GW Event Alerts

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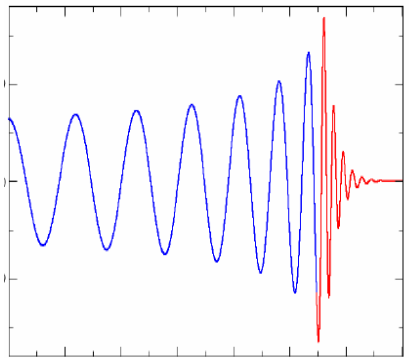
LIGO-G1300846-v5

Searches for GW transient sources

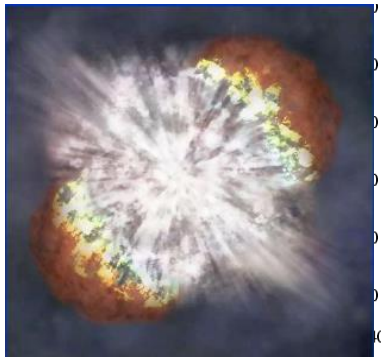
- GW data streams are analyzed jointly
  - Initially LIGO Hanford+Livingston and Virgo; later others too
- Two main types of transient searches:

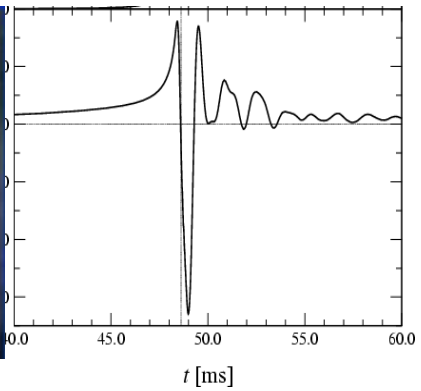


Compact Binary Coalescence (CBC)

Known waveform ➔ Matched filtering

Templates for a range of component masses (spin affects waveforms too, but not so important for initial detection)



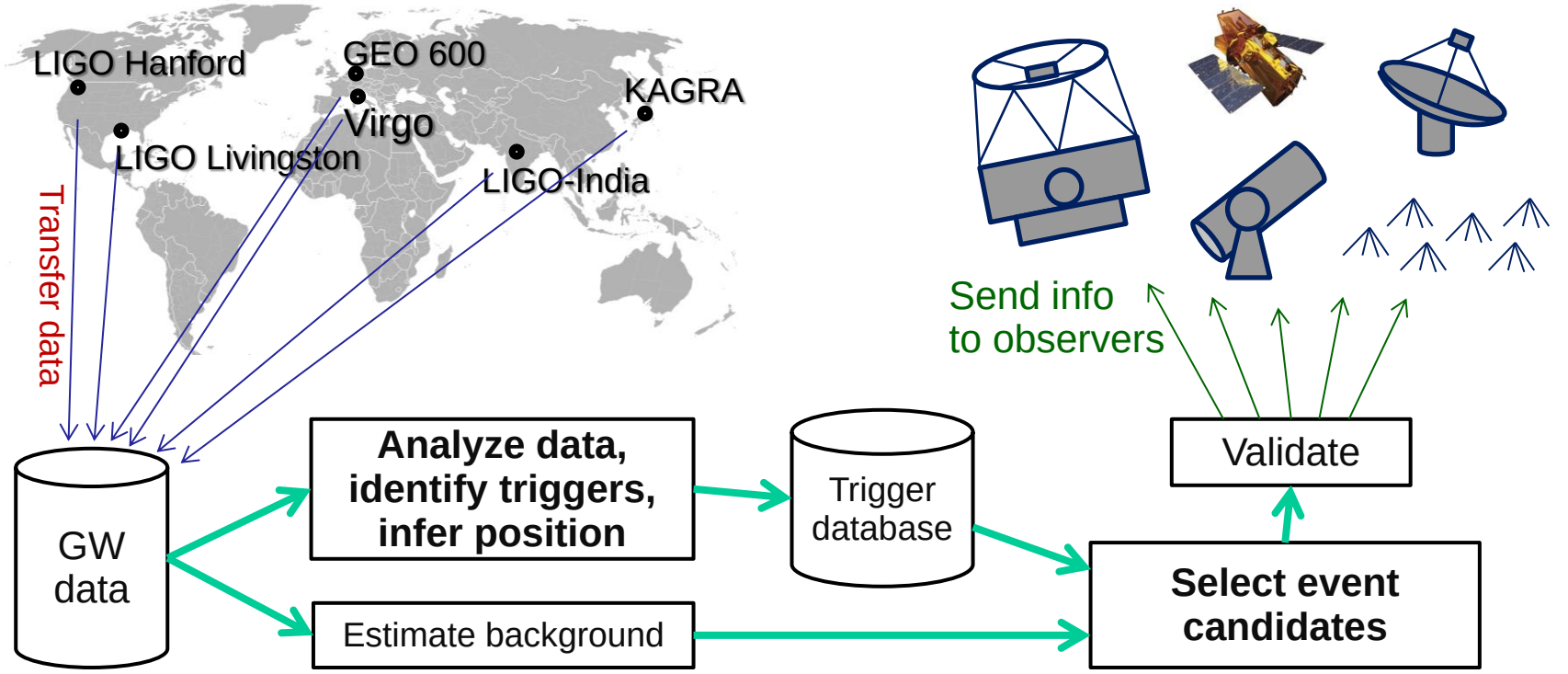


Unmodelled GW Burst (< ~1 sec duration)

Arbitrary waveform ➔ Excess power

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

Low-latency GW event candidates



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

- Multiple analysis pipelines running as data is collected
- Generate *triggers* from apparent transients in the data
- Estimate significance by comparing with *background* distribution from time-shifted analysis

How quickly?

- Currently developing and testing analysis software in “engineering runs” with simulated aLIGO / AdVirgo data
- Typical latency to generate triggers with sky position info: 3 to 6 minutes
- Additional time required for validation: not yet known
  - In 2009–10, manual data quality checks took ~15-30 min; about 1/3 of triggers were discarded as questionable
  - Efforts underway to develop better low-latency data quality checks, but these will be brand new detectors

➔ Likely to require human validation before sending out an alert, at least at first

(GW alerts also support less time-critical counterpart searches)

What info we can provide

- Time of the GW candidate
  - At Earth, with precision of order ~10 ms (direction-dependent)
- Significance of the candidate
  - Expressed as an effective false alarm rate (FAR)
- Sky position probability map
  - HEALPix grid in FITS file
- A few additional properties of the apparent event that could influence observing strategy

Expect to **distribute GW alerts as VOEvents** over (initially) **private** GCN/TAN, VOEventNet and/or SkyAlert

VOEvent content for a GW alert

preliminary

	CBC	GW burst
IVORN	`ivo://gwnet/[GraceDBID]-[version]`	
Who	LIGO Scientific Collaboration and Virgo Collaboration	
WhereWhen	**Estimated geocentric arrival time**	
What	GraceDB ID	
Alert version number	1 for first alert, etc	
	Link to FITS skymap	
	Link to GraceDB event page	
	Chirp mass	Peak frequency
	Symmetric mass ratio	Burst duration
	Approx. maximum distance	Energy fluence at Earth
Why	All-sky all-time search or triggered search (by a GRB, e.g.)	
How	Name of the event trigger generator which found this event (e.g. "gstlal", "MBTA", "cWB", "cWB-linear")	
	List of the LIGO-Virgo detectors contributing to this event	

Sample VOEvent xml file (prototype)

```
<?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"
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/G71782-1">
   <Who>
      <Author><contactName>LIGO Scientific Collaboration and Virgo Collaboration</contactName></Author>
   </Who>
   <What>
      <Param name="GraceID" dataType="string" value="G71782" ucd="meta.id" unit="">
         <Description>Identifier in the Gracedb database</Description></Param>
      <Param name="AlertVersion" dataType="int" value="1" ucd="meta.version" unit="">
         <Description>Sequence number for alerts about this event</Description></Param>
      <Param name="FAR" dataType="float" value="9.53745202173e-05" ucd="arith.rate;stat.falsealarm" unit="Hz">
         <Description>False alarm rate for this candidate GW event</Description></Param>
      <Param name="FITSSkymap" dataType="string" value="https://ldas-jobs.phys.uwm.edu/gracedb/data/G71782/private/skymap.fits.gz,0" ucd="meta.ref.url" unit="">
         <Description>Skymap as a Healpix/FITS file</Description></Param>
      <Param name="EventPage" dataType="string" value="https://gracedb.ligo.org/events/G71782" ucd="meta.ref.url" unit="">
         <Description>Web page for evolving status of this candidate event</Description></Param>
      <Param name="chirpMass" dataType="float" value="3.52247953415" ucd="phys.mass" unit="solar mass">
         <Description>Estimated CBC chirp mass</Description></Param>
      <Param name="CBCType" dataType="string" value="LowMass" ucd="meta.code" unit="">
         <Description>Apparent CBC type(s)</Description></Param>
      <Param name="MaxDistance" dataType="float" value="974.71838" ucd="pos.distance" unit="Mpc">
         <Description>Estimated maximum distance for CBC event</Description></Param>
      <Param name="Eta" dataType="float" value="0.13312872" ucd="phys.mass;arith.factor" unit="No units">
         <Description>Estimated ratio of reduced mass to total mass</Description></Param>
      <Group name="H1,V1"/>
   </What>
   <WhereWhen>
      <ObsDataLocation>
         <ObservatoryLocation id="LIGO Virgo"/>
         <ObservationLocation>
            <AstroCoordSystem id="UTC-FK5-GEO"/>
            <AstroCoords coord_system_id="UTC-FK5-GEO">
               <Time>
                  <TimeInstant><ISOTime>2013-06-24T15:50:07.65</ISOTime></TimeInstant>
               </Time>
               <Position2D>
                  <Value2>
                     <C1>0.000000</C1>
                     <C2>0.000000</C2>
                  </Value2>
                  <Error2Radius>180.000000</Error2Radius>
               </Position2D>
            </AstroCoords>
         </ObservationLocation>
      </ObsDataLocation>
   </WhereWhen>
   <Description>Report of a candidate gravitational wave event</Description>
</voe:VOEvent>
```

GW alert VOEvent notes

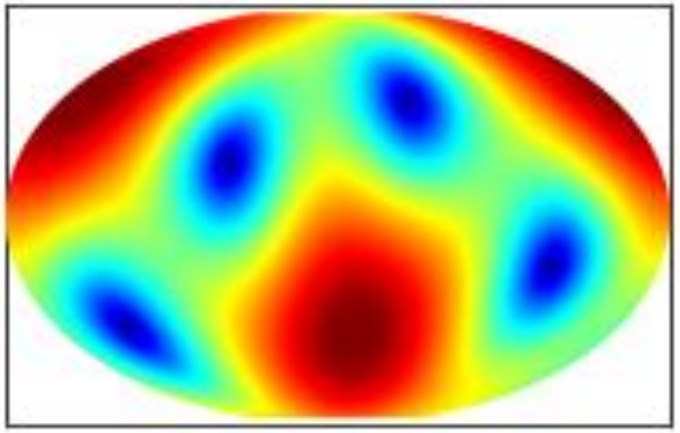
- We might provide **multiple skymaps** with different assumptions about the source
  - CBC orbit inclination: unconstrained, or face-on
  - GW burst polarization: unconstrained, linear, or elliptical
- We may send **updated information** about an event after the initial alert
  - e.g. refined skymap or significance estimate
  - Will send a VOEvent referencing the first one, incrementing the version number in the IVORN
- VOEvent format preferred, but could support other format(s) too if there is demand
  - Not generally able to represent skymap well as error ellipse

Data quality and event significance

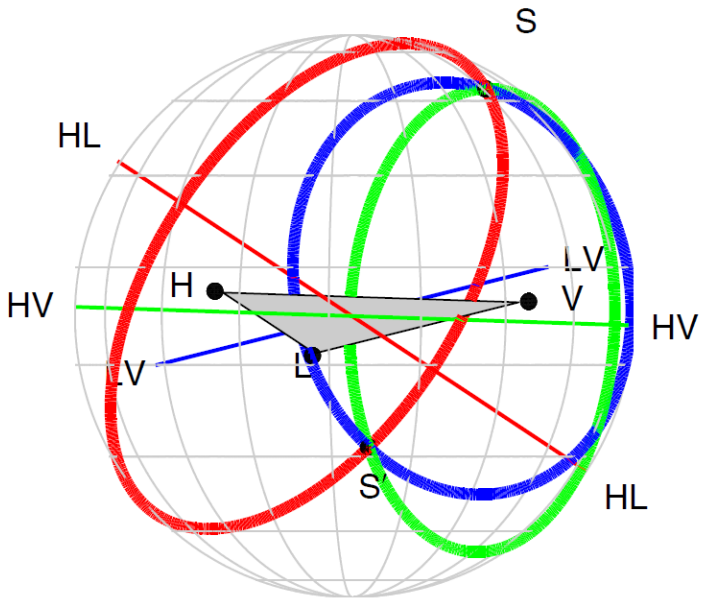
- We veto GW triggers due to known instrumental glitches
- We estimate our background from detector noise with a “time-slide analysis”
  - Repeat analysis using “surrogate data” obtained by time shifting between data stream with non-physical delays
  - The event significance is the occurrence frequency (False Alarm Rate) of a comparable background event
- We will generate alerts for GW events with FAR below some threshold to be defined
- Updates will be communicated if further analysis modifies the event significance

Source direction reconstruction

Antenna beam pattern

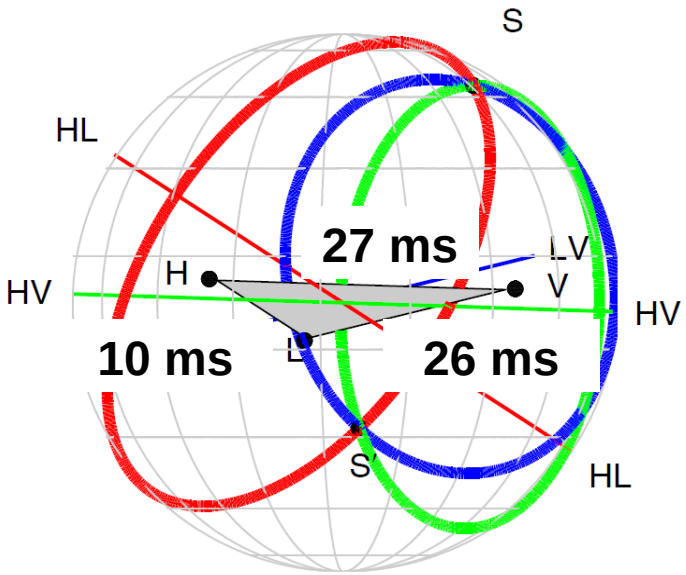


$$(F_+^2 + F_\times^2)^{1/2}$$



- GW detectors are quadrupole antennas ➔ broad beam pattern
- Basic principle: “triangulation”
  - Timing info only: leading order approximation
  - Two detectors localize to a ring in the sky
  - Three detectors to two points
- Better estimate possible using amplitude/phase information
  - Posterior probability skymap from fully coherent analysis

Angular accuracy – analytic estimate



- Triangulation (timing info only)
  - Width of a ring is determined by the timing uncertainty, from

$$\sigma_t \approx 1/(2\pi\rho\sigma_f)$$

    where ρ is the signal-to-noise ratio in a given detector, and σ_f is the effective bandwidth of the signal

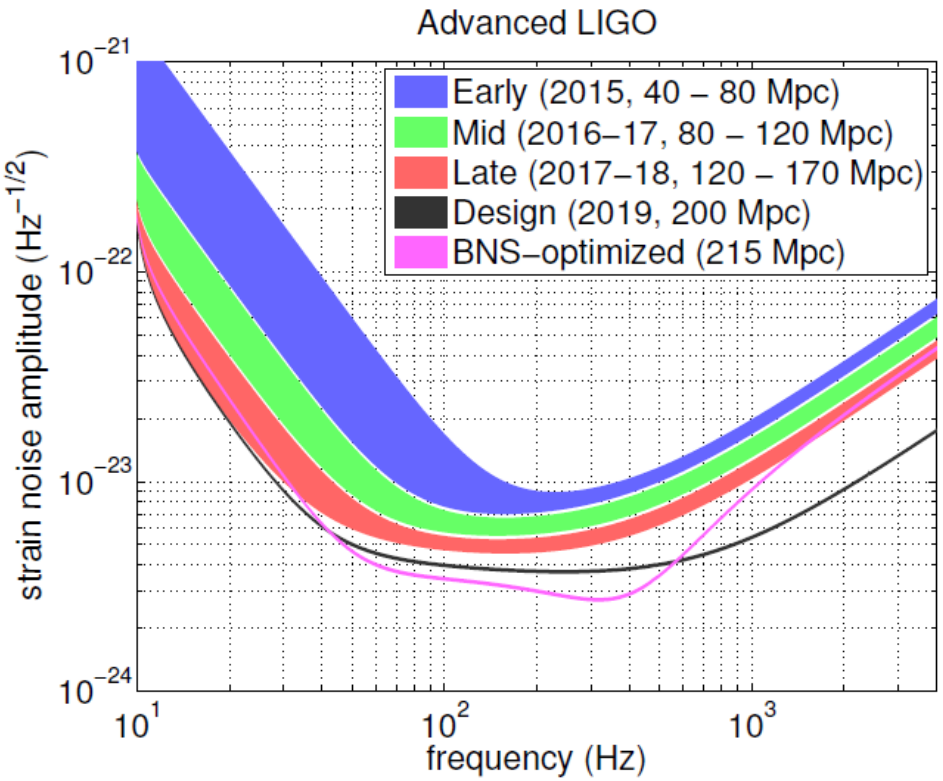
$$\sin\theta\, d\theta = \frac{\sqrt{\sigma_{t1}^2 + \sigma_{t2}^2}}{\Delta t} \Rightarrow \delta\theta \sim \frac{2\langle\sigma_t\rangle}{\Delta t}$$

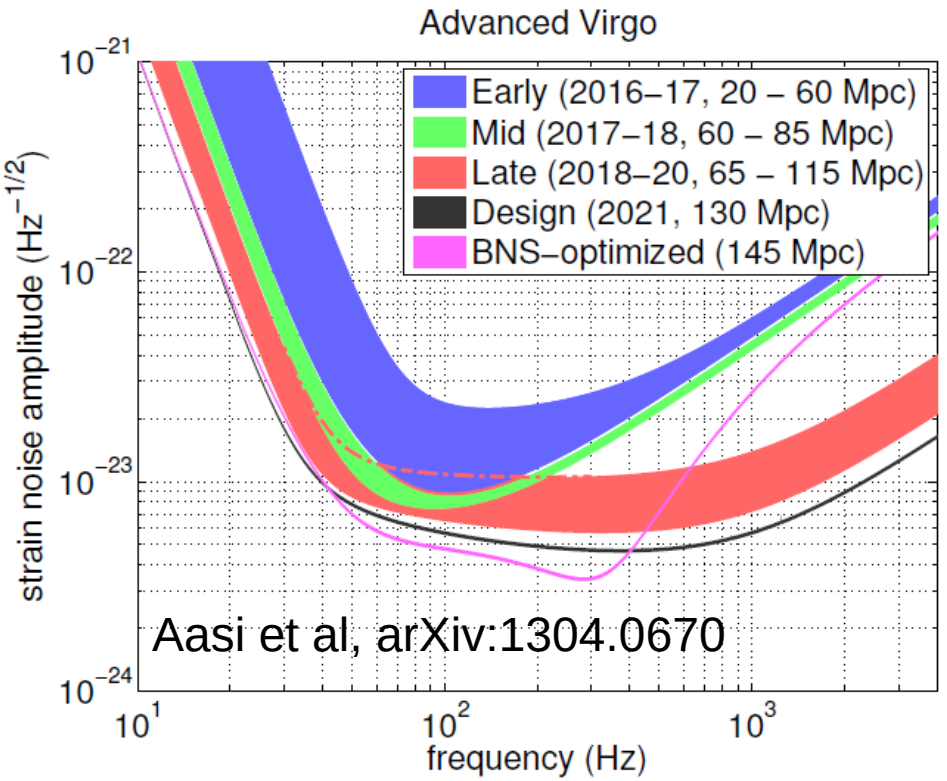
- For a fairly strong signal,

$$\rho = 10 \text{ and } \sigma_f = 100\,\text{Hz} \rightarrow \delta\theta \sim 2\,\text{deg}$$

  - Net area depends on overlap of rings

Angular accuracy – change over time

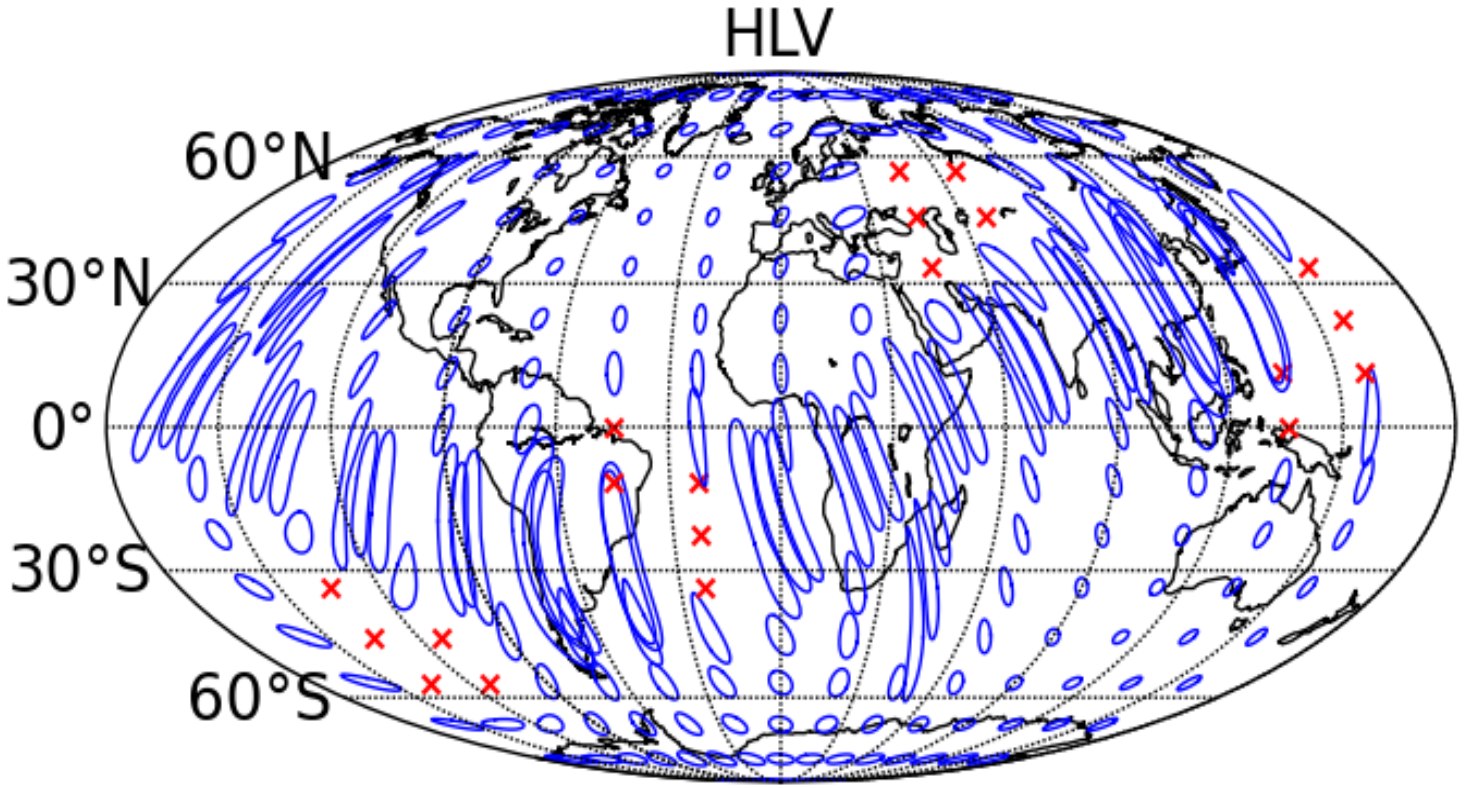




- For CBC, projected sensitivity improvements increase both SNR and bandwidth for a given event
- However, it will always be the case that most detected events will have SNR near the detection threshold

Angular accuracy – sky position dependence

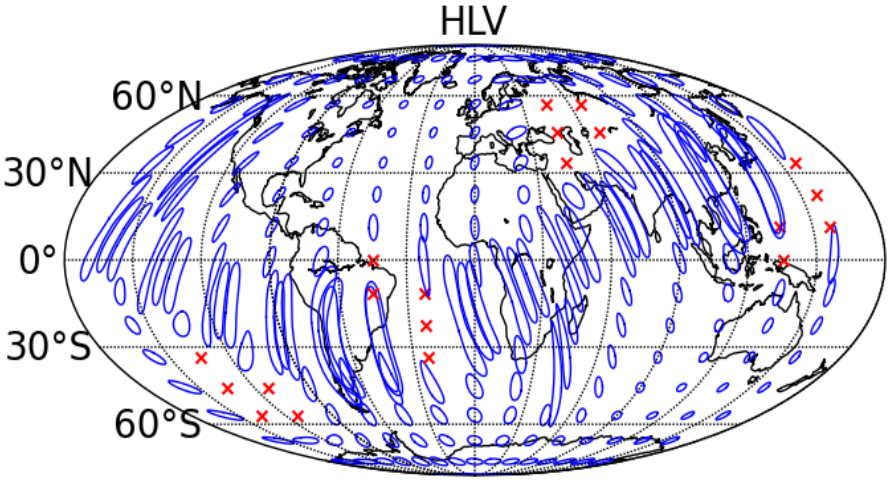
Face-on BNS 80 Mpc HLV 2016-17
Timing triangulation only; V half as sensitive as H,L
~8 % contained in 20 deg^2



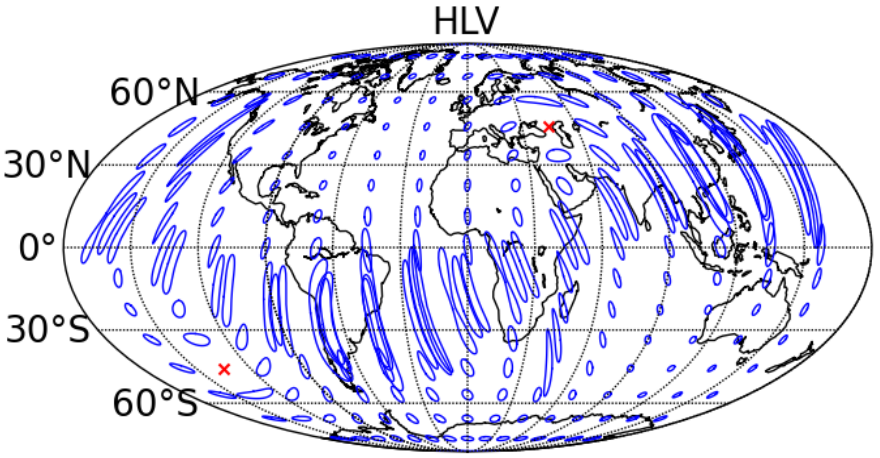
Aasi et al, arXiv:1304.0670

Improvement with later networks

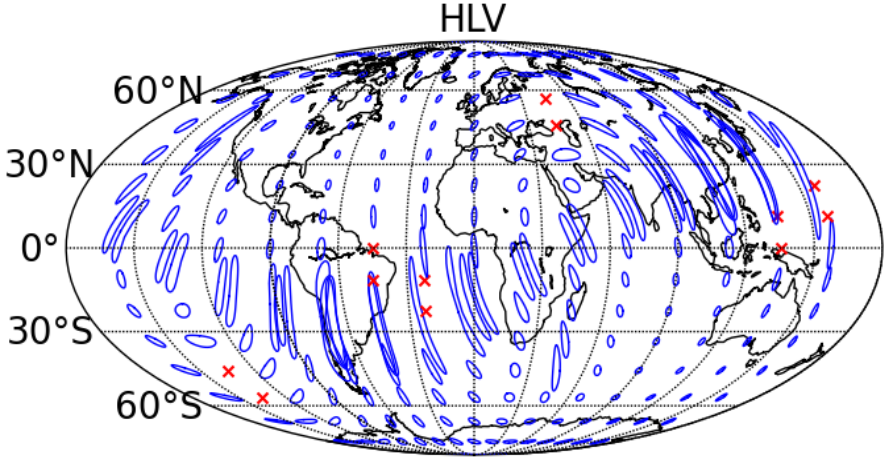
Face-on BNS 80 Mpc **HLV 2016-17**
~8 % contained in 20 deg^2



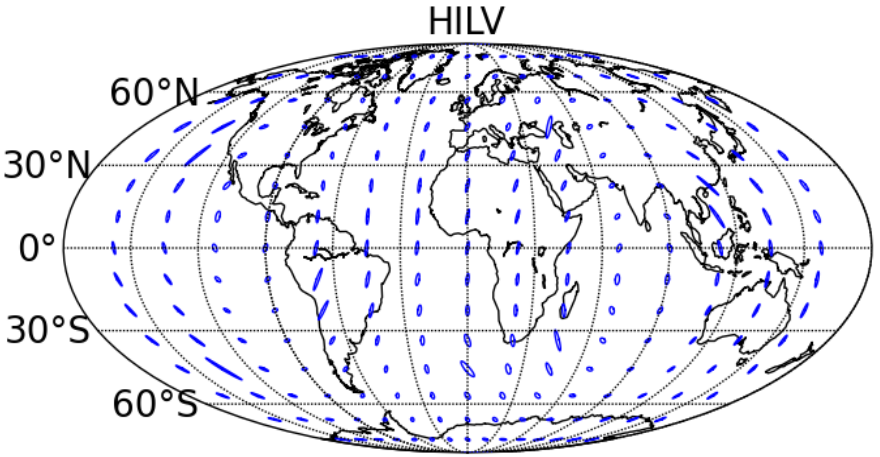
Face-on BNS 80 Mpc **HLV 2017-18**
~10 % contained in 20 deg^2



Face-on BNS **160 Mpc HLV 2019+**
~30 % contained in 20 deg^2

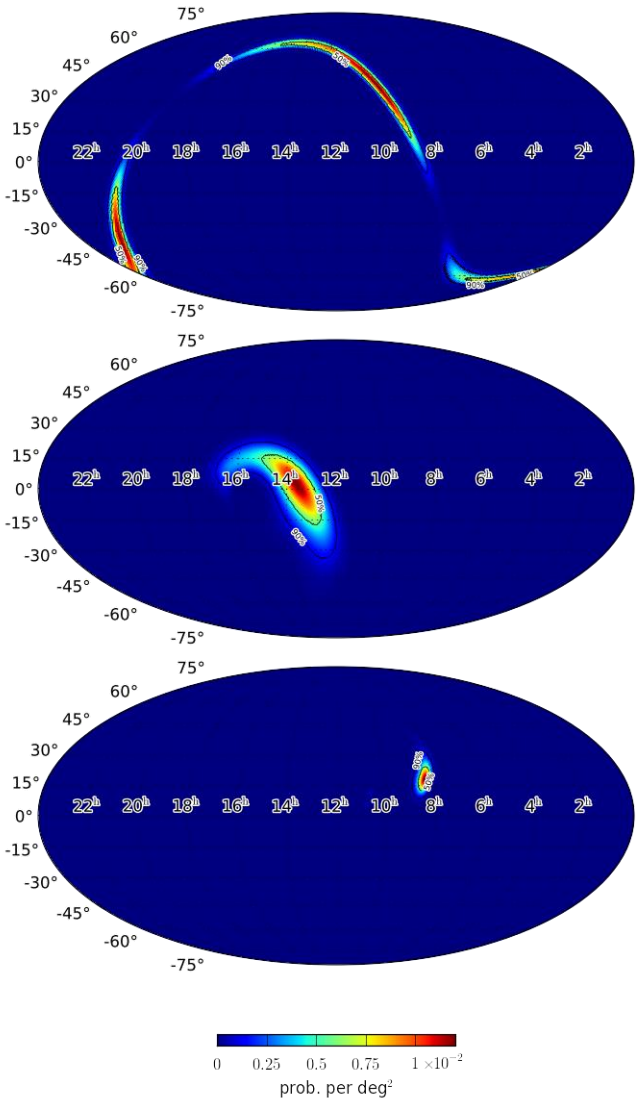


Face-on BNS 160 Mpc **HILV 2022+**
~50 % contained in 20 deg^2



Actual skymaps

Examples of BAYESTAR skymaps from simulated signals



- Posterior probability skymaps are obtained from coherent analysis
  - Fast coherent position reconst. (~min) cWB for bursts, BAYESTAR for CBC
  - Full MCMC parameter estimation can be done, but currently is slow (~days)
    - Effort underway to speed it up (maybe ~hour?)
- Error region geometry can be non-trivial
  - Banana shape
  - Disconnected islands – especially for narrowband GW burst candidates

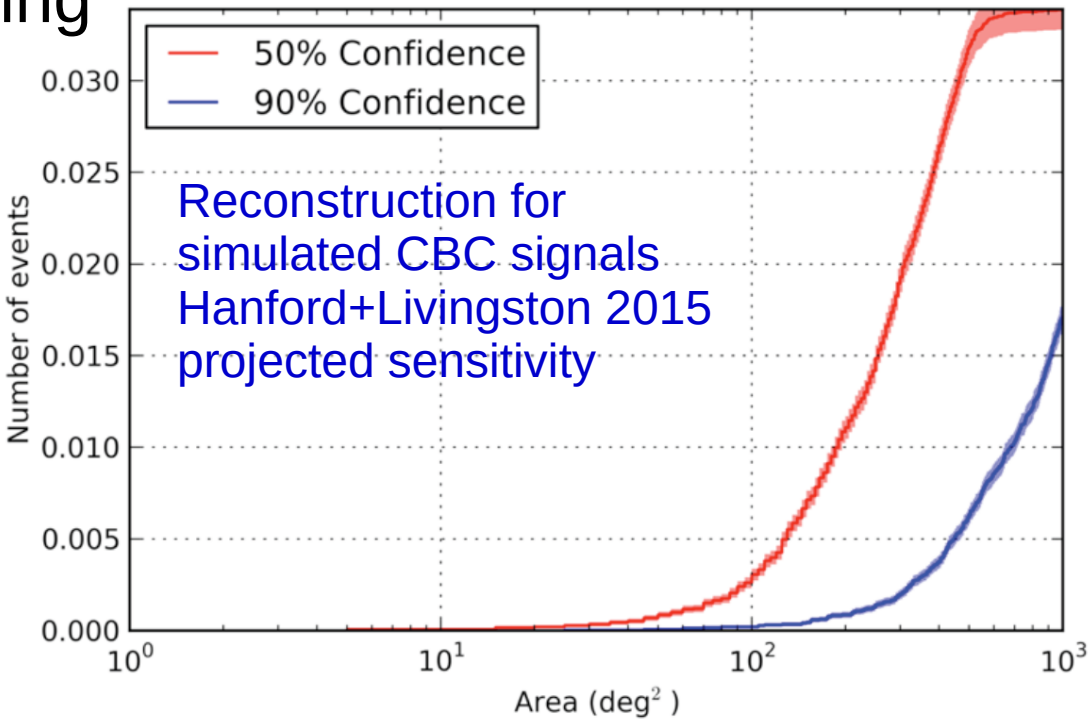
Possible strategies to deal with large sky areas (tens to hundreds of deg^2)

- Rely on wide-field telescopes and instruments
- “Tile” error region with many images
- Target nearby galaxies
  - Assumes sources are in/near them, of course
- Make assumptions about source to constrain signal params
  - e.g. assume face-on CBC orbit ➔ circularly polarized signal

Position info from two detectors?

- First science run, in 2015, will likely only have LIGO Hanford+Livingston operating with usable sensitivity
  - Capable of *detecting* a GW signal (if lucky, given projected sensitivity level and understanding of rates)
- Bayesian analysis with priors gives somewhat better position info than just a ring
  - Still hundreds of deg^2

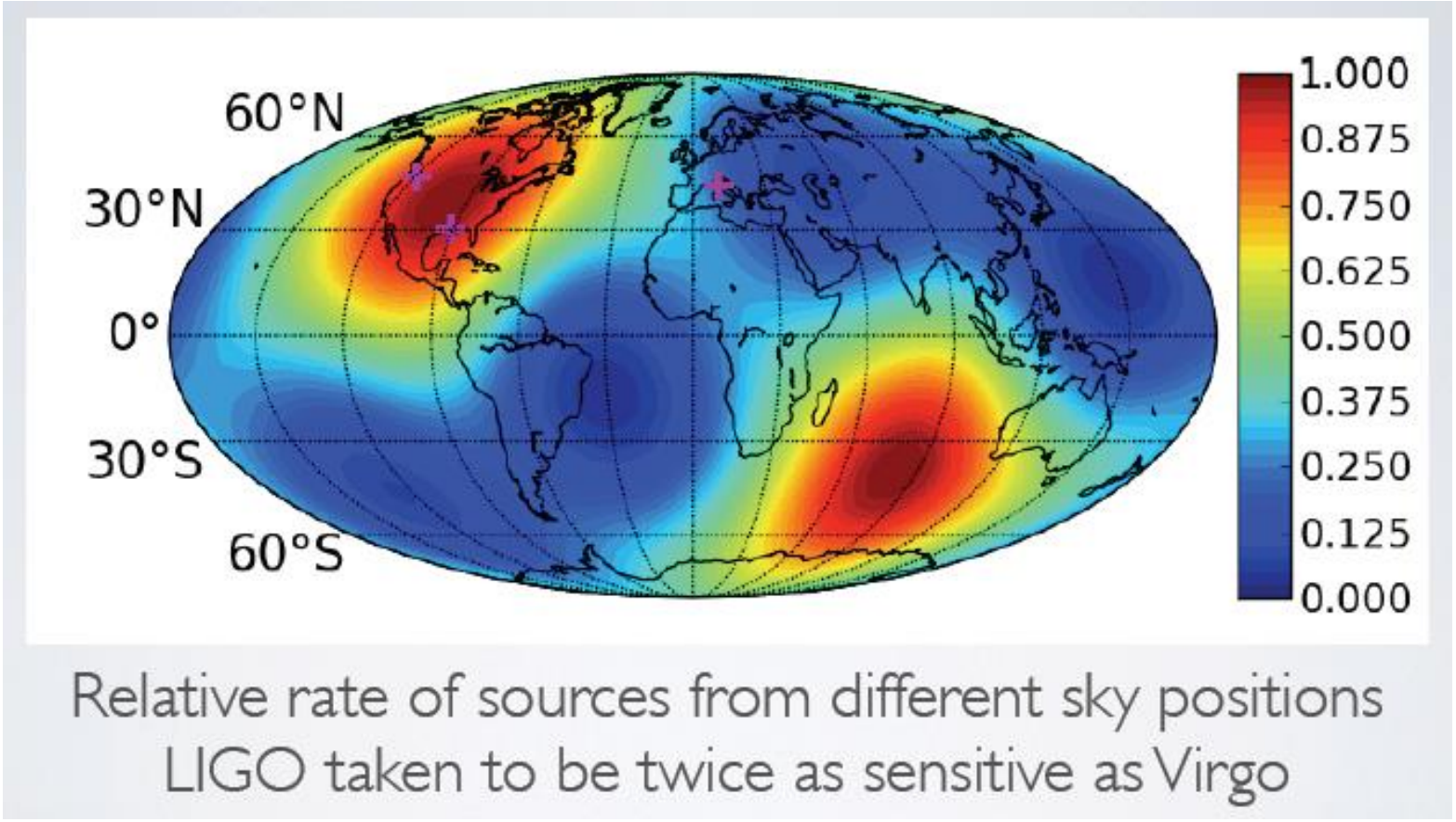
(Will have event time and some position info to correlate with ongoing EM transient surveys, in any case)



Singer, Price, et al., in preparation

Most likely locations of detected GW events

- Range depends on location relative to GW detector network
- Assuming uniform distribution, $\text{rate} \propto (\text{range})^3$



S. Fairhurst

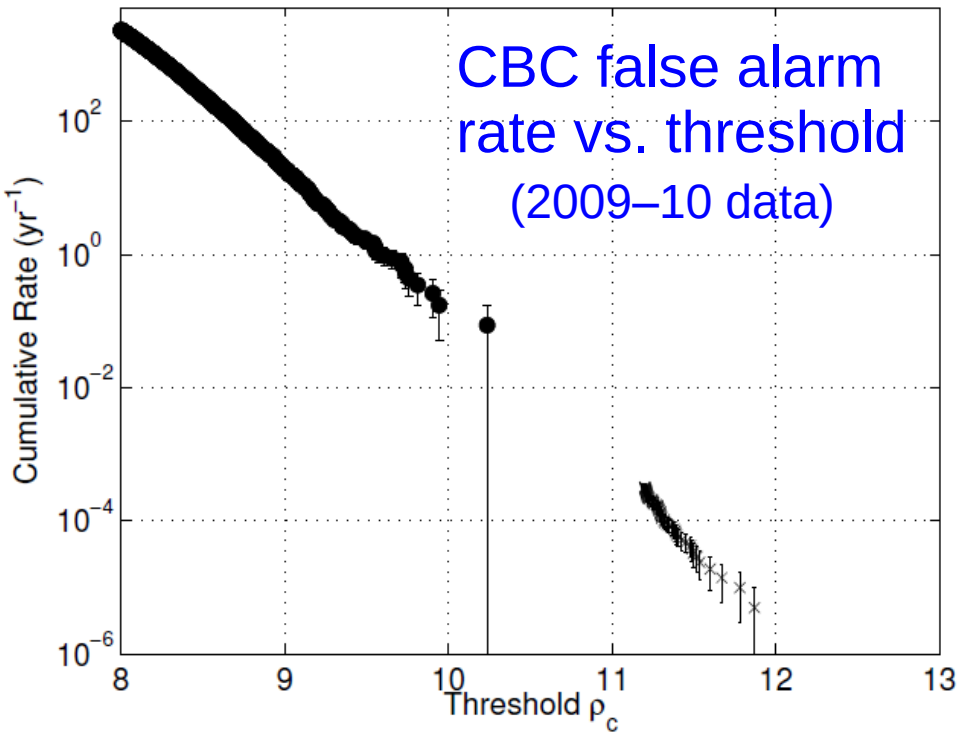
Potential impact of EM follow-up observations

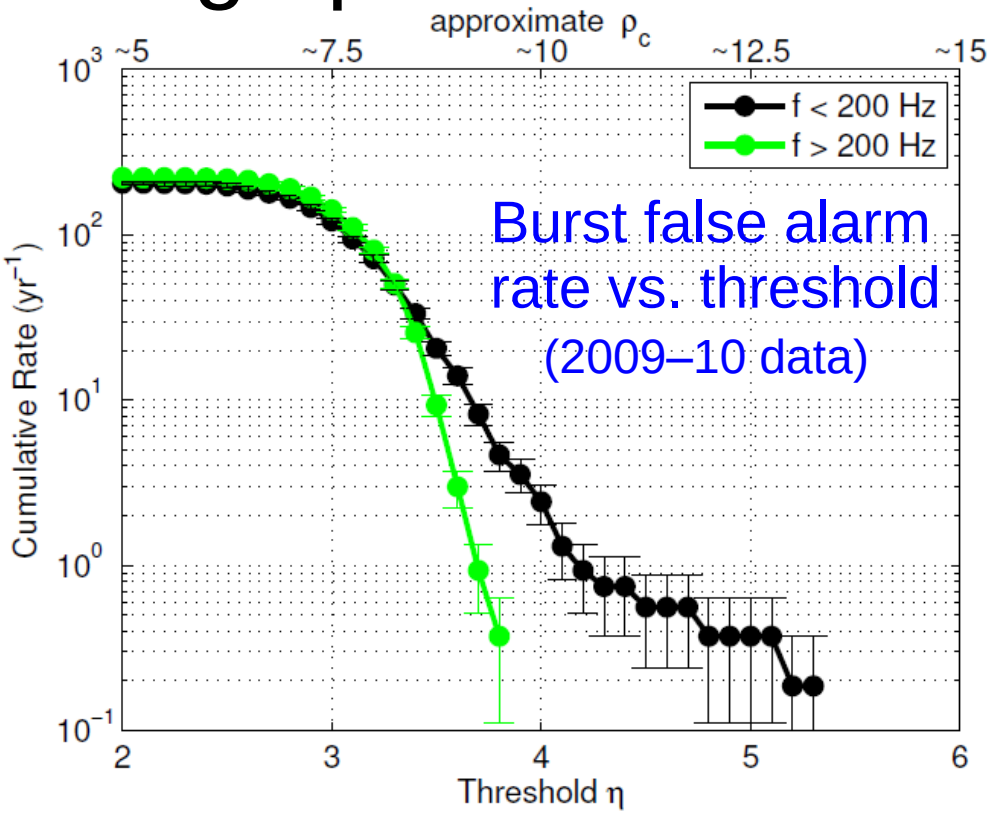
- Better results from GW data analysis
  - Being more confident in the detected GW signals
  - Precise sky position from EM enables better GW parameter estimation – in particular distance and orientation of the source
- Better source modelling from multi-messenger info
  - Compare times, energies, polarization, redshift/distance, etc.
  - Connection to astrophysical events, e.g. gamma-ray bursts

Crucial issue: Understanding the false coincidence rate

- There are lots of transients and variable sources in the sky, especially in the optical band
  - Need to have a handle on false coincidence rate to not overestimate importance
  - A GW candidate with a FAR of, say, 1 per week would need a pretty convincing EM counterpart to give us enough confidence that it's real
- We will have high standards for claiming the first GW detection, or first few
  - Probably will relax as time goes on and we get more detections
  - GW event validation is likely to take a lot of time and effort at first – impacts publication timeline (will discuss tomorrow)

What rate of GW candidates is worth following up?





- False (background) rate rises rapidly if threshold is lowered
- True rate $\propto (\text{threshold})^{-3}$; overall factor not yet known
  - Also, weaker events are more poorly localized
- Rate of useful alerts to be decided; maybe ~1 per week?

How should we collaborate?

- Many astronomers have expressed interest, with a wide range of observing capabilities and collaboration styles
- We propose **two modes of participation:**
  - Independent: partners who make all their own decisions
  - Coordinated: consortium of partners interested in coordinating observations

What is the same for all

- All partners will share information with all other partners and LIGO/Virgo about what observations they make and any possible counterparts they find, using something like a "private ATel" (maybe just a mailing list)
- All partners will retain ownership of their own data
- All partners will analyze and interpret their own data, or else ensure that it is done promptly by someone competent

What is different

- Independent: where and when to observe is entirely up to you
- Coordinated: joint working group consisting of all Coordinated partners plus involved LIGO/Virgo members will establish observing strategies and *recommend* where/when to observe
  - Not a *legal* obligation, just a practical strategy for the science
  - Consortium model may affect authorship of papers – will discuss tomorrow

Who would most appropriately be Coordinated?

- If your scope can only **cover a small fraction** of the GW error region
  - e.g., optical telescopes that can cover a few to several square degrees
  - Join forces and divide up the sky to ensure complete coverage for an initial search for possible counterparts
- If you are offering a facility but **want someone else to recommend** when and where to point it
  - e.g., when a promising possible counterpart is found by the initial search and your facility can target it for spectroscopy, deep photometry, other EM bands (radio to gamma), etc.

Have to work out with the Coordinated working group how an observation with your scope should be triggered, who makes it happen, how data gets processed and interpreted

Preparations before data collection begins

- Receive and decode (test) GW alerts
  - Integrate into your facility's scheduling paradigm and test
- Define observing strategies
- Coordinated group: figure out how to coordinate observations
  - Including how/when to deploy deep photometry or spectroscopy for possible counterparts
- Evaluate chance of false coincidence with an unrelated transient, given the chosen strategy

Questions for discussion

- What do you think about the planned event latencies? Is there a strong science case for minimizing validation time?
- Is this the right info to send out for a GW event candidate?
- Do LIGO/Virgo need to provide software to decode alerts?
- How many alerts per year do you think you would follow up?
- Does the “private ATel” communication model sound OK?
- How can the Coordinated working group be effective?
- Should there be shared tools for targeting nearby galaxies or implementing other observing strategies?
- How can we keep track and visualize what observations have been made by all partners?
- Any other issues?

Bibliography

References from 2009/2010 science run (initial LIGO and Virgo detectors)

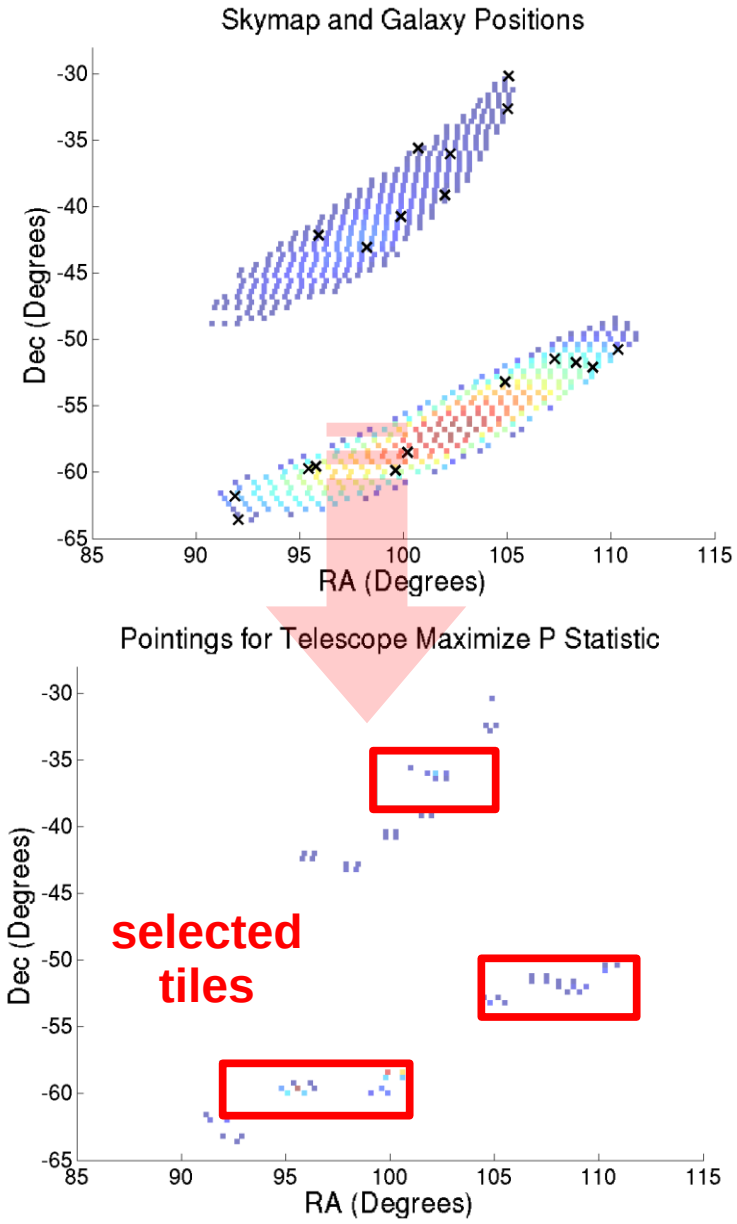
Abadie et al, Implementation and testing of the 1st prompt search […] *A & A* 539 (2012) A124, arXiv:1109.3498
Abadie et al, First low-latency search for binary inspirals […] *A & A* 541 (2012) A155, arXiv:1112.6005
Evans et al, Swift follow-up […] 2012 *ApJS* 203 28, arXiv:1205.1124

References in preparation of the advanced detector science runs

Aasi et al, Prospects for localization [...] for Advanced LIGO and Advanced Virgo, arXiv:1304.0670

Back-up slides

Pointing strategy (1)

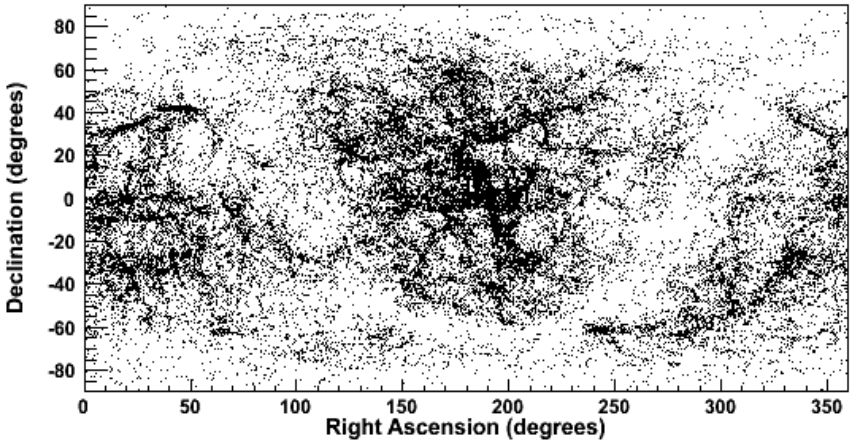


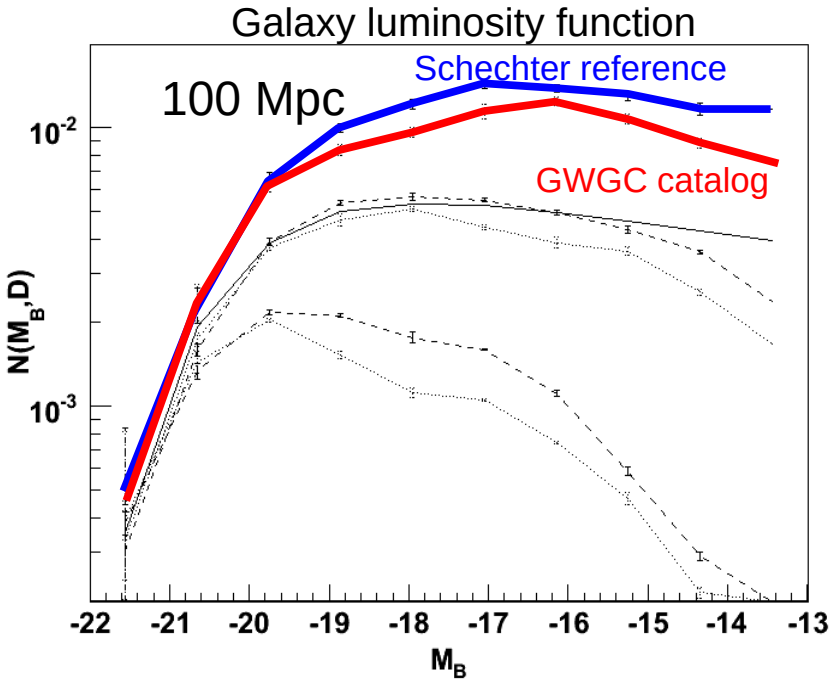
- Posterior sky map
  - ✔ May be composed of disconnected islands
- Galaxy weighing
  - ✔ Local distrib. of mass is heterogeneous at small distances
  - ✔ **Observe close and massive galaxies first**
  - ✔ Ad-hoc ranking statistic

$$P = \sum_{\text{gal} \in \text{pixel}} \frac{\text{mass(gal) likelihood (pixel)}}{\text{distance(gal)}}$$

  - ✔ Used catalog of close galaxies: GWGC
  - ✔ Factor of 2 improvement in the probability of a correct pointing for initial detectors (out to 50 Mpc)

Pointing strategy (2)





- Galaxy catalogs incomplete from 100 Mpc
  - ✔ Surveys of local galaxies (WALLABY and Hα) are upcoming
- Galaxy distribution to 400 Mpc becomes essentially isotropic
  - ✔ No significant gain in simple galaxy weighting
- Other ideas?
  - ✔ Select hosts that are consistent with binary distance estimate
  - ✔ Select potential hosts based on their type