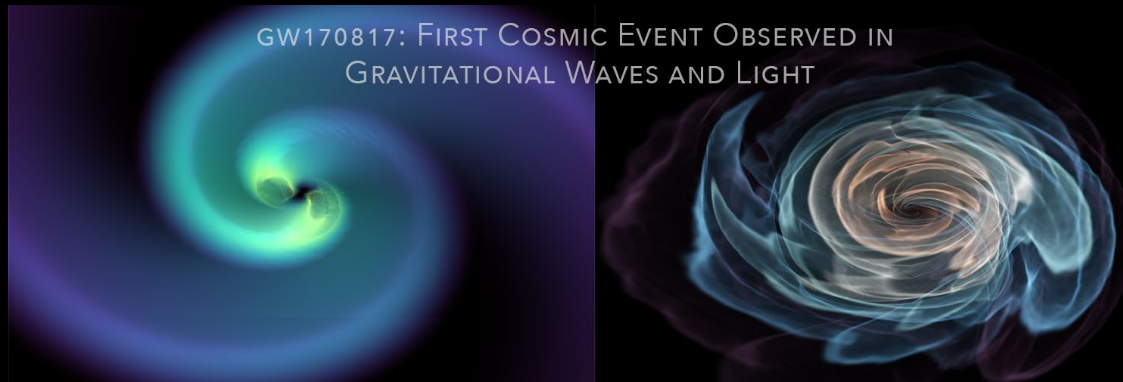



# Peter Nugent

DEPARTMENT HEAD COMPUTATIONAL SCIENCE

LAWRENCE BERKELEY NATIONAL LABORATORY

(MAJOR HELP FROM DANNY GOLDSTEIN (WEIGHTS & BIASES) & MANSI KASLIWAL (CALTECH)

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

NSF

NASA

MOUNT CUBA ASTRONOMICAL FOUNDATION

HEISING-SIMONS FOUNDATION

the David & Lucile Packard FOUNDATION

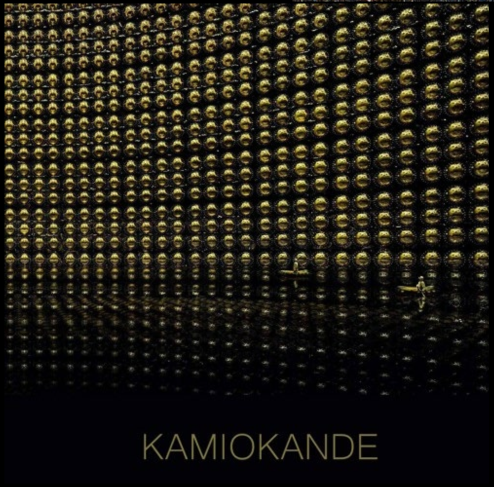
BERKELEY LAB Lawrence Berkeley National Laboratory

NERSC

# When Did Multi-Messenger Astronomy Begin?

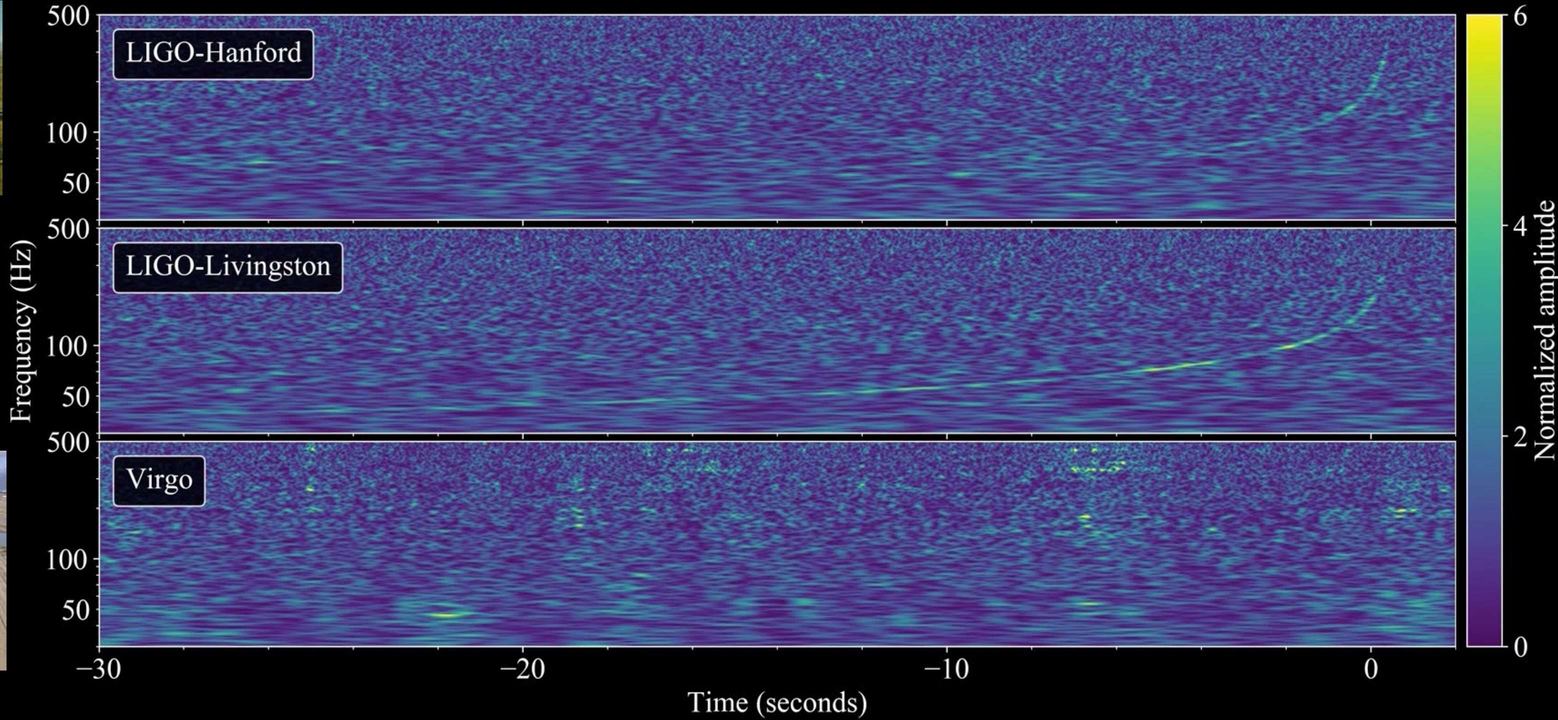
On February 24, 1987 Ian Shelton and Oscar Duhalde, at the Las Campanas Observatory in Chile, looked up in the sky and saw a supernova in the Large Magellanic Cloud.

Approximately two to three hours before the visible light from SN 1987A reached Earth, a burst of neutrinos was observed at Kamiokande II (as well as 2 other neutrino detectors). Neutrino emission, is a by-product of core collapse, but occurs before visible light is seen as it takes time for the shock wave to reach the stellar surface and for the supernova to emit light.



# August 17, 2017, 12:41:04 UTC

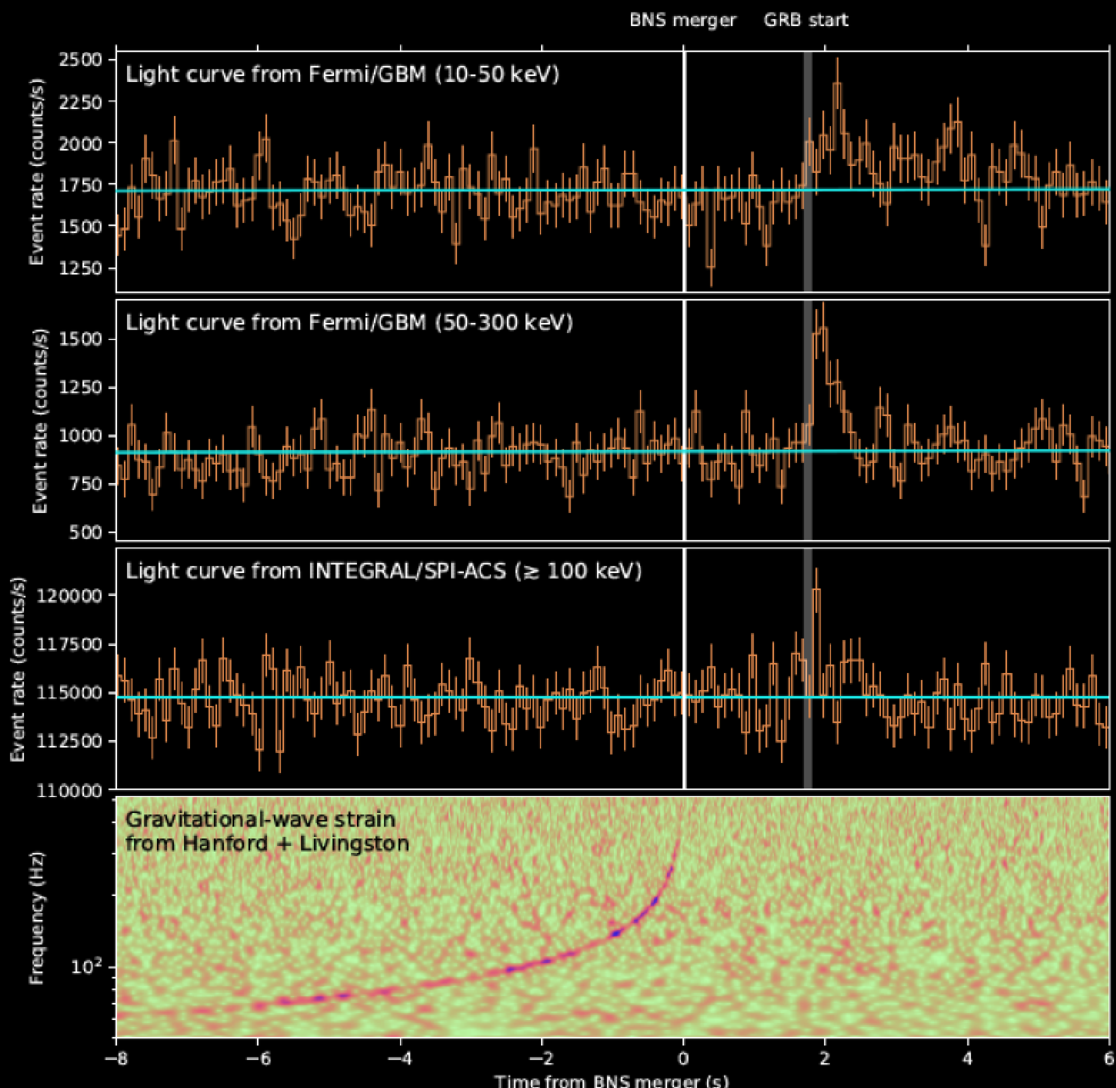


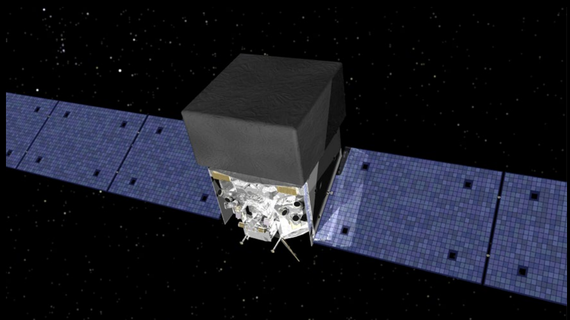




LVC, *Phys. Rev. Lett.* 119, 161101 (2017)

**The longest (~ 100 s), loudest (SNR ~ 32), closest (40 Mpc) signal we've ever observed!**

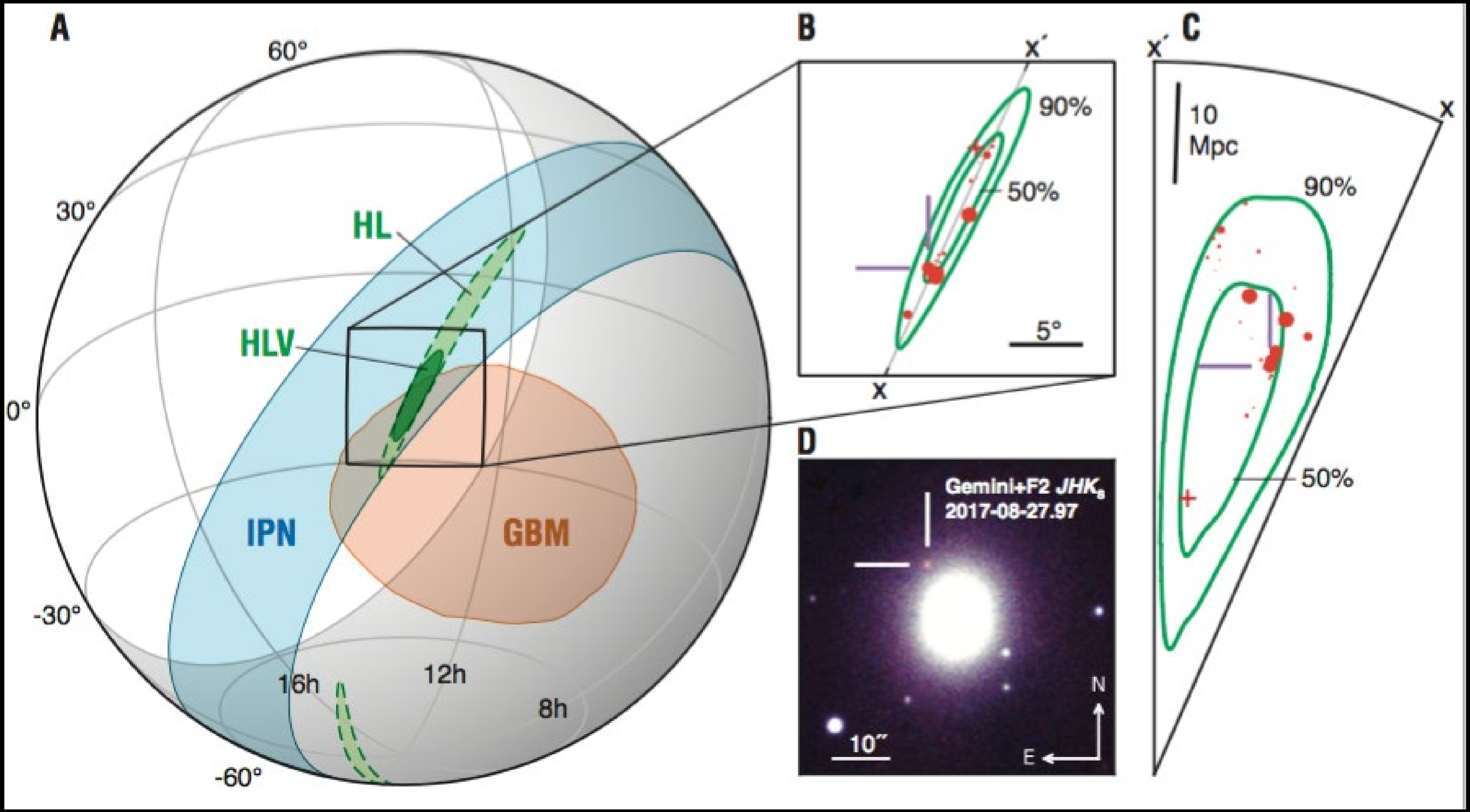
# Just 1.7 seconds later:
# a burst of gamma-rays!



LVC, Fermi, Integral *Astrophys. J. Lett., 2017; Goldstein et al. 2017*

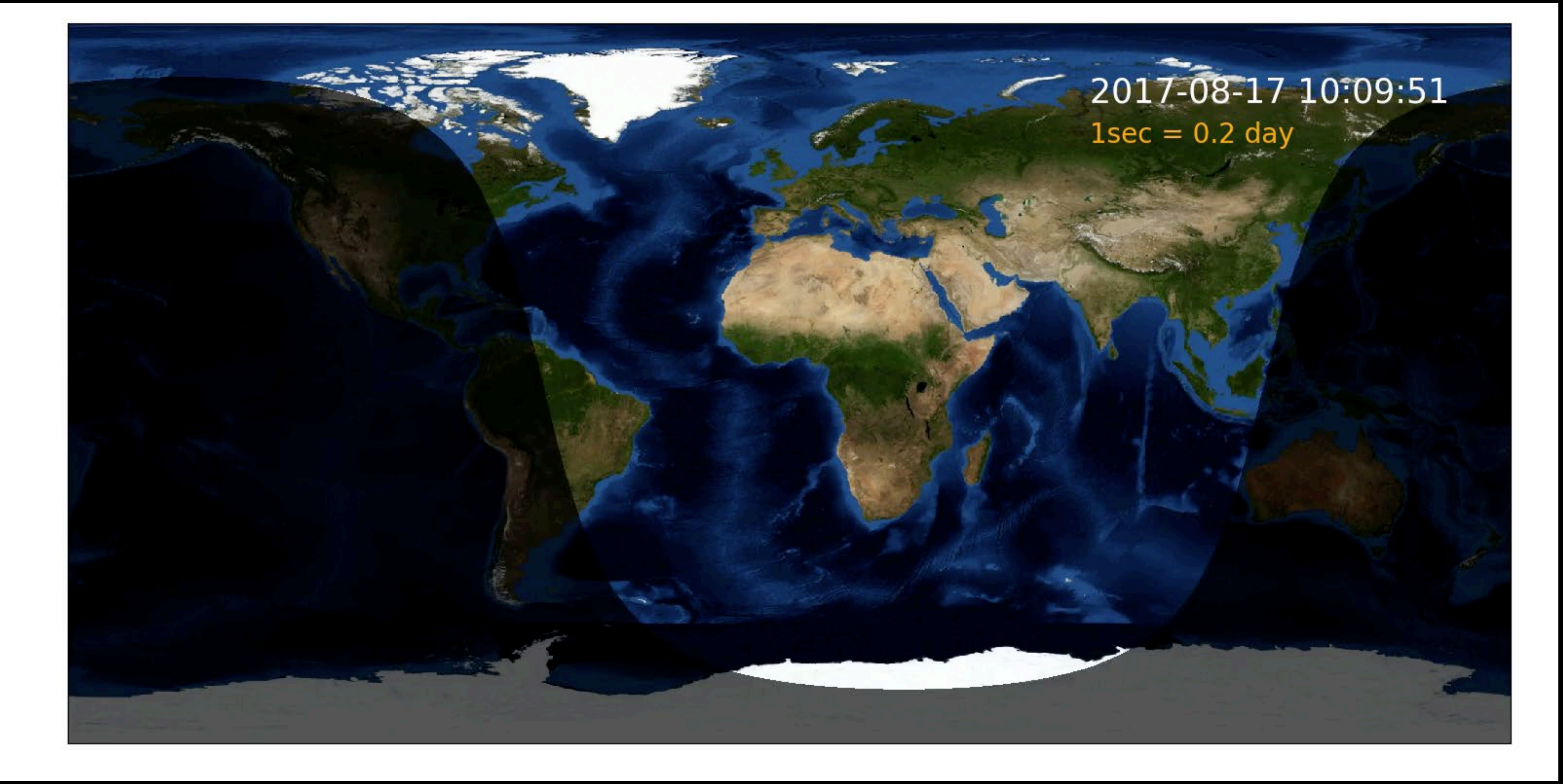
# GW170817: Binary Neutron Star Merger




Kasliwal et al. 2017c, Science

GROWTH
Global Relay of Observatories Watching Transients Happen

# A Global Effort




Movie Credit: GROWTH co-I V. Bhalerao

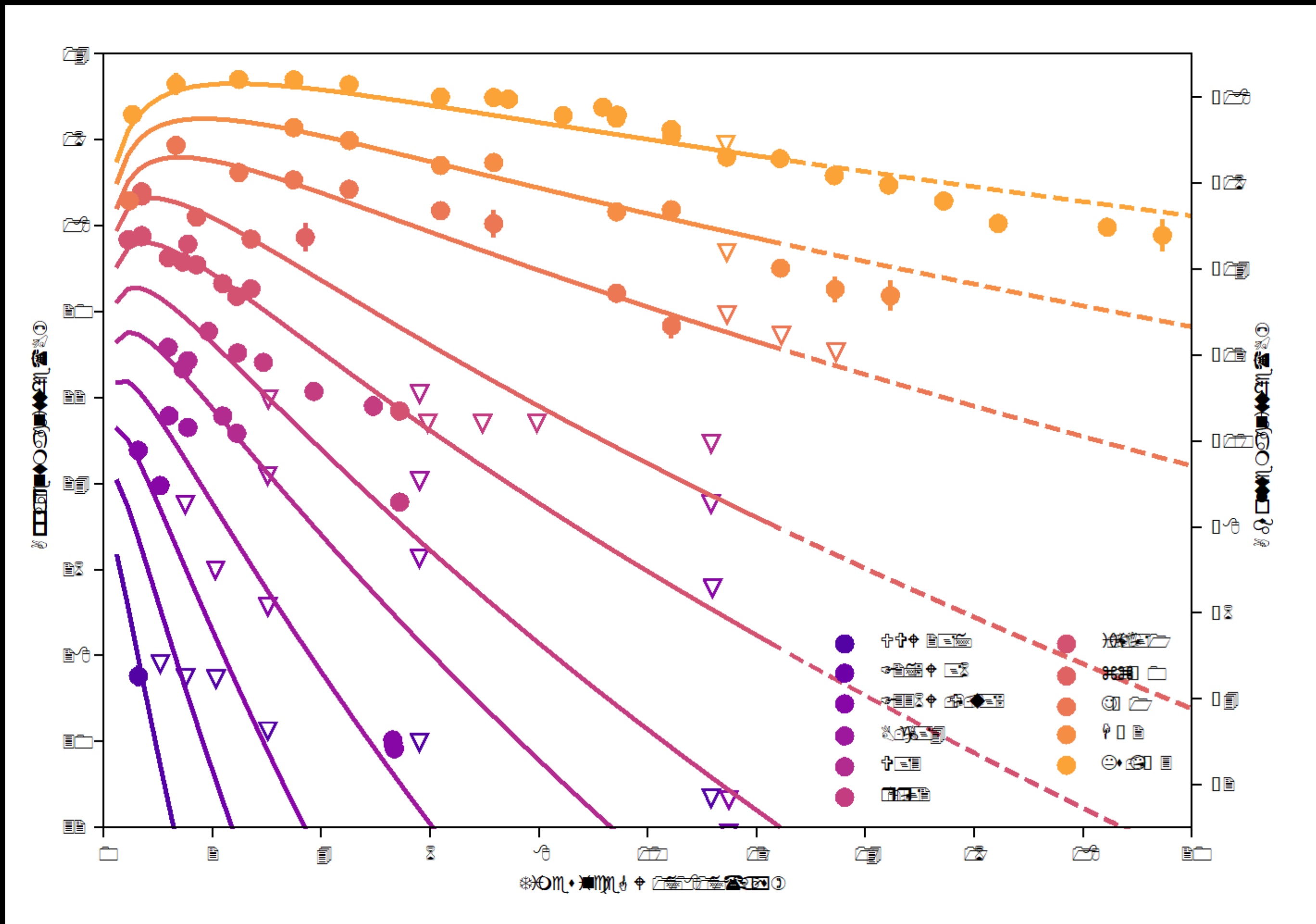
The GROWTH Team: 18 telescopes, 6 continents, 100+ people

# Q1. Nucleosynthesis

*Are neutron star mergers the long-sought sites of heavy element production?*

Lattimer & Schramm 1974

# UVOIR Light Curve

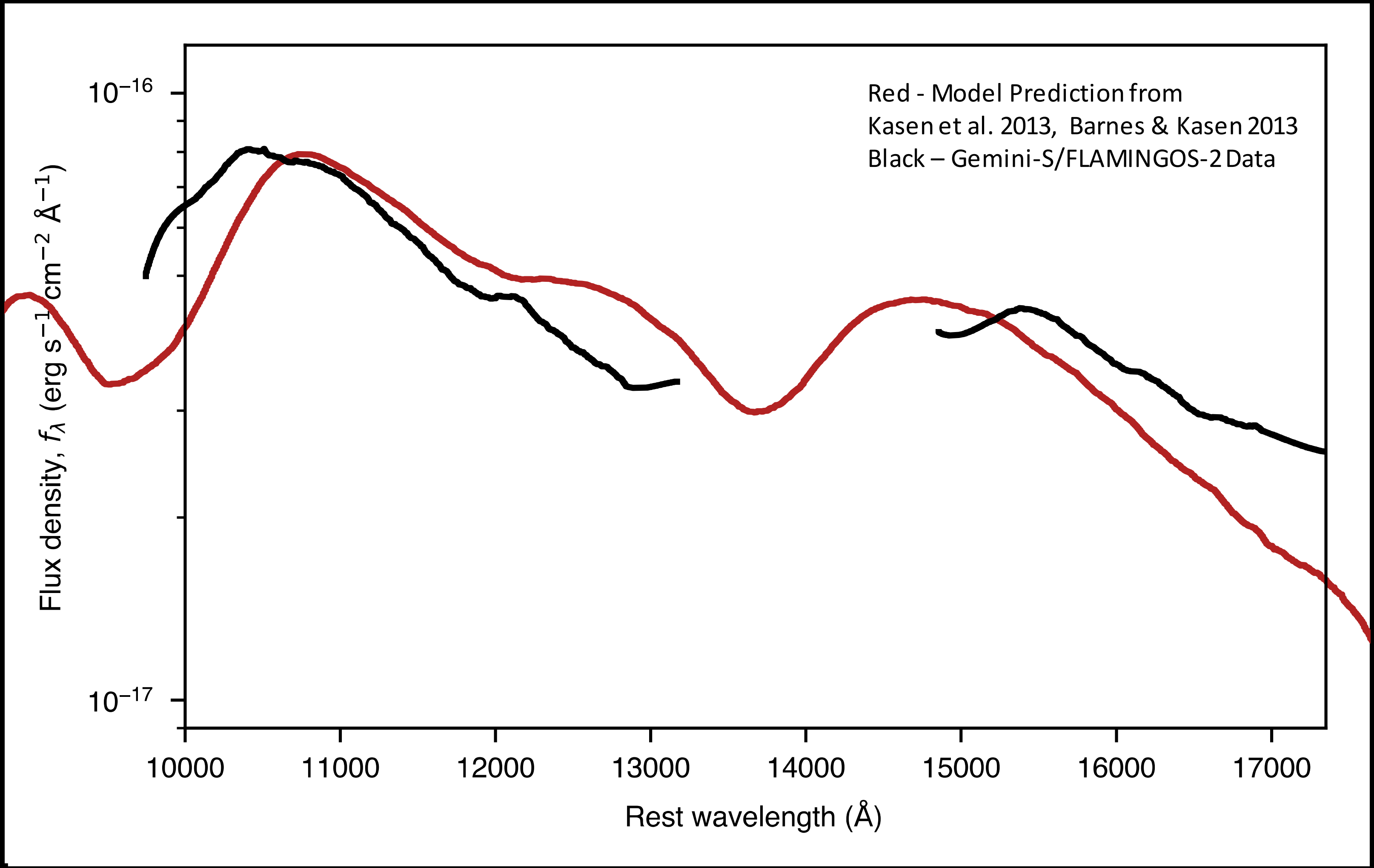


Evans et al. 2017, Kasliwal et al. 2017c, Science

See also:
Andreoni et al. 2017
Arcavi et al. 2017
Cowperthwaite et a.
Coulter et al. 2017
Drout et al. 2017
Lipunov et al. 2017
Lyman et al. 2017
Pian et al. 2017
Soares-Santos et al. 2
Smartt et al. 2017
Tanvir et al. 2017
Utsumi et al. 2017
Villar et al. 2017

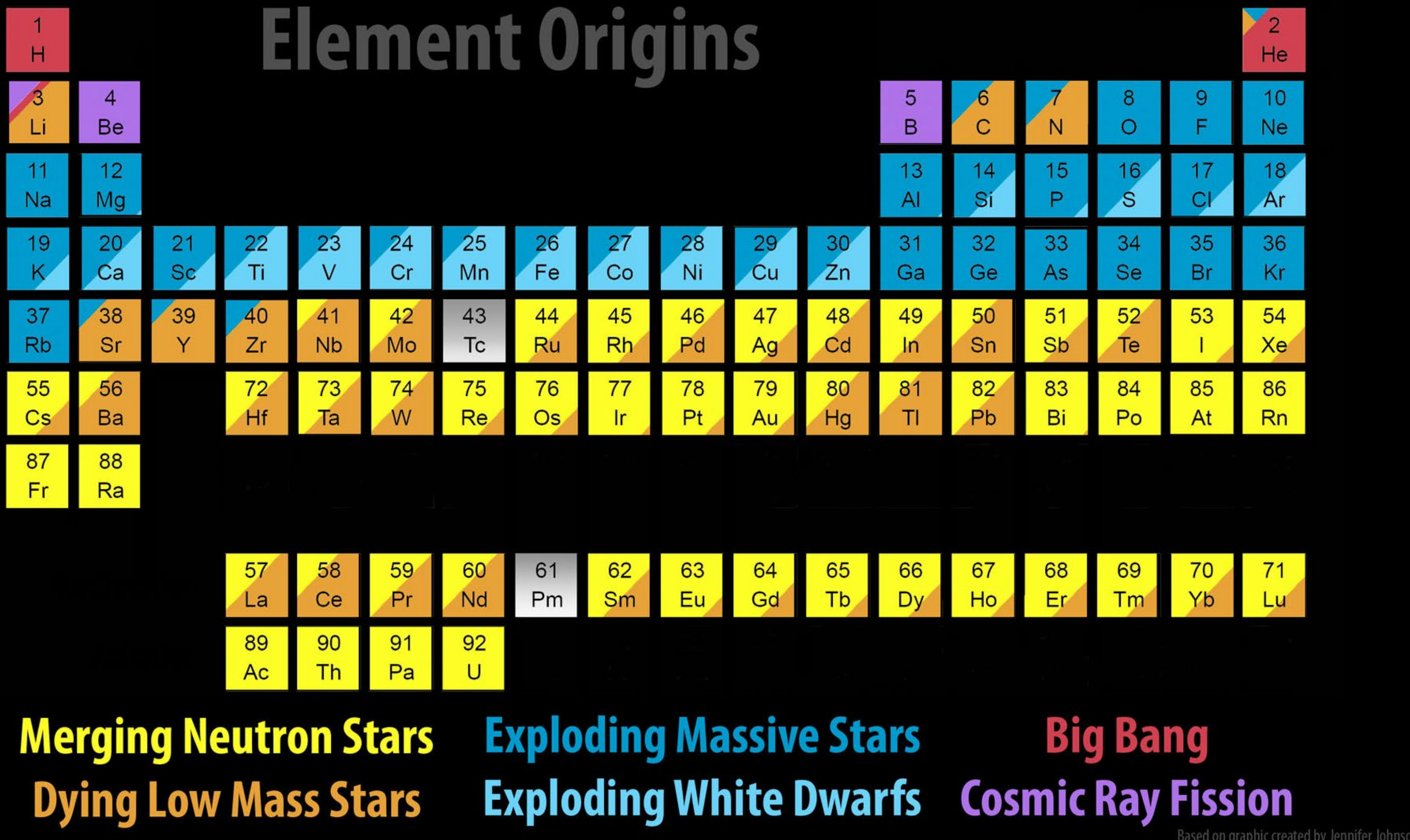
## Heavy Elements were Synthesized.

# Thumbprint of Heavy Elements

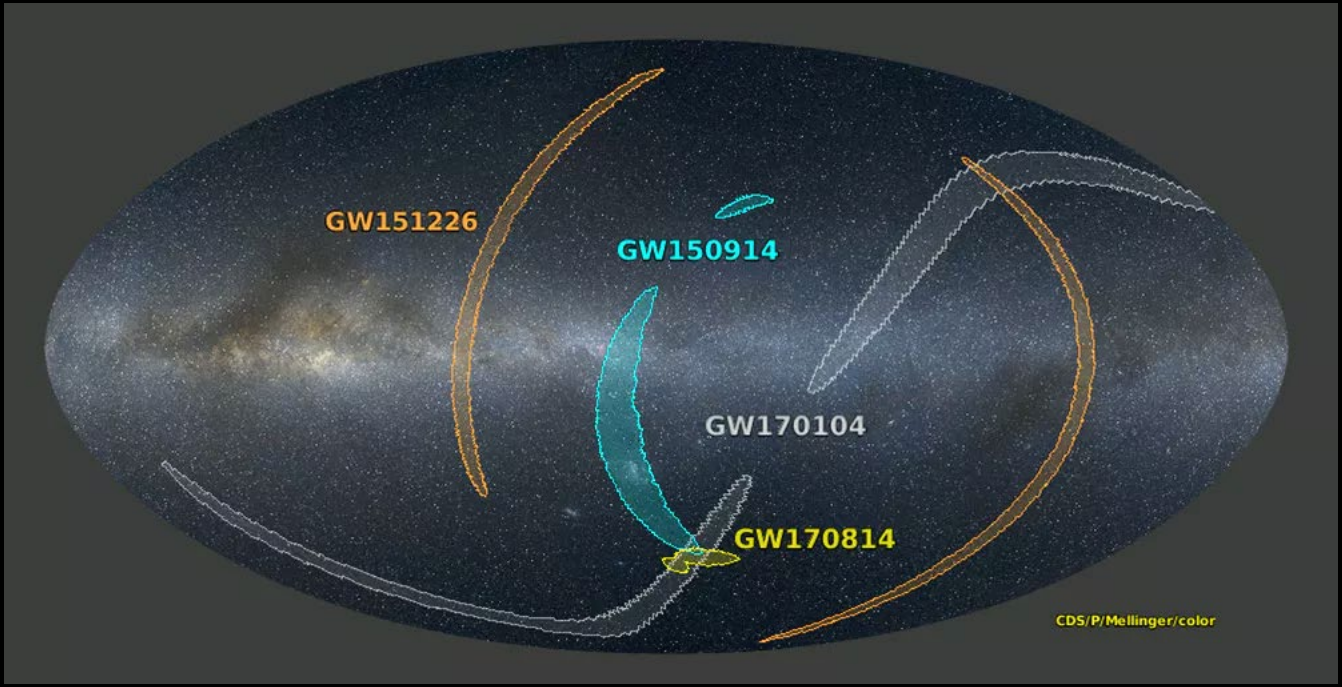



Kasliwal et al. 2017c, Science

See also Chornock et al. 2017, Troja et al. 2017


Element Origins
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
Merging Neutron Stars
Exploding Massive Stars
Big Bang
Dying Low Mass Stars
Exploding White Dwarfs
Cosmic Ray Fission
Based on graphic created by Jennifer Johnson

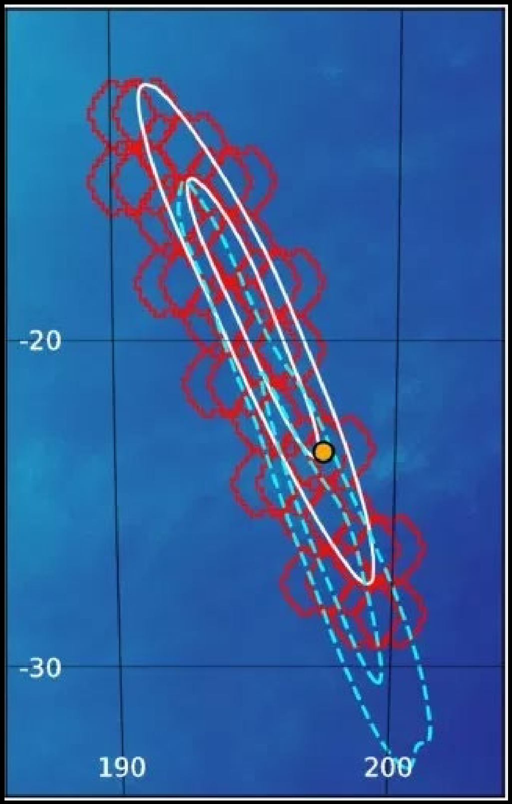
# Typical GW Localizations are hundreds of square degrees




Want an imager which can pave the sky quickly.

# DECam is the best instrument in the southern hemisphere to follow-up GWs


4m telescope, red-sensitive




**Soares-Santos et al. 2017**

# Speed is the Key

- Events fade away very rapidly

- Other people are searching your data, in real time

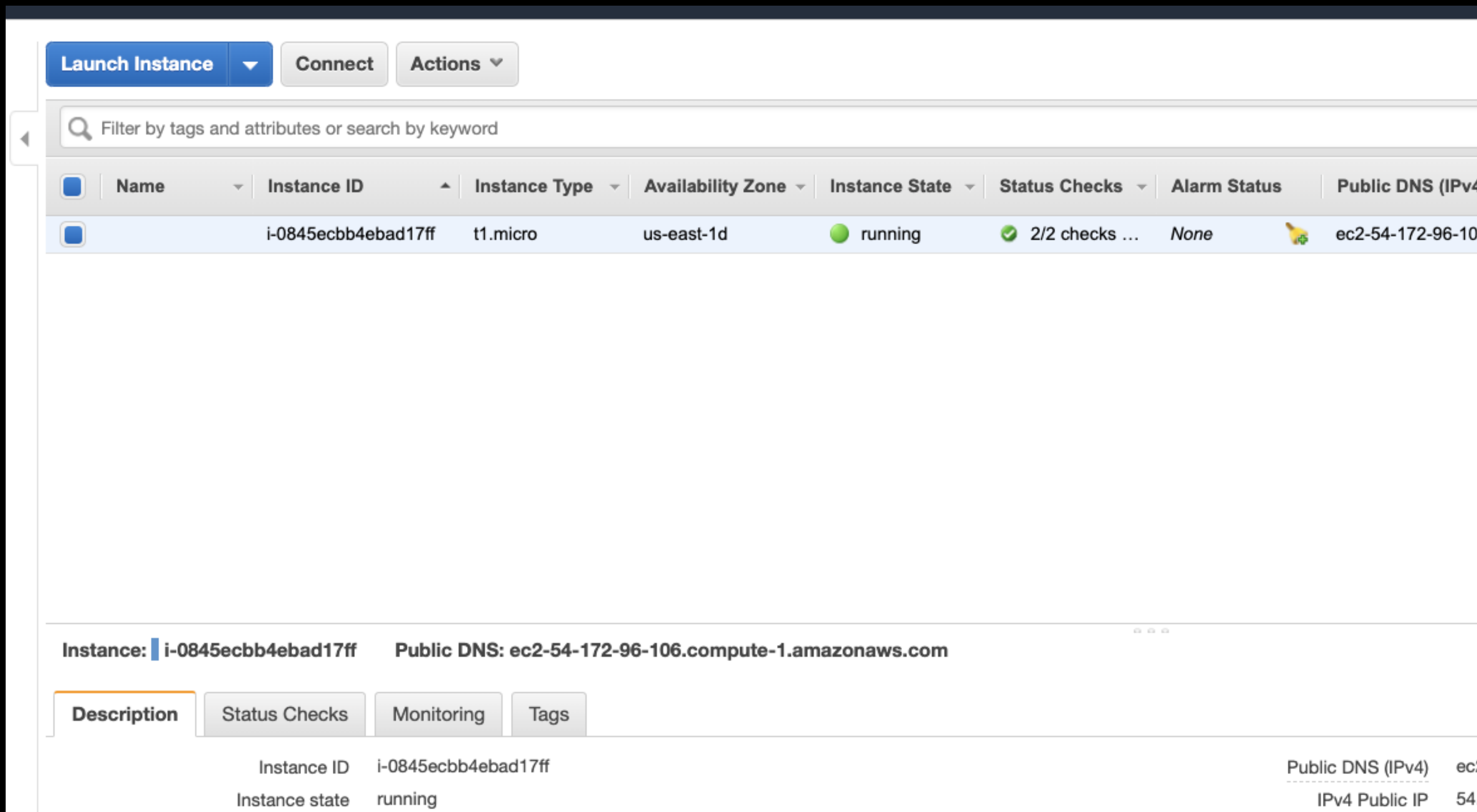
- Need to be first

# Why look to AWS?

NERSC has some issues we are still working on…

- Python + Lustre bugs with Astropy (a major astronomy software tool package)
- Maintenance
- Our good friend PG&E: PSPS

# AWS benefits




No queues - start processing immediately

# 10 seconds later — You have all the instances you need for as long as you need

Launch Instance | Connect | Actions

Filter by tags and attributes or search by keyword

| Name | Instance ID | Instance Type | Availability Zone | Instance State | Status Checks | Alarm Status | Public DNS (IPv4) | IPv4 Public IP | IPv6 IPs | Key Name |
|---|---|---|---|---|---|---|---|---|---|---|
| | i-0036d6b87ec6088c3 | c5.18xlarge | us-east-1d | running | Initializing | *None* | ec2-18-232-174-43.co… | 18.232.174.43 | - | test-us-east- |
| | i-006b84e76e25238ce | c5.18xlarge | us-east-1d | running | Initializing | *None* | ec2-34-224-166-142.co… | 34.224.166.142 | - | test-us-east- |
| | i-01f01a6bd1035b8f8 | c5.18xlarge | us-east-1d | running | Initializing | *None* | ec2-3-93-162-76.comp… | 3.93.162.76 | - | test-us-east- |
| | i-023d1eb92f235051b | c5.18xlarge | us-east-1d | running | Initializing | *None* | ec2-34-234-95-74.com… | 34.234.95.74 | - | test-us-east- |
| | i-0284e2ebbe362dd… | c5.18xlarge | us-east-1d | running | Initializing | *None* | ec2-34-207-151-121.co… | 34.207.151.121 | - | test-us-east- |
| | i-030946837ca6ffffa | c5.18xlarge | us-east-1d | running | Initializing | *None* | ec2-54-146-249-240.co… | 54.146.249.240 | - | test-us-east- |
| | i-036442f11b2ceeea5 | c5.18xlarge | us-east-1d | running | Initializing | *None* | ec2-18-212-202-130.co… | 18.212.202.130 | - | test-us-east- |
| | i-044257b9a34a63a… | c5.18xlarge | us-east-1d | running | Initializing | *None* | ec2-54-235-42-191.co… | 54.235.42.191 | - | test-us-east- |
| | i-04b39a296d70cecd1 | c5.18xlarge | us-east-1d | running | Initializing | *None* | ec2-3-94-182-35.comp… | 3.94.182.35 | - | test-us-east- |
| | i-05d7eb81e4bcdc936 | c5.18xlarge | us-east-1d | running | Initializing | *None* | ec2-3-87-169-206.com… | 3.87.169.206 | - | test-us-east- |

**Select an instance above**

# Why AWS

- Instances are “yours” — you are root and can do whatever you want
- Everything is containerized — you can use full docker (instead of docker derivatives with less functionality)
- Sophisticated batch system
- We got a grant from them ;-) Free is good.
- Can scale up as much as we want - no limits on resource usage

# Why not AWS?

Nothing is ever "free"….

Think the roach motel: Your data can check in, but it can't check out - without a heavy charge…

Pipeline:

- We process ~10,000 X 32 MB images per night
- Typical runs are 2-3 nights, data is needed for one month
- The images get blown up from int's to real's, subtracted from a reference image whose results are shoved into a db specifying location and characteristics of the transient (brightness, time, color, etc.) → expand 10X
- Total of ~< 10 TB of data in imaging


AWS charges:

- \$0.005 iops-month – 300,000 files = \$1500
- \$0.08 Gb-month – 9600 GB = \$768
- And we have a trigger each month…

# The Cheat…

We process everything at AWS and delete the data immediately, save 100X100 pixel cut-outs around best candidates. Reprocess later at NERSC…

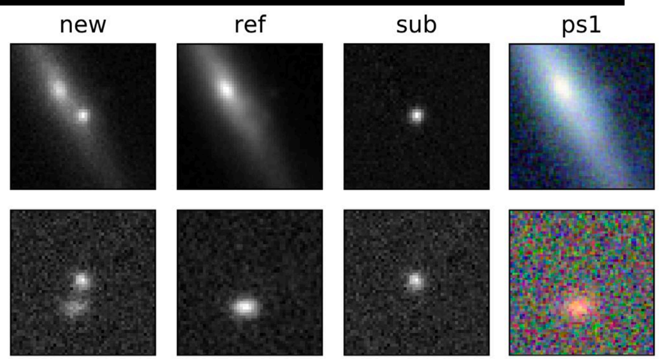



**Figure 3.** Postage-stamp cutouts of some transients identified by the pipeline (top: DG19vkgf, bottom: DG19ytre). Each transient has at least one detection in both *r* and *z*, separated by at least 30 minutes (to reject asteroids). Full color images from Pan-STARRS1 (PS1) are shown for reference.

CrossMark

## GROWTH on S190426c: Real-time Search for a Counterpart to the Probable Neutron Star–Black Hole Merger using an Automated Difference Imaging Pipeline for DECam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*Received 2019 May 16; revised 2019 July 2; accepted 2019 July 6; published 2019 August 5*



### Abstract

The discovery of a transient kilonova following the gravitational-wave (GW) event GW170817 highlighted the critical need for coordinated rapid and wide-field observations, inference, and follow-up across the electromagnetic spectrum. In the southern hemisphere, the Dark Energy Camera (DECam) on the Blanco 4 m telescope is well suited to this task, as it is able to cover wide fields quickly while still achieving the depths required to find kilonovae like the one accompanying GW170817 to ~500 Mpc, the binary neutron star (NS) horizon distance for current generation of LIGO/Virgo collaboration (LVC) interferometers. Here, as part of the multi-facility follow-up by the Global Relay of Observatories Watching Transients Happen collaboration, we describe the observations and automated data movement, data reduction, candidate discovery, and vetting pipeline of our target-of-opportunity DECam observations of S190426c, the first possible NS–black hole merger detected in GWs. Starting 7.5 hr after S190426c, over 11.28 hr of observations, we imaged an area of 525 $deg^2$ (*r* band) and 437 $deg^2$ (*z* band); this was 16.3% of the total original localization probability, and nearly all of the probability visible from the southern hemisphere. The machine-learning-based pipeline was optimized for fast turnaround, delivering transients for human vetting within 17 minutes, on average, of shutter closure. We reported nine promising counterpart candidates 2.5 hr before the end of our observations. One hour after our data-taking ended (roughly 20 hr after the announcement of S190426c), LVC released a refined skymap that reduced the probability coverage of our observations to 8.0%, demonstrating a critical need for localization updates on shorter (~hour) timescales. Our observations yielded no detection of a bona fide counterpart to $m_z = 21.7$ and $m_r = 22.2$ at the $5\sigma$ level of significance, consistent with the refined LVC positioning. We view these observations and rapid inferencing as an important real-world test for this novel end-to-end wide-field pipeline.



*Key words:* gravitational waves – stars: black holes – stars: neutron – surveys

# What's next?

- Exploring hybrid models: AWS, LBNL IT, NERSC, LCF's.
- Need to harden the containerization.
- Need to work on federated ID's and group accounts.
- Need to explore db options at all facilities and automated mirroring.
- Need to come up with a seamless way to switch from one resource to another.
- Need to understand, fully, the cost-benefit analysis of running at each facility.

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