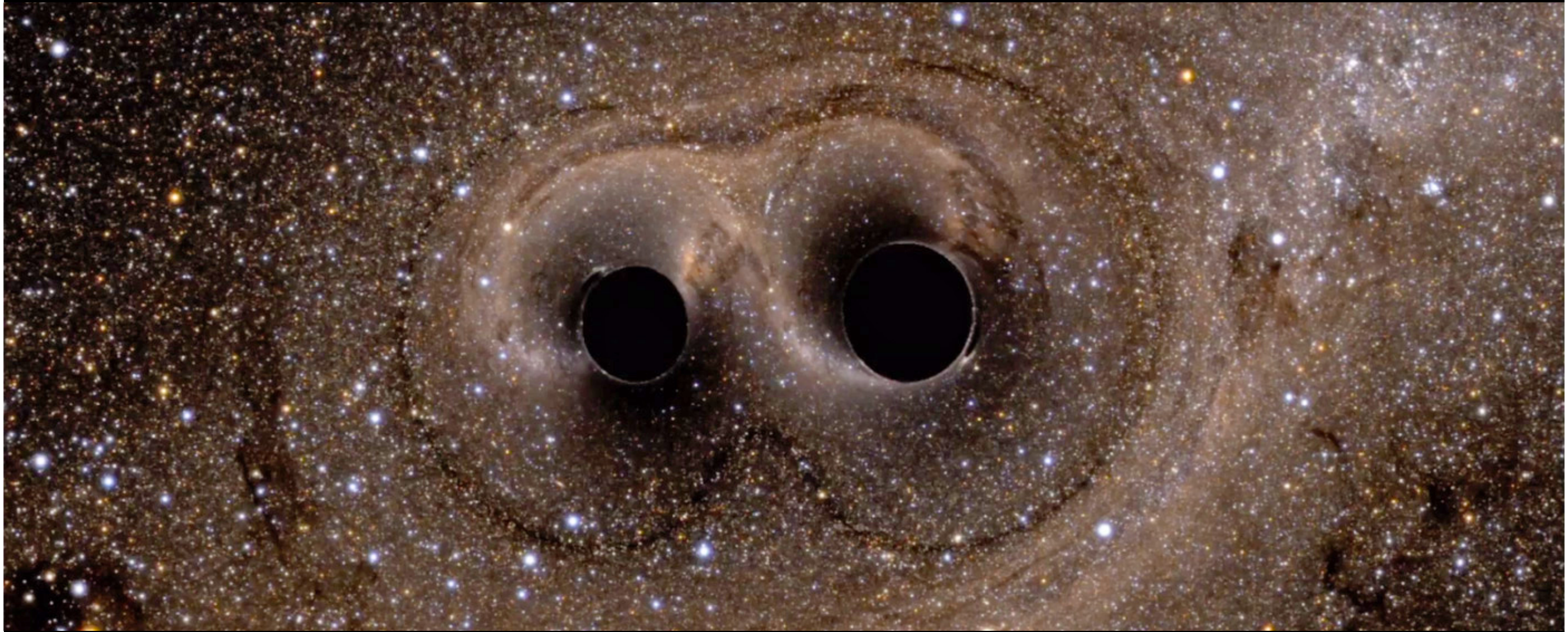
Gravitational Waves:
Nature's Biggest Explosions

Patrick Sutton
Cardiff University




The INDEPENDENT

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Give to GOSH: Our thanks for the £3.56m raised P.21

Syria's dangerous new ingredient Patrick Cockburn on Saudi Arabia's planned deployment

'You don't know what you get paid?' When Google's European boss appeared before MPs

The monumental cruelty of London Why does the capital glorify our colonial savagery?

The softer side of Louis van Gaal An exclusive interview with Manchester United's manager

The theory of relativity proved

Gravitational ripples were first predicted by Einstein a century ago. Yesterday it was revealed that they have finally been detected – from two massive black holes colliding 1.3 billion light years away. The consequences for our understanding of the universe are out of this world

SPECIAL REPORT BY STEVE CONNOR P.4-8


New Scientist

WEEKLY February 20 - 26, 2016

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SPECIAL REPORT

GRAVITATIONAL WAVES

What they will reveal about reality

Neutron stars Black holes Big bang Dark energy Theory of everything

Science and technology news
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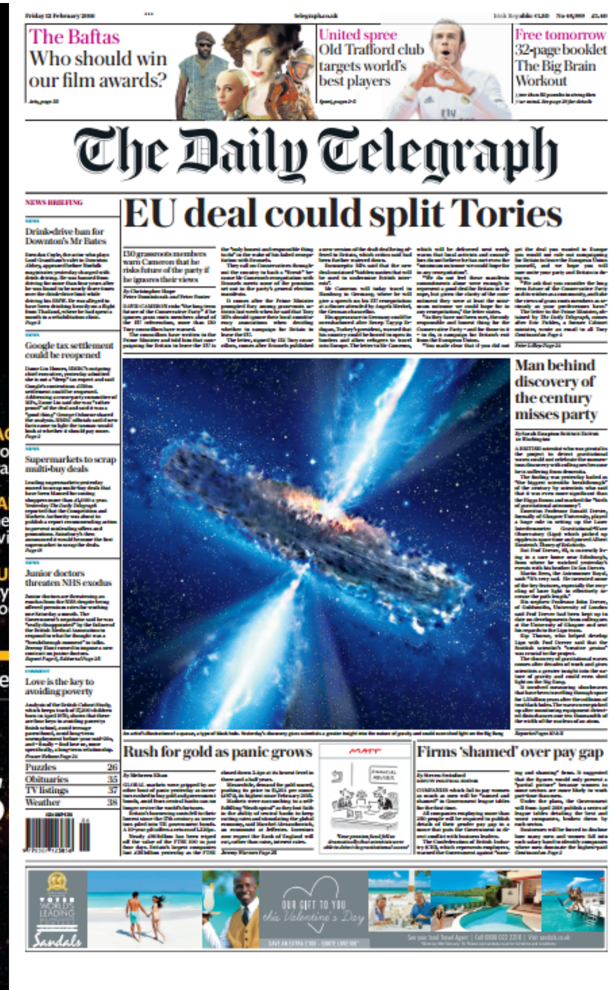
HOW CONSCIOUS ARE YOU? The number that defines self-awareness


The Baftas Who should win our film awards?

United spree Old Trafford club targets world's best players

Free tomorrow 32-page booklet The Big Brain Workout

The Daily Telegraph

EU deal could split Tories

Drink-drive ban for Downton's Mr Bates

Google tax settlement could be reopened

Supermarkets to scrap multi-buy deals

Junior doctors threaten NHS exodus

Love is the key to avoiding poverty

Man behind discovery of the century misses party

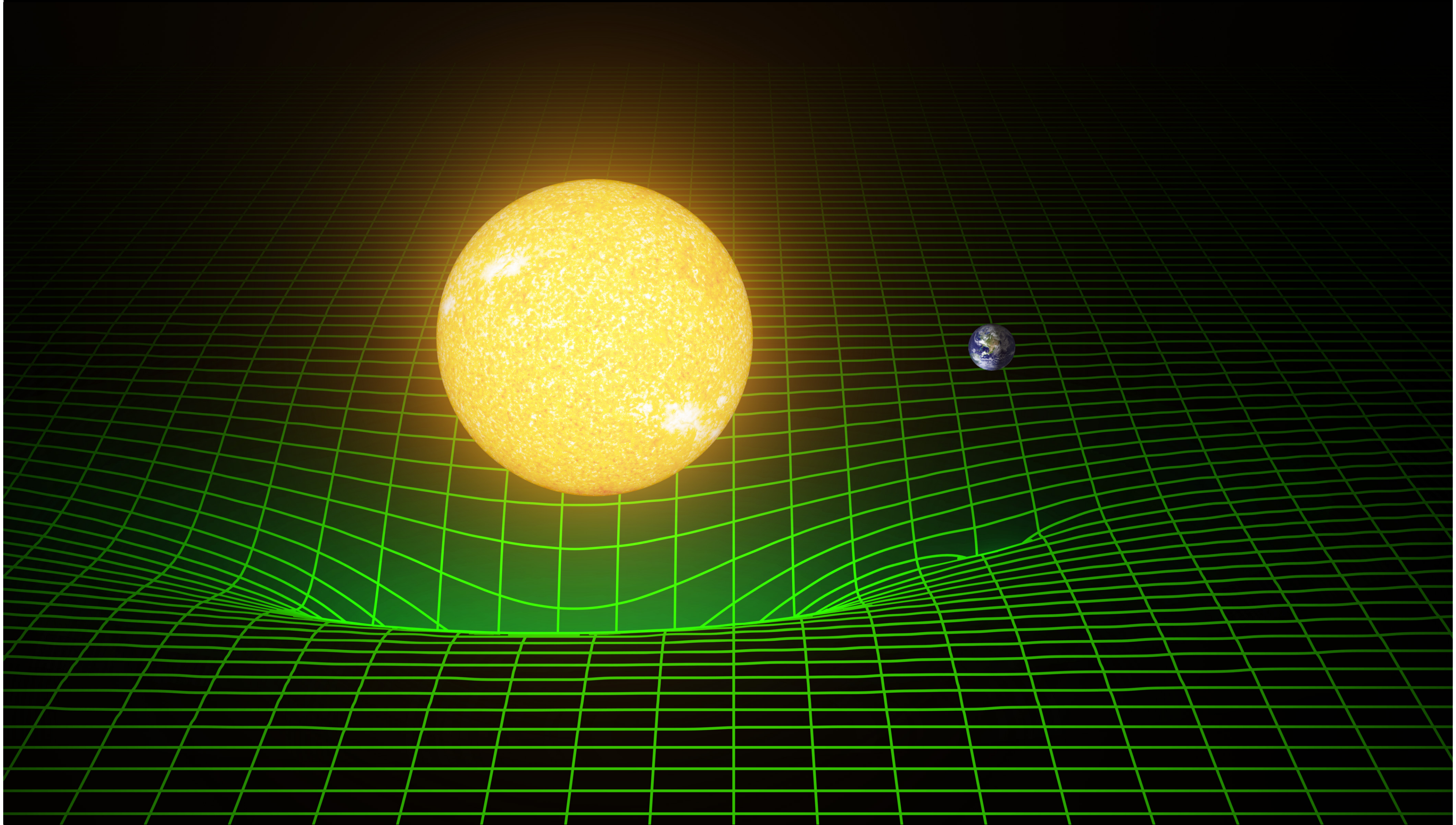
Rush for gold as panic grows

Firms 'shamed' over pay gap

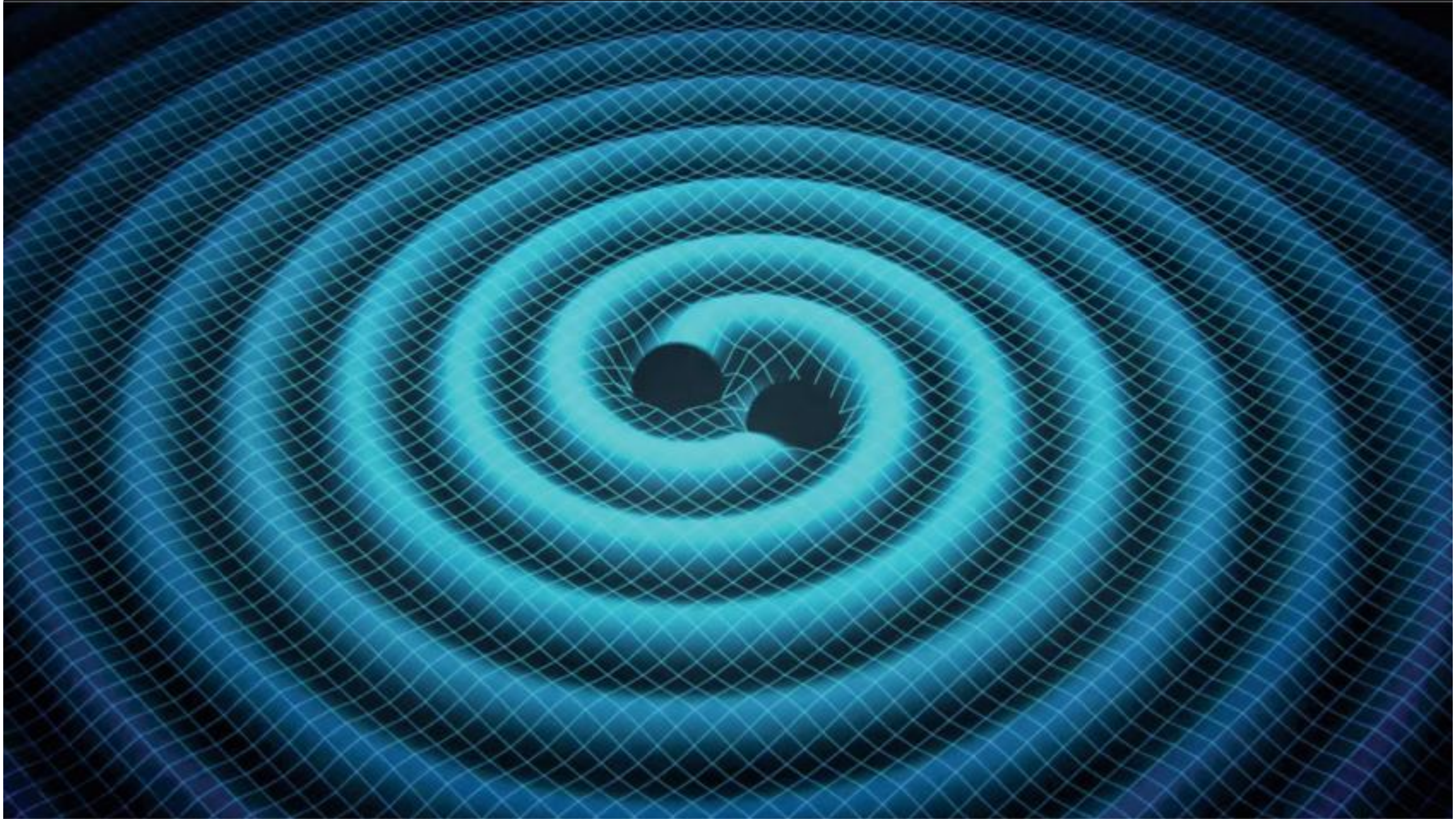
The Discovery

- First direct detection of Gravitational Waves
- First direct observation of a black hole
- First observation of a black hole binary

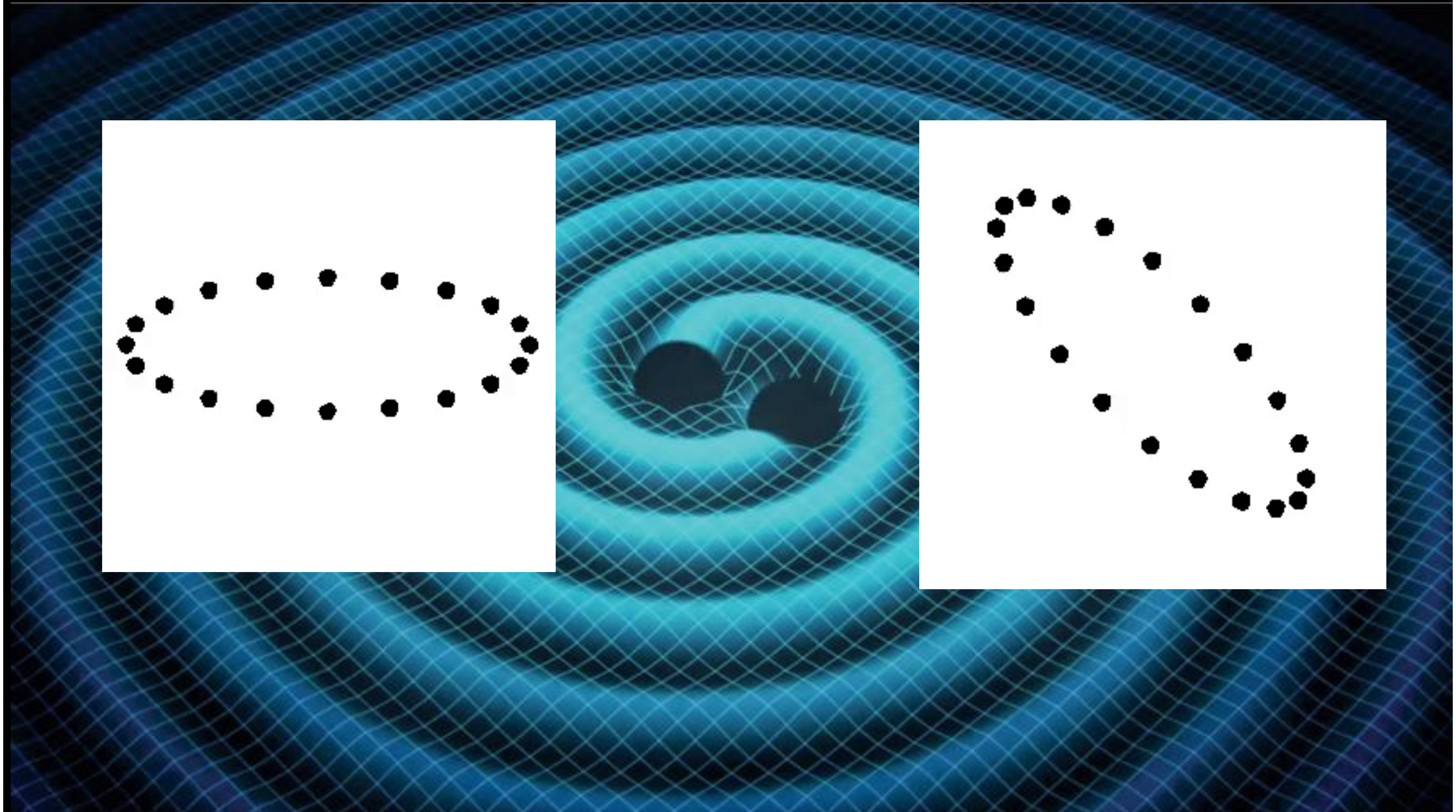
Einstein: gravity = curved spacetime



Accelerating Mass: Gravitational Waves



Accelerating Mass: Gravitational Waves



Space-time is very stiff!

Wave medium	**elastic modulus (Gpa)**
rubber	0.1
wood	10
steel	200
diamond	1200
spacetime	10^{24}

The Hard Truth

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h_{ab} = -\frac{16\pi G}{c^4} T_{ab}$$

source (mass, energy)

wave operator

GW

coupling constant (10^{-42} / N)

wave amplitude:

$$h \approx \frac{G}{c^4}\frac{MR^2\Omega^2}{r}$$

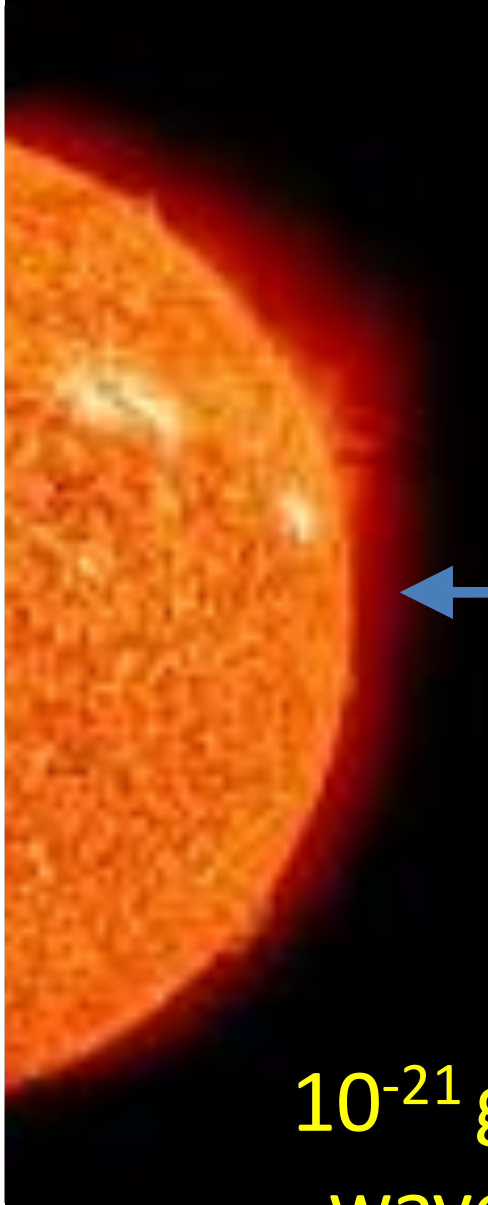
ridiculously small

The Challenge

- Strongest GW sources are rapidly rotating dumb-bells (binaries).
- Maximum strain from a neutron-star binary merger in a nearby galaxy: 10^{-21}

NASA/Swift/Dana Berry

The Challenge



Sun – Earth distance: 150 million km

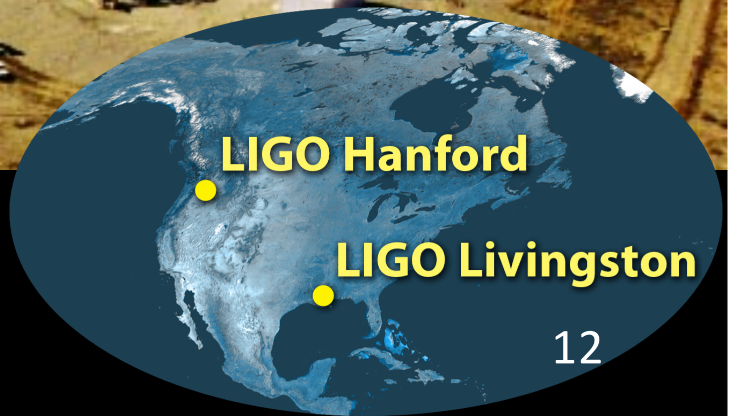
10^{-21} gravitational wave stretching: size of an atom!

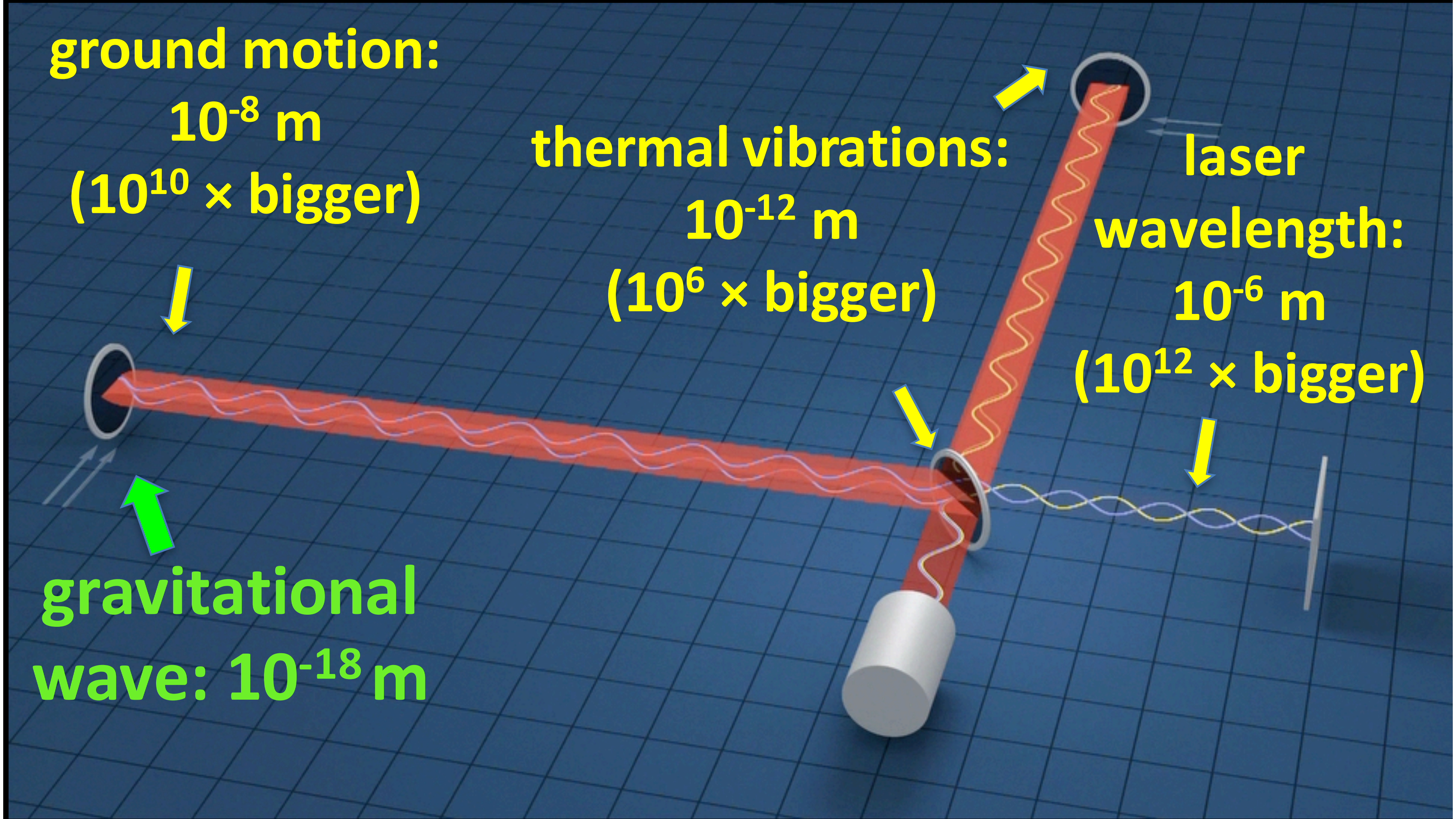
LIGO Livingston Observatory

LIGO Hanford Observatory

The Challenge:

few x 10^{-22} change in length of a LIGO arm: 10^{-18} m



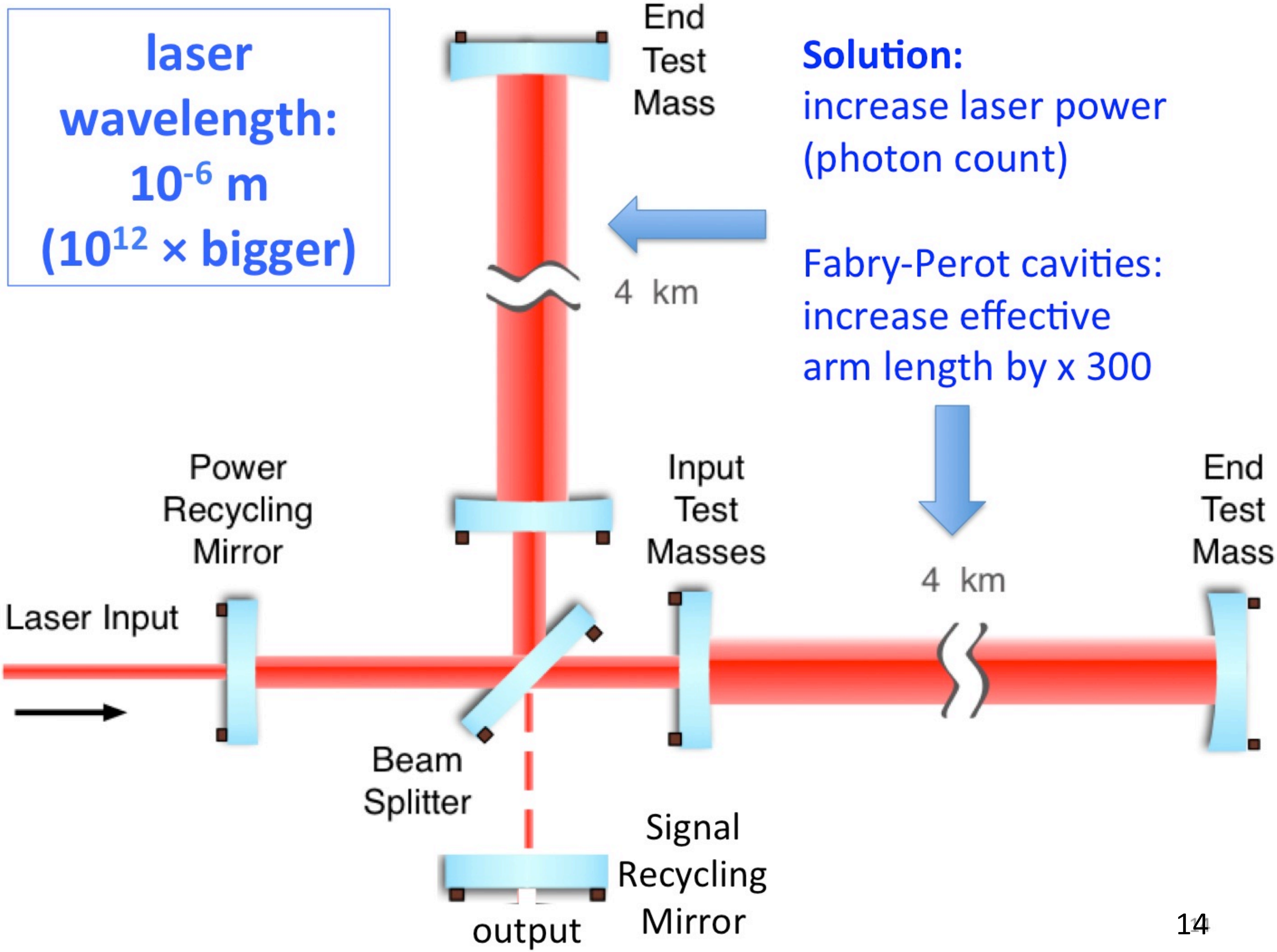


ground motion:
10^{-8} m
(10^{10} × bigger)
thermal vibrations:
10^{-12} m
(10^{6} × bigger)
laser
wavelength:
10^{-6} m
(10^{12} × bigger)
gravitational
wave: 10^{-18} m

laser wavelength: 10^{-6} m (10^{12} × bigger)

Solution:
increase laser power (photon count)

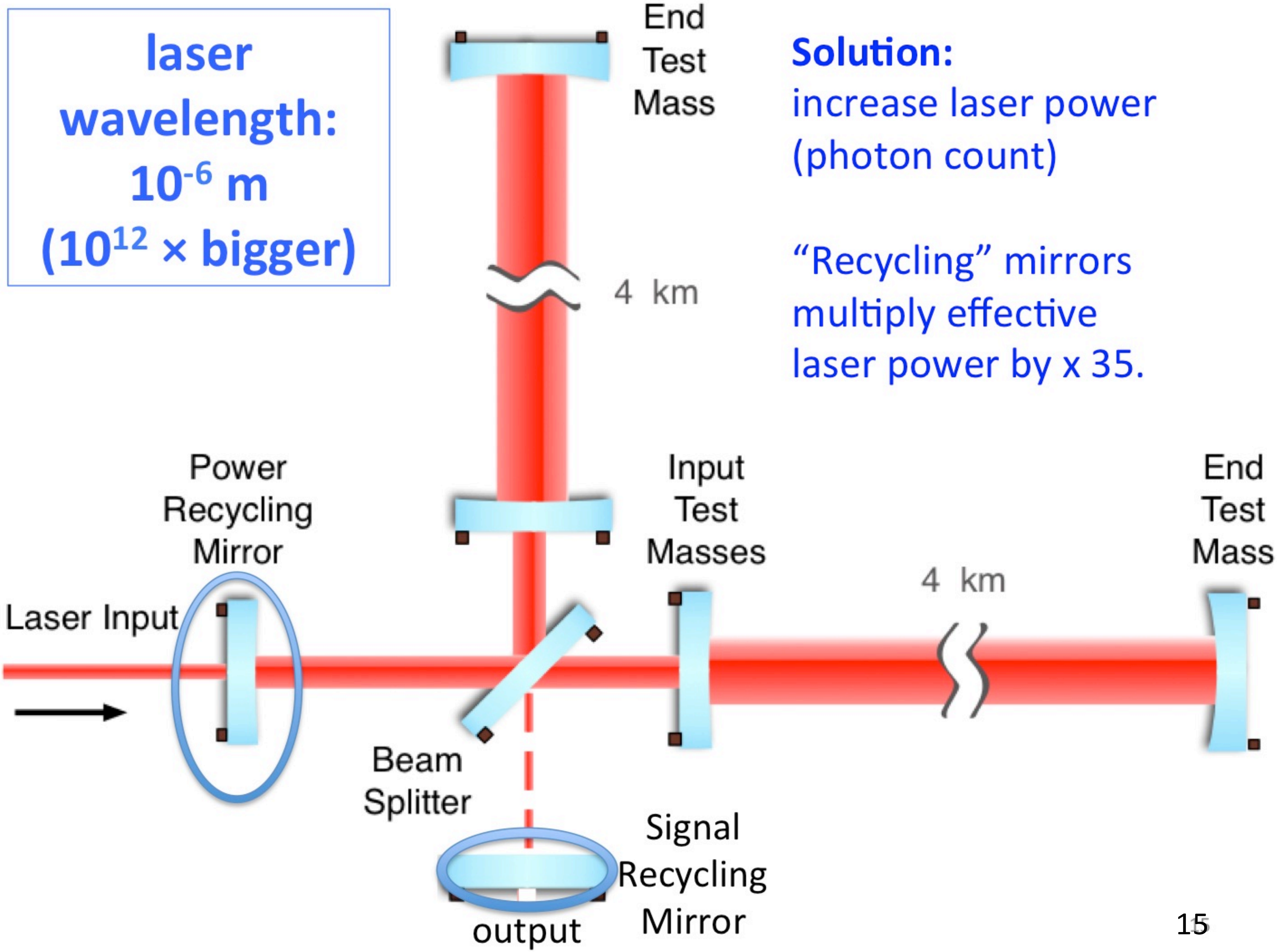
Fabry-Perot cavities: increase effective arm length by x 300



laser wavelength: 10^{-6} m ($10^{12} \times$ bigger)

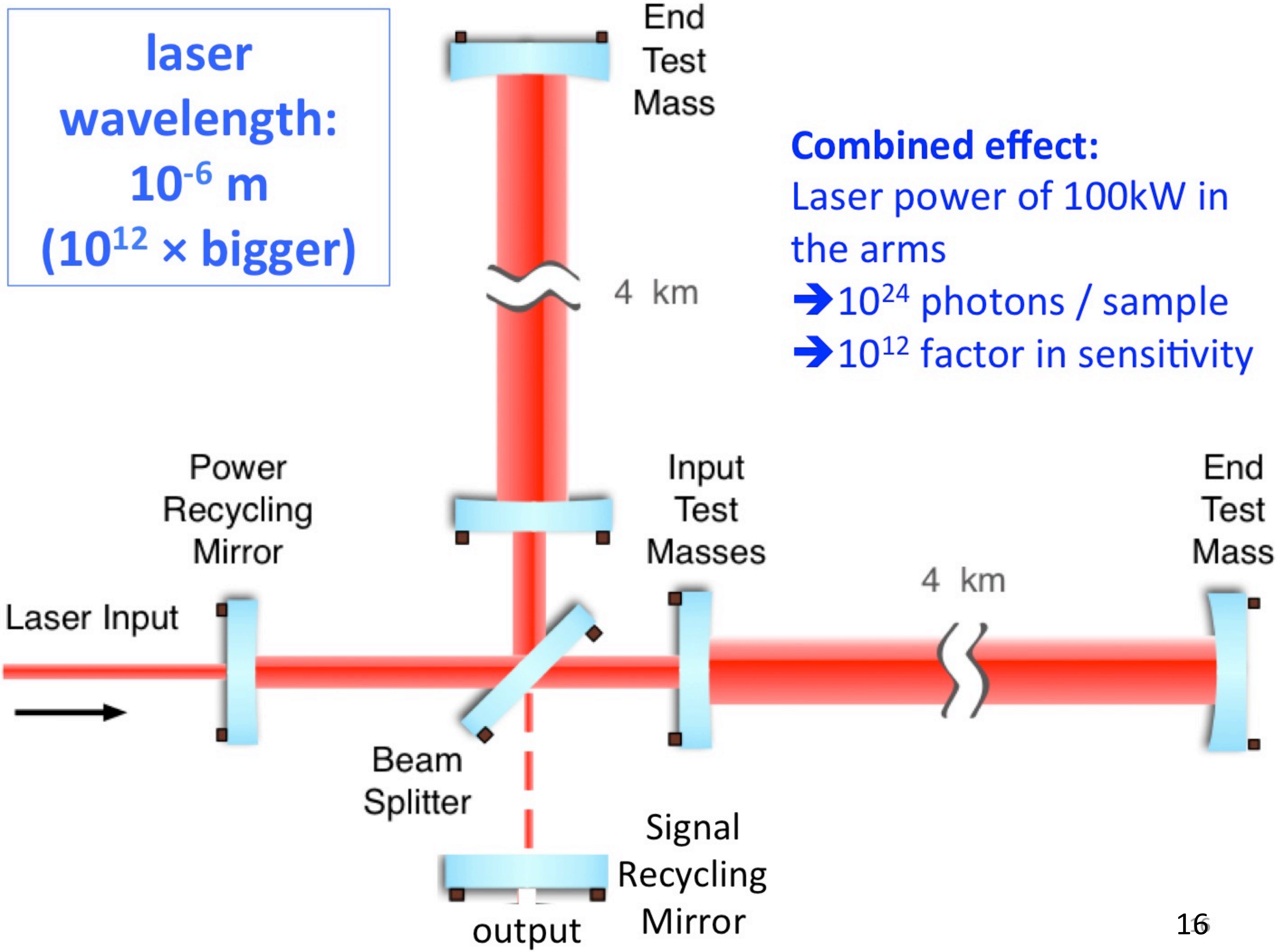
Solution:
increase laser power (photon count)

"Recycling" mirrors multiply effective laser power by x 35.

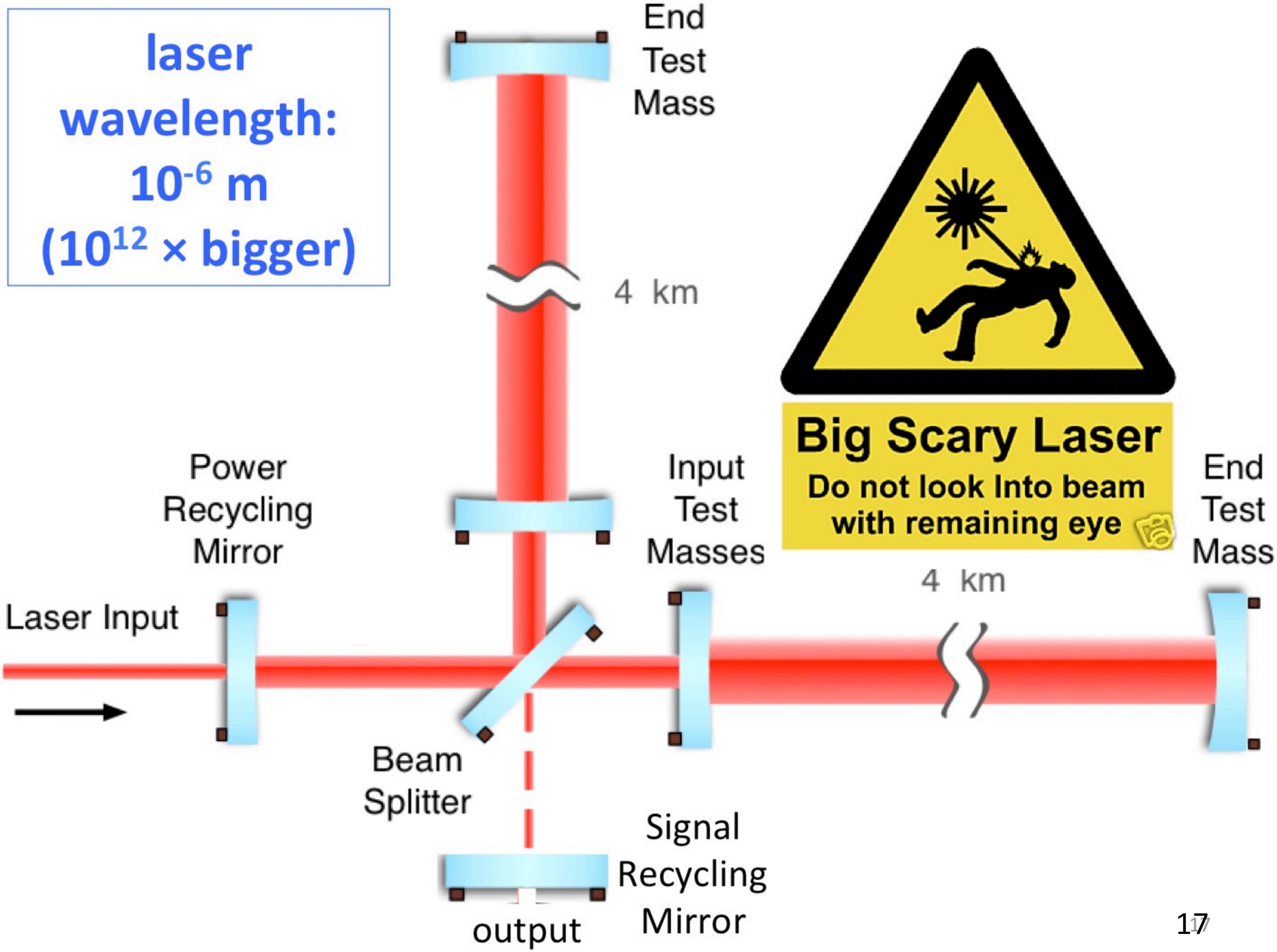


laser wavelength: 10^{-6} m (10^{12} × bigger)

Combined effect:
Laser power of 100kW in the arms
→10^{24} photons / sample
→10^{12} factor in sensitivity



laser wavelength:
10^{-6} m
(10^{12} × bigger)

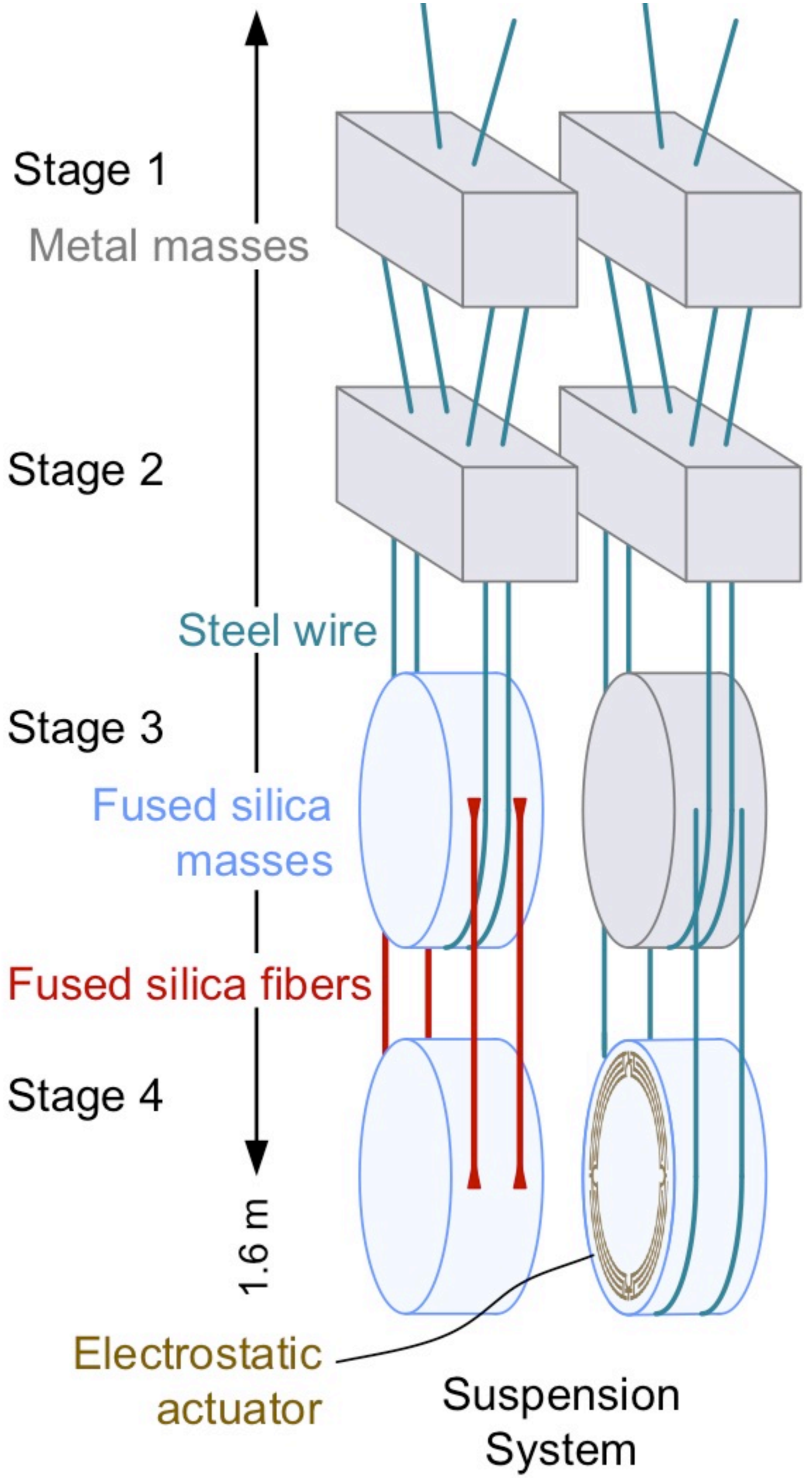


ground motion:
10^{-8} m
(10^{10} × bigger)

Quadruple pendulum suspension system: **10^7**

+

Active seismic isolation: **10^3**

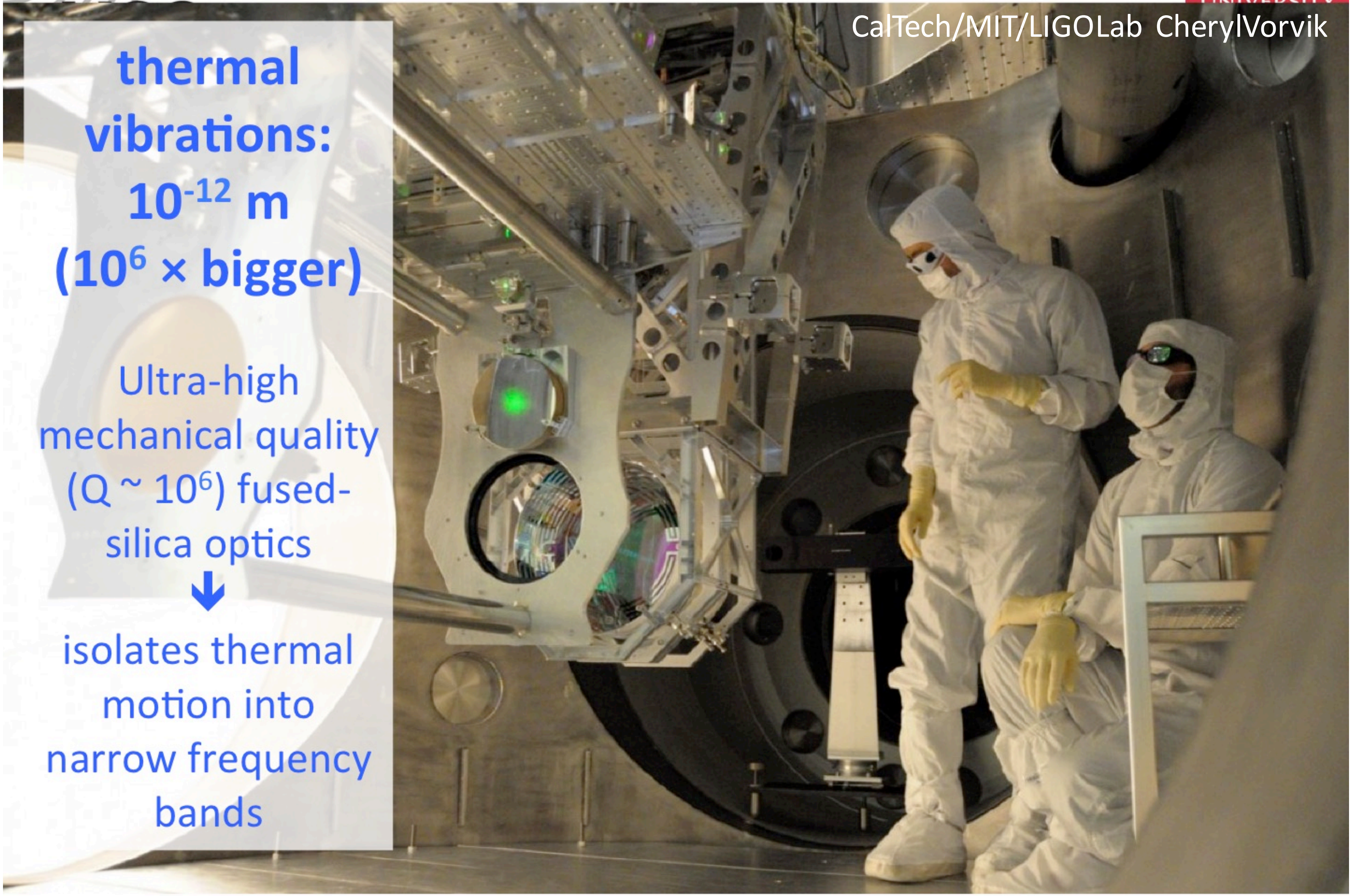


thermal vibrations: 10^{-12} m ($10^6 \times$ bigger)

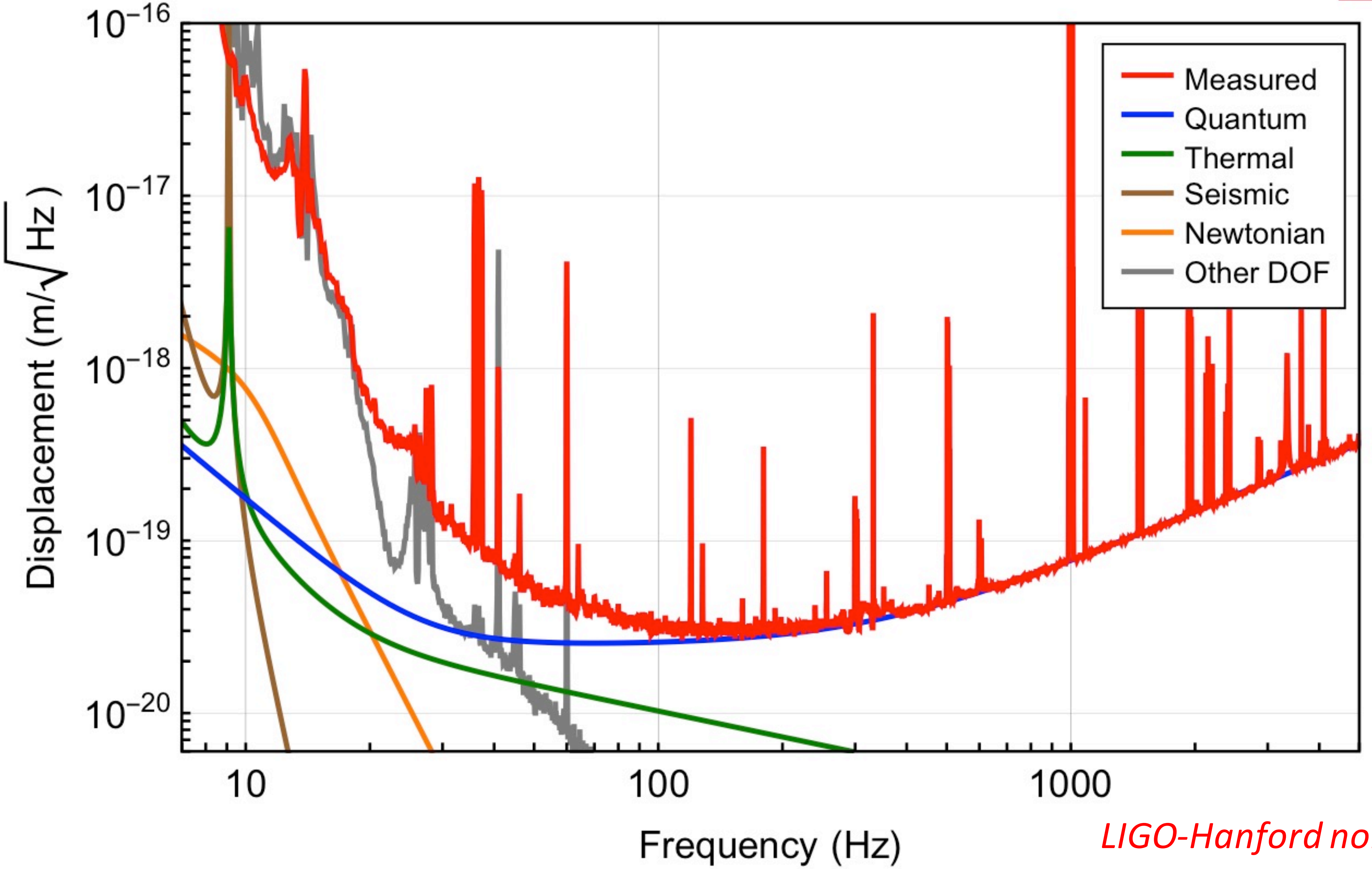
Ultra-high mechanical quality ($Q \sim 10^6$) fused-silica optics

↓

isolates thermal motion into narrow frequency bands



The Final Result!

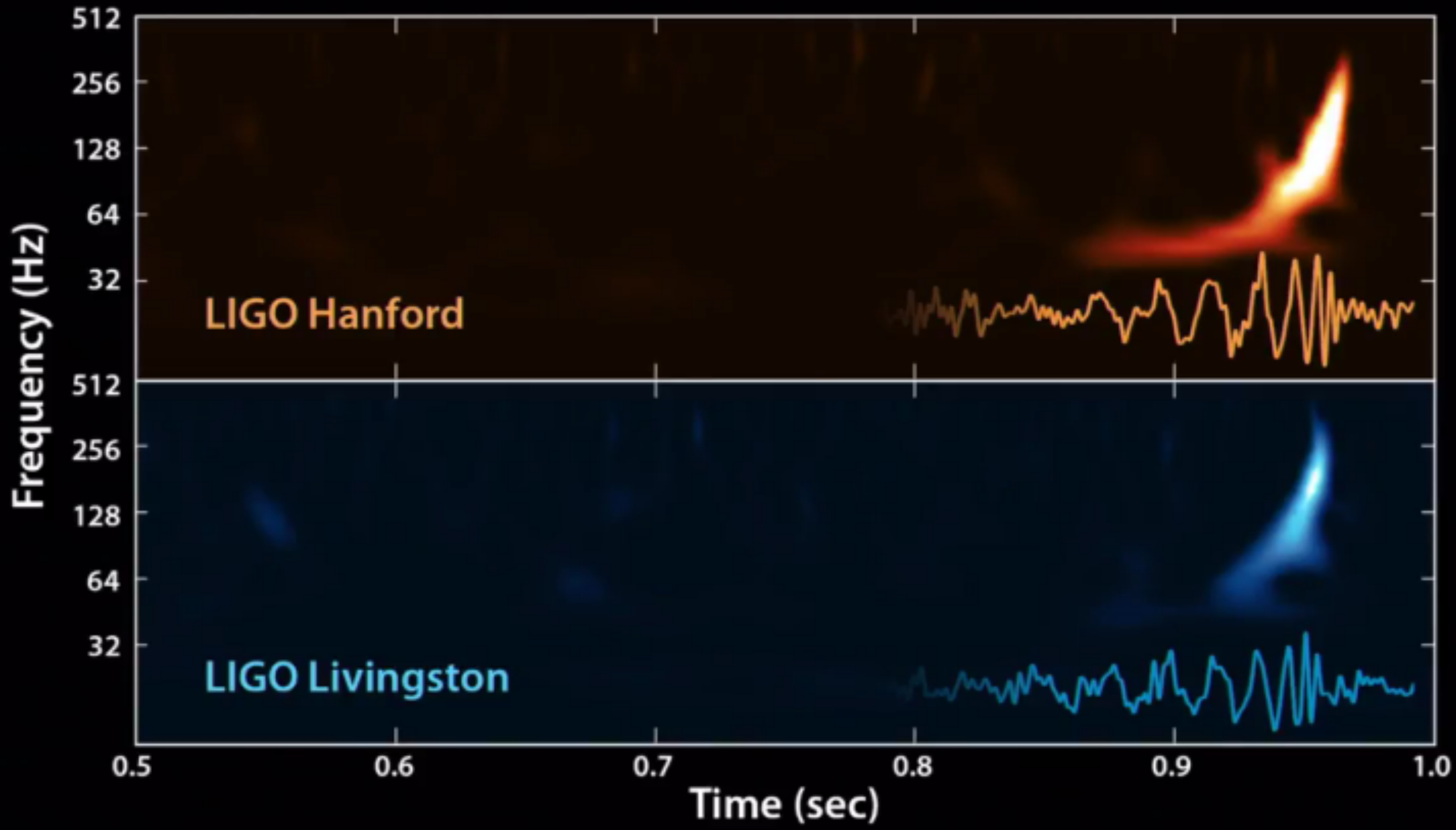


LIGO-Hanford noise spectrum

GW150914

- Mid-September 2015: final stages of preparation for first Advanced LIGO observing run (O1).
- The very last step is a short "Engineering Run," during which on Sept 14 our online monitor recorded GW150914.
- We identified the signal within 3 minutes.
- We responded by starting the data run officially, keeping all settings fixed and ran for 16 live days coincidence time (long enough to assess background levels, etc)
- We report on that data, including GW150914.

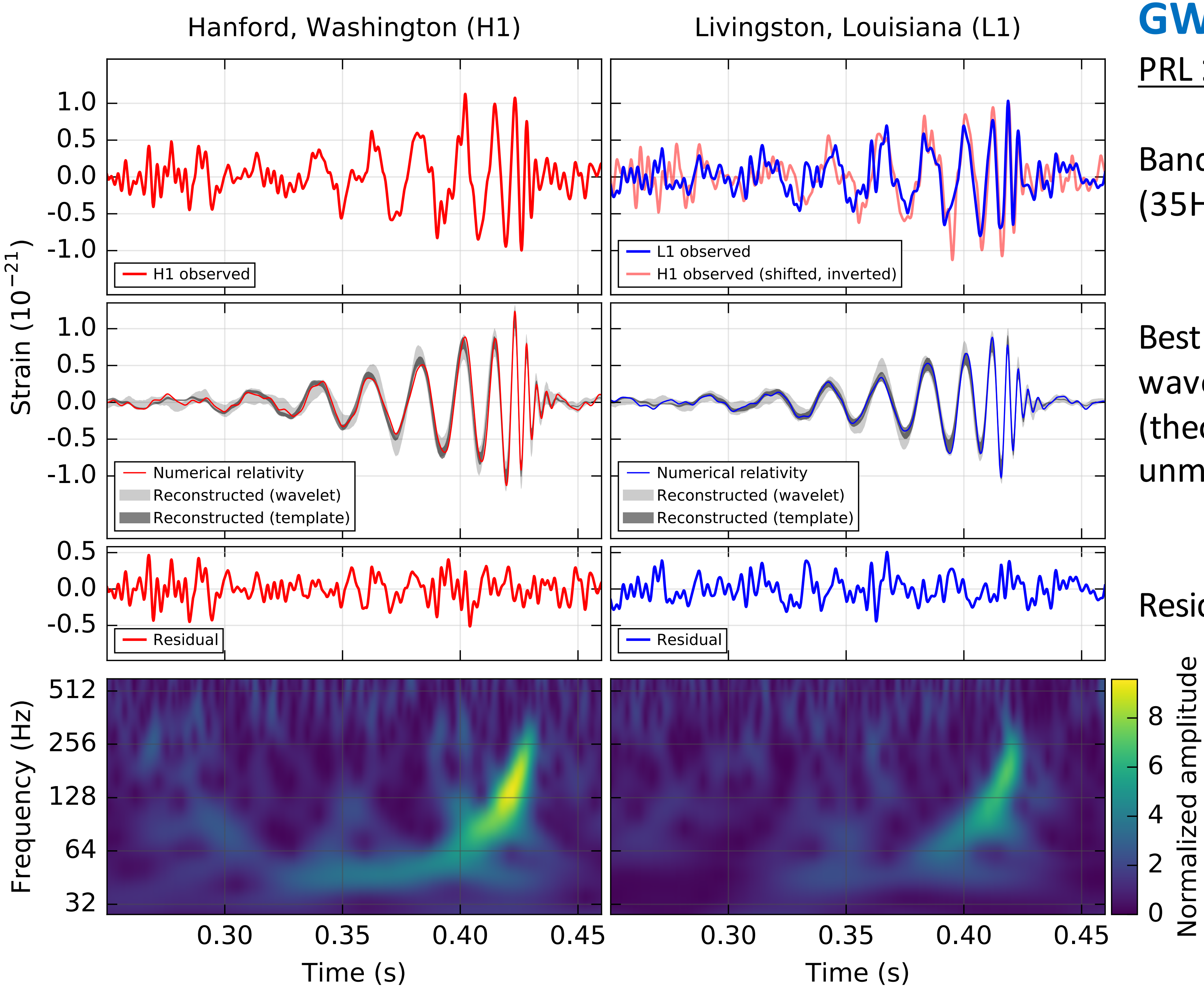
- O1 continued data taking until 19 Jan 2016 and will report on those results, as soon as the data analysis is complete.



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)

GW150914

PRL **116** 061102



Band-passed data (35Hz - 350 Hz)

Best fit waveforms (theoretical & unmodelled)

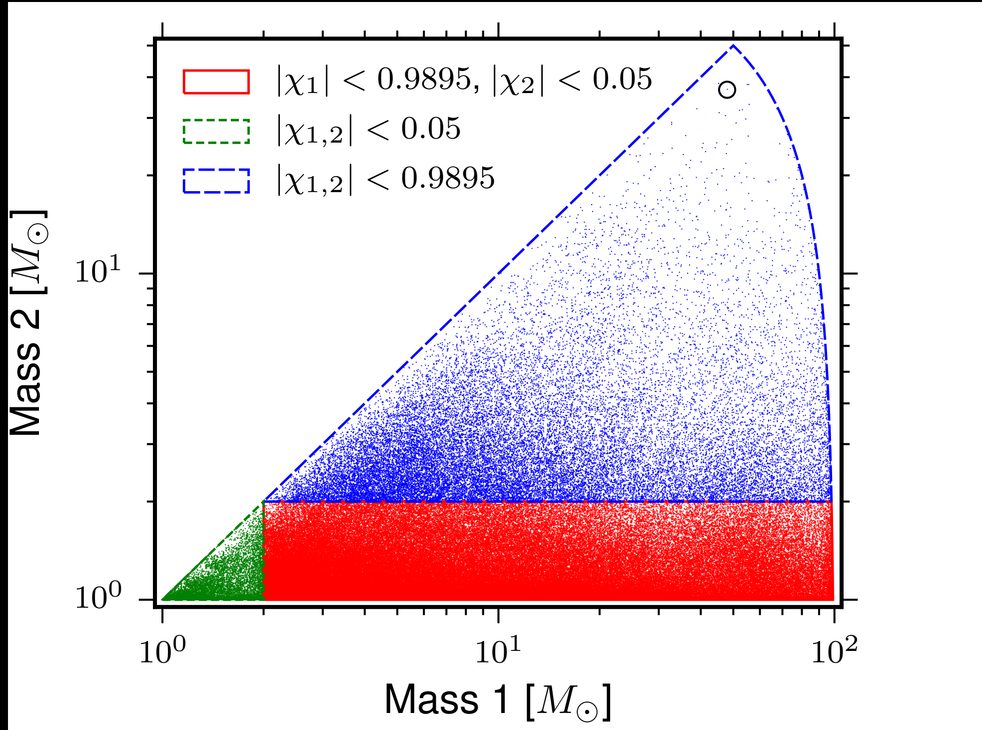
Residuals

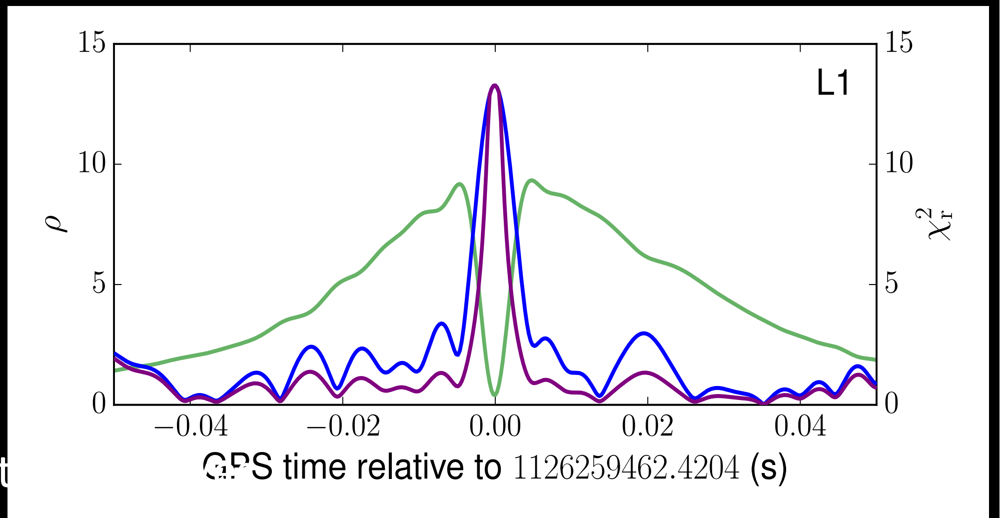
Time-frequency plot

Binary merger search

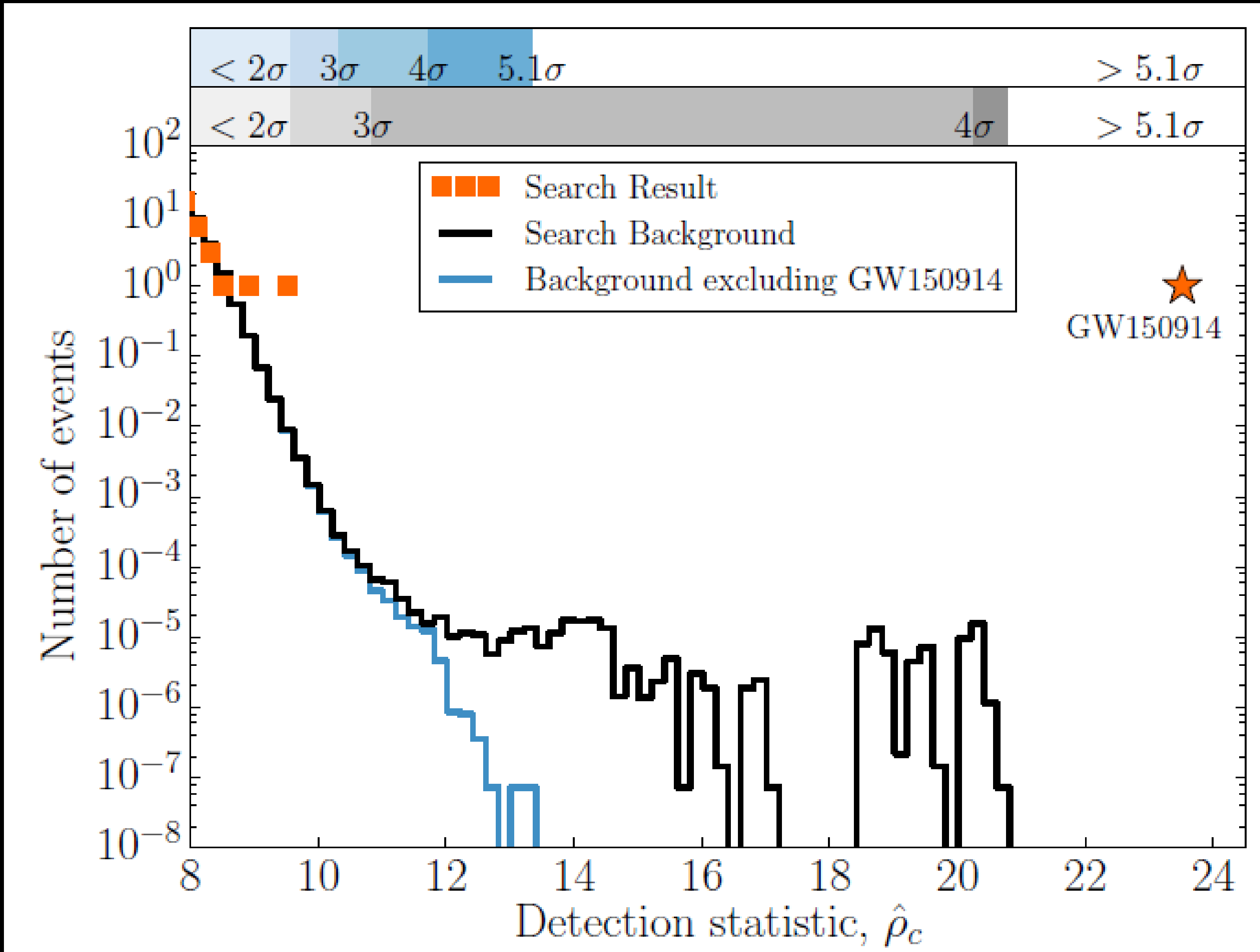
Abbott et al., 1602.03839

- Use known waveforms to search for binary signals.
- Calculate matched filter signal to noise as function of time ρ(t), identify maxima, and weight by a χ2 consistency measure.
- Require coincidence between detectors within 15 msec.
- Detection statistic: quadrature sum of the signal to noise in each detector.
- Background: Time shift by multiples of 0.1 seconds and repeat search.





Statistical Significance of GW150914



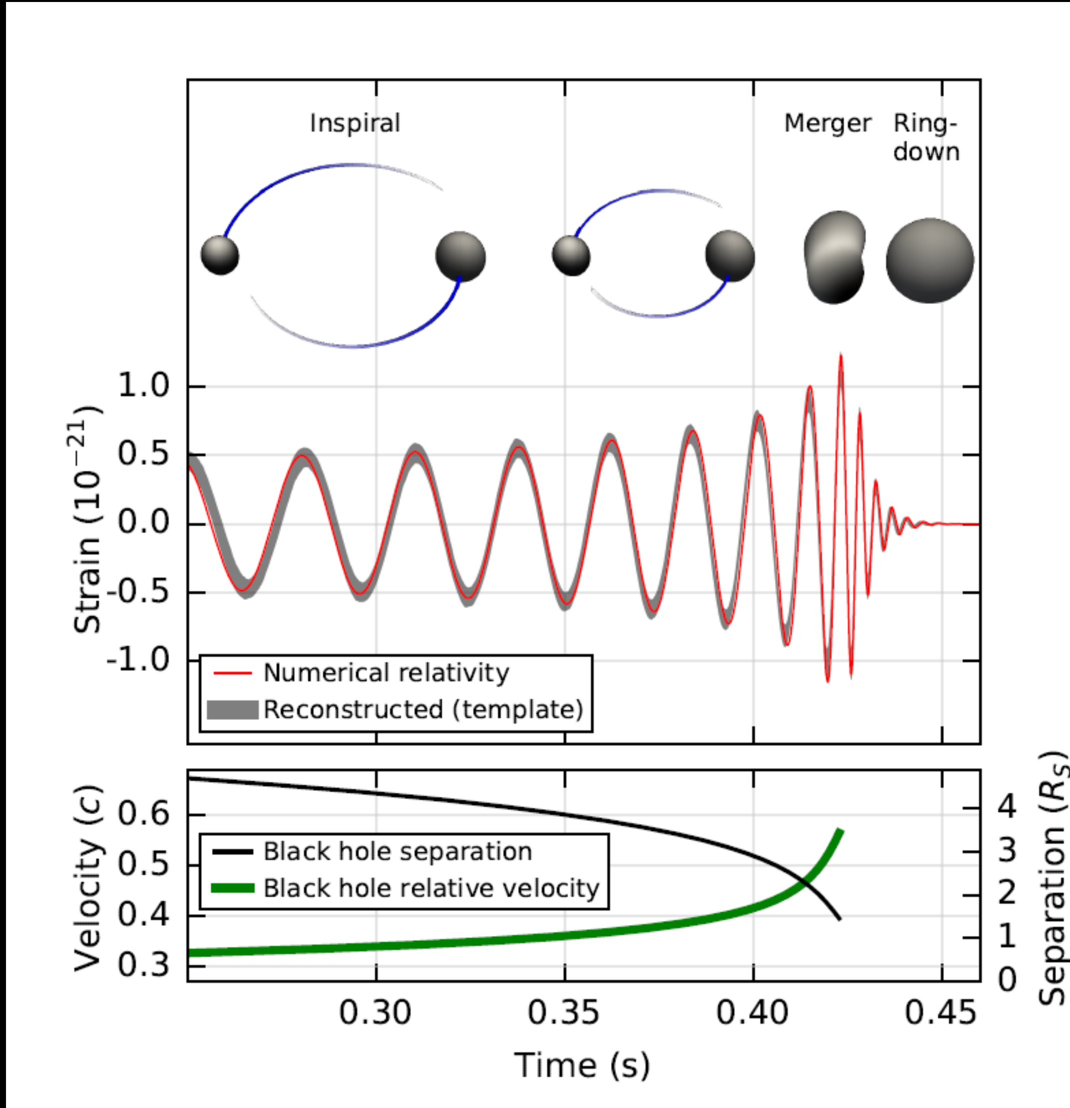
A Black Hole Binary

Abbott et al., PRL **116** 061102

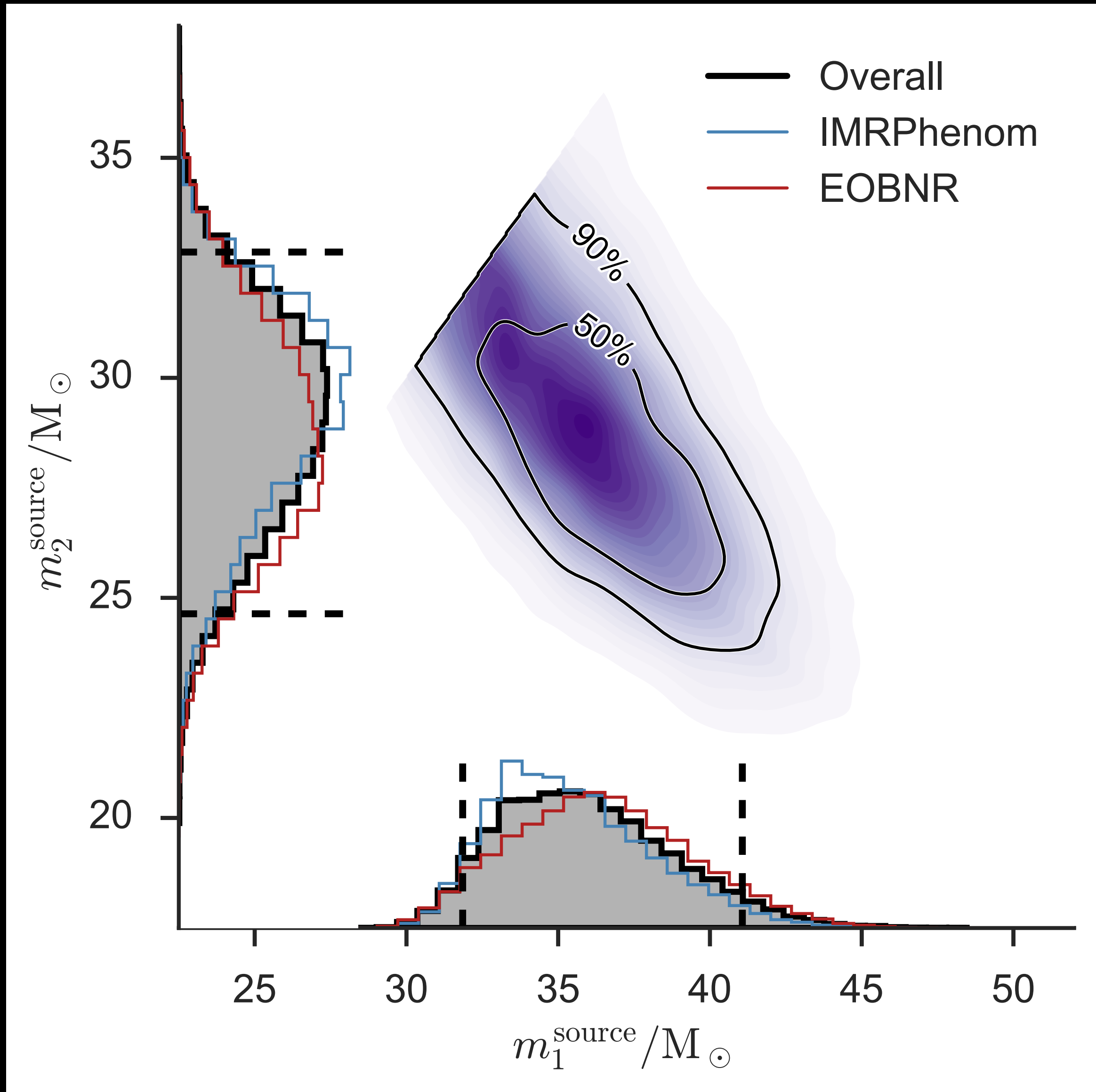
- Orbital decay via GW emission determined by the “chirp mass”

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$$

- Total mass is greater than 60 $M_\odot$.
- Bodies orbit until centres are separated by only 350 km, moving at half the speed of light.

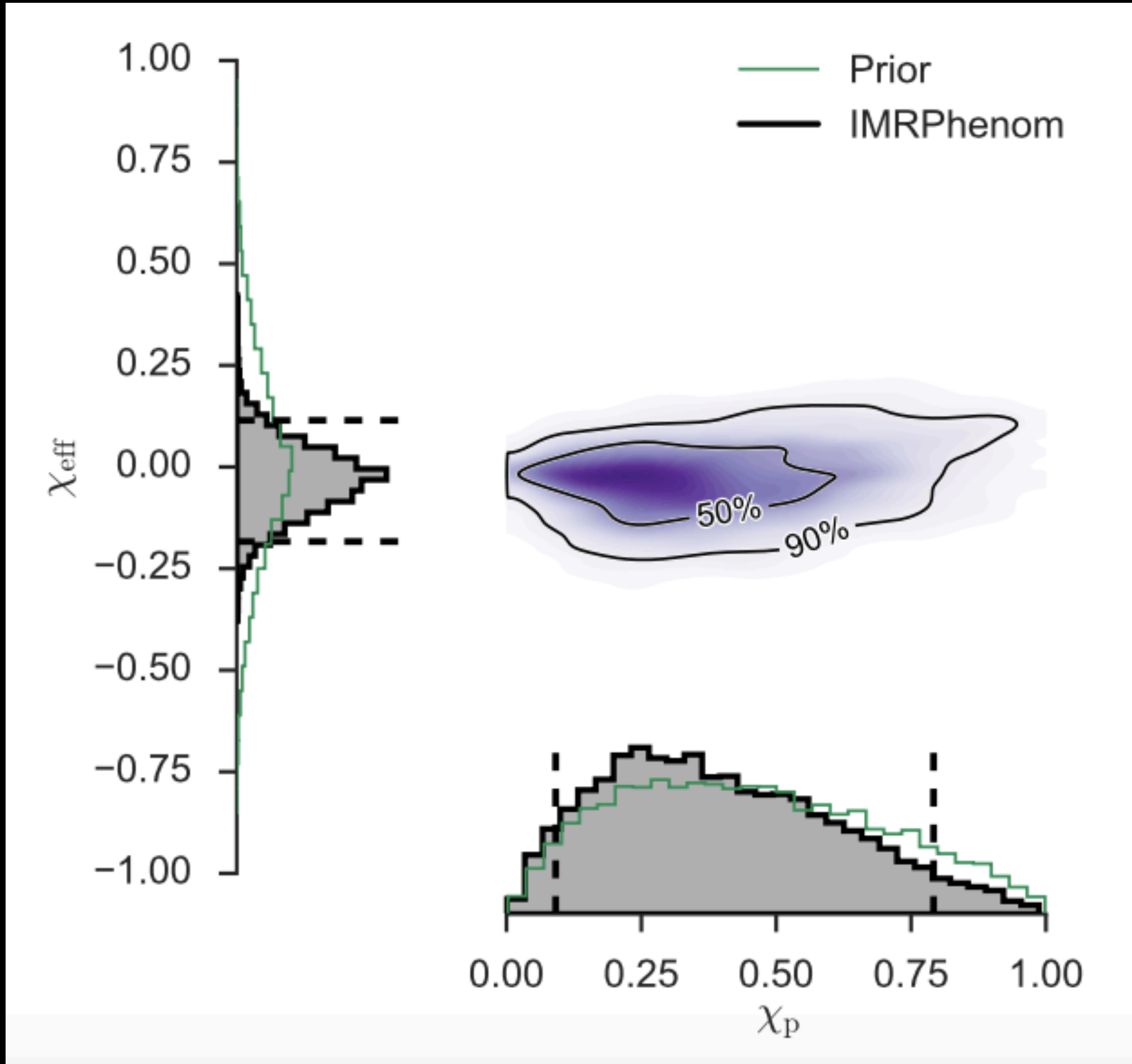


Black Hole Masses



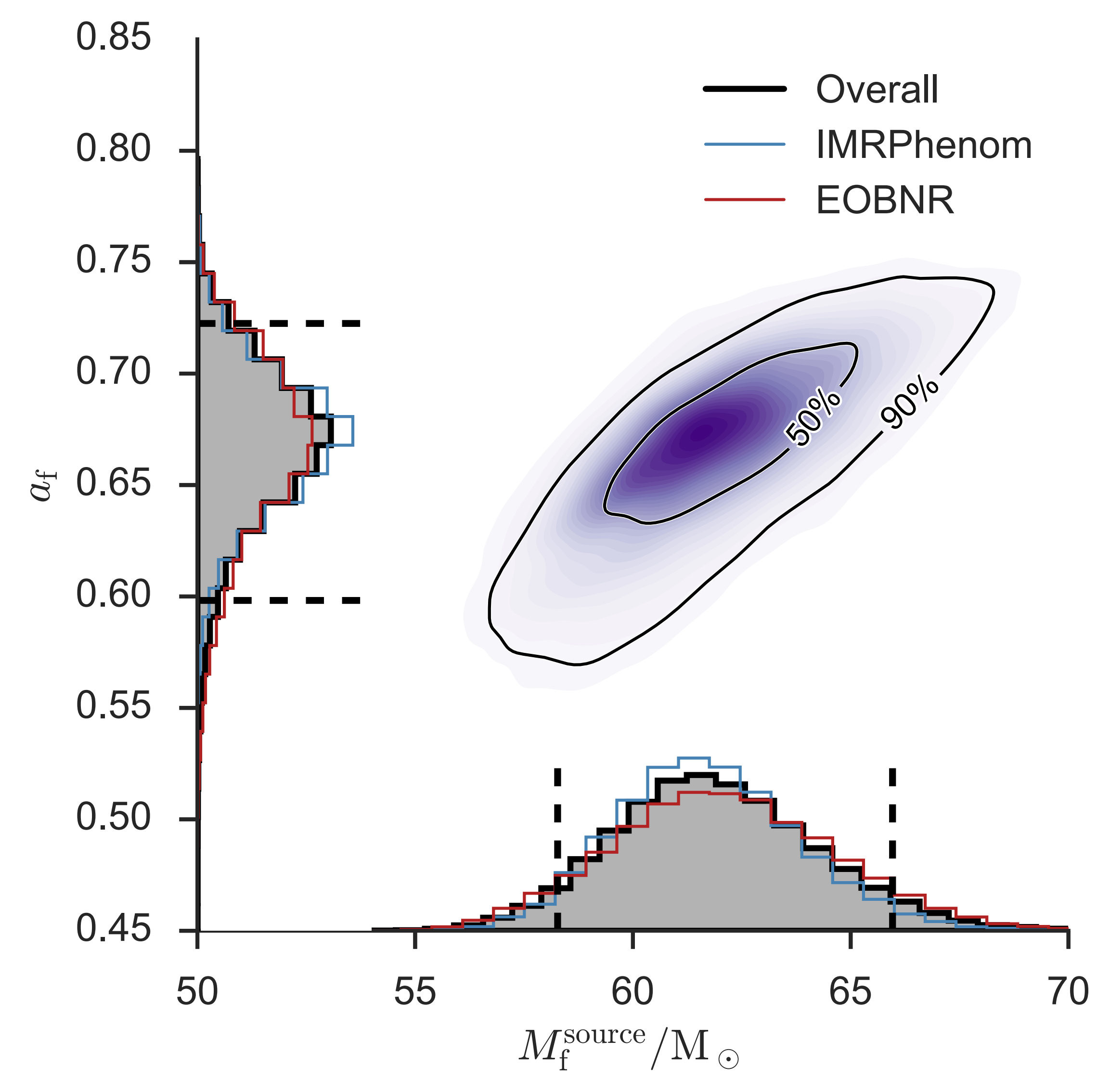
Abbott et al., 1602.03840

Black Hole Spins

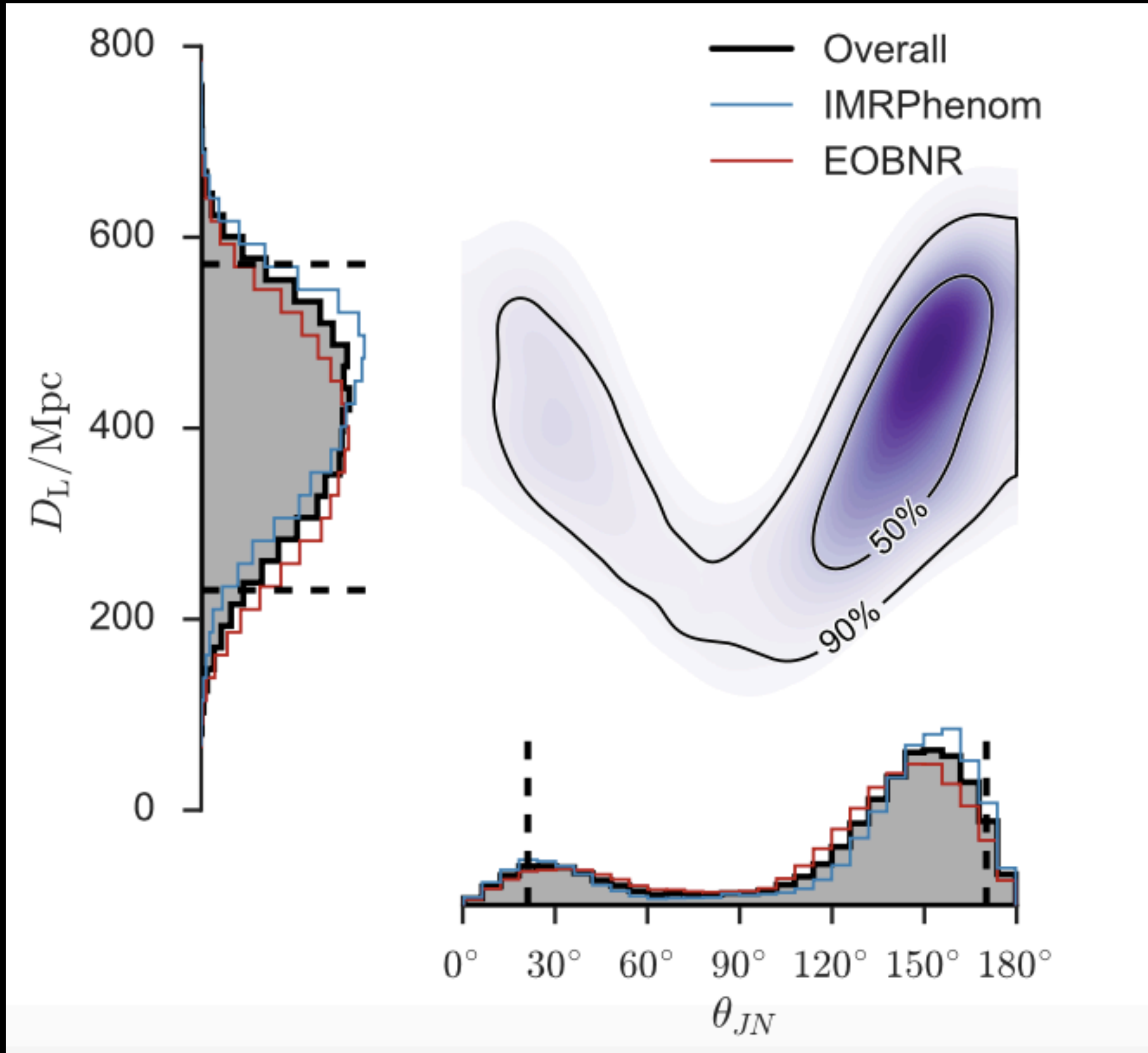


Abbott et al., 1602.03840

Final Black Hole Spin & Mass



Distance & Inclination

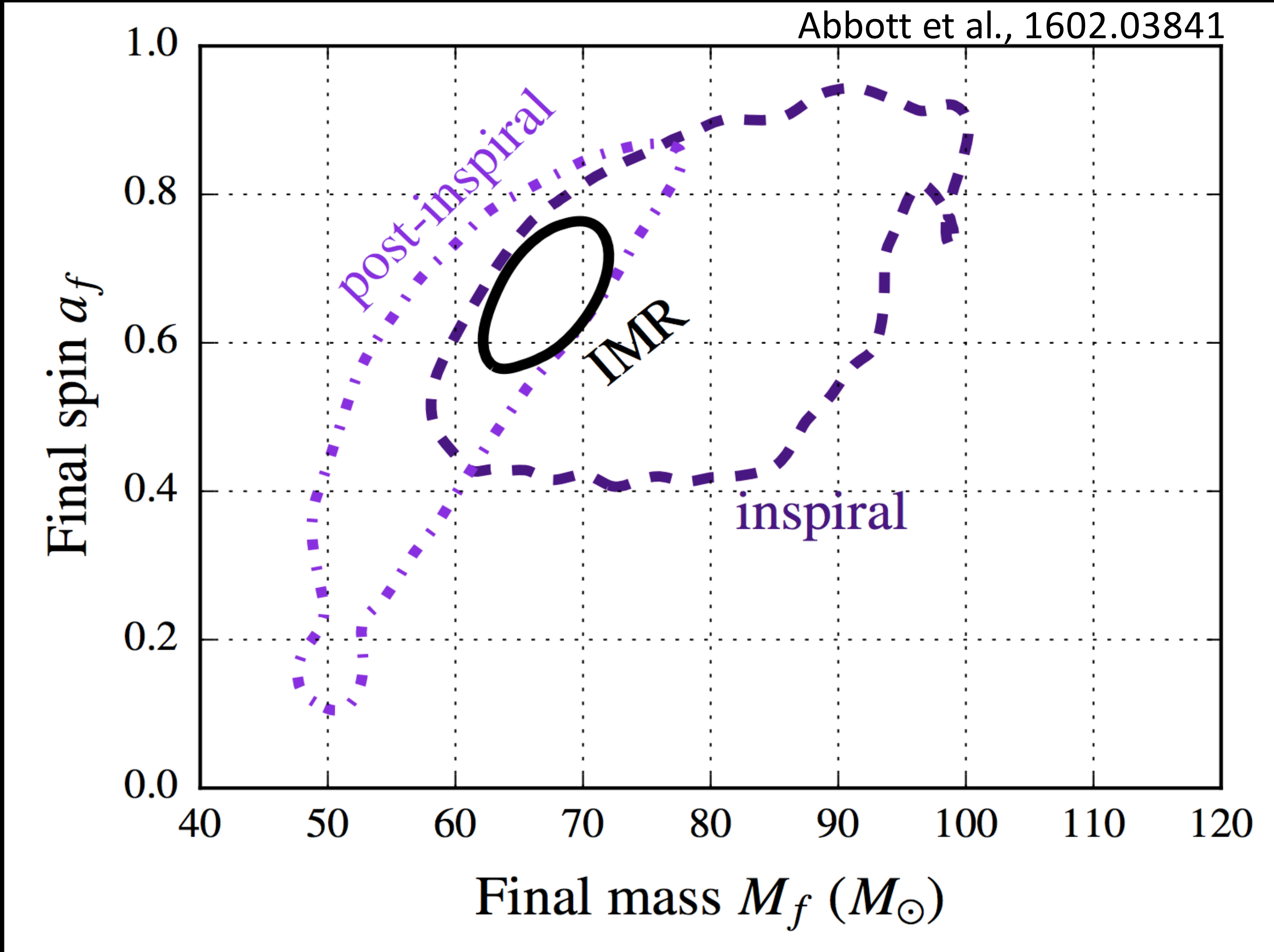


Primary black hole mass	$36^{+5}_{-4}\ M_\odot$
Secondary black hole mass	$29^{+4}_{-4}\ M_\odot$
Final black hole mass	$62^{+4}_{-4}\ M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

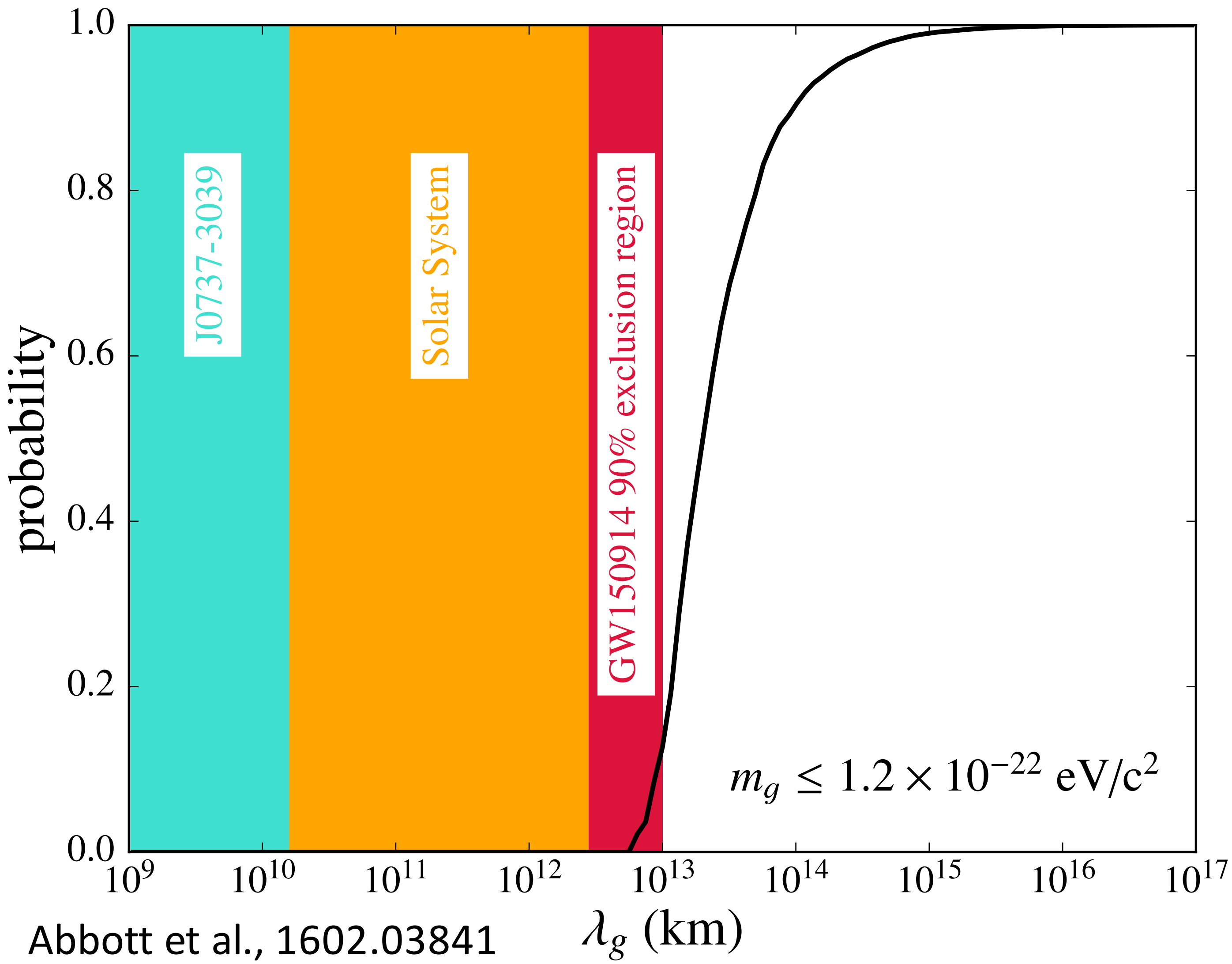
Total energy emitted: $3\ M_\odot$

Peak luminosity: $200\ M_\odot/s$ (3.6×10^{56} erg/s).

Testing General Relativity

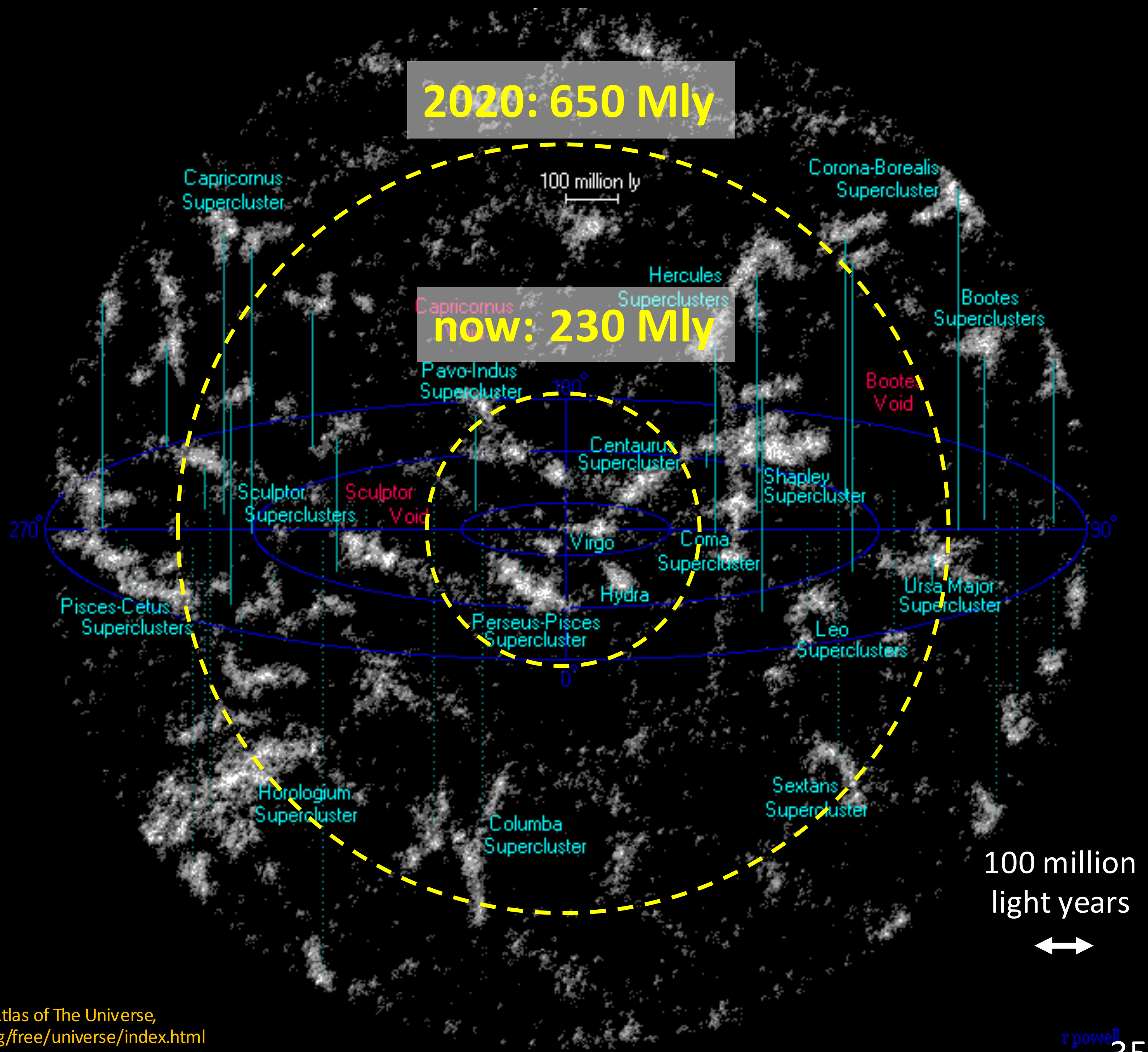


Compton Wavelength of the Graviton



Abbott et al., 1602.03841

What Next?



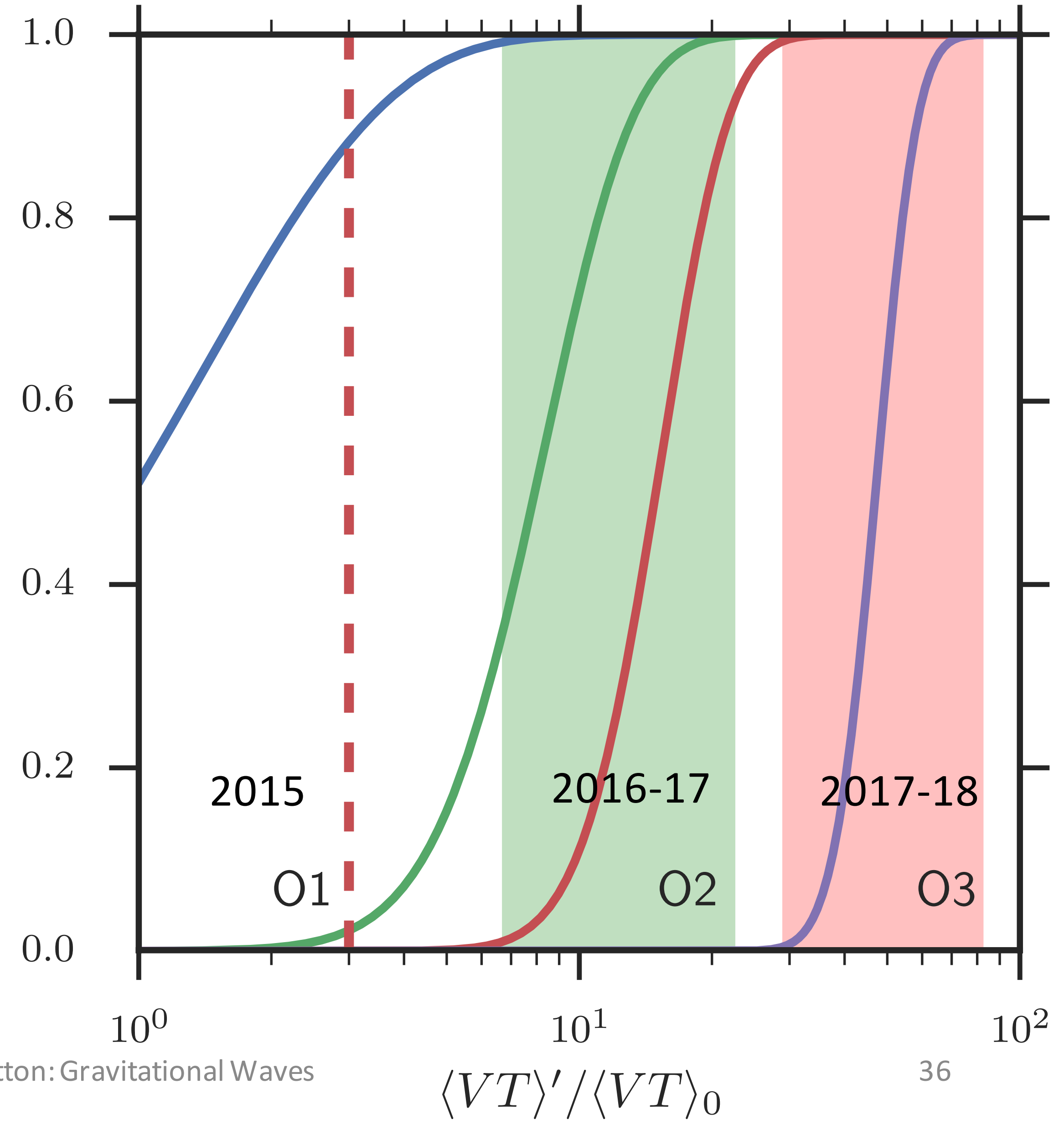
Images: R. Powell, The Atlas of The Universe,
http://www.anzwers.org/free/universe/index.html

Expectations for future runs

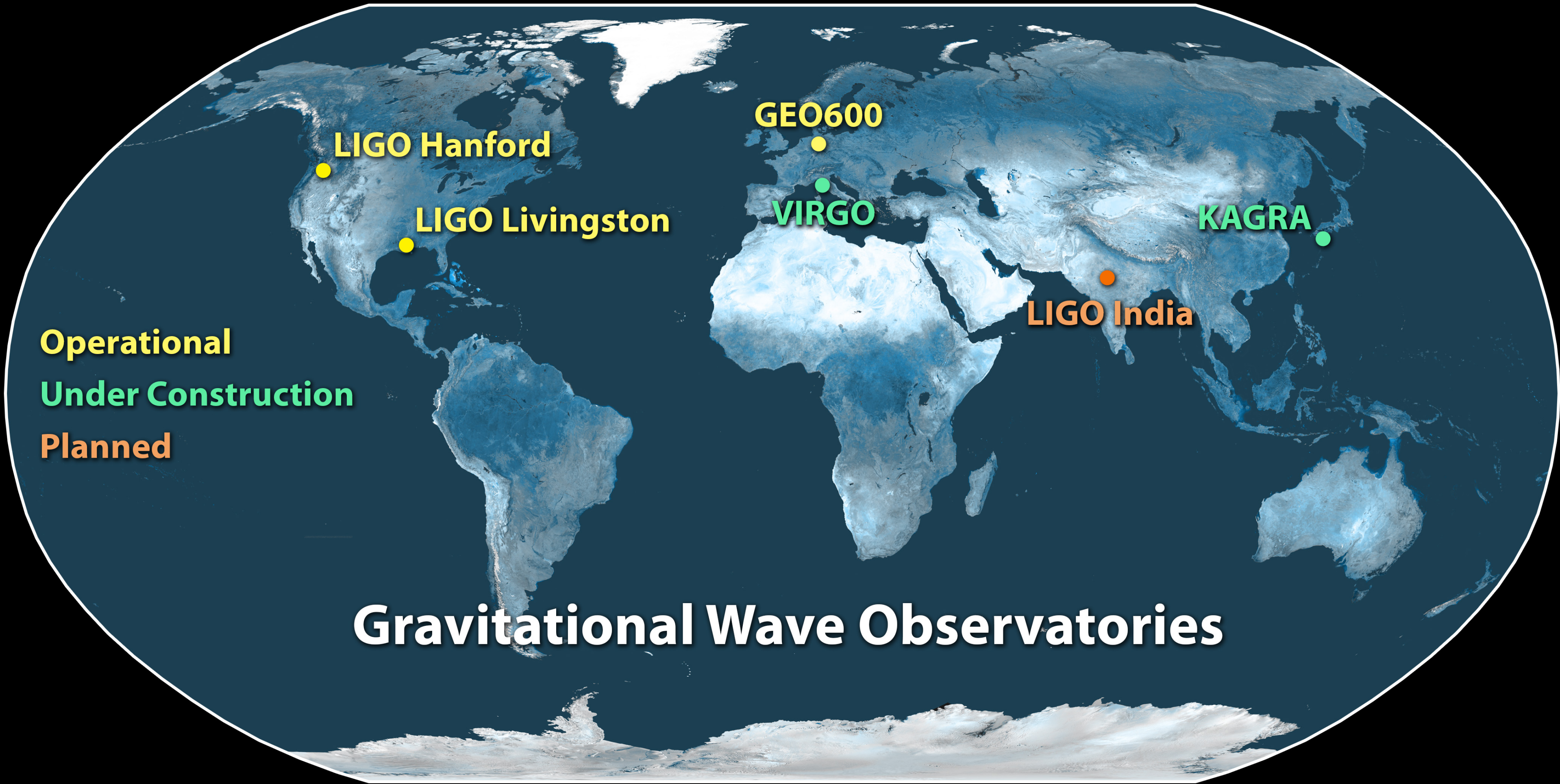
Probability of observing

- N > 0 (blue)
- N > 5 (green)
- N > 10 (red)
- N > 35 (purple)

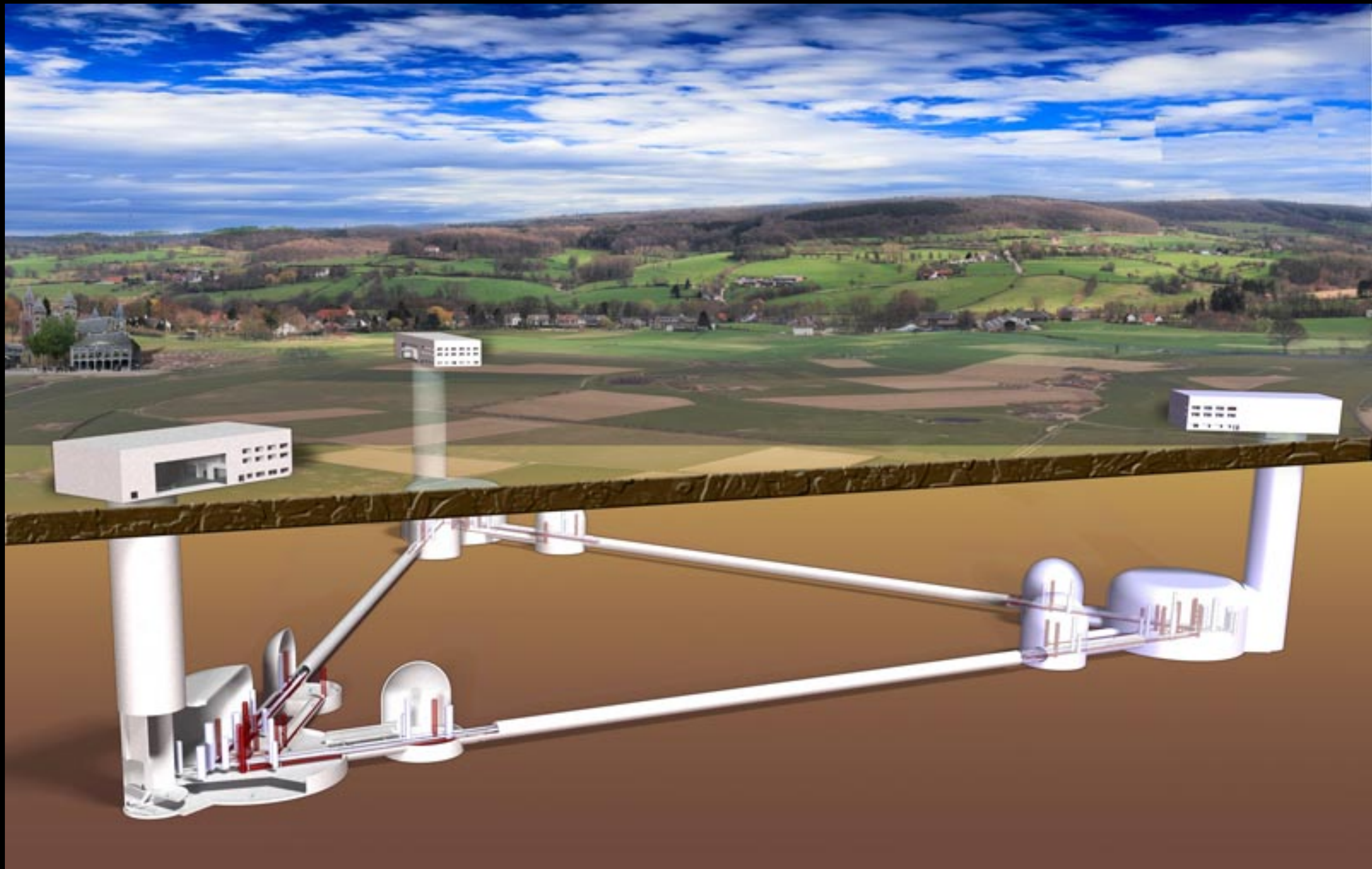
highly significant events, as a function of surveyed time-volume.



Expanded Detector Network

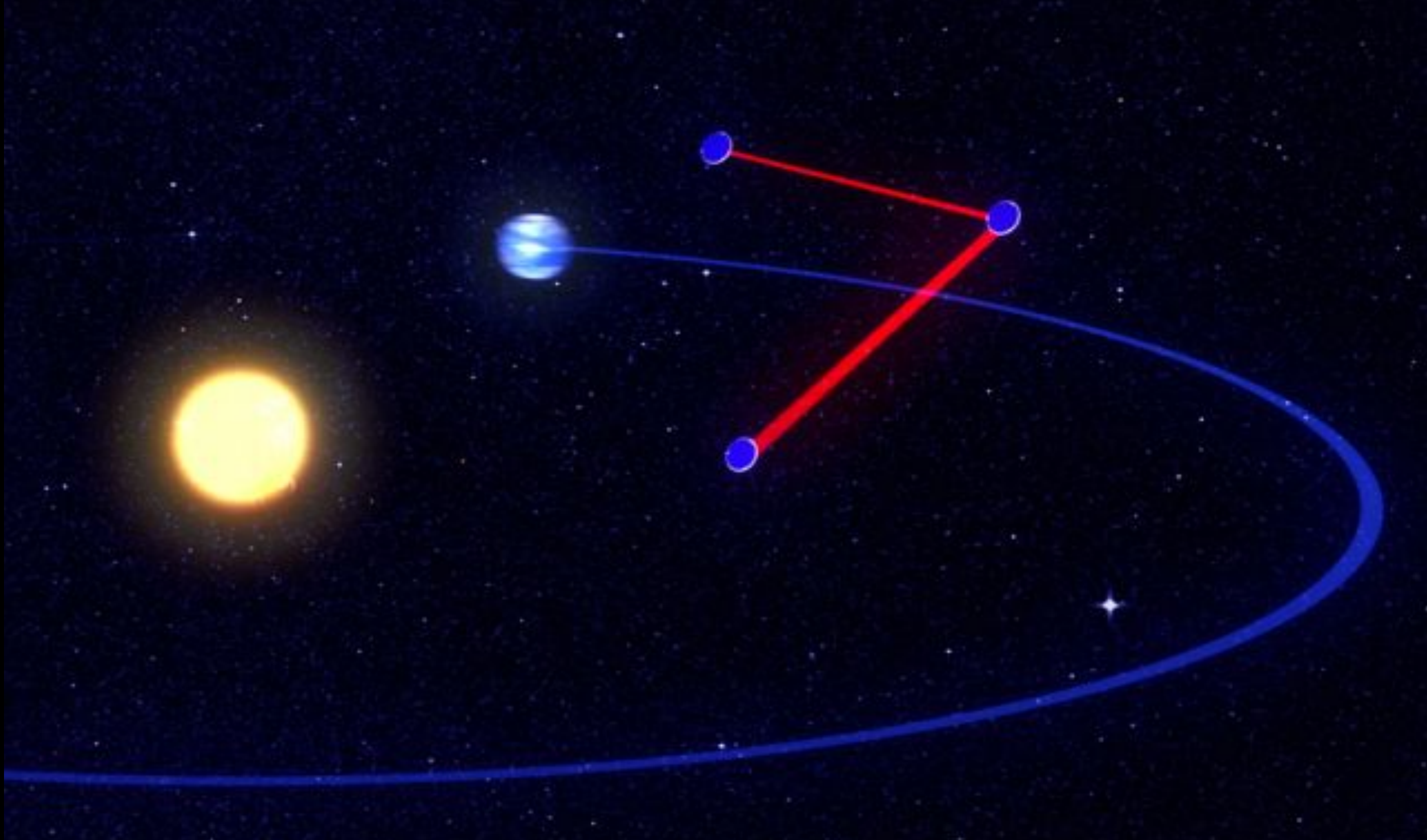


"Einstein Telescope" (2030s)
underground cryogenic detector in Europe



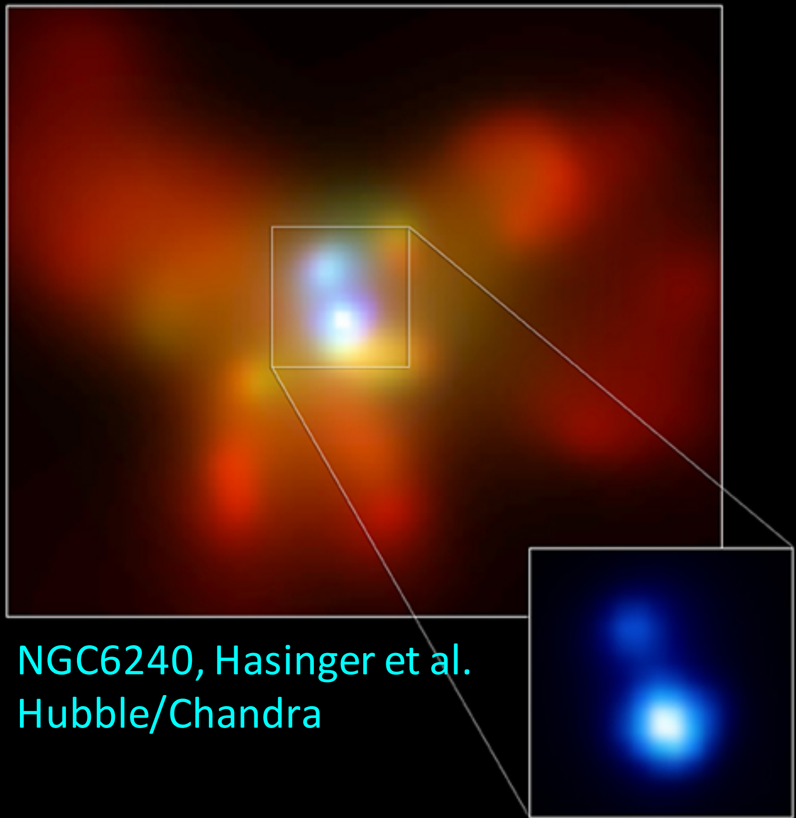
Interferometers in Space: eLISA

(ESA "L3" mission, launch 2034)



Super-Massive BH Mergers

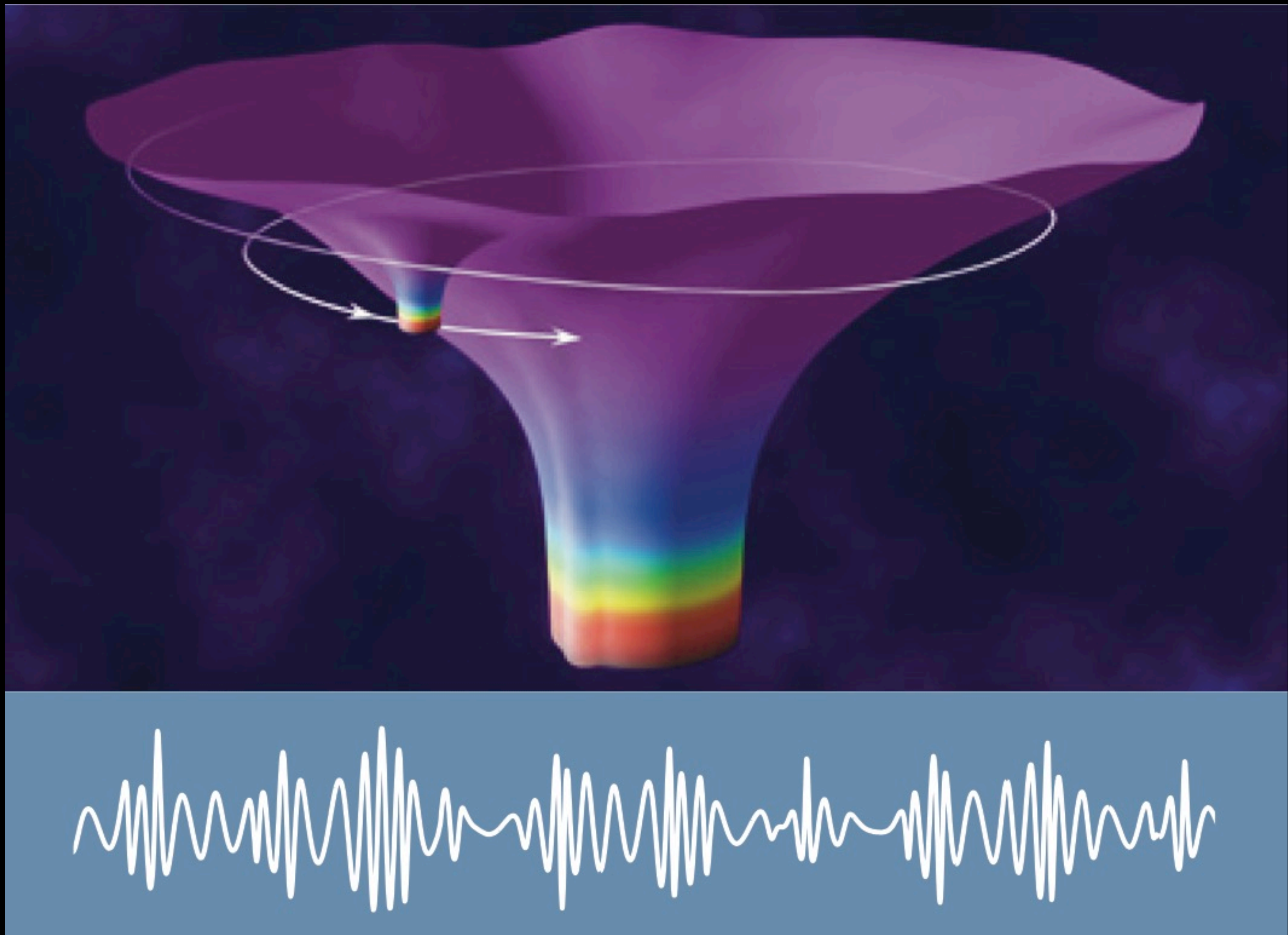
($z \approx 20$, 10^4-10^7 M_o)



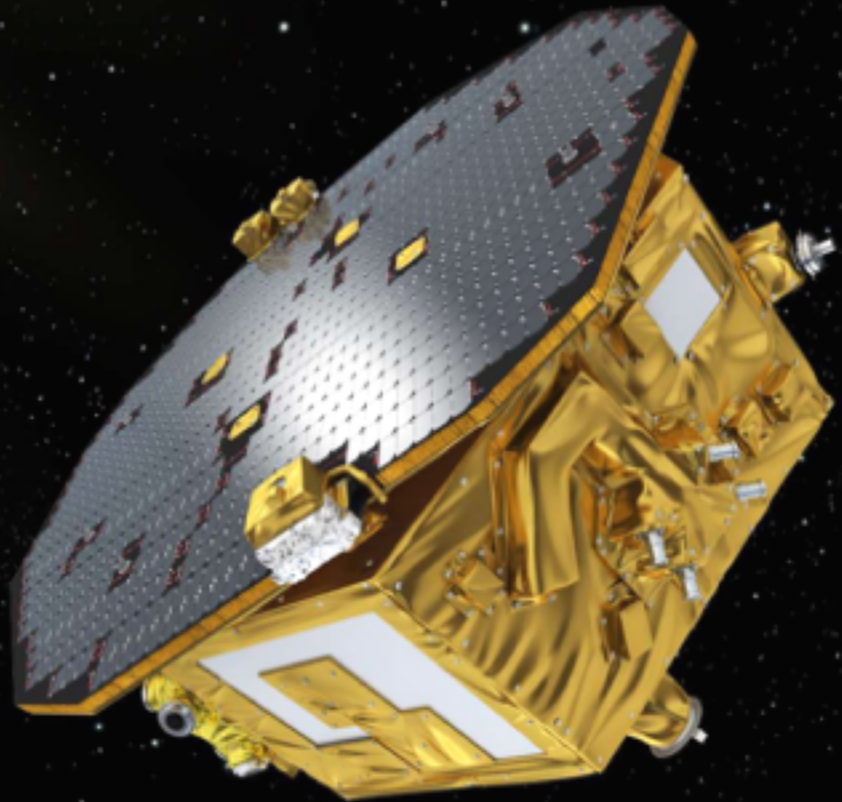
NGC6240, Hasinger et al.
Hubble/Chandra

image: NASA / eLISA; sound: S. Hughes

Supermassive Black-Holes



LISA PathFinder



- Launched Dec 2015.
- Tests key technologies for eLISA (drag-free tracking, optical technology).
- Also possibility to test MOND via mission extension.

- *Press conference on June 15.*

GW150914 Papers

- Phys. Rev. Lett. 116, 061102 (2016) *Observation of Gravitational Waves from a Binary Black Hole Merger*
- ApJL, 818, L22, 2016 *Astrophysical Implications of the Binary Black-Hole Merger GW150914*
- 1602.03841 *Tests of general relativity with GW150914*
- 1602.03840 *Properties of the binary black hole merger GW150914*
- 1602.03839 *GW150914: First results from the search for binary black hole coalescence with Advanced LIGO*
- 1602.03842 *The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914*
- 1602.03847 *GW150914: Implications for the stochastic gravitational-wave background from binary black holes*
- 1602.05411 *High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES* (+ Antares, IceCube)
- 1602.08492 *Localization and broadband follow-up of the gravitational-wave transient GW150914* (+25 astro teams)
- 1602.03838 *GW150914: The Advanced LIGO Detectors in the Era of First Discoveries*
- 1602.03843 *Observing gravitational-wave transient GW150914 with minimal assumptions*
- 1602.03844 *Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914*
- 1602.03845 *Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914*