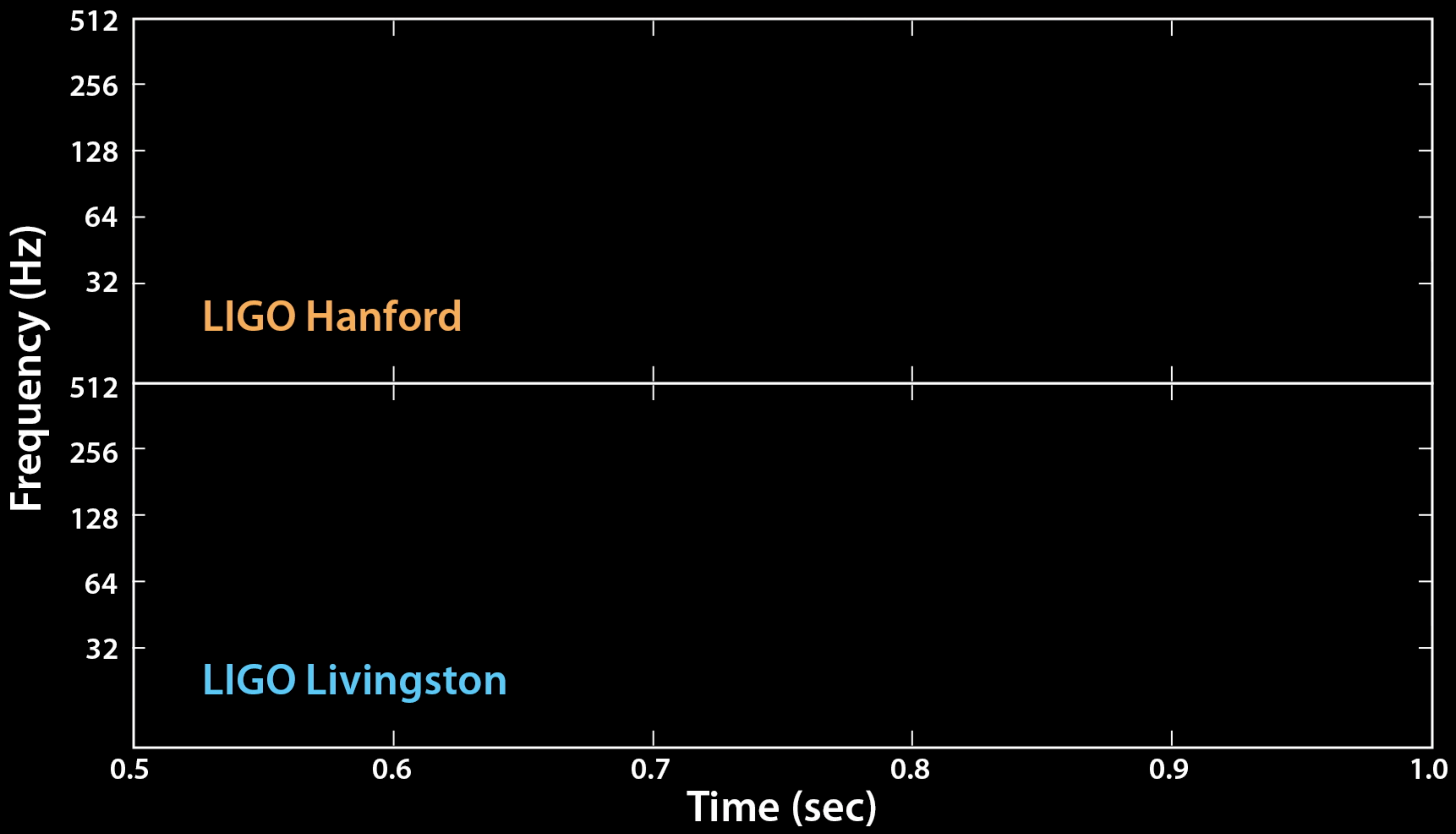
0.7
0.8
0.9
1.0
Time (sec)

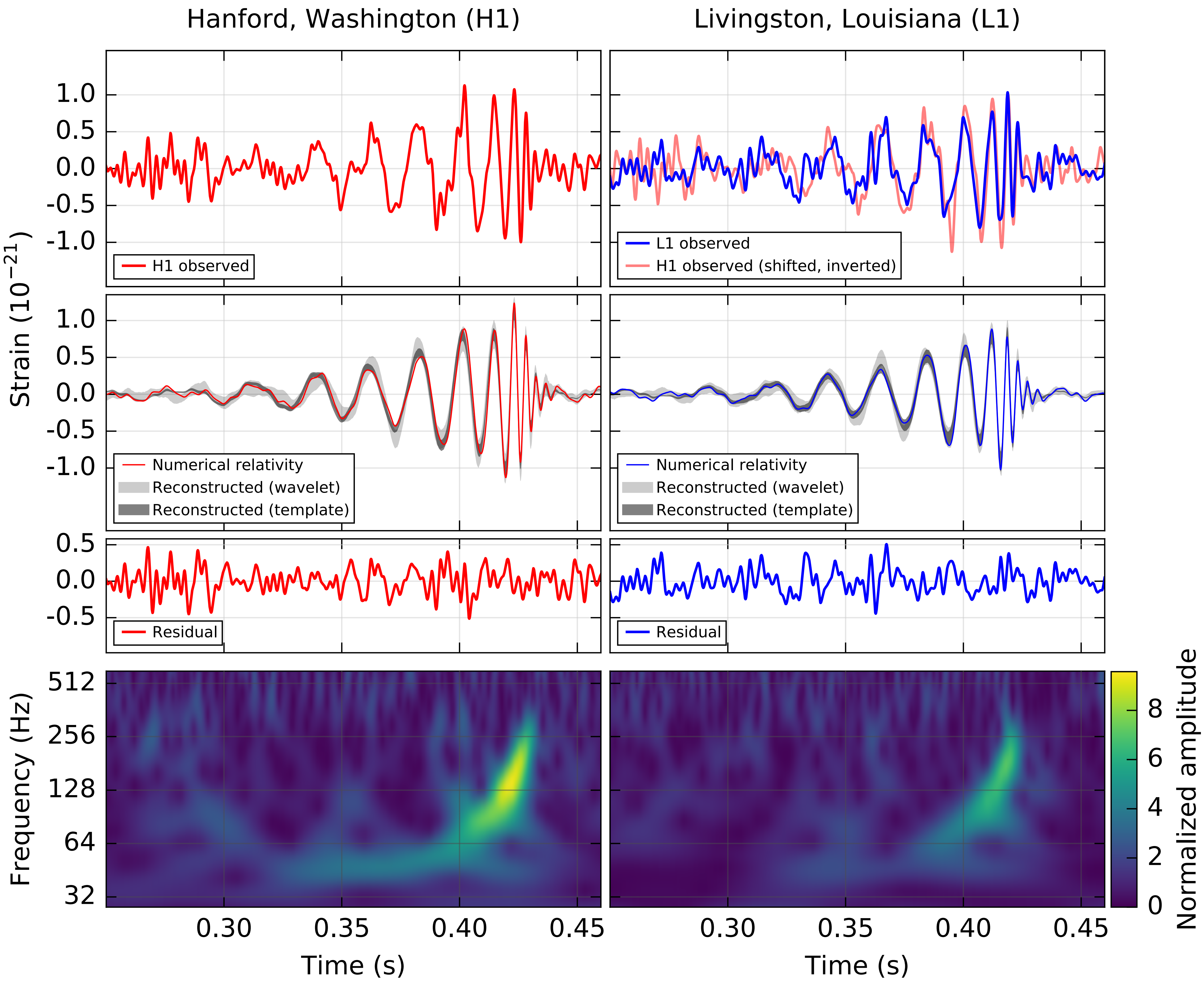
The sound of black holes colliding



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}

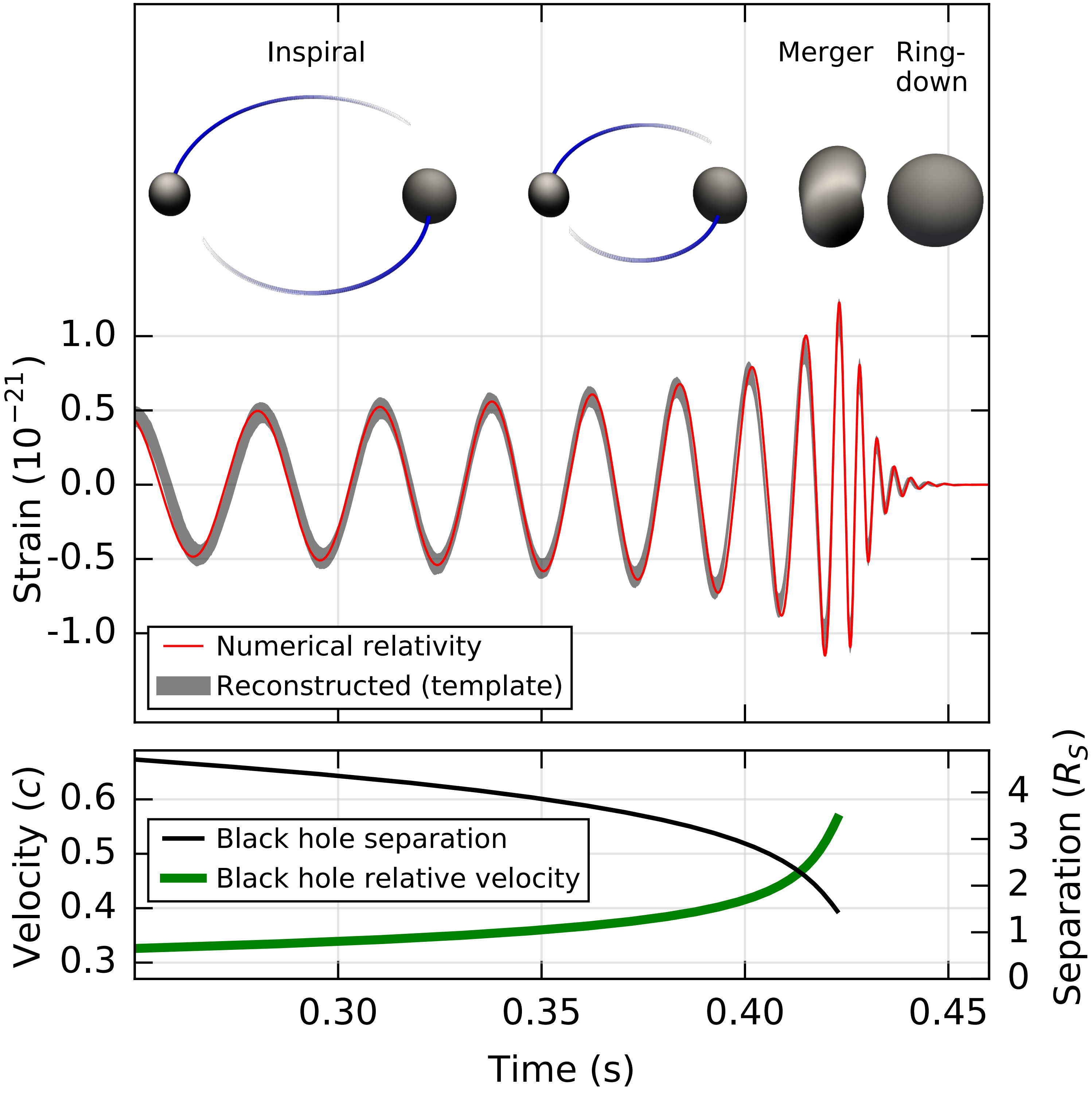
Final Mass:

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

Distance

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}

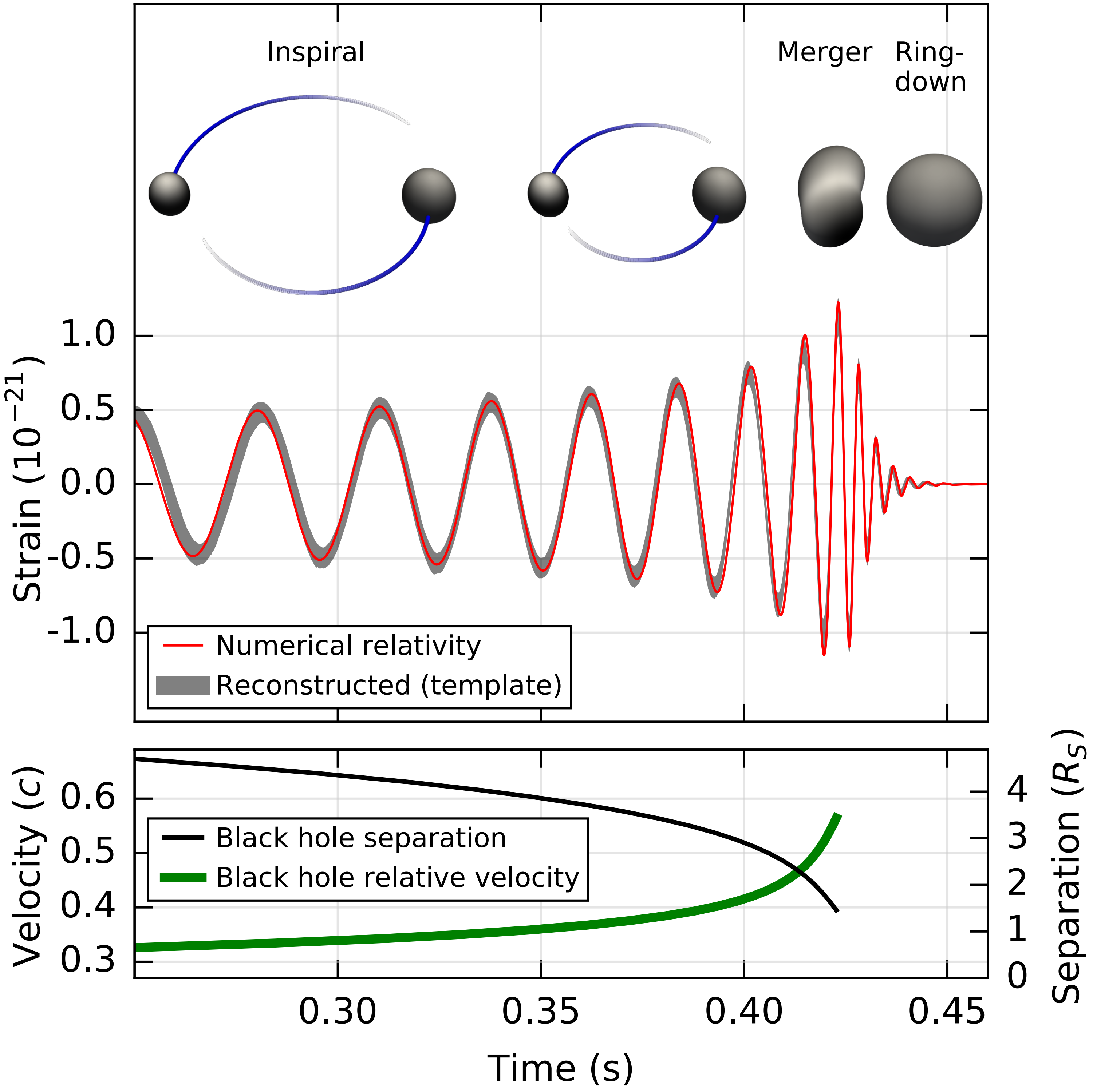
Energy radiated

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

Distance

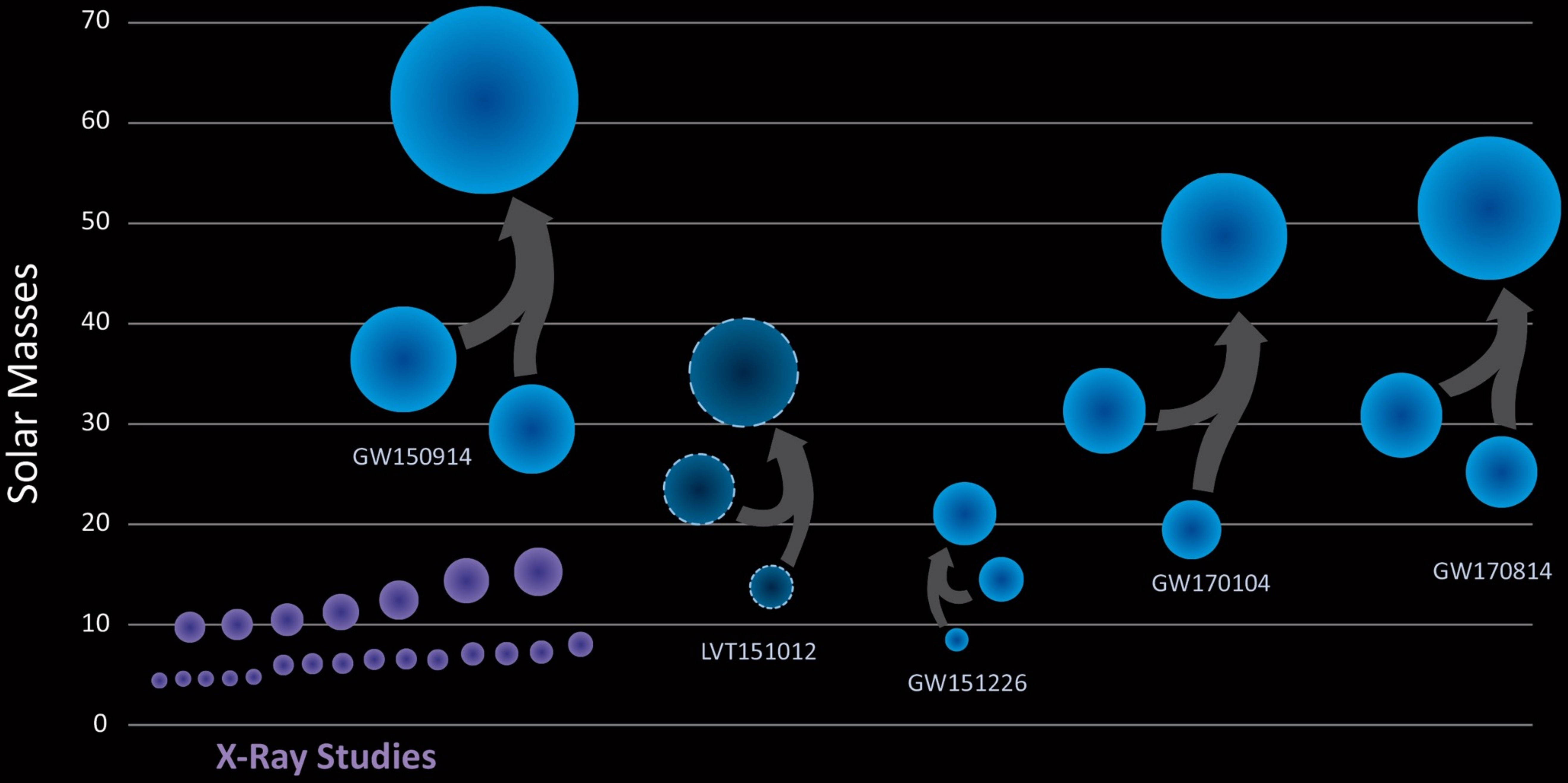
420 (+160/-180) MPc

(1.3 Billion light years)



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

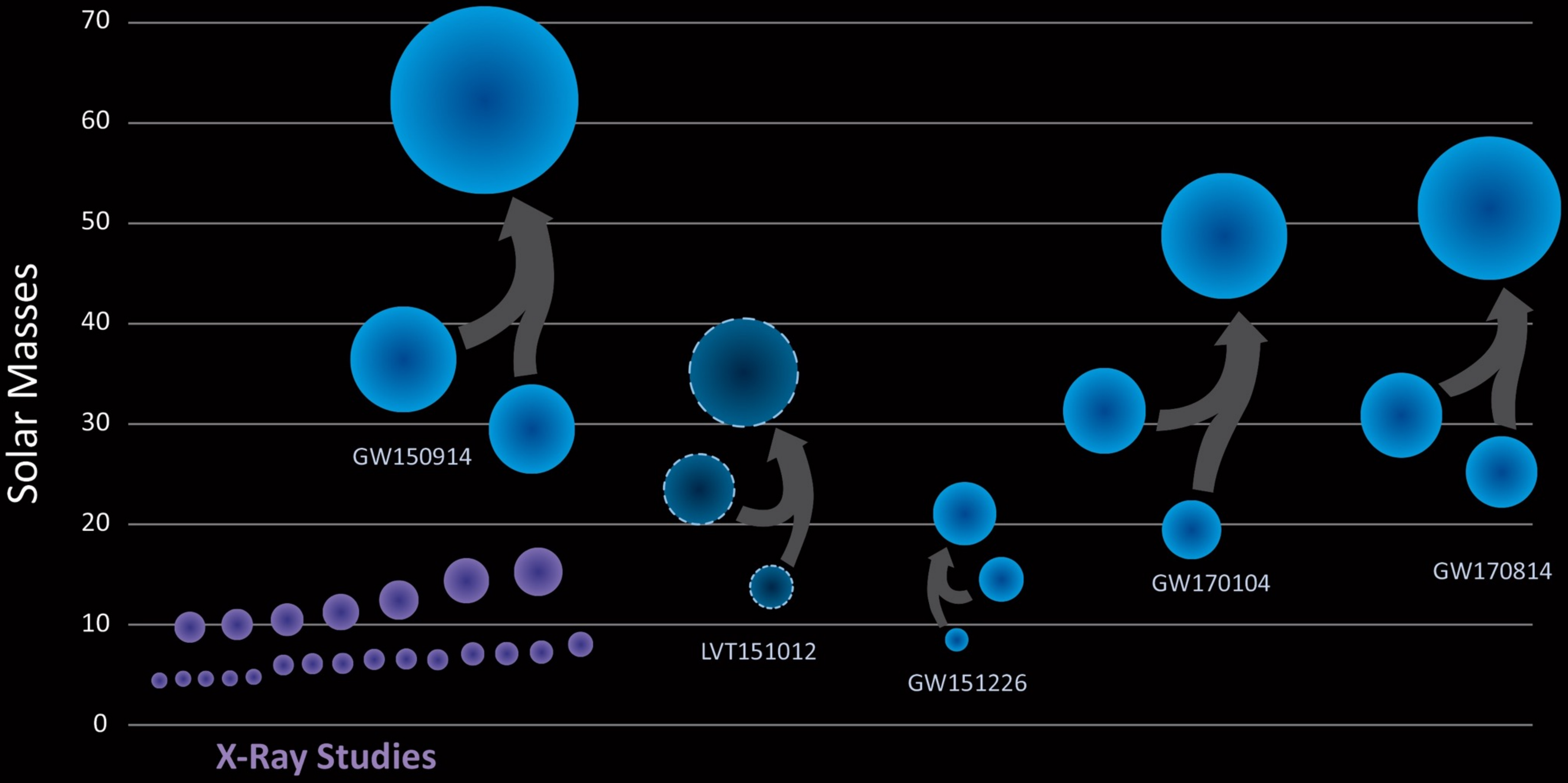
Black Holes of Known Mass



LIGO/VIRGO

Lots of new astrophysics

Black Holes of Known Mass



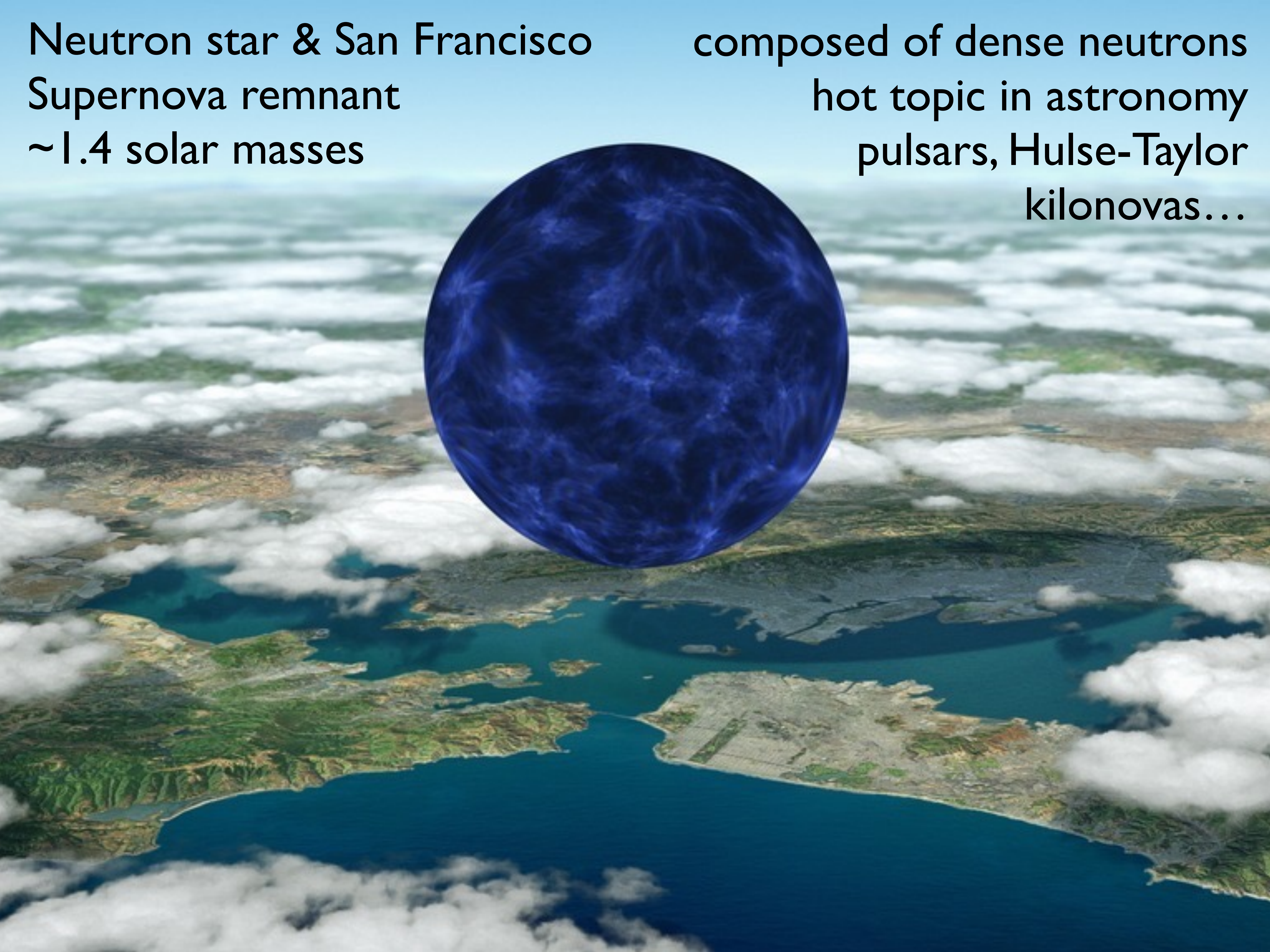
LIGO/VIRGO

Lots of new astrophysics

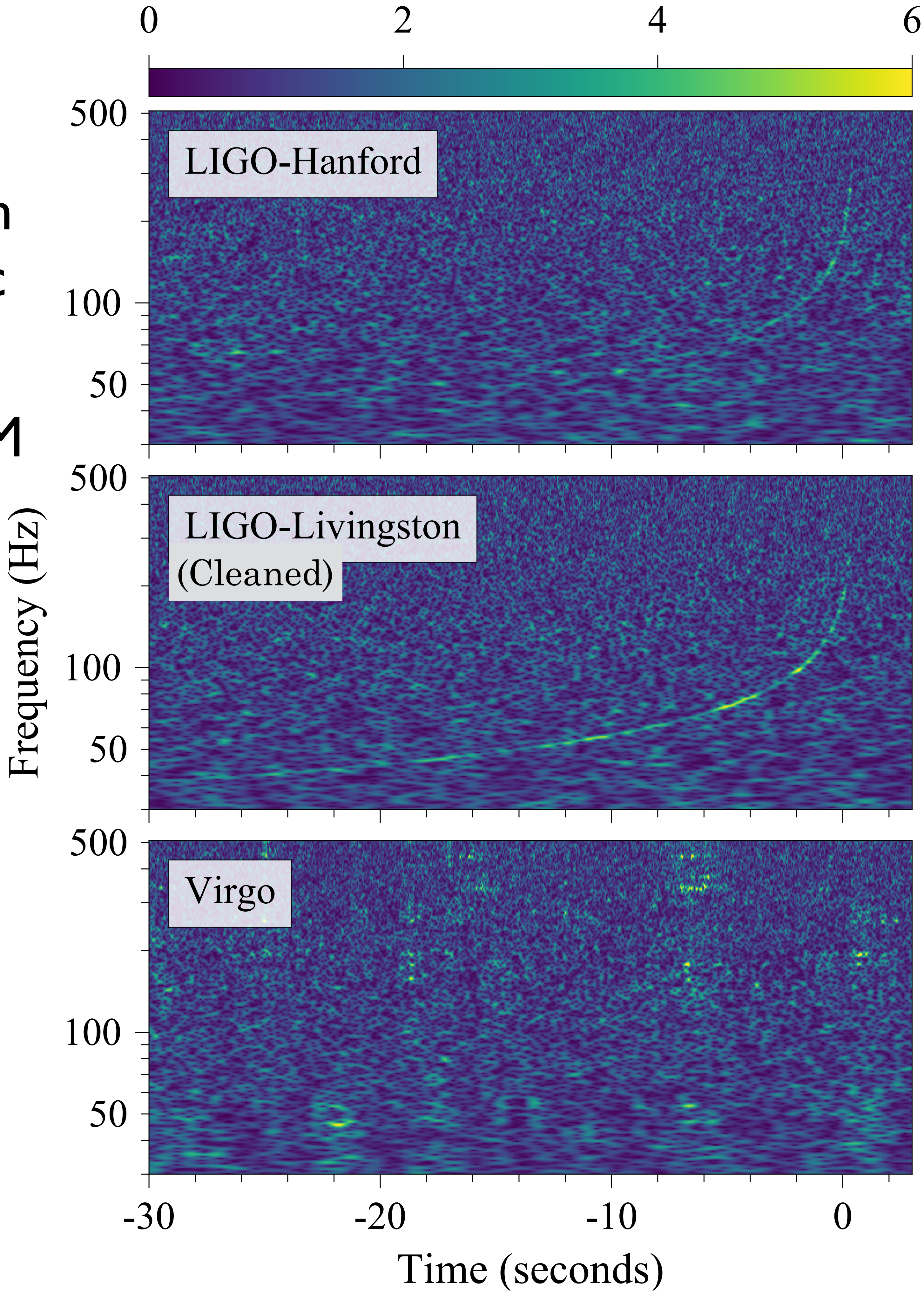
but no light

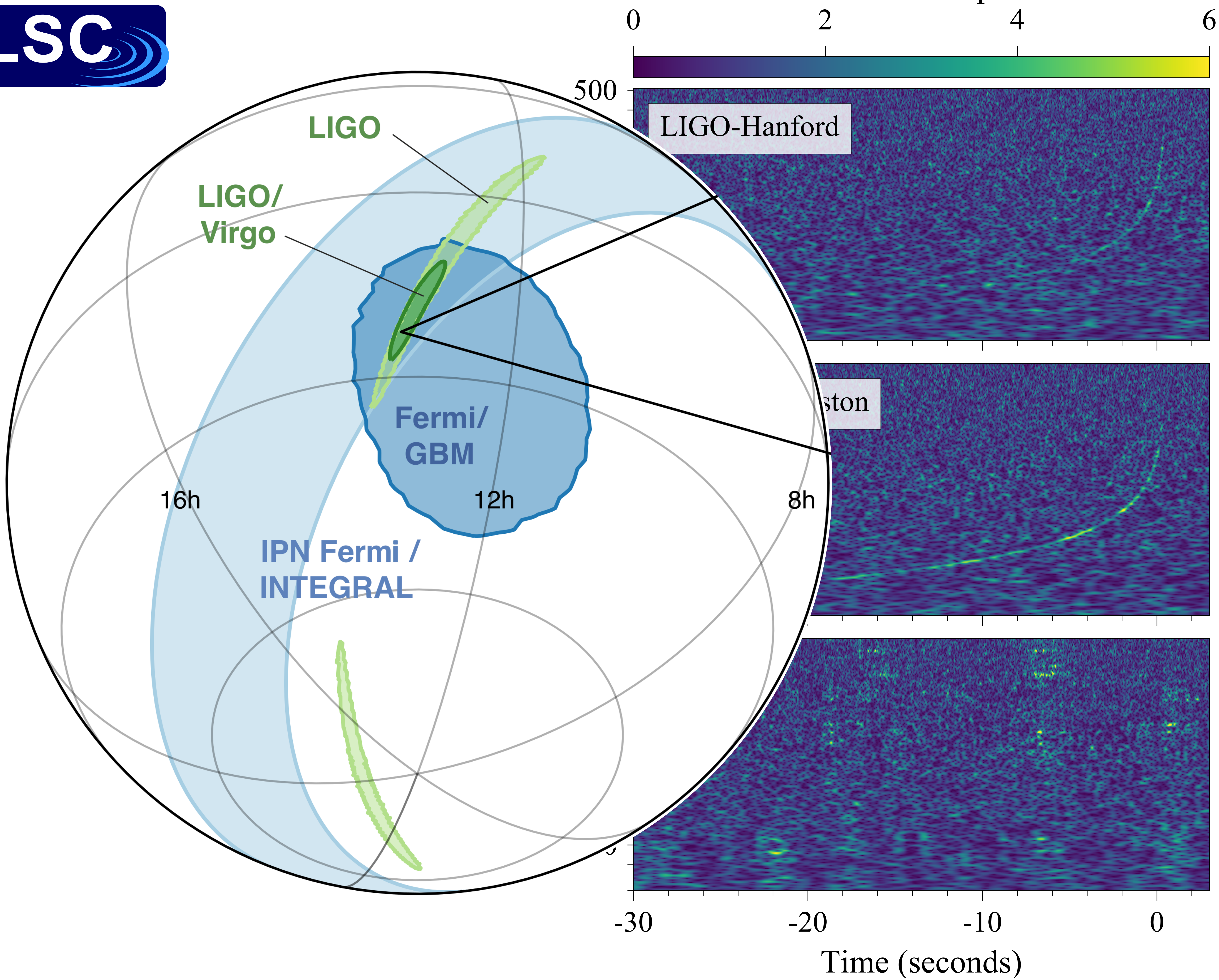
Neutron star & San Francisco
Supernova remnant
~1.4 solar masses

composed of dense neutrons
hot topic in astronomy
pulsars, Hulse-Taylor
kilonovas…

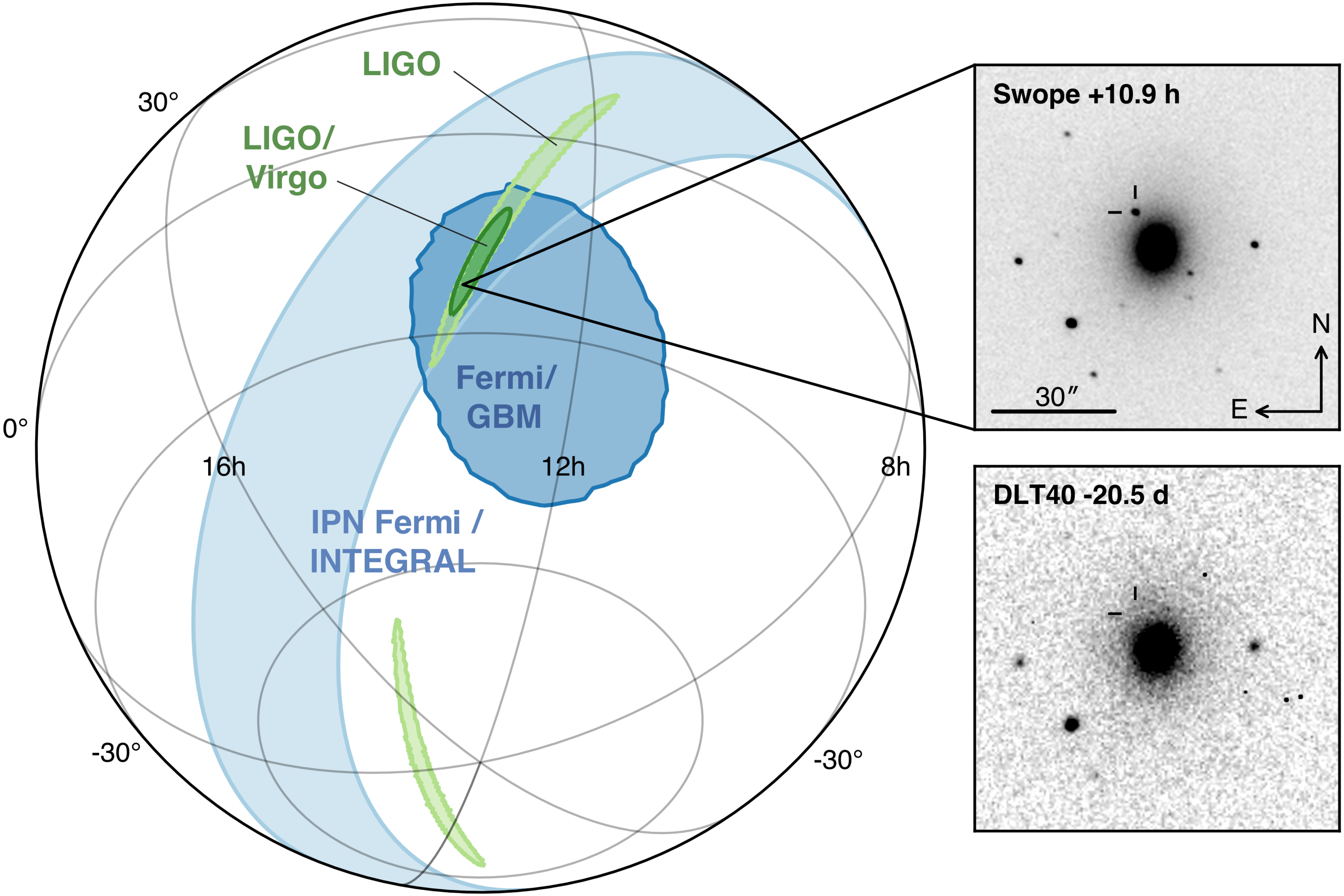


- LIGO software finds trigger in LHO data - 5:41:04 am Pacific time, August 17.
- LIGO realizes that Fermi GBM has triggered on event 1.7 seconds after GW merger.
- Thus, BNS mergers cause short gamma-ray bursts.
- Finally solving a mystery uncovered by Vela-4 in 1967. (as predicted by many).
- Forcing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



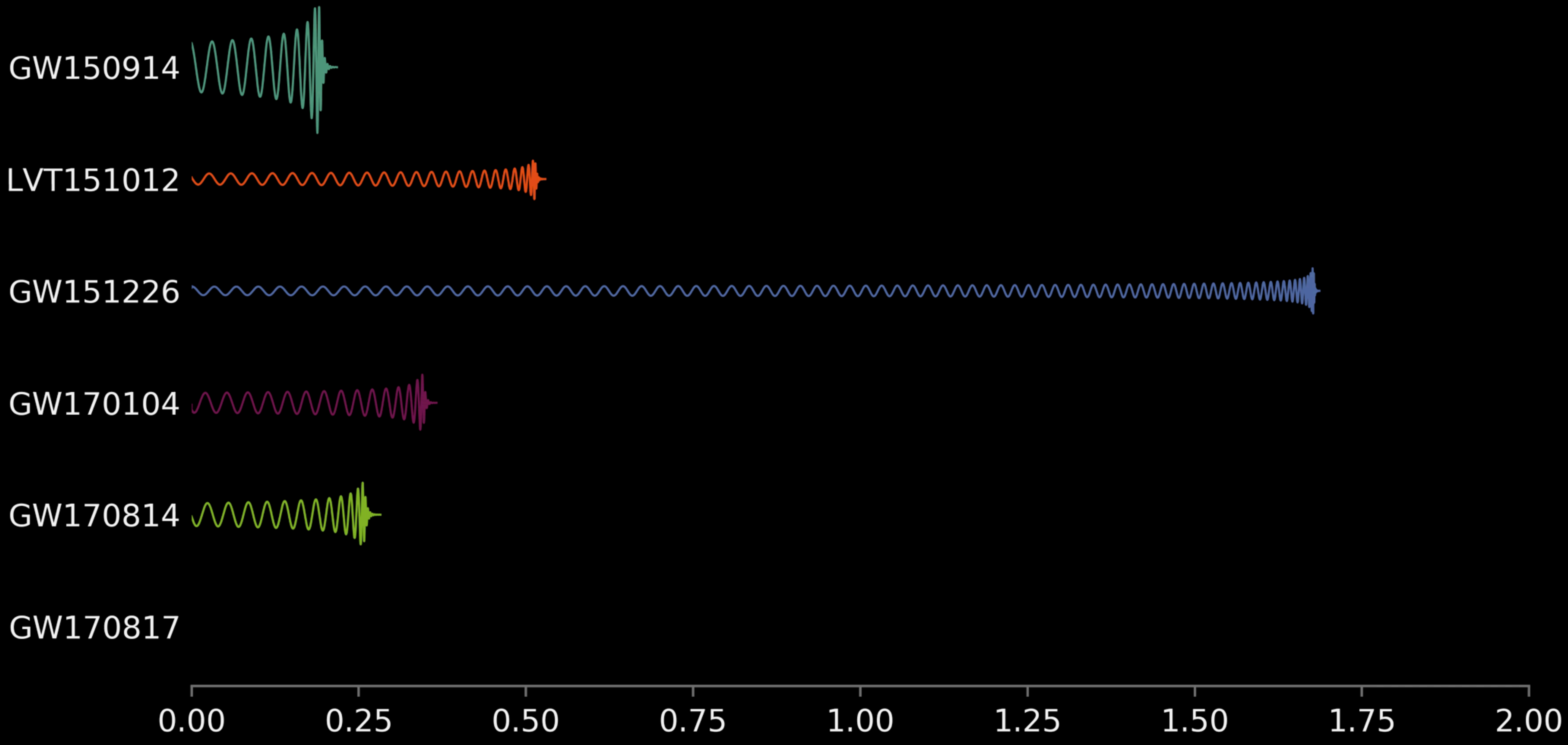

0
2
4
6
500
LIGO-Hanford
ston
LIGO
LIGO/
Virgo
Fermi/
GBM
16h
12h
8h
IPN Fermi /
INTEGRAL
-30
-20
-10
0
Time (seconds)

GW + GRB + Kilonova



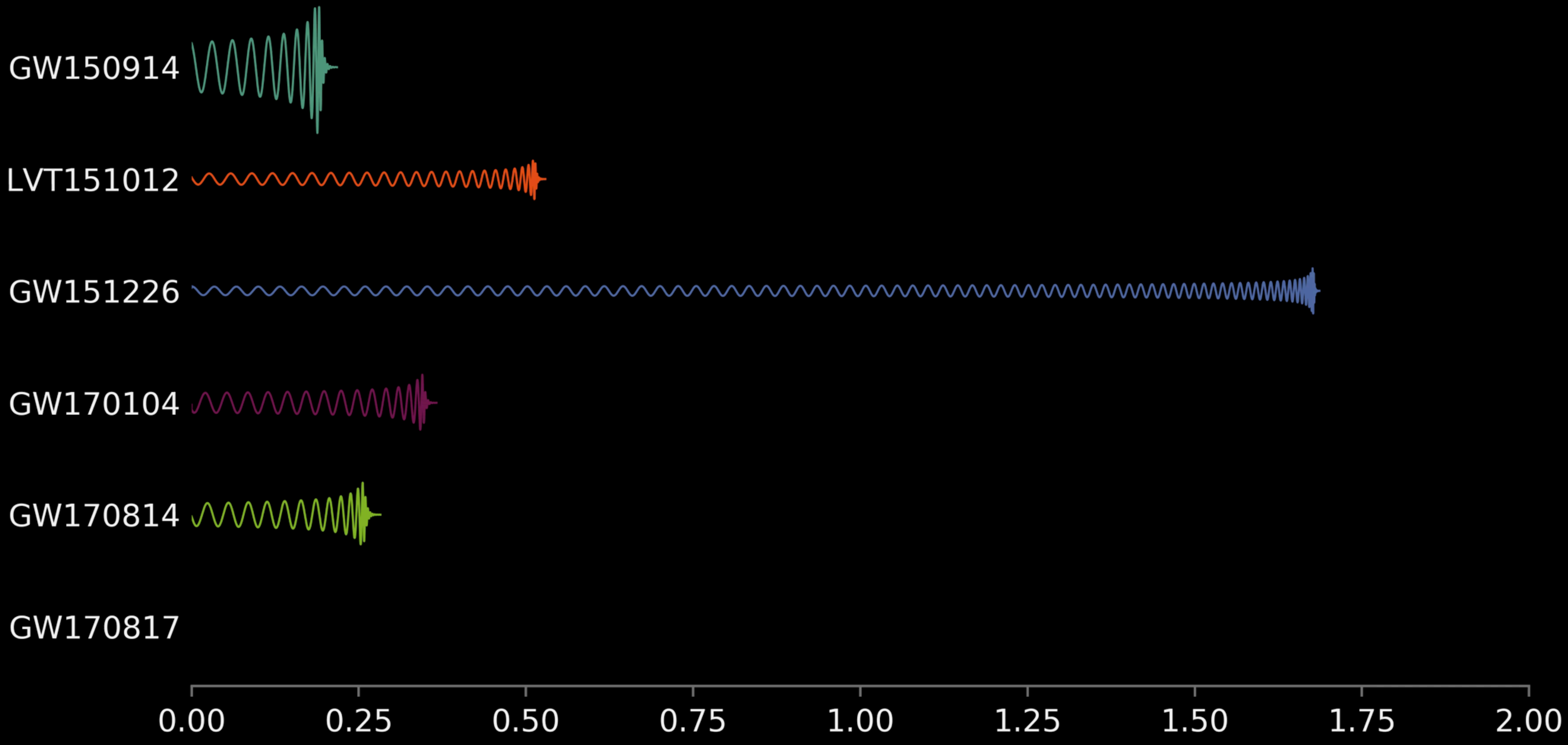
There is matter, and we can watch it

The sound of the Gravitational Wave



LIGO/Virgo/University of Oregon/Ben Farr

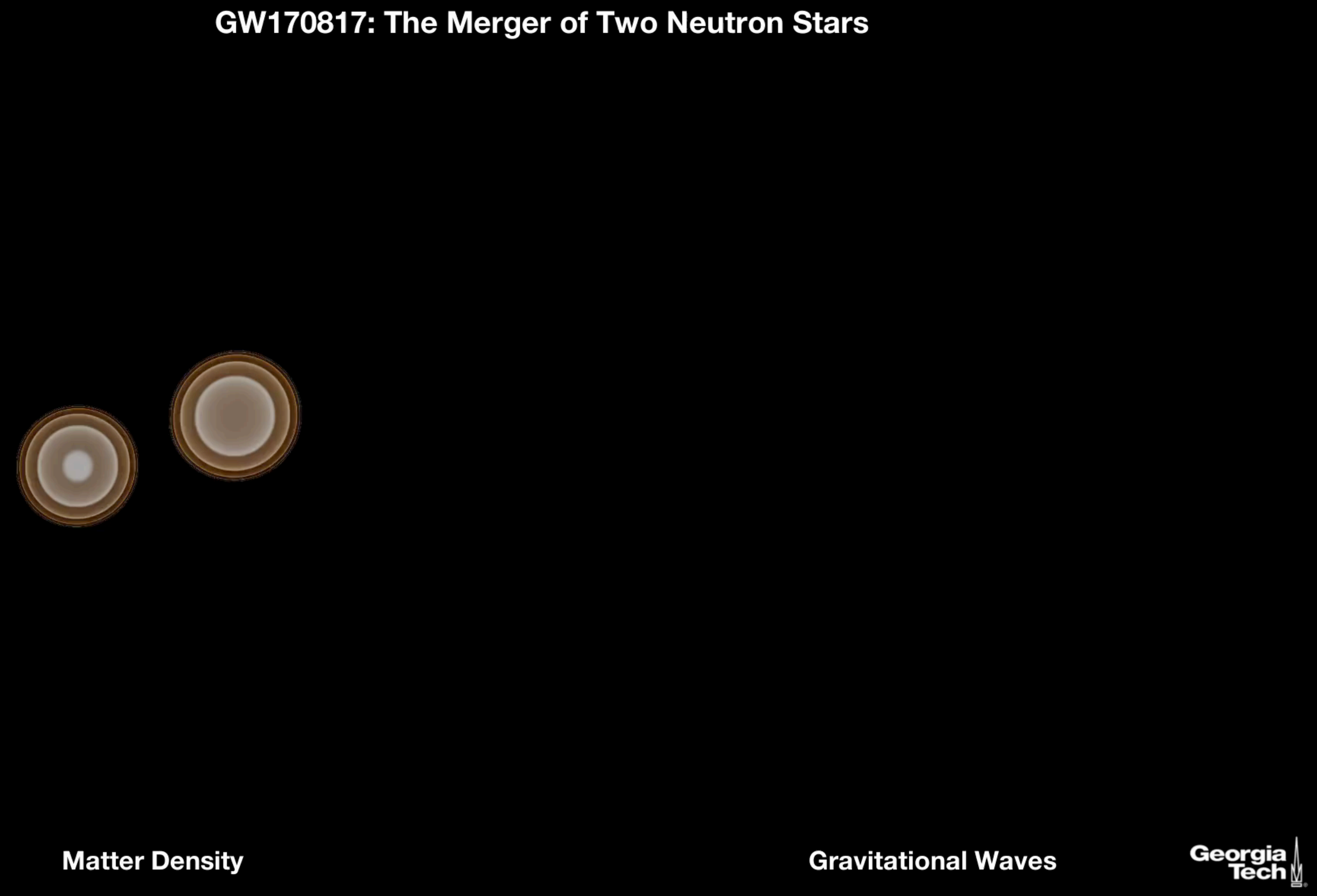
The sound of the Gravitational Wave



LIGO/Virgo/University of Oregon/Ben Farr

What are they looking for?

We suspect that ~1/2 of all heavy elements are created in kilonovas.
Energetic explosion in a neutron rich environment -> nuclei in ejecta

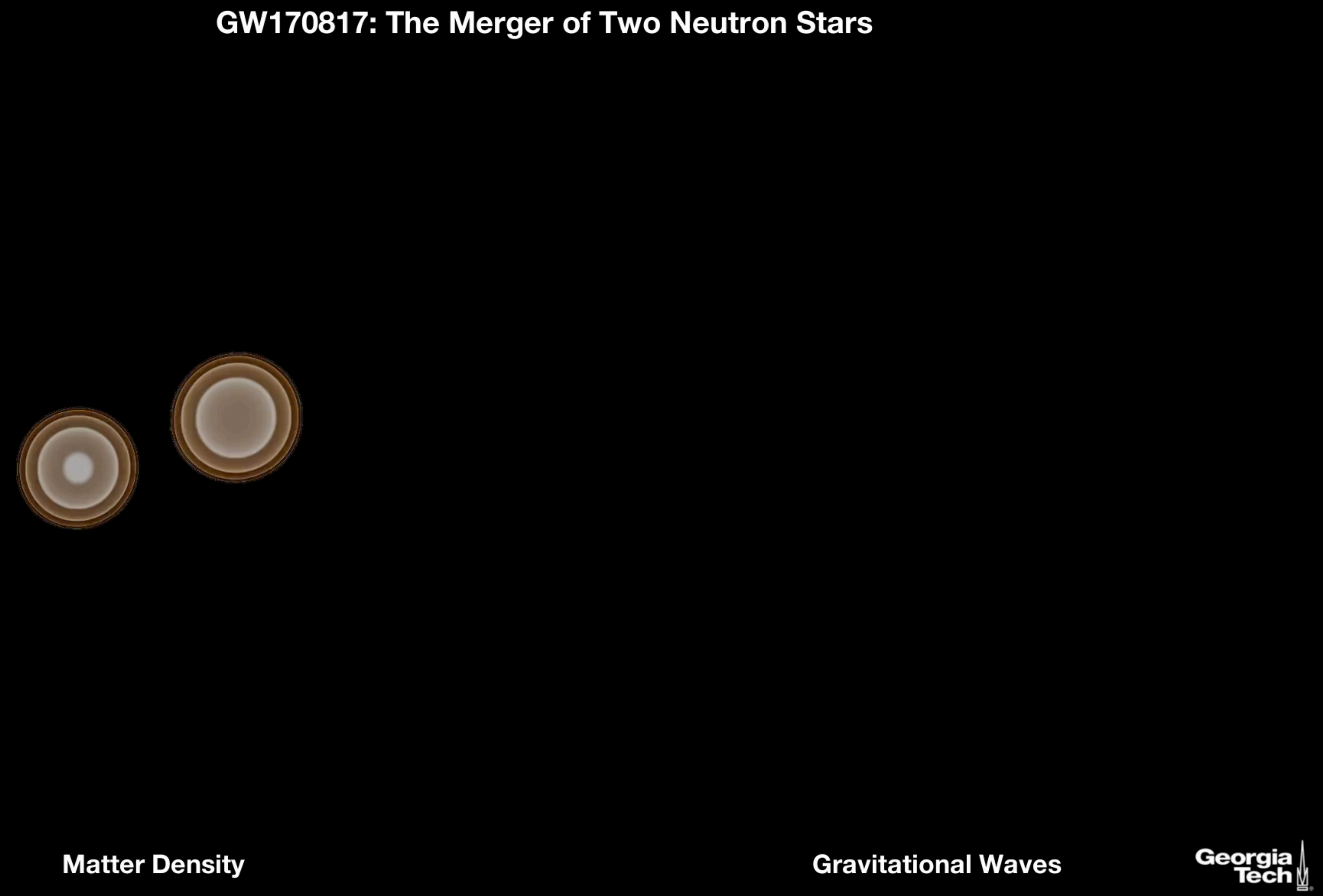


GW170817: The Merger of Two Neutron Stars

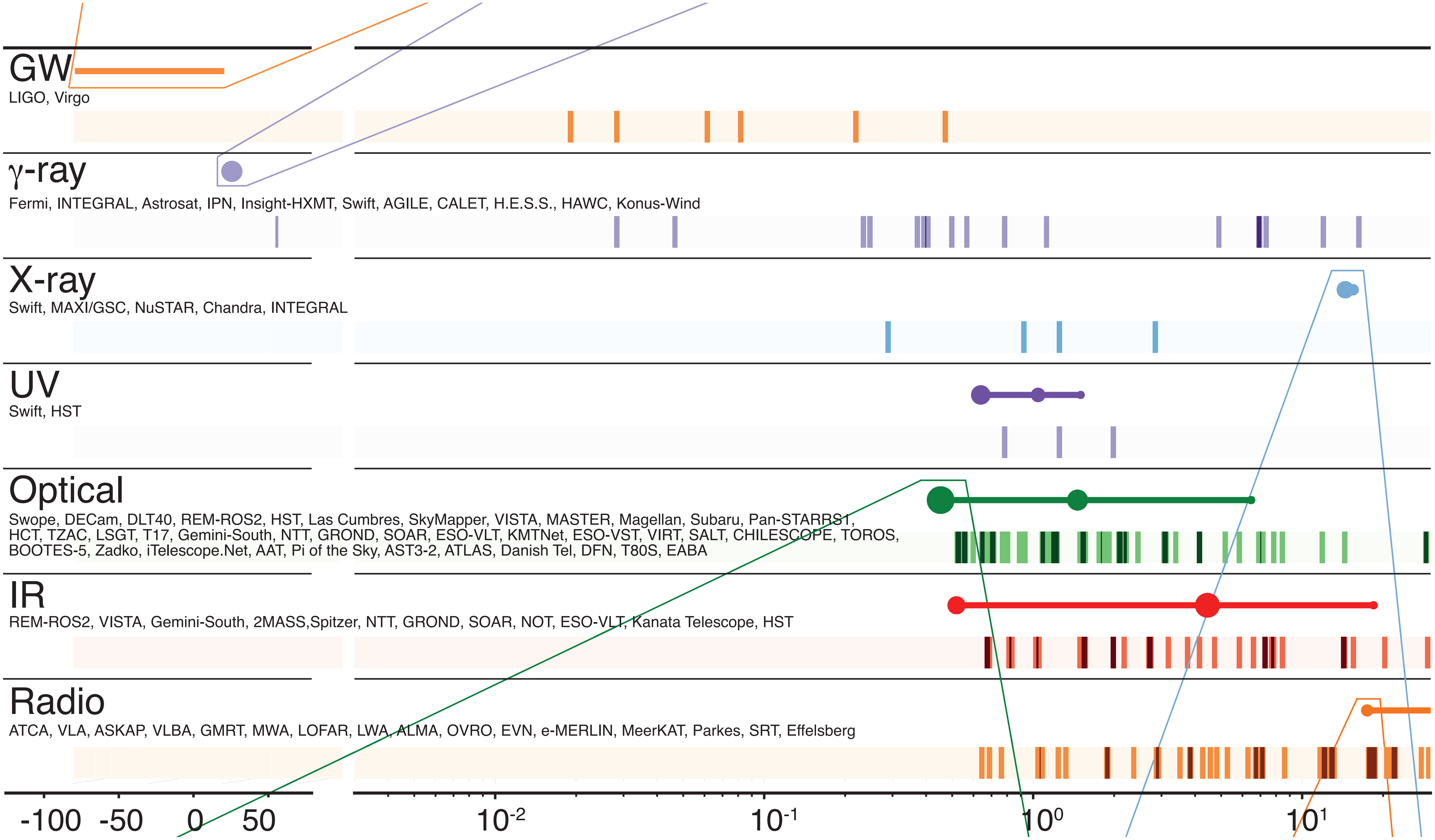
What are they looking for?

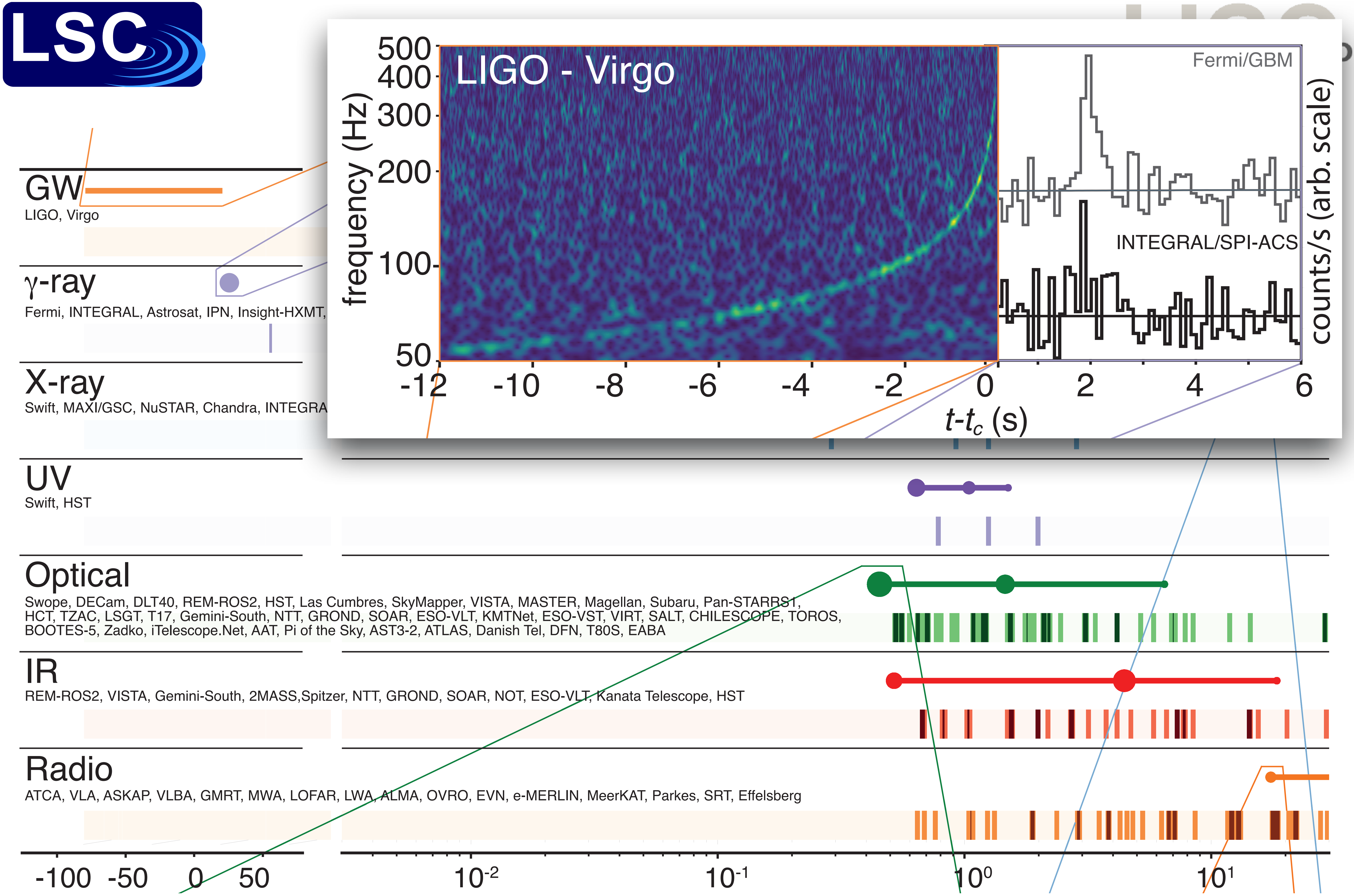
We suspect that ~1/2 of all heavy elements are created in kilonovas.

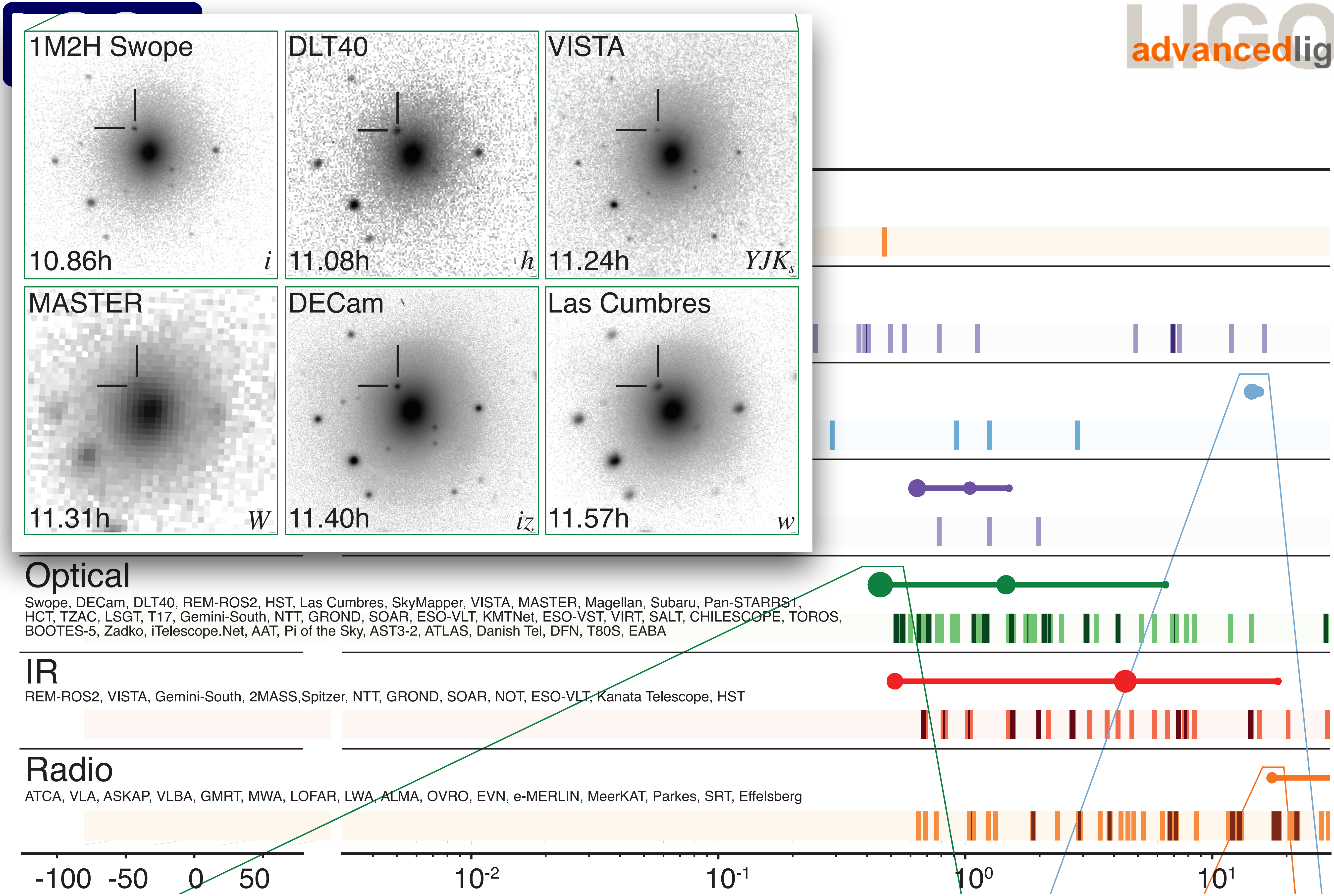
Energetic explosion in a neutron rich environment -> nuclei in ejecta



Amazing measurement set




LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12
-10
-8
-6
-4
-2
0
2
4
6
t-tc (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}



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

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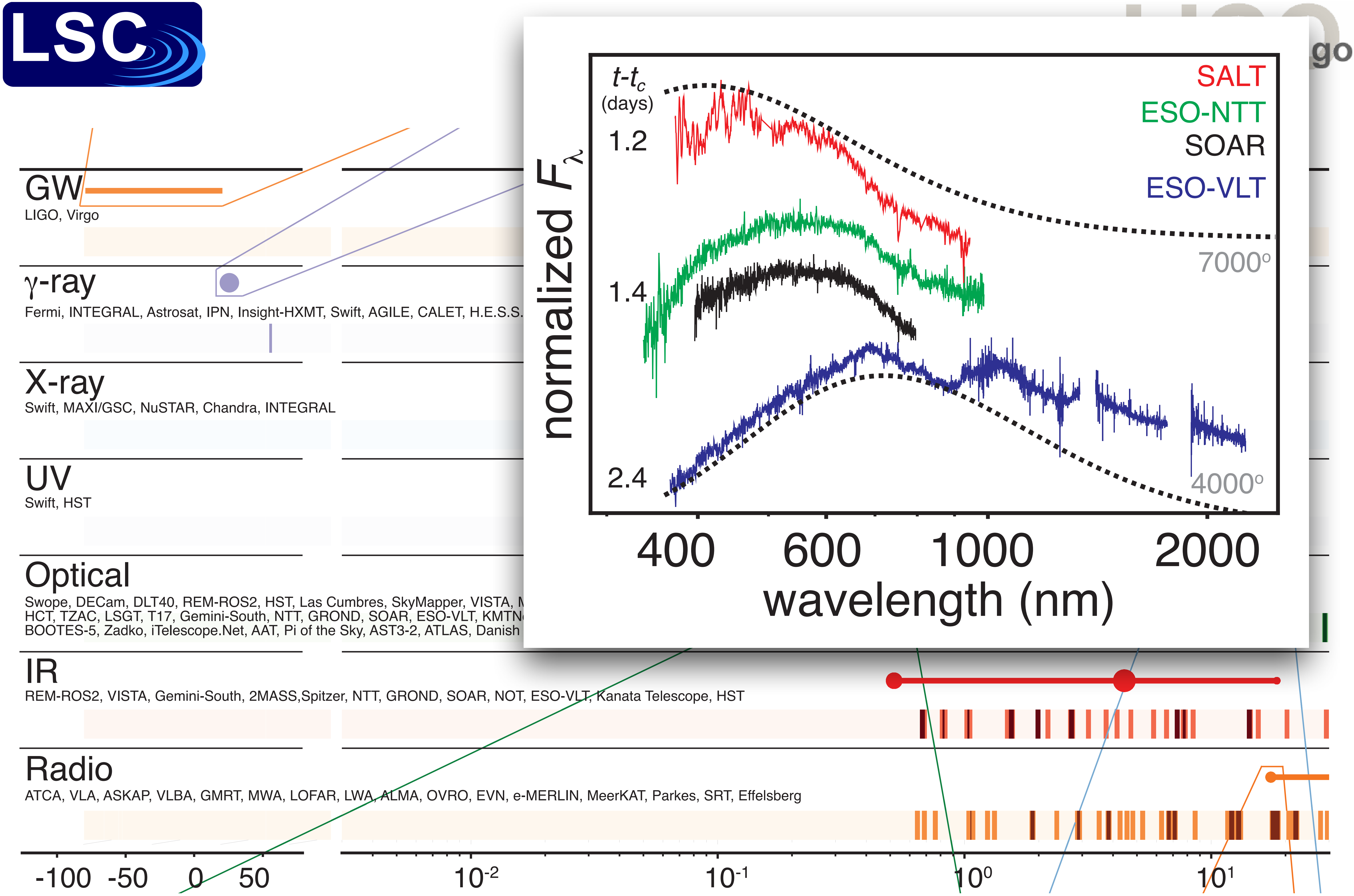
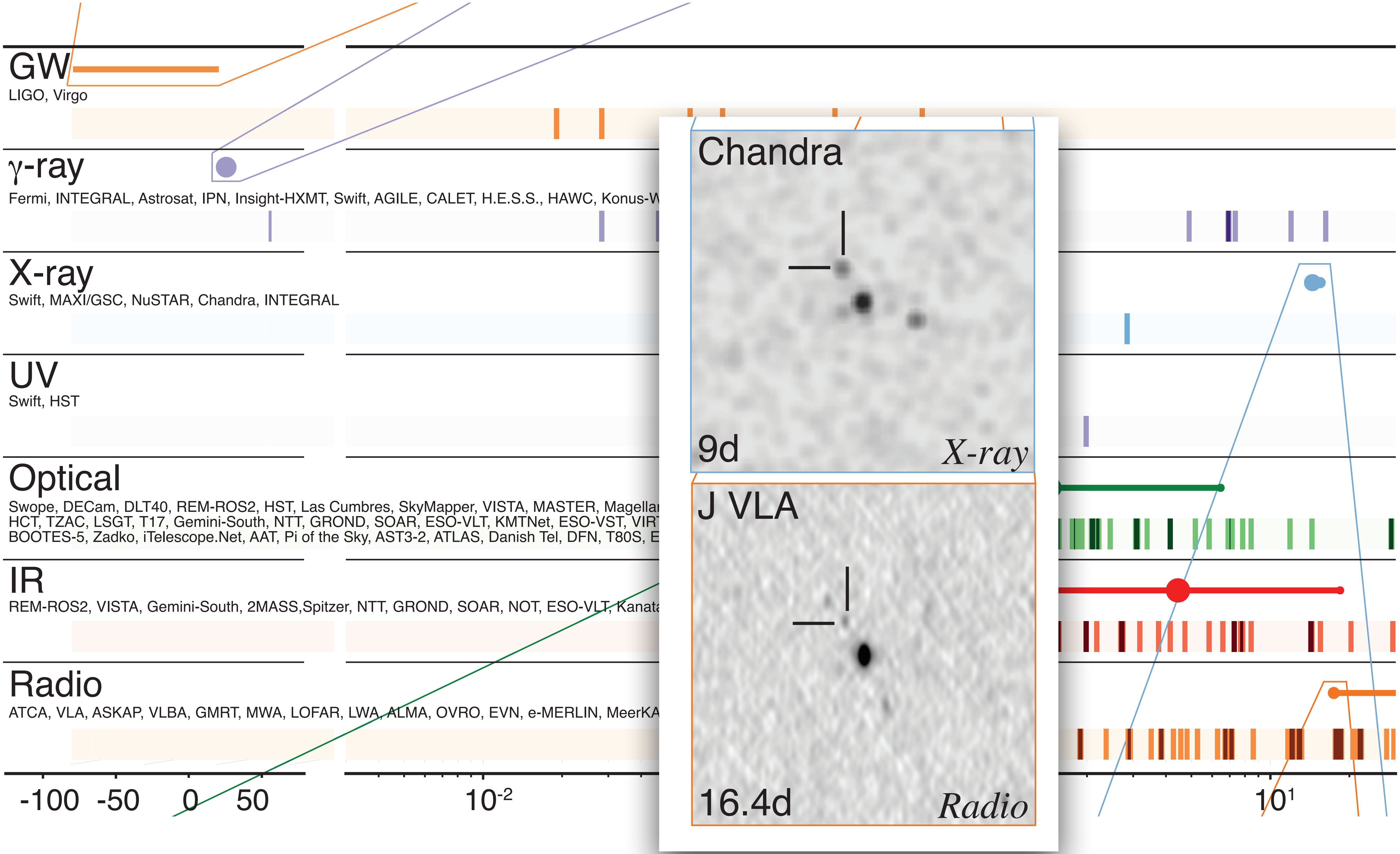

GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S.
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, M
HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTN
BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish
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}
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

NASA makes pretty videos

I watch them for the science

NASA makes pretty videos

I watch them for the science

Many things learned

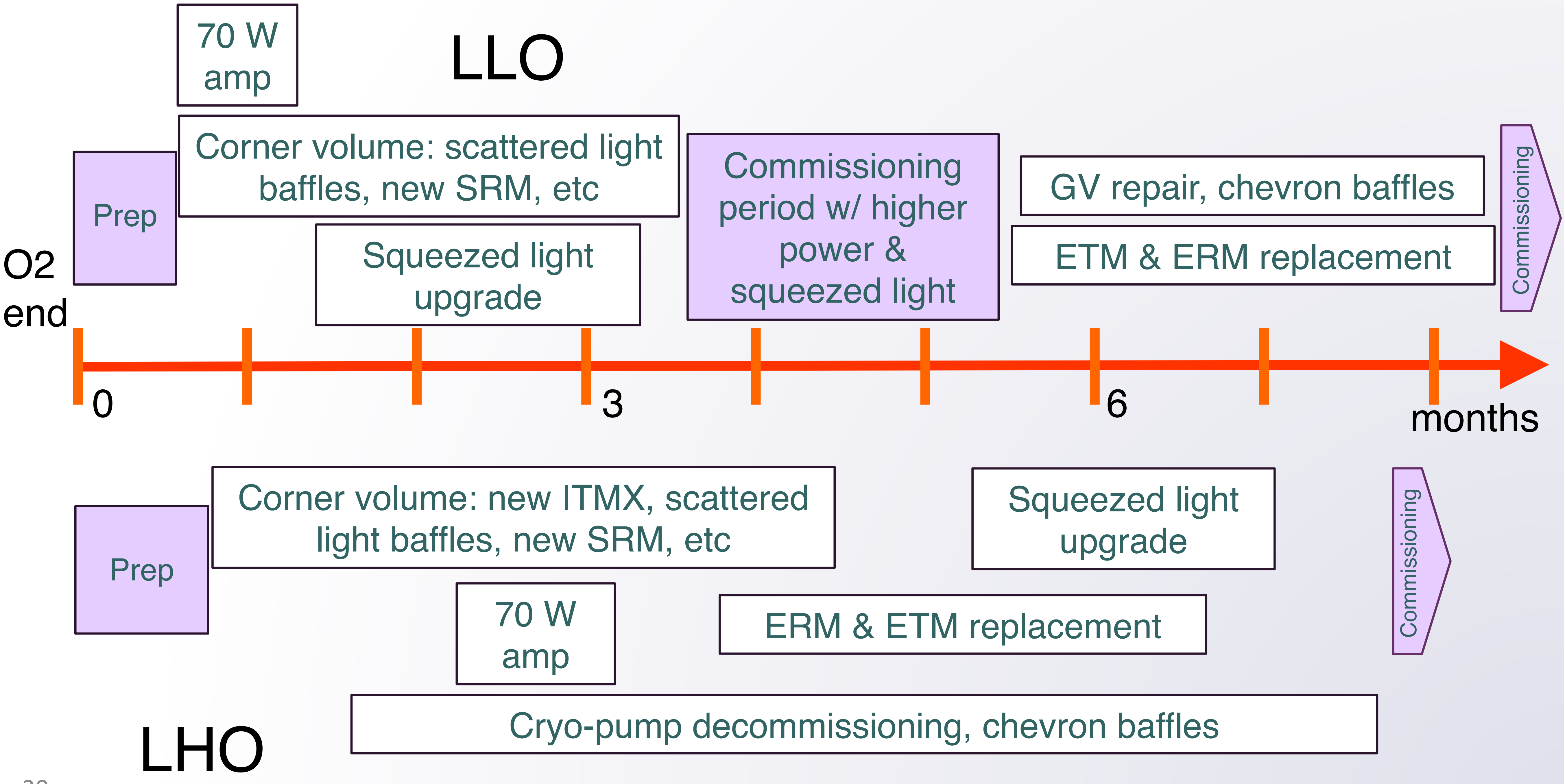
- These events do happen!
- These events happen (330 - 4500) times / $\mathrm{GPc}^3\,\mathrm{Yr}^1$
- They follow an evolution similar to kilonova predictions
- They constrain the ‘stiffness’ or Equation of State of neutron stars
- You can get an estimate for the Hubble constant
- Many papers out now, 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?

and we will be looking.

- LIGO is down for ~ 1 year making upgrades, preparing for O3.



LLO

O2 end

Prep

70 W amp

Corner volume: scattered light baffles, new SRM, etc

Squeezed light upgrade

Commissioning period w/ higher power & squeezed light

GV repair, chevron baffles

ETM & ERM replacement

Commissioning

0

3

6

months

LHO

Prep

Corner volume: new ITMX, scattered light baffles, new SRM, etc

70 W amp

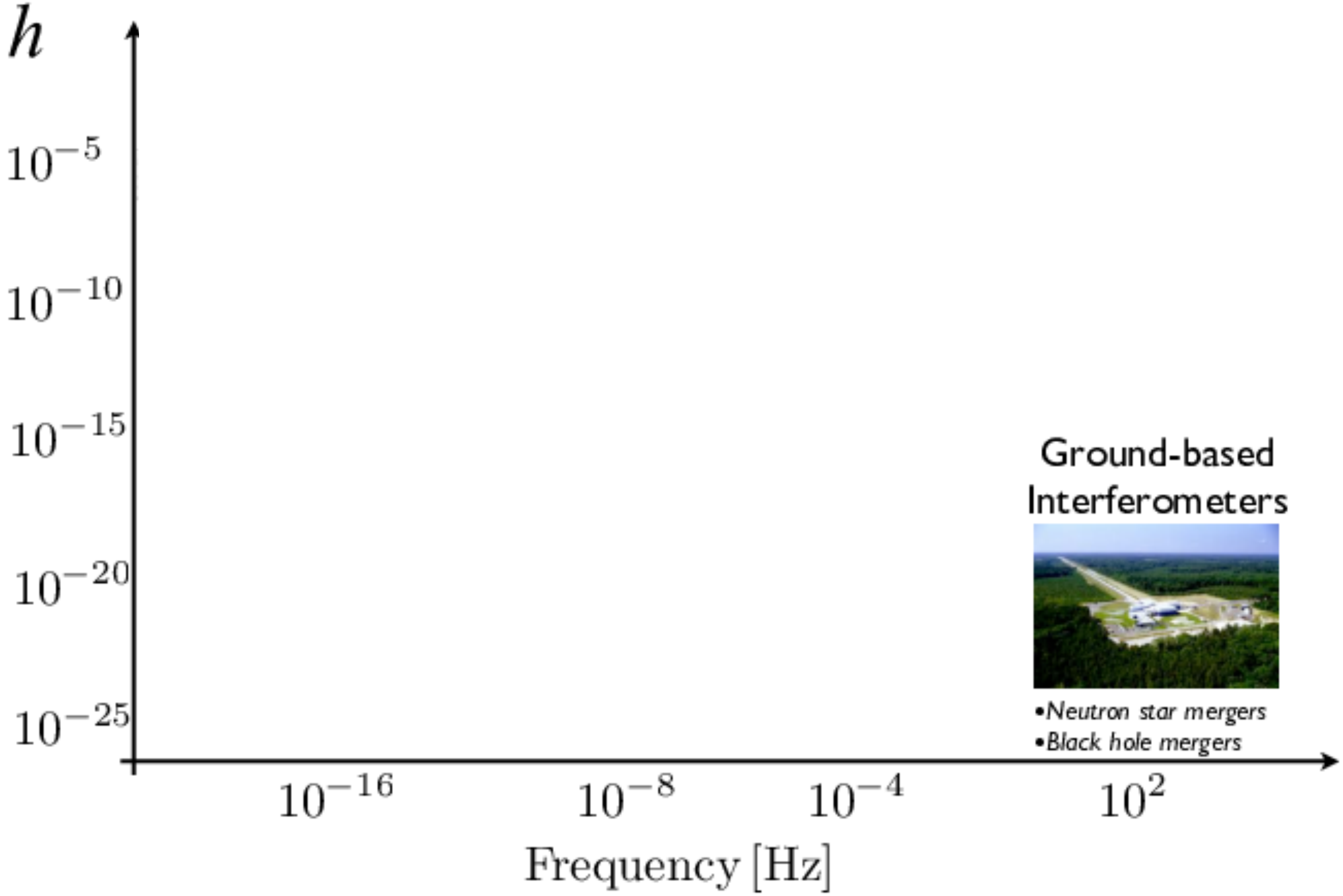
Cryo-pump decommissioning, chevron baffles

ERM & ETM replacement

Squeezed light upgrade

Commissioning

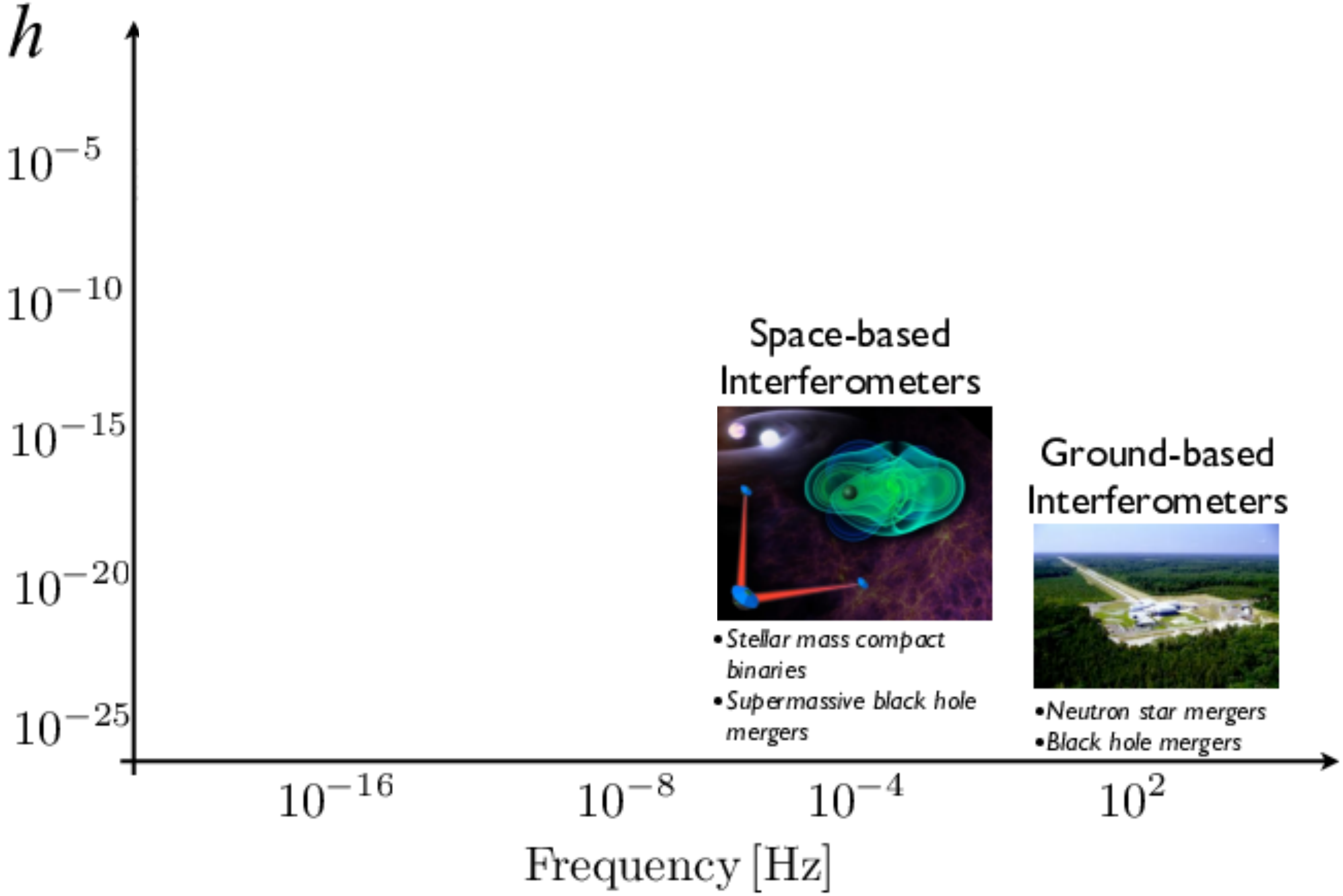
The spectrum of gravitational wave astronomy



Ground-based Interferometers

- *Neutron star mergers*
- *Black hole mergers*

The spectrum of gravitational wave astronomy



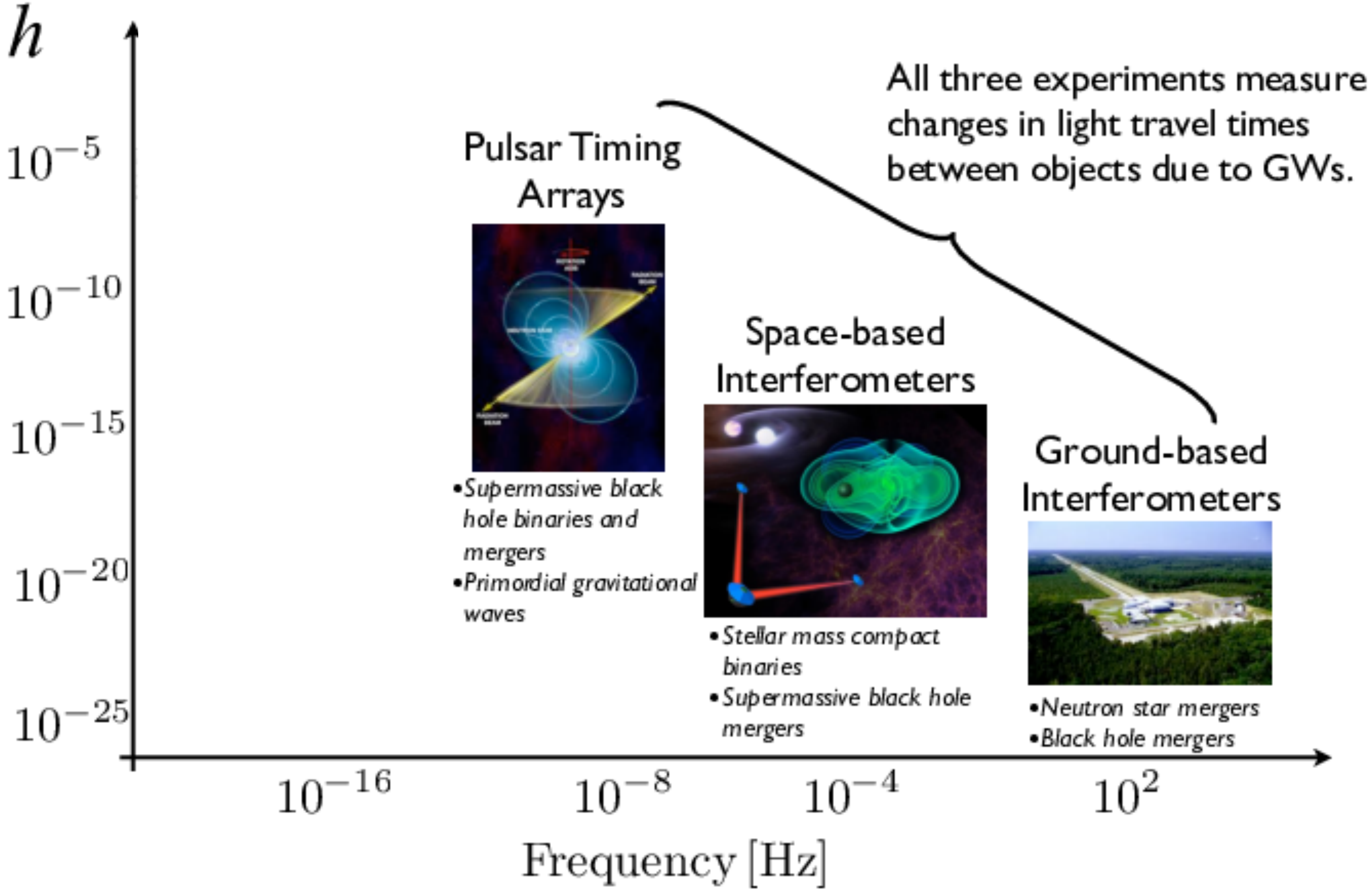
Space-based Interferometers

- *Stellar mass compact binaries*
- *Supermassive black hole mergers*

Ground-based Interferometers

- *Neutron star mergers*
- *Black hole mergers*

The spectrum of gravitational wave astronomy



All three experiments measure changes in light travel times between objects due to GWs.

Pulsar Timing Arrays

- *Supermassive black hole binaries and mergers*
- *Primordial gravitational waves*

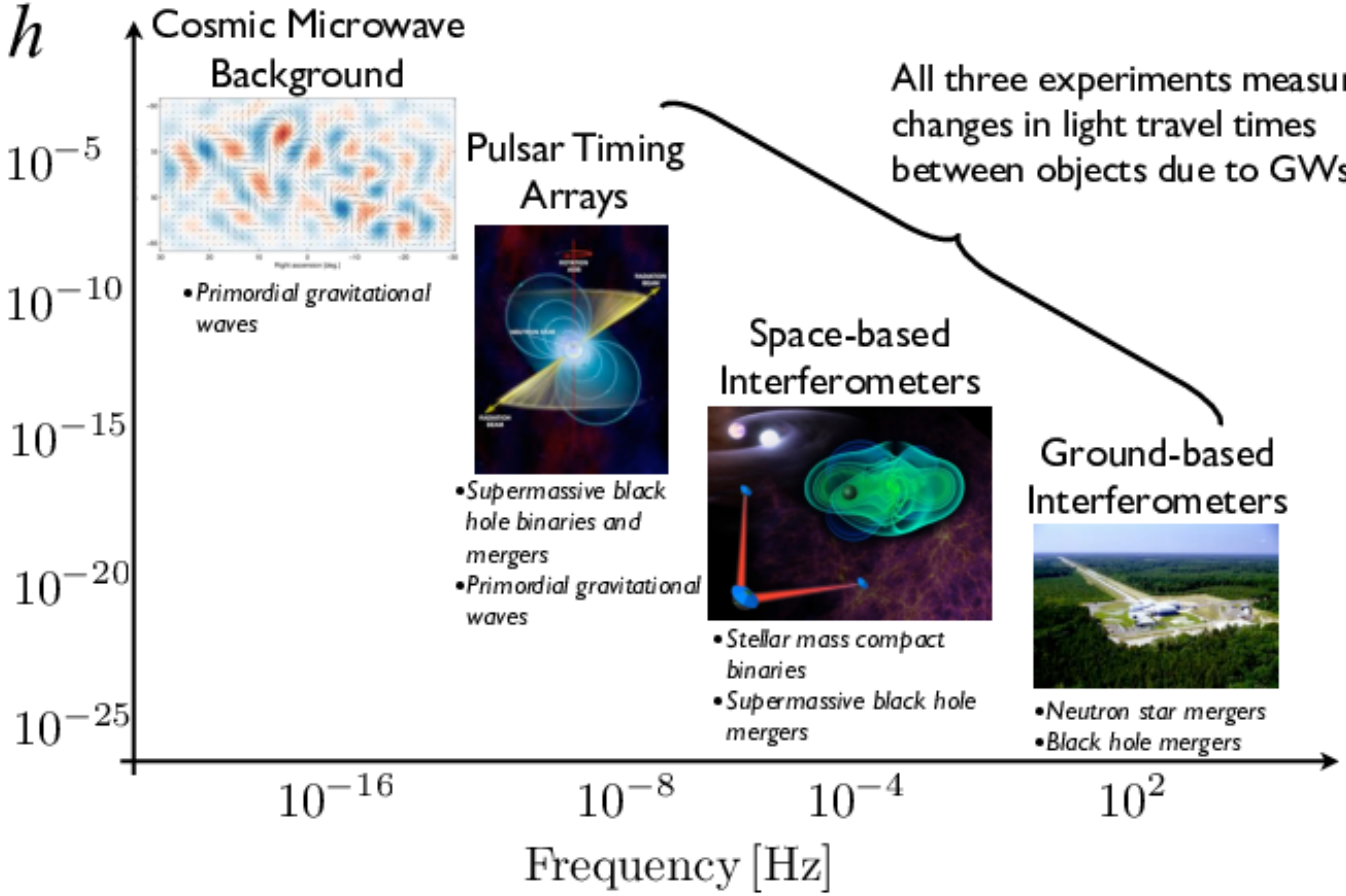
Space-based Interferometers

- *Stellar mass compact binaries*
- *Supermassive black hole mergers*

Ground-based Interferometers

- *Neutron star mergers*
- *Black hole mergers*

The spectrum of gravitational wave astronomy



Cosmic Microwave Background

- *Primordial gravitational waves*

Pulsar Timing Arrays

- *Supermassive black hole binaries and mergers*
- *Primordial gravitational waves*

Space-based Interferometers

- *Stellar mass compact binaries*
- *Supermassive black hole mergers*

Ground-based Interferometers

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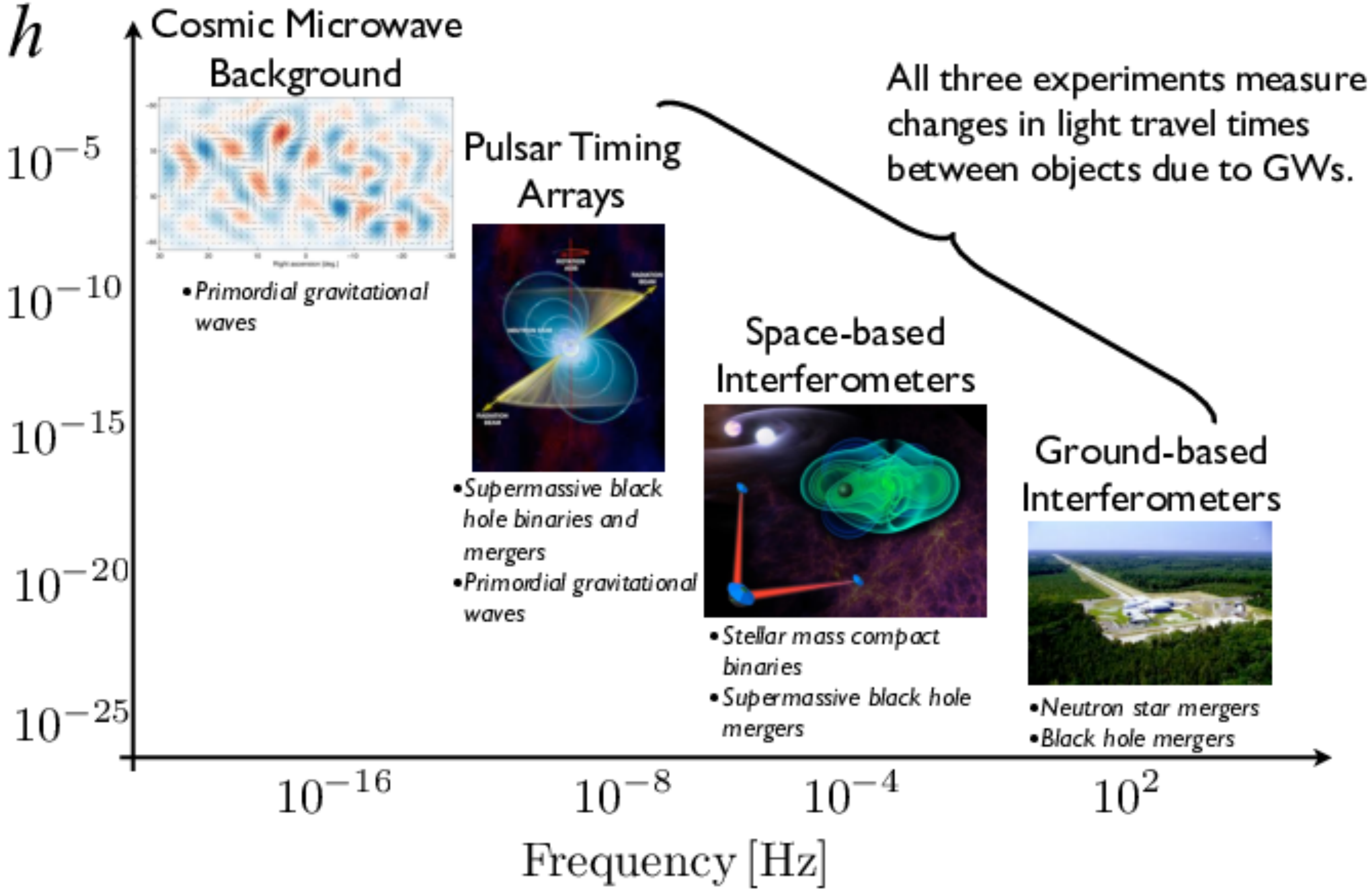
- *Black hole mergers*

All three experiments measure changes in light travel times between objects due to GWs.

The spectrum of gravitational wave astronomy



Cosmic Microwave Background

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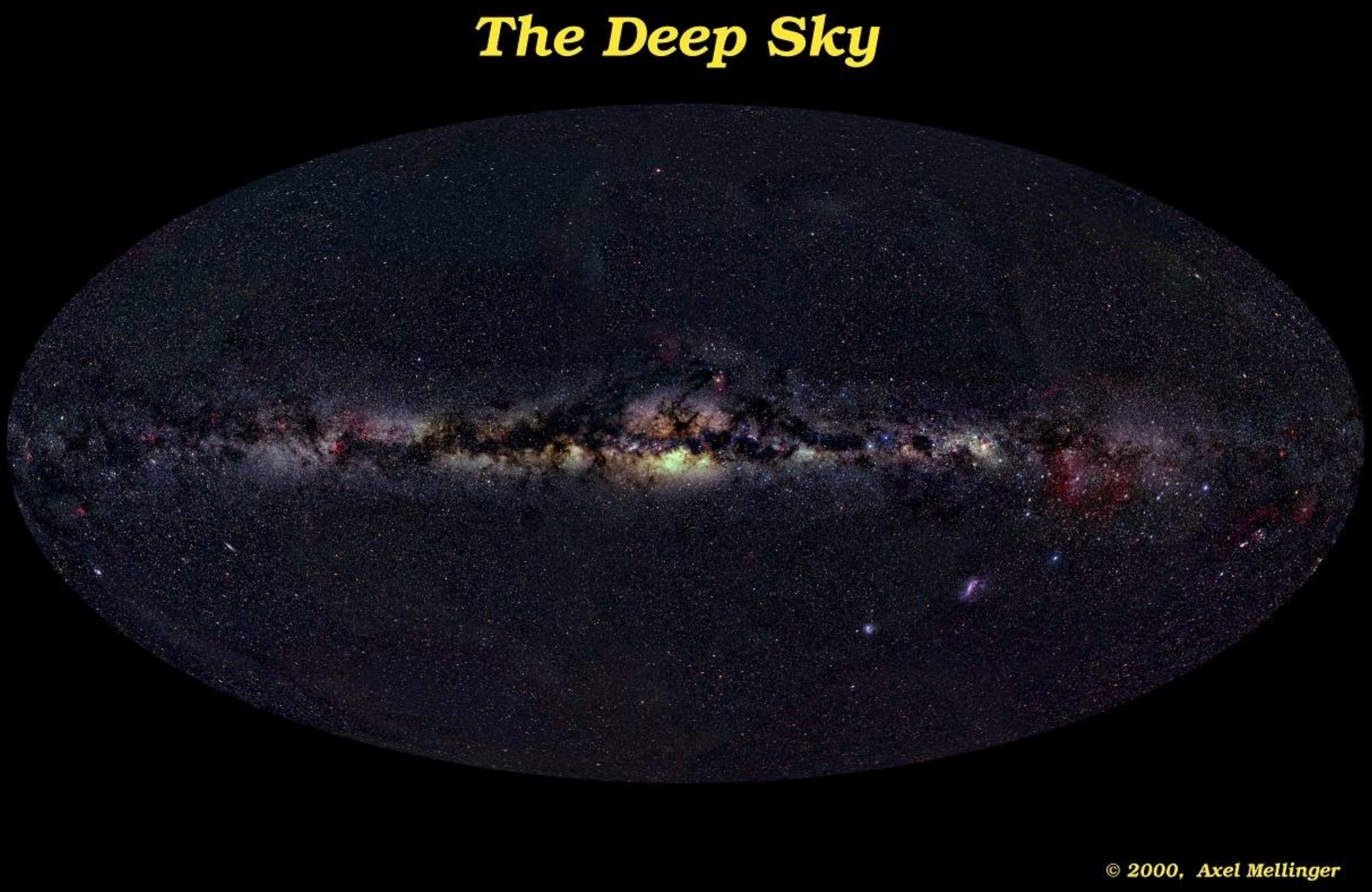
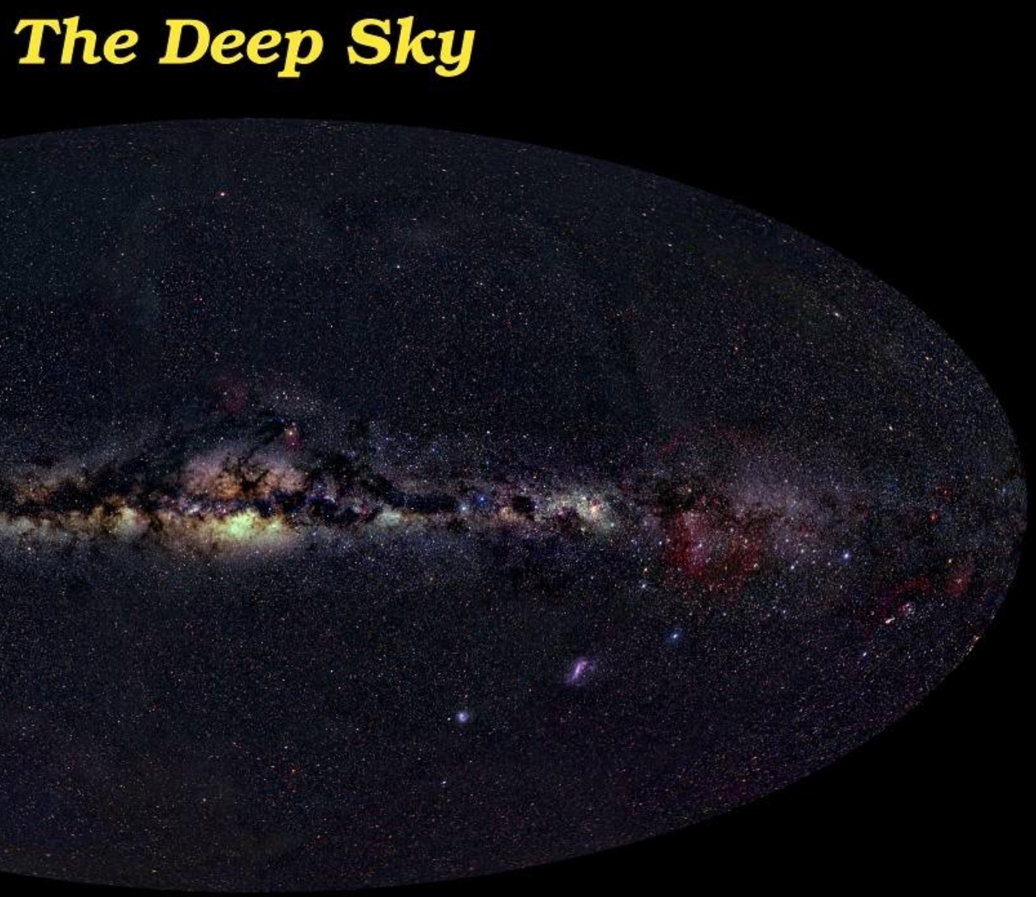
new ways to see the sky



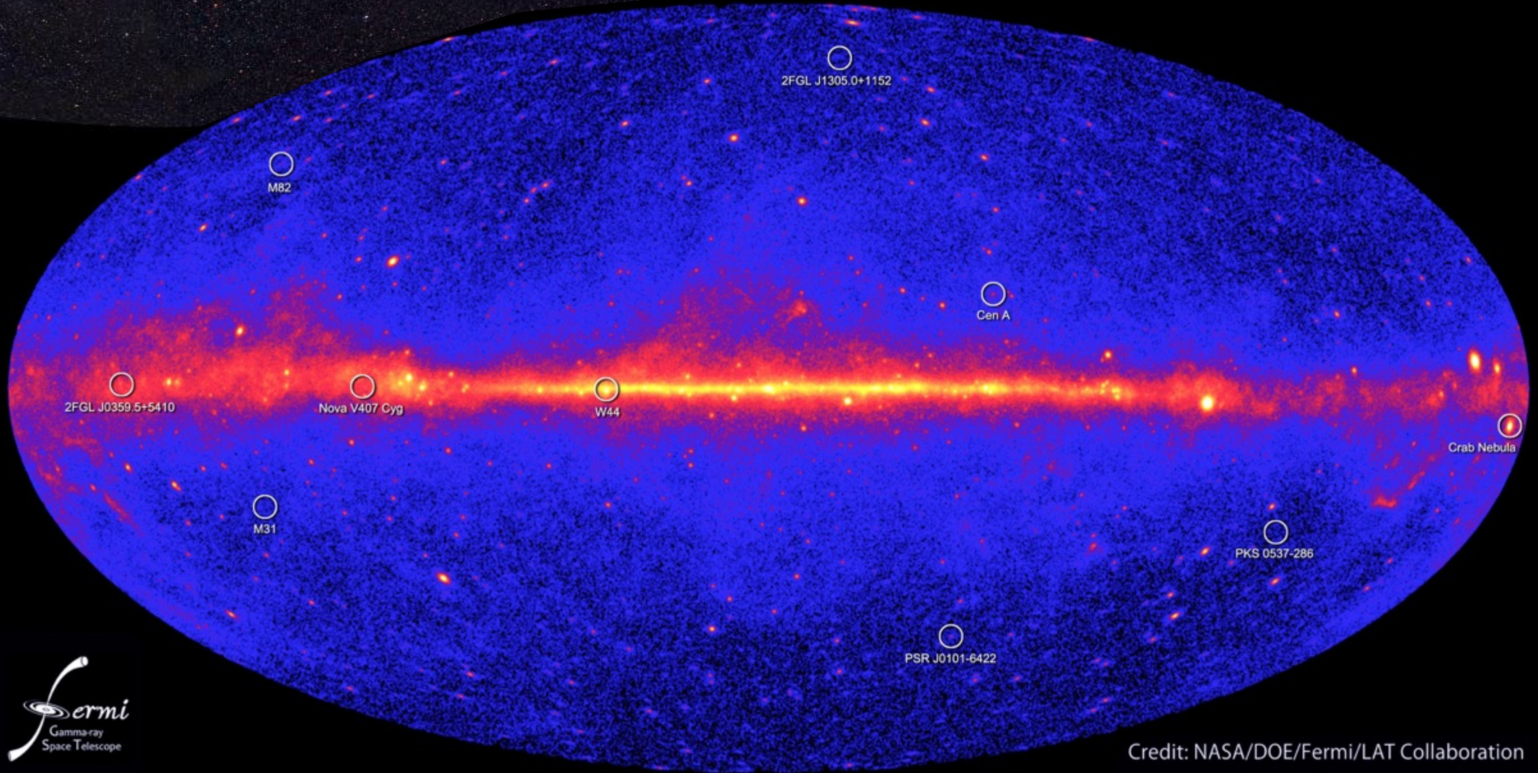
The Deep Sky

© 2000, Axel Mellinger

new ways to see the sky



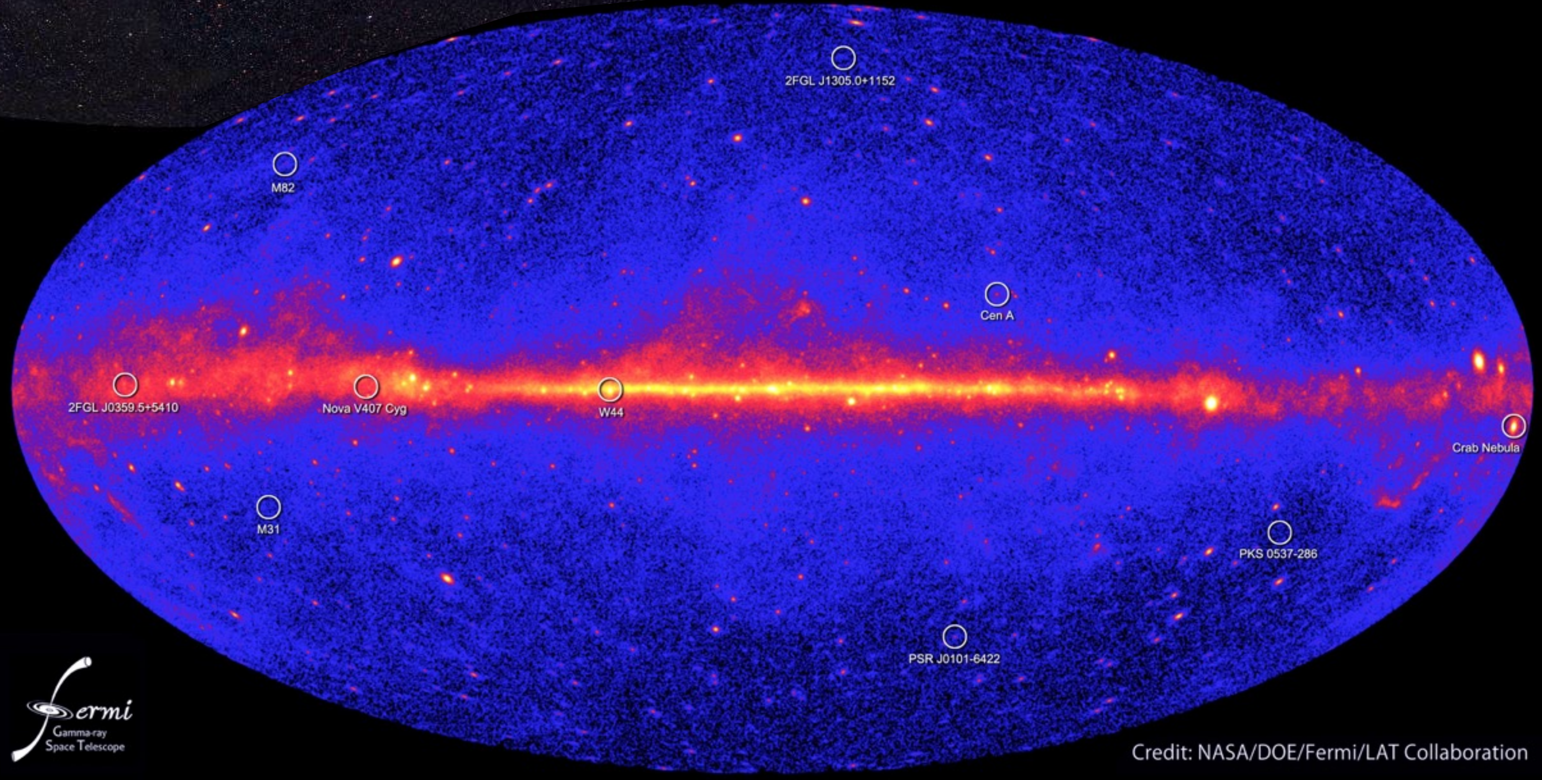
new ways to see the sky



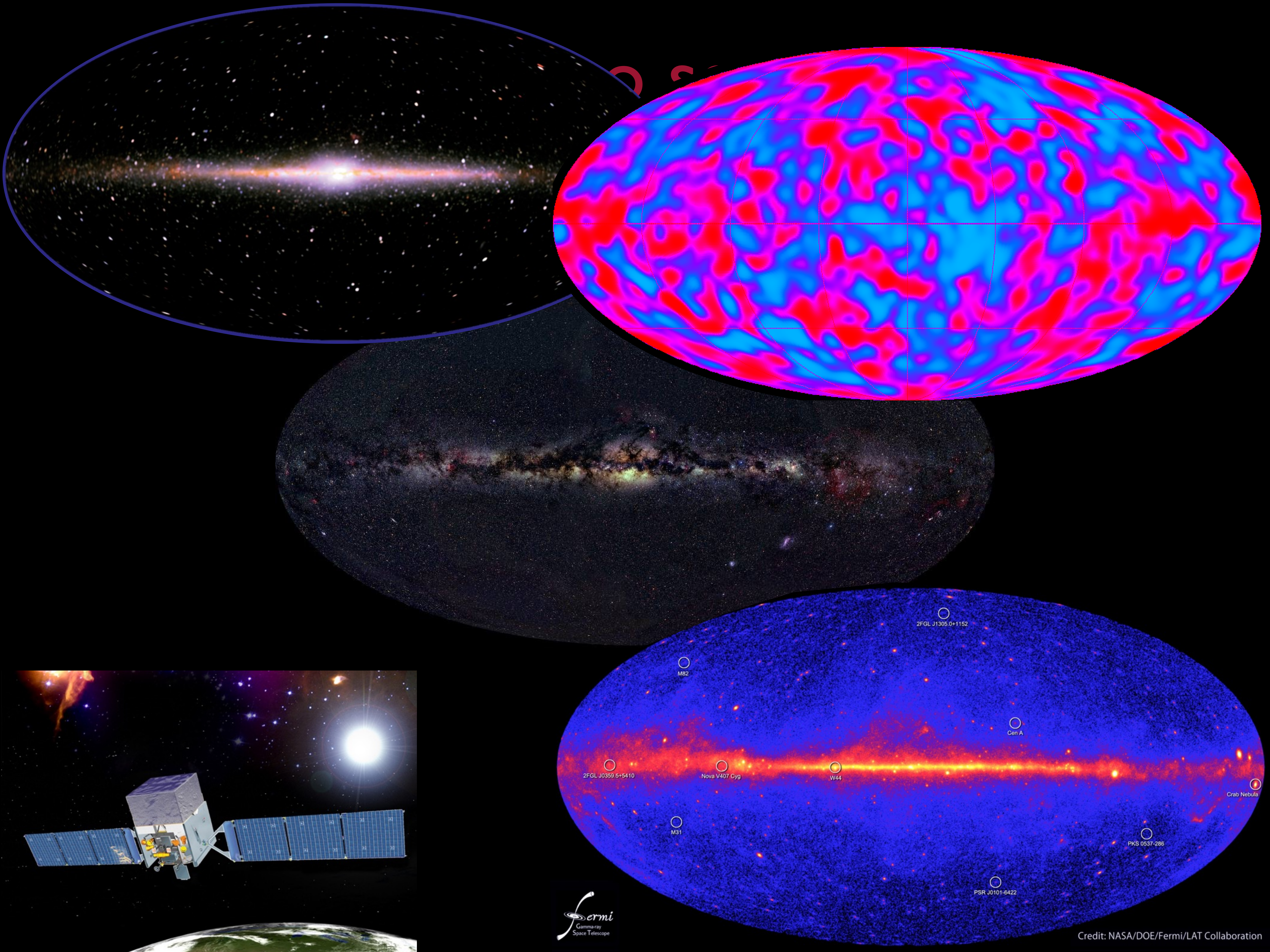
Credit: NASA/DOE/Fermi/LAT Collaboration

o see the sky

ep Sky



Credit: NASA/DOE/Fermi/LAT Collaboration

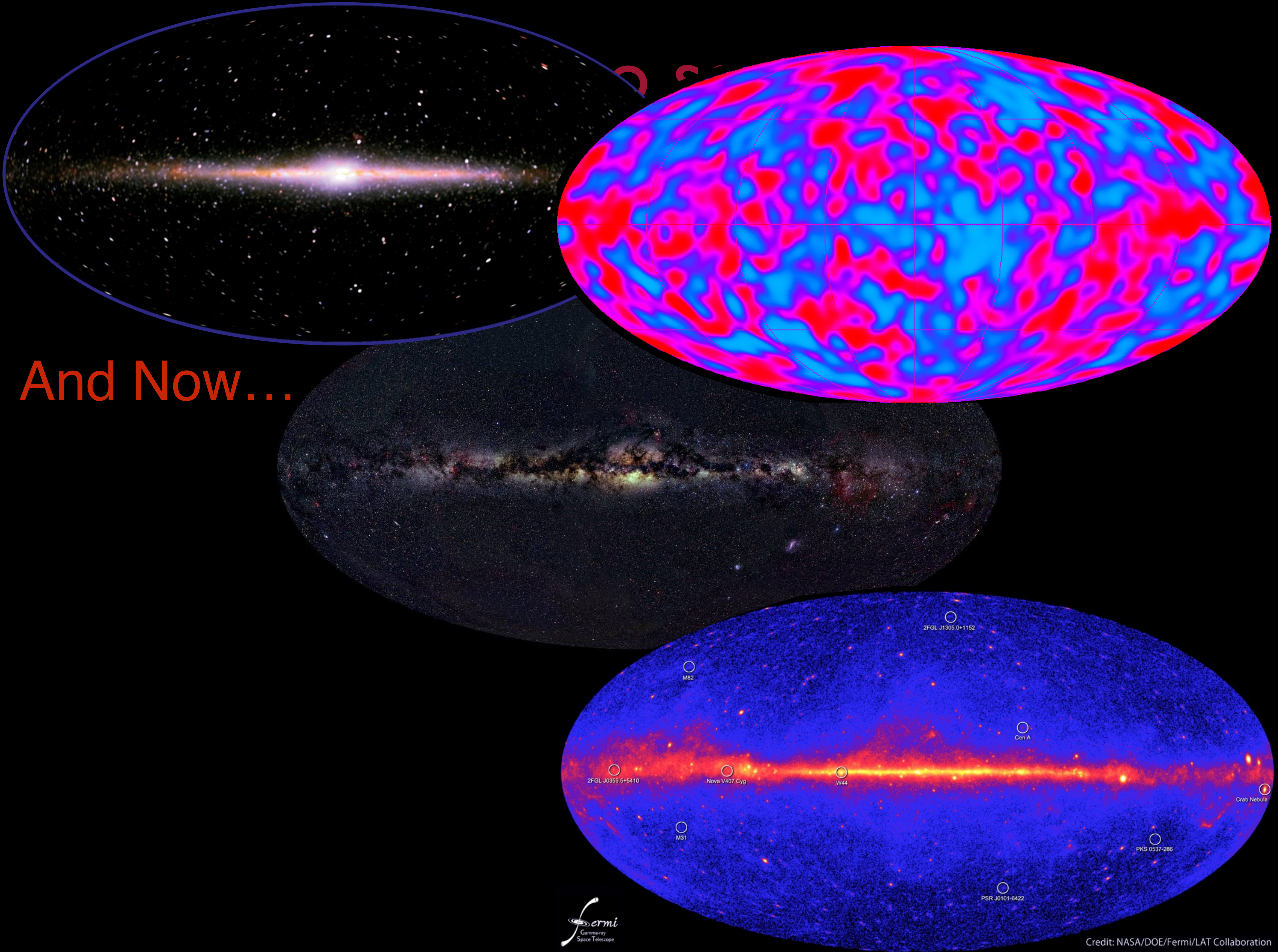


Credit: NASA/DOE/Fermi/LAT Collaboration

And Now…

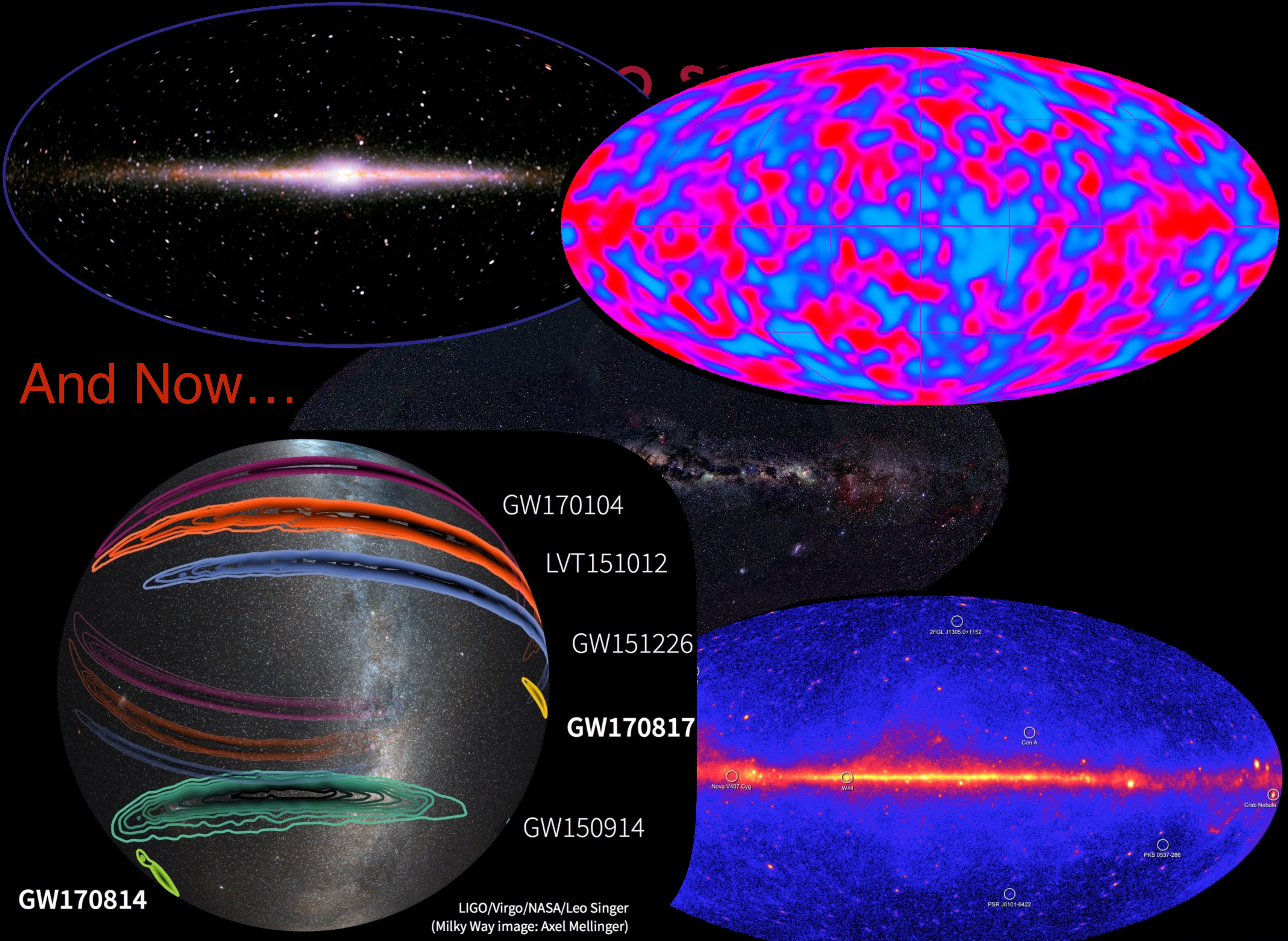
Credit: NASA/DOE/Fermi/LAT Collaboration

And Now…



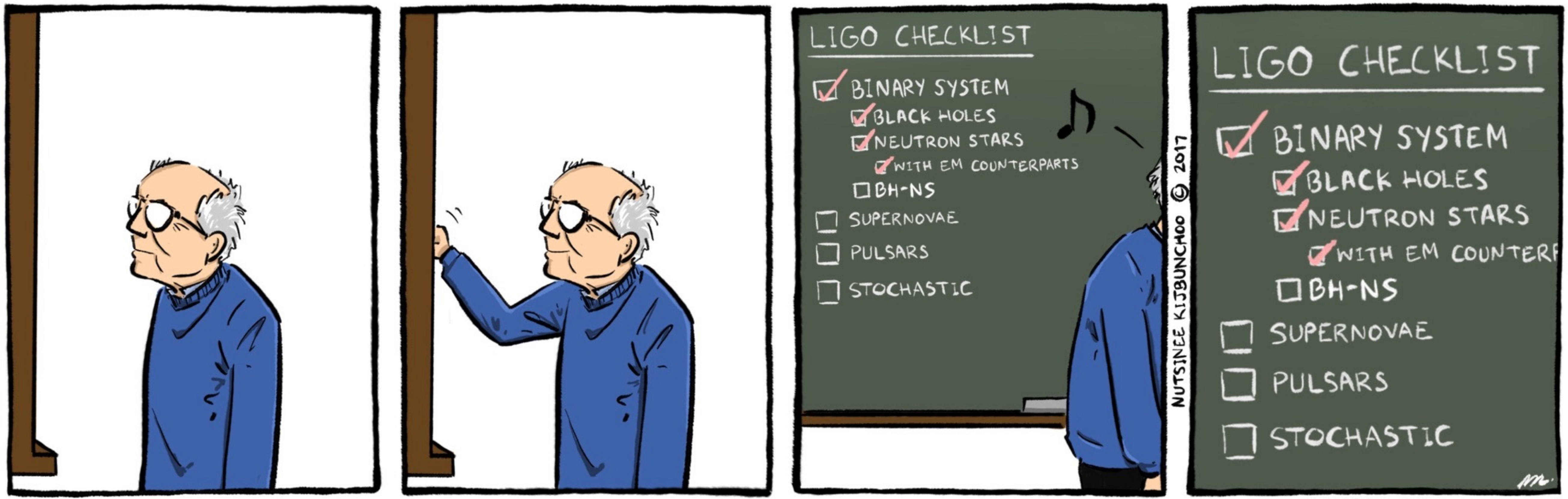
Credit: NASA/DOE/Fermi/LAT Collaboration

And Now…

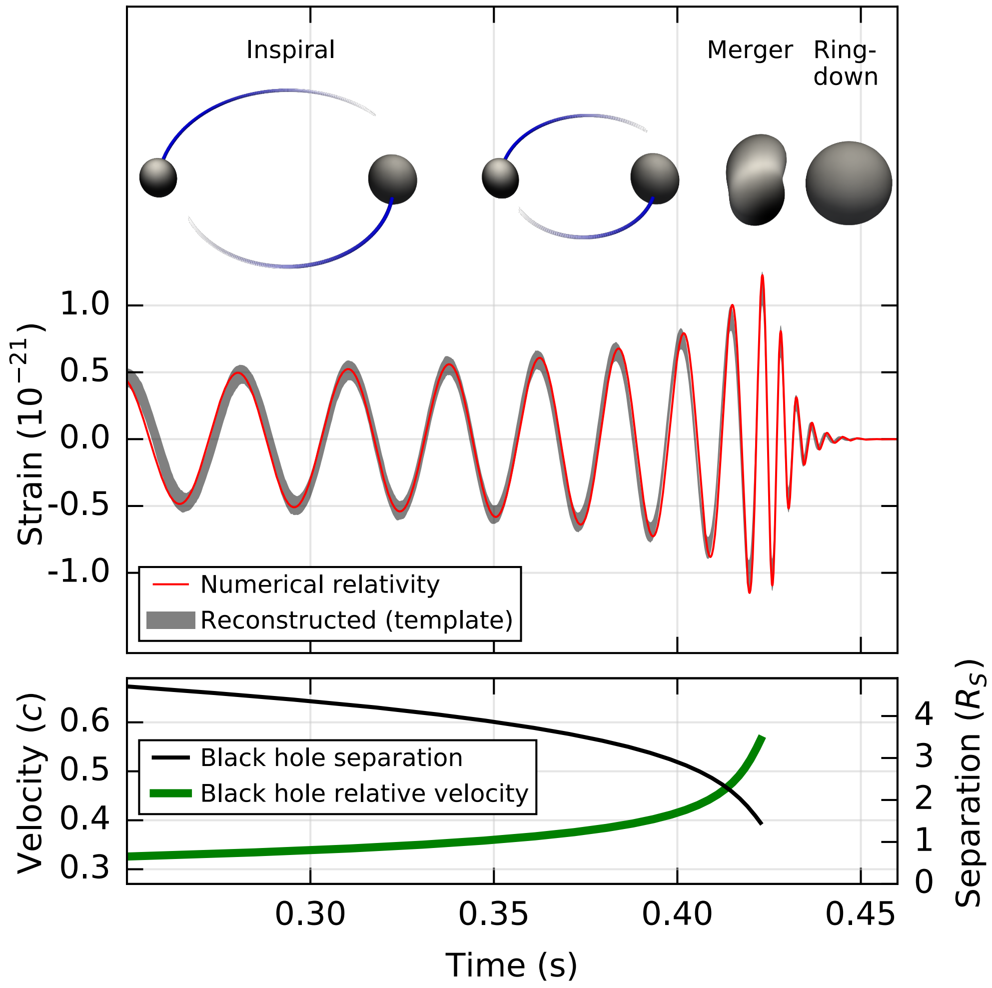


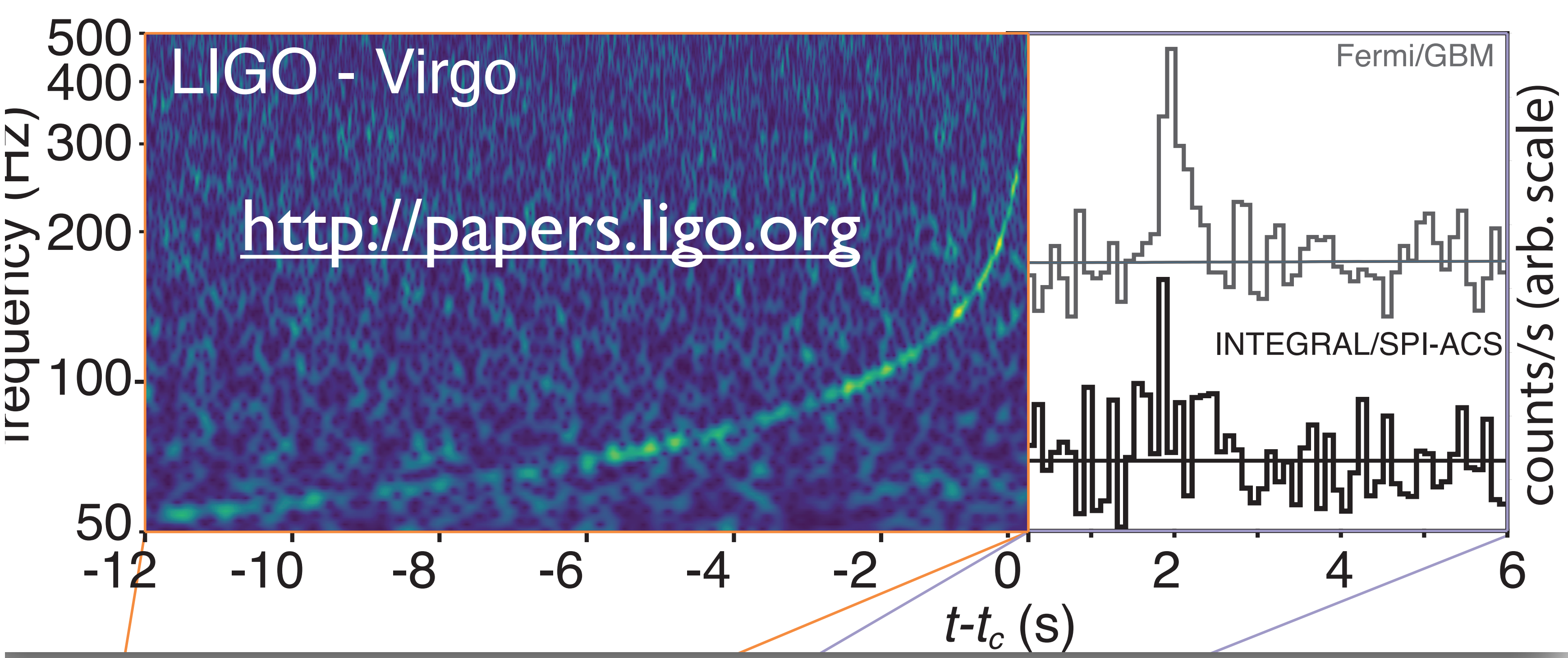
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

Credit: NASA/DOE/Fermi/LAT Collaboration

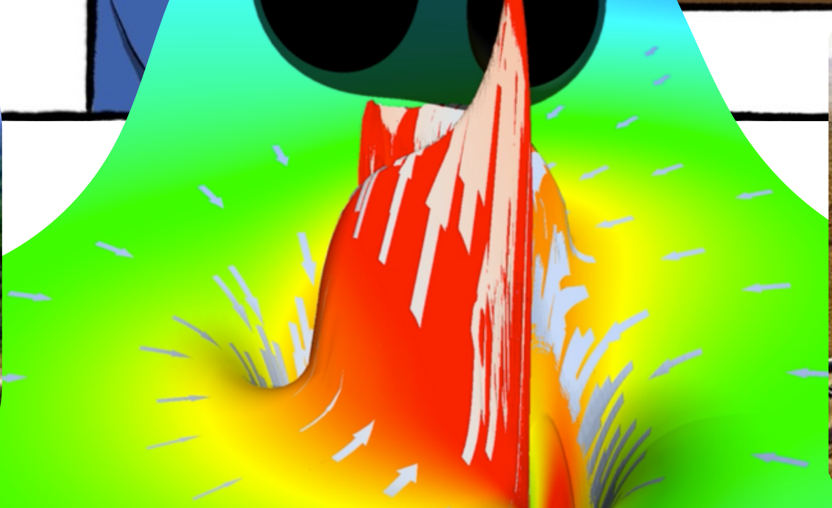


ANTIMATTERWEBCOMICS.COM



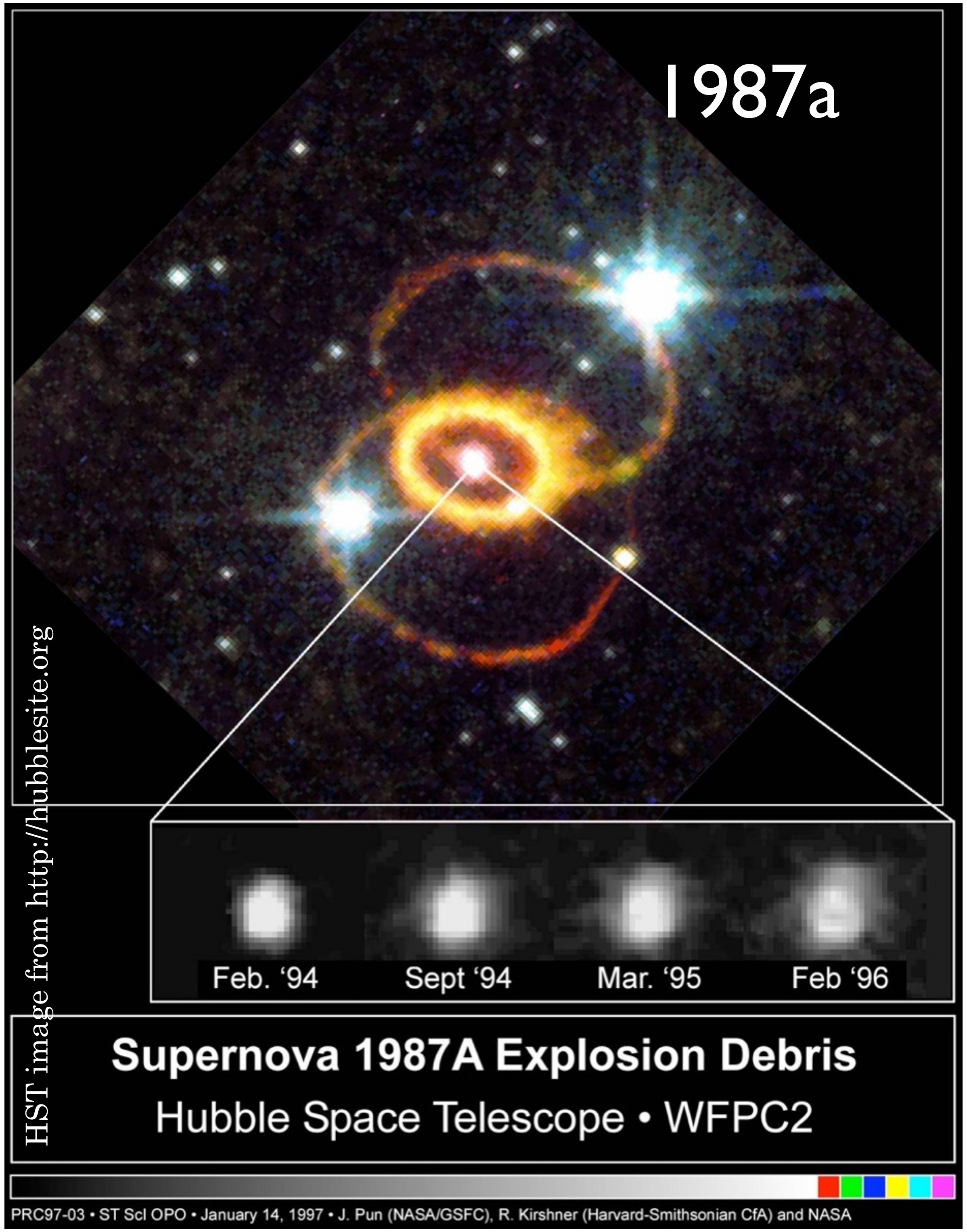


http://papers.ligo.org



extra slides

Supernovas and remnants

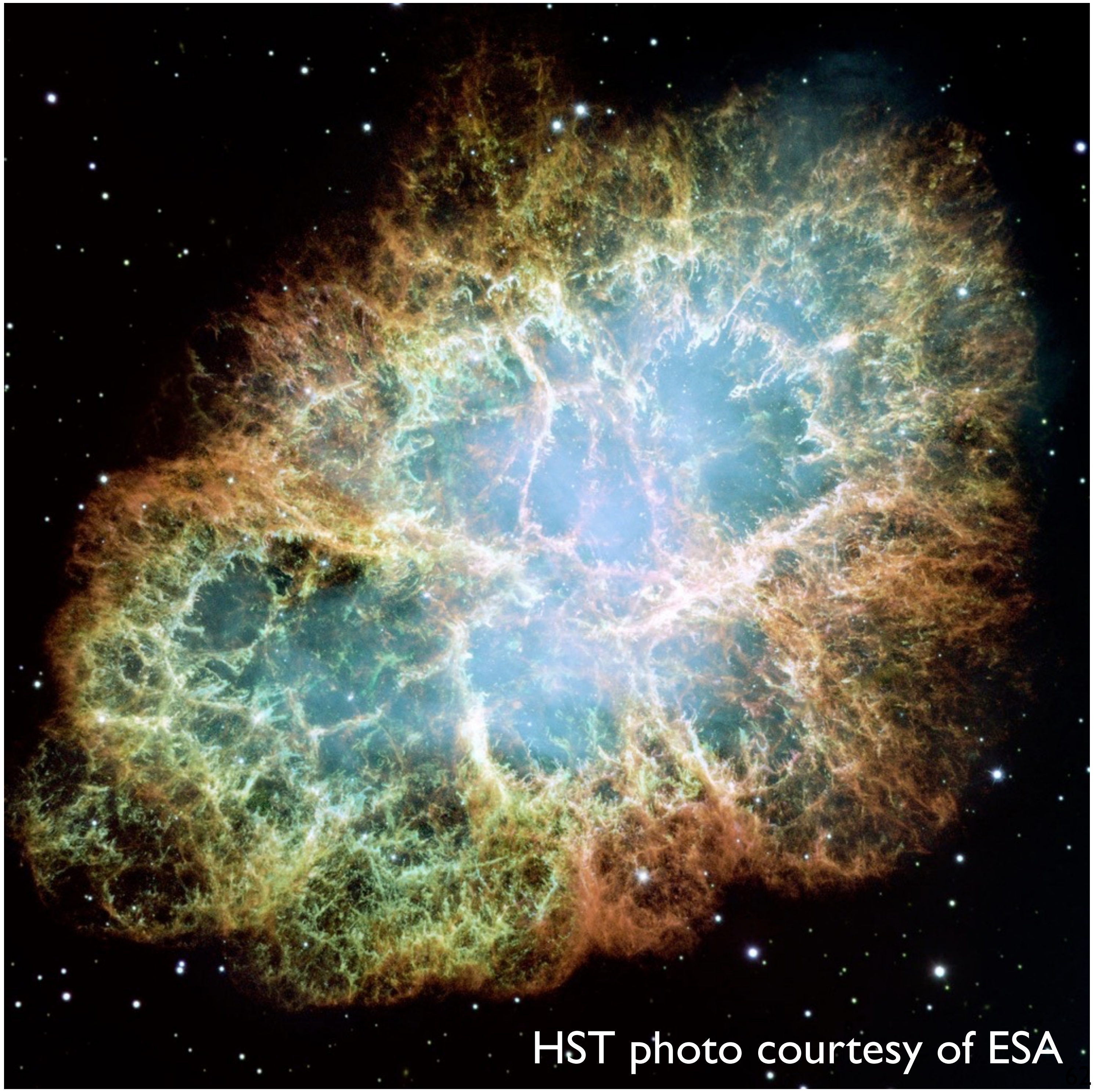


Supernova 1987A Explosion Debris
Hubble Space Telescope • WFPC2

PRC97-03 • ST ScI OPO • January 14, 1997 • J. Pun (NASA/GSFC), R. Kirshner (Harvard-Smithsonian CfA) and NASA

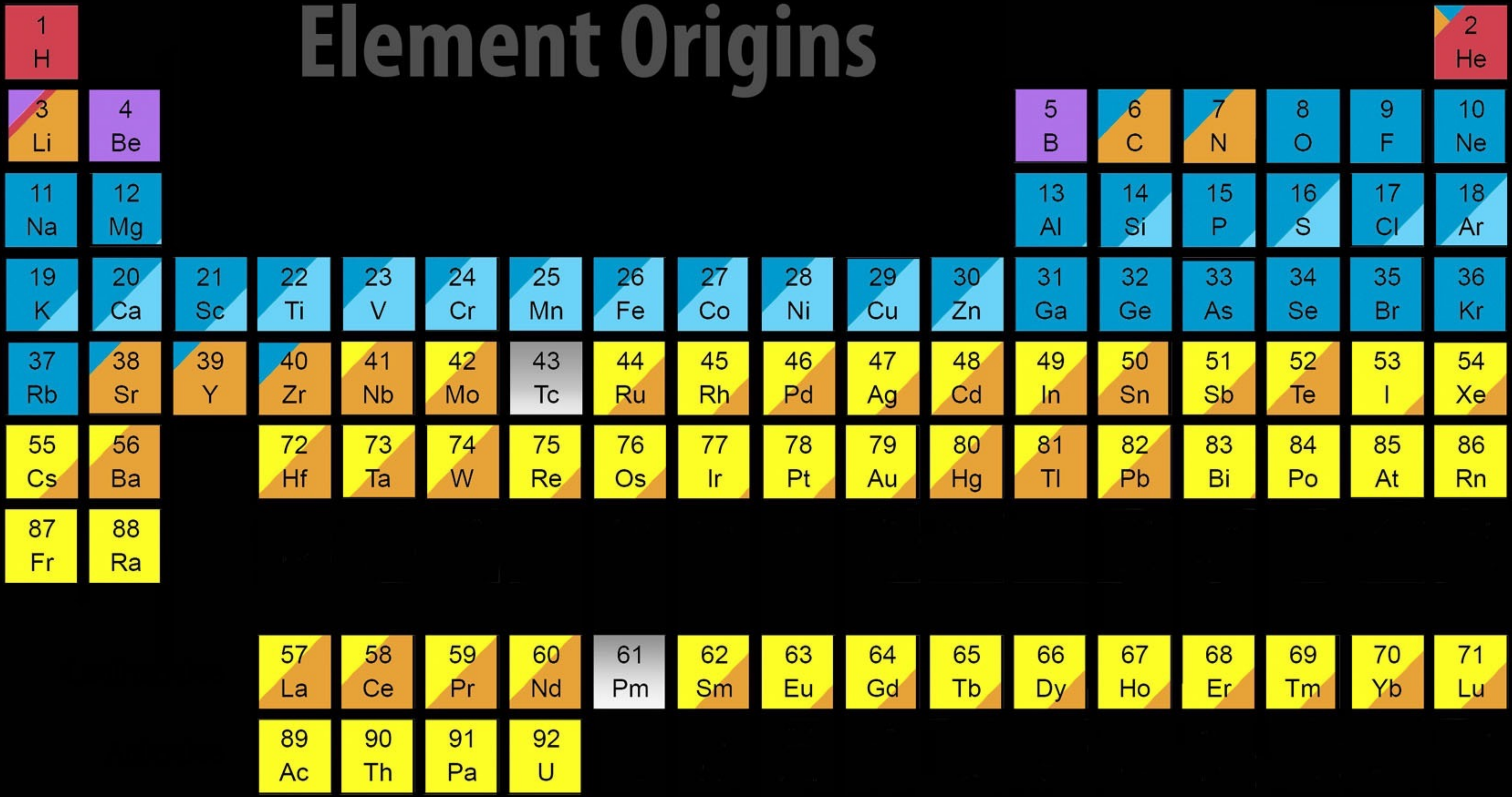
HST image from http://hubblesite.org

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



HST photo courtesy of ESA

Element Origins



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											

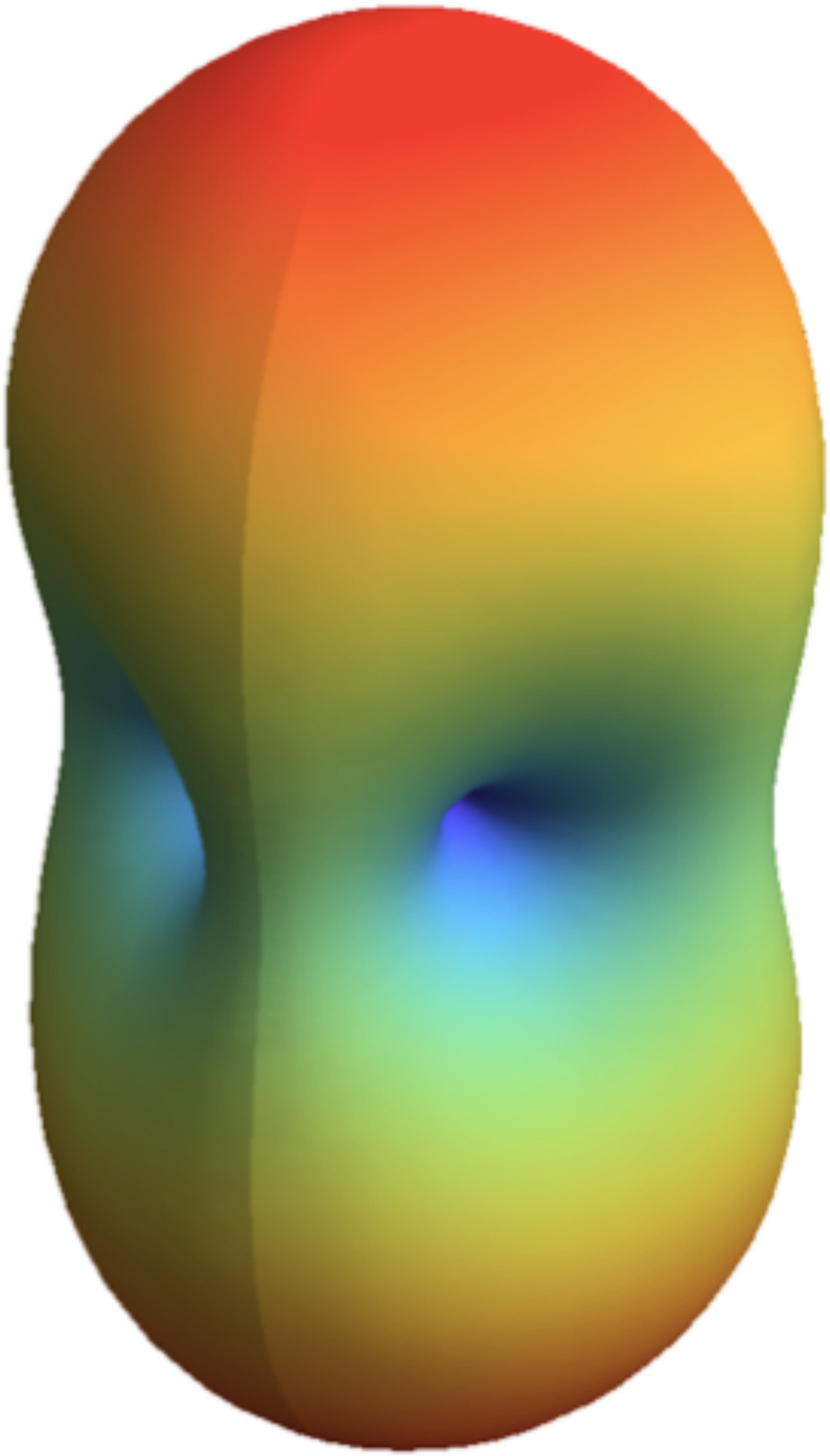
Merging Neutron Stars **Exploding Massive Stars** **Big Bang**

Dying Low Mass Stars **Exploding White Dwarfs** **Cosmic Ray Fission**

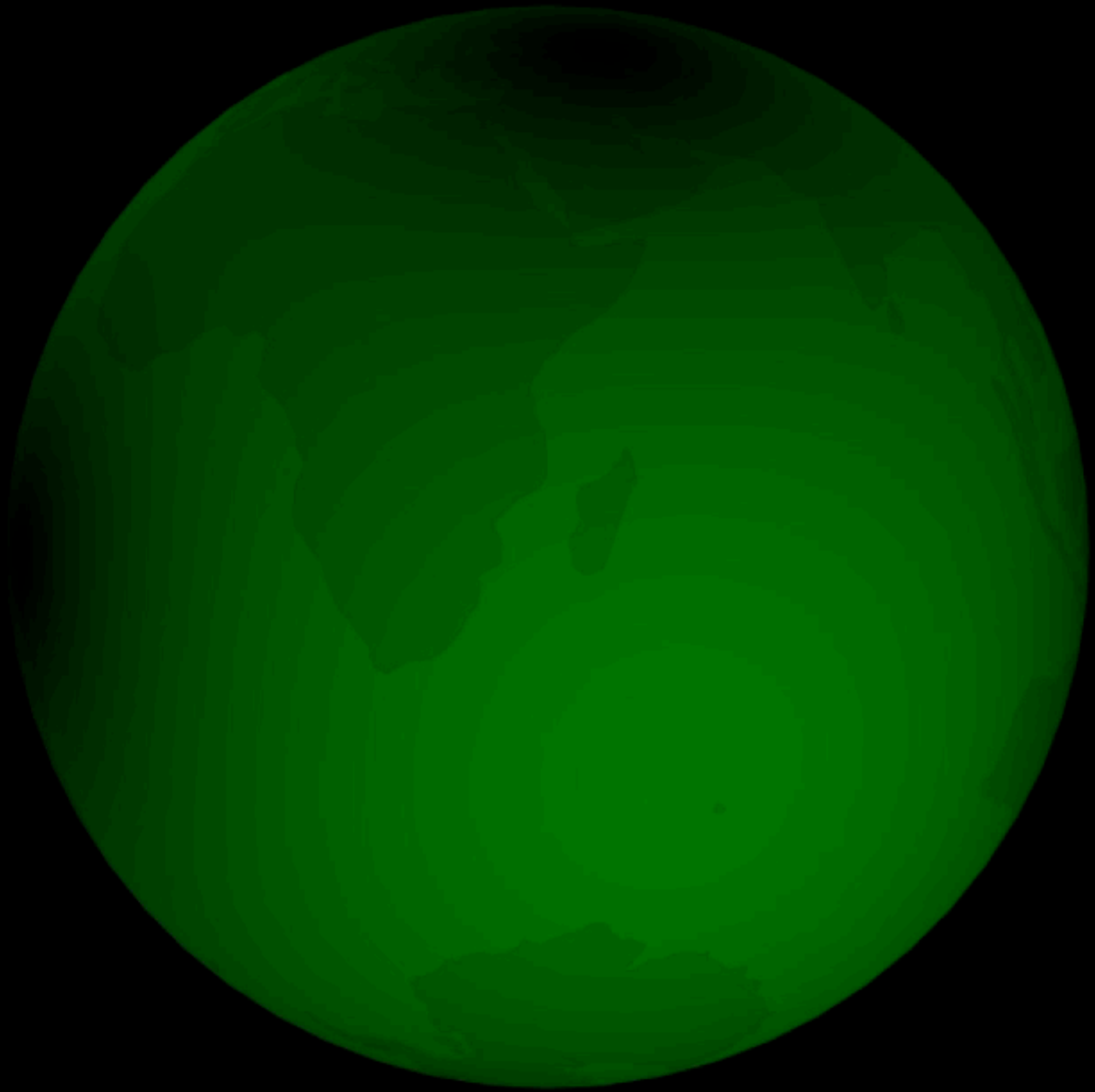
Based on graphic created by

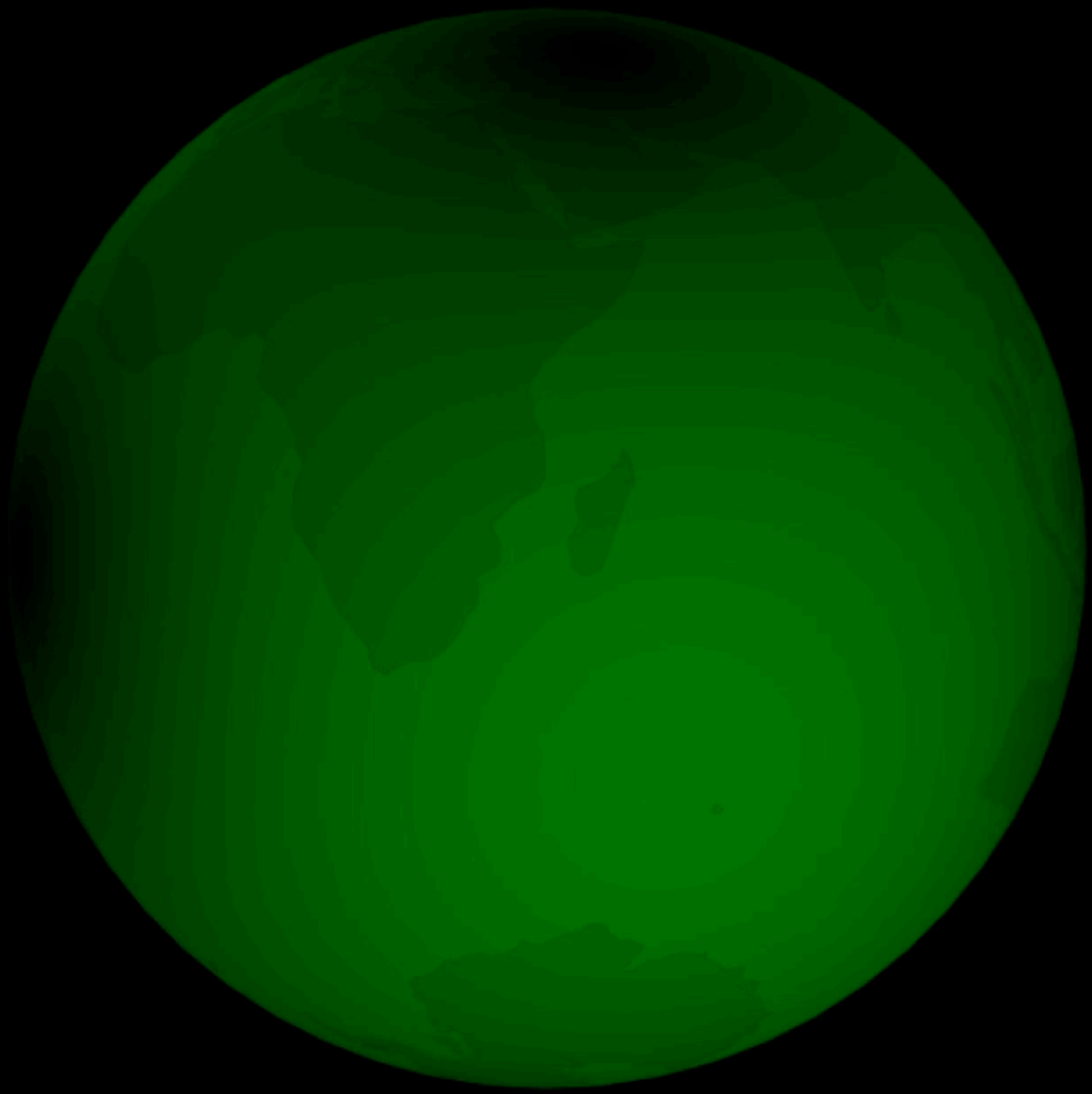
Interferometer's Antenna Pattern
LIGO is not an Imaging Detector

- 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.





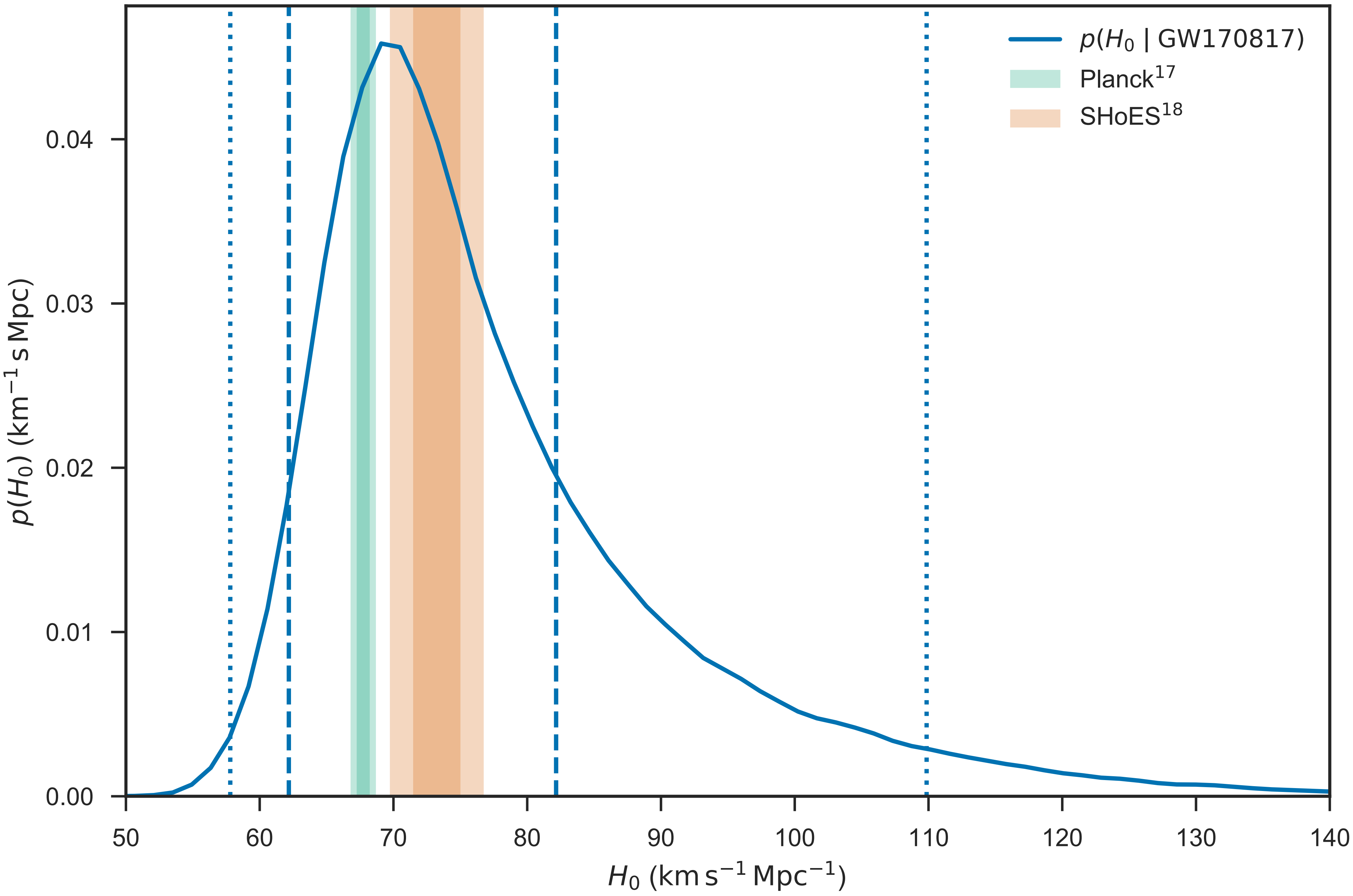
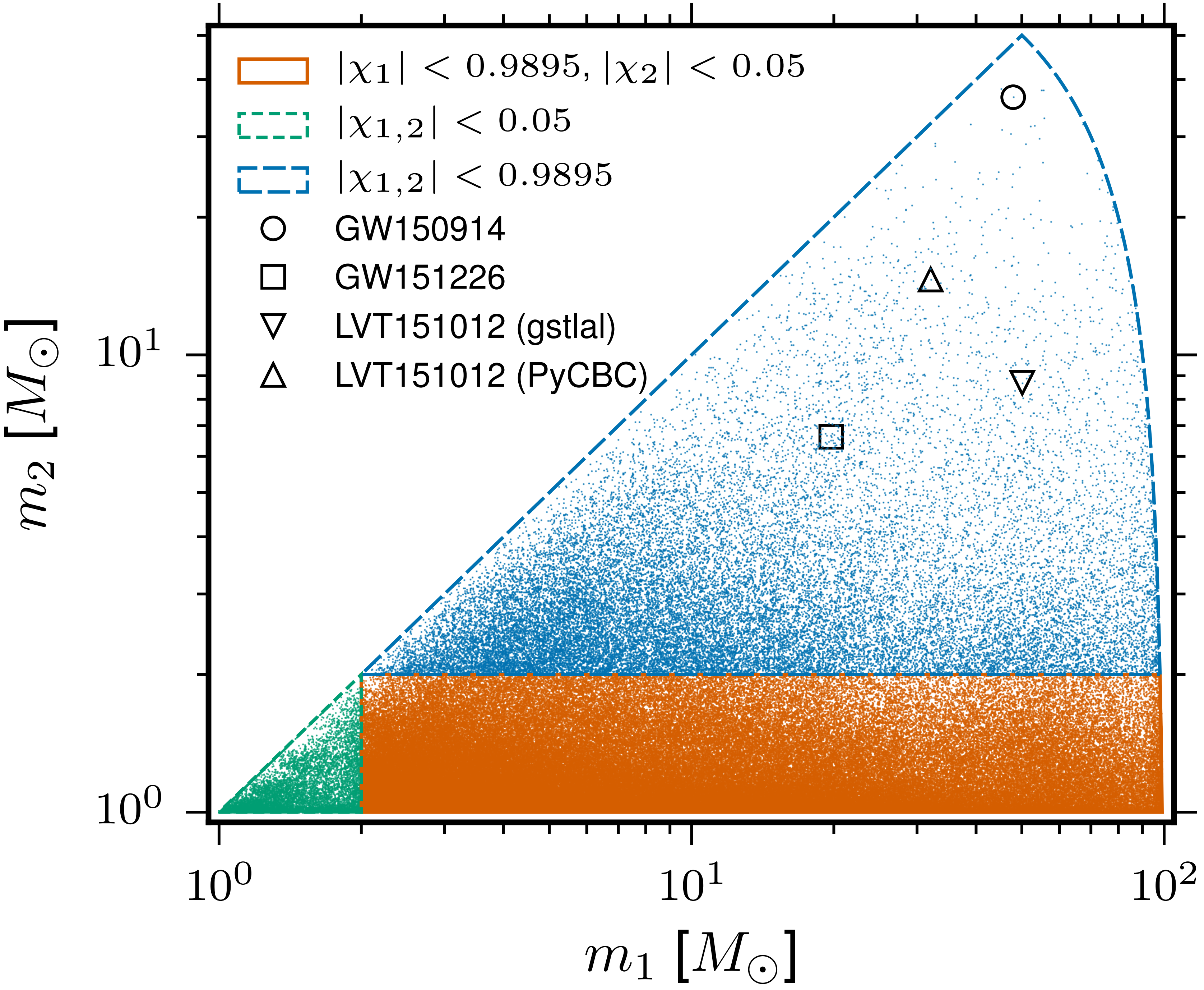


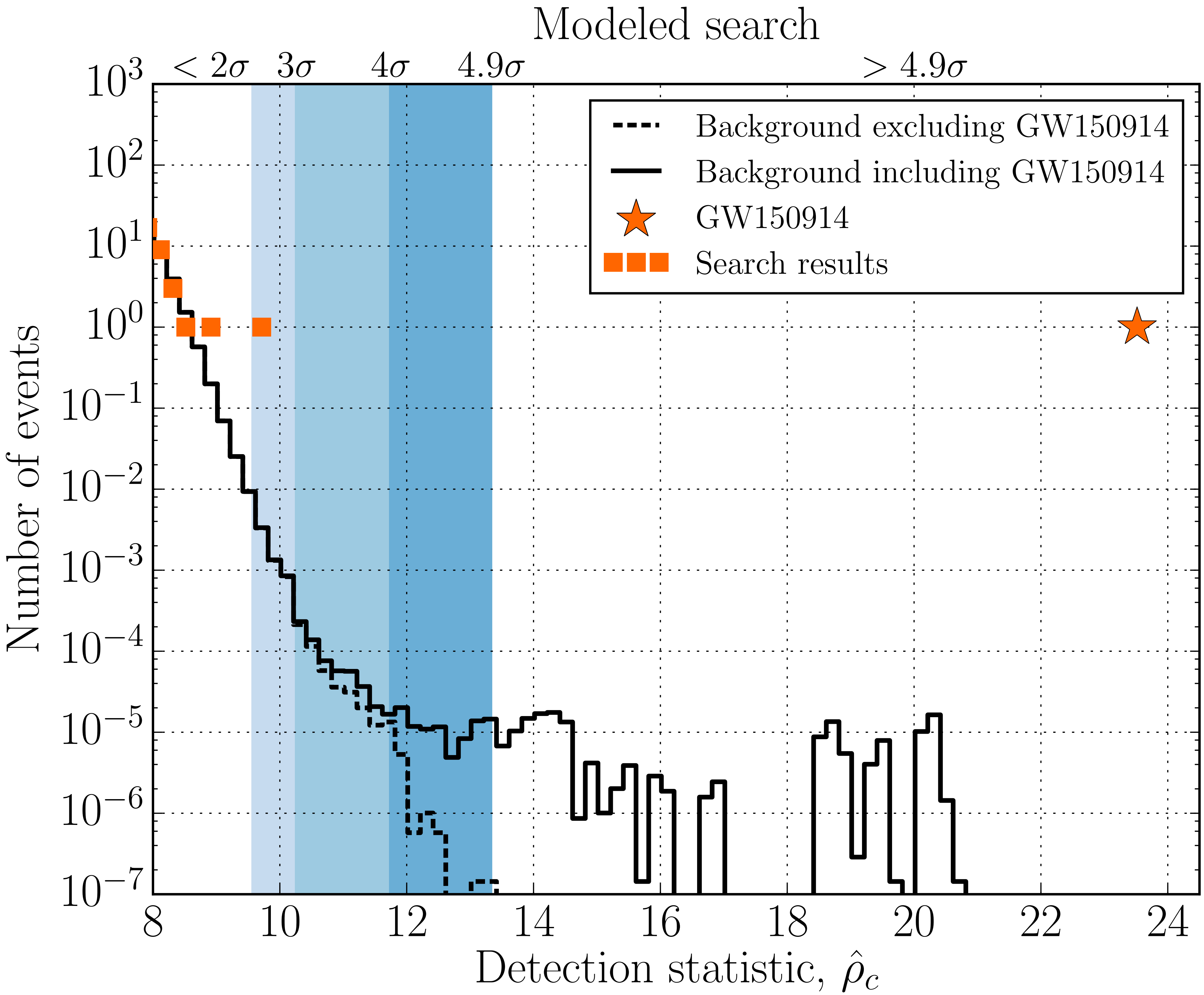
Figure 1 GW170817 measurement of H_0 . Marginalized posterior density for H_0 (blue curve). Constraints at 1- and 2σ from Planck and SHoES are shown in green and orange. The maximum a posteriori value and minimal 68.3% credible interval from this PDF is $H = 70.0^{+12.0, -8.0}$ km s^{-1} Mpc^{-1}. The 68.3% (1σ) and 95.4% (2σ) minimal credible intervals are indicated by dashed and dotted lines.

A gravitational-wave standard siren measurement of the Hubble constant

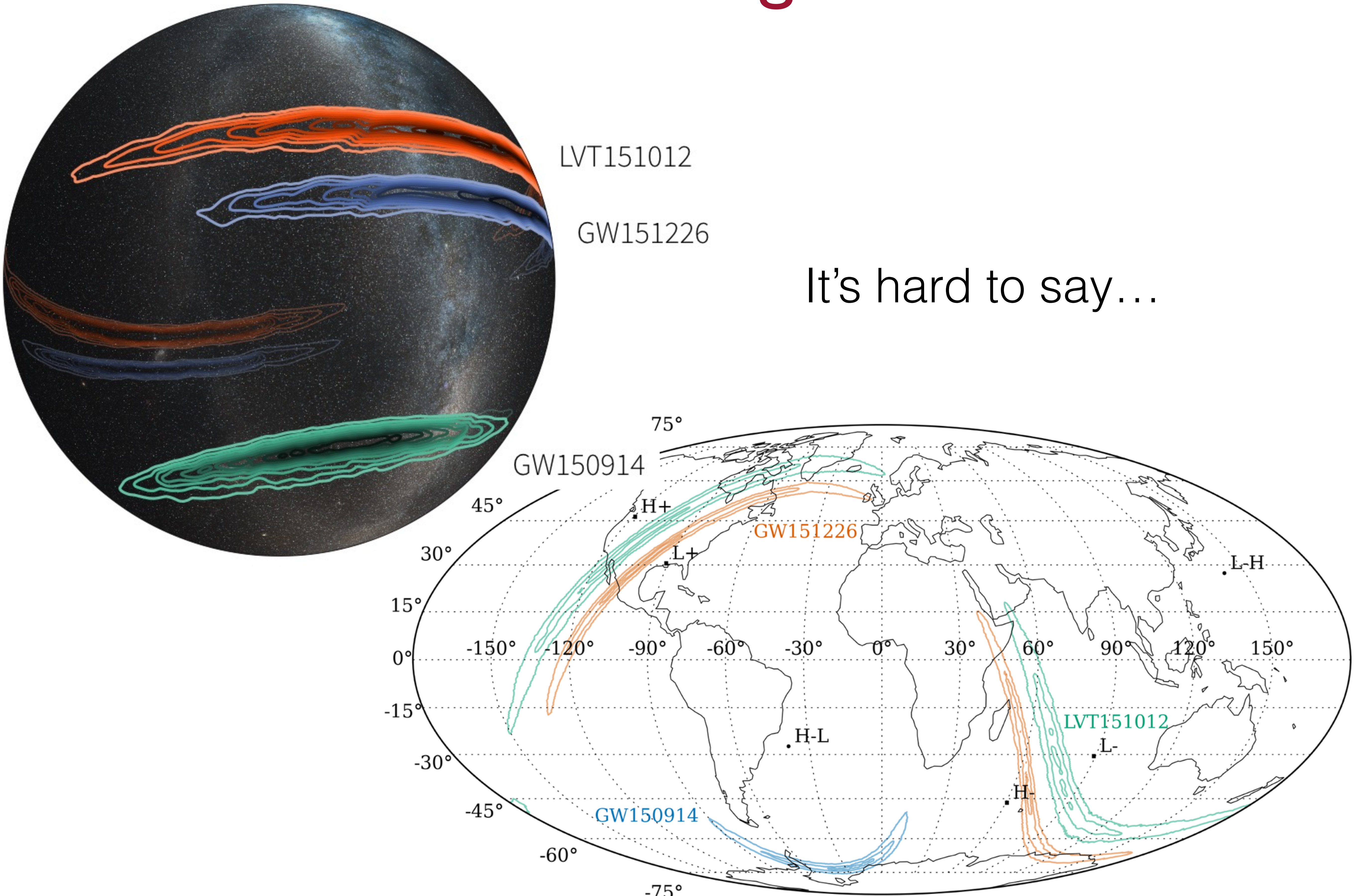
The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration & The MASTER Collaboration


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

Detection statistic



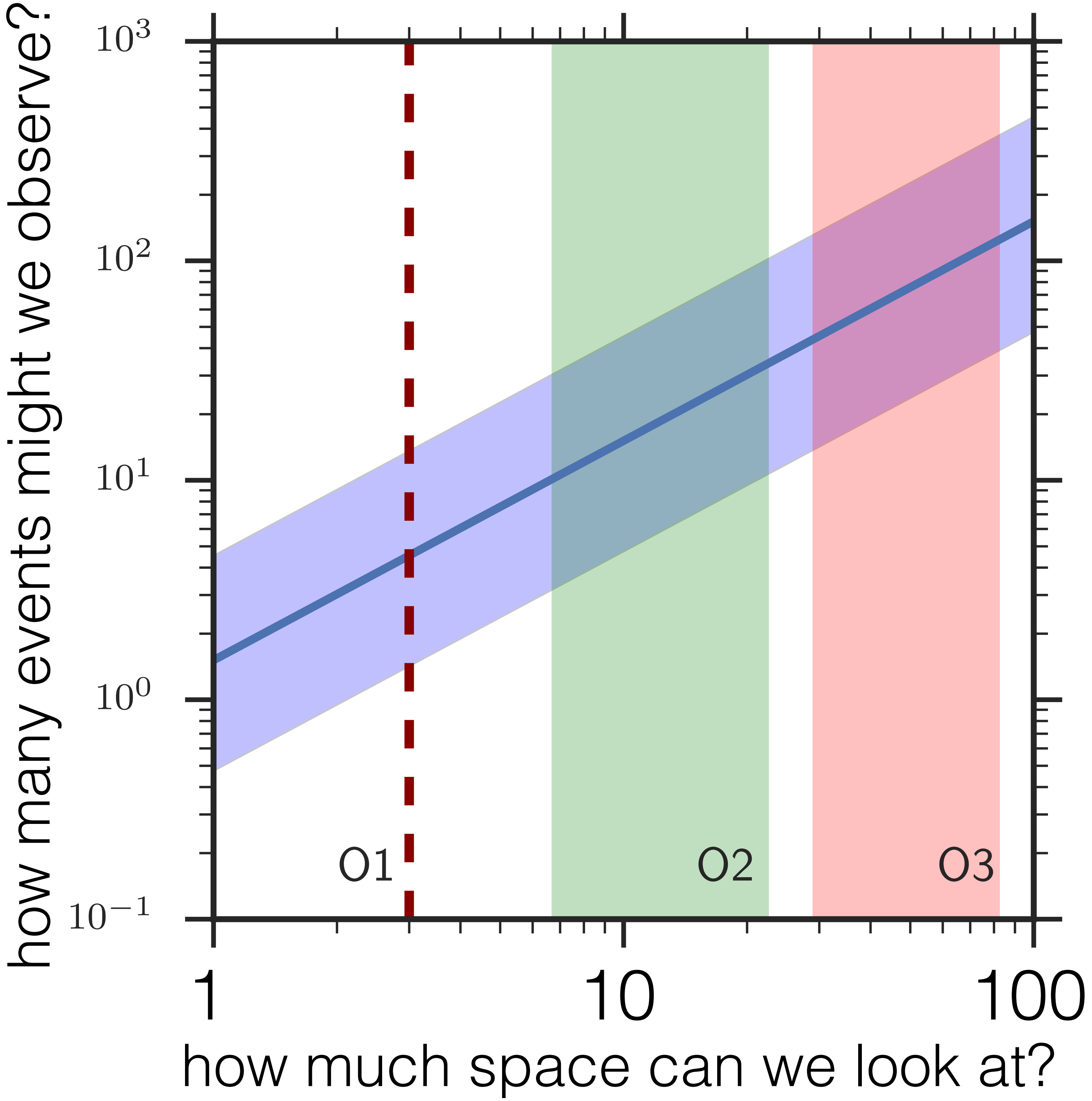
Where did that signal come from?



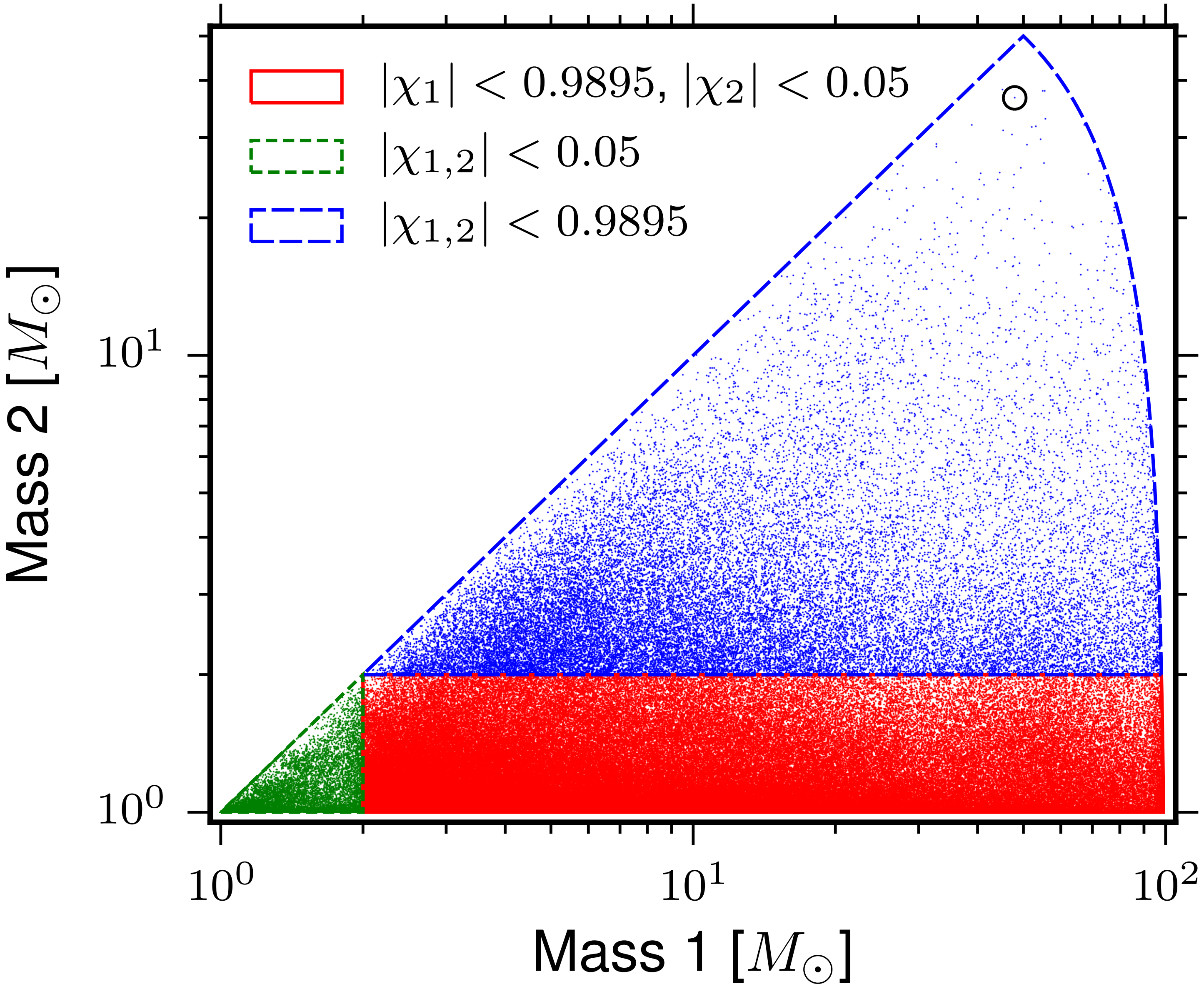
It’s hard to say…

The End/ The Beginning…

How many black hole collisions can we see?

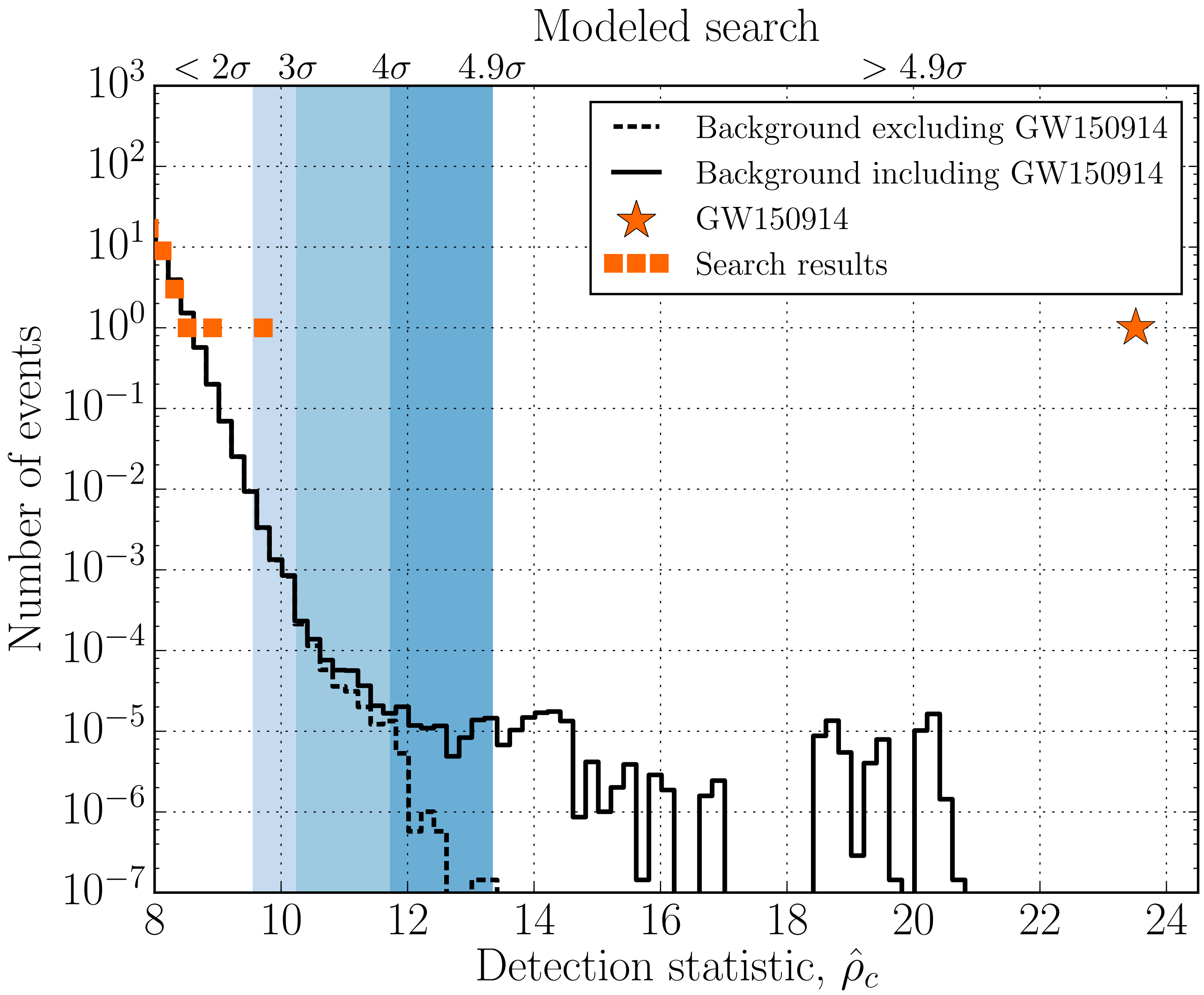


CBC template bank



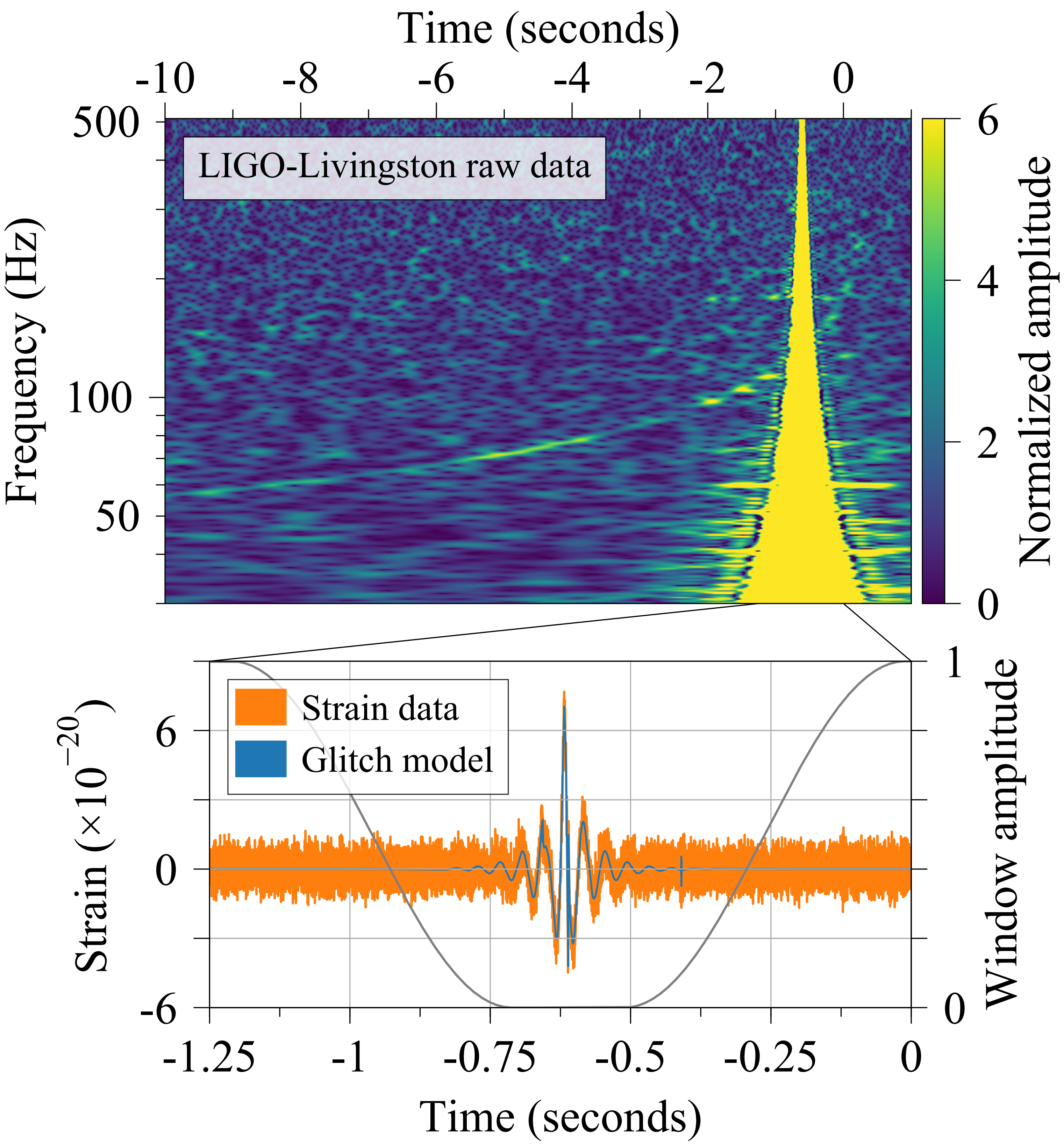
(just at the edge…)

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



Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ ($\mathrm{M}_\odot$)	m_1 ($\mathrm{M}_\odot$)	m_2 ($\mathrm{M}_\odot$)	χ_{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}

FIG. 2. Mitigation of the glitch in LIGO-Livingston data. Times are shown relative to August 17, 2017 12:41:04 UTC. *Top panel:* A time-frequency representation [57] of the raw LIGO-Livingston data used in the initial identification of GW170817 [62]. The coalescence time reported by the search is at time 0.4 s in this figure and the glitch occurs 1.1 s before this time. The time-frequency track of GW170817 is clearly visible despite the presence of the glitch. *Bottom panel:* The raw LIGO-Livingston strain data (orange curve) showing the glitch in the time domain. To mitigate the glitch in the rapid re-analysis that produced the sky-map shown in Figure 3 [63], the raw detector data was multiplied by an inverse Tukey window (grey curve, right axis) that zeroed out the data around the glitch [64]. To mitigate the glitch in the measurement of the source's properties, a model of the glitch based on a wavelet reconstruction [65] (blue curve) was subtracted from the data. The time-series data visualized in this figure have been band-passed between 30 Hz and 2 kHz so that the the detector's sensitive band is emphasized. The gravitational-wave strain amplitude of GW170817 is of the order of 10^{-22} and so is not visible in the bottom panel.



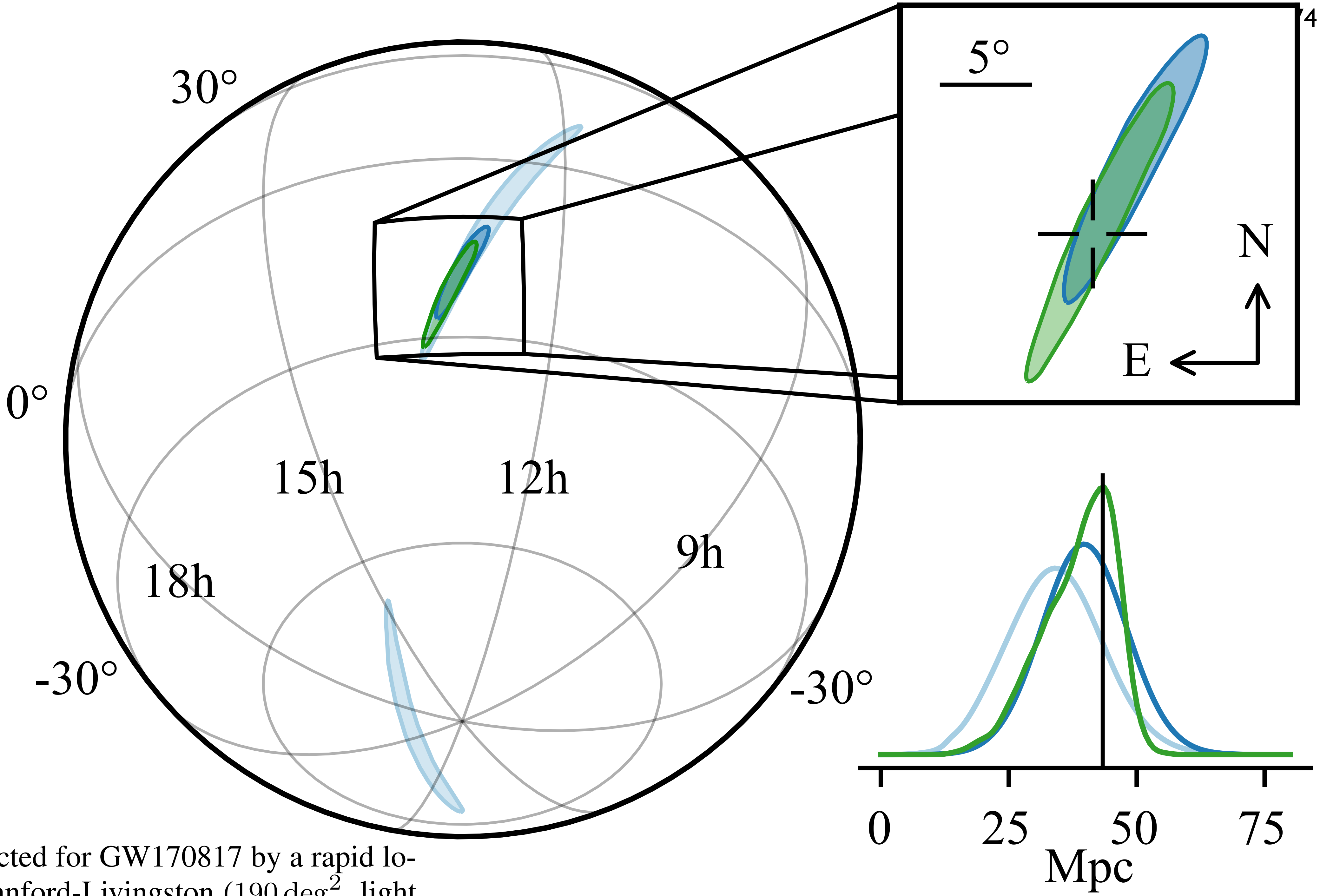


FIG. 3. Sky location reconstructed for GW170817 by a rapid localization algorithm from a Hanford-Livingston (190 $\deg^2$, light blue contours) and Hanford-Livingston-Virgo (31 $\deg^2$, dark blue contours) analysis. A higher latency Hanford-Livingston-Virgo analysis improved the localization (28 $\deg^2$, green contours). In the top-right inset panel, the reticle marks the position of the apparent host galaxy NGC 4993. The bottom-right panel shows the a posteriori luminosity distance distribution from the three gravitational-wave localization analyses. The distance of NGC 4993, assuming the redshift from the NASA/IPAC Extragalactic Database [91] and standard cosmological parameters [92], is shown with a vertical line.

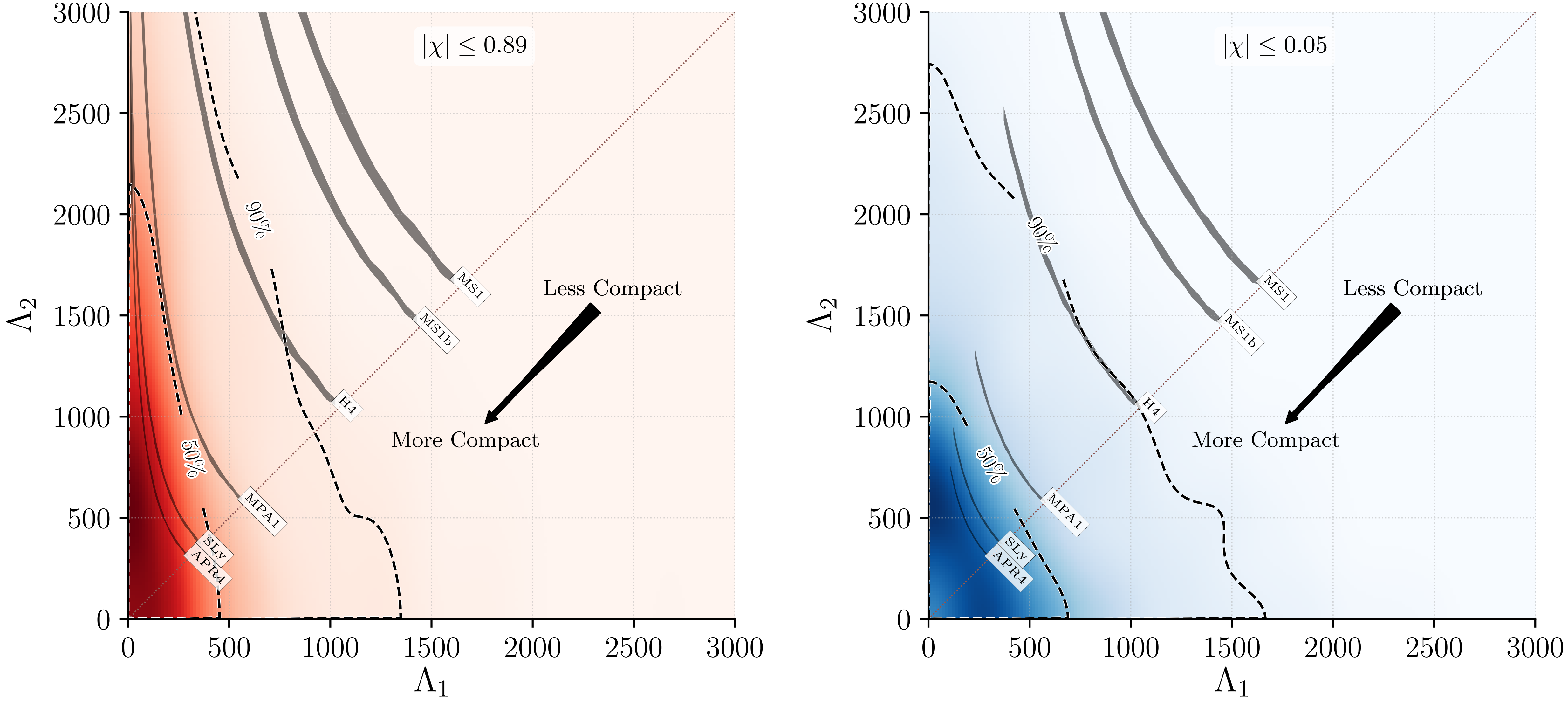
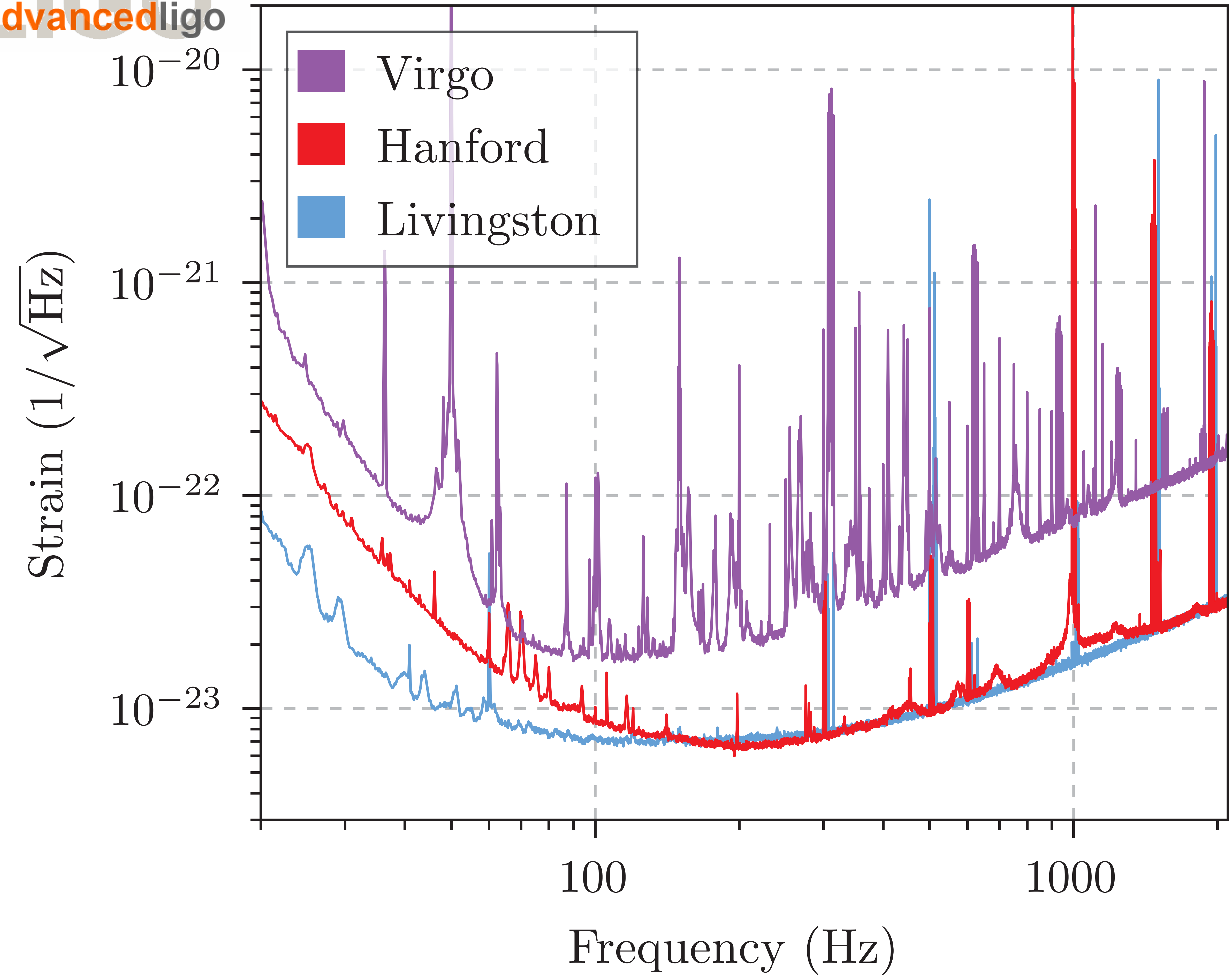
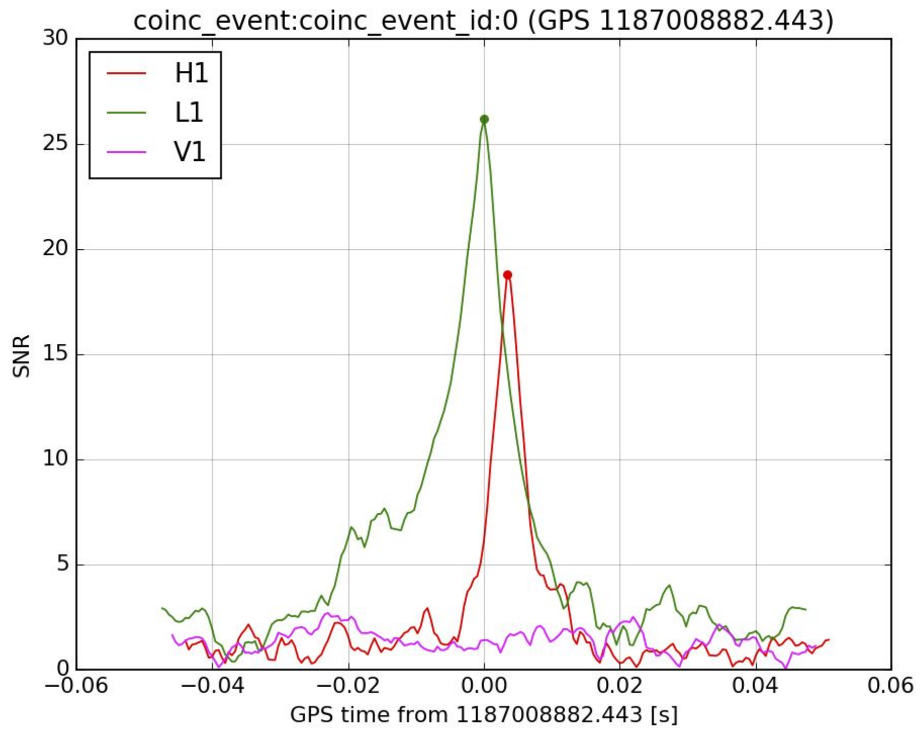


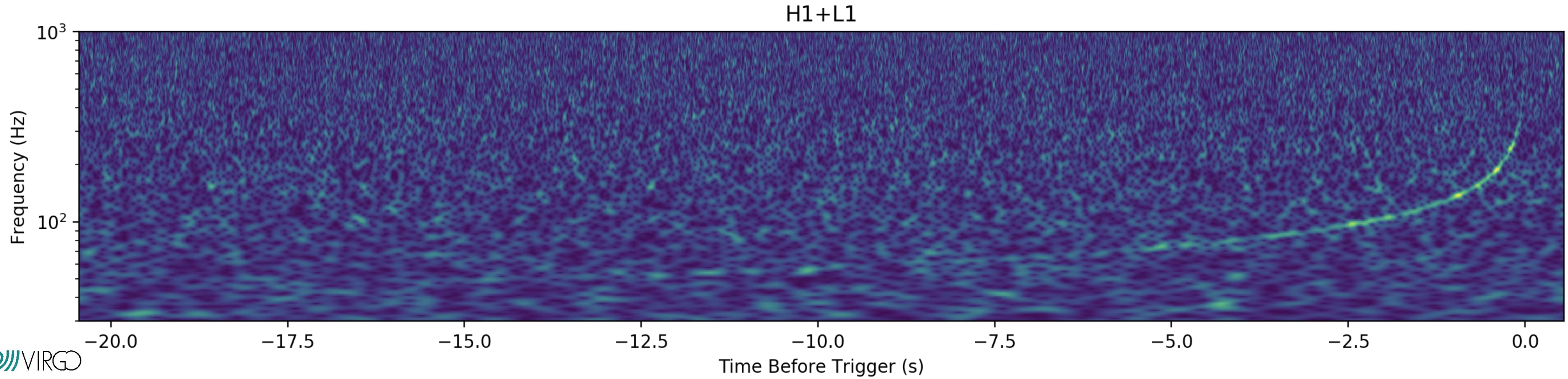
FIG. 5. Probability density for the tidal deformability parameters of the high and low mass components inferred from the detected signals using the post-Newtonian model. Contours enclosing 90% and 50% of the probability density are overlaid (dashed lines). The diagonal dashed line indicates the $\Lambda_1 = \Lambda_2$ boundary. The Λ_1 and Λ_2 parameters characterize the size of the tidally-induced mass deformations of each star and are proportional to $k_2(R/m)^5$. Constraints are shown for the high-spin scenario, $|\chi| \leq 0.89$, (left panel) and for the low-spin, $|\chi| \leq 0.05$, (right panel). As a comparison, we plot predictions for tidal deformability given by a set of representative equations of state [148–152] (shaded filled regions), with labels following [153], all of which support stars of $2.01\ M_\odot$. Under the assumption that both components are neutron stars, we apply the function $\Lambda(m)$ prescribed by that equation of state to the 90% most probable region of the component mass posterior distributions shown in Figure 4. EOS that produce less compact stars, such as MS1 and MS1b, predict Λ values ouside our 90% contour.


10^{-20}
10^{-21}
10^{-22}
10^{-23}
Strain $(1/\sqrt{\mathrm{Hz}})$
100
1000
Frequency (Hz)
Virgo
Hanford
Livingston

GW170817

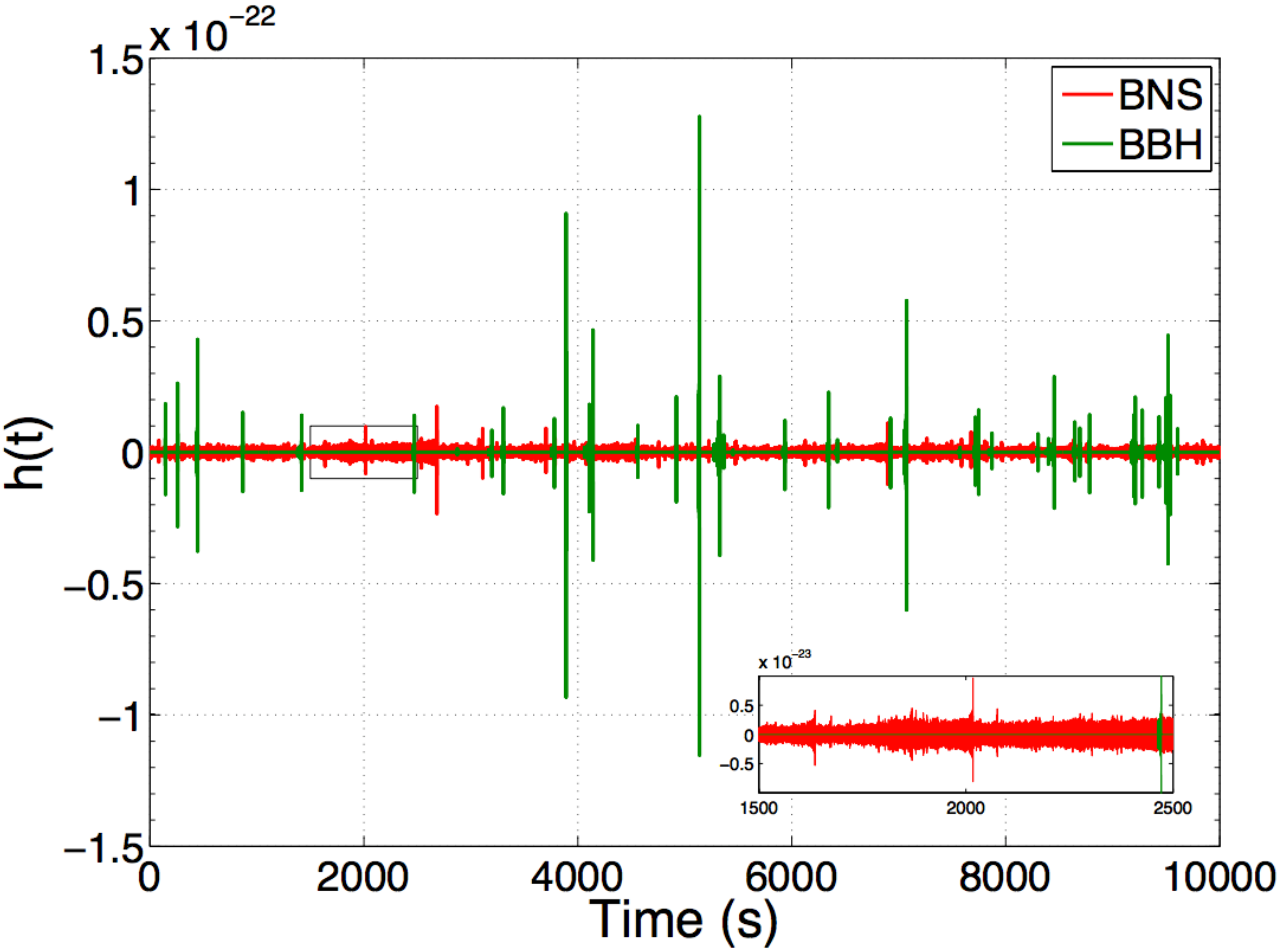
- Finally, a BNS!!
- ... also associated with a GRB
- ... and an optical counterpart





Stochastic Background

specific realization of BNS + BBH backgrounds



- BBH background is ‘popcorn-like’
- BNS is continuous

	τ
BNS	13^{+50}_{-9} s
BBH	229^{+360}_{-118} s
Total	12^{44}_{-8} s

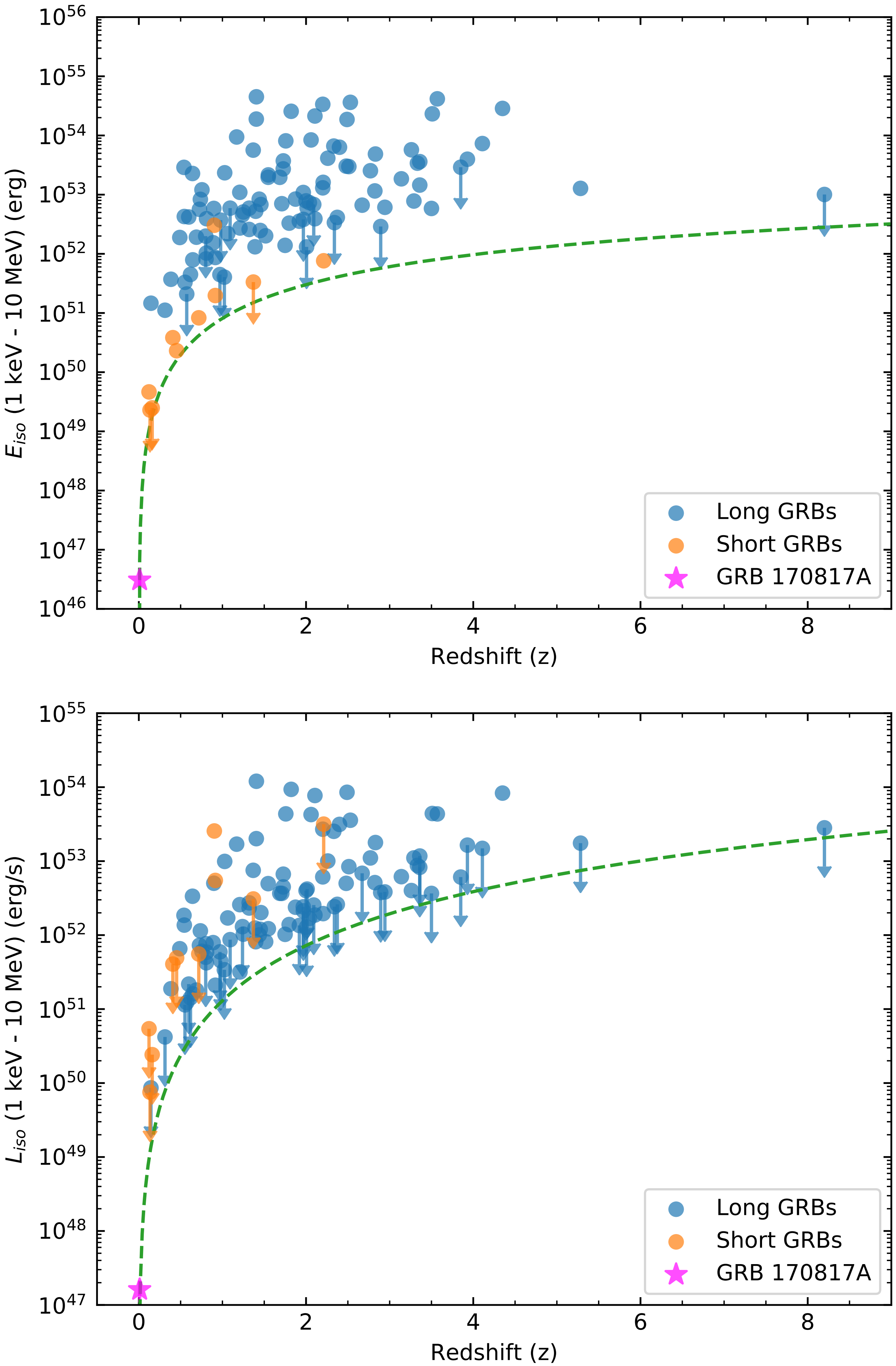


Figure 4. GRB 170817A is a dim outlier in the distributions of $E_{\rm iso}$ and $L_{\rm iso}$, shown as a function of redshift for all GBM-detected GRBs with measured redshifts. Redshifts are taken from GRBOX (`http://www.astro.caltech.edu/grbox/grbox.php`) and Fong et al. (2015). Short and long duration GRBs are separated by the standard $T_{90} = 2\,$s threshold. For GRBs with spectra best modeled by a power law, we take this value as an upper limit, marking them with downward pointing arrows. The power law spectra lack a constraint on the curvature, which must exist, and therefore, will overestimate the total value in the extrapolated energy range. The green curve demonstrates how the (approximate) GBM detection threshold varies as a function of redshift. **All quantities are calculated in the standard 1 keV–10 MeV energy band.**