Universität Zürich[UZH] | Physik–Institut

Multi-messenger astrophysics with galaxies and compact binary coalescences

ICTP-SAIFR School on Astroparticle and Multi-messenger Astrophysics

Marcelle Soares-Santos

with contributions by
Léonard Lebrun

São Paulo, June 22–26 2026

Course program

Plan for the module on multi-messenger astrophysics with galaxies and compact binary coalescences

Monday

- Introduction / Motivation
- Discovery of GW170817
- "What if a GW170817-like event would happen today?"

Tuesday

- "What if a GW170817-like event would have happened yesterday?"
- Searches for EM counterparts of BBH events

Wednesday

- Colloquium: Building for Discovery
- CBCs as standard sirens

Thursday

- CBCs as stochastic GW background sources

Friday

- CBCs for precision cosmology
- Conclusion

Introduction / Motivation

Why pursue multi-messenger astrophysics with gravitational-wave events?

A brief personal introduction

Prof. Marcelle Soares-Santos

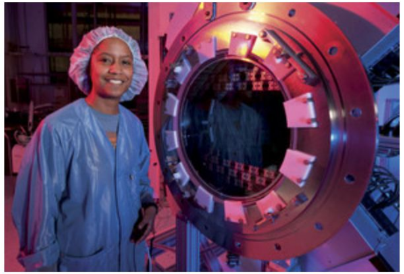
- I lead an an experimental group focused on cosmology. In particular, we work towards integrating gravitational waves into the portfolio of physical cosmology observables.
- I am originally from Vitória, Espírito Santo.
- I got my PhD at the IAG/USP (in 2010) and built most of my professional career since then in the USA (moved to Zurich in 2024).
- Fun fact: I had "5-minutes of fame" with a brief appearance in the TV Globo Fantástico, série "Mulheres Fantásticas" (episódio #3, 2019).

Revista Pesquisa FAPESP, Nov 2017.

Marcelle Soares-Santos: Caçadora de colisões

Física brasileira coordena grupo que procura emissões luminosas associadas à produção de ondas gravitacionais

Na manhã de 16 de outubro, a física Marcelle Soares-Santos era a única brasileira entre os 16 líderes de grupos de pesquisa que anunciaram em uma entrevista na sede da National Science Foundation, nos Estados Unidos, a observação de um fenômeno que pode transformar o que se conhece sobre o Universo.



Marcelle e a câmera que ajudou a construir, usada no projeto Dark Energy Survey

Collaborator introduction

Léonard Lebrun

- LeBrun is presently a PhD student in the multi-messenger cosmology group at UZH, where he works on both analysis and instrumentation for multi-messenger astrophysics.
- He was hired at UZH after obtaining his Masters degree at the Swiss Federal Technology Institute of Lausanne (EPFL), in Switzerland.
- For the hands-on session of this course, LeBrun has kindly agreed to adapt a code he had developed for our ongoing search and discovery program for EM counterparts of GW events.

Welcome to the GW multi-messenger astro world!

Combining gravitational waves with traditional astronomy observations for new discoveries in physics

This course module of the ICTP-SAIFR school addresses the physics background and data analysis methods currently in use in the exciting new field of multi-messenger astrophysics with gravitational waves, including:

- Search, discovery, and characterization of electromagnetic (EM) counterparts of GW events
- Use of individual GW events, in combination with galaxy survey data, for cosmology
- Possibility of discovery of the stochastic gravitational-wave background, from a population of GW events

The lectures will be complemented by:

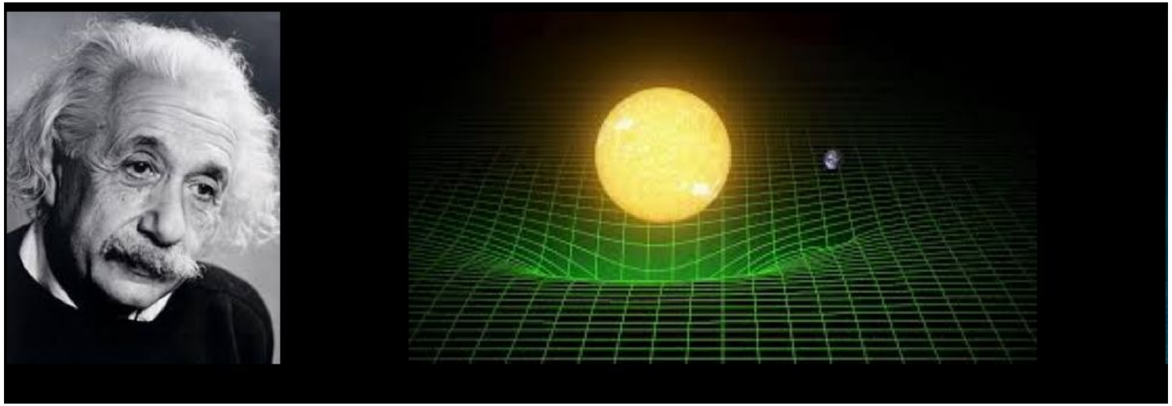
- A hands-on session on how you (yes, you!) can use publicly available resources for this type of research.
- One colloquium on new instrumentation developments in this field.

Notable omissions:

- GW sources outside of the LIGO-band (e.g., LISA, Pulsar Timing Array)
- Primordial gravitational waves and their imprints on the CMB

Compact Binary Coalescences as GW sources

GR in a nutshell: “Space tells matter how to move. Matter tells space how to curve.”



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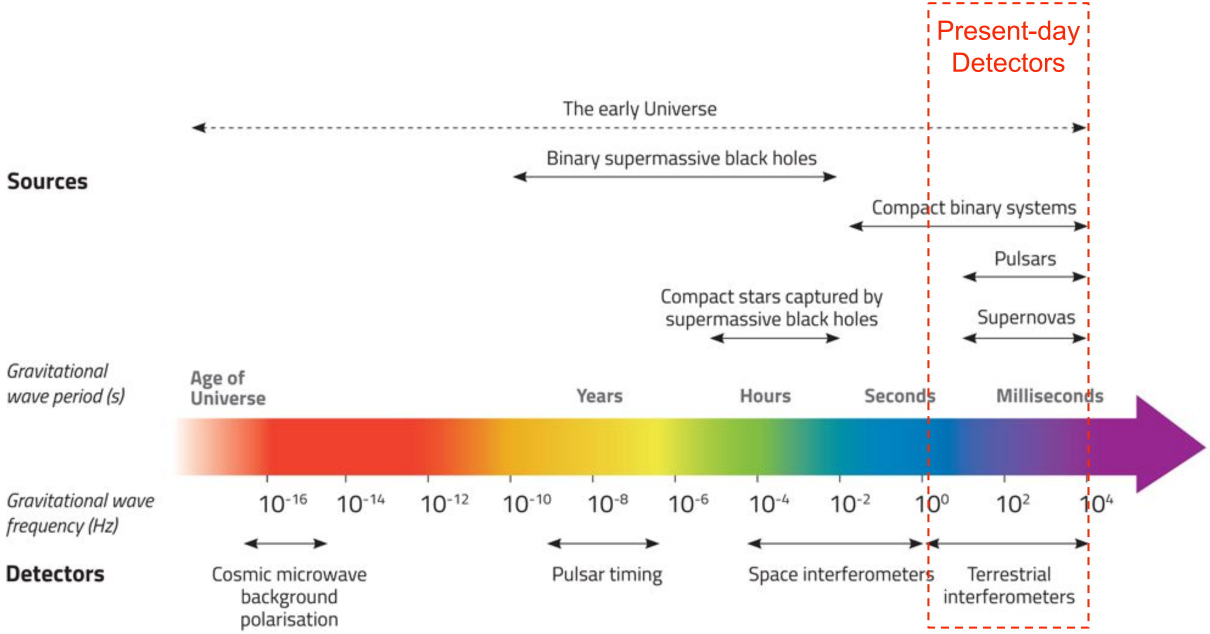
Taxonomy of GW sources and detectors

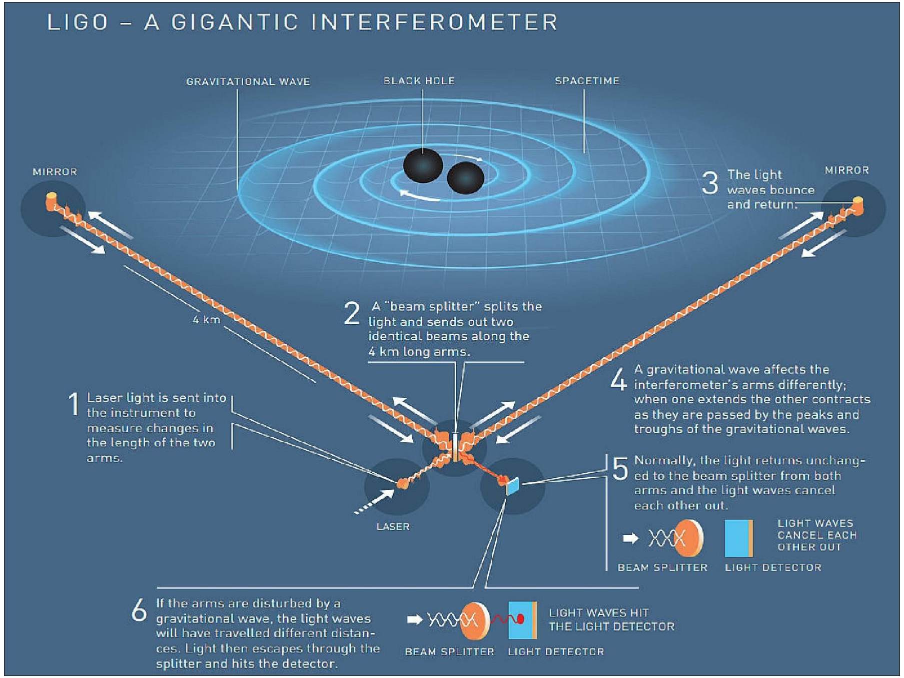
CBCs are dominant sources in the sensitivity band of present-day GW antennas



LIGO and the second-generation GW detectors

Large scale laser interferometers to measure tiny displacement of test masses as GWs pass through.

- LIGO was founded in 1984 in the US, with a long term vision to improve the technology and eventually achieve GW sensitivity.
- The first generation (Initial LIGO) operated from 2002 to 2010. It did not detect any GWs, but proved the viability of the technology.
- The second-generation (Advanced LIGO) started its first run in 2015.
- Other second-generation detectors exist in Europe (Virgo) and Japan (KAGRA). Together, the three detectors form a network known as LIGO-Virgo-KAGRA (LVK).



Why combine EM and GW data sets?

Bringing the "visual action" to life

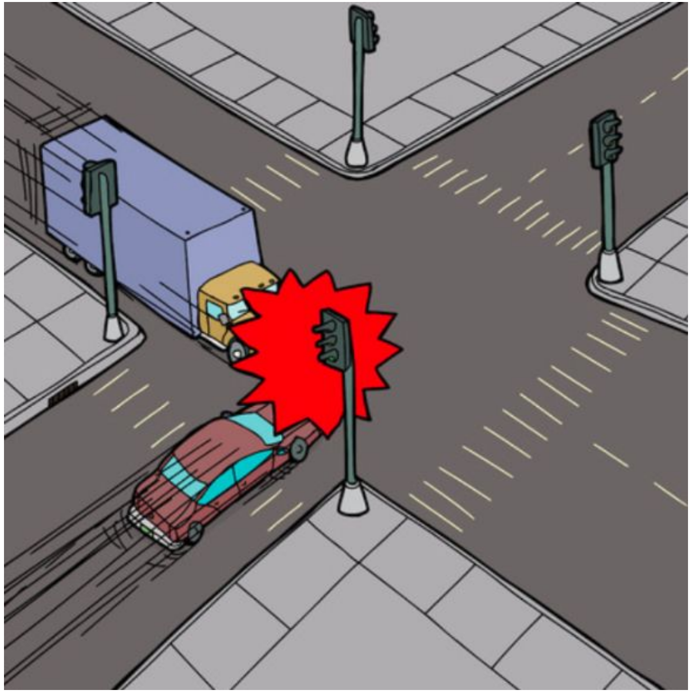
- Silent movies had soundtracks (initially performed live, later recorded) to convey emotions and help the audience understand what was happening in the films.
- For centuries (up to 2015) astronomy, had been presenting the "silent movie" of the cosmos without a dedicated sound track!
- With the new developments in GW detection, we now can better understand of what is happening in the "film", answering scientific questions that would otherwise remain beyond our reach.

"The Jazz Singer", released in 1927, was the first film with a recorded soundtrack, which made it a fundamental milestone. This innovation not only revolutionized the film industry of the time, but also laid the foundation for the development of soundtracks to this day.

Why combine EM and GW data sets?

Obtaining complementary information to better understand complex events, and their environments

- A person who is sitting in their living room and hears a car crash outside can tell a lot about the event only on the basis of the sound of it:
  - Time (very precise: just look at your watch)
  - Location (imprecise, general direction only)
  - Energy (fender bender vs. major crash)
  - Distance (closer = louder)
- But, if the person stands up and rush to look out their window, they may learn a lot more:
  - Location (very precise: “that cross-section!”)
  - Progenitors (Make and model of the vehicles)
  - Environment (Rain / slippery road? Low visibility?)
  - Remnants (material spills, injured parties)

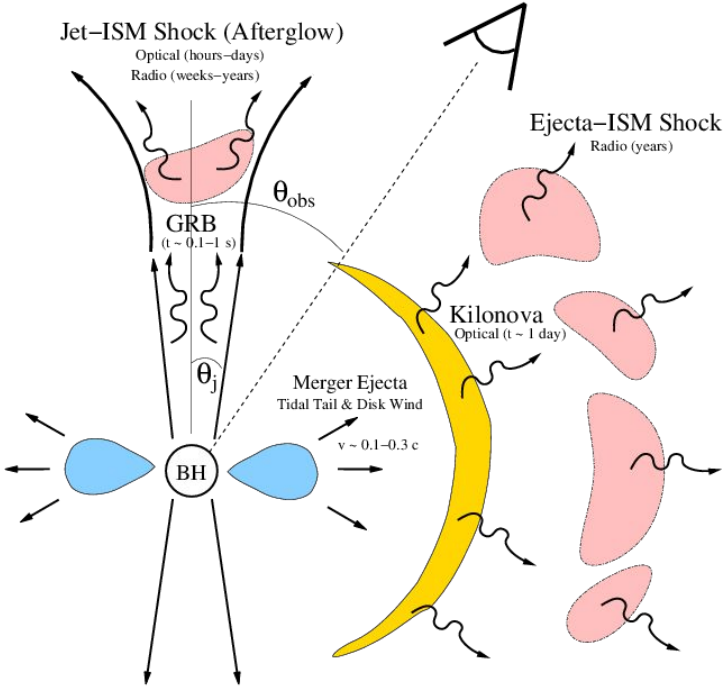


Case in point: Kilonova

What happens when two neutron stars collide?

- Kilonovae (KNe) are analogous to Supernovae (SNe) in the sense that they are explosive events at the end of the life of a stellar system.
- They were hypothesised in the early 2000s as the result of the merger of neutron star binaries whose orbits have decayed due to GW radiation (e.g., Metzger et al. 2010).
- They are short-lived EM transients that are 10^4x fainter than Supernovae — so, it is hard to find them if you don't know where to look.
- Key parameters: ejecta mass, velocity, opacity.

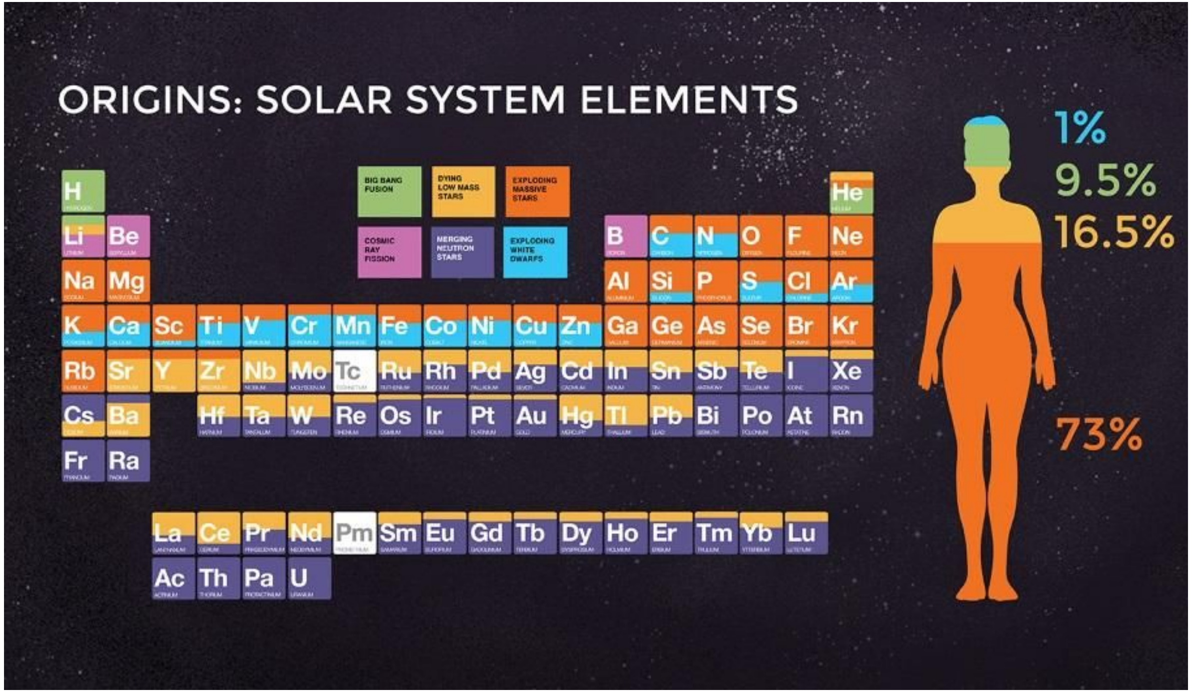
Metzger, **LLR** 23, 1, 2020
(the original version of this article was published on May 2017)



Case in point: Kilonova

What happens when two neutron stars collide?

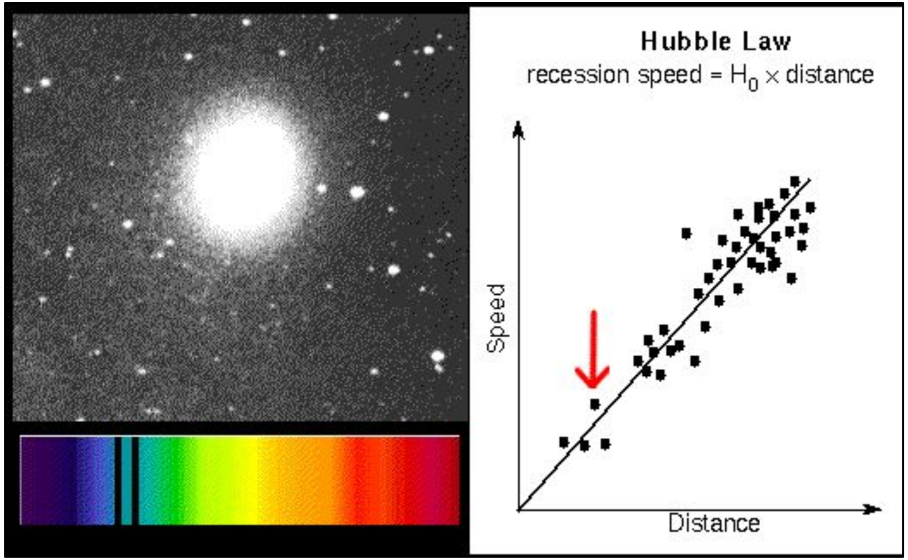
- The KN optical and near-IR brightness comes from the radioactive decay of isotopes of heavy elements produced via r-process nucleosynthesis.
- KNe, in fact, produce the bulk of heavy elements — such as gold and platinum — in the universe!



Case in point: Standard Sirens

An exciting possibility to expand our portfolio of cosmological probes.

- The Hubble law tells us that, in an expanding universe, the further a galaxy is from us, the faster it recedes from us (greater redshift).
- To measure the rate of cosmic expansion, we need precise and accurate determination of distances, but distance determination on such scales is extraordinarily difficult.
- Type-Ia Supernovae can be used as "Standard Candles", after a complex series of calibrations (the cosmic distance ladder).
- GW "Standard Sirens" can bypass this step!



Case in point: Standard Sirens

An exciting possibility to expand our portfolio of cosmological probes.

- In a merging binary, the change in GW signal frequency, gives the size of the system.
- Once we know the size, we can predict the intrinsic amplitude to compare with the observed amplitude in our detectors!

Nature 323 310, 1986

Determining the Hubble constant from gravitational wave observations

Bernard F. Schutz

Department of Applied Mathematics and Astronomy, University College Cardiff, PO Box 78, Cardiff CF1 1XL, UK

I report here how gravitational wave observations can be used to determine the Hubble constant, H_0. The nearly monochromatic gravitational waves emitted by the decaying orbit of an ultra-compact, two-neutron-star binary system just before the stars coalesce are very likely to be detected by the kilometre-sized interferometric gravitational wave antennas now being designed[1–4]. The signal is easily identified and contains enough information to determine the absolute distance to the binary, independently of any assumptions about the masses of the stars. Ten events out to 100 Mpc may suffice to measure the Hubble constant to 3% accuracy.

Case in point: Standard Sirens

An exciting possibility to expand our portfolio of cosmological probes.

- In a merging binary, the change in GW signal frequency, gives the size of the system.
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Nature 323 310, 1986

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frequency). The standard quadrupole formula' of general relativity[6,7] shows that the waves will have amplitude (r.m.s.-averaged over detector and source orientations)

$$\langle h\rangle = 1\times 10^{-23} m_{\mathrm{T}}^{2/3}\mu f_{100}^{2/3} r_{100}^{-1} \quad (1)$$

and that their frequency will change on a timescale

$$\tau = f/\dot{f} = 7.8 m_{\mathrm{T}}^{-2/3}\mu^{-1} f_{100}^{-8/3}\ \mathrm{s} \quad (2)$$

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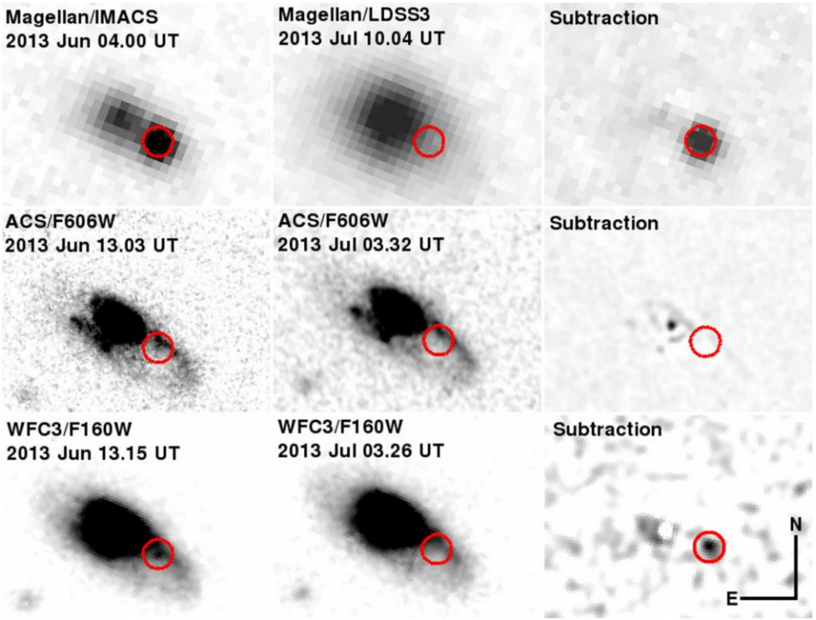
How can we search for Kilonovae?

Short-GRB triggered searches yielded an interesting candidate…

- Binary neutron star mergers produce, in addition to gravitational waves, a short Gamma-Ray Burst (GRB) immediately after the merger.
- The GRB can be used to search for the Kilonova, but we must be very lucky — the beam needs to point directly to Earth!
- One candidate was observed in 2013, but its spectrum and light curves could not be studied in much detail.
- The GW emission is more isotropic than the GRB. Therefore, a GW-EM discovery program is likely more efficient.

Berger, Fong, & Chornock, **ApJL** 774 L23, 2013



The challenge: find a needle in a haystack

In 2013, LIGO/Virgo issued call to the community, ahead of the start of Advanced LIGO operations

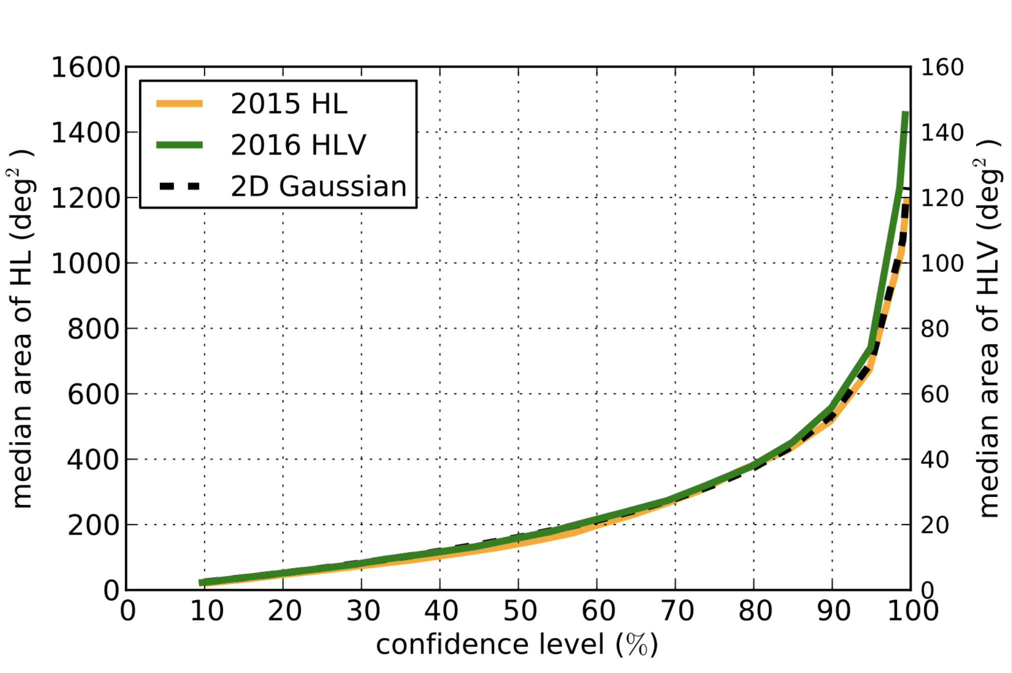
GW antennas:

- LIGO Hanford (H)
- LIGO Livingston (L)
- Virgo (V)

Typical area for HLV detector network:

- 16 sq-deg @ 50% c.l.
- 55 sq-deg @ 90% c.l.

With less than three detectors, the situation is 10x worse!



An instrument well matched to the challenge

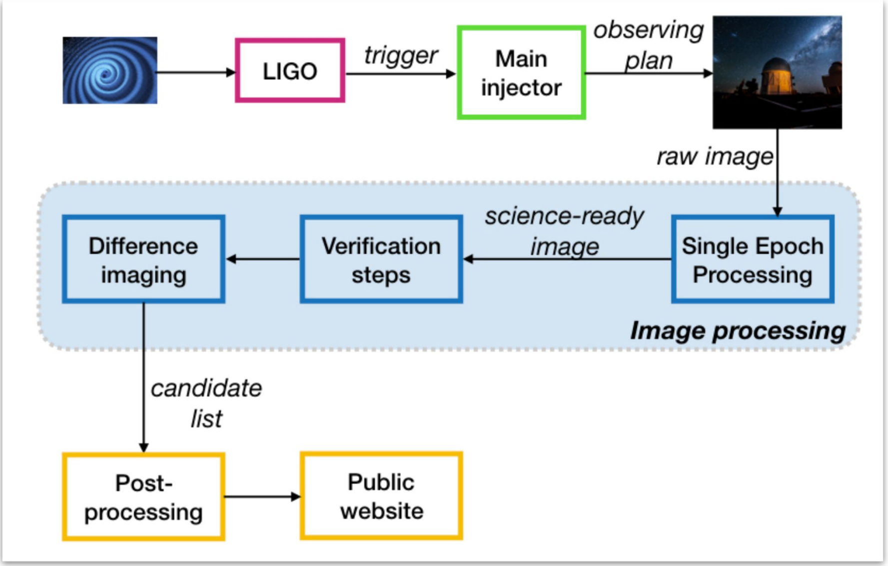
The Dark Energy Camera

- DECam is an optical/near-IR camera featuring 62 CCDs totalling 570 Mpix. It is installed on the Blanco 4-meter telescope in Chile and has a field of view of 3 deg^2.
- DECam was commissioned in 2011 and remained the most powerful instrument of its kind until 2025 — when the LSST came online.

The DESGW project

Challenge accepted: a search and discovery program for EM counterparts of GW events using DECam

- Started in 2014
- Partnered with the LVK
- Engaged external collaborators for follow-ups
- Secured DECam community time
- Completed four observing campaigns to date
- Has received support from:
  - Fermilab LDRD program (2015-2017)
  - U. Chicago Strategic Initiative (2016)
  - Sloan Fellowship (2019)
  - US NSF (2019-2023)
  - Cottrell Scholar Award (2021)
  - University of Zurich (2024-present)
  - Swiss NSF (2024-present)



Summary and Up Next…

We will pause here for 10 minutes.

So far, we have…

- Motivated the pursuit of multi-messenger studies that combine EM and GW observations of the same astrophysical events — particular BNS events!
- Discussed some of the challenges involved in this pursuit,
- Introduced a project, DESGW, that has been conceived to address them.

After the break, we will learn about:

- Accomplishments of DESGW (and the broader community) with the BNS event GW170817.
- Prospects for more BNS KN discoveries in the LSST era.

Discovery of GW170817

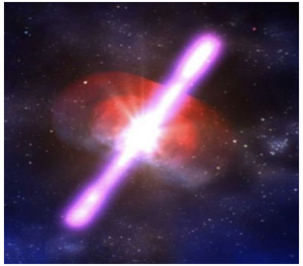
Inaugurating the era of multi-messenger astrophysics with gravitational waves

GW170817 — first BNS merger observed by the LVK

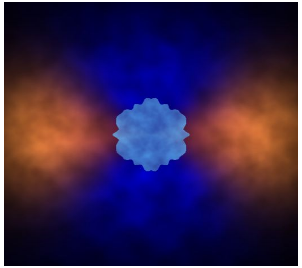
GW170817, which occurred at the end of the 2nd observing run (O2), was ideal for KN searches

- **Time:** Aug 17, 2017 at 12:41:04.4 UTC
- **Distance:** 40 Mpc (VERY NEARBY!)
- **Type:** Binary Neutron Star
- **<u>Expected EM emission mechanisms</u>:**

Relativistic outflows
non-thermal, beamed
(gamma-ray, x-ray, radio)



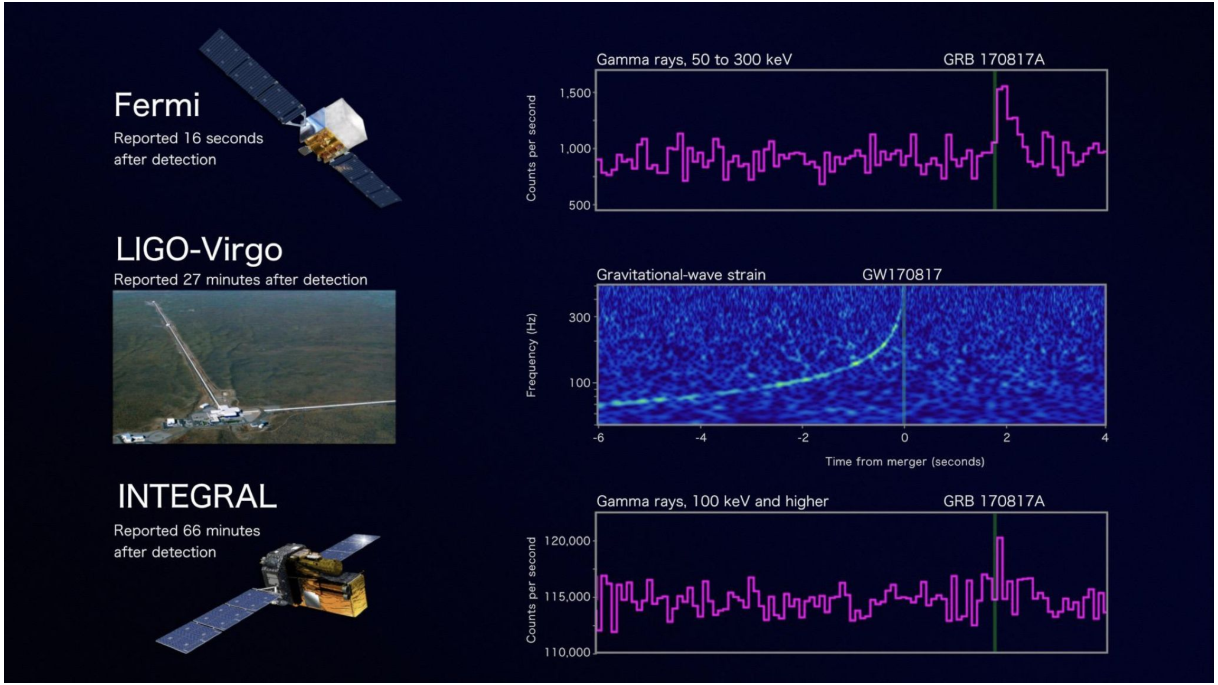
Sub-relativistic outflows
thermal, nearly isotropic
(UV, optical, infrared)



A multi-messenger event

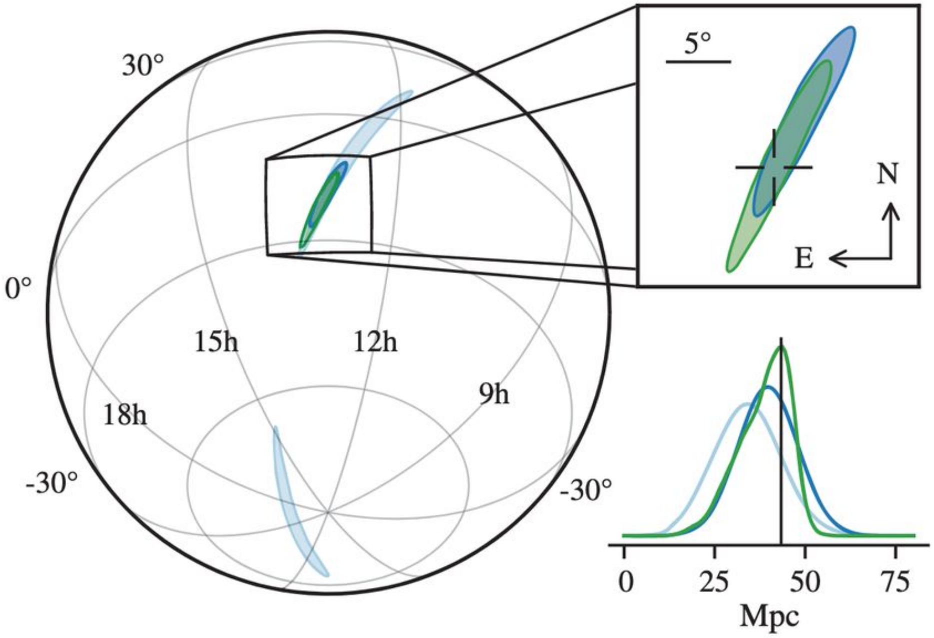
GW and EM signals were 2 seconds apart.

- Detection of GWs followed by detection of a short GRB.
- Result confirms the prediction from the **relativistic outflow** mechanism!
- But where is the source?
- And how about the sub-relativistic outflow?



GW-only sky localization of GW170817

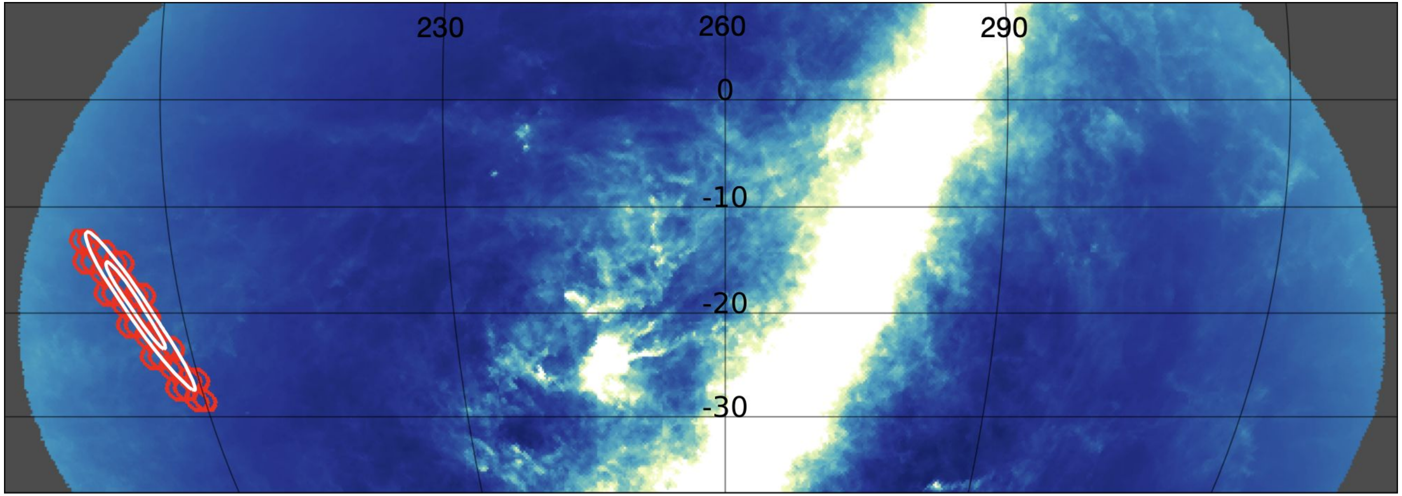
The treasure map!

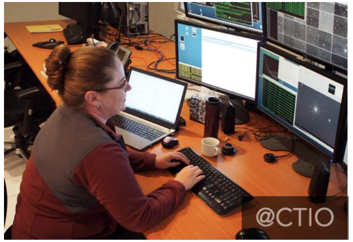


A needle in a haystack

Challenging search area!

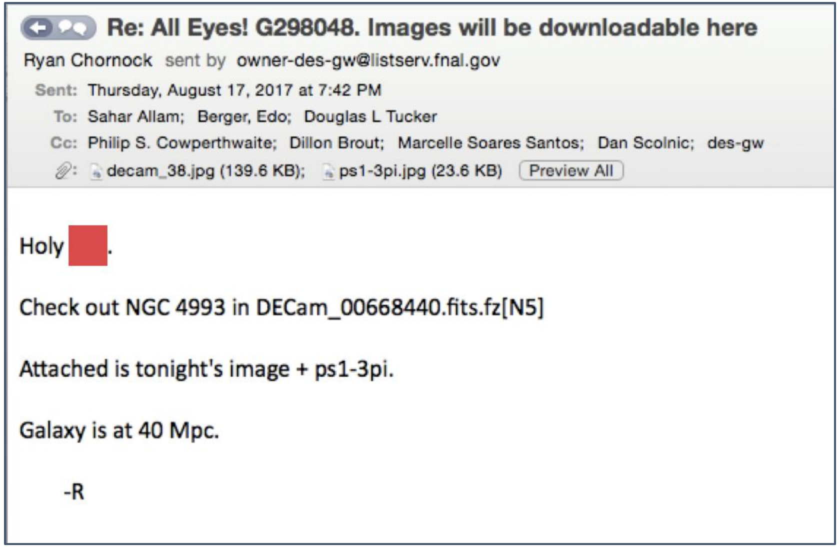
GW170817 localization region is in the far west and set ~1.5 hours after twilight.
Start observing as soon as it gets dark: 8:13 pm Chile time (23:13 UT), 10.5 hours after GW event.
With a wide field of view imager (DECam) on a 4m telescope, our team can cover the entire area.
Teams in place to eyeball the images on-site (at CTIO) and at Fermilab.





DESGW discovery of GW170817

We found it! (Along with six other teams that had seen it as well…)



Re: All Eyes! G298048. Images will be downloadable here

Ryan Chornock sent by owner-des-gw@listserv.fnal.gov

Sent: Thursday, August 17, 2017 at 7:42 PM

To: Sahar Allam; Berger, Edo; Douglas L Tucker

Cc: Philip S. Cowperthwaite; Dillon Brout; Marcelle Soares Santos; Dan Scolnic; des-gw

decam_38.jpg (139.6 KB); ps1-3pi.jpg (23.6 KB) Preview All

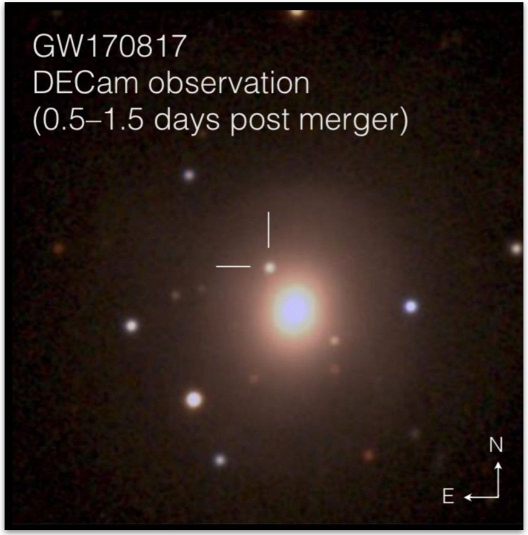
Holy [redacted].

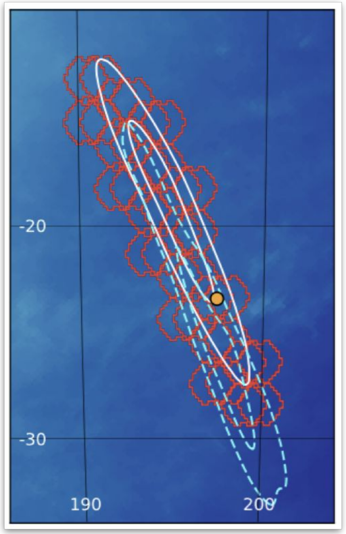
Check out NGC 4993 in DECam_00668440.fits.fz[N5]

Attached is tonight's image + ps1-3pi.

Galaxy is at 40 Mpc.

-R



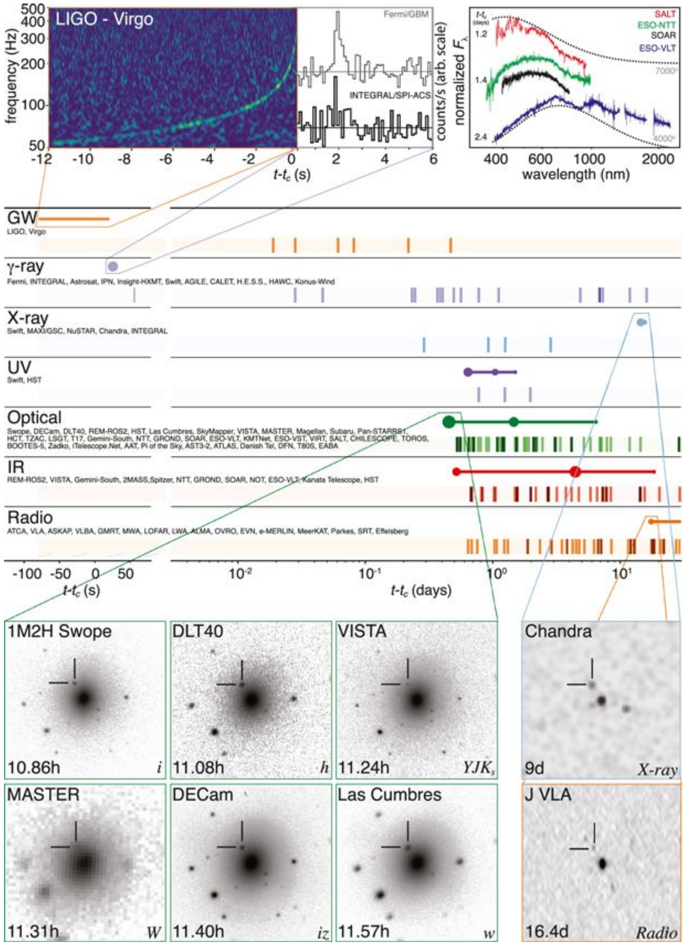


Soares-Santos et al. 2017

GW170817

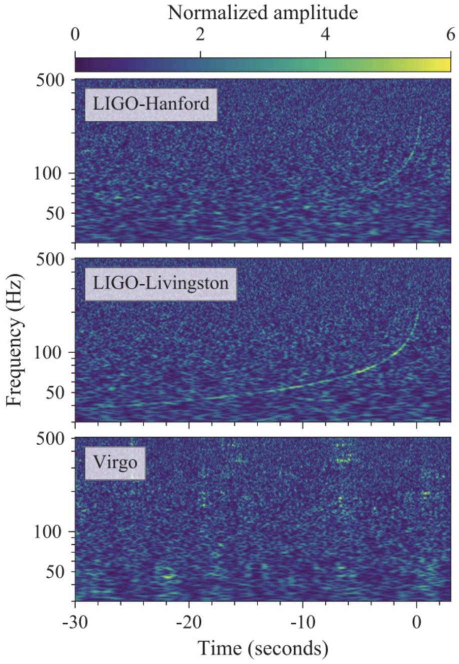
A global search and discovery

- More than 50 teams world-wide had signed MOUs with LIGO/Virgo for EM searches.
- These teams ensured that searches were carried out across the entire EM spectrum.
  - The first EM signal observed, 2 sec post-merger, was the GRB
  - The second, 11.5 hours post-merger, was the optical signal
  - Rapid follow-ups included spectroscopic information, and IR+UV and X-ray data.
  - Long term follow-up in Radio



GW170817 properties

Using the GW+EM information



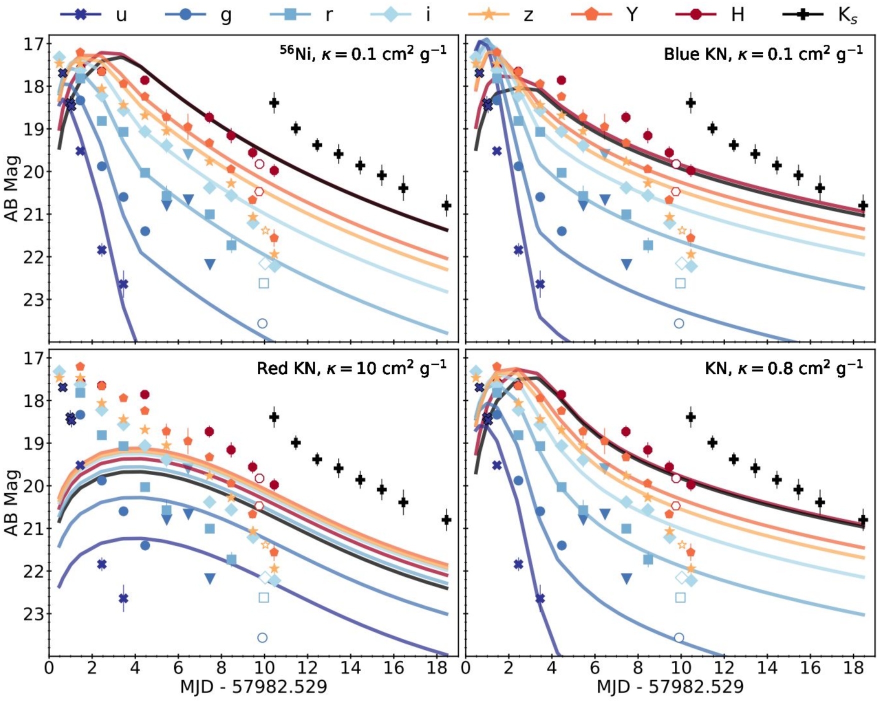
Abbott et al. ApJL12, 59 (2017).

	Low-spin priors ($\|\chi\| \leq 0.05$)
Primary mass m_1	1.36–$1.60\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$
Using NGC 4993 location	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800

GW170817 light curves

Kilonova models proven a good fit to the data!

- The hypothesis of r-process nucleosynthesis was proven wit the wealth of data obtained from optical and NIR follow-up of GW170817.
- In particular, it was shown that efficient production of heavy elements does happen after disruption of the neutron stars.
- But the reality seems more complex than the simple theory, with at least two components needed to fit the data.



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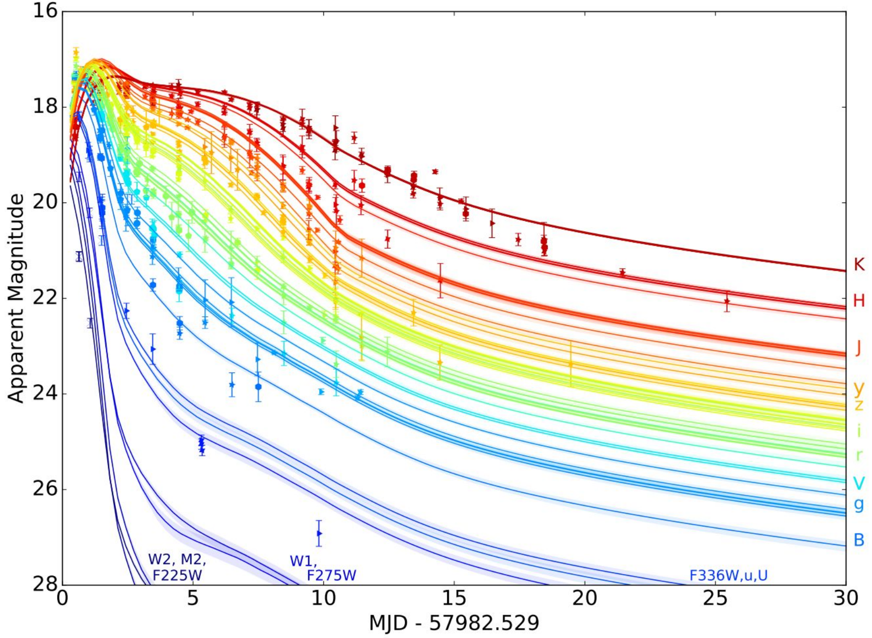
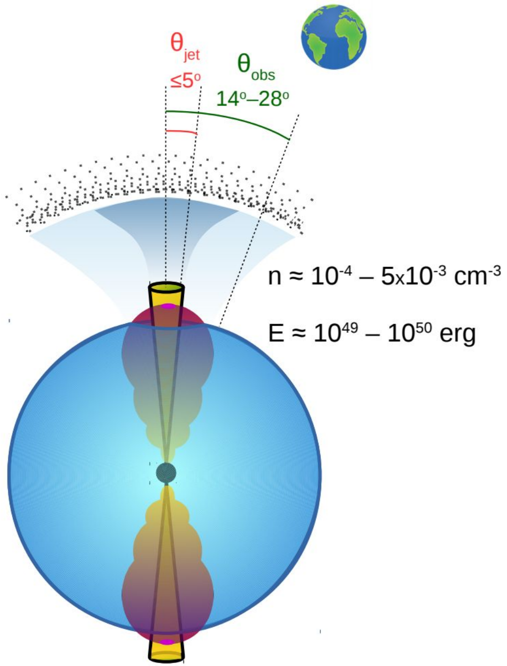
- In particular, it was shown that efficient production of heavy elements does happen after disruption of the neutron stars.
- But the reality seems more complex than the simple theory, with at least two components needed to fit the data.
    - Early blue, Late red



GW170817 jet modeling

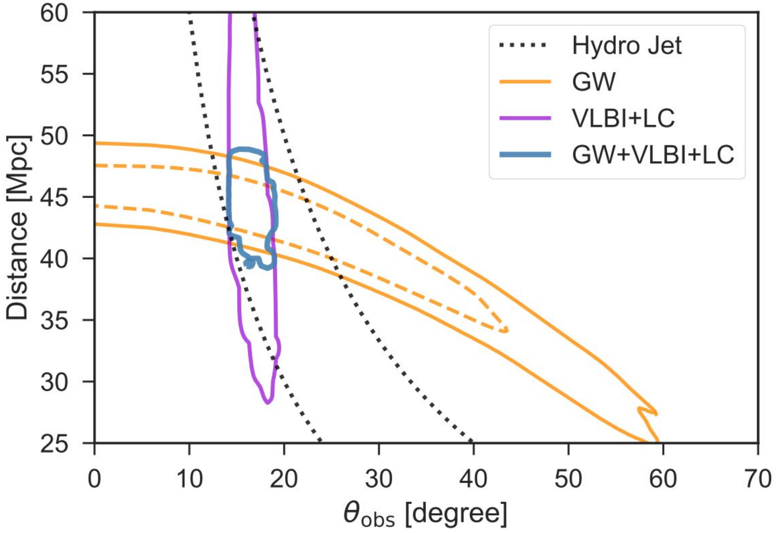
Analysis of Radio data 200+ days post-merger enables constraints on geometry and orientation of the jet

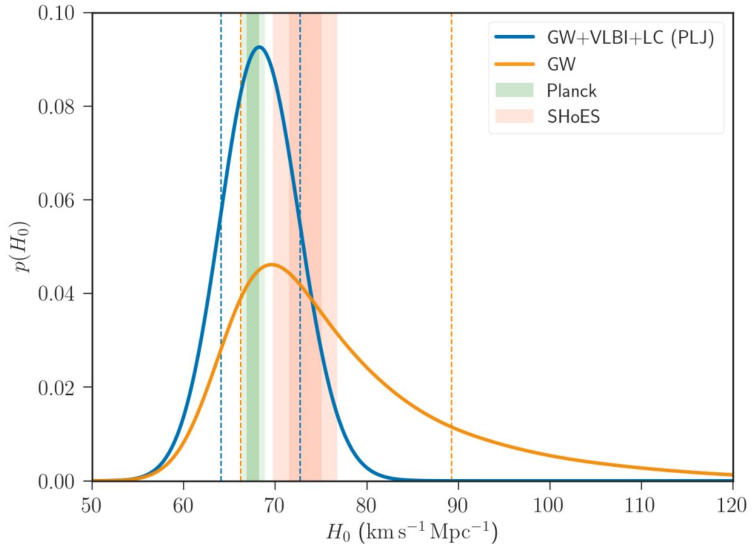
- The radio and X-ray afterglows of GW170817 exhibited delayed onset, peaking 150 after days peak at about 150 days.
- Initial analysis was inconclusive about whether GW170817 successfully launched a jet or had a choked-jet cocoon.
- Later analyses (Mooley et al. 2018) using Very Long Baseline
- Interferometry 230 days post-merger showed that early-time radio emission was powered by a wider-angle outflow (cocoon), but the late-time emission was dominated by an energetic and narrowly-collimated jet:
    - opening angle of < 5 degrees
    - observed from a viewing angle of about 20 degrees



GW170817 cosmology

Measurement of the Hubble constant without the distance ladder

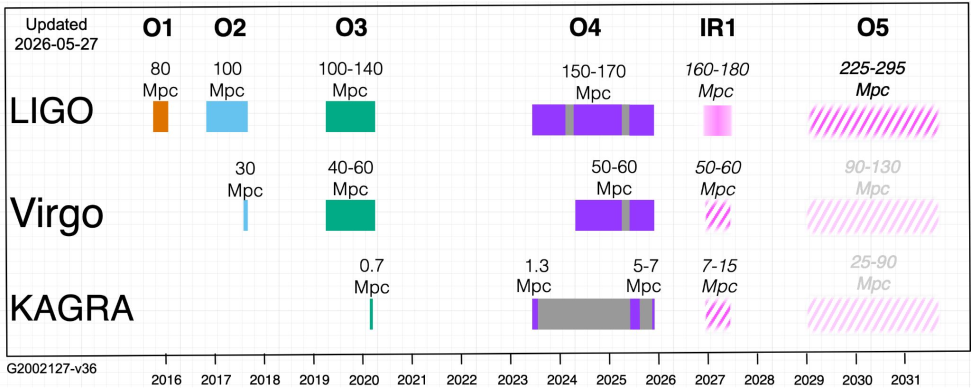




GW170817 was great! Now, do it again!

Not so fast…

- These events are rare, so we need GW detectors with sensitivity over a very large volume — GW170817 was exceptionally close. LVK has seen over 300 GW events, but only a couple of them were BNS events, and none other than GW170817 could be localized so far.
- But prospects are good, as detectors are upgraded. Next observing run is coming soon!



Entering the LSST era

Surpassing DECam (by several orders of magnitude) in survey depth, area, and speed!

LSSTCam, key features:

- 3.1 Gpix
- 9.6 deg^2 FOV
- 6.5 m telescope

Optimal for rapid search and discovery of EM counterparts of GW events!

The Rubin Observatory, which runs the LSST, issues public alerts every night about transients.

Rubin has a Target of Opportunity program that will be active in IR1 searching for LVK counterparts!

Summary and Up Next…

Lecture 1 down, 4 to go!

So far, we have…

- Introduced the motivations for (and challenges of) the pursuit of multi-messenger studies that combine EM and GW observations of the same astrophysical events — particular BNS events!
- Reviewed the discovery of the spectacular GW170817 and the prospects for more BNS KN discoveries in the LSST era.

Coming up next…

- <u>Later today:</u> A hands-on session on how to use the LSST public data stream to look for EM counterparts of LVK events.
- <u>Tomorrow:</u> What about the BBHs? They outnumber BNSs over 200 to 1 in the LVK data? Could they have EM counterparts as well?

“What if a GW170817-like event would happen today?”

Searching for counterparts in the era of the newly commissioned LSST

The GW treasure hunt in the LSST era

Using LSST brokers and LVK maps

- In this session, we will learn to
    - Retrieve information from LVK about GW events
    - Retrieve information about LSST’s observing plans
    - Create a “watchmap” for our selected event in an alert broker
- Useful links:
    - The code we will be using was prepared by LeBrun: https://github.com/Lgtlebrun/LSST-GW
    - We will also use the alert broker link here: https://lasair.lsst.ac.uk/
    - Instructions here : https://github.com/Lgtlebrun/LSST-GW/blob/main/INSTRUCTIONS_Sao_Paolo_workshop.md
- Homework:
    - Tomorrow, check your watchmap and see if there are any treasures!

“What if a GW170817-like event would have happened yesterday?”

Discussion of hands-on exercise results

Step 1: Will LSST cover the region of interest tonight?

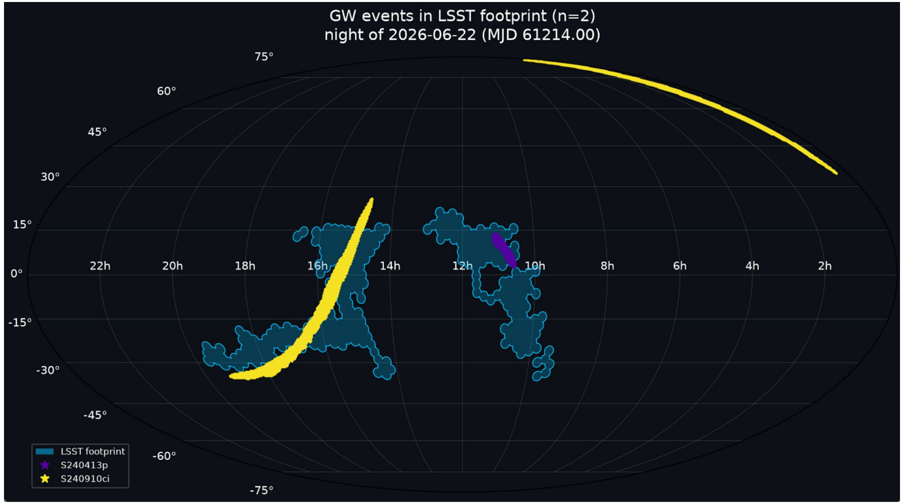
In this exercise, we imagine a scenario where there is a golden BNS event and you, the researcher, wants to watch that region of interest for any transient kilonova candidate that LSST may report.

```
marcelle@Marcelles-MacBook-2 LSST-GW % source .venv/bin/activate
(.venv) marcelle@Marcelles-MacBook-2 LSST-GW % lsst-gw-select-events --public-only --mjd 61214
WARNING: AstropyDeprecationWarning: reproject.healpix.utils is a private module and will be removed in a
future version.  Please use the public API from reproject.healpix instead.
[ligo.skymap.plot.reproject_from_healpix_moc]
INFO eventsSelector: Selecting events for night of 2026-06-22 (MJD 61214.00)
INFO eventsSelector: 0/415 scheduled pointings were actually executed (execution_status == 'Performed')
INFO eventsSelector: Fetched 415 scheduled pointings
INFO eventsSelector: Found 177 candidate events
DEBUG : path = /Users/marcelle/.gwutils/skymaps/S250114ax_Bilby.multiorder.fits
DEBUG : path = /Users/marcelle/.gwutils/skymaps/S250119cv_Bilby.multiorder.fits
DEBUG : path = /Users/marcelle/.gwutils/skymaps/S250118dp_Bilby.multiorder.fits
...........
DEBUG : path = /Users/marcelle/.gwutils/skymaps/S190408an_GW190408_181802_PublicationSamples.multiorder.fits
INFO eventsSelector: Saved overview figure to
/Users/marcelle/LSST-GW/output/lsst_gw_selection/gw_footprint_overlap.png
INFO eventsSelector: Selected events: ['S240413p', 'S240910ci']
```

Step 1: Will LSST cover the region of interest tonight?

In this exercise, we imagine a scenario where there is a golden BNS event and you, the researcher, wants to watch that region of interest for any transient kilonova candidate that LSST may report.

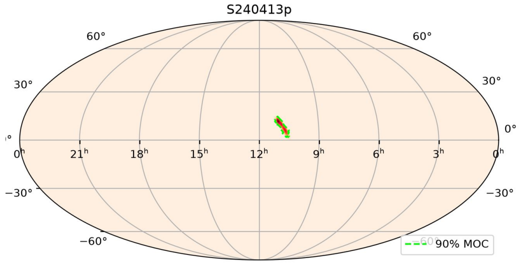
- **<u>Yes!</u>** In this case, there are actually two events with at least particle coverage.
- In a real-world application, you would check if any of these event IDs corresponds to your golden BNS ID. For the sake of this exercise, let's say that was **<u>S240413p</u>**.



Step 2: Let’s configure our watch map… and wait!

Our event will likely be observed, so let’s prepare to watch for new LSST data!

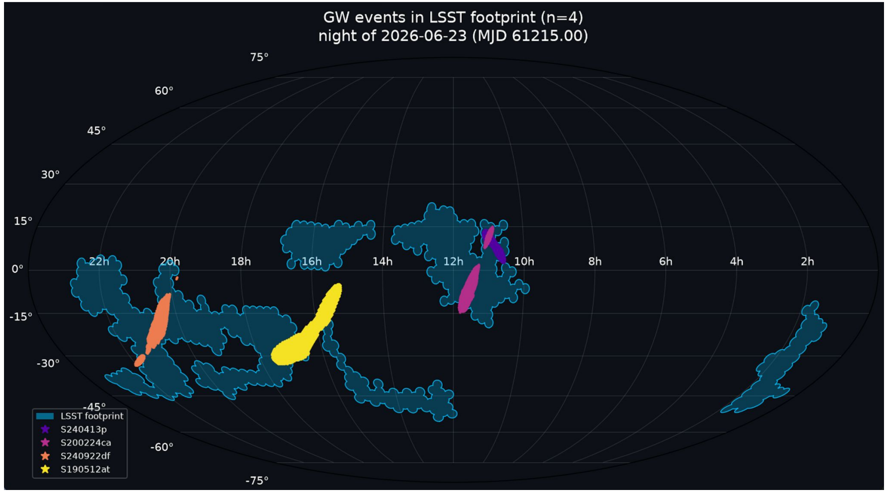
```
(.venv) marcelle@Marcelles-MacBook-2 LSST-GW % lsst-gw-visualise-event S240413p
Superevent ID             : S240413p
Catalog                   : GWTC-5.0
Coalescence time (UTC)    : 2024-04-13 02:20:19 UTC
FAR [Hz]                  : 1.00e-05
Network SNR               : 18.1
Detectors                 : LIGO_Hanford, LIGO_Livingston, Virgo
Classification            : BBH (98.0%) [BBH=98.0%, BNS=0.0%, NSBH=0.0%, Terrestrial=2.0%]
Mass 1                    : 7.9 (-1.2/+2.8) M_sun
Mass 2                    : 5.57 (-1.4/+0.96) M_sun
Chirp mass                : 5.74 (-0.11/+0.23) M_sun
Total mass                : 13.6 (-0.52/+1.4) M_sun
Final mass                : 12.9 (-0.52/+1.5) M_sun
Luminosity distance       : 570 (-2.2e+02/+1.1e+02) Mpc
Redshift                  : 0.12 (-0.04/+0.02)
Effective spin (chi_eff)  : 0.07 (-0.04/+0.14)
GraceDB: https://gracedb.ligo.org/superevents/S240413p/view/
INFO eventVisualisation: Saved skymap figure to
/Users/marcelle/LSST-GW/output/event_visualisation/S240413p_skymap.png
INFO eventVisualisation: Saved ROI MOC to /Users/marcelle/LSST-GW/output/event_visualisation/S240413p_roi.fits
```



Step 3: Did we receive any alerts?

With the result of the previous step, you should have been able to setup your watch map in the LASAIR alert broker, following LeBrun's instructions.

- You should see a list of transients generated when you go to the broker website and click "run" on your map. You should also have notifications on your inbox (if you chose to receive them).
- You can run the script with the option "**`--executed-only`**" to check what portion of the plan was executed.
- Looks like we were unlucky (due to weather) and there were no new images last night. But stay tuned, because that region is on the plan for tonight!
- Other good events to watch: S240922df, S200224ca

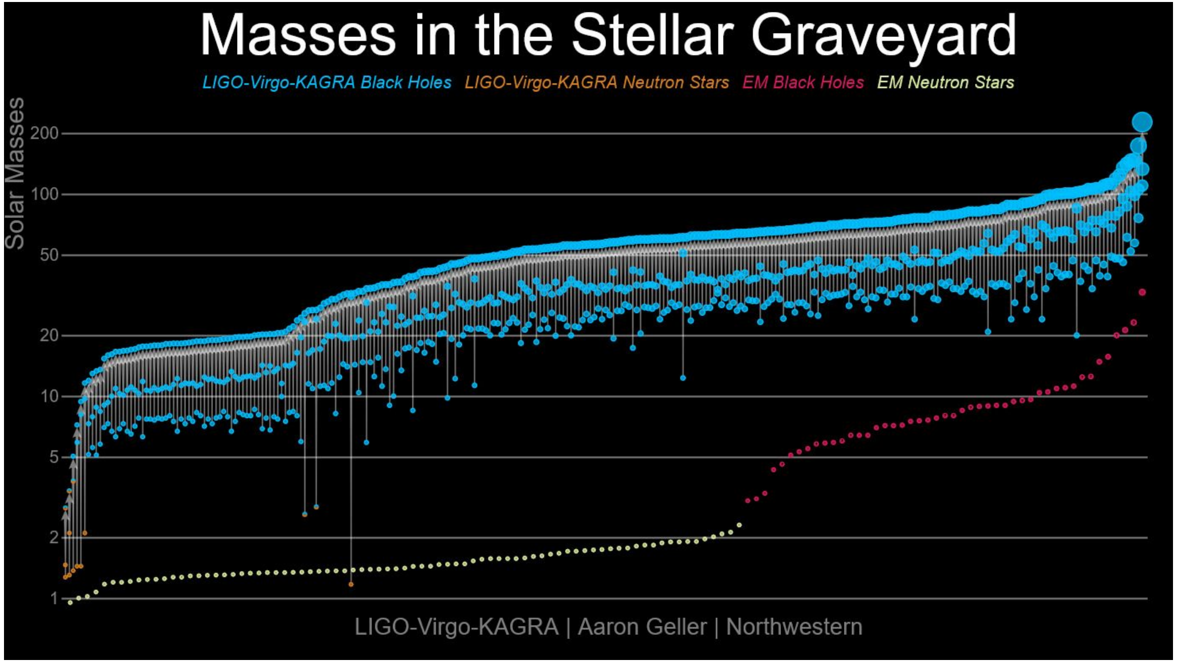


Searches for EM counterparts of BBH (and NSBH) events

Potential for discovery of an entire new class of astrophysical objects

While we wait for that golden BNS…

BBHs greatly outnumber BNSs in the LVK data. Maybe we can do multi-messenger work with them too?



BBH EM discovery would be huge — but it is hard!

We can estimate rough limits on optical signatures following (Annis & Soares-Santos arXiv:1609.09517)

- For a given event, the probability that an imaging element detected a source is:

$$P = \Sigma_{spatial} \cdot \varepsilon_{camera} \cdot \varepsilon_{area} \cdot$$

- What is the probability that, after N attempts we would cover at least one merger?

$$P_{one} = 1 - \prod_i (1 - P_i)$$

where P_i corresponds to the i-th event.

Assuming P=50% for all events, we would have P_{one} = 0.984 after "only" 6 attempts!

- Assuming no background and a non-zero uniform prior, the cumulative posterior PDF is

$$F(s|0) = \int_0^s \frac{t^n e^{-t}}{n!} \mathrm{d}t = 1 - e^{-s}$$

where s is the sum of P for all N events.

If one wants to place a 95% confidence limit at a given magnitude, one needs s ≥ 3.

- But note that the reality is more complicated than this: we do have backgrounds!

GW150914 — the very first CBC observation

This BBH merger requires no introduction: was the first LIGO detection, a Nobel prize winning detection!

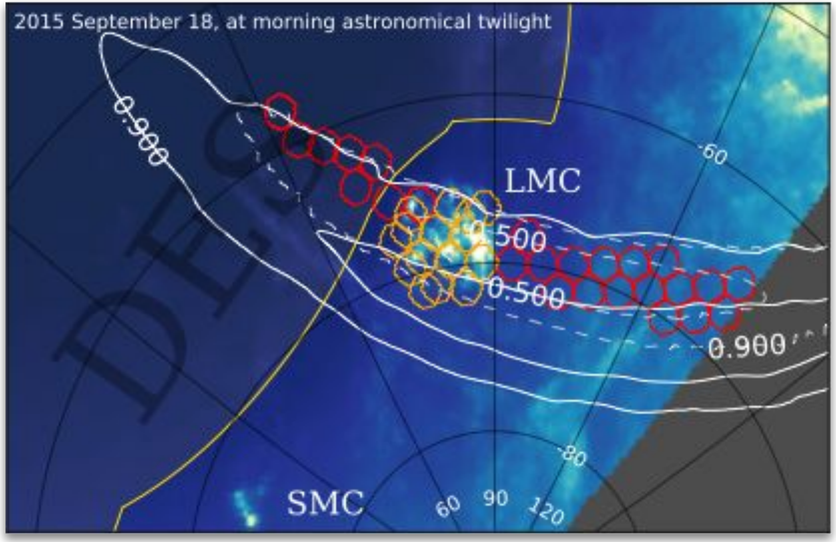
- The community pursued several searches for EM counterparts of GW170817.
- It was a great “hands-on” exercise in preparation for GW170817!

Event	Experiment	Magnitude	$\Sigma_{spatial}$	ε_{camera}	ε_{sky}	P_{total}
GW150914	Master 2x0.4m	18.4-19.9 O	49%	1.0		
	DESGW 4.0m Blanco, DECam	22.1 i	11%	$0.8 \cdot 0.34^{\dagger}$	0.8	.024
	PanSTARRS 1.8m	19.7 i	4.2%	$1.0^{\dagger\dagger}$	$0.5^{\ddagger}$	.021
	iPTF 1.1m Oschint, CFH12K	20.6 R	0.2%	$1.0^{\S}$		
	JGEM 1.1m Kiso, KWFC	19.0 i	0.1%			
	TOROS 1.5m EABA	21.7 r	galaxy	1.0		

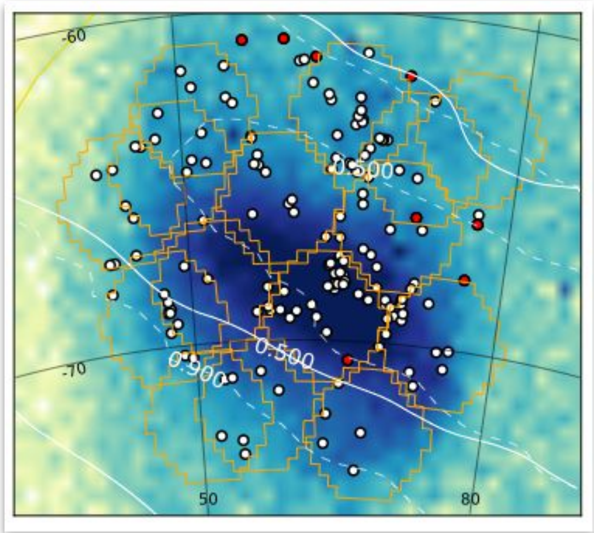
GW150914 — the very first CBC observation

This BBH merger requires no introduction: was the first LIGO detection, a Nobel prize winning detection!

DESGW general search: Soares-Santos et al. 2016



DESGW LMC search: Annis et al. 2016



GW150914: main search

Looking for a decaying transient — a hands-on exercise for kilonova searches

- Area (square degrees)
  - Total observed:102
  - Excluding LMC: 84
  - Considering fill-factor: 67
  - Good after diffimg: 40
    - 30% loss to missing templates
- Sample selection (all cuts in i and z bands)
  - Good detection in 1st epoch
  - 2nd epoch S/N>2
  - 3+ sigma 1st to 2nd epoch flux decline
  - S/N < 3 sigma in the 3rd epoch

- Efficiency estimates
  - Assumptions: decay rate: 0.3 mag/day
  - Recovery depth at 50%:
    - color: (i-z) ~ 1 i = 21.5
    - color: (i-z) ~ 0 i = 21.1
    - color: (i-z) ~-1 i = 20.1
- This result supported the claim that our search program would have been sensitive to kilonova as far as 200 Mpc — it as a great proof of concept run for our BNS search and discovery program!

GW150914: LMC search

Looking for a missing stars in the LMC — a hands-on exercise for burst event searches

- If GW150914 were a burst event, instead of a CBC, it could be due to a core-collapse (CC) nearby.
- CC's often result in supernova explosions (e.g. 1987A), but ~ 20% of the CC's are expected to fail to produce supernovae.
- Therefore, searches for a missing star in the region of interest of burst events that are not immediately followed by a supernova explosion would be very interesting!
- Under the assumption that the event was a burst event coming from the LMC, we:
  - Took possible progenitors (152 red supergiants) catalogued in the literature, and
  - Searched for them via visual inspection.
- 144 red supergiants were in the observed area; all were accounted for.
- This search was proof of concept for future searches of this type.

What about the other 200+ BBHs?

After GW150914, we built a search & discovery program that could scale-up as detectors improve

2021arXiv210913351T 2021/09 cited: 3

SOAR/Goodman Spectroscopic Assessment of Candidate Counterparts of the LIGO--Virgo Event GW190814

Tucker, Douglas; Wiesner, Matthew; Allam, Sahar *and 141 more*

2020EPJWC.24501008H 2020/11

The updated DESGW processing pipeline for the third LIGO/VIRGO observing run

Herner, Kenneth; Annis, James; Garcia, Alyssa *and 10 more*

2020ApJ...903...75G 2020/11 cited: 9

A DESGW Search for the Electromagnetic Counterpart to the LIGO/Virgo Gravitational-wave Binary Neutron Star Merger Candidate S190510g

Garcia, A.; Morgan, R.; Herner, K. *and 90 more*

2020A&C....3300425H 2020/10 cited: 9

Optical follow-up of gravitational wave triggers with DECam during the first two LIGO/VIRGO observing runs

Herner, K.; Annis, J.; Brout, D. *and 82 more*

2020ApJ...901...83M 2020/09 cited: 22

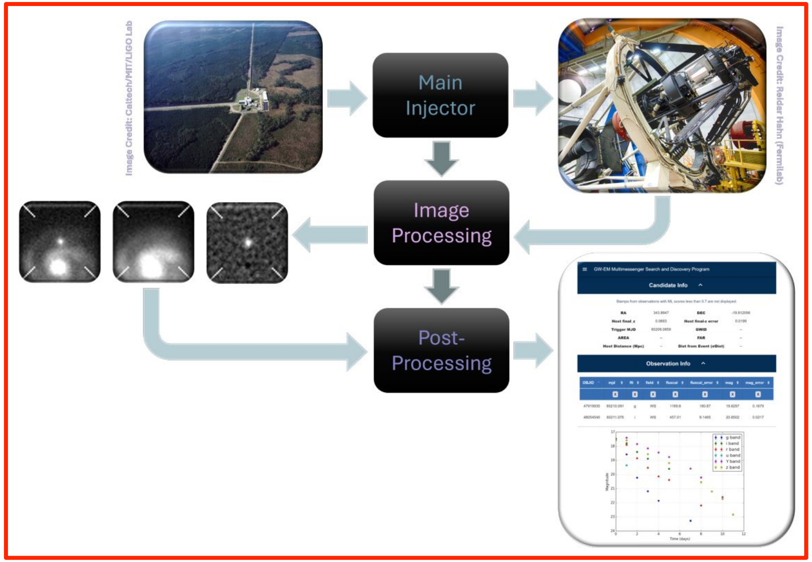
Constraints on the Physical Properties of GW190814 through Simulations Based on DECam Follow-up Observations by the Dark Energy Survey

Morgan, R.; Soares-Santos, M.; Annis, J. *and 100 more*

2020ApJ...900L..33P 2020/09 cited: 38

A Statistical Standard Siren Measurement of the Hubble Constant from the LIGO/Virgo Gravitational Wave Compact Object Merger GW190814 and Dark Energy Survey Galaxies

Palmese, A.; deVicente, J.; Pereira, M. E. S. *and 87 more*



Adding spectroscopic follow-up

Classification of EM candidates is crucial to eliminate false positives!

2021arXiv210913351T 2021/09 cited: 3

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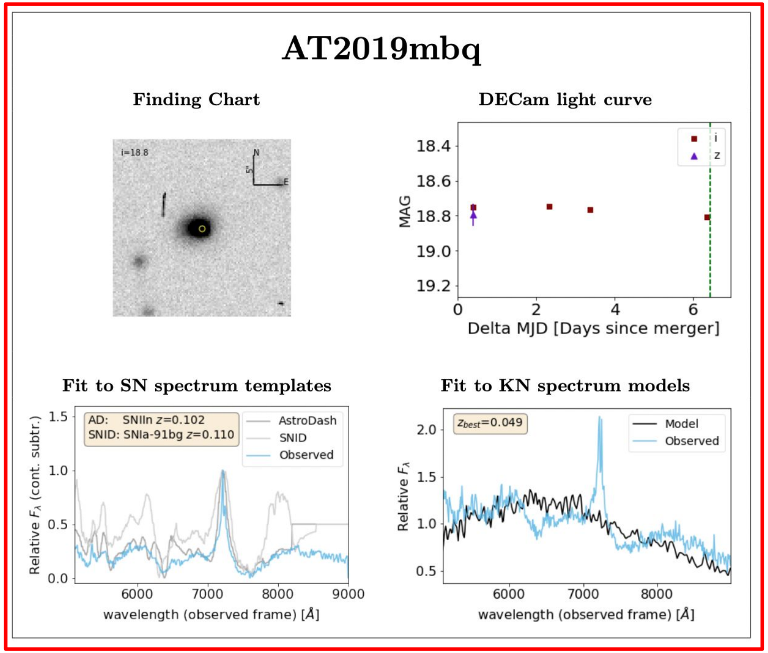

What do we do when searches find ‘nothing’?

We can learn a lot from null results, by constraining emission models and excluding some mechanisms.

2021arXiv210913351T 2021/09 cited: 3
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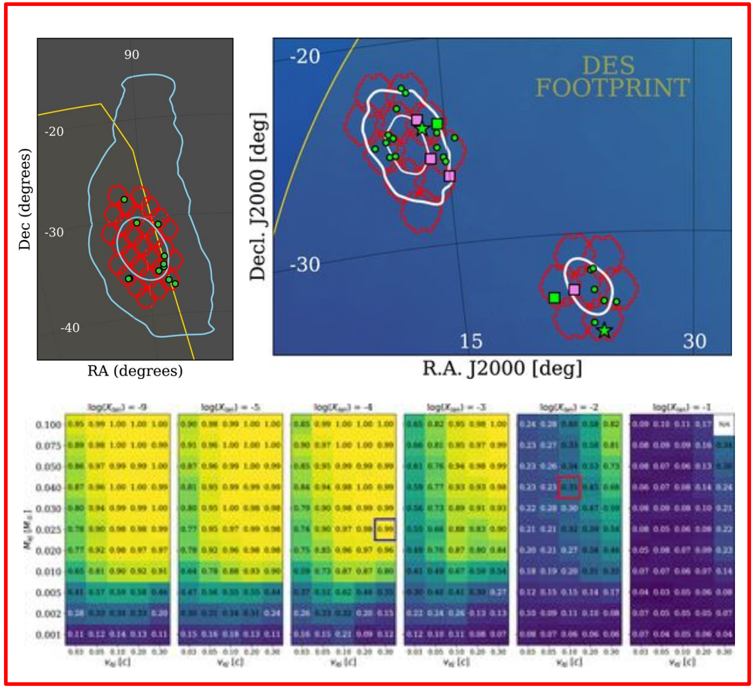
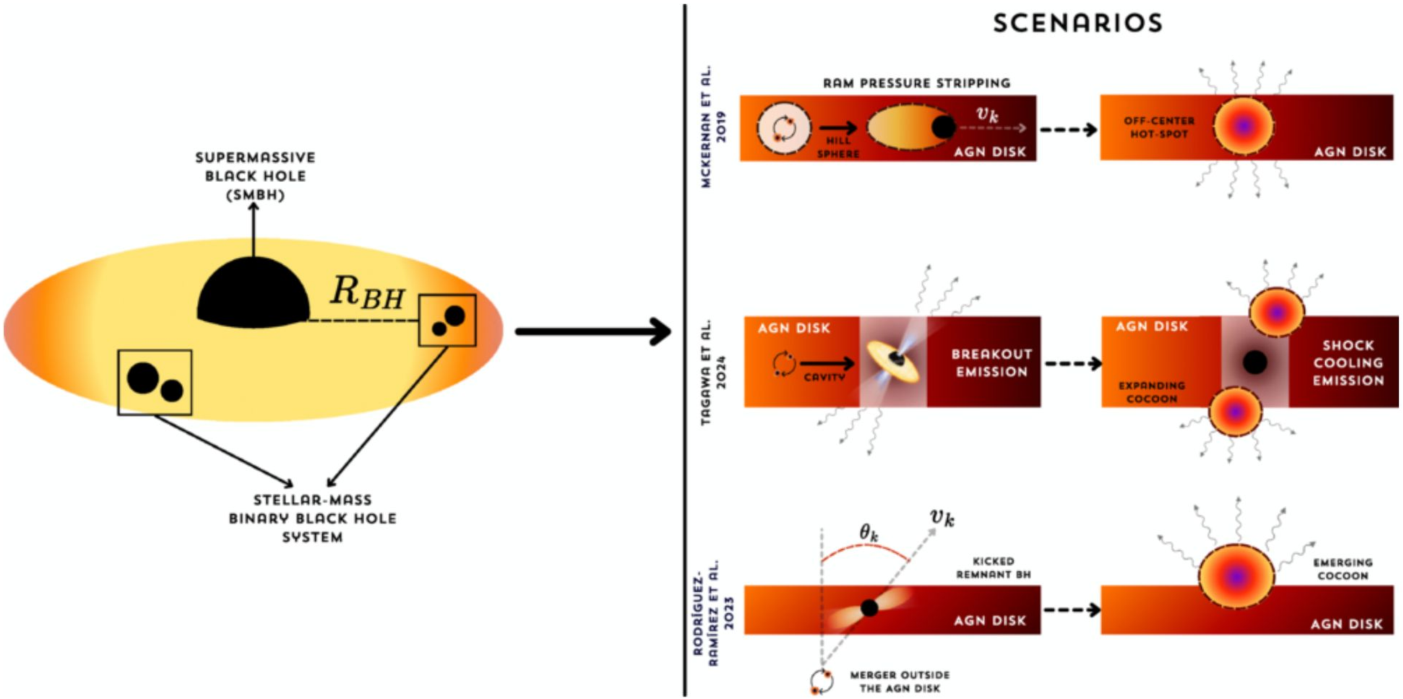


What mechanisms could lead to EM signatures in BBHs?

The AGN driven scenarios have been proposed in the literature

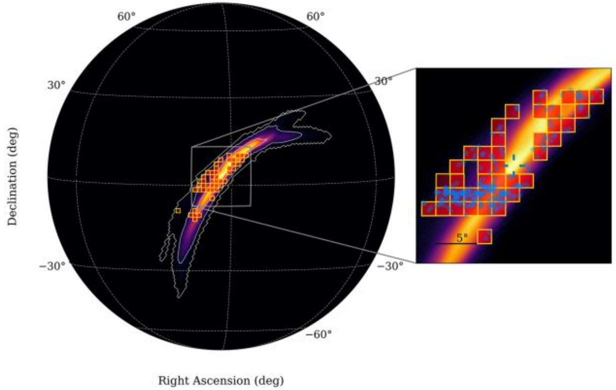


The community is pursuing constraints on BBH models

First searches focusing on the AGN-driven scenario, in particular, look promising!

- Notably, this analysis (by Darc et al. 2025), including data taken up to 318 days post merger is the most comprehensive to date.

- All candidates were ruled out; this was a great proof of concept for this type of search!



PHYSICAL REVIEW D **112,** 063019 (2025)

Long-term optical follow up of S231206cc: Multimodel constraints on BBH merger emission in AGN disks

P. Darc,[1*] C. R. Bom,[1] C. D. Kilpatrick,[2] A. Souza Santos,[1] B. Fraga,[1] J. C. Rodríguez-Ramírez,[1] D. A. Coulter,[3] C. Mendes de Oliveira,[4] A. Kanaan,[5] T. Ribeiro,[6] W. Schoenell,[7] and E. A. D. Lacerda[4]

[1]*Centro Brasileiro de Pesquisas Físicas Rua Dr. Xavier Sigaud 150, CEP 22290-180, Rio de Janeiro, RJ, Brazil*
[2]*Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) Northwestern University, Evanston, Illinois 60201, USA*
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[4]*Universidade de São Paulo, IAG, Rua do Matão 1225, São Paulo, SP, Brazil*
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[6]*Rubin Observatory Project Office, 950 N. Cherry Avenue, Tucson, Arizona 85719, USA*
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(Received 18 June 2025; accepted 17 July 2025; published 10 September 2025)

The majority of gravitational wave events detected by the LIGO/Virgo/Kagra Collaboration originate from binary black hole (BBH) mergers, for which no confirmed electromagnetic counterparts have been identified to date. However, if such mergers occur within the disk of an active galactic nucleus (AGN), they may generate observable optical flares induced by relativistic jet activity and shock-heated gas. We present results from a long-term optical follow-up of the GW event S231206cc, conducted with the T80-South telescope as part of the S-PLUS Transient Extension Program (STEP). Our search prioritized AGN-hosted environments by crossmatching the GW localization with known AGN catalogs. No candidate met the criteria for a viable optical counterpart. We explored three BBH merger scenarios predicting optical emission in AGN disks: (i) ram pressure–stripping, (ii) long term emission of an emerging jet-cocoon, and (iii) jet breakout and shock cooling. Using our observational cadence and depth, we constrained the BBH parameter space, including the remnant's location within the AGN disk, kick velocity, and supermassive black hole (SMBH) mass. Detectable flares are most likely when mergers occur at 0.01–0.1 parsecs from SMBHs of 10^7–10^8 solar masses, where short delay times and long durations best aligns with our follow-up strategy. These results provide a framework for identifying AGN-hosted BBH counterparts and guiding future multimessenger efforts.

DOI: 10.1103/6rg8-2xxz

Summary and Up Next…

Lecture 2 down, 3 to go!

So far, we have…

- Introduced the motivations for (and challenges of) the pursuit of multi-messenger studies that combine EM and GW observations of the same astrophysical events — particularly, BNS (yesterday) and BBH (today)!
- Reviewed the discovery of the spectacular GW170817 and explored, in our hands-on session, the prospects for more BNS KN discoveries in the LSST era.

Coming up next…

- Tomorrow we will focus more on the application of CBCs for multi-messenger cosmology — regardless of whether or not an EM counterpart is identified. Stay tuned!

CBCs as standard sirens

Using gravitational-wave standard sirens to measure the expansion rate of the Universe

CBCs as stochastic GW background sources

Searching for the combined signal of an entire population of CBCs

CBCs for precision cosmology

Playing on the same league as supernovae, and the CMB?

Conclusion

Backup slides