Searches of gravitational-wave transients with low latency

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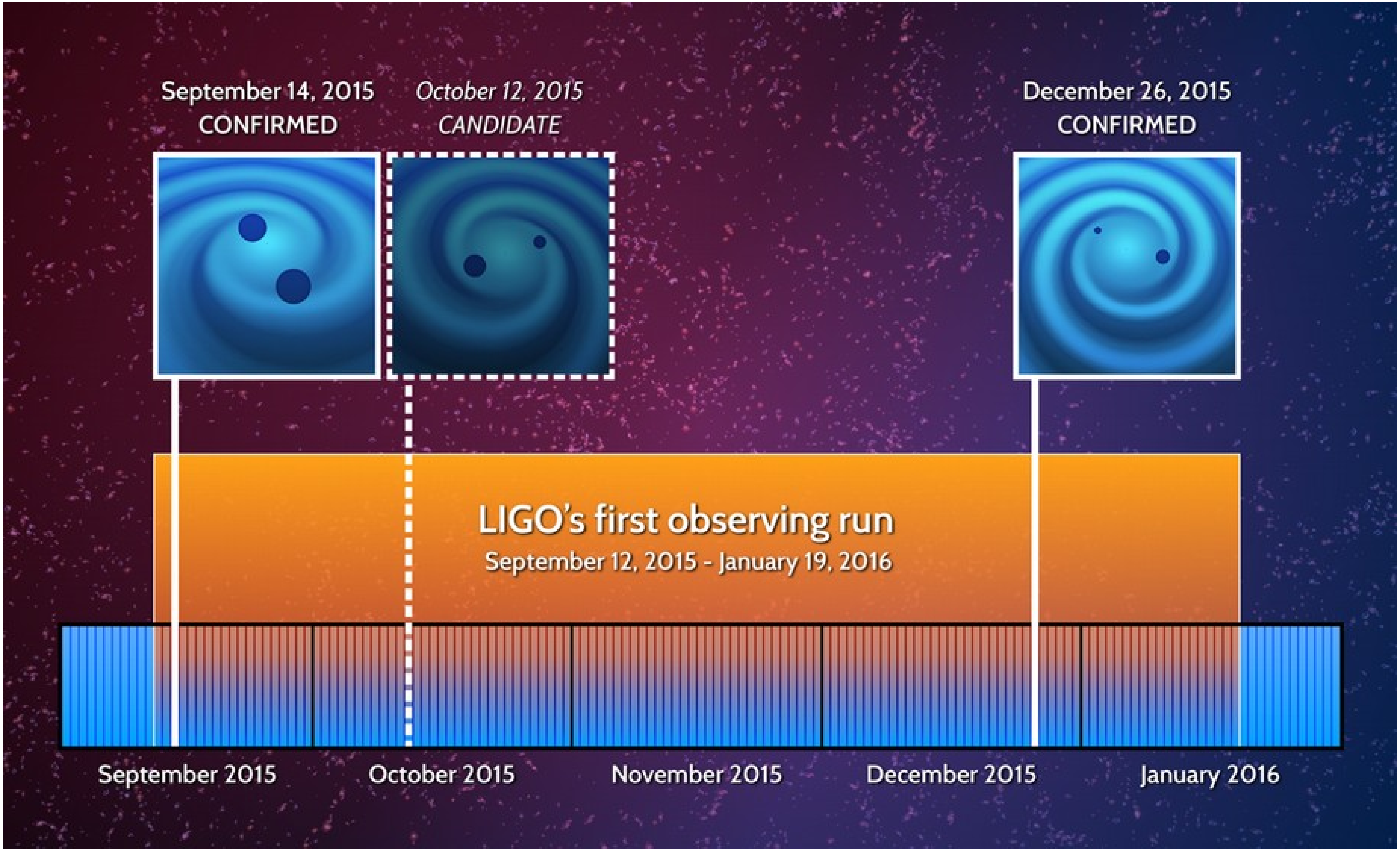
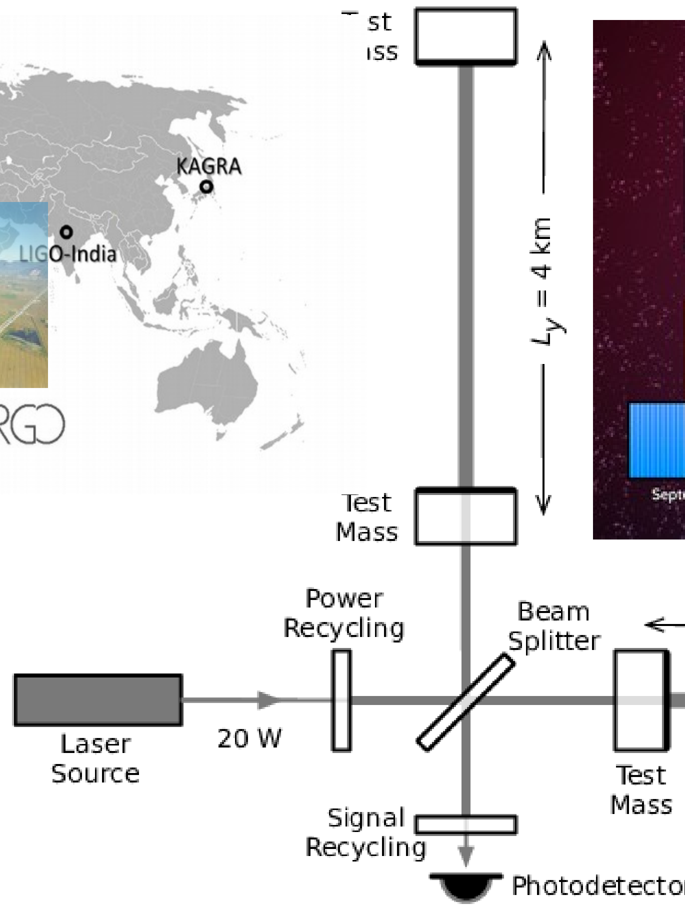
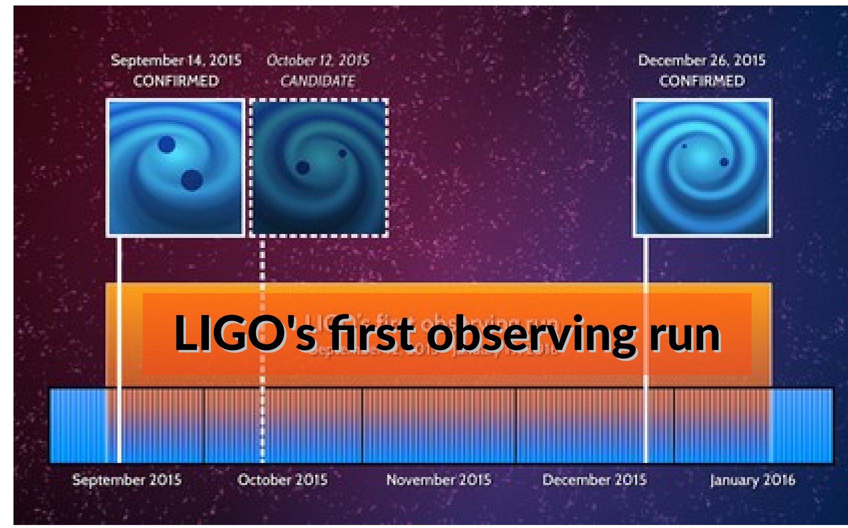
for the LIGO Scientific Collaboration
and the Virgo Collaboration

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





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

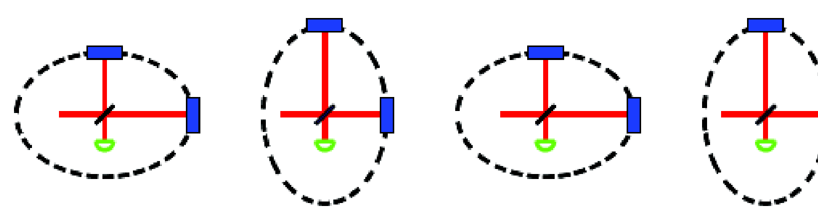
$\delta\ell \sim 10^{-18}\mathrm{m}$

1000$^{\text{th}}$ 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

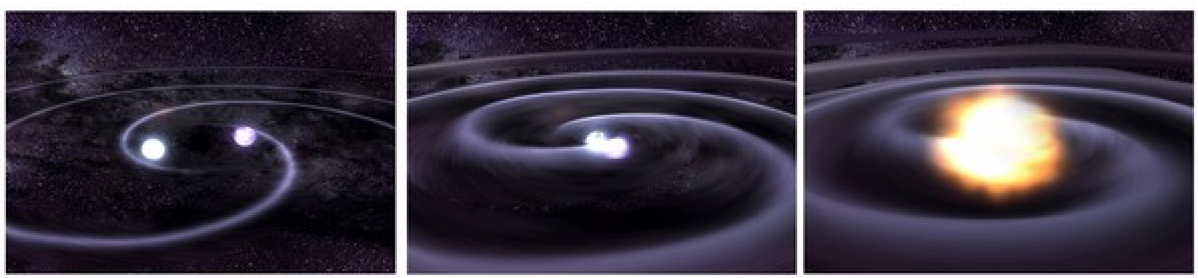
- **This is the birth of gravitational astronomy**
- Review of **low-latency searches**
  - Enables follow-up of GW alerts by other observatories in the electromagnetic spectrum

    Bridge to "conventional" astronomy

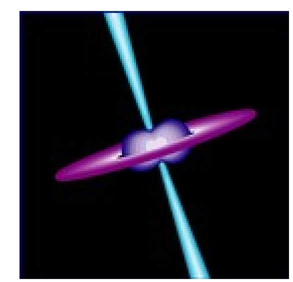
- Motivations
- Low-latency data analysis methods and infrastructure
  - Searches, data quality, source reconstruction, alert handling
- Outlook

Electromagnetic counterparts to gravitational wave events

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

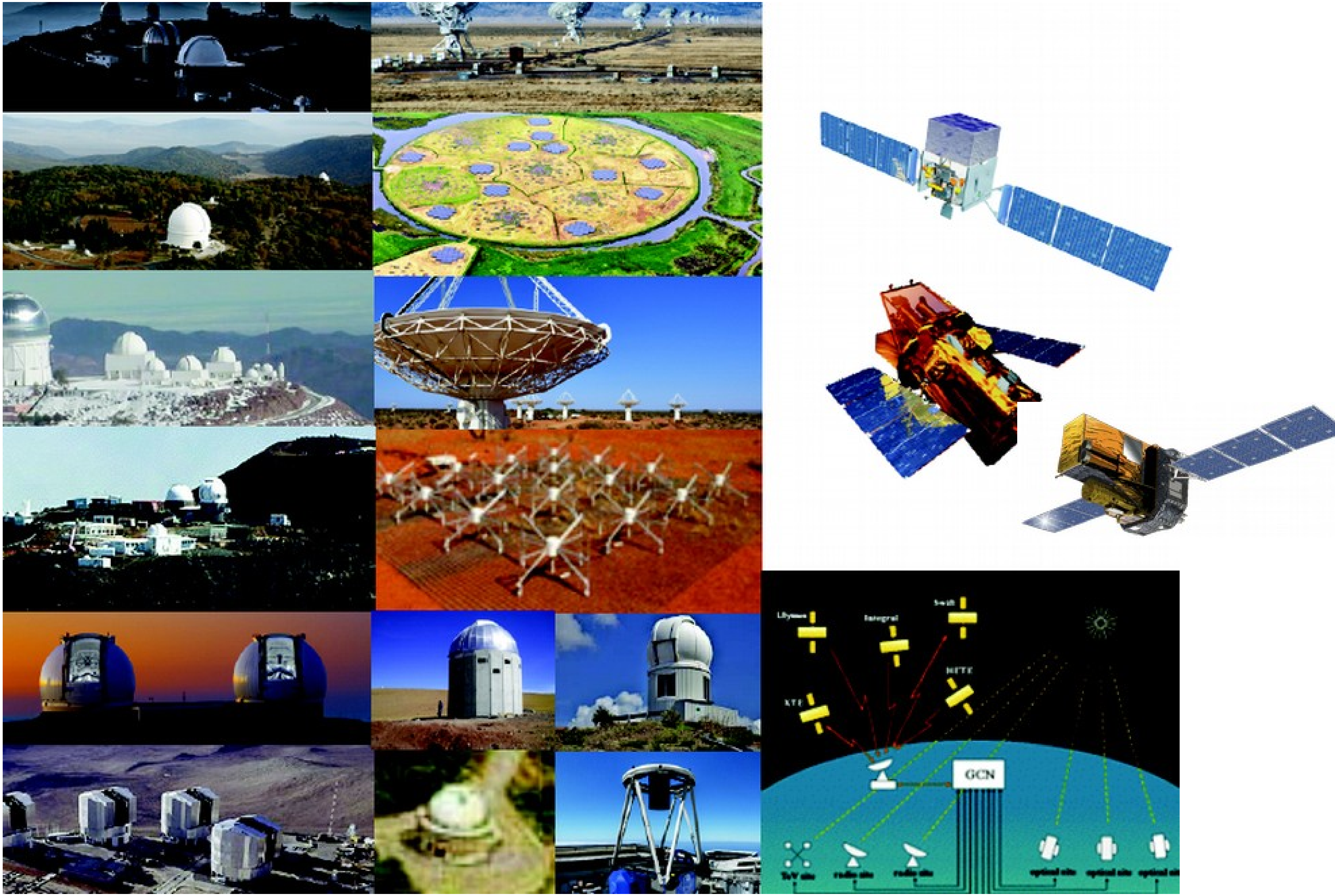


P.J.T. Leonard (NASA/GSFC)

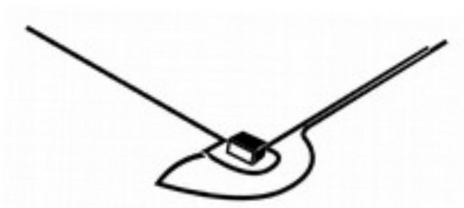
- Are **short gamma-ray bursts** associated with compact binary mergers (incl. neutron star)?
  - **Prompt gamma-ray** emission (beamed – 5 to 10 degrees)
  - X-ray or optical **afterglow** (observable for small inclination)
  - **Kilonova** (or macronova) due to radioactive decay of heavy elements in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


Integral
Swift
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

events

mins to
hours

position
reconstruction

skymaps

hours to
days

parameter
estimation

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

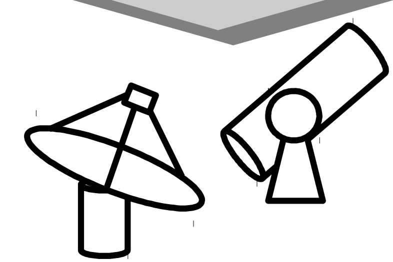
`gracedb.ligo.org`

event database

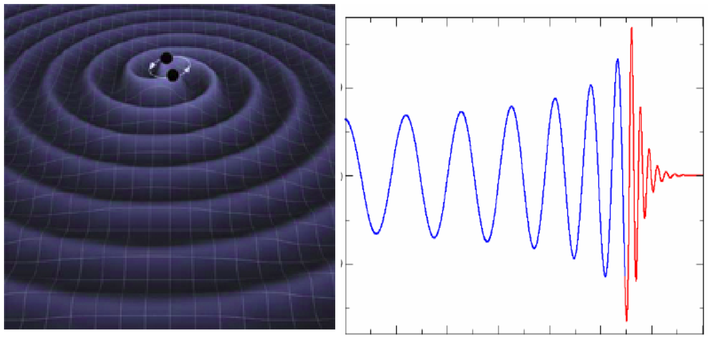
`event+annotations`
`[log,labels,files]`

O(1000) events/run

private GCN network
VOevent



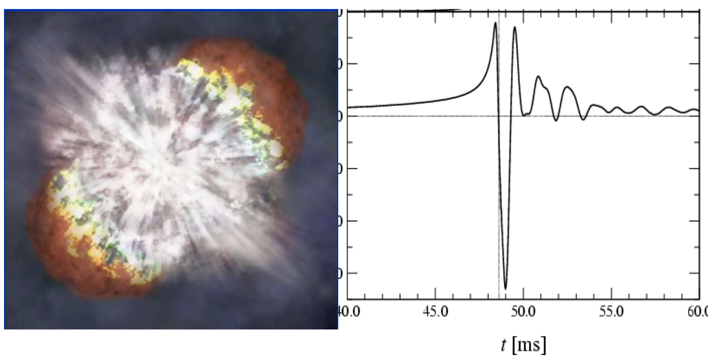
GW transient searches



Compact Binary Coalescence (CBC)

Known waveform – **Matched filtering**

Templates for a range of component masses and spin



Unmodelled GW Burst (< ~1 sec duration)

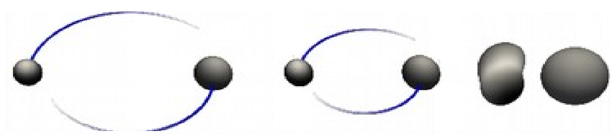
e.g. from stellar core collapse

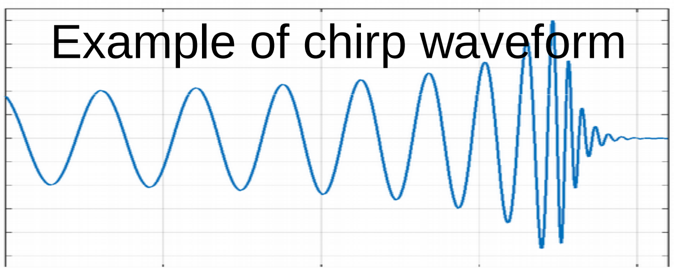
Arbitrary waveform – **Excess power**

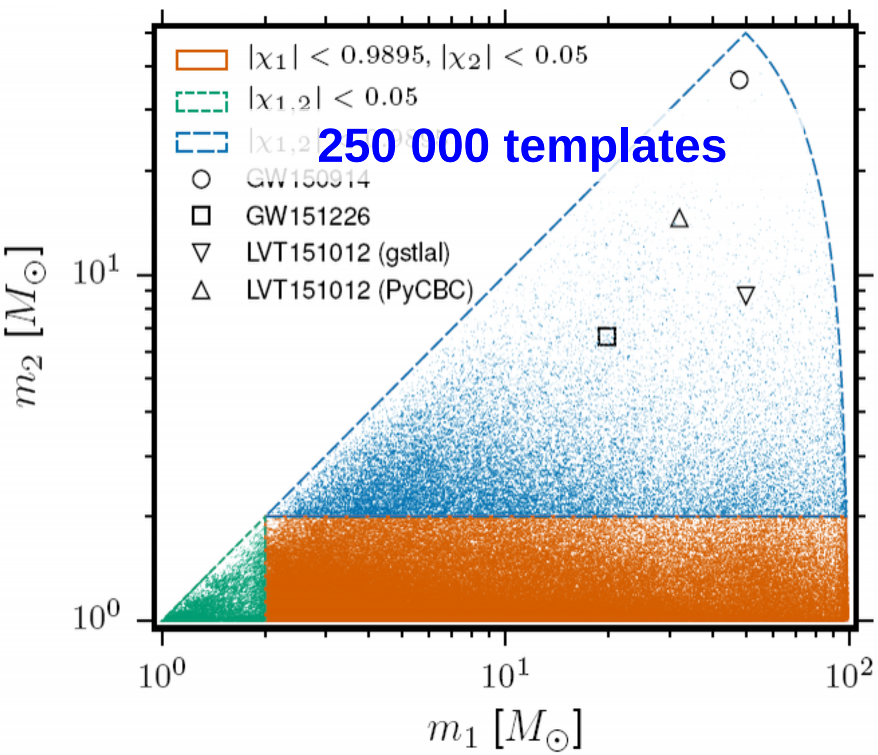
Require coherent signals in detectors,
using direction-dependent antenna response

- **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)



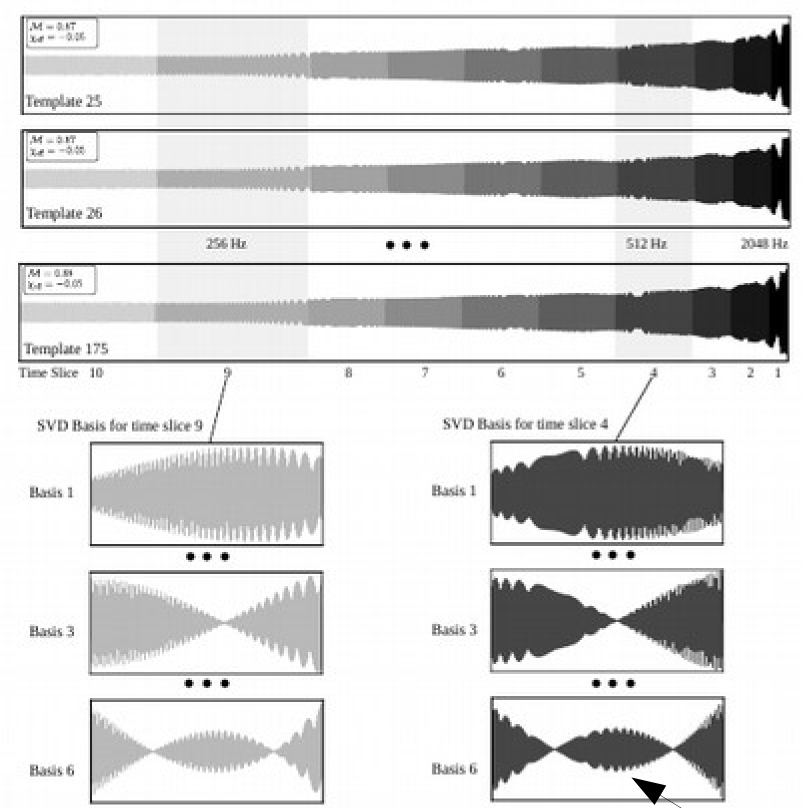




- Pattern matching
  - **Correlate data with the expected waveform** from astrophys. model
  - **Template bank** that covers the space of astrophysical signals
- Reject background
  - **Control goodness-of-fit** using χ^2 test of candidate's spectra to mitigate instrumental transient noise (glitch)
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

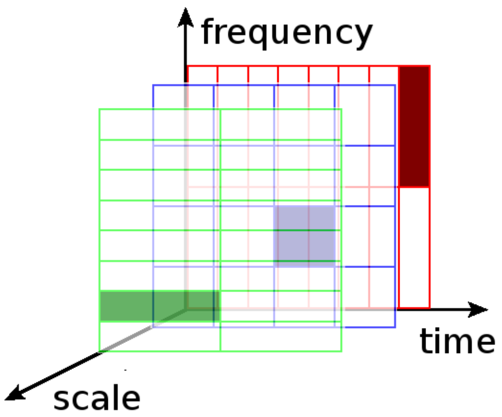
  - divides freq. band into low/high subbands → lower number of templates in each subbands and lower sample rate – arxiv:1507.01787

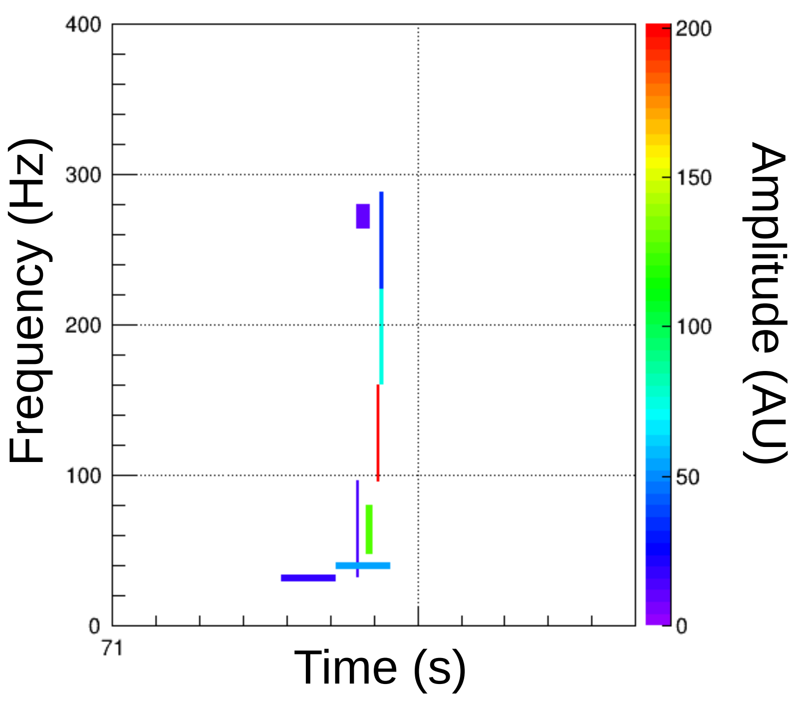
GstLAL (derived from Gstreamer lib)

  - 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

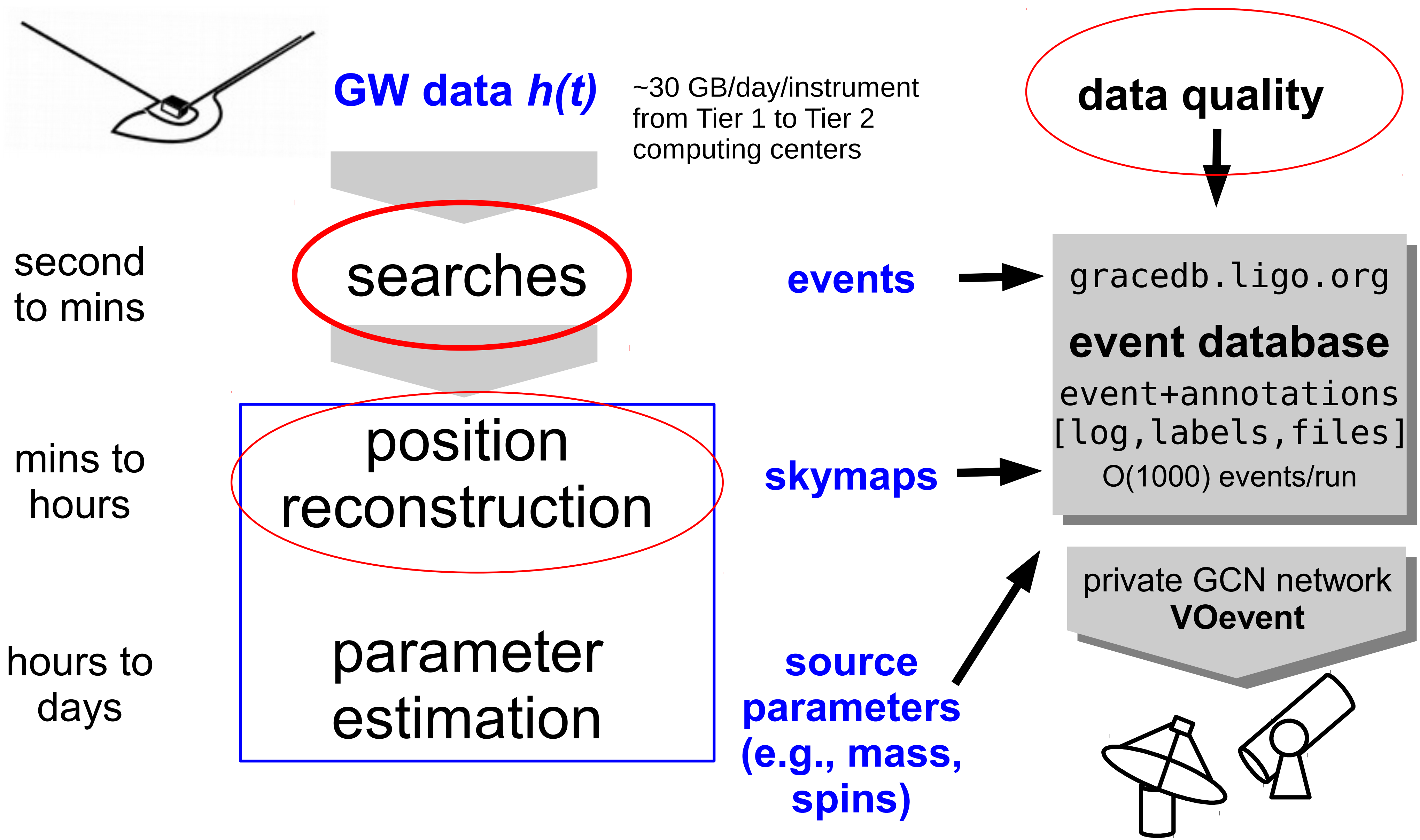
Searches for generic GW transients





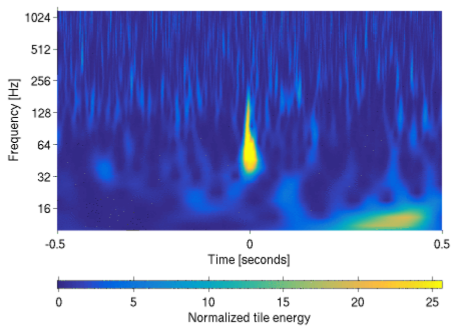
- Principle
  - Search for **excess-power occurring coherently across detectors**
  - Multiple low-latency pipelines: cWB, oLIB, Bayeswave – arXiv:1602.03843
- **Coherent waveburst** arXiv:1511.05999
  - Data are transformed into **time-frequency** domain (multiscale Wilson transform)
  - Retain time-frequency "**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**

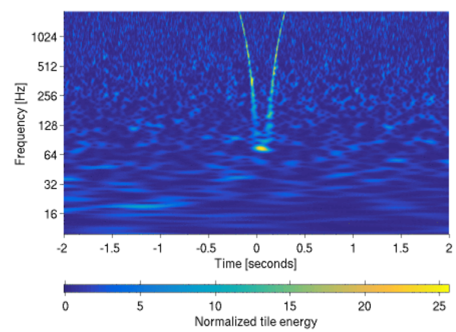
Workflow – Big picture

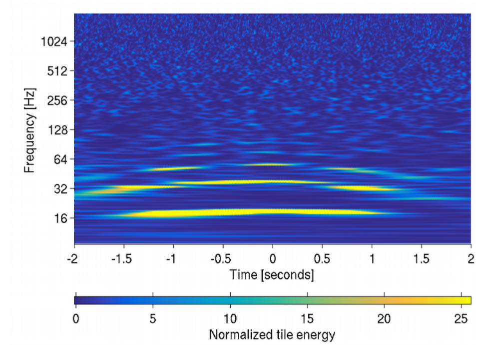


Low-latency data quality

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



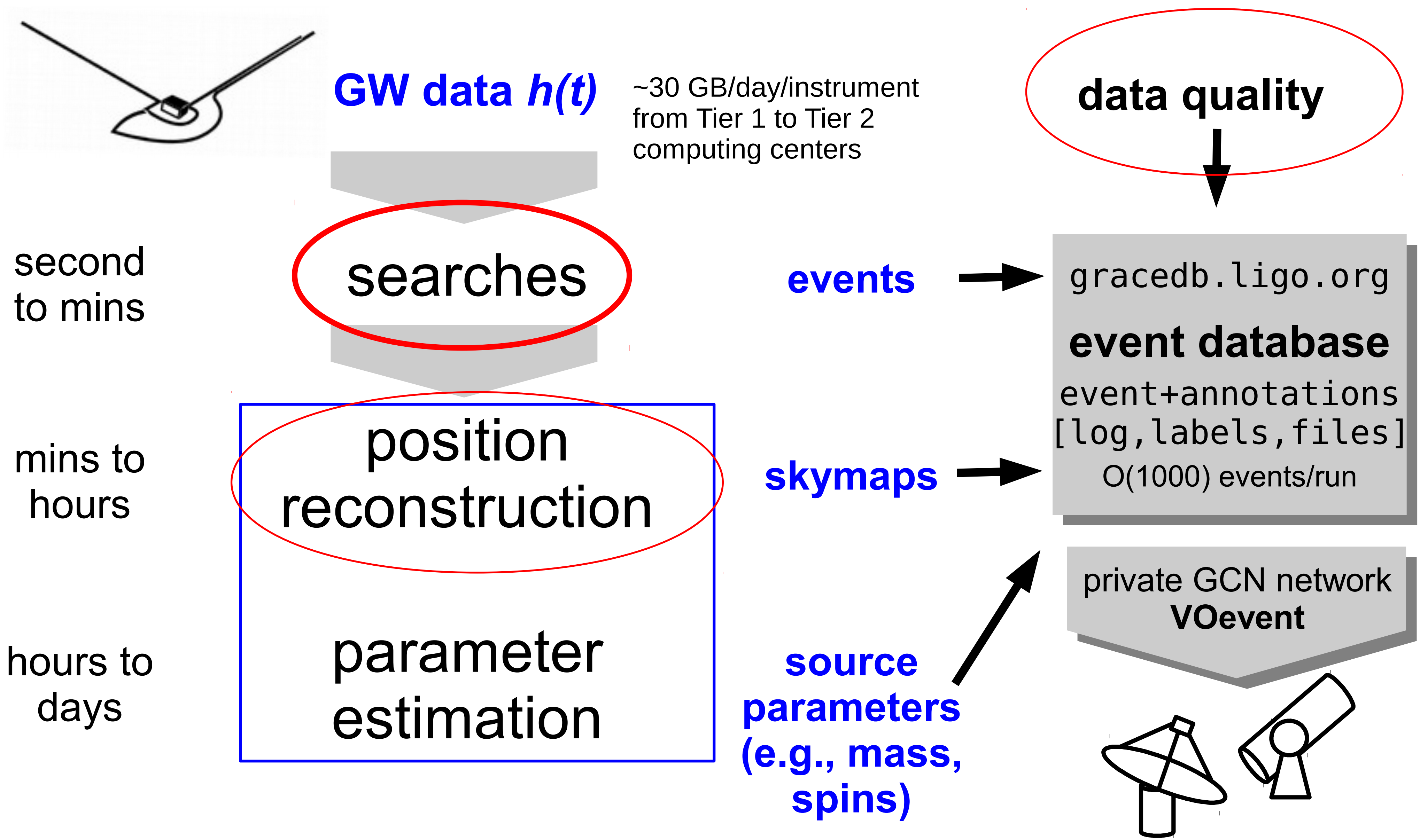




- The origin of glitches can be traced from auxiliary channels and control loop signals
  - 200 000 auxiliary channels (seismometers, magnetometers, …)
  - Large effort to characterize detector noise
  - Attempts to automatize using machine learning
- When eligible events occur, `lvalert` daemon interrogates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

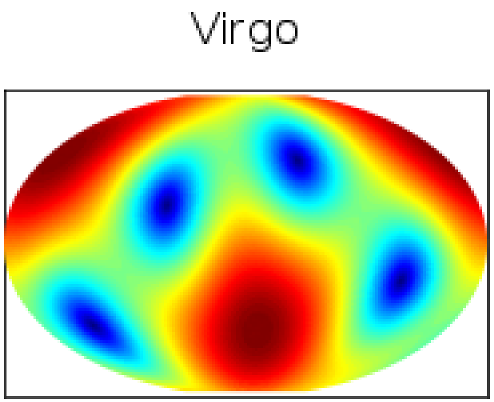
Credits for the glitches: Coughlin, Smith et al, Gravity-spy `zooniverse.org`

Workflow – Big picture

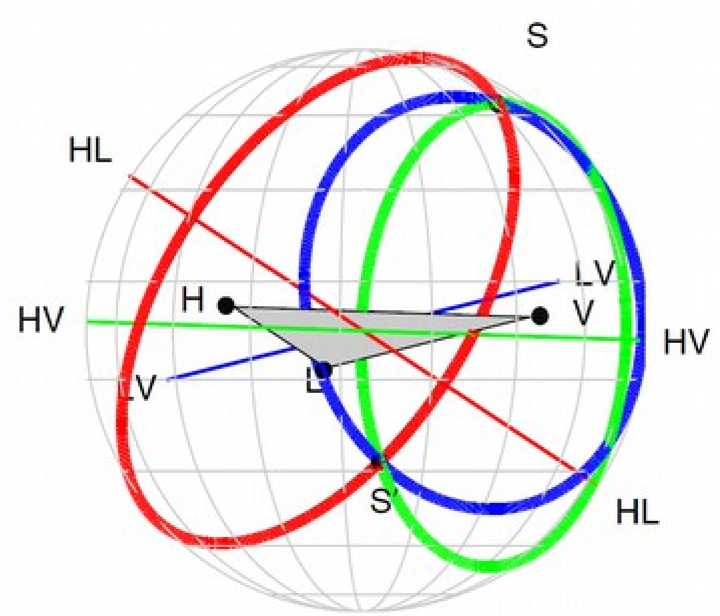


Source direction reconstruction

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

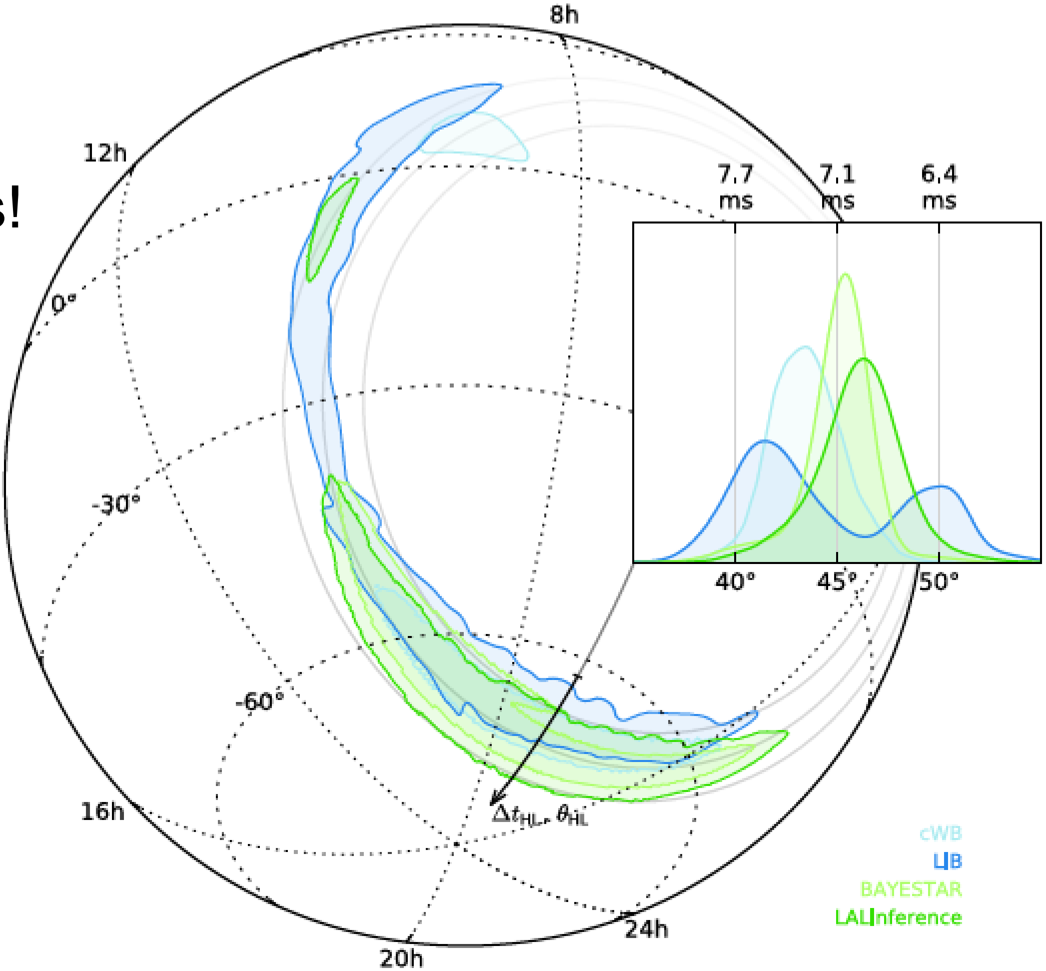
Sep 14, 2015 (1)

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

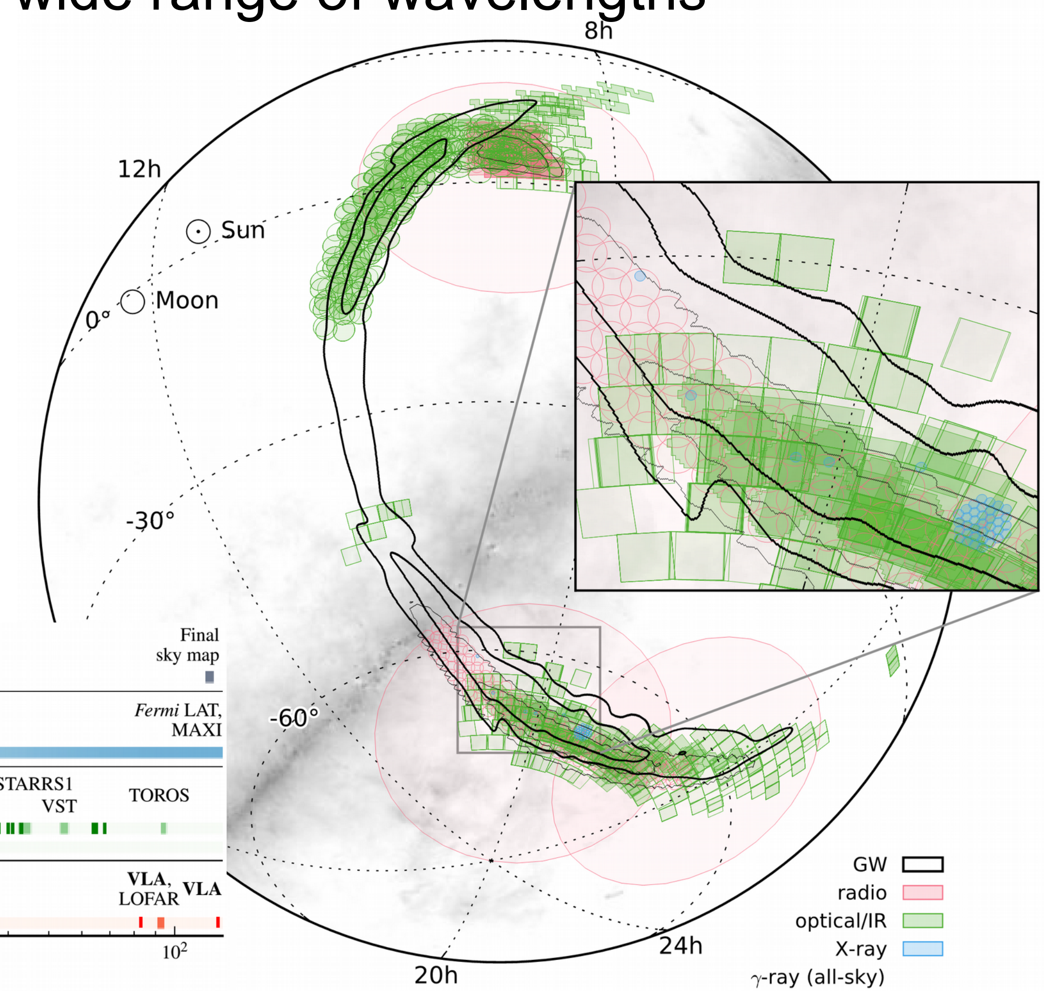
Abbott et al, ApJL 826, L13

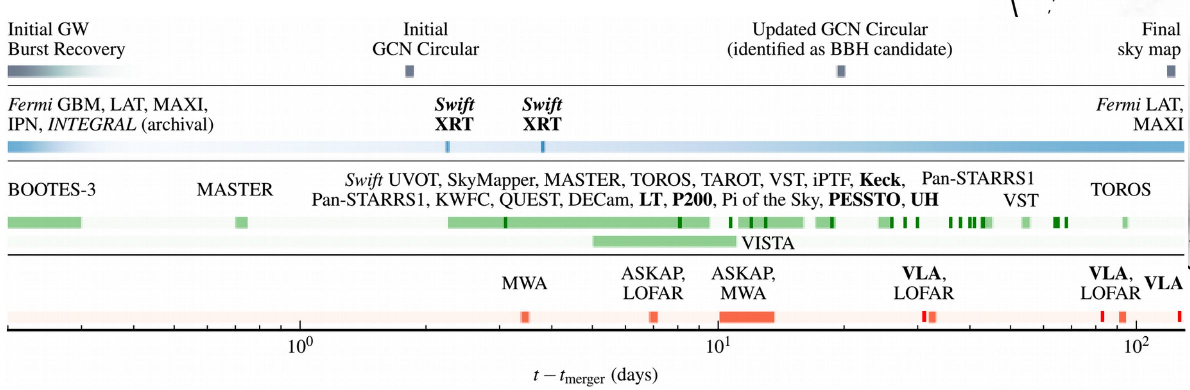
Sep 14, 2015 (2)

25 observing teams, 50 GCN Circulars, 12 publications

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

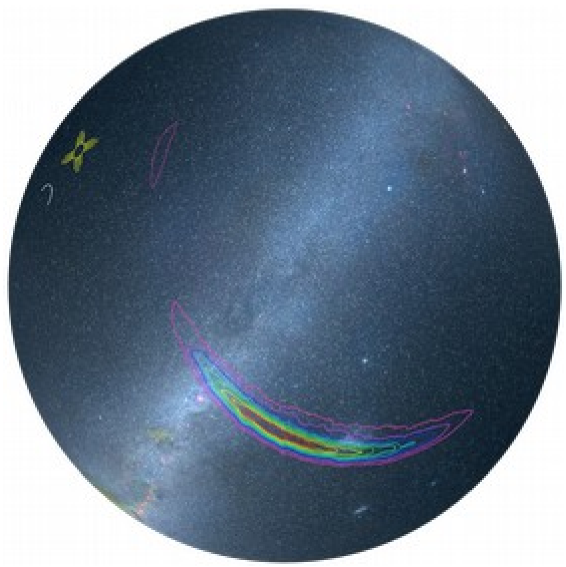
Key element: archival data from high-energy instruments in orbit

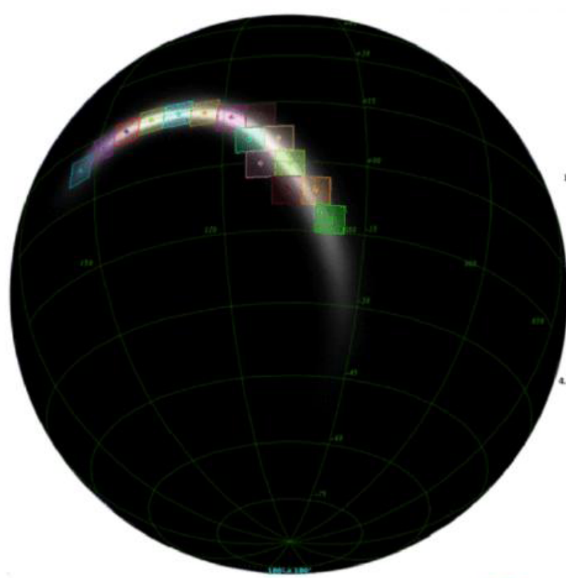




Abbott et al, ApJL 826, L13

Support to astronomers





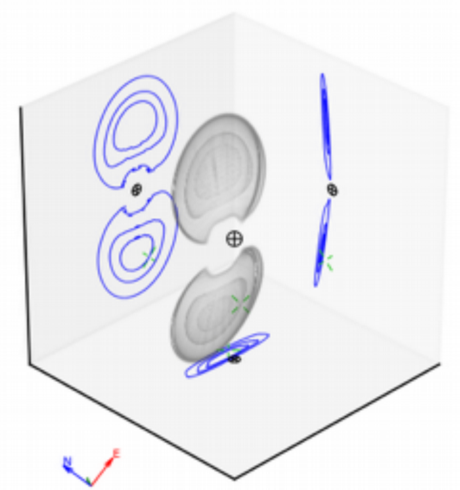
- **Skymap viewer**
  `http://losc.ligo.org/skymapViewer`
  - Web-based tool to visualize GW skymap and other relevant information for follow-up
- **GWsky**
  `https://github.com/ggreco77/GWsky`
  - Set of python scripts that allows to process GW skymaps (tile to a given FOV) and interface with other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

      `http://asd.gsfc.nasa.gov/Leo.Singer/going-the-distance`



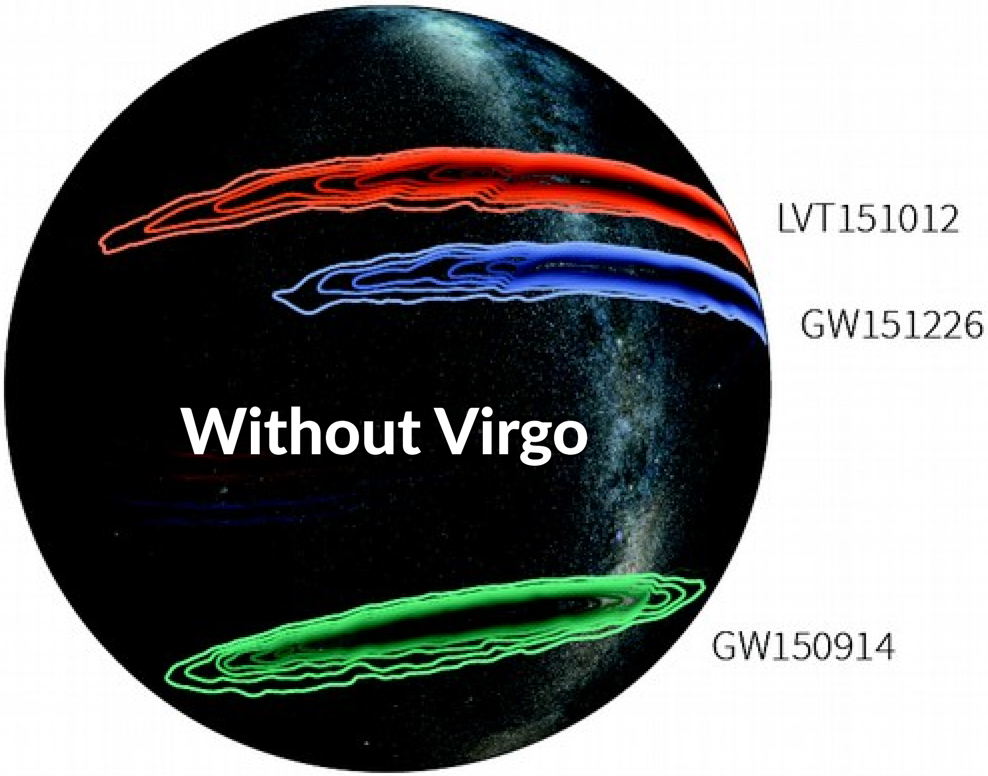
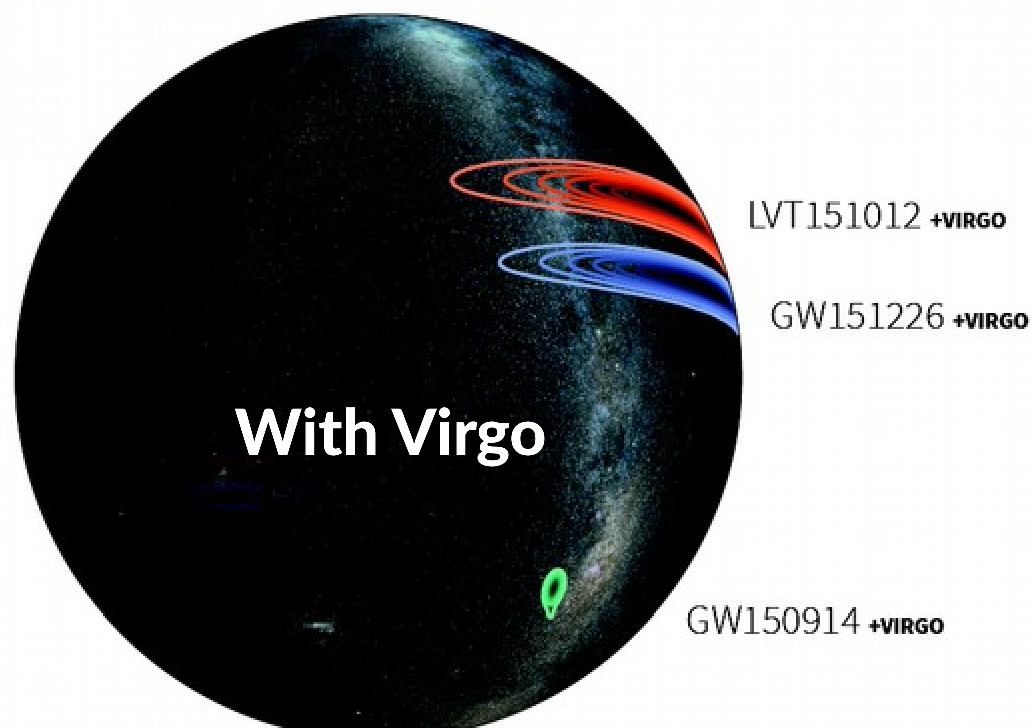


image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)



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