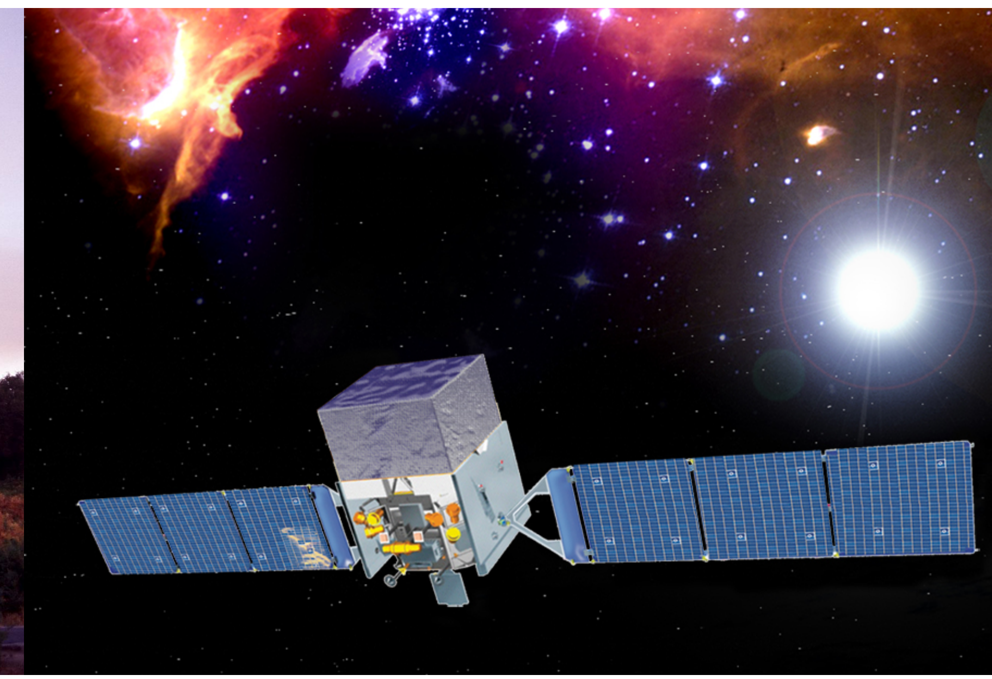
ADVANCED LIGO FIRST LIGHT

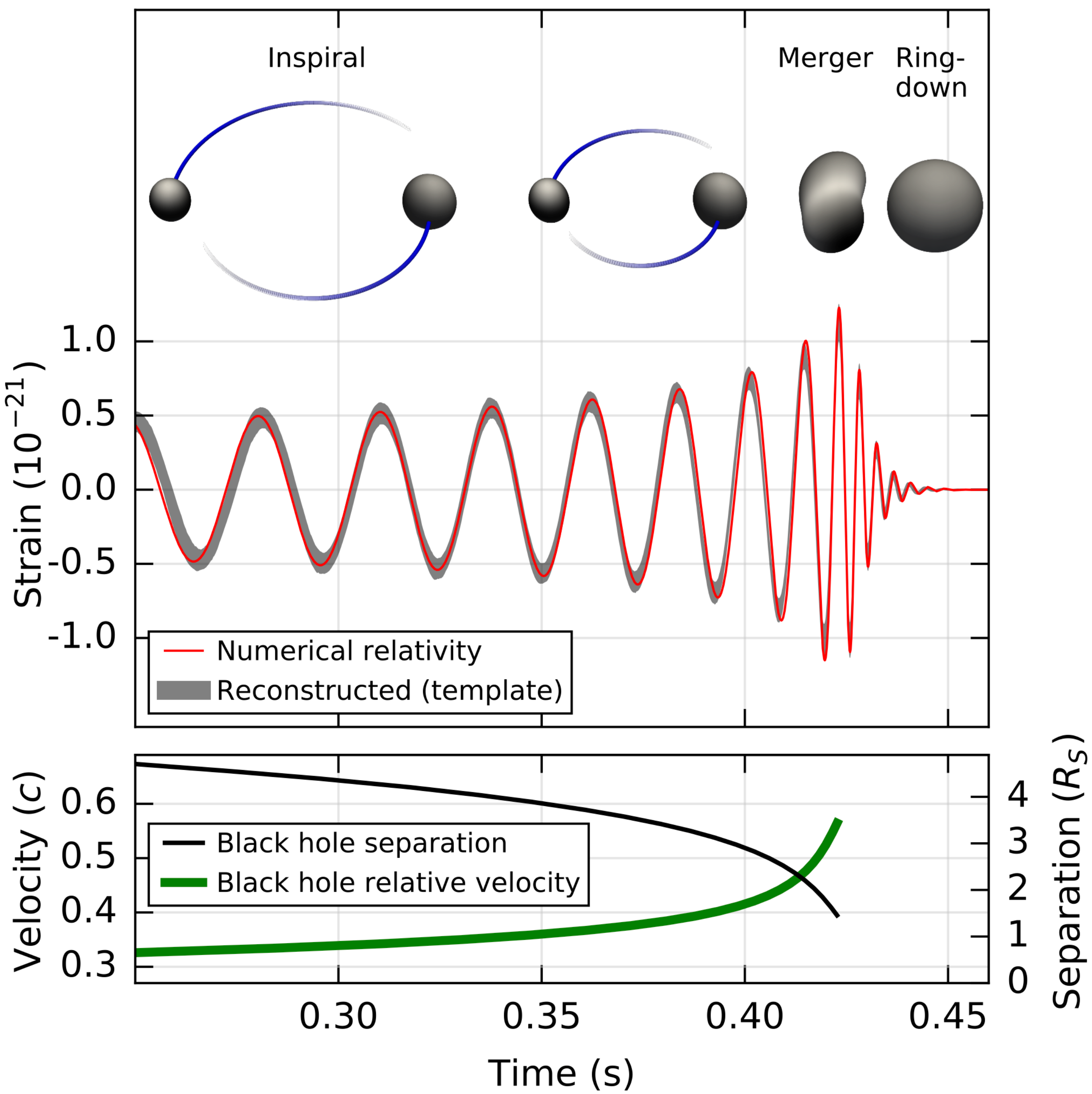
ASTROPHYSICS IN THE AGE OF GRAVITATIONAL WAVE OBSERVATORIES





LEO P. SINGER / NASA Postdoctoral Fellow
NASA Goddard Space Flight Center
leo.p.singer@nasa.gov

GW150914: **first light**



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

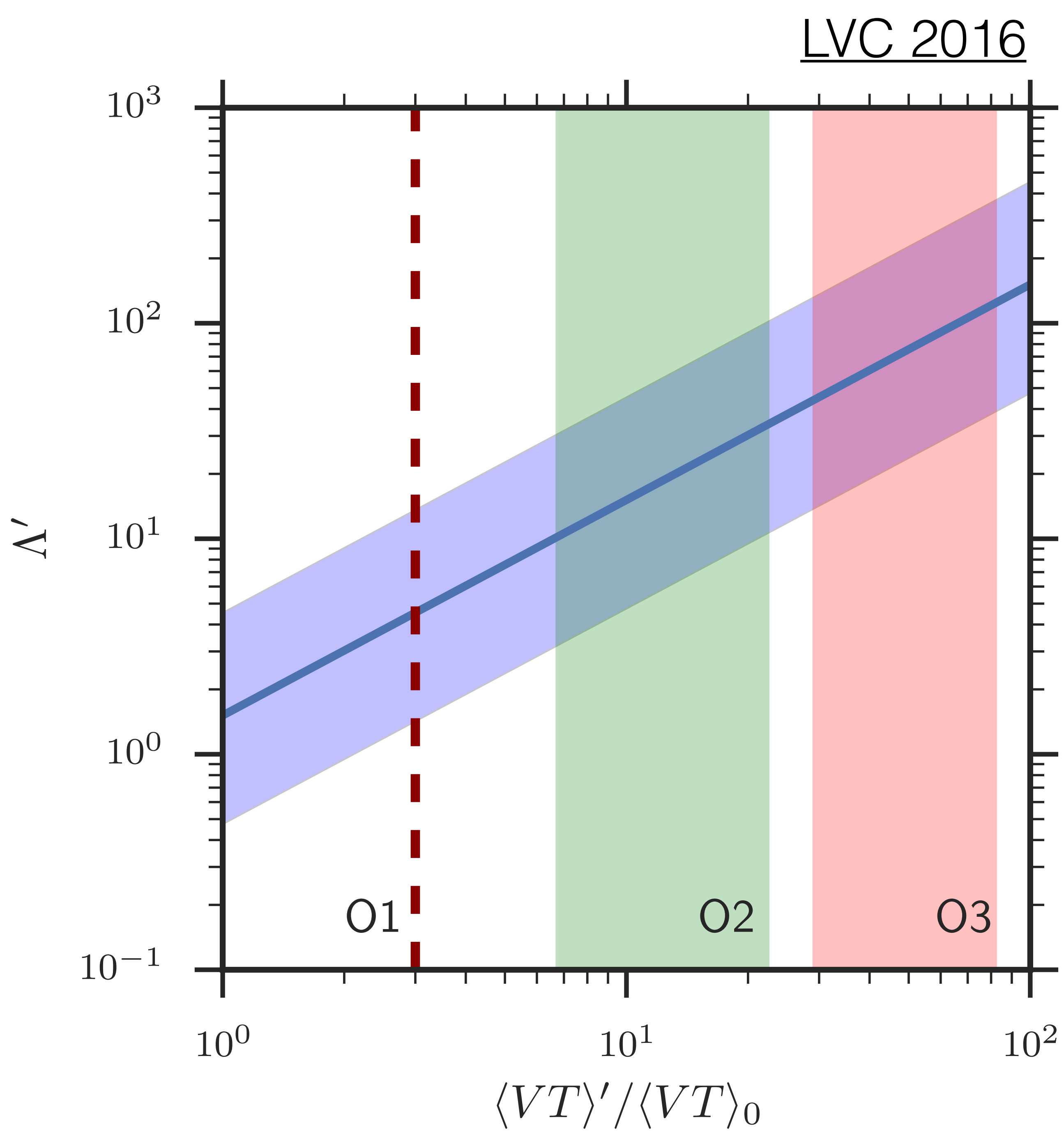
  much heavier than BHs known in X-ray binaries → low-metallicity formation scenario

  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: $\lambda_g > 10^{13}$ km, $m_g < 10^{-22}$ eV

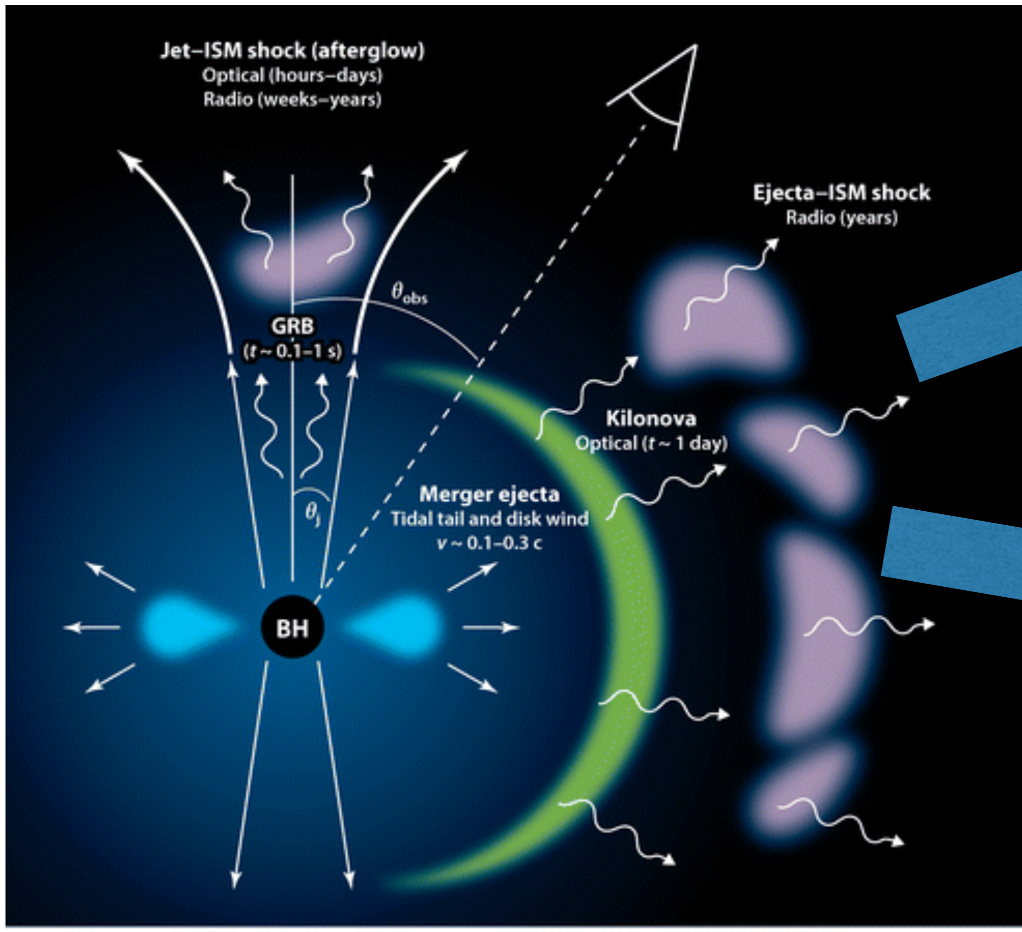
What will we find in the next year of LIGO observation?



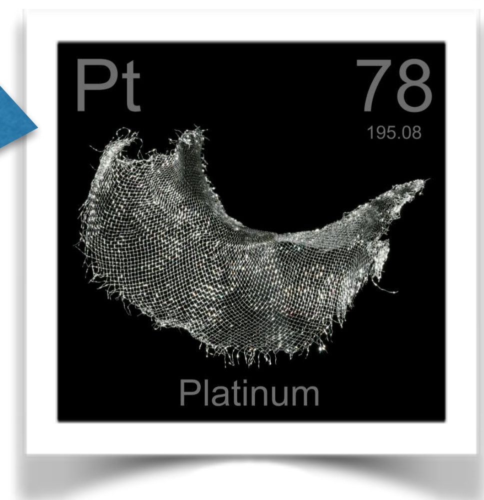
- Based on O1:
  ~10 BBHs by O2, ~100 by O3 ***(!!)***
- History of stellar BH masses and spins **through cosmic time**

  → Compare with pop. synth to indirectly deduce host properties (though small lever arm of z~0.1–0.3)
- Much *more* exciting:
  asymmetric masses, spin precession, **binary neutron star** and **neutron star–black hole** mergers

The future is ***bright!***



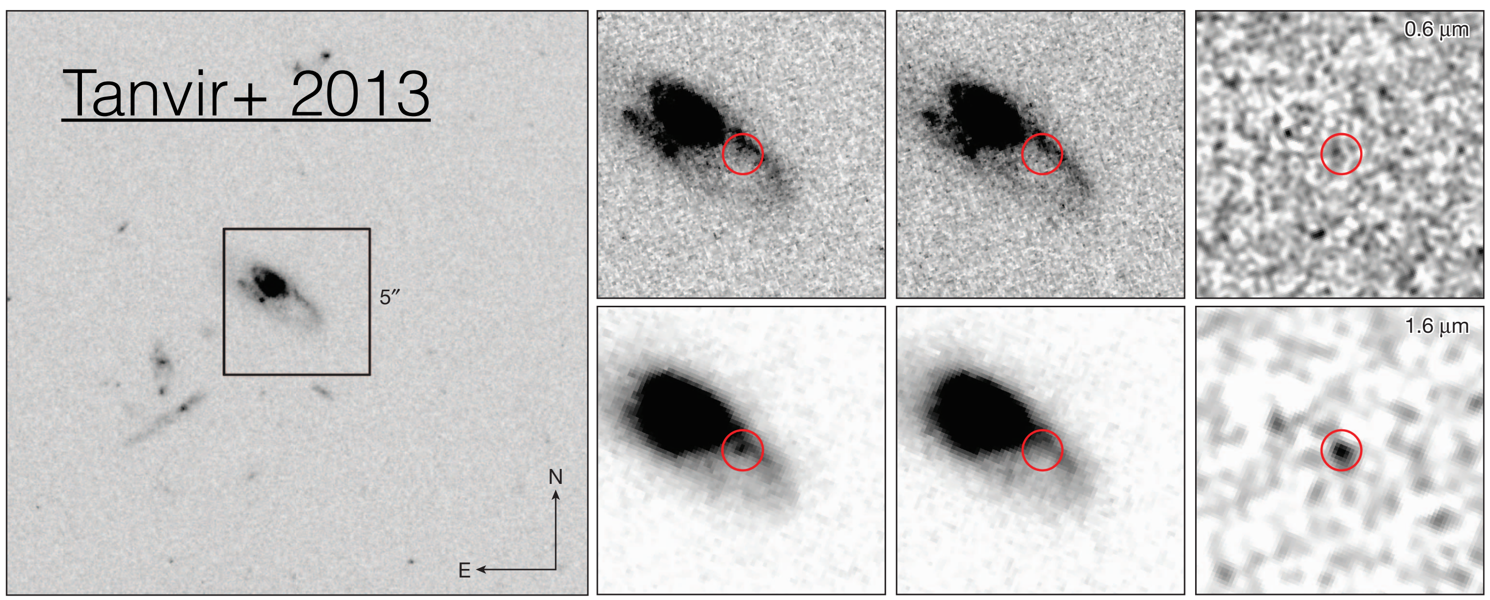
Berger E. 2014.
Annu. Rev. Astron. Astrophys. 52:43–105

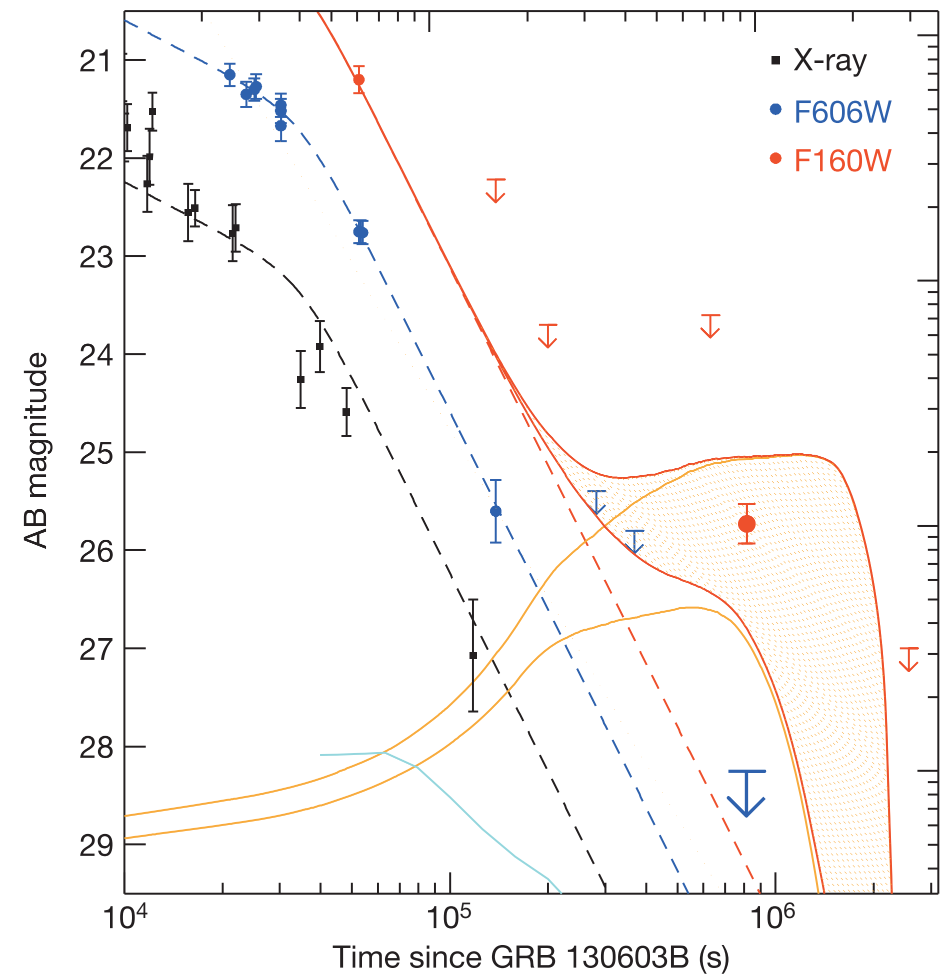


- **EM counterparts of LIGO sources**
- **Central engine** vs. **external fireball** and ejecta
- **Pinpoint host galaxy**, determine formation environment
- **Standard sirens**: Calibration-free rung on cosmological distance ladder
- Explain cosmic abundance of heavy elements – **“bling nova”**
- Explain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

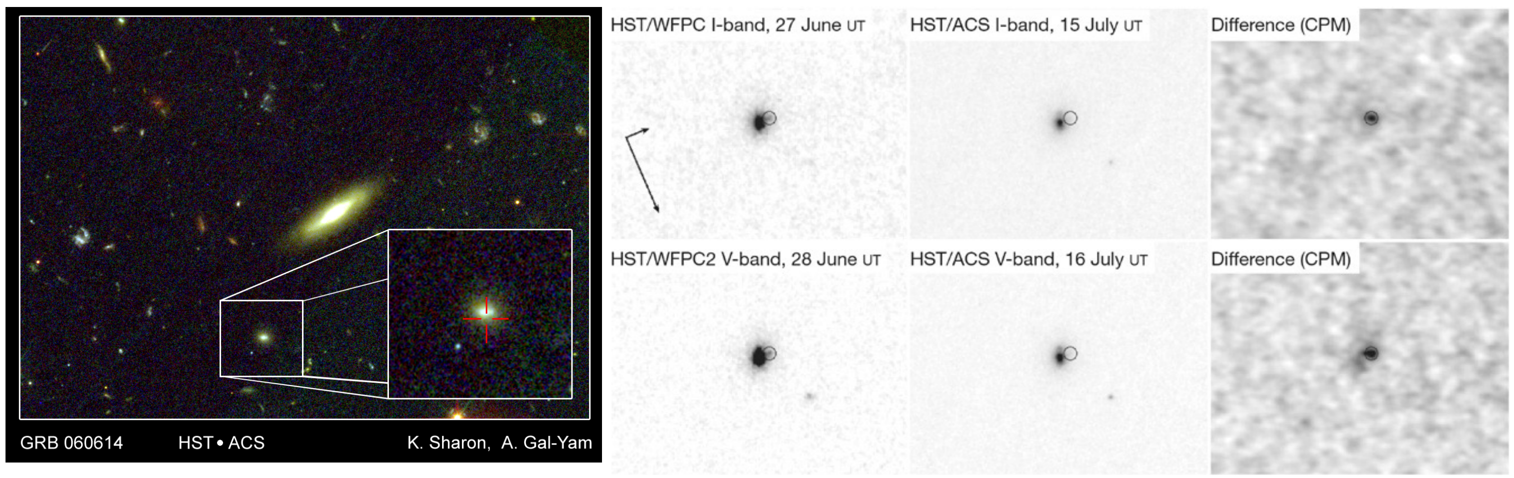
Understanding **the full astrophysical richness of compact binaries** will take not just LIGO, but the broad astronomy community across many wavelengths!

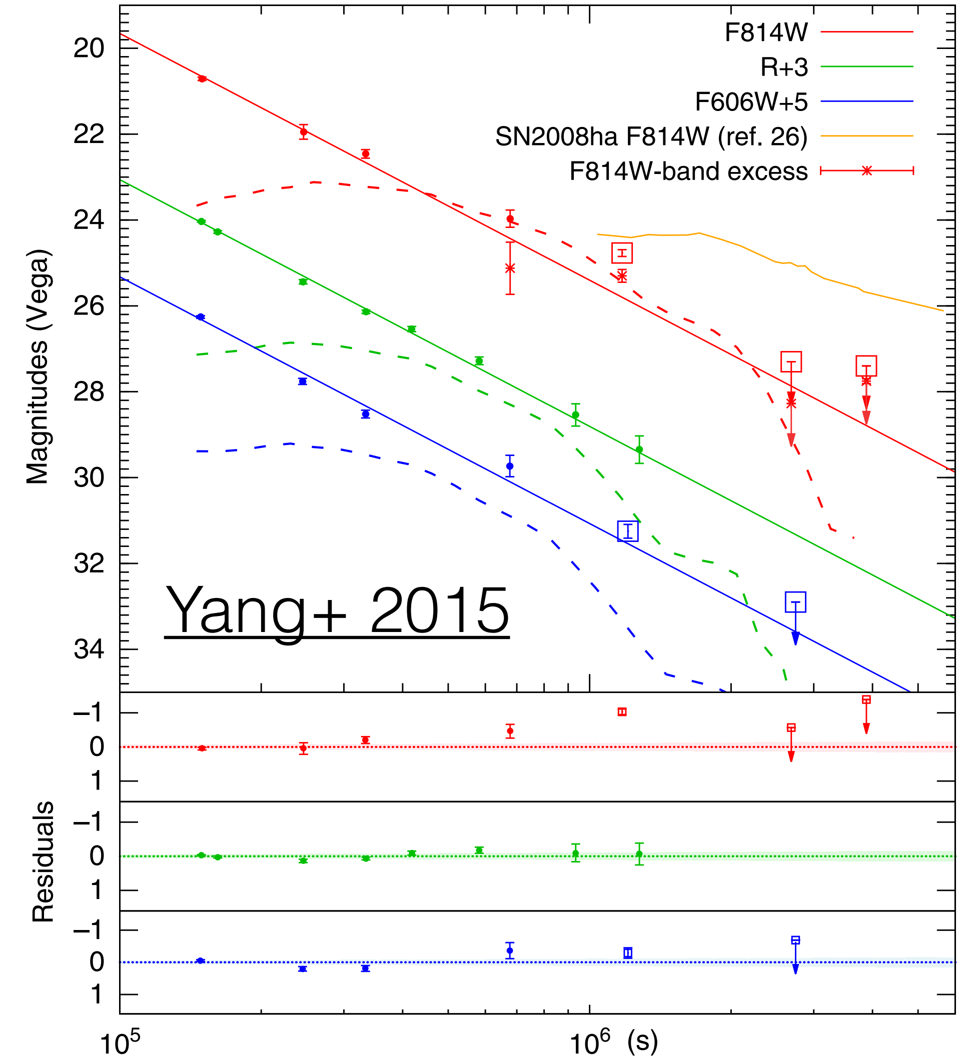
GRB 130603B:
a smoking gun



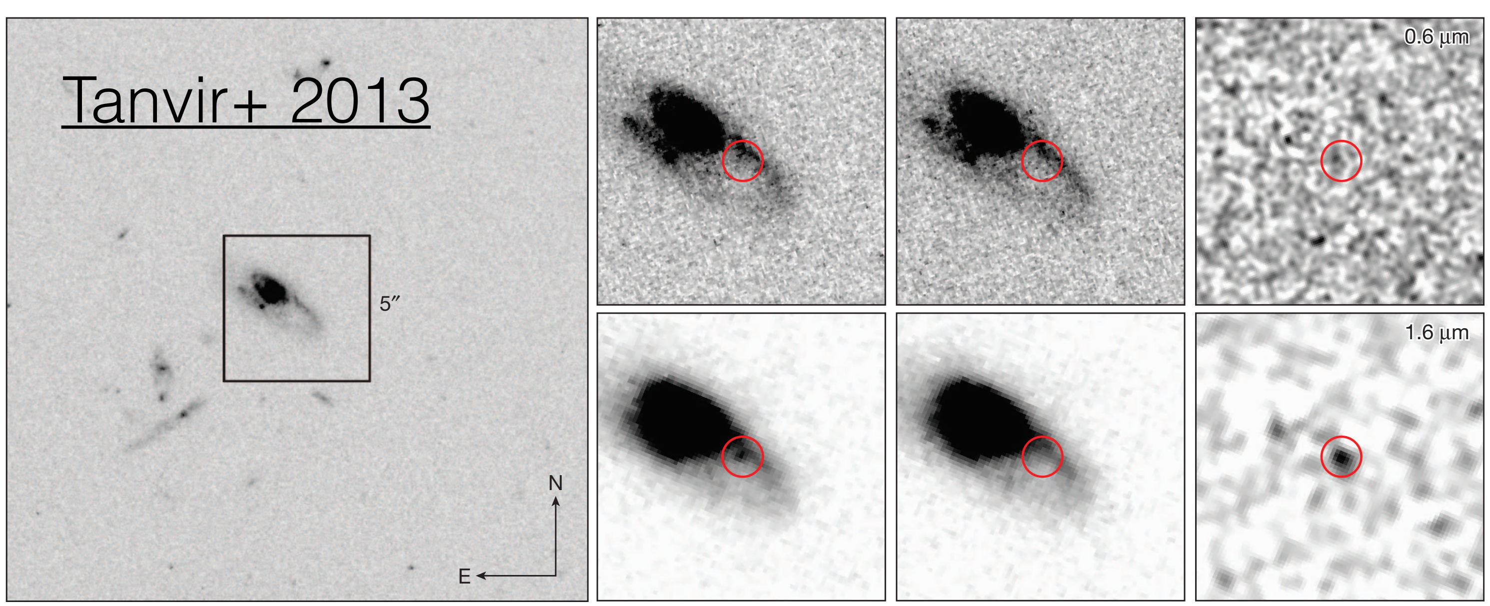


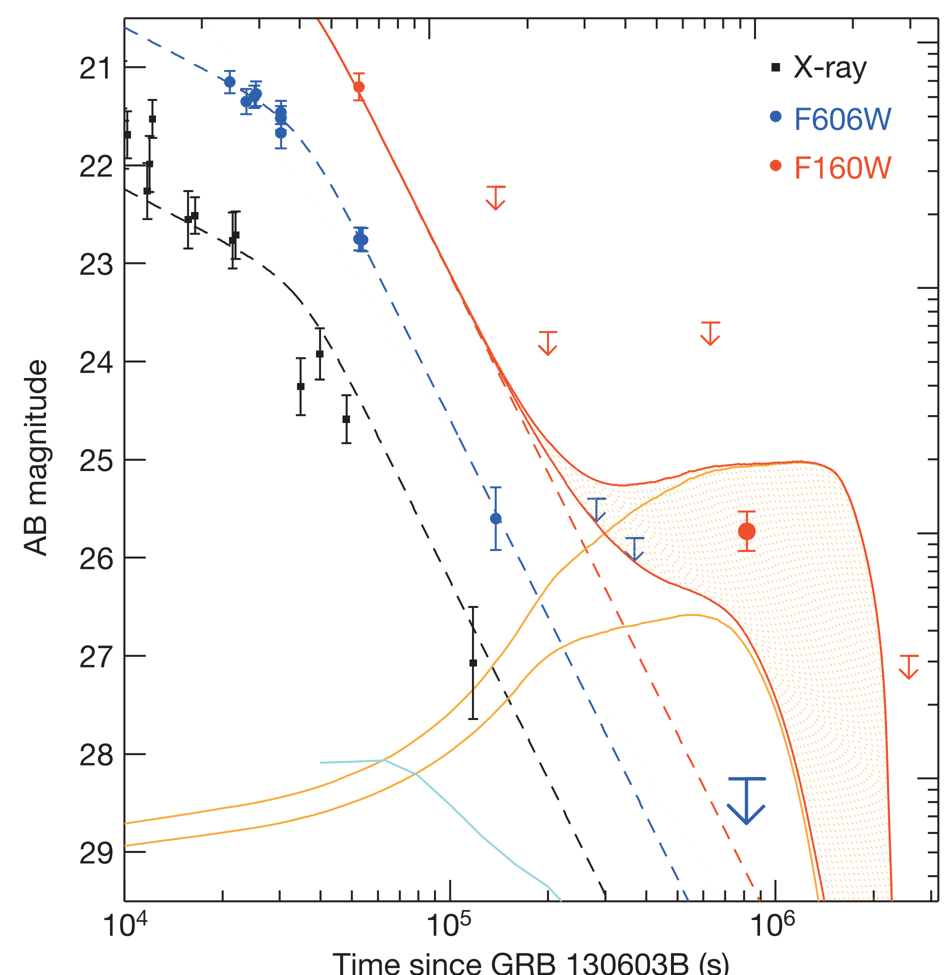
GRB 060614:
a short GRB in disguise?





GRB 130603B:
a smoking gun

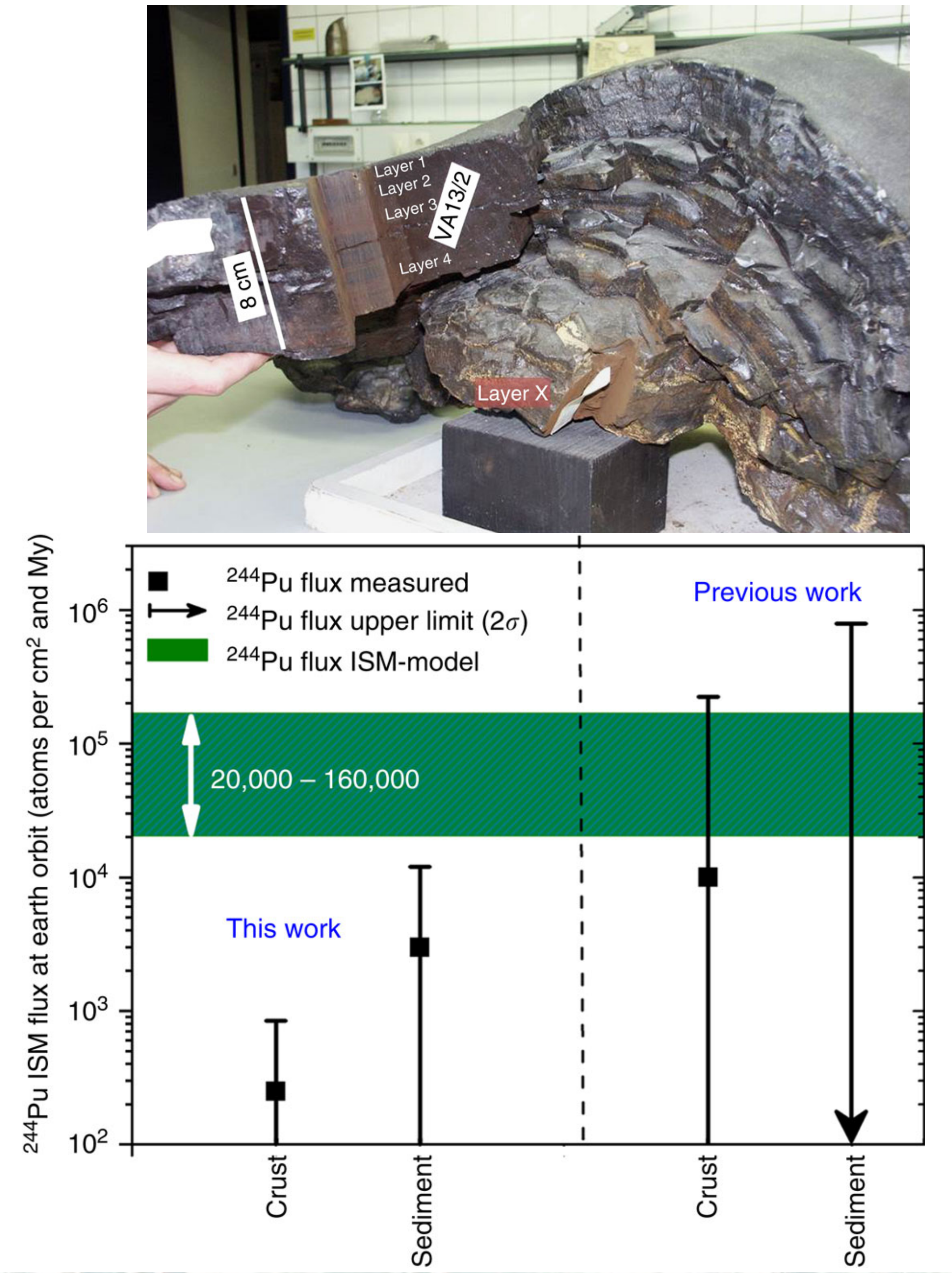




TO FIND NEUTRON STAR MERGERS, **look no further than the sea**

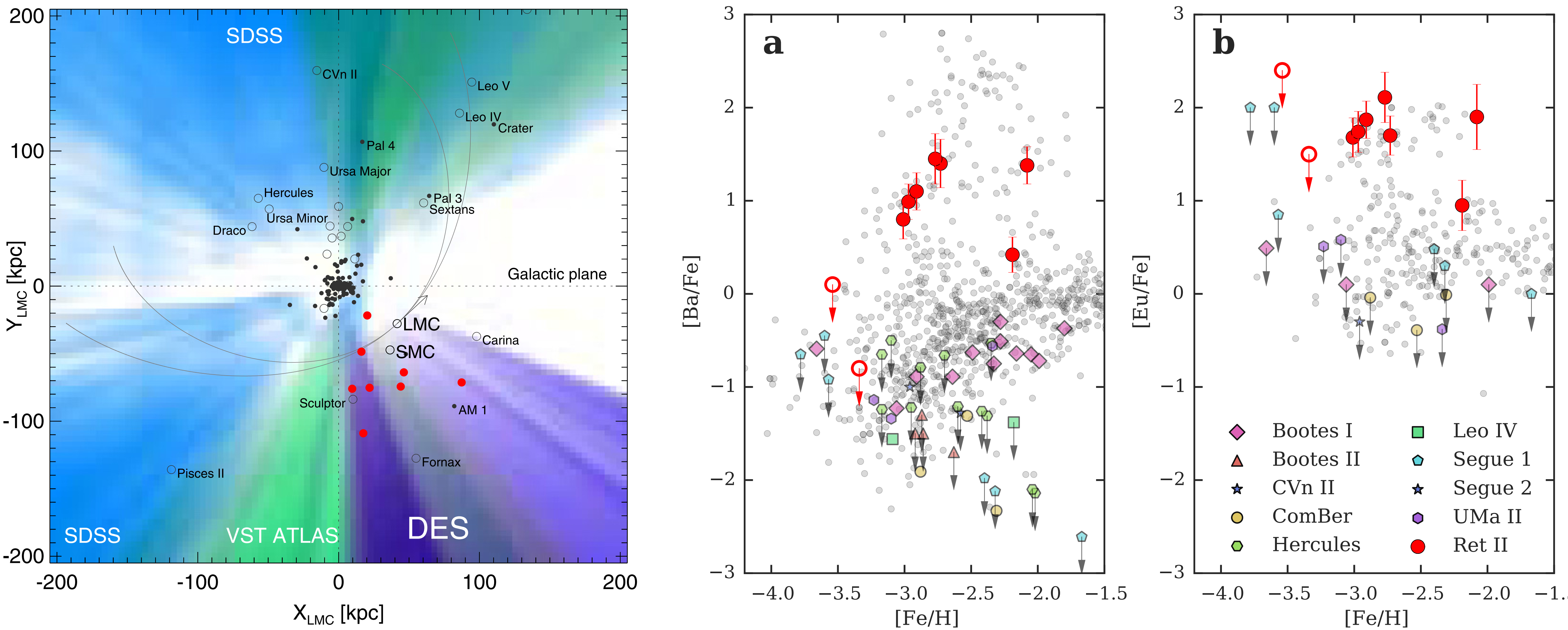
- Concentration of ^{244}**Pu** in deep-sea sedimentary rock
- Half-life = 85 My, so no active contribution from solar system
- Lower concentration than expected for r-process dominated by supernovae (Wallner+ 2015)
- Low-rate, high-yield process preferred over high-rate, low-yield process → **NS binaries**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

Wallner+ 2015



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

Ji+ 2016



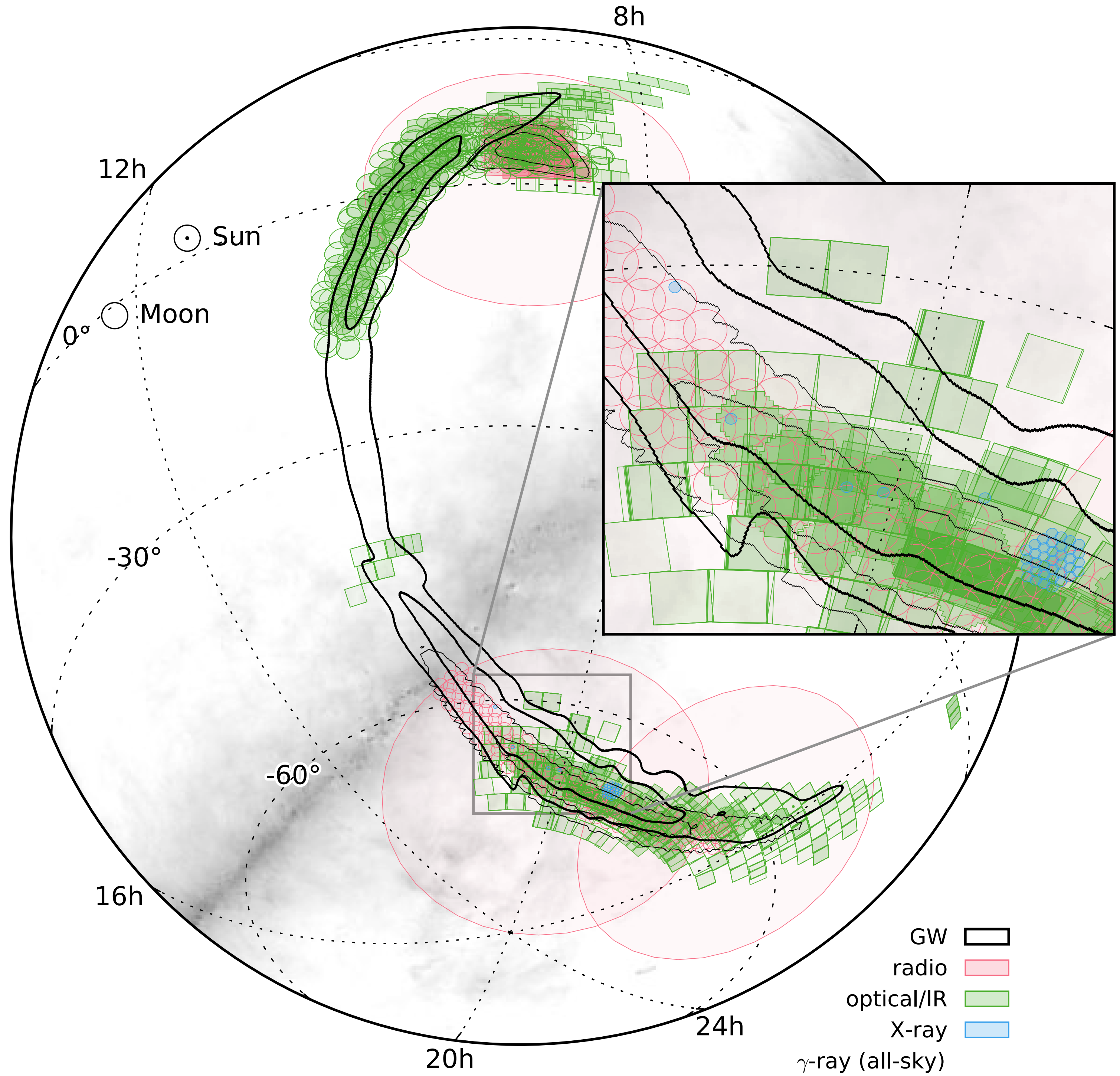
Ultra-faint dwarf galaxy Reticulum II discovered by Dark Energy Survey, has 2–3 orders of magnitude higher abundances of *r*-process elements than other MW satellites → evidence for ***a single r-process enrichment event***

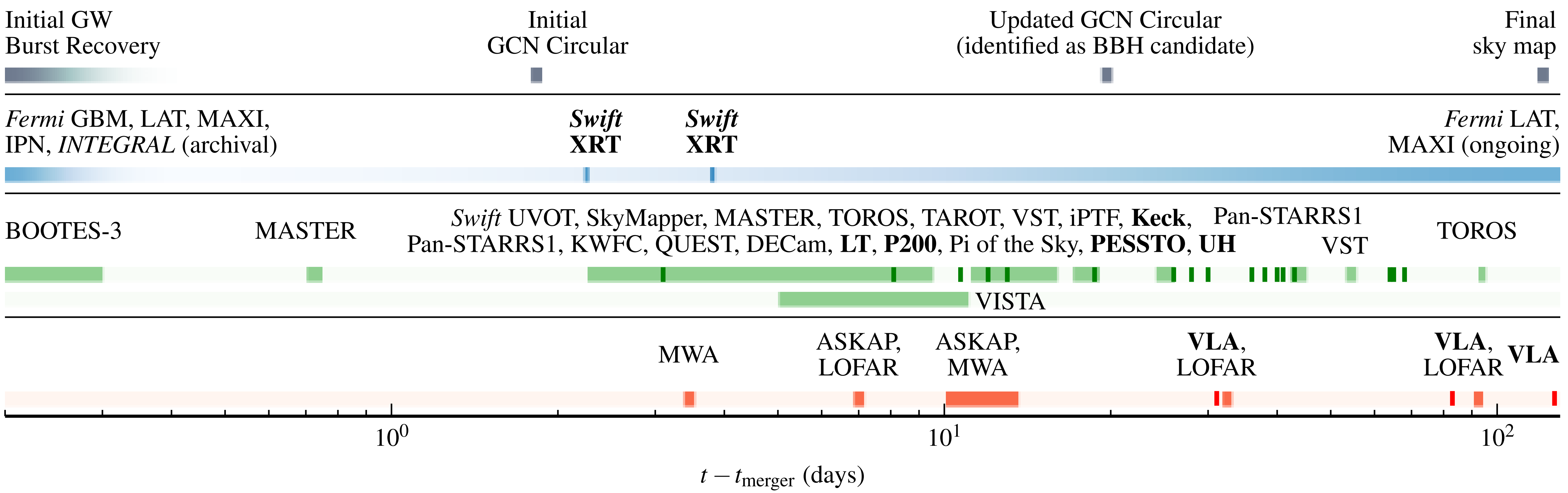
LOCALIZATION AND BROADBAND FOLLOW-UP

OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

ApJL, in press

arXiv:1602.08492





LOCALIZATION AND BROADBAND FOLLOW-UP

OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

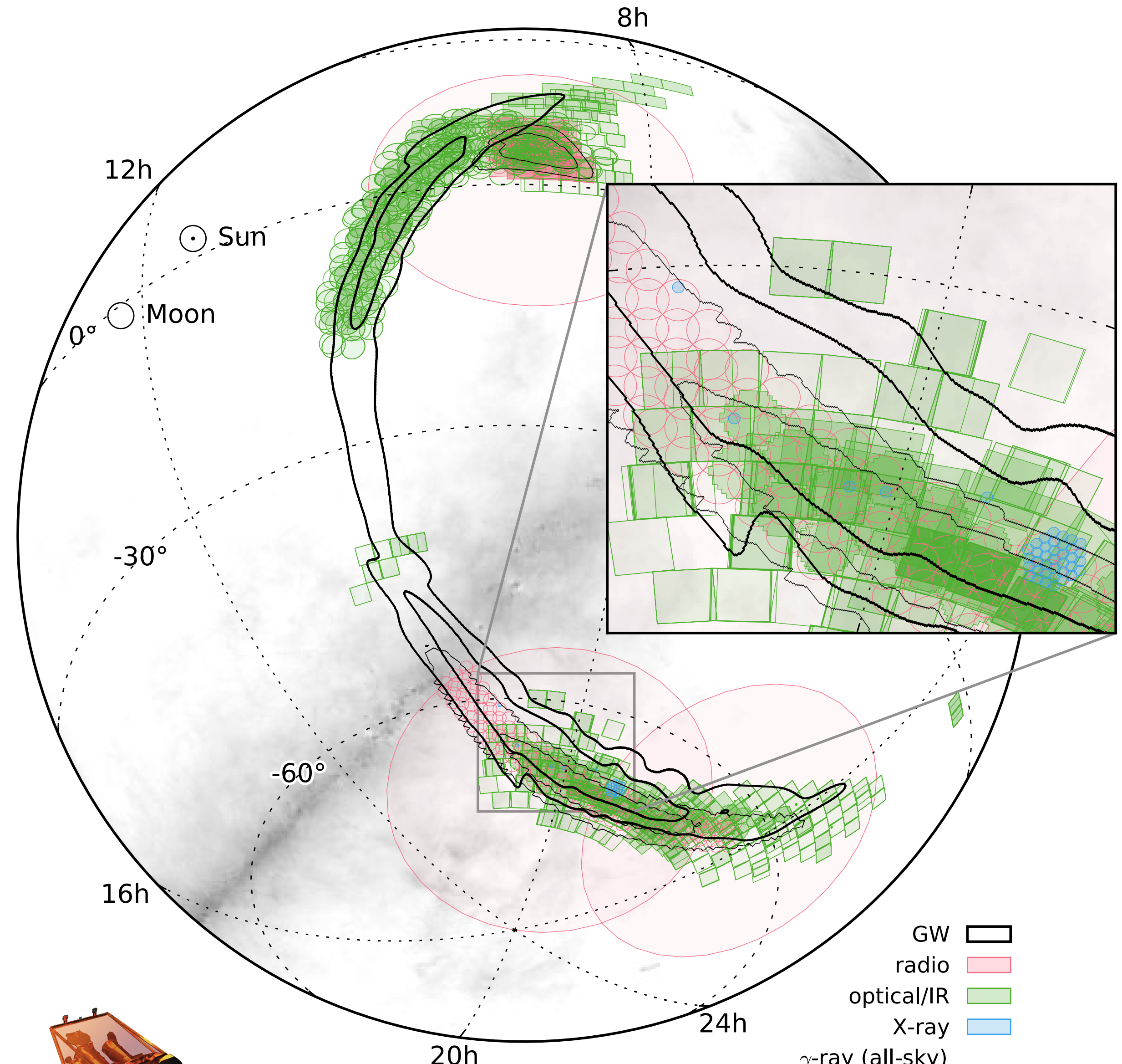
25 observing teams (+LIGO, Virgo), **1551 authors**

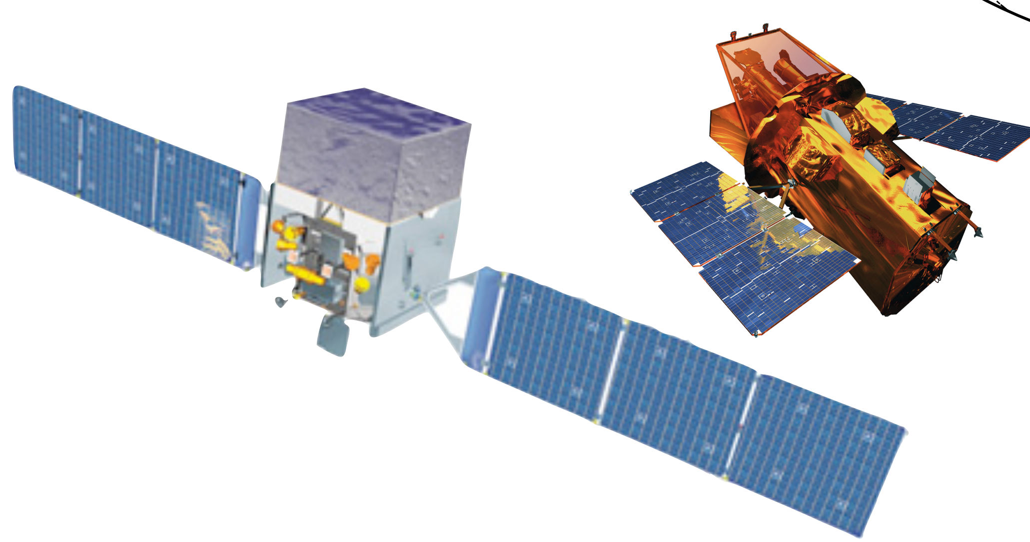
unprecedented: *broke ApJL author portal!*

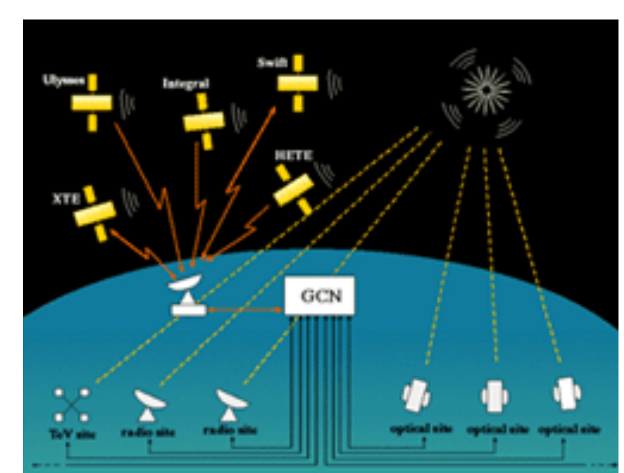
ASKAP, LOFAR, MWA, Fermi/GBM, Fermi/LAT, INTEGRAL, IPN, Swift, MAXI, BOOTES, MASTER, Pi of the Sky, DES/DECam, INAF/GRAWITA, **iPTF**, J-GEM/KWFC, La Silla–QUEST, Liverpool Telescope, PESSTO, Pan-STARRS, SkyMapper, TAROT, Zadko, TOROS, VISTA

Localization and **broadband follow-up** of the first LIGO event

- Consortium between LIGO and 63 teams using ground and space facilities
- Gamma-ray, X-ray, optical, infrared, and radio wavelengths
- Key NASA contributions come from high-energy observational assets: ***Fermi***, ***Swift***, ***GCN network***







SELECTED HIGHLIGHTS **from O1**
localization + follow-up campaign

- **Prompt, accurate localization of the first LIGO signal**
  (although LIGO/Virgo alert sent two days late)

- **Possible γ-ray transient** (*Fermi* GBM, though not seen by *INTEGRAL* SPI-ACS)
  Connaughton+ 2016, Savchenko+ 2016

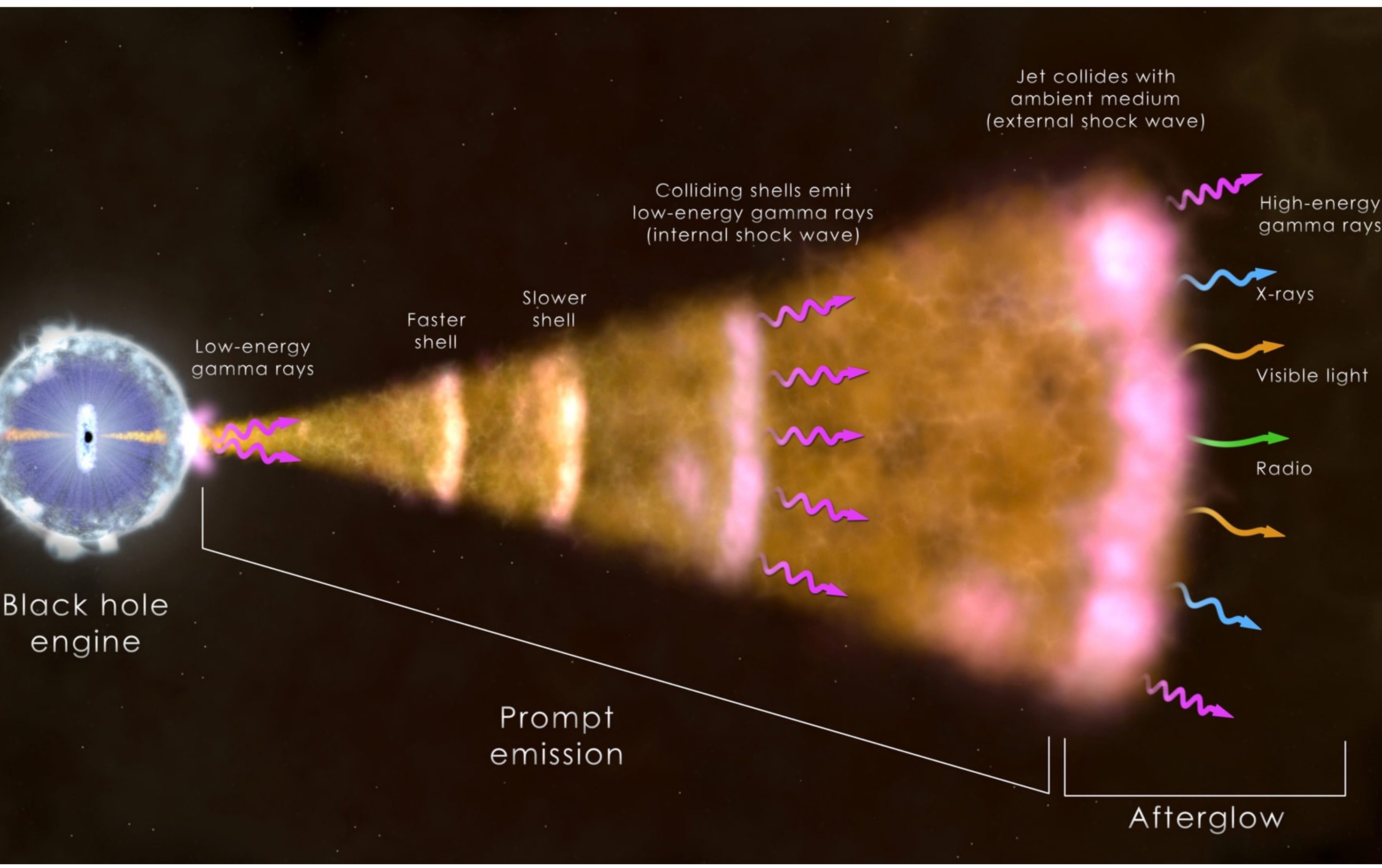
- **Follow-up of nearby galaxies with *Swift* XRT**
  Evans, Kennea, Barthelmey+ 2016

- **DECam search for failed missing supergiants/failed SN** in LMC
  Annis+ 2016

- **Keck spectroscopy of iPTF candidates <1 hr after discovery images; superluminous supernova** discovered in iPTF follow-up
  Kasliwal, Cenko, Singer+ 2016

- **DECam** (Soares-Santos+), ***AGILE*** (Tavani+), ***XMM*** (Troja+), ***Fermi* LAT** (LAT Collab.), **Pan-STARRS/PESSTO** (Smartt+), +**many more** in preparation

Bootstrap with model problem: *Fermi* gamma-ray bursts



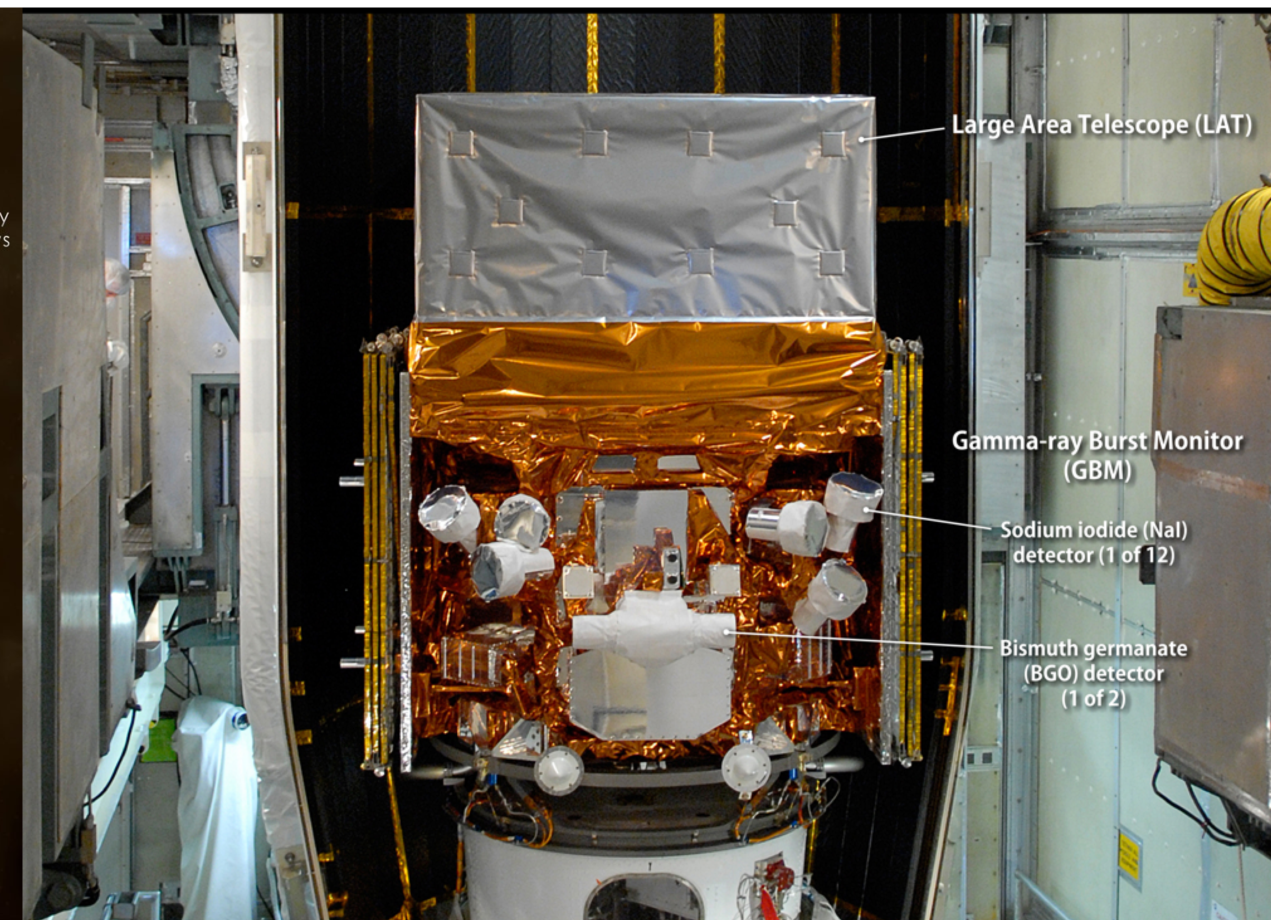
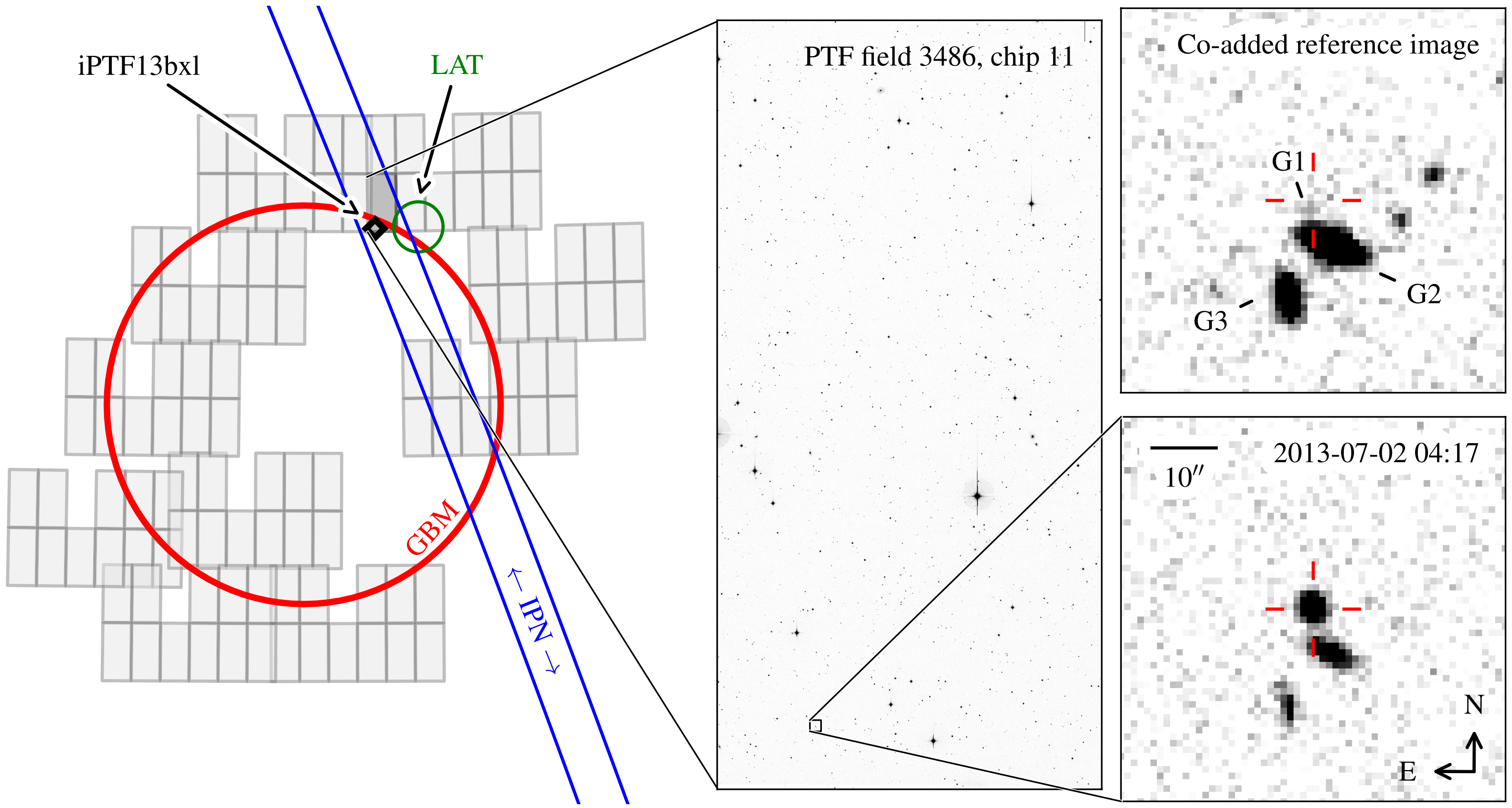


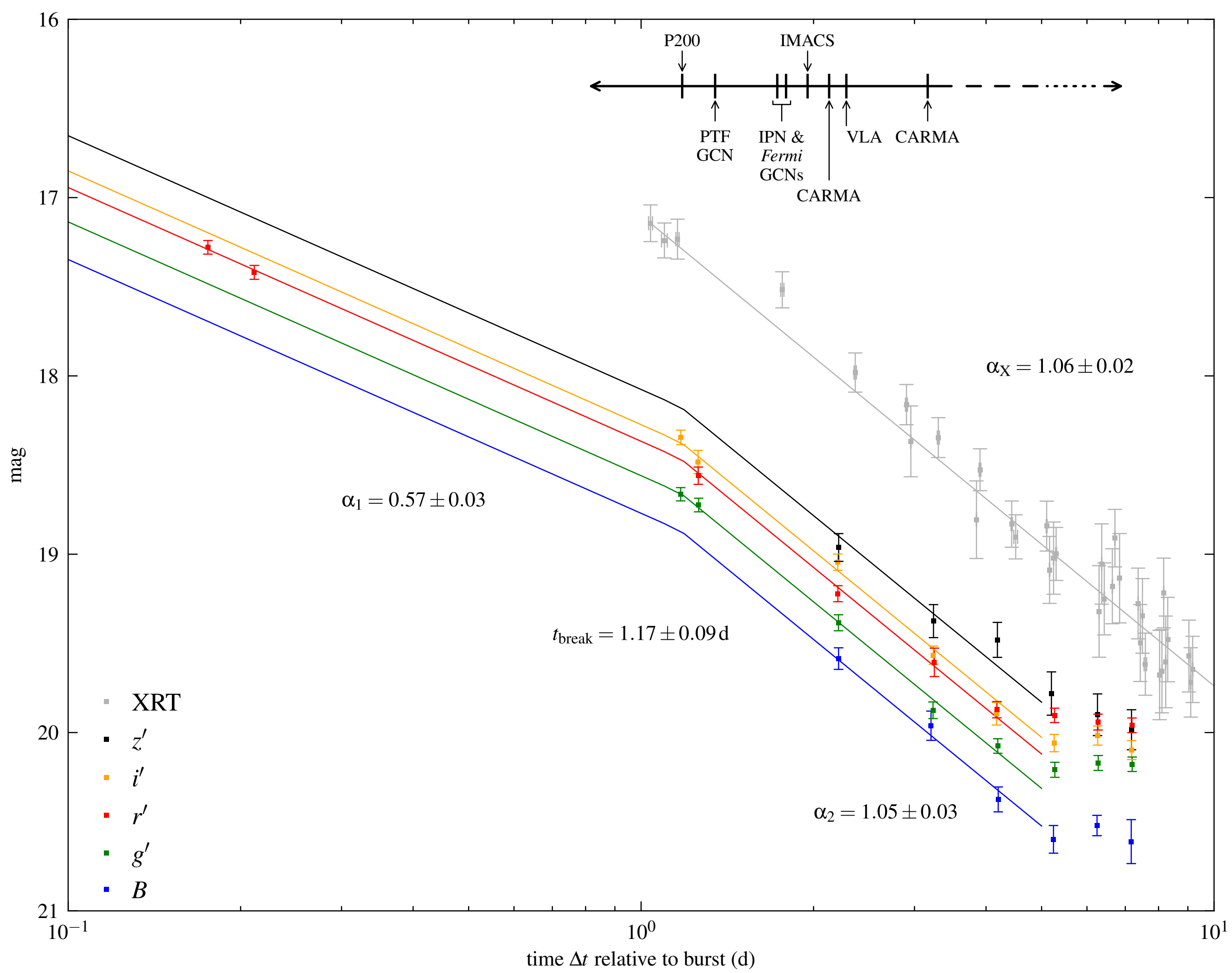
Image credit: NASA/Jim Grossmann
http://www.nasa.gov/mission_pages/GLAST/news/vision-improve.html

image: NASA/GSFC



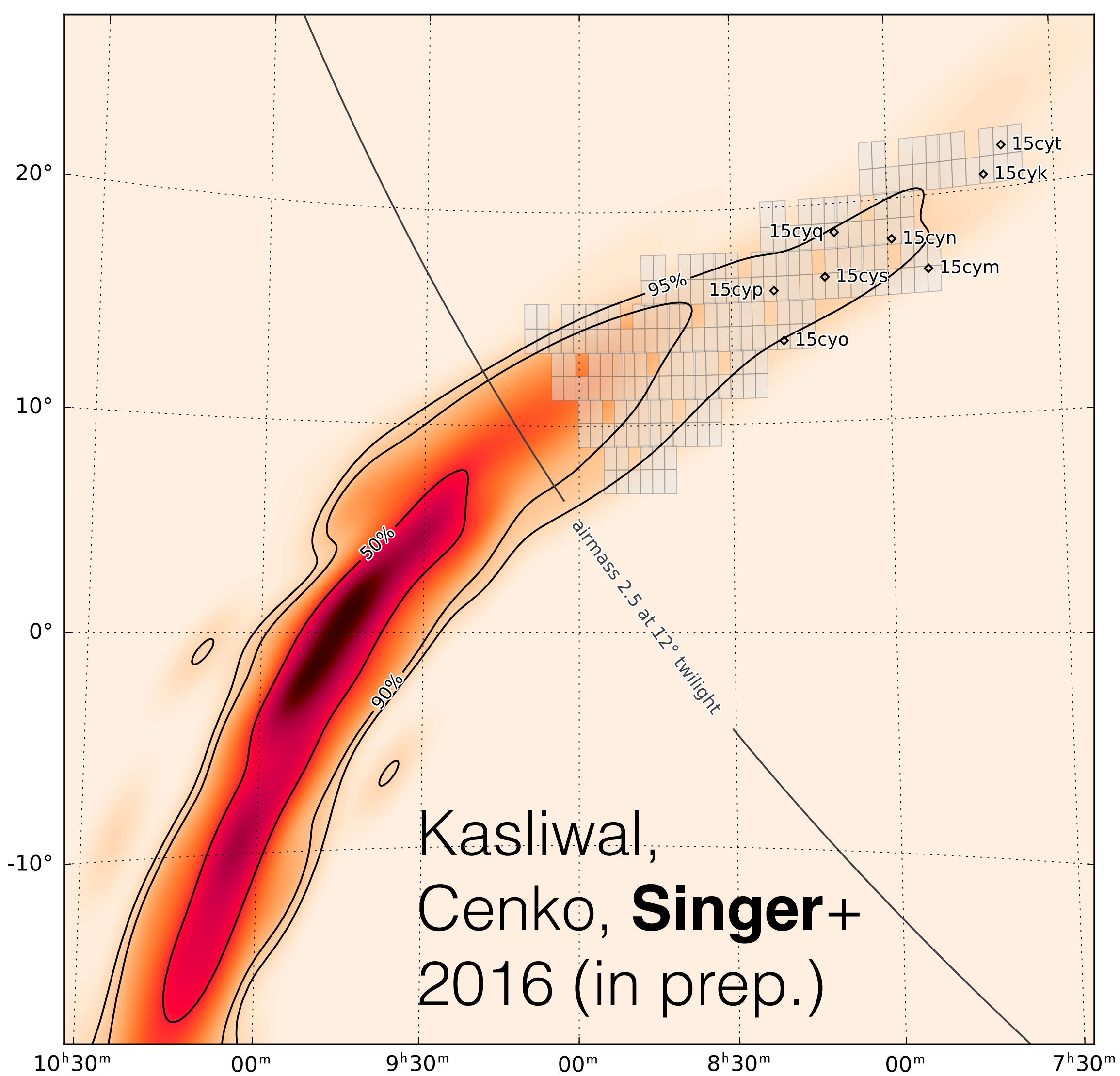
Discovery & redshift of a an optical afterglow in 71 deg²

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, … + Singer (2016)**
- **Detailed afterglow modeling**: A. J. van der Horst+
- 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, PhD thesis, PSU)

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

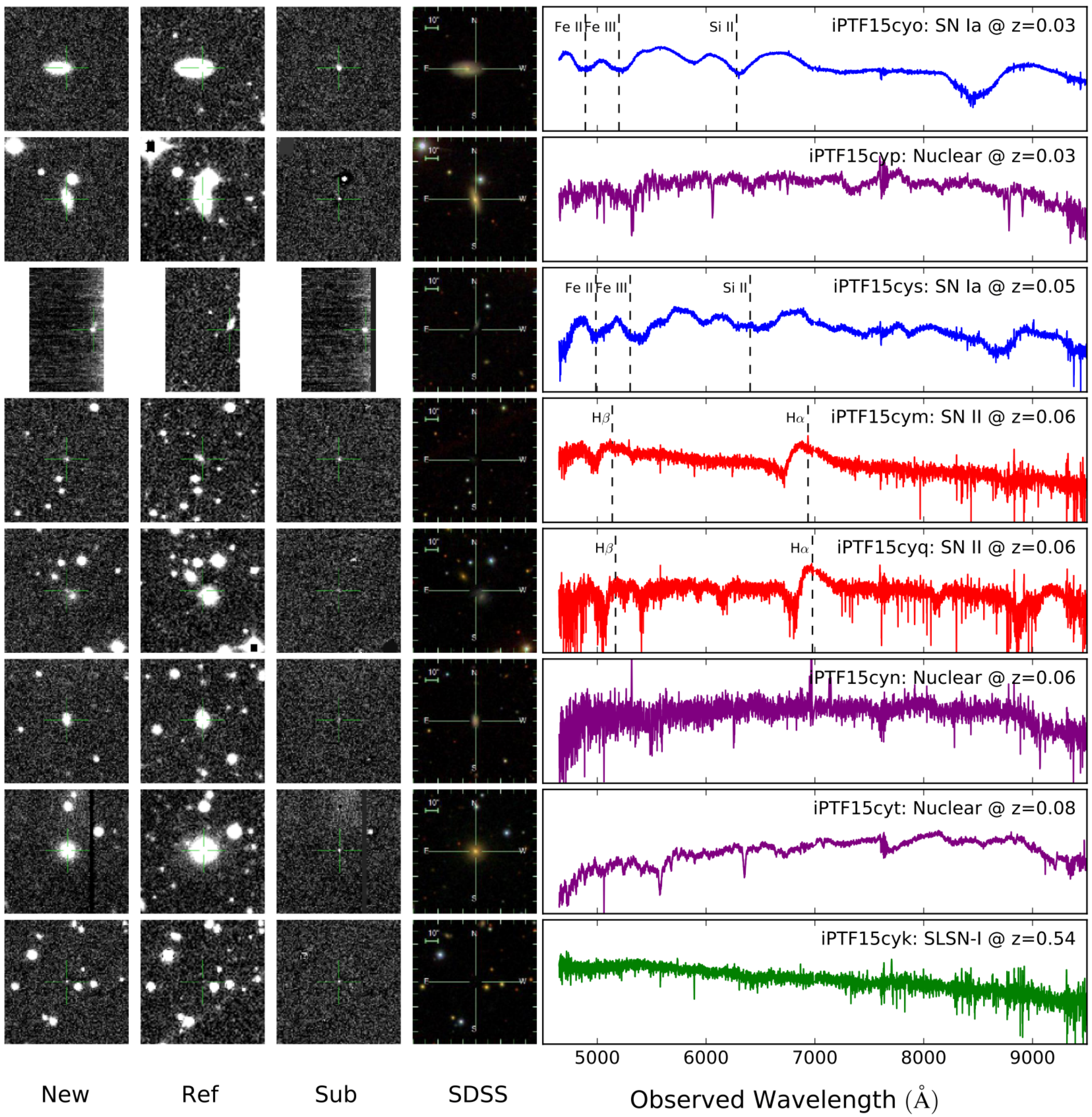



```
TITLE:   GCN CIRCULAR
NUMBER:  18337
SUBJECT: LIGO/Virgo G184098: iPTF Optical Transient Candidates
DATE:    15/09/20 01:39:01 GMT
FROM:    Leo Singer at NASA/GSFC  <leo.p.singer@nasa.gov>

[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).
```

Kasliwal, Cenko, Singer+ 2016 (ApJL, in press)

KECK CLASSIFICATION SPECTRA

less than an hour after discovery!



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>

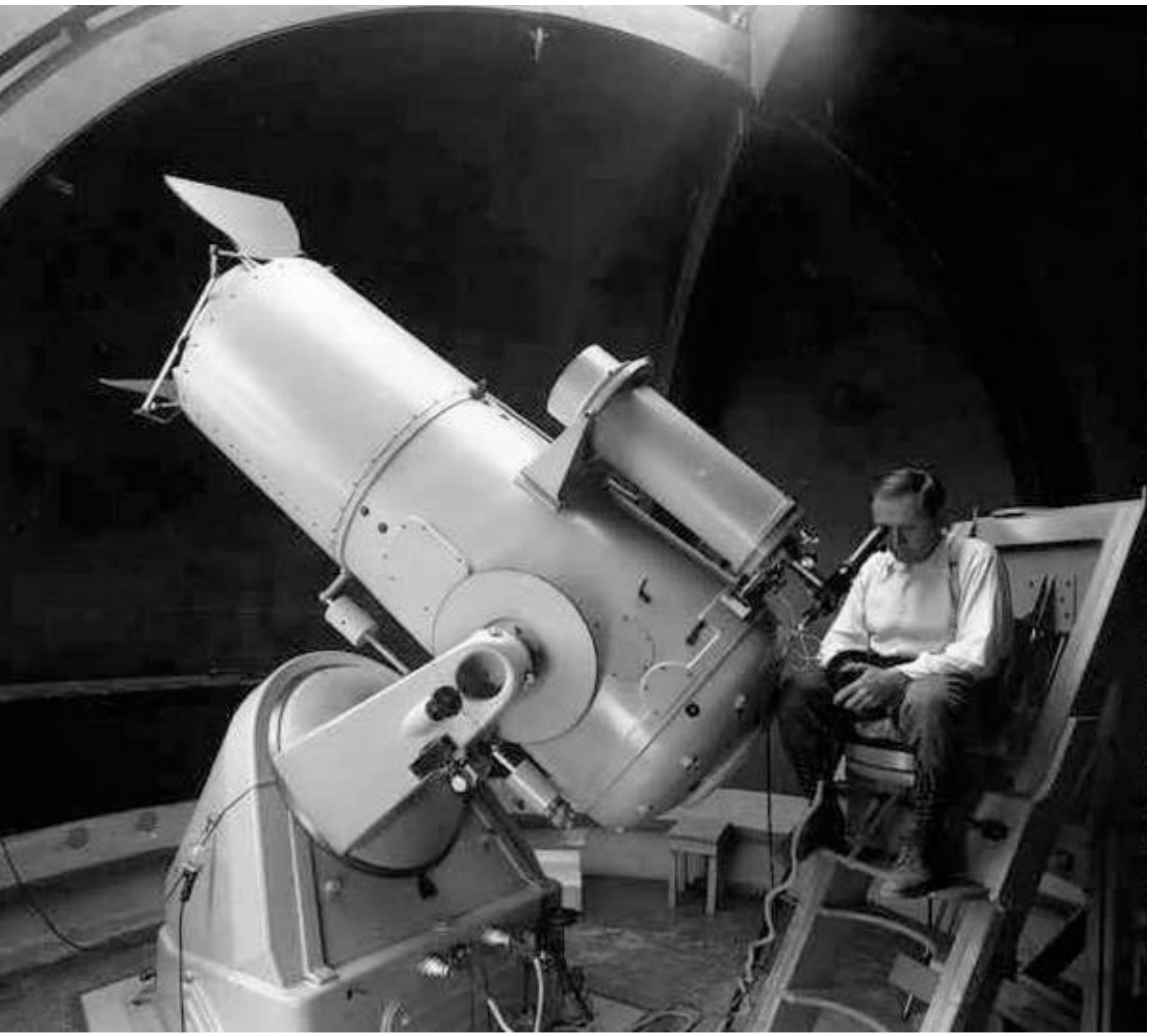
[GCN OPS NOTE(19sep15): This Circular was originally published on 09:28 18-Sep-2015 UT.]

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.

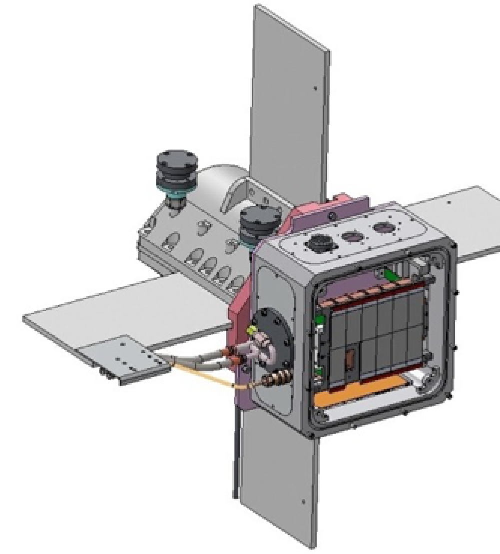


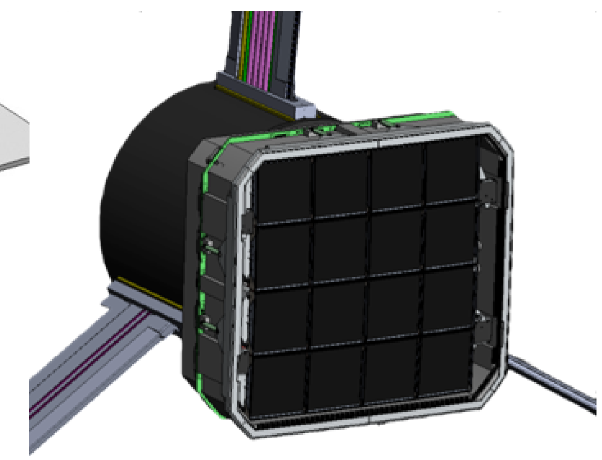
THE ZWICKY TRANSIENT FACILITY

ipac Caltech DESY Los Alamos NATIONAL LABORATORY EST.1943 Oskar Klein centre

UST UWM מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE UNIVERSITY OF MARYLAND 1856 POMONA COLLEGE 1887 NSF

Zwicky Transient Facility





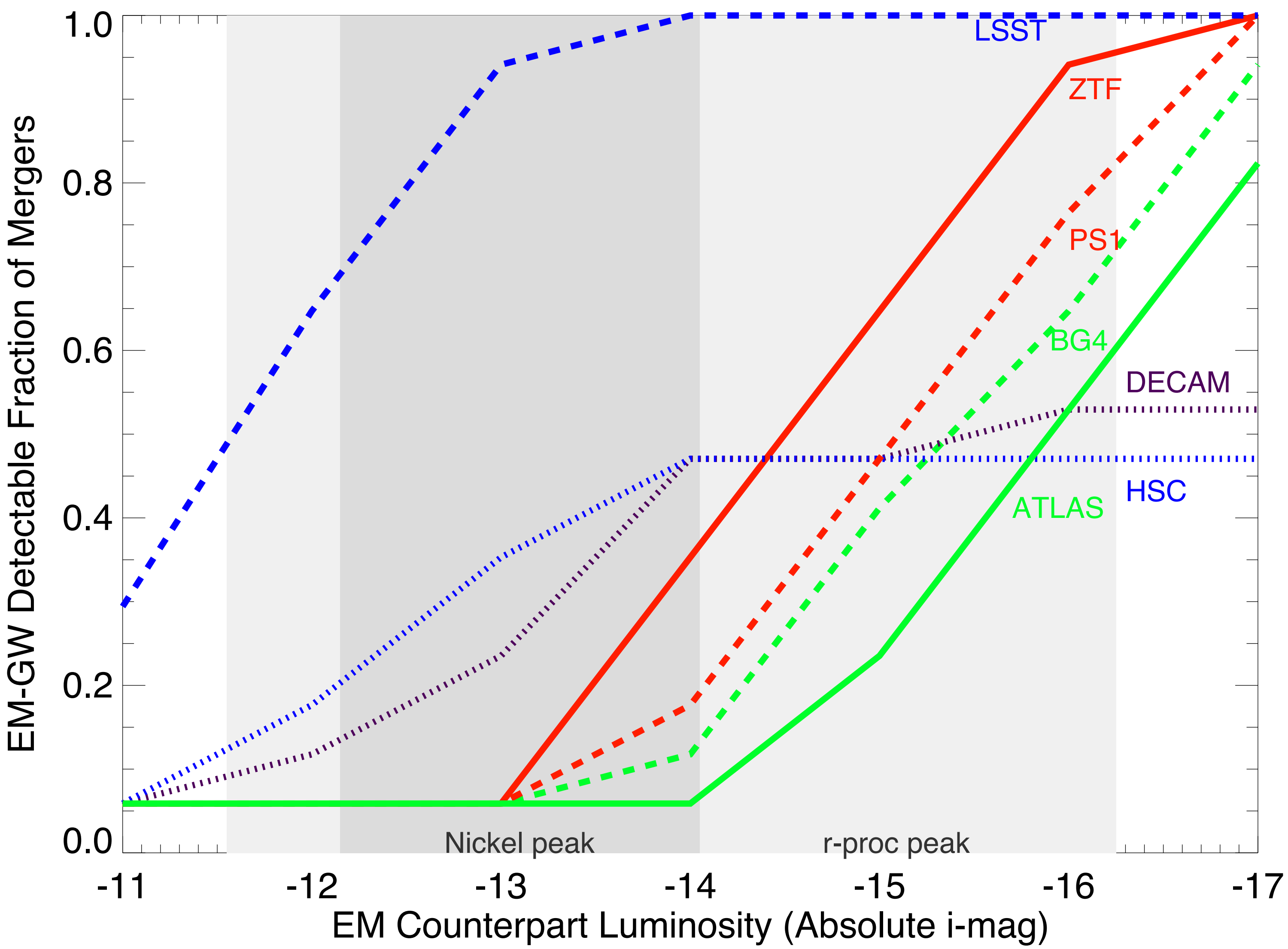
- New camera, 7x larger FOV,
  order of magnitude faster survey rate
- 3800 deg2/hour ⇒ 3π survey in 8 hours
- Faster readout for deep co-adds,
  guide camera for long exposures
- New real-time P48 pipeline at IPAC based on PTF science archive calibration, being deployed now
- More filters: *g r* (*i*)
- Improved real/bogus classification
  →higher purity discovery stream
- In process of adapting TOO Marshal for GW events

	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**

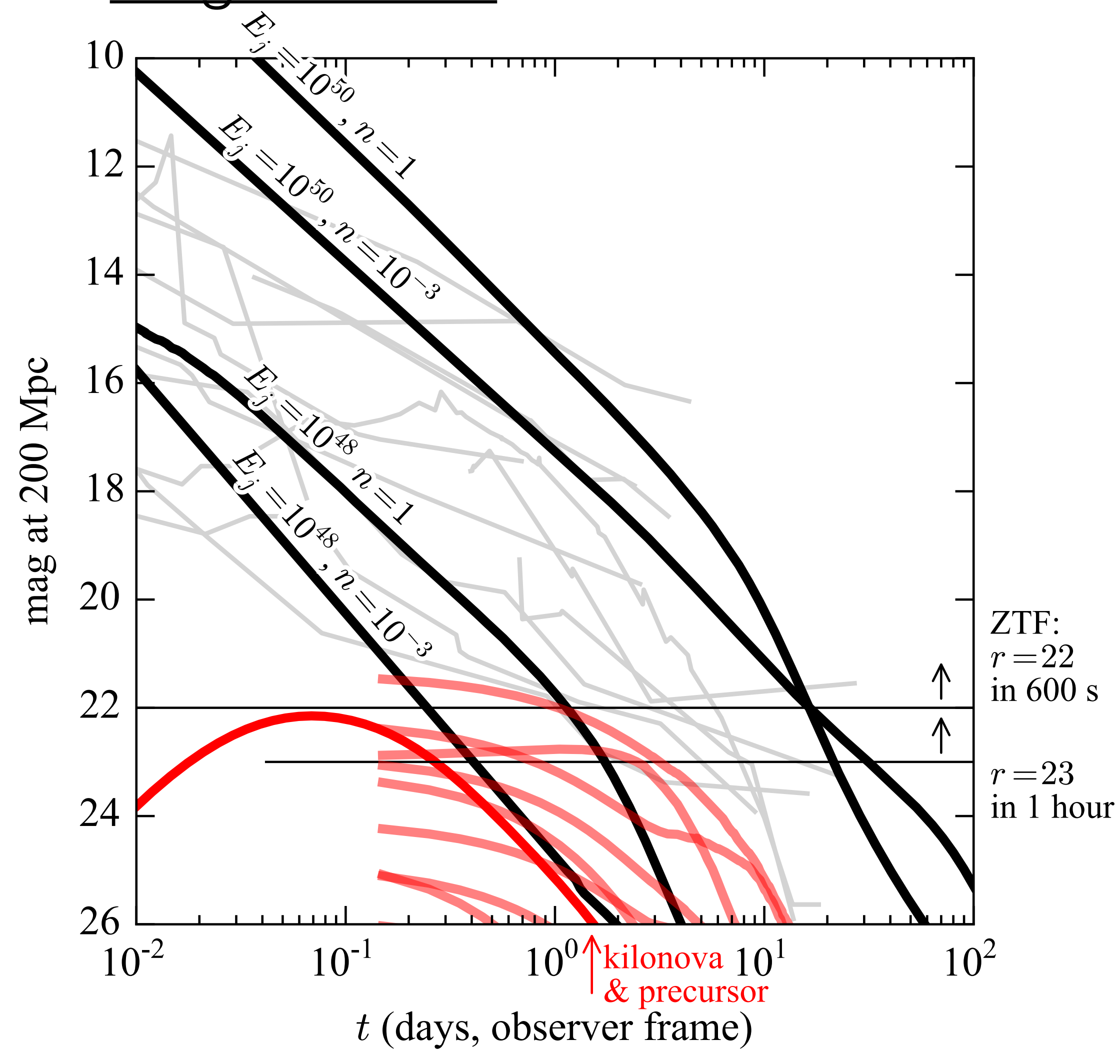
E. Bellm
Bellm+ 2014
Smith+ 2014

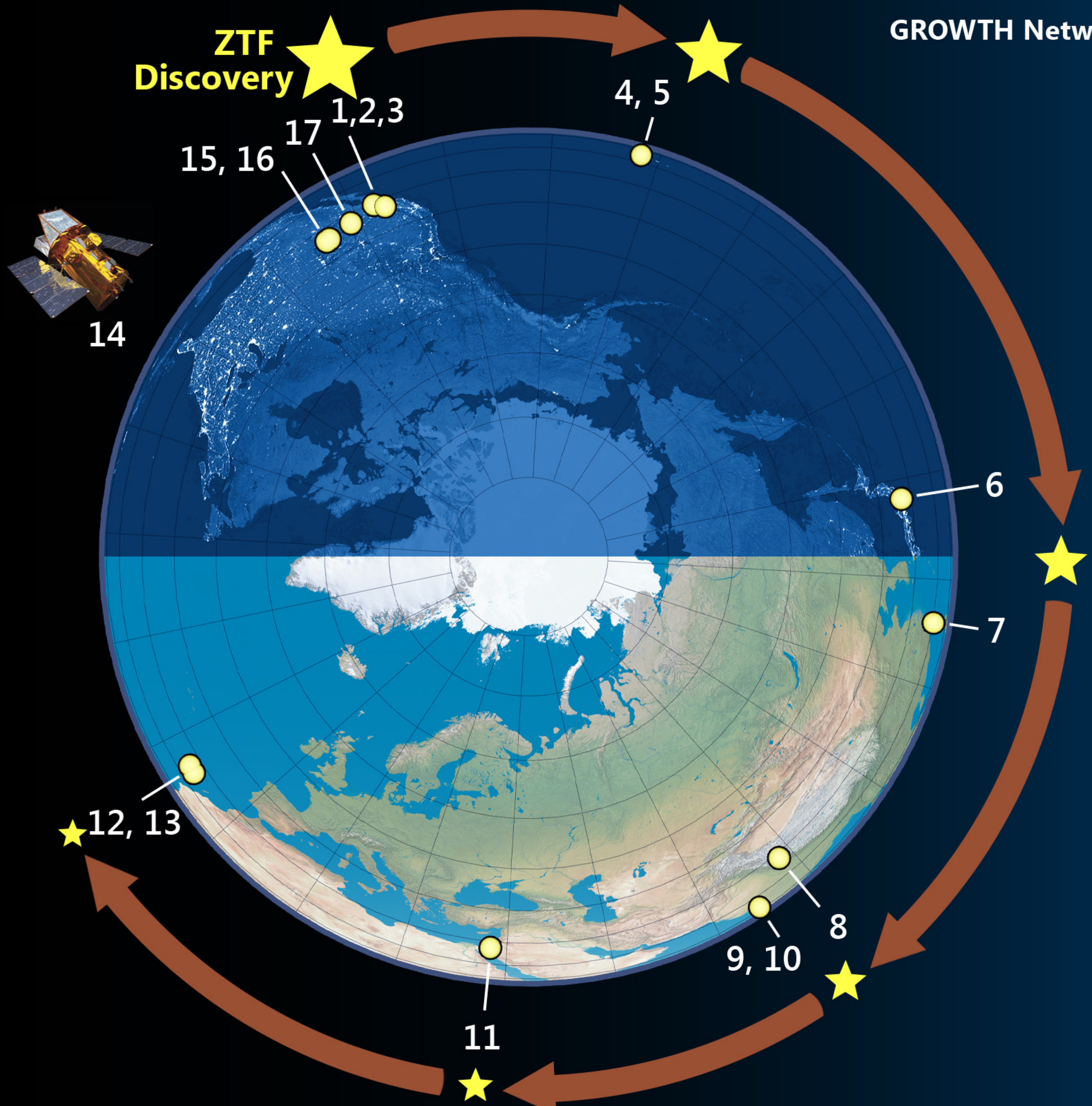
ZTF REACH **into kilonova phase space**

Kasliwal & Nissanke (2014)



Singer+ 2015





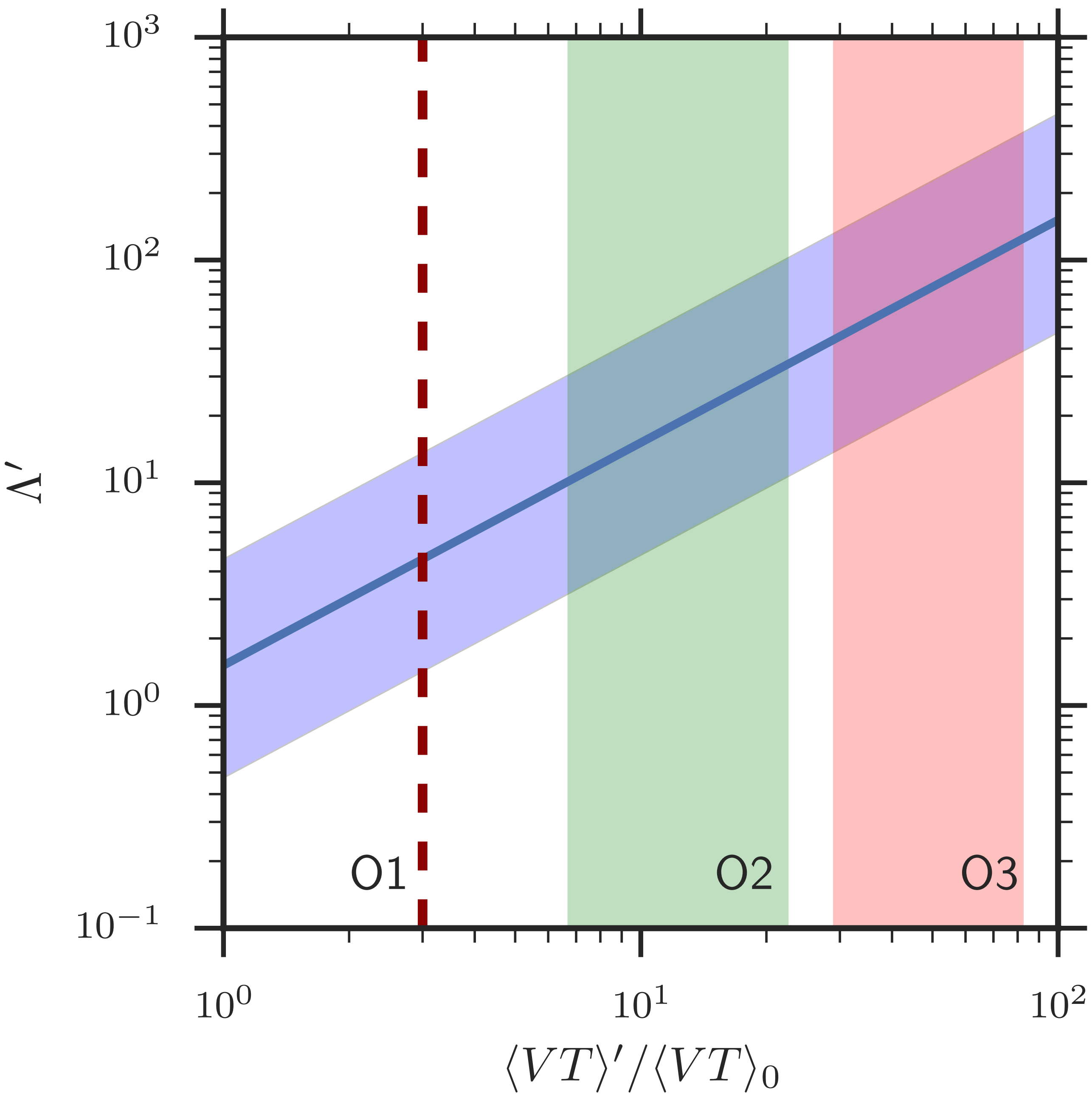
GROWTH Network:

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**

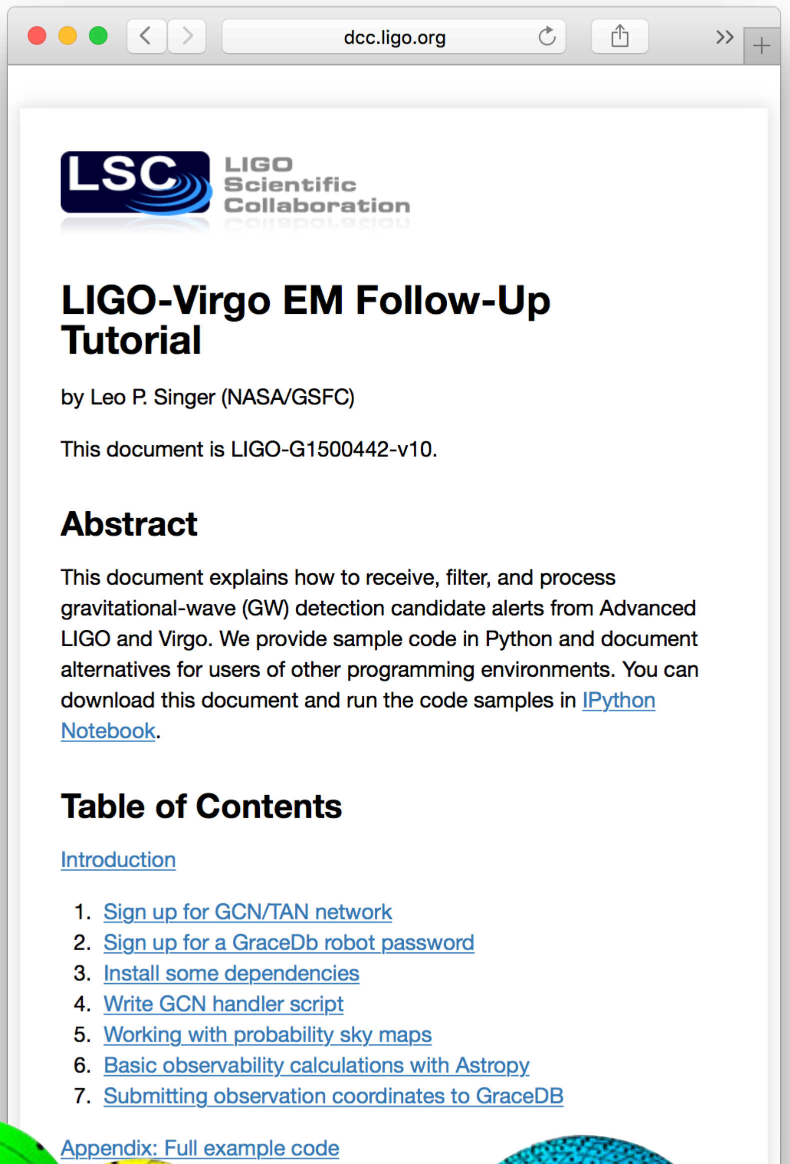
WHERE WE WILL GO IN O2

Real-time, **open**, **public alerts** after 4 published events. By beginning of O3?



- Both **population statistics** and distinctive **single-object analysis**
- Alerts with **distance and GW classification** must go out within half an hour (**<1 minute**, with more practice!)
- An alert every 1–2 weeks → need to **select which GW events to follow up** based on GW mass estimates and localization

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


dcc.ligo.org

LSC LIGO Scientific Collaboration

LIGO-Virgo EM Follow-Up Tutorial

by Leo P. Singer (NASA/GSFC)

This document is LIGO-G1500442-v10.

Abstract

This document explains how to receive, filter, and process gravitational-wave (GW) detection candidate alerts from Advanced LIGO and Virgo. We provide sample code in Python and document alternatives for users of other programming environments. You can download this document and run the code samples in IPython Notebook.

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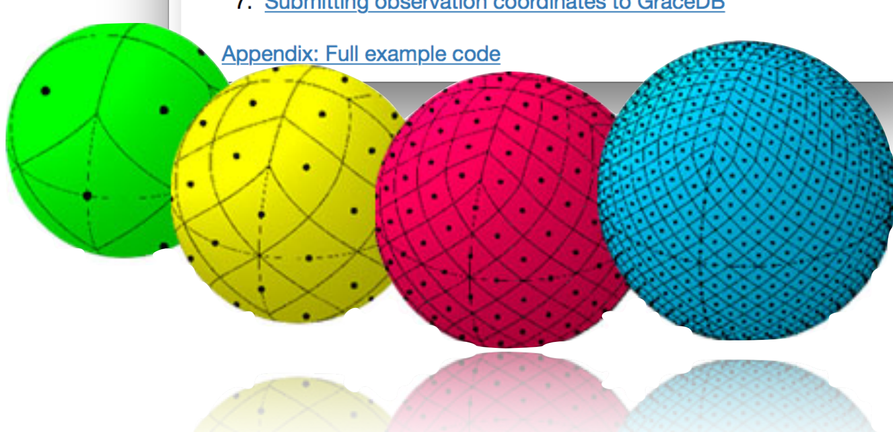
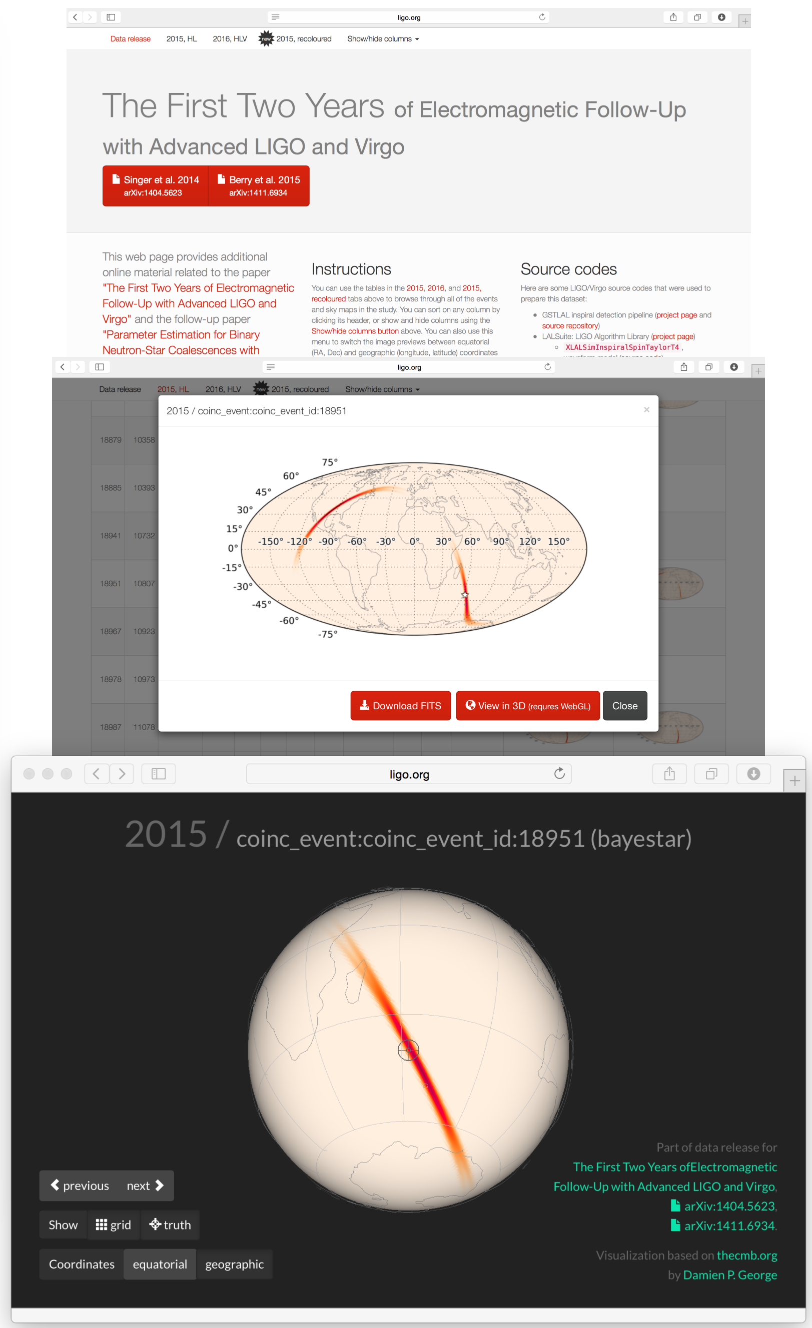




Singer+ 2014 (arXiv:1404.5623)
Berry+ 2015 (arXiv:1411.6934)
Essick+ 2015 (arXiv:1409.2435)
LVC+ 2016 (arXiv:1304.0670)

- **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

SPACE POTATO CHIPS
Typical GW localization
in three dimensions

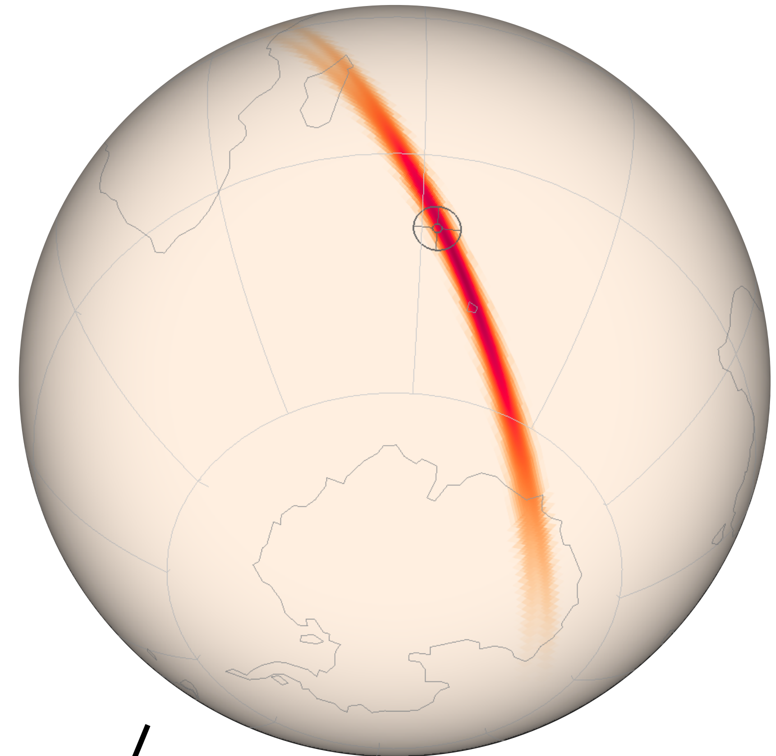
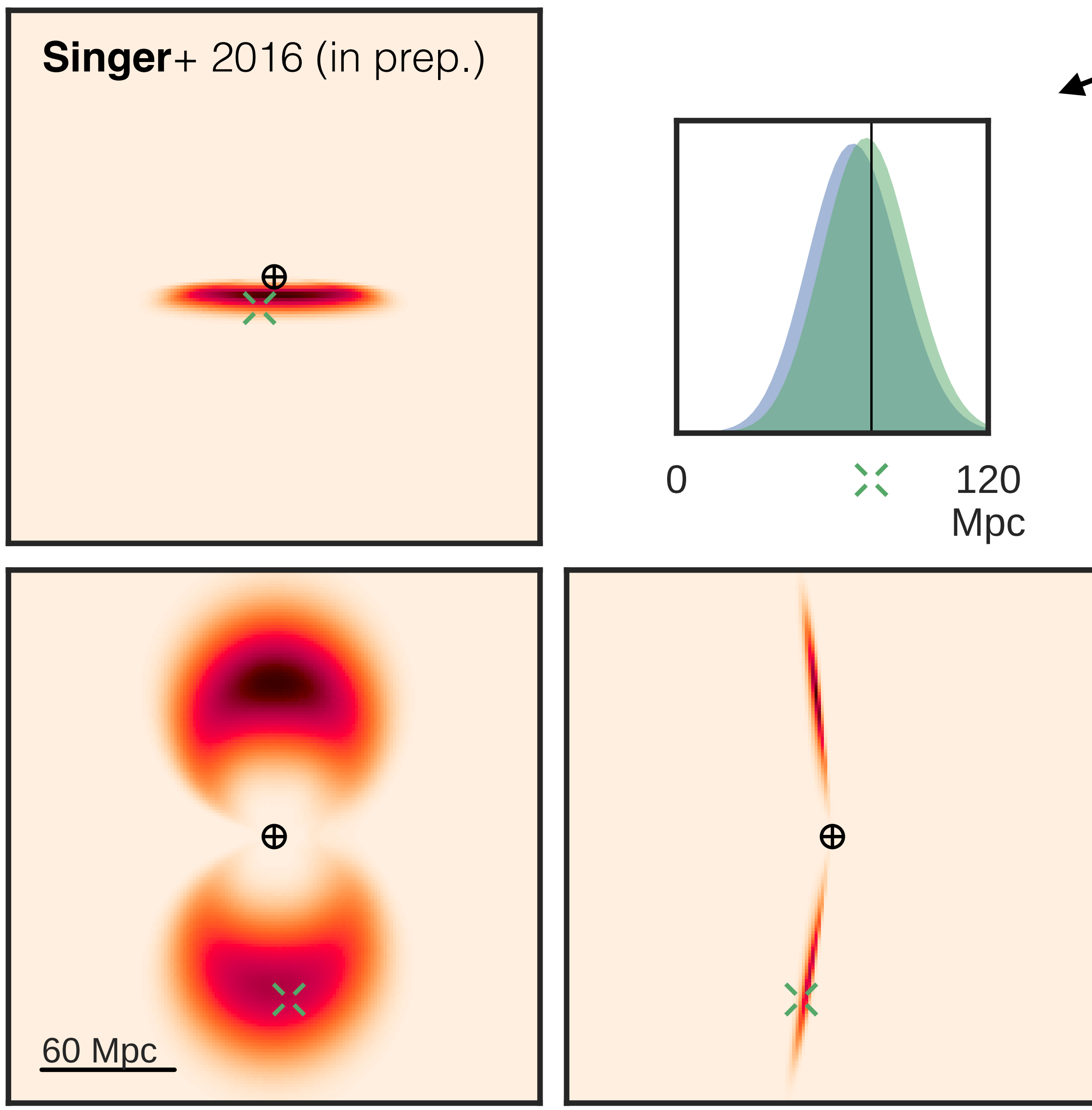
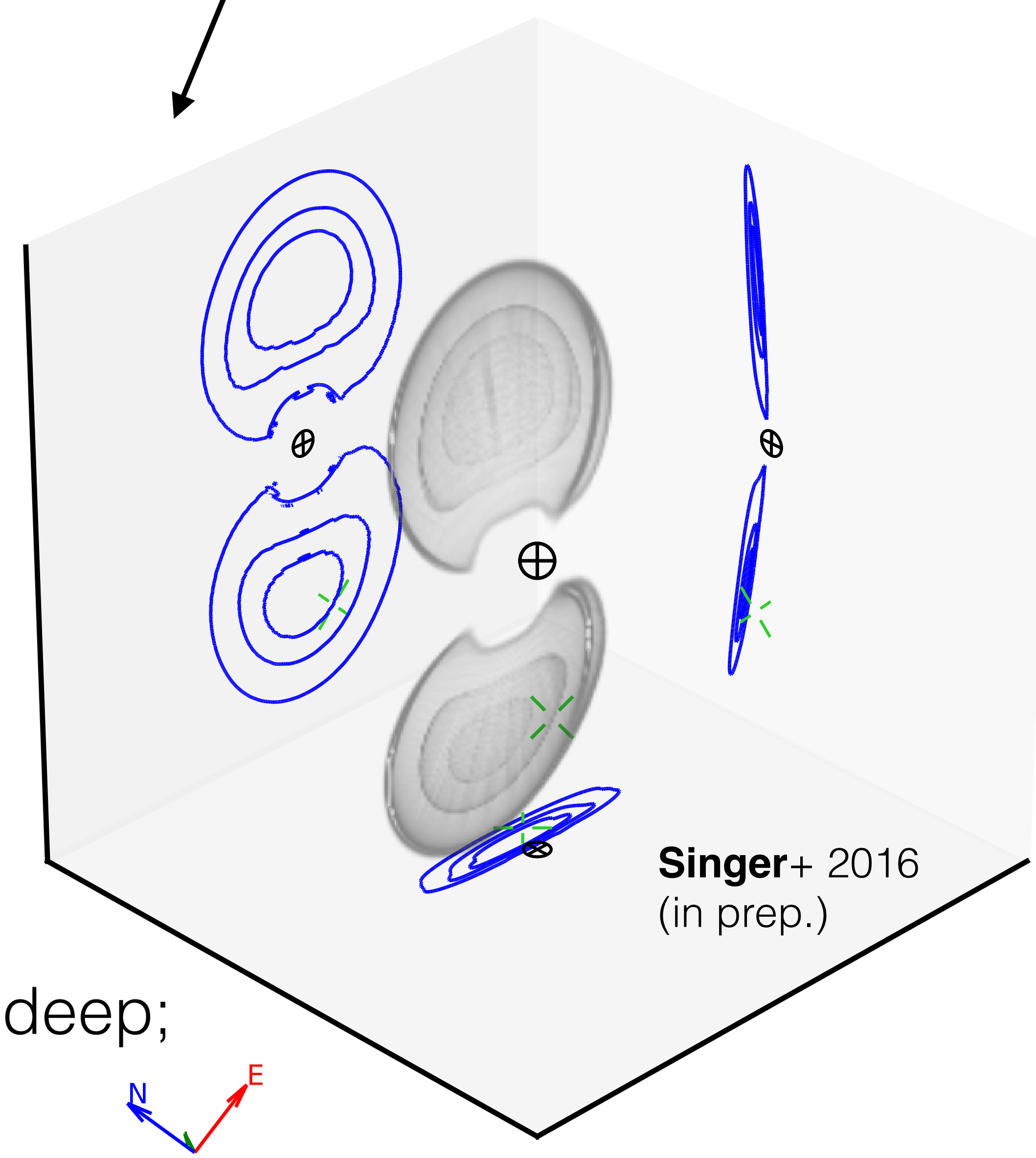


image: “First Two Years”

http://ligo.org/scientists/first2years

Singer+ 2014
Berry+ 2015



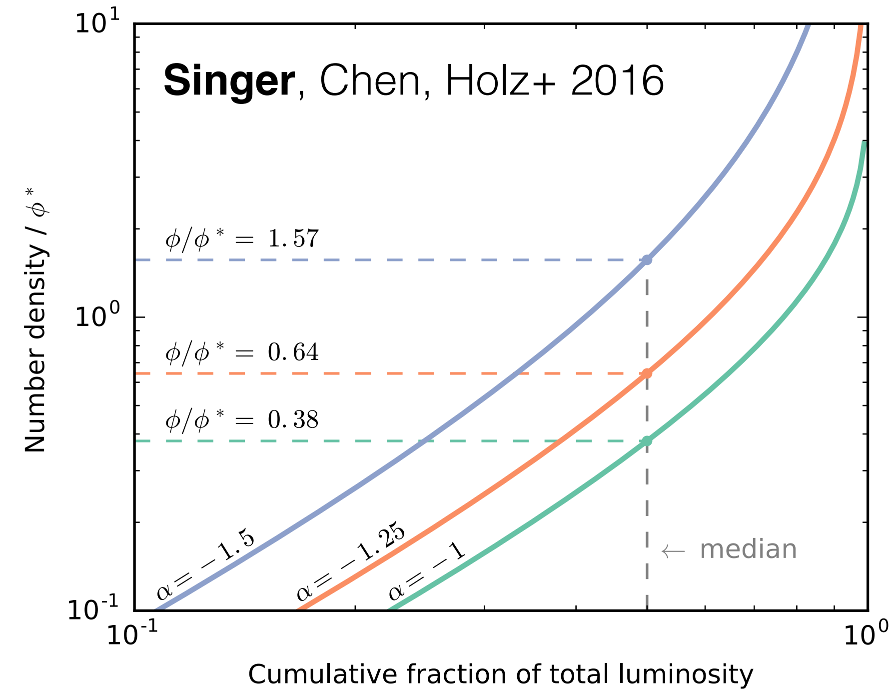


Double arcs become two **petals**:
~1° wide, **10-100°** in breadth, **~100 Mpc** deep;
Volume **$\sim 30\times10^3$ Mpc^3**


1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
1 2 3 4 5 6 7 8 9 10

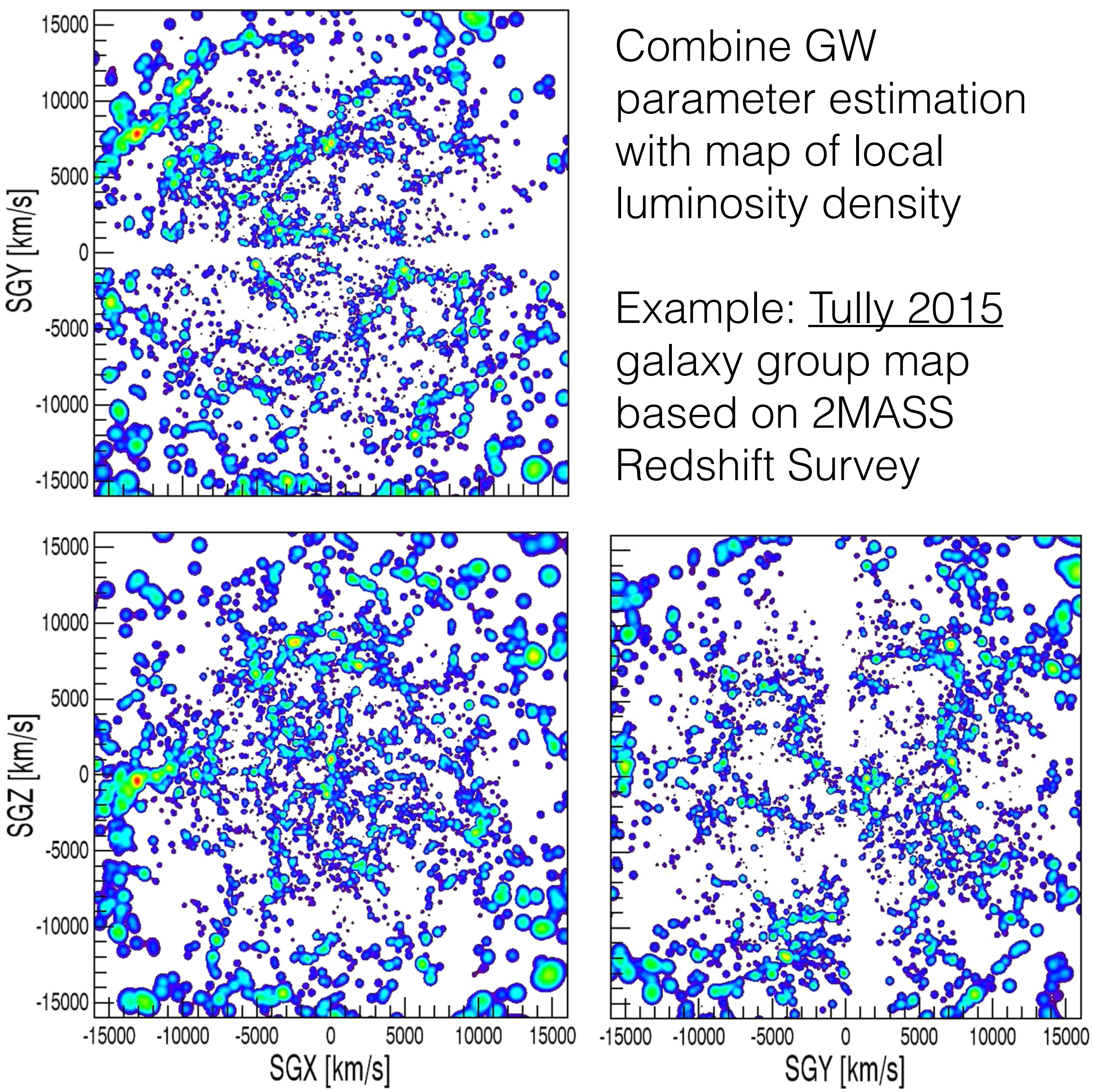
Singer, Chen, Holz+ 2016 (**arXiv:1603.07333**)

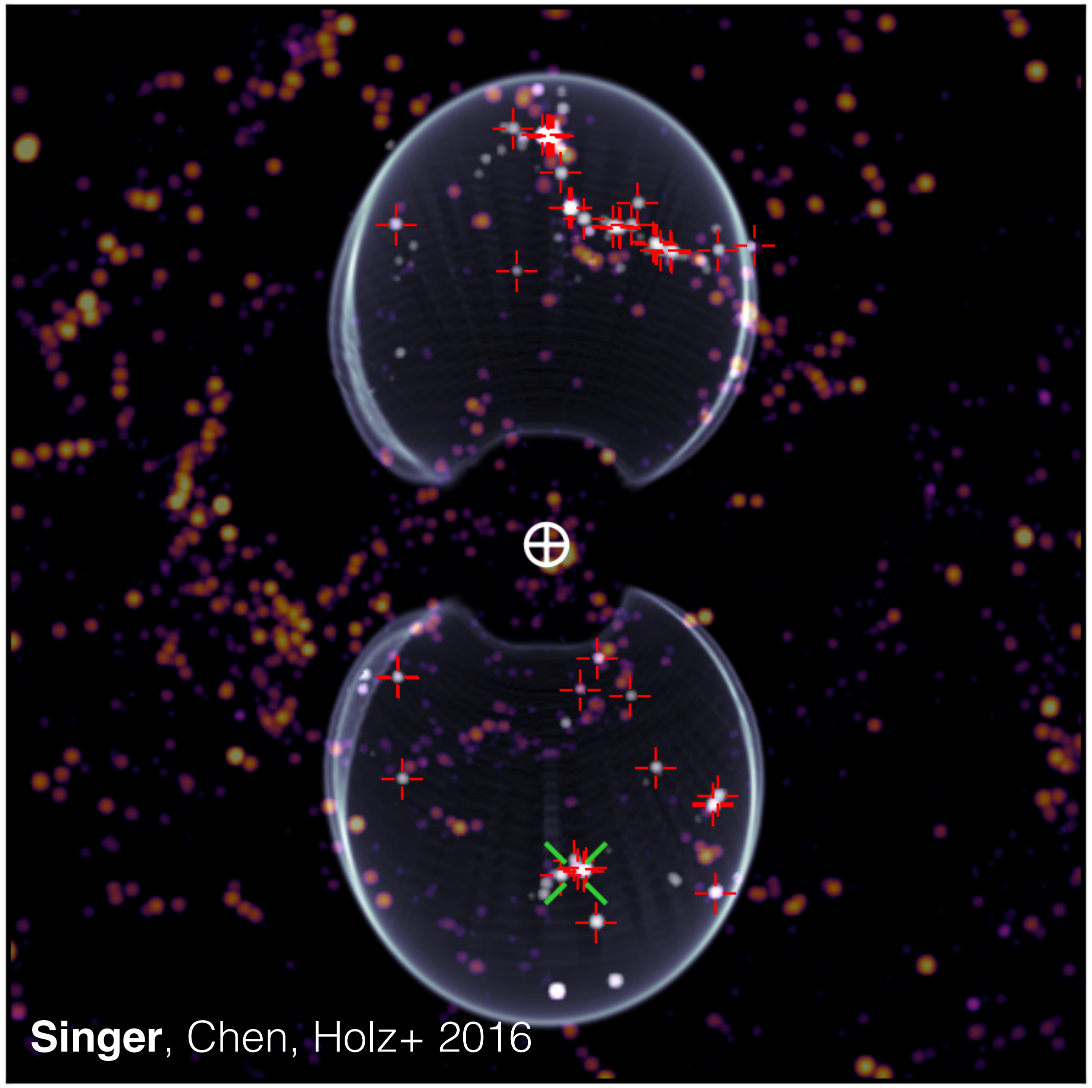
COSMOGRAPHY for **fun and profit**



Combine GW parameter estimation with map of local luminosity density

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

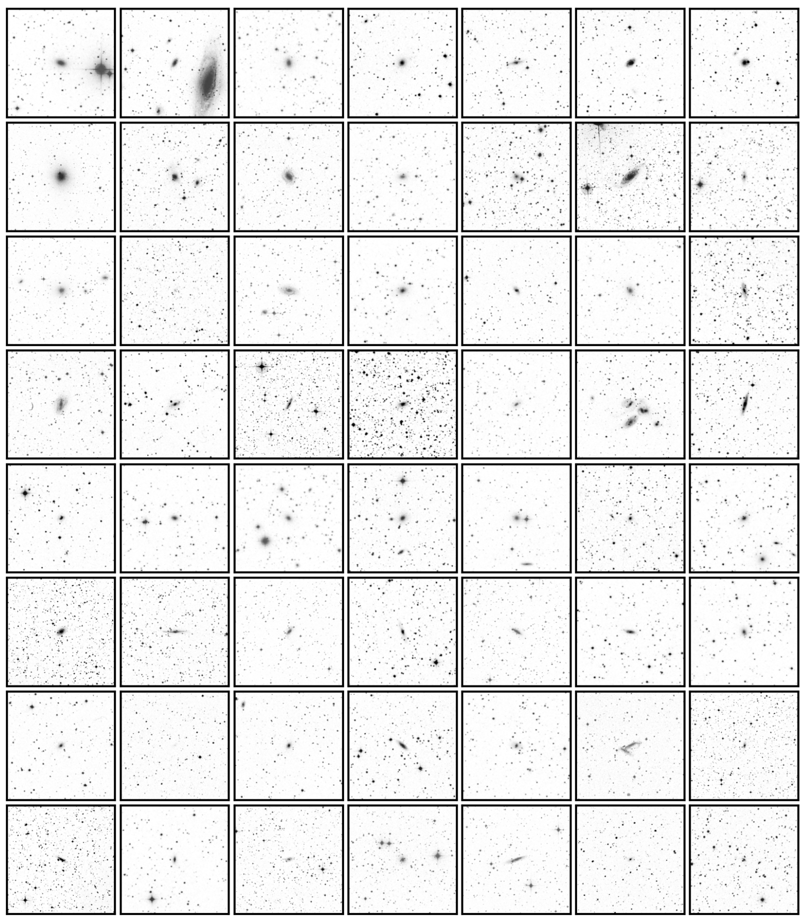


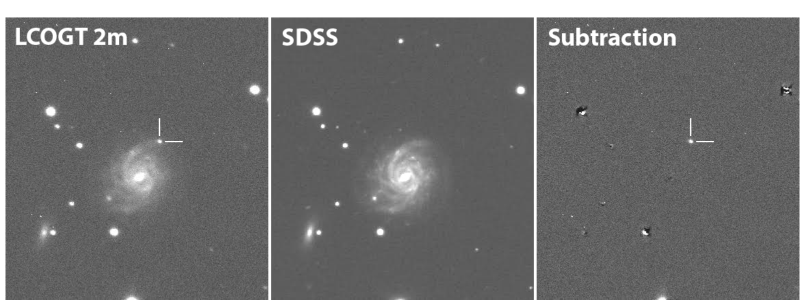


Singer, Chen, Holz+ 2016 (**arXiv:1603.07333**)

GOING THE DISTANCE

Targeted O/IR kilonova search





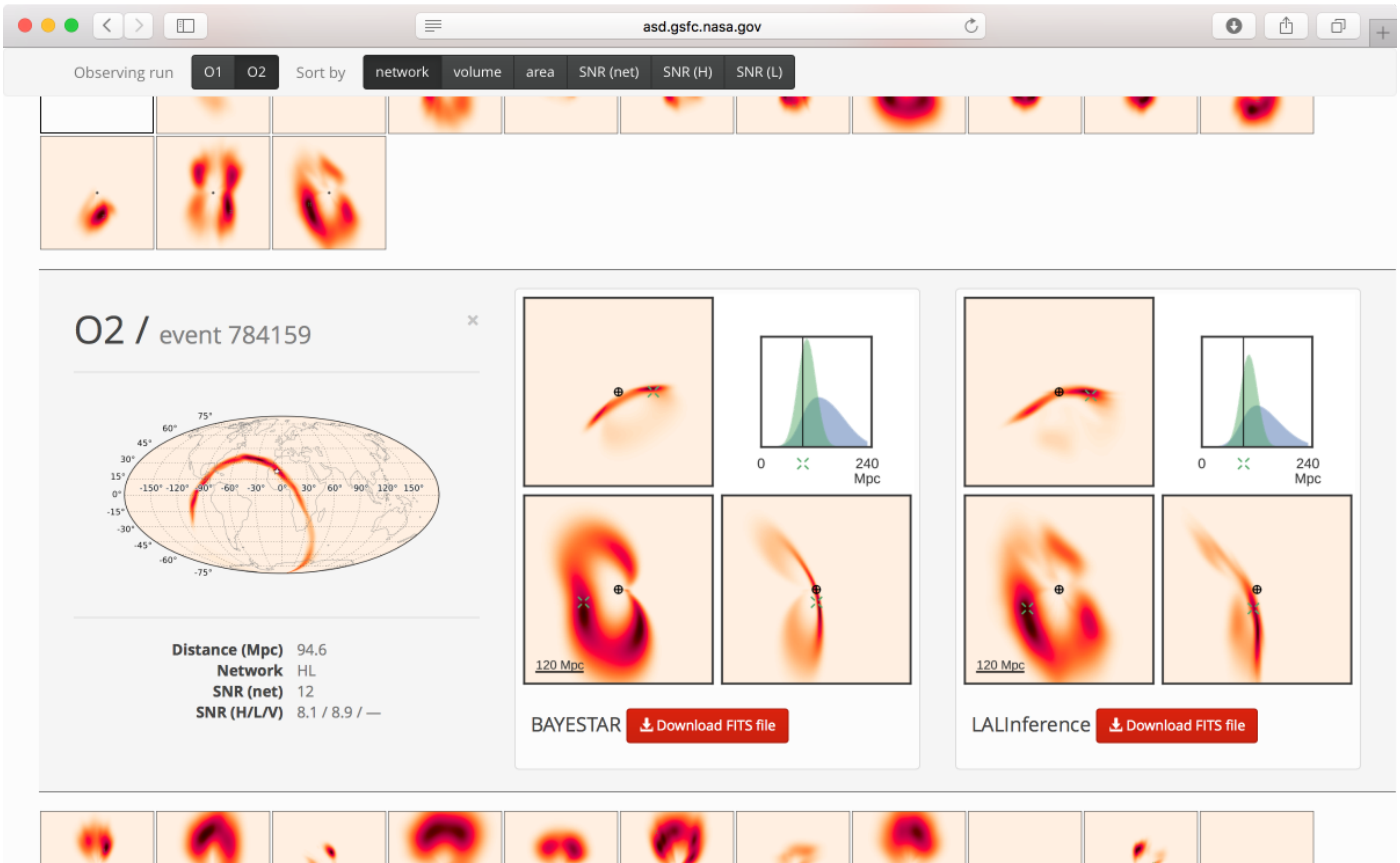
"Searching for Optical Counterparts to Gravitational Wave Sources" LCOGT 2016A (Arcavi, Howell, Valenti, **Singer** ....)

Ideal facilities:

LCOGT (2m) + Spectral
NOT (2.6m) + ALFOSC
Discov. Chan. (4.3m) + LMI
Magellan (6.5m) + FourStar
Gemini (8.2m) + GMOS
VLT (8.2m) + FORS2
Keck (10m) + LRIS
GTC (10.4m) + OSIRIS

arXiv:1603.07333

http://asd.gsfc.nasa.gov/Leo.Singer/going-the-distance/



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**, possibly with *or without* a counterpart.
- In the Northern hemisphere and during the pre-LSST era, **ZTF+GROWTH ought to be the linchpin of the multimessenger GW–EM effort**.


THE FUTURE IS BRIGHT

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

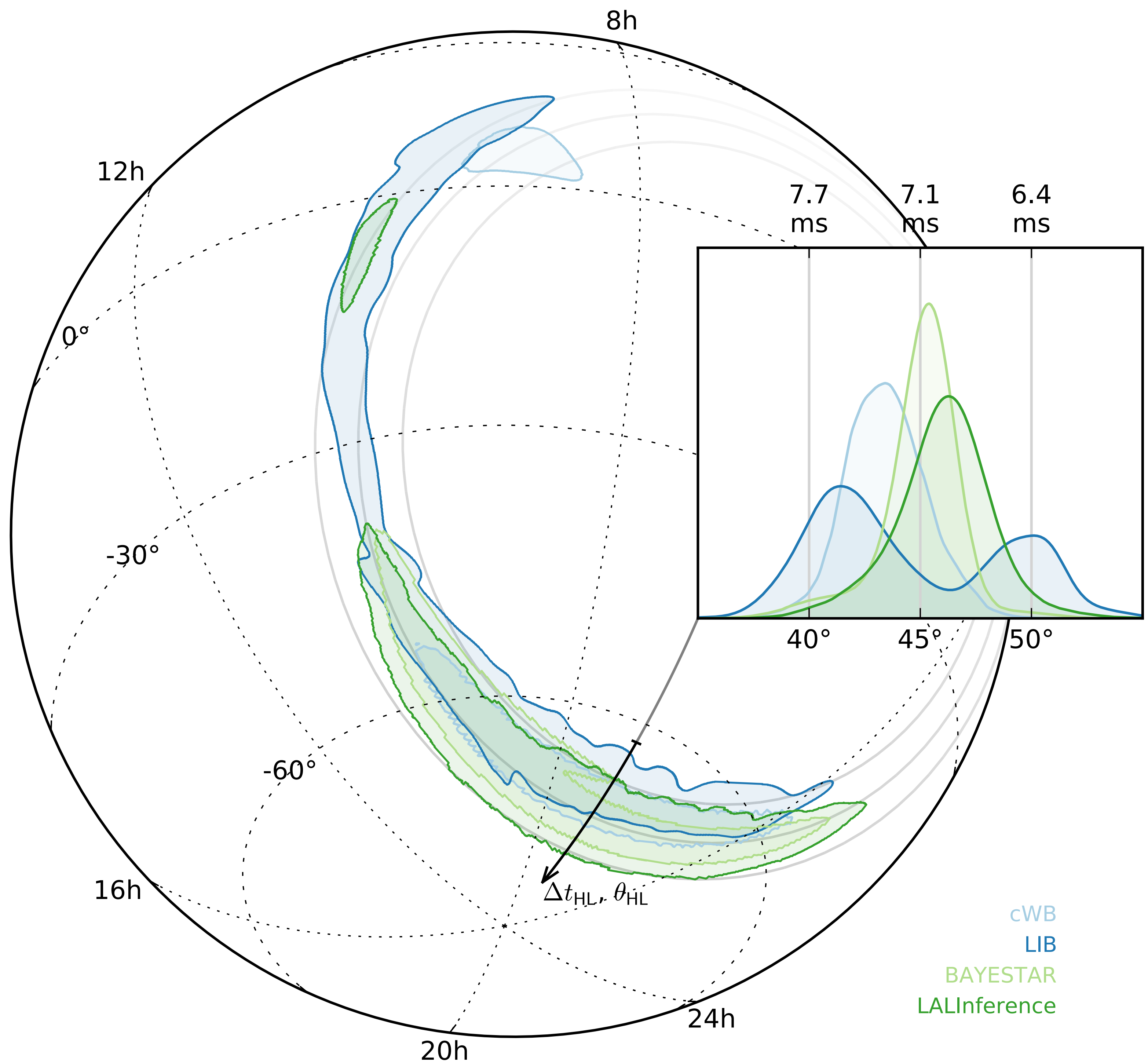
Tutorials and technical info
https://gw-astronomy.org/wiki/LV_EM/TechInfo

GW150914 data release (includes sky maps)
https://losc.ligo.org/events/GW150914/

Extra slides

Two online GW transient searches: unmodeled **bursts**, modeled **compact binary coalescences**.

Rapid localization within **minutes** of data acquisition, **refined** parameter estimation within **hours to weeks**.



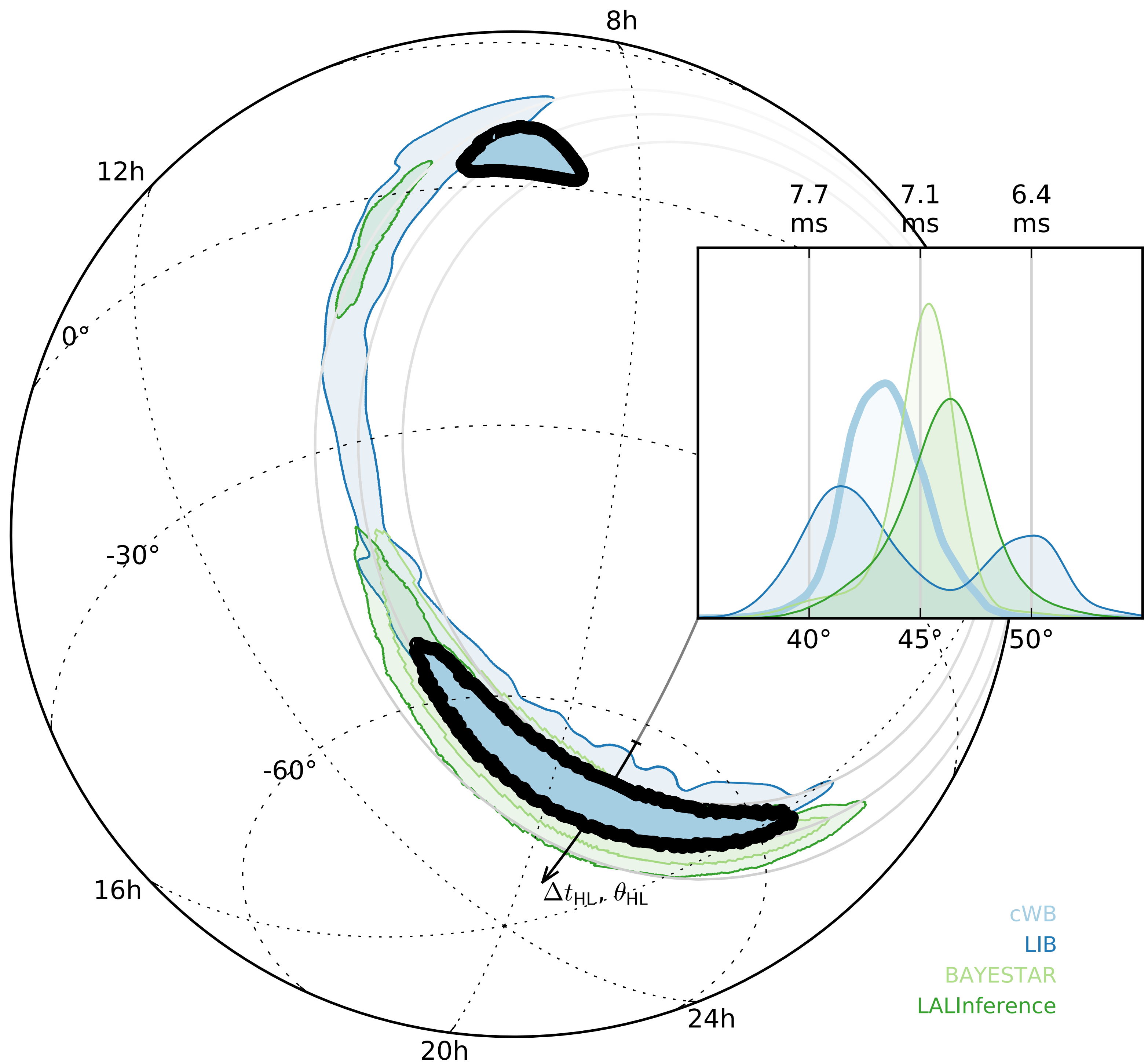
Coherent WaveBurst (cWB)

Wavelet-based un-modeled detection, reconstruction, and localization of GW signals.

Rapid burst localization within **minutes** of data acquisition.

Not limited to the GW polarization that would be produced by a compact binary.

Klimenko+ 2016

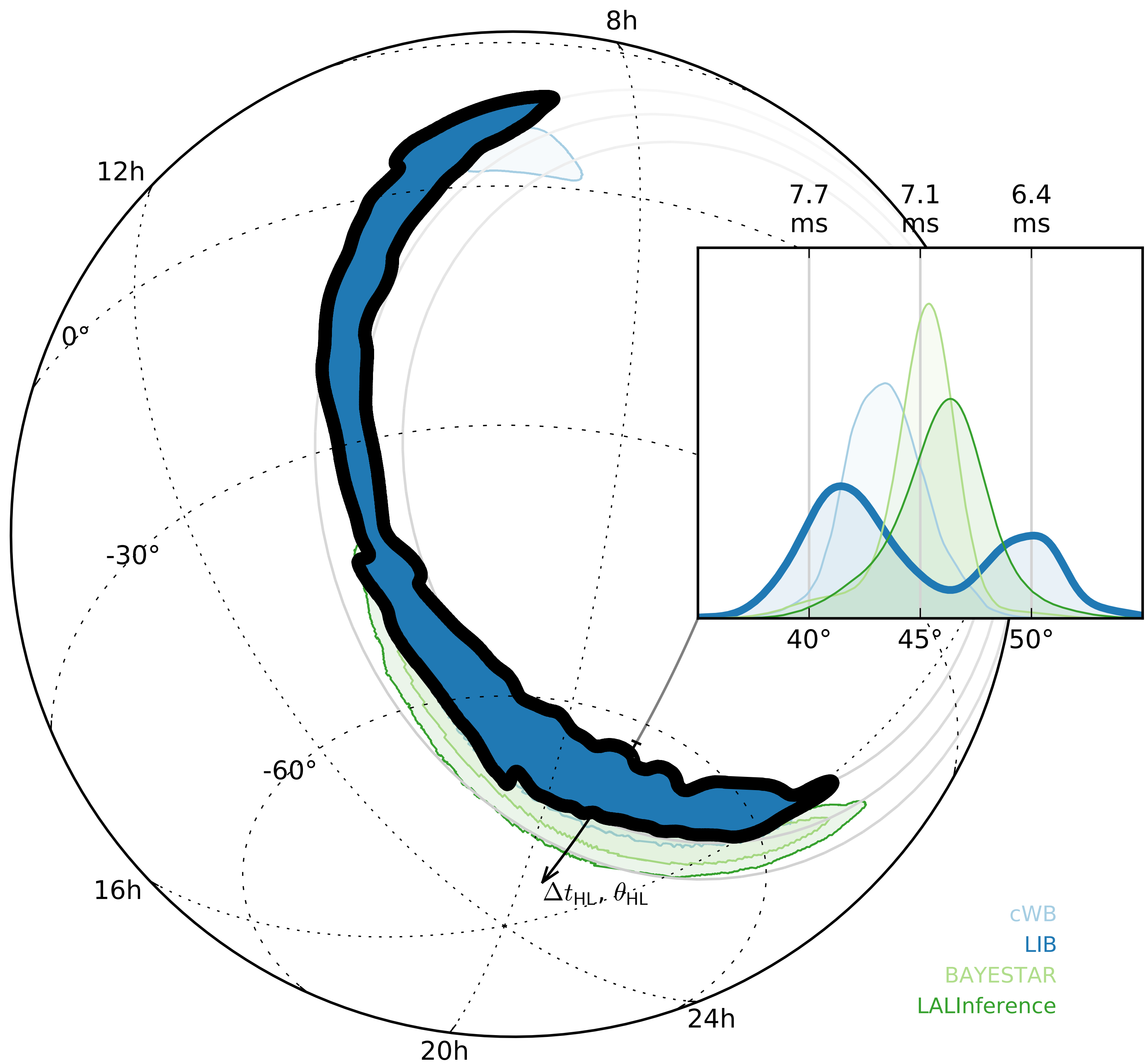


LALInference Burst (LIB)

MCMC analysis assuming that the GW signal is a sine-Gaussian.

Refined burst localization within **10 minutes–hours** of data acquisition.

Lynch+ 2016

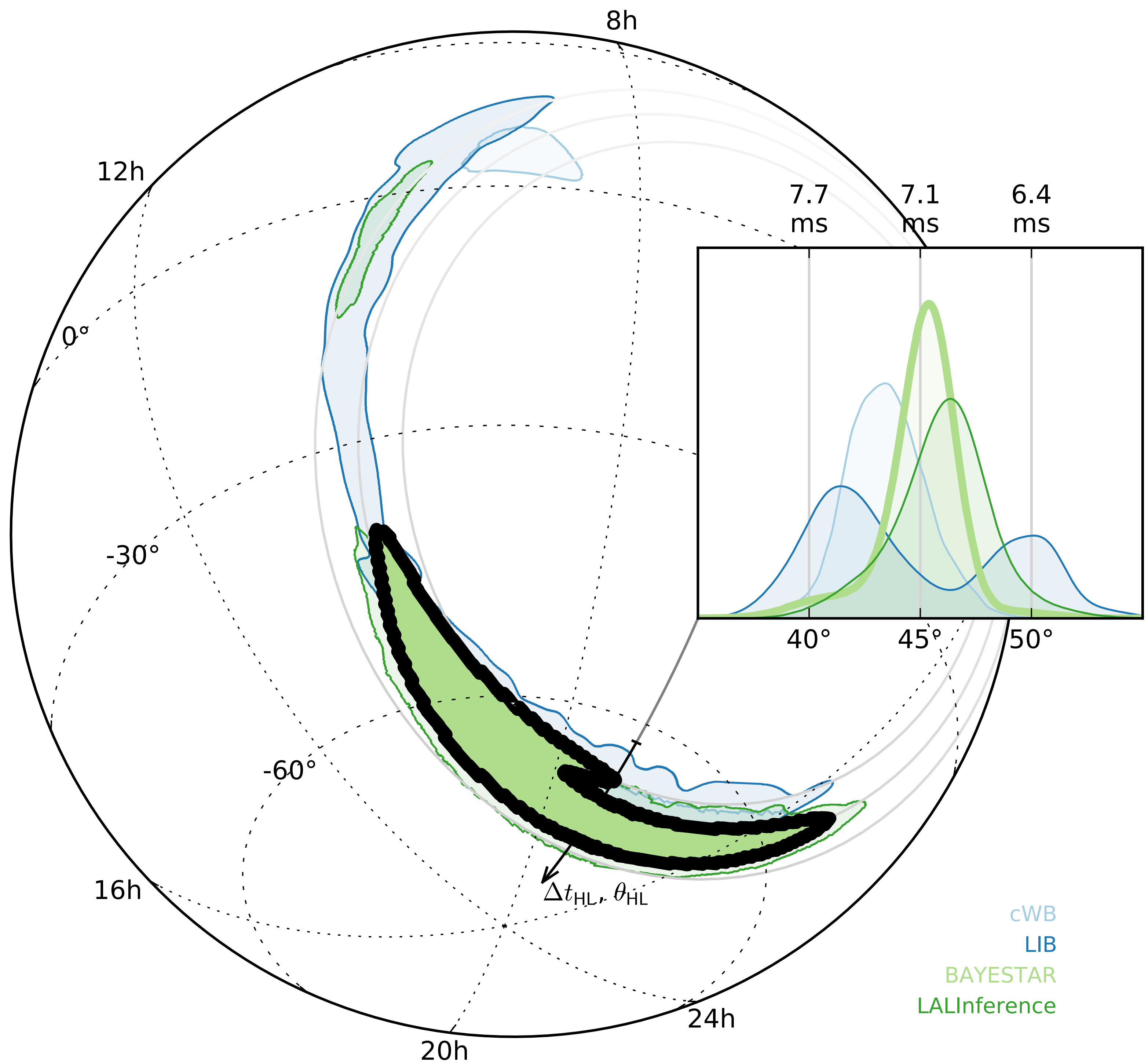


BAYESTAR

Bayesian triangulation of times, amplitudes, and phases on arrival as estimated by online CBC pipeline.

Rapid CBC localization within **minutes** of data acquisition.

Singer+Price 2016

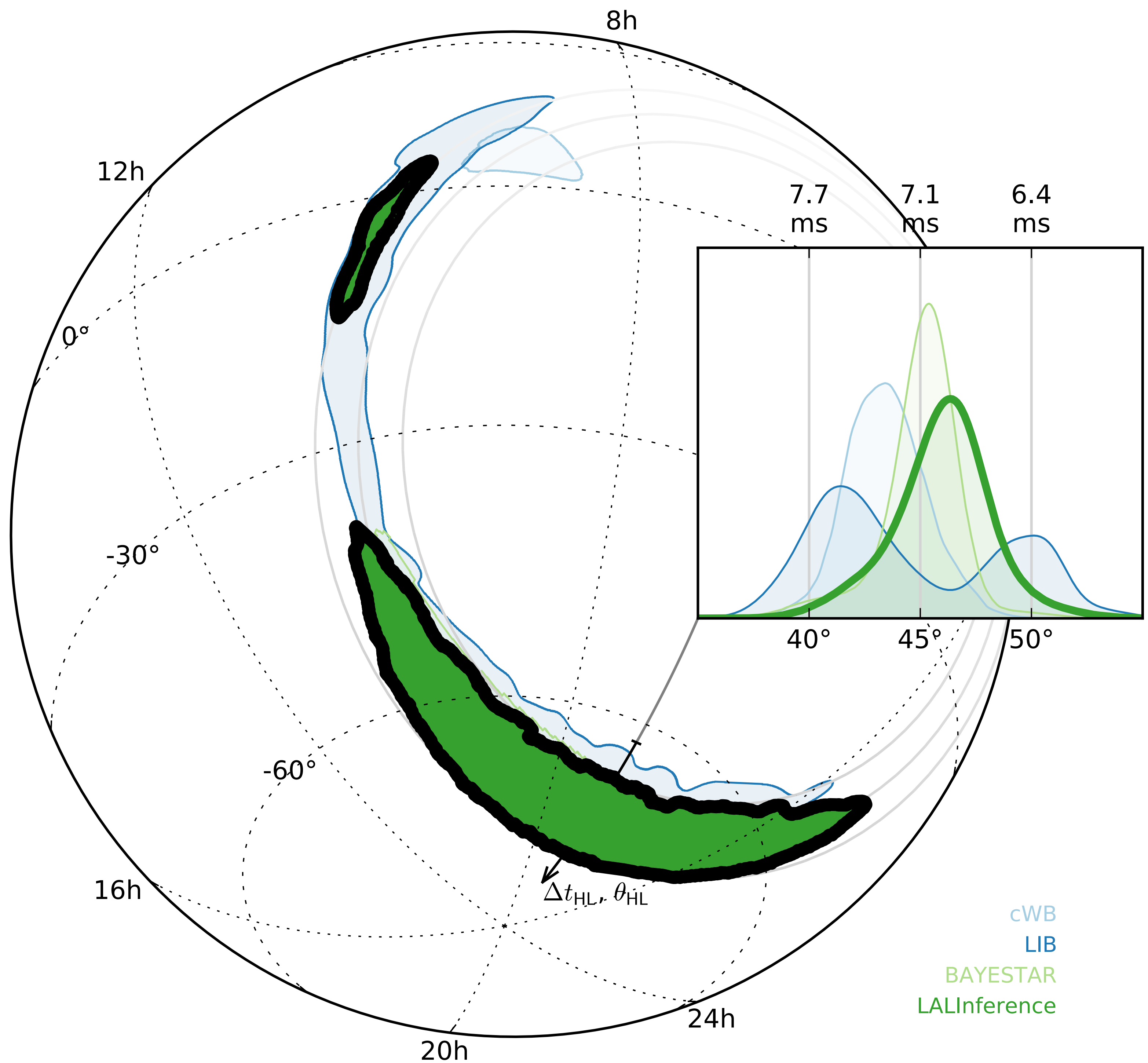


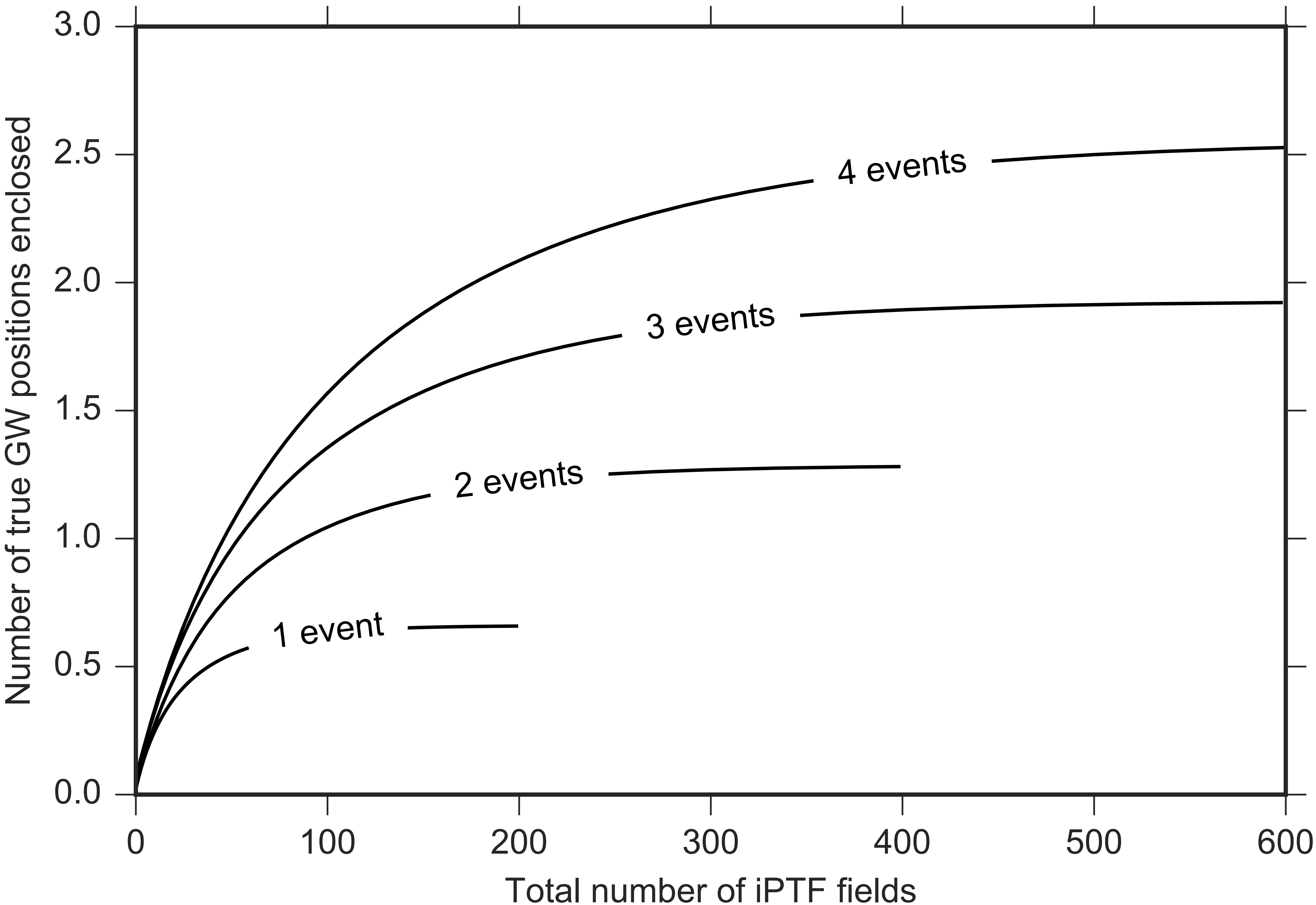
LALInference

MCMC analysis assuming that the GW signal is a sinusoidally modified Gaussian.

Refined CBC parameter estimation + localization within **days to months** of data acquisition.

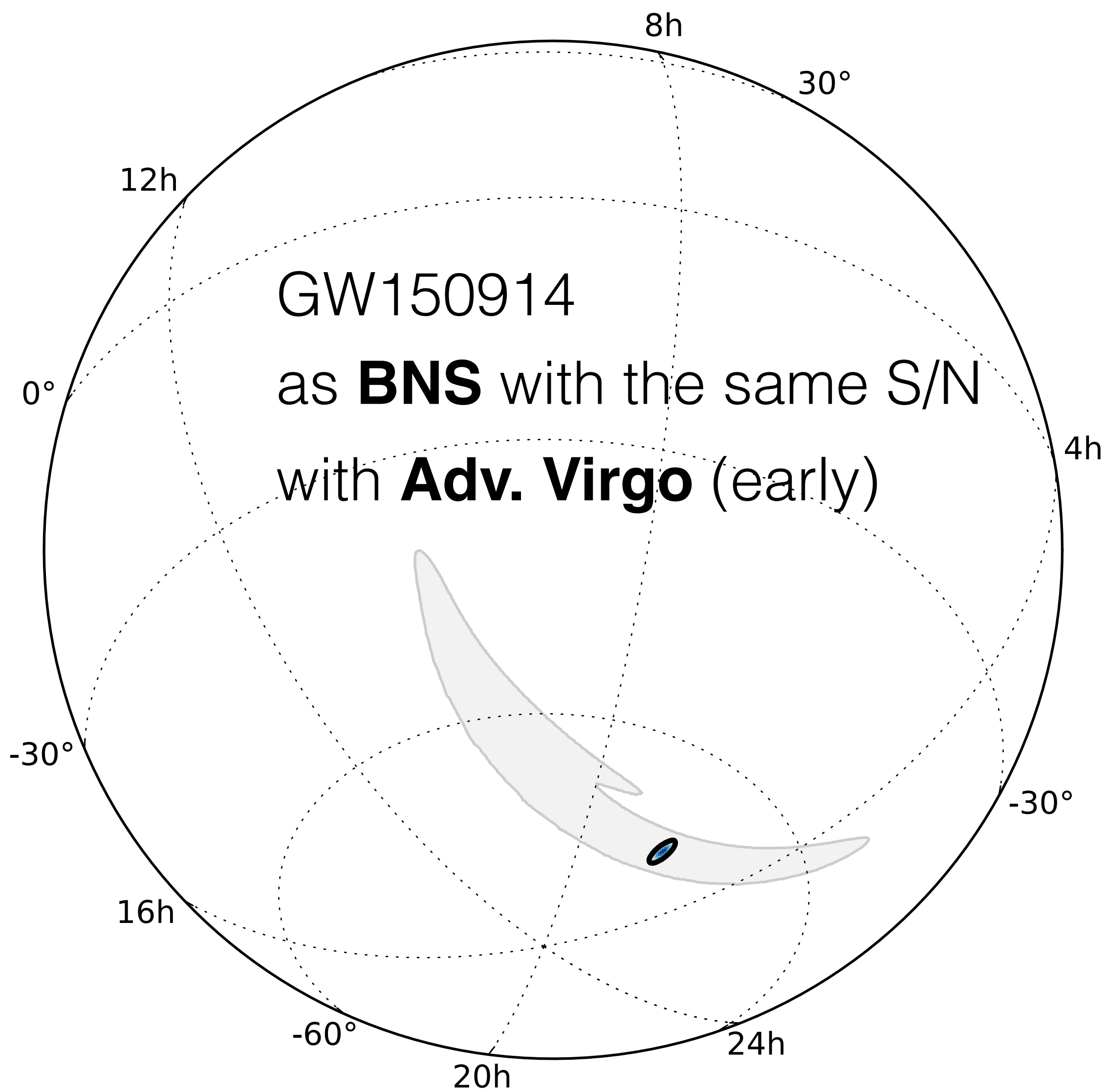
Veitch+ 2015





Number of true GW positions enclosed
Total number of iPTF fields
4 events
3 events
2 events
1 event
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
100
200
300
400
500
600

THE NEED FOR **Advanced Virgo**



Even with at "early" sensitivity, Advanced Virgo will **fundamentally transform** the character of GW observations.

Area (deg^2)	GW 150914	NSBH	NSNS
HL	400	300	200
HLV	11	11	5
HLI	6	7	4