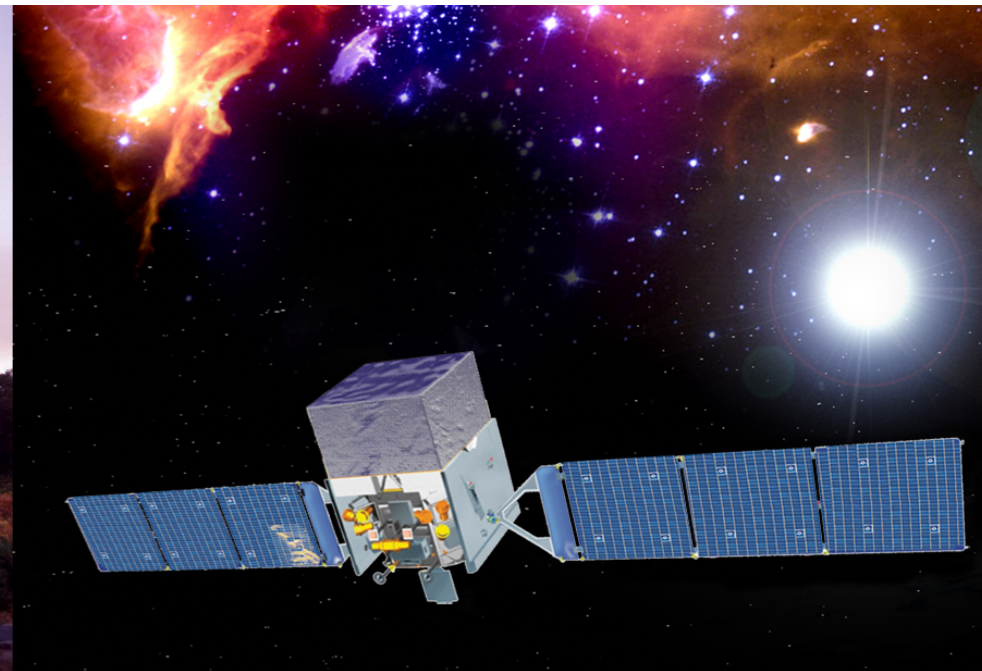


LEO P. SINGER

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Astroparticle Physics Laboratory
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ADVANCED LIGO FIRST LIGHT

BROADBAND FOLLOW-UP OF COMPACT BINARY MERGERS



7 YEARS OF MAXI

RIKEN, Japan, 2016 December 7

FIRST LIGHT

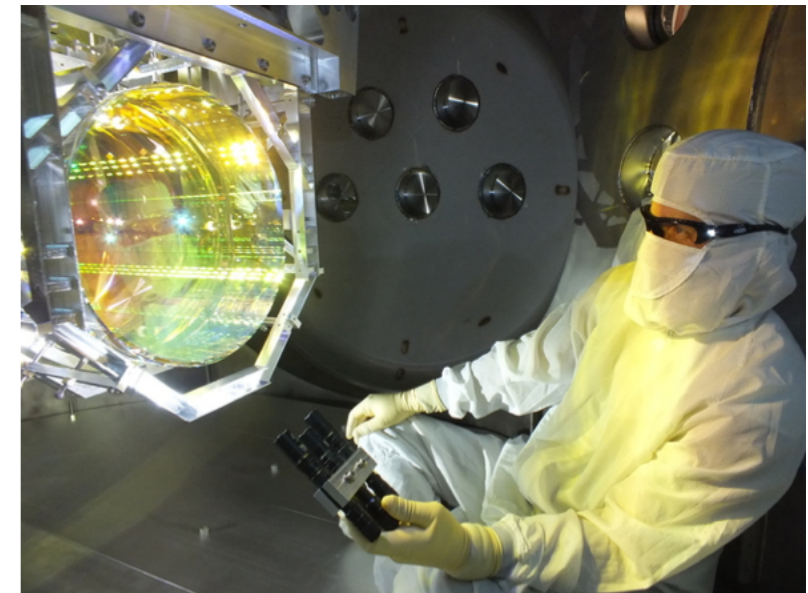
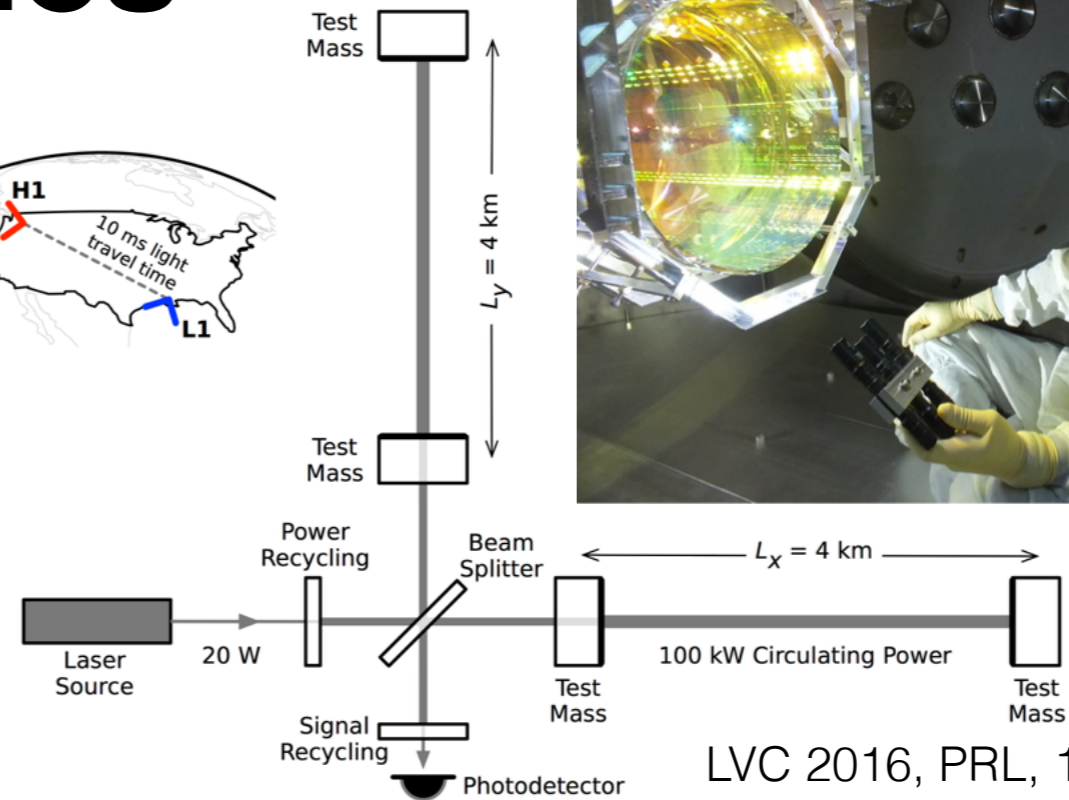
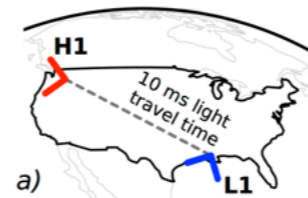
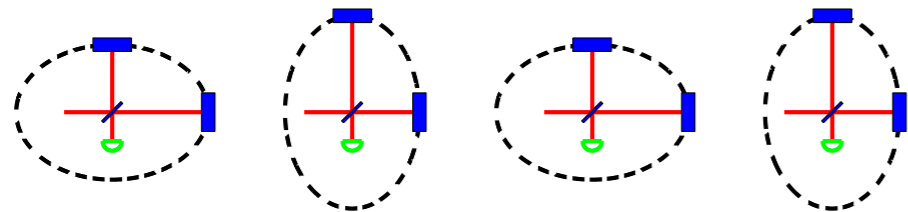
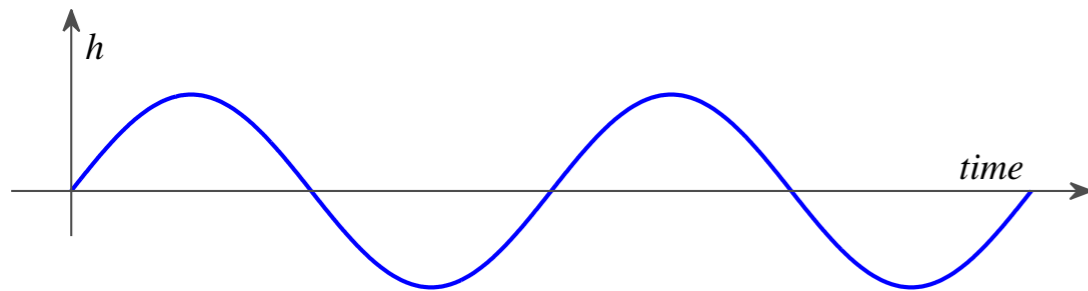
— *noun* 1. In astronomy, first light is the first use of a telescope (or, in general, a new instrument) to take an astronomical image **after it has been constructed**. This is often **not the first viewing** using the telescope; optical tests will probably have been performed during daylight **to adjust the components**... first light is always a moment of **great excitement**, both for the **people who design and build the telescope** and for the **astronomical community**, who may have **anticipated the moment** for many years **while the telescope was under construction**. A well-known and **spectacular** astronomical object is usually chosen as a subject.

(Wikipedia)



I. ADVANCED LIGO FIRST LIGHT

A GLOBAL NETWORK of GW observatories



LVC 2016, PRL, 116, 061102

- **LIGO: Laser Interferometer Gravitational-wave Observatory**

- Senses fractional arm displacements (strain) of 10^{-21}
 - changes in length of $\sim 2 \times 10^{-16} \text{ cm}$
 - = 1/500 of charge radius of proton
 - like measuring distance to Proxima Centauri to the width of a human hair

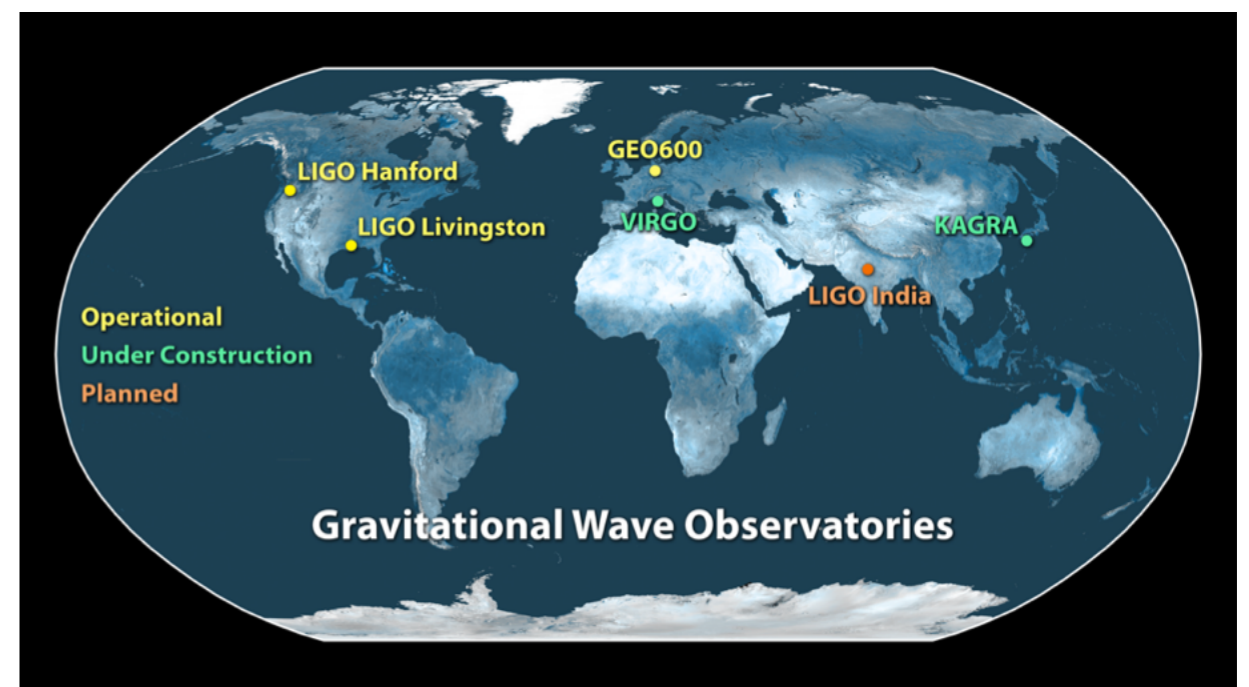
- **A tour de force of precision measurement:**

40 kg “test masses” suspended from fused silica fibers, multi-stage pendula, active seismic isolation

20 W laser power → 100 kW circulating in arm cavities

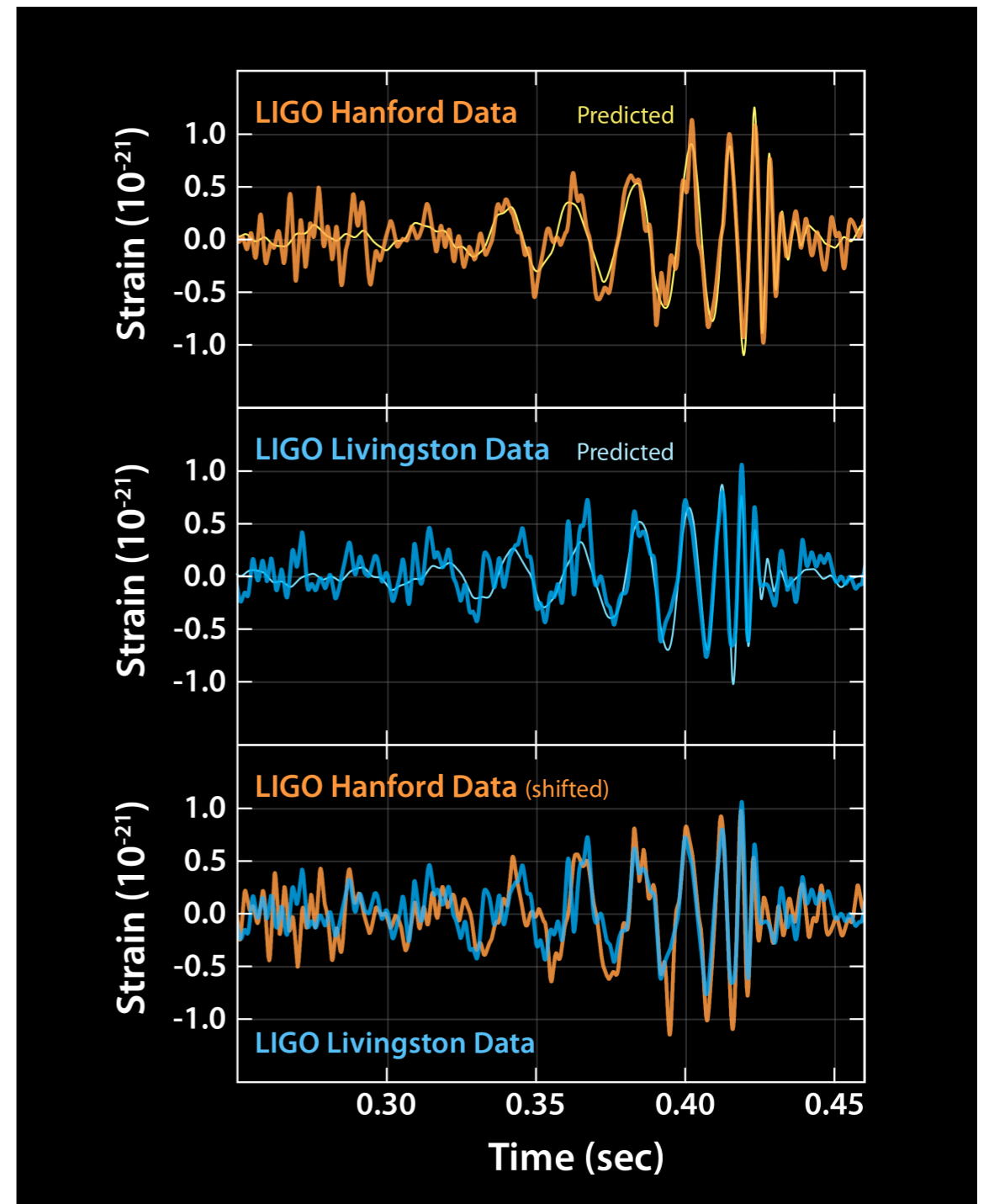
Thermal deformation of mirrors must be compensated by ring heaters and CO_2 lasers

...

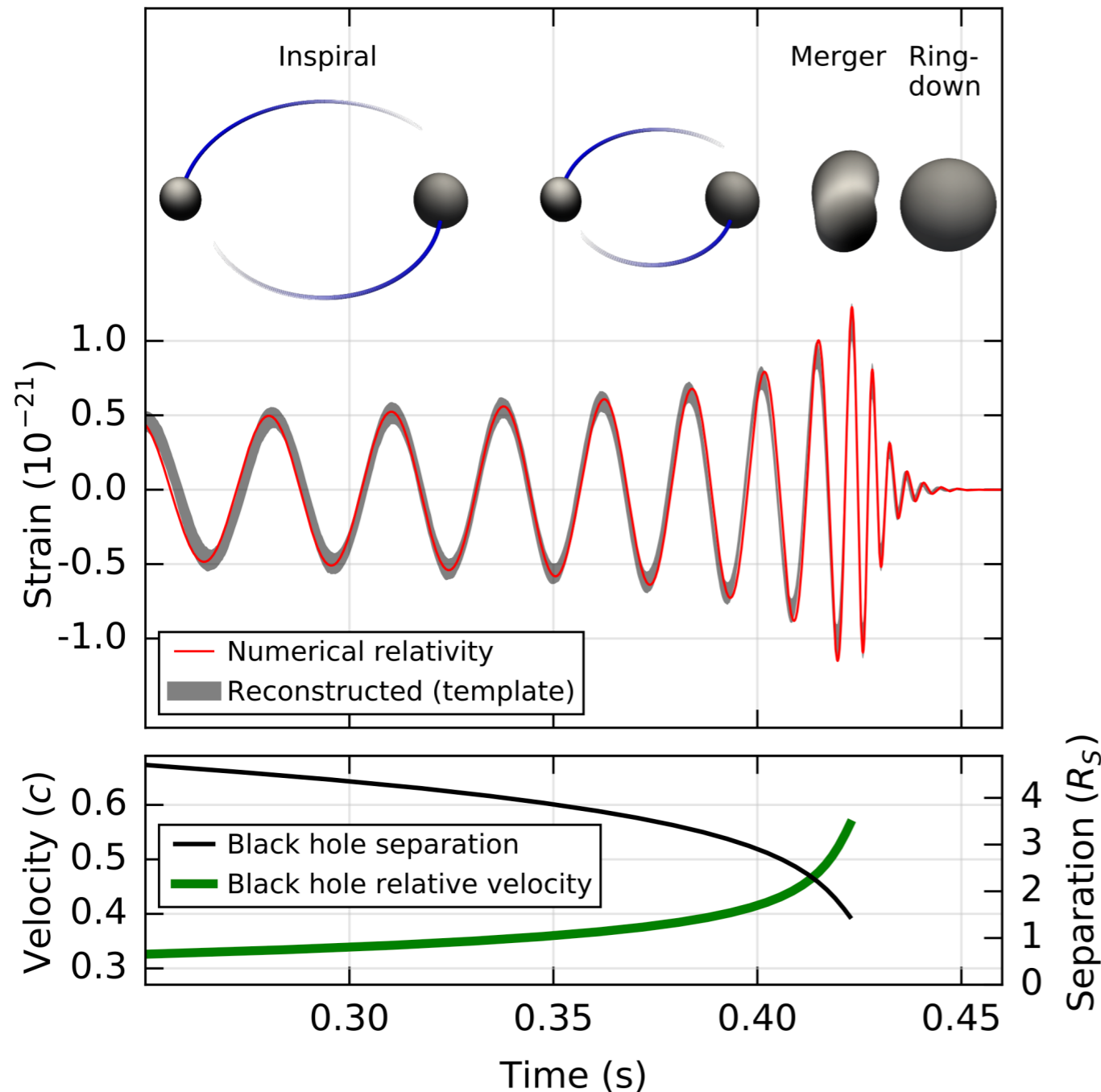


GW150914: first light

- Chirp signal recorded at LLO and 7 ms later at LHO during pre-observing engineering operations
- Swept from 35 to 250 Hz in 0.2 s
- Inspiral and merger of two stellar-mass black holes as predicted by general relativity



GW150914: first light



- **Surprising properties...**

Masses: $36 + 29 \rightarrow 62 M_{\odot}$

$3 M_{\odot}$ radiated in GWs!

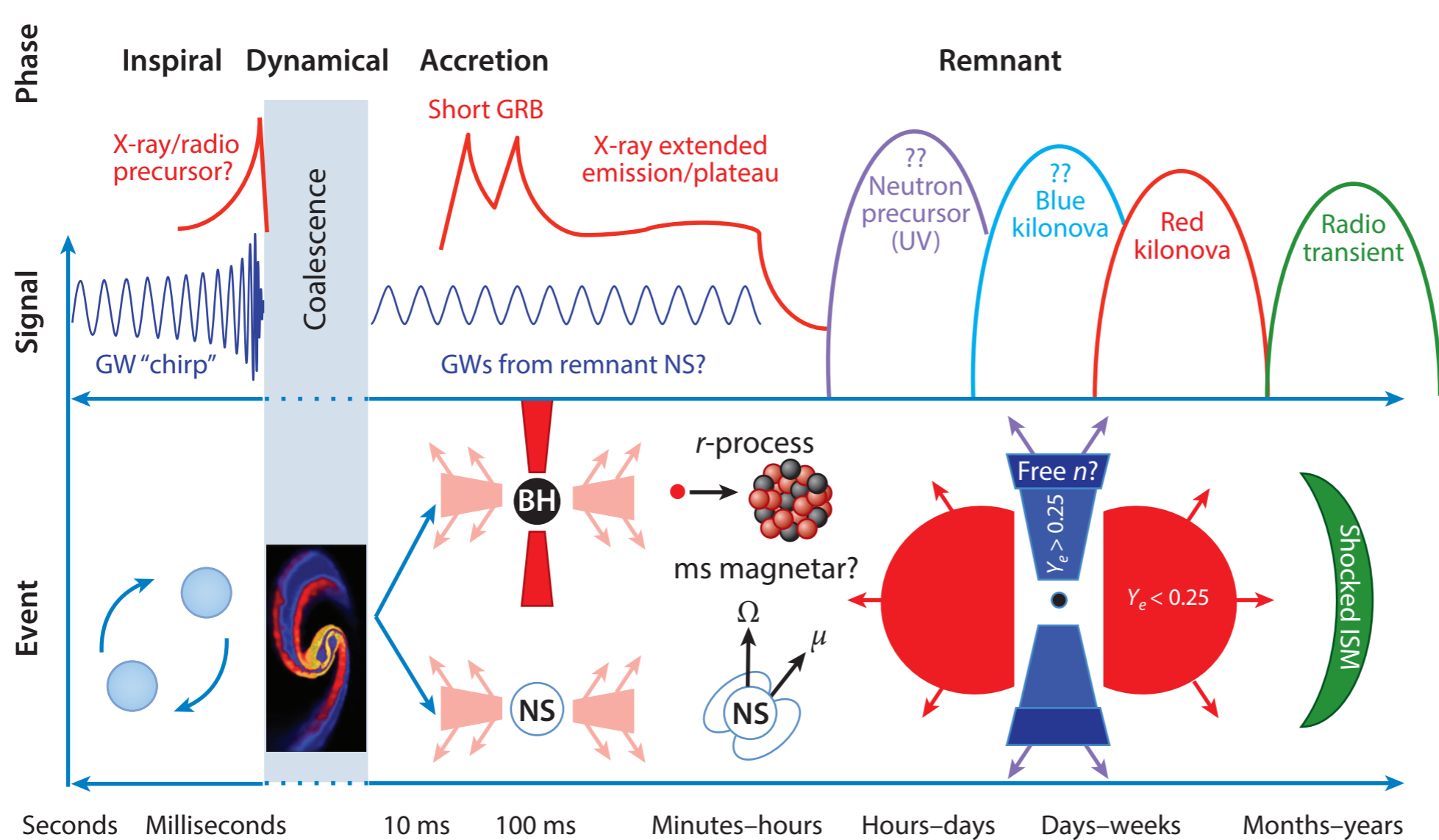
much heavier than BHs known in X-ray binaries \rightarrow low-metallicity formation scenario

Spins weakly constrained, but **nowhere near maximal:**
 $<0.7 + <0.9 \rightarrow \sim 0.6$

- Distance: $\sim 400 \pm 200$ Mpc, $z \sim 0.09$

- **Stringent tests** of general relativity...
Best ever measurement of graviton mass: $m_g < 10^{-22}$ eV

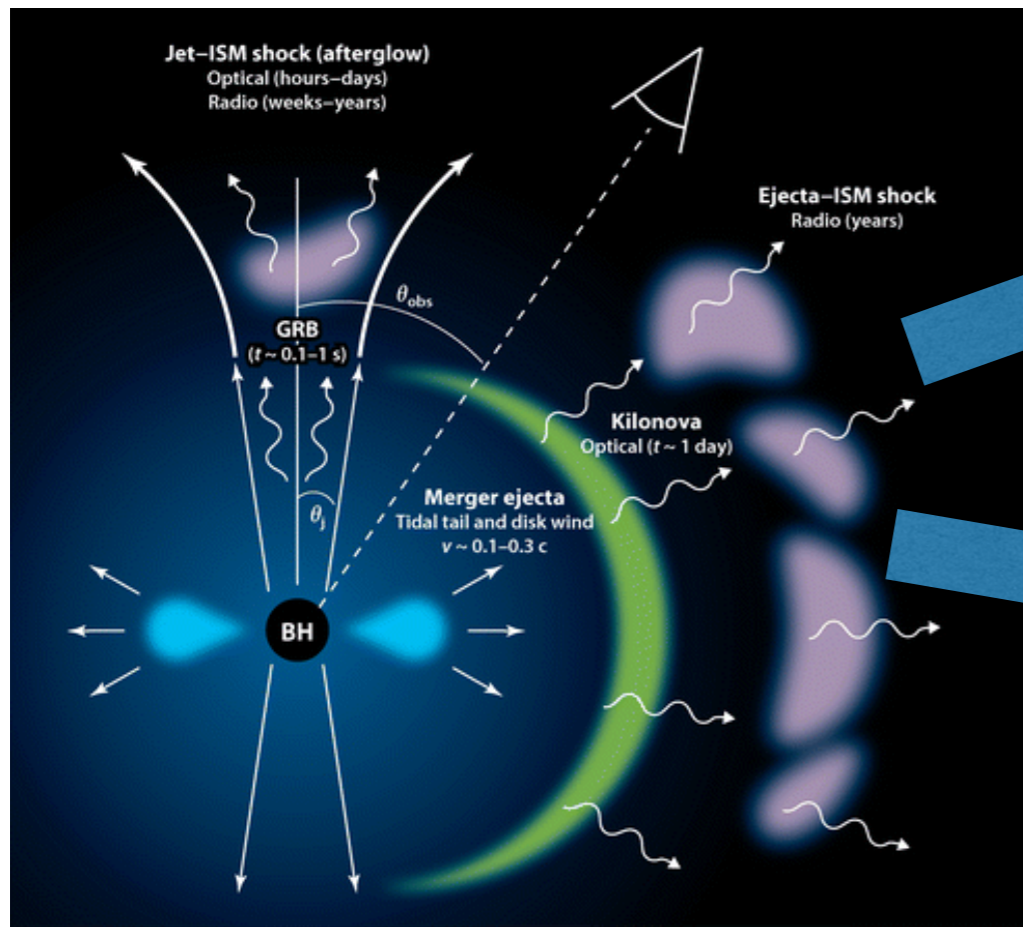
THROWING MATTER INTO THE MIX: EM signatures of neutron star mergers



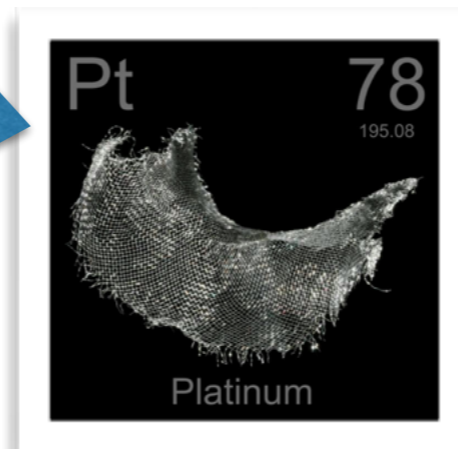
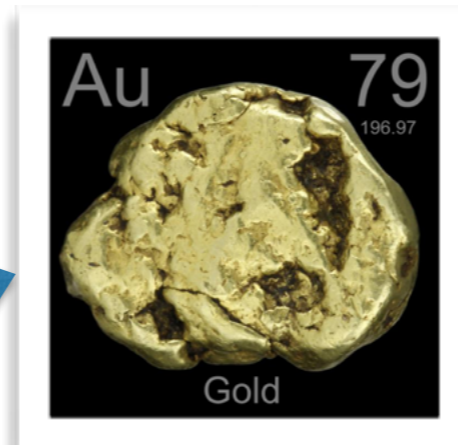
- Resonant shattering of NS crust \rightarrow X-ray/radio precursor
- Rapid accretion, relativistic fireball \rightarrow short GRB
- Central engine (magnetar wind) \rightarrow extended, isotropic X-ray emission
- Synchrotron cooling of shock-accelerated relativistic electrons \rightarrow broadband afterglow
- Radioactive ejecta \rightarrow macronova/kilonova
- Ejecta-shocked ISM \rightarrow slow radio remnant

image: [Fernández & Metzger 2016](#)

The future is *bright!*



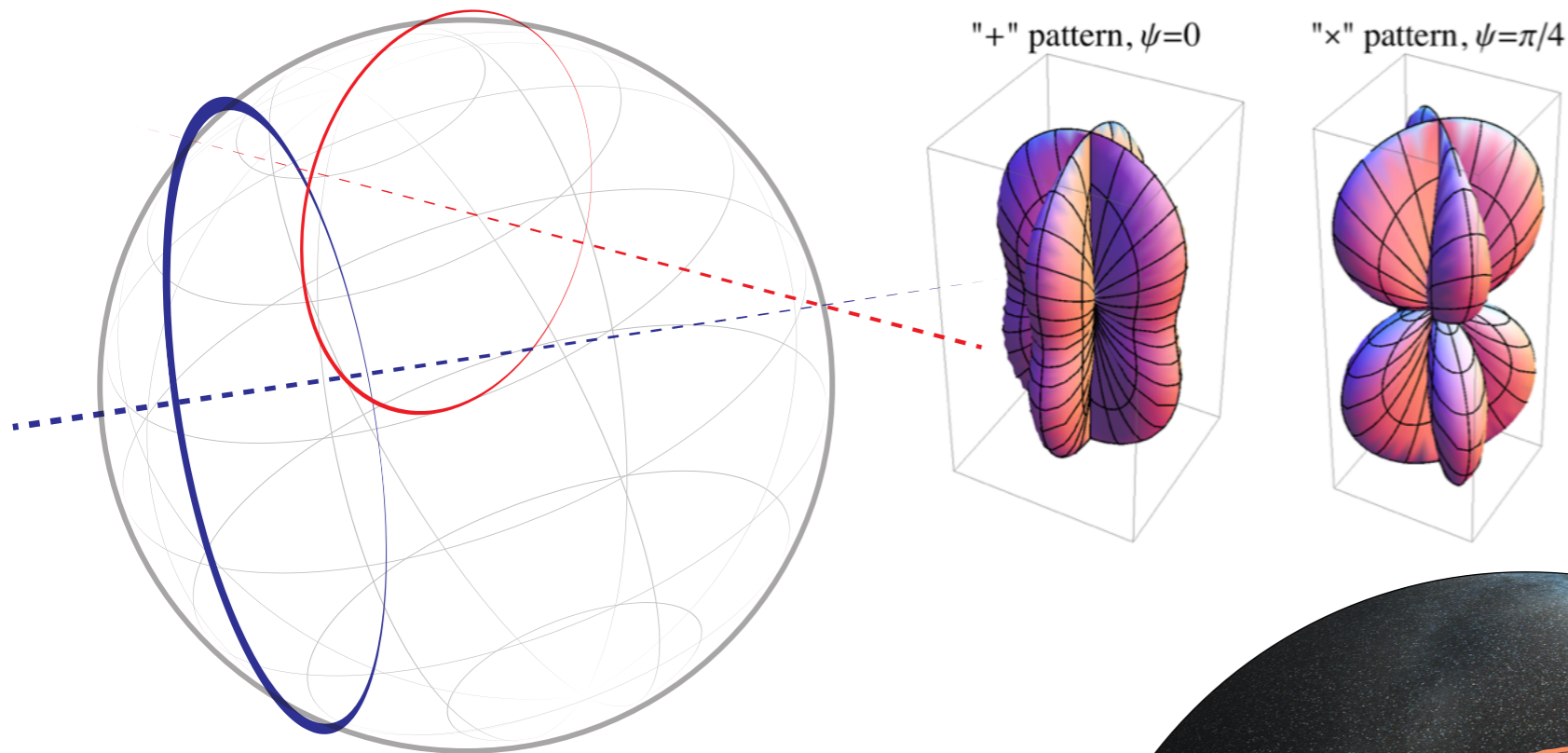
AR Berger E. 2014.
Annu. Rev. Astron. Astrophys. 52:43-105



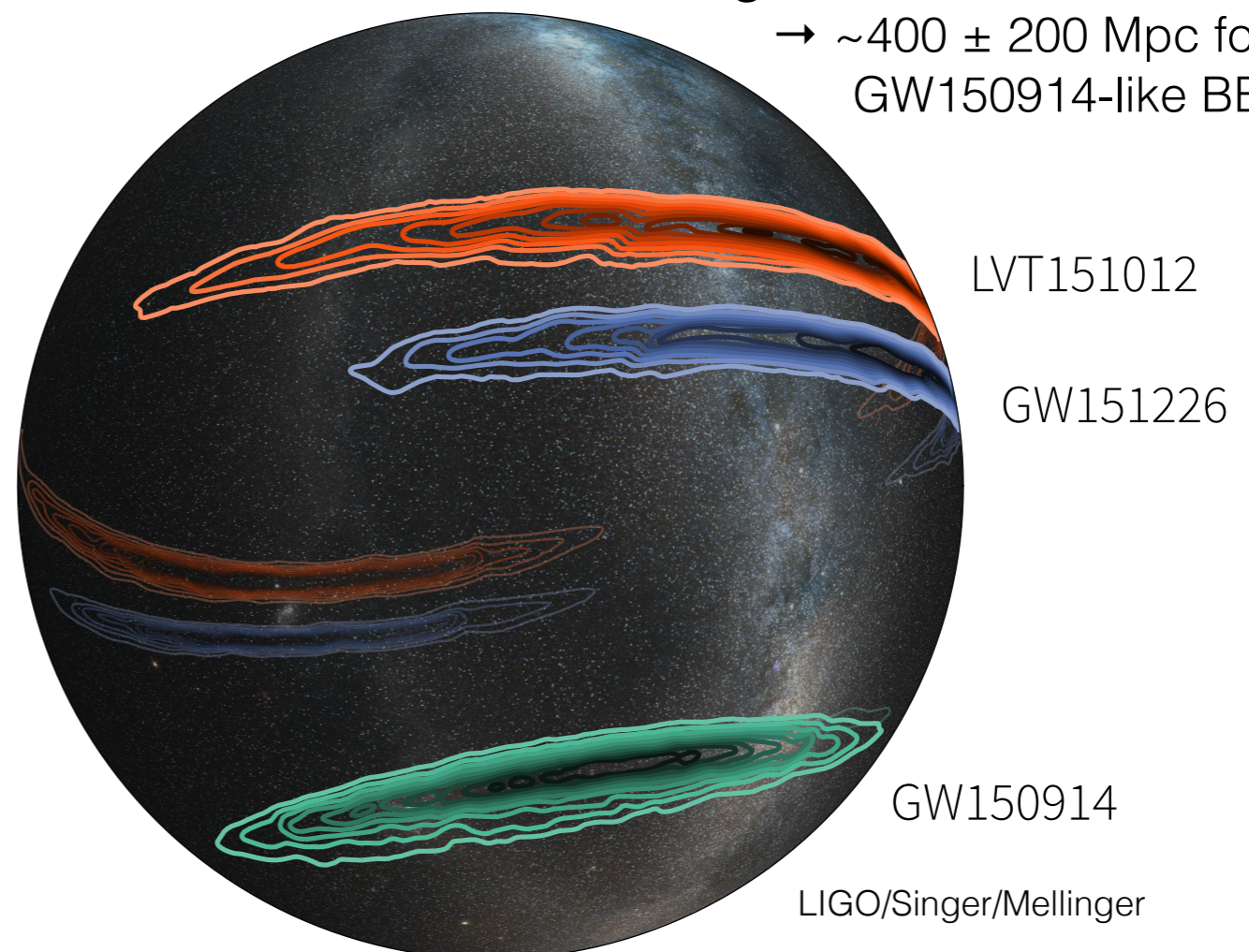
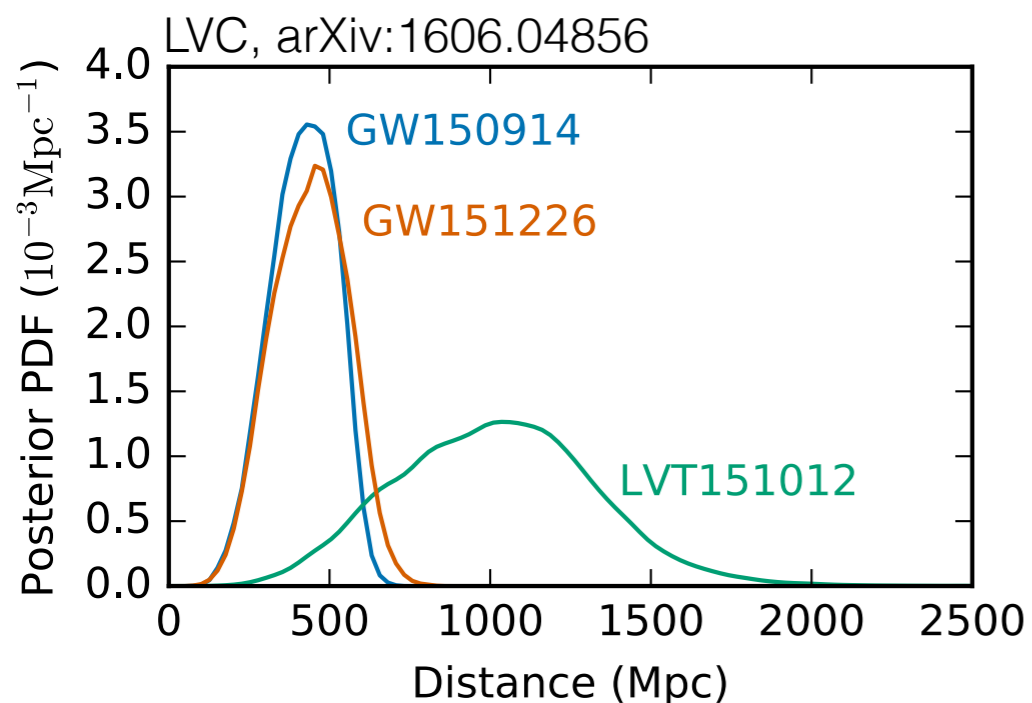
- **EM counterparts of LIGO sources**
- **Central engine** vs. **external fireball** and ejecta
- **Pinpoint host galaxy**, determine formation environment
- **Standard sirens**: Calibration-free rung on cosmological distance ladder
- Explain cosmic abundance of heavy elements – “**bling nova**”
- Explain **nature of short GRBs**
- ...and (uh oh): challenge whether stellar BBHs are truly barren of matter!

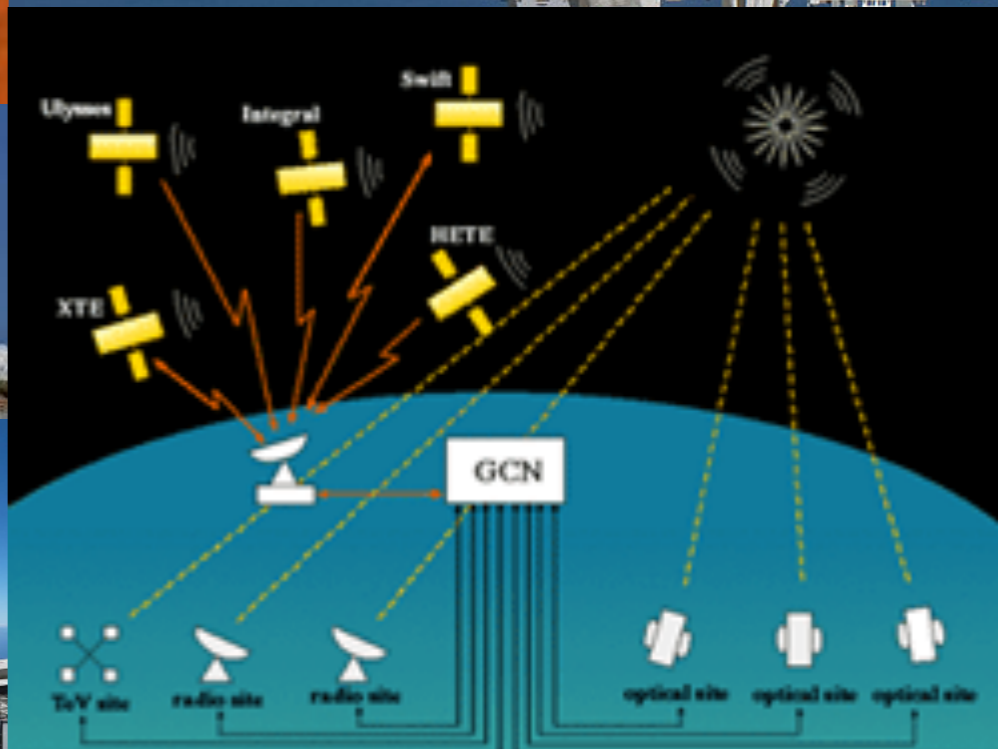
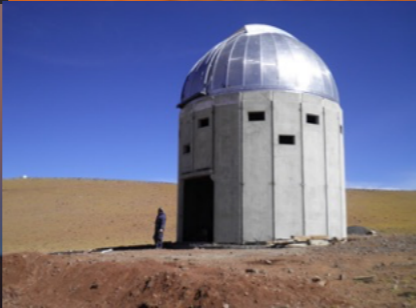
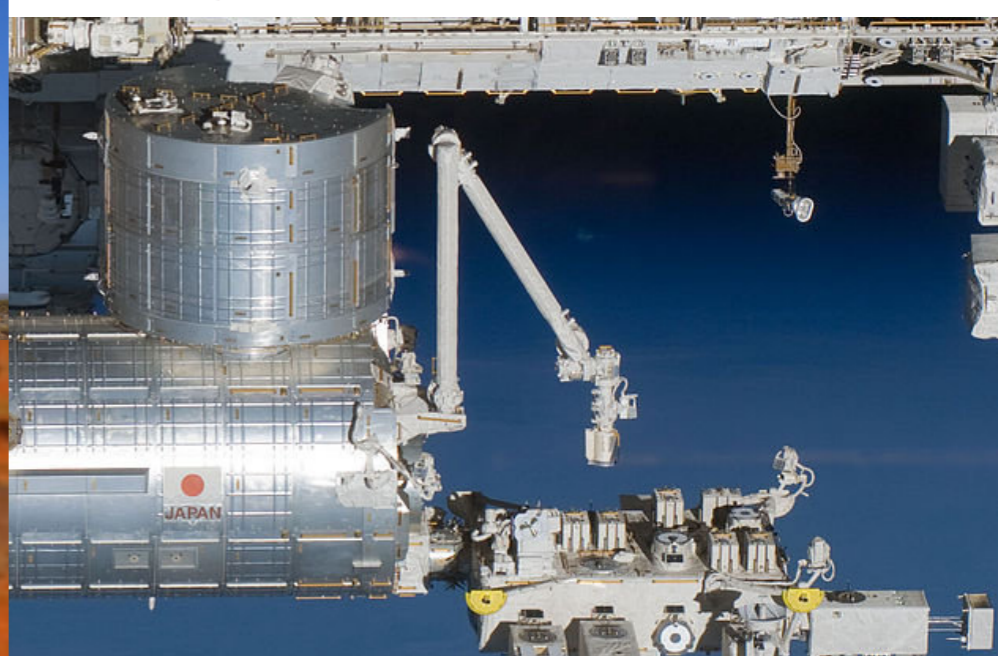
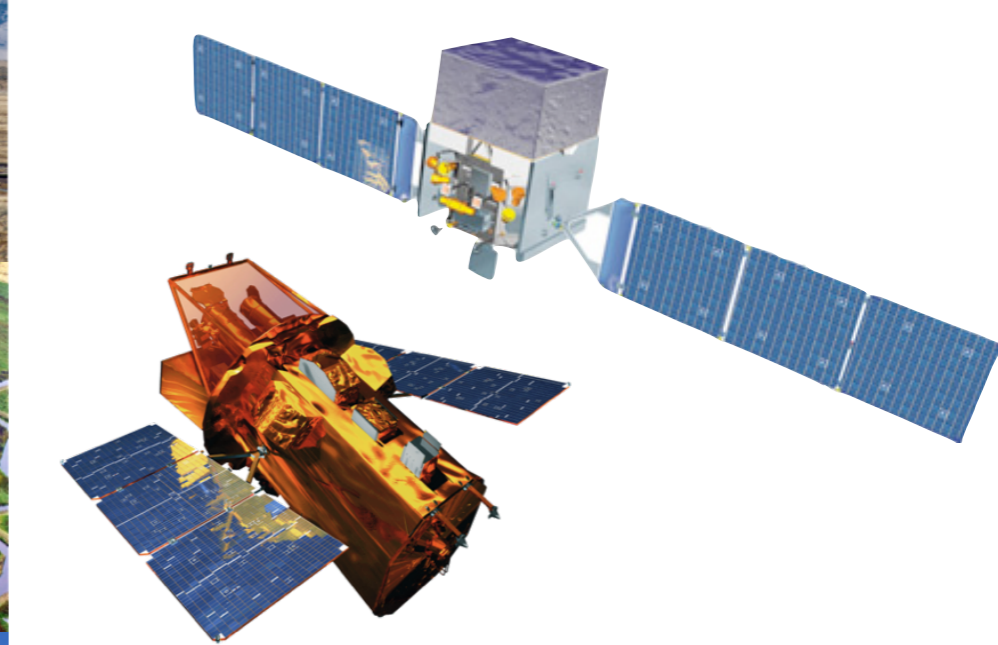
Understanding **the full astrophysical richness of compact binaries** will take not just LIGO, but the broad astronomy community across many wavelengths!

SKY LOCATION AND DISTANCE: a phased array of gravitational antennas



- **Sky location** inferred from triangulation of times, phases, and amplitudes on arrival \rightarrow bimodal rings of 100–1000 of deg^2 with only 2 detectors
- **Distance** inferred by signal amplitude and directional antenna patterns, but **degenerate** with inclination $\rightarrow \sim 400 \pm 200$ Mpc for GW150914-like BBH mergers





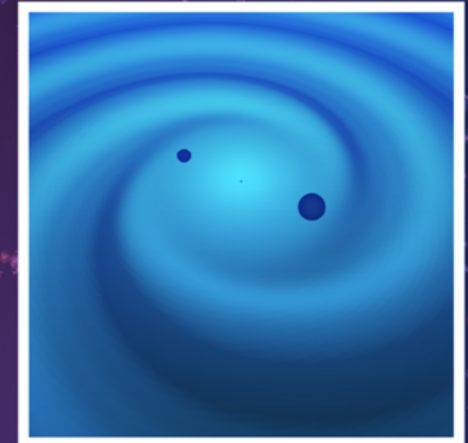
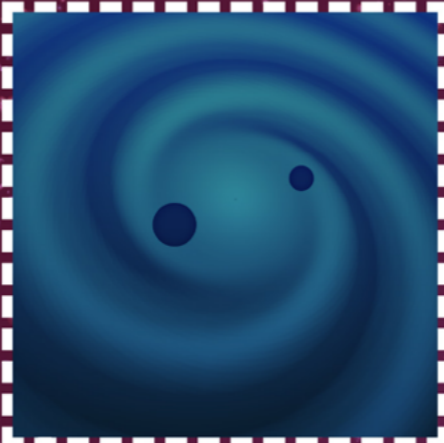
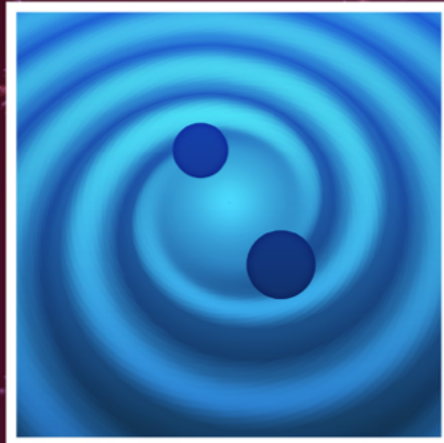
An aerial photograph showing a broadband network in a vast, flat, brownish landscape. A central hub with several buildings is connected to two long, straight lines that extend outwards. The lines terminate in small structures, likely antennas or towers. The background shows rolling hills under a clear blue sky.

II. BROADBAND FOLLOW-UP IN O1

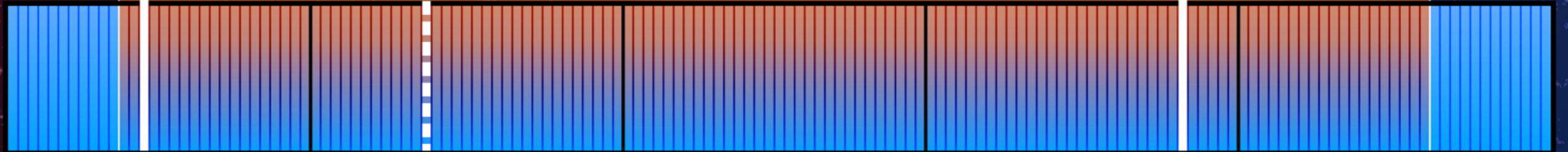
September 14, 2015
CONFIRMED

October 12, 2015
CANDIDATE

December 26, 2015
CONFIRMED



LIGO's first observing run
September 12, 2015 - January 19, 2016



September 2015

October 2015

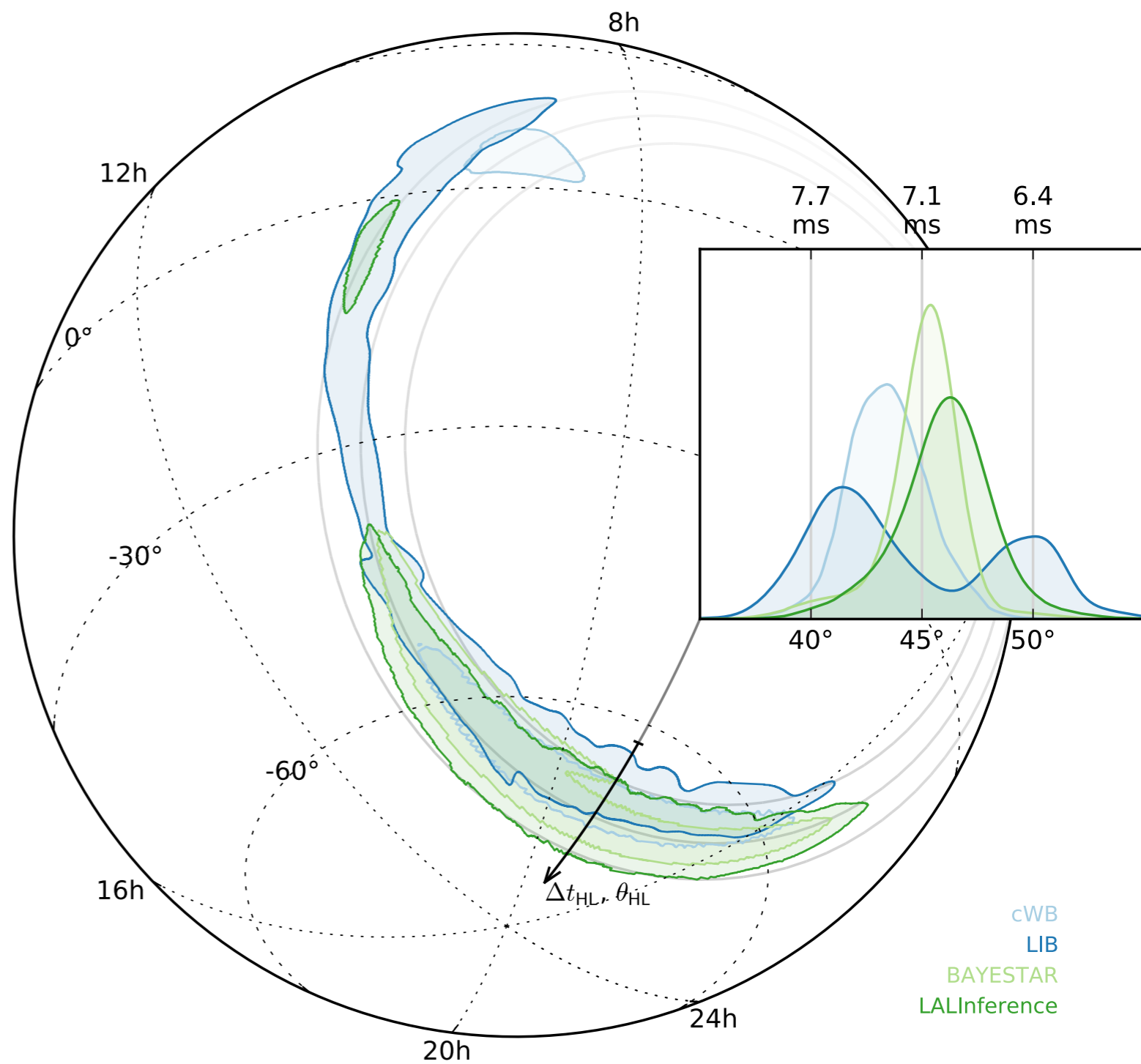
November 2015

December 2015

January 2016

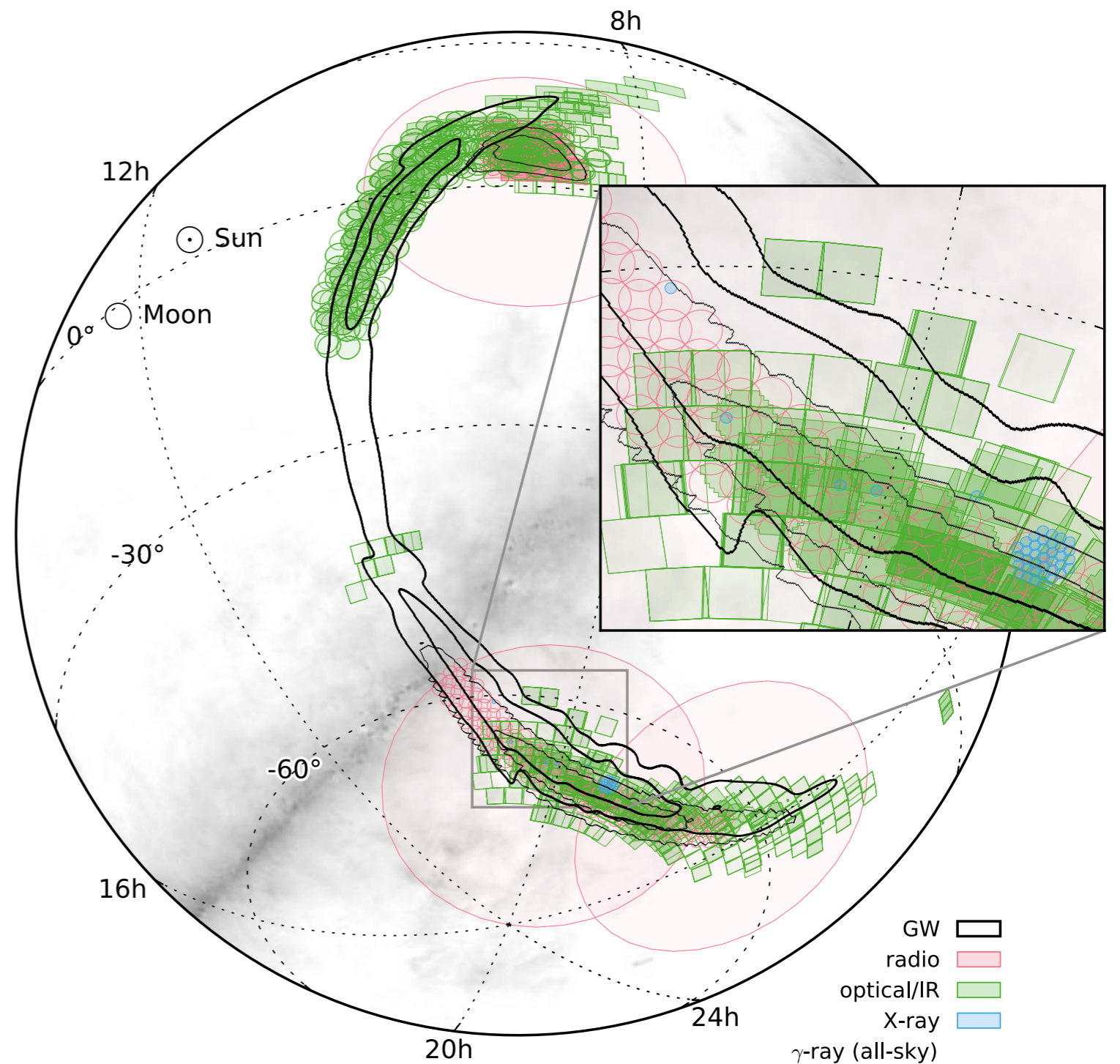
LOCALIZATION AND BROADBAND FOLLOW-UP OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

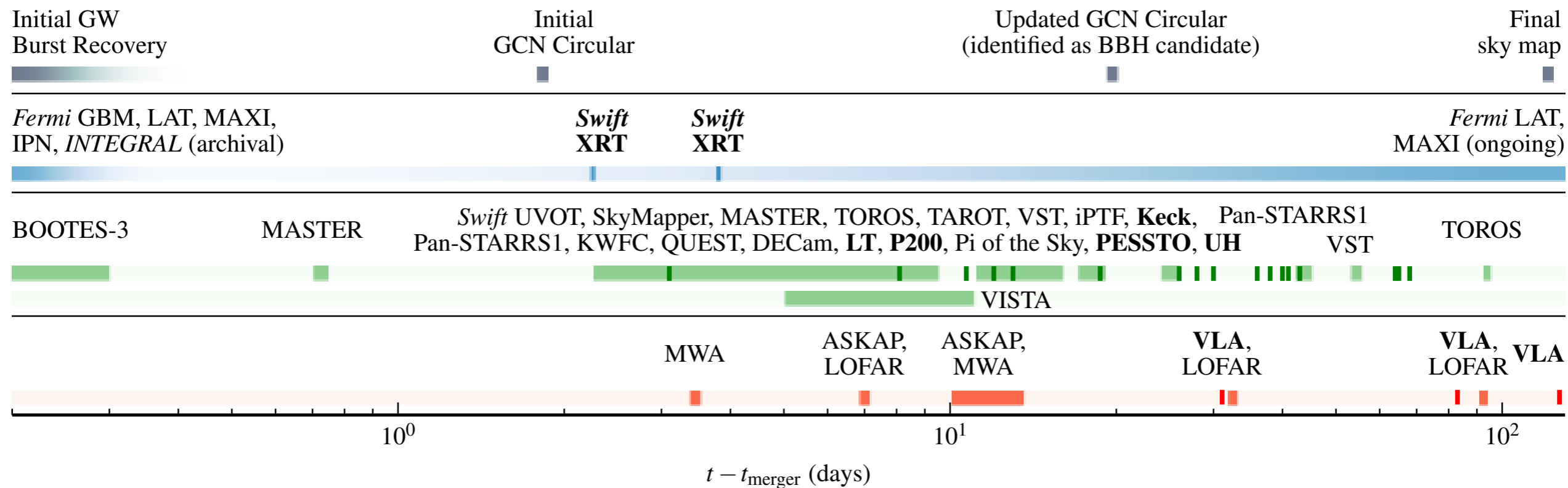
ApJL, 826, L13
arXiv:1602.08492



LOCALIZATION AND BROADBAND FOLLOW-UP OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

ApJL, 826, L13
arXiv:1602.08492





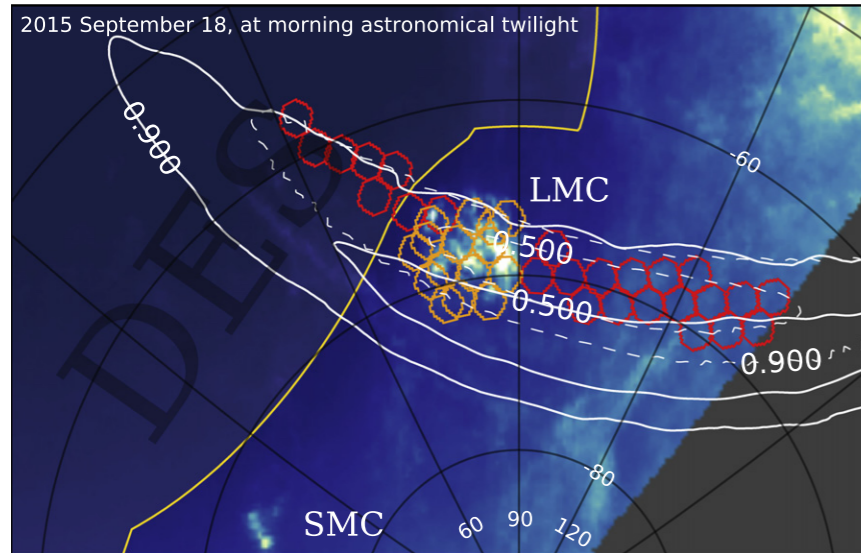
**LOCALIZATION
AND BROADBAND
FOLLOW-UP
OF THE
GRAVITATIONAL-WAVE
TRANSIENT GW150914**

25 observing teams (+LIGO, Virgo), 1551 authors

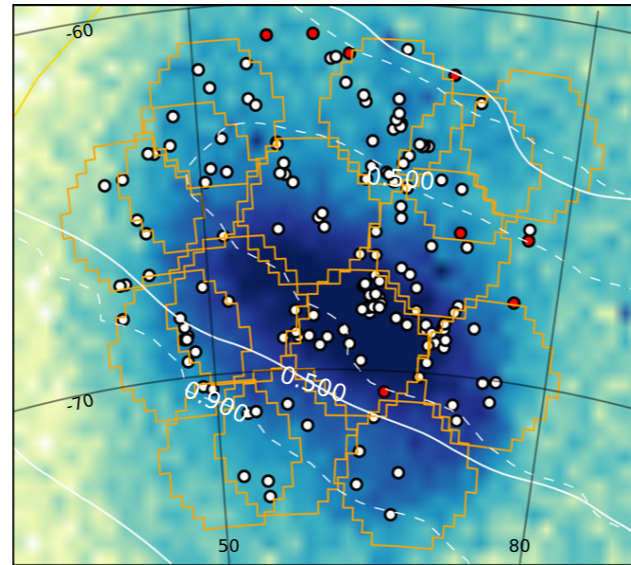
unprecedented: *broke ApJL author portal!*

ASKAP, LOFAR, MWA, Fermi/GBM, Fermi/LAT, INTEGRAL, IPN, Swift, MAXI, BOOTES, MASTER, Pi of the Sky, DES/DECam, INAF/GRAWITA, iPTF, J-GEM/KWFC, La Silla-QUEST, Liverpool Telescope, PESSTO, Pan-STARRS, SkyMapper, TAROT, Zadko, TOROS, VISTA

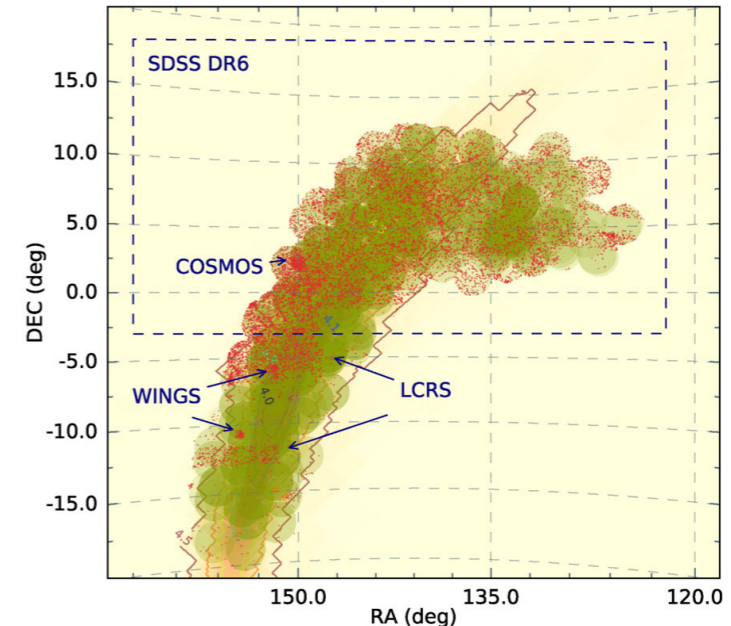
GW FOLLOW-UP WITH LARGE SYNOPTIC SURVEY INSTRUMENTS



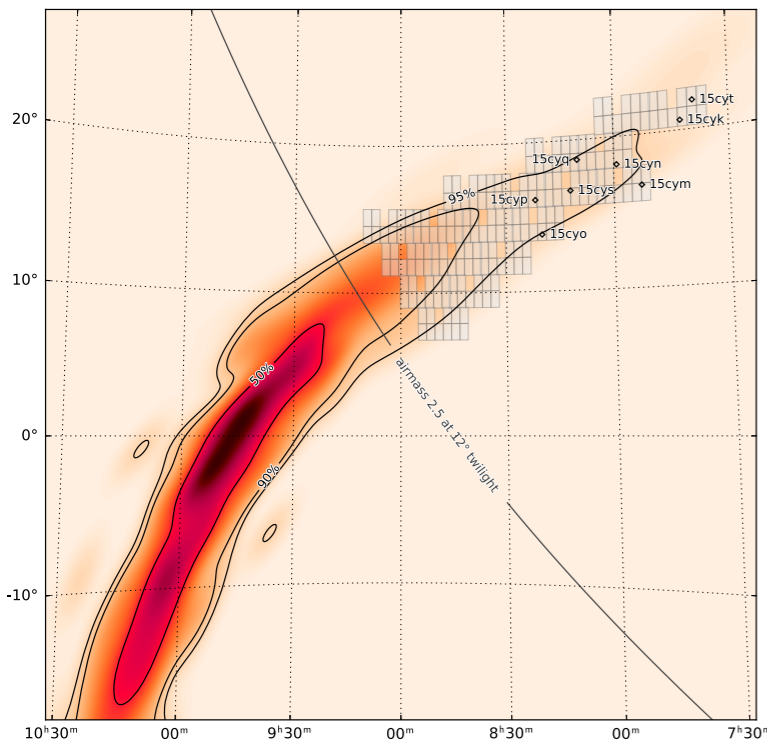
Soares-Santos+ 2016 Deep, wide-field follow-up with DECam to $i=22.5$



Annis+ 2016 DECam search for missing supergiants in LMC

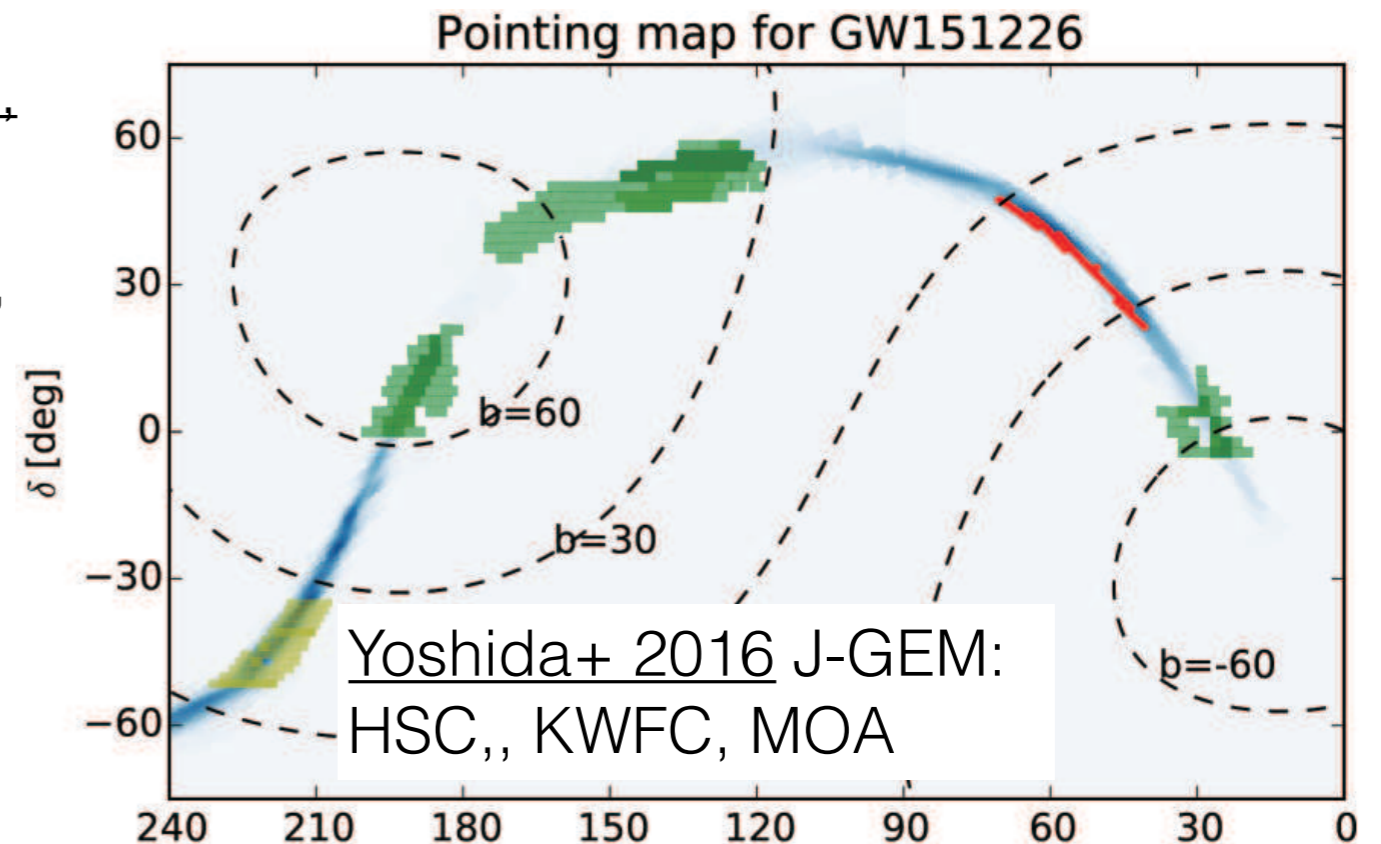


Smartt+ 2016 Pan-STARRS



Kasliwal, Cenko, Singer+ 2016

iPTF OT search, Keck spectra <1 hour after discovery, + a serendipitous superluminous supernova



Yoshida+ 2016 J-GEM: HSC,, KWFC, MOA

JOINT GW- HIGH ENERGY SEARCHES

- Strong indirect evidence that **NS binary mergers power most or all short, hard GRBs** (Paczynski, Eichler, Narayan, Rezzolla, Fong, etc.)
- GW or GRB threshold can be lowered due to reduction in trials from assuming **know time, inclination, and sky location**
- Three kinds of joint GW-HE searches:
 1. Coincidence between GW candidates and GRB (see A. Urban Ph.D thesis)
 2. Sub-threshold targeted searches of GW data triggered by GRB (notable example: GRB 051103, [LVC+ 2012](#))
 3. Sub-threshold targeted searches of gamma-ray data triggered by LIGO (see [Blackburn 2014](#))
- Notable synergies with: **Fermi, Swift, INTEGRAL, IPN, MAXI**

image: GRB 051103, [LVC+ 2012](#)

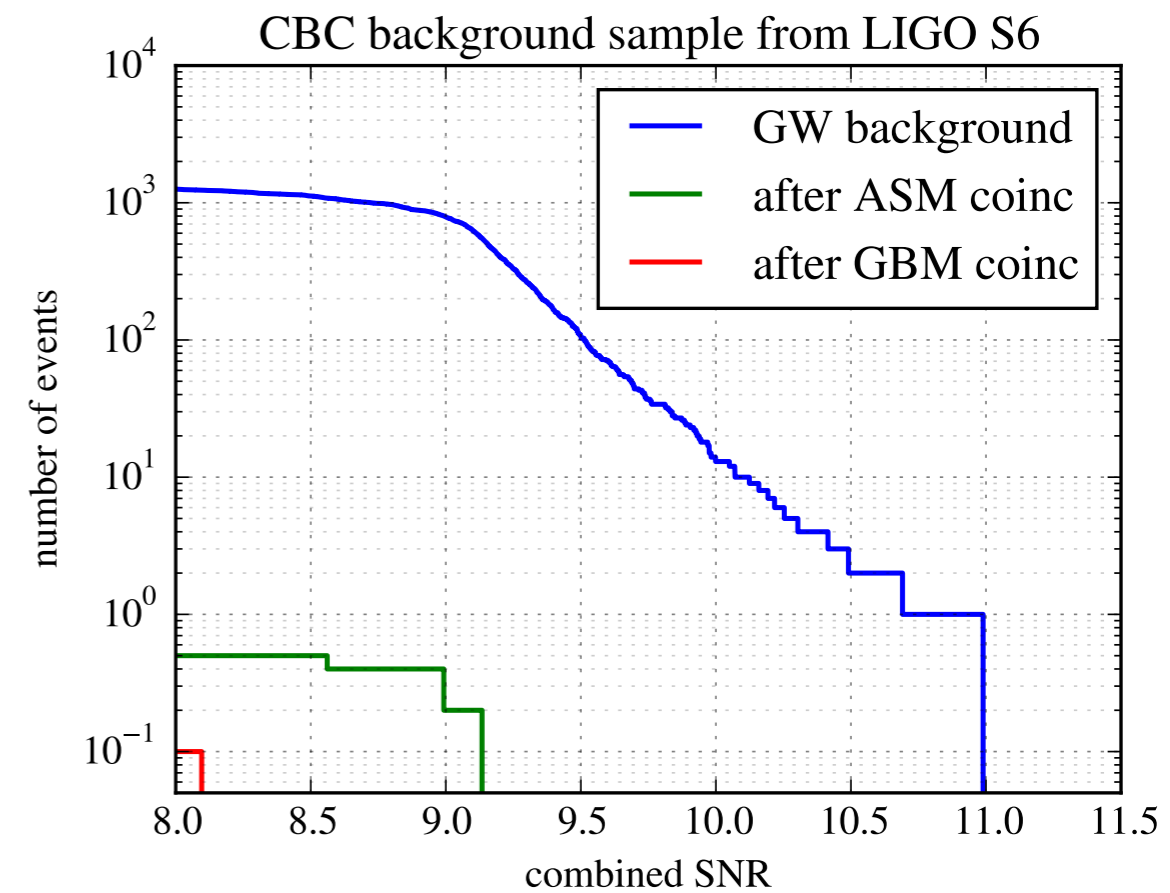
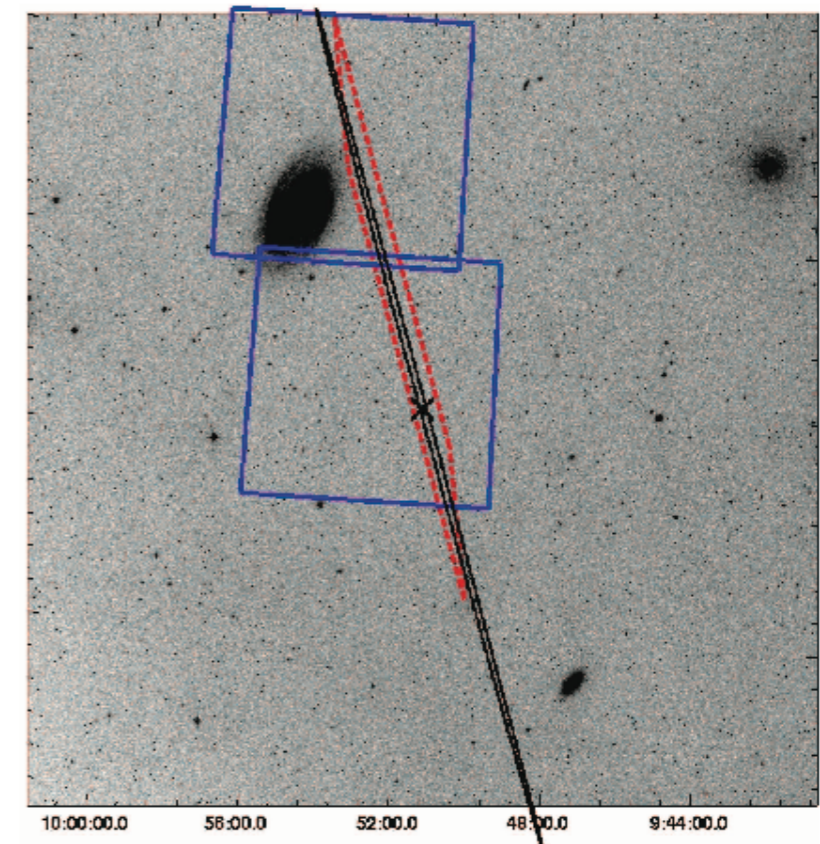
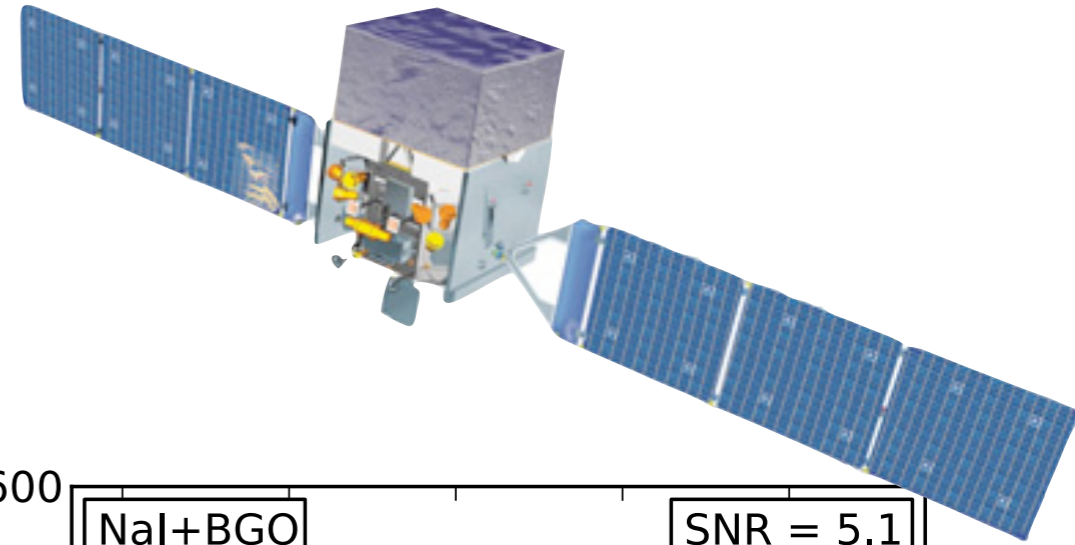


image: [Blackburn+ 2015](#)

GW150914 *Fermi* GBM candidate



- **Faint coincident gamma-ray transient** present in *Fermi* Gamma-ray Burst Monitor (GBM) 0.4s after GW150914 ([Connaughton+ 2016](#)), estimated false alarm probability of 0.002 (2.9σ)
- **Unclear if astrophysical** ([Connaughton+ 2016](#), [Greiner+ 2016](#)), not seen by INTEGRAL ([Savchenko+ 2016](#)) or AGILE ([Tavani+ 2016](#))
- If astrophysical, **would constitute a novel GRB mechanism** because EM emission is not expected a priori from *stellar-mass* BBH mergers
- Some **exotic scenarios** proposed ([Loeb 2016](#), [Perna+ 2016](#), etc.)

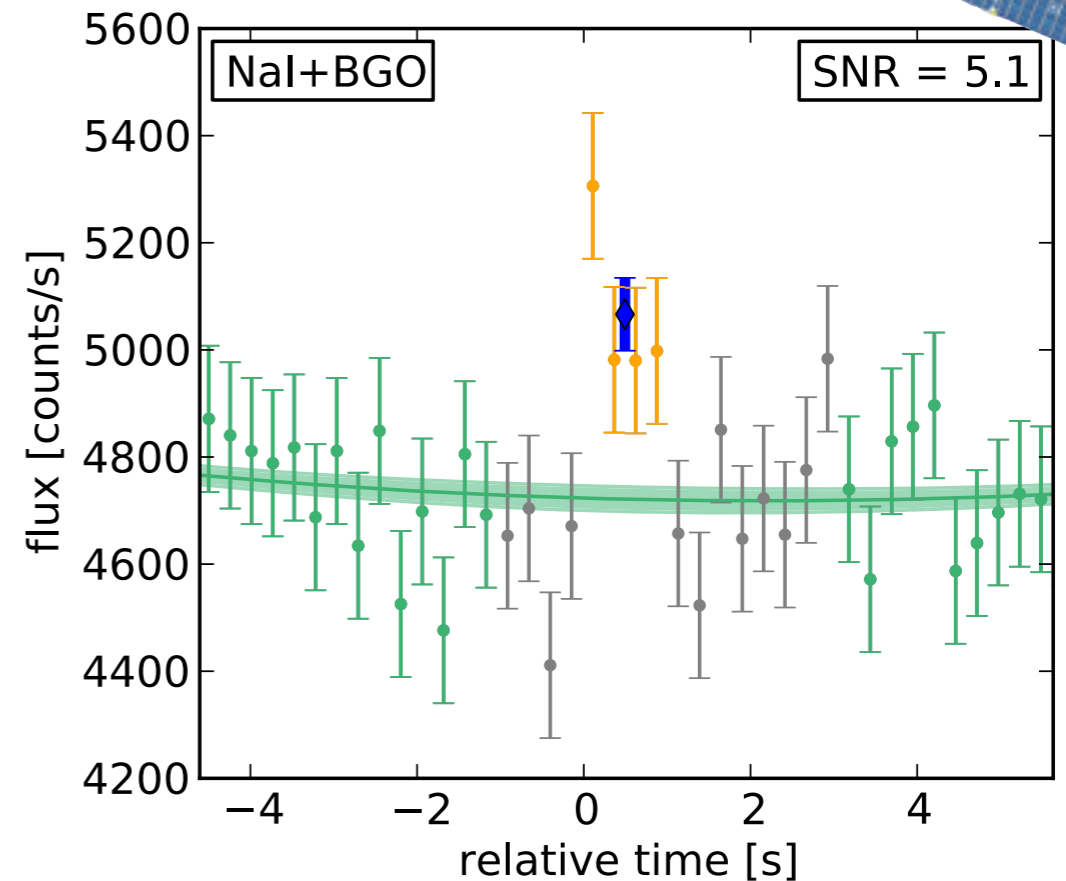


image: [Connaughton+ 2016](#)

- LIGO/Virgo pipelines must and will be able to produce rapid alerts for BBHs going forward

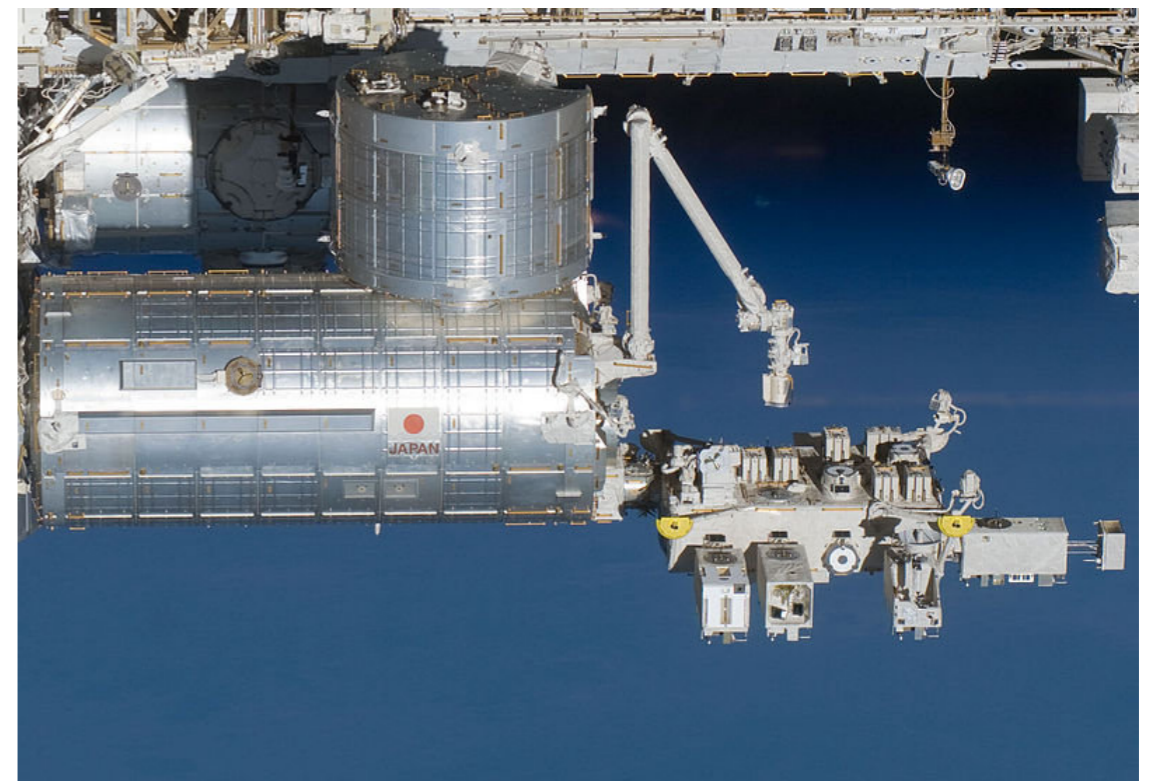
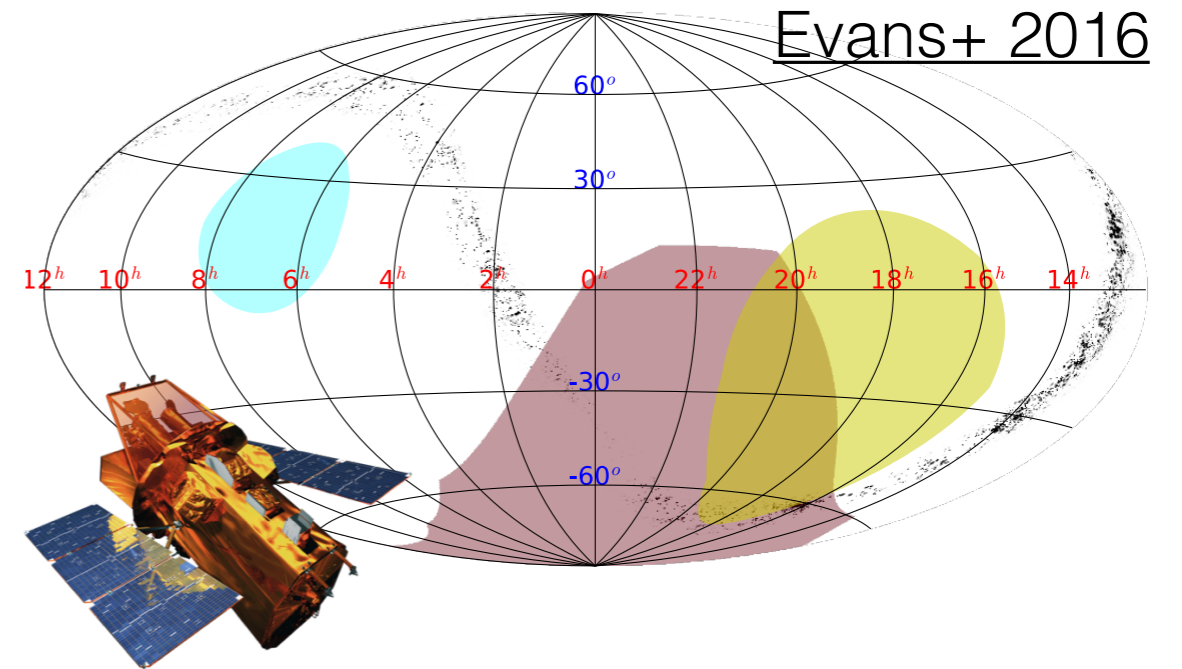
X-RAY FOLLOW-UP

- *Swift* XRT → new ToO modes, large tiling patterns, galaxy-targeted searches (Evans, Kenna +2016)
- →MAXI/GSC → covers almost full GW localization every 92 minutes

N. Kawai's talk, this session

GCN 18557, 18784, 19013

- CALET (Adriani+ 2016)

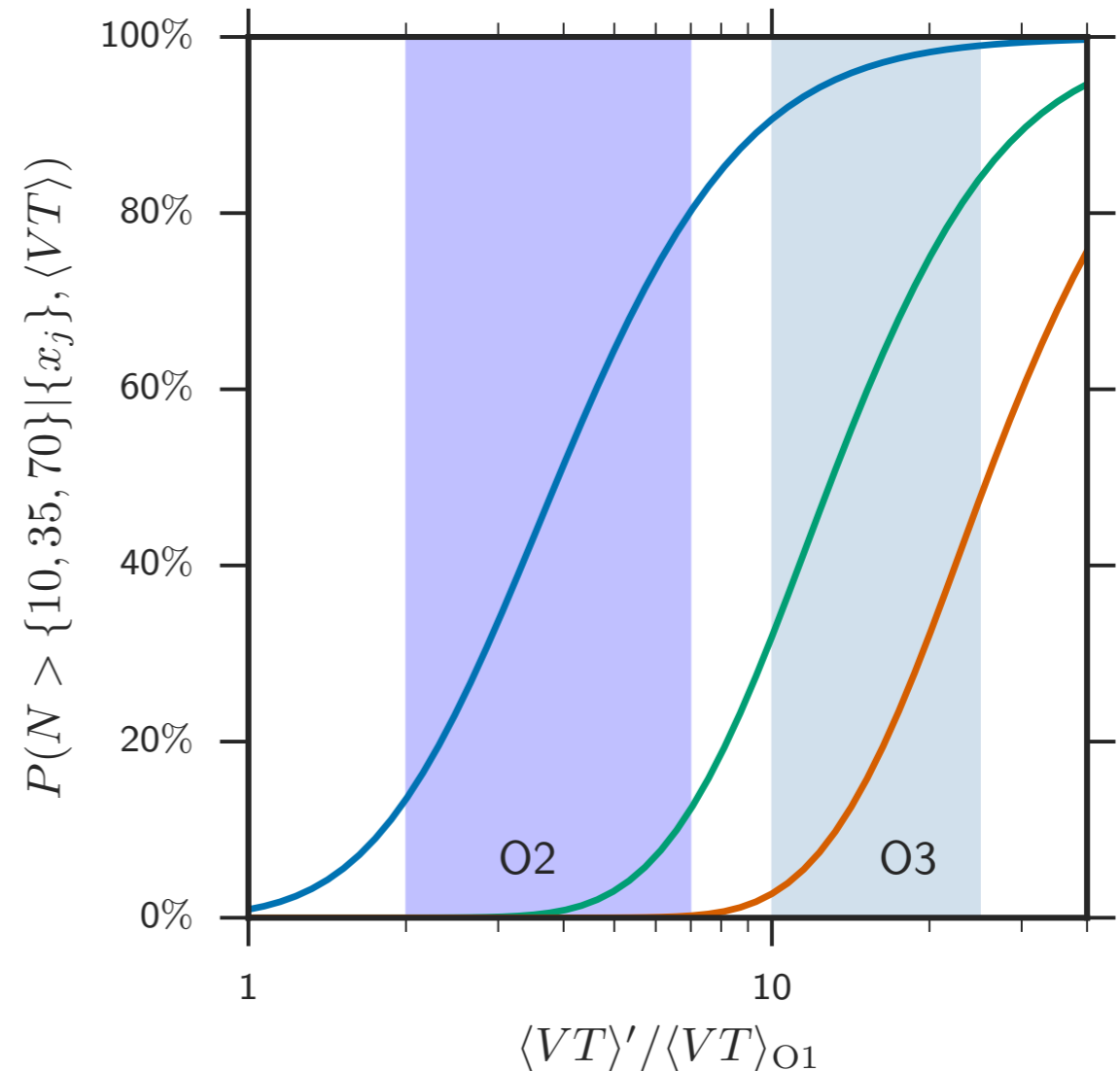


An aerial photograph showing a vast agricultural landscape. In the foreground, a large, circular processing facility with several white buildings is situated. Two long, straight blue canals extend from this facility across the fields, forming a V-shape. The fields are a mix of green and brown, indicating different stages of crop growth or harvest. In the background, a city is visible, followed by a range of mountains under a clear blue sky.

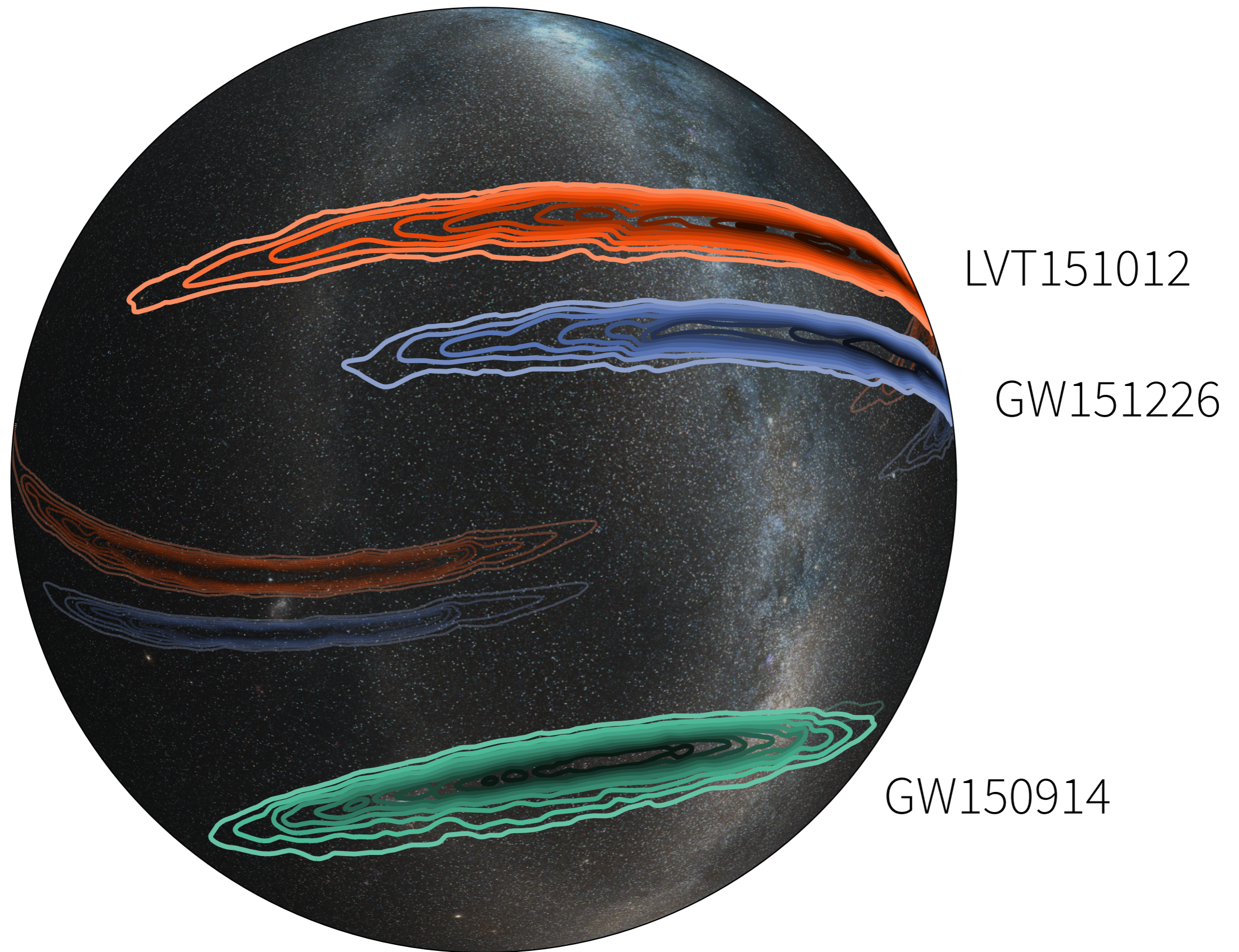
III. WHERE WE WILL GO IN O2

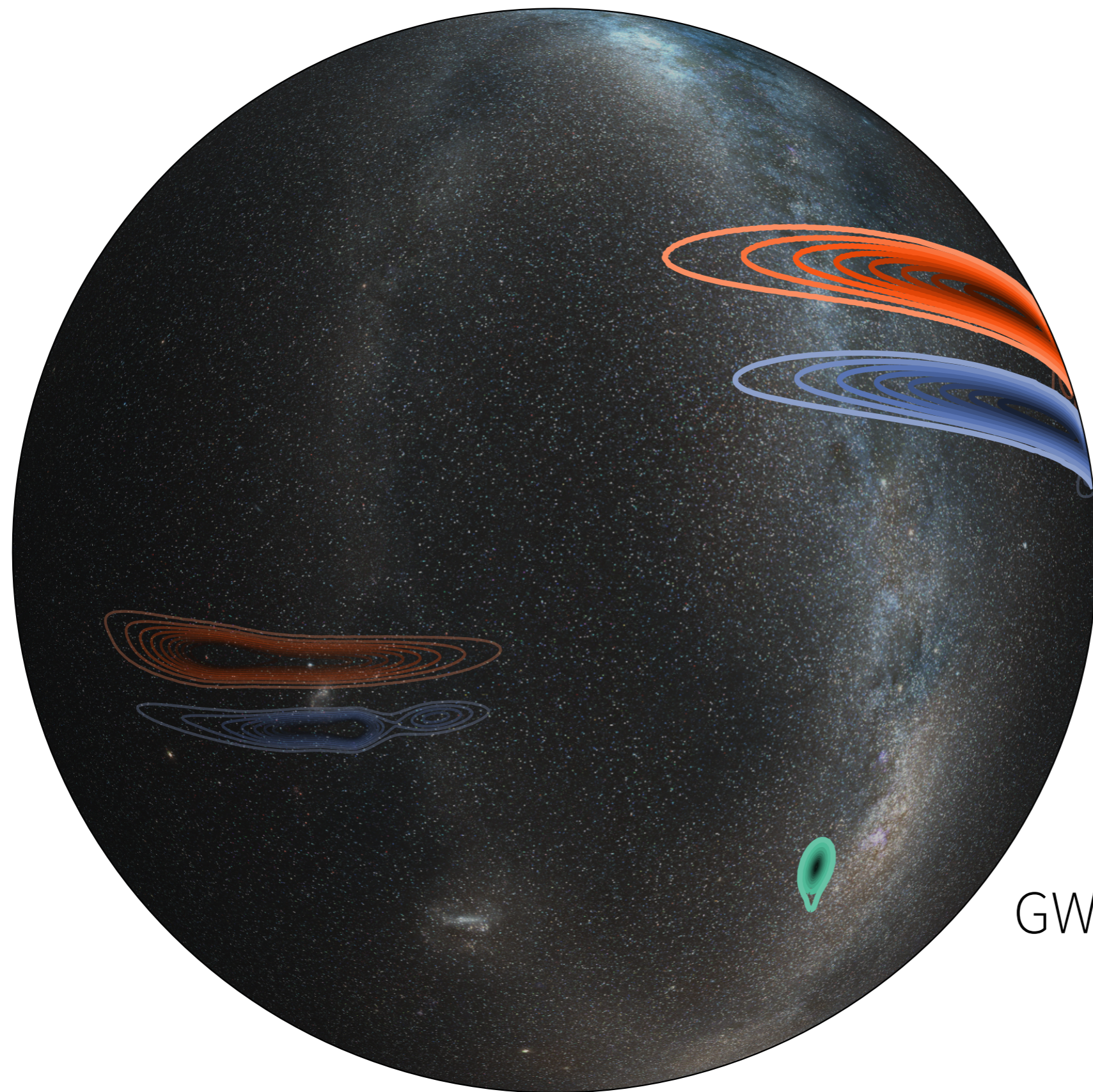
WHERE WE WILL GO IN O2

- Based on O1:
~10 BBHs by O2, ~100 by O3 (**!!**)
- Both **distinctive single-object** analysis and **population statistics**
 - History of stellar BH masses and spins **through cosmic time**
- Even *more* exciting:
more highly asymmetric masses, spin precession, **binary neutron star** and **neutron star–black hole** mergers
- An **alert every 1–2 weeks**
 - Alerts with **distance and GW classification** must go out within half an hour (**~1 minute**, with more practice!)



Based on all O1 events.
LVC 2016, [arXiv:1606.04856](https://arxiv.org/abs/1606.04856)





LVT151012 +**VIRGO**

GW151226 +**VIRGO**

GW150914 +**VIRGO**

GCN NOTICES: CONTENTS IN O1

	CBC	Burst
IVORN	ivo://nasa.gsfc.gcn/LVC#{G,M}nnnnnn- {1,2,3}-Preliminary,Initial,Update	
Who	LIGO Scientific Collaboration and Virgo Collaboration (lv-em@gw-astronomy.org)	
What	GraceDB ID: {G,M}nnnnnn	
Search Group	CBC	Burst
Pipeline	Gstlal or MBTA	CWB
Internal	0 or 1 (0 causes distribution to partners)	
FAR	estimated FAR in Hz	
Network	Binary flag for each detector (LHO_participated, etc.)	
Skymap	SKYMAP_URL_{FITS,PNG}_{SHIB,X509,BASIC} (not included in a Preliminary alert)	
WhereWhen	Arrival time (UTC, ISO-8601), e.g., 2010-08-27T19:21:13.982800	



GCN NOTICES: NEW FOR O2

Two “EM bright” classifiers:

- Possible **presence of a NS** ($m_2 < 3 M_\odot$)
→ Relatively model independent
- Probability of sufficient **tidally disrupted material** to form a disk (e.g., to power a GRB)
→ Based on Foucart disk mass fits to numerical simulations (arXiv: 1207.6304) as implemented by Pannarale & Ohme (arXiv:1406.6057)
→ Highly model dependent, but conservative assumptions made (e.g. stiff NS EoS)

	CBC	Burst
...	...	
What	GraceDB ID: {G,M}nnnnnn	
...	...	
PROPOSED Search-specific parameters (Initial, Update)	Distance: <i>a posteriori</i> mean luminosity distance in Mpc	N/A
	DistanceError: <i>a posteriori</i> standard deviation of luminosity distance in Mpc	
	ContainsNeutronStar: Probability (0-1) that the less massive companion has a source-frame mass $< 3 M_\odot$	
	EMBright: Probability (0-1) that the system ejected a significant amount of NS material, as calculated by method of Pannarale & Ohme (2014)	
...	...	



Both **real-time** and **full parameter estimation** versions in final stages of development for O2: Shaon Ghosh et al.

SPACE POTATO CHIPS

Typical GW localization in three dimensions

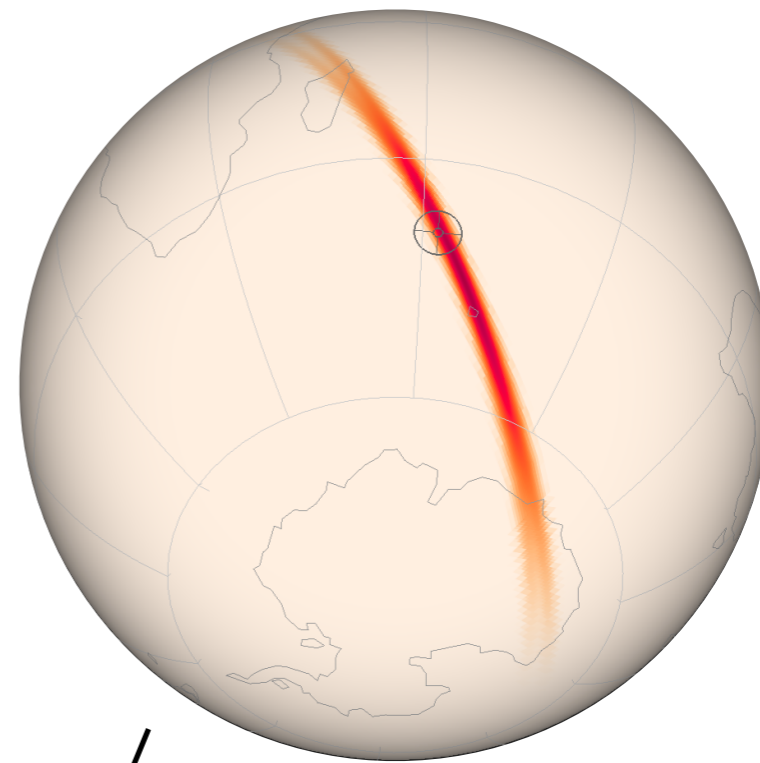
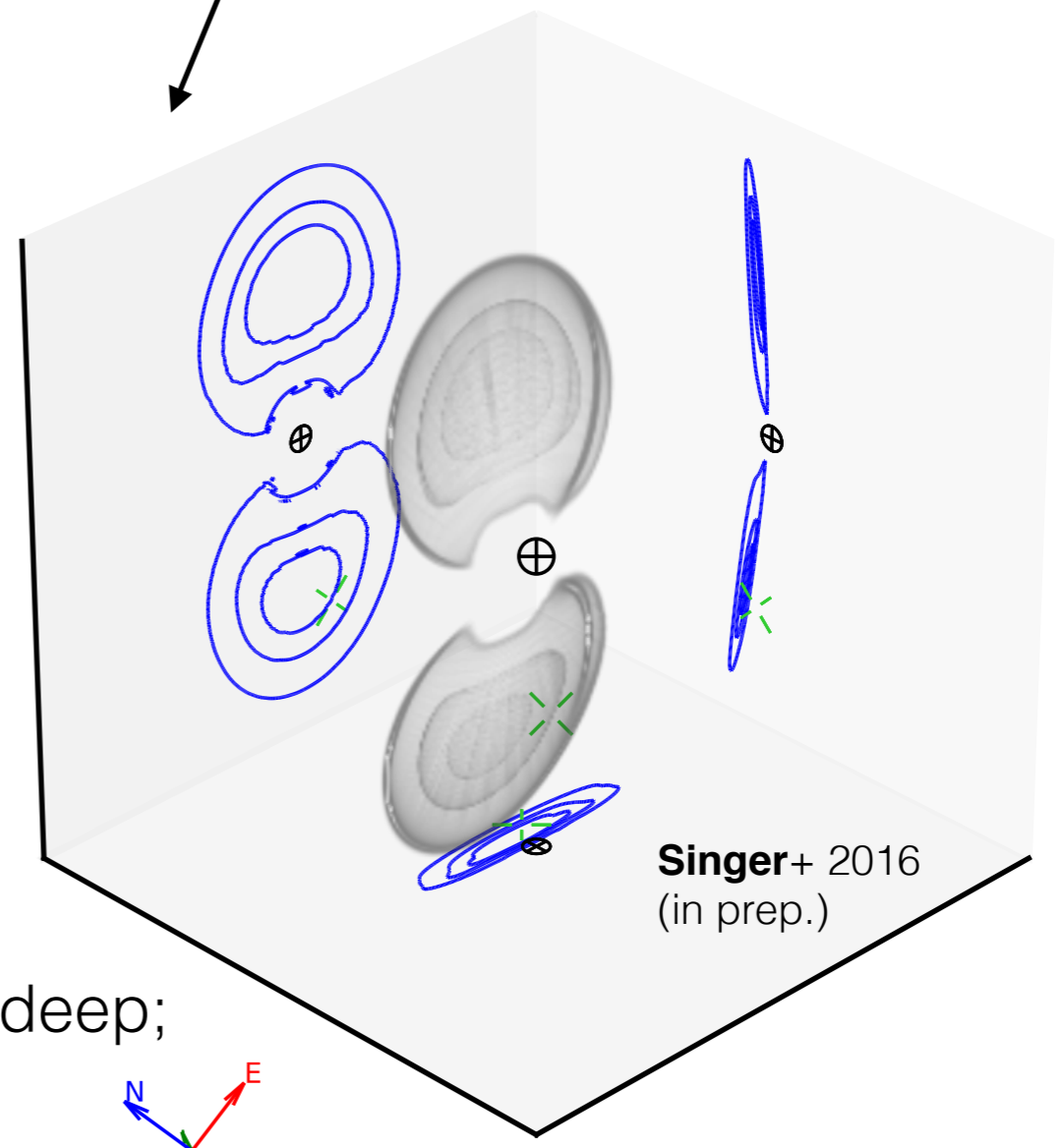
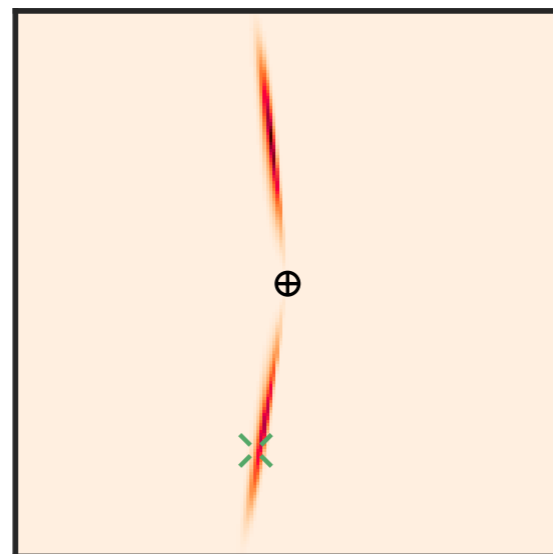
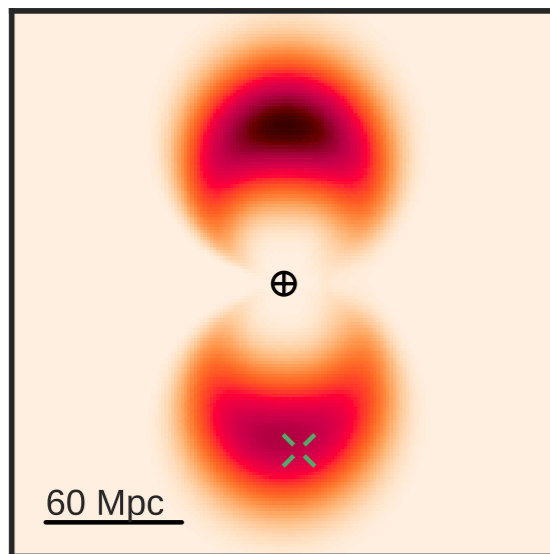
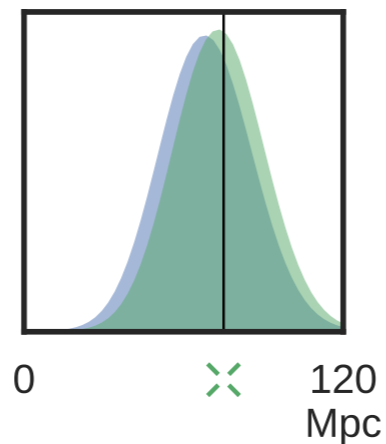
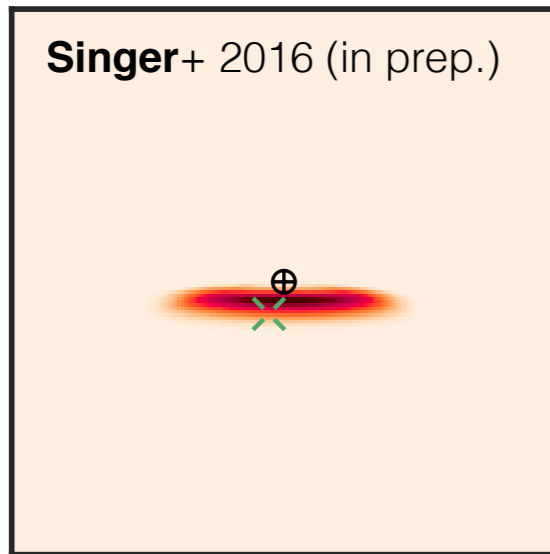


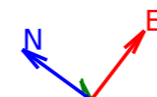
image: "First Two Years"

<http://ligo.org/scientists/first2years>

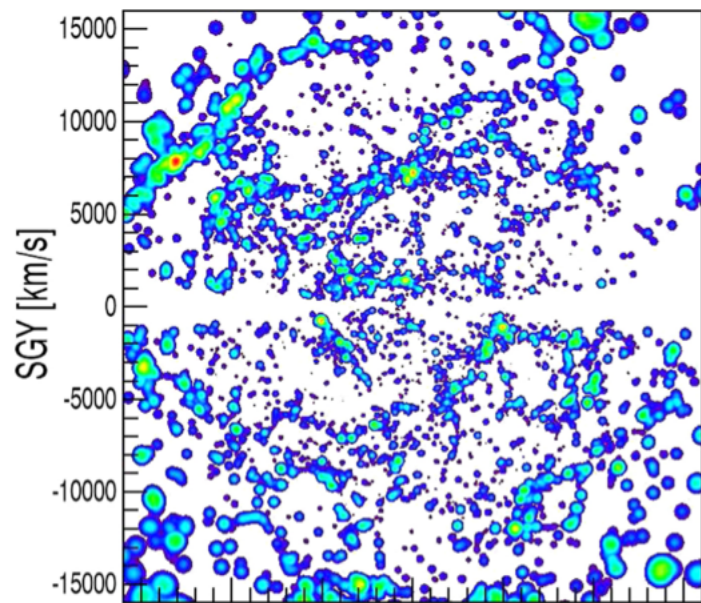
Singer+ 2014
Berry+ 2015



Double arcs become two **petals**:
 $\sim 1^\circ$ wide, **10-100**° in breadth, **~ 100 Mpc** deep;
 Volume **$\sim 30 \times 10^3 \text{ Mpc}^3$**

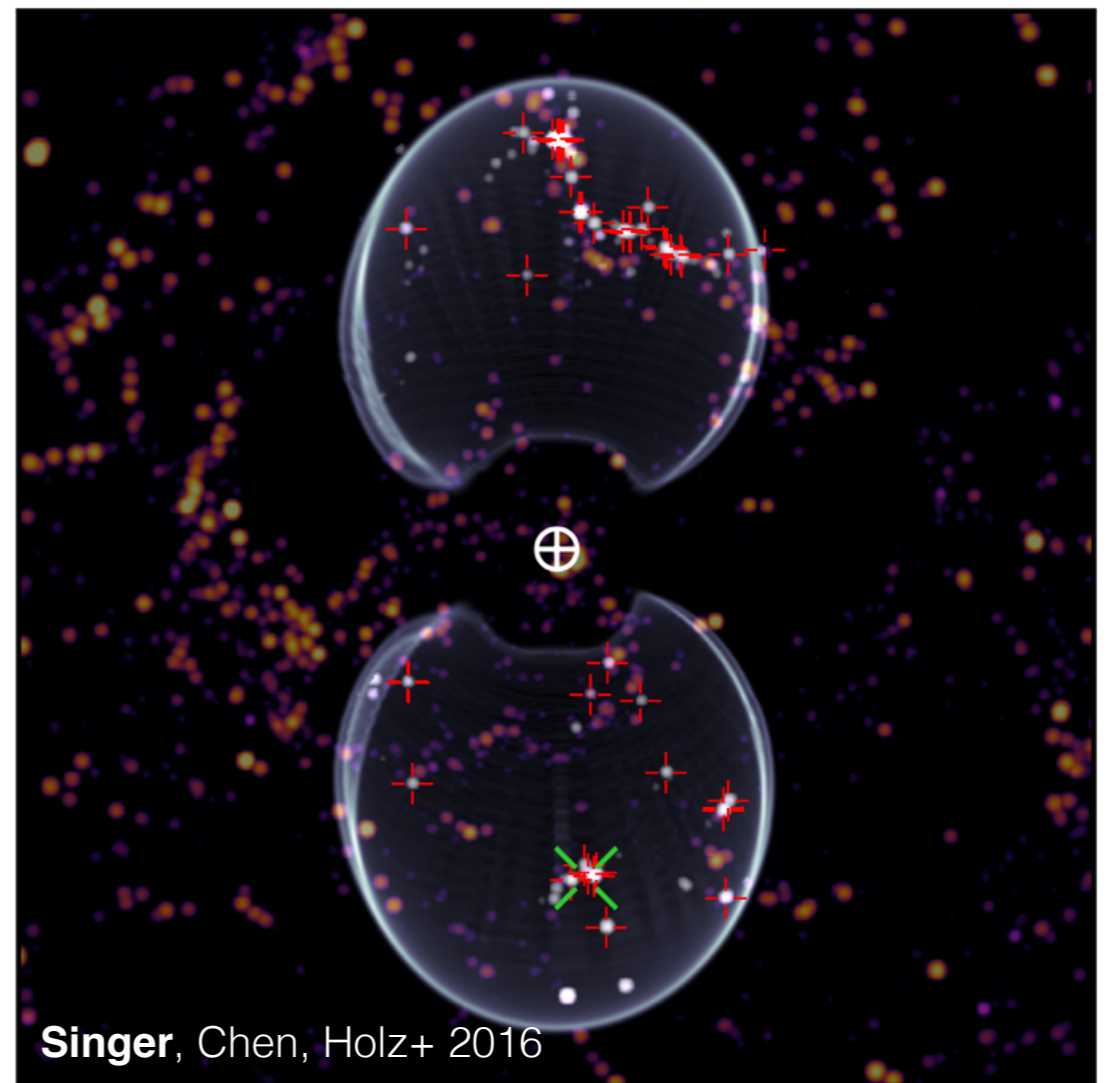
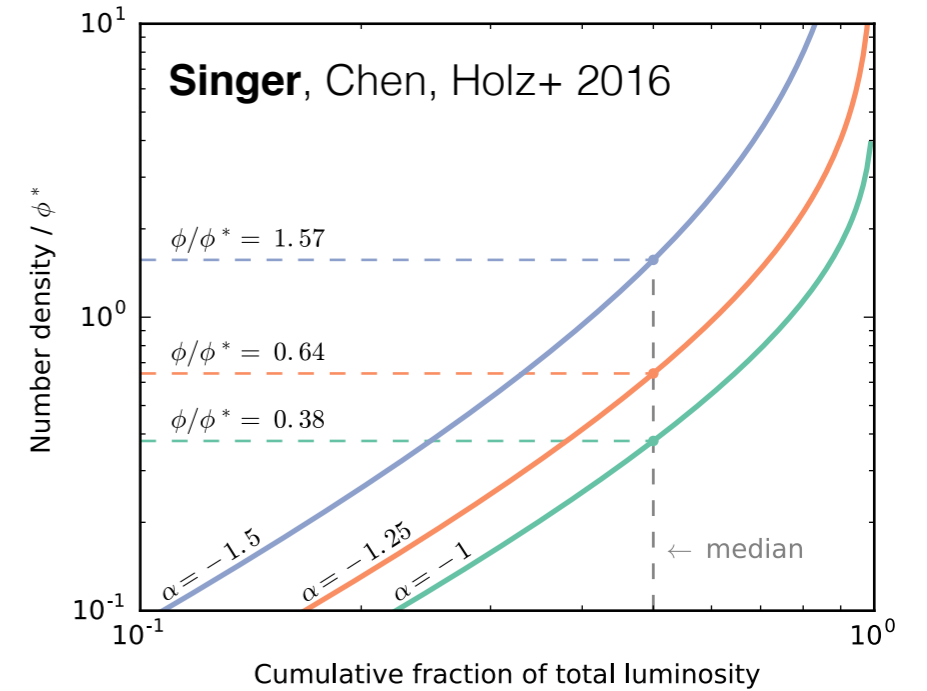
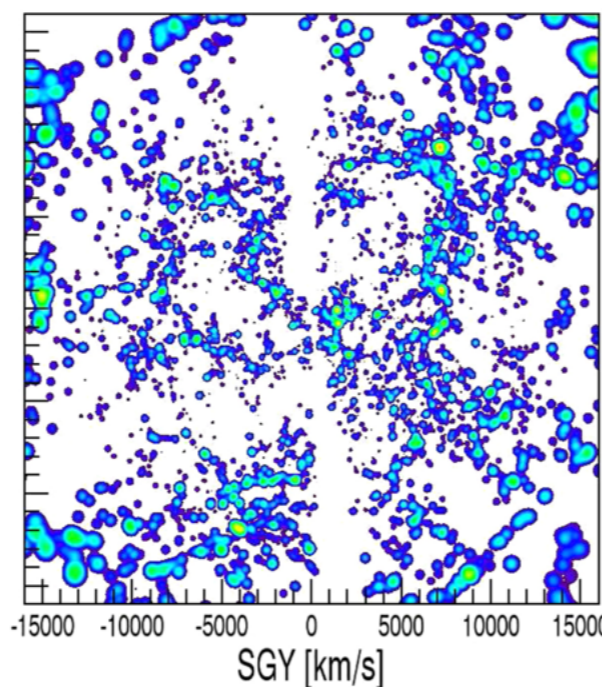
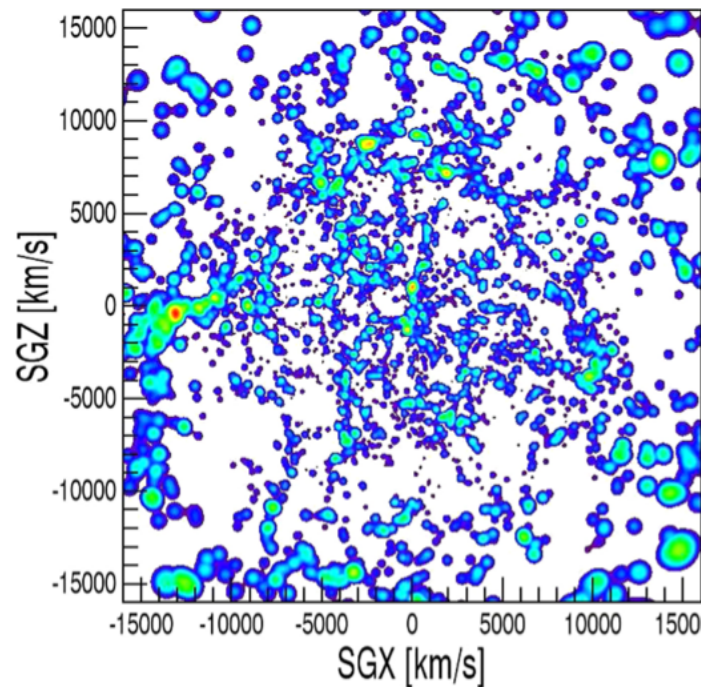


COSMOGRAPHY for fun and profit



Combine GW parameter estimation with map of local luminosity density

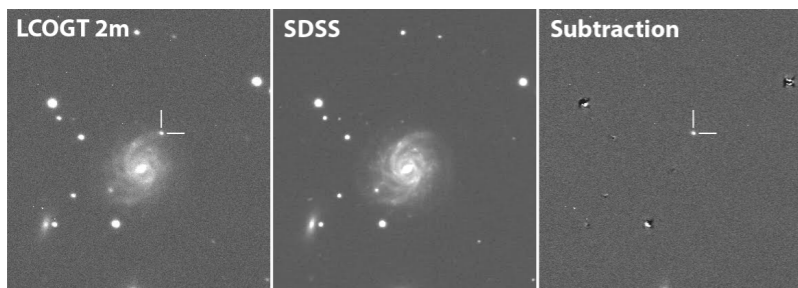
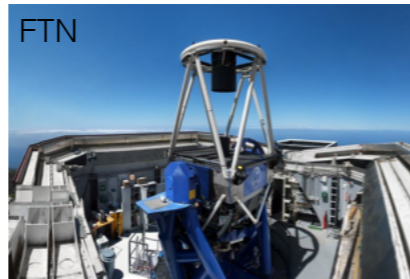
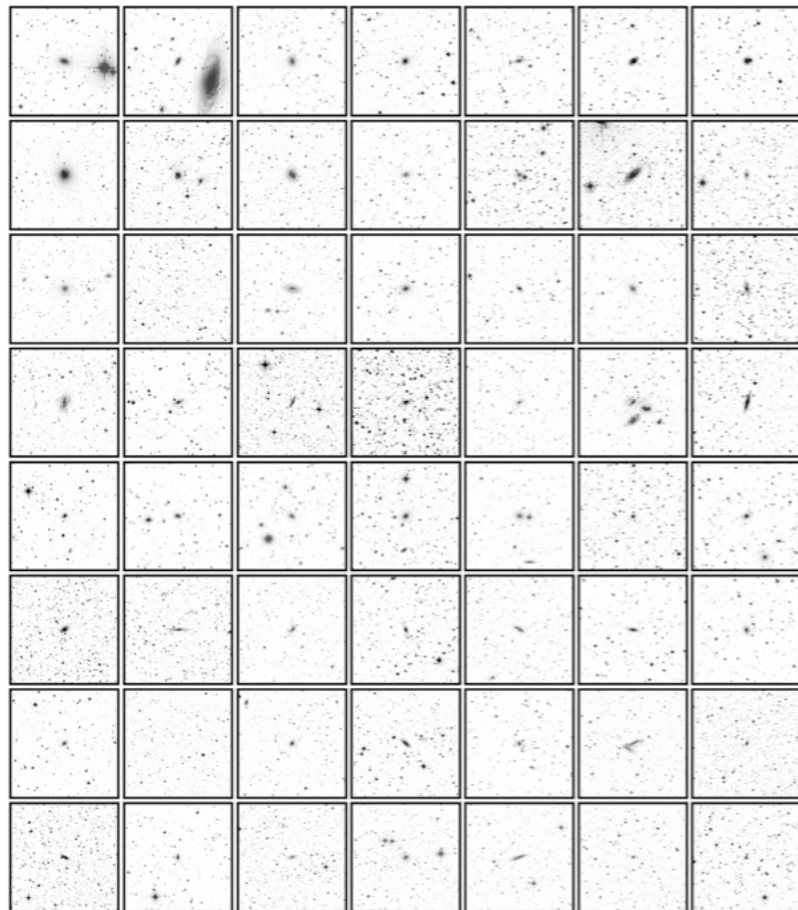
Example: Tully 2015 galaxy group map based on 2MASS Redshift Survey



GOING THE DISTANCE

Targeted **O/R** kilonova search

red=accepted
orange=proposed



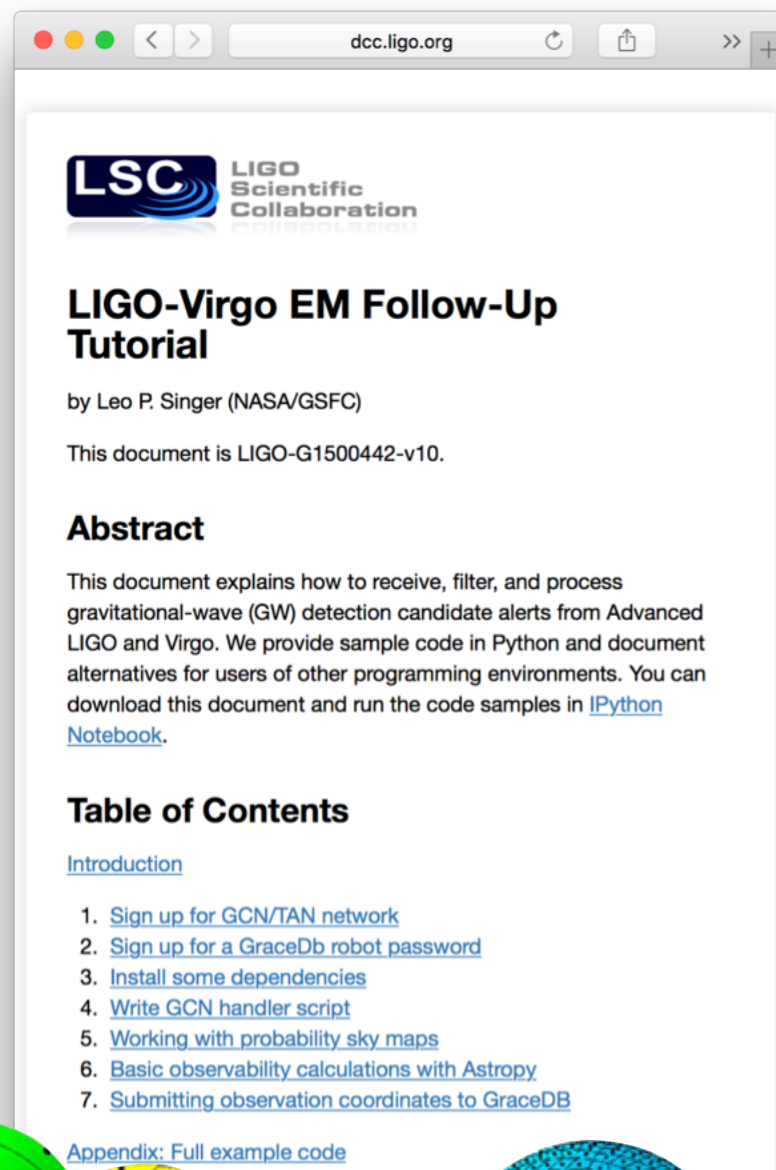
“Searching for Optical Counterparts to Gravitational Wave Sources” LCOGT 2016A (Arcavi, Howell, Valenti, Singer)

- Ideal facilities:
- LCOGT** (2m) + Spectral
 - NOT** (2.6m) + ALFOSC
 - Discovery Chan.** (4.3m) + LMI
 - Magellan** (6.5m) + FourStar
 - Gemini** (8.2m) + NIRI, Flamingos-2
 - VLT** (8.2m) + FORS2
 - Keck** (10m) + LRIS
 - GTC** (10.4m) + OSIRIS

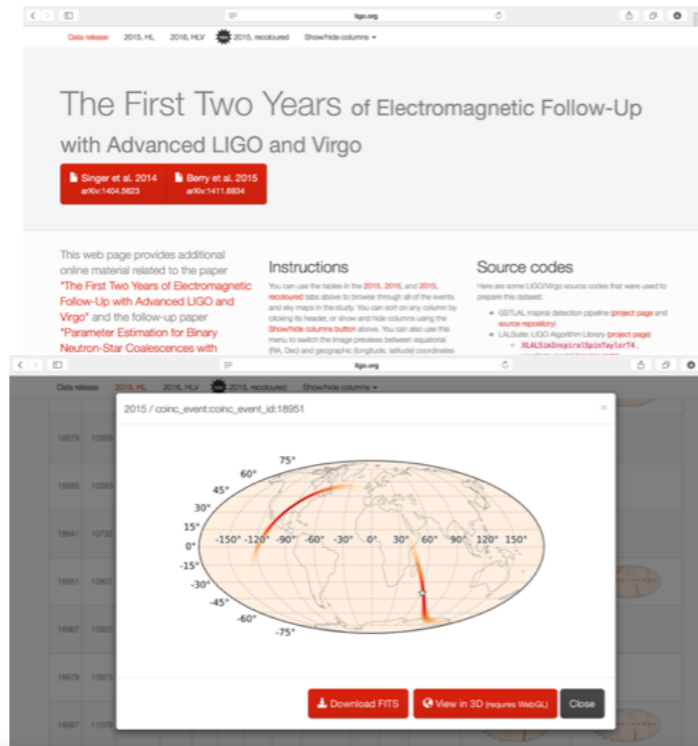
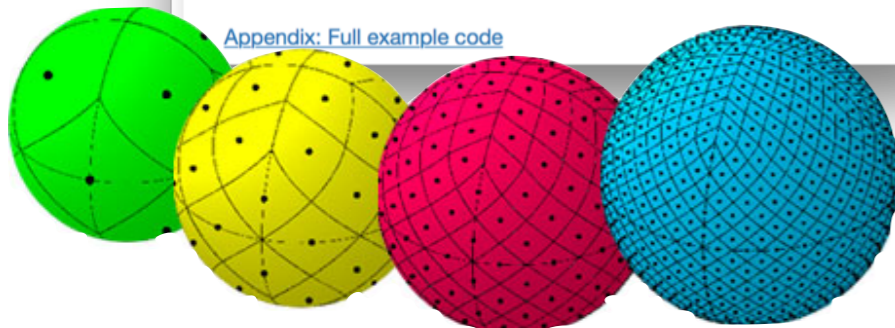


SCIENCE OUTREACH

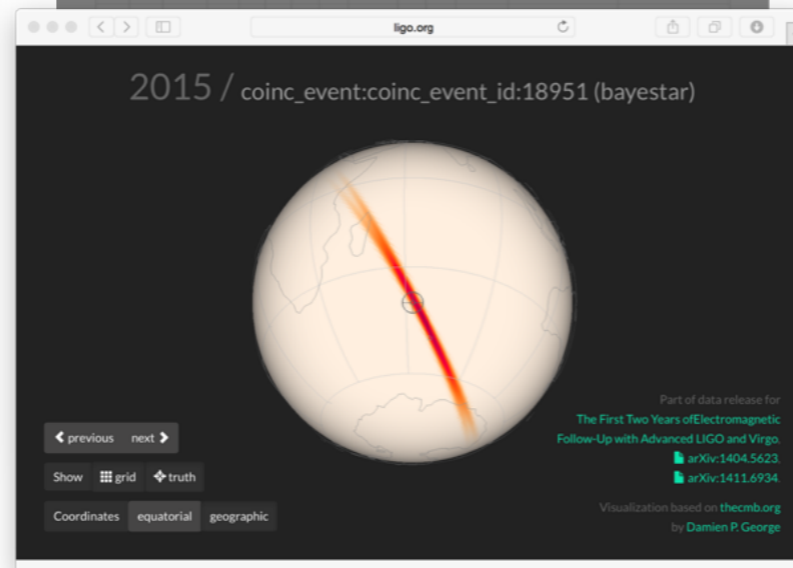
How to **get started** with **LIGO/Virgo alerts**



The screenshot shows the LIGO Scientific Collaboration logo at the top left. Below it is the title "LIGO-Virgo EM Follow-Up Tutorial" by Leo P. Singer (NASA/GSFC). The document ID is LIGO-G1500442-v10. The abstract explains how to receive, filter, and process gravitational-wave (GW) detection candidate alerts from Advanced LIGO and Virgo. A table of contents lists seven steps: 1. Sign up for GCN/TAN network, 2. Sign up for a GraceDb robot password, 3. Install some dependencies, 4. Write GCN handler script, 5. Working with probability sky maps, 6. Basic observability calculations with Astropy, and 7. Submitting observation coordinates to GraceDB. An appendix for full example code is also mentioned.



The screenshot shows the LIGO website with the title "The First Two Years of Electromagnetic Follow-Up with Advanced LIGO and Virgo". It lists authors Singer et al. 2014 and Berry et al. 2015. The page provides instructions and source codes for using the data. A map of the sky is shown, with a red line indicating the location of a gravitational wave event.



The screenshot shows the LIGO website with the title "2015 / coinc_event:coinc_event_id:18951 (bayestar)". It displays a 3D visualization of the event location on the sky, with a red line indicating the location. The visualization is based on thecm.org by Damien P. George.

Singer+ 2014 ([arXiv:1404.5623](https://arxiv.org/abs/1404.5623))
Berry+ 2015 ([arXiv:1411.6934](https://arxiv.org/abs/1411.6934))
Essick+ 2015 ([arXiv:1409.2435](https://arxiv.org/abs/1409.2435))
LVC+ 2016 ([arXiv:1304.0670](https://arxiv.org/abs/1304.0670))

- **Minimize surprise** by reusing technologies with heritage: **GCN**, **FITS**, **HEALPix**
- Rich sample catalogs, modern and simple toolchain (**Astropy**, **Healpy**, **PyGCN**)
- Sample code, tutorials, and more

Conclusions

- **LIGO discovery firehose:** expect $O(10)$ GW signals by end of 2016, $O(100)$ by end of 2017
- **NS binary mergers** are likely around the corner: $O(0.1-10)$ events possible in O2
- **Wealth of information can be learned from joint GW+brodband EM observations**

A wide-angle landscape photograph featuring a large, metallic pipe in the foreground on the right, extending towards the horizon. The pipe is set against a backdrop of rolling hills and mountains under a dramatic, cloudy sky. The sky is filled with dark, heavy clouds, with a bright, golden light breaking through near the horizon, suggesting a sunrise or sunset. The ground is covered in sparse, dry vegetation and patches of dark soil. The overall mood is one of vastness and natural beauty.

THANK YOU

HOW TO GET INVOLVED IN LIGO/VIRGO FOLLOW-UP

EM alerts during proprietary period (O1/O2)

<http://www.ligo.org/scientists/GWEMAlerts.php>

For inquiries

emf@ligo.org, L. Singer, P. Shawhan, M. Branchesi

Tutorials and technical info

https://gw-astronomy.org/wiki/LV_EM/TechInfo

LIGO open data (including sky maps)

<https://losc.ligo.org/>