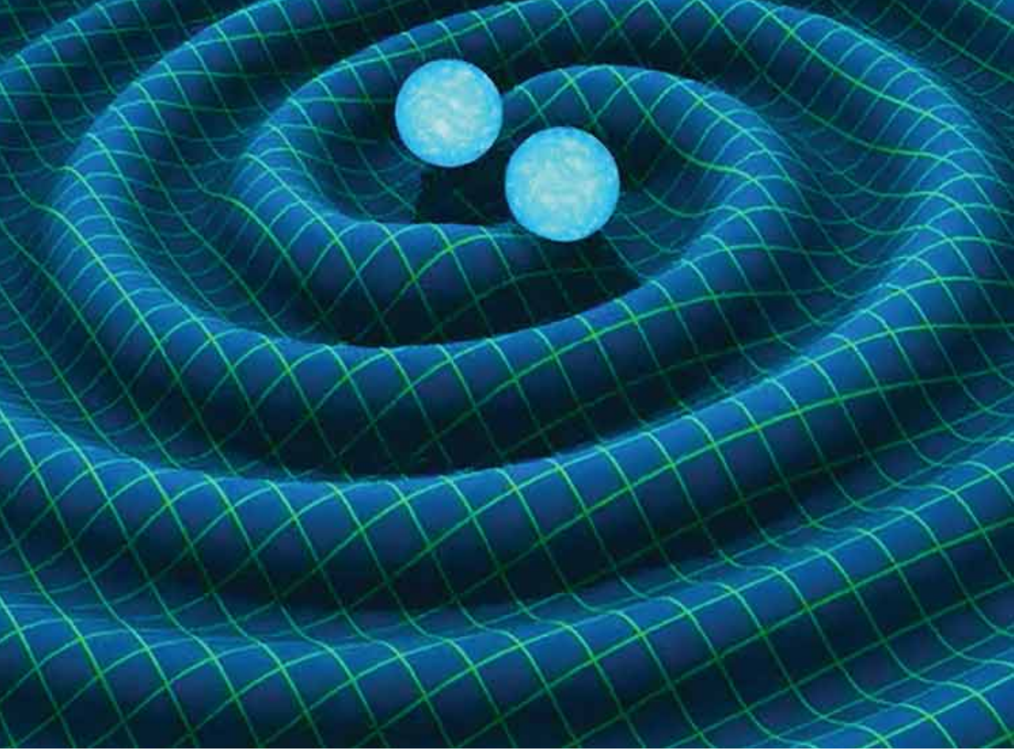
LEO P. SINGER Research Astrophysicist
NASA Goddard Space Flight Center leo.p.singer@nasa.gov

ADVANCED LIGO

ELECTROMAGNETIC FOLLOW-UP IN THE LIGO-INDIA ERA



2017 MAY 19
29TH METING OF THE INDIAN ASSOCIATION FOR GRAVITY AND GENERAL RELATIVITY

INDIAN INSTITUTE OF TECHNOLOGY, GUWAHATI


t = 0.2270 ms
10^{12} g/cm^3
10^{11} g/cm^3
10^{10} g/cm^3
10^{9} g/cm^3

THROWING MATTER INTO THE MIX:

EM signatures of neutron star mergers

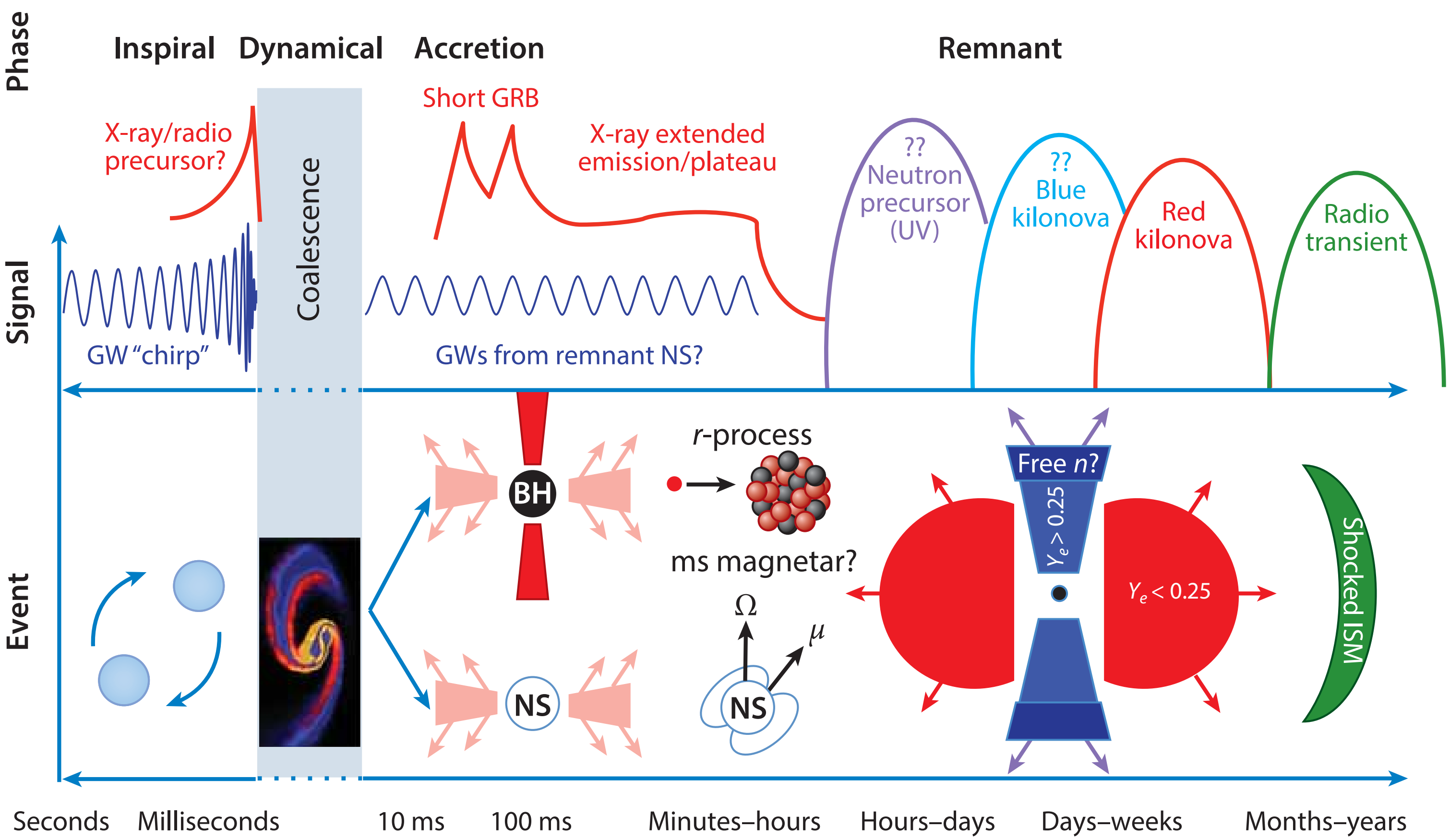
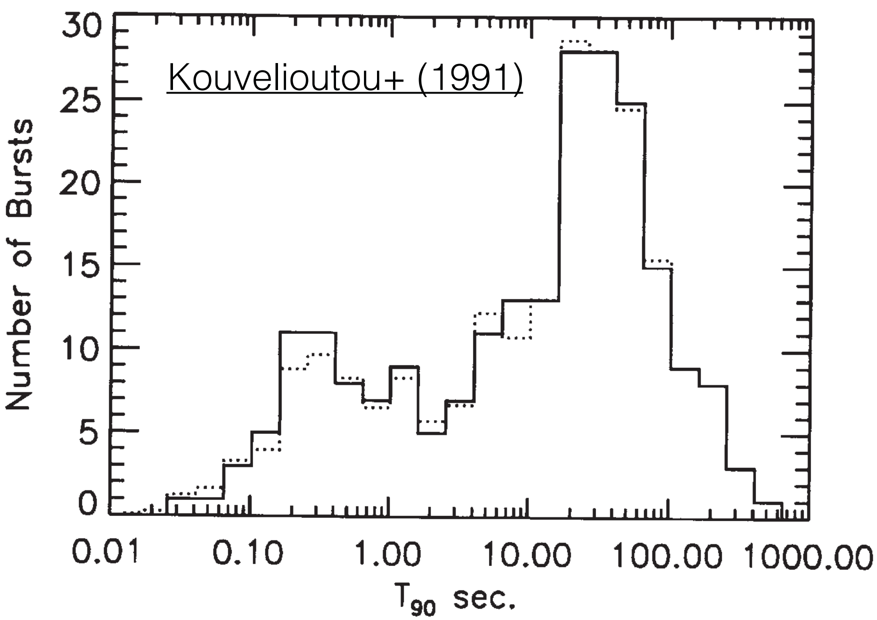
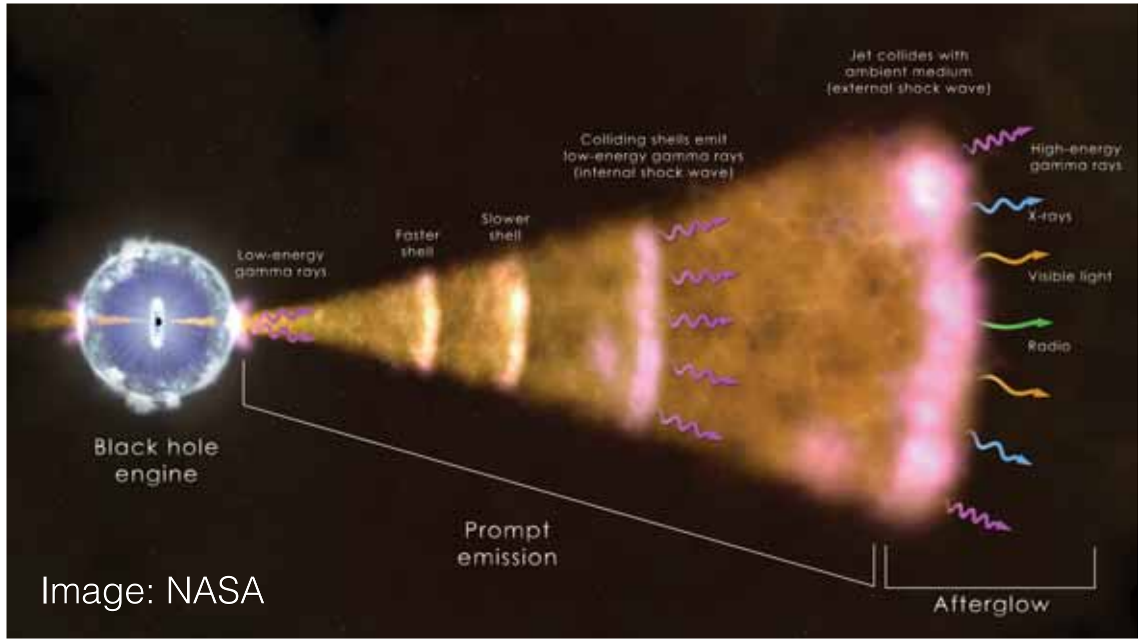


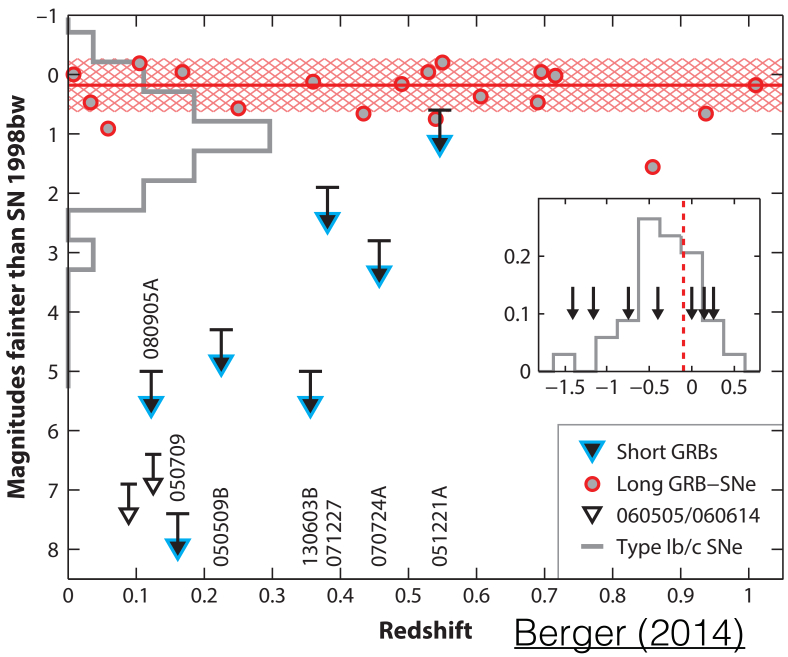
image: Fernández & Metzger 2016

- Resonant shattering of NS crust → gamma, X-ray 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

GAMMA-RAY BURSTS
relativistic explosions and their afterglows

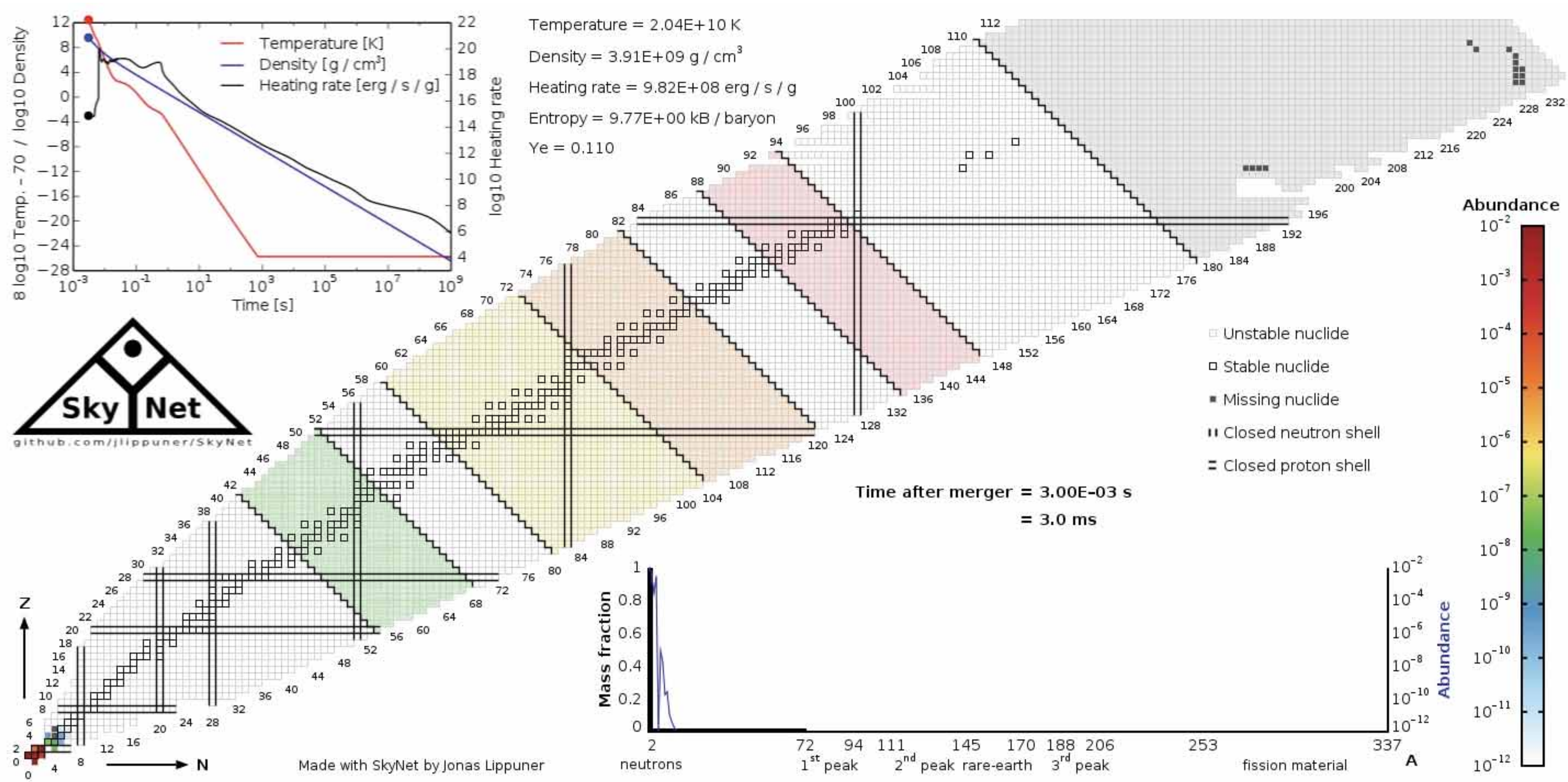






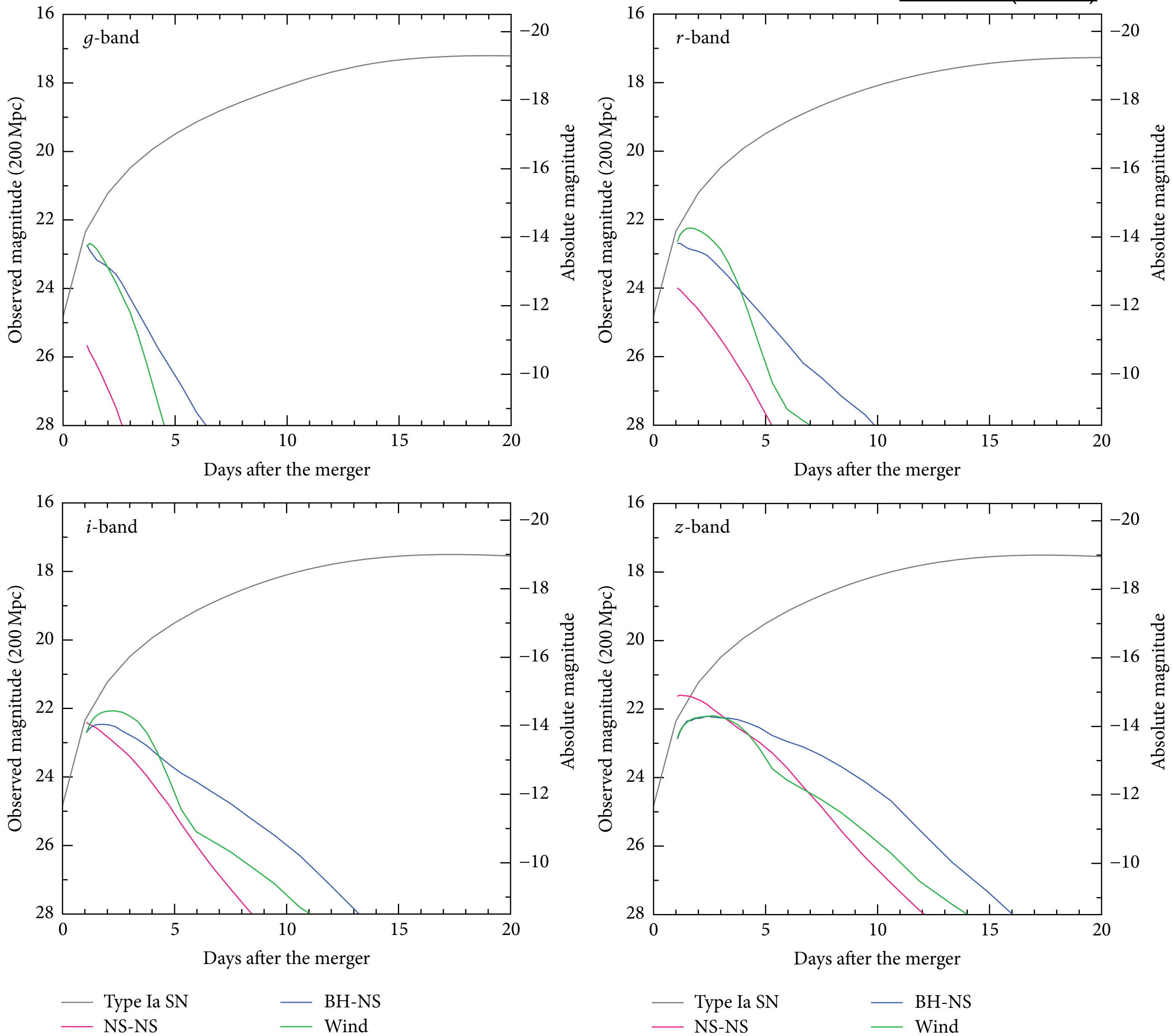
- **Long/soft** versus **short/hard** population
- **ALL** long GRBs co-occur with broad-line Type Ic supernovae; **short GRBs do not**
- Long GRBs usually occur in highly star-forming galaxies; short GRBs occur near both star-forming galaxies and ellipticals
- Long GRBs are powered by the **collapse of massive, rapidly rotating stars**
- Hypothesis: short GRBs are powered by **neutron star binary mergers**

R-PROCESS NUCLEOSYNTHESIS:
a parable on the interconnectedness of science



FAST, RED, FAINT

Tanaka (2016)



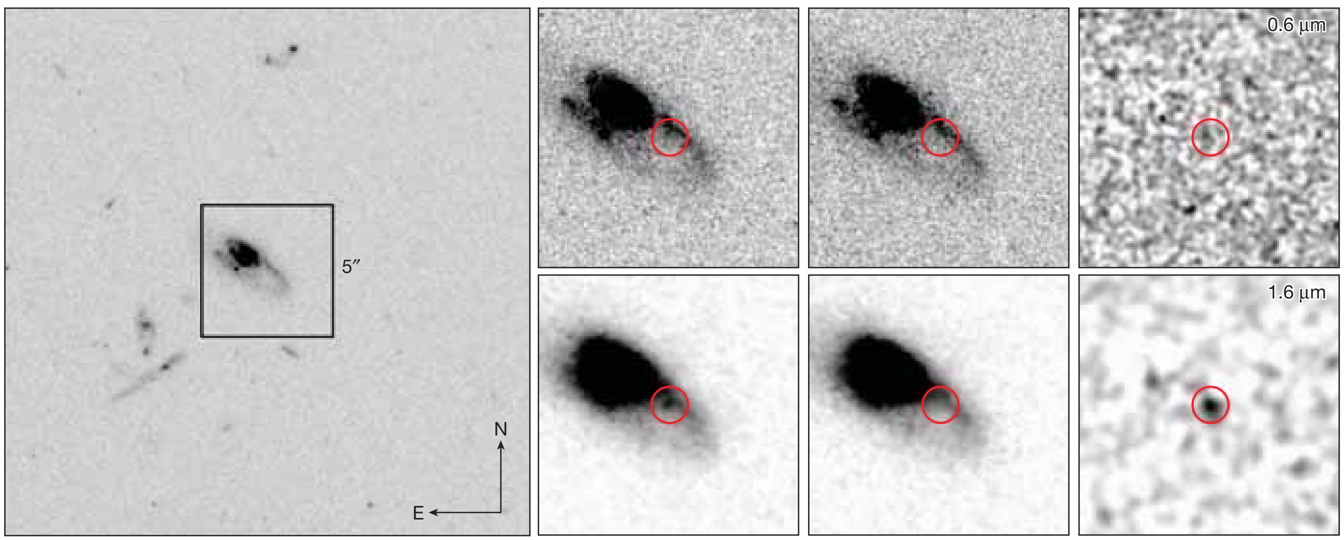
The first ever observation of a kilonova?

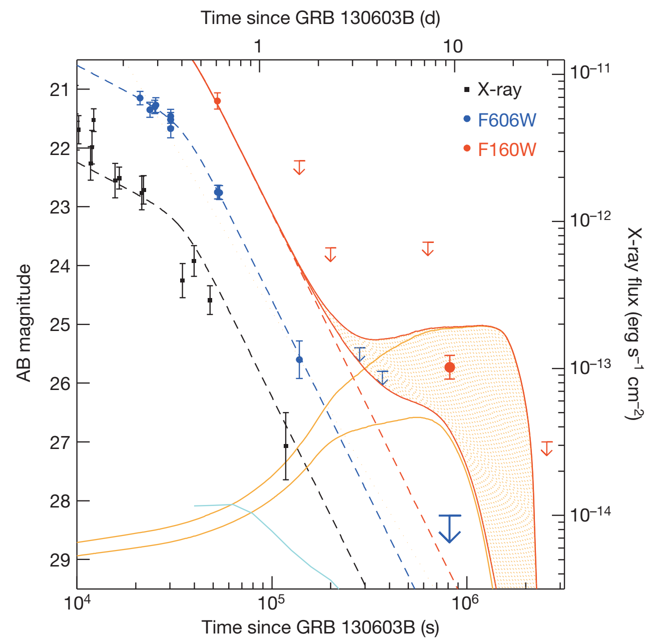
LETTER

doi:10.1038/nature12505

A ‘kilonova’ associated with the short-duration γ-ray burst GRB 130603B

N. R. Tanvir[1], A. J. Levan[2], A. S. Fruchter[3], J. Hjorth[4], R. A. Hounsell[3], K. Wiersema[1] & R. L. Tunnicliffe[2]

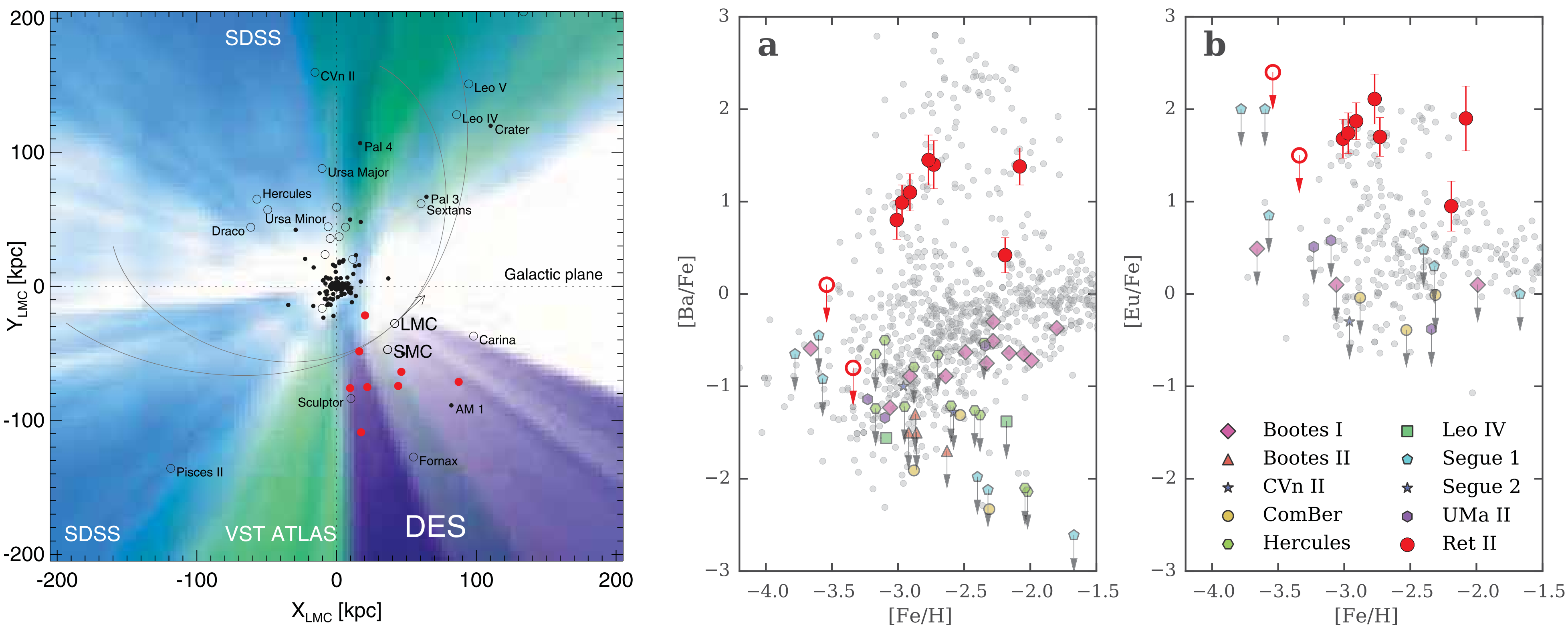




“Bling nova:” kilonovae in neutron star mergers may be important sites for the production of heavy *r*-process elements with *A*>140 (Goriely+ 2011, Wanajo+ 2014, etc.)

DIGGING UP FOSSILS OF NEUTRON STAR MERGERS **in our own backyard**

Ji+ 2016

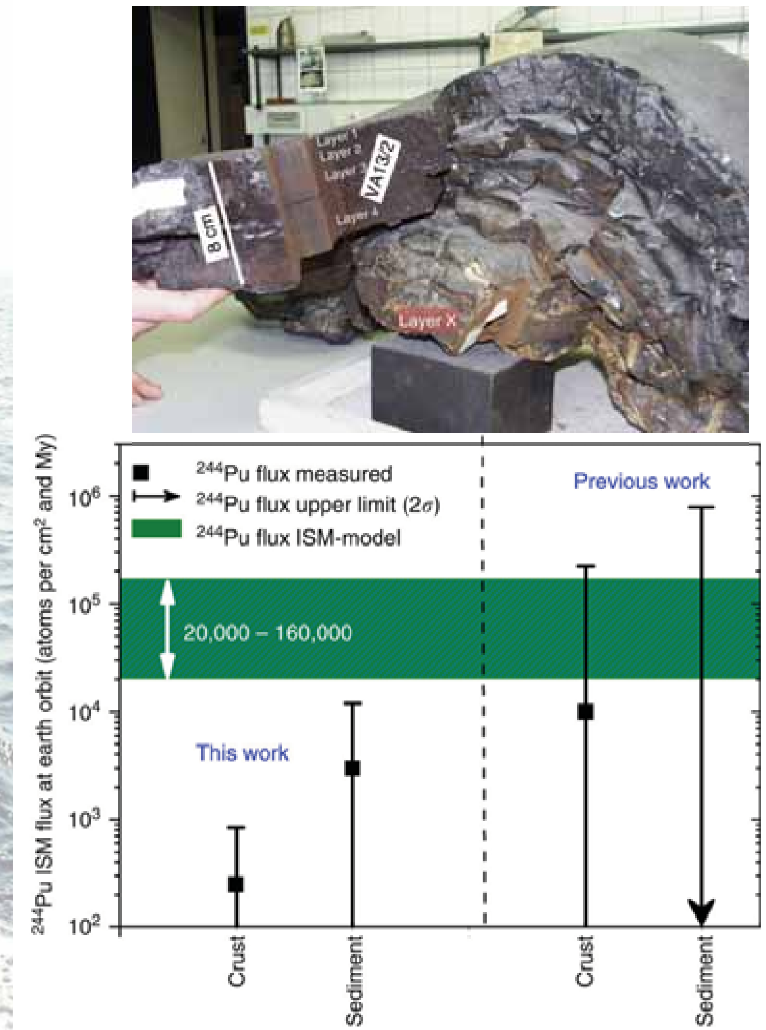


Ultra-faint dwarf galaxy Reticulum II discovered by Dark Energy Survey, has 2–3 orders of magnitude higher abundances of *r*-process elements than other MW satellites → evidence for ***a single r-process enrichment event***

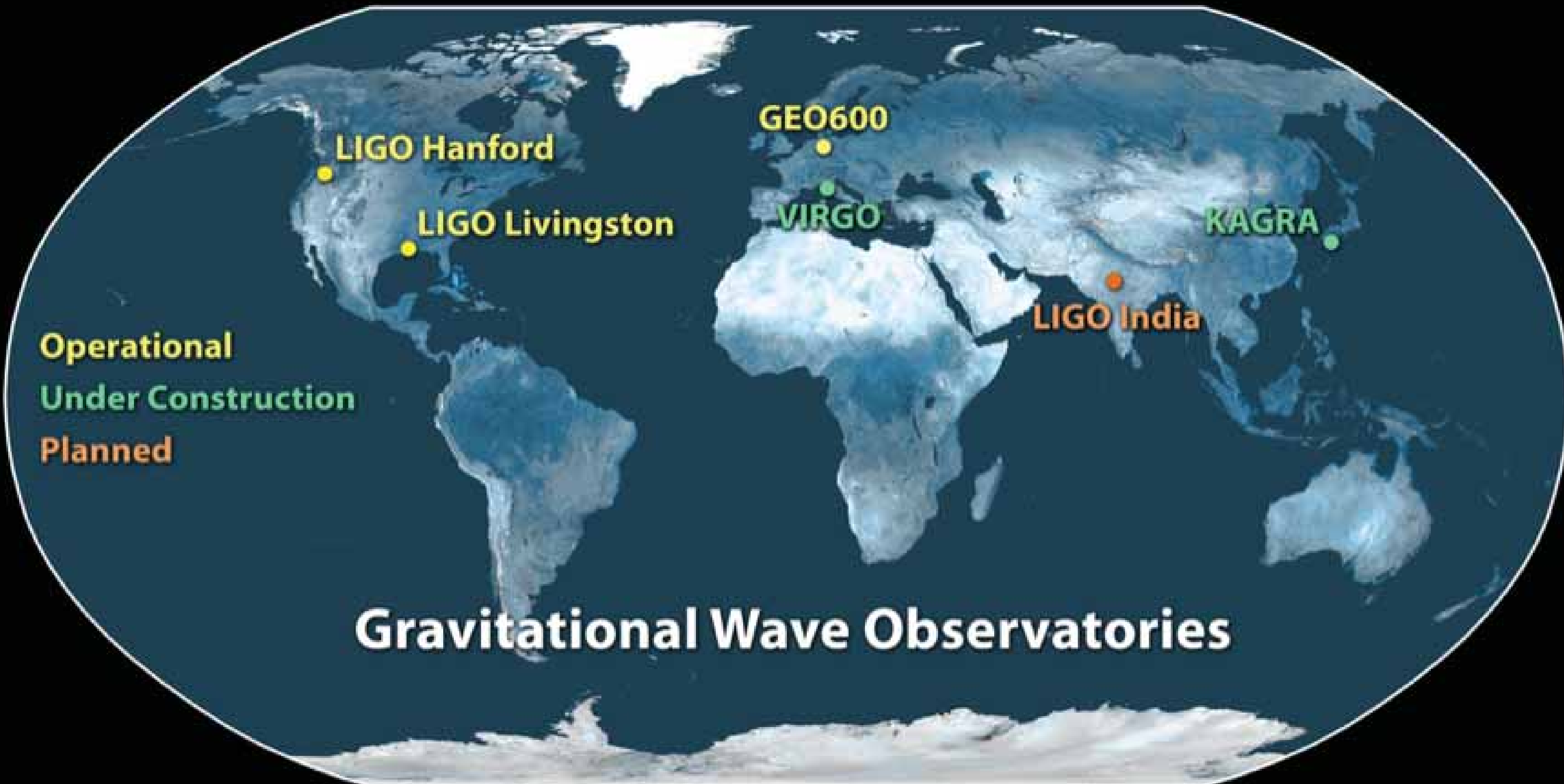
TO FIND NEUTRON STAR MERGERS, **look no further than the sea**

- Concentration of ^{244}**Pu** in deep-sea sedimentary rock
- Half-life = 85 My, so no active contribution from solar system
- Lower concentration than expected for r-process dominated by supernovae (Wallner+ 2015)
- Low-rate, high-yield process preferred over high-rate, low-yield process → **NS binaries** (Hotokezaka+ 2015)

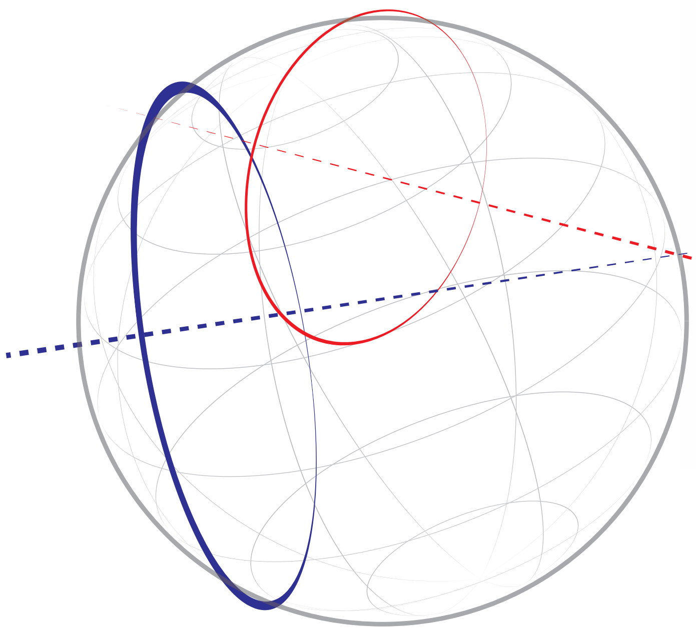
Wallner+ 2015

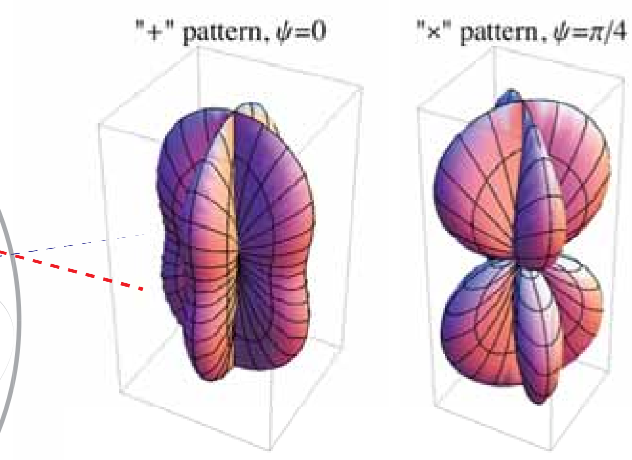


A GLOBAL NETWORK
of gravitational wave observatories



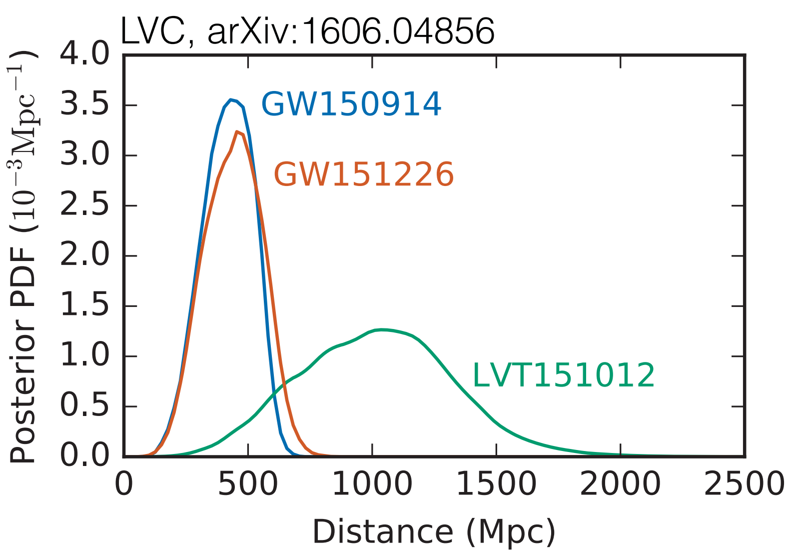
SKY LOCATION AND DISTANCE:
a phased array of gravitational antennas

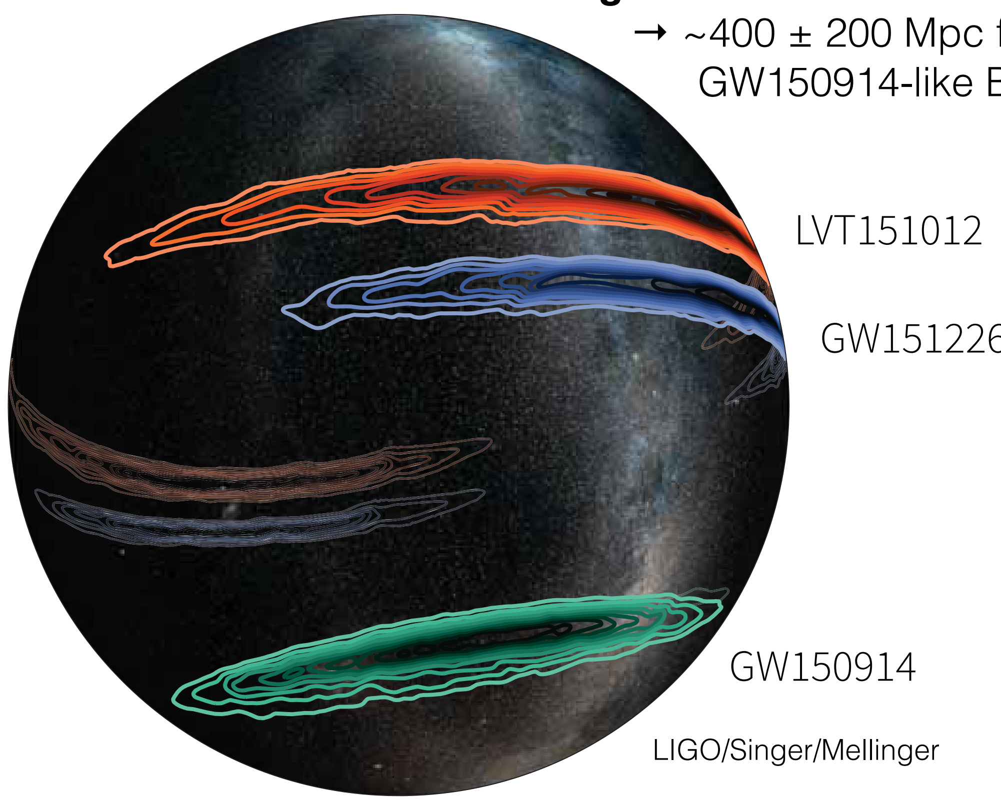




- **Sky location** inferred from triangulation of times, phases, and amplitudes on arrival → bimodal rings of100–1000 of deg^2 with only 2 detectors

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



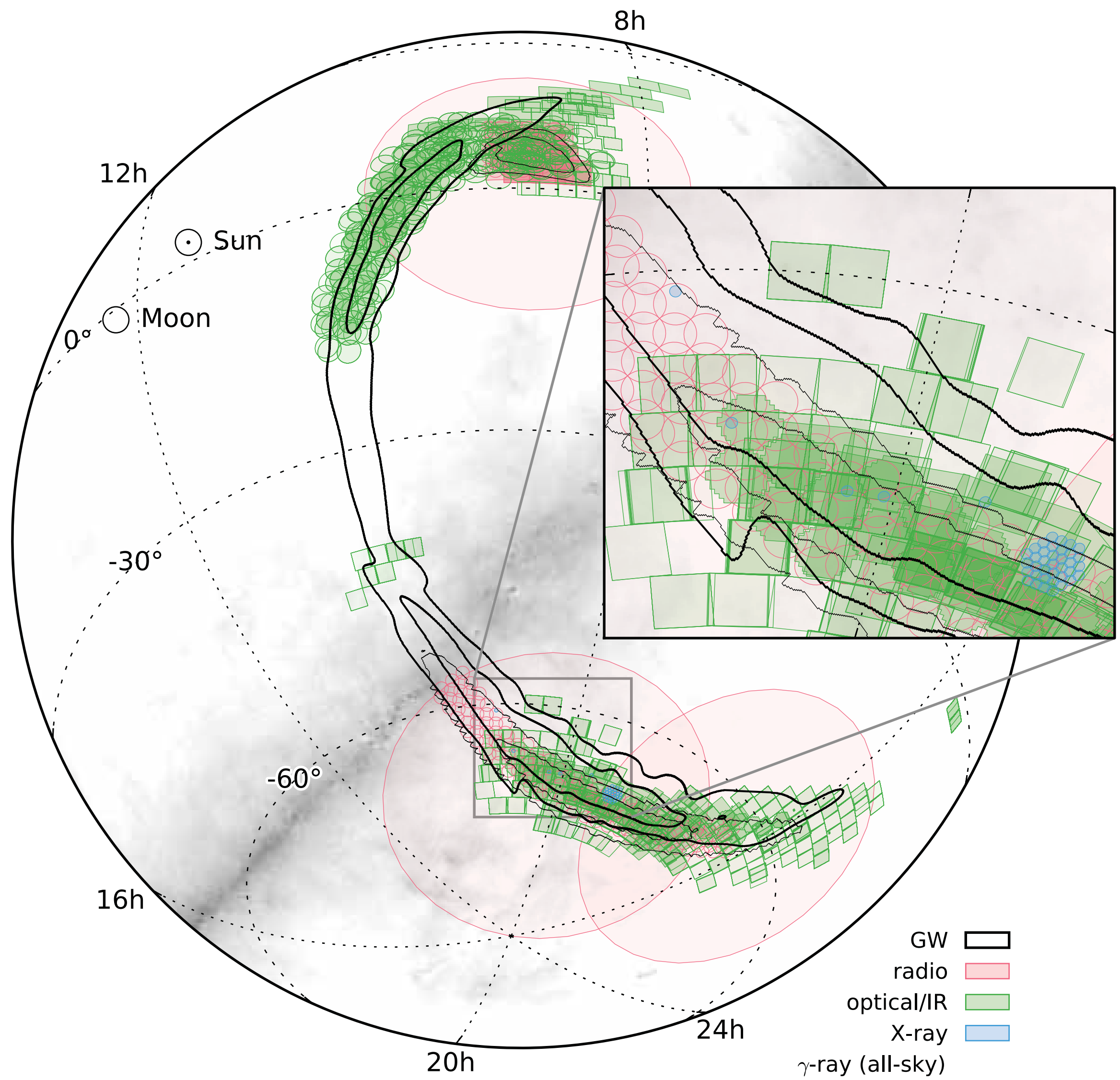


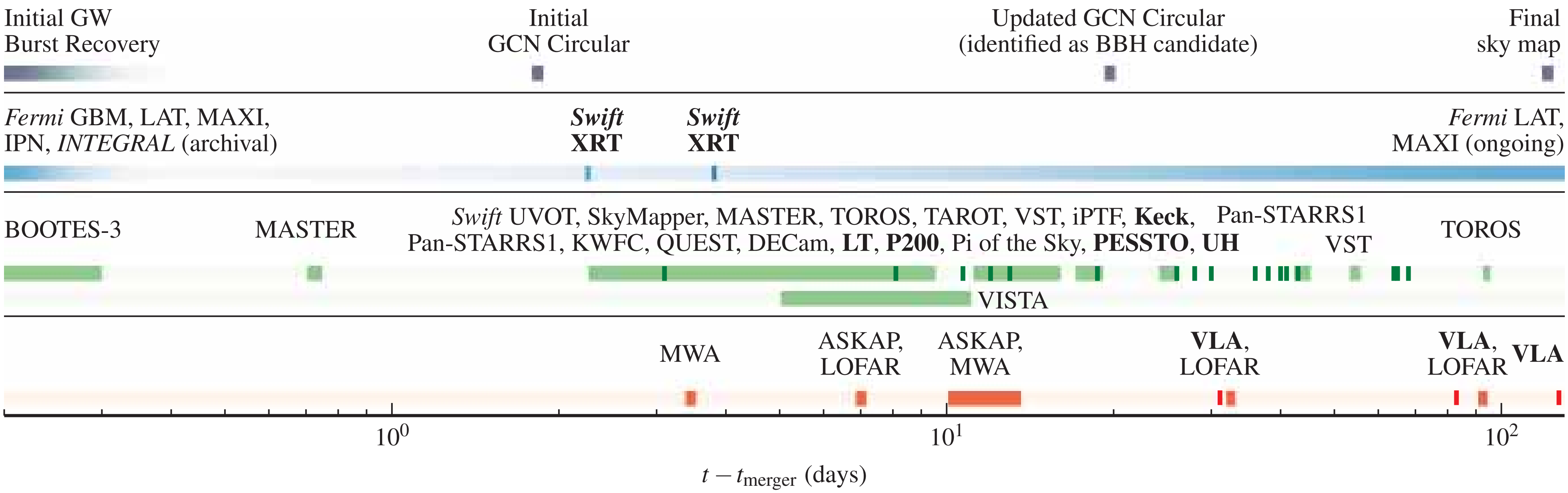
LIGO/Singer/Mellinger

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!*

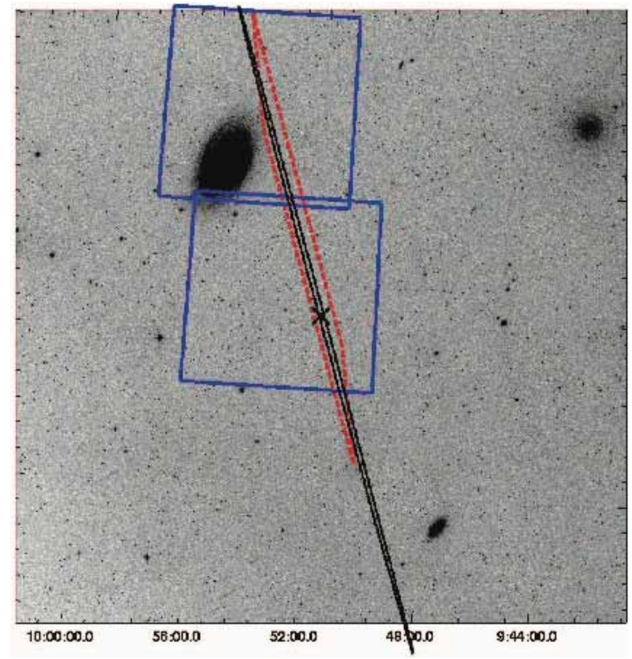
ASKAP, LOFAR, MWA, Fermi/GBM, Fermi/LAT, INTEGRAL, IPN, Swift, MAXI, BOOTES, MASTER, Pi of the Sky, DES/DECam, INAF/GRAWITA, iPTF, J-GEM/KWFC, La Silla–QUEST, Liverpool Telescope, PESSTO, Pan-STARRS, SkyMapper, TAROT, Zadko, TOROS, VISTA


Ulysses
Integral
Swift
HETE
XTE
GCN

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



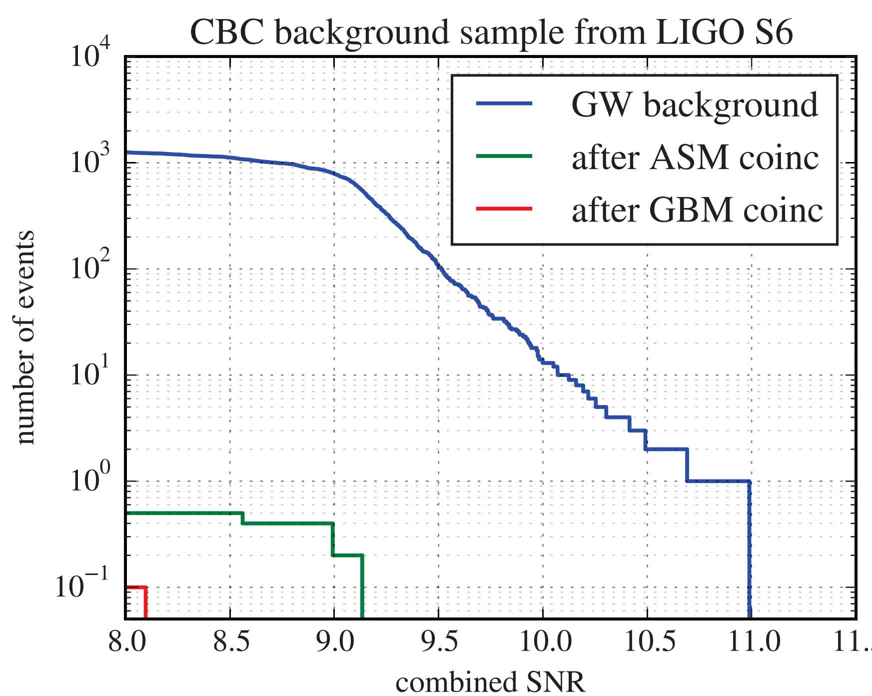


image: Blackburn+ 2015

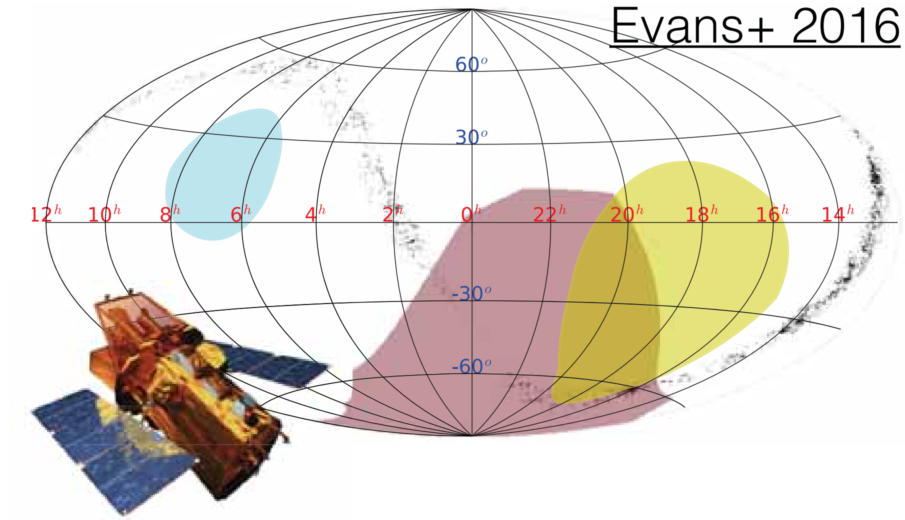
X-RAY FOLLOW-UP

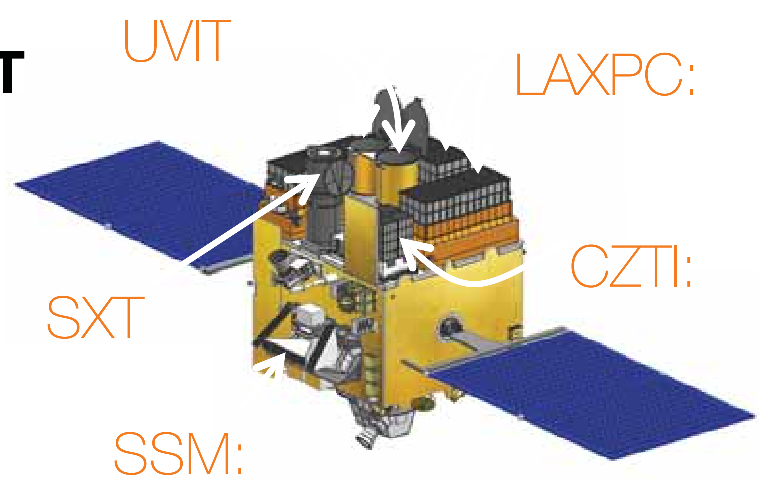
- *Swift* XRT → **new ToO modes**, large tiling patterns, galaxy-targeted searches (Evans, Kenna +2016)

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

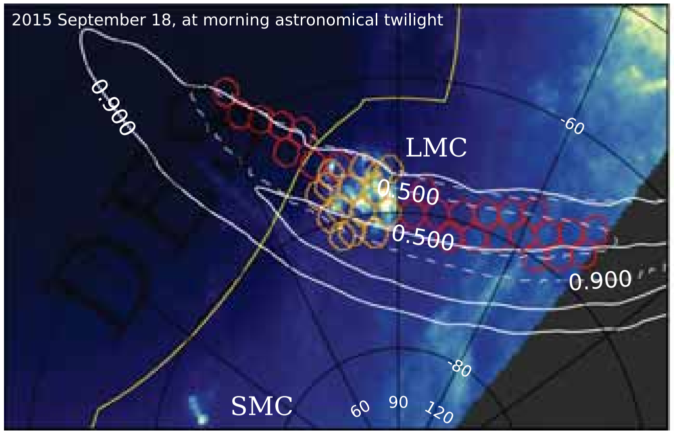
- **CALET** (Adriani+ 2016)

- **AstroSAT**

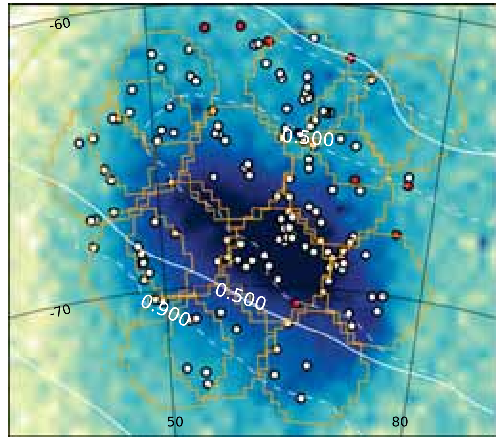




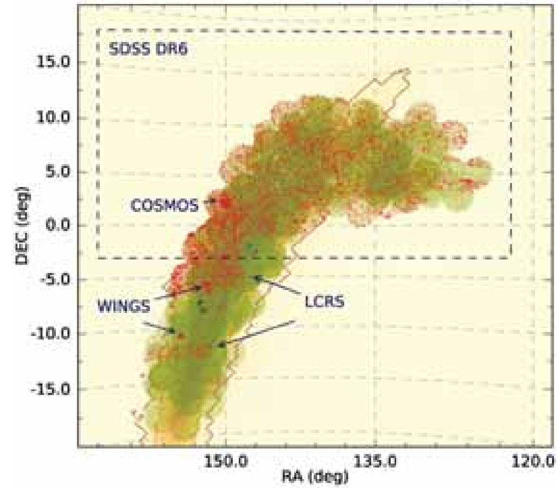
GW FOLLOW-UP WITH **LARGE SYNOPTIC SURVEY INSTRUMENTS**



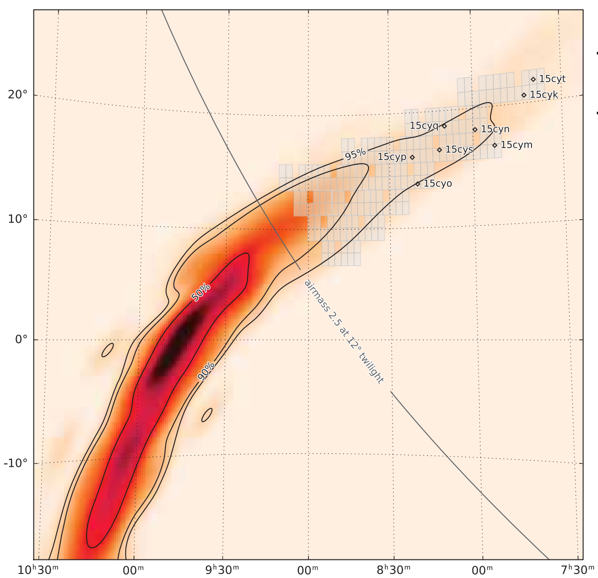
Soares-Santos+ 2016 Deep, wide-field follow-up with DECam to *i*=22.5



Annis+ 2016 DECam search for missing supergiants in LMC

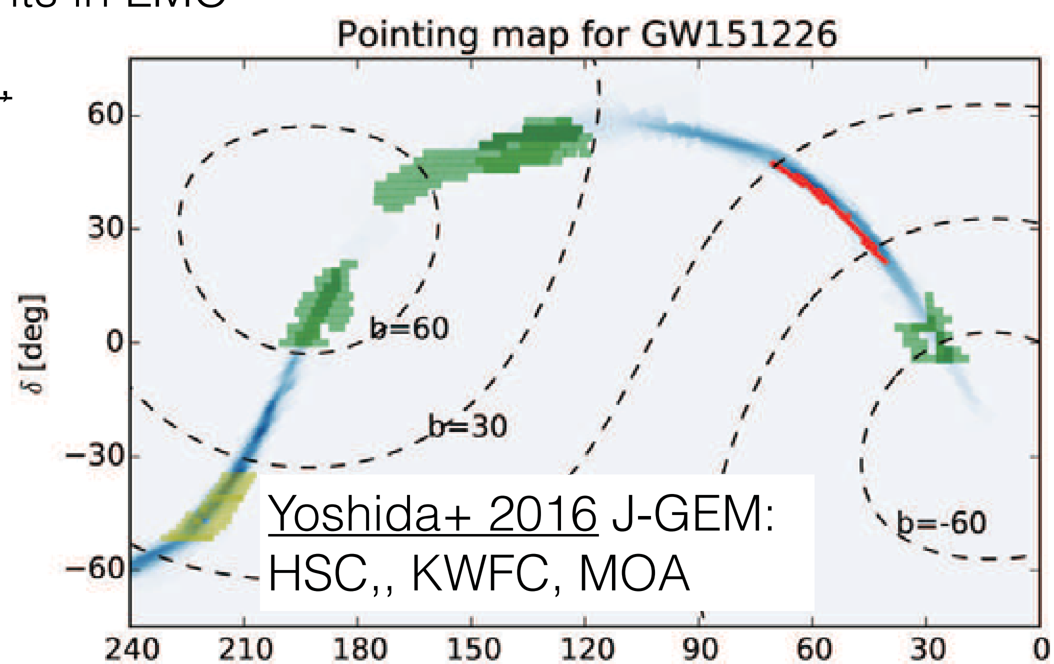


Smartt+ 2016 Pan-STARRS



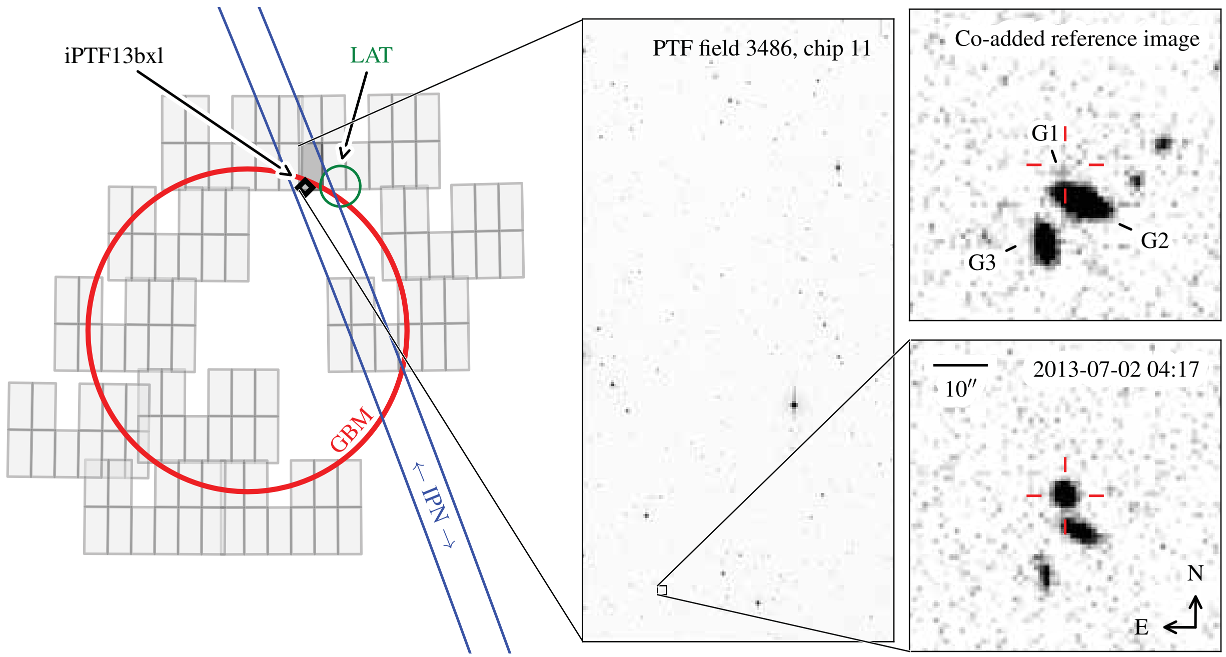
Kasliwal, Cenko, Singer+ 2016

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



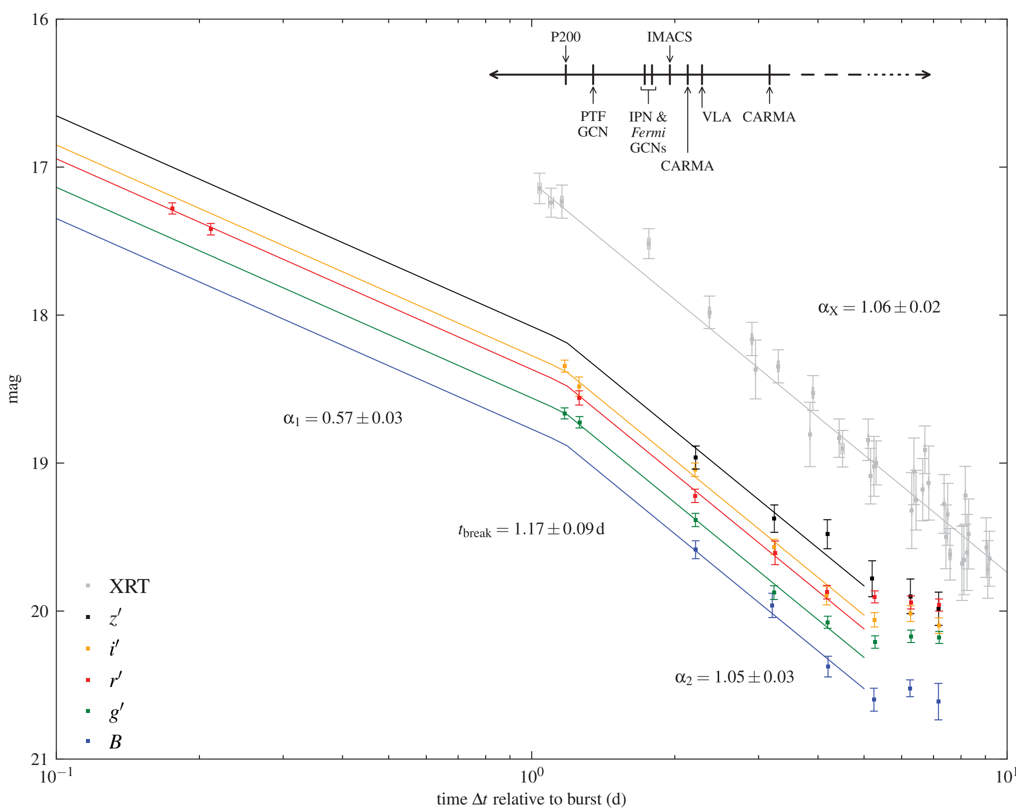
Yoshida+ 2016 J-GEM: HSC,, KWFC, MOA


P60: Followup
P48: Discovery
P200: Classification



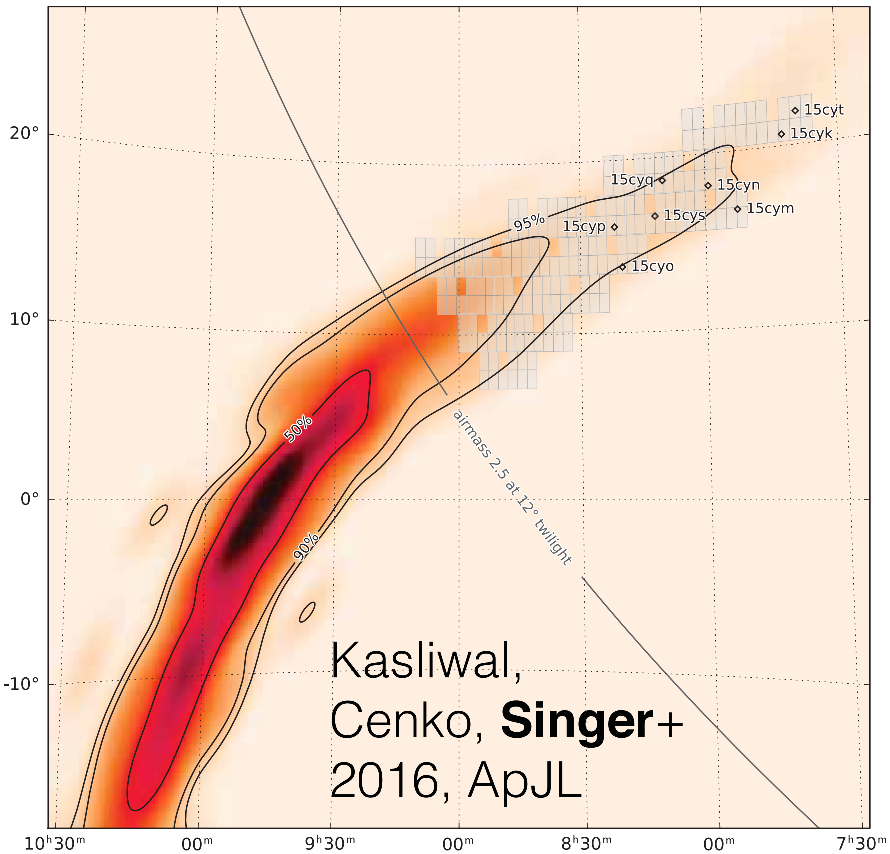
Discovery & redshift of a an optical afterglow in 71 deg²

Singer et al. 2013, ApJL arXiv:1307.5851



- Low redshift: z = 0.145. Energetics bridge gap between “standard” GRBS and llGRBs.
- iPTF13bxl / GRB 130702A = SN 2013dx! Detailed spectroscopy of SN: D’Elia+ 2015, Toy + Cenko (in prep.)
- Detailed afterglow modeling: A. J. van der Horst+, in prep.
- Low-metallicity dwarf satellite of a higher-metallicity host Kelly+ 2013
- First clear identification of a galaxy cluster or group containing a GRB host D’Elia+ 2015
- Search for other SNe associated with *Fermi* GBM bursts Kovacevic+ 2014
- LAT-detected burst at low redshift → search for TeV emission with HAWC (Woodle 2015)

PALOMAR TRANSIENT FACTORY **FOLLOW-UP OF GW150914**



Kasliwal, Cenko, **Singer**+ 2016, ApJL

```
TITLE:   GCN CIRCULAR
NUMBER:  18337
SUBJECT: LIGO/Virgo G184098: iPTF Optical Transient Candidates
DATE:    15/09/20 01:39:01 GMT
FROM:    Leo Singer at NASA/GSFC  <leo.p.singer@nasa.gov>

[GCN OPS NOTE(19sep15): This Circular was originally published
on 03:09 18-Sep-2015 UT.]

L. P. Singer (NASA/GSFC), M. M. Kasliwal (Caltech), S. B. Cenko
(NASA/GSFC), V. Bhalerao (IUCAA), A. Miller (Caltech), T. Barlow
(Caltech), E. Bellm (Caltech), I. Manulis (WIS), A. Singhal (IUCAA), and
J. Rana (IUCAA) report on behalf of the intermediate Palomar Transient
Factory (iPTF) collaboration:

We have performed tiled observations of LIGO/Virgo G184098 using the
Palomar 48-inch Oschin telescope (P48). We imaged 18 fields spanning 135
deg2. Based on the LIB localization, we estimate a 2.3% prior probability
that these fields contain the true location of the source. The small
containment probability is because the southern mode of the updated
("LIB") localization was too far south to be observable from Palomar,
whereas most of the northern mode rose after 12° twilight.

Sifting through candidate variable sources using image subtraction by both
our NERSC and IPAC pipelines, and applying standard iPTF vetting
procedures, we flagged the following optical transient candidates for
further follow-up:


iPTF15cyo, at the coordinates:
  RA(J2000)  =  8h 19m 56.18s (124.984069 deg)
  Dec(J2000) = +13d 52' 42.0" (+13.878337 deg)

Our P48 photometry includes:
  -483 days: R > 20.88
    +3 days: R = 17.75 +/- 0.01

The position is consistent with the galaxy SDSS J081956.62+135241.7, whose
spectroscopic redshift of z = 0.02963 implies an absolute magnitude for
the transient of M_R = -17.8, suggestive of a supernova.

iPTF15cyq, at the coordinates:
  RA(J2000)  =  8h 10m 00.86s (122.503586 deg)
  Dec(J2000) = +18d 42' 18.1" (+18.705039 deg)

. . .

We have obtained Keck II + DEIMOS spectra of all of the above targets.
We will report our analyses of these spectra shortly.

Times are relative to the LIGO/Virgo trigger. Magnitudes are in the Mould
R filter and in the AB system, calibrated with respect to point sources in
SDSS as described in Ofek et al. (2012, http://dx.doi.org/10.1086/664065).
```

The needle in the haystack

127,676 optical transient candidates in difference images

78,951 not coincident with point source in reference image (rejects stellar sources)

15,624 detected in two images separated by >30 minutes (rejects main belt asteroids)

5,803 passed strict machine-learning real-bogus cut

1,007 coincident with nearby galaxy (<200 Mpc)

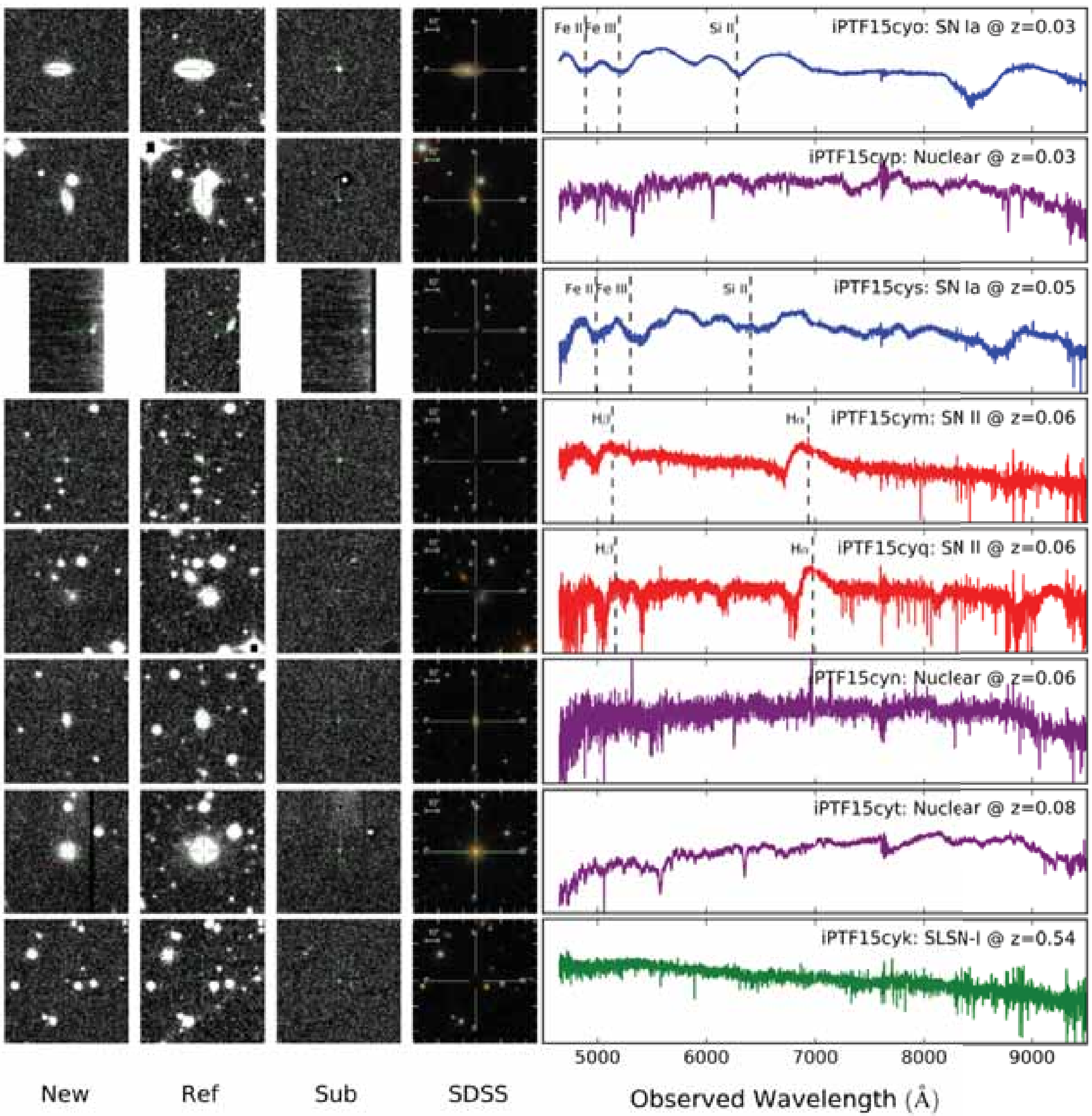
13 candidates selected by human vetting of light curve properties and archival analysis

8 had no history of prior variability in PTF archive

Kasliwal, Cenko, **Singer**+ 2016, ApJL

KECK CLASSIFICATION SPECTRA

less than an hour after discovery!

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TITLE:    GCN CIRCULAR
NUMBER:   18341
SUBJECT: LIGO/Virgo G184098: Keck II DEIMOS
Spectra of iPTF Optical Candidates
DATE:     15/09/20 01:53:22 GMT
FROM:     Mansi M. Kasliwal at Caltech
<mansi@astro.caltech.edu>

[GCN OPS NOTE(19sep15): This Circular was
originally published on 09:28 18-Sep-2015 UT.]

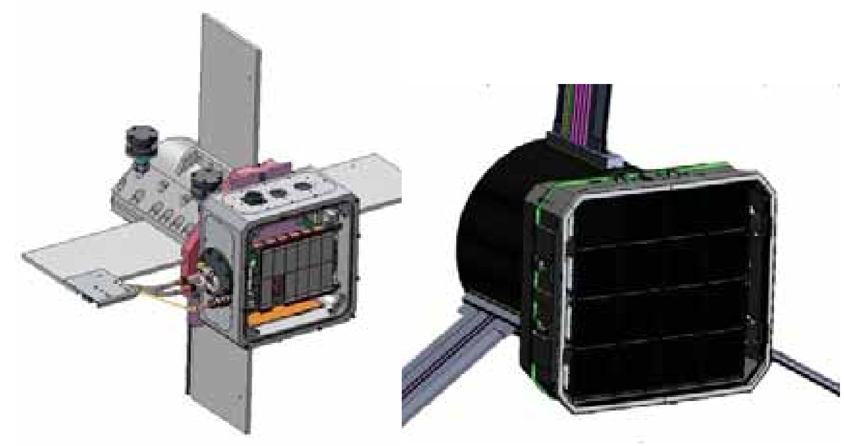
M. M. Kasliwal (Caltech), S. B. Cenko (NASA
GSFC), Y. Cao (Caltech) and G. Duggan (Caltech)

report on behalf of a larger collaboration

We obtained spectra of the following iPTF
candidates with the DEIMOS spectrograph on the
Keck II telescope on 2015 Sep 17 between approx.
11.3 and 13.3 UTC. Cross-correlating with
supernova spectral libraries (SNID and
Superfit), we find the following candidates are
unlikely to be related:
iPTF15cym: Supernova, Type II, z~0.055
iPTF15cyo: Supernova, Type Ia, z=0.0296
iPTF15cyq: Supernova, Type II, z=0.063
iPTF15cys: Supernova, Type Ia, z~0.05

In addition, we note that iPTF15cyk is unlikely
to be related due to its high redshift.
iPTF15cyn, iPTF14cyp and iPTF5cyt spectra are
dominated by nuclear continuum. Further analysis
and follow-up is underway. We thank S. R.
Kulkarni for the DEIMOS observing time.
```

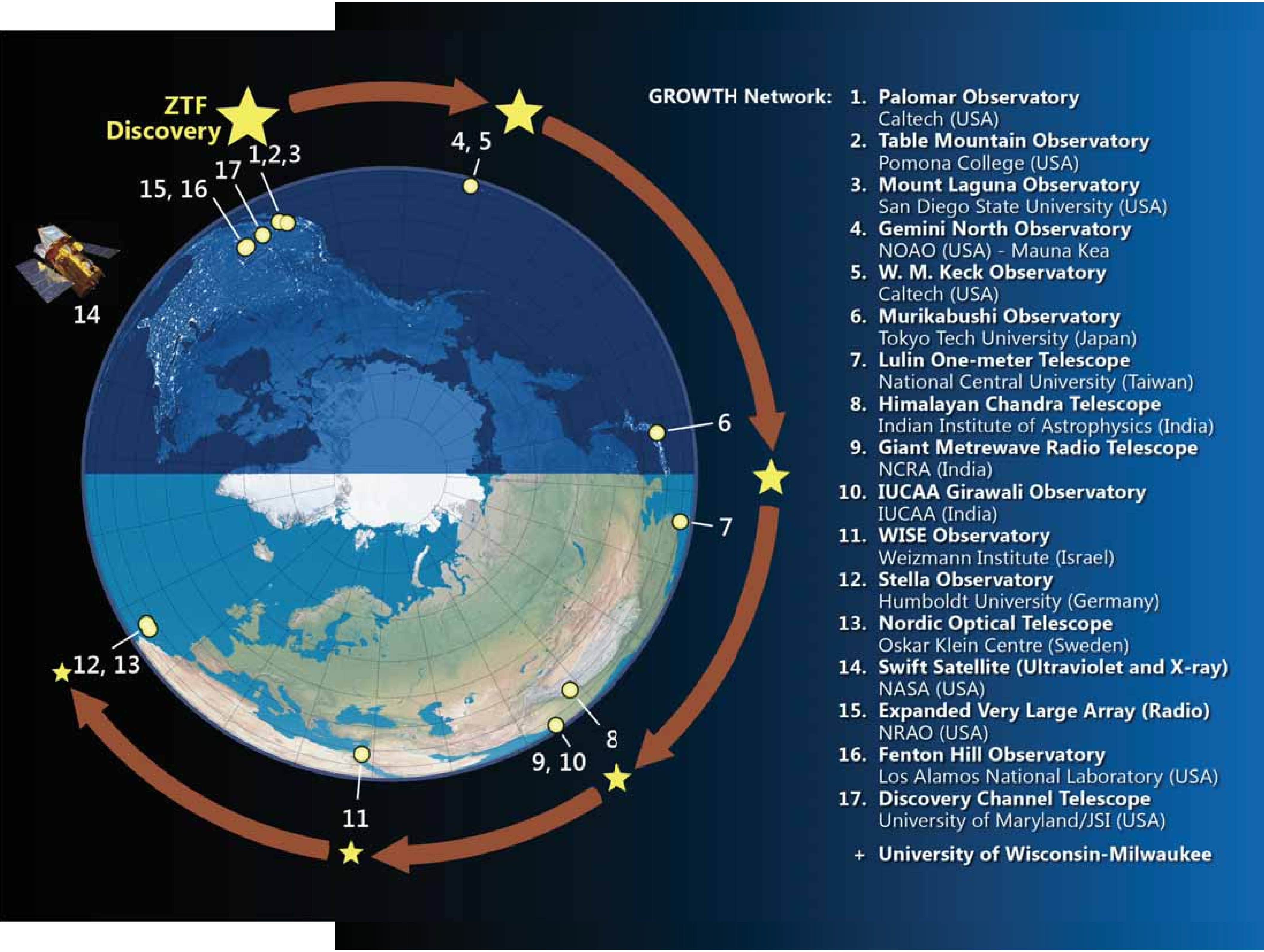
LIGO + ZTF



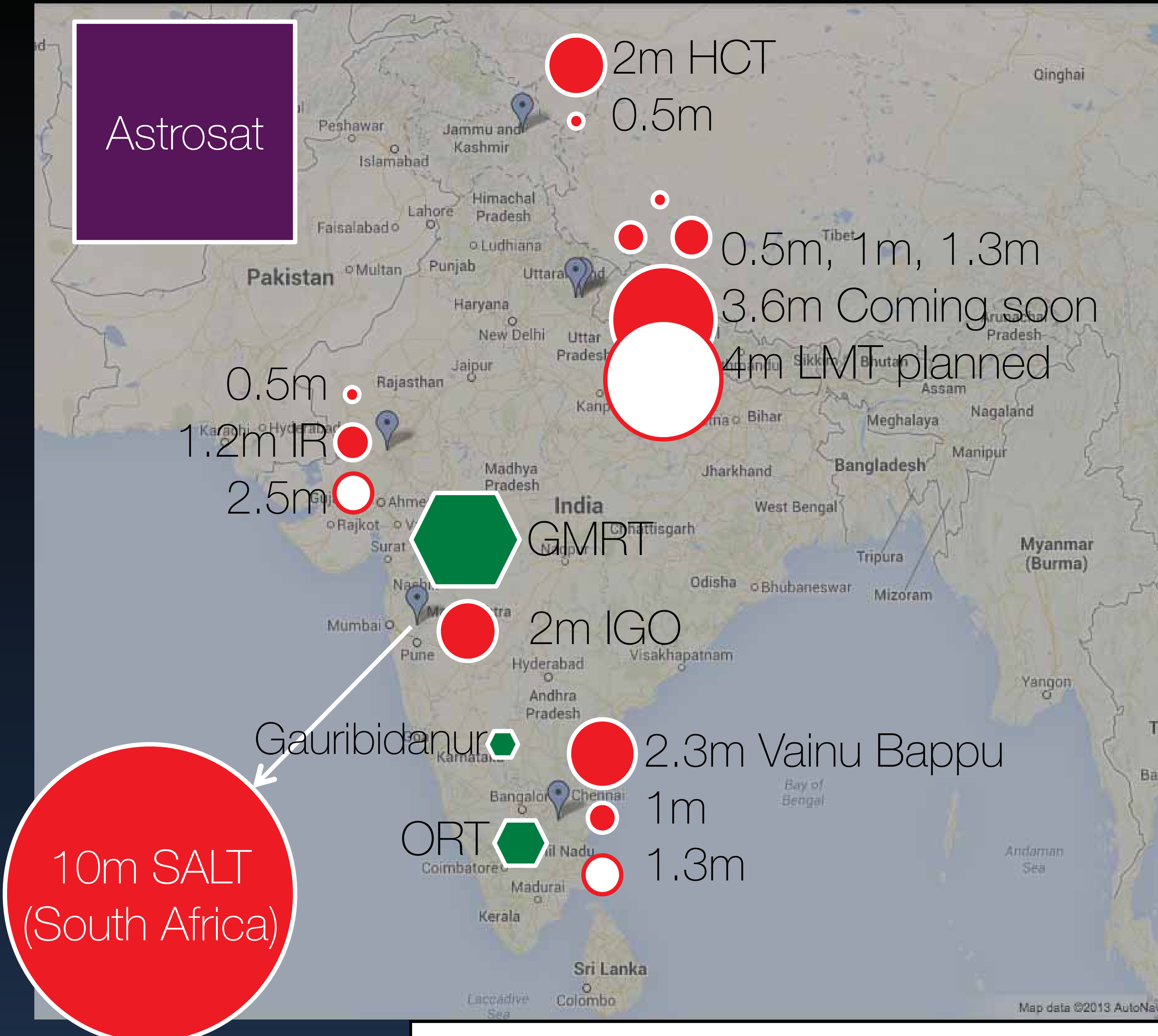
- Zwicky Transient Facility
- New camera, 7x increase in FOV; order of magnitude faster survey rate
- Faster readout for deep co-adds, guiding for long exposures
- Improved real/bogus classification →higher purity discovery stream
- Combine GW posterior with local universe galaxy catalog (Nissanke+ 2013)

	PTF	ZTF
Active Area	7.26 deg^2	47 deg^2
Readout Time	36 sec	10 sec
Exposure Time	60 sec	30 sec
Relative Areal Survey Rate	1x	**14.7x**
Relative Volumetric Survey Rate	1x	**12.3x**

E. Bellm
Bellm+ 2014
Smith+ 2014


ZTF
Discovery
1,2,3
17
15, 16
4, 5
14
6
7
8
9, 10
11
12, 13
GROWTH Network:
1. **Palomar Observatory**
Caltech (USA)
2. **Table Mountain Observatory**
Pomona College (USA)
3. **Mount Laguna Observatory**
San Diego State University (USA)
4. **Gemini North Observatory**
NOAO (USA) - Mauna Kea
5. **W. M. Keck Observatory**
Caltech (USA)
6. **Murikabushi Observatory**
Tokyo Tech University (Japan)
7. **Lulin One-meter Telescope**
National Central University (Taiwan)
8. **Himalayan Chandra Telescope**
Indian Institute of Astrophysics (India)
9. **Giant Metrewave Radio Telescope**
NCRA (India)
10. **IUCAA Girawali Observatory**
IUCAA (India)
11. **WISE Observatory**
Weizmann Institute (Israel)
12. **Stella Observatory**
Humboldt University (Germany)
13. **Nordic Optical Telescope**
Oskar Klein Centre (Sweden)
14. **Swift Satellite (Ultraviolet and X-ray)**
NASA (USA)
15. **Expanded Very Large Array (Radio)**
NRAO (USA)
16. **Fenton Hill Observatory**
Los Alamos National Laboratory (USA)
17. **Discovery Channel Telescope**
University of Maryland/JSI (USA)
+ **University of Wisconsin-Milwaukee**

Large Indian Telescopes



Slide courtesy of Varun Bhalerao

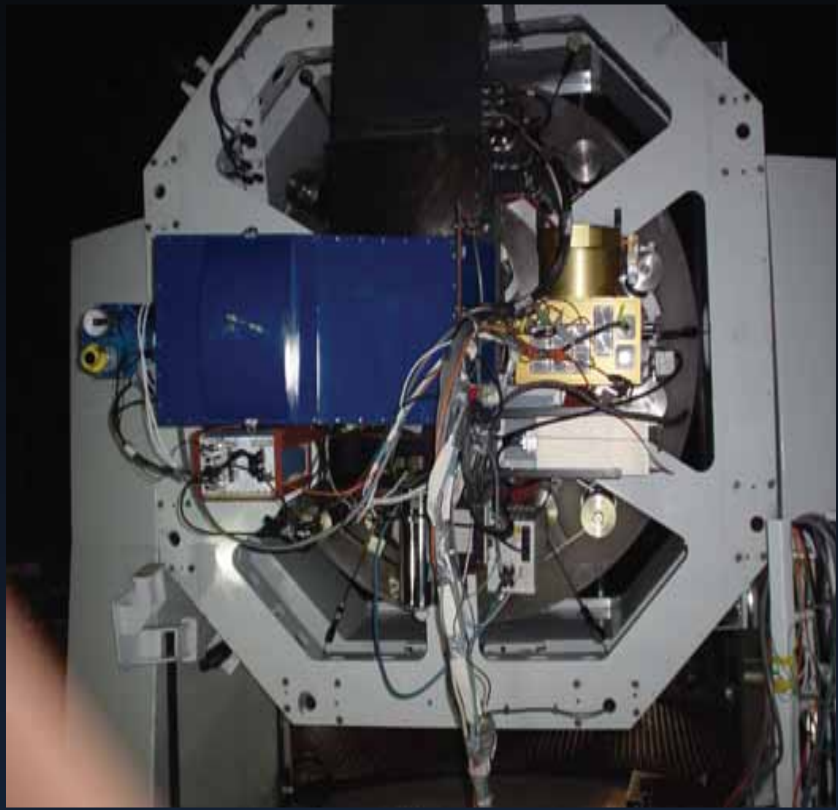
GROWTH – India

- New fully robotic optical telescope, dedicated to time domain studies
- Specifications:
  - » 0.7m alt-az telescope
  - » 2 side ports
  - » Low noise camera (4k * 4k back illuminated)
  - » 1 degree field of view
  - » 70% time for GROWTH 30% other projects

Slide courtesy of Varun Bhalerao

Himalayan Chandra Telescope

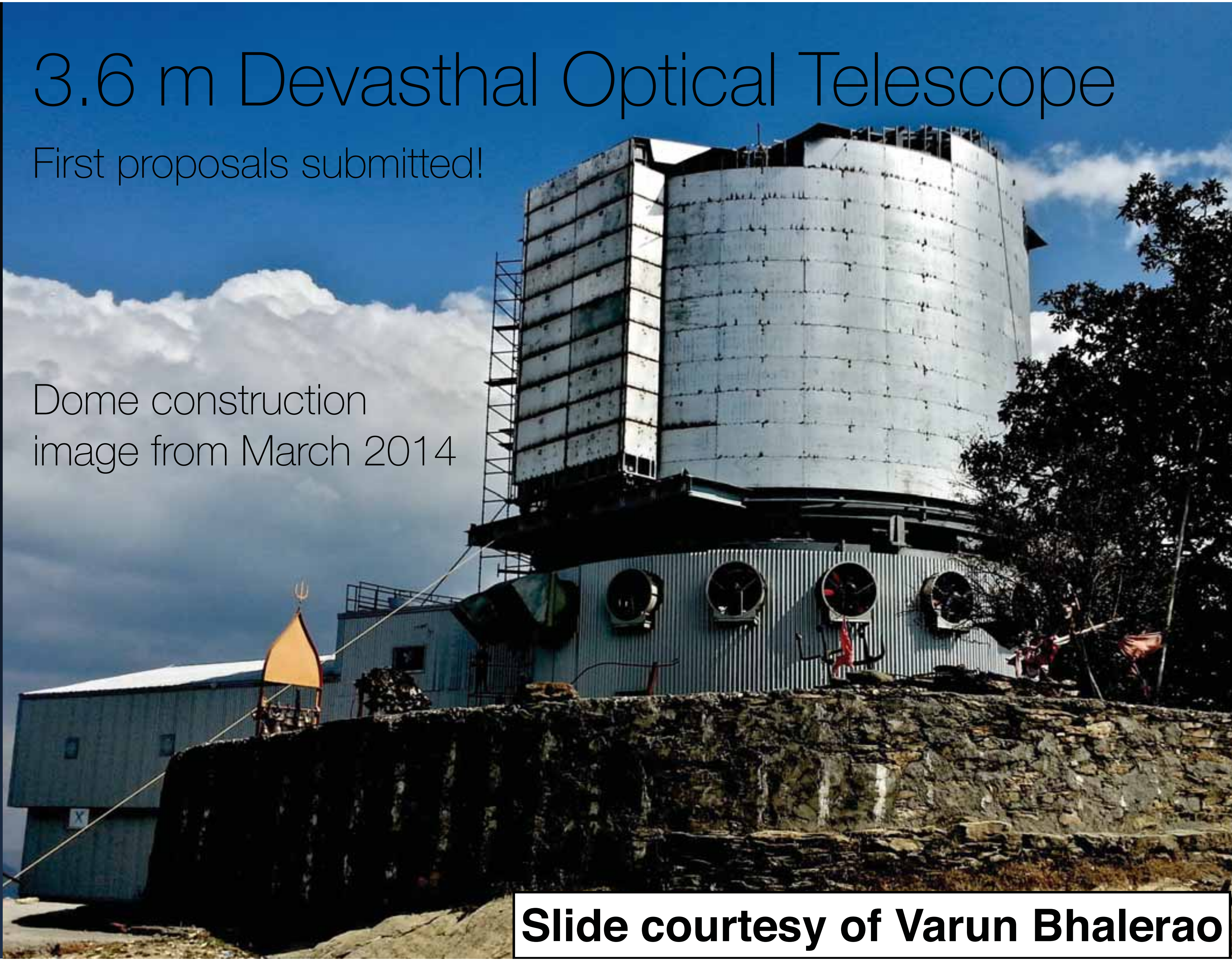
- Spectroscopy:
  - » R ≈ 150 – 4500
- Optical imaging:
  - » Broad / narrow band filters
  - » FOV1: 10'X10' @ 0.297"/px
  - » FOV2: 5.9'X11.8'@0.17"/px
- Near-infrared imager
  - » JHK bands
  - » FOV: 1.8'X1.8'; 3.6'X3.6'



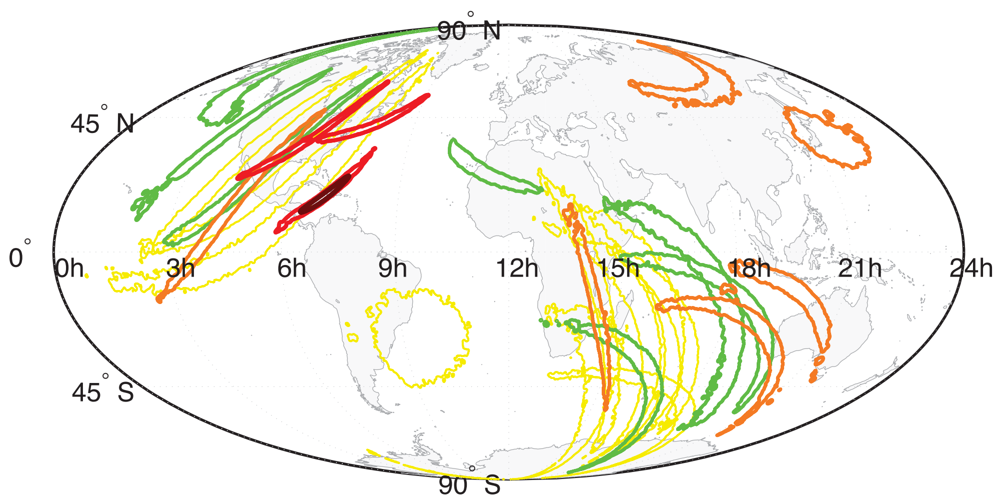
Instruments mounted on an instrument cube and available all the time.

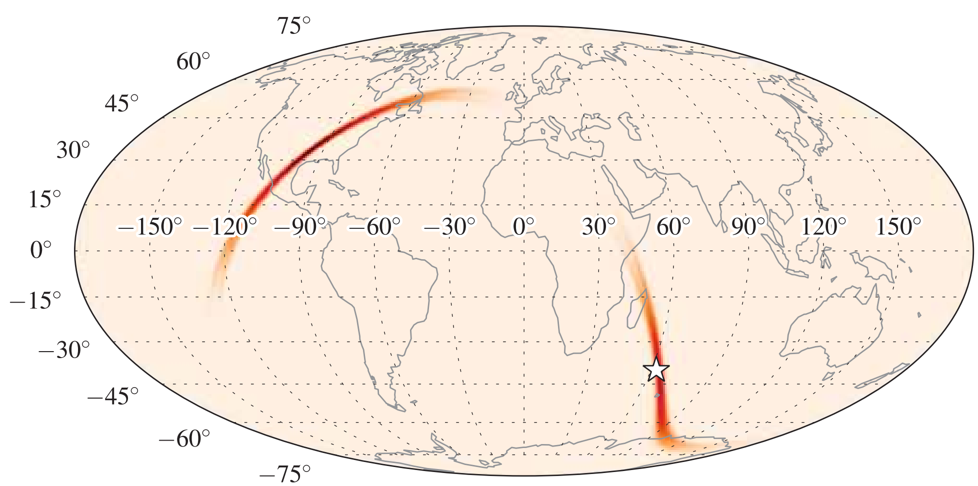
http://www.iiap.res.in/iao_telescope

Slide courtesy of Varun Bhalerao


3.6 m Devasthal Optical Telescope
First proposals submitted!
Dome construction
image from March 2014
Slide courtesy of Varun Bhalerao

Localization in O1 and O2 was expected to be coarse because we have only two detectors.



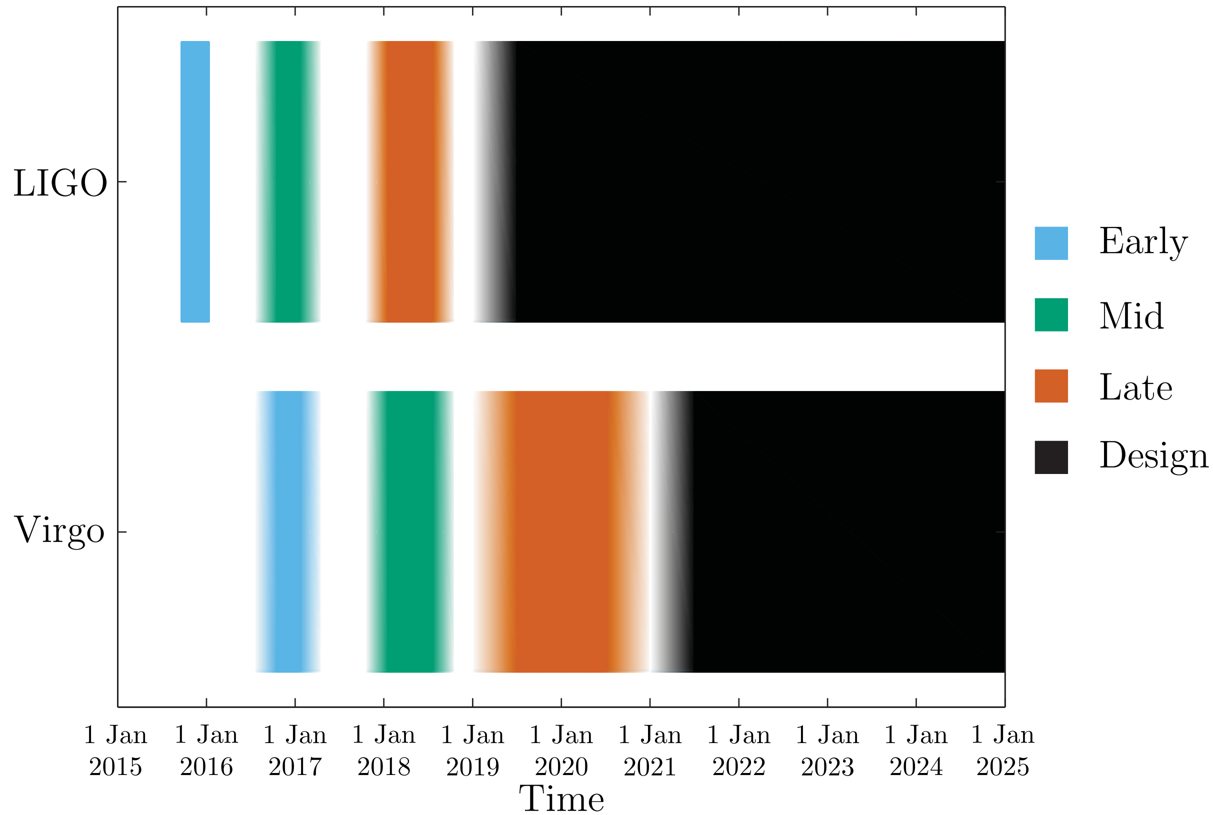


- Kasliwal & Nissanke (2014), Singer+ (2014): showed that we could localize sources to 100-1000 deg^2 with a 2-detector GW network.
- Challenged assumptions about LIGO observing scenarios that were based on timing only.
- KN 2014 argued that kilonova follow-up would be challenging but possible with ground-based optical surveys (ZTF, DES, LSST, etc.) even with 2 LIGO detectors.
- An optimistic message about early Advanced LIGO, but may have created unrealistically pessimistic expectations about the future.

THE LSST ERA: **final design sensitivity**

Based on LIGO Observing Scenarios document (arXiv: 1304.0670). Numbers for 2019–2022+ use timing only.

HLVI network, BNS sources:
>20% localized to <5 deg²,
>50% localized to <20 deg².



Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg²	< 1	2	> *1 – 2*	> *3 – 8*	> *20*
		20 deg²	< 1	14	> *10*	> *8 – 30*	> *50*
		median/deg²	480	230	—	—	—

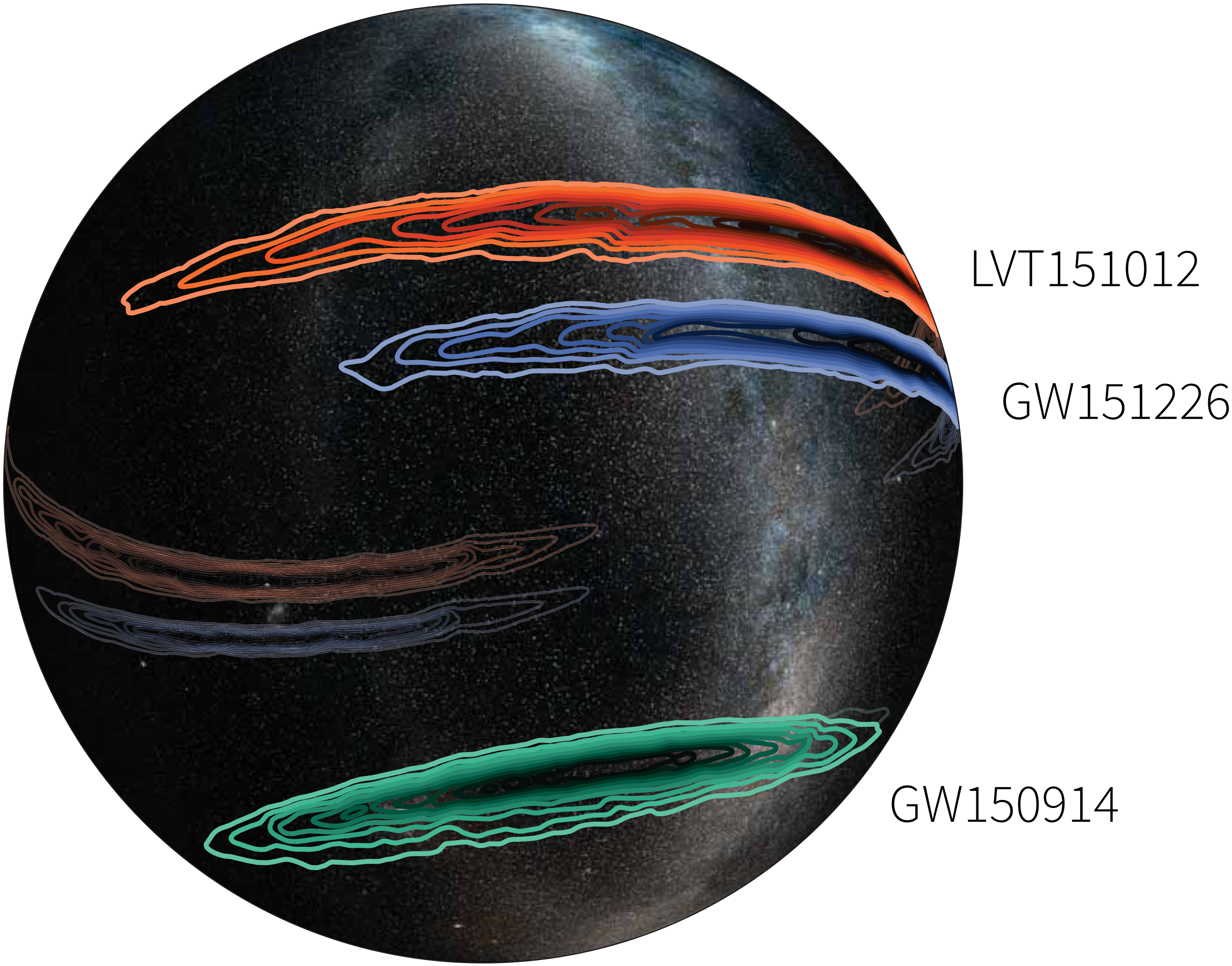


image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)

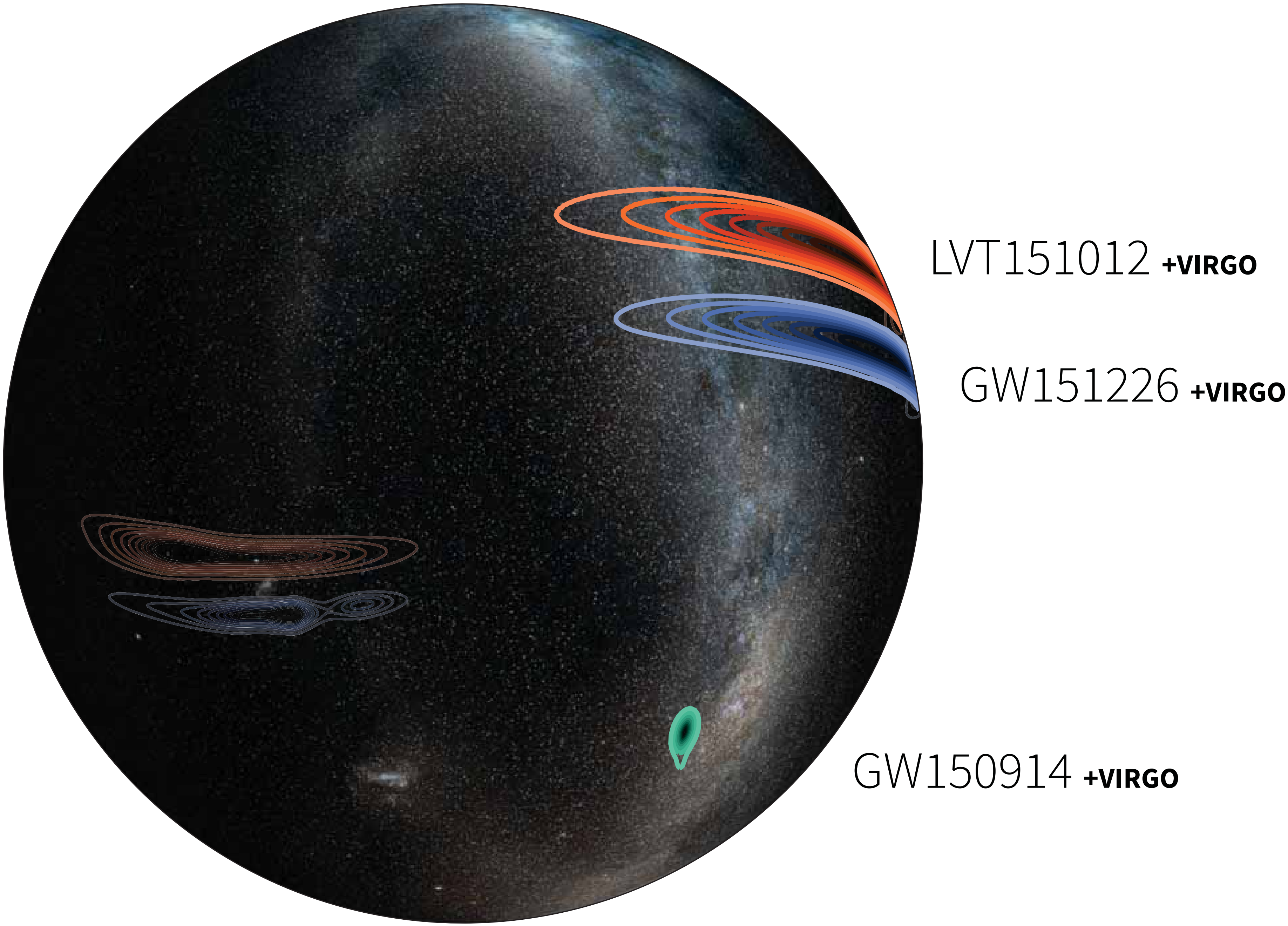
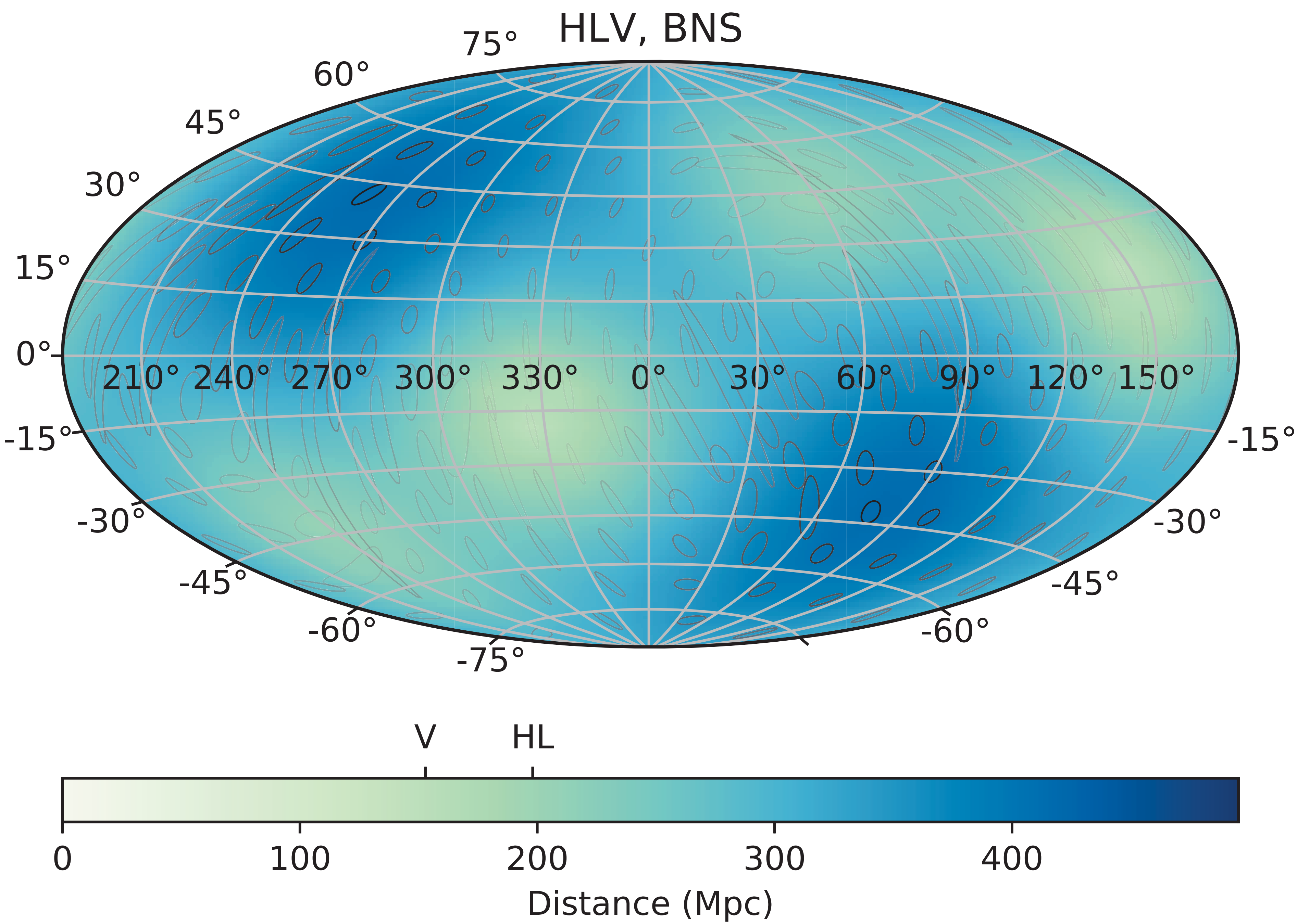
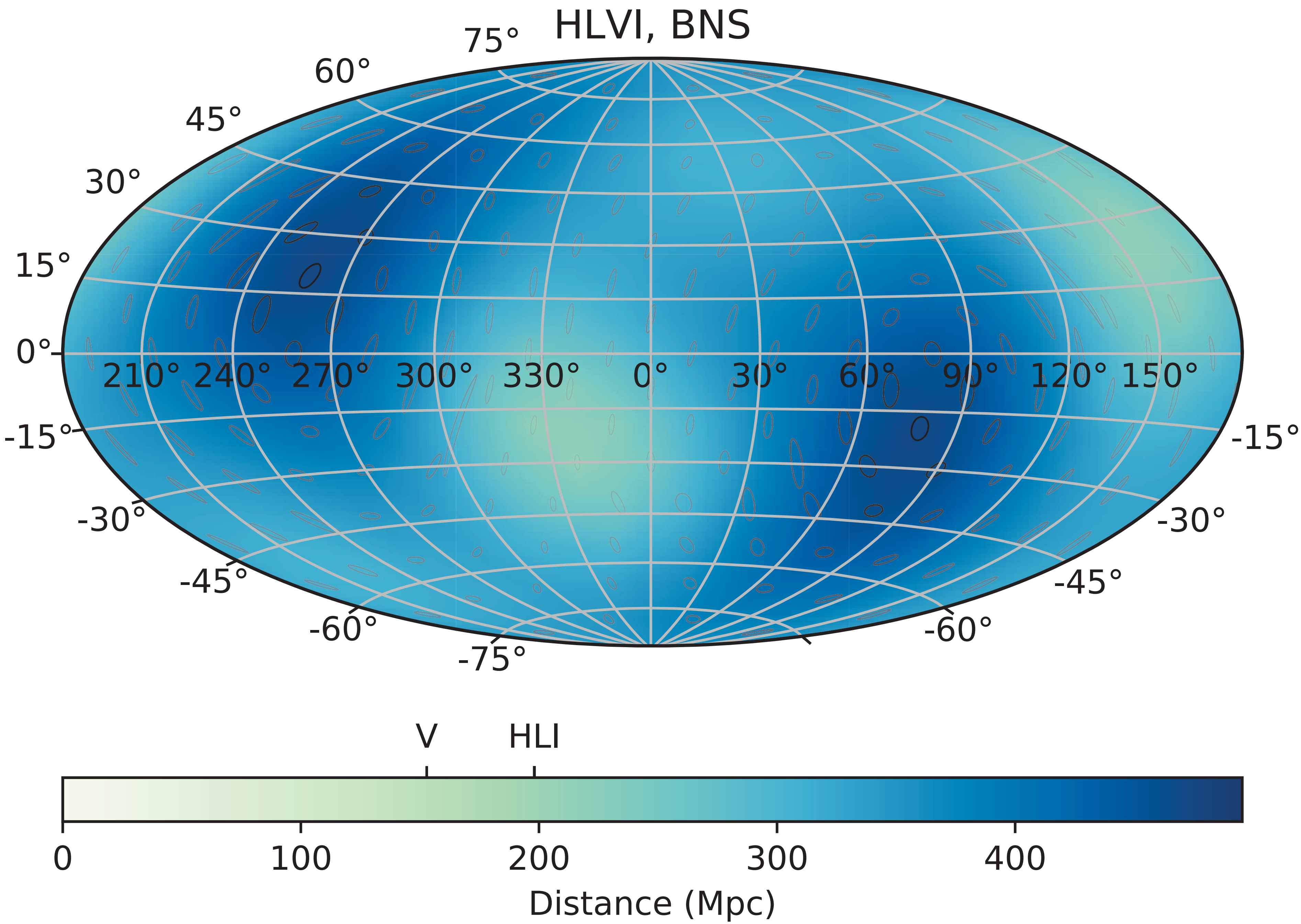
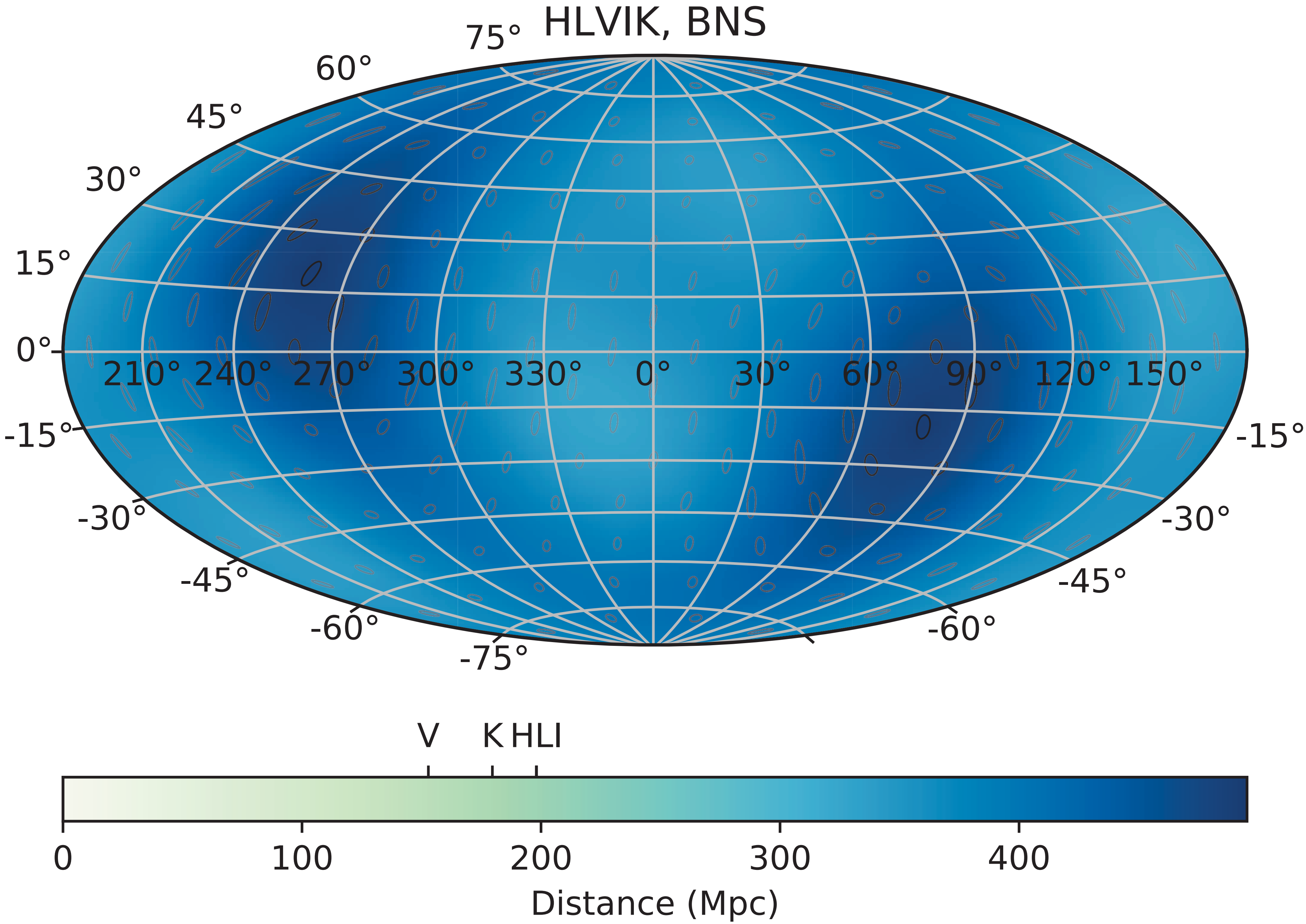


image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)


HLV, BNS
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
210° 240° 270° 300° 330° 0° 30° 60° 90° 120° 150°
V
HL
0
100
200
300
400
Distance (Mpc)

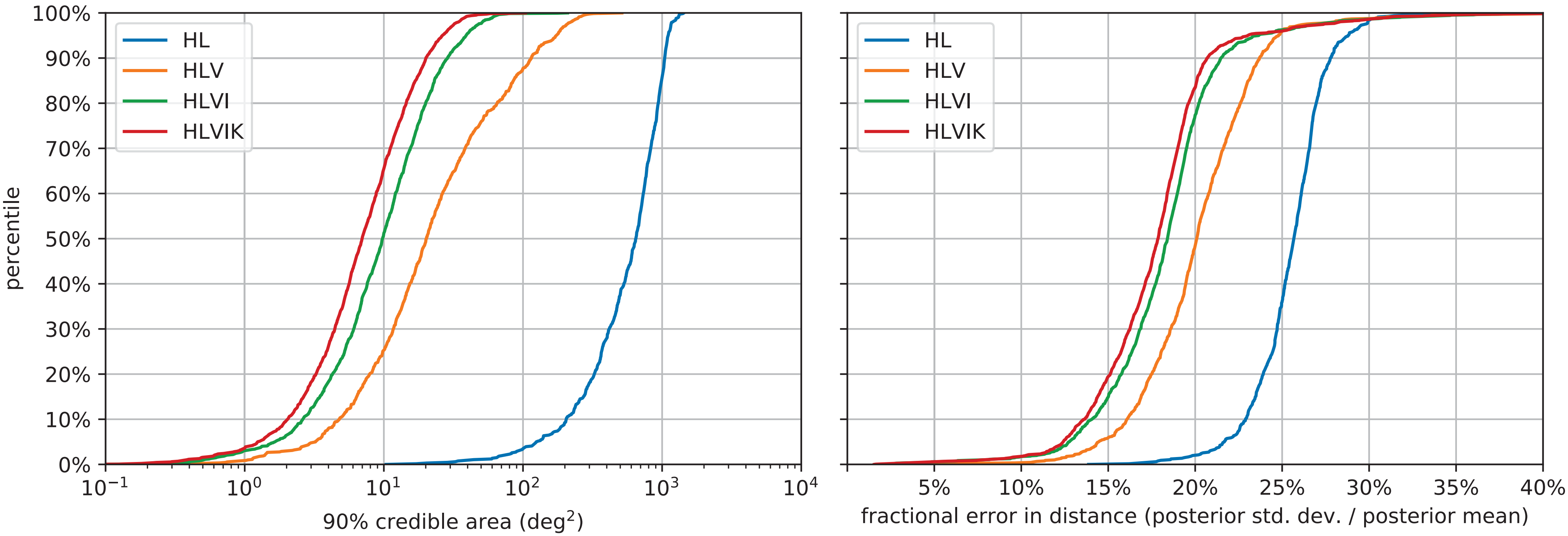


HLVI, BNS
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
210°
240°
270°
300°
330°
0°
30°
60°
90°
120°
150°
V
HLI
0
100
200
300
400
Distance (Mpc)



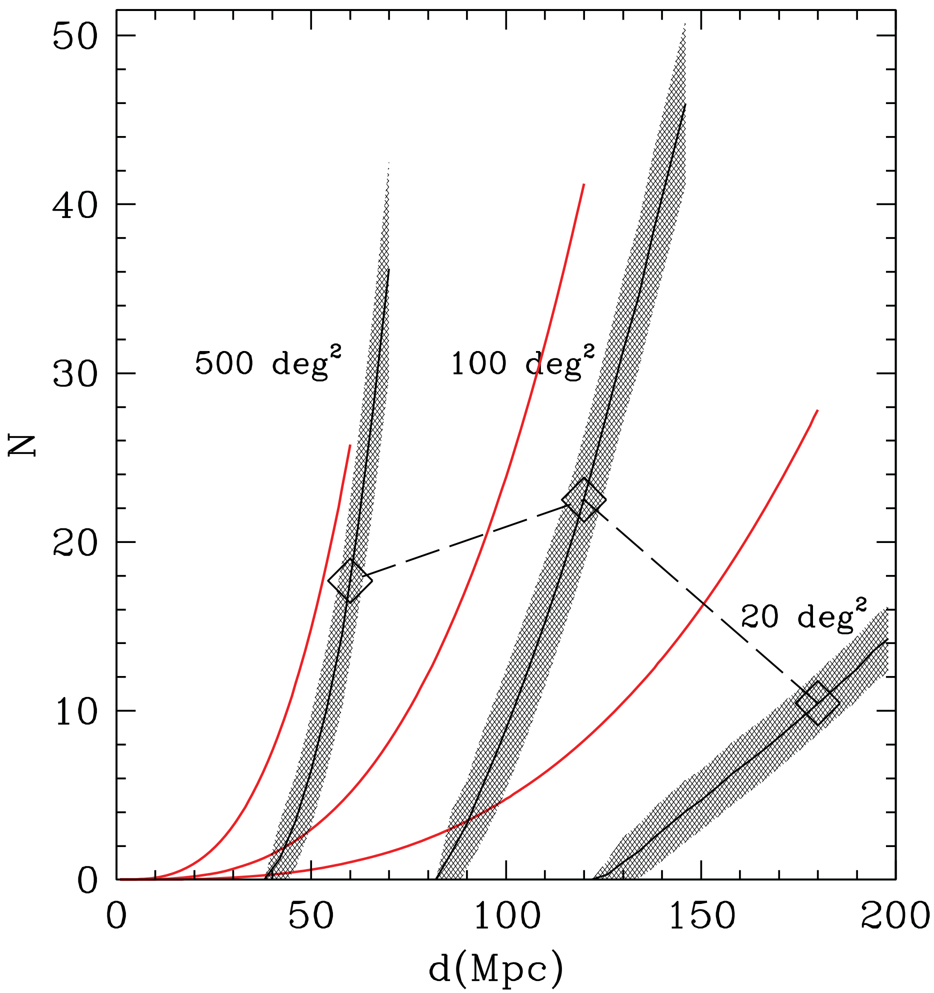
HLVIK, BNS
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
210° 240° 270° 300° 330° 0° 30° 60° 90° 120° 150°
V
K
HLI
0
100
200
300
400
Distance (Mpc)

ENHANCEMENT IN LOCALIZATION AND DISTANCE MEASUREMENT **with a network of 5 GW detectors**



(binary neutron star mergers at final design sensitivity)

GALAXY STRATEGY
for LIGO-Virgo Counterpart Searches



- Increased detector sensitivity→ **increased range**
- Increased number of detectors→ **decreased sky area**
- **Localized volume** & number of galaxies roughly **constant** throughout advanced detector era
- Incomplete galaxy catalogs→archival compilation supplemented with narrowband Hα photometric redshifts from P48 (CLU, Kasliwal & Cook)
- Also select brightest 50th percentile of galaxies
- Strategy devised for *Swift* XRT, but applicable in other wavelengths

Gehrels, Cannizzo, Kanner, Kasliwal, Nissanke, & Singer 2016 (ApJ)

SPACE POTATO CHIPS
Typical GW localization
in three dimensions

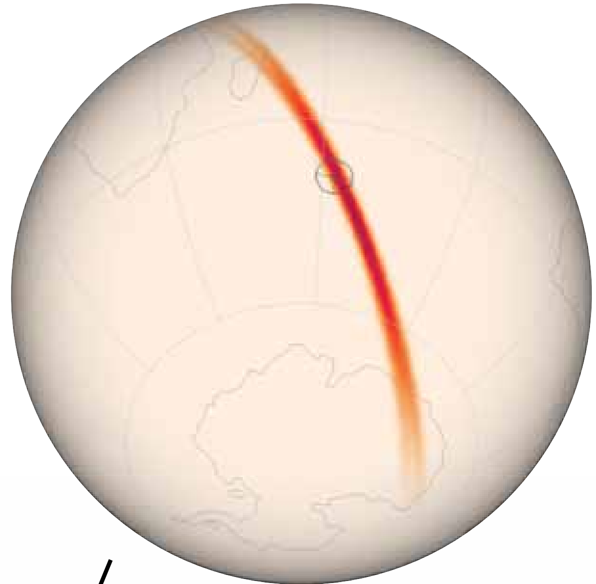
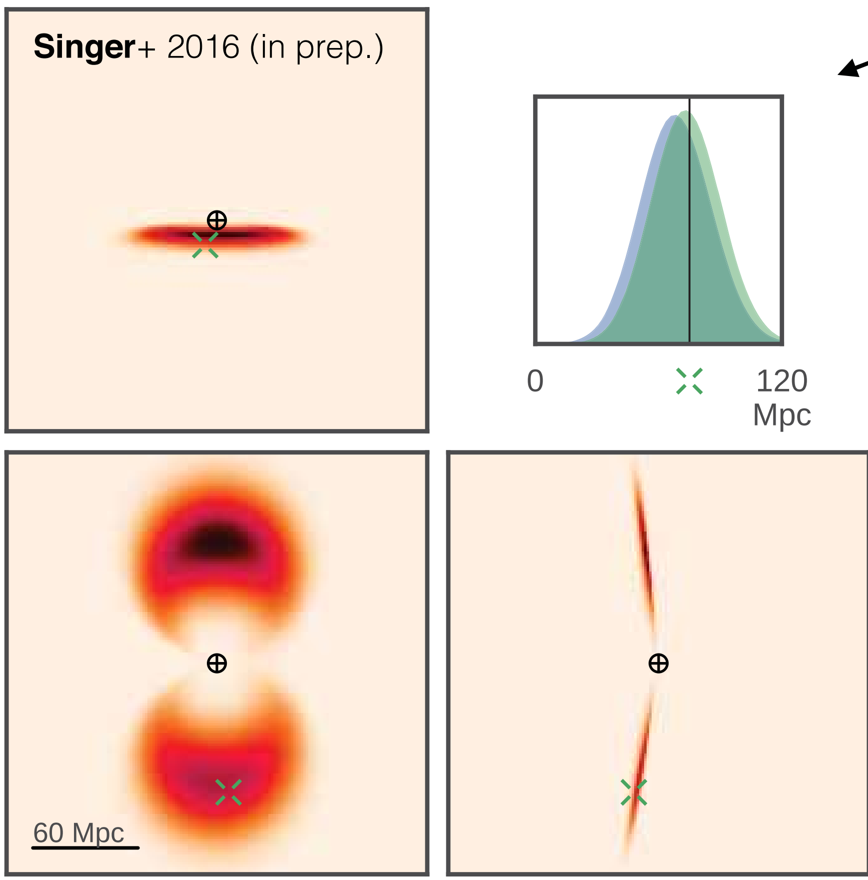
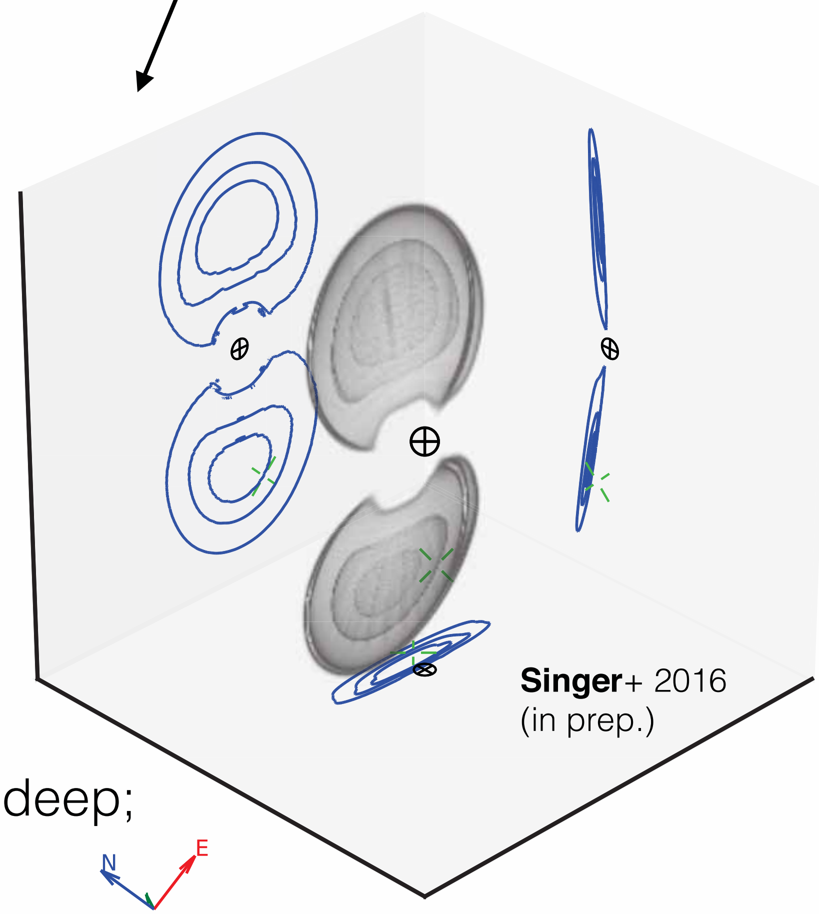


image: “First Two Years”

http://ligo.org/scientists/first2years

Singer+ 2014
Berry+ 2015

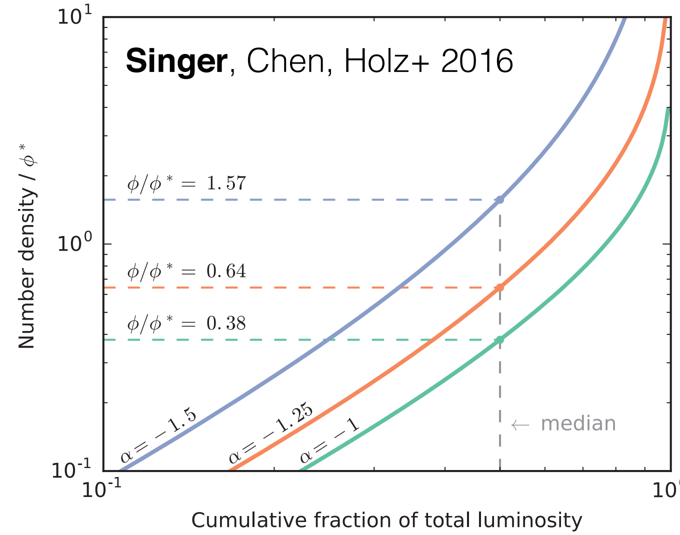


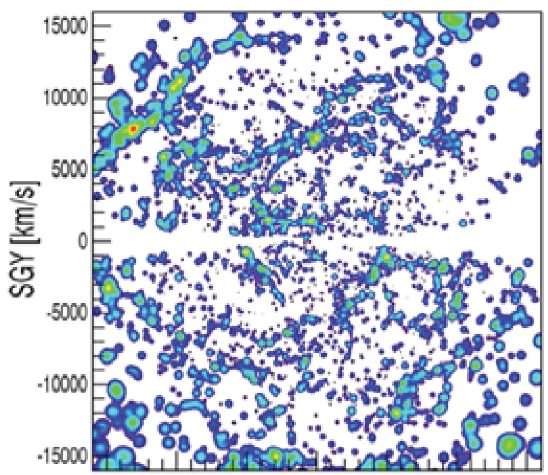


Double arcs become two **petals**:
~1° wide, **10-100°** in breadth, **~100 Mpc** deep;
Volume **~30×10³ Mpc³**

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

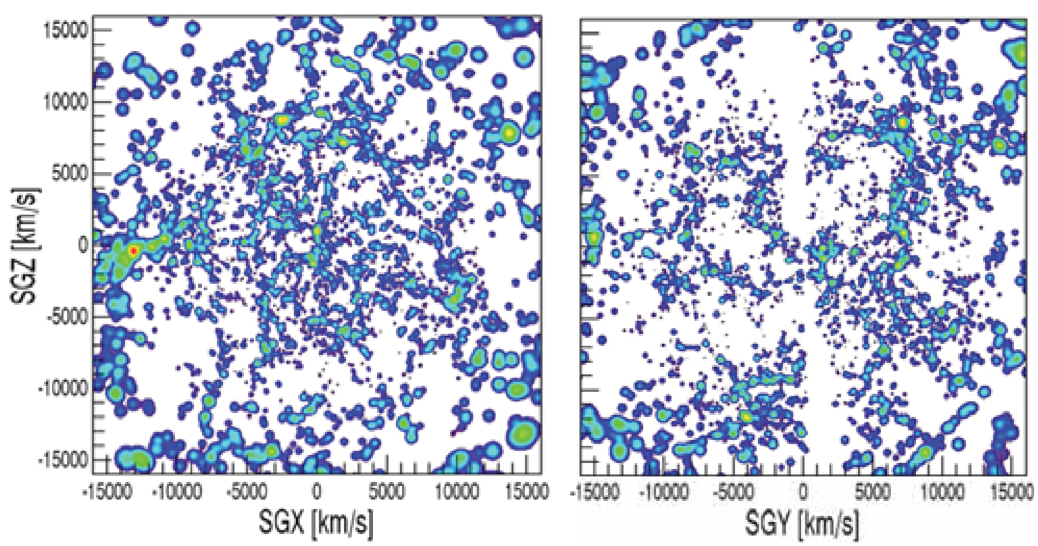
COSMOGRAPHY
for **fun and profit**

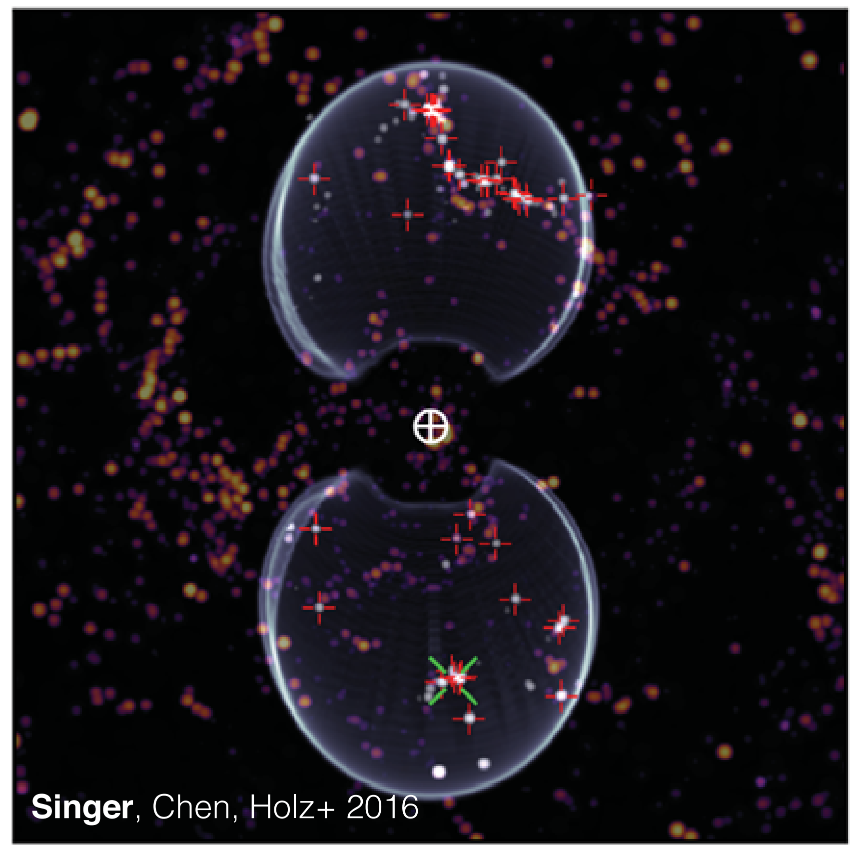




Combine GW parameter estimation with map of local luminosity density

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



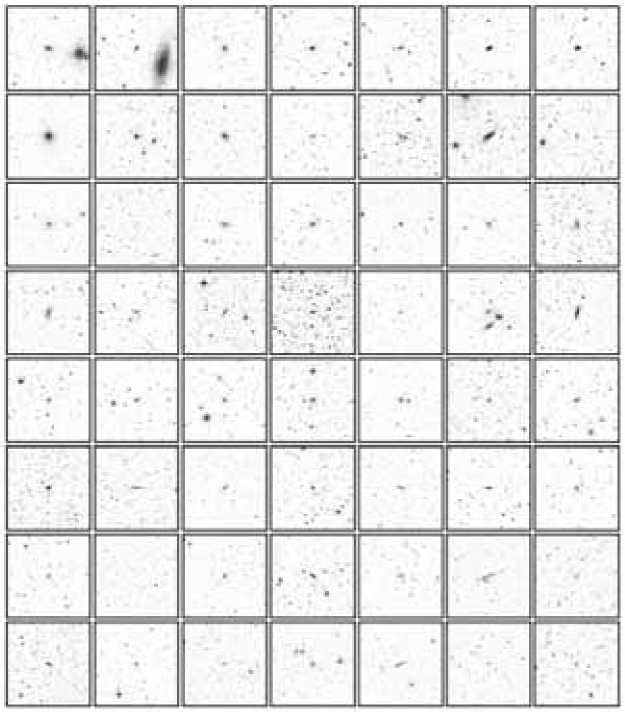


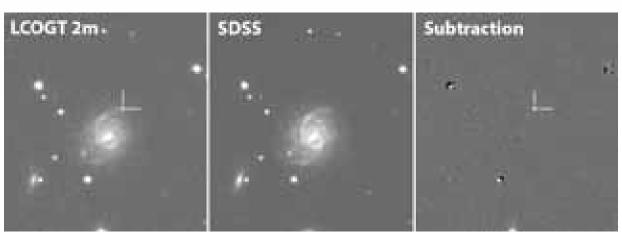
Singer, Chen, Holz+ 2016 (arXiv:1603.07333, ApJL)

GOING THE DISTANCE

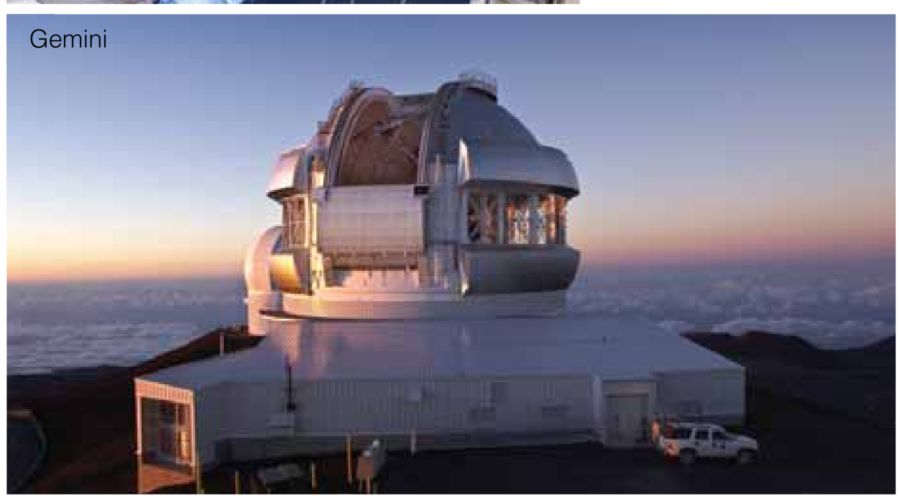
red=programs approved for O2

Targeted O/IR kilonova search





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

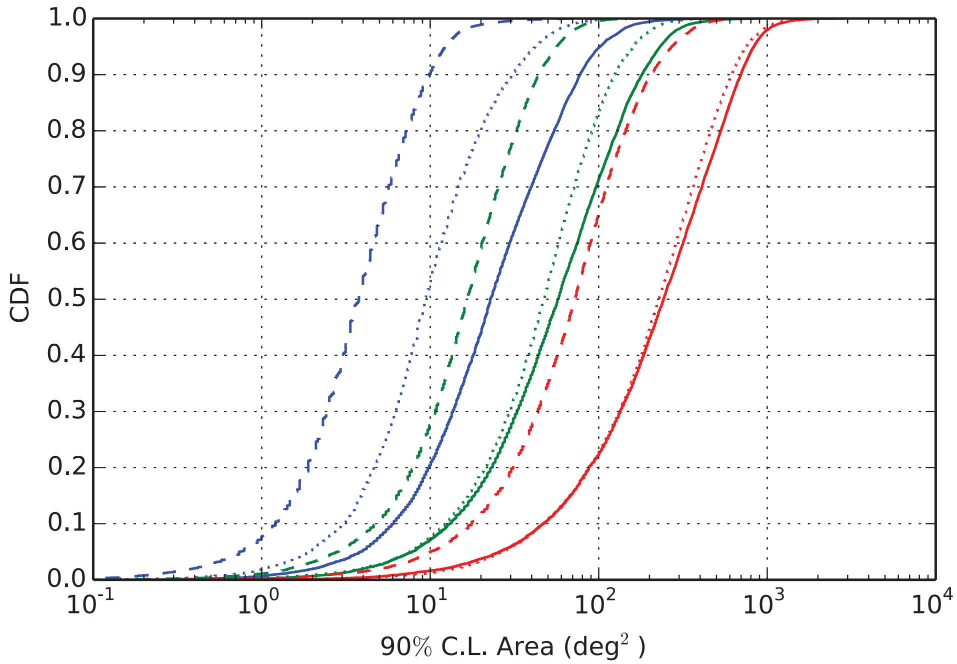


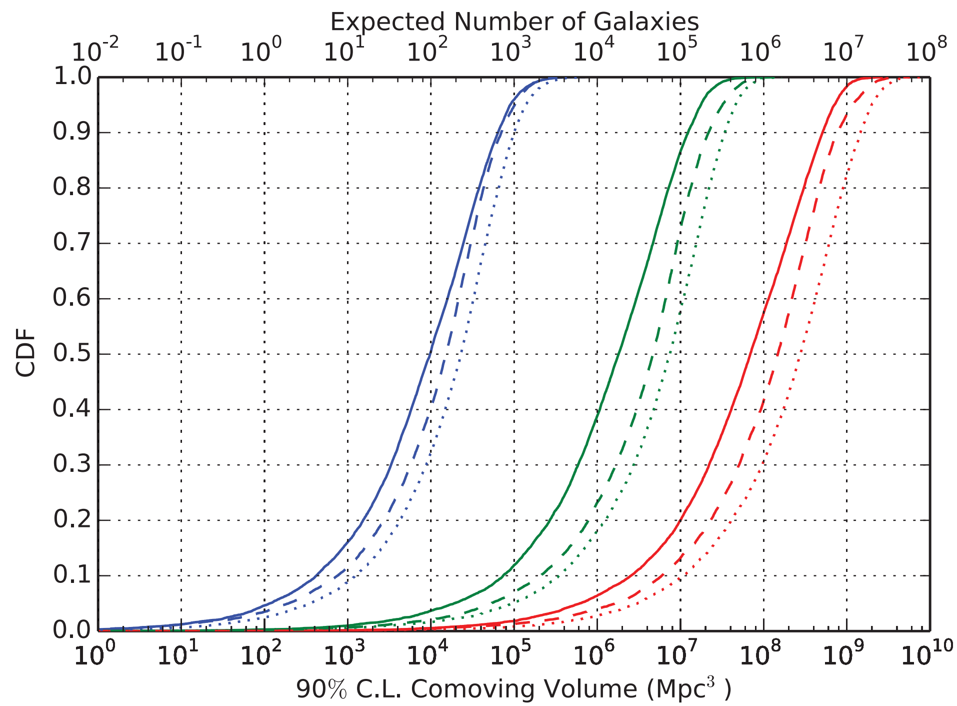
Ideal facilities:

LCOGT (2m) + Spectral **(PI: Aracavi)**
NOT (2.6m) + ALFOSC
DCT (4.3m) + LMI **(PI: Troja)**
Magellan (6.5m) + FourStar
Gemini (8.2m) + F2 **(PI: Singer)**
VLT (8.2m) + FORS2
Keck (10m) + LRIS
GTC (10.4m) + OSIRIS

Other wavelengths:
VLA (PI: Mooley)
Swift (PI: Evans)

FINDING THE ONE:
follow-up of the best-localized GW sources





Chen & Holz (2016) consider prospects of identifying the host galaxies of the choice, loudest, closest LIGO sources.

Solid: HLV-O3, dotted: HLV-design, dashed: HVLIJ-design.
Blue: BNS (1.4–1.4 $M_\odot$), Green: BBH (10–10 $M_\odot$), Red: BBH (30-30 $M_\odot$)

LSST: an **EM-GW discovery engine**

Large Synoptic Survey Telescope

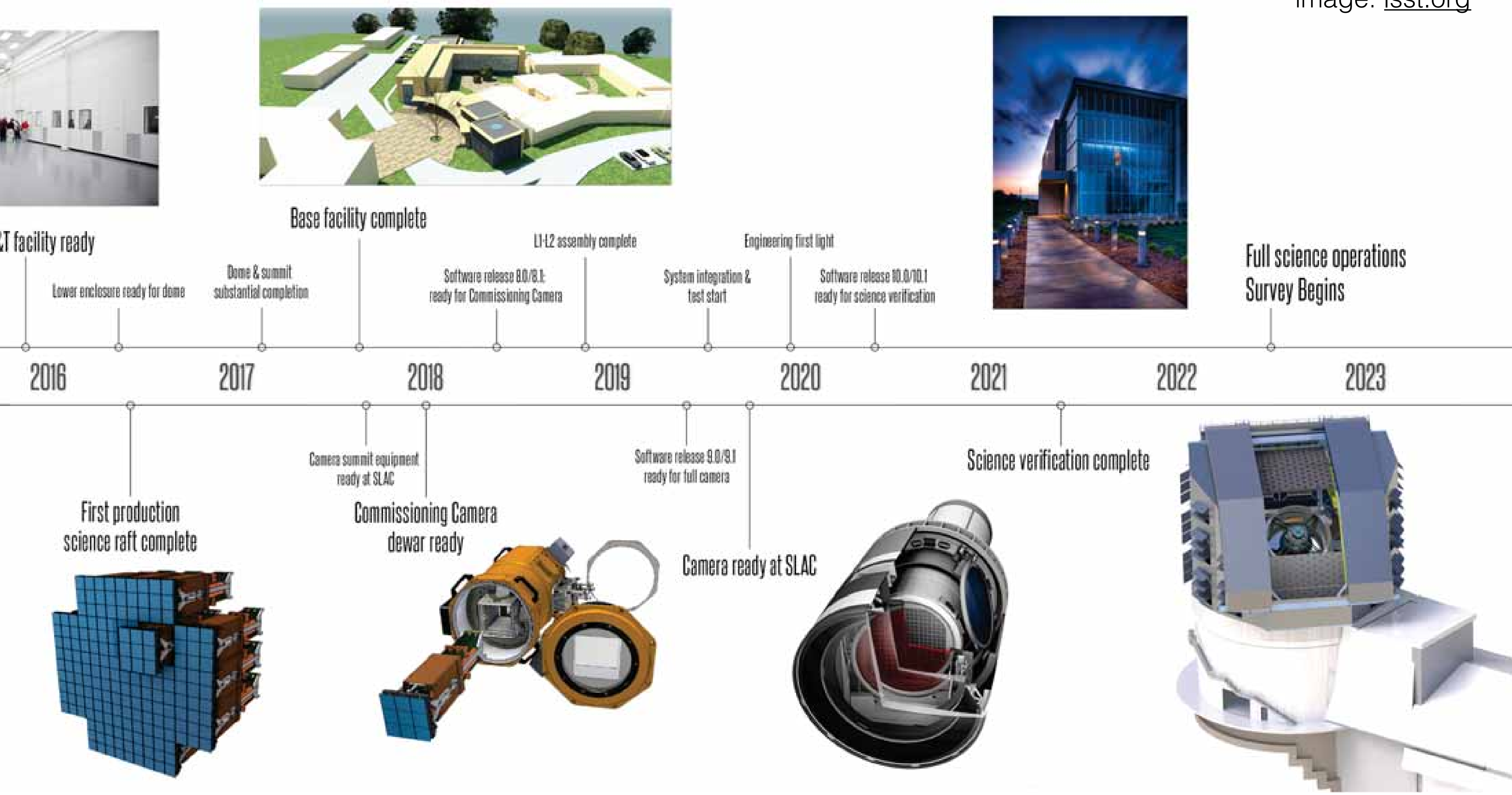
- **9.6 deg^2 camera on an 8.4 m telescope**
- **Single visit depth of r~24.5 in 2×15 s**
- **Filters: *ugrizy* (320–1050 nm)**
- **15 TB/night, 10 million transient alerts per night with 60 second latency**
- **Average slew time of 5–10 seconds**
- **With HLVIK network, a typical BNS localization will fit in 1–2 footprints**
- **Potentially an EM-GW discovery engine, but TOOs are currently a low science priority**

image: lsst.org

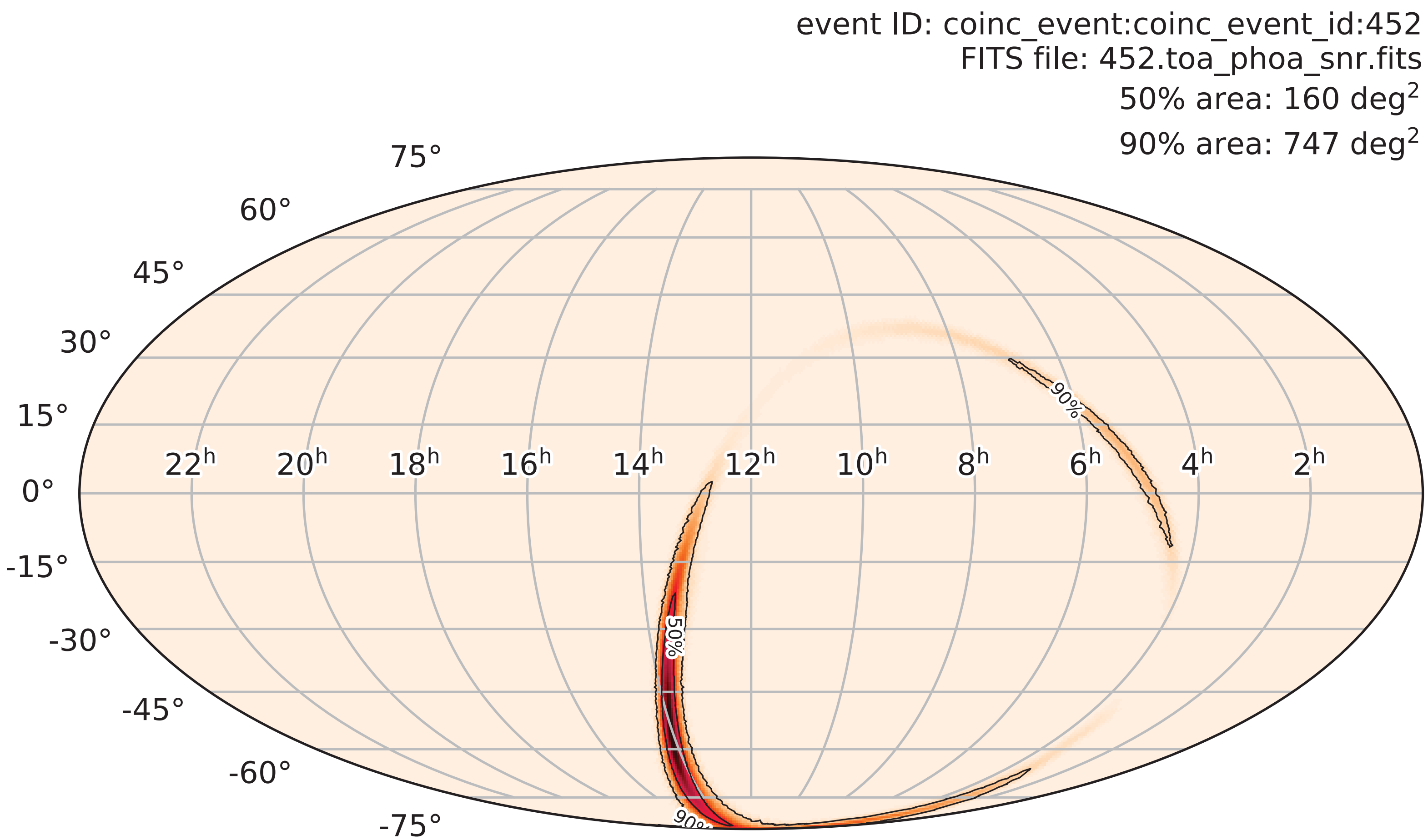
potential convergence of

FIRST LIGHT FOR LSST AND LIGO-INDIA

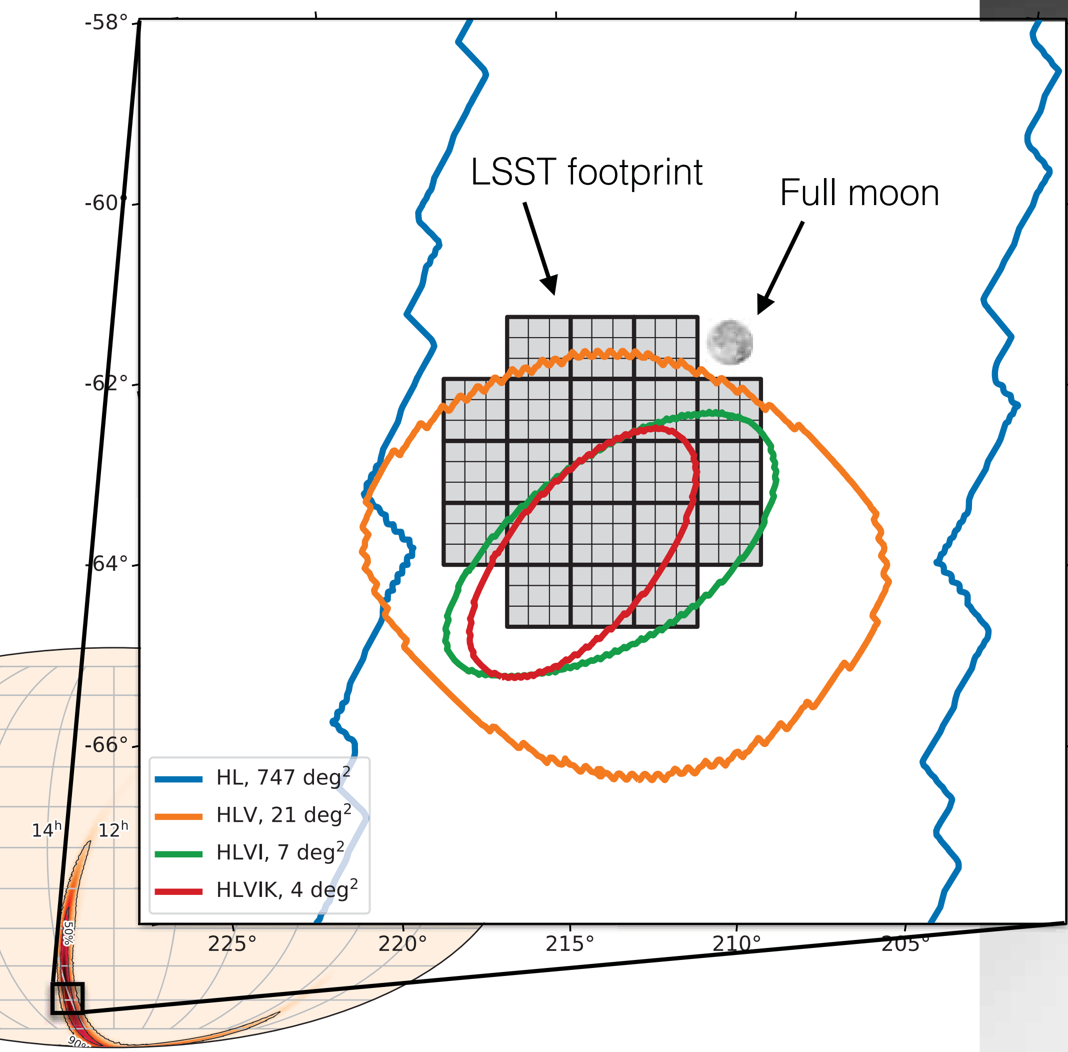
image: lsst.org



LSST plus a five-detector network: Toward routine EM-GW discoveries



LSST plus a five-detector network: Toward routine EM-GW discoveries



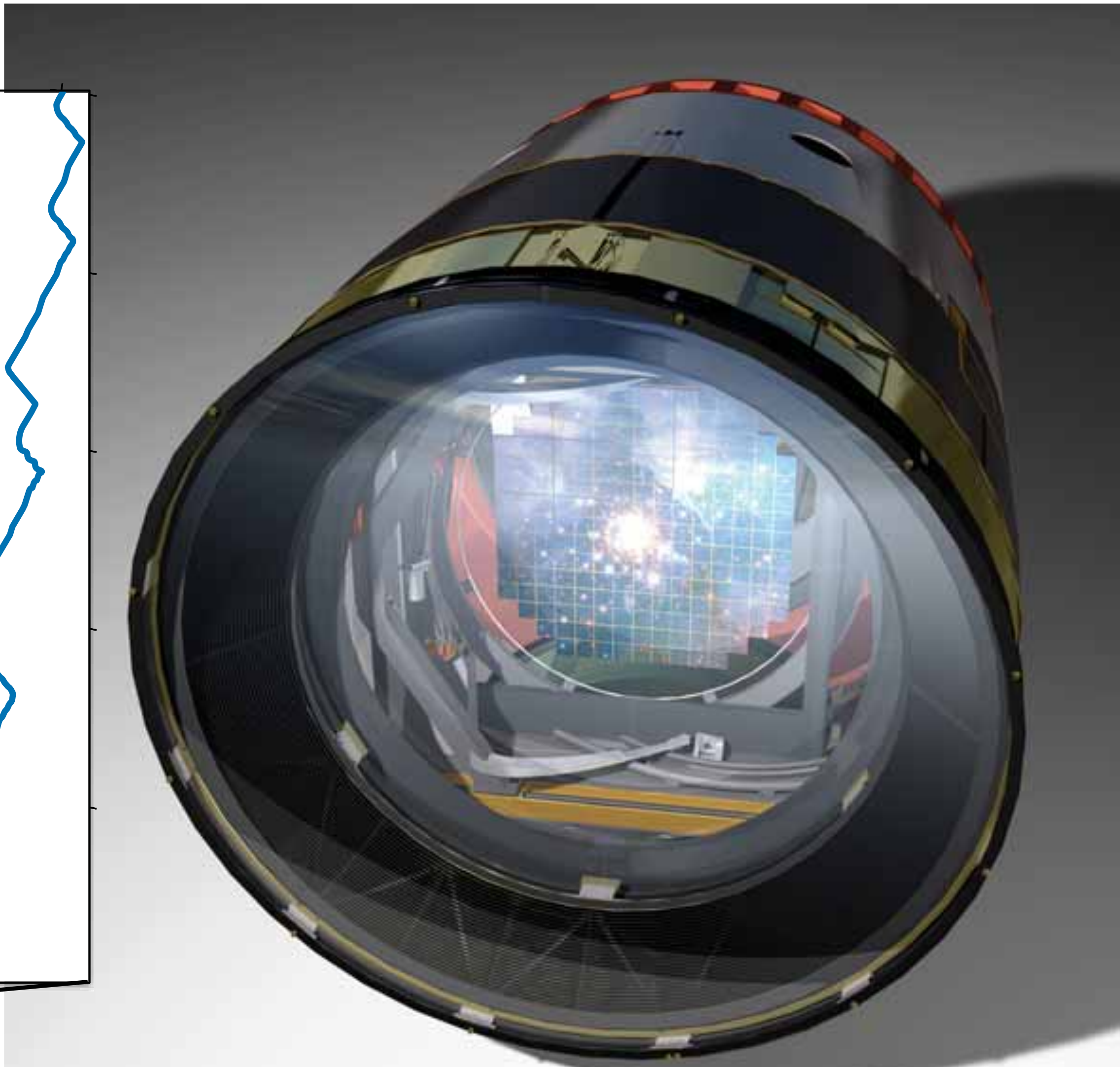


image: lsst.org


THANK YOU

CONCLUSIONS

LIGO-India will produce a paradigm shift in multimessenger GW astronomy.
It will transform the heroic follow-up campaigns of today to routine observation (and discovery!) of EM counterparts of neutron star binary mergers.

But vocal participation in international astronomy collaborations (e.g. LSST, SKA) is a must!

Many potential EM counterparts are fast, faint, and peak at challenging wavelengths.
It will take a convergence of wide-field surveys (LSST) with other next-generation ground and space based facilities to find them.

Can multimessenger observations of LIGO sources provide scientific output even in the absence of an EM counterpart (e.g. spatial correlation of localizations with nearby galaxies or large scale structure)?