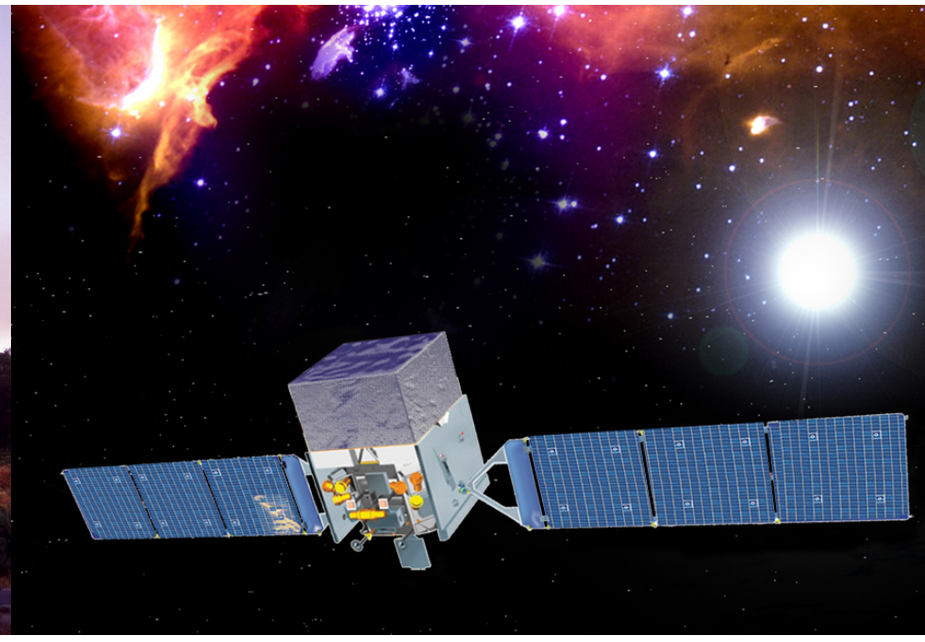
ADVANCED LIGO FIRST LIGHT

MULTIMESSENGER ASTROPHYSICS IN THE AGE OF GRAVITATIONAL WAVE OBSERVATORIES



TeVPA 2016

CERN, Geneva, 2016-09-15

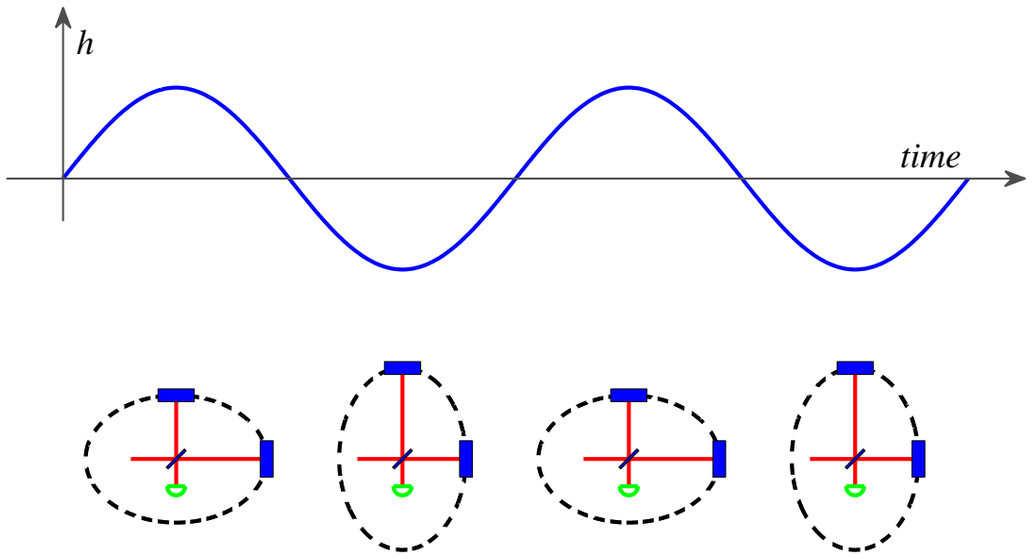
LIGO-G1601933-v1

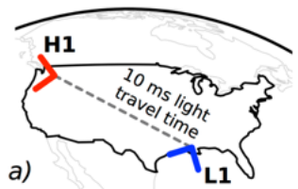
LEO P. SINGER / NASA Postdoctoral Fellow

NASA Goddard Space Flight Center

leo.p.singer@nasa.gov

A global network of grav. wave observatories





LVC 2016, PRL, 116, 061102

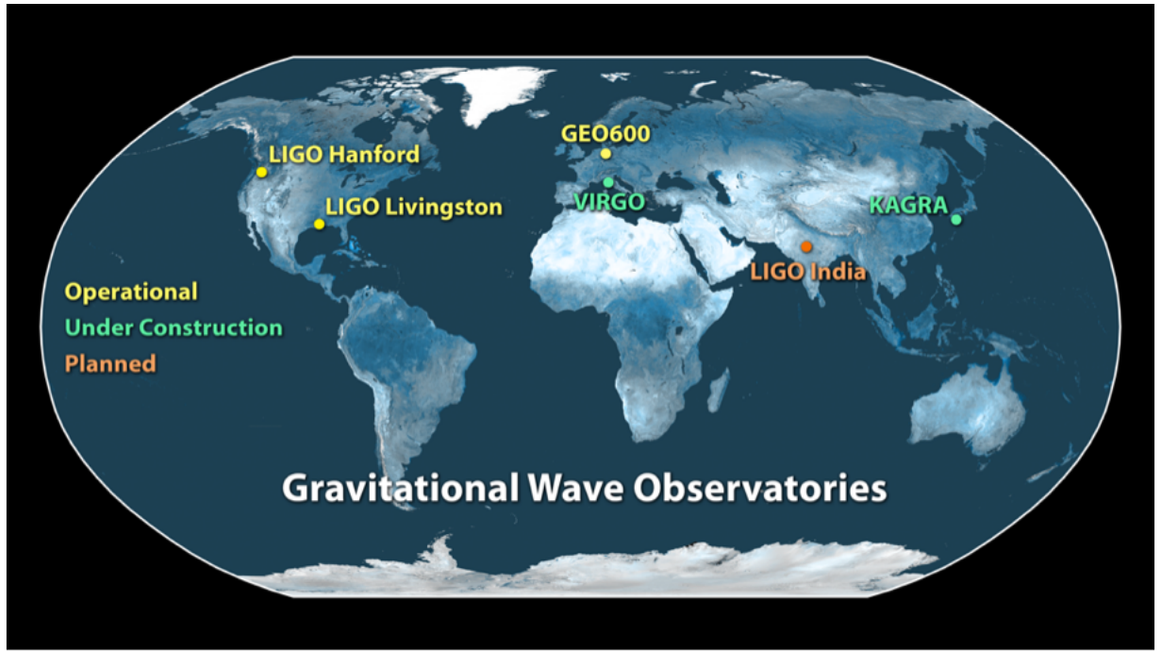
- **LIGO**: **L**aser **I**nterferometer **G**ravitational-wave **O**bservatory

- 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
  …



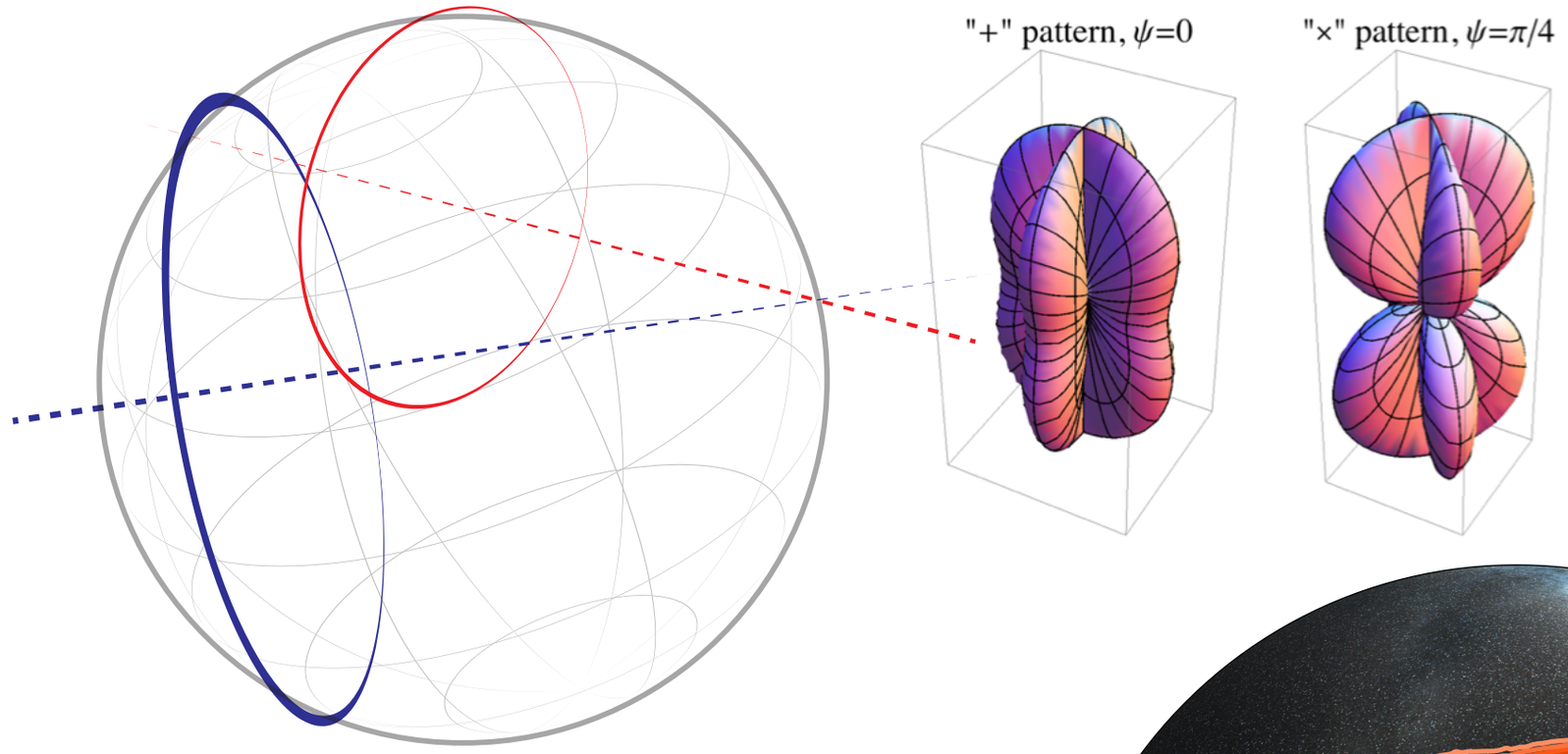
September 14, 2015
CONFIRMED

October 12, 2015
CANDIDATE

December 26, 2015
CONFIRMED

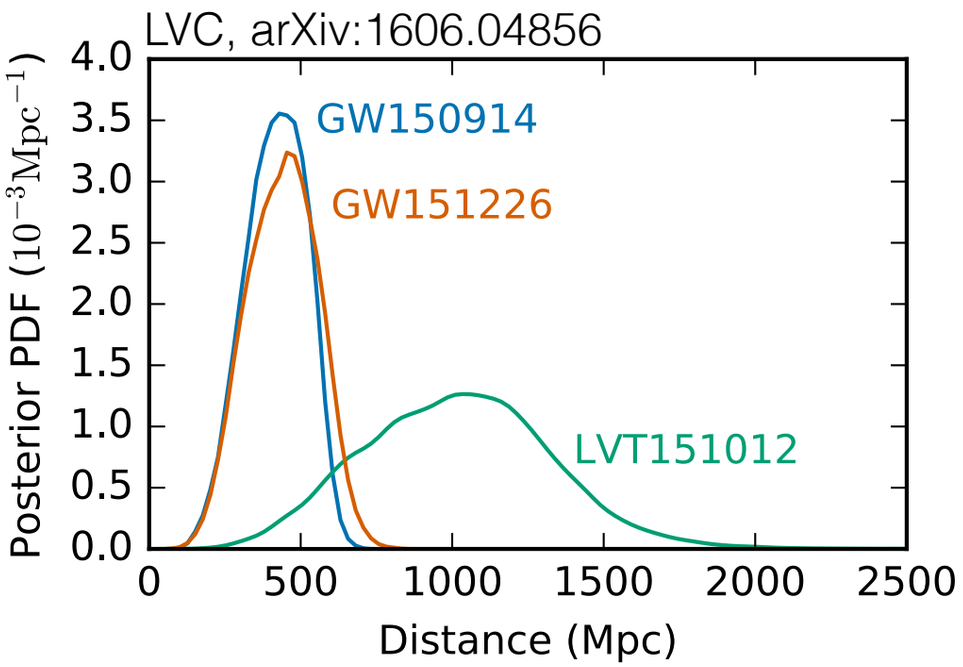
Credit: LIGO/Caltech

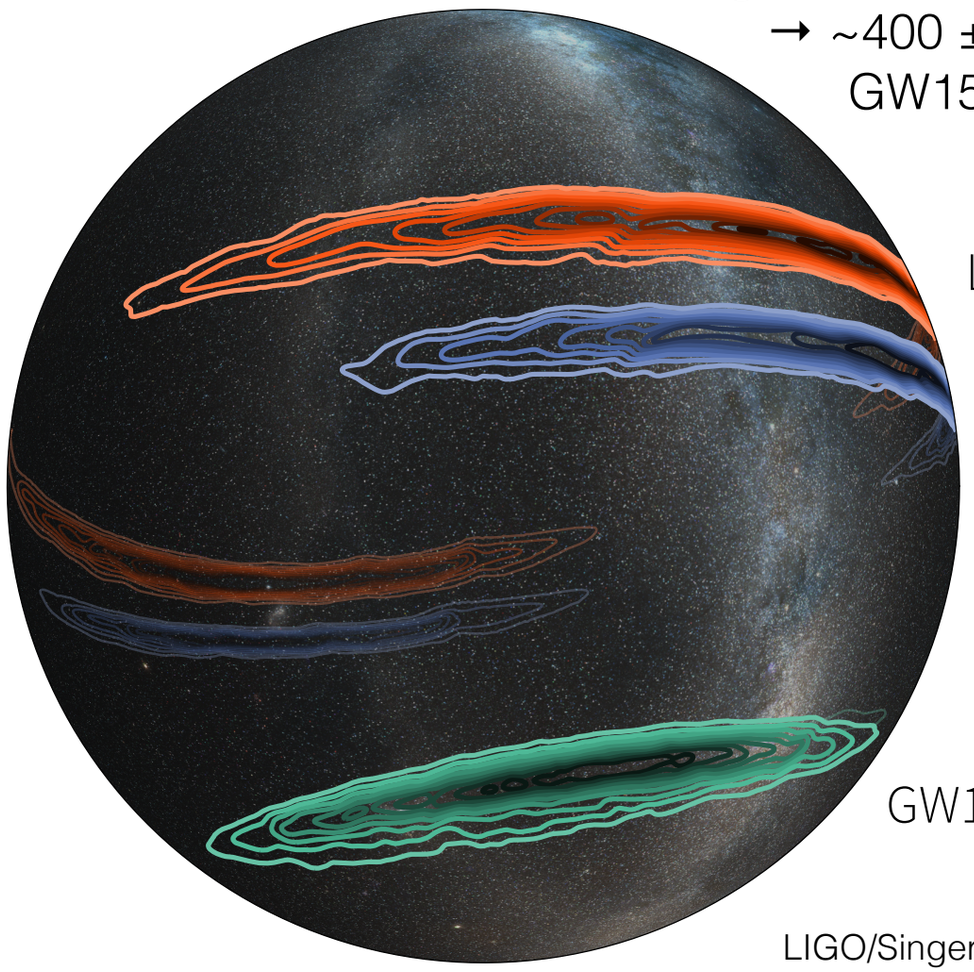
Sky location and distance



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

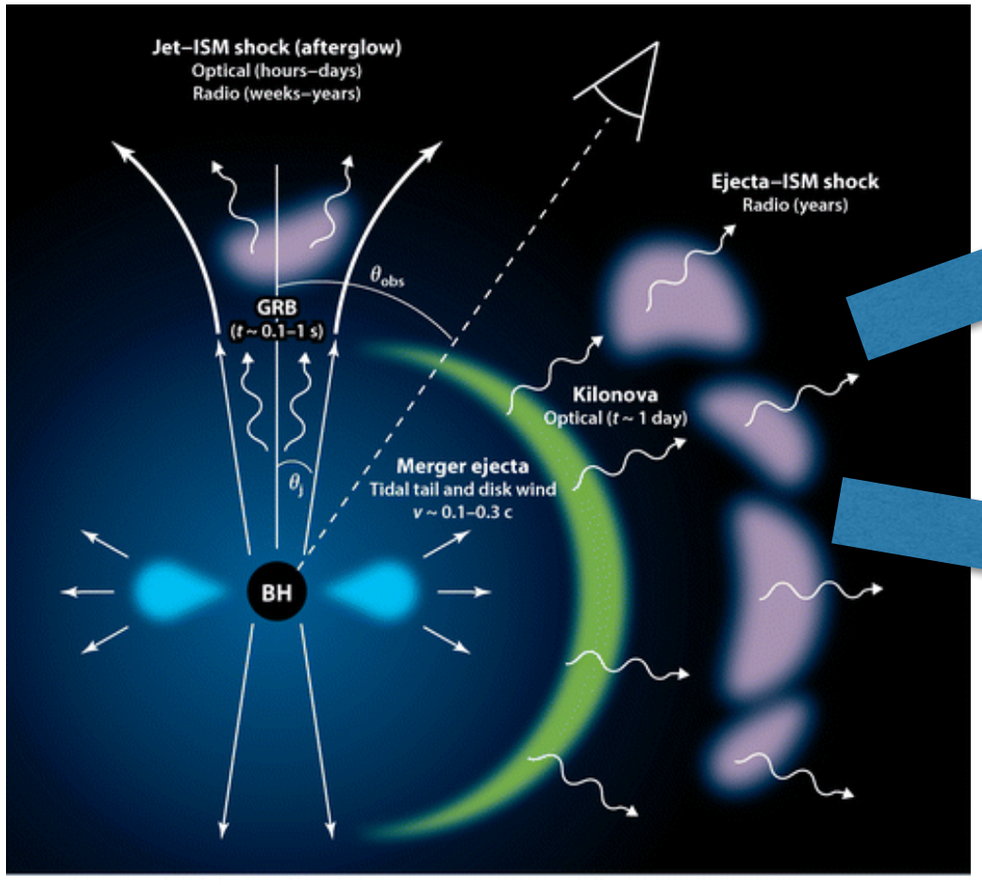
- **Distance** inferred by signal amplitude and directional antenna patterns, but **degenerate** with inclination
  → ~400 ± 200 Mpc for GW150914-like BBH mergers



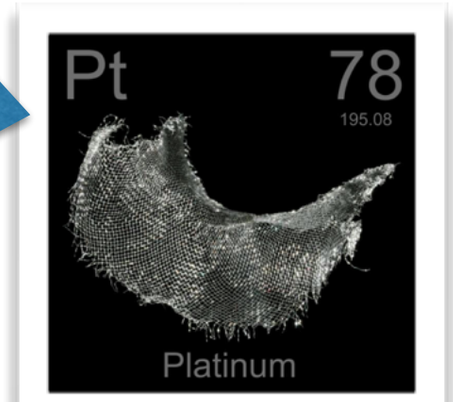


LIGO/Singer/Mellinger

The future is ***bright!***



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

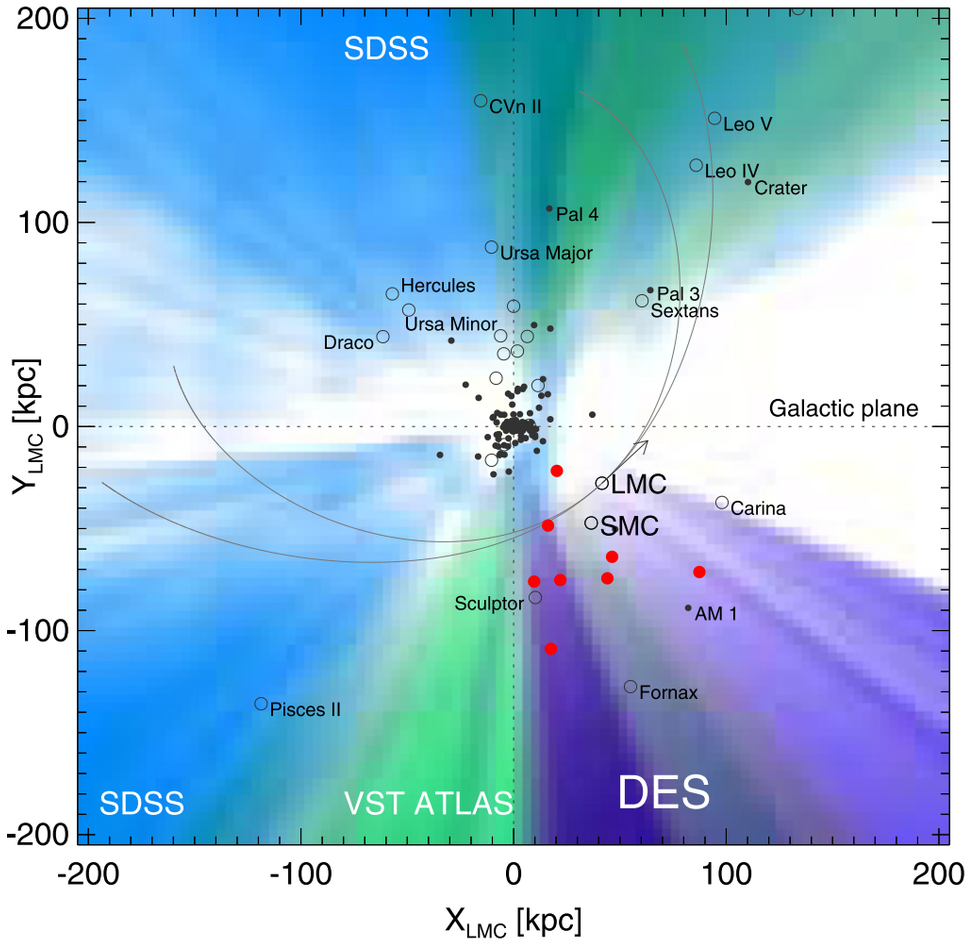


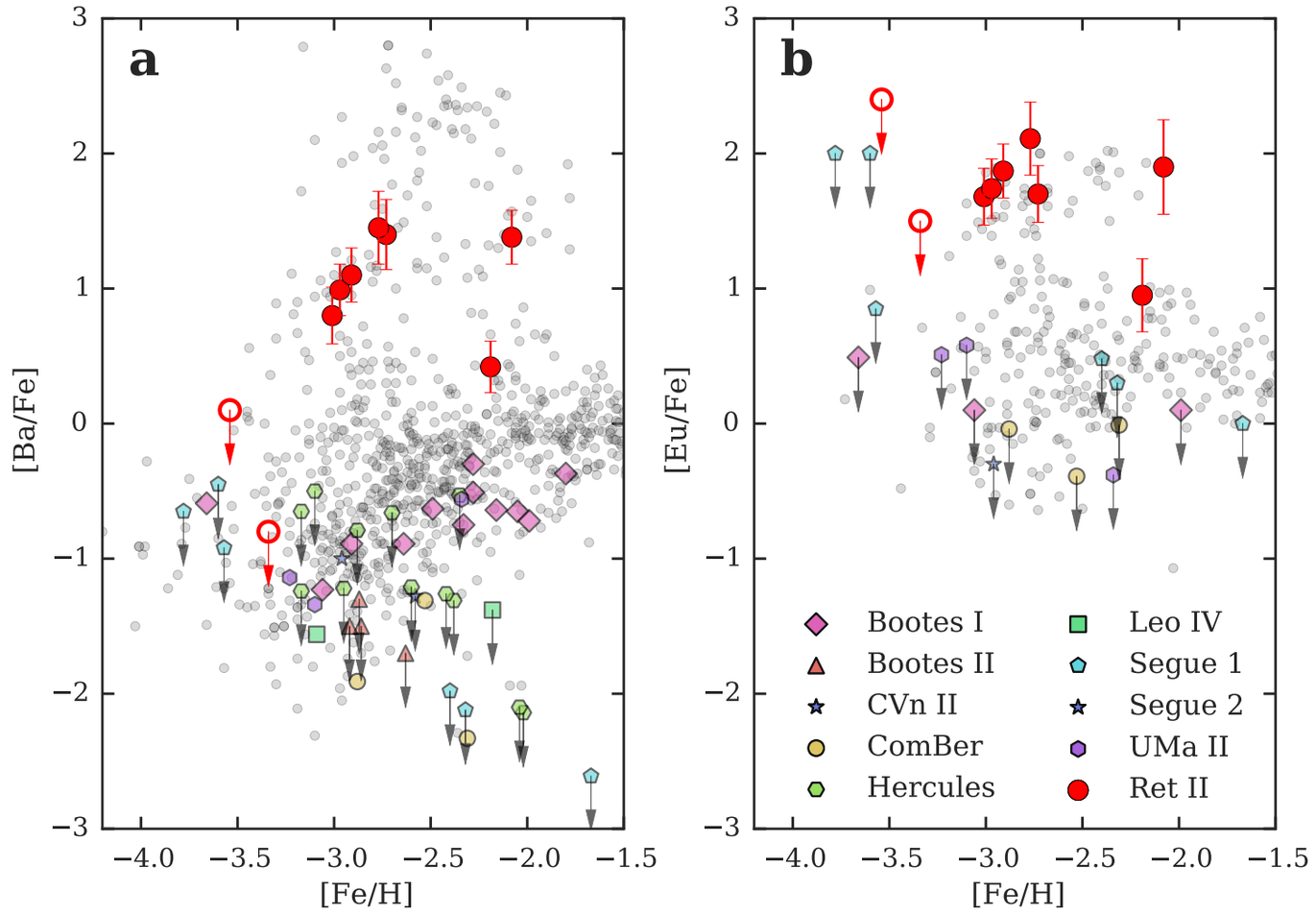
- **EM counterparts of LIGO sources**
- **Central engine** vs. **external fireball** and ejecta
- **Pinpoint host galaxy**, determine formation environment
- **Standard sirens**: Calibration-free rung on cosmological distance ladder
- Explain cosmic abundance of heavy elements – **“bling nova”**
- Explain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

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**

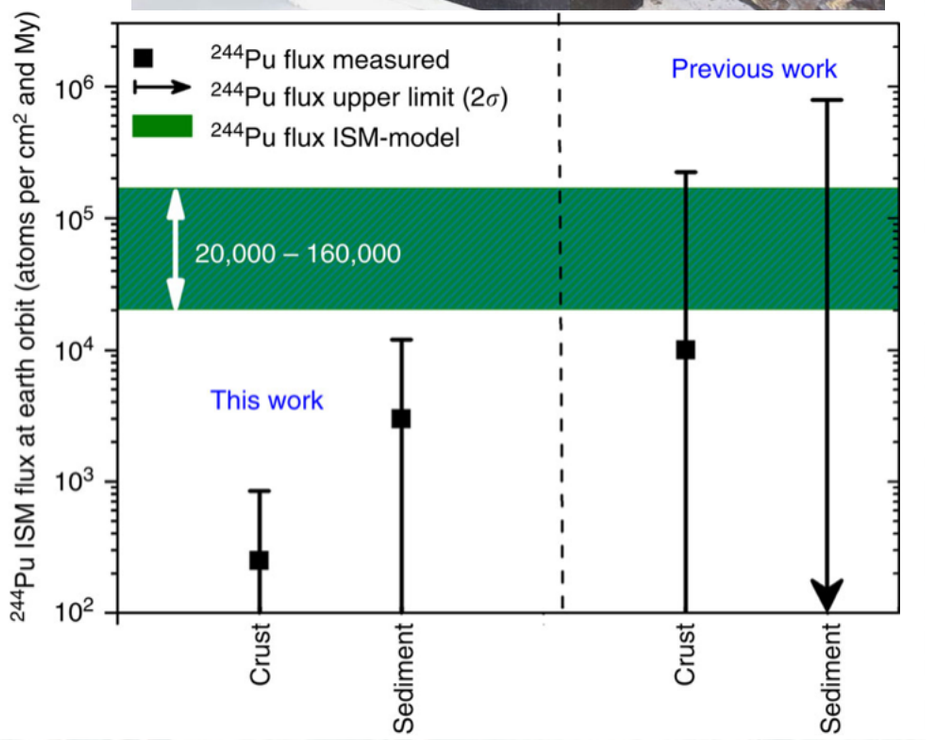
- Concentration of **^{244}Pu** in deep-sea sedimentary rock

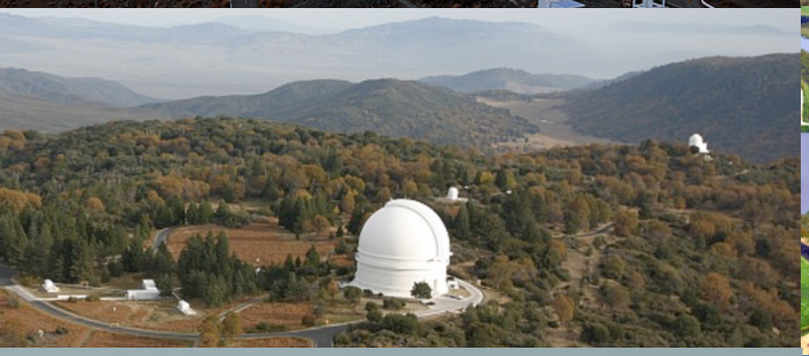
- Half-life = 85 My, so no active contribution from solar system

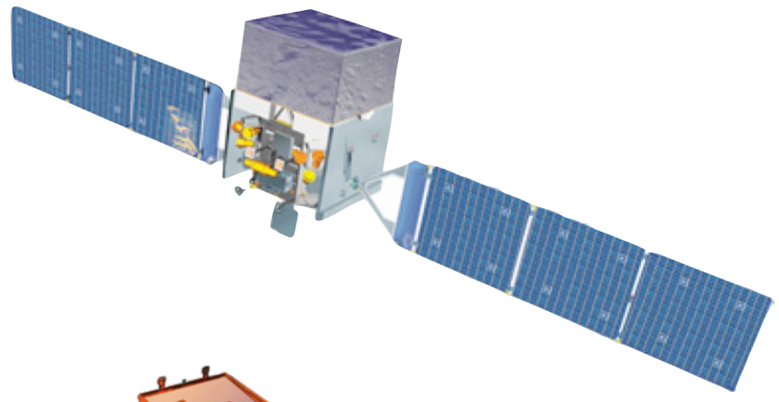
- Lower concentration than expected for r-process dominated by supernovae (Wallner+ 2015)

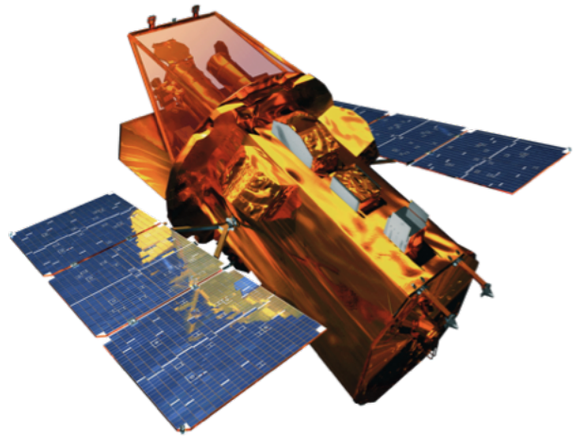
- Low-rate, high-yield process preferred over high-rate, low-yield process → **NS binaries** (Hotokezaka+ 2015)

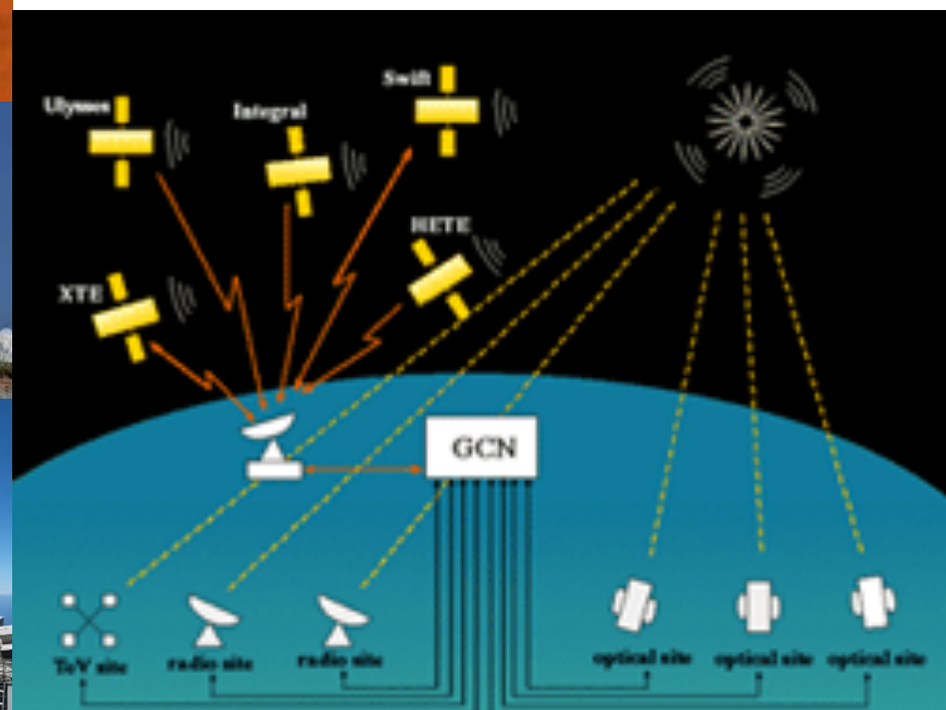
Wallner+ 2015





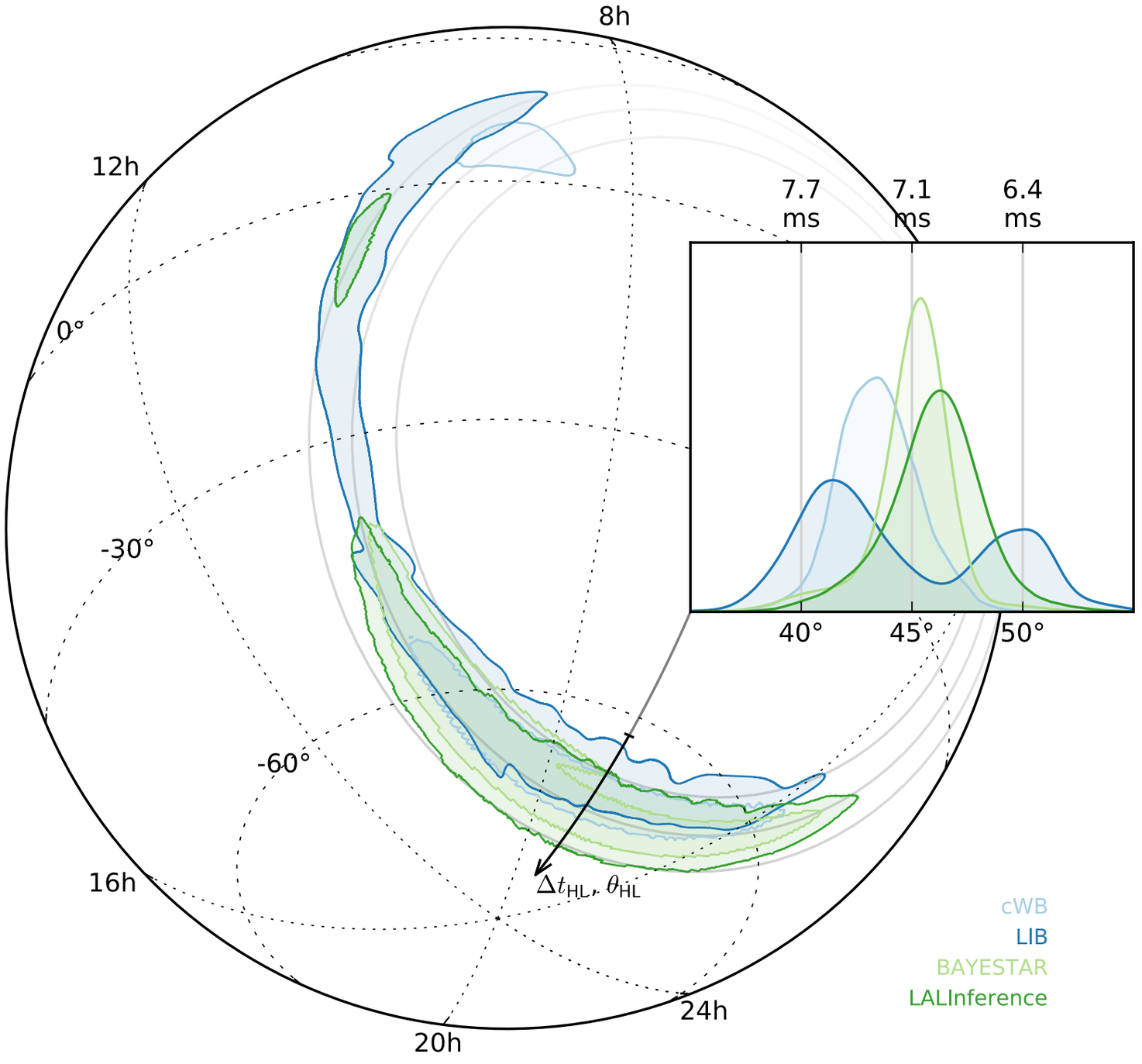





Ulysses
Integral
Swift
HETE
XTE
GCN
TeV site
radio site
radio site
optical site
optical site
optical site

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

ApJL, 826, L13
arXiv:1602.08492



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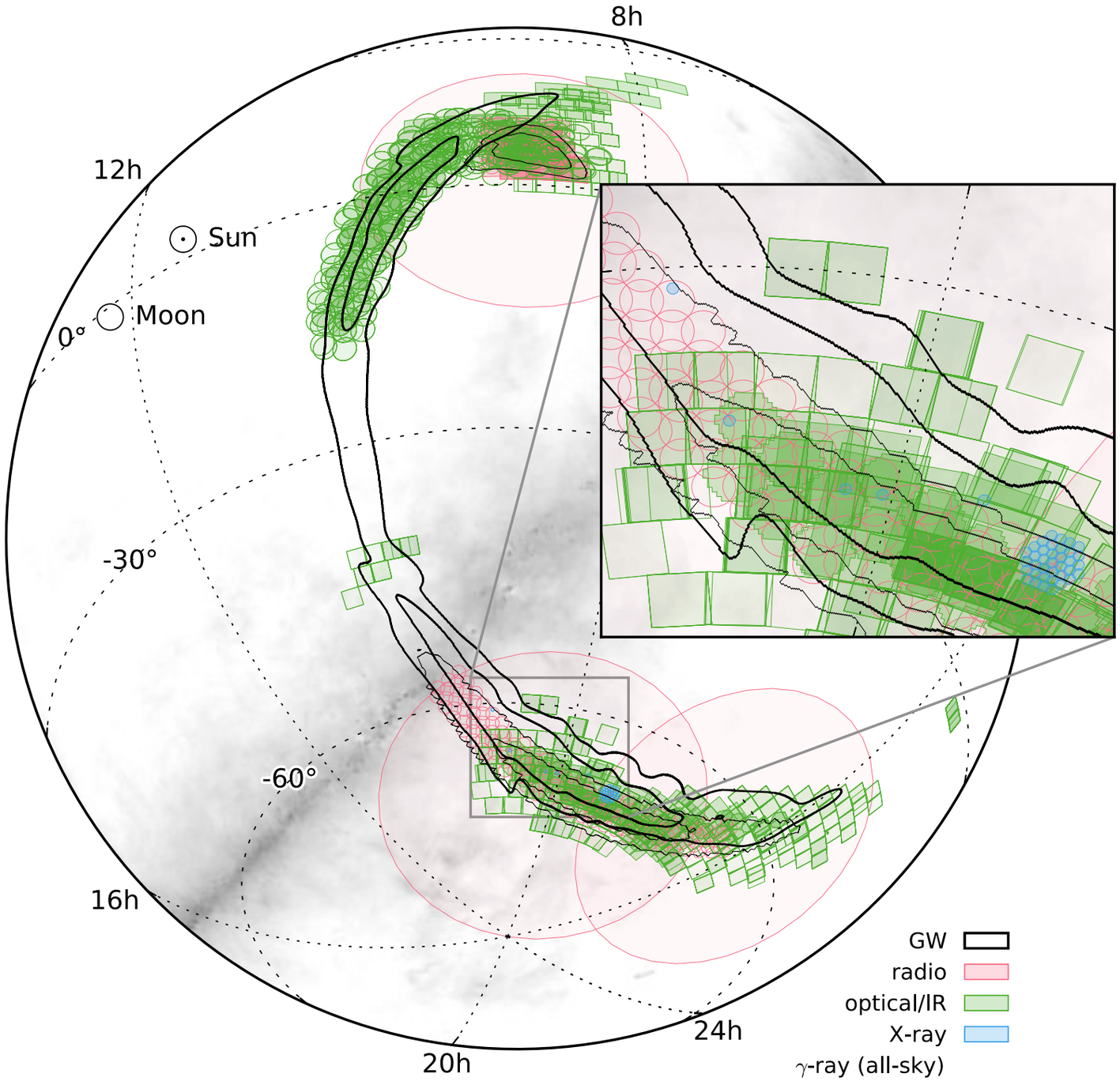
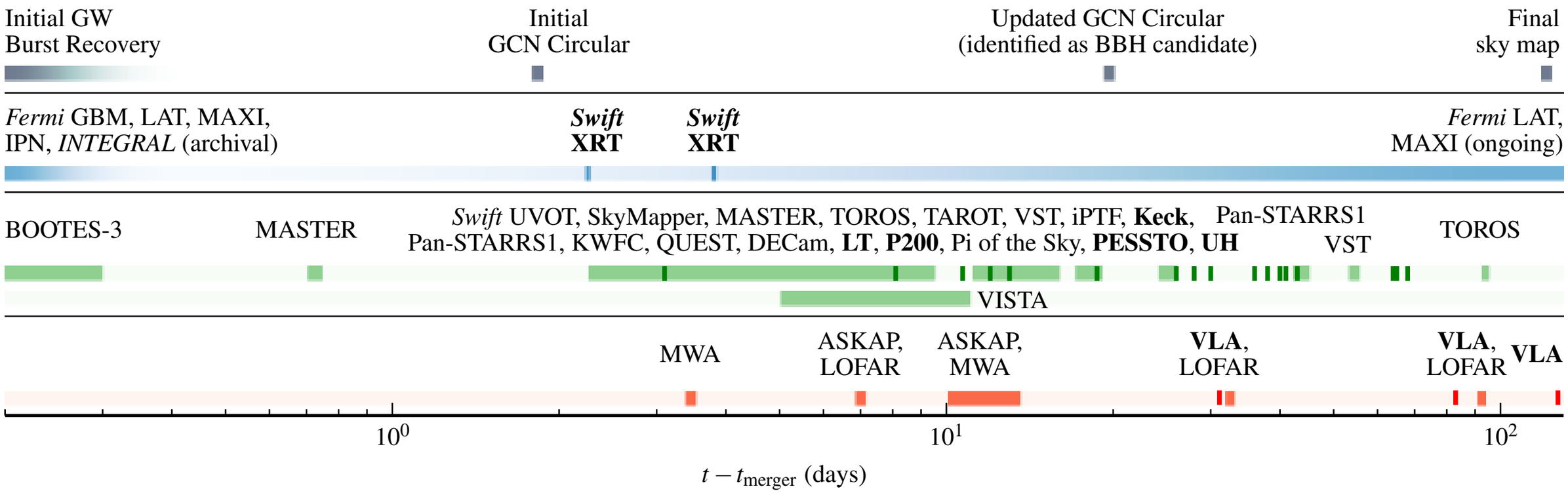




LOCALIZATION AND BROADBAND FOLLOW-UP OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

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

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

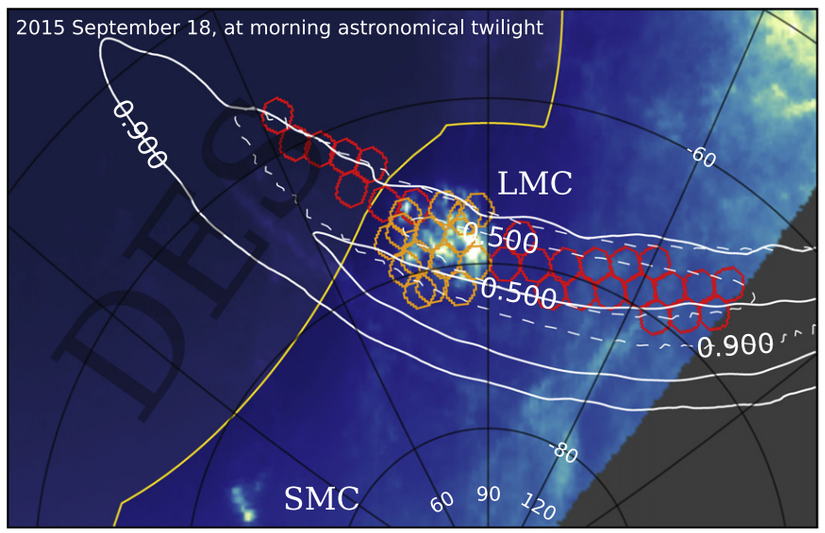
- **DECam search for failed missing supergiants/failed SN** in LMC
  Annis+ 2016

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

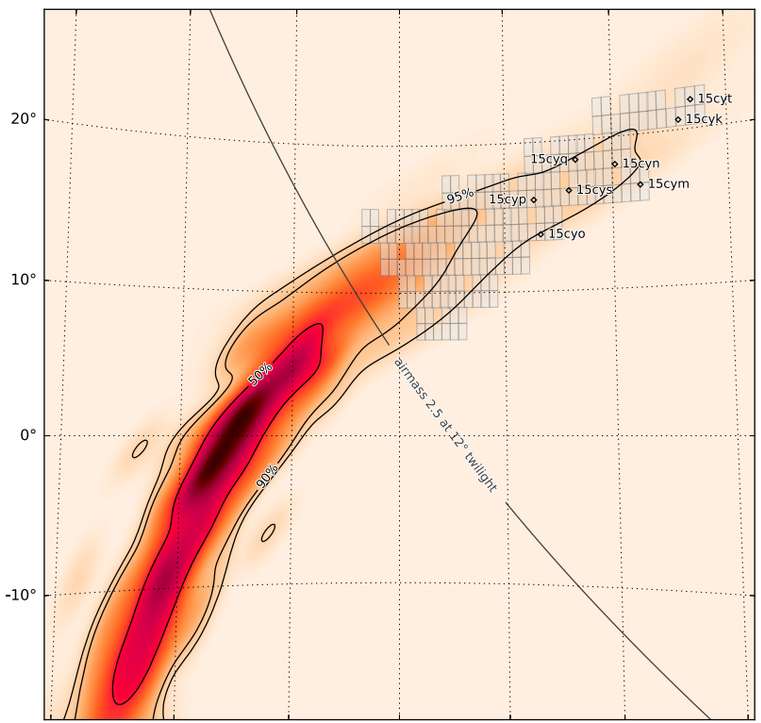
- **DECam** (Soares-Santos+), ***AGILE*** (Tavani+), ***XMM*** (Troja+), ***Fermi* LAT** (LAT Collab.), **Pan-STARRS/PESSTO** (Smartt+), **Subara+HSC**

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

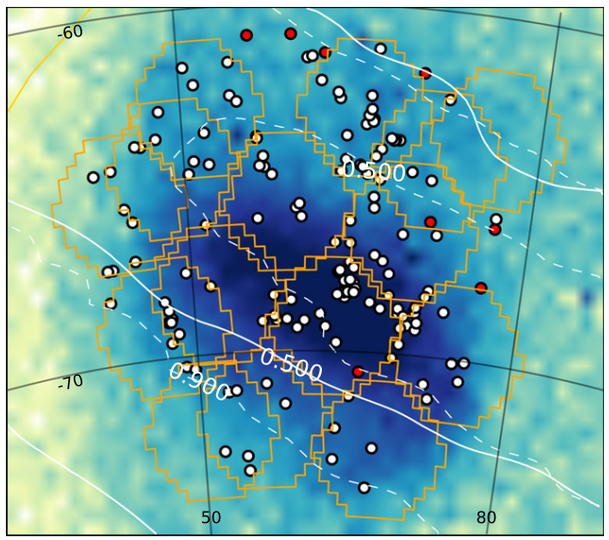
Soares-Santos+ 2016



Deep, wide-field follow-up with DECam to *i*=22.5

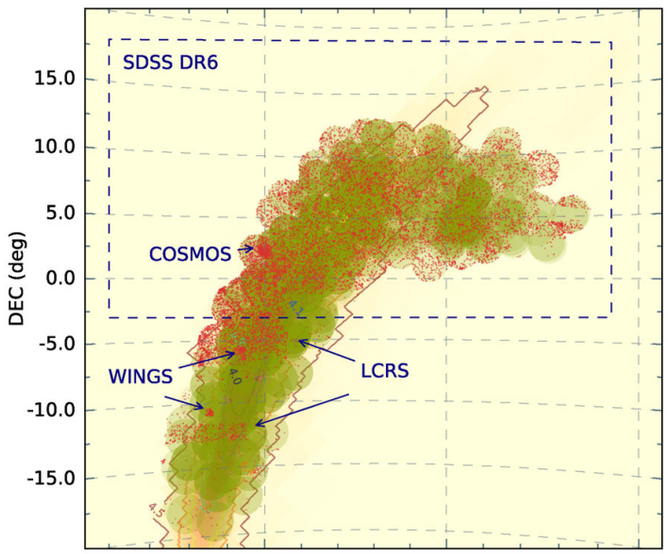


Annis+ 2016



DECam search for missing supergiants in LMC

Smartt+ 2016



Kasliwal, Cenko, Singer+ 2016

iPTF optical transient search + Keck classification spectra <1 hour after discovery, plus a serendipitous superluminous supernova

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:

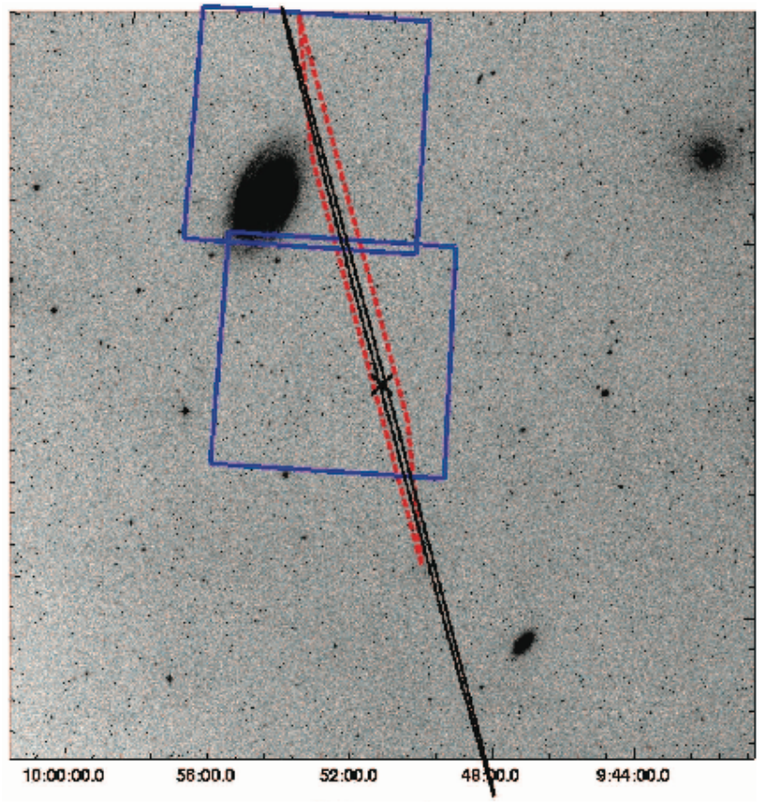
    1. Coincidence between GW candidates and GRB (see A. Urban Ph.D thesis)

    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



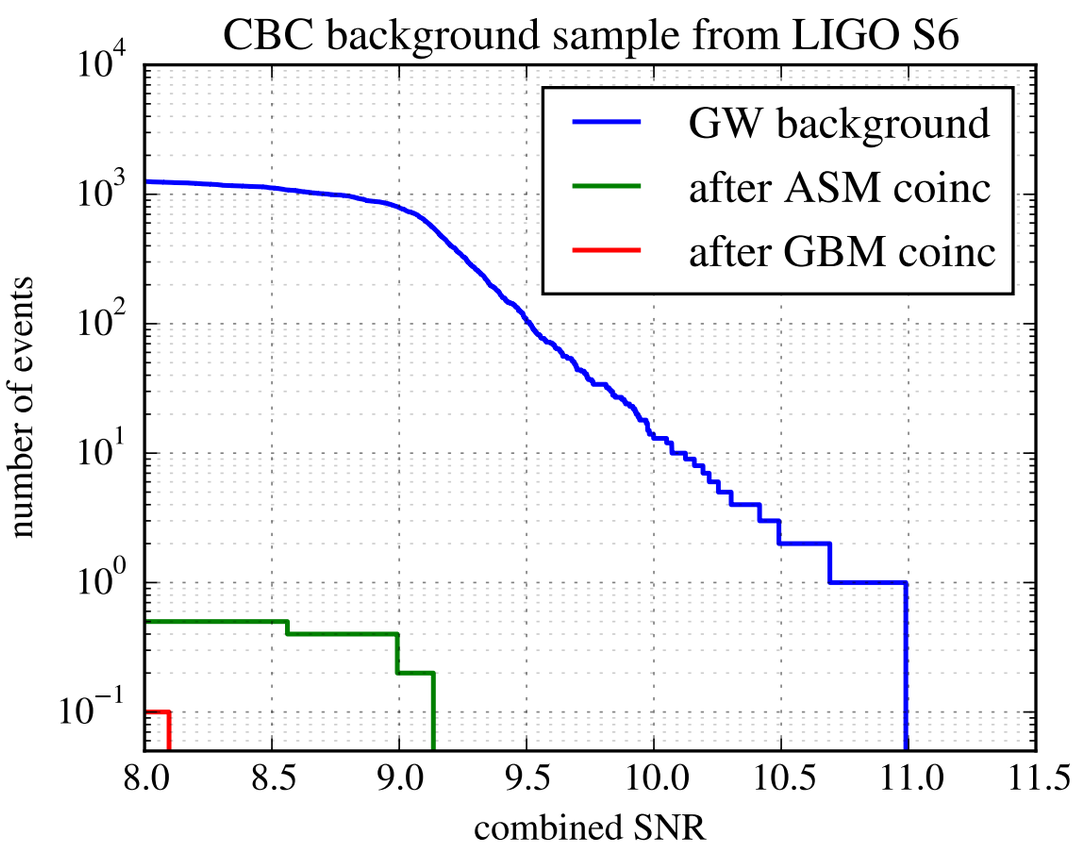
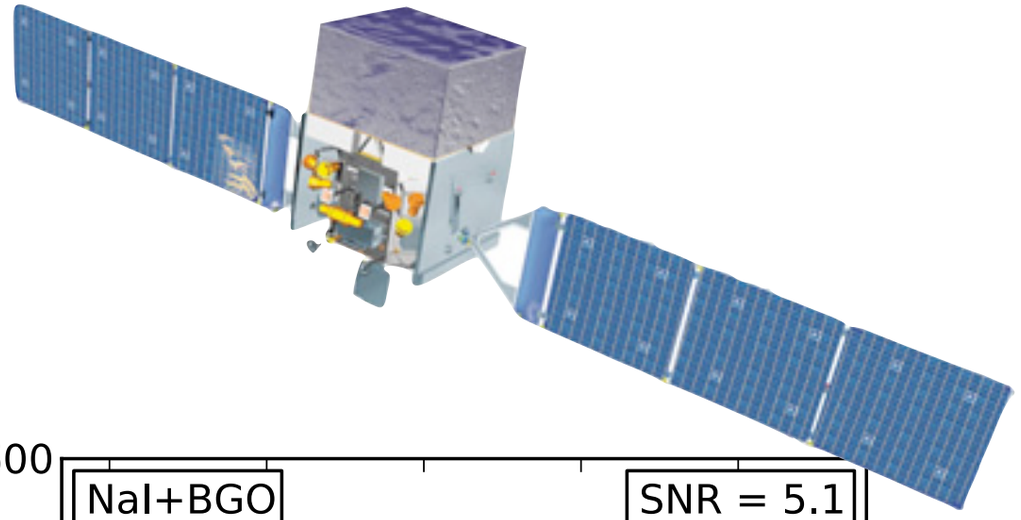


image: Blackburn+ 2015

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.)

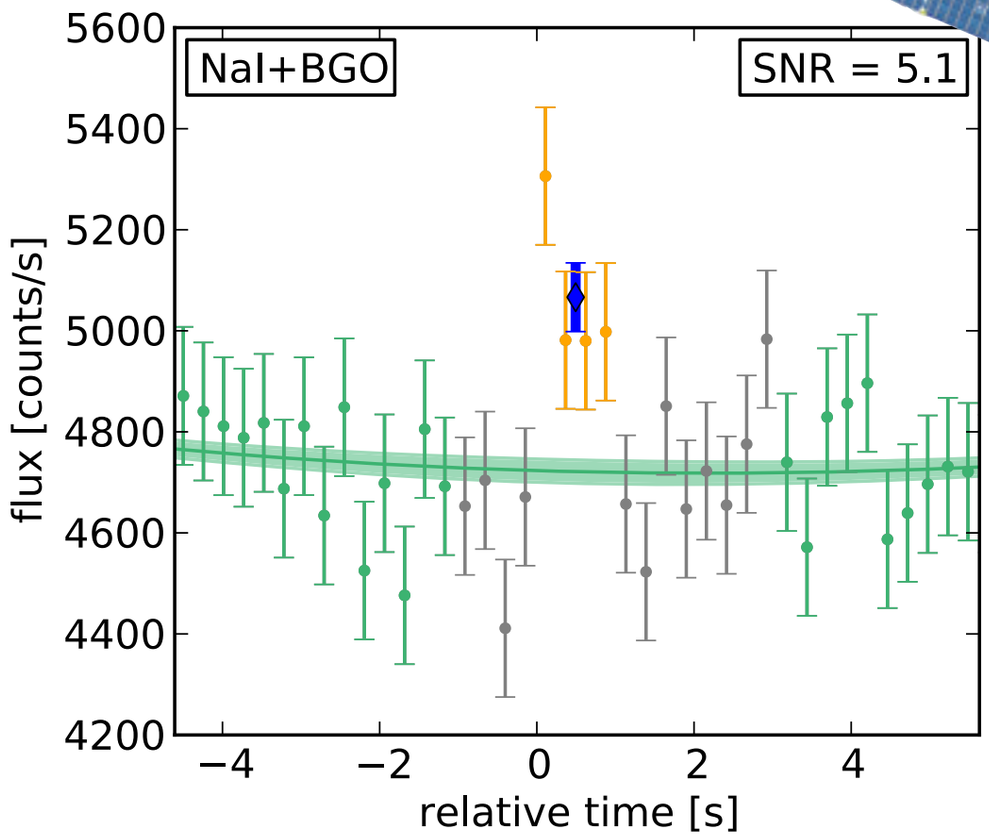
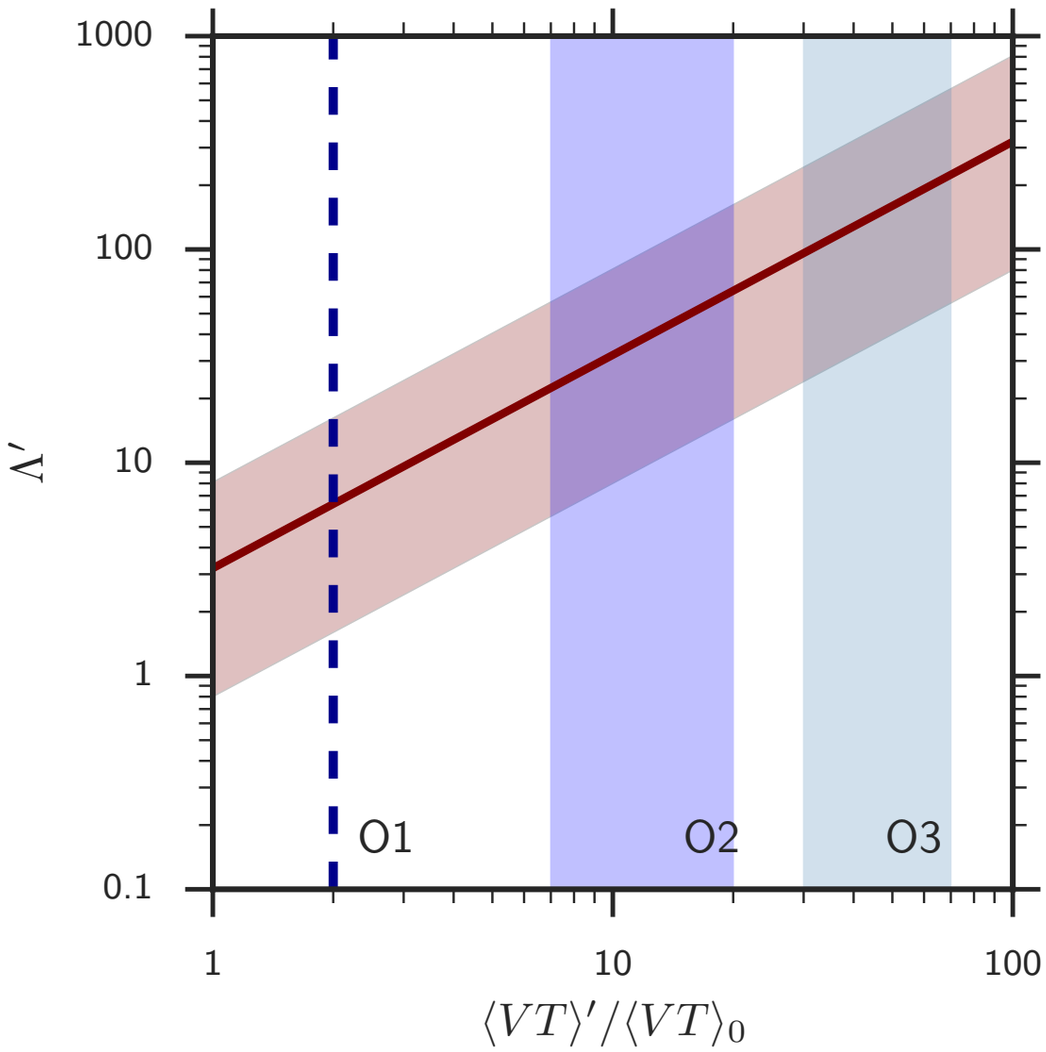


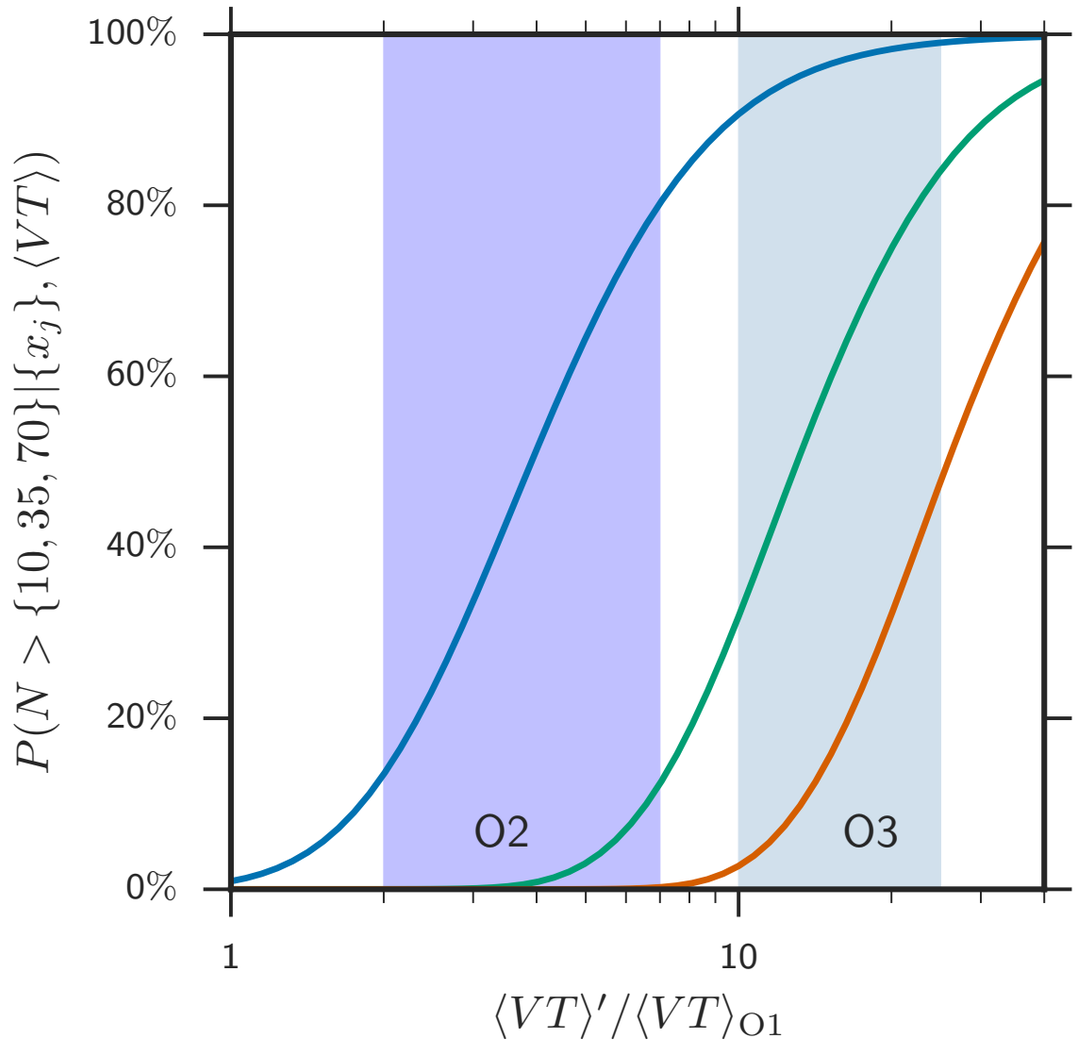
image: Connaughton+ 2016

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

WHERE WE WILL GO IN O2



Based on GW150914 alone.
LVC 2016, PRL, arXiv:1602.03842



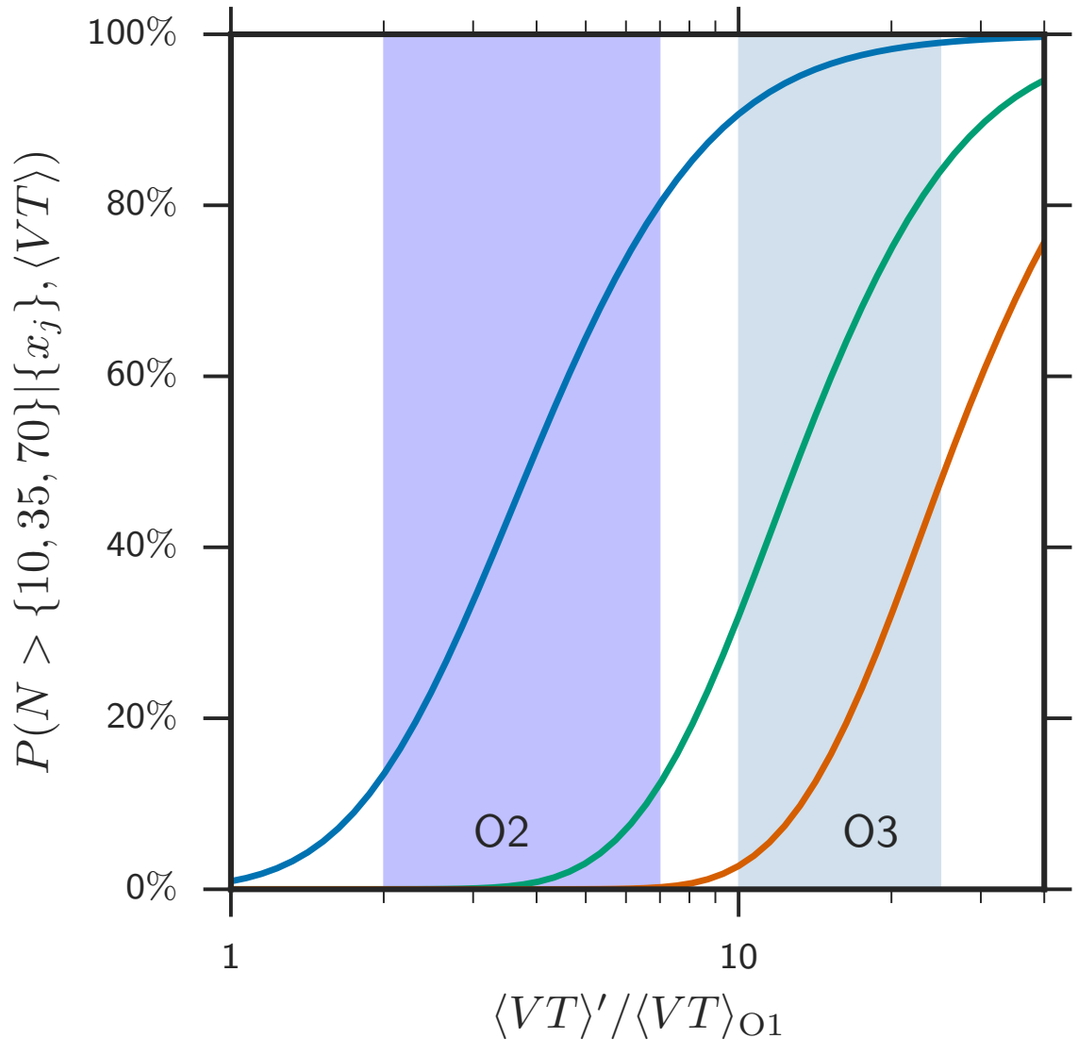
Based on all O1 events.
LVC 2016, arXiv:1606.04856

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!)

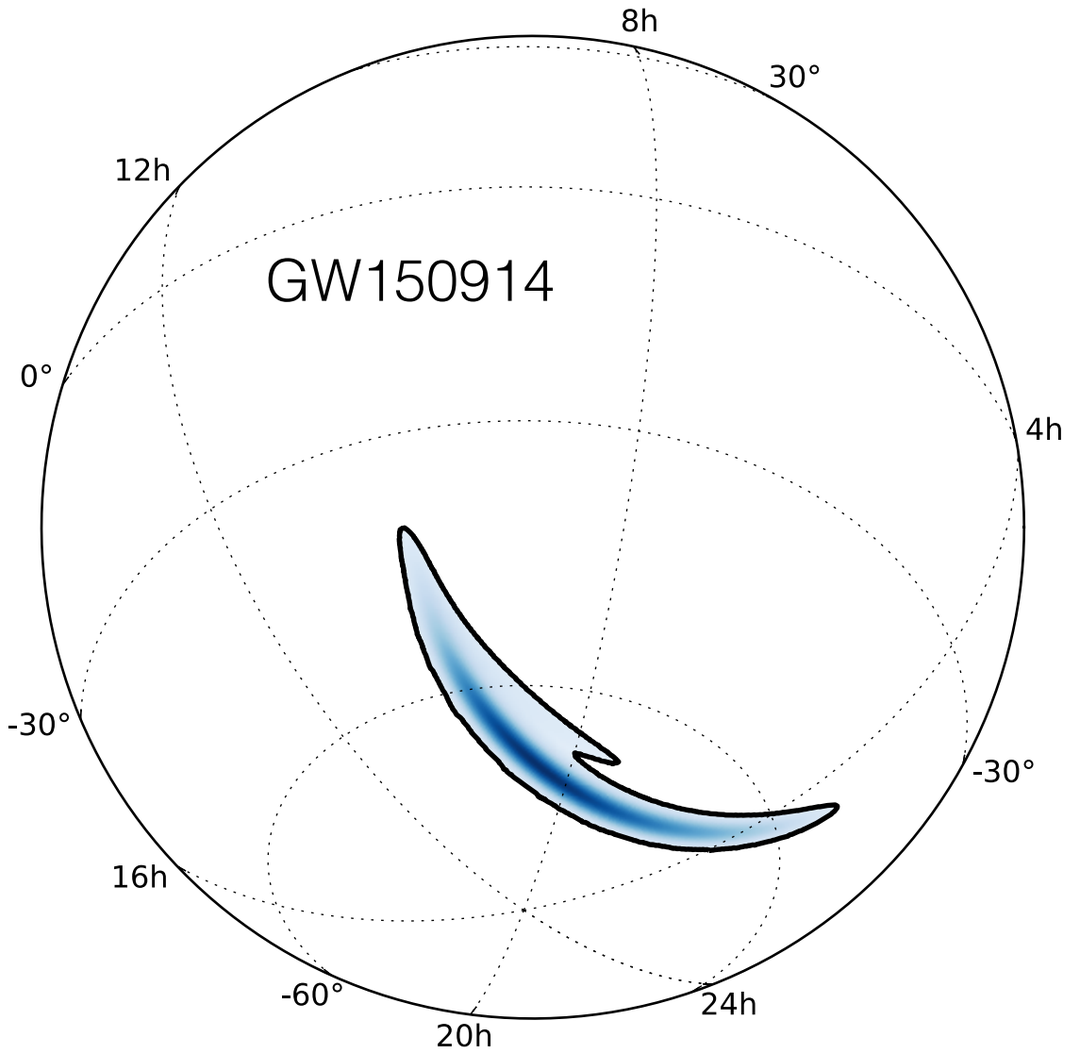


Based on all O1 events.
LVC 2016, arXiv:1606.04856

VIRGO

CASCINA, ITALY

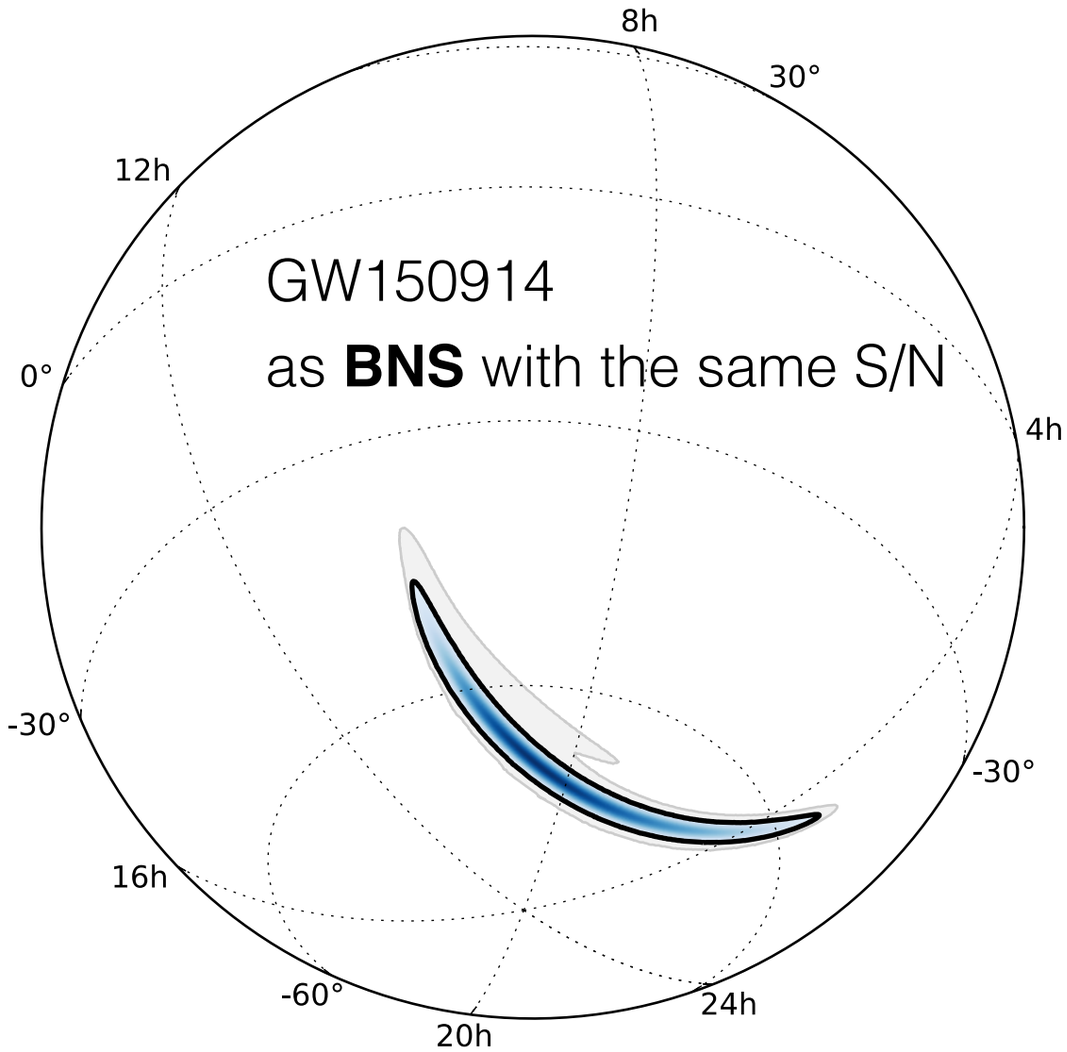
PARADIGM SHIFT with **Advanced Virgo**



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

PARADIGM SHIFT with **Advanced Virgo**



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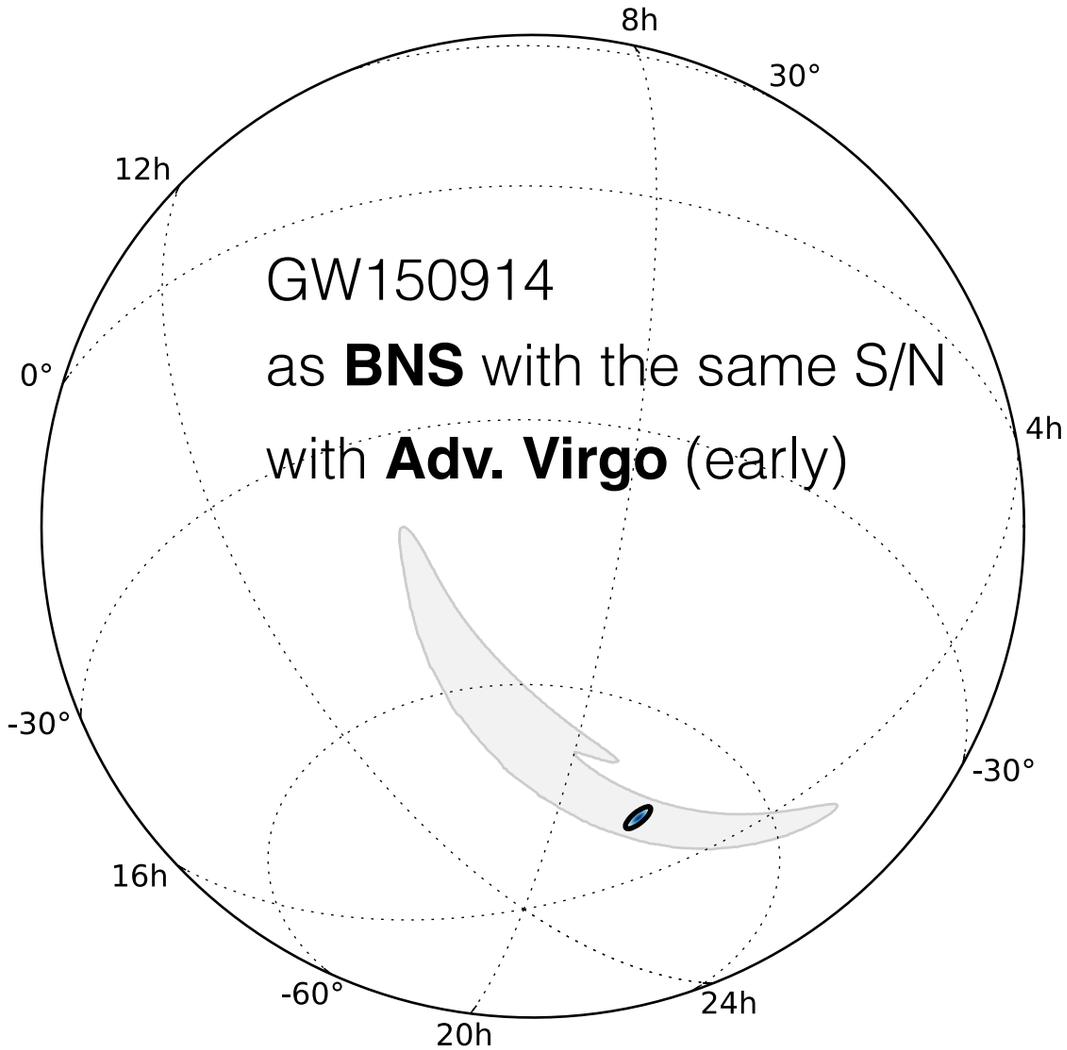

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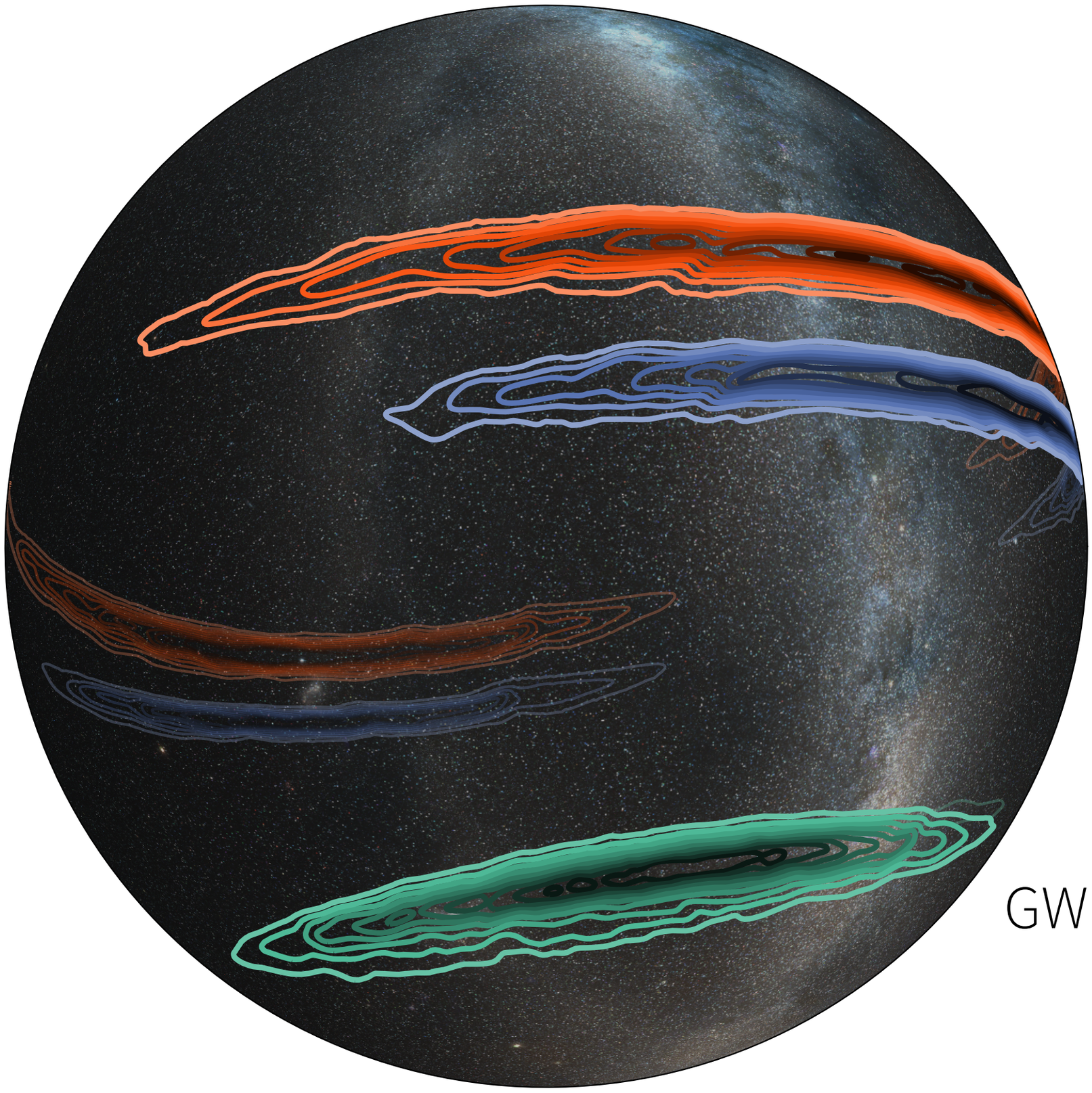
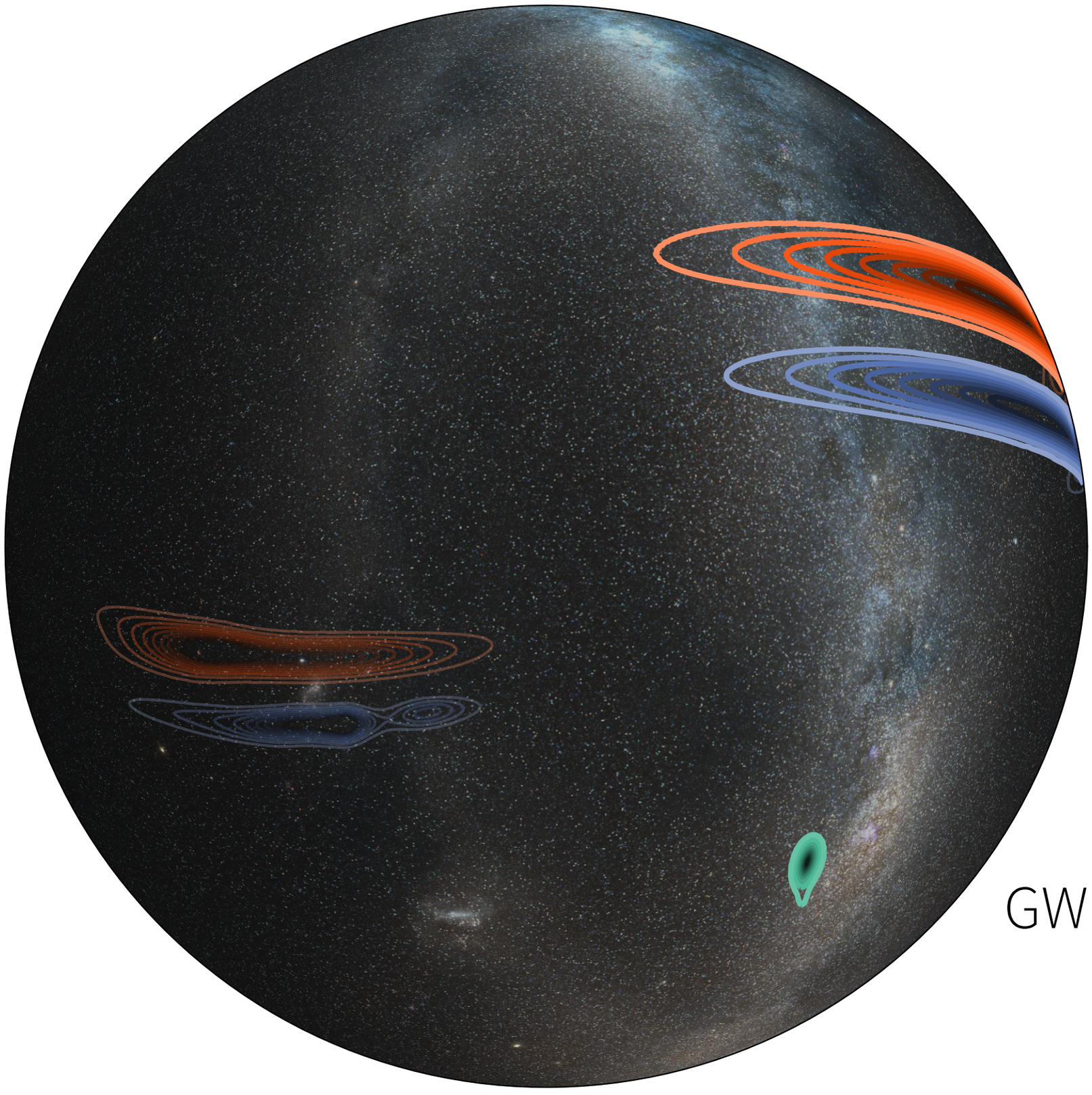


image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)

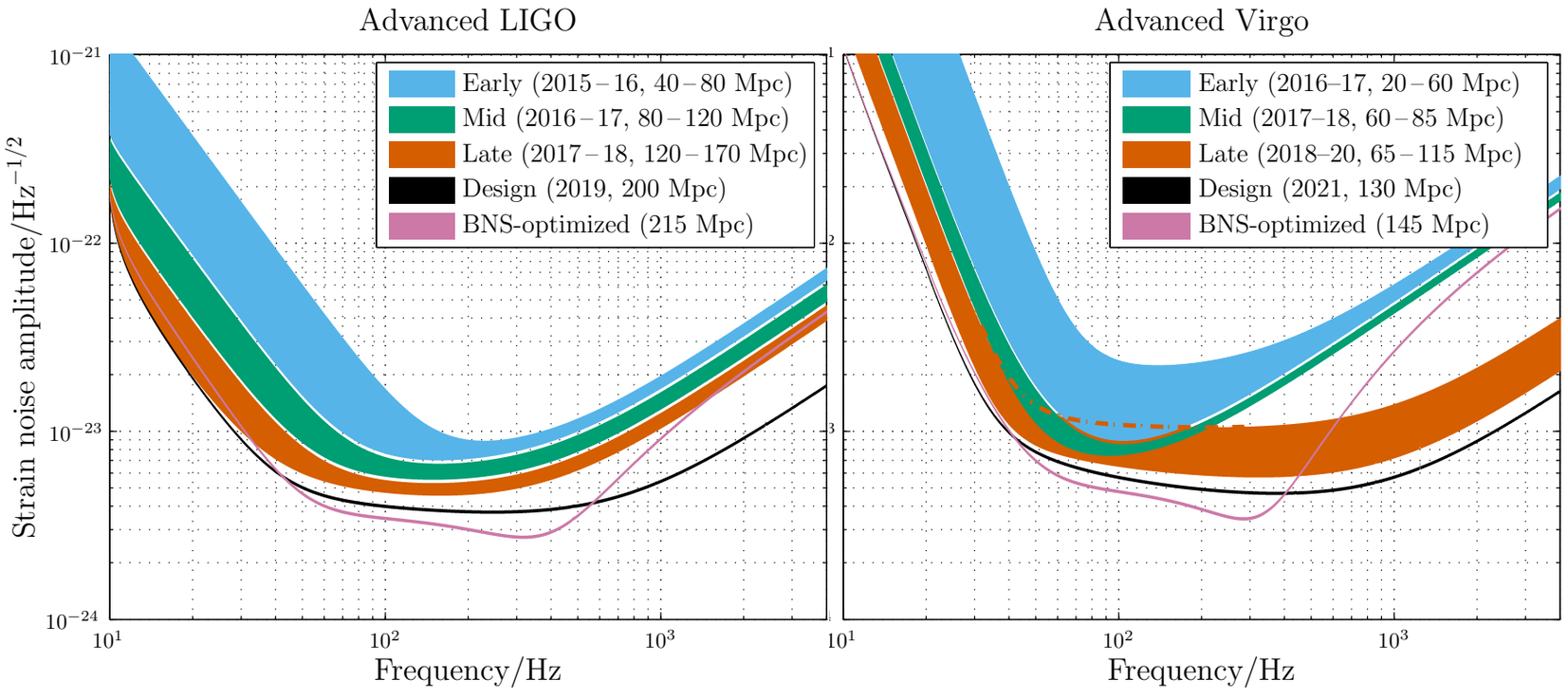


LVT151012 **+VIRGO**

GW151226 **+VIRGO**

GW150914 **+VIRGO**

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

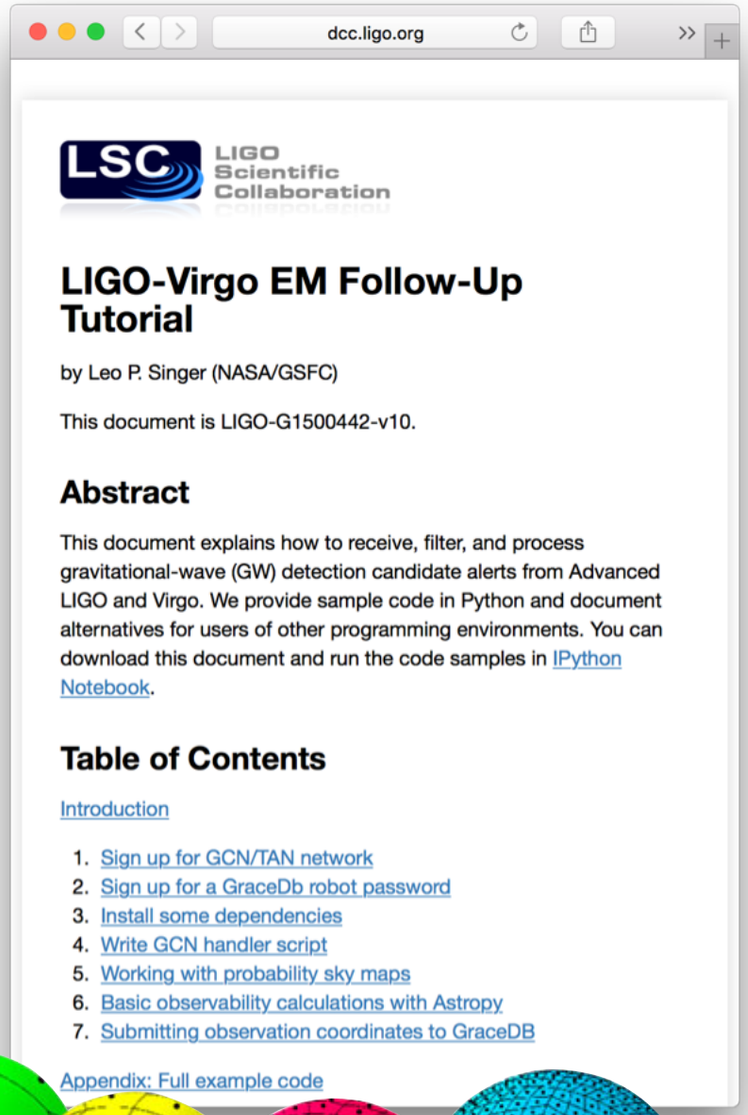


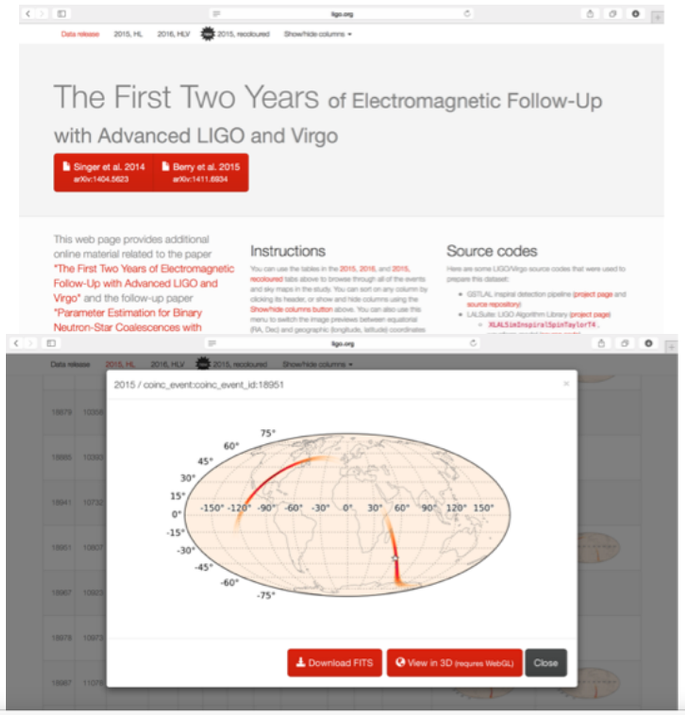
We anticipate **neutron star binary** detections or astrophysically interesting rate constraints by O2/O3.

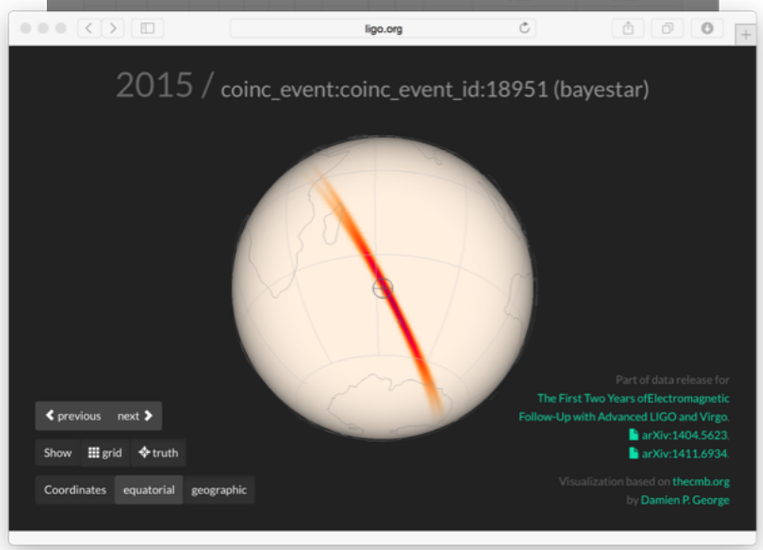
We expect routine O(10-100) deg2 or less once Advanced Virgo ramps up (maybe as early as late O2).

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 deg^2	< 1	2	*> 1–2*	*> 3–8*	*> 20*
		20 deg^2	< 1	14	*> 10*	*> 8–30*	*> 50*
	median/deg^2		480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
	median/deg^2		88	29	—	—	—

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**

- **Currently ramping up for O2**: contact us to learn about joint GW-EM observing opportunities and MOUs

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/