The Cyberinfrastructure of Gravitational-Wave Astronomy and the March Towards Open Data

Duncan Brown
Syracuse University
About 1.3 billion years ago...

As massive objects move around, the curvature of space changes. Information about the changing spacetime curvature propagates out at the speed of light as gravitational waves.
Typical strains from astrophysical sources when the waves arrive at the Earth are

\[ h \sim \frac{G}{c^4} \frac{E_{\text{NS}}}{r} \sim 10^{-21} \]

However, the energy radiated is enormous

\[ L_{\text{GW}} \sim \left( \frac{c^5}{G} \right) \left( \frac{v}{c} \right)^6 \left( \frac{R_S}{r} \right)^2 \sim 10^{59} \text{erg/s} \]

Solar luminosity \( L \sim 10^{33} \text{ erg/s} \)
Gamma Ray Bursts \( L \sim 10^{49-52} \text{ erg/s} \)
Imagine measuring this distance to a precision of ten microns. Smaller than the width of a human hair!
Advanced LIGO
GW150914

- Observed September 14, 2015 09:50:45 UTC
- The signal is seen first by the Livingston detector and then 7ms later at Hanford
- Over 0.2 seconds, the signal increases in frequency and amplitude in about 8 cycles from 35 Hz to a peak amplitude at 150 Hz

• Use this to measure the "chirp mass"

\[ M = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G} \left[ \frac{5}{96} \pi^{-8/3} f^{-11/3} \dot{f} \right]^{3/5} \]

• From this we can bound the total mass \( M = m_1 + m_2 \gtrsim 70M_\odot \)

• The components must reach an orbital frequency of 75 Hz without touching each other

• Black holes are the only known objects compact enough to do this

To detect signals from compact-object binaries, we construct a bank template waveforms and matched-filter the data

$$\rho = \frac{\langle s | h \rangle}{\sqrt{\langle h | h \rangle}}$$

$$\langle a | b \rangle = 4 \text{Re} \int_{f_{\text{low}}}^{f_{\text{high}}} \frac{\tilde{a}(f) \tilde{b}(f)}{S_n(f)} df$$

Apply additional waveform-consistency tests to separate signal from noise

Significance of the Signal

• Matched filter search for signals from compact-object mergers in data taken between Sep 12 and Oct 20, 2015

• Approximately 250,000 templates

• Measure the noise background by introducing artificial "time-shifts" and re-analyzing these data

• False alarm rate < 1 in 203,000 yr

GW170817

Abbott,..., DAB et al. PRL 119 161101 (2017)
GCN 21509 at 10:09 am EDT announcing significant BNS candidate coincident with the Fermi GBM trigger...

The LIGO Scientific Collaboration and the Virgo Collaboration report:

A binary neutron star candidate was identified in data from the LIGO Hanford detector at gps time 1187008882.4457 (Thu Aug 17 12:41:04 GMT 2017). The signal is clearly visible in time-frequency representations of the gravitational-wave strain in data from H1. The current significance estimate of ~1/10,000 years is based on data from H1 alone. Information about this candidate is available in GraceDb here

https://gracedb.ligo.org/events/view/G298048

The effective distance to this candidate is approximately 58 Mpc and the current localization estimate using gravitational-wave data alone is quite broad because it only makes use of data from H1. We note that this is only an estimate of the effective distance, and the actual luminosity distance to the source is likely larger.

The neutron star coalescence candidate is also clearly visible in data from the LIGO Livingston detector, although there is a coincident noise artifact in the L1 data. To be clear, the binary neutron star candidate is clearly visible in the L1 data on top of the noise artifact. There is no evidence for any noise artifact at H1. Virgo was online at the time, although its data was not used to estimate the candidate’s significance. It is expected to be visible in all detectors once the data has been analyzed.

The gravitational-wave candidate was found in coincidence with Fermi GBM trigger 524666471/170817529, which occurred at gps time 1187008884.47 (Thu Aug 17 12:41:06 GMT 2017). This is approximately 2 seconds after the gravitational-wave candidate’s coalescence time. The Fermi trigger’s localization estimate from Fermi data alone can be found here


Analyses including data from H1, L1, and V1 are ongoing and a sky-map using gravitational-wave data will be made available as quickly as possible.

[GCN OBS NOTE{17aug17}: Per author's request, the LIGO/VIRGO ID was added to the beginning of the Subject-line.]
Signal-to-noise ratio

Time from 1187008882 (seconds)

The LIGO Scientific Collaboration and the Virgo Collaboration report:

We performed a preliminary offline analysis using the PyCBC search (Nitz et al. arxiv:1705.01513, 2017) of the binary neutron star candidate G298048 (LSC and Virgo, GCN 21505, 21509, 21510) identified in low-latency by the gstlal online search (Messick et al. Phys. Rev. D 95, 042001, 2017).

A trigger consistent with a binary neutron star merger is observed at GPS time 1187008882.443 (2017-08-17 12:41:04 UTC) in both the LIGO Livingston (L1) and LIGO Hanford (H1) detectors. The trigger is below threshold in Virgo because of the antenna pattern for Virgo (V1) at the time and location of this event, but the Virgo instrument contributes to the localization. The duration of the gravitational-wave signal is approximately 74 seconds from the searchâ€™s low-frequency cutoff of 27 Hz to the binary merger.
Core science funding through: NSF Gravity program grants to PIs; Max Planck Society; UK/EU investigators

Infrastructure through NSF ACI grants

Relies on Pegasus and HTCondor for job execution

https://pycbc.org

PyCBC
Open software to study gravitational waves.

PyCBC is a software package used to explore astrophysical sources of gravitational waves. It contains algorithms that can detect coalescing compact binaries and measure the astrophysical parameters of detected sources. PyCBC was used in the first direct detection of gravitational waves by LIGO and is used in the ongoing analysis of LIGO and Virgo data. PyCBC was featured in Physics World as a good example of a large collaboration publishing its research products, including its software.

Getting Started
You can start using the PyCBC library now in an interactive notebook!
• I joined the LIGO Scientific Collaboration in 1999

• First LIGO paper:


• Author 38 out of 368 co-authors

• Cited by 145 since 2004
• Last LIGO paper:


• Author 137 out of 1125 co-authors

• Cited by 2057 since October 2017

• Left the LIGO Scientific Collaboration in January 2018
the future of science is OPEN
fosteropenscience.eu
• LIGO Data Management Plan: https://dcc.ligo.org/M1000066/public

• "Release of events and important non-detections will occur with publication of one or more papers discussing these observational results in the scientific peer-reviewed literature."

• All O1 and O2 events available now

• "The transition to Open Data, with the regular release of data during observation runs and prompt public alerts of transient events [will begin in April 2019]"
• O3 alerts can be viewed at https://gracedb.ligo.org

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"Releases will occur every 6 months, in blocks of 6 months of data, with a latency of 18 months from the end of acquisition of each observing block (Expect to shorten the 18 month period)"

- O1 and O2 data available now

- O3A April 2019 + 6 months + 18 months = April 2021
Large Data Sets for High Performance Computing

For users of computing clusters, CernVM-FS is the preferred method to access large data sets:

**O2 Data Release**

**O2 Time Range:** November 30, 2016 through August 25, 2017  
**Detectors:** H1, L1 and V1

**O1 Data Release**

**O1 Time Range:** September 12, 2015 through January 19, 2016  
**Detectors:** H1 and L1
Calibrated LIGO gravitational-wave strain data is (basically) CD-quality audio.

- 16 kHz sample rate, 64 bit, 2 x channels
- + Virgo (32 bit) makes three channels
- ~ 1 hour of strain data can be downloaded for each event

signal(t) = detector noise(t) + gravitational-wave strain(t)

Full O1 strain data set O(10 Tb)
```
Filesystem  512-blocks  Used  Available Capacity  iused  ifree  %iused  Mounted on
/dev/disk1  974496000  901859432  72124568  93%  112796427  9015571  93%  /
devfs        507       507         0      100%       878       0      100%  /dev
map -hosts   0         0         0      100%       0         0      100%  /net
map auto_home 0         0         0      100%       0         0      100%  /home
drivefs      974496000  905491264  69004736  93%  18446744069414608791  4294967295  75385141272638368%  /Volumes/GoogleDrive
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```

```
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[[dbrown@Duncans-MacBook-2 1125122048]$ ls
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```

Caches in network & at endpoints

CalTech
SDSC
UNL
FNAL
U Chicago

Amazon Direct Connect
Google Dedicated Interconnect
Microsoft Azure ExpressRoute

In Service
Planned

OSG Data Origin
Internet 2
CENIC

Cache at I2 peering point with Cloud providers in Chicago

Syracuse
The SciTokens Model

Capability-based authorization for science

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1-OGC: The First Open Gravitational-wave Catalog of Binary Mergers from Analysis of Public Advanced LIGO Data

Alexander H. Nitz\textsuperscript{1,2} ID, Collin Capano\textsuperscript{1,2} ID, Alex B. Nielsen\textsuperscript{1,2} ID, Steven Reyes\textsuperscript{3} ID, Rebecca White\textsuperscript{3,4} ID, Duncan A. Brown\textsuperscript{3} ID, and Badri Krishnan\textsuperscript{1,2} ID


The Astrophysical Journal, Volume 872, Number 2
Instructions for generating the 1-OGC catalog on the Open Science Grid

Alexander H. Nitz\textsuperscript{1,2}, Collin Capano\textsuperscript{1,2}, Alex B. Nielsen\textsuperscript{1,2}, Steven Reyes\textsuperscript{3}, Rebecca White\textsuperscript{4,3}, Duncan A. Brown\textsuperscript{3}, Badri Krishnan\textsuperscript{1,2}

1. Albert-Einstein-Institut, Max-Planck-Institut for Gravitationsphysik, D-30167 Hannover, Germany
2. Leibniz Universität Hannover, D-30167 Hannover, Germany
3. Department of Physics, Syracuse University, Syracuse, NY 13244, USA
4. Fayetteville-Manlius High School, Manlius, NY 13104, USA

This directory contains the scripts and configuration files necessary to reproduce the 1-OGC catalog using public data and code using the Open Science Grid.

These instructions are designed for users familiar with PyCBC, Pegasus WMS, HTCondor, and OSGConnect and who would like to reproduce our results. We assume that the reader has familiarity with running PyCBC in Singularity containers and is able to troubleshoot HTCondor errors that can happen when running large workflows.

The contents of this directory are:

1. A script for generating, planning, and running the workflow on the Open Science Grid
2. A script for generating, planning, and running the workflow on Syracuse University's Orange Grid
• Only requirement is an account on OSG Connect
• Run PyCBC from a Singularity container
• Create a workflow which is planned using Pegasus WMS and run under HTCondor
• LIGO Open Data is read from CVMFS
• stashcp is used to stage intermediate data products and store output
• SciTokens is used for authentication
There are two datasets within the file, /complete and /bbh. The complete set is the full dataset from our analysis. The bbh set includes BBH candidates from a select portion of the analysis. See the 1-OGC paper for additional information.

```python
import h5py

catalog = h5py.File('./1-OGC.hdf', 'r')

# Get a numpy structured array of the candidate event properties.
all_candidates = catalog['complete']
bbh_candidates = catalog['bbh']

# Accessing a column by name
ranking_values = all_candidates['stat']

# Selecting parts of the catalog
region = all_candidates['mass1'] + all_candidates['mass2'] < 4
lowmass_candidates = all_candidates[region]
```

File format

Both datasets are structured arrays which have the following named columns. Some of these columns give information specific to either the LIGO Hanford or Livingston detectors. Where this is the case, the name of the column is prefixed with either a H1 or L1.
GW150914

$m_1^{\text{src}}(M_\odot) = 35.3^{+5.0}_{-3.1}$

$m_2^{\text{src}}(M_\odot) = 29.9^{+3.0}_{-4.4}$

$q = 1.17^{+0.38}_{-0.16}$

$X_{\text{eff}} = -0.035^{+0.012}_{-0.018}$

Biwer, Capano, De, Cabero, DAB, Nitz PASP 131 024503 (2019)

De, Biwer, Capano, Nitz, DAB Nature Scientific Data 6, 81 (2019)
\[ p(\vec{\theta} | \vec{d}(t), H) = \frac{p(\vec{\theta} | H) p(\vec{d}(t) | \vec{\theta}, H)}{p(\vec{d}(t) | H)} \]

Need the data, \( \vec{d}(t) \) from GWOSC ✓

Need a model, \( H \equiv h(t; \alpha, \delta, m_1, m_2, \vec{s}_1, \vec{s}_2, \lambda_1, \lambda_2, \ldots) \) from PyCBC ✓

Need a likelihood, \( p(\vec{d}(t) | \vec{\theta}, H) \) from PyCBC ✓

Need priors, marginalization, and visualization, from PyCBC ✓

Biwer, Capano, De, Cabero, DAB, Nitz PASP 131 024503 (2019)

This repository contains all of the tutorials and talks that were presented at the workshop; it provides a good introduction to PyCBC Inference, and Bayesian inference in general. We recommend following the [Program](#). The links listed there link to the tutorials/lectures in this repository.

**How to run the tutorials**

**Using SciServer**

To run the tutorials, we recommend using [SciServer]:

1. If you don’t already have one, create a SciServer account (it’s free). Then go to [apps.sciserver.org/compute](http://apps.sciserver.org/compute).
2. Click "Create container". Give it a name; in the "Compute Image" drop-down menu click "Python + R". Then click "Create."
3. Click on the container you just created; this will open a new tab in your browser that is a Jupyter notebook interface.
4. Clone this repository into your SciServer container: Click "New" -> "Terminal". This will open another tab that with a bash terminal in it. Change directory into "workspace" by typing `cd workspace`. Now type:

   ```bash
git clone https://github.com/gwastro/PyCBCInferenceWorkshopMay2019.git
```

This will download a copy of this repository to your directory on SciServer.
Viewing angle is $32_{-13}^{+10} \pm 1.7$ deg

Lower limit of $\geq 13$ deg robust to choice of prior

Daniel Finstad

Distance-constrained GW observations of viewing angle are consistent with EM observations.

Mooley et al. report 14 - 28 deg from radio.

Troja et al. report 21 - 29 deg from broad band observations.

GW and EM observations support successful-jet cocoon model (structured jet).


Troja et al. arXiv:1808.06617
Measuring the viewing angle of GW170817 with electromagnetic and gravitational waves

https://arxiv.org/abs/1804.04179
Using the posterior probability data

The posterior data is stored as flattened arrays in the samples group of the hdf files in this repository. The parameter names for each of the arrays that exist in a file can be accessed through a variable_args attribute of the file:

```python
In [2]:
fp = h5py.File("gw_only_posteriors.hdf", "r")
print fp.attrs['variable_args']
fp.close()

['tc' 'ra' 'dec' 'mass1' 'mass2' 'coa_phase' 'inclination' 'polarization'
 'distance' 'spin1z' 'spin2z']
```

Each of these parameter names can then be used to access that parameter’s data in the samples group of the file. For example, the inclination angle posterior samples (in radians) from our run using the GW signal as well as EM sky location and Gaussian distance prior can be accessed this way:

```python
In [3]:
fp = h5py.File("gw_skyloc_and_dist_posteriors.hdf", "r")
icc_samples = fp['samples/inclination'][:]
fp.close()
print icc_samples

[2.74223087 2.58393159 2.49176962 ... 2.53901635 2.61125559 2.45446383]
```

By default, the PyCBC software used to create these files stores the mass parameters only as mass1 and mass2, but other mass parameters like chirp mass and mass ratio can be derived from these. For example, using the PyCBC toolkit:

```python
In [4]: from pycbc import conversions

fp = h5py.File("gw_and_skyloc_posteriors.hdf", "r")
mass1 = fp['samples/mass1'][:]
mass2 = fp['samples/mass2'][:]
fp.close()
```
Haas et al. PRD 93, 124062 (2016)
\[ \langle R \rangle = 10.8 \text{ km} \]

\[ 8.9 \leq \hat{R} \leq 13.2 \text{ km} \]
Crush Cloud: A Medium-Scale Virtualized Research Cloud
Scavenged HTC Resources from Campus Desktop Computing.

(Not just undergrad labs!)

Virtualization and containerization makes both ITS and researcher happy.
module load singularity

singularity shell --home /home/dabrown/pycbc_test/:/srv --pwd /srv --bind /cvmfs --bind /tmp --contain --ipc --pid /cvmfs/singularity.opensciencegrid.org/sugwg/dbrown/:latest

Singularity: Invoking an interactive shell within container...

PyCBC Singularity d76c65d7aee60864bad32abe226cc761ddba479b757c144a0cf2c2cc888ec8:~ pycbc_inspiral --version
--- PyCBC Version ------------------------------
Version: 786b52
Branch: master
Tag: None
Id: 786b5243147c94c9236d54617c3bd0fcd37cf618
Builder: Unknown User <>
Build date: 2019-05-18 00:06:43 +0000
Repository status is CLEAN: All modifications committed

[Imported from: /usr/lib64/python2.7/site-packages/pycbc/__init__.pyc

--- LAL Version ------------------------------
Branch: None
Tag: lalsuite-v6.54
Id: 1dd42e82f34cab2e3e66c71823a60f4938ffaeb8
]
Tidal Deformabilities and Radii of Neutron Stars from the Observation of GW170817

Soumi De, Daniel Finstad, James M. Lattimer, Duncan A. Brown, Edo Berger, and Christopher M. Biwer
InCommon Entity Categories

<table>
<thead>
<tr>
<th>Entity Category</th>
<th># of SPs</th>
<th># of IdPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>hide-from-discovery</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>research-and-scholarship</td>
<td>109</td>
<td>105</td>
</tr>
<tr>
<td>research-and-scholarship</td>
<td>0</td>
<td>78</td>
</tr>
</tbody>
</table>

Check out these NEW Entity Categories!

- Hide From Discovery Category
- Registered By InCommon Category

Entities in the latter category are filtered from these web pages since currently all entities in production metadata are in the Registered By InCommon Category.

Note: Service Providers (SPs) marked in green meet the requirements of the REFEDS R&S Entity Category specification. Identity Providers (IdPs) marked in green release attributes to all R&S SPs, including R&S SPs in other federations, whereas the remaining IdPs release attributes to R&S SPs registered by InCommon only.

The following identity providers either belong to or support the indicated entity category:

<table>
<thead>
<tr>
<th>Identity Provider Name</th>
<th>Entity Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Museum of Natural History - Richard Gilder Graduate School</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>American University</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>Arizona State University</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>Auburn University</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>Augusta University</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>Bates College</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>Baylor University</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>Binghamton University</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>Boston College</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>Boston University</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>Bowling Green State University</td>
<td>hide-from-discovery</td>
</tr>
<tr>
<td>Brookhaven National Laboratory</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>Brookhaven National Laboratory</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>Brown University</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>Bucknell University</td>
<td>research-and-scholarship</td>
</tr>
<tr>
<td>California Community Colleges Chancellors Office</td>
<td>hide-from-discovery</td>
</tr>
<tr>
<td>California Institute of Technology</td>
<td>research-and-scholarship</td>
</tr>
</tbody>
</table>
Apache

Apache 2.4 Support

You should review this page and the `htaccess` page thoroughly because Apache 2.4 is much more complicated than earlier versions. In particular, if you're trying to combine Shibboleth with other authentication schemes (like Basic), you may need to enable the `ShibCompatValidUser` option, documented below.

Half of Shibboleth runs within the web server. For Apache, this half is implemented in a module called `mod_shib_13.so`, `mod_shib_20.so`, `mod_shib_22.so`, or `mod_shib_24.so` depending on the Apache version. Like all Apache modules, the initial configuration is controlled with Apache's configuration file(s), but one of the primary options there (normally implicit/defaulted) is to point the module at the overall SP configuration file (`shibboleth2.xml`) where a lot of the options not specific to Apache are controlled.

At runtime, the module has the ability to process both a variety of Apache commands and rules specified in the SP configuration and make sense of both. This allows for a choice of approaches based on the need for native integration with Apache or for portability between web servers. Native integration using Apache commands is the better choice and is more secure.

- Prepping Apache
- Loading the Module
- Properly Routing Handler URLs
- Global Options
- Server / VirtualHost Options
- AuthConfig Options
- Enabling the Module for Authentication
- Authorization
- Content Settings
Please select an identity provider to login

Choose an identity provider from the options in the box below

The first time that you log in, you should pick from the list or enter an or organization name. Your previous choice(s) will differnt provider from this list.

Use a suggested selection:
- Syracuse University
- ORCID Id
- Max-Planck-Gesellschaft

Or enter your organization's name

Allow me to pick from a list

Which provider should I choose?

- LSC/Virgo collaboration members should select one of the LIGO providers and log in with their LIGO.ORG creden is available at my.ligo.org.
- Syracuse University Gravitational Wave Group members who are not part of the LSC can log in with their NetID. Y myslice.syr.edu
- Other scientists can log in with an ORCID Id, which can be obtained from orcid.id.
Using a .htaccess file to control access

You can override the default access settings to any sub-directory in your `~/secure_html` directory by creating a file in that directory called `.htaccess` and adding authorization directives in there.

Setting up Shibboleth

The first two lines of this file should be the directives that turn on Shibboleth authentication and authorization:

```
AuthType shibboleth
ShibRequestSetting requireSession true
```

Then you can add lines to give access to specific people. These are implemented as a logical OR so you can specify multiple people on multiple lines.

Syracuse users

For Syracuse users, you can authorize people using their `eduPersonPrincipalName`, which is their Syracuse NetID. For example, the following lines authorize people in our group:

```
require shib-attr eduPersonPrincipalName dabrown@syr.edu
require shib-attr eduPersonPrincipalName sde101@syr.edu
require shib-attr eduPersonPrincipalName sdreyes@syr.edu
require shib-attr eduPersonPrincipalName dfinstad@syr.edu
require shib-attr eduPersonPrincipalName elawsonk@syr.edu
require shib-attr eduPersonPrincipalName chafele@syr.edu
require shib-attr eduPersonPrincipalName cmbiwer@syr.edu
```

LIGO/Virgo users

LIGO users can be authorized using their LIGO.ORG username as the `eduPersonPrincipalName`, for example:
But...

Only 94 of 530 IdPs in InCommon support research and scholarship internationally (many don't support R&S at all!)
• Open data, open code, and open analysis allow new, reproducible science

• The community should push for more openness in gravitational-wave astronomy to get the best science for everyone and for the long-term health of the field

• Federated identity management tools can make collaboration much easier