Enabling the Discovery of Kilonovae Associated with Neutron Star Mergers with Electromagnetic Follow-up

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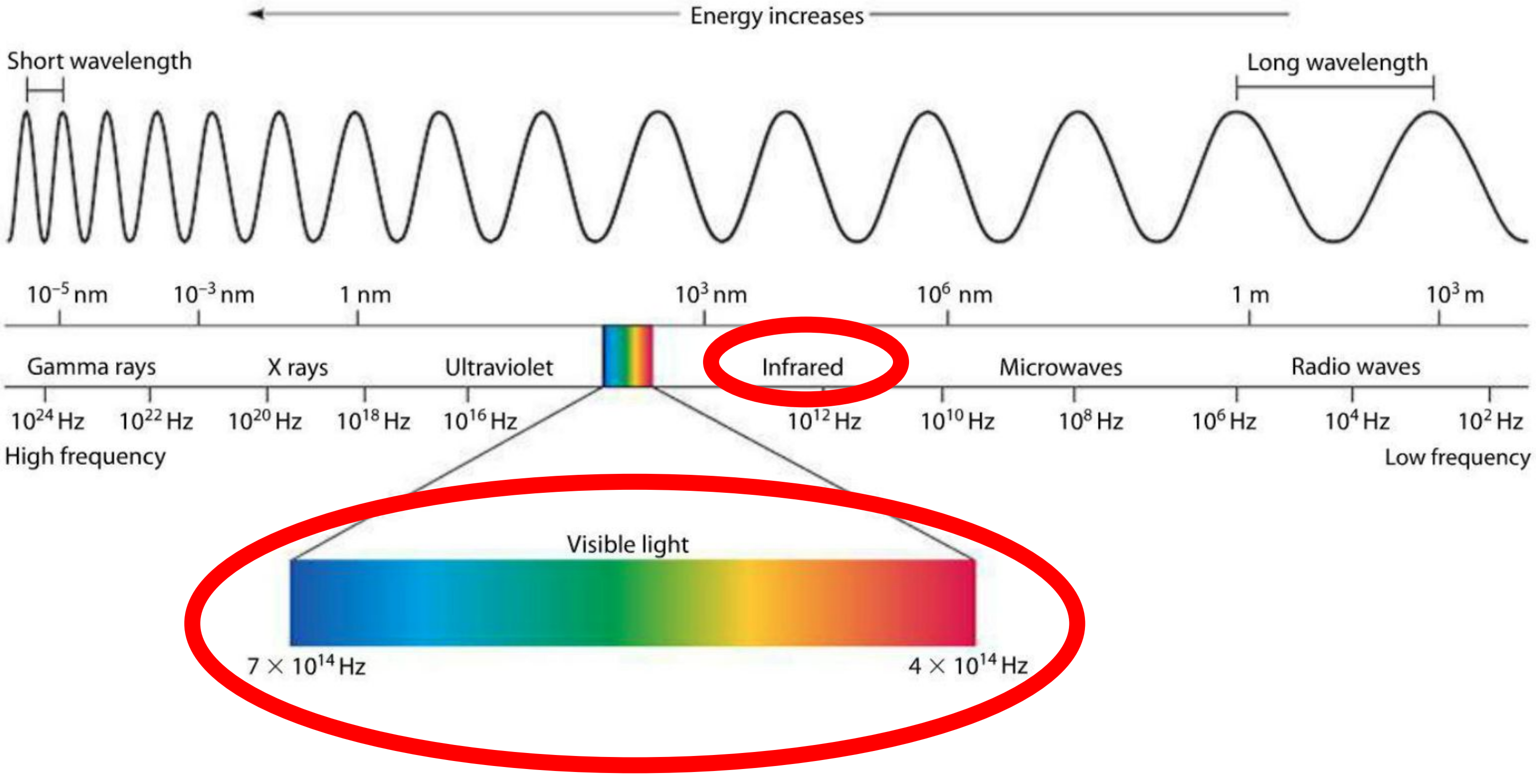
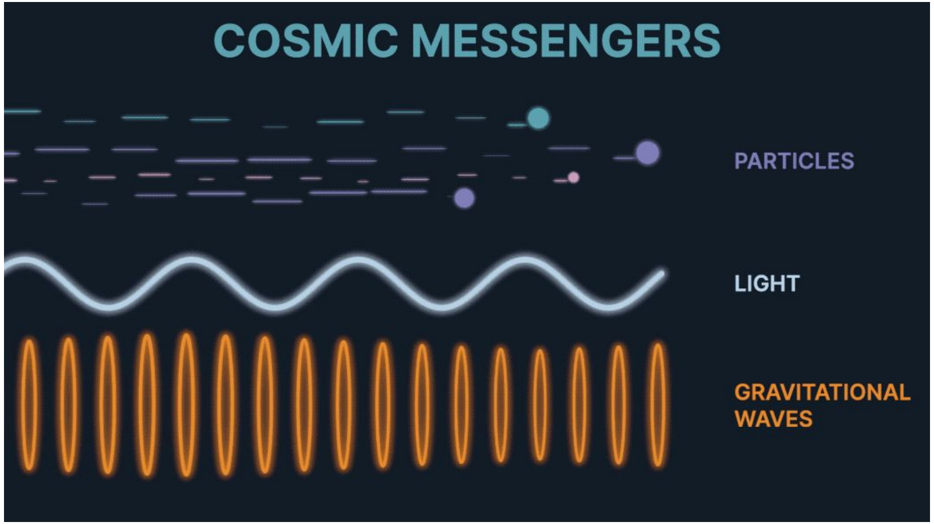
Focusing on the Electromagnetic Spectrum

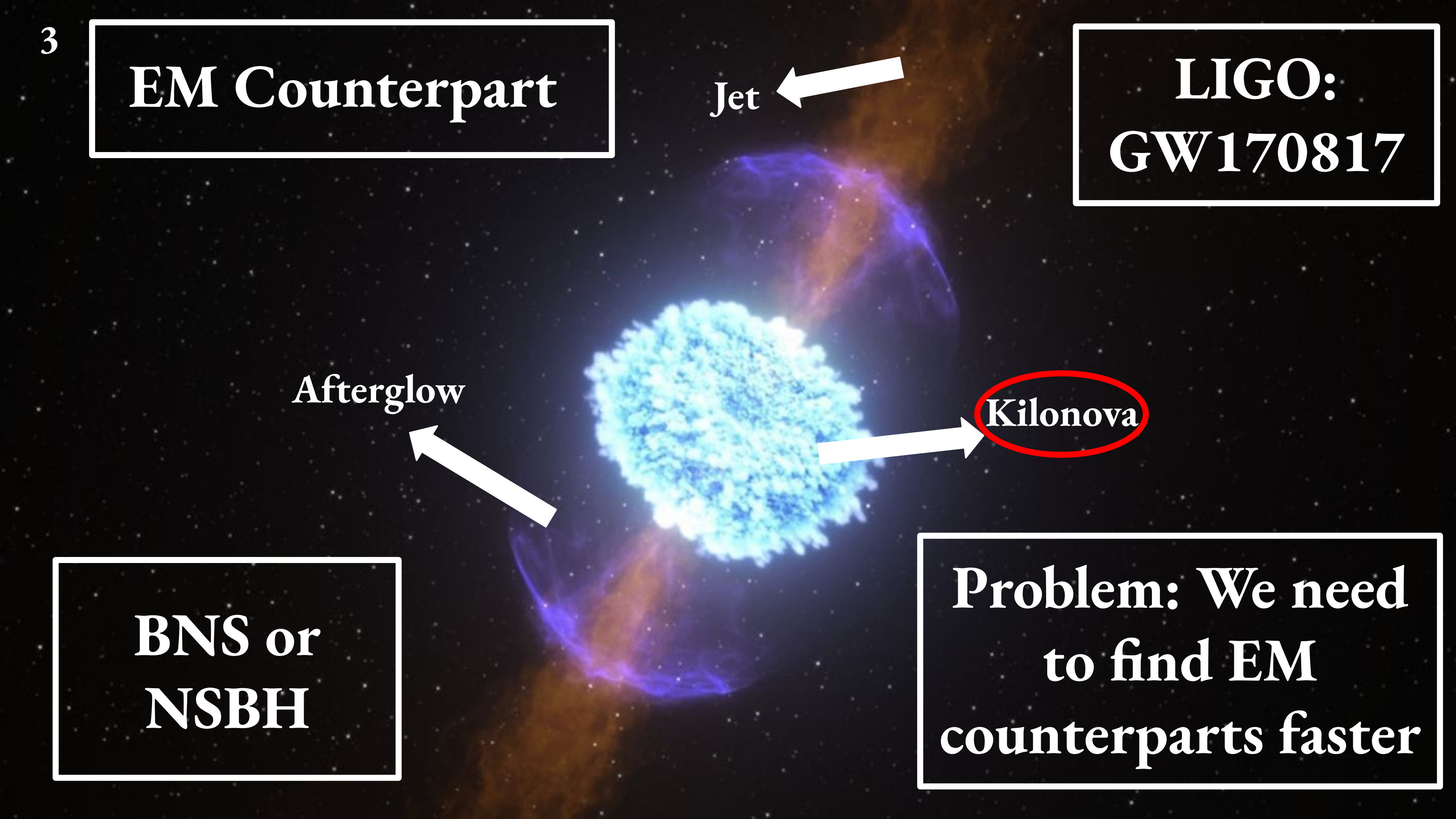


Multi-Messenger Astronomy (MMA)

MMA: The process of gathering information using multiple detection methods

- **Gravitational Waves (GWs): LIGO**
- **Electromagnetic Radiation (Light): Telescopes**

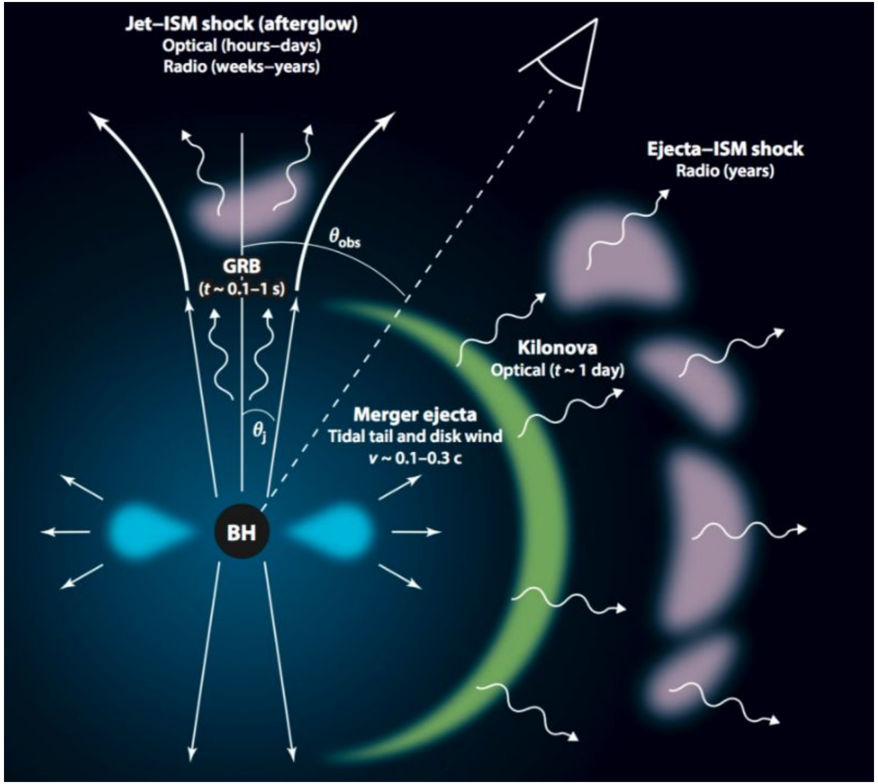



EM Counterpart
Jet
LIGO:
GW170817
Afterglow
Kilonova
BNS or
NSBH
Problem: We need
to find EM
counterparts faster

Kilonova

- The EM counterpart powered by the radioactive decay of heavy elements produced during a BNS or NSBH merger

- Tidal ejecta result from the tidal forces experienced by the neutron stars during the merger
- Wind ejecta are produced by the high-speed winds that emanate from the merged object



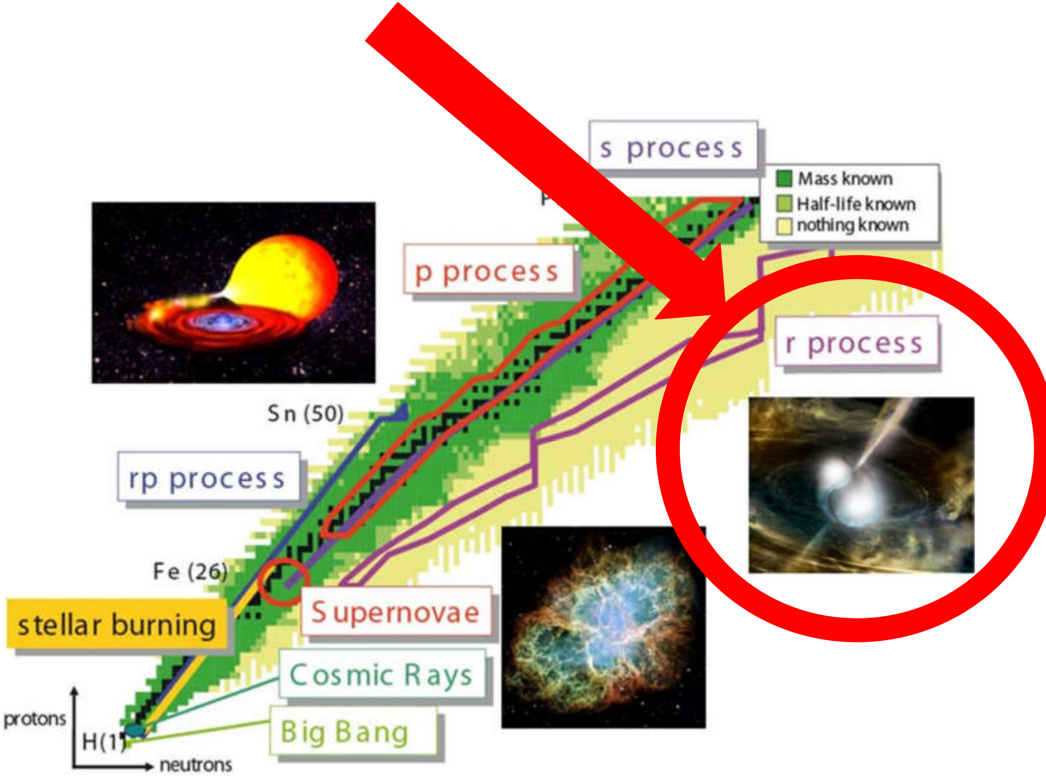
Why is this important?

Before GW170817, people theorized that heavy elements were created in BNS and NSBH mergers.

Rapid neutron-capture process (*r*-process nucleosynthesis)

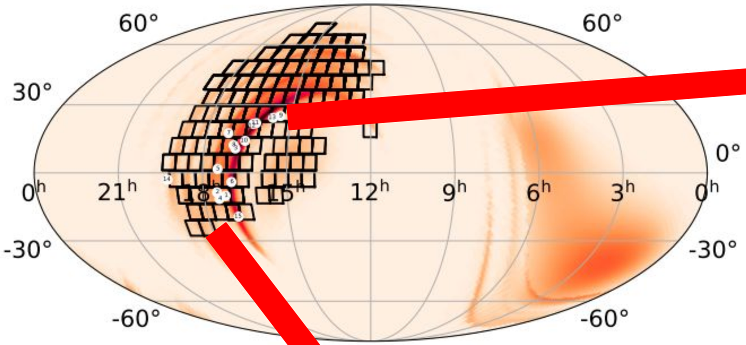
- Process by which heavy atomic nuclei in elements like gold, platinum, and uranium are synthesized

Now we can learn more about the elements on Earth.

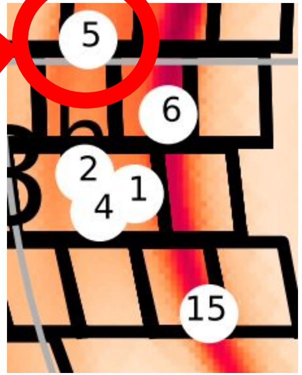


Zwicky Transient Facility (ZTF)

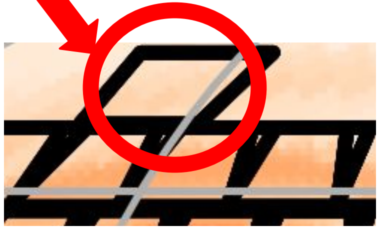
- Large field of view (FOV) of 47 sq deg
- Surveys the entire northern sky every few nights
- Searches for KN counterparts
- “Triggered” after a compelling GW event



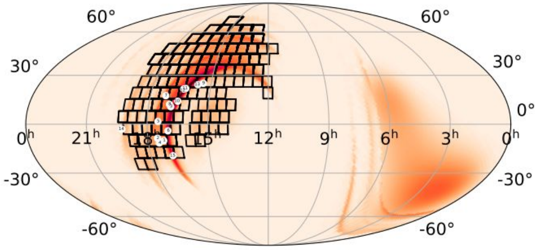
Each white circle is a candidate

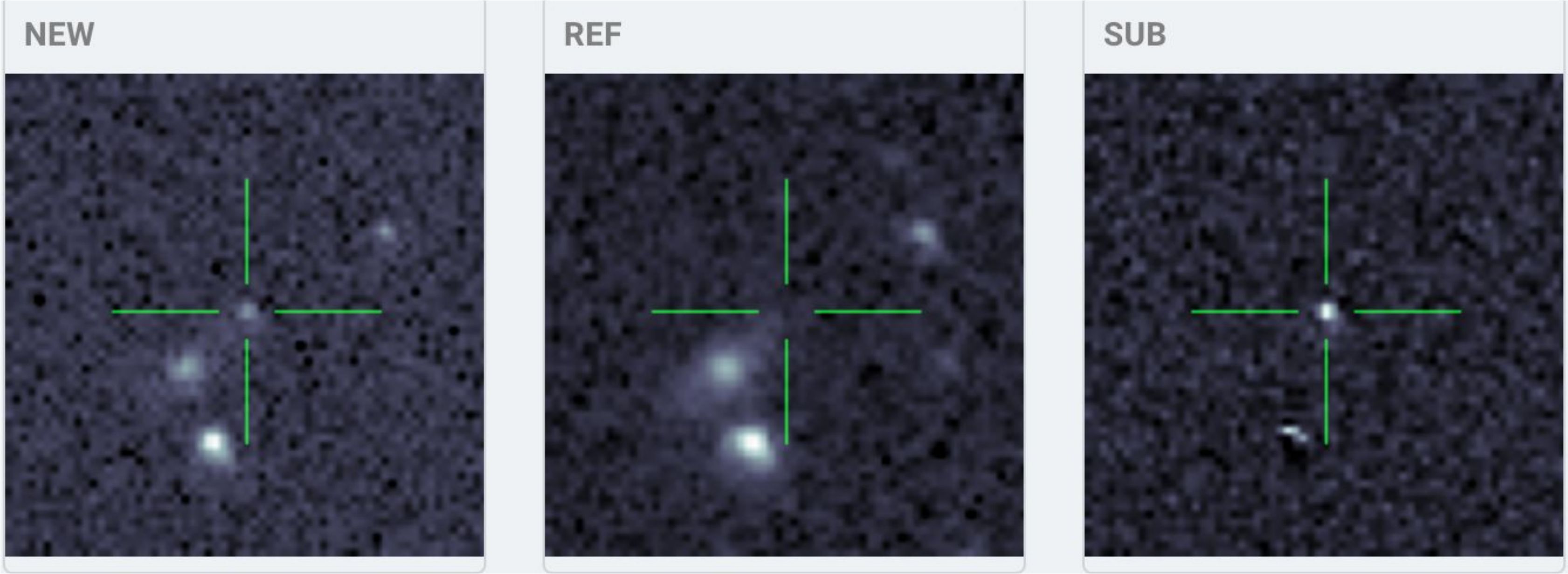


Each square is a ZTF field



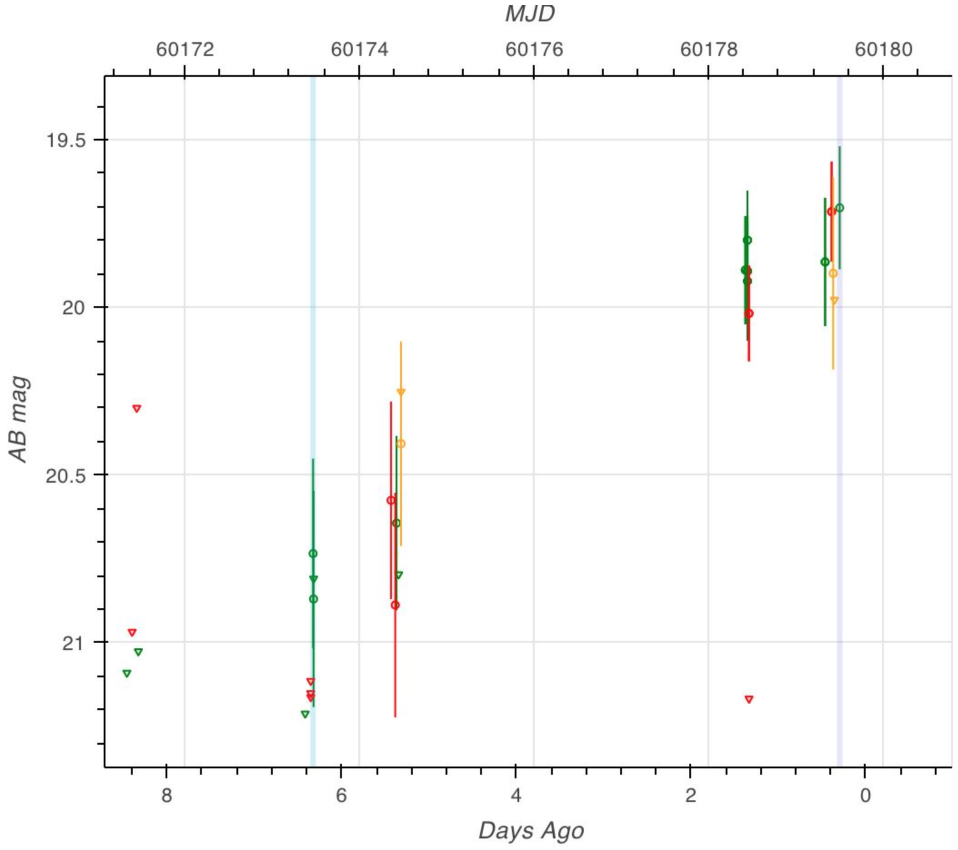
What Do We Get From ZTF?





Lightcurve of a S230627c KN candidate

- S230627c: detected by LIGO
- ZTF was triggered and generated candidates
- The lightcurve shown is for a good candidate
- A good candidate has fast evolution (fast-fading)
- For follow-up observations, telescopes like Keck, Gemini, GIT, LCO P60, P200 are used
- No KN was found for S230627c



Gemini Multi-Object Spectrograph (GMOS)

- **Gemini North and Gemini South (8 meter - very large)**
- **Gemini is a telescope that could be triggered once we have promising KN candidates**
- **GMOS: instrument used to acquire spectroscopy**
- **Spectroscopy is used to study heavy elements produced in the mergers**

DRAGONS pipeline

<u>DRAGONS:</u> Data Reduction for Astronomy from Gemini Observatory North and South

<u>Tasks:</u>

- **Learn the DRAGONS pipeline**
- **Use this pipeline to analyze Sample Data**
- **Overlay spectral lines on the spectrum extracted from the Sample Data**

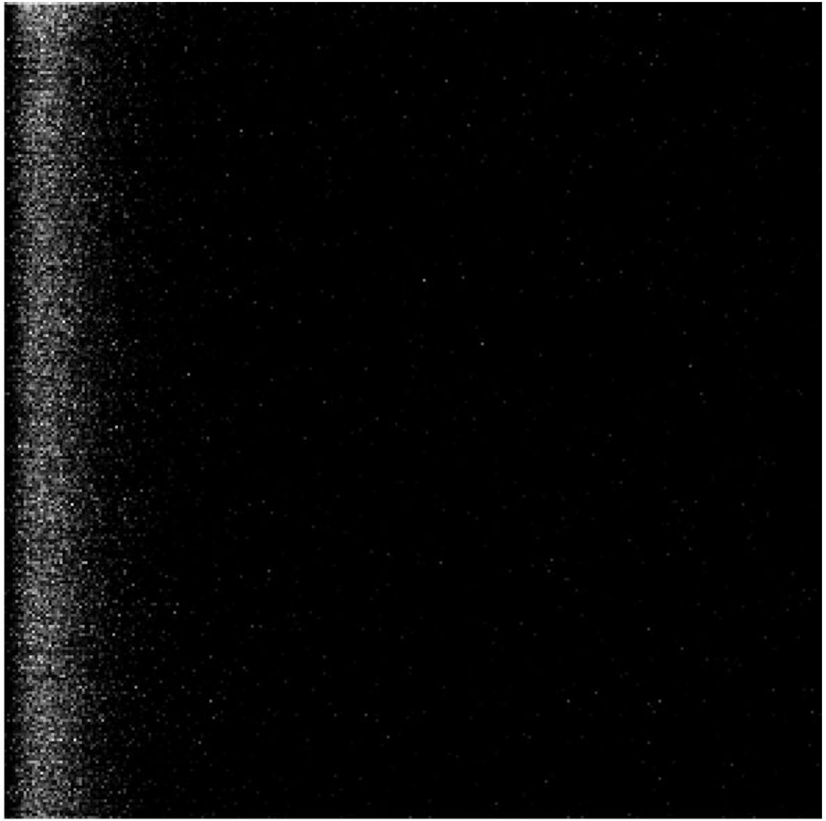
DRAKE pipeline

DRAKE: Data Reduction and Analysis for Kilonovae Exploration
*Modified from the DRAGONS pipeline

Tasks:
- Download GW170817 data from the Gemini Archives
- Modify DRAGONS pipeline to form a new, generalized pipeline (DRAKE)
- Reduce the GW170817 data using the DRAKE pipeline, and reproduce the associated spectrum
- Overlay spectral lines on the GW170817 spectrum

Bias Frames (Biases)

- Calibrates the image of the target of interest
- Images taken with no light hitting the imaging sensor
- Shortest exposure time possible
- Used to remove any dust or grime that is on the sensor itself
- Biases were combined into one Master Bias

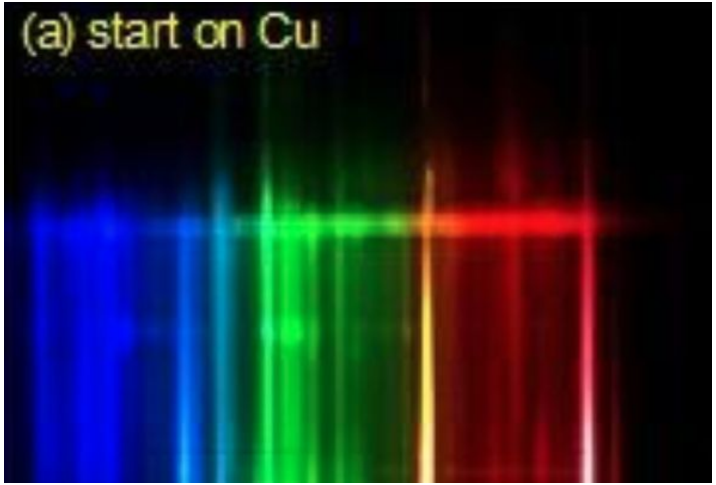


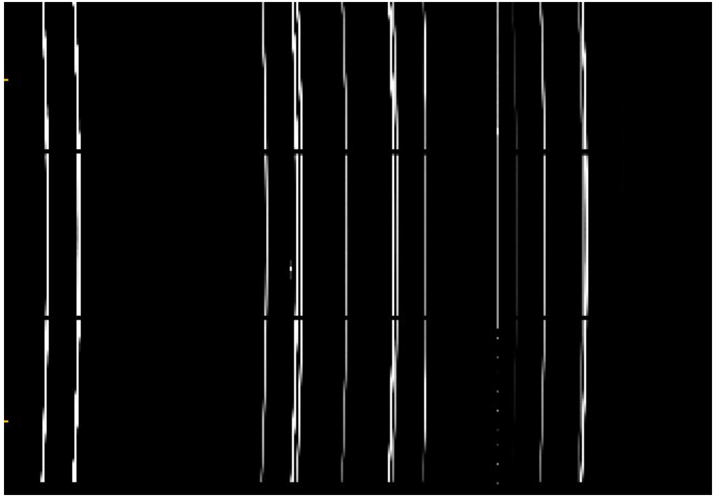
Flat Frames (Flats)

- Calibrates the image of the target of interest
- Images taken of something known to be illuminated in the same way throughout the entire frame
- Screen can be used as a filter to get symmetric illumination for a flat
- Flats are used to remove vignetting and calibrate the light illumination
- Flats were combined into one Master Flat

Arc Frames (Arcs)

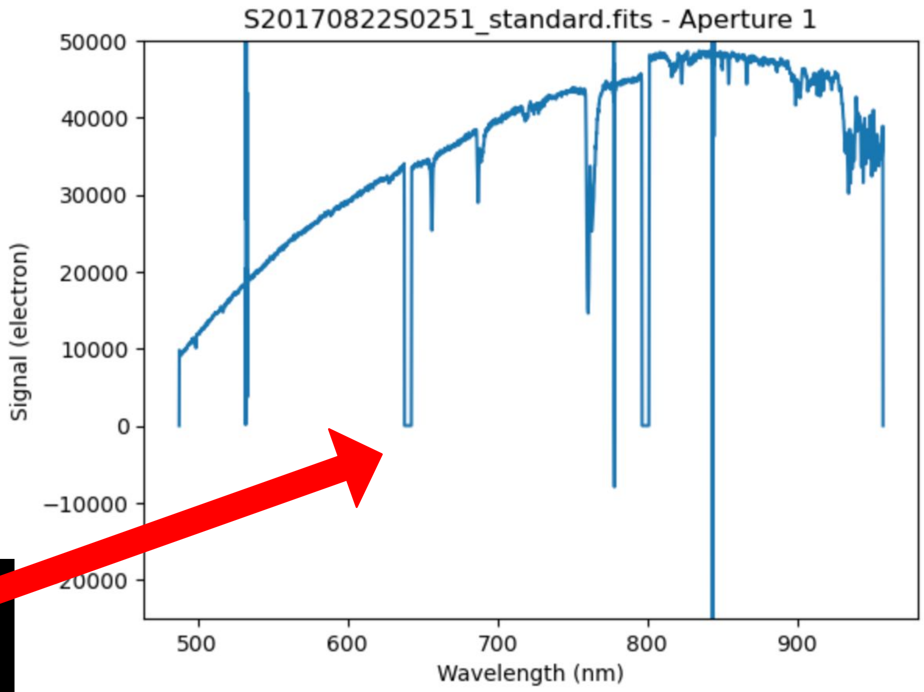
- Calibrates the target image of interest using the light from known elements
- Arcs tell us where the wavelength lines are
- Arcs convert from pixel to wavelength
- Used CuAr lamp for this project (the CuAr lines calibrated for the wavelength
- Arcs were combined into one Master Arc





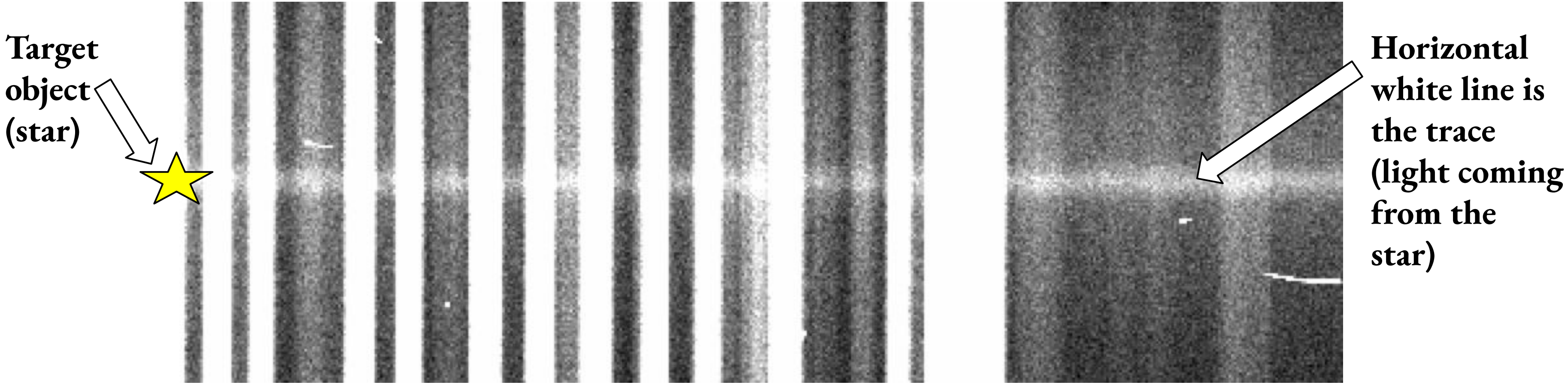
Spectrophotometric Standard Star (SSS)

- Reference star to calibrate the new, unstudied object
- The reference SSS with the same airmass as the target object will be used
- SSSs were combined into two Processed Standards (one for each object)



Science Observation (SO)

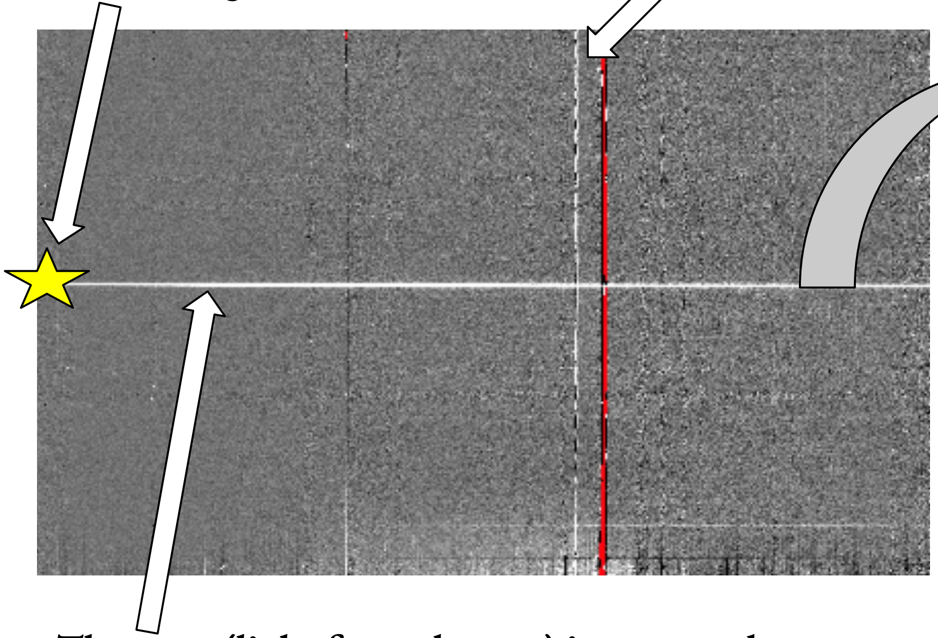
- The SOs are the images of the target of interest
- SOs were combined into one Science Observation
- Subtract the Master Bias
- Normalize (divide) by the Master Flat
- Pixel to wavelength calibration using Master Arc
- Standard calibration using the Processed Standard

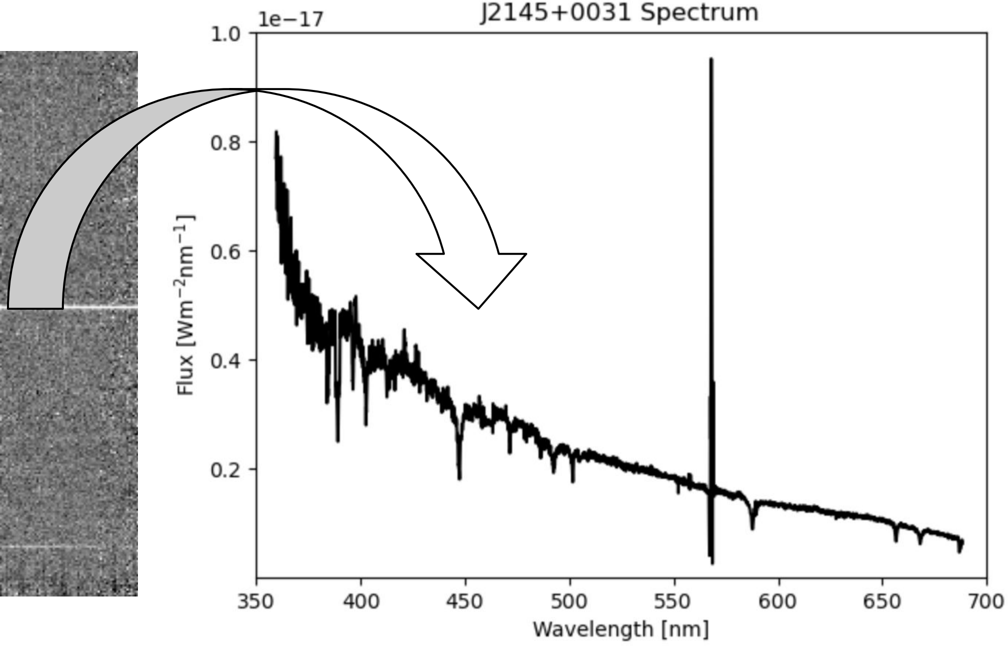


Sample Data with DRAGONS Pipeline

Target star with light being shone through a slit

Spectrum contamination

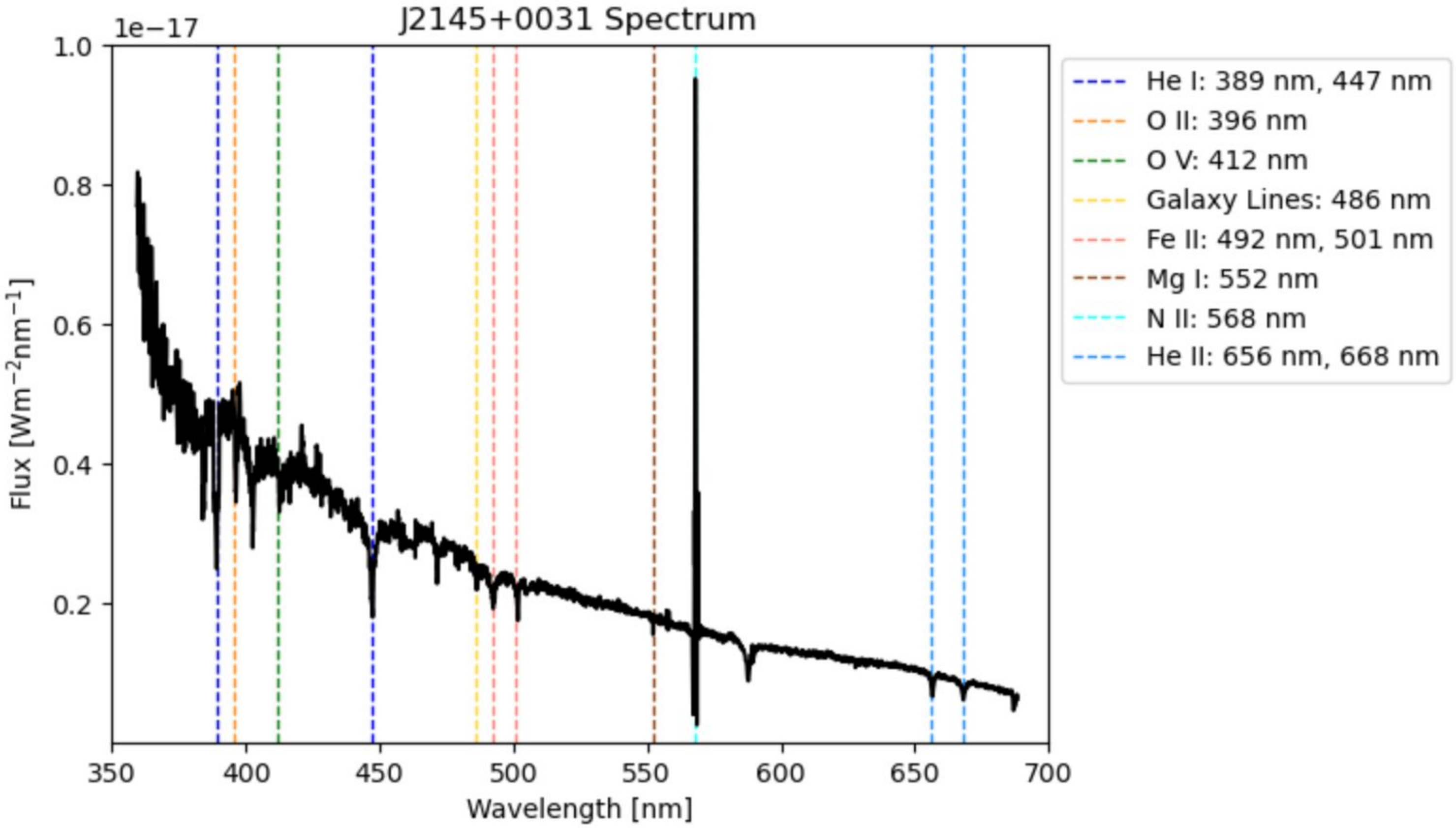




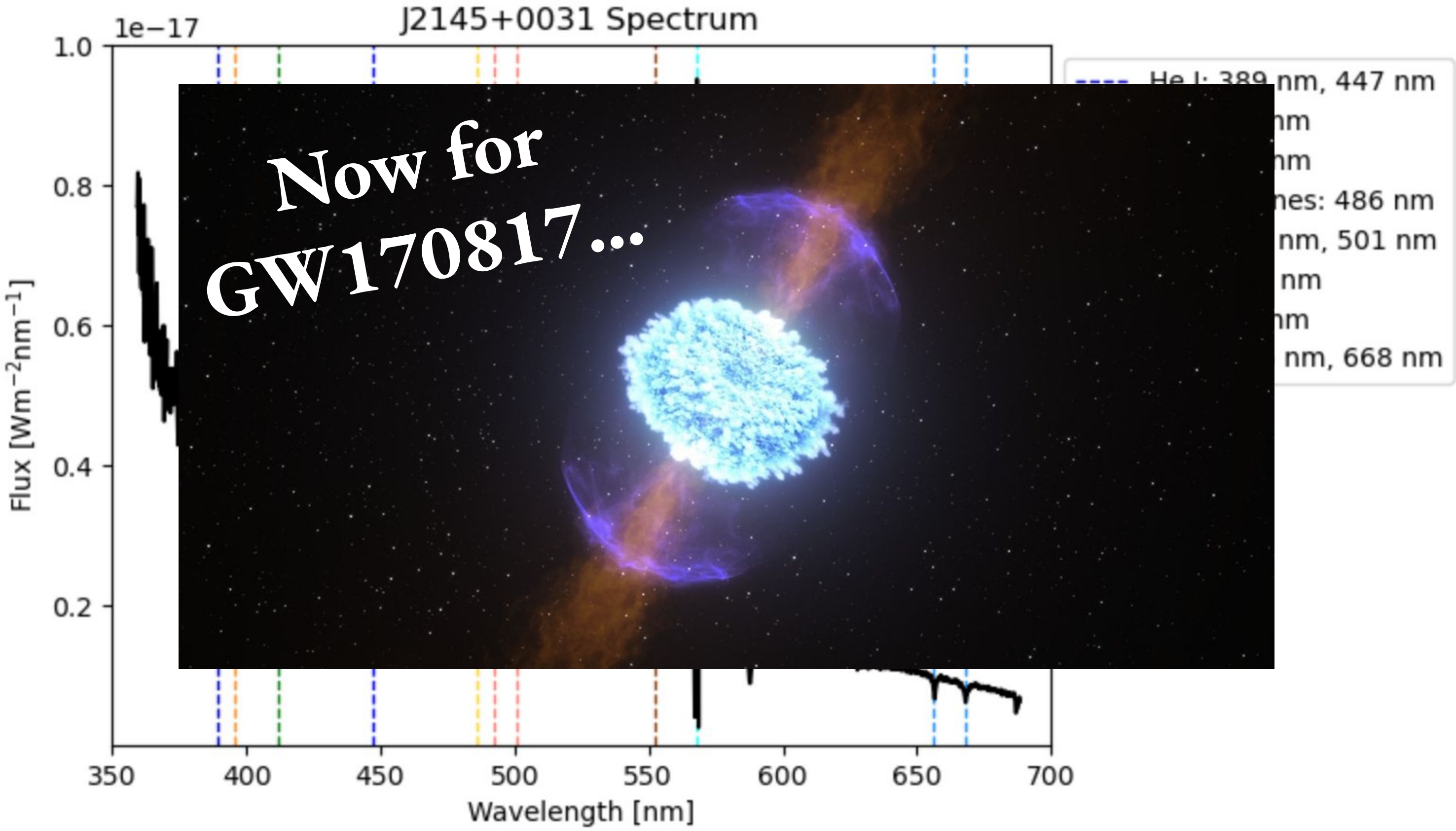
The trace (light from the star) is extracted into the spectrum shown on the right.

Starlight is decomposed into wavelengths

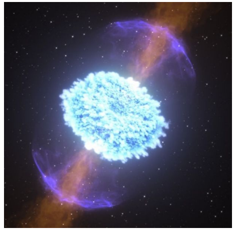
Spectrum Produced with DRAGONS Pipeline



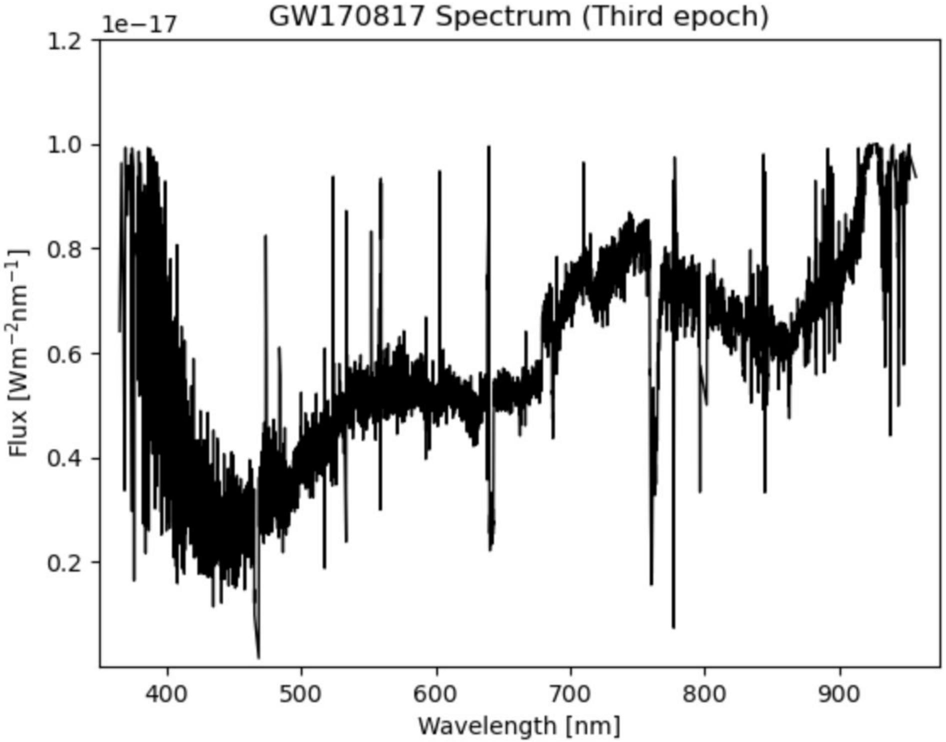
Spectrum Produced with DRAGONS Pipeline



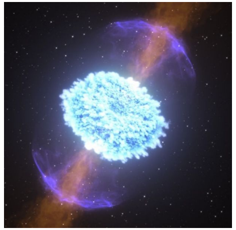
GW170817 Spectrum with DRAKE pipeline



- Bias subtraction
- Flat normalization
- Wavelength calibration
- Flux calibration

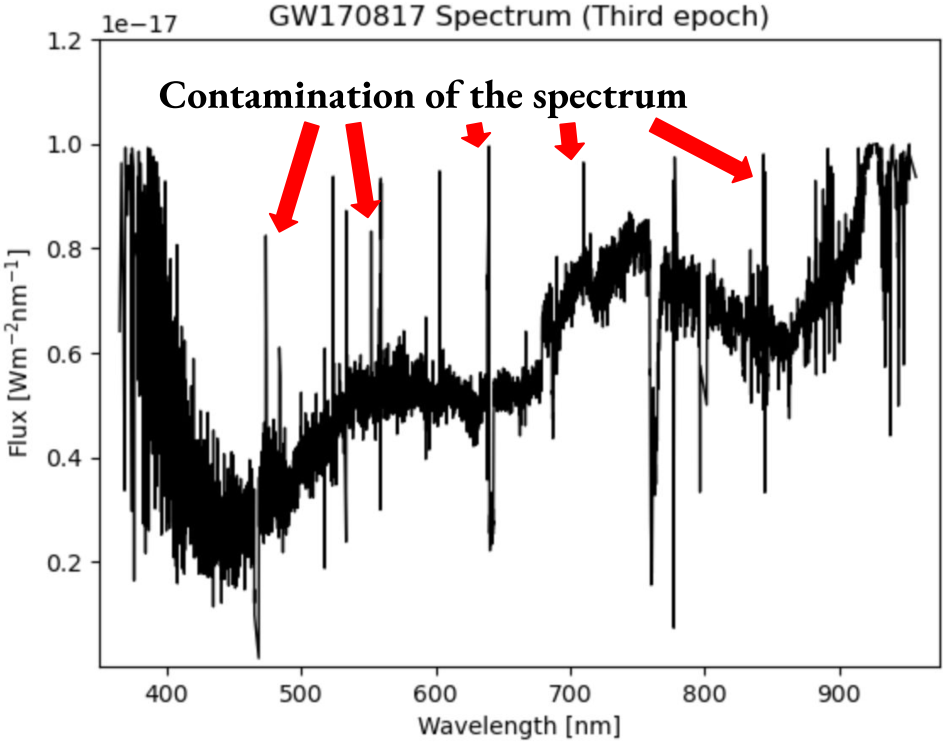


Removing Contamination

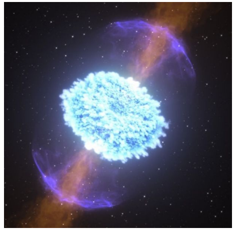


- Bias subtraction
- Flat normalization
- Wavelength calibration
- Flux calibration

We need to remove contamination!

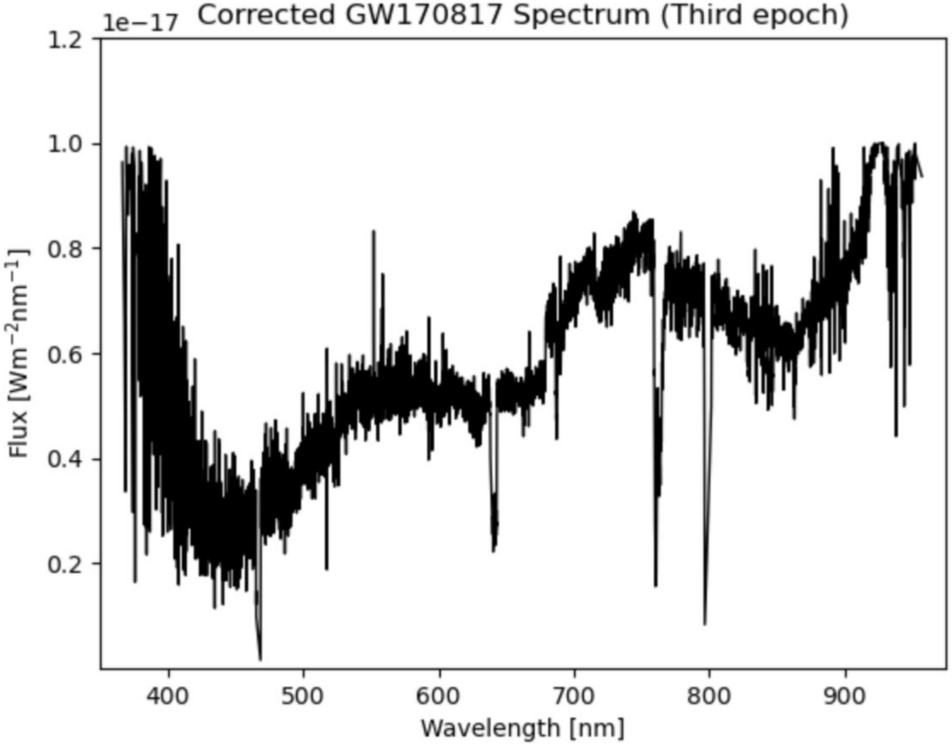


Final Spectrum for GW170817

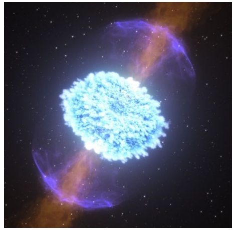


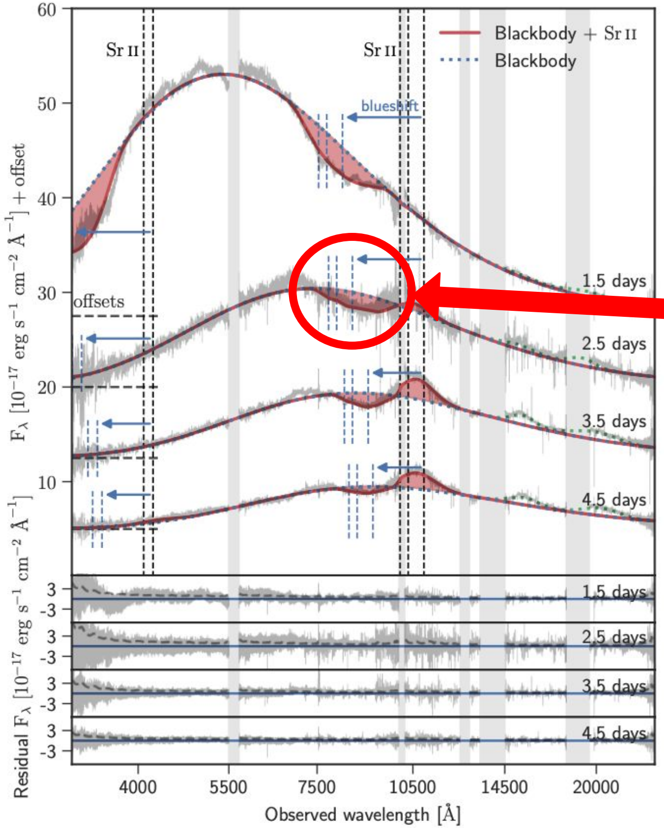
- Bias subtraction
- Flat normalization
- Wavelength calibration
- Flux calibration

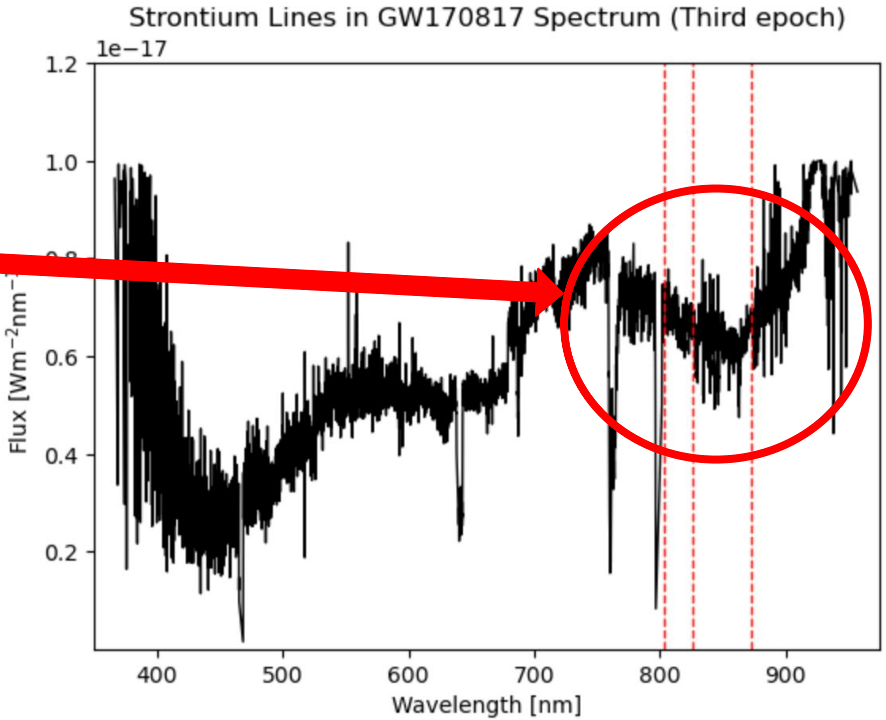
- Contamination removed



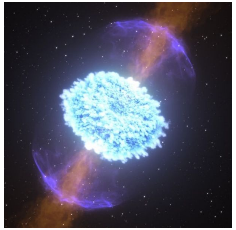
Comparing Results

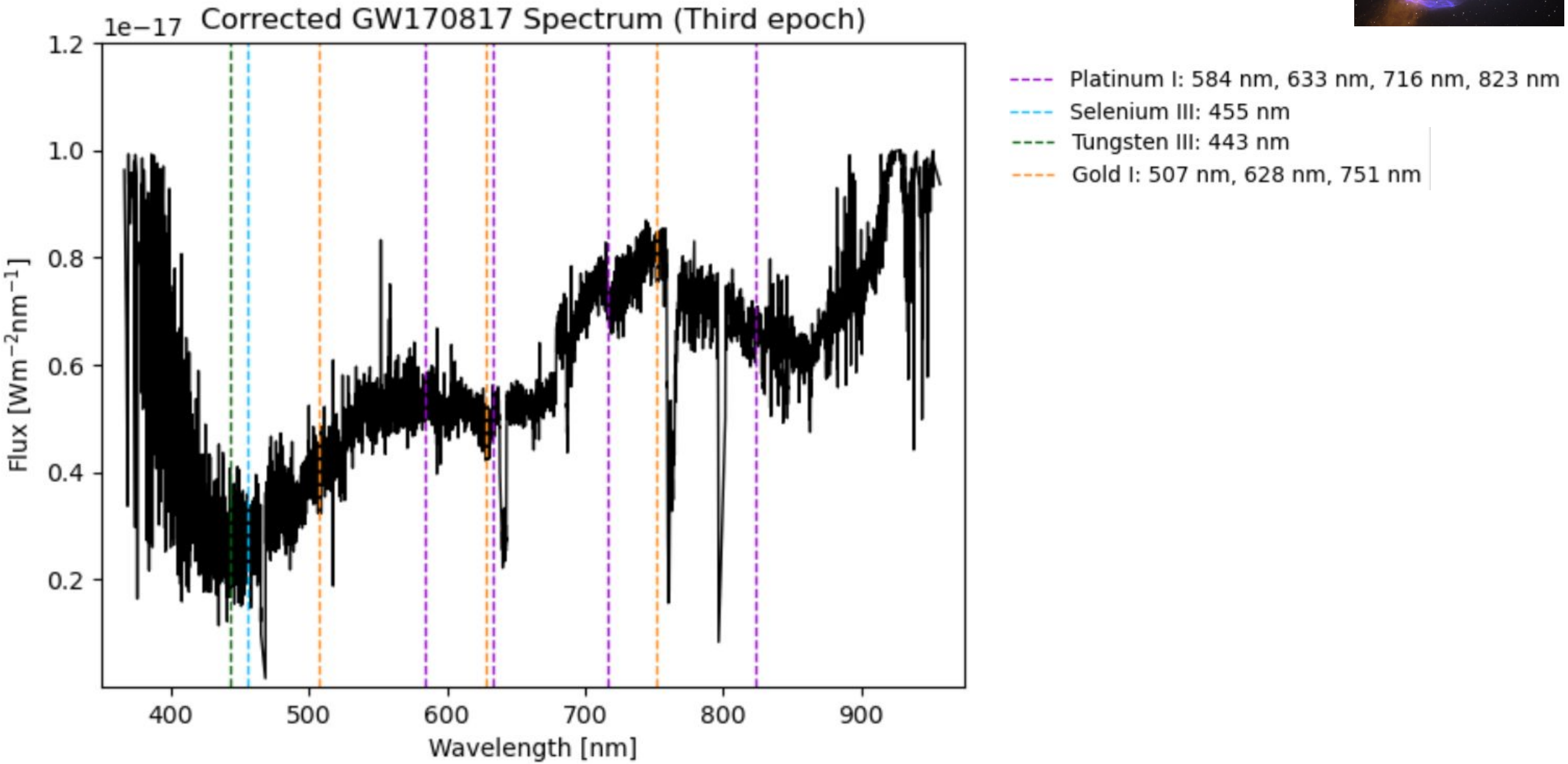






More Possible Elements Produced?





Future Endeavors

- Provide faster candidate elimination in the near future using heavy element spectroscopy
- Produce more consistent blackbody temperature estimation
- Classify more KN candidates
- Provide a more in depth study of heavy element emission
- Add current supernova classification algorithms to the DRAKE pipeline

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- **Supervisors: Alan Weinstein and Mansi Kasliwal**

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