Title: Observation of a Gravitational Wave Emitting Neutron Star Merger with the Dark Energy Camera

Date: Oct 24, 2017 01:00 PM

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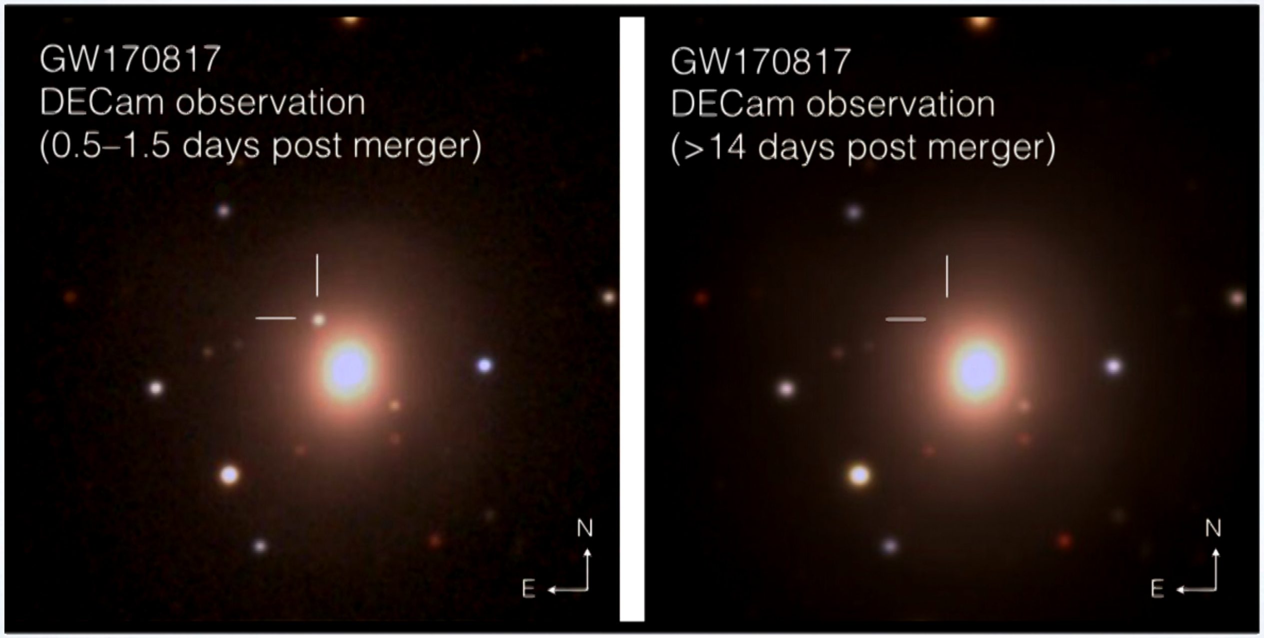
Abstract: <p>Motivated by the exciting prospect of new wealth of information arising from the first observations of gravitational and electromagnetic radiation from the same astrophysical phenomena, the Dark Energy Survey (DES) has performed a broad range follow-up program for LIGO/Virgo events using the Dark Energy Camera (DECam). In this talk, I present the discovery of the optical transient associated with the neutron star merger GW170817 using DECam and discuss its implications for the emerging field: multi-messenger cosmology with gravitational waves and optical data.</p>

OBSERVATION OF A GRAVITATIONAL WAVE EMITTING NEUTRON STAR MERGER WITH THE DARK ENERGY CAMERA

Marcelle Soares-Santos ◆ Brandeis University ◆ DES Collaboration



Perimeter Institute Seminar ◆ October 24, 2017

THE DESGW TEAM

M. Soares-Santos, D. E. Holz, J. Annis, R. Chornock, K. Herner, E. Berger, D. Brout, H. Chen, R. Kessler, M. Sako, S. Allam, D. L. Tucker, R. E. Butler, A. Palmese, Z. Doctor, H. T. Diehl, J. Frieman, B. Yanny, H. Lin, D. Scolnic, P. Cowperthwaite, E. Neilsen, J. Marriner, N. Kuropatkin, W. G. Hartley, F. Paz-Chinchón, K. D. Alexander, E. Balbinot, P. Blanchard, D. A. Brown, J. L. Carlin, C. Conselice, E. R. Cook, A. Drlica-Wagner, M. R. Drout, F. Durret, T. Eftekhari, B. Farr, D. A. Finley, R. J. Foley, W. Fong, C. L. Fryer, J. García-Bellido, M. S .S. Gill, R. A. Gruendl, C. Hanna, D. Kasen, T. S. Li, P. A. A. Lopes, A. C. C. Lourenço, R. Margutti, J. L. Marshall, T. Matheson, G. E. Medina, B. D. Metzger, R. R. Muñoz, J. Muir, M. Nicholl, E. Quataert, A. Rest, M. Sauseda, D. J. Schlegel, L. F. Secco, F. Sobreira, A. Stebbins, V. A. Villar, K. Vivas, A. R. Walker, W. Wester, P. K. G. Williams, A. Zenteno, Y. Zhang,

Brandeis U, U Chicago, Fermilab, Ohio U, Harvard, U Penn, Indiana U, UCL, U Zurich, NCSA/IUIC, U Surrey, Syracuse, LSST, Nottingham, TAMU, UCSC, IAP, UCSC, Northwestern, LANL, IFT/Madrid, SLAC, Penn State, Berkeley, UFRJ/OV, U Chile, U Michigan, STSCI/JHU, Unicamp, NOAO/CTIO

GW+EM OPPORTUNITIES

Astrophysics

- **First observations of NS-NS**, NS-BH mergers
- **Evolution of binary systems and their environment**
- **Origin of r-process elements in the Universe**
- **Neutron Star equation of state**
- Potential for discovery of new astrophysical phenomena

Cosmology

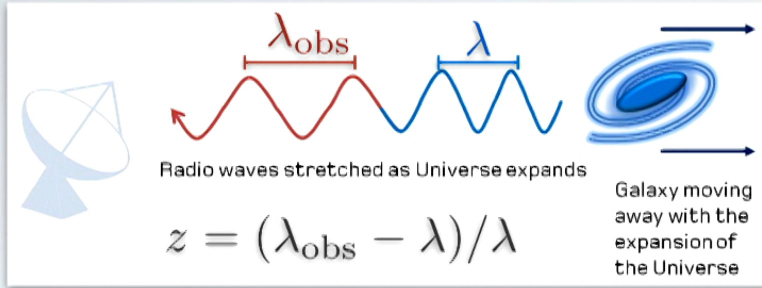
- **Standard sirens** (the GW-equivalent of standard candles)*

Physics of space-time

- Time of flight experiments (including neutrinos)
- Tests of General Relativity

***Speaker's favorite!**

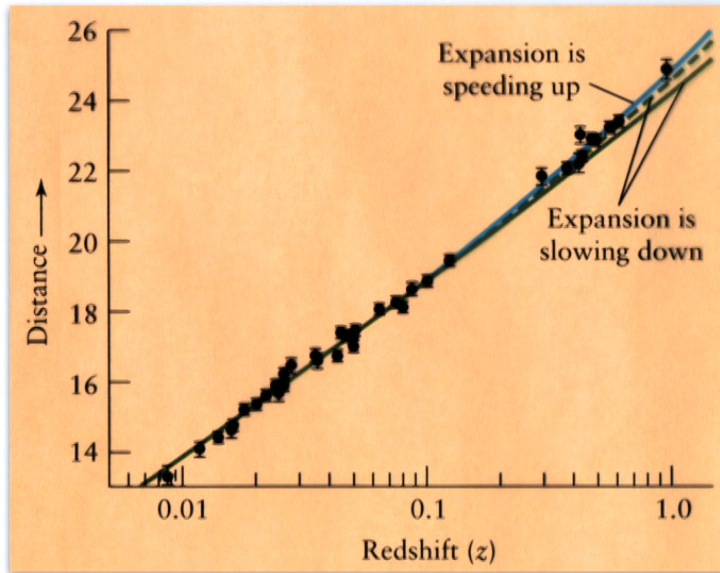
DISTANCE–REDSHIFT RELATION



Redshift (**z**) is an observable effect of the expansion of the Universe.

Faraway sources are more affected then nearby ones.

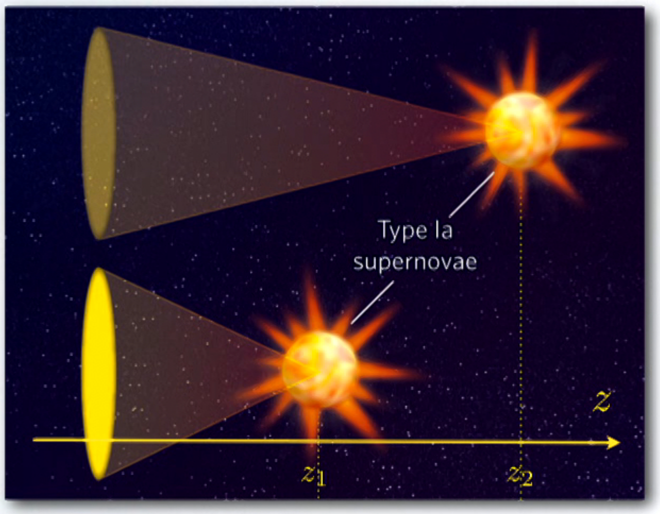
We can measure the rate of expansion using the **distance–redshift** relation!



ASTROPHYSICAL OBSERVABLES TO MEASURE DISTANCES

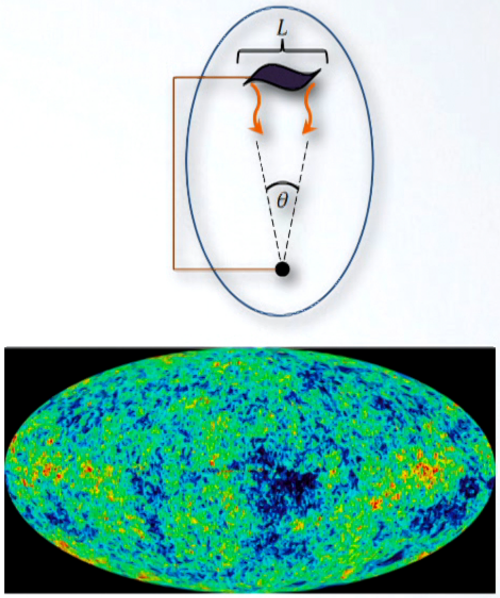
standard candle

Type Ia Supernovae (SNe)



standard ruler

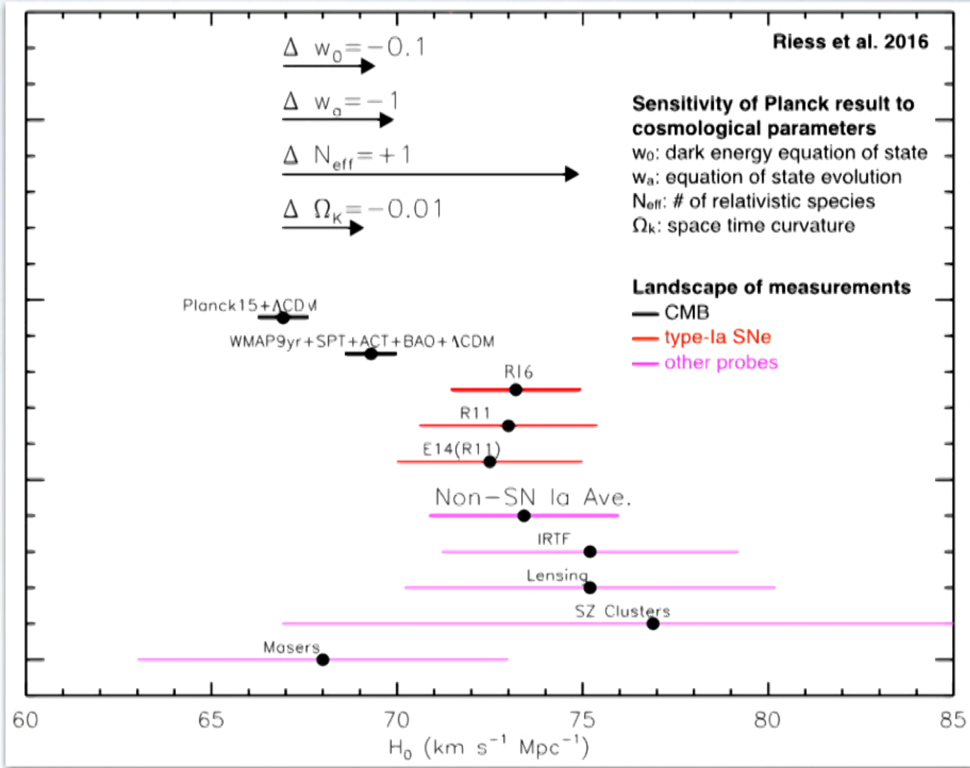
Cosmic Microwave Background (CMB)



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!



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

ASTROPHYSICAL OBSERVABLES TO MEASURE DISTANCES

standard candle

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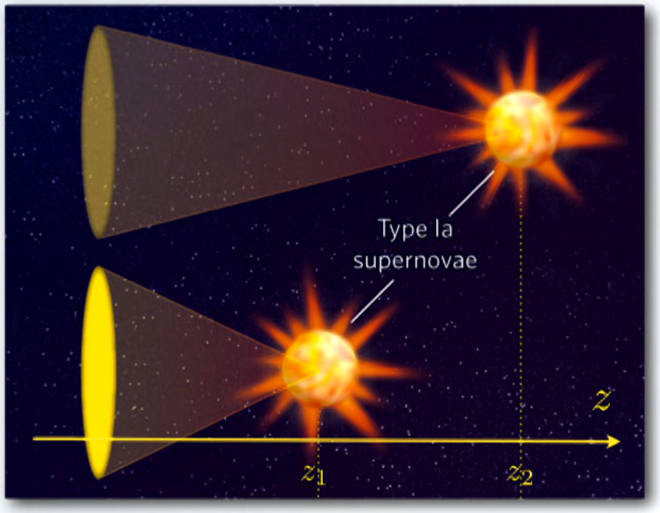
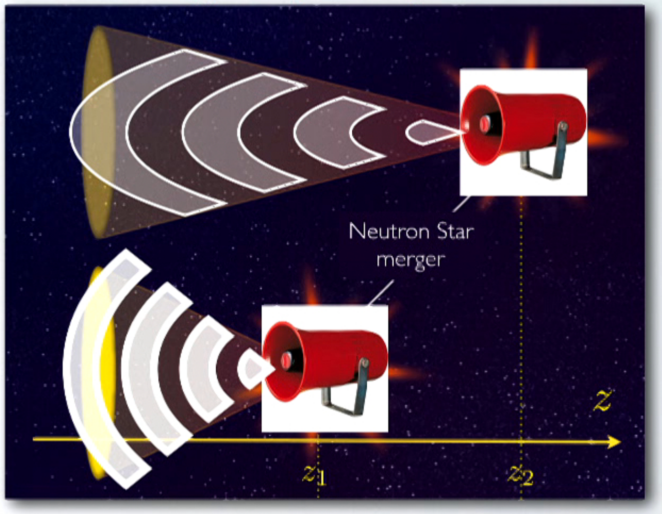


standard siren

Binary Neutron Star mergers (BNS)
Binary Black Hole mergers (BBH)
Mixed mergers (NSBH)



DESGW: THE PROGRAM

Can we take advantage of this new way to observe the universe, with Gravitational Waves, to add a new Dark Energy probe to our repertoire and beat down the systematics? With this motivation, we launched the DESGW project in 2013.

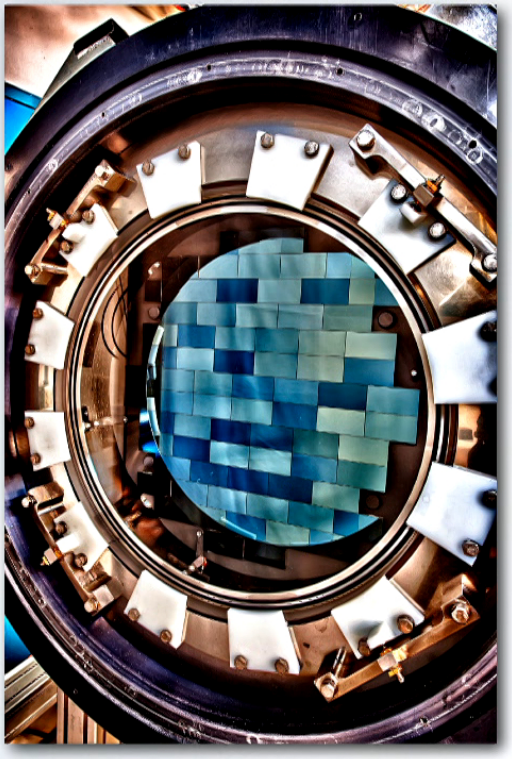
We obtained strong support from the DES Collaboration (Annis, Diehl, et al.) including experts from the SNe group (Kessler, Sako, Brout, Scolnic, Frieman, et al.).

We established a joint effort with LIGO members (Holz, Chen, Doctor, Farr) and non-DES DECam community users (Berger, Cowperthwaite et al.).

We developed an analysis that is sensitive to NS-NS, BH-NS mergers out to 400Mpc. We didn't see an optical counterpart in 2015-2016 run, but those results were encouraging. **This talk covers the results of the 2016-2017 run.**

Funding: Fermilab LDRD (FY15, FY16), UChicago SCI grant (FY17).
Telescope time: DECam nights (3 in 2015B, 5 in 2016B, 13 in 2017A, 3 in 2017B).

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.

MIND THE GAPS!

Blanco Images of the Southern Sky (BLISS)

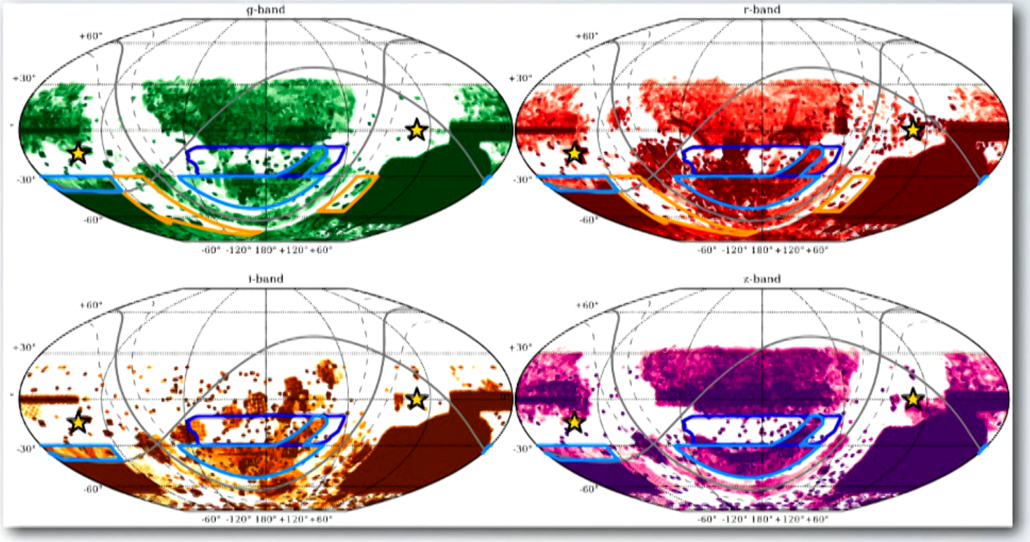
Designed to complete the accessible sky coverage before LSST.

Science cases:

— GW
— Dwarf galaxies
— Planet 9

Pilot program: 10^3deg²
11.5 nights in 2017A
(PIs: Soares-Santos, Drlica-Wagner)

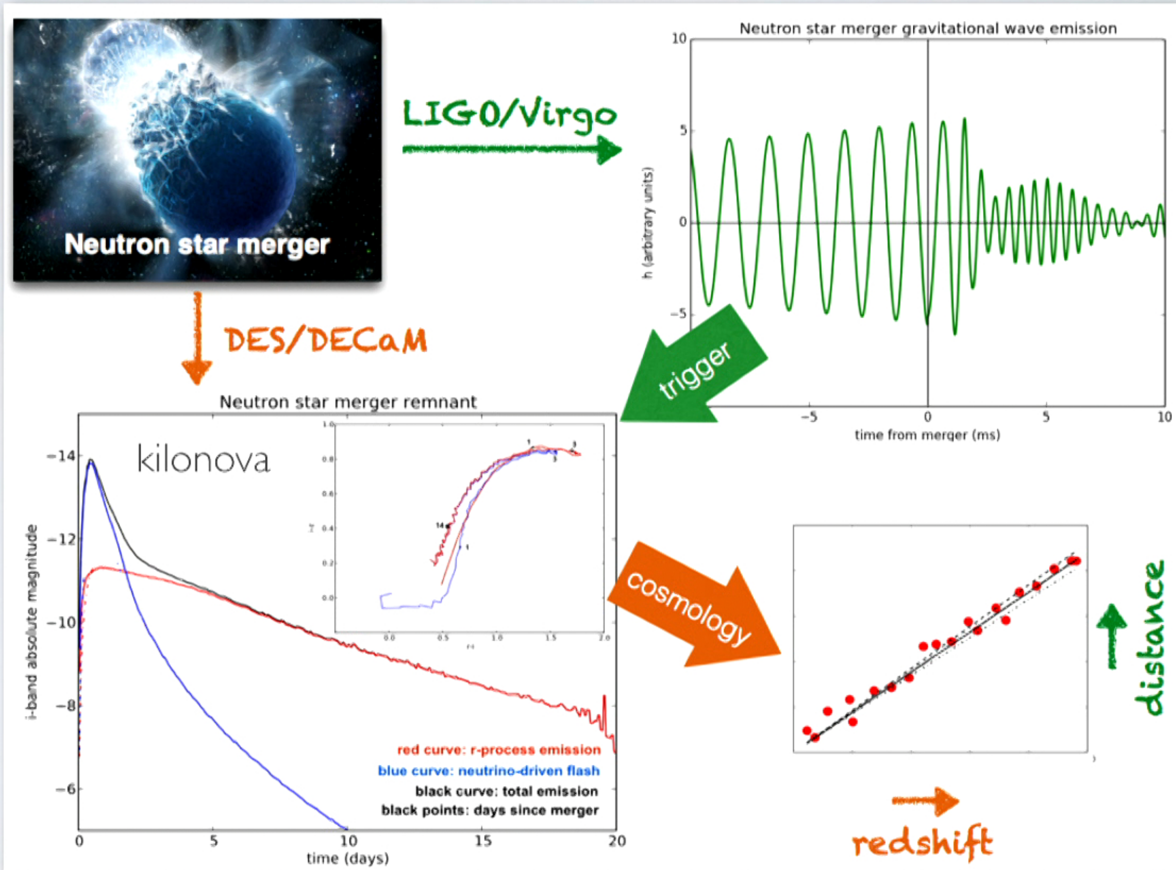
DECam sky coverage as of September 2017



Proposed for 2018A: 3,000 deg² (yellow stars)

Coordinating with MagLiteS and DeROSITAs

DESGW: A CARTOON



Marcelle Soares-Santos ◆ marcelle@brandeis.edu ◆ GW170817 optical transient discovery with DECam ◆ October 2017

NS-NS MERGER EM SIGNATURES

Tidal forces cause the neutron star to drop from degenerate to normal state.

Neutrons then can convert; r-process nucleosynthesis

Small fraction of the total mass is ejected

Electromagnetic signatures:

— **short Gamma-Ray Burst**
— **kilonova (r-process)**
— **X-ray emission**
— **radio afterglow**

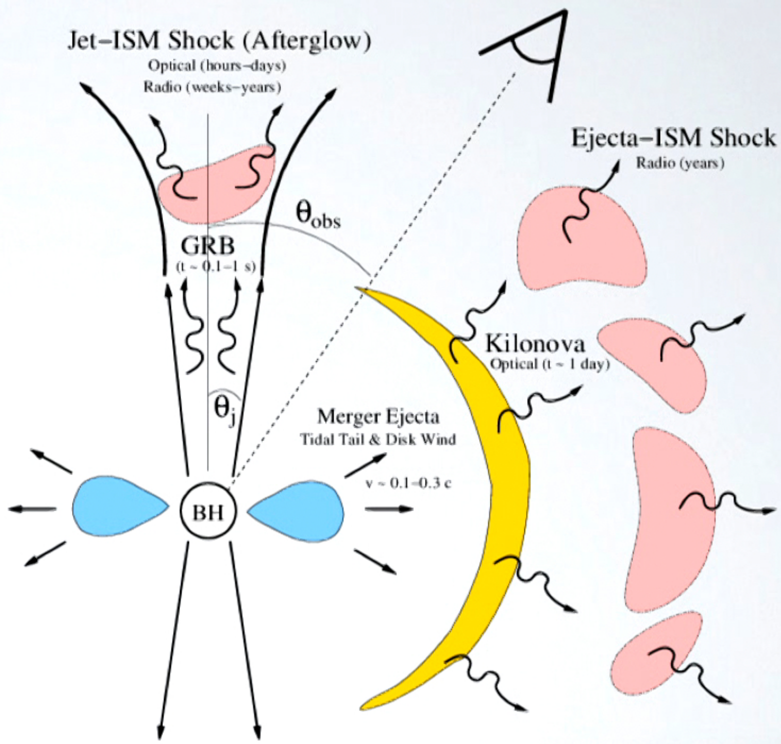
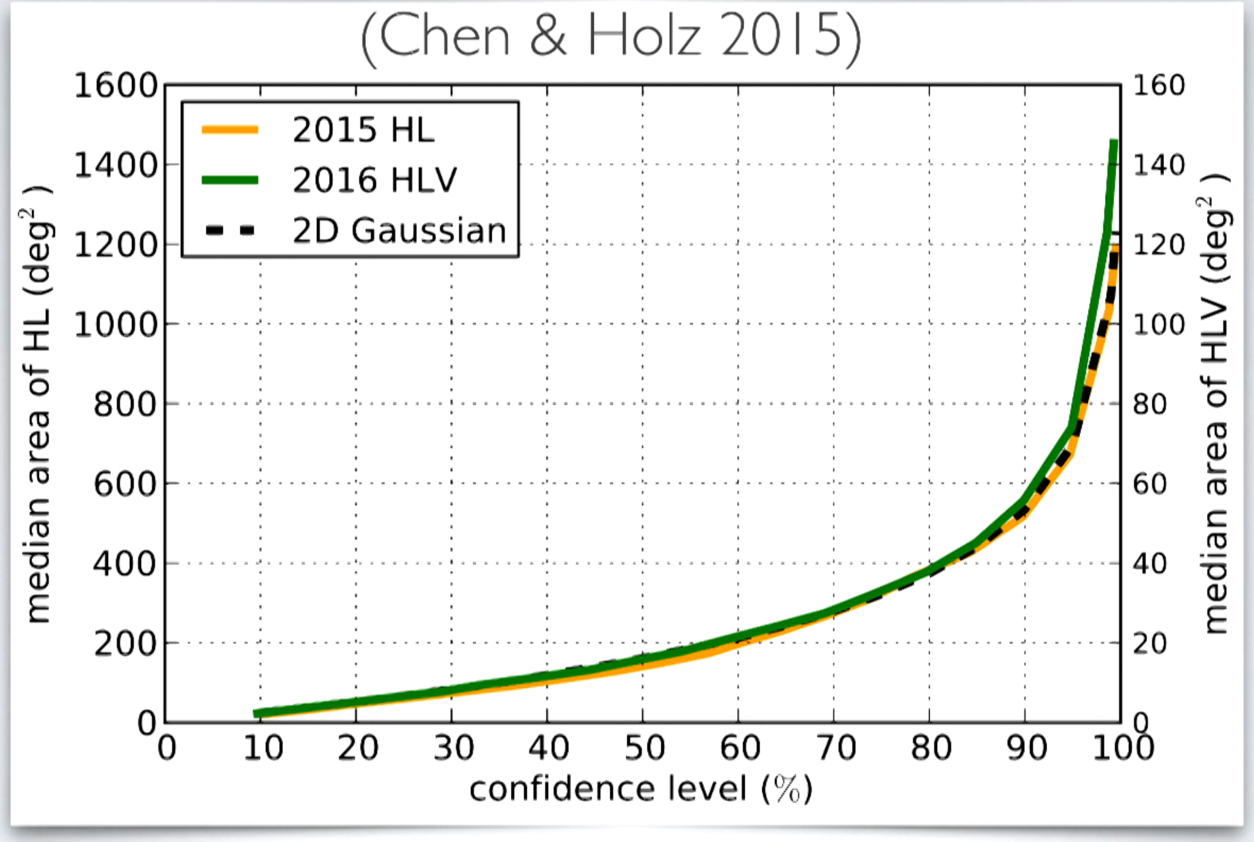
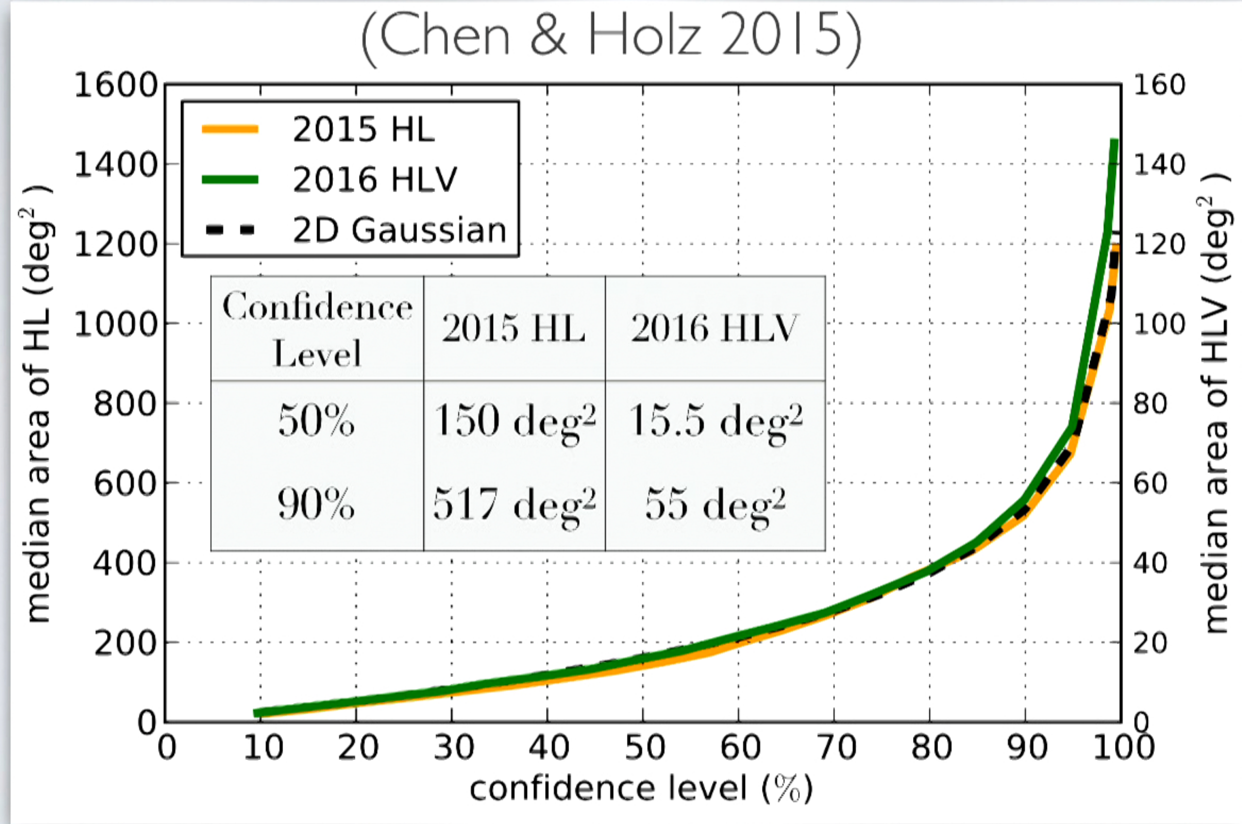


Figure: Metzger & Berger (arXiv: 1108.6056)

CHALLENGING SEARCH AREAS

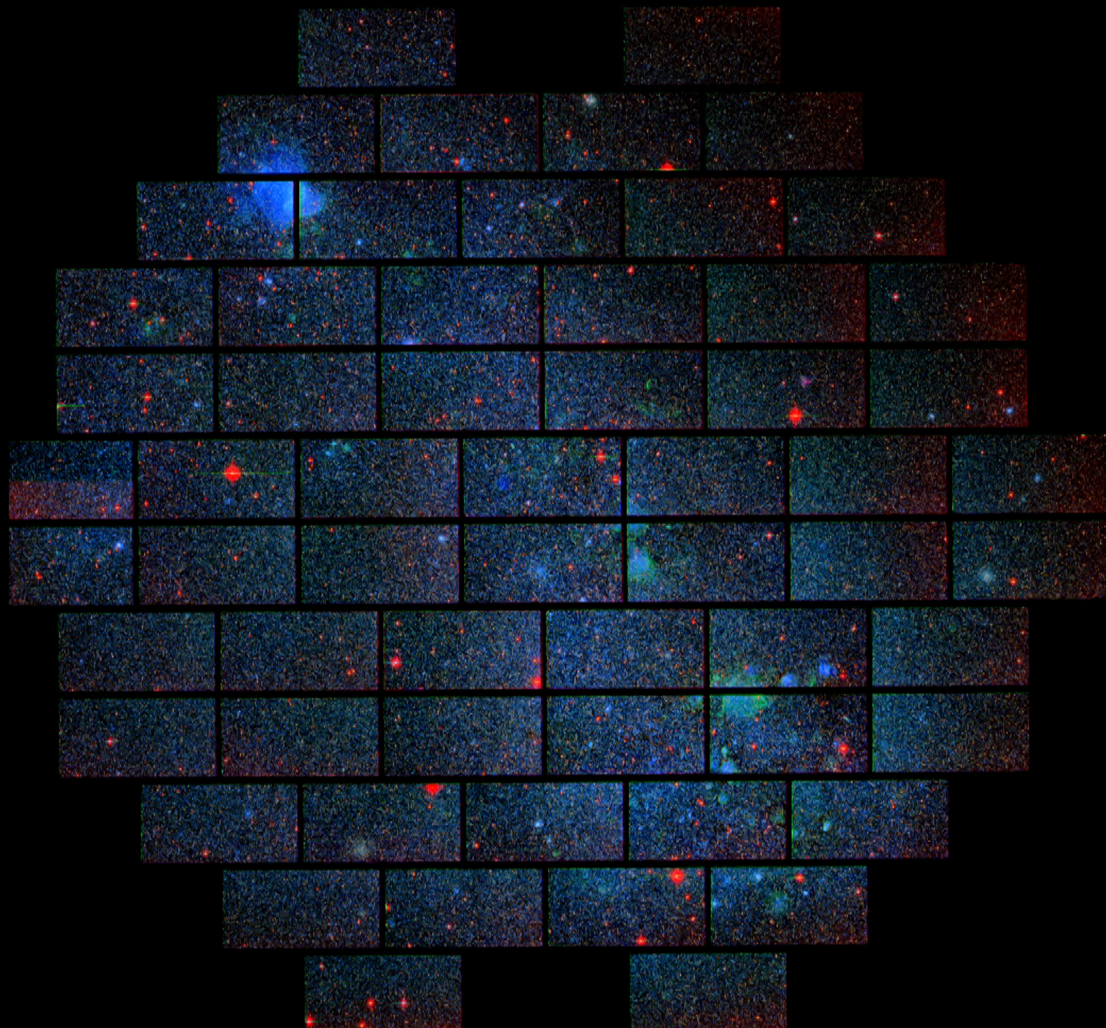


CHALLENGING SEARCH AREAS



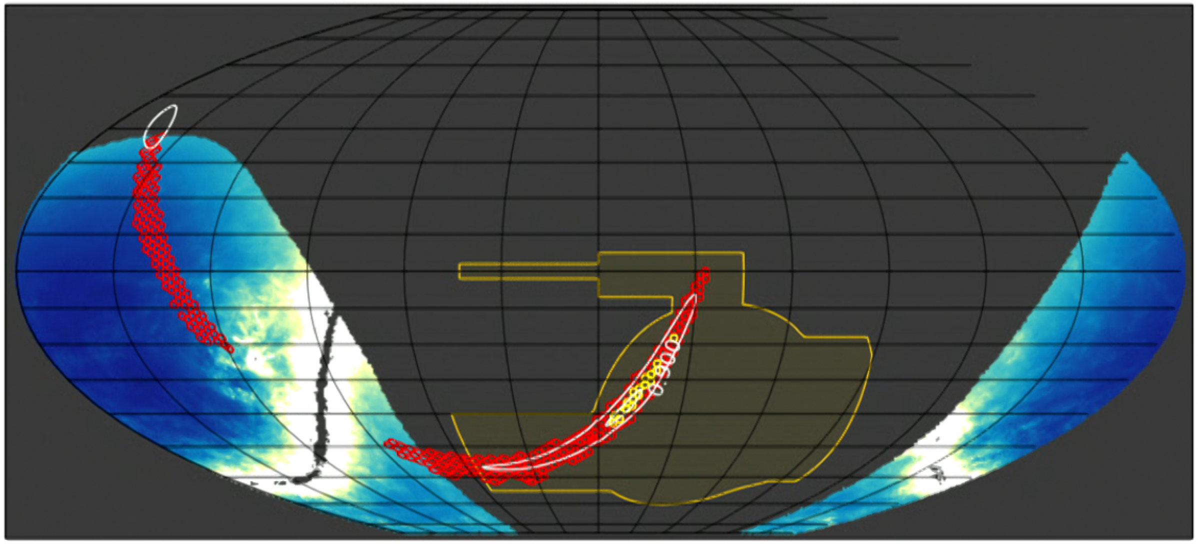
Confidence Level	2015 HL	2016 HLV
50%	150 deg²	15.5 deg²
90%	517 deg²	55 deg²

3 square degree FOV on a 4-meter telescope!



The Small Magellanic Cloud, DES 1st light image, Sep 12 2012

SIMULATED EVENT EXAMPLE



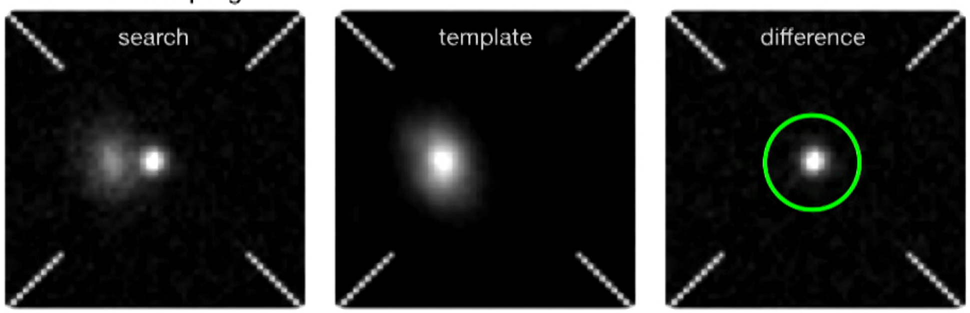
DIFFERENCE IMAGING

Each search image and template run through ***single epoch*** processing (~hrs each)

Then each CCD goes through ***difference imaging*** in parallel (~1hr/job)

Finally ***post-processing*** does assessment of outputs and creates the candidates list.

Example of transient source detected using the DES difference imaging pipeline. Template images (preferably taken before the search) are a crucial element of this program!



The Difference Imaging Pipeline for the Transient Search in the Dark Energy Survey

Kessler, et al. 2015, AJ, 150, 172

IMAGE PROCESSING WORKFLOW

Fermilab SCD project grew out of the LDRD initiative:

- Detect candidates via difference imaging (diffimg) within 24hours
- Run diffimg using GRID resources
- Machine learning algorithms applied to candidates to reject junk
- Detection efficiencies calculated by overlaying fake candidates on search images
- Post-processing to create analysis data products
- Details of the project described in Herner et al. 2016

DESGW 2015-2016 RESULTS

4. A search for Kilonovae in the Dark Energy Survey

Doctor, et al. arXiv:1611.08052, ApJ accepted

3. A DECam Search for an Optical Counterpart to the LIGO Gravitational Wave Event GW151226

Cowperthwaite, et al. 2016, ApJL, 826, 29

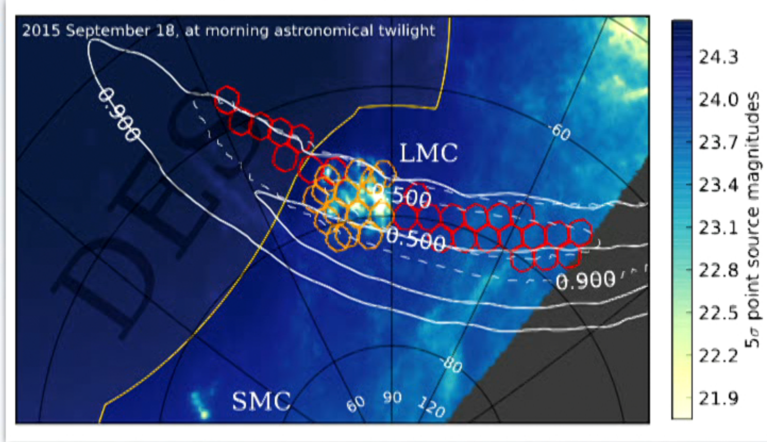
2. A Dark Energy Camera Search for Missing Supergiants in the LMC after the Advanced LIGO Gravitational Wave Event GW150914

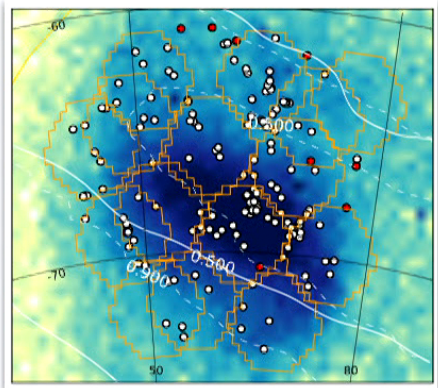
Annis, et al. 2016, ApJL, 823, 34

1. A Dark Energy Camera Search for an Optical Counterpart to the First Advanced LIGO Gravitational Wave Event GW150914

Soares-Santos, et al. 2016, ApJL, 816, 98

Soares-Santos et al. 2016





Annis et al. 2016

DESGW COSMOLOGY PROGRAM IN ACTION

The 1st Neutron Star merger event:
GW170817

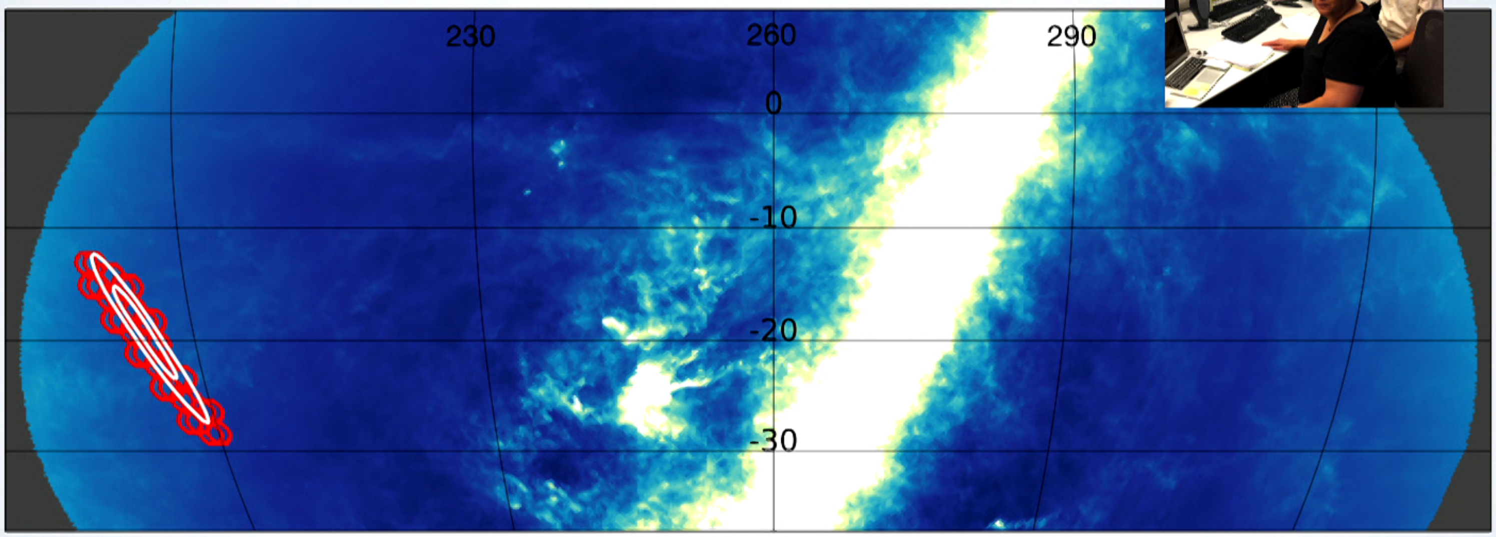
Trigger: Aug 17, 2017 at 07:41am Chicago time

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.

Team in place to eyeball the images; Remote observing team at Fermilab



WE FOUND IT!

Soares-Santos et al. 2017
(arXiv: 1710.05459)

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

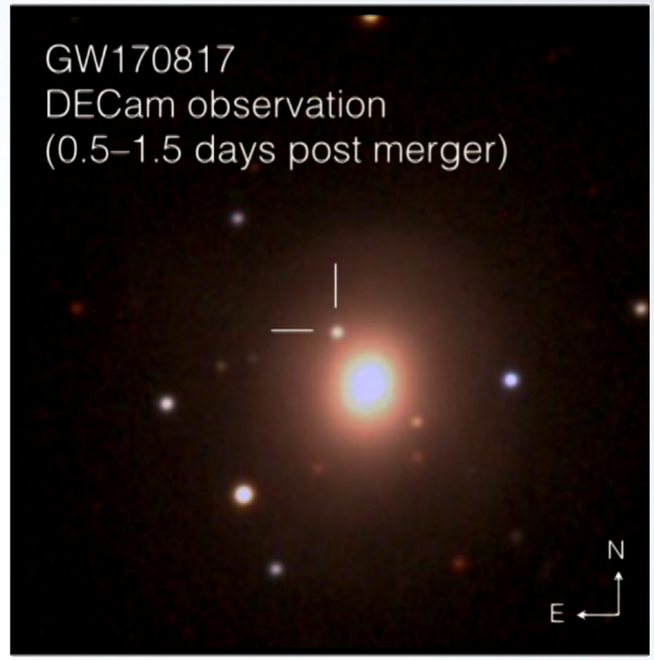
Holy [redacted].

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

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

Galaxy is at 40 Mpc.

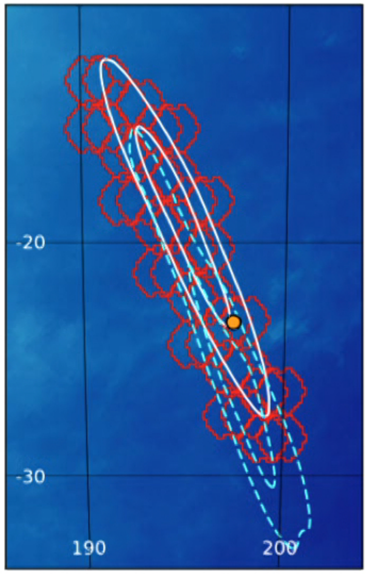
-R



Several teams independently discovered the source within minutes from each other!
DESGW had the 2nd announcement to the network of teams.

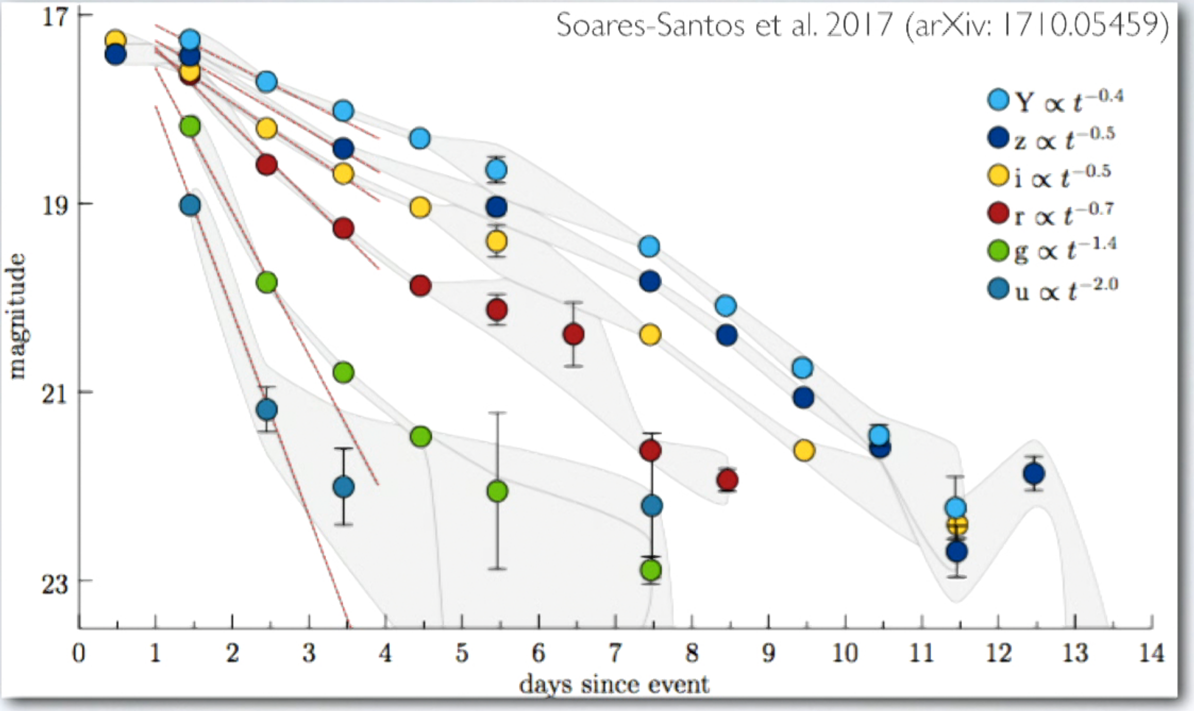
INDEPENDENT DISCOVERY OF OPTICAL TRANSIENT

Soares-Santos et al. 2017
(arXiv:1710.05459)



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 near 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.

COUNTERPART OBSERVATIONS



DECam light curve:

i. followed source in 6 filters for 2 weeks;
ii. three independent reductions;
iii. photometry good to 2%.

Simple implications:

i. bluer filters faded much faster than redder;
ii. for ~3 days consistent with cooling blackbody;
iii. peak of light curve ~1 day.

PROPERTIES OF THE SYSTEM

From the LIGO/Virgo data alone

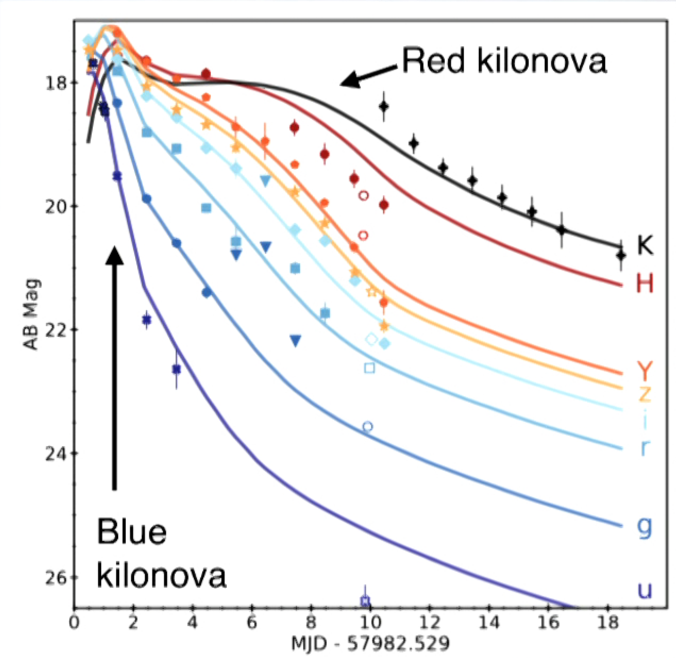
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely ≲ 14 km

Marcelle Soares-Santos ◆ marcelle@brandeis.edu ◆ GW170817 optical transient discovery with DECam ◆ October 2017

A TWO-COMPONENT MODEL

1. Photometry
   i. DECam optical at day 0.5-10.5
   ii. Gemini NIR at days 1.5-18.5;
   iii. HST optical & NIR at day 9.8.
2. At day 0.6, the source has T ~ 8300K, which implies an expansion velocity of 0.3c.
3. The optical and infrared lightcurves can be modeled as 2 components, blue opacity fixed at 0.5 cm^2/gm, then:
   i. blue component:
      i. ejecta mass = 0.01 M_sun;
      ii. ejecta velocity = 0.3c;
   ii. red component:
      i. ejecta mass = 0.04 M_sun;
      ii. ejecta velocity = 0.1c;
      iii. opacity = 3.3 cm^2/gm.

Cowperthwaite et al. 2017 (arXiv:1710.05840)



Blanco 4m telescope and DECam,
Gemini-South 8m Telescope and Flamingos-2 H&Ks, &
Hubble Space Telescope and WFC3 & ACS observations

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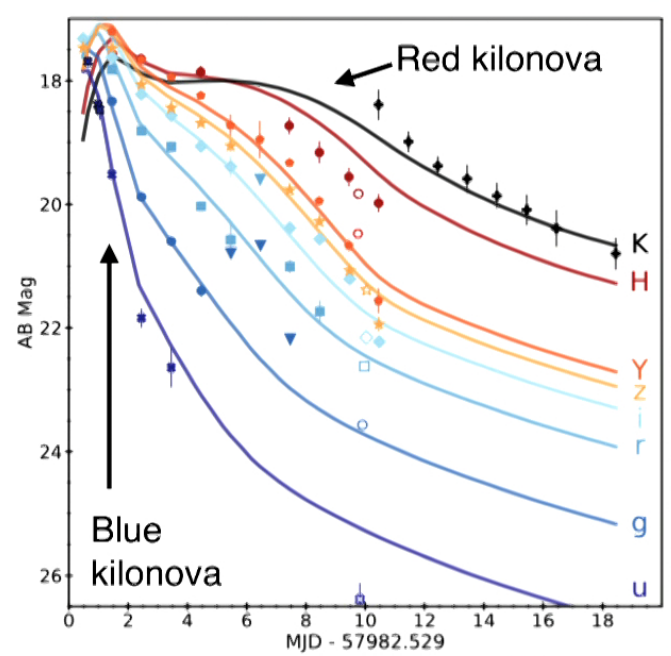
Cowperthwaite et al. 2017 (arXiv:1710.05840)



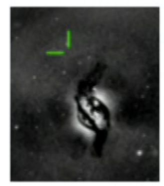
Blanco 4m telescope and DECam,
Gemini-South 8m Telescope and Flamingos-2 H&Ks, &
Hubble Space Telescope and WFC3 & ACS observations

THE MERGER ENVIRONMENT

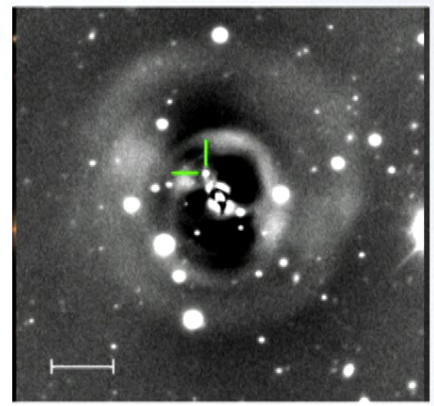
The host galaxy is an unremarkable elliptical galaxy, except…

1. **There is evidence NGC4993 suffered a merger with another galaxy**:
   i. DECam imaging shows shells, which the source is on or near;
   ii. HST imaging shows complex dust lanes in the center;
   iii. 6dF spectroscopy shows an AGN at the center.
2. Given the position of the shells and the velocity dispersion of NGC4993, the galaxy merger happened 25 Myr ago.
3. **Shell galaxies are indicative of minor mergers- the lesser galaxy < 10% of NGC4993 mass.**
4. **The galaxy merger may have aided the formation and evolution of the neutron star binary system.**

Palmese et al. 2017
(arXiv:1710.06748)



ACS

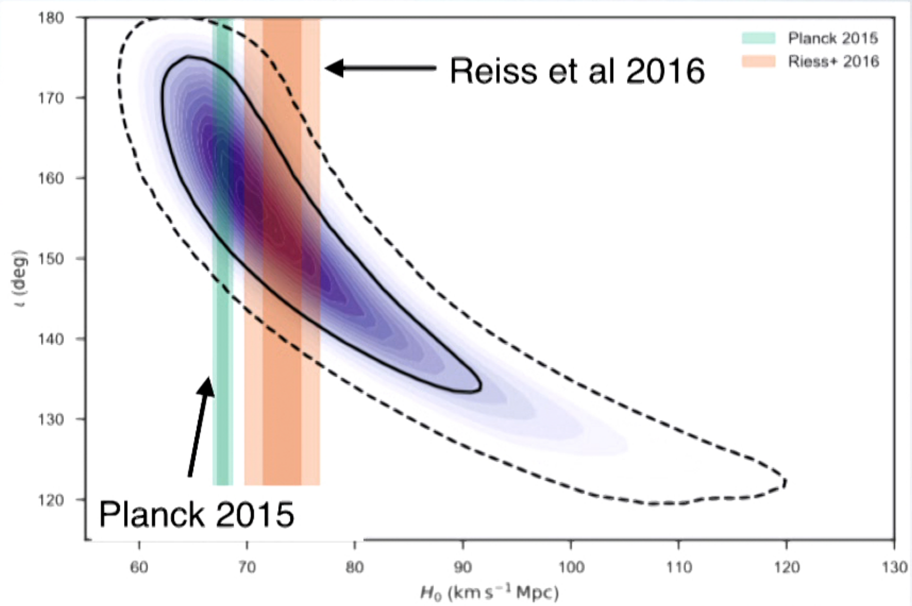


DECam

HUBBLE PARAMETER RESULT

1. GW waveform parameter estimation finds the distance to GW170817 to be
   i. d=39.7 +- 5.7 Mpc
   ii. 15% uncertainty due to noise, calibration, and inclination angle.
2. H_0 = cz/d where z is the Hubble flow
3. Determine velocity:
   i. group velocity = 3327 ±72km/s
   ii. groups can flow along filaments: estimate peculiar velocity using 8Mpc Gaussian kernel on 6dF peculiar velocity map (~10 glxs inside 1sigma), v_p = 304 ±68 km/s
   iii. Hubble flow velocity is v_H = 3010 ±95 km/s
4. $H_0 = 69.3^{+12}_{-6}$ km/s/Mpc, independent of both the distance ladder (cephieds) and inverse distance ladder (BAO/CMB)

LIGO/Virgo Collaboration et al. 2017 (including DESGW team; arXiv:1710.05835)



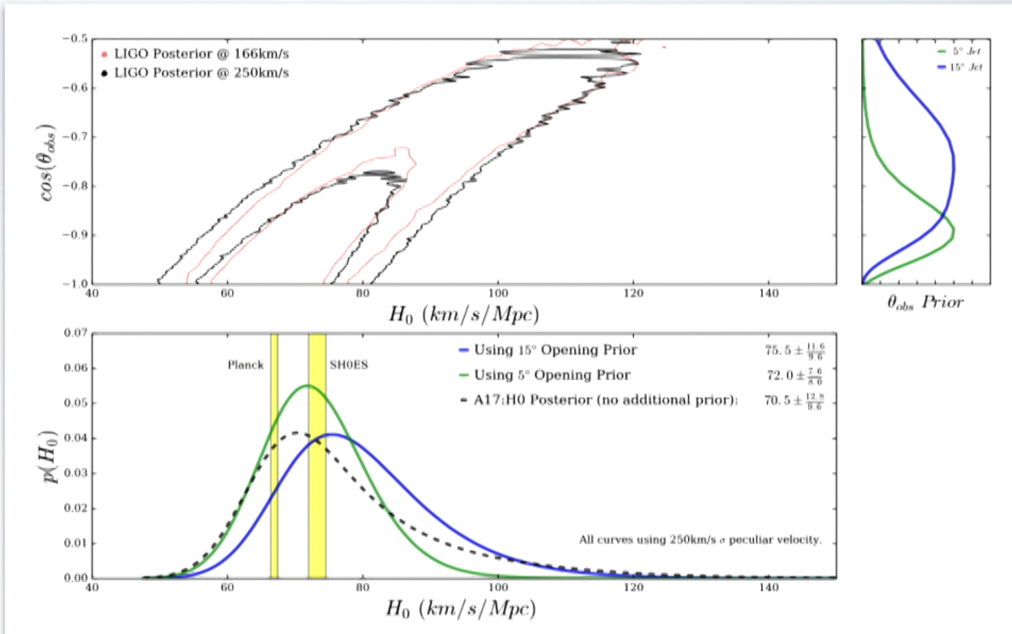
HUBBLE PARAMETER RESULTS

We can improve the Hubble parameter measurements significantly if we can put a prior on the inclination angle of the angle.

The X-ray data modeling indicates that we have an off-axis jet with an opening angle of ~15 deg and an off axis angle ~25-50 deg.

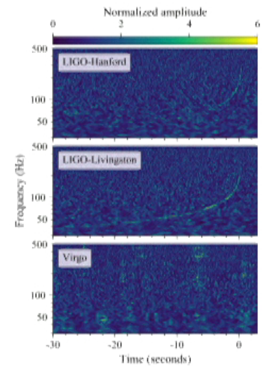
This results in an Hubble parameter measurement that is **slightly more consistent with the SNe measurements than with the CMB**.

Guidorzi et al. 2017 (arXiv:1710.06426)



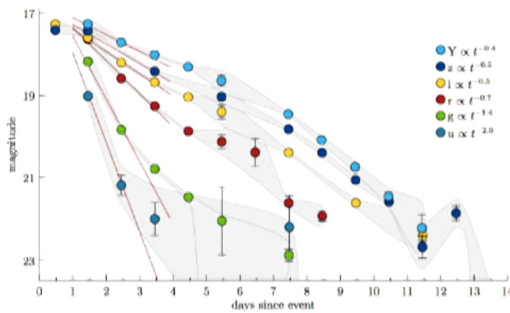
DESGW: BEYOND A CARTOON!

LIGO/Virgo

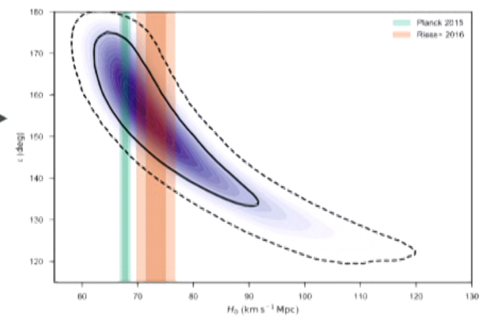


LIGO/Virgo 2017

DES/DECaM



Soares-Santos et al. 2017

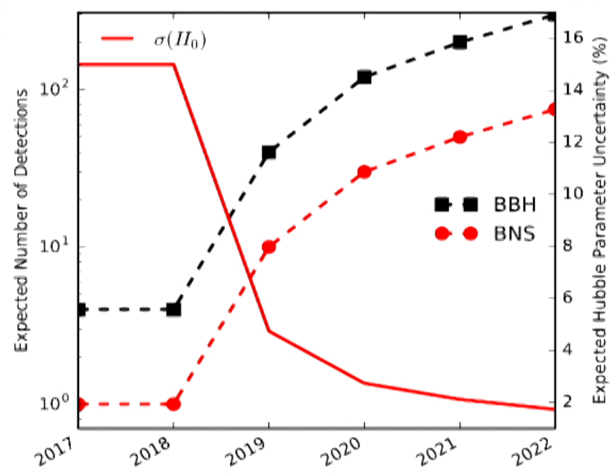


LIGO/Virgo et al. 2017

Marcelle Soares-Santos ◆ marcelle@brandeis.edu ◆ GW170817 optical transient discovery with DECam ◆ October 2017

FUTURE PROSPECTS

- Can use "Dark" (BBH) and "Bright" (BNS, NS-BH) Standard Sirens to measure H_0
  - Bright: Distance from GW component; redshift from EM component $cz = H_0 d$
    - **Independent** measurement from SNe, CMB results; no cosmic distance ladder
- Roughly 3% precision with ~20 BNS events
- 1-2% precision possible in the LSST era
  - LSST already thinking about transient science
  - Now's the time to apply the lessons from DES!
    - Observation economics, systematics...



These are exciting times for science with
the **Dark Energy Survey** & **Gravitational Waves**.

DECam enabled us to participate on the discovery of the first neutron star merger with an associated electromagnetic counterpart, **inaugurating the golden era of multi-messenger astronomy**, and **blazing a new trail for cosmology**.