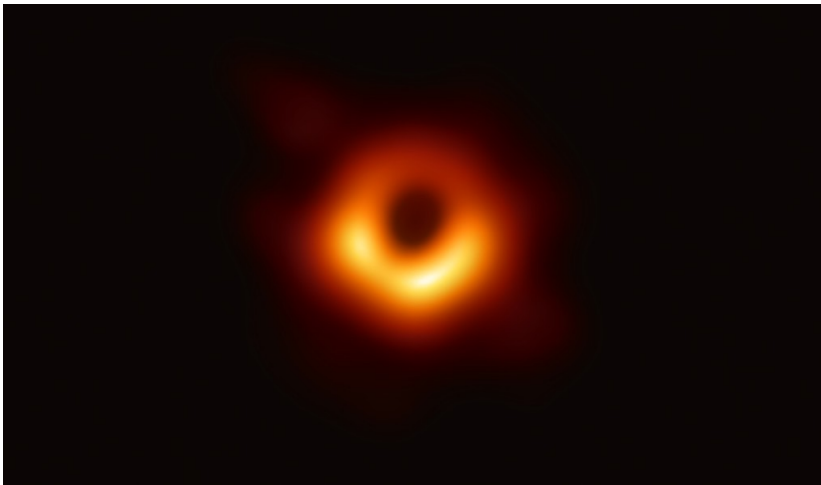


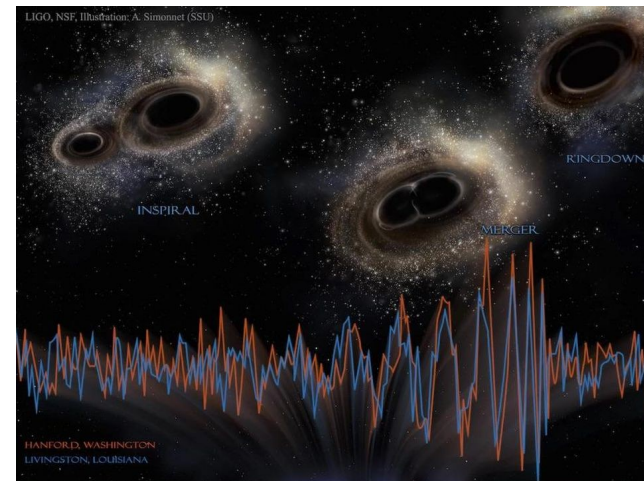
Event Horizon Telescope and LIGO Gravitational Waves---News



Bill Gabella

Monday 24 June 2019

Vanderbilt-QuarkNet Workshop



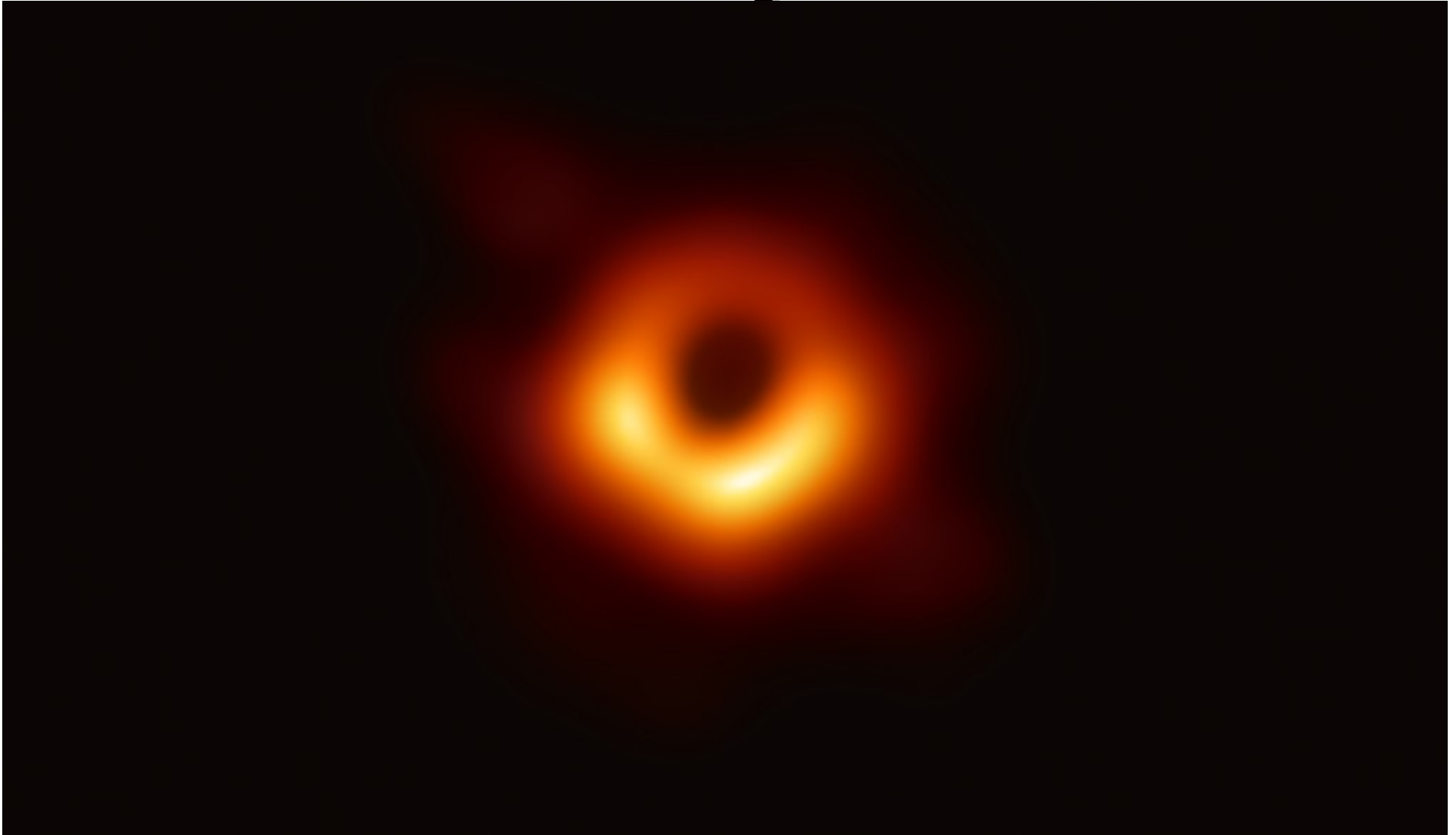
Ref: <https://eventhorizontelescope.org/>

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*

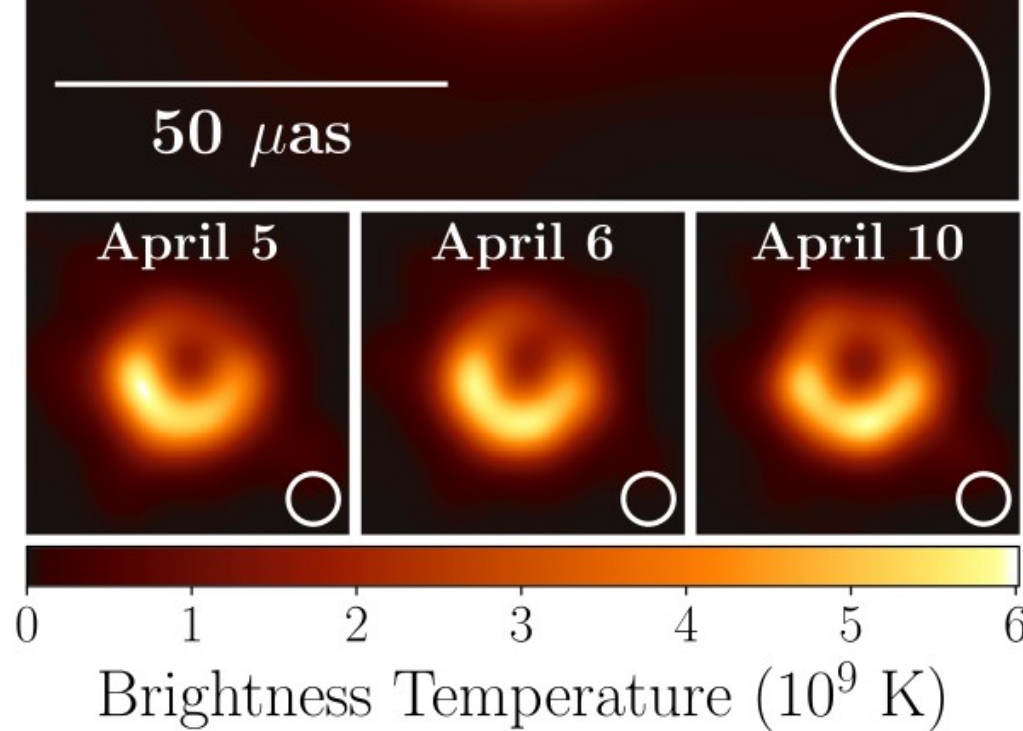
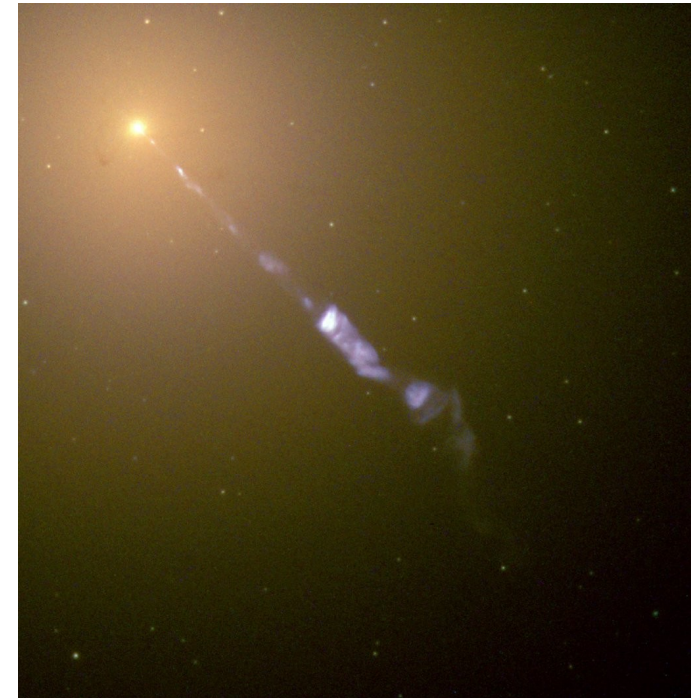
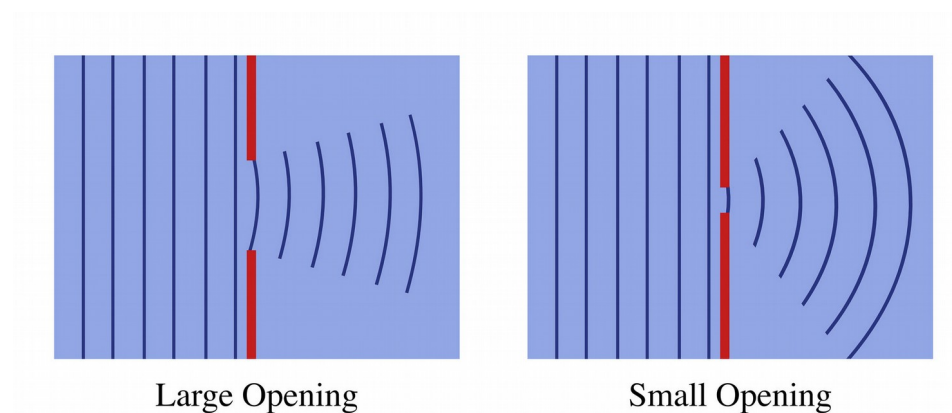


Figure 3. Top: EHT image of M87* from observations on 2017 April 11 as a representative example of the images collected in the 2017 campaign. The image is the average of three different imaging methods after convolving each with a circular Gaussian kernel to give matched resolutions. The largest of the 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, λ is the observing wavelength, k_B is the Boltzmann constant, and Ω 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.



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

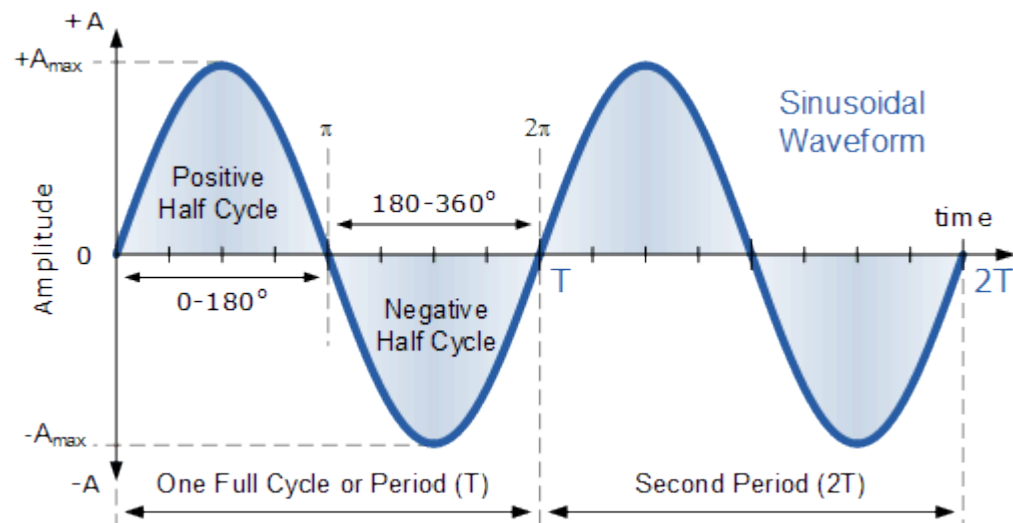
Same wavelength, different beam sizes.

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.

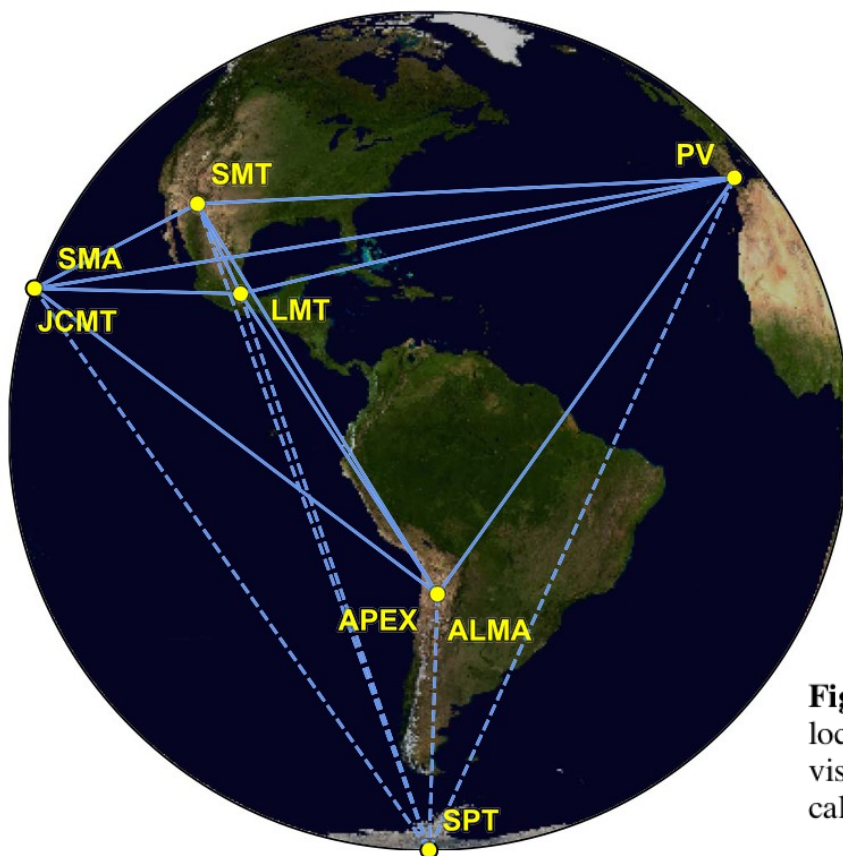
Light/Radio at $\lambda = 1.3$ mm

- 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

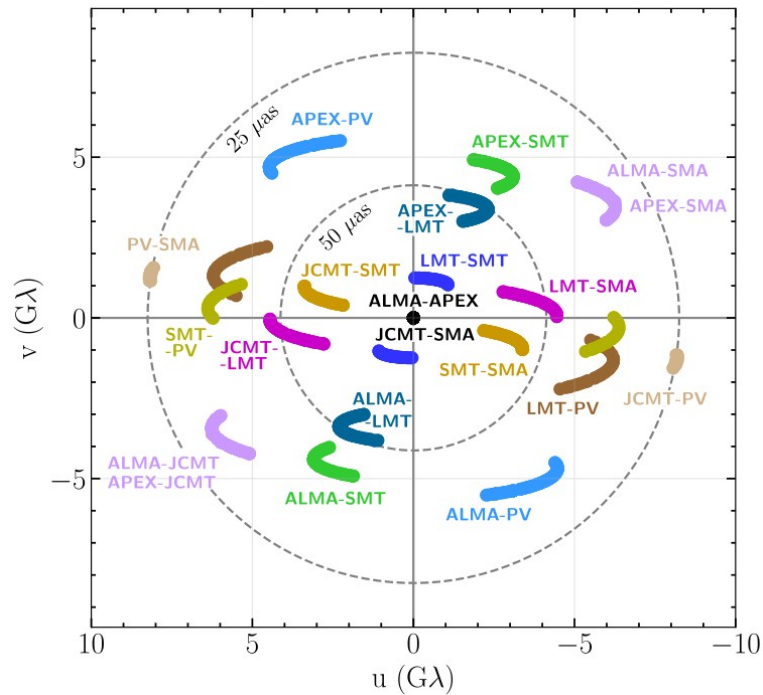
APEX = Atacama Pathfinder Experiment
Telescope

ALMA = Atacama Large Millimeter/
Submillimeter Array

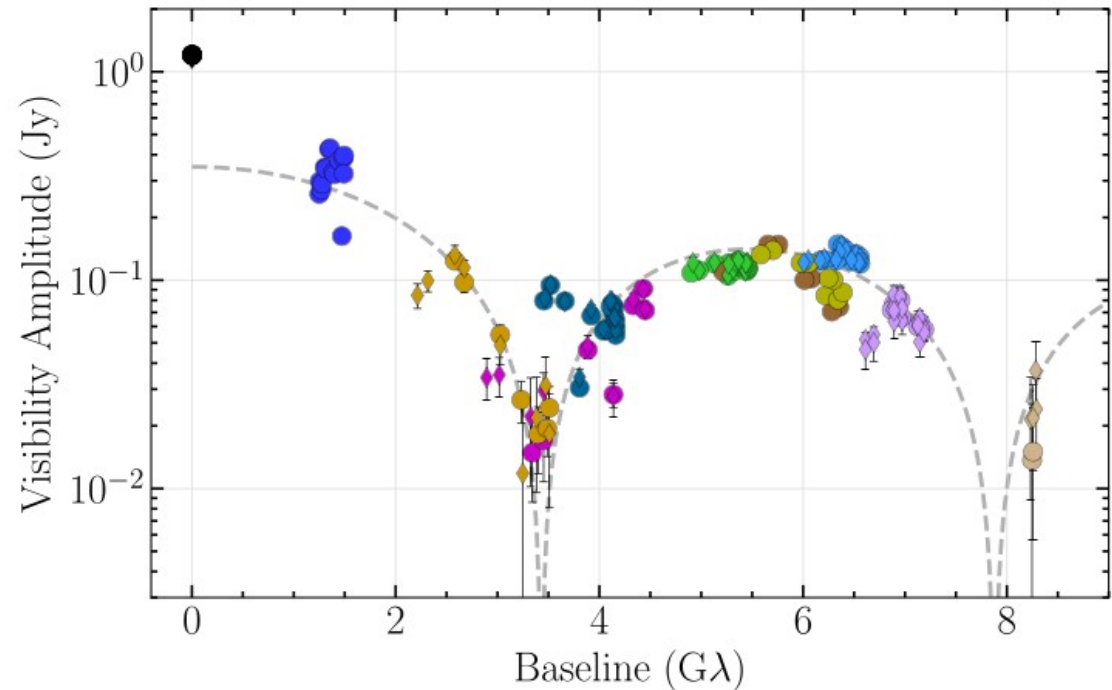
SPT = South Pole Telescope

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

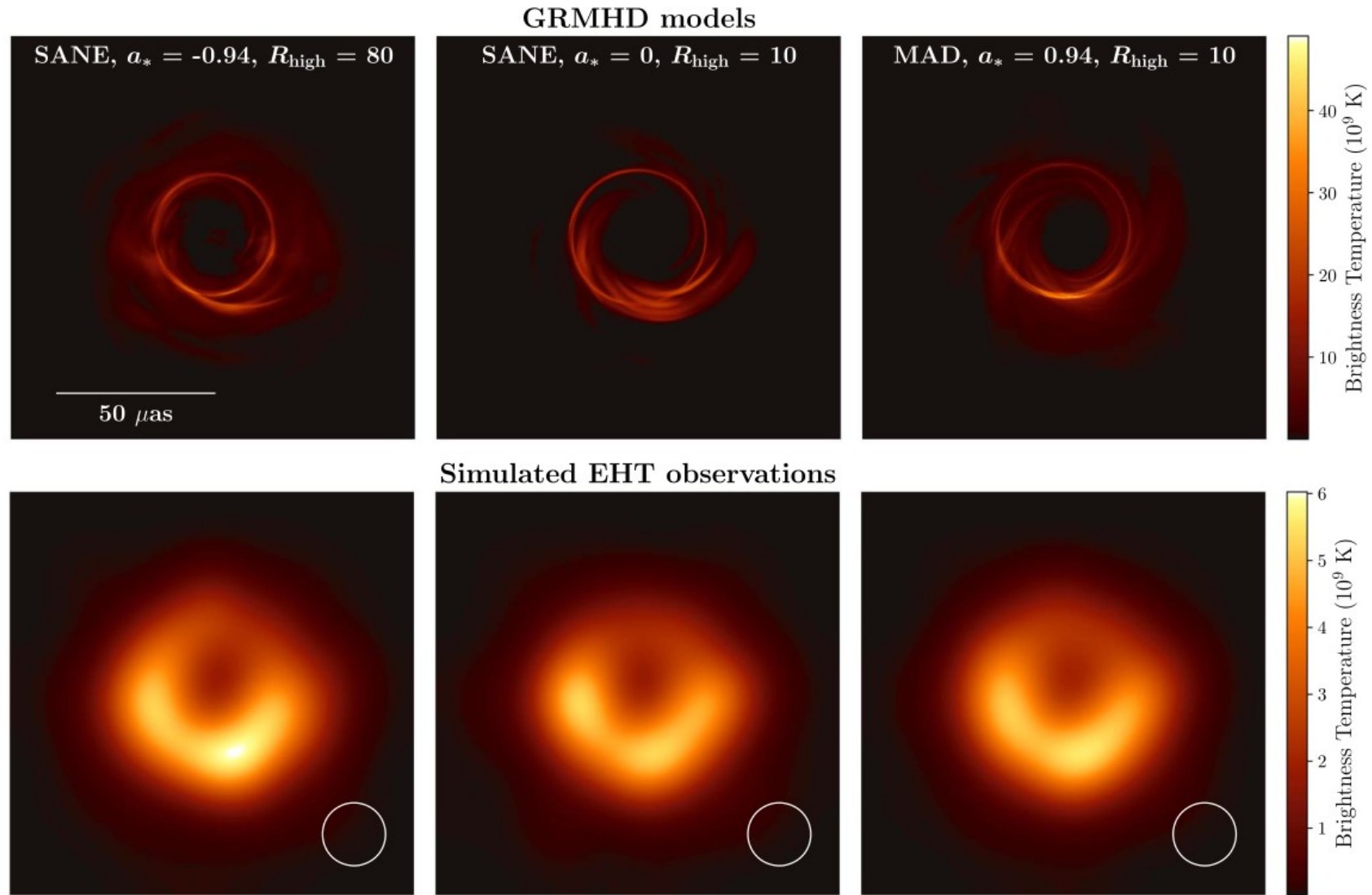


The EHT Array as a
“Radio Telescope Dish”



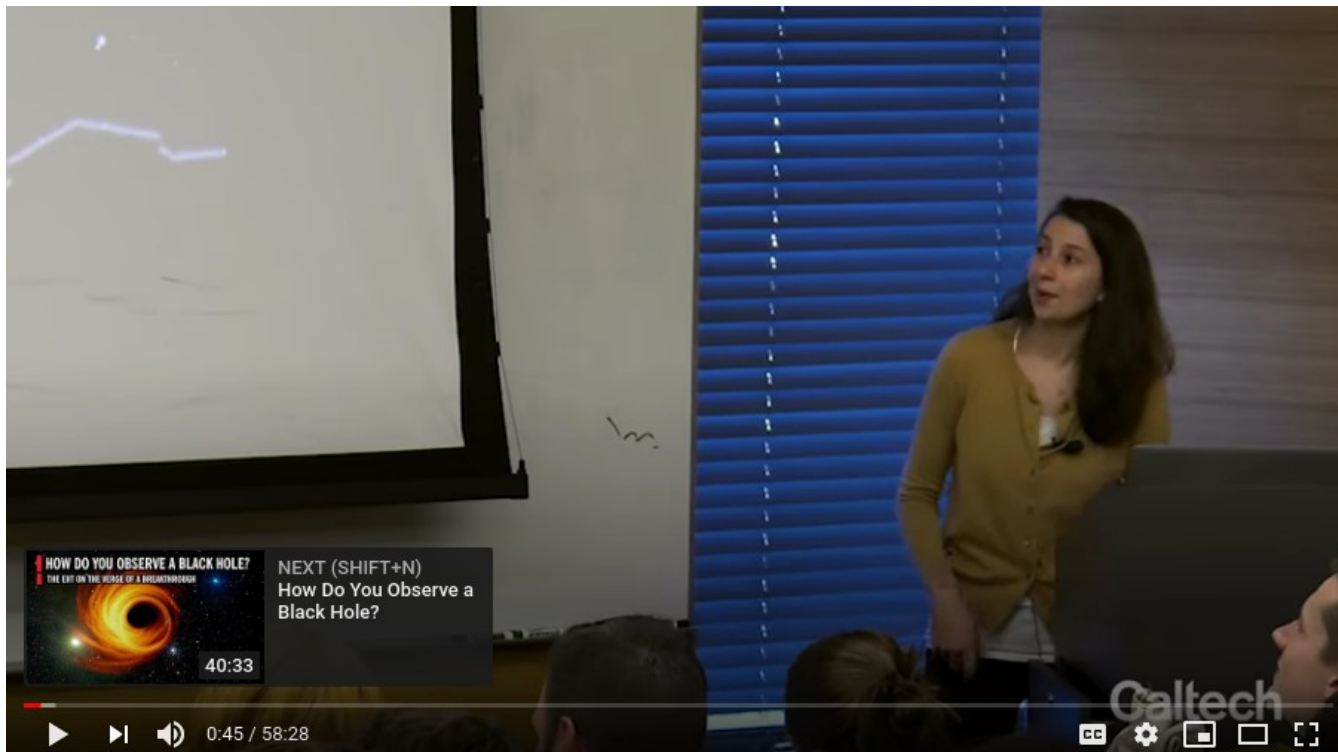
EHT Array acts as if on a mirror

Image from a lot of processing!



Katie Bouman's Talk at CalTech

- Bouman worked on the imaging analysis
https://youtu.be/UGL_OL3OrCE
- aa



Gravitational Waves – aLIGO & VIRGO

VIRGO, Cascina, Italy



LIGO, Livingston, LA

LIGO, Hanford, WA



Gravitational Waves – aLIGO & VIRGO

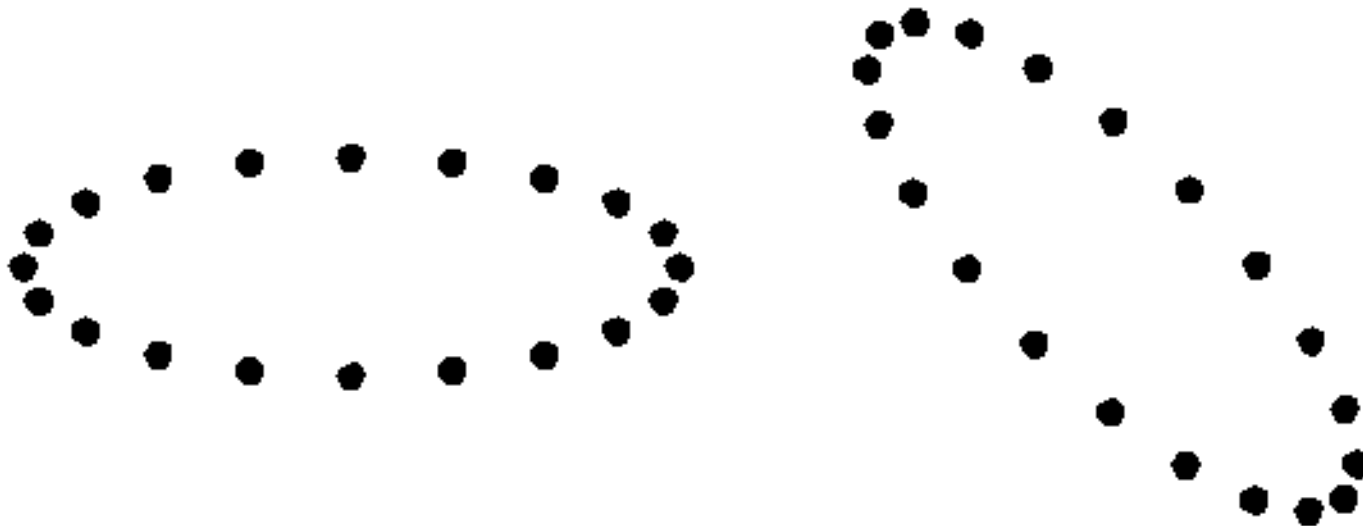
- aLIGO = Advanced Laser Interferometer Gravitational-Wave Observatory, <https://www.ligo.org/> and <https://www.ligo.caltech.edu/>
- Restarted observations on 1 April 2019, so-called “O3” run.
- Seeing a binary black hole merger every week, more or less, <https://gracedb.ligo.org/latest/>

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.

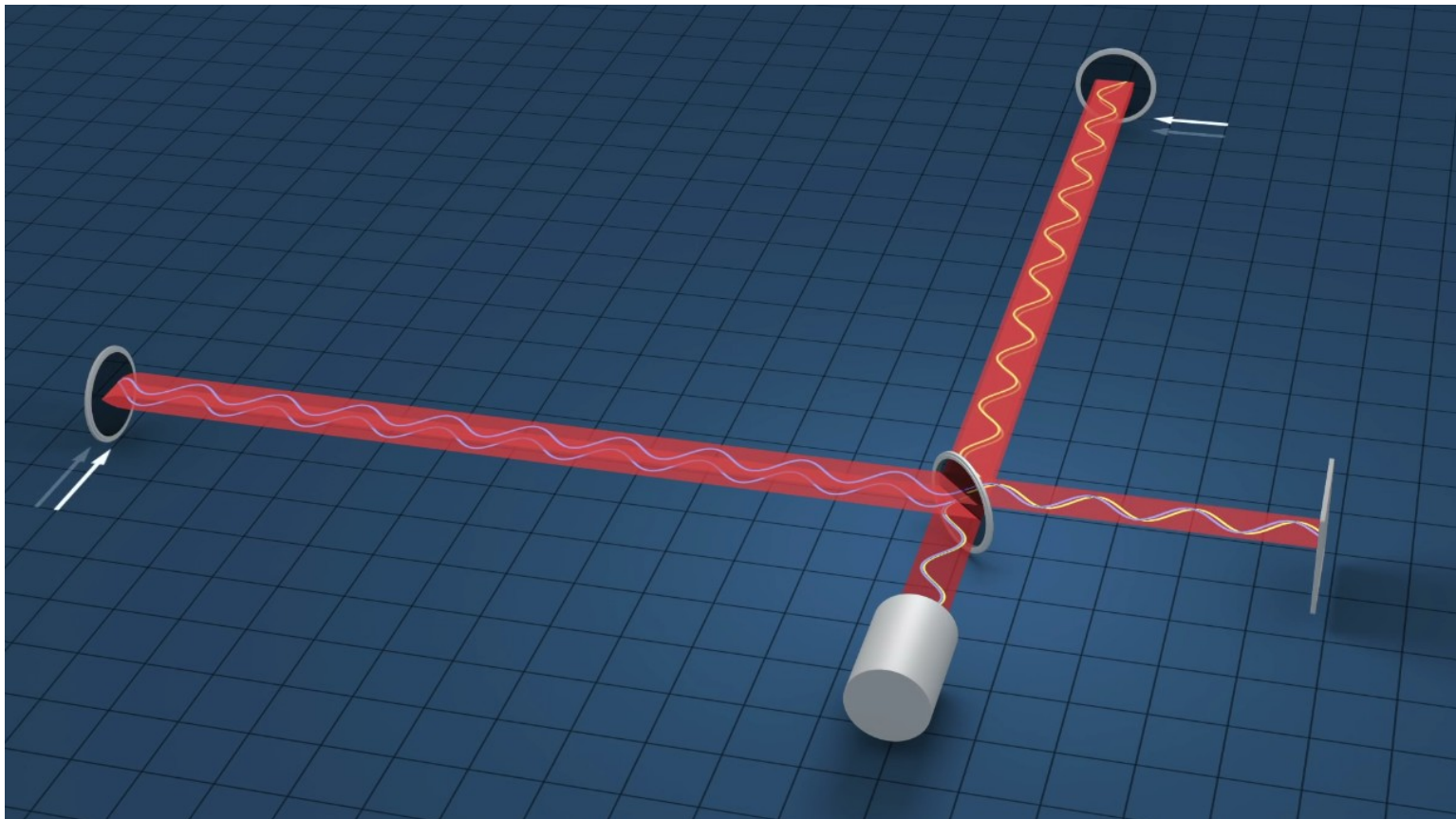
Gravitational Waves – In a Picture

- 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





LIGO GraceDB Latest

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

→ ↻ ↺ 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
S190602aq	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
S190524q	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
S190521r	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
S190521g	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
S190519bj	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
S190518bb	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
S190517h	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
S190513bm	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
S190512at	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
S190510g	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
S190503bf	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
S190426c	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
S190425z	DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY ADVOK	1240215502.011549	1240215503.011549	1240215504.018222	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	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
S190412m	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
S190408an	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
S190405ar	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

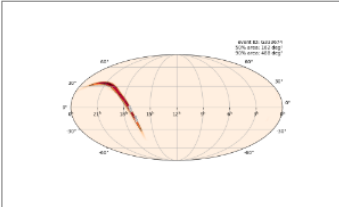
Superevent ID	Category	Labels	FAR (Hz)	FAR (yr ⁻¹)	t_start	t_0	t_end	UTC Submission time	Links
S190521r	Production	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	3.168e-10	1 per 100.04 years	1242459856.453418	1242459857.460739	1242459858.642090	2019-05-21 07:44:22 UTC	Data

Preferred Event Info

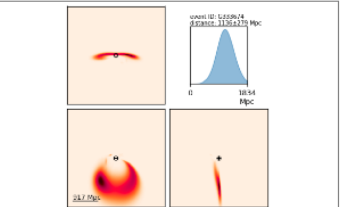
Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
CBC	pycbc	AllSky	H1,L1	1242459857.4634	2019-05-21 07:44:33 UTC

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 bayestar.fits.gz
May 21, 2019 07:50:08 UTC	LIGO/Virgo EM Follow-Up	FITS headers for bayestar.fits bayestar.html
May 21, 2019 07:50:07 UTC	LIGO/Virgo EM Follow-Up	Localization copied from G333674 bayestar.fits

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 S190521r-2-Initial.xml
May 21, 2019 07:50:19 UTC	LIGO/Virgo EM Follow-Up	New VOEvent S190521r-1-Preliminary.xml

EM Observations

No EM observation entries so far.

Full Superevent Log



Links

- aa



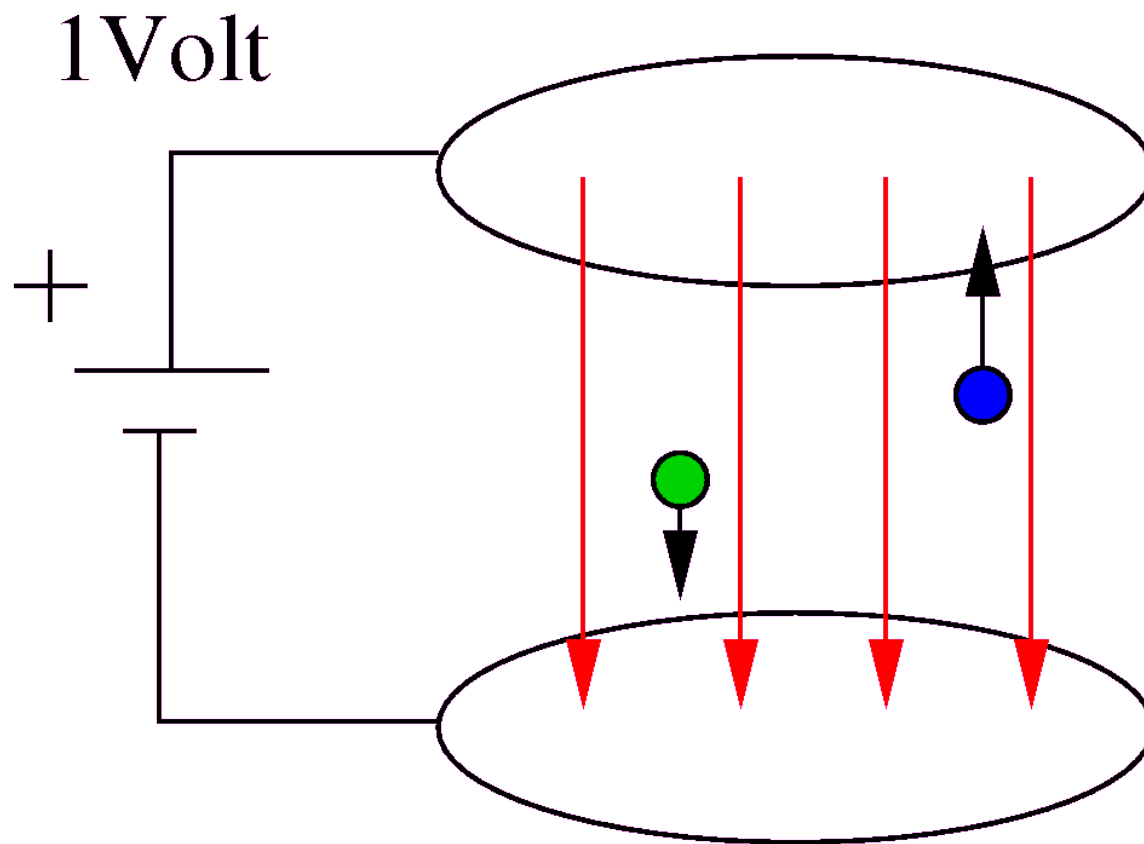
Backup

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	μ
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 m/s

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

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

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

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