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

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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

$$h \sim \frac{G}{c^4}\frac{E_{\rm NS}}{r} \sim 10^{-21}$$

However, the energy radiated is enormous

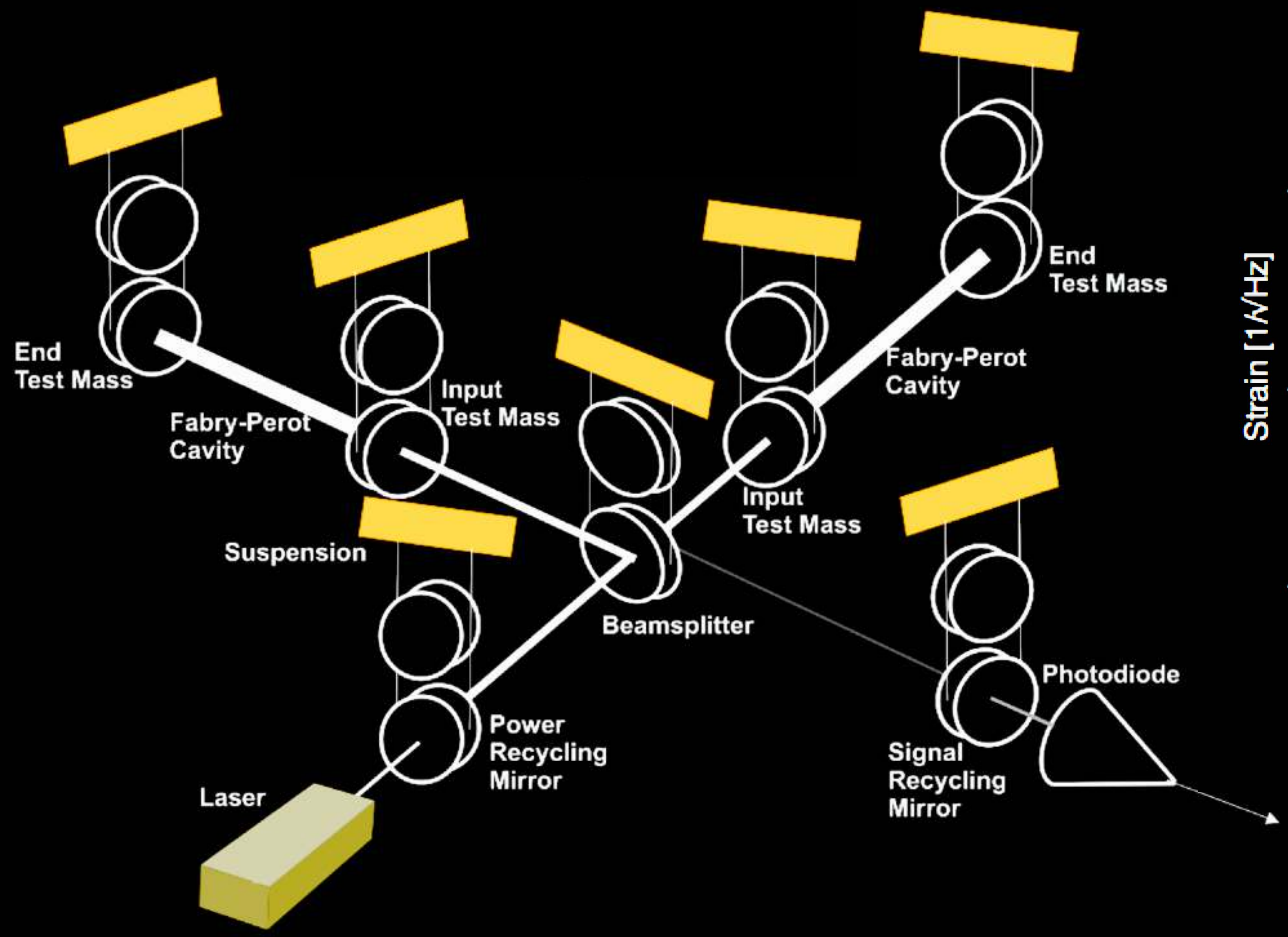
$$L_{\rm GW} \sim \left(\frac{c^5}{G}\right)\left(\frac{v}{c}\right)^6\left(\frac{R_{\rm S}}{r}\right)^2 \sim 10^{59}{\rm erg/s}$$

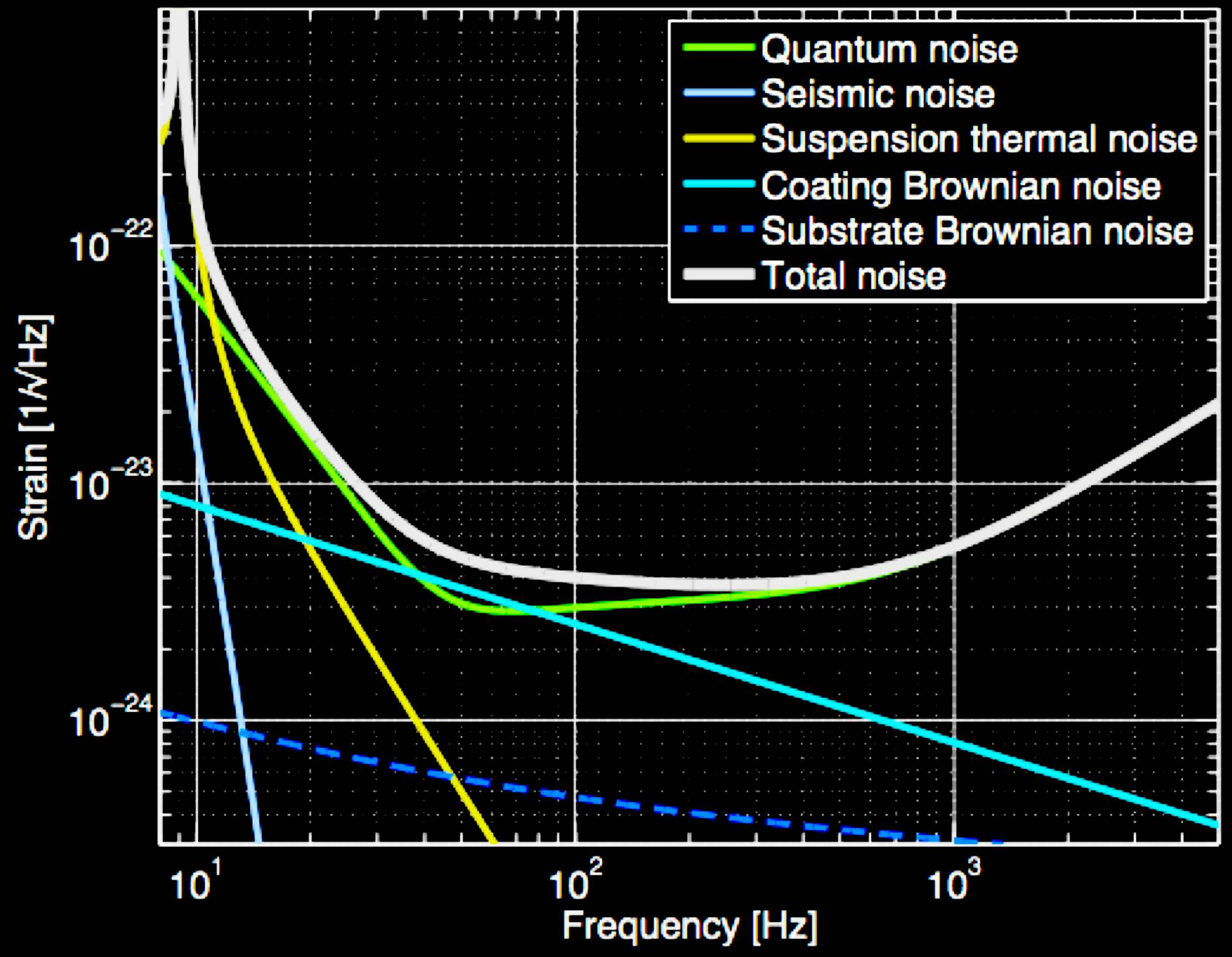
Solar luminosity L ~ 10^{33} erg/s

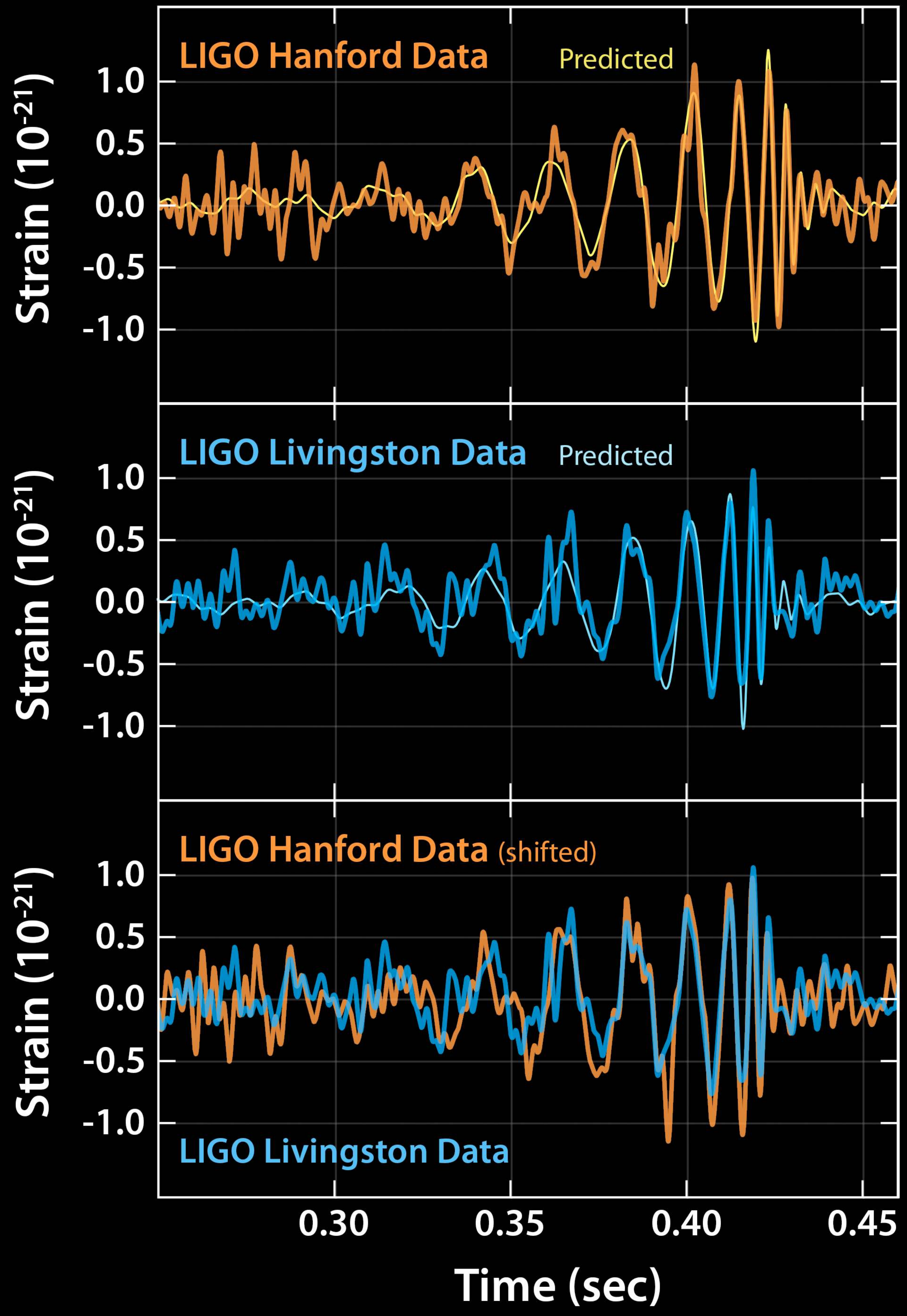
Gamma Ray Bursts L ~ 10^{49-52} erg/s


Proxima Centauri
250,000,000,000,000 miles
(4.2 light years)
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

Abbott, ..., DAB, et al. PRL **116** 061102 (2016)

- Use this to measure the "chirp mass"

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

- From this we can bound the total mass $M = m_1 + m_2 \gtrsim 70 M_\odot$
- 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

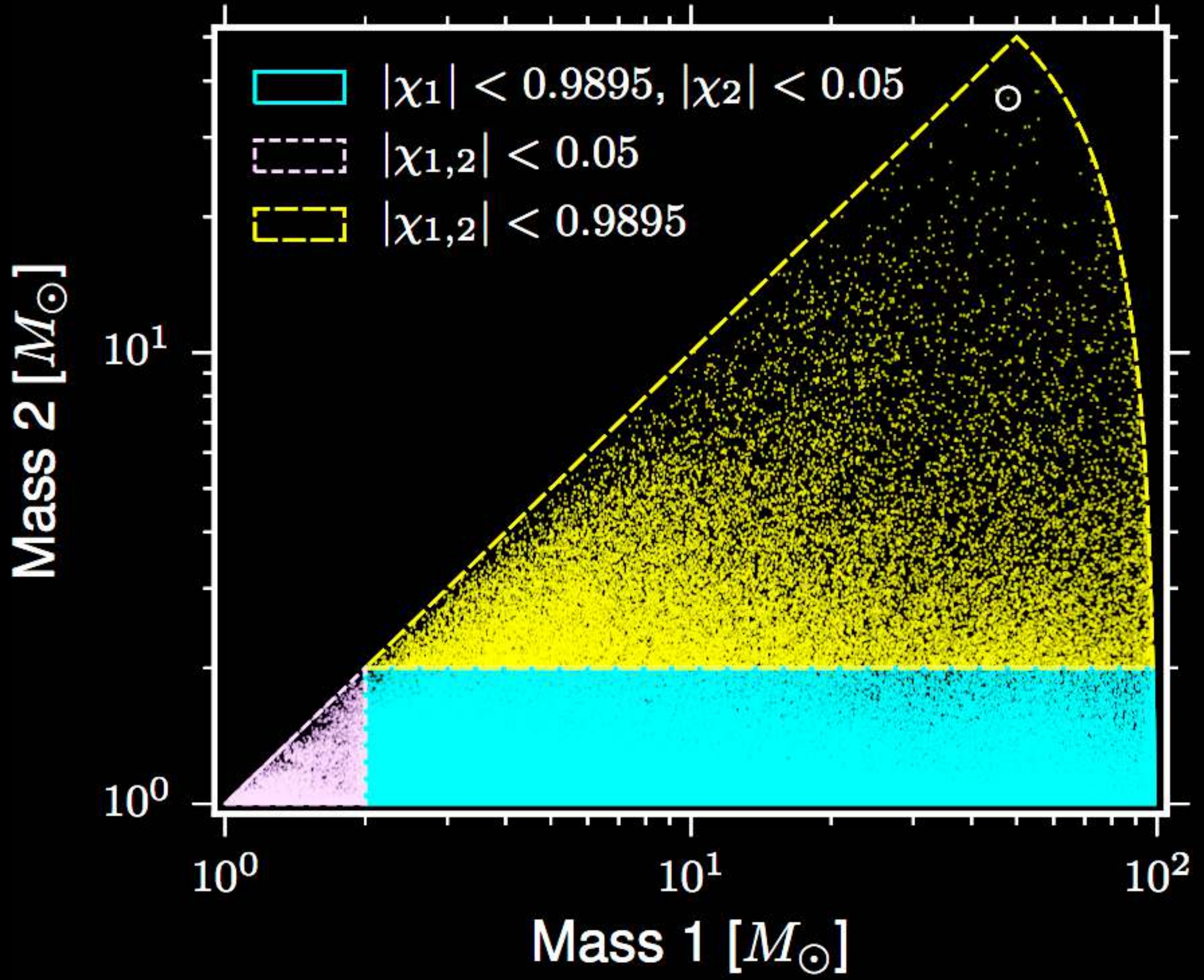
Abbott, ..., DAB, et al. Annalen der Physik, **529,**1600209 (2017)

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

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

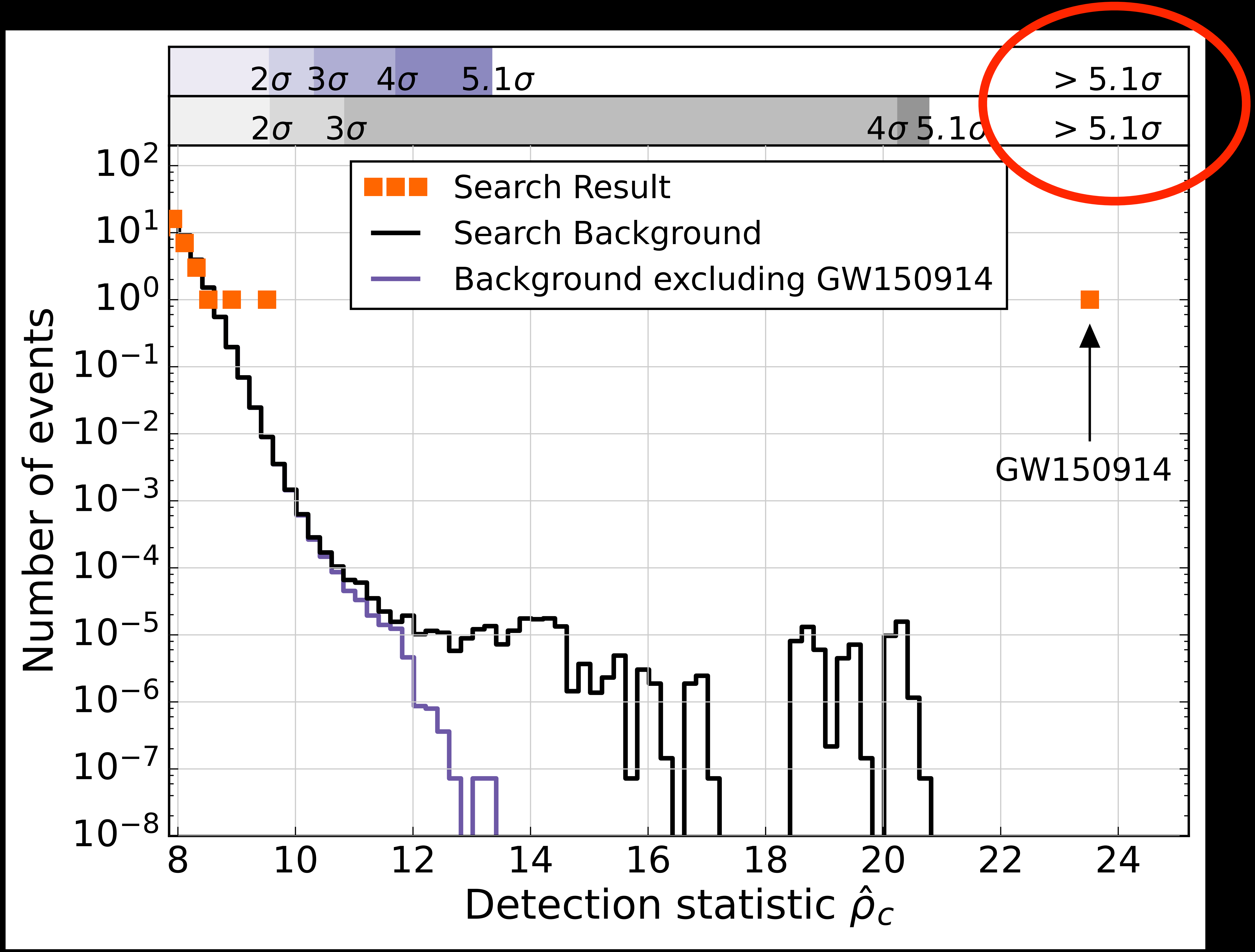
$$\langle a|b\rangle = 4\mathrm{Re}\int_{f_{\mathrm{low}}}^{f_{\mathrm{high}}} \frac{\tilde{a}(f)\tilde{b}(f)}{S_n(f)}\, df$$

Apply additional waveform-consistency tests to separate signal from noise



Allen,... , DAB, et al. Phys Rev D 85 122006 (2012)
Babak,..., DAB, et al. Phys Rev D 87 024033 (2013)
Usman,... DAB, et al. arXiv:1508.02357
Capano, et al. arXiv:1602.03509
Abbott, ..., DAB, et al. arXiv:1602.03839
DAB, et al., Phys. Rev. D 86 084017 (2012)

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

Abbott, ..., DAB, et al. Phys. Rev. D **93**, 122003 (2016)

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...

TITLE: GCN CIRCULAR
NUMBER: 21509
SUBJECT: LIGO/Virgo G298048: Identification of a binary neutron star candidate coincident with Fermi GBM trigger 524666471/170817529
DATE: 17/08/17 14:09:25 GMT
FROM: Reed Clasey Essick at MIT <ressick@mit.edu>

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.

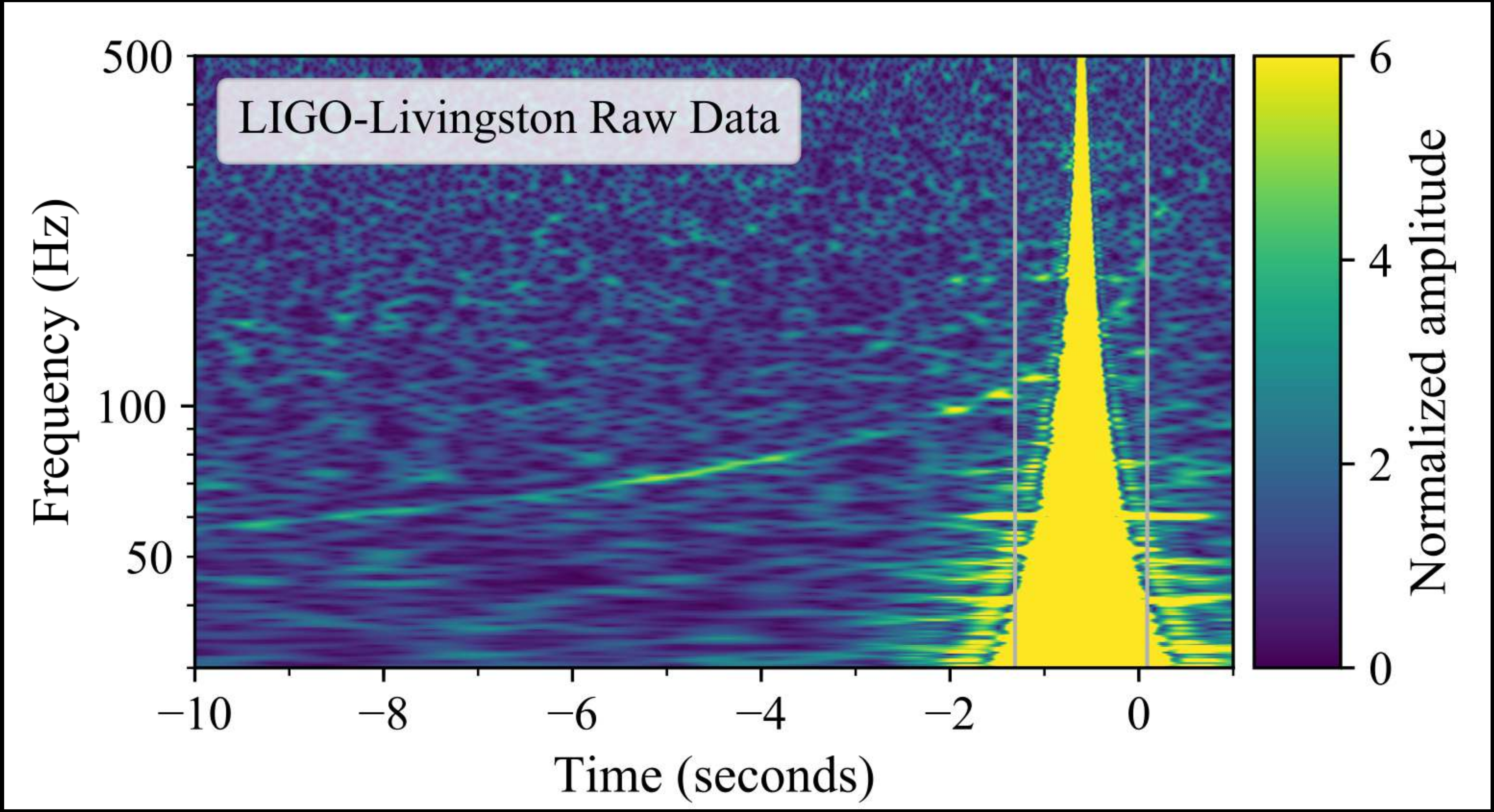
The neutron star coalescence candidate is also clearly visible in data from the LIGO Livingston detector, although there is a coincident noise artifact in the L1 data. To be clear, the binary neutron star candidate is clearly visible in the L1 data on top of the noise artifact. There is no evidence for 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

https://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/triggers/2017/bn170817529/quicklook/glg_locplot_all_bn170817529.png
https://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/triggers/2017/bn170817529/quicklook/glg_locprob_all_bn170817529.fit

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 OPS NOTE(17aug17): Per author's request, the LIGO/VIRGO ID
was added to the beginning of the Subject-line.]



Usman,... DAB, et al. Class. Quant. Grav.**33** 215004 (2016)

Abbott,..., DAB et al. PRL **119** 161101 (2017)

Nitz, Dent, Dal Canton, Fairhurst, DAB. Astrophys. J. **849** 118 (2017)

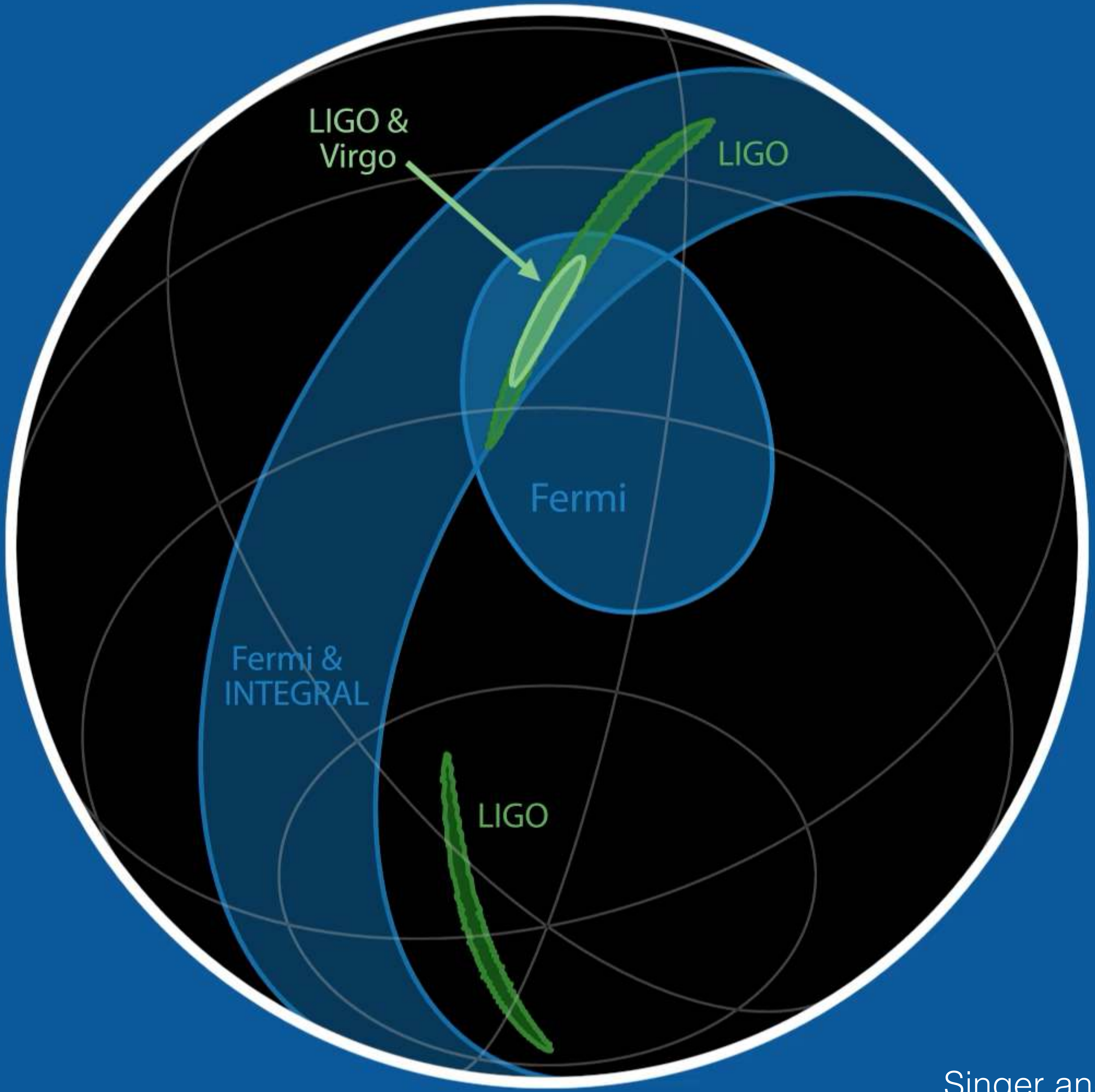
GCN 21513 at 1:54 pm EDT with localization...

TITLE: GCN CIRCULAR
NUMBER: 21513
SUBJECT: LIGO/Virgo G298048: Further analysis of a binary neutron star candidate
DATE: 17/08/17 17:54:51 GMT
FROM: Leo Singer at NASA/GSFC <leo.p.singer@nasa.gov>

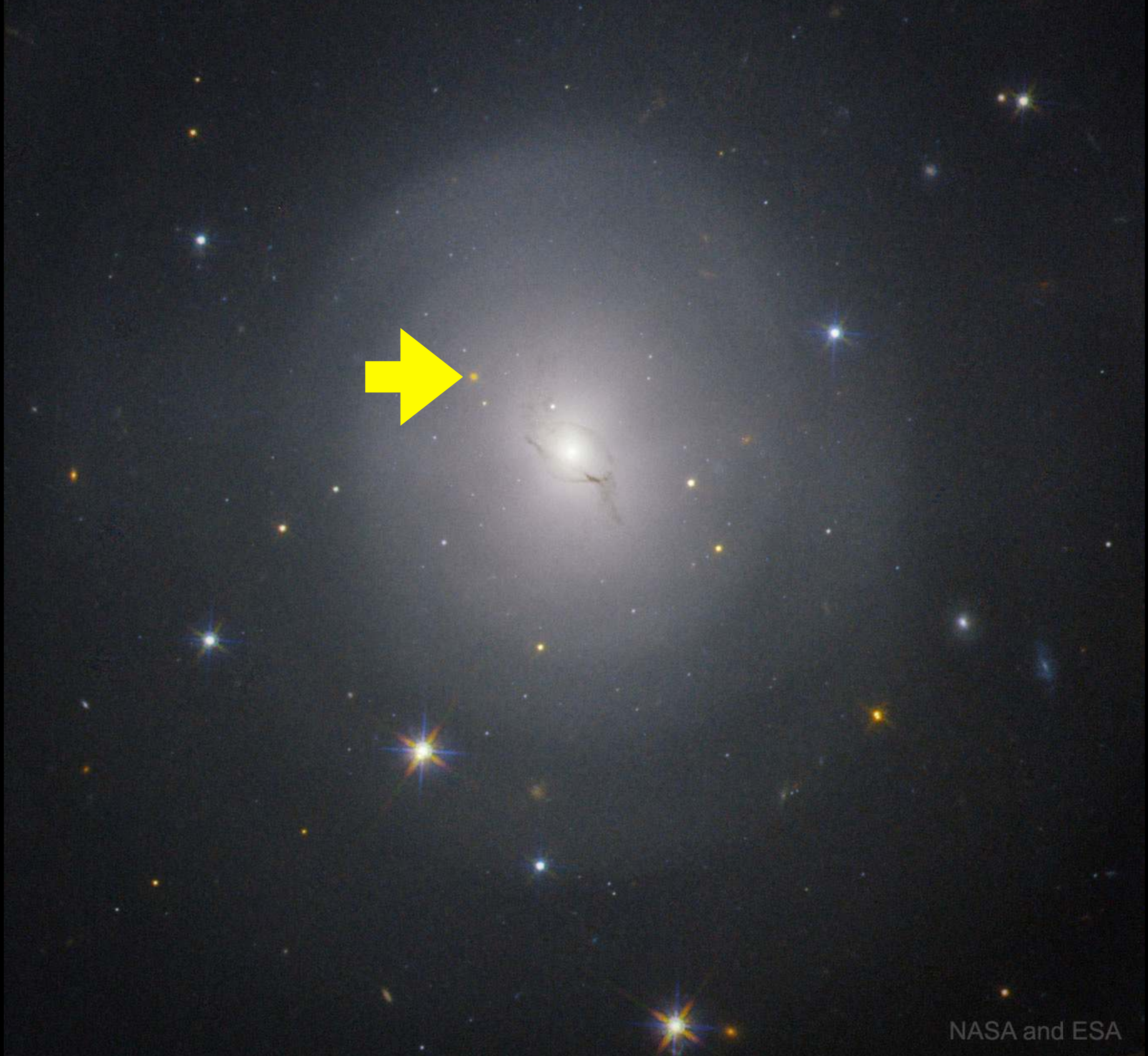
The LIGO Scientific Collaboration and the Virgo Collaboration report:

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.



Singer and Price PRD **93**, 024013 (2016)

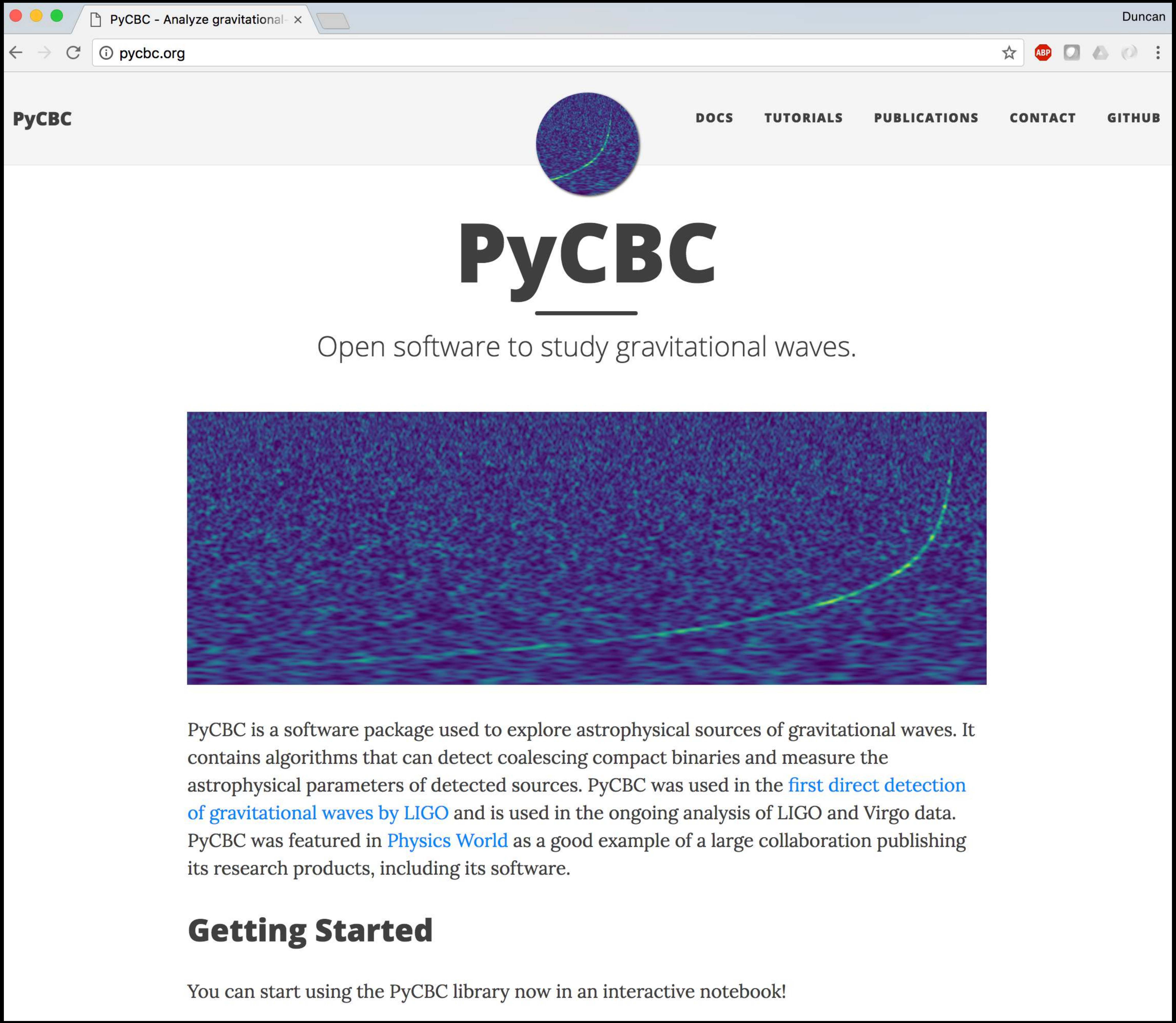

NASA and ESA

- https://pycbc.org

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



Chris Biwer

Collin Capano

Soumi De

Alex Nitz

Miriam Cabero

Daniel Finstad

Tito Dal Canton

Ian Harry

- I joined the LIGO Scientific Collaboration in 1999
- First LIGO paper:

  Abbott,…, DAB,…, Zweizig, “Analysis of LIGO data for gravitational waves from binary neutron stars” Phys. Rev. **D69** 122001 (2004)
- Author 38 out of **368** co-authors
- Cited by **145** since 2004

- Last LIGO paper:

  Abbott,…, DAB,…, Zweizig, “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral” Phys. Rev. Lett. **119**, 161101 (2017)

- 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

UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC Created
S190602aq	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51 UTC
S190524q	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30 UTC
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
S190519bj	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04 UTC
S190518bb	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242242376.474609	1242242377.474609	1242242380.922655	1.004e-08	2019-05-18 19:19:39 UTC
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S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
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S190405ar	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

- *"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:

CernVM FS

O2 Data Release

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

4KHz Data | 16KHz Data | Documents | Timeline

O1 Data Release

O1 Time Range: September 12, 2015 through January 19, 2016
Detectors: H1 and L1

4KHz Data | 16KHz Data | Documents | Timeline

- 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)

```
Duncans-MacBook-2:~ root# df
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 7538514127263836%   /Volumes/GoogleDrive
cvmfs2        33554432000 2505007344 31049424656       8%         32          0  100%   /cvmfs/config-osg.opensciencegrid.org
cvmfs2         8388608000 6215123376  2173484624      75%     118085          0  100%   /cvmfs/gwosc.osgstorage.org
cvmfs2        33554432000 2505007344 31049424656       8%      81964   11615465    1%   /cvmfs/oasis.opensciencegrid.org
cvmfs2        33554432000 2505007344 31049424656       8%       2722  232938041    0%   /cvmfs/singularity.opensciencegrid.org
```

1125122048 — -bash — 80×24

```
[dbrown@Duncans-MacBook-2 1125122048]$ pwd
/cvmfs/gwosc.osgstorage.org/gwdata/O1/strain.16k/frame.v1/H1/1125122048
[dbrown@Duncans-MacBook-2 1125122048]$ ls
H-H1_LOSC_16_V1-1126072320-4096.gwf     H-H1_LOSC_16_V1-1126113280-4096.gwf
H-H1_LOSC_16_V1-1126076416-4096.gwf     H-H1_LOSC_16_V1-1126117376-4096.gwf
H-H1_LOSC_16_V1-1126080512-4096.gwf     H-H1_LOSC_16_V1-1126121472-4096.gwf
H-H1_LOSC_16_V1-1126084608-4096.gwf     H-H1_LOSC_16_V1-1126125568-4096.gwf
H-H1_LOSC_16_V1-1126088704-4096.gwf     H-H1_LOSC_16_V1-1126137856-4096.gwf
H-H1_LOSC_16_V1-1126092800-4096.gwf     H-H1_LOSC_16_V1-1126146048-4096.gwf
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H-H1_LOSC_16_V1-1126100992-4096.gwf     H-H1_LOSC_16_V1-1126154240-4096.gwf
H-H1_LOSC_16_V1-1126105088-4096.gwf     H-H1_LOSC_16_V1-1126158336-4096.gwf
H-H1_LOSC_16_V1-1126109184-4096.gwf     H-H1_LOSC_16_V1-1126162432-4096.gwf
[dbrown@Duncans-MacBook-2 1125122048]$
```
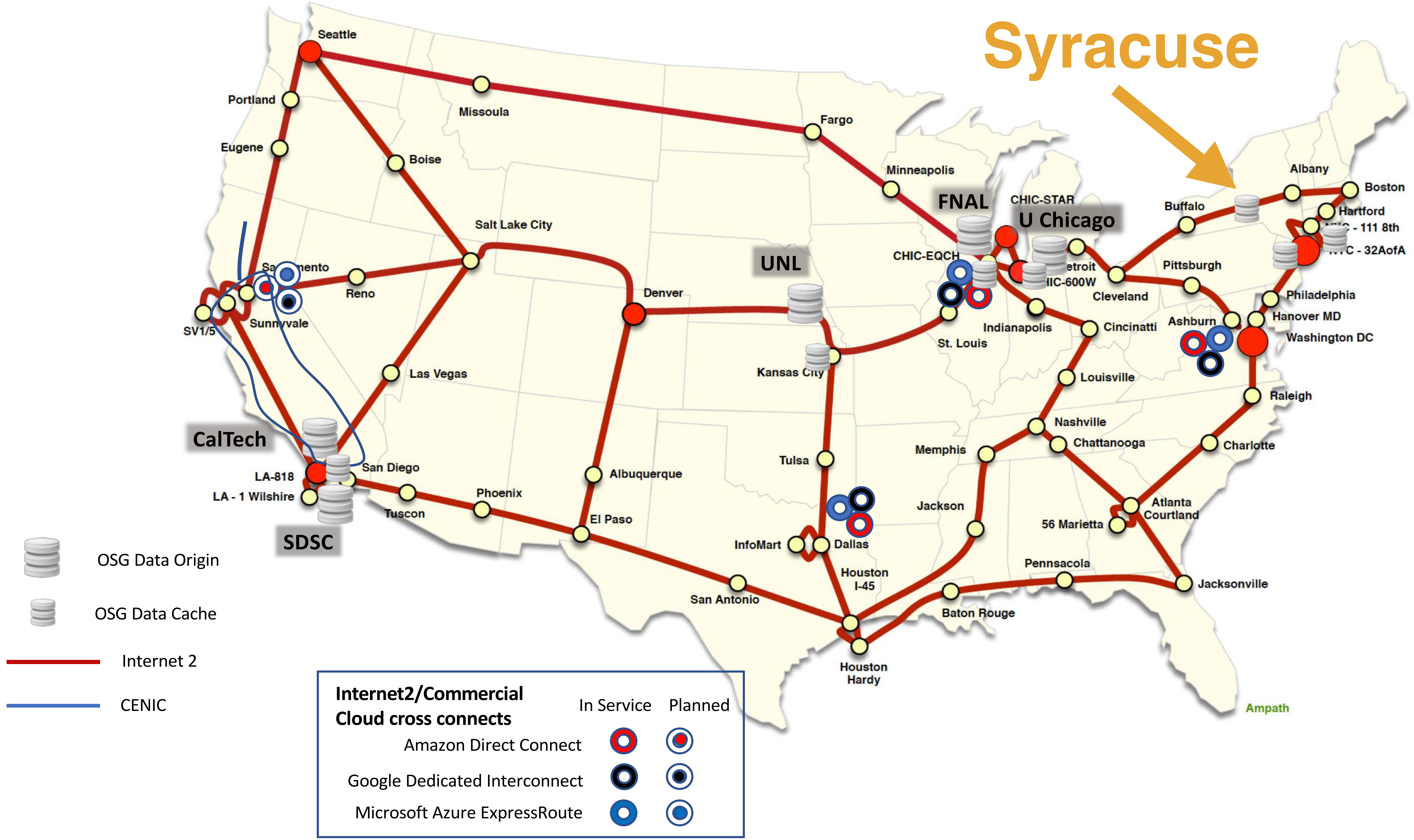
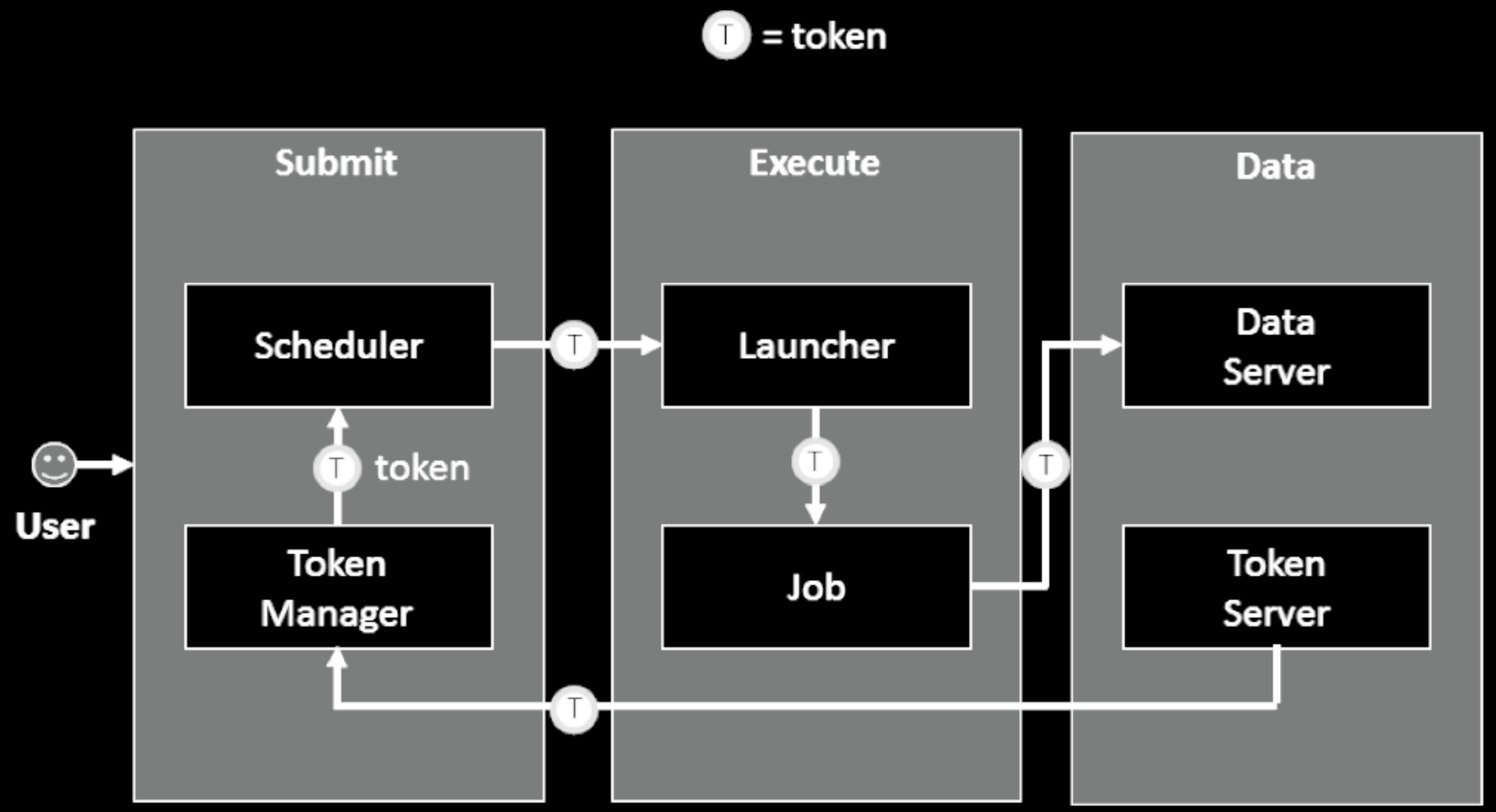


Syracuse
Seattle
Portland
Eugene
Missoula
Boise
Fargo
Minneapolis
Salt Lake City
Reno
Sunnyvale
SV1/5
Las Vegas
Denver
UNL
Kansas City
FNAL
CHIC-STAR
U Chicago
CHIC-EQCH
St. Louis
Indianapolis
Cleveland
Cincinatti
Pittsburgh
Buffalo
Albany
Boston
Hartford
Philadelphia
Hanover MD
Washington DC
Ashburn
Louisville
Raleigh
Nashville
Chattanooga
Charlotte
Memphis
Jackson
Atlanta Courtland
56 Marietta
Pennsacola
Jacksonville
Baton Rouge
Houston I-45
Houston Hardy
Dallas
InfoMart
Tulsa
San Antonio
El Paso
Albuquerque
Phoenix
Tuscon
San Diego
CalTech
LA-818
LA - 1 Wilshire
SDSC
Ampath
OSG Data Origin
OSG Data Cache
Internet 2
CENIC
Internet2/Commercial Cloud cross connects
In Service
Planned
Amazon Direct Connect
Google Dedicated Interconnect
Microsoft Azure ExpressRoute

scitokens.org

The SciTokens Model

Capability-based
authorization
for science



Withers, Bockelman, Weitzel, DAB, Gaynor, Basney, Tannenbaum, Miller PEARC '18 (2018) arXiv:1807.04728

Directory	Bytes
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/pnfs/fnal.gov/usr/des	744.692TB
/pnfs/fnal.gov/usr/minerva	502.826TB
/user/ligo	200.539TB
/user/bbockelm	184.699TB
/pnfs/fnal.gov/usr/dune	131.776TB
/pnfs/fnal.gov/usr/nova	34.639TB
/user/cwalter	18.966TB
/user/jeanjack	17.566TB

THE ASTROPHYSICAL JOURNAL

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

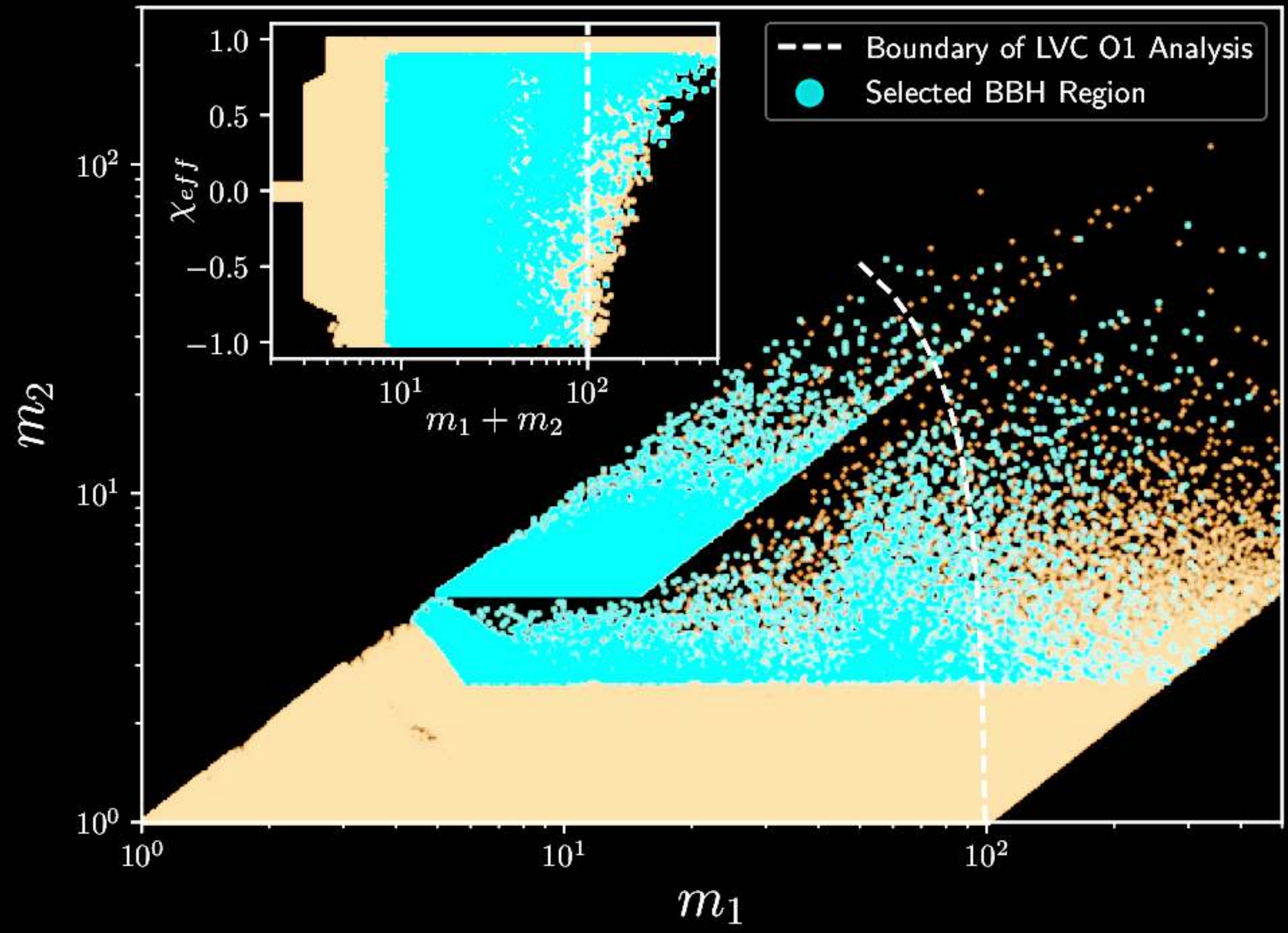
Alexander H. Nitz[1,2], Collin Capano[1,2], Alex B. Nielsen[1,2], Steven Reyes[3], Rebecca White[3,4], Duncan A. Brown[3], and Badri Krishnan[1,2]

Published 2019 February 25 •

The Astrophysical Journal, Volume 872, Number 2

Article PDF

Article ePub



Nitz, Capano, Nielsen, Reyes, White, DAB, Krishnan ApJ **872** 195 (2019)

README.md

Instructions for generating the 1-OGC catalog on the Open Science Grid

Alexander H. Nitz[1,2], Collin Capano[1,2], Alex B. Nielsen[1,2], Steven Reyes[3], Rebecca White[4,3], Duncan A. Brown[3], Badri Krishnan[1,2]

1. Albert-Einstein-Institut, Max-Planck-Institut for Gravitationsphysik, D-30167 Hannover, Germany
2. Leibniz Universitat 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

Accessing the Catalog: 1-OGC.hdf

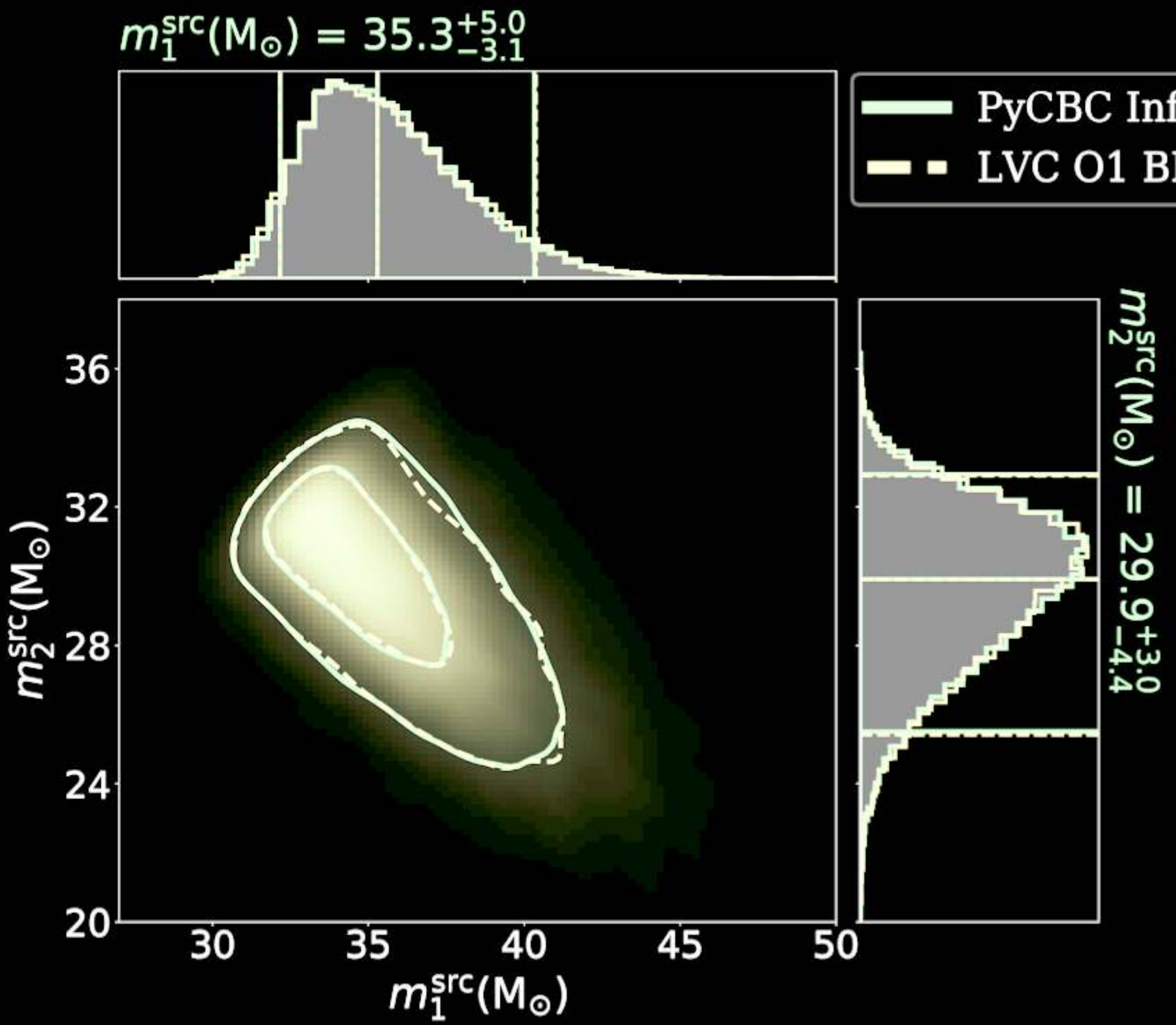
There are two datasets within the file, `/complete` and `/bbh`. The `complete` set is the full dataset from our analysis. The `bbh` set includes BBH candidates from a select portion of the analysis. See the 1-OGC paper for additional information.

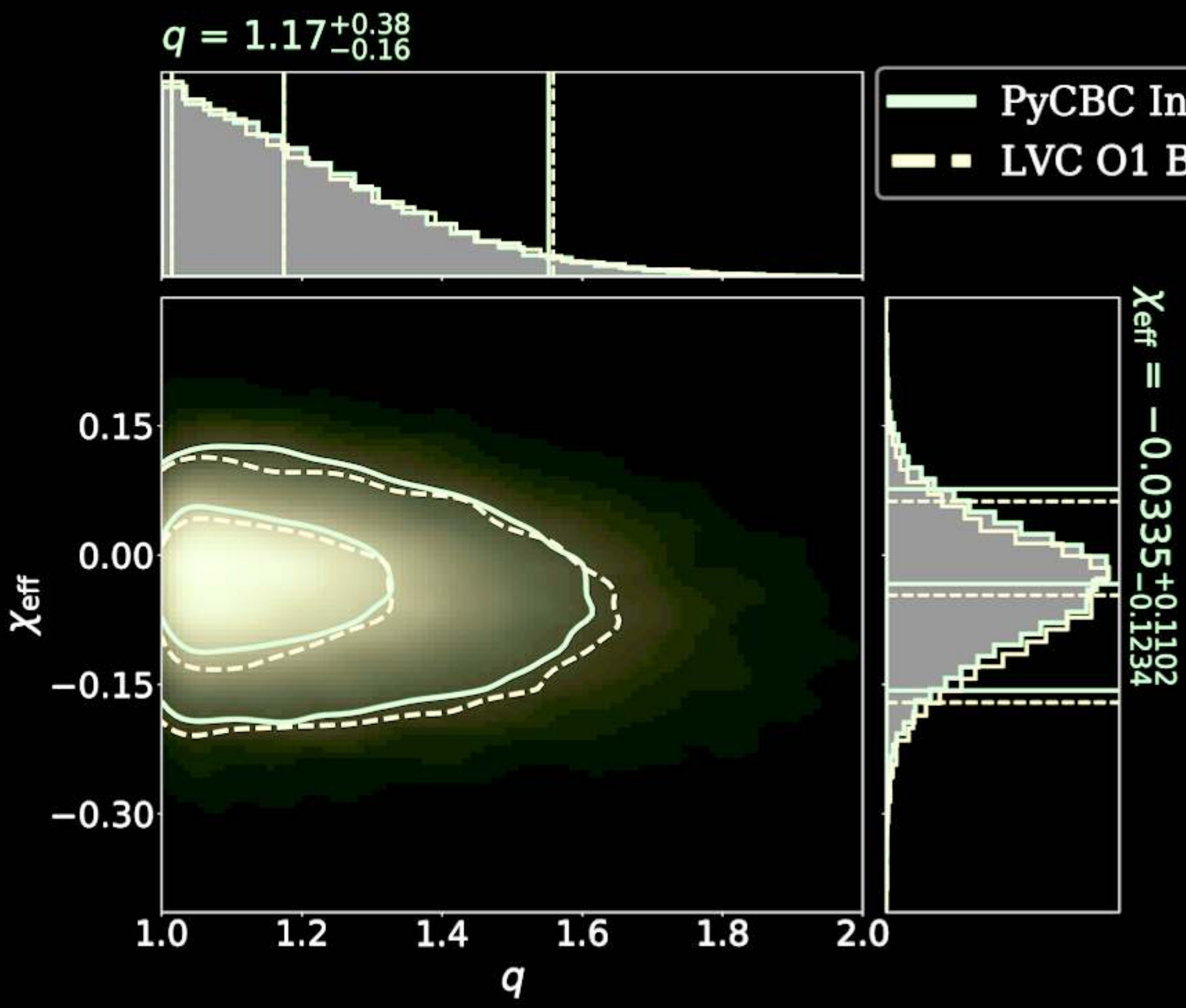
```
import h5py

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





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

De, Biwer, Capano, Nitz, DAB Nature Scientific Data **6**, 81 (2019)

$$p(\vec{\theta}|\vec{d}(t), H) = \frac{p(\vec{\theta}|H)\ p(\vec{d}(t)|\vec{\theta}, H)}{p(\vec{d}(t)|H)}$$

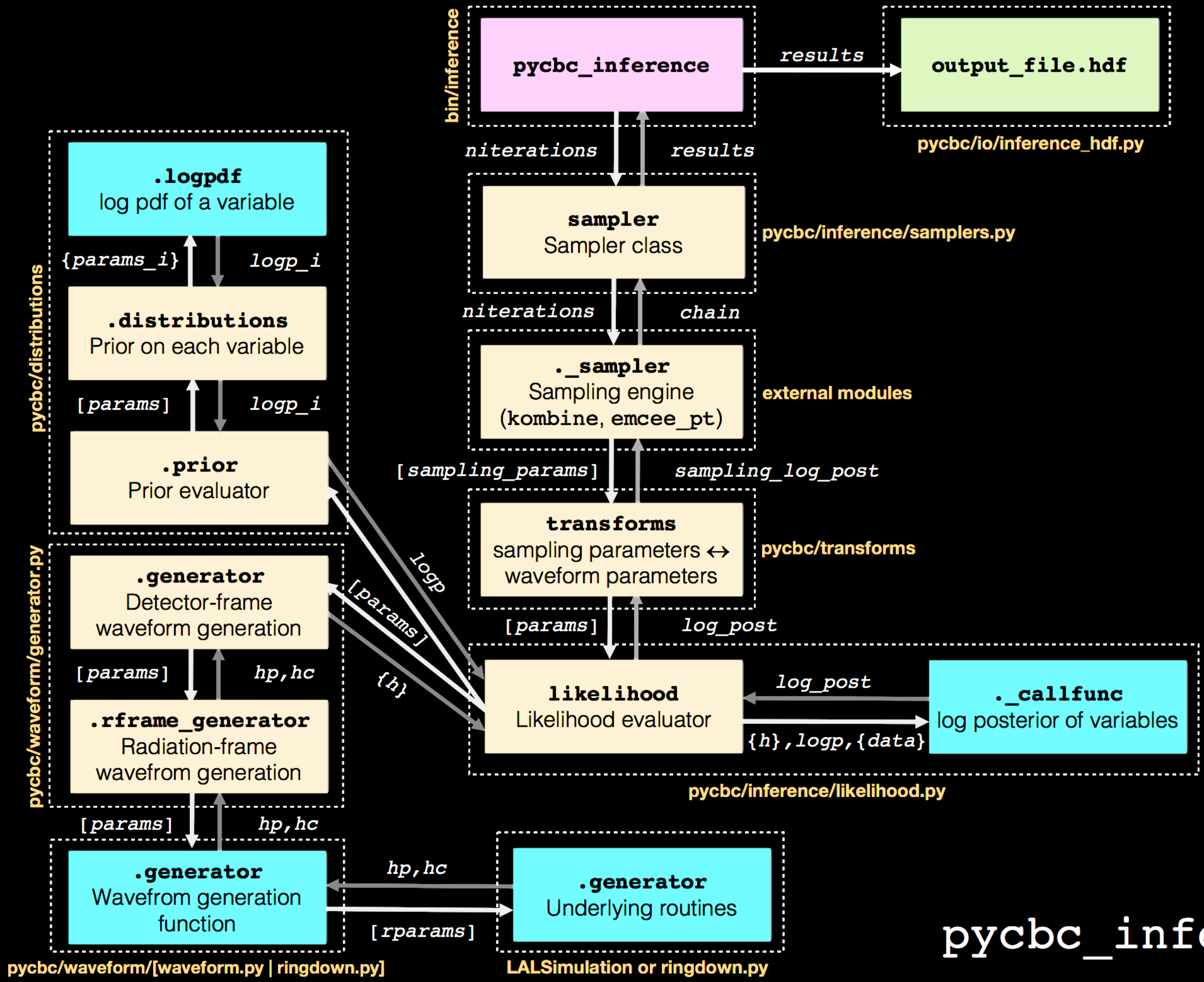
Need the data, $\vec{d}(t)$ from GWOSC ✓

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)



Key

(pink)	Executable
(beige)	Class
(cyan)	Function
(green)	File
(dashed box)	Module
niterations:	Number of samples to get
[sampling_params]:	List of sampling-frame parameter values to test
[params]:	List of parameter values to test
[rparams]:	Radiation-frame parameter values
{params_i}:	Dictionary of parameters for i-th prior
logp_i:	Log pdf of the i-th prior at {params_i}
logp:	Log pdf of the prior at [params]
hp,hc:	Plus and cross polarization of the model waveform at [rparams]
{h}:	Dictionary of the model waveform at [params] in each detector
{data}:	Dictionary of the data in each detector
log_post:	Log of the posterior probability at [params]
sampling_log_post:	Log of the posterior probability in the sampling-frame
chain:	Accepted parameters, in whatever form returned by the sampling engine.
results:	FieldArray of accepted [params] over niterations and their log_post values

pycbc_inference Call Graph

PyCBCInferenceWorkshopMay2019

Repository for the PyCBC Inference workshop in Portsmouth, UK, 14 May - 16 May 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

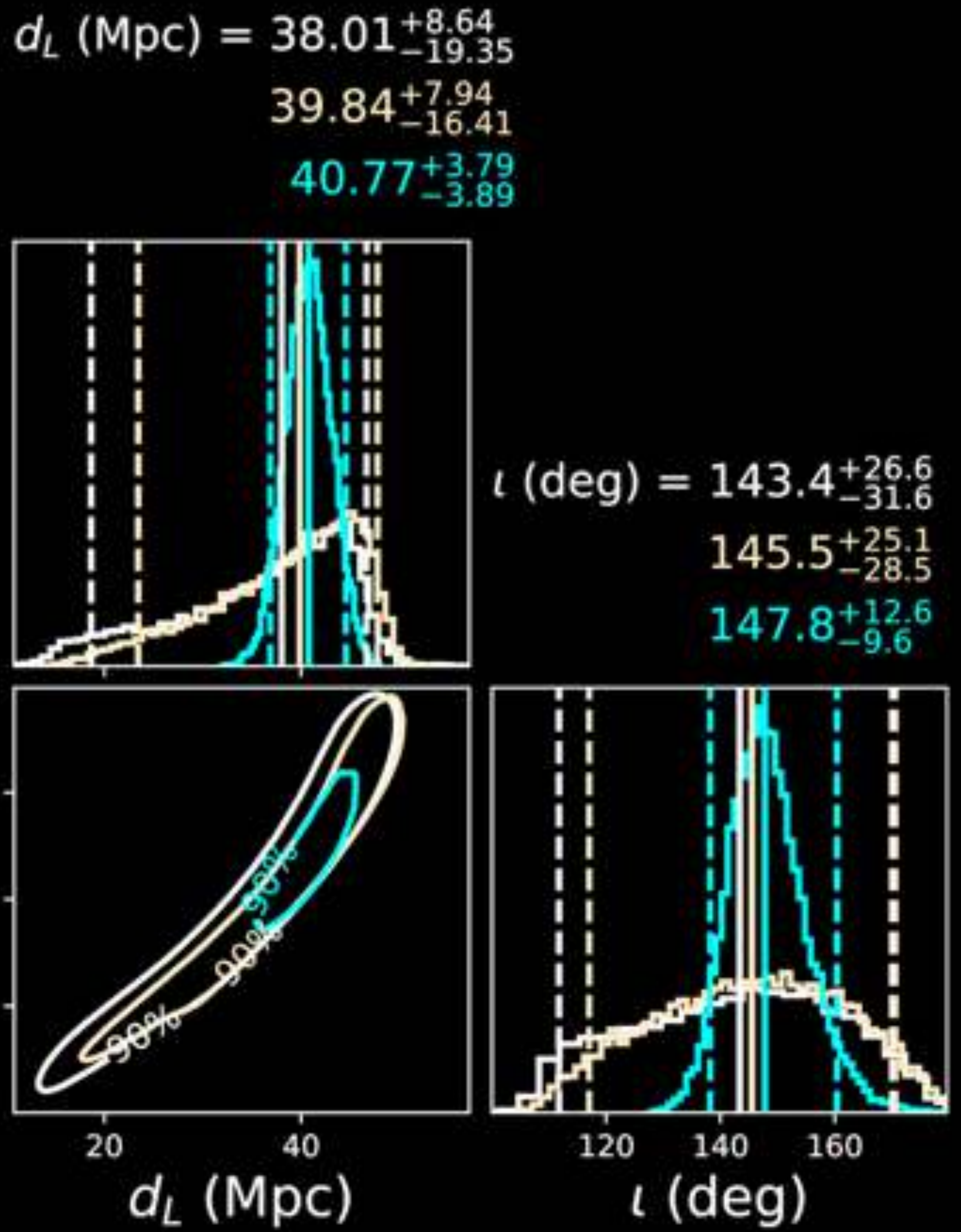
Using SciServer

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.
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:

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

   This will download a copy of this repository to your directory on SciServer.



Viewing angle is $32^{+10}_{-13} \pm 1.7$ deg

Lower limit of ≥ 13deg

robust to choice of prior

Daniel Finstad

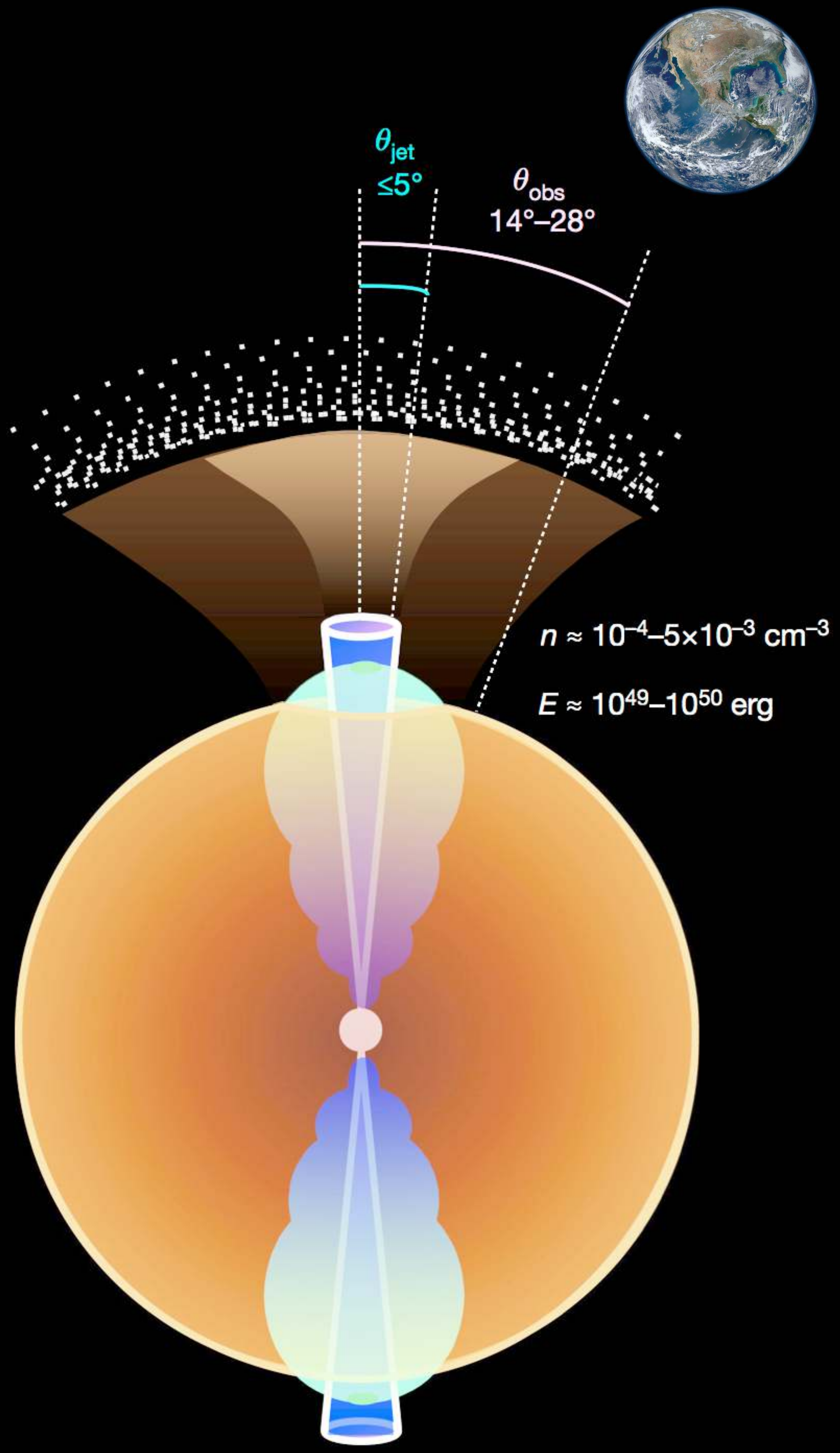
Finstad, De, DAB, Berger, Biwer ApJ **860** L2 (2018)

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)



Mooley et al. Nature **561**, 355 (2018)

Troja et al. arXiv:1808.06617

https://github.com/sugwg/gw170817-inclination-angle

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:

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']
```

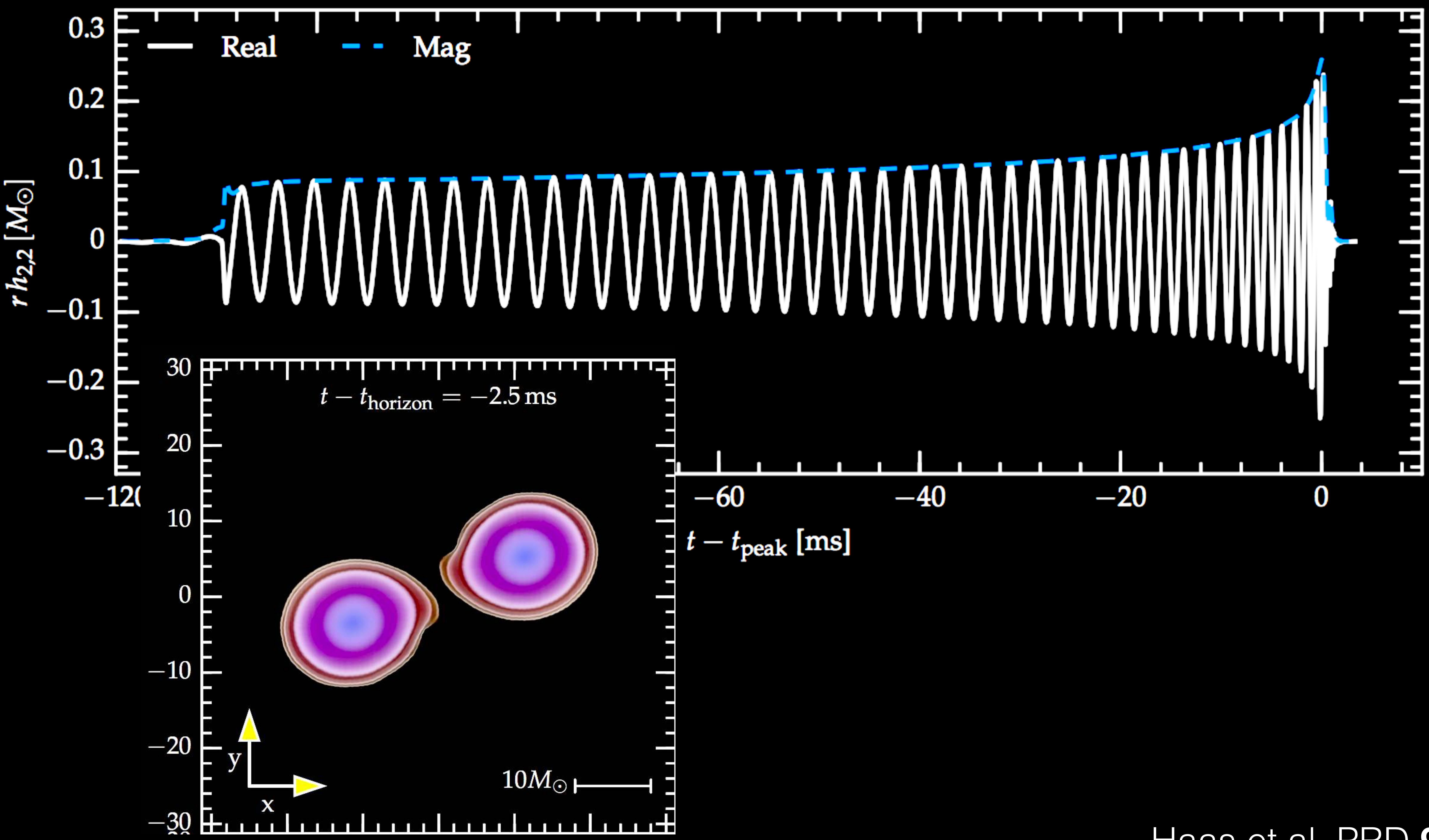
Each of these parameter names can then be used to access that parameter's data in the `samples` group of the file. For example, the inclination angle posterior samples (in radians) from our run using the GW signal as well as EM sky location and Gaussian distance prior can be accessed this way:

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

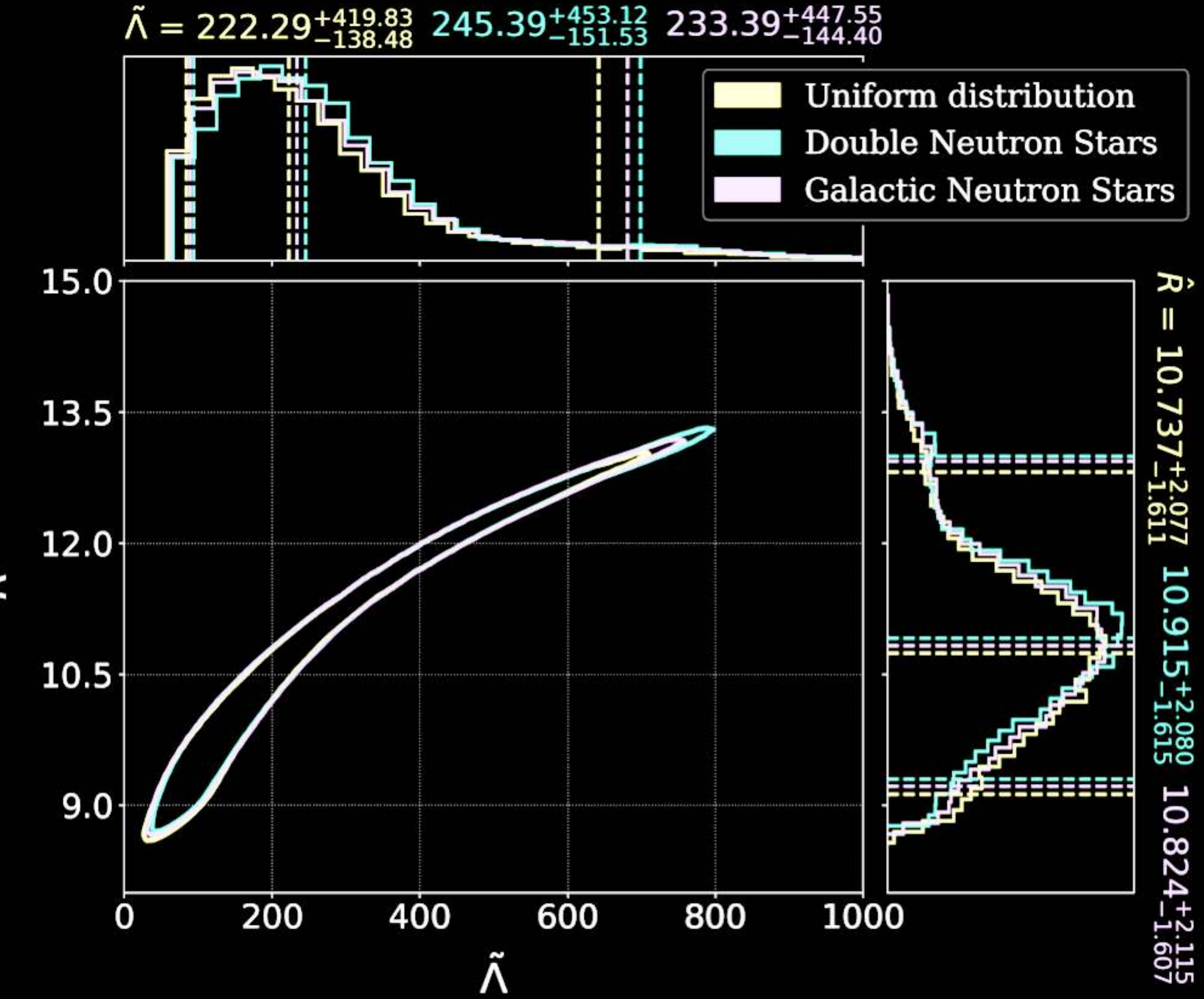
```
[2.74223087 2.58393159 2.49176962 ... 2.53901635 2.61125559 2.45446383]
```

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:

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)



$$\langle \hat{R} \rangle = 10.8 \text{ km}$$

$$8.9 \leq \hat{R} \leq 13.2 \text{ km}$$

Soumi De

De, Finstad, Lattimer, DAB, Berger, Biwer, Phys. Rev. Lett. **121**, 091102 (2018)

Syracuse University | Research Computing

Crush Cloud: A Medium-Scale Virtualized Research Cloud

GRID

Scavenged HTC Resources from Campus Desktop Computing.

(Not just undergrad labs!)

Virtualization and containerization makes both ITS and researcher happy.

Singularity

CernVM File system

ubuntu

Microsoft Hyper-V

CVMC

Microsoft Active Directory

Windows 10

PyCBC

Free and open software to study gravitational waves.

GitHub

Singularity

CernVM File system

ubuntu

Microsoft Hyper-V

CVMC

Microsoft Active Directory

Windows 10

GRID

CernVM File system

dbrown — dabrown@comet-ln3:~ — ssh -l dabrown login.xsede.org — 117×24

```
[dabrown@comet-ln3 ~]$ module load singularity
[dabrown@comet-ln3 ~]$ 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
```

duncan-brown / pycbc-inference-comet

Unwatch | Star 1 | Fork

<> Code | Issues 0 | Pull requests 0 | Projects 0 | Wiki | More | Settings

Files for running PyCBC Inference on SDSC Comet

Edit

Manage topics

3 commits | 1 branch | 0 releases | 1 contributor

Branch: master | Create new file | Find File | Clone or download | Gitpod

duncan-brown Create README.md — Latest commit bd46995 5 days ago

Dockerfile	initial entry	6 days ago
README.md	Create README.md	5 days ago
astropy.tar.gz	initial entry	6 days ago
inference_chi_0.4.ini	initial entry	6 days ago
mpi-demo-sub.sh	initial entry	6 days ago
mpi-demo-wrapper.sh	initial entry	6 days ago
mpi-demo.py	initial entry	6 days ago
pycbc-inference-sub.sh	initial entry	6 days ago
pycbc-inference-wrapper.sh	initial entry	6 days ago

PHYSICAL REVIEW LETTERS

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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

Phys. Rev. Lett. **121**, 091102 – Published 29 August 2018; Erratum Phys. Rev. Lett. **121**, 259902 (2018)

Syracuse University

VE RI TAS HARVARD

Stony Brook University

https://incommon.org/federation/info/all-entity-categories.html#IdPs

InCommon FEDERATION

BETA

Federation Info: About Organizations Entities

InCommon Entity Categories

Entity Category	# of SPs	# of IdPs
hide-from-discovery	0	30
research-and-scholarship	109	105
research-and-scholarship	0	78

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*.

IdPs SPs

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

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

https://wiki.shibboleth.net/confluence/display/SP3/Apache

Apache

Created by Rod Widdowson, last modified by Scott Cantor on Oct 16, 2018

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.

Syracuse University Gravitatior ×

https://sugwg-jobs.phy.syr.edu/shibboleth-ds/index.html?entityID=https%3A%2F%2Fsugwg-job...

NYTimes Wash Post ADS GitHub Overleaf LIGO GCN LHO LLO Pegasus Bo

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 l different provider from this list.

Use a suggested selection:

Syracuse University

ORCID Id

MAX-PLANCK-GESELLSCHAFT

Max-Planck Institutes (in MetaDir...

Or enter your organization's name

Continue

Allow me to pick from a list

Help

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 specifiy 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 chafle@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

HTCondor
High Throughput Computing

CernVM
File system

globus

Open Science Grid

INTERNET2®

Pegasus

INTERNET2®

eduGAIN

Shibboleth®

Grouper™

InCommon®

COmanage ™

CILogon

MOO

spherical cow
group

Friday, 04 March, 2011 01:13:57

PyCBC Development History