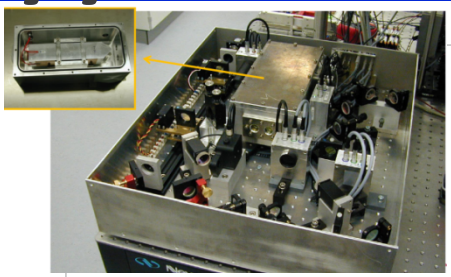
Gravitational Wave Follow-up:
Expectations, Tools, and Choices

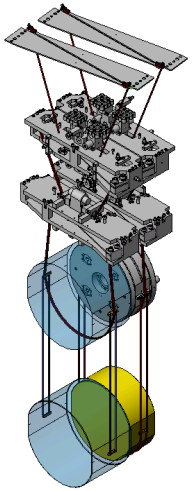
Roy Williams (Caltech)
for the LIGO Scientific Collaboration
and Virgo Collaboration

Time Domain Forum, Caltech
May 9, 2014

LIGO-G1400497

Advanced Gravitational Wave Detectors





Long-planned upgrades of initial GW detectors: Advanced LIGO (shown) and Advanced Virgo

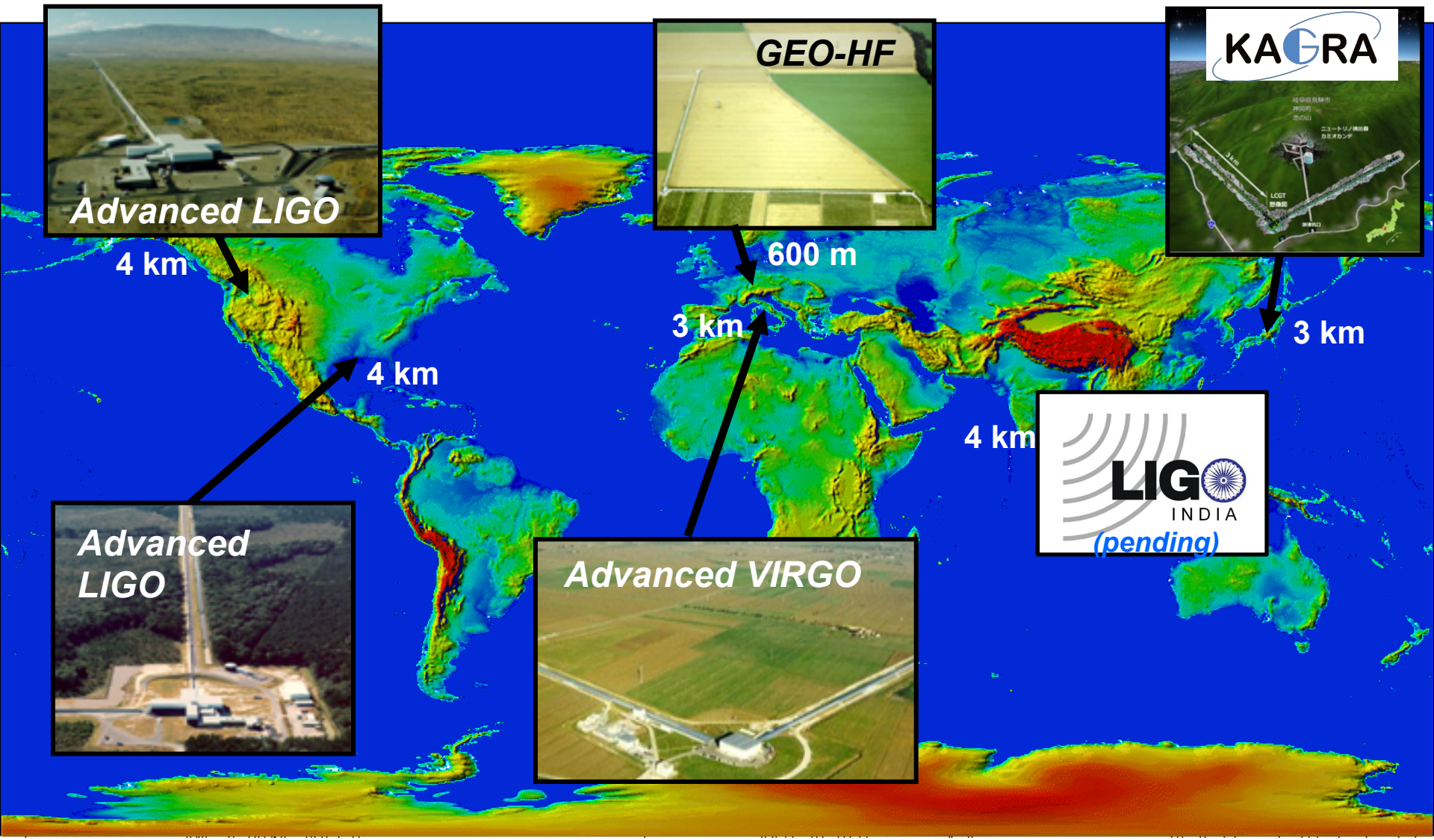
Factor 10 in strain means factor 1000 in volume.

courtesy P. Shawhan

Now Being Installed and Tested !

courtesy P. Shawhan

Advanced Detector Network – Under Construction



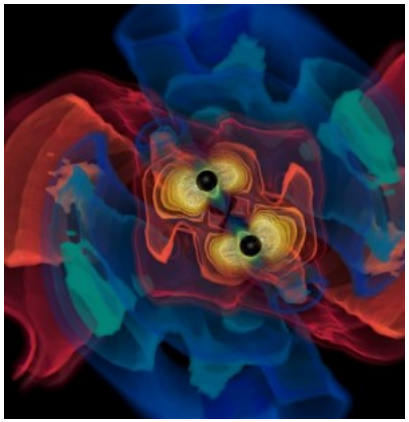
courtesy P. Shawhan

Searches for GW Transient Sources

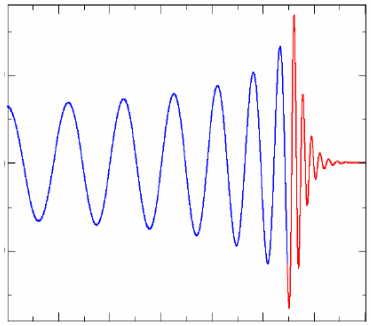
GW data streams are analyzed jointly

Initially LIGO Hanford+Livingston and Virgo; later others too

Two main types of transient searches:



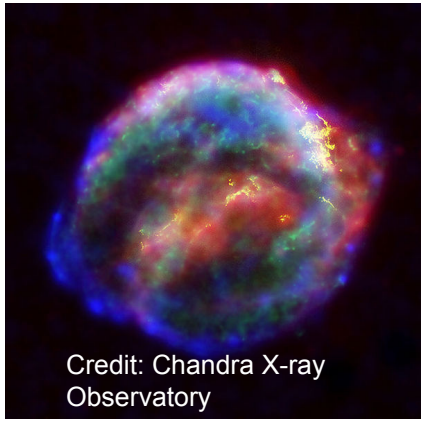
Credit: AEI, CCT, LSU



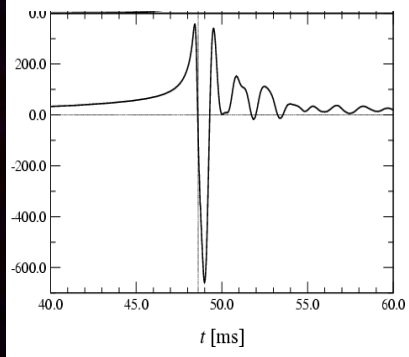
Compact Binary Coalescence (CBC)

Known waveform ➔ Matched filtering

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



Credit: Chandra X-ray Observatory



Unmodelled GW Burst (< ~1 sec duration)

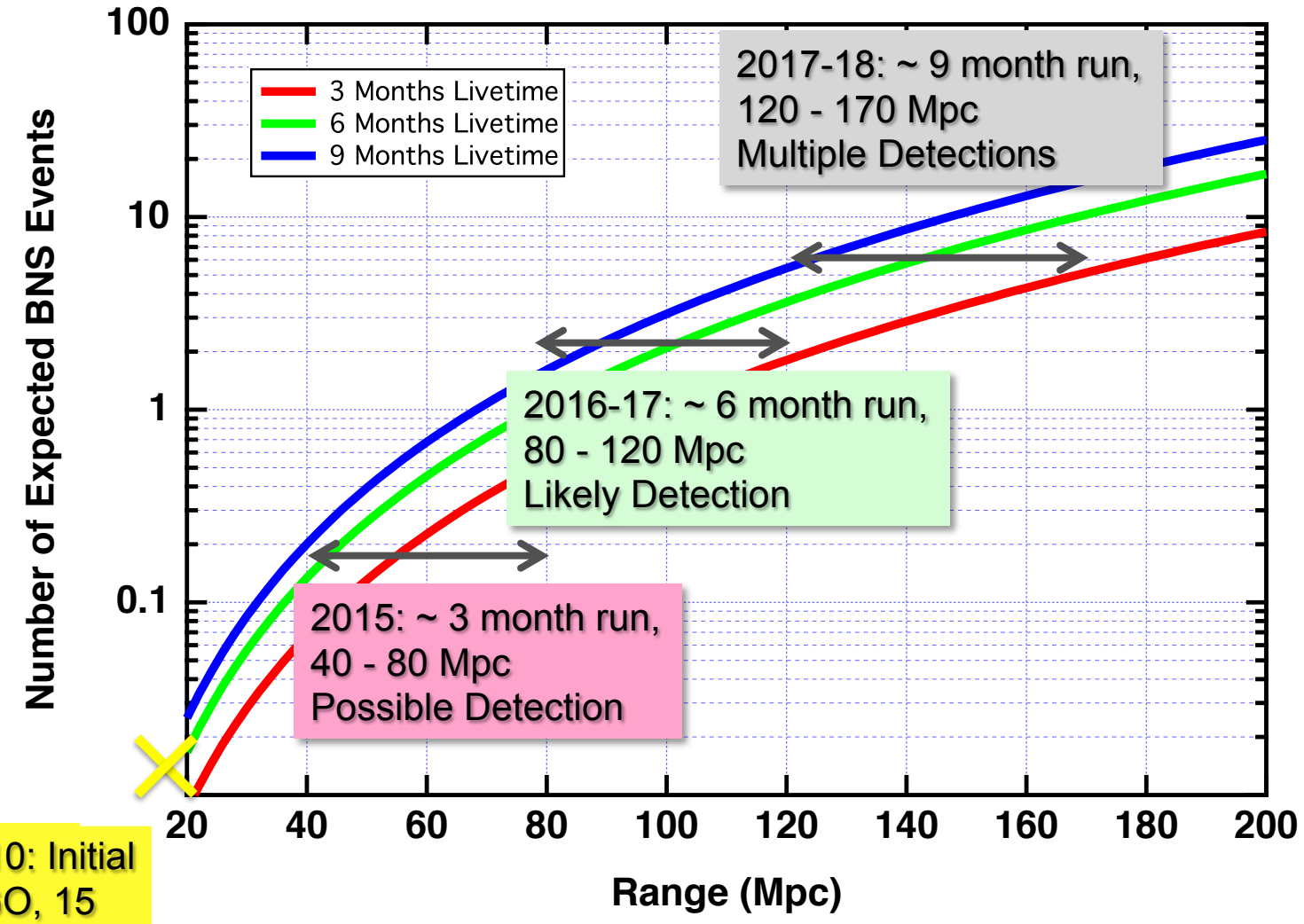
e.g. from stellar core collapse

Arbitrary waveform ➔ Excess power

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

courtesy P. Shawhan

Projecting Advanced LIGO Sensitivity Progression 2015-2018



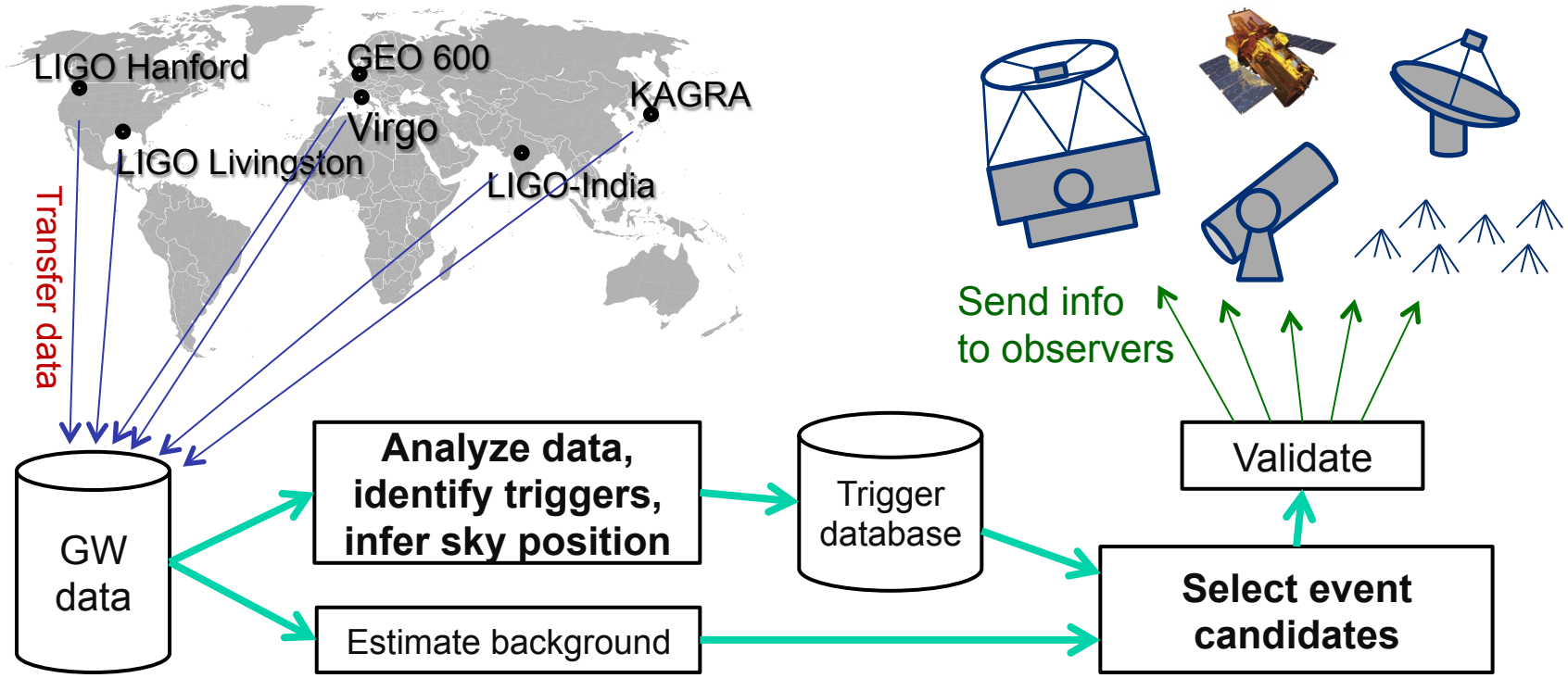
From *"Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories"*

arXiv: 1304.0670

2010: Initial LIGO, 15 Mpc

z=0.05

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

courtesy P. Shawhan

Alert Latency and Notes

Typical latency to generate triggers with sky position info: 3 to 6 minutes

Additional time needed for validation: not yet known, but maybe ~20 min

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

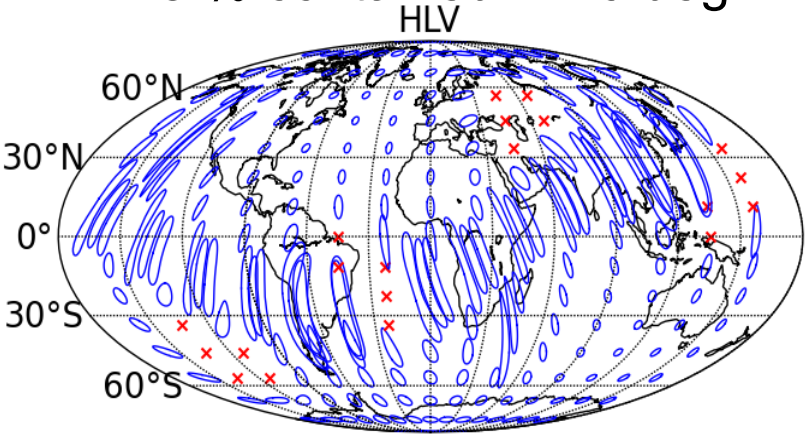
e.g. refined skymap (PE analysis) or significance estimate

Will send a VOEvent referencing the first one, incrementing the version number in the IVORN

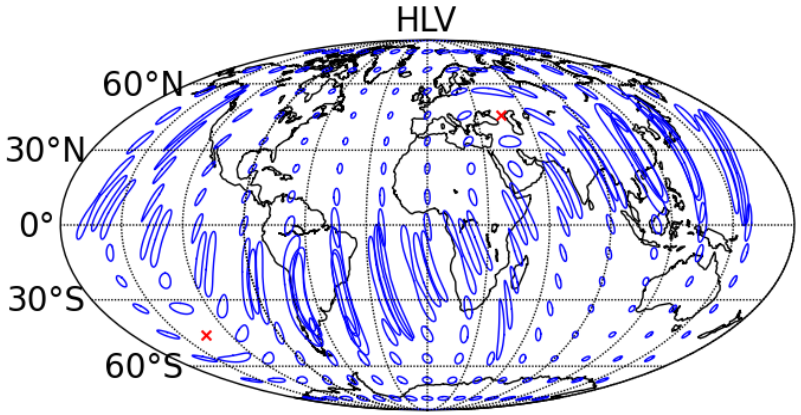
Position Reconstruction Accuracy vs. Time

http://arxiv.org/abs/1304.0670

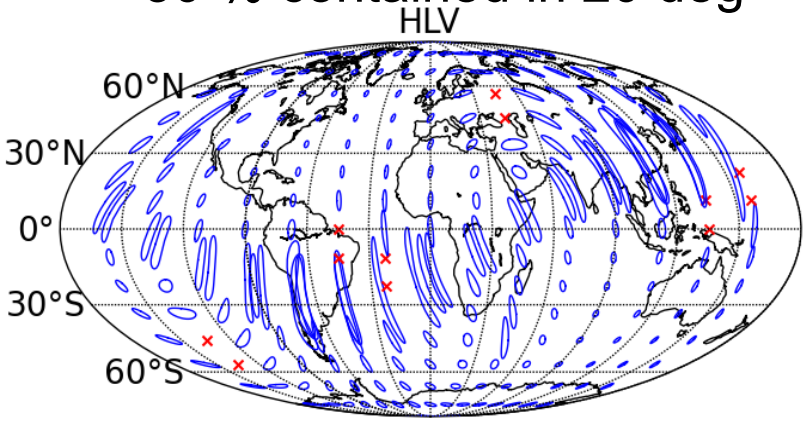
Face-on BNS 80 Mpc **HLV 2016-17**
~8 % contained in 20 deg^2



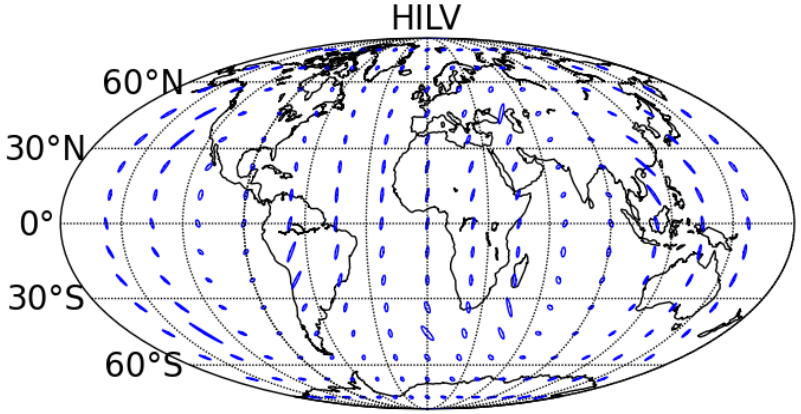
Face-on BNS 80 Mpc **HLV 2017-18**
~10 % contained in 20 deg^2



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



Follow-up Scenario

- Expect to distribute GW alerts as *Notices*/*VOEvents* over (initially) private GCN/TAN
- Responses by Notices and Circulars
- With private wiki, bulletin board, email for MOU partners
- **Interactions between LVC and EM partners will start soon**

What's in the Alert?

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

Programs (eg Healpy/Healpix)
Astro viz apps (eg DS9 or Aladin)
Derived data like **Skymap.json**
Specialist viz like **Skymap Viewer**

Maximum Distance

Although the source could be much closer

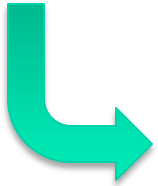
Follow-up Observer wants:

(1) Automatic neglect of what I cannot observe

too close to sun or moon

too close to galactic plane

wrong hemisphere



Skymap.json

Time UTC and MJD
Which detectors were involved
Declination histogram
Decile contour areas
Decile contours as polylines
Sun and Moon

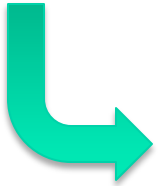
(2) If good, let me look carefully

when can I observe it?

which survey fields are relevant?

which galaxies could it be?

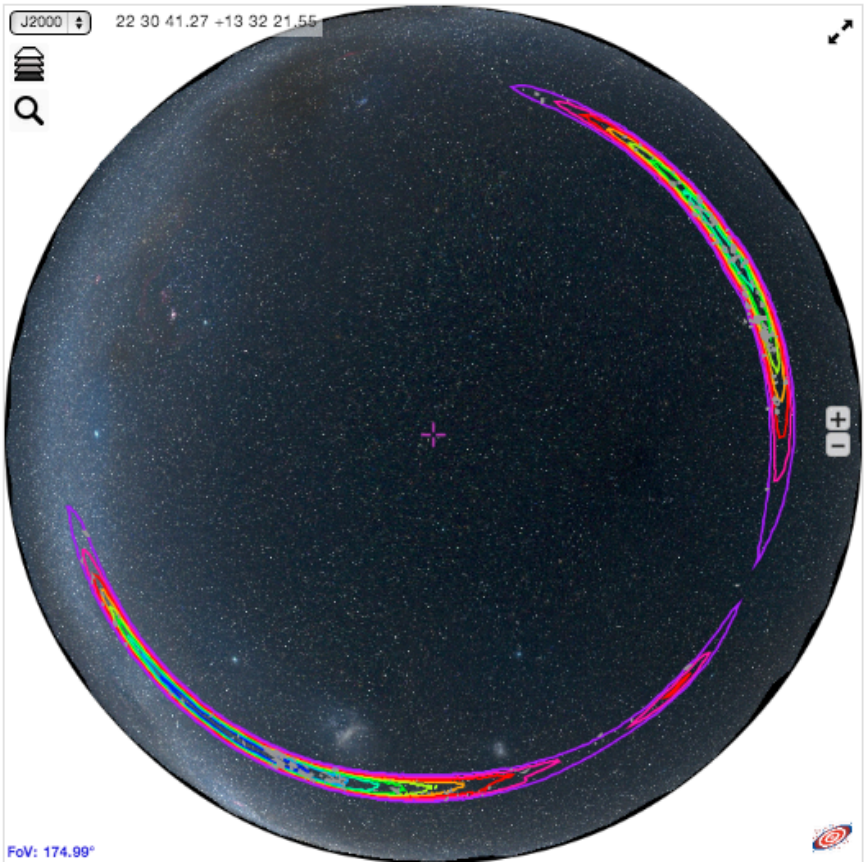
what are my partners doing?

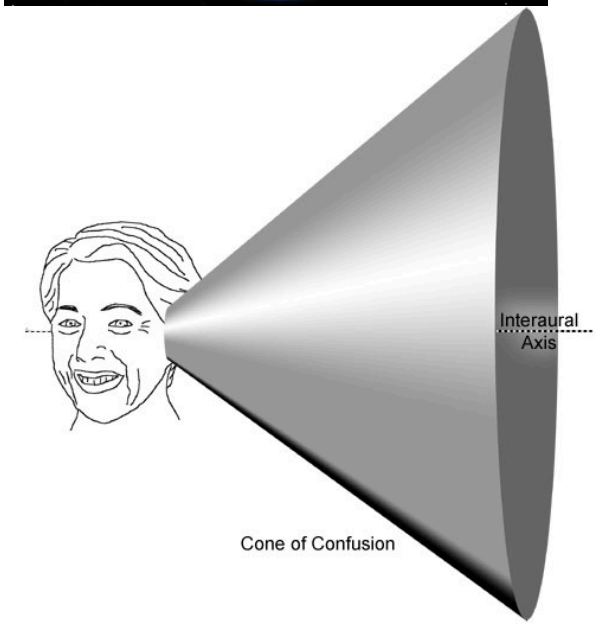


Skymap Viewer

Sky atlas with contour map
Local horizon
Catalogs of galaxies etc

Ring-shaped Skymaps





http://www.ligo.caltech.edu/~rwilliam/skymapViewer

Simulated skymaps

Posterior probability skymaps are obtained from coherent analysis

Fast coherent position reconst. (~min)

Full parameter estimation can be done, but currently is slow (~days), effort underway to reduce to ~hour)

Examples of simulated skymaps

L. Singer+ http://arxiv.org/abs/1404.5623

Data release: http://www.ligo.org/science/first2years/

Skymap Gallery from First2Years

Gallery of Skymaps

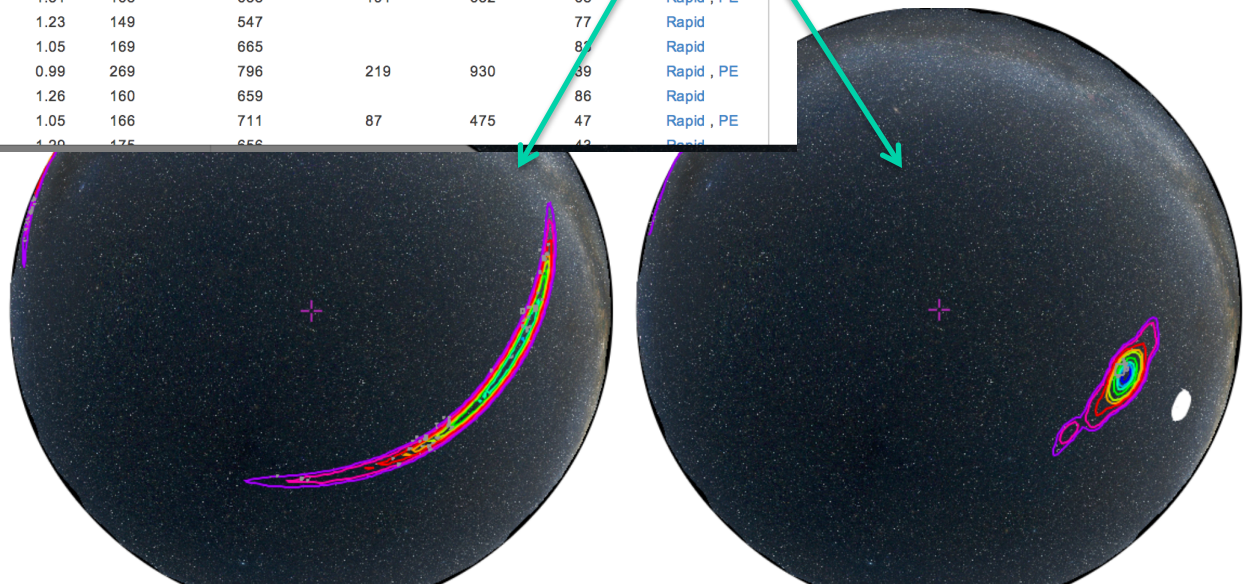
This page shows 1605 skymaps from the pa
at the end have skymaps from two analysis
Lalinference_MCMC or Lalinference_Nest).

- Year: The year label from the paper, which can be 2015 or 2016.
- Figure: The figure number from the paper if this event is illustrated.
- Detection ID: The identifier of the event.
- network: List of detectors involved in the detection, can
- snr-net: Network SNR for the detection
- mass1: Recovered mass 1, solar masses
- mass2: Recovered mass 2, solar masses
- rapid-50: Area in sq degrees of 50% of the probability for rapid localization
- rapid-90: Area in sq degrees of 90% of the probability for rapid localization
- pe-50: Area in sq degrees of 50% of the probability for MCMC/Nest localization
- pe-90: Area in sq degrees of 90% of the probability for MCMC/Nest localization
- Distance: Injected distance in Mpc
- Links: To the Rapid and to the MCMC/Nest skymaps

Click to Sort

Rapid is ~Minute
PE is ~Hours
Can make a big difference

Year	Figure	Detection ID	network	snr-net	mass1	mass2	rapid-area50	rapid-area90	pe-area50	pe-area90	distance	Links
2015		1087	H1.L1	13.2	1.37	1.09	217	1022	241	953	43	Rapid , PE
2015		10116	H1.L1	18.9	1.43	1.16	99	440			41	Rapid
2015		10148	H1.L1	13.6	1.35	1.26	134	722	174	880	84	Rapid , PE
2015		10184	H1.L1	13.6	1.39	1.28	183	815	162	825	57	Rapid , PE
2015		10202	H1.L1	13.1	1.61	1.04	249	898	178	786	61	Rapid , PE
2015		10206	H1.L1	12.3	1.36	1.25	316	994	346	1106	72	Rapid , PE
2015		10389	H1.L1	14.5	1.53	1.2	168	635			46	Rapid
2015		10405	H1.L1	12.7	1.53	1.12	236	904			87	Rapid
2015		10458	H1.L1	15.9	1.43	1.31	168	638	191	652	68	Rapid , PE
2015		10478	H1.L1	13.2	1.46	1.23	149	547			77	Rapid
2015		10498	H1.L1	12.1	1.64	1.05	169	665			83	Rapid
2015		10529	H1.L1	12.2	1.66	0.99	269	796	219	930	39	Rapid , PE
2015		10690	H1.L1	13.1	1.37	1.26	160	659			86	Rapid
2015		10697	H1.L1	14.9	1.57	1.05	166	711	87	475	47	Rapid , PE



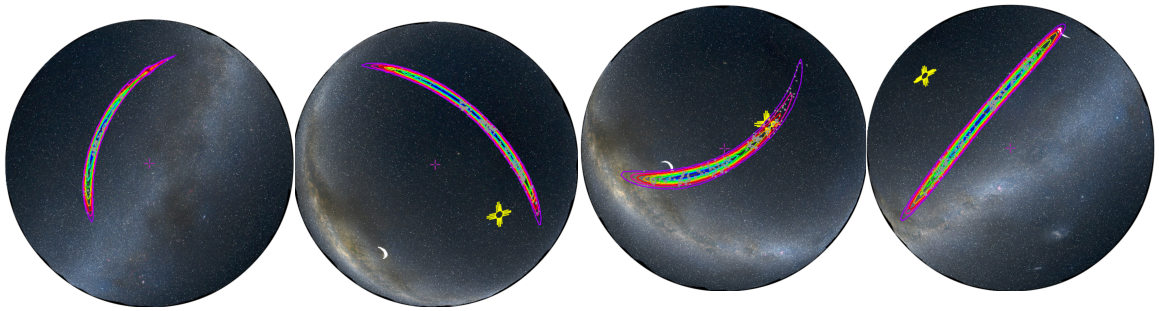
Simulated Skymaps

Warning: My Contours are Too Fat!

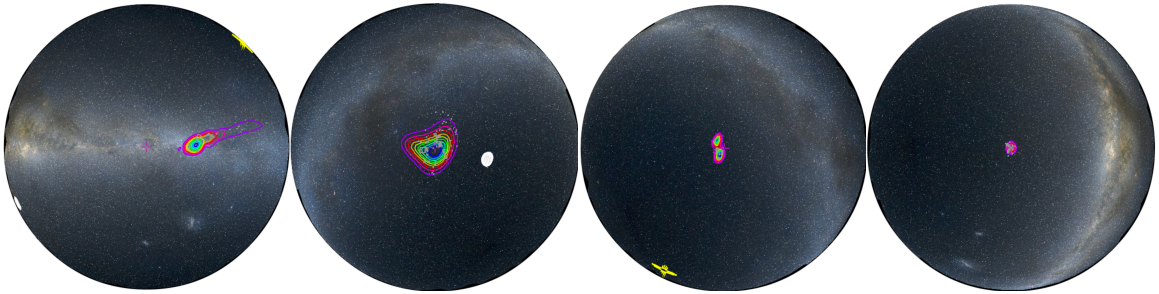
Error region geometry can be non-trivial

Banana shape and/or

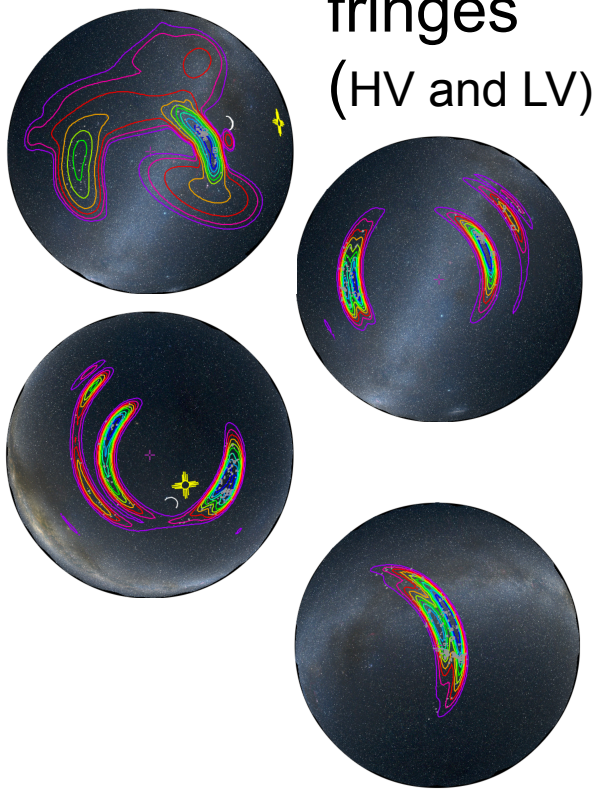
disconnected islands – especially for narrowband GW burst candidates



2-detector arc 2015



3-detector spot 2016



fringes

(HV and LV)

http://www.ligo.caltech.edu/~rwilliam/skymapViewer

Skymap Viewer

LIGO Caltech (US) + CDS Strasbourg (FR)

http://www.ligo.caltech.edu/~rwilliam/skymapViewer

★ **Skymap as decile contours**

100's of simulations 2015/2016

★ **Multi-scale**

allsky to arcsecond

★ **Multi-wavelength**

DSS, Fermi, XMM, SDSS etc

★ **Observing (Sun/moon/horizon)**

horizon for given long + lat + UTC

sun and moon

★ **Catalogs of galaxies/clusters**

or any catalog from Vizier

your suggestions welcome!

★ **Browser only**

nothing to install

Skymap Viewer

A sky atlas for understanding LIGO-Virgo skymaps. Help here, and skymaps here.

LIGO-Virgo Skymaps

This skymap visualizes the sky-location probability distribution for candidate event number **646923**

Detected by L1,V1

50%,90% areas 291.5, 1089.

Time and Place

Universal time

2014-05-02T12:40:26 Now Show Sky

E Longitude -118 Latitude 34

Sun = and = Moon

Catalog Sources

Click the Layers icon to switch on catalogs. If you click on the sources on the sky, information will appear here with links to Simbad and NED.

Zoomable Multiwavelength Sky

Zoom in on the sky with the mouse or the +/- icons on the right of the sky. To change the image layer, click the Layers icon and select an Base

J2000 09 41 8.03 -52 42 26.17

FoV: 175.66°

Choose image & catalogs

About the skymap

Time and place

Watch this space

LIGO-G1400497

Skymap Viewer

A sky atlas for understanding LIGO-Virgo skymaps. Help here, and skymaps here.

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Time and Place

Universal time
2014-05-02T12:40:26 Now Show Sky
E Longitude -118 Latitude 34
Sun = and = Moon

Catalog Sources

NGC3763
BMAG=-22.47, Dist=79.56
Simbad NED

Zoomable Multiwavelength Sky

Zoom in on the sky with the mouse or the +/- icons on the right of the sky. To change the image layer, click the Layers icon and select on Base

J2000 11 35 0.09 -11 56 33.16

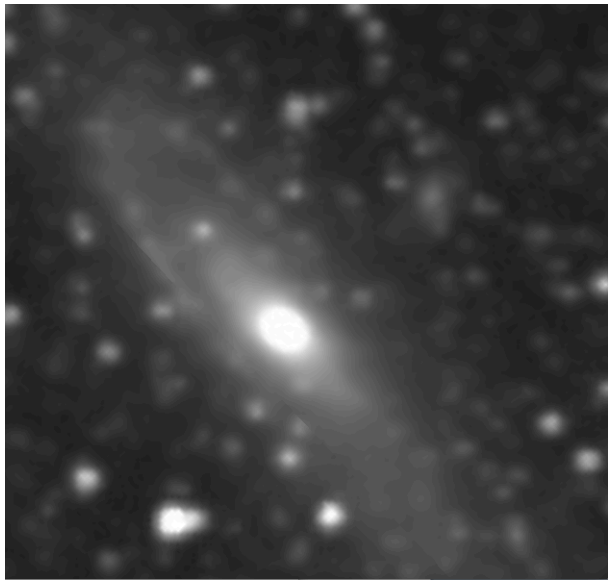
GWGC galaxy position x and abs mag M
→ size = $skymap(x).10^{-2BMAG/5}$

Click catalog source

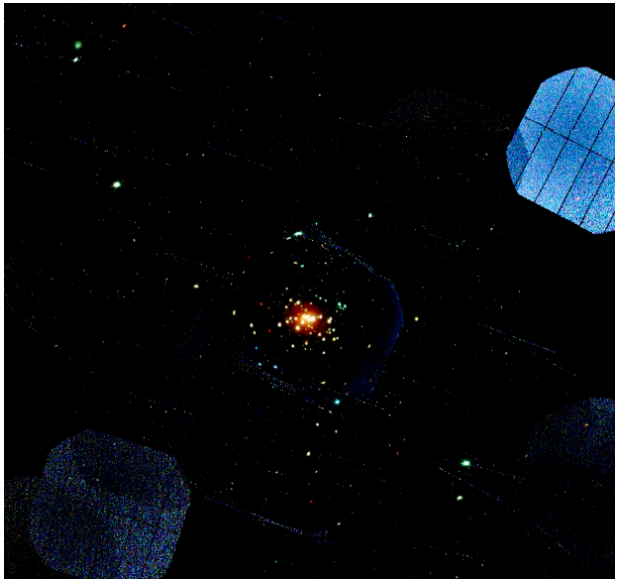
http://www.ligo.caltech.edu/~rwilliam/skymapViewer

Multi-wavelength: M31 in Skymap Viewer

Optical (DSS)



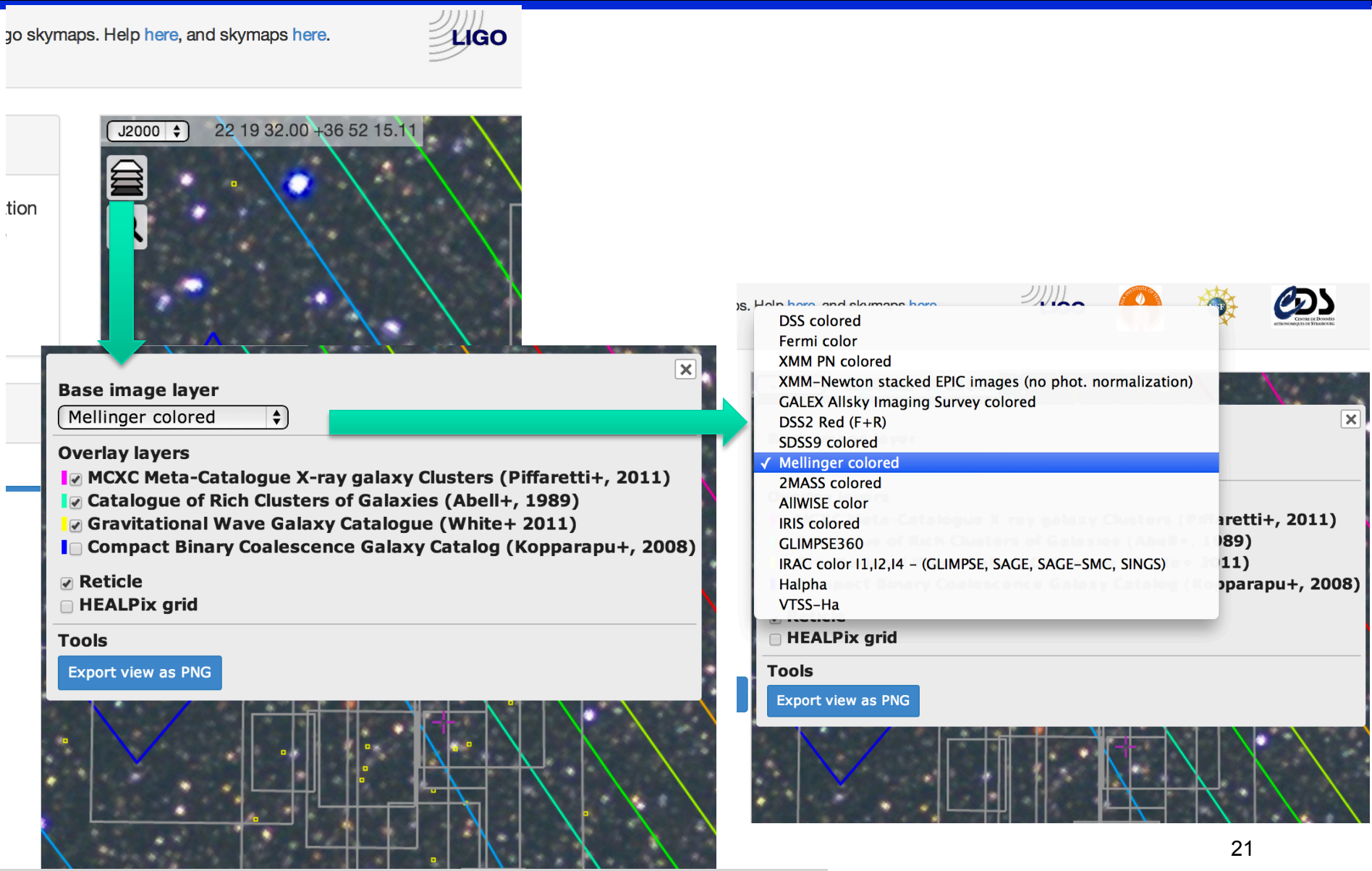
H-alpha (VTSS)



X-ray (XMM)

Infrared (Allwise)

Catalogs and Imagery



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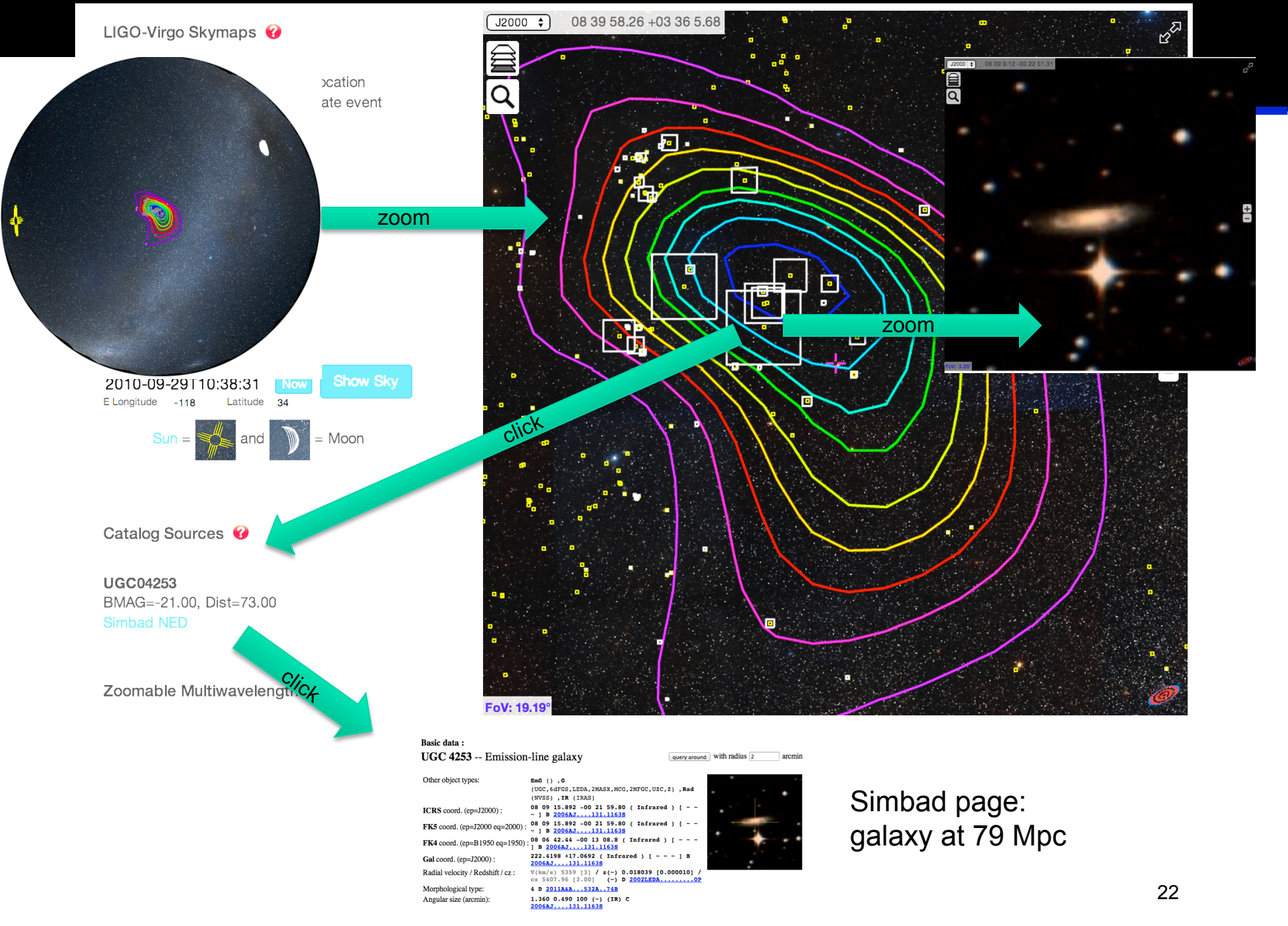
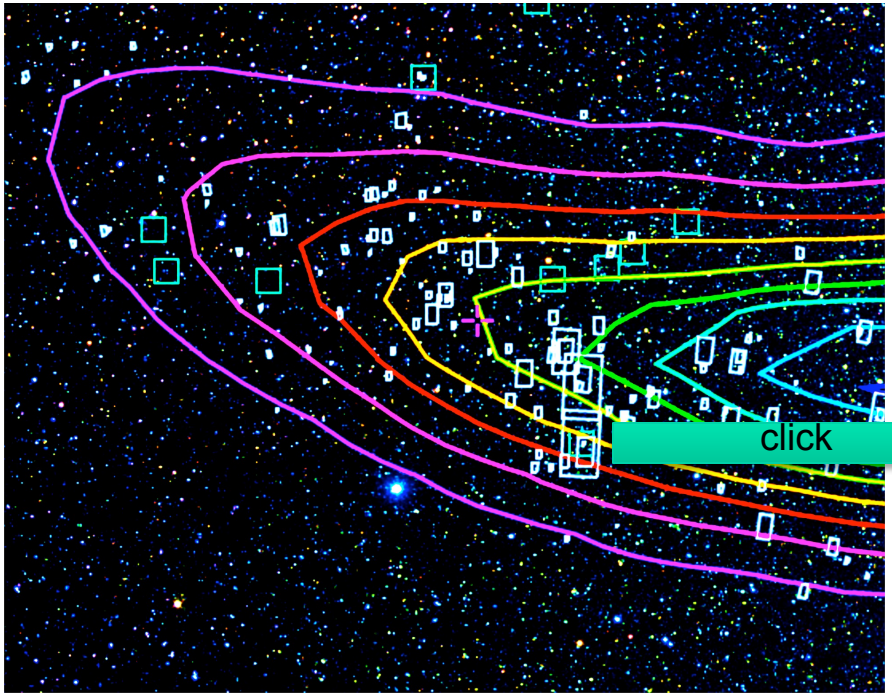


Simbad page:
galaxy at 79 Mpc

http://www.ligo.caltech.edu/~rwilliam/skymapViewer

Abell Galaxy Cluster catalog



Catalog Sources

840S
Abell 840 z=0.0152 Rich=0
Simbad NED

cluster Abell 840S is at 67 Mpc

http://www.ligo.caltech.edu/~rwilliam/skymapViewer

Bulletin Board?

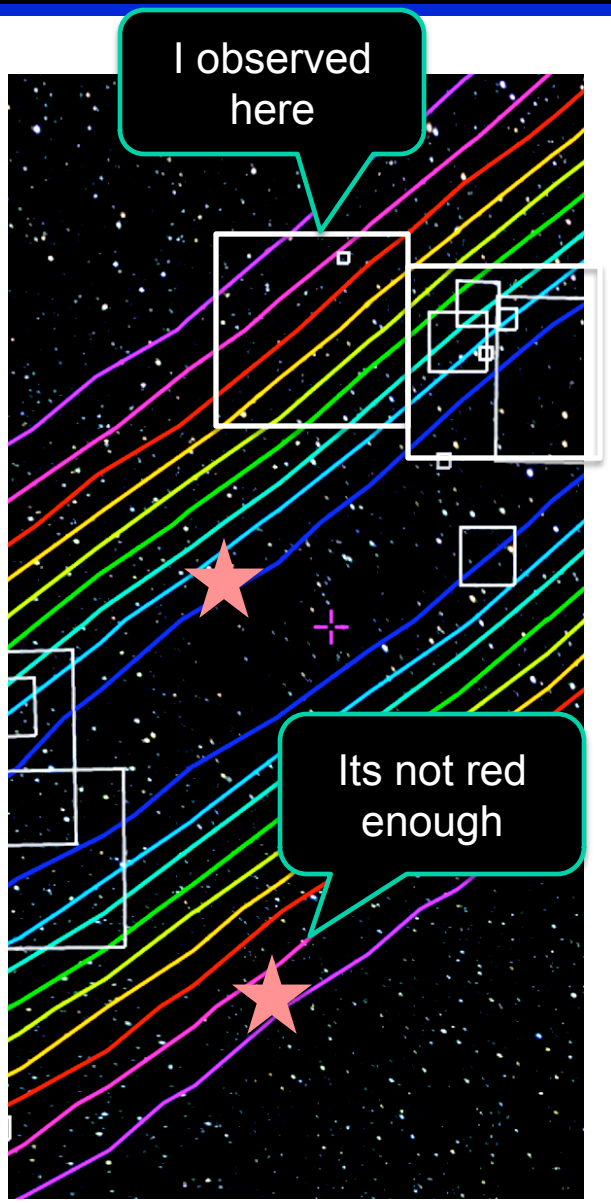
Transients found as catalog

Candidates, each with comment stream

Footprints of images acquired

Locating Notices and Circulars in the sky

Do follow-up observers want to communicate this way?



Summary

- **Gravitational wave detectors operate as a global network**
  - Data combined and analyzed coherently
  - Japan and/or India critical for good localization
- **Advanced LIGO and Virgo upgrades are well underway**
  - First science run is only about 1 year away. Livingston in lock 2014 May
  - Sensitivity and position reconstruction accuracy will improve over time
- **EM follow-ups are exciting**
  - Building tools to help the EMfollow groups
  - Sensitivity and position reconstruction accuracy will improve over time

Questions for Discussion

Would observers use the Bulletin Board if provided?

What other catalogs can go in Skymap Viewer

both candidates and false positives?

Is it useful to have last ~week of GRBs shown on skymap?

How can Notices and Circulars be enhanced?