GW170817-Like Disk Produces a Blue Kilonova

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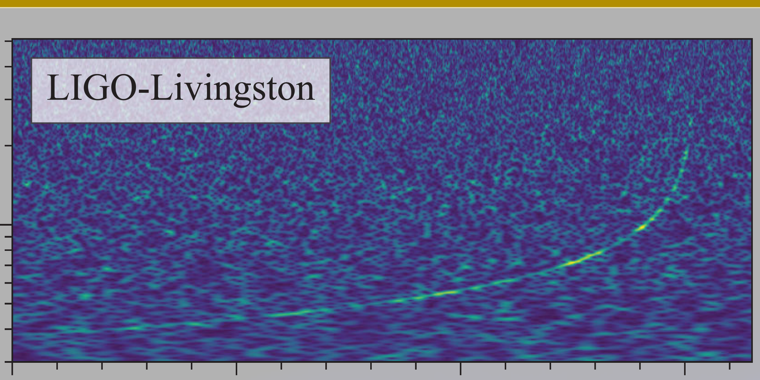
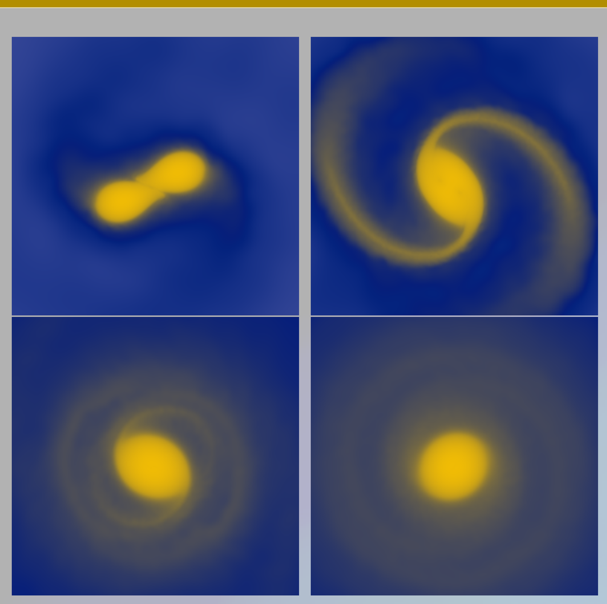
A Groundbreaking Discovery

- On August 17, 2017, the in-spiral and merger of two neutron stars was observed. This event is called *GW170817*.
- Events like this one drive *short gamma ray bursts*, some of the most energetic events in the universe.
- Mergers are sites of *r-process nucleosynthesis*, where the heaviest elements in our universe are formed.
- Many more events to come!



Above: A spectrogram showing the characteristic gravitational wave chirp due to GW170817. Image from [1].

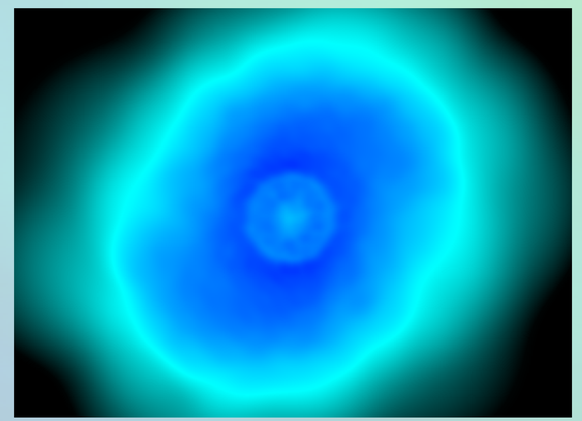
An In-Spiral Story



Above: Snapshots from a simulation of a binary neutron star merger The tidal tails (top right) contain neutron rich material which is a site of robust r-process nucleosynthesis.

- Neutron stars are ultra-dense remnants of stellar core-collapse, supported against gravity by the strong nuclear force and neutron degeneracy pressure.
- Natural laboratories for high-density nuclear physics
- A two solar mass neutron star will have a radius less than 15km!
- As stars get close, "tidal tails" of material are thrown off.
- Eventually the stars form a remnant object surrounded by a disk of accreting material. This accretion can drive a jet of ultrarelativistic material, producing a *gamma ray burst*.
- The central object may or may not eventually collapse into a black hole.
- Called a Binary Neutron Star (BNS) Merger

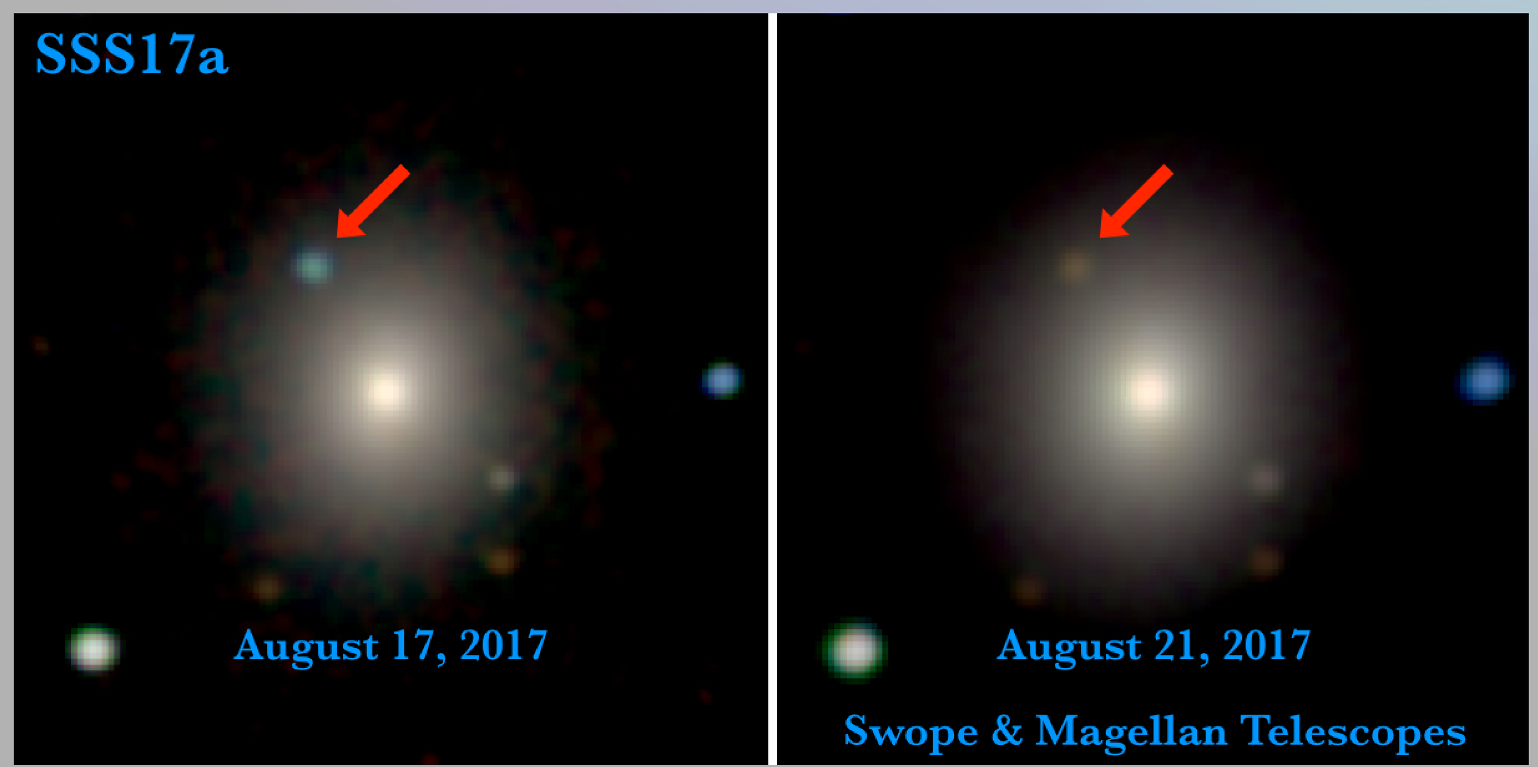
- Tidal ejecta eventually forms expanding doughnut of material.
- This neutron rich material is an ideal site for r-process nucleosynthesis of heavy elements.
- Neutron star mergers may be the primary source of heavy elements in the universe.
- Radioactive decay of these heavy elements can produce a radioactive afterglow, the *kilonova*.



Above: "Expanding doughnut" of tidal ejecta.

A Surprising Observation

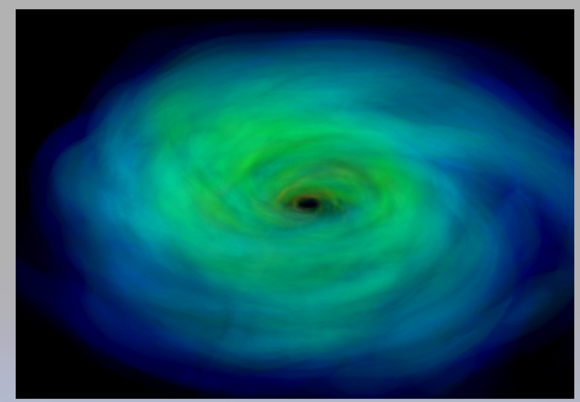
- Robust r-process in tidal tails produces material opaque to optical light, resulting in red kilonova.
- The *observed* kilonova had both red and blue components. The blue component may have been produced by a site with *less robust* r-process.



Above: Composite optical images from the Swope and Magellan telescope of the GW170817 kilonova zero (left) and four (right) days after the merger. The visible spectrum clearly transitions from blue to red [2]. Image compositing by R. Foley.

The Case For the Disk

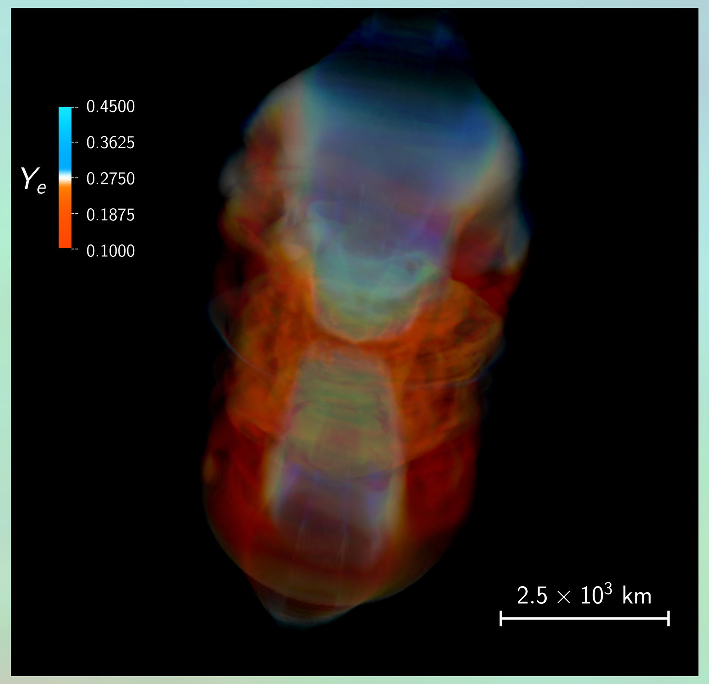
- Heat, neutrinos, and magnetic fields can drive a wind off the disk.
- This wind may produce a less-robust r-process and be a source for the blue kilonova.
- Depends on *electron fraction* Y_e. Low Y_e means robust r-process and implies a red kilonova. High means less robust r-process and implies a blue kilonova.
- Literature is sparse and divided on wind and r-process [3, 4, 5].
- Result depends sensitively on complex interplay of neutrino transport, general relativity, magnetic fields, and fluid dynamics.



Above: Volume rendering of a simulated accretion disk formed by a BNS merger.

Presenting νbhlight

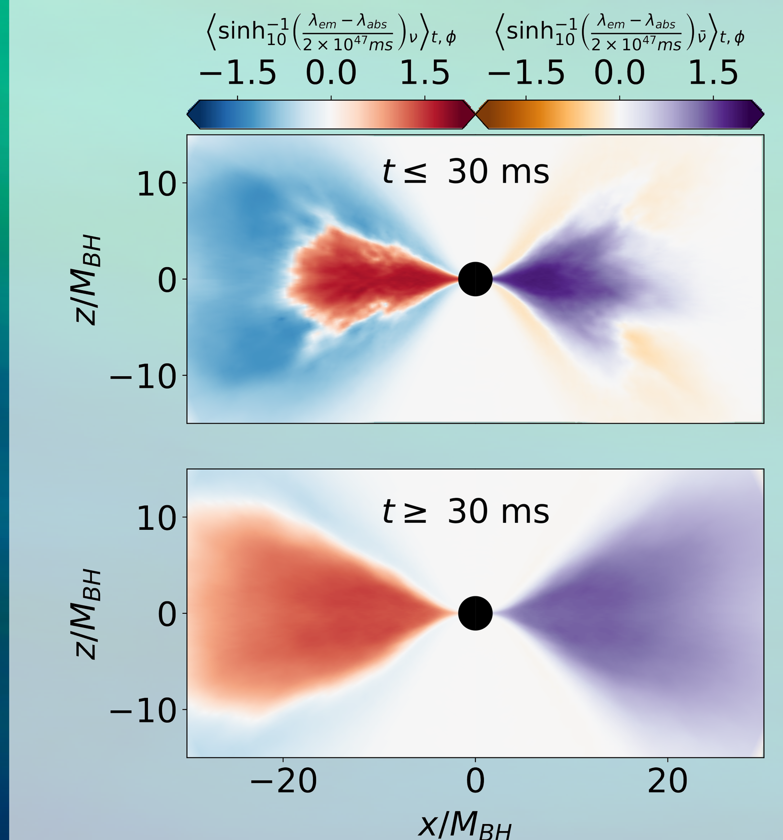
- General relativistic magnetohydrodynamics
- Accurate fully general-relativistic and frequency dependent neutrino transport
- Radiation-fluid interaction implemented via operator splitting
- Capable of solving the post-merger disk problem in **full 3D** and with all **relevant physics**.



Right: Volume rendering of electron fraction in outflow from a νbhlight simulation of a disk formed by a binary-neutron star merger. Red means a robust r-process. Blue means less robust r-process.

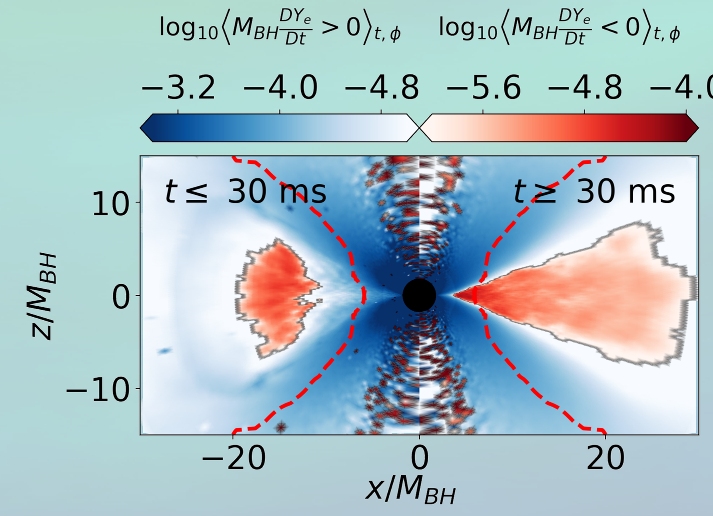
Transport in the Disk

- Neutrino transport drives Y_e down in core and up in corona.



Above: Rate of emitted neutrinos minus the rate of absorbed neutrinos for electron neutrinos ($x < 0$) and electron antineutrinos ($x > 0$). Averaged over azimuthal angle ϕ and in time from 0 to 30 ms (top) and from 30 ms to 127 ms (bottom).

- **Early Times:**
  - Neutrinos emitted in core of disk and absorbed in corona.
- **Late Times:**
  - More emission than absorption everywhere



Above: Lagrangian derivative of electron fraction due to emission or absorption of neutrinos: blue for an increase in Y_e and red for a decrease. Averaged over azimuthal angle ϕ and in time from 0 to 30 ms (left) and from 30 ms to 127 ms (right).

References

[1] B. P. Abbott et al.
Gw170817: Observation of gravitational waves from a binary neutron star inspiral.
Phys. Rev. Lett., 119:161101, Oct 2017.

[2] D. A. Coulter et al.
Swope supernova survey 2017a (sss17a), the optical counterpart to a gravitational wave source.
Science, 358(6370):1556–1558, 2017.

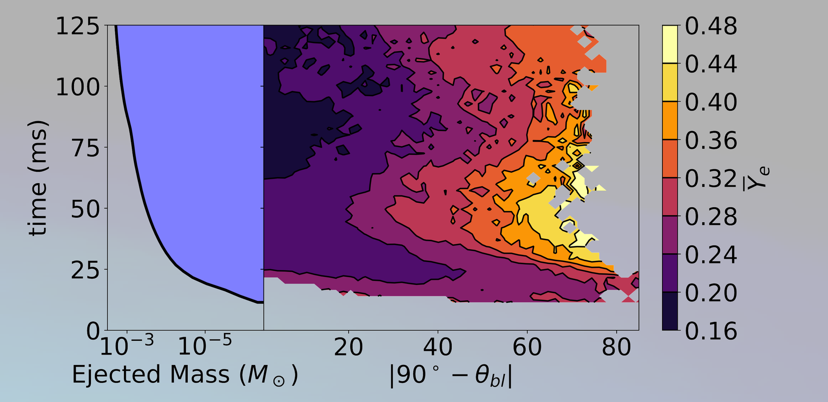
[3] Francois Foucart et al.
Post-merger evolution of a neutron star-black hole binary with neutrino transport.
Phys. Rev. D, 91:124021, Jun 2015.

[4] D. M. Siegel and B. D. Metzger.
Three-dimensional grmhd simulations of neutrino-cooled accretion disks from neutron star mergers.
The Astrophysical Journal, 858(1):52, 2018.

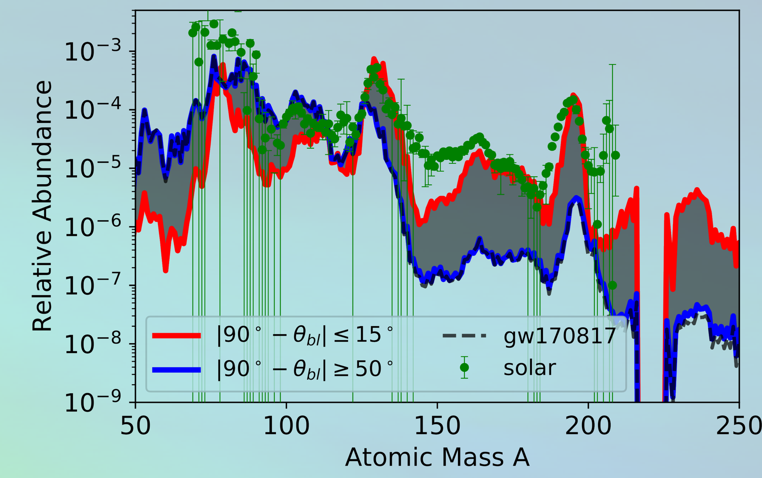
[5] R. Fernández et al.
Long-term GRMHD Simulations of Neutron Star Merger Accretion Disks: Implications for Electromagnetic Counterparts.
ArXiv e-prints, August 2018.

Nucleosynthesis

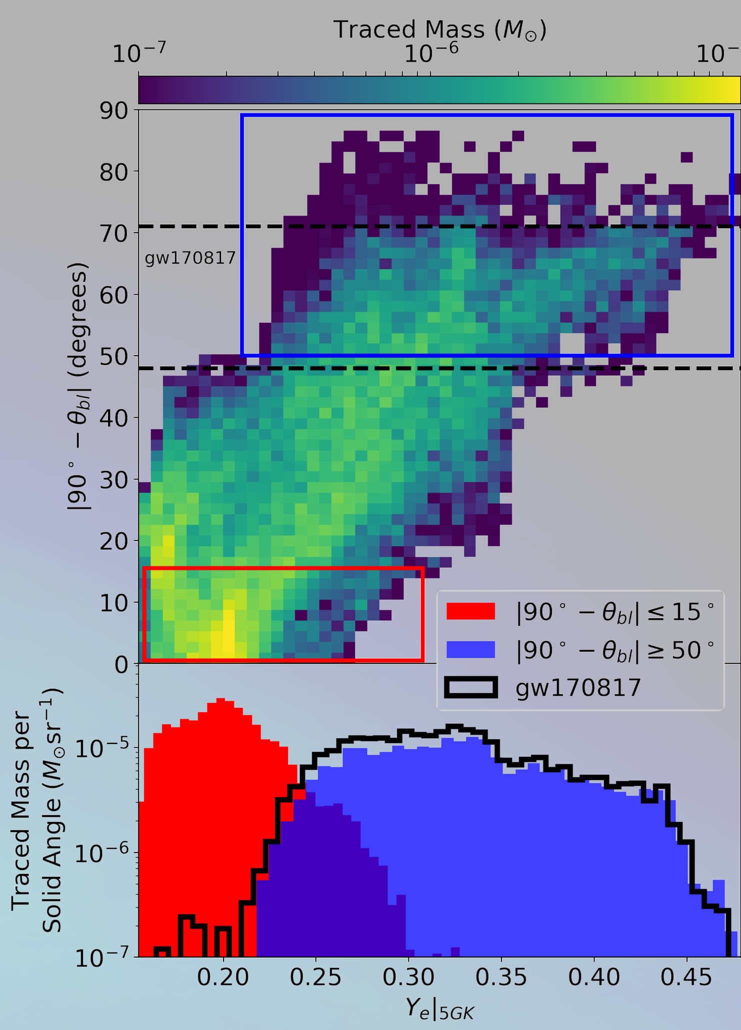
- We find **structured outflow.**
  - Polar material has high Y_e and produces less-robust r-process.
  - Midplane material has low Y_e and produces more-robust r-process.
- Structure persists in time!



Above: Left: Total mass in the outflow as a function of time. Right: Average Y_e of gravitationally unbound material as a function of latitude and time.



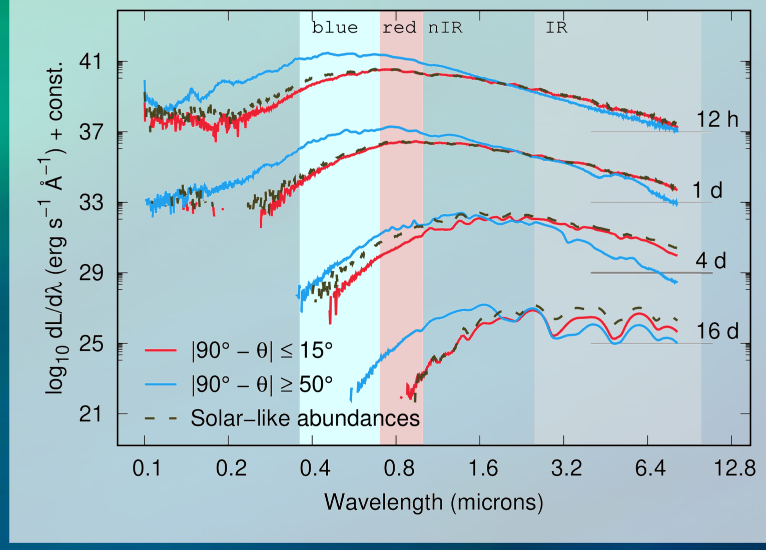
Above: Relative abundance of yields for disk outflow: red for material with $< 15^\circ$ off the midplane and blue for material $> 50^\circ$. Gray shading shows the range of values that can be attained at intermediate angles.



Above: Top: Electron fraction of gravitationally unbound material at 5 GK vs. latitude. Boxes represent cuts through the data. Red is neutron-rich, blue is neutron-poor. Bottom: Distribution per solid angle of electron fraction in material in boxed regions.

Electromagnetic Counterpart

- We perform Monte Carlo radiative transfer to predict what wind-driven kilonova would look like on Earth.
  - **Polar** outflow is blue.
  - **Midplane** outflow is red.



Left: Electromagnetic spectra for spherically symmetric outflow composed of nucleosynthetic yields produced in material $< 15^\circ$ off the midplane, $> 50^\circ$ degrees off the midplane, and of solar abundances such as those produced in tidal ejecta or outflows like those reported in [4]. At 5000Å, the polar outflow is $\sim 12\times$ more luminous than the more neutron-rich outflows.

Outlook

- We **simulate**, for the first time, the **accretion disk** formed by a binary neutron star merger with full general relativistic **magnetohydrodynamics** and **neutrino transport**.
- We **find** a structured outflow with Y_e increasing with angle off of midplane.
- We **perform** nucleosynthesis on disk outflow and find robust r-process in the midplane and less robust r-process in polar regions.
- We **model** via radiative transfer what the disk-driven kilonova looks like from Earth and show that it is blue.
- We **showcase** the end-to-end capability of LANL's multi-disciplinary team.
- Our work **implies** that:
  - The disk must be included in models of the GW170817 event.
  - Neutrino transport is critical for modeling this problem.
  - In future events, a blue kilonova may be produced by the disk from a binary neutron star merger or a black hole neutron star merger.
- For more info, see arXiv:1905.07477

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