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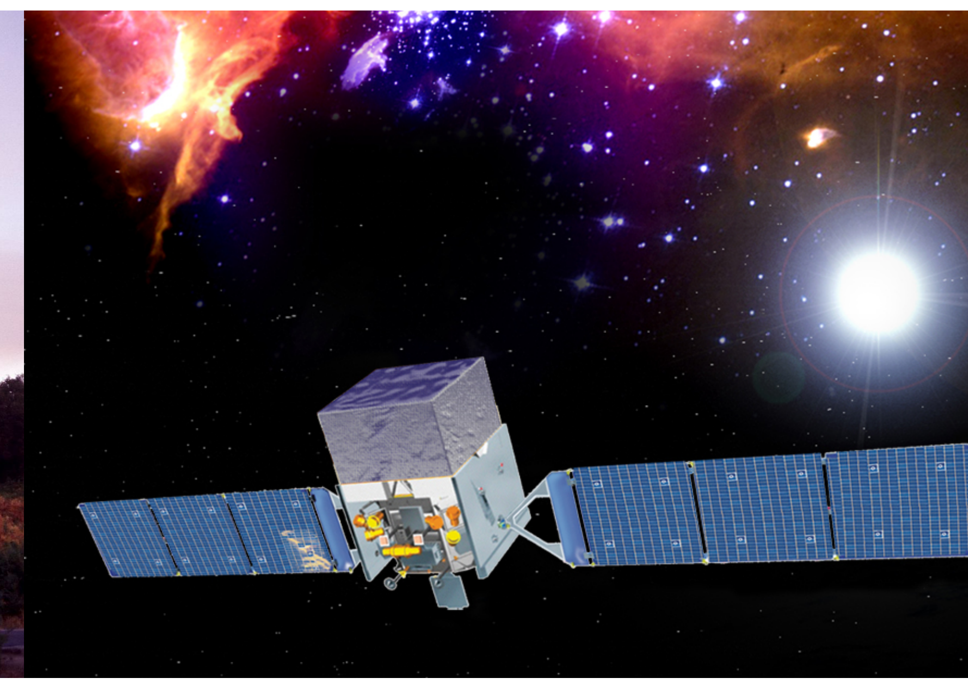
ADVANCED LIGO FIRST LIGHT

BROADBAND FOLLOW-UP OF COMPACT BINARY MERGERS



LSC VIRGO

7 YEARS OF MAXI

RIKEN, Japan, 2016 December 7

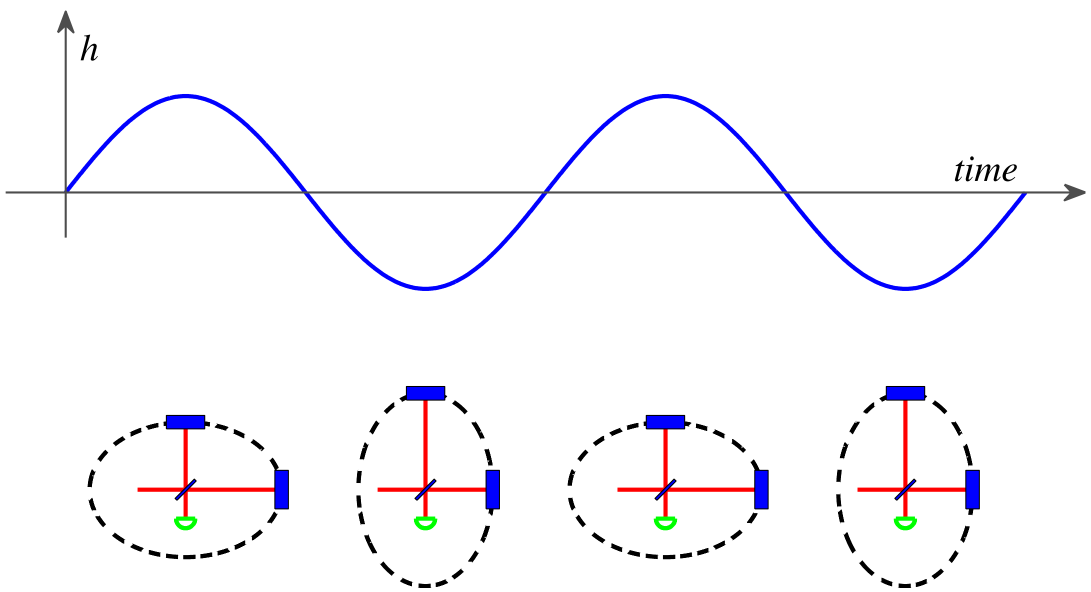
FIRST LIGHT

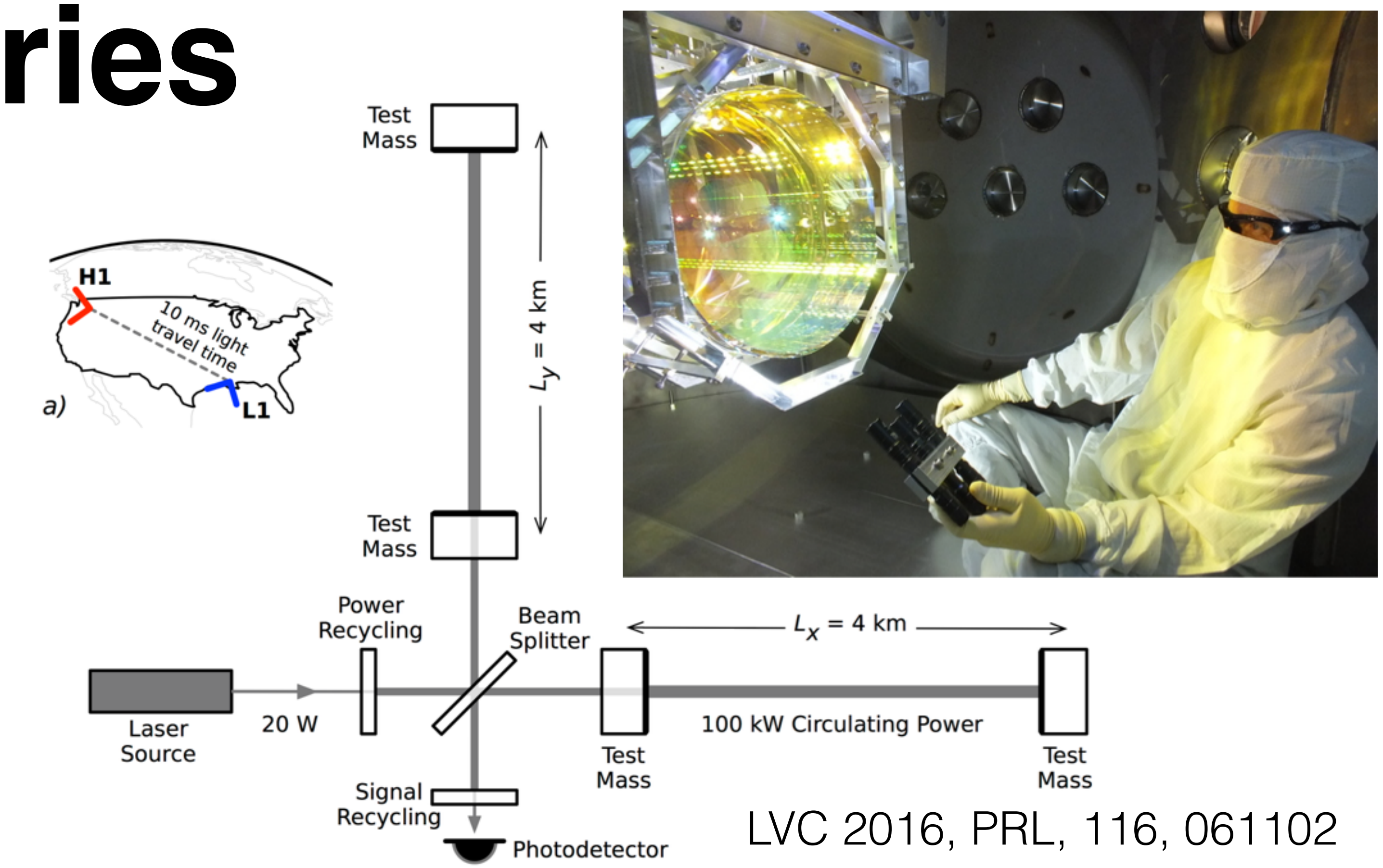
— *noun* 1. In astronomy, first light is the first use of a telescope (or, in general, a new instrument) to take an astronomical image **after it has been constructed**. This is often **not the first viewing** using the telescope; optical tests will probably have been performed during daylight **to adjust 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

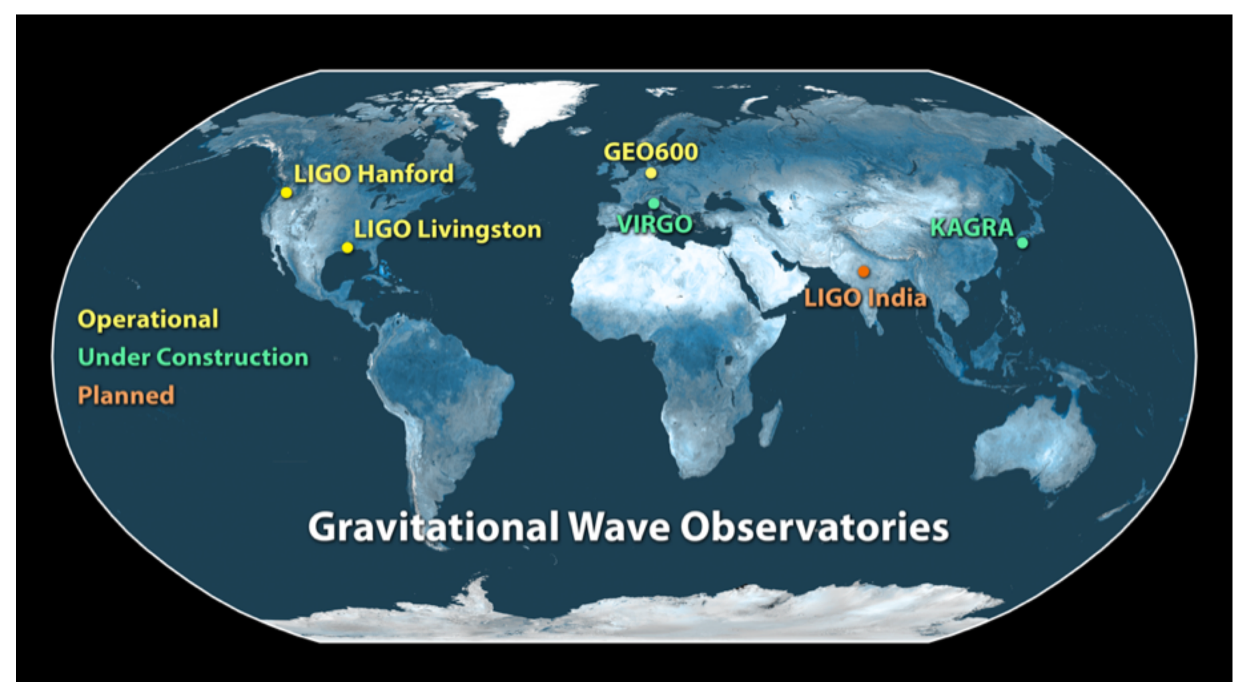
- **LIGO**: **L**aser **I**nterferometer **G**ravitational-wave **O**bservatory

- Senses fractional arm displacements (strain) of 10^{-21}
  → changes in length of ~2×10^{-16} 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 from fused silica fibers, multi-stage pendula, active seismic isolation

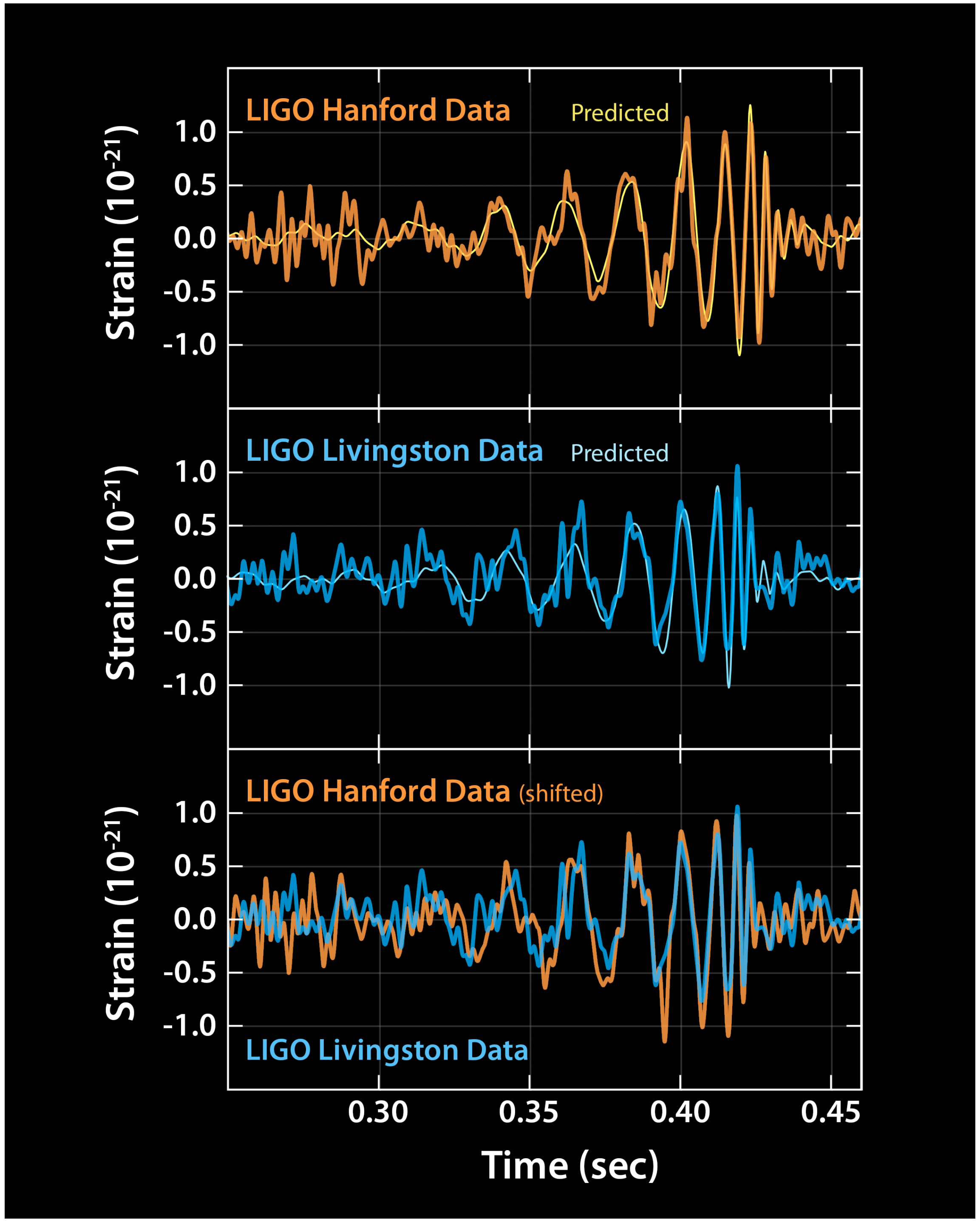
  20 W laser power → 100 kW circulating in arm cavities

  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**

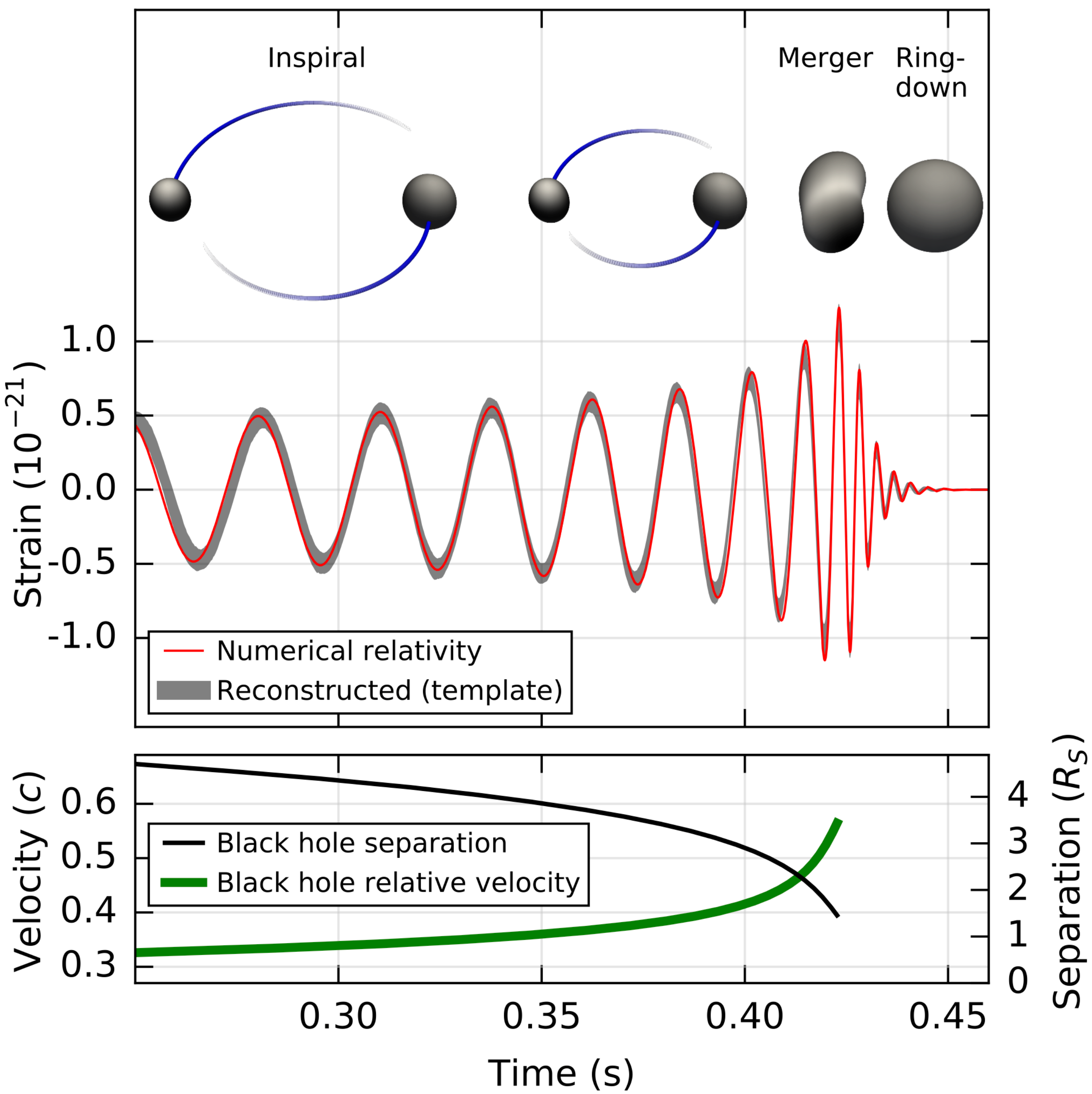


image: LVC 2016, PRL, arXiv:1602.03837

- **Surprising properties…**
  Masses: 36 + 29 → 62 $M_\odot$
  3 $M_\odot$ radiated in GWs!

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

  Spins weakly constrained, but **nowhere near maximal**:
  <0.7 + <0.9 → ~0.6

- Distance: ~400±200 Mpc, z~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

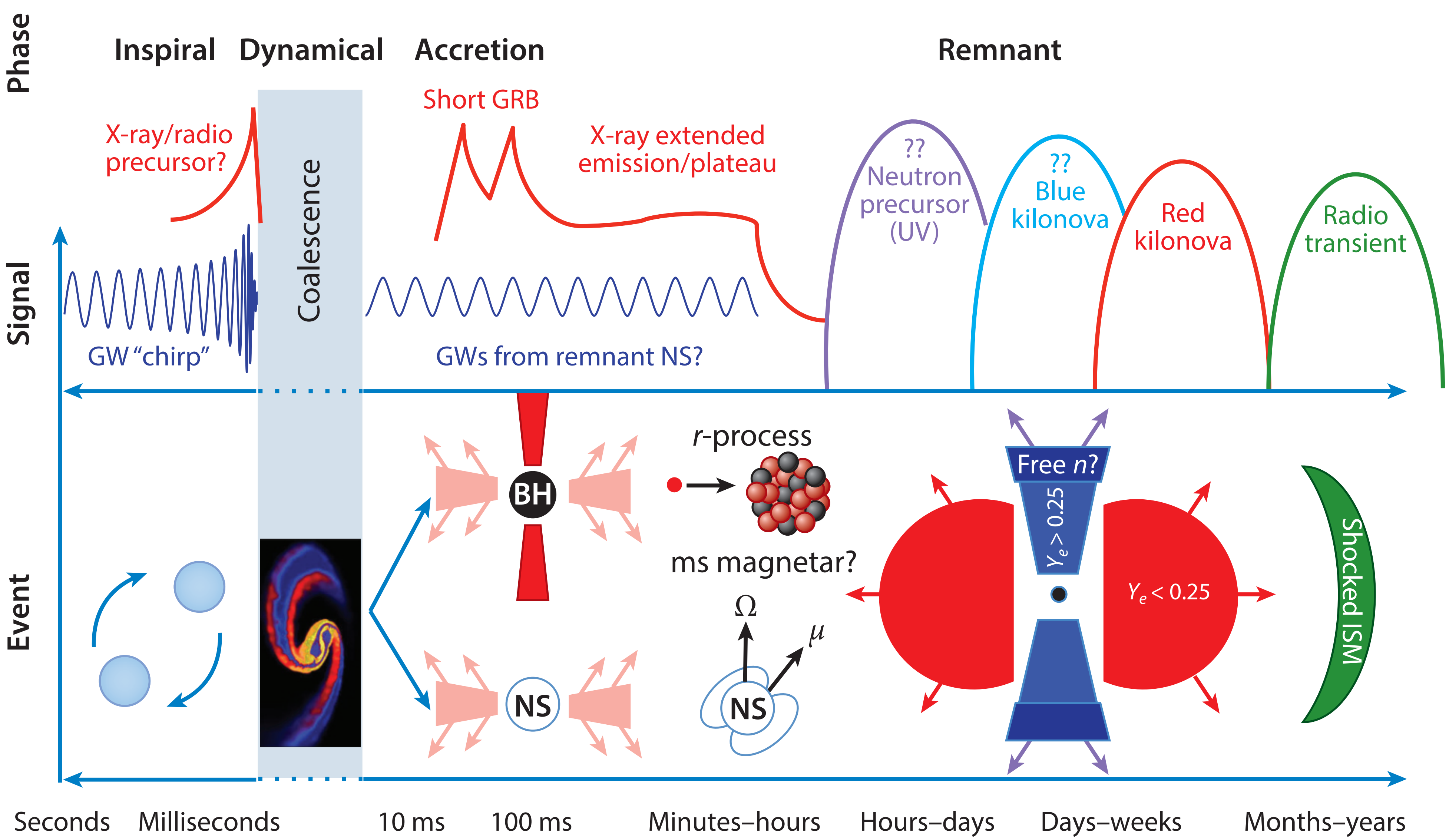
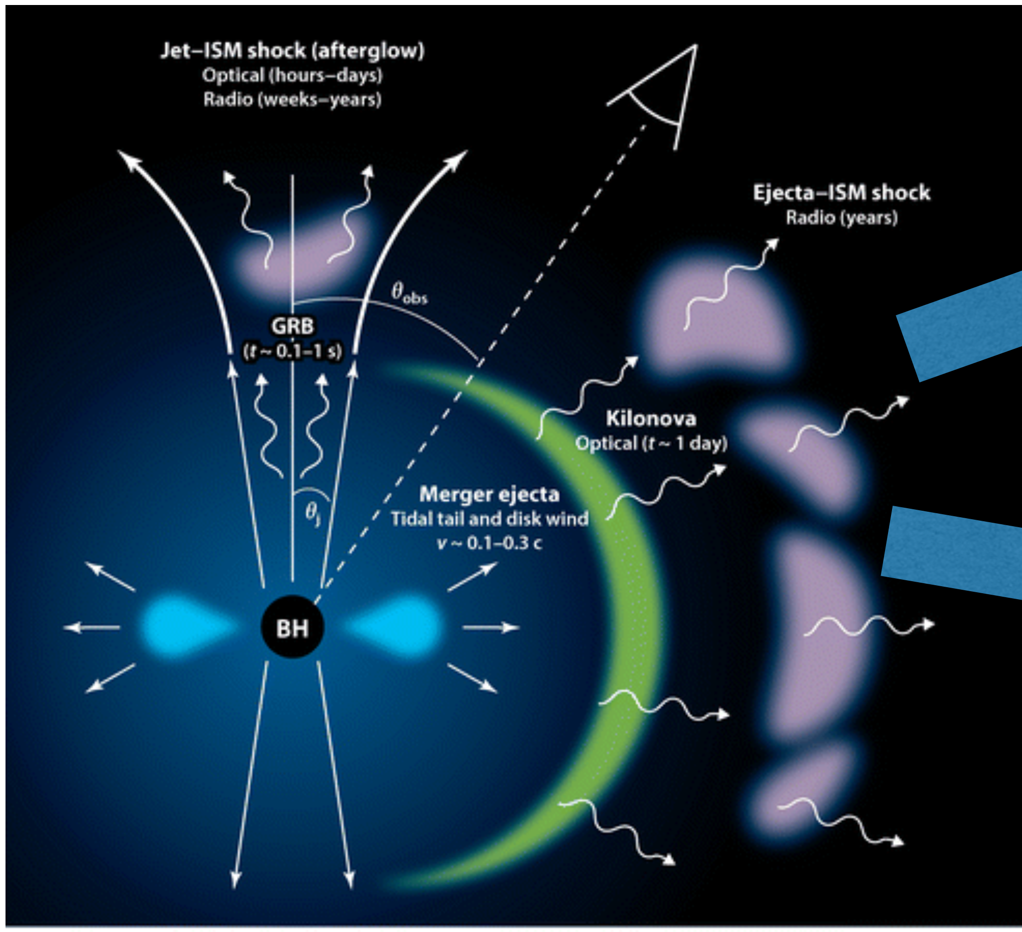


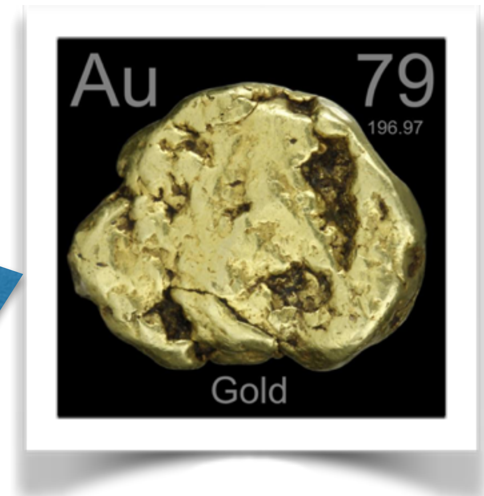
image: Fernández & Metzger 2016

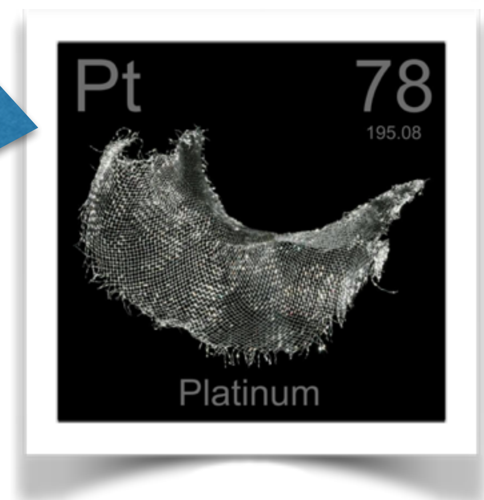
- Resonant shattering of NS crust → X-ray/radio precursor
- Rapid accretion, relativistic fireball → short GRB
- Central engine (magnetar wind) → extended, isotropic X-ray emission
- Synchrotron cooling of shock-accelerated relativistic electrons → broadband afterglow
- Radioactive ejecta → macronova/kilonova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

The future is ***bright!***



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

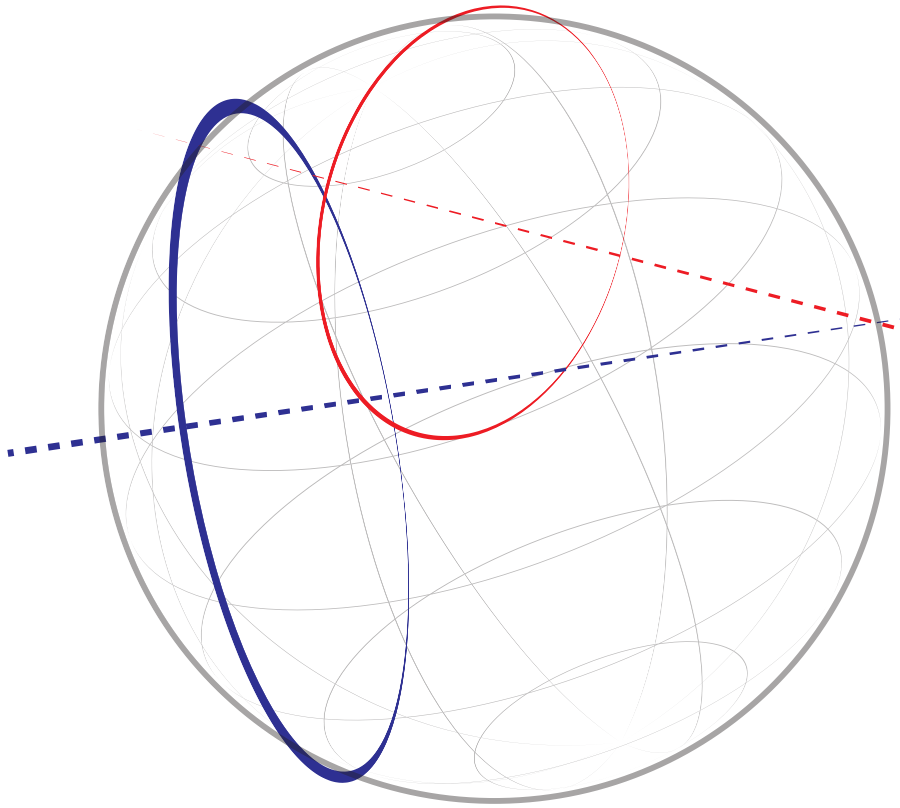


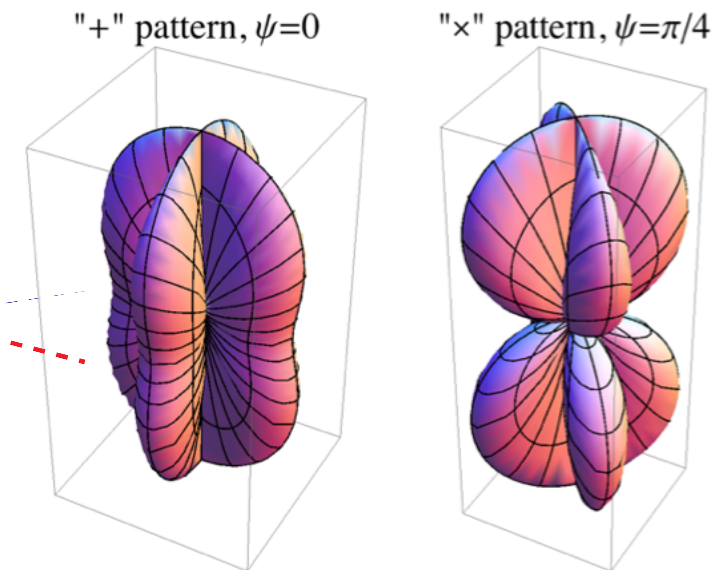


- **EM counterparts of LIGO sources**
- **Central engine** vs. **external fireball** and ejecta
- **Pinpoint host galaxy**, determine formation environment
- **Standard sirens**: Calibration-free rung on cosmological distance ladder
- Explain cosmic abundance of heavy elements – **"bling nova"**
- Explain **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!

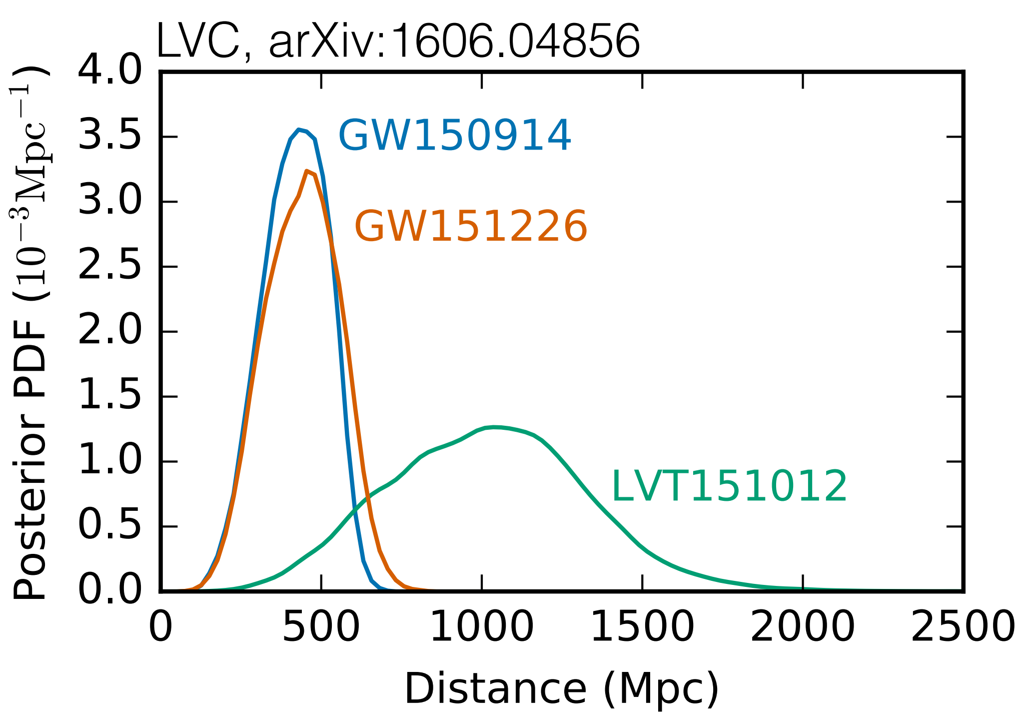
SKY LOCATION AND DISTANCE:
a phased array of gravitational antennas

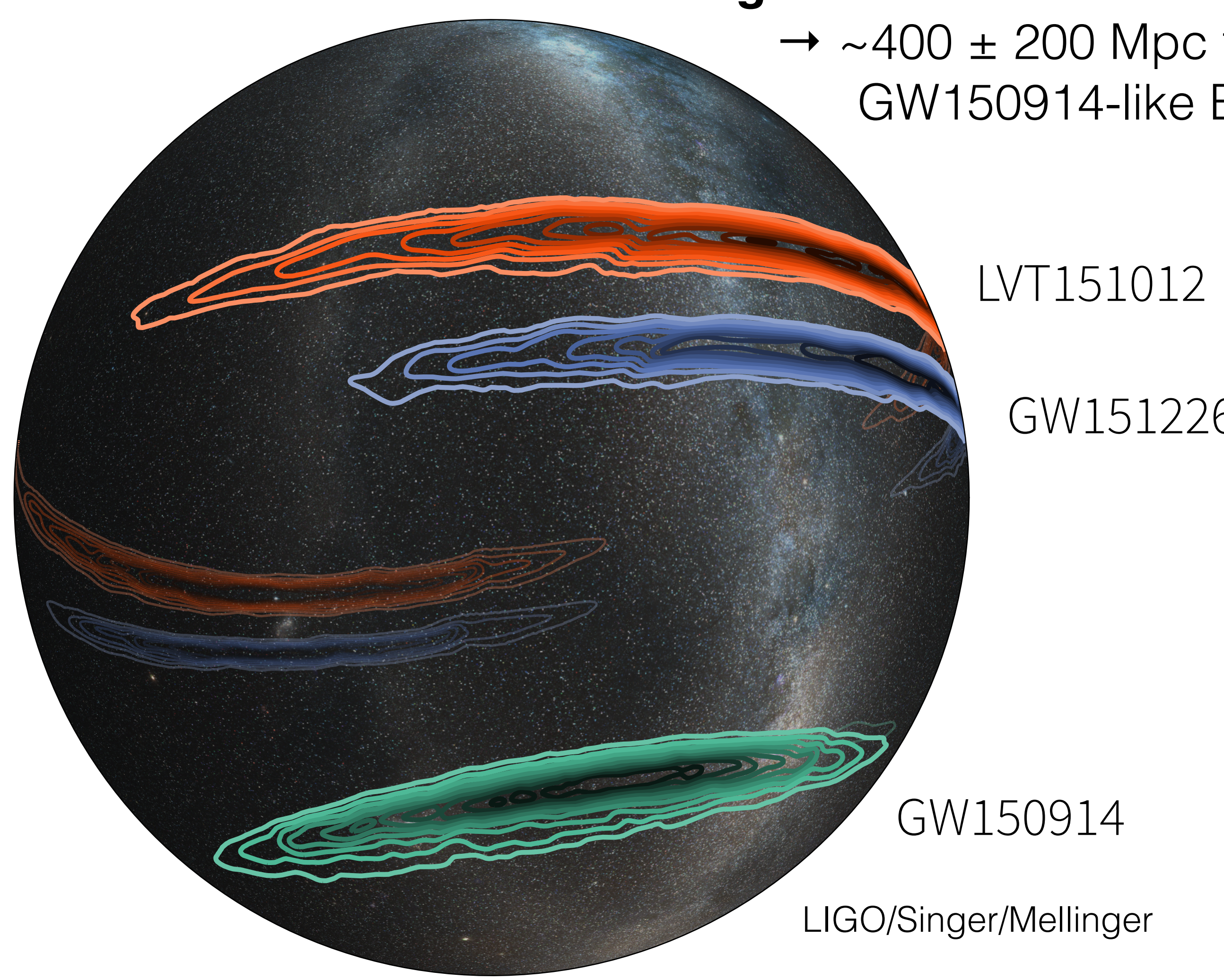




- **Sky location** inferred from triangulation of times, phases, and amplitudes on arrival → bimodal rings of100–1000 of deg^2 with only 2 detectors

- **Distance** inferred by signal amplitude and directional antenna patterns, but **degenerate** with inclination
  → ~400 ± 200 Mpc for GW150914-like BBH mergers

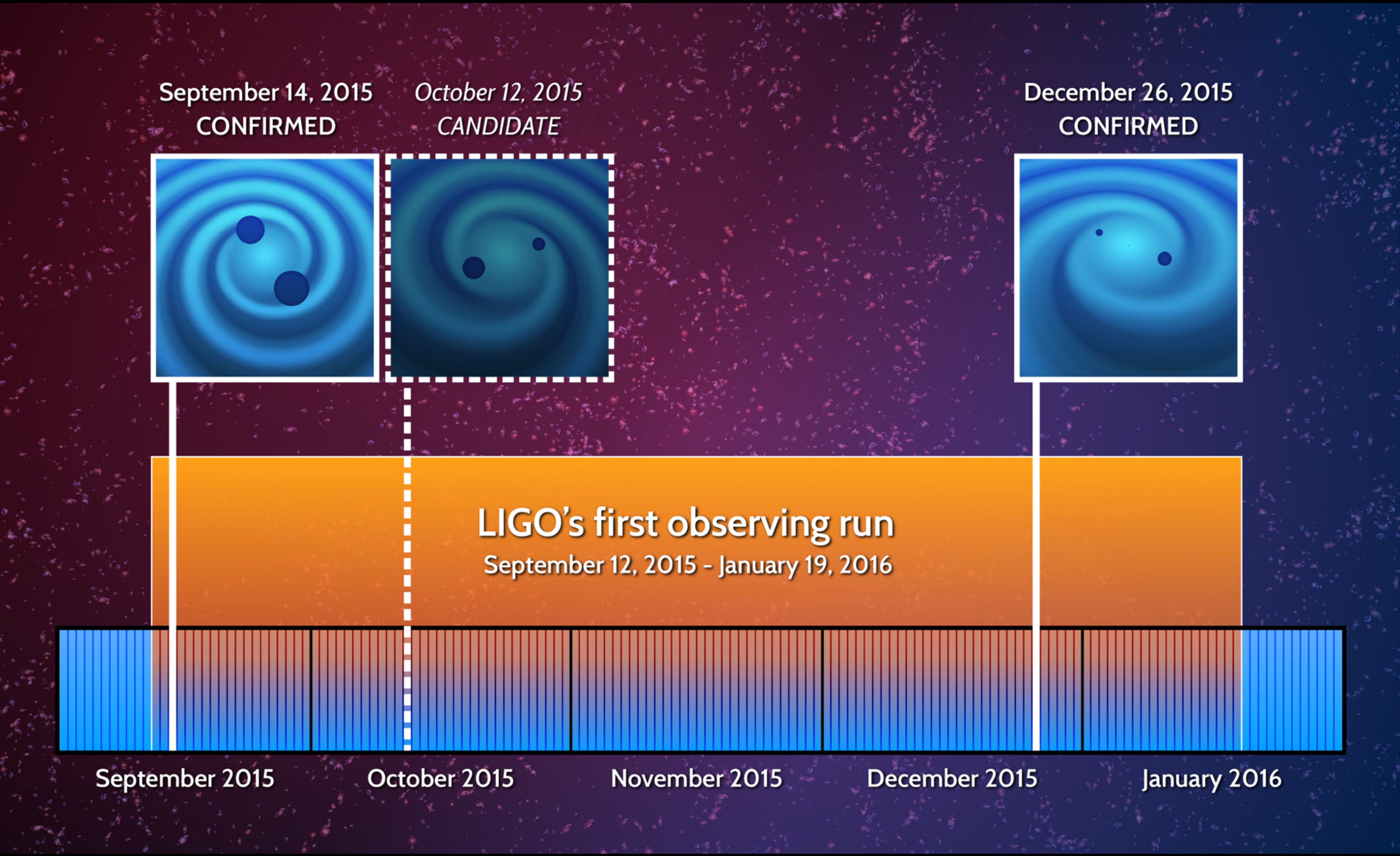




LIGO/Singer/Mellinger


JAPAN
Ulysses
Integral
Swift
HETE
XTE
GCN

II. BROADBAND FOLLOW-UP IN O1

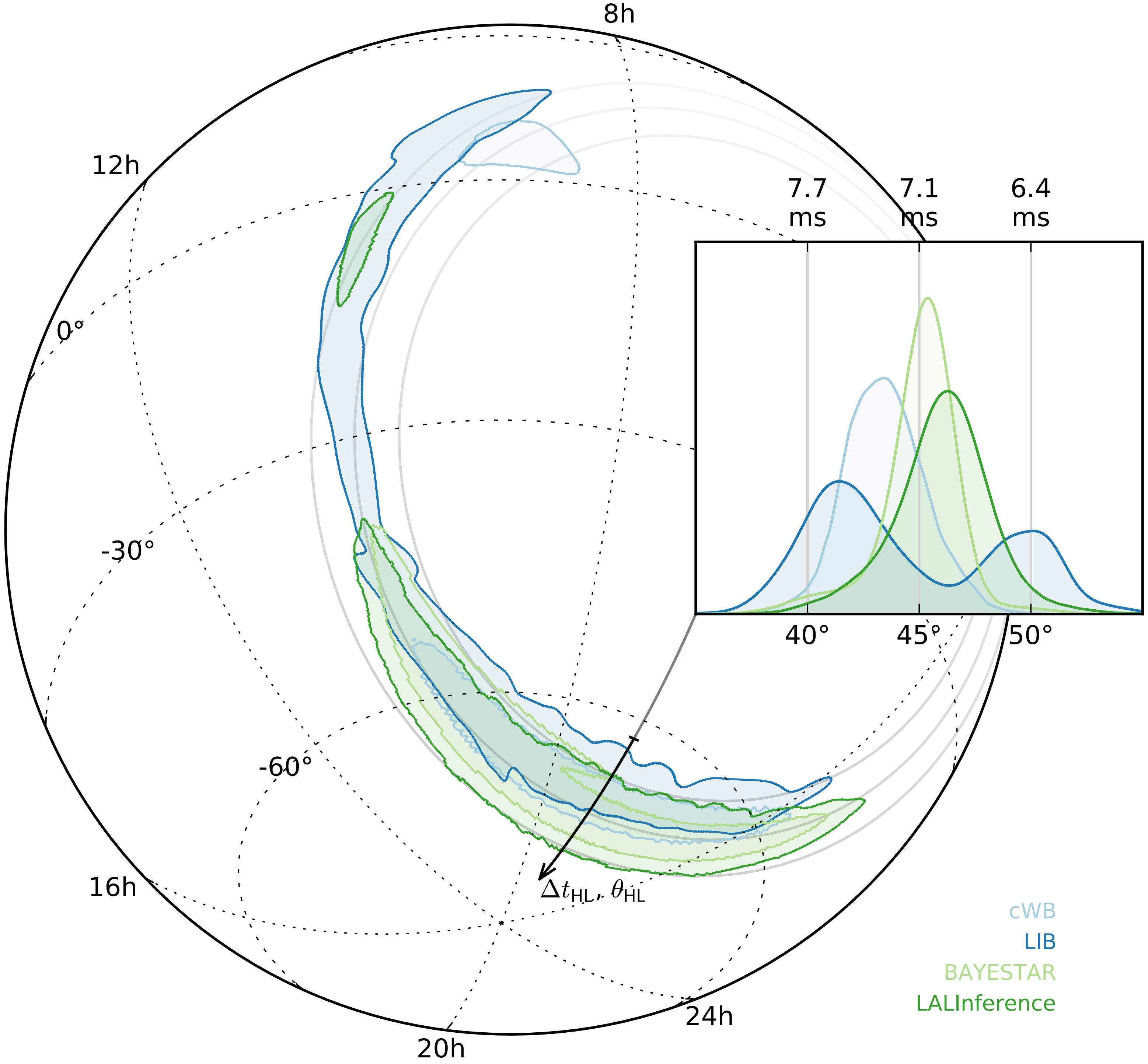


Credit: LIGO/Caltech

LOCALIZATION AND BROADBAND FOLLOW-UP

OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

ApJL, 826, L13
arXiv:1602.08492



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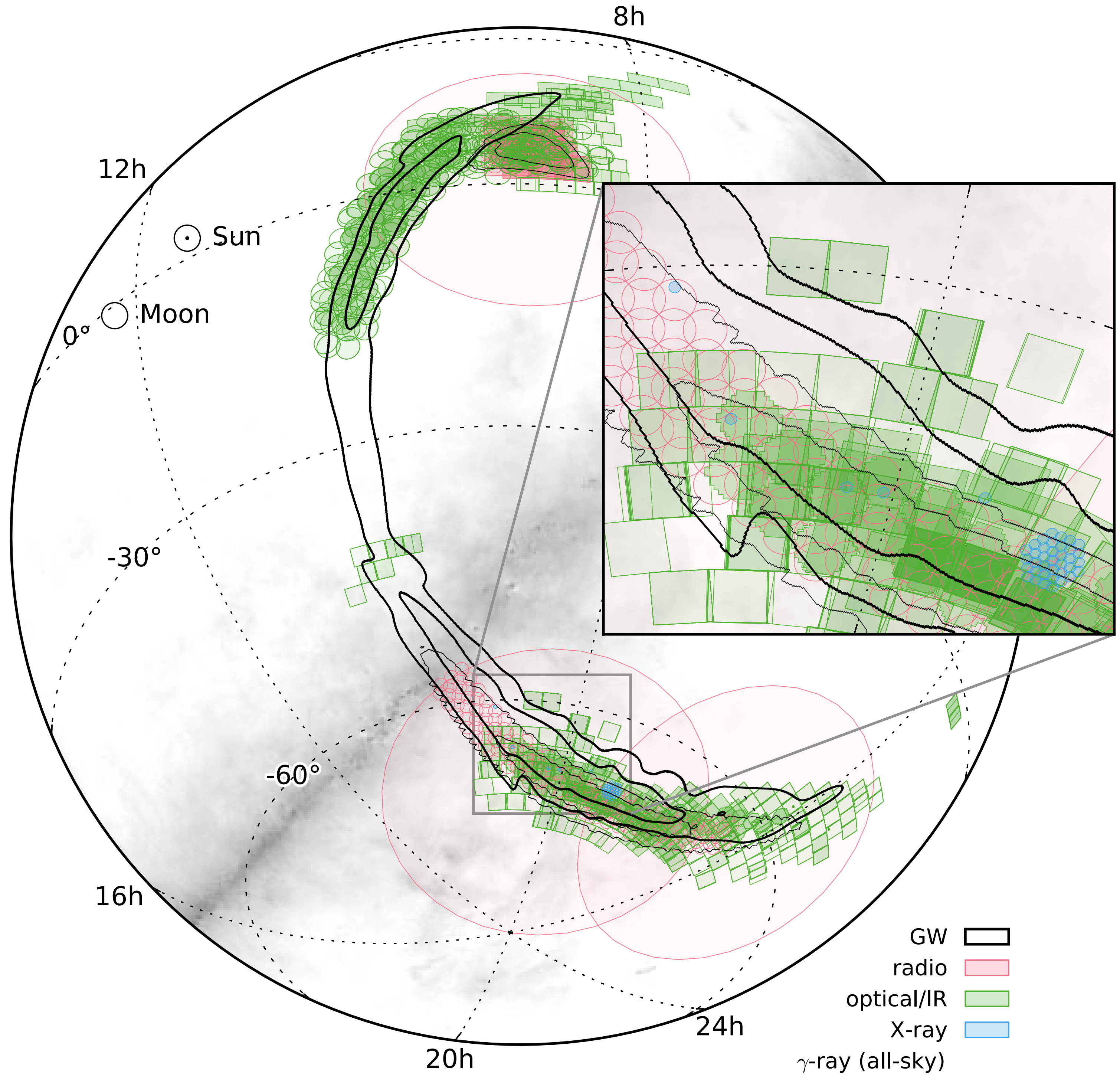

ApJL, 826, L13
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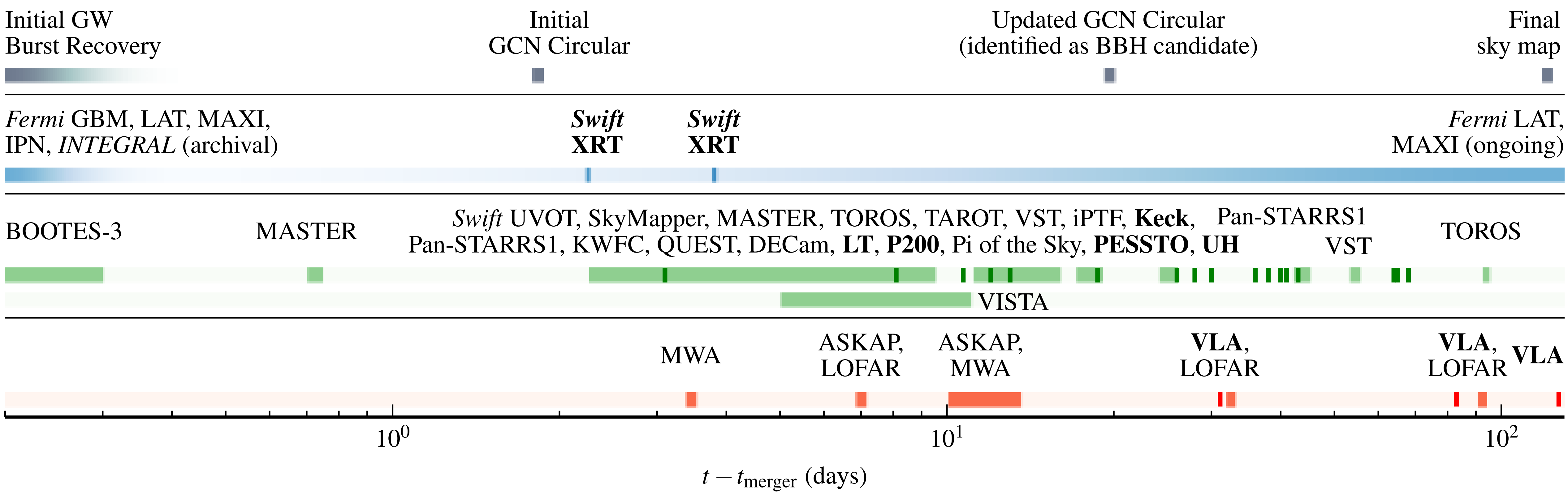


LOCALIZATION AND BROADBAND FOLLOW-UP

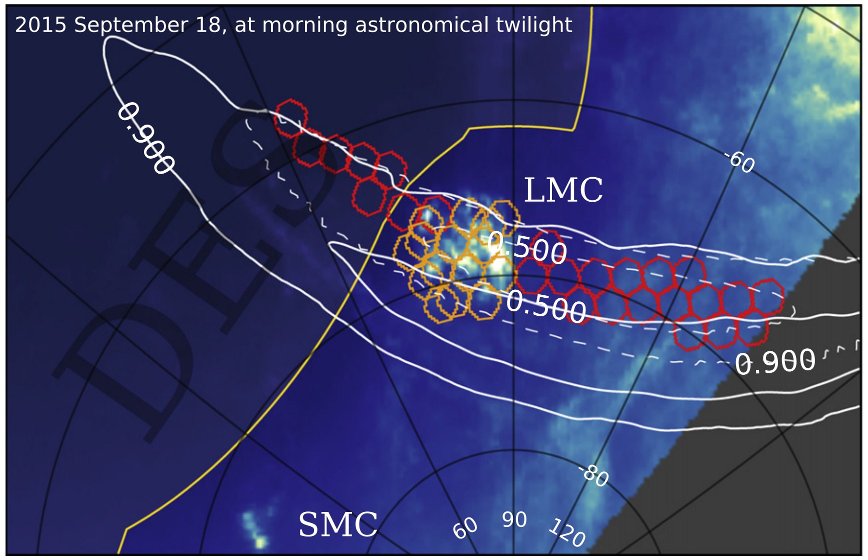
OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

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

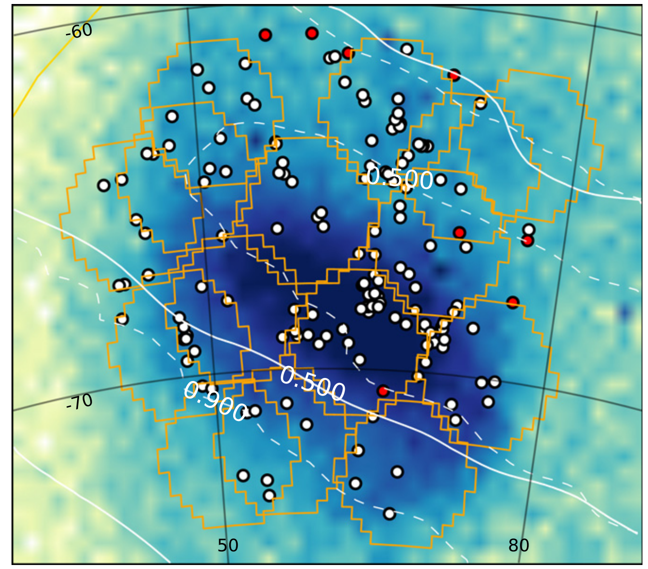
unprecedented: *broke ApJL author portal!*

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

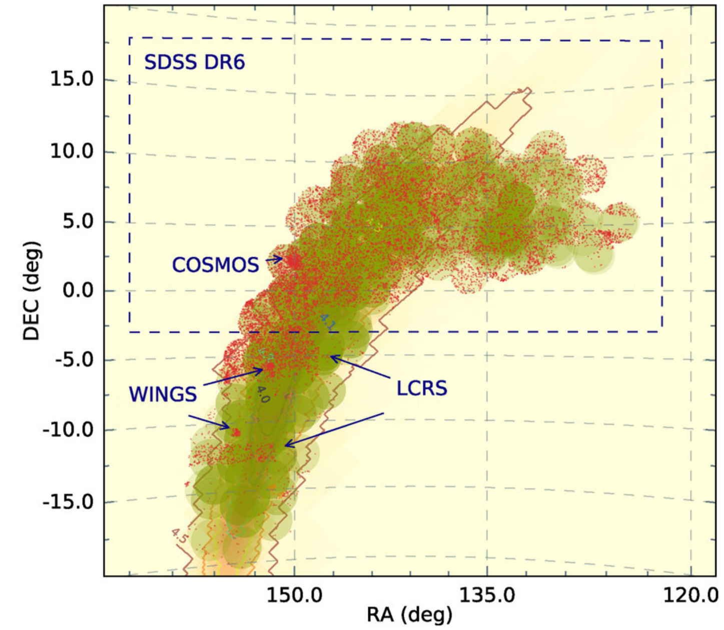
GW FOLLOW-UP WITH **LARGE SYNOPTIC SURVEY INSTRUMENTS**



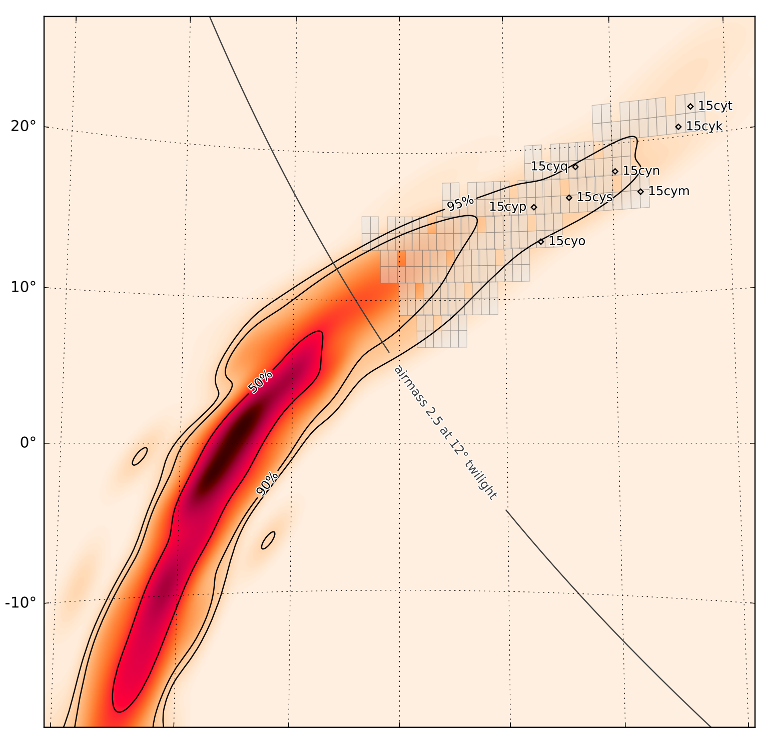
Soares-Santos+ 2016 Deep, wide-field follow-up with DECam to *i*=22.5



Annis+ 2016 DECam search for missing supergiants in LMC

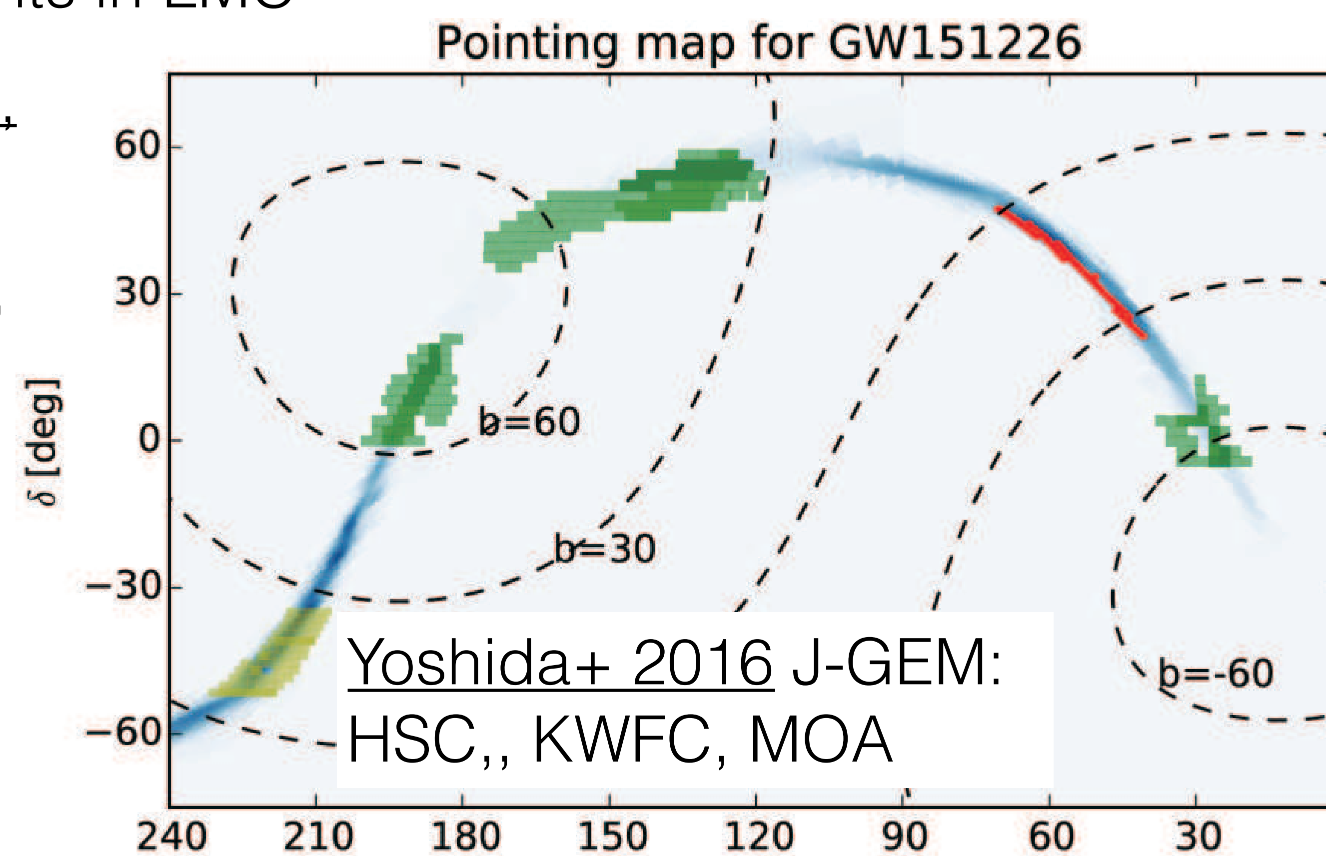


Smartt+ 2016 Pan-STARRS



Kasliwal, Cenko, Singer+ 2016

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

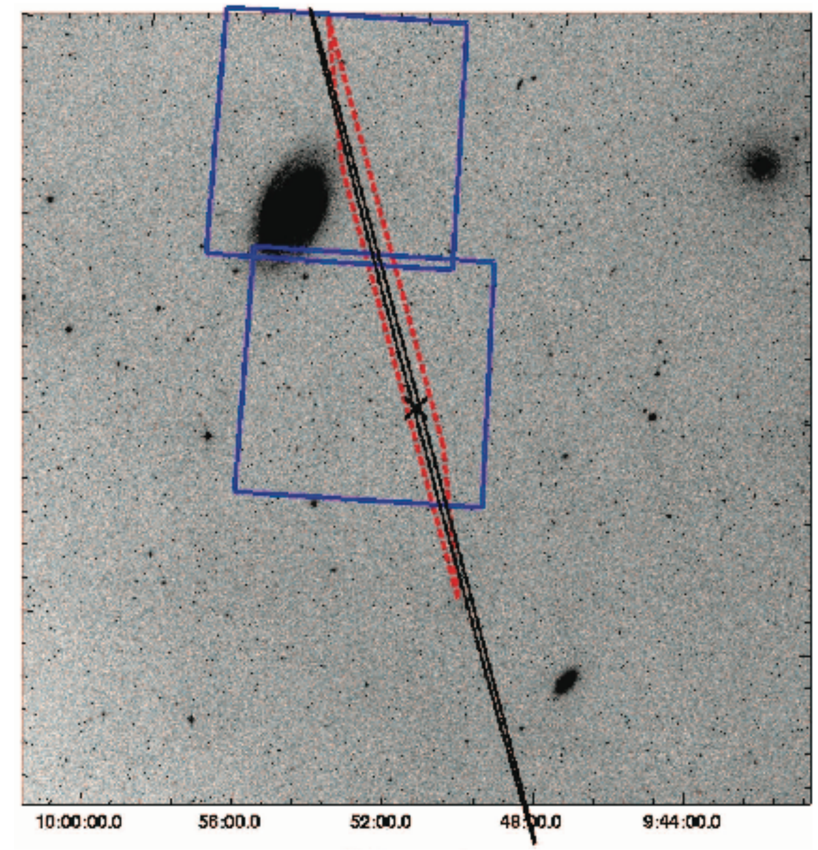


Yoshida+ 2016 J-GEM: HSC,, KWFC, MOA

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



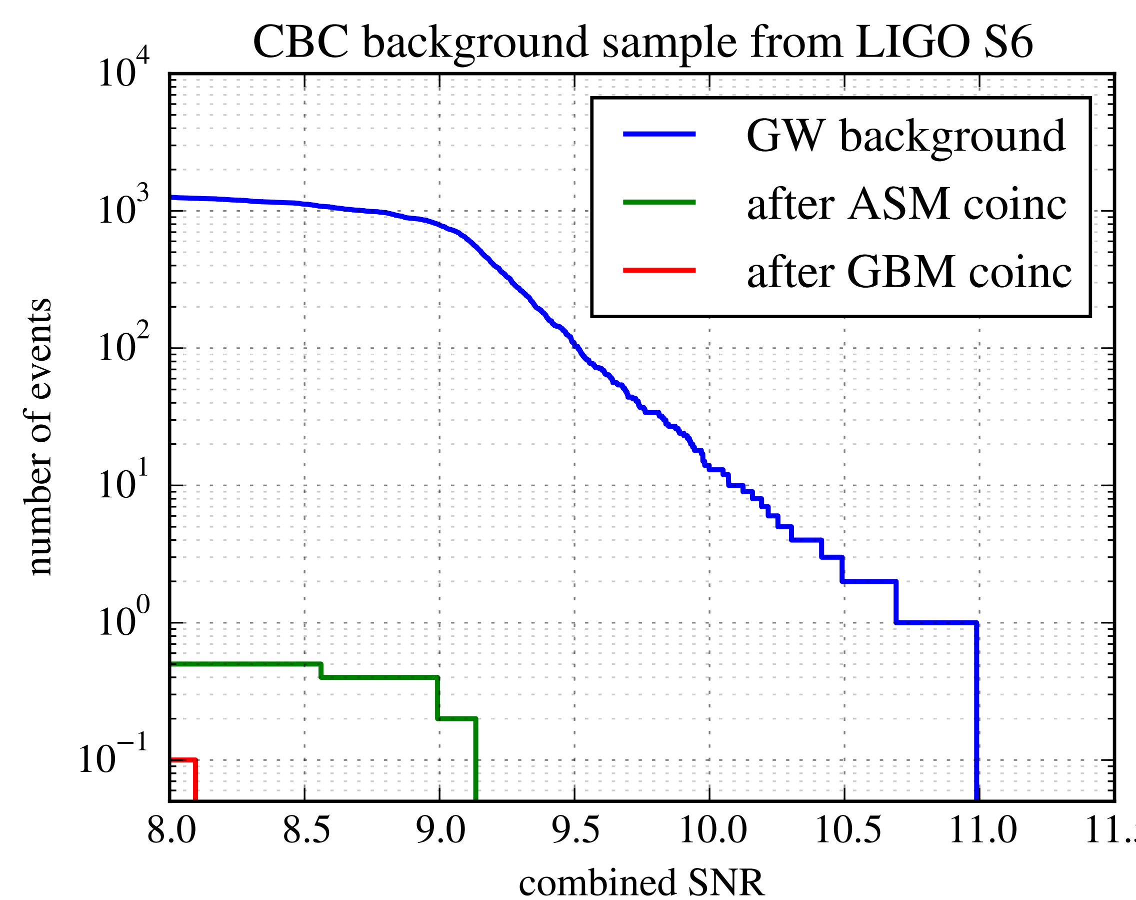
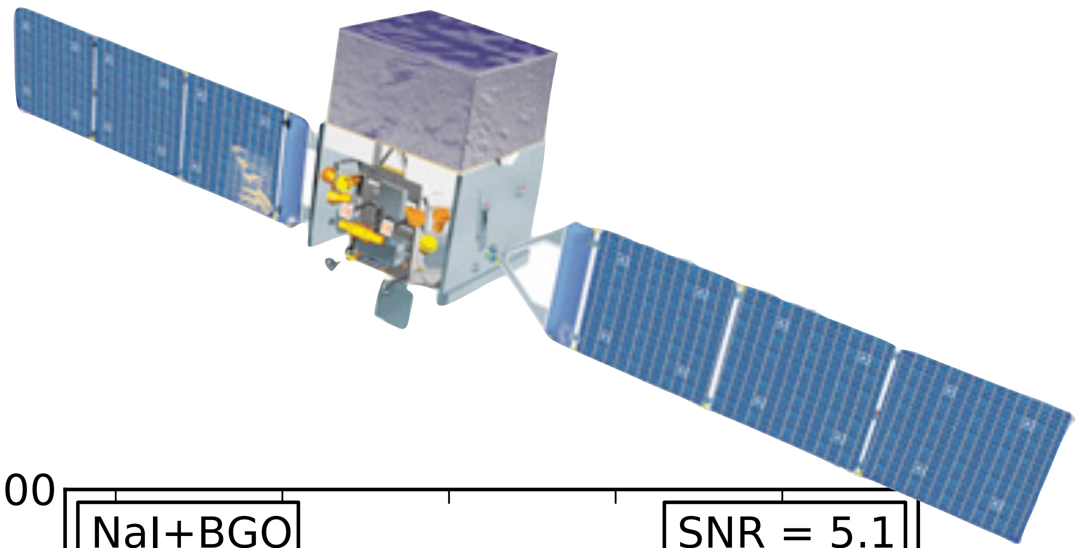


image: Blackburn+ 2015

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.)

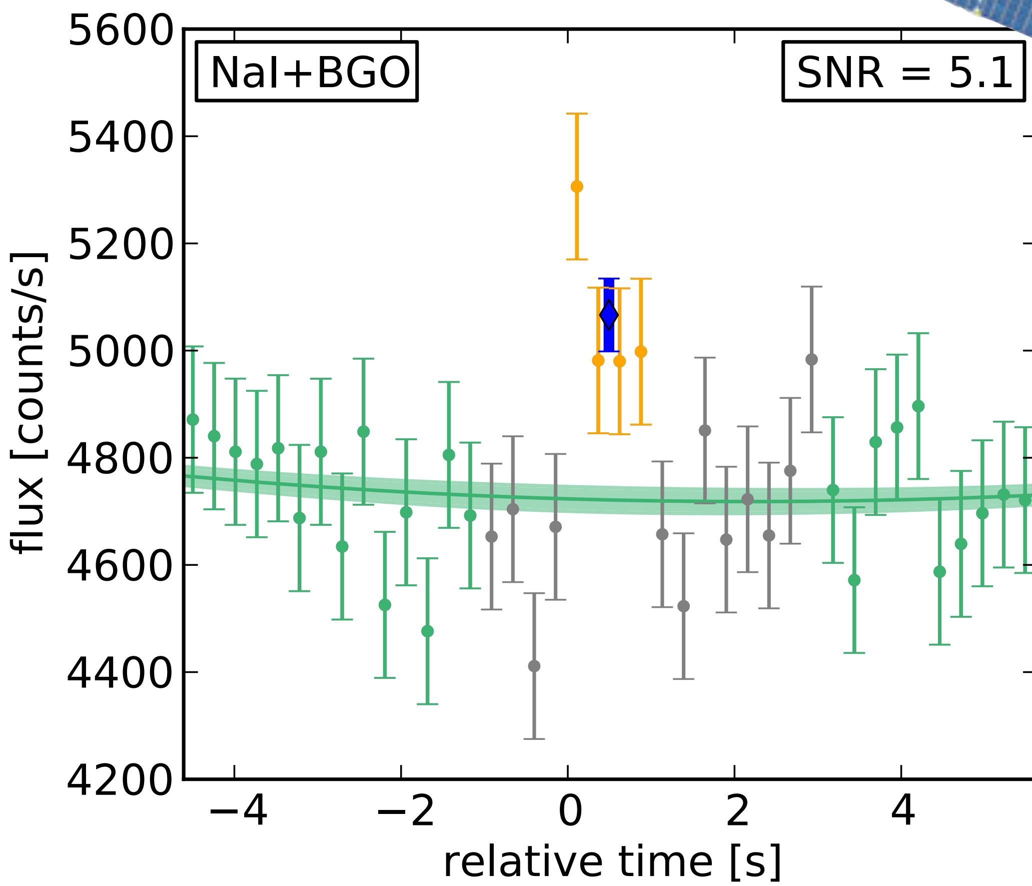


image: Connaughton+ 2016

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

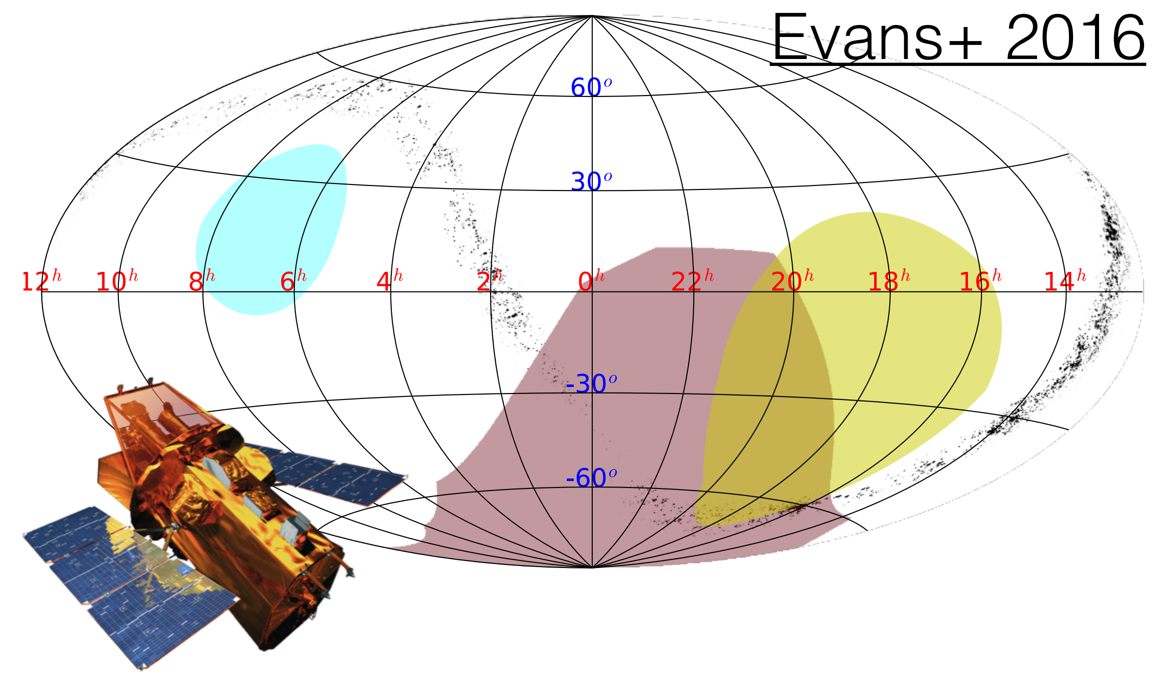
X-RAY FOLLOW-UP

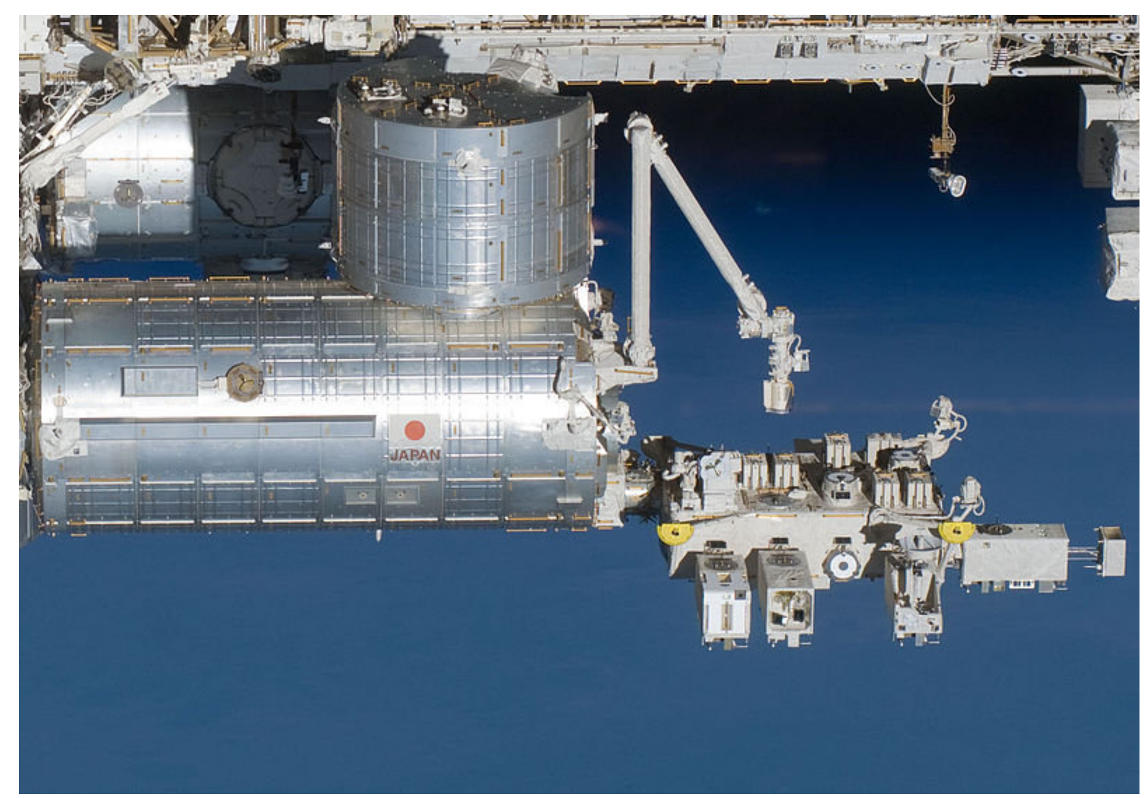
- *Swift* XRT → new ToO modes, large tiling patterns, galaxy-targeted searches (Evans, Kenna +2016)

- →MAXI/GSC → covers almost full GW localization every 92 minutes

  N. Kawai's talk, this session
  GCN 18557, 18784, 19013

- CALET (Adriani+ 2016)





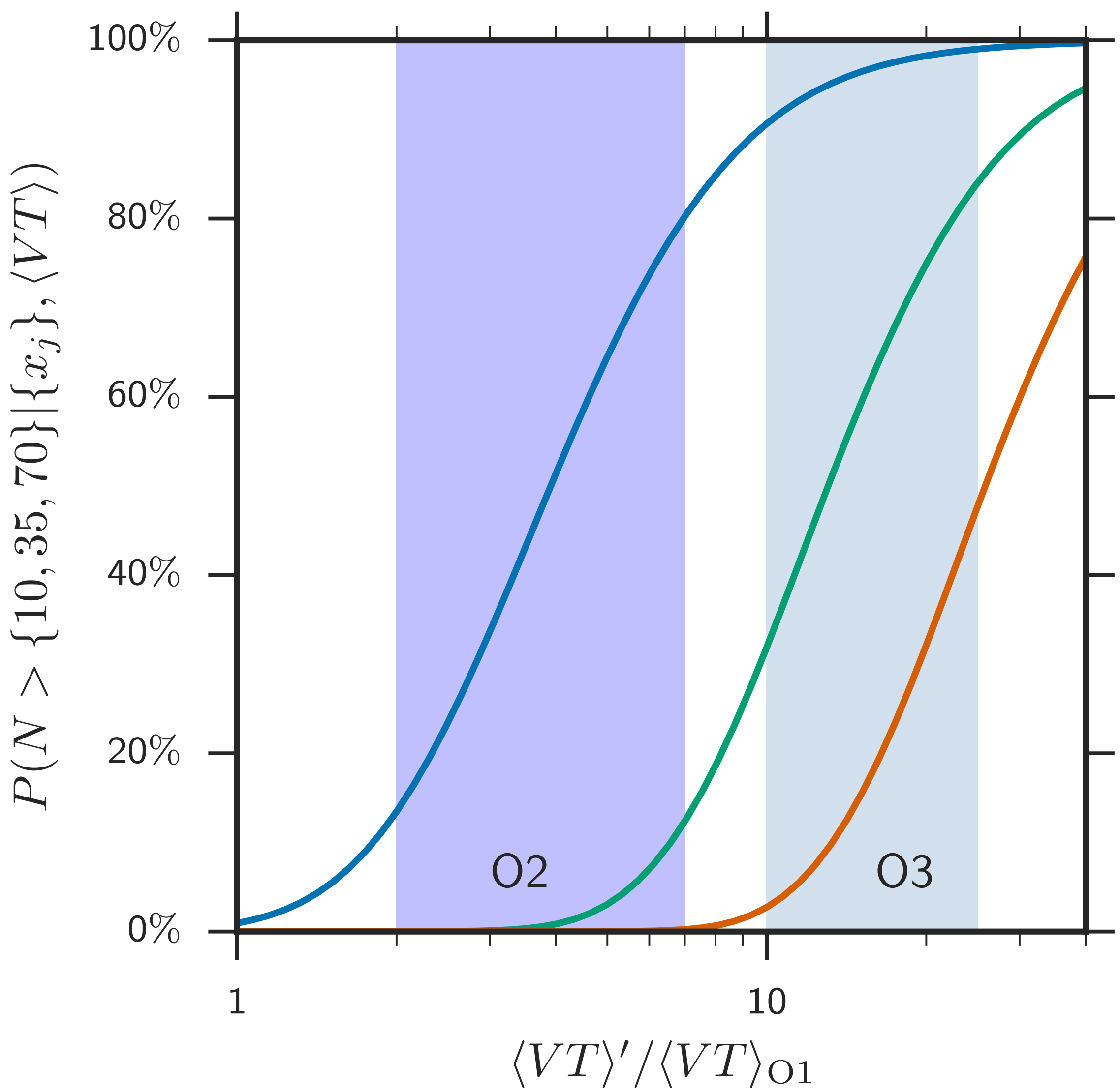
III. WHERE WE WILL GO IN O2

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

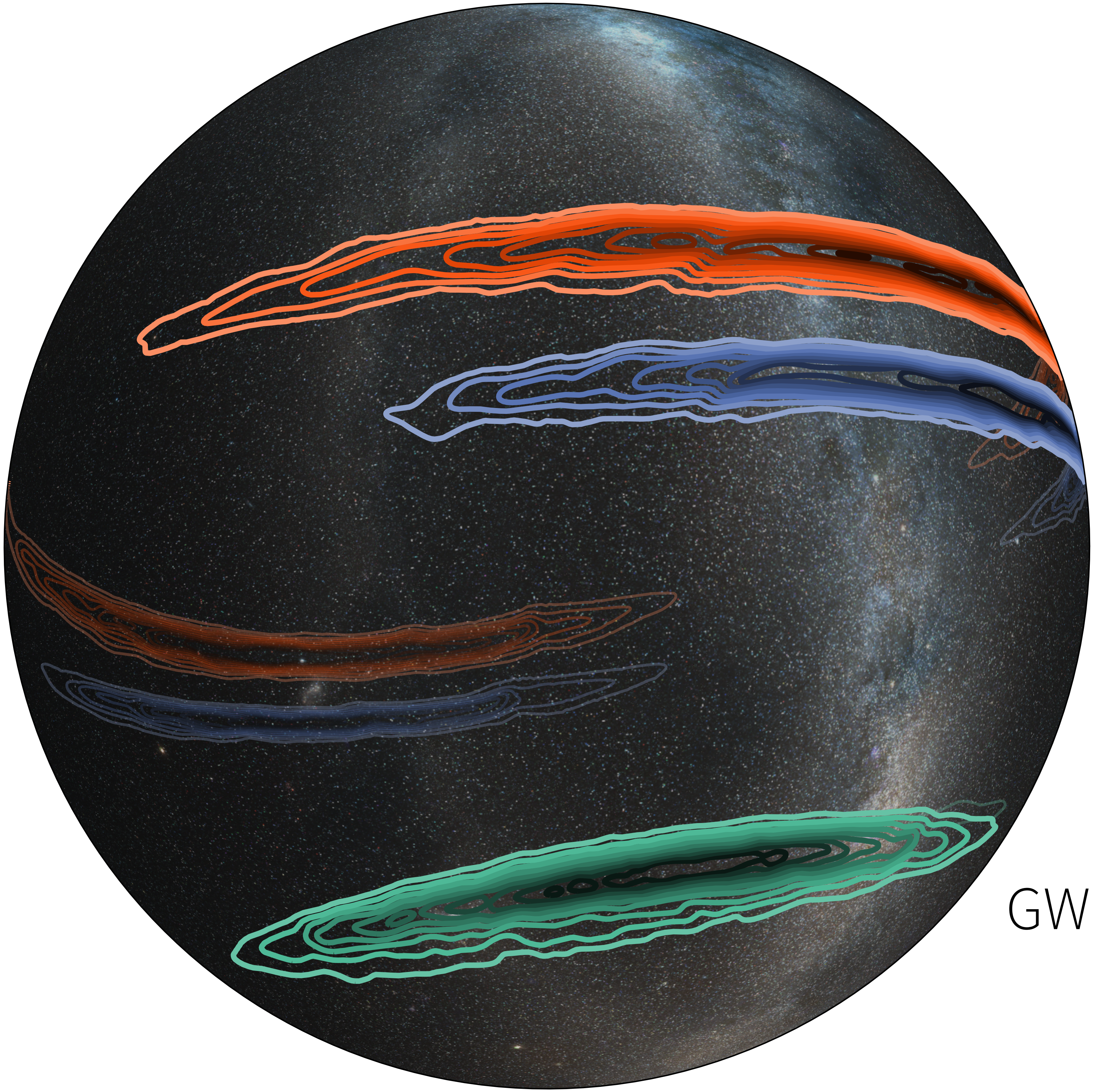


image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)

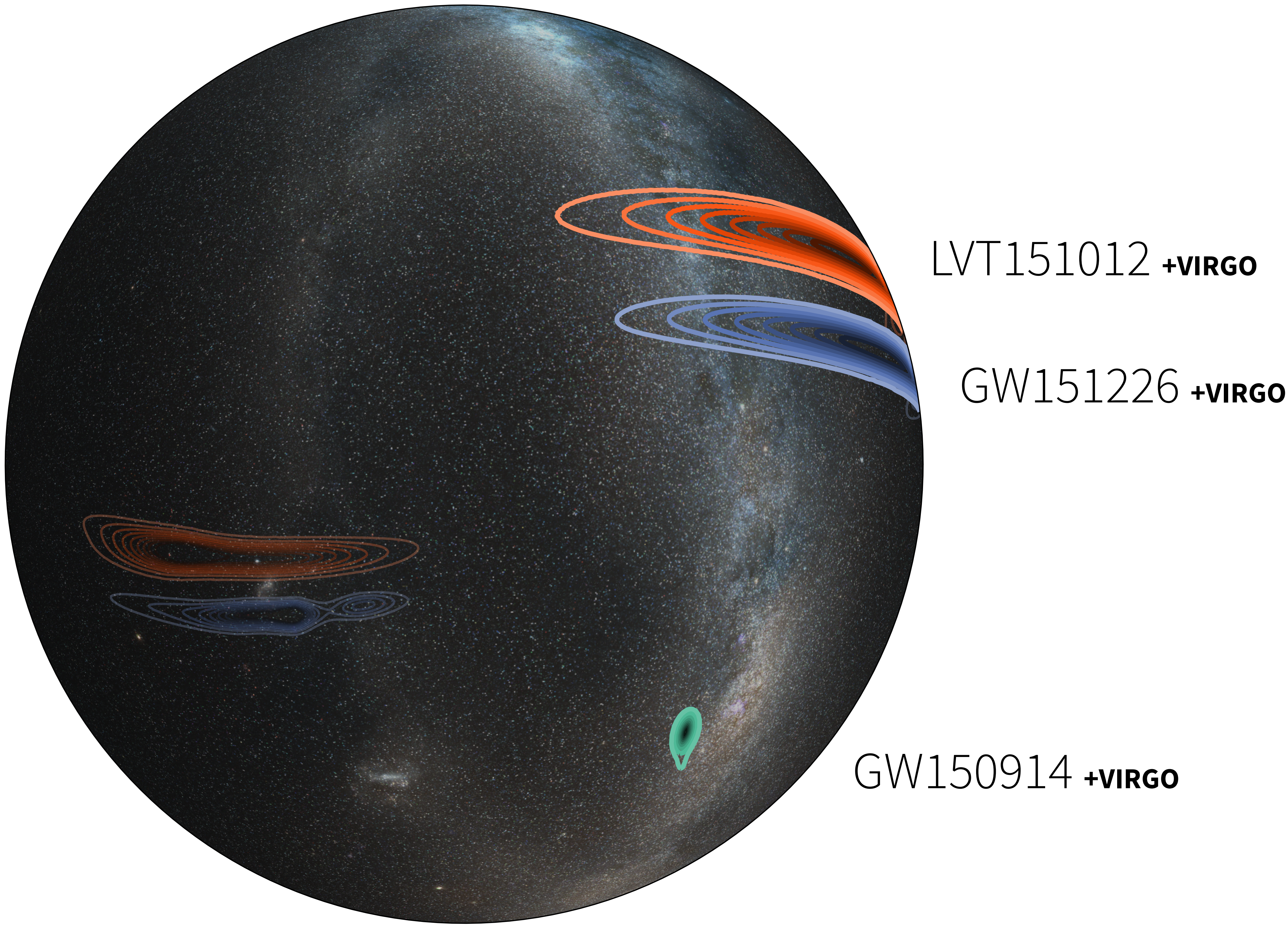


image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)

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

	CBC	Burst
...	...	
What	GraceDB ID: *{G,M}nnnnnn*	
...	...	
PROPOSED Search-specific parameters (Initial, Update)	Distance: *a posteriori* mean luminosity distance in Mpc	N/A
	DistanceError: *a posteriori* 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)	
...	...	

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)

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

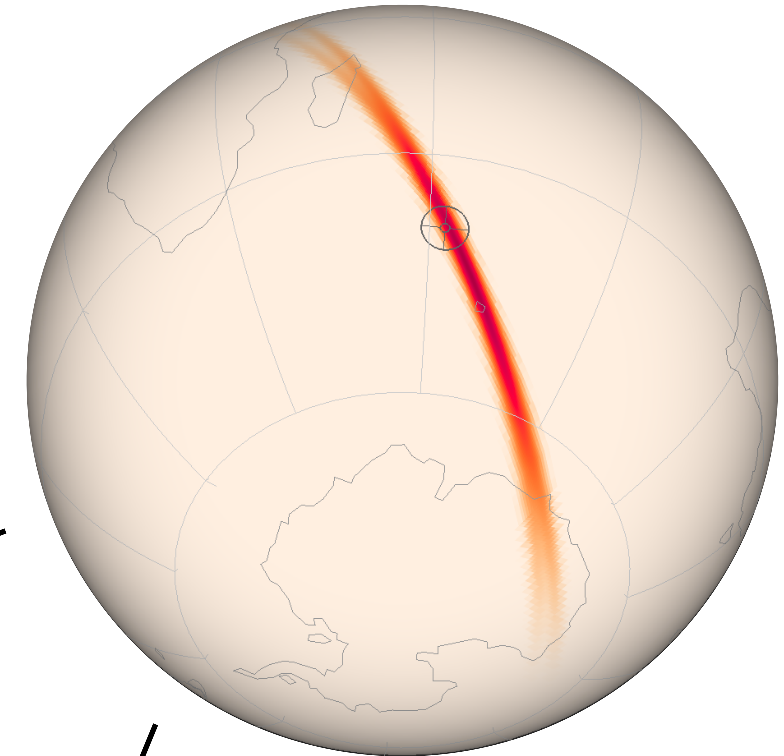
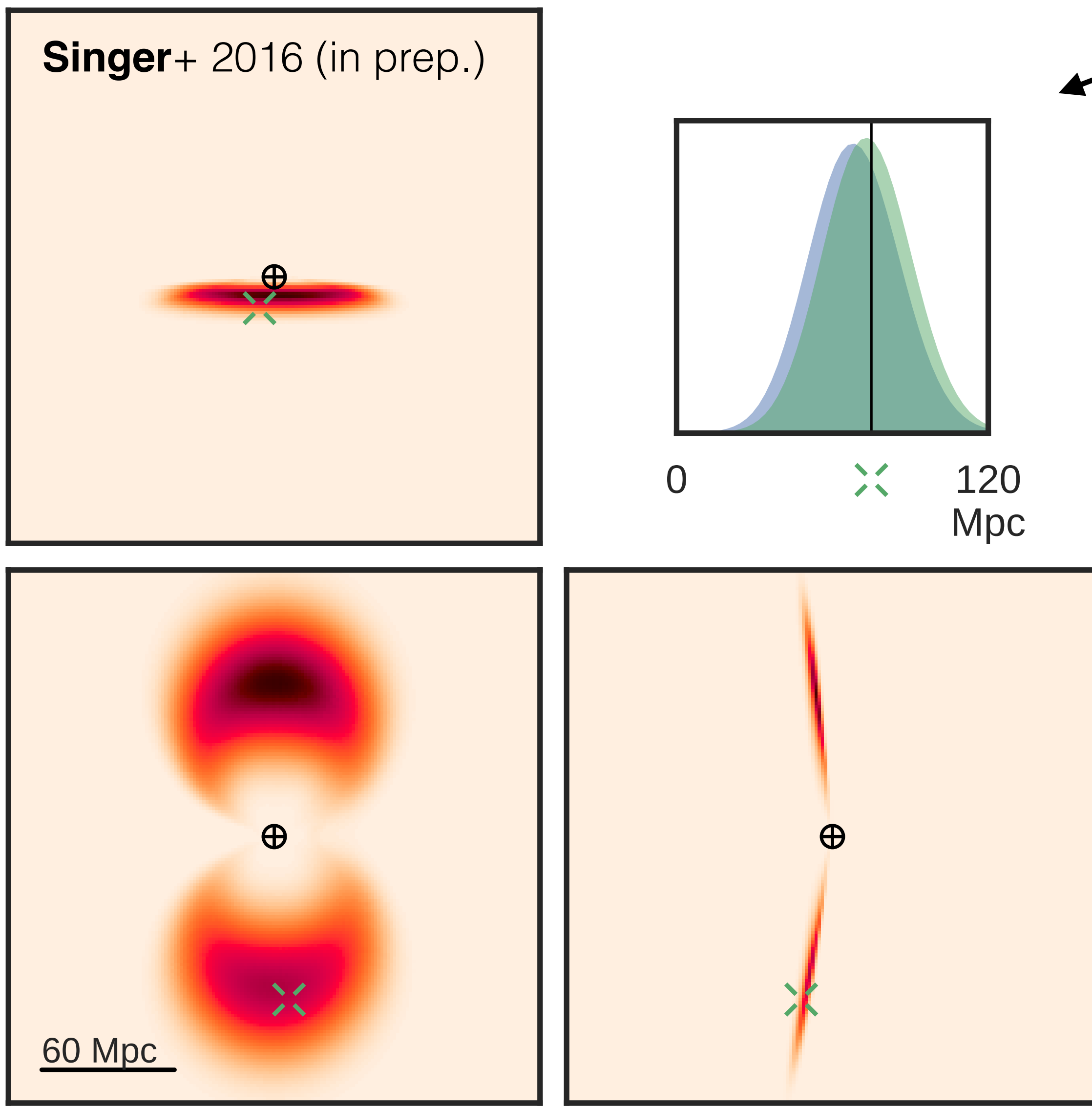
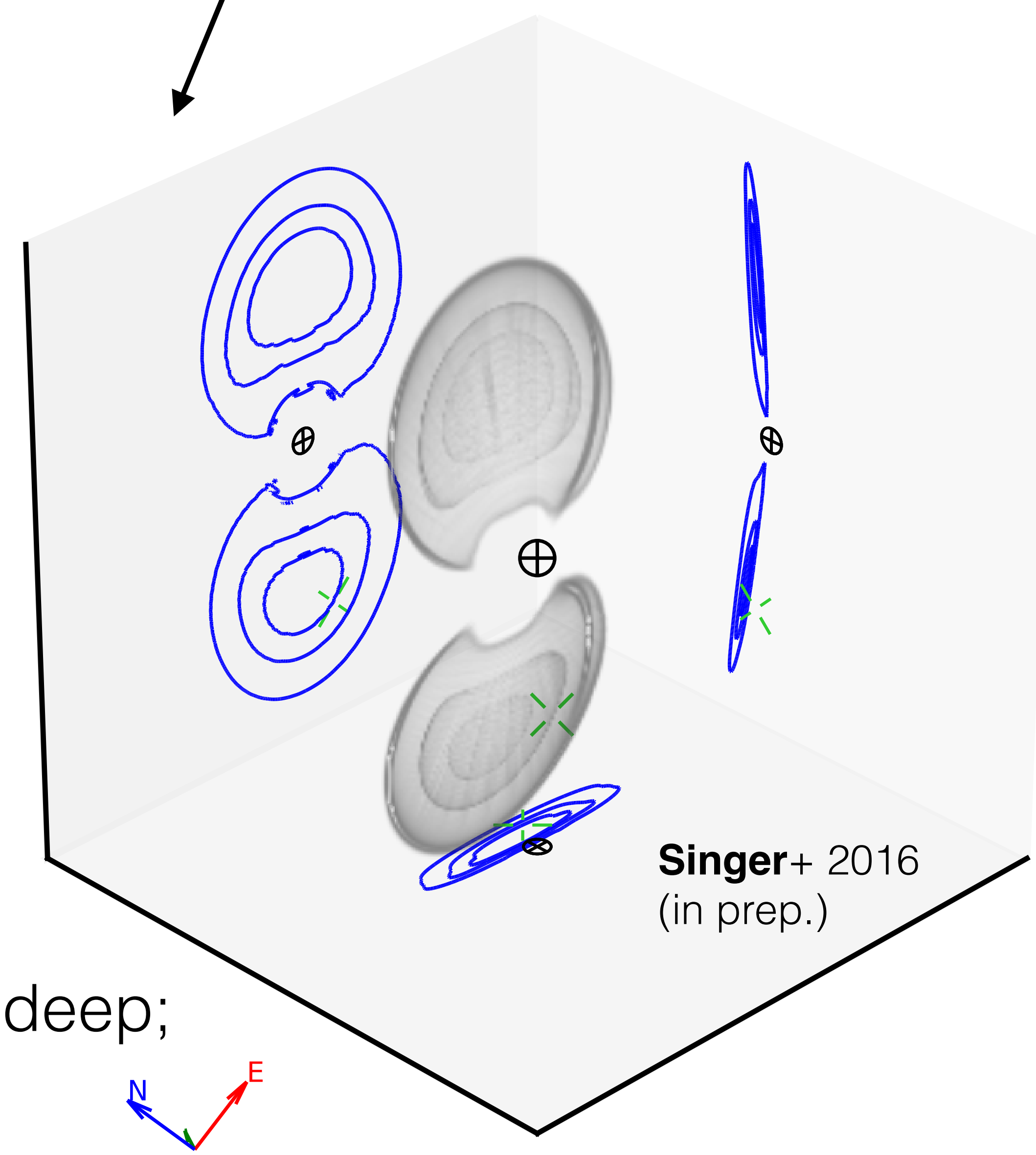


image: “First Two Years”

http://ligo.org/scientists/first2years

Singer+ 2014
Berry+ 2015

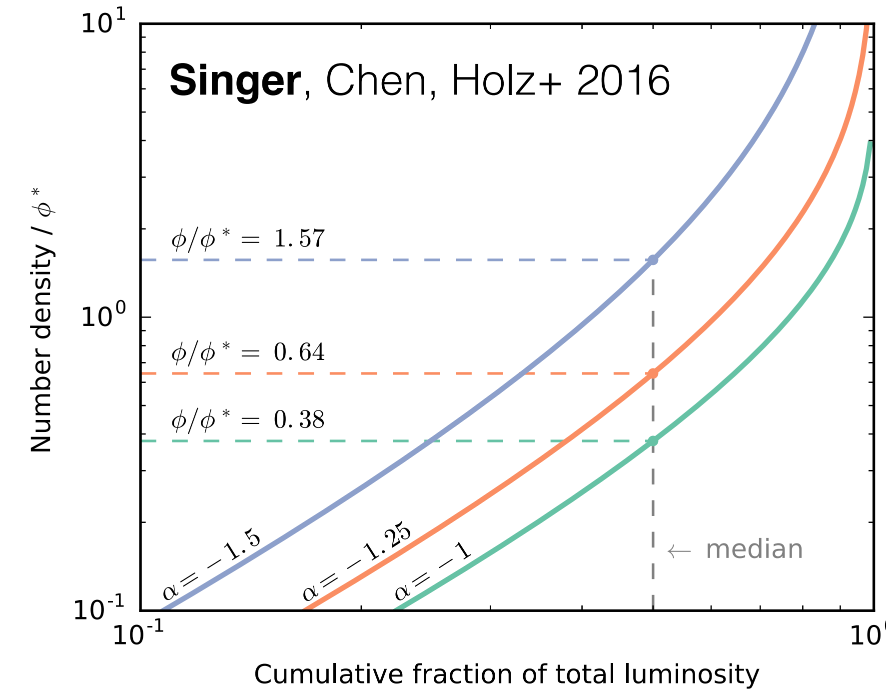


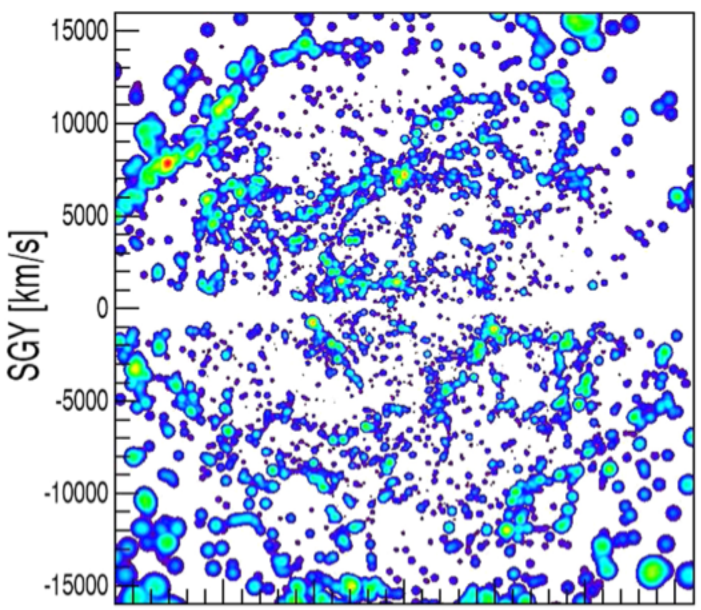


Double arcs become two **petals**:
~1° wide, **10-100°** in breadth, **~100 Mpc** deep;
Volume **~30×10³ Mpc³**

Singer, Chen, Holz+ 2016 (arXiv:1603.07333, ApJL)

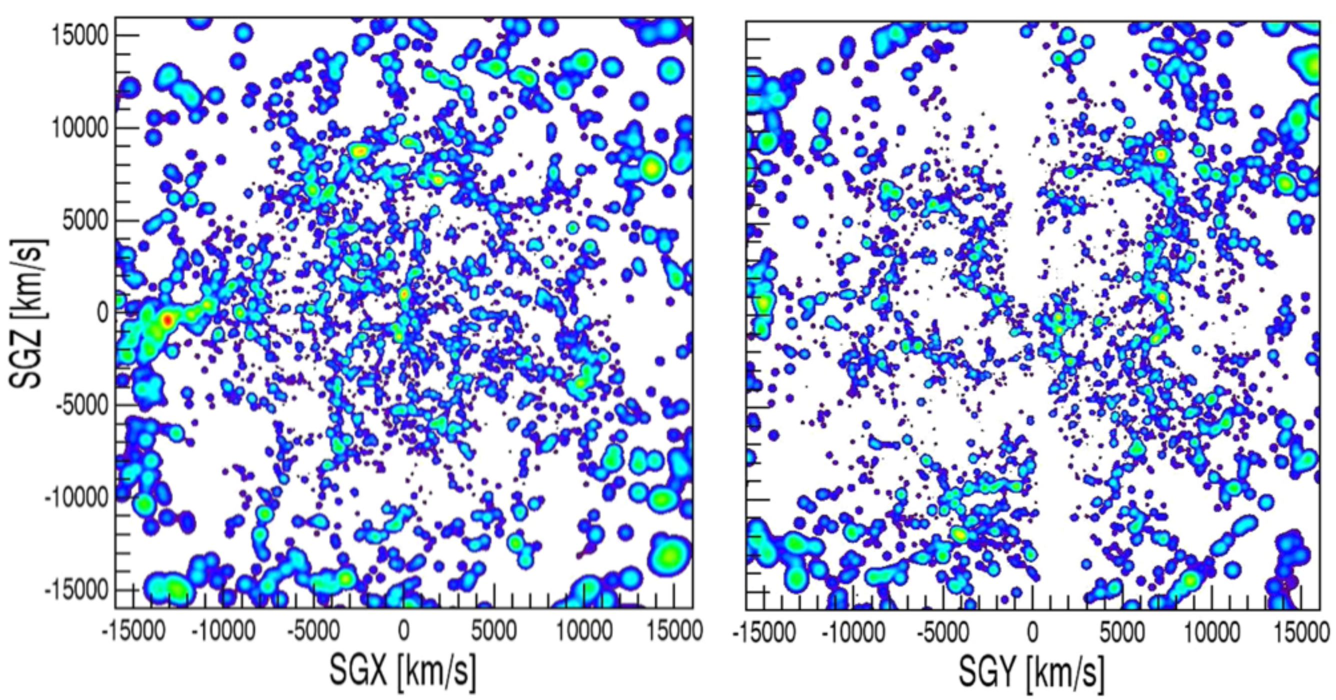
COSMOGRAPHY for **fun and profit**

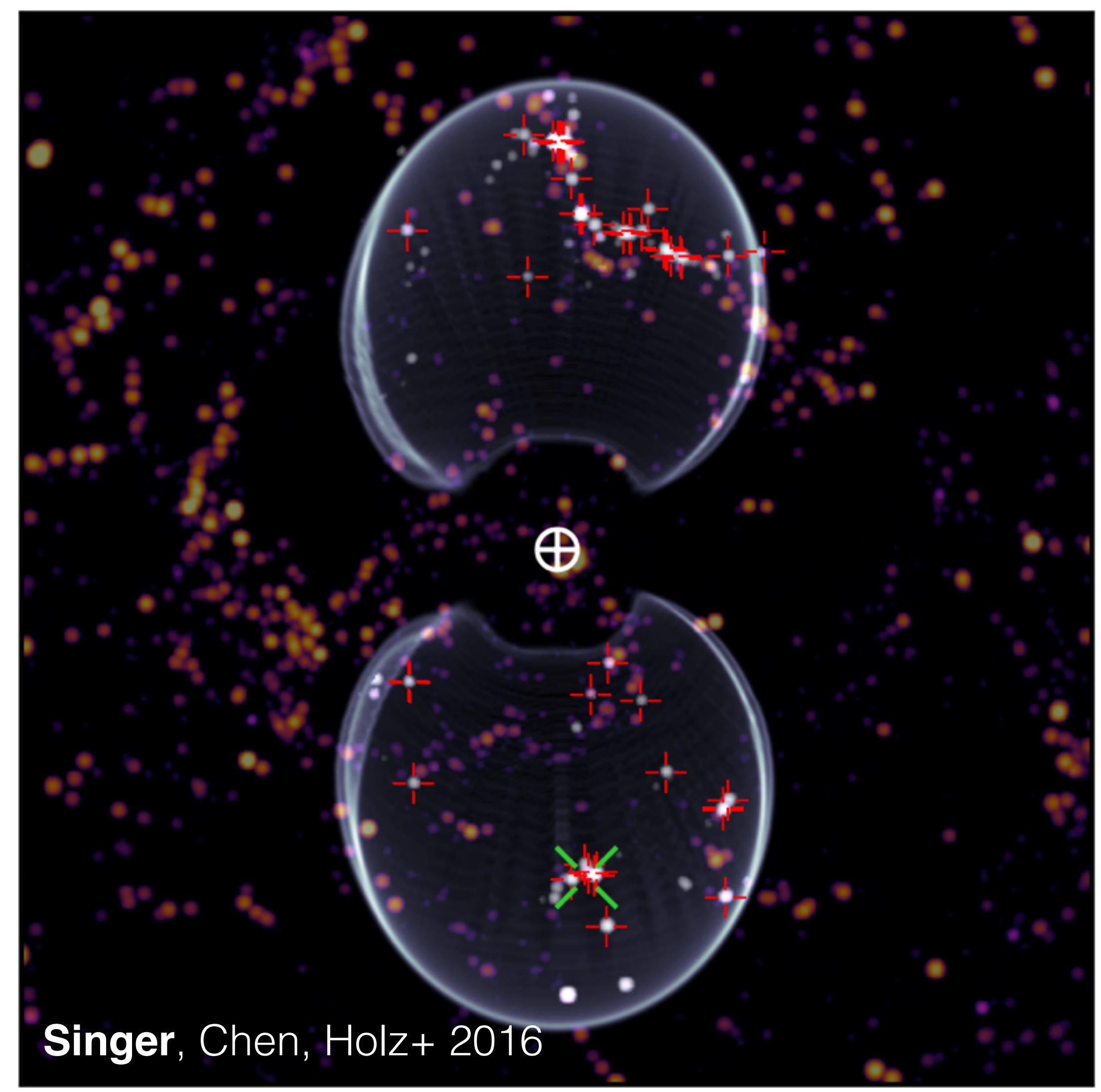




Combine GW parameter estimation with map of local luminosity density

Example: <u>Tully 2015</u> galaxy group map based on 2MASS Redshift Survey



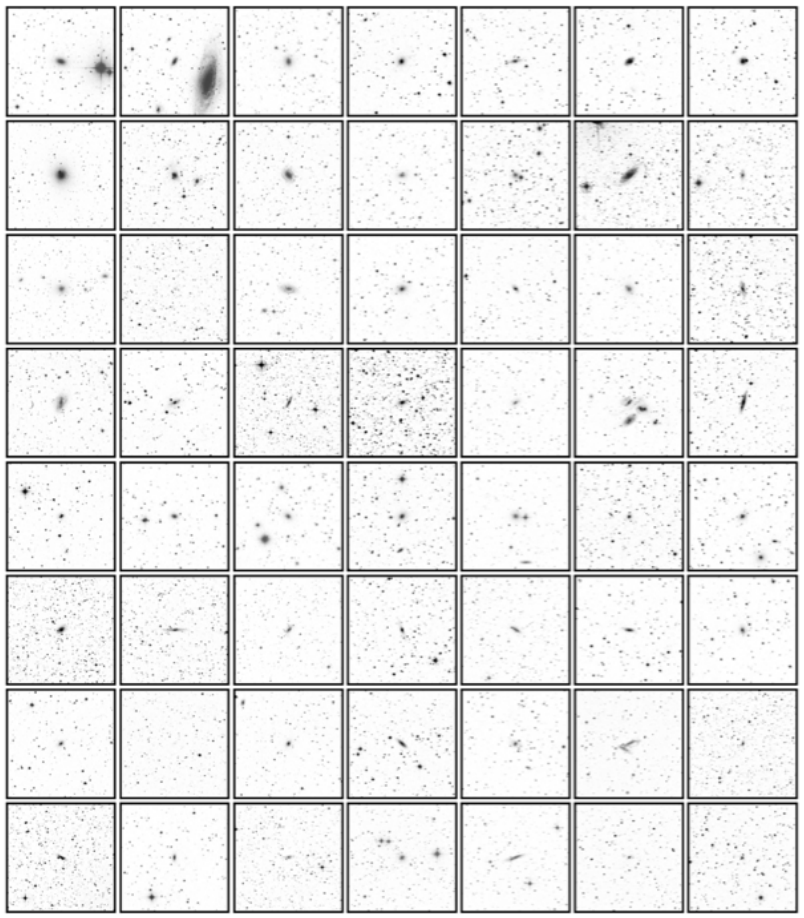


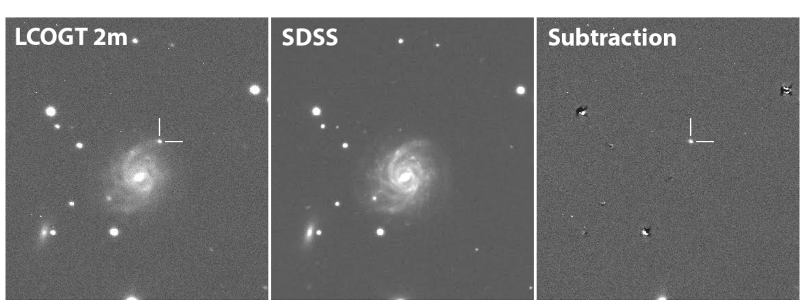
Singer, Chen, Holz+ 2016 (arXiv:1603.07333, ApJL)

GOING THE DISTANCE

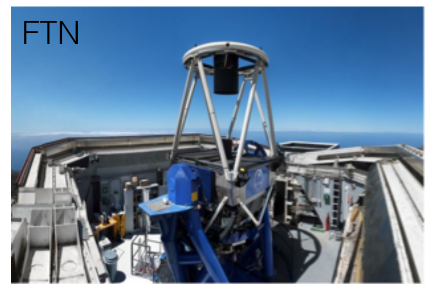
Targeted O/IR kilonova search

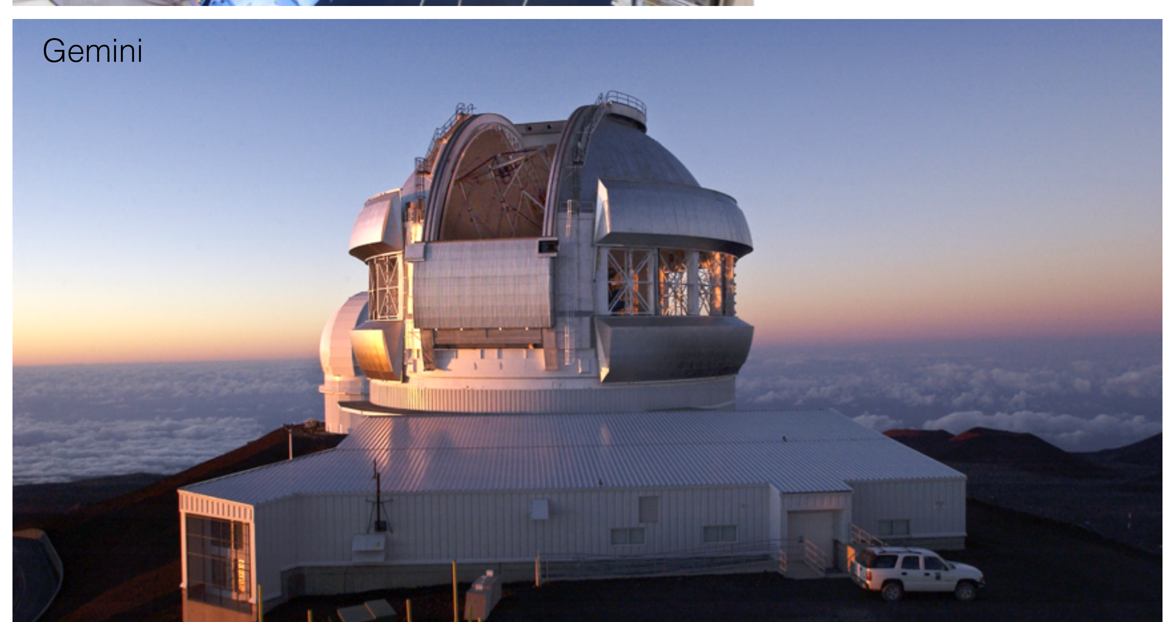
red=accepted
orange=proposed





"Searching for Optical Counterparts to Gravitational Wave Sources" LCOGT 2016A (Arcavi, Howell, Valenti, **Singer** ....)

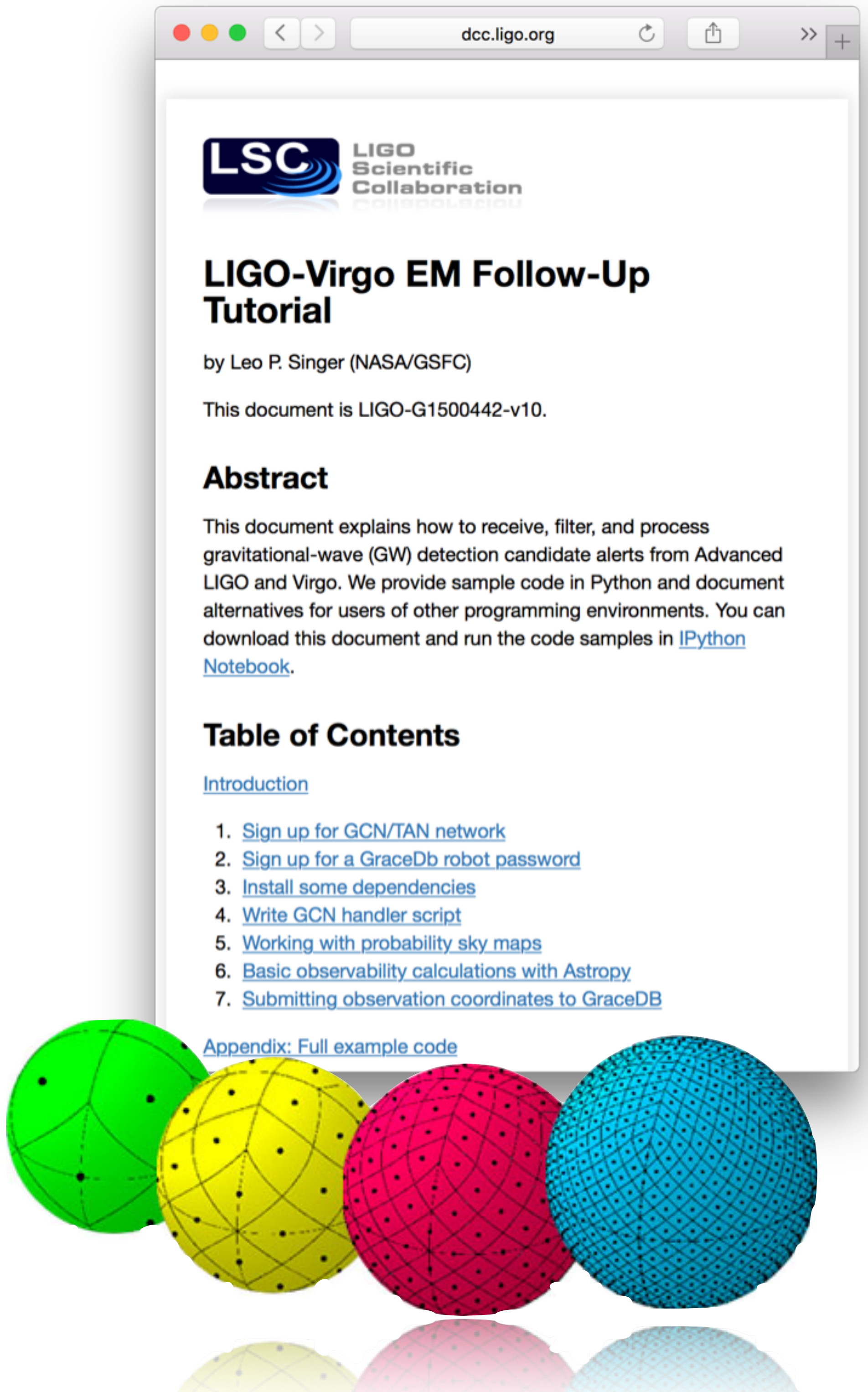


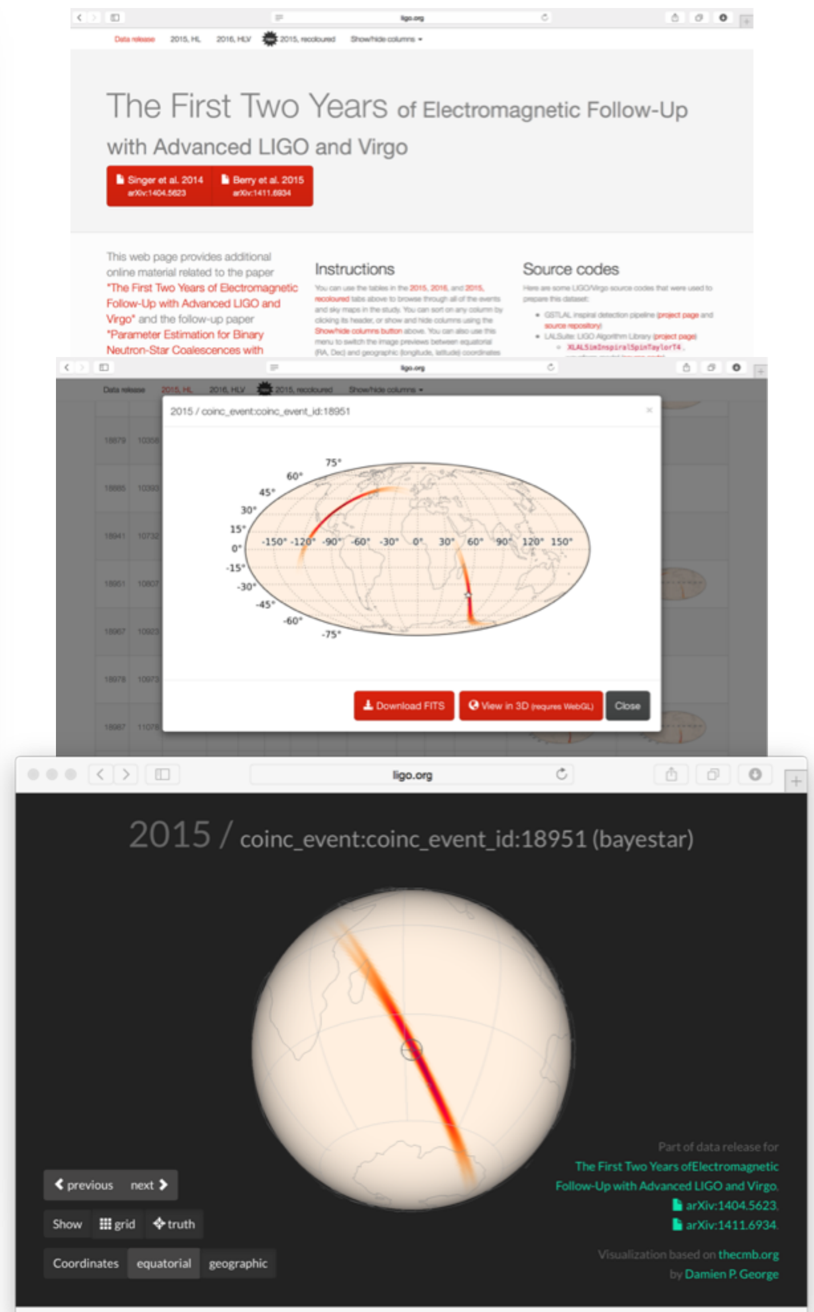


Ideal facilities:

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**





Singer+ 2014 (arXiv:1404.5623)
Berry+ 2015 (arXiv:1411.6934)
Essick+ 2015 (arXiv:1409.2435)
LVC+ 2016 (arXiv: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+broadband EM observations**


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/