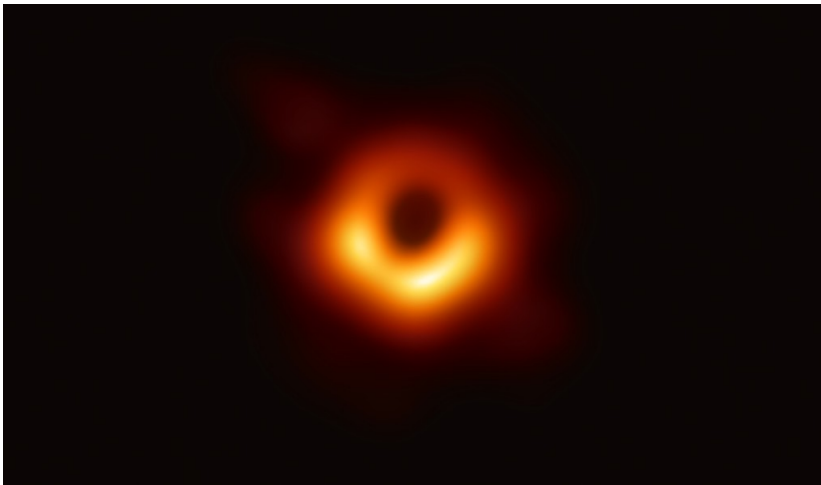


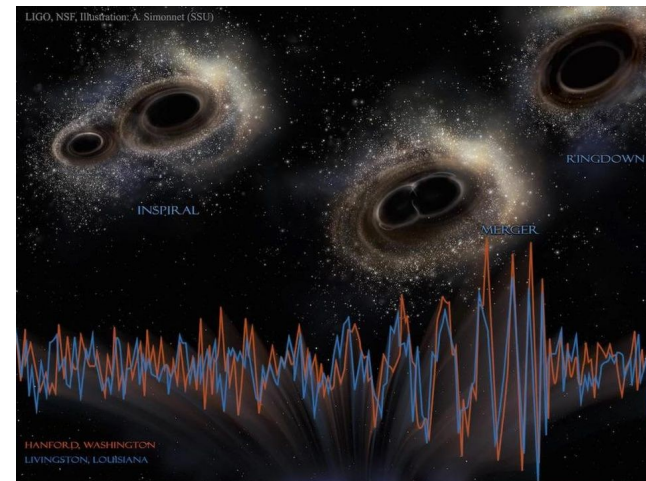
# Event Horizon Telescope and LIGO Gravitational Waves---News



Bill Gabella

Monday 24 June 2019

Vanderbilt-QuarkNet Workshop



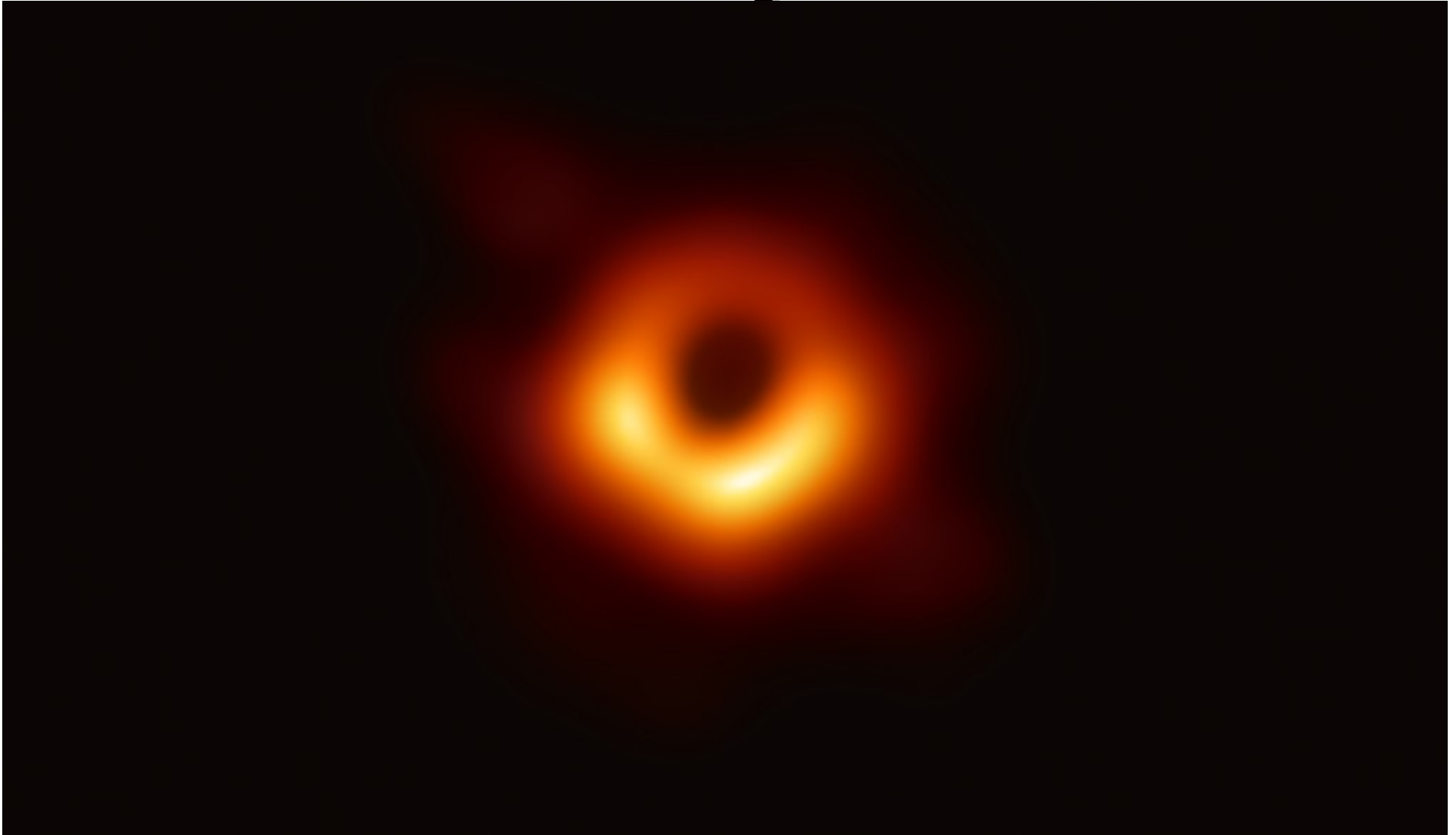
Ref: <https://eventhorizontelescope.org/>

Ref: <https://gracedb.ligo.org/>

# Event Horizon Telescope (EHT)---the Announcement

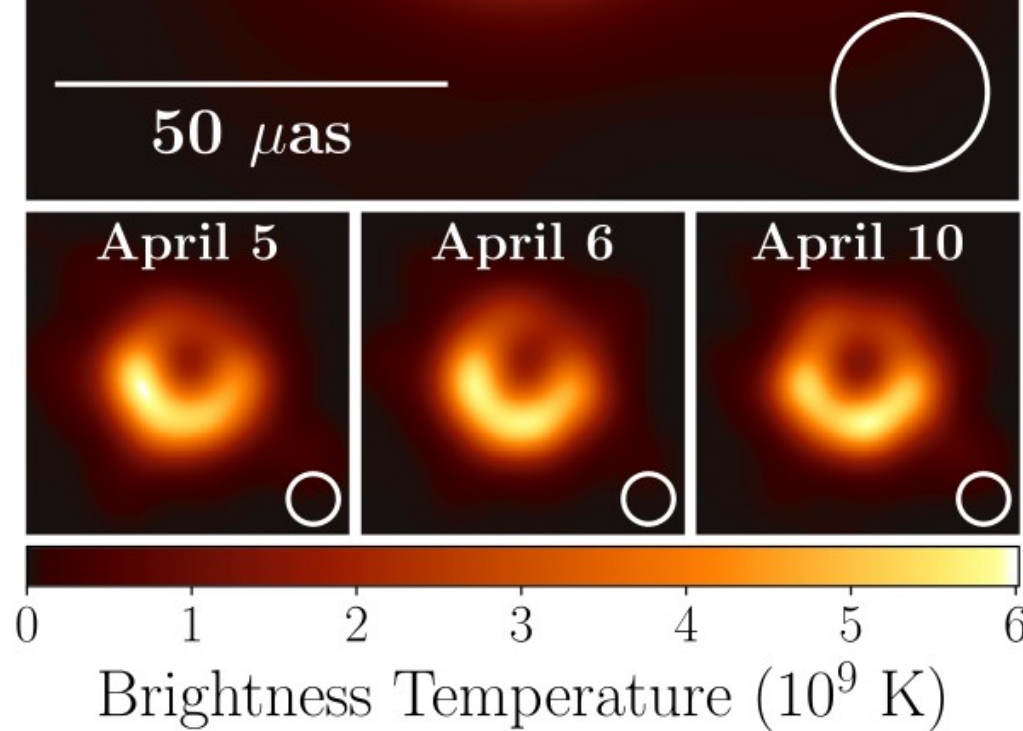
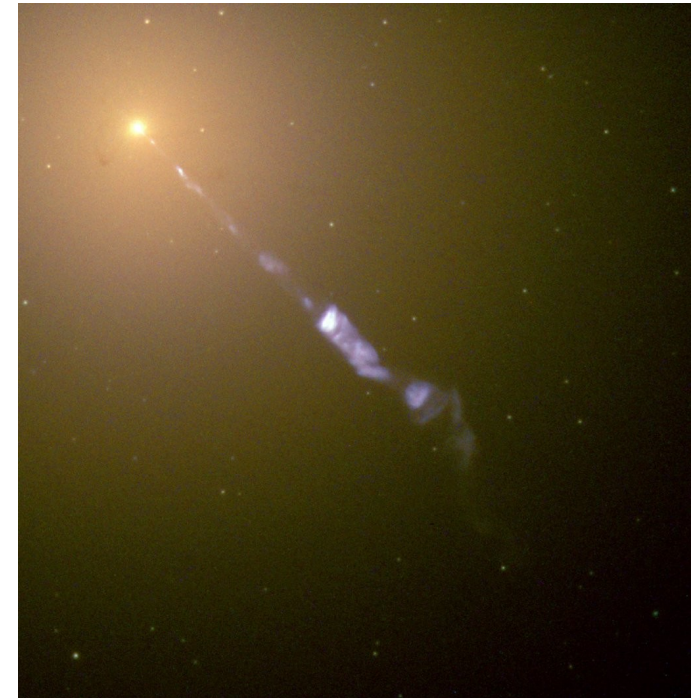
- Announced on 10 April 2019 for image of M87\* (the supermassive black hole at the center of the galaxy M87).
  - Press Conference <https://youtu.be/InJi0Jy692w>
- Data taken April 2017 and stored on hard drives from 8 radio telescopes around one hemisphere of the Earth.
- Imaged the light (radio waves) emitted around the SMBH M87\* as it reached us. Shows a “shadow” characteristic of, and related to, the size of the event horizon of the black hole.
- Also they have data for Sgr A\*, the SMBH in the Milky Way. For which they do not have image reconstructions yet.
- Routinely imaged a well known quasar, aka active galactic nuclei (AGN), 3C 279 for calibrating the array of radio telescopes.

# Event Horizon Telescope (EHT)---the Image



- Intensity of 1.3 mm (240 GHz) radio waves coming from M87 \*.

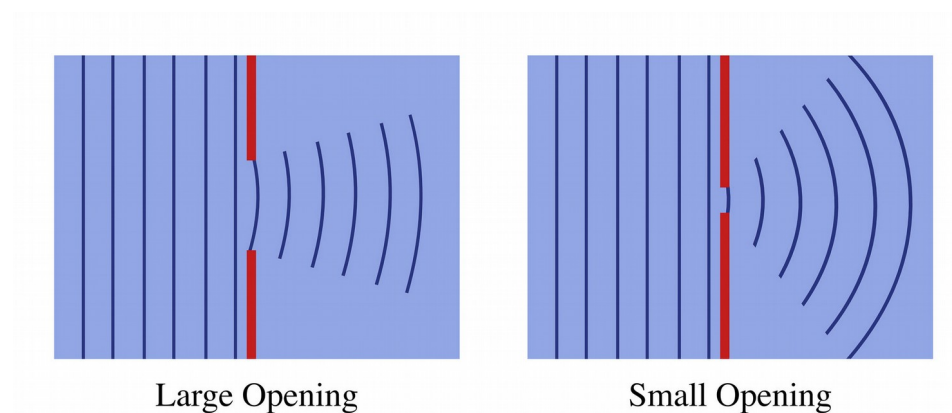
## Galaxy M87 and its Jet from M87\*



**Figure 3.** Top: EHT image of M87\* from observations on 2017 April 11 as a representative example of the images collected in the 2017 campaign. The image is the average of three different imaging methods after convolving each with a circular Gaussian kernel to give matched resolutions. The largest of the three kernels ( $20 \mu\text{as}$  FWHM) is shown in the lower right. The image is shown in units of brightness temperature,  $T_b = S\lambda^2/2k_B\Omega$ , where  $S$  is the flux density,  $\lambda$  is the observing wavelength,  $k_B$  is the Boltzmann constant, and  $\Omega$  is the solid angle of the resolution element. Bottom: similar images taken over different days showing the stability of the basic image structure and the equivalence among different days. North is up and east is to the left.

# Diffraction

- Light's wave nature leads to the spreading of a beam of light.
  - Both for the creation of the beam and for the imaging of the beam.
- The so-called self-diffraction gives rise to an angle related to the wavelength and the beam diameter.



$$\theta \sim \frac{\lambda}{D}$$

Same wavelength, different beam sizes.

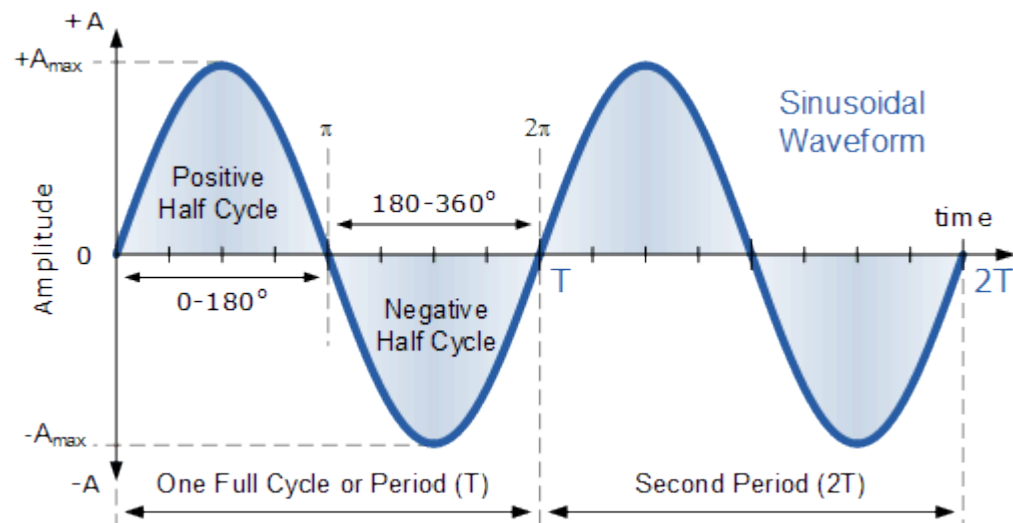
# Resolving Small, Far Things

- For the telescope, diffraction limits resolution of angles to  $\theta \sim \frac{\lambda}{D}$ 
  - Baselines 160 m to 10700km and 1.3mm for ~25 micro arc-sec resolution.
- And the angular size of a (nearby-ish) object is  $\theta \sim \frac{diam}{dist}$
- Sgr A\* is 8.178 kpc away and the Schwarzschild diameter is about 0.16 AU, so it subtends an angle of 9.6e-11 rads, aka 19.8 micro arc-sec.
- M87\* is 16.4 Mpc away and “diameter” is 257 AU for an angle of 7.6e-11 rads or 15.7 micro arc-sec.
- “Shadow” is  $3 \cdot \sqrt{3} / 2 = 2.6$  diameters, or 51.5 and 40.8 micro arc-secs.



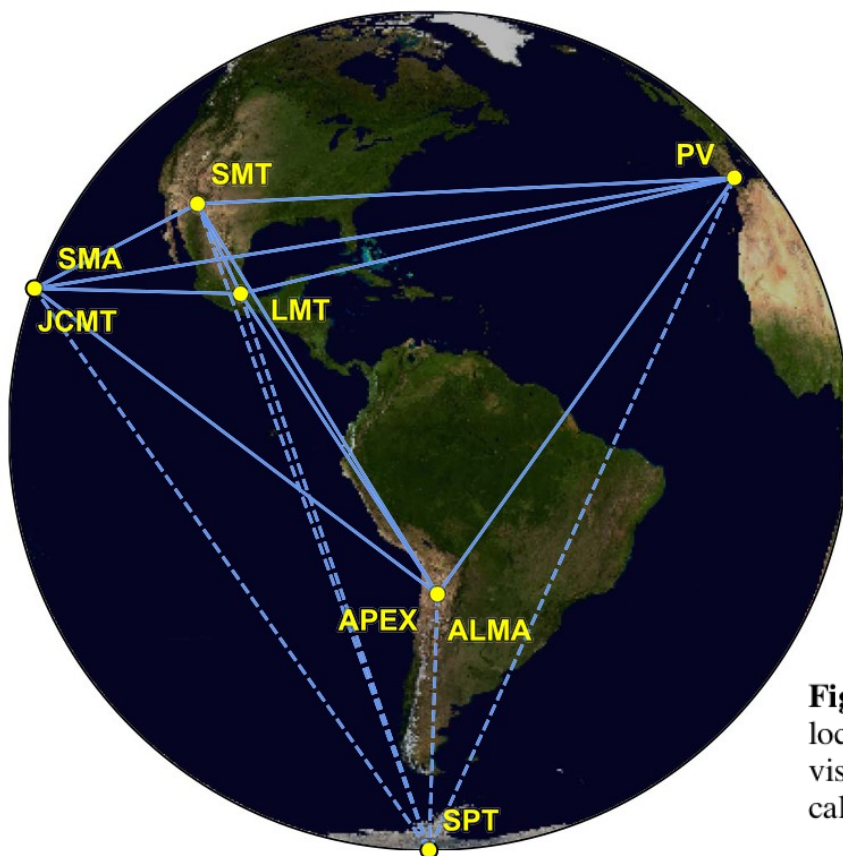
# Light/Radio at $\lambda = 1.3$ mm

- 1.3 mm wavelength, is a frequency of 230 GHz, is a period of  $4.3\text{e-}12$  sec
- Bandwidth is important, and aggregate BW was 16 GHz (ALMA)
- Mix with 230 GHz wave to see the BW signal, so final sine wave is 16 GHz.
- Record data at a rate 64 Gbps (32x the standard VLBI array)
  - So 4 points per 16 GHz wavelength



# Array of Radio Telescopes---VLBI

- VLBI = Very Long Baseline Interferometry
- Sometimes array of arrays of telescopes: SMT, SMA, JCMT, LMT, PV, APEX, ALMA, and SPT.



SMT = Sub-Millimeter Telescope

SMA = Sub-Millimeter Array

JCMT = James Clerk Maxwell Telescope

LMT = Large Millimeter Telescope Alfonso  
Serrano

PV = Pico Veleta 30 m

APEX = Atacama Pathfinder Experiment  
Telescope

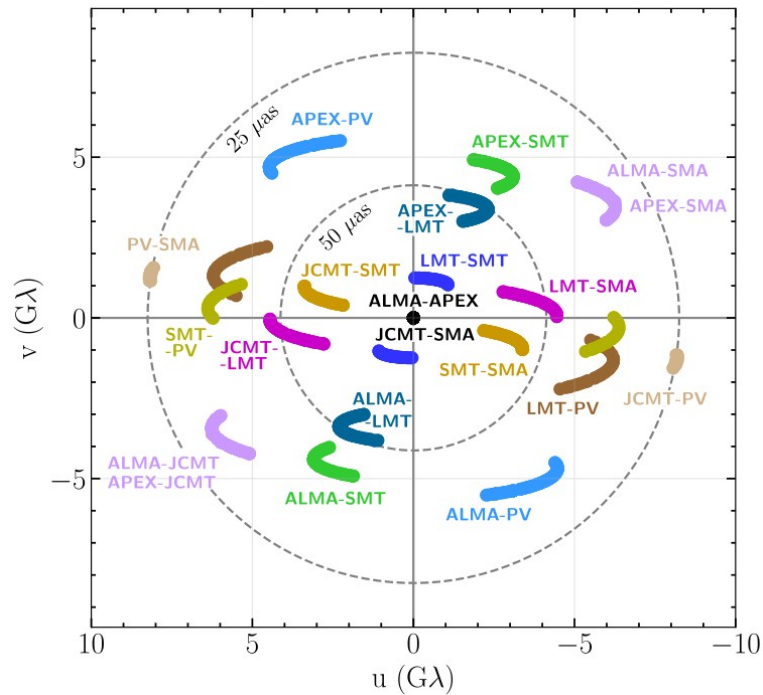
ALMA = Atacama Large Millimeter/  
Submillimeter Array

SPT = South Pole Telescope

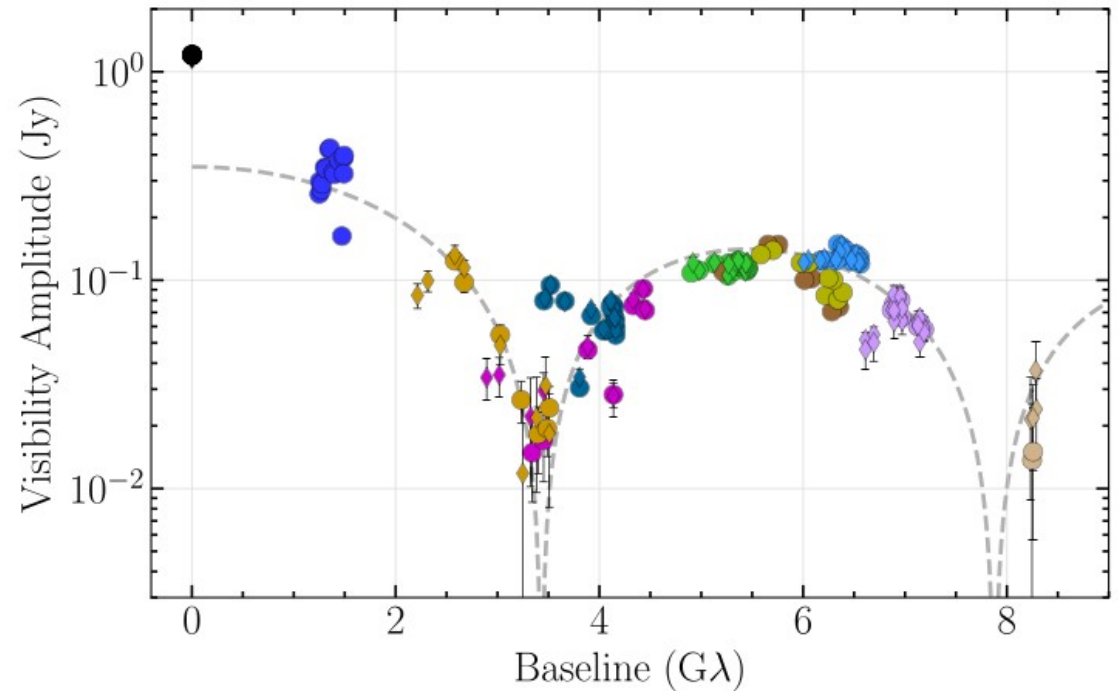
**Figure 1.** Eight stations of the EHT 2017 campaign over six geographic locations as viewed from the equatorial plane. Solid baselines represent mutual visibility on M87\* (+12° declination). The dashed baselines were used for the calibration source 3C279 (see Papers [III](#) and [IV](#)).



# EHT Array Images Target at Same Time

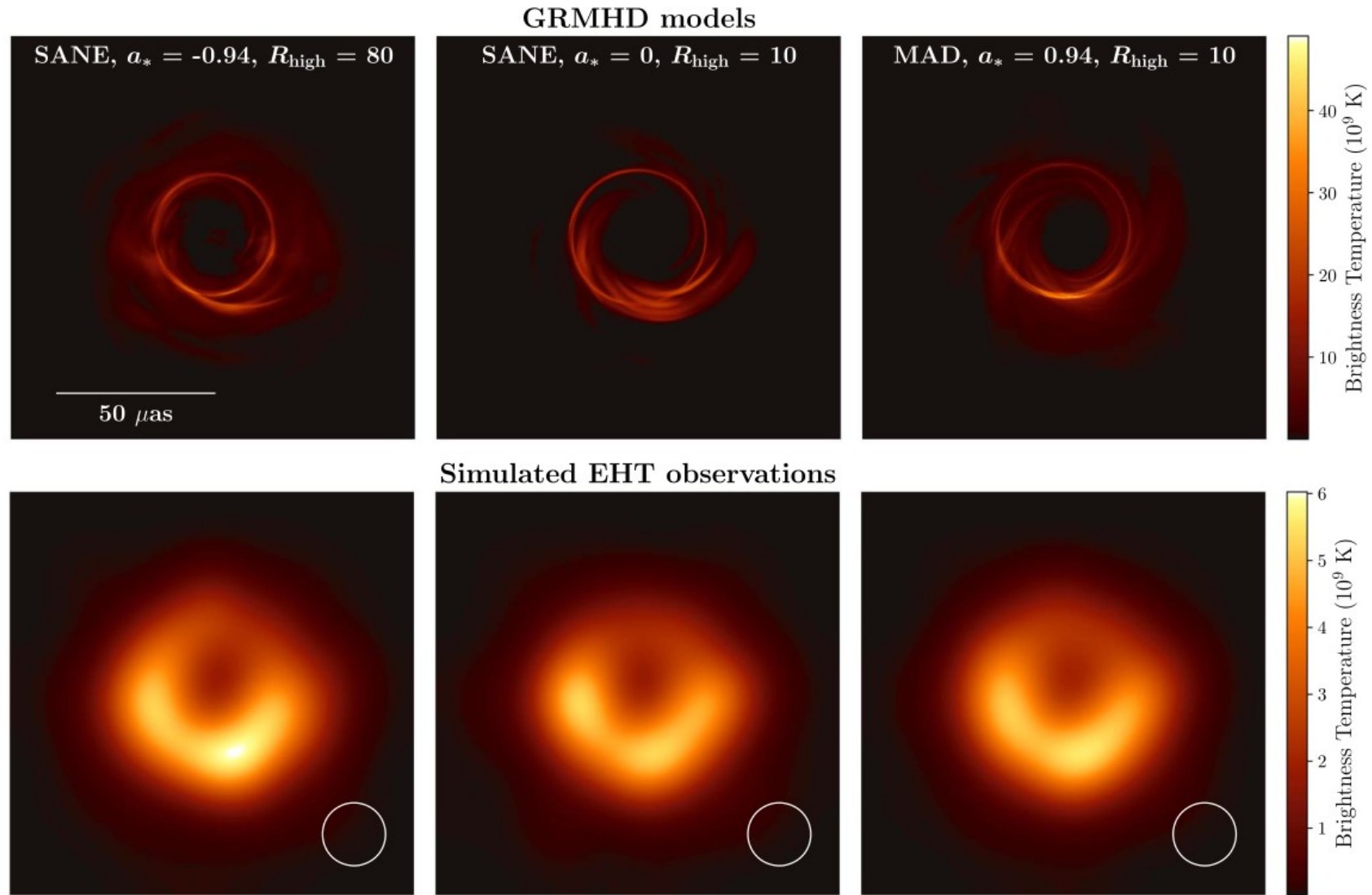


The EHT Array as a  
“Radio Telescope Dish”



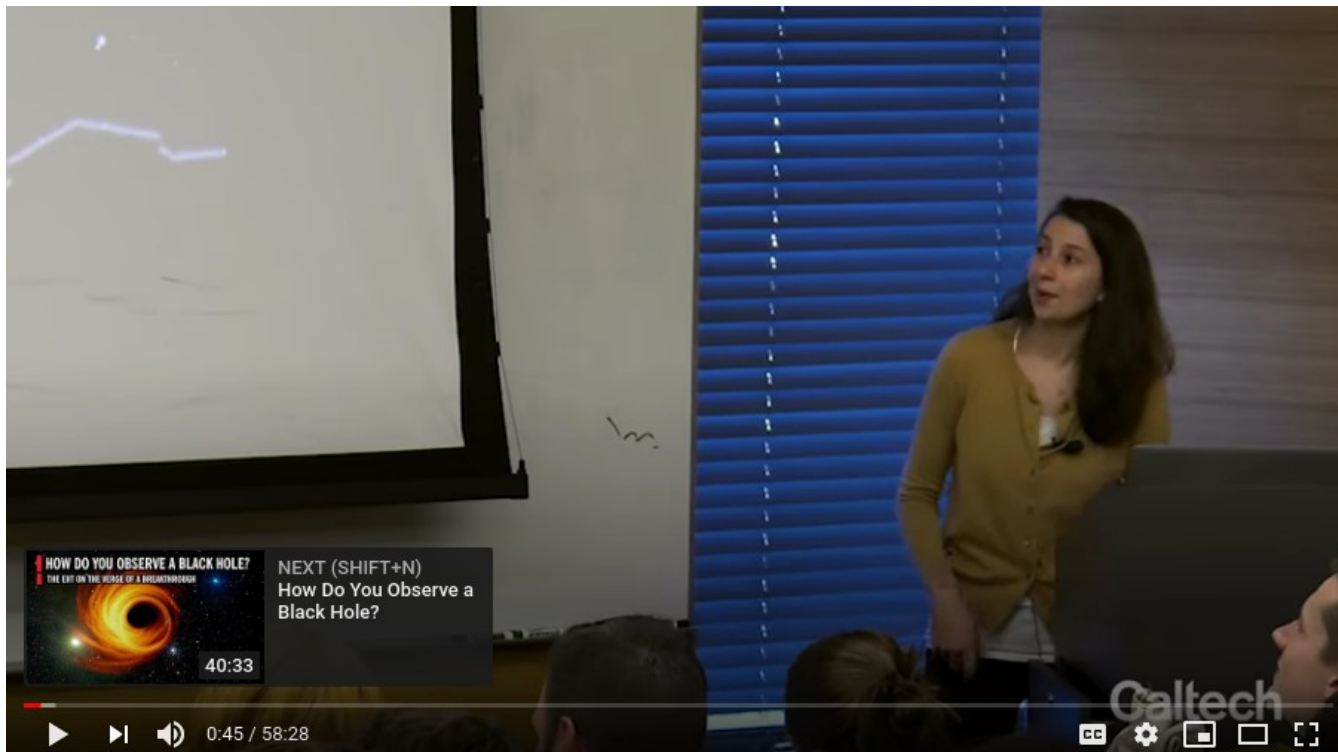
EHT Array acts as if on a mirror

# Image from a lot of processing!



# Katie Bouman's Talk at CalTech

- Bouman worked on the imaging analysis  
[https://youtu.be/UGL\\_OL3OrCE](https://youtu.be/UGL_OL3OrCE)
- aa





# Gravitational Waves – aLIGO & VIRGO

VIRGO, Cascina, Italy



LIGO, Livingston, LA

LIGO, Hanford, LA



# Gravitational Waves – aLIGO & VIRGO

- aLIGO = Advanced Laser Interferometer Gravitational-Wave Observatory, <https://www.ligo.org/> and <https://www.ligo.caltech.edu/>
- Restarted observations on 1 April 2019, so-called “O3” run.
- Seeing a binary black hole merger every week, more or less, <https://gracedb.ligo.org/latest/>

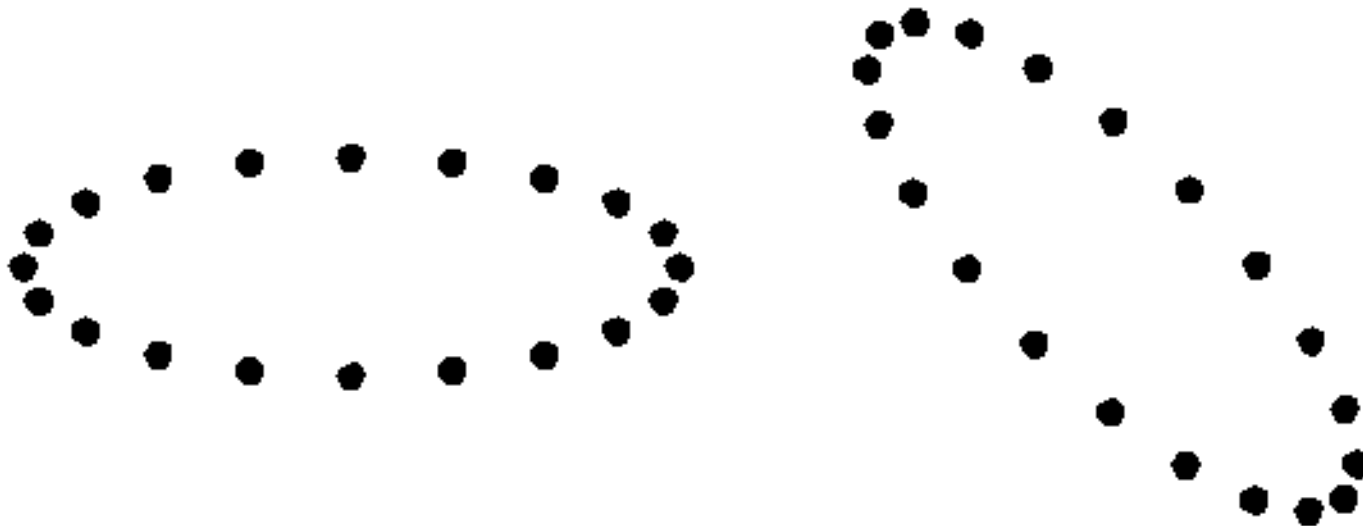


# Gravitational Waves – In a Picture

- Source of Gravitational Waves is mass-energy motion that is not spherically symmetric.
- Strong GW sources have small sizes, high mass, and fast motion.
- The first “order” in the expansion is quadrupole radiation.
  - In Electricity and Magnetism it is dipole radiation.

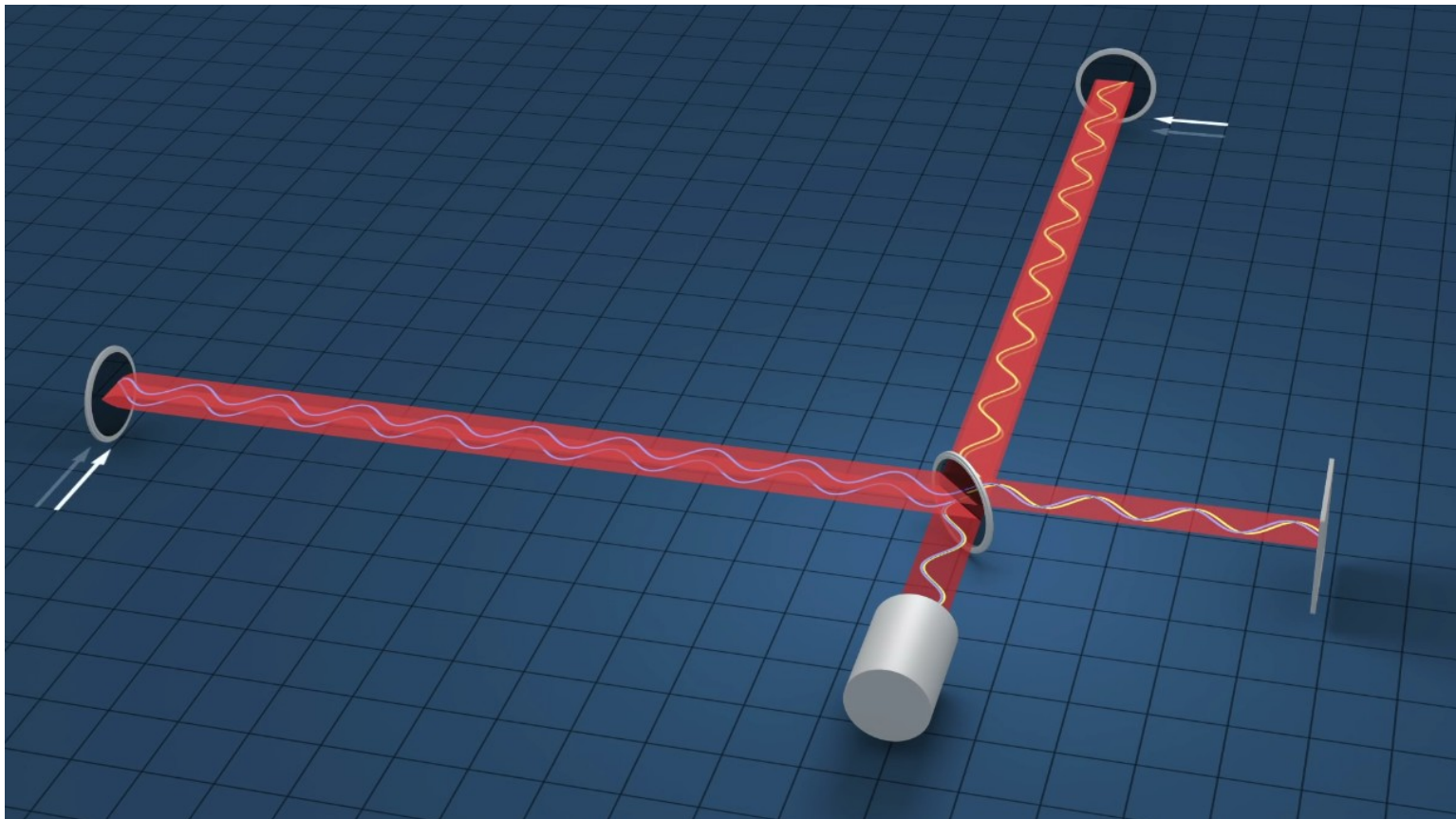
# Gravitational Waves – In a Picture

- Two modes, + and X
- Dots are masses hanging out in space with little self-attraction. They are NOT a metal ring! That is bound by atomic forces and the effect of the GW is miniscule.



# Big Michelson Interferometer, 4 km arms


- YouTube link [https://youtu.be/tQ\\_telUb3tE](https://youtu.be/tQ_telUb3tE)





# LIGO GraceDB Latest

- Gracedb Latest at <https://gracedb.ligo.org/latest/>

→ [https://gracedb.ligo.org/latest/?query=&query\\_type=S&get\\_neighbors=&results\\_format=](https://gracedb.ligo.org/latest/?query=&query_type=S&get_neighbors=&results_format=) ☆ ABP 01 |  :  
Apps GWs Physics CERN Software Hardware Vandy Misc Web Meet Google D... ★ Bookmarks | Other bookmark

## GraceDB — Gravitational Wave Candidate Event Database

HOME SEARCH **LATEST** DOCUMENTATION LOGIN

Latest — as of 23 June 2019 15:56:25 UTC

Test and MDC events and superevents are not included in the search results by default; see the [query help](#) for information on how to search for events and superevents in those categories.

Query:   
Search for:

**False Alarm Rate in per sec  
once per year is  $3.3e-8$  Hz**






UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC Created
<a href="#">S190602aq</a>	DQOK ADVOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY GCN_PRELIM_SENT PE_READY	1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51 UTC
<a href="#">S190524q</a>	DQOK ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133311	6.971e-09	2019-05-24 04:52:30 UTC
<a href="#">S190521r</a>	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT PE_READY	1242459856.453418	1242459857.460739	1242459858.642000	3.168e-10	2019-05-21 07:44:22 UTC
<a href="#">S190521g</a>	DQOK ADVOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY GCN_PRELIM_SENT PE_READY	1242442966.447266	1242442967.606934	1242442968.888344	3.801e-09	2019-05-21 03:02:49 UTC
<a href="#">S190519bj</a>	ADVOK DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT PE_READY	1242315361.378873	1242315362.655762	1242315363.676370	5.702e-09	2019-05-19 15:36:04 UTC
<a href="#">S190518bb</a>	DQOK ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1242242376.474609	1242242377.474609	1242242380.922355	1.004e-08	2019-05-18 19:19:39 UTC
<a href="#">S190517h</a>	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT PE_READY	1242107478.819517	1242107479.994141	1242107480.994411	2.373e-09	2019-05-17 05:51:23 UTC
<a href="#">S190513bm</a>	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869341	3.734e-13	2019-05-13 20:54:48 UTC
<a href="#">S190512at</a>	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT PE_READY	1241719651.411441	1241719652.416286	1241719653.518366	1.901e-09	2019-05-12 18:07:42 UTC
<a href="#">S190510g</a>	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293385	8.834e-09	2019-05-10 03:00:03 UTC
<a href="#">S190503bf</a>	DQOK PASTRO_READY EMBRIGHT_READY SKYMAP_READY ADVOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422352	1.636e-09	2019-05-03 18:54:26 UTC
<a href="#">S190426c</a>	DQOK EMBRIGHT_READY PASTRO_READY SKYMAP_READY ADVOK GCN_PRELIM_SENT PE_READY	1240327332.331668	1240327333.348145	1240327334.353316	1.947e-08	2019-04-26 15:22:15 UTC
<a href="#">S190425z</a>	DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY ADVOK	1240215502.011549	1240215503.011549	1240215504.018222	4.538e-13	2019-04-25 08:18:26 UTC
<a href="#">S190421ar</a>	DQOK EMBRIGHT_READY PASTRO_READY SKYMAP_READY GCN_PRELIM_SENT ADVOK PE_READY	1239917953.250977	1239917954.409180	1239917955.409100	1.489e-08	2019-04-21 21:39:16 UTC
<a href="#">S190412m</a>	DQOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY ADVOK GCN_PRELIM_SENT PE_READY	1239082261.146717	1239082262.222168	1239082263.229490	1.683e-27	2019-04-12 05:31:03 UTC
<a href="#">S190408an</a>	DQOK ADVOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY GCN_PRELIM_SENT PE_READY	1238782699.268296	1238782700.287958	1238782701.359860	2.811e-18	2019-04-08 18:18:27 UTC
<a href="#">S190405ar</a>	DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY ADVNO	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC



# LIGO GraceDB Latest – S190521r

- FAR 1/100yrs <https://gracedb.ligo.org/superevents/S190521r/view/>

GraceDb | x +

← → ↺ ⌂ <https://gracedb.ligo.org/superevents/S190521r/view/> ☆     01 | 

Apps GWs Physics CERN Software Hardware Vandy Misc Web Meet Google D... ★ Bookmarks | Other bookmark

## GraceDB — Gravitational Wave Candidate Event Database

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### Superevent Info

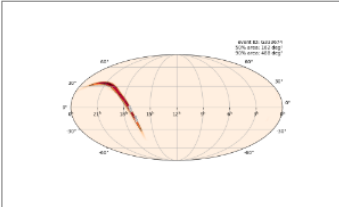
Superevent ID	Category	Labels	FAR (Hz)	FAR (yr <sup>-1</sup> )	t_start	t_0	t_end	UTC Submission time	Links
S190521r	Production	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	3.168e-10	1 per 100.04 years	1242459856.453418	1242459857.460739	1242459858.642090	2019-05-21 07:44:22 UTC	<a href="#">Data</a>

### Preferred Event Info

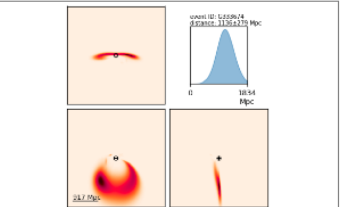
Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
CBC	pycbc	AllSky	H1,L1	1242459857.4634	2019-05-21 07:44:33 UTC

### Superevent Log Messages

▼ Sky Localization



Mollweide projection of [bayestar.fits](#) [bayestar.png](#). Submitted by LIGO/Virgo EM Follow-Up on May 21, 2019 07:50:11 UTC



Volume rendering of [bayestar.fits](#) [bayestar.volume.png](#). Submitted by LIGO/Virgo EM Follow-Up on May 21, 2019 07:50:40 UTC

UTC Log Entry Created	Submitter	Comment
May 21, 2019 07:50:09 UTC	LIGO/Virgo EM Follow-Up	Flattened from multiresolution file bayestar.fits <a href="#">bayestar.fits.gz</a>
May 21, 2019 07:50:08 UTC	LIGO/Virgo EM Follow-Up	FITS headers for <a href="#">bayestar.fits</a> <a href="#">bayestar.html</a>
May 21, 2019 07:50:07 UTC	LIGO/Virgo EM Follow-Up	Localization copied from G333674 <a href="#">bayestar.fits</a>



# LIGO GraceDB Latest – S190521r

EM Followup

BBH

>99%

Terrestrial

<1%

NSBH

0%

MassGap

0%

BNS

0%

Source classification visualization from [p\\_astro.json](#)  
[p\\_astro.png](#), Submitted by LIGO/Virgo EM Follow-Up on May 21, 2019 07:50:18 UTC

UTC

Log Entry Created	Submitter	Comment
May 21, 2019 08:17:50 UTC	LIGO/Virgo EM Follow-Up	New VOEvent <a href="#">S190521r-2-Initial.xml</a>
May 21, 2019 07:50:19 UTC	LIGO/Virgo EM Follow-Up	New VOEvent <a href="#">S190521r-1-Preliminary.xml</a>

EM Observations

No EM observation entries so far.

Full Superevent Log



# Links

- aa



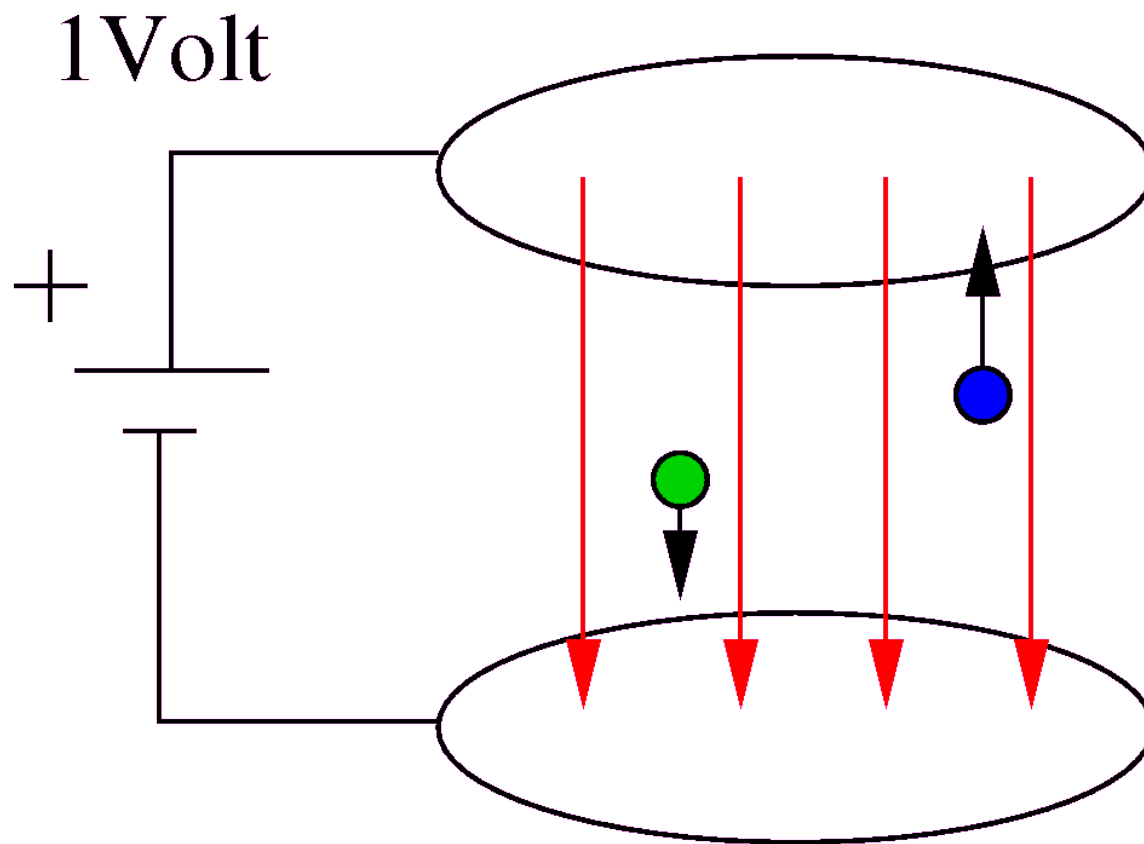
# Backup

# SI Prefixes

**Table 5. SI prefixes**

Factor	Name	Symbol	Factor	Name	Symbol
$10^{24}$	yotta	Y	$10^{-1}$	deci	d
$10^{21}$	zetta	Z	$10^{-2}$	centi	c
$10^{18}$	exa	E	$10^{-3}$	milli	m
$10^{15}$	peta	P	$10^{-6}$	micro	$\mu$
$10^{12}$	tera	T	$10^{-9}$	nano	n
$10^9$	giga	G	$10^{-12}$	pico	p
$10^6$	mega	M	$10^{-15}$	femto	f
$10^3$	kilo	k	$10^{-18}$	atto	a
$10^2$	hecto	h	$10^{-21}$	zepto	z
$10^1$	deka	da	$10^{-24}$	yocto	y

# Units?



- Proton,  
heavy,  $+e$
- Electron,  
light,  $-e$



# Speed of Light

Fastest possible speed is the speed of light in vacuum.

**Defined as**  $299792458 \text{ m/s}$

$$3.0 \times 10^8 \text{ m/s}$$

$$30 \text{ cm/ns}$$

$$300 \text{ m}/\mu\text{s}$$

$$300 \mu\text{m}/\text{ps}$$