UCL

Fermilab

50 Years of Discovery

DECam follow up of GW170817 and its host galaxy

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LINEA Web Seminar

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Introduction

- DECam currently premier instrument for follow up in the Southern hemisphere (*ugrizY*, wide field)
- GW170817: 4 DES papers (+2: all-EM, H_0) :
    1. DECam discovery (Soares-Santos et al., 2017)
    2. DECam lightcurves (Cowperthwaite et al., 2017)
    3. KN searches (Scolnic et al., 2017)
    4. DECam analysis of host galaxy (Palmese et al., 2017)
- Motivation: Binary Neutron stars (BNS) formation and evolution is still uncertain
- By studying the host galaxy we can infer what the star formation history of the galaxy is and therefore how the stars in the binary might have formed
- Outline:
    1. DES-GW follow up program and the discovery of the kilonova for GW170817
    2. The host galaxy NGC 4993

The EM counterpart

- BBH: no EM counterpart expected (but plenty of creative ideas)
- BNS or BH+NS:

1. Prompt radio emission

$t \sim t_{mer}$+secs

→

2. sGRB

$t \sim t_{mer}$+2s

↓

3. Optical-NIR kilonova

$t \sim t_{mer}$+h/days

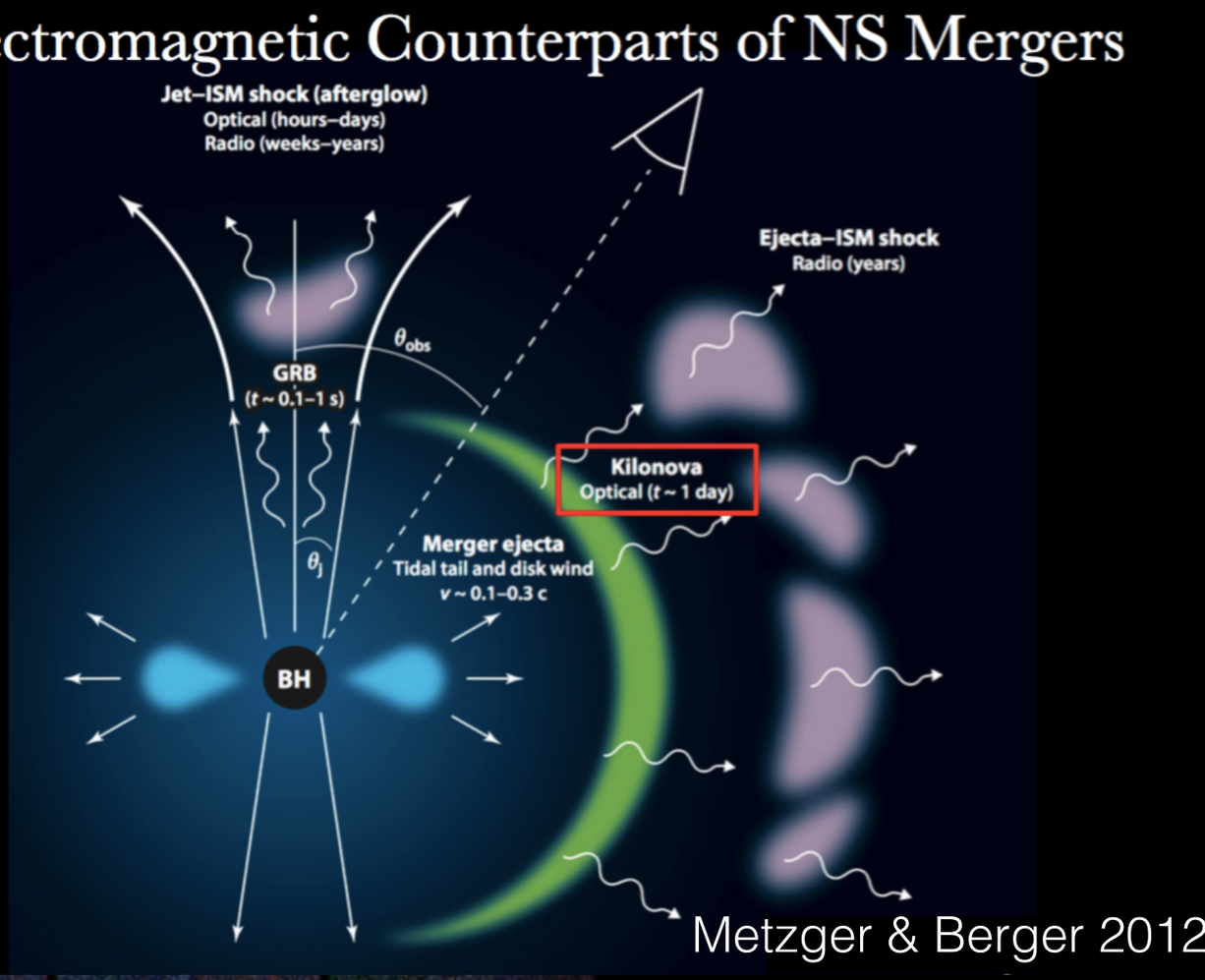
↓

4. Slow radio remnant

$t \sim t_{mer}$+month/yr

←

Isotropic thermal transient powered by the radioactive decay of rapid neutron capture elements synthetized in the merger ejecta



Metzger & Berger 2012

GW+EM motivation

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: a new independent measurement with different systematics may help solving current tensions on H_0

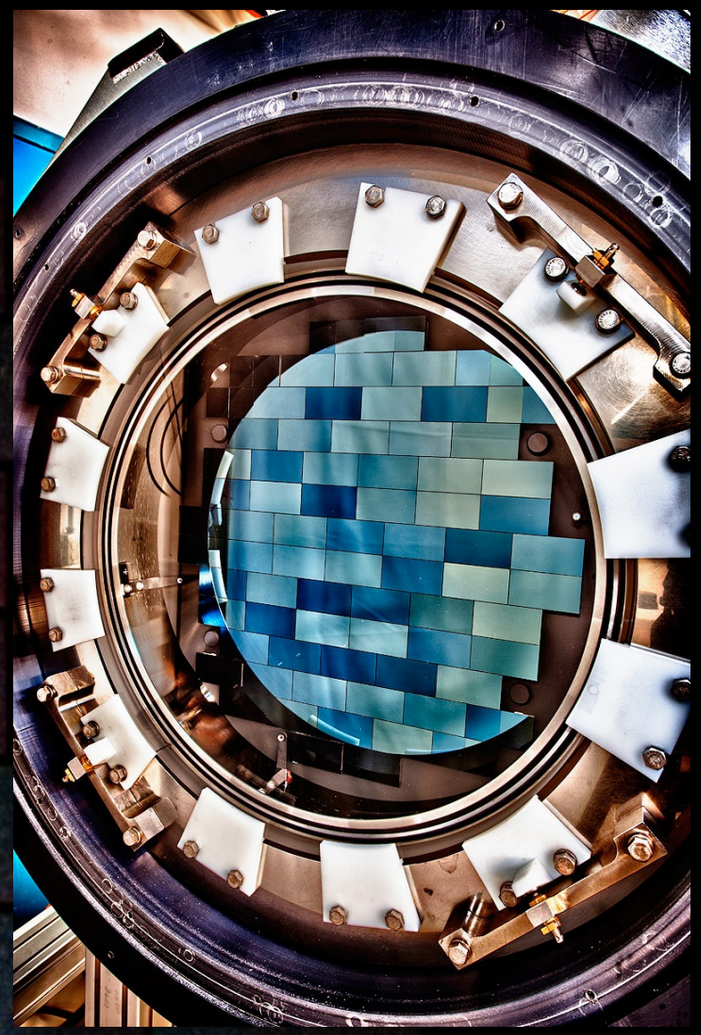
Physics of space-time

Tests of General Relativity

The 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
Neutrinos: followup of **Icecube events**
GW: followup of **LIGO/Virgo events**

DES-GW - since 2013

Strong support from the DES Collaboration (Annis, Diehl, et al.) including expertise from the SNe group (Kessler, Sako, Brout, Scolnic, Frieman, et al.)

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

Telescope time: DECam nights (3 in 2015B, 5 in 2016B, 13 in 2017A, 3 in 2017B)

We developed an analysis that is sensitive to mergers out to 400 Mpc. No optical counterpart observed in 2015-2016 run, but bright encouraging results

DES-GW follow up

- Kilonova: Redder, dimmer, shorter-lived (~1 week) than SN

- Given imperfect localization from LIGO (area used to be ~1000 sq deg to 60 sq deg), must decide where to observe each night -> complicated in a short timescale but DECam is an ideal instrument for this type of search given its field of view

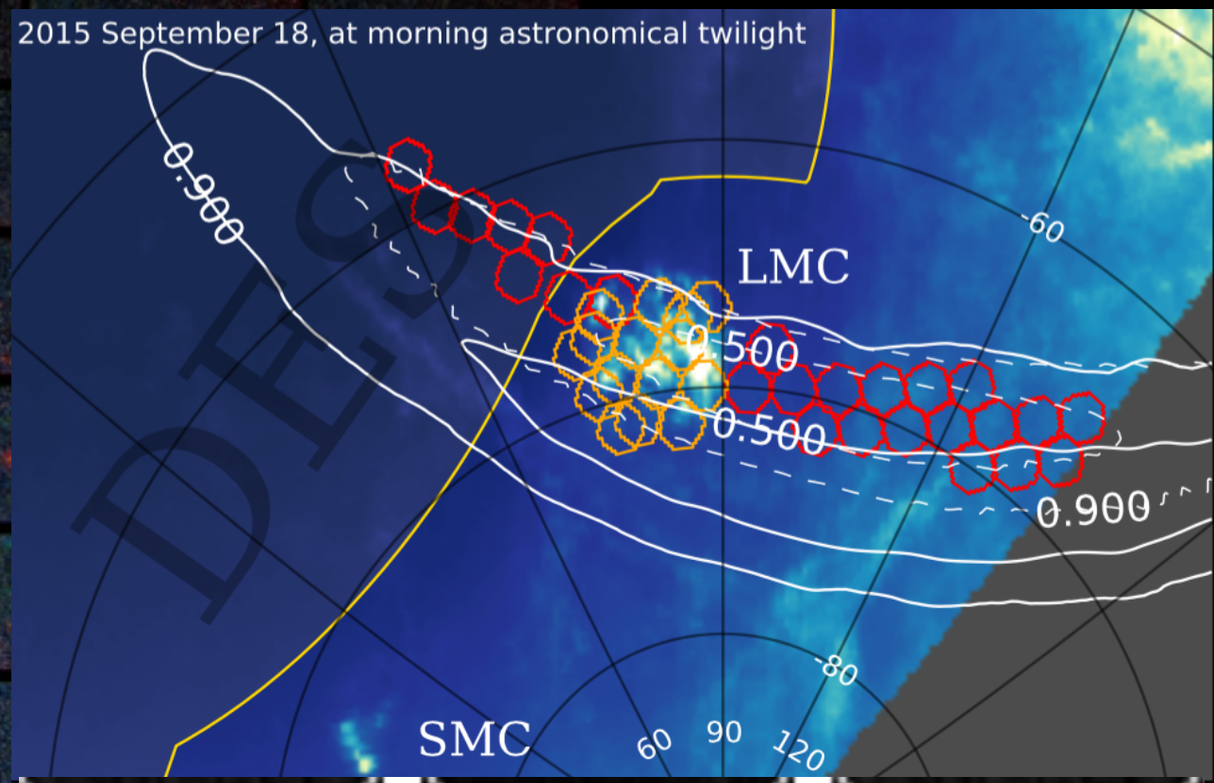
- Ideally three passes over region: immediately, a few days later, and 2-3 weeks later: want to observe decline in flux for candidates

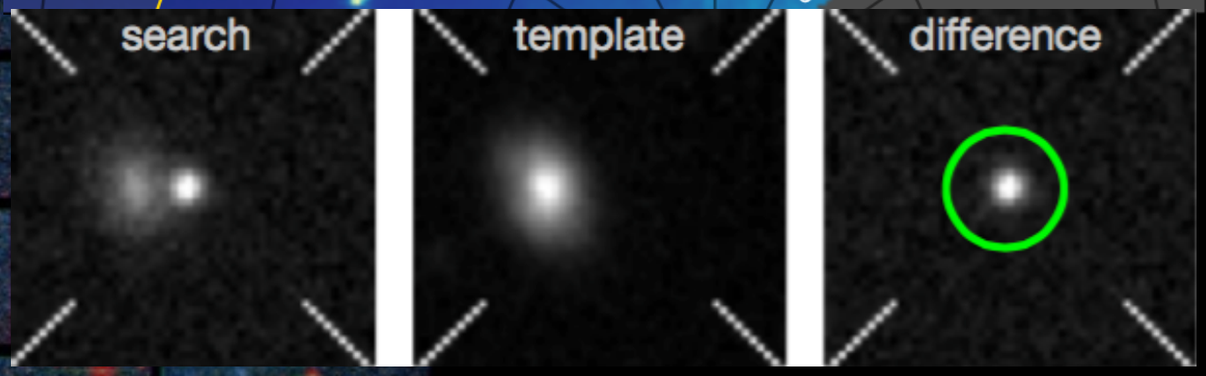
- Detect candidates via difference imaging: subtract template images (previous images of same region of sky) from search images, scan for "new" objects.

  - Each CCD is run in parallel (~1 hr/job)

  - Machine learning method to reject artifacts

  - Detection efficiencies from fakes



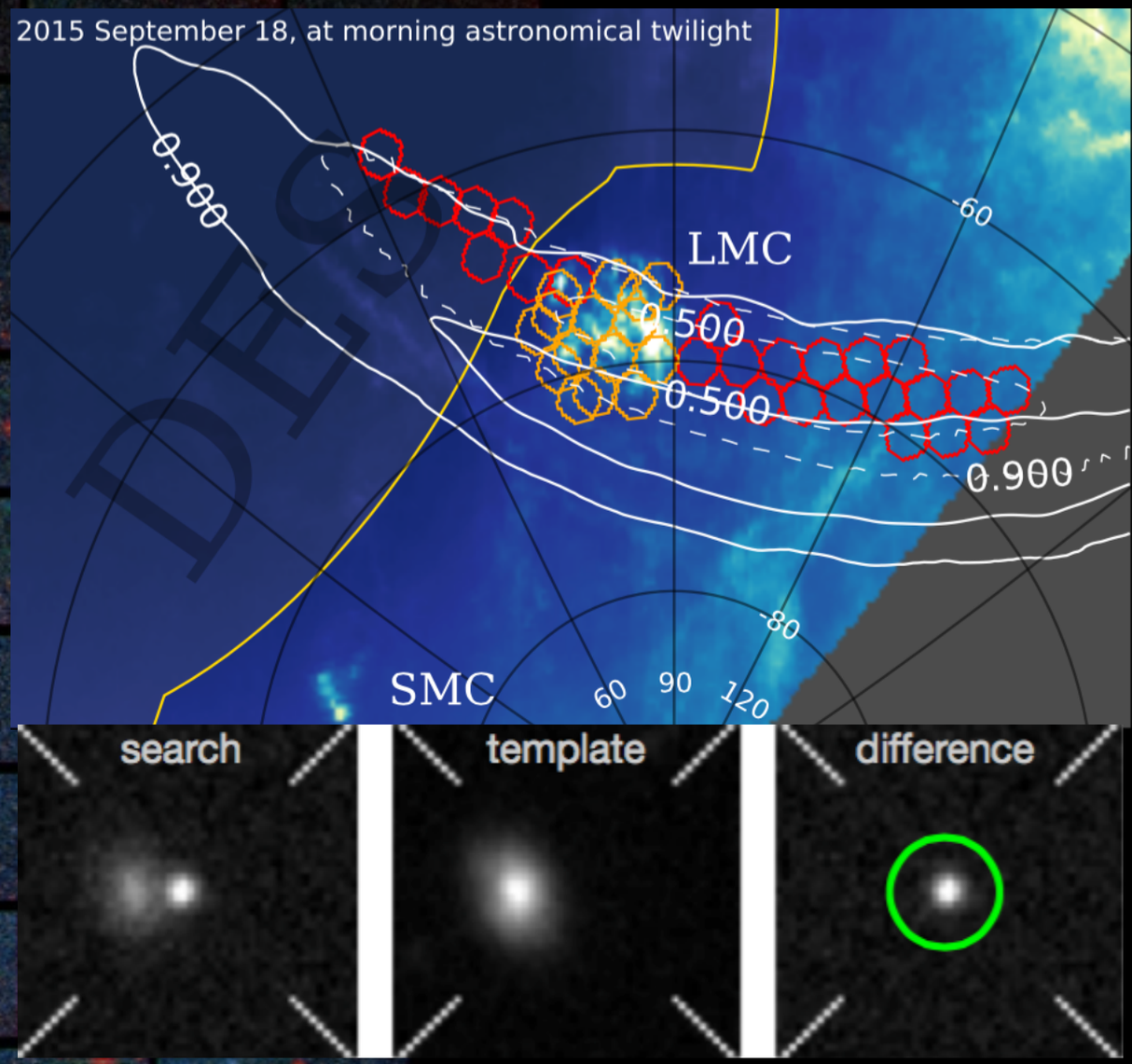


The Difference Imaging Pipeline for the Transient Search in the Dark Energy Survey

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

DES-GW follow up

- Post processing: assessment of outputs and creation of candidate list
- Galaxy catalog 1: **200 Mpc galaxy catalog** for galaxy host search
- Galaxy catalog 2: a giant **Franken catalog** for SN rejection (WISE, 2MASS, DES Y3…) - by far most likely transient contaminant
  - a close KN may look like a further SN
  - Produce catalog (including photozs) and candidate matching included in the pipeline



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

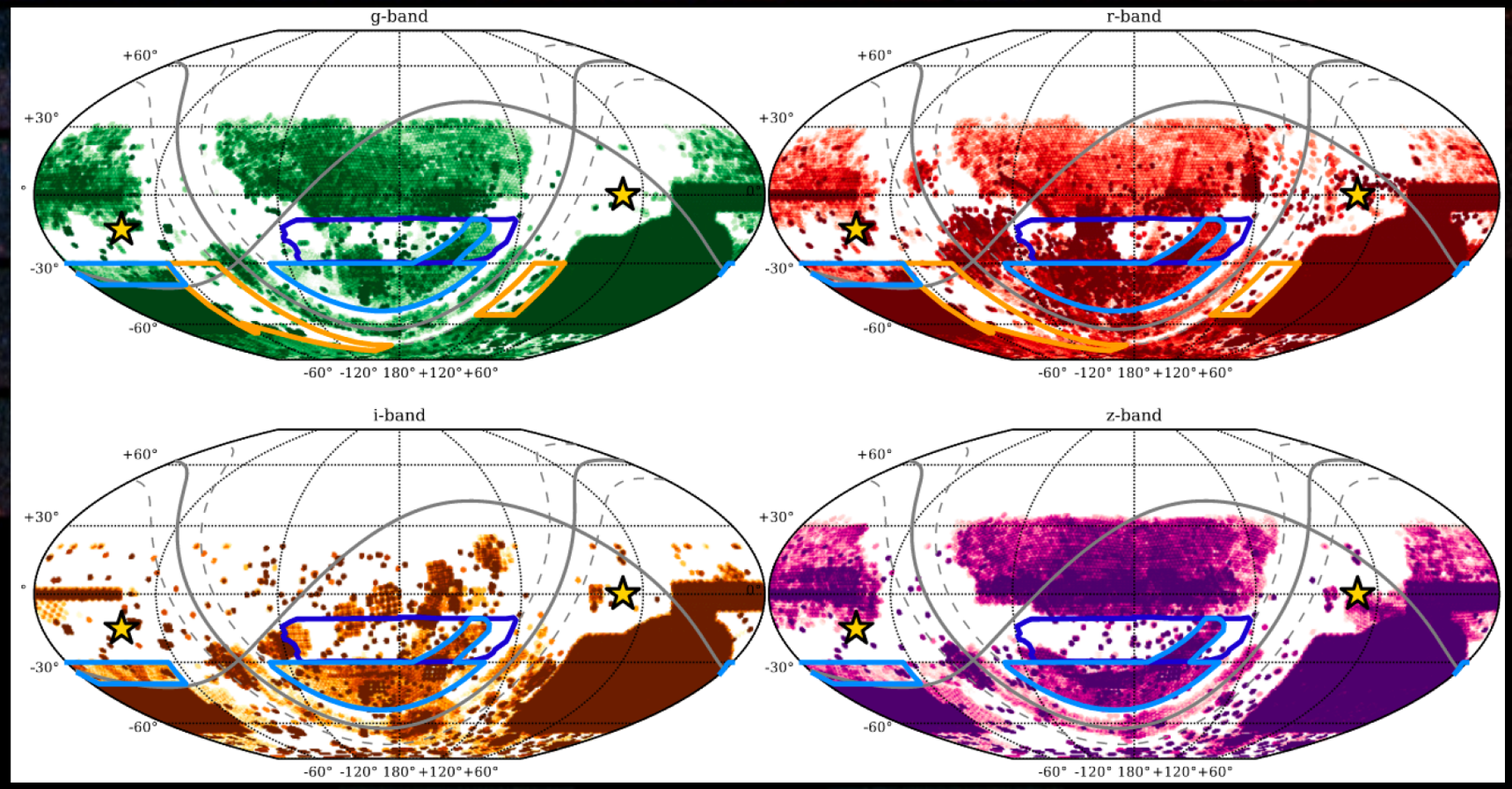
Kessler, et al. 2015, AJ, 150, 172

BLISS

Blanco Imaging of the Southern Sky

- Complete observations of accessible southern sky with DECam before LSST
- Templates for the whole southern sky
- Other science goals: MW dwarfs, Planet 9

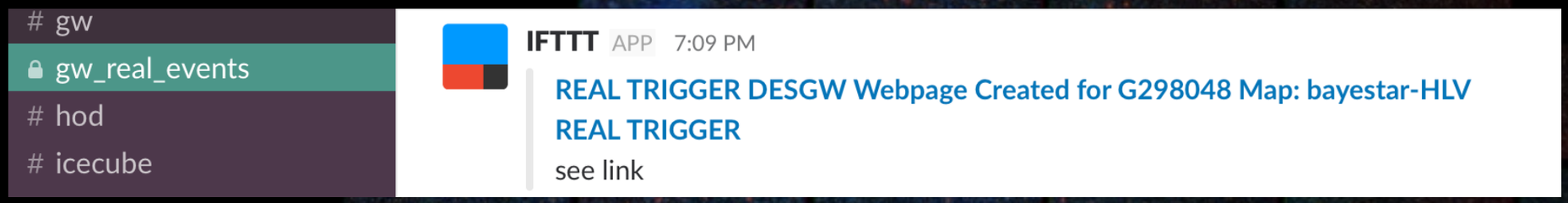
Pilot program: 1000 deg² in 2017A (PIs: Soares-Santos, Drlica-Wagner



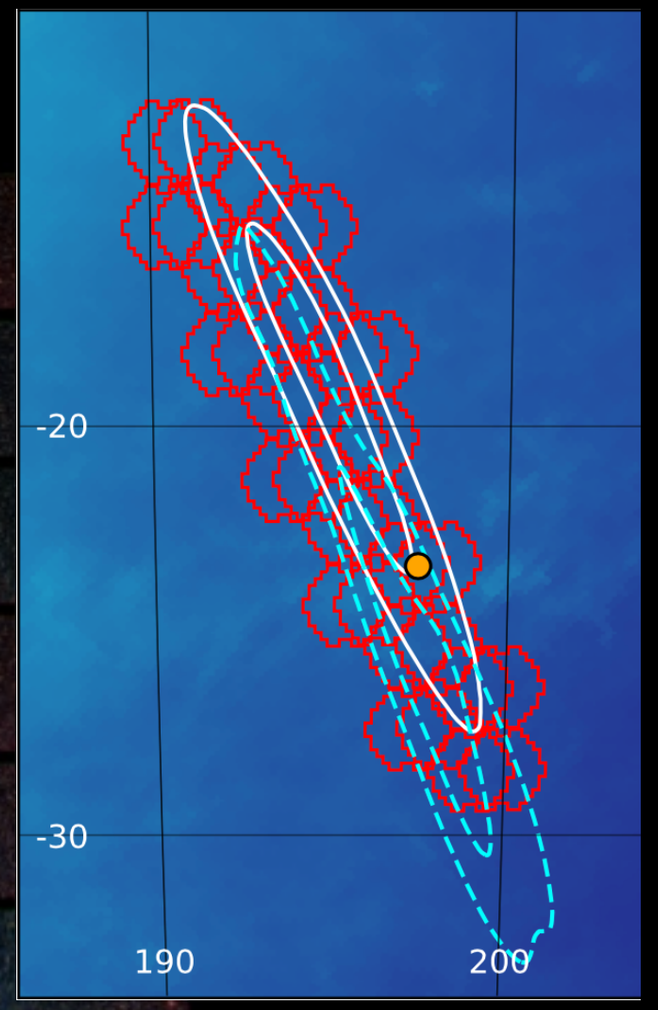
DECam coverage (September 2017)

3000 deg² proposed for 2018A

GW170817 - Discovery



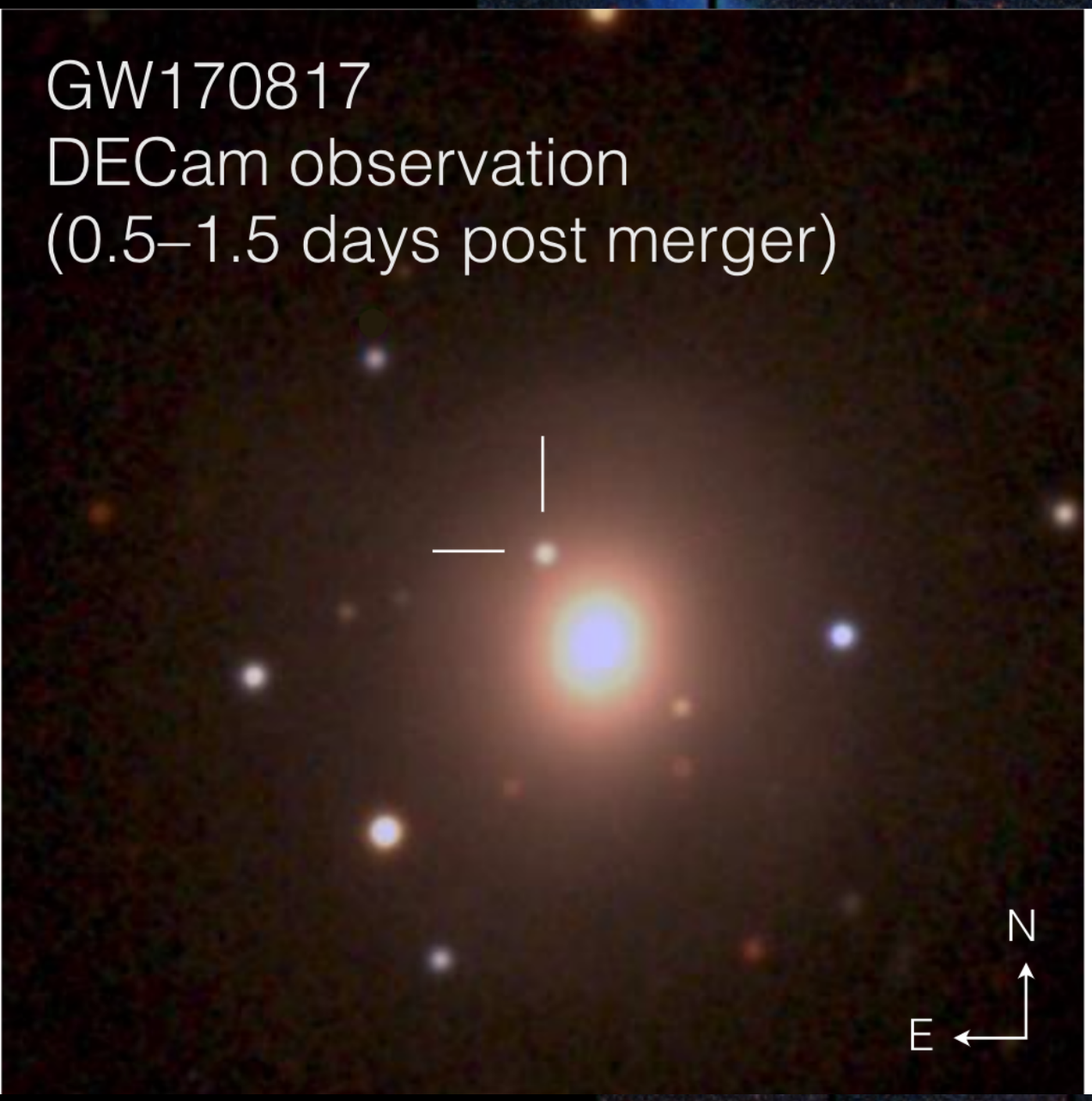
- Observations started: 10.53h post merger
- 30s exposures in i (5sigma 22.0),z (21.3)
- 18 pointings + 2nd offset series
- 70.4 deg^2 , 93.4% initial sky map, 80.7% new
- Visual inspection and comparison with Pan-STARRS : discovery of the KN in NGC 4993 (40 Mpc away)
- Independently discovered by 5 groups (and etymology of “discovery”)
- Templates in g,r
- Observed 17-31 August 2017 + until 2 September for templates
- Candidate selection:
  - ★ At least 1 detection in i and z
  - ★ ML score >0.7 in all detections
  - ★ Significantly faded in the last observations
- Uniqueness of the candidate is the strength of the DECam search

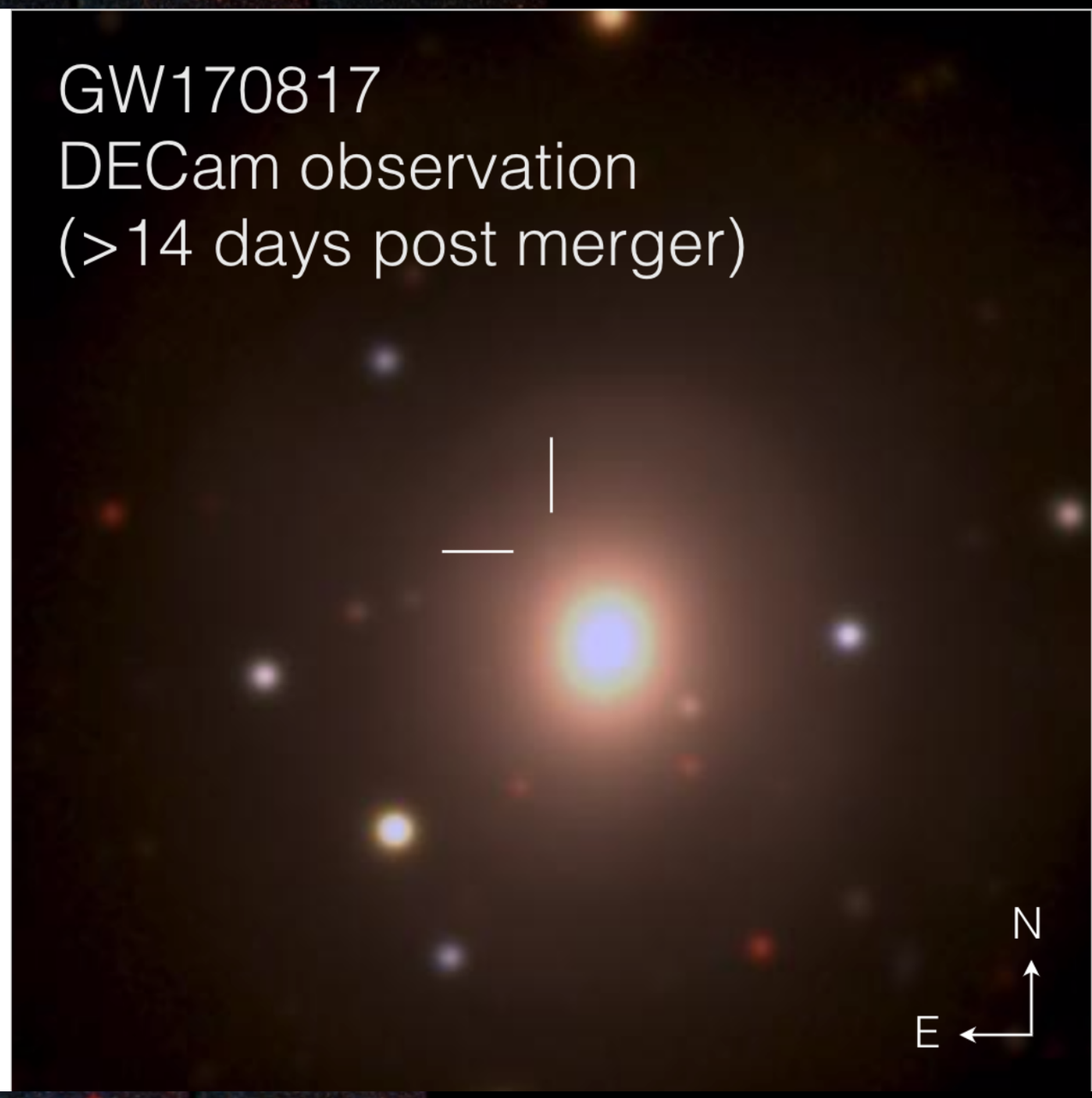


mag(i)	Raw	Cut 1	Cut 2	Cut 3
15.5–16.5	4	0	0	0
16.5–17.5	11	7	3	1
17.5–18.5	26	15	7	0
18.5–19.5	296	63	27	0
19.5–20.5	1163	167	44	0
Total	1500	252	81	1

Soares-Santos et al.2017

GW170817

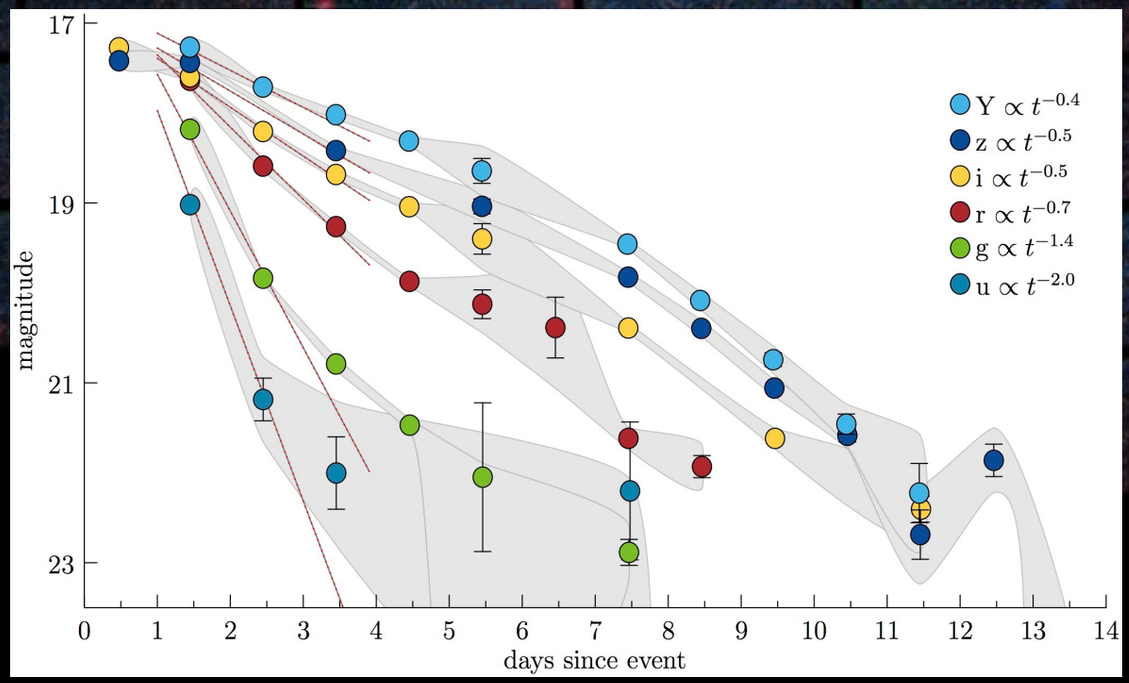




Soares-Santos et al.2017

GW170817 - Lightcurves

- Magnitudes from diffimg
- Bluer bands: fading below detection limit more quickly
- Redder bands: slow decline 1.5 d+shoulder at 4d+decline
- Properties of KN emission depend strongly on on the ejecta composition
- Models with 2 components are a good fit: lanthanide (A>140) poor (blue)+ lanthanide rich (red) ejecta
- Consistent with estimated r-process production from MW abundances: BNS can be a dominant site for r-process enrichment

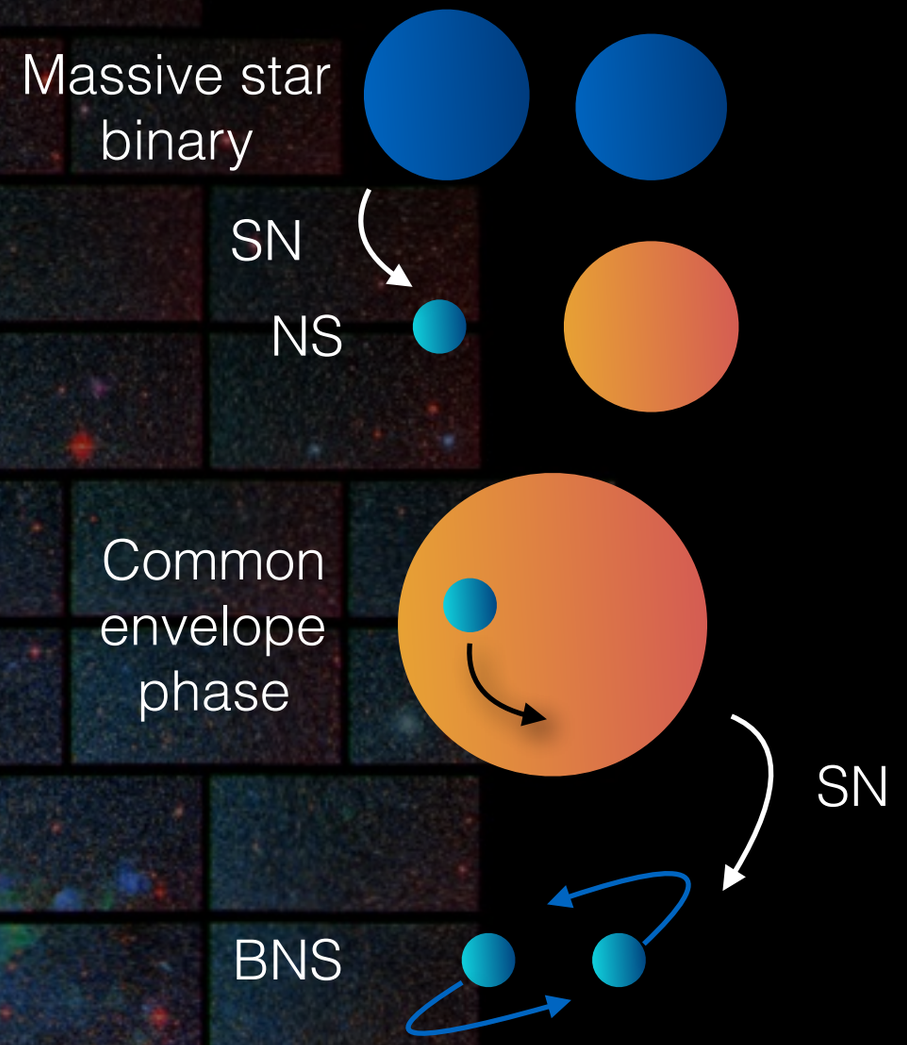


Cowperthwaite et al.2017

Binary Neutron star formation

BNS formation scenarios completely different:

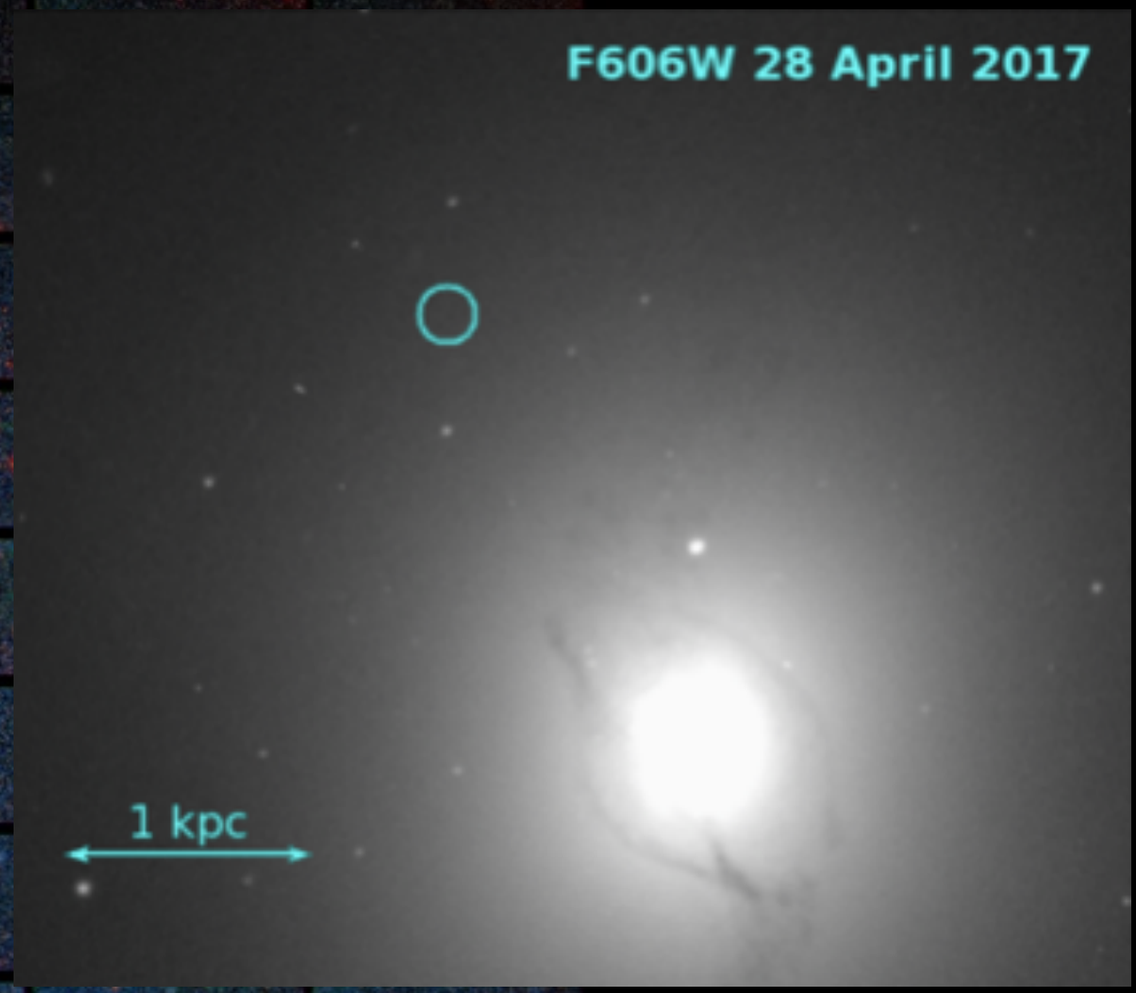
- **Pure star formation** - components were originally in binaries before becoming NS
- **Dynamical interactions** - through close interaction of compact objects most likely in dense stellar environments



Palmese et al. 2017, ApJL, 849, L34
https://arxiv.org/abs/1710.06748

No evidence of progenitor

- No evidence of a progenitor to GW170817 at absolute magnitude M=-7 or brighter
- No supergiant present, half globular cluster population would be brighter than this limit



Blanchard et al. 2017

Host galaxy NGC 4993: a normal elliptical

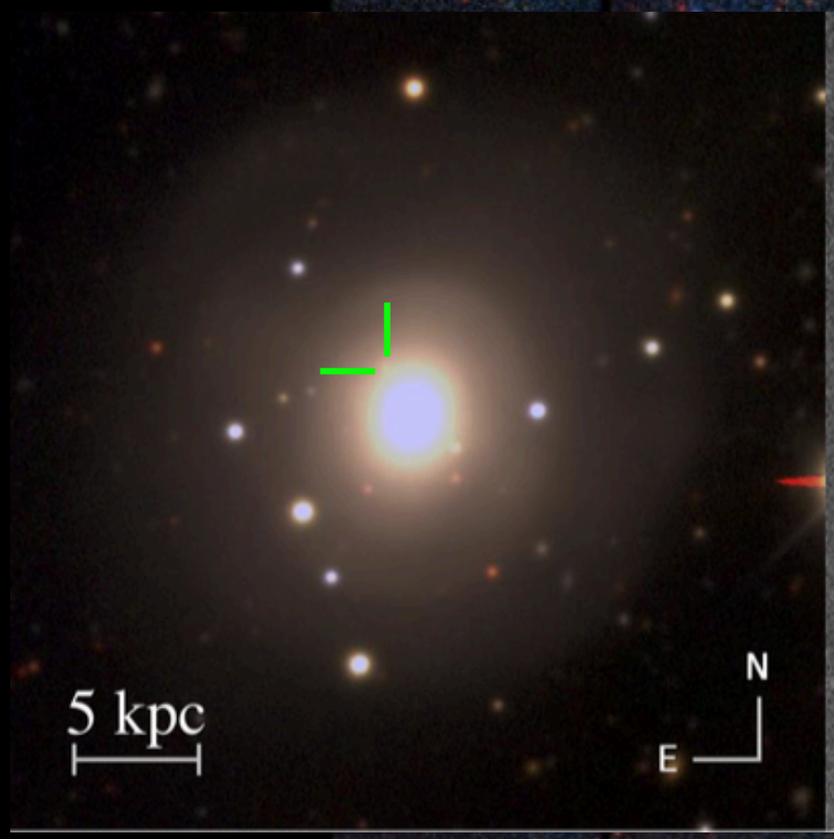
Credit: W. Hartley

- Data: DECam *ugrizY* + HST F606W + VHS + WISE (imaging) 6dF + AAT (spectra)
- Extensive morphology study: early type galaxy with some asymmetry
- Galfit runs: Rotation in position angle ⟶ a disturbed galaxy

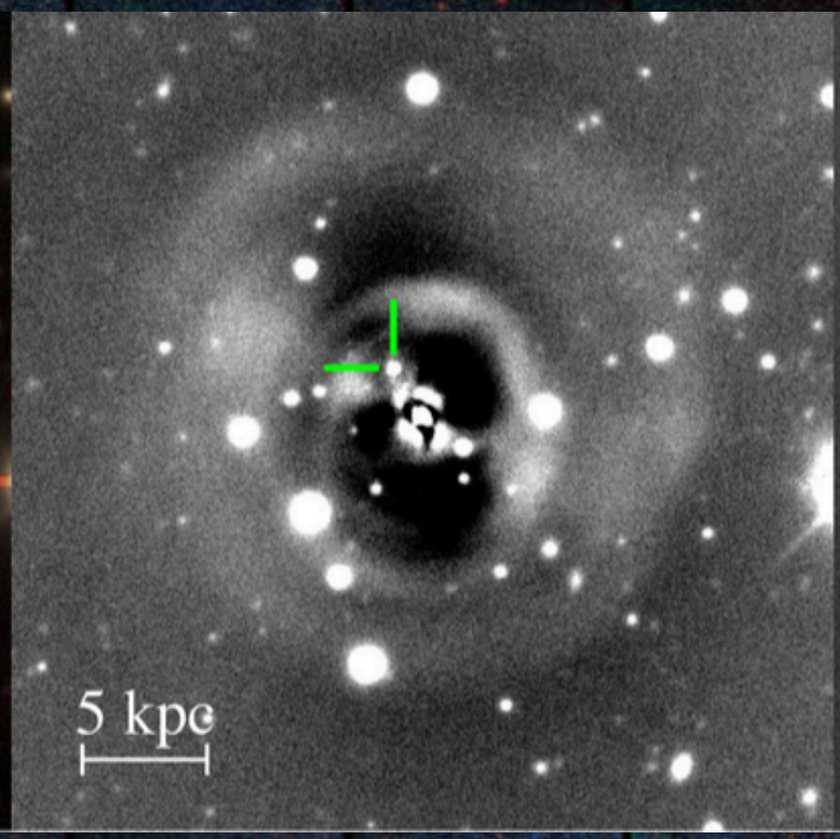
Filter	MAG_AUTO	Mag	r_e	n	ϵ	θ
u	14.24	14.15	61.8	3.2	0.15	-13.9
g	12.95	12.80	62.5	3.4	0.15	-12.8
r	12.08	11.90	63.5	3.7	0.16	-11.2
i	11.65	11.45	64.4	4.0	0.16	-9.9
z	11.34	11.13	65.3	4.3	0.16	-8.4
Y	11.13	10.96	65.7	4.4	0.16	-7.7
$Y_{\rm VHS}$	11.27	11.00	65.9	4.5	0.16	-7.5
J	11.00	10.77	67.3	5.0	0.17	-5.2
K_s	11.08	10.68	72.9	6.7	0.19	+3.5
		$\pm 5 \times 10^{-4}$	± 0.07	$\pm 3 \times 10^{-3}$	$\pm 4 \times 10^{-5}$	$\pm 5 \times 10^{-3}$

Host galaxy NGC 4993: a shell galaxy

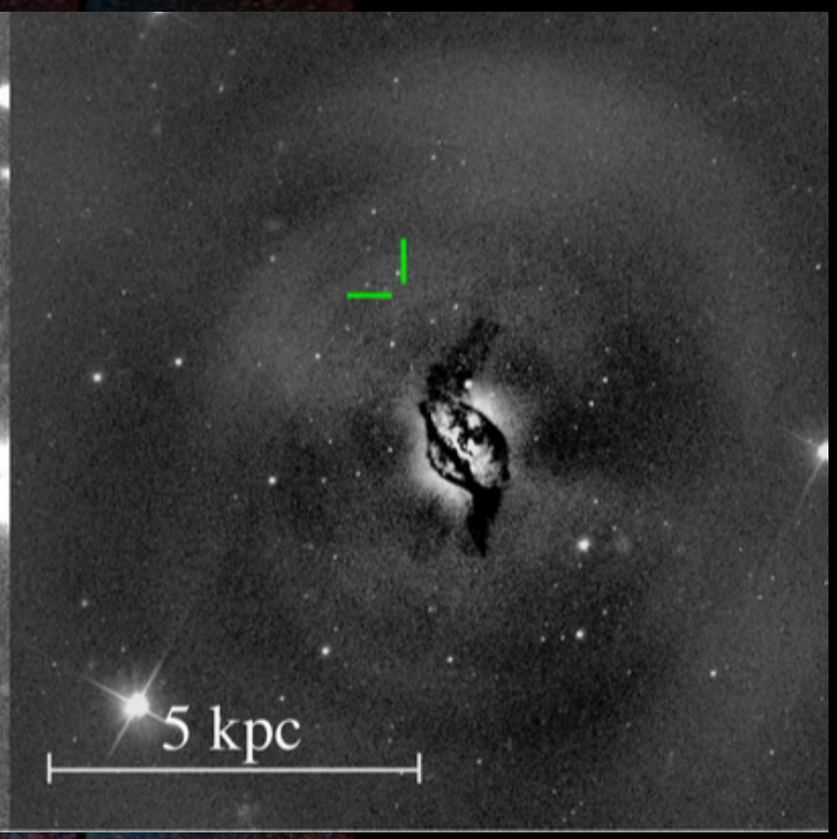
DECam



DECam



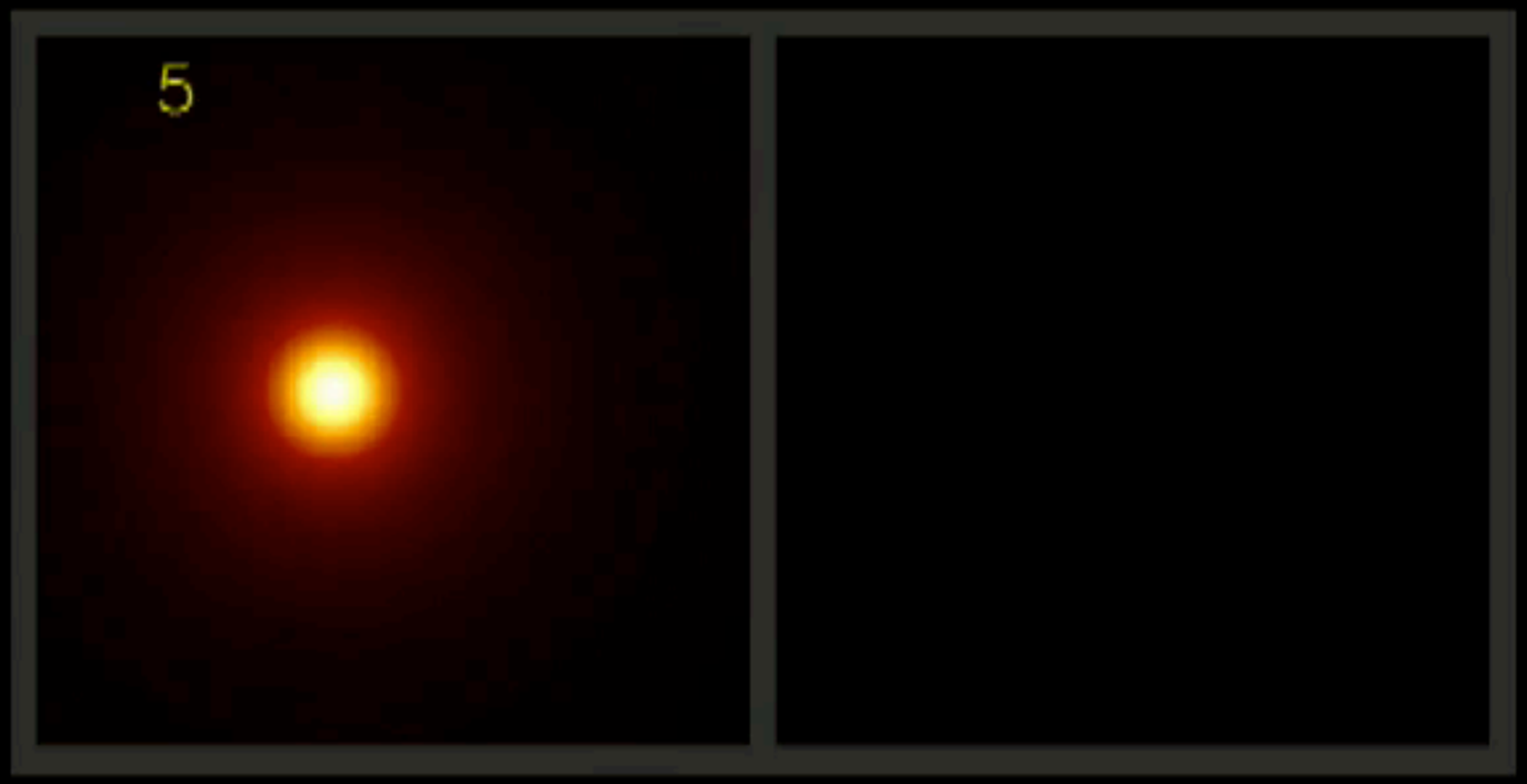
HST



- Residual images from DECam and HST
- At least 4 shell structures
- HST: a possible inner shell on which the transient seem to lie and dust lanes

Host galaxy NGC 4993: a recent galaxy merger

http://hubblesite.org/video/558/news/4-galaxies

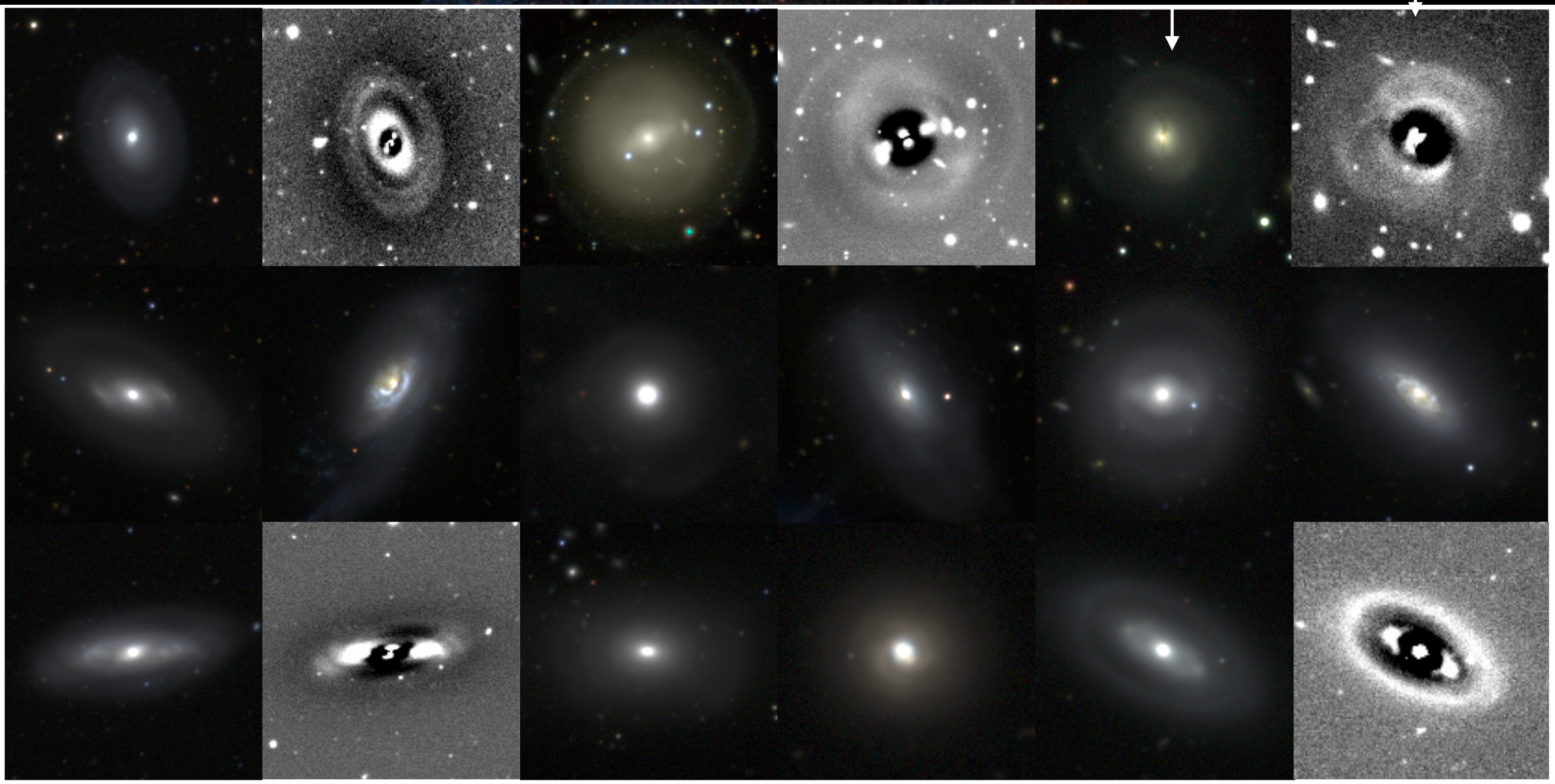


Shells are arcs of enhanced surface brightness corresponding to higher stellar densities, relics of a galaxy merger

Shell galaxies in DES Y1

Original image

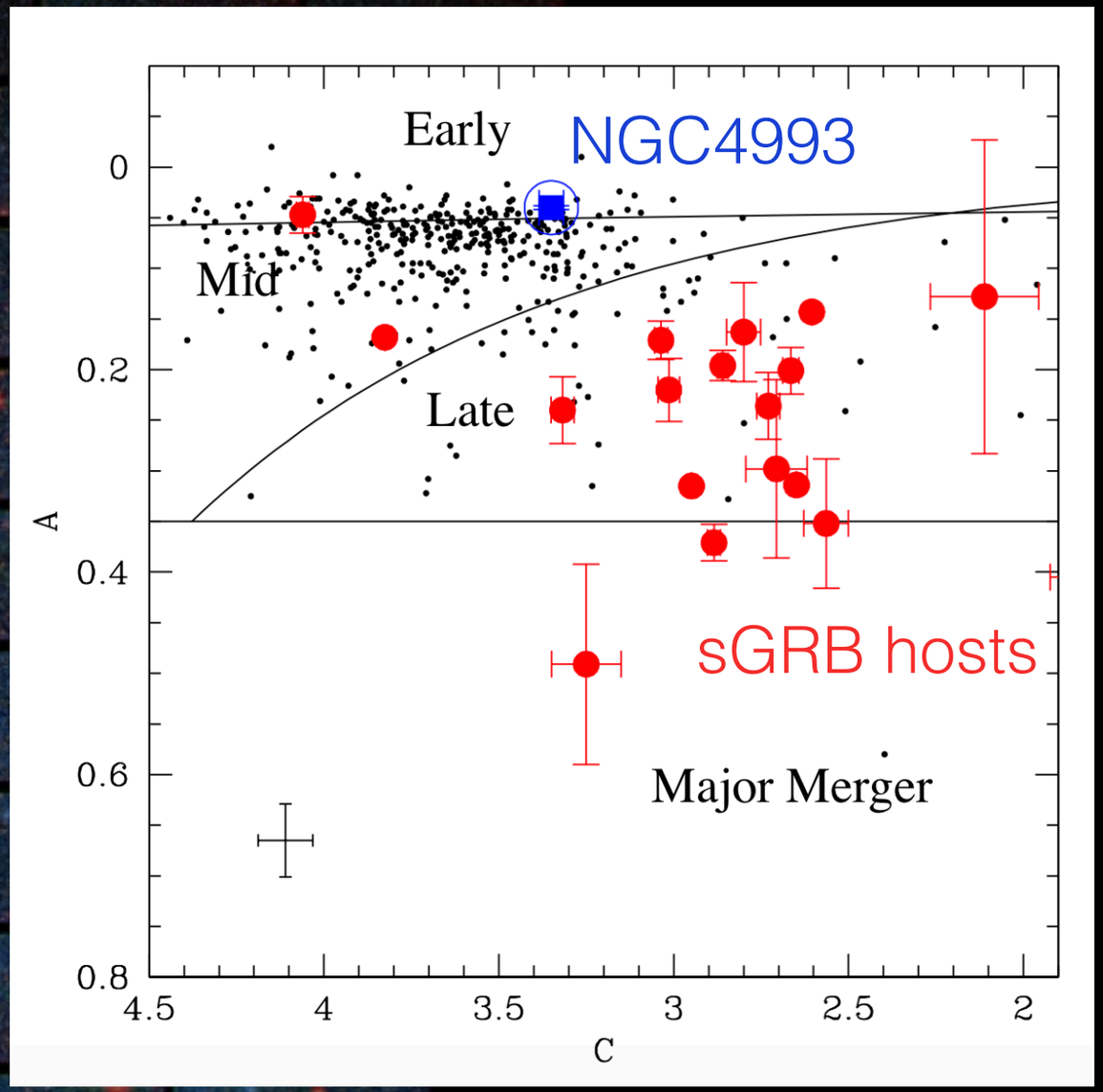
Residual



~15% of selected early-type galaxies present shells

Host galaxy - Comparison to sGRB hosts

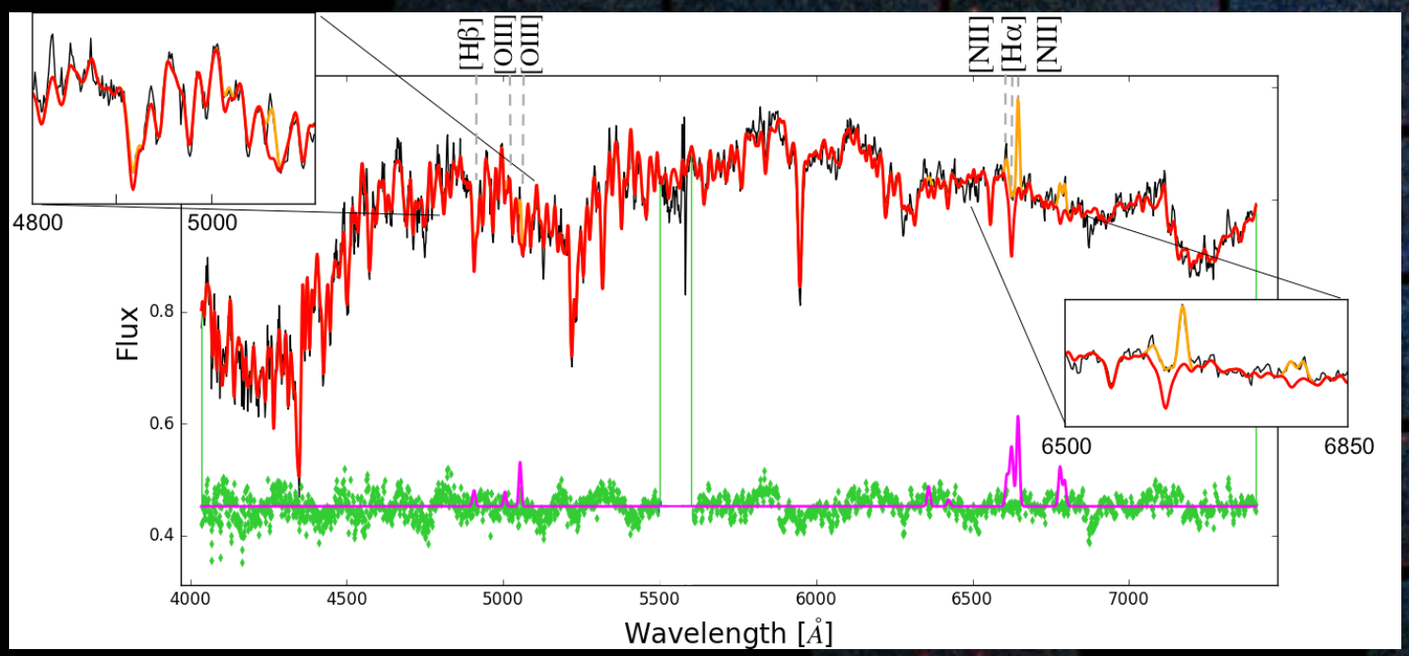
- Asymmetry and concentration consistent with early-type galaxies but unusual for sGRB hosts
- Clear major galaxy mergers are unusual amongst sGRB hosts
- Other sGRBs are at cosmological distances and thus are mostly undergoing extensive galaxy formation through star formation or merging
- Common feature: merging activity
- Minor merger such that the bulk morphology is still elliptical



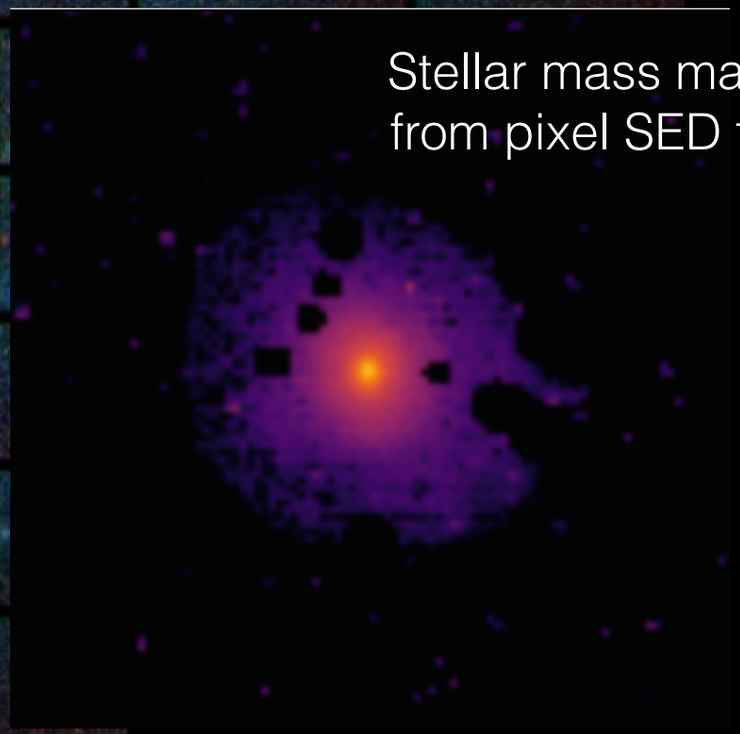
→ Is the BNS formation or evolution related to a recent galaxy merger history?

Host galaxy - SED analysis

- Spectral (6dF) and photometric (DECam+VHS) SED fit
- $M^*=(3.8 \pm 0.20)\times10^{10}\ M_\odot$, Age~11 Gyr
- Stellar model fit reveals weak ionized gas emission lines
- AGN region of the BPT diagram suggests they are produced by a harder ionizing source than star-formation
- Pixel SED fit, also allowing late SF bursts
- Younger ages (by 2 Gyr) in the stellar halo: superimposed stellar populations
- No evidence for recent (last few Gyr) star formation
- When did the binary form if it was through pure SF?

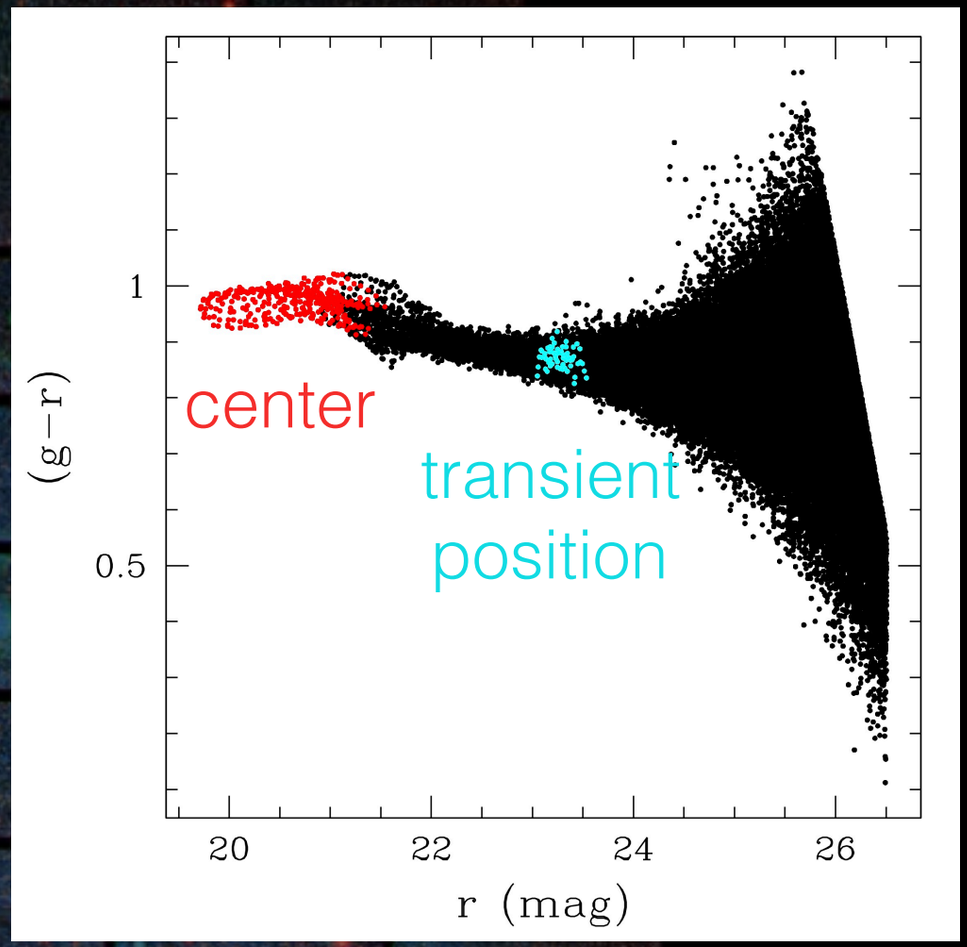


Stellar mass map from pixel SED fit



Host galaxy - pCMD

- Well represented by a pixel “main sequence” that is bluer at fainter levels, typical of early–type galaxy color gradients
- Supports scenario in which BNS is not related to local SF events



Evidence for a recent dry minor galaxy merger (no SF)

Galaxy merger and environment

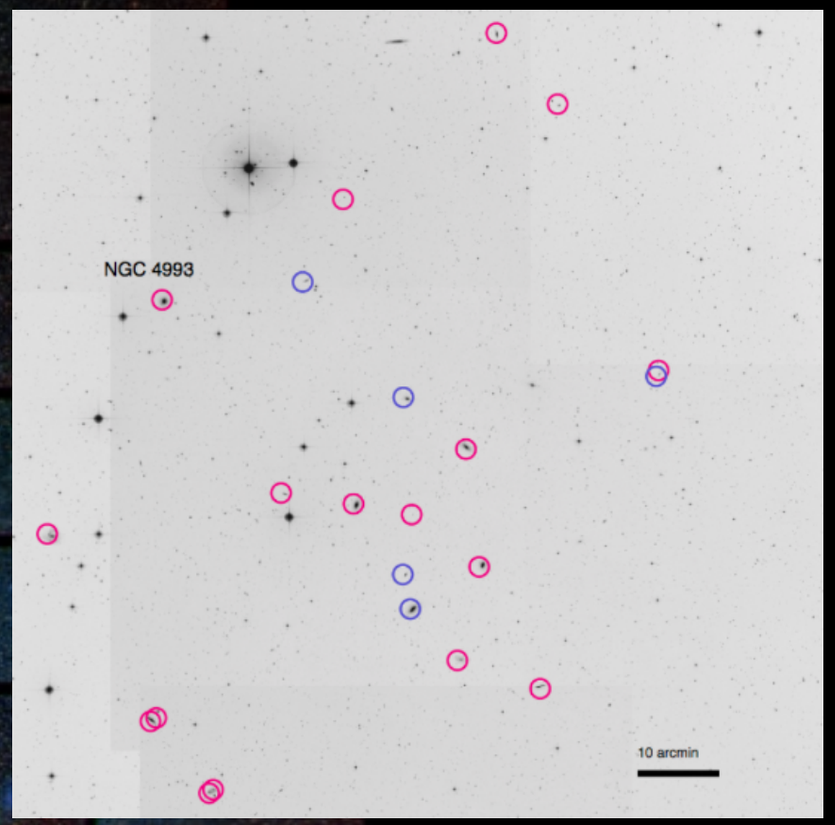
- If galaxy mergers can boost the BNS formation, then these are more likely to be observed in galaxy groups
- For this group:

$$t_{\rm cr} \sim R_v/(\sqrt{2.5}\sigma_v) \sim 1.6\ {\rm Gyr}$$

- Survival time of the innermost shell from DECam data

$$t_{\rm dyn} \equiv R/\sigma_v$$

- $t_{mer} < t_{dyn} < 200$ Myr



Hjorth et al.2017

SFH

~11 Gyr ago ~13.5 Gyr ago

Most stars are formed in NGC 4993

Age of the Universe

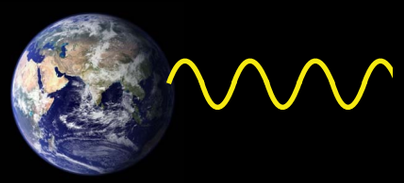
~130 Myr ago ~330 Myr ago

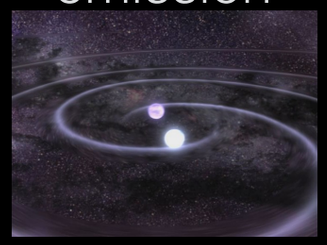
Shell survival time

Today

BNS coalescence+GW emission

Galaxy merger





If the BNS formation was triggered by the galaxy merger, then delay time=$t_{formation}$ - $t_{coalescence}$<200 Myr

BNS coalescence rates from SF

- Expected rates from current BNS formation models and observed SFH **assuming the BNSs are formed though pure SF**

$$R_{NS\,M}(t) = \alpha R_{NS}(t')$$

Fraction of NS in BNS

$$t' = t - \Delta t_{NS\,M}$$

Delay time

$$R_{NS}(t') = \int dM_\star \Phi(M_\star)\Psi(t_\star)\Theta_{NS}(M_\star)$$

- Scale the per-solar-mass rate with the stellar mass in early and late type galaxies
- Assume SMF + cosmic SFR density:

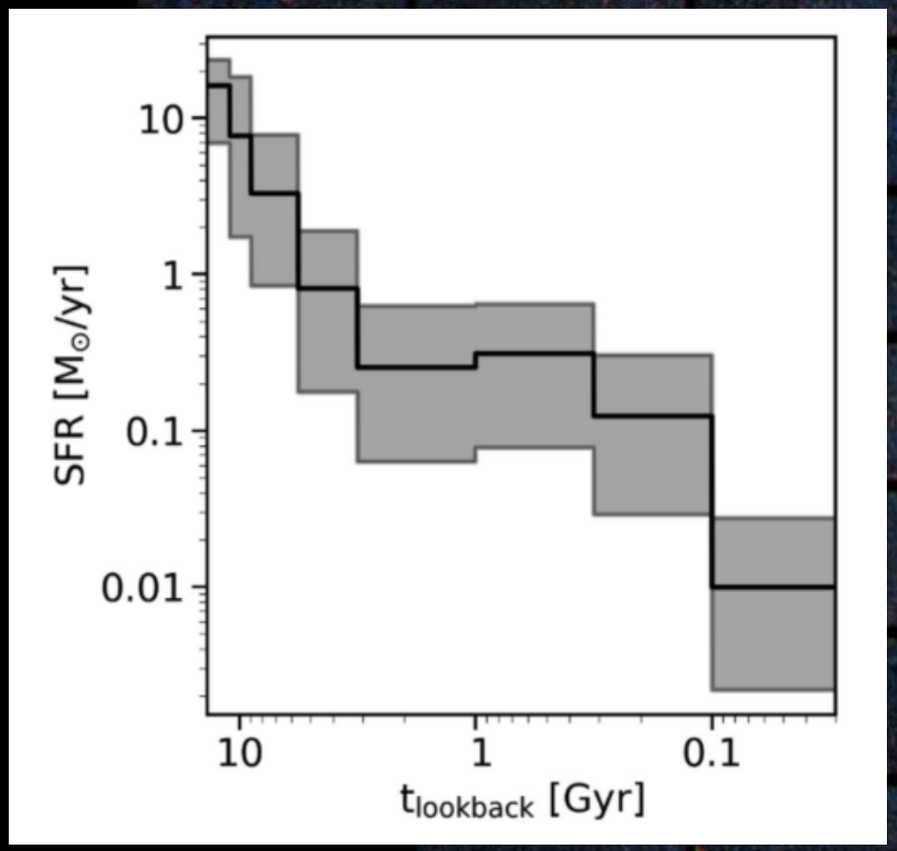
$$R^{\rm early}_{NS\,M} = 23^{+2}_{-14}\ {\rm yr}^{-1}{\rm Gpc}^{-3}; \quad {\rm R}^{\rm all}_{NS\,M} \approx 270\ {\rm yr}^{-1}{\rm Gpc}^{-3}$$

Expected observable events for BNS in LIGO O1+O2
Early type galaxies: 0.04
All galaxies: ~0.5

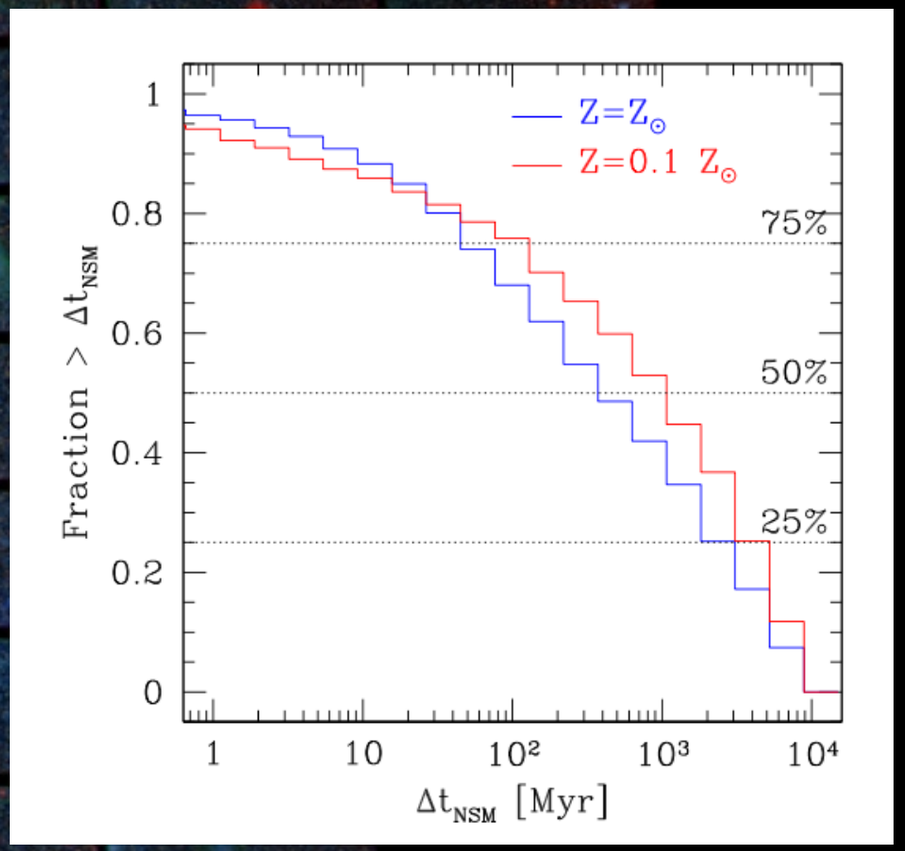
→ Pure SF may not be the only cause of BNS formation

Alternative interpretation

- No prior knowledge on the delay time assumed
- Exponentially declining SFH, low SFR observed
- 50% of mass formed by ~11 Gyr ago, 90% by ~7 Gyr
- 11 Gyr is the median delay timescale inferred



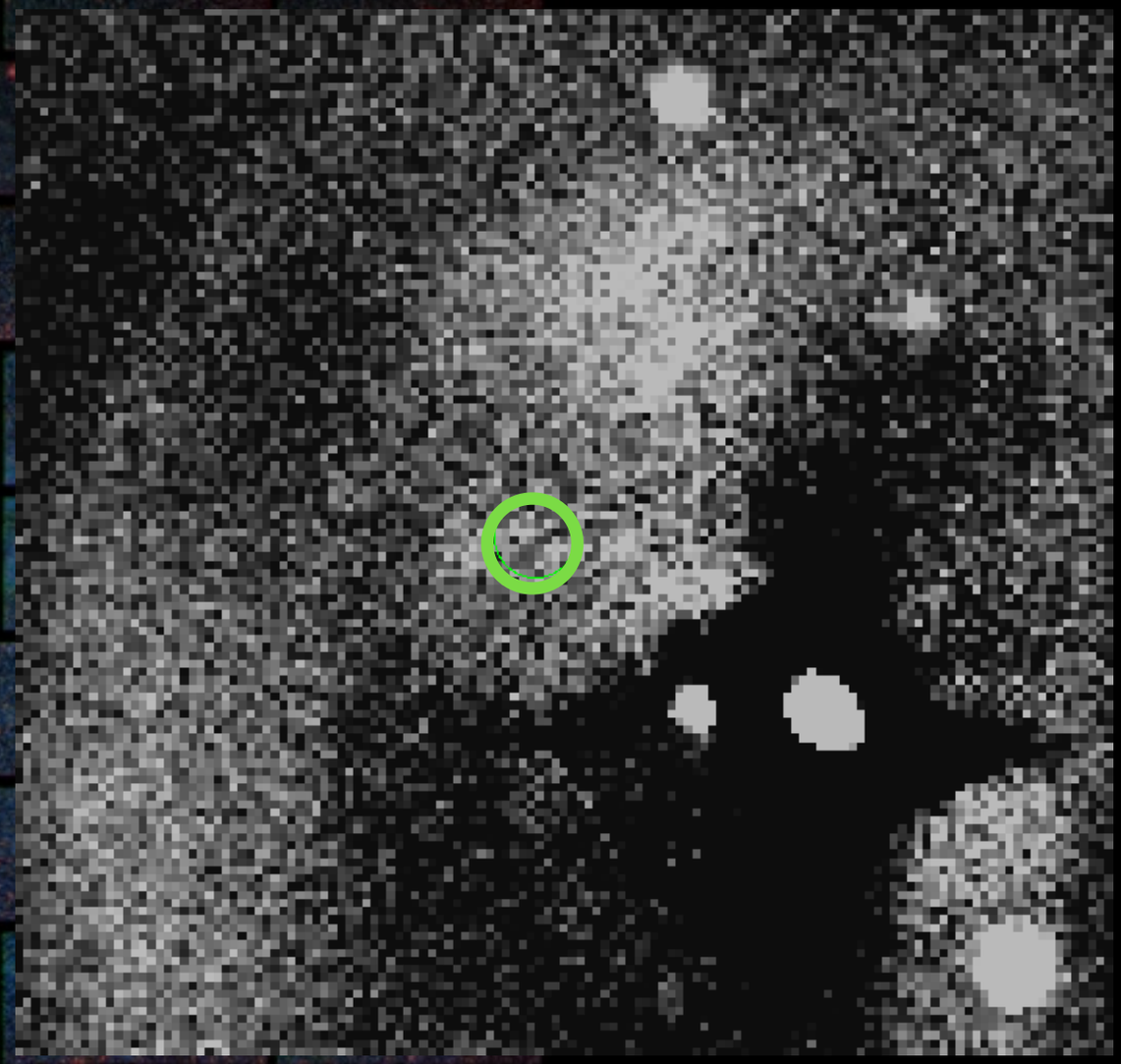
Blanchard et al. 2017



Vangioni et al. 2017

A star cluster?

- *r*-band absolute magnitude from a 4 sq.arcsec region around the transient location in the galaxy-subtracted image is –10.65
- Dynamical interactions are more likely within star clusters and in galaxy nucleus (higher stellar density in ellipticals), where infalling stars may have passed
- Cannot exclude kicks



How many kilonovae?

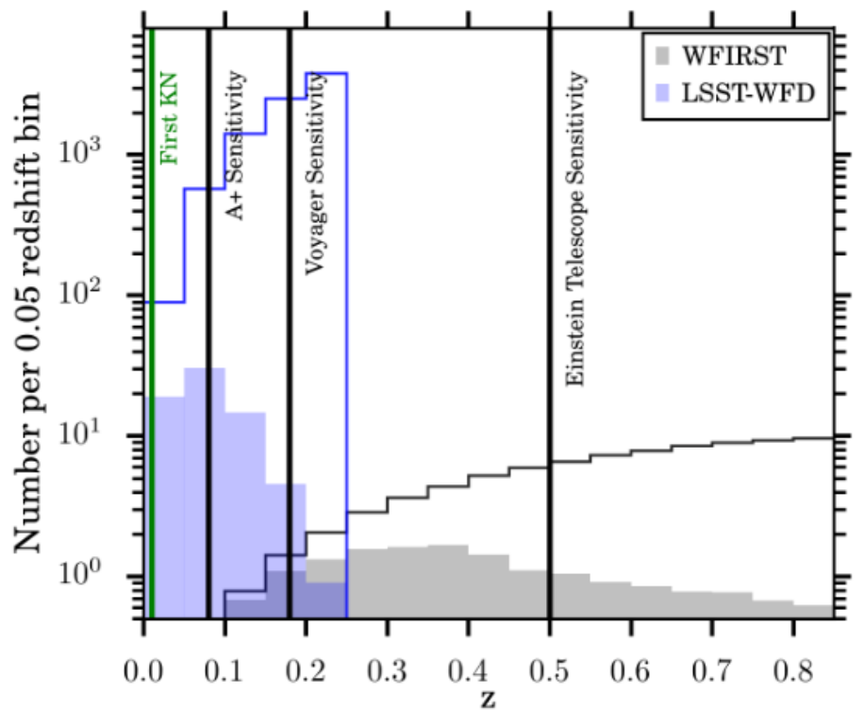
- Studies of host galaxies and environments can help optimize KN search without a GW trigger
- Simulation of light curve using DECam data
- Assumptions:
  - Rate 10^3 Gpc^{-3}/yr
  - all KN are the same and constant in volume
- Ability to explore the cosmic history of KN
- Caveats include: SN background (~3%), host galaxy image subtraction artifacts

Scolnic et al. 2017

TABLE 2
EXPECTED NUMBER OF KNE FOUND IN EACH SAMPLE.

Survey	# KNe[a]	Survey Years	KN Redshift Range
SDSS	0.13	2	0.02 – 0.05
SNLS	0.11	4	0.05 – 0.20
PS1	0.22	4	0.03 – 0.11
DES	0.26	5	0.05 – 0.20
ASAS-SN	< 0.001	3	—
SMT	0.001	5	0.01 – 0.01
ATLAS	8.3	5	0.01 – 0.03
ZTF	10.6	5	0.01 – 0.04
LSST WFD	69	10	0.02 – 0.25
LSST DDF	5.5	10	0.05 – 0.25
WFIRST	16.0	2	0.1 – 0.8

[a]Total for entire duration of survey.



Conclusions

- Indication for a BNS formation different from usual scenario
- Galaxy merger could have triggered dynamical interactions
- No strong conclusions about BNS formation from one event, but the coincidence of evidence for a recent merger in a galaxy for which a BNS event was otherwise improbable is compelling
- Future work:
  - ★ MUSE proposal - SF from spectral data across the galaxy + shell velocity dispersion
  - ★ Extend to future BNS events
  - ★ Cross-correlate galaxy catalogs with BBH events to understand BBH formation
  - ★ Use DES for galaxies/clusters-sGRB cross correlations

Thank you!