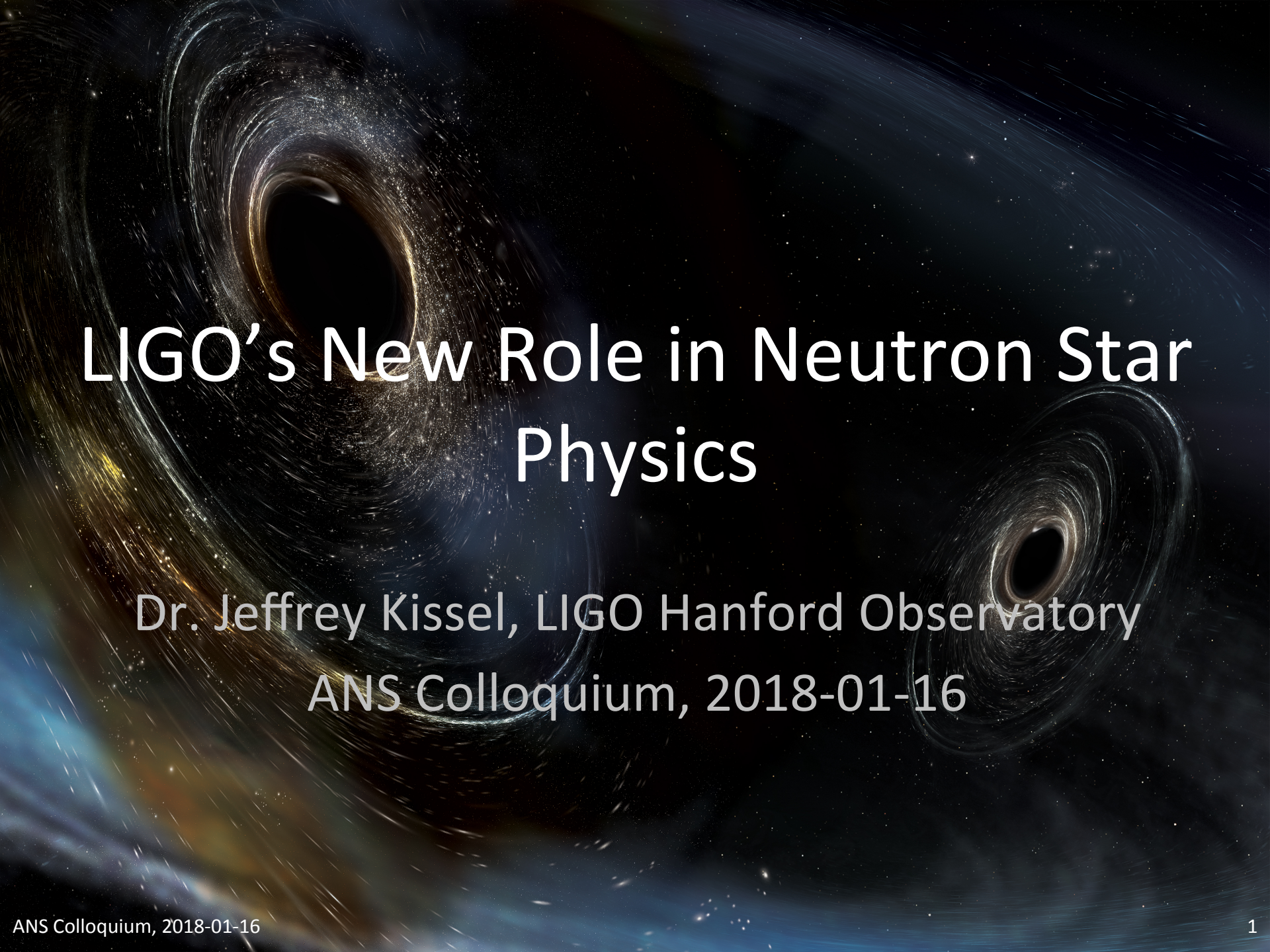
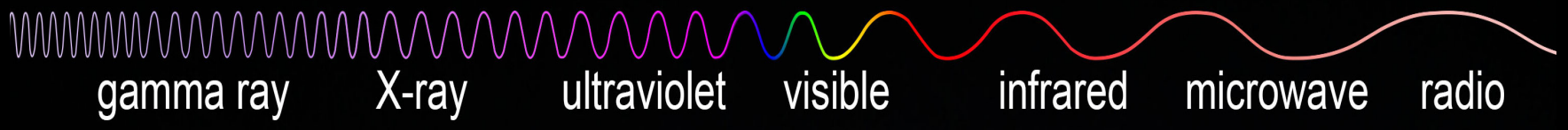


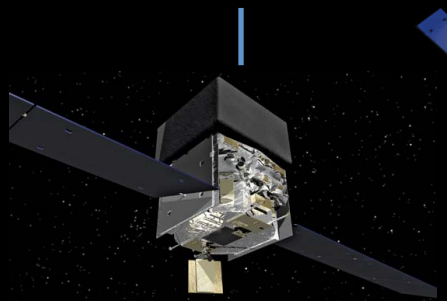
LIGO's New Role in Neutron Star Physics

Dr. Jeffrey Kissel, LIGO Hanford Observatory

ANS Colloquium, 2018-01-16

New Telescope – New Astronomy





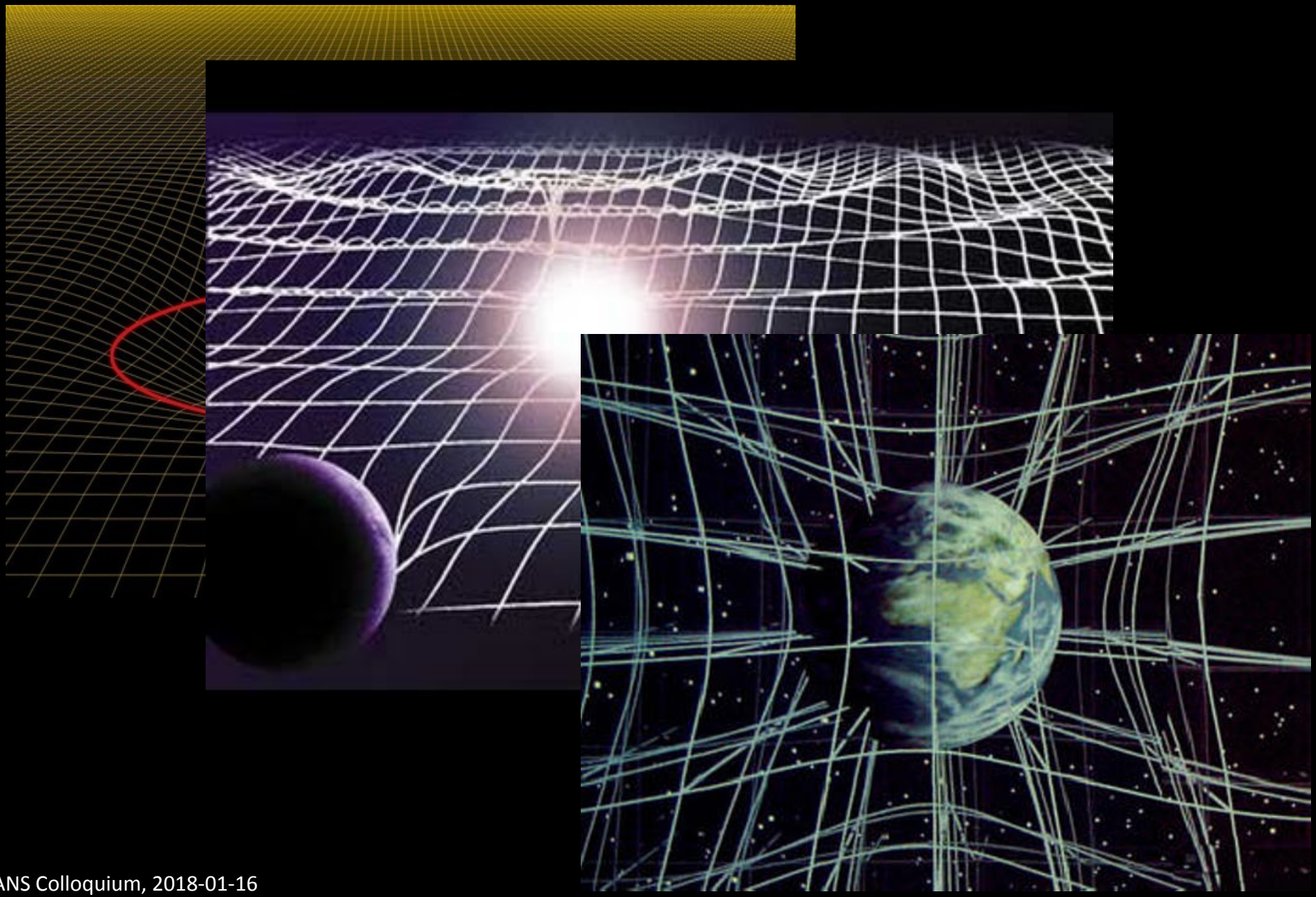
$$Mc^2 = E$$ ← Energy

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

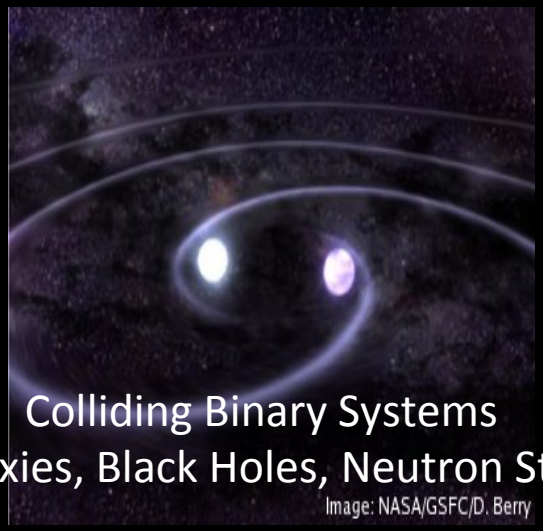
Gravitational Wave Periods

Milliseconds | **Minutes to Hours** | **Years to Decades** | **Billions of Years**

Gravitational Waves



What Produces Detectable Gravitational Waves?

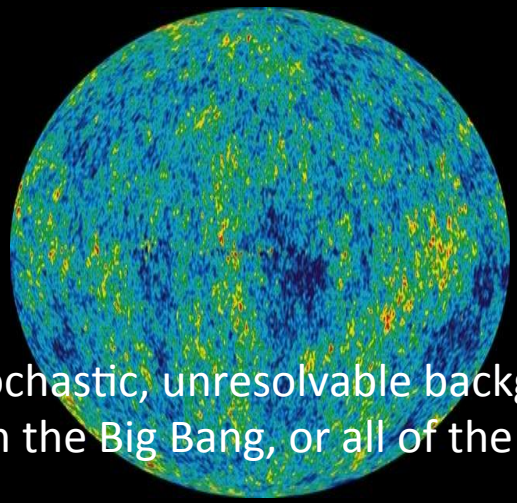


Colliding Binary Systems
(Galaxies, Black Holes, Neutron Stars)

Rapidly Rotating Neutron Stars
(with lumps on them)

Anything with a time-dependent mass quadrupole!

Asymmetric Core Collapse Supernovae
Other poorly modeled explosions



A stochastic, unresolvable background
from the Big Bang, or all of the above

Colliding Black Holes!

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

Einstein's Messengers

Tim Dietrich / AEI / BAM Collaboration
https://youtu.be/xfj-8WnORhg

When space-time is wrenched, three-dimensional waves are sent into the universe in all directions!

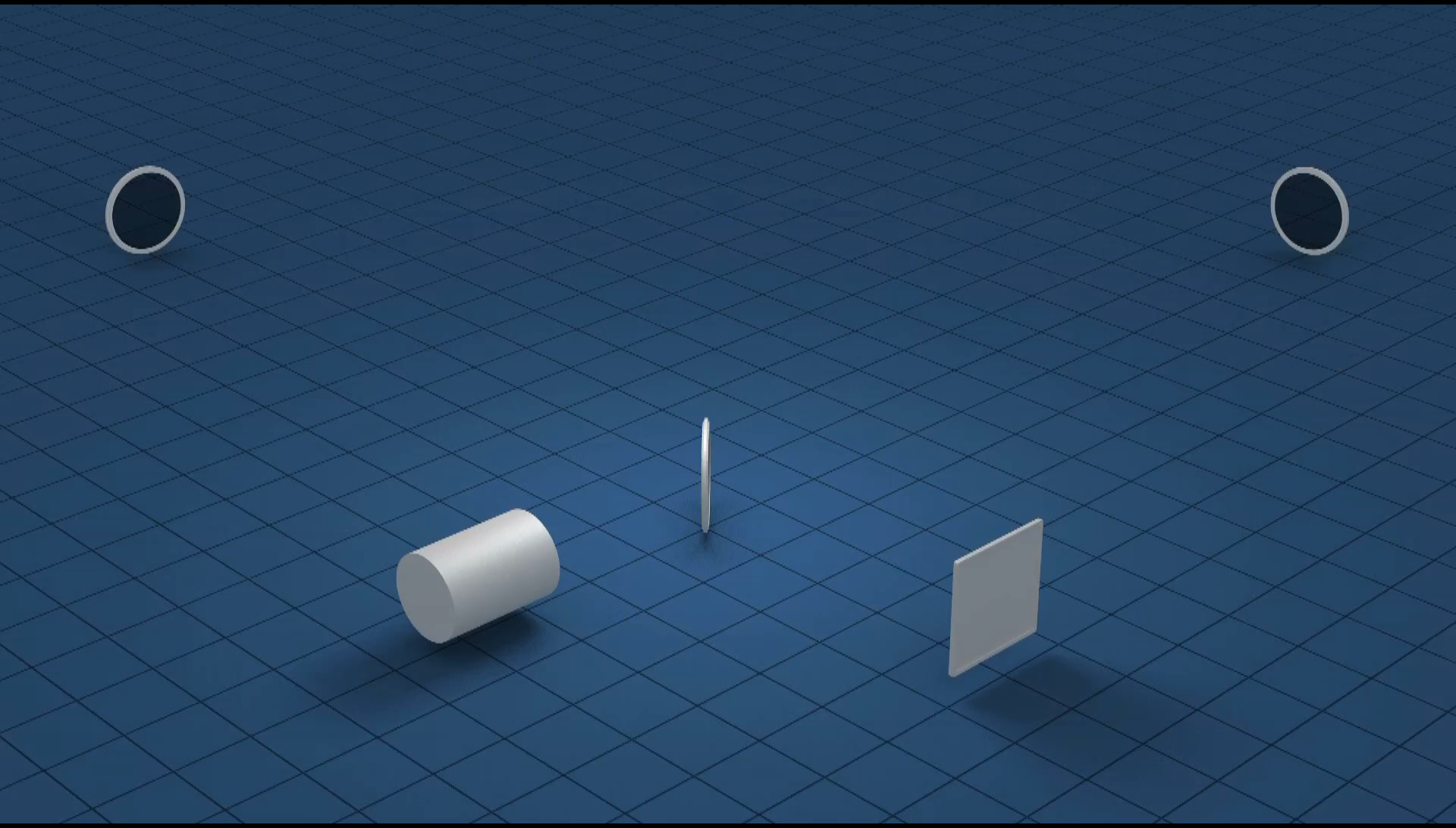
New Telescope – New Astronomy

Milliseconds

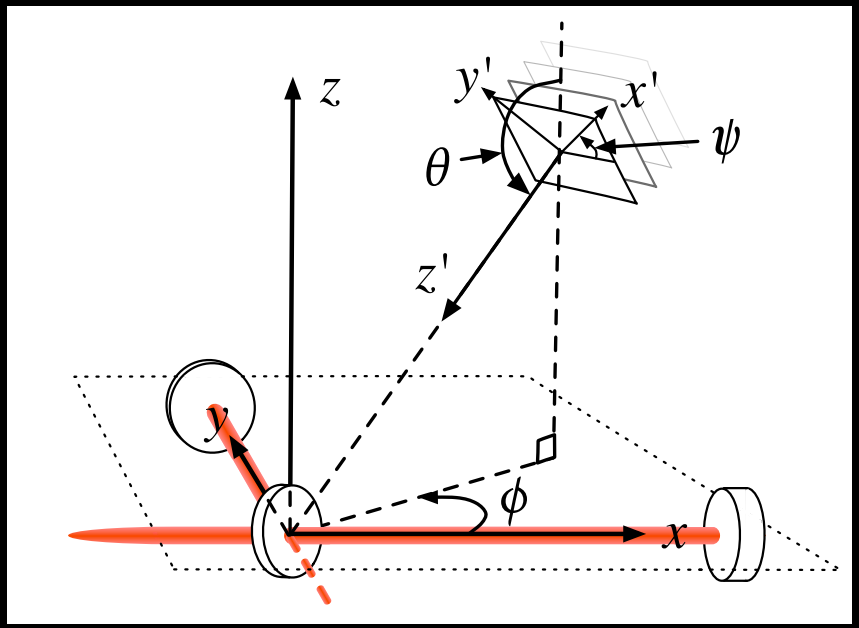
L I G O

Laser **I**nterferometer
Gravitational wave **O**bservatory

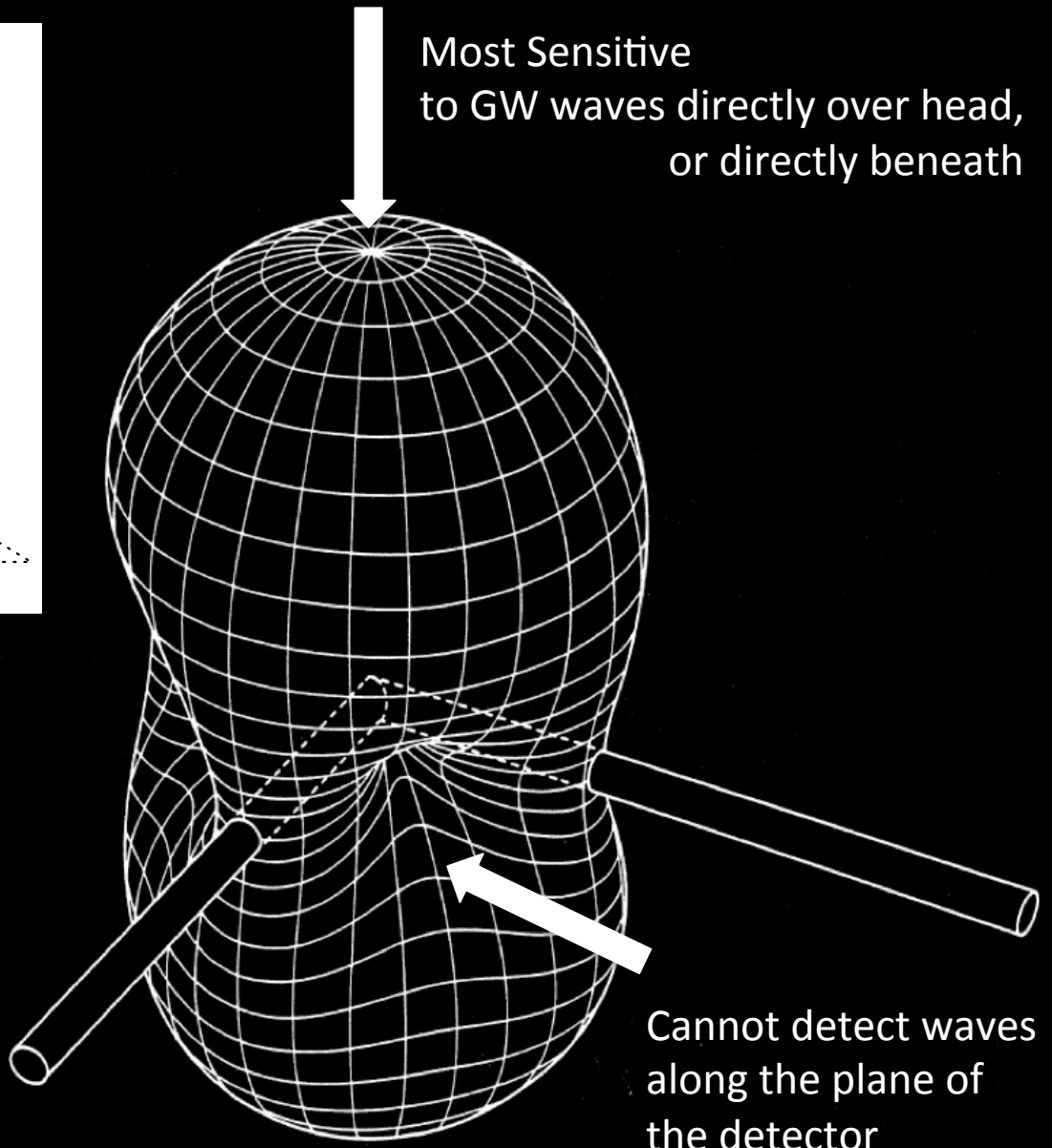
How does it work?



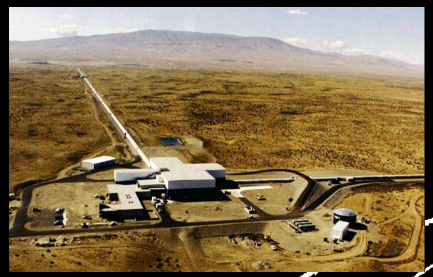
Directional Sensitivity?



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



LIGO's Global Partners



LIGO Hanford

LIGO Livingston

GEO600

VIRGO

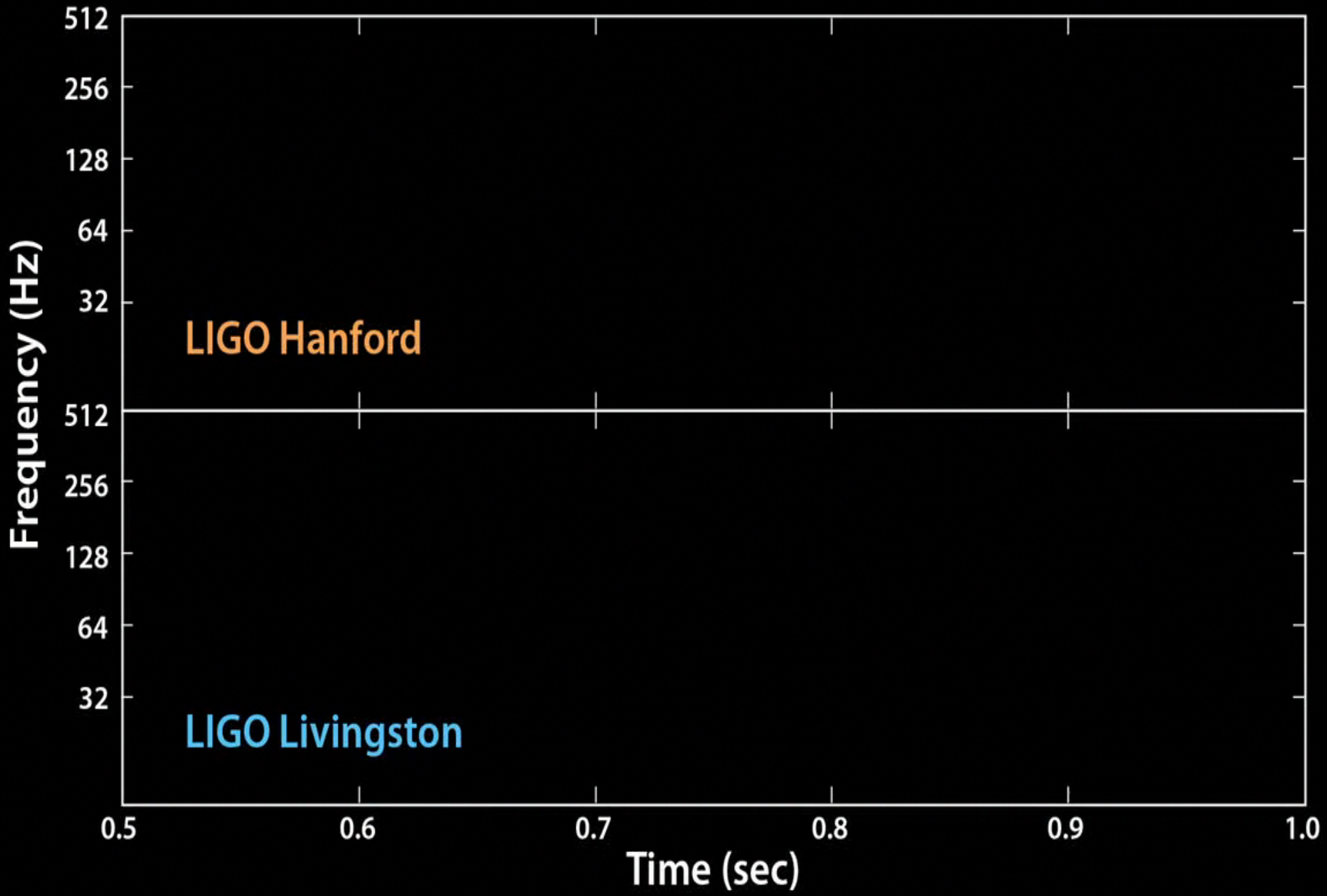
Future Detectors:

KAGRA

LIGO India

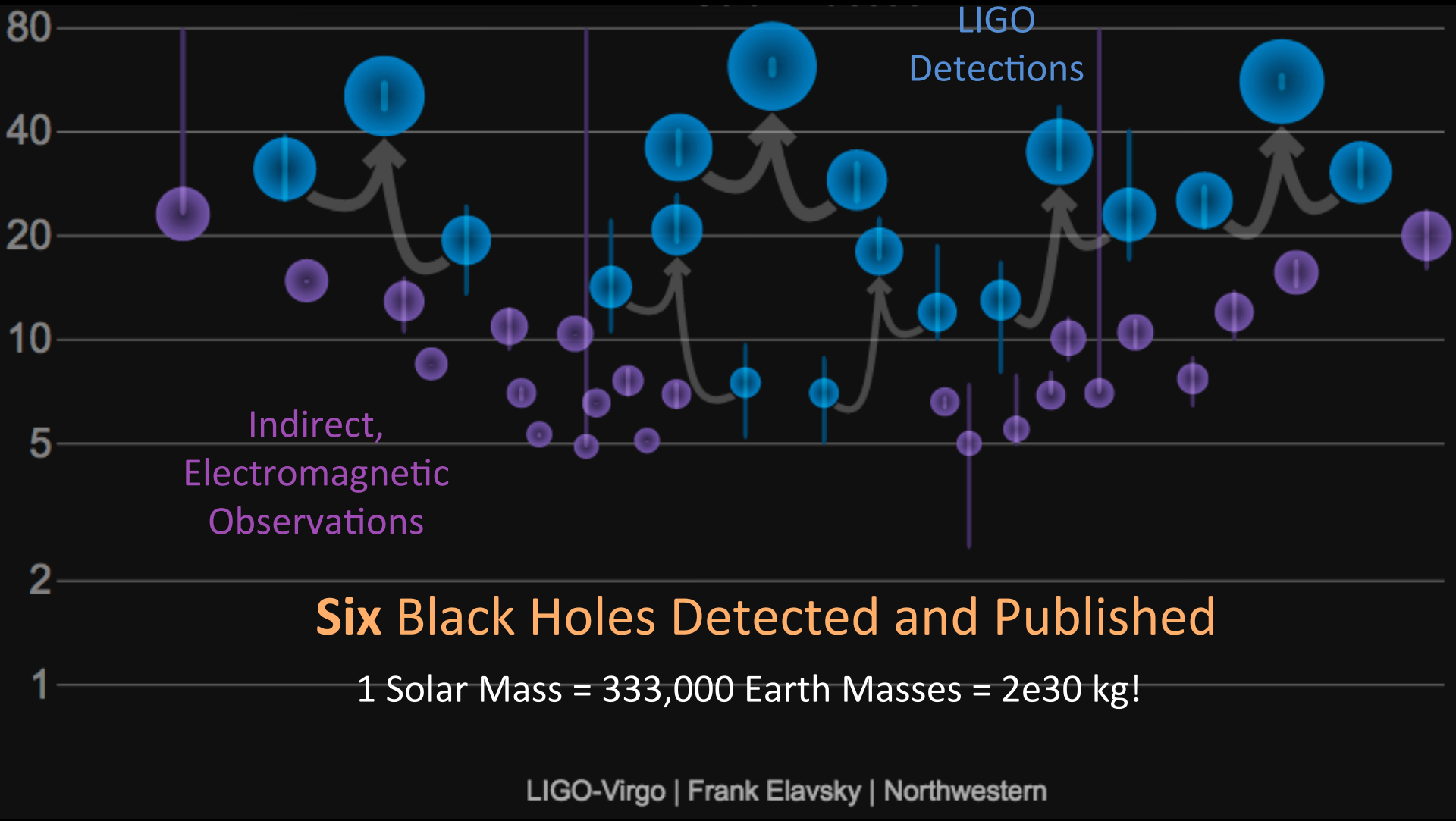
With a network, you gain directional sensitivity!

What LIGO “Hears”

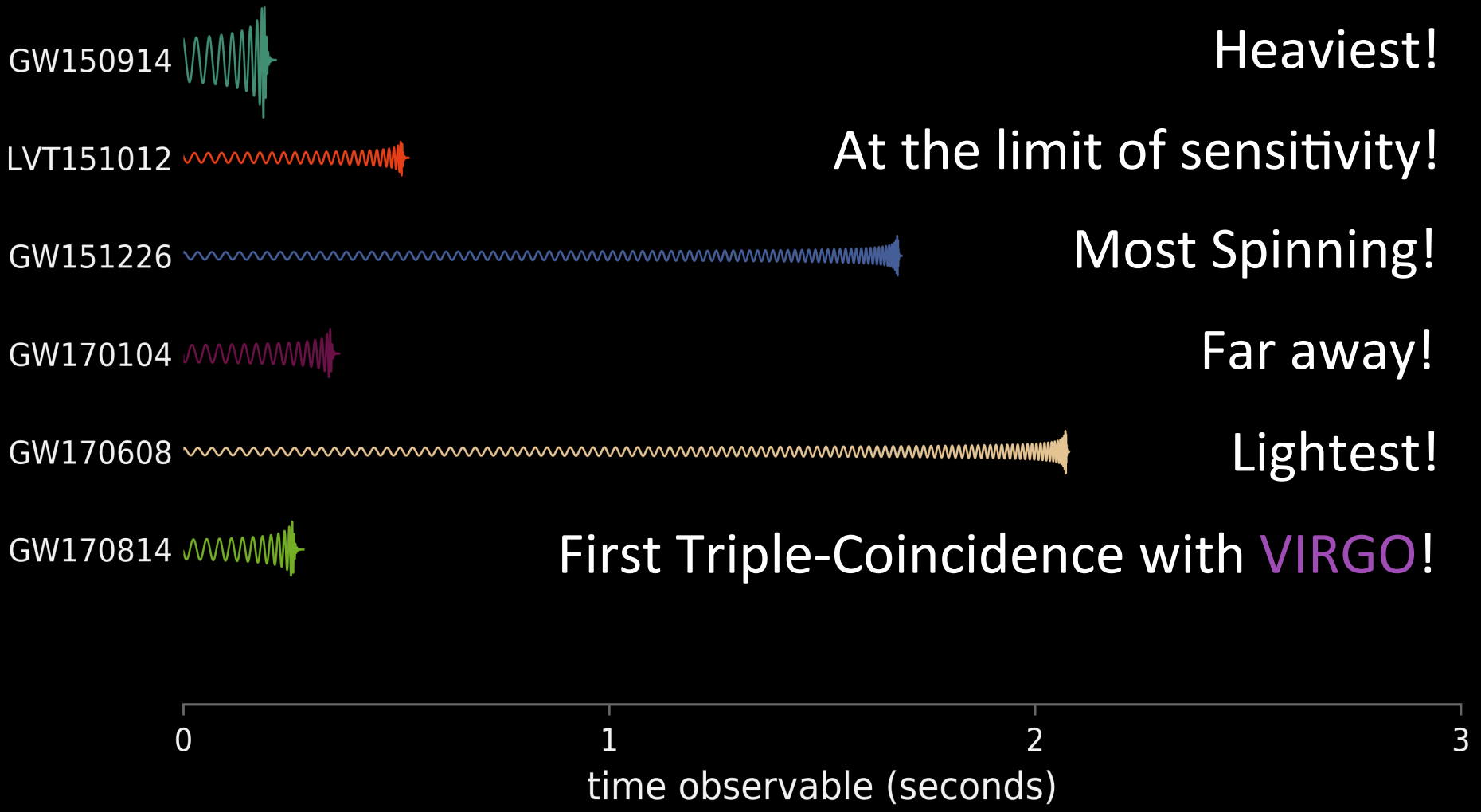


PRL 116.6 (2016): 061102.

How Many Have We Detected?



How Diverse Have They Been?



ApJ Lett 851.2 (2017): L35.

What LIGO "Hears"

LIGO Mirrors are 88 lbs of Glass

those 23 light bulbs of equivalent power only move the mirrors about

1×10^{-19} meters

1 / 10,000th the width of a proton

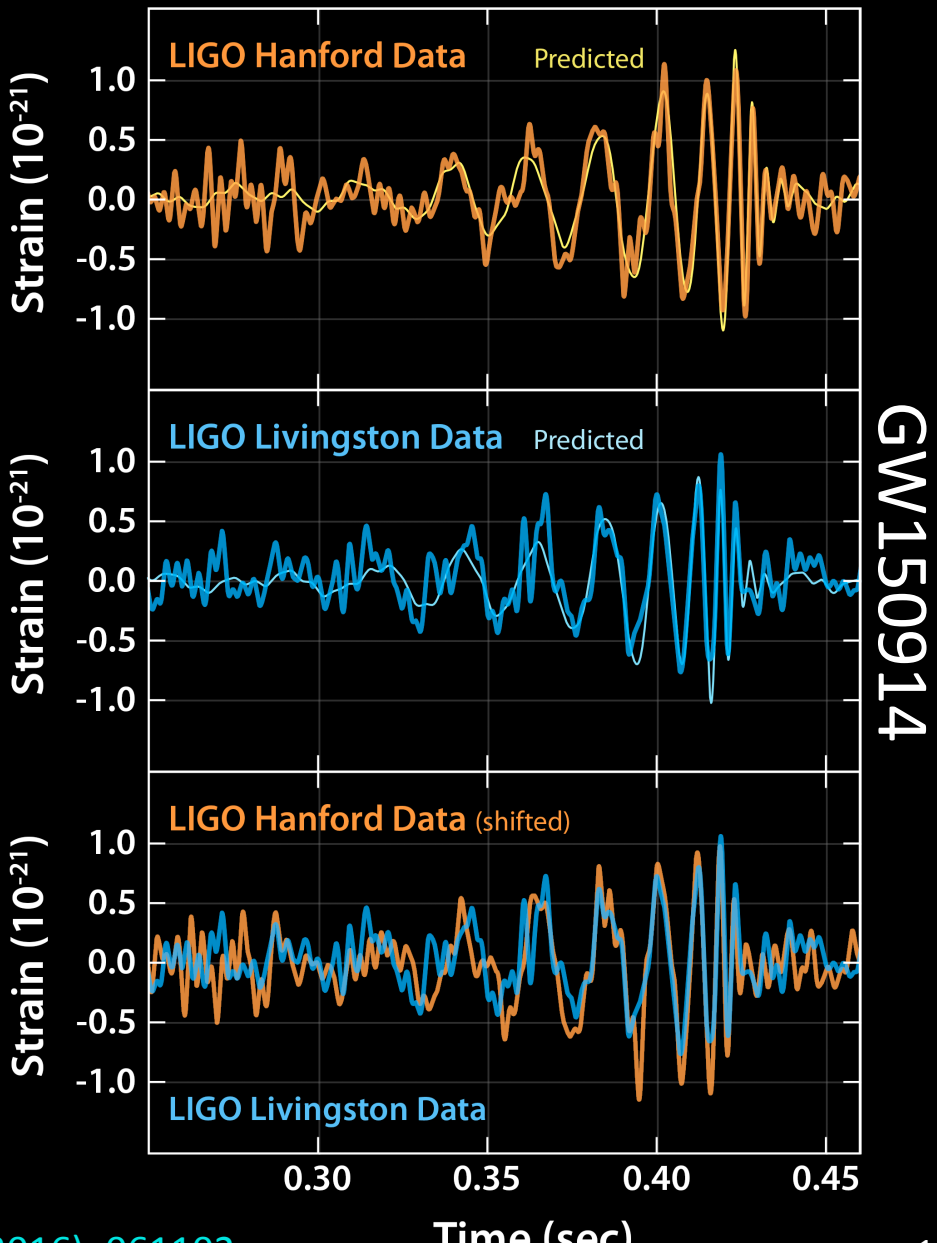
Characterized in "Strain"

strain = displacement / length

units: meters / meter

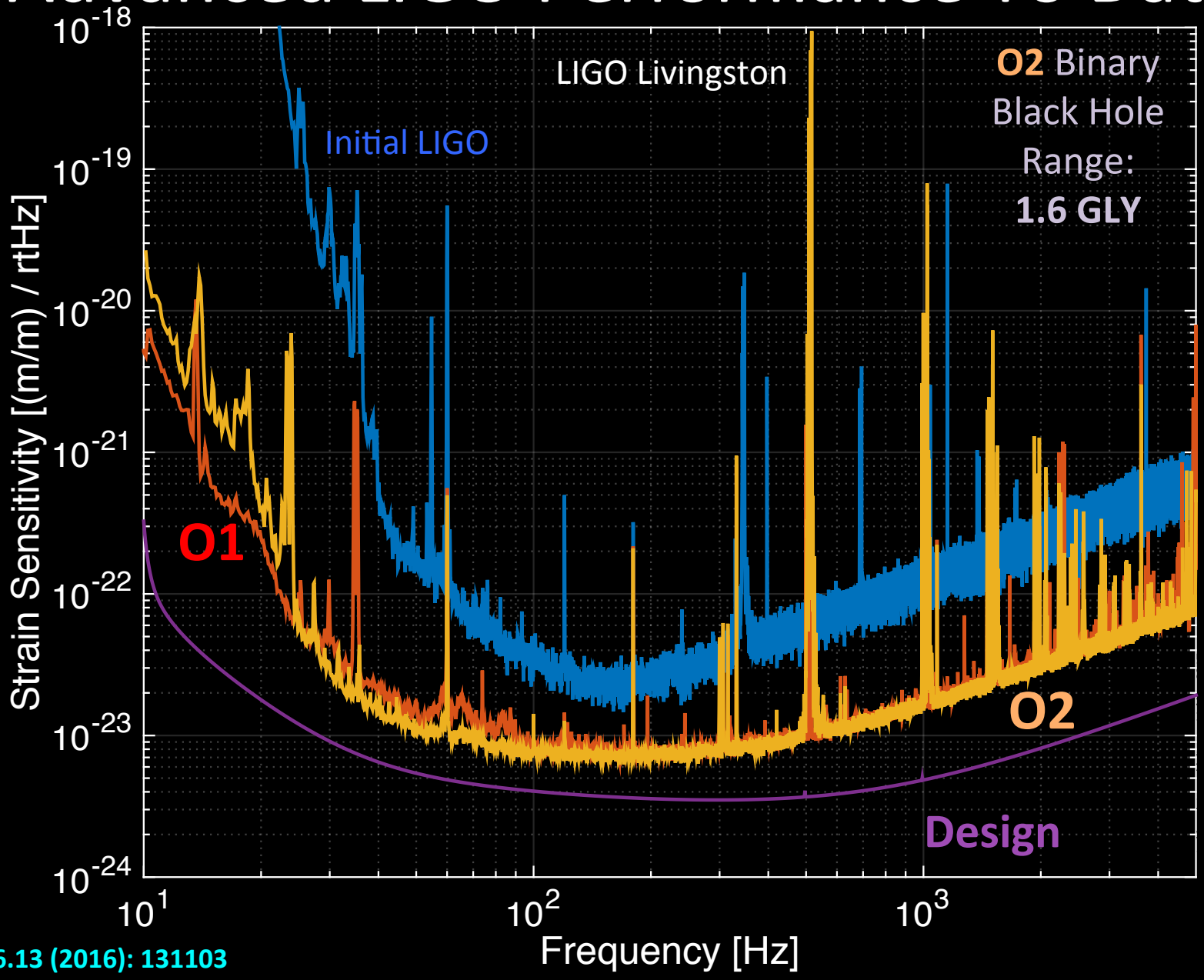
1×10^{-19} meters / 4000 meters

strain = 2.5e-23 m/m



PRL 116.6 (2016): 061102.

Advanced LIGO Performance To Date:



PRL 116.13 (2016): 131103

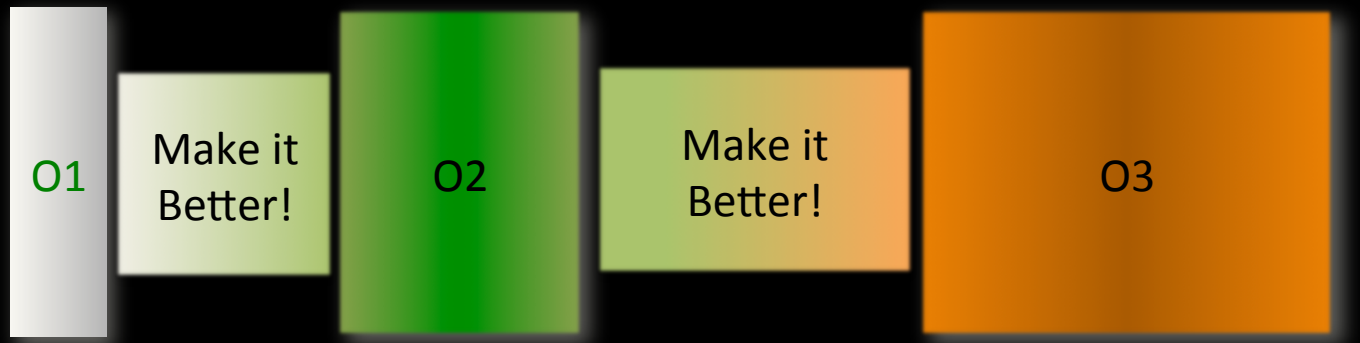
Current Observing Roadmap

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

Goal 20-20 $M_\odot$ Black Hole Detectable Range

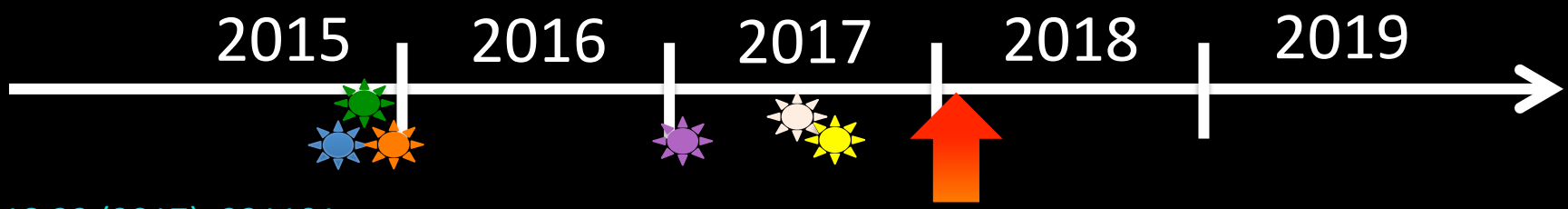
~1.3 Gly **~1.6** Gly **~2.3** Gly

Advanced LIGO Observing runs



4 mo ~8 mo ~12-15 mo

Living Rev. Relativ. 19 (2016).

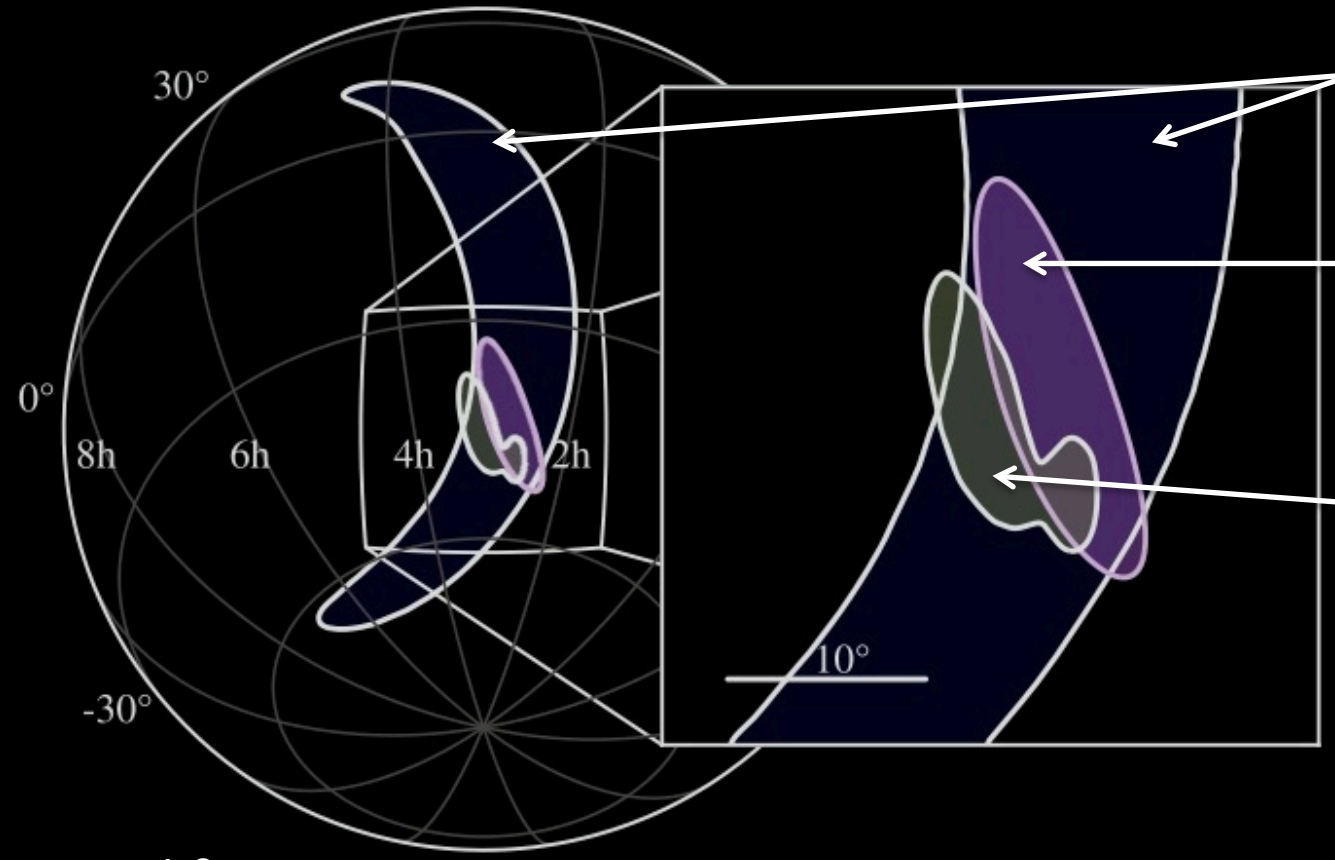


PRL 118.22 (2017): 221101.

BBH Rate = 0.34–6.15 Gly $^{-3}$ yr $^{-1}$

YOU ARE HERE

GW170814: Triple Coincidence!

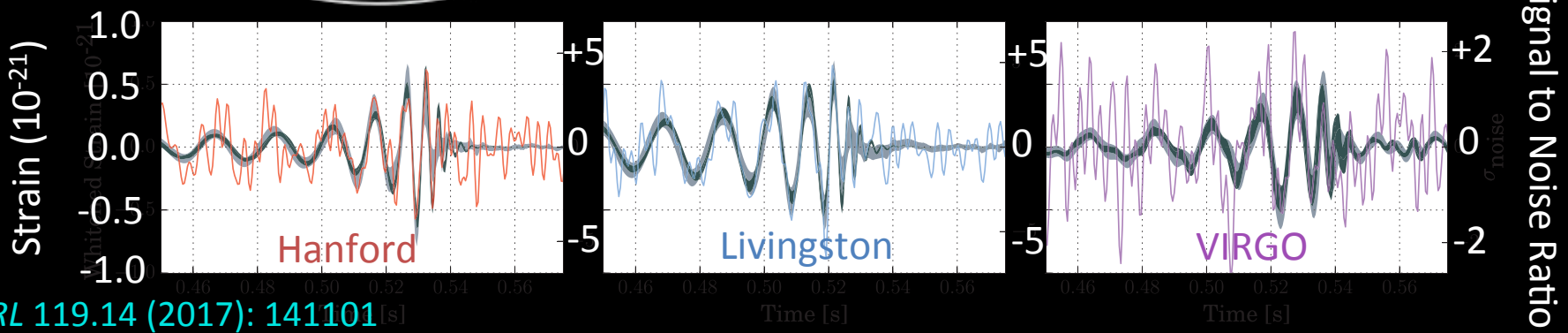


Rapid Response
LIGO Only: 1160 deg^2

Rapid Response
LIGO and VIGO: 90 deg^2

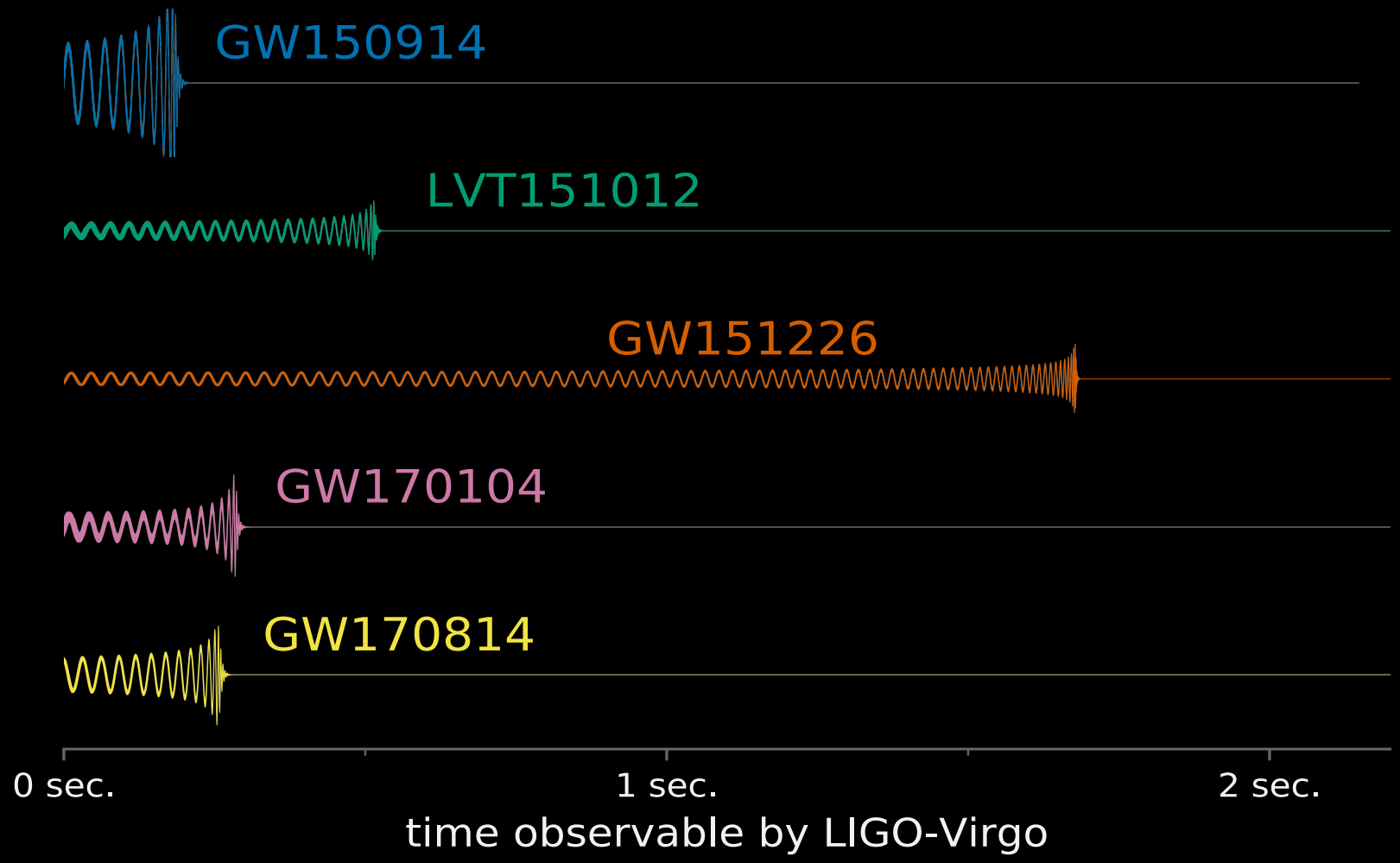
Finalized Location
LIGO and VIGO: 60 deg^2

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

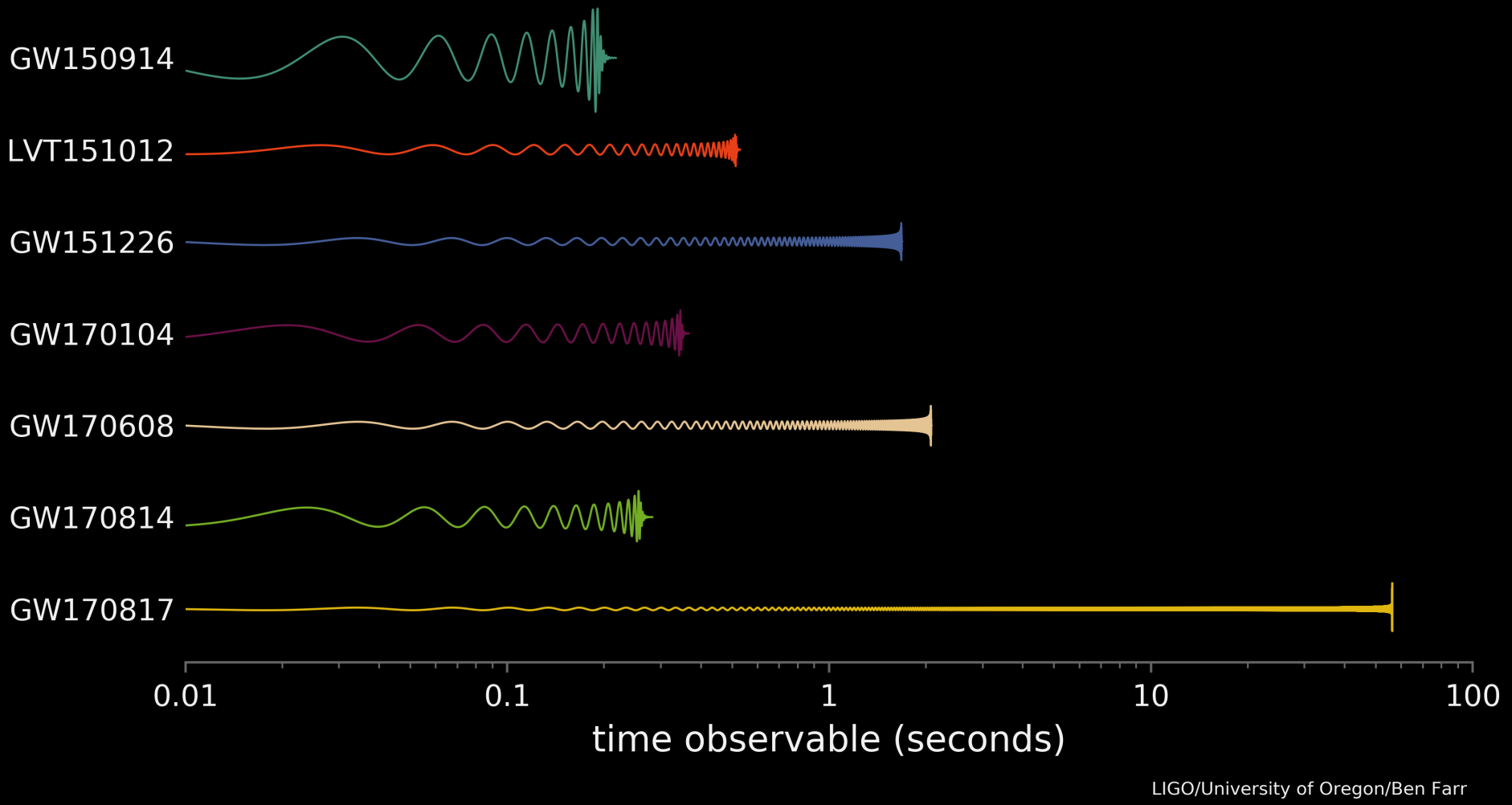


PRL 119.14 (2017): 141101

Oh – One More Thing…

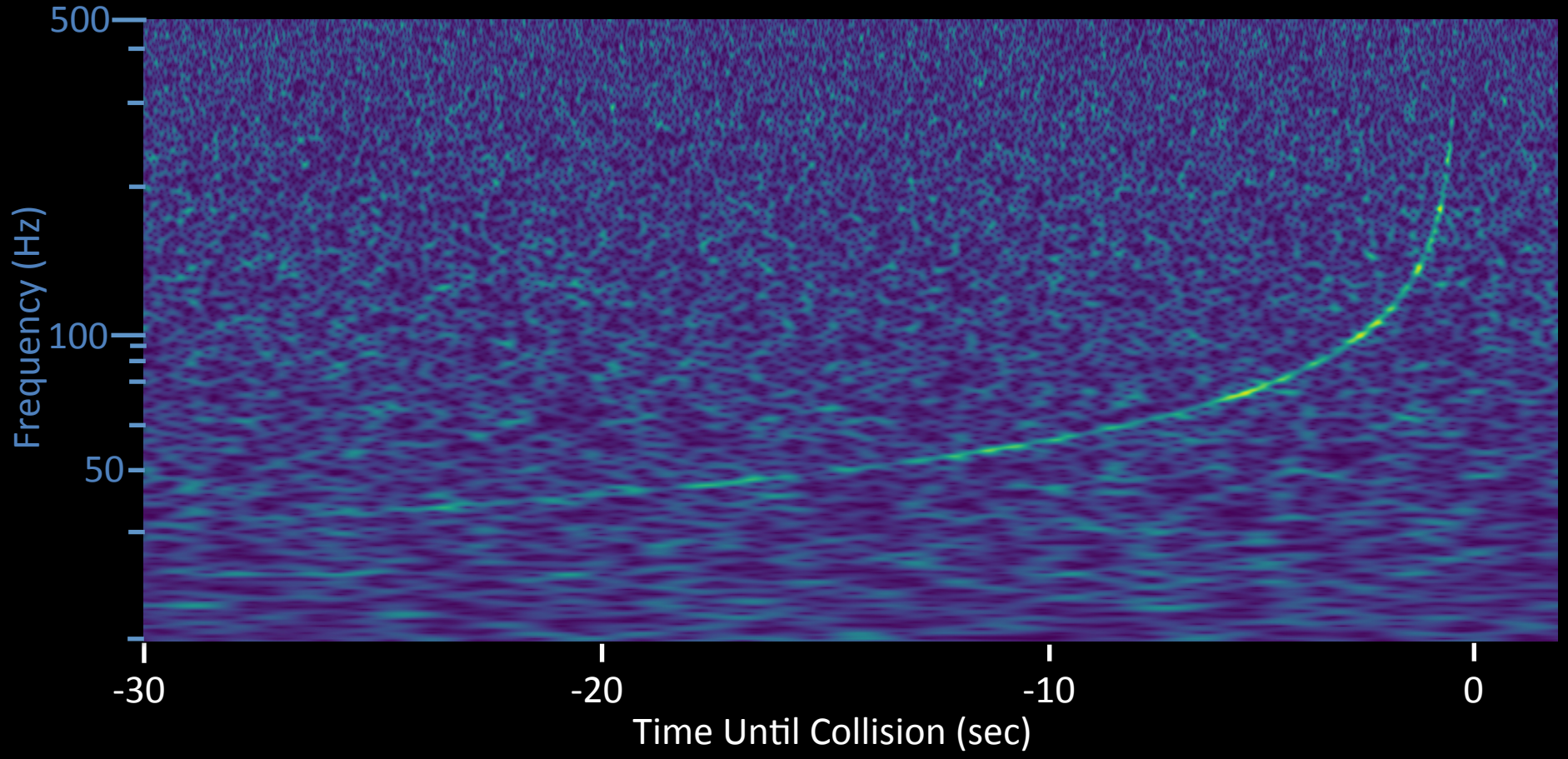


Finally -- A Neutron Star Collision!



PRL 119.16 (2017): 161101

GW170817



Primary: 1.36–1.60 solar masses

Secondary: 1.17–1.36 solar masses

40^{+8}_{-14} = 0.13 billion light years

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

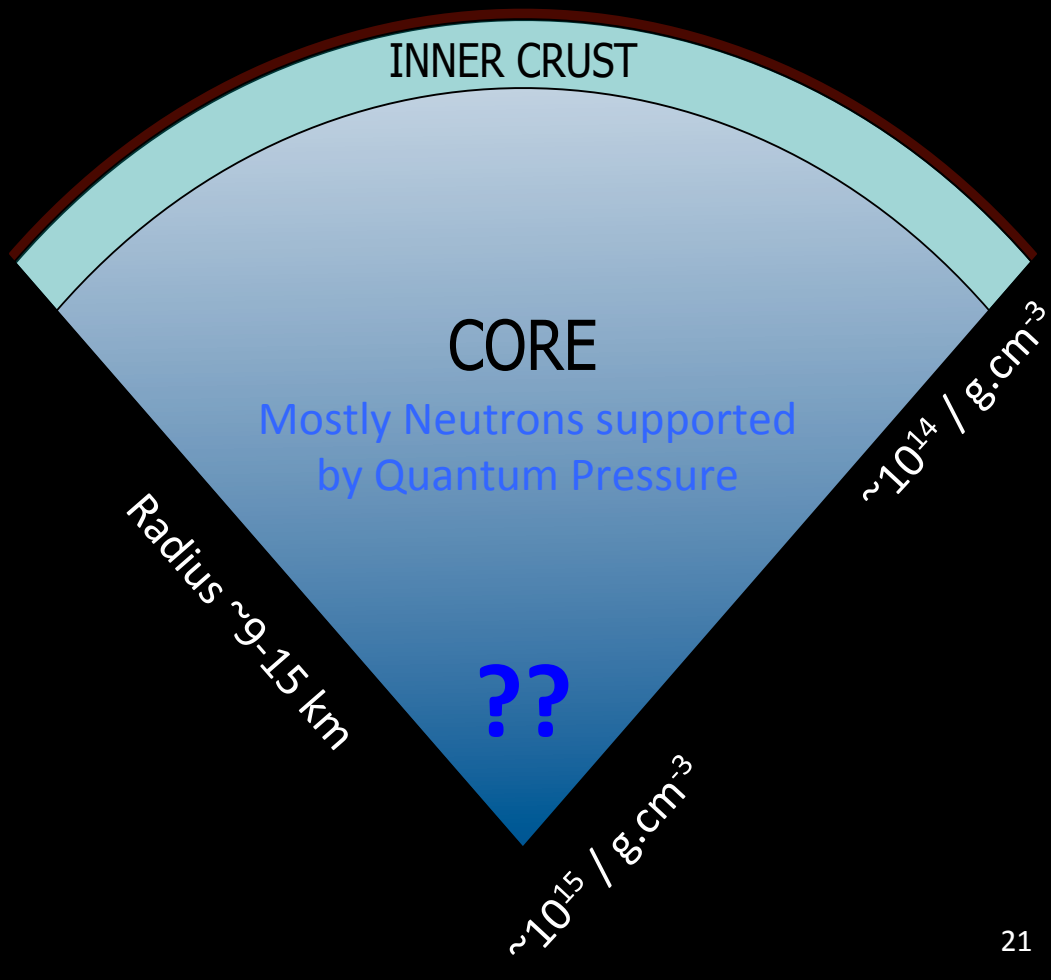
PRL 119.16 (2017): 161101

The Physics of Neutron Stars

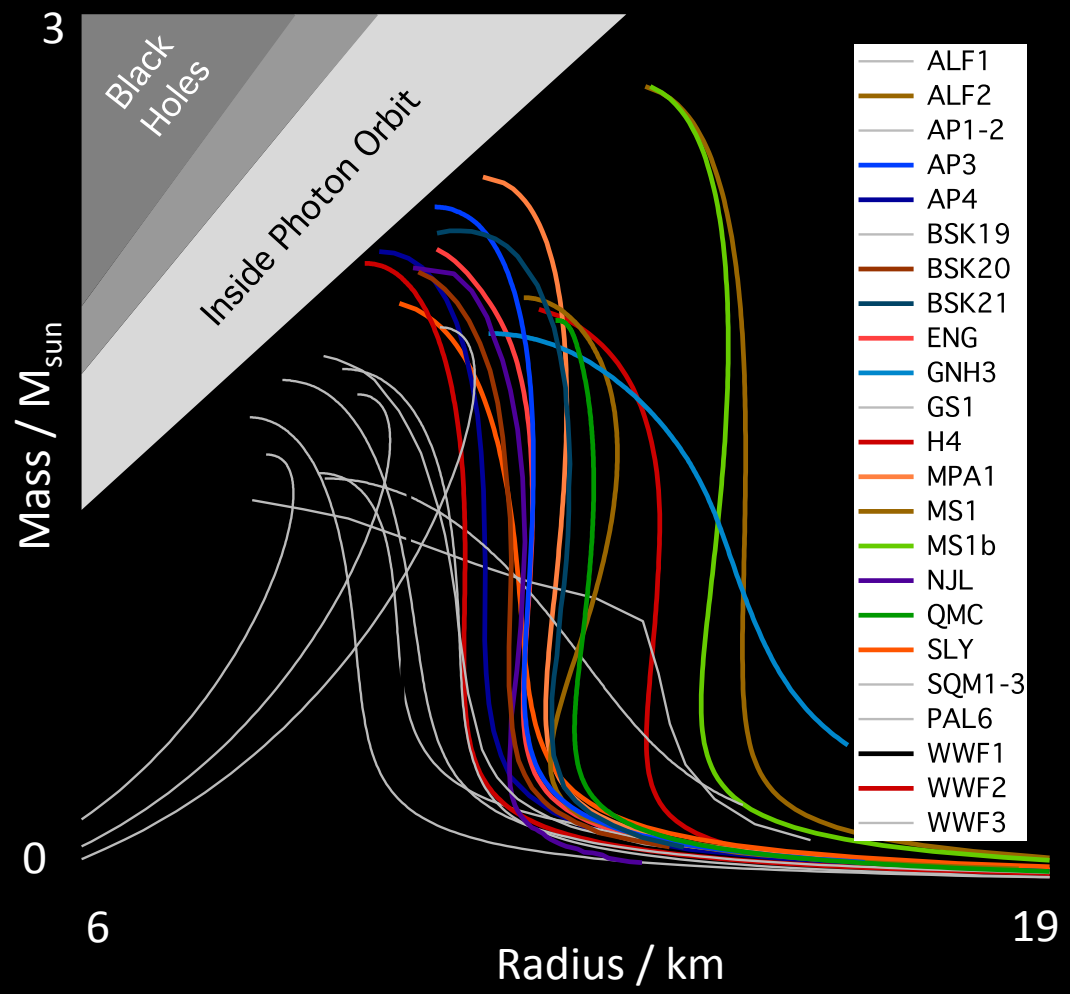
- The end of a heavy star's life cycle
  - A red super giant's fusion can't support it's weight beyond iron
  - Core-Collapse Supernova

- After Failure of Electron/ Nucleus Degeneracy Pressure, Neutrons are supported by Pauli Exclusion of Neutrons

- What's in the middle??

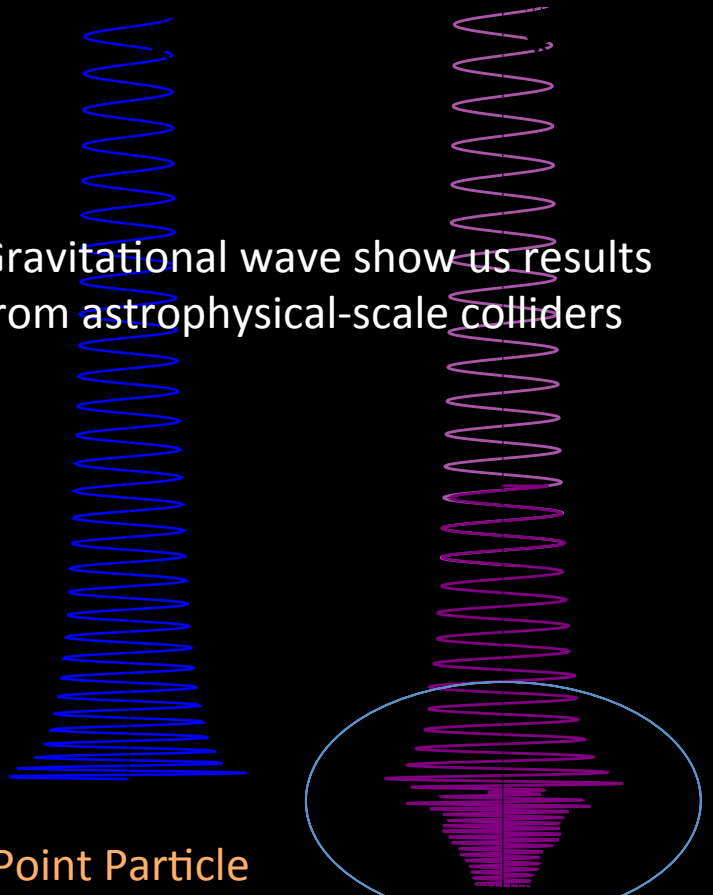


Gravitational Waves from Neutron Stars

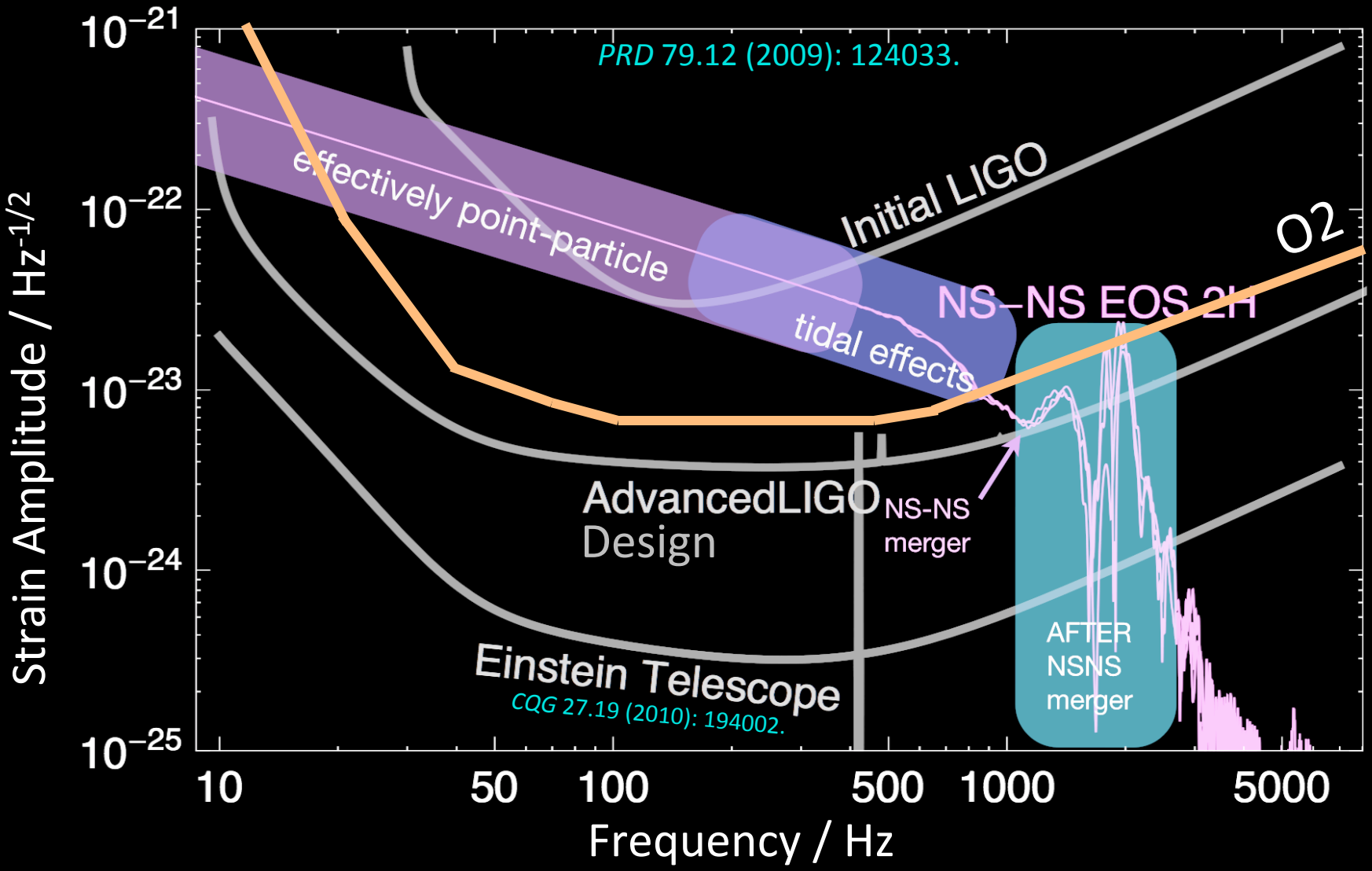


- State-of-the-art nuclear theorists haven't been able to constrain models very well … still LOTS of options...

Gravitational wave show us results from astrophysical-scale colliders

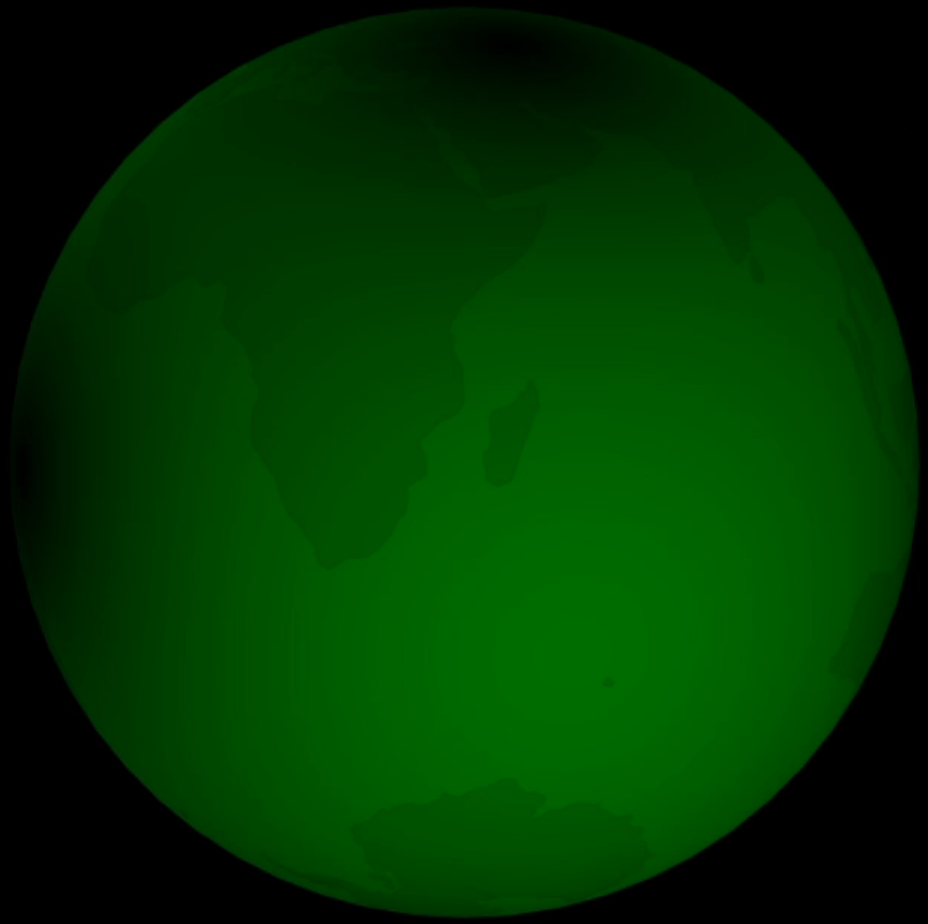


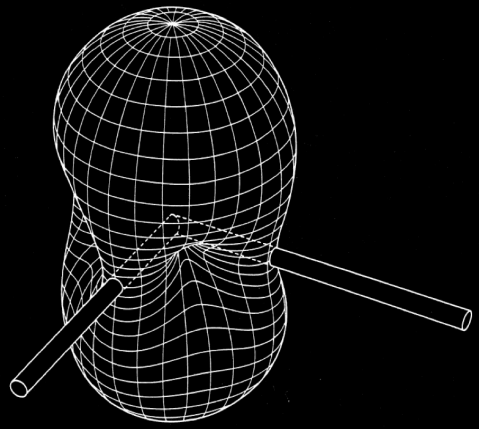
Equation of State: Unknown!



For now we must still rely on electromagnetic observations…

GW170817: Virgo didn’t see it? GREAT!





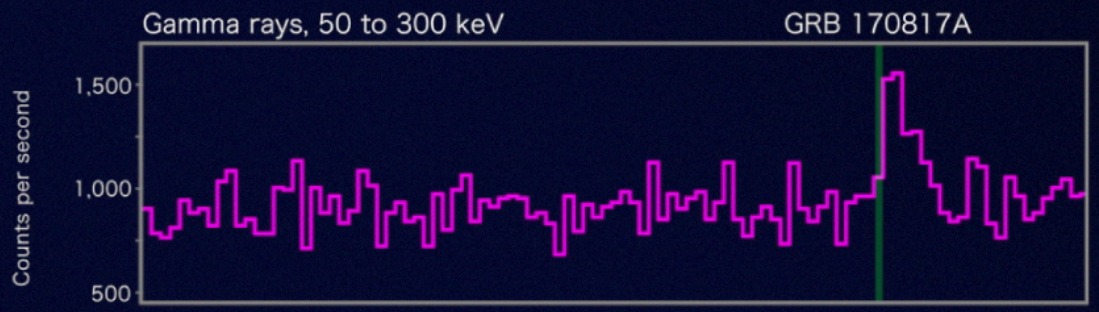
Courtesy of LIGO/Virgo/NASA/Leo Singer

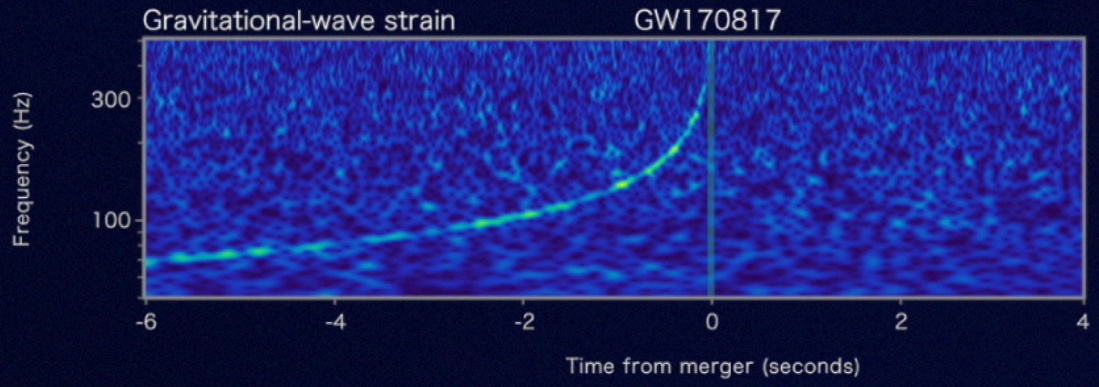
GW170817 and Gamma Ray Bursts

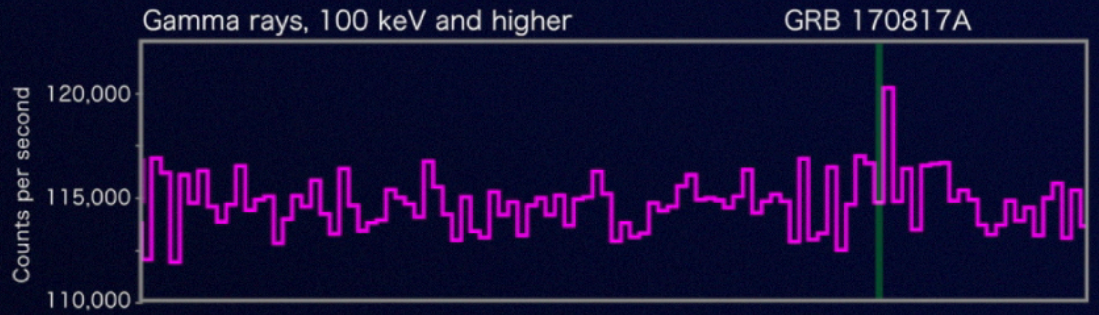
Fermi

LIGO-Virgo

INTEGRAL







ApJ Lett. 848.2 (2017): L15. *ApJ Lett.* 848.2 (2017): L13.

GW170817: Where on the sky?

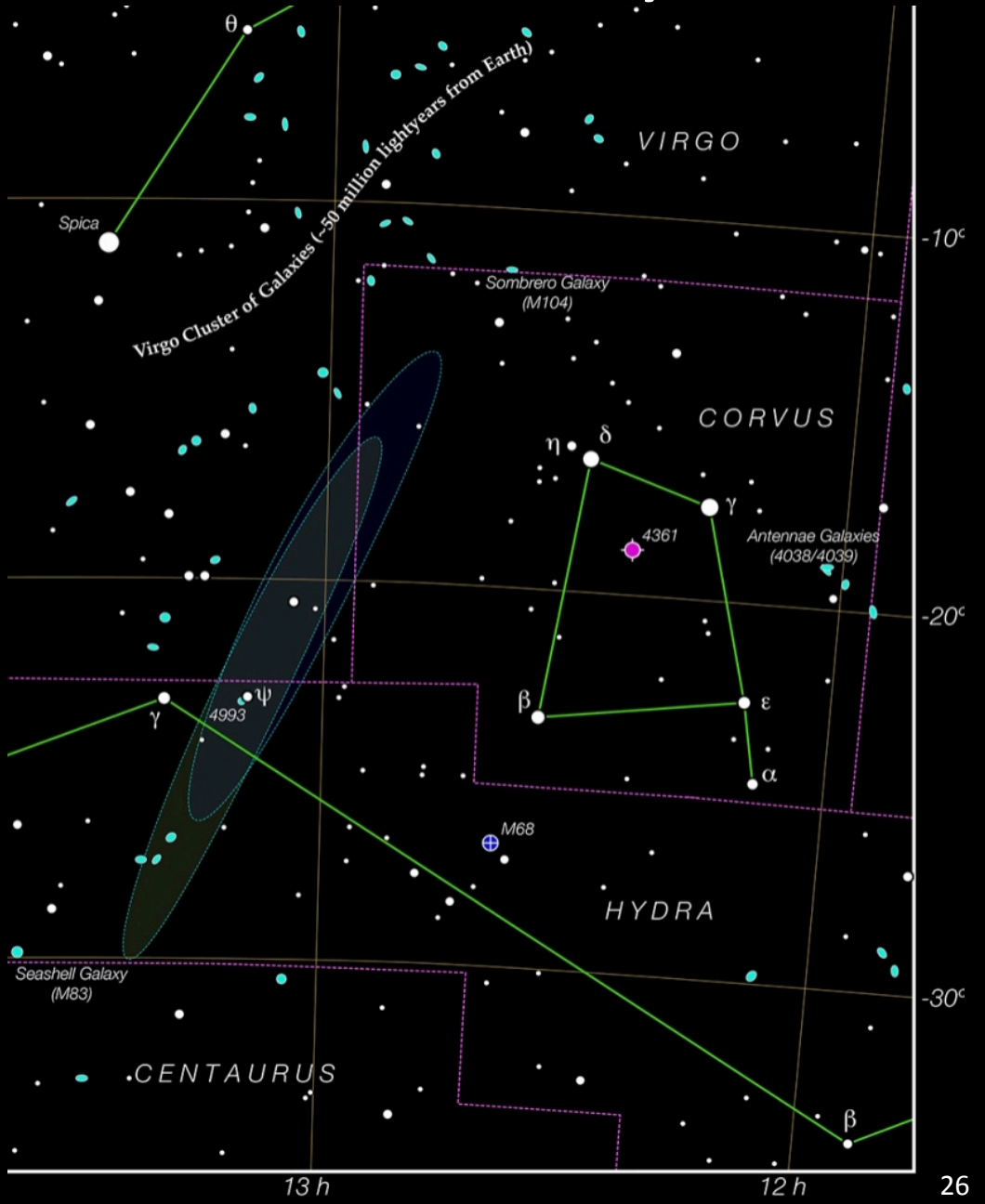
The incredibly small region on the sky

LIGO Only: 190 deg^2

Rapid LIGO & VIRGO: 31 deg^2

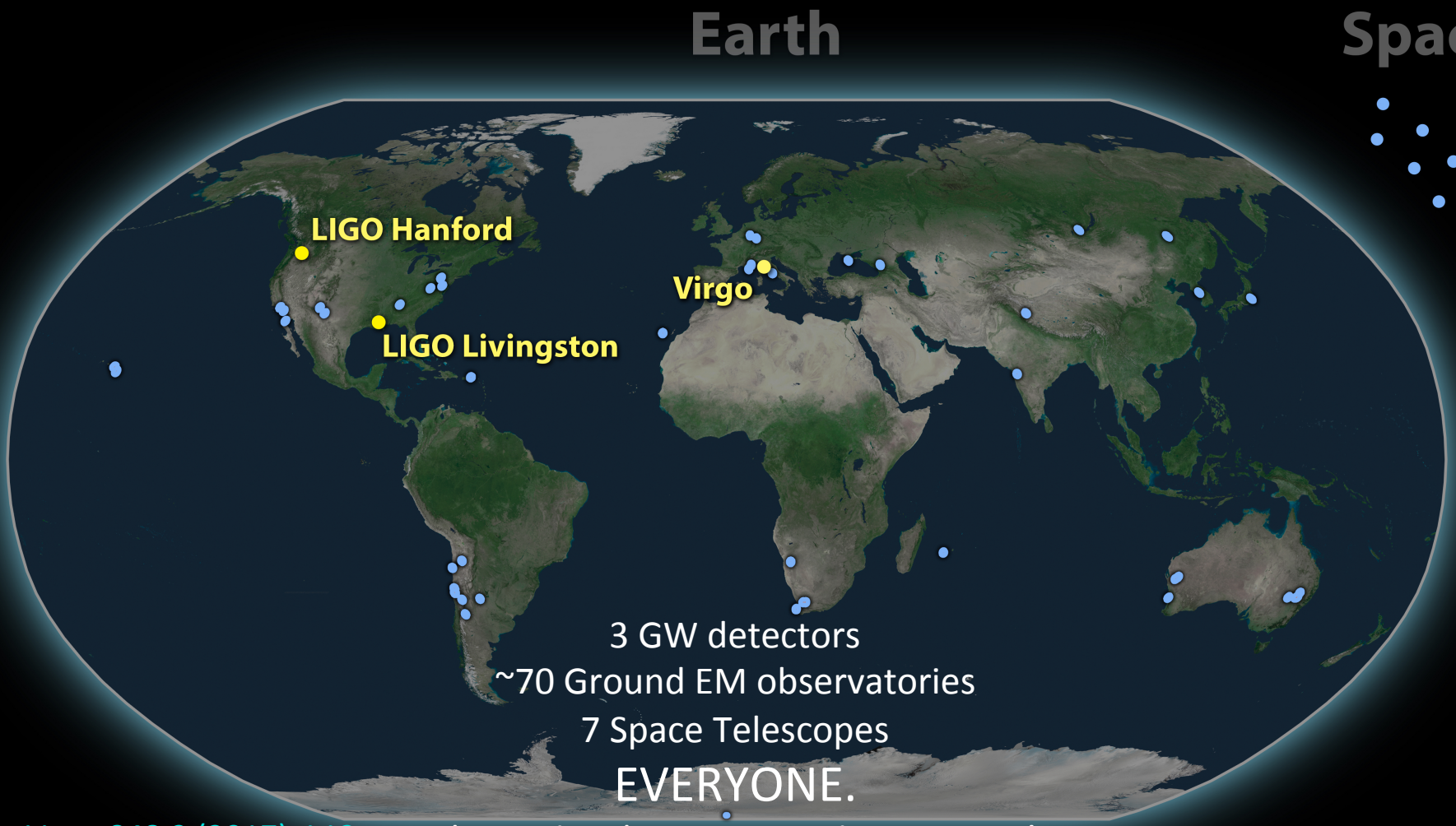
Final LIGO & VIRGO: 28 deg^2

~30 galaxies are within LIGO/Virgo error box



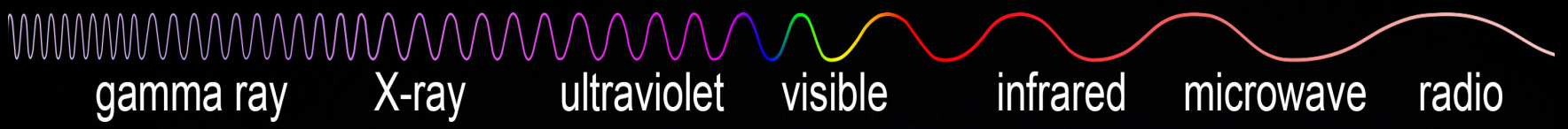
Nature 551.7678 (2017): nature24291

Who saw GW170817?

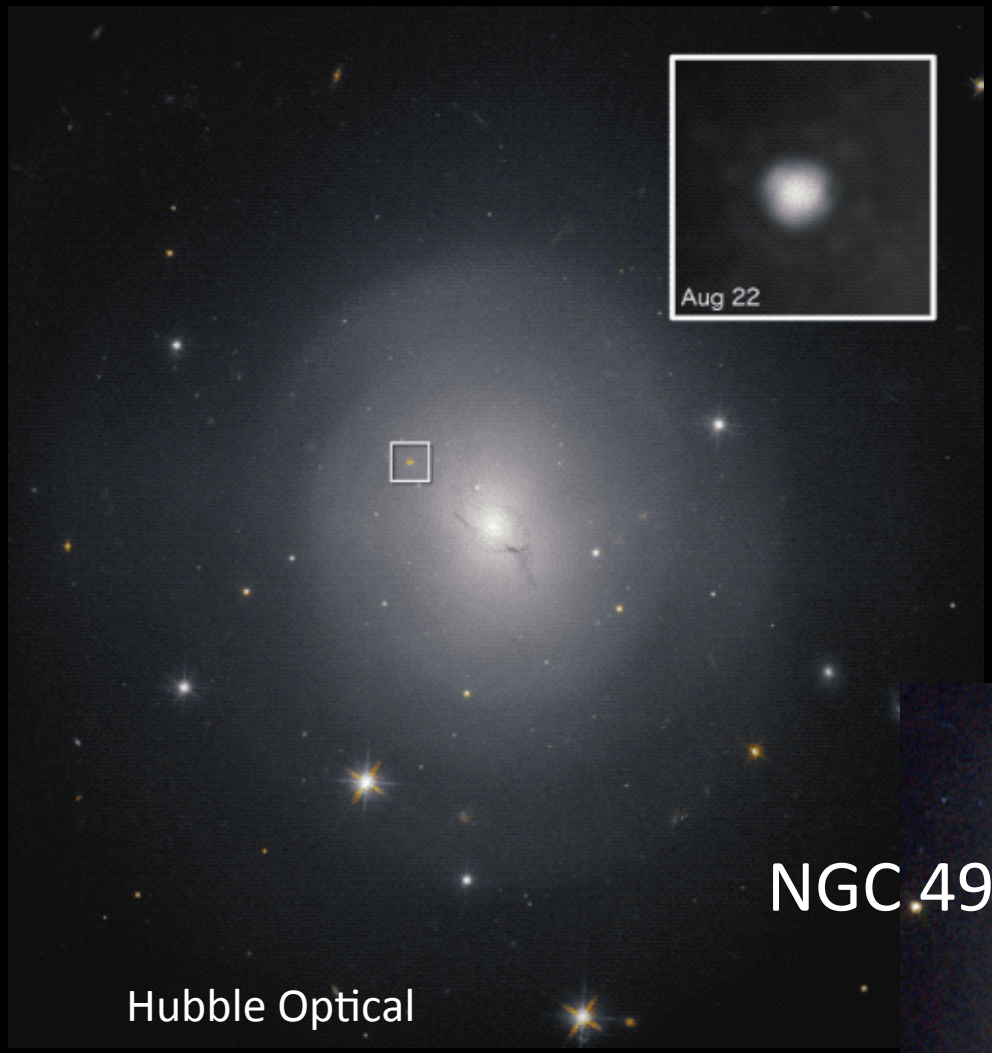


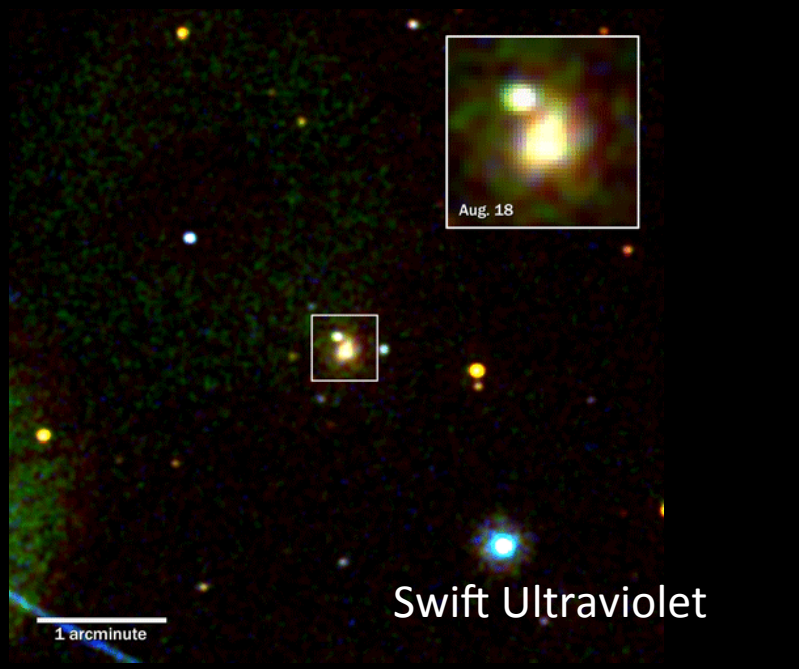
ApJ Lett. 848.2 (2017): L12.

The *entire* electromagnetic spectrum!

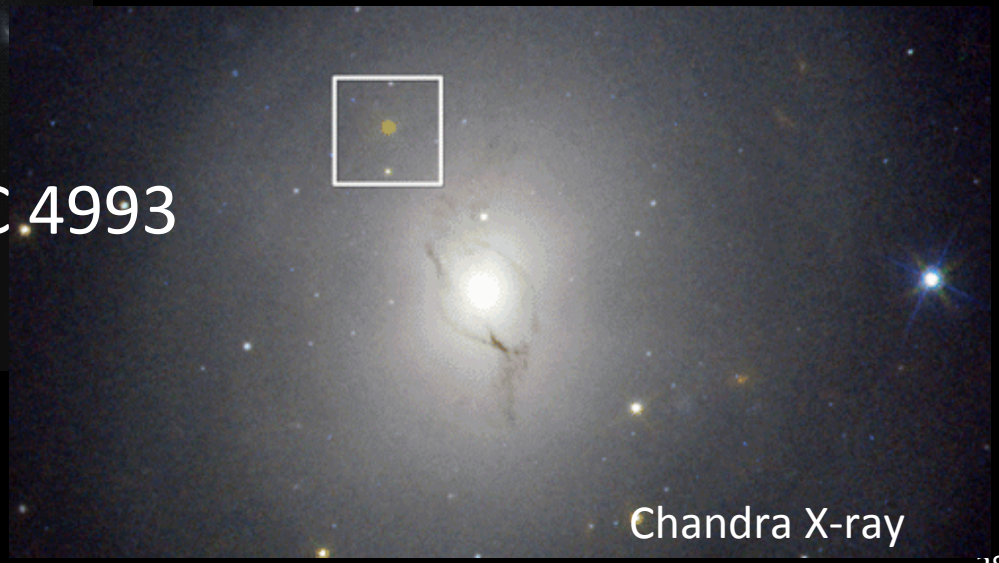


Found It! And They Saw it Evolve!



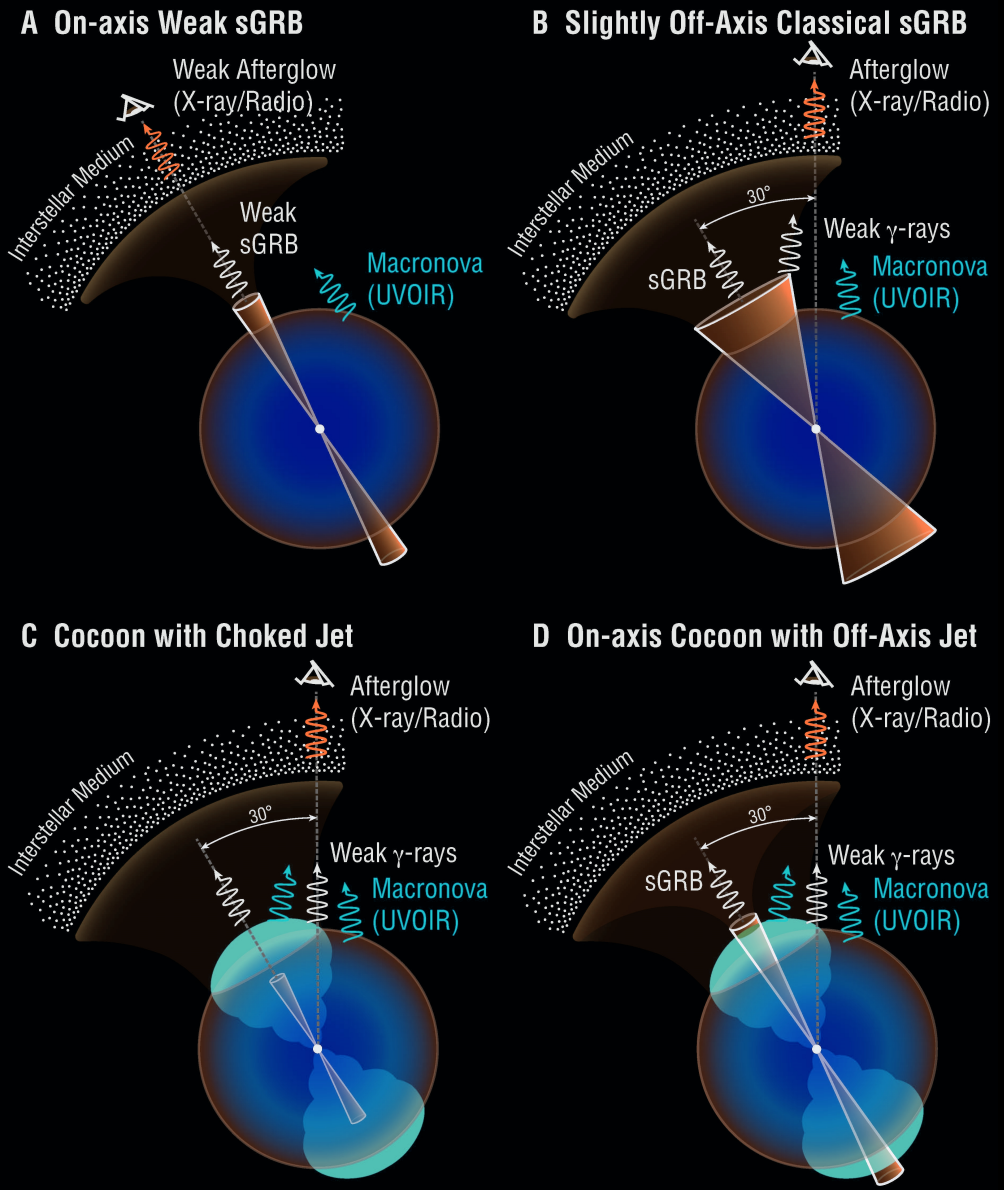


NGC 4993



Images courtesy of NASA / ESA

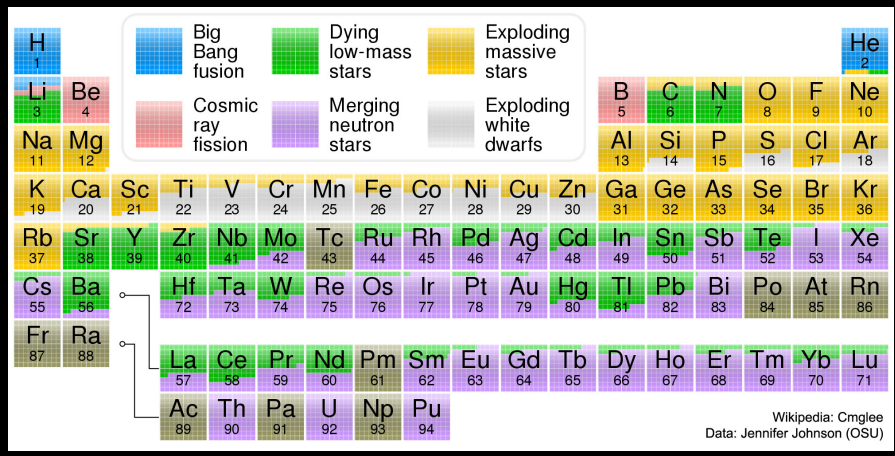
So What was GW170817?



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

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

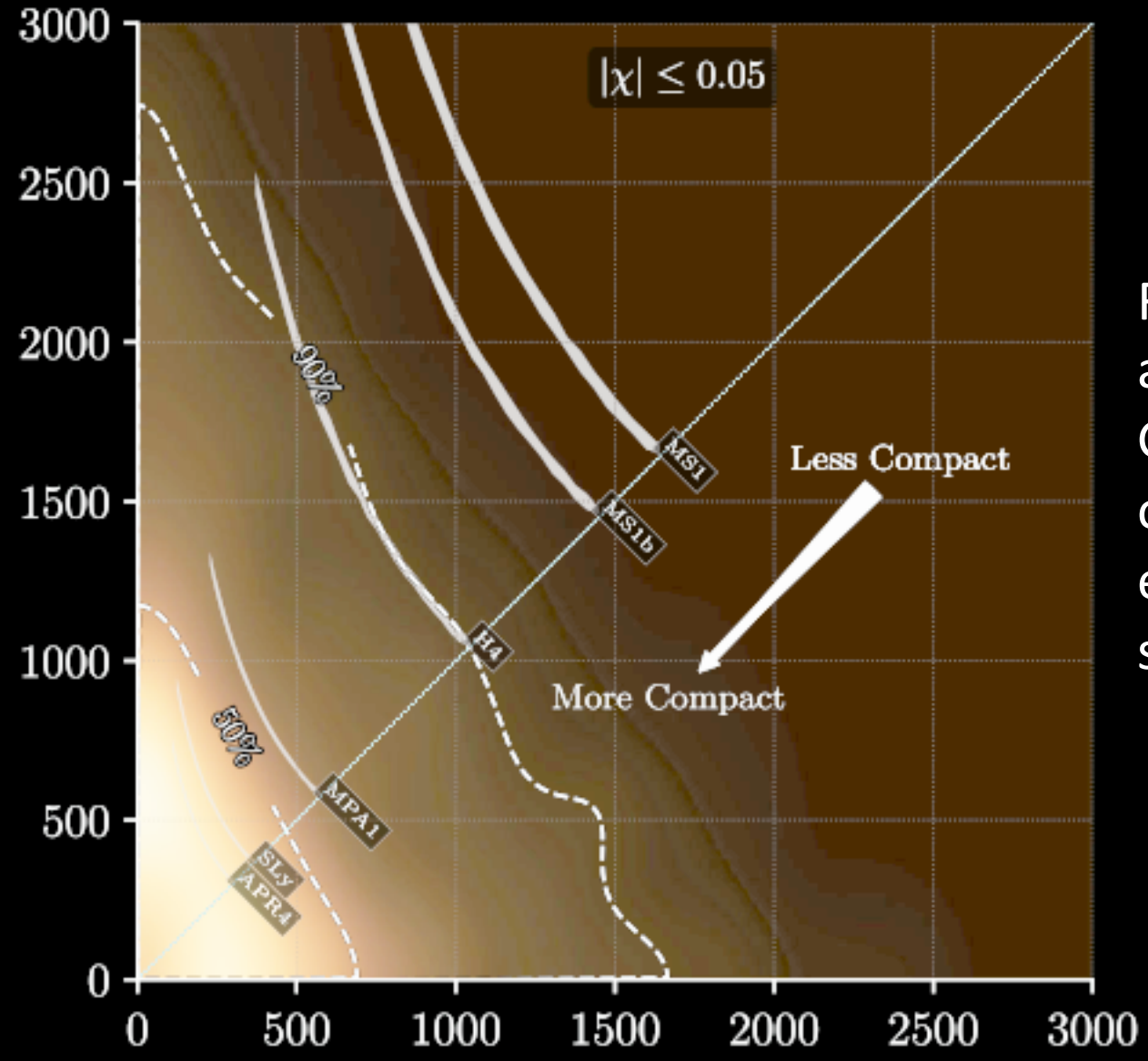
n. /ˈkiːləʊːnəʊvə/ A collision of neutron stars, which emit a jet of gamma rays, that explode into the surrounding stellar media



Jennifer Johnson/SDSS

They produce most of the heavy / precious metals!

Neutron Star Physics: We're "On the Board!"



From its g-waves alone, GW170817 rules out some "stiff" equation of state models

PRL 119.16 (2017): 161101

Why is LIGO/VIRGO Important for Neutron Star Physics?

- We are able to pin-point the location on the sky
- We were able to directly measure the mass, and therefore confirm the mechanism
- We have an independent distance measure
- Turned 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
- Beginning to rule out some neutron star equations of state
- **A brand new way to look at the bright and dark universe**

Image Credit: Aurore Simonnet

facebook.com/
LigoScientificCollaboration/

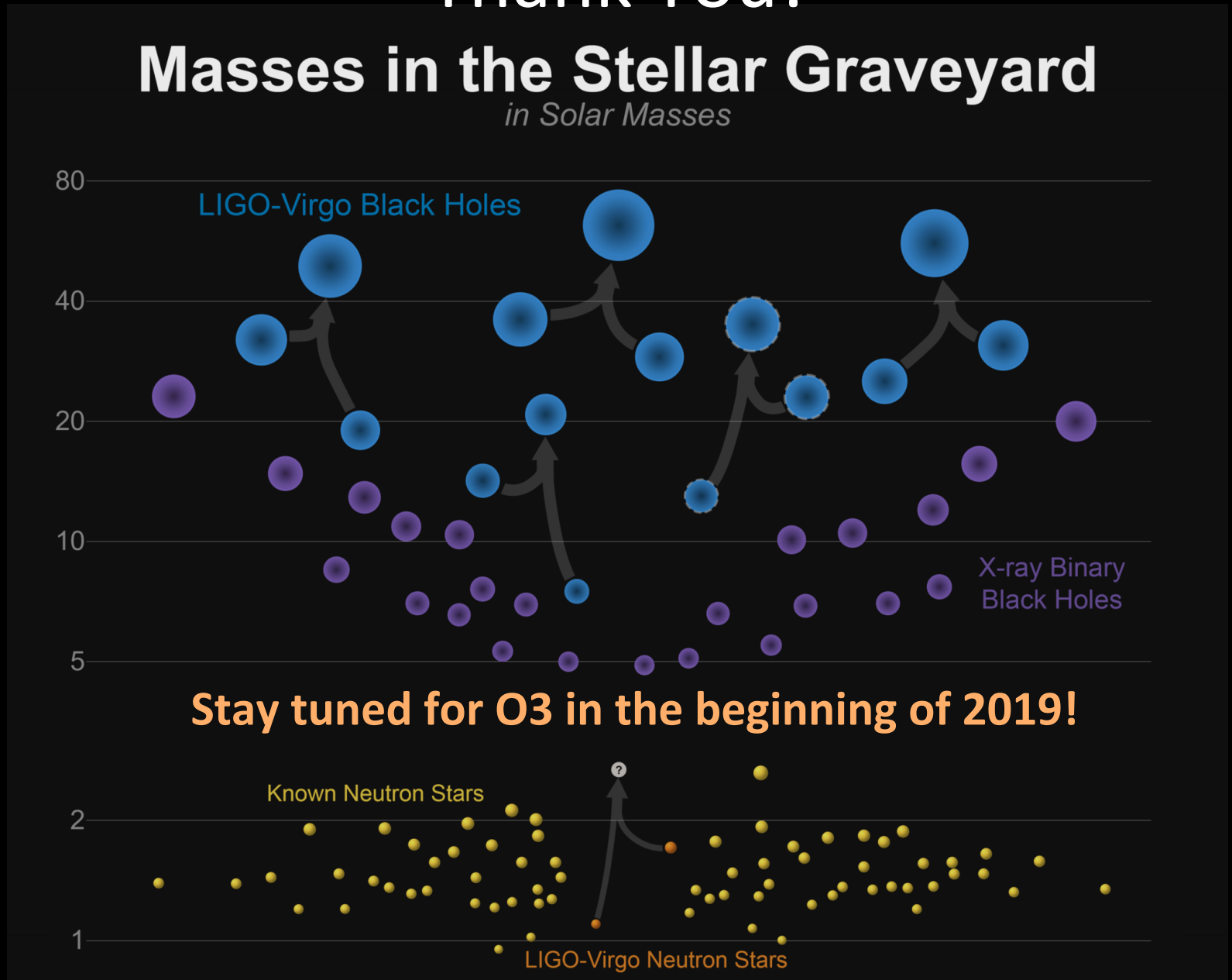
@LIGO,
@LIGOWA, @LIGOLA

Come Visit in REAL LIFE!

Public tours every 2nd **Saturday** of the Month,
1:30p & 3:30p, with a talk in the middle

Next tour Feb 10th 2018!

Thank You!


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
LIGO-Virgo Black Holes
X-ray Binary
Black Holes
Stay tuned for O3 in the beginning of 2019!
2
1
Known Neutron Stars
?
LIGO-Virgo Neutron Stars

Bonus: Planck Stars?

- Theoretical concoction to avoid the Information Paradox
- Model hinges on a quantum gravitational "force" just like electron or neutron degeneracy pressure, the authors argue for a quantum
- "Just before singularity" phase – short in proper time, but very long to an external observer – but still within a Hubble time
- Universe may have these "primordial" black holes
- Depending on your cosmological religion (top down, or bottom up), these very old black holes could be supermassive ($>10^6$ M_{sun}), or stellar mass (~10 M_{sun})
- If super massive – out of LIGO's frequency band, we need LISA (give us more time & money)
- If stellar mass – they'd currently be too far away for this generation of ground based detectors (give us more time & money)