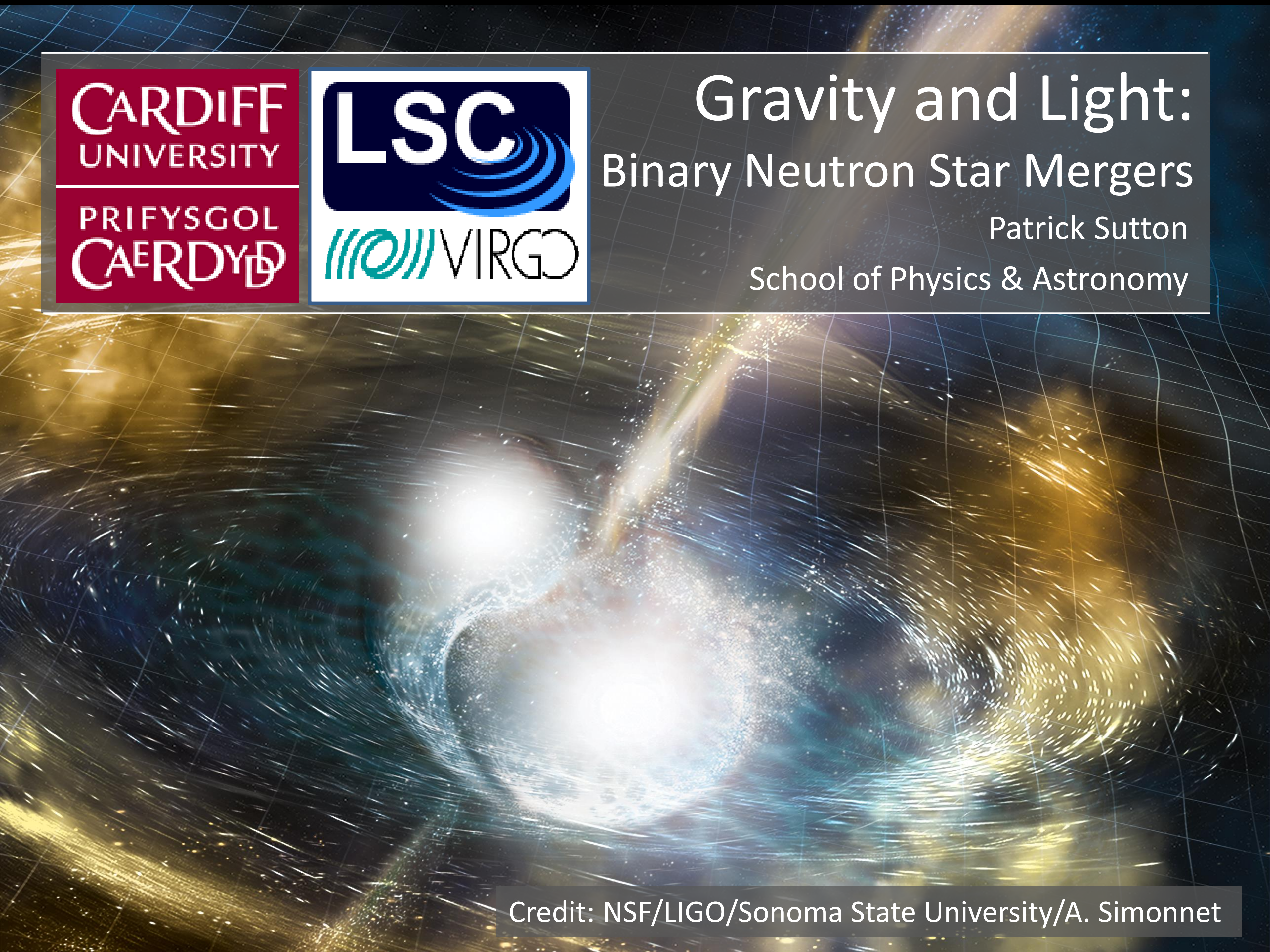
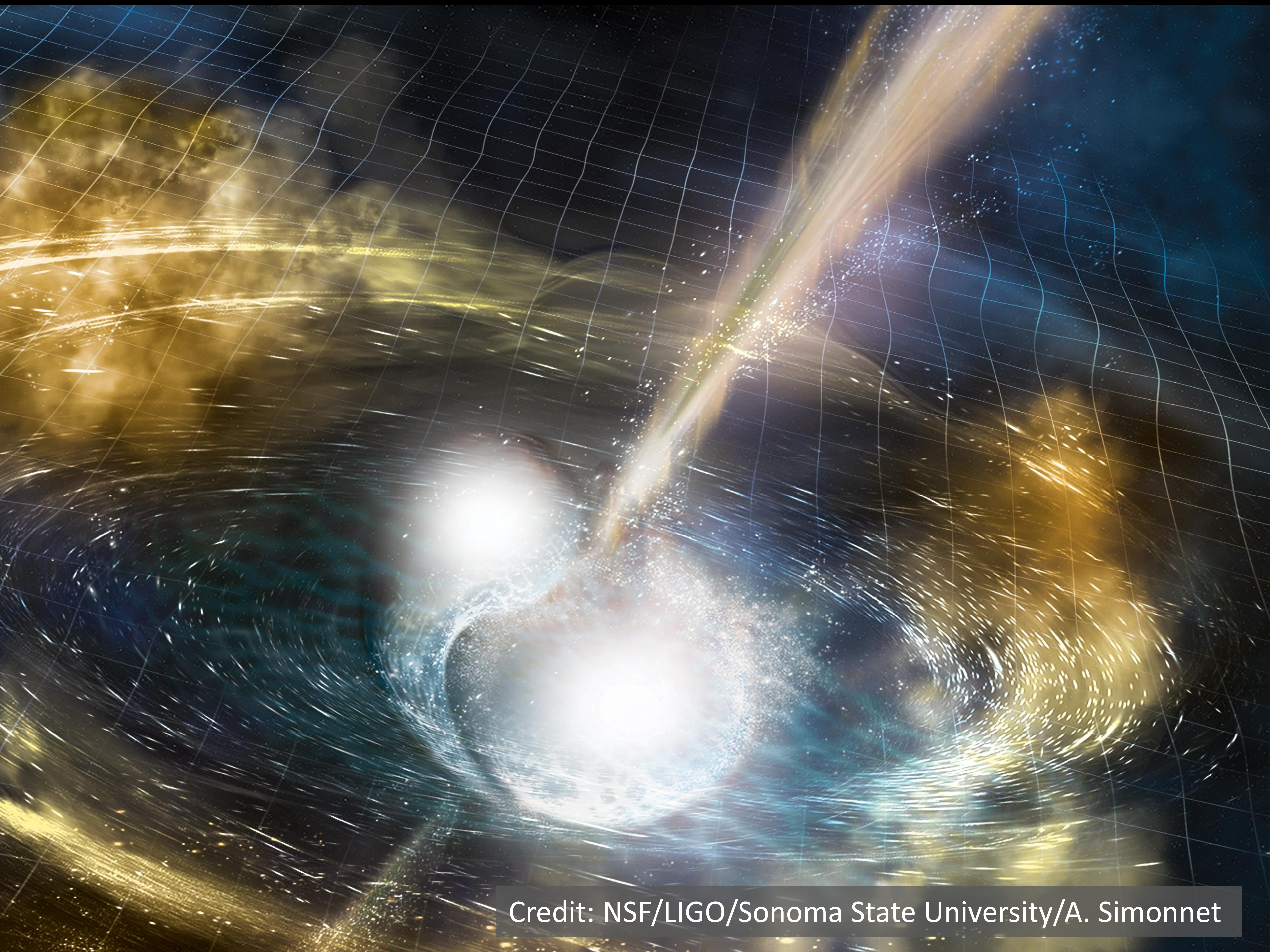
Gravity and Light:
Binary Neutron Star Mergers

Patrick Sutton
School of Physics & Astronomy

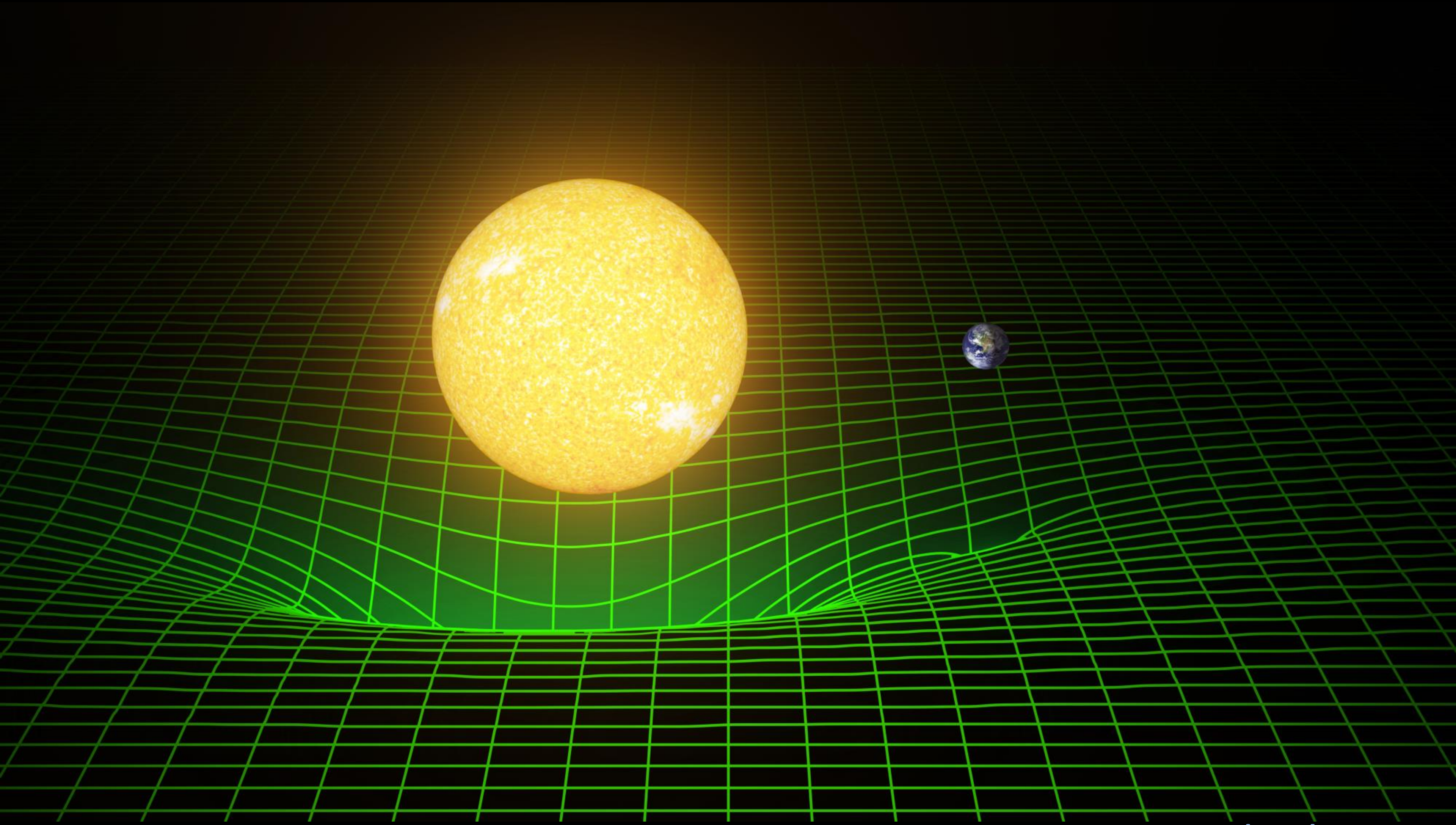


Credit: NSF/LIGO/Sonoma State University/A. Simonnet



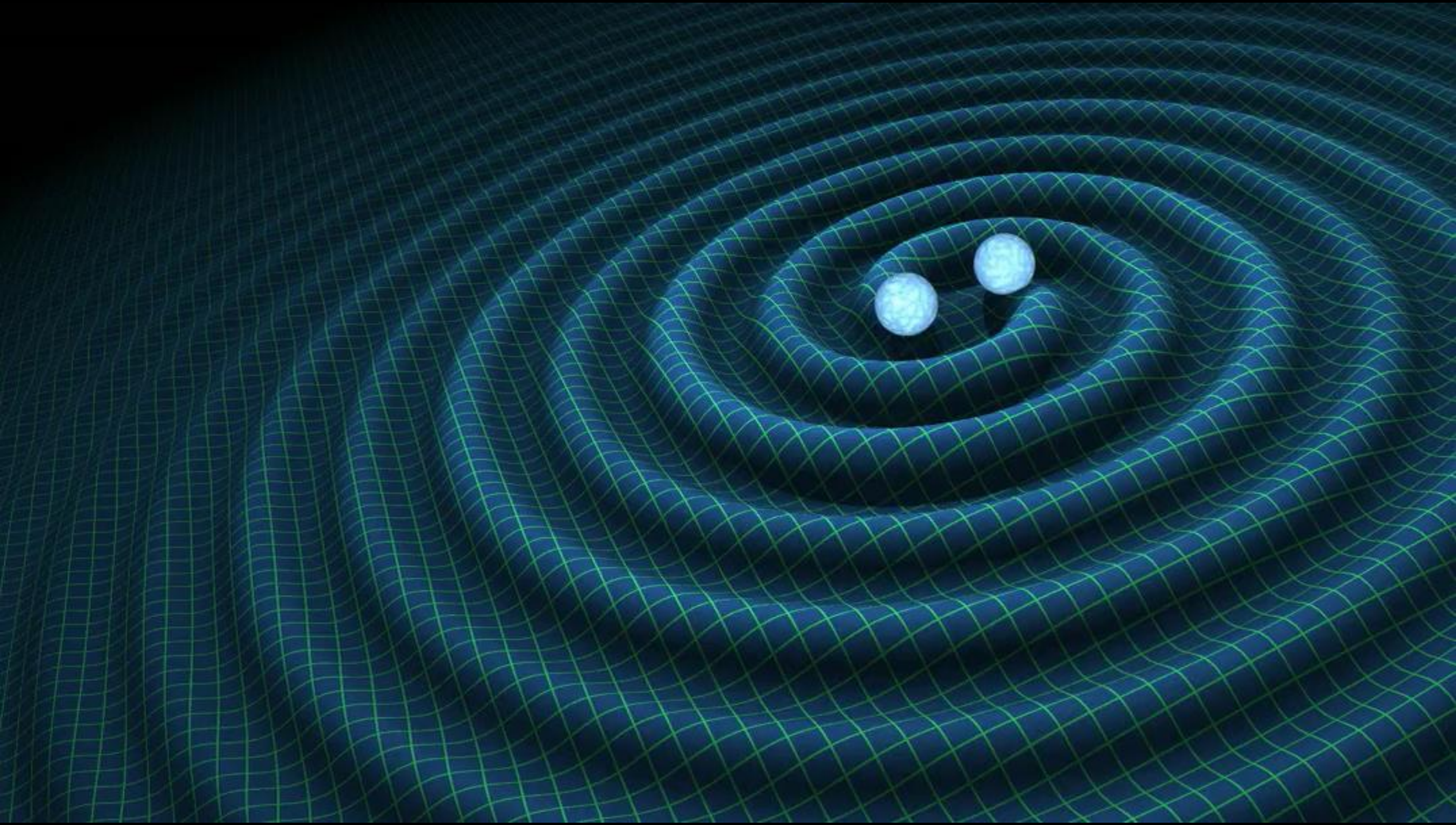
Credit: NSF/LIGO/Sonoma State University/A. Simonnet

Einstein: gravity = curved spacetime



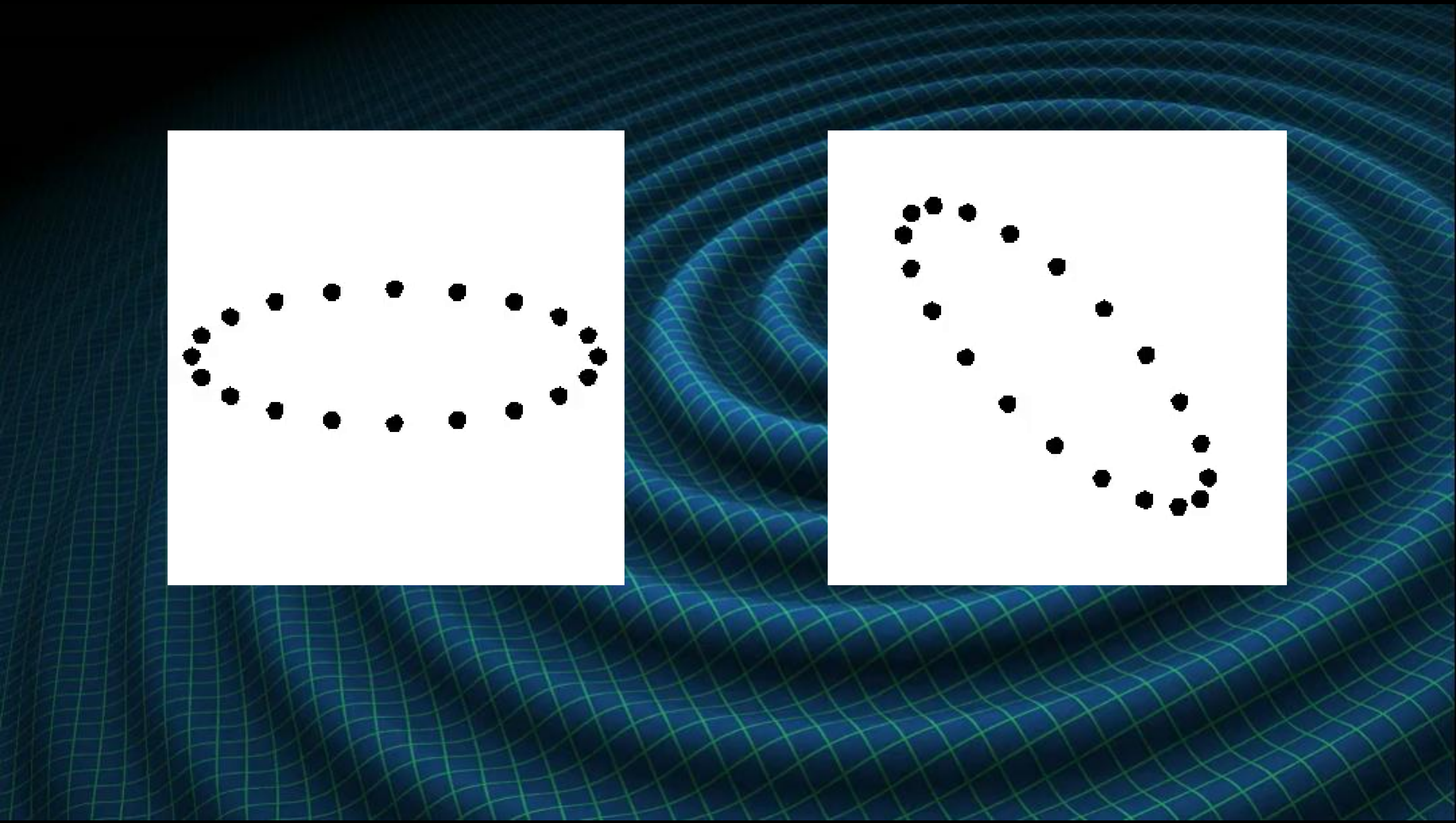
T. Pyle, Caltech/MIT/LIGO Lab

Accelerating Mass: Gravitational Waves



Courtesy Caltech/MIT/LIGO Laboratory

Accelerating Mass: Gravitational Waves



Courtesy Caltech/MIT/LIGO Laboratory

The Hard Truth

spacetime line element (Pythagoras):

$$ds^2 = (\eta_{\alpha\beta} + h_{\alpha\beta})\, dx^\alpha dx^\beta$$

wave equation:

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

stress tensor of the source

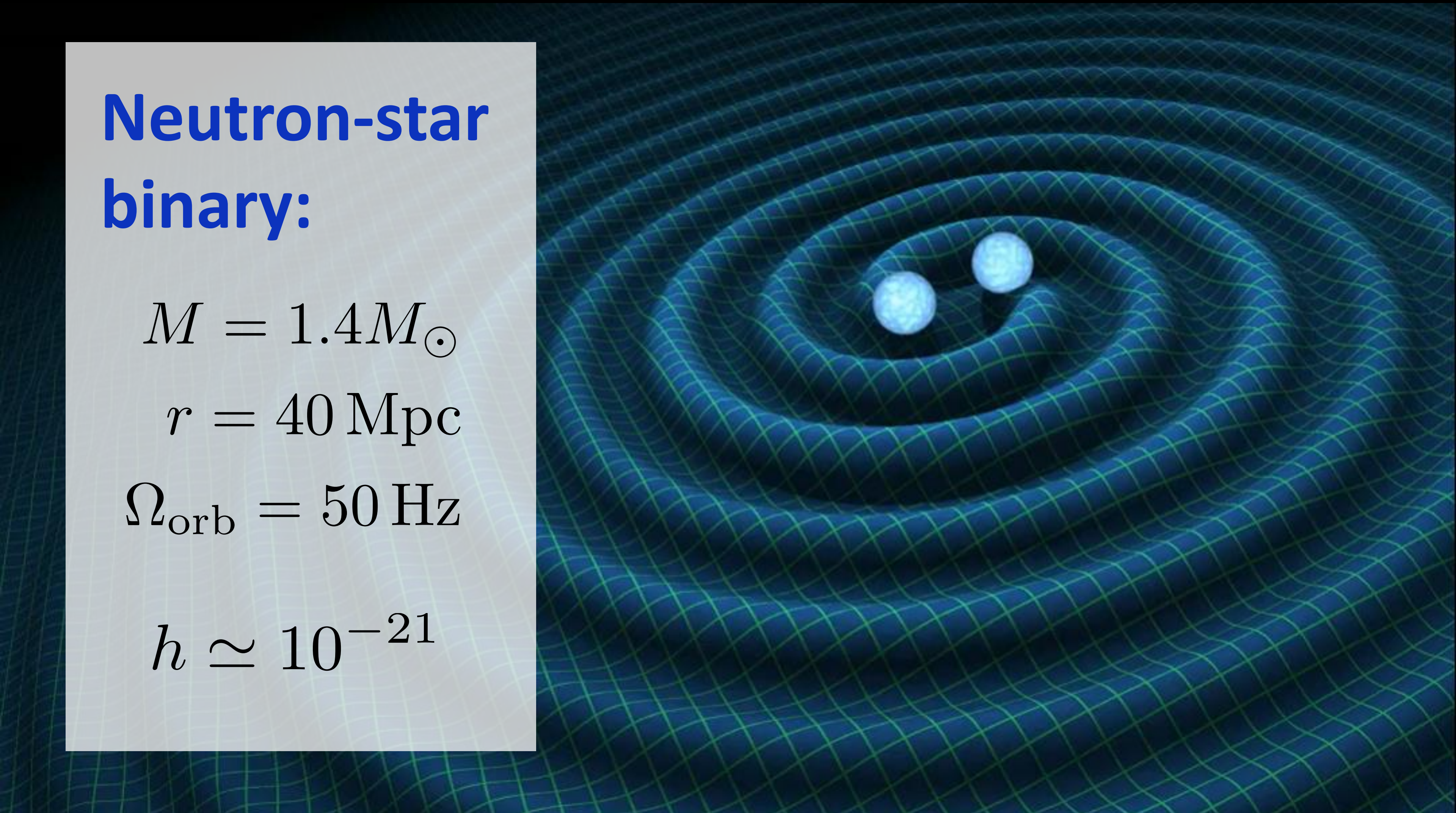
quadrupole approximation:

$10^{-44}\ N^{-1}$

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

Courtesy Caltech/MIT/LIGO Laboratory

The Challenge



Neutron-star binary:

$$M = 1.4 M_{\odot}$$

$$r = 40\,\mathrm{Mpc}$$

$$\Omega_{\mathrm{orb}} = 50\,\mathrm{Hz}$$

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

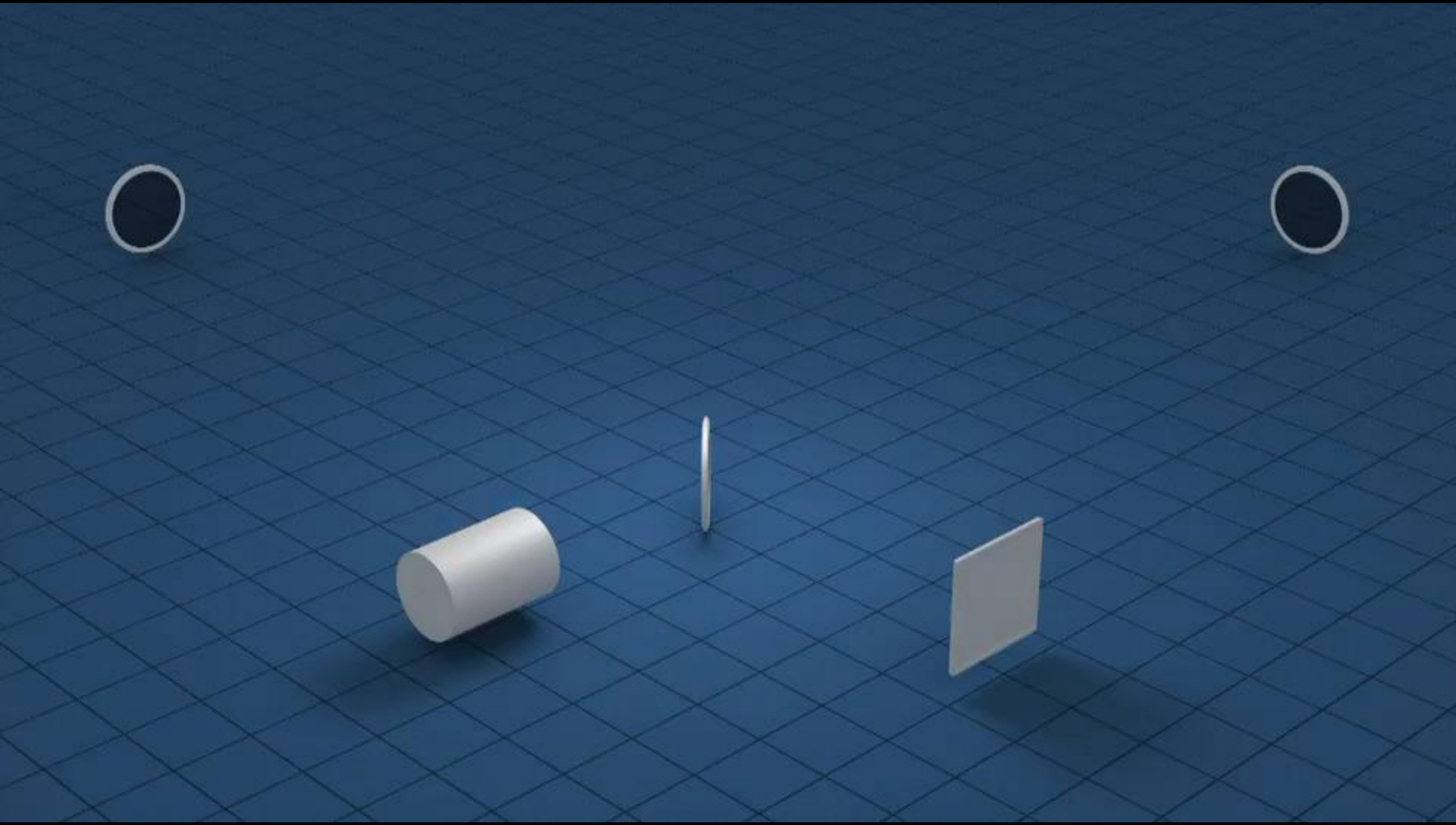
Courtesy Caltech/MIT/LIGO Laboratory

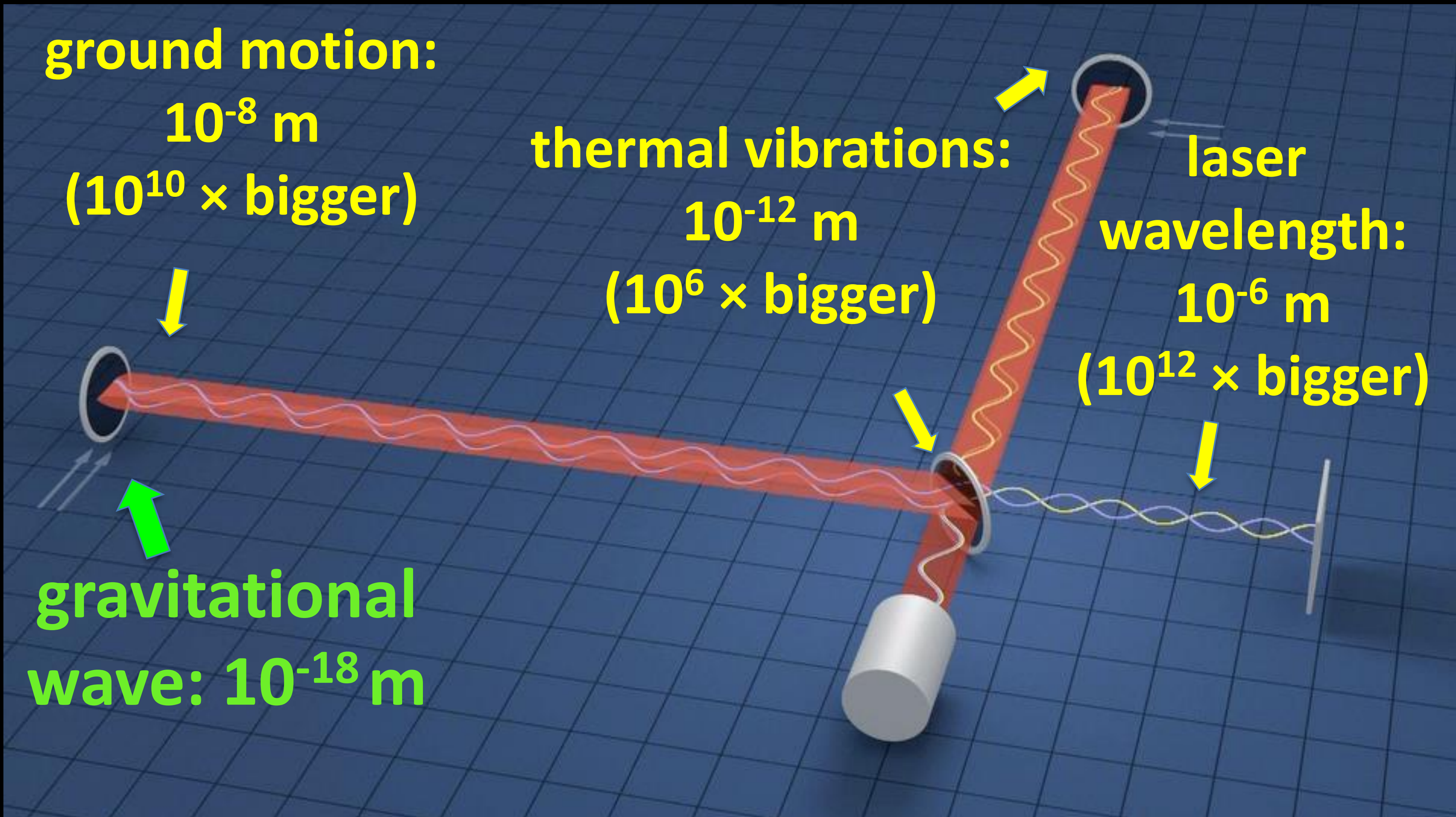
LIGO Hanford Observatory

LIGO Livingston Observatory

Virgo Observatory (Italy)

T. Pyle, Caltech/MIT/LIGO Lab

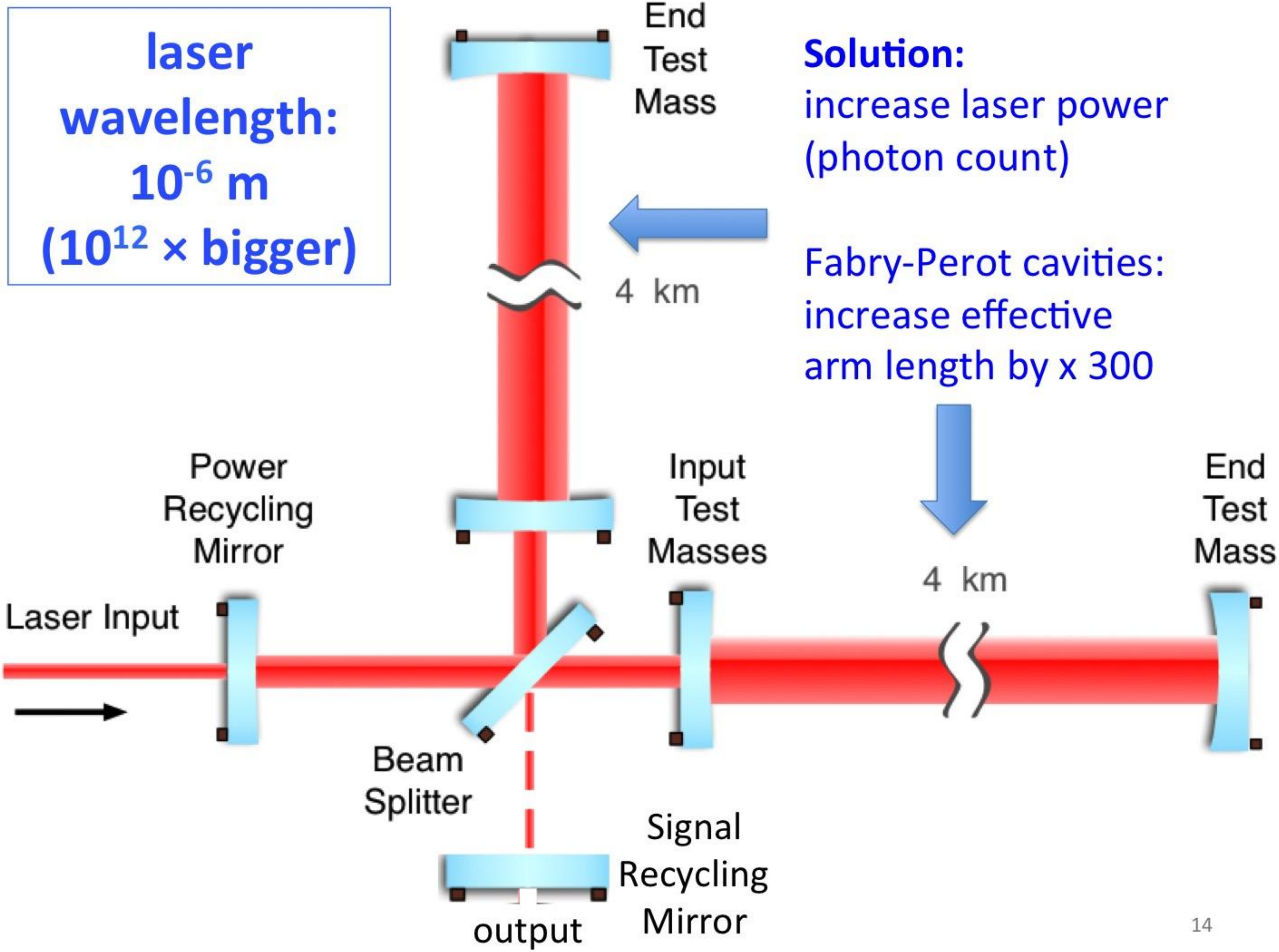



ground motion:
10^{-8} m
(10^{10} × bigger)
thermal vibrations:
10^{-12} m
(10^{6} × bigger)
laser
wavelength:
10^{-6} m
(10^{12} × bigger)
gravitational
wave: 10^{-18} m

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

Solution:
increase laser power (photon count)

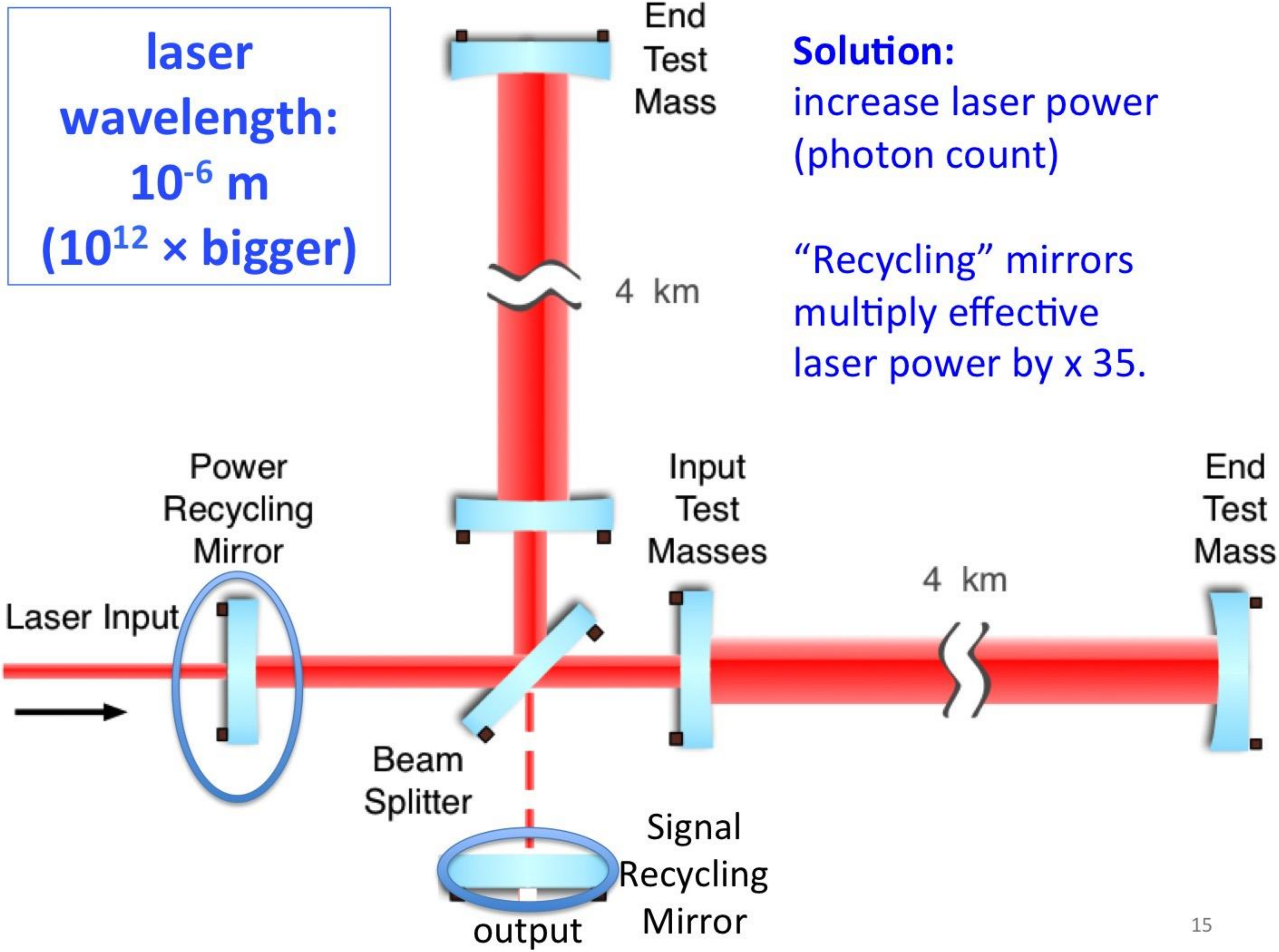
Fabry-Perot cavities: increase effective arm length by x 300



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

Solution:
increase laser power (photon count)

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



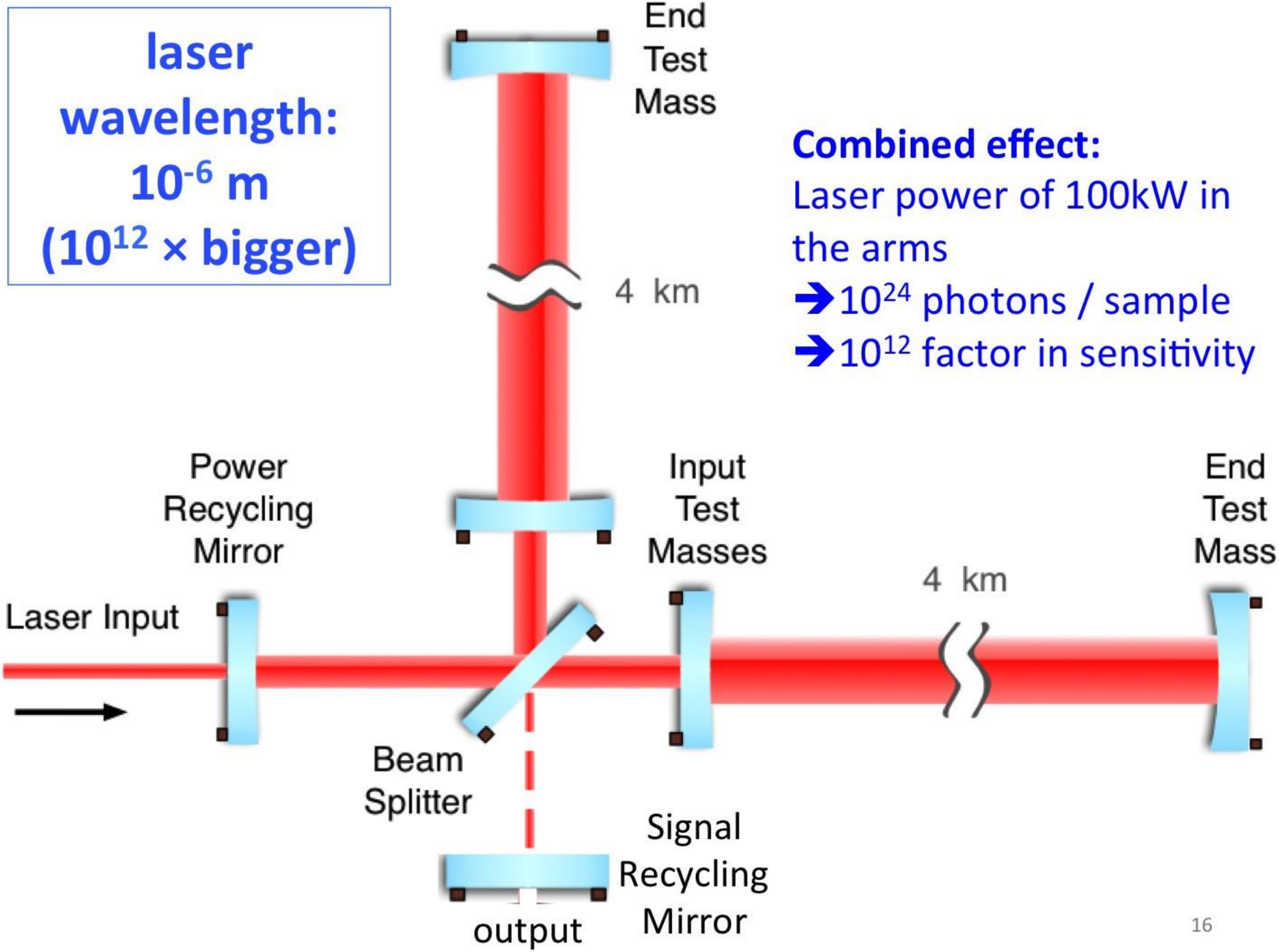
laser wavelength: 10^{-6} m (10^{12} × bigger)

Combined effect:

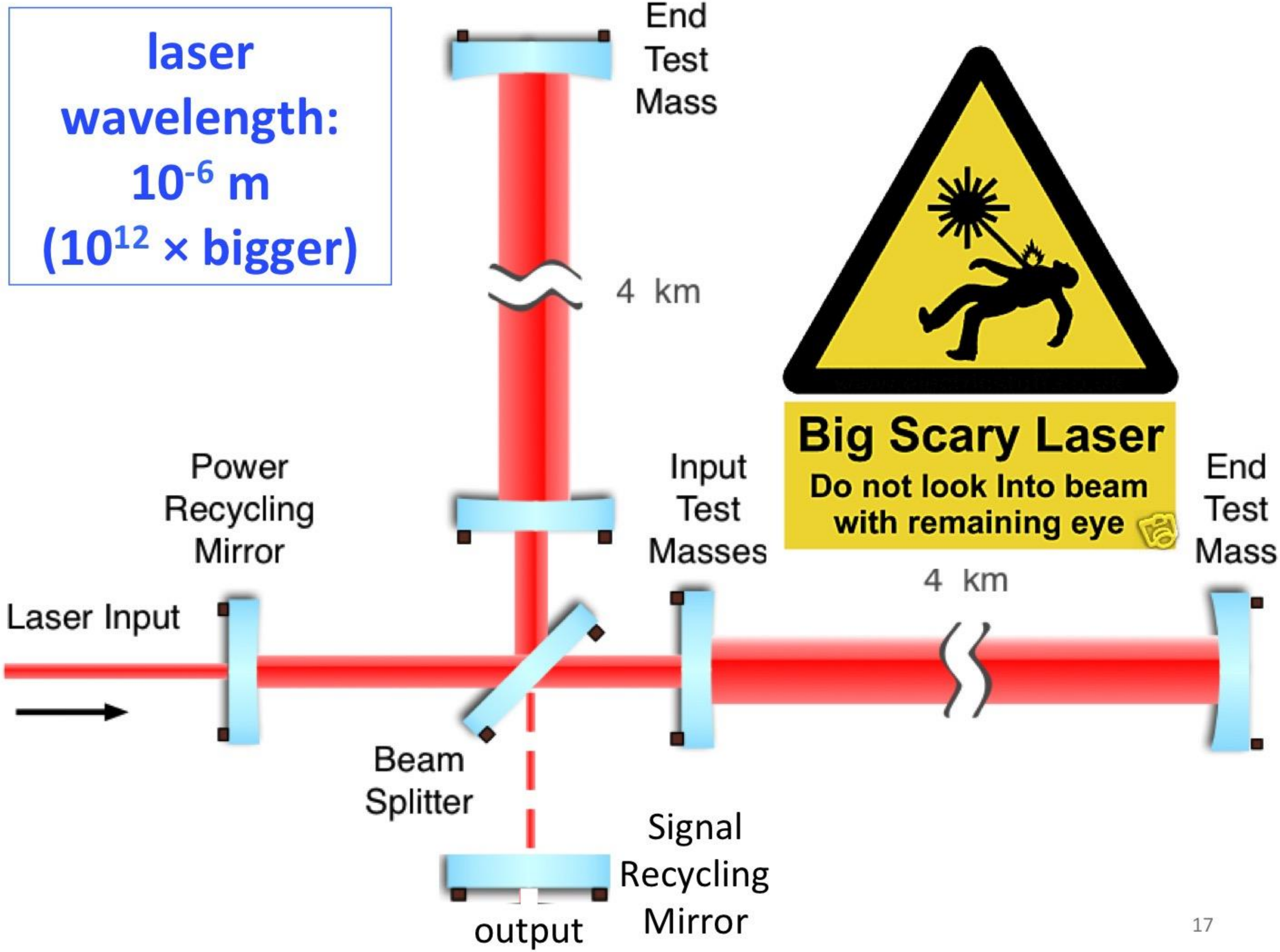
Laser power of 100kW in the arms

➔ 10^{24} photons / sample

➔ 10^{12} factor in sensitivity



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

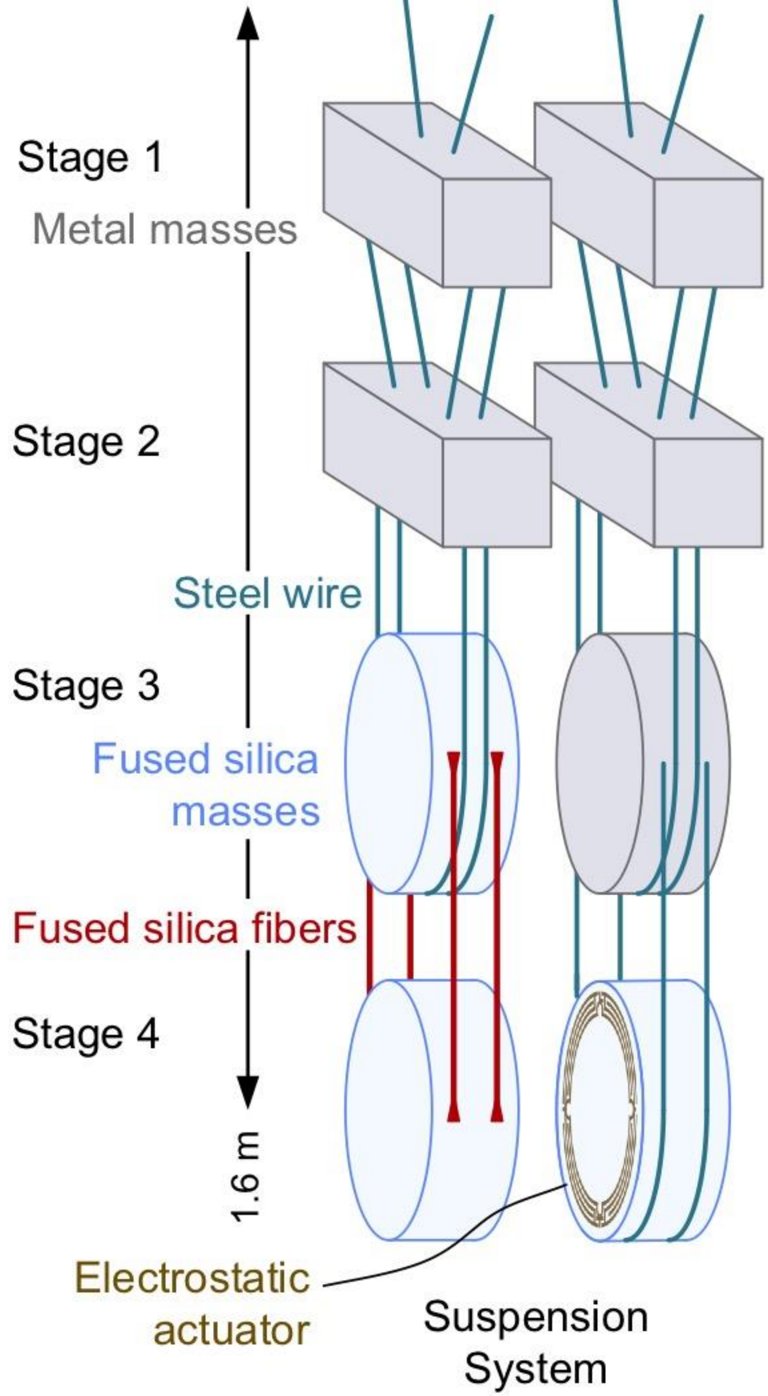


ground motion: 10^{-8} m (10^{10} × bigger)

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

+

Active seismic isolation: **10^{3}**



f^{-2} per stage

thermal vibrations: 10^{-12} m (10^6 × bigger)

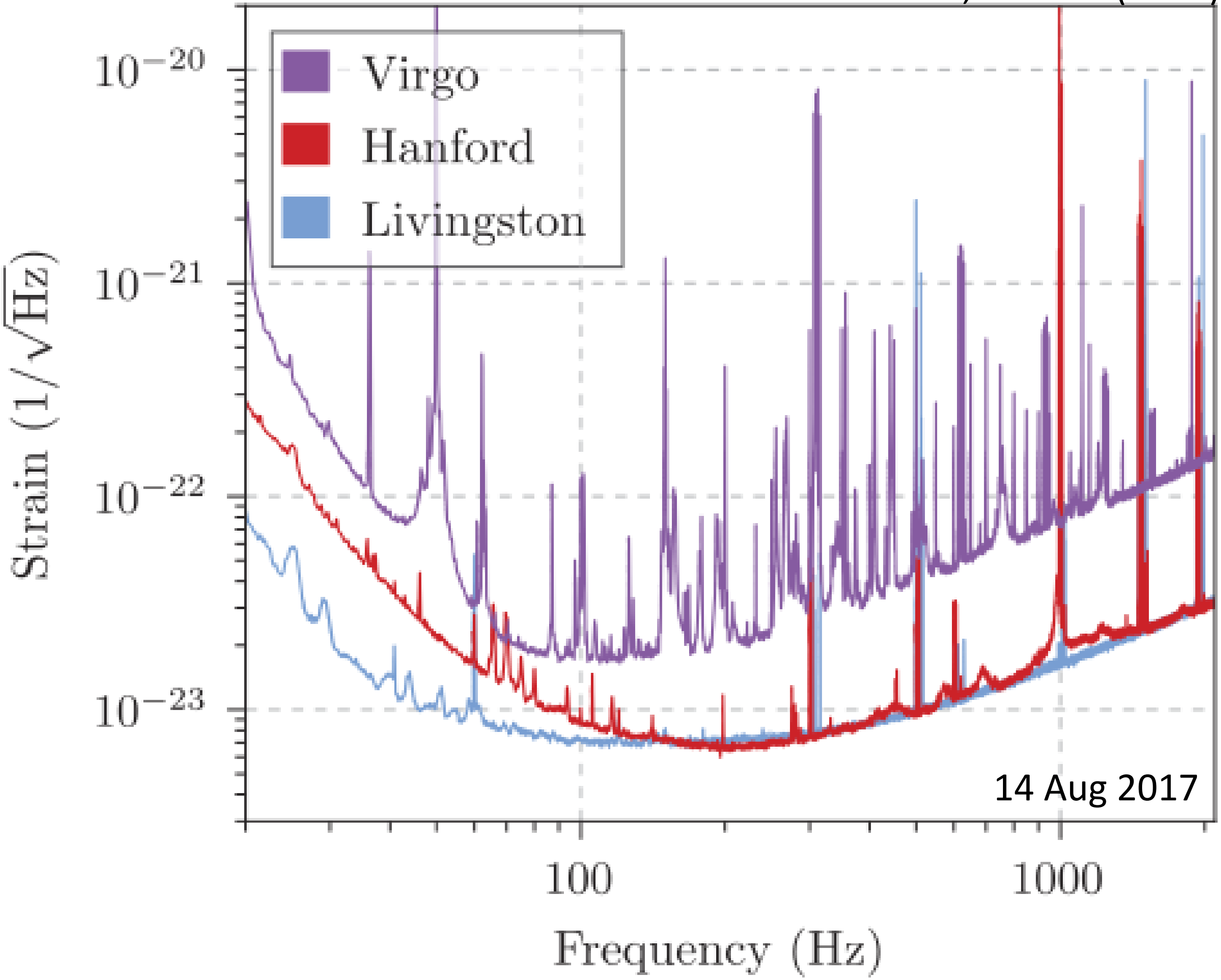
Ultra-high mechanical quality ($Q \sim 10^6$) fused-silica optics

↓

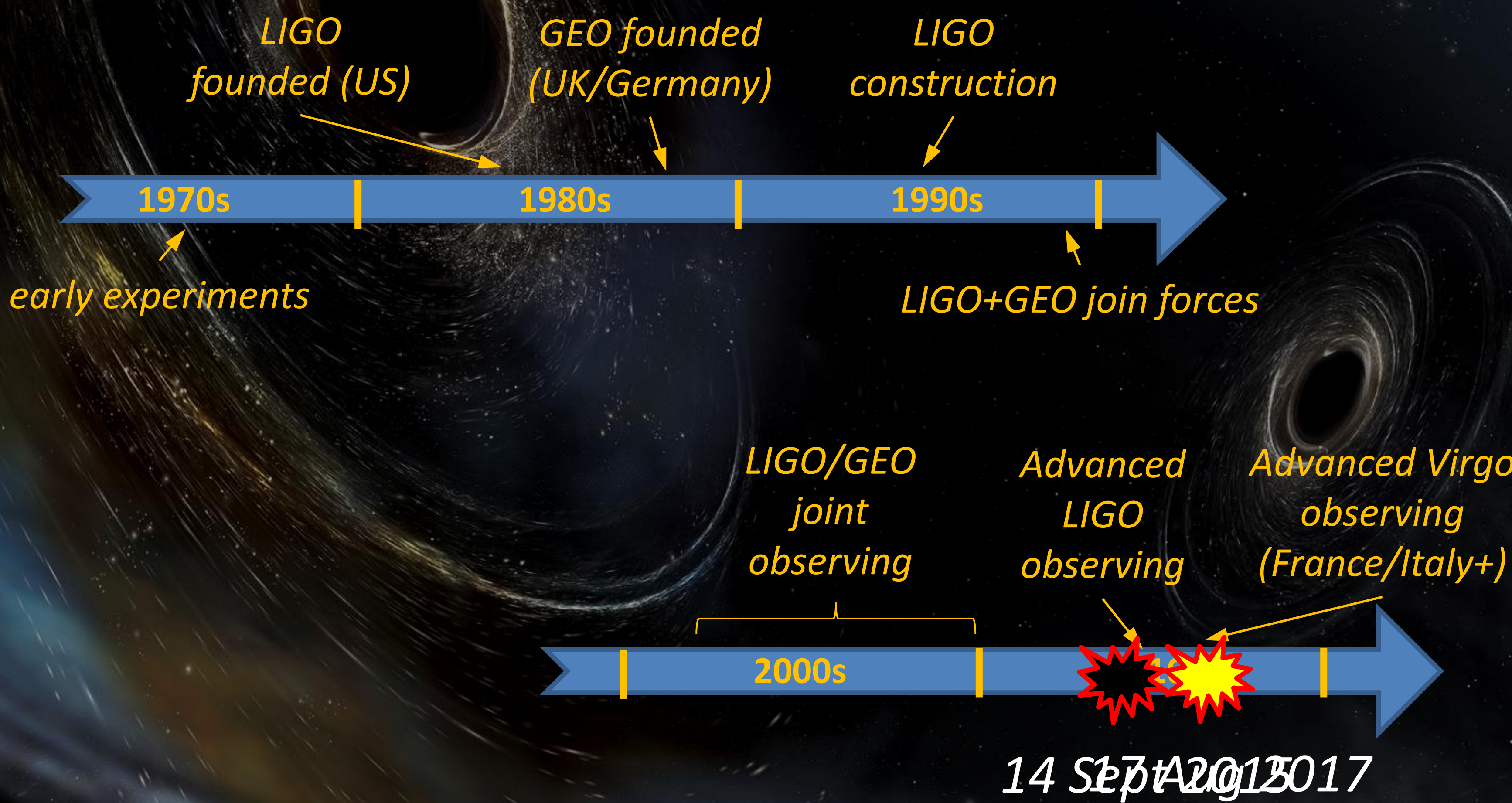
isolates thermal motion into narrow frequency bands

LIGO-Virgo noise spectra

PRL 119, 141101 (2017)

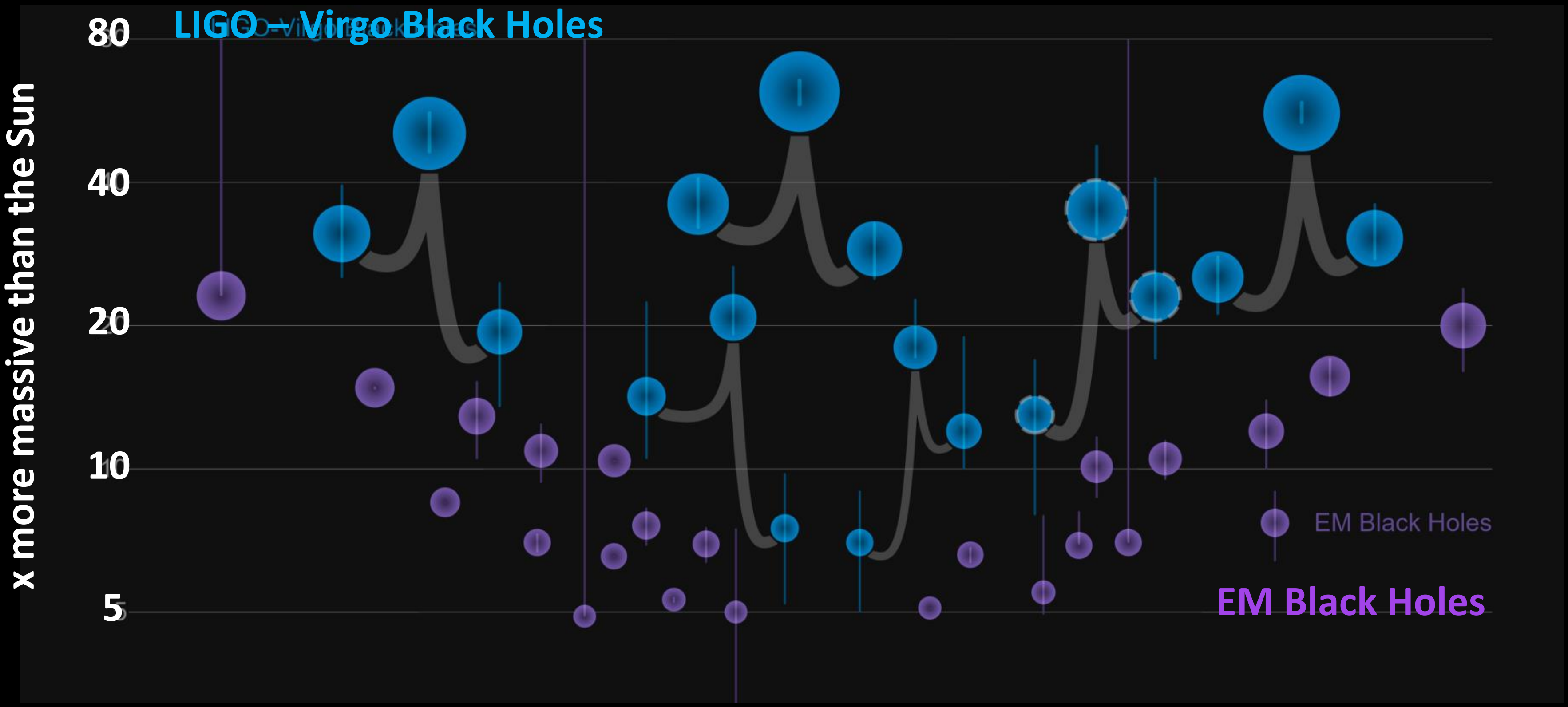


A Potted History



LIGO-Virgo Black Hole Detections

(so far)

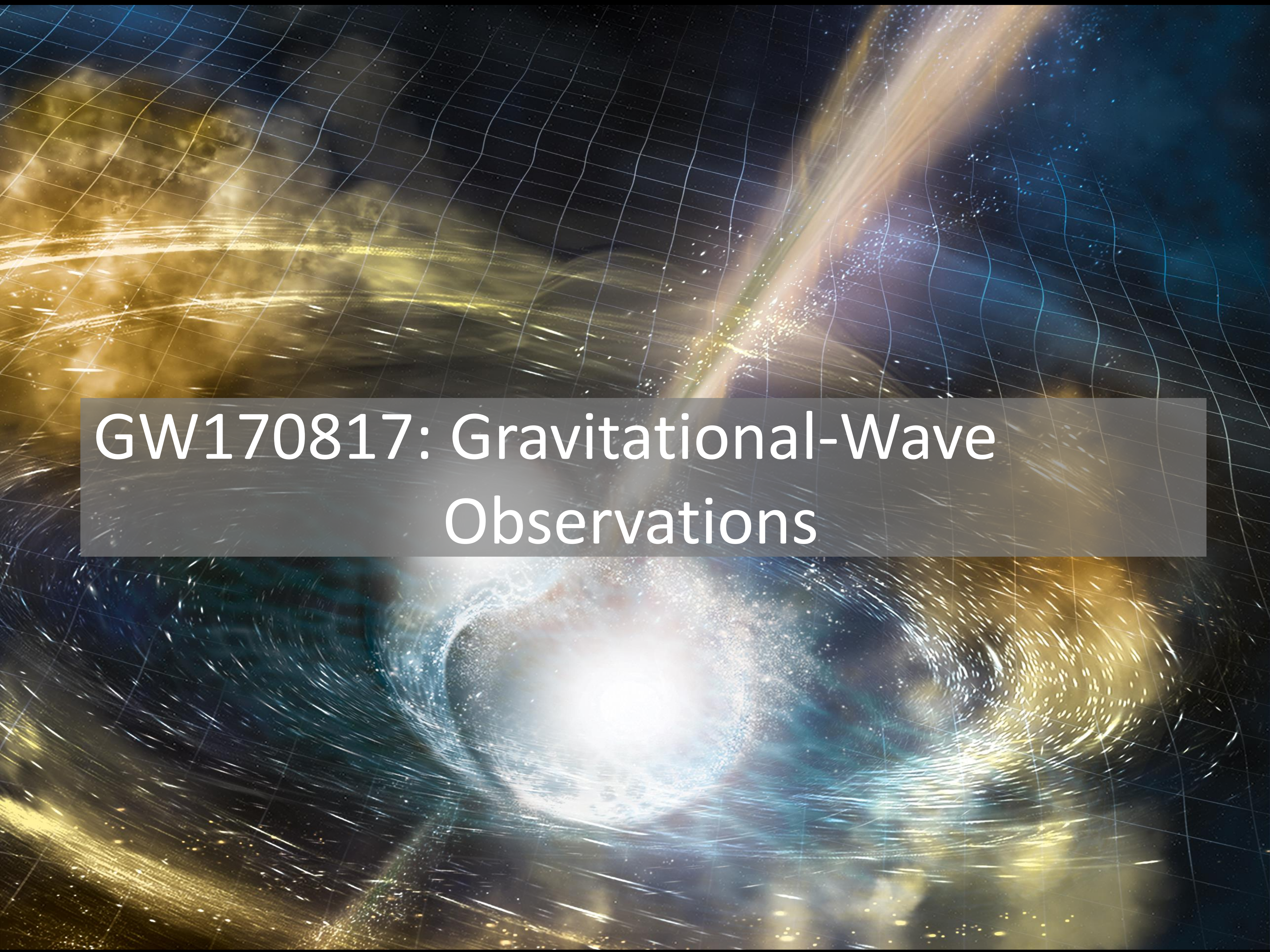


LIGO-Virgo / Frank Elavsky / Northwestern (modified)

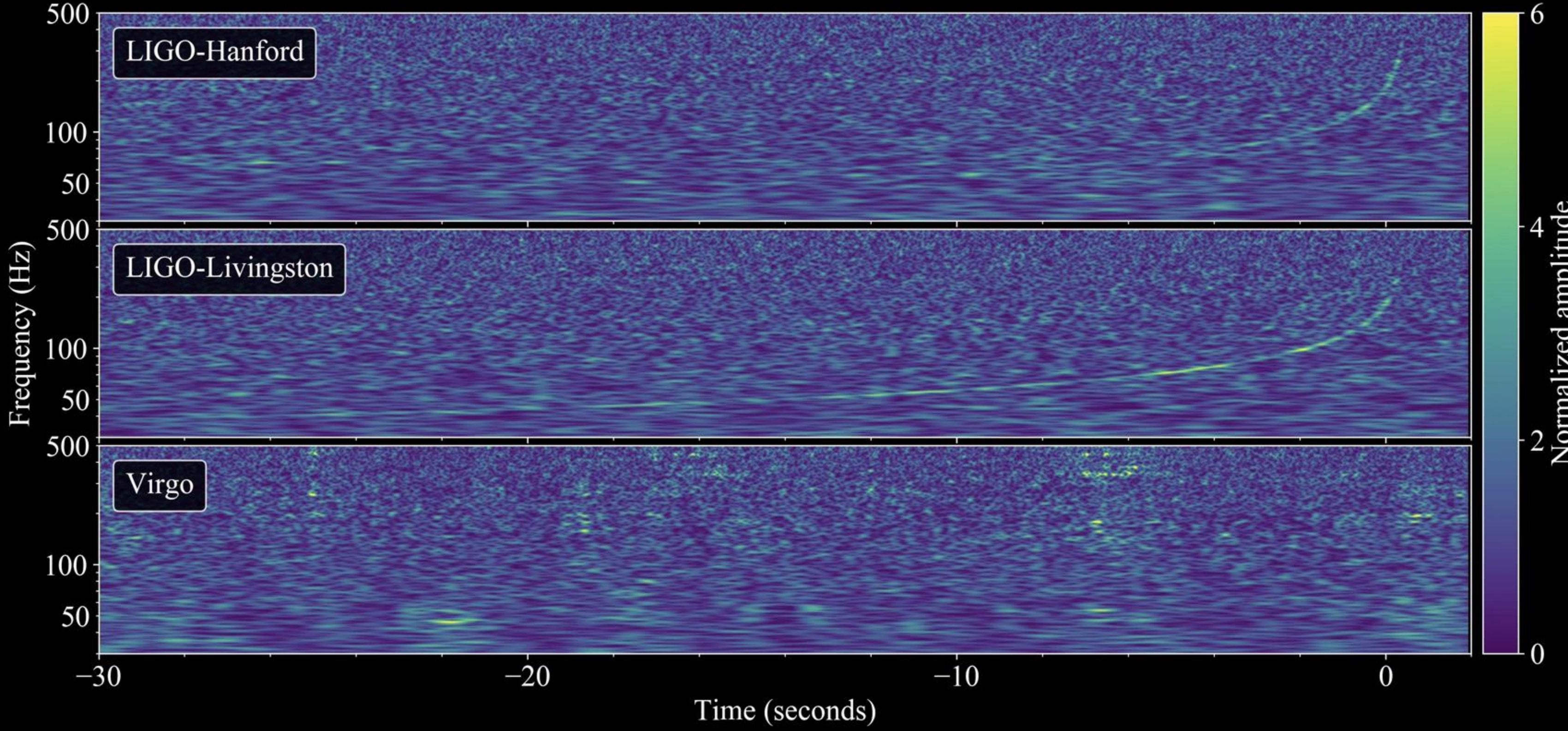
See ECR prize talk by Christopher Berry (17:05)

Gravitational-wave astronomy and black hole astrophysics

GW170817: Gravitational-Wave Observations



A New Phenomenon

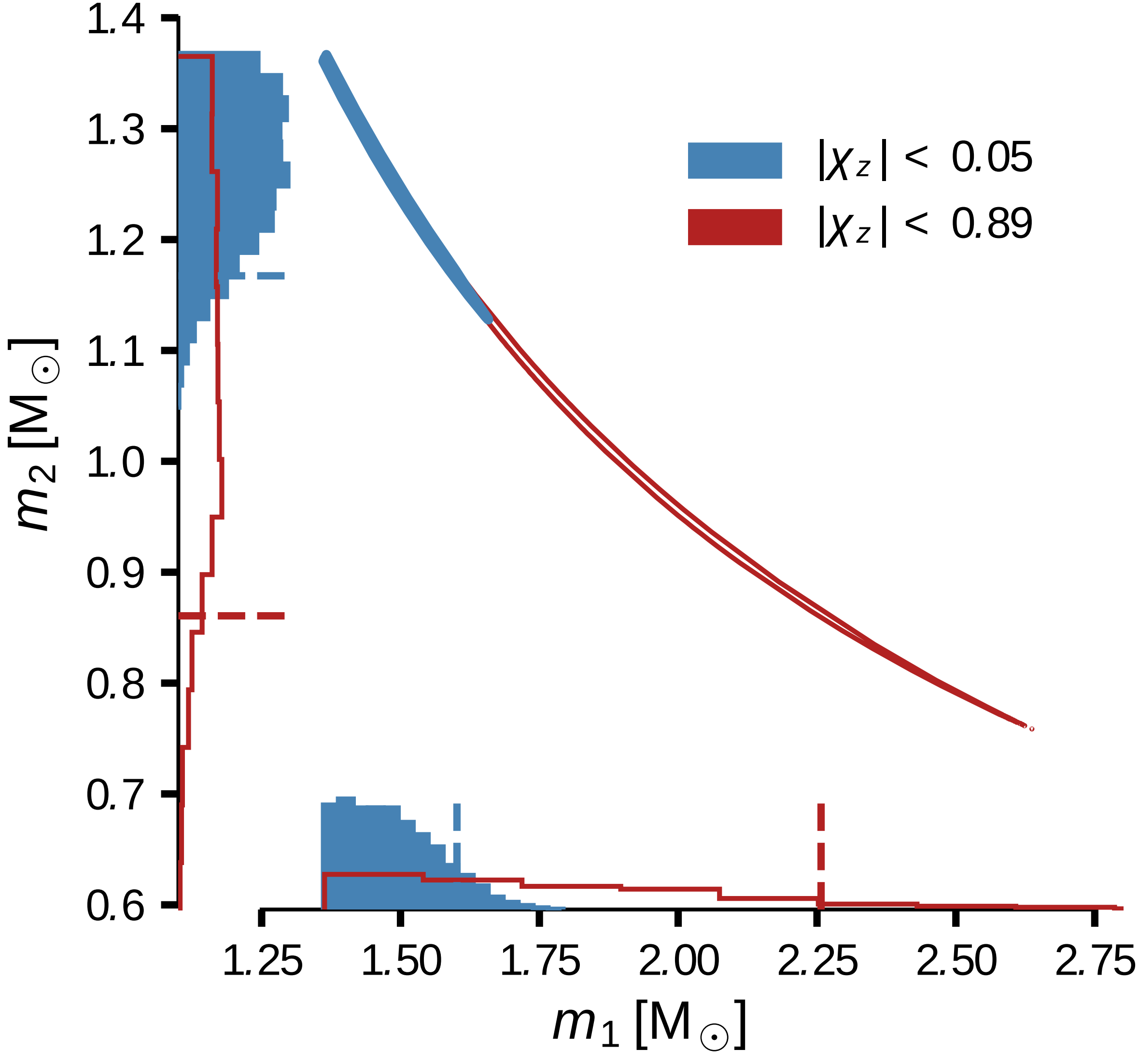


2017 Aug 17, 12:41 UTC

A Binary Neutron Star Merger

Neutron-Star Masses

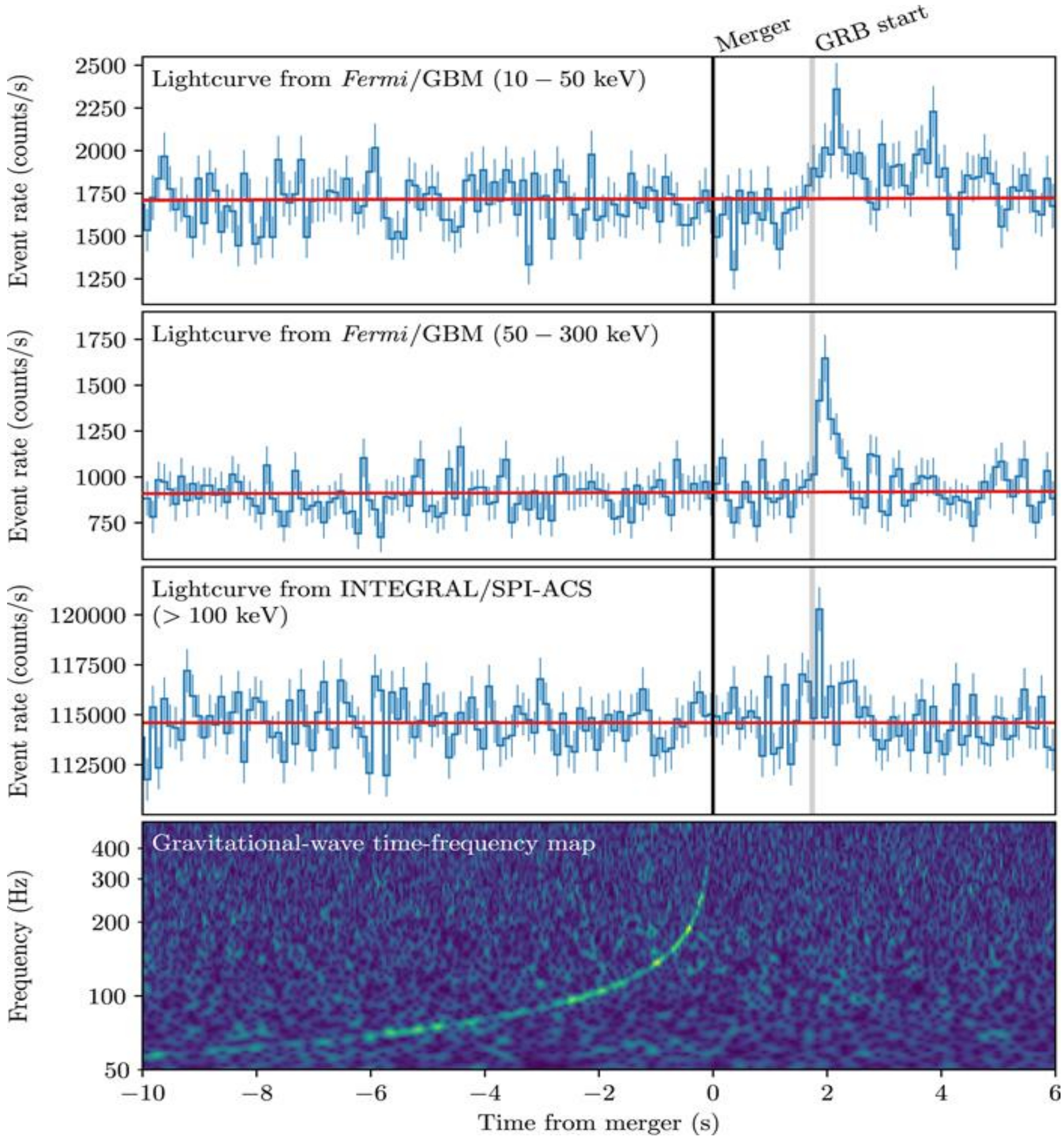
LSC, Virgo Phys. Rev. Lett. 119, 161101 (2017)



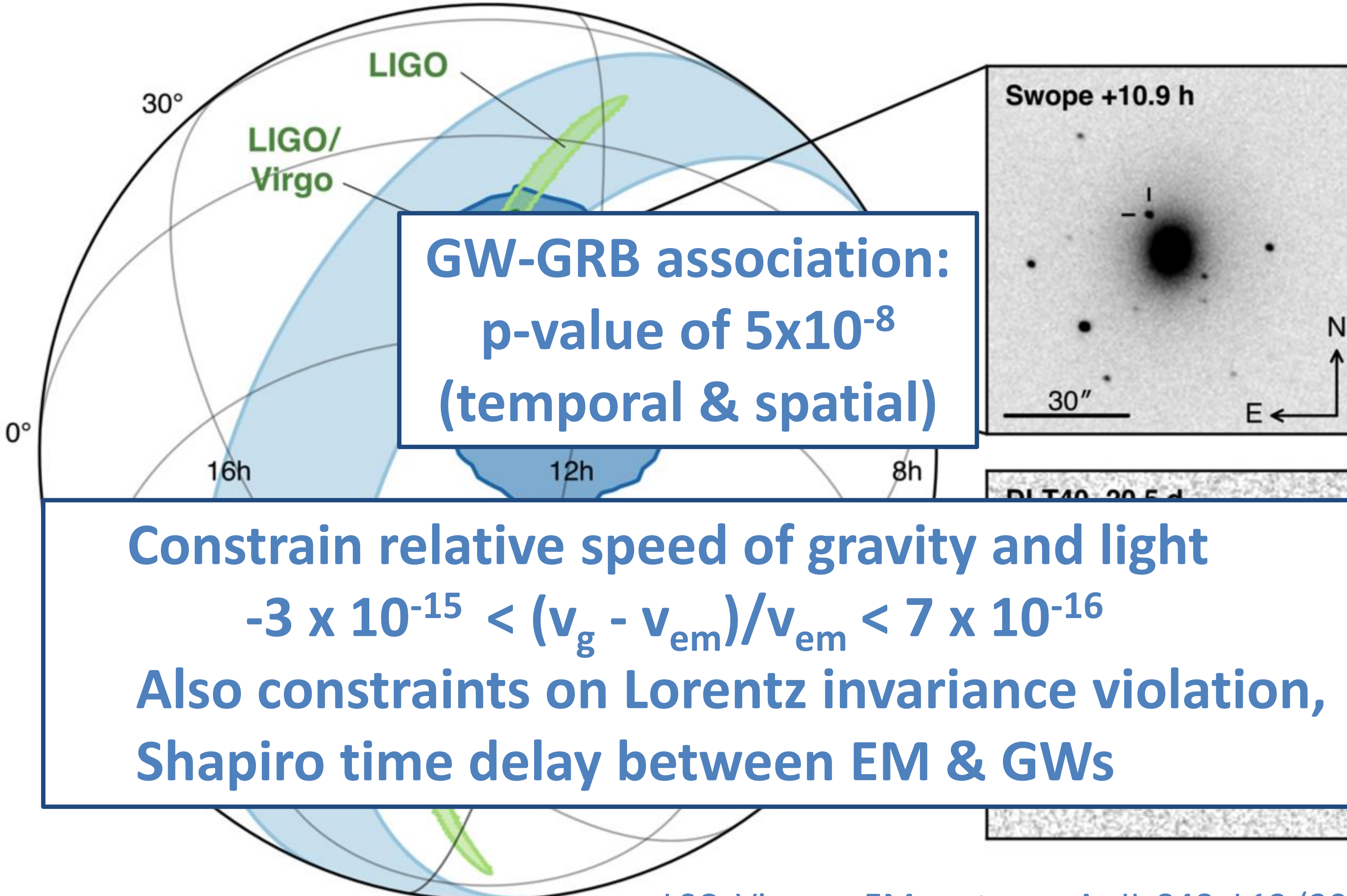

GW170817: Multi-Messenger
Observations

GRB 170817A

LSC, Virgo, Fermi, INTEGRAL, ApJL 848, L13 (2017)



Source Localisation



GW-GRB association:
p-value of 5×10^{-8}
(temporal & spatial)

Constrain relative speed of gravity and light

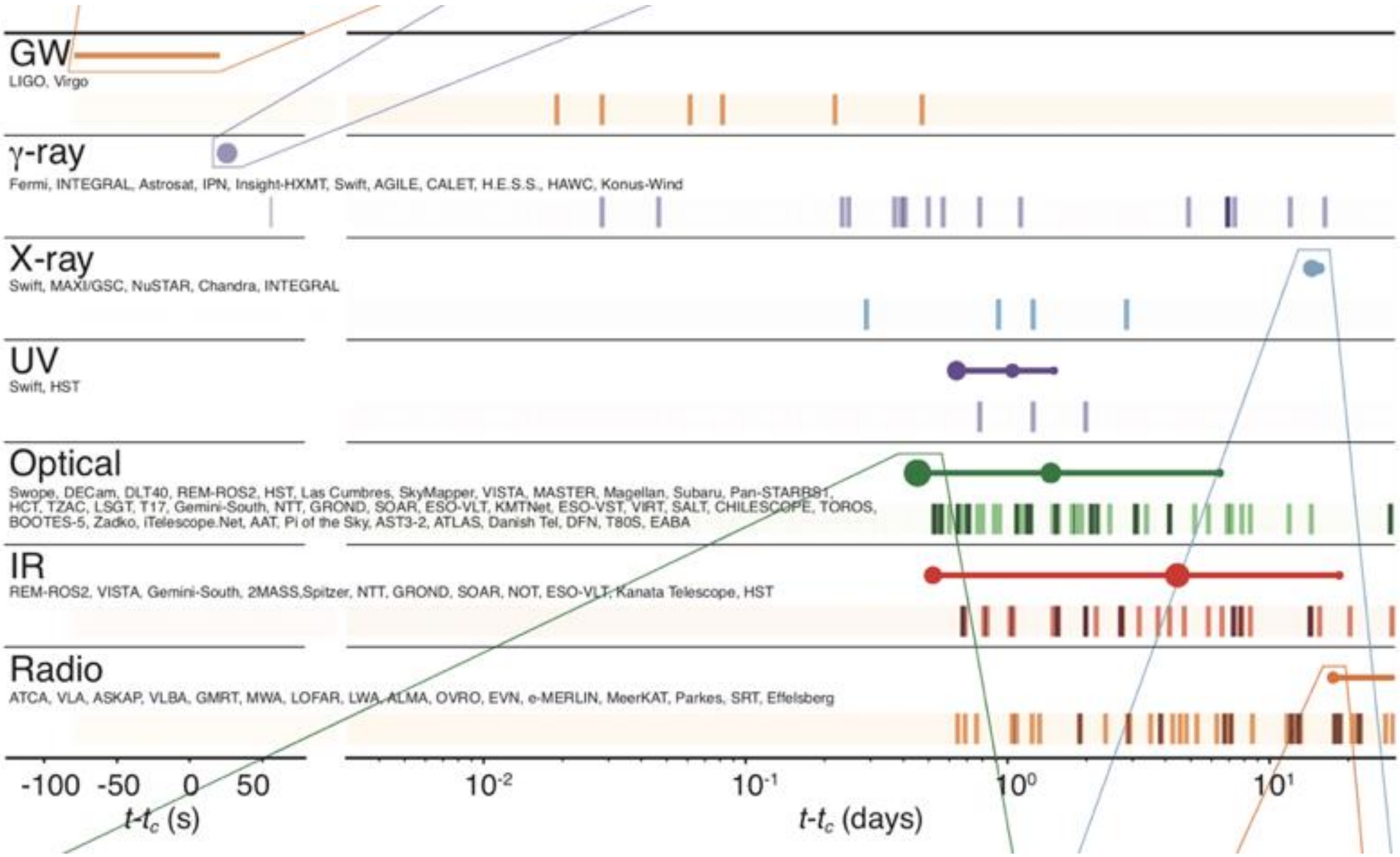
$$-3 \times 10^{-15} < (v_g - v_{em})/v_{em} < 7 \times 10^{-16}$$

Also constraints on Lorentz invariance violation, Shapiro time delay between EM & GWs

LSC, Virgo, + EM partners, ApJL 848, L12 (2017)

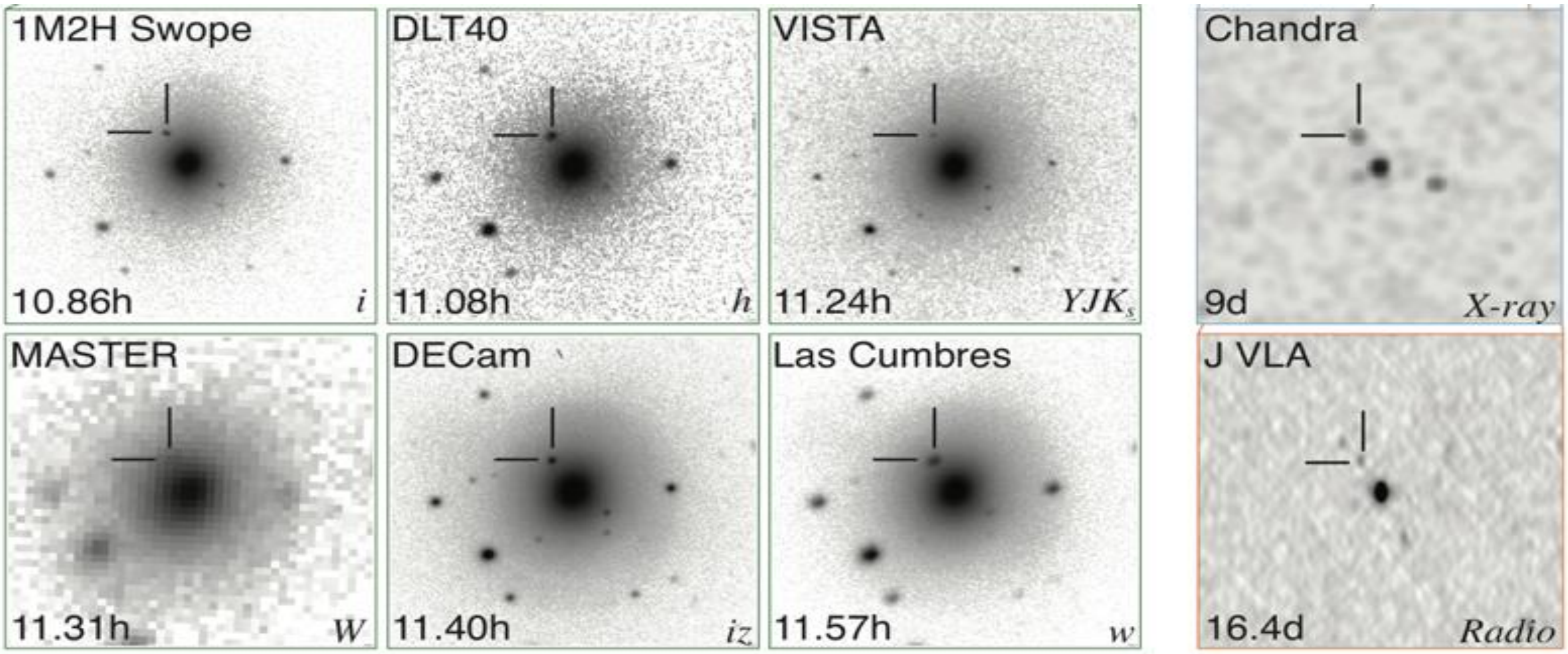
Multi-Messenger Observatories

Multi-Messenger Observations

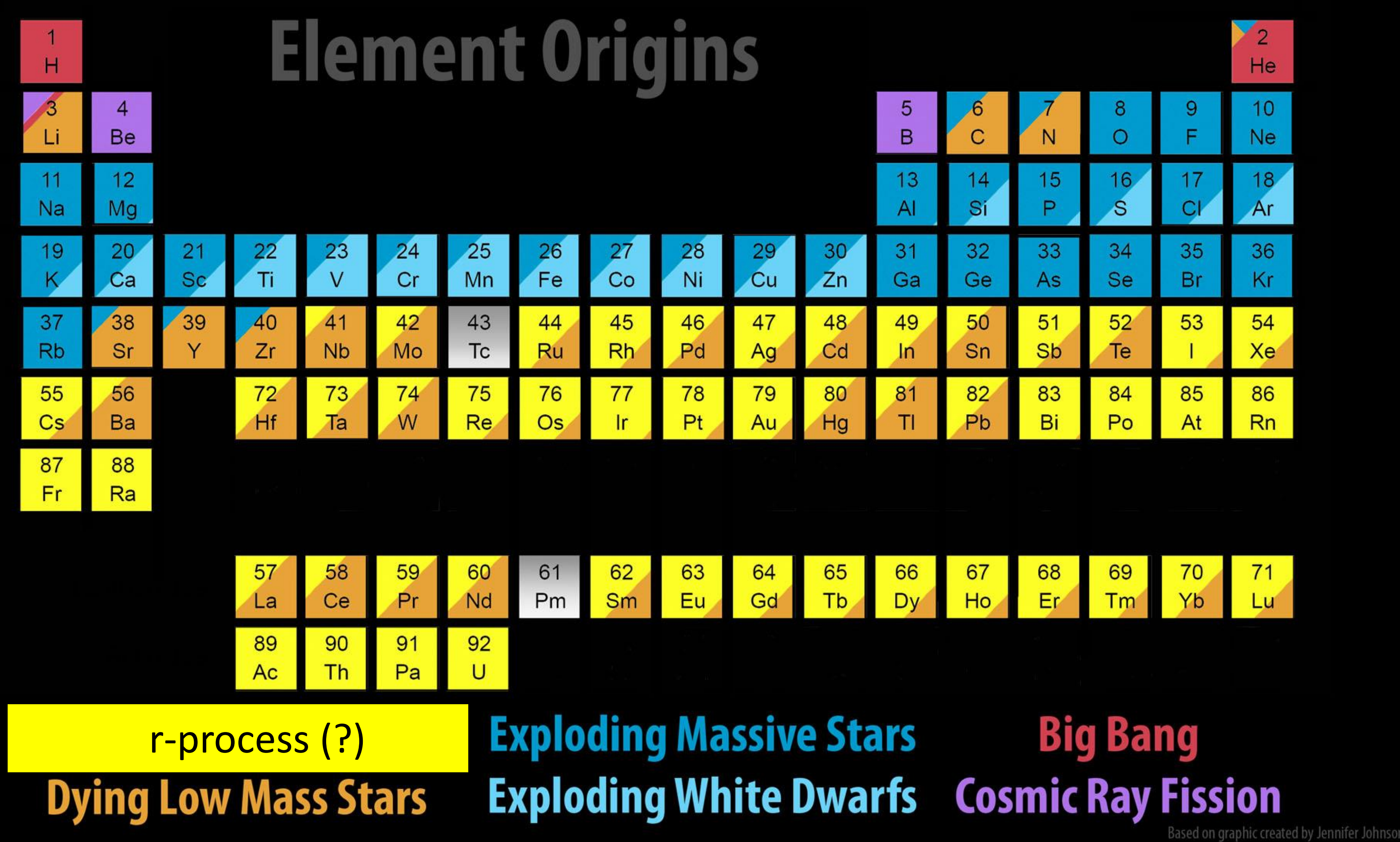


LSC, Virgo, + EM partners, ApJL 848, L12 (2017)

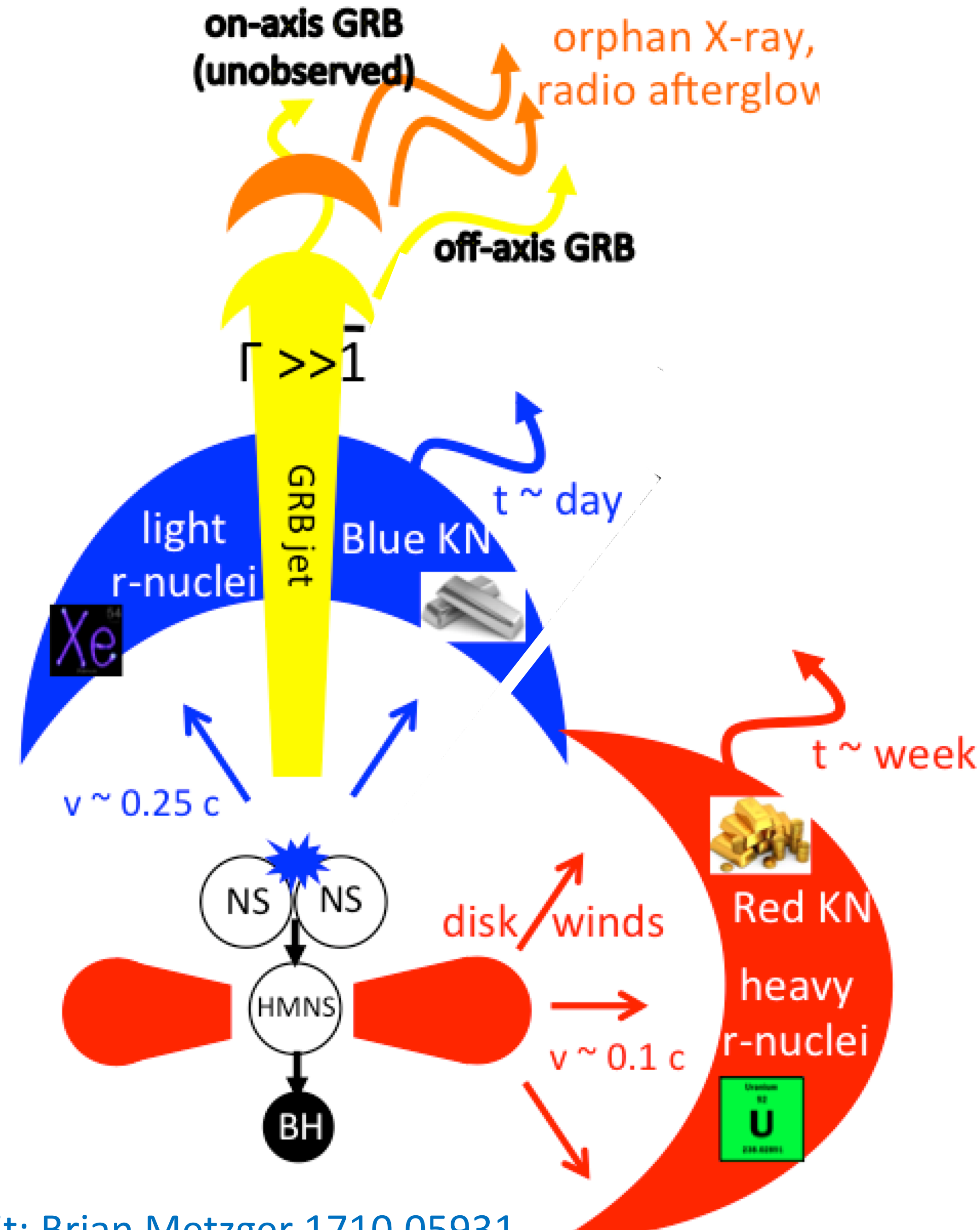
SSS17a / AT 2017gfo



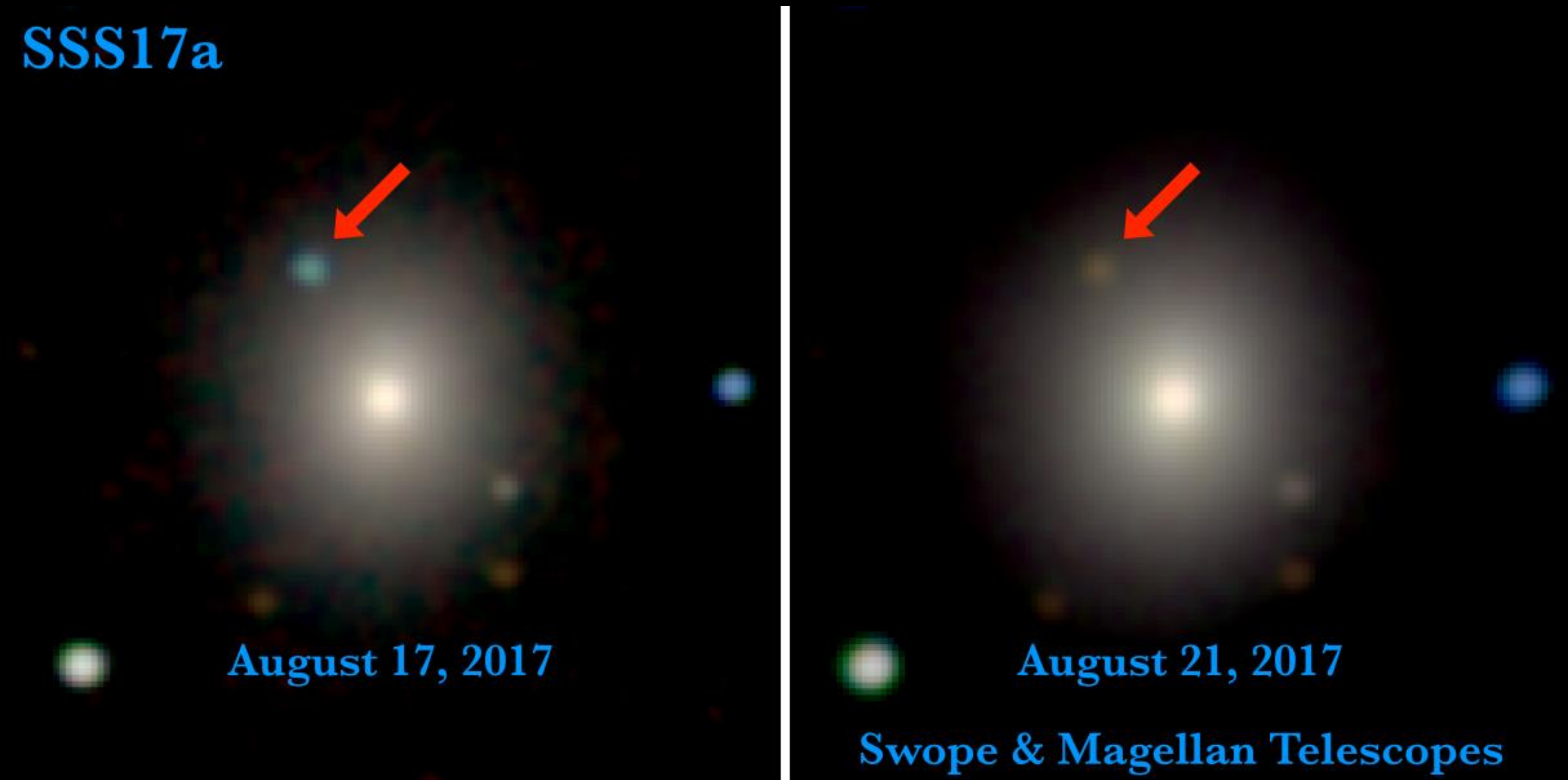
LSC, Virgo, + EM partners, ApJL 848, L12 (2017)



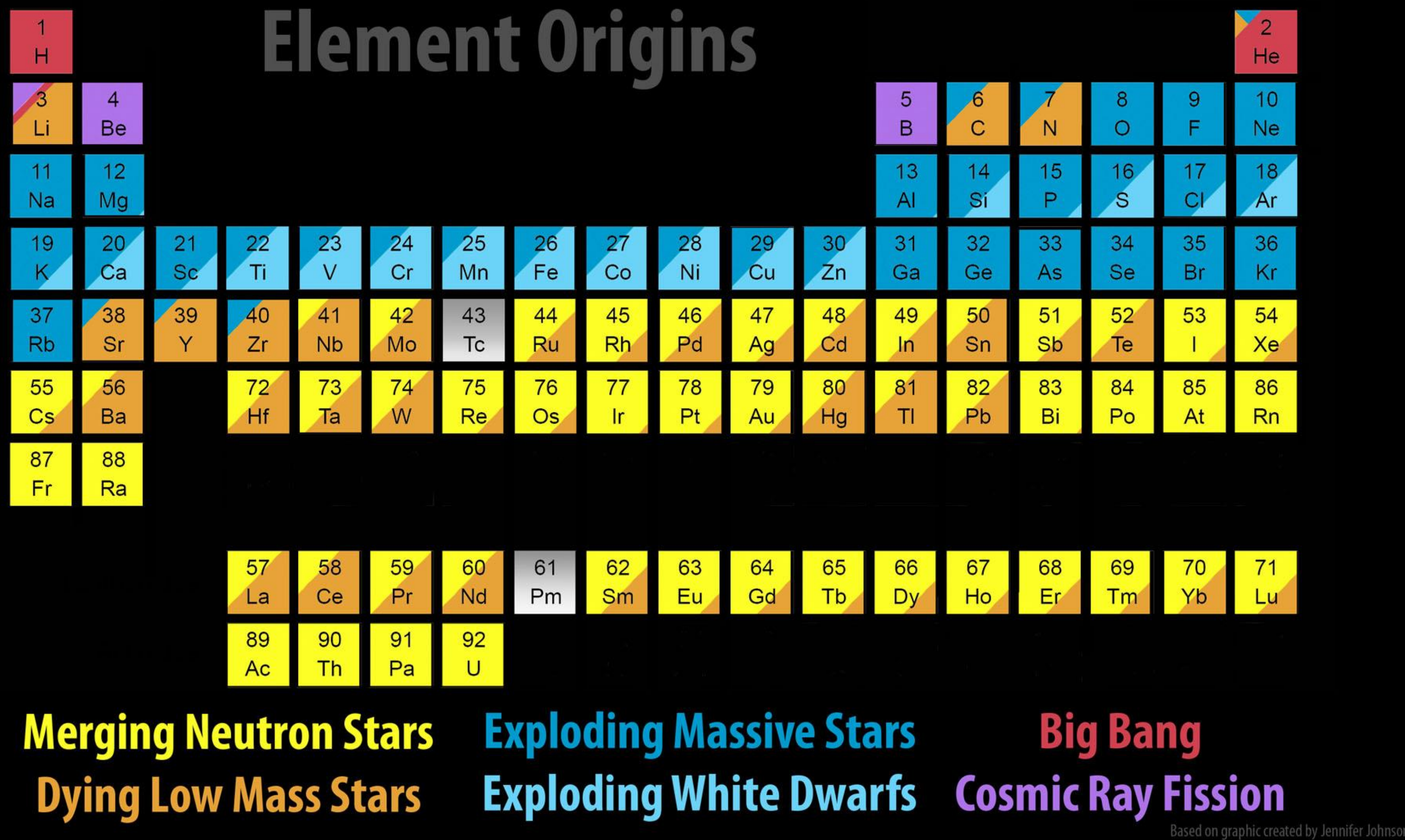
Credit: Jennifer Johnson/SDSS / CC BY 2.0 (modified)



Credit: Brian Metzger 1710.05931

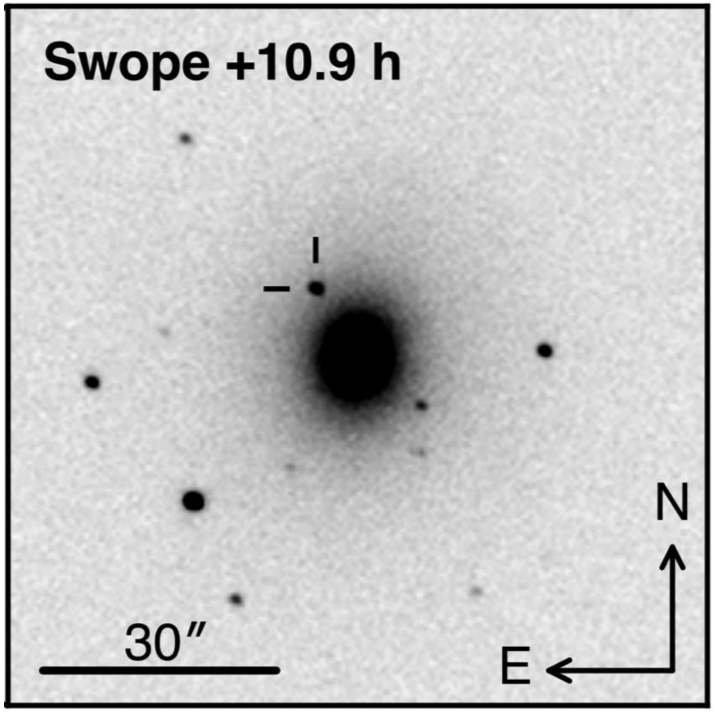


1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

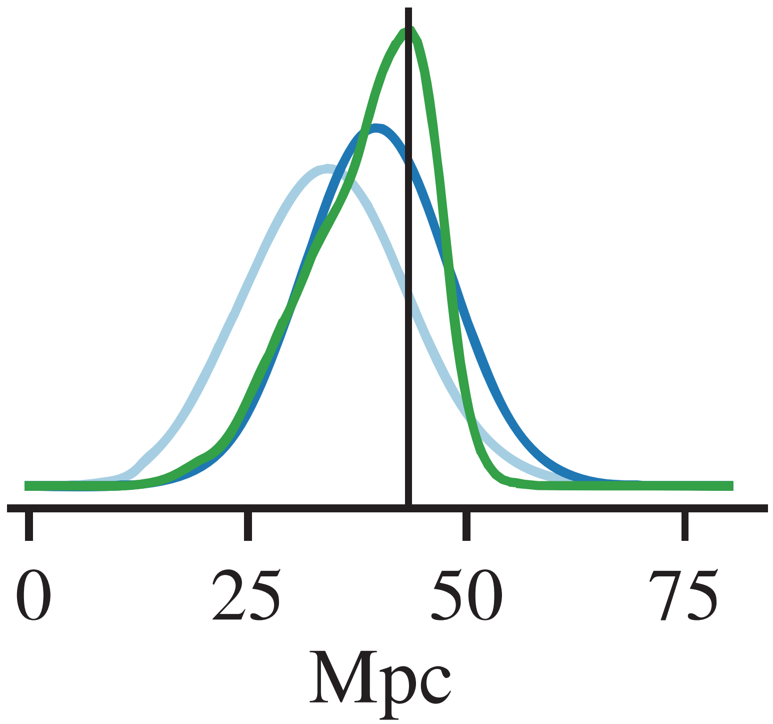

Element Origins
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
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 Jennifer Johnson

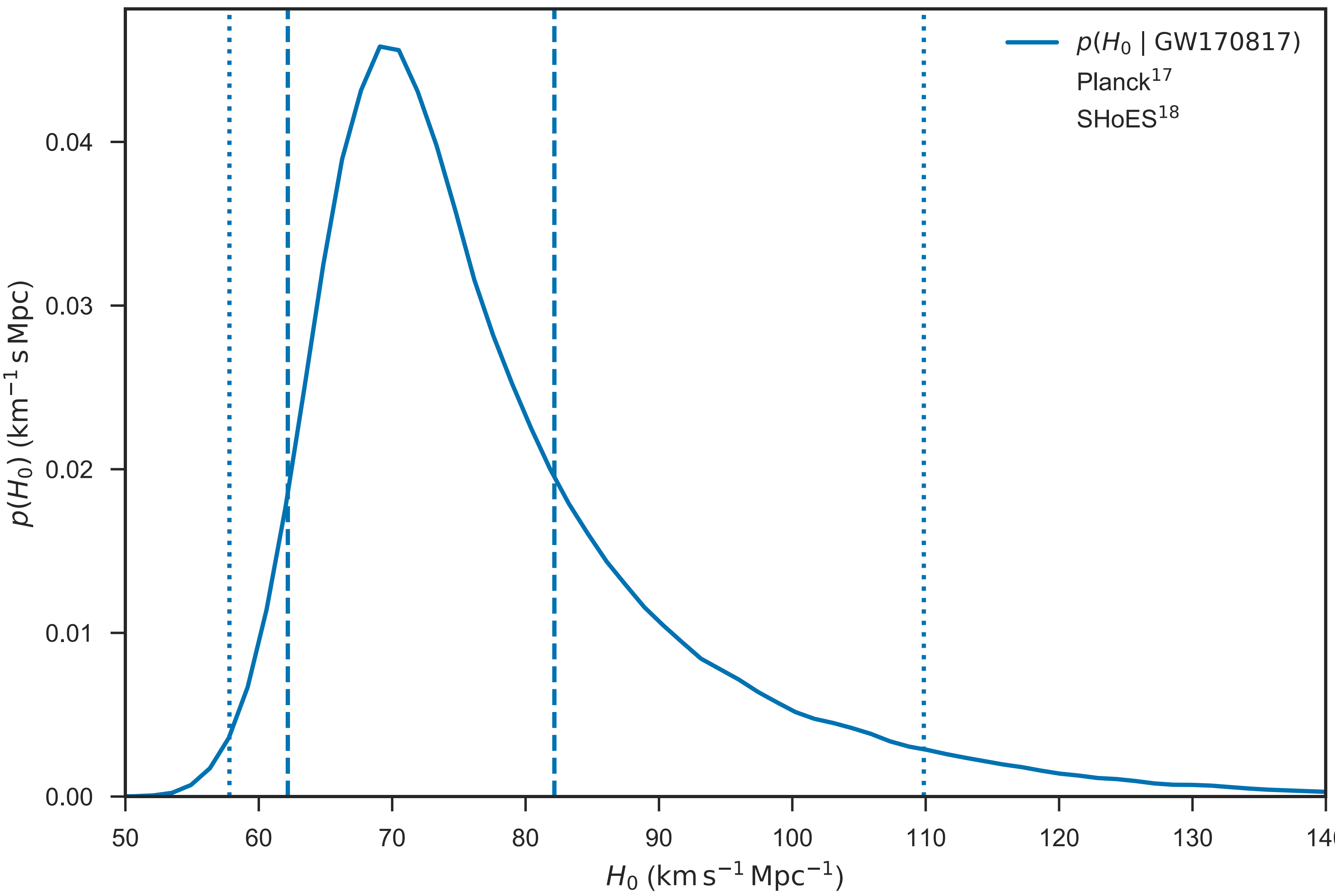
Standard Siren Cosmology

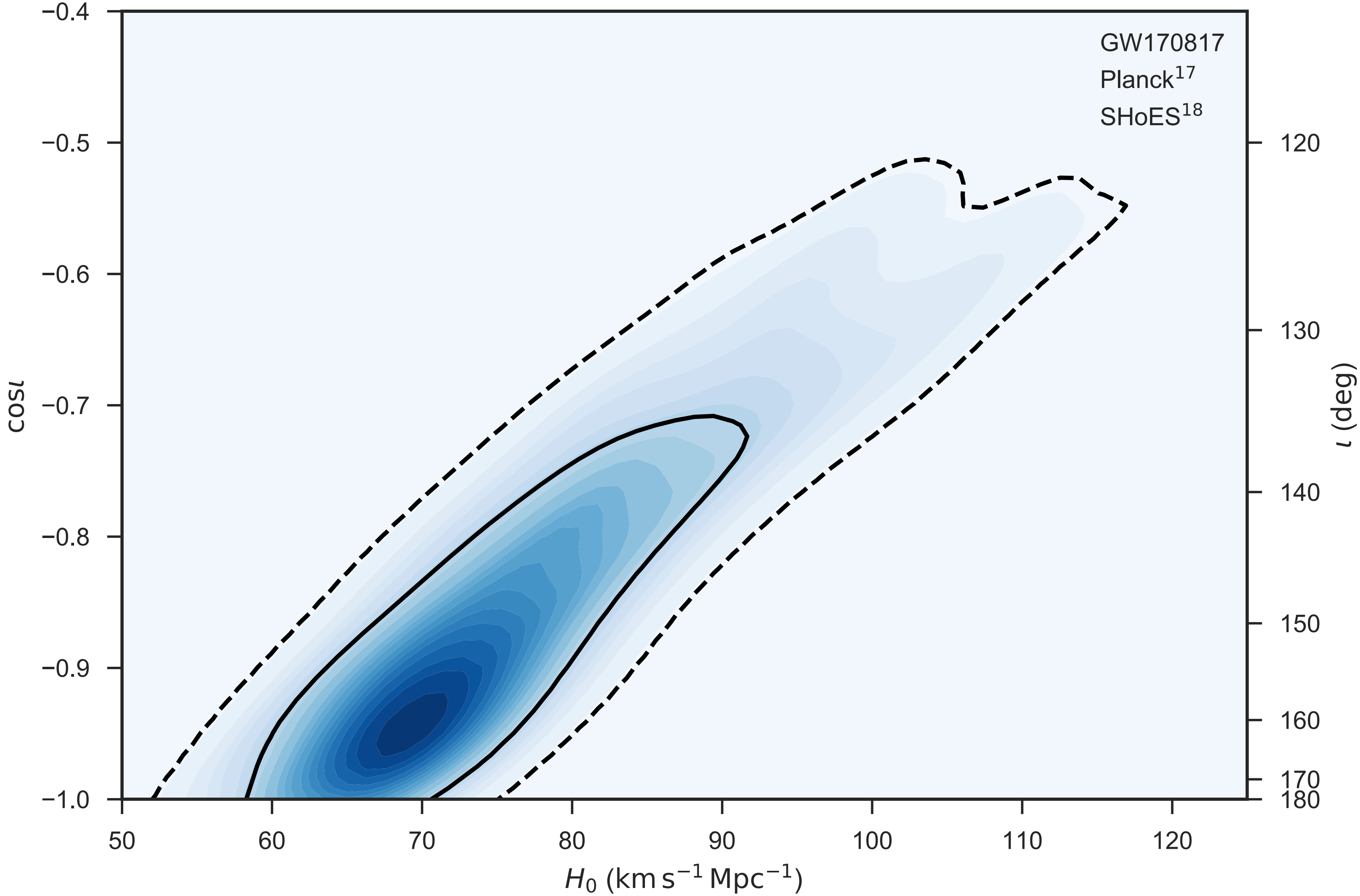
Host galaxy: NGC 4993

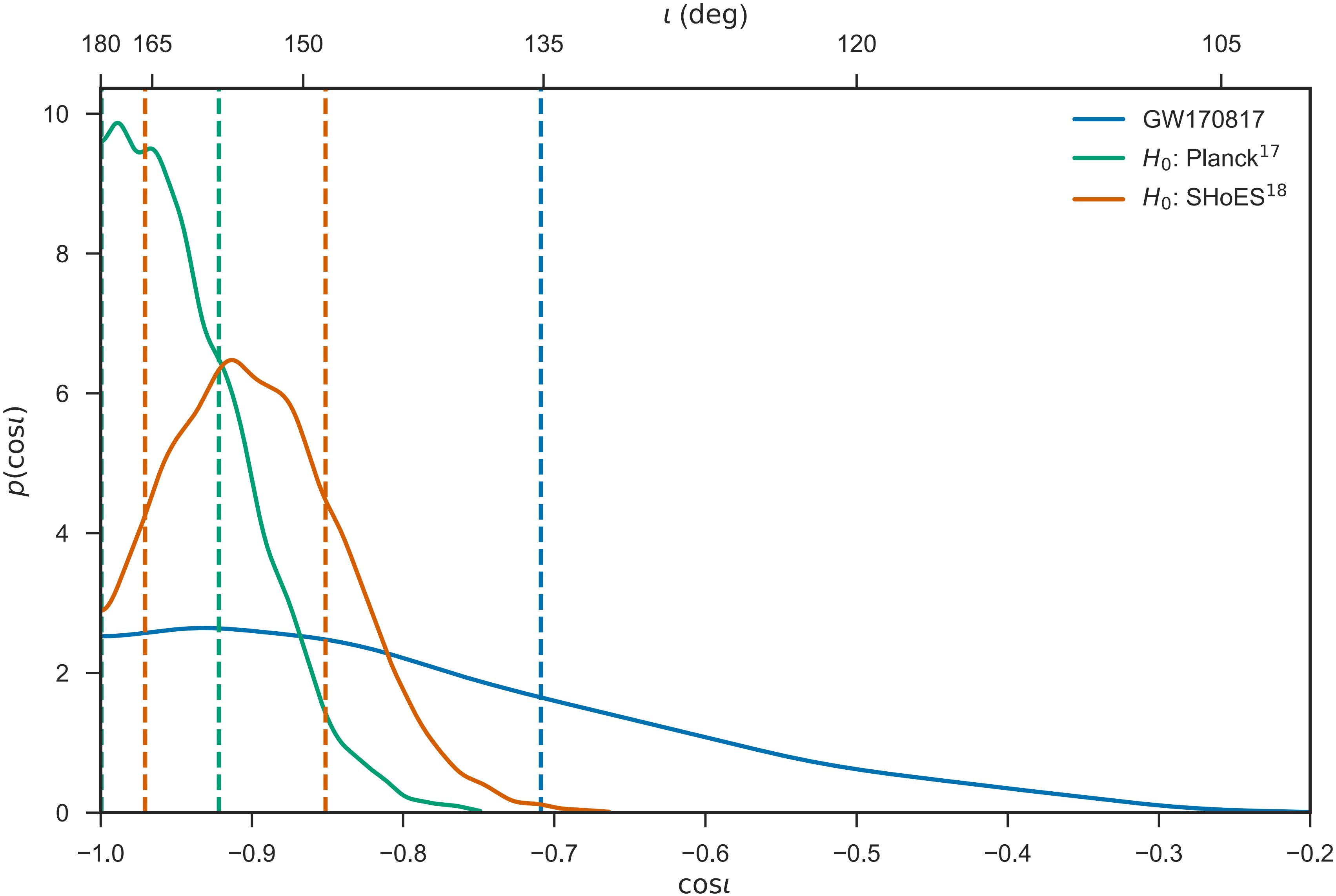


Distance to GW Source




$p(H_0 \mid \mathrm{GW170817})$
Planck[17]
SHoES[18]
0.00
0.01
0.02
0.03
0.04
$p(H_0)$ (km^{-1} s Mpc)
50
60
70
80
90
100
110
120
130
140
H_0 (km s^{-1} Mpc^{-1})

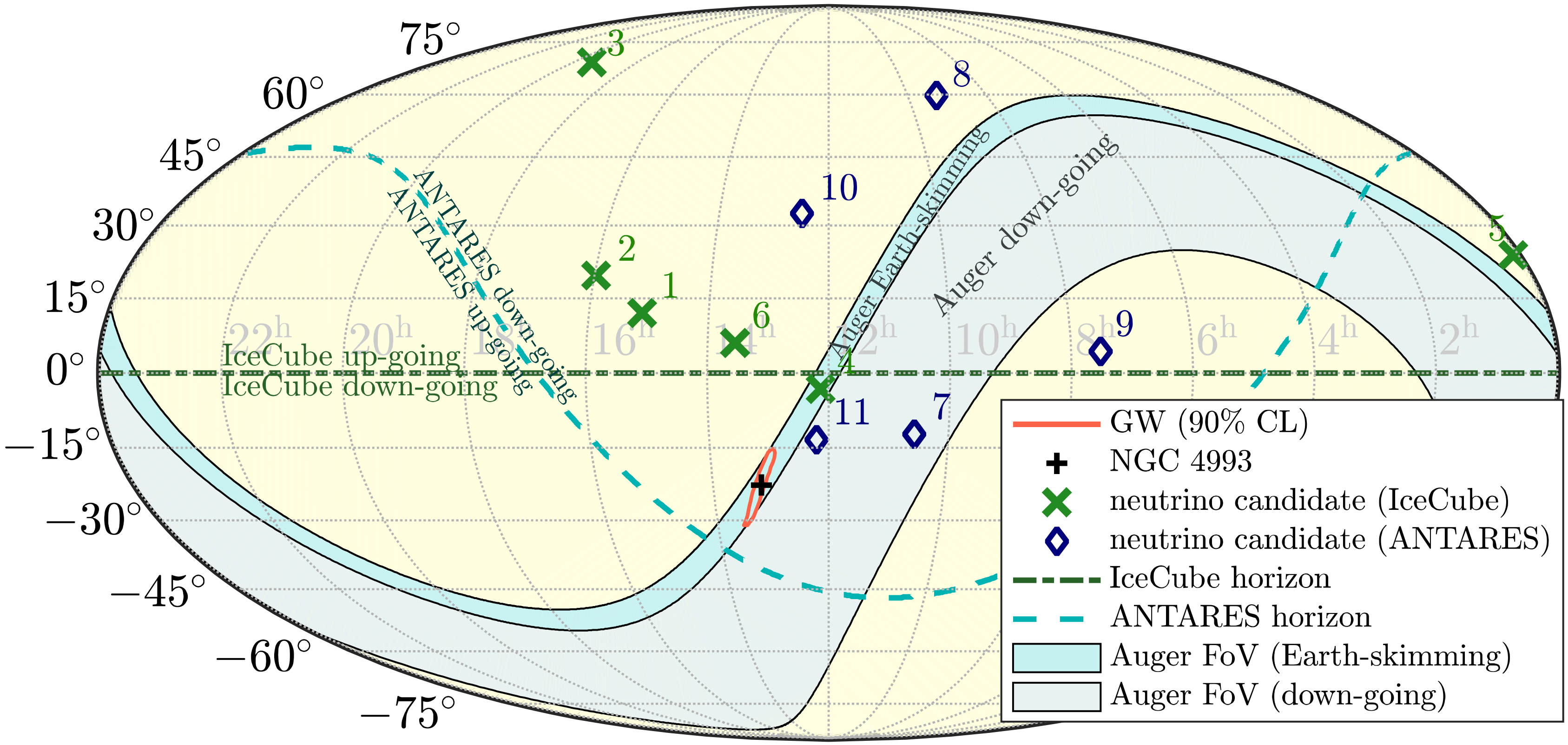

GW170817
Planck[17]
SHoES[18]
cos ι
ι (deg)
H_0 (km s^{-1} Mpc^{-1})
−0.4
−0.5
−0.6
−0.7
−0.8
−0.9
−1.0
120
130
140
150
160
170
180
50
60
70
80
90
100
110
120



ι (deg)
180
165
150
135
120
105
GW170817
H0: Planck17
H0: SHoES18
p(cos ι)
10
8
6
4
2
0
−1.0
−0.9
−0.8
−0.7
−0.6
−0.5
−0.4
−0.3
−0.2
cos ι

Neutrino Observations

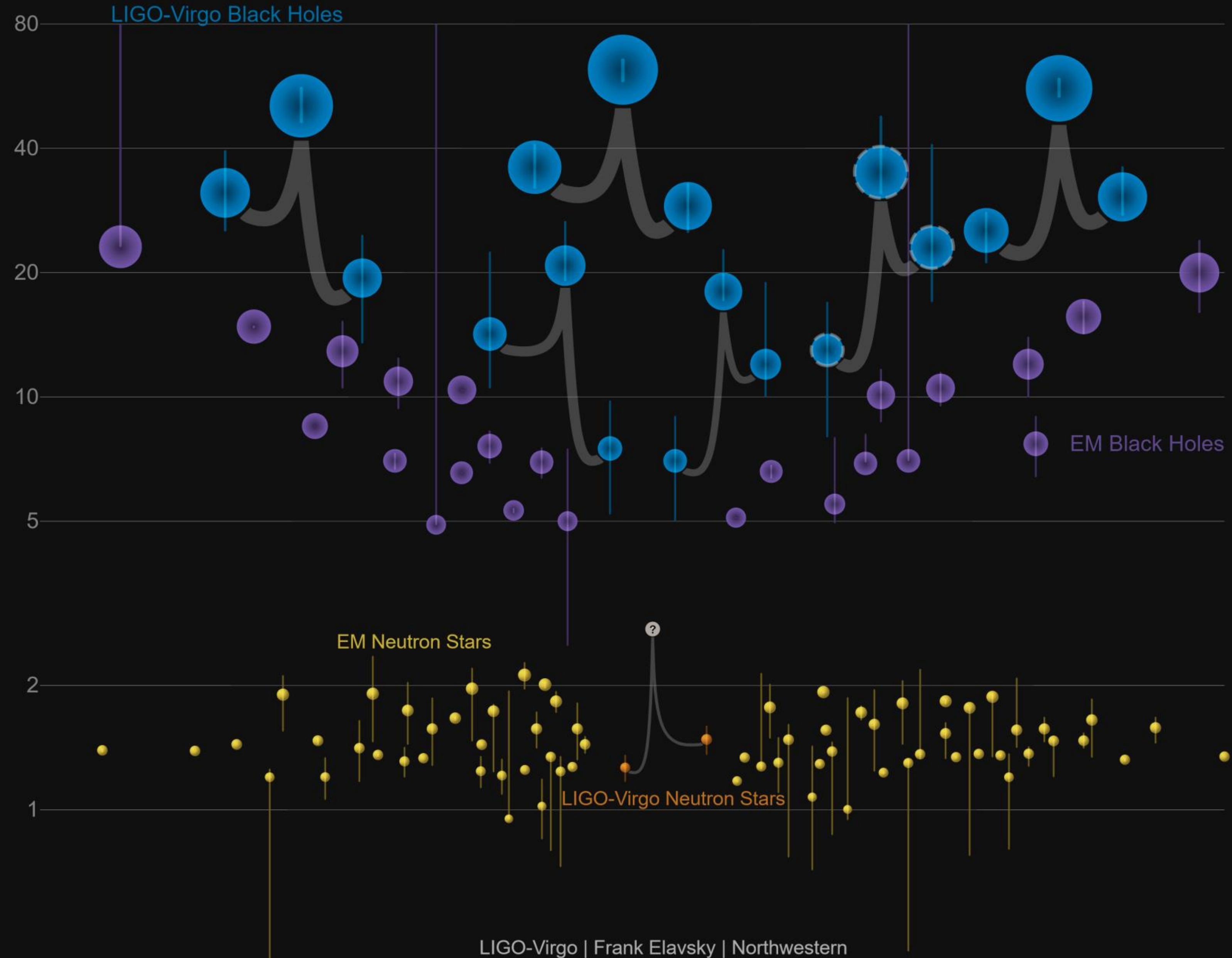
(t_{GW} +/- 500 s) – no associated νs



ANTARES/IceCube/Pierre Auger/LIGO/Virgo ApJ 850 (2017) L35

Masses in the Stellar Graveyard

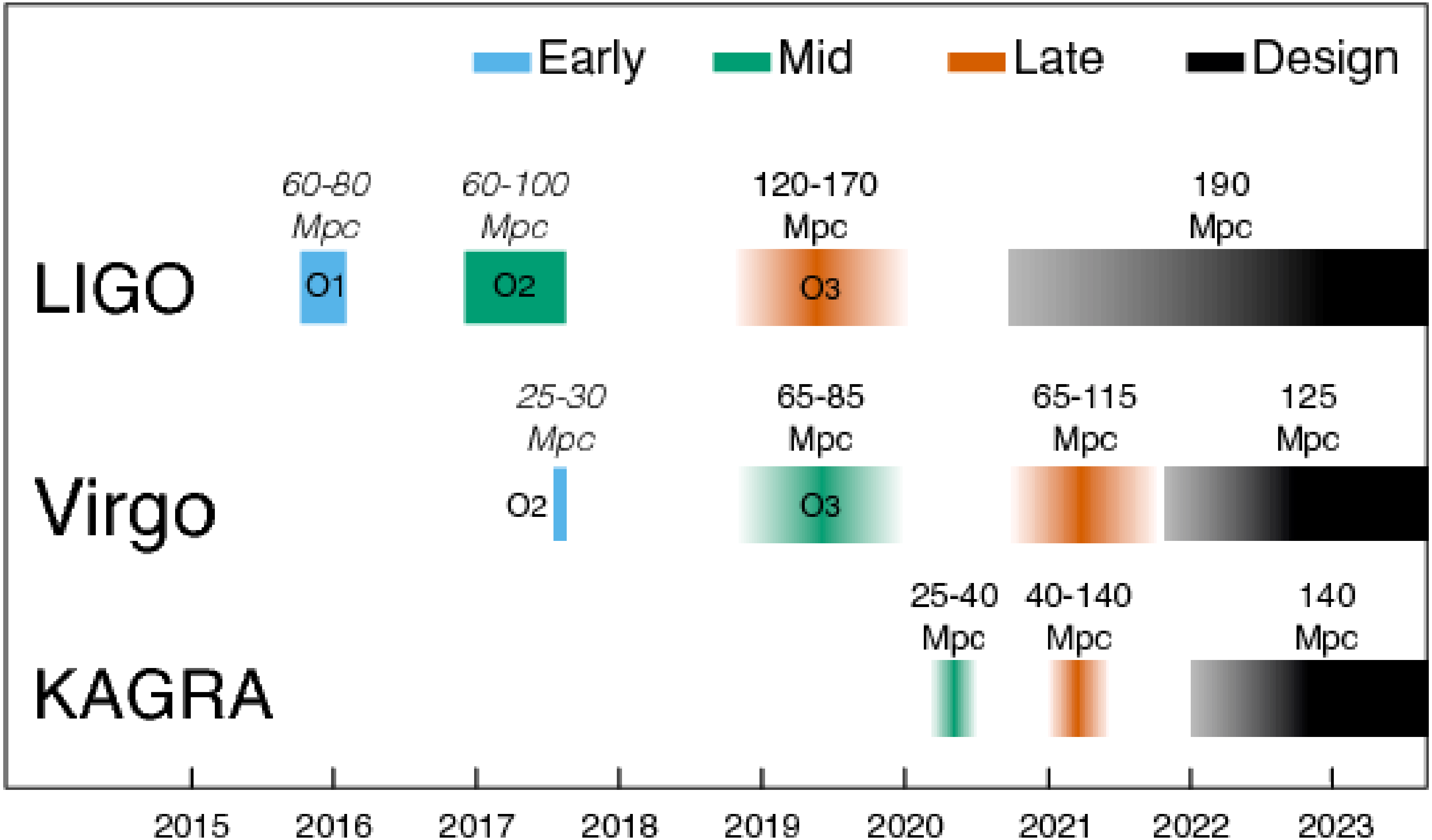
in Solar Masses



LIGO-Virgo | Frank Elavsky | Northwestern

Observing Plans

KAGRA/LIGO/Virgo https://arxiv.org/abs/1304.0670 / Living Rev.Rel. 19 (2016)



GW170817

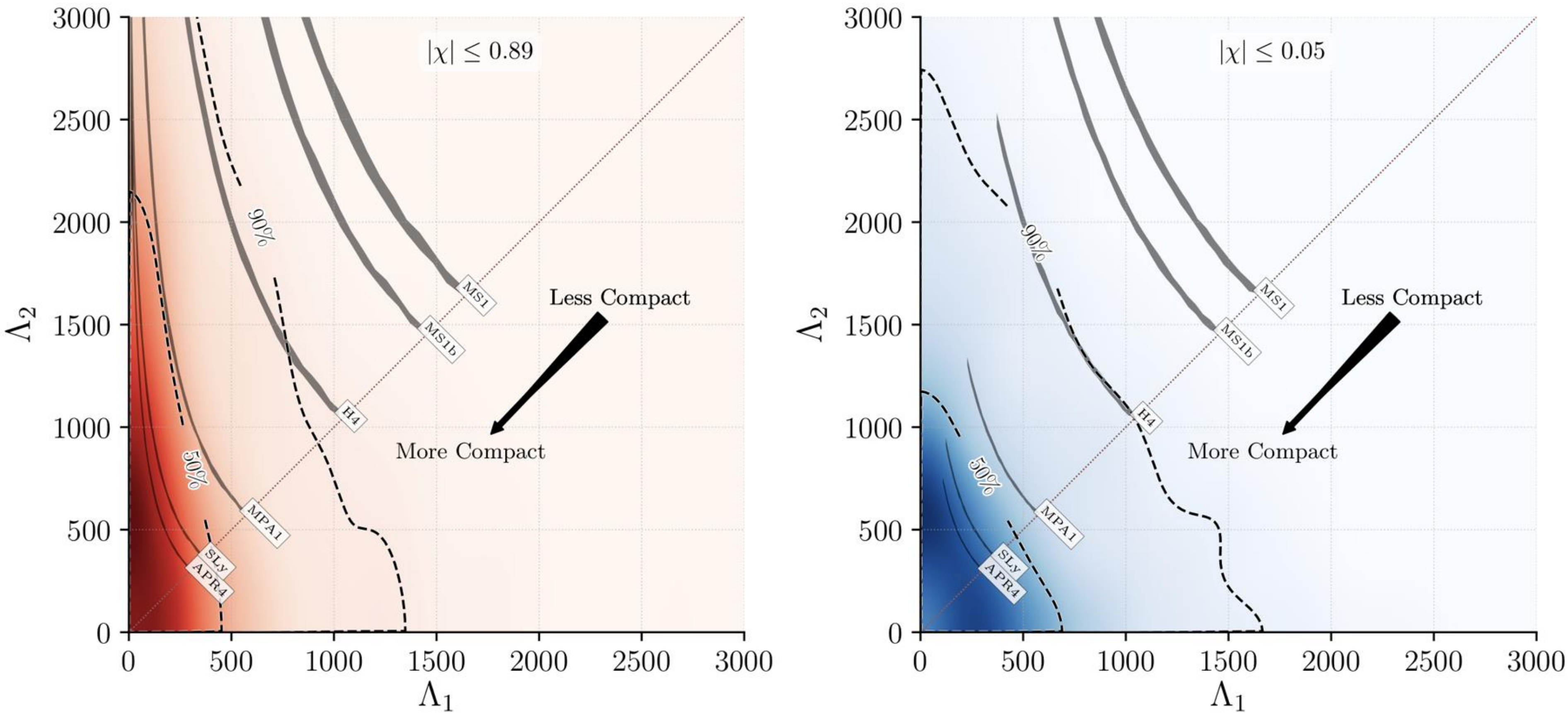
- First detection of a binary neutron star coalescence.

- Coincident with:
  - a short GRB
  - an optical kilonova counterpart
  - plus X-ray and radio afterglows
- No detected neutrinos

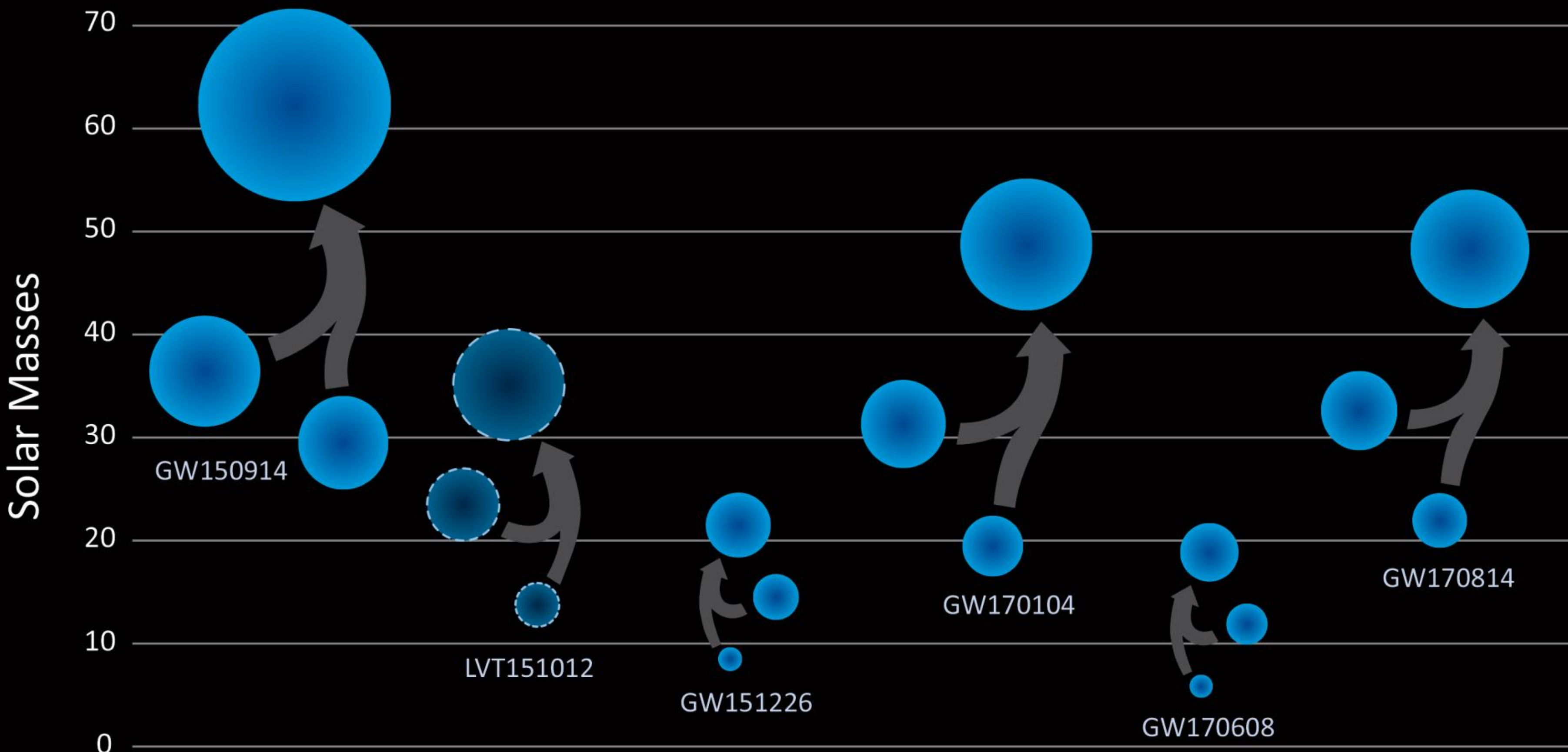
- Implications for:
  - Origin of short GRBs
  - Speed of gravity
  - Origin of heavy elements
  - Measurement of the Hubble constant
  - … and more!

SUPPLEMENTAL SLIDES

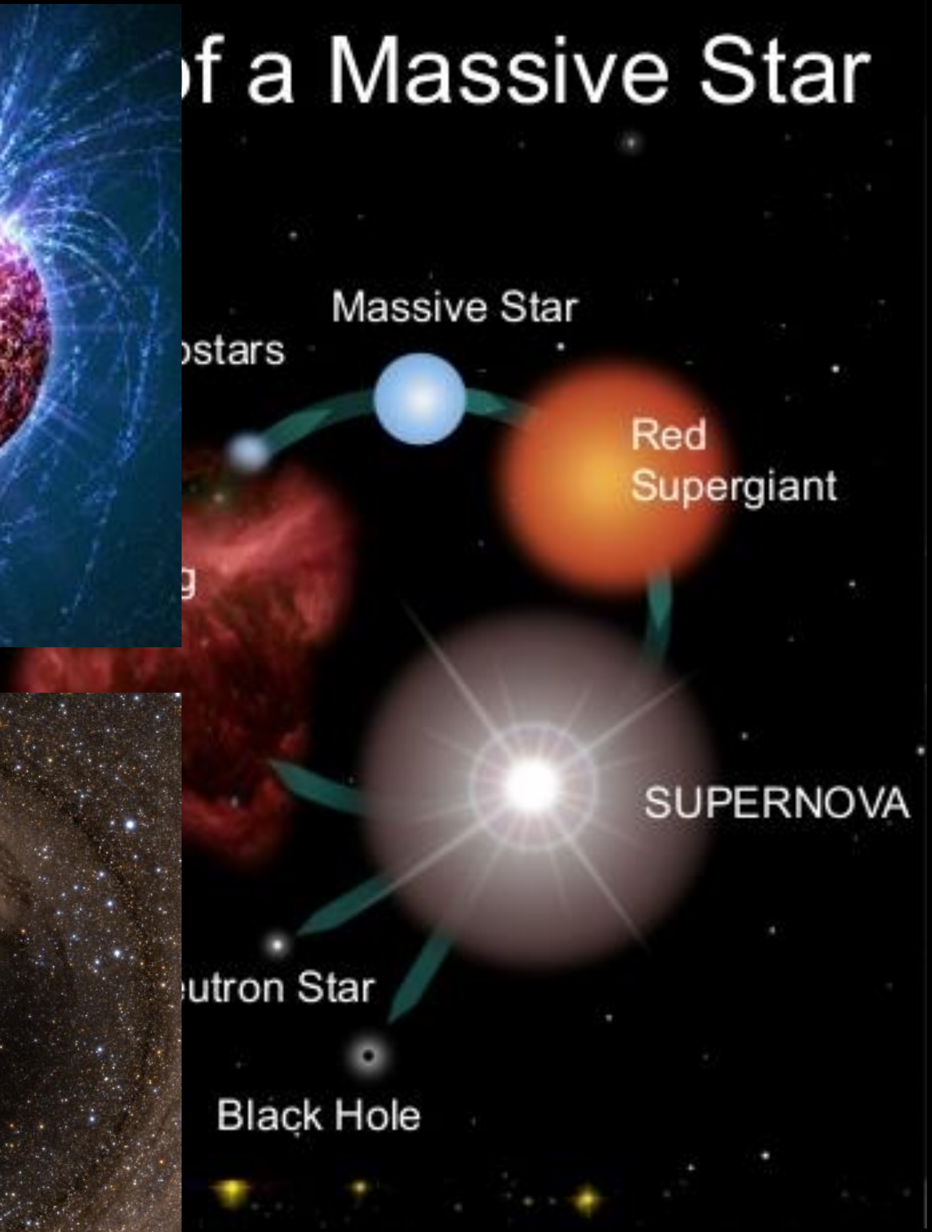
Neutron Star Deformability



Black Holes of Known Mass



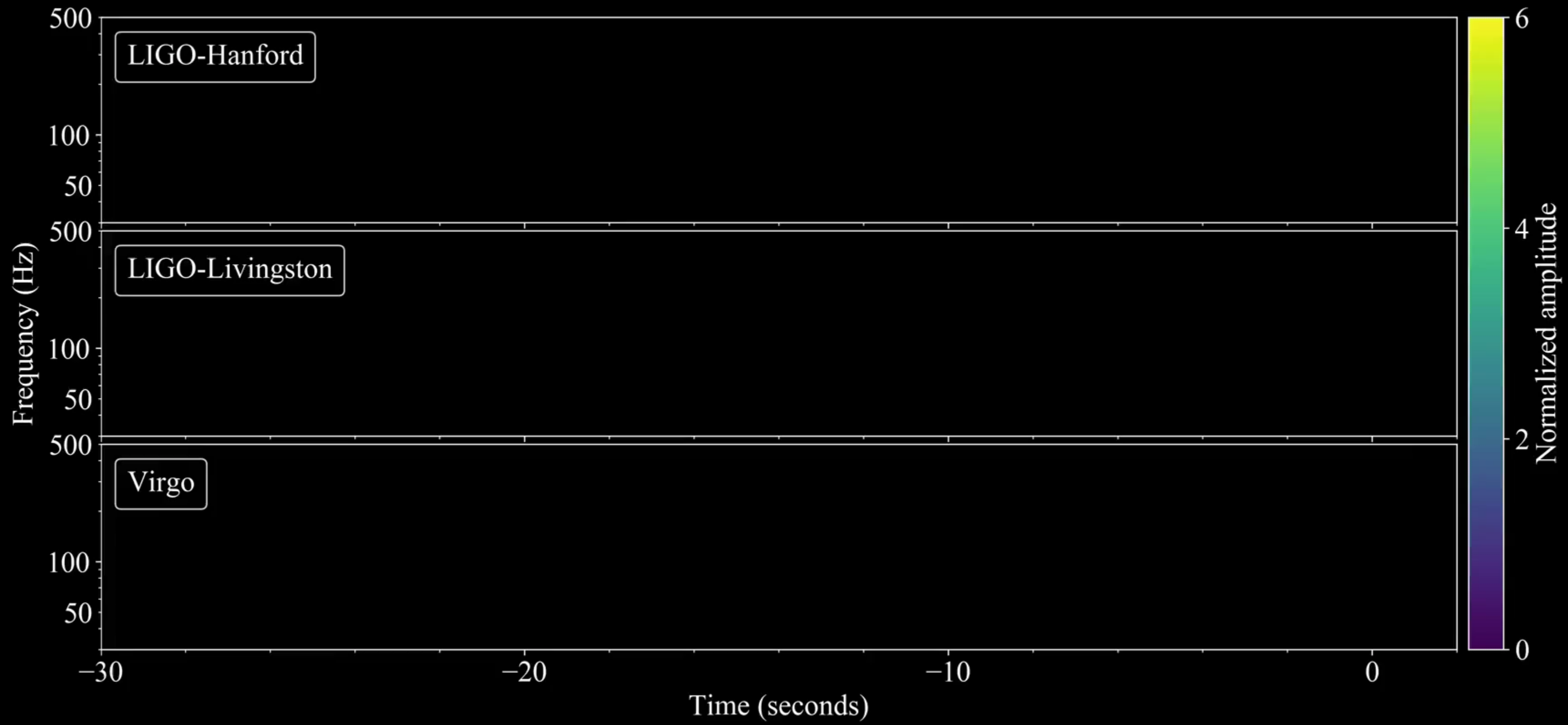
LIGO/VIRGO


f a Massive Star
Massive Star
Red
Supergiant
SUPERNOVA
Black Hole


Neutron Star


Black Hole

A New Phenomenon



2017 Aug 17, 1:41 pm

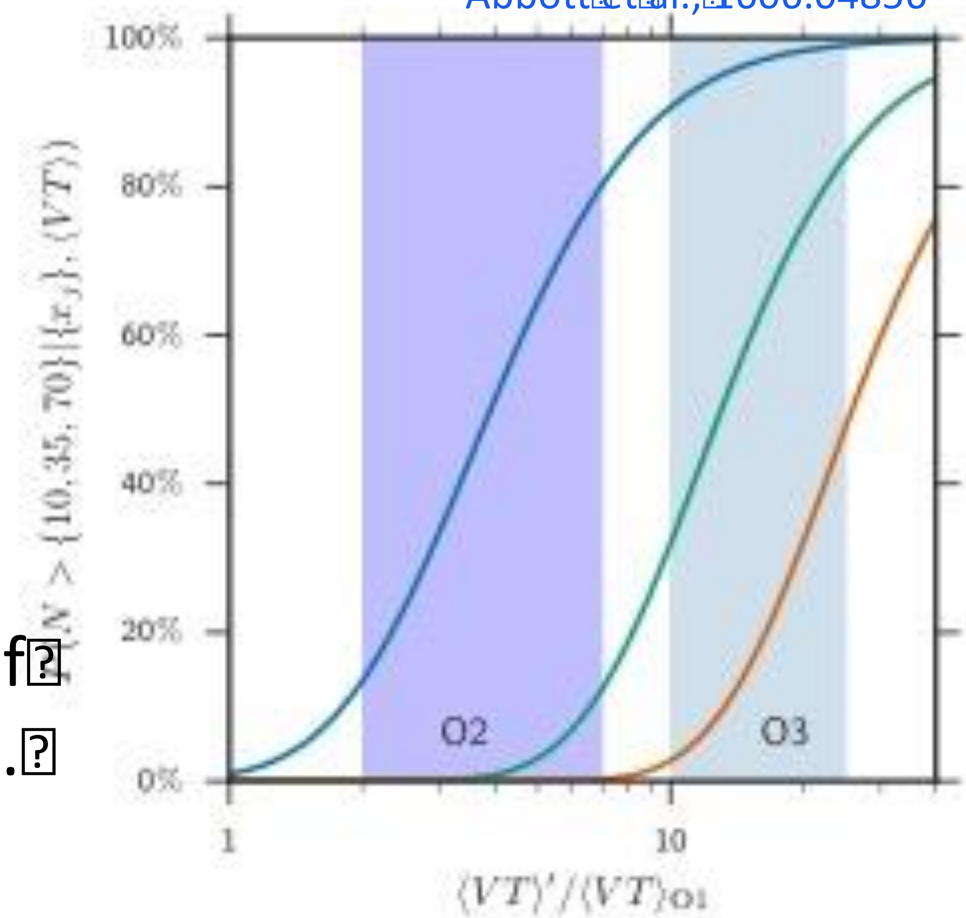
Expectations for Future Runs

Abbott et al., 1606.04856

Probability of observing

- N > 10 (blue)
- N > 35 (green)
- N > 70 (red)

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



3-Detector Localisation