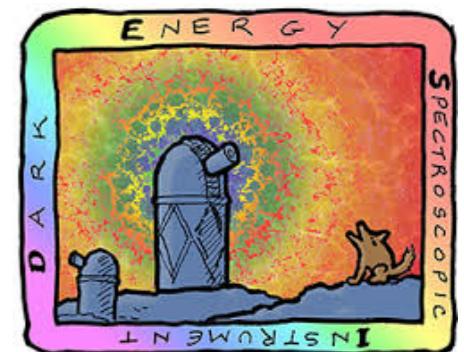




Measuring H_0 with gravitational wave binary black hole mergers and galaxy surveys

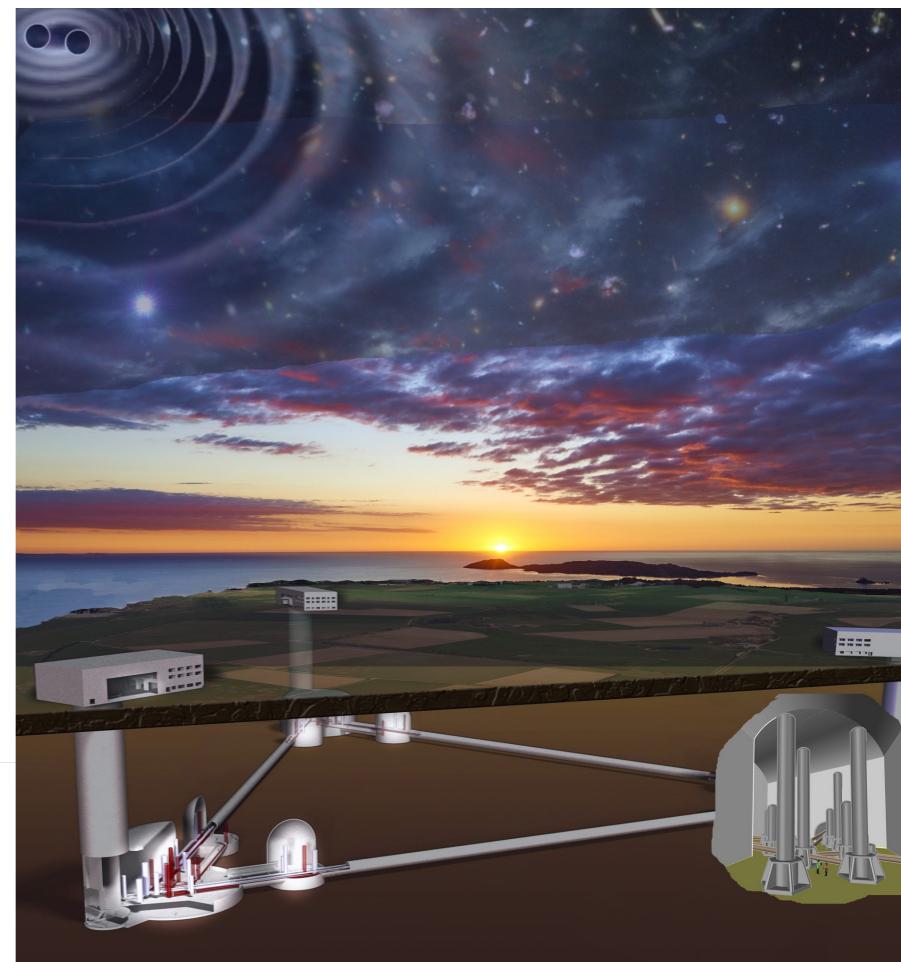
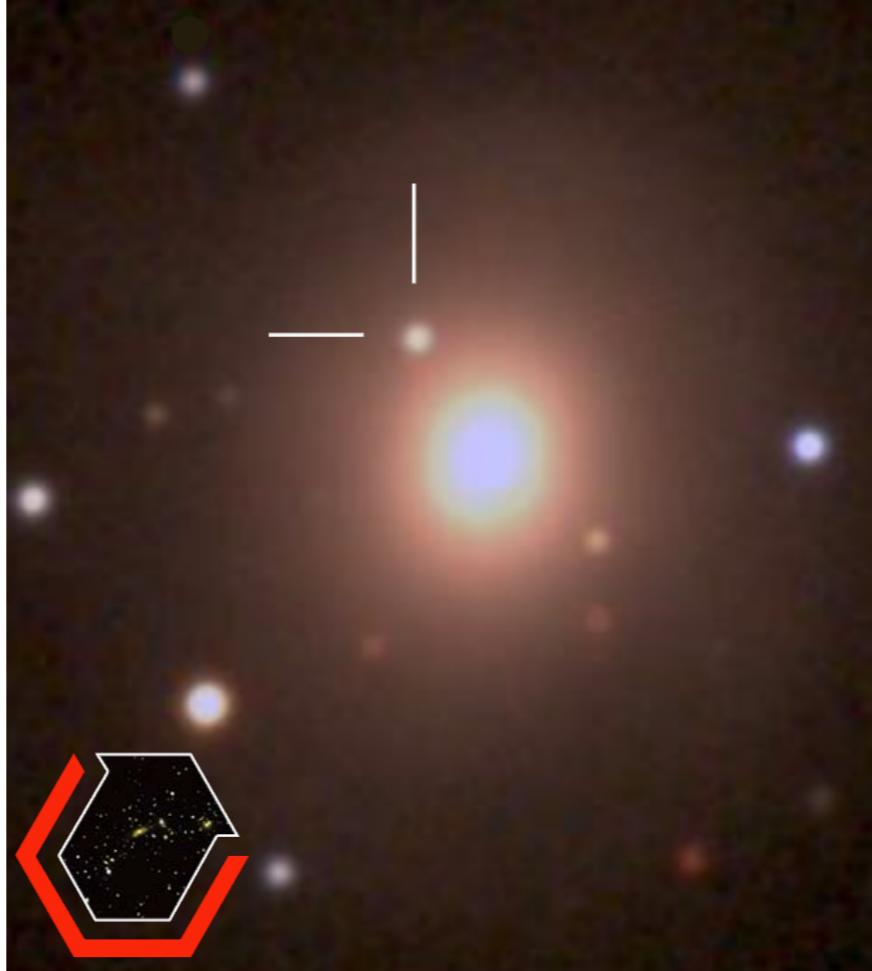


Antonella Palmese
16 September 2019
KICC Symposium



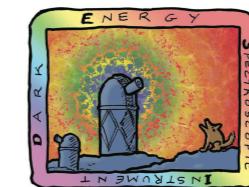
In Collaboration with DES, LVC, DESI time-domain:
M. Soares-Santos, J. Annis, Z. Doctor, W. Farr, M. Fishbach, J. Gair, J. Garcia-Bellido, W. Hartley, D. Holz, O. Lahav, H. Lin, I. Magaña Hernandez, S. BenZvi, O. Graur & more

Introduction



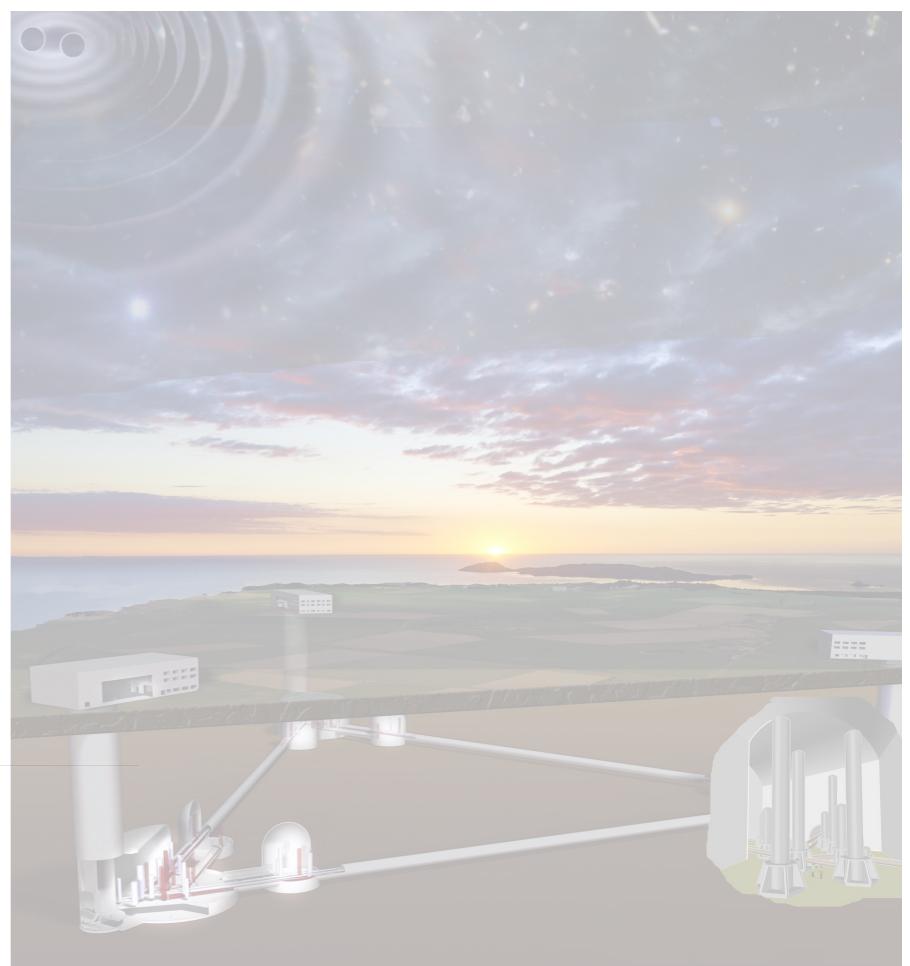
DES
Motivation

Current measurements
Limits/systematics



LSST
Large Synoptic Survey Telescope

Ways forward



DES Motivation

Current measurements
Limits/systematics



→ **Ways forward**

LSST
Large Synoptic Survey Telescope

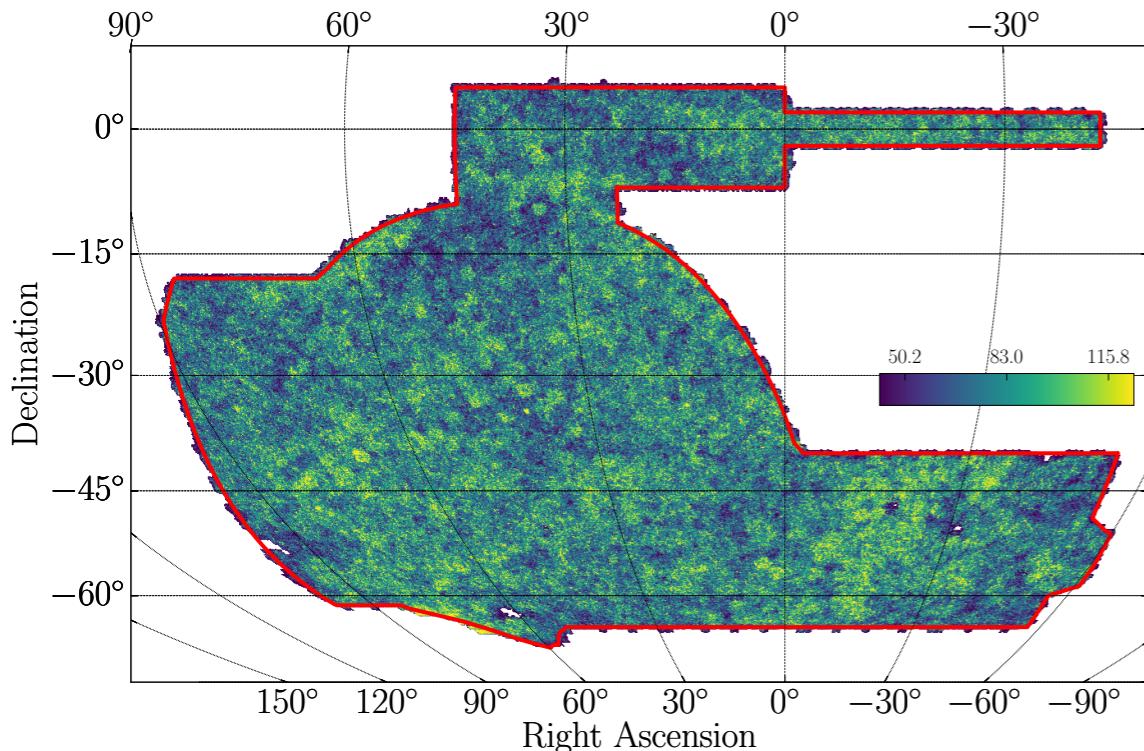
The Dark Energy Survey (DES)

- First/last light: 12-12-12 / 01-08-19
- 300M galaxies over 5000 sq. deg.

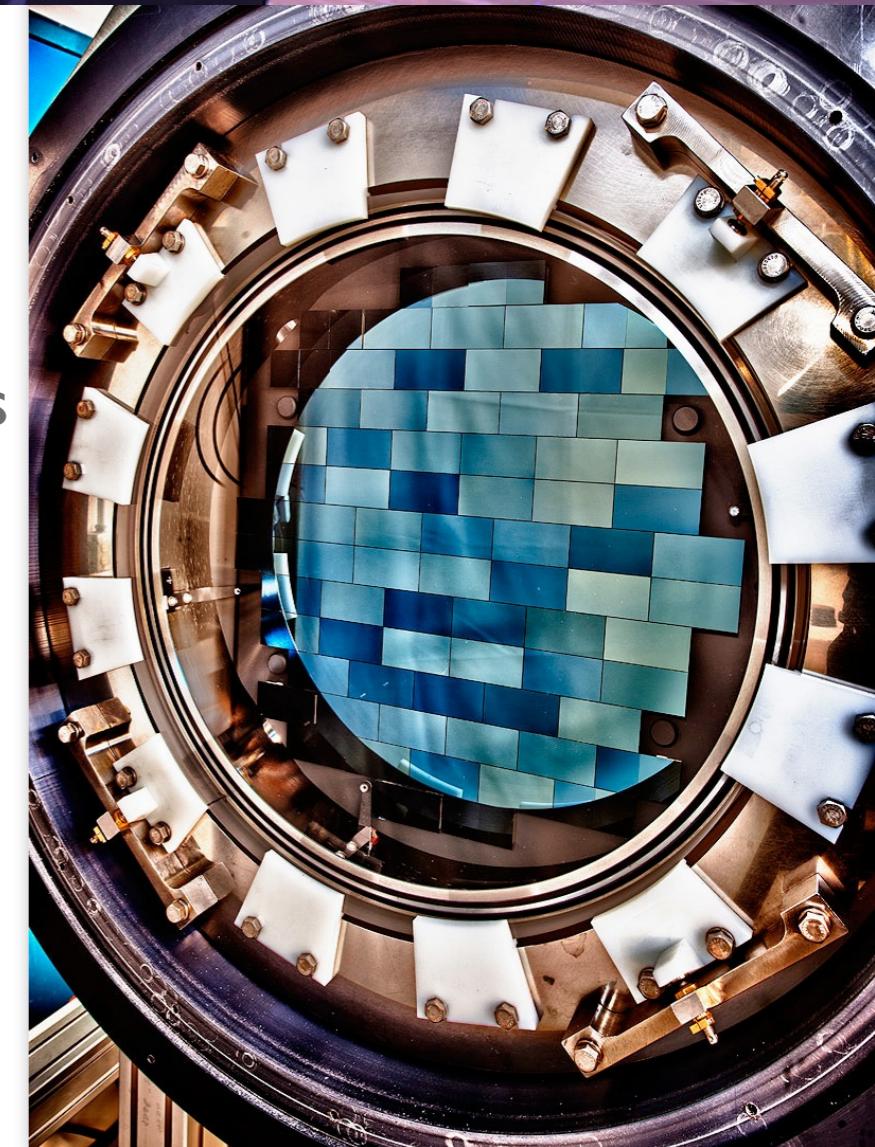
DECam

Premier instrument for GW optical follow up in the Southern hemisphere

3 sq deg FOV, 570 Mpix optical CCD camera
CTIO Blanco 4-m telescope (Chile)



DECam follow-up continues



Public data

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

DRI (Y3) - 400M objects ($r \sim 24$)

Schutz 1986

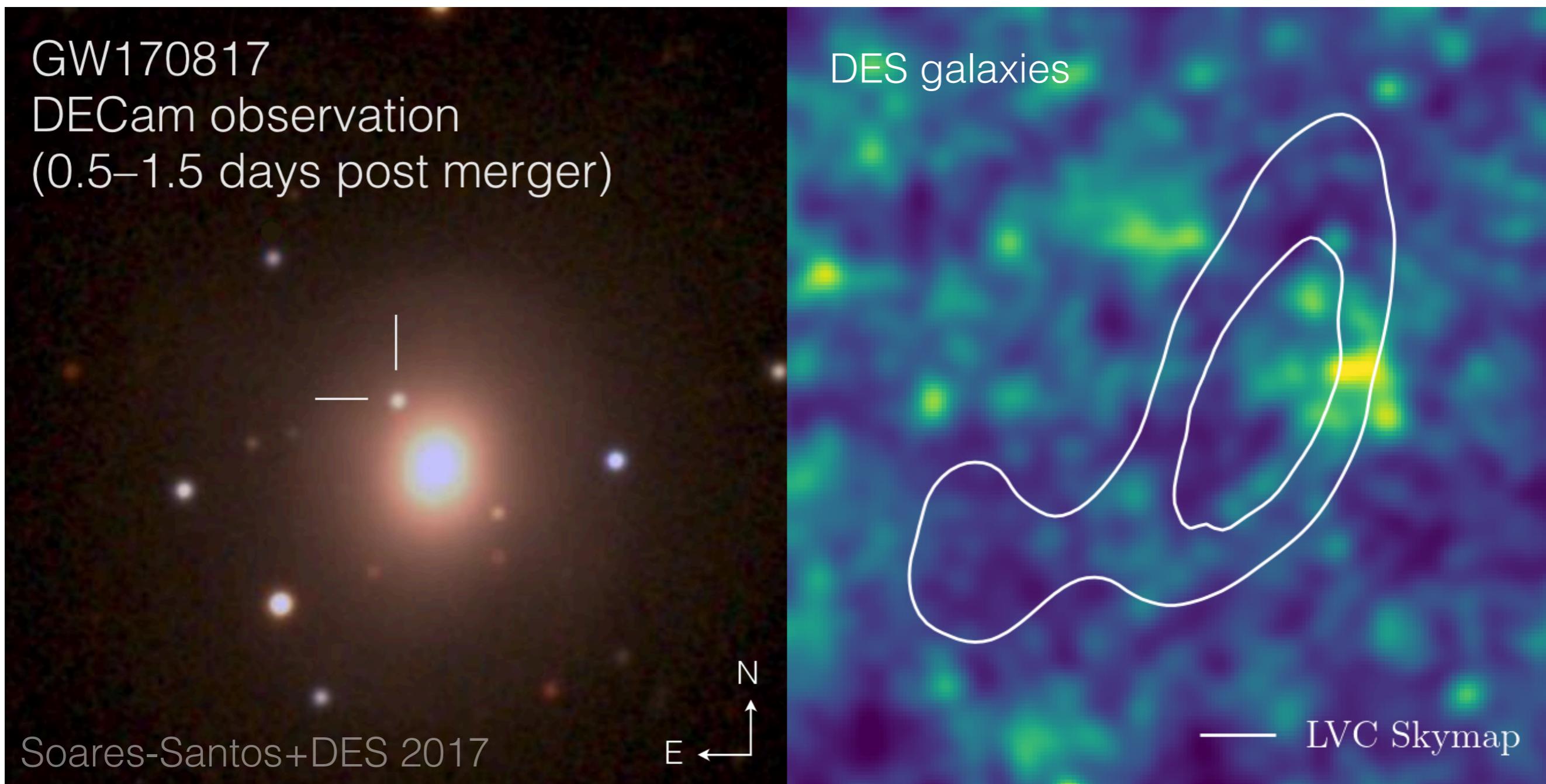
Holz & Hughes 2005

MacLeod & Hogan 2008

Nissanke+2010

Del Pozzo 2012

Standard Sirens



Bright standard sirens

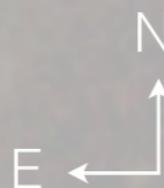
Dark standard sirens / statistical method

Dark Standard Sirens - why?

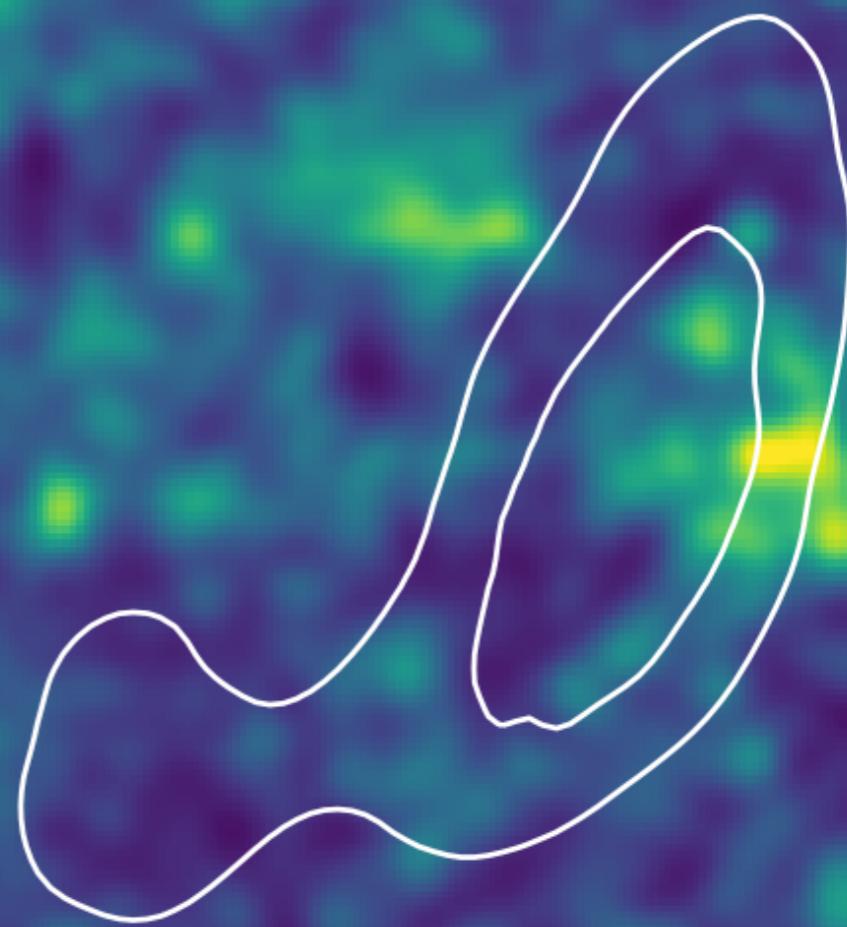
GW170817
DECam observation
(0.5–1.5 days post merger)

- Factor \sim 10 more BBH events
- Will miss some EM counterparts to BNS (and NSBH?)
- Further away - can do more than H_0

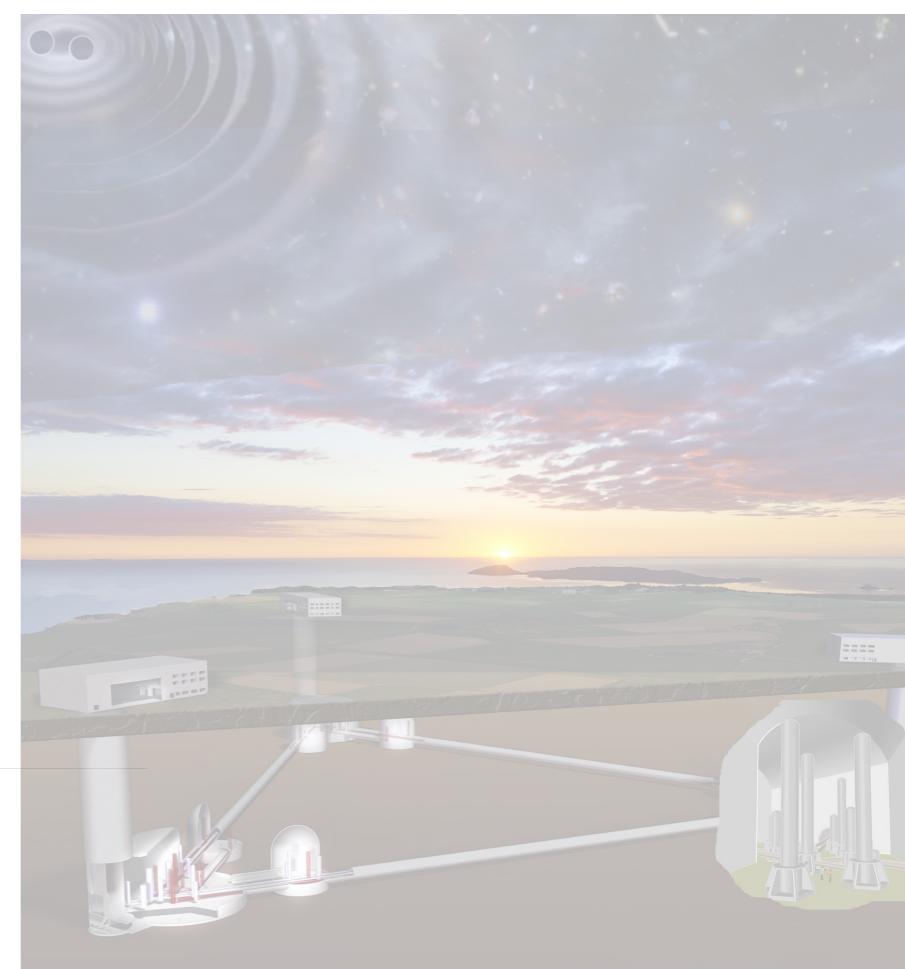
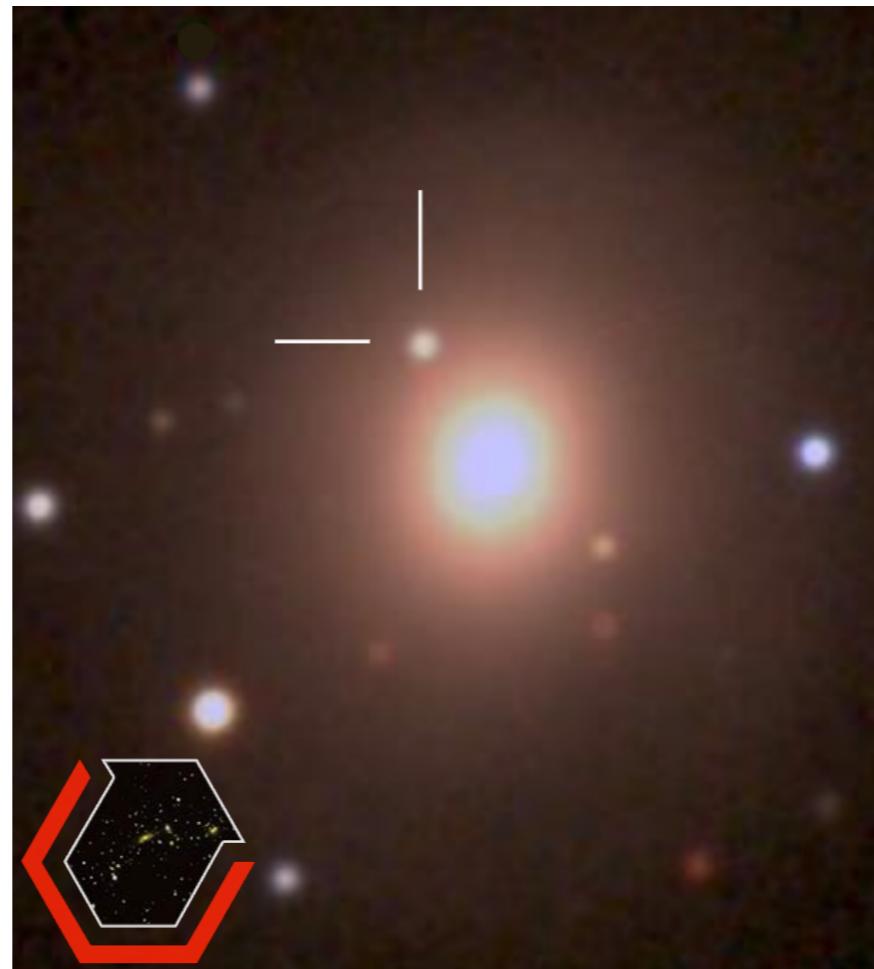
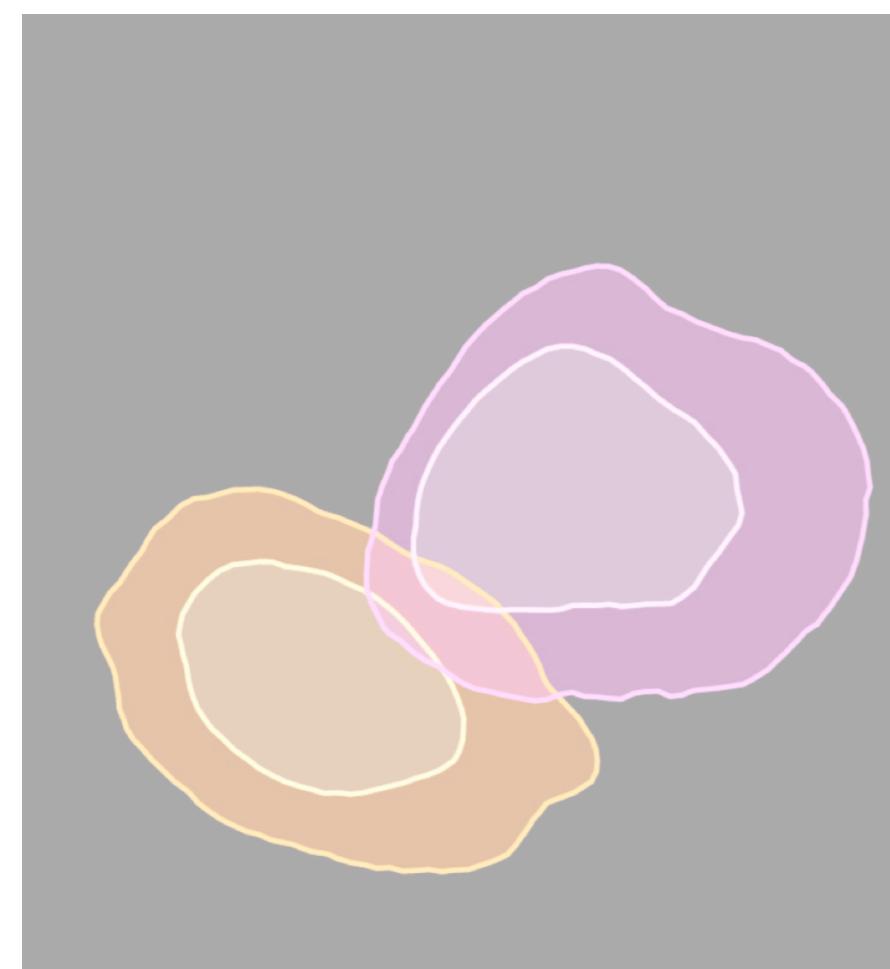
Soares-Santos+DES 2017



DES galaxies



— LVC Skymap



Motivation
DES

Current measurements
Limits/systematics

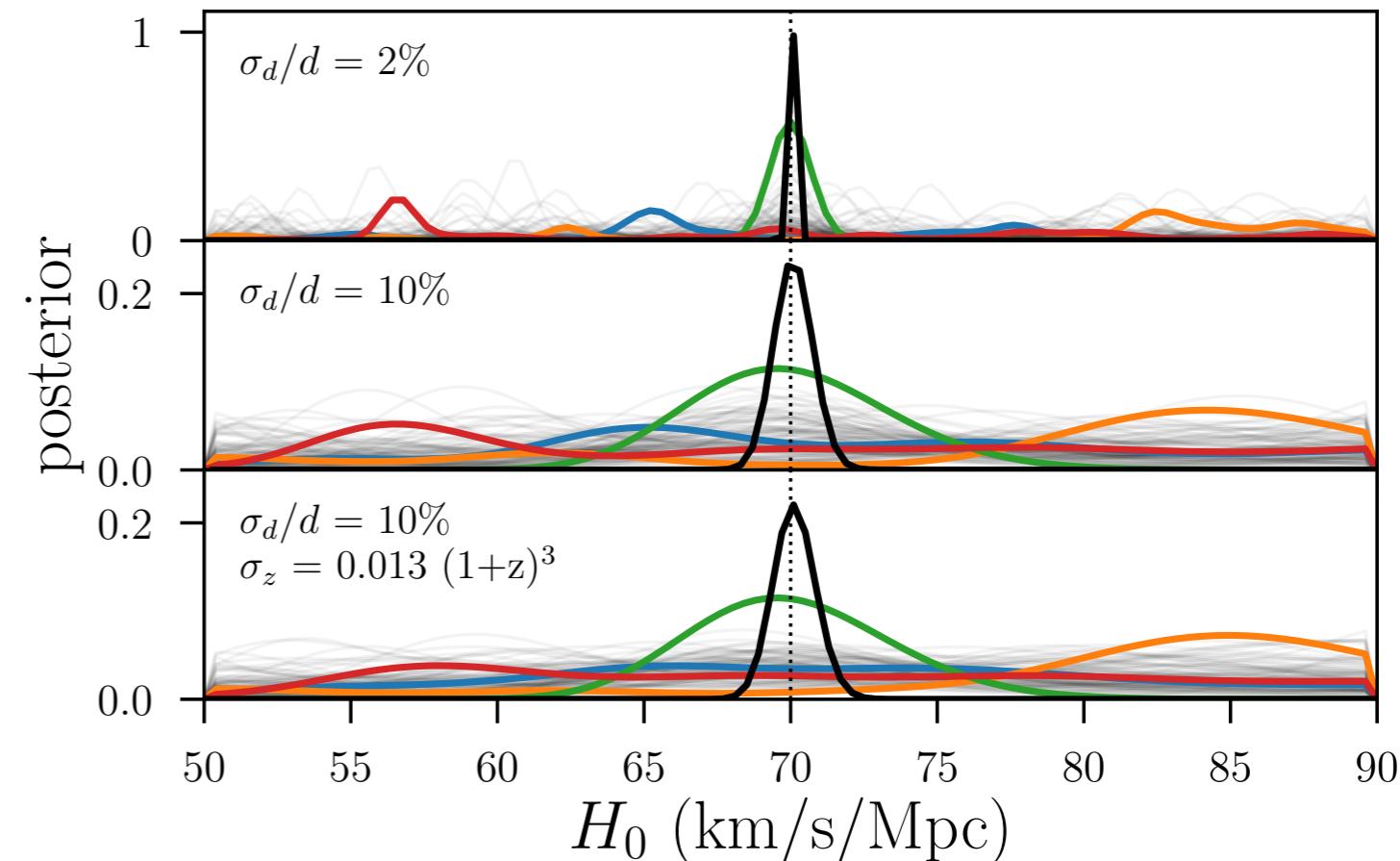


LSST
Large Synoptic Survey Telescope

→ Ways forward

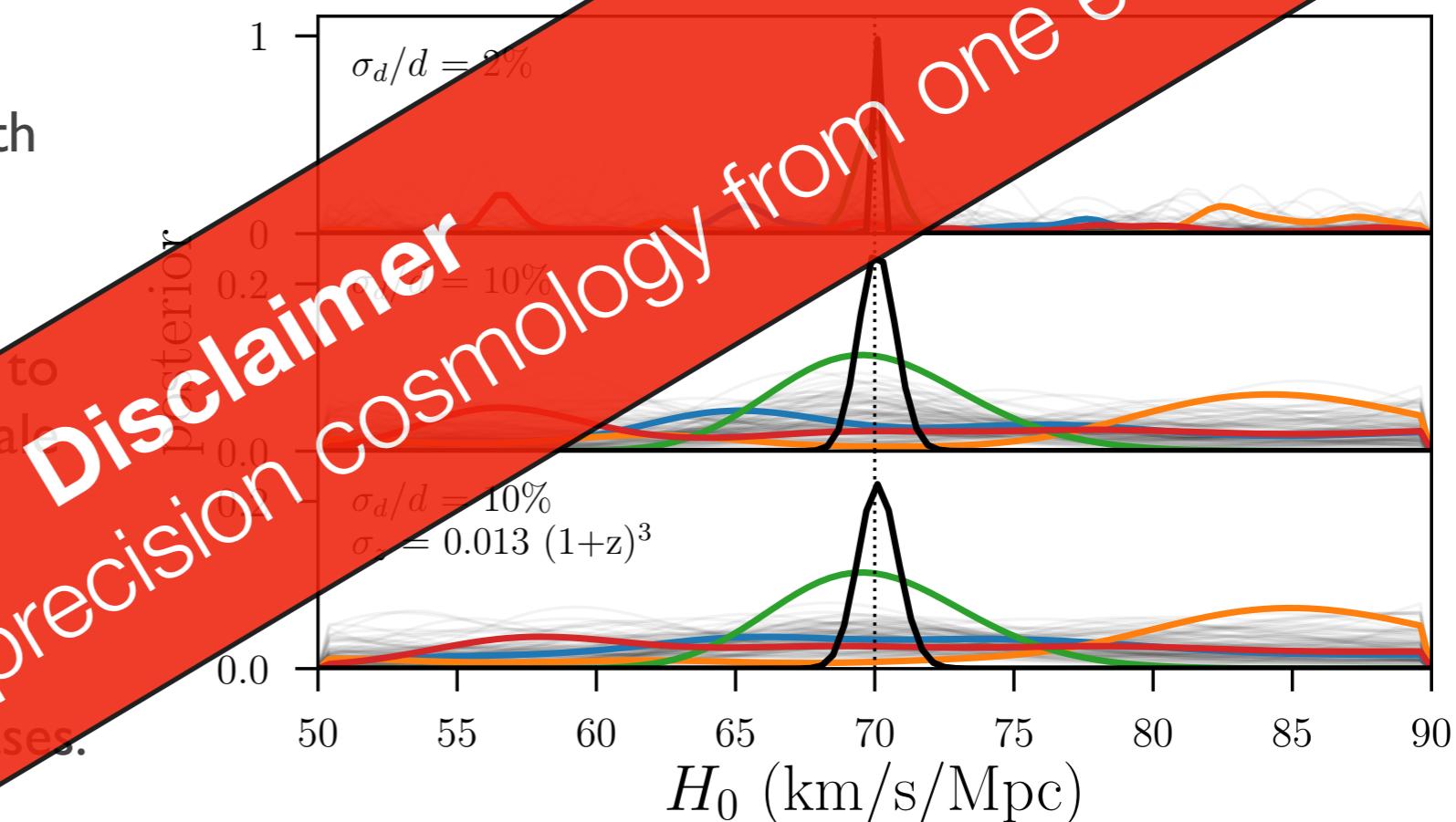
Dark standard sirens - simulations

- BCC galaxy simulations (DeRose et al. 2019, Wechsler et al. in prep.)
- Simulated GW events in uniform comoving volume on a galaxy at z with $H_0=70 \text{ km/s/Mpc}$
- **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



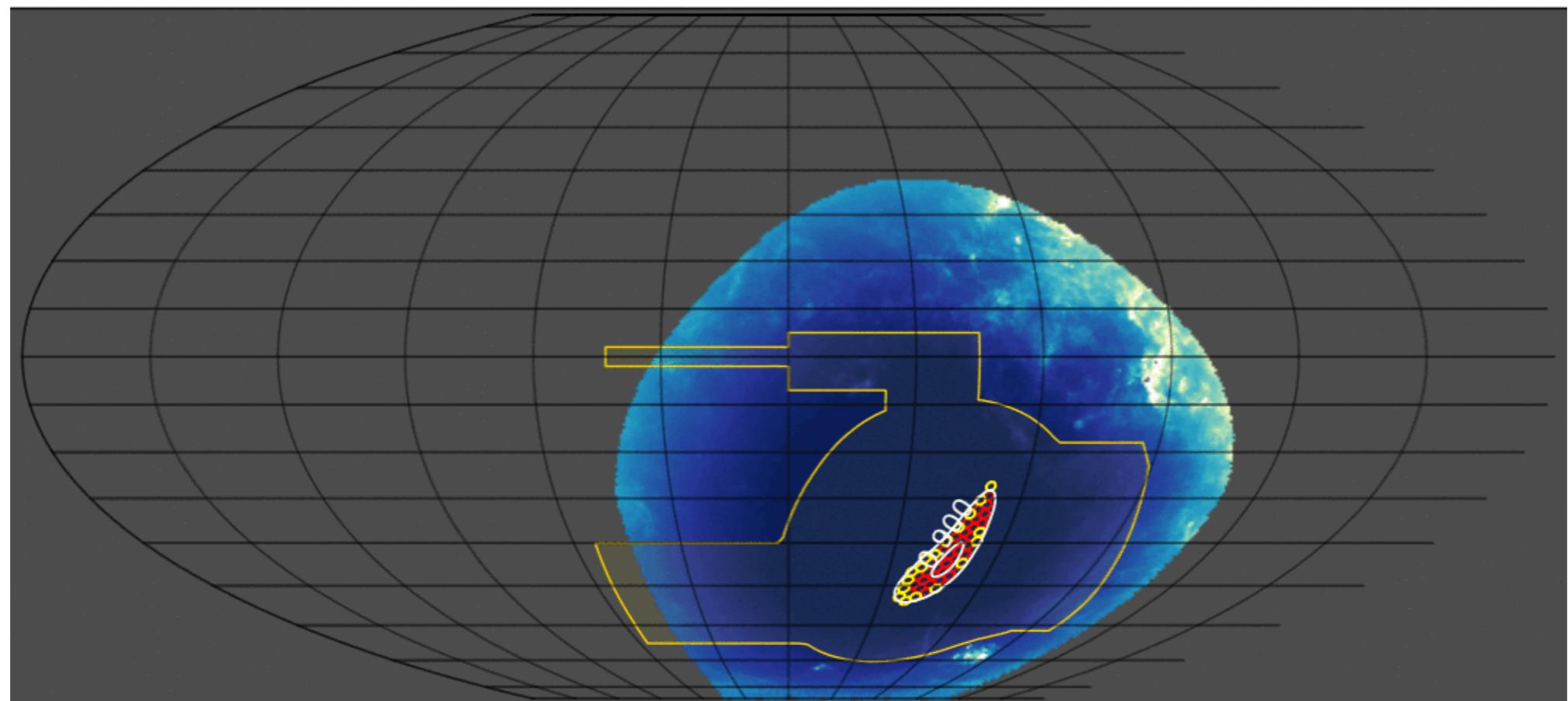
Dark standard sirens - simulations

- BCC galaxy simulations (DeRose et al. 2019, Wechsler et al. in prep.)
- Simulated GW events in uniform comoving volume on a galaxy at z with $H_0=70 \text{ km/s/Mpc}$
- **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



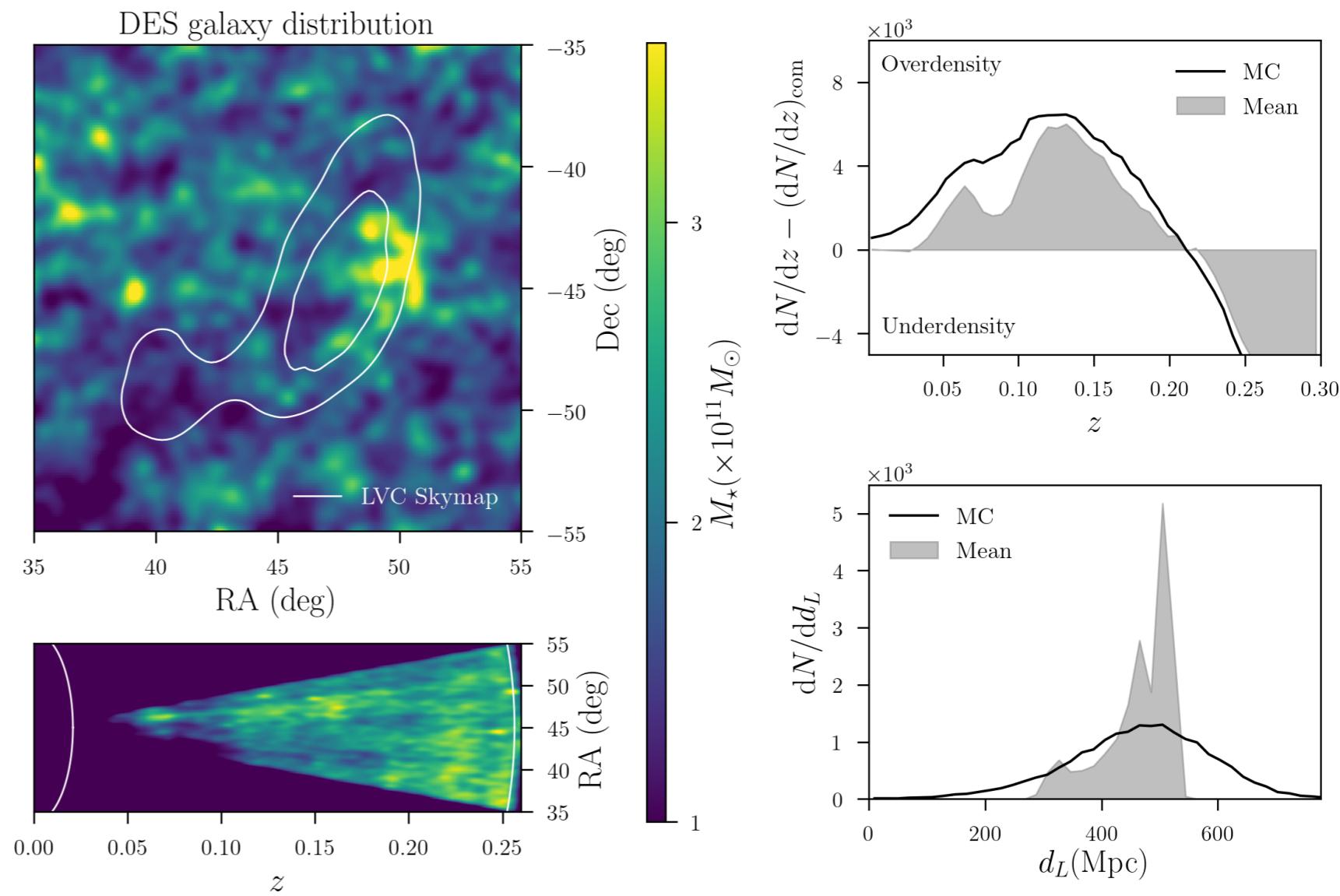
GW170814: the golden event (for DES)

- 25-30 M_{\odot} BHs
- ~540 Mpc away
- First BBH event LIGO+Virgo: 90% probability in 60 sq deg
- 90%+ covered by DECam-GW follow up → Doctor, Kessler, Herner, AP et al. 2018 arxiv:1812.01579
- Falls in the DES footprint



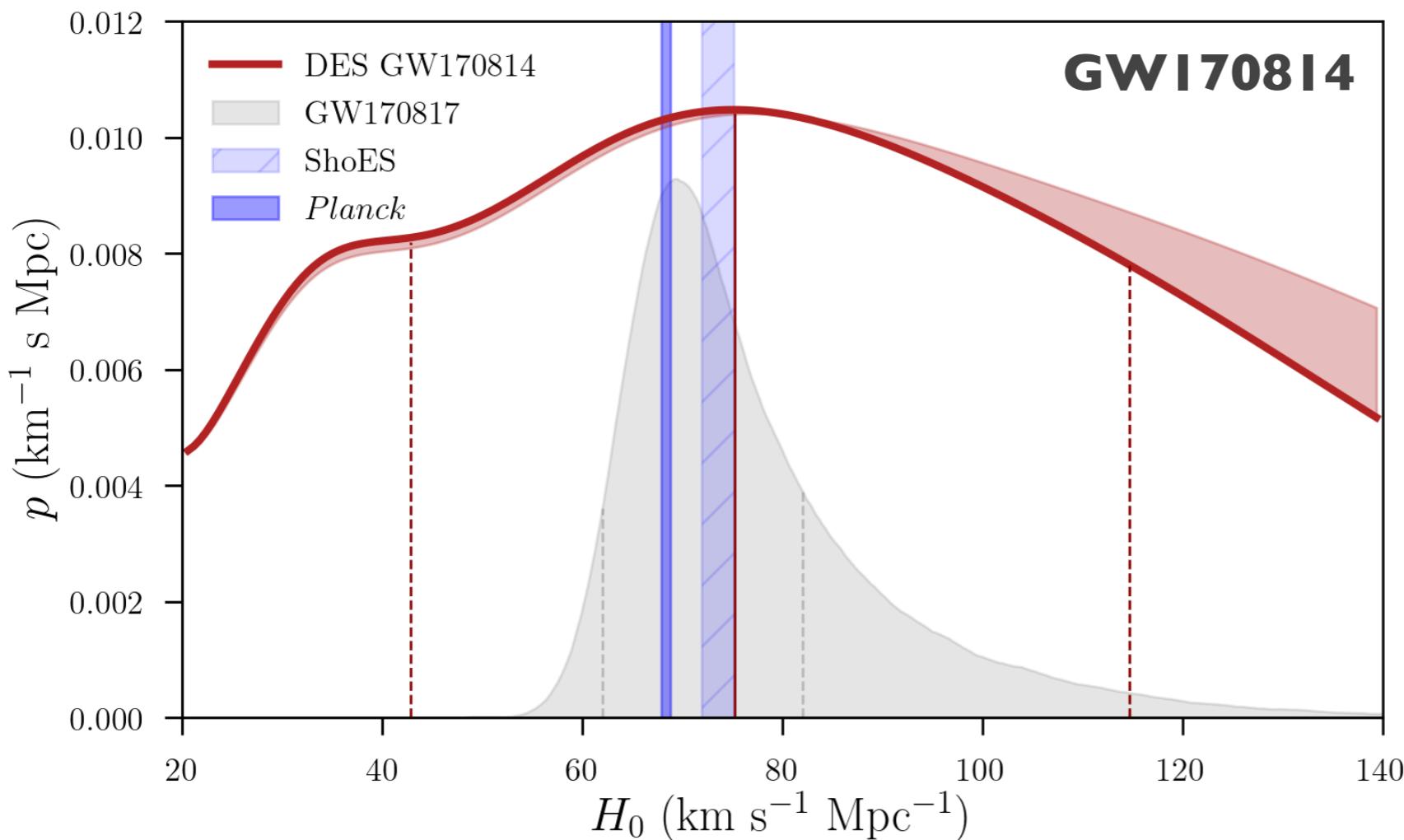
GW170814: the golden event (for DES)

- Define a complete volume limited galaxy sample down to $4 \times 10^8 M_{\odot}$ (77% of total stellar mass) using **Year 3 data**
- $\sim 77,000$ galaxies
- Assumption: event happened in one of the observed galaxies, or that it follows the LSS



GW170814 - Results

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



First measurement of the
Hubble constant using a
BBH
DES & LVC 2019
[arxiv:1901.01540](https://arxiv.org/abs/1901.01540)

LVC 20191908.06060 combines all O1+O2 events
Only 170814 improves 170817
→ Need for complete/deep galaxy catalogs

Systematics/assumptions/limitations

EM

- Analysis can be reduced to a study of the **dn/dz** in pixels
- **Need for complete/deep galaxy catalogs:** sweet spot between redshift accuracy/precision and completeness?

GW

- Gaussianity of **d posterior**
- Marginalization over M distribution and rate models

Systematics/assumptions/limitations

EM

- Analysis can be reduced to a study of the dn/dz in pixels
- **Need for complete/deep galaxy catalogs:** sweet spot between redshift accuracy/precision and completeness?

GW

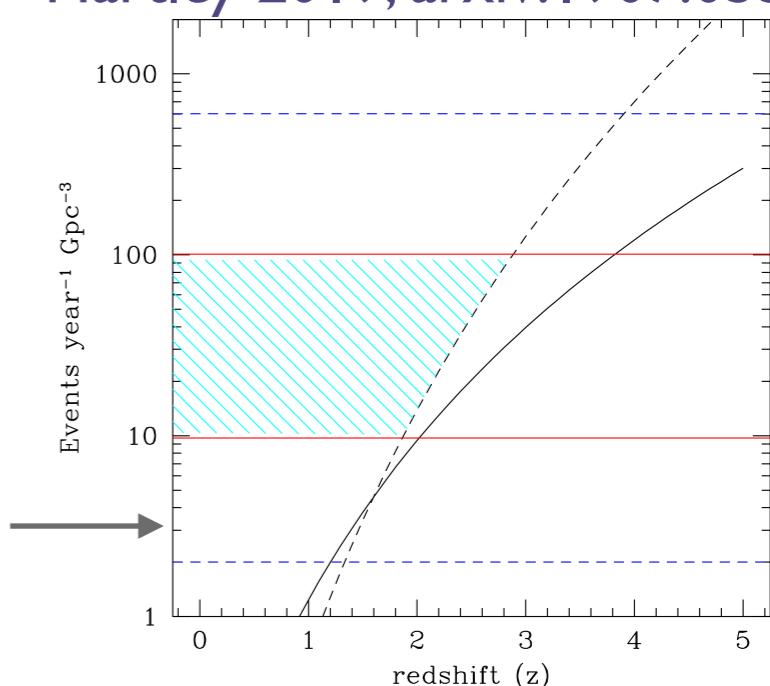
- Gaussianity of d posterior
- Marginalization over M distribution and rate models

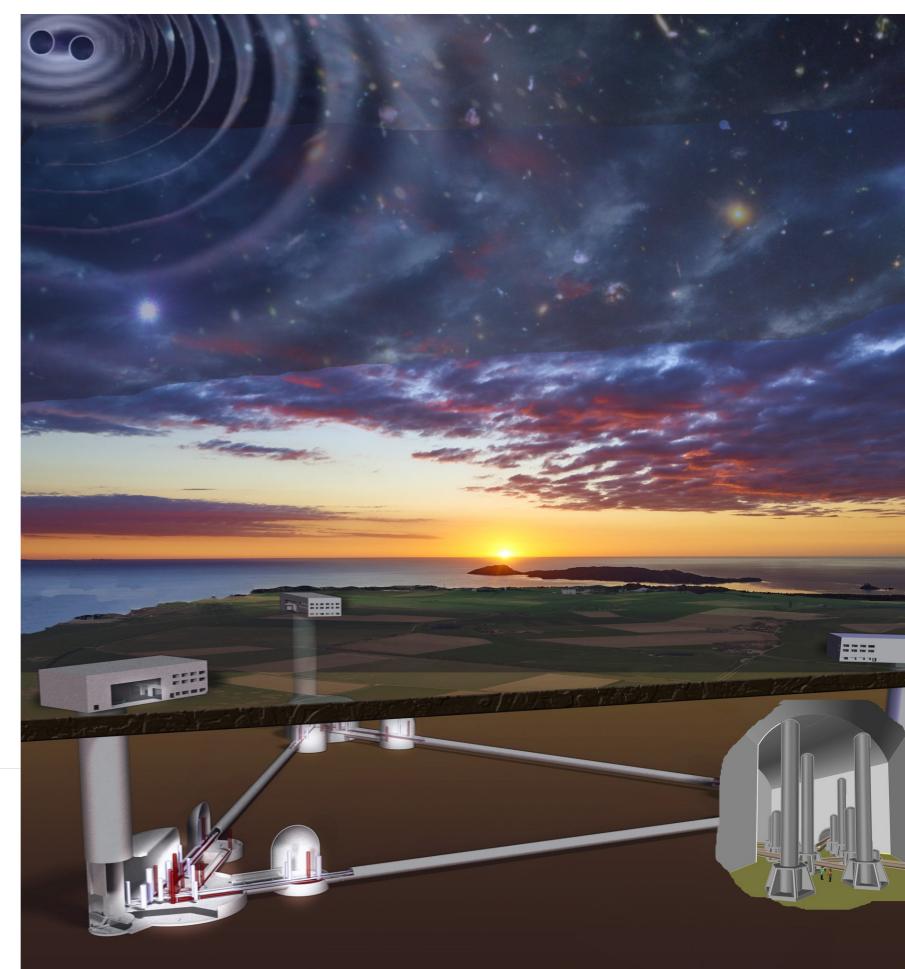
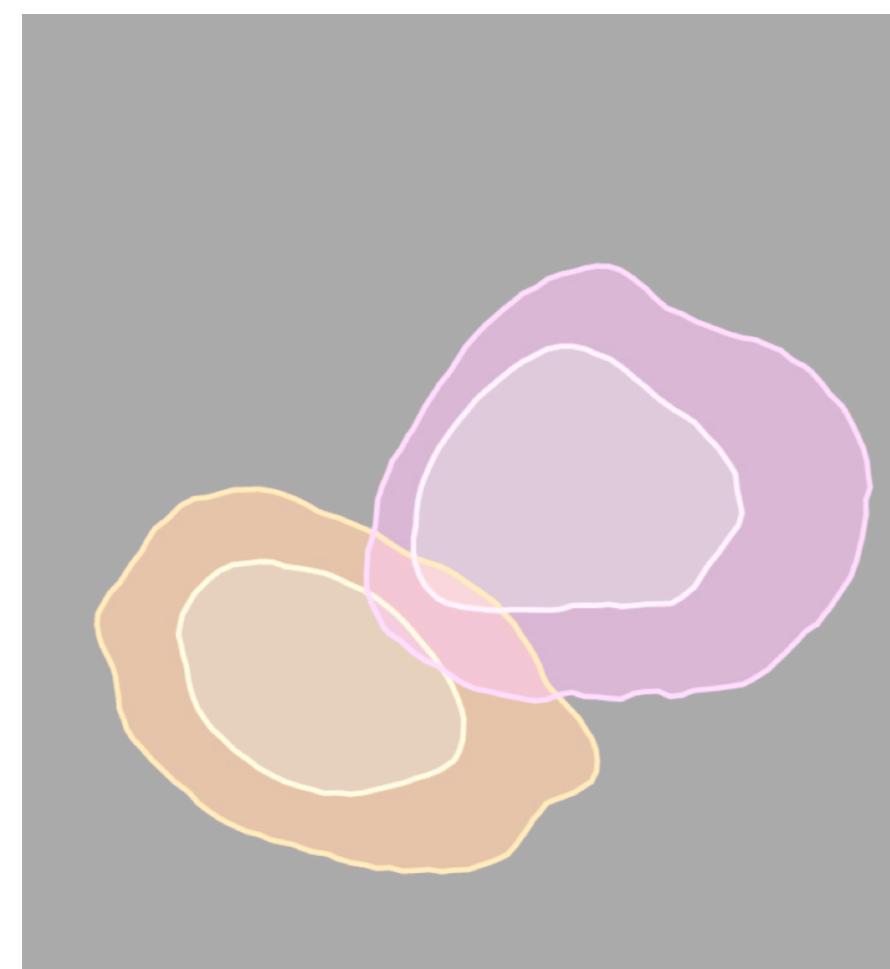
⋮
⋮

Selection function Galaxy weights:

- Depend on BBH formation channels
- ★ Stellar evolution (low Z environments, Belczynski+16)
 - ★ Dynamical interactions (Portegies+00)
 - ★ PBH (Hawking 71)
 - ★ AGN disks (Stone+16)
 - ★ Central BHs of merging ultra-dwarf galaxies

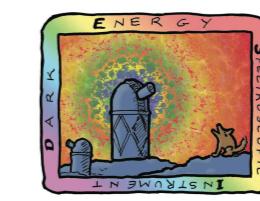
Conselice, Bhatawdekar, AP & Hartley 2019, arxiv:1907.05361





Motivation
DES

Current measurements
Identify limits/
systematics

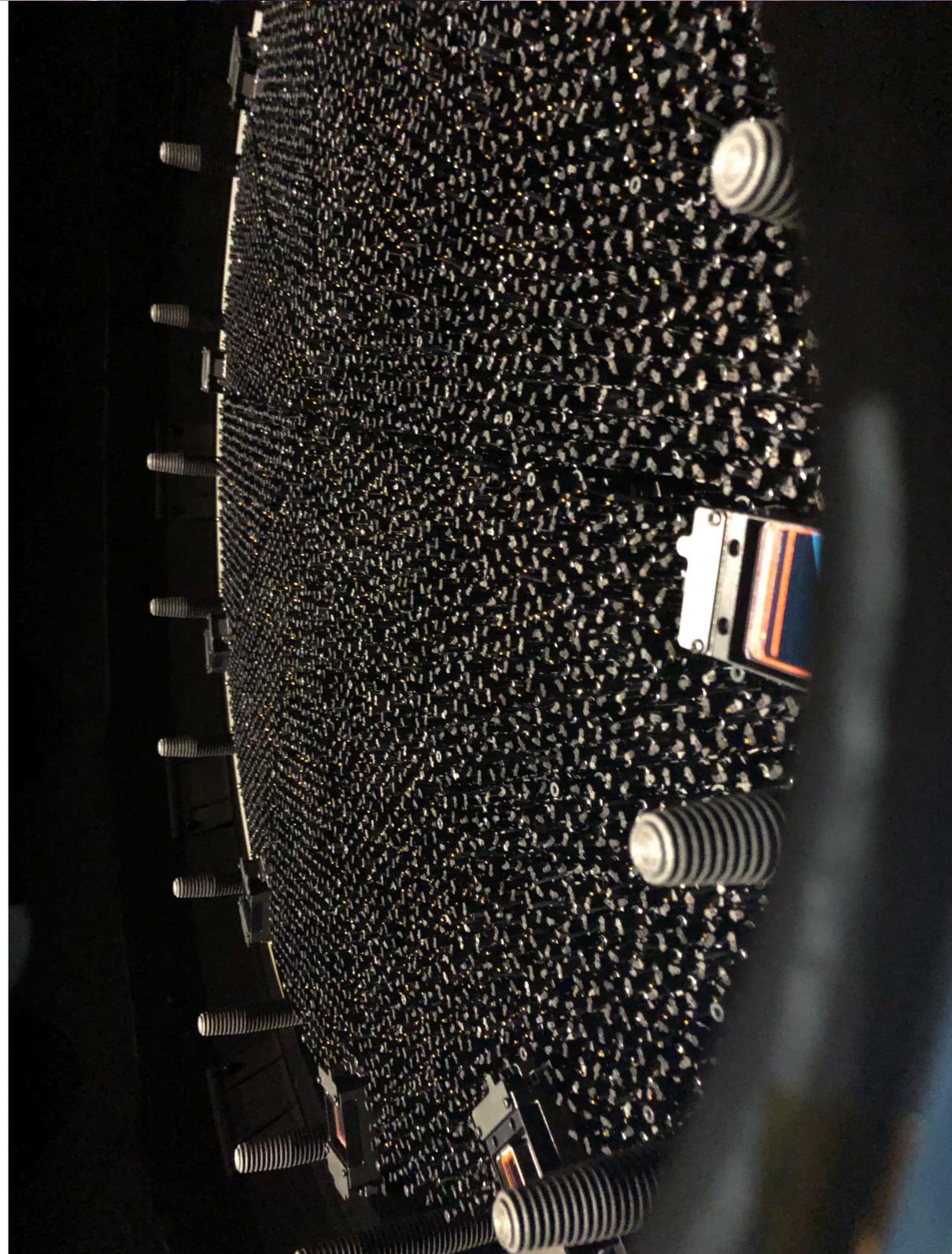


LST
Large Synoptic Survey Telescope

→ **Ways forward**

The Dark Energy Spectroscopic Instrument (DESI)

- **5000-fiber spectrograph** on Kitt Peak Mayall 4m Telescope (AZ)
- **8 deg² FoV**
- **Stage-IV BAO/RSD DE experiment**
- **14,000 sq. deg. over 5 years**
- Starting **SV** in Feb 2020
- **Bright Galaxy Sample:** mag limited sample of 10M galaxies ($r < 19.5$, $z < 0.4$)



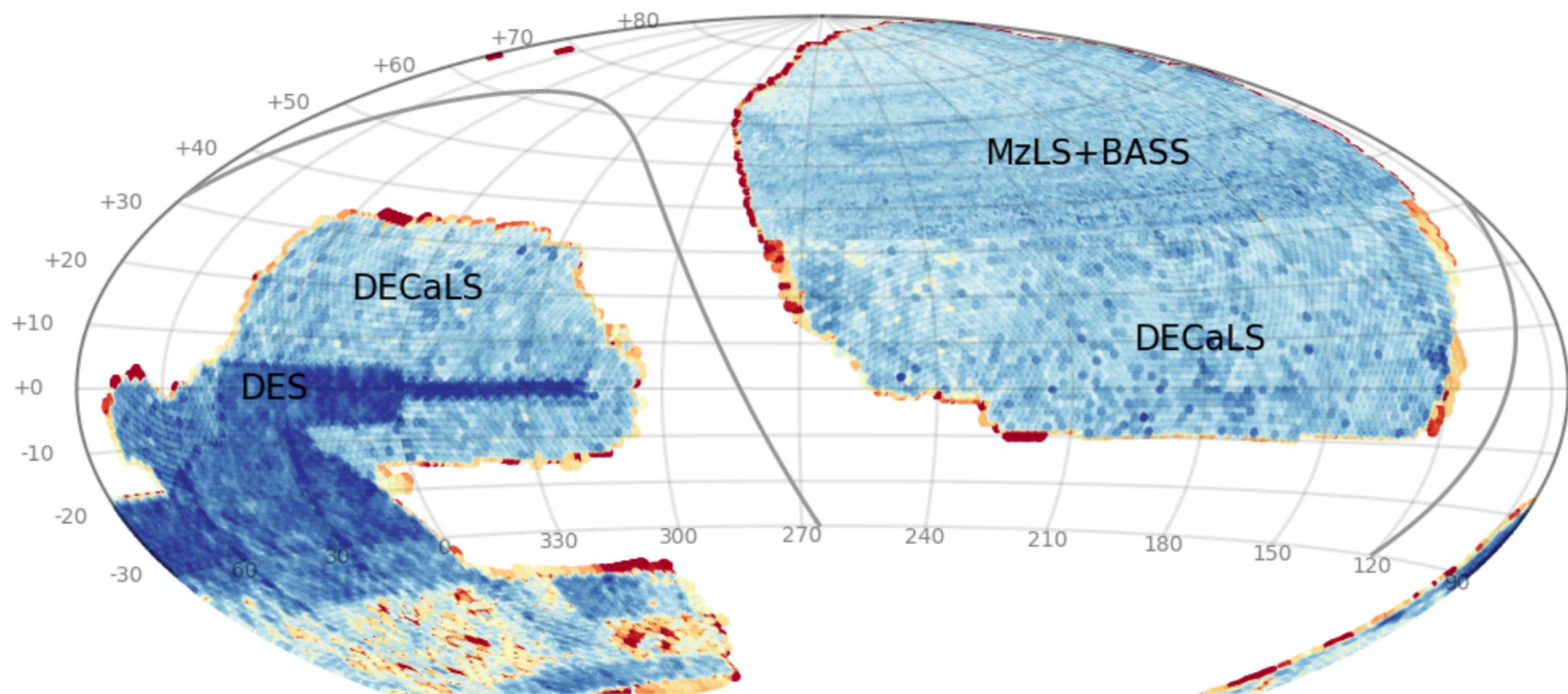
O3 Dark standard sirens with DES+DESI Imaging



DESI Imaging (+WISE):

- Dark Energy Camera Legacy Survey (DECaLS)
- Beijing-Arizona Sky Survey (BASS)
- Mayall z-band Legacy Survey (MzLS)

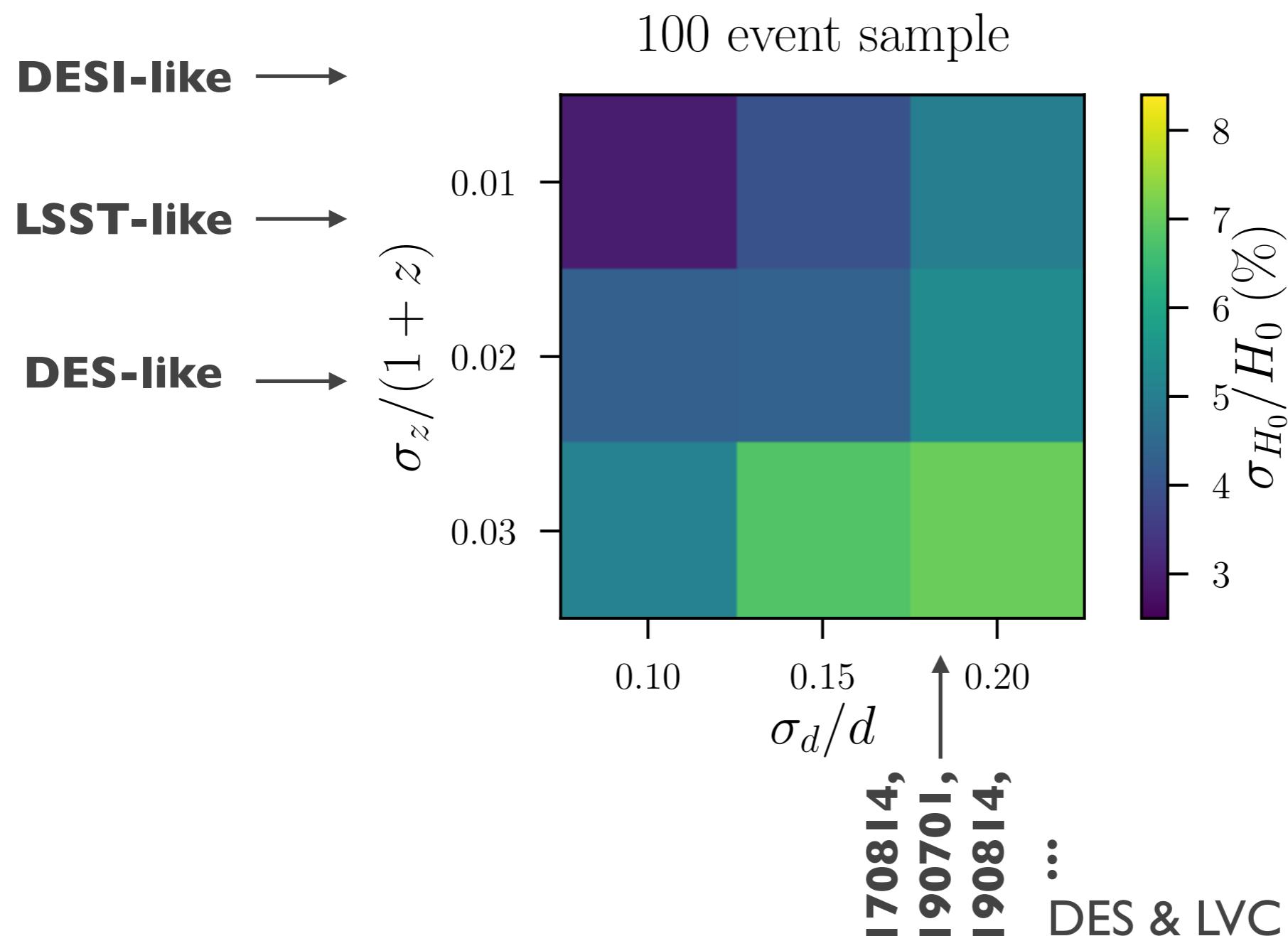
Photo-zs perform well down to $r \sim 21$ (DR7, R. Zhou & J. Newman)
25-30% of O3 BBH well localized and covered by these programs



Prospects for dark standard sirens

- 5% statistical precision with DESI-like data and ~ 100 GW170814-like events
- Science that will come for free with DESI nominal targets (+ try to allocate fibers to deeper mags)

AP et al. 2019, [arxiv: 1903.04730](https://arxiv.org/abs/1903.04730)



Conclusions



- ★ **Other than transient discovery, synergies between GW experiments and galaxy surveys enable a new cosmological probe**
- ★ Lessons from LVC O2:
 - **First measurement** of H_0 with BBH+DES galaxies
 - Identified sources of **systematics/limitations**
- ★ Prospects:
 - Interesting results already from O3 & O4 with upcoming surveys (**DESI, TAIPAN, LSST...**)
 - StSs may help understanding the Hubble constant tension
 - Make an impact on targeting for next surveys (e.g. DESI-II)

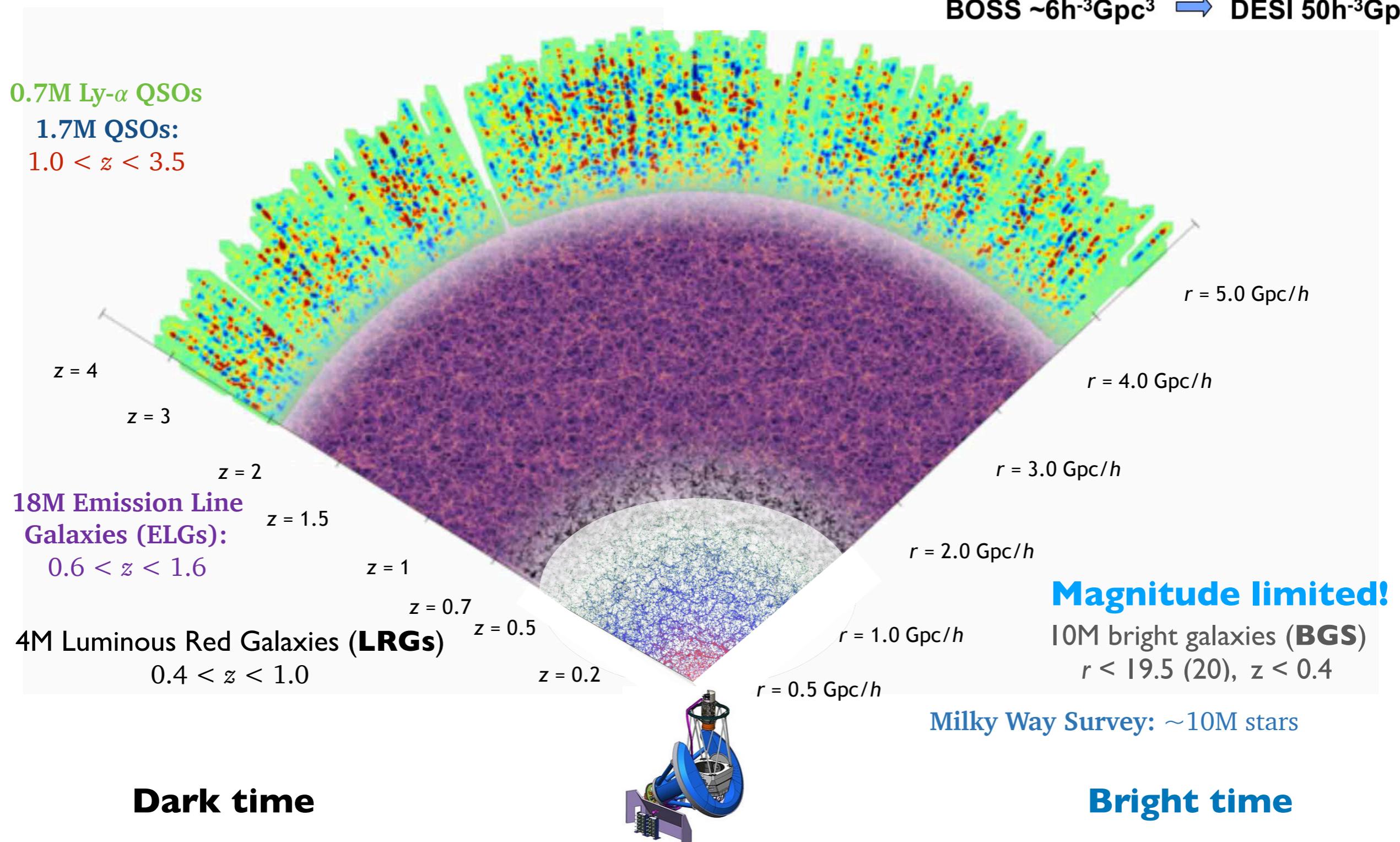
A photograph of a large telescope dome at night. The dome is illuminated from within, showing a complex internal structure of red and white panels. The sky behind the dome is filled with numerous long, curved white lines, known as star trails, which appear to radiate from a central point. The dome is situated on a rocky hillside with some dark bushes in the foreground.

Thank you!

The Dark Energy Spectroscopic Instrument (DESI)

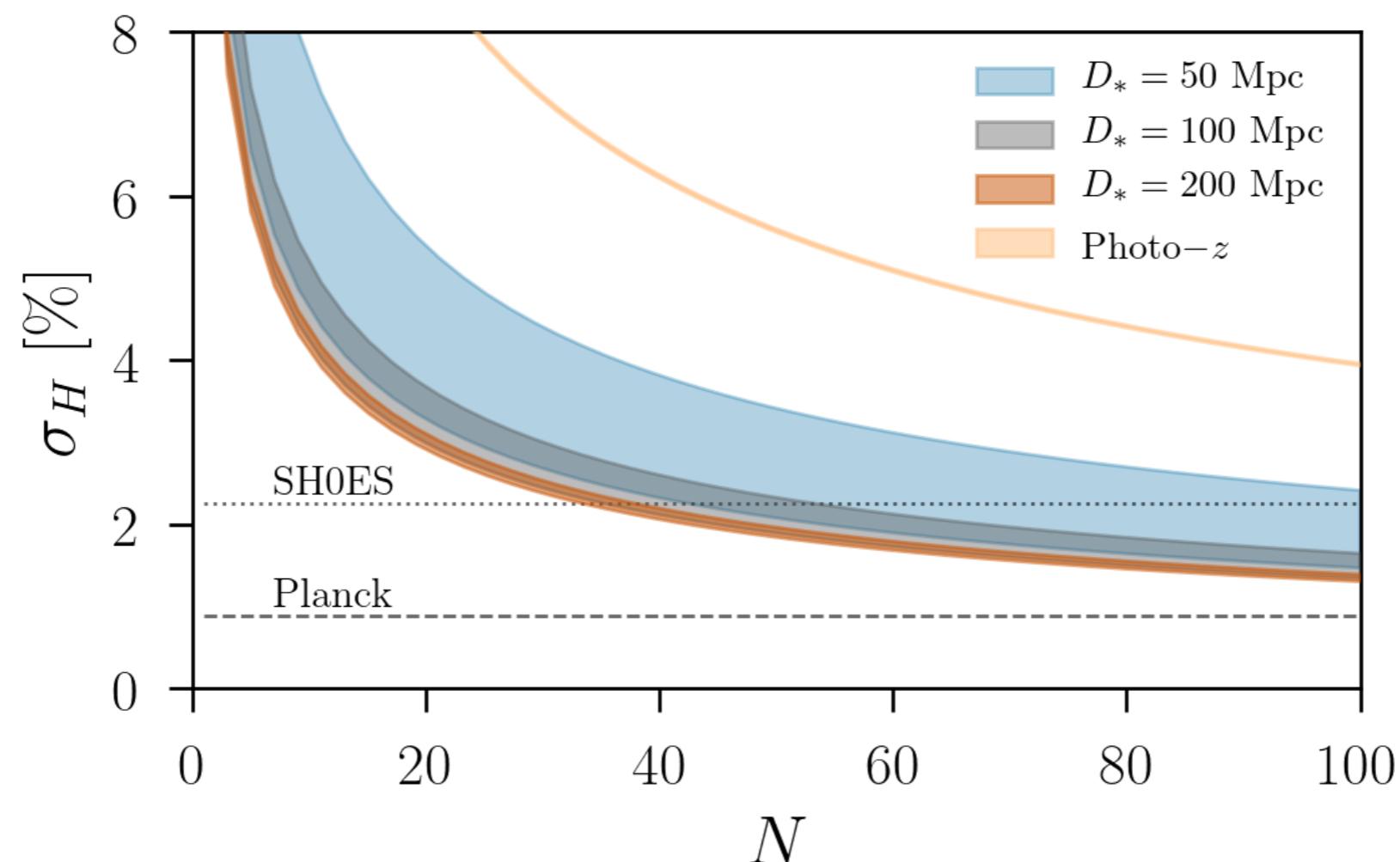


BOSS $\sim 6 h^{-3} \text{Gpc}^3$ → DESI $50 h^{-3} \text{Gpc}^3$

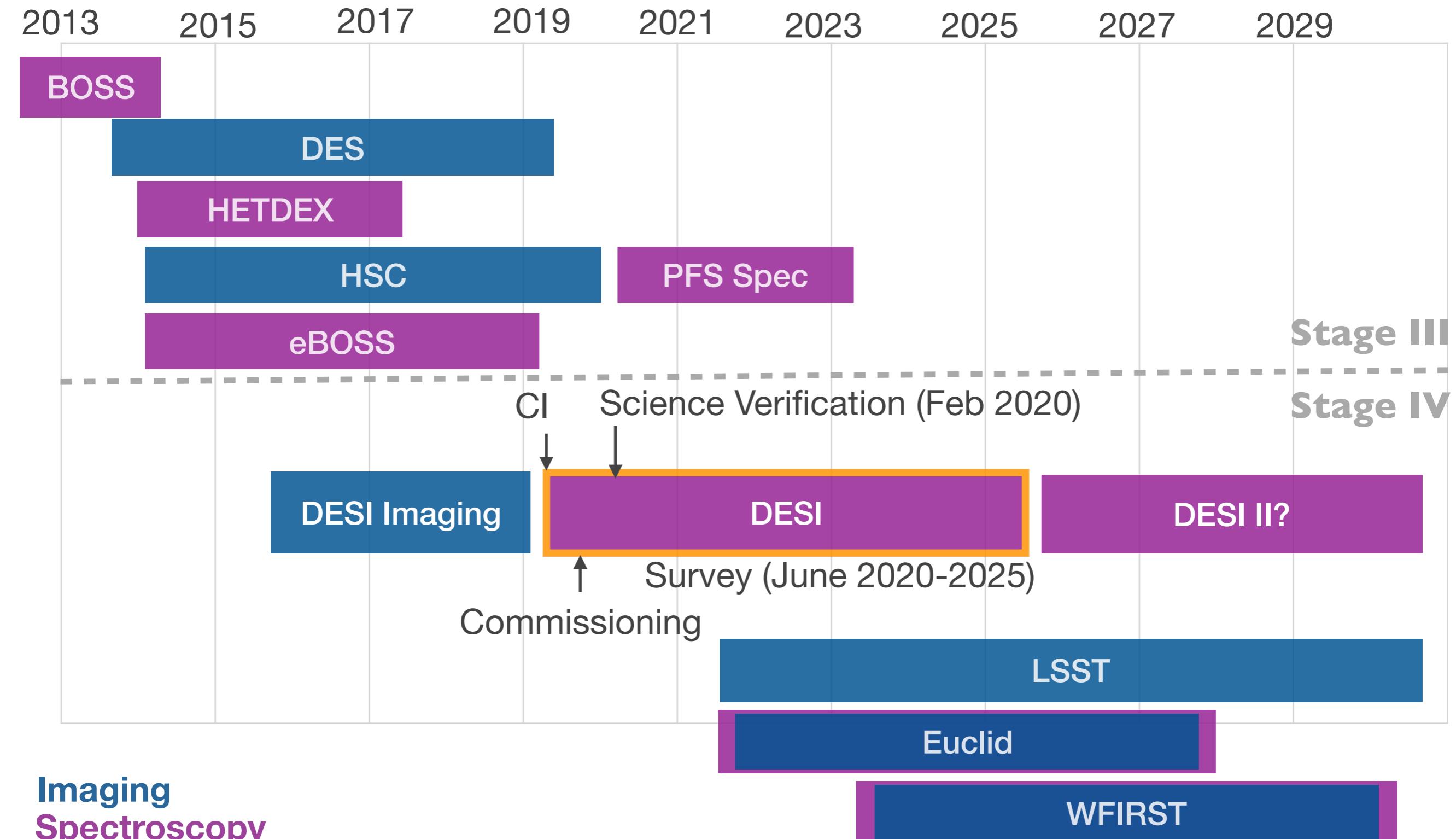


Bright Standard Sirens

- DESI can help with quick classification, **host galaxy redshifts and peculiar velocities**
- ~2% measurement in ~2023: enough to solve H_0 tension - **Chen, Fishbach & Holz 2017**
- DESI+CMB+StS: up to factor 3 improvement on dynamical DE EoS constraints - **Di Valentino et al. 2018**



DESI timeline

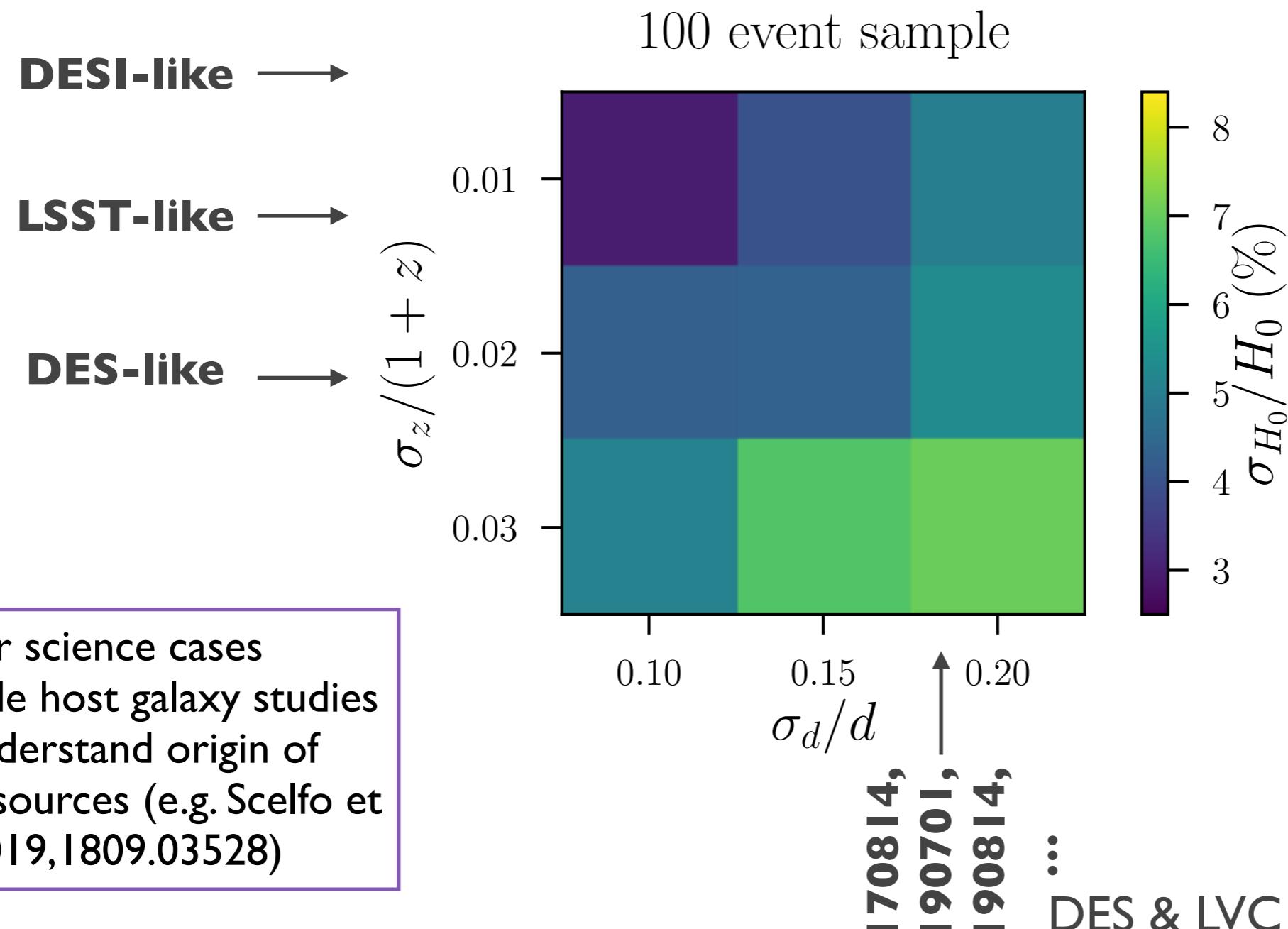


Imaging
Spectroscopy

Dark standard sirens with DESI BGS

Science that will come for free with DESI nominal targets

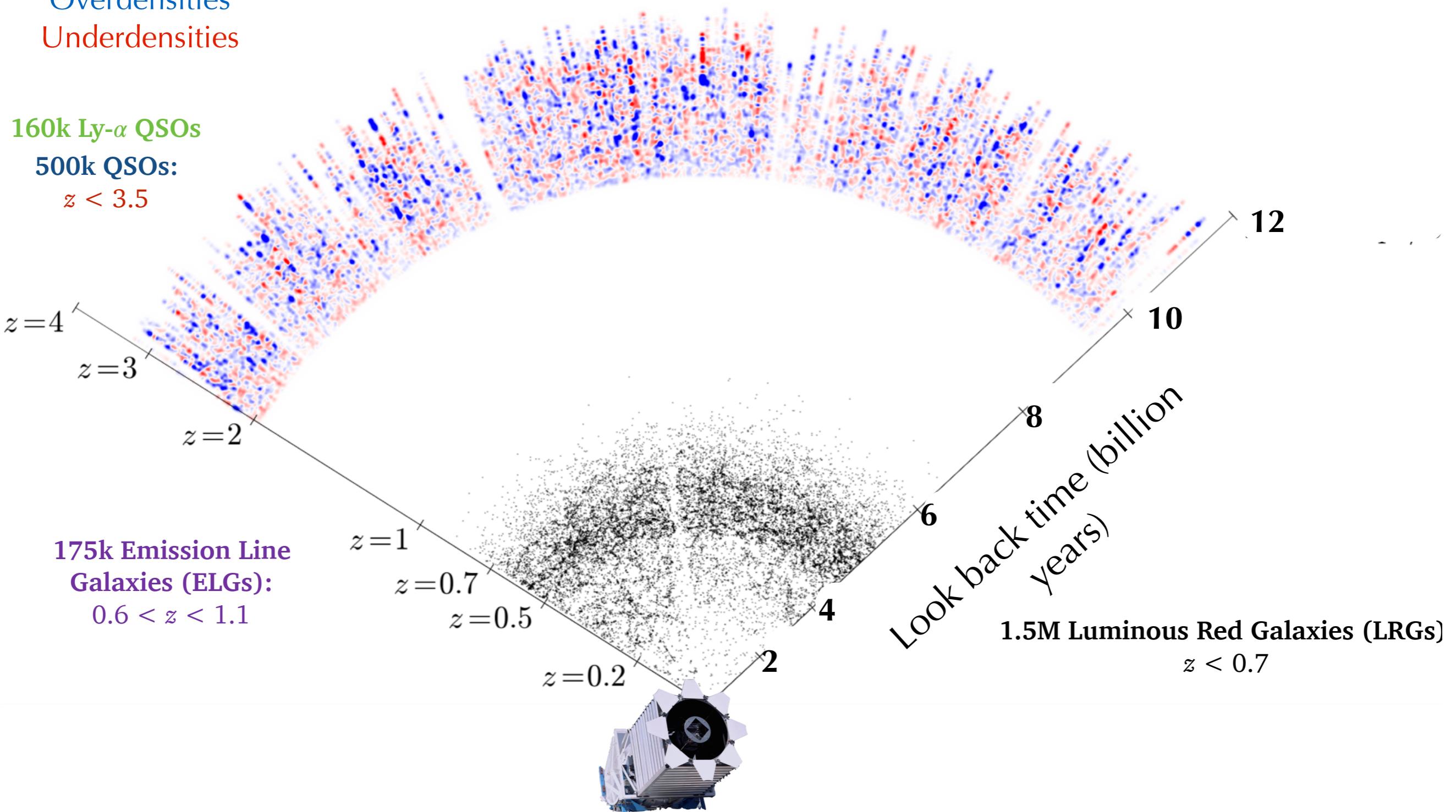
- 4-5% statistical precision with DES-like data and ~ 100 GW170814-like events



SDSS+eBOSS



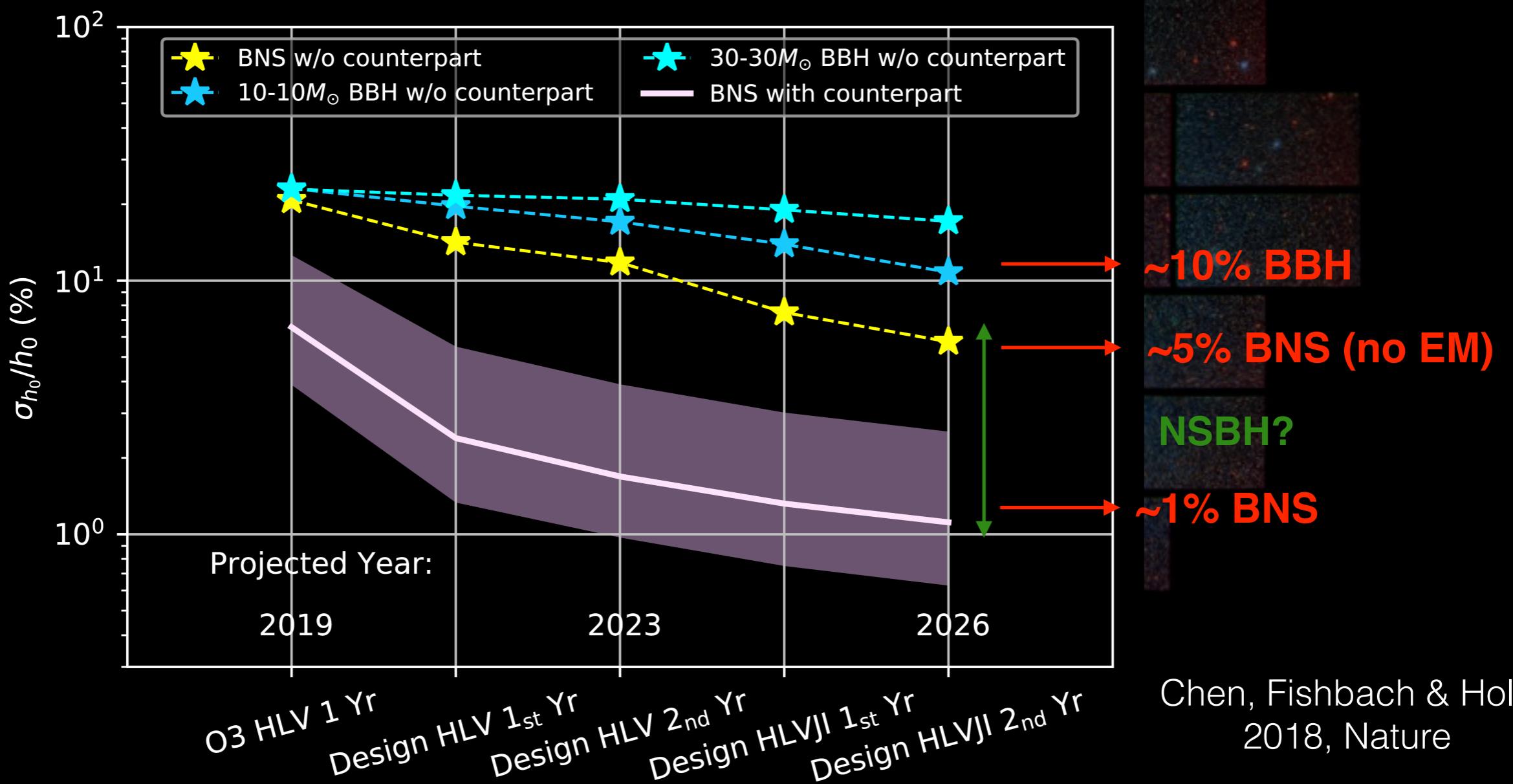
Overdensities
Underdensities



Prospects for current detectors



- Few % measurement in ~2022 from **bright sirens**: enough to **solve H_0 tension**
- **Dark sirens from BBH worse**. Need more well-localized events
- **NSBHs** can provide competitive constraints, if rate >1/10 BNS (Vitale & Chen 2019, PRL)



Impact on full cosmology



- Combining upcoming GW H_0 constraints + future CMB + BAO significantly **improves constraints beyond Λ CDM**
- **Breaks geometrical degeneracies** between parameters from CMB
- Factor 1.6-2.8 improvement on dynamical DE parameters

