

Dark Energy Experiments

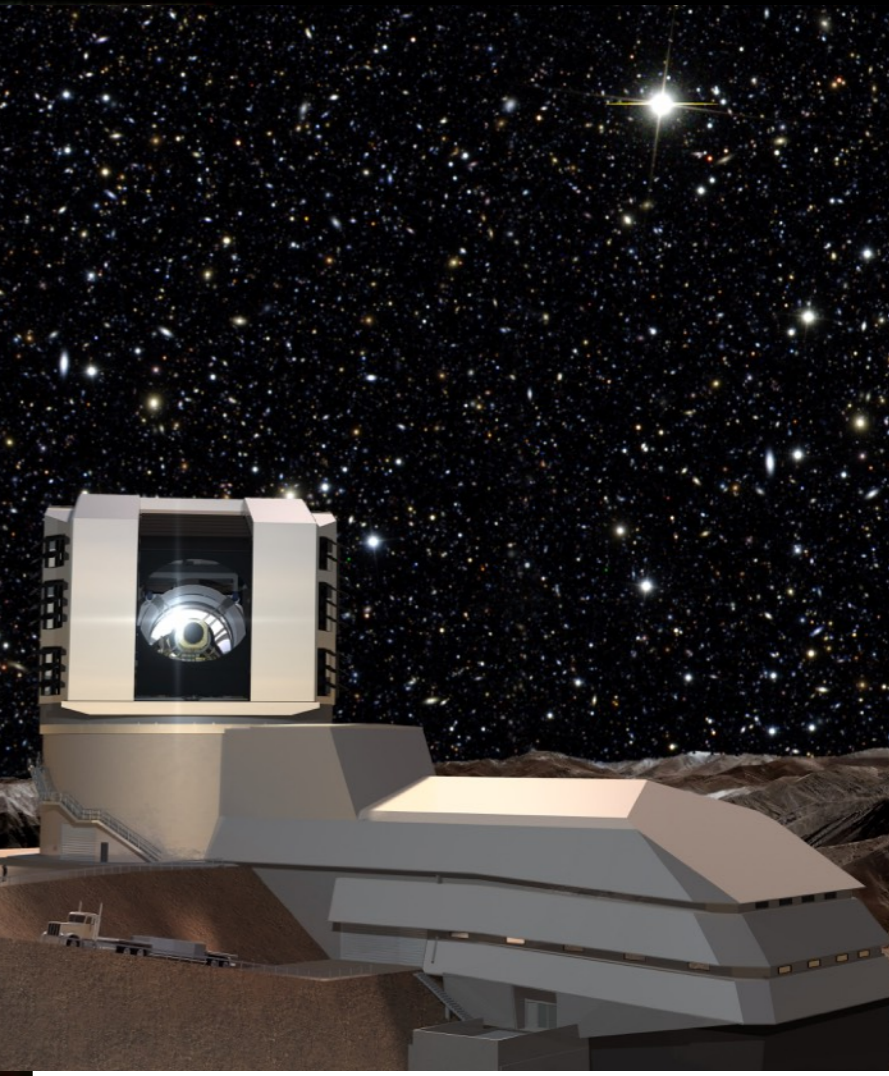
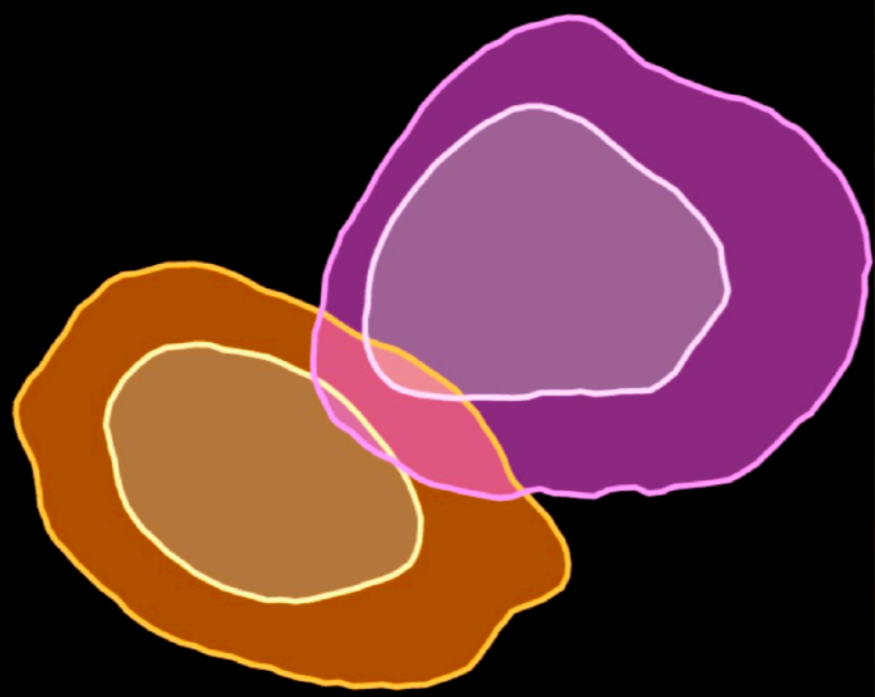
Antonella Palmese (Fermilab)
52nd Users Meeting
13 June 2019

On behalf of the Dark Energy Survey Collaboration
GW Dark sirens in collaboration with LIGO/Virgo

Introduction

Results

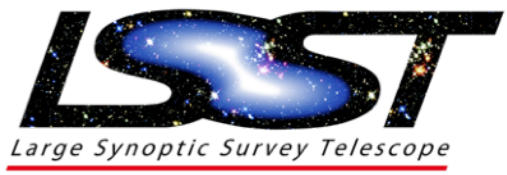
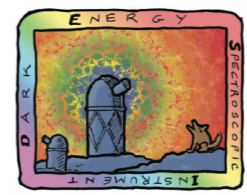
Predictions



Dark Energy Survey (DES)
Cosmological probes

- Latest DES cosmology results
- SNe
 - Combined probes
 - GW

**Cosmology with
current and upcoming
galaxy surveys**



Dark Energy Survey

Fermilab-led experiment - Operations completed

Last night - January 8th 2019
NGC 1365

Funded by:



The Dark Energy Survey

darkenergysurvey.org
facebook.com/darkenergysurvey

~450 scientists from
25 institutions in 7
countries



Dark Energy Survey



DECam

3 sq deg FOV, 570 Mpix optical CCD camera
Built at Fermilab
Blanco telescope (Chile)

DES programs

Wide: 5000 sq deg (**1/8 of the sky & data for 300 Million galaxies**)

SNe: 30 sq deg ~every week

Neutrinos: followup of Icecube events

GW: followup of LIGO/Virgo events

DES-GW effort continues

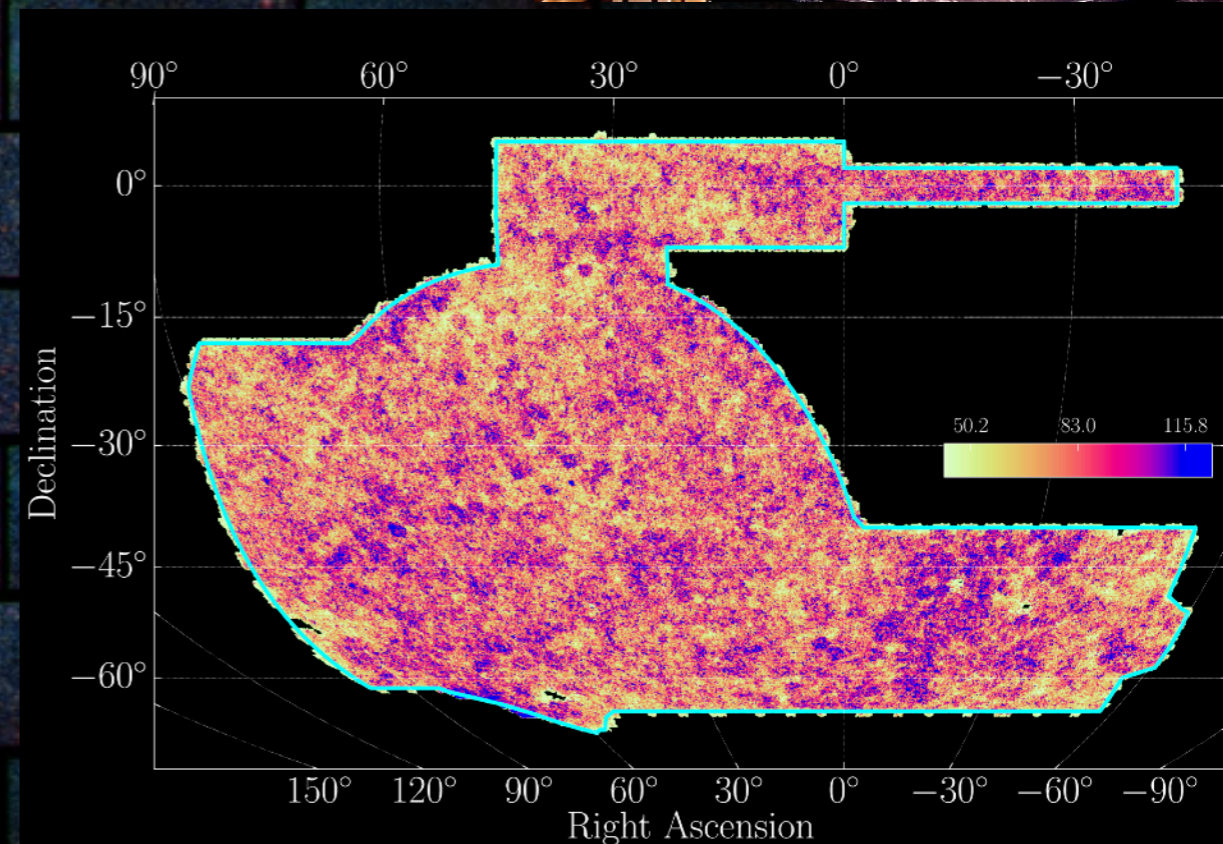
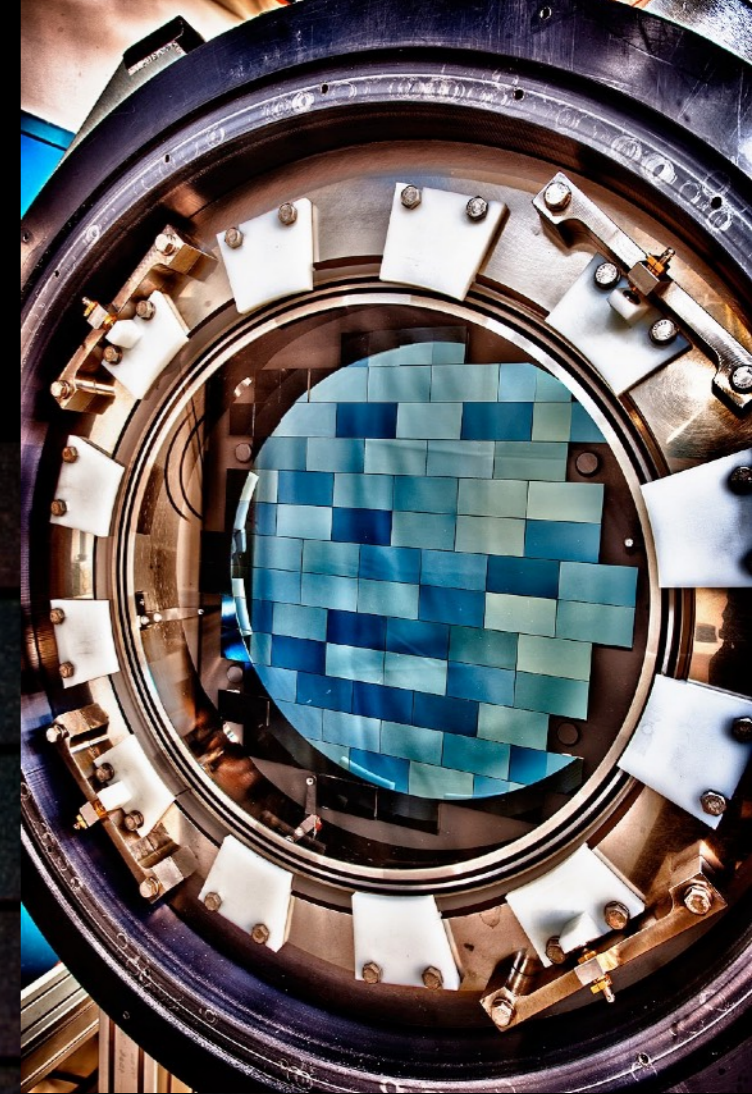
Datasets

Year 1 (Y1): <2000 sq deg, not full depth

Year 3 (Y3): Full area, not full depth (DR1,

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

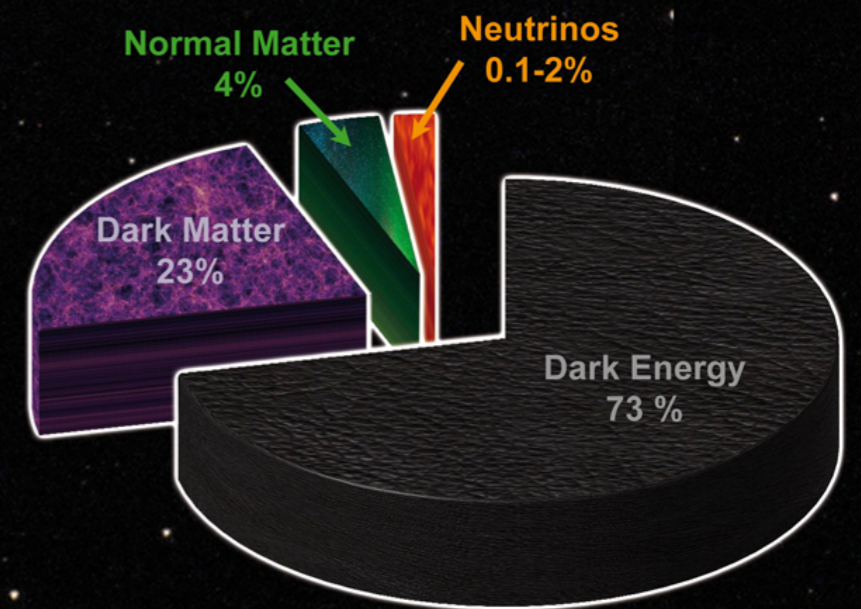
Year 5 (Y5): Final



Dark Energy



- Makes up ~70% of the mass-energy of the Universe, causes the observed accelerated expansion
- DE equation of state parameter w : $P = w\rho$
- **Cosmological constant Λ** : energy density constant in time, $w=-1$.
- **Most successful cosmological model - flat Λ CDM** spatially flat expanding Universe governed by GR, where Λ and CDM (Cold Dark Matter) are the main components at times close to present. Works well with just 6 parameters!
- Dynamical DE (CPL): $w(a) = w_0 + w_a(1 - a)$



Content of the Universe

How do you measure DE?



DE leaves 2 observable imprints:

Geometry of the Universe

Increases distances and volumes

Supernovae (SNe)
Standard candles

Gravitational wave (GW)
Standard sirens

Baryon Acoustic Oscillations (BAO)
Standard ruler

Cosmic Microwave Background (CMB)

Growth of cosmic structure

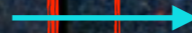
Suppresses the growth

Galaxy clustering

Gravitational lensing

Galaxy clusters

Adam's talk



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DES

Adam's talk

The effects of DE can also be mimicked by variations in other cosmological components, other physical models, and systematics

With DE experiments, we are interested in **a set of cosmological parameters**, measured by **combining different, complementary probes/experiments**

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DE leaves 2 observable imprints:

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SNe as standard candles

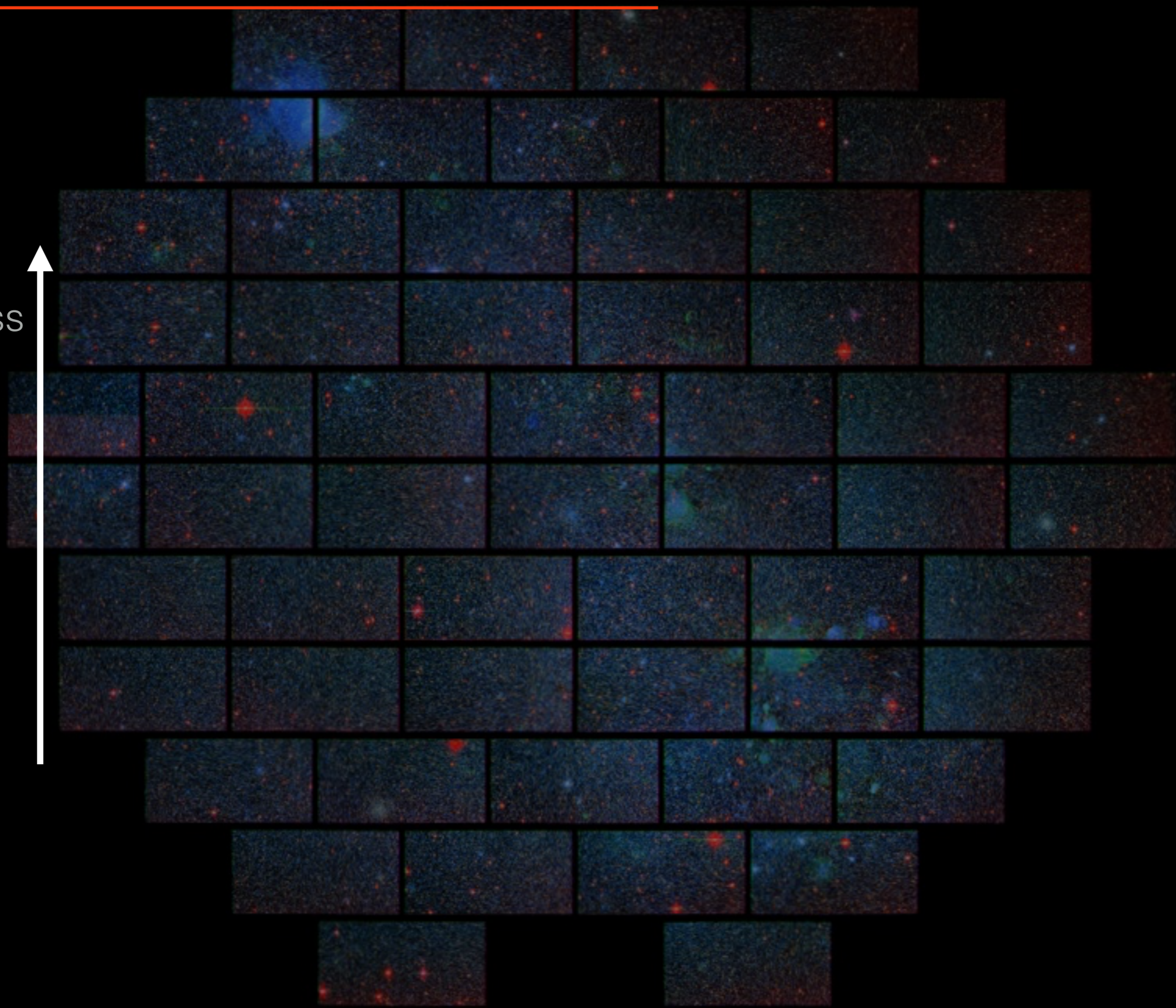


SNe as standard candles

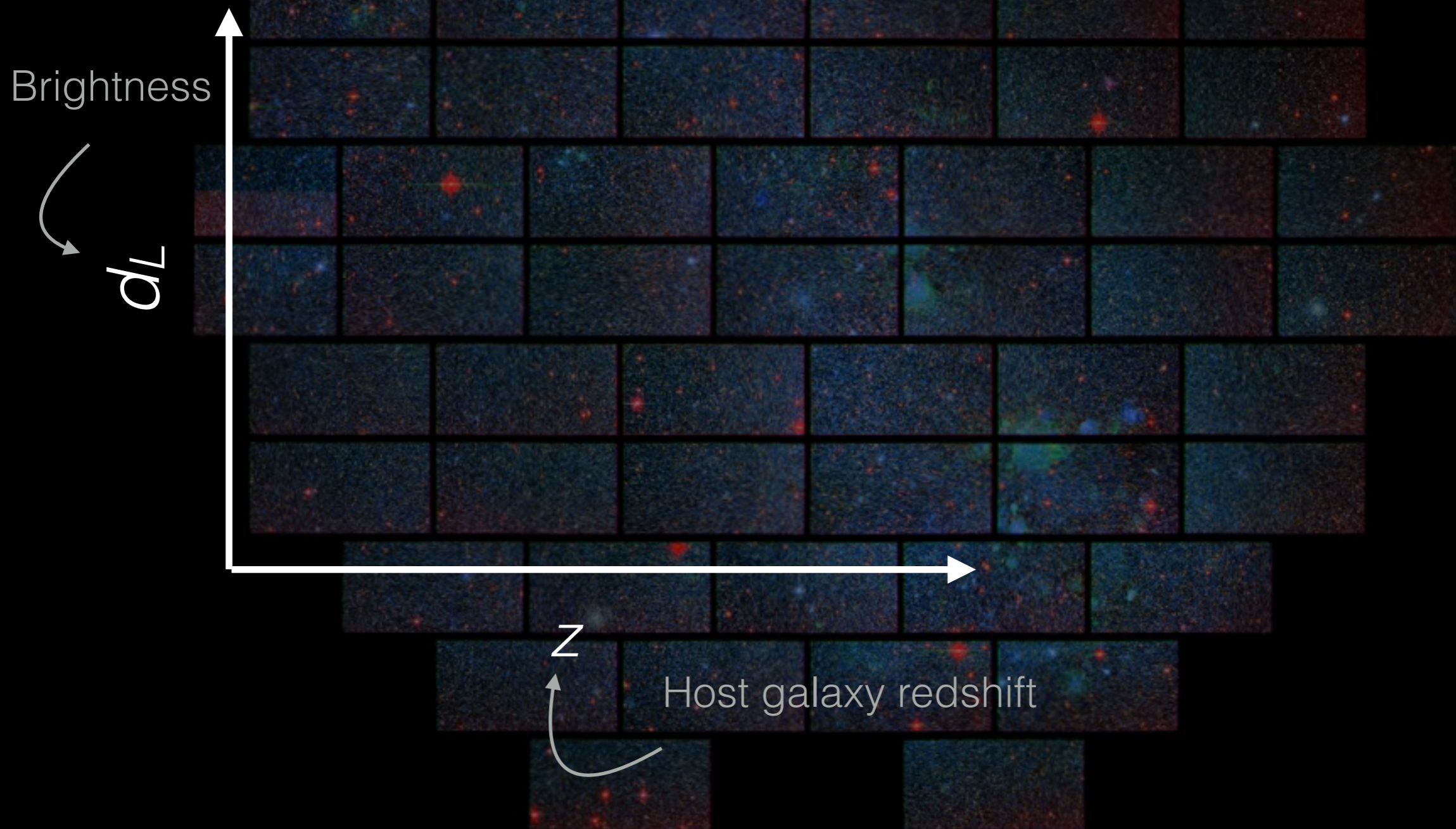


Brightness

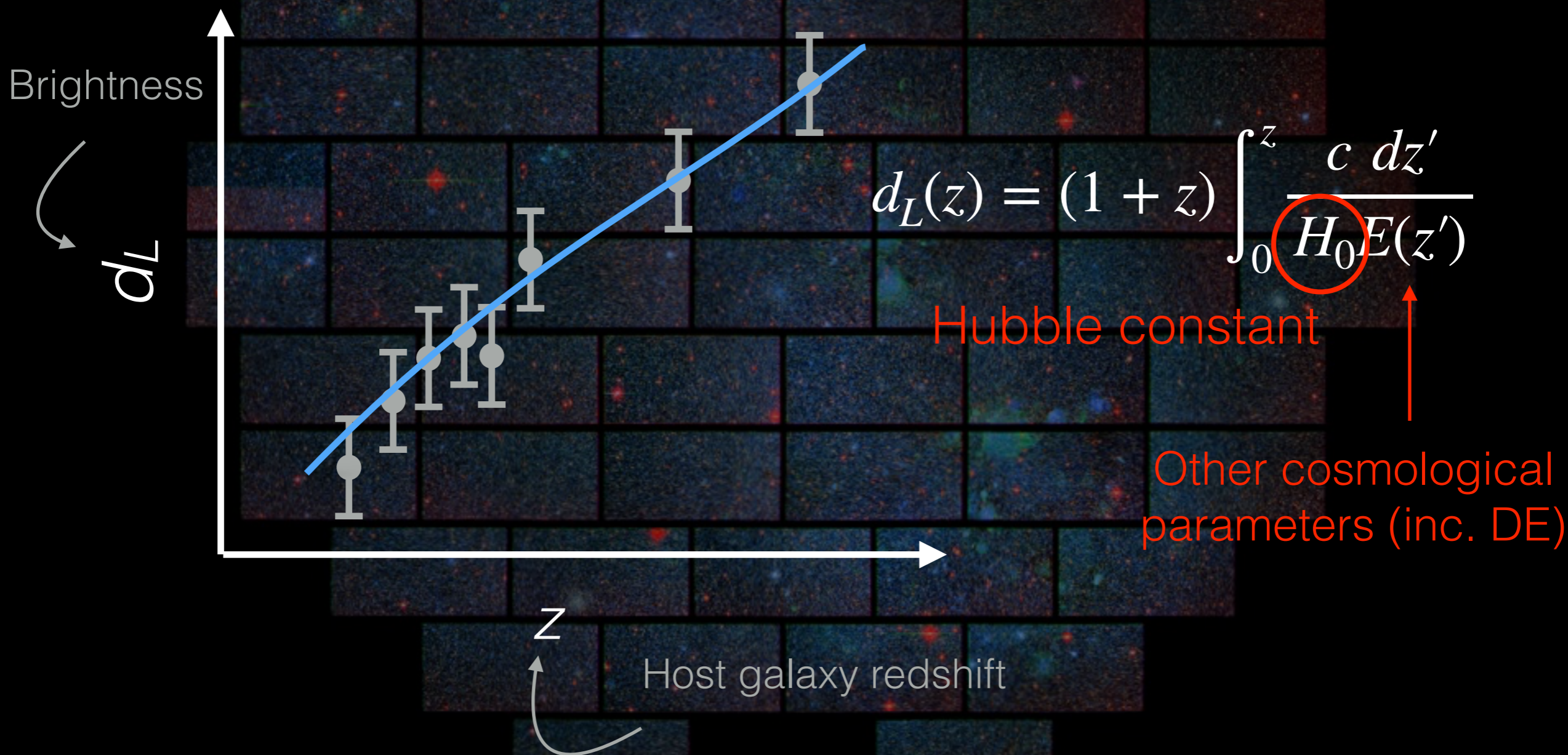
d_L



SNe as standard candles



SNe as standard candles

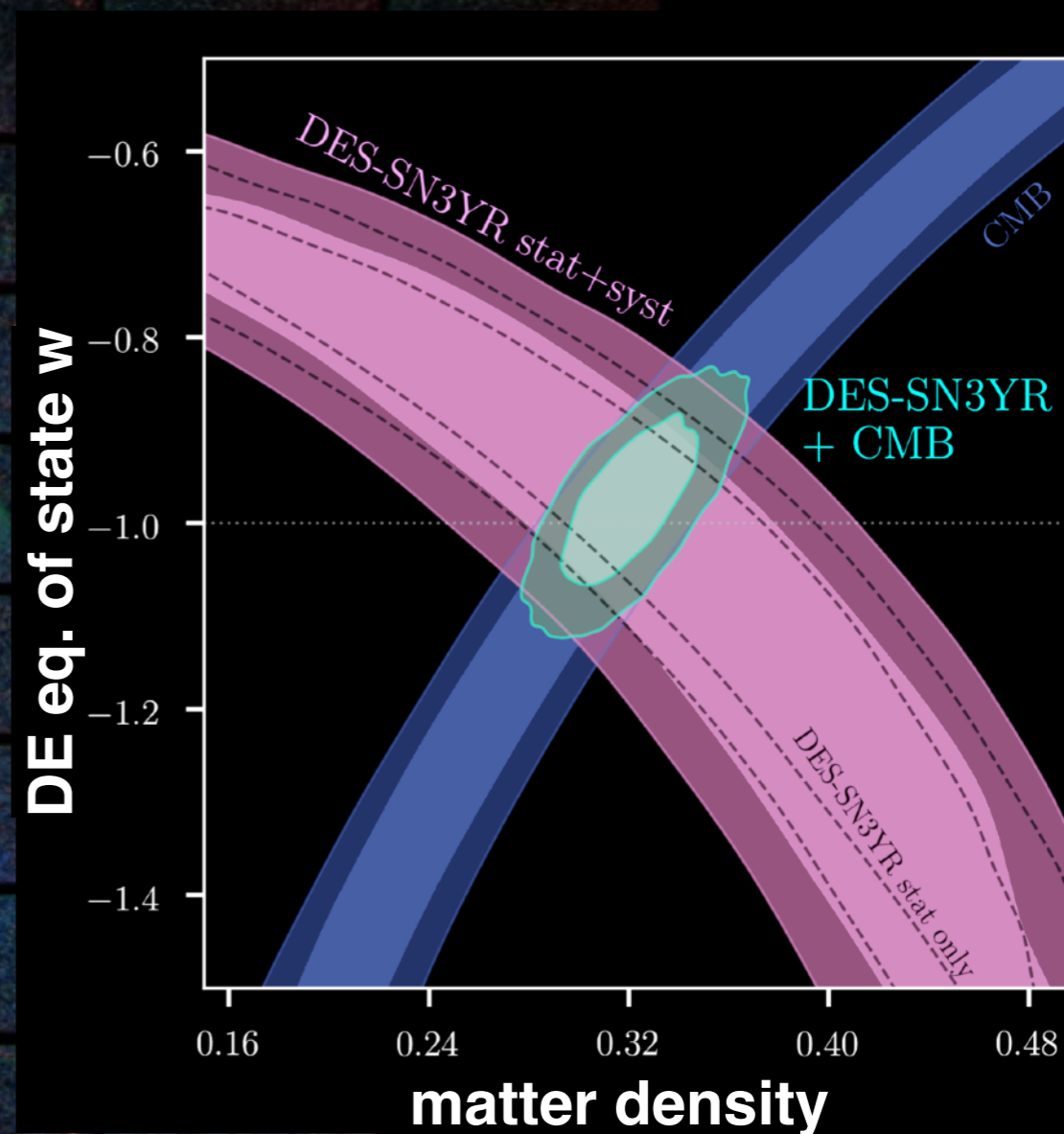


First DES Supernovae results



$$w = -0.978 \pm 0.059$$

- 207 DES Y3 spectroscopically confirmed SN
- ~10% of final DES sample
- Size < 1/3 state-of-the-art combined SN sample, w constraints only 1.4x larger: excellent DES data quality
- Consistent with flat LCDM

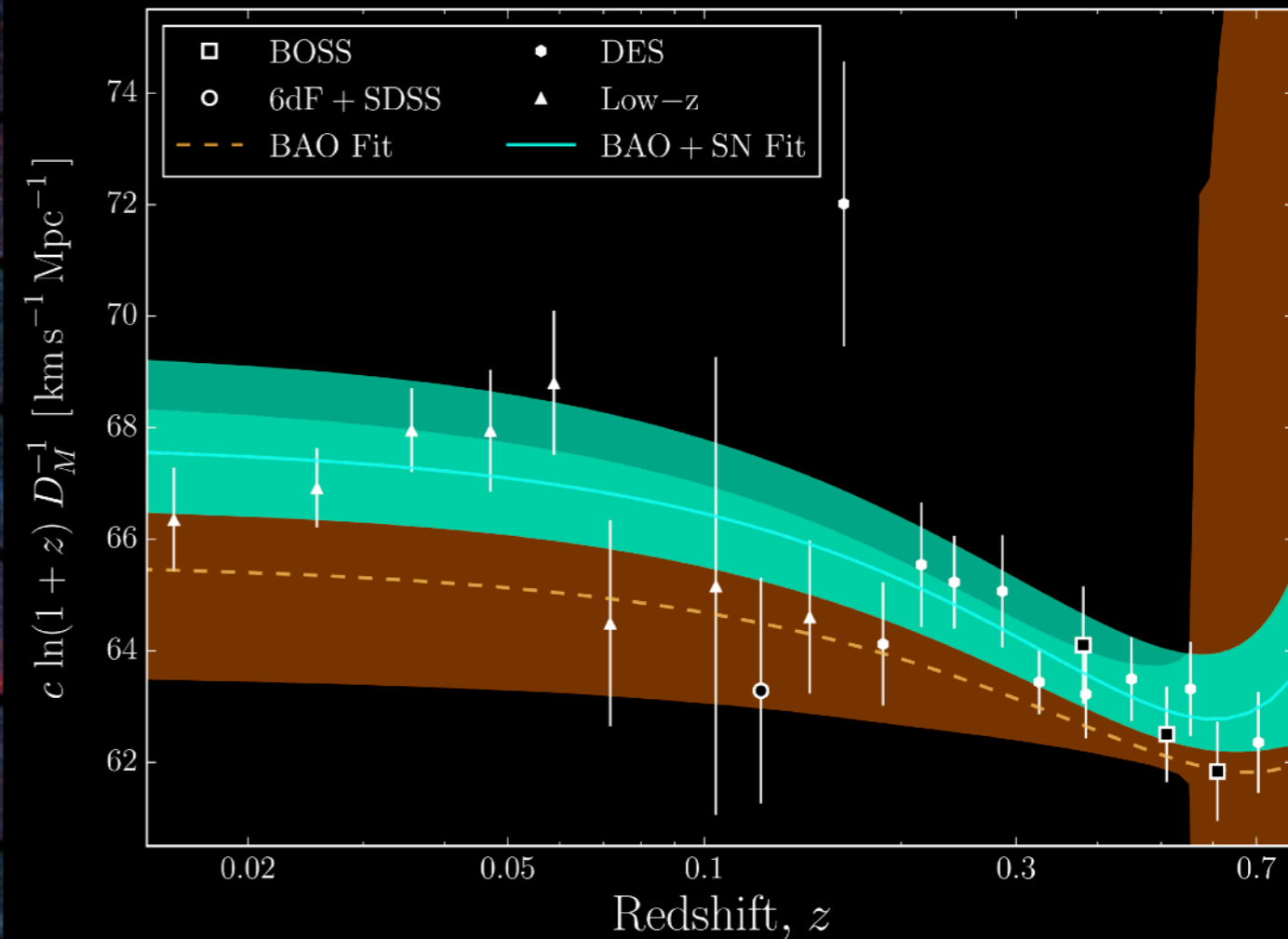




First DES Supernovae results: H_0

$$H_0 = 67.8 \pm 1.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

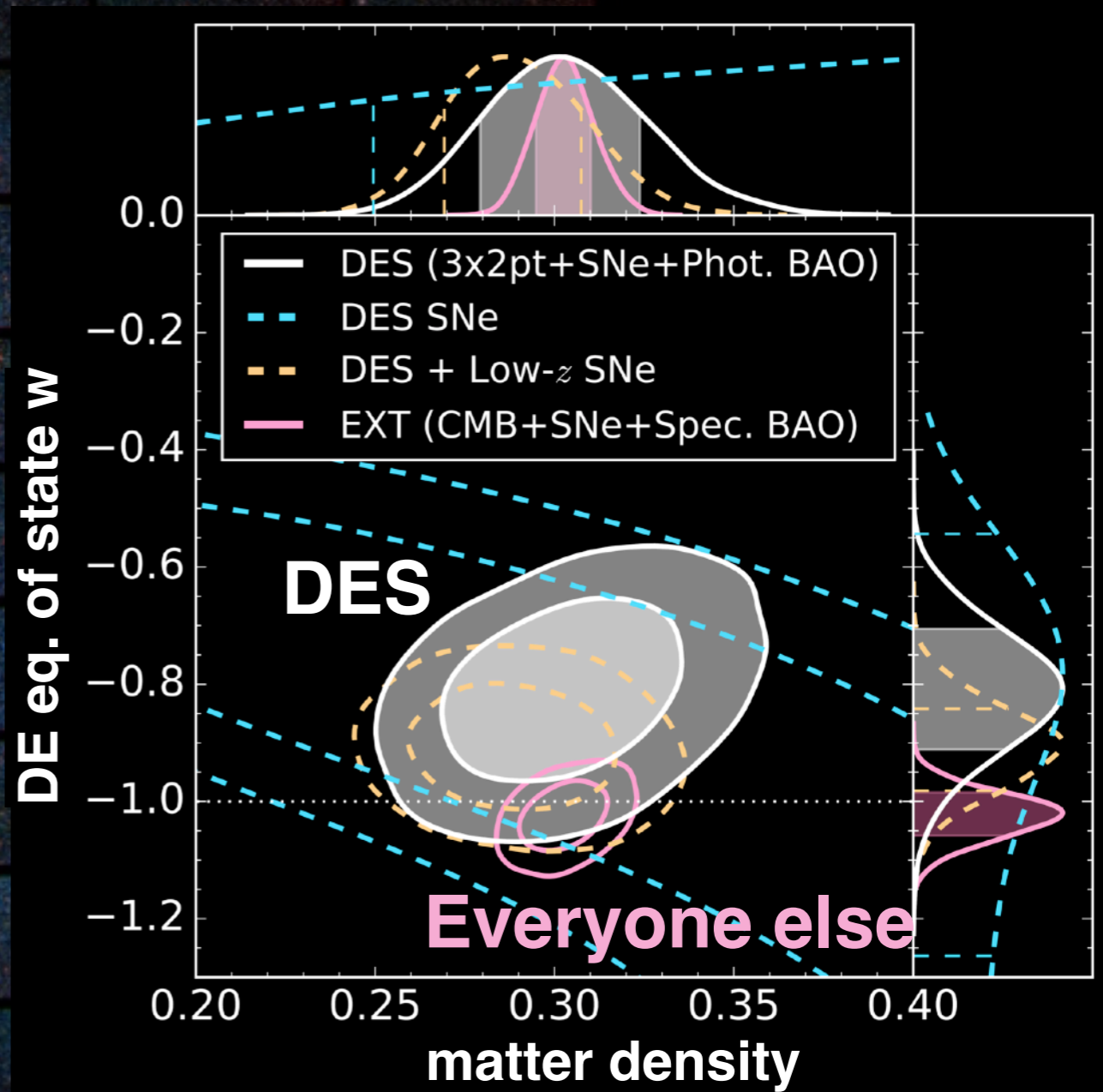
- Need a “distance ladder”
- DESY3 + low- z + BAO + Planck CMB prior on sound horizon
- Minimal assumptions about cosmological model
- Consistent with CMB measurements of H_0



Macaulay+DES 2019 1811.02376

DES Y1/Y3 combined probes

- DES Y1 3x2pt (weak lensing+clustering) & BAO + Y3 SNe
- Consistently validated analysis across all probes
- Probes from this single photometric experiment **rule out a Universe with no Dark Energy**





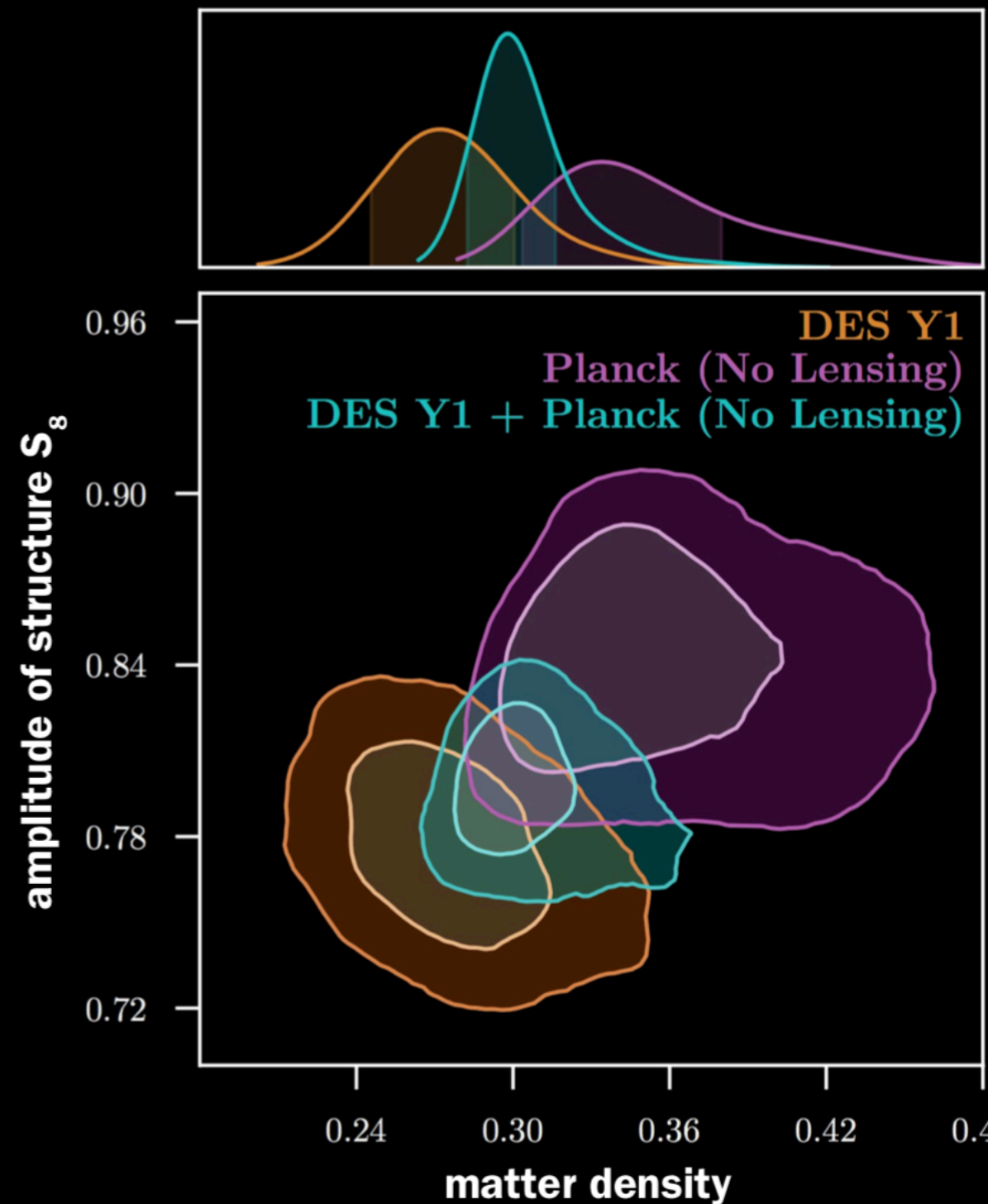
Is the Universe boring?

Current measurements consistent with flat Λ CDM

Game of tensions pt 1



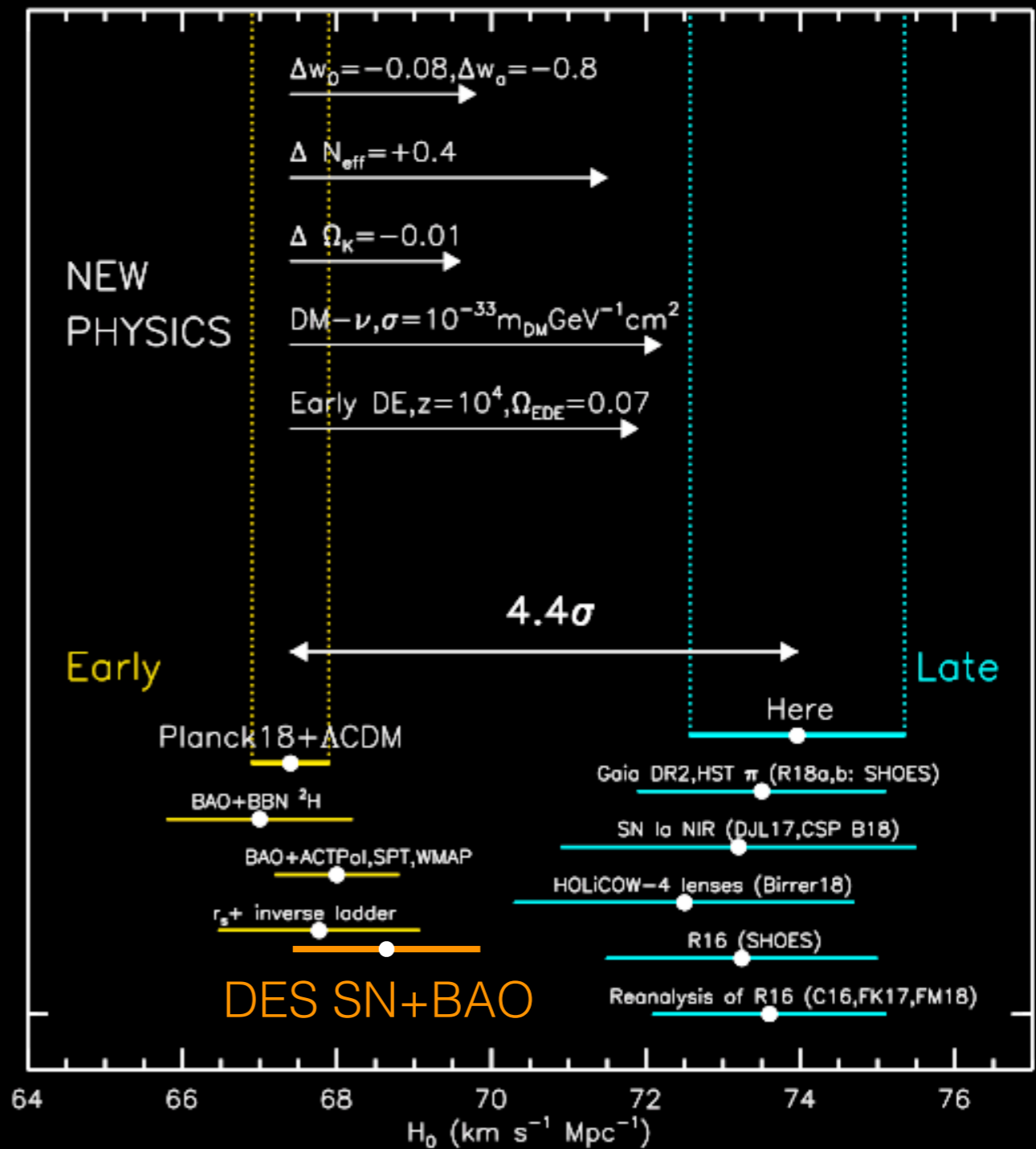
- DES Y1 constrains on clustering amplitude and matter density
- **Mild visual tension:** Bayesian evidence shows consistency
- Worse for KiDS
- **Future DES measurements** will be able to confirm consistency or show tension



Hubble constant tension



- **4.4 sigma discrepancy** between early and late time Universe measurements
- Systematics or new physics?





Is the Universe boring?

Need more precise cosmological parameter measurements and new probes.



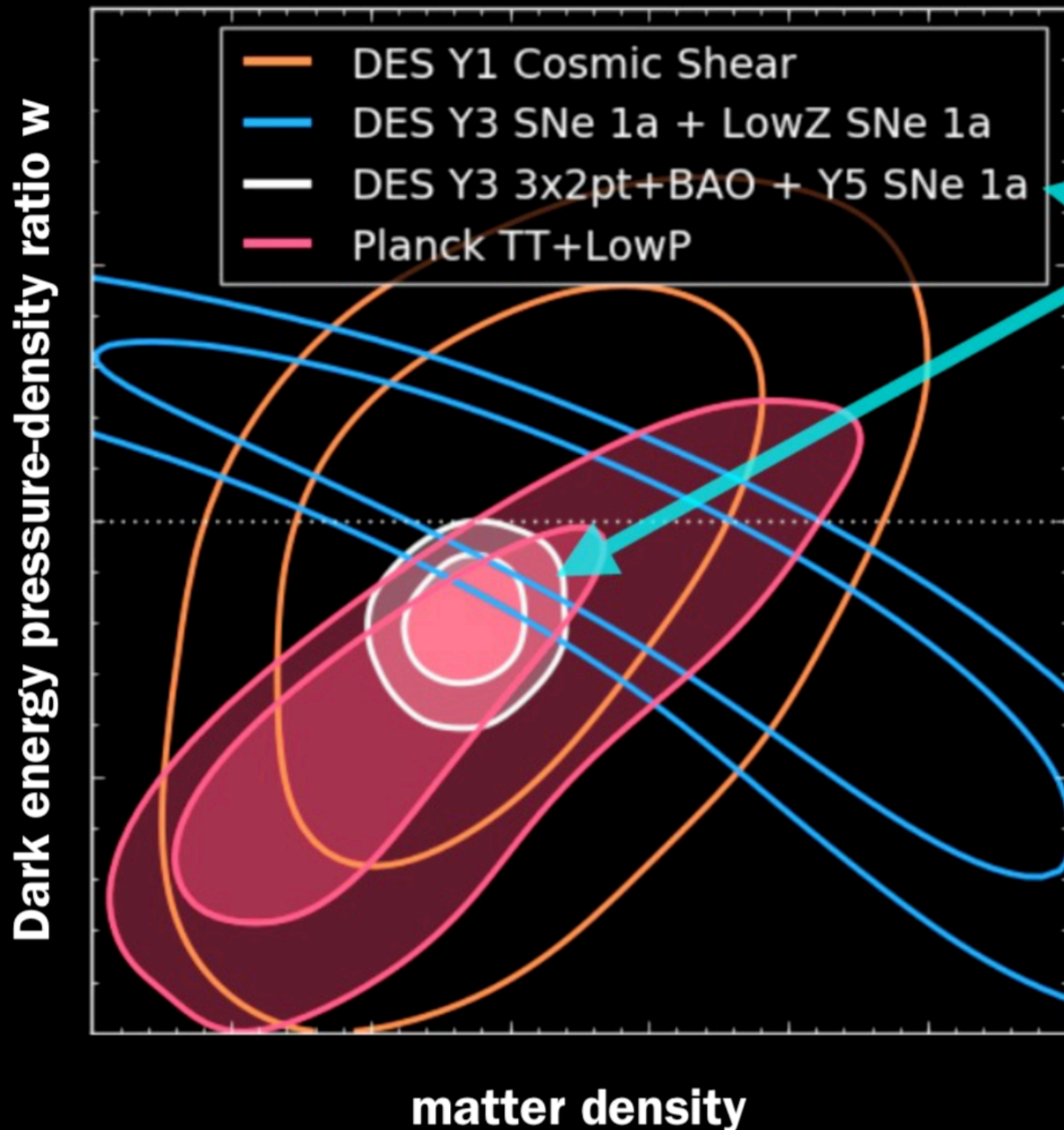
Is the Universe boring?

Need more precise cosmological parameter measurements and new probes.



DES Y3/Y5 projections

Fermilab highly involved in Y3 cluster cosmology



Projection based on statistical and analysis improvement - **not data**

Contour position is artificial

- **More constraining than current CMB measurements of these parameters** (historically, the most powerful cosmic probe)
- **Y5/Y5 analysis** will be even more constraining!

Figure: Michael Troxel

Is the Universe boring?

Current measurements consistent with flat Λ CDM

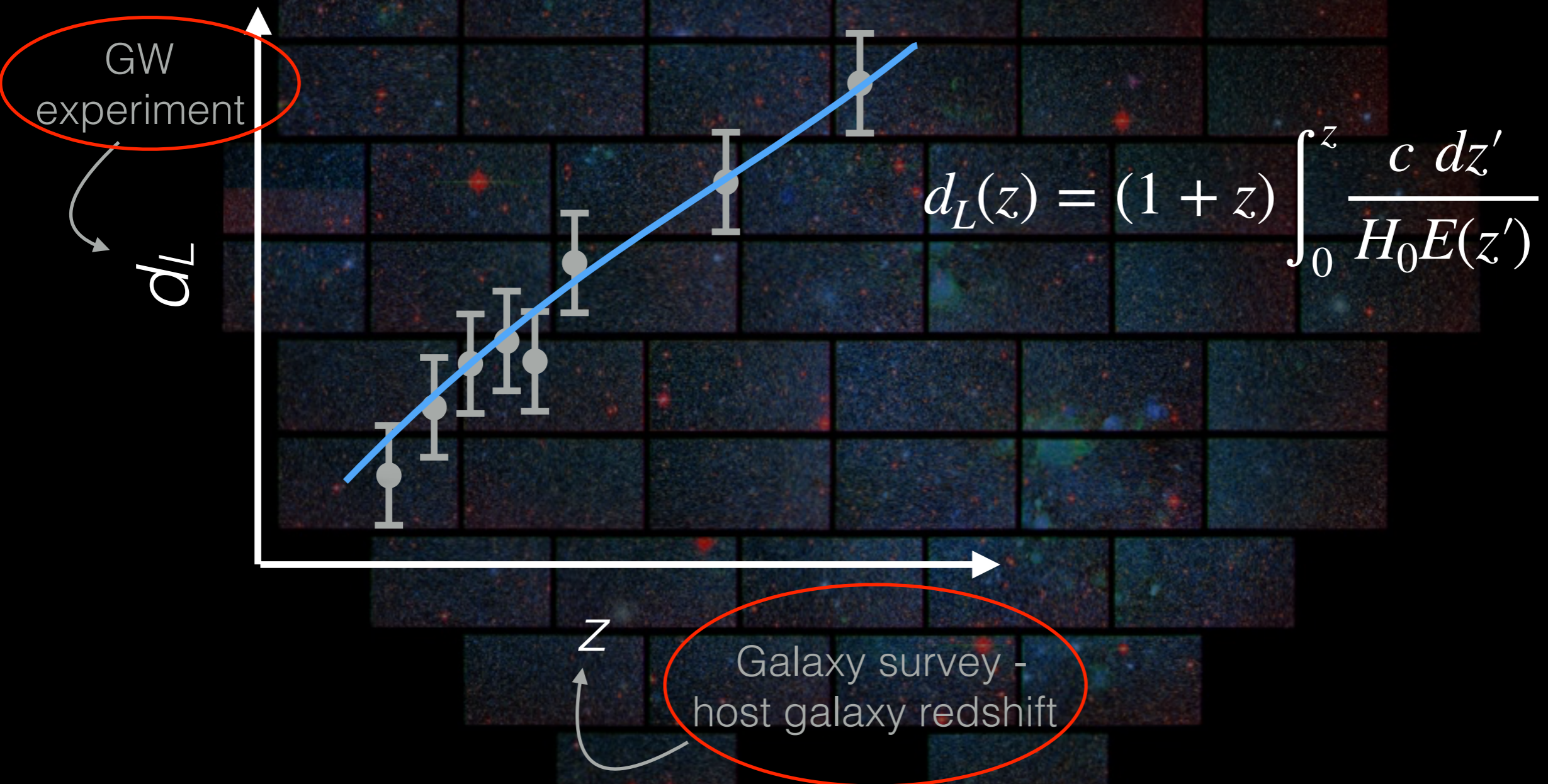
Need more precise cosmological parameter measurements and **new probes.**

GW Standard sirens



- Similar to SN cosmology:

Self-calibrating: No distance ladder





GW+EM standard siren methods

Unique host galaxy

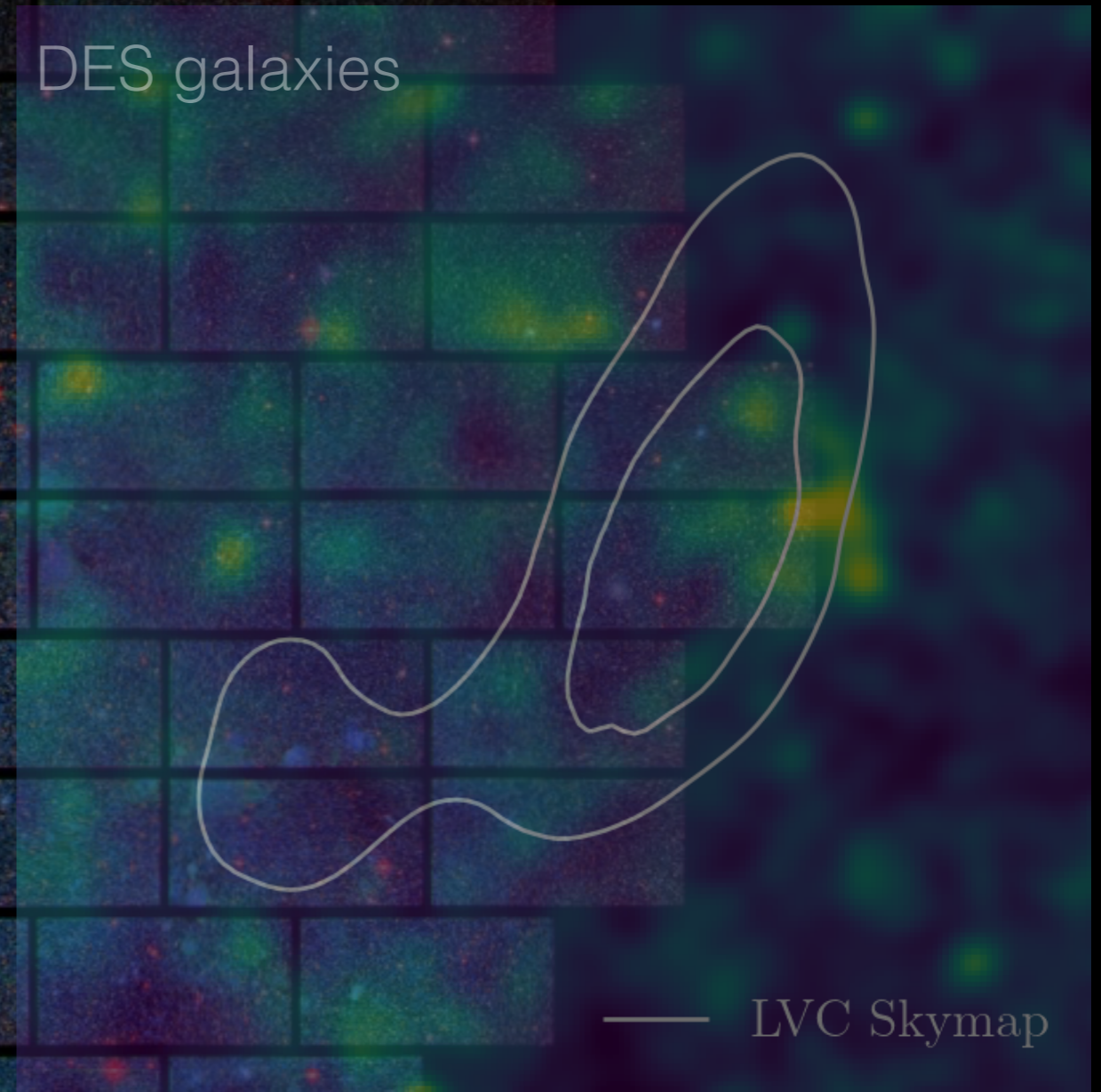
GW170817
DECam observation
(0.5–1.5 days post merger)



Bright standard sirens

No EM counterpart: potential host galaxies

DES galaxies



— LVC Skymap

Dark standard sirens / statistical method

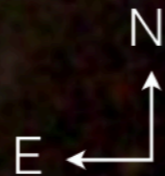


GW+EM standard siren methods

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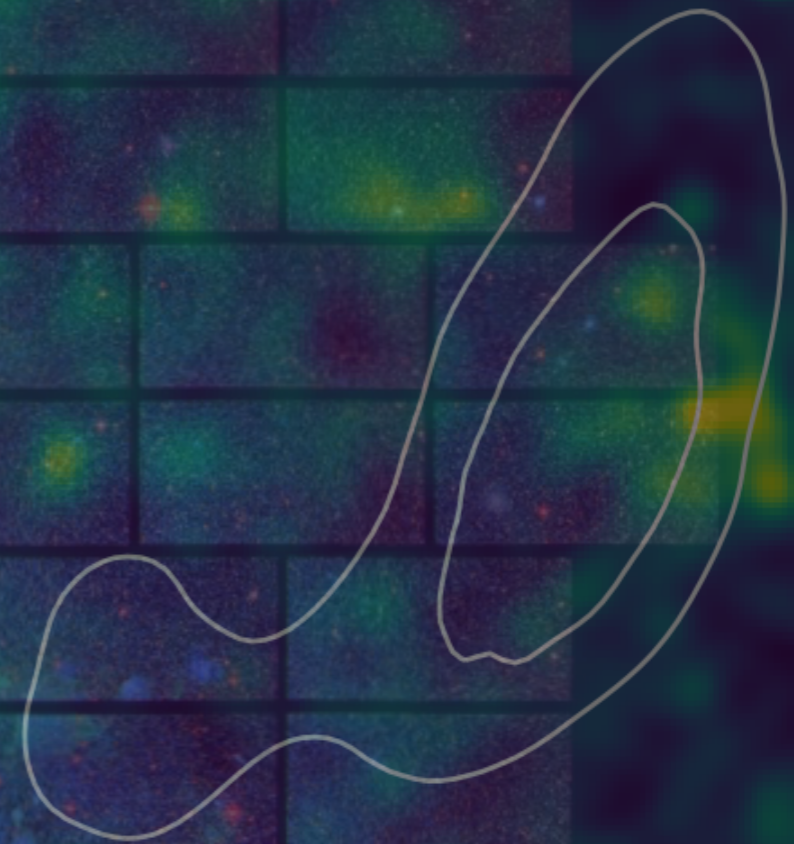
Few % precision in ~2022
(Chen, Fishbach & Holz 2018)



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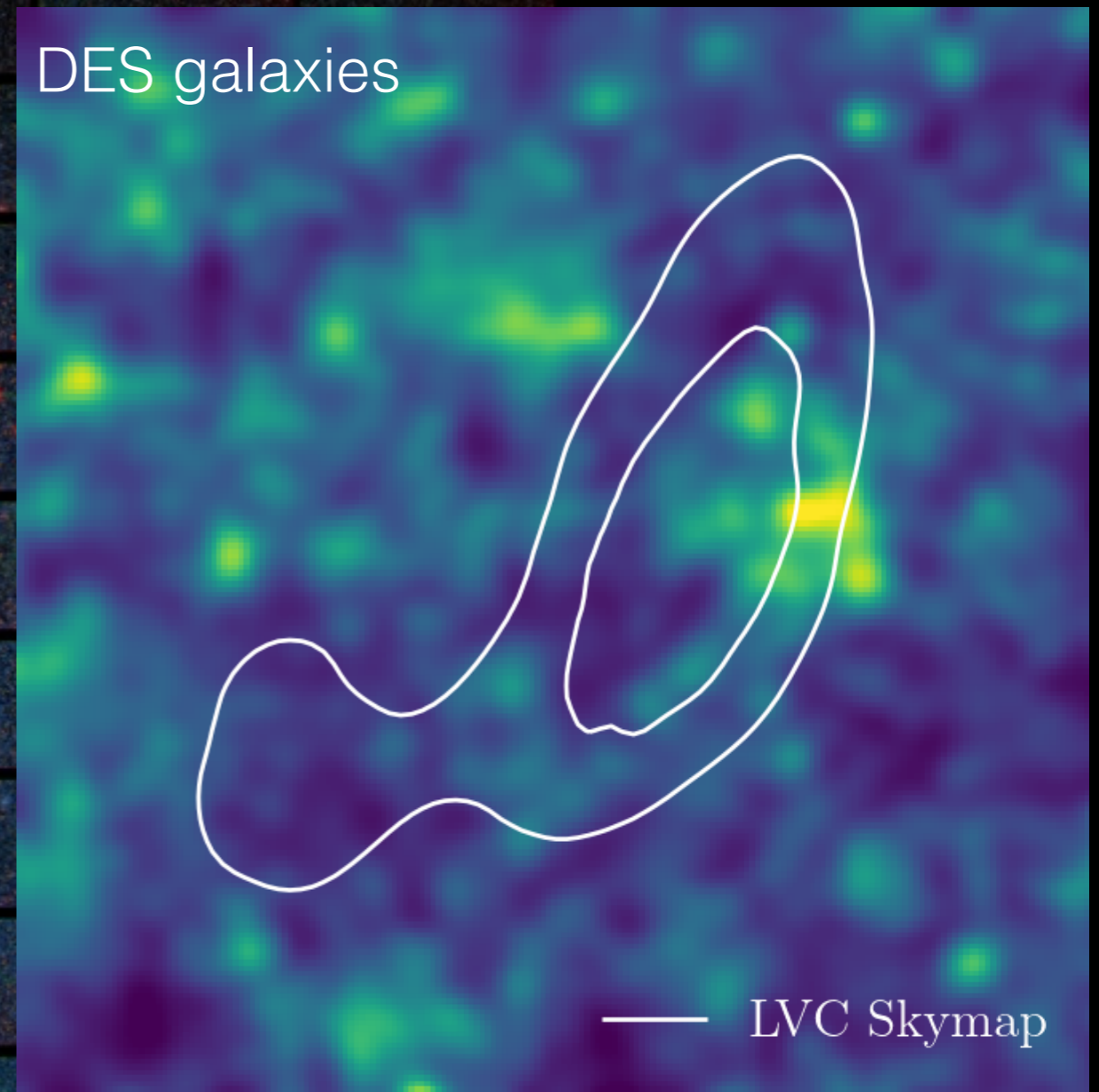
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Soares-Santos+DES 2017

Bright standard sirens

No EM counterpart: potential host galaxies

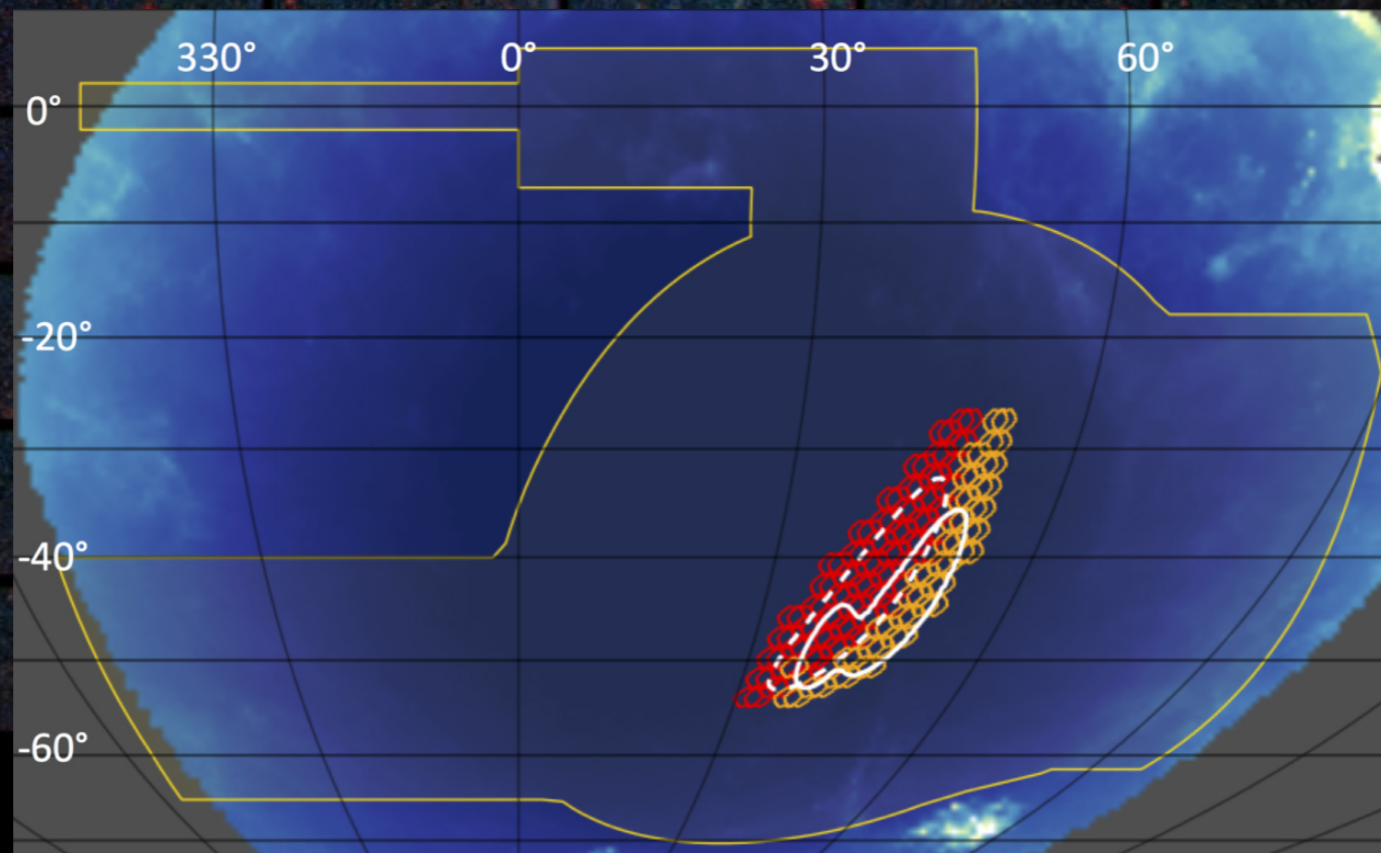


Dark standard sirens



GW170814: the golden event (for DES)

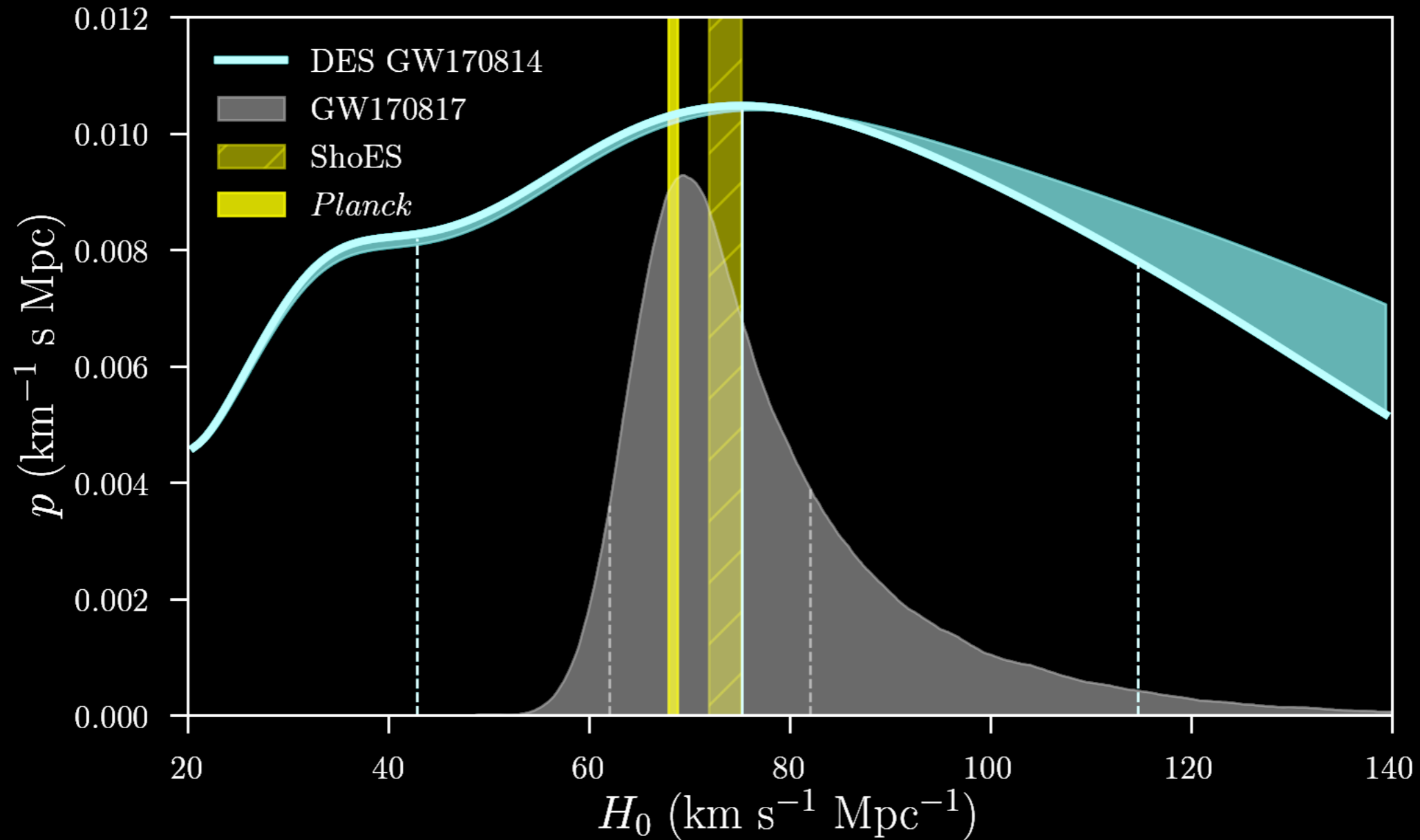
- First binary black hole merger event from LIGO+Virgo: well localized
- 90%+ covered by DES-GW follow up (no counterpart)
- Falls in the DES footprint
- Complete potential host galaxy catalog using **Y3**



Doctor+DES 2019



First measurement of H_0 from a binary black hole



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

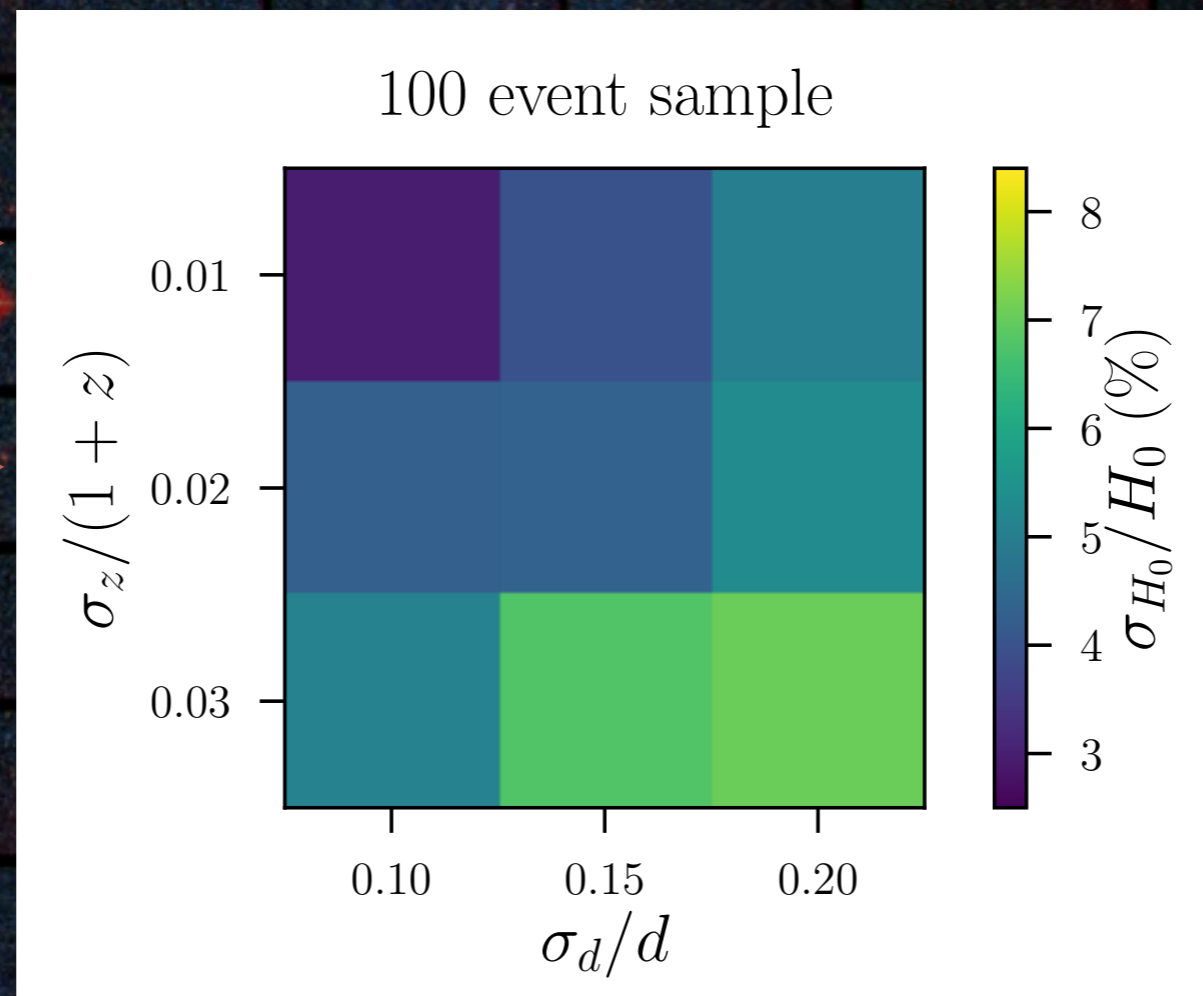
Dark sirens prospects



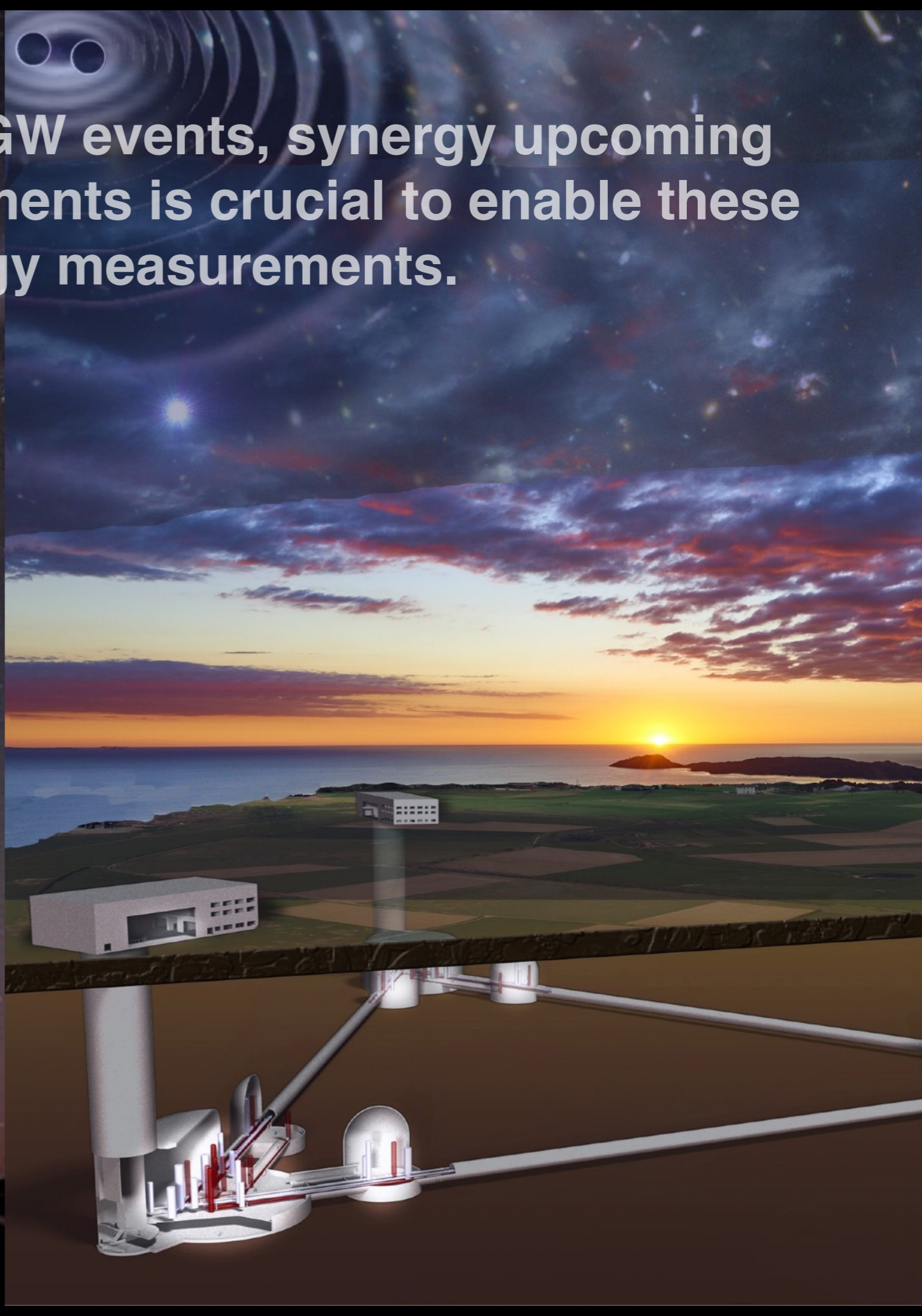
4-5% statistical precision with DES-like data and ~ 100 GW170814-like events

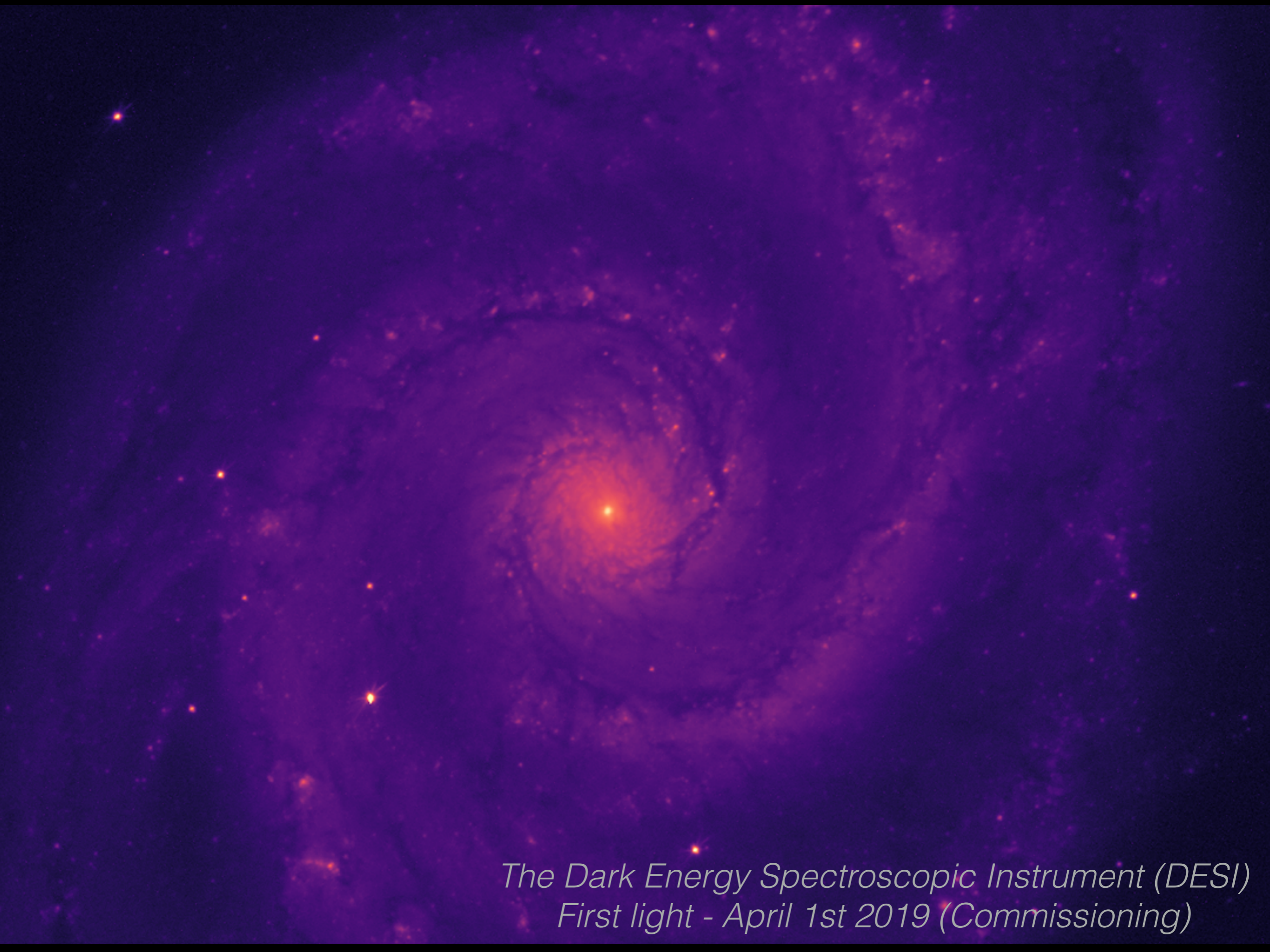
LSST-like \rightarrow

DES-like \rightarrow



In the era of hundreds of GW events, synergy upcoming galaxy surveys-GW experiments is crucial to enable these new cosmology measurements.



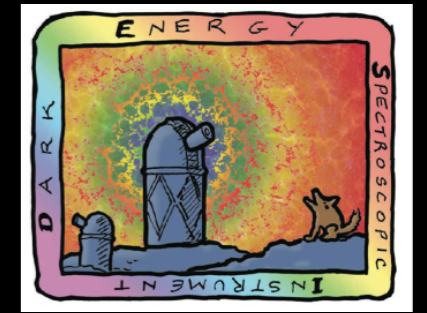


*The Dark Energy Spectroscopic Instrument (DESI)
First light - April 1st 2019 (Commissioning)*

DESI



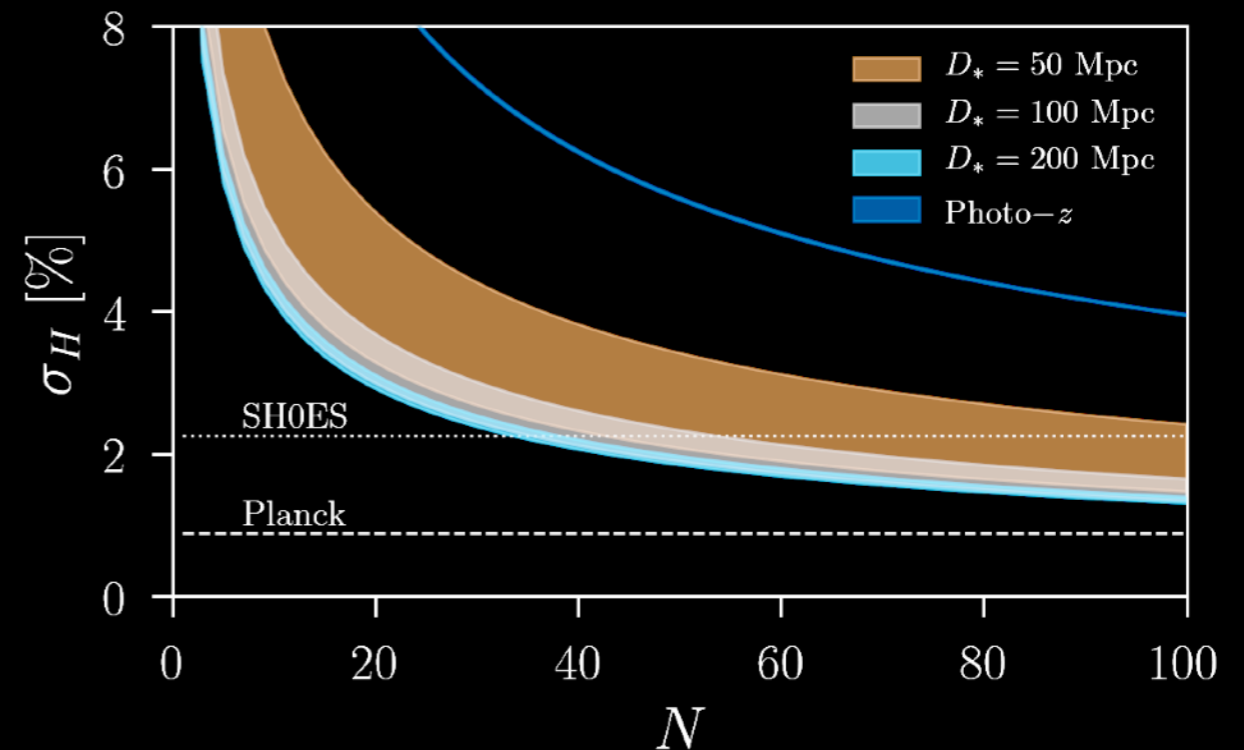
Dark Energy Spectroscopic Instrument



- ★ **Fermilab** involvement crucial for construction & operations
- ★ Spectroscopic survey that will create **3D map of the Universe** out to $z \sim 2$
- ★ Almost all of the Northern sky over **5 years**
- ★ **Main probes:** BAO & RSD
- ★ Stage IV DE experiment: improves DES dynamical DE constraints by a factor ~ 10

Prospects for standard sirens:

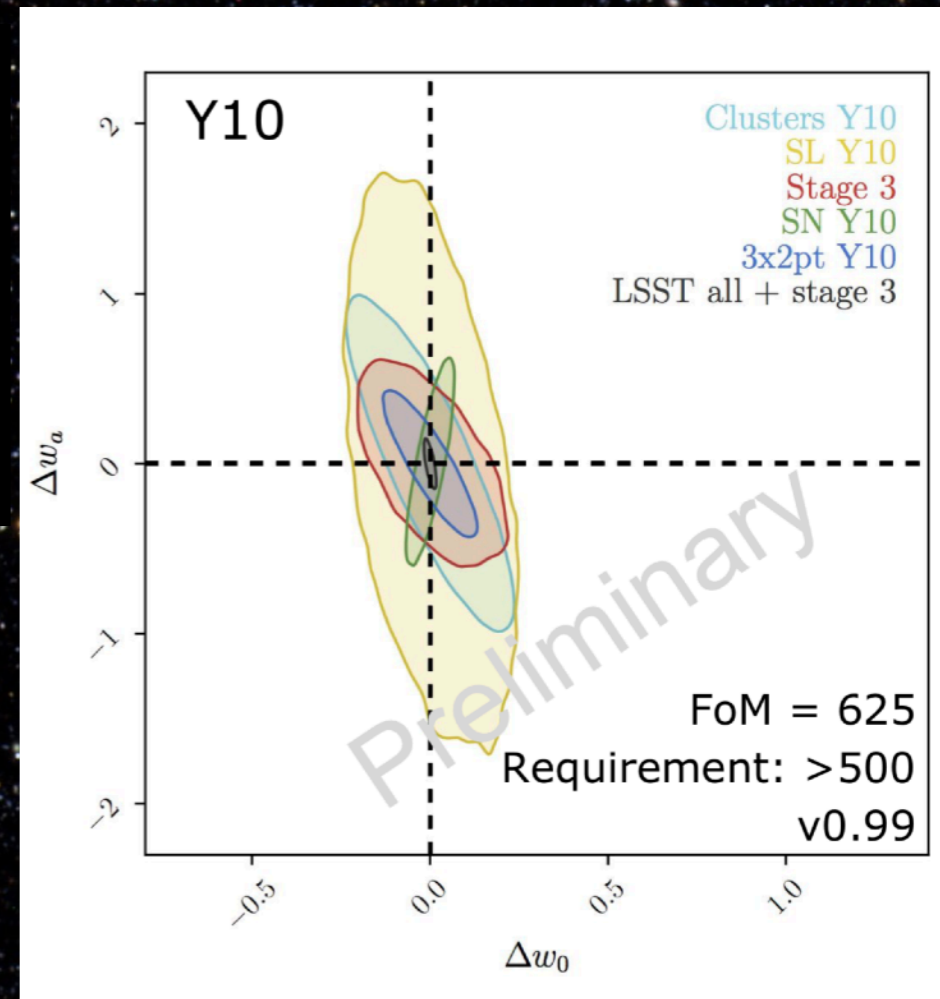
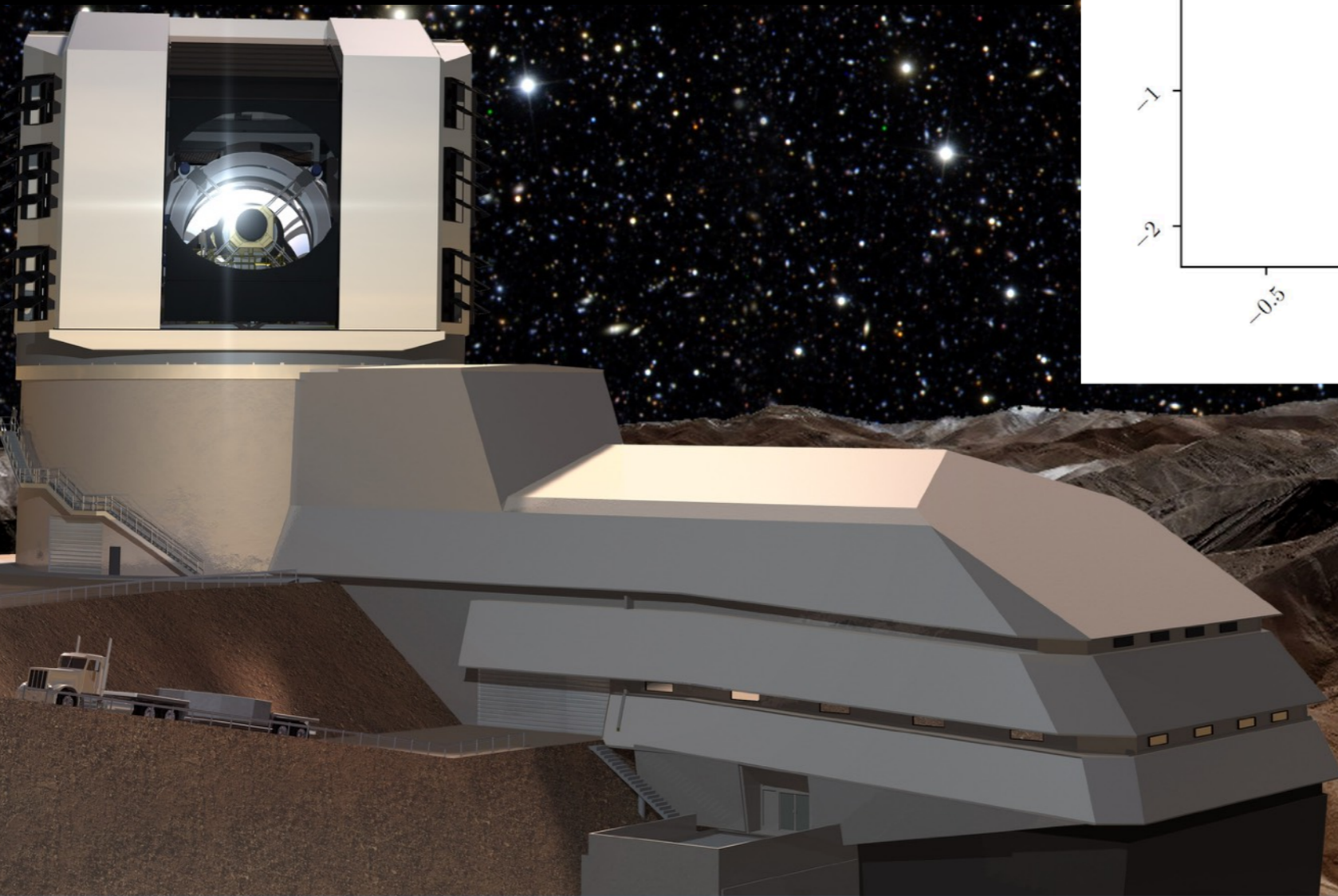
- **Bright sirens:**
Host galaxy redshift and peculiar velocities
- **Dark sirens:**
More precise-end of forecasts
- Combining upcoming GW H_0 constraints + future CMB + DESI significantly **improves constraints beyond Λ CDM** (mostly DE, Di Valentino et al. 2018)



LSST

Large Synoptic Survey Telescope

- **Entire Southern sky every few nights for 10 years**
- Same **probes as DES but more precise**
- DE FoM constraints improvement by factor ~ 10 compared to Stage-III - **constrain dynamical DE**
- **FNAL** involvement in LSST-DESC computing, operations, science analyses



Credit: Collett et al.

Conclusions



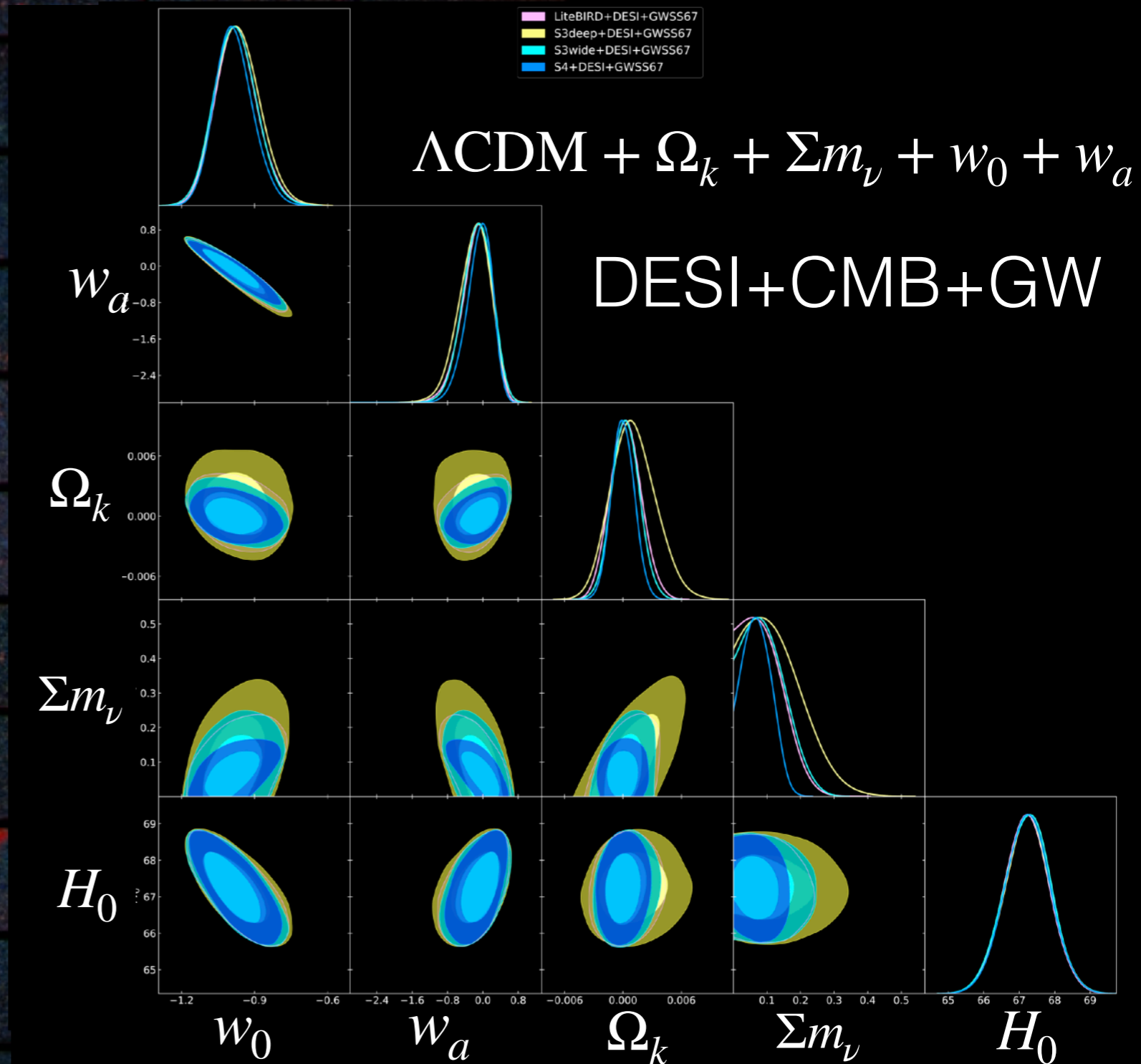
- DES is a lot more than Dark Energy & what shown here:
 - **Milky Way and stellar streams** (N. Shipp's talk on Monday, A. Drlica-Wagner, T. Li)
 - Cosmology and astrophysics with **galaxy clusters** (Zhang+2019, Palmese+2019)
 - **Quasars** (H. Lin, E. Buckley-Geer)
 - **Strong lensing** (B. Nord, T. Diehl)
- **Combining probes is the key** to precision cosmology, and **GW StSs** are a powerful probe to be added to "standard" DE probes
- Upcoming **Y3/Y5 DES cosmology** analyses (and even more with LSST & DESI later on) will be a huge step towards solving the Dark Energy puzzle
- Fermilab already looking ahead: DESI-II, MSE, SSSI

A vast field of galaxies, including spirals, ellipticals, and irregular shapes, scattered across a dark background. The galaxies are rendered in various colors, including yellow, orange, red, blue, and purple, suggesting different spectral types or redshifts. The density of galaxies is high, with many appearing as small, distant points of light.

Thank you!

Combining DE experiments

- Combining upcoming GW H_0 constraints + future CMB + DESI significantly **improves constraints beyond Λ CDM**
- Factor up to 3 improvement on dynamical DE parameters
-



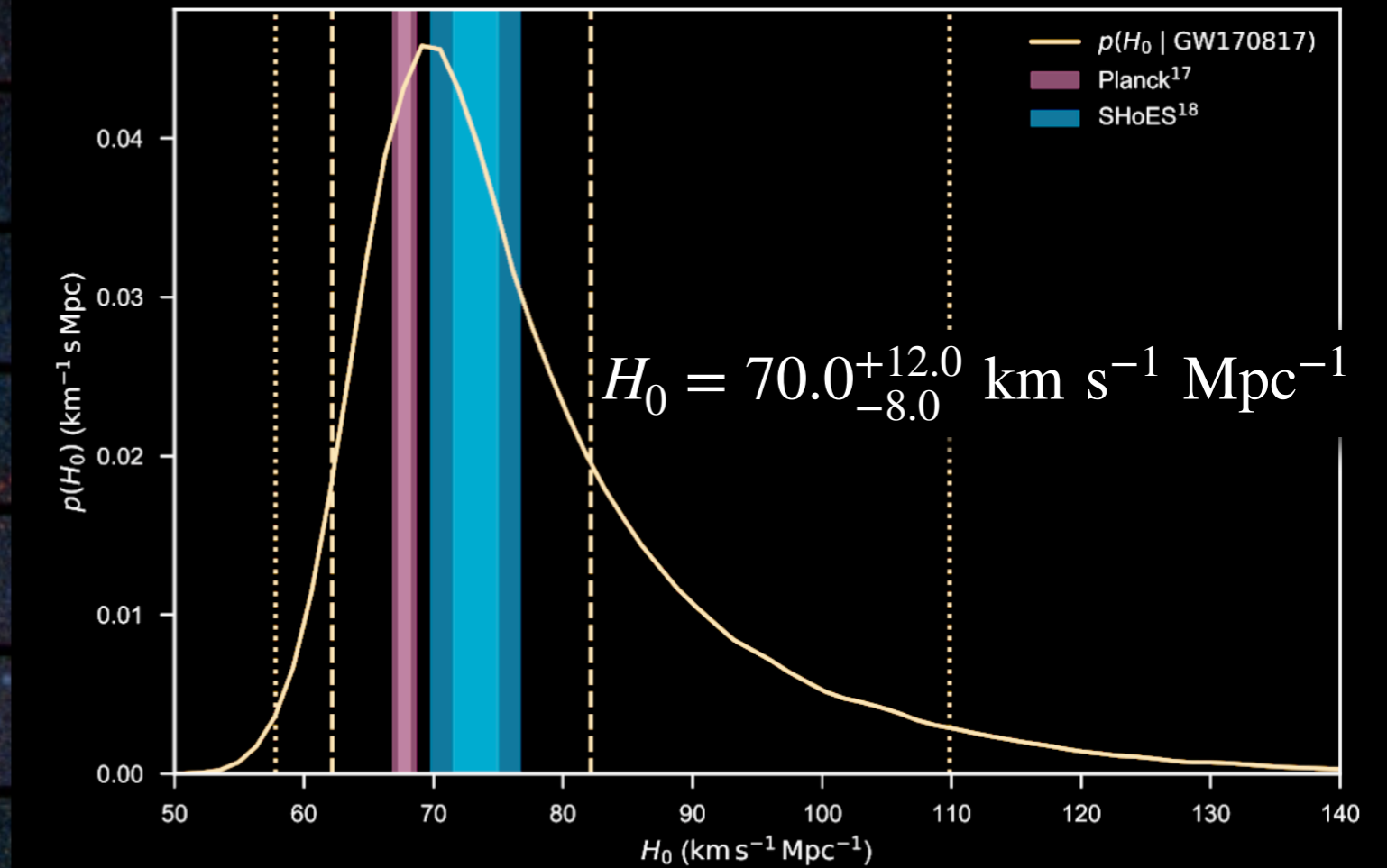
Bright sirens



GW170817 counterpart discovery
DECam observation
(0.5–1.5 days post merger)



Soares-Santos+DES, ApJL 2017



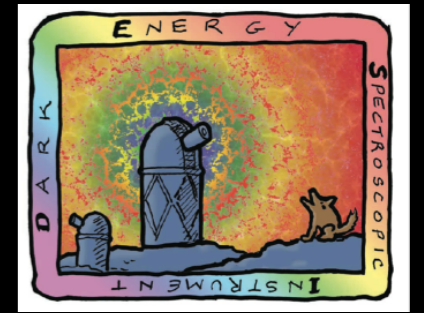
LVC+DES et al. 2017, Nature

- **Few % precision in ~2022** (Chen, Fishbach & Holz 2018)
- DES-GW team, mostly at Fermilab, working hard to make this possible during LIGO/Virgo O3

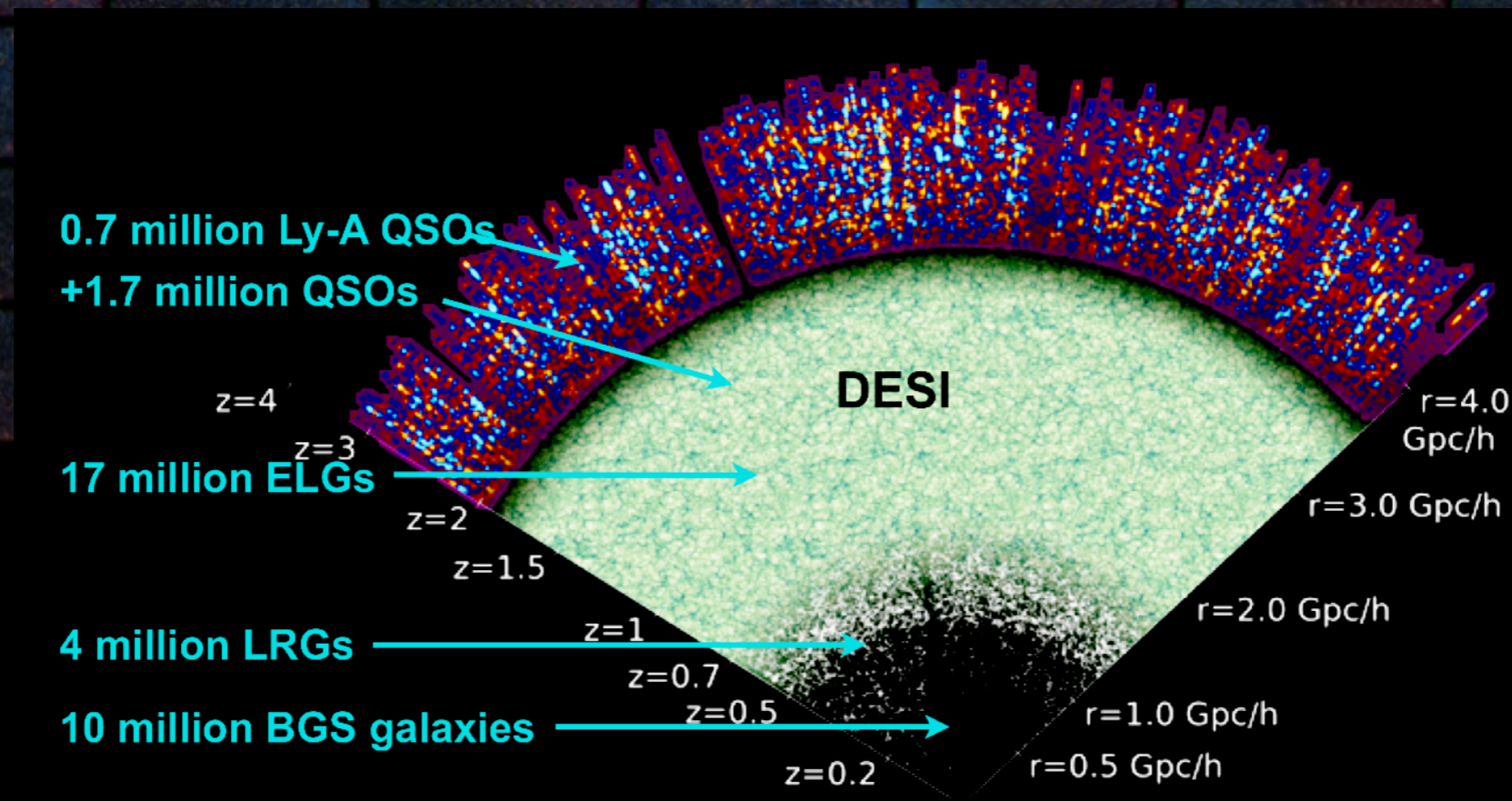


DESI

Dark Energy Spectroscopic Instrument



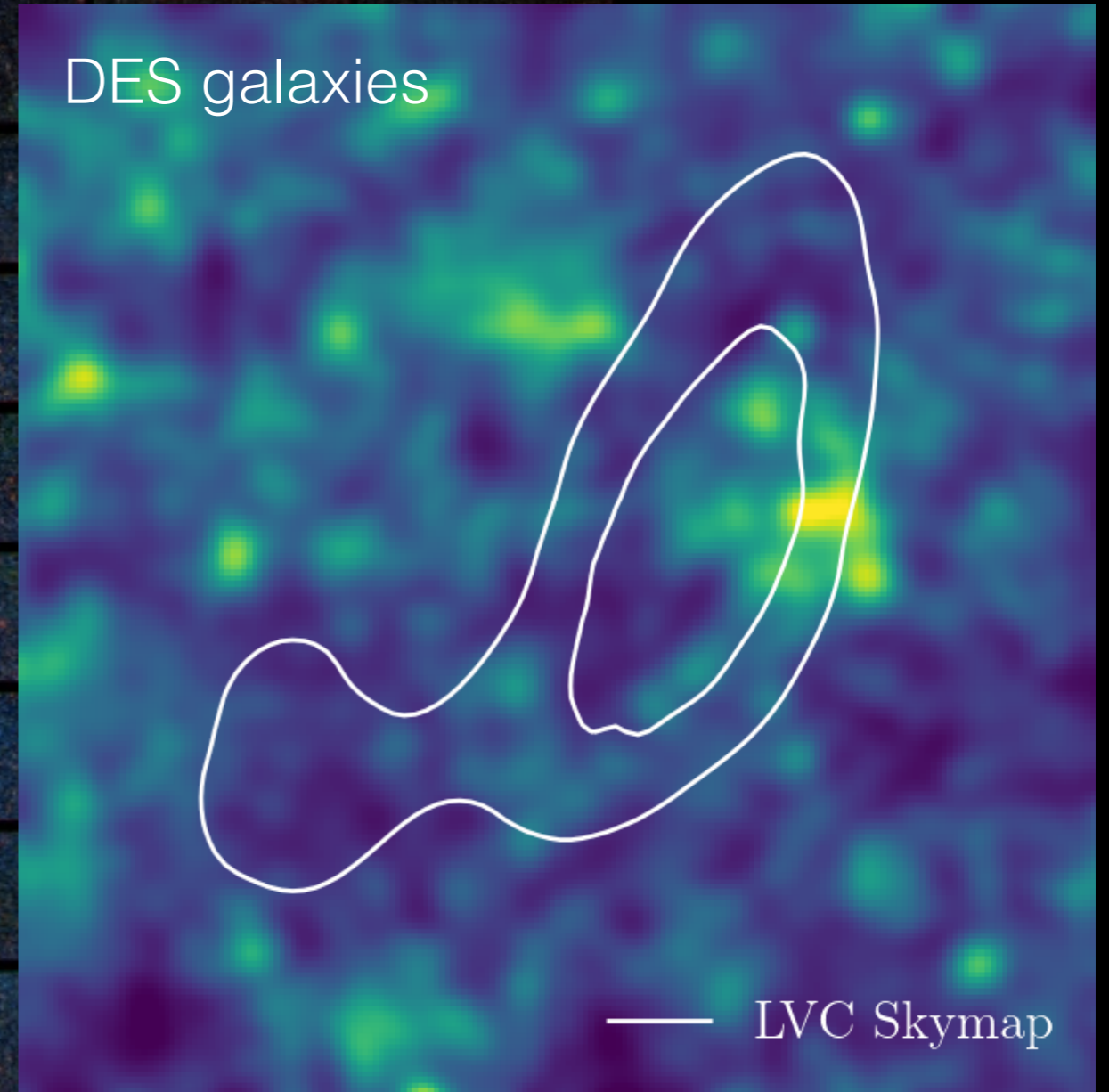
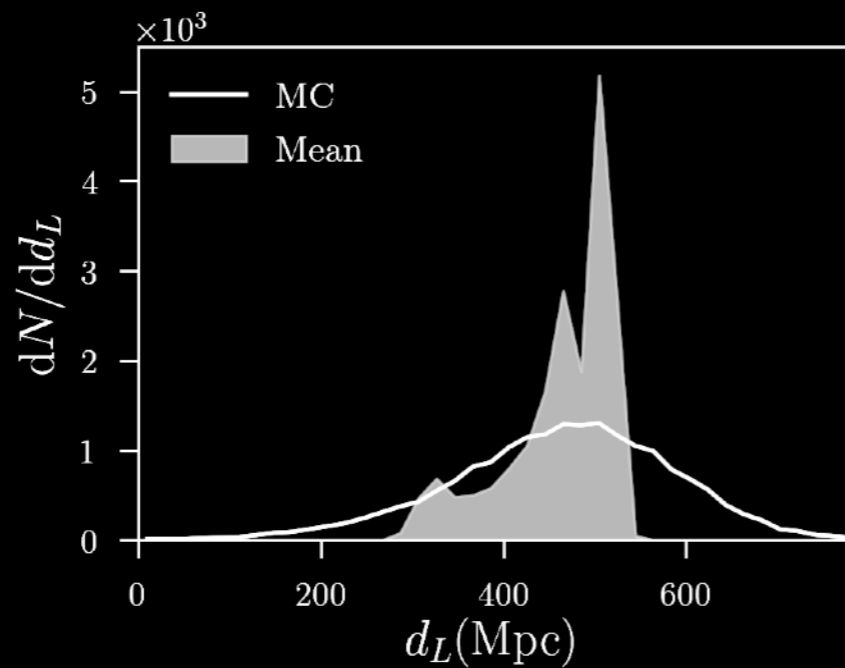
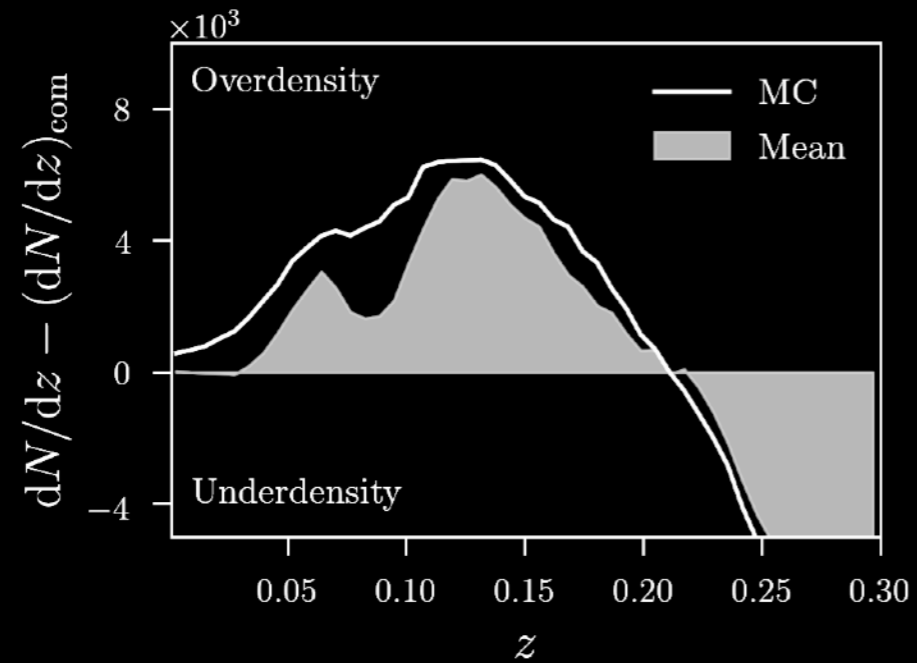
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Dark sirens



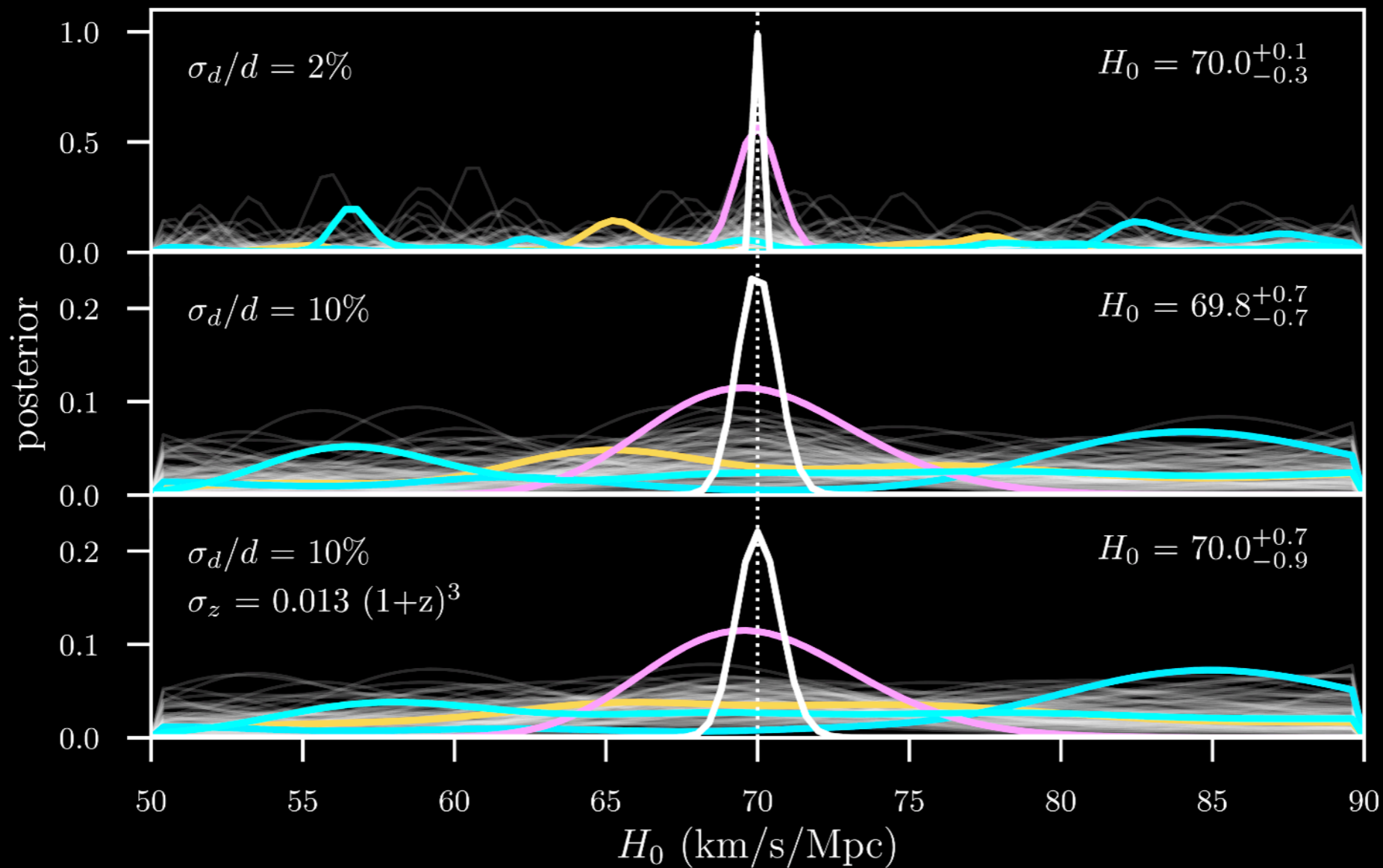
Standard sirens with no EM counterpart





Back-up slides

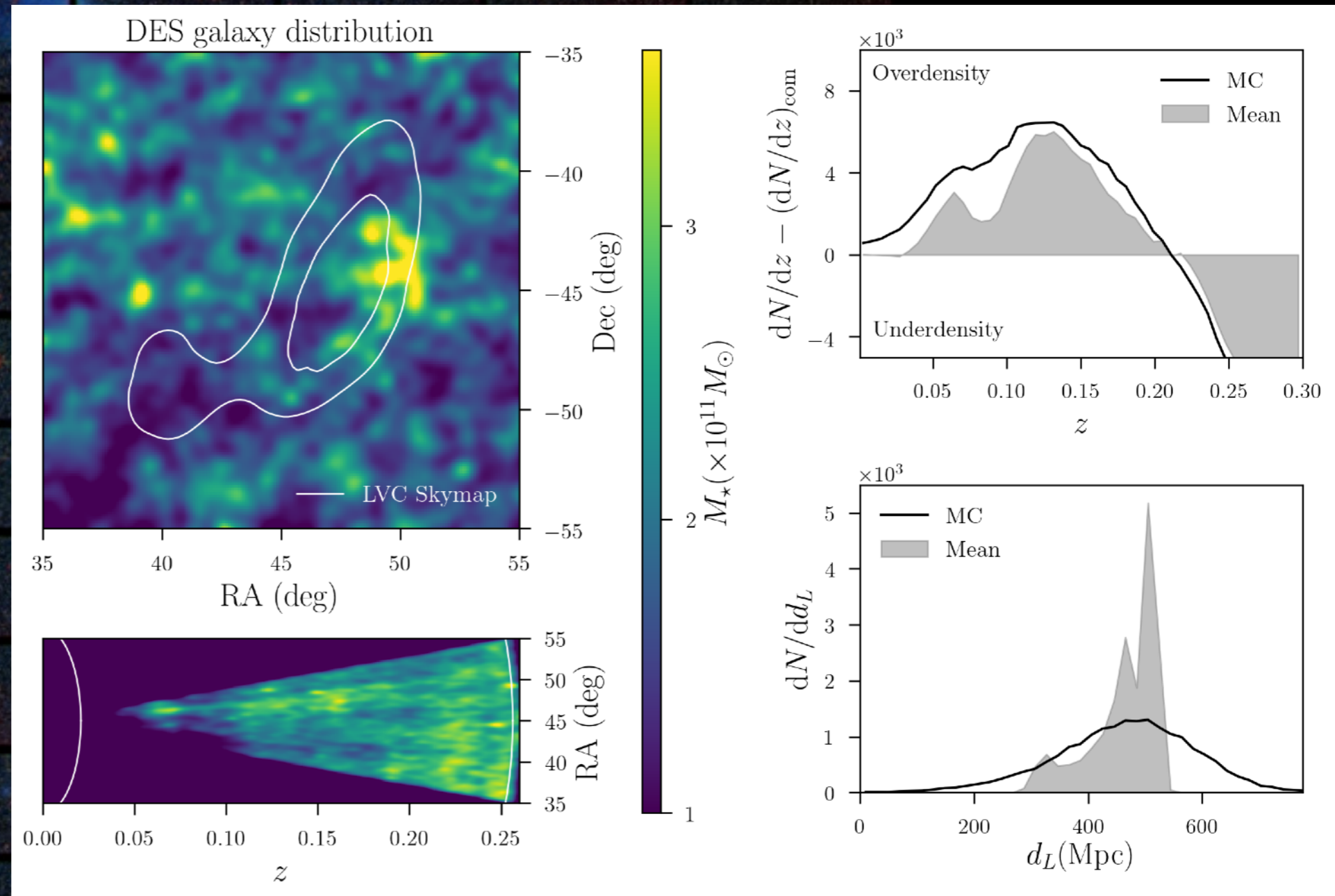
Simulations



- 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

GW170814: the golden event (for DES)

- Define a complete **volume limited galaxy sample down to $4 \times 10^8 M_{\text{Sun}}$** (77% of total stellar mass) using **Year 3 data**
- $\sim 77,000$ galaxies

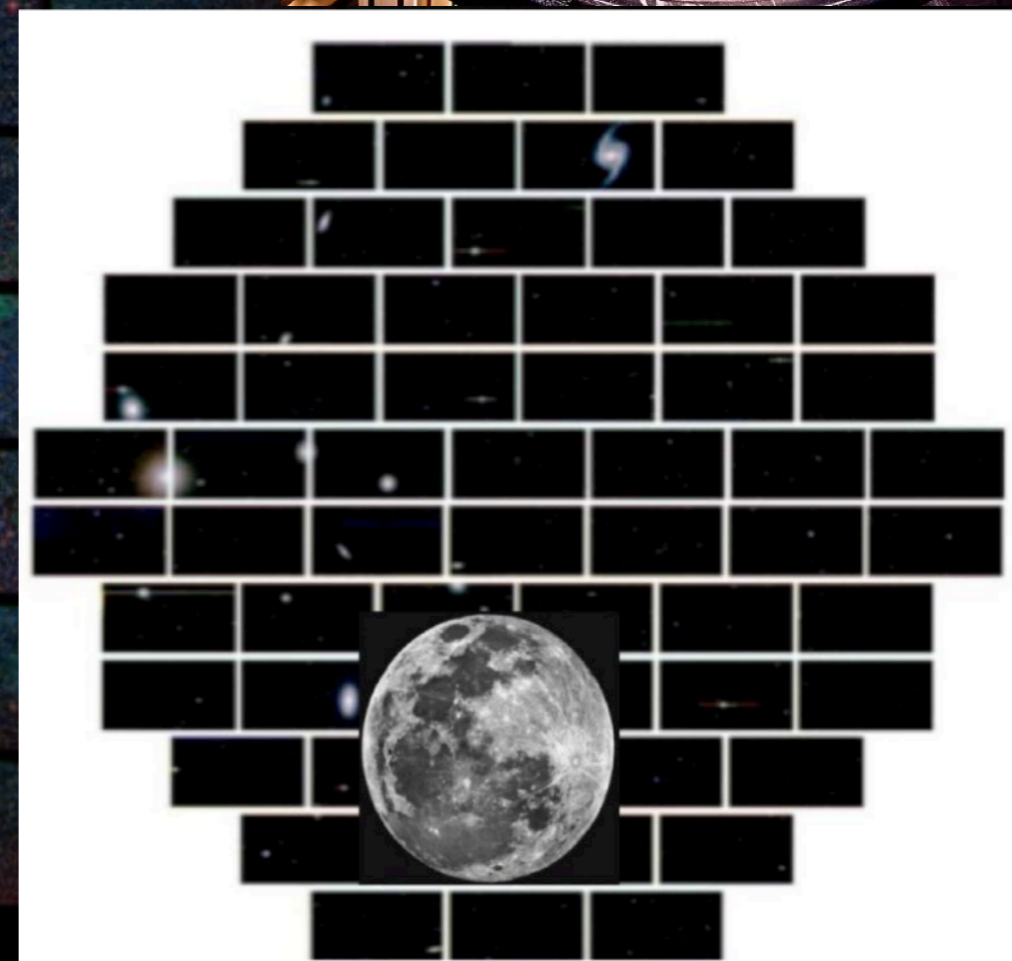
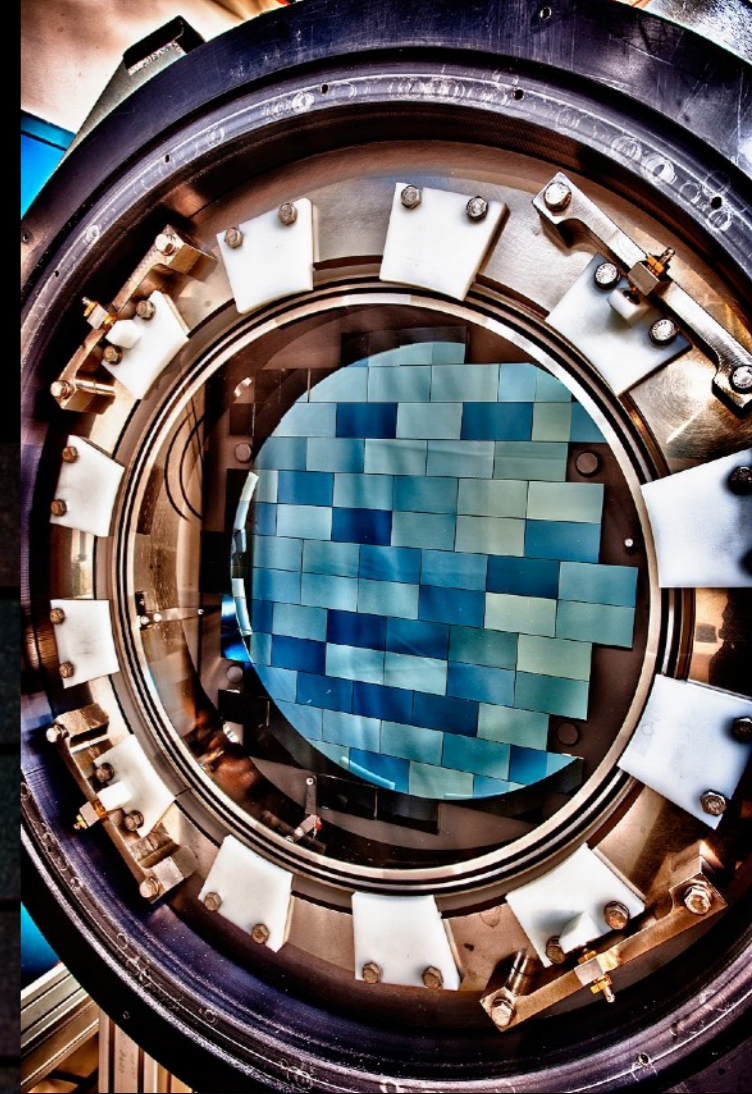


Dark Energy Survey



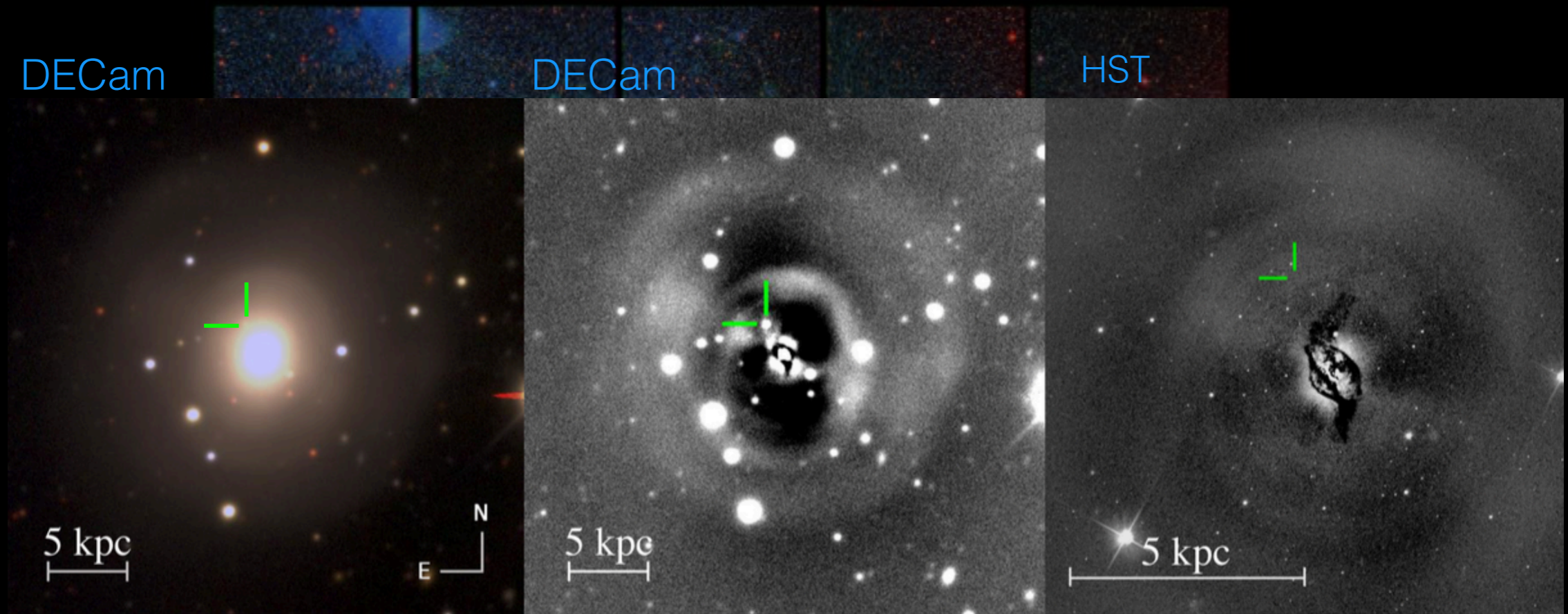
DECam

3 sq deg FOV, 570 Mpix optical CCD camera
Built at Fermilab
CTIO Blanco telescope (Chile)



Host galaxy of GW170817

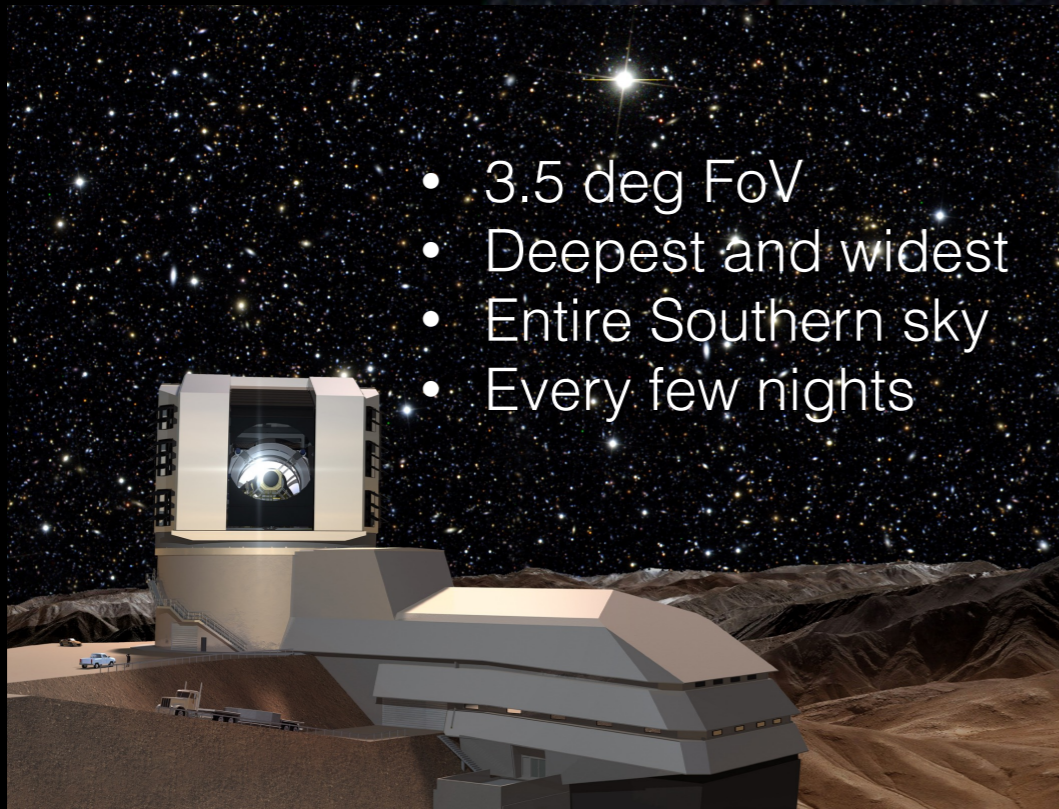
Synergy GW-large galaxy survey extends to astrophysics of GW sources



Suggest that galaxy mergers can boost the BNS formation/merging

Larger statistics of GW hosts will shed light on formation channels of GW sources

LSST & other imaging surveys

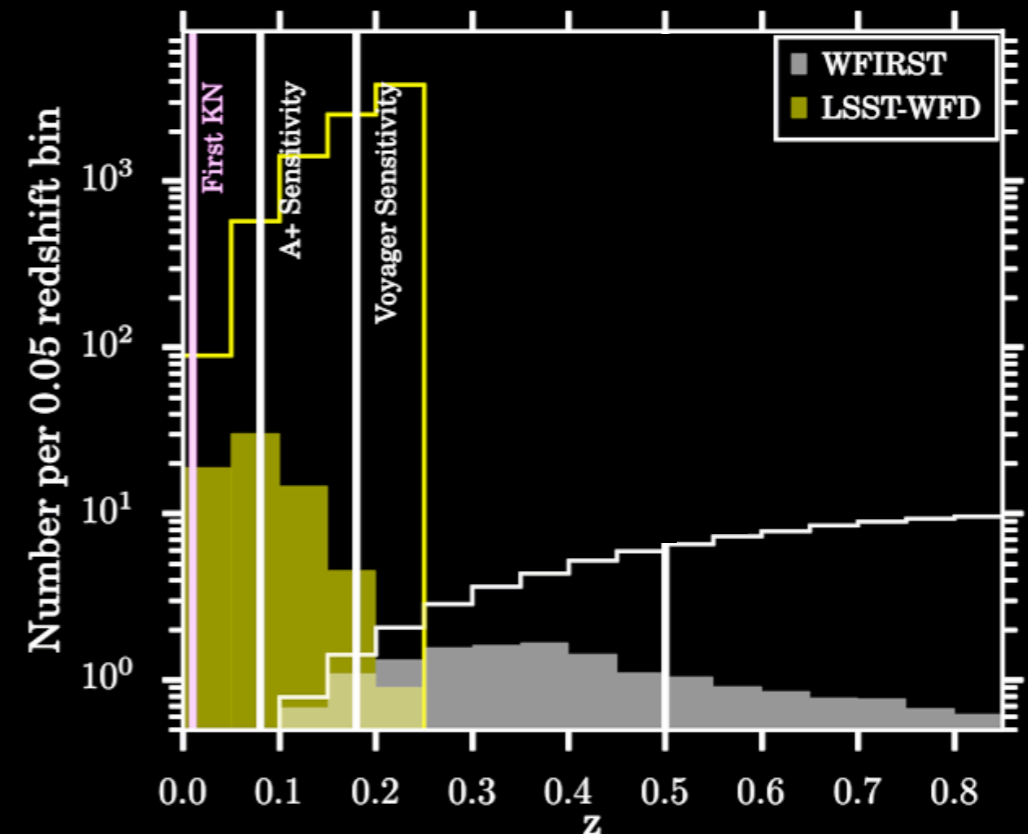


- 3.5 deg FoV
- Deepest and widest
- Entire Southern sky
- Every few nights

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

- Serendipitous discoveries of KNe
- **KN Redshift reach** of different experiments
- Potentially detect most KNe at A+ sensitivity: no need to rely on GRB only
- LSST & WFIRST ongoing activities for potential GW follow-up

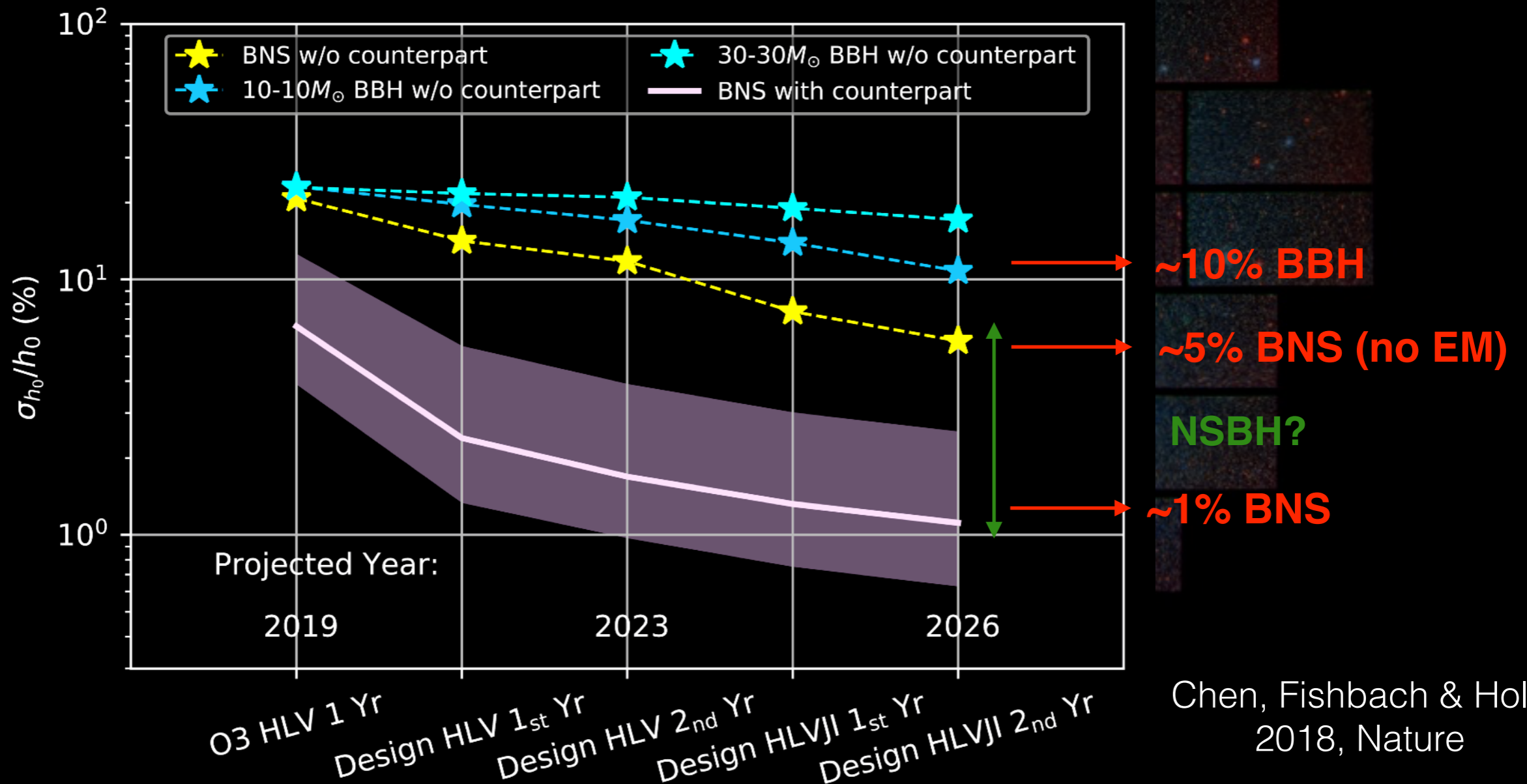


Scolnic+DES 2017

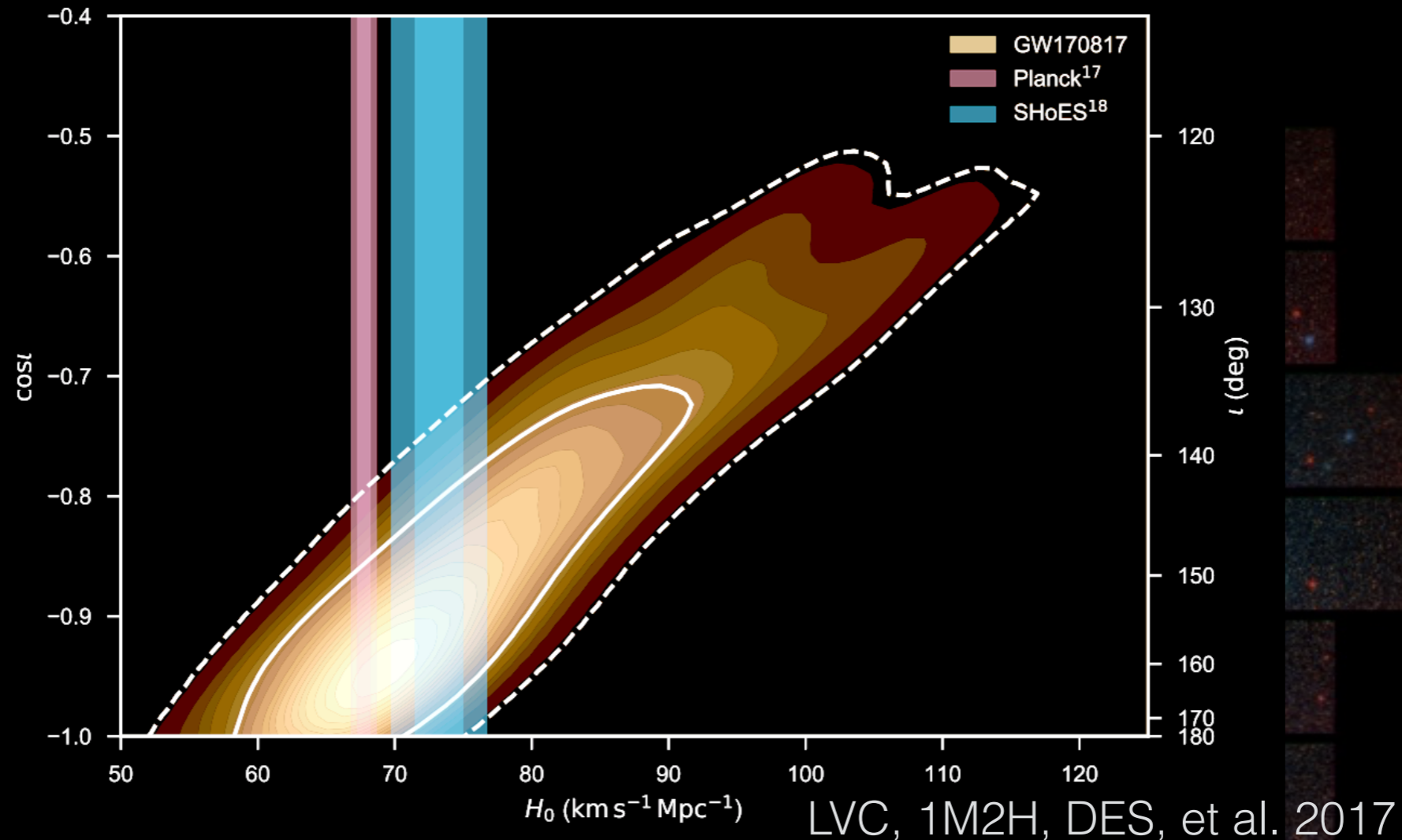


Prospects for current detectors

- 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)



GW170817 as bright standard siren



- Limitations:
 - ★ Peculiar velocity
 - ★ Inclination angle is correlated with D
- Can break degeneracy by constraining i from EM
- Improve precision by factor 2-3 (Guidorzi+17, Hotokezaka+18)

Prospects for 3G detectors

- Direct impact on cosmological parameters beyond H_0 because of higher D reach
- D - z relation sensitive to: $H_0, \Omega_m, \Omega_k, w_0, w_a$
- ET + sGRB: ~ 1000 events. Still needs host galaxies. Improve with KNe?
- Cannot constrain all parameters competitively with current DE experiments by itself (Sathyaprakash+09, Zhao+11)
- Combination with experiments that constrain some parameters (e.g. Planck) will lead to DE constraints competitive with DE experiments (in particular Taylor & Gair 2012, no EM)

