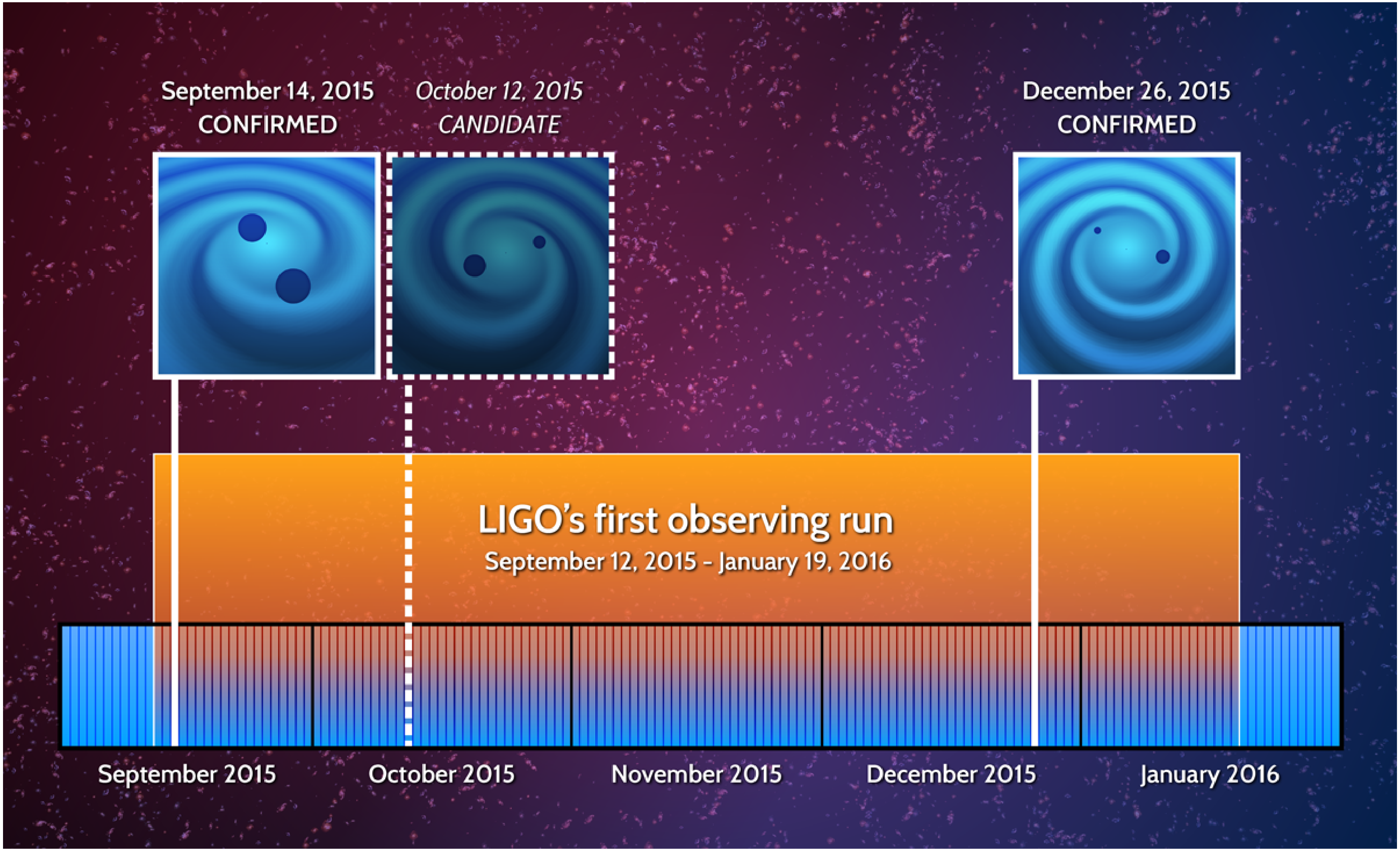
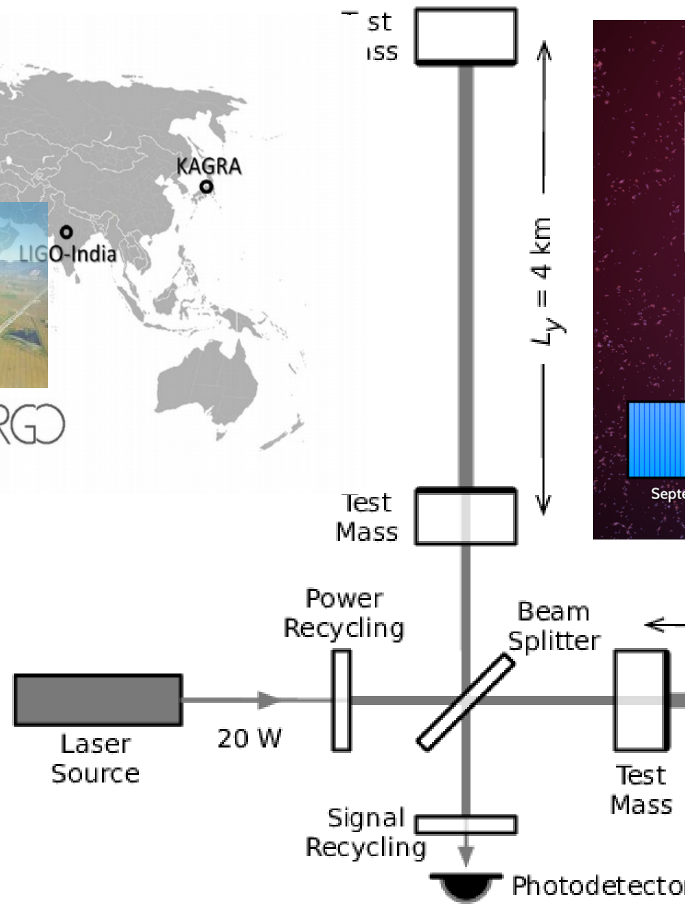
Searches of gravitational-wave transients with low latency

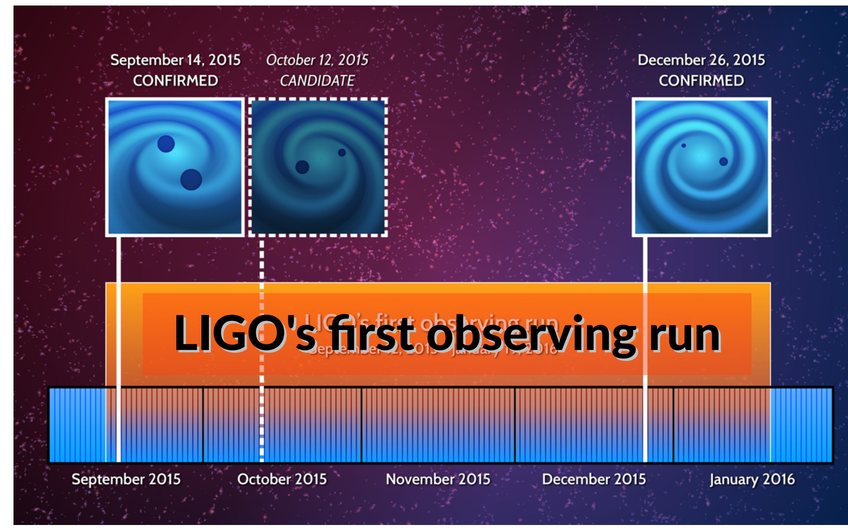
Eric Chassande-Mottin
CNRS AstroParticule et Cosmologie
Paris, France

Coalescence of two black holes (credits: SXS)


September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

Advanced detectors
First science run





$$h = \frac{\delta\ell}{L} \sim 10^{-21}$$

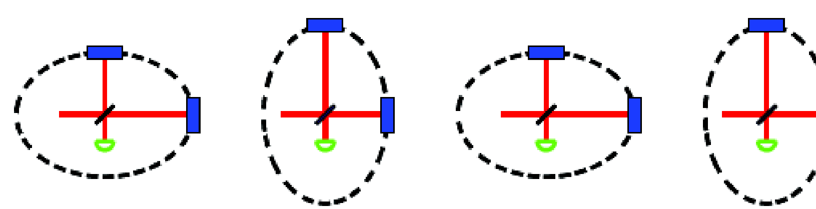
$$\delta\ell \sim 10^{-18}\mathrm{m}$$

1000th of nucleus radius!

3 to 5 x more sensitive than “initial” detectors

x 100 more sensitive at low frequencies (40 Hz)

10 x space-time volume surveyed so far



Outline

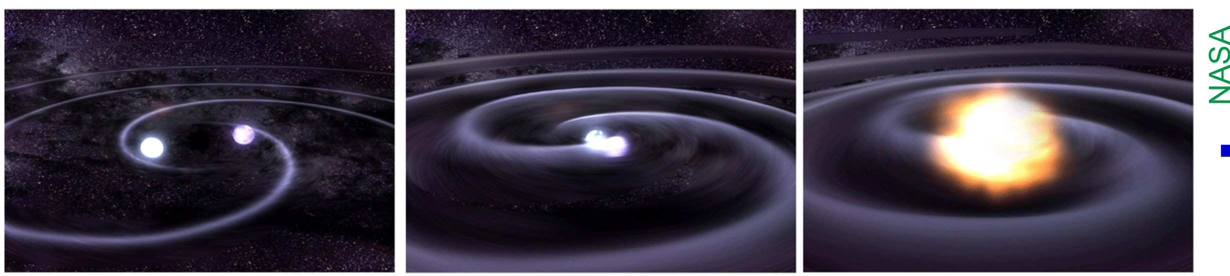
- **This is the birth of gravitational astronomy**
- Review of **low-latency searches**
  - Enables follow-up of GW alerts by other observatories in the electromagnetic spectrum

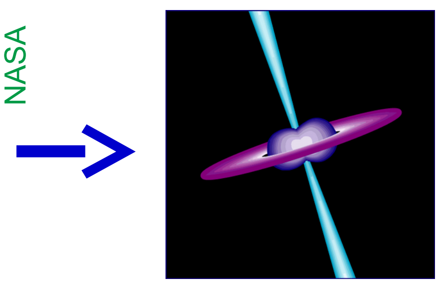
    Bridge to “conventional” astronomy

- Motivations
- Low-latency data analysis methods and infrastructure
  - Searches, data quality, source reconstruction, alert handling
- Outlook

Electromagnetic counterparts to gravitational wave events

- **GW emitted energy is enormous**
  - GW150914 – 3 M_{sun} c^2 ~ 10^{54} erg in 100 msec!
  - A (small) fraction of that energy could leak to the electromagnetic spectrum ***but*** ...
  - Light unlikely to escape from compact objects such as black holes



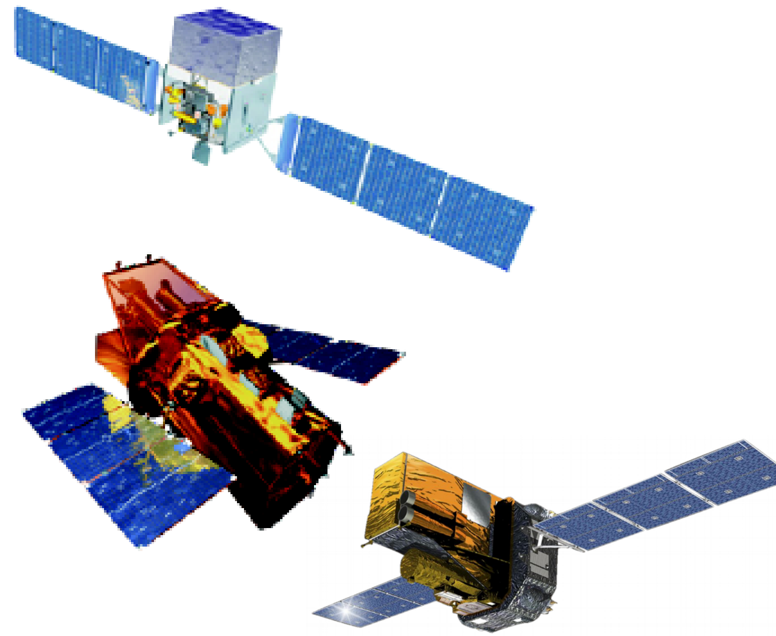


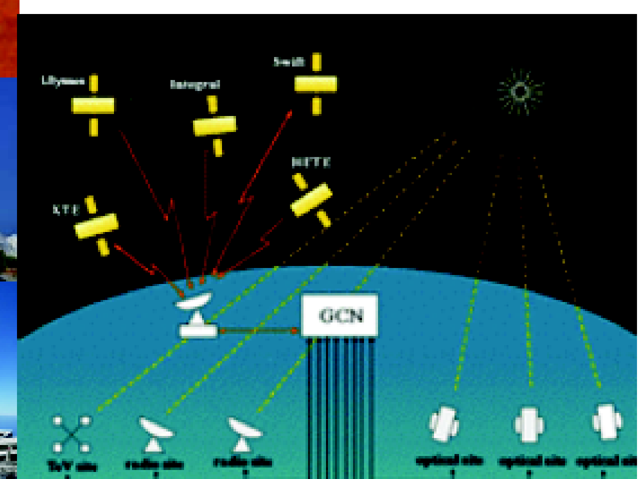
P.J.T. Leonard (NASA/GSFC)

- Are **short gamma-ray bursts** associated with compact binary mergers (incl. neutron star)?
  - **Prompt gamma-ray** emission (beamed – 5 to 10 degrees)
  - X-ray or optical **afterglow** (observable for small inclination)
  - **Kilonova** (or macronova) due to radioactive decay of heavy elements in neutron-rich ejecta

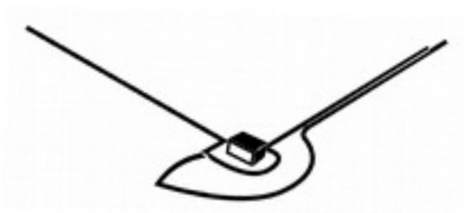
Multimessenger astronomy

- Two approaches for joint GW and EM search
  - **“Externally triggered” GW searches**
    - Gamma-ray bursts, pulsar glitches, SGR flares, fast radio bursts, near-by supernovae, …   ~20 publications
  - **Electromagnetic follow-up of GW alerts (this talk)**
    - LIGO & Virgo have signed MOUs with **~80 astronomer groups** Cover all accessible wavelengths from radio to very high energies
    - MOU = standard framework to share information promptly while maintaining confidentiality
    - Encourage free communication “inside the bubble”
    - Once GW detections become routine (≥ 4 published), there will be prompt **public alerts of high-confidence detections**




Swift
XTE
GCN

Workflow – Big picture



GW data *h(t)*

~30 GB/day/instrument
from Tier 1 to Tier 2
computing centers

data quality

second to mins — searches

mins to hours — position reconstruction

hours to days — parameter estimation

events

skymaps

source parameters (e.g., mass, spins)

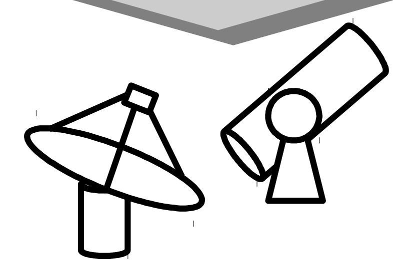
`gracedb.ligo.org`

event database

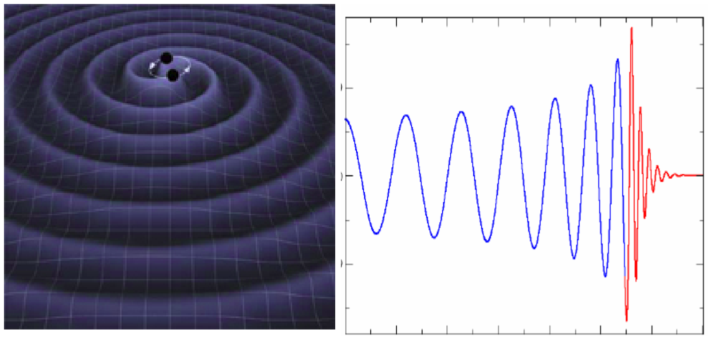
`event+annotations`
`[log,labels,files]`

O(1000) events/run

private GCN network
VOevent



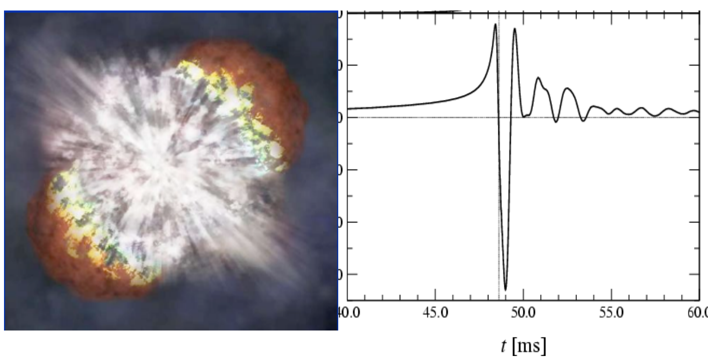
GW transient searches



Compact Binary Coalescence (CBC)

Known waveform – **Matched filtering**

Templates for a range of component masses and spin



Unmodelled GW Burst (< ~1 sec duration)

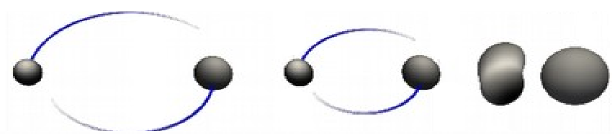
e.g. from stellar core collapse

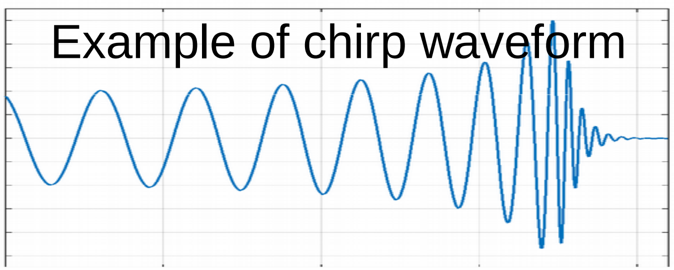
Arbitrary waveform – **Excess power**

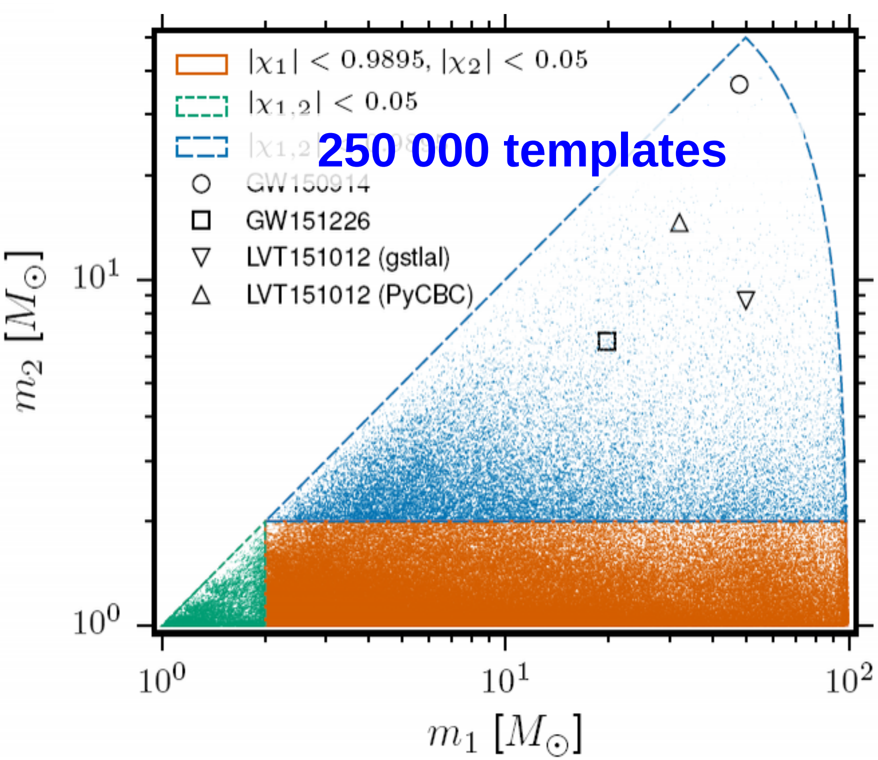
Require coherent signals in detectors,
using direction-dependent antenna response

- **What's special with low-latency searches?**
  - **Run continuously** whenever data from two or more detectors are available – Feed immediately the event database
  - Provide event significance against **background estimate obtained from limited data**

Searches for compact binary coalescences (1)



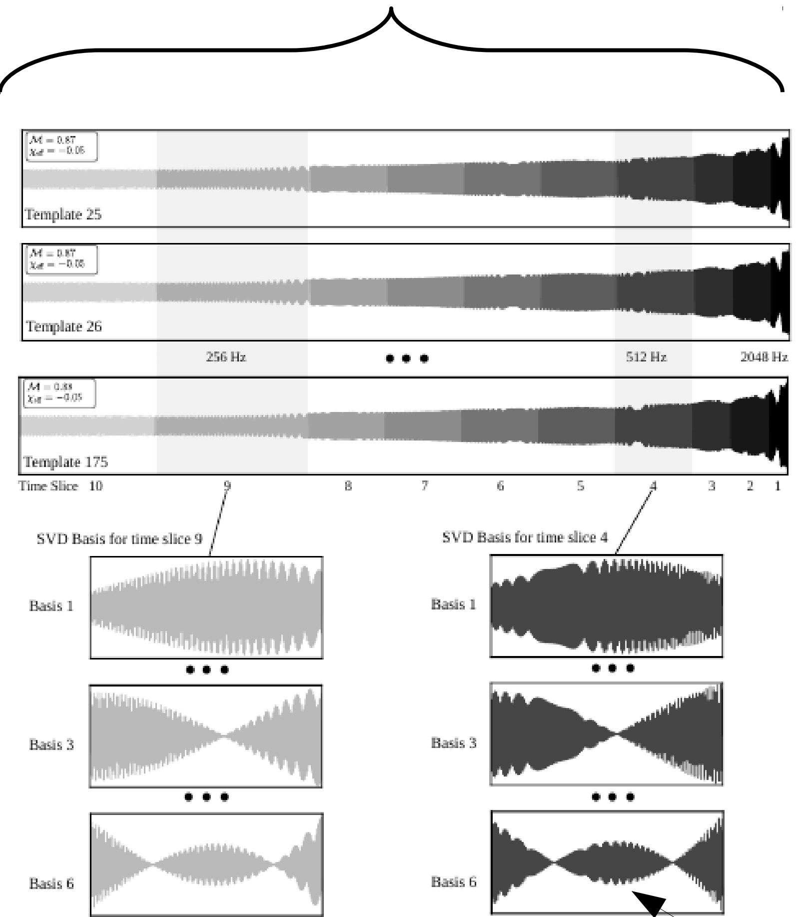




- Pattern matching
  - **Correlate data with the expected waveform** from astrophys. model
  - **Template bank** that covers the space of astrophysical signals
- Reject background
  - **Control goodness-of-fit** using χ^2 test of candidate's spectra to mitigate instrumental transient noise (glitch)
  - **Get coincident event across detectors** (time and source params)
- Measure candidate significance
  - From surrogate data obtained by **time-shifting detector streams** with unphysical delays

Searches for compact binary coalescences (2)

Block of similar template waveforms is time-sliced



- **Two low-latency pipelines**
  - Includes tricks to run faster

Multi-Band Template Analysis (MBTA)

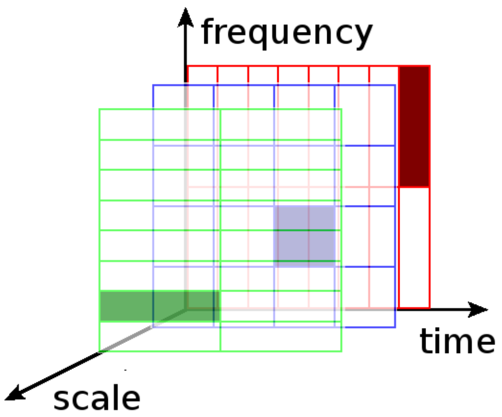
- divides freq. band into low/high subbands → lower number of templates in each subbands and lower sample rate – arxiv:1507.01787

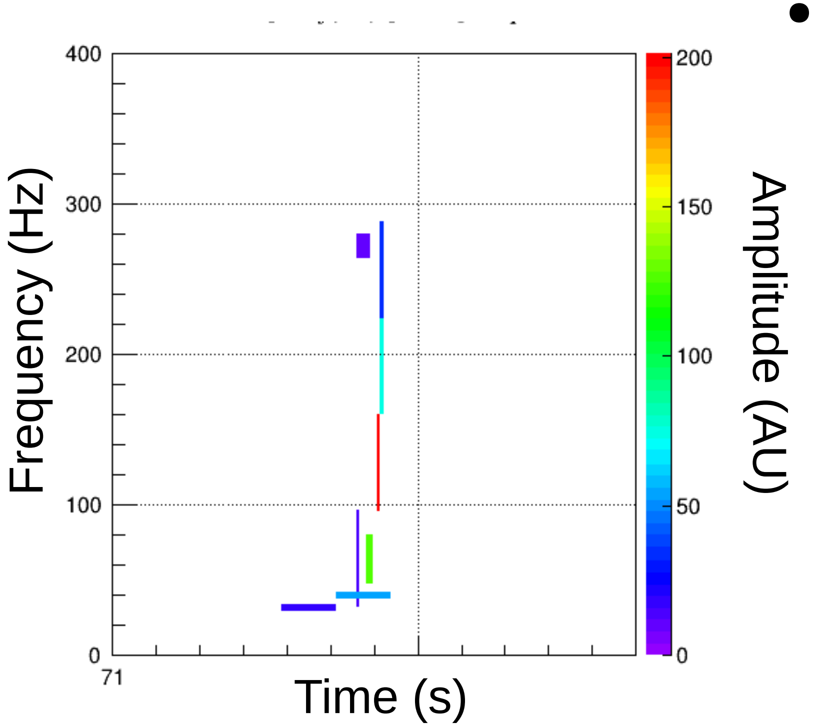
GstLAL (derived from Gstreamer lib)

- Time-domain filtering rather than frequency-domain (allows second latency)
- Template bank transformed into reduced set of orthonormal filters by block-wise SVD
- … and other tricks, arXiv:1604.04324

< 10 SVD basis filters per slice

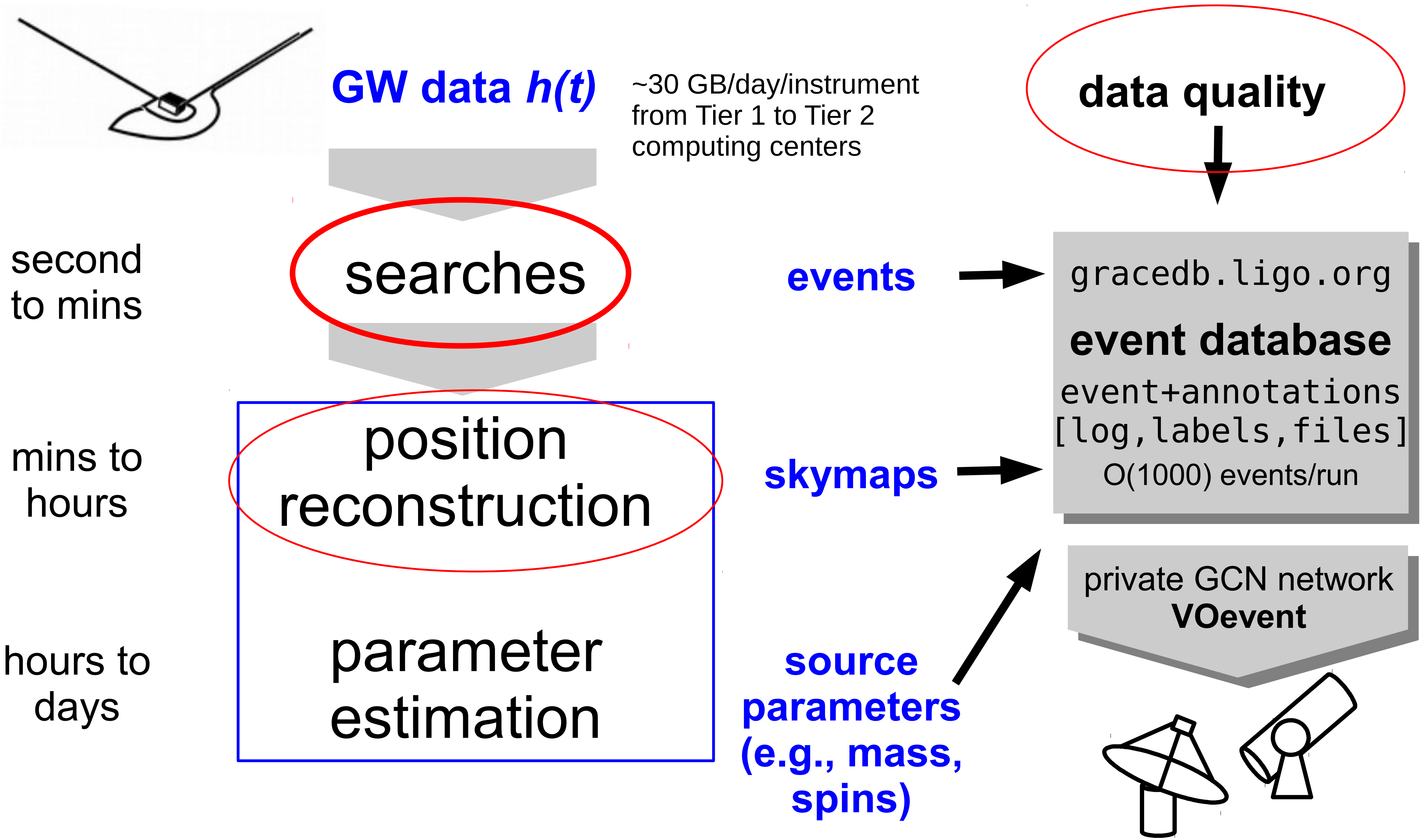
Searches for generic GW transients





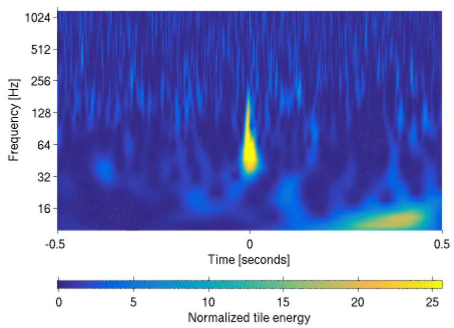
- Principle
  - Search for **excess-power occurring coherently across detectors**
  - Multiple low-latency pipelines: cWB, oLIB, Bayeswave – arXiv:1602.03843
- **Coherent waveburst** arXiv:1511.05999
  - Data are transformed into **time-frequency** domain (multiscale Wilson transform)
  - Retain time-frequency "**outliers**" and **combine coherently**:
    compensate time and phase offset at each detector (aking to synthetic aperture, beamforming)
  - Select clusters that appears **"phase"-coherent for a given sky location**

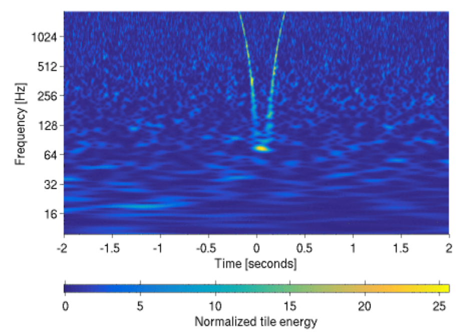
Workflow – Big picture

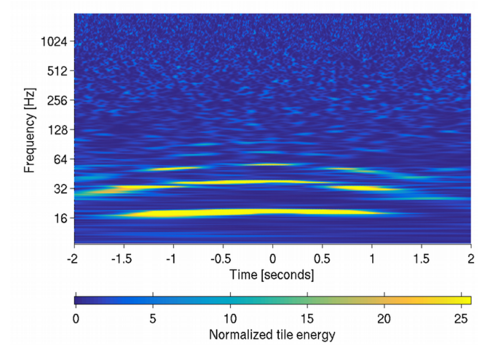


Low-latency data quality

- **Glitches** – non-Gaussian component of instrumental noise



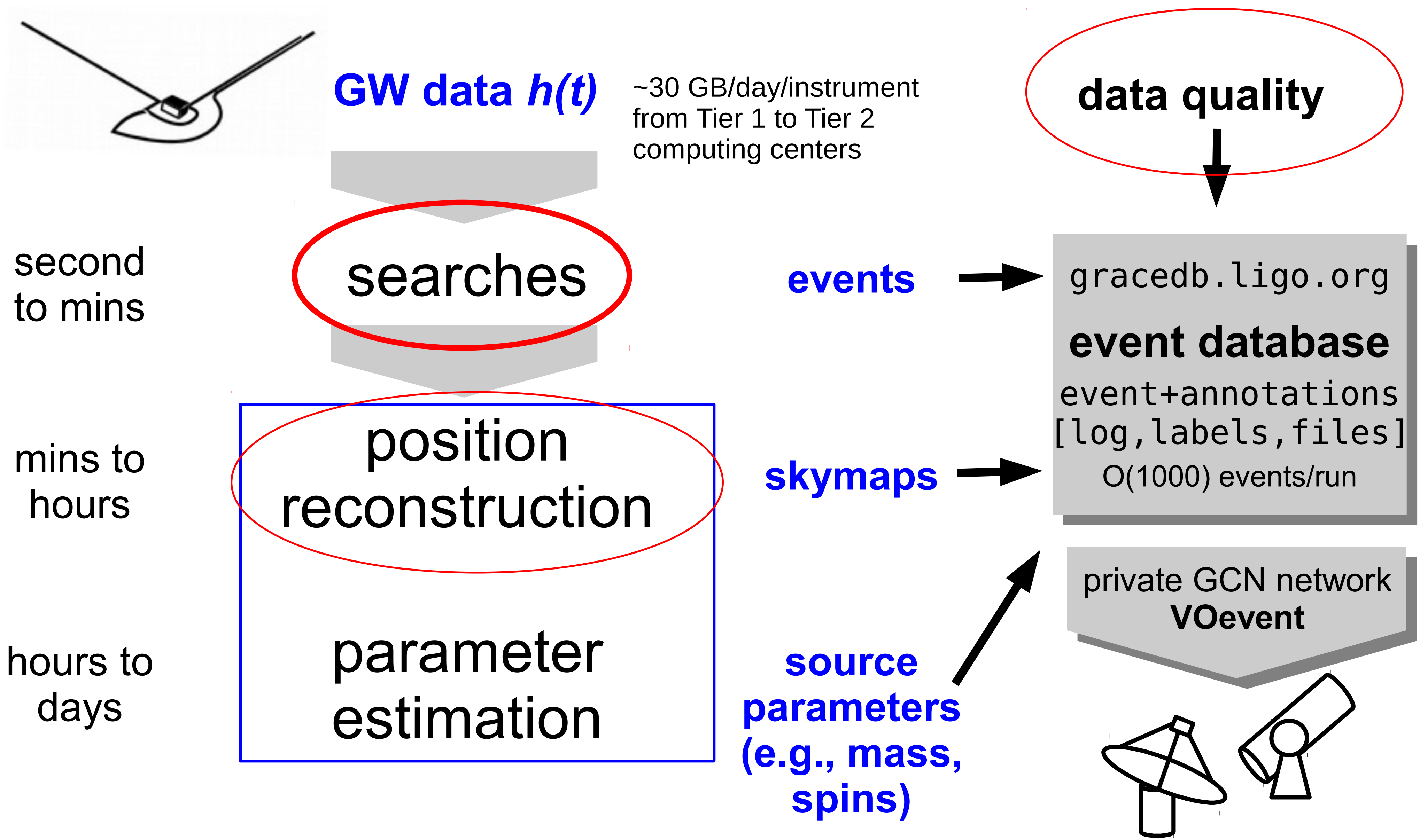




- The origin of glitches can be traced from auxiliary channels and control loop signals
  - 200 000 auxiliary channels (seismometers, magnetometers, …)
  - Large effort to characterize detector noise
  - Attempts to automatize using machine learning
- When eligible events occur, `lvalert` daemon interrogates
  - an **online data-quality monitor** (iDQ) – “glitchiness report”
  - the **data quality segment database** (and data quality vector state)

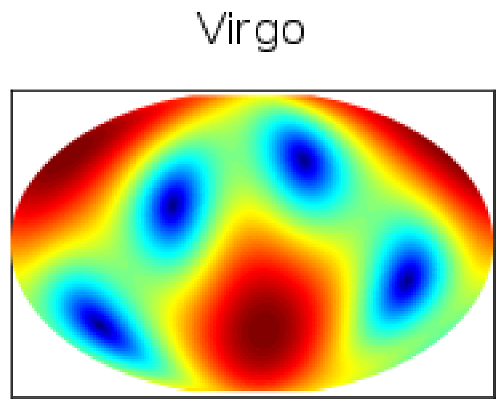
Credits for the glitches: Coughlin, Smith et al, Gravity-spy `zooniverse.org`

Workflow – Big picture

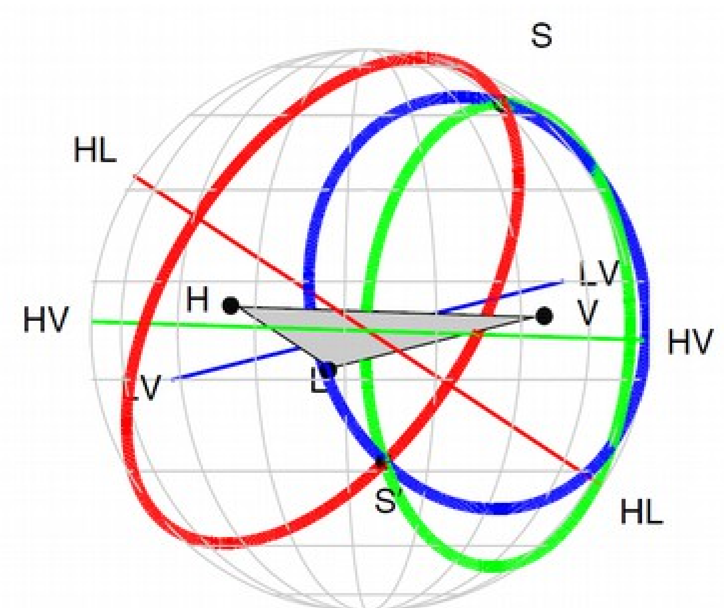


Source direction reconstruction

Antenna beam pattern



$$(F_+^2 + F_\times^2)^{1/2}$$



- Each detector have a broad antenna beam pattern (**non directional**)
- Basic principle: **triangulation from times of flight**
  - Two detectors localize to a ring in the sky
  - Including phases and amplitudes on arrival improves localization

    Can be done within minutes arXiv:1508.03634
- Ideally: **coherent analysis**
  - **Posterior probability skymap** from Bayesian full-scale parameter estimation
  - [11 parameters total for binaries with aligned spins]

    Can be done within hours or days

Sep 14, 2015 (1)

GW localization regions are large!

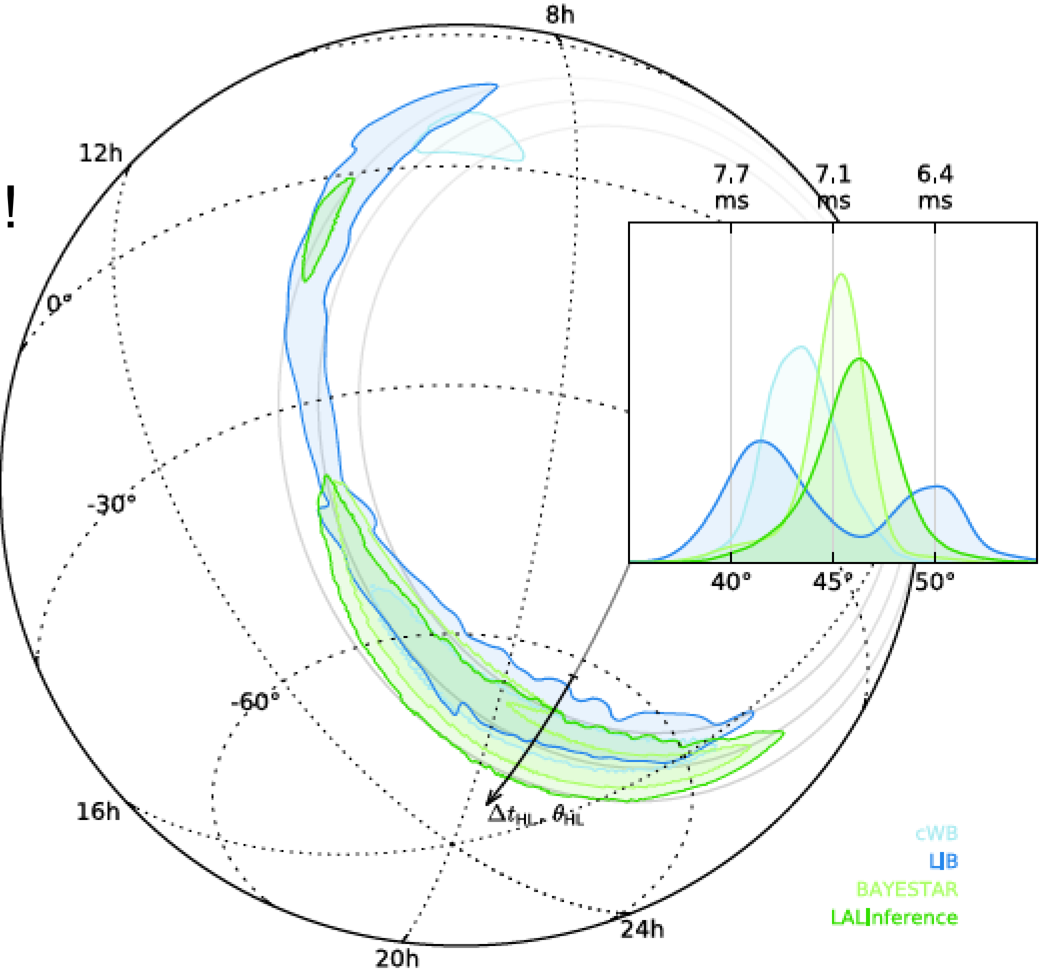
With two detectors only, bimodal rings of 100–1000 of deg^2 typically

GW150914

90 % localization is 600 sq degrees!

Challenging!

Coverage and
lots of associated transients



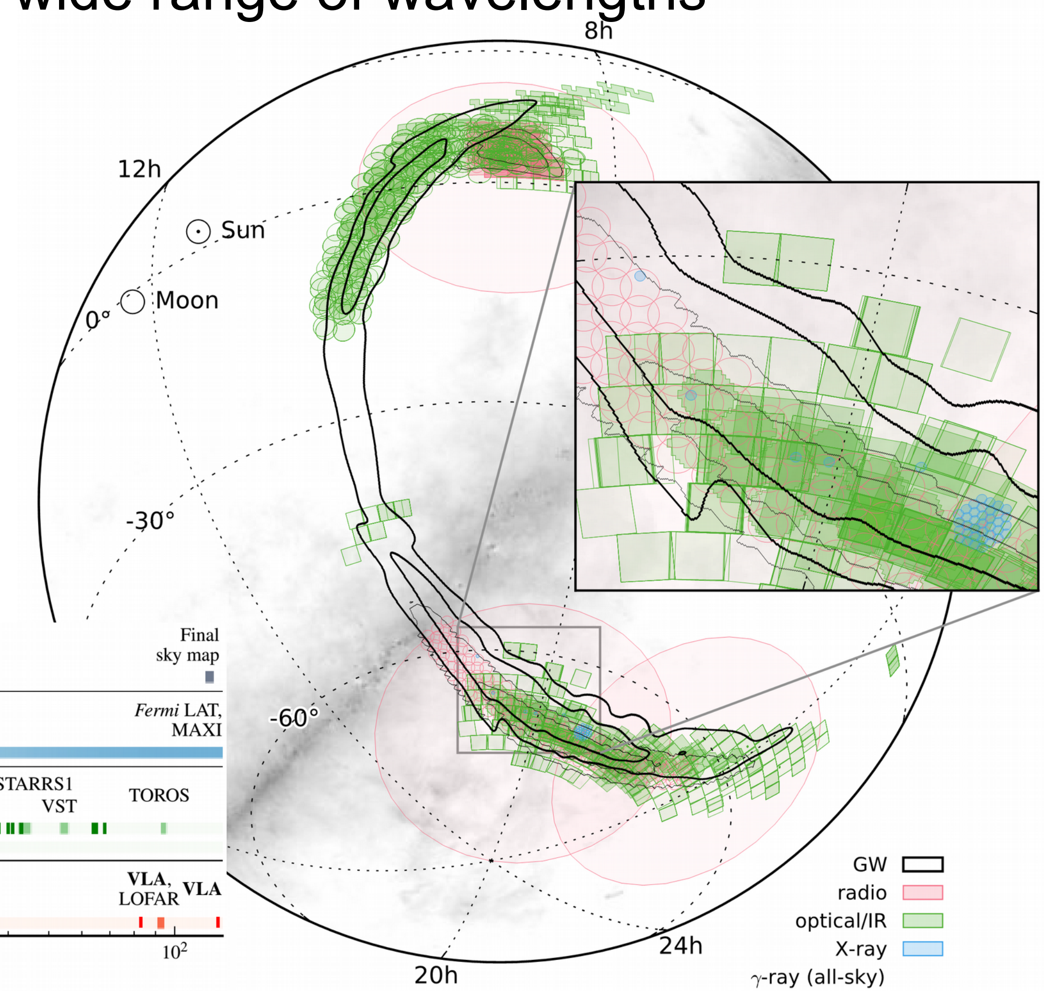
Abbott et al, ApJL 826, L13

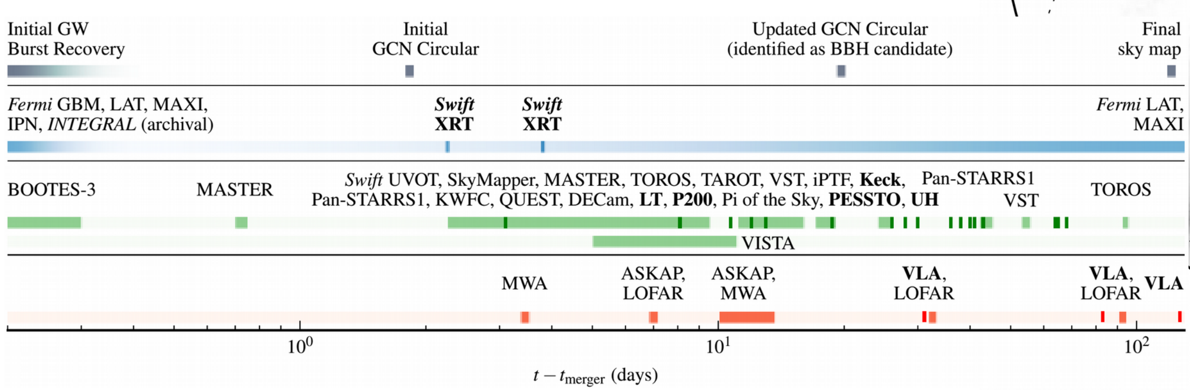
Sep 14, 2015 (2)

25 observing teams, 50 GCN Circulars, 12 publications

Covered most of skymap area at a wide range of wavelengths starting within a few hours

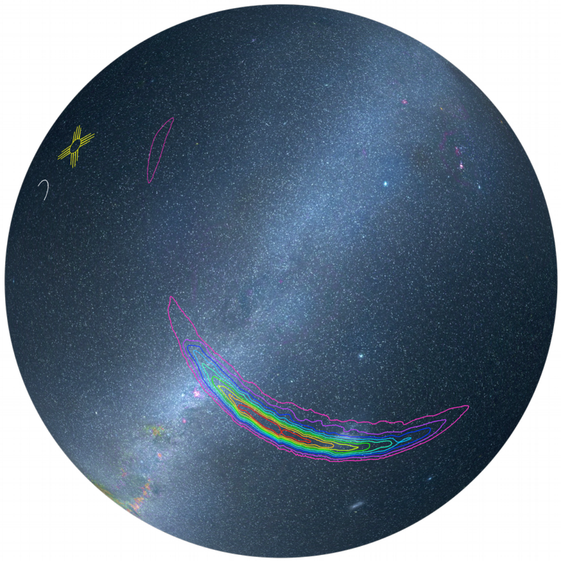
Key element: archival data from high-energy instruments in orbit

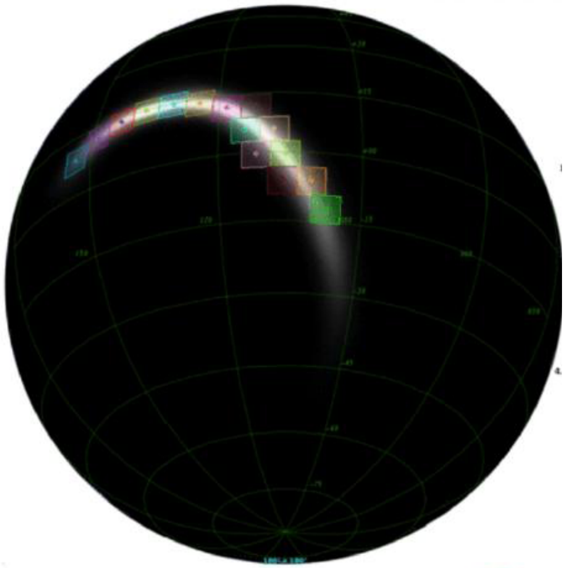




Abbott et al, ApJL 826, L13

Support to astronomers



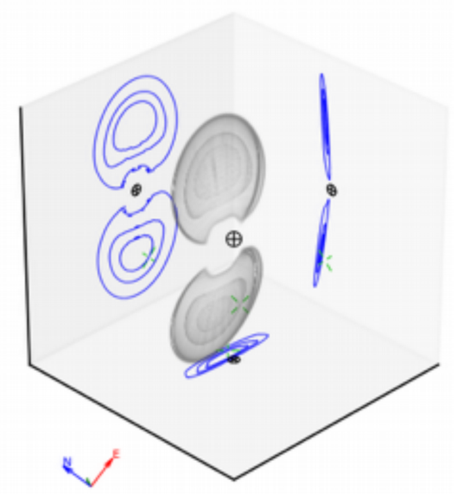


- **Skymap viewer**
  http://losc.ligo.org/skymapViewer
  - Web-based tool to visualize GW skymap and other relevant information for follow-up
- **GWsky**
  https://github.com/ggreco77/GWsky
  - Set of python scripts that allows to process GW skymaps (tile to a given FOV) and interface with other data (catalog of near-by galaxies, airmass)

Both use VO tools

Outlook

- **Next run starting in November**
  - Commissioning/noise hunting on-going at LIGO
  - Virgo will likely begin with modest sensitivity – possible significant **improvement on localization**
- Electromagnetic follow-up program
  - Lessons learned from first run
    - Get **alerts out more quickly** (aim for 30 mins or less)
    - Specify the **preferred skymap** at any given time
  - Two major new developments
    - Prompt **binary classification** (BNS, NS-BH, BBH)
      Probability that there is at least one neutron star in the system and that there is mass in the NS ejecta (e.g., *Foucart 2012)*
    - **3D sky maps with direction-dependent distance** estimates into our rapid and final localizations (e.g. Singer et al. 2016, ApJL 829, L15).



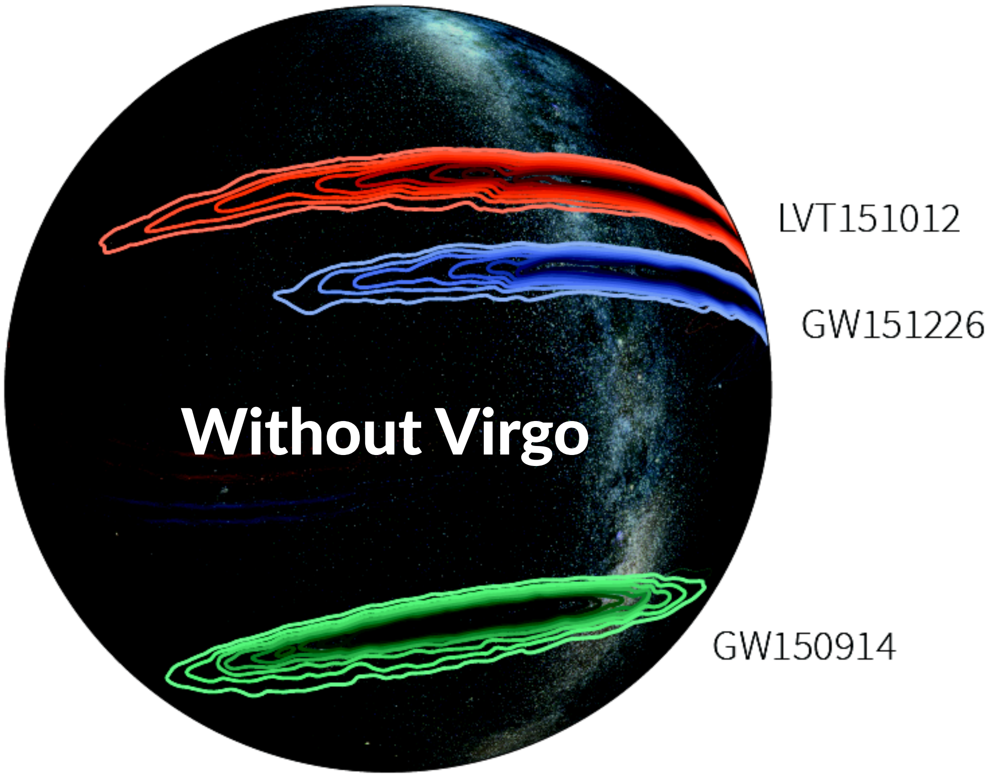


image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)

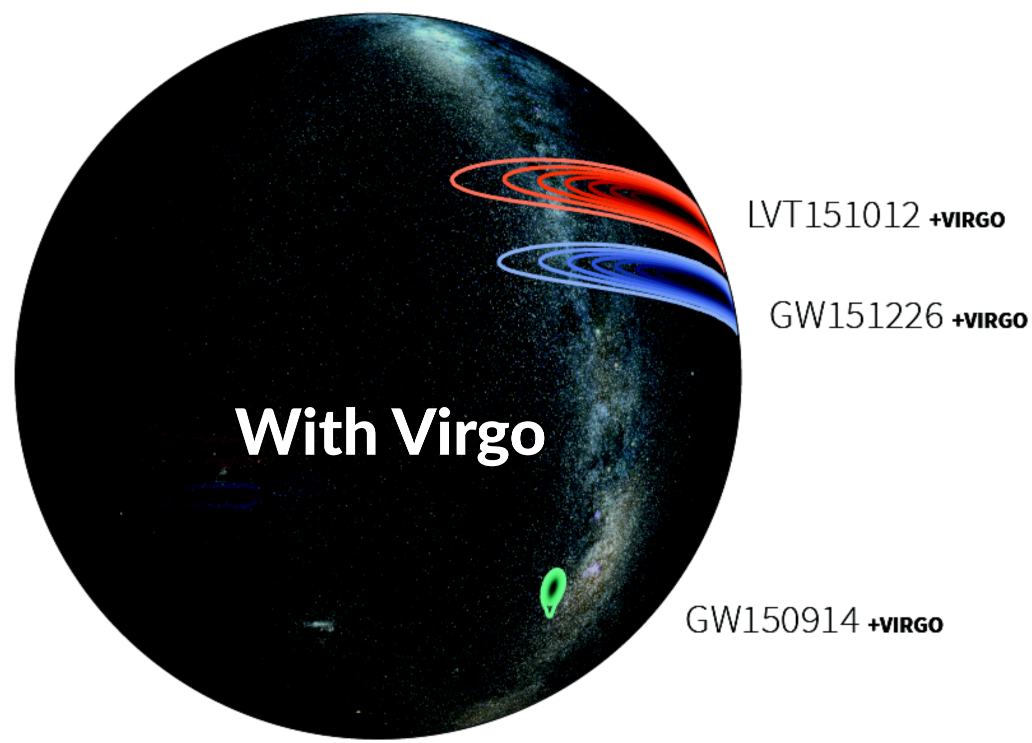
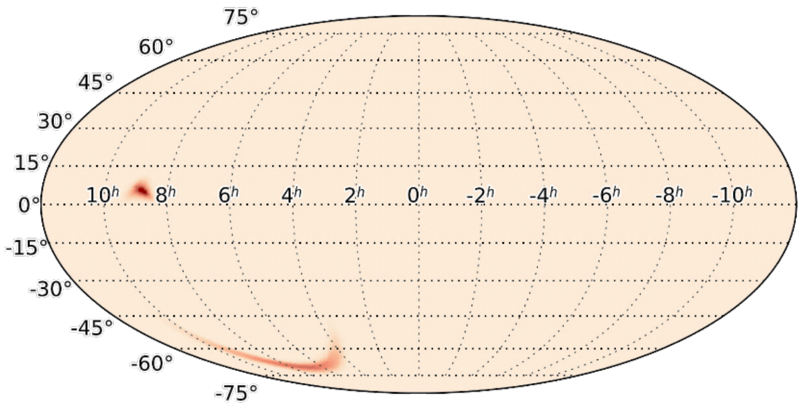
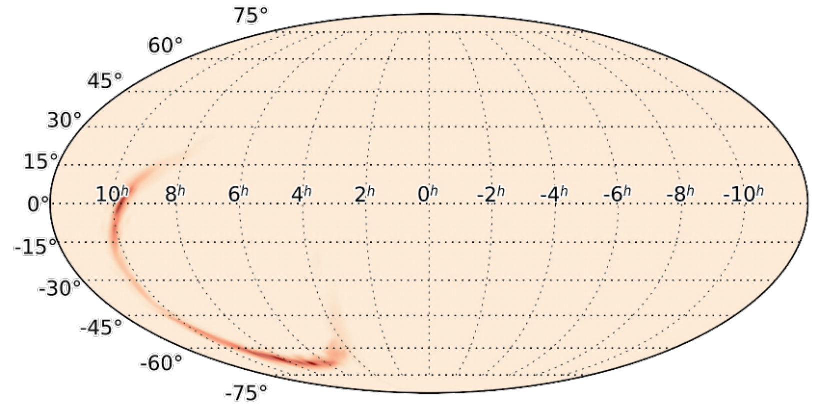


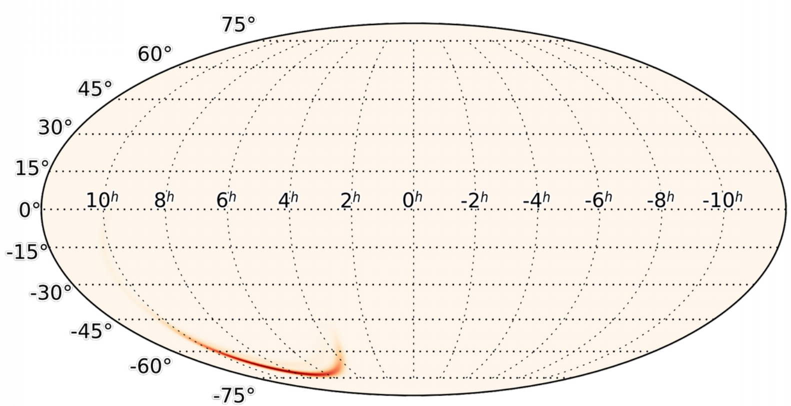
image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)



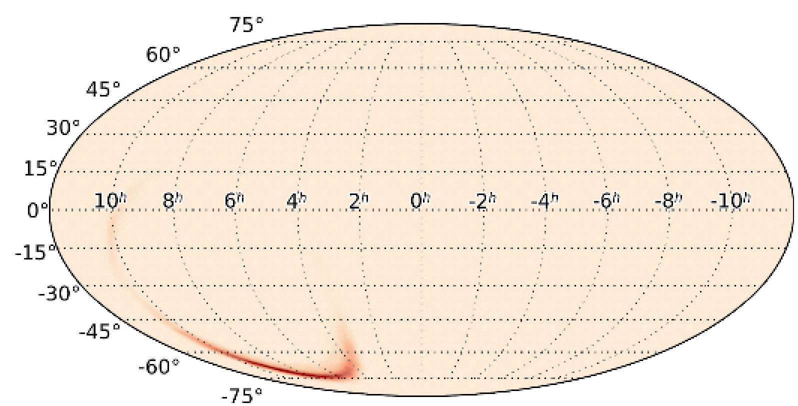
coherent WaveBurst
(first skymap communicated)



oLIB
(first skymap communicated)



Bayestar



Final, LAL inference
(full Bayesian param estimation)

Can a binary black hole merger produce a detectable EM transient?

We don't expect a stellar-mass binary black hole system to have enough matter around for the final BH to accrete and form a relativistic jet [e.g., Lyutikov, arXiv:1602.07352] — or can it?

Various models have been proposed:

Single star [Fryer+ 2001; Reisswig+ 2013; Loeb 2016, ApJL 819]: collapse of a very massive, rapidly rotating stellar core, which fissions into a pair of black holes which then merge; but see Woosley, arXiv:1603.00511v2 for modeling that does not support

Instant BBH [Janiuk+ 2013, A&A 560; arXiv:1604.07132]: massive star-BH binary triggers collapse of star to BH, then immediate inspiral and merger; final BH can be kicked into circumbinary disk and accrete from it

BBH with fossil disk [Perna+ 2016, ApJL 821]: activates and accretes long-lived cool disk

BBH embedded in AGN disk [Bartos+, arXiv:1602.03831; Stone+ 2016, MNRAS]: binary merger assisted by gas drag and/or 3-body interactions in AGN disk, which provides material to accrete

Third body [Seto&Muto 2011, cited in Murase+ 2016, ApJL 822]: tidal disruption of a star in a hierarchical triple with the BBH at time of merger

Charged BHs [Zhang 2016, ApJL 827; Liebling&Palenzuela 2016, PRD 84]: Merging BHs with electric (or magnetic monopole!) charge could produce a detectable EM transient

Magnetic reconnection [Fraschetti, arXiv:1603.01950]

Also models for high-energy neutrino and ultra-high energy cosmic ray emission

Review – courtasy of Peter Shawhan (Maryland)

How is the information communicated?

GraceDB – Gravitational Wave Candidate Event DB

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AUTHENTICATED AS: ERIC CHASSANDE-MOTTIN

Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	FAR (Hz)	Links	UTC Submitted
G158249		CBC	MBTAOnline		H1,L1	1117621400.2060	1.372e-06	Data	2015-06-06 10:24:49 UTC

Coinc Tables

End Time	1117621400.2060
Total Mass	9.2271
Chirp Mass	3.0849
SNR	13.6718
False Alarm Probability	

Single Inspiral Tables

IFO	L1	H1
Channel		
End Time	1117621400.219121932	1117621400.206010103
Template Duration	None	None
Effective Distance	177.7525	459.68568
COA Phase	-0.2746053	-1.0825006
Mass 1	7.365417	7.365417
Mass 2	1.861673	1.861673
η	0.16105389	0.16105389
F Final	None	None
SNR	12.637432	5.2167654
χ^2	None	None
χ^2 DOF	None	None
spin1z	-0.2383012	-0.2383012
spin2z	0.0005419254	0.0005419254

Neighbors [-5,+5]

No neighbors in range.

Low latency analysis

Preliminary alert <u>in 3-5 mins</u>

Rapid preliminary sky position

Initial alert <u>issued in 5-10 mins</u>

includes: time, significance, sky map

Source parameters

Alert updates or retraction <u>within hours</u>

Event Log Messages (add)

Analyst Comments

LLO Local

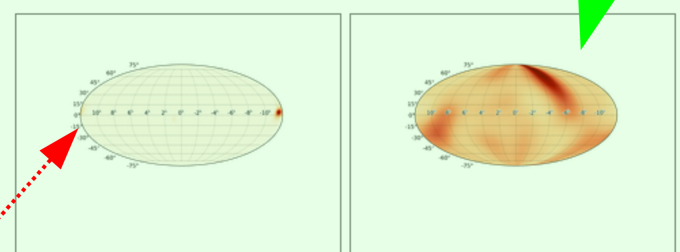
Log Entry Created	Submitter	Comment
Jun 7, 2015 5:18:52 PM	GDB Processor	No unblind injections in window [-5,+5] seconds
Jun 7, 2015 5:06:33 PM	GDB Processor	No unblind injections in window [-5,+5] seconds

Noise Curves

LLO Local

Log Entry Created	Submitter	Comment
Jun 6, 2015 5:24:54 AM	MBTA Alert	PSDs psd.xml.g

Sky Localization



skymap.png. Submitted by GDB Processor on Jun 7, 2015 10:06:16 PM

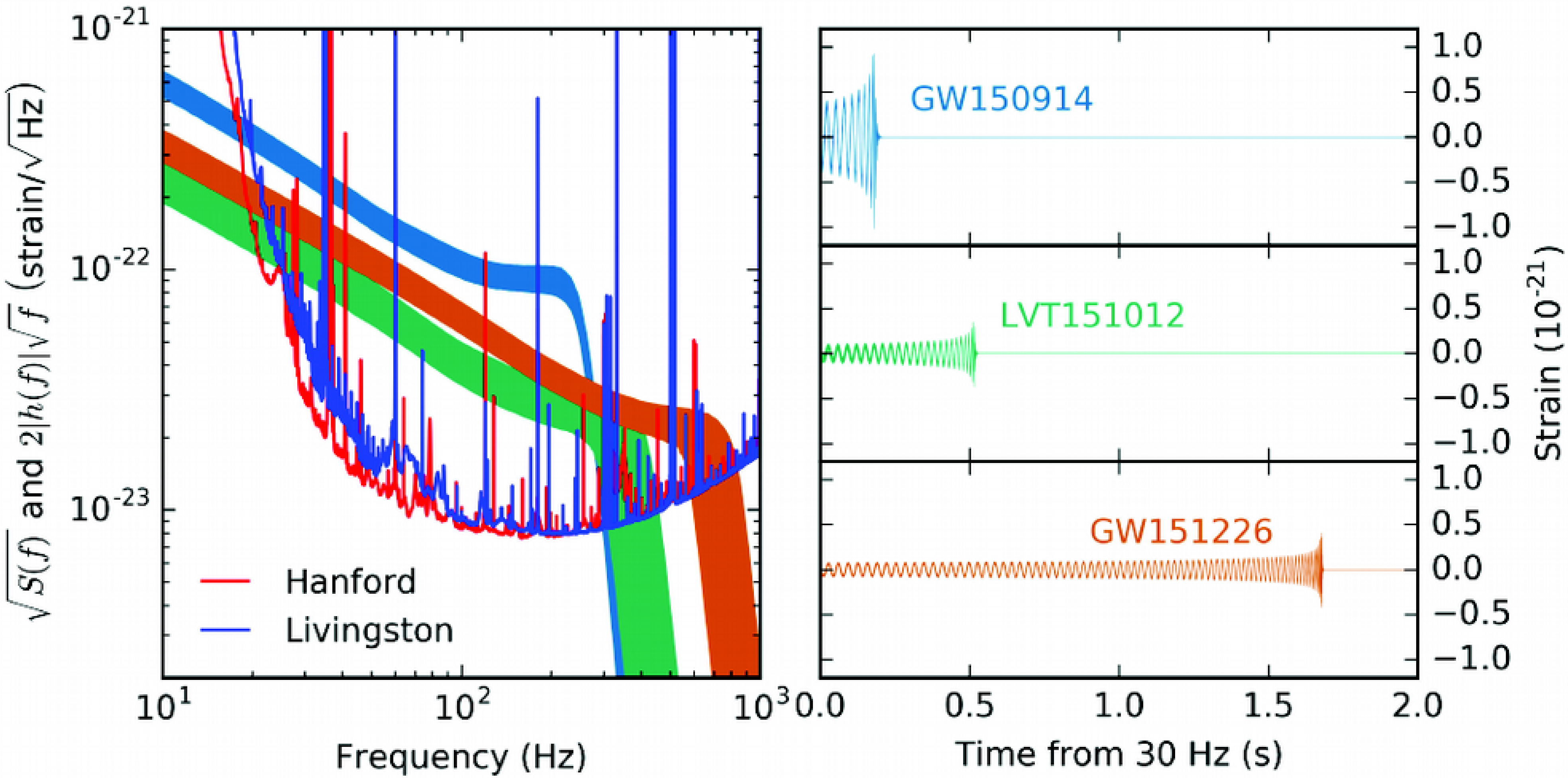
LALInference_skymap.png. Submitted by GDB Processor on Jun 7, 2015 10:18:34 PM

LLO Local

Log Entry Created	Submitter	Comment	
Jun 7, 2015 5:18:25 PM	SkymapViewer	LALInference_skymap.json	View in SkymapViewer!
Jun 7, 2015 5:06:01 PM	SkymapViewer	skymap.json	View in SkymapViewer!
Jun 7, 2015 5:05:55 PM	GDB Processor	INFO:BAYESTAR:uploaded sky map skymap.fits	

- External Coincidence
- Parameter Estimation
- EM Observations
- Full Event Log

Coincident astrophysical event or EM follow-up observations



10^{-21}
10^{-22}
10^{-23}
$\sqrt{S(f)}$ and $2|h(f)|\sqrt{f}$ (strain/$\sqrt{\text{Hz}}$)
Hanford
Livingston
10^1
10^2
10^3
Frequency (Hz)
GW150914
LVT151012
GW151226
1.0
0.5
0.0
−0.5
−1.0
Strain (10^{-21})
0.0
0.5
1.0
1.5
2.0
Time from 30 Hz (s)

Sep 14, 2015 09:50:45 UTC

GraceDB — Gravitational Wave Candidate Event Database

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3 mins later

Basic Info

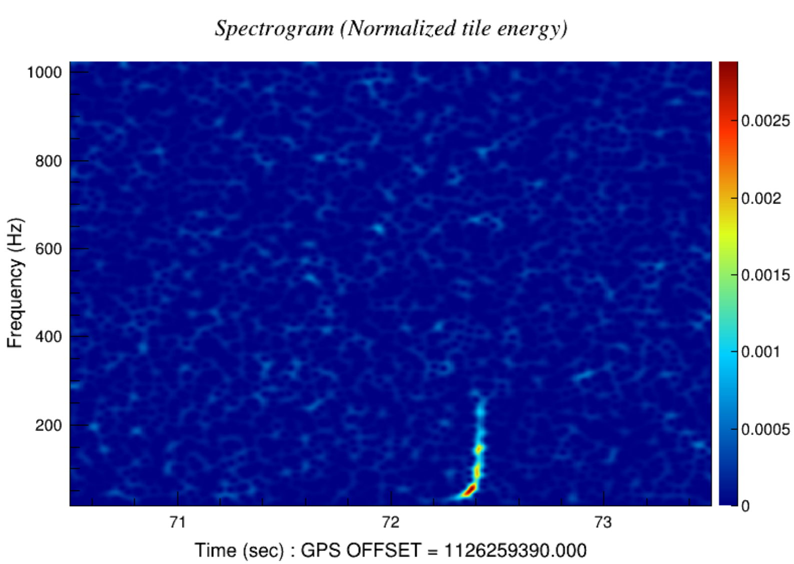
UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	FAR (Hz)	Links	UTC Submitted
G184098	H1OK L1OK	Burst	CWB	AllSky	H1,L1	1126259462.3910	1.178e-08	Data	2015-09-14 09:53:51 UTC

Analysis-Specific Attributes

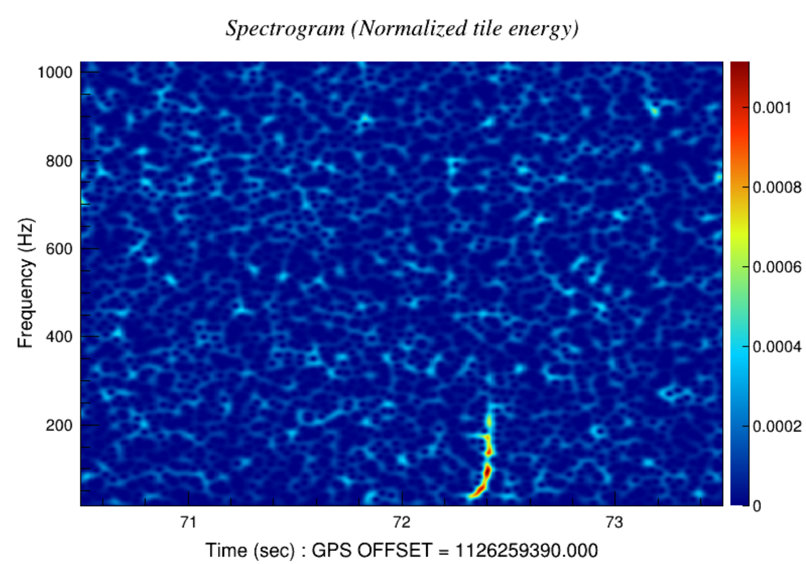
start_time	1126259461	central_freq	123.8285	false_alarm_rate	
start_time_ns	750000000	bandwidth	51.8386	ligo_axis_ra	130.9219
duration	2.477e-02	amplitude	1.410e+01	ligo_axis_dec	4.4808
peak_time	None	snr	23.4521	ligo_angle	None
peak_time_ns	None	confidence		ligo_angle_sig	None

SNR = 23.45

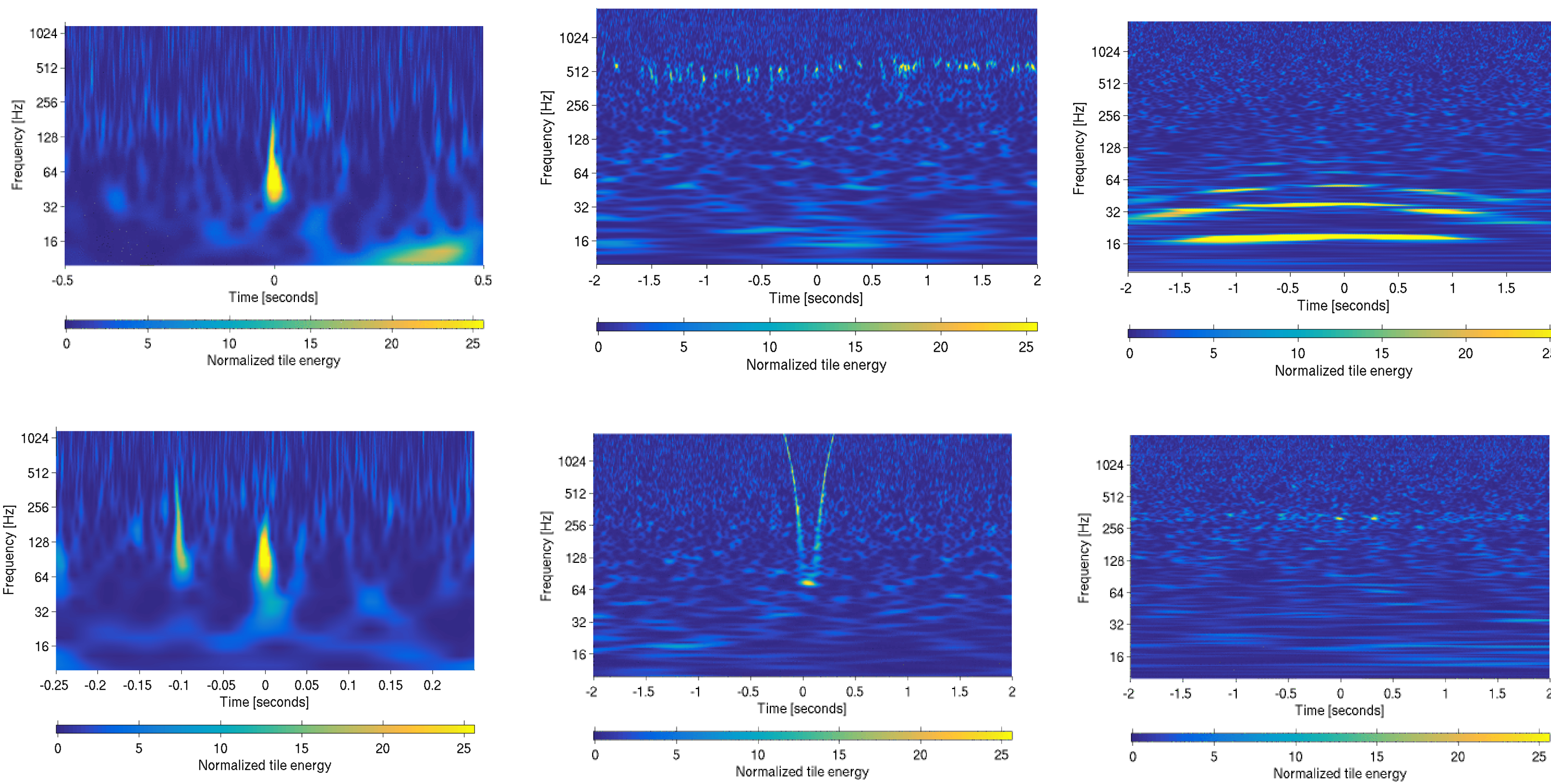
Hanford H1



Livingston H1



Glitch zoo



Credits: Coughlin, Smith et al, Gravity-spy zooniverse.org

VOevent

Example of preliminary alert formatted as a VO event


```xml
<?xml version="1.0" encoding="UTF-8"?>
<voe:VOEvent xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xmlns:voe="http://www.ivoa.net/xml/VOEvent/v2.0"
xsi:schemaLocation="http://www.ivoa.net/xml/VOEvent/v2.0
http://www.ivoa.net/xml/VOEvent/VOEvent-v2.0.xsd" version="2.0" role="test"
ivorn="ivo://gwnet/gcn_sender#M137606-1-Preliminary">
    <Who>
        <Date>2015-04-22T21:12:08</Date>
        <Author>
            <contactName>LIGO Scientific Collaboration and Virgo Collaboration</contactName>
        </Author>
    </Who>
    <What>
        <Param name="Pkt_Ser_Num" dataType="string" value="1"/>
     <Param name="GraceID" dataType="string" value="M137606" ucd="meta.id">
         <Description>Identifier in GraceDB</Description>
     </Param>
     <Param name="AlertType" dataType="string" value="Preliminary" ucd="meta.version" unit="">
         <Description>VOEvent alert type</Description>
     </Param>
     <Param name="EventPage" dataType="string" value="https://gracedb.ligo.org/events/M137606" ucd="meta.ref.url">
         <Description>Web page for evolving status of this candidate event</Description>
     </Param>
     <Param name="Instruments" dataType="string" value="H1,L1" ucd="meta.code">
         <Description>List of instruments used in analysis to identify this event</Description>
     </Param>
     <Param name="FAR" dataType="float" value="3.77232633462e-14" ucd="arith.rate;stat.falsealarm" unit="Hz">
         <Description>False alarm rate for GW candidates with this strength or greater</Description>
     </Param>
     <Param name="Pipeline" dataType="string" value="gstlal" ucd="meta.code" unit="">
         <Description>Low-latency data analysis pipeline</Description>
     </Param>
     <Param name="Search" dataType="string" value="MDC" ucd="meta.code" unit="">
         <Description>Specific low-latency search</Description>
     </Param>
     <Param name="ChirpMass" dataType="float" value="1.12945318222" ucd="phys.mass" unit="solar mass">
         <Description>Estimated CBC chirp mass</Description>
     </Param>
     <Param name="Eta" dataType="float" value="0.245523989341" ucd="phys.mass;arith.factor" unit="">
         <Description>Estimated ratio of reduced mass to total mass</Description>
     </Param>
     <Param name="MaxDistance" dataType="float" value="111.63056" ucd="pos.distance" unit="Mpc">
         <Description>Estimated maximum distance for CBC event</Description>
     </Param>
    </What>
    <WhereWhen>
      <ObsDataLocation>
        <ObservatoryLocation id="LIGO Virgo"/>
        <ObservationLocation>
          <AstroCoordSystem id="UTC-FK5-GEO"/>
          <AstroCoords coord_system_id="UTC-FK5-GEO">
            <Time>
              <TimeInstant>
                <ISOTime>2010-09-27T14:09:05.425029</ISOTime>
              </TimeInstant>
            </Time>
            <Position2D>
              <Value2>
                <C1>0.000000</C1>
                <C2>0.000000</C2>
              </Value2>
              <Error2Radius>180.000000</Error2Radius>
            </Position2D>
          </AstroCoords>
        </ObservationLocation>
      </ObsDataLocation>
    </WhereWhen>
    <How>
      <Description>Candidate gravitational wave event identified by low-latency analysis</Description>
      <Description>H1: LIGO Hanford 4 km gravitational wave detector</Description>
      <Description>L1: LIGO Livingston 4 km gravitational wave detector</Description>
    </How>
    <Description>Report of a candidate gravitational wave event</Description>
</voe:VOEvent>
```