Data-related issues in gravitational wave astronomy

Eric Chassande-Mottin
CNRS AstroParticule et Cosmologie
Paris, France

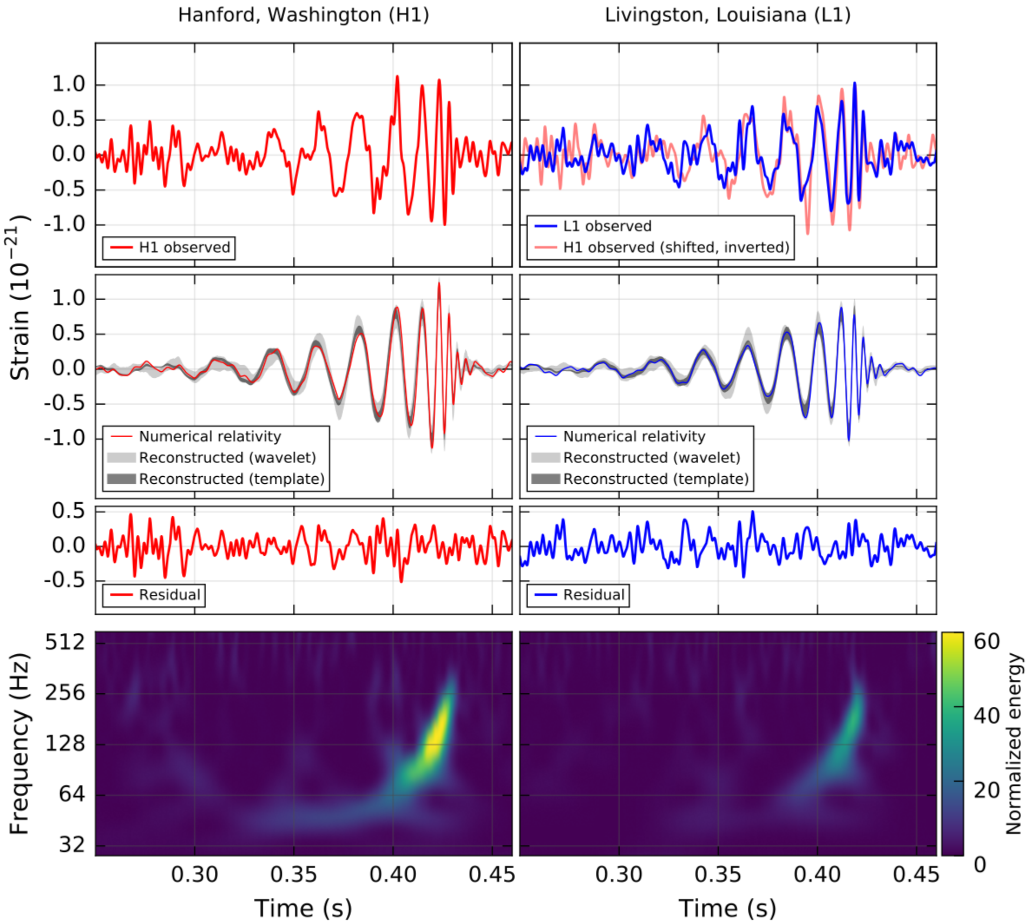
Coalescence of two black holes (credits: SXS)

Outline

- Context – **direct detection of gravitational waves**
- Description of **GW data products**
- **Highlights and lessons learned** from recent workshop in Strasbourg
  - VO and multimessenger astronomy
  - Vision for the next future – open data

Sep 14, 2015 09:50:45 UTC

GW signal received by the LIGO detectors

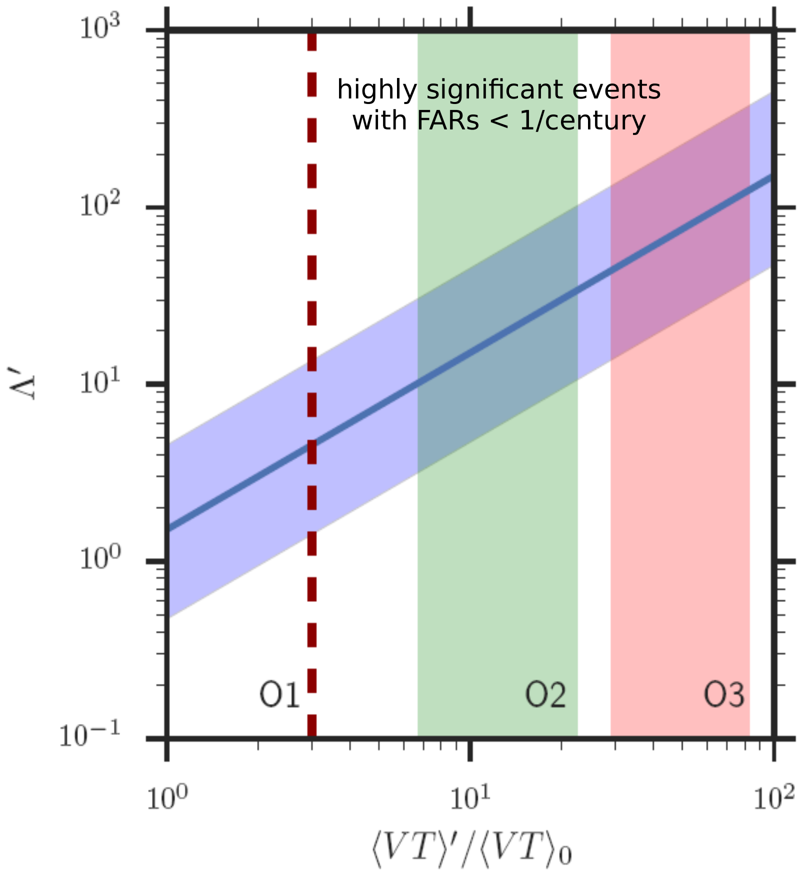


- First **direct detection of gravitational waves**
- First **observation of massive (> 20 M_{sun}) stellar-mass black hole**
- First **observation of a black hole binary**
- **Most luminous** event ever detected

Today 19:15 CET: press conference announced

Webcast: `https://aas.org/aas-briefing-webcast`

This is a landmark discovery



- This is just the **beginning**...
  - Expect **tens or more of binary black-hole mergers** in future runs
  - Other types of sources? e.g., neutron stars
  - Breath of science (physics and abundance of compact objects and consequences on star formation, tests of GR, cosmology?)
- **New era of gravitational wave astronomy**
  - Connection to conventional/photon-based astronomy

    EM counterpart to GW is the next “big thing”
  - Real-time alerts, open data

Data products and management

- **Observation science data**
  - **Time series** for calibrated *h(t)* + data quality
  - Month/year data stretches (with breaks) at 4 kHz

    [few 100 GB – This is a small subset of full raw data – many TB]
  - Closed model with **proprietary period** (typ. few years)
  - LIGO: data “snippet” released together with publication
- Processed data
  - **Alerts/events**
    - GW event descriptor (VOevent) and skymap [small volume]
    - Distributed to MOU partners over a private GCN-type network
    - Policy: release public alerts after 4 published events (O3 ?)
  - Other scientific by-products
    - Posterior samples from Bayesian parameter estimations

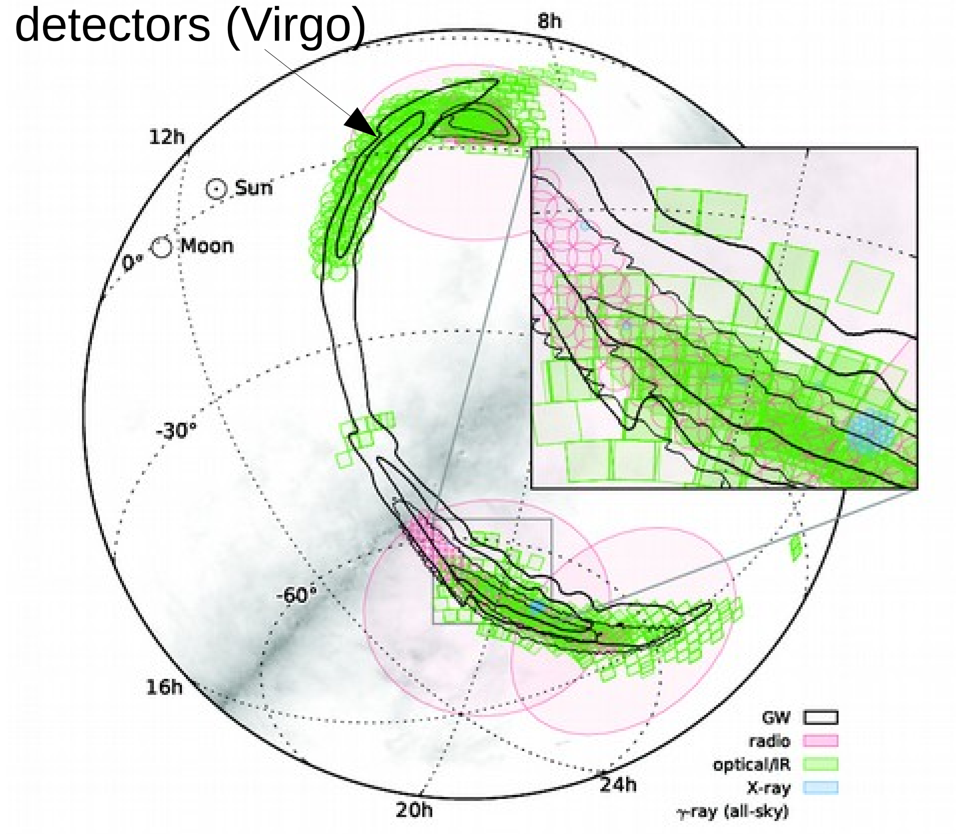
Workshop in Strasbourg
May 31-Jun 1st 2016

- ~20 participants (~10 from GW, 5 countries – also robotic wide-field optical telescope)
- **Discussion topics / Presentations**
  - Intro on VO/tutorial on VO tools
  - Electromagnetic follow-up
    - Alerts and VOevent
    - GW skymap visualization and processing
    - Galaxy catalogs – follow-up prioritization
    - Time-domain observations with robotic telescopes
  - Open science data
- Summary available in last WP4 activity report

https://www.asterics2020.eu/dokuwiki/doku.php?id=open:wp4:wp4gwstrasbourg2016

GW alerts and skymaps (1)

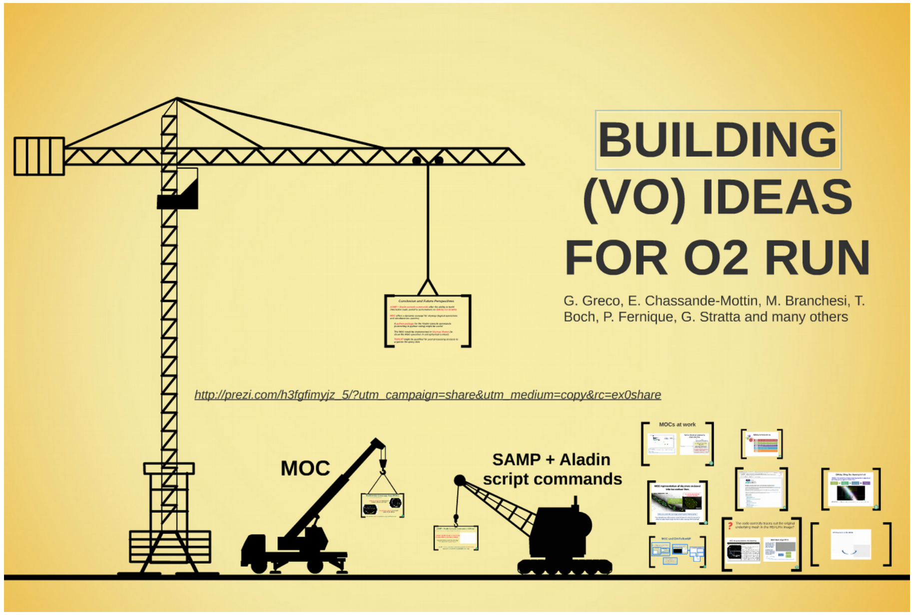
Skymap from GW data
600 deg^2 – will improve with more detectors (Virgo)



- Alerts from low-latency analysis
  - Goal for next run: **~10 mins**
  - Distributed in various formats including **VOevent**
- Source position reconstructed in a **large error area** from GW data
  - **Where to point first?**

    Strategy to prioritize fields in order to maximize chance of detection

GW alerts and skymaps (2)



Credits: Giuseppe Greco (INFN)

- Help to define follow-up strategy
  - **Visualize, tile and combine skymaps with other information** (e.g., galaxy catalog for “mass targetting”)
  - On-going collaboration to demonstrate usage of VO tools (Multi Order Coverage Map)
  - Skymaps will soon include a distance estimate for binary mergers

LIGO Open Science Center (1)

www.losc.caltech.edu

LOSC Event Datasets

Event GW150914 (1 hr)
Detectors: **L1 , H1**
Time: **2015-09-14T09:50:45.390000** = 1126259462.39

- About this event (doi)
- About this event (direct)
- Bulk data

7 DQ bits and 5 INJ bits
Frame type: %s_HOFT_C01

LOSC Run Datasets

Run S6 (2006-10, ~2.5 yrs total)
Detectors: **H1 , L1**
Start **2009-07-07T21:00:00** (= 931035615)
End **2010-10-20T15:00:00** (= 971622015)

- About this run
- Bulk data
- Data quality / injection information
- Timelines

17 DQ bits and 4 INJ bits
Frame type:

Run S5
Detectors: **L1 , H1 , H2**
Start **2005-11-04T16:00:00** (= 815155213)
End **2007-10-01T00:00:00** (= 875232014)

- About this run
- Bulk data
- Data quality / injection information
- Timelines

18 DQ bits and 6 INJ bits
Frame type:

- Motivations
  - Maximize science impact
  - Long-term preservation
  - Facilitate access to collaborators (e.g., students) that are not part of the Collaborations
- Current status
  - *h(t)* @ 4kHz and 1-Hz data quality bitmask in frame format, HDF5, txt.gz
  - Test signals (injections), documentation, tutorials

LIGO Open Science Center - Iceweasel

LIGO Open Science Center

https://www.losc.ligo.org/archive/S5/

Search

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

- Getting Started
- Tutorials
- Data
  - Events
  - Bulk Data
- Timelines
- My Sources
- Software
- GPS ↔ UTC
- About LIGO
- Data Analysis Projects
- Acknowledgement

Archive for S5 dataset

Each data file corresponds to 4096 seconds of GPS time, and may contain up to 130 MB. The file may be downloaded i either HDF5 or Frame format. For documentation, see the tutorials.

S5 start GPS: 815155213

S5 end GPS: 875232014

Next choose your gravitational wave detector:

- ○ L1 in S5
- ○ H1 in S5
- ◉ H2 in S5

Now choose the start and end time of the data that you want, either Universal time or GPS. Change either side and the other responds immediately.

	Universal Time (ISO8601)		GPS Time	
Start Time	2005-11-04T16:00:00	⇔	815155213	OK
End Time	2007-10-01T00:00:00	⇔	875232014	OK

Choose your output format:

- ◉ Time series data in HDF5 and Frame files
- ○ Time series data in HDF5 and Frame files, with data quality guide
- ○ Includes statistics of each file: min/max, band-limited RMS, etc.
- ○ JSON formatted table of files and data quality

Click the button to continue

Continue

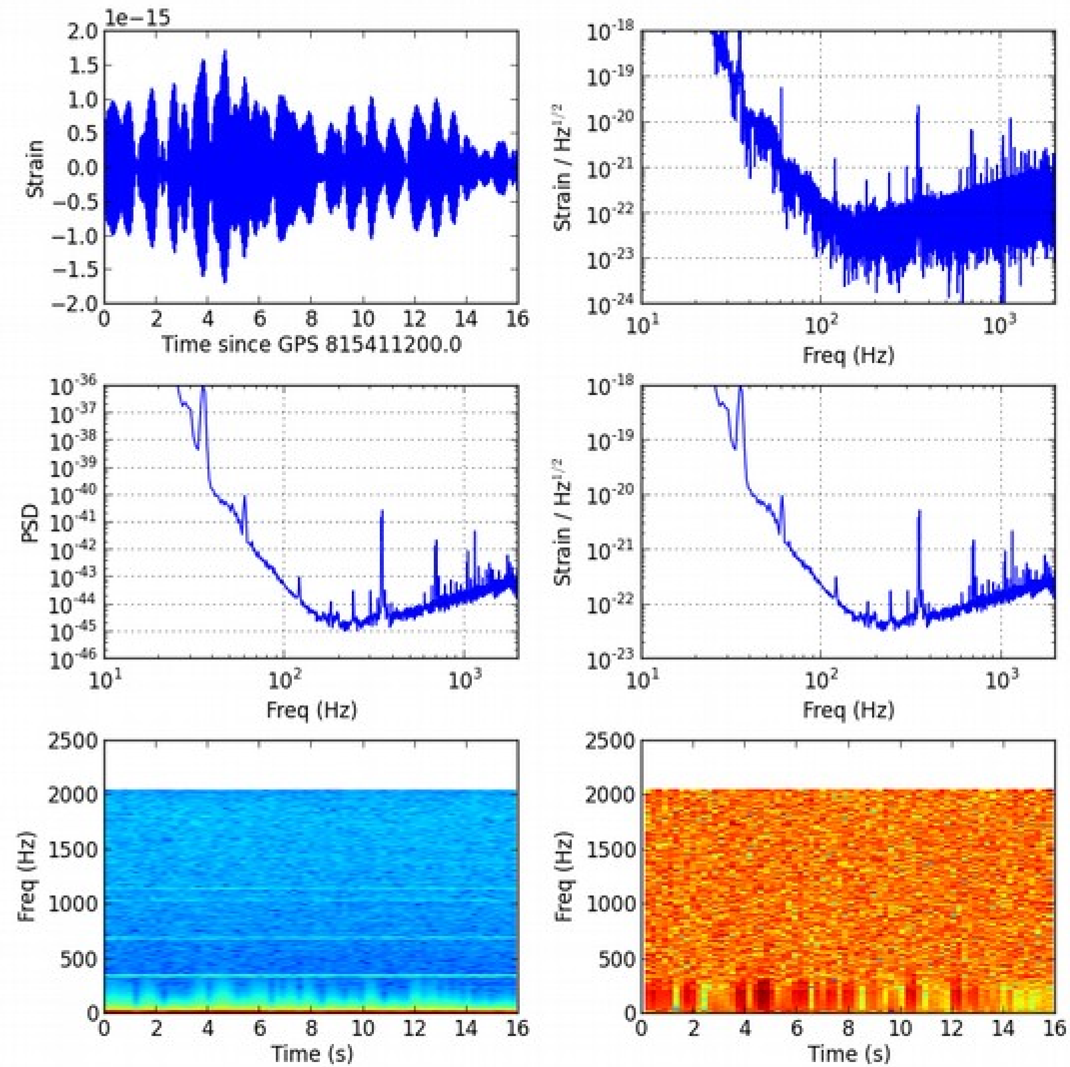
LOSC (3): open code and computing

```
[…]

#---------------------
# Plot the time series
#----------------------
fig = plt.figure(figsize=(10,10))
fig.subplots_adjust(wspace=0.3, hspace=0.3)
plt.subplot(321)
plt.plot(time_seg - time_seg[0], strain_seg)
plt.xlabel('Time since GPS ' + str(time_seg[0]))
plt.ylabel('Strain')
#------------------------------------------
# Apply a Blackman Window, and plot the FFT
#------------------------------------------
window = np.blackman(strain_seg.size)
windowed_strain = strain_seg*window
freq_domain = np.fft.fft(windowed_strain)
freq = np.arange(0, fs, 1.0/length)
plt.subplot(322)
plt.loglog( freq, abs(freq_domain)/4096.0)
plt.axis([10, fs/2.0, 1e-24, 1e-18])
plt.grid('on')
plt.xlabel('Freq (Hz)')
plt.ylabel('Strain / Hz$^{1/2}$')
#----------------------------------
# Make PSD for first chunk of data
#----------------------------------
plt.subplot(323)
Pxx, freqs = mlab.psd(strain_seg, Fs = fs, NFFT=fs)
plt.loglog(freqs, Pxx)
plt.axis([10, 2000, 1e-46, 1e-36])
plt.grid('on')
plt.ylabel('PSD')
plt.xlabel('Freq (Hz)')
#------------------------
# Plot the ASD
#-------------------------------
plt.subplot(324)
plt.loglog(freqs, np.sqrt(Pxx))
plt.axis([10, 2000, 1e-23, 1e-18])
plt.grid('on')
plt.xlabel('Freq (Hz)')
plt.ylabel('Strain / Hz$^{1/2}$')

[...]
```

iPython notebooks
for demos using LIGO data

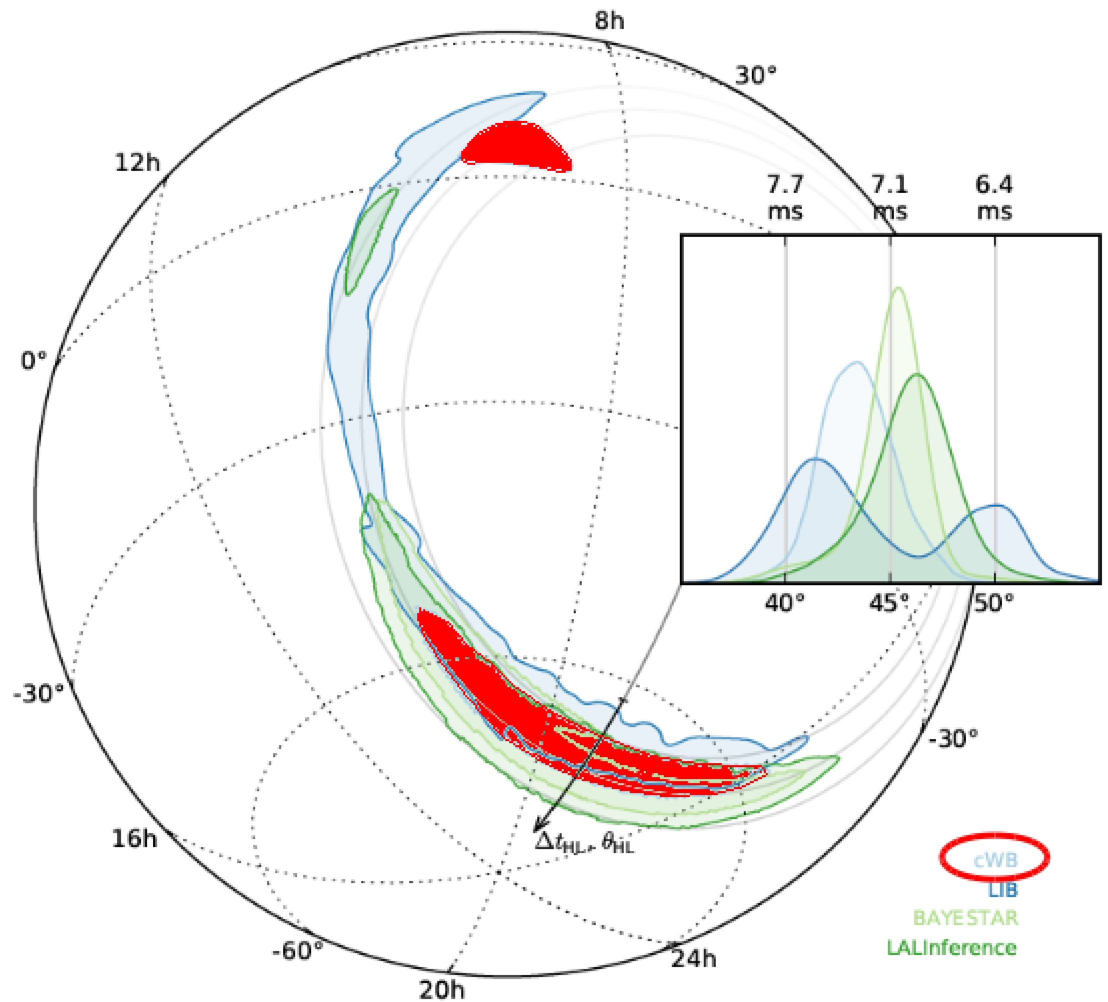


Credits: `https://www.losc.caltech.edu`

Meeting outcome and lessons learned

- New projects added on-going collaborations
  - Aladin customization for GW skymap handling
  - Glade galaxy catalog pushed to VizieR
  - Multi-dimensional cross-matching tool
- Provided use cases (BlackGEM telescope array) in view of VOevent std evolution
  - Footprints for robotic telescope pointings with time stamps
    Coordination for the coverage of large parts of the sky in a given time interval
- Provided use cases for time series in VO
  - Inclusion of time series observations in VO is still to be defined
  - Internal discussion in Virgo about Open Science Center.
    Will likely follow the LIGO model

Low latency search



Four **low-latency search pipelines**

T0+3 min = Event uploaded to DB
T0+17 min = First sky map
T0+2 days = Alert sent
T0+2 months = Final sky map

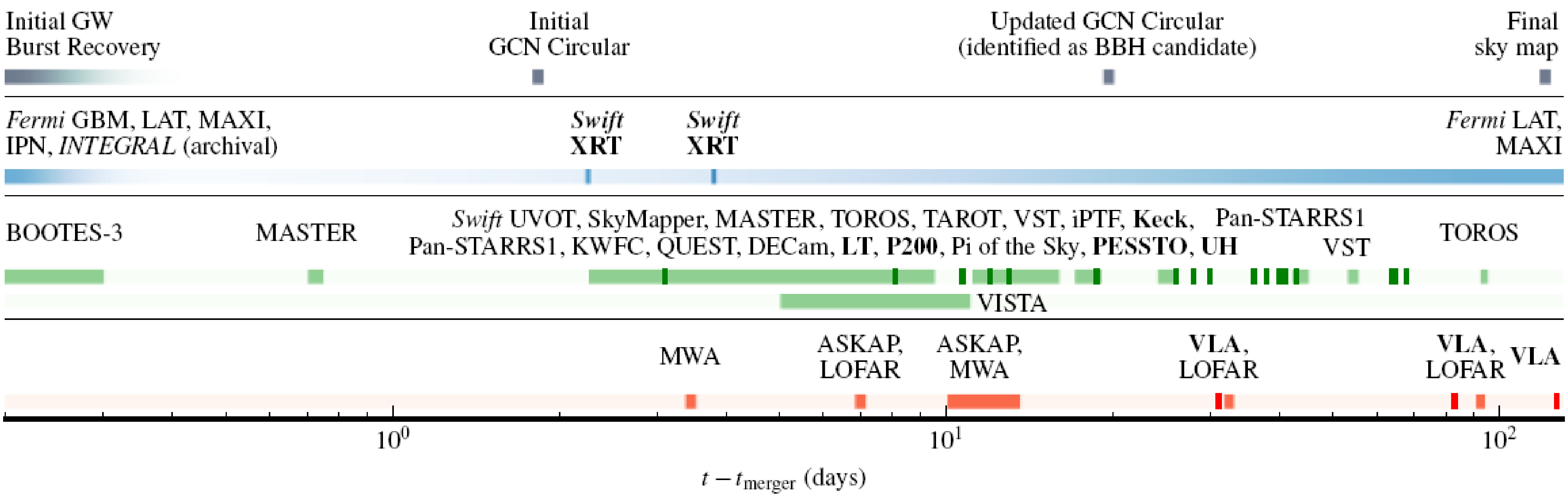
GW error region is ~600 deg^2

With Virgo on, with full sensitivity, the GW error region reduces to ~10 deg^2

Electromagnetic follow-up

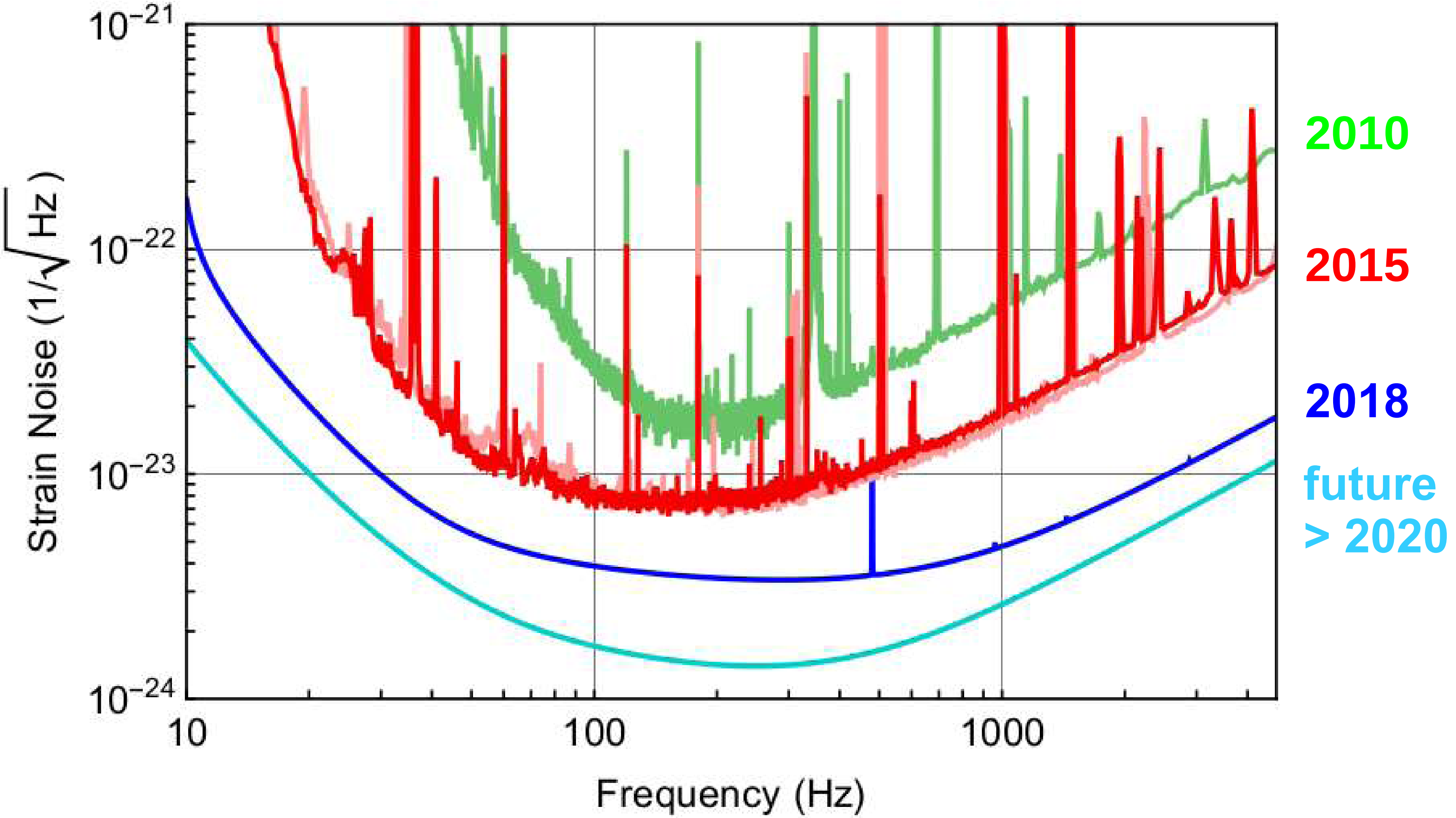
25 teams of observers responded to the GW alert

Multiwavelength: from radio to gamma-rays



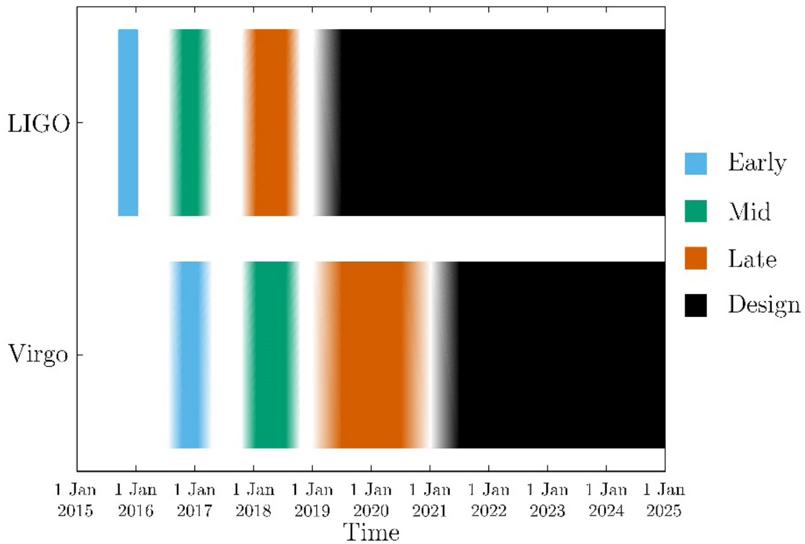
T0+2 days

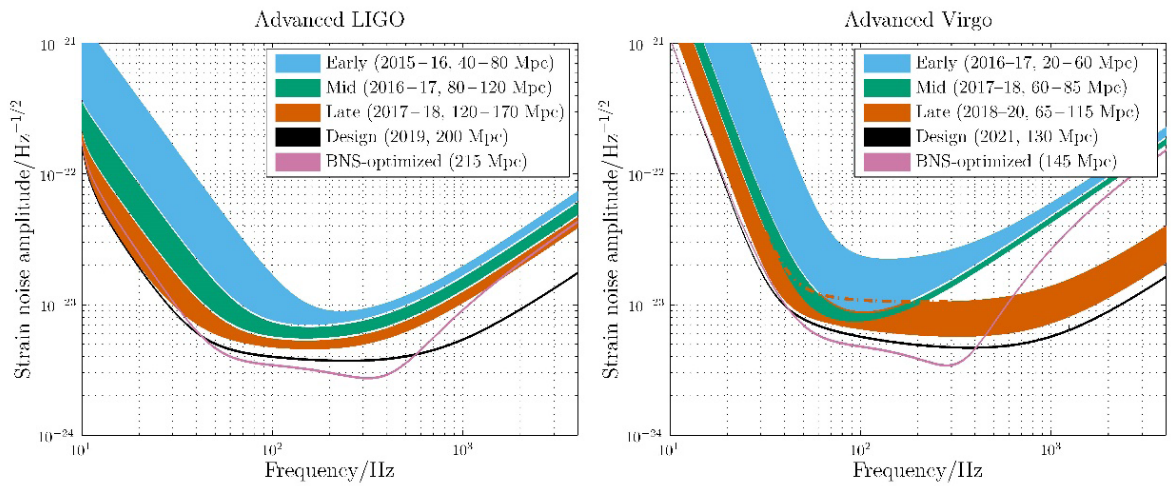
What's next?



10^{-21}
10^{-22}
10^{-23}
10^{-24}
Strain Noise ($1/\sqrt{Hz}$)
10
100
1000
Frequency (Hz)
2010
2015
2018
future
> 2020

What's next?





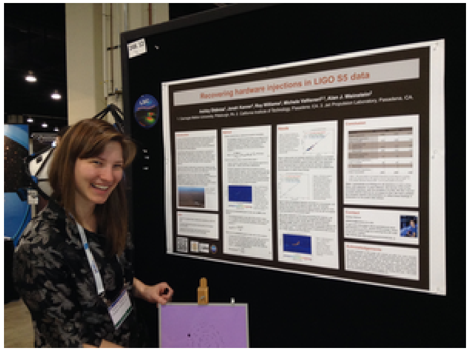
Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	*> 1 – 2*	*> 3 – 8*	*> 20*
		20 deg^2	< 1	14	*> 10*	*> 8 – 30*	*> 50*
		median/deg^2	480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
		median/deg^2	88	29	—	—	—

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

Data Analysis Projects with LOSC data

The LOSC can be a great resource for education and outreach. The tutorials provide an introduction to both data access and basic data anlysis techniques, so new students can quickly begin work. Some examples of past projects are shown on this page. For more project ideas, contact the the LOSC team.



Student Ashley Disbrow presents her work at the 2014 American Astronomical Society meeting in Washington, DC.

2016

Gravitational Wave Detection in the Introductory Lab

Lior M. Burko
Georgia Gwinnett College,
See arxiv:1602.04666

2014

Searching for Compact Binaries in LIGO Data

Shannon Wang
Date Completed: September 2014
Report: Paper

Recovering S5 Burst Injections

Alexander Cole
Date Completed: May 2014
Presentation: Paper | Slides

S5 Data Time Dependence of Duty Cycles and Spacetime Detection Volumes

Gary LaMotte
Date Completed: April 2014
Presentation: Slides

2013

Recovering Hardware Injections in LIGO S5 Data

Ashley Disbrow
Date Completed: September 2013
Presentations: Poster | Slides

Start your own LIGO data project

For help getting started on a LIGO data project, or if you have completed work that you would like to share, please contact the LOSC team.

EM signal from BBH mergers?

To explain possibly associated gamma-rays:

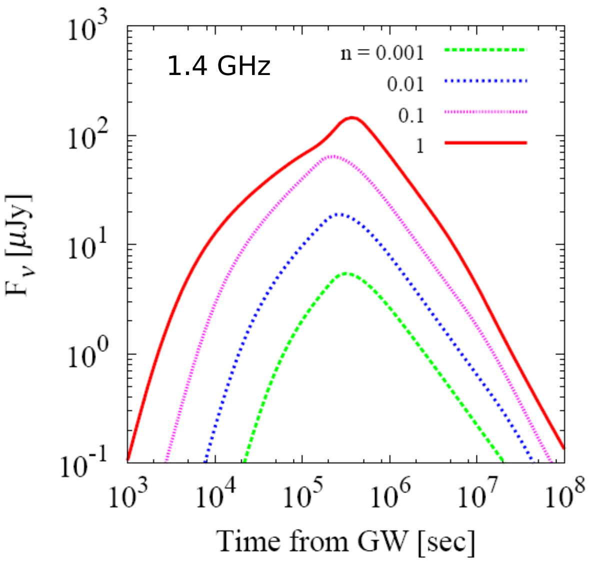
BBH with very small separation formed in the collapse of a massive star, resulting in GRB nearly simultaneously with GWs? (Loeb, 2016)

Unusually long-lived disk around BBH produces GRB at the time of coalescence? (Perna et al. 2016)

If matter ("mini-disk") exists around (B)BH

Strong disk wind may be driven by radiation or magnetic fields → **Fast optical transient around 22 mag in V-band** may be produced when thermal photons break out of the outflow

Ultra-fast flow associated with a mini-disk wind develops a blast wave which decelerates and can **generate a radio afterglow**



From Corsi, talk at APS April 2016
Murase et al Astrophys.J. 822 (2016) L9
Yamazaki et al. arXiv:1602.05050

Past and future visibility of GW150914