Title: Gravitational Waves: Discoveries and Future Detectors

Date: Apr 11, 2018 02:00 PM

URL: http://pirsa.org/18040051

Abstract: <p>Two years ago the Laser Interferometer Gravitational-wave Observatory.</p>

<p>(LIGO) announced the first direct detection of gravitational waves; minute distortions in space-time caused by cataclysmic events far away in the universe. Very recently, the merger of a binary neutron star system was detected by both of the Advanced LIGO detectors and the Advanced Virgo detector in Italy, triggering a massive follow-up campaign by ground and space-based telescopes. A counterpart to the gravitational-wave source was located, and transient emission was detected from gamma rays to radio. I will talk about the sources of the signals we detected, the physics behind the detectors, and prospects for the future of this emerging field.</p>

Massachusetts Institute of Technology

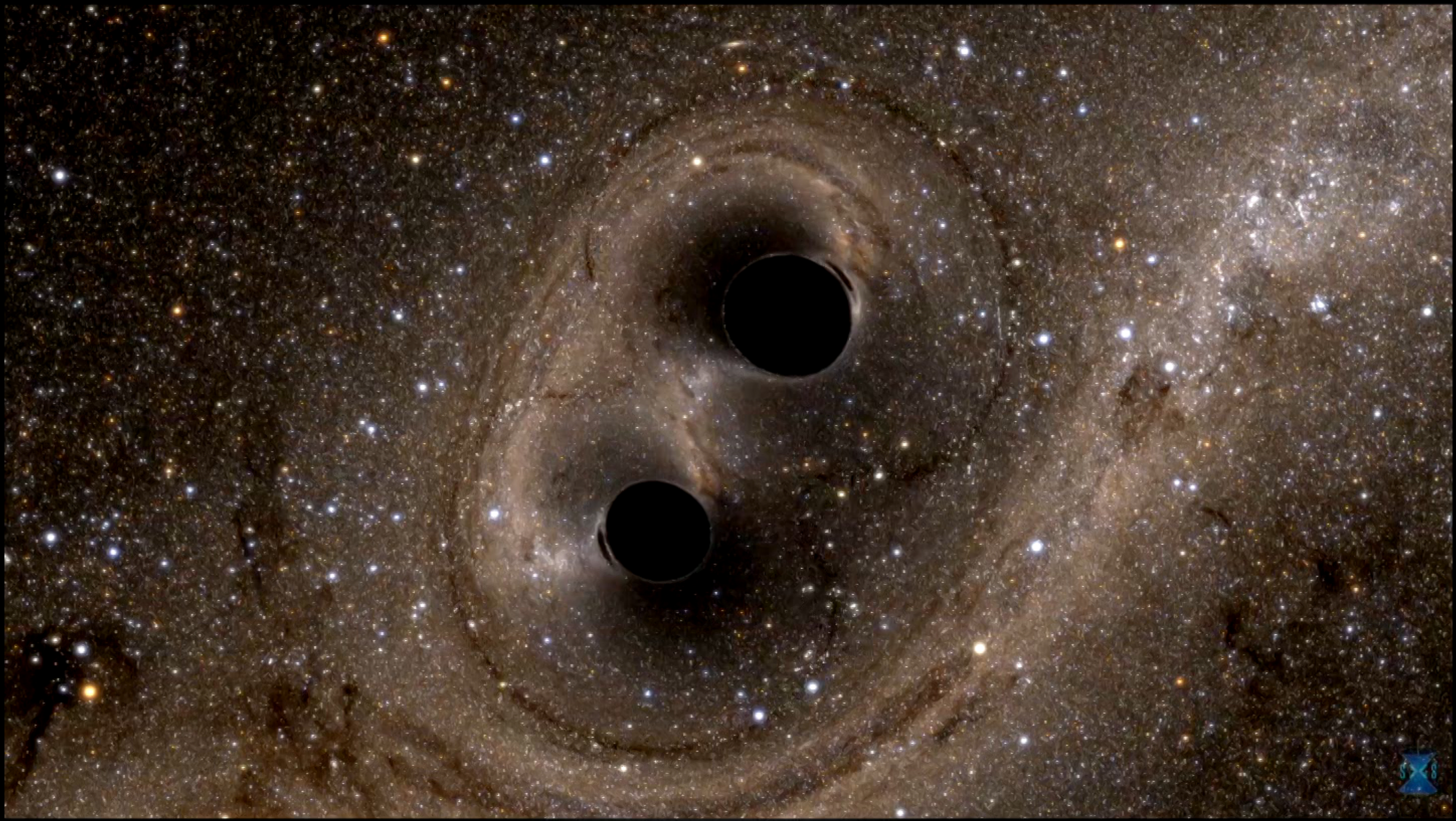
MIT KAVLI INSTITUTE

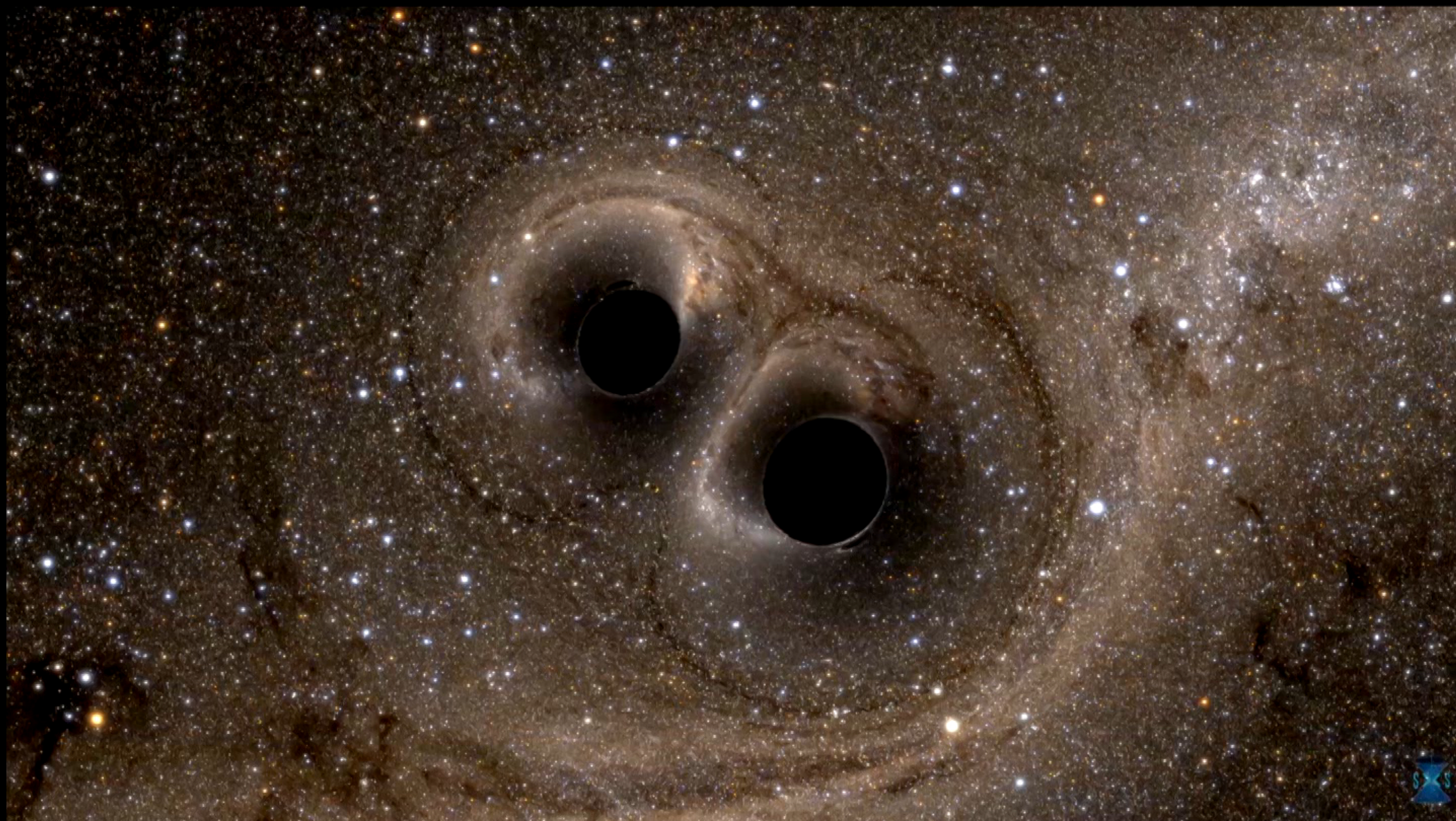
LIGO

NATIONAL SCIENCE FOUNDATION

Gravitational Waves: Discovery and Future Detectors

Matthew Evans, MIT





Apr, 2018 M. Evans, PI 2

Simulating eXtreme Spacetimes (SXS) Project
www.black-holes.org

California Institute of Technology
California State University Fullerton
Canadian Institute for Theoretical Astrophysics
Cornell University
Max Planck Institute for Gravitational Physics
Oberlin College
Washington State University

We gratefully acknowledge support by

Canada Research Chairs, CFI, CIFAR, Compute Canada,
Max Planck Society, NASA, NSERC, NSF, Ontario MEDI, Research Corporation
for Science Advancement, Sherman Fairchild Foundation, XSEDE

What we know about the first binary black hole merger observed by LIGO

- The two black holes that merged were very massive, about 30 times the mass of the sun

$$36^{+5}_{-4}\ \mathrm{M}_{\odot}\ \text{and}\ 29^{+4}_{-4}\ \mathrm{M}_{\odot}$$

- The black holes merged 1.3 billion light-years away (410 Mpc)
- These (and subsequently observed) black holes were NOT close to maximally spinning
  (and most consistent with zero spin)

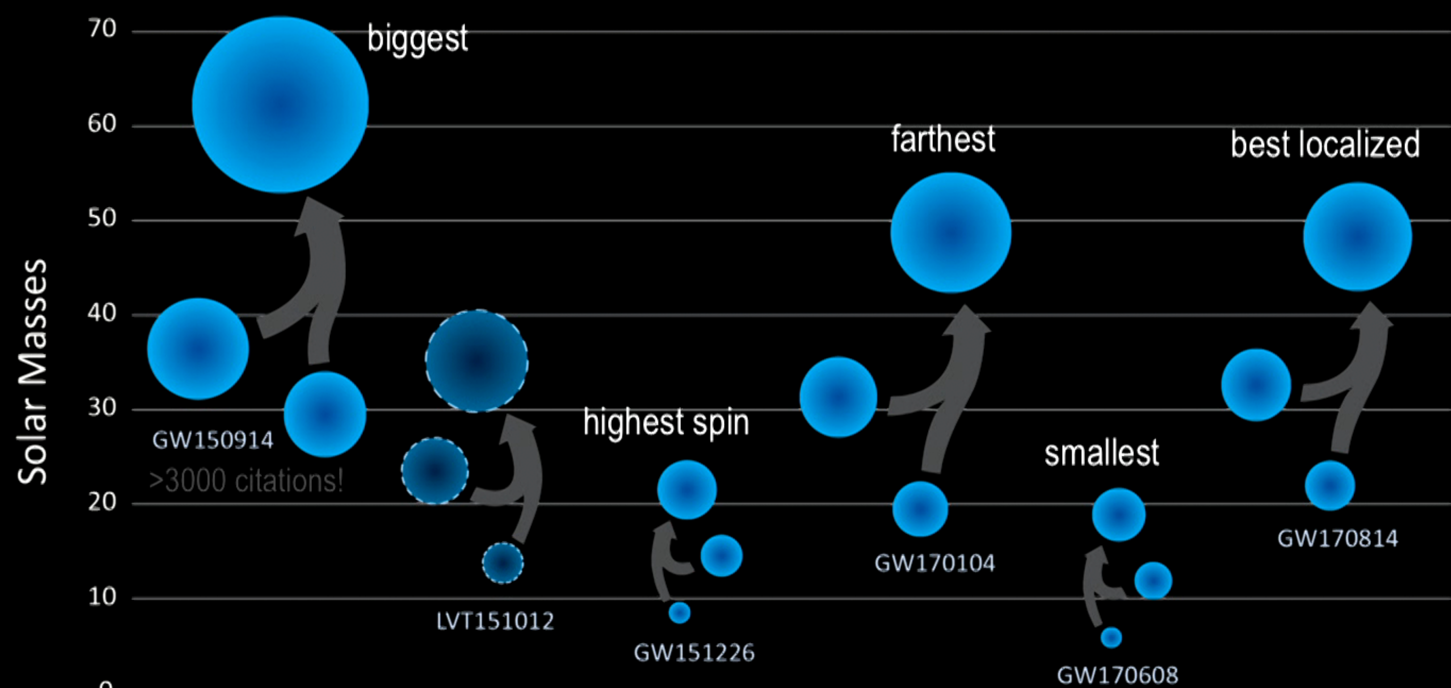
Energy, and Luminosity – Fun Statistics

- The two black holes merged to form a single black hole of 62 times the mass of the sun
- As they merged, the equivalent of ~3 times the mass of our Sun was emitted in gravitational waves

$E = m c^2$

- That is a lot!!! Let's compare:
  - Our Sun has lost 0.03% of its mass in 5 billion years, through electromagnetic emission (so this was 10,000 times more, in < 1s)
  - The power output was briefly larger than all of the light from all of the stars in the visible universe. Luminosity at Earth similar to full moon!
- And still, it produced only a tiny distortion here on Earth: space-time is very, very stiff!

Since GW150914 we have detected several other BBH mergers.



Apr, 2018 M. Evans, PI 5

With binary black holes, we have

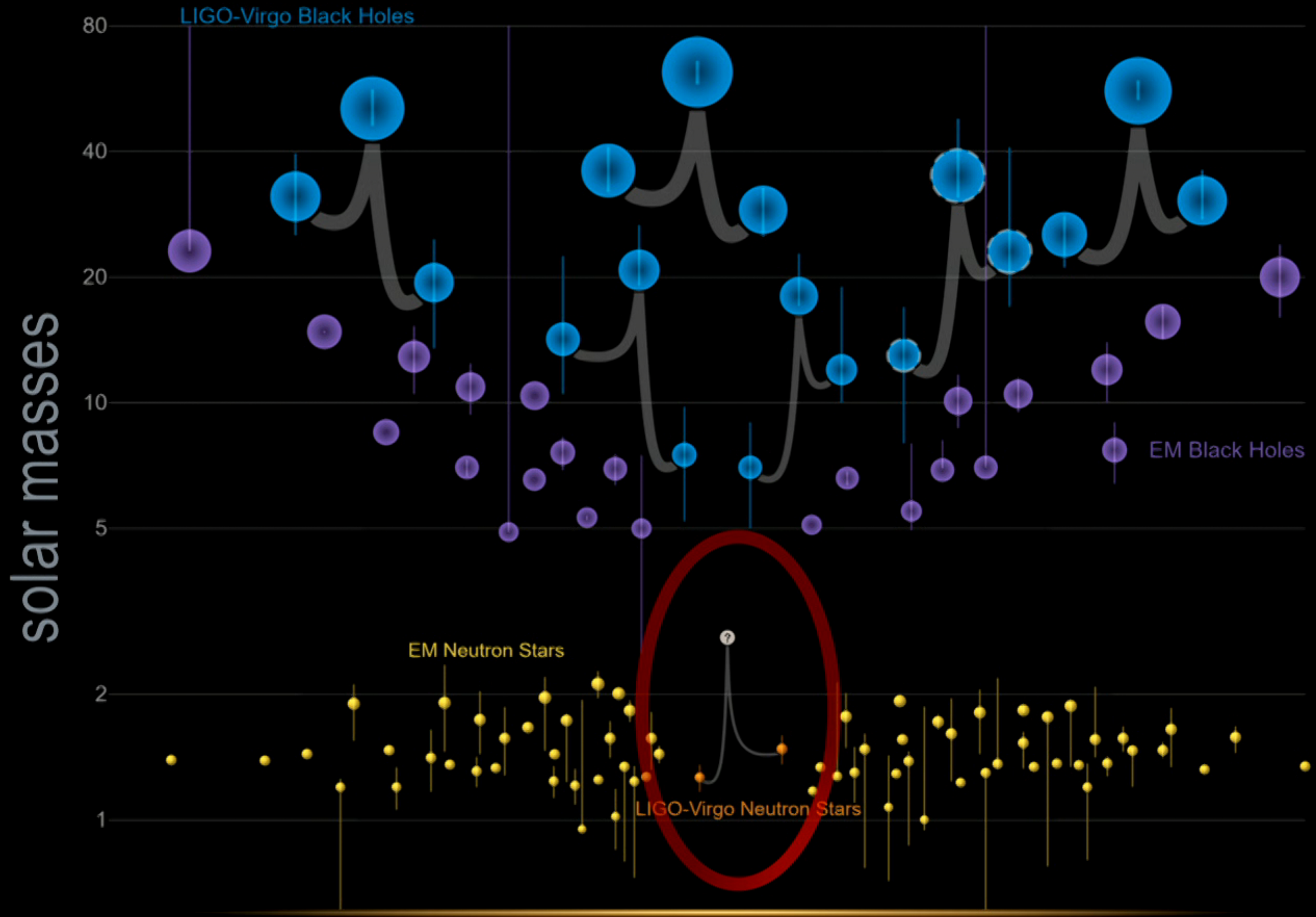
- tested General Relativity in the strong field regime, improving constraints on deviations from GR by orders of magnitude

Binary Black Hole Mergers in the first Advanced LIGO Observing Run
LSC (2016) PRX 6.041015

- discovered a previously unknown population of high-mass stellar remnants
  - from field binaries, or clusters?

Astrophysical Implications of Binary Black Hole Merger GW150914
LSC (2016) ApJL 818 L22

Recently, our first binary neutron star merger!



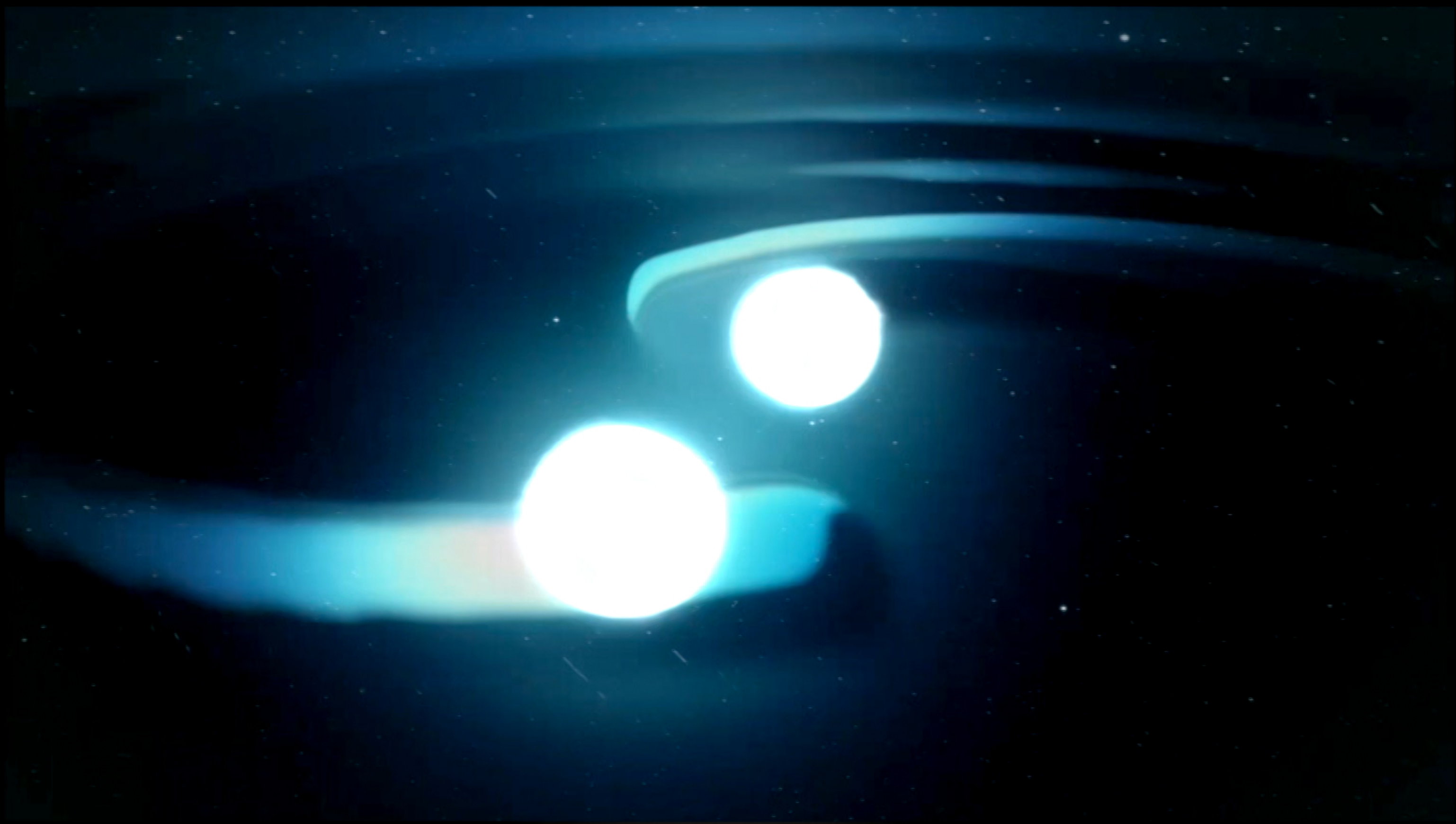
Apr, 2018

M. Evans, PI

7

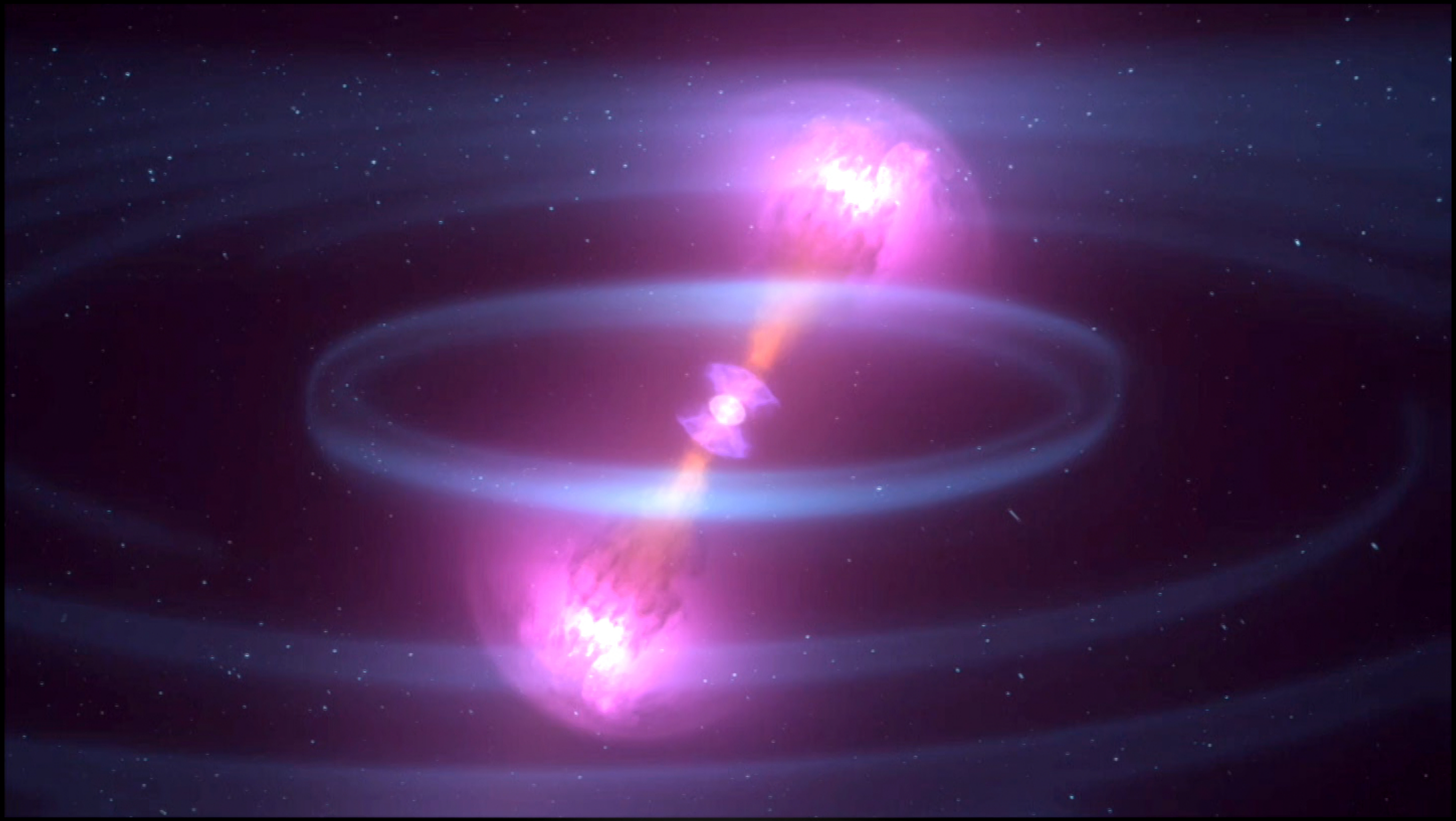
Apr, 2018 M. Evans, PI 8

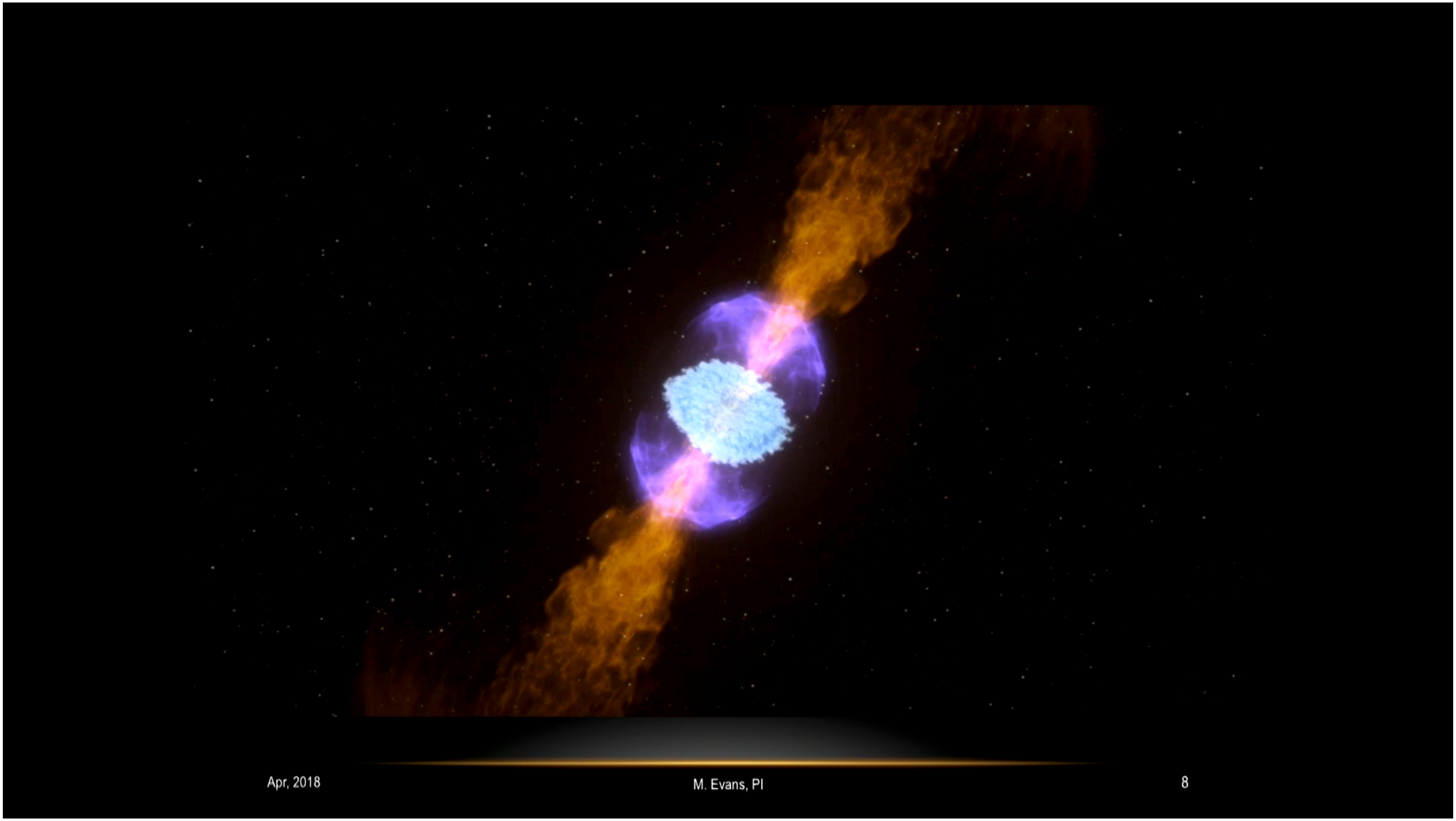
Apr, 2018 M. Evans, PI 8

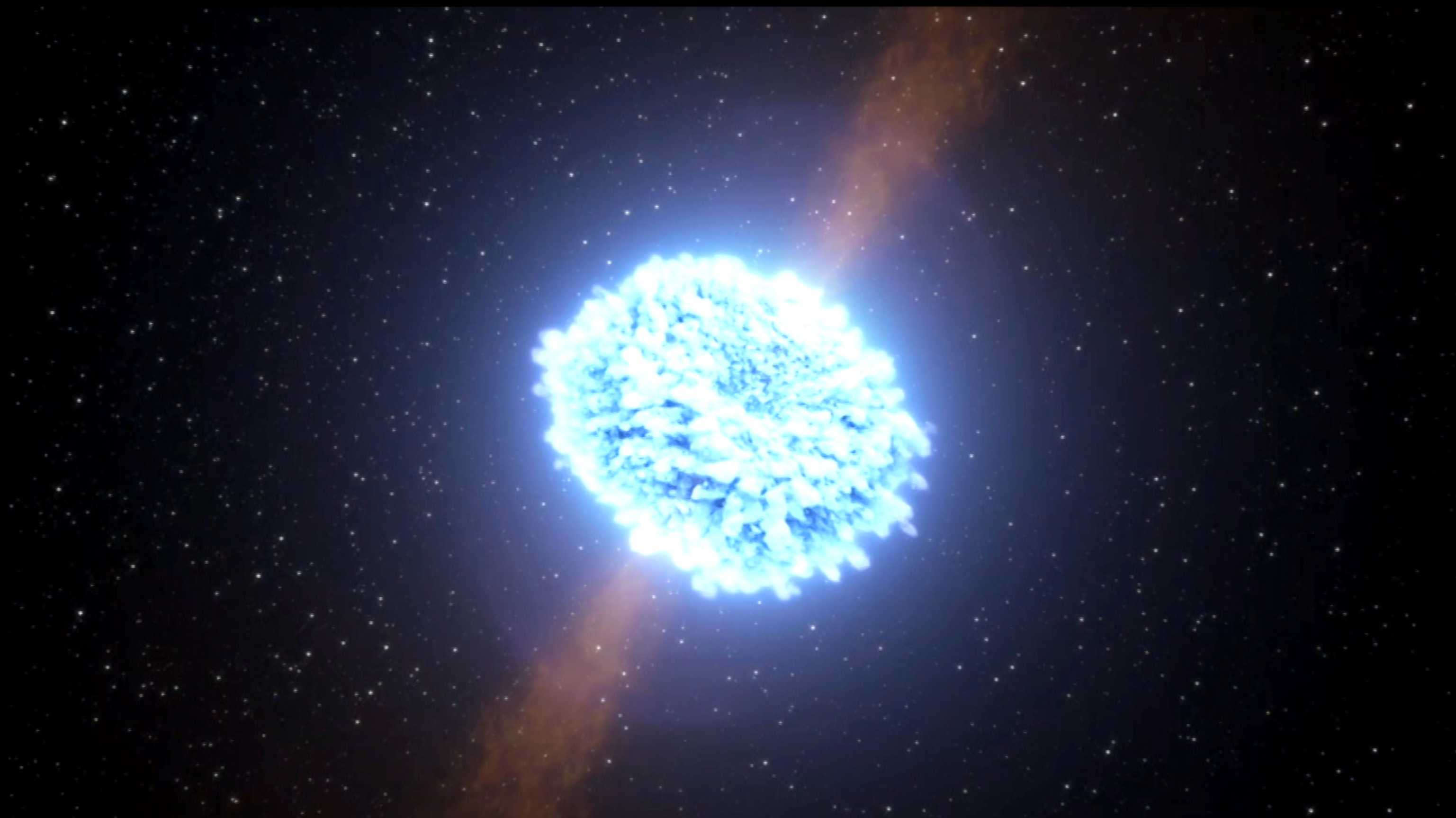


Apr, 2018 M. Evans, PI 8

Apr, 2018 M. Evans, PI 8



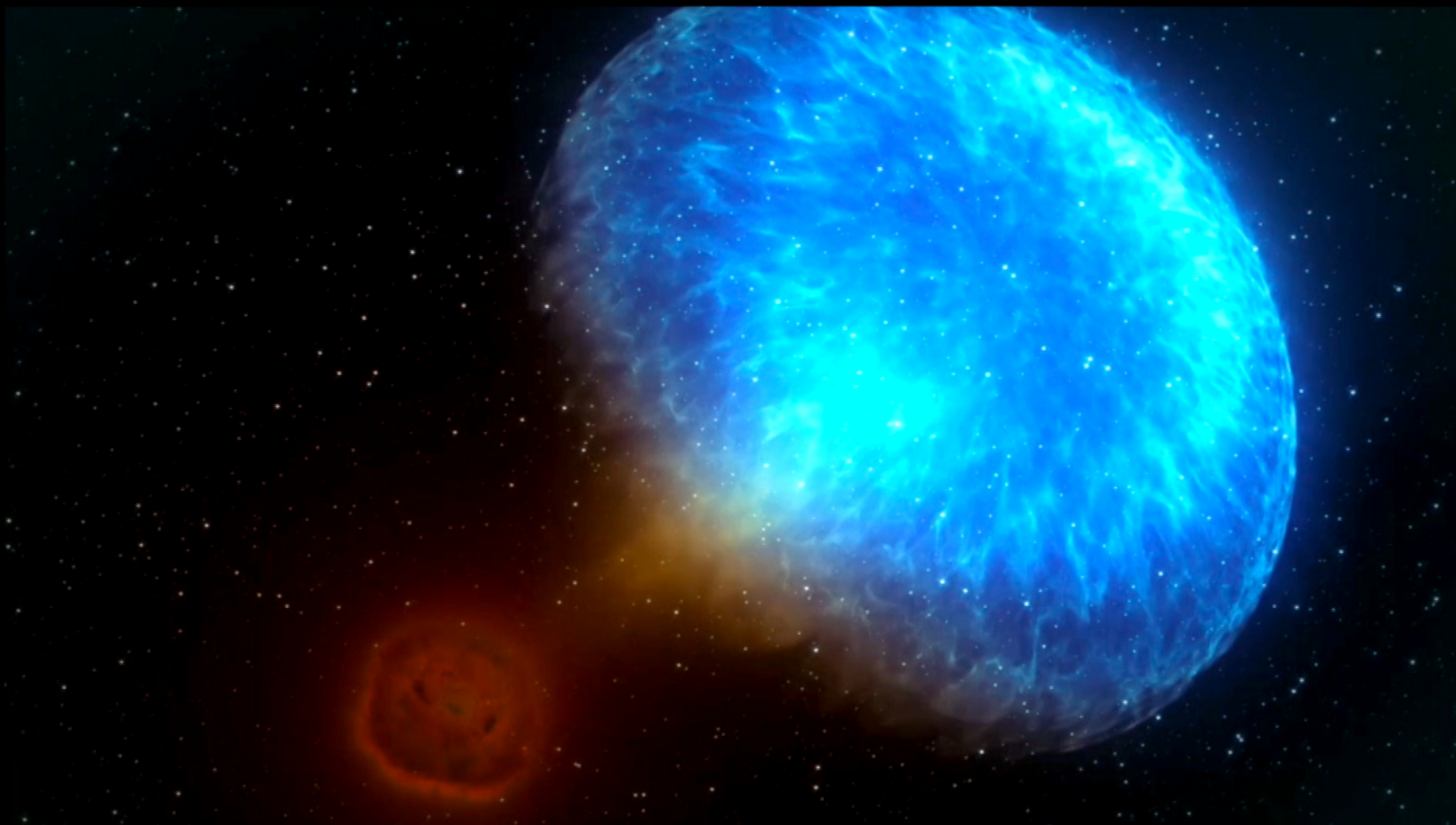

Apr, 2018
M. Evans, PI
8



Apr, 2018

M. Evans, PI

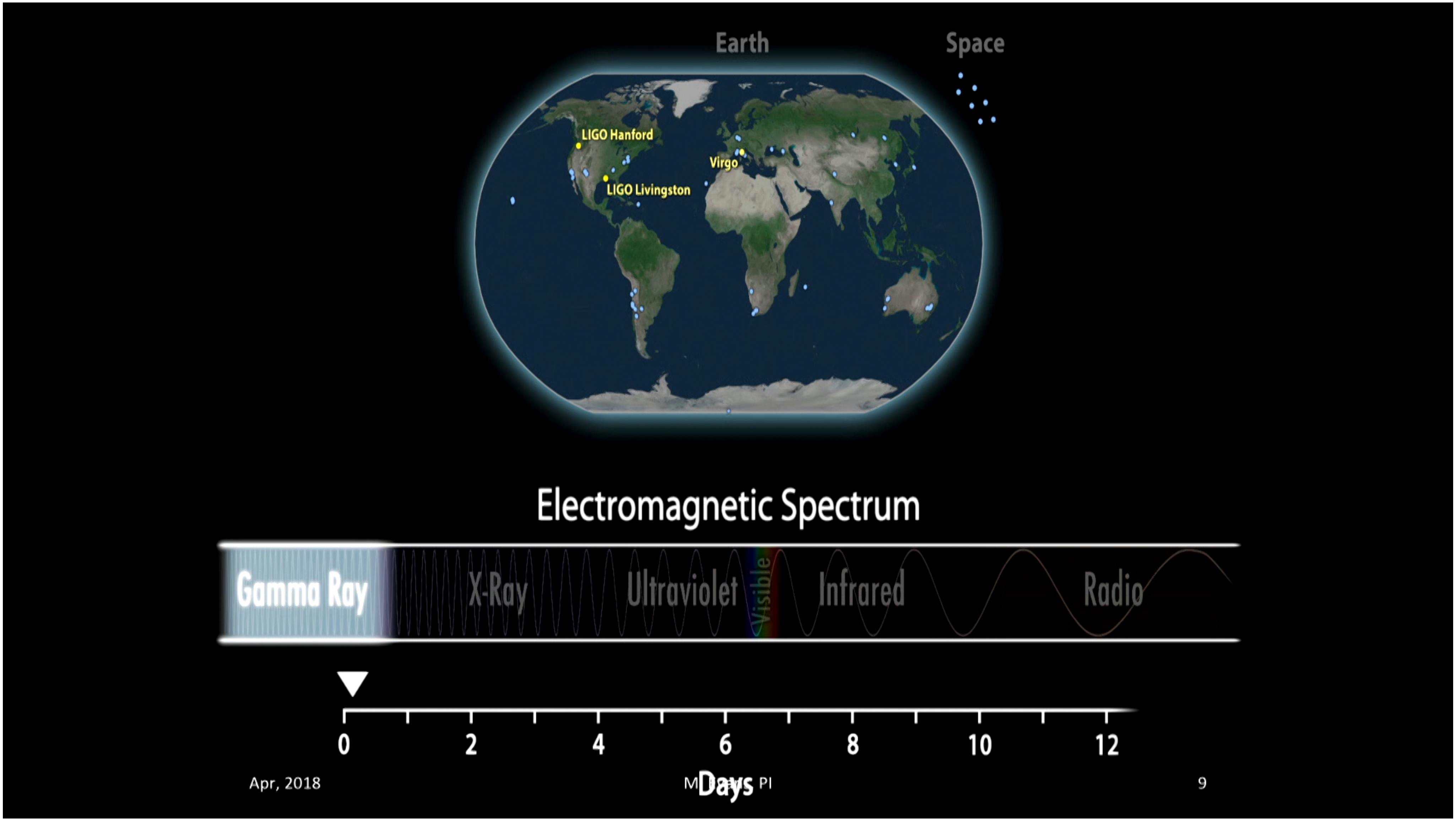
8

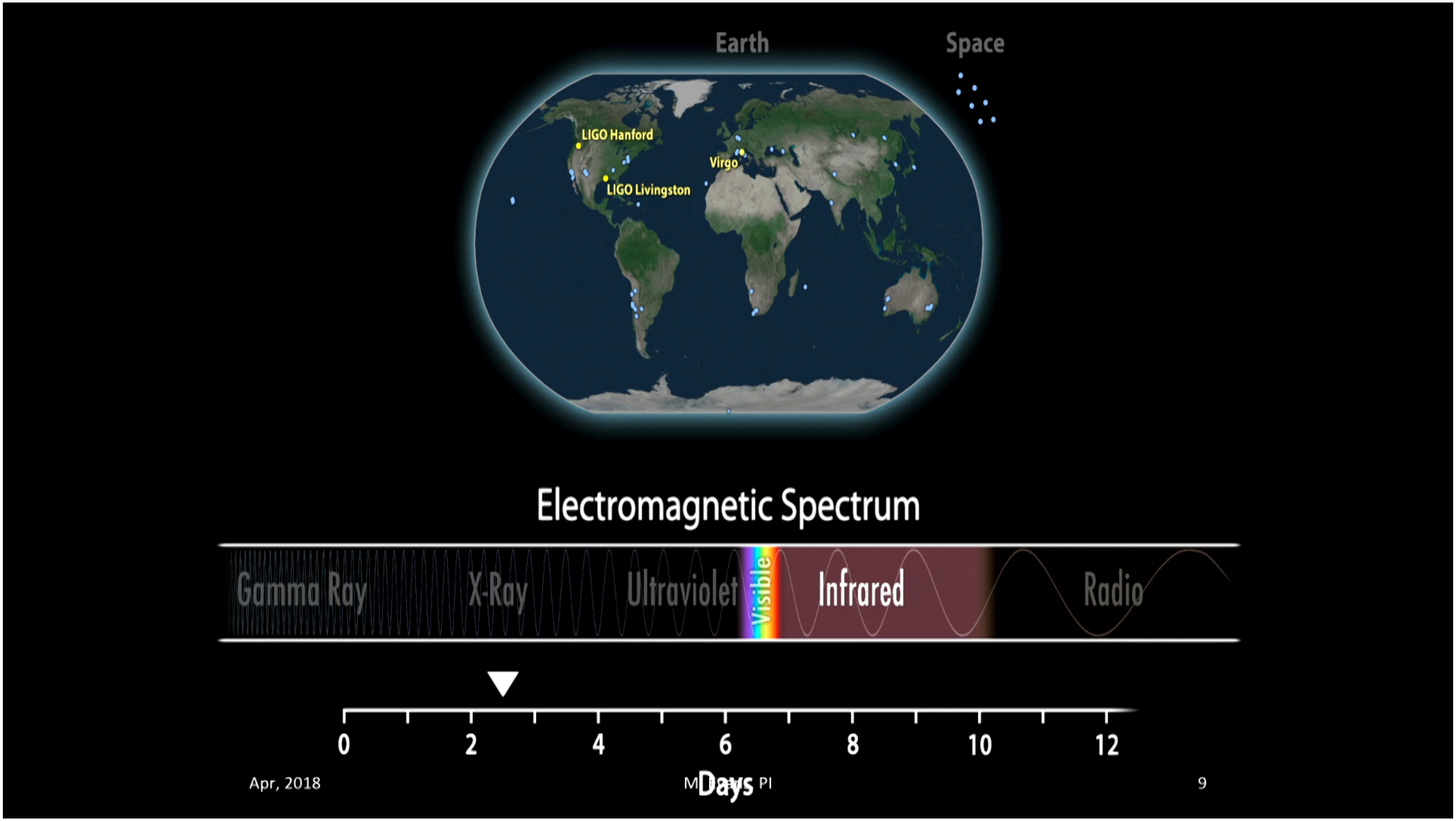


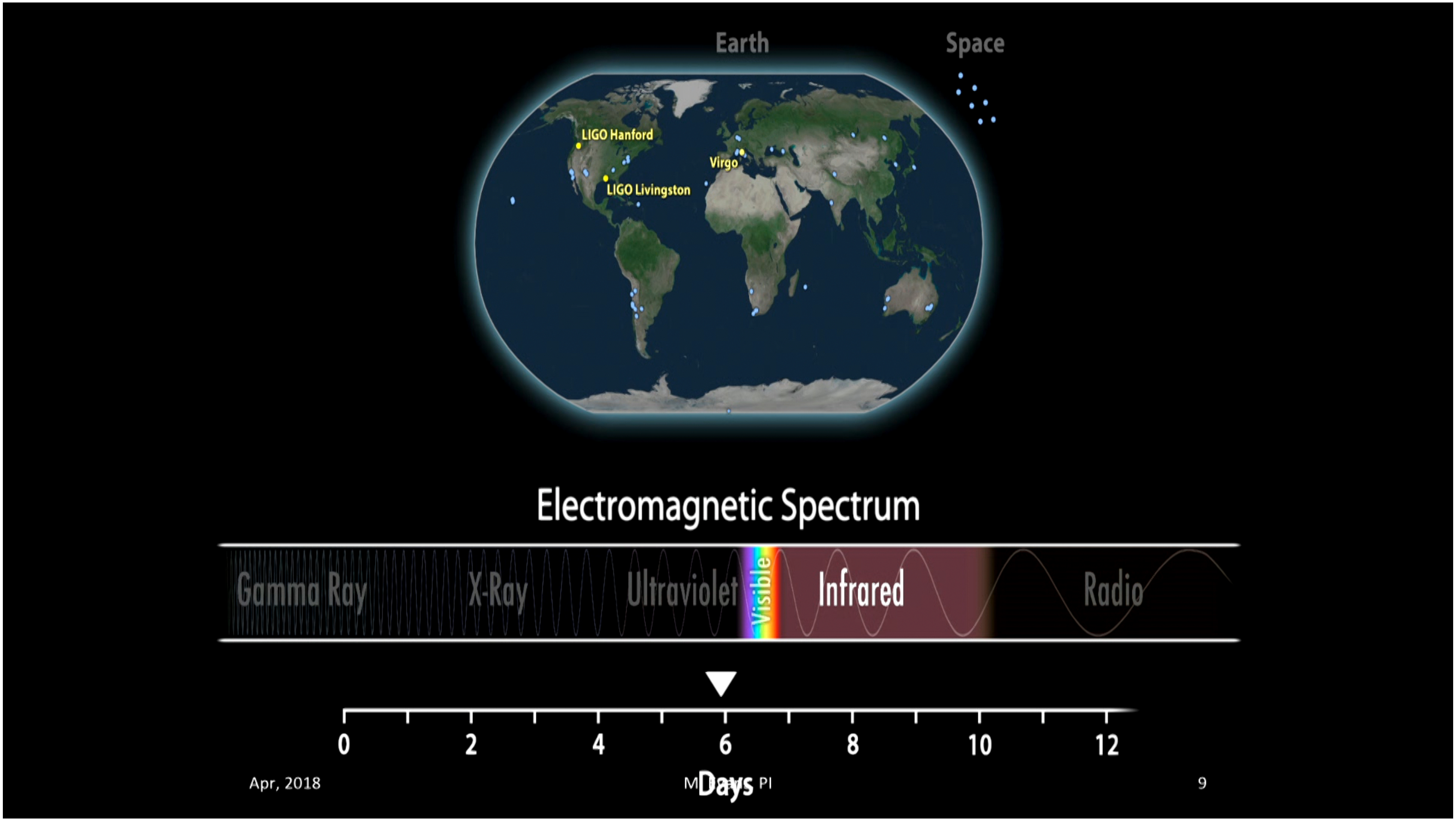
Apr, 2018 M. Evans, PI 8

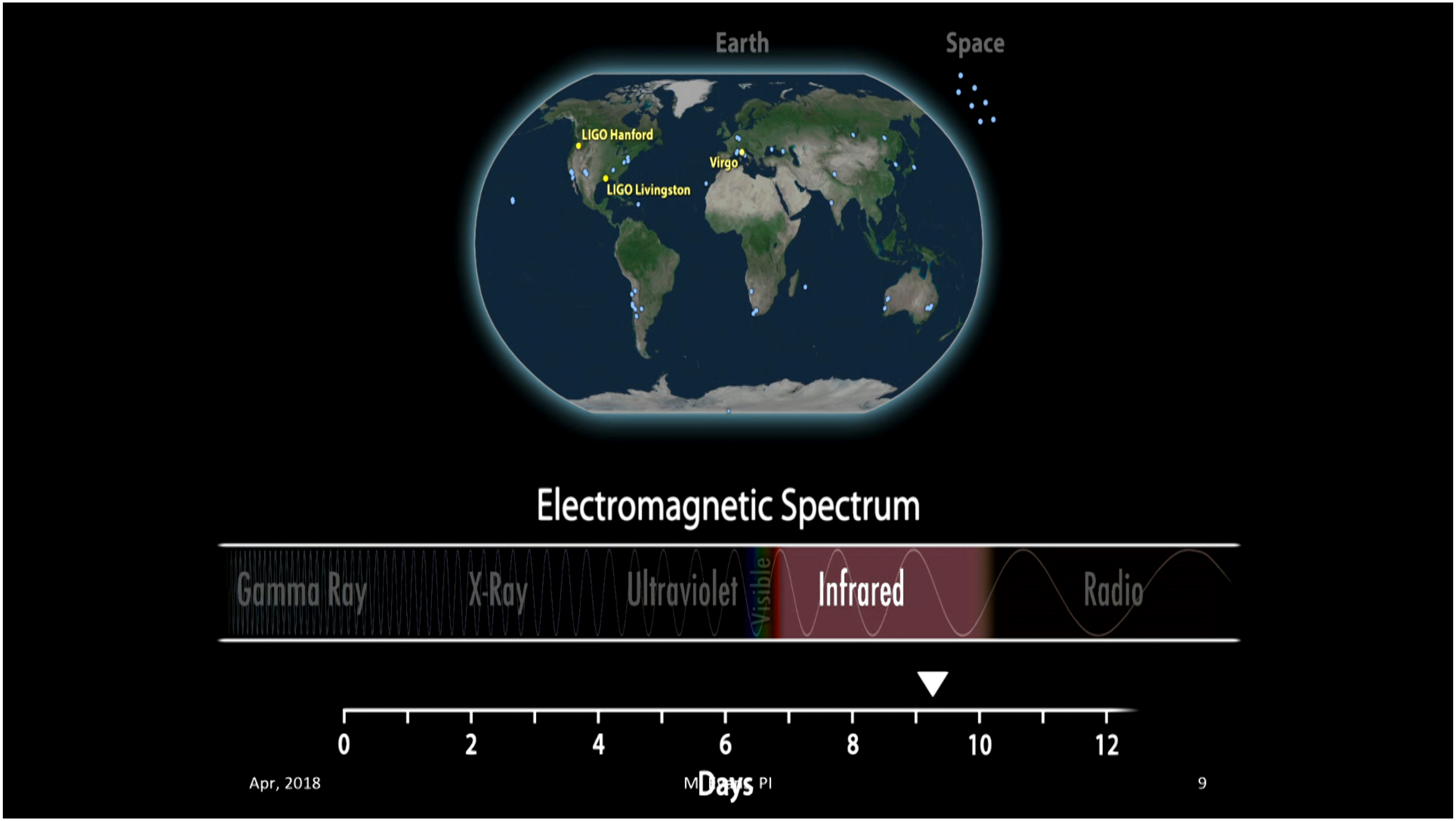

NASA ASTROPHYSICS

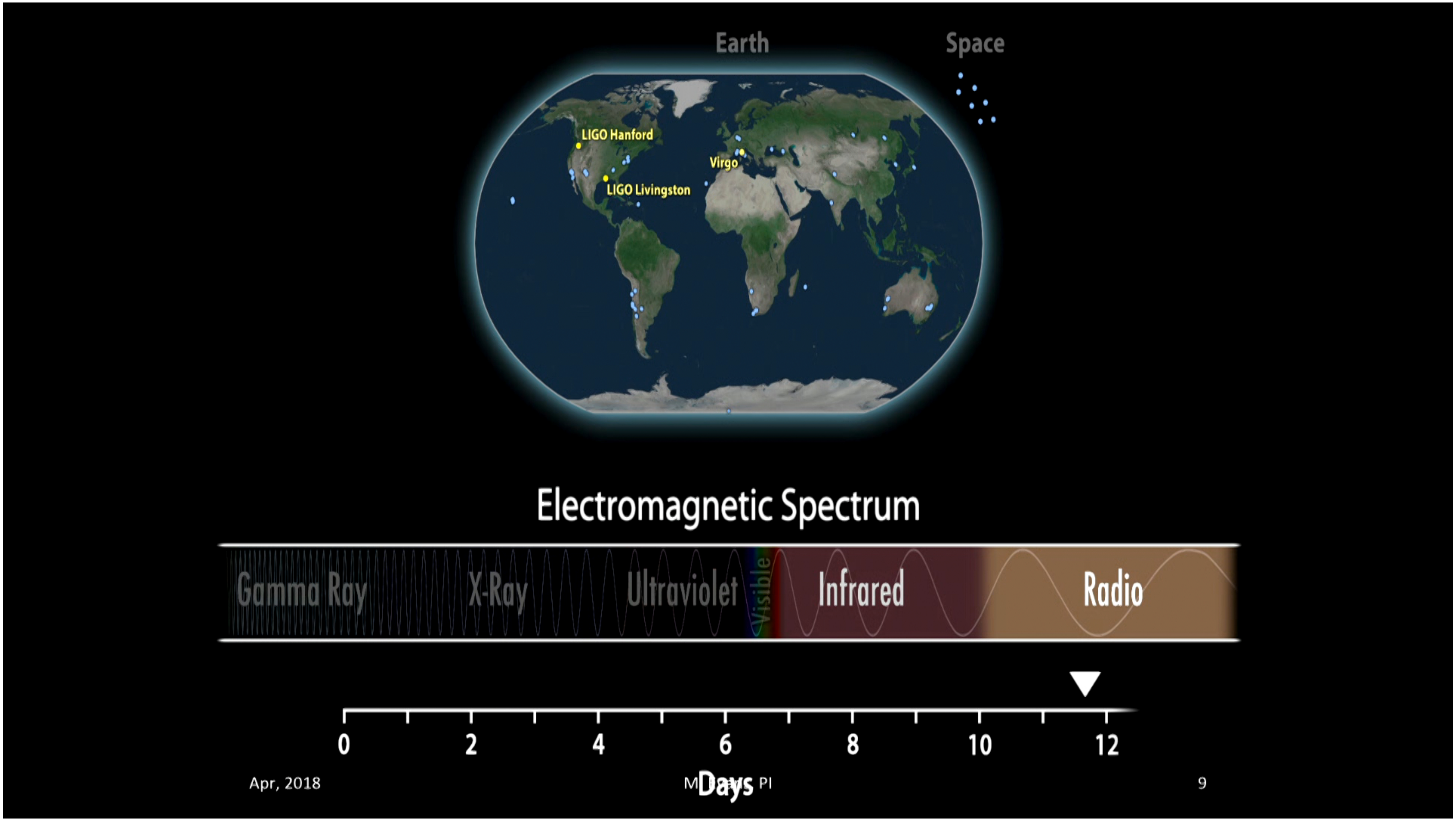
Apr, 2018 M. Evans, PI 9


Earth
Space
LIGO Hanford
Virgo
LIGO Livingston
Electromagnetic Spectrum
Gamma Ray
X-Ray
Ultraviolet
Visible
Infrared
Radio
0
2
4
6
8
10
12
Days
Apr, 2018
9

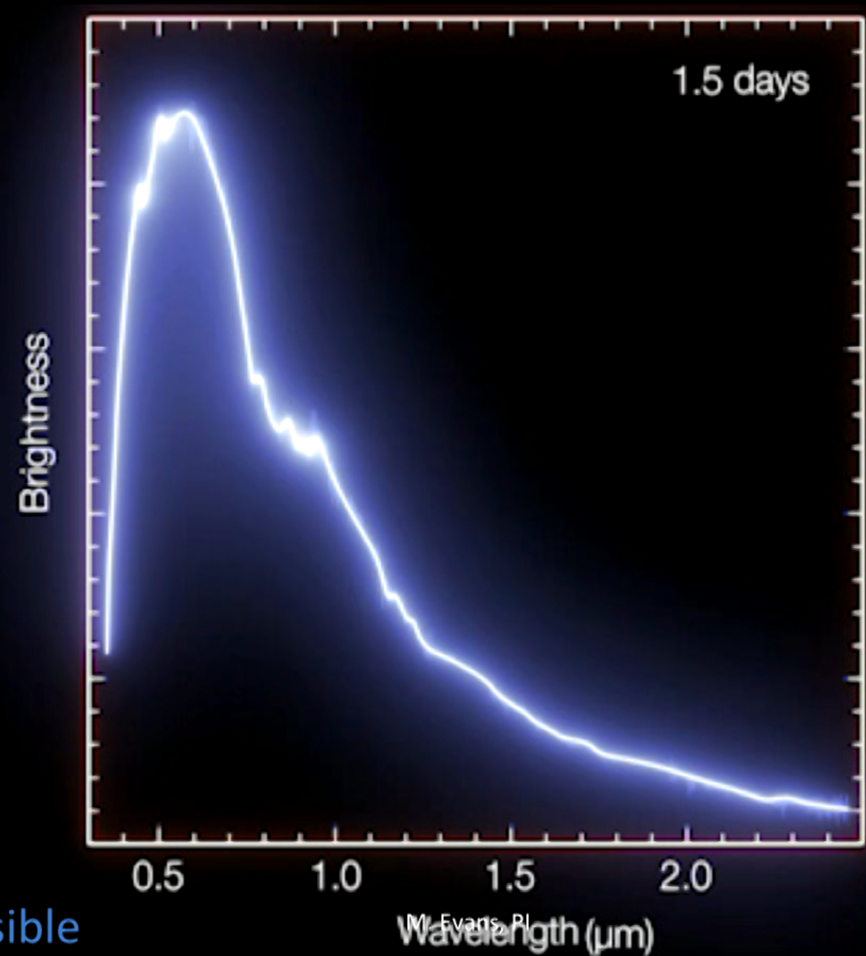

Earth
Space
LIGO Hanford
Virgo
LIGO Livingston
Electromagnetic Spectrum
Gamma Ray
X-Ray
Ultraviolet
Visible
Infrared
Radio
0
2
4
6
8
10
12
Days
Apr, 2018
9


Earth
Space
LIGO Hanford
Virgo
LIGO Livingston
Electromagnetic Spectrum
Gamma Ray
X-Ray
Ultraviolet
Visible
Infrared
Radio
0
2
4
6
8
10
12
Days
Apr, 2018
PI
9


Earth
Space
LIGO Hanford
Virgo
LIGO Livingston
Electromagnetic Spectrum
Gamma Ray
X-Ray
Ultraviolet
Visible
Infrared
Radio
0
2
4
6
8
10
12
Days
Apr, 2018
9


Earth
Space
LIGO Hanford
Virgo
LIGO Livingston
Electromagnetic Spectrum
Gamma Ray
X-Ray
Ultraviolet
Visible
Infrared
Radio
0
2
4
6
8
10
12
Days
Apr, 2018
9

Spectrum of GW170817 counterpart
a blue kilonova which fades to red over time

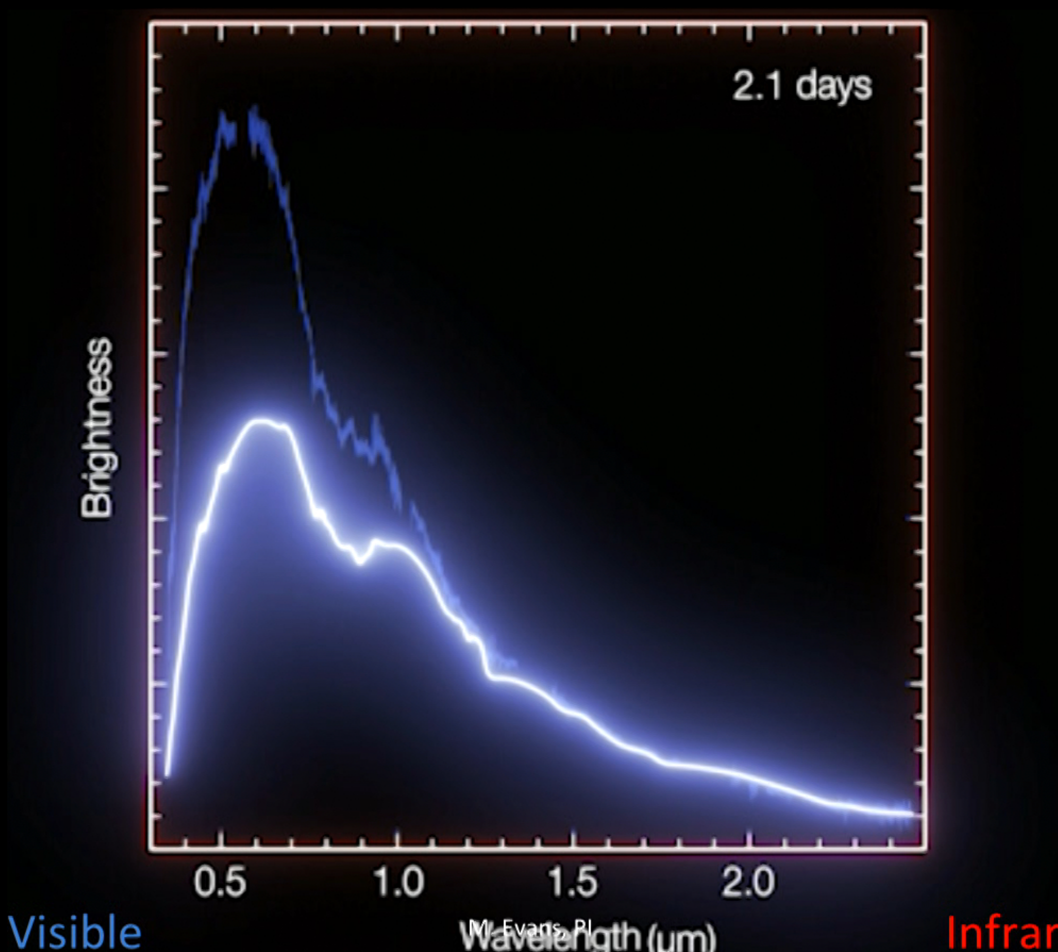


Visible

Infrared

Multi-messenger Observations of a Binary Neutron Star Merger
3000+ authors, 900+ institutions (2017) ApJL 848 L12

Spectrum of GW170817 counterpart
a blue kilonova which fades to red over time

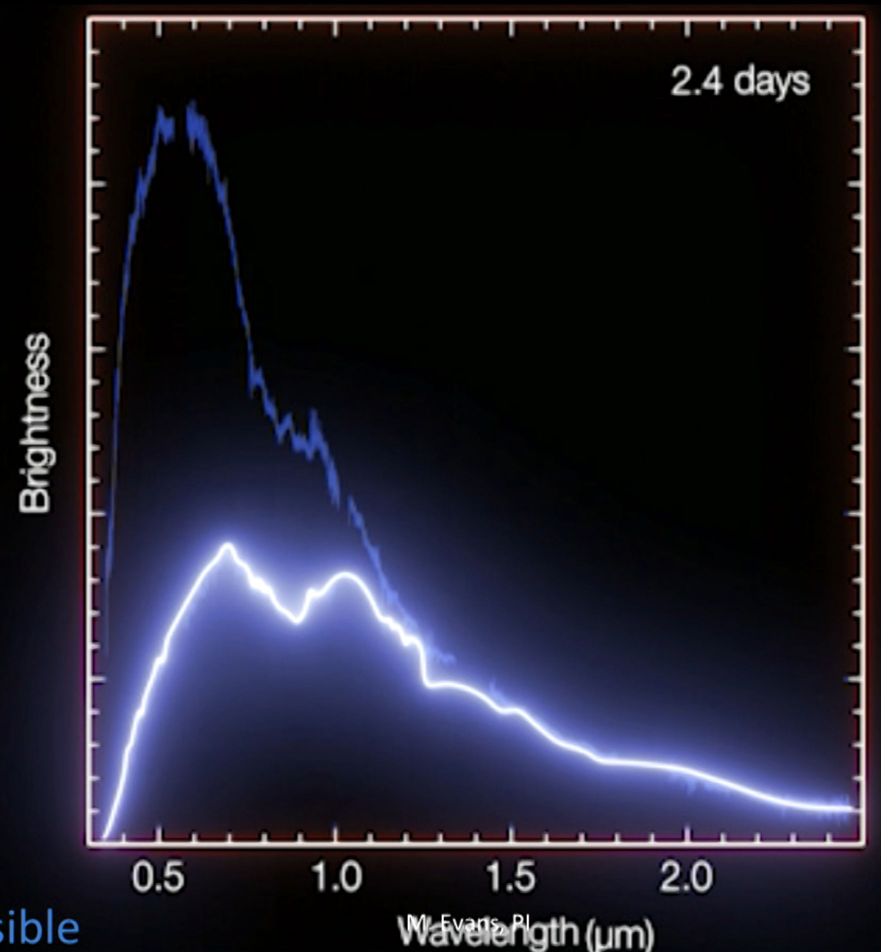


Visible

Infrared

Multi-messenger Observations of a Binary Neutron Star Merger
3000+ authors, 900+ institutions (2017) ApJL 848 L12

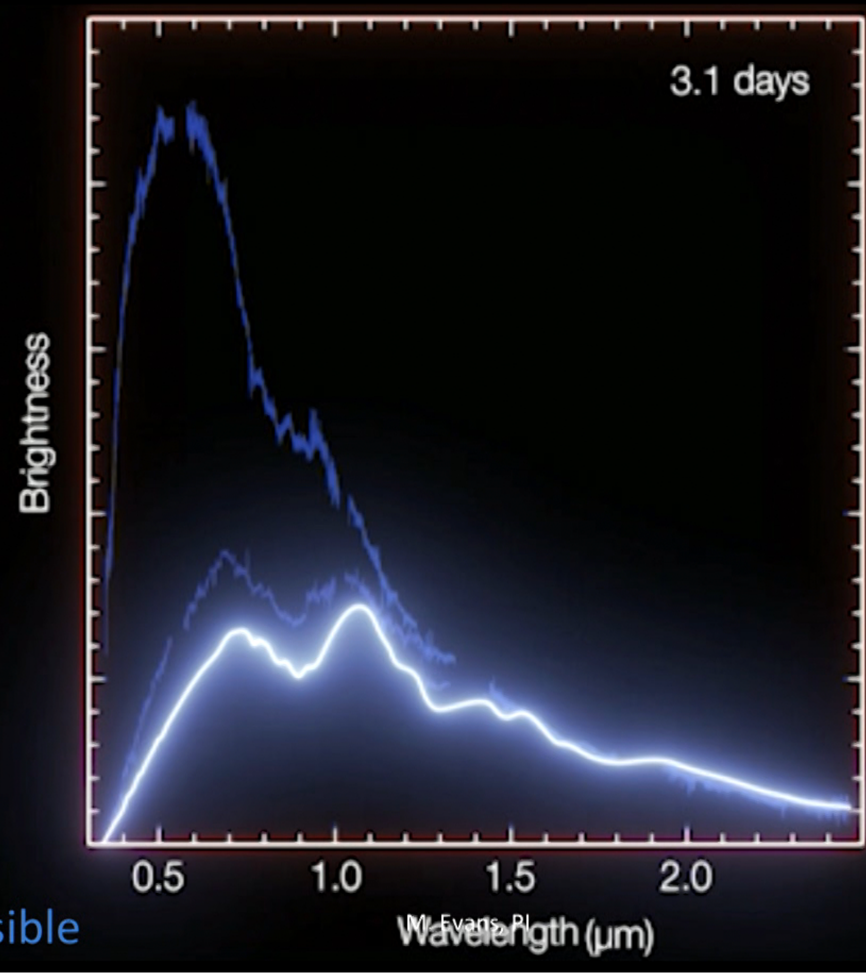
Spectrum of GW170817 counterpart
a blue kilonova which fades to red over time



Visible Infrared

Multi-messenger Observations of a Binary Neutron Star Merger
3000+ authors, 900+ institutions (2017) ApJL 848 L12

Spectrum of GW170817 counterpart
a blue kilonova which fades to red over time

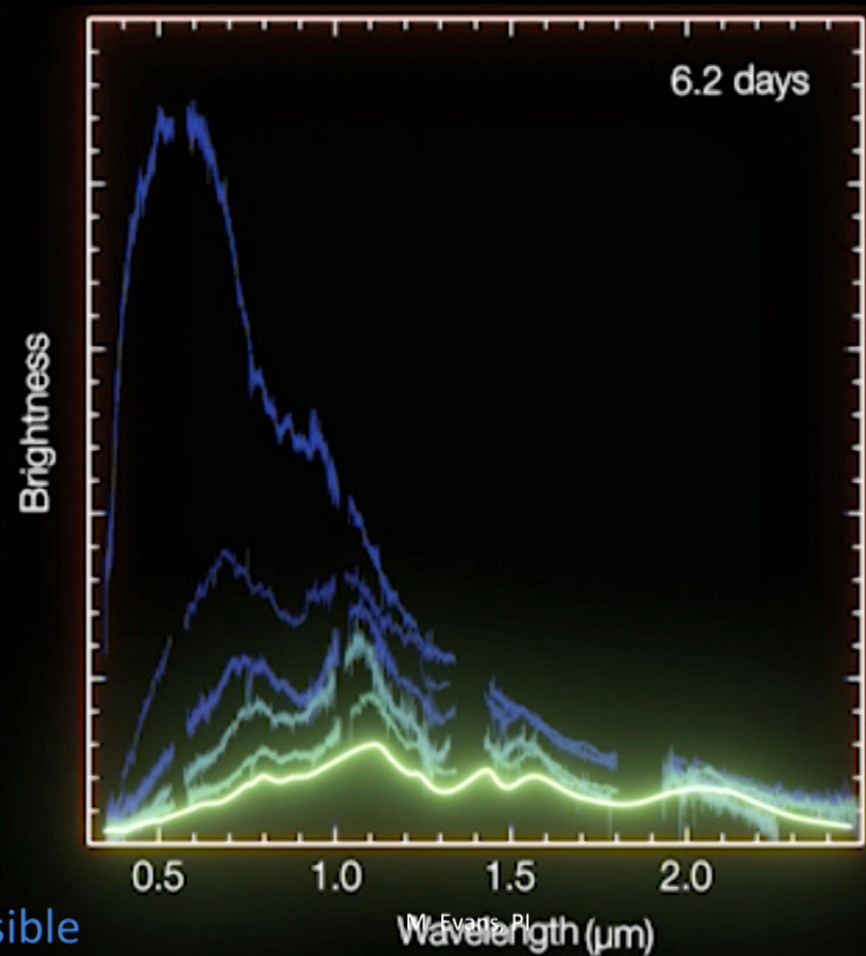


Visible

Infrared

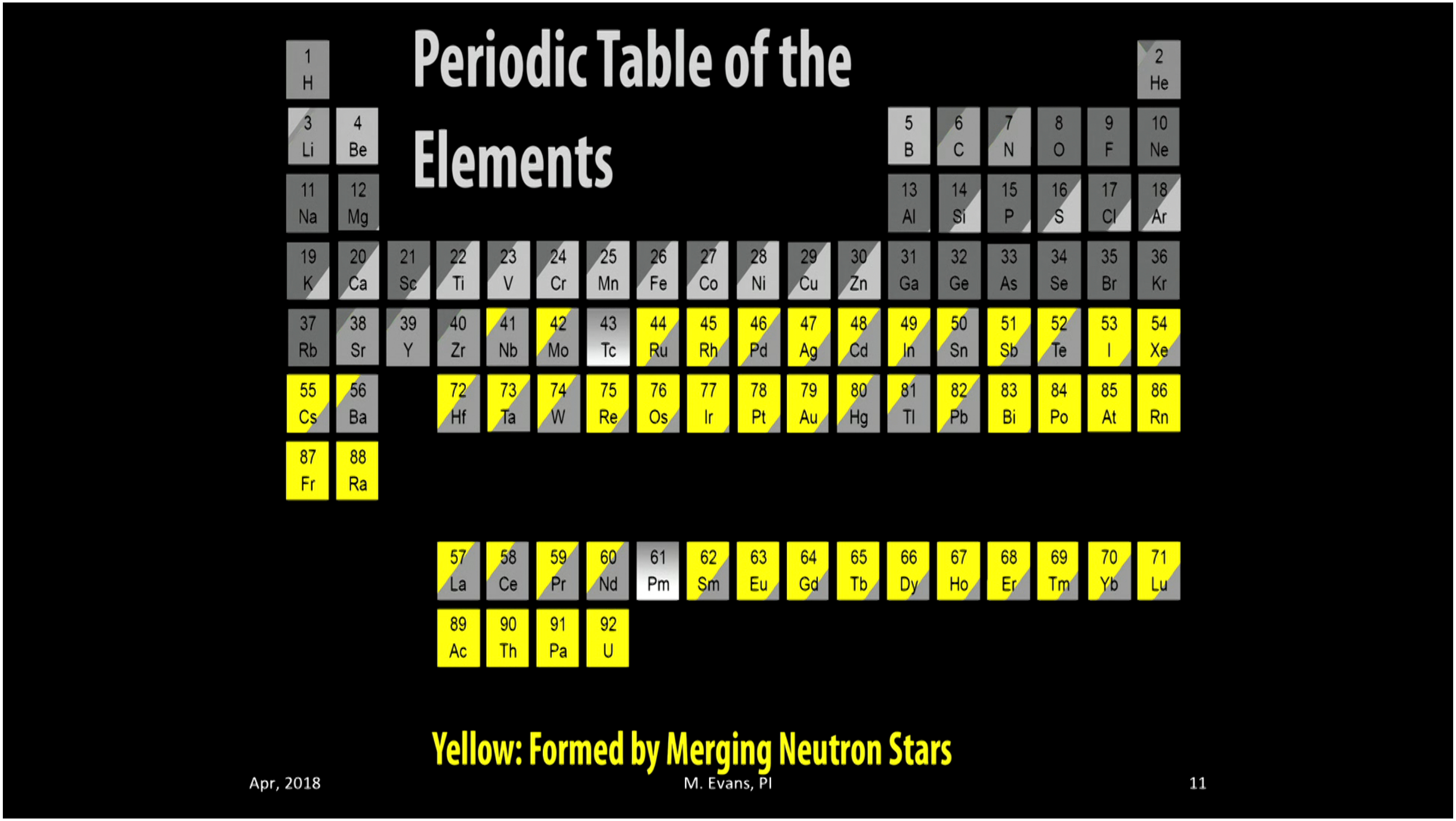
Multi-messenger Observations of a Binary Neutron Star Merger
3000+ authors, 900+ institutions (2017) ApJL 848 L12

Spectrum of GW170817 counterpart
a blue kilonova which fades to red over time

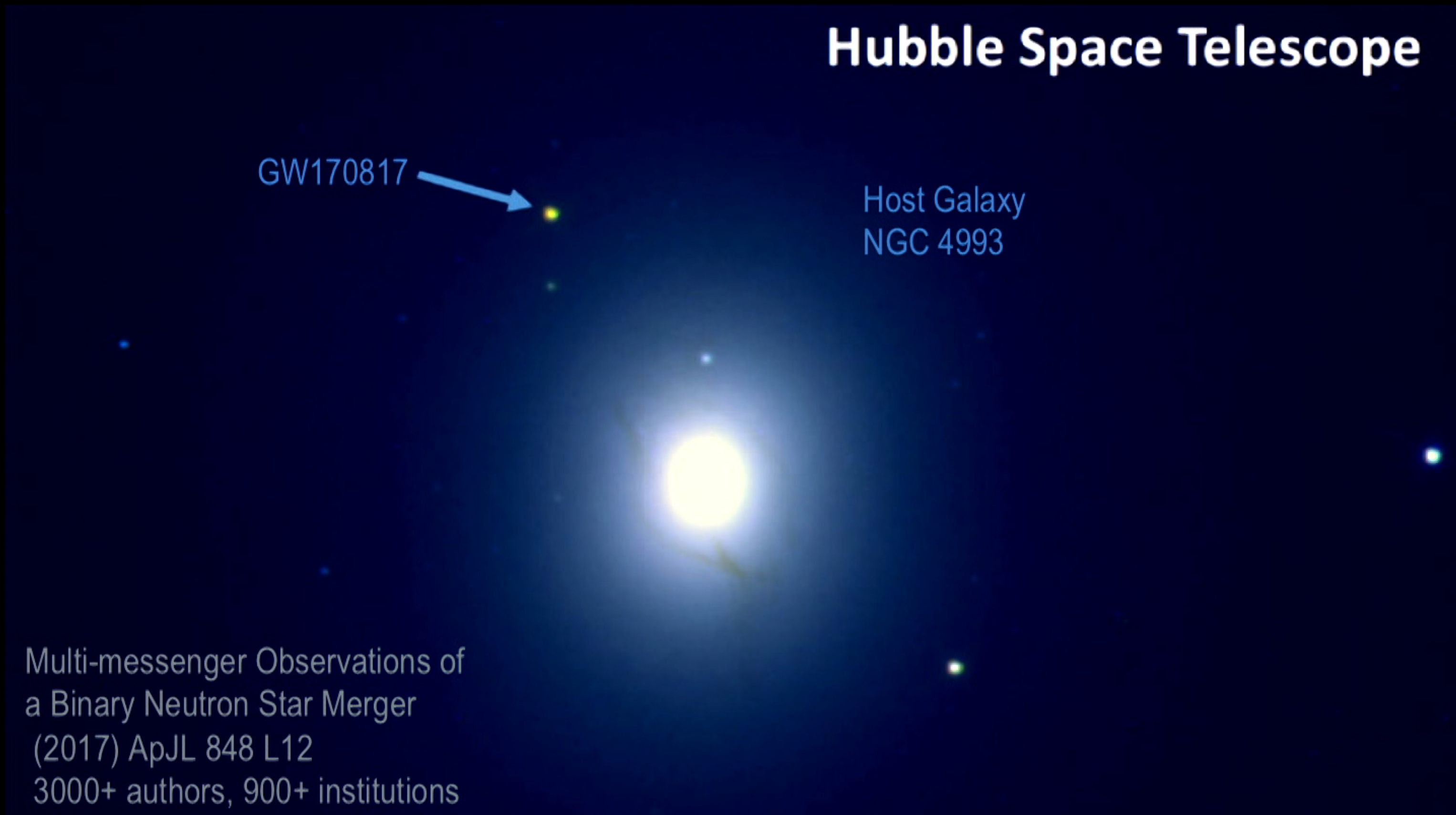


Visible | Infrared

Multi-messenger Observations of a Binary Neutron Star Merger
3000+ authors, 900+ institutions (2017) ApJL 848 L12


Periodic Table of the Elements
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
Yellow: Formed by Merging Neutron Stars
Apr, 2018
M. Evans, PI
11

Many, many images were made of GW170817
This is my favorite…



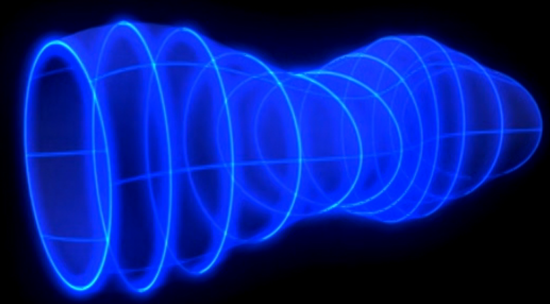
With the binary neutron star detection we have

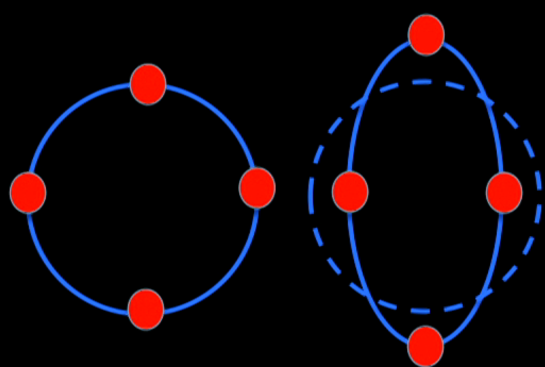
- Made first joint GW-EM source observation
- Linked short gamma-ray bursts to BNS and kilonovae
- Independently measured the local Hubble constant
- Measured the speed of gravitational-wave propagation
- Made initial constraints on the NS EOS
- Constrained the rate of BNS mergers in the local Universe (and thus their production of heavy metals)
- … the work on this event is ongoing.

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. LSC (2017) PRL 119, 161101

But what are gravitational waves?
And how do we detect them?

Gravitational Wave Strain

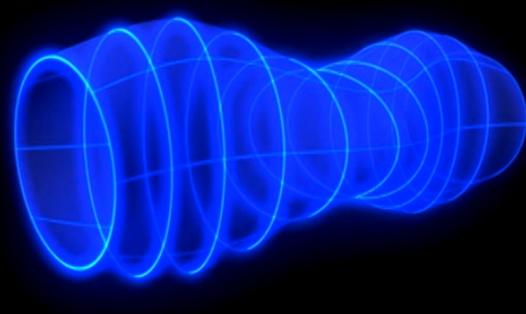


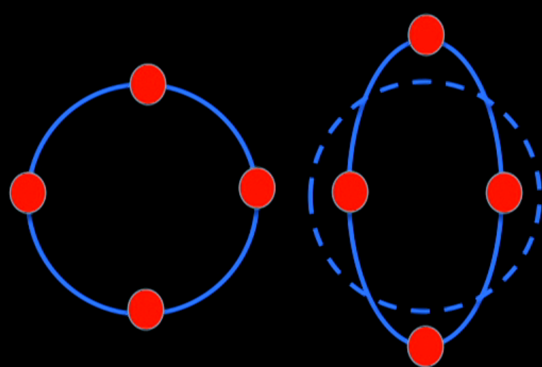


If you have masses that are free to move, you can (at least in principle) measure space-time distortion by watching how they move

Gravitational Wave Strain

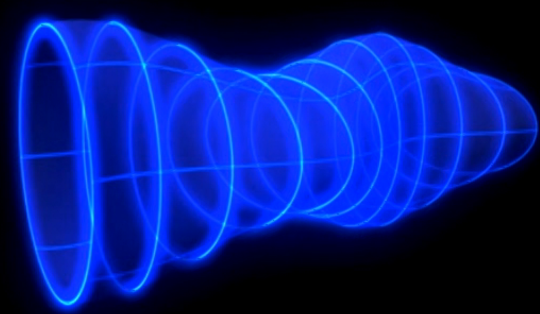
esa

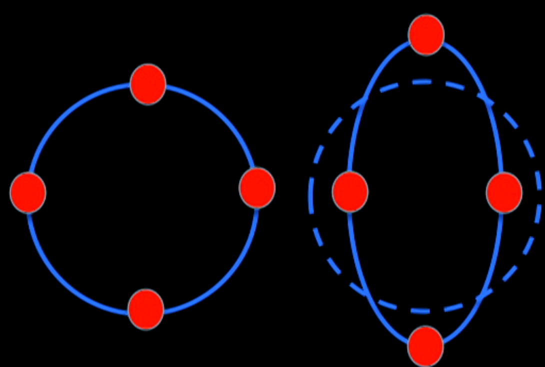




If you have masses that are free to move, you can (at least in principle) measure space-time distortion by watching how they move

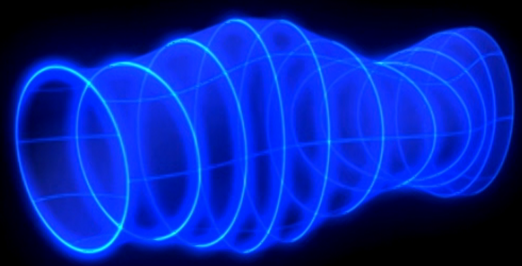
Gravitational Wave Strain

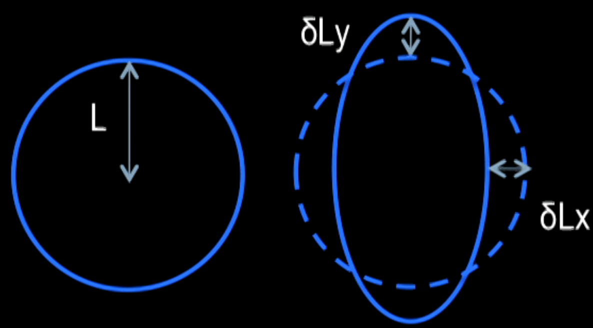




If you have masses that are free to move, you can (at least in principle) measure space-time distortion by watching how they move

Gravitational Wave Strain





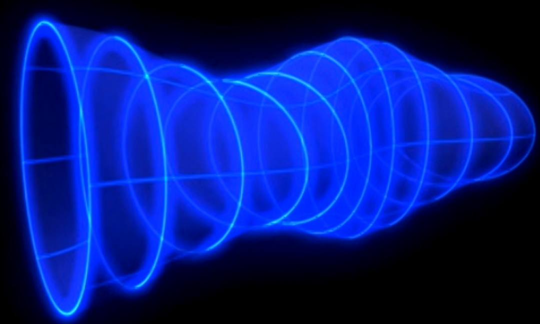
Strain over distance L

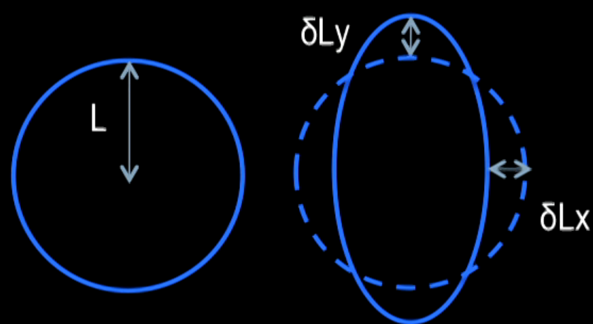
$$\frac{\Delta L}{L} = \frac{\delta L_x - \delta L_y}{L} = h$$

Amplitude of the gravitational wave

$$h \sim 10^{-21}$$

Gravitational Wave Strain





Strain over distance L

$$\frac{\Delta L}{L} = \frac{\delta L_x - \delta L_y}{L} = h$$

Amplitude of the gravitational wave

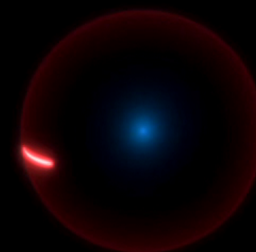
$$h \sim 10^{-21}$$

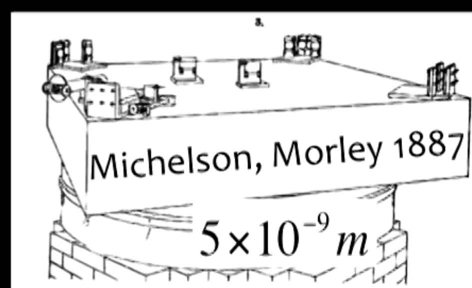
Need to measure VERY small displacements!

Even if you can make L very long (but reasonable for the surface of the Earth), let's say L = 4km, you still need to measure:

$$\Delta L = h \times L = 10^{-21} \times 4000 = 4 \times 10^{-18} m$$

4×10^{-18} m =
Proton diameter / 200

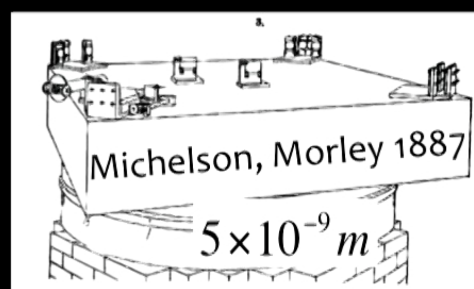




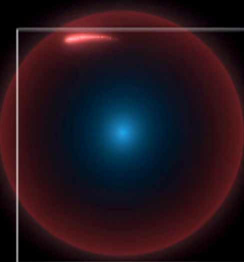
Need to measure VERY small displacements!

Even if you can make L very long (but reasonable for the surface of the Earth), let's say L = 4km, you still need to measure:

$$\Delta L = h \times L = 10^{-21} \times 4000 = 4 \times 10^{-18} m$$



4×10^{-18} m =
Proton diameter / 200



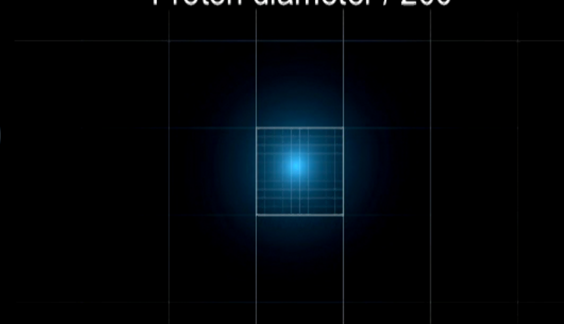
10^{-10} m

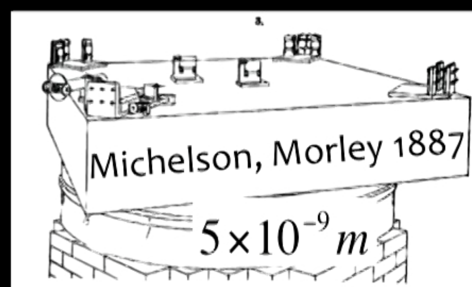
Need to measure VERY small displacements!

Even if you can make L very long (but reasonable for the surface of the Earth), let's say L = 4km, you still need to measure:

$$\Delta L = h \times L = 10^{-21} \times 4000 = 4 \times 10^{-18} m$$

4×10^{-18} m =
Proton diameter / 200





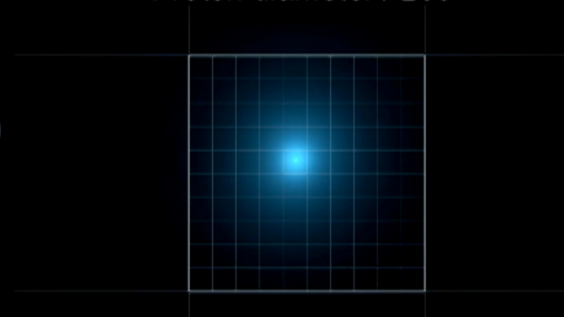
10^{-12} m

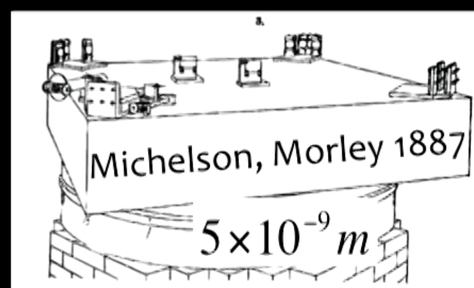
Need to measure VERY small displacements!

Even if you can make L very long (but reasonable for the surface of the Earth), let's say L = 4km, you still need to measure:

$$\Delta L = h \times L = 10^{-21} \times 4000 = 4 \times 10^{-18} m$$

4×10^{-18} m =
Proton diameter / 200





10^{-13} m

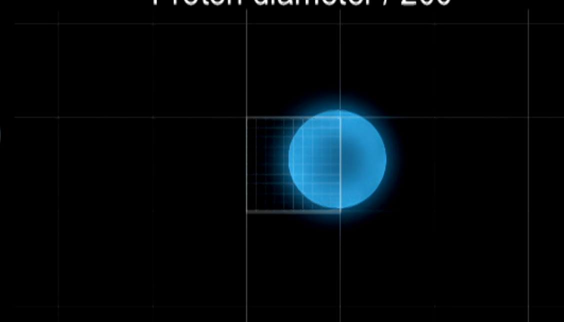
Apr, 2018 M. Evans, PI

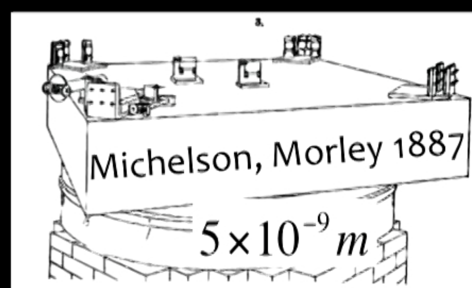
Need to measure VERY small displacements!

Even if you can make L very long (but reasonable for the surface of the Earth), let's say L = 4km, you still need to measure:

$$\Delta L = h \times L = 10^{-21} \times 4000 = 4 \times 10^{-18} m$$

4×10^{-18} m =
Proton diameter / 200





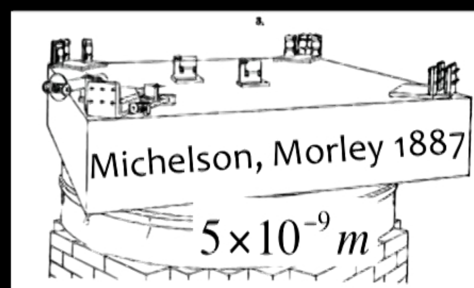
10^{-15} m

Need to measure VERY small displacements!

Even if you can make L very long (but reasonable for the surface of the Earth), let's say L = 4km, you still need to measure:

$$\Delta L = h \times L = 10^{-21} \times 4000 = 4 \times 10^{-18} m$$

4×10^{-18} m =
Proton diameter / 200



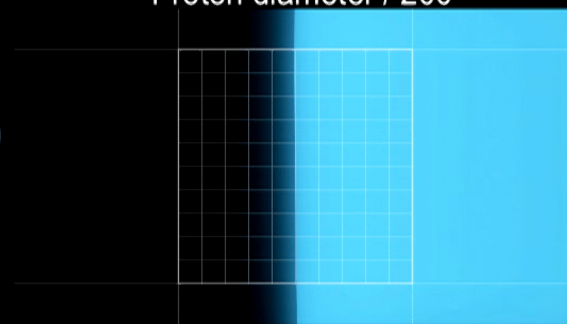
10^{-16} m

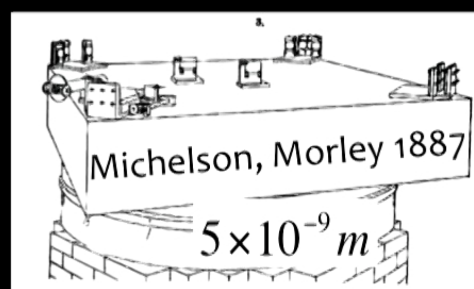
Need to measure VERY small displacements!

Even if you can make L very long (but reasonable for the surface of the Earth), let's say L = 4km, you still need to measure:

$$\Delta L = h \times L = 10^{-21} \times 4000 = 4 \times 10^{-18} m$$

4×10^{-18} m =
Proton diameter / 200





10^{-17} m

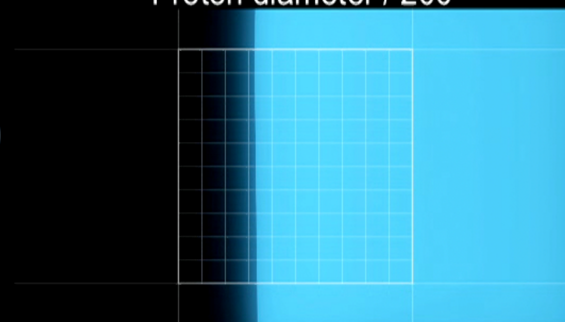
Apr, 2018 M. Evans, PI 17

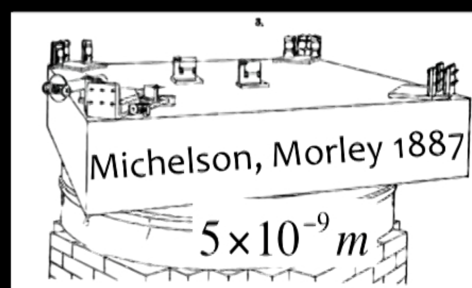
Need to measure VERY small displacements!

Even if you can make L very long (but reasonable for the surface of the Earth), let's say L = 4km, you still need to measure:

$$\Delta L = h \times L = 10^{-21} \times 4000 = 4 \times 10^{-18} m$$

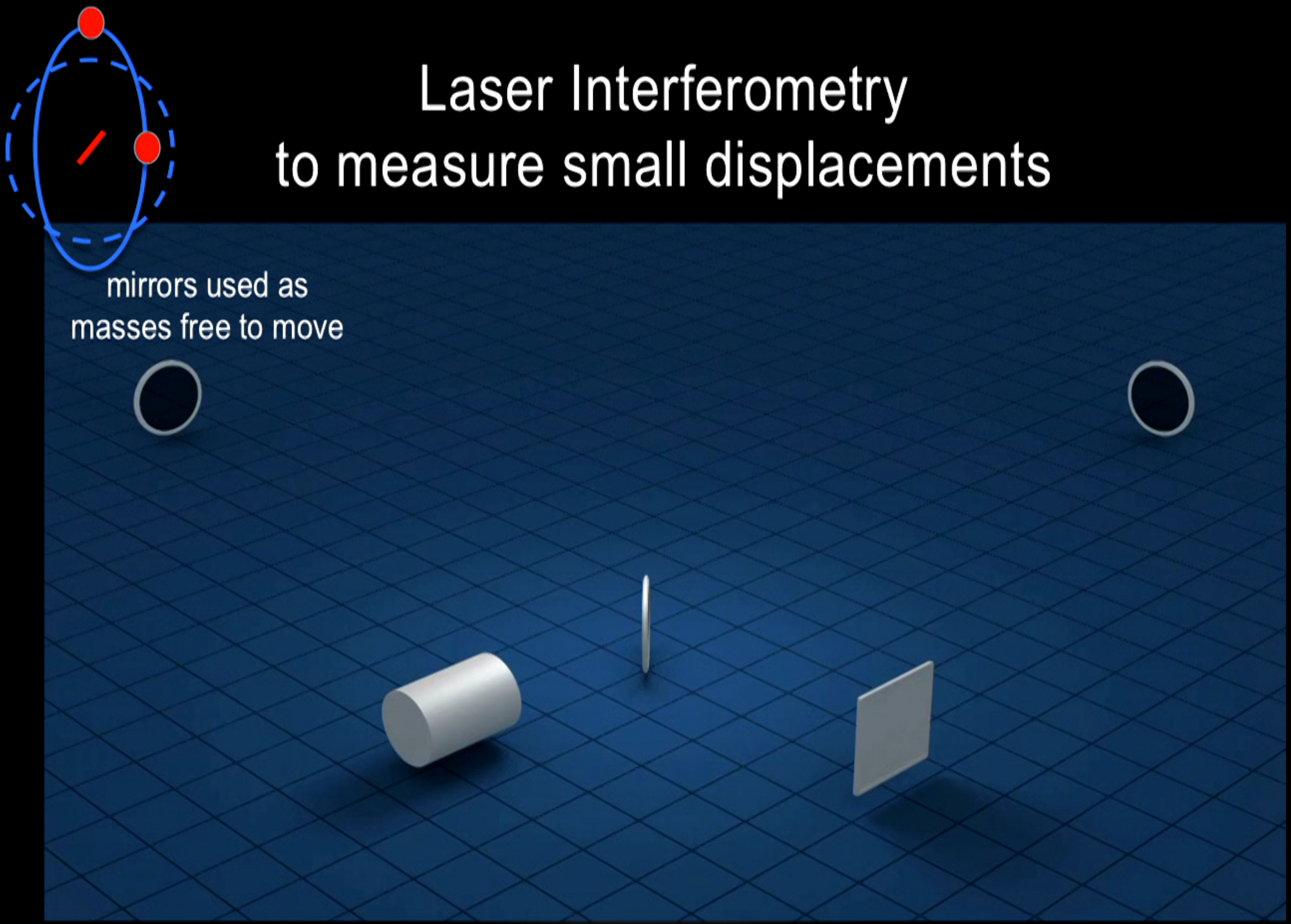
4×10^{-18} m =
Proton diameter / 200



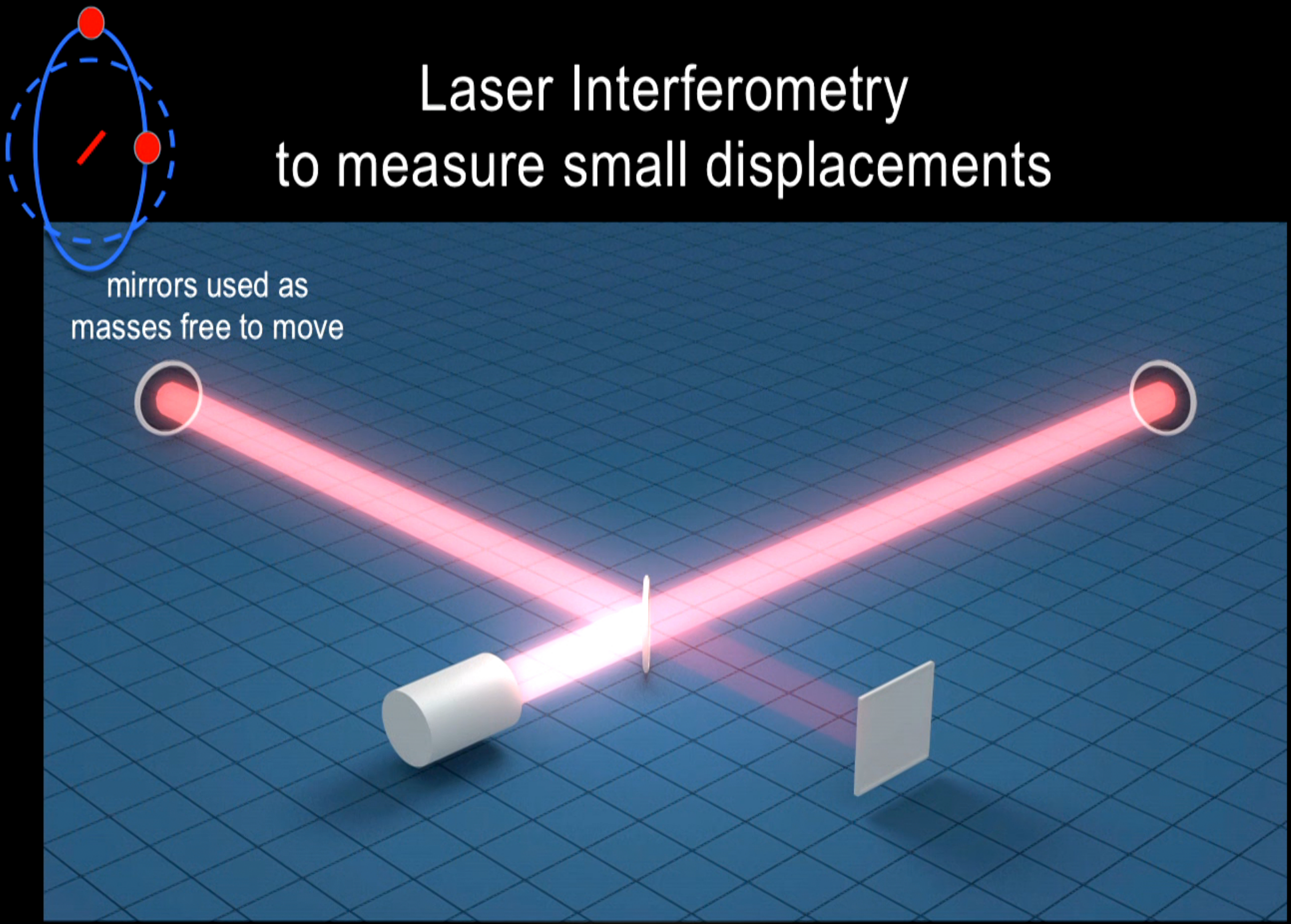


10^{-17} m

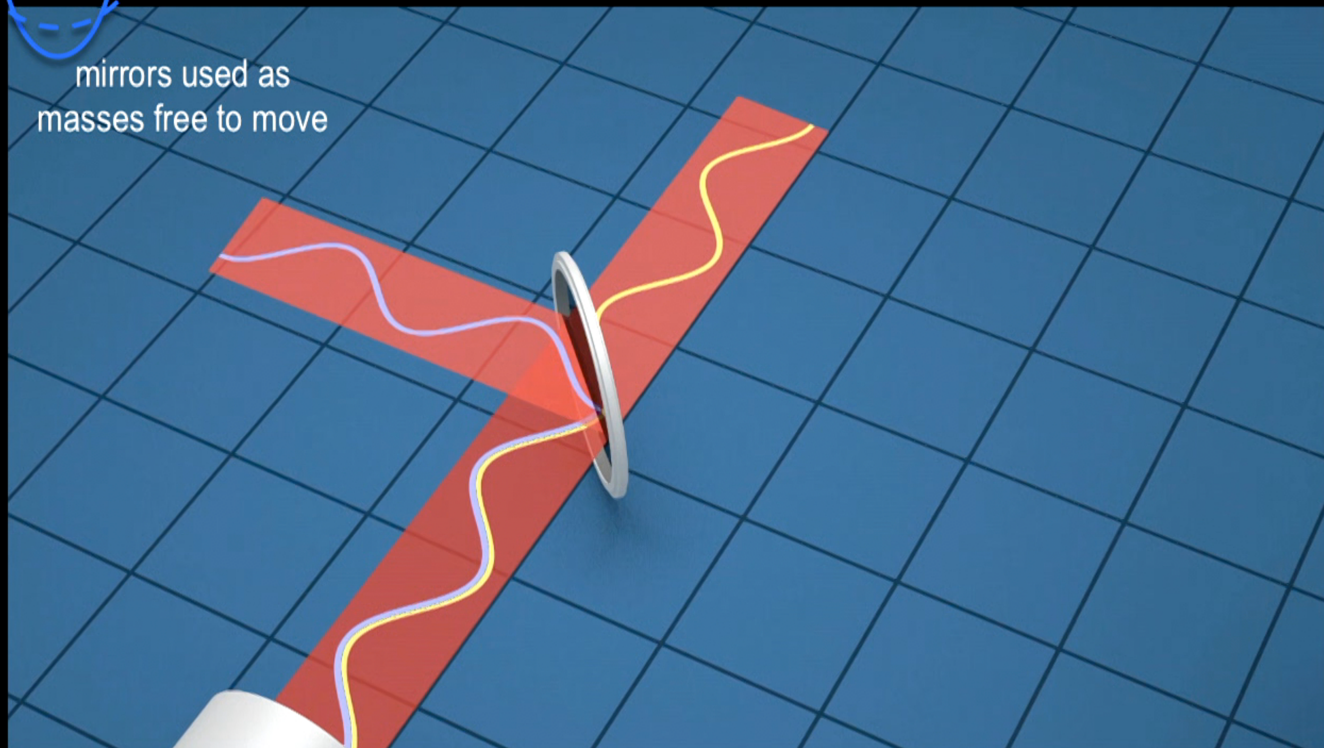
Laser Interferometry
to measure small displacements



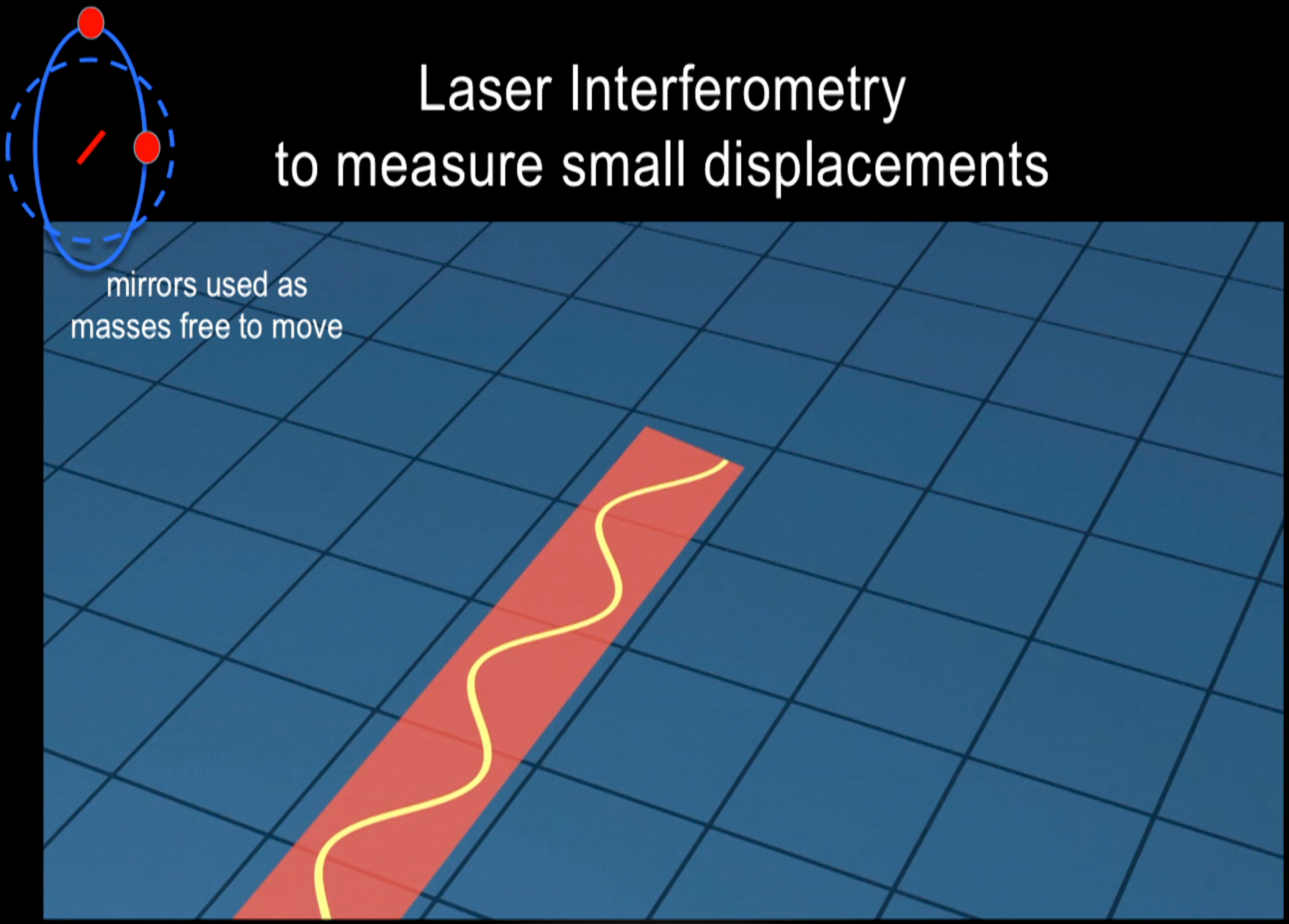
Laser Interferometry
to measure small displacements



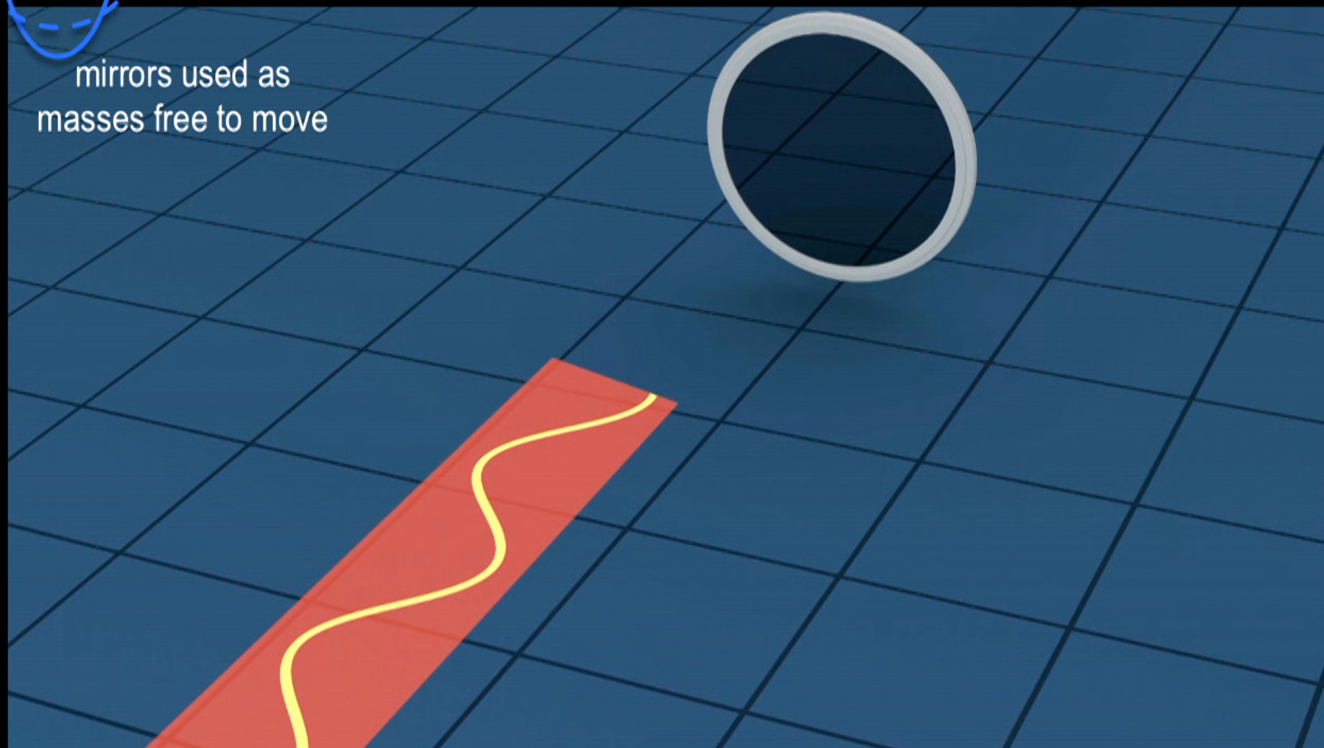
Laser Interferometry
to measure small displacements

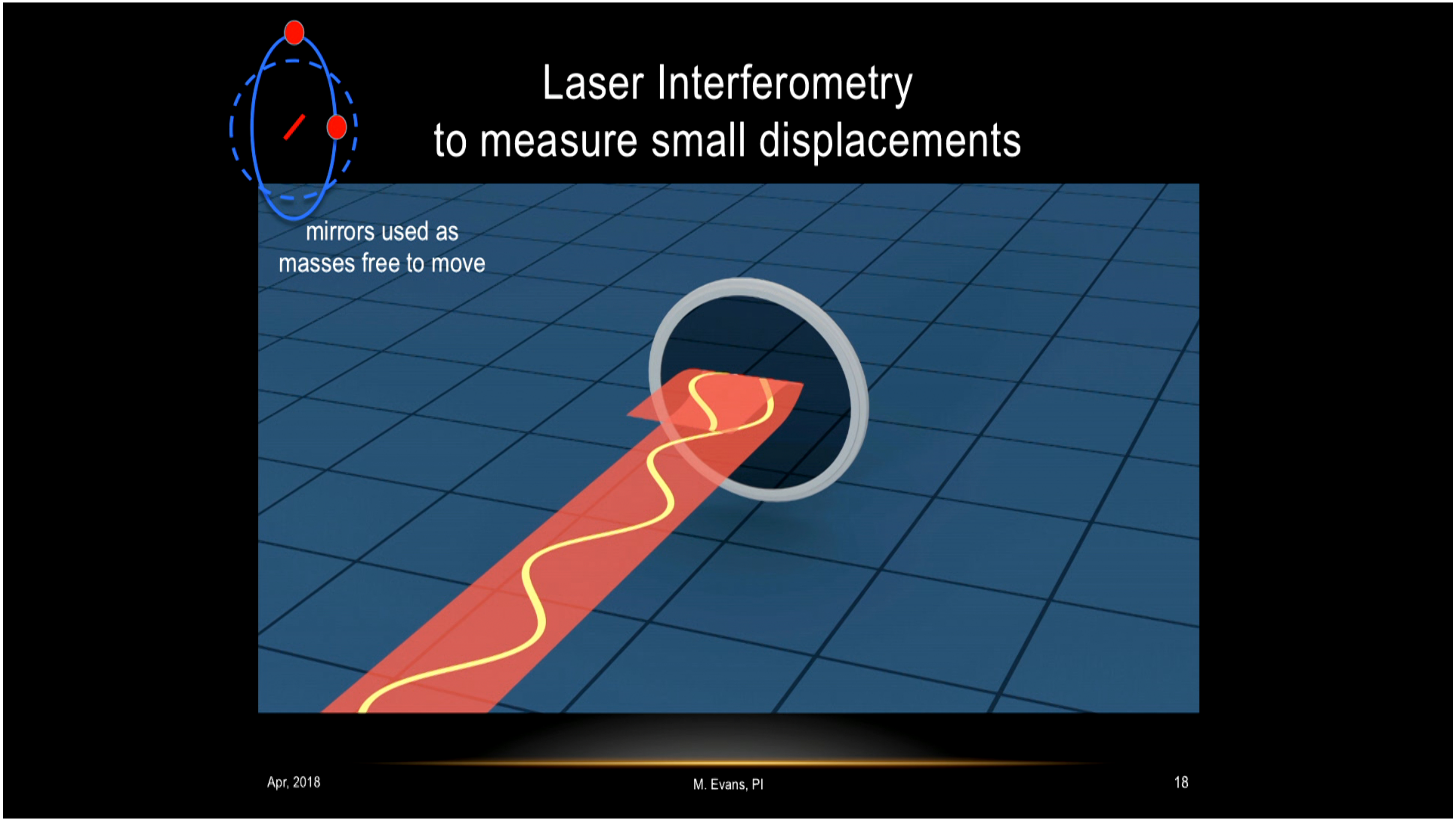


Laser Interferometry
to measure small displacements



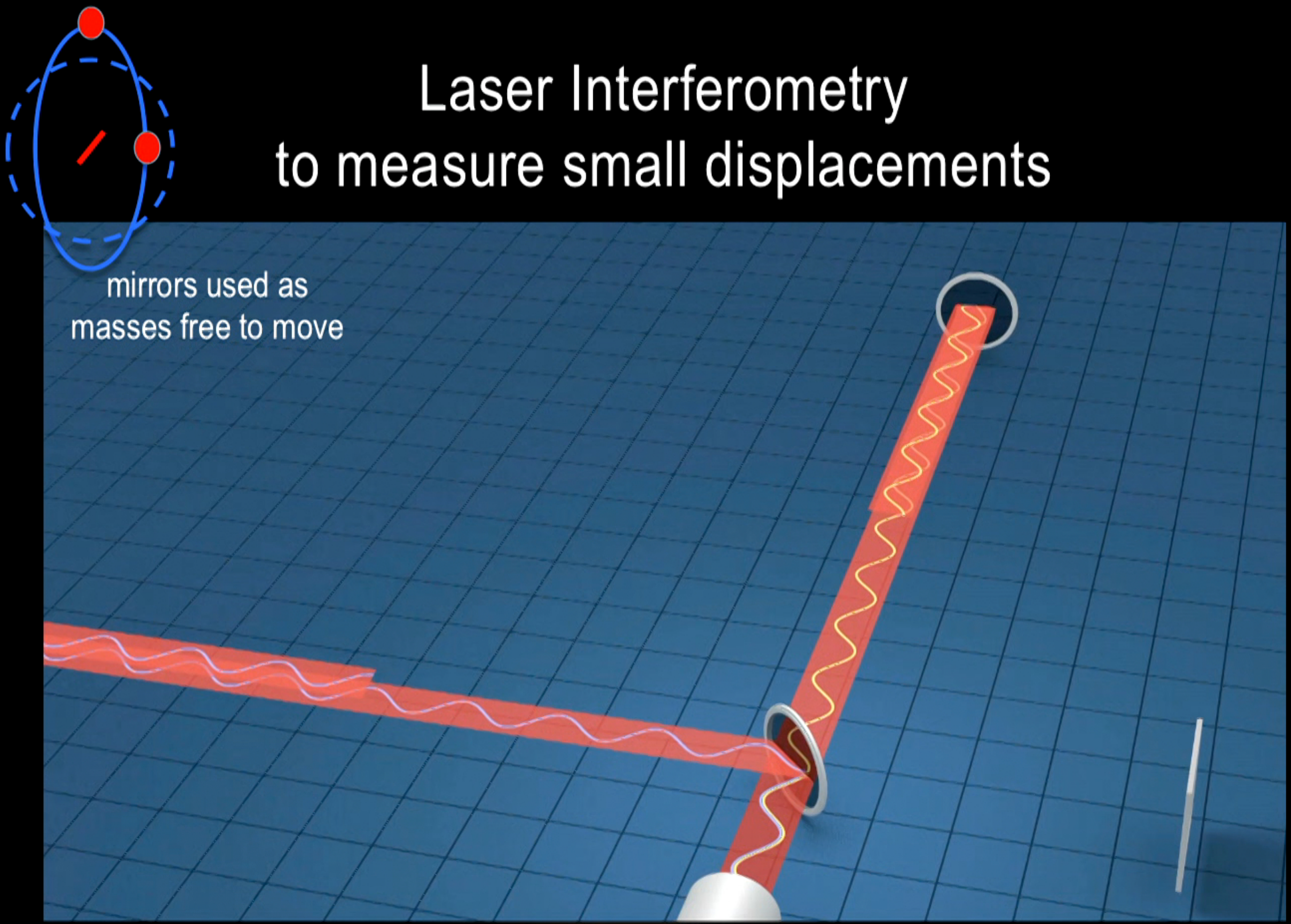
Laser Interferometry
to measure small displacements



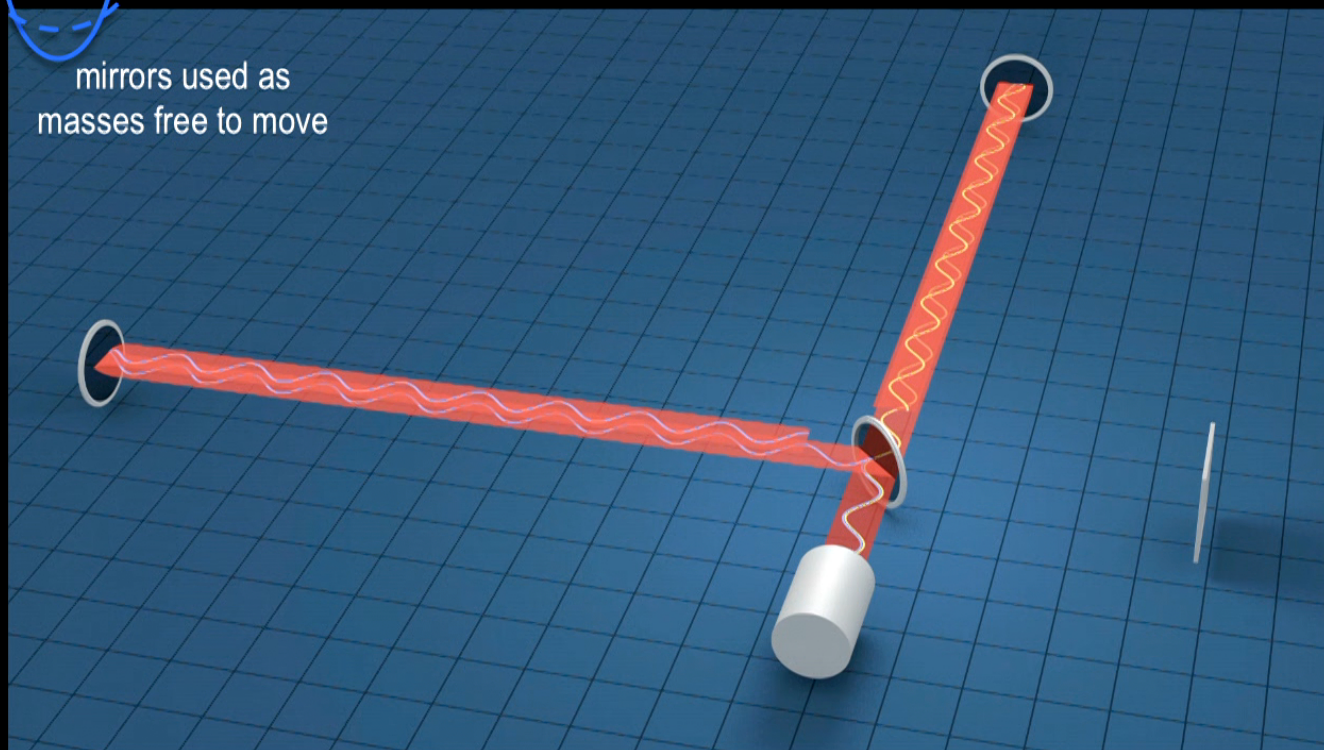


Laser Interferometry
to measure small displacements
mirrors used as
masses free to move
Apr, 2018
M. Evans, PI
18

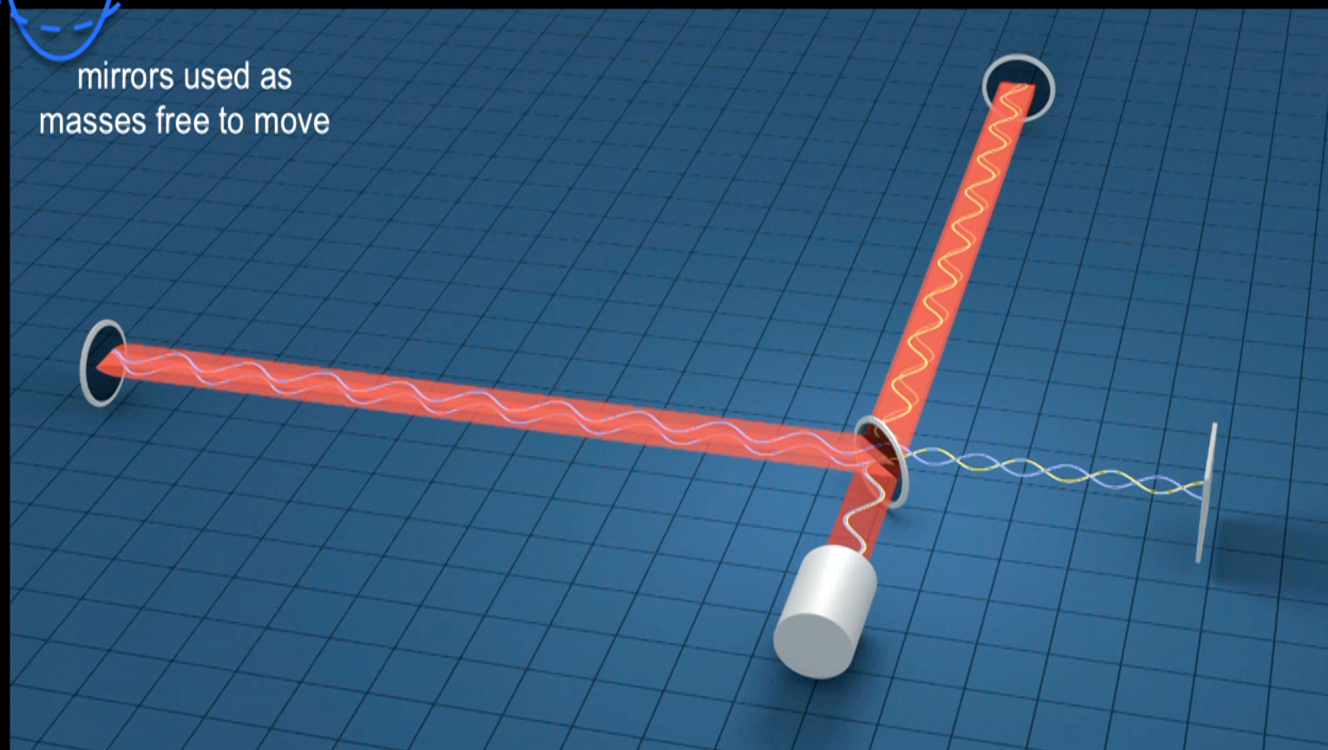
Laser Interferometry
to measure small displacements



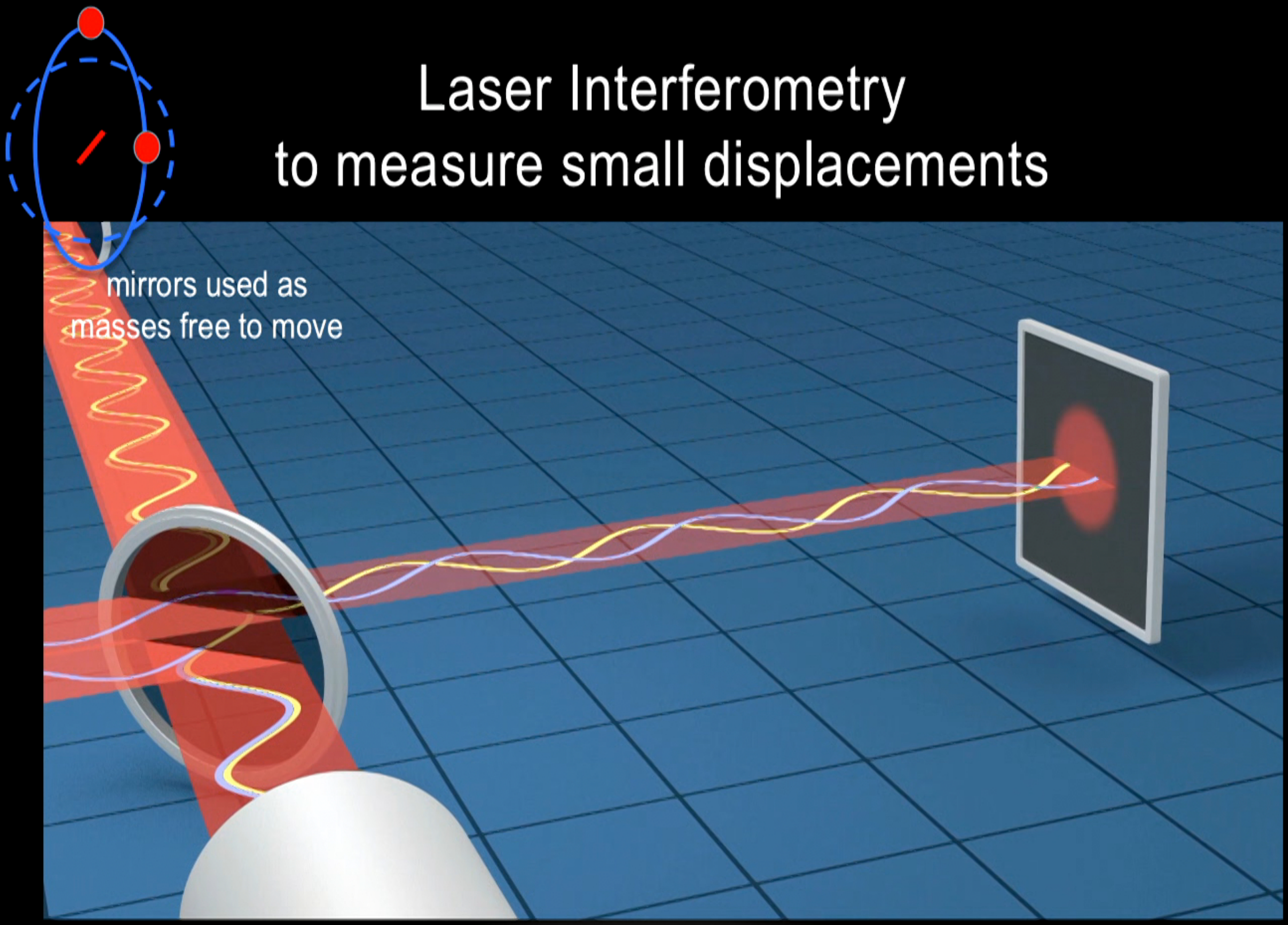
Laser Interferometry
to measure small displacements

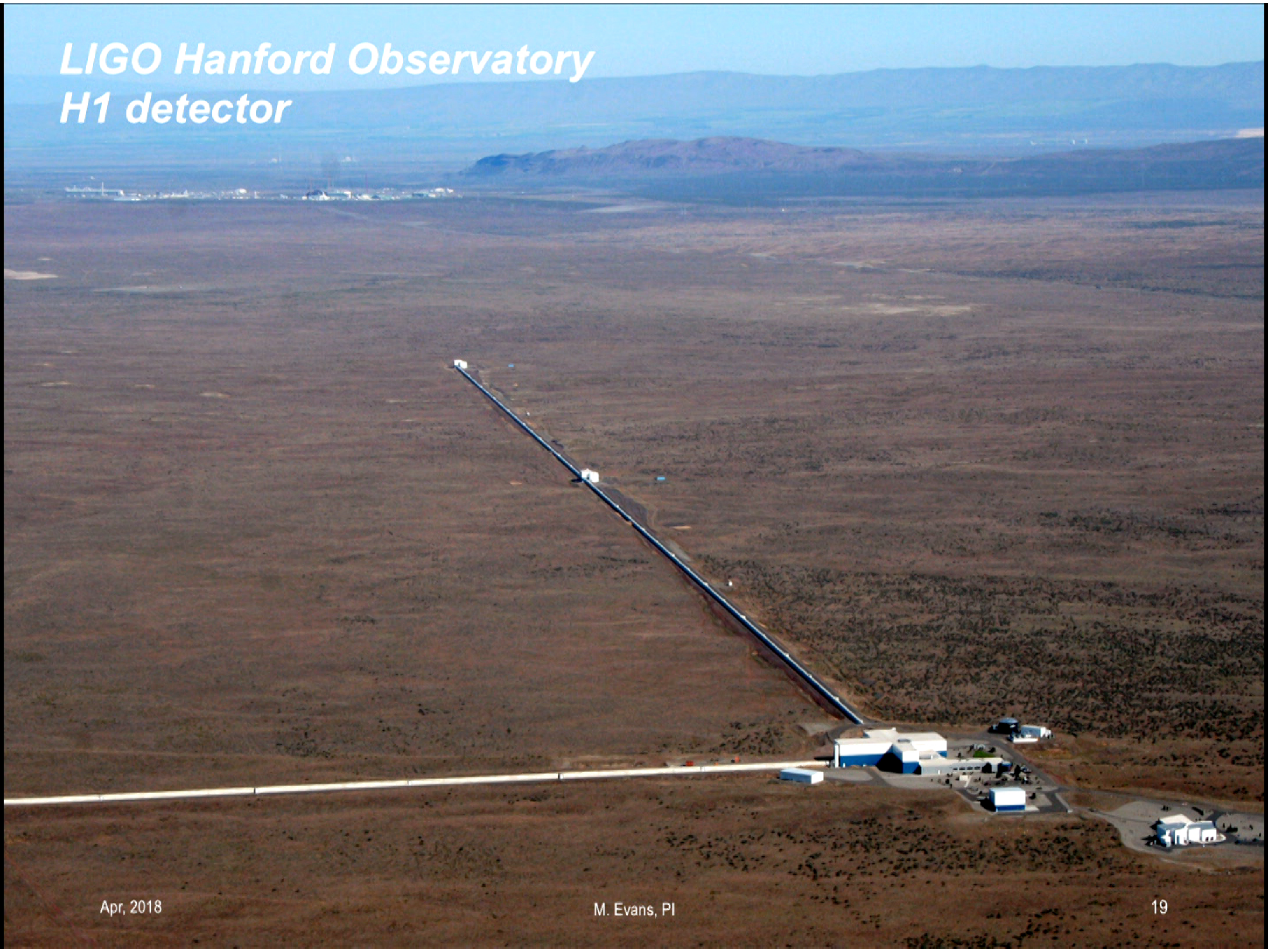


Laser Interferometry
to measure small displacements



Laser Interferometry
to measure small displacements



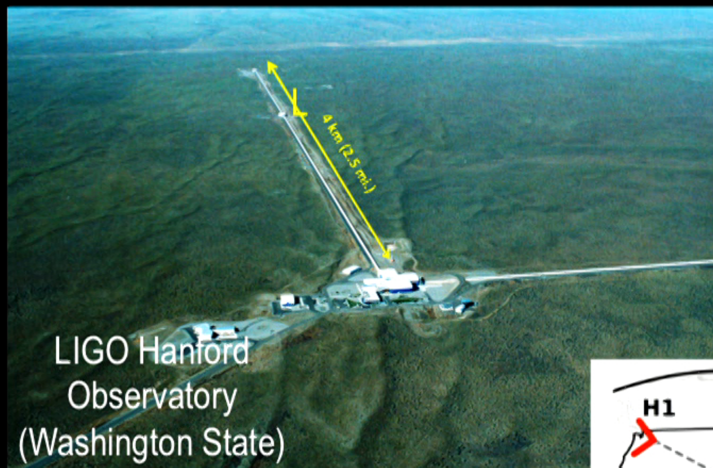


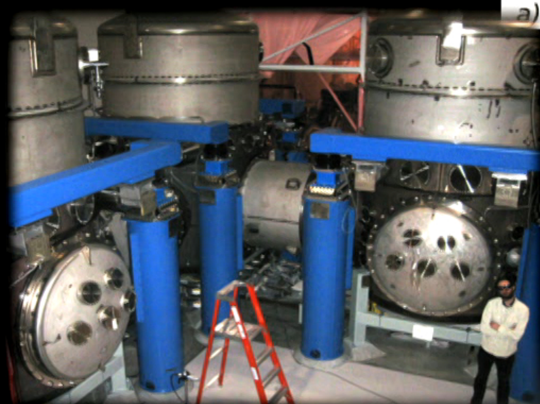
LIGO Hanford Observatory
H1 detector
Apr, 2018
M. Evans, PI
19

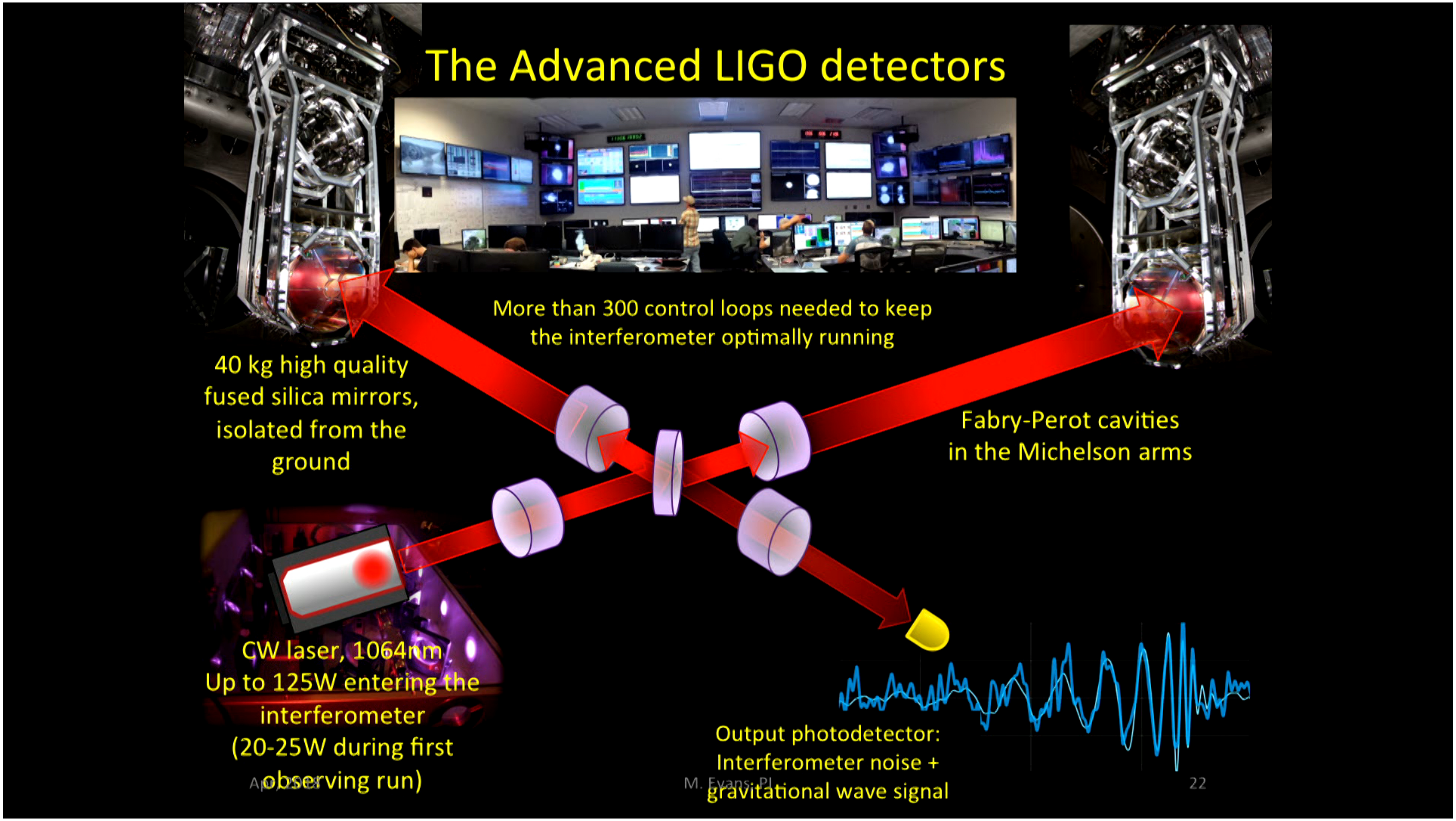

LIGO Livingston Observatory
L1 detector
Apr. 2018
M. Evans, PI
20


LIGO Livingston Observatory
L1 detector
Apr. 2018
M. Evans, PI
20

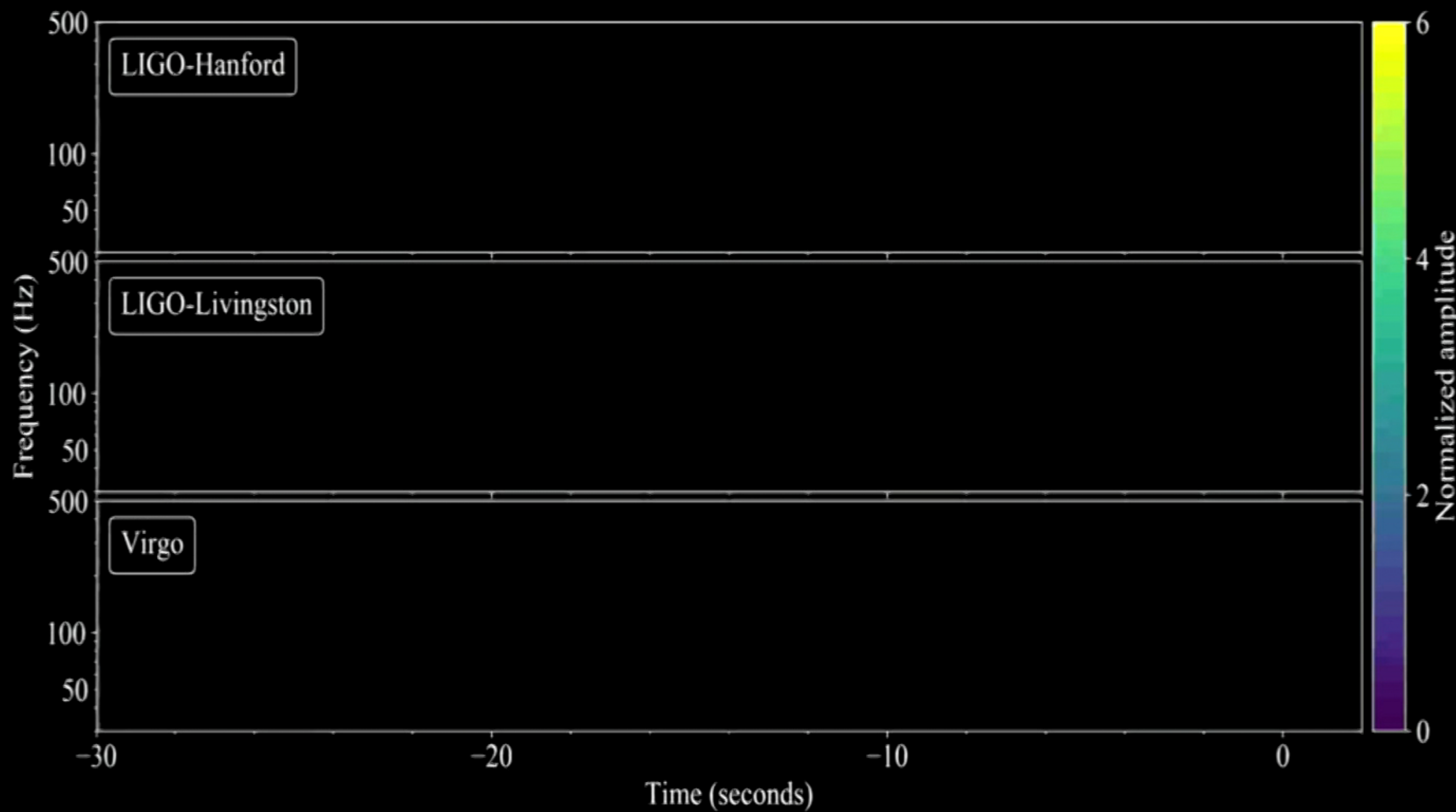
2 LIGO Observatories, each with one laser interferometer with 4 km arms



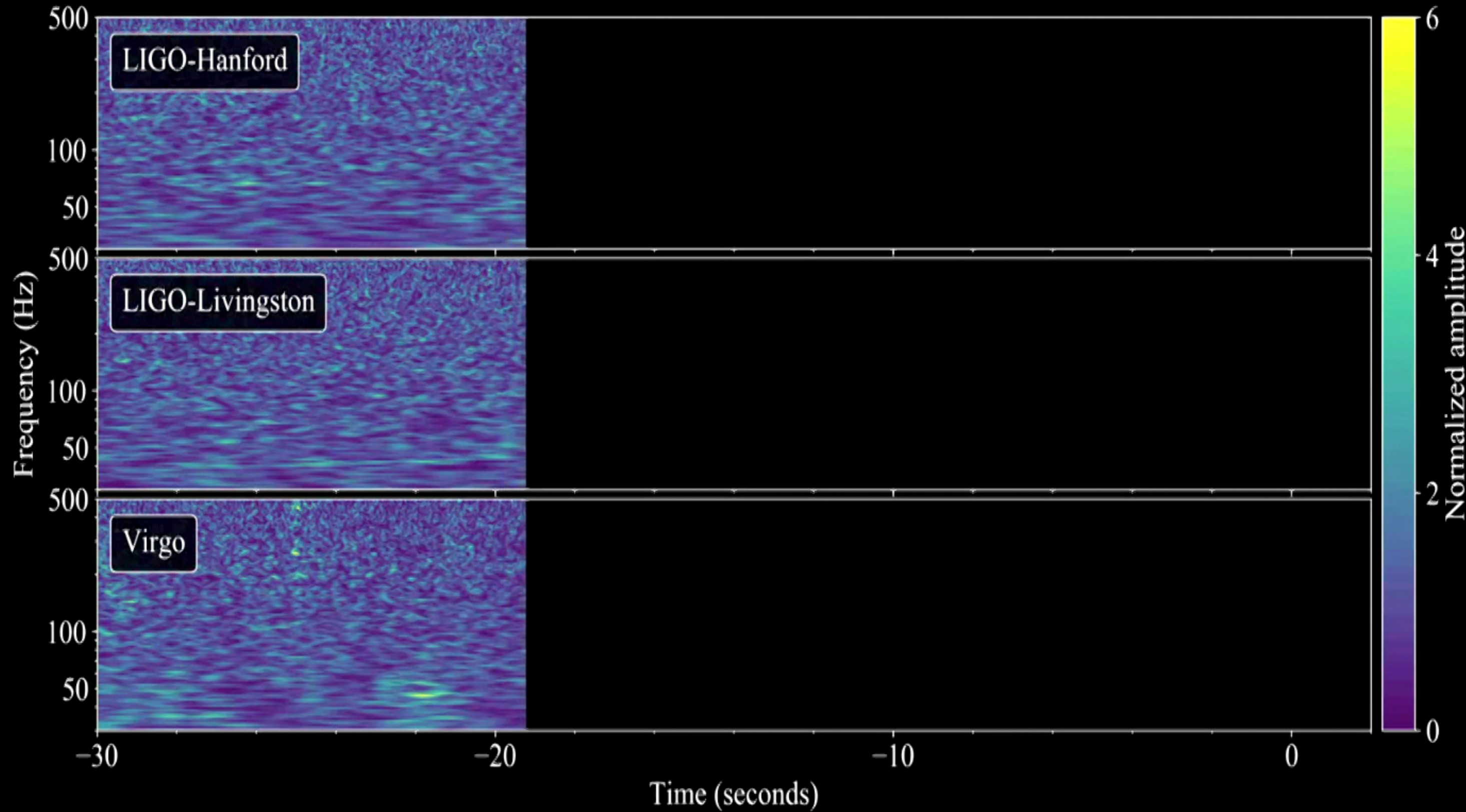



The Advanced LIGO detectors
More than 300 control loops needed to keep the interferometer optimally running
40 kg high quality fused silica mirrors, isolated from the ground
Fabry-Perot cavities in the Michelson arms
CW laser, 1064nm
Up to 125W entering the interferometer
(20-25W during first observing run)
Output photodetector: Interferometer noise + gravitational wave signal
M. Evans, PI
22

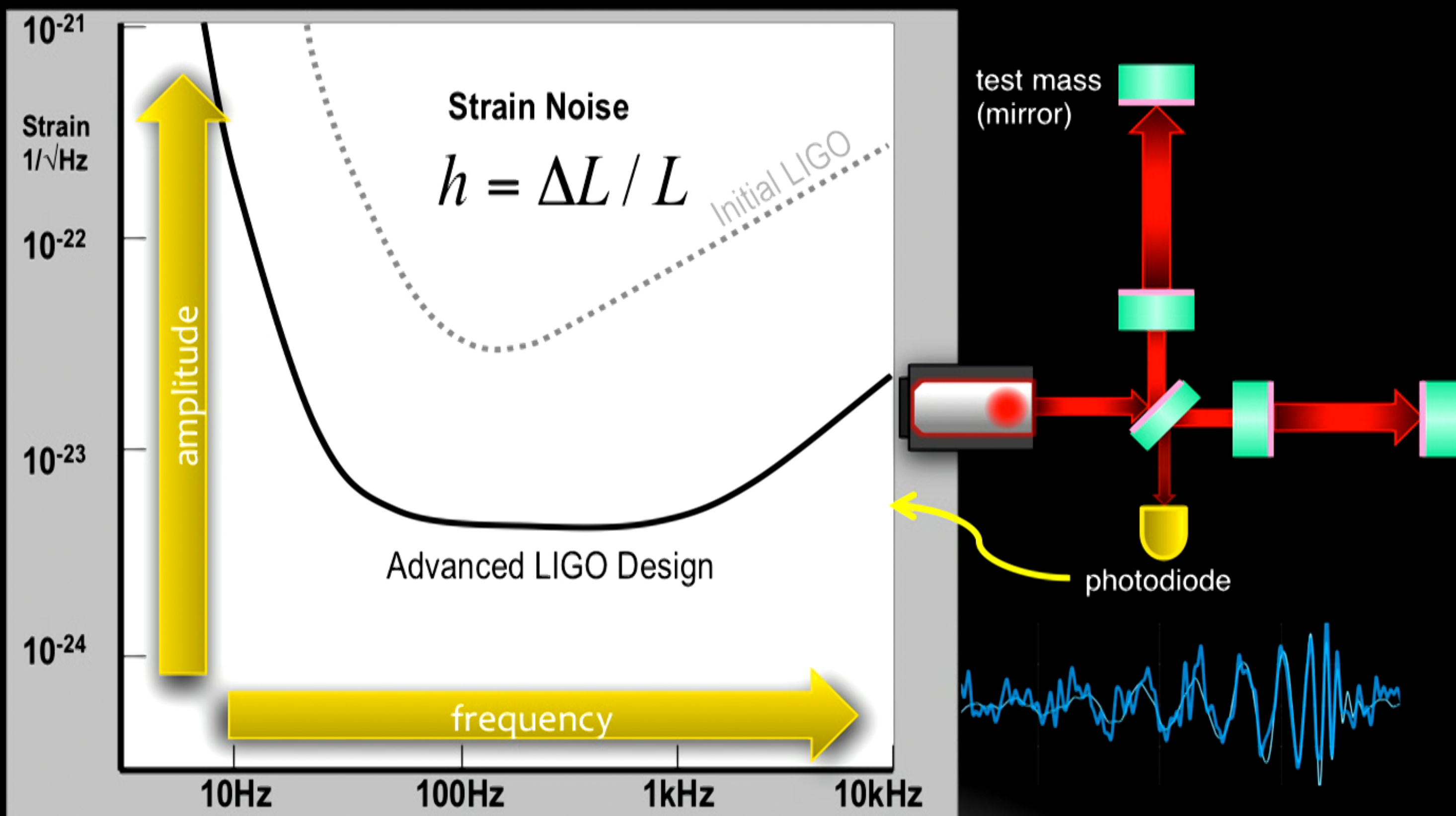
The BNS signal, with and without noise…



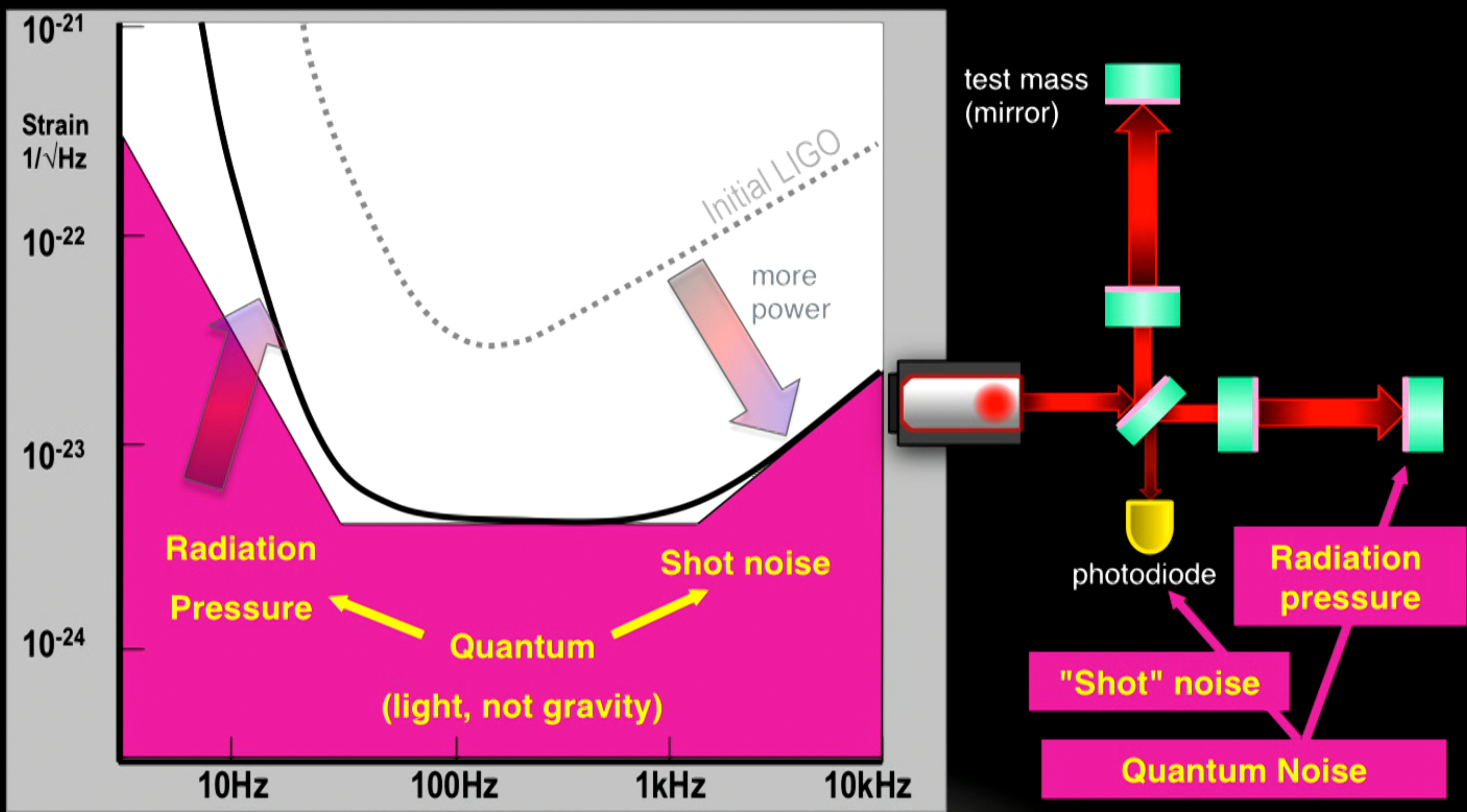
The BNS signal, with and without noise…



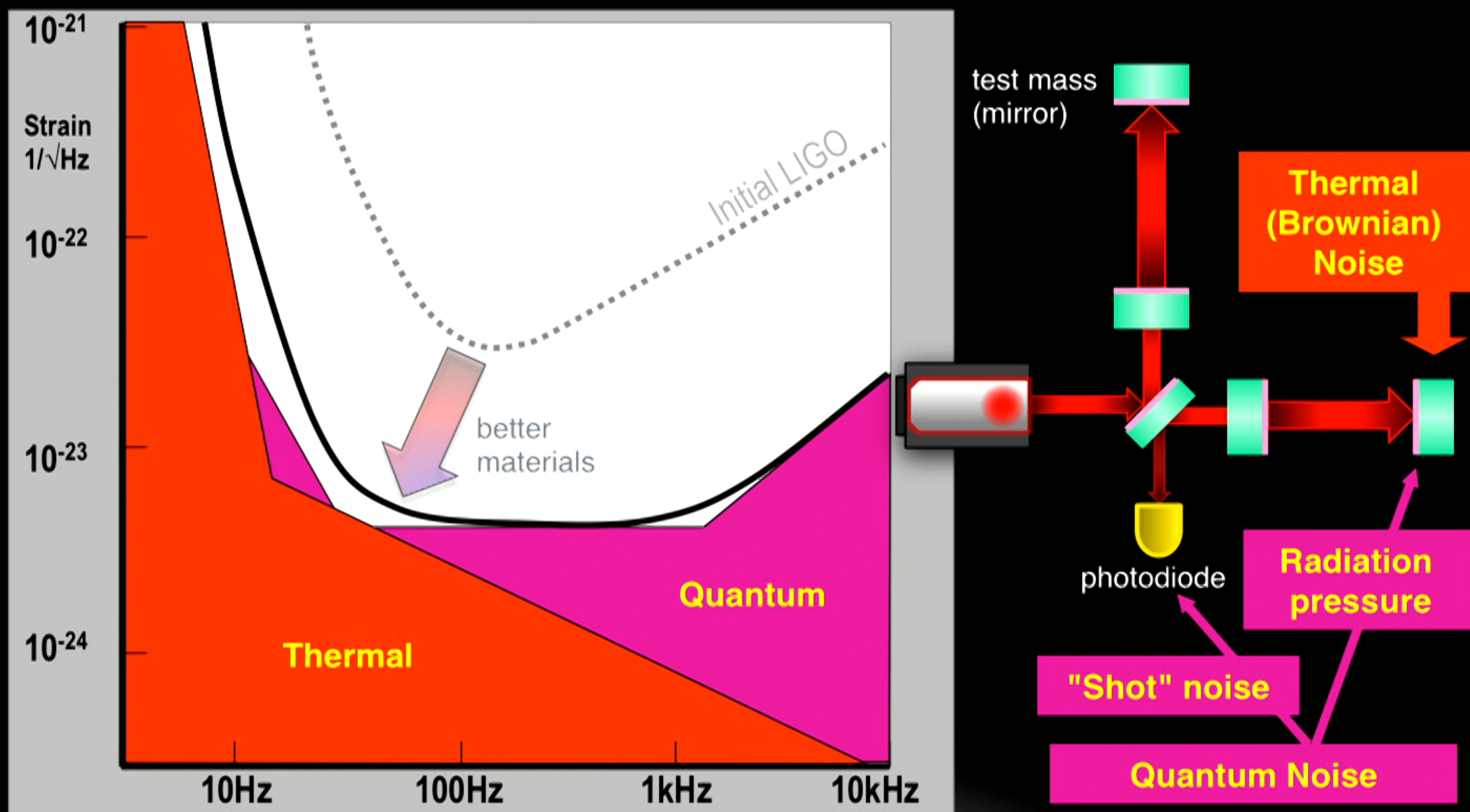
Advanced LIGO Noise, in the Frequency Domain



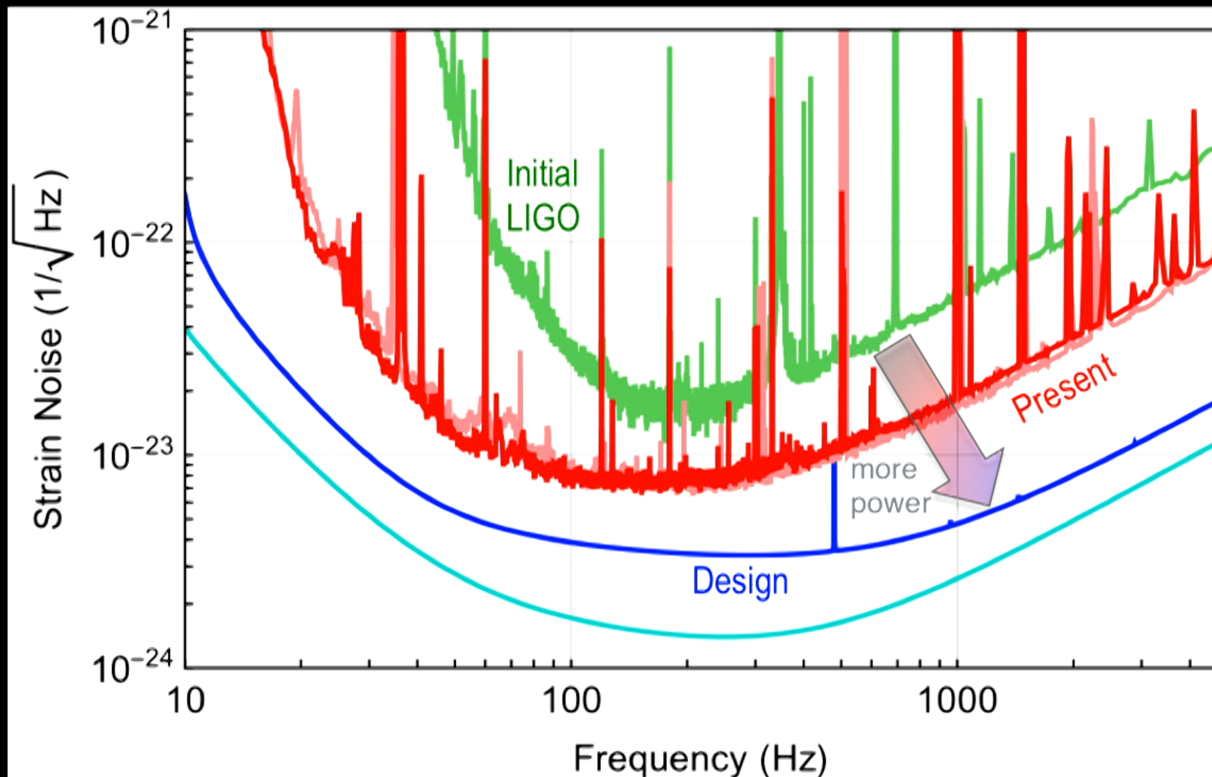
Quantum Noise:
Shot Noise and Radiation Pressure Noise



Thermal Noise

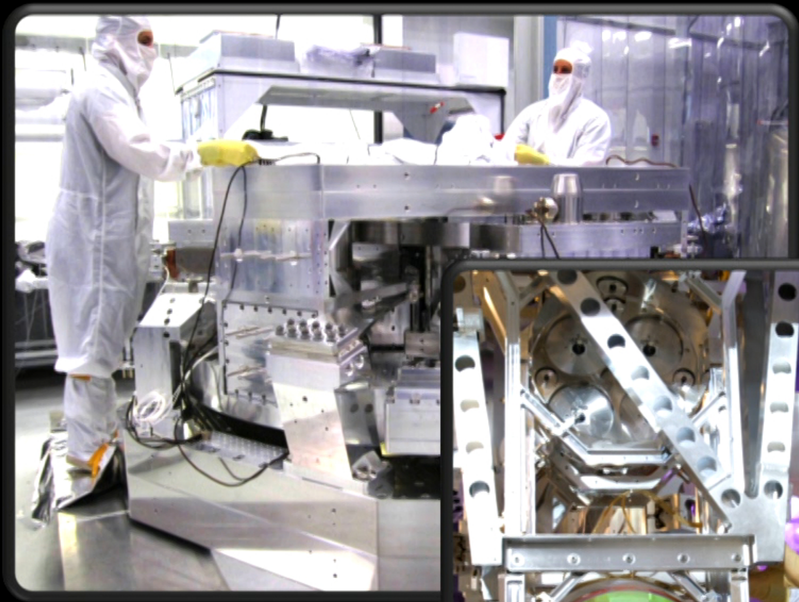


Advanced LIGO Noise: Progress

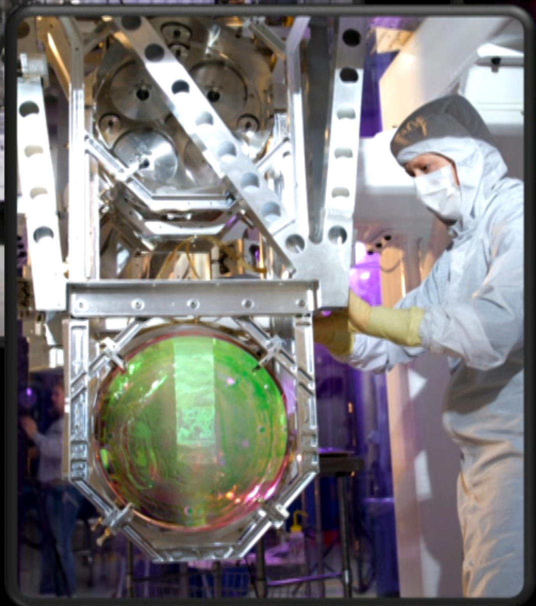


GW150914: The Advanced LIGO Detectors in the Era of First Discoveries. LSC (2016) PRL 116, 131103

Better isolation

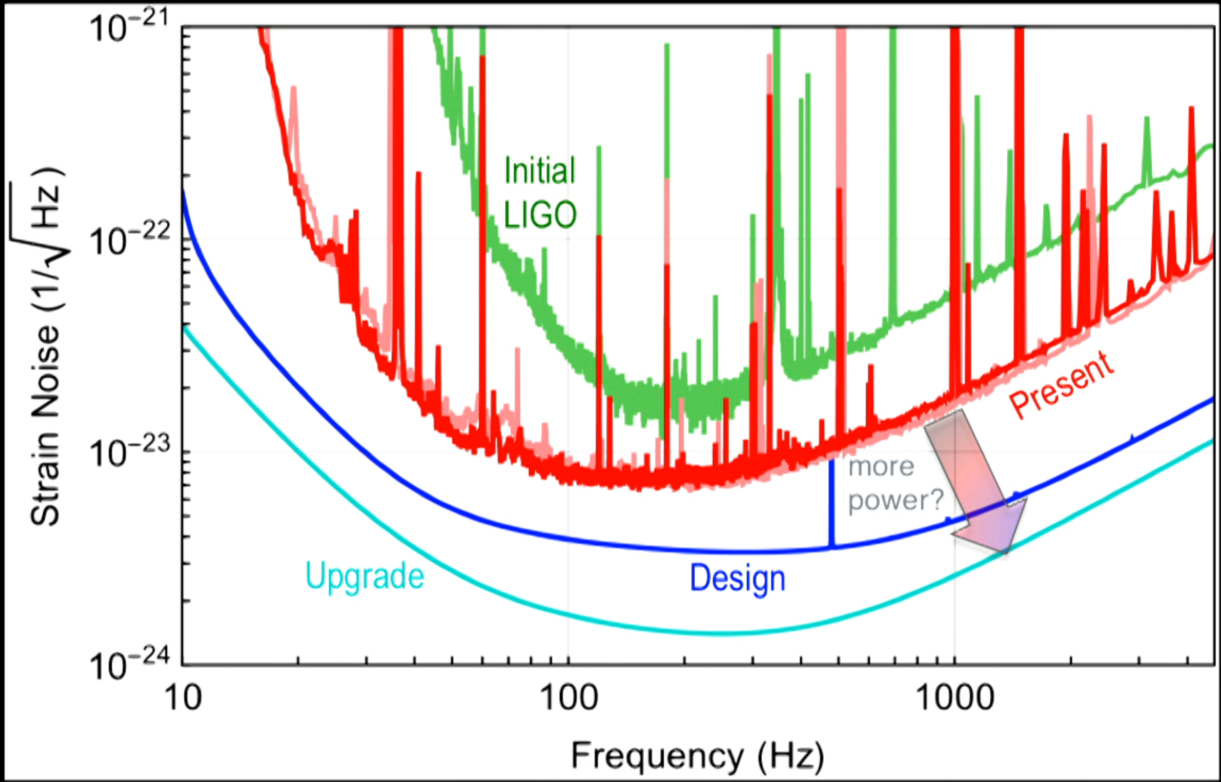


More laser power



Better coatings

Advanced LIGO Noise: Progress



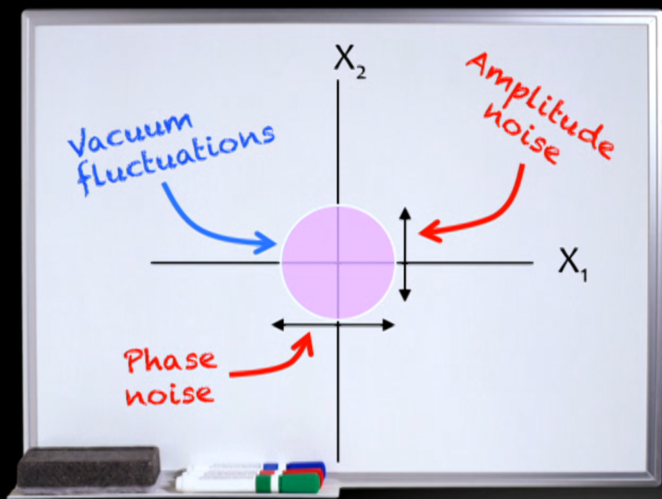
GW150914: The Advanced LIGO Detectors in the Era of First Discoveries. LSC (2016) PRL 116, 131103

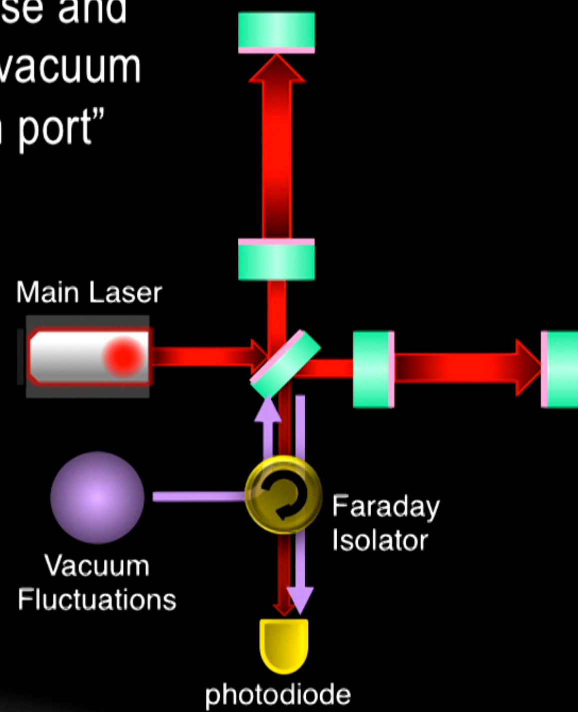
Squeezing Light to Reduced Quantum Noise

- We can’t continue to increase the power in the interferometer beyond Advanced LIGO design due to
  - thermal effects
  - radiation pressure driven instabilities
  - quantum radiation pressure noise
- How can we improve?
  - to understand the answer, we have to start from the beginning…

What is Quantum Noise?

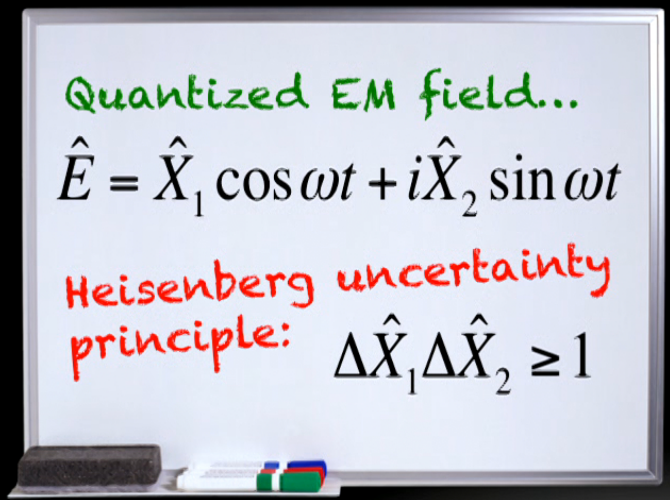
- Quantum optics tells us that shot noise and radiation pressure noise result from vacuum fluctuations that enter at every “open port”

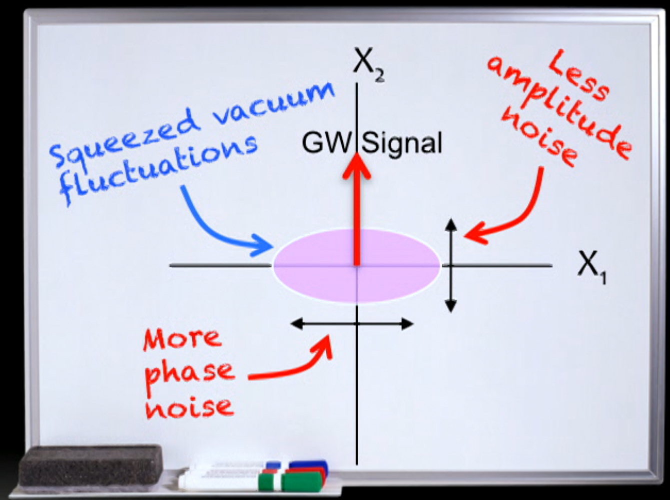




So, what can we do about it?

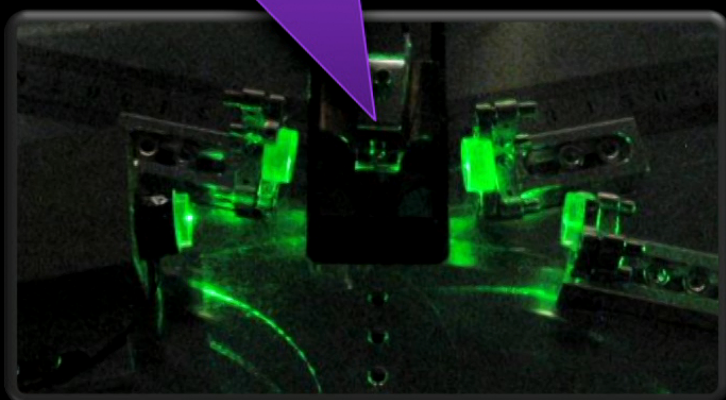
- Heisenberg says we can't make the noise smaller, but we can change its shape.
- Can we use a squeezed vacuum state in our detector?

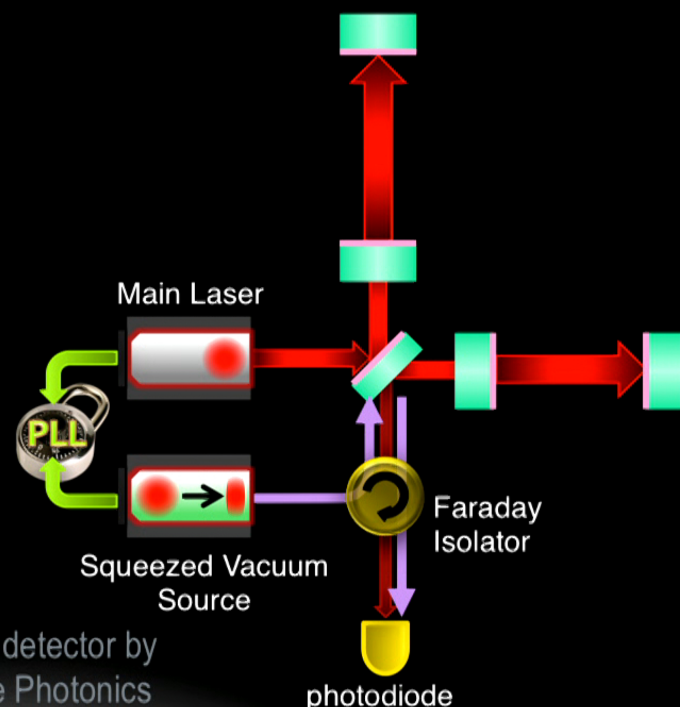




In theory, sure… but in practice?

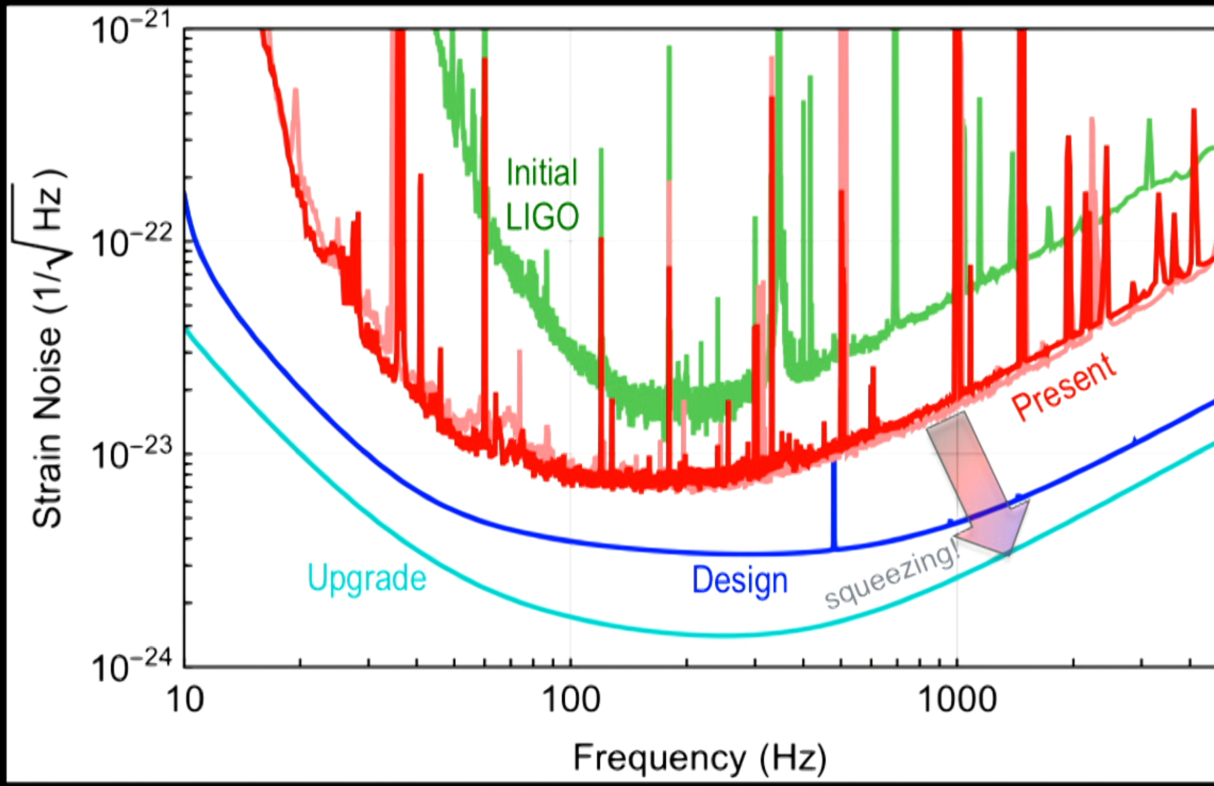
Nonlinear crystal creates entangled photon pairs by parametric down-conversion





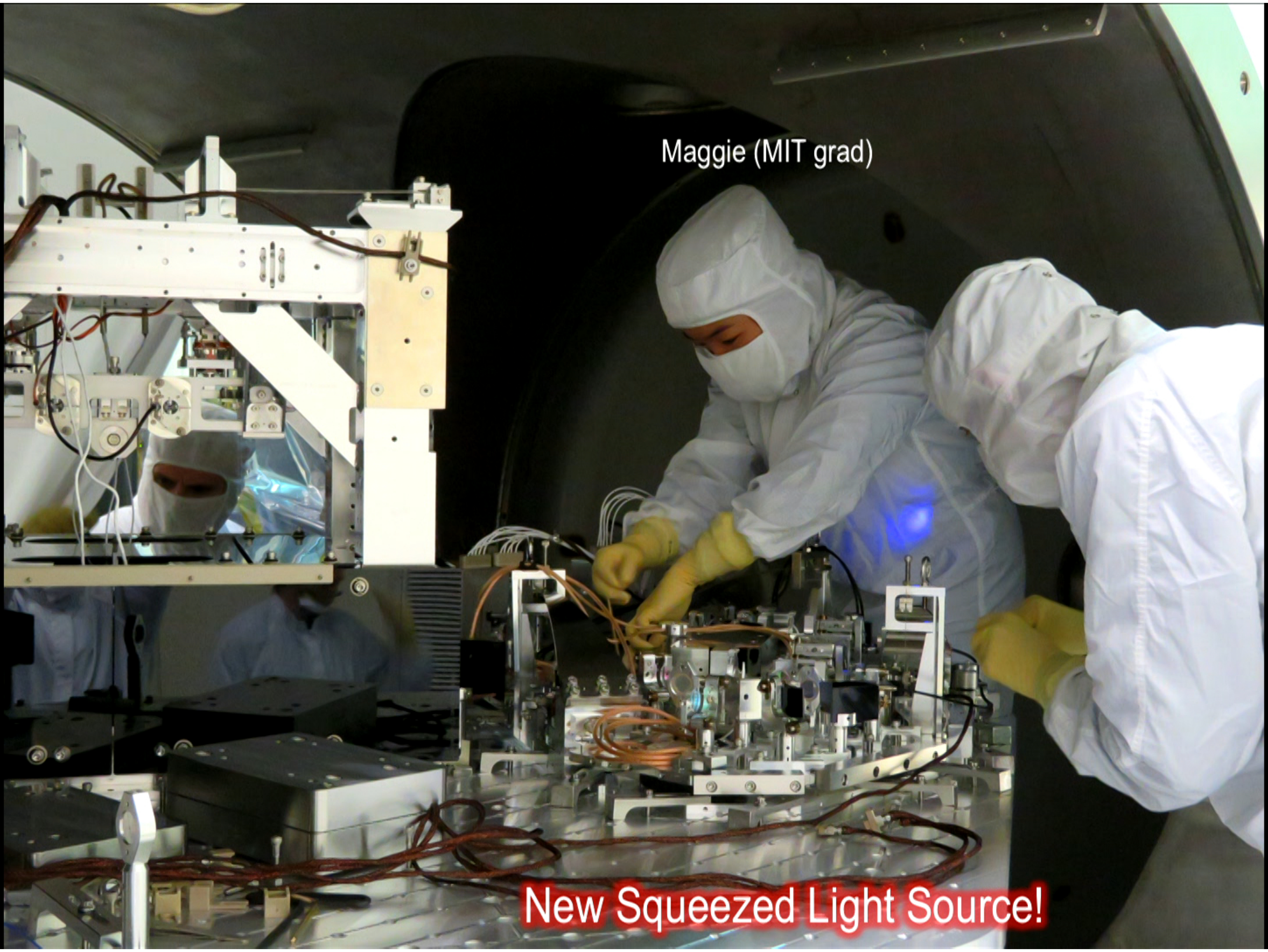
Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light. LSC (2015) Nature Photonics

Advanced LIGO Noise: Progress



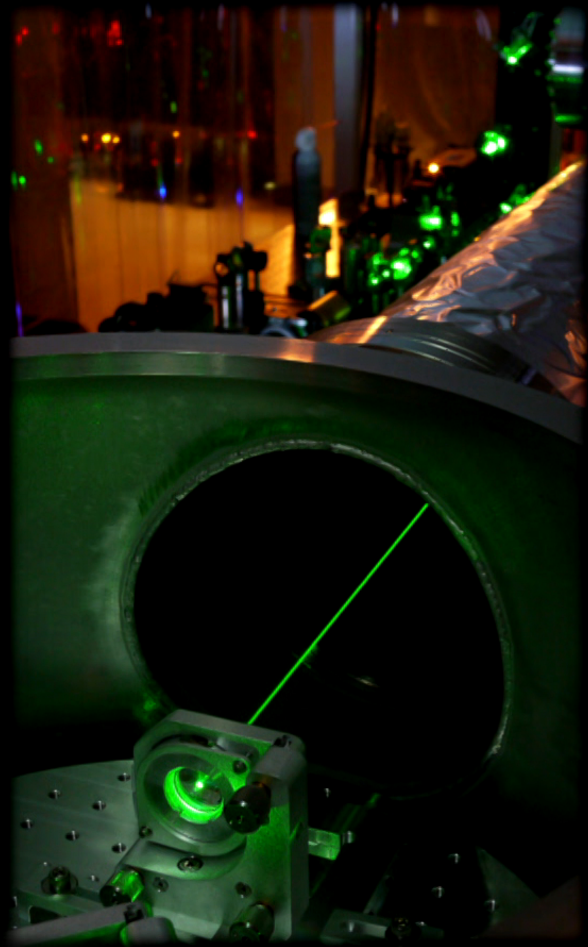
GW150914: The Advanced LIGO Detectors in the Era of First Discoveries. LSC (2016) PRL 116, 131103


The MIT crew at
LIGO Louisiana
Lisa
(MIT scientist)
Alvaro (MIT grad)
Me!
Maggie (MIT grad)

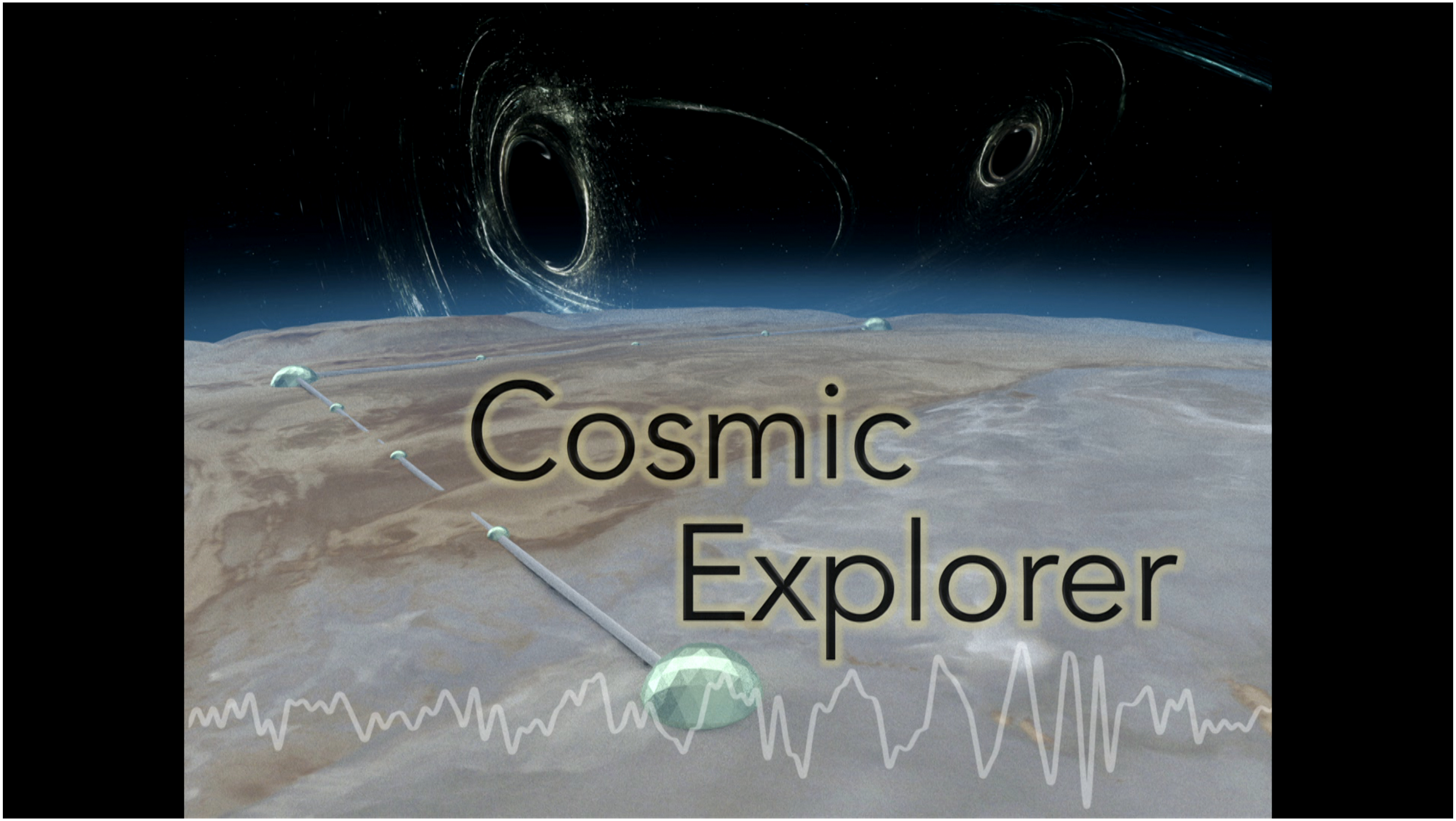

Maggie (MIT grad)
New Squeezed Light Source!

Future Improvements

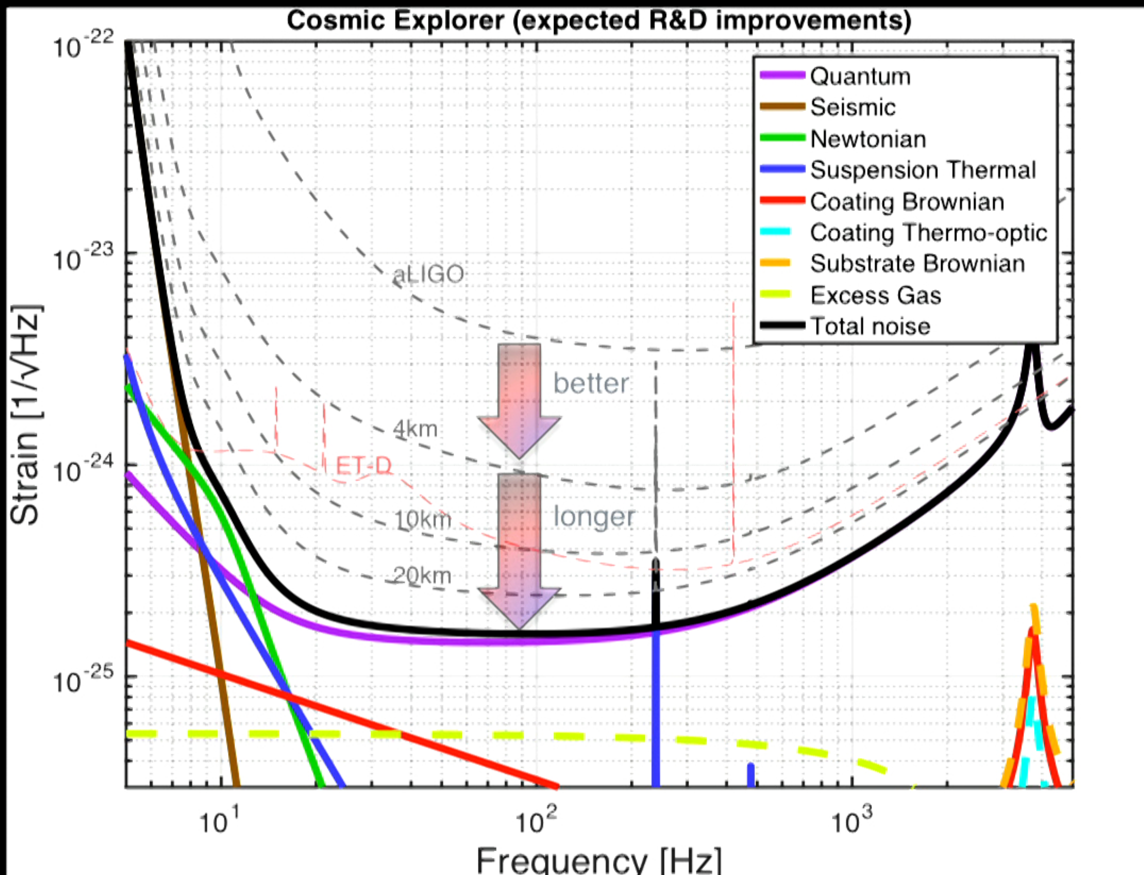
- R&D is driven not only by how to make Advanced LIGO better, but also by the longer term potential of the field
- The next big leap in sensitivity will come from a longer interferometer…




Going Beyond Advanced LIGO


Cosmic
Explorer

A 40km facility with new coatings and squeezing



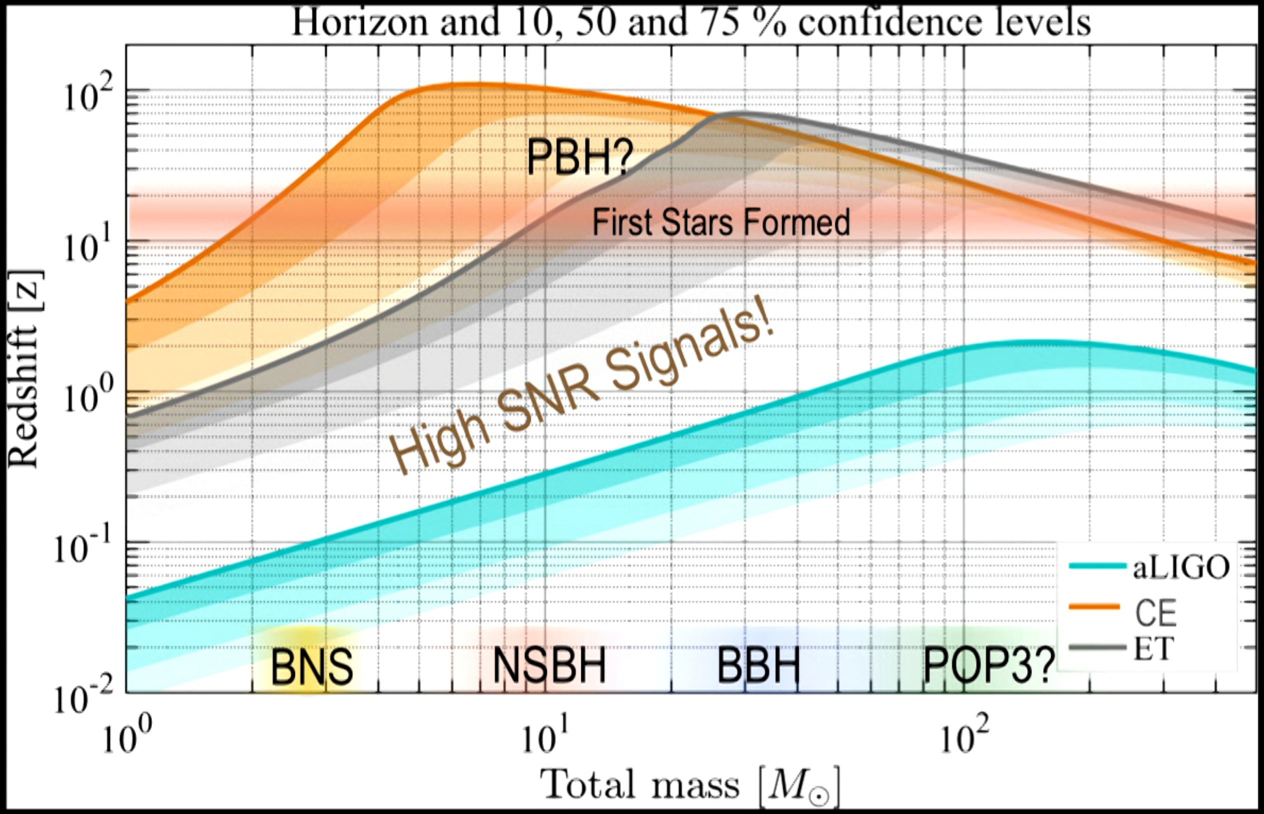
Exploring the sensitivity of next generation gravitational wave detectors (2017) CQG 34, 044001

Apr, 2018

M. Evans, PI

40

BBH and BNS from the entire Universe!

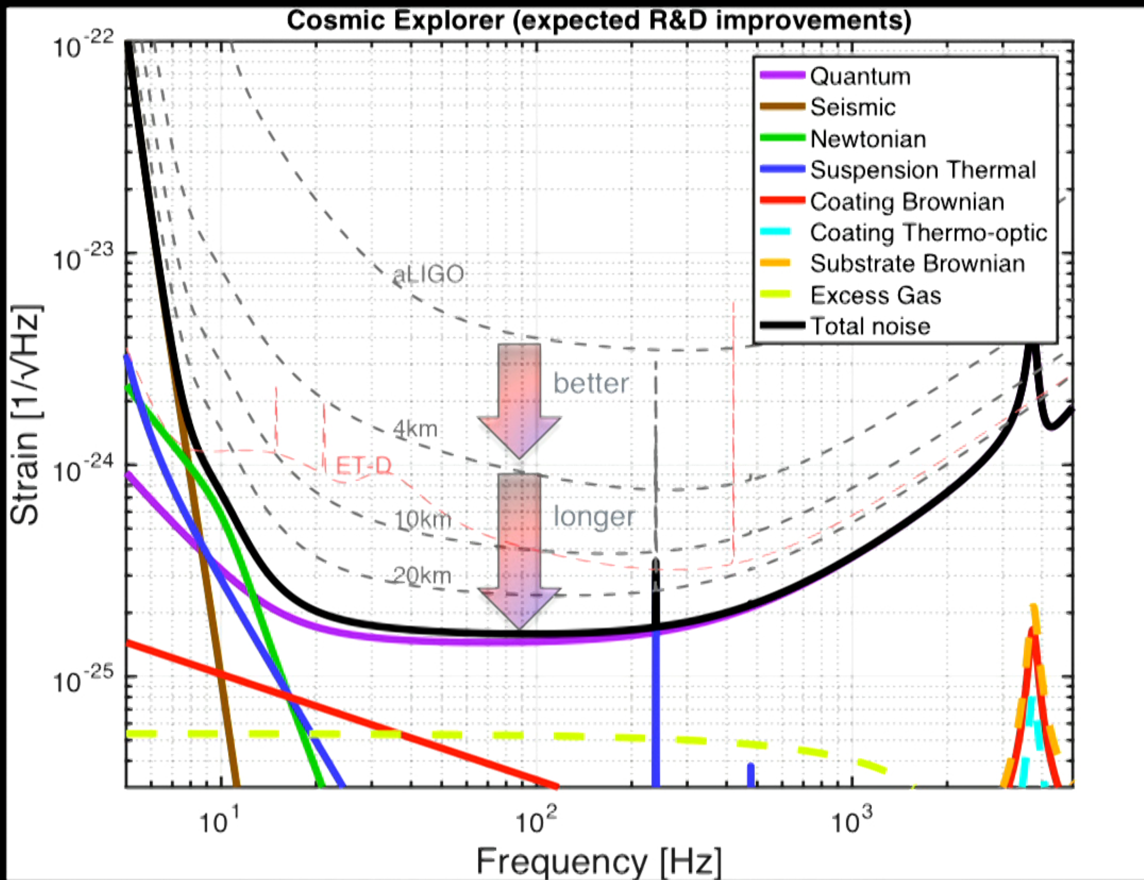


Parameter estimation for binary black holes with networks of third-generation gravitational-wave detectors. Vitale, Evans (2017) PRD 95, 064052

Observing primordial gravitational waves below the binary-black-hole-produced stochastic background Regimbau, Evans, …, Vitale, (2017) PRL 118, 151105

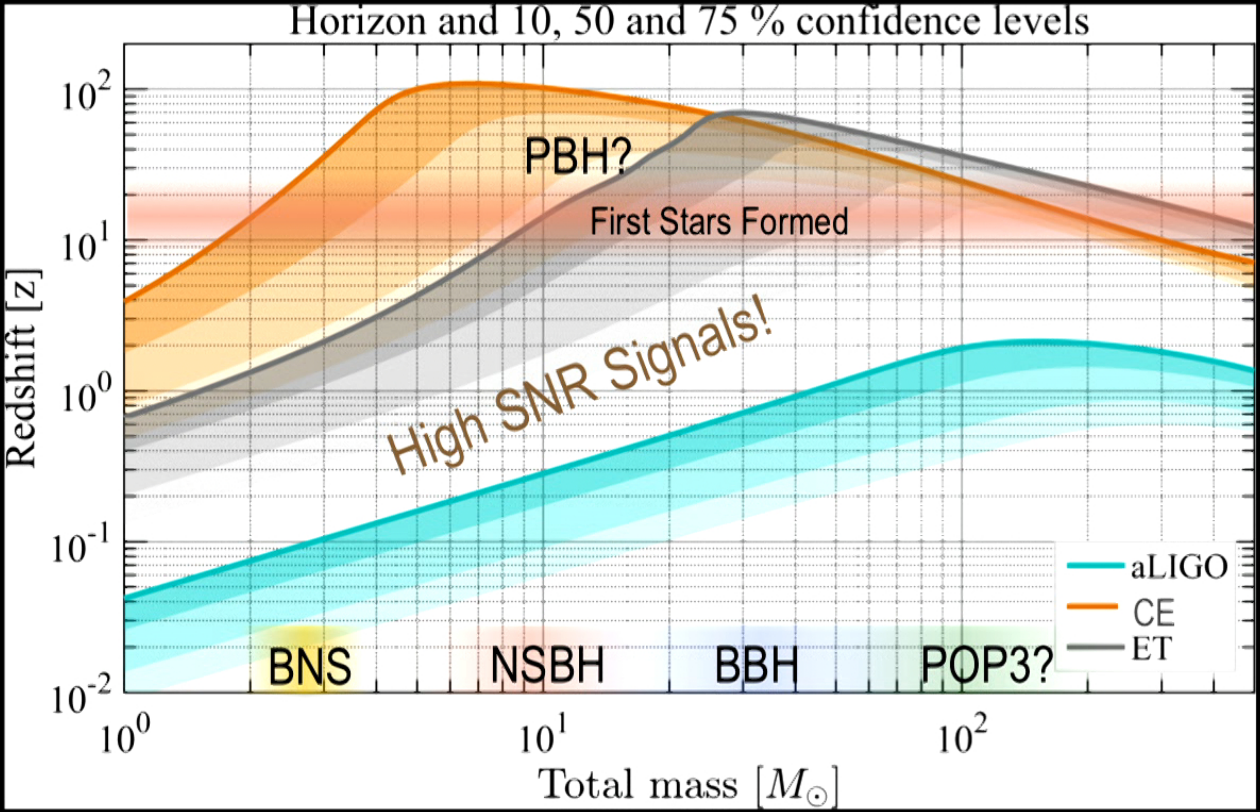
41

A 40km facility with new coatings and squeezing



Exploring the sensitivity of next generation gravitational wave detectors (2017) CQG 34, 044001

BBH and BNS from the entire Universe!

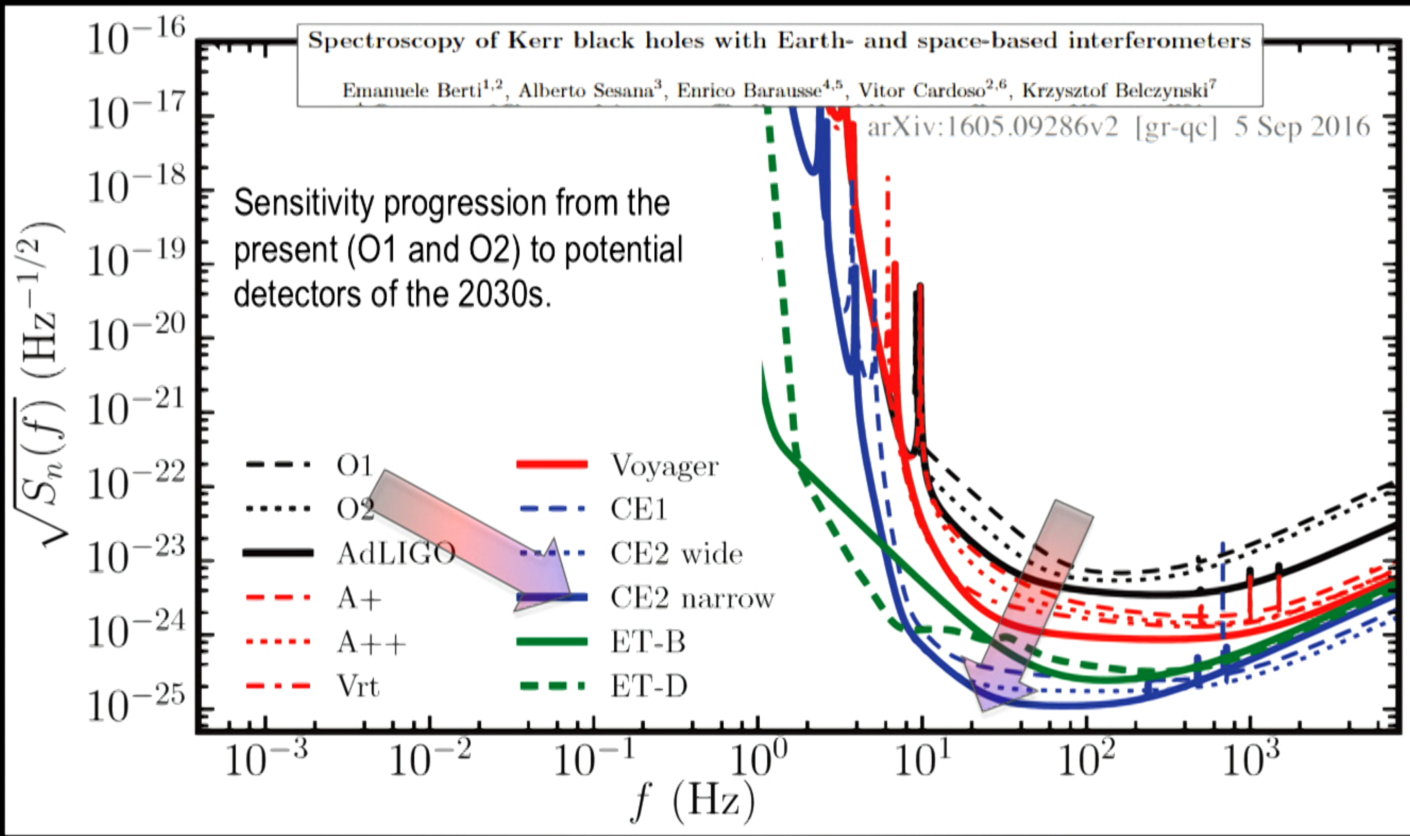


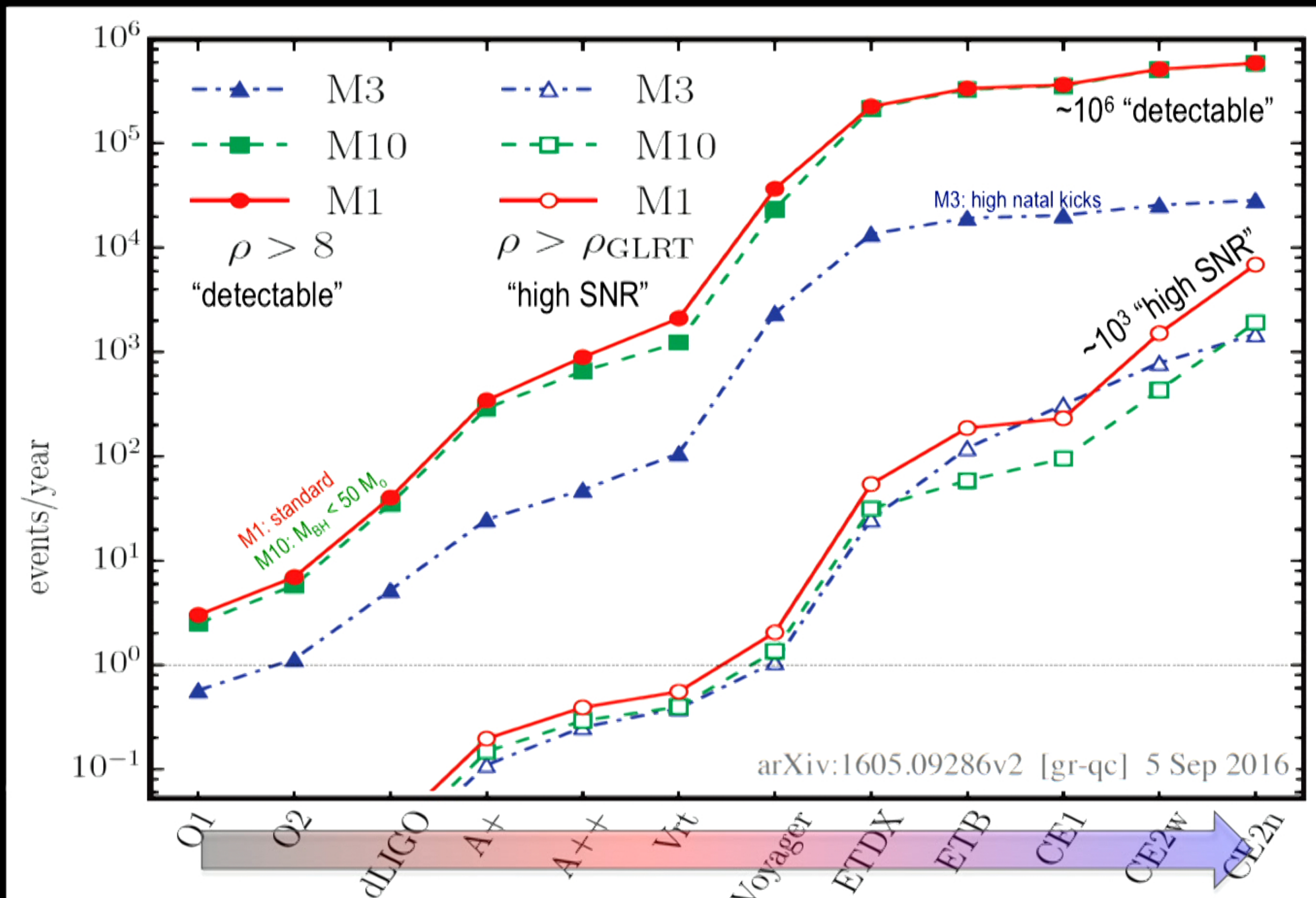
Parameter estimation for binary black holes with networks of third-generation gravitational-wave detectors.
Vitale, Evans (2017) PRD 95, 064052

Observing primordial gravitational waves below the binary-black-hole-produced stochastic background
Regimbau, Evans, …, Vitale, (2017) PRL 118, 151105

41

Over the next 20 years…

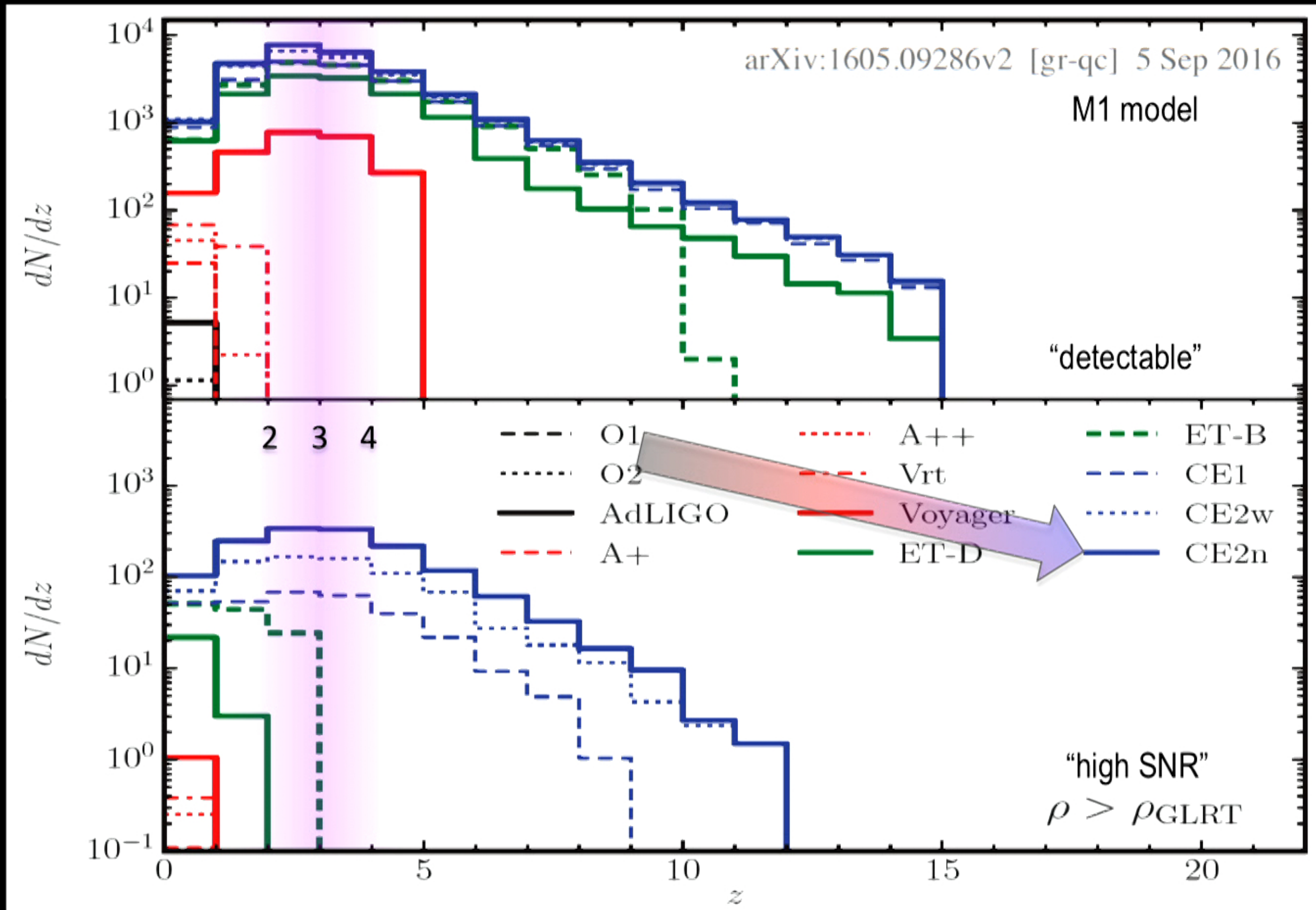




Apr, 2018

M. Evans, PI

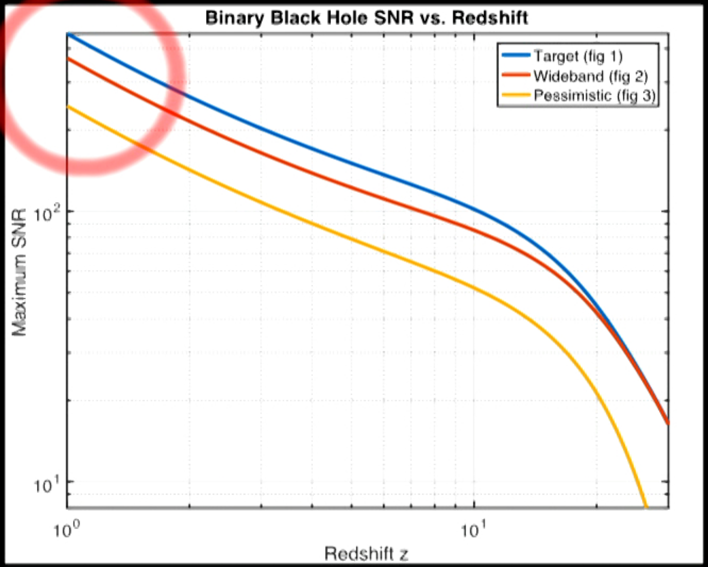
43



arXiv:1605.09286v2 [gr-qc] 5 Sep 2016
M1 model
"detectable"
2
3
4
O1
O2
AdLIGO
A+
A++
Vrt
Voyager
ET-D
ET-B
CE1
CE2w
CE2n
"high SNR"
$\rho > \rho_{GLRT}$
dN/dz
z

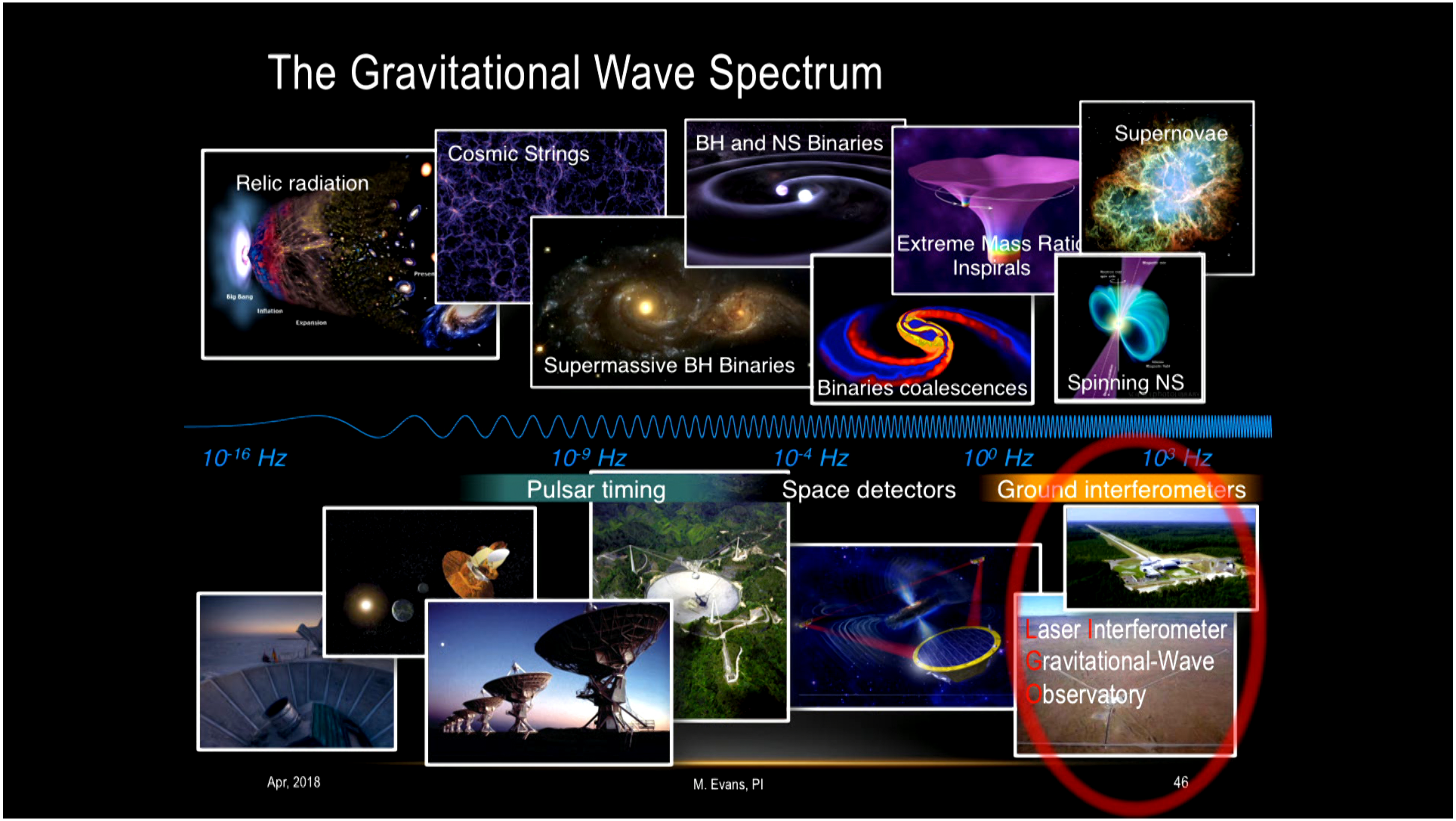
Close BBH Mergers will have high SNR

- SNR > 1000 for BBH like GW150914
- This will allow tests of
  - BH quasi normal modes
  - GW memory effect
  - …



Exploring the sensitivity of next generation gravitational wave detectors

CQG doi:10.1088/1361-6382/aa51f4


The Gravitational Wave Spectrum
Relic radiation
Cosmic Strings
BH and NS Binaries
Extreme Mass Ratio Inspirals
Supernovae
Supermassive BH Binaries
Binaries coalescences
Spinning NS
10^{-16} Hz
10^{-9} Hz
10^{-4} Hz
10^{0} Hz
10^{3} Hz
Pulsar timing
Space detectors
Ground interferometers
Laser Interferometer Gravitational-Wave Observatory
Apr, 2018
M. Evans, PI
46

The Message

- Advanced LIGO is producing results
  - we are testing fundamental physics
  - and improving our understanding of the Universe,
  - but we still have a lot of room for detector improvement (high power, squeezing, better coatings…)
- Near-term upgrades will reduce the noise by ~2 beyond design
  - event rate may be ~1 per day
- Next generation detectors will reach the entire Universe (high redshift)
  - BBH and BNS detection rate will be mostly determined by astrophysical population (>10^5 per year?), not detector sensitivity (peak near z ~ 3?)
  - high SNR signals will allow for detailed tests of GR, NS EOS, …
- This is just the beginning!