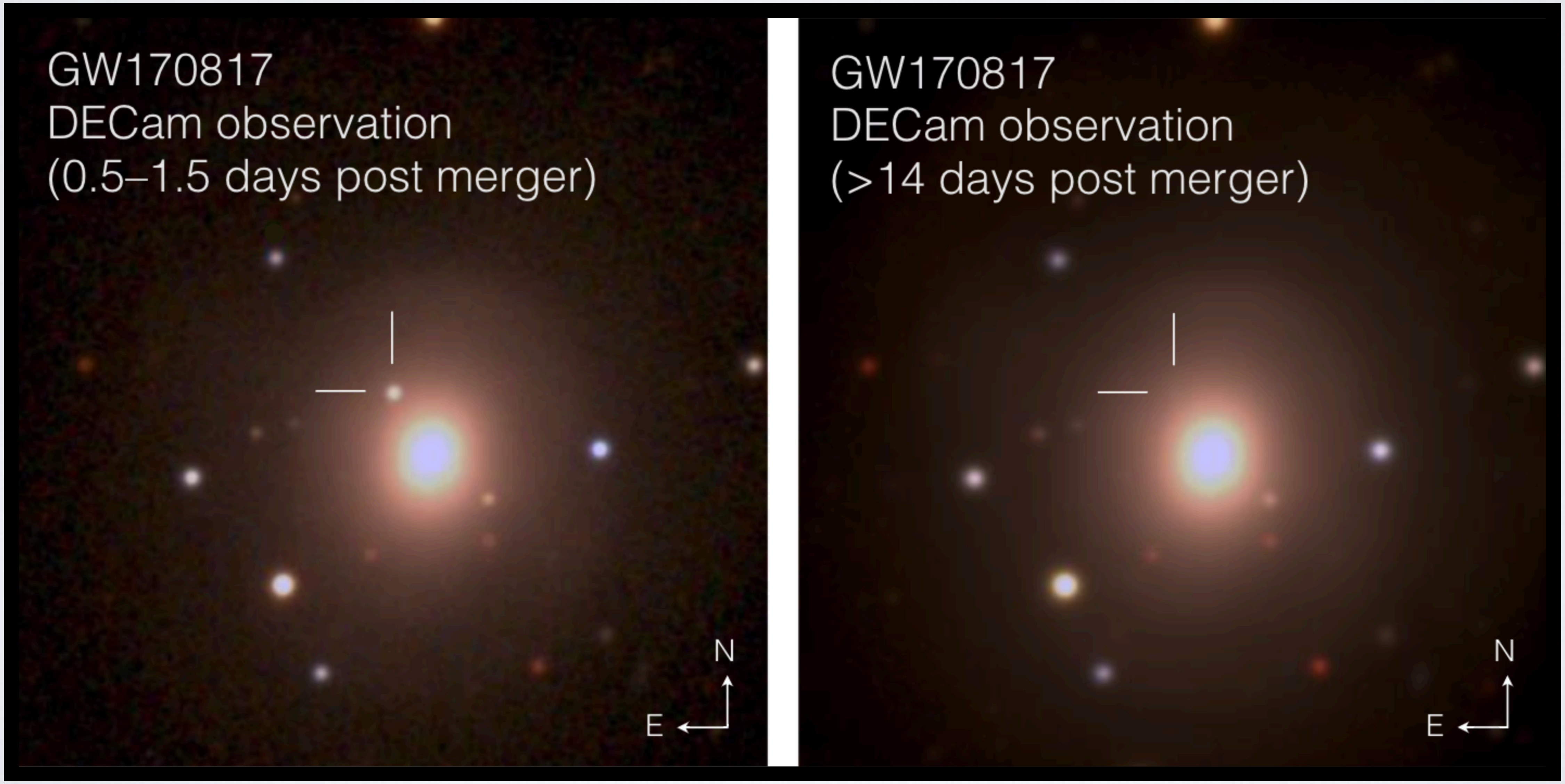
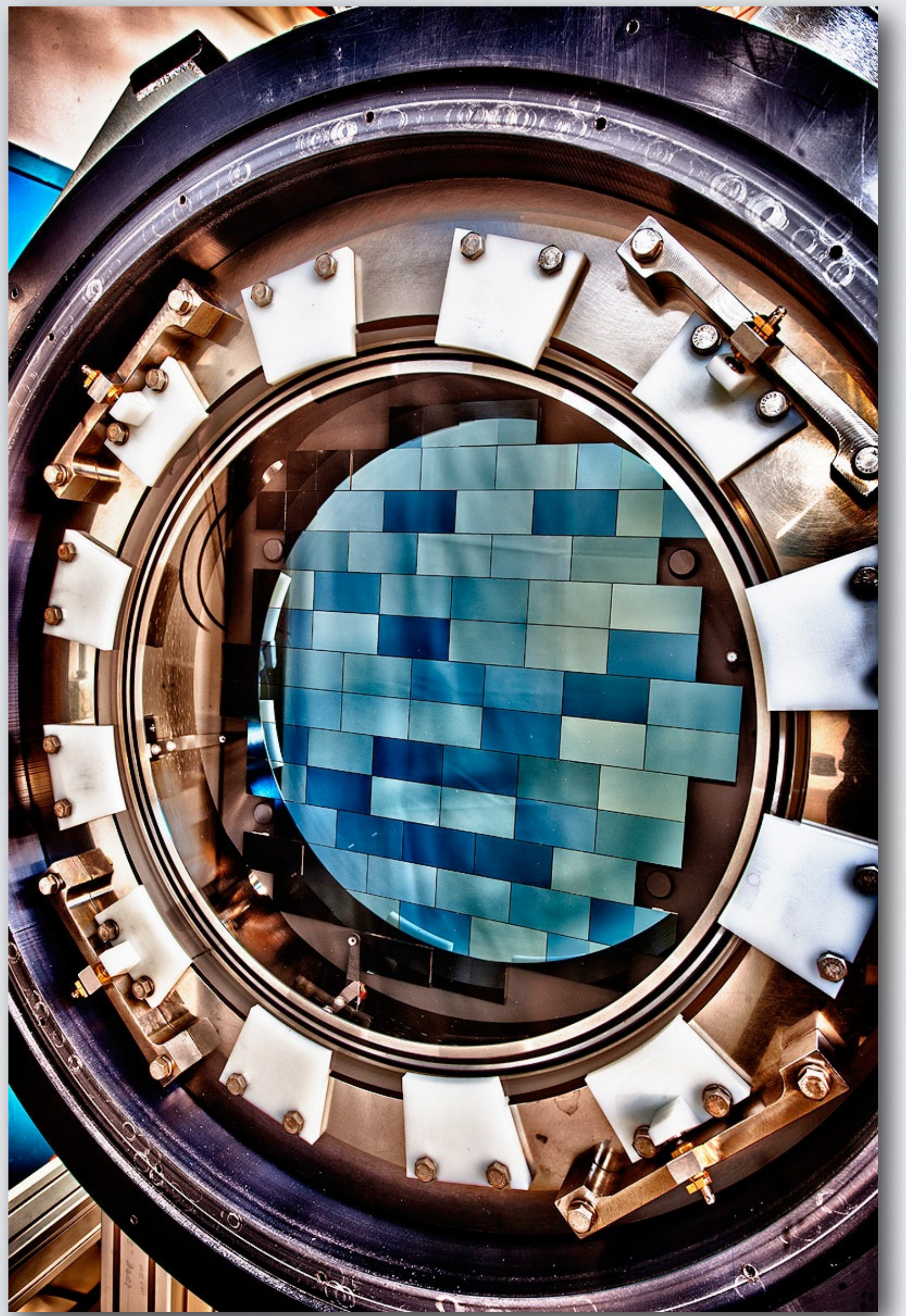
MULTI-MESSENGER COSMOLOGY WITH GRAVITATIONAL WAVES IN THE DARK ENERGY SURVEY

Marcelle Soares-Santos ◆ Brandeis University ◆ **DES** Collaboration



Subaru 20th Anniversary Conference ◆ Hawaii ◆ Nov 21, 2019

DARK ENERGY SURVEY



DECam

3 sq deg FOV, **570 Mpix** optical CCD camera

Facility instrument at **CTIO Blanco 4-m telescope in Chile**

First light: Sep 2012

DES programs

Wide: **5000 sq deg** grizY

SNe: **30 sq deg** SNe survey

GW: followup of **LIGO/Virgo events**

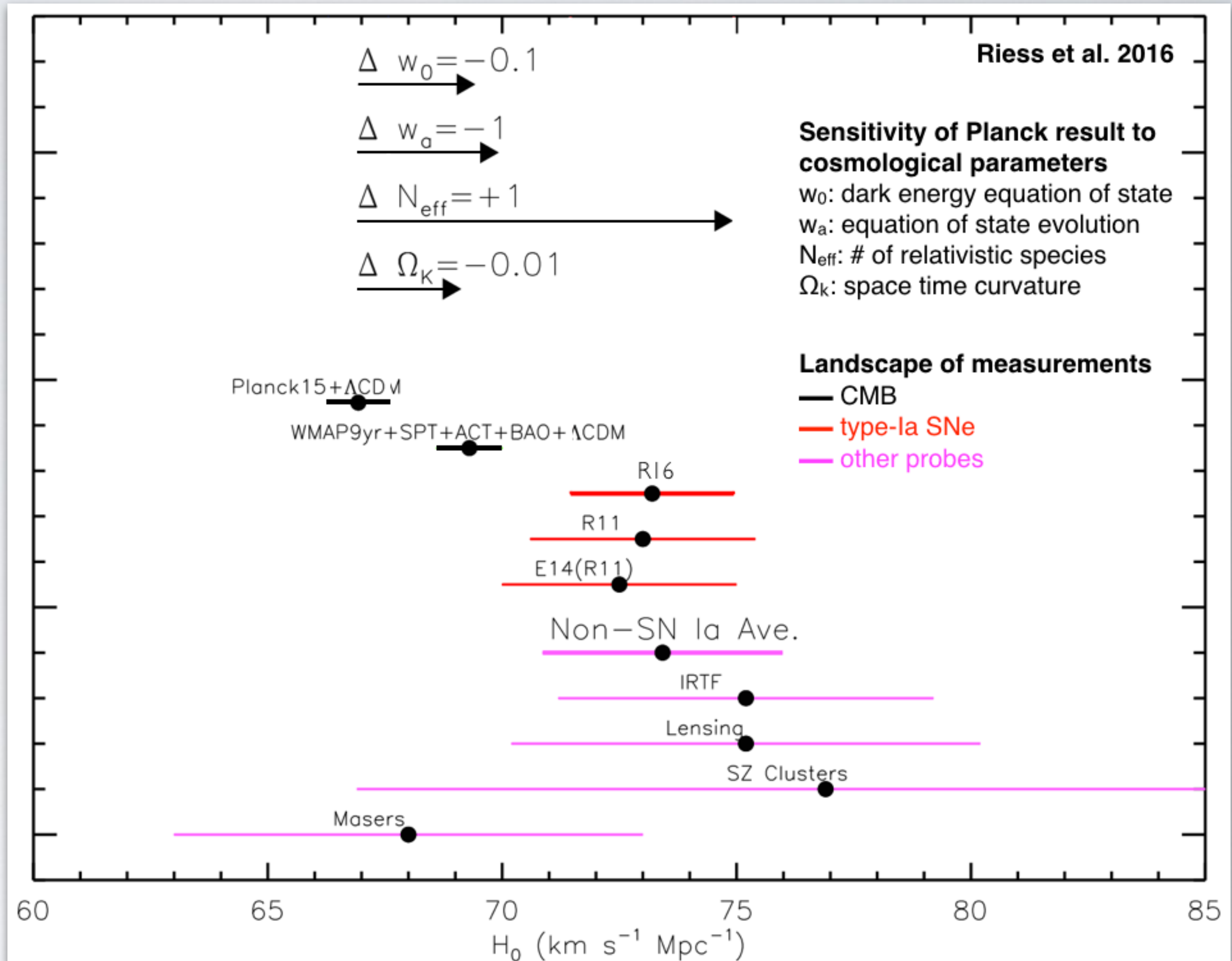
Neutrinos: followup of **Icecube events**

Goal to combine multiple Dark Energy Probes based on measurements of distance and growth of structures.

COSMOLOGY MOTIVATION

Growing discrepancy between SNe and CMB-based measurements of the current rate of expansion: systematic effects, or new physics?

A new, independent, measurement will be most helpful here!

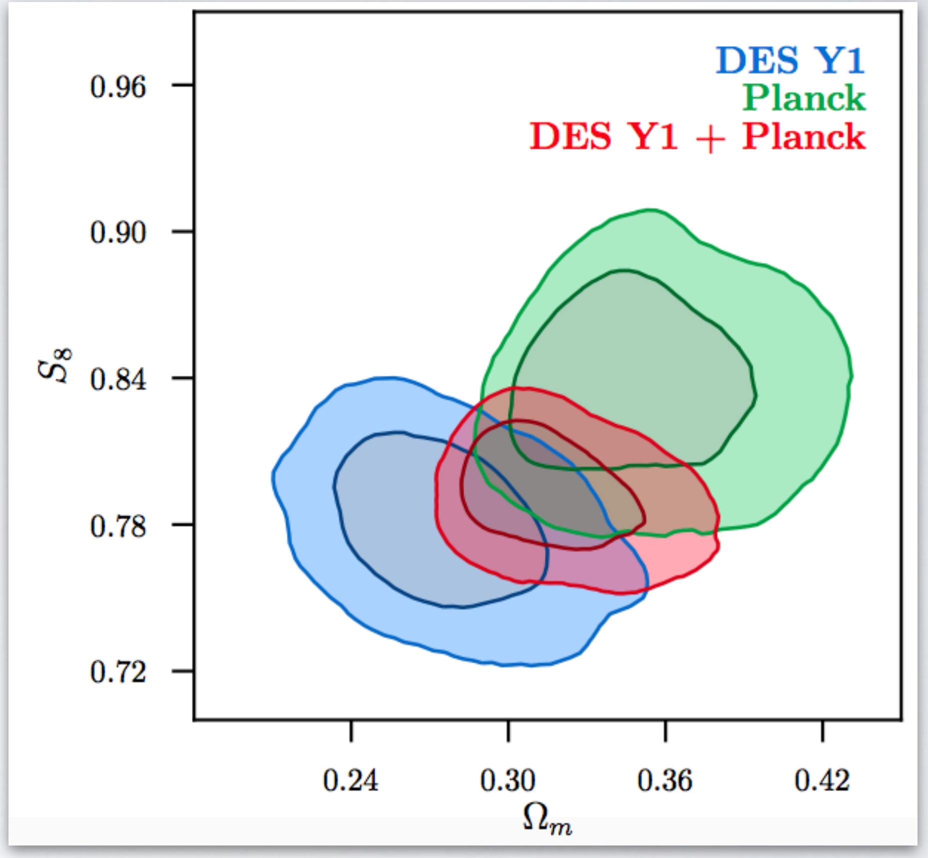


$$H \equiv \dot{a}/a \text{ , where } a = 1/(1+z)$$
$$H(z) = H_0 \cdot f(z; \Omega_m, \Omega_k, \Omega_{DE}, w_0, w_a)$$

DES FIRST COSMOLOGY RESULTS

Results including cosmic shear, galaxy-galaxy lensing, and galaxy-galaxy clustering:

https://www.darkenergysurvey.org/des-year-1-cosmology-results-papers/



arXiv: 1708.01530

WHAT ARE STANDARD SIRENS?

(1) In a merging binary system, the change in GW signal frequency, gives us the size of the system.

(2) Once we know the size, we can predict the intrinsic amplitude, and compare that with the observed amplitude in our detectors!

NATURE VOL. 323 25 SEPTEMBER 1986

Determining the Hubble constant from gravitational wave observations

Bernard F. Schutz

Department of Applied Mathematics and Astronomy, University College Cardiff, PO Box 78, Cardiff CF1 1XL, UK

I report here how gravitational wave observations can be used to determine the Hubble constant, H_0. The nearly monochromatic gravitational waves emitted by the decaying orbit of an ultra-compact, two-neutron-star binary system just before the stars coalesce are very likely to be detected by the kilometre-sized interferometric gravitational wave antennas now being designed[1–4]. The signal is easily identified and contains enough information to determine the absolute distance to the binary, independently of any assumptions about the masses of the stars. Ten events out to 100 Mpc may suffice to measure the Hubble constant to 3% accuracy.

WHAT ARE STANDARD SIRENS?

(1) In a merging binary system, the change in GW sig… gives us… system…

(2) Once v… size, we… intrinsi… compa… observ… our det…

NATURE VOL. 323 25 SEPTEMBER 1986

Determining the Hubble constant from gravitational wave observations

Bernard F. Schutz

systems with circular orbits[5]. Consider a binary at a distance $100 r_{100}$ Mpc, with total mass $m_T M_\odot$ and reduced mass $\mu M_\odot$, emitting waves at frequency $100 f_{100}$ Hz (twice its orbital frequency). The standard quadrupole formula' of general relativity[6,7] shows that the waves will have amplitude (r.m.s.-averaged over detector and source orientations)

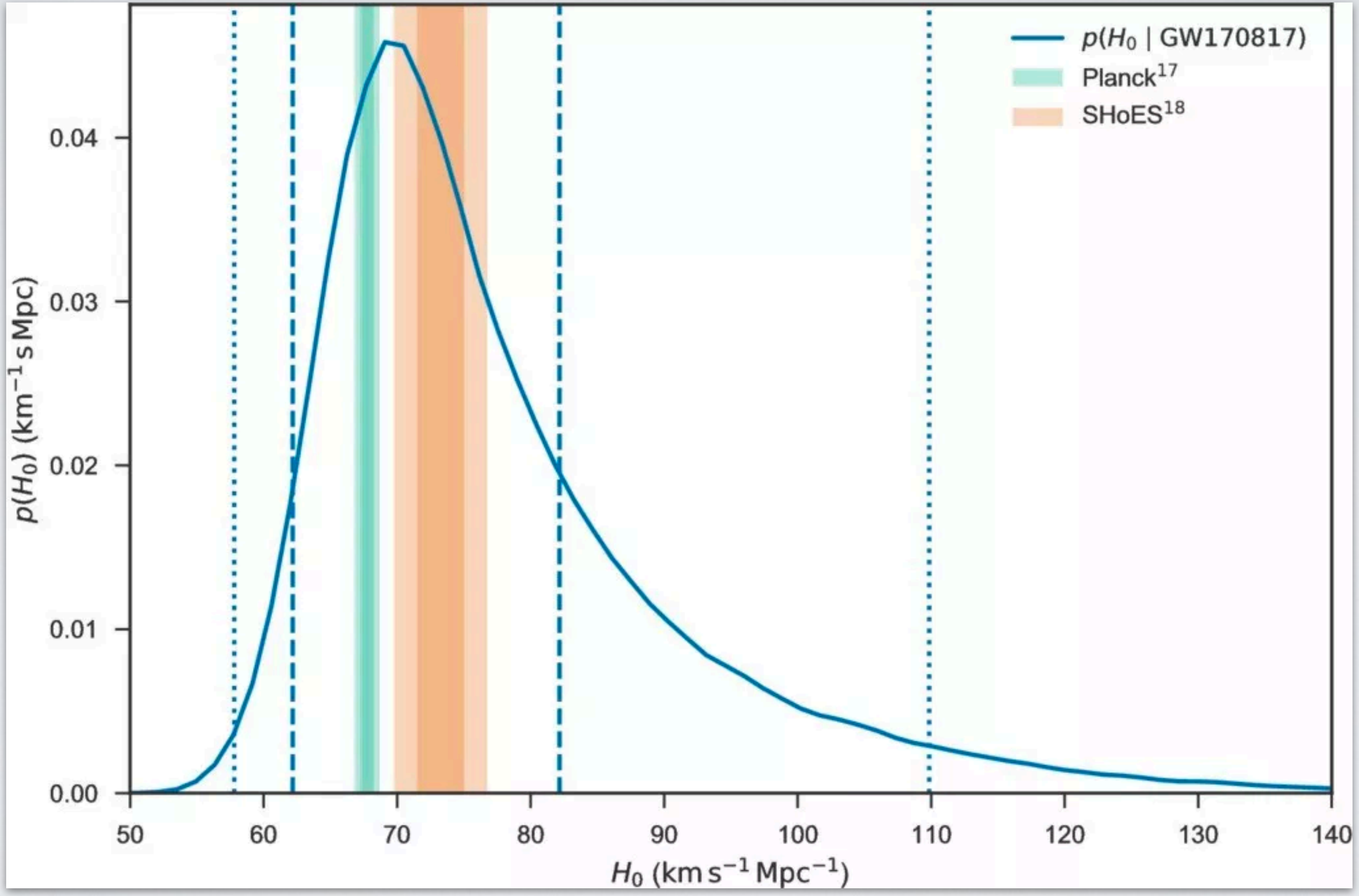
$$\langle h \rangle = 1 \times 10^{-23} m_T^{2/3} \mu f_{100}^{2/3} r_{100}^{-1} \quad (1)$$

and that their frequency will change on a timescale

$$\tau = f/\dot{f} = 7.8 m_T^{-2/3} \mu^{-1} f_{100}^{-8/3} \text{ s} \quad (2)$$

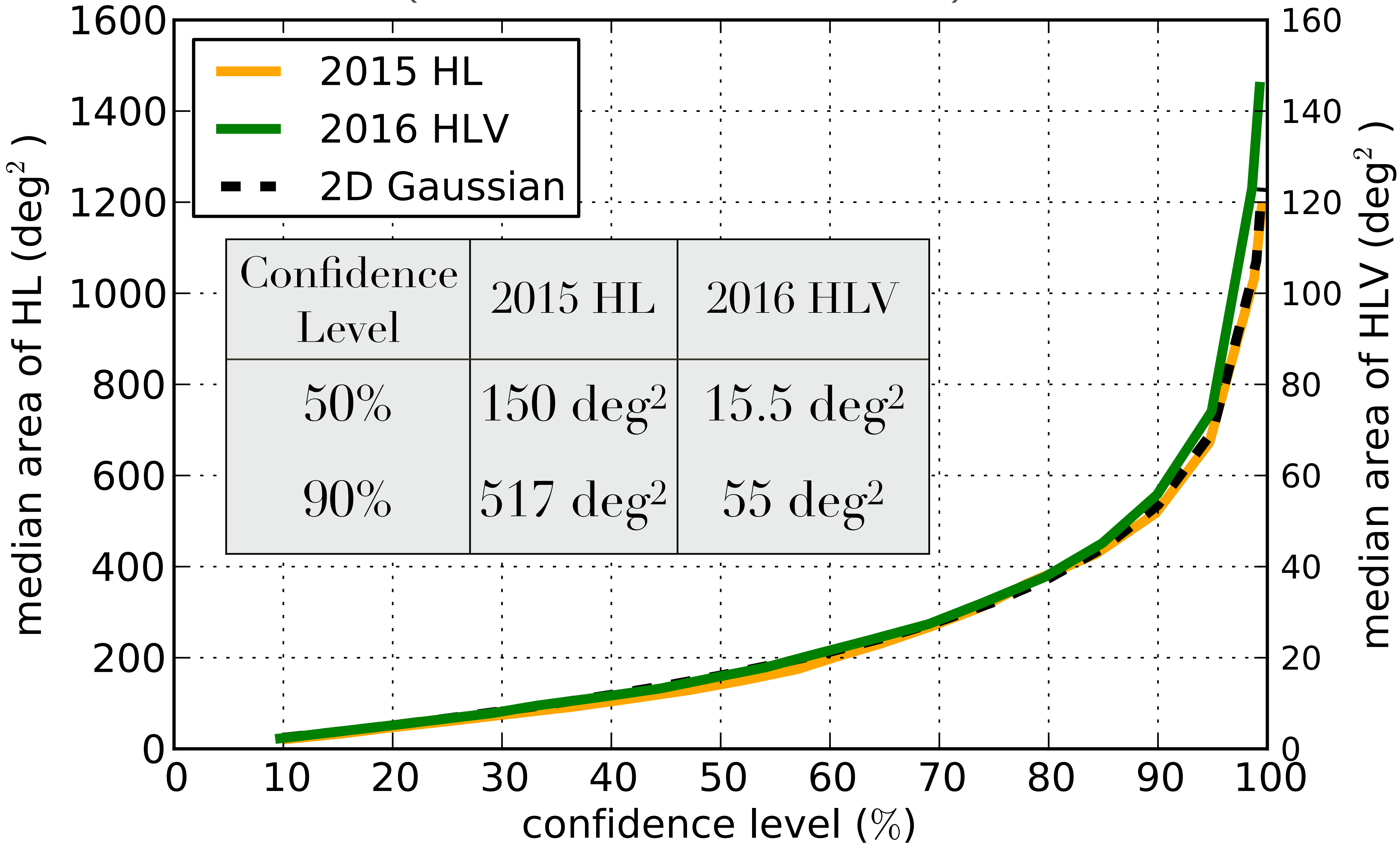
https://www.nature.com/articles/323310a0.pdf

COSMOLOGY: BRIGHT SIRENS



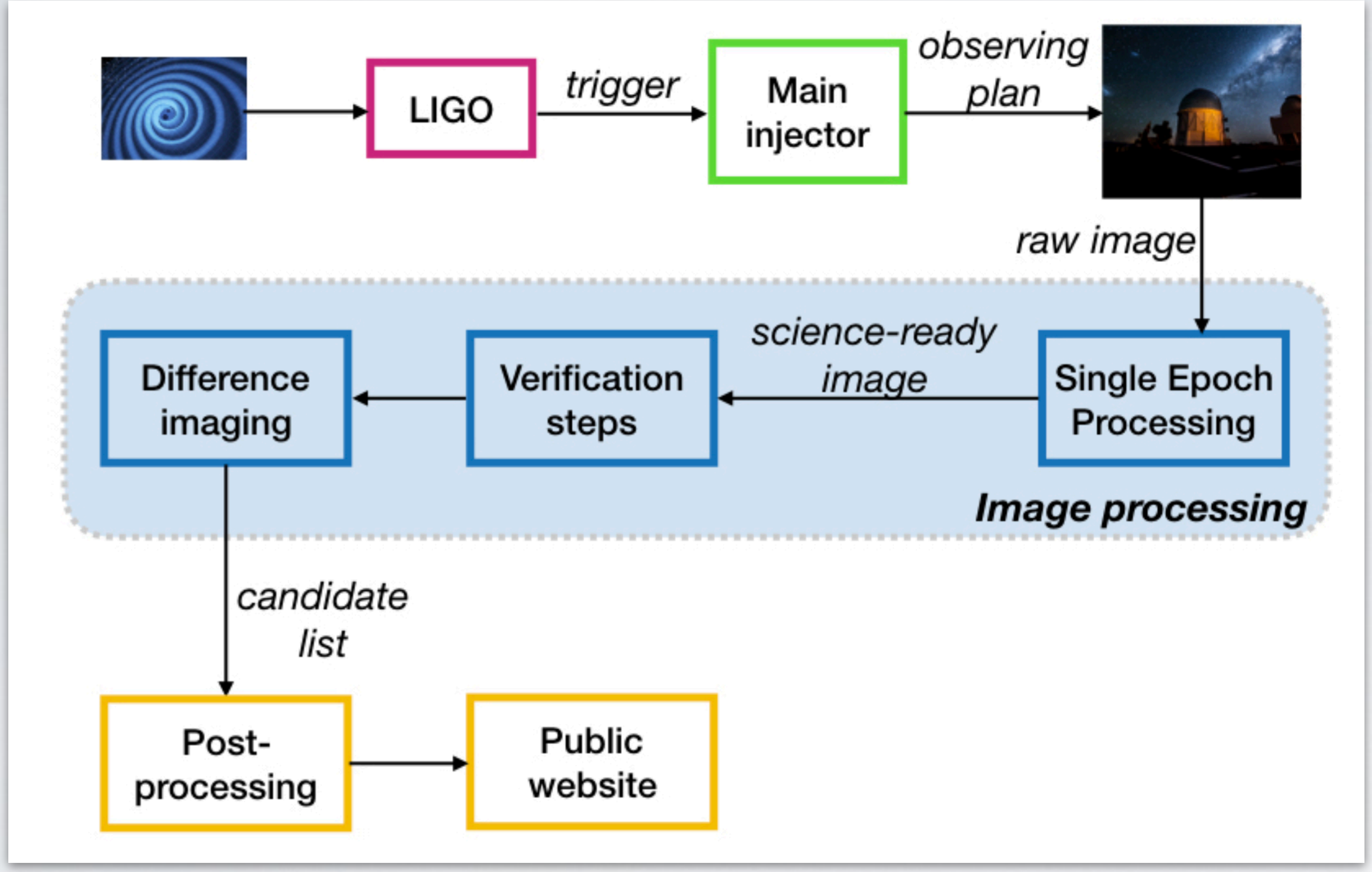
CHALLENGING SEARCH AREAS

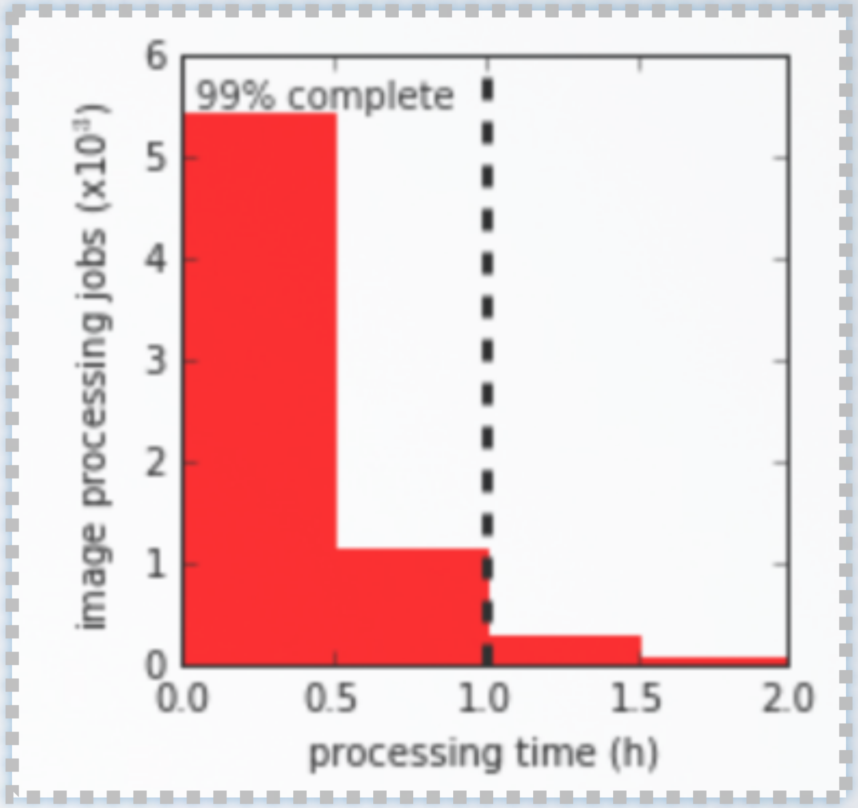
(Chen & Holz 2015)



Confidence Level	2015 HL	2016 HLV
50%	150 deg^2	15.5 deg^2
90%	517 deg^2	55 deg^2

SEARCH & DISCOVERY PIPELINE





Soares-Santos, Herner, Garcia, Annis, Brout, Sherman, et al.

GW170817

Time: Aug 17, 2017 at 12:41:04.4 UTC
Distance: 40 Mpc
Type: Binary Neutron Star

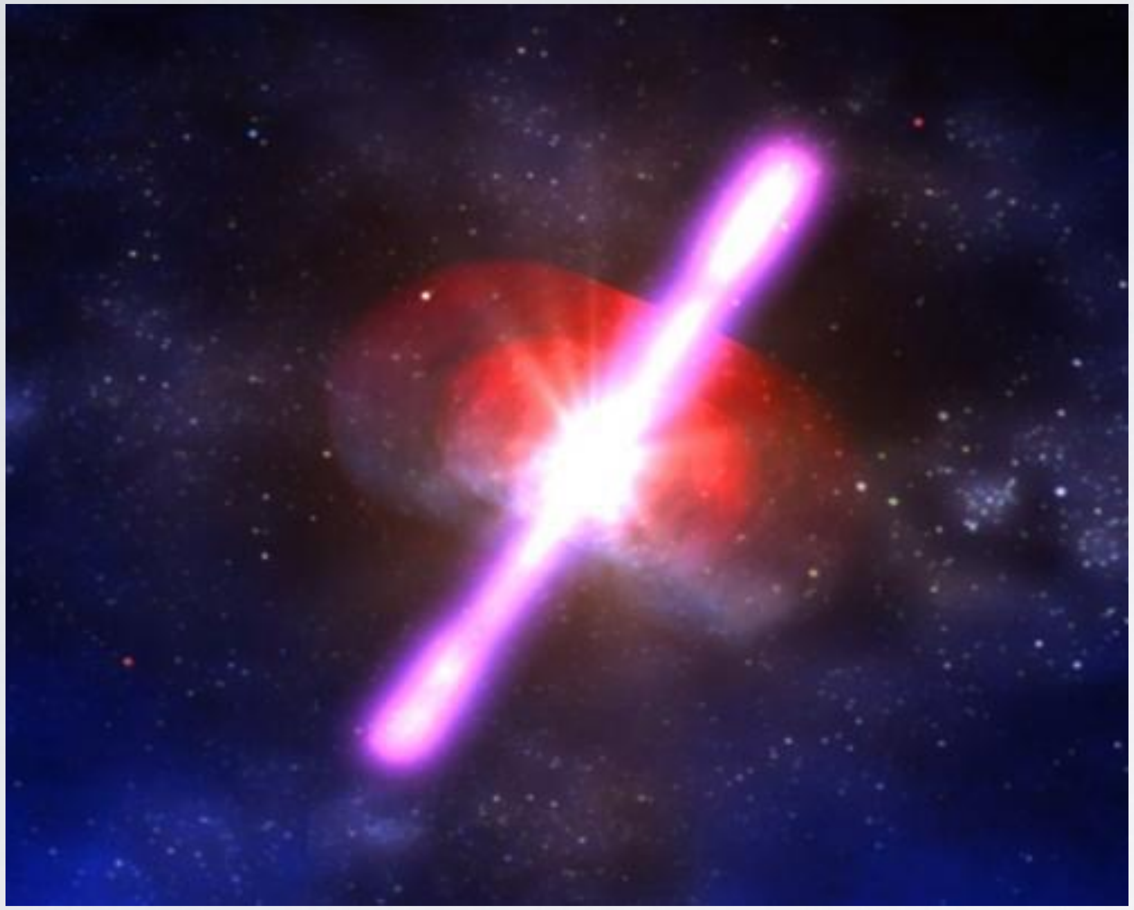
IT TAKES A VILLAGE…

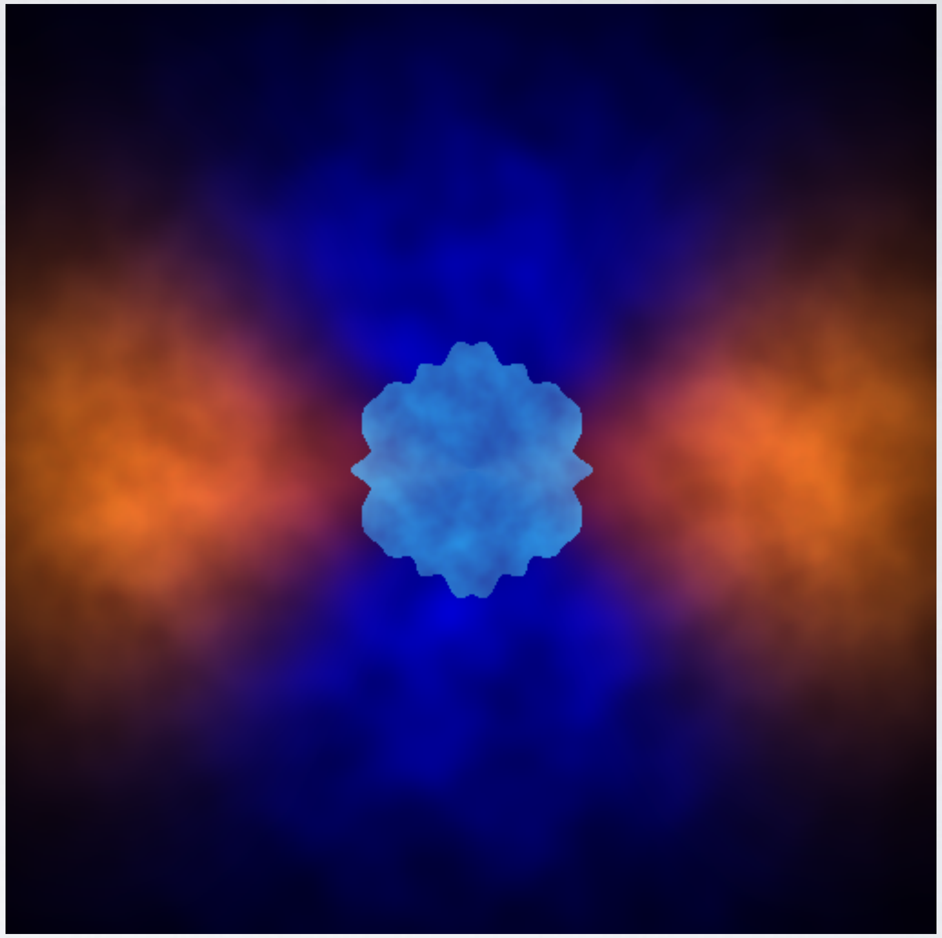
50+ teams, 1000+ authors, 100+ institutions, ~500 related papers (to date)

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-HXMT Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the **DES Collaboration***, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, CaltechNRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT

***Speaker's favorite**

BNS MERGER EM SIGNATURES



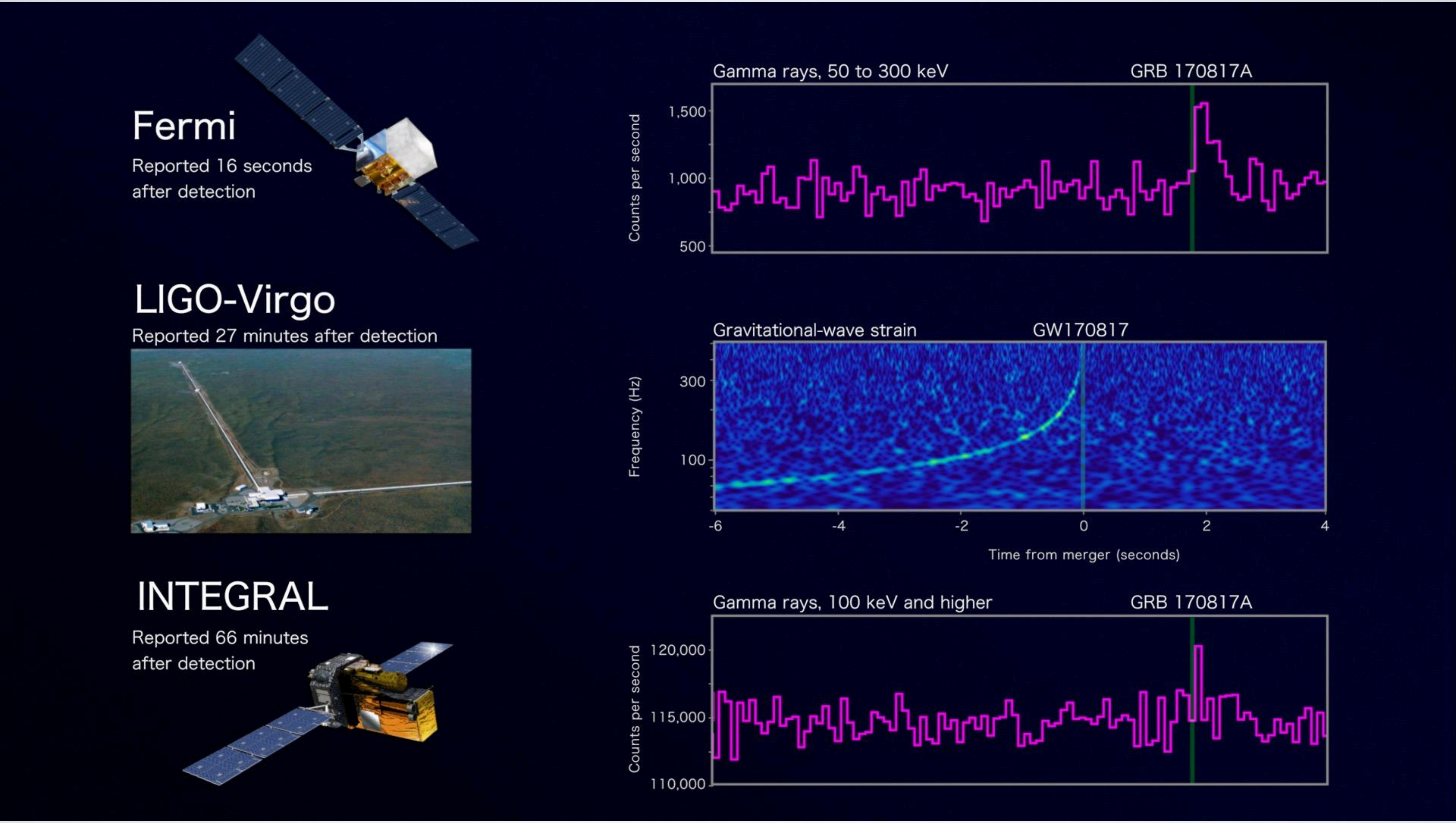


relativistic outflows
M ~ 10^{-7} M_{sun} ; Γ~ 2 - 100
non-thermal, beamed
(gamma-ray, x-ray, radio)

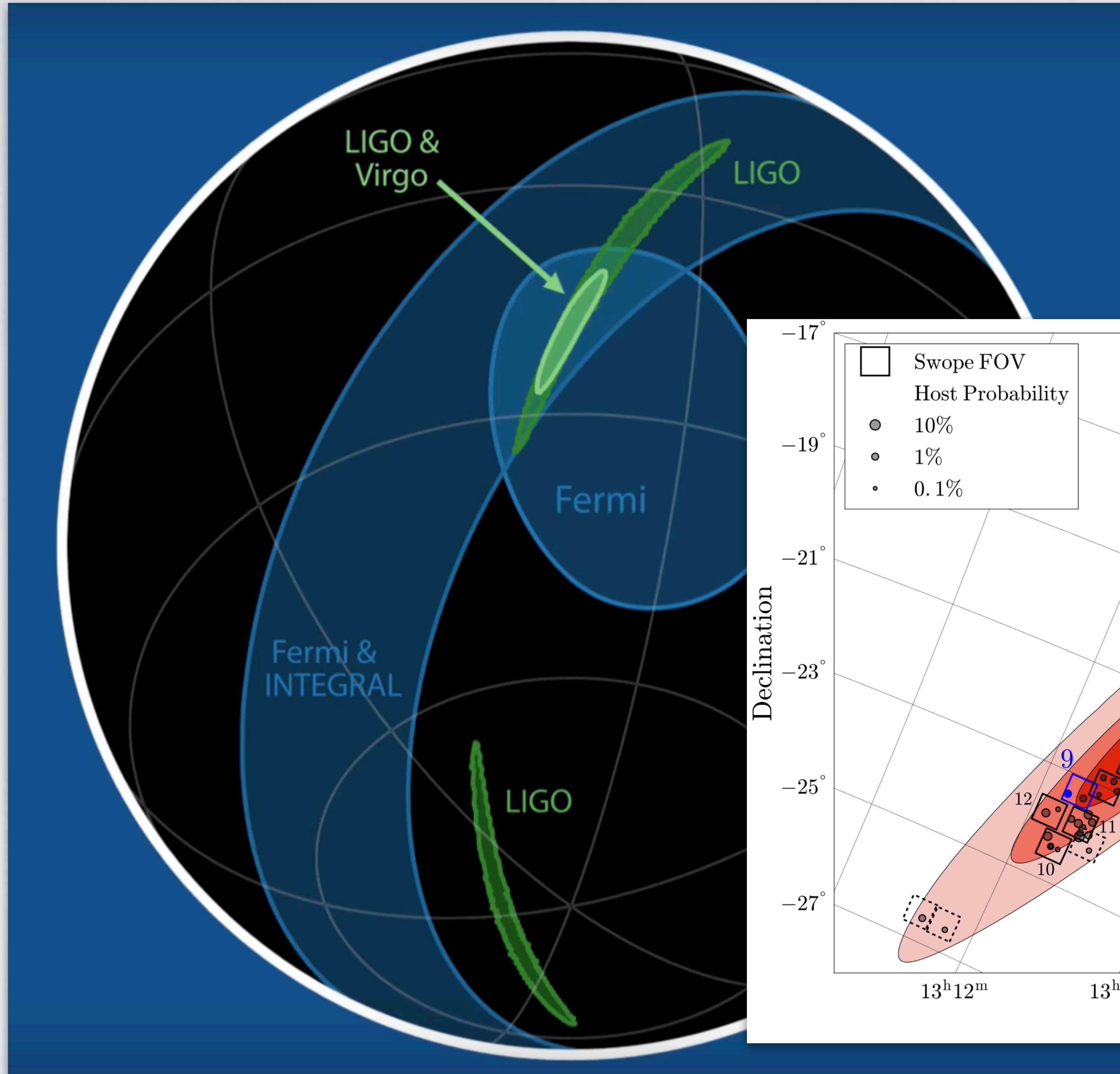
sub-relativistic outflows
M ~ 0.01 M_{sun}; v ~ 0.1c-0.3c
thermal, isotropic
(UV, optical, infrared)

(c.f. Metzger+ 2017, Rosswog+ 2017, Tanaka+ 2018)

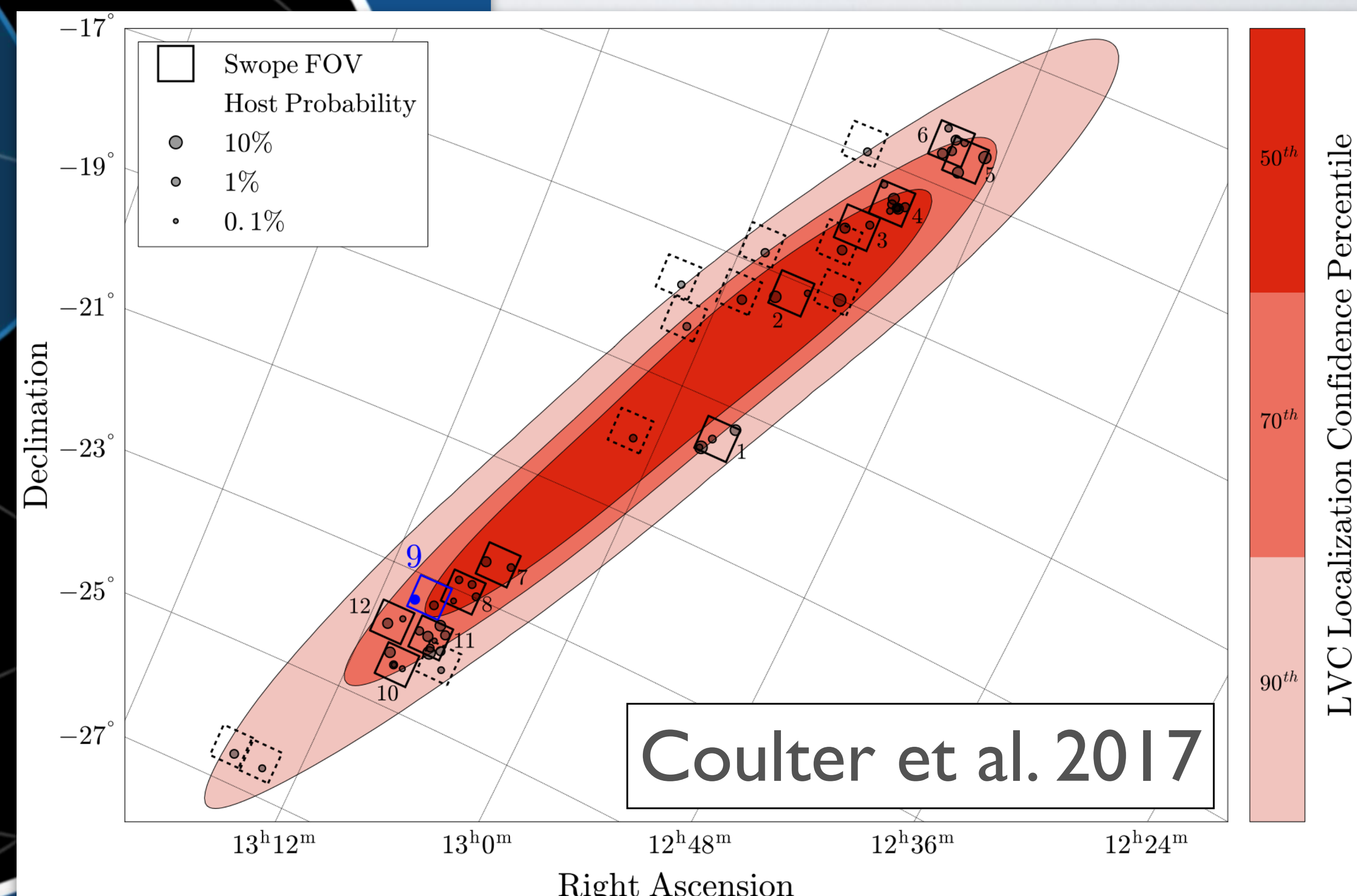
A MULTI-MESSENGER EVENT



BUT WHERE IS THE SOURCE?



Several bright galaxies in the region of interest — more if considering faint ones too.



A NEEDLE IN THE HAYSTACK

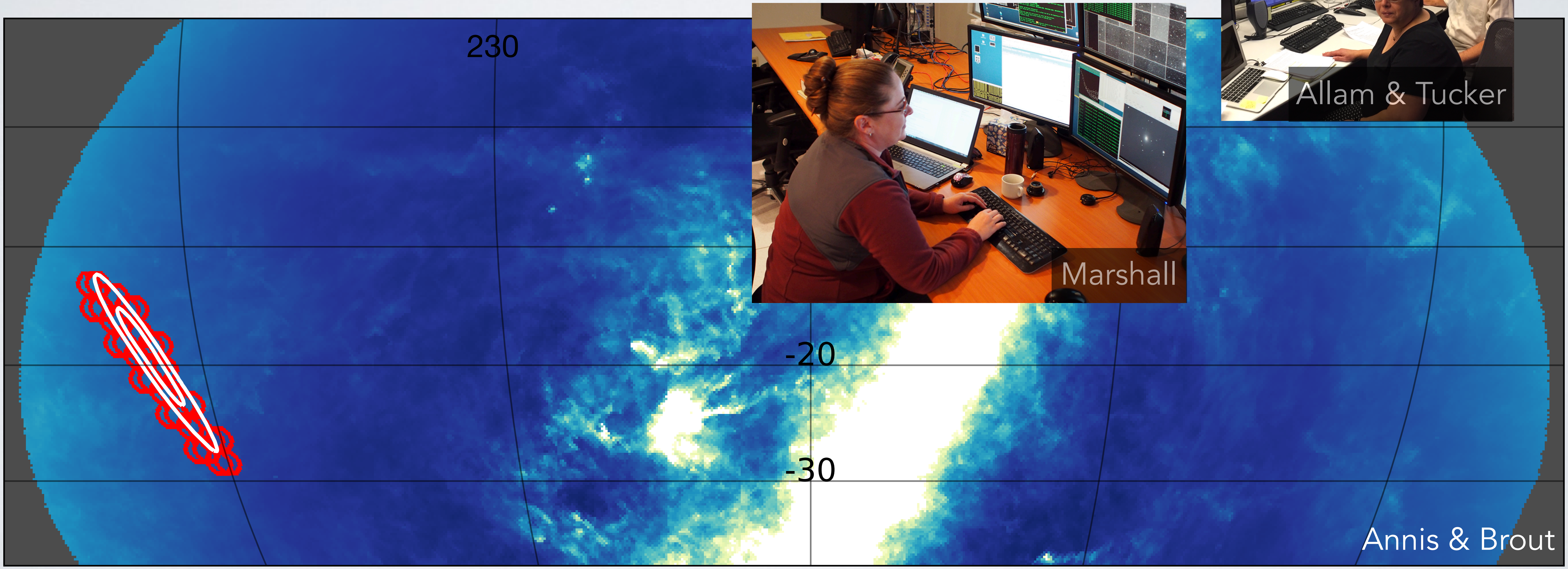
Localization region is in the far West and set ~1.5 hours after twilight.

Start observing as soon as it gets dark: 8:13 pm Chile time (23:13 UT), 10.5 hours after GW event.

With a wide field of view imager (DECam) on a 4m telescope, our team can cover the entire area.

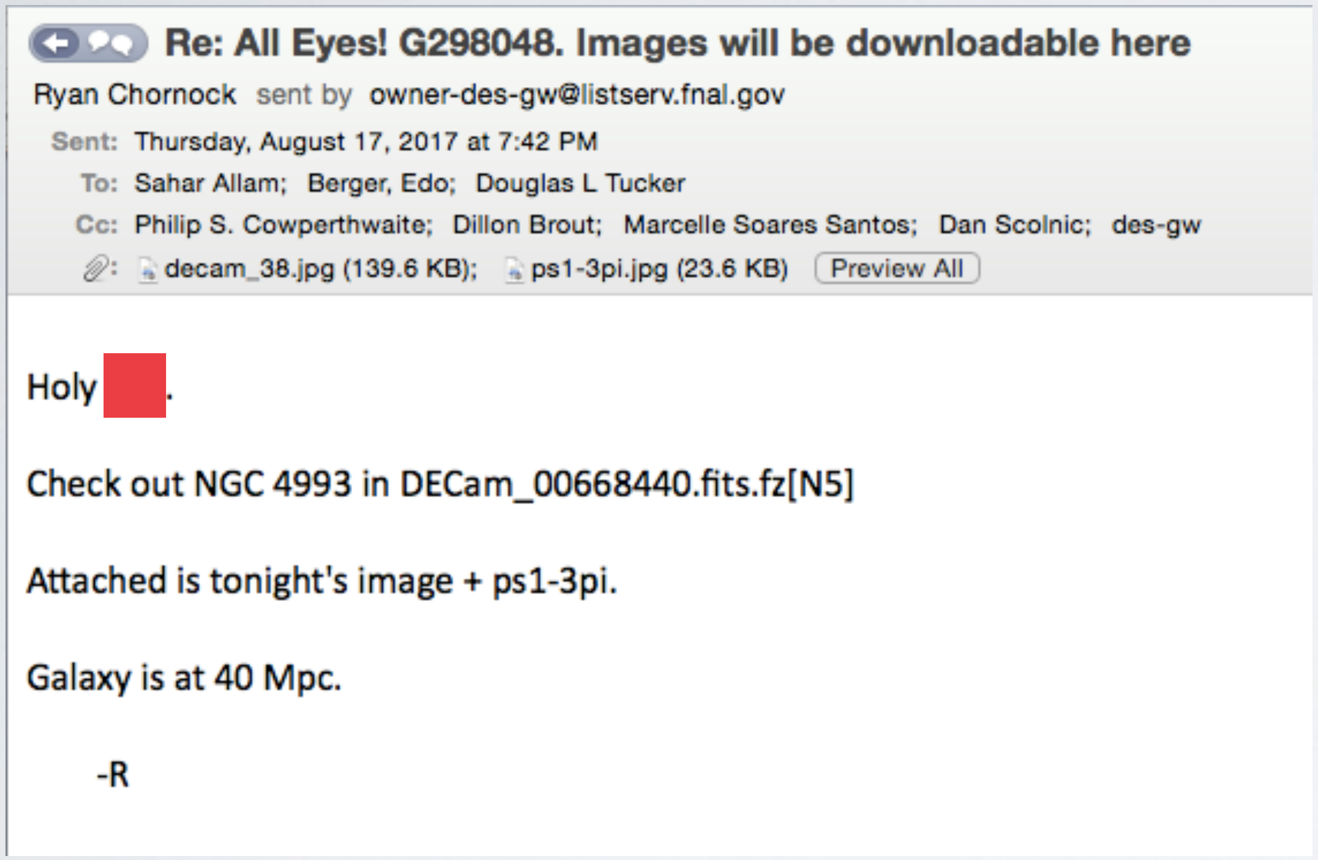
Smaller camera/telescope systems call for a galaxy-by-galaxy approach.

Teams in place to eyeball the images (on-site team and remote team at Fermilab).



WE FOUND IT!

Soares-Santos et al. 2017


Re: All Eyes! G298048. Images will be downloadable here

Ryan Chornock sent by owner-des-gw@listserv.fnal.gov

Sent: Thursday, August 17, 2017 at 7:42 PM
To: Sahar Allam; Berger, Edo; Douglas L Tucker
Cc: Philip S. Cowperthwaite; Dillon Brout; Marcelle Soares Santos; Dan Scolnic; des-gw
decam_38.jpg (139.6 KB); ps1-3pi.jpg (23.6 KB) Preview All

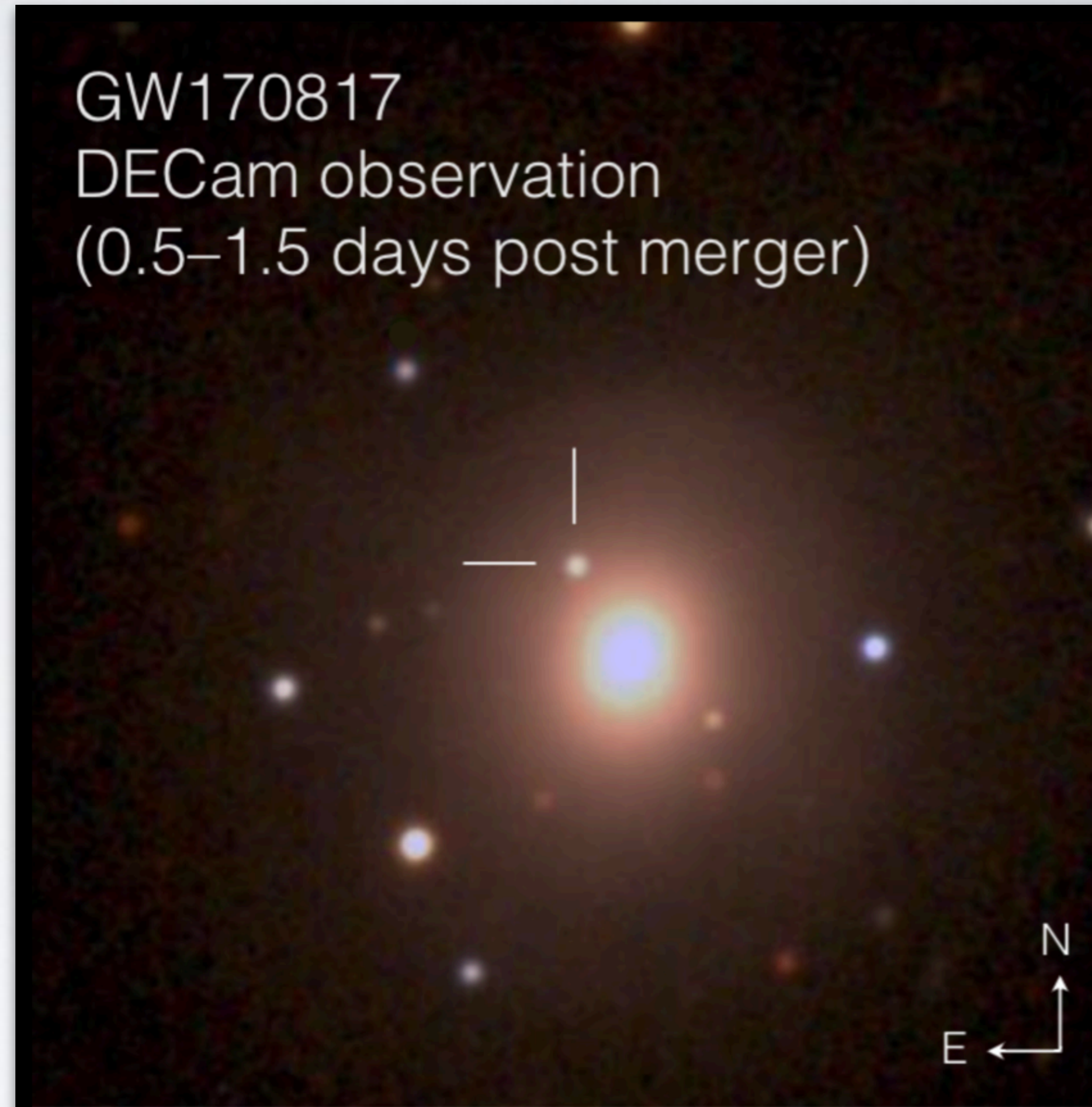
Holy [redacted].

Check out NGC 4993 in DECam_00668440.fits.fz[N5]

Attached is tonight's image + ps1-3pi.

Galaxy is at 40 Mpc.

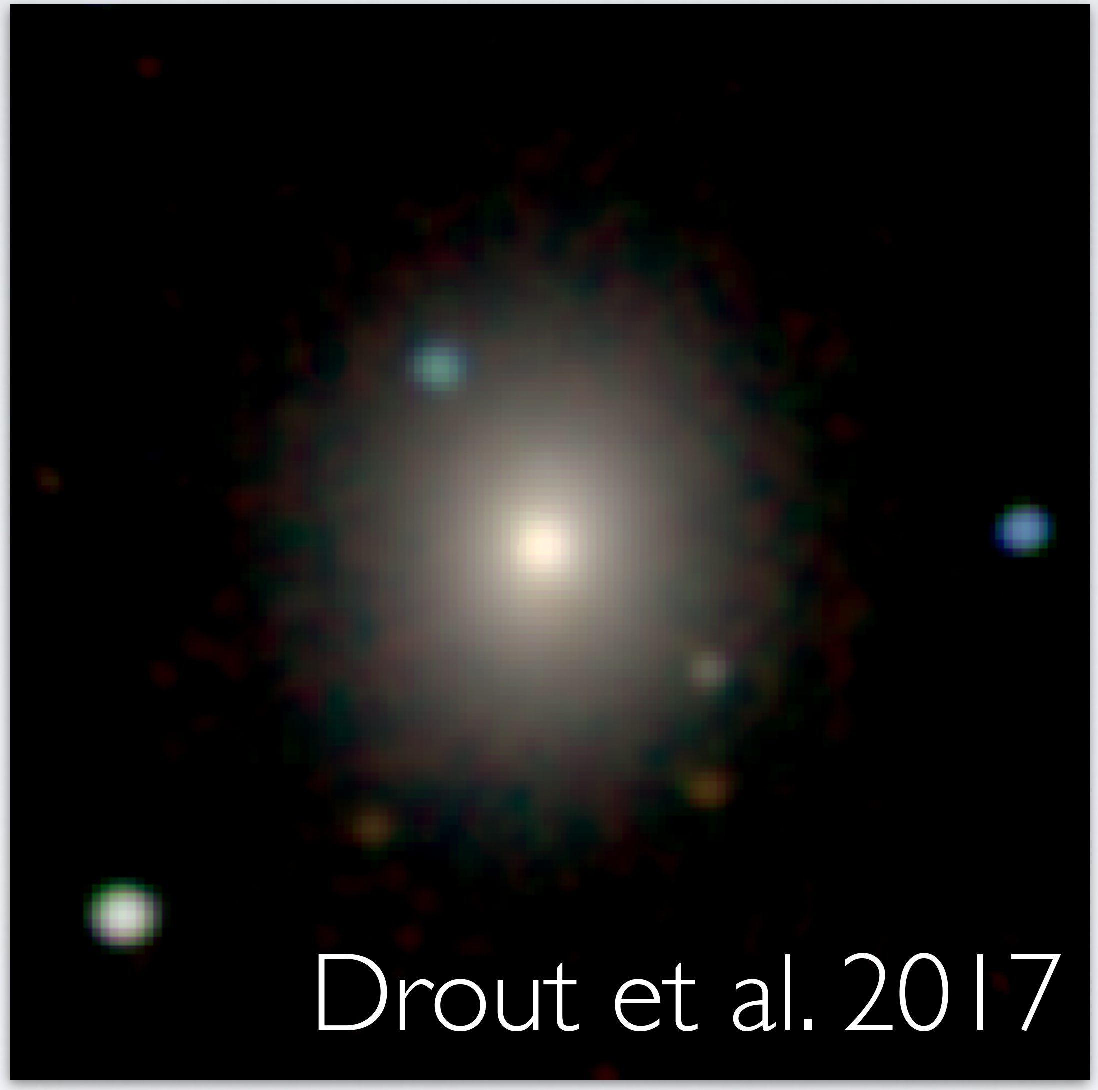
-R



But another team (SWOPE) had seen it first…

SWOPE TELESCOPE DISCOVERY IMAGE FOR GW170817

Several teams independently reported the discovery within minutes from each other.



SWOPE is a 1-meter telescope with a narrow field of view.

If GW170817 is typical, these small telescopes can play a significant role in searches for nearby BNS events in the future.

INDEPENDENT OBSERVATIONS

Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source
(Coulter et al. 2017)

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. I. Discovery of the Optical Counterpart Using the Dark Energy Camera
(Soares-Santos et al. 2017)

The Discovery of the Electromagnetic Counterpart of GW170817: Kilonova AT 2017gfo/DLT17ck
(Valenti et al. 2017)

Optical emission from a kilonova following a gravitational-wave-detected neutron-star merger
(Arcavi et al. 2017)

The Emergence of a Lanthanide-rich Kilonova Following the Merger of Two Neutron Stars
(Tanvir et al. 2017)

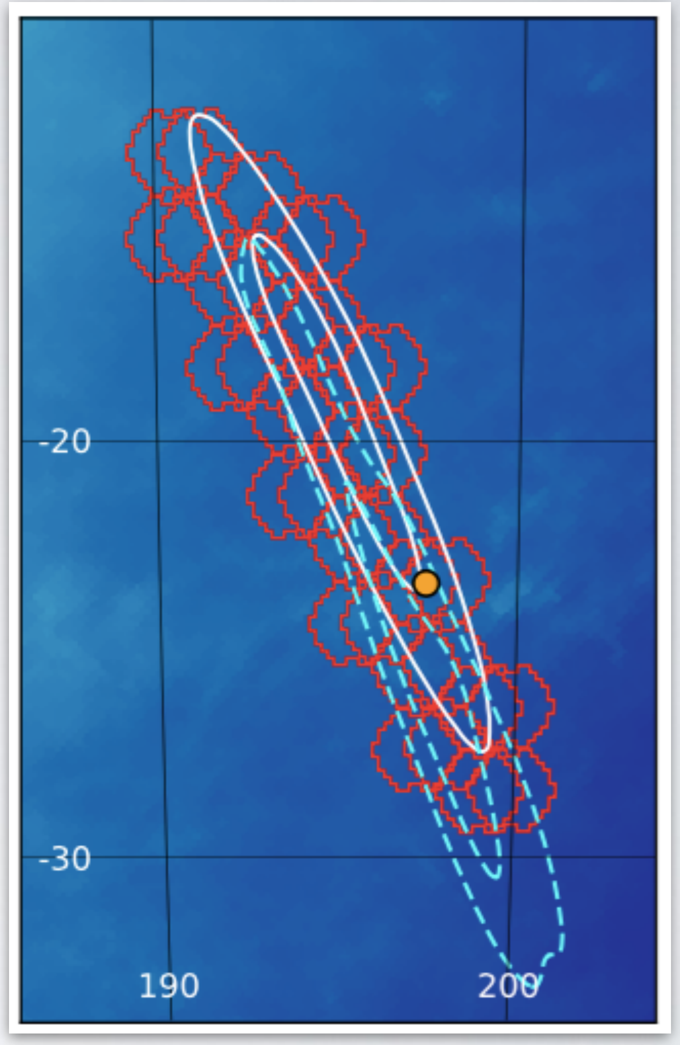
MASTER Optical Detection of the First LIGO/Virgo Neutron Star Binary Merger GW170817
(Lipunov et al. 2017)

What if the source was farther away, e.g., at 120Mpc which is the average expected distance in upcoming runs?

ARE THERE OTHER VIABLE SOURCES? — NO.

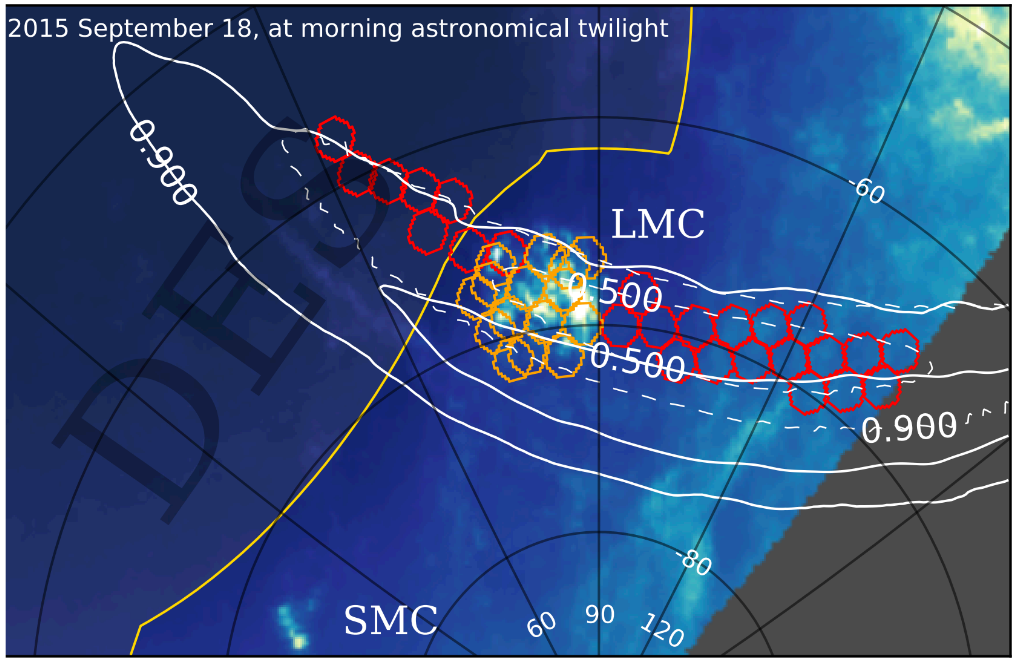
1. DECam observations
   i. commenced at 10.5 hours past merger;
   ii. covered 70 sq-degrees to i<22, which in turn covers
      i. 93% of initial LIGO localization;
      ii. 80% of revised LIGO localization;
2. Located a source 11" away from NGC4993 with
   i. i=17.3 & z=17.5
   ii. M_i = -15.7 for H_0 = 70 km/s/Mpc
3. Searching the entire area:
   i. 1500 transient candidates at i<20.5;
   ii. only one passes a set of simple cuts,
      i. require detection in i and z (n=1500-> 252),
      ii. pass machine learning junk rejection (252->81), &
      iii. faded by more than 3-sigma in 2 weeks (81->1).
   iii. The single remaining candidate is the one on NGC 4993.
4. Distance/redshift was not used in the analysis, therefore the redshift of the source can be used as an independent variable in the joint cosmological analysis.

Soares-Santos et al. 2017



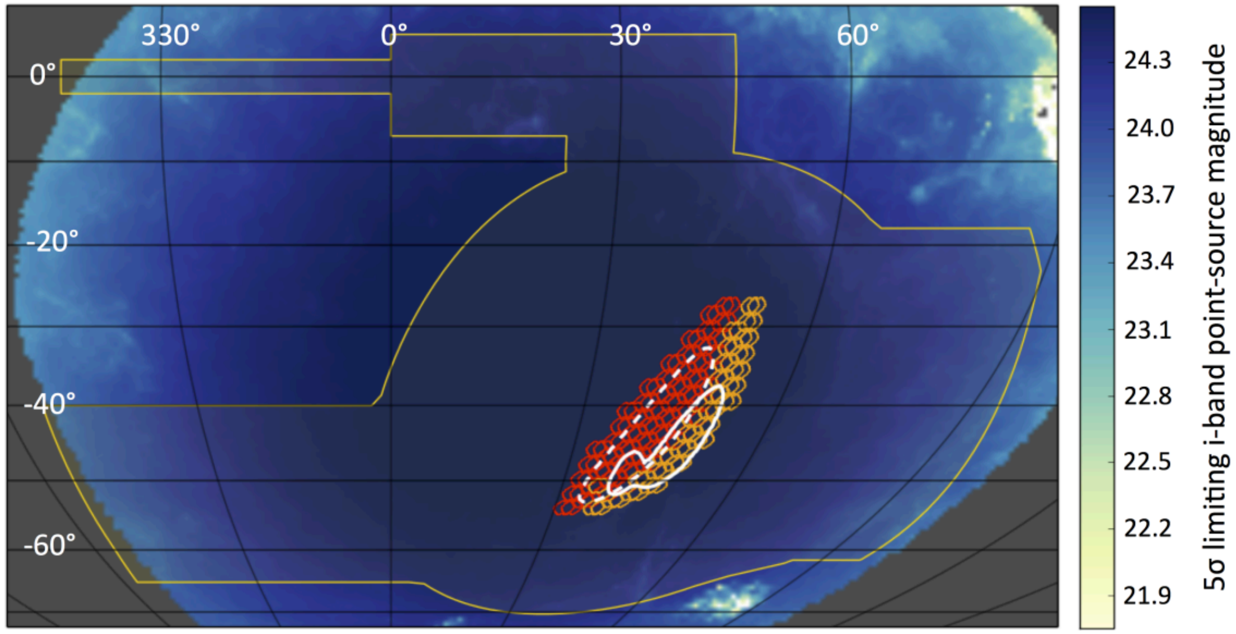
WHAT ABOUT THE BLACK HOLES?

GW150914



Soares-Santos et al. 2016

GW170814

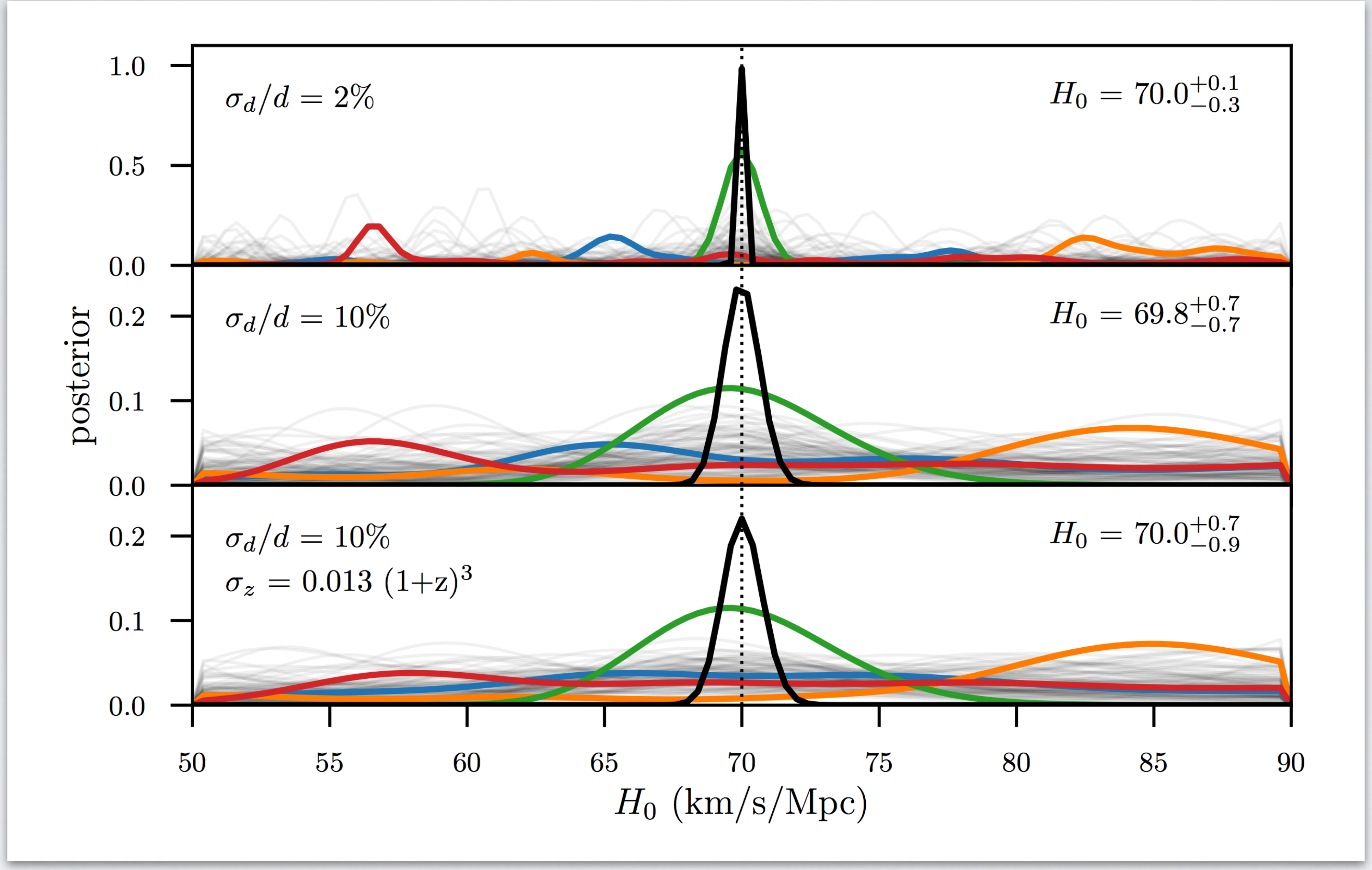


Doctor et al. 2016

Ongoing search. No counterparts… yet.

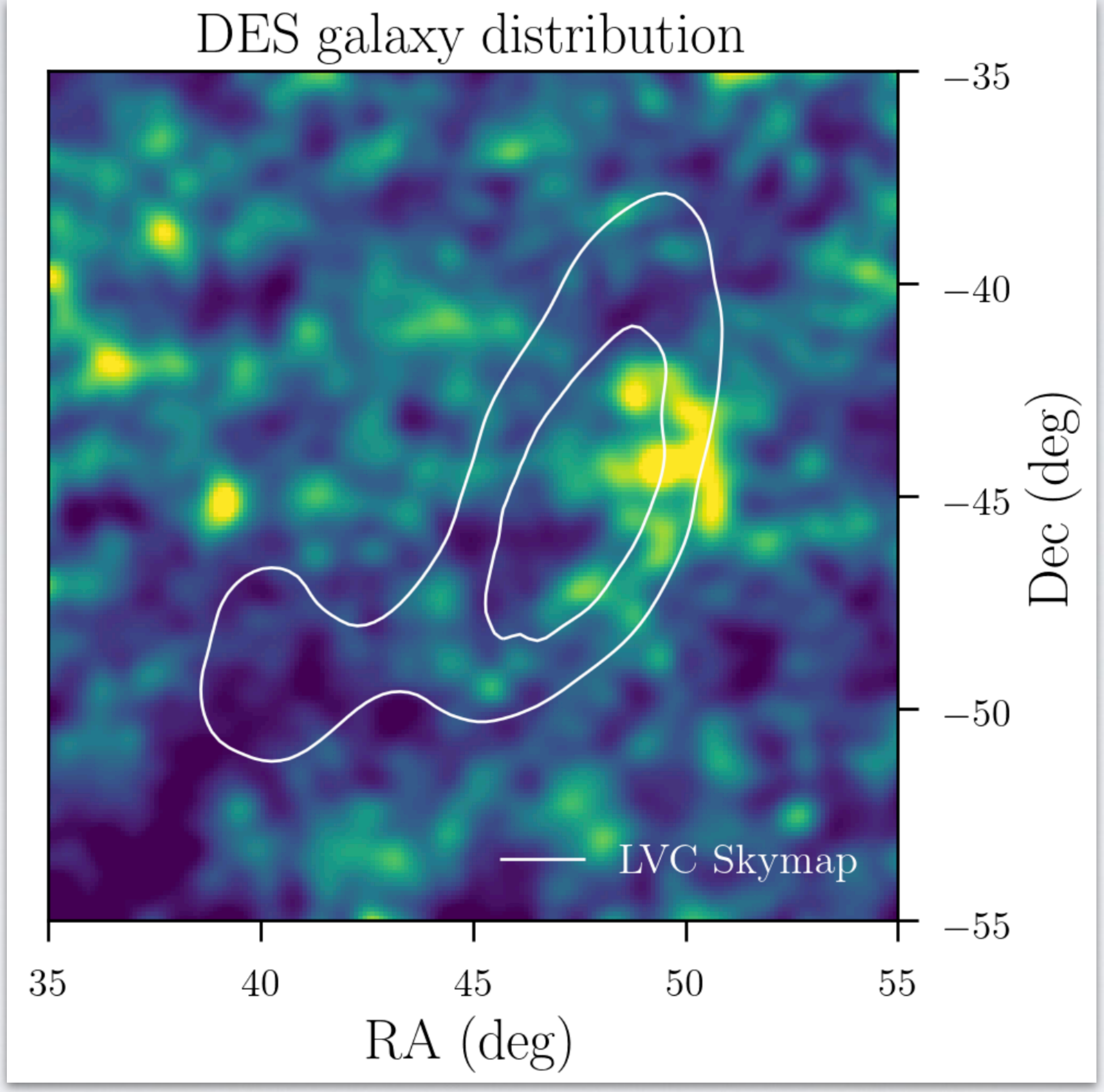
Even if BBH mergers are too dark to pinpoint, we can do cosmology!

(IDEALIZED) SIMULATIONS

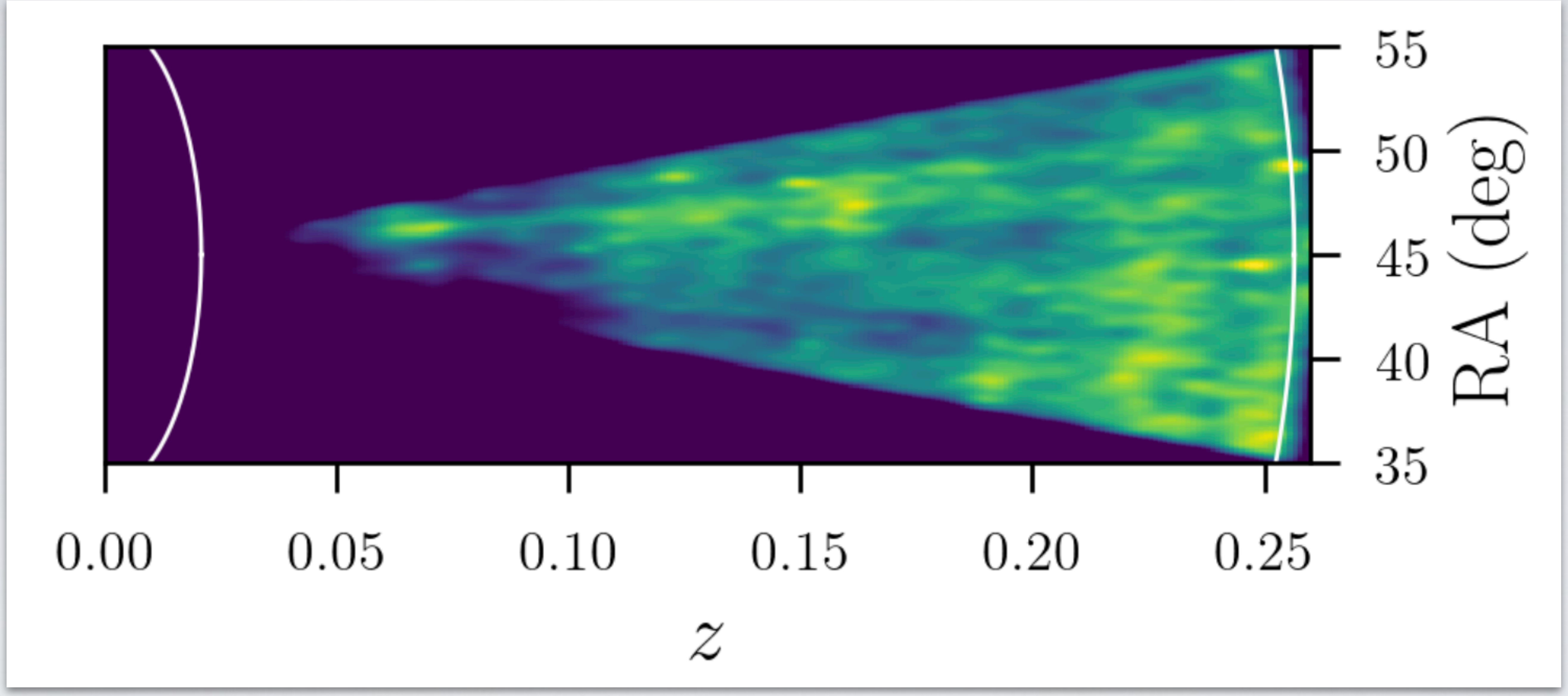


We need 100+ well localized BBH events to make a significant statement.

GW170814 — A DARK SIREN?

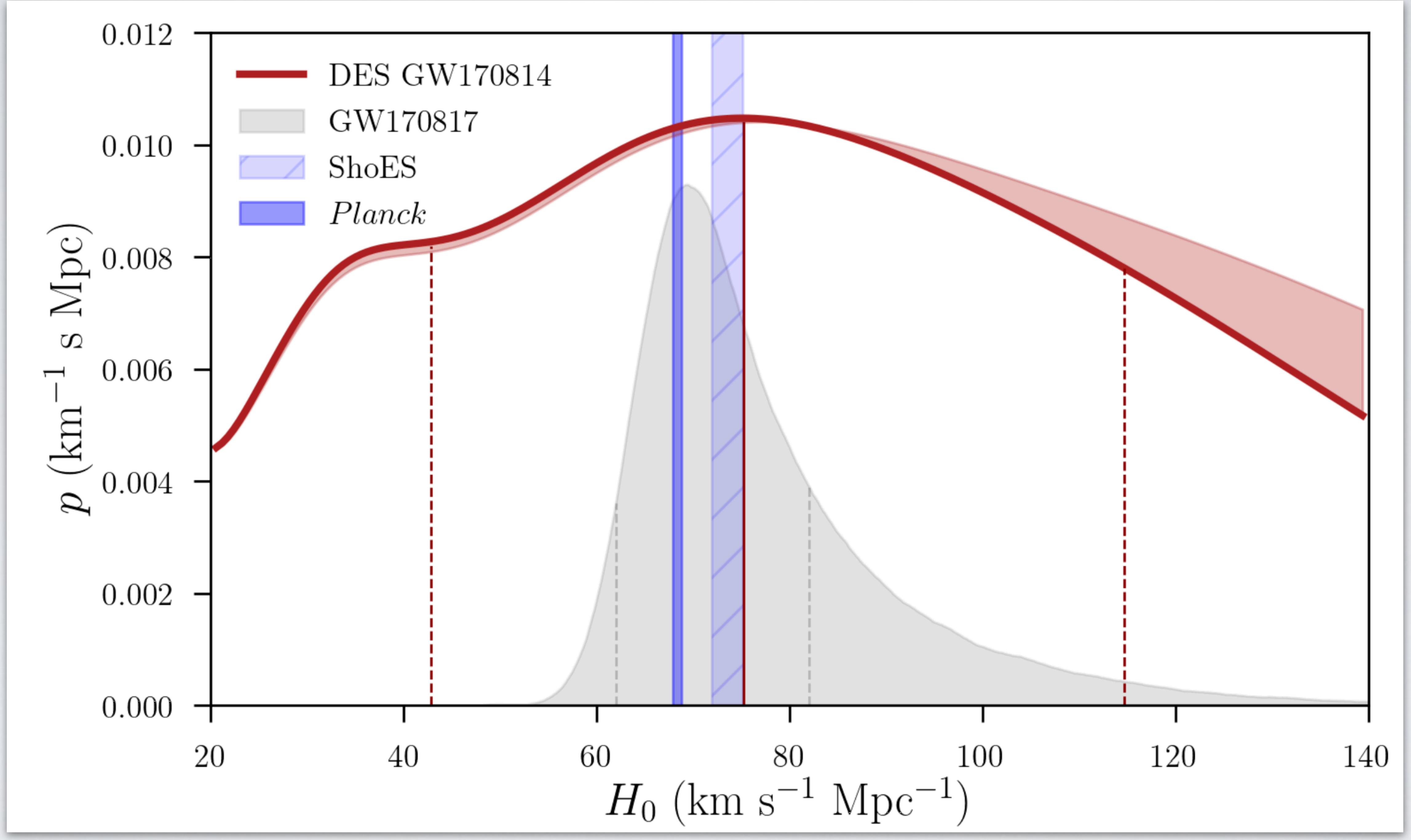


GW170814 — A DARK SIREN?



GW170814 — A DARK SIREN

Soares-Santos, Palmese, & the DES and LIGO/Virgo Collaborations, 2019 (arXiv:1901.01540)

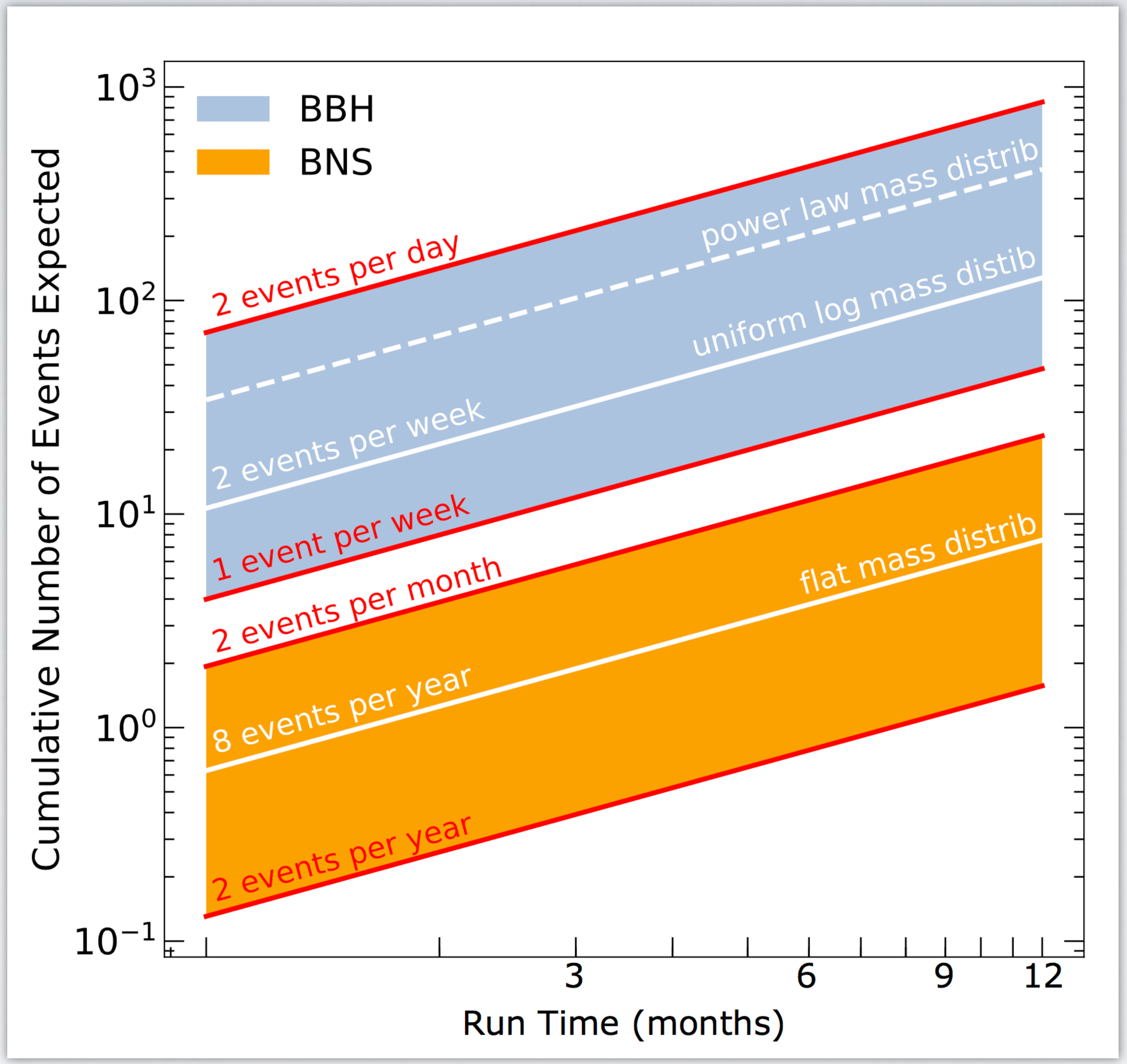


Future Prospects

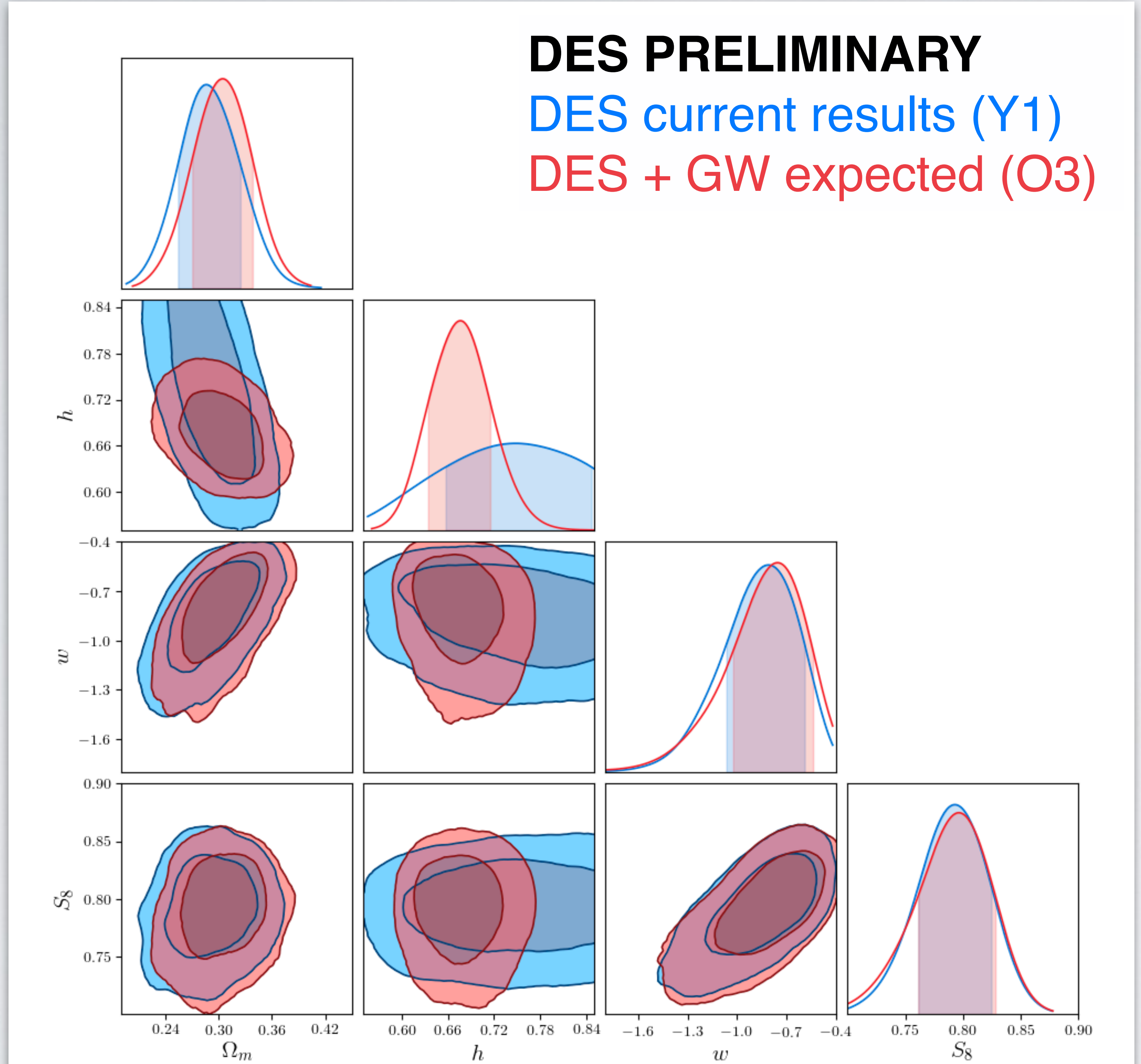
EXPECTED # OF EVENTS IN O3

O1/O2:
10 BBH
1 BNS

O3:
~50 BBH
~2 BNS



DES GW COSMOLOGY



(Soares-Santos, Pereira & Garcia)

Assumptions:

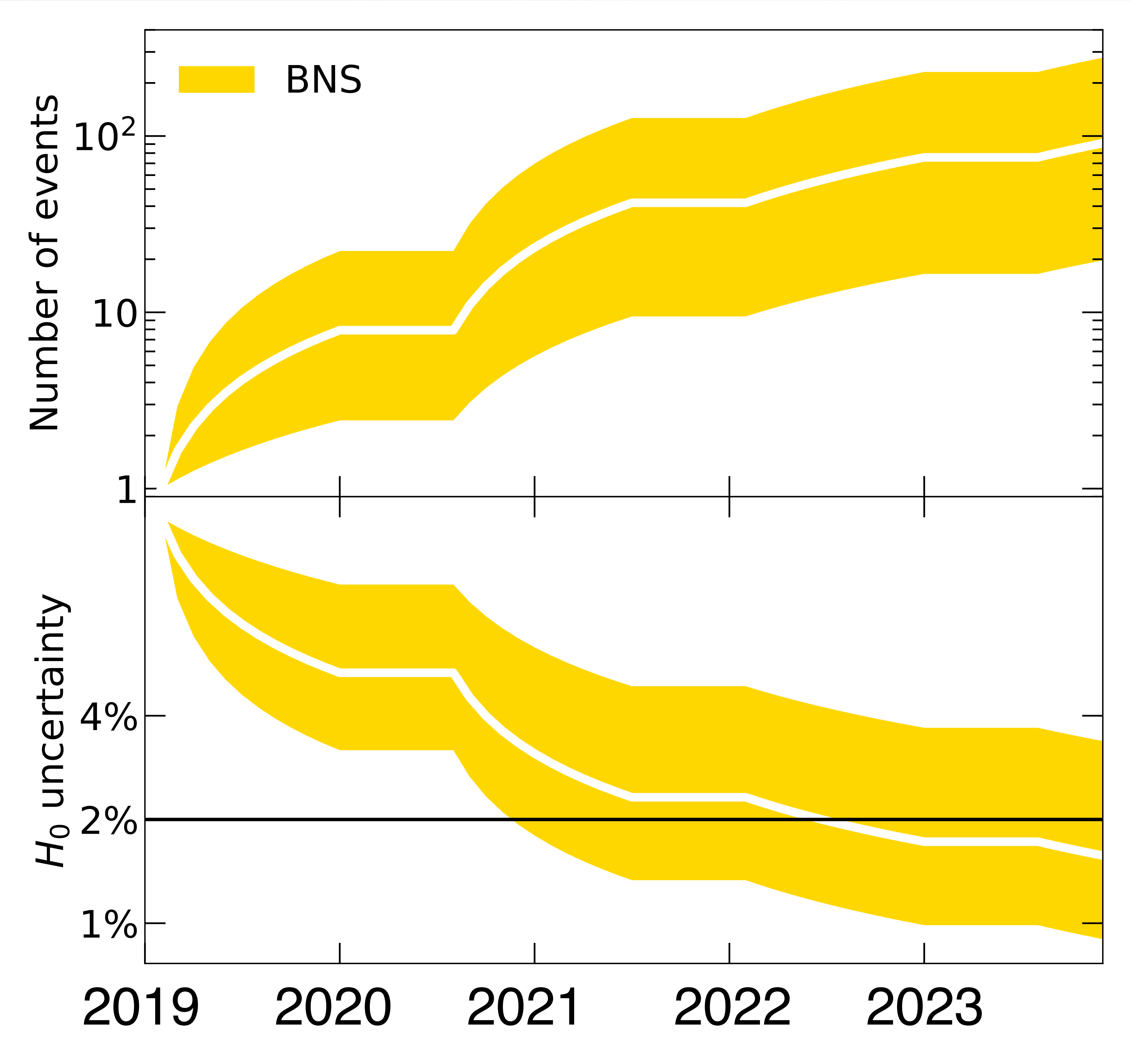
Bright siren events only.

8 GW170817-like events.

25% uncertainties in distance.

300 km/s uncertainties from peculiar velocities.

(NEAR) FUTURE PROSPECTS



Approximate timeline:

2019 - **DES** Y6 science run [DONE!]

2019 - LIGO/Virgo O3 **[NOW!]**

2020 - **DESI** year 1 science run

2021 - **DES** legacy results published

2021 - LIGO/Virgo O4 (design)

2022 - **LSST** year 1 science run

2024 - A+ GW network ?

2025 - **Post-LSST** survey ?

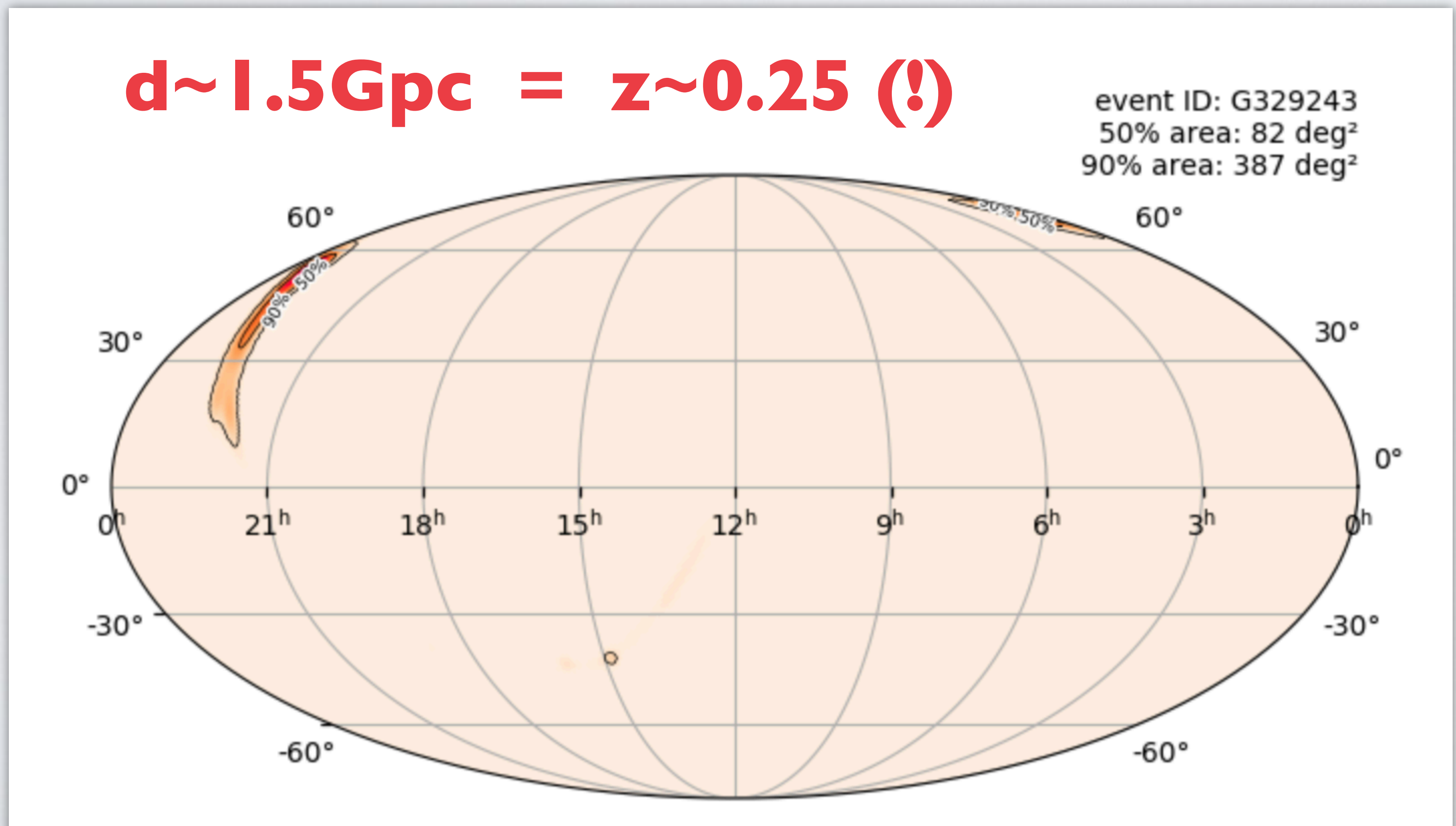
The future is closer than you think: Status of O3 effort

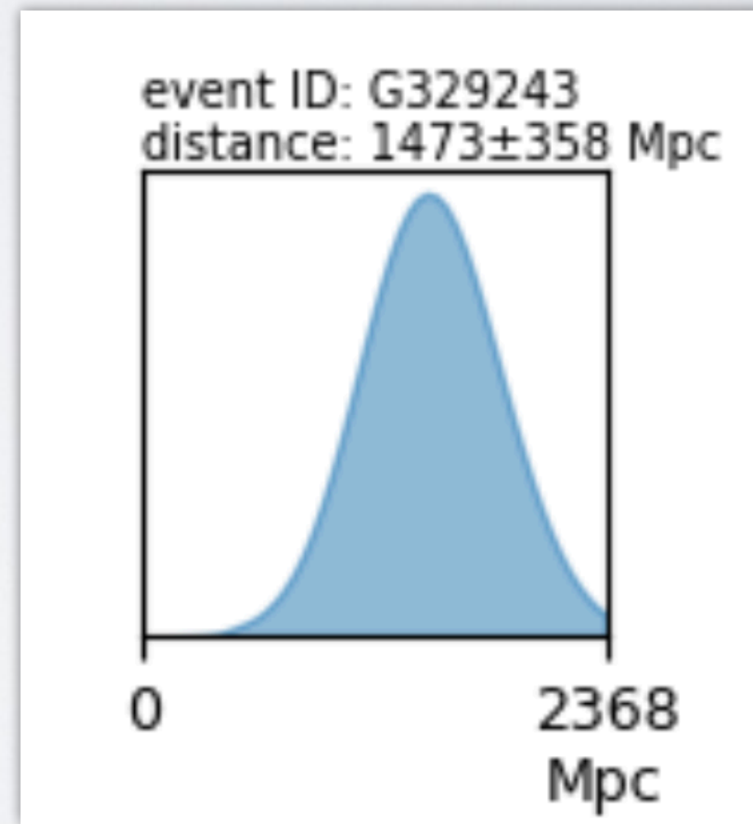
FIRST O3 EVENT — 190408 !

automated-desGW@fnal.gov via fermicloud.onmicrosoft.com
to djbrout, alyssag94, annis, marcelle

REAL Trigger S190408an
Alert Type: Preliminary
FAR: 11280762947.1 Years
Map: bayestar
URL: https://gracedb.ligo.org/events/view/S190408an
Analysis has begun, please hold tight for a DESGW webpage which will be located here shortly:
http://des-ops.fnal.gov:8080/desgw/Triggers/S190408an/S190408an_trigger.html

Too far north for DECam :-(





SUMMARY OF SUPER EVENTS

33 GW candidate events detected by the LVC (Apr–Sep)

- 6 potentially containing at least one NS
- 3 pursued with DECam

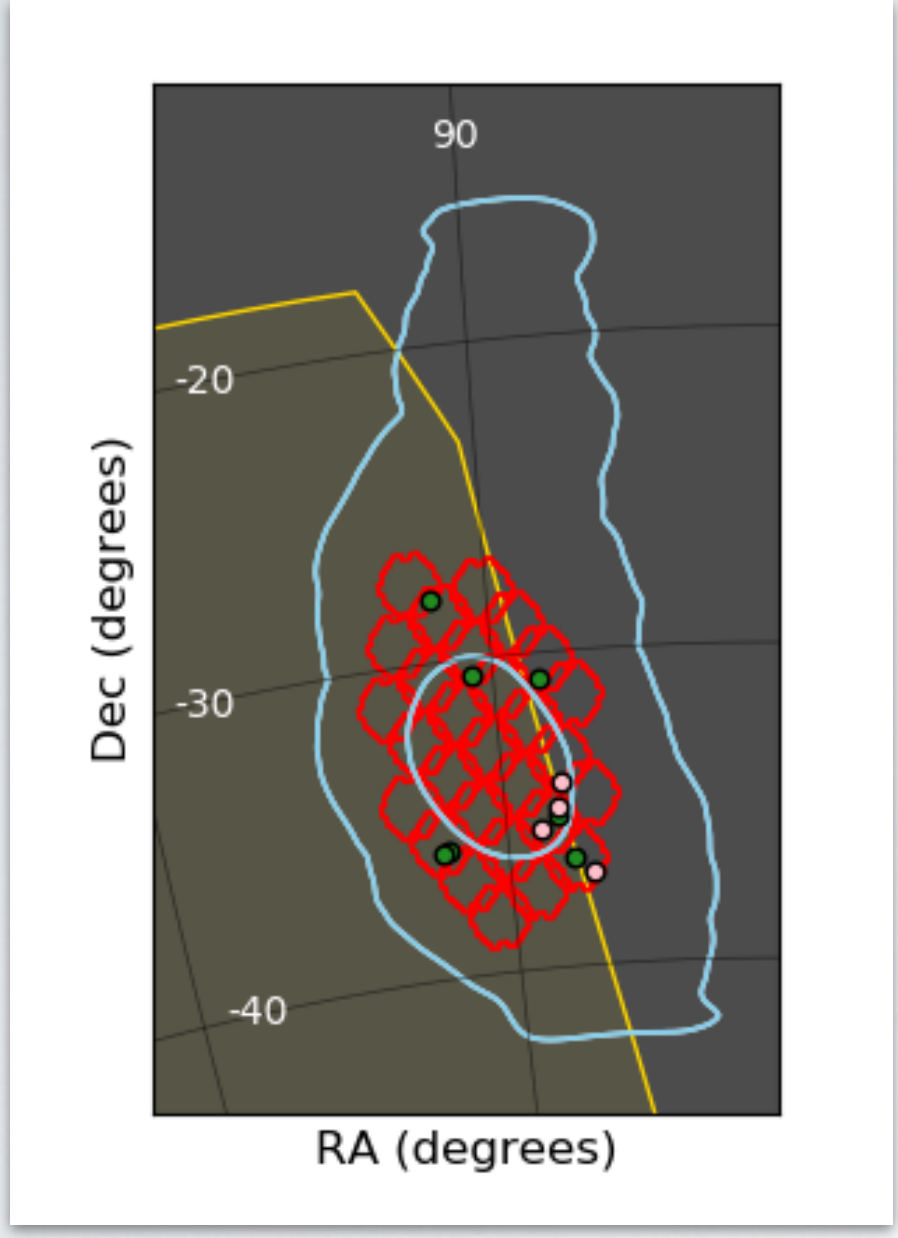
S190510g (BNS merger, low significance, **227 Mpc**)
1 night of DECam data, covering 50% prob (**31 sq-deg**)

S190728q (BBH merger, high significance, **875 Mpc**)
4 nights of DECam data, covering 90% prob (**104 sq-deg**)

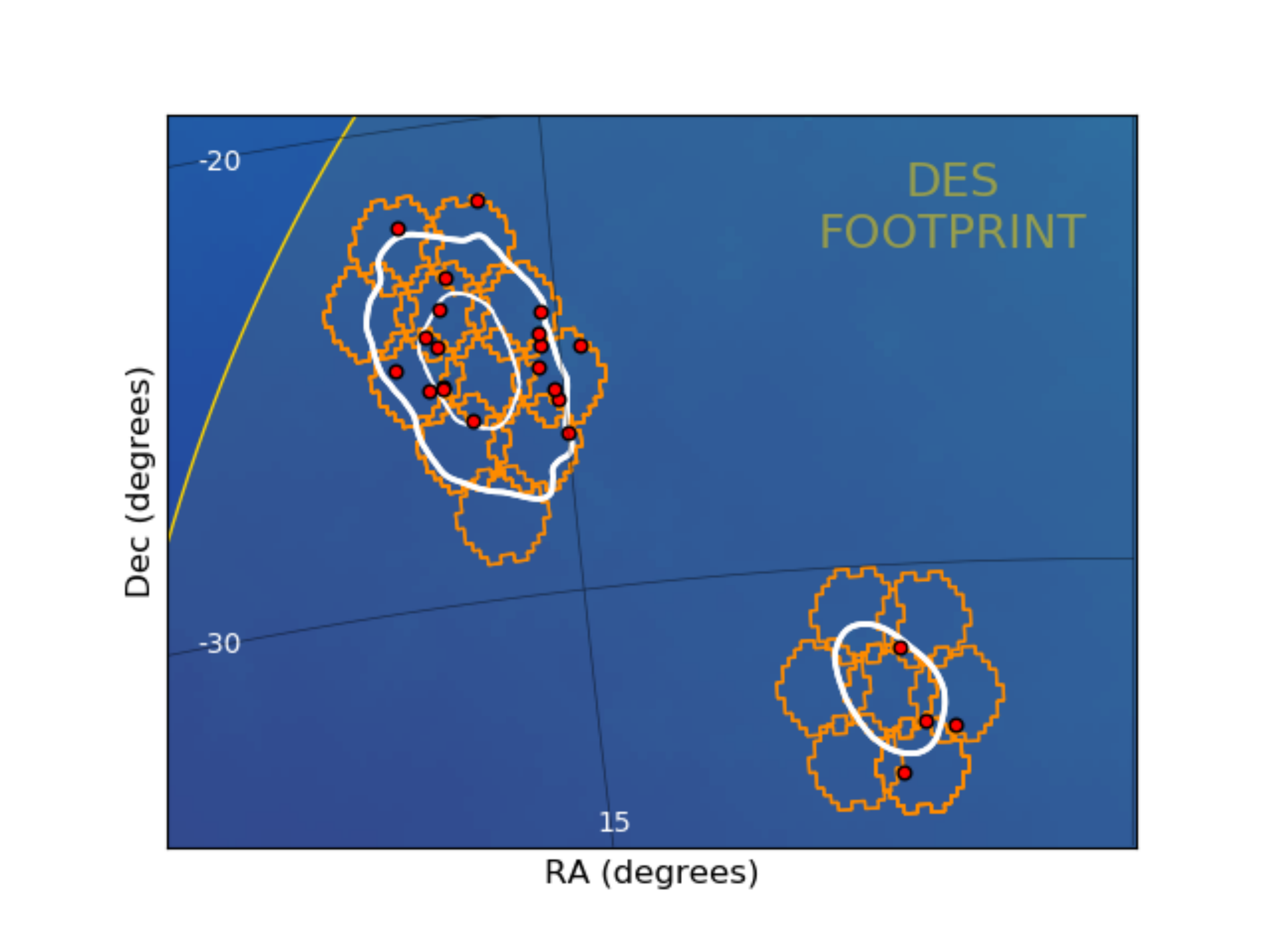
S190814bv (NSBH merger, high significance, **267 Mpc**)
5 nights of DECam data, covering 90% prob (**23 sq-deg**)

BRIGHT SIRENS?

S190510g



S190814bv



Analysis is ongoing! Stay tuned for results coming soon!

SYNERGIES WITH SUBARU

J-GEM team uses Subaru (**HSC** and other instruments):

- c.f. upcoming talks later in this session:
  - **Tanaka, Sasada, Ohgami**

DESGW + J-GEM partnership:

- **Sky coverage** in the north and south
- **Multi-band** complementarity
- **Short cadence** of observations
- **Weather** impact mitigation
- **Spectroscopic classification** of candidates

SYNERGIES WITH SUBARU

DESGW + J-GEM partnership:

- Initial contact after GW170817 (**Tominaga**)
- **Separate** trigger decisions and observing **strategy**
- **Separate analysis** efforts
- **Shared** strategy information and **data** between teams

Improvements planned/to discuss:

- Develop **joint** optimal **strategy** and **analysis**
- Take advantage of **long shutdown** (20 months)
  - e.g. consider observing potential **host galaxies**

Get some sleep…

SUMMARY

— DESGW leads search & discovery of EM counterparts of GW events

— With GW170817 we have helped to inaugurate the era of multi-messenger astrophysics and cosmology with gravitational waves

— Rapid discovery of the EM counterpart of GW170817 enabled panchromatic studies of the source and its environment

— We are also pursuing (selected) black hole events

— With GW170814 we performed the first measurement of a cosmological parameter using a black hole merger (a dark siren)

— There are many more results not covered in this talk

— Now we are working on the 3rd observing campaign. **Stay tuned!**

Mahalo!