Gravitational wave astrophysics and cosmology with (DES)* galaxies

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Midwest workshop on SN and transients @ KICP

25 February 2019

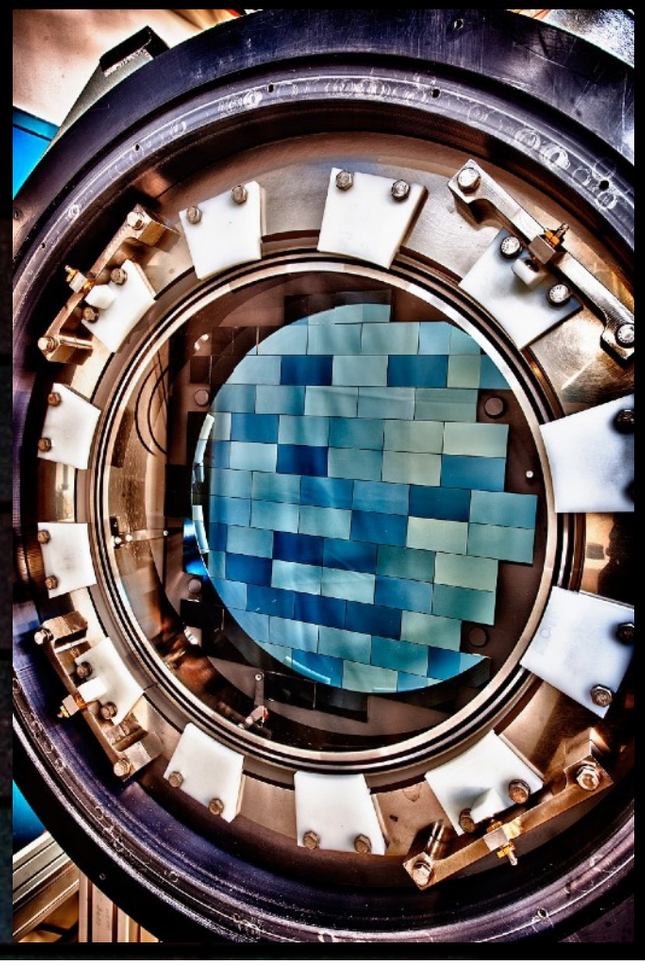
In collaboration with: M. Soares-Santos, J. Annis, C. Conselice, Z. Doctor, W. Farr, M. Fishbach, J. Gair, D. Holz, O. Lahav, H. Lin, W. Hartley, F. Tarsitano, & many more (DES & LVC)

*DECam+other surveys

Introduction

- DECam currently **one of the best instrument** for GW optical follow up in the Southern hemisphere
- **4 DES studies** on **GW170817** → DECam analysis of host galaxy
- By studying the **host galaxy** → binary formation
- Synergy between GW experiments and galaxy surveys also allows **cosmology**
- First measurement of H_0 from a dark siren using GW170814 (DES+LVC)
- **Outline**:
  - ★ What we learned from DES/DECam galaxies
  - ★ Science with future surveys (DELVE, DESI, LSST)

Dark Energy Survey (DES)

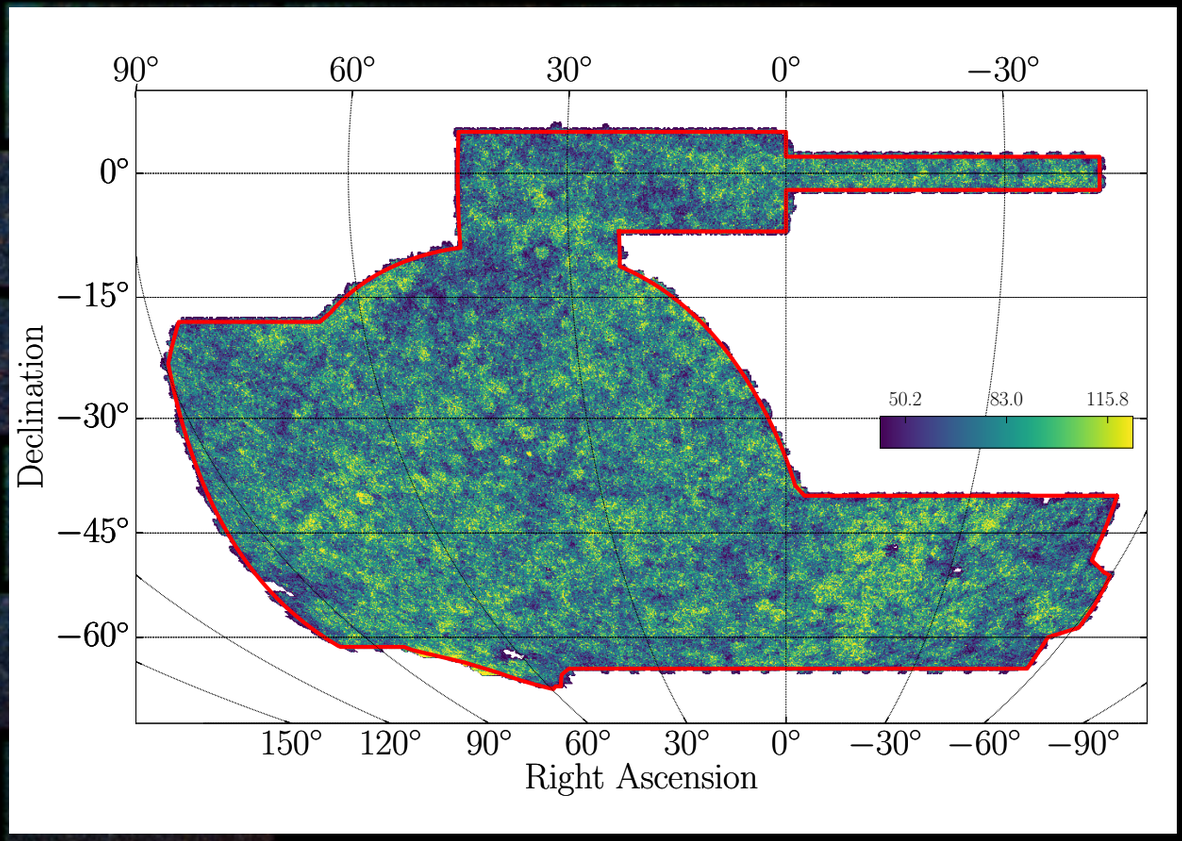


DECam

- 3 sq deg FOV, 570 Mpix optical CCD camera
  CTIO Blanco 4-m telescope (Chile)
- First/last light: 12-12-12 / 01-08-19

DES programs

Wide: 5000 sq deg grizY
SNe: 30 sq deg SNe survey
Neutrinos: followup of Icecube events
GW: followup of LIGO/Virgo events



Public data

https://des.ncsa.illinois.edu/home

- ★ DR1 (Y3) - 400M objects (*r*~24)
- ★ Value added Y1 catalogs
- ★ Y3 Supernovae

The Dark Energy Survey

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DECam follow-up continues

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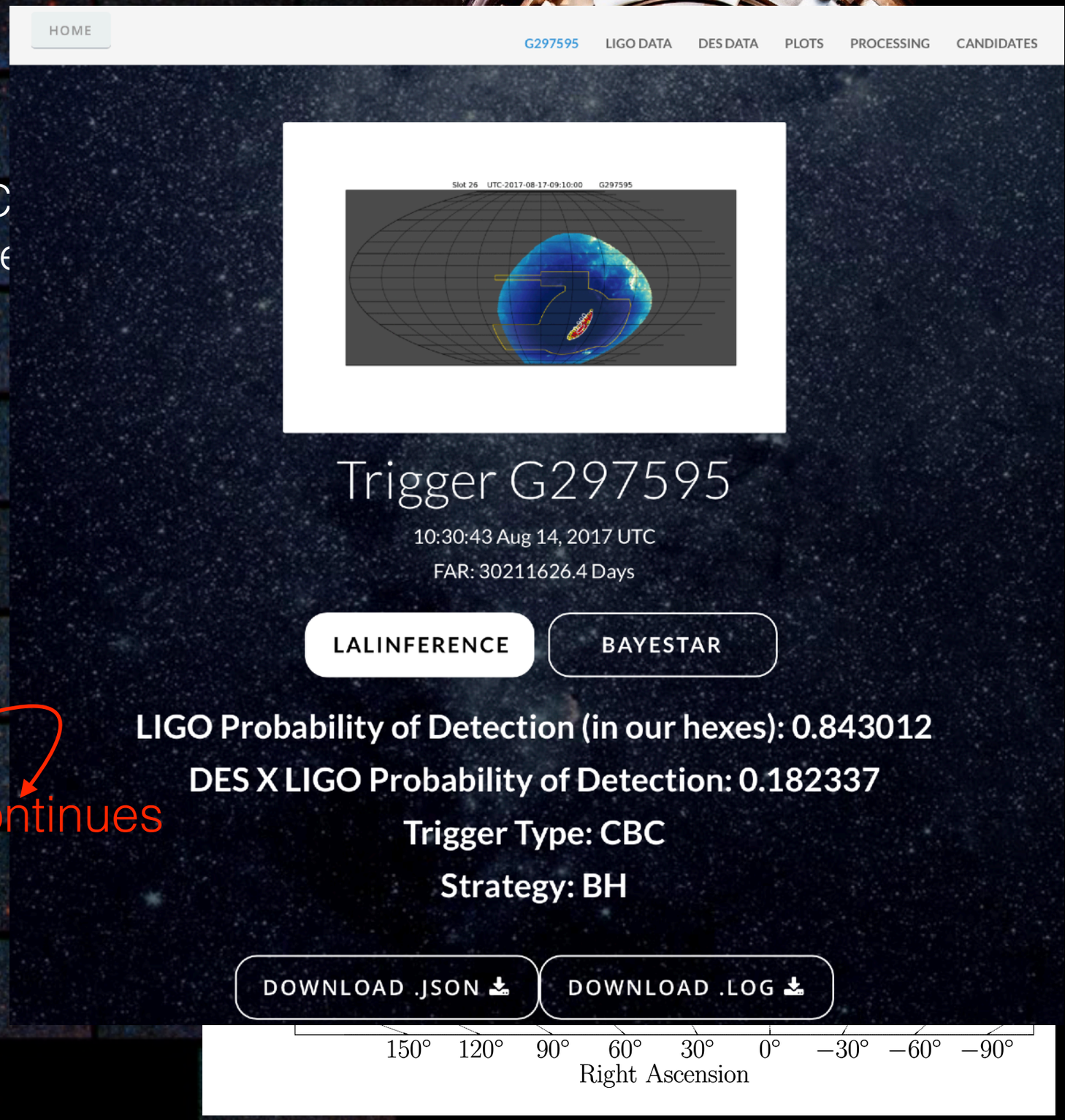


Part I

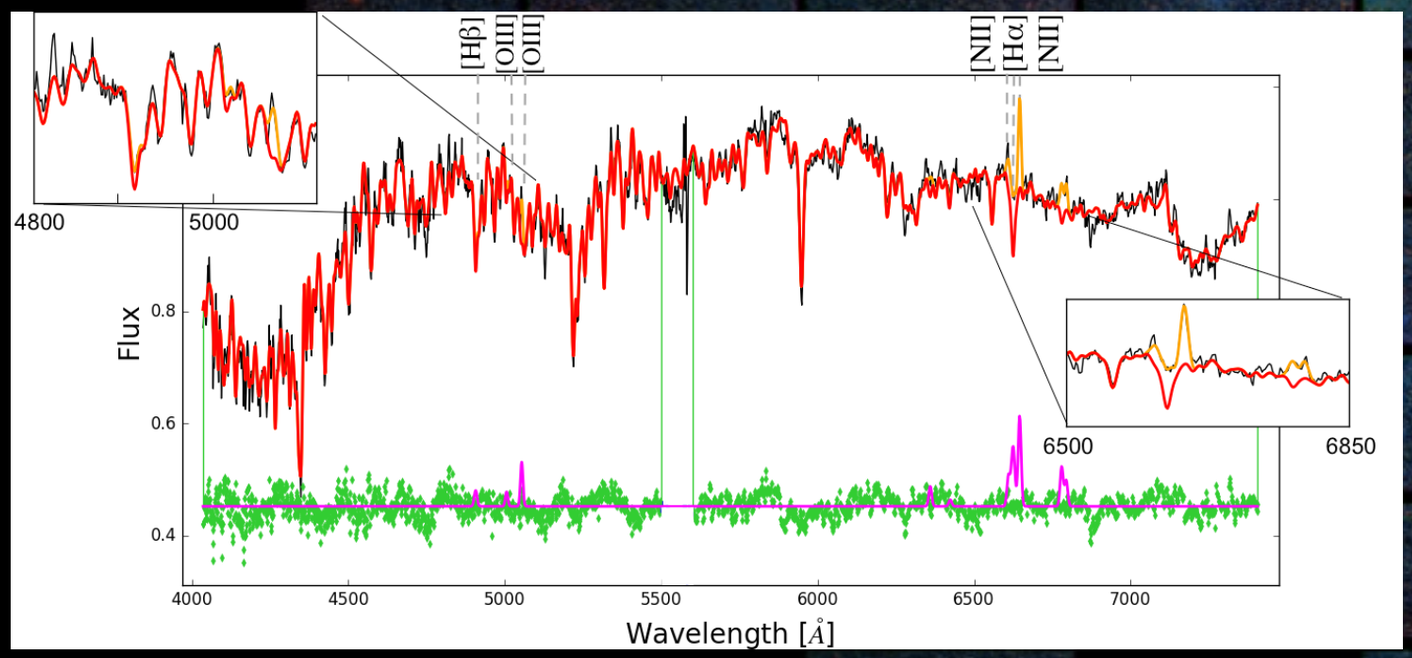
Bright events

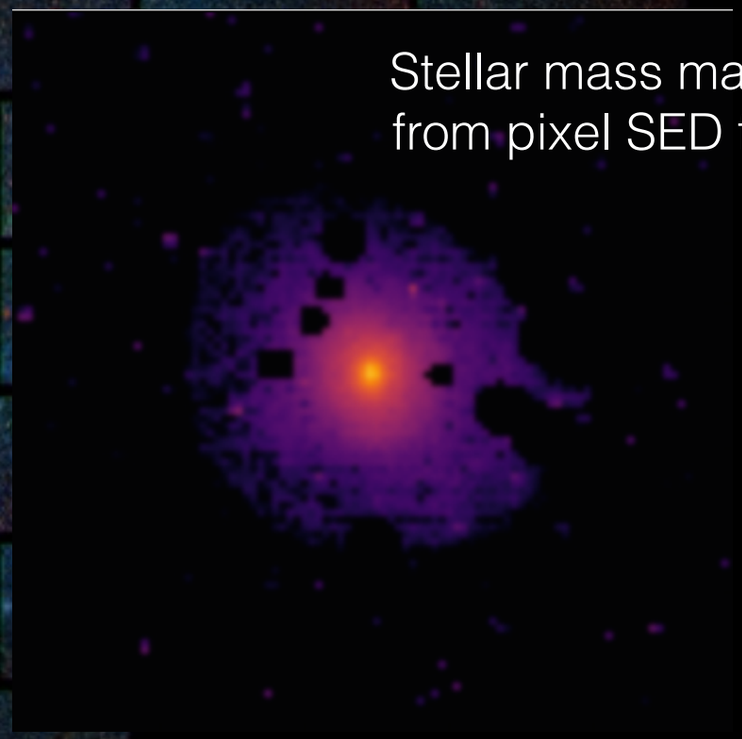
Astrophysics

Cosmology

GW170817 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
- Weak **ionized gas emission lines by AGN**
- **Pixel SED fit**, also allowing late SF bursts
- No evidence for recent star formation
- Surprising for isolated binary scenario





Palmese et al. (2017) arxiv:1710.06748

Expected rate in early type galaxies

- Assuming BNSs are formed as isolated binaries

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

Fraction of NS in BNS

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

Delay time

Vangioni et al. 2016

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

- 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

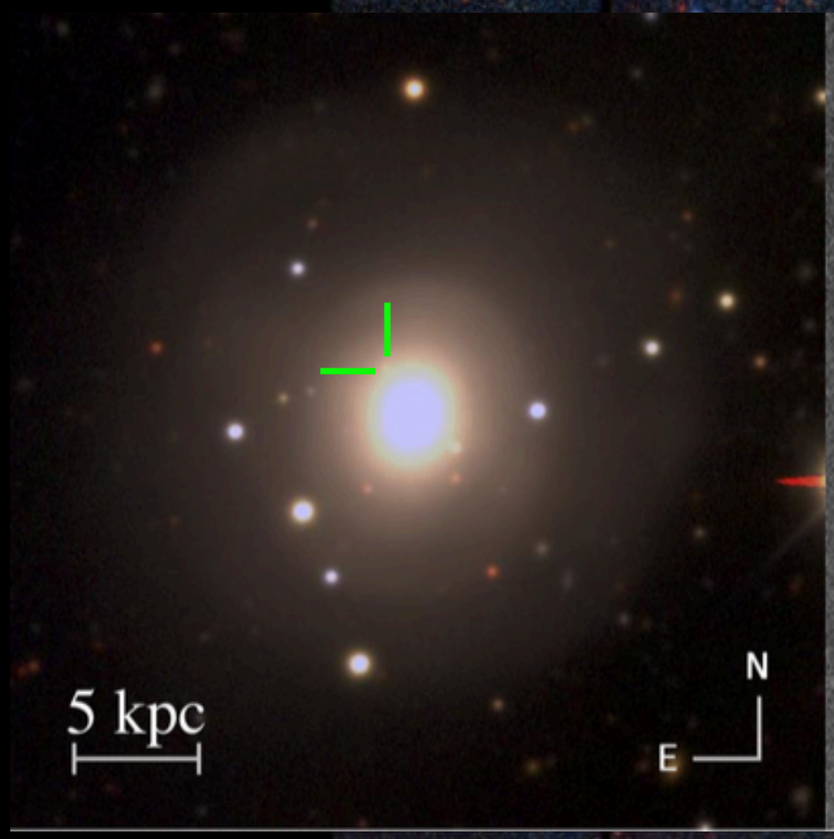
→ Observing a merger of isolated binary in this type of galaxy unlikely

NGC 4993: a normal elliptical?

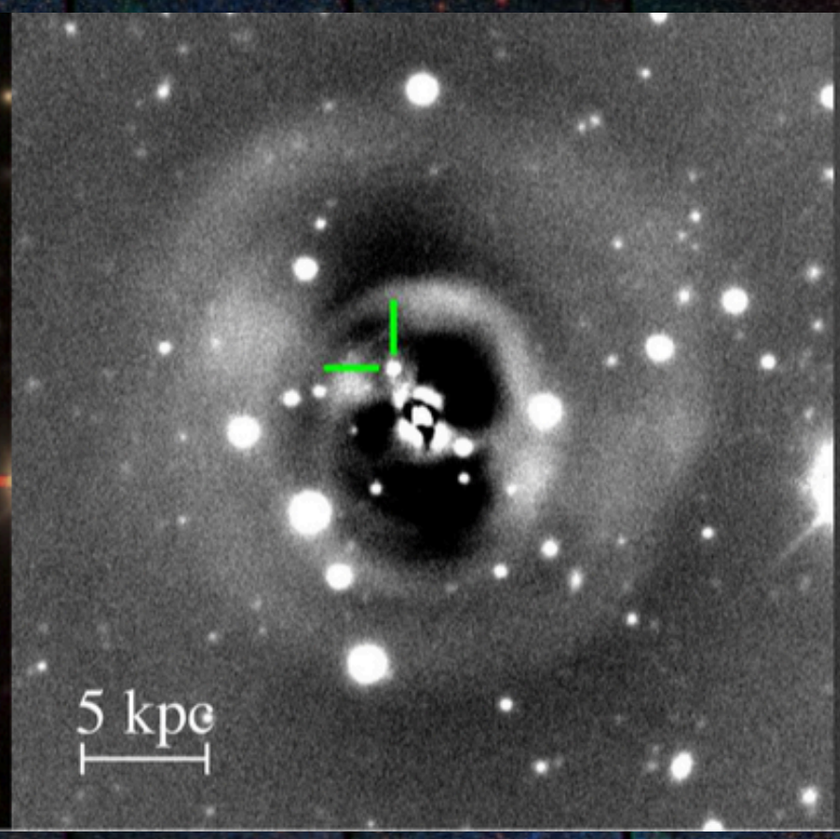
- DECam *ugrizY* + HST F606W + VHS + WISE
- **Extensive morphology study**
- A **disturbed galaxy** (extended stellar halo, some asymmetry, 2 superimposed stellar populations…)

NGC 4993: a shell galaxy

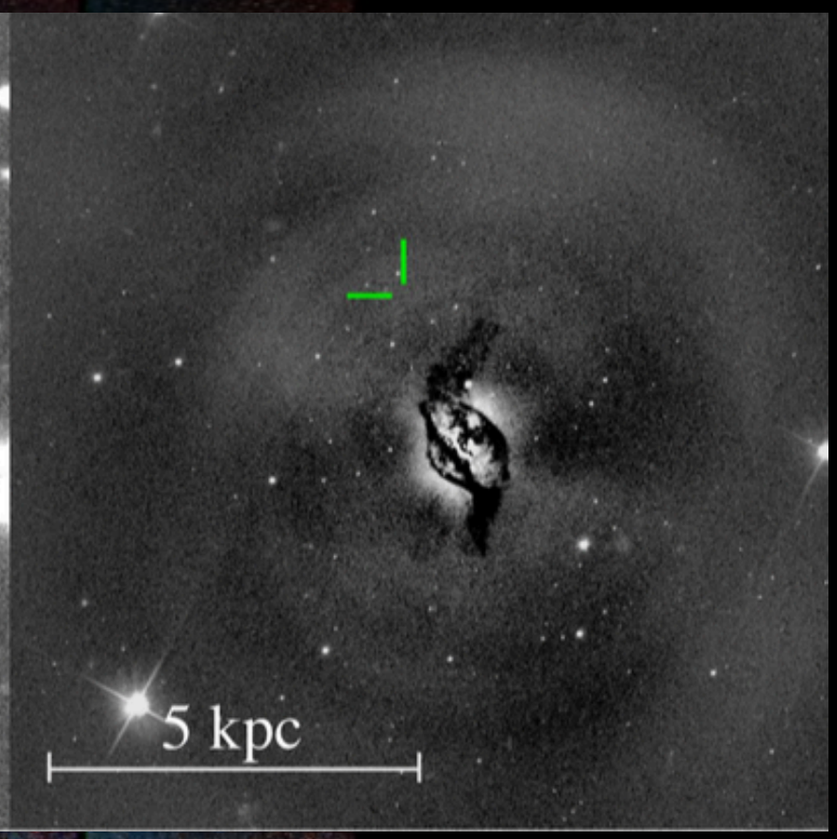
DECam



DECam



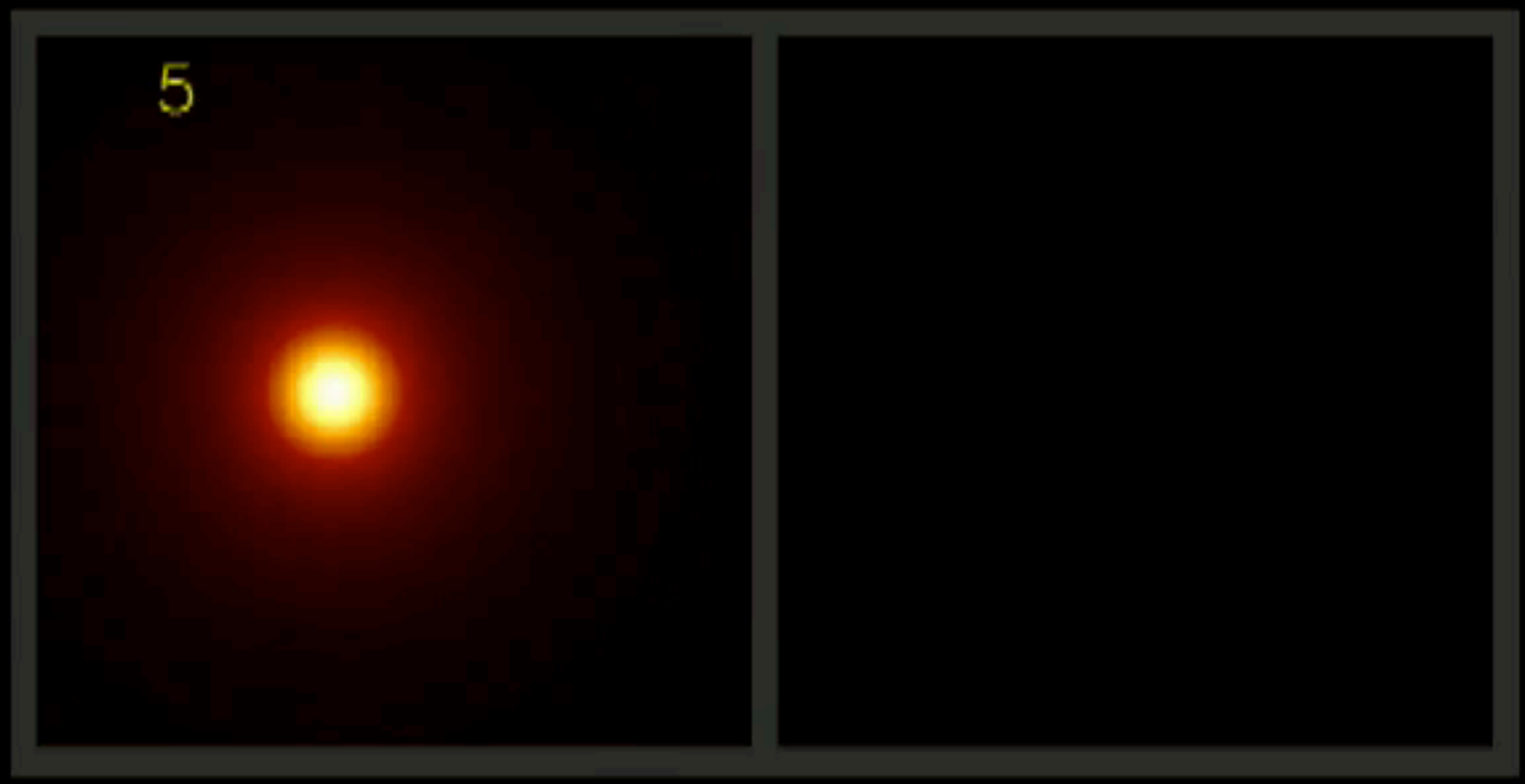
HST



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

NGC 4993: a recent galaxy merger

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



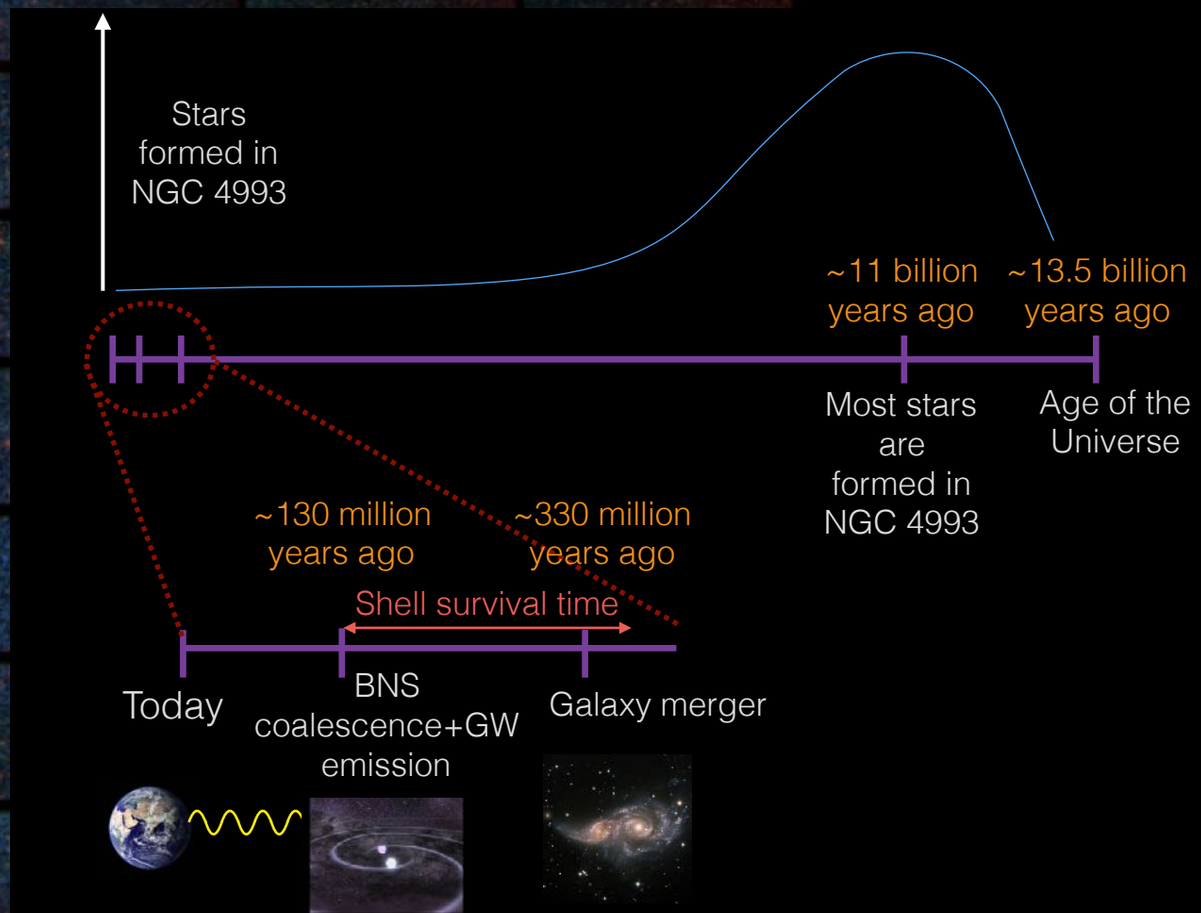
Shells are arcs of enhanced surface brightness corresponding to higher stellar densities, relics of a galaxy merger

Galaxy merger and environment

Distribution of shells can constrain the time of the galaxy merger

Survival time of the innermost shell: $t_{mer} < t_{dyn} <$ 200 Myr

- ★ Unlikely the binary formed as isolated binary
- ★ Position of the transient lies on a shell
- ★ Galaxy merging activity may relate sGRB hosts



- **Suggest that galaxy mergers can boost the BNS formation/merging by boosting dynamical interactions**
- More likely to be observed in galaxy groups
- For this group:

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

Part I

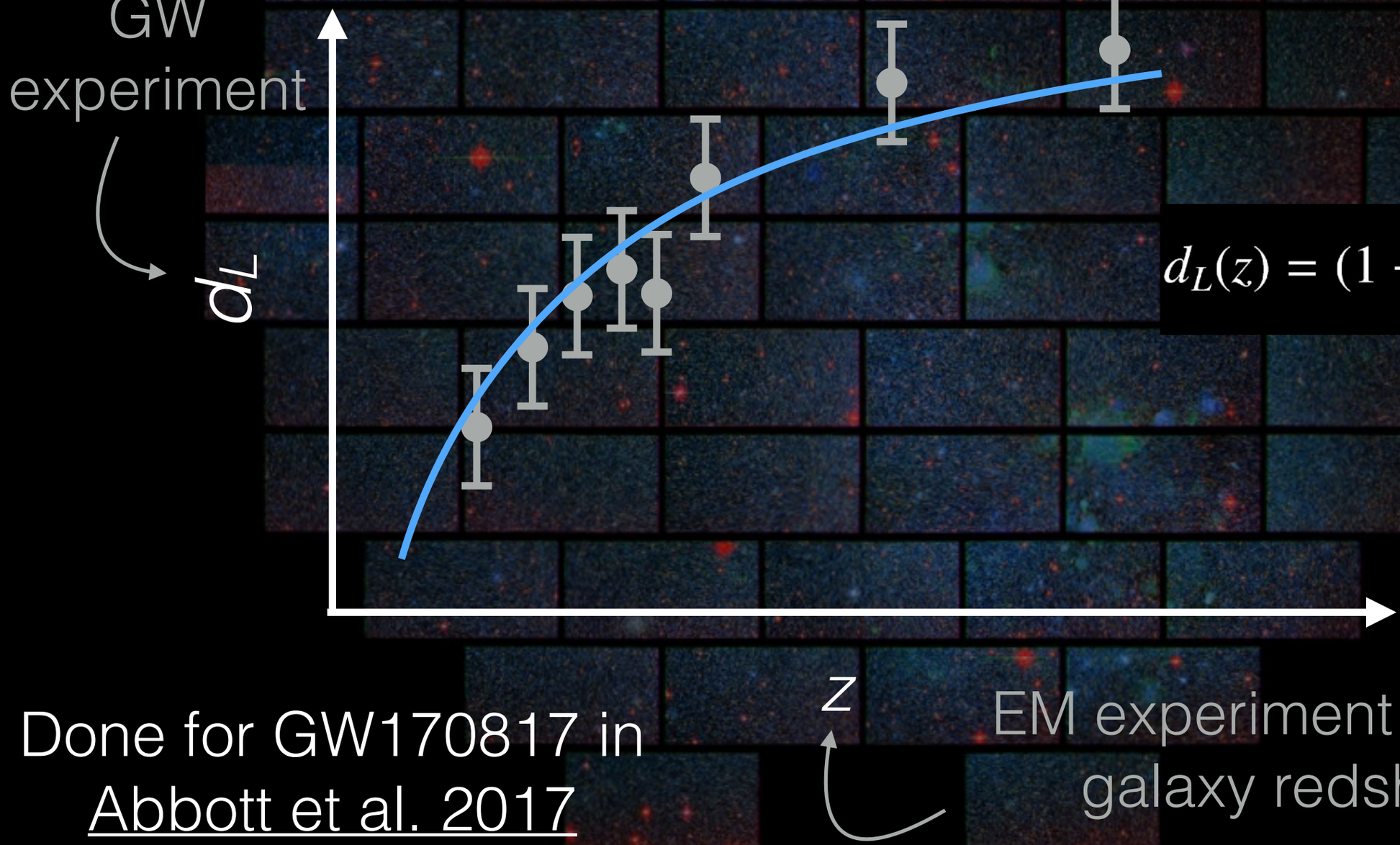
Bright events

Astrophysics

Cosmology

Standard sirens

- Similar to SN cosmology:



$$d_L(z) = (1+z)\int_0^z \frac{dz'}{H_0\,E(z')}$$

Done for GW170817 in Abbott et al. 2017

Part II

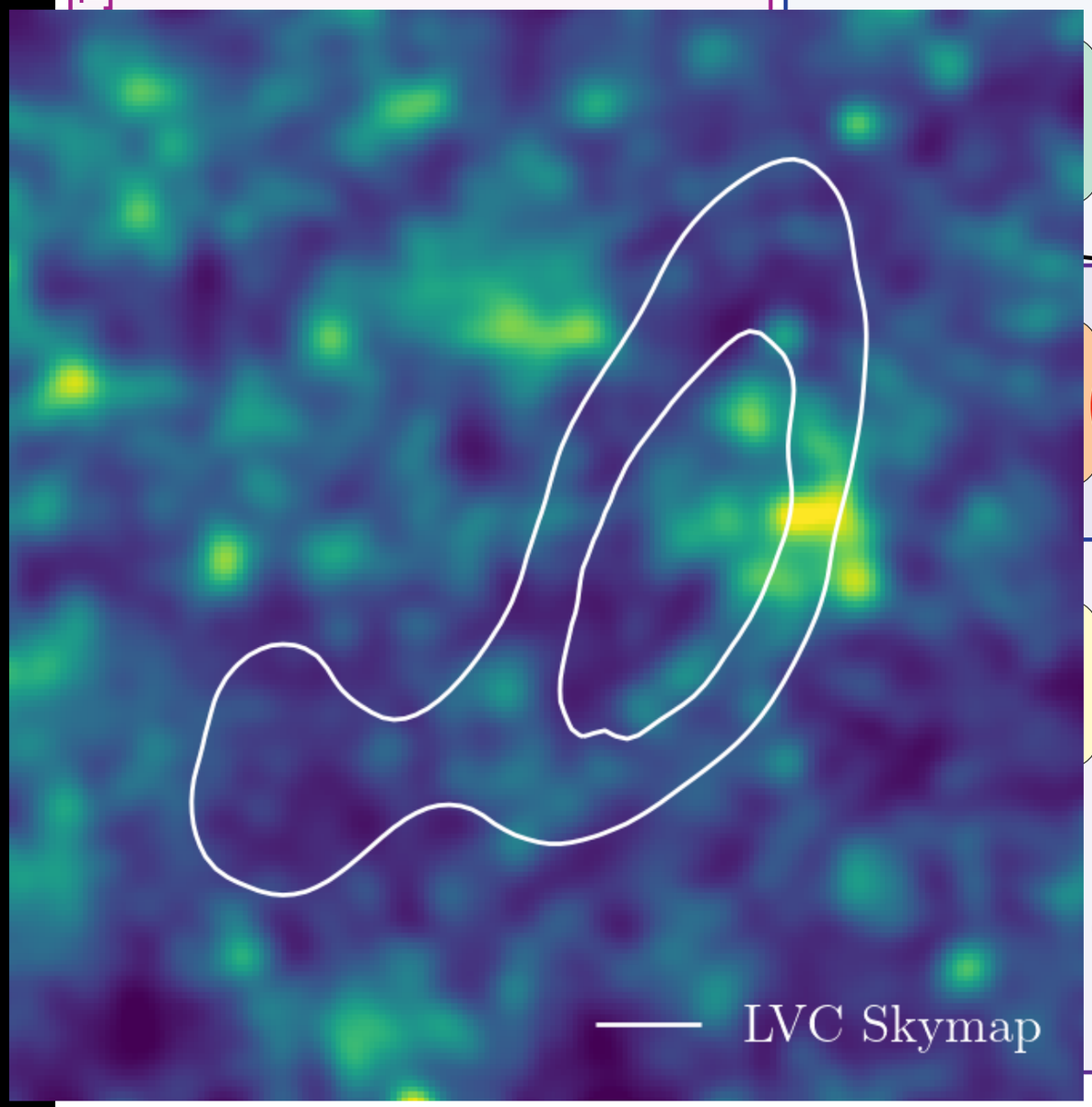
Dark events

Astrophysics

Cosmology

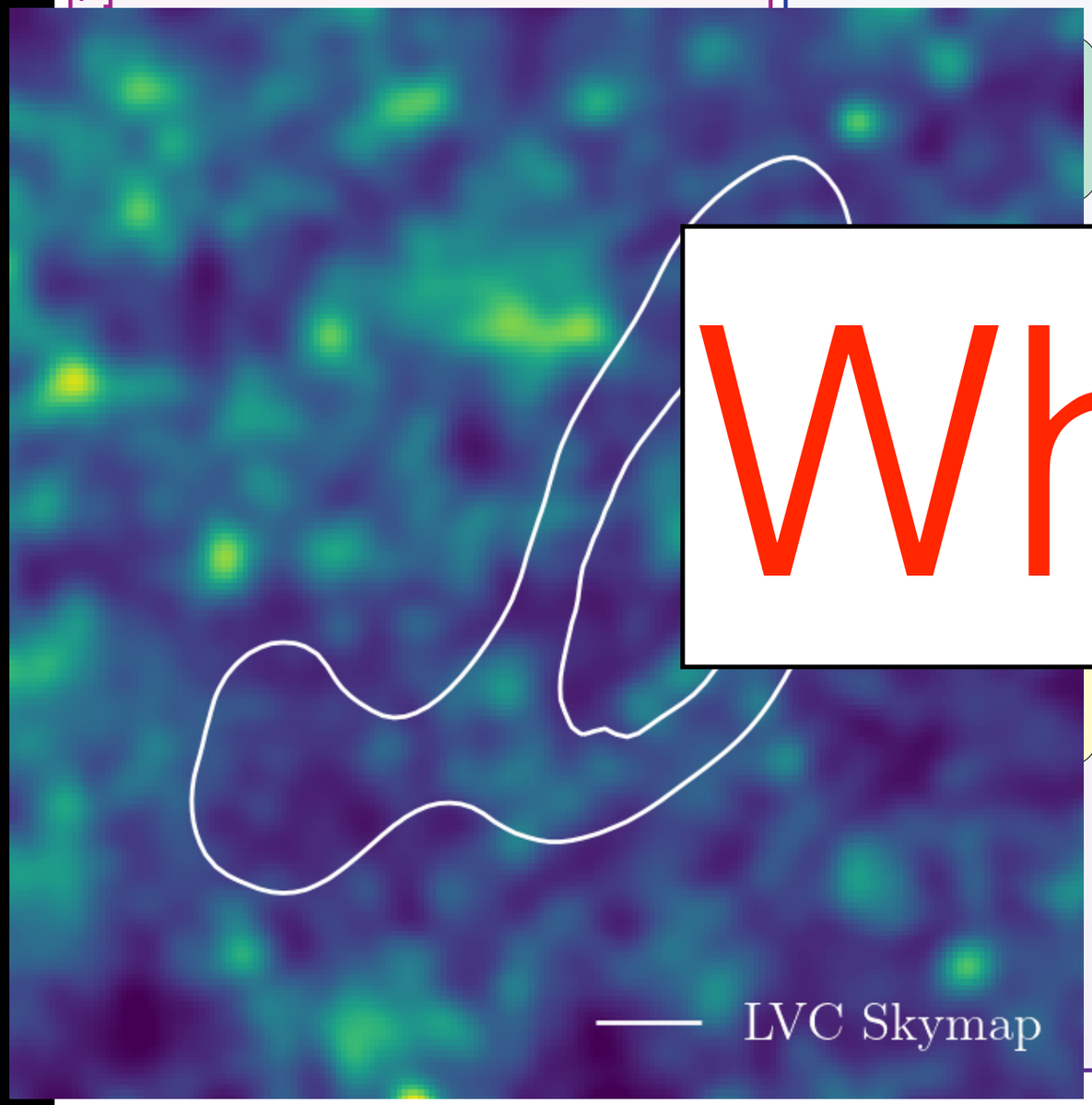
Dark sirens

Standard sirens with no EM counterpart



Dark sirens

Standard sirens with no EM counterpart



Why?

- Factor ~10 more BBH events
- May miss some EM counterparts to BNS
- Further away - can do more than H_0

Method

Proposed by Schutz in 1986

- Bayes' theorem:

LIGO data (source position & distance)

DES data (galaxies' positions & redshifts)

$$p(H_0|d_{\rm GW}, d_{\rm EM}) \propto p(d_{\rm GW}, d_{\rm EM}|H_0)p(H_0)$$

- Source **position assumption**: it lives in galaxies *i*
- Marginalize over all galaxies

$$p(H_0|d_{\rm GW}, d_{\rm EM}) \propto \frac{p(H_0)}{\beta(H_0)} \sum_i w_i \int {\rm d}z_i \, p(d_{\rm GW}|d_L(z_i, H_0), \Omega_i) \; p(d_{\rm EM}|z_i) \; \frac{r^2(z_i)}{H(z_i)}$$

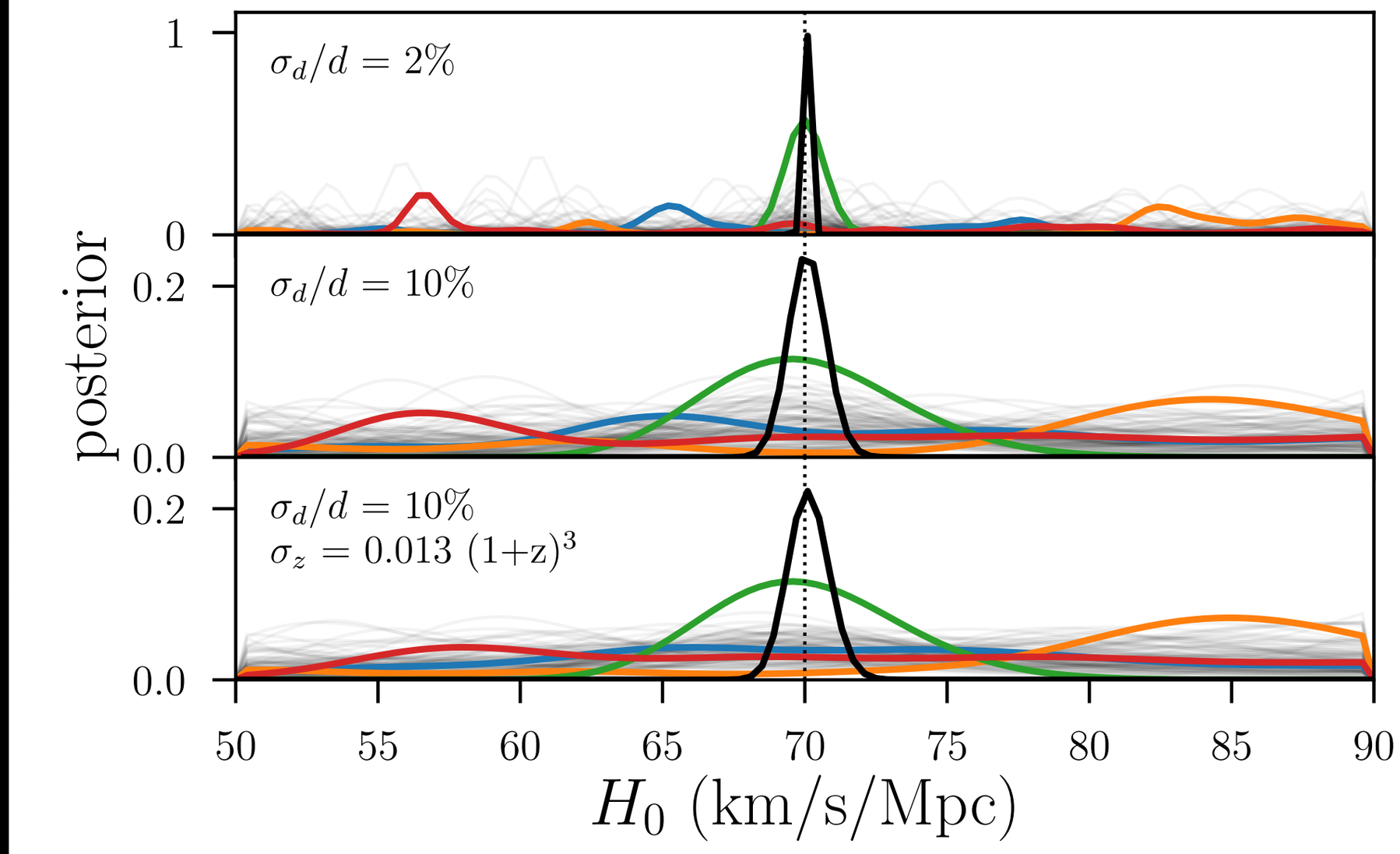
LIGO/Virgo

DES

Selection effects

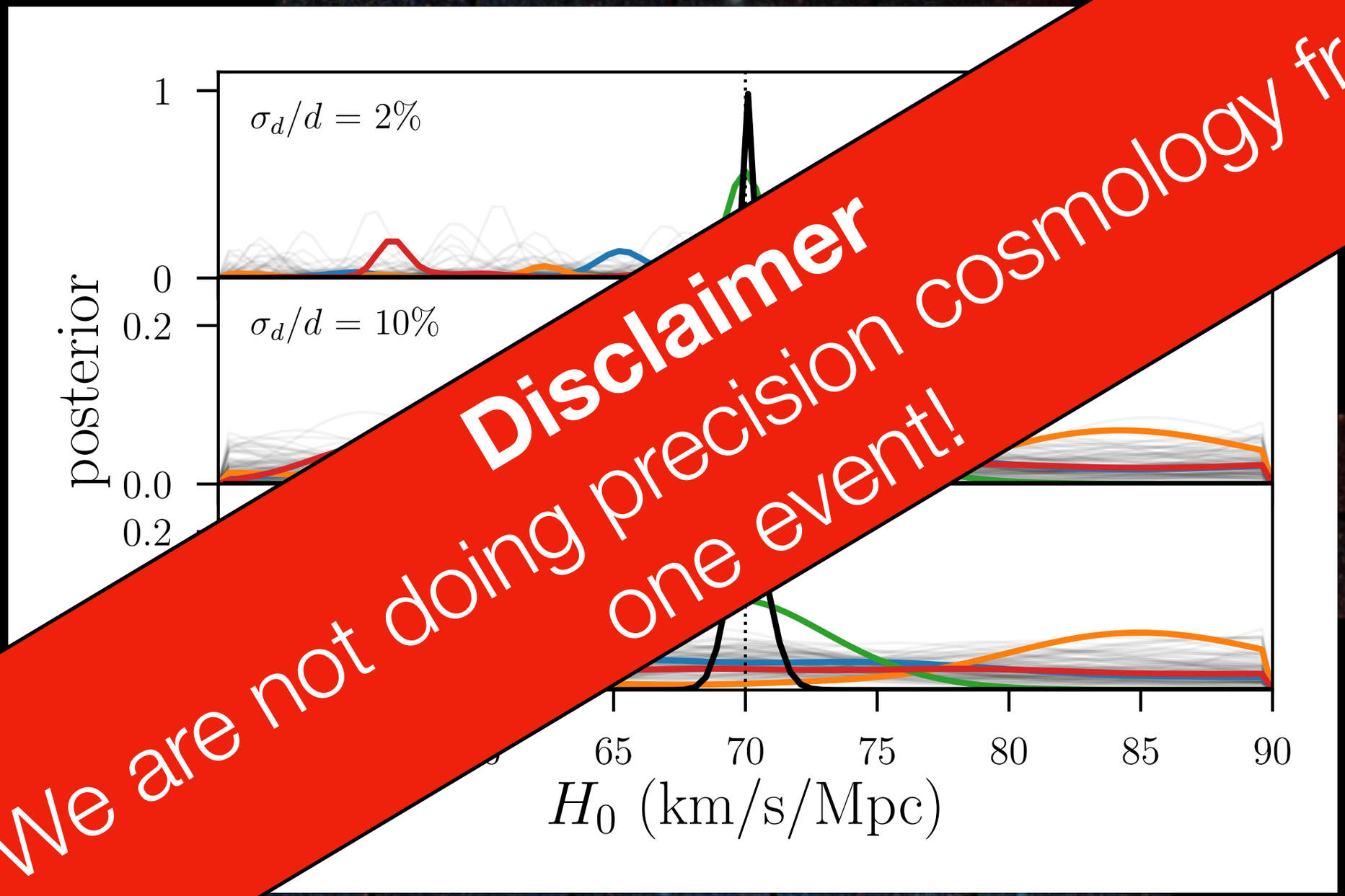
Chen, Fishbach & Holz (2018)

Simulations



- Single events: posterior expected to have peaks corresponding to large scale structure along the los
- Peaks are broadened and blended if *d* or *z* uncertainty increases.
- Converge to the input value of H_0 from combining enough events

Simulations



Disclaimer
We are not doing precision cosmology from one event!

- …sterior expected to have peaks corresponding to large scale structure along the los
- Pea… are broadened and blended if *d* or *z* uncertainty increases.
- Converge to the input value of H_0 from combining enough events

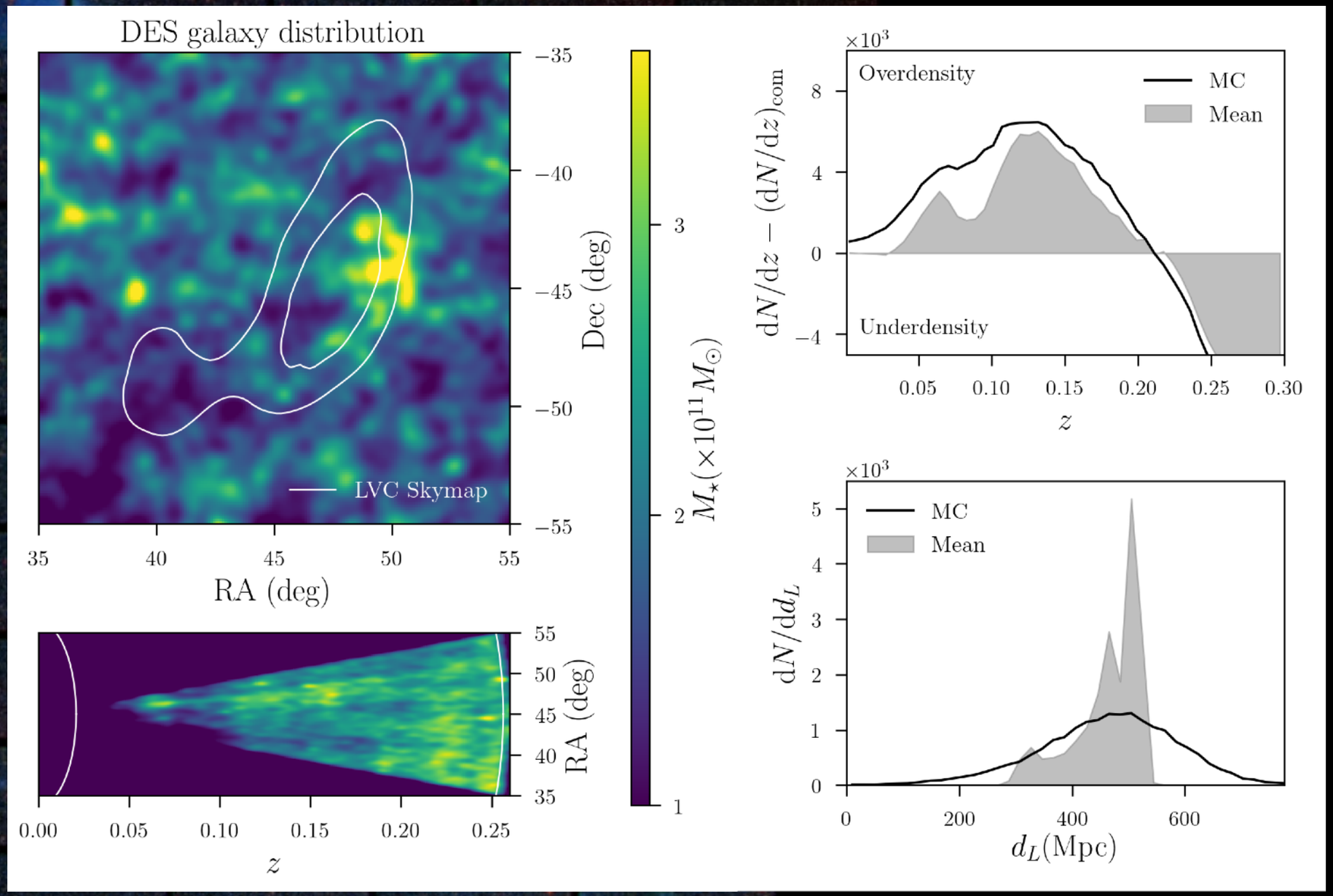
GW170814: the golden event (for DES)

- LIGO+Virgo: 90% probability in 60 sq deg
- 90%+ covered by DES-GW follow up (see Zhoeyr Doctor talk tomorrow)
- Falls in the DES footprint

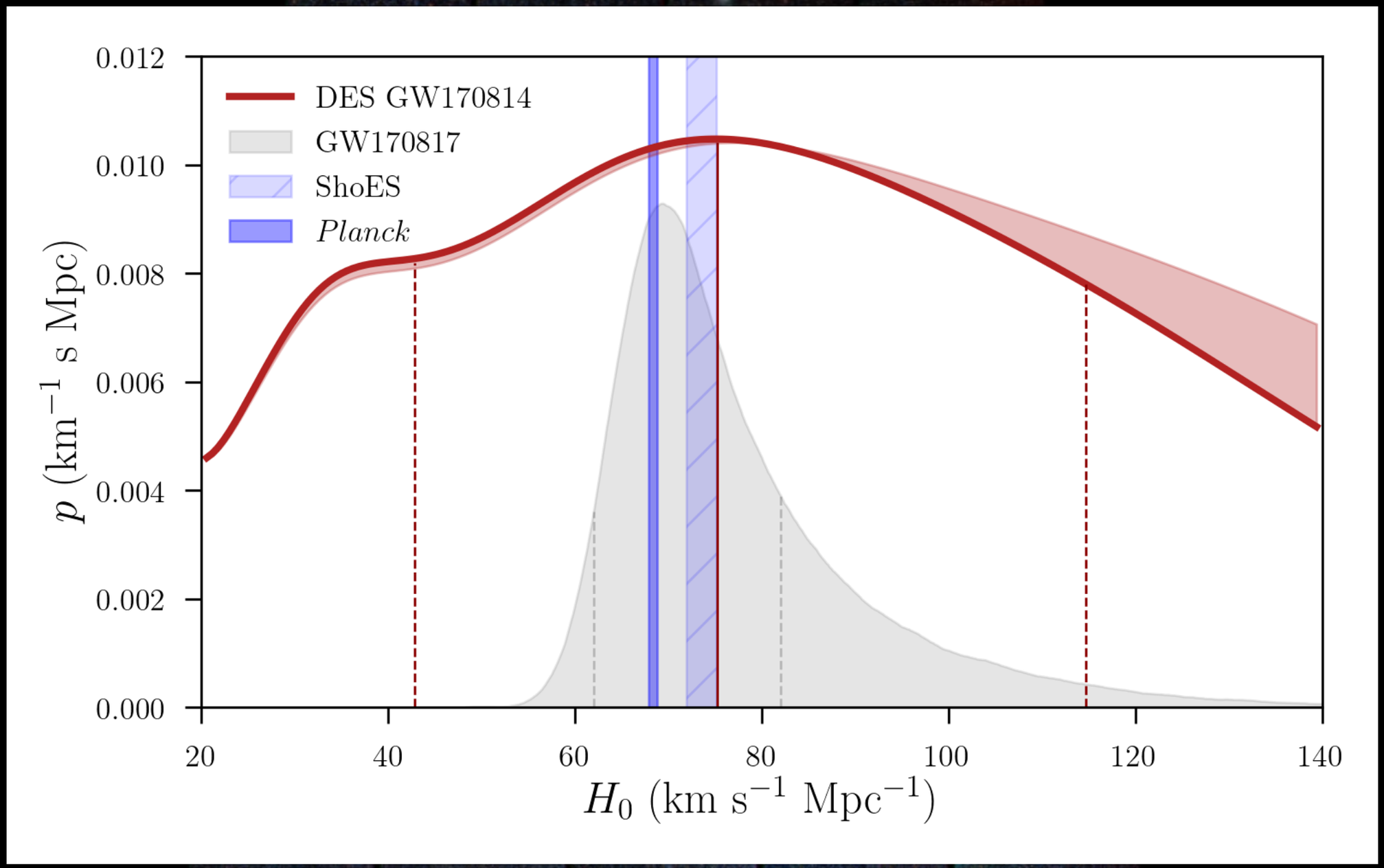
GW170814: the golden event (for DES)

- Define a complete volume limited galaxy sample down to 4×10^8 M_{Sun} (77% of total stellar mass) using **Year 3 data**

- ~77,000 galaxies



Results



$$H_0 = 75.2^{+39.5}_{-32.4}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

DES & LVC (2019) arxiv:1901.01540

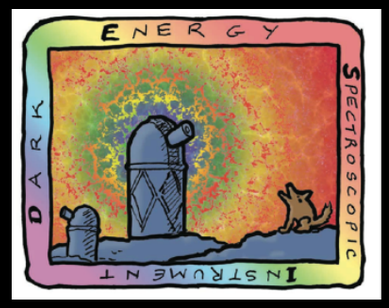
Part III

(Near) future galaxy surveys

Astrophysics

Cosmology

DESI



- 5000 fibers spectrograph at Kitt Peak (AZ)
- 5 years, first light 2019

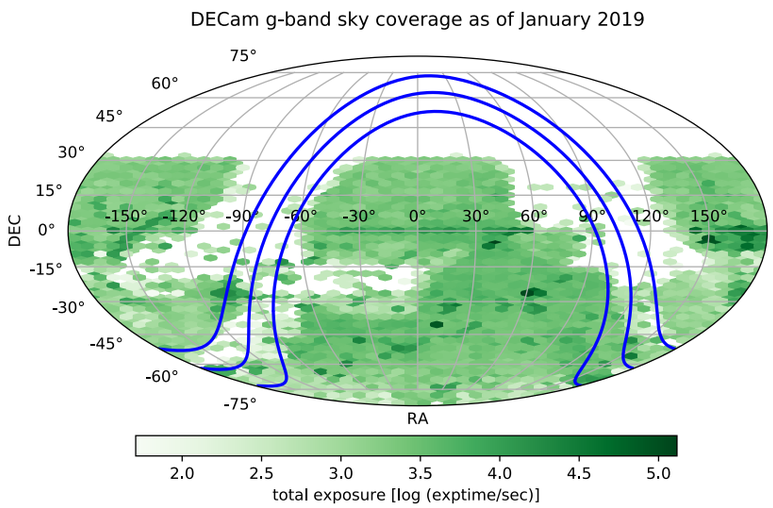
The Bright Galaxy Survey (BGS)

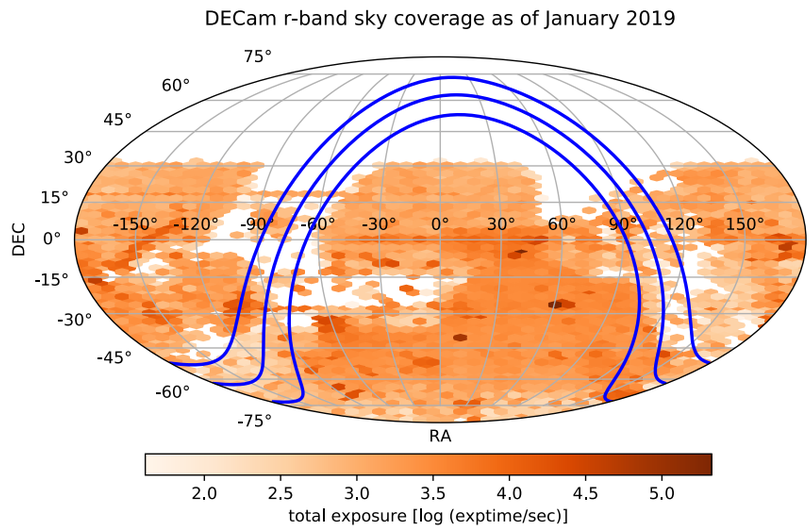
- 14,000 sq deg
- Magnitude limited survey (r=19.5) out to z~0.4 (median 0.2)
- 10M galaxies
- Precision σ_z ~0.0005

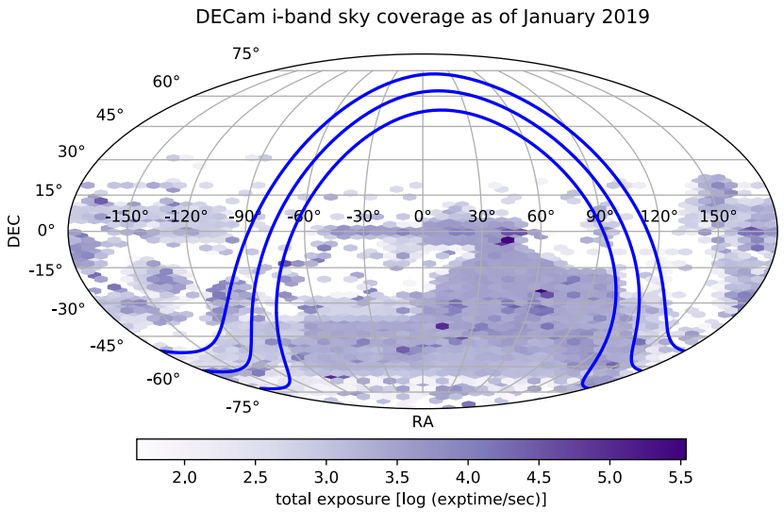
BLISS+DELVE

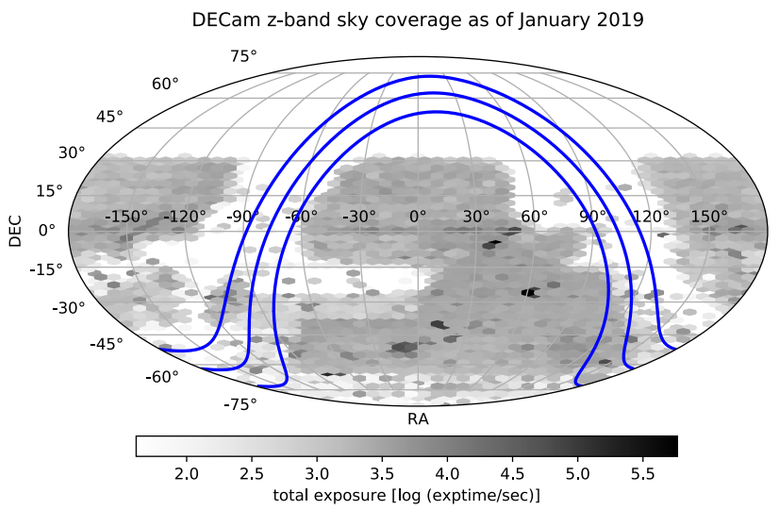
PI: Alex Drlica-Wagner

While we wait for LSST…









Conclusions

- **Synergies between GW experiments and large galaxy surveys allow studies of both the formation of GW sources and cosmological parameter inference, other than transient discovery**
- Lessons from DES+LIGO/Virgo:
  - Indication for **BNS formation different from isolated binary scenario**
  - **First measurement** of H_0 with GW170814+DES galaxies
  - Proof of concept and identification of sources of systematics/ansatz

Future work

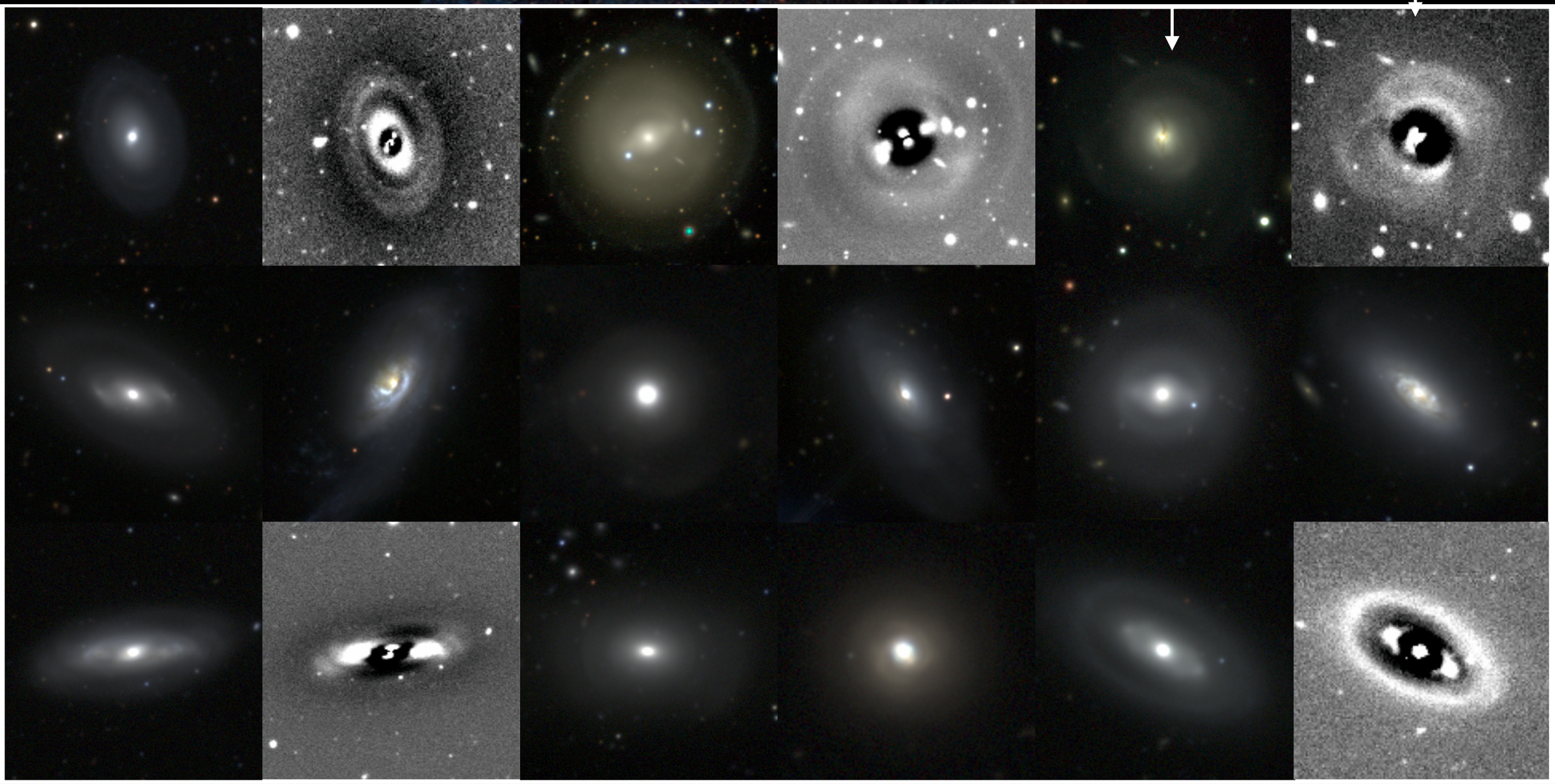
- Systematics of dark sirens
- Similar method for dark events host galaxy properties
- DESI and LSST GW science
- Full sky galaxy catalog for dark siren cosmology & follow-up (DES+BLISS+public catalogs)

Back-up slides

Shell galaxies in DES Year 1

Original image

Residual



~15% of selected early-type galaxies present shells

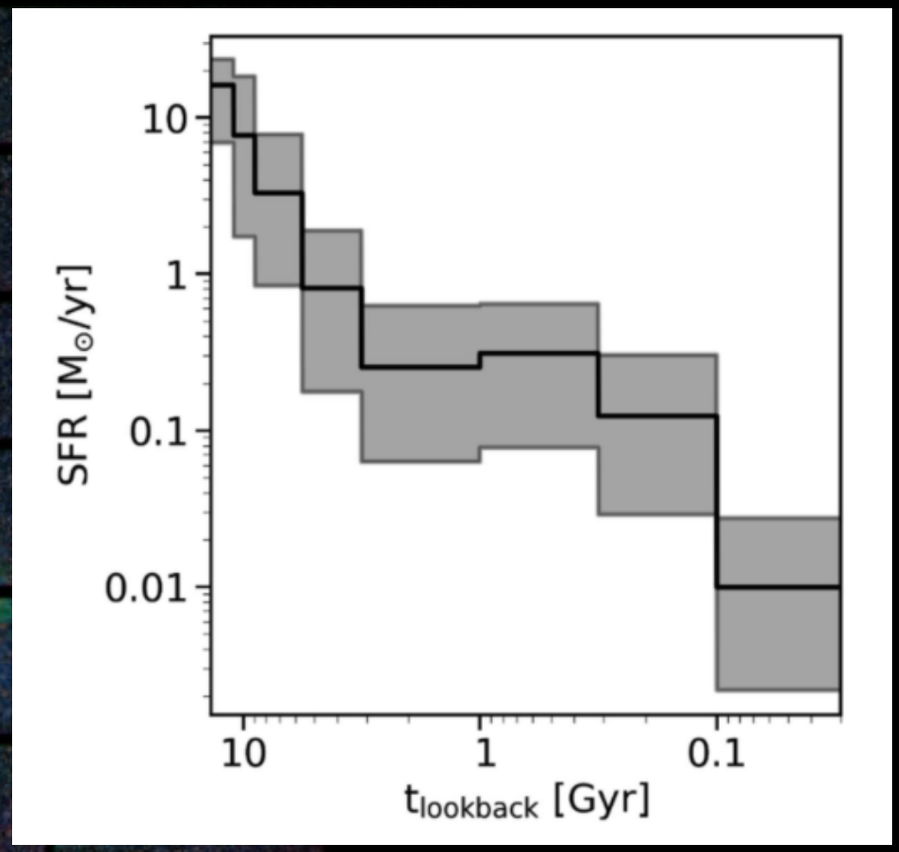
Public morphological catalog:

Tarsitano & DES 2018: https://arxiv.org/abs/1807.10767

Alternative interpretation

No strong conclusions about BNS formation from one event, but the coincidence of a recent merger in a galaxy for which a BNS event was otherwise improbable is compelling

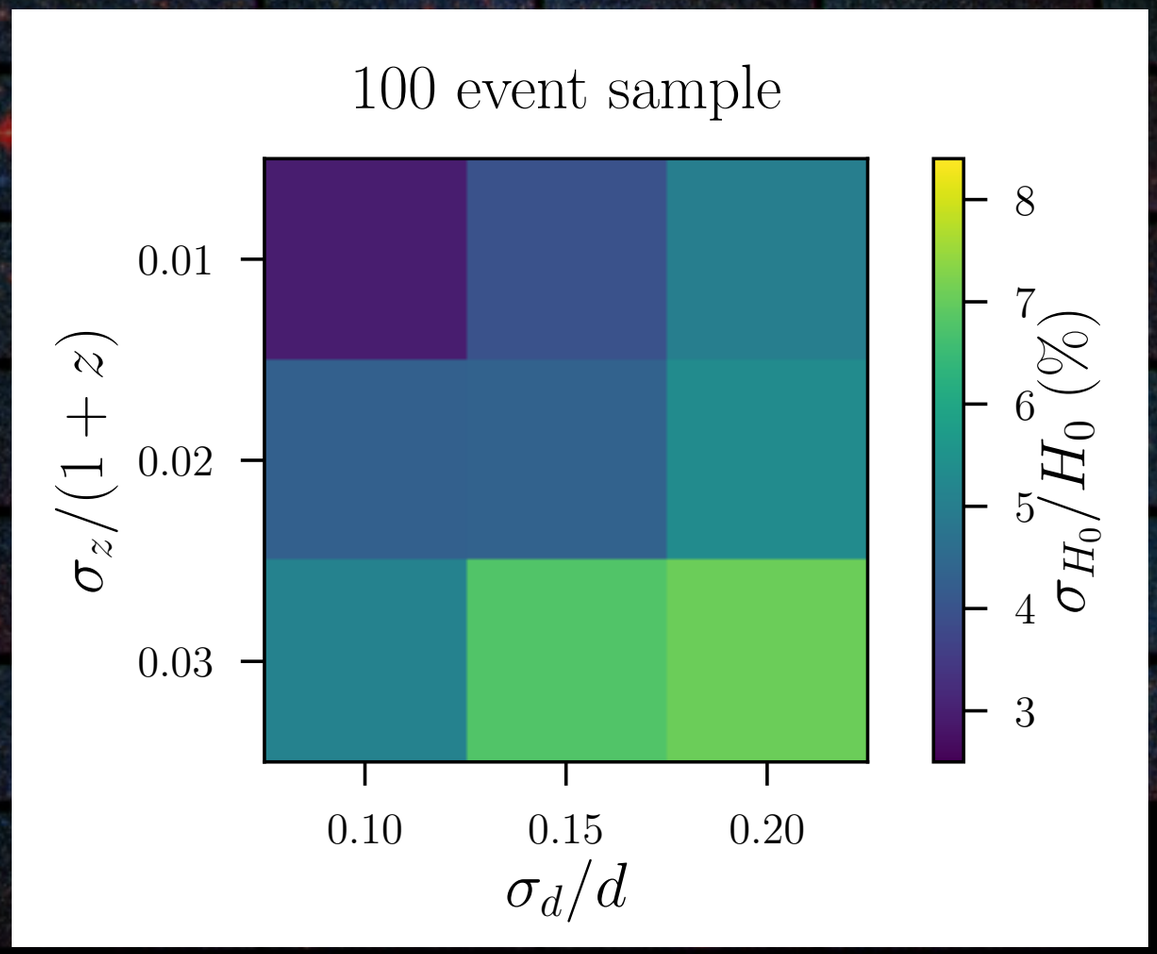
- Belczynski et al. 2018 follows similar motivation to suggest alternative formation scenario
- 50% of mass formed by ~11 Gyr ago -> median delay timescale



Blanchard et al. 2017

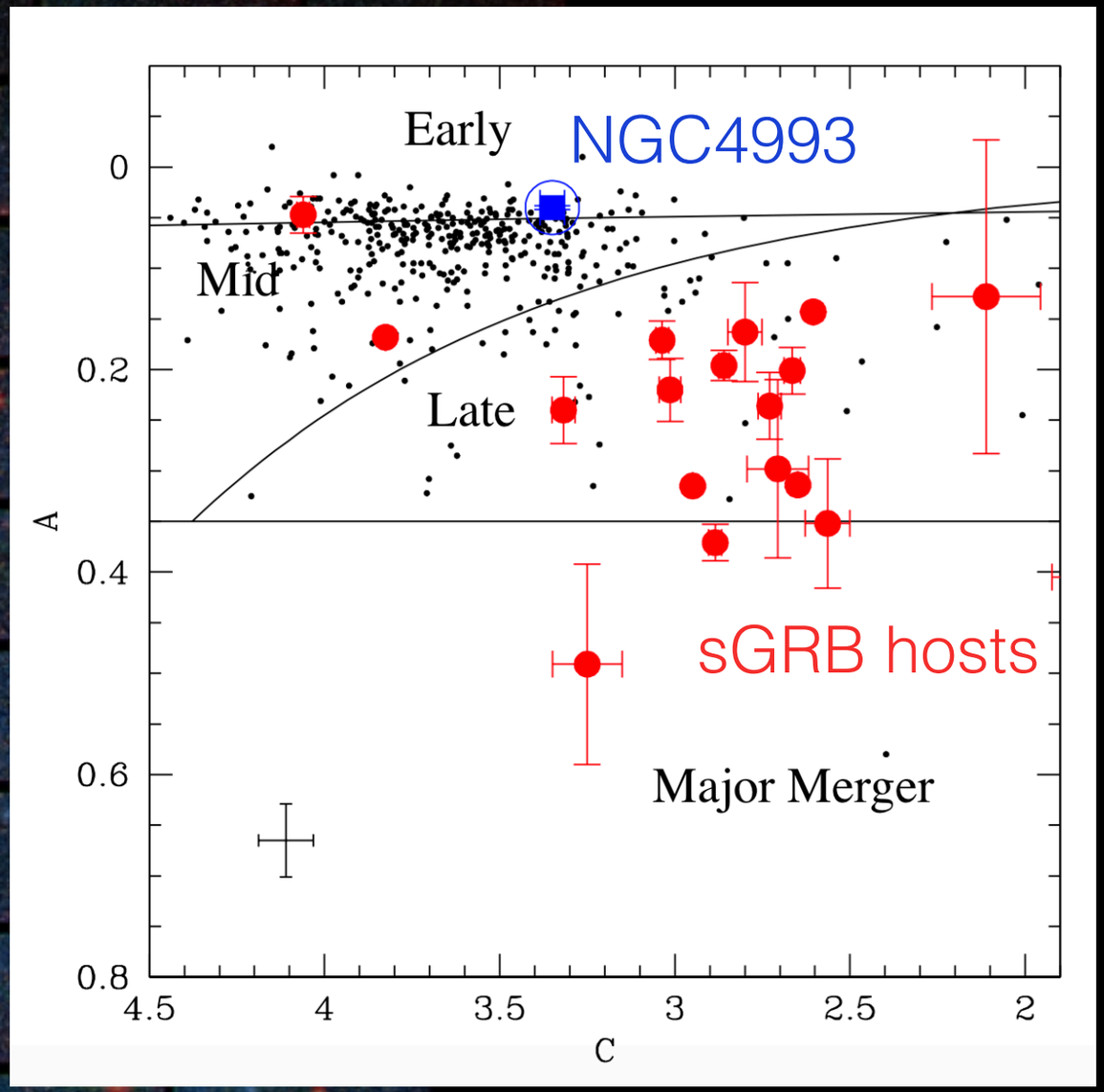
Results from simulations

- 4-5% statistical precision with DES-like data and ~100 GW170814-like events



Host galaxy - Comparison to sGRB hosts

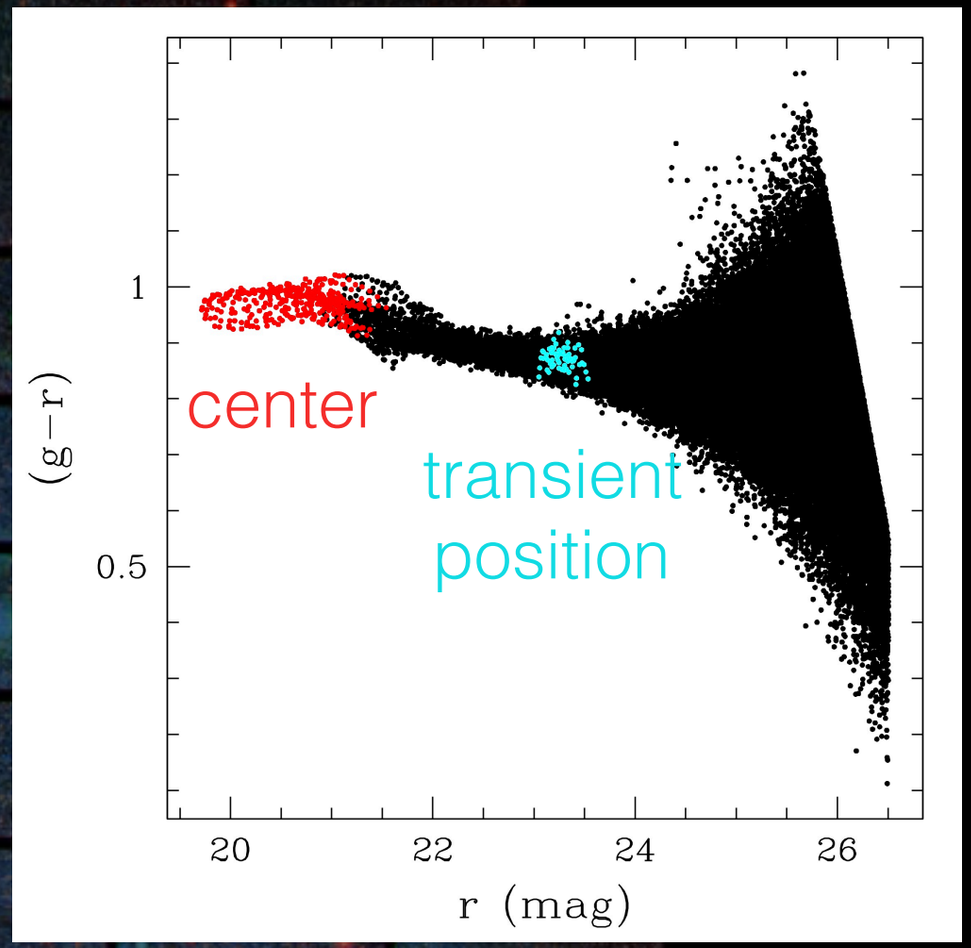
- **Asymmetry and concentration** consistent with early-type galaxies but **unusual** for sGRB hosts
- **Clear major galaxy mergers** are unusual amongst sGRB hosts
- Other sGRBs are at **cosmological distances** and thus are mostly undergoing extensive galaxy formation through star formation or merging
- **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 - 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)

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