Electromagnetic follow-up of gravitational waves

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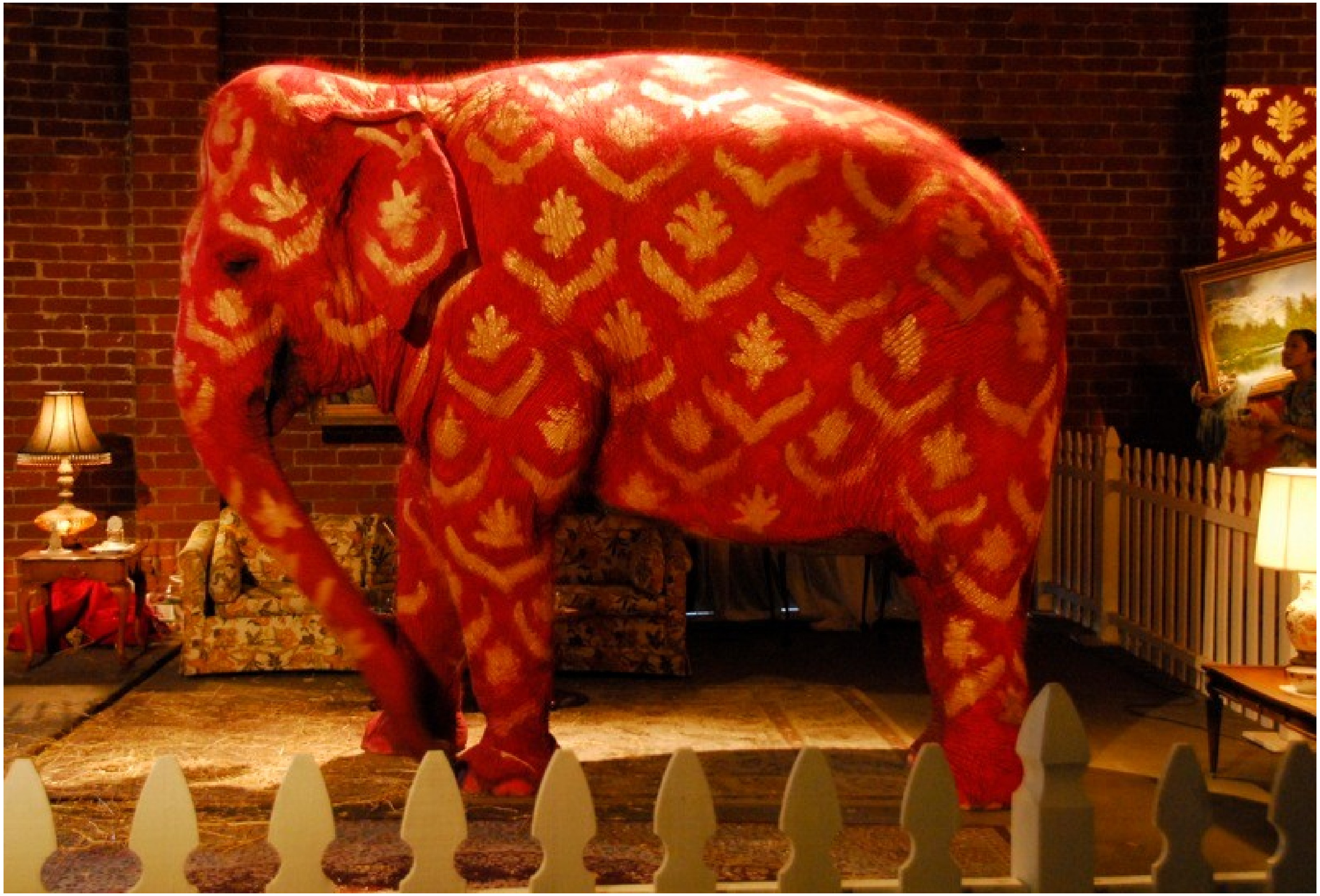
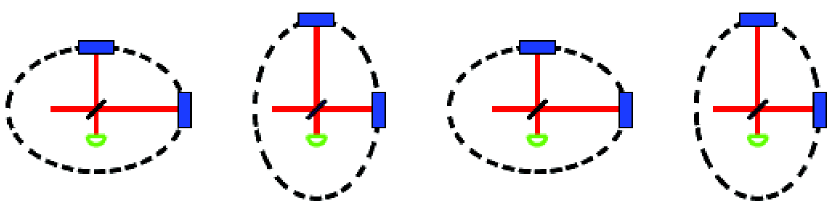
(for the LIGO Scientific Collaboration
and the Virgo Collaboration)

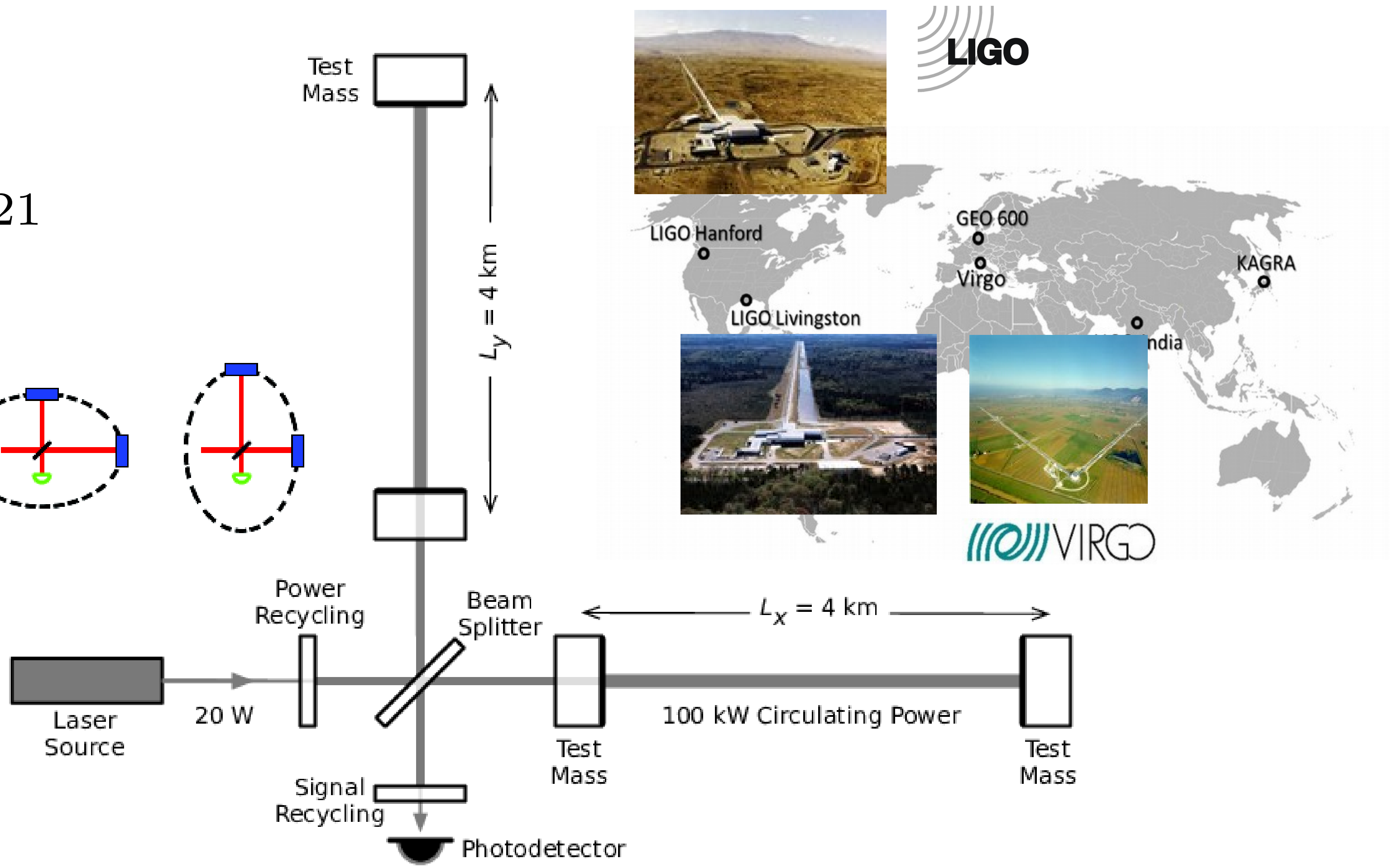
Coalescence of two black holes (credits: SXS)



Advanced detectors of gravitational waves

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





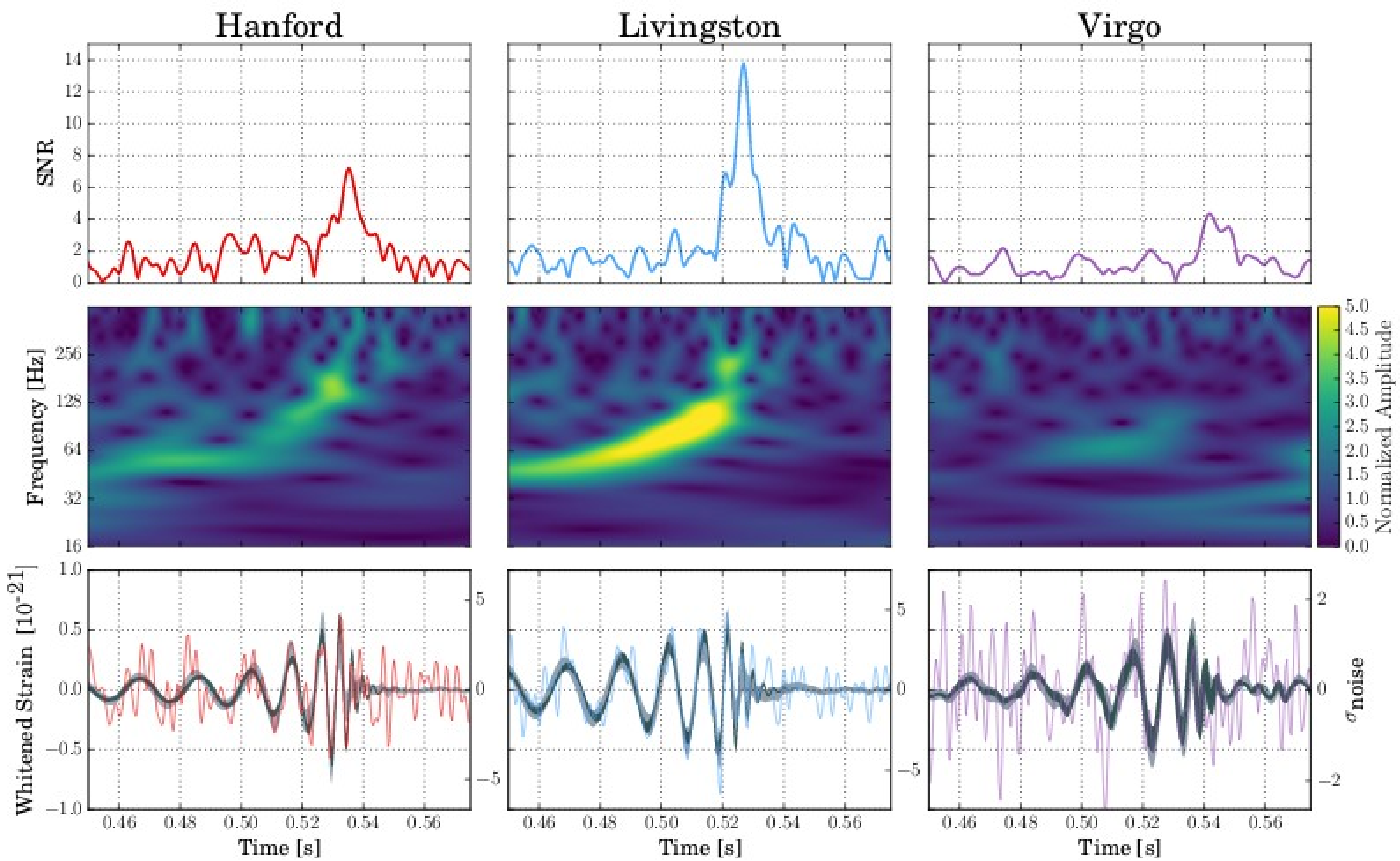
3 to 5 x more sensitive than "initial" detectors

x 100 more sensitive at low freq (40 Hz)

Where do we stand?

- aLIGO 1st science run O1 – Sep 2015-Jan 2016
  - 2 confirmed BBH events: GW150914, GW151226
  - 1 event candidate: LVT151012
- aLIGO 2nd science run O2 – Part 1: Nov 30 2016-Jul 31 2017
  - 1 confirmed BBH event: GW170104
- Advanced Virgo joined O2 – Part 2: Aug 1st – Aug 25 2017
  - **1 confirmed BBH event: GW170914 announced in Turin yesterday!**
- For O2 Parts 1 & 2:
  - BNS range: LIGO L1 at 80-100 Mpc, H1 at 60-70 Mpc, V1 at ~27 Mpc
  - Only partial results announced so far. Work in progress… Stay tuned!

GW170814: three-detector BBH event



30 Msun – 25 Msun, z ~ .11

Much better sky localization (60 sq deg), non-GR polarization

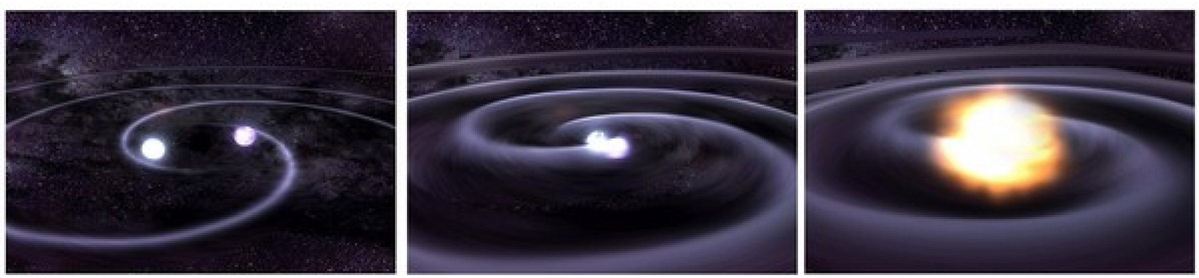
https://dcc.ligo.org/P170814 – Phys. Rev Letters accepted

Outline

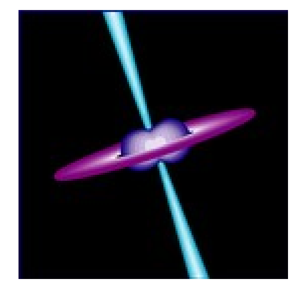
- Motivations and context
- Overview of the low-latency data analysis infrastructure
  - Searches, data quality, source reconstruction, alert handling
- Next steps and outlook

Electromagnetic counterparts to gravitational wave events

- GW emitted energy is enormous
  - GW150914 – 3 $M_{sun}\,c^2 \sim 10^{54}$ 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



NASA

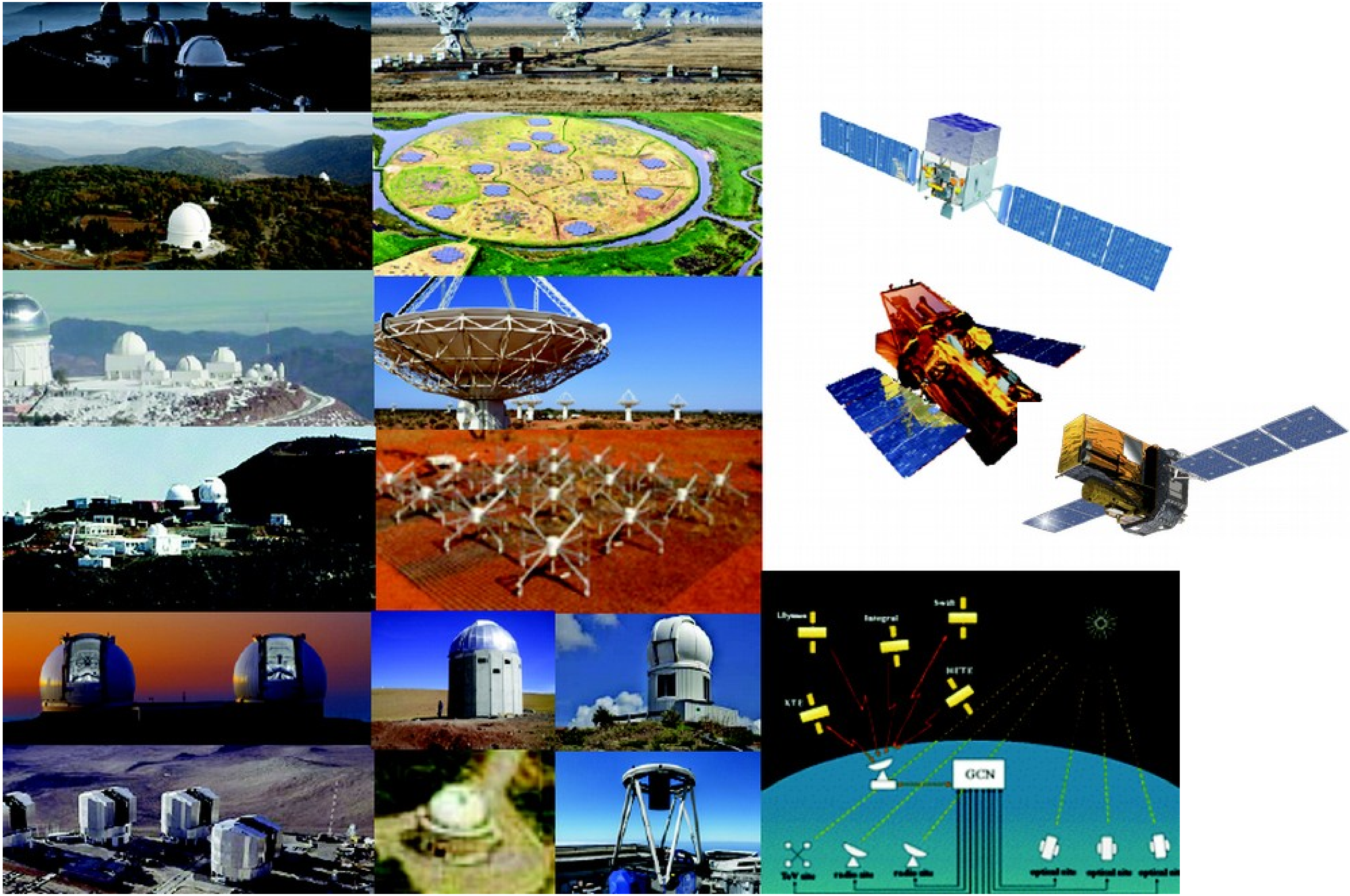


P.J.T. Leonard (NASA/GSFC)

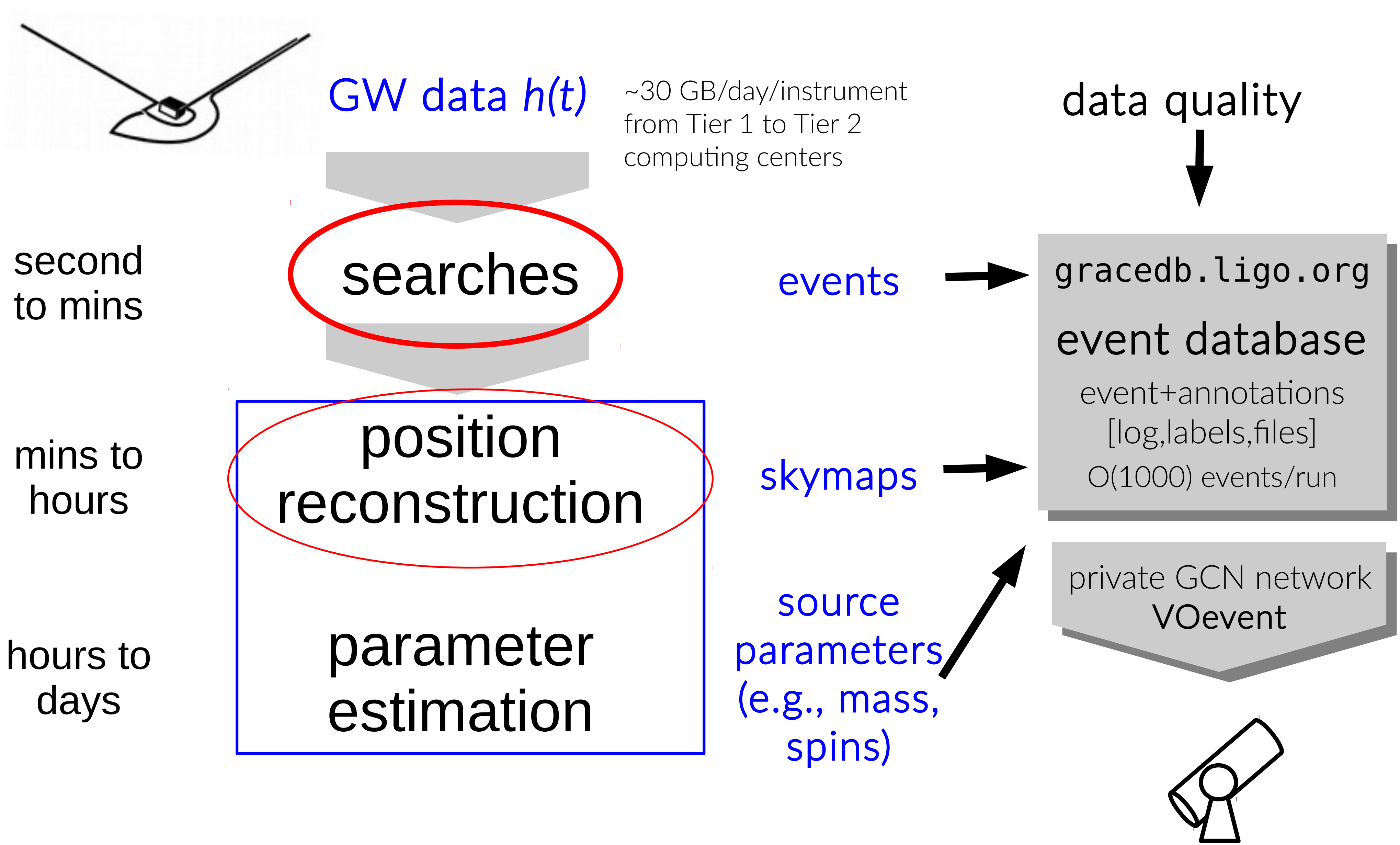
- Are short gamma-ray bursts associated with compact binary mergers (incl. neutron star)?
  - Prompt gamma-ray emission (beamed – 5 to 10 degrees)
  - X-ray or optical afterglow (observable for small inclination)
  - Kilonova (or macronova) due to radioactive decay of heavy elements in neutron-rich ejecta

Multimessenger astronomy

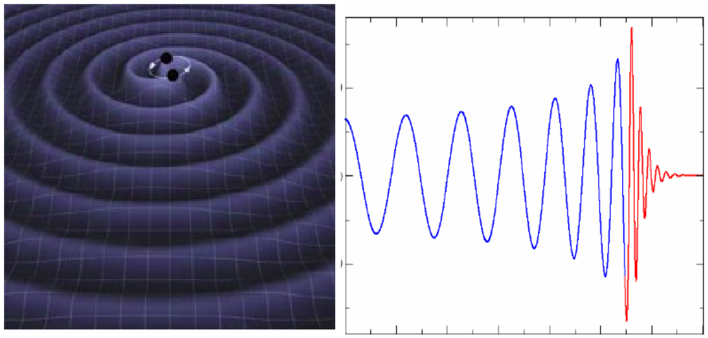
- Two approaches for joint GW and EM search
  - “Externally triggered” GW searches
    - Gamma-ray bursts, pulsar glitches, SGR flares, fast radio bursts, near-by supernovae, … + 20 publications
  - Electromagnetic follow-up of GW alerts (this talk)
    - LIGO & Virgo have signed MOUs with ~80 astronomer 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


GCN

Workflow – Big picture



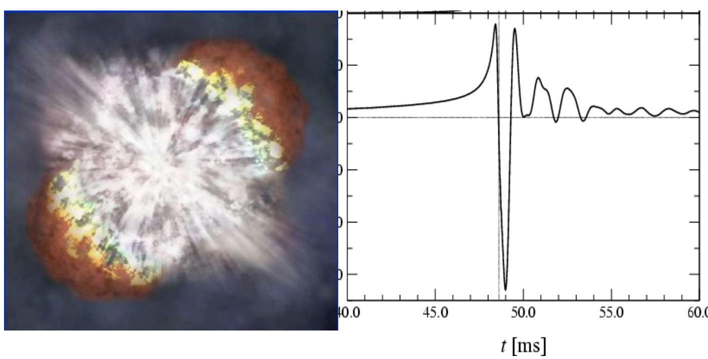
GW transient searches



Compact Binary Coalescence (CBC)

Known waveform – Matched filtering

Templates for a range of component masses and spin



Unmodelled GW Burst (< ~1 sec duration)

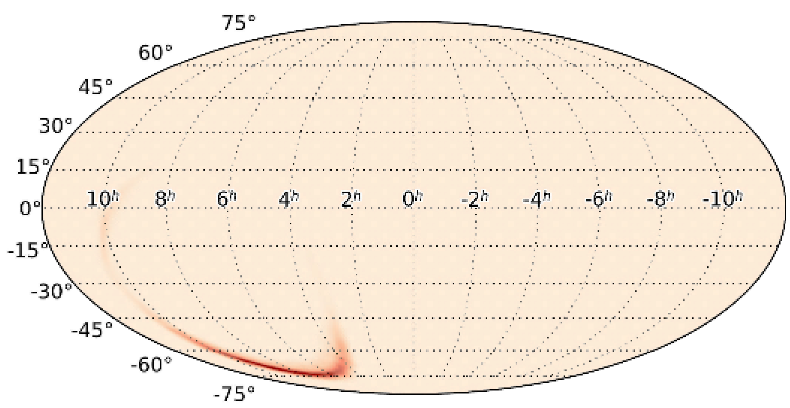
e.g. from stellar core collapse

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

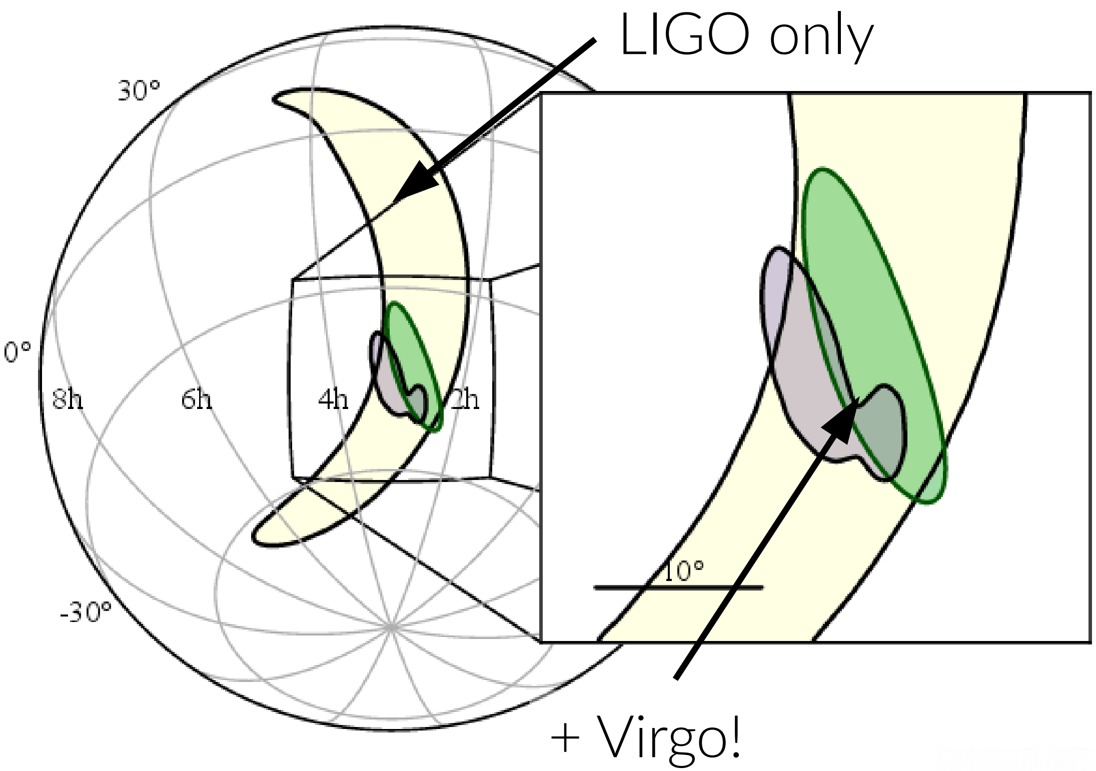
Source direction reconstruction



- Sky localization from multiple detectors
  - "Triangulation" or "aperture synthesis"
  - Uncertainty given by an irregular "banana"-shape region in probably skymap
  - Few 100 to 1000 sq degrees with 2 detectors
    Few 10 to 100 sq degrees with 3 detectors

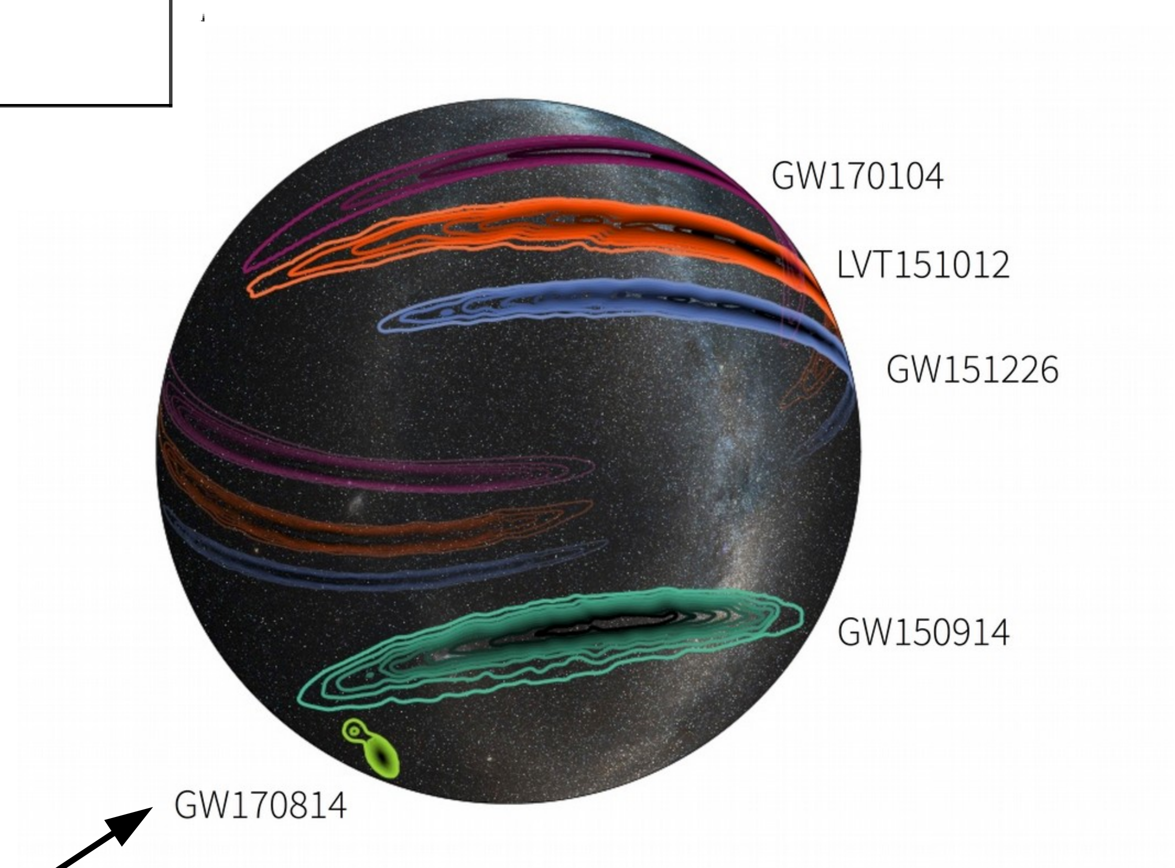
- Rapid localization
  - From arrival times, phases and amplitudes at each detectors
  - Minute latency, arXiv:1508.03634
  - Position dependent distance estimate – 3D skymap

- Full Bayesian estimation
  - Bayesian coherent parameter estimation
  - Hours or days latency



GW170814
Three-detector sky localization

LIGO LH	1160 sq degrees
+Virgo	60 sq degrees

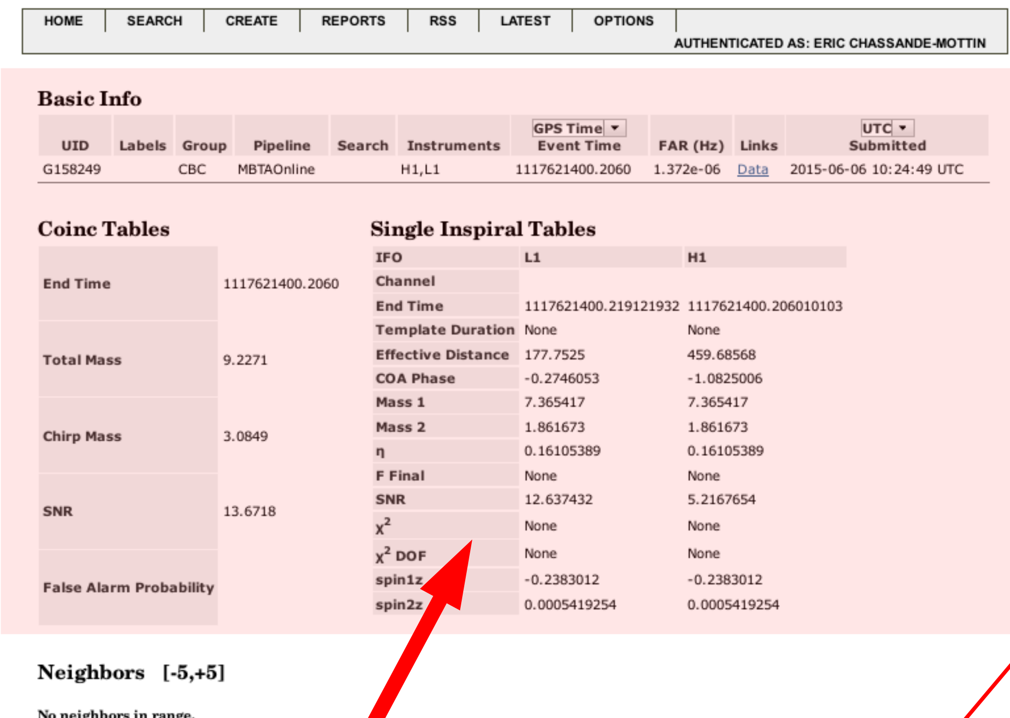


+ Virgo!

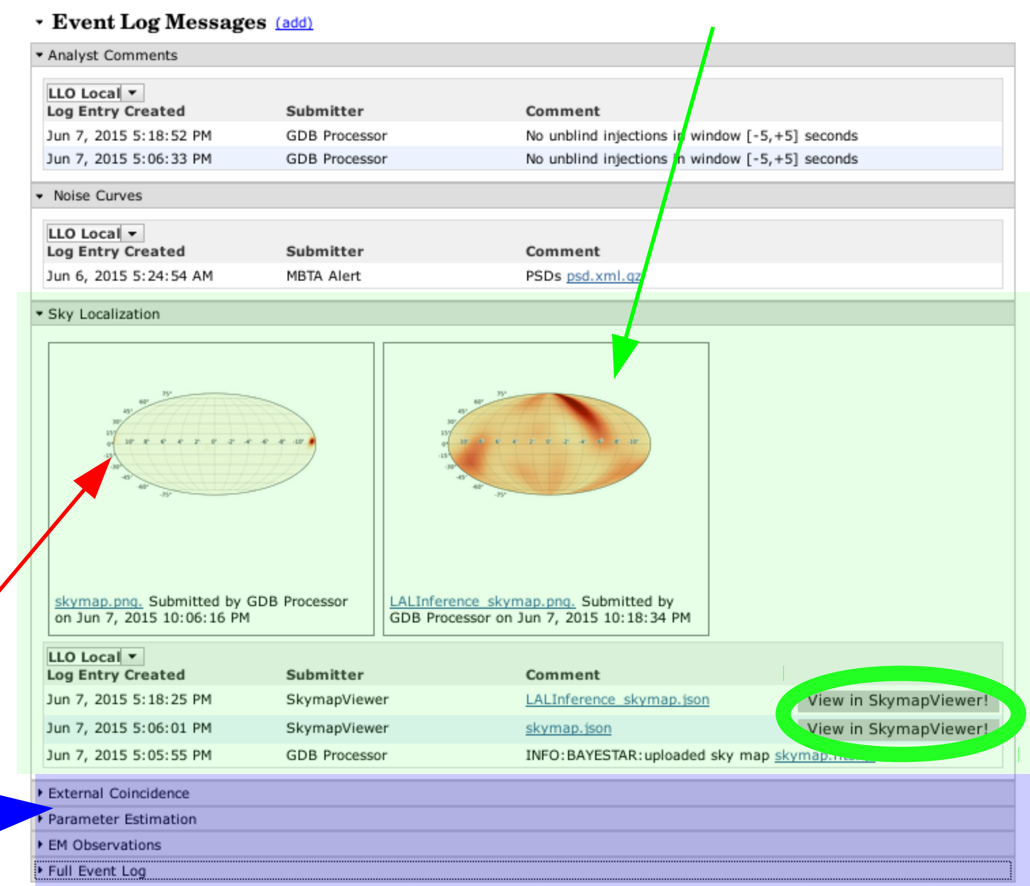
LIGO/Caltech/MIT/Leo Singer (Milky Way image: Axel Mellinger)

How is the information communicated?

GraceDB – Gravitational Wave Candidate Event DB



Alert updates or retraction <u>within hours</u>
Full parameter estimation



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

Initial alert <u>issued in 30 mins</u>
With rapid preliminary sky position

Coincident astrophysical event
or EM follow-up observations

GW alerts

Initial alerts

- Rapid sky localization
- Prompt binary classification (BNS, NS-BH, BBH) based on preliminary mass estimates
- ~30 mins latency on average during O2 with exceptions (special case, human in the loop)

Update alerts

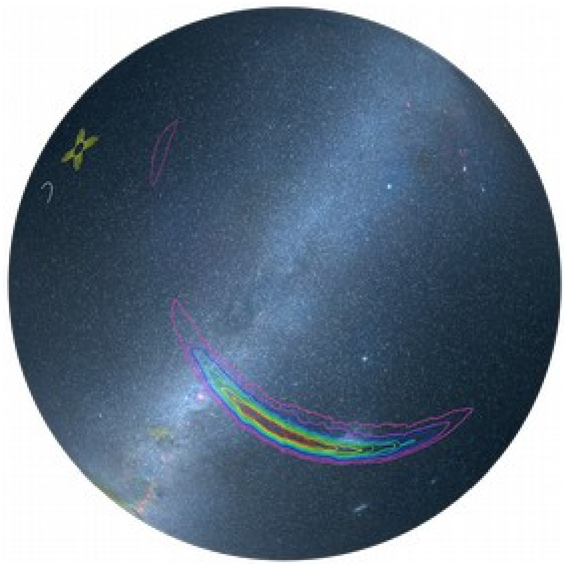
- Full Bayesian estimation
- Hours to days

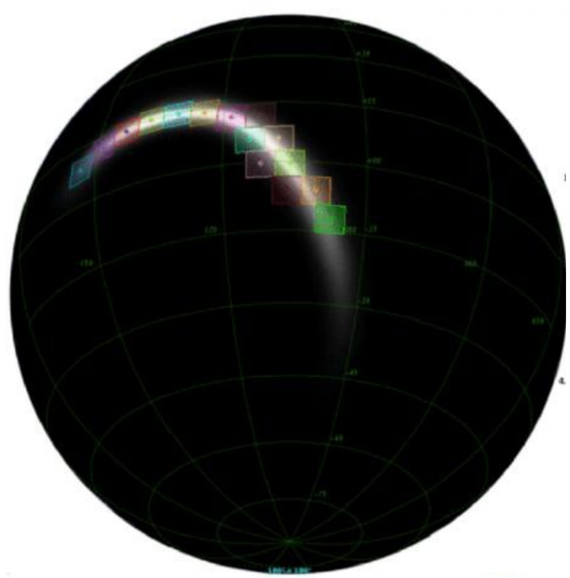
Layout of a GCN Notice

```
TITLE:              GCN/LVC NOTICE
NOTICE_DATE:        XXXXXX
NOTICE_TYPE:        TEST LVC Initial Skymap
TRIGGER_NUM:        XXXXXX
TRIGGER_DATE:       XXXXXX
TRIGGER_TIME:       XXXXXX
GROUP_TYPE:         X
SEARCH_TYPE:        X
PIPELINE_TYPE:      X
FAR:                XXXXXX [Hz]
TRIGGER_ID:         XXX
MISC:               XXXXXX
SKYMAP_URL:         https://gracedb.ligo.org/XXX
SKYMAP_BASIC_URL:   https://gracedb.ligo.org/XXX
EVENT_URL:          https://gracedb.ligo.org/XXX
```

We also send GCN Circulars

Useful software tools





- Skymap viewer
  https://losc.ligo.org/s/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)

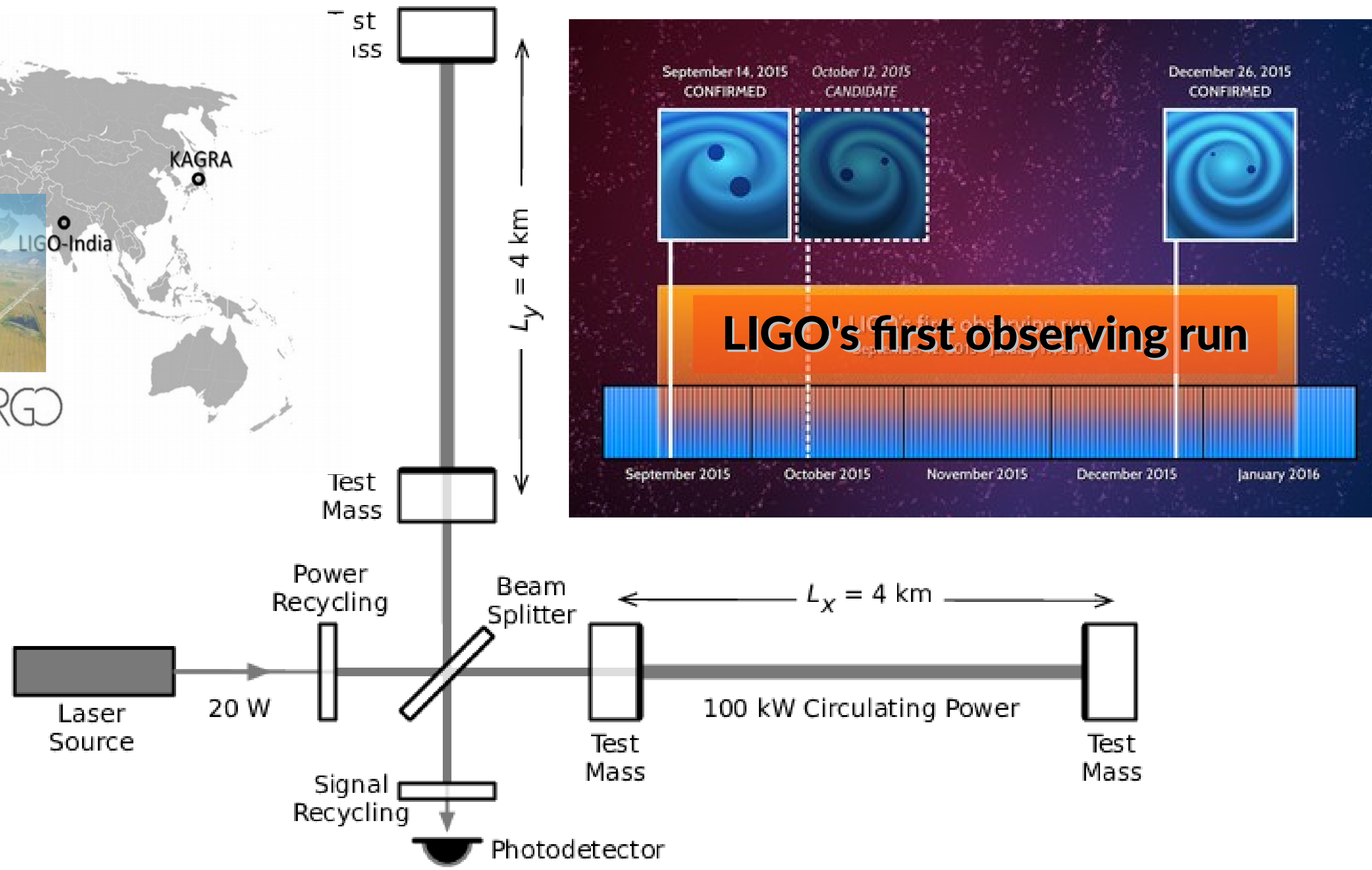
Outlook

- The world-wide network of gravitational-wave detectors has expanded
  - Three detector in operation!
  - > x 10 better sky localization → 10^{th} sq degree (full coverage "feasible")
- Electromagnetic follow-up program
  - So far, so good!
  - Infrastructure has enabled low-latency of LV data and communication with a large team of astronomer teams around the globe
  - Further improvements planned to further reduce the alert latency
  - Personal comment: reached the limit of GCN Circulars

    Centralized database for follow-up information **(detection and non detection), using queryable machine-readible data is likely to be an important tool for maximizing science in the future**

Fin.

Advanced detectors
First science run



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

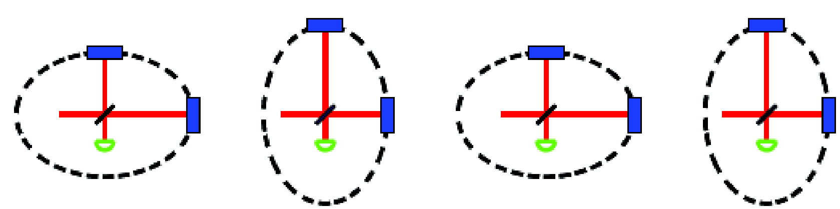
$$\delta \ell \sim 10^{-18} \mathrm{m}$$

1000th of nucleus radius!

3 to 5 x more sensitive than "initial" detectors

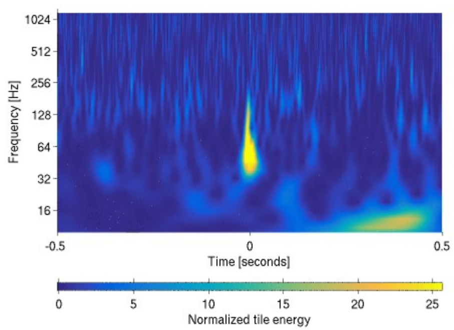
x 100 more sensitive at low frequencies (40 Hz)

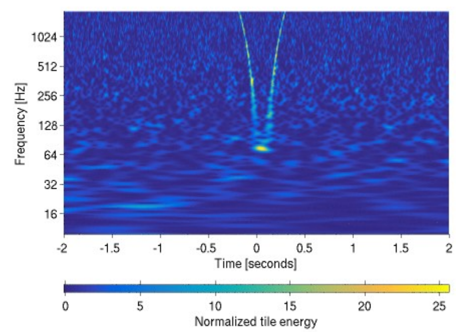
10 x space-time volume surveyed so far

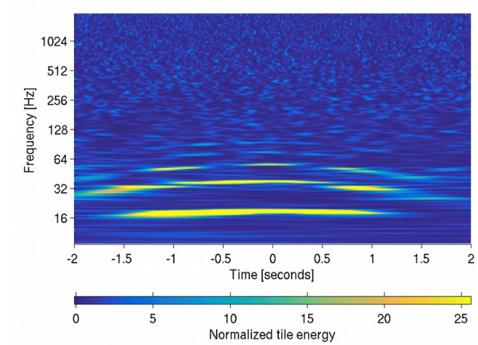


Low-latency data quality

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

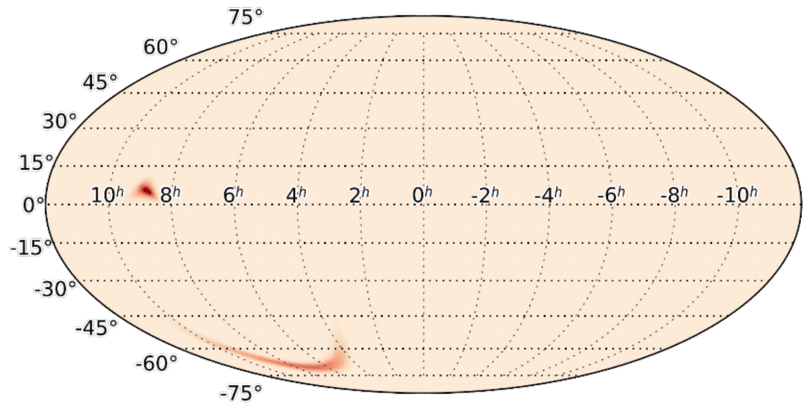




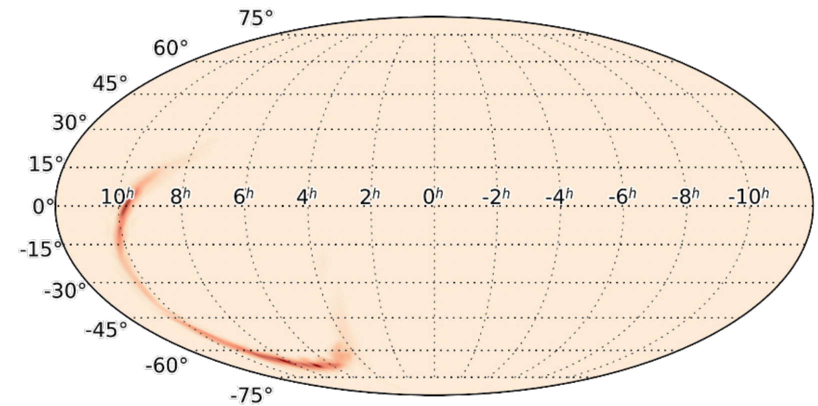


- The origin of glitches can be traced from auxiliary channels and control loop signals
  - 200 000 auxiliary channels (seismometers, magnetometers, …)
  - Large effort to characterize detector noise
  - Attempts to automatize using machine learning
- When eligible events occur, lvalert daemon interrogates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

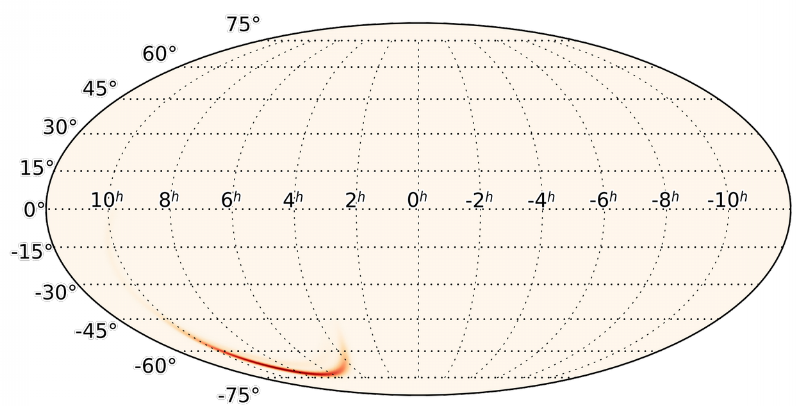
Credits for the glitches: Coughlin, Smith et al, Gravity-spy `zooniverse.org`



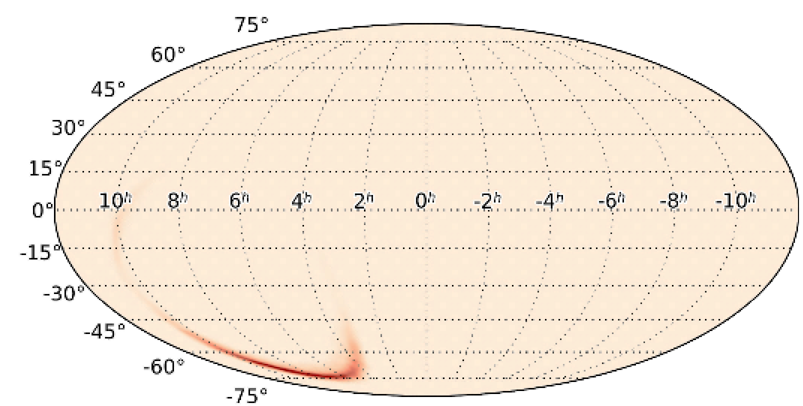
coherent WaveBurst
(first skymap communicated)



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

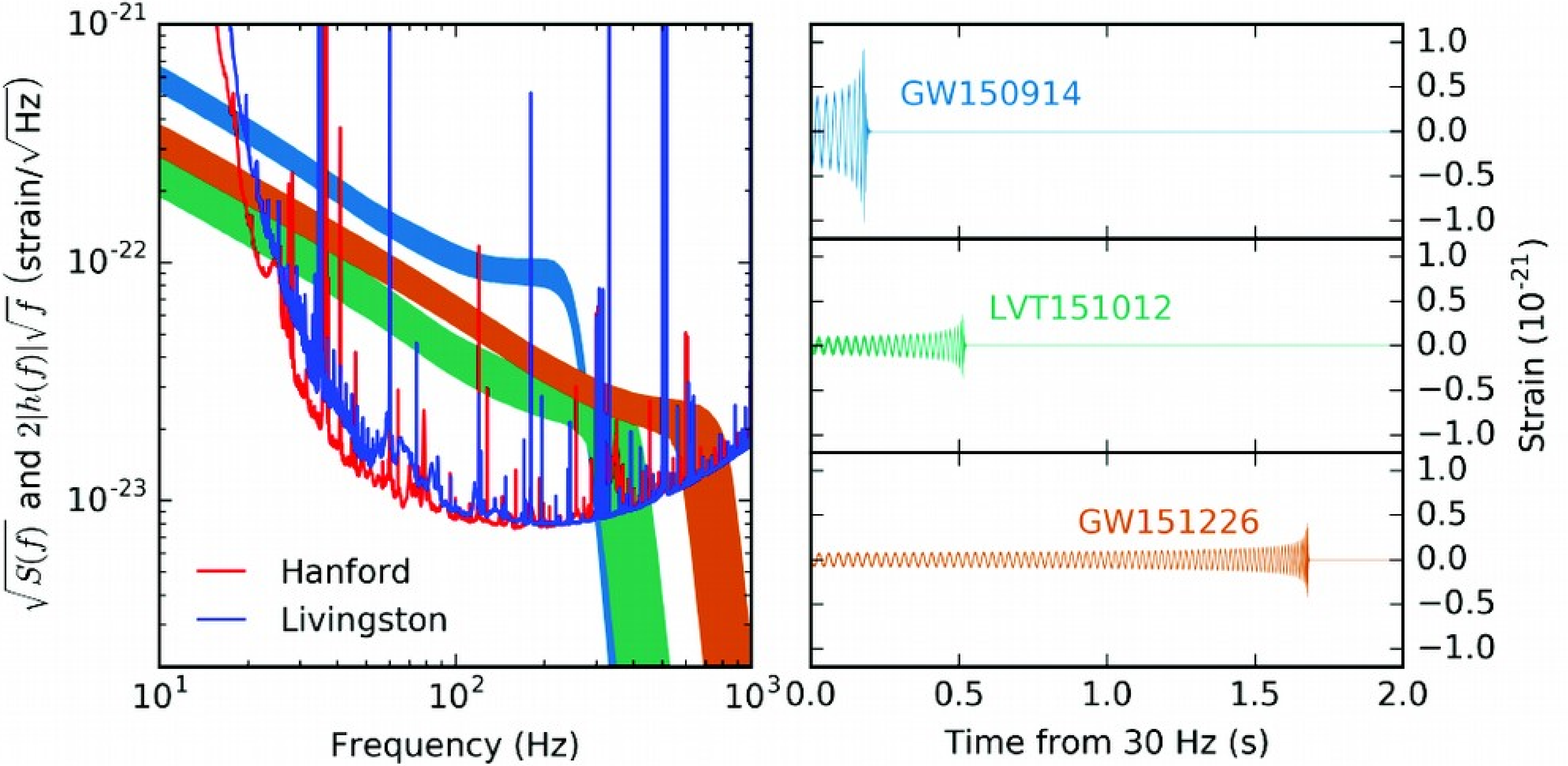
Third body [Seto&Muto 2011, cited in Murase+ 2016, ApJL 822]: tidal disruption of a star in a hierarchical triple with the BBH at time of merger

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)



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

Sep 14, 2015 09:50:45 UTC

GraceDB — Gravitational Wave Candidate Event Database

HOME | SEARCH | CREATE | REPORTS | RSS | LATEST | OPTIONS | DOCUMENTATION

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

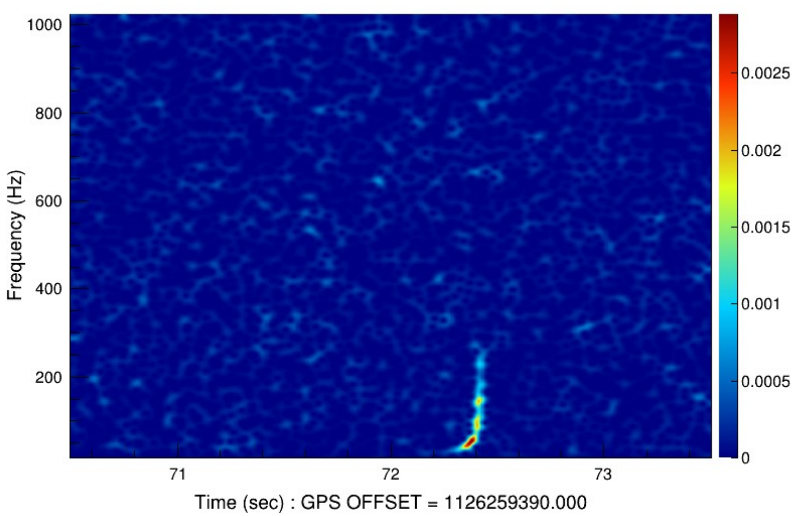
Analysis-Specific Attributes

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

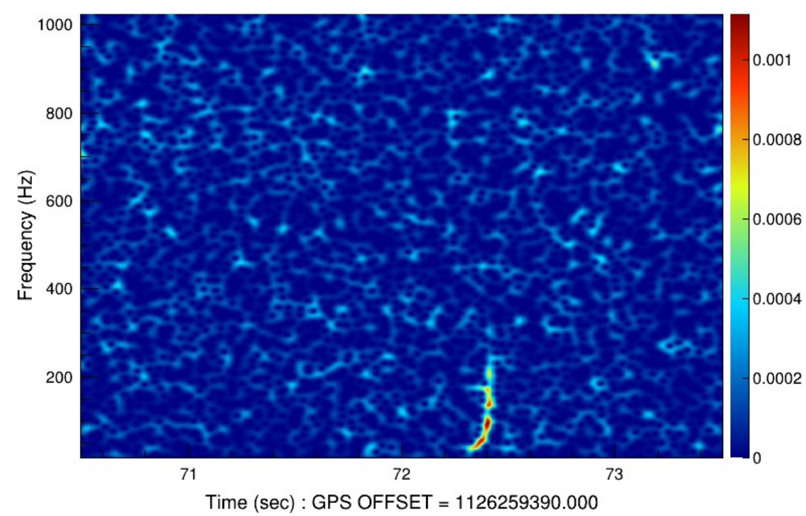
Hanford H1

Spectrogram (Normalized tile energy)

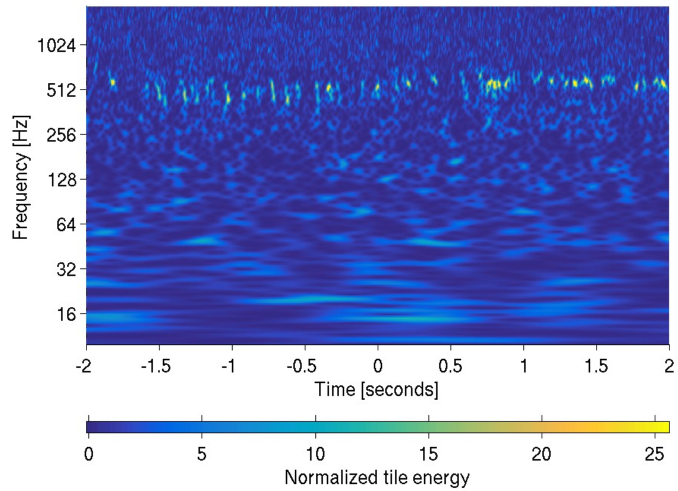


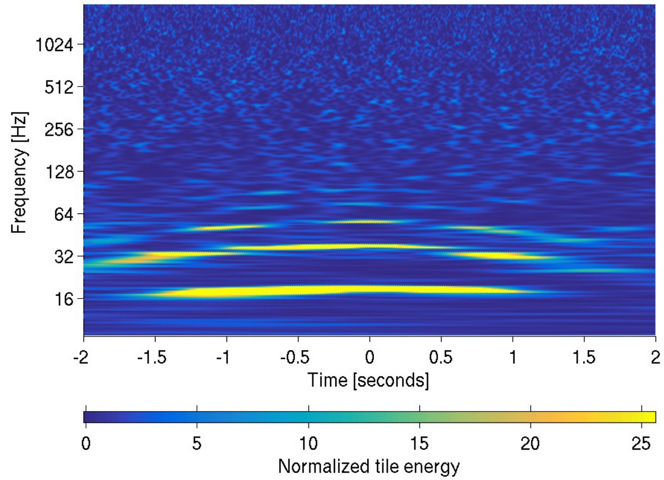
Livingston H1

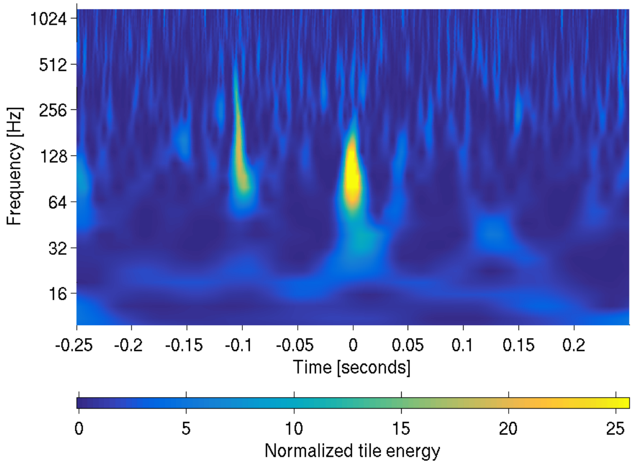
Spectrogram (Normalized tile energy)

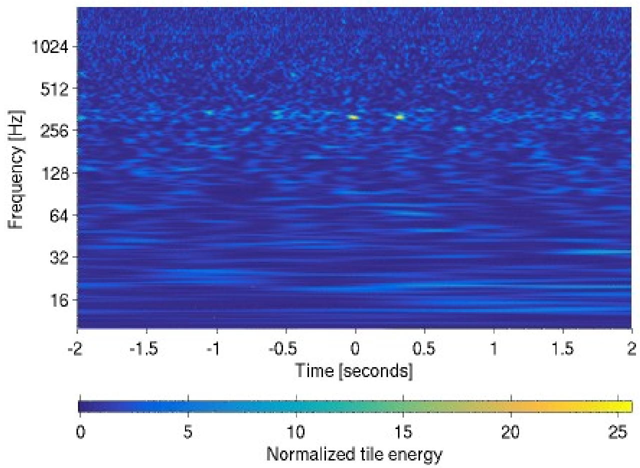


Glitch zoo









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"?>
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ivorn="ivo://gwnet/gcn_sender#M137606-1-Preliminary">
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        <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">
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     </Param>
     <Param name="AlertType" dataType="string" value="Preliminary" ucd="meta.version" unit="">
         <Description>VOEvent alert type</Description>
     </Param>
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         <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="">
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     </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>
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        <ObservatoryLocation id="LIGO Virgo"/>
        <ObservationLocation>
          <AstroCoordSystem id="UTC-FK5-GEO"/>
          <AstroCoords coord_system_id="UTC-FK5-GEO">
            <Time>
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                <ISOTime>2010-09-27T14:09:05.425029</ISOTime>
              </TimeInstant>
            </Time>
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        </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>
```
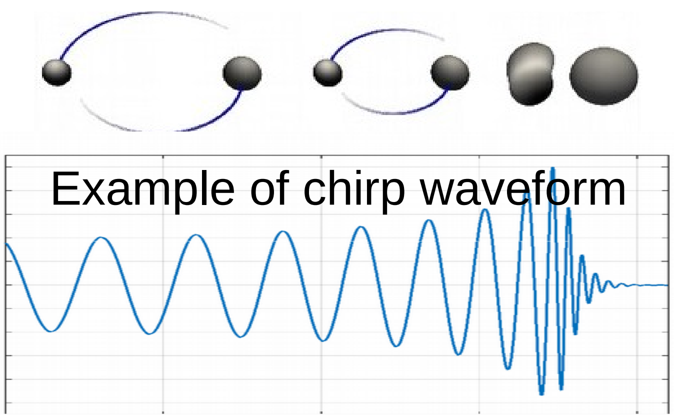
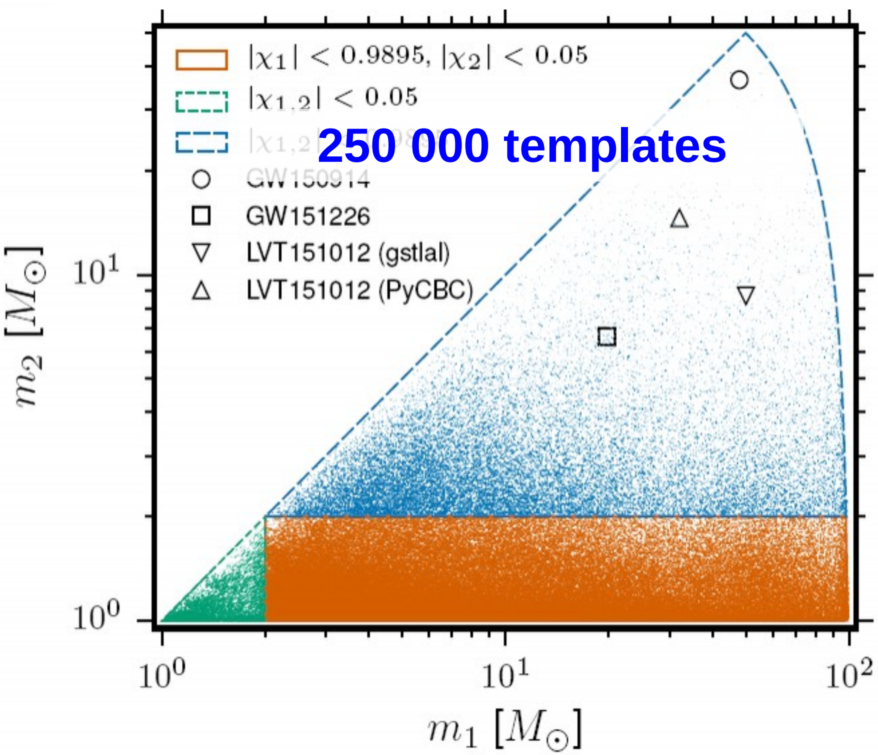

Searches for compact binary coalescences (1)

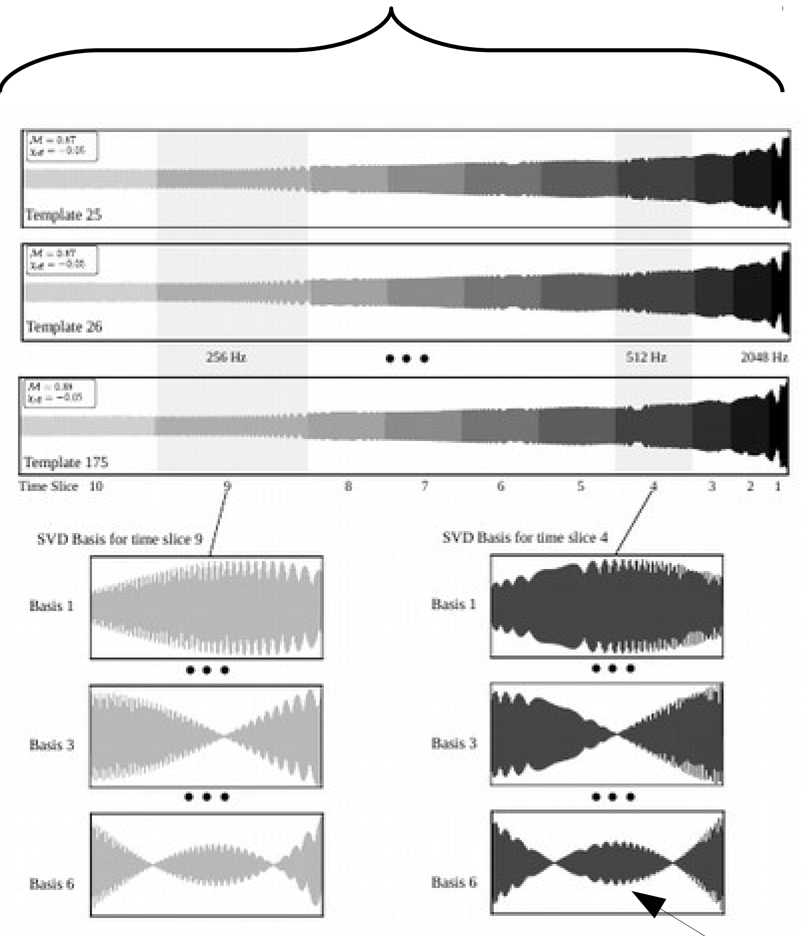




- Pattern matching
  - **Correlate data with the expected waveform** from astrophys. model
  - **Template bank** that covers the space of astrophysical signals
- Reject background
  - **Control goodness-of-fit** using χ^2 test of candidate's spectra to mitigate instrumental transient noise (glitch)
  - **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



< 10 SVD basis filters per slice

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

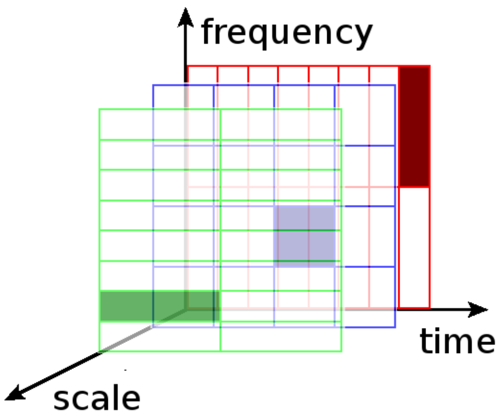
Multi-Band Template Analysis (MBTA)

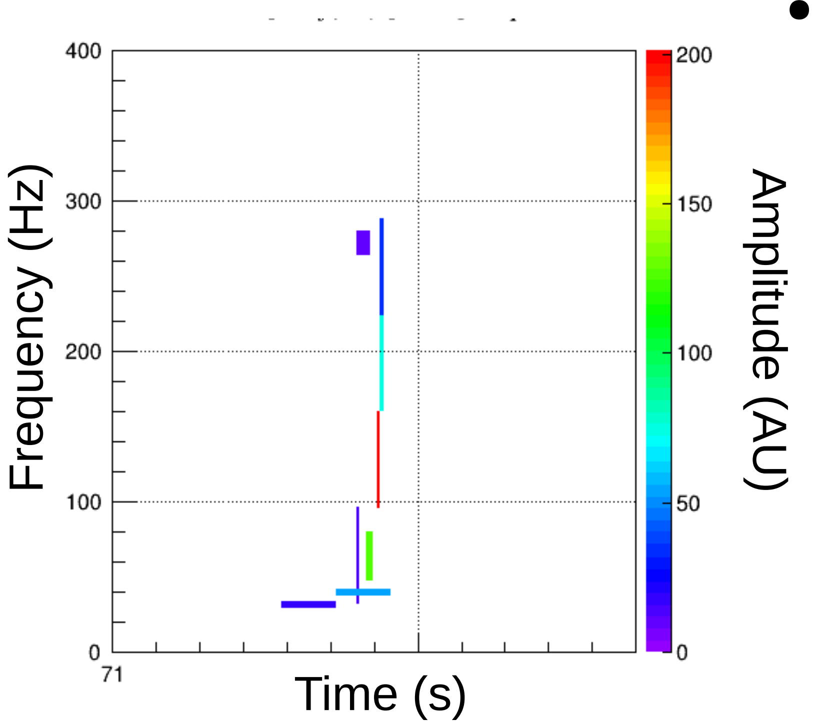
- divides freq. band into low/high subbands → lower number of templates in each subbands and lower sample rate – arxiv:1507.01787

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

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**

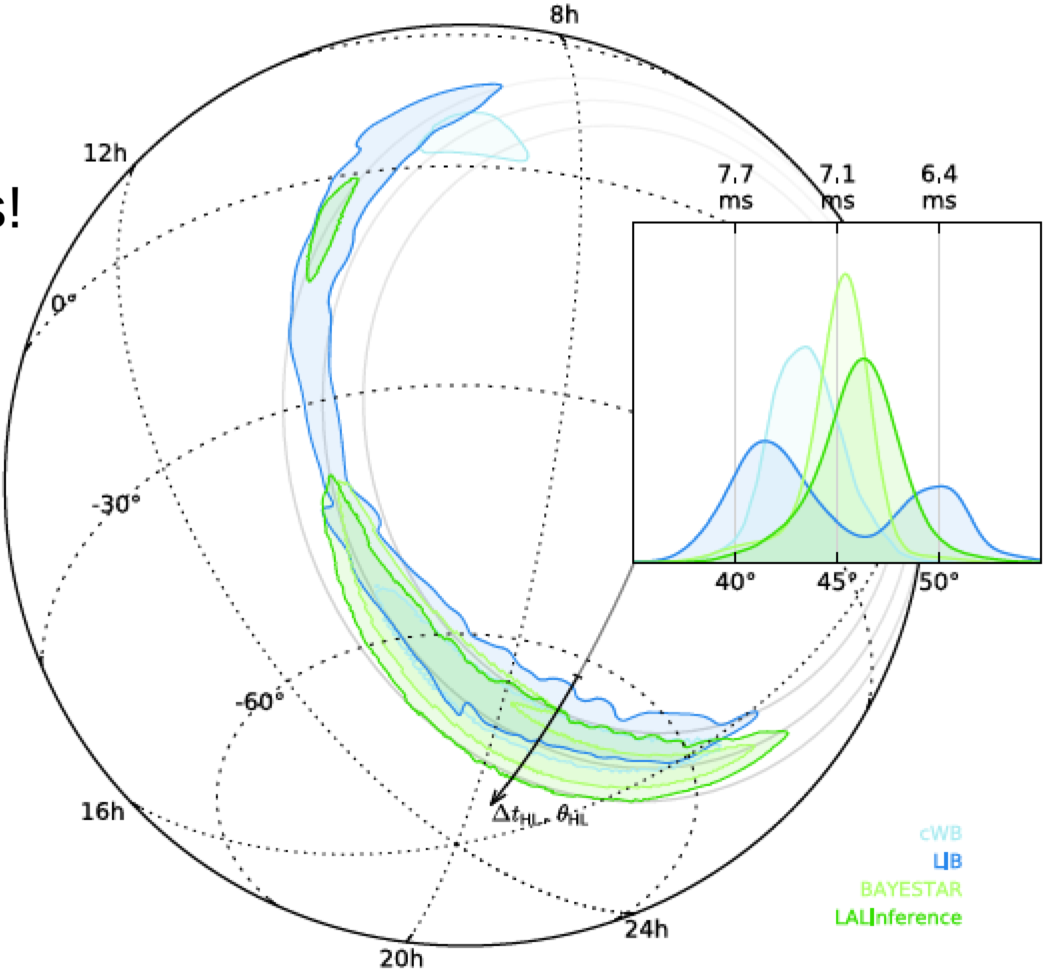
Sep 14, 2015 (1)

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

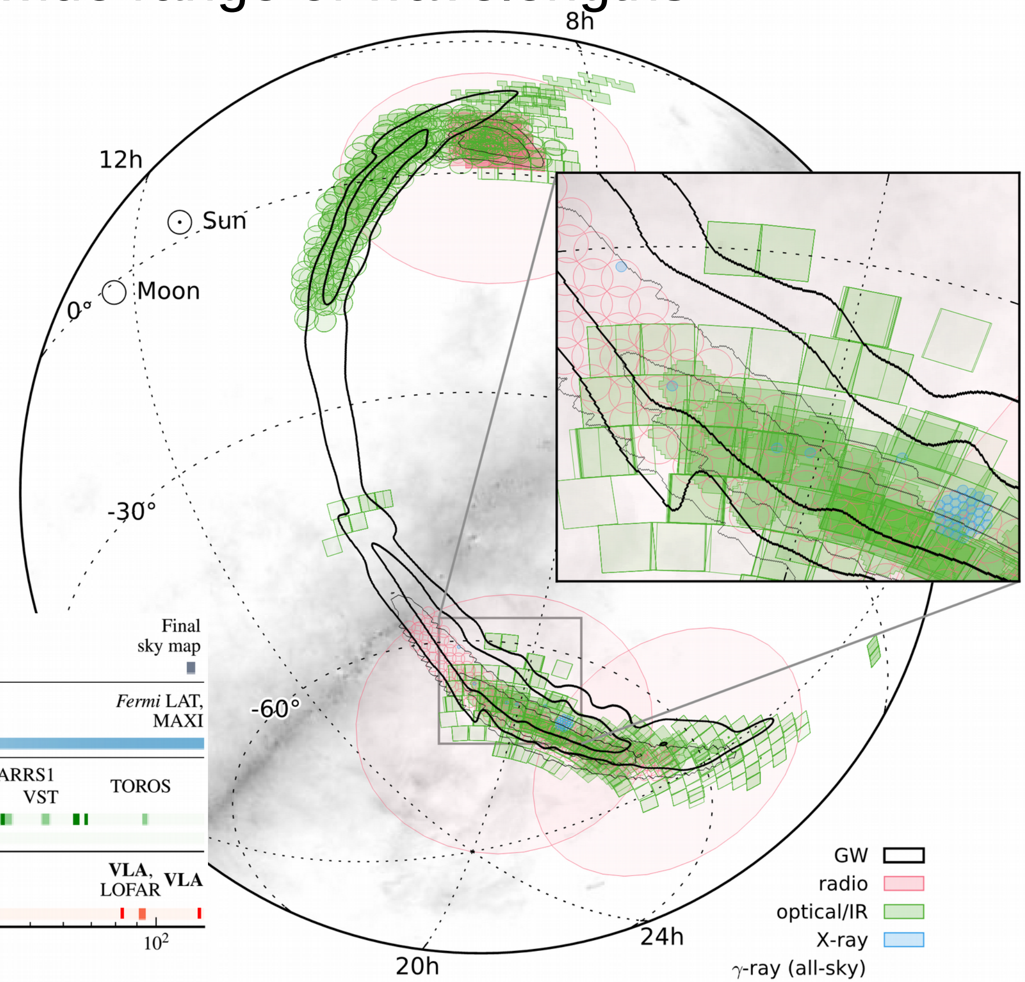
Abbott et al, ApJL 826, L13

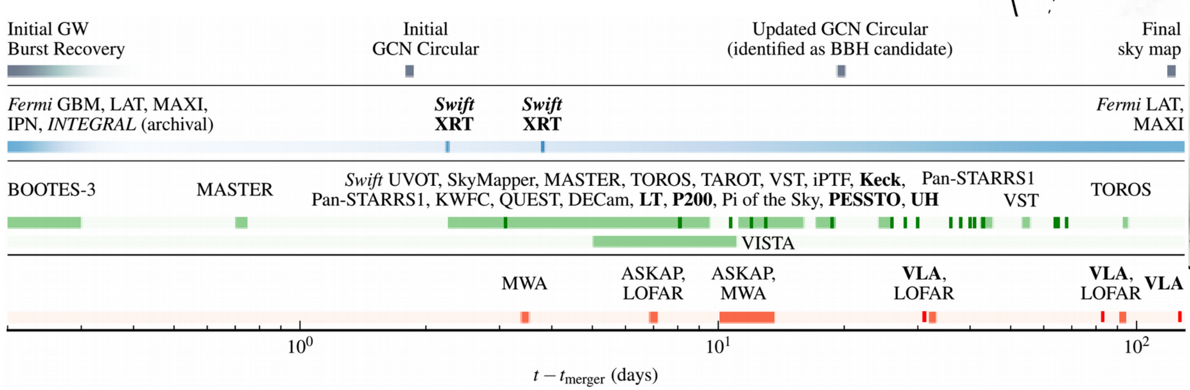
Sep 14, 2015 (2)

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