Hunting Kilonovae in the Near Infrared

Detection Efficiency and Automated Galaxy Targeting Follow Up

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Kilonova Strategy Project

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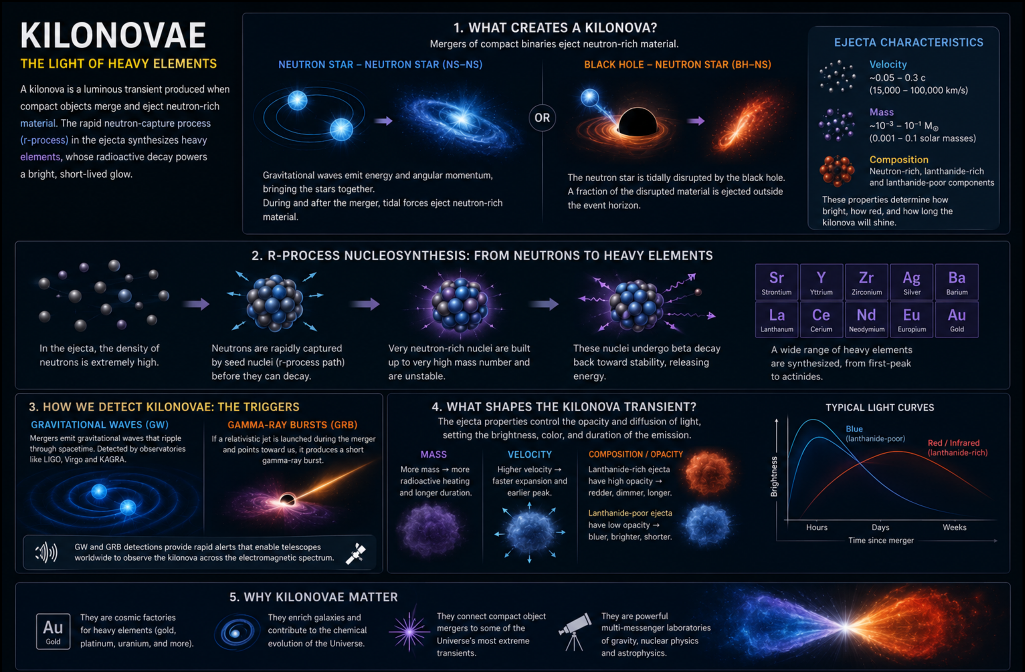


KILONOVAE
THE LIGHT OF HEAVY ELEMENTS
A kilonova is a luminous transient produced when compact objects merge and eject neutron-rich material. The rapid neutron-capture process (r-process) in the ejecta synthesizes heavy elements, whose radioactive decay powers a bright, short-lived glow.
1. WHAT CREATES A KILONOVA?
Mergers of compact binaries eject neutron-rich material.
NEUTRON STAR – NEUTRON STAR (NS–NS)
OR
BLACK HOLE – NEUTRON STAR (BH–NS)
Gravitational waves emit energy and angular momentum, bringing the stars together.
During and after the merger, tidal forces eject neutron-rich material.
The neutron star is tidally disrupted by the black hole. A fraction of the disrupted material is ejected outside the event horizon.
EJECTA CHARACTERISTICS
Velocity
~0.05 – 0.3 c
(15,000 – 100,000 km/s)
Mass
~10^{-3} – 10^{-1} $M_\odot$
(0.001 – 0.1 solar masses)
Composition
Neutron-rich, lanthanide-rich and lanthanide-poor components
These properties determine how bright, how red, and how long the kilonova will shine.
2. R-PROCESS NUCLEOSYNTHESIS: FROM NEUTRONS TO HEAVY ELEMENTS
In the ejecta, the density of neutrons is extremely high.
Neutrons are rapidly captured by seed nuclei (r-process path) before they can decay.
Very neutron-rich nuclei are built up to very high mass number and are unstable.
These nuclei undergo beta decay back toward stability, releasing energy.
Sr Strontium
Y Yttrium
Zr Zirconium
Ag Silver
Ba Barium
La Lanthanum
Ce Cerium
Nd Neodymium
Eu Europium
Au Gold
A wide range of heavy elements are synthesized, from first-peak to actinides.
3. HOW WE DETECT KILONOVAE: THE TRIGGERS
GRAVITATIONAL WAVES (GW)
Mergers emit gravitational waves that ripple through spacetime. Detected by observatories like LIGO, Virgo and KAGRA.
GAMMA-RAY BURSTS (GRB)
If a relativistic jet is launched during the merger and points toward us, it produces a short gamma-ray burst.
GW and GRB detections provide rapid alerts that enable telescopes worldwide to observe the kilonova across the electromagnetic spectrum.
4. WHAT SHAPES THE KILONOVA TRANSIENT?
The ejecta properties control the opacity and diffusion of light, setting the brightness, color, and duration of the emission.
MASS
More mass → more radioactive heating and longer duration.
VELOCITY
Higher velocity → faster expansion and earlier peak.
COMPOSITION / OPACITY
Lanthanide-rich ejecta have high opacity → redder, dimmer, longer.
Lanthanide-poor ejecta have low opacity → bluer, brighter, shorter.
TYPICAL LIGHT CURVES
Blue (lanthanide-poor)
Red / Infrared (lanthanide-rich)
Brightness
Hours
Days
Weeks
Time since merger
5. WHY KILONOVAE MATTER
Au Gold
They are cosmic factories for heavy elements (gold, platinum, uranium, and more).
They enrich galaxies and contribute to the chemical evolution of the Universe.
They connect compact object mergers to some of the Universe's most extreme transients.
They are powerful multi-messenger laboratories of gravity, nuclear physics and astrophysics.

PRIME: a wide-field NIR eye for kilonovae

PRime-focus **I**nfrared **M**icrolensing **E**xperiment

- 1.8 m telescope, SAAO Sutherland (South Africa)
- Wide-field NIR imager: **FoV** $= 1.56$ **deg**^{2} (4 H4RG detectors)
- Bands **Z, Y, J, H** (0.9 to 1.6 μm), observed in **simultaneous pairs**
- Survey speed in the NIR $\Rightarrow$ ideal for tiling large GW localization regions where *red* kilonovae shine

5σ limiting magnitudes (AB), Chase et al. 2021:

Band	λ (μm)	$m_{\rm lim}$ (100 s)
Z	0.90	**20.5**
Y	1.02	20.0
J	1.24	19.6
H	1.63	**18.4**

H is the reddest band but $\sim$*2 mag the shallowest (high NIR sky background).*

The scientific questions

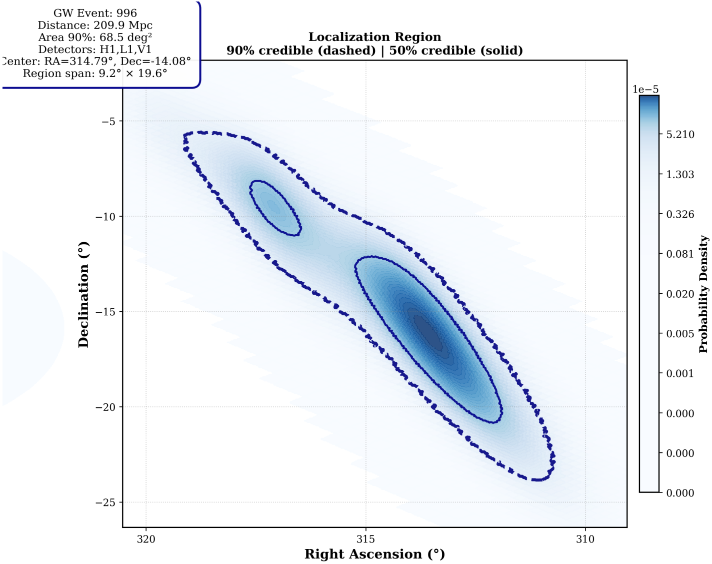
We trigger **ToO observations on GW skymaps** and ask how to best *find* and *characterize* a kilonova:

1. **Which filters** maximize detection in a wide GW-triggered survey?
2. **Which cadence?** (daily vs. 2-day, early vs. late start)
3. **How many filters / which pairs?** (companion + H)
4. Can **NIR colors** (Z−H, J−H) separate kilonovae from supernova contaminants?
5. **Automated galaxy-targeting** of the localization volume (GLADE catalogue) for the follow-up.

Approach

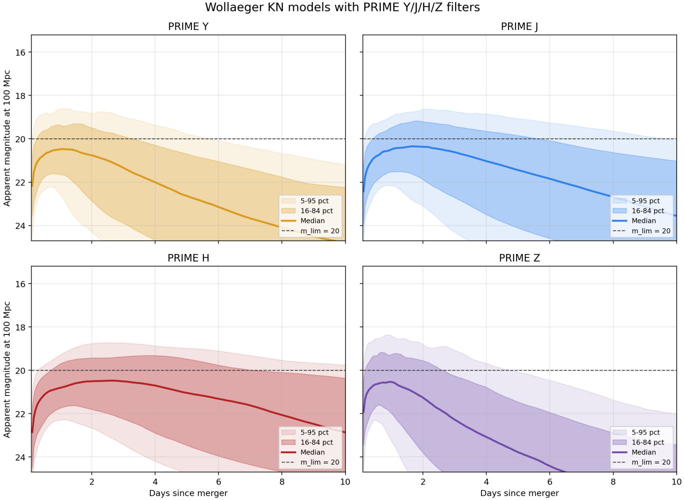
Inject LANL kilonova models at distances drawn from the **O5 skymaps**, apply PRIME per-filter depths, measure detection & color efficiency.

Ingredient 1: O5 gravitational-wave skymaps



- 34 simulated **O5 BNS** skymaps
- Injection distances sampled from the **90% credible region**
- **Median distance** $\approx$ 158 **Mpc** (16 to 84%: 100 to 218 Mpc)
- Sets the realistic population PRIME must reach

Ingredient 2: LANL/Wollaeger kilonova models



- LANL radiative-transfer grid: **900 simulations** $\times$ **54 viewing angles**
- Parameters: dynamical & wind ejecta mass/velocity, geometry, composition
- Light curves in Z/Y/J/H (AB), generated with `cocteau`
- Kilonovae are **red and fast-reddening** $\Rightarrow$ NIR color evolution is a unique fingerprint

Conclusions & the key caveat

What we find

- Optimal NIR strategy: **Z-anchored detection + H for color**, **daily cadence**; automated galaxy targeting to prioritize tiles.

Caveat: the grid is treated *uniformly*

Current results use kilonova models living on a **regular parameter grid**, but every combination of $(m_{\rm dyn}, v_{\rm dyn}, m_{\rm wind}, v_{\rm wind}, \theta)$ is weighted **equally**.

This is *not* astrophysically realistic: some ejecta configurations are far more probable than others. **Next step:** re-weight the grid with physical priors (NS mass distribution, EOS, viewing-angle geometry).

Thank you!