LIGO & Virgo and their historical and future roles in multi-messenger/time domain astronomy

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For NSF's NOIRLab

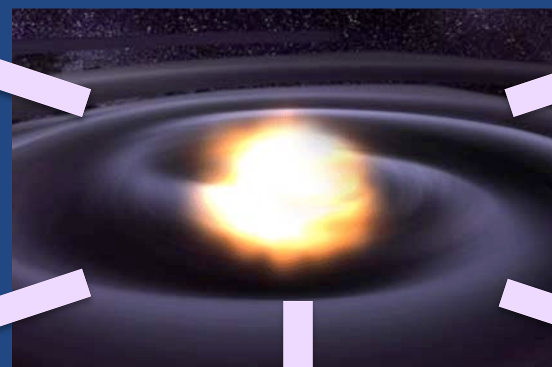
Discovering Our Universe Together

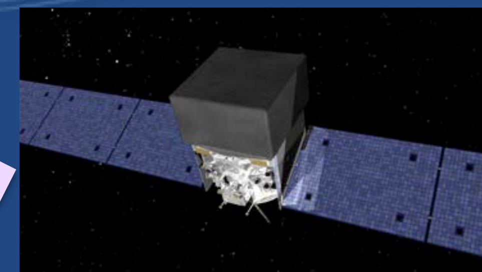
LIGO-G2100002-v1

Multi-messenger Astronomy with Gravitational Waves

Gravitational Waves

Binary Neutron Star Merger

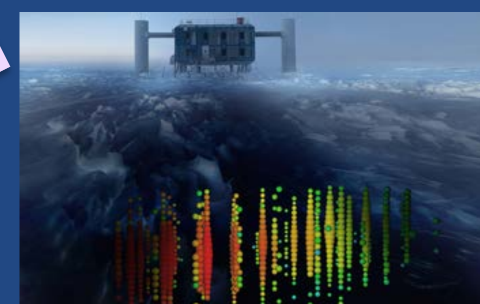




X-rays/Gamma-rays

Visible/Infrared Light

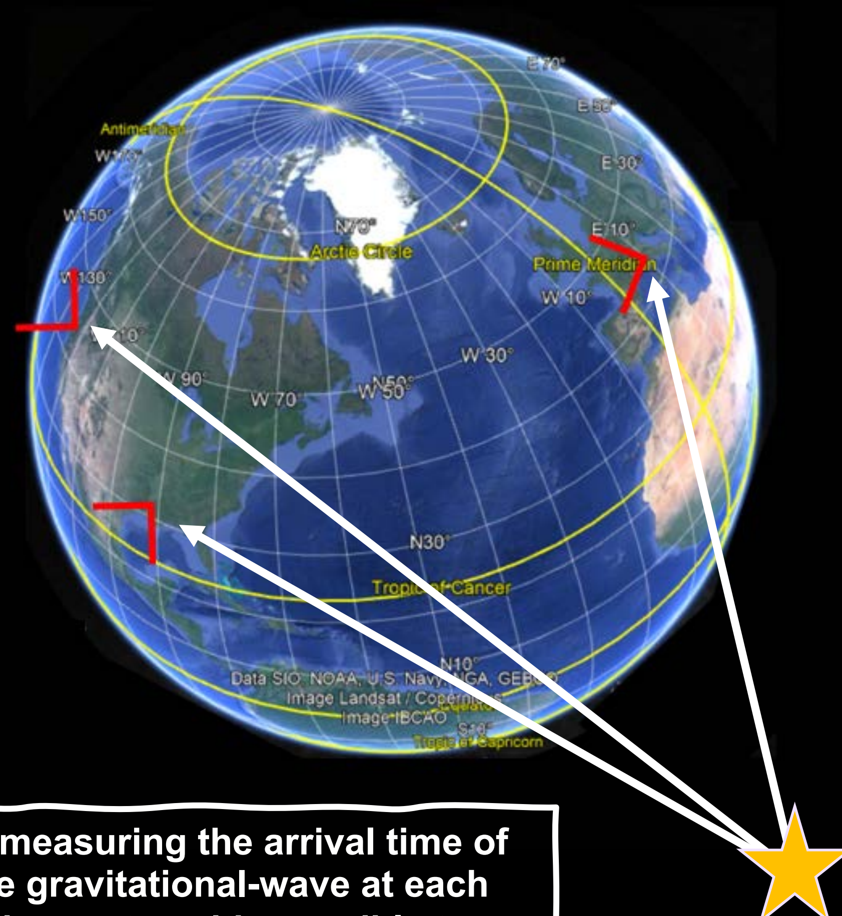
Radio Waves



Neutrinos

High energy cataclysmic astrophysical events can reveal themselves through the emission of gravitational-waves, electromagnetic radiation (photons), neutrinos, and cosmic rays

Localizing Gravitational-wave Events

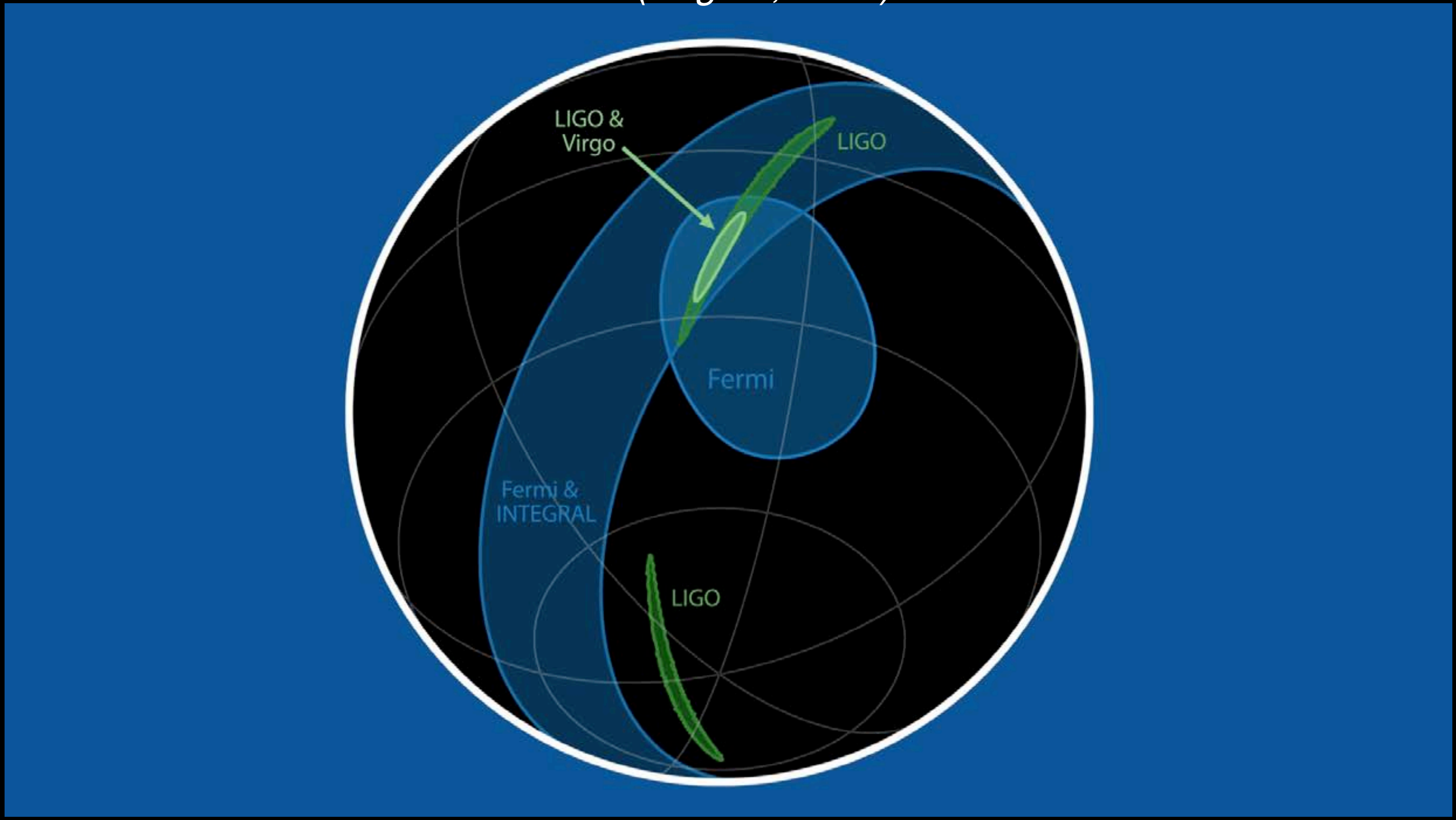


By measuring the arrival time of the gravitational-wave at each observatory, it's possible to identify its location on the sky

A single GW observatory is mostly insensitive to the sky location;
we want two and preferably three or more observatories

The First Gravitational-wave Multi-Messenger Event GW170817

(Aug 17, 2017)



Credit: R. Hurt, Caltech IPAC

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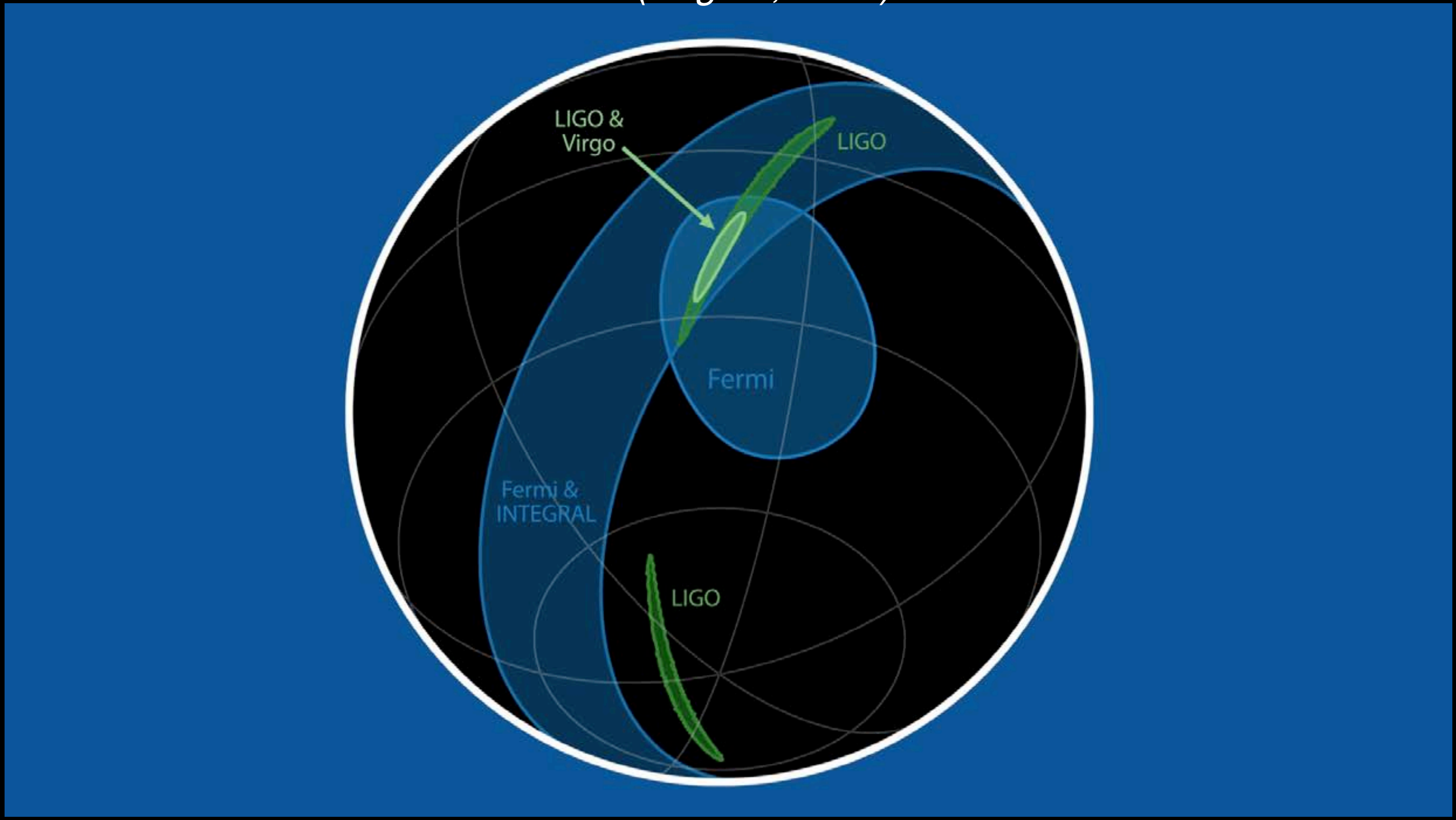

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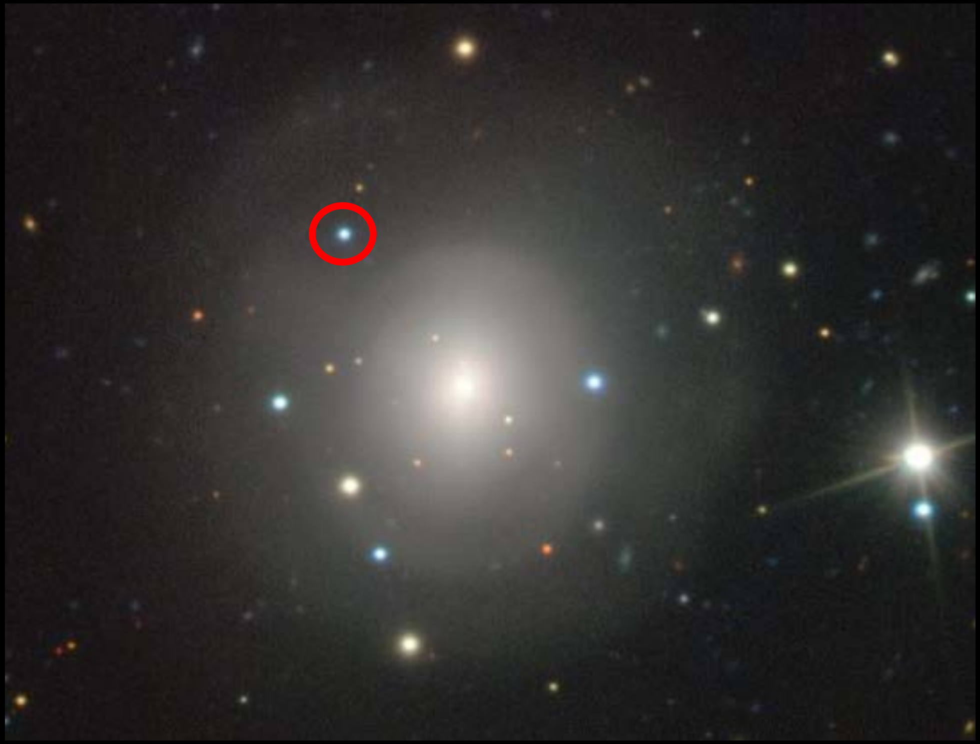
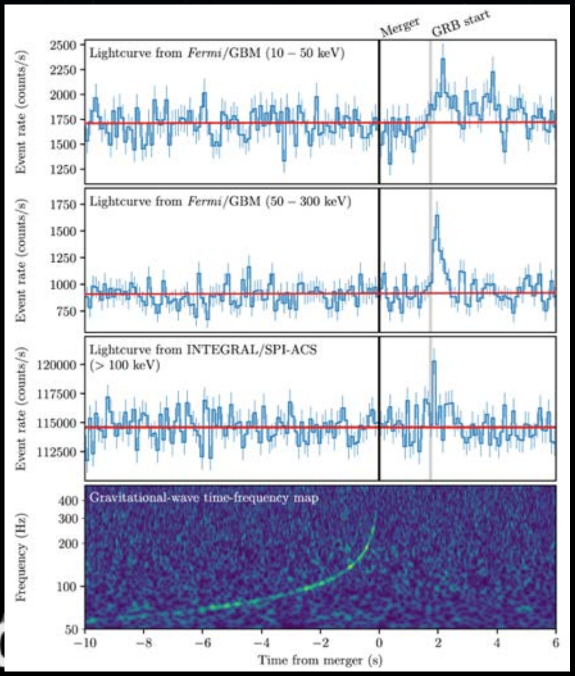


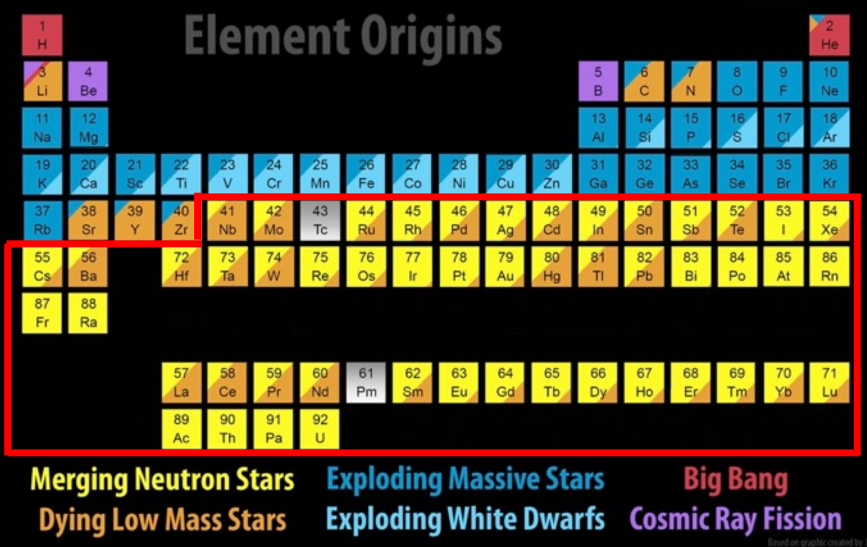
Galaxy NGC 4993

The First Gravitational-wave Multi-Messenger Event GW170817

(Aug 17, 2017)

Binary neutron star merger (Credit: NASA)





Together

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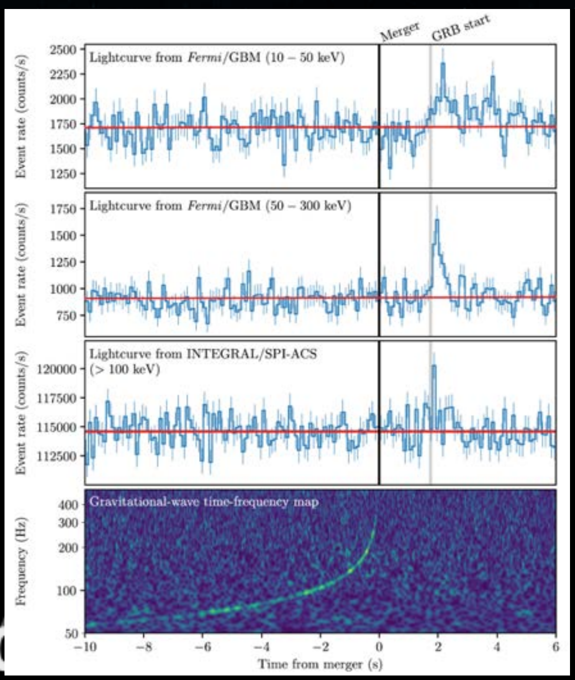
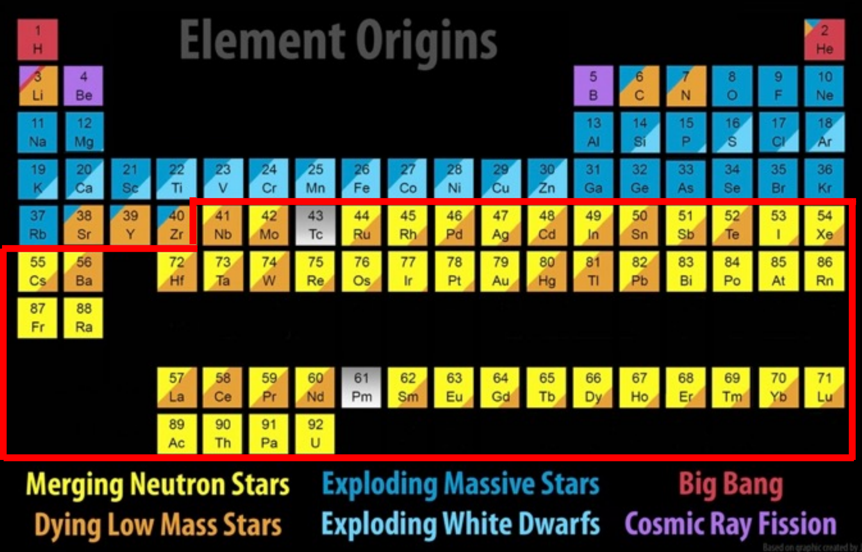
Binary neutron star merger (Credit: NASA)





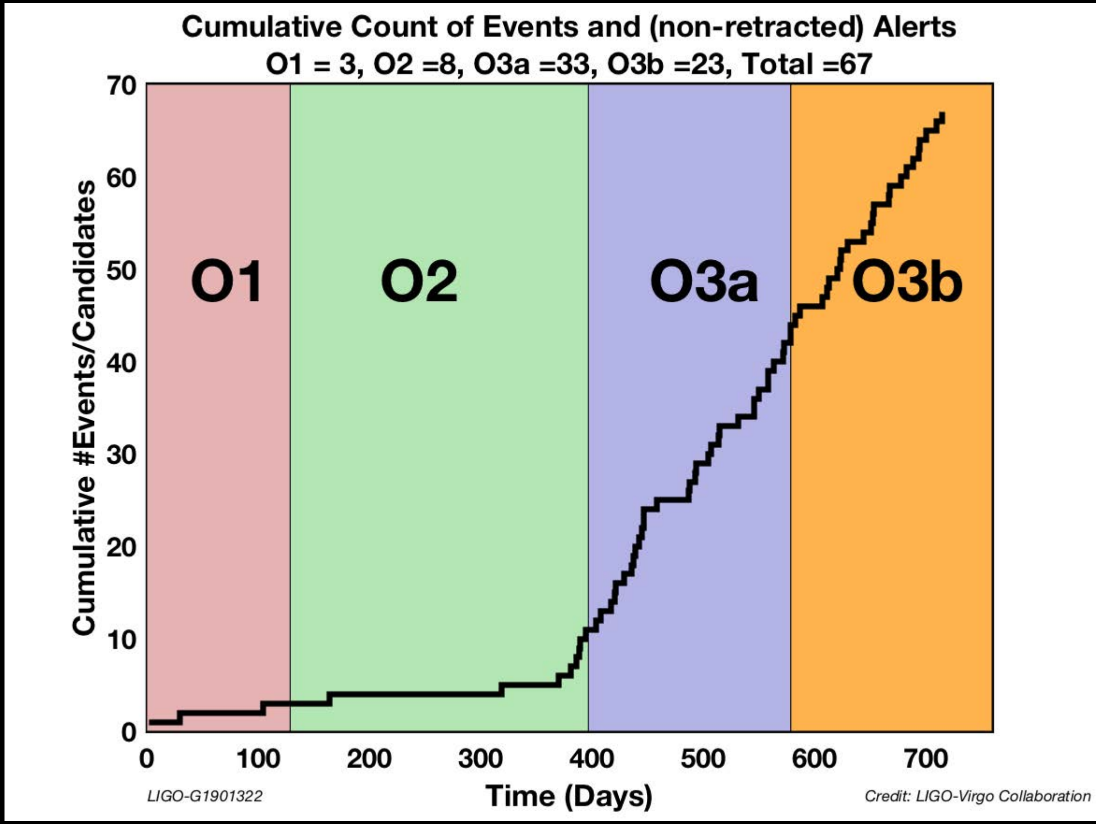
Together

Selected Highlights from the LIGO-Virgo O3 Run

The LIGO-Virgo O3 Observing Run

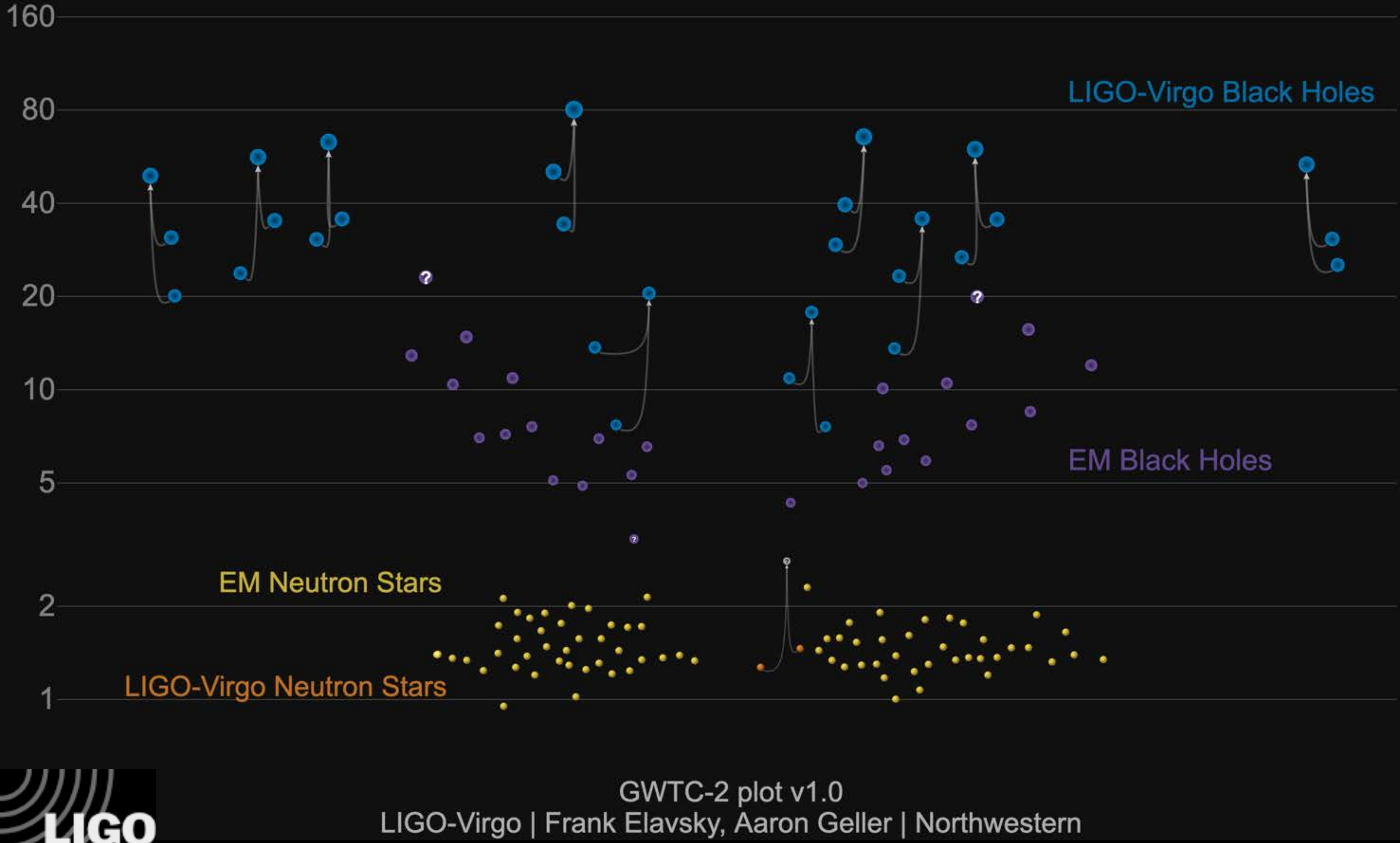
- The LIGO-Virgo observing run 'O3'
  - **O3a** from Apr 1, 2019 to Sept 30, 2019
  - **O3b** from Nov 1, 2019 to Mar 27, 2020
  - Run ended one month earlier than planned early due to COVID-19
- The LIGO and Virgo detectors were operating in their most sensitive configurations to date:
  - LIGO Livingston: 142 Mpc* (463 Mly)
  - LIGO Hanford: 120 Mpc* (391 million lightyears)
  - Virgo: 61* Mpc (199 Mly)
- …and also had the best 'uptime' to date:
  - Triple coincidence 47.4% of O3

*range is to a binary neutron star merger averaged over sky and orbital orientation



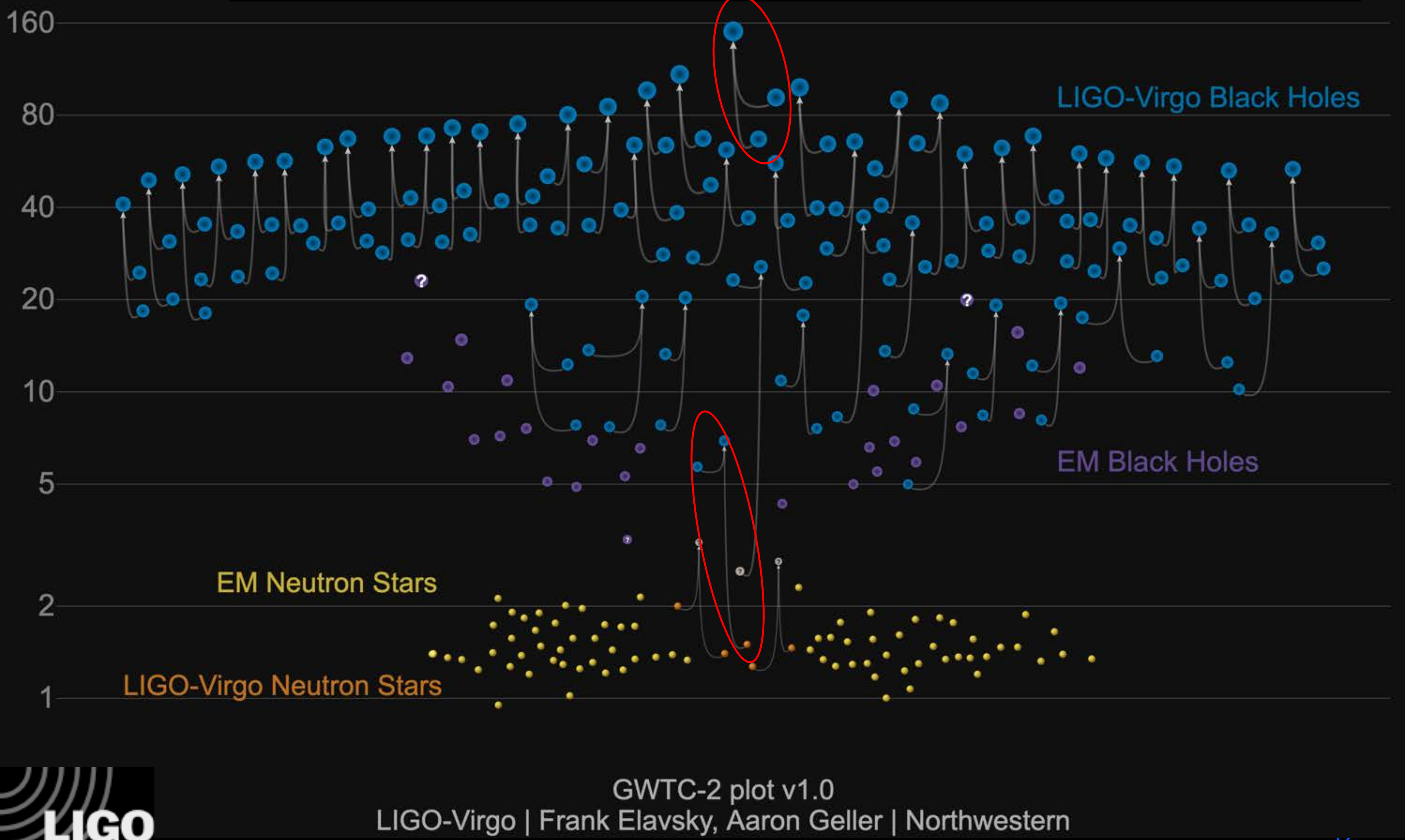
A gravitational wave event candidate was detected about once every six days

Detected Events in the First Two LIGO-Virgo Observing Runs



LIGO

Detected Events in the First Two LIGO-Virgo Observing Runs and the O3a Run

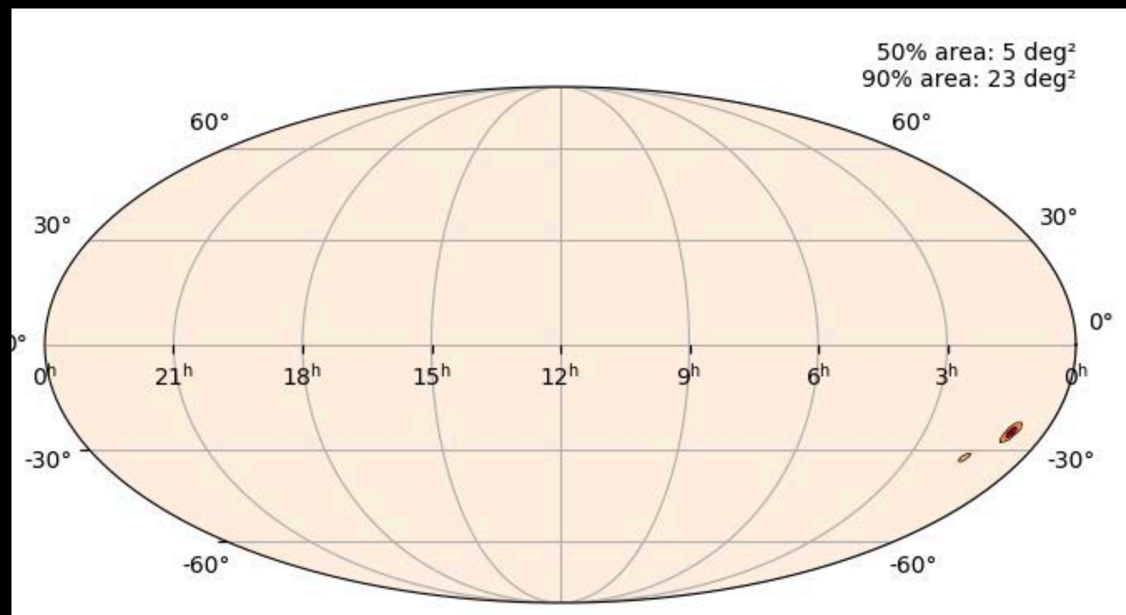


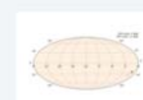
Localizing Gravitational-wave Events: ‘It’s Complicated’

The ability to localize GW events depends on:

- The number of GW detectors online
  - More is better!
  - Also depends on sensitivities of the observatories
- Location of the GW source on the sky
  - Optimal positions for GW observatory network
- Distance to event -> larger (‘louder’) signal
  - Closer is better
- The parameters of the GW source -> larger (‘louder’) signal
  - Masses, orbital orientation
- Coincidence with other ‘messengers’
  - Gamma rays, X-ray, UV, optical/IR, radio, neutrinos

GW190814 (black hole - ?? merger)
90% localization contour: 23 deg^2
50% localization contour: 5 deg^2



S190814bv	NSBH (>99%)	Aug. 14, 2019 21:10:39 UTC	GCN Circulars Notices | VOE		1 per 1.559e+25 years

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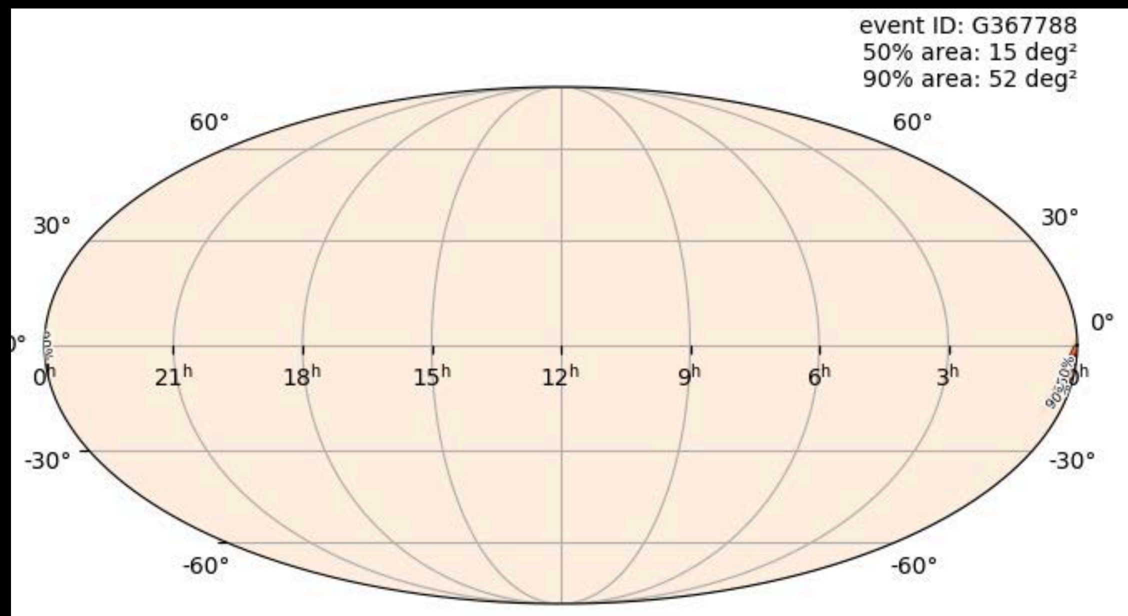
S2000311bg (under evaluation)
90% localization contour: 52 deg²
50% localization contour: 15 deg²



S200311bg	BBH (>99%)	March 11, 2020 11:58:53 UTC	GCN Circulars Notices | VOE		1 per 3.5448e+17 years

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- The parameters of the GW source -> larger ('louder') signal
  - Masses, orbital orientation
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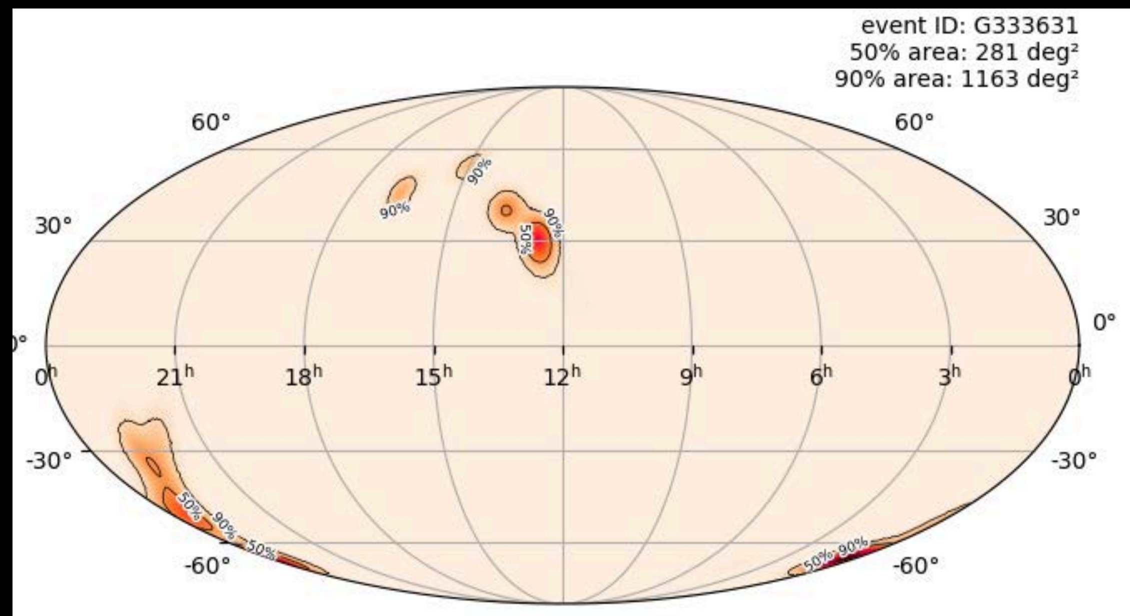
GW190521 (black hole – black hole merger)
90% localization contour: 1163 deg^2
50% localization contour: 281 deg^2



S190521g	BBH (97%), Terrestrial (3%)	May 21, 2019 03:02:29 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years

LIGO

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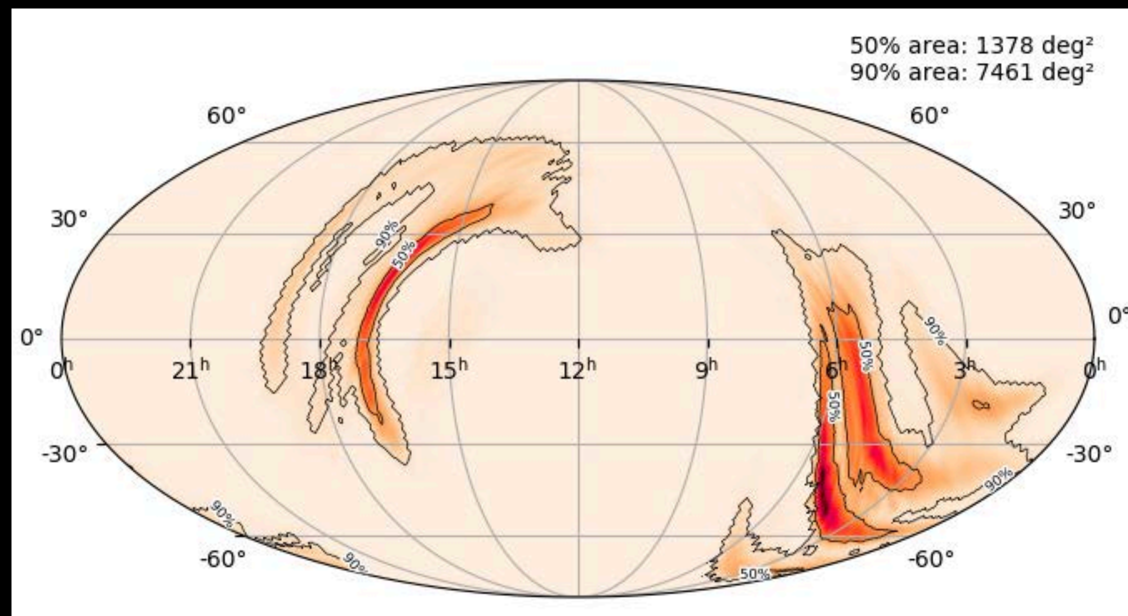
Localizing Gravitational-wave Events: ‘It’s Complicated’

The ability to localize GW events depends on:

- The number of GW detectors online
  - More is better!
  - Also depends on sensitivities of the observatories
- Location of the GW source on the sky
  - Optimal positions for GW observatory network
- Distance to event -> larger (‘louder’) signal
  - Closer is better
- The parameters of the GW source -> larger (‘louder’) signal
  - Masses, orbital orientation
- Coincidence with other ‘messengers’
  - Gamma rays, X-ray, UV, optical/IR, radio, neutrinos

GW190425 (neutron star – neutron star merger)
90% localization contour: 7461 deg^2
50% localization contour: 1378 deg^2



S190425z	BNS (>99%)	April 25, 2019 08:18:05 UTC	GCN Circulars Notices | VOE		1 per 69834 years

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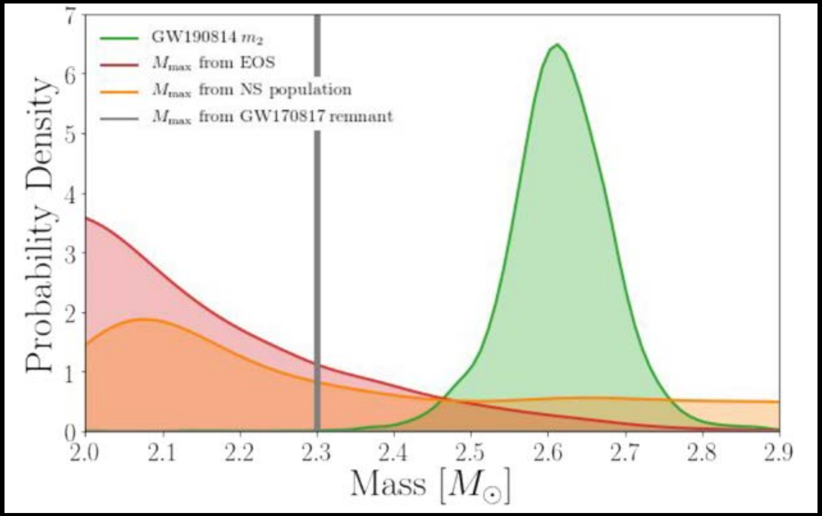
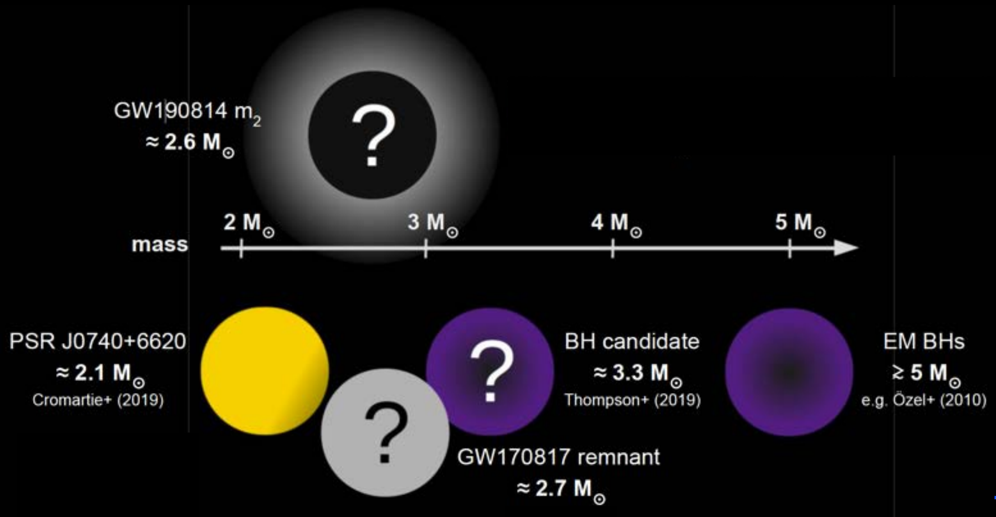
Mystery Merger: GW190814
(Aug 14, 2018)

- The most asymmetric mass ratio merger ever observed, with a mass ratio $m_1/m_2 = 9$
- The secondary mass of 2.6 M_{sun} lies in a *'mass gap'*;
  - it's greater than estimates the maximum possible NS mass and less than masses of the lightest black holes ever observed
  - Mass of this object comparable to the final merger product in GW170817, which was more likely a black hole.
- How did this system form? This detection again challenges existing binary formation scenarios
  - young dense star clusters and disks around active galactic nuclei are slightly favored, but many other possibilities
- Many follow up observations by electromagnetic observatories, but no confirmed counterpart found



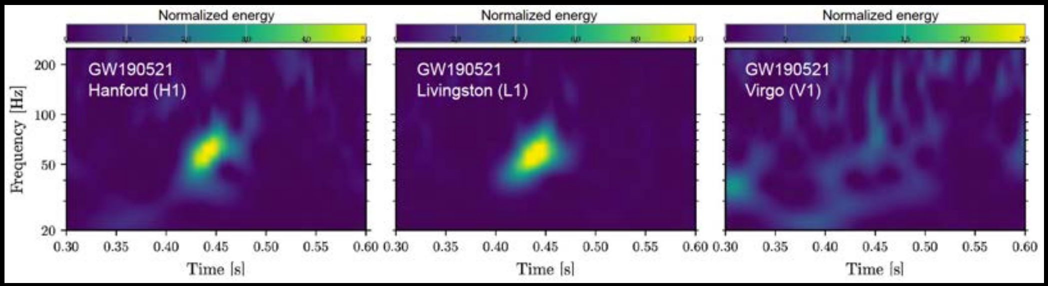


Abbott, et al., "GW190814: Gravitational Waves from the Coalescence of a 23 M_{sun} Black Hole with a 2.6 M_{sun} Compact Object, Ap. J. Lett. 896, L44 (2020)

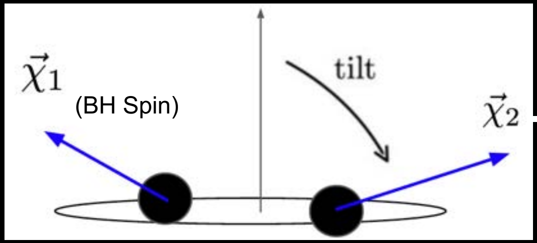
The Most Massive & Distant Black Hole Merger Yet: GW190521

(May 21, 2019)

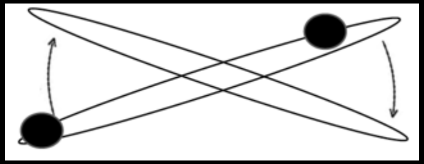
- Many new discoveries and insights from GW190521!
- The furthest GW event ever recorded: ~ 7 Glyr distant
- At least one of the progenitor black holes (85 M_{sun}) lies in the pair instability supernova gap
  - Stars with helium cores in the mass range 64 - 135 M_{sun} undergo an instability and obliterate upon explosion
- The final black hole mass (85 M_{sun}) places it firmly in the intermediate mass category (between 10^2 – 10^5 M_{sun}) → *the first ever observation of an intermediate mass black hole*
- Strong evident for spin precession; both progenitor black holes were spinning
  → Implications for how these black holes formed
  - Hierarchical black hole mergers?
  - Hierarchical giant He core – main sequence merger in dense star clusters?
  - Mergers in the gaseous environments of active galactic nuclei?

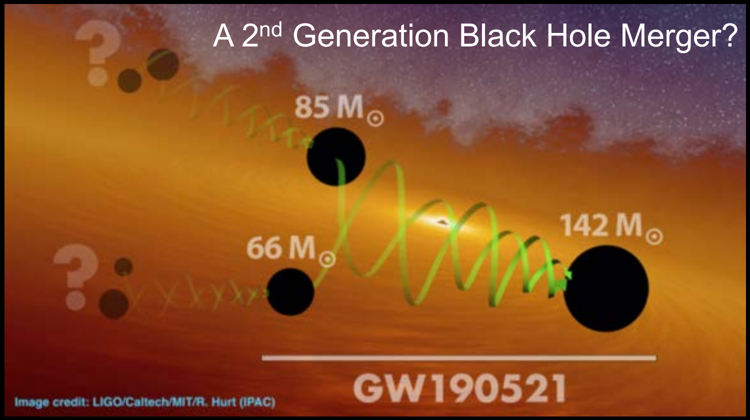


Orbital Angular Momentum



Orbital Plane Precession



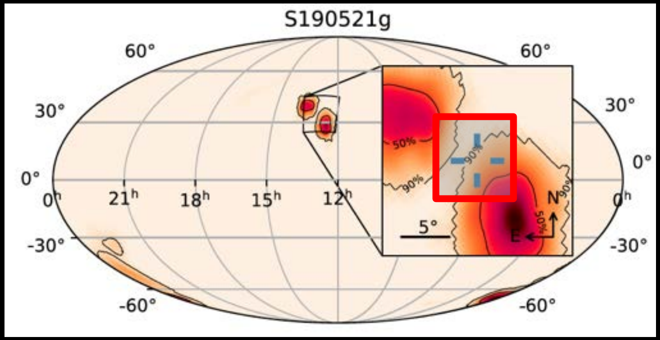


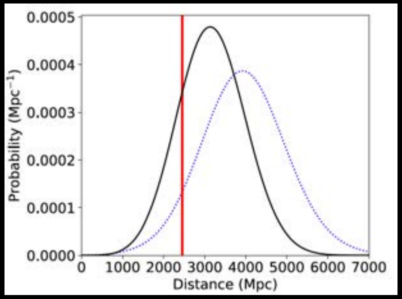
Abbott, et al., "GW190521: A Binary Black Hole Merger with a Total Mass of 150 M_{sun}, Phys. Rev. Lett. 125, 101102 (2020).

Abbott, et al., "Properties and Astrophysical Implications of the 150 M_{sun} Binary Black Hole Merger GW190521, Ap. J. Lett. **900**, L13 (2020).

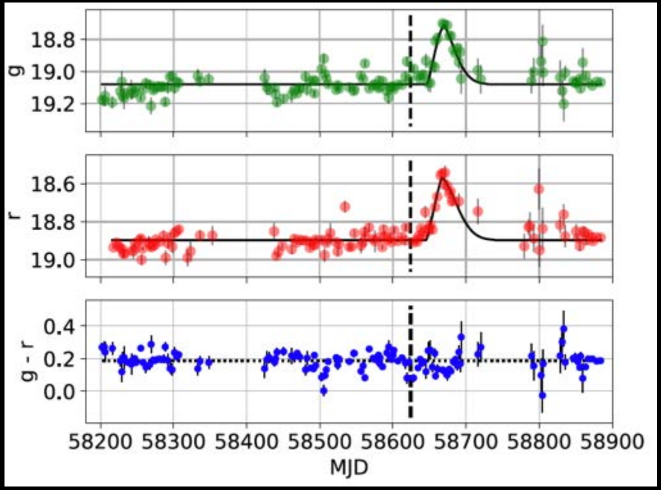
A Possible Electromagnetic Counterpart to GW1901521?

- Zwicky Transient Facility surveyed 48% of the LIGO-Virgo 90% error box for GW190521
- An electromagnetic flare in the visible was found within the initial 90% LIGO-Virgo contour beginning ~ 25 days after GW190521, lasting for ~ 100 days
  - Consistent with LIGO-Virgo initial distance estimates
  - But less consistent with updated maps
- The EM flare is consistent with emission from gas in the accretion disk an active galactic nucleus (AGN) excited by the 'kicked' black hole passing through the AGN disk
- Graham, et al. estimate the final black hole mass to be ~ 100 M_{sun} with significant spin





EM Flare from S190521g (g-band, r-band)

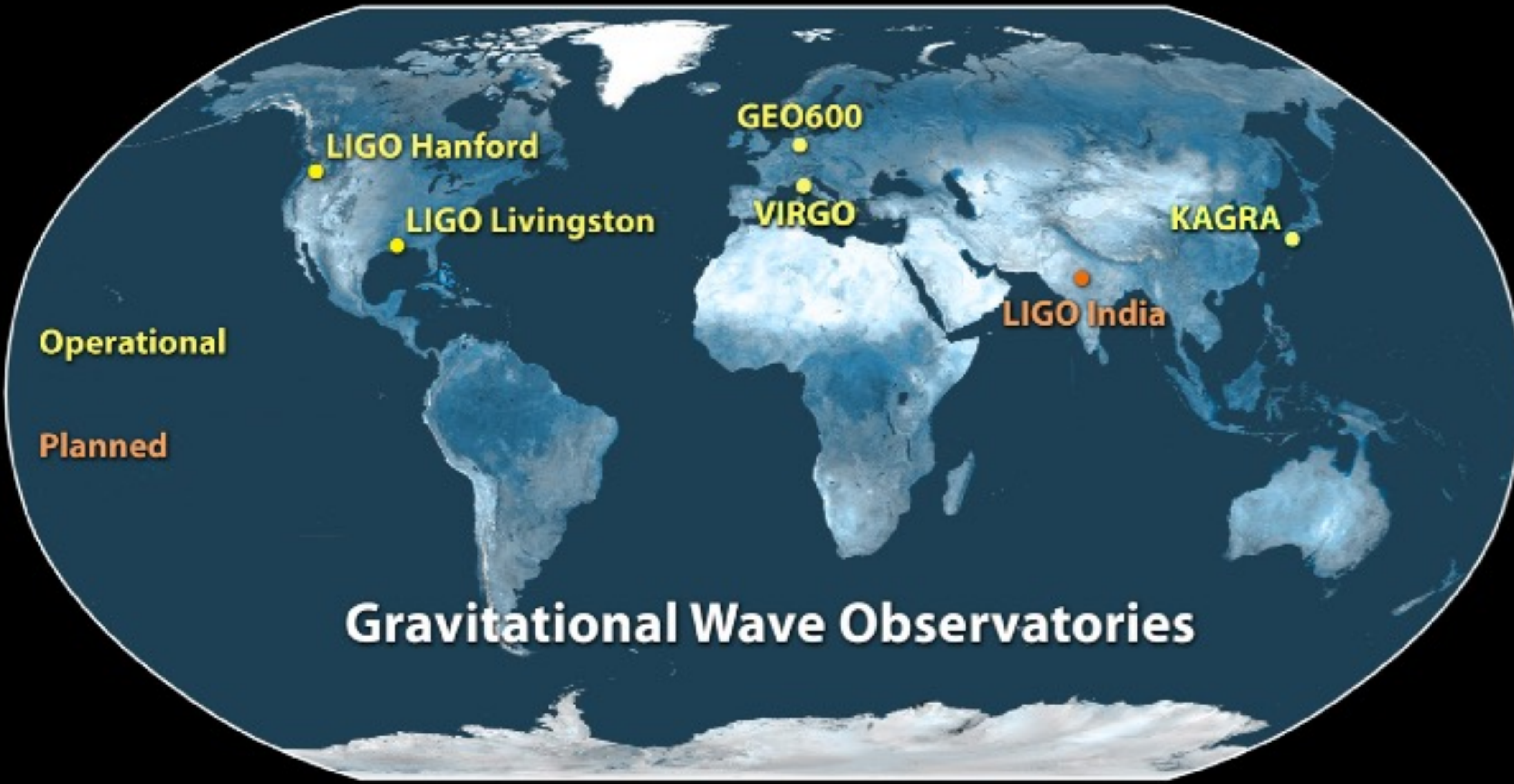


Graham, et al., "Candidate Electromagnetic Counterpart to the Binary Black Hole Merger Gravitational-Wave Event S190521g*, Phys. Rev. Lett. **124**, 251102 (2020).

Future Run and Upgrade Plans

For the Global Gravitational–wave Observatory Network

The Global Ground-based Gravitational-wave Observatory Network in the 2020s

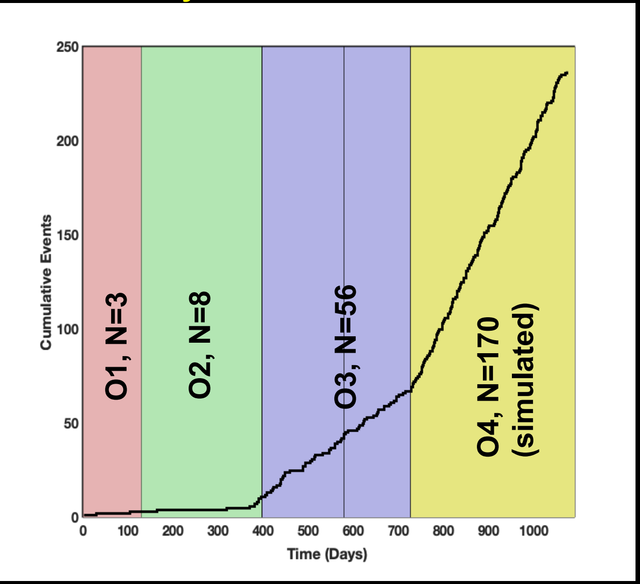


The Next O4 Observing Run

- LIGO and Virgo are currently engaged in an extended upgrade period in advance of the next O4 observing run
  - Advanced LIGO 'A+' and Advanced Virgo + upgrade program will implement frequency-dependent squeezing to reduce low frequency noise
    - NSF: $20.5M
    - UK STFC: $12.0M
    - Australia ARC: $600k
  - Also, LIGO will replace many of the primary 'test mass mirrors
- O4 will include the two LIGO Observatories, the Virgo Observatory, and the KAGRA Observatory
  → *the first LIGO-Virgo-KAGRA 4-detector run*
- Target sensitivities (binary neutron star inspiral range):
  - LIGO: 160-190 Mpc (520 - 620 Mly)
  - Virgo: 90 MPc (200 Mly)
  - KAGRA: 25 - 130 MPc (80 - 425 Mly)

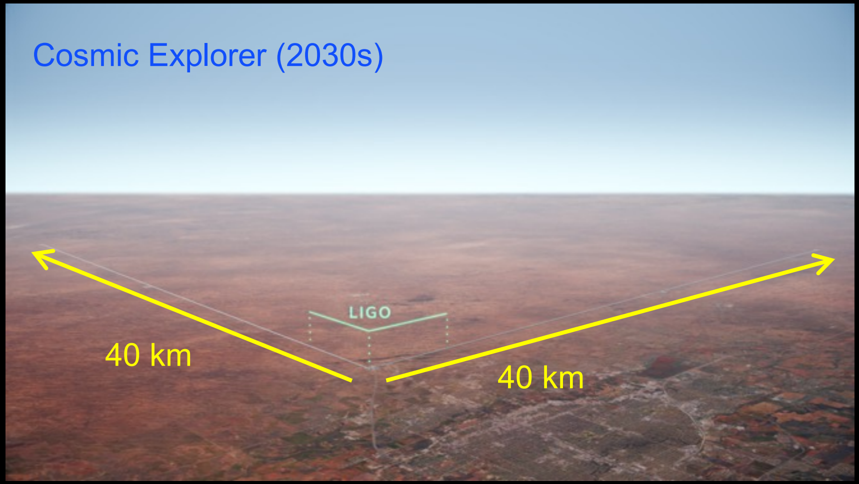
  →*A 2X to 3X increase in GW event rate*
- *O4 will start no earlier than June 2022*
- O4 run duration is still not set, but likely somewhere in the 12 – 18 month range

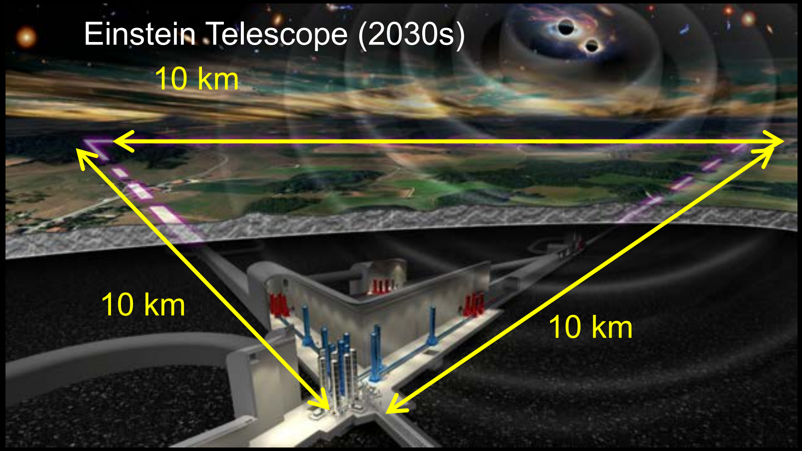
Simulated Event Stream for a one year duration O4 run



Further in the Future

- After O4, another break will be taken to complete upgrades and to continue improving KAGRA 's sensitivity
  - Start and end states are to be determined
- Following these upgrades, the O5 run is planned in the middle of the decade
  - ***A few events every day!***
- Later this decade: LIGO-India
  - A third LIGO Observatory identical to two US LIGO Observatories located in Maharashtra, India
  - Project approved by India in 2016, now awaiting construction funding
- 2030s: Aiming for the construction of a new generation of GW observatories targeting a 10X increase in sensitivity over the current GW observatory network
  - Europe: Einstein Telescope
  - USA: Cosmic Explorer





- The LIGO-Virgo O3 run completed in late March 2020, with 56 event candidates
  - A number of exceptional events have been reported, including GW190814, GW190521
- A possible electromagnetic counterpart reported to GW190521 (resulting from a binary black hole merger!)
- The O4 run will include LIGO and Virgo detectors (improved with respect to O3) as well as the new KAGRA detector
- We are aiming to begin the O4 Observing Run in the summer of 2022

Acknowledgements:
LIGO Laboratory
LIGO Scientific Collaboration
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Virgo Collaboration
NSF
Caltech
MIT