LIGO EM Follow-Up Search Overview

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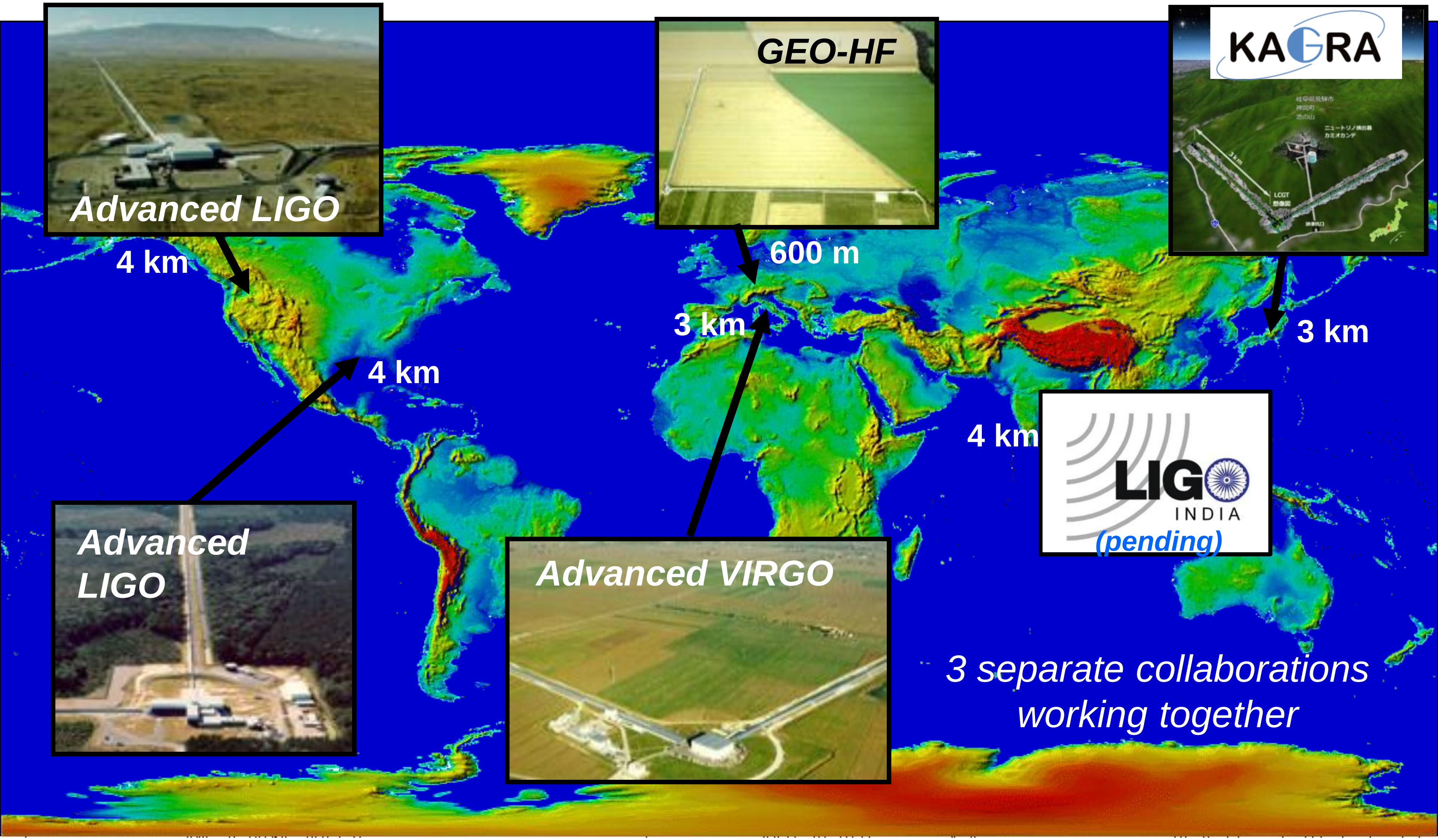
LIGO-G1500268-v1

GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/Goddard) and T. Nielsen (Univ. of Hawaii)

Advanced Detector Network – Under Construction



Responses of Detectors in the Network

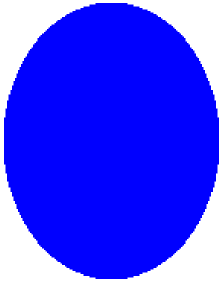
Location → Relative time delay

e.g., LIGO Hanford and Livingston are separated by 3000 km = 10 ms

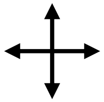
Orientation → Polarization-dependent antenna response

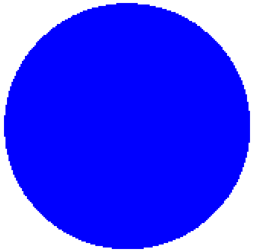
An interferometer measures the (variation in the) difference between the lengths of the two arms → signed strain amplitude $h(t)$ [i.e., not just power]

Projects out a certain linear combination of GW polarization components

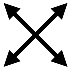


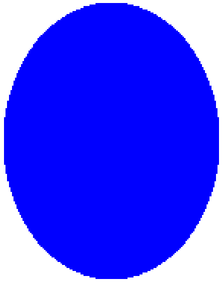
“Plus” polarization



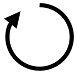


“Cross” polarization





Circular polarization

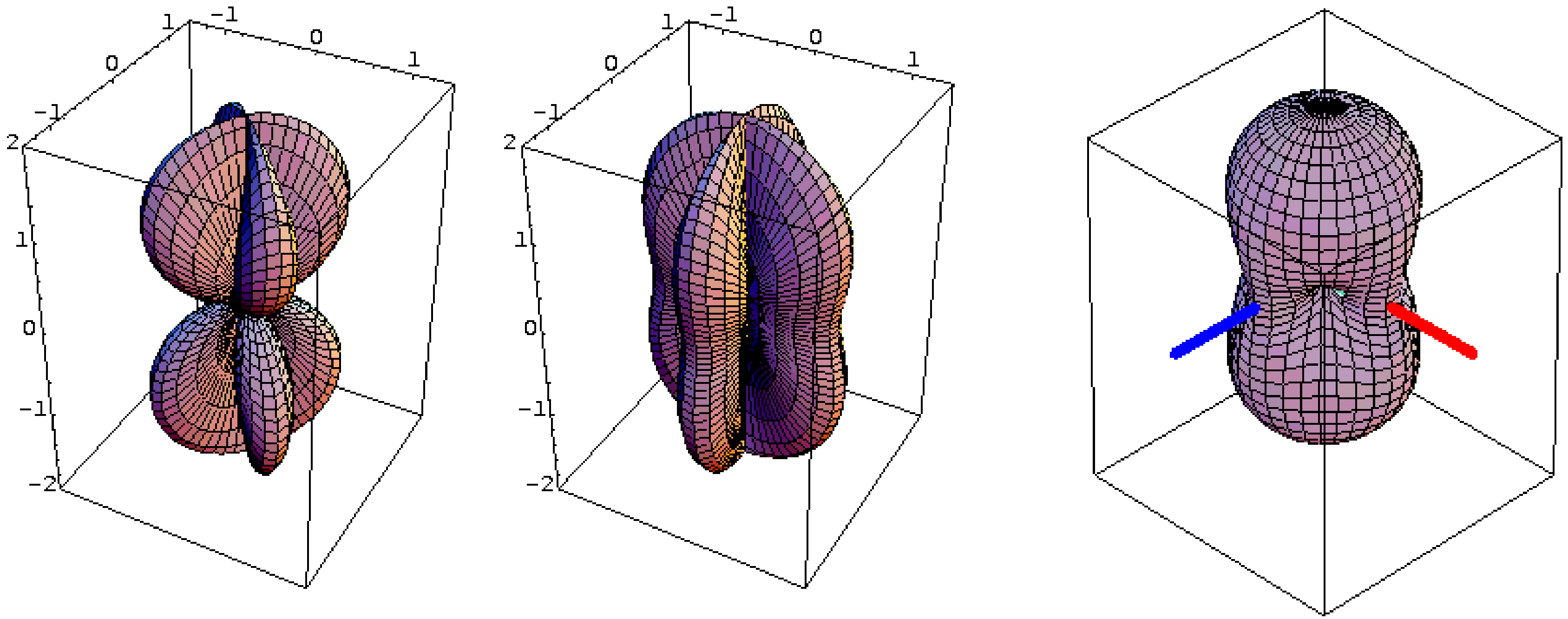


and other polarization combinations …

Antenna Pattern of a Laser Interferometer

Directional sensitivity vs. polarization, in a particular basis chosen with respect to the interferometer arms:

“×” polarization   “+” polarization   RMS sensitivity



Can demand time, amplitude and phase consistency between putative strain waveforms in the different detectors, i.e., **coherent analysis**

Low-Latency Searches for GW Transients

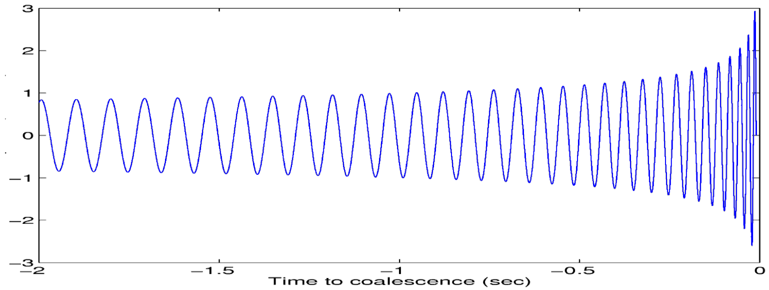
Binary Merger (CBC) Search

Waveforms known accurately

➔ Use optimal matched filtering with a bank of templates

Generally think we should focus on binaries with at least one neutron star to be disrupted

gstlal-svd, gstlal-spiir, MBTA



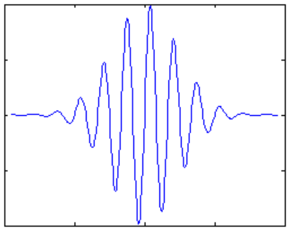
GW Burst Search

Consider arbitrary waveforms

➔ Use robust "coherent excess power" search algorithms

Sensitive to essentially any signal in the LIGO/Virgo frequency band with duration up to ~1 second

Coherent WaveBurst



?

Need a minimum of two detectors to do a believable search; having three or more detectors is preferable

CBC Search Details

For computational efficiency, CBC searches initially filter the data from the different detectors separately

[Unless doing a GRB-triggered deep coherent search, as Dipongkar talked about]

Gloss over amplitude, $+/\times$ polarization mixture, and coalescence phase – i.e., all the things which depend on the GW arrival direction and phase convention (“extrinsic” parameters)

Compare triggers from different detectors, requiring coincidence in coalescence time and intrinsic waveform parameters

Once a coincident event candidate has been identified, go back and reconstruct sky position and other physical parameters

BAYESTAR: Bayesian reconstruction of sky position computed from times, amplitudes and phases of single-detector filter outputs for a set of coincident triggers from compatible templates. Fast (<1 minute).

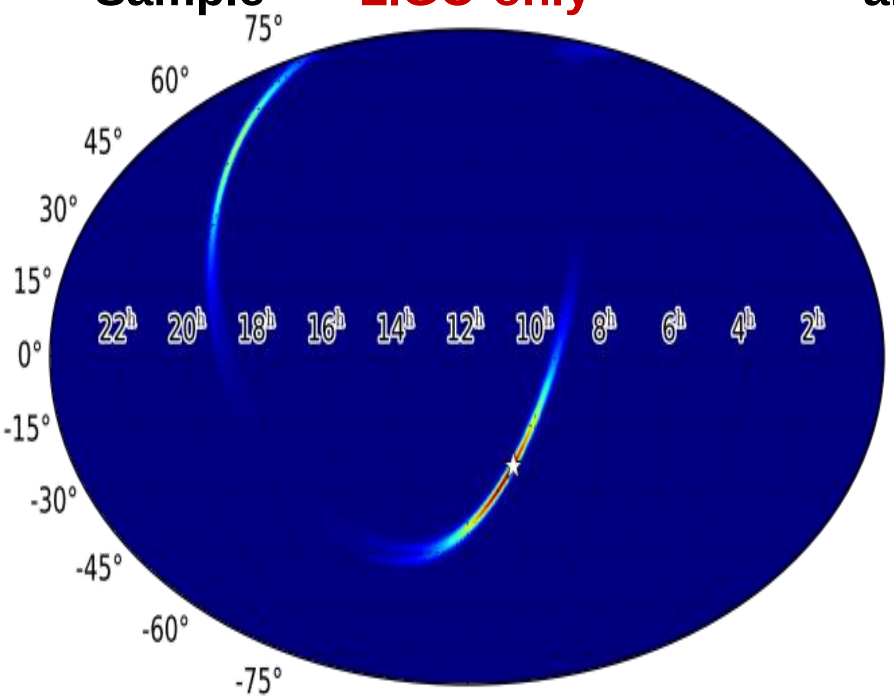
Full parameter estimation, going back to time series data and determining posterior density in high-dimensional parameter space, e.g. using LALInference with one of several sampling approaches. Slower (hours).

CBC Position Reconstruction Examples

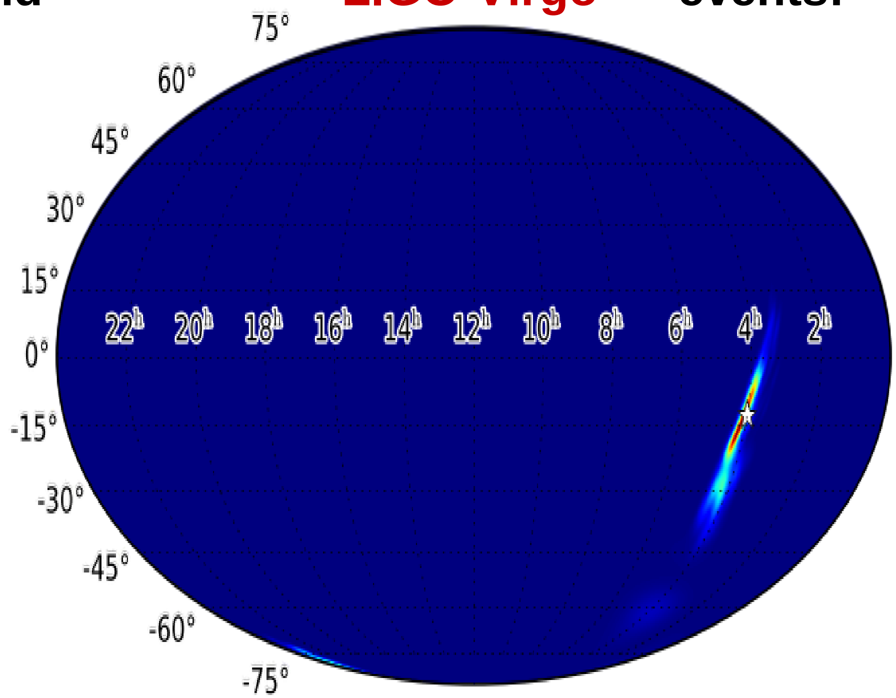
Sky position estimation methods tested and compared with simulated events from first 2 years of advanced GW detectors

Singer et al., arXiv:1404.5623; Berry et al., arXiv:1411.6934;
http://www.ligo.org/scientists/first2years/

Sample LIGO-only and LIGO-Virgo events:



Fast reconstruction (BAYESTAR)



MCMC-based reconstruction

Coherent Burst Analysis

Each detector measures a linear combination of $h_+(t)$ & $h_\times(t)$ *
with antenna response factors and relative time delay depending on direction of arrival

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} F_1^+ & F_1^\times \\ F_2^+ & F_2^\times \\ \vdots & \vdots \\ F_N^+ & F_N^\times \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix}$$

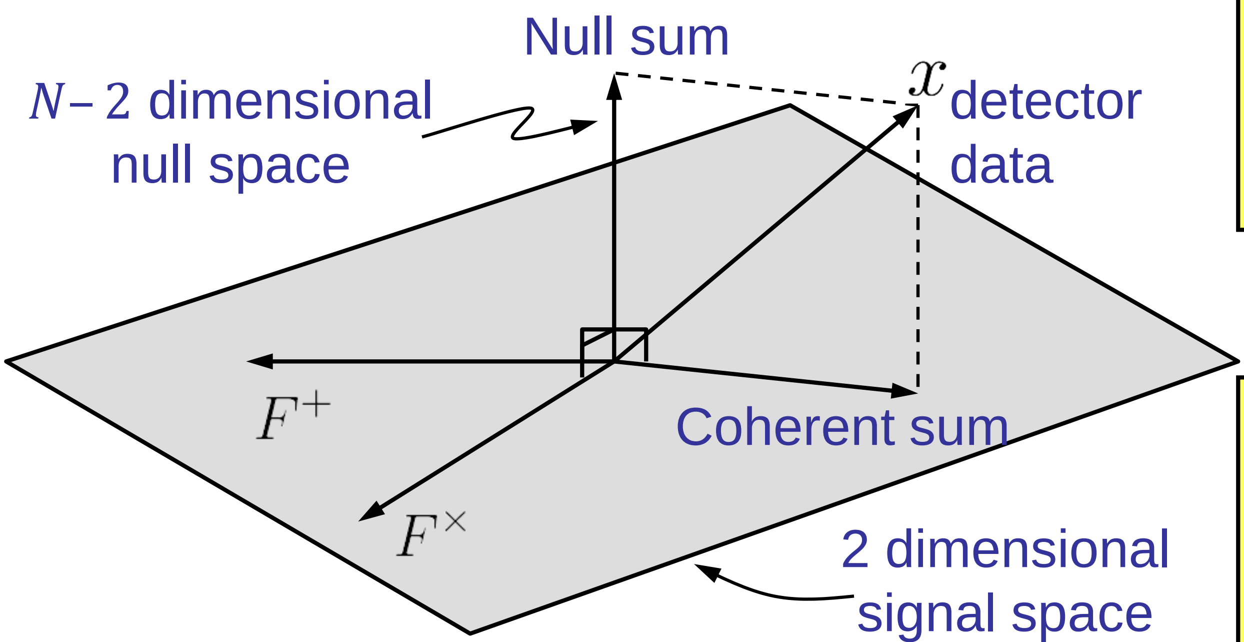
data = response × signal + noise

$\Rightarrow$ Data from 2 sites can uniquely determine $h_+(t)$ and $h_\times(t)$ for an arbitrary signal, *in the absence of noise and if the arrival direction is known*

$\Rightarrow$ Data from 3 or more sites *over-determines* $h_+(t)$ and $h_\times(t)$ if the arrival direction is known

** Assuming that GR is correct !*

Geometric View of Coherent Analysis



Coherent sum:
Find linear combination of detector data that maximizes signal to noise ratio

Null sum:
Linear combination of detector data that has no GW signal—provides consistency test

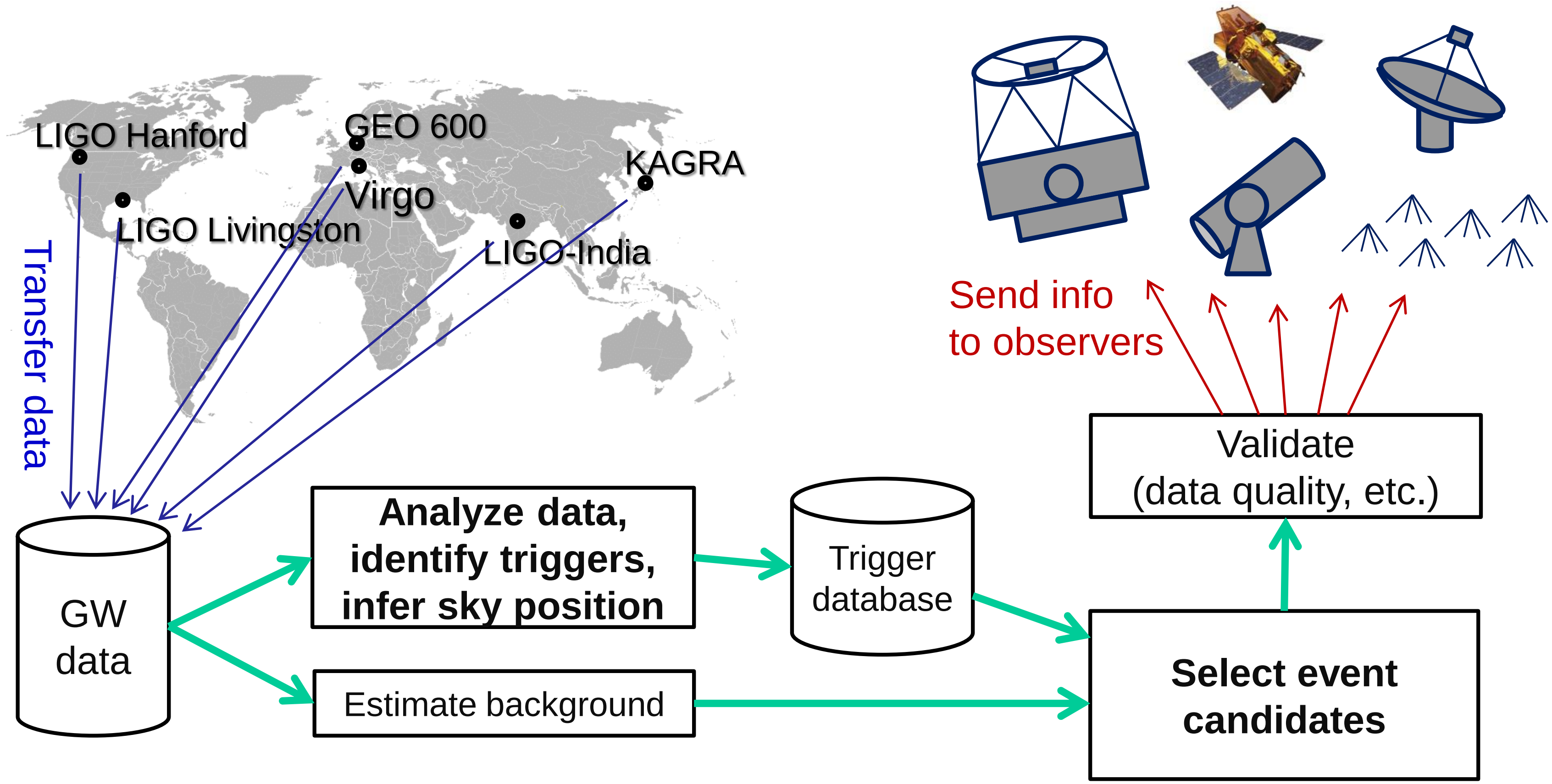
Treat this as a maximum likelihood problem

Find most likely $h_+(t)$ & $h_\times(t)$, maximizing over arrival directions

Regulator penalizes physically unlikely signal hypotheses

Initial burst search with cWB uses wavelet decomposition of the data as basis; then can follow up with full parameter estimation (LALInference-Burst)

What We Have to Do



Swift: NASA E/PO, Sonoma State U., Aurore Simonnet

Generation of Alerts

Will analyze all data from two or more detectors for alerts

- Two-detector candidates have poor localization, but sufficient for correlating with other surveys or very-wide-field instruments
- Fold in additional detectors (Virgo, KAGRA, LIGO-India) as network grows

Estimate background by considering GW data streams with an artificial time shift, either by re-running full analysis algorithm or from expected coincidence rate of single-detector triggers. Look at distribution of detection statistic values
→ **Assign a false alarm rate (FAR) to each candidate**

Working to reduce or eliminate latency from manual data quality checks
→ **Aiming to distribute alerts in 5-10 minutes**

Forming Partnerships

Confident detection of first few GW signals will require time and care—need to avoid misinformation / rumors / media circus

- LIGO/Virgo data has a proprietary period

Have signed MOUs with over 50 groups so far, with more coming!

- Broad spectrum of transient astronomy researchers and instruments
- Optical, Radio, X-ray, gamma-ray, VHE
- Transient surveys and various instruments that can be pointed to follow up
- Telescope owners, instrument science teams and ToO proposers

Have begun some discussions of science strategies, logistical details and testing plans – need to ramp this up this year

Communication Tools

GW event candidates will be distributed to partners via GCN

- With a controlled list of recipients

Primary alert format is VOEvent

- Significance indicated as estimated false alarm rate (FAR)
- Sky probability maps are FITS files containing HEALpix pixel data

Four different types of alerts:

- **Preliminary**: A transient in the GW data has been detected, but not yet checked for good data quality. Intended for making preparations.
- **Initial**: Event candidate has passed basic data quality checks, and a sky-position probability map is available
- **Update**: Updated sky map and/or estimate of significance
- **Retraction**: In case we later find reason to reject the candidate

“GraceDB” database allows users to view detailed records

“Bulletin Board” interfaces allow observers to report observations

Example VOEvent – part 1


```xml
<?xml version="1.0" ?>
<voe:VOEvent xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:voe="http://www.ivoa.net/xml/VOEvent/v2.0"
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role="test" ivorn="ivo://gwnet/gcn_sender#G127992-3-Update">
  <Who>
    <Date>2014-12-03T16:03:34</Date>
    <Author>
      <contactName>LIGO Scientific Collaboration and Virgo Collaboration</contactName>
    </Author>
  </Who>
  <What>
    <Param name="Pkt_Ser_Num" dataType="string" value="3"/>
    <Param name="GraceID" dataType="string" value="G127992" ucd="meta.id" unit="">
      <Description>Identifier in the GraceDb database</Description>    </Param>
    <Param name="AlertType" dataType="string" value=“Update" ucd="meta.version" unit="">
      <Description>VOEvent alert type</Description>    </Param>
    <Param name="EventPage" dataType="string" value="https://gracedb.ligo.org/events/G96195" ucd="meta.ref.url" unit="">
      <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="7.80321138878e-12" 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-spiir" ucd="meta.code" unit="">
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    <Param name="Search" dataType="string" value="LowMass" ucd="meta.code" unit="">
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    <Param name="ChirpMass" dataType="float" value="0.912880957127" ucd="phys.mass" unit="solar mass">
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    <Param name="MaxDistance" dataType="float" value="57.5933" ucd="pos.distance" unit="Mpc">
      <Description>Estimated maximum distance for CBC event</Description>    </Param>
    <Param name="Eta" dataType="float" value="0.2484173" ucd="phys.mass;arith.factor" unit="">
      <Description>Estimated ratio of reduced mass to total mass</Description>    </Param>
```

Example VOEvent – part 2


```
   <Group type="GW_SKYMAP" name="BAYESTAR">
      <Param name="skymap_png_x509" dataType="string" value="https://gracedb.ligo.org/api/events/G127992/files/skymap.png"
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        <Description>Sky Map image X509 protected</Description>      </Param>
      <Param name="skymap_fits_x509" dataType="string" value="https://gracedb.ligo.org/api/events/G127992/files/skymap.fits.gz"
ucd="meta.ref.url" unit="">
        <Description>Sky Map FITS X509 protected</Description>      </Param>
      <Param name="skymap_png_shib" dataType="string" value="https://gracedb.ligo.org/events/G127992/files/skymap.png" ucd="meta.ref.url"
unit="">
        <Description>Sky Map image Shibboleth protected</Description>      </Param>
      <Param name="skymap_fits_shib" dataType="string" value="https://gracedb.ligo.org/events/G127992/files/skymap.fits.gz"
ucd="meta.ref.url" unit="">
        <Description>Sky Map FITS Shibboleth protected</Description>      </Param>
    </Group>
  </What>
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        <AstroCoords coord_system_id="UTC-FK5-GEO">
          <Time>   <TimeInstant>   <ISOTime>2014-03-01T03:57:59.719037</ISOTime>      </TimeInstant>    </Time>
          <Position2D>
            <Value2>   <C1>0.000000</C1>    <C2>0.000000</C2>    </Value2>    <Error2Radius>180.000000</Error2Radius>
          </Position2D>
        </AstroCoords>
      </ObservationLocation>    </ObsDataLocation>
  </WhereWhen>
  <How>
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    <Description>L1: LIGO Livingston 4 km gravitational wave detector</Description>
    <Description>Candidate gravitational wave event identified by low-latency analysis</Description>
  </How>
  <Citations>
    <EventIVORN cite="supersedes">ivo://gwnet/gcn_sender#G127992-2-Initial</EventIVORN>
    <EventIVORN cite="supersedes">ivo://gwnet/gcn_sender#G127992-1-Preliminary</EventIVORN>
    <Description>Updated localization is now available</Description>
  </Citations>
  <Description>Report of a candidate gravitational wave event</Description>
</voe:VOEvent>
```