What’s Next for Gravitational Wave Astronomy?

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2018-10-24

Artist’s Conception: Aurore Simonnet

New Telescope – New Astronomy

gamma ray X-ray ultraviolet visible infrared microwave radio

$$Mc^2 = E$$ ← Energy

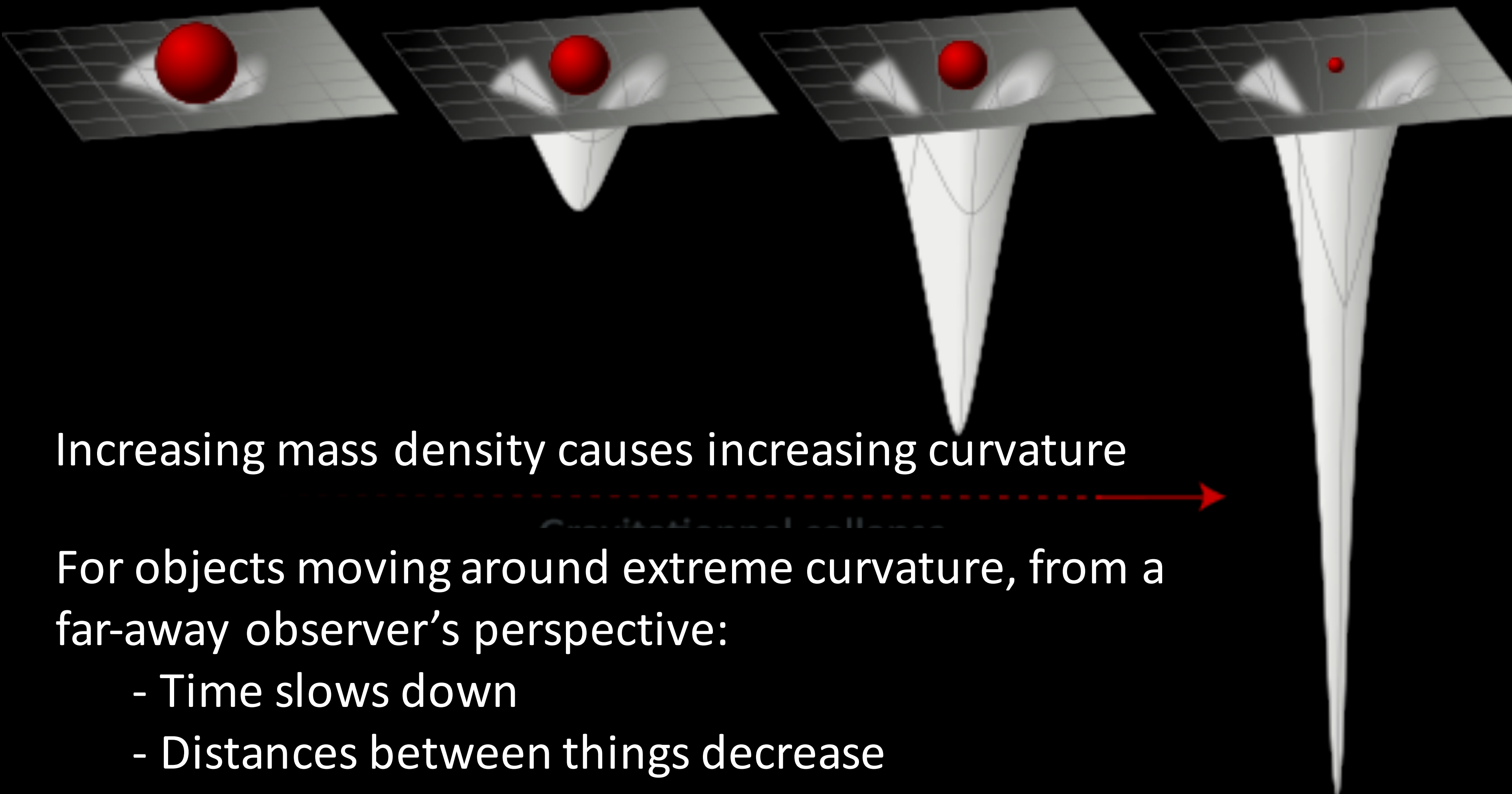
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$ → Wave Equation

Gravitational Wave Periods

Milliseconds	Minutes to Hours	Years to Decades	Billions of Years

Mass tells space-time how to curve…

Average Star White Dwarf Neutron Star Black Hole



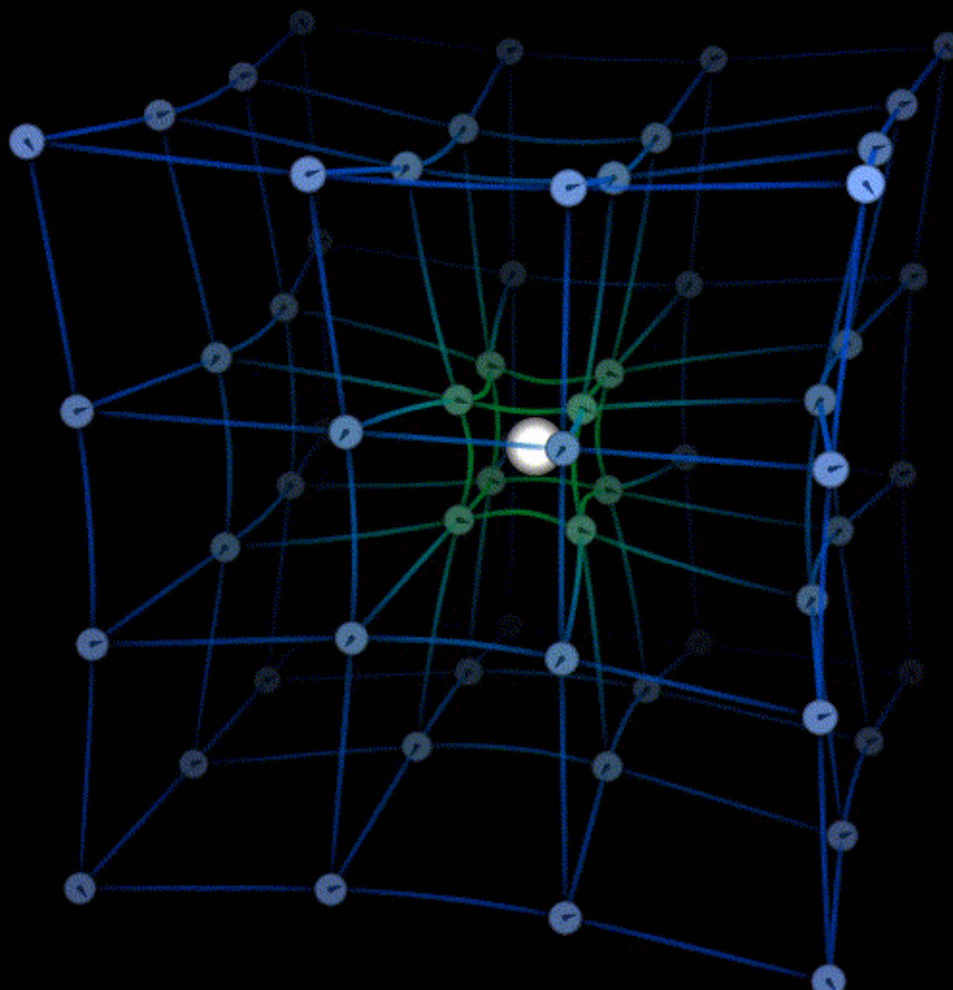
Increasing mass density causes increasing curvature

For objects moving around extreme curvature, from a far-away observer's perspective:

- Time slows down
- Distances between things decrease

… in 4 dimensions …

The shortest distance between two points gets **shorter** near heavy mass



Independent clocks near heavy mass **slows down**

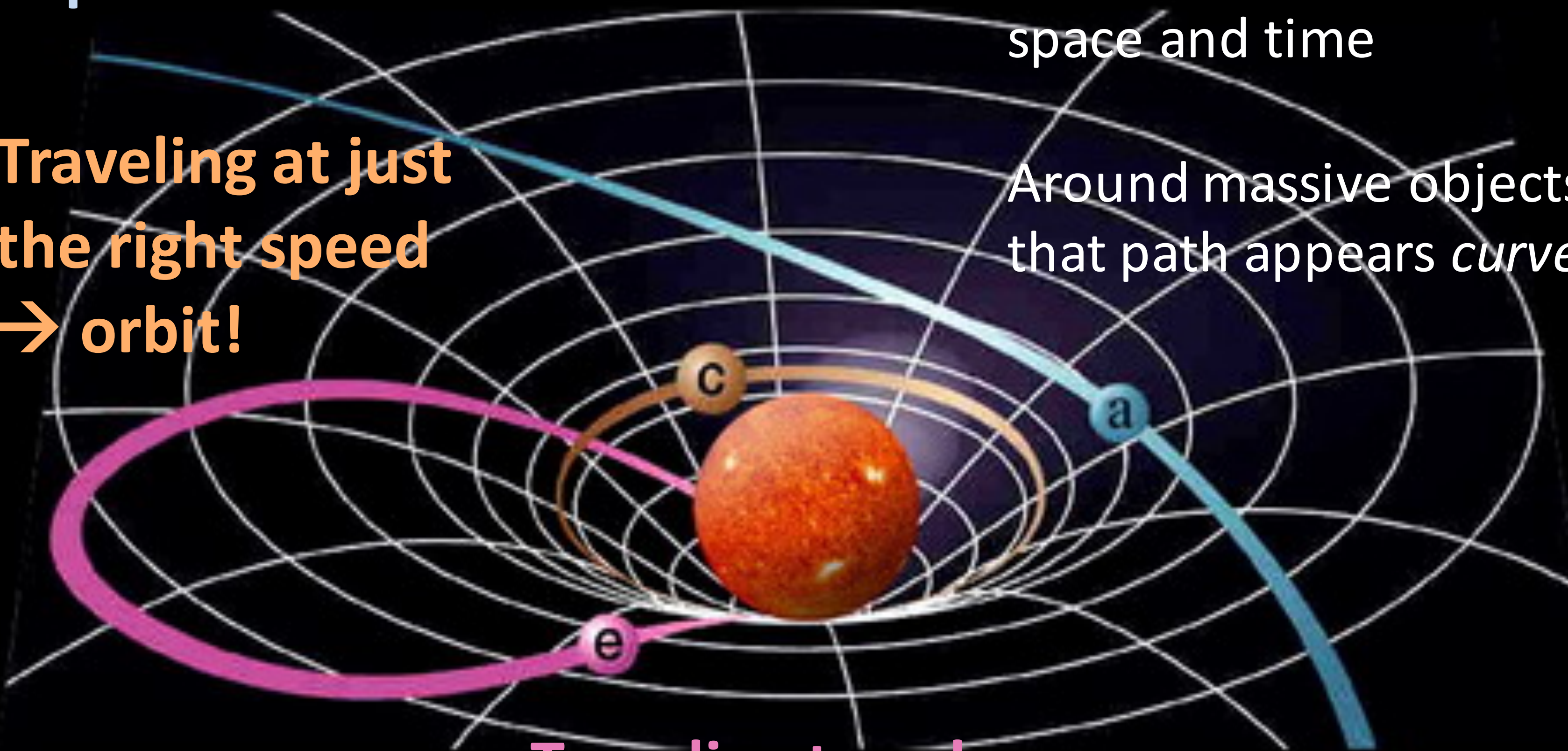
… and space-time curvature tells mass how to move

Traveling fast past curvature
→ path "bends" to follow

Objects travel along the shortest path through space and time

Traveling at just the right speed
→ orbit!

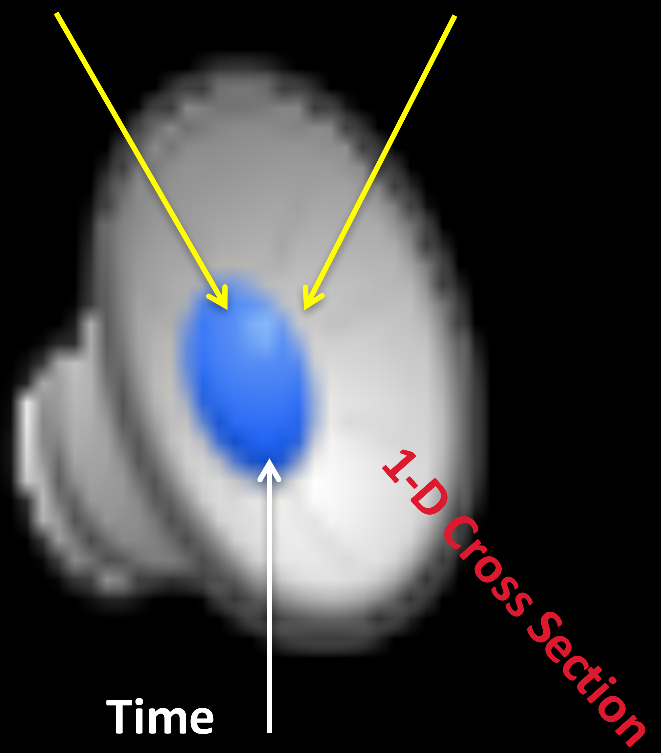
Around massive objects, that path appears *curved*



Traveling too slow
→ path "falls" into source → Collision!

Colliding Black Holes!

Tim Dietrich / AEI / BAM Collaboration
https://youtu.be/YnCccVDpmrw



1-D Amplitude

Time

Predicted Gravitational Waveform

A Gravitational Wave Telescope

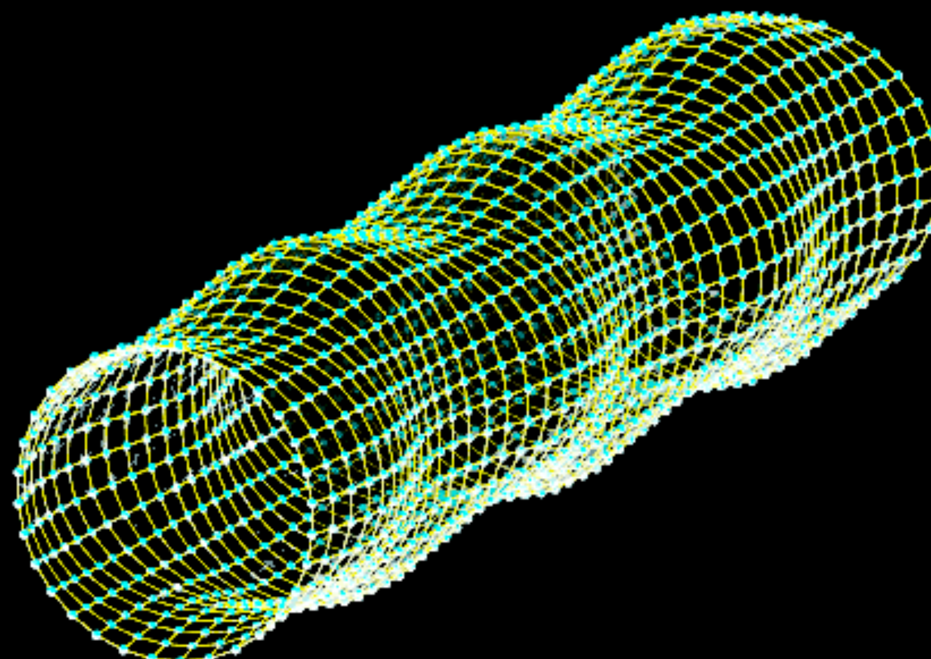
Gravitational Wave Periods

Milliseconds

Minutes
to Hours

Years
to Decades

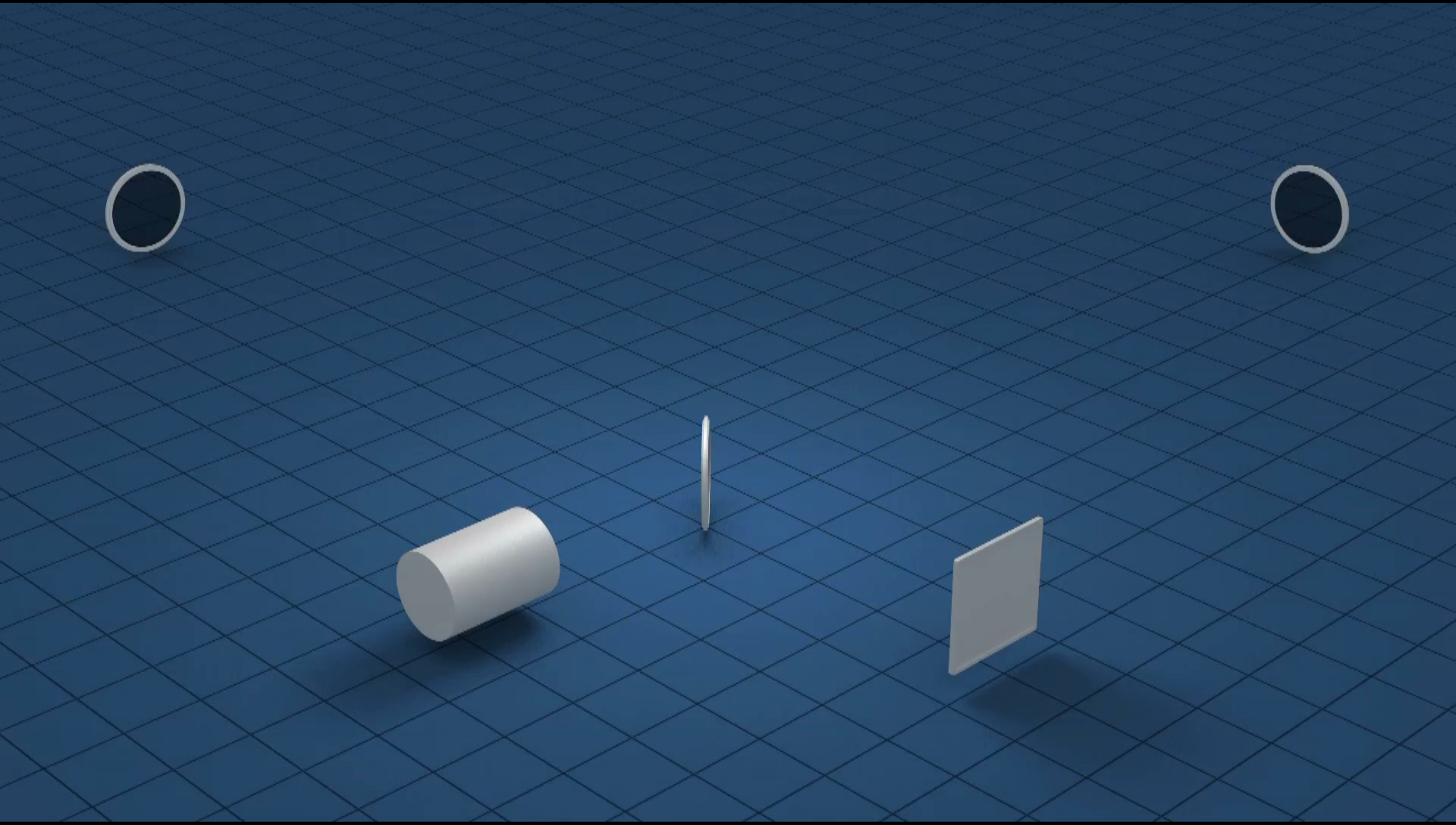
Billions
of Years



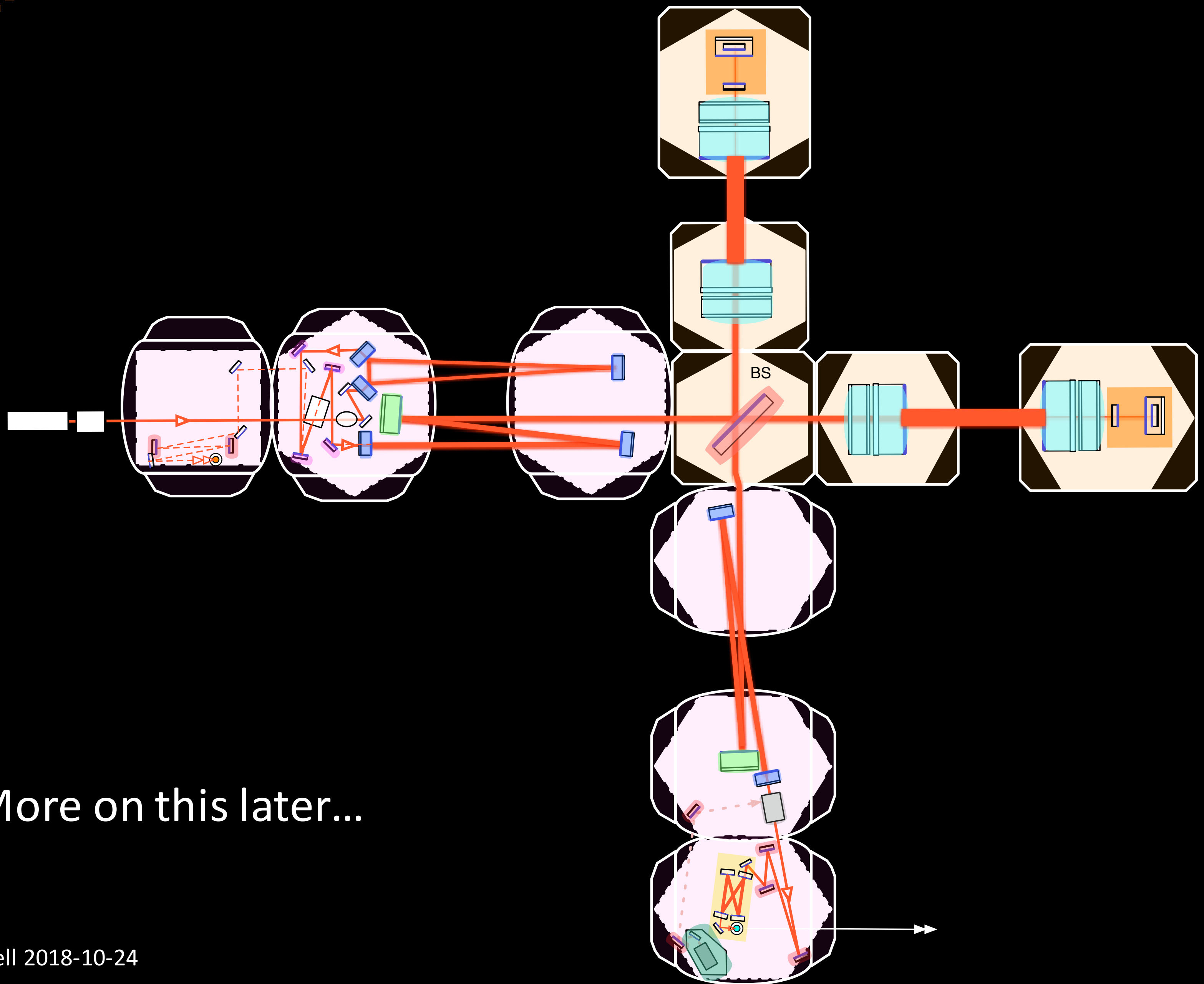
www.einstein-online.info

Gravitational wave **O**bservatory

How Do Interferometers Work?

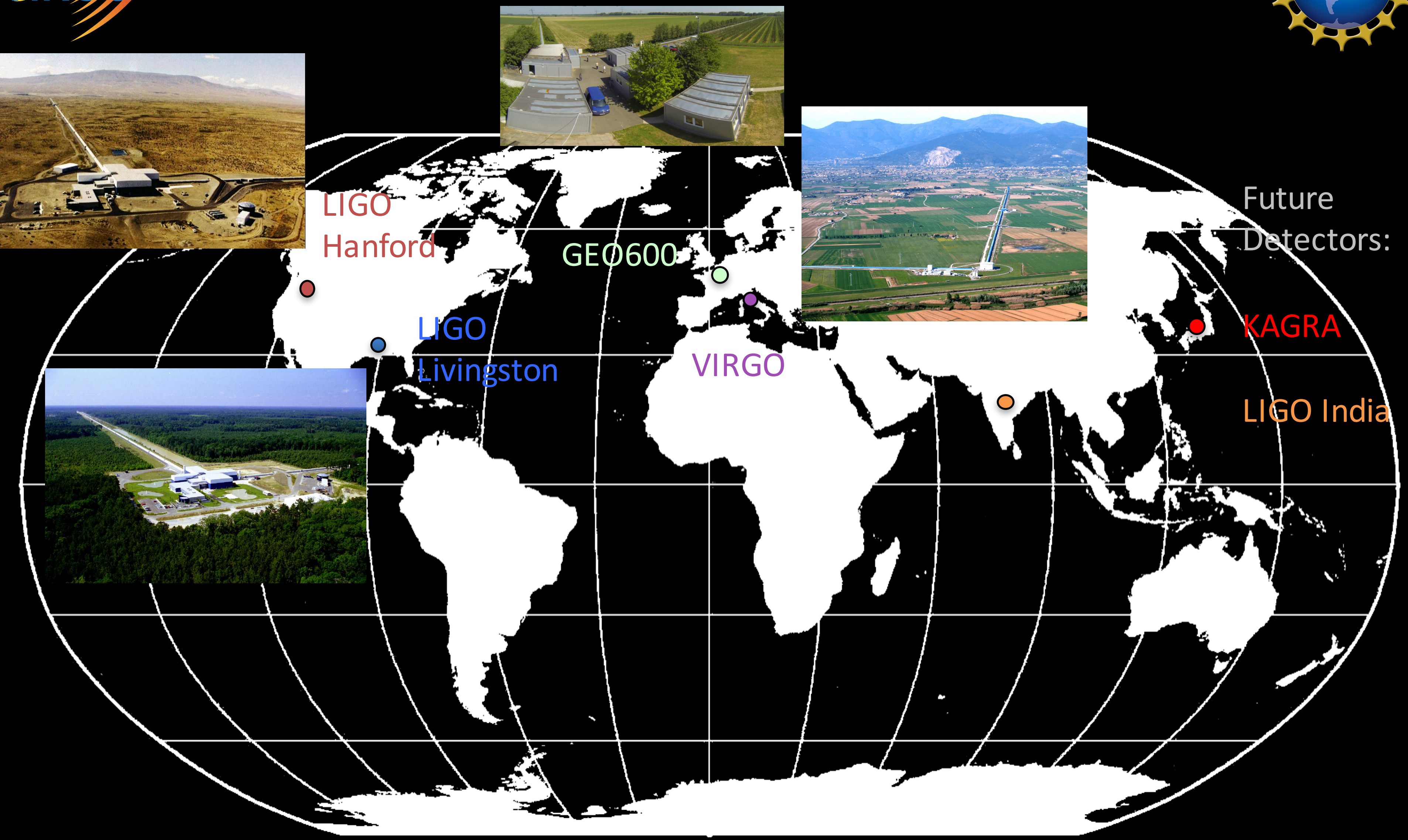


How does LIGO *really* work?



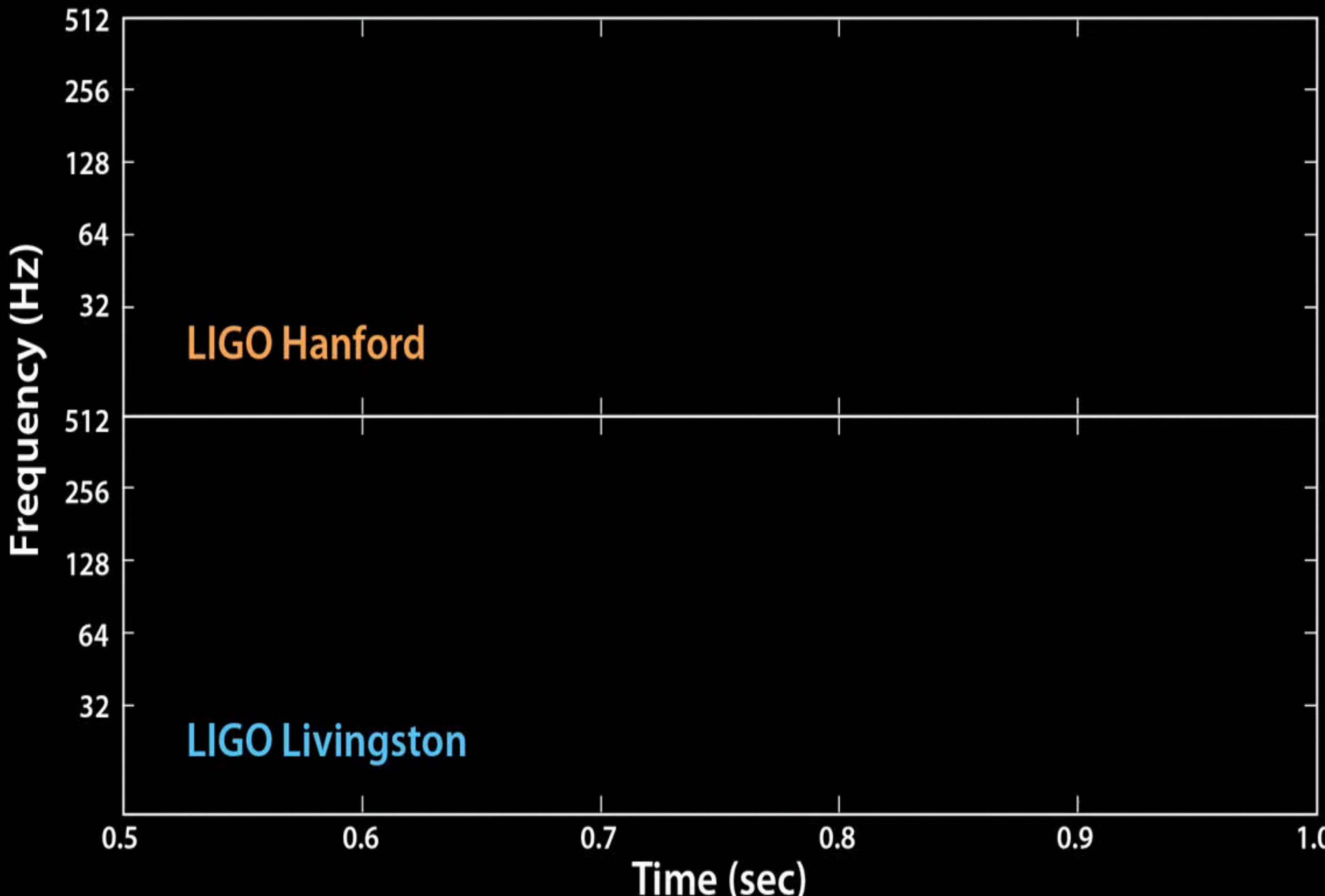
More on this later…

LIGO's Global Partners

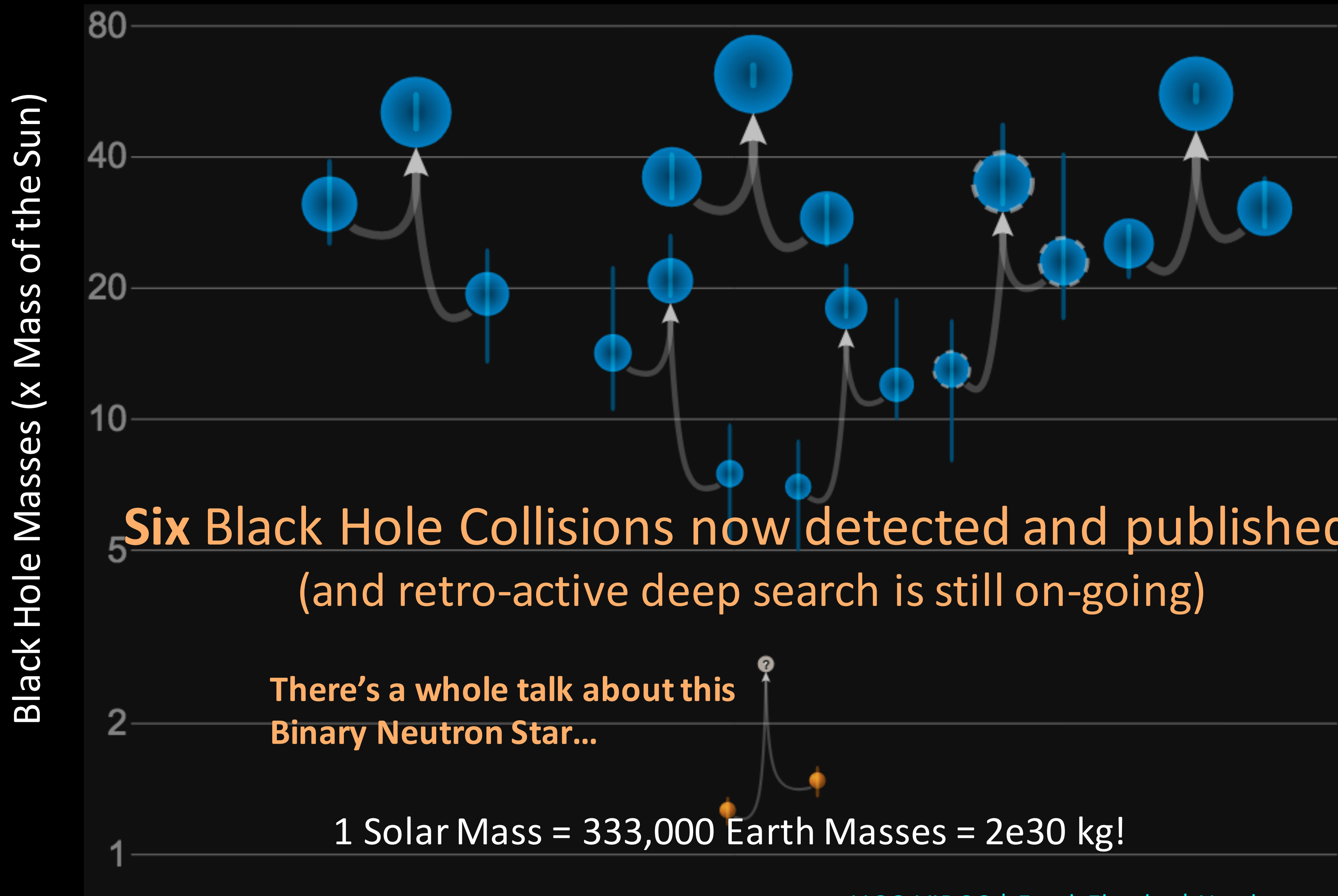


With a network, you gain directional sensitivity!

What LIGO "Hears"



How Many Have We Detected?



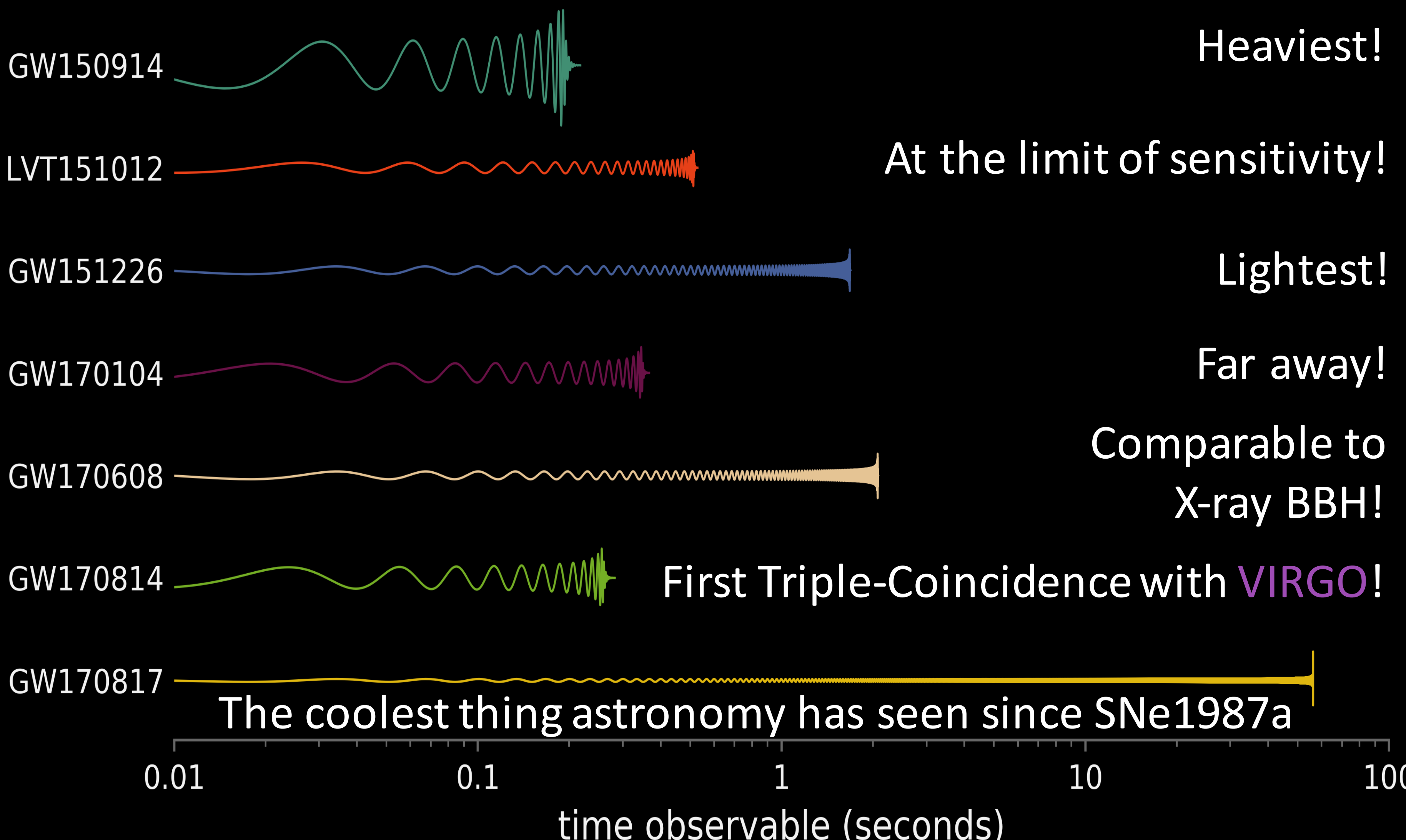
Six Black Hole Collisions now detected and published!

(and retro-active deep search is still on-going)

There's a whole talk about this Binary Neutron Star…

1 Solar Mass = 333,000 Earth Masses = 2e30 kg!

How Diverse Have They Been?



What LIGO "Hears"

LIGO Mirrors are 40 kg 88 lbs of Glass

Detectors have a *frequency-dependent* **background noise**, moving the arms about

1 x 10^{-19} meters

1 / 10,000th the width of a proton

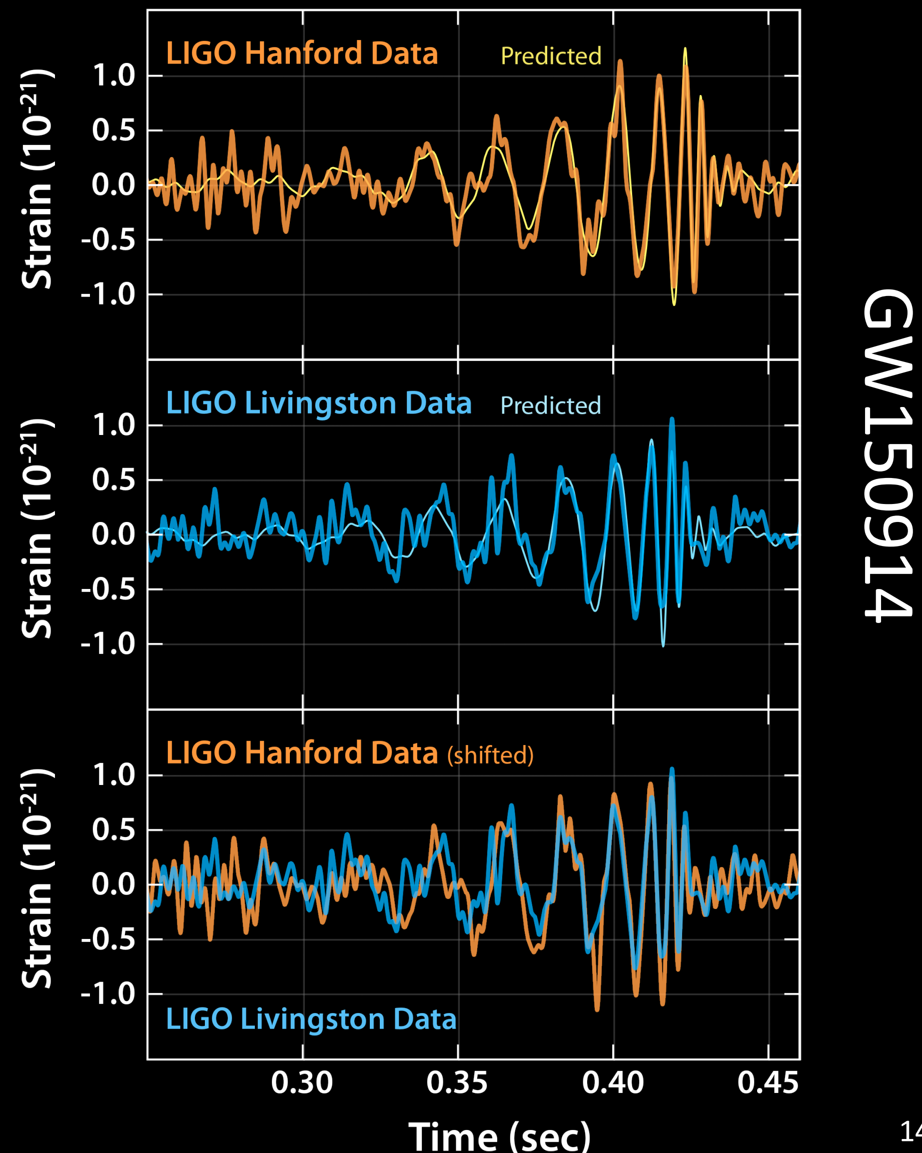
Characterized in "Strain"

strain = displacement / length

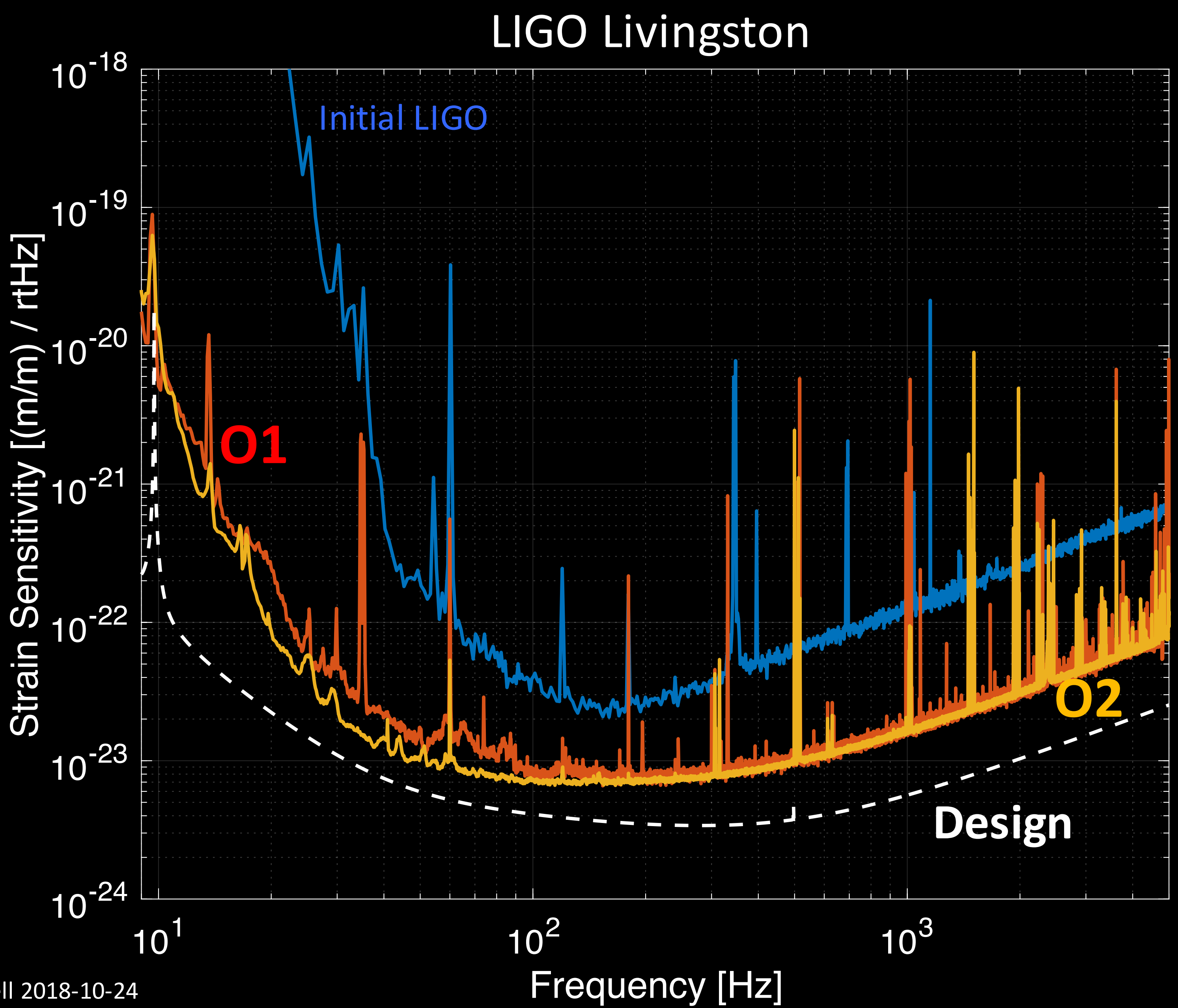
units: meters / meter

1 x 10^{-19} meters / 4000 meters

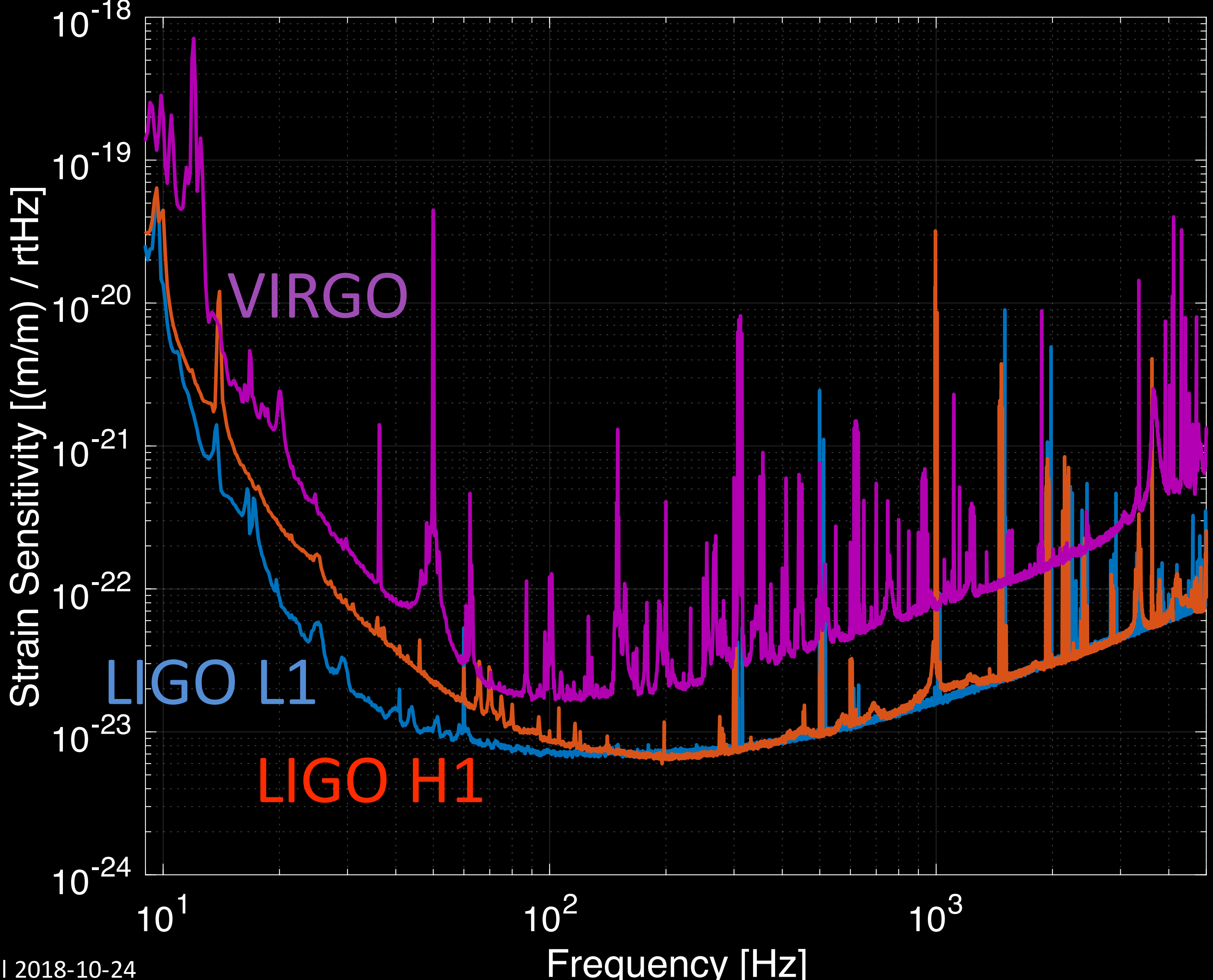
strain = 2.5e-23 m/m



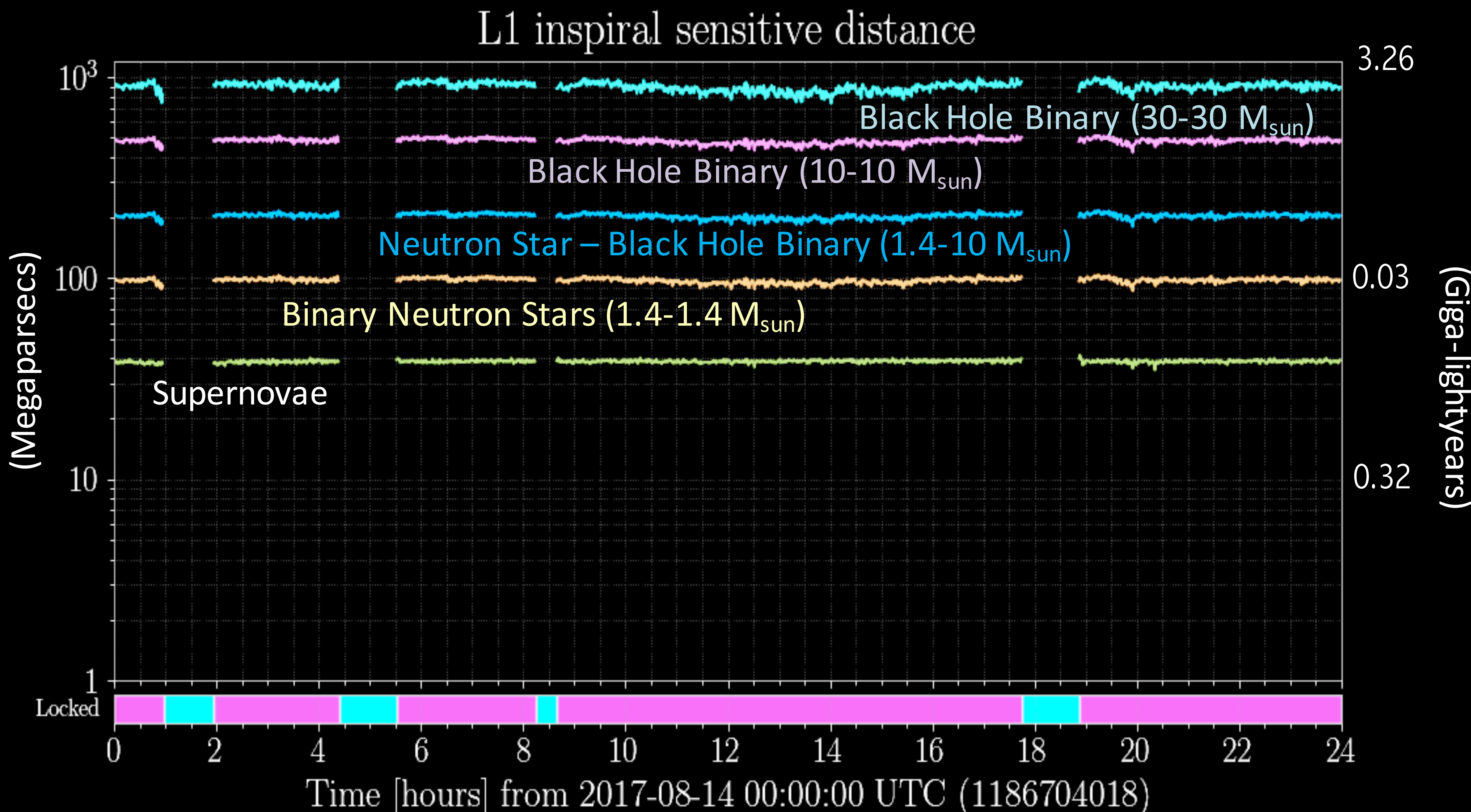
LIGO Improvement Over Time



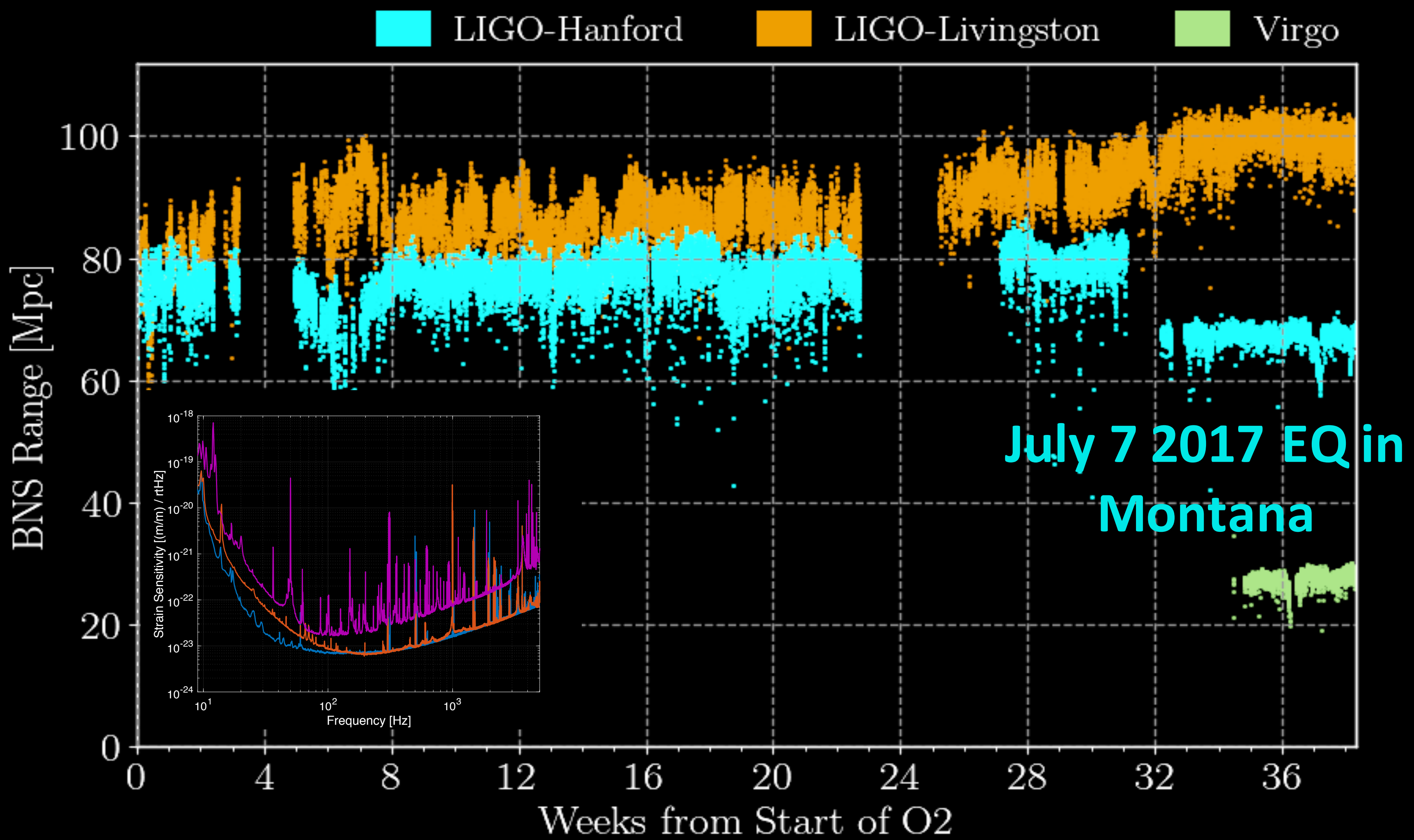
Network Performance During GW170814



Sensitivity as a Function of Source Distance



The Binary Neutron Star Range during **O2**



Recent Timeline of Observation / Detections

1 billion light years = 1 Gig light year = 1 Gly

Goal Binary Neutron Star Detectable Range

~70 Mpc

~90 Mpc

~120 Mpc

Advanced LIGO Observing runs

O1

Make it Better!

O2

Make it Better!

O3

4 mo

~8 mo

~12-15 mo

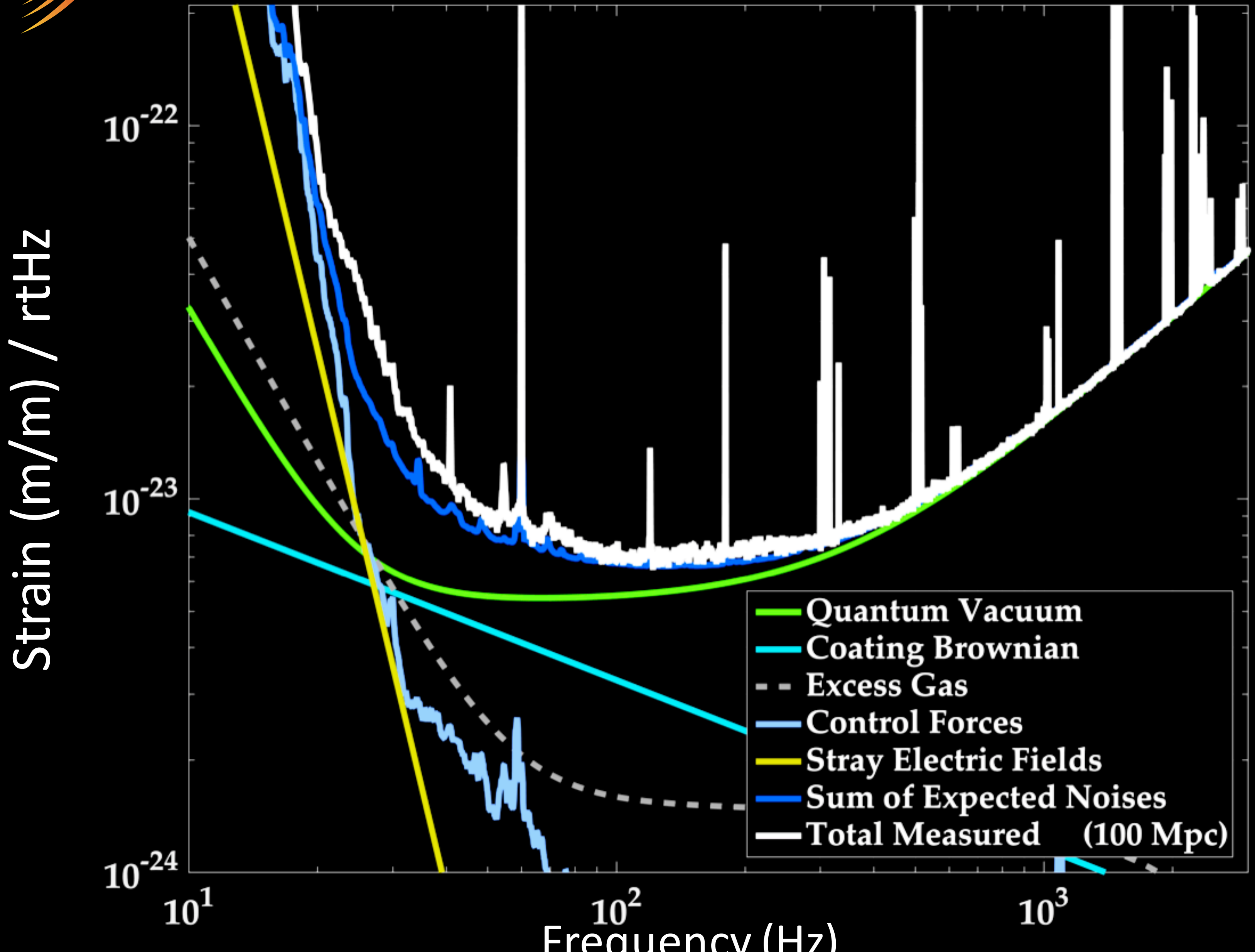
2015 2016 2017 2018 2019

YOU ARE HERE

Estimated

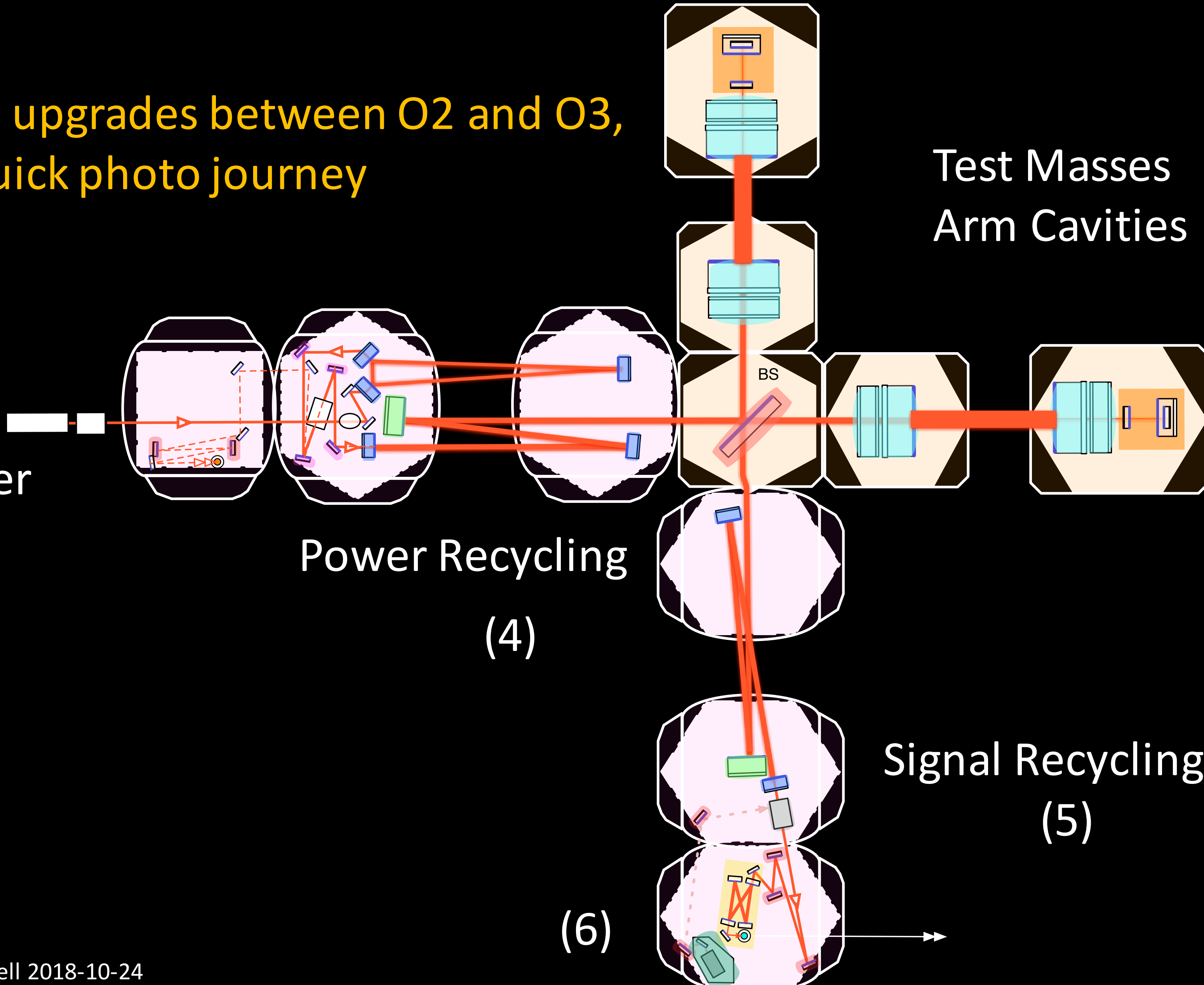
Black Hole Collision Rate = 12–213 Gpc $^{-3}$ yr $^{-1}$

Make it Better You Say?



The Real LIGO Layout

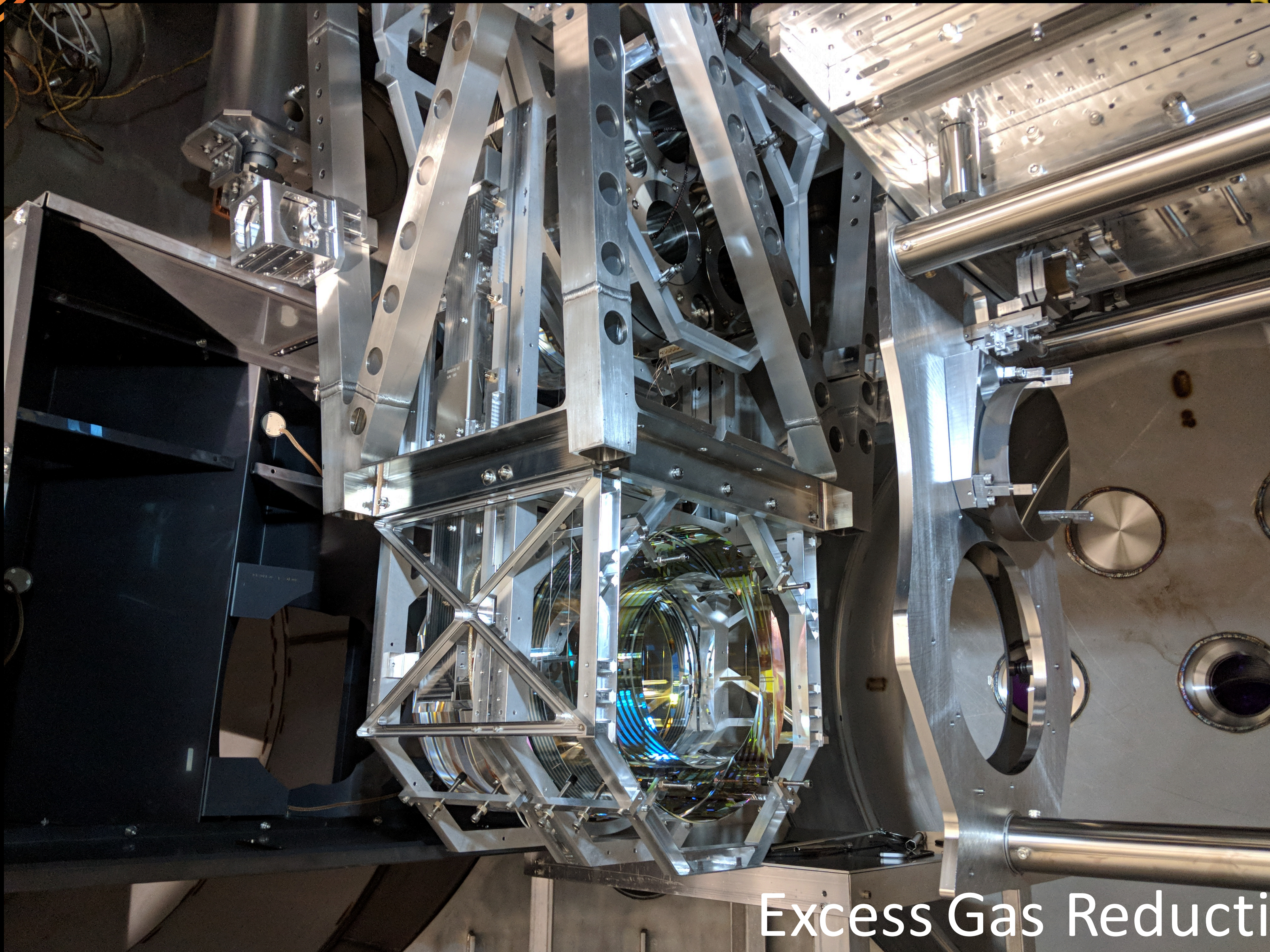
The upgrades between O2 and O3,
a quick photo journey



(1) Replace 5 of 8 Test Masses

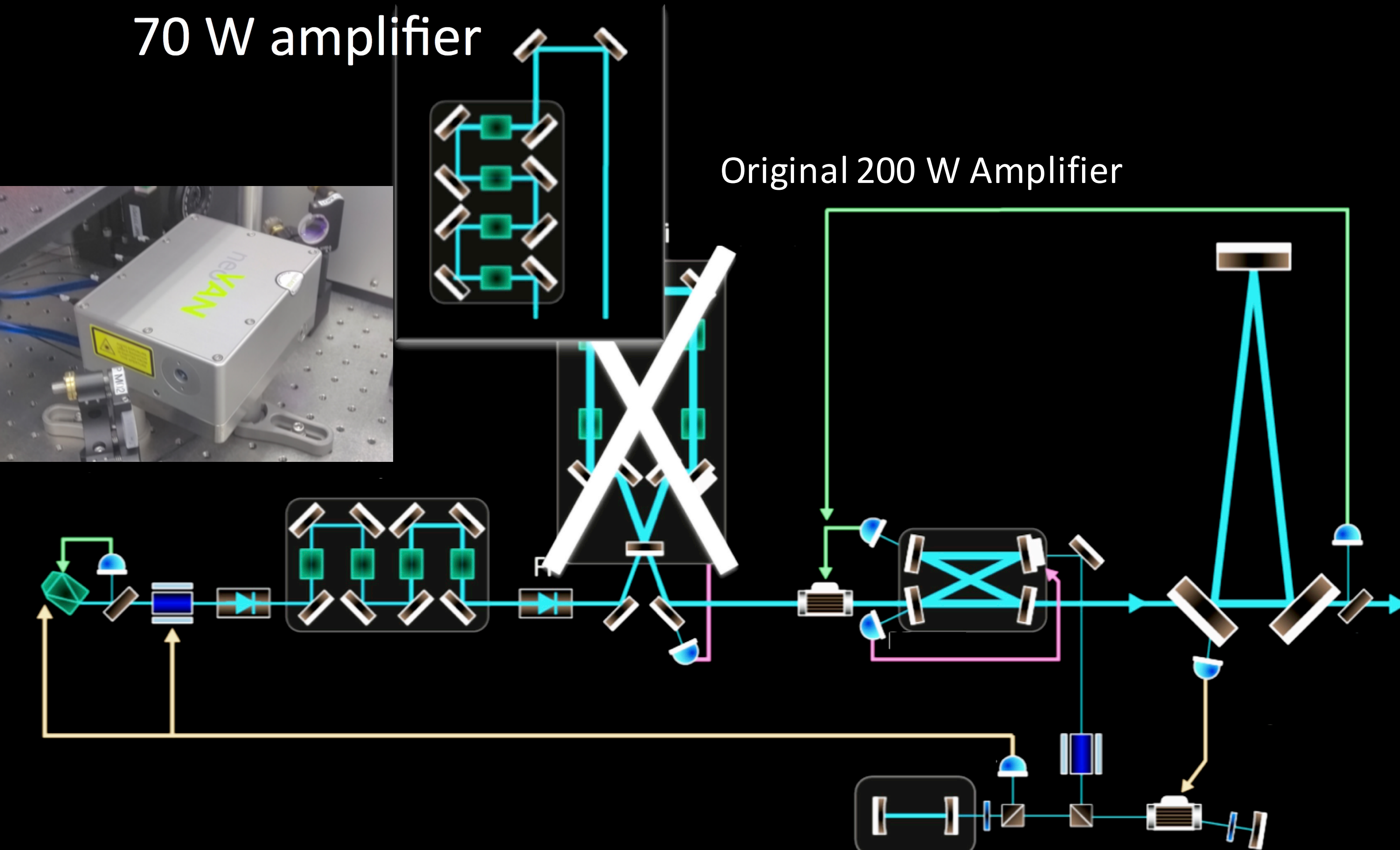
Lower Arm Cavity Loss:
More power!

(2) Replace All End Reaction Masses

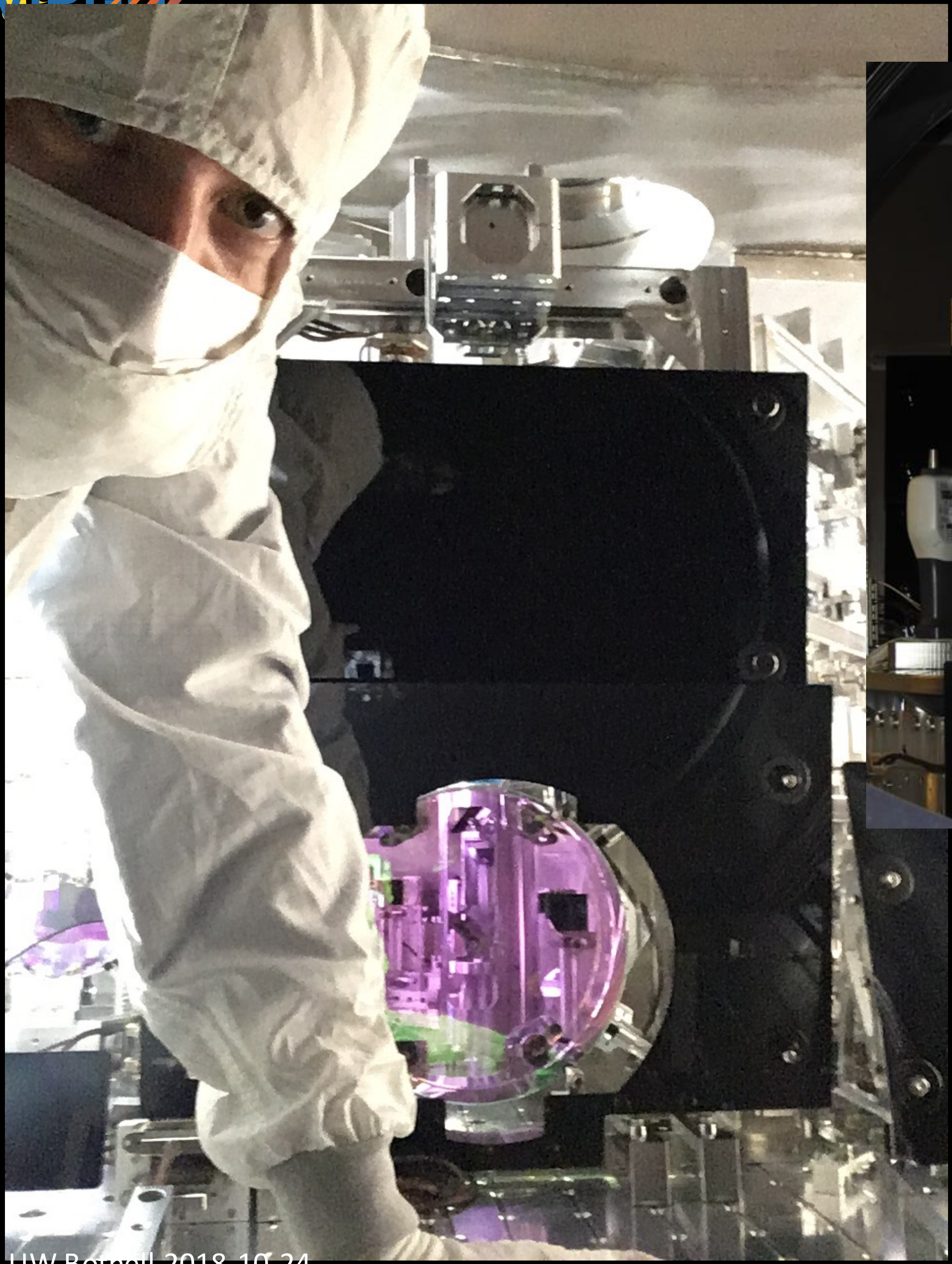


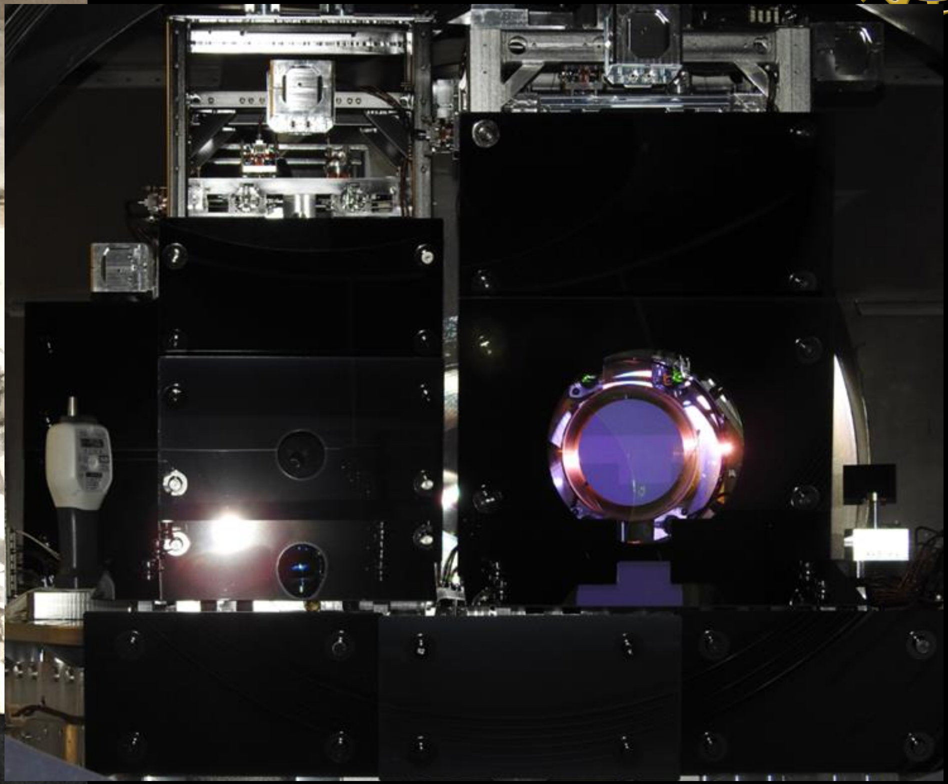
(3) Replace the Laser

New
70 W amplifier



(4) Add Light-Capturing Baffles Everywhere

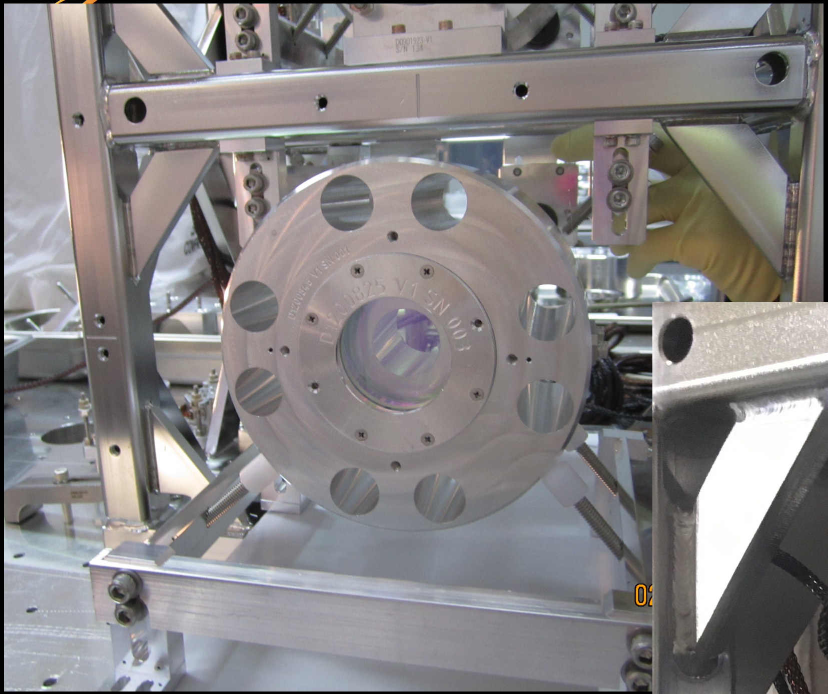


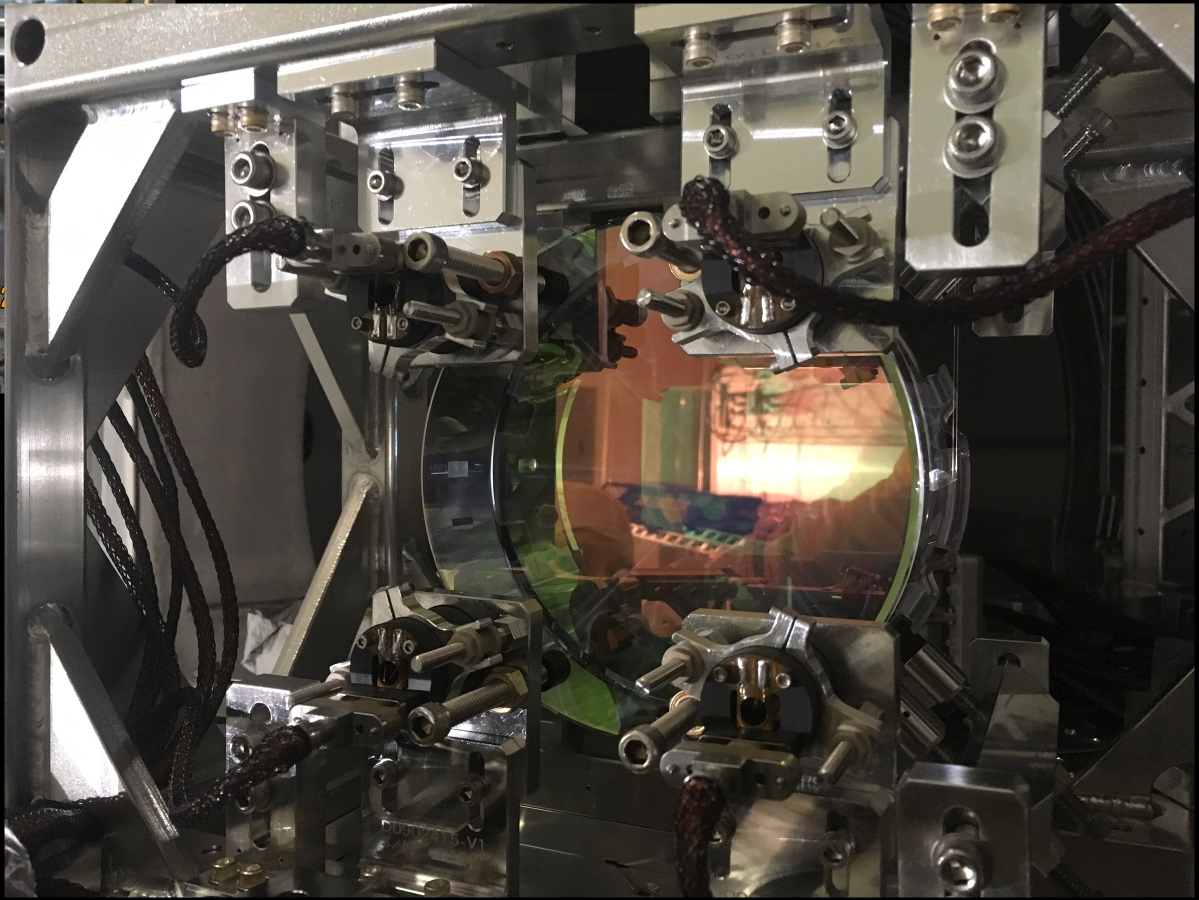


Keep light inside cavities where it belongs!

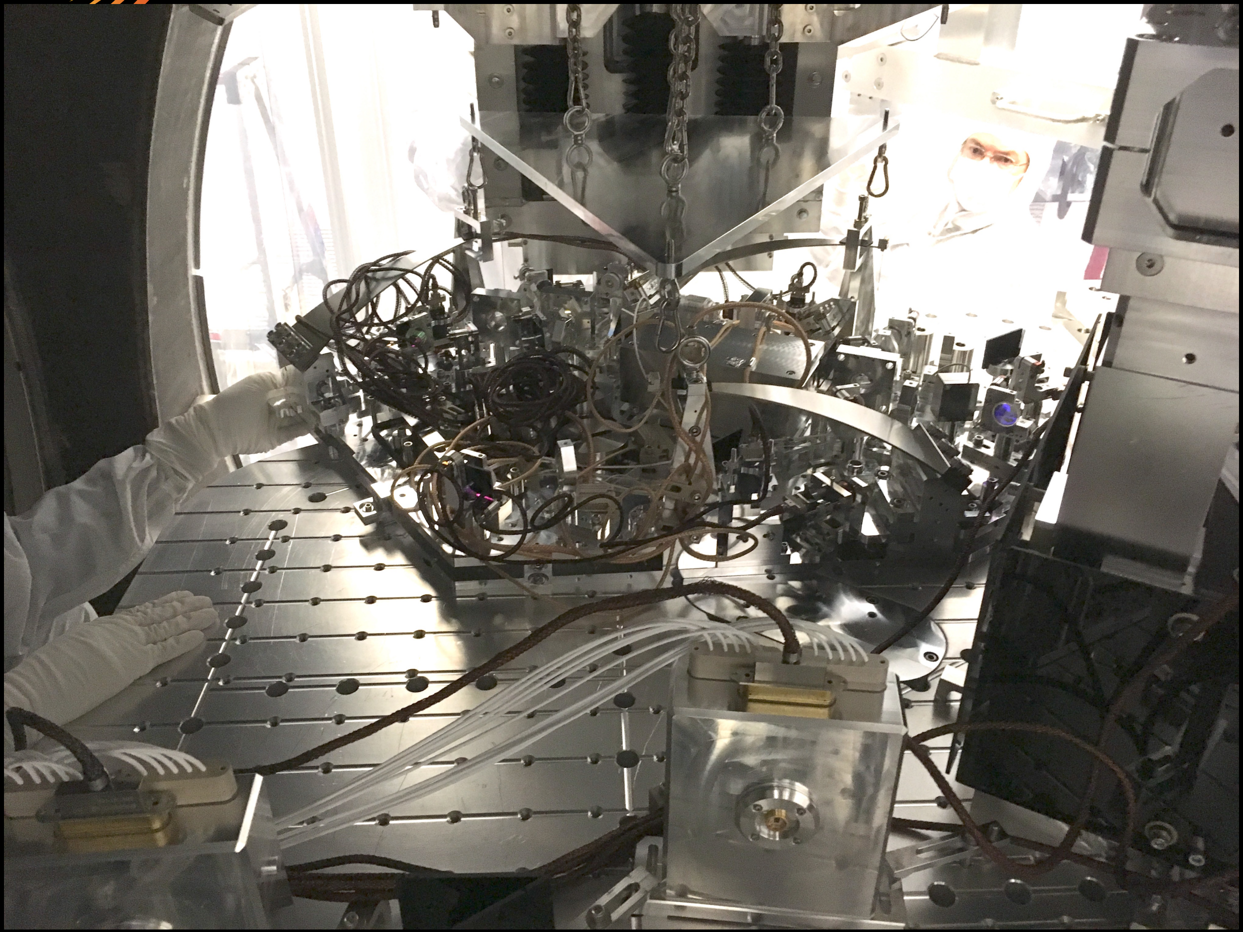
(5) New Signal Recycling Mirror

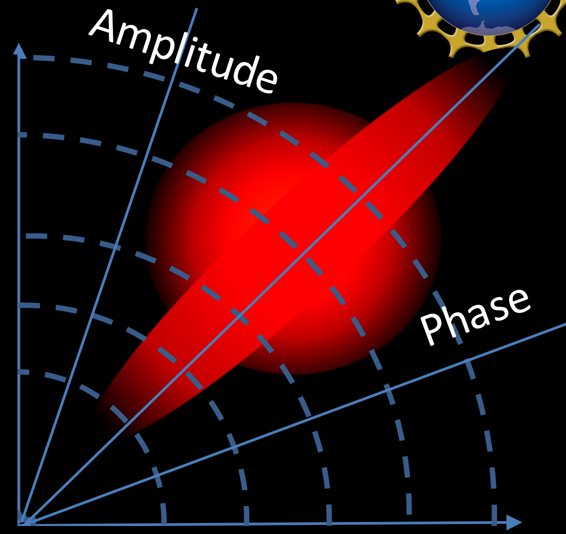
Increase detector bandwidth
Mitigate thermal noise
Improve control noise





(6) Squeezed Light

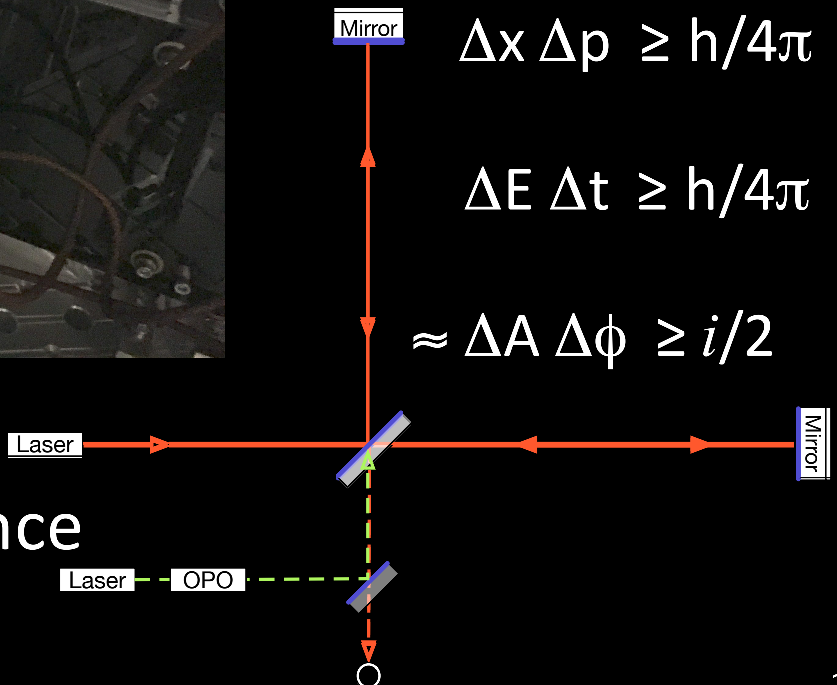




$\Delta x \, \Delta p \geq h/4\pi$

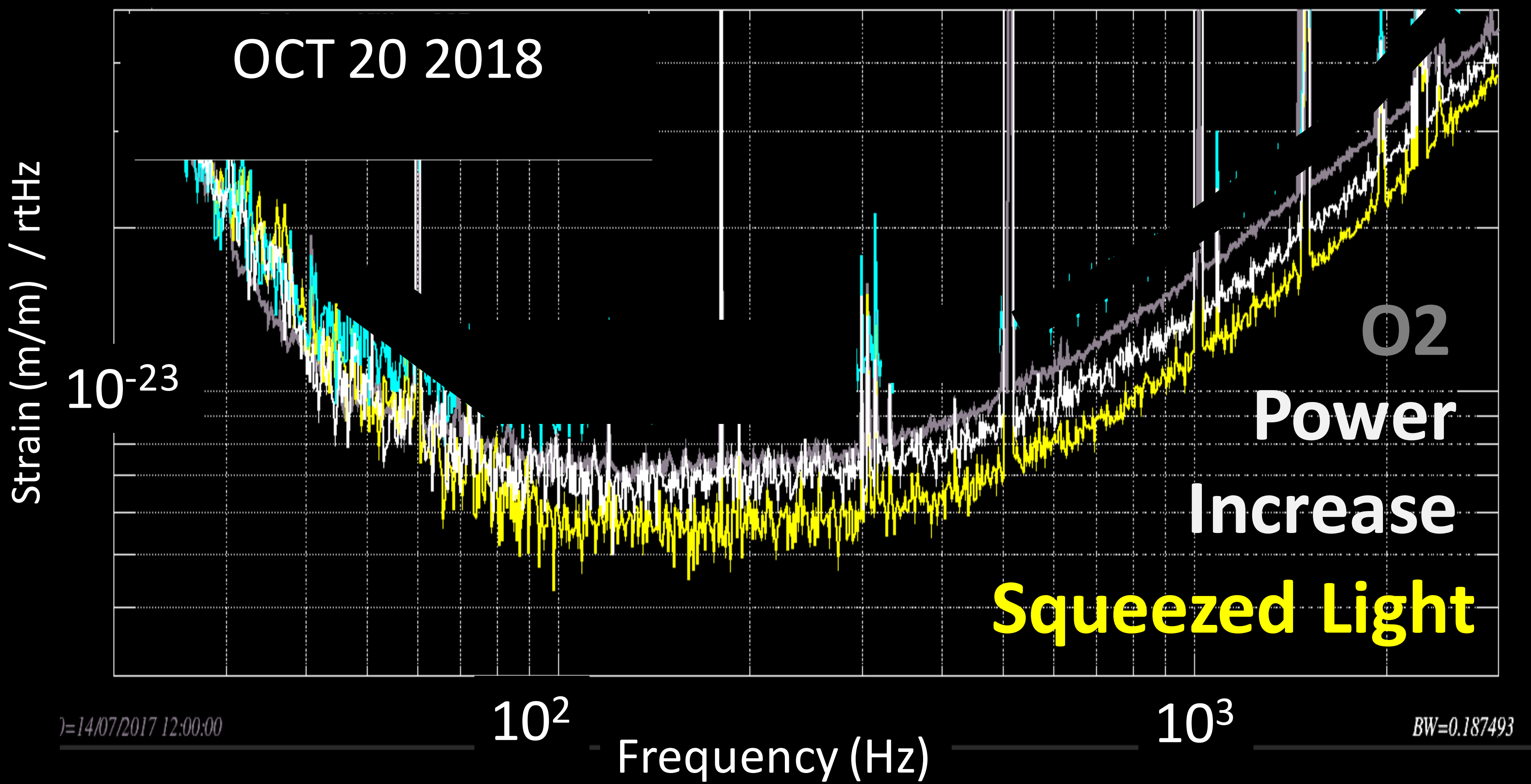
$\Delta E \, \Delta t \geq h/4\pi$

$\approx \Delta A \, \Delta \phi \geq i/2$



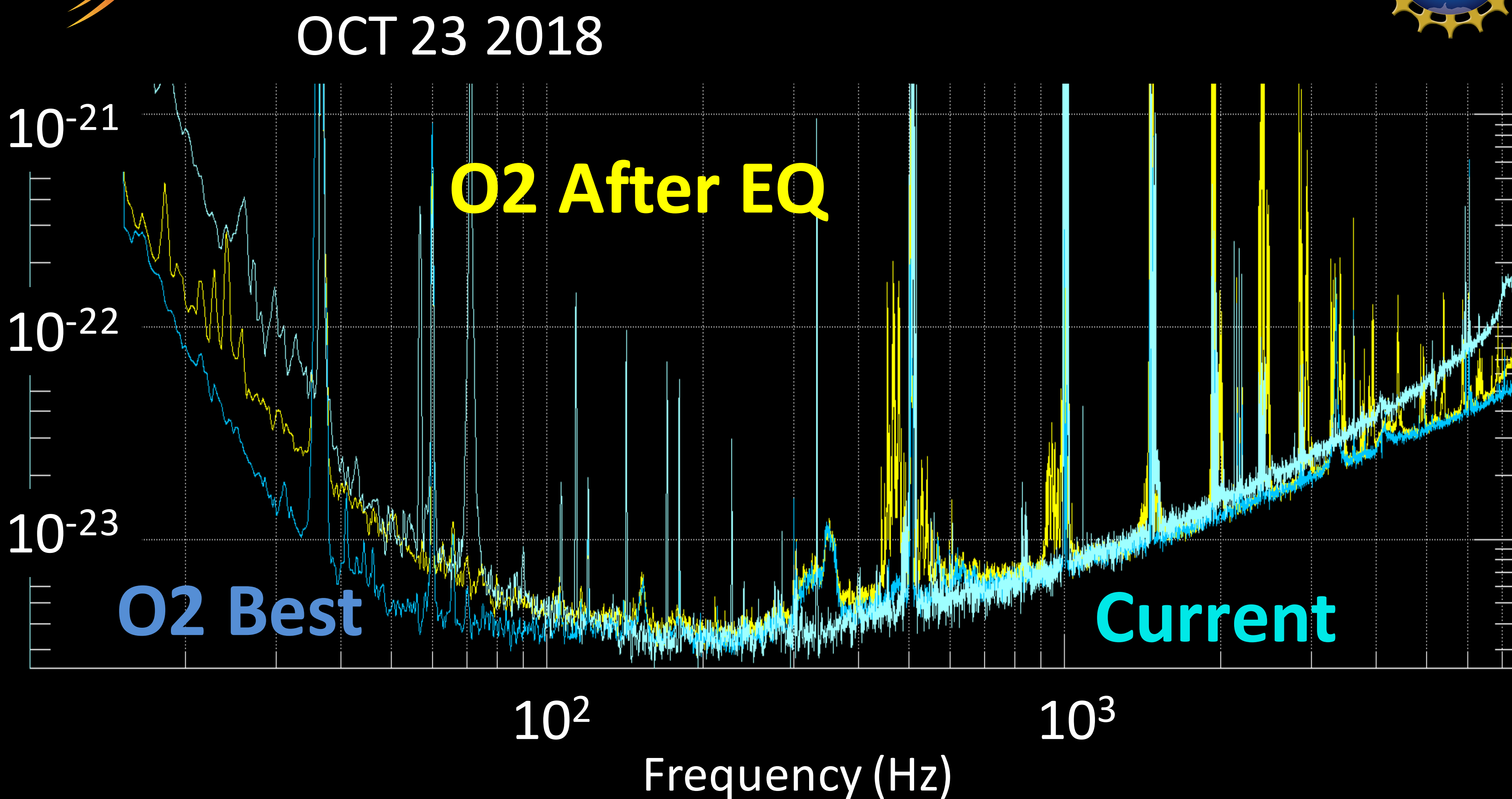
Improved phase resolution >>
Better high-frequency performance

Getting There!



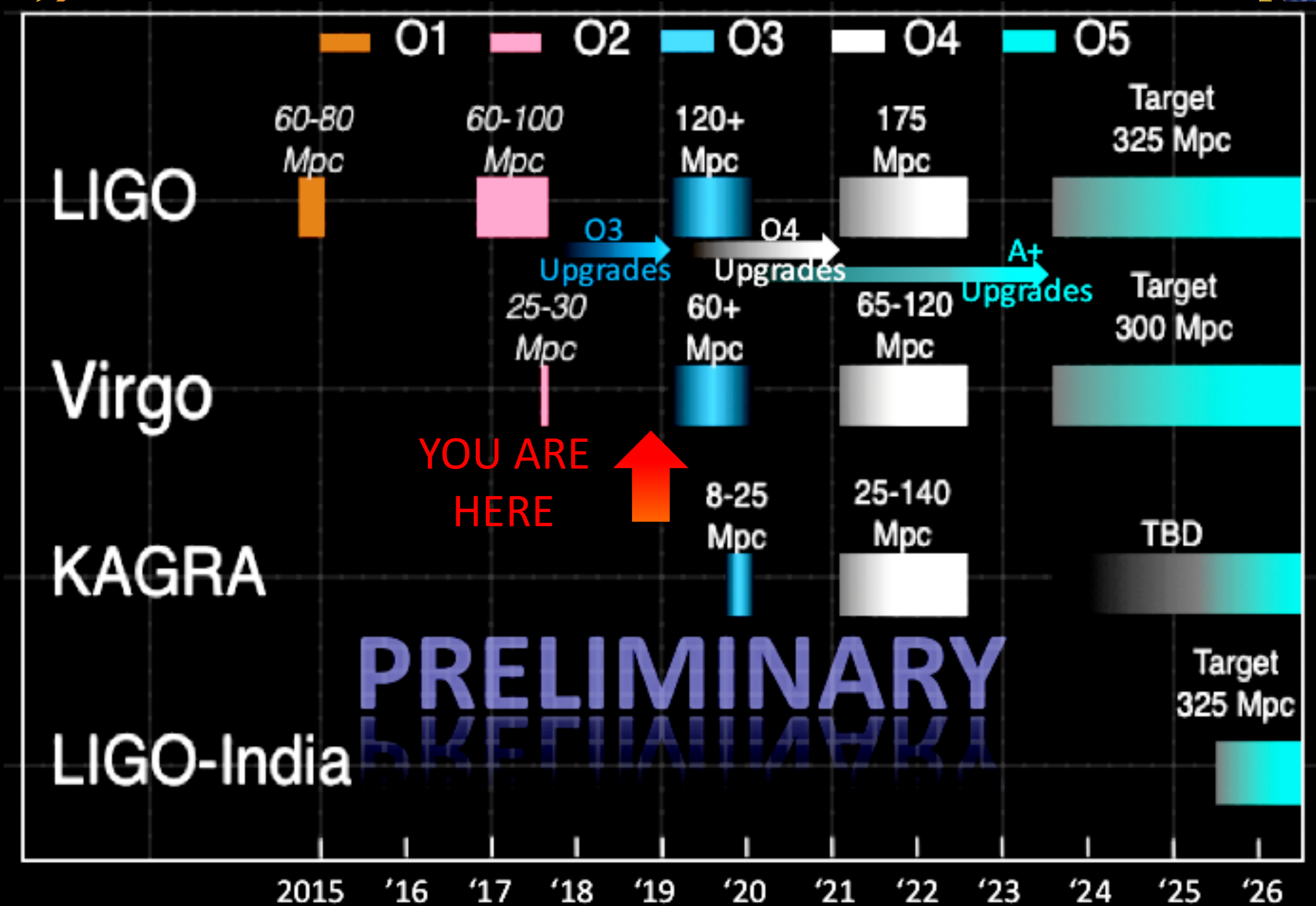
L1 is showing signs of ~115-120 Mpc
this past weekend...

Getting There…



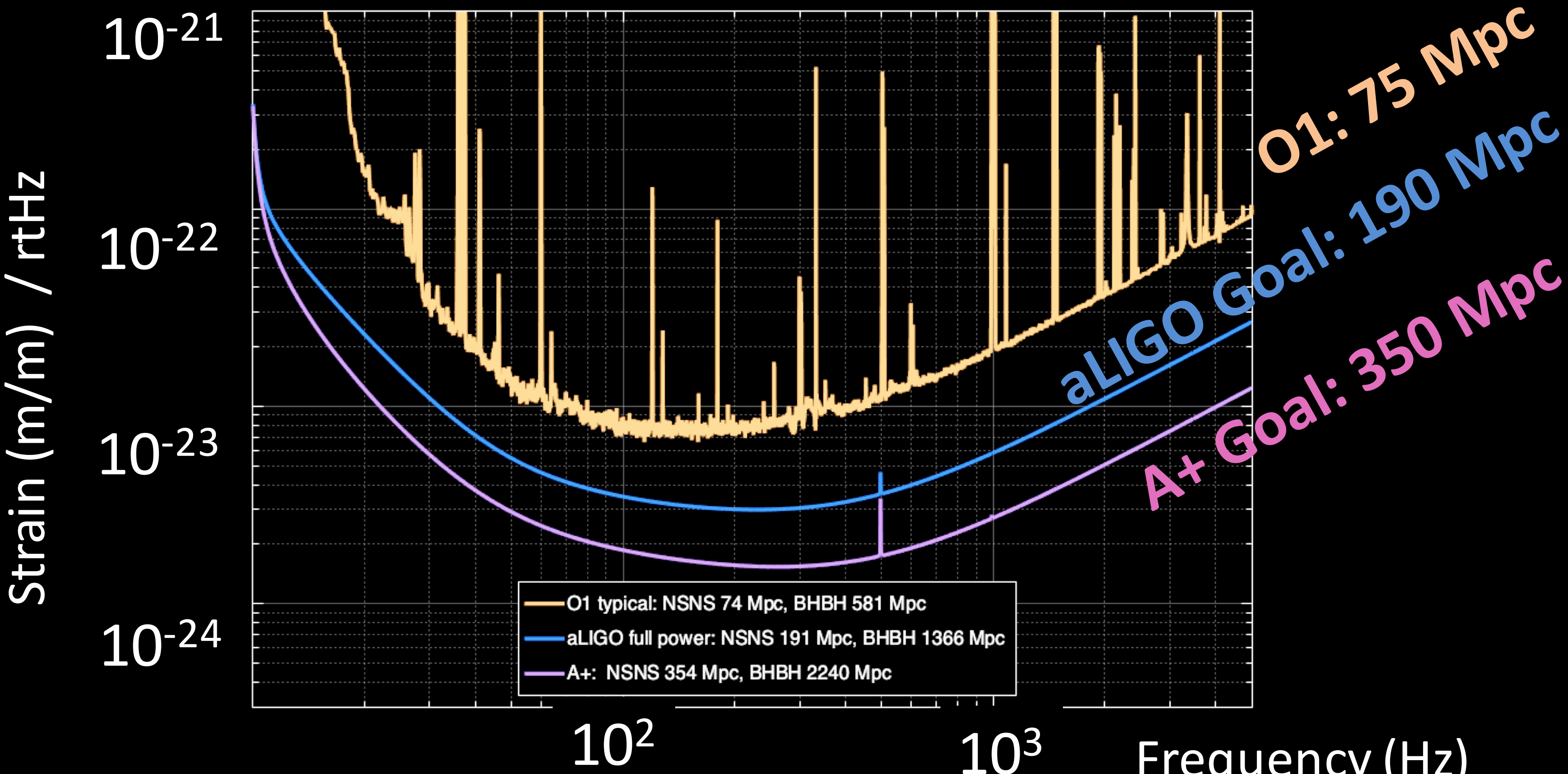
H1 just starting to dig into dirty laundry pile at ~60 Mpc. *Tons* of work ahead.

What's Next -- even further!



“A+”

- Funding awarded and landed Oct 2018
- Fancy squeezing
- Gravitational Wave Readout System Upgrade

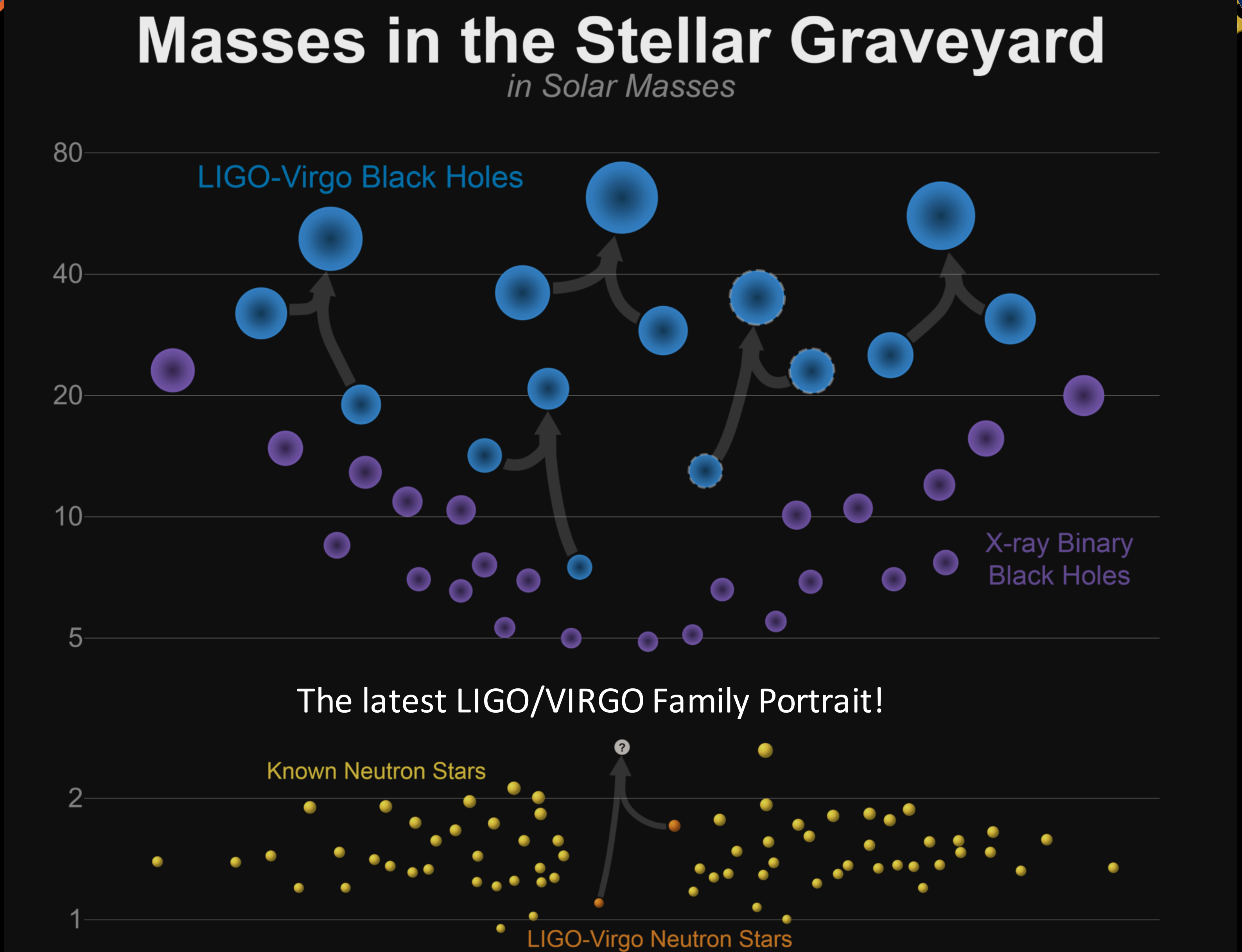


What's Next?

- LIGO Detectors need to improve their noise. STAT!
- VIRGO becomes a constant part of the network in O3
- KAGRA joins the network for the first time in O3
- We're already looking at / building hardware changes beyond O3 – "A+"

Honestly – a LOT of work!

Thank You!



The latest LIGO/VIRGO Family Portrait!

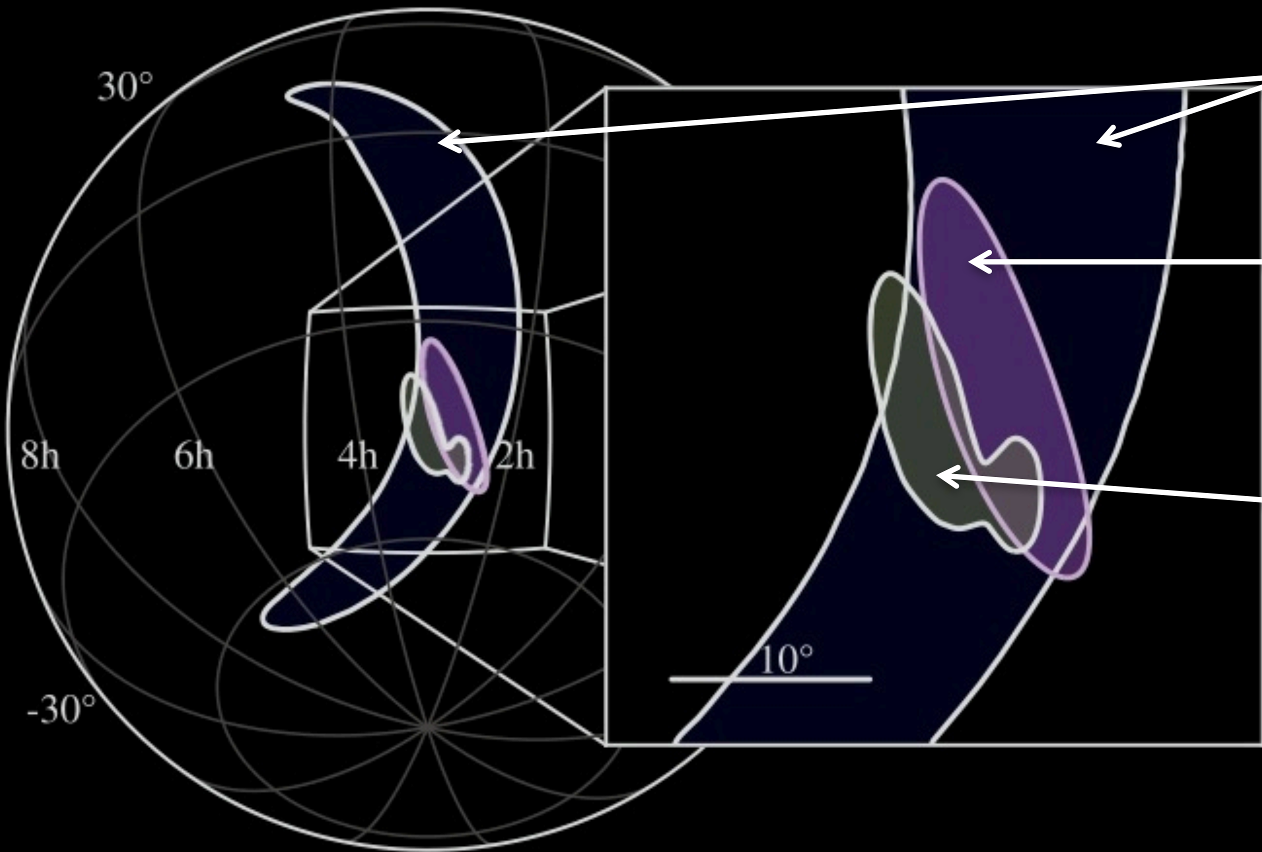
Bonus Material

Why is LIGO/VIRGO Important?

- Observing a brand new population of Binary Black Holes
- We are able to pin-point locations on the sky
- We were able to directly measure the mass, and therefore can confirm mechanism of electromagnetic observations
- We have an independent distance measure to source
- Can turn an un-impressive gamma burst into an off-axis kilonova
- Experimental evidence of what makes a large fraction of precious / rare-earth metals found in the universe
- **A brand new way to look at the bright and dark universe**

Image Credit: Aurore Simonnet

GW170814: Triple Coincidence!

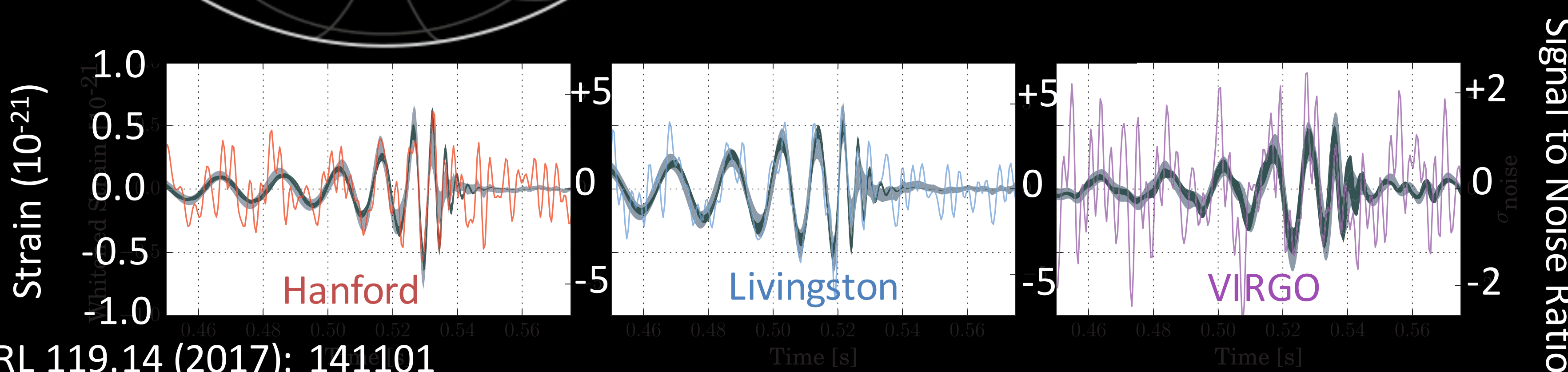


Rapid Response
LIGO Only: 1160 deg^2

Rapid Response
LIGO and VIGO: 90 deg^2

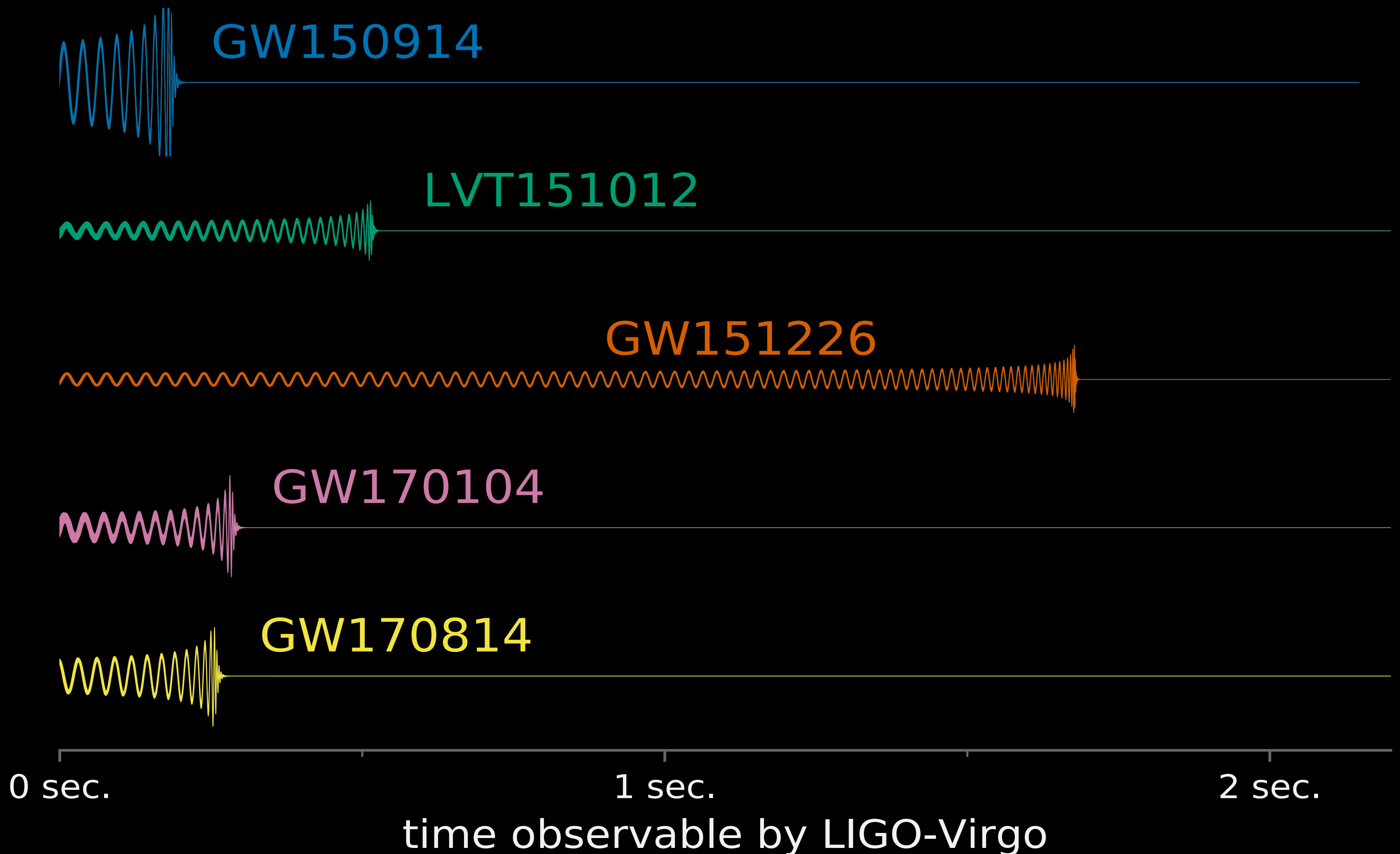
Finalized Location
LIGO and VIGO: 60 deg^2

The Moon and Sun
(from Earth)
0.2 deg^2

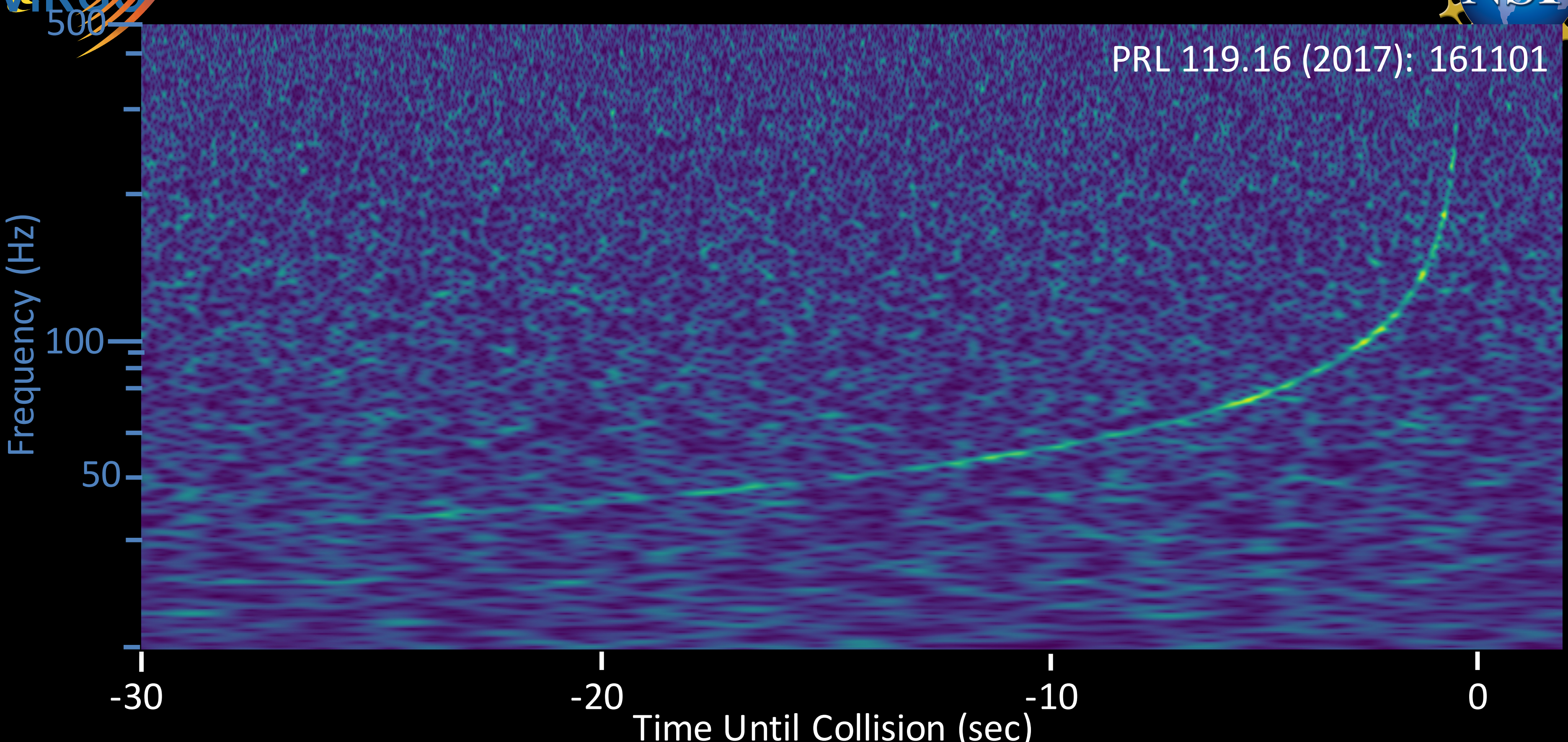


PRL 119.14 (2017): 141101

Oh – One More Thing…



GW170817



Primary: 1.36–1.60 solar masses

Secondary: 1.17–1.36 solar masses

D $= 40^{+8}_{-14}$ Mpc

= 0.13 billion light years

= 4.1 quadrillian light sec

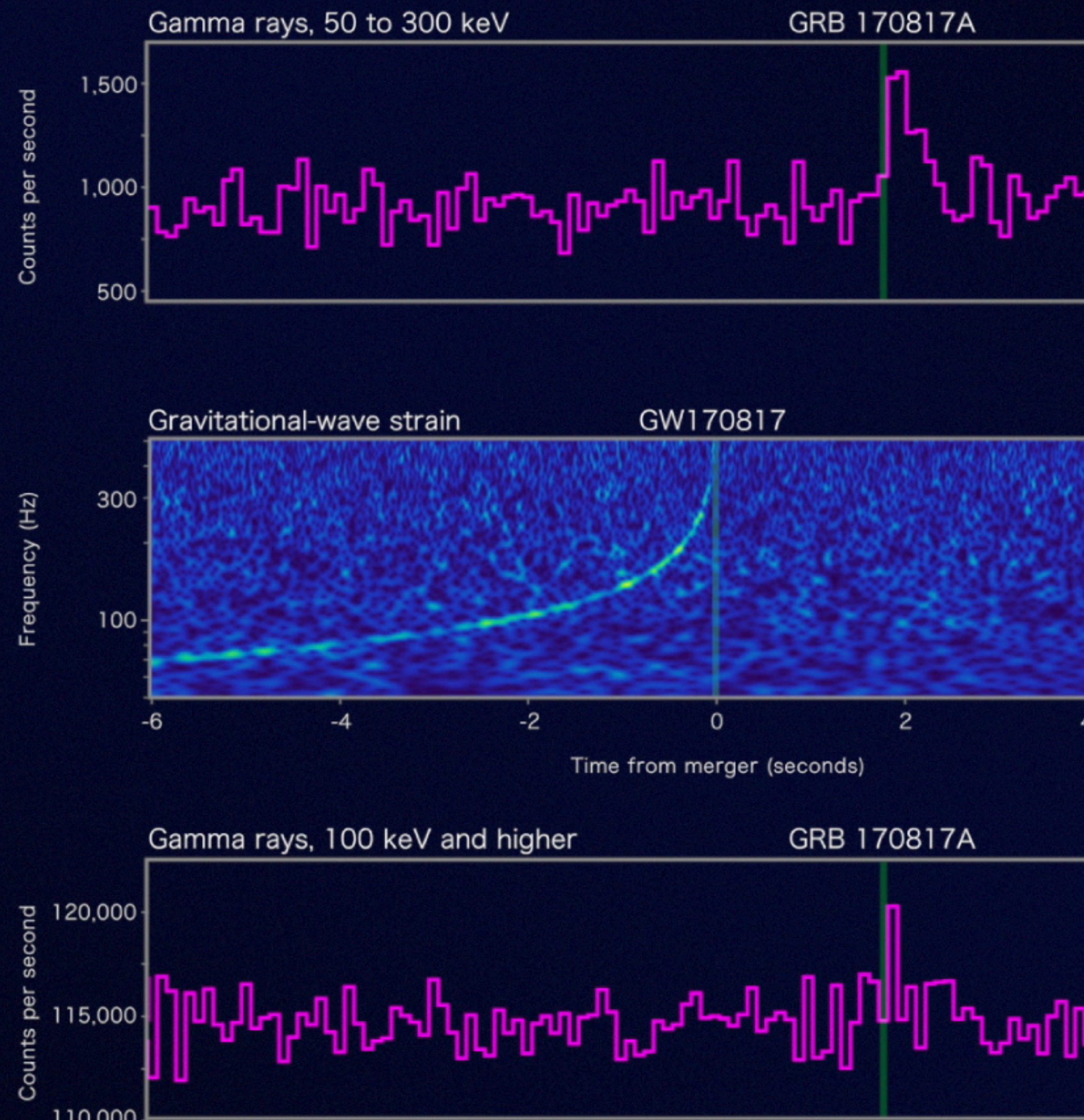
This is a really close, binary *neutron star* collision!

GW170817 and Gamma Ray Bursts

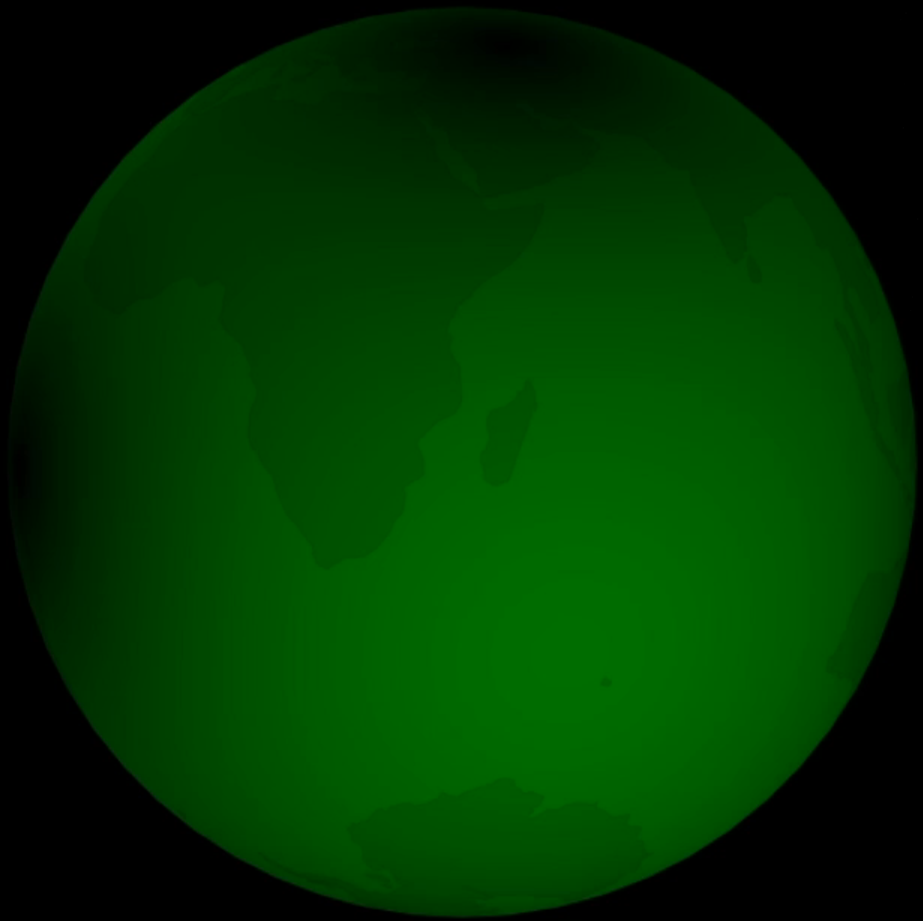
Fermi

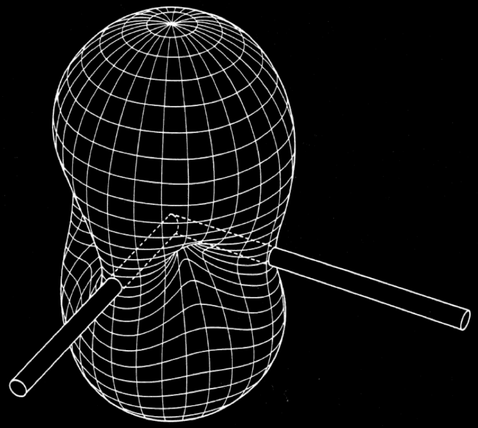
LIGO-Virgo

INTEGRAL

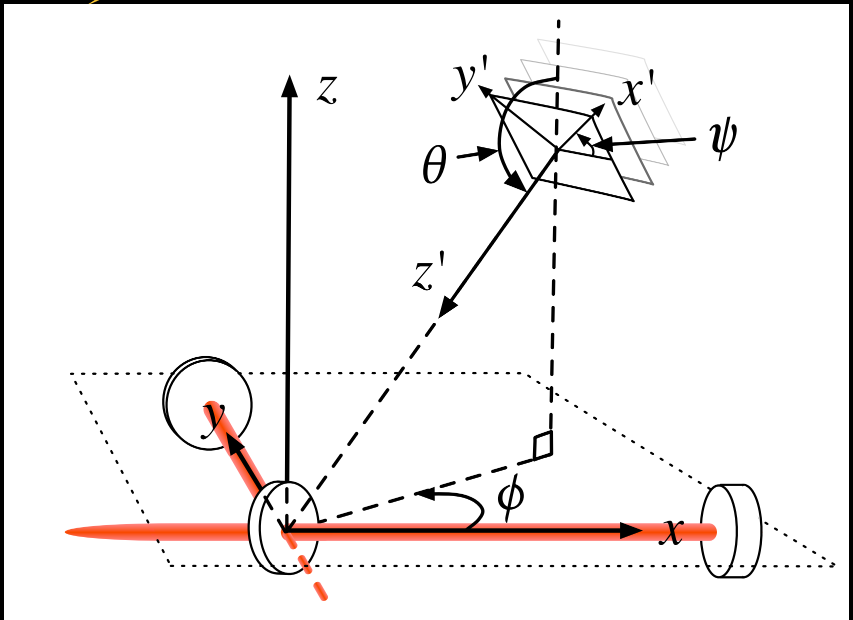


GW170817: Virgo didn't see it? GREAT!

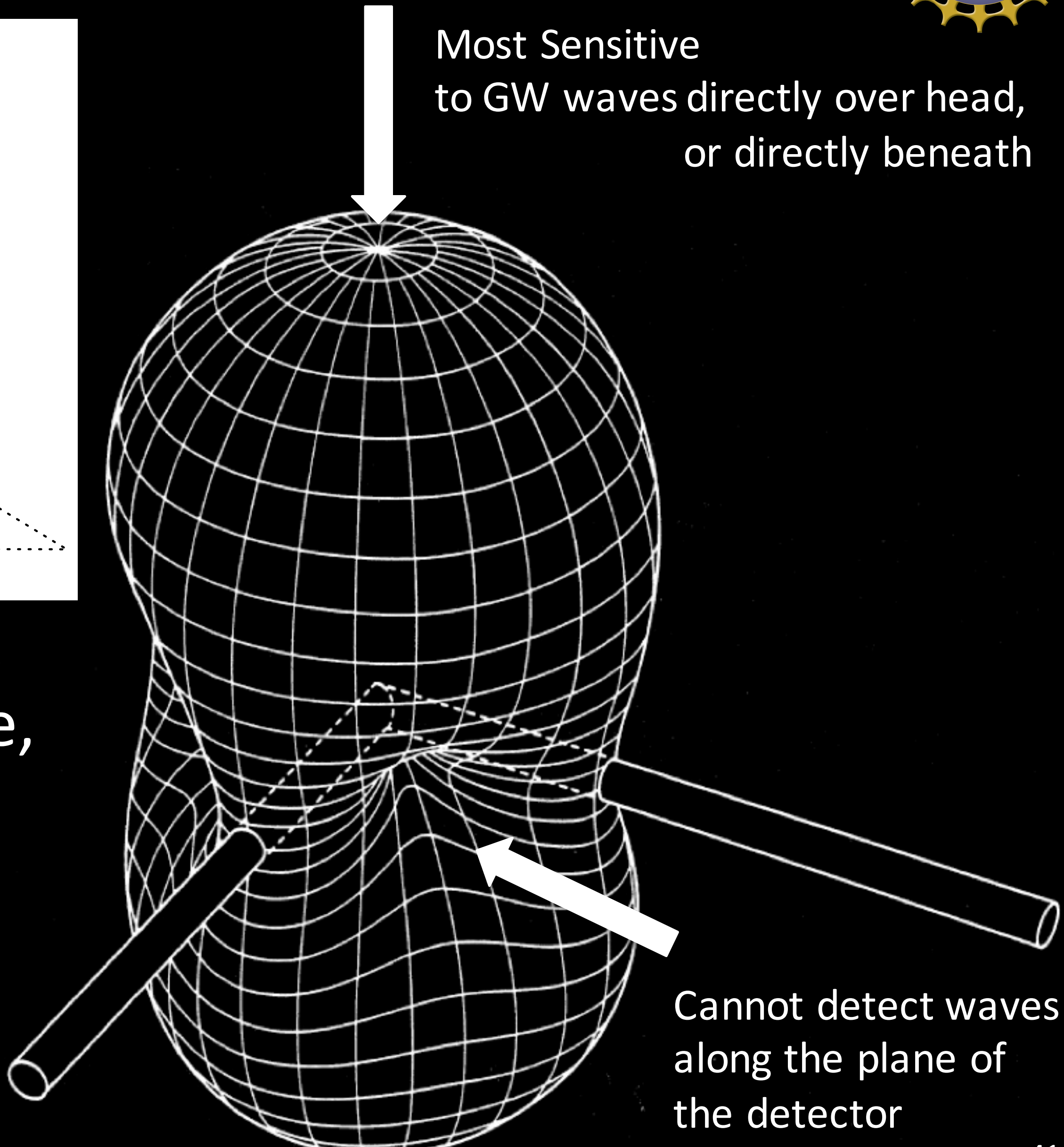




Directional Sensitivity?



Most Sensitive
to GW waves directly over head,
or directly beneath



Cannot detect waves
along the plane of
the detector

Like a single microphone, only one detector, can't tell much about from where a gravitational wave has come

GW170817: Where on the sky?

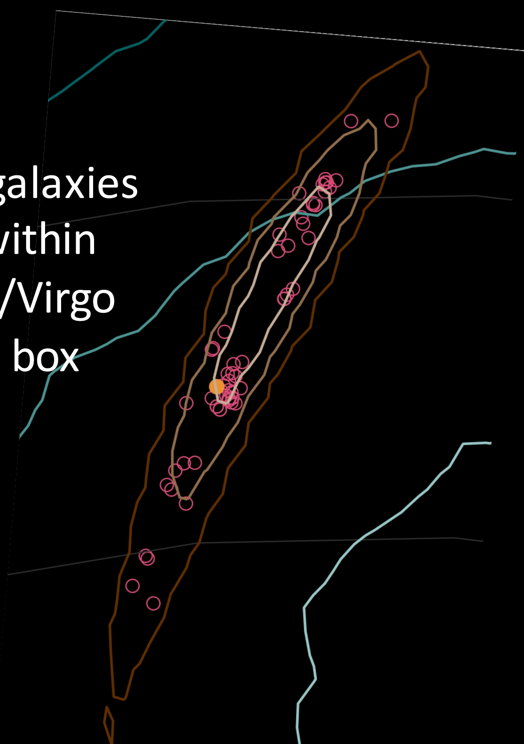
The incredibly small region on the sky

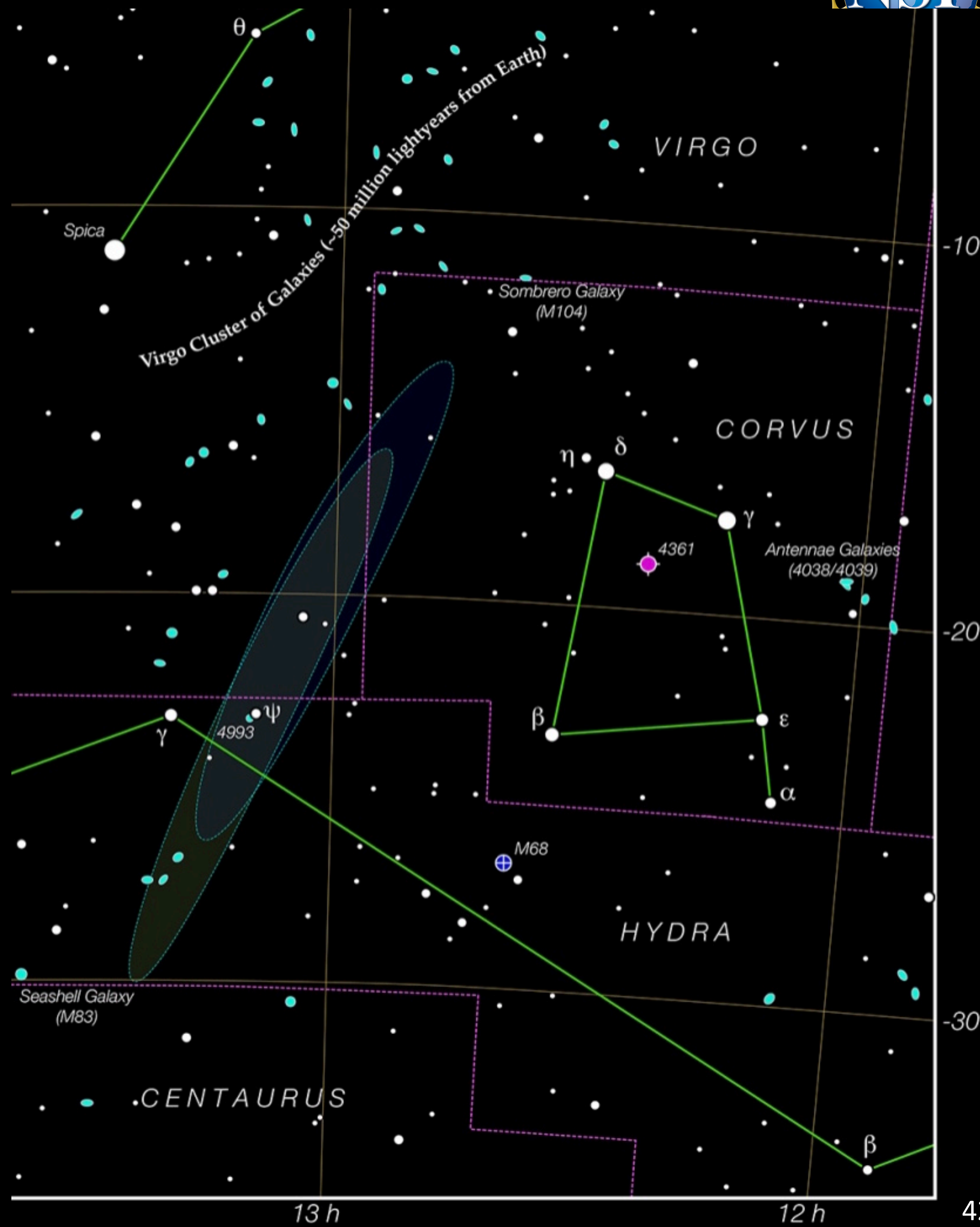
LIGO Only: 190 deg^2

Rapid LIGO & VIRGO: 31 deg^2

Final LIGO & VIRGO: 28 deg^2

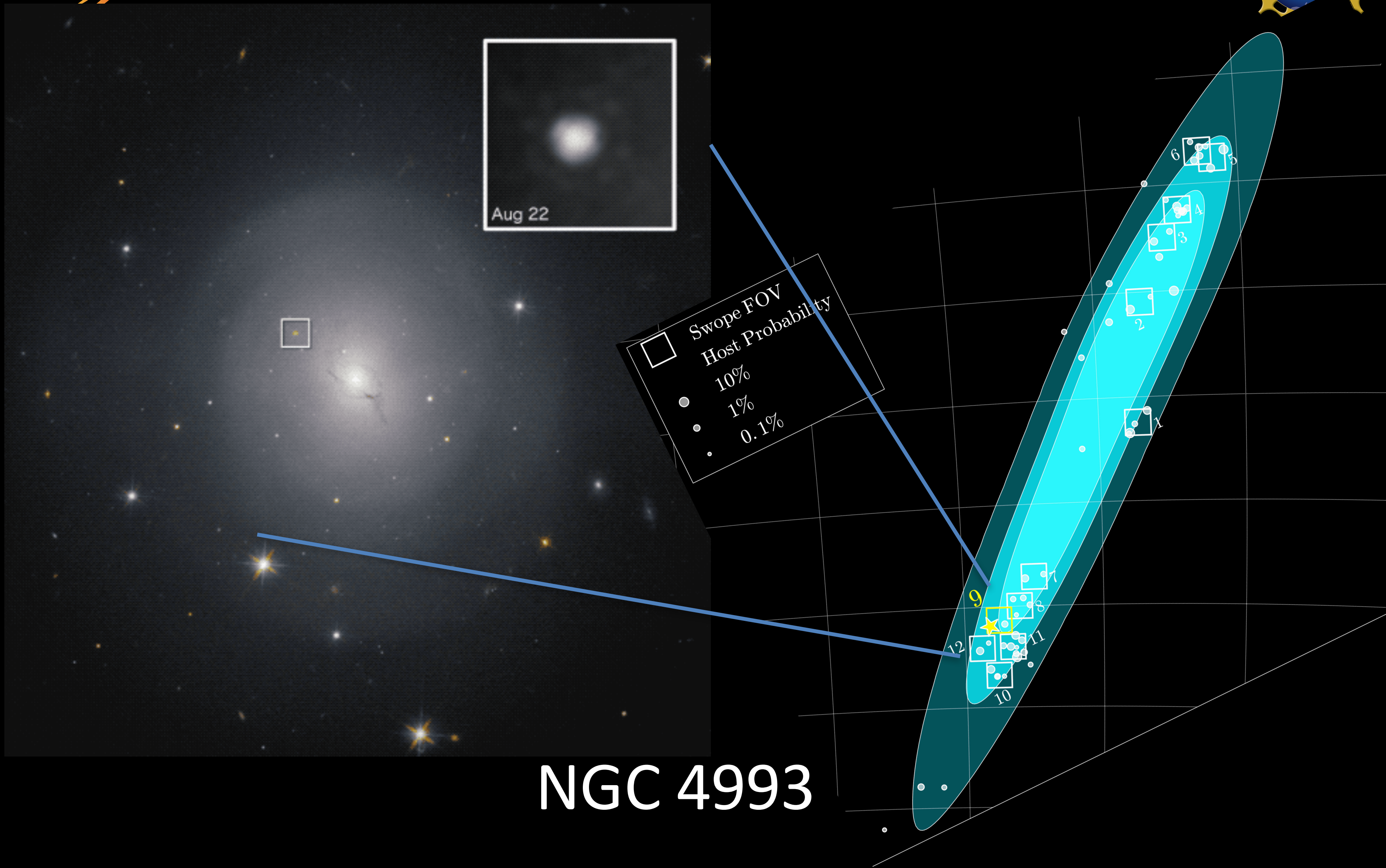
~30 galaxies are within LIGO/Virgo error box





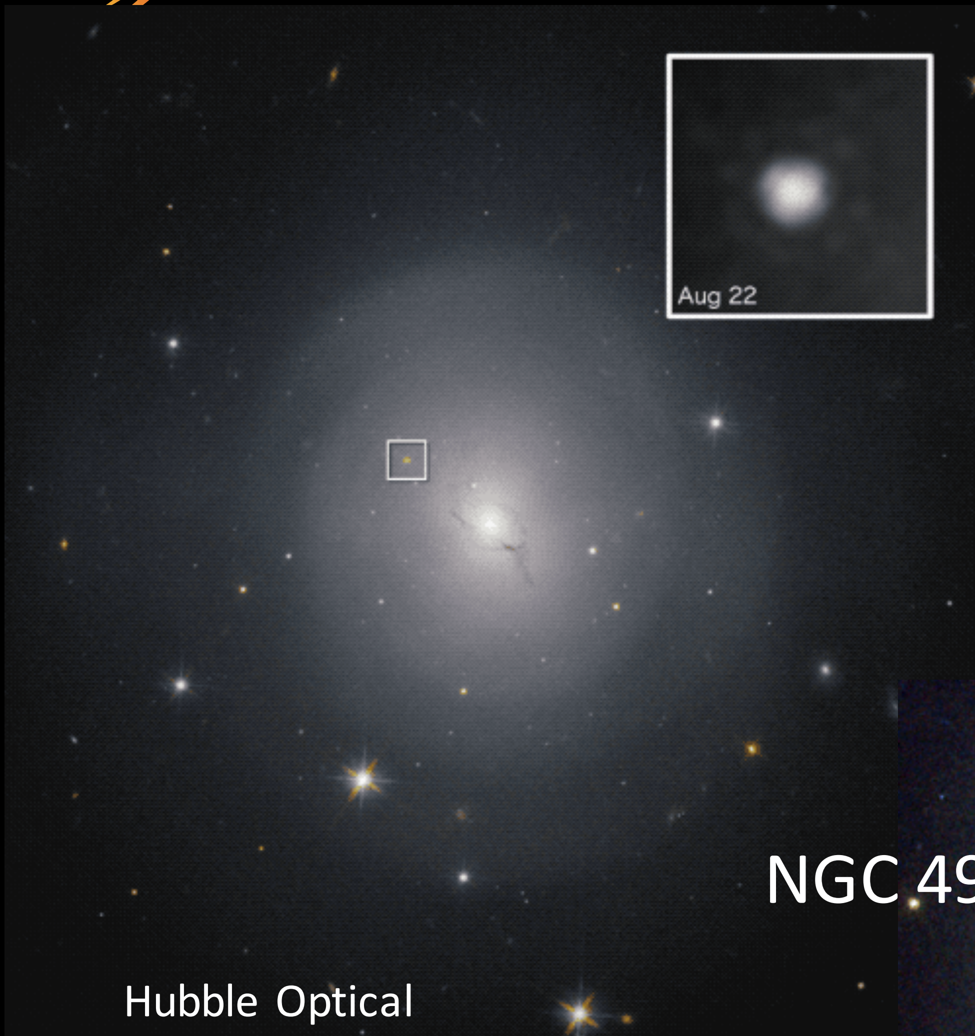
Nature 551.7678 (2017): nature24291

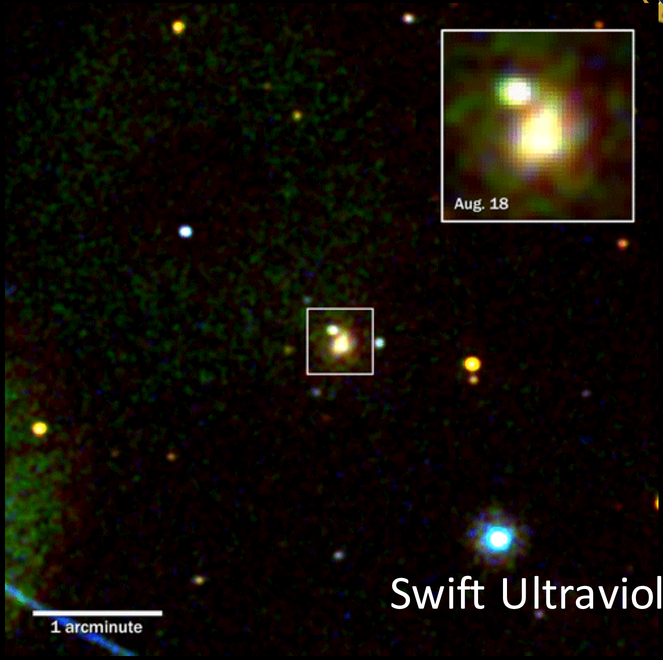
GW170817: Where on the sky?



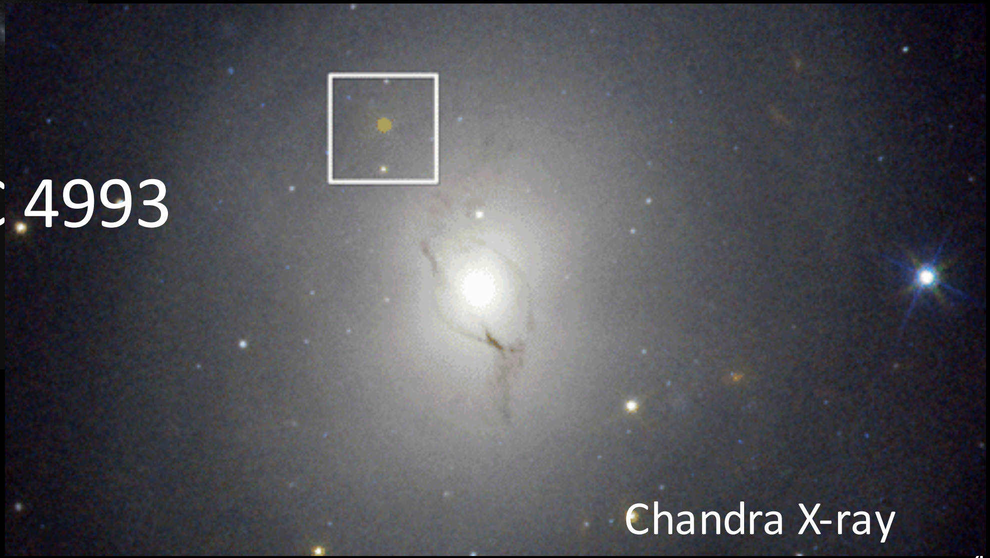
NGC 4993

Found It! And They Saw it Evolve!





NGC 4993

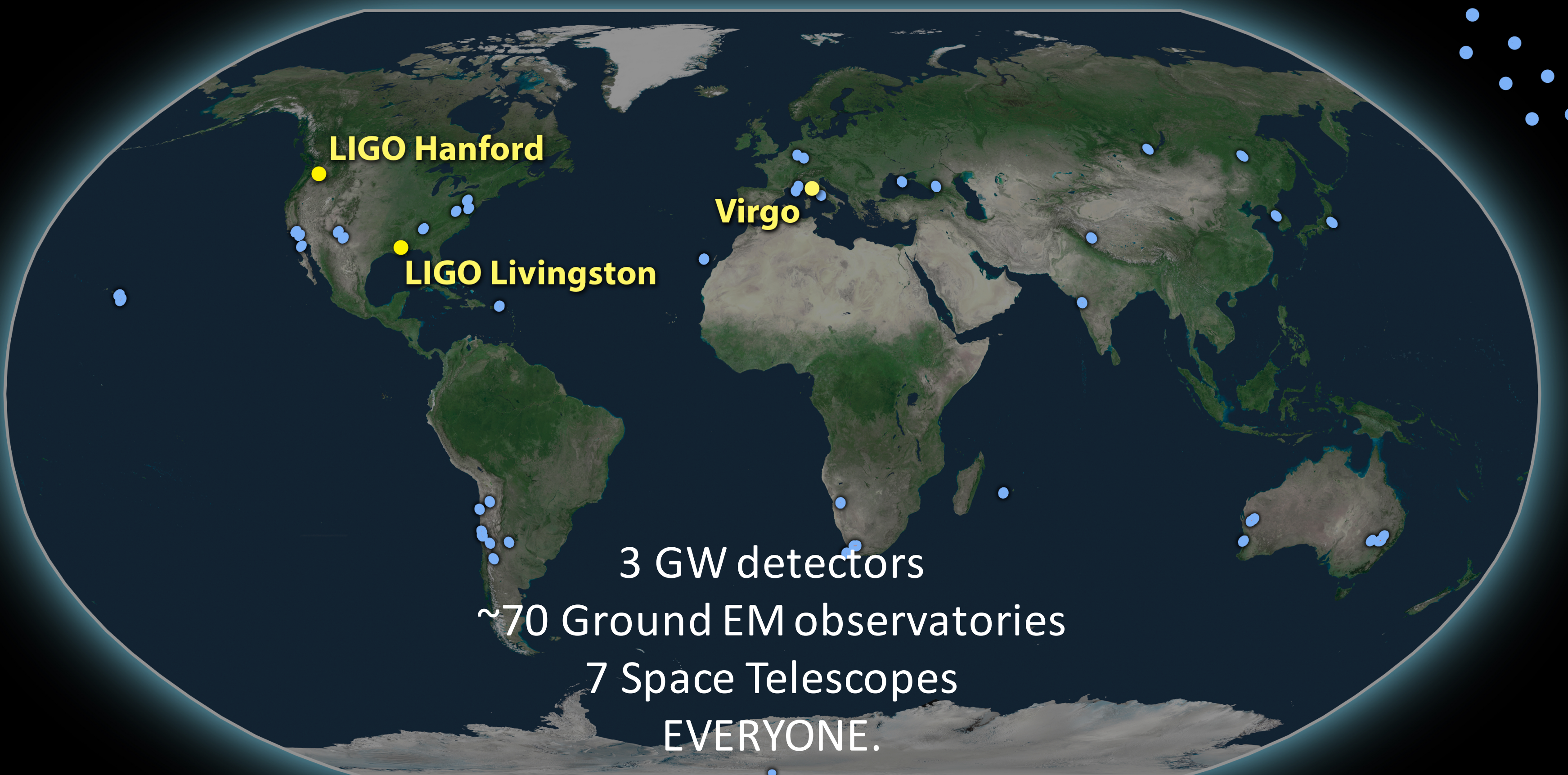


Images courtesy of NASA / ESA

Who saw GW170817?

Earth

Space



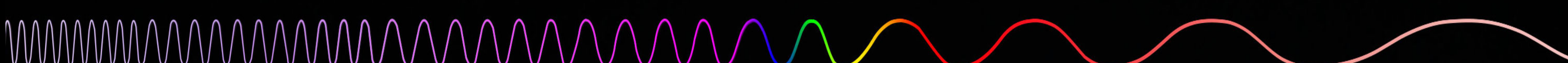
3 GW detectors

~70 Ground EM observatories

7 Space Telescopes

EVERYONE.

The *entire* electromagnetic spectrum!

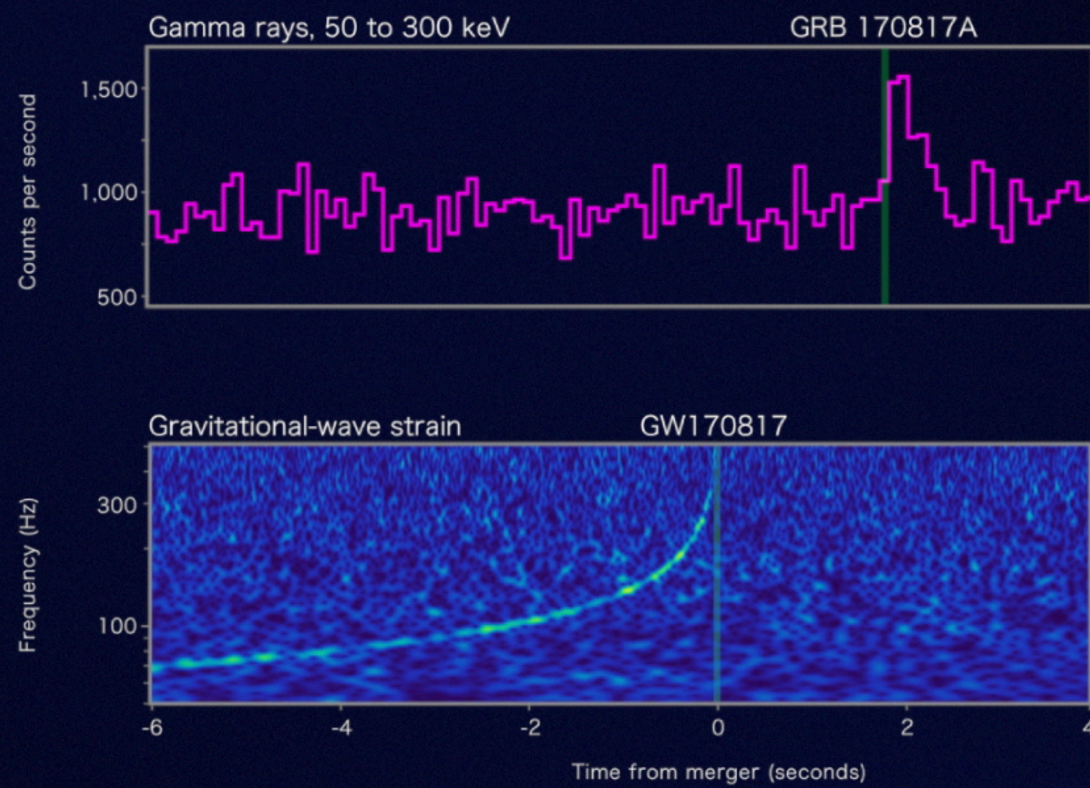


GW170817 and Gamma Ray Bursts

$D = 40^{+8}_{-14}$ Mpc
= 0.13 billion light years
= 0.76 sextillion miles
= 1.2 septillion meters

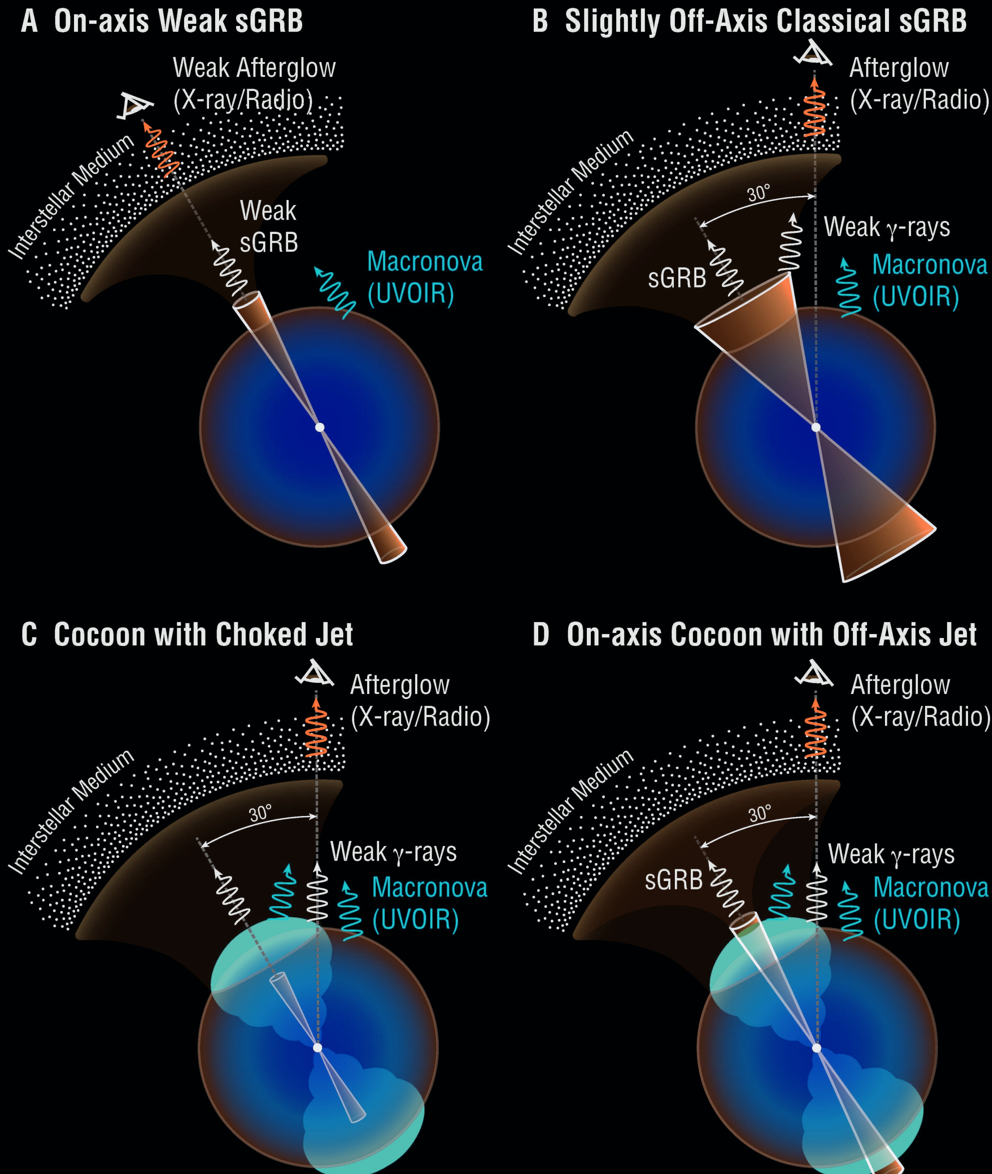
$t_{light} - t_{GW} = \Delta t = 2$ sec

$v = D / t$
c = speed of light



$$\frac{c - v_{GW}}{c} = c\,\frac{\Delta t}{D} = 5\,e\,\text{-}16$$

So What Is It?



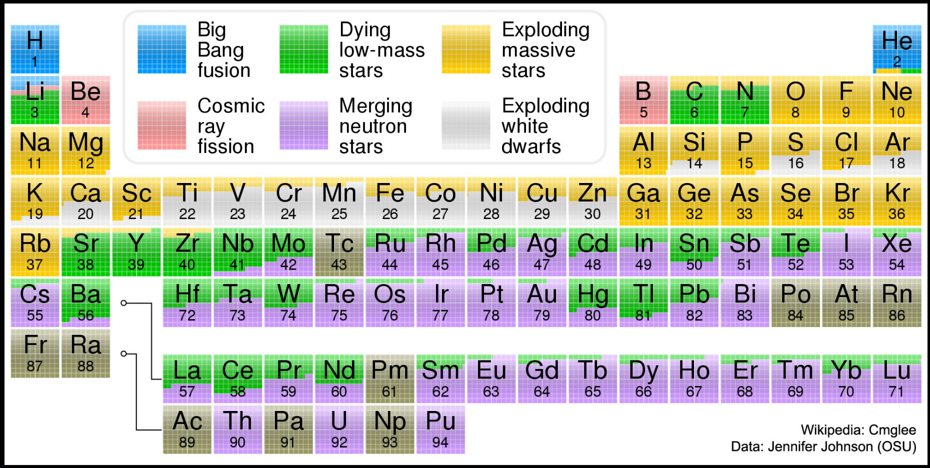
Kasliwal, M. M., et al. Science (2017): eaap9455

Not a nova,

Not a supernova,

but a **KILONOVA**:

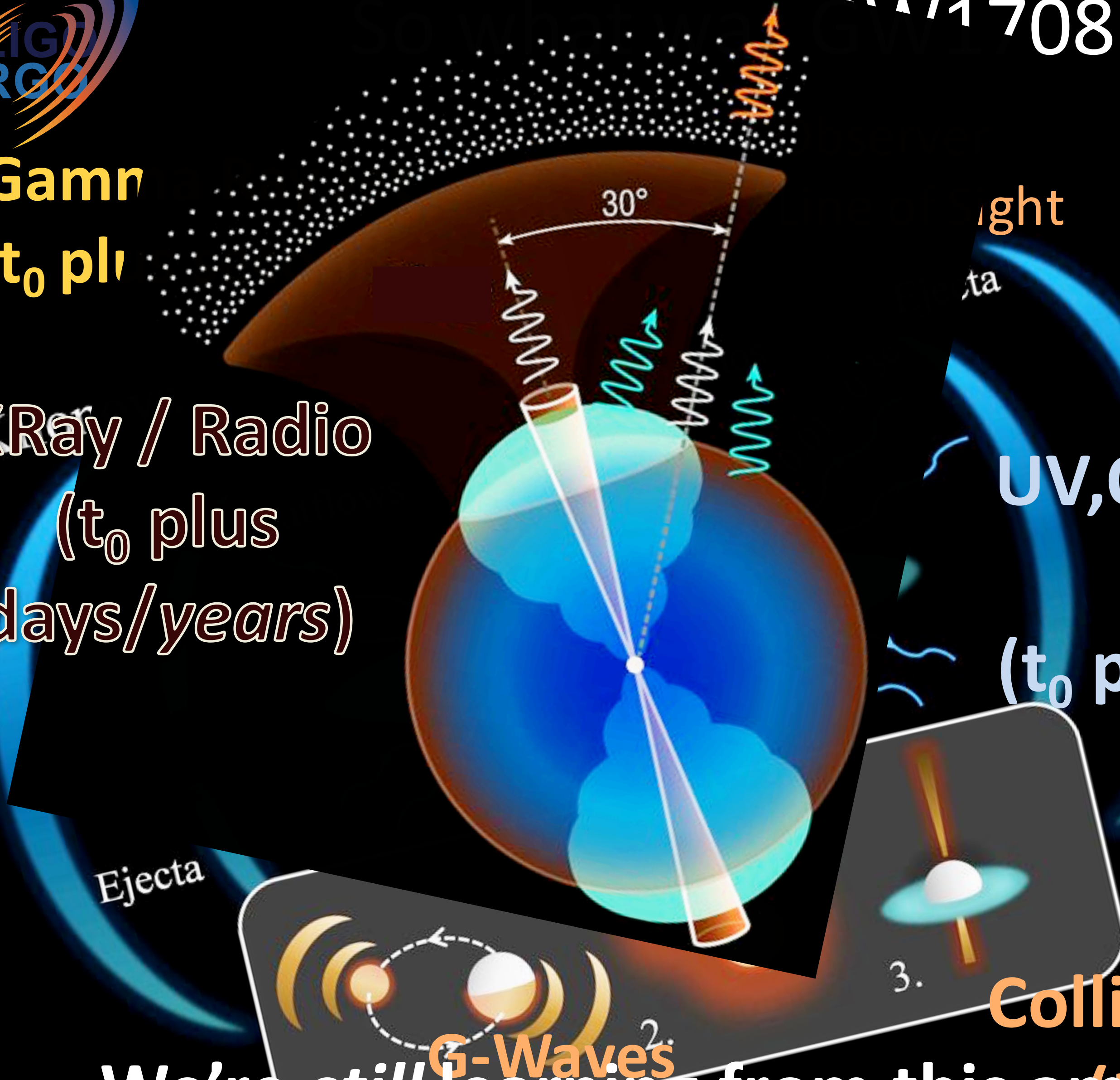
n. /ˈkiːləʊːnəʊvə/ A collision of neutron stars, which emit a jet of gamma rays, that explode into the surrounding stellar media



Credit:Jennifer Johnson/SDSS

They produce most of the heavy / precious metals!

Not a nova,
Not a supernova,
but a **KILONOVA:**



XRay / Radio
(t_0 plus days/*years*)

UV,Optical, Infrared Radiation
(t_0 plus hours/days)

Collision!
(t_0)

G-Waves
(t_0 minus minutes)

We're *still* learning from this amazing event

Kasliwal, M. M., et al. *Science* (2017): eaap9455

Yi, Tuan et. al *MNRAS* 476.1 (2018): 683-689