



Science & Technology  
Facilities Council



# Gravitational Waves: 5 years on

Dr Chris North  
Cardiff University







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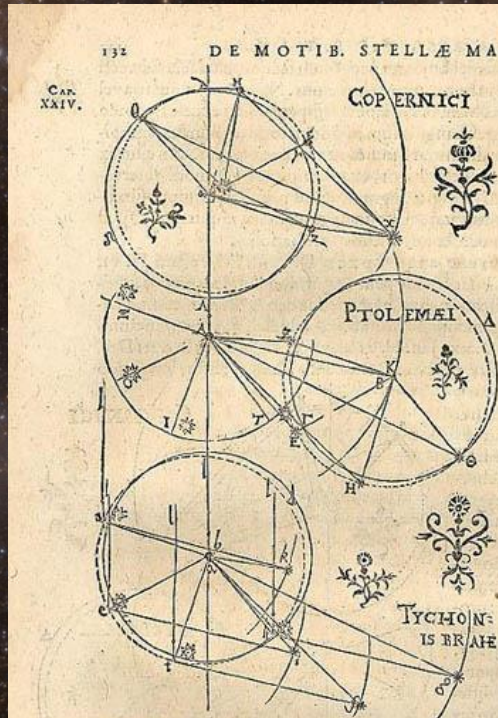
NorthCE@cardiff.ac.uk  
@chrisenorth





# Planetary Motions

Johannes Kepler (1571-1630)



*Astronomia nova* (1609)



Tycho  
Brahe



Galileo Galilei

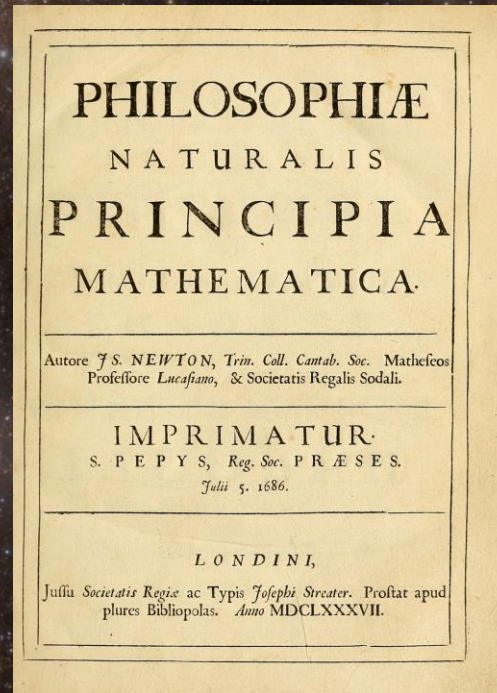
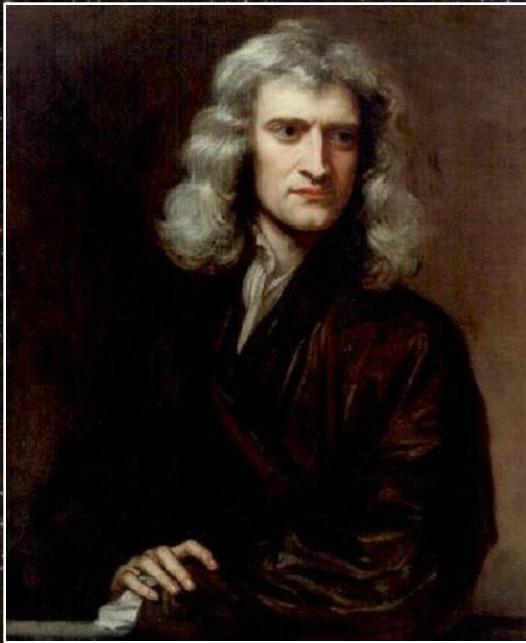


Nicolaus  
Copernicus



# Newtonian Gravity

Isaac Newton (1642-1727)



*Philosophiæ Naturalis  
Principia Mathematica*  
(1687)



Robert  
Hooke



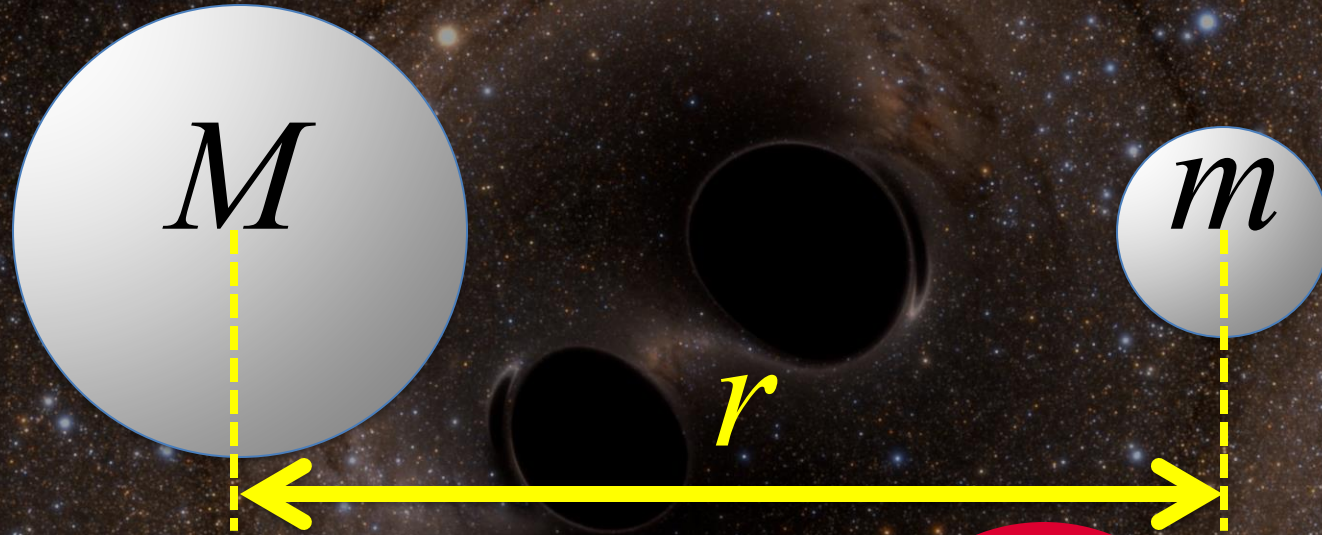
Christopher  
Wren



Edmund  
Halley



# Newtonian Gravity



How matter moves

$$F = G \frac{Mm}{r^2}$$

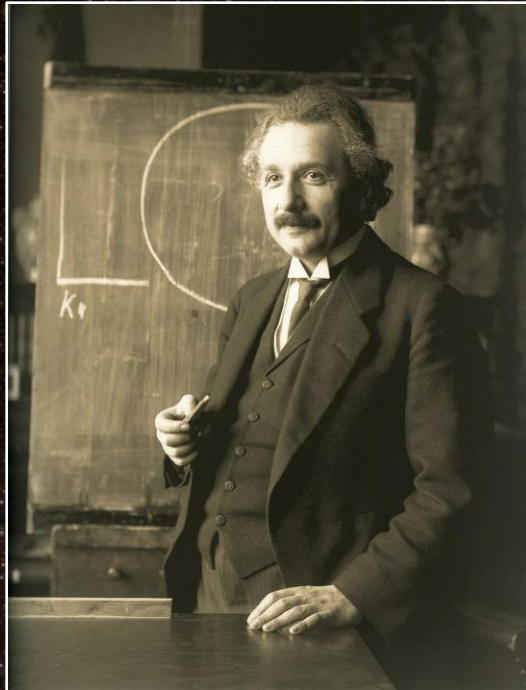
Where matter is

$$G = 0.0000000000667 \text{ N/kg/m}^2$$



# General relativity

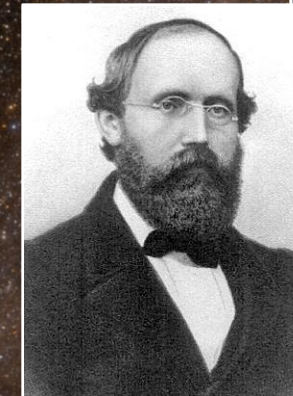
Albert Einstein (1879-1955)



*On the General Theory of Relativity (1915)*



*David Hilbert*



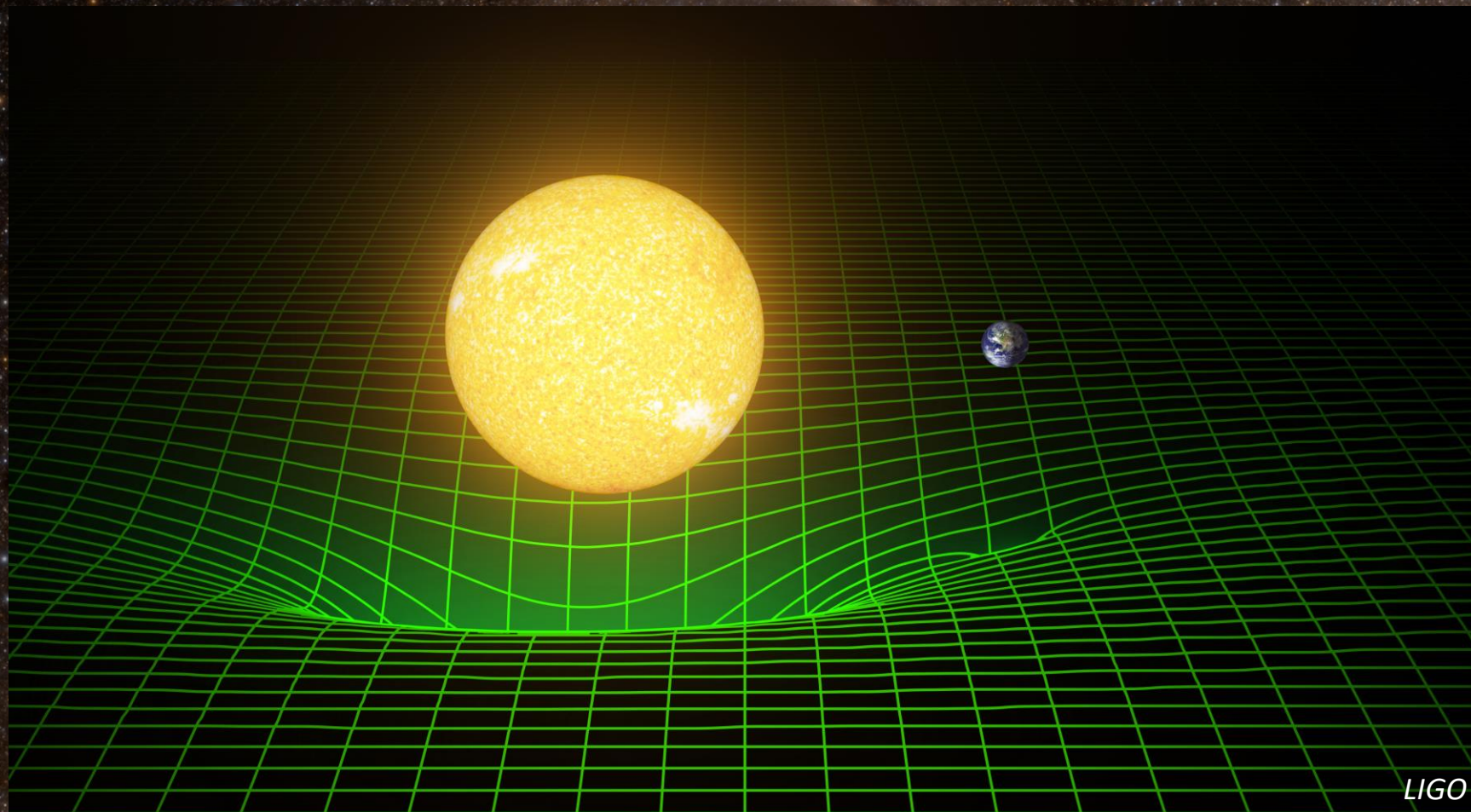
*Bernhard Riemann*



*Hermann Minkowski*



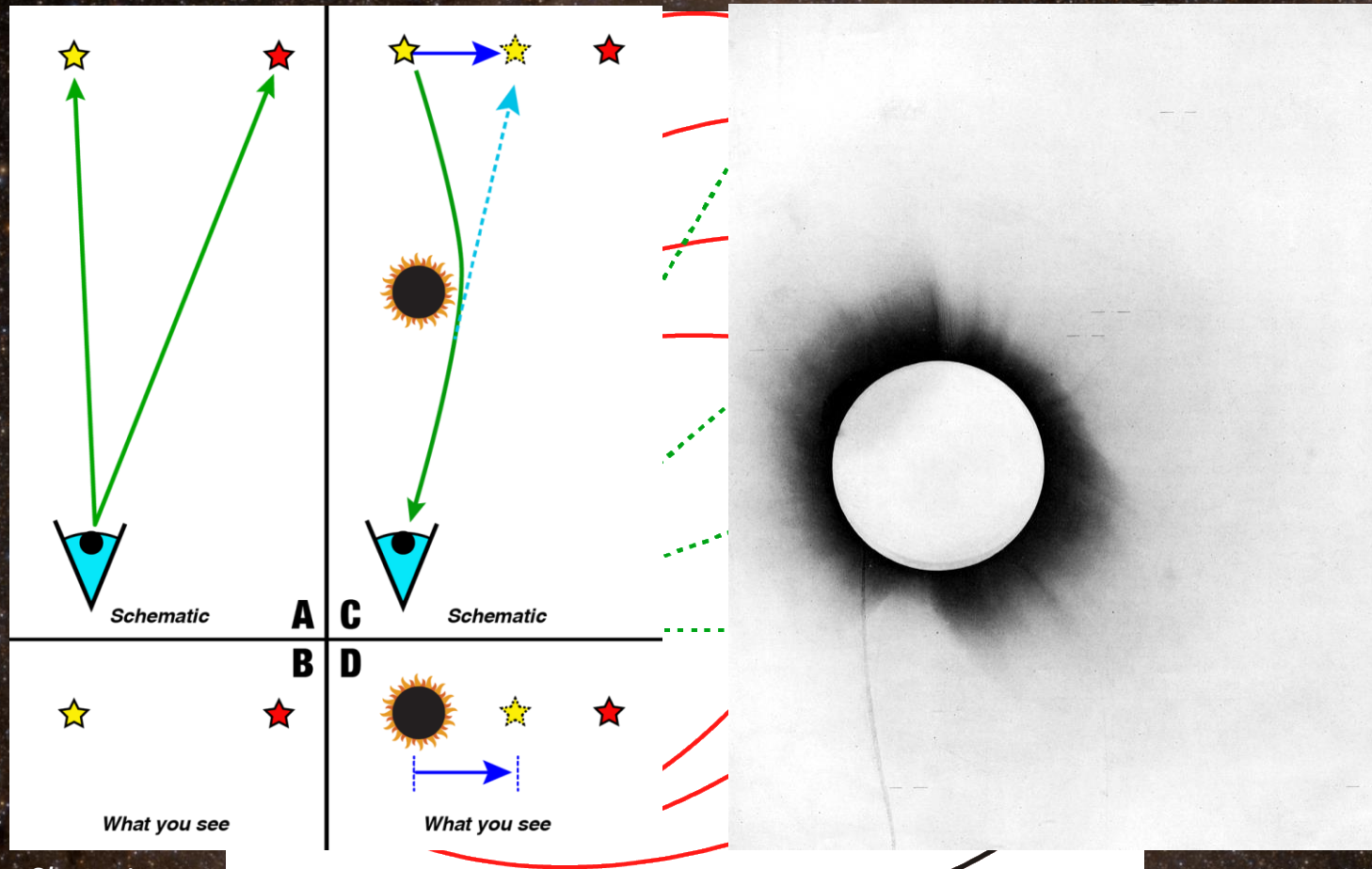
# Gravity Revisited



LIGO



# General Relativity: Predictions

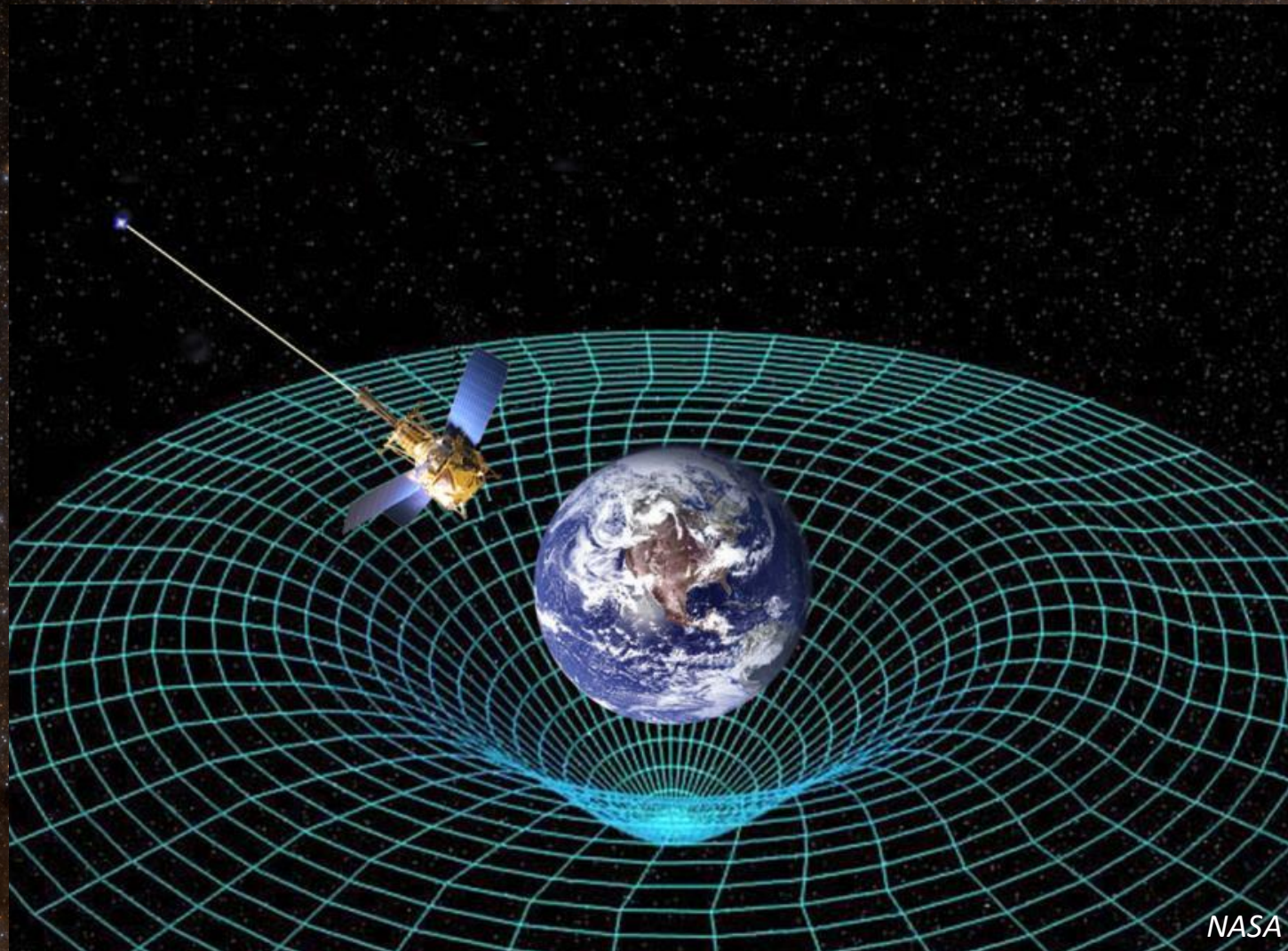


Shane Larson

Dyson, Eddington & Davidson (1919)  
Shane Larson



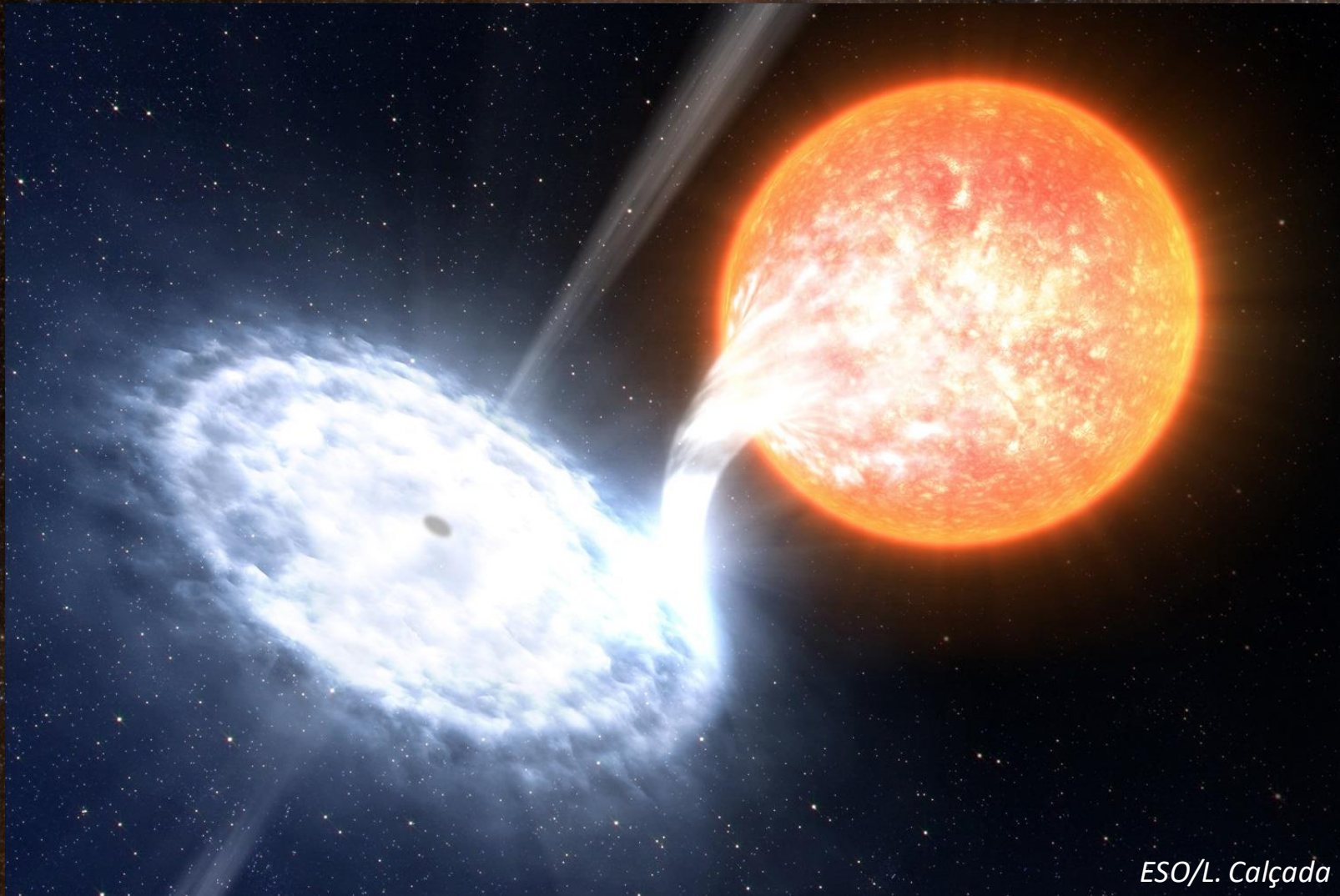
# General Relativity: Predictions



NASA



# Black holes

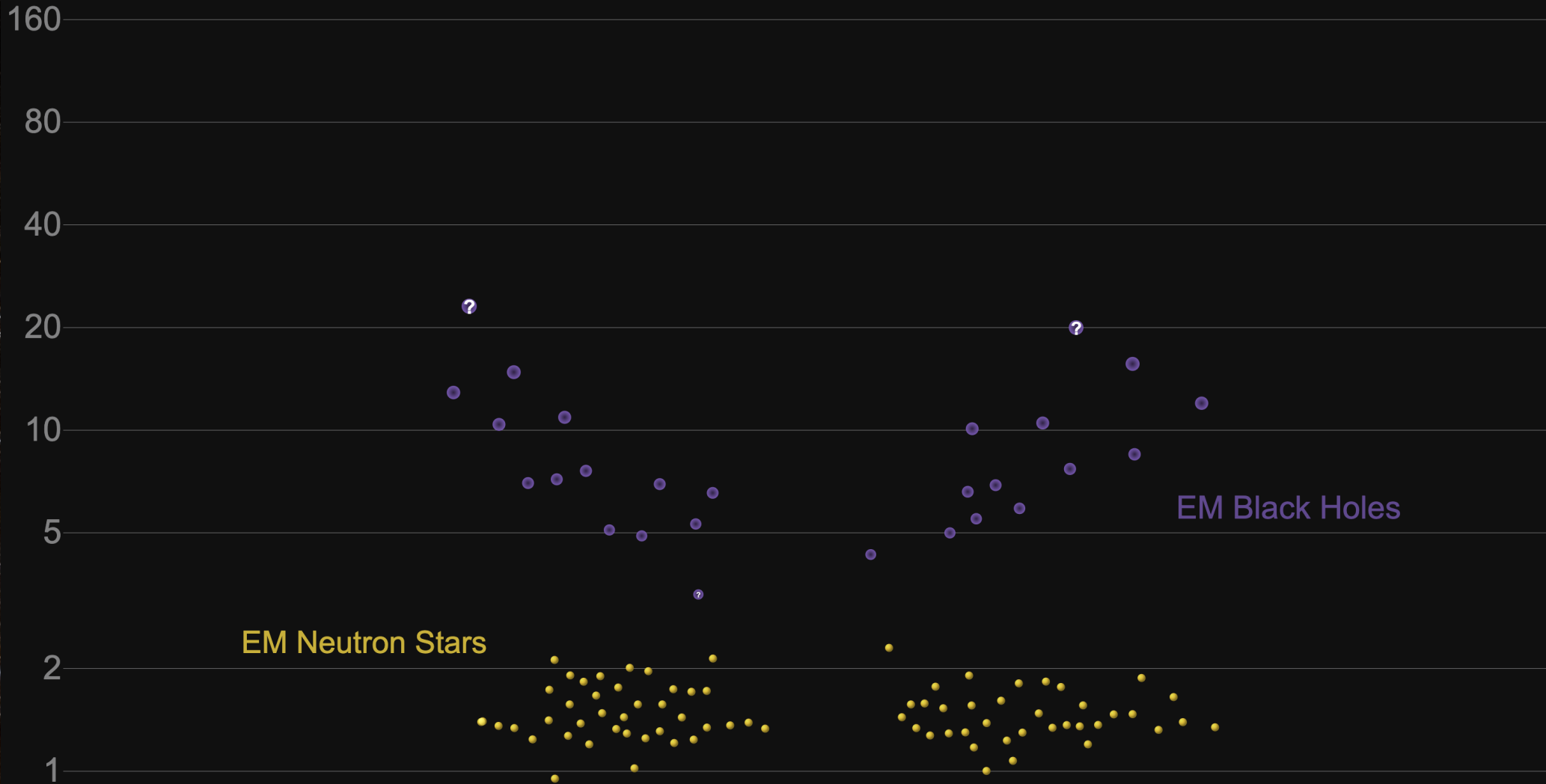


ESO/L. Calçada



# Masses in the Stellar Graveyard

*in Solar Masses*



EM Neutron Stars

EM Black Holes

GWTC-2 plot v1.0

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern



# Black Holes



[www.eso.org](http://www.eso.org)



# General Relativity

How space  
bends

$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

Where  
matter is

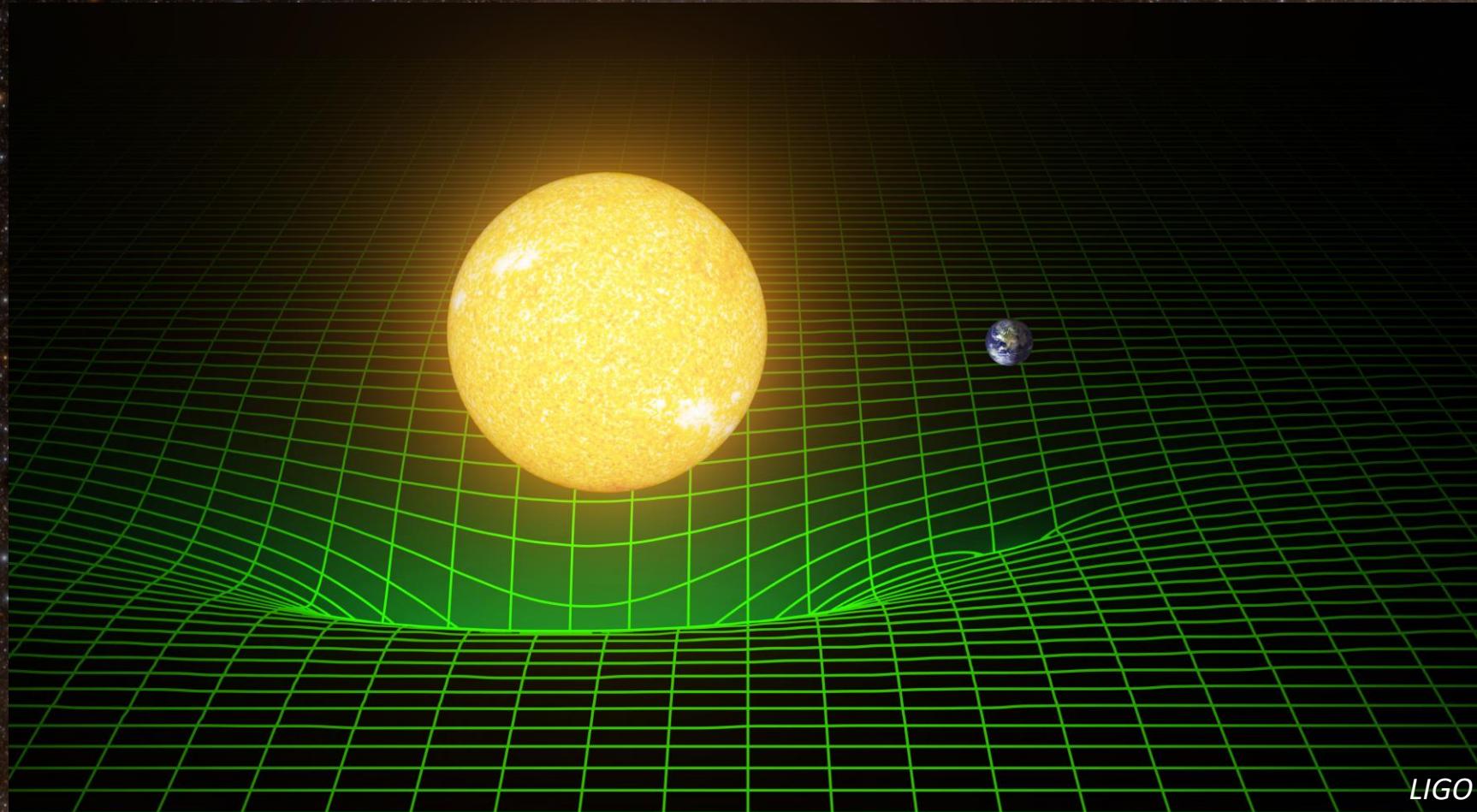
$$\frac{G}{c^4} \sim 10^{-44}$$

$$\frac{G}{c^4} = 0.0000000000 \ 0000000000 \ 0000000000 \ 0000000000 \ 0001$$





# Spacetime



LIGO



# Spacetime

Material	Elastic modulus (GPa)
Rubber	0.1
Wood	10
Concrete	15
Steel	200
Diamond	1200
Spacetime	1,000,000,000,000,000,000,000,000

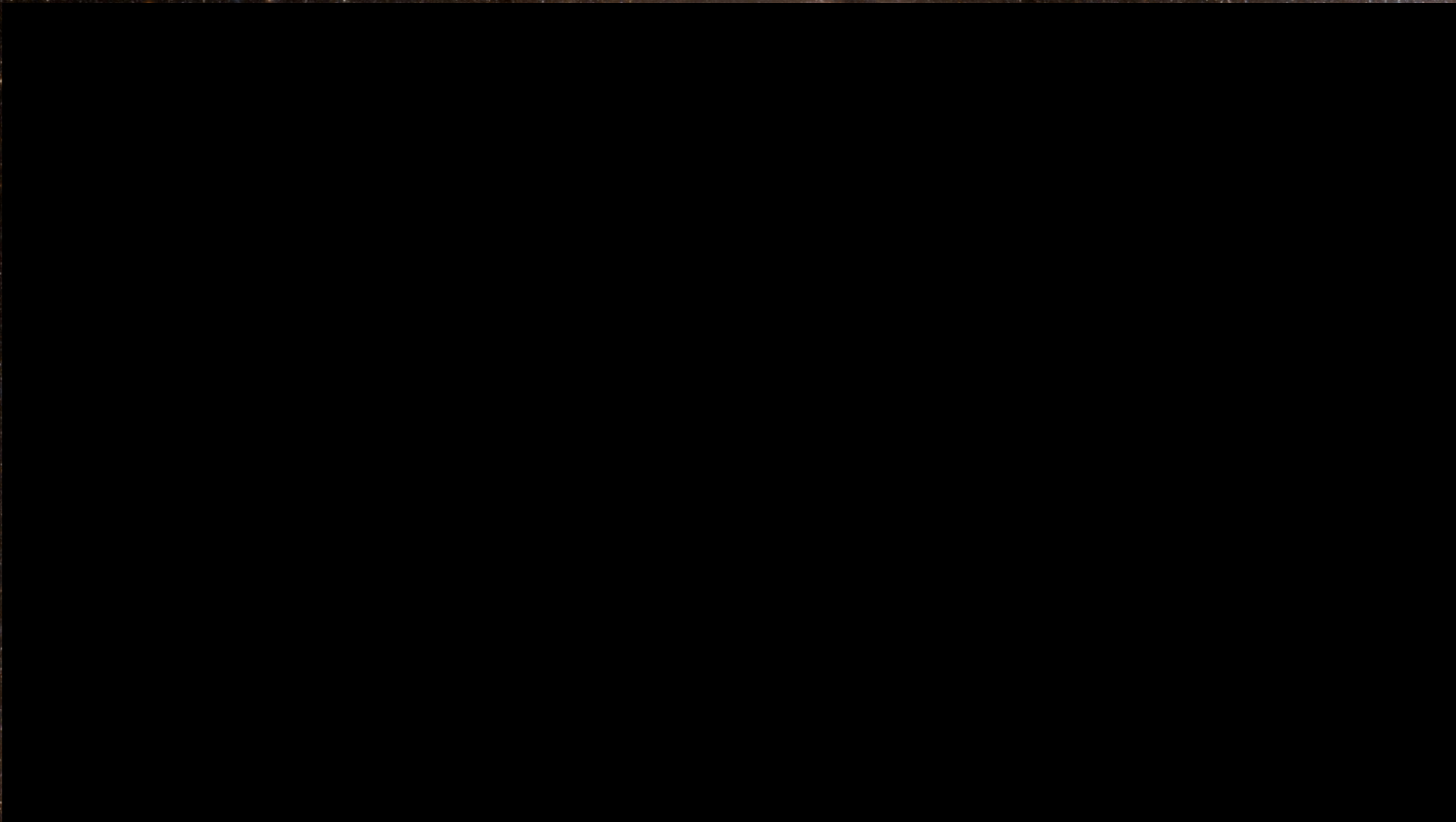


# Steve Mould demonstration



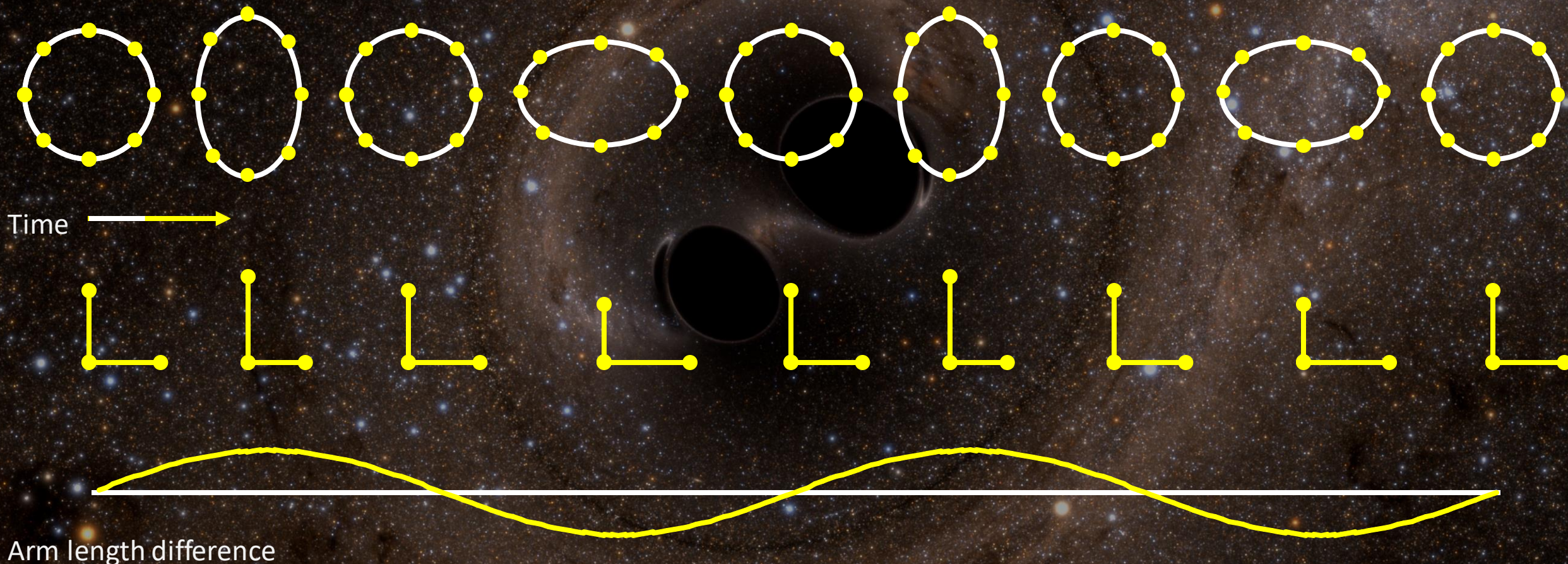


# Gravitational Waves





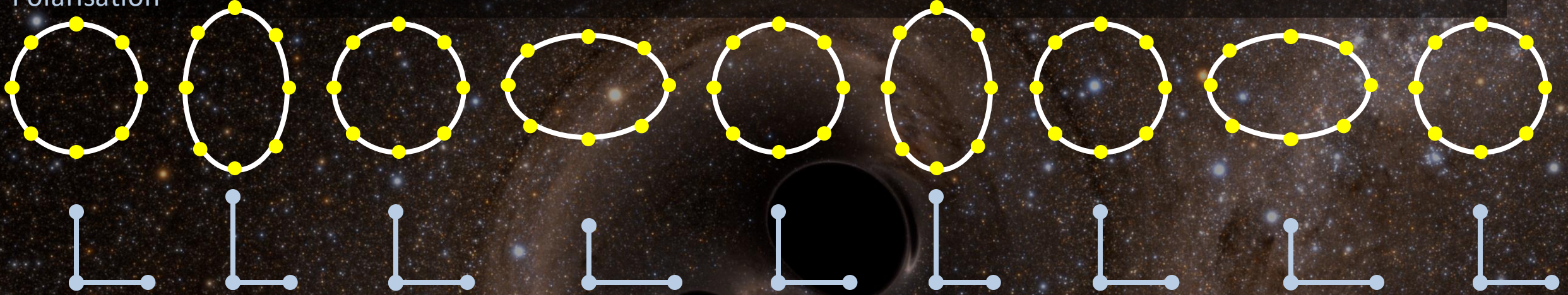
# Gravitational Waves



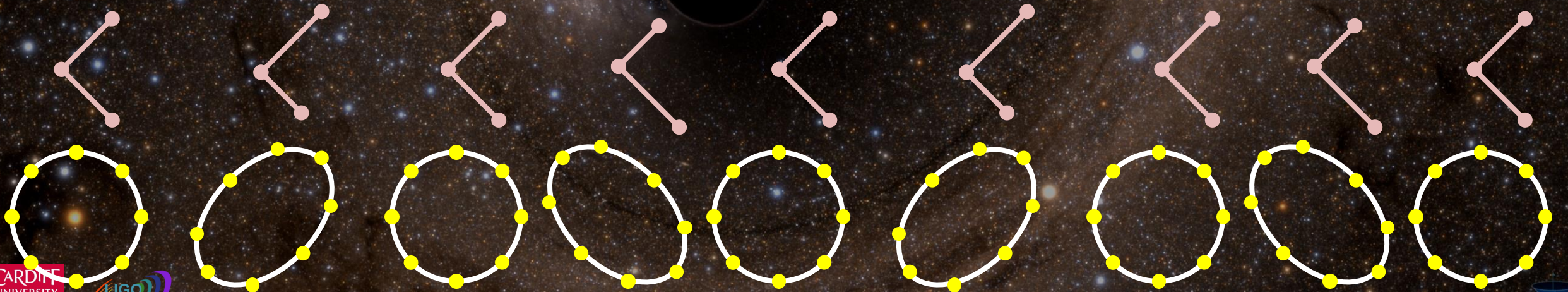
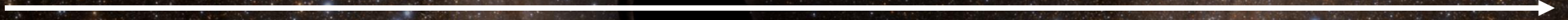


# Gravitational Wave Polarisation

+ Polarisation



Time





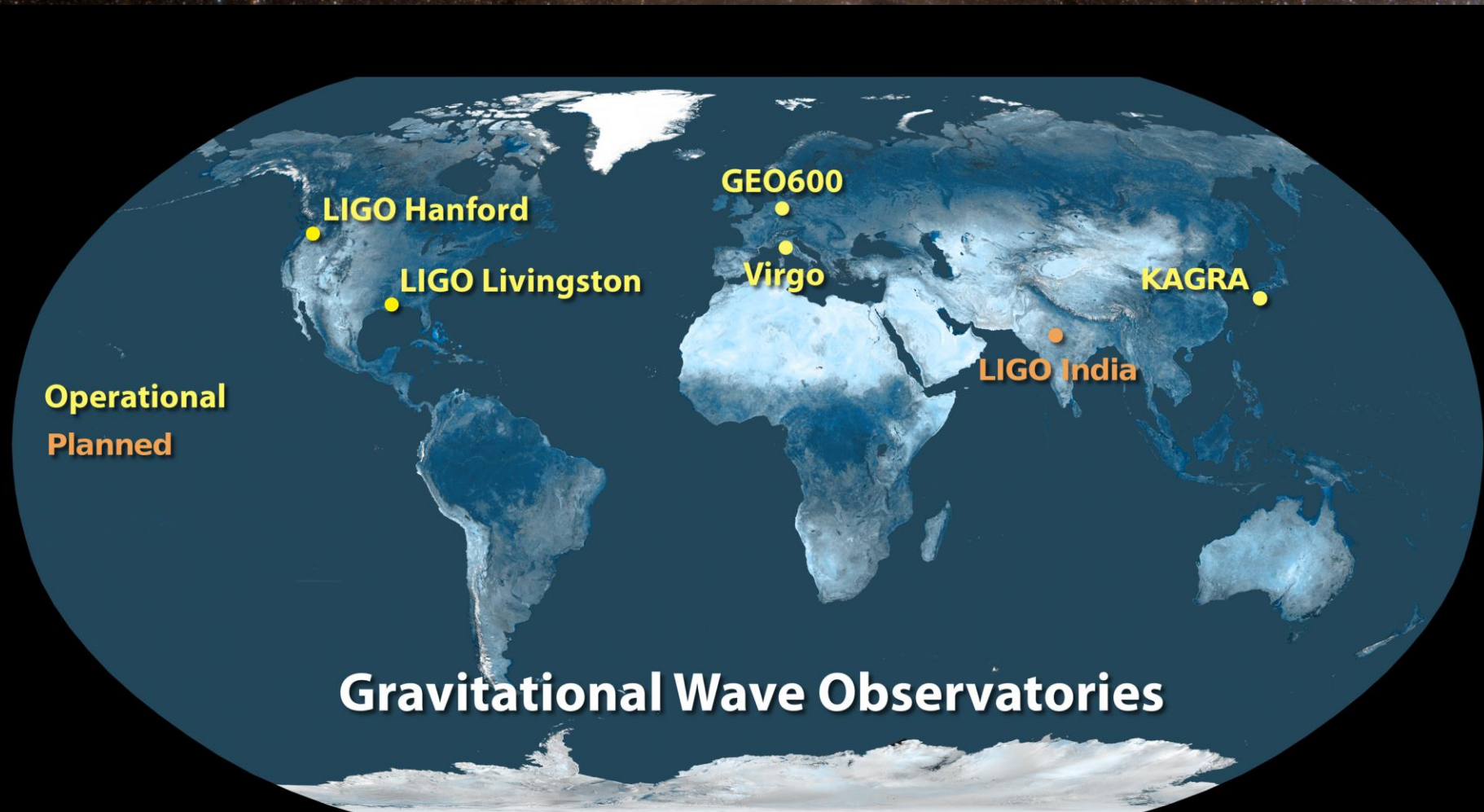
# Earthly effects



Scale of Effect Vastly Exaggerated

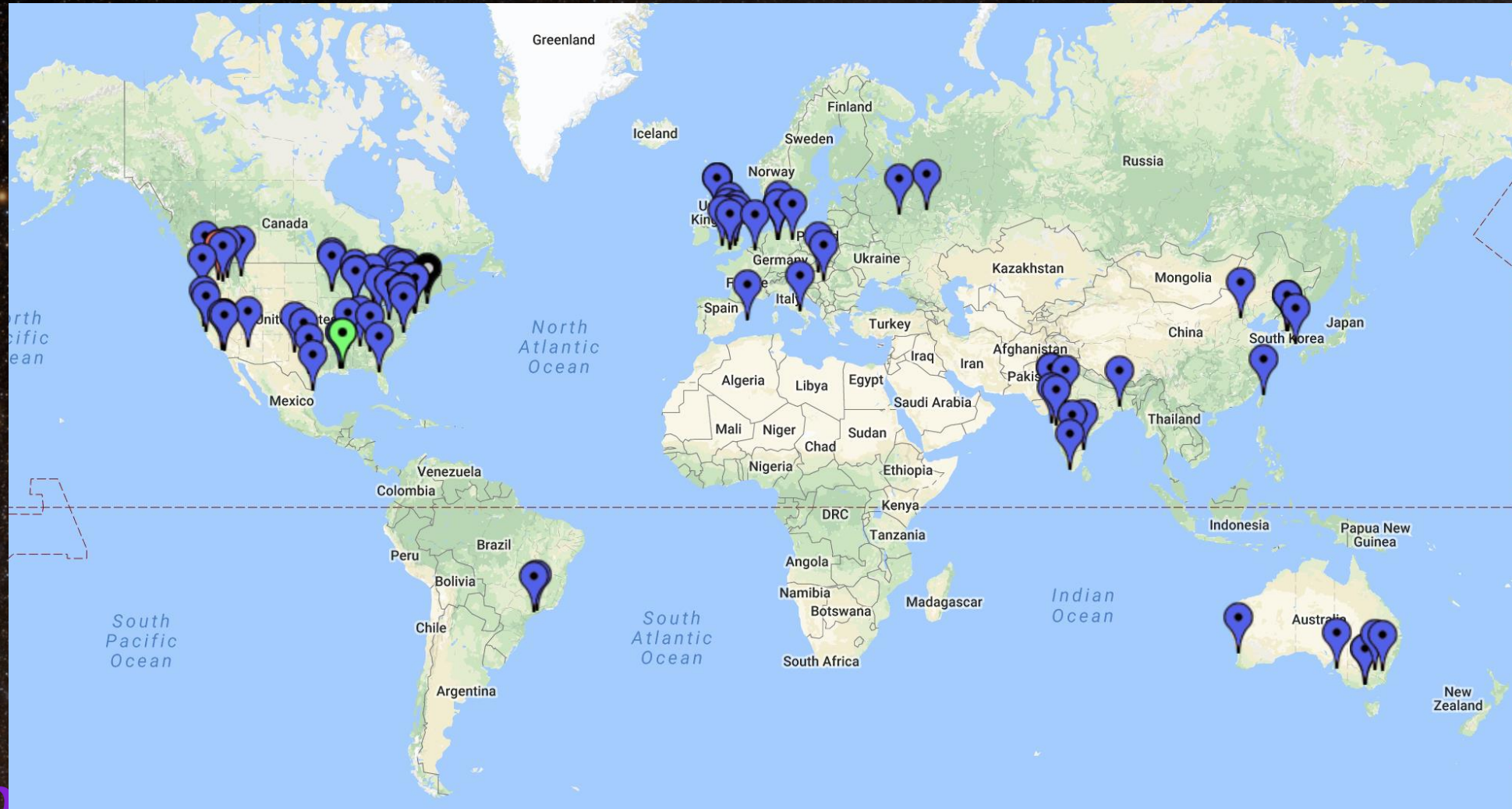


# Detecting Gravitational Waves





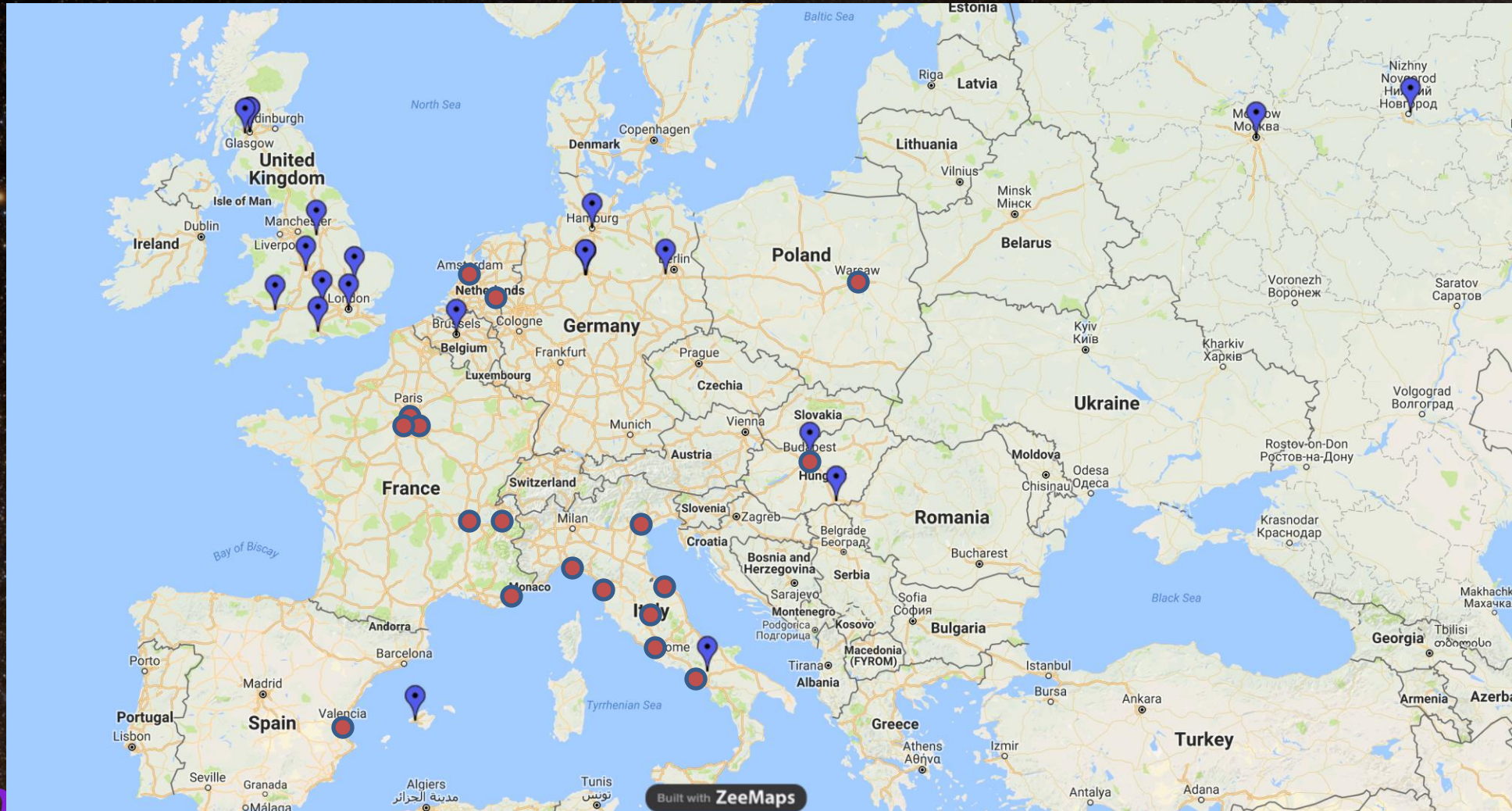
# The LIGO Scientific Collaboration



[www.ligo.org](http://www.ligo.org)



# The LIGO-Virgo Collaboration



Built with ZeeMaps

[www.virgo-gw.eu](http://www.virgo-gw.eu)





# Humans of LIGO – [humansofligo.blogspot.com](http://humansofligo.blogspot.com)





# LIGO-Virgo-KAGRA



LIGO Hanford



LIGO Livingston



Virgo



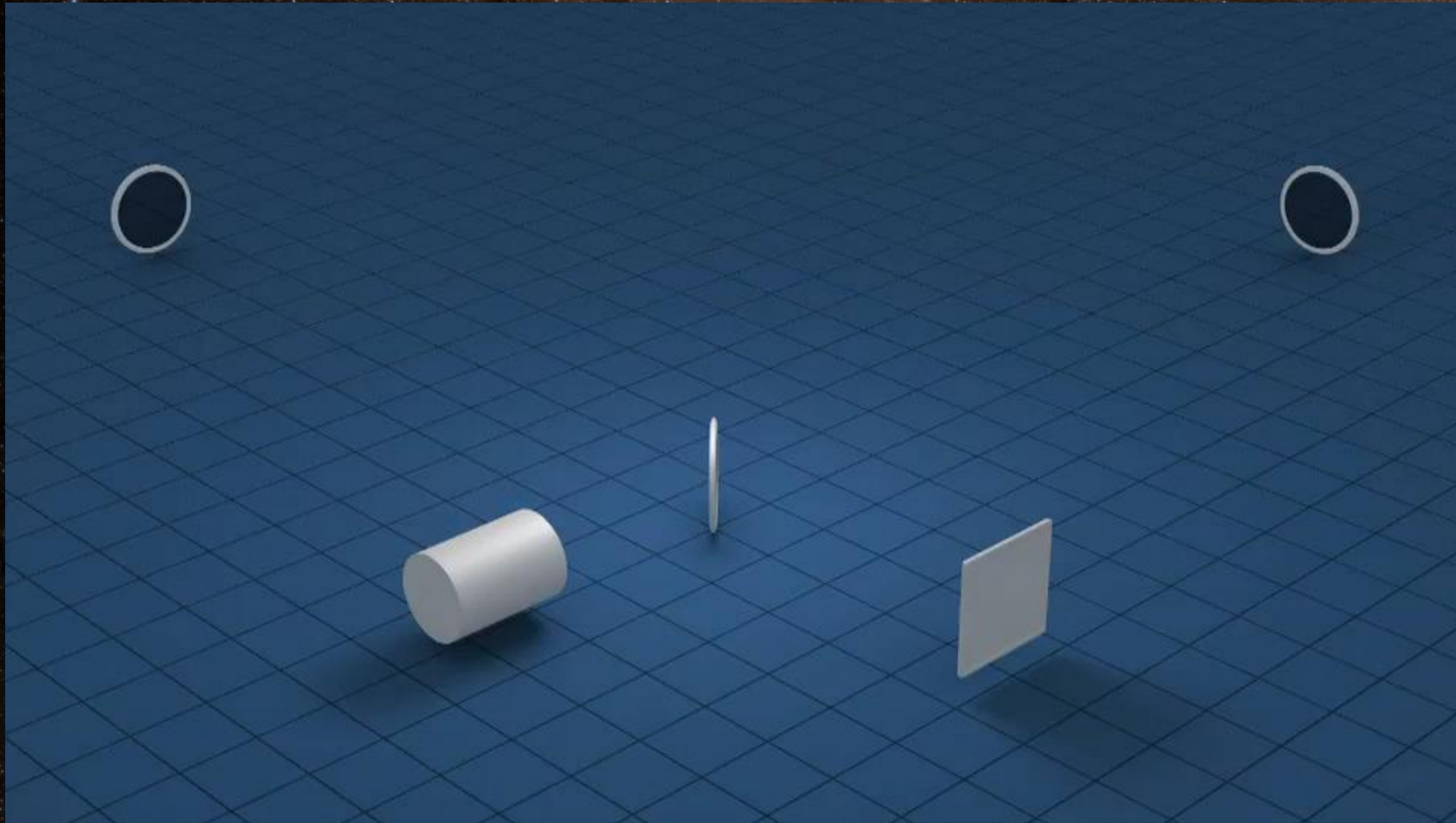
GEO600



KAGRA



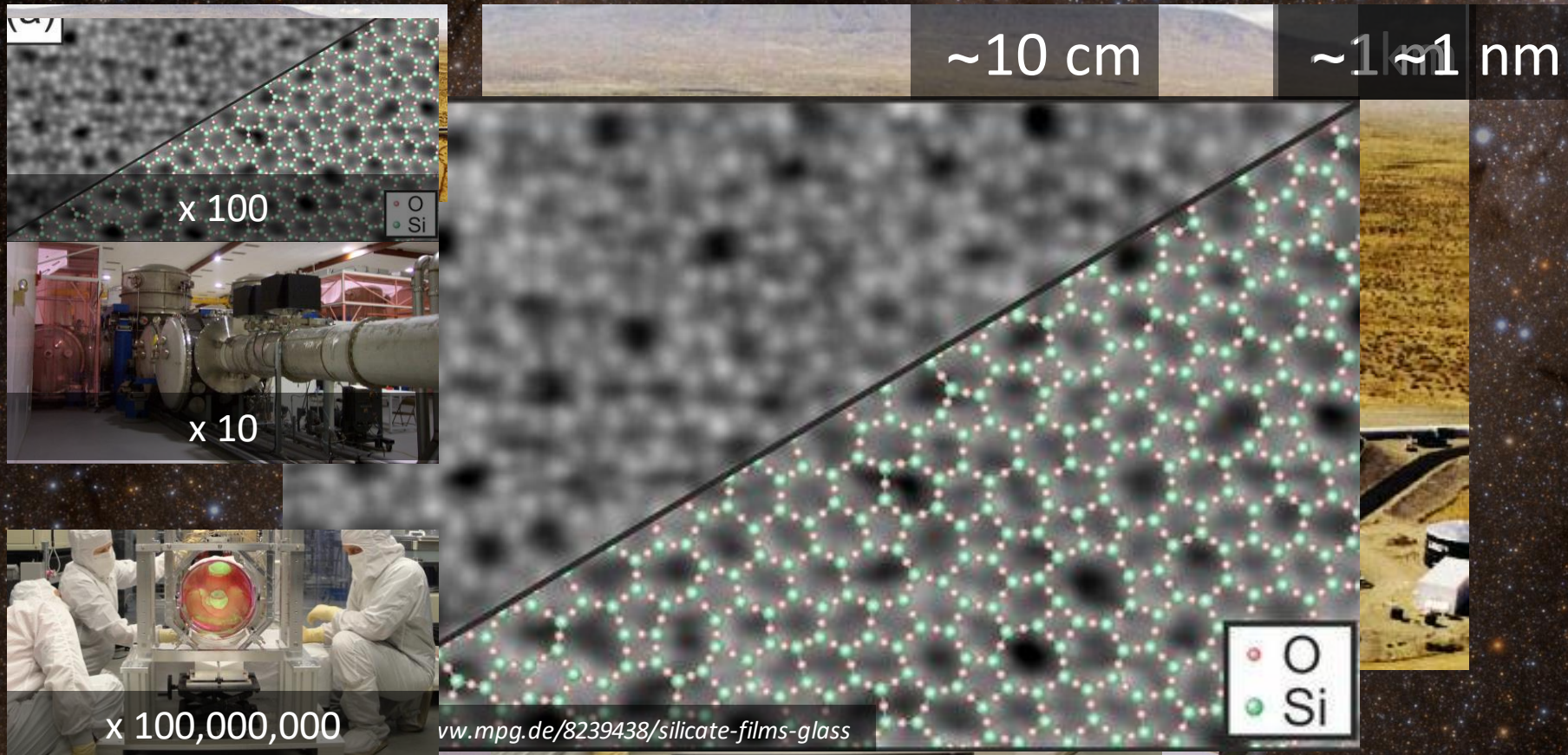
# Laser Interferometer





# Zooming in

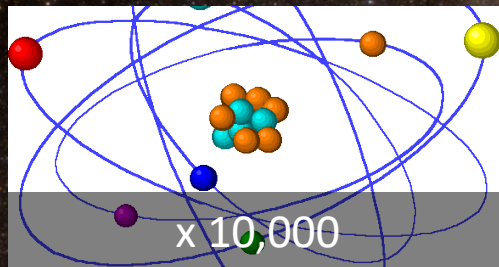
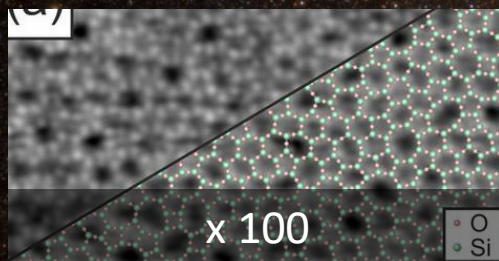
Zoom level: x 1,000,000,000,000 (1 trillion)





# Zooming in

Zoom level: x 1000,000,000,000,000,000,000 (1 sextillion)



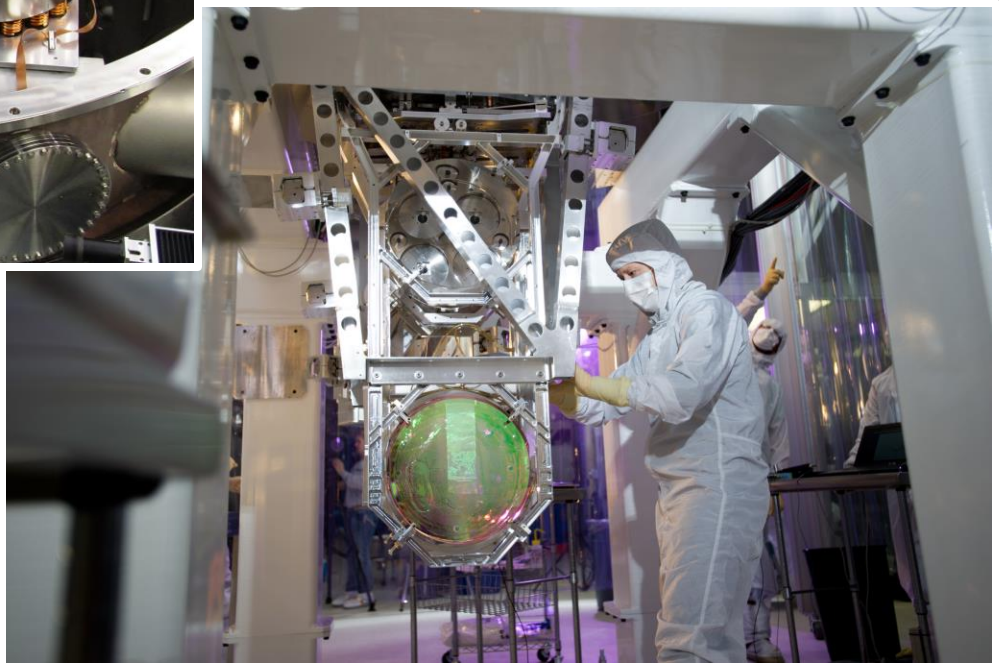
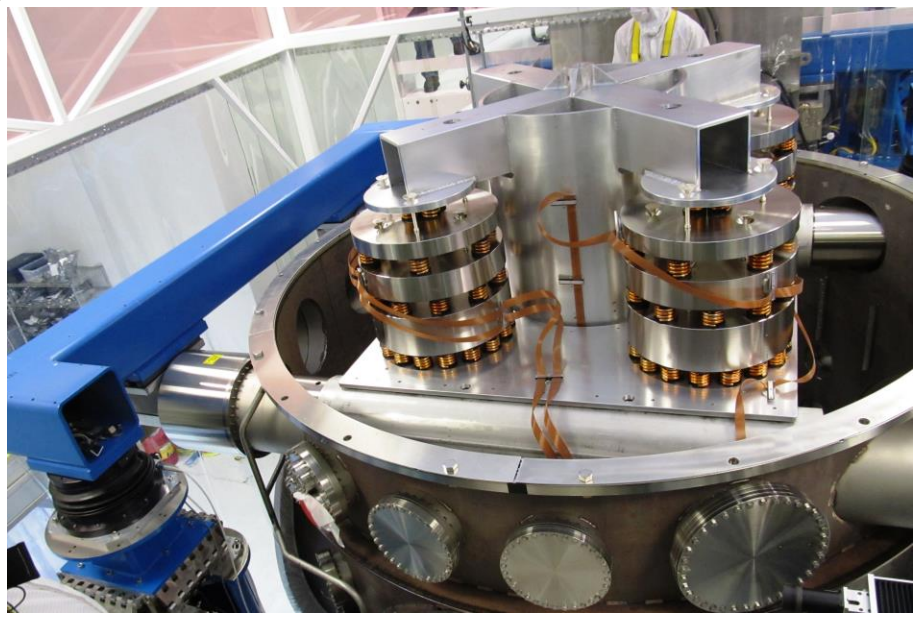
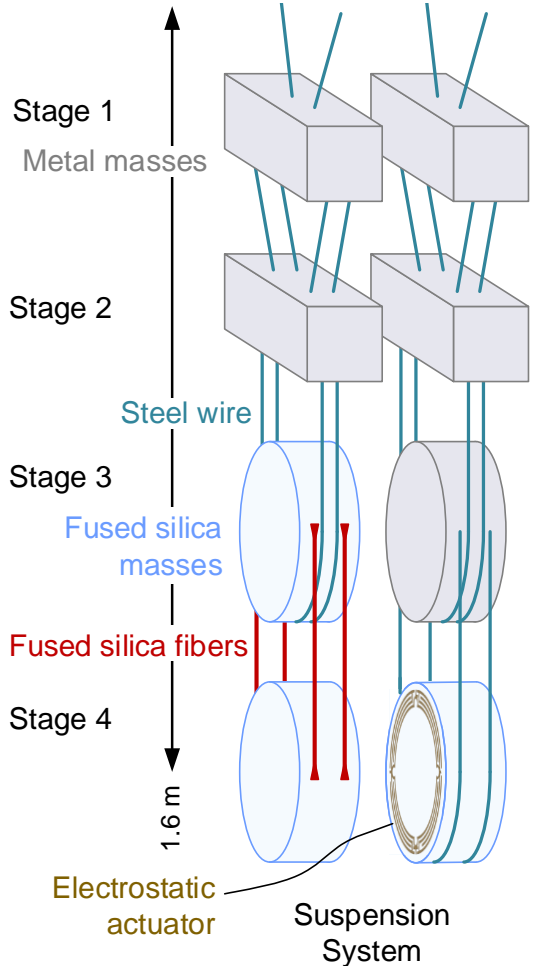


# Technical Challenges

- Seismic oscillations
- Thermal variations
- Scattering
- Quantum noise
- Laser variation

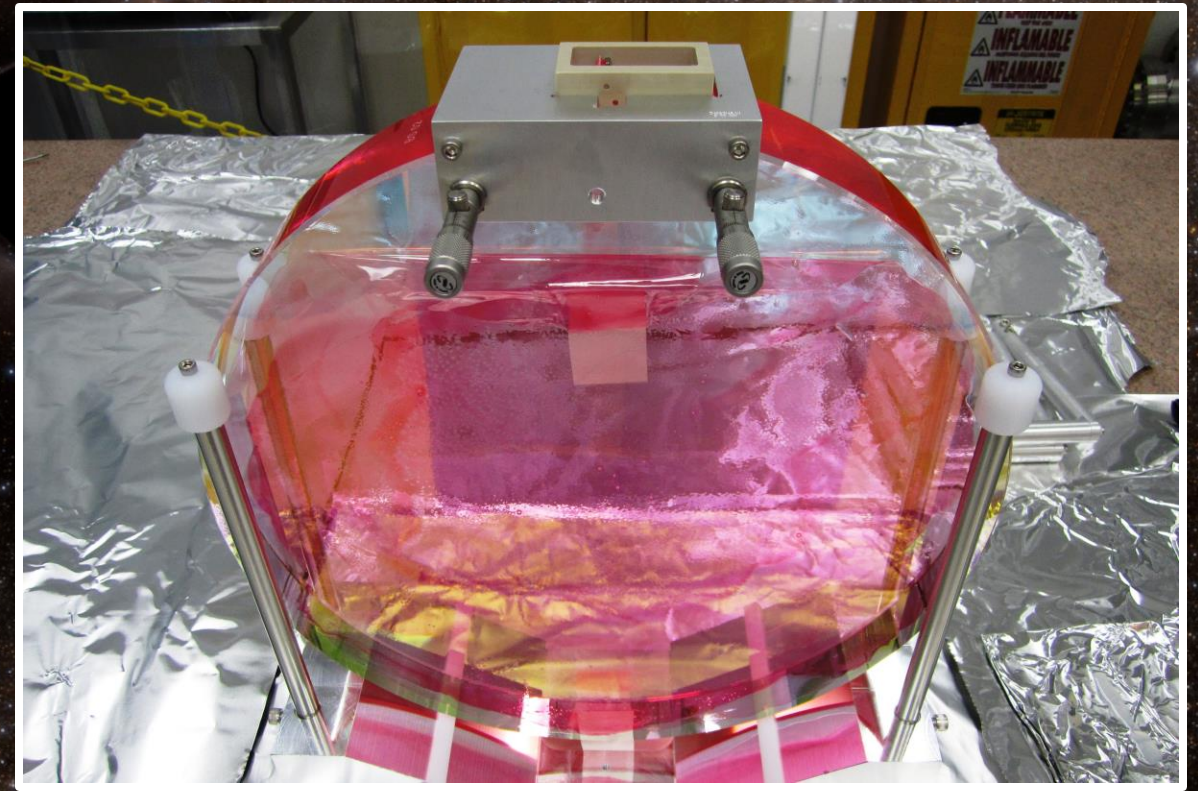
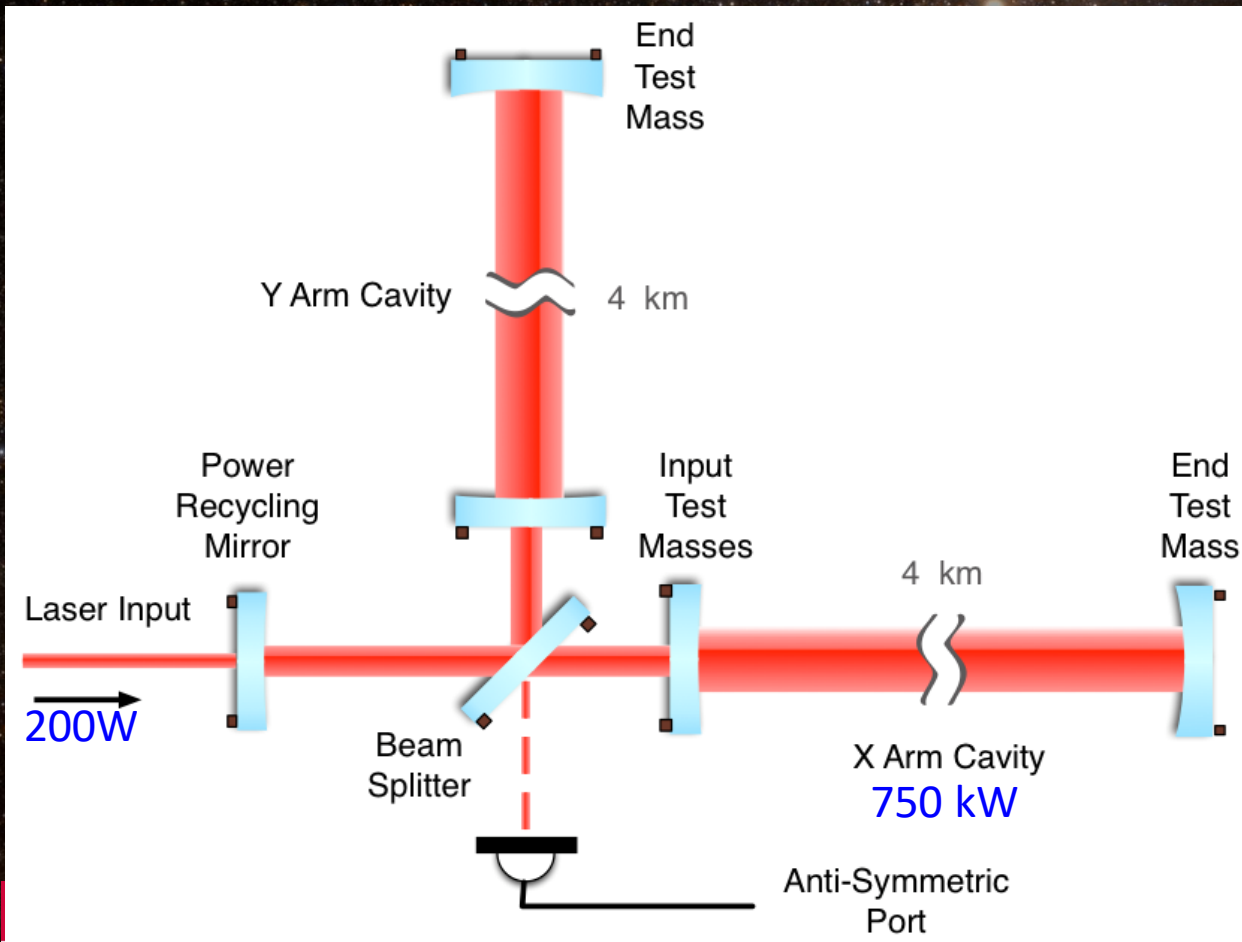


# Seismic Isolation



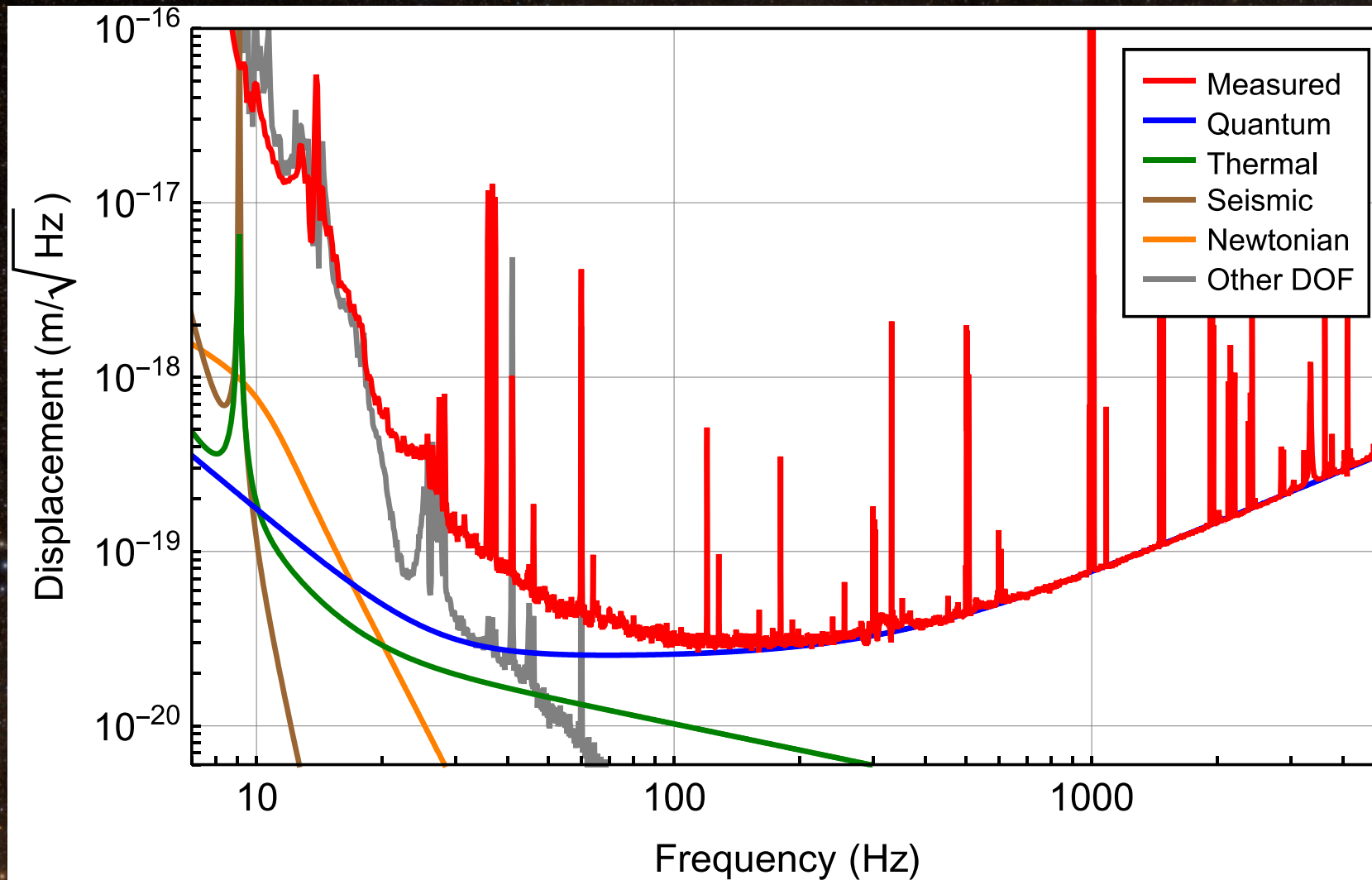


# Power Recycling

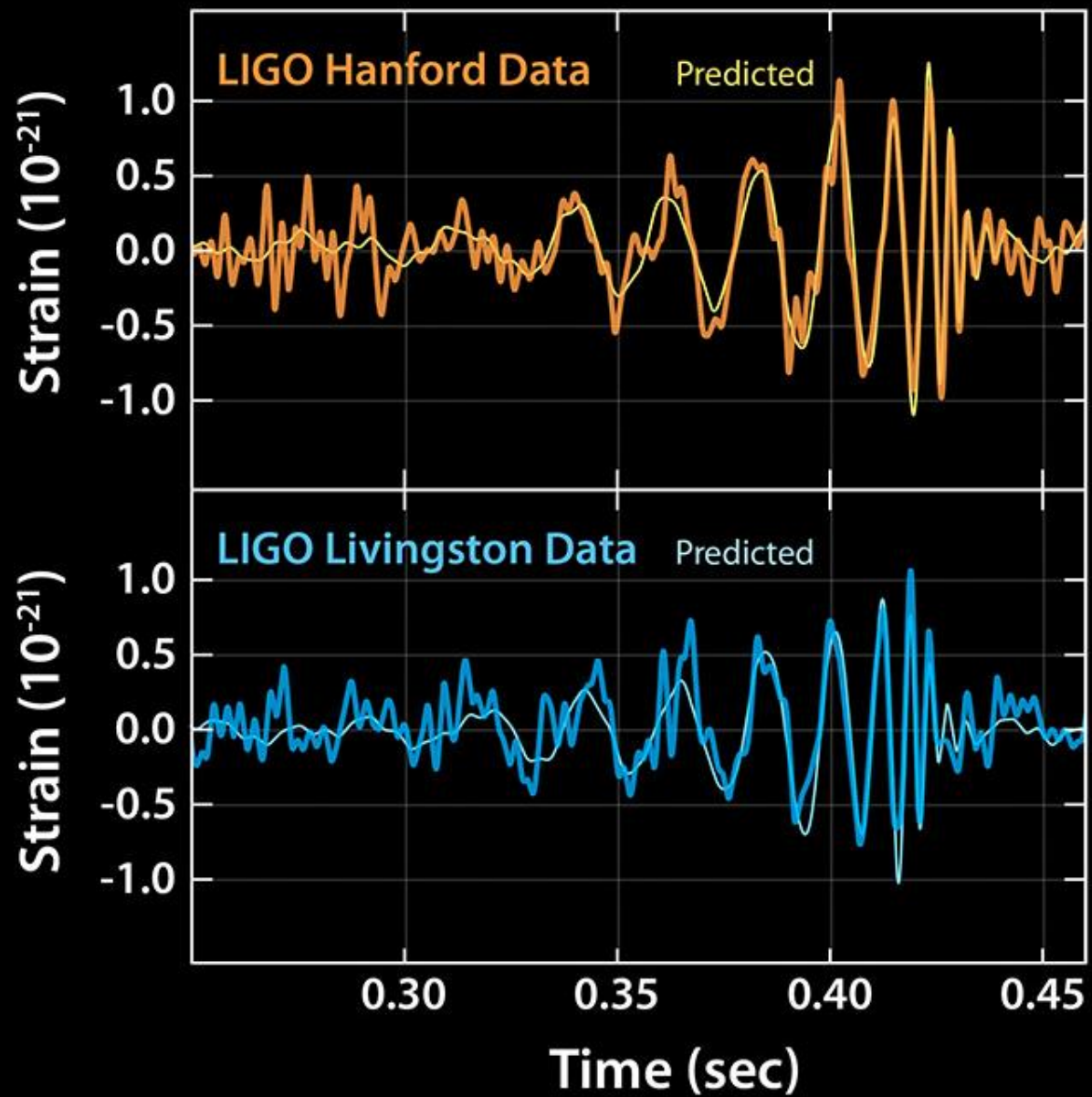




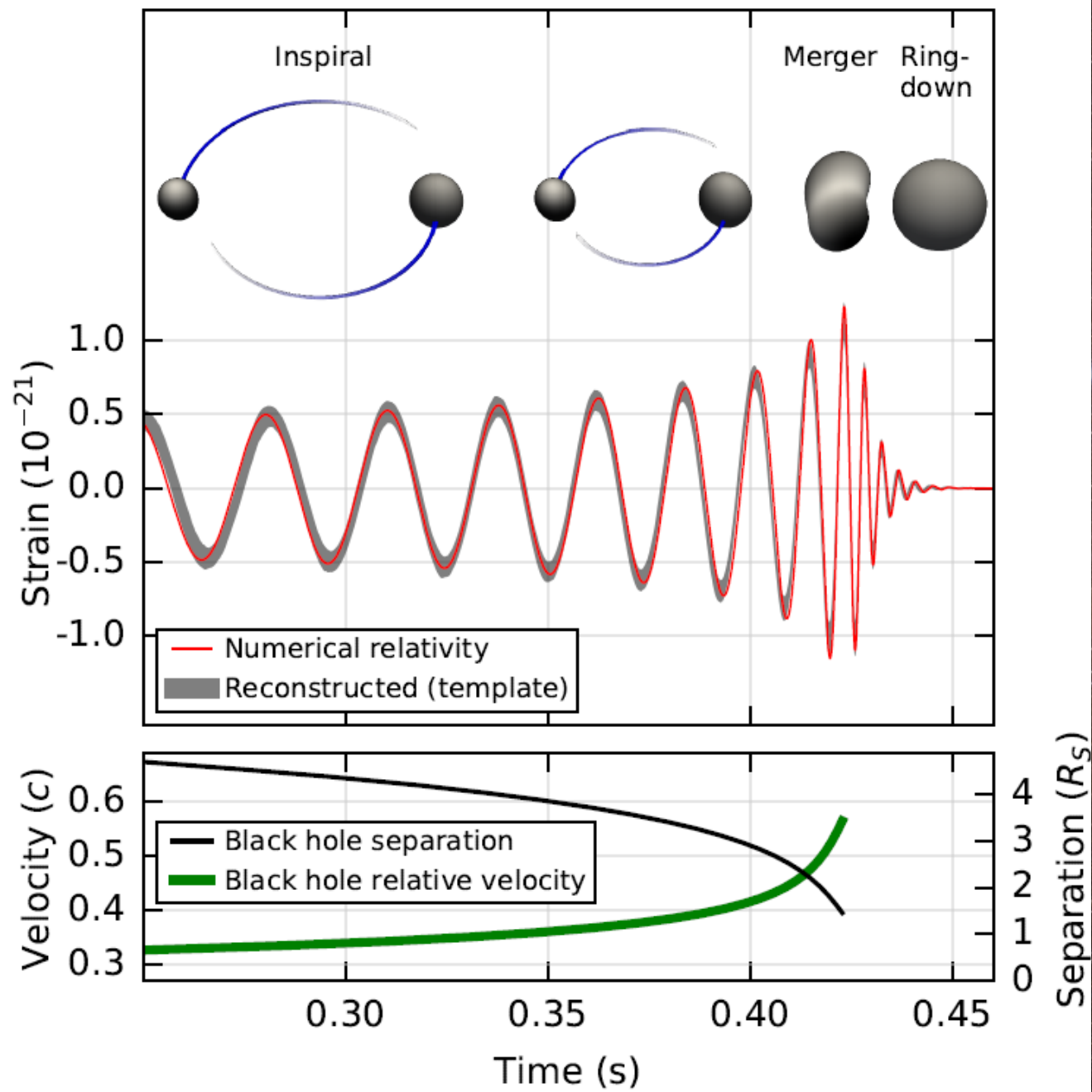
# Advanced LIGO Sensitivity





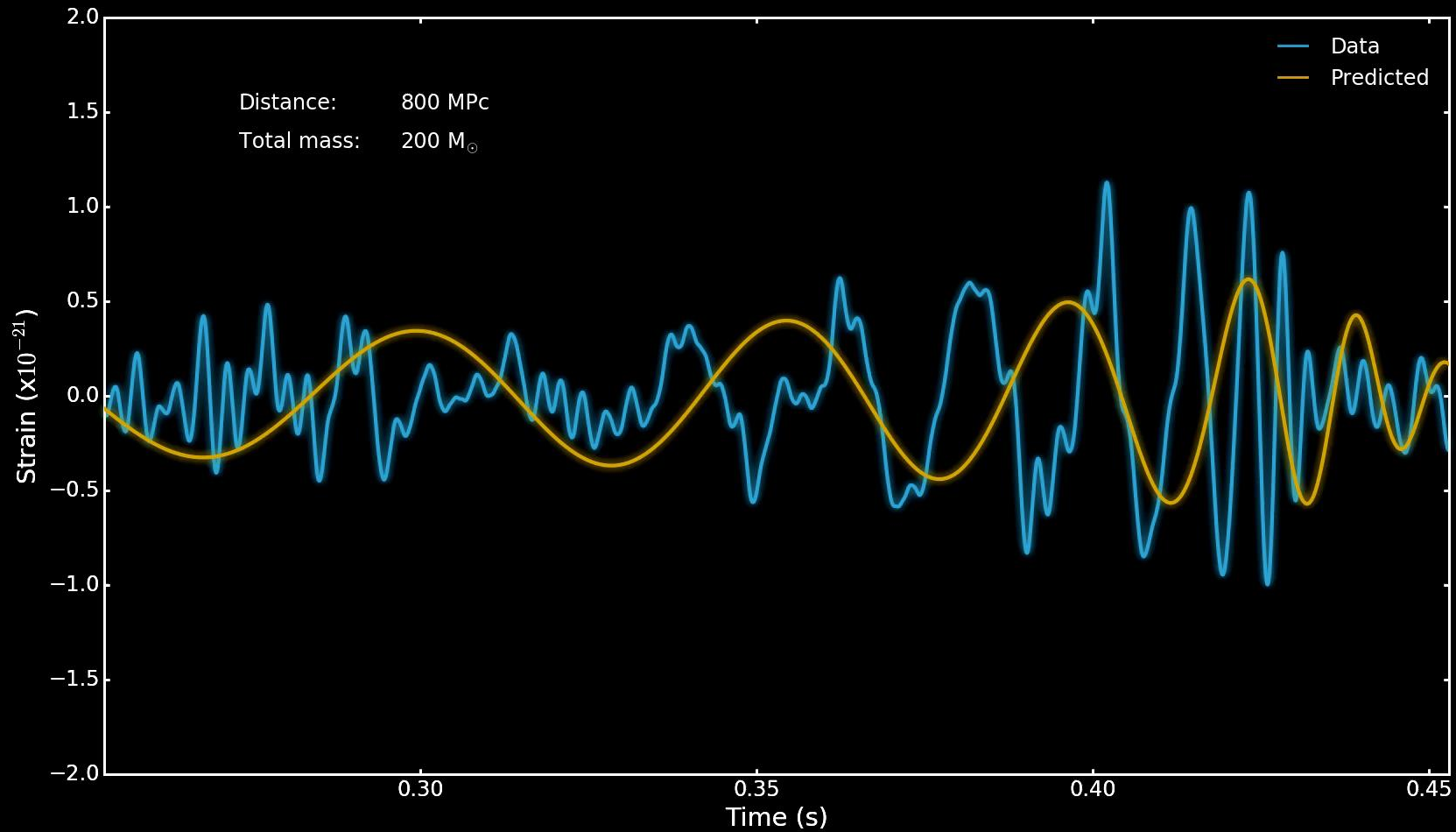








# Parameter Estimation



Credit: LIGO/Cardiff University/C.North/M.Hannam

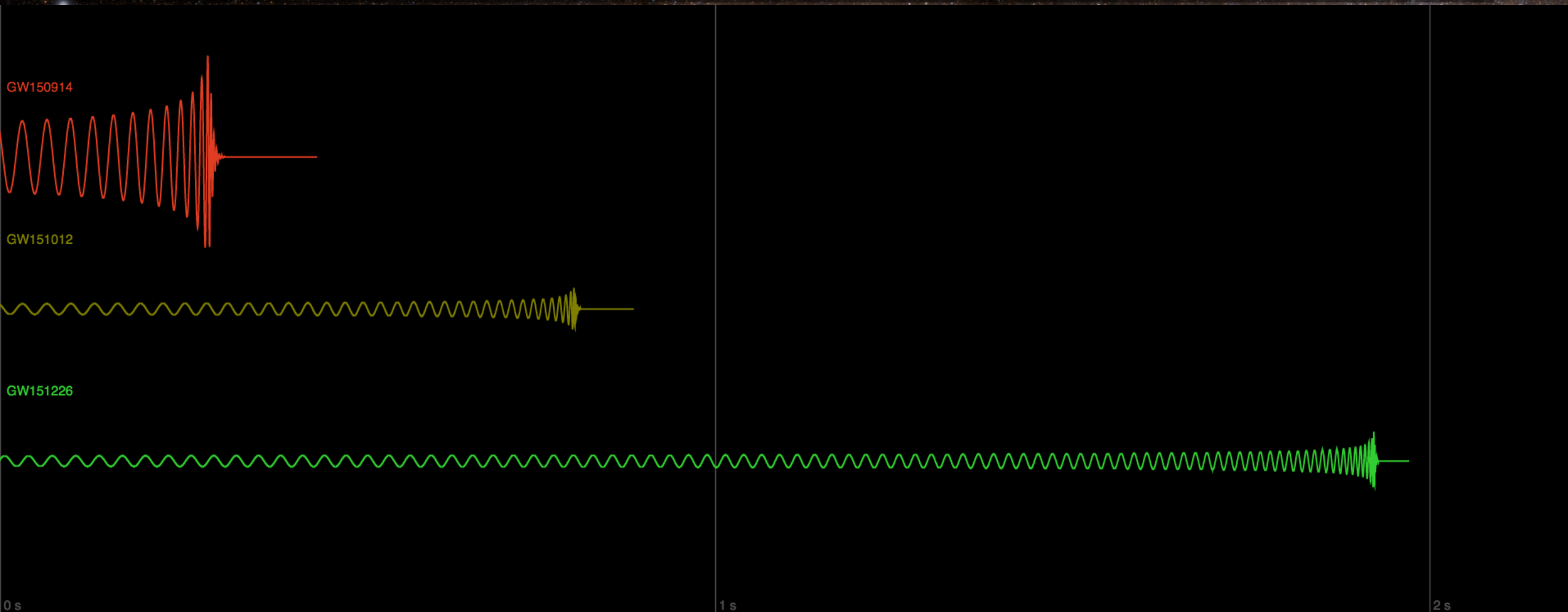


# System Parameters

Initial Black Hole Masses	$29 M_{\odot}$ & $36 M_{\odot}$
Distance	$\sim 1300$ Mly ( $z \sim 0.09$ )
Max speed of black holes	$\sim 0.6 c$
Final Black Hole Spin rate	$\sim 100$ Hz
Final Black Hole Mass	$62 M_{\odot}$
Energy released	$6 \times 10^{47}$ J ( $3 M_{\text{Sun}} c^2$ )
Peak power	$3.6 \times 10^{49}$ W



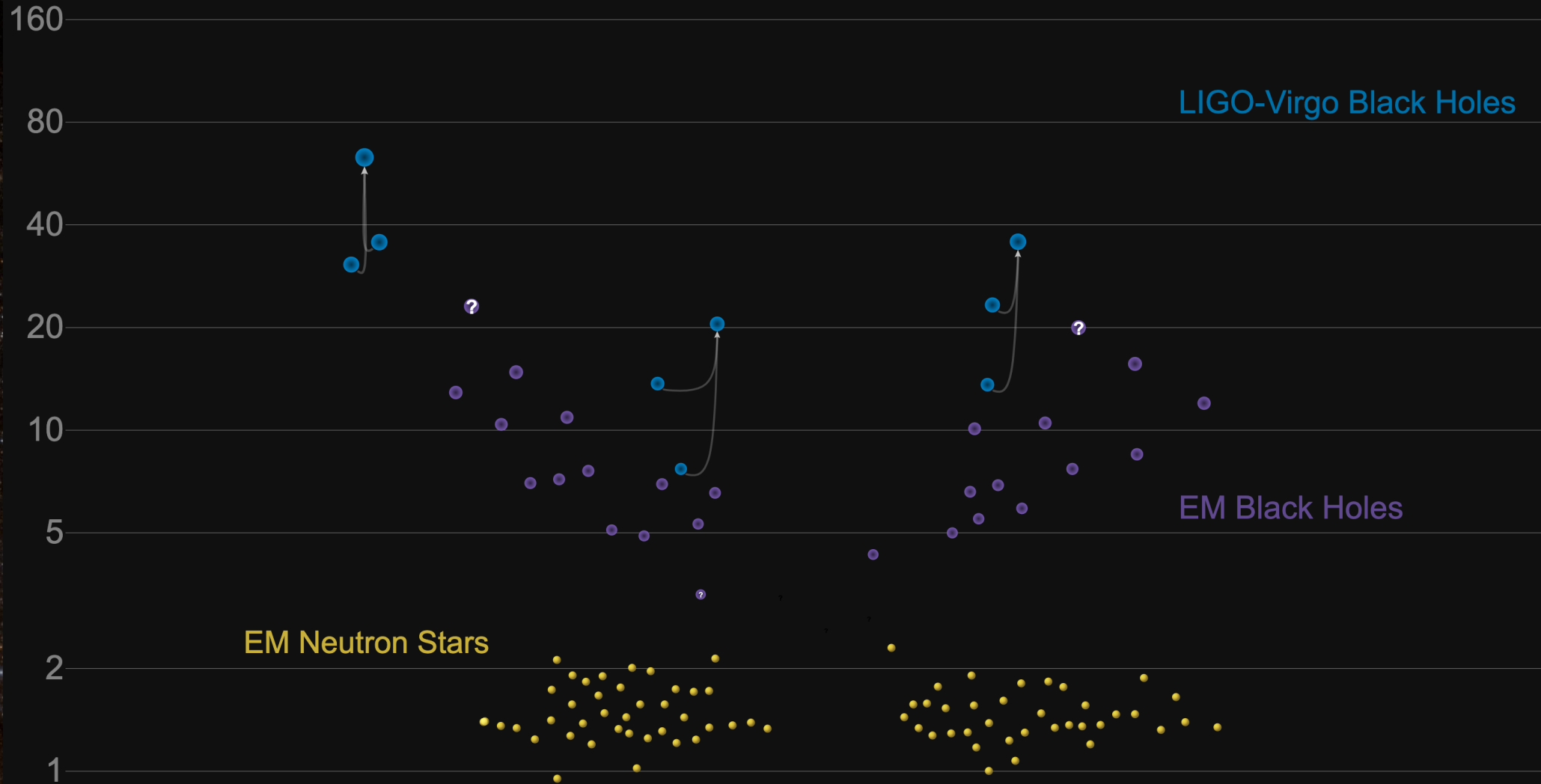
# waveview.cardiffgravity.org – Observing Run 1





# Masses in the Stellar Graveyard

*in Solar Masses*



EM Neutron Stars

LIGO-Virgo Black Holes

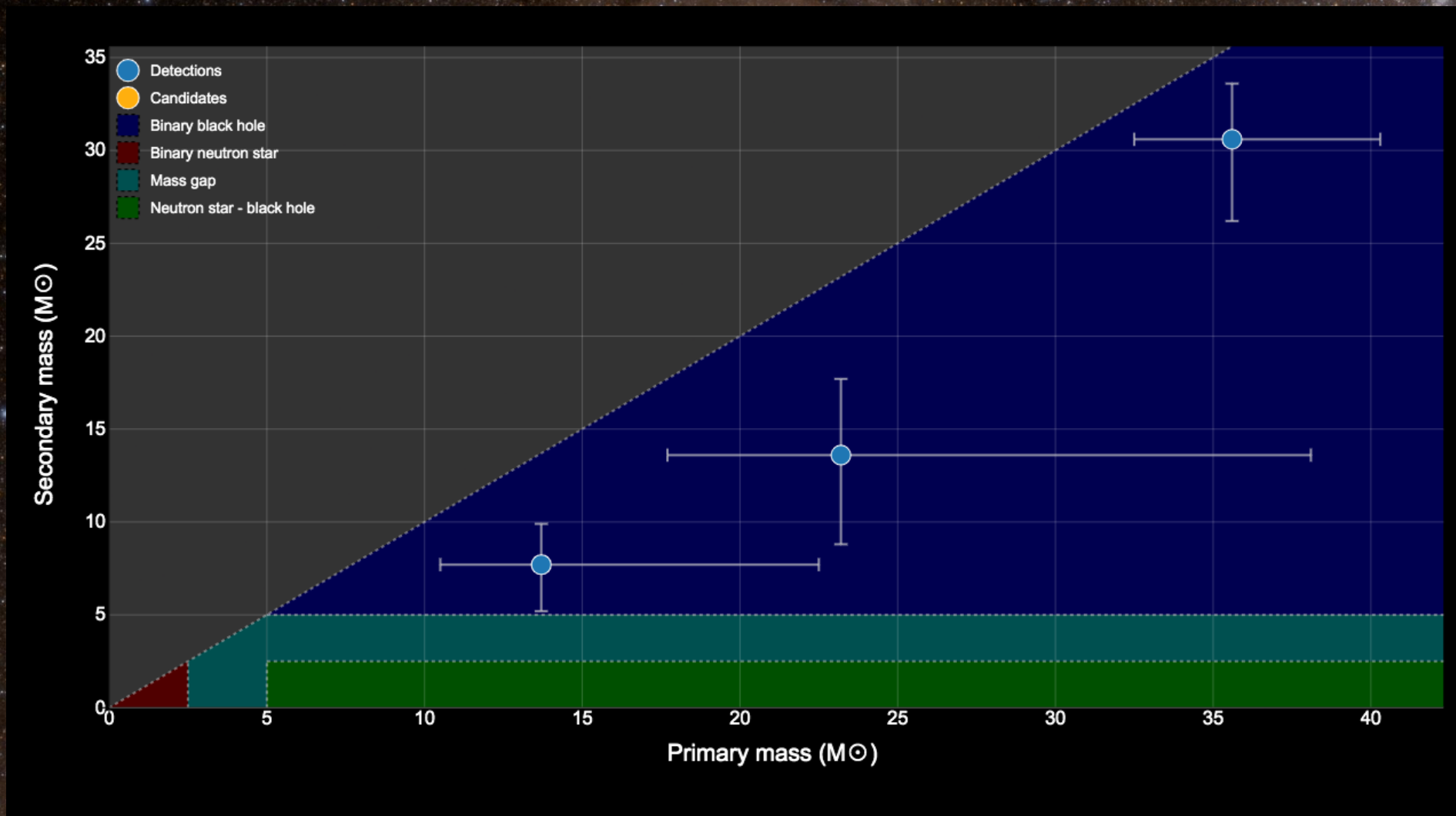
EM Black Holes

GWTC-2 plot v1.0

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

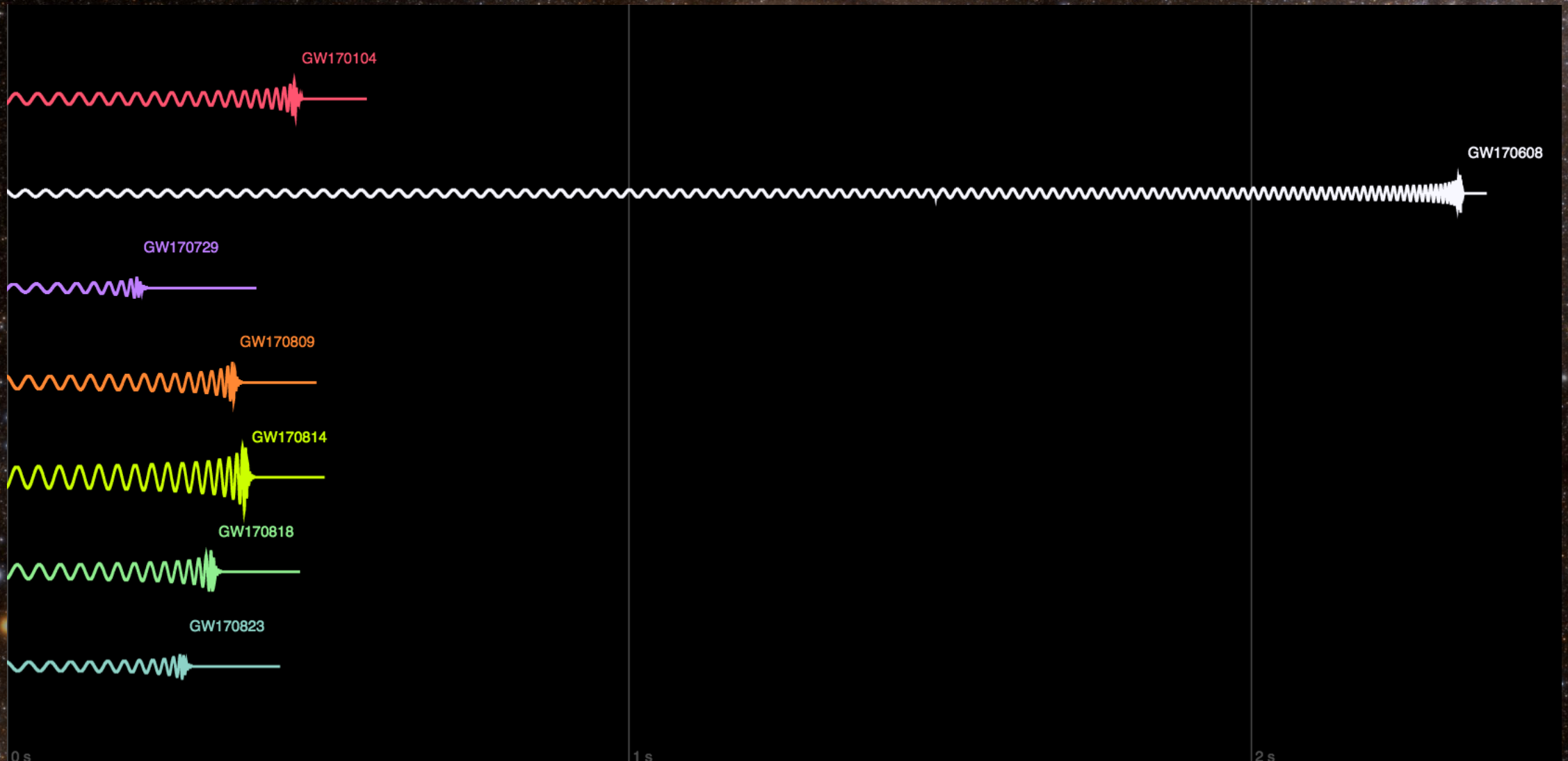


# catalog.cardiffgravity.org – Observing Run 1

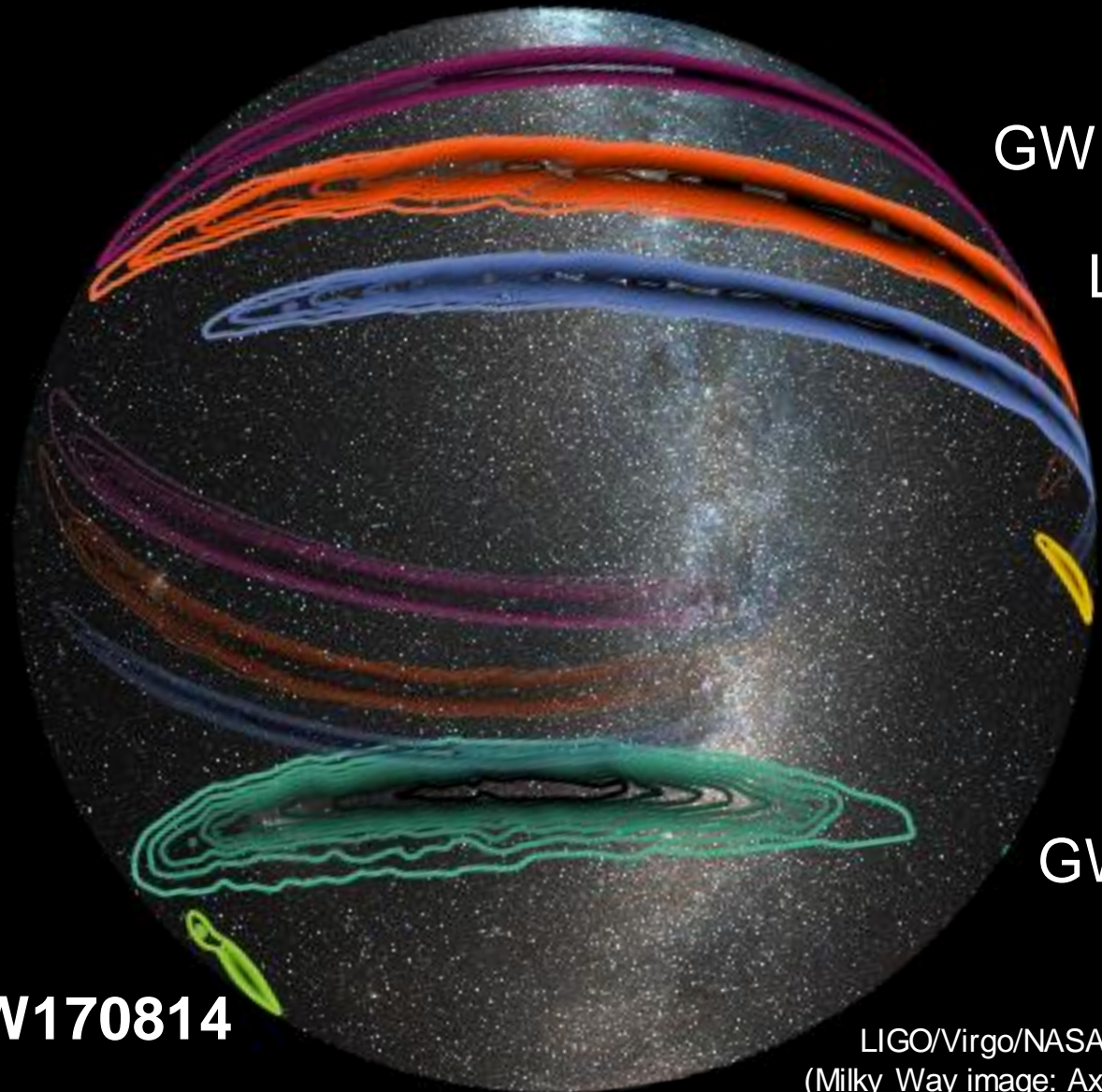




# Multiple Detections







GW170104

LVT151012

GW151226

GW170817

GW150914

GW170814

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



[gwcatalog.cardiffgravity.org/skymaps](http://gwcatalog.cardiffgravity.org/skymaps)

GW150914

GW151012

GW151226

GW170104

GW170608

GW170729

GW170809

GW170814

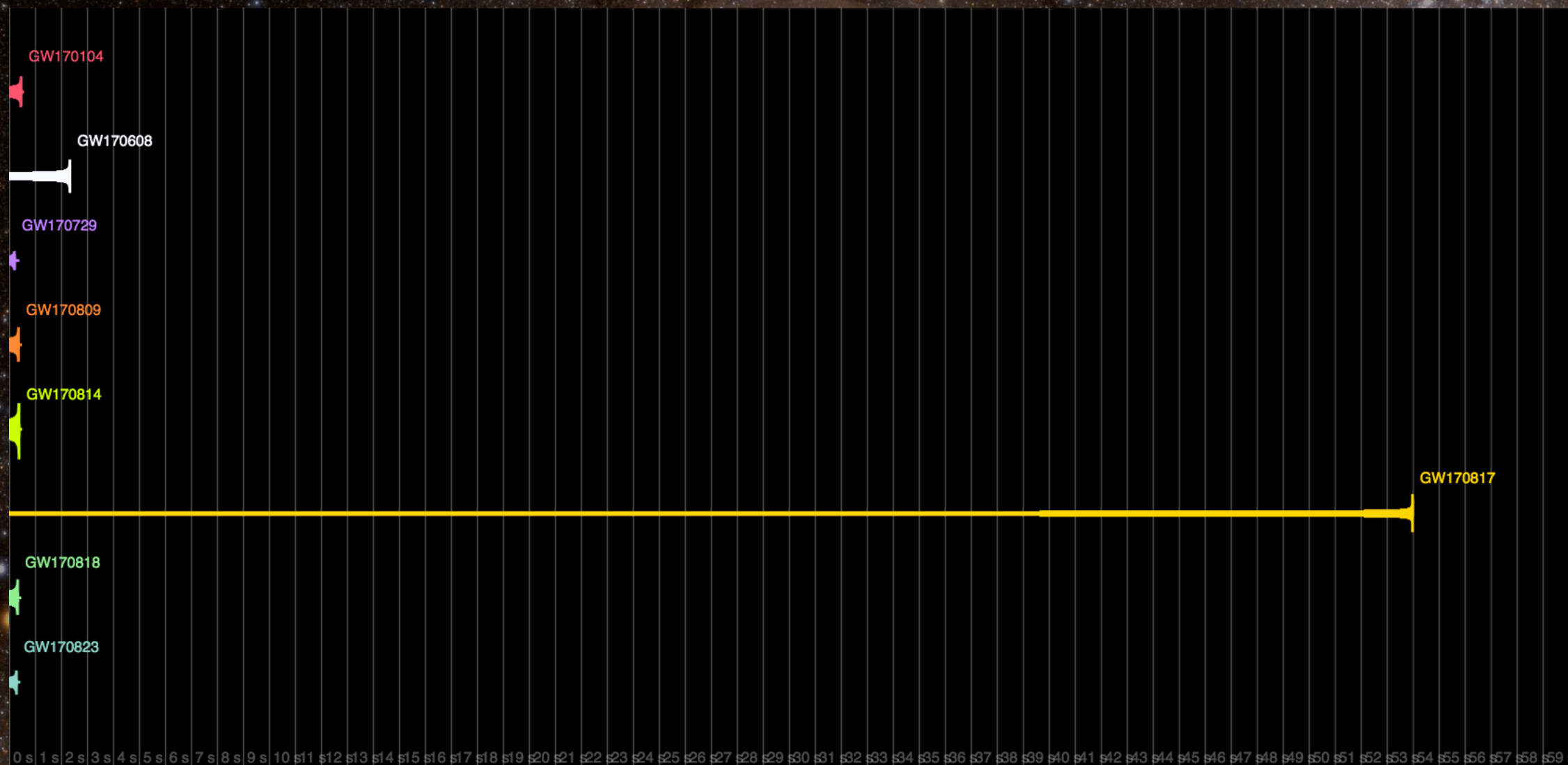
GW170817

GW170818

GW170823



# Multiple Detections





Fermi



Gamma rays, 50 to 300 keV

GRB 170817A

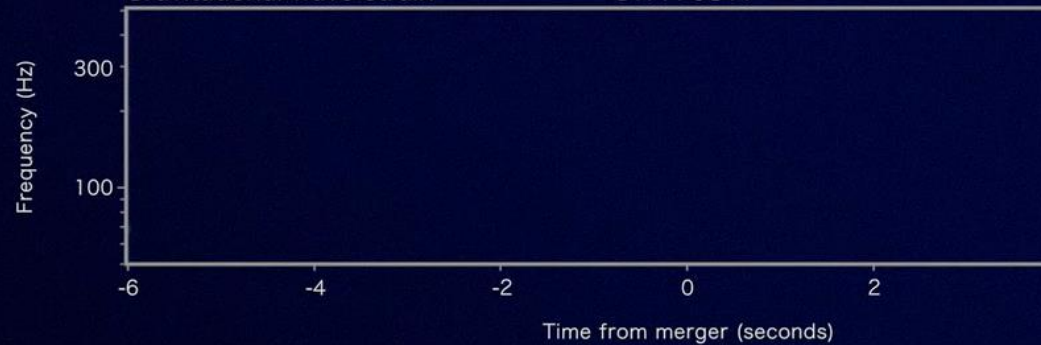


LIGO



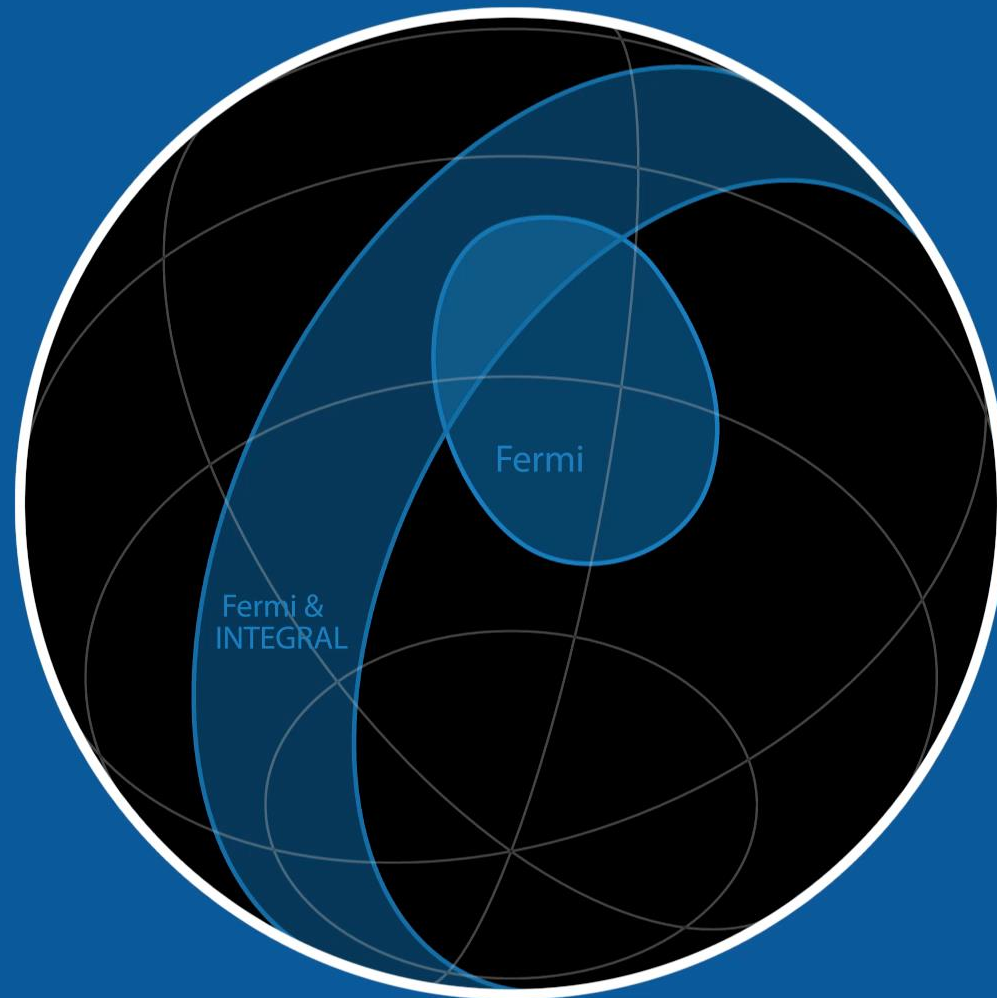
Gravitational-wave strain

GW170817



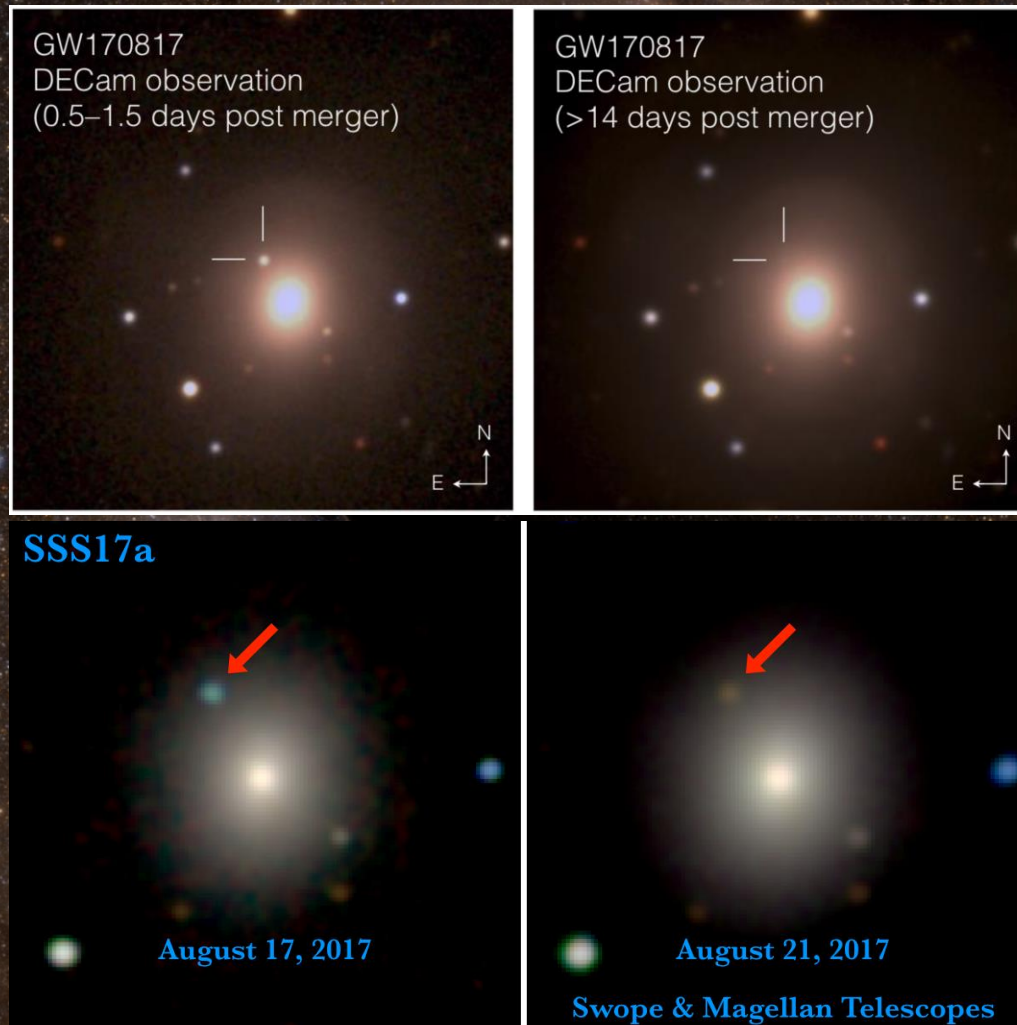


# Finding the source



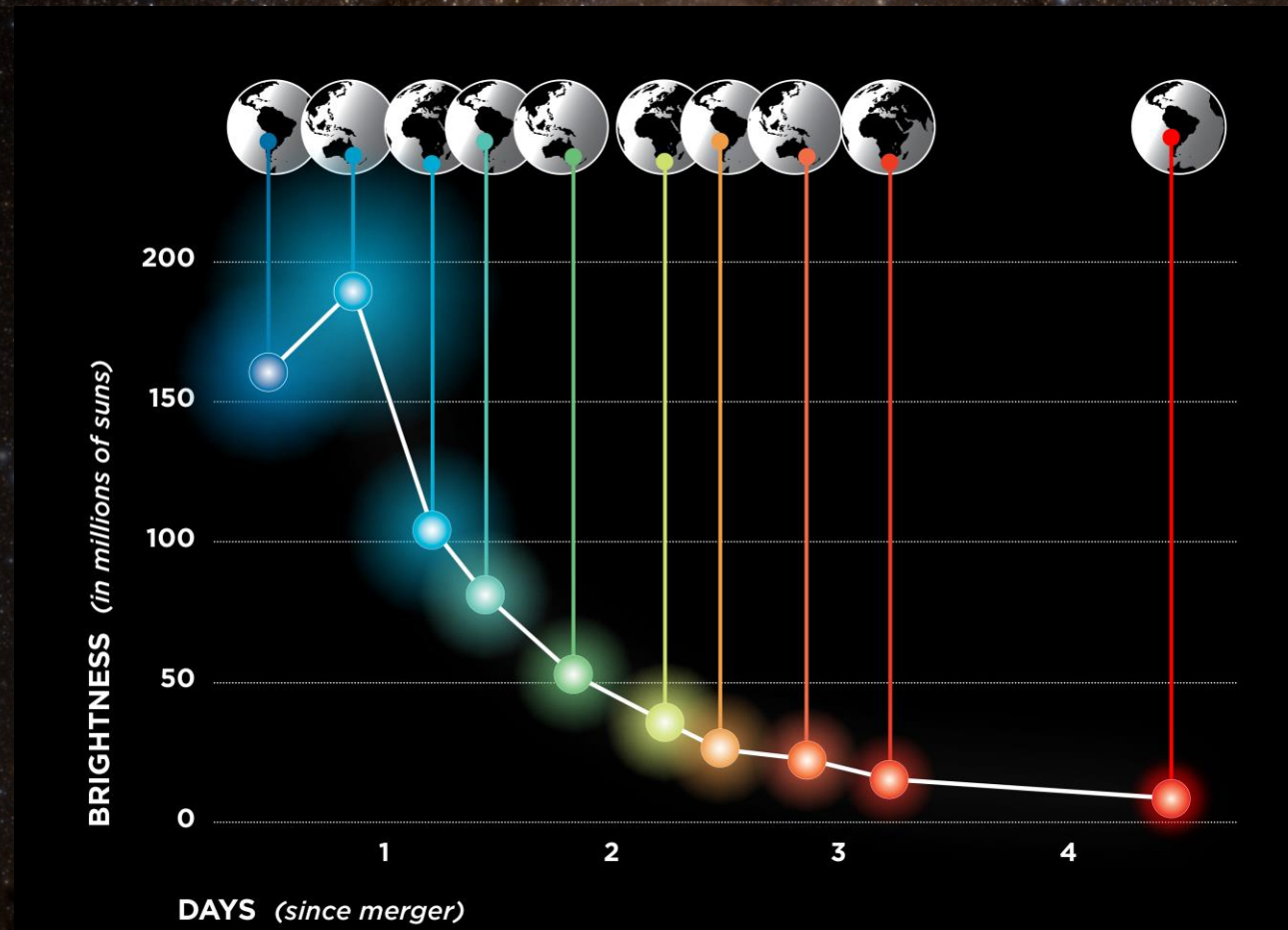


# Electromagnetic Followup





# Worldwide Followup











# Across the spectrum





# The Origin of the Solar System Elements

1 H	big bang fusion 										cosmic ray fission 					2 He	
3 Li	4 Be	merging neutron stars 					exploding massive stars 					5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	dying low mass stars 					exploding white dwarfs 					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												

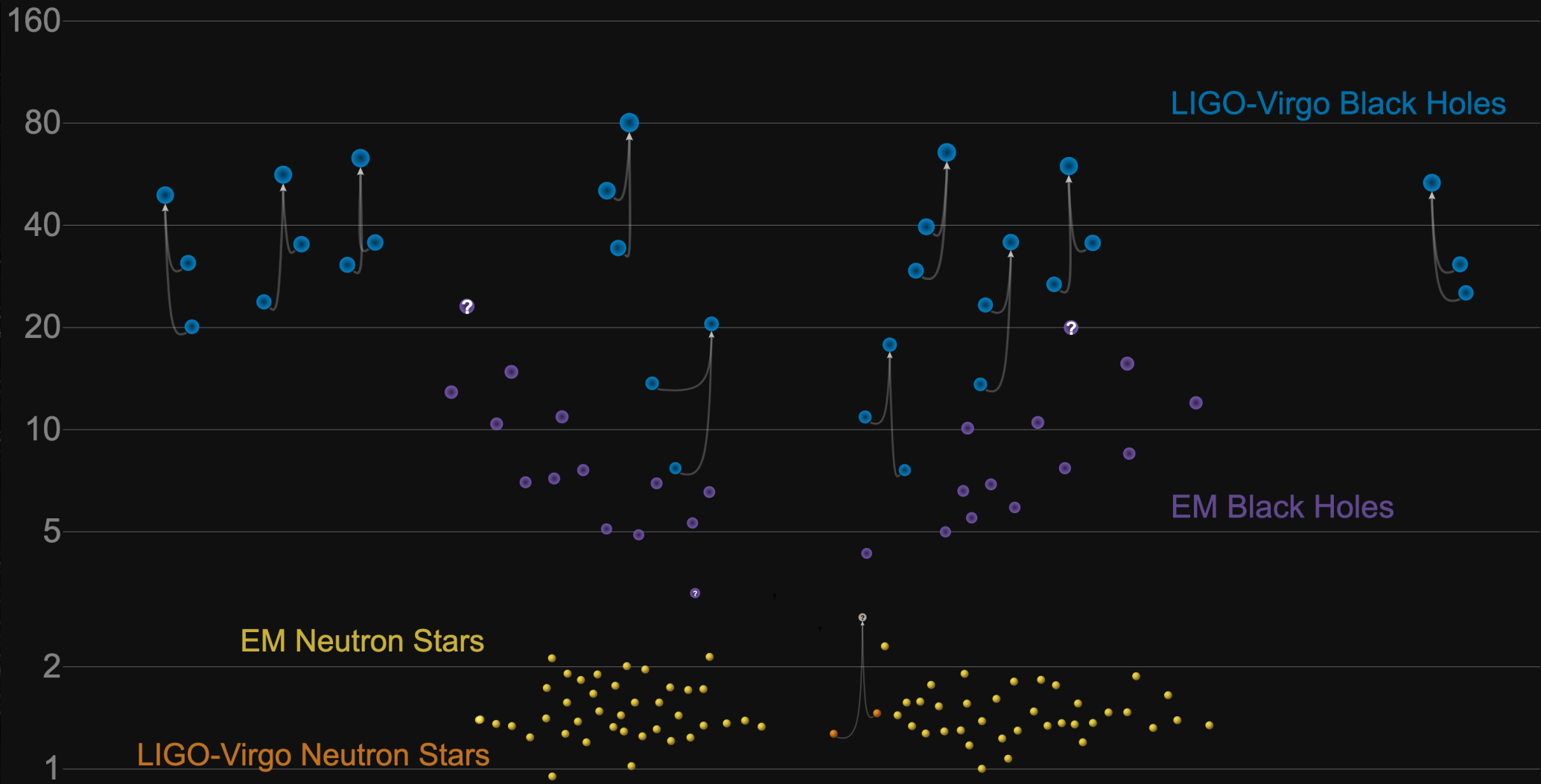
Graphic created by Jennifer Johnson

Astronomical Image Credits:  
ESA/NASA/AASNova



# Masses in the Stellar Graveyard

*in Solar Masses*



GWTC-2 plot v1.0

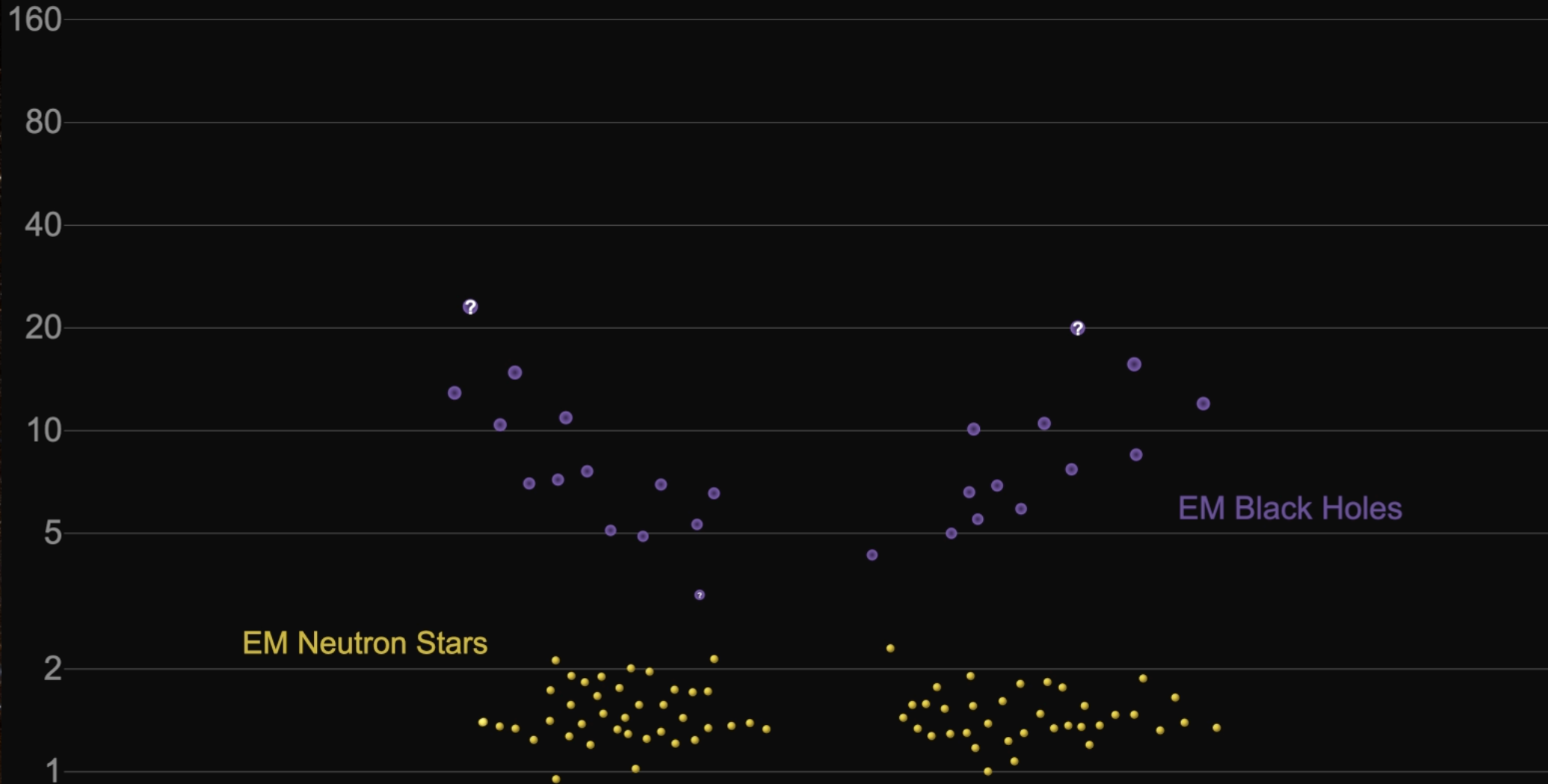
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern





# Masses in the Stellar Graveyard

*in Solar Masses*

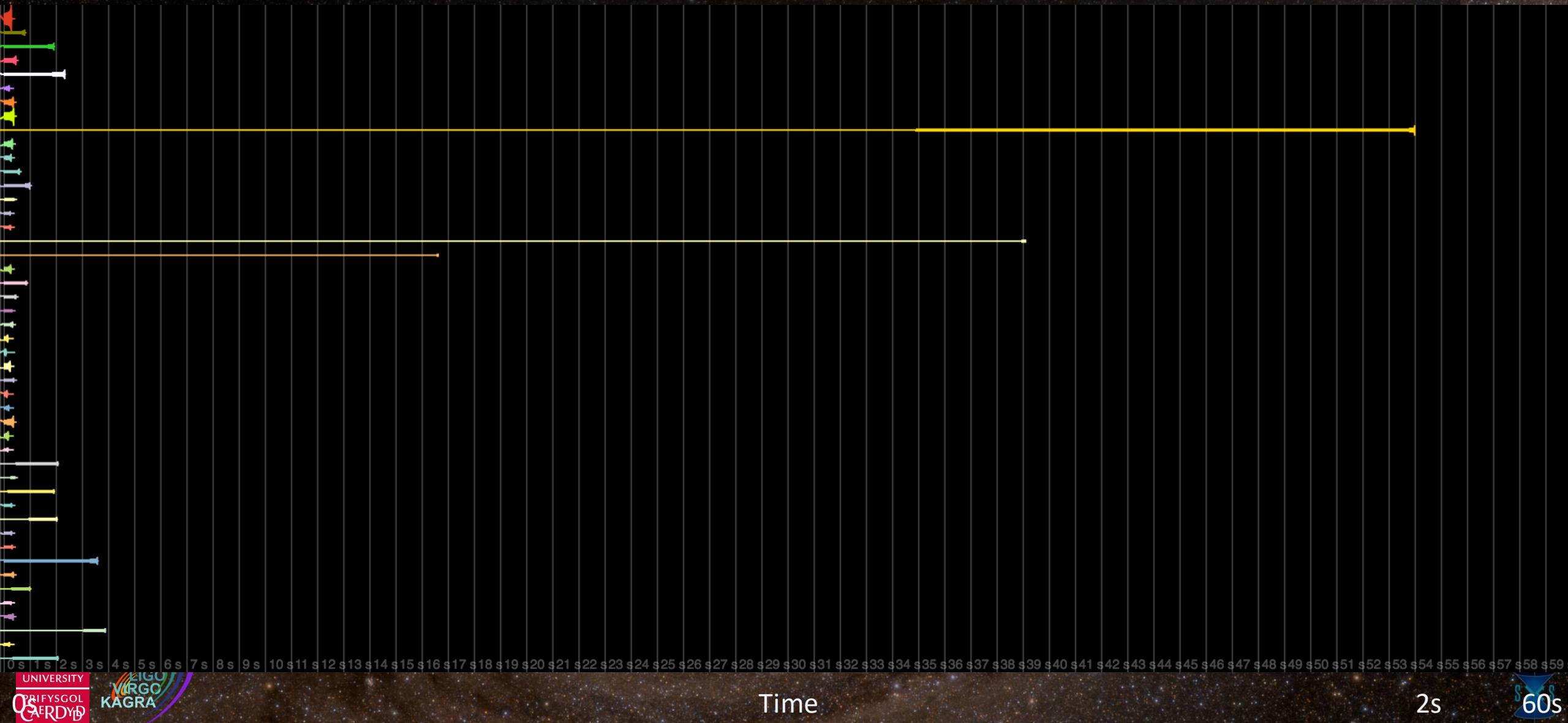


EM Neutron Stars

EM Black Holes

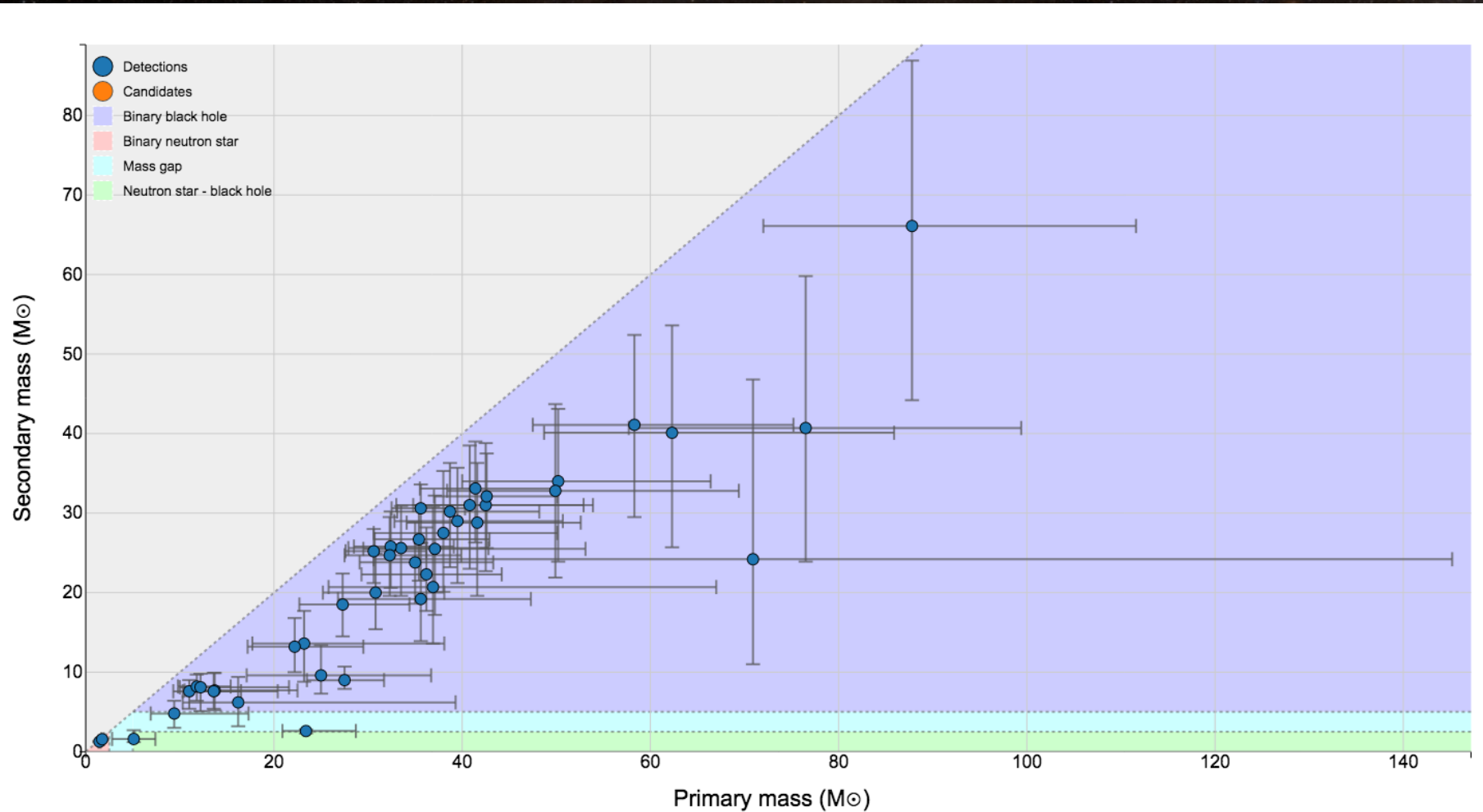


# Obs Run 1-3

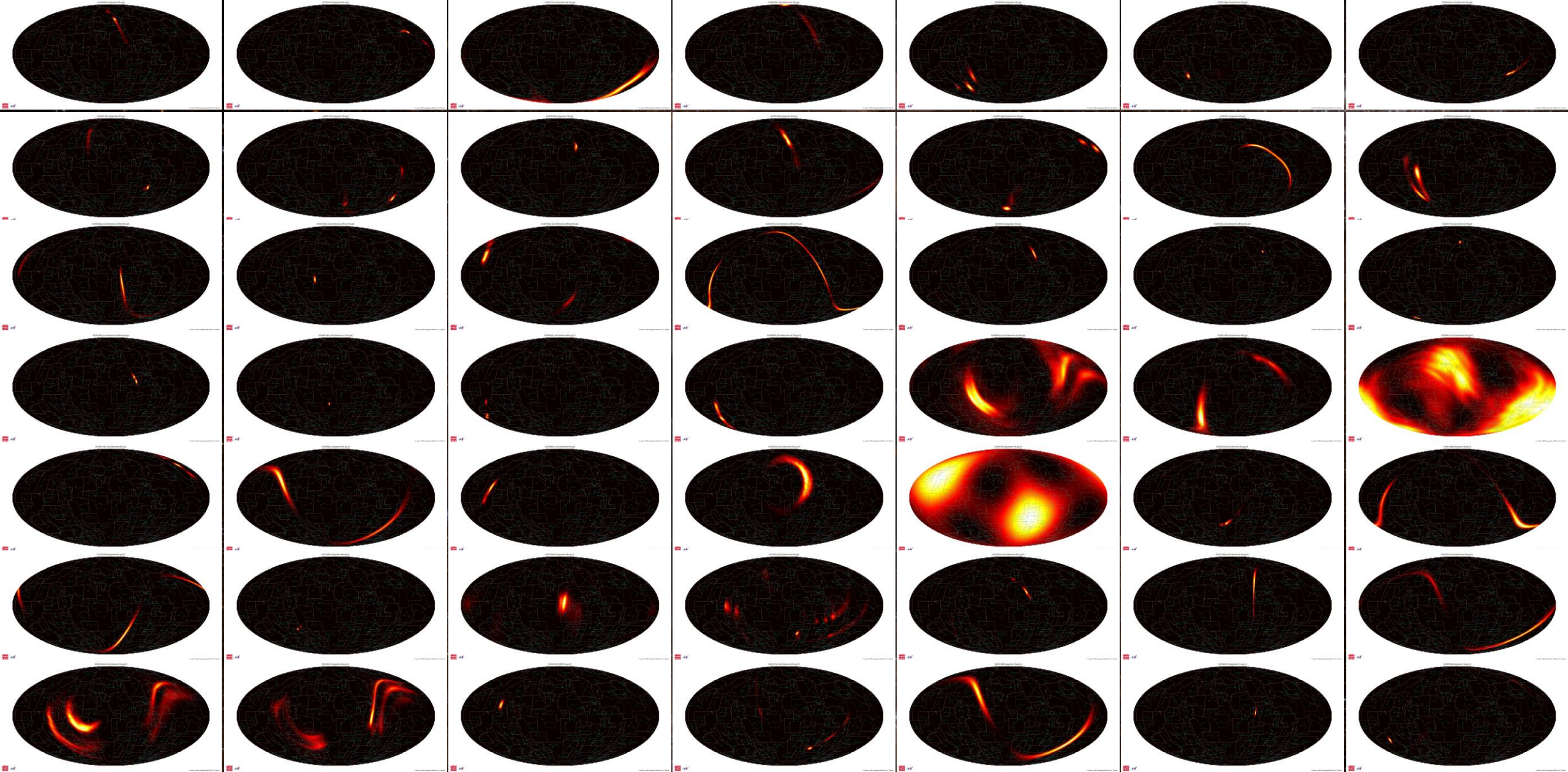




# catalog.cardiffgravity.org

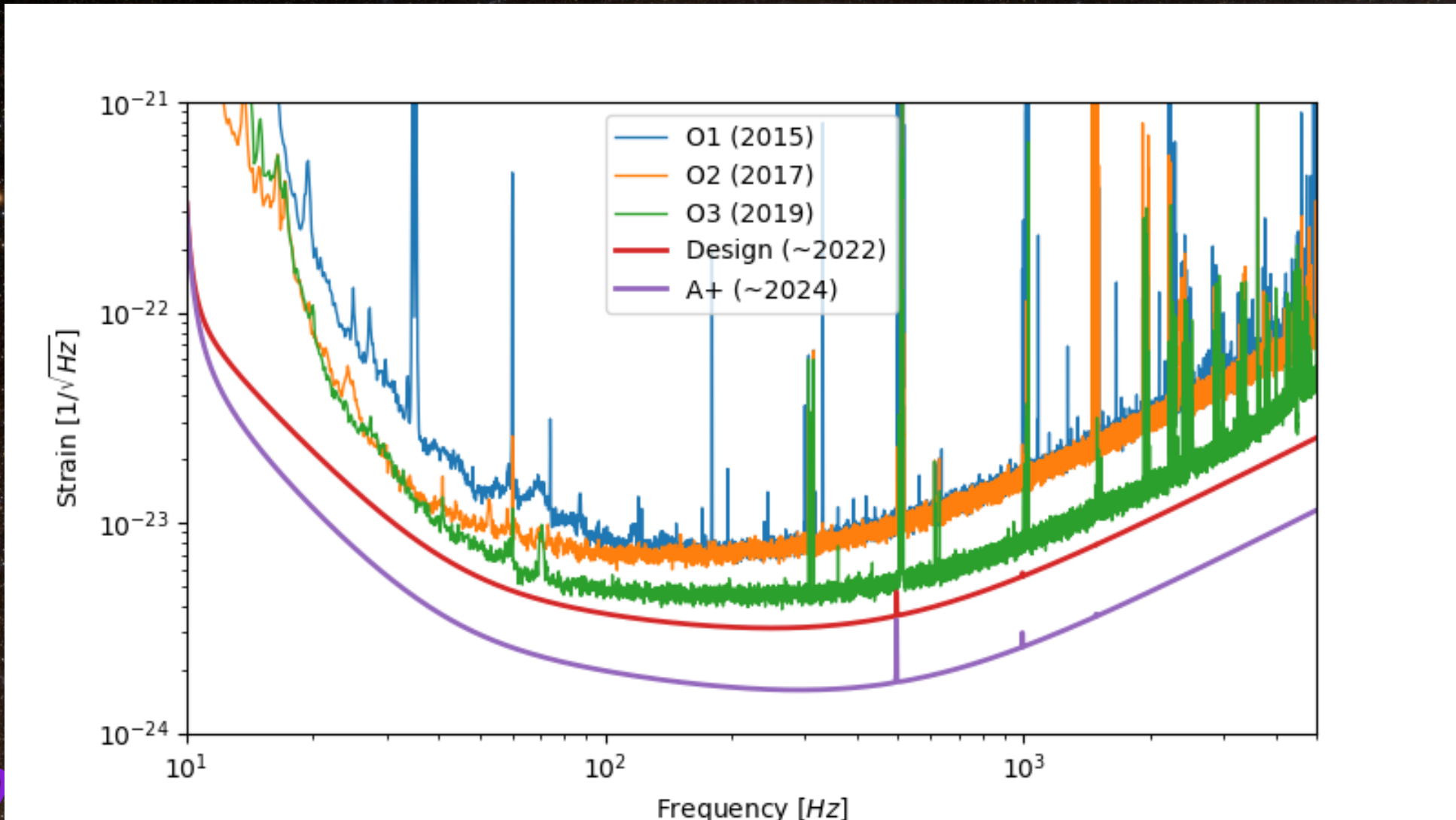






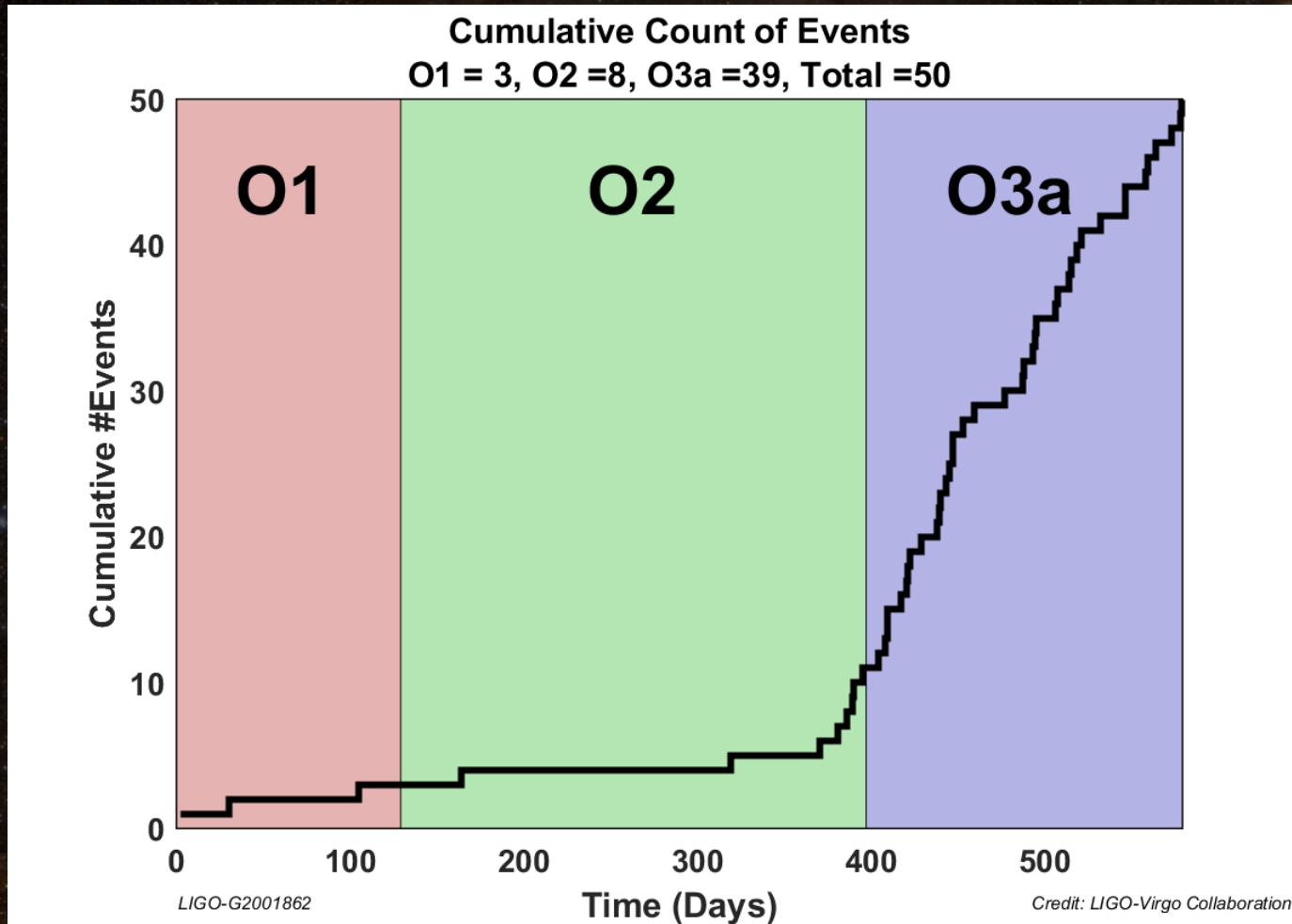


# Future upgrades





# Expected rates





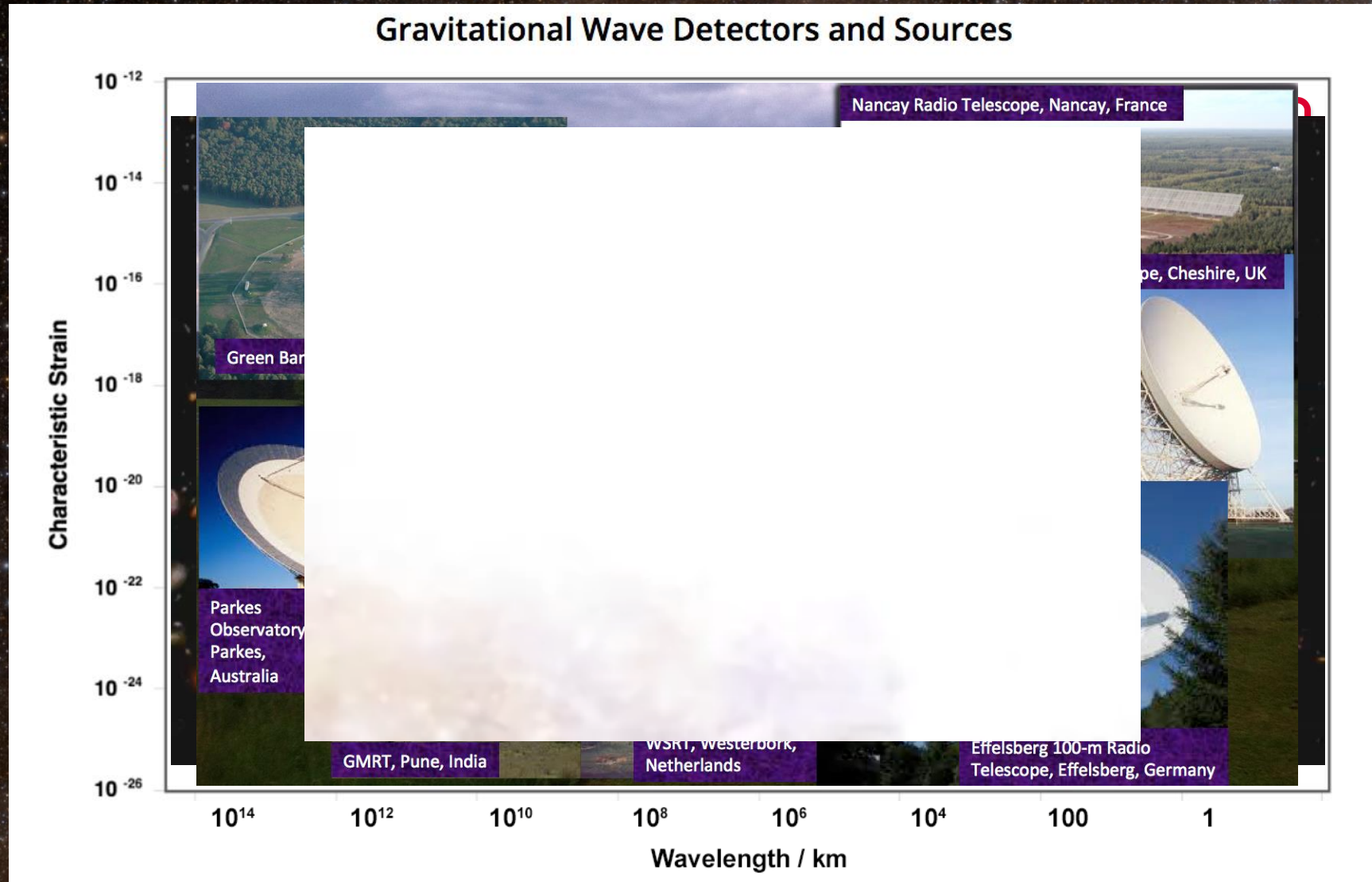
# Future prospects (rough numbers)

	O1 [2015-16]	O2 [2016-17]	O3 [2019-20]	Design [~2023]	A+ [~2025]
<b>LIGO BNS range</b> (1.5 + 1.5 Msun)	~220-260 Mly (70-80 Mpc)	~260-330 Mly (75-100 Mpc)	~330-420 Mly (100-130 Mpc)	~580 Mly ~180 Mpc	~1100 Mly ~340 Mpc
<b>LIGO BBH range</b> (15 + 15 Msun)	~0.4 Gpc	~0.5 Gpc	~0.6 Gpc	~1 Gpc	~1.8 Gpc
<b>LIGO BBH Volume</b>	~0.3 Gpc <sup>3</sup>	~0.5 Gpc <sup>3</sup>	~1 Gpc <sup>3</sup>	~4 Gpc <sup>3</sup>	~24 Gpc <sup>3</sup>
<b>Observing time</b>	~4 months	~9 months	~1 year		
<b>Number of events</b>	3	8	~50	~daily?	6/day?
<b>Detection Rate</b>	~1 per month	~1 per month	~weekly!		

Estimated BBH rate 25-100 Gpc<sup>-3</sup> yr<sup>-1</sup> (# events per cubic-Gigaparsec per year)



# What the future holds...





# Stay Tuned!

## Observing Run 4: 2021-2022

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[pythagastro.uk](http://pythagastro.uk)  
[blogs.cardiff.ac.uk/physicsoutreach](https://blogs.cardiff.ac.uk/physicsoutreach)

