Mansi M. Kasliwal

Professor of Astronomy

California Institute of Technology
Kasliwal Research Group

Kishalay De (Grad, 5th Year)
Shreya Anand (Grad, 3rd year)
Viraj Karambelkar (Grad, 2nd year)
Kaustav Das (Grad, 1st year)
Christoffer Fremling (Postdoc)
Igor Andreoni (Postdoc)

Jacob Jencson (Graduated 2020!)
Samaporn Tinyanont (Graduated 2020!)
Matt Hankins (Now faculty)
Ragnhild Lunnan (Now faculty)
Nadia Blagorodnova (Veni Fellow)
Dave Cook (Staff Scientist)
Ryan Lau (ITYF Fellow)

Undergrads: Andy Tzanidakis, Gokul Srinivasaragavan, Stephanie Kwan, Lindsey Whitesides, Chris Cannella + SURF students

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Landscape for multi-messenger astrophysics

Masses in the Stellar Graveyard

in Solar Masses

LIGO-Virgo Gravitational Wave Interferometers
GW170817 & GW190521

IceCube High Energy Neutrino Detector
IceCube-170922A, IceCube-191001A
Landscape for time-domain astronomy

- **Radio**: 10^4
- **Microwave**: 10^2
- **Infrared**: 10^-2
- **Visible**: 10^-5
- **Ultraviolet**: 10^-6
- **X-ray**: 10^-8
- **Gamma Ray**: 10^-10

Wavelength in centimeters

**LWA; From DSA-110 to DSA-2000 (PI Hallinan)**

**From PTF to ZTF (PI Kulkarni)**

**From ROSAT to Spektr-RG (Russian-German Satellite)**

References:
- Abbott, B. P., et al. 2018, LRR, 21, 3
Why Infrared?

1. **Dust extinction**
   - Classical Novae
   - White Dwarf Mergers

2. **Self-enshrouding**
   - Stellar Mergers
   - Obscured Supernovae

3. **Opacity**
   - Binary Neutron Star Merger
   - Neutron Star Black Hole Merger

How?

*To reduce detector cost:*
- ✔ Software Algorithms
- ✔ InGaAs Detectors
- ✔ MBE on Si Detectors

*To mitigate sky background:*
- ✔ Space
- ✔ Antarctica
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1. Infrared Overcomes Extinction by Dust

Visible Light

Infrared Light

Spitzer/NASA-JPL/T. Bourke

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Palomar Gattini IR (PGIR) field of view is 40 times larger than any other current near infrared instrument.
Palomar Gattini IR: The first wide-field infrared surveyor

Palomar Gattini IR maps 15,000 sq. deg. every 2 nights to J=15.7 AB mag

In Partnership with Anna Moore (ANU)
Galactic Fast Radio Burst

De et al. 2020

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Caltech
Discoveries by Palomar Gattini IR

PGIR has more than doubled the discovery rate of novae!

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"I’ve often wondered about the CNe (like Fermi, on intelligent life):
Where are they?
I guess your answer is: extincted!"
(Bob Williams)
Rate of Classical Novae: 46 per year

Most obscured novae are likely missed in optical searches.

Null hypothesis probability < 0.01%.
White Dwarf Merger Products

Palomar Gattini IR light curves suggest 149 new R Cor Bor candidates

Karambelkar et al. 2021

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Spectroscopy of R Cor Bor stars

Karambelkar et al. 2021
Infrared Polarization of Supernovae

**SN 2018hna**

Possible Circumstellar Ring

- SN ejecta
- North (80 d)
- \( \theta = 70^\circ \)
- \( b/a \approx 0.48 \)
- \( R_{\text{ring}} \approx 6 \times 10^{17} \text{ cm} \)

Tinyanont et al. 2021, Nature Astronomy

WIRC+Pol near-infrared spectropolarimeter at Palomar 200-in (PI Mawet)

Samaporn Tinyanont

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Additional Results from Palomar Gattini IR

• Young star FU Ori outburst (Hillenbrand et al. 2021)
• 300d period of a Wolf Rayet binary (Lau et al. 2021)

In prep:
• Nearby core-collapse supernovae (undergrad Srinivasaragavan, collaborator Sollerman)
• Microlensing sample (postdoc P. Mroz)
• Galactic X-ray binary (grad Y. Yao)
• RR Lyrae light curves (collaborator Freeman)
• AGN (multi-wavelength monitoring for collaborators Kara & Gorjian)
• Long period Mira variables (SURF project)
• Supergiant Fast X-ray Transients (SURF project)
• X-ray binaries (De postdoc project, collaborator Soria)
• Radio follow-up to probe shocks in novae (collaborator Sokoloski)
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To mitigate sky background:
✓ Space
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2. Infrared Overcomes Self-obscurcation
**SPitzer InfraRed Intensive Transients Survey**

- 1690 hours over 6 years with *Spitzer*/IRAC
- 194 galaxies, <35 Mpc
- Cadence baselines spanning one week to several years

Pl: M Kasliwal, Project Scientist: J Jencson
Team: S Adams, R Lau, S Tynanont, M Hankins, D Perley, F Masci, G Helou, L Armus, S Van Dyk, A Cody, M Boyer, H Bond, J Bally, O Fox, R Williams, P Whitelock, R Gehrz, N Smith, J Johansson, E Hsiao, M Phillips, N Morell, C Contreras, M Ressler+

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Phase Space of Infrared Transients in 2014
SPIRITS discovered a treasure trove of infrared transients.

- Identified 80+ transients:
  - 50+ known supernovae
  - 23 especially red intermediate luminosity transient events (SPRITEs; Kasliwal+ 2017)

- We are missing half 38.5$^{+26}_{-22}$% the supernovae in our backyard! (Jencson PhD 2019)

- 4 Targets will be observed by the James Webb Space Telescope in Cycle 1!

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Jencson PhD (2019)
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**How?**

*To reduce detector cost:*
- ✓ Software Algorithms
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*To mitigate sky background:*
- ✓ Space
- ✓ Antarctica
3. Infrared Overcomes Bound-bound Opacity
The Majestic GW170817

When two neutron stars merge…

…a black hole is born,
a cocoon breaks out,
heavy elements are made.
A trio of papers in Science:
**UVOIR Light Curve**

See also:
- Andreoni et al. 2017
- Arcavi et al. 2017
- Cowperthwaite et al. 2017
- Coulter et al. 2017
- Drout et al. 2017
- Lipunov et al. 2017
- Lyman et al. 2017
- Pian et al. 2017
- Soares-Santos et al. 2017
- Smartt et al. 2017
- Tanvir et al. 2017
- Utsumi et al. 2017
- Villar et al. 2017

**Surprise # 1: Too Bright and Blue at Early Time**

Evans et al. 2017, Kasliwal et al. 2017c

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Spectra are the chemical thumbprint

Infrared Confirms that Heavy Elements were Synthesized.

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Pian et al. 2017

Caltech
A Site or The Site:
Was the production rate of heavy elements enough to explain the observed solar abundance?
Direct evidence that the heaviest elements were indeed synthesized!

We did strike gold!

Kasliwal et al. 2019a

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Cosmic Mines

Element Origins

Merging Neutron Stars
Dying Low Mass Stars
Exploding Massive Stars
Exploding White Dwarfs
Big Bang
Cosmic Ray Fission

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ZTF Promptly Mapped **Coarse** O3 localizations

Median localization in O3: 4480 sq deg

LVC O3a Summary: 13 Triggers

BNS: Five triggers  
(median distance: 227 Mpc)

NSBH: Eight triggers  
(median distance: 354 Mpc)
137 Scientists
37 Telescopes
38 Science Programs
100,000 events/night
5603 Supernovae to date
182 Refereed Journal Papers in 5 years
8236 citations
h-index 42

A Dynamic Collaborative Platform

In collaboration with UCB, the next generation open-source Fritz is now live
Spectrum is Truth

Example text and diagram content: Scaled flux $F_{\lambda}$ vs. rest wavelength ($\mu$m) for various sources:

- PGIR 20emj (Nova) DBSP
- PGIR 20dsv (Nova) DBSP
- PGIR 20dcr (YSO) DBSP
- PGIR 20eig (Nova) DBSP
- PGIR 20dcl (Nova) DBSP

The spectrum is shown for different wavelengths ranging from 0.4 to 1.0 $\mu$m on the left, and from 1.0 to 2.25 $\mu$m on the right.
Next Generation Palomar Spectrograph
2,116,846 ZTF alerts inside 13 GW event localizations within 3 days of merger

2199 ZTF candidates selected by multi-step machine learning
(presented for human vetting)

127 ZTF candidates selected and announced
(via GCN circulars)

70 remaining after follow-up spectroscopy
(Keck, GTC, Gemini, P200, LDT, SALT, APO, HCT, LT)

14 remaining after follow-up photometry
(LT, LCO, KPED, GIT, LOT, P60, P200, Gemini, Keck, GTC, LDT, APO, Swift)

0 remaining after new GW map/archival analysis/detailed inspection

0 kilonovae

Kasliwal et al. 2020
Is GW170817 the norm?

Figure 12. Constraints on the underlying luminosity function of kilonovae represented as the maximum allowed fraction of kilonovae brighter than a given peak absolute magnitude. Constraints are derived at a 90% confidence level. We show constraints assuming flat photometric evolution (orange squares) and fading by 1 mag day$^{-1}$ (green stars). We also show the event-by-event constraint based on a median estimate (yellow circles, dotted line). We correct this median estimate by the probability that the GW alert was terrestrial (red circles, dotted line). We compare to a model grid published in Kasen et al. 2017 (dashed black line) and find the limiting line suggests some kilonovae must either have $M_{\text{ej}} < 0.03 M_\odot$ or $X_{\text{lan}} > 10^4$. The limiting line (blue dashed line) for another model grid (Dietrich et al. 2020; Bulla 2019) suggests that some kilonovae must be fainter than GW170817 with $M_{\text{ej, dyn}} < 0.005 M_\odot$ or $M_{\text{ej, pm}} < 0.05 M_\odot$ or $> 30$.
But what is the rate?

<table>
<thead>
<tr>
<th>Source</th>
<th>Neutron star merger rate [Gpc⁻³ y⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZTF, this work</td>
<td>R &lt; 900 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>ZTF, Andreoni+20</td>
<td>R &lt; 1775 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>DES</td>
<td>R &lt; 24000 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>ATLAS</td>
<td>R &lt; 30000 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>DLT40</td>
<td>R &lt; 99000 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>PTF</td>
<td>R &lt; 800 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>GW170817</td>
<td>320 &lt; R &lt; 4740 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>GW170817+GW190425</td>
<td>250 &lt; R &lt; 2810 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>GWTC-2</td>
<td>80 &lt; R &lt; 810 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>Coward+12</td>
<td>5 &lt; R &lt; 1800 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>Fong+15</td>
<td>90 &lt; R &lt; 1850 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>DellaValle+18</td>
<td>7 &lt; R &lt; 1162 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>Jin+18</td>
<td>452 &lt; R &lt; 2541 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>Chruslinska+18</td>
<td>60 &lt; R &lt; 360 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>Kalogera+04</td>
<td>300 &lt; R &lt; 1200 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>Kim+15</td>
<td>169 &lt; R &lt; 2921 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td>Pol+20</td>
<td>70 &lt; R &lt; 490 Gpc⁻³ y⁻¹</td>
</tr>
<tr>
<td></td>
<td>260 &lt; R &lt; 610 Gpc⁻³ y⁻¹</td>
</tr>
</tbody>
</table>

Andreoni et al. 2020d
Why Infrared?

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GROWTH Team undertook a co-ordinated search mapping the full area with four discovery engines worldwide.
Andreoni, Goldstein et al. 2019c

Upper limits suggest that either opacity was too high or the mass ratio was too high.

See also Morgan et al. 2020 (independent analysis by DESGW team)
A Radio Search by ASKAP

**Figure 1.** ASKAP image of the localisation region of S190814bv centered on 00:50:37.5, 25:16:57.371 observed 2 days post-merger. The 30deg field of view covers \( \sim 89\% \) of the localisation region, with 50\% (90\%) contours shown in red dashed (solid) lines. The large object near the centre of the image is the radio-emitting starburst galaxy NGC 253. Note: there is a secondary lobe of the localisation towards the south-east that is outside the ASKAP footprint.

We selected candidates by identifying sources that were significant outliers in both variability metrics calculated by TraP: \( \chi^2 \), which is the weighted reduced \( \chi^2 \), and the variability index \( V \) (equivalent to the fractional variability). This was done by fitting a Gaussian function to the distributions of both metrics in logarithmic space, with \( \chi > 1.5 \) and \( V > 1 \). The thresholds were adapted from Rowlinson et al. (2019), which gives approximate recall and precision rates of 90\% and 50\% respectively.

This resulted in 285 transient or variable candidates, which was reduced to 89 sources after manual inspection to remove imaging artefacts and components of complex extended sources.

### 3.1. Analysis of candidates for possible association with S190814bv

The 89 variable sources were filtered to remove those that were not consistent with the predicted emission of S190814bv, which should not exhibit more than a single rise and decline on these timescales (Hotokezaka et al. 2016), according to the following criteria:

- Rise and decline timescale.
- Source brightness.
- Source position.

These criteria were used to identify potential associations with S190814bv.
Neutron Star + Black Hole Merger
Could the neutron star be swallowed whole by the black hole?

The hallmark signature is a red source that rapidly reddens.
Figure 1 | Schematic illustration of the components of matter ejected from neutron-star mergers. Red colours denote regions of heavy r-process elements, which radiate red/infrared light. Blue colours denote regions of light r-process elements which radiate blue/optical light. During the merger, tidal forces peel off tails of matter, forming a torus of heavy r-process ejecta in the plane of the binary. Material squeezed into the polar regions during the stellar collision can form a cone of light r-process material. Roughly spherical winds from a remnant accretion disk can also contribute, and are sensitive to the fate of the central merger remnant.

\( a \), If the remnant survives as a hot neutron star for tens of milliseconds, its neutrino irradiation lowers the neutron fraction and produces a blue wind.

\( b \), If the remnant collapses promptly to a black hole, neutrino irradiation is suppressed and the winds may be red.

\( c \), In the merger of a neutron star and a black hole, only a single tidal tail is ejected and the disk winds are more likely to be red.

Kasen et al. 2017

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The Wide-field Infrared Transient Explorer

B.1. Electromagnetic signatures of the r-process nucleosynthesis, which yields half the elements in the periodic table heavier than iron (peak elements e.g. Au and Pt) synthesized. What elements are made when neutron star mergers occur? (d) When a neutron star remnant prompt collapses to a black hole, neutrino irradiation lowers the neutron fraction and produces a blue light. (a) Optical emission is never predicted for NS+BH mergers, or high mass ratio NS events. Even with high mass ratio NS events, winds are red infrared. (b,c) Mergers result in bright, blue optical counterparts, conducive to localization by telescopes.

Now that the first unambiguous r-process event has been observed in GW170817, we can study the properties of these events in detail. Over 20 square degrees, the Wide-field Infrared Transient Explorer (WINTER) will search for kilonova counterparts to NS+NS mergers, and indeed this will come online just as LIGO and Virgo achieve advanced phase.

WINTER: In Partnership with Rob Simcoe (MIT)
DREAMS: In Partnership with Anna Moore (ANU)

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Why Dome C?

- Sky is 40x Darker
- Seeing is fantastic
Two Technology Challenges

Challenge: Affordable Detectors
Solution: Molecular Beam Epitaxy on Silicon

Challenge: Thermal Noise
Solution: Fully Cryogenic Telescope System
Namaskar

नमस्कार