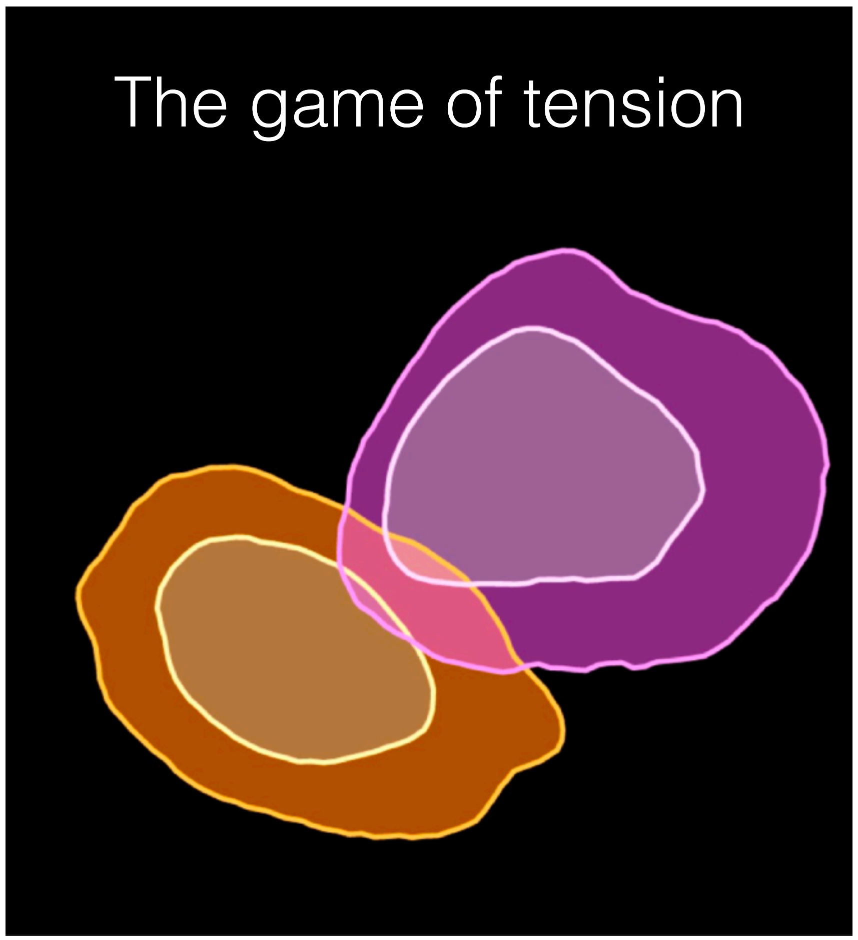
Gravitational wave cosmology with large galaxy surveys

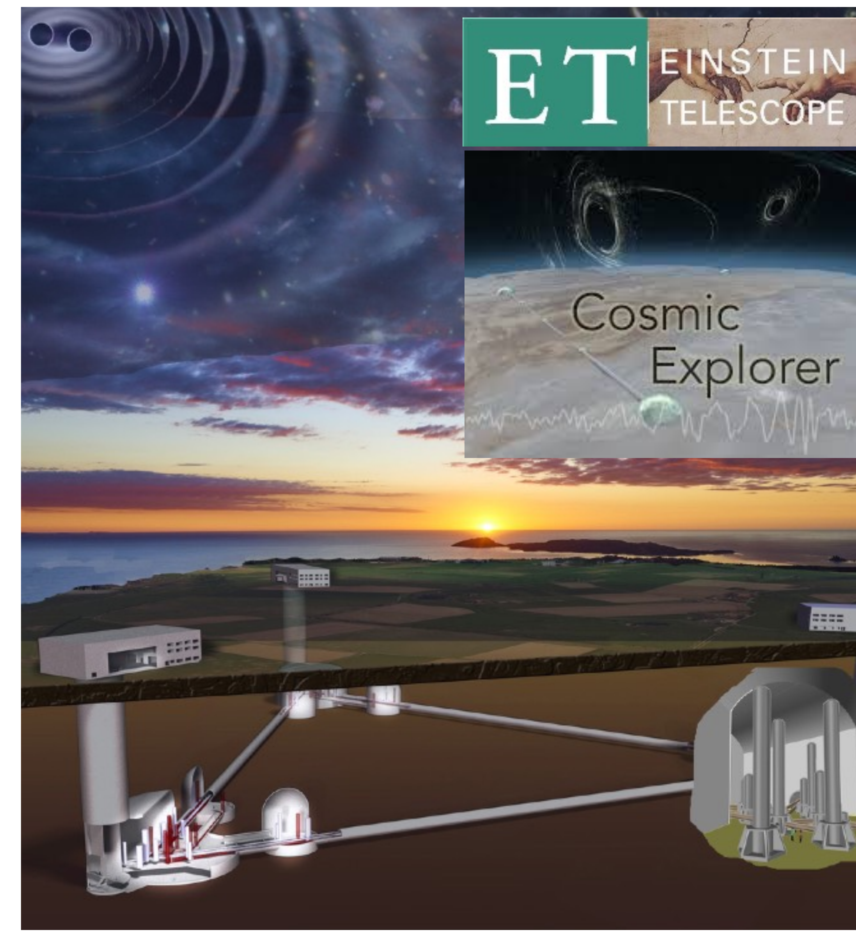
Antonella Palmese (Fermilab)
GWADW @ Elba
20 May 2019

GW170814 H_0 in collaboration with: M. Soares-Santos, J. Annis, Z. Doctor, W. Farr, M. Fishbach, J. Gair, J. Garcia-Bellido, D. Holz, O. Lahav, H. Lin, W. Hartley, & many more (DES & LVC)

Synergy between GW experiments and galaxy surveys allows **cosmology**, other than counterpart discovery and GW astrophysics.

Introduction **Results** **Ways forward**





Motivation
Dark Energy Survey (DES,KiDS/HSC)
Standard sirens

Impact on cosmology
Identify limits/systematics

Cosmology with next generation GW detectors & galaxy surveys

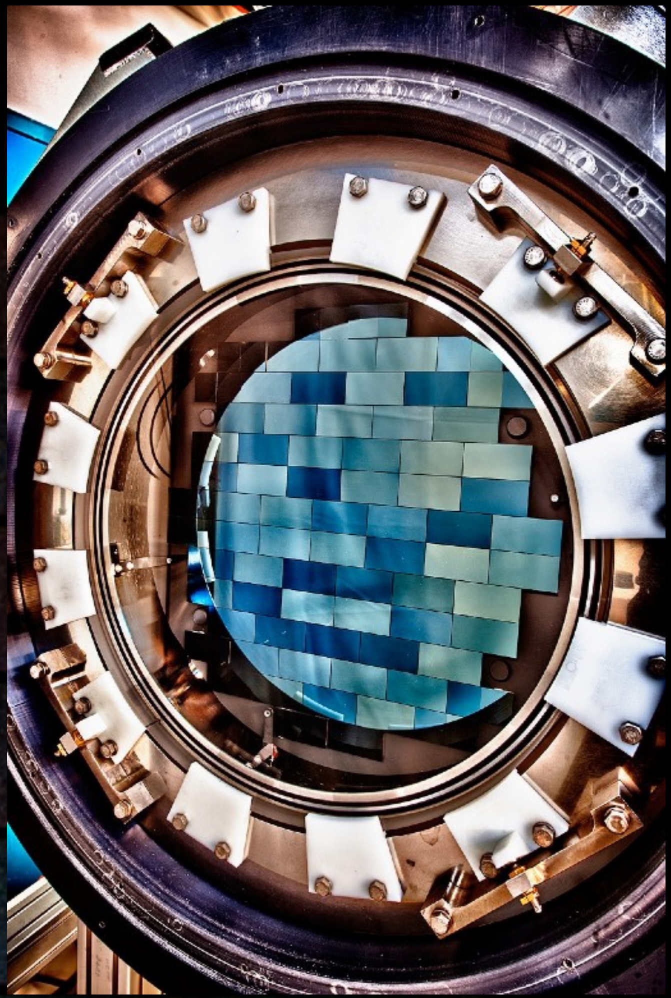
DARK ENERGY SPECTROSCOPIC INSTRUMENT

LSST
Large Synoptic Survey Telescope

Dark Energy Survey (DES)

- First/last light: 12-12-12 / 01-08-19
- Main goal: multi-probe cosmology

DECam currently **premier instrument** for GW optical follow up in the Southern hemisphere



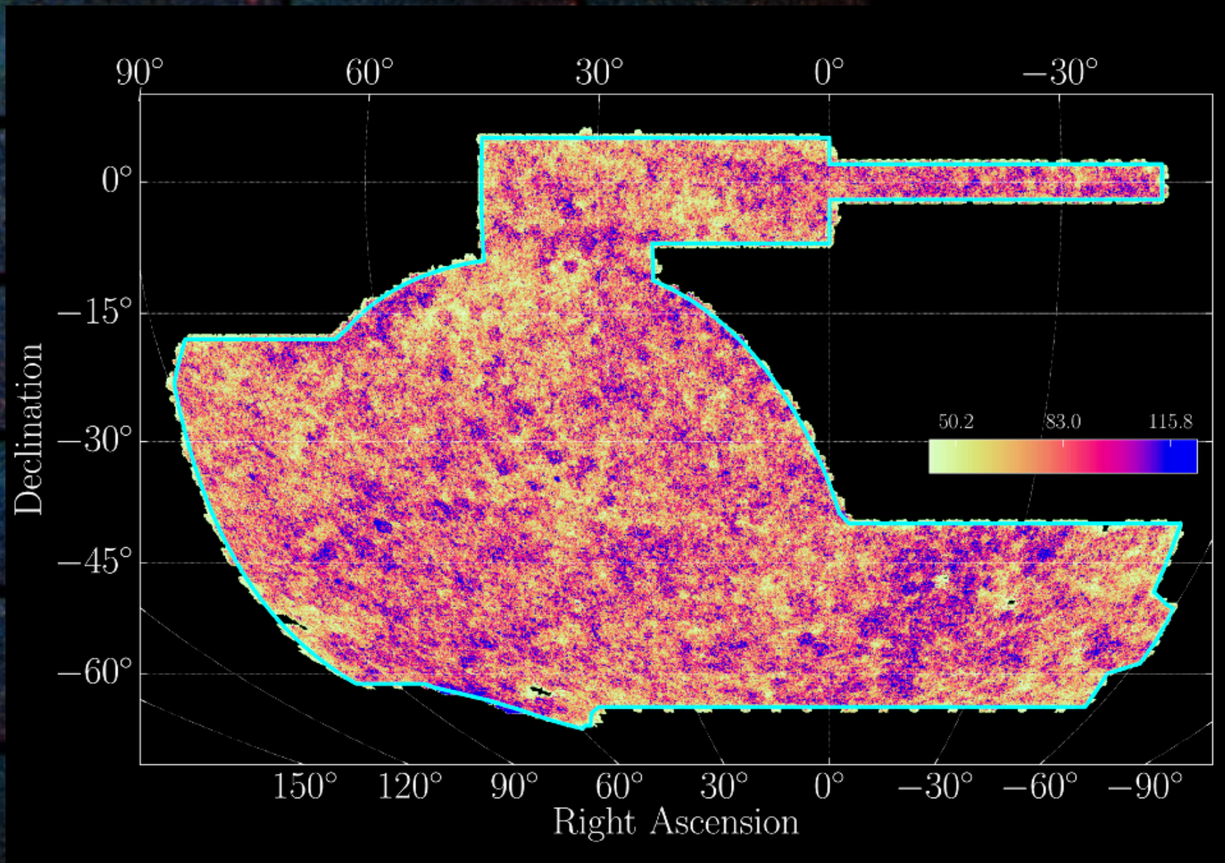
DECam

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

DES programs

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

DECam follow-up continues

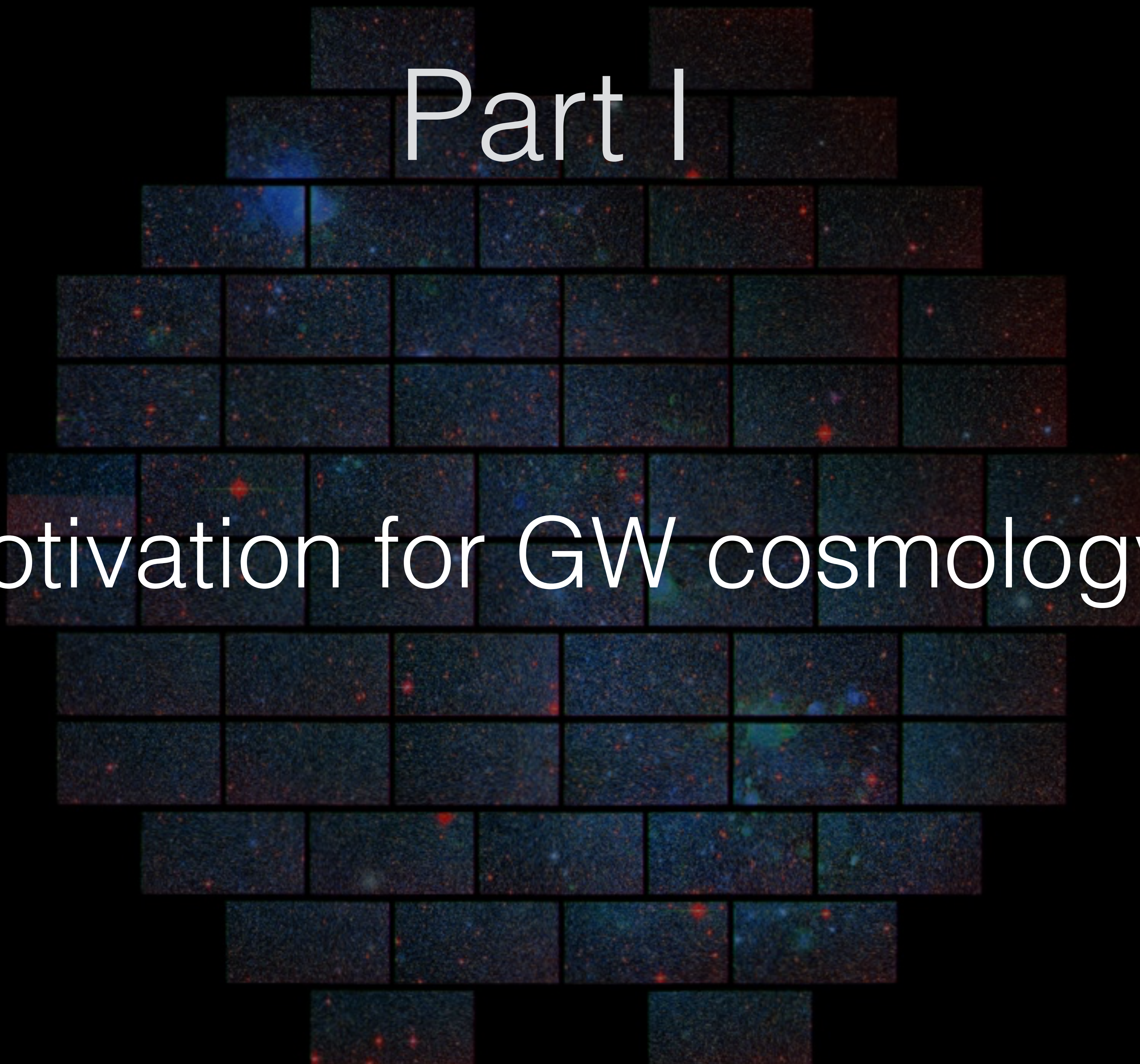


Public data

https://des.ncsa.illinois.edu/home
DR1 (Y3) - 400M objects (*r*~24)

Part I

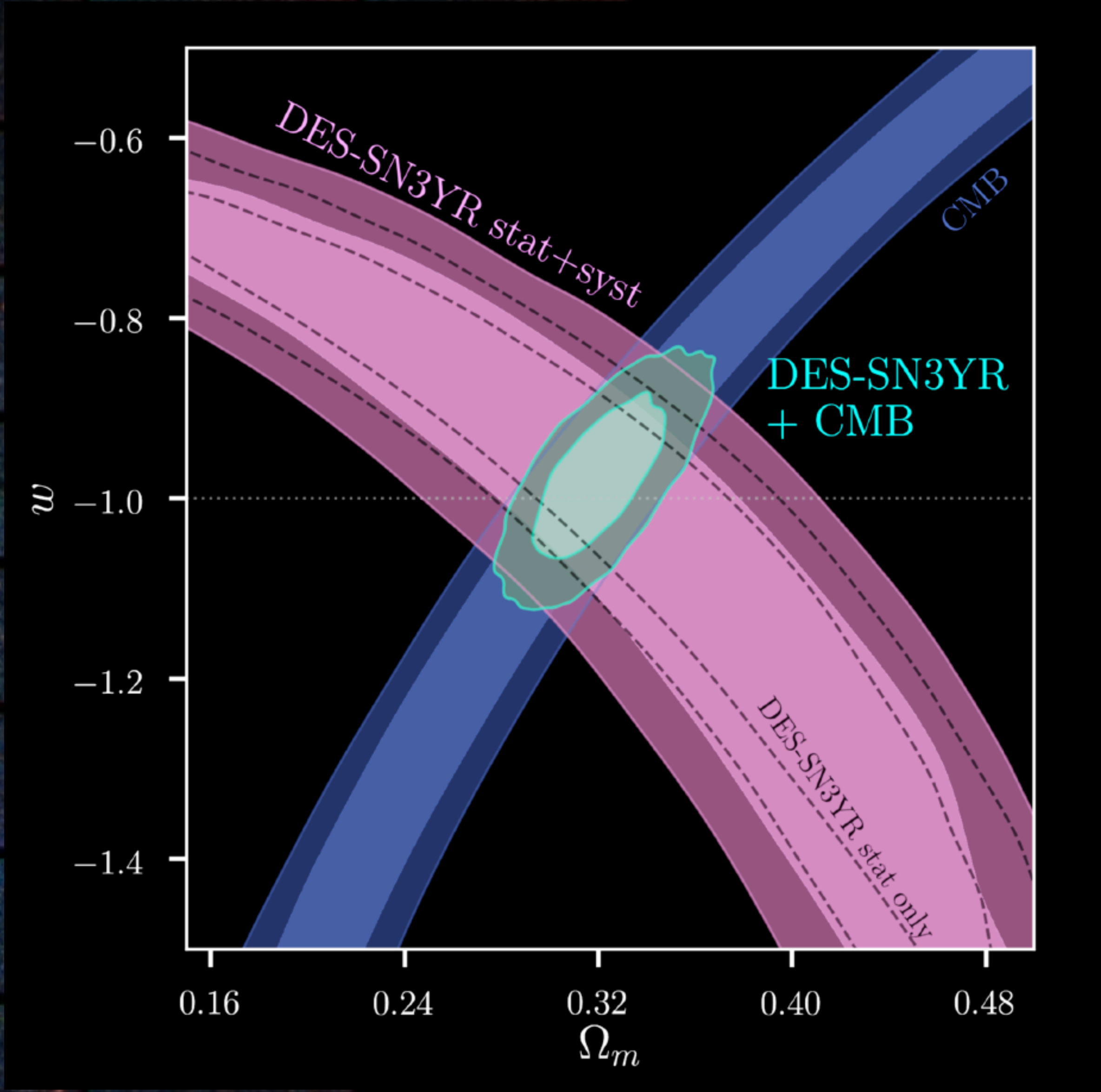
Motivation for GW cosmology



Is the Universe boring?

- 70% of the mass-energy of the Universe is an unknown substance, Dark Energy (DE). Universe well described by flat ΛCDM
- DE equation of state parameter *w*: $P = w\rho$
- **Cosmological constant** Λ : energy density constant in time, *w*=-1.
- Current results consistent with *w*=-1
- Dynamical DE (CPL): $w(z) = w_0 + w_a(1-a)$
- No evidence for dynamical DE

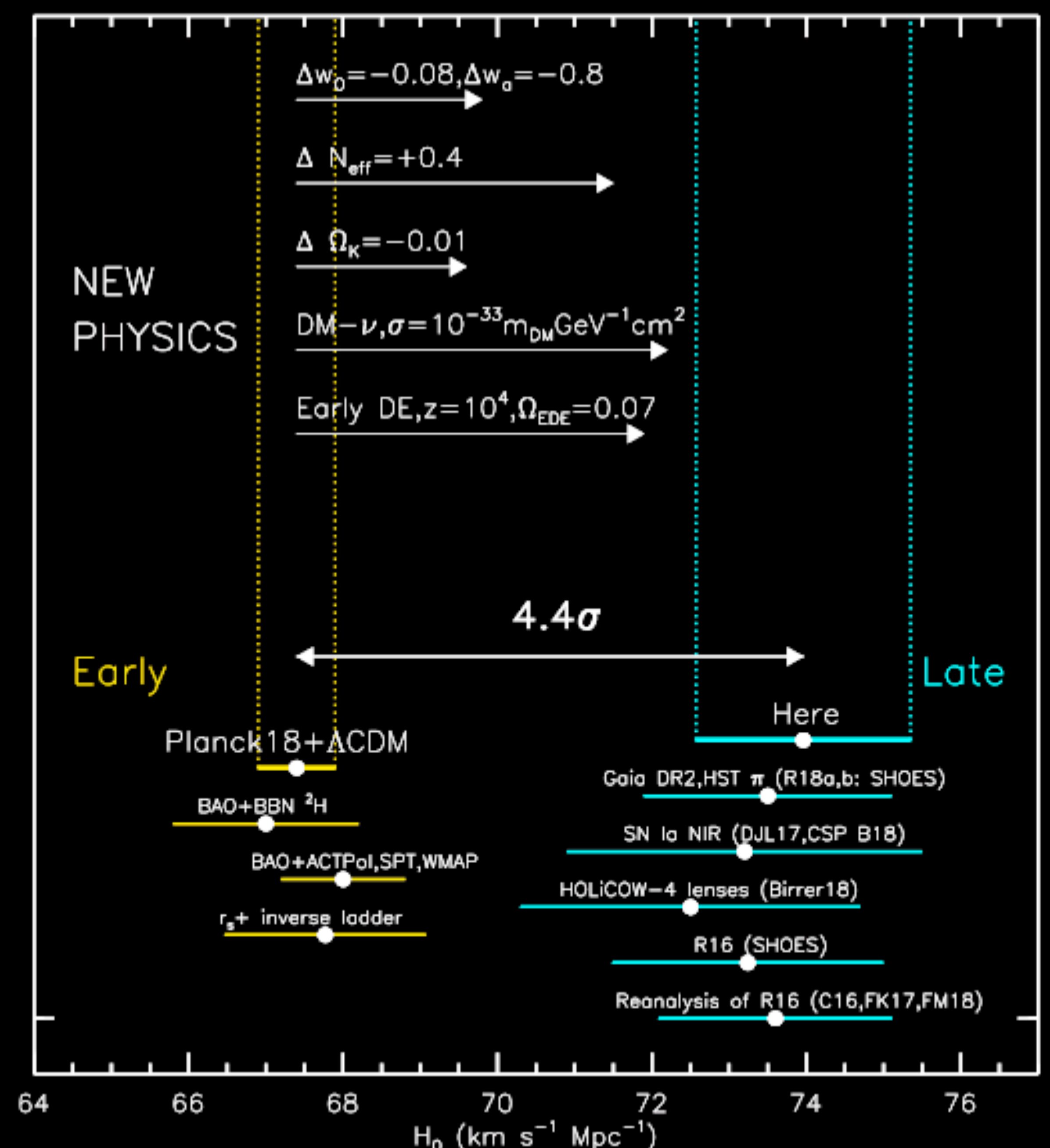
$w = -1.00^{+0.05}_{-0.04}$ (DES+Plank+JLA+BAO, DES 2019 1708.01530)



DES 2019 1811.02375

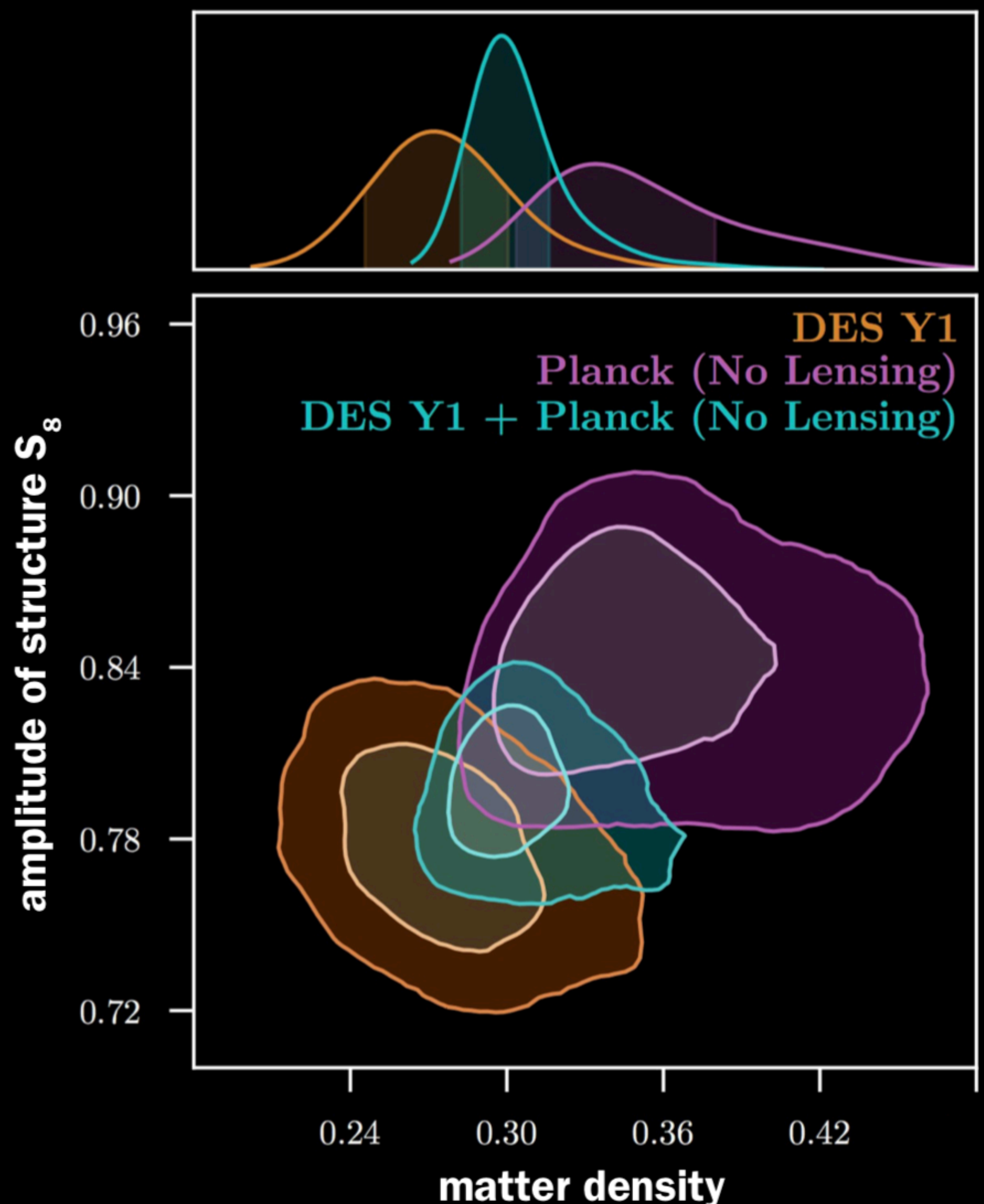
Hubble constant tension

- **4.4 sigma discrepancy** between early and late time Universe measurements
- Systematics or new physics?
- Need for an independent measurement. If from late Universe: ideally independent of distance ladder.

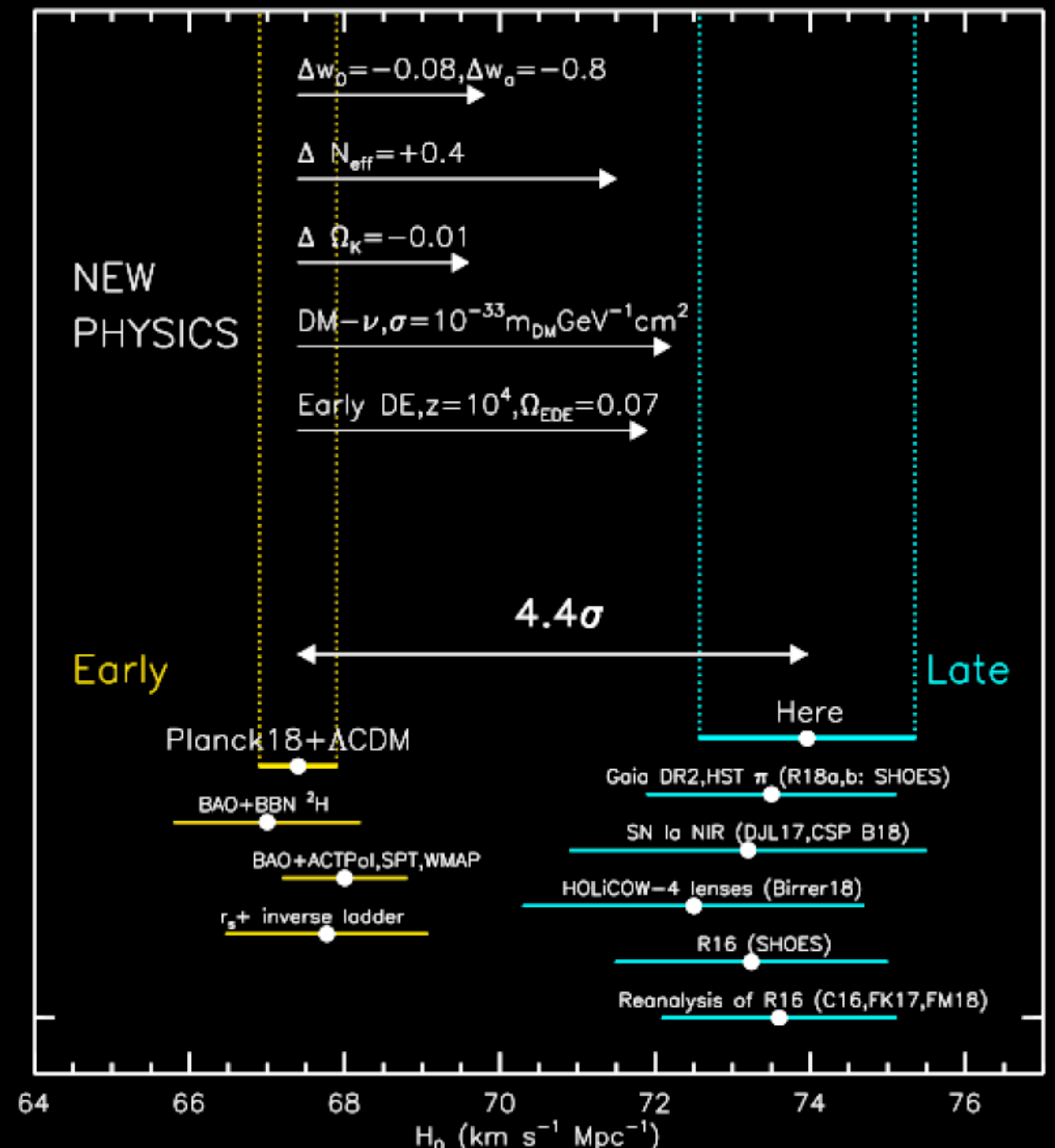


Riess+2019

Hubble constant tension



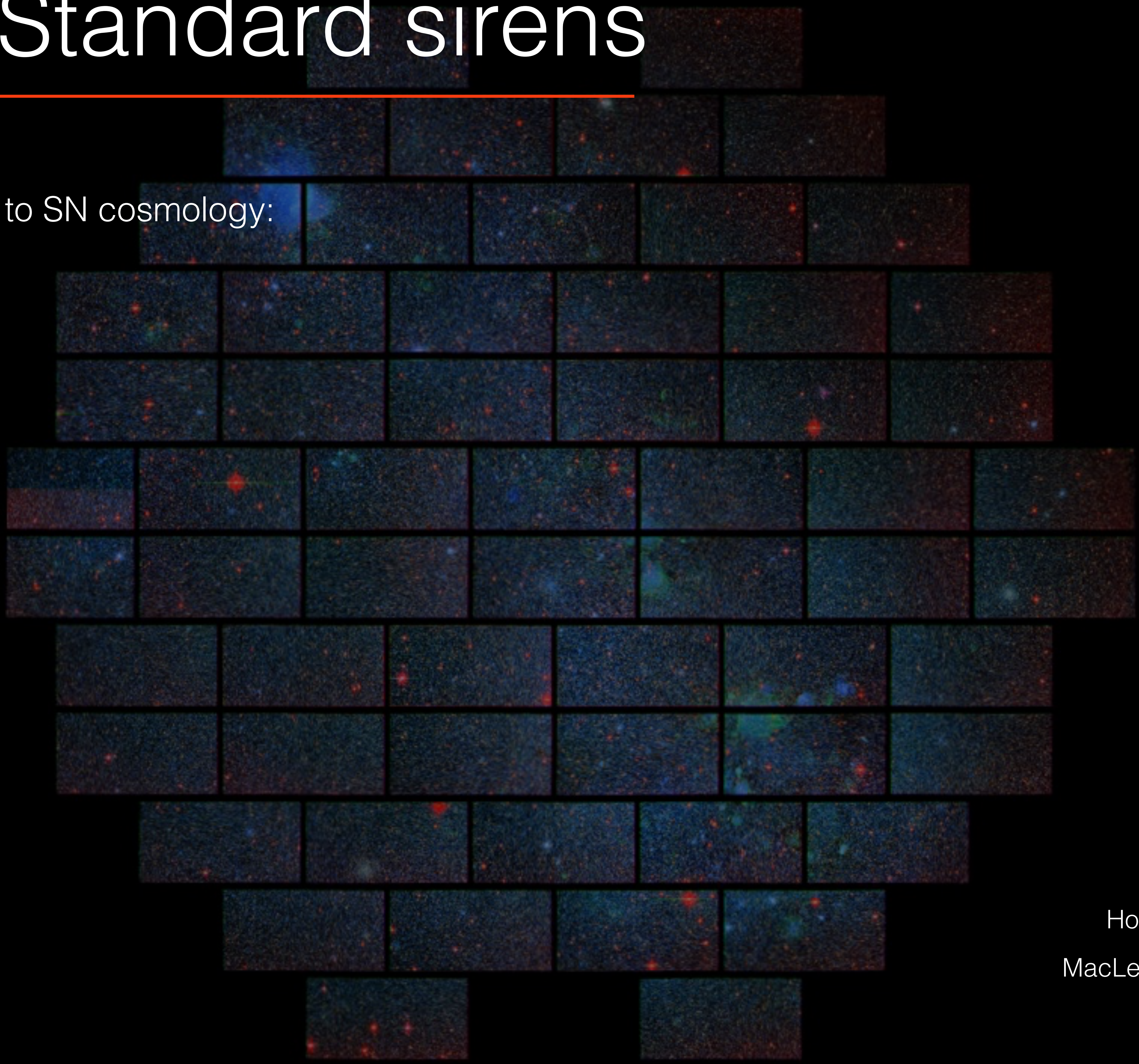
DES 2018a



Riess+2019

Standard sirens

- Similar to SN cosmology:



Schutz 1986

Holz & Hughes 2005

MacLeod & Hogan 2008

Nissanke+2010

Del Pozzo 2012

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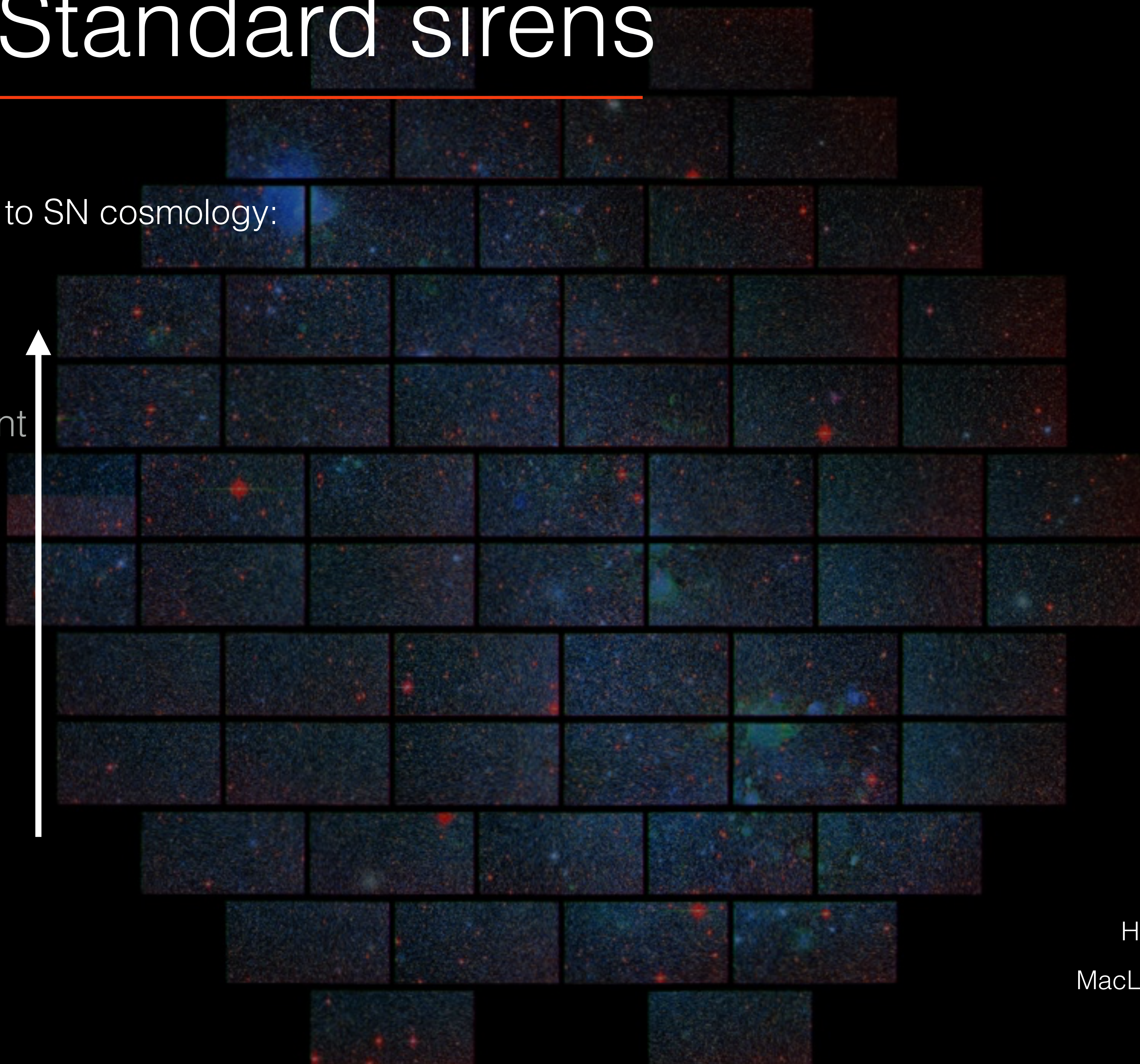

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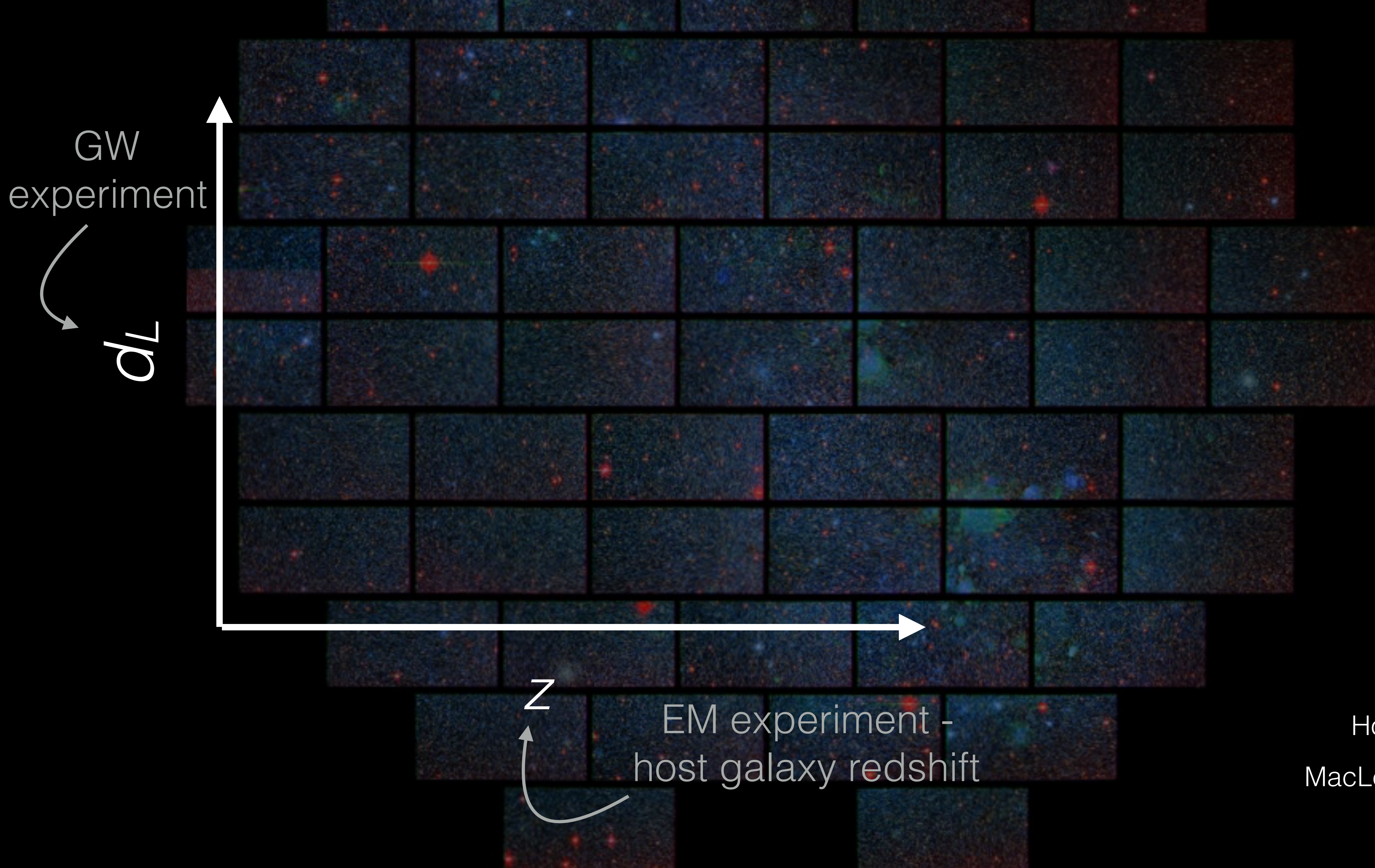

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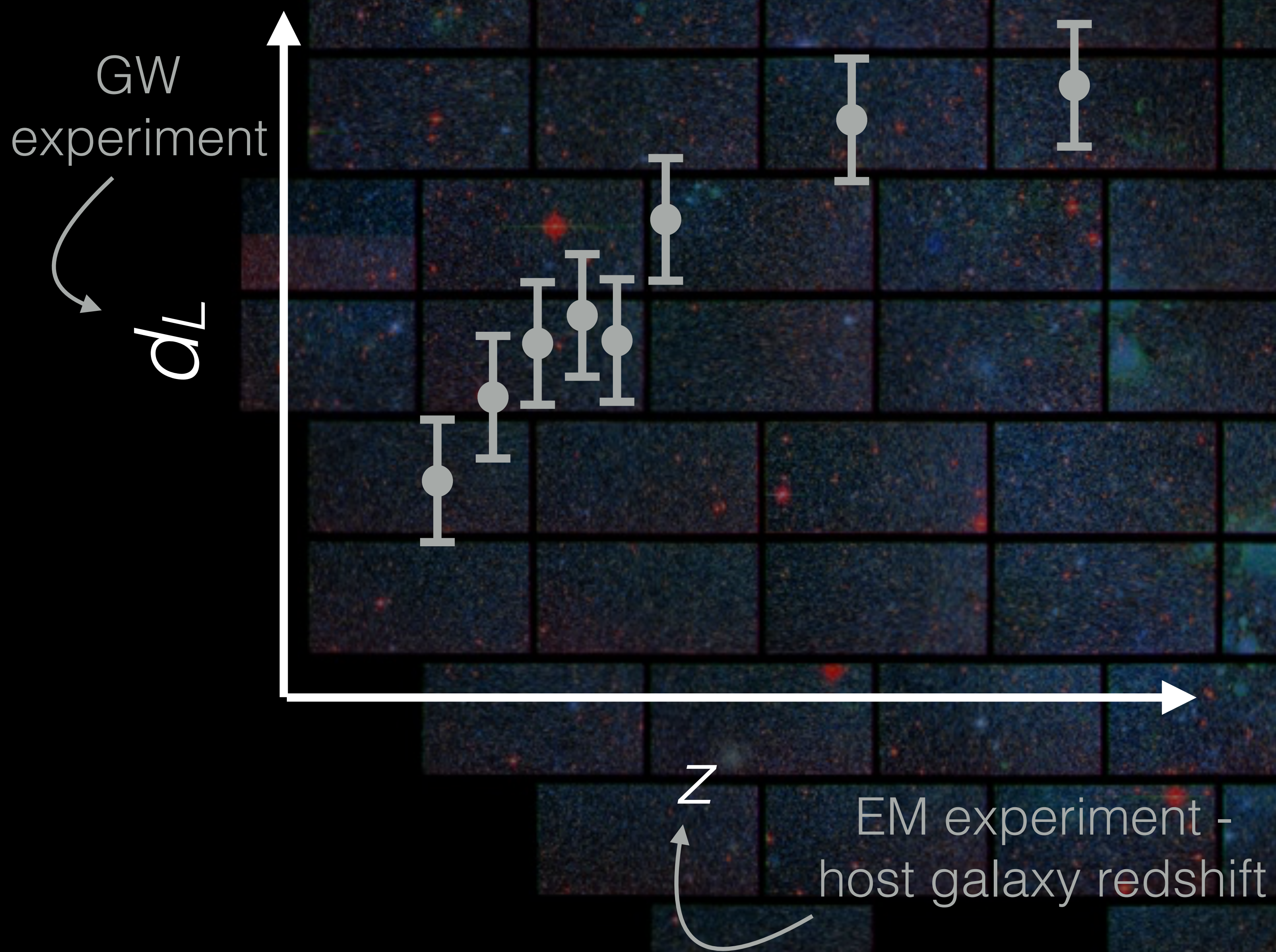

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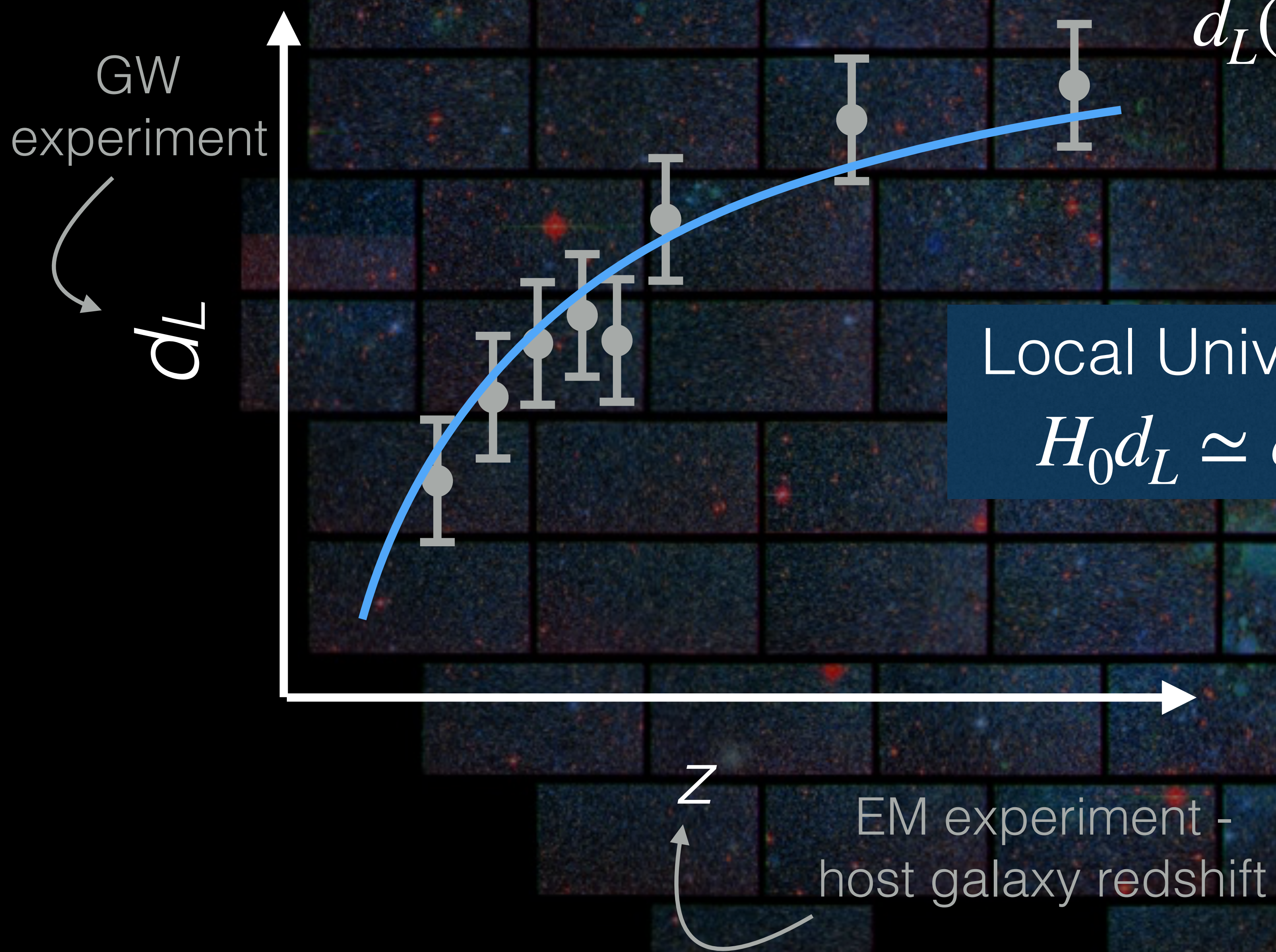

$$d_L(z) = (1+z)\int_0^z \frac{c\, dz'}{H_0 E(z')}$$

Local Universe:

$$H_0 d_L \simeq cz$$

$z \gtrsim 0.1$:

$$E(z) = \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$$

Schutz 1986

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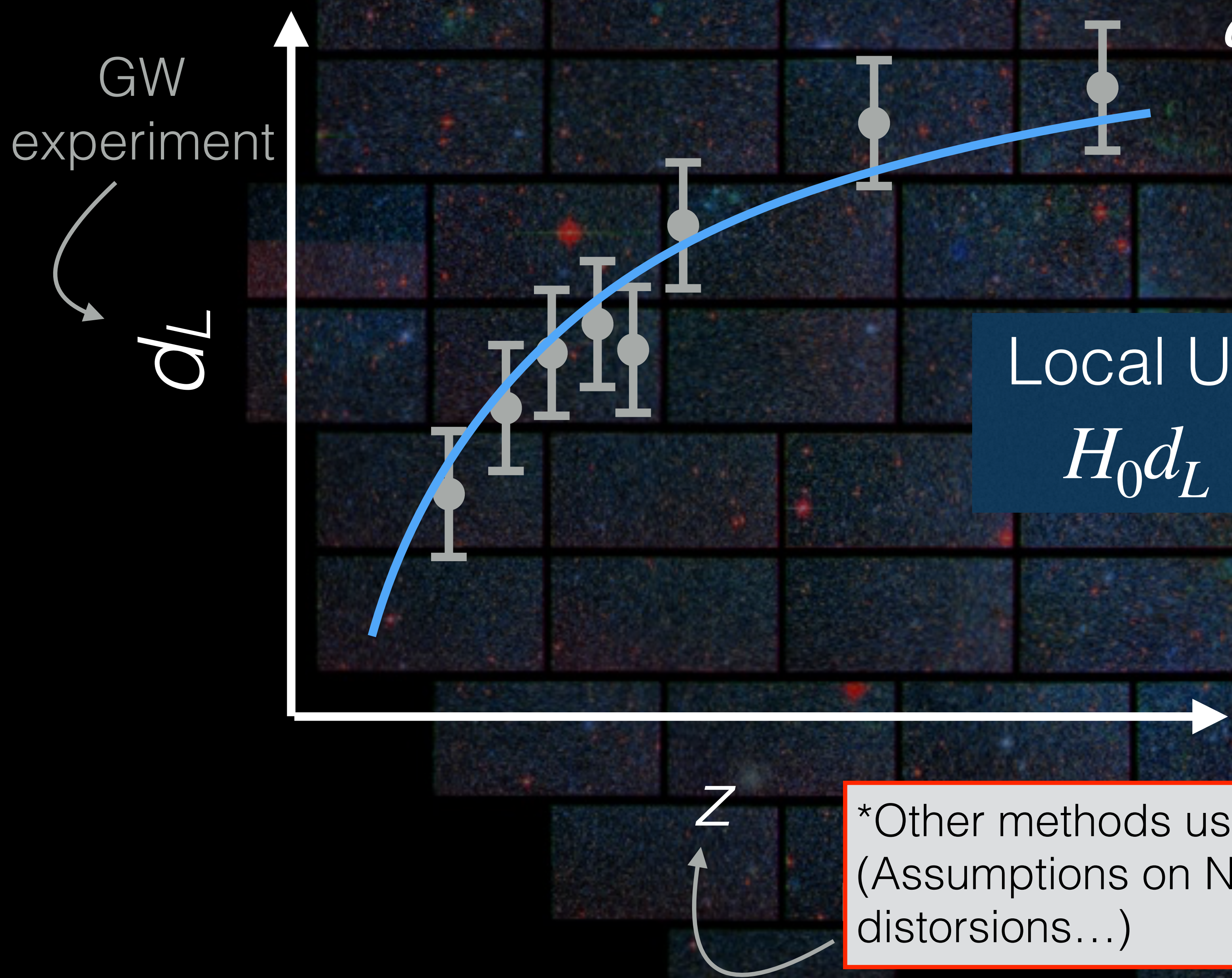

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*Other methods use GW only (Assumptions on NS MF, EOS, tidal distorsions…)

Markovic 1993, Taylor & Gair 2012…

Schutz 1986

Holz & Hughes 2005

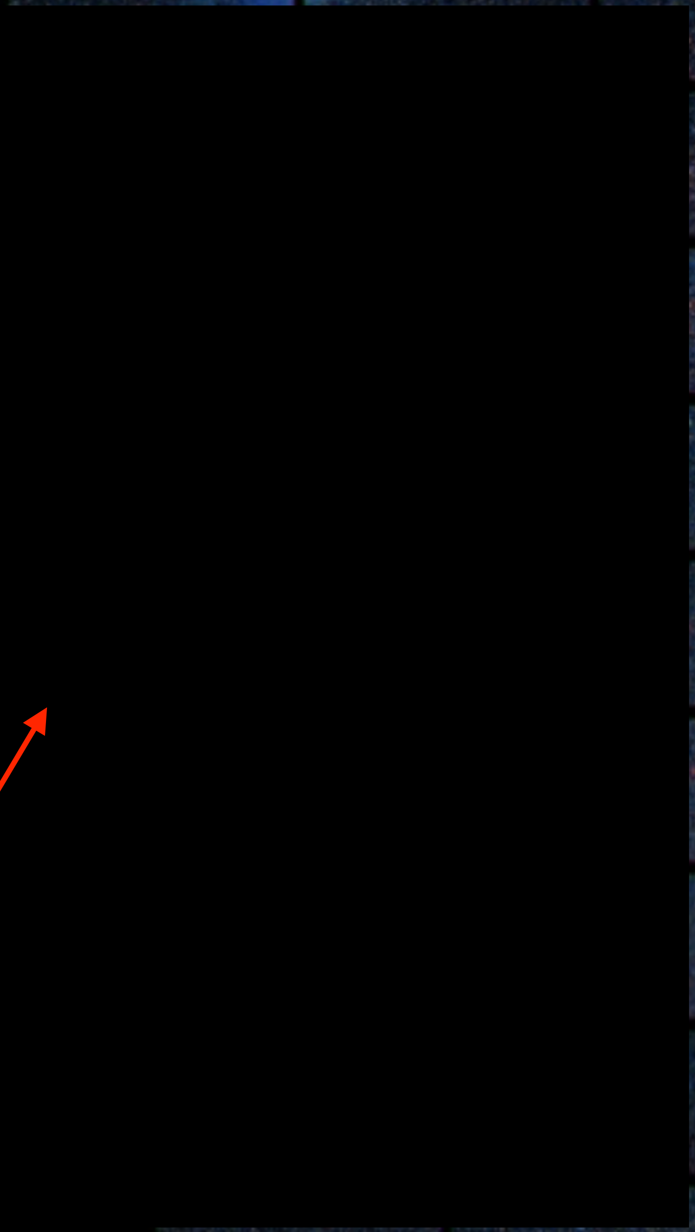
MacLeod & Hogan 2008

Nissanke+2010

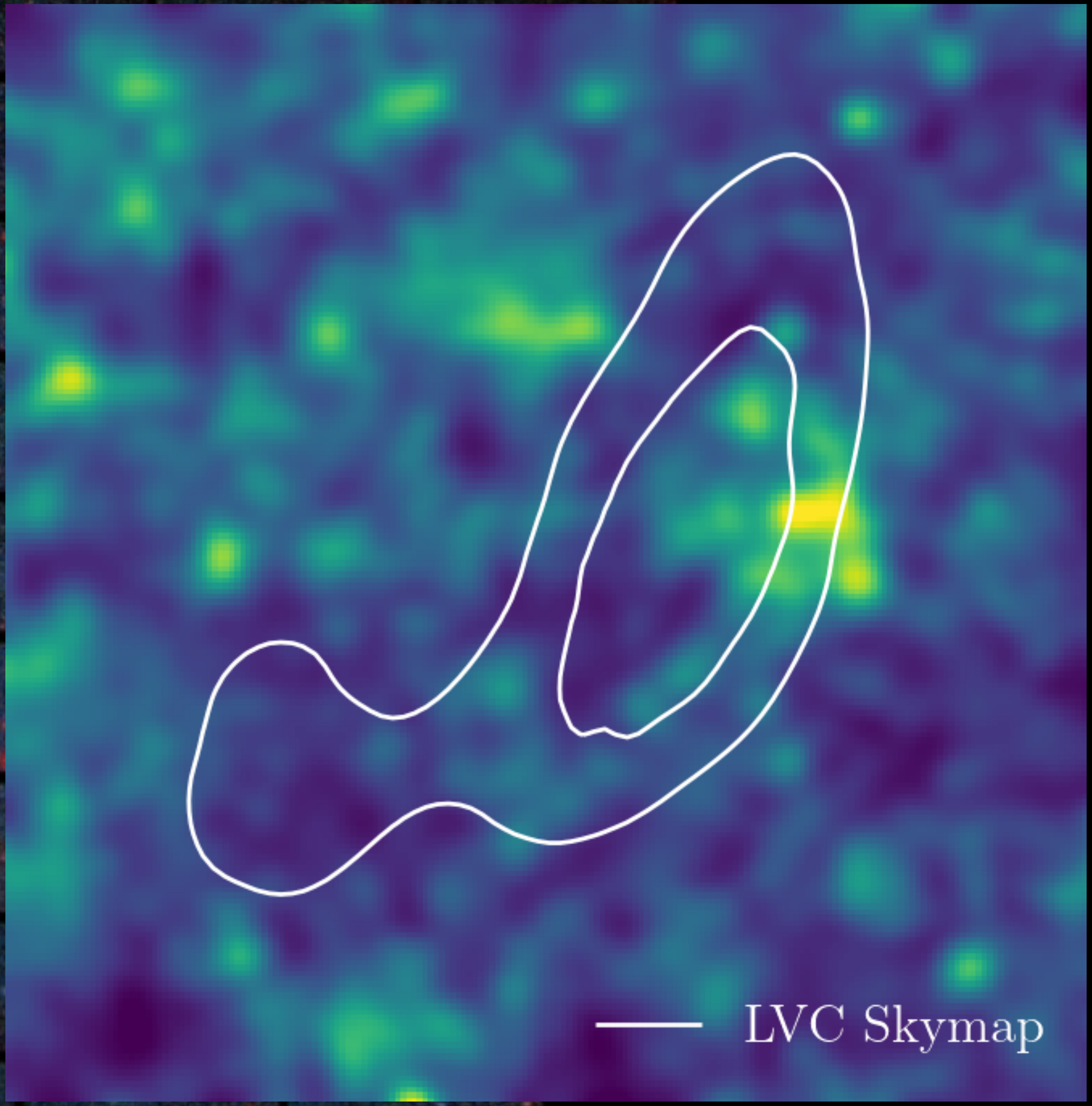
Del Pozzo 2012

GW+EM standard siren methods

Unique host galaxy



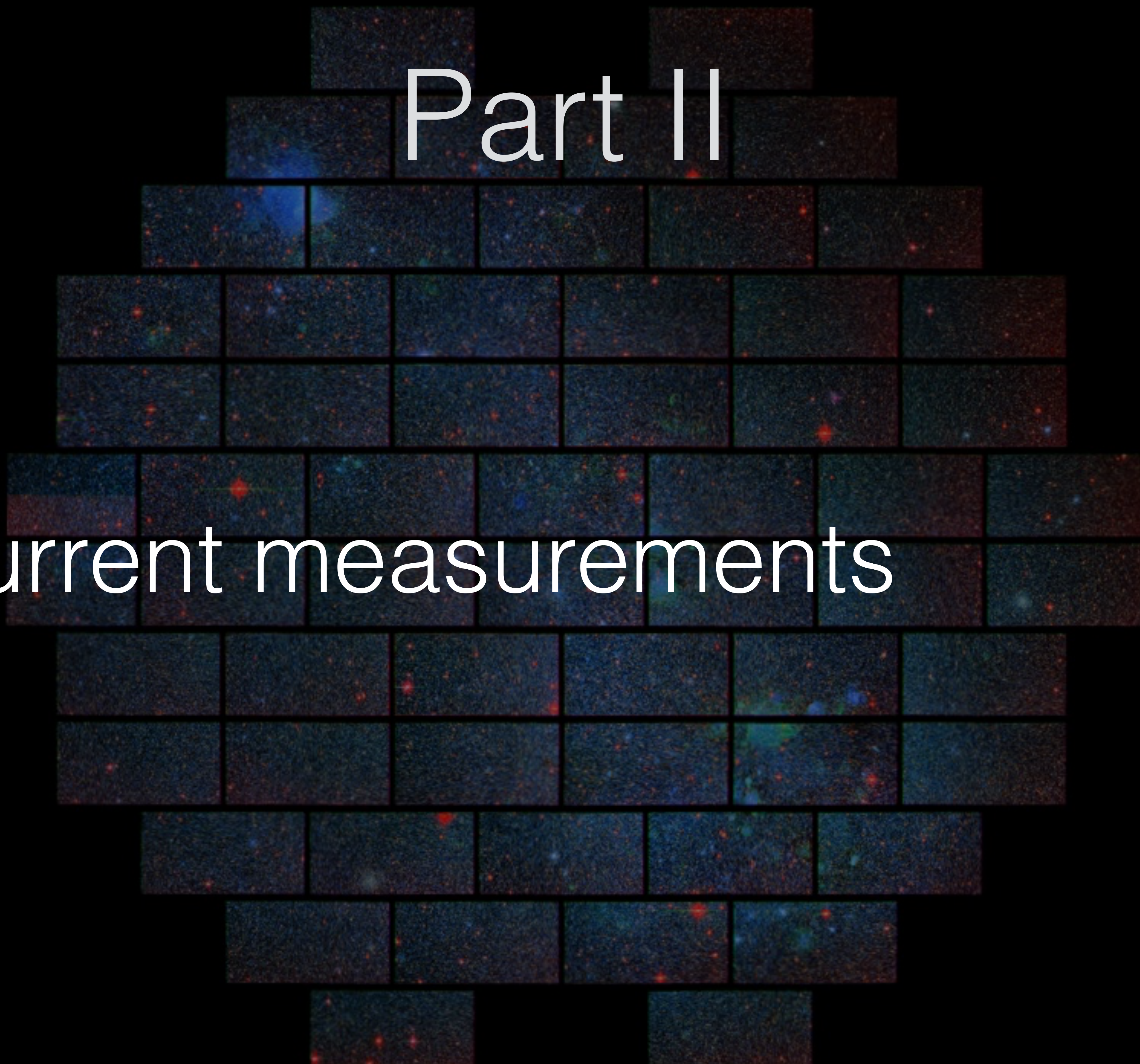
No EM counterpart: potential host galaxies



Bright standard sirens

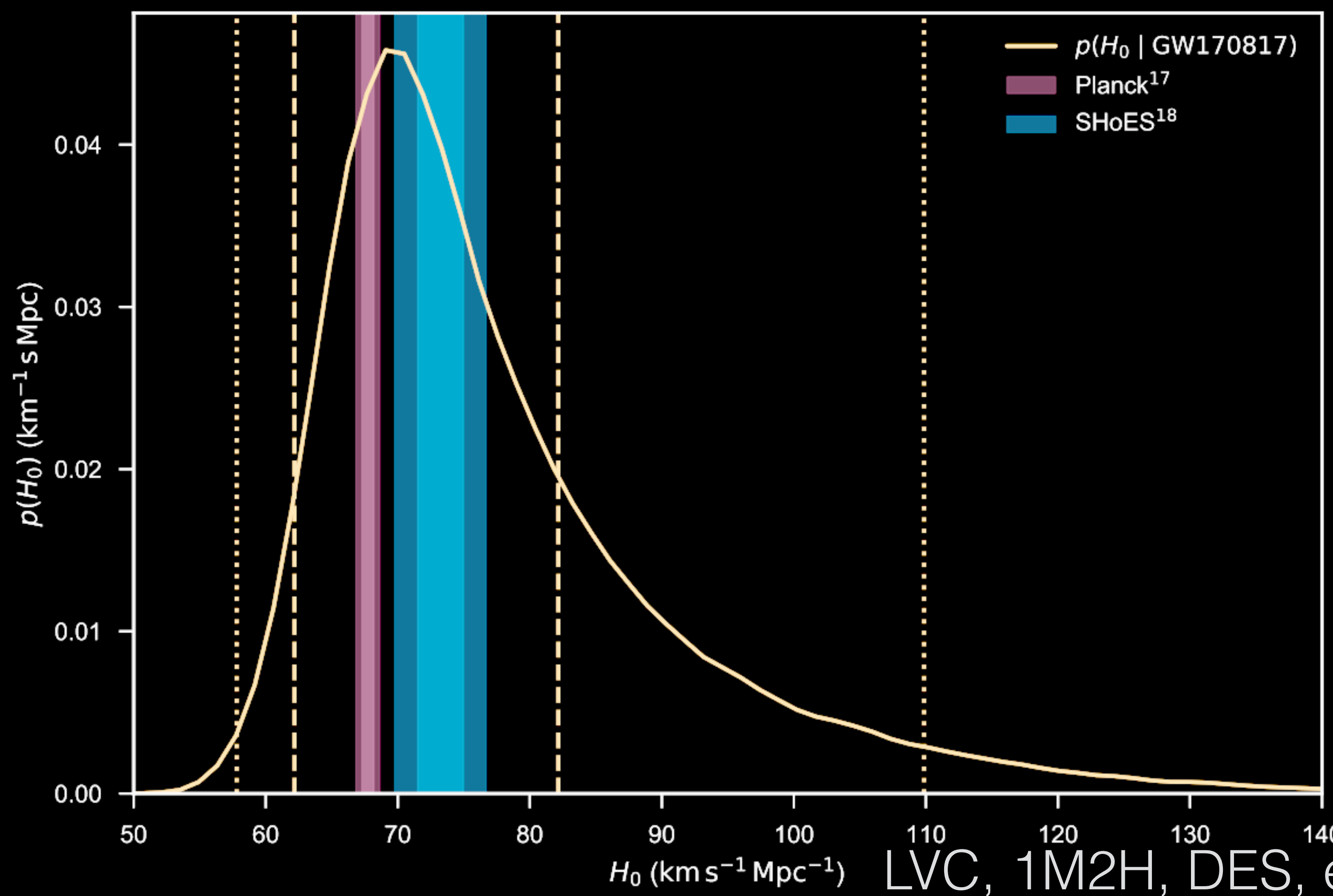
Dark standard sirens / statistical method

Part II



Current measurements

GW170817 as bright standard siren



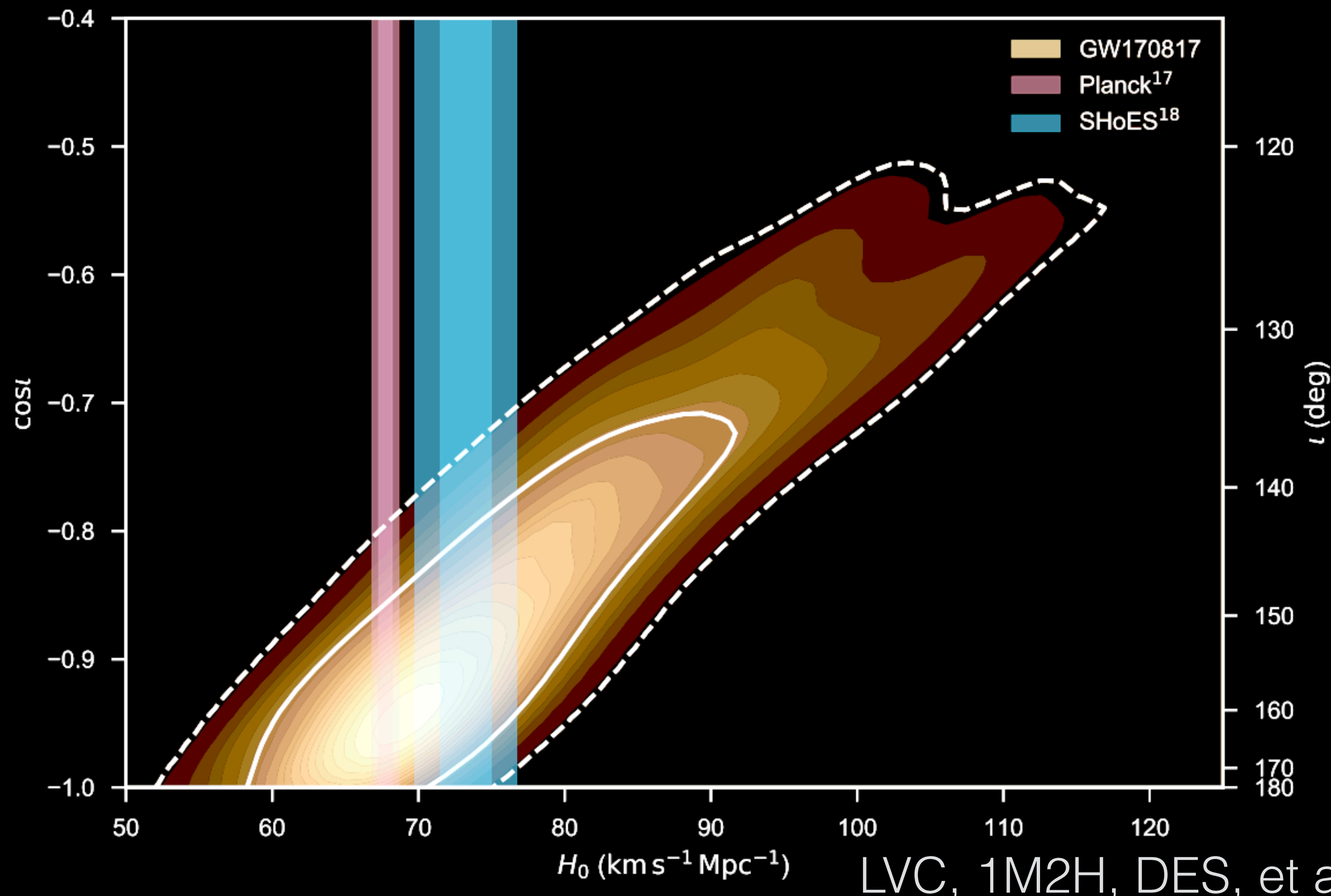
LVC, 1M2H, DES, et al. 2017

- NGC 4993 (z~0.01)

$$H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

- **Ideal to solve the Hubble constant tension:**
  1. Self-calibrating: Independent of distance ladder
  2. Cosmological model independent

GW170817 as bright standard siren



LVC, 1M2H, DES, et al. 2017

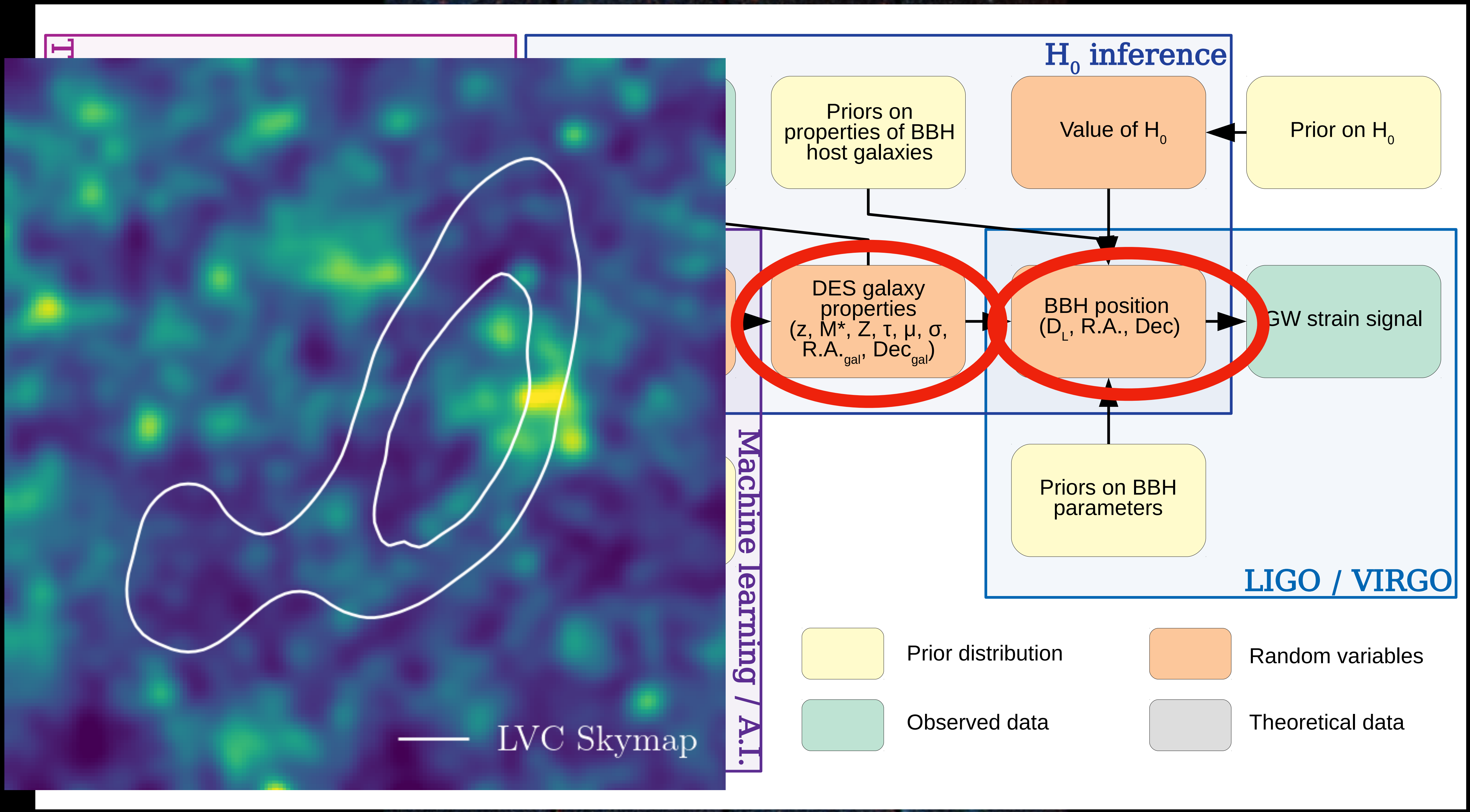
- Limitations:
  - ⋆ Peculiar velocity
  - ⋆ Inclination angle is correlated with *D*
- Can break degeneracy by constraining ι from EM
- Improve precision by factor 2-3 (Guidorzi+17,Hotokezaka+18)

Dark sirens

Standard sirens with no EM counterpart

Proposed by Schutz in 1986

Del Pozzo 2012
Chen, Fishbach & Holz (2018)



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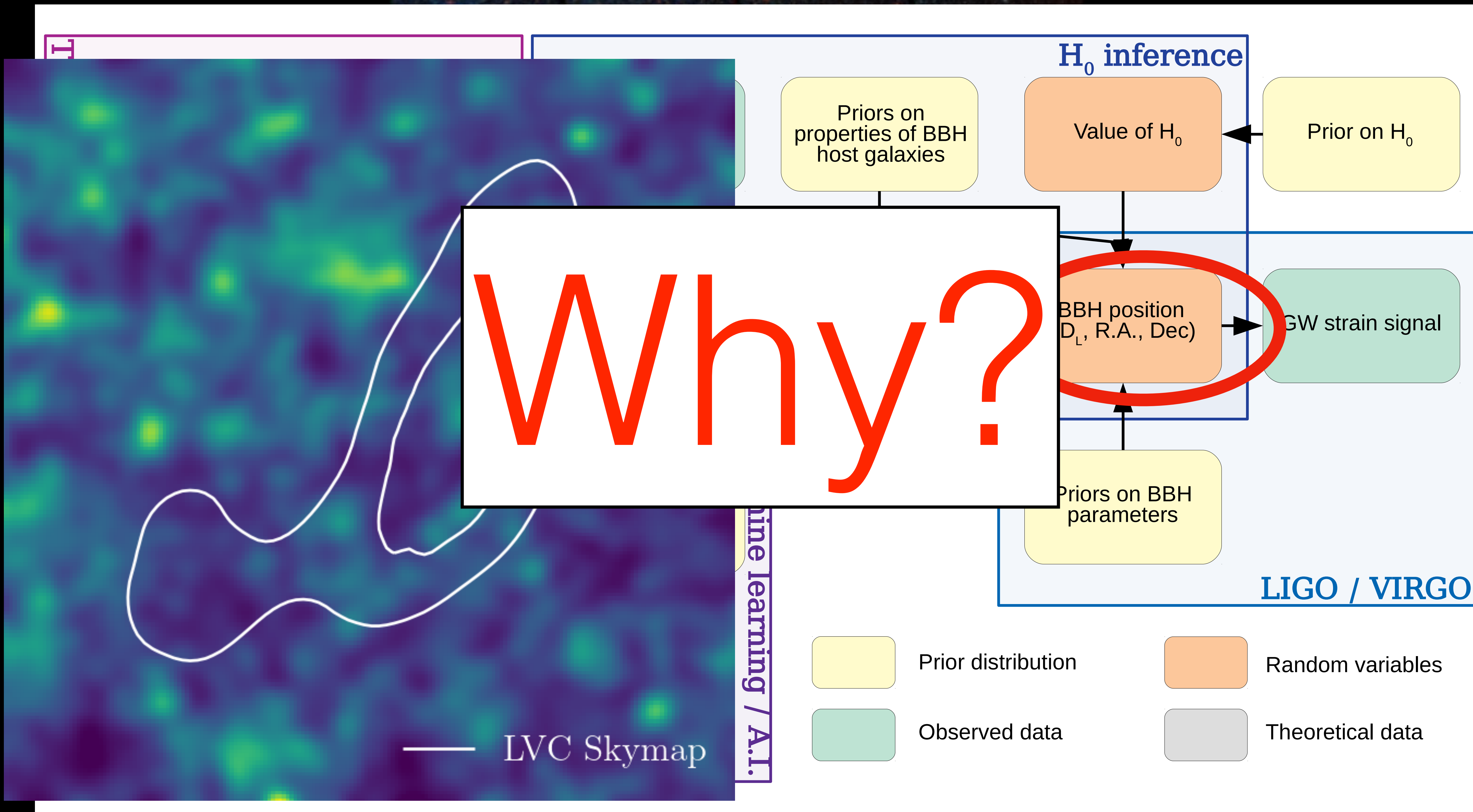
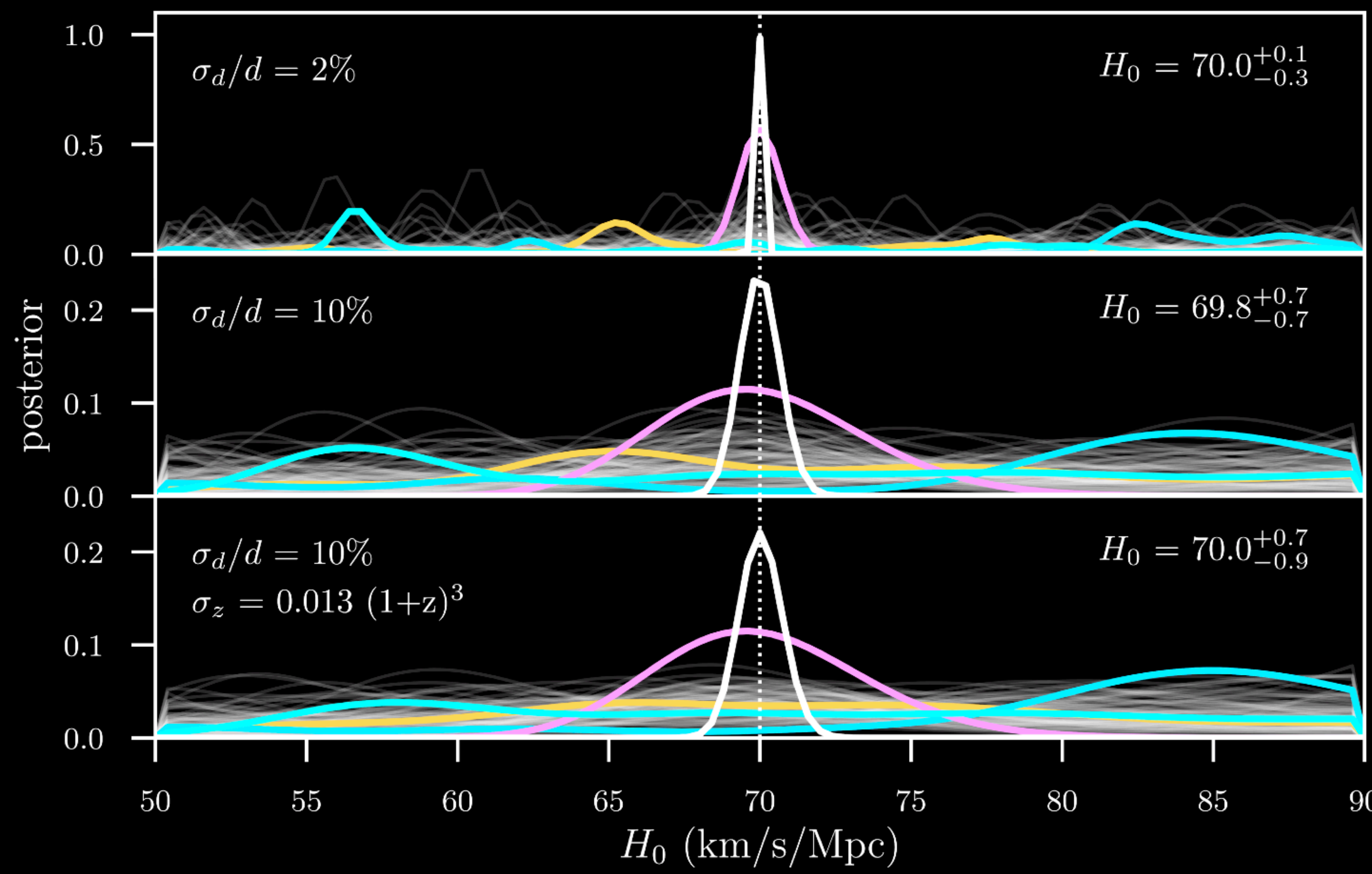


Why?

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

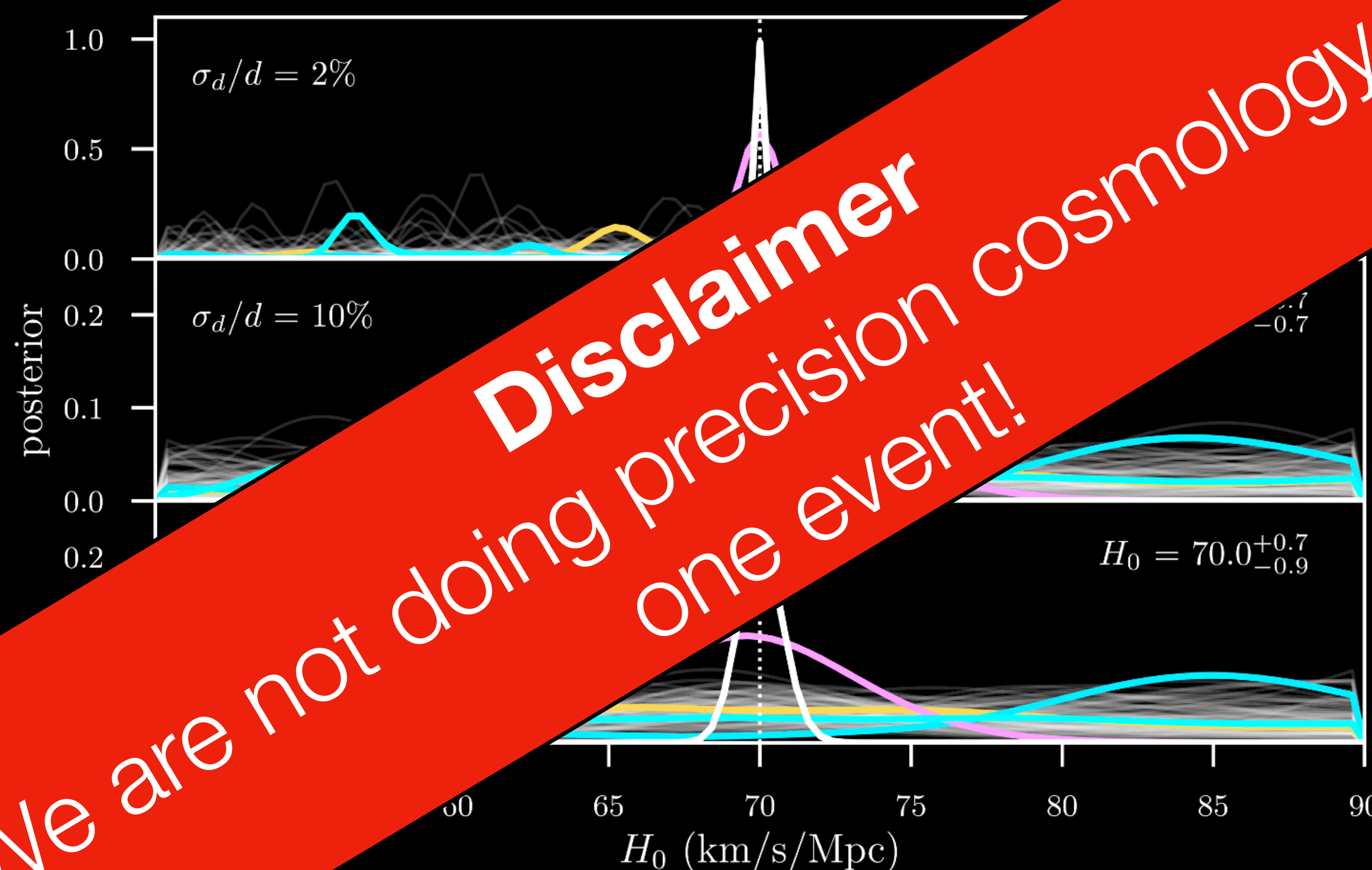
Simulations



- 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

DES & LVC (2019) arxiv:1901.01540

Simulations



Disclaimer

We are not doing precision cosmology from one event!

- ... sterior expected to have peaks corresponding to large scale structure along the los
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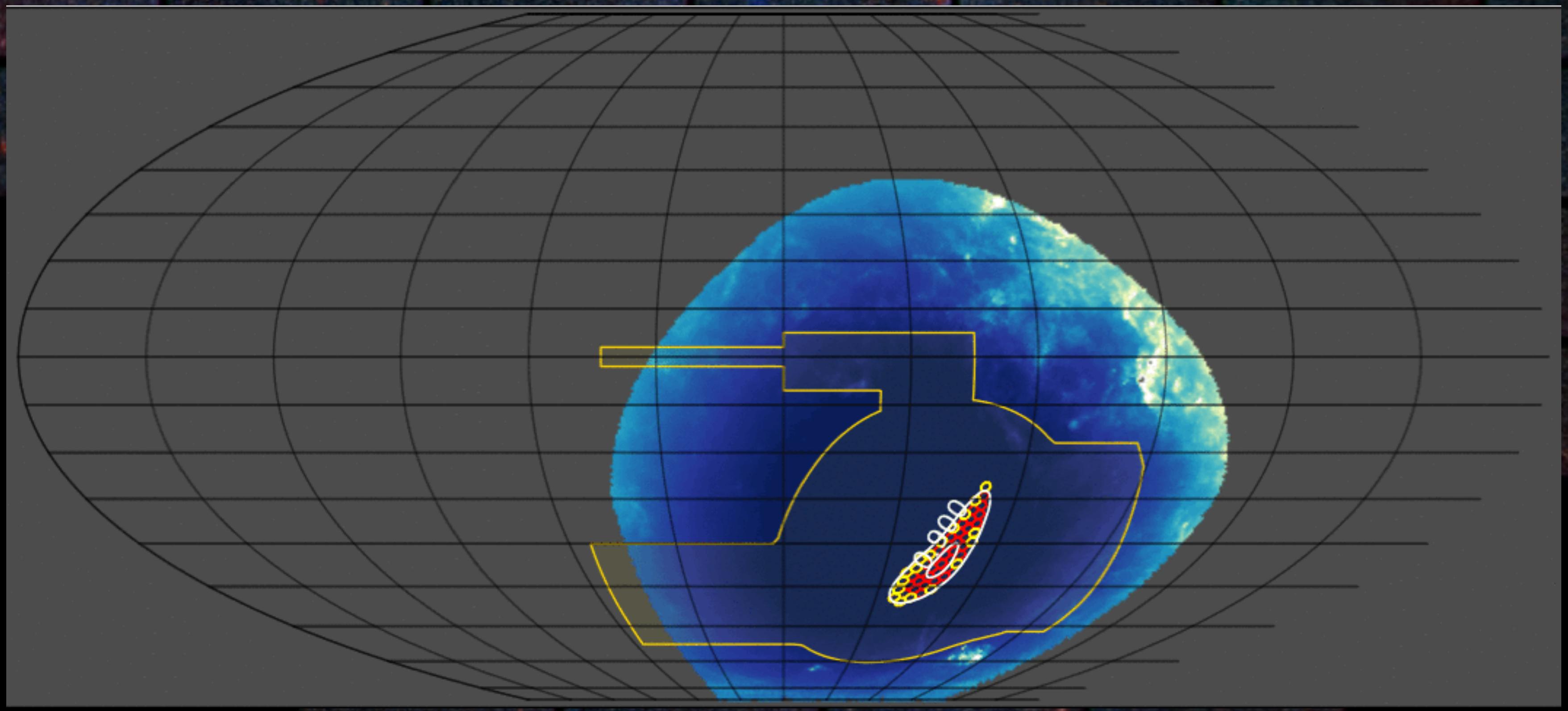
DES & LVC (2019) arxiv:1901.01540

GW170814: the golden event (for DES)

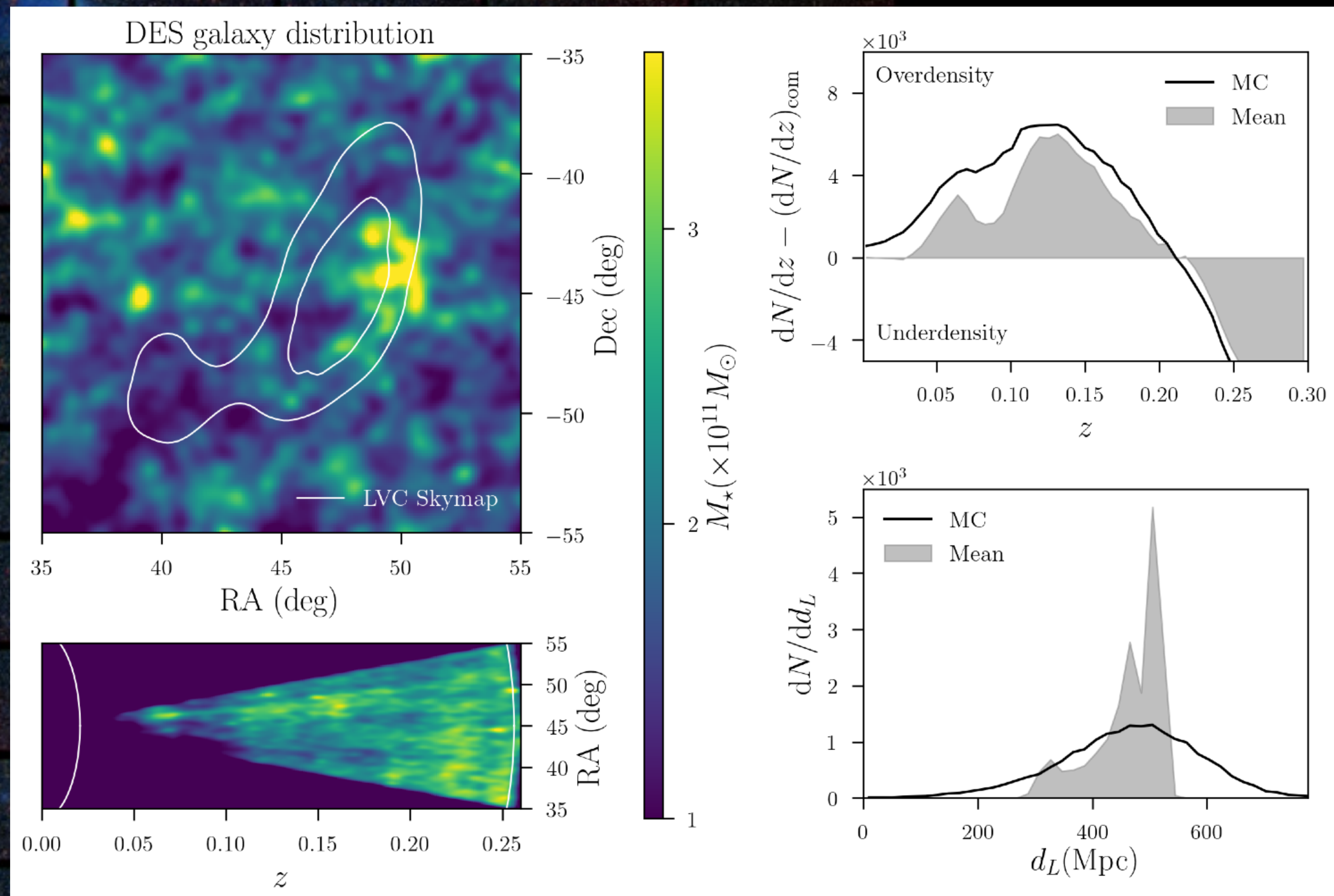
- First BBH event from LIGO+Virgo: 90% probability in 60 sq deg
- 90%+ covered by DES-GW follow up (no counterpart - Doctor et al. 2019)
- Falls in the DES footprint



DES & LVC (2019) arxiv:1901.01540

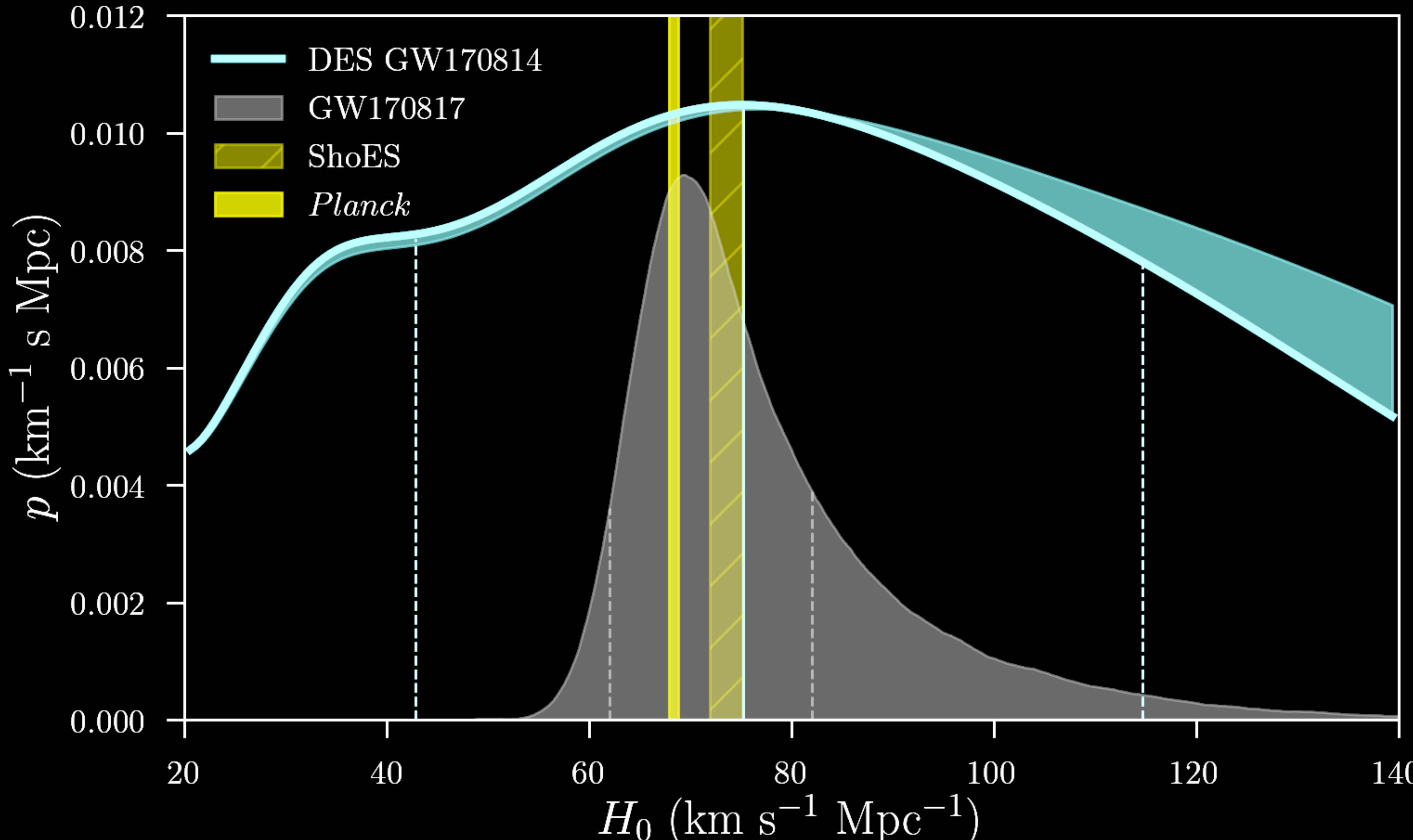
GW170814: the golden event (for DES)

- 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



DES & LVC (2019) arxiv:1901.01540

Results

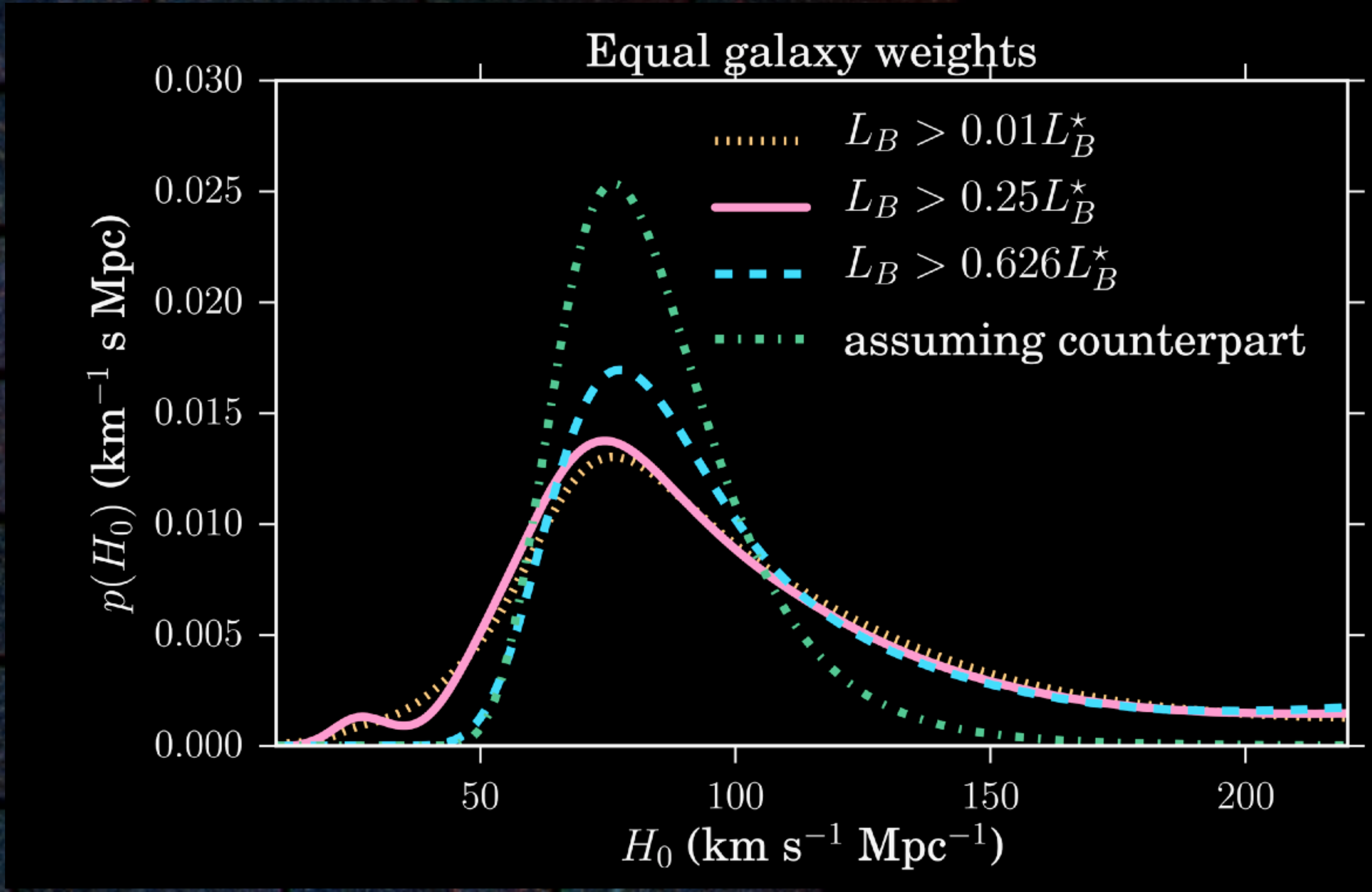


$$H_0 = 75.2^{+39.5}_{-32.4} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

DES & LVC (2019) [arxiv:1901.01540](https://arxiv.org/abs/1901.01540)

GW170817 as a dark siren

- Localization **volume** is **crucial**!
- Ignore counterpart and use GW170817 as a dark siren
- 1.7x more precise than GW170814
- 2x less precise than bright siren



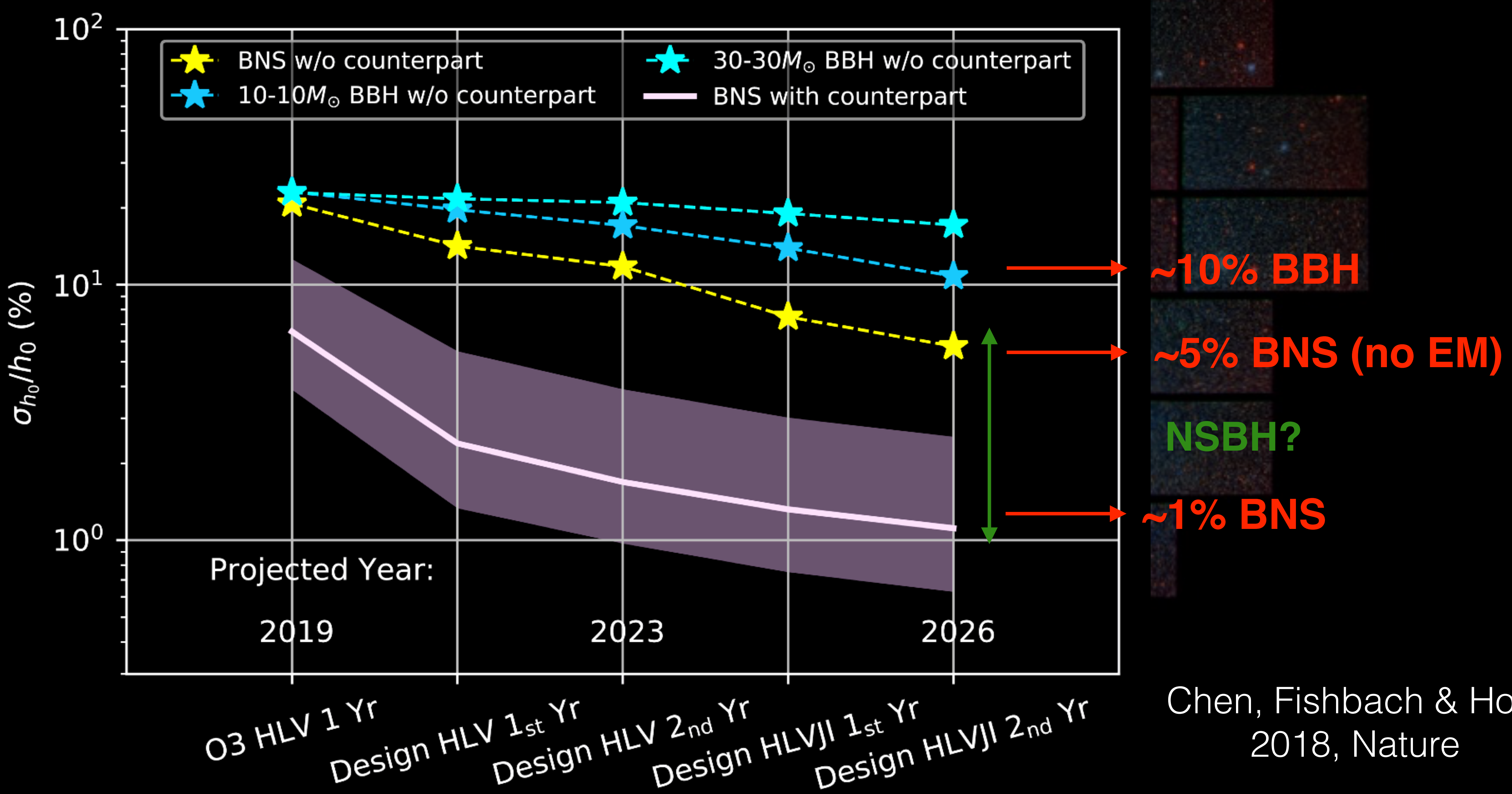
Fishbach+LVC (2018) arxiv:1807.05667

Part III

Prospects for current GW detectors & 3G

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)



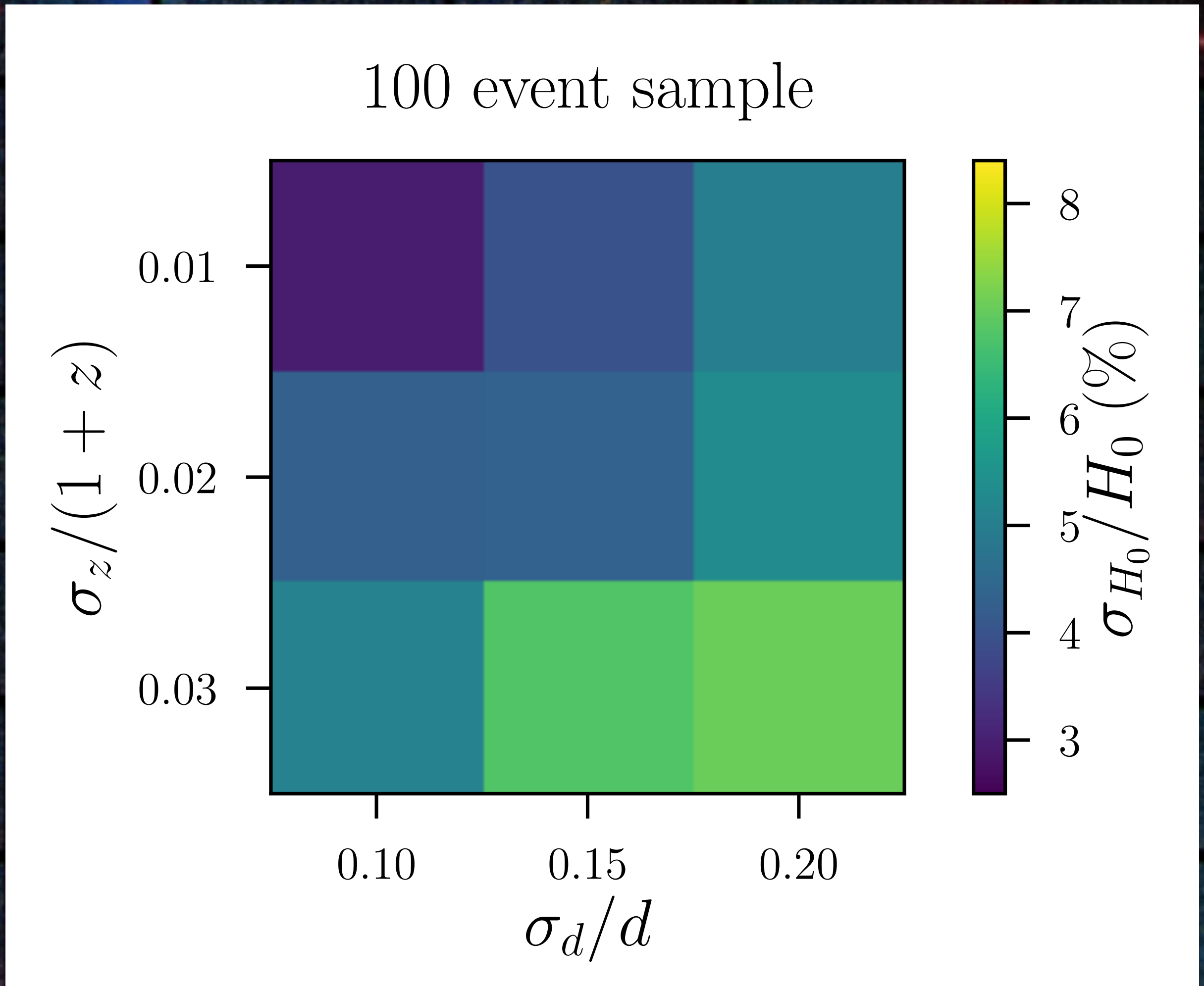
Chen, Fishbach & Holz 2018, Nature

Dark sirens precision

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

LSST-like →

DES-like →

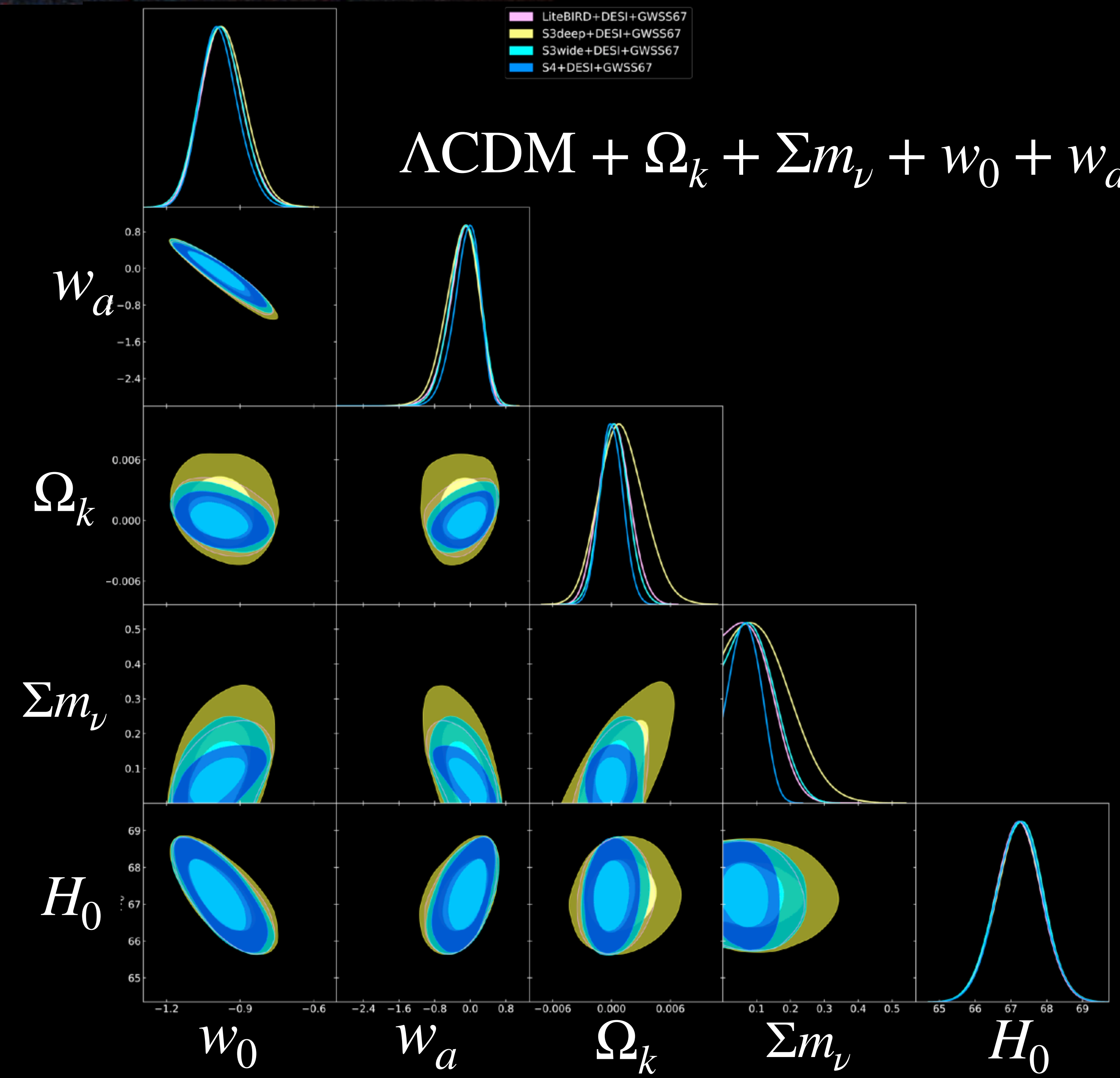


Ansatz, systematics to be understood before precision cosmology is allowed:

- ⋆ Impact of galaxy bias
- ⋆ Photo-z systematics or spec-z greater incompleteness?
- ⋆ Clustering of typical host galaxies

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

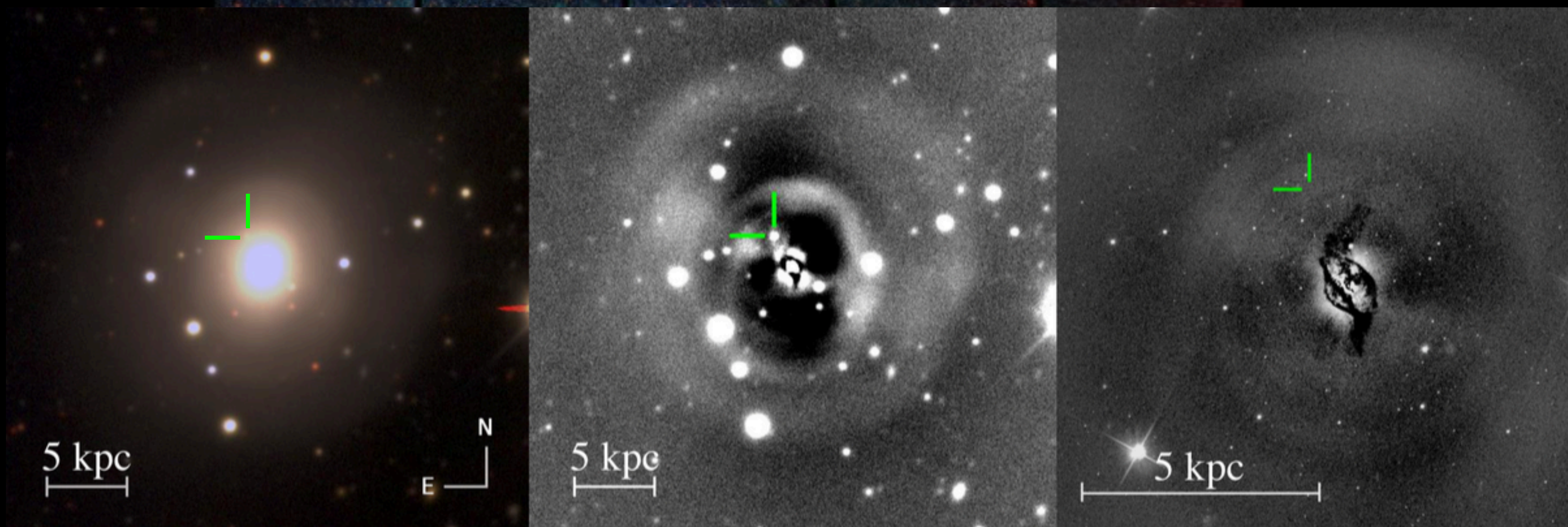


Di Valentino, Holz, Melchiorri, Renzi 2018

Host galaxy of GW170817

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

DECam DECam HST



- ⋆ Unlikely the binary formed as isolated binary in this type of galaxy
- ⋆ Position of the transient lies on a shell, remnant of galaxy merger
- ⋆ Galaxy merging activity may relate sGRB hosts

Suggest that galaxy mergers can boost the BNS formation/merging by boosting dynamical interactions

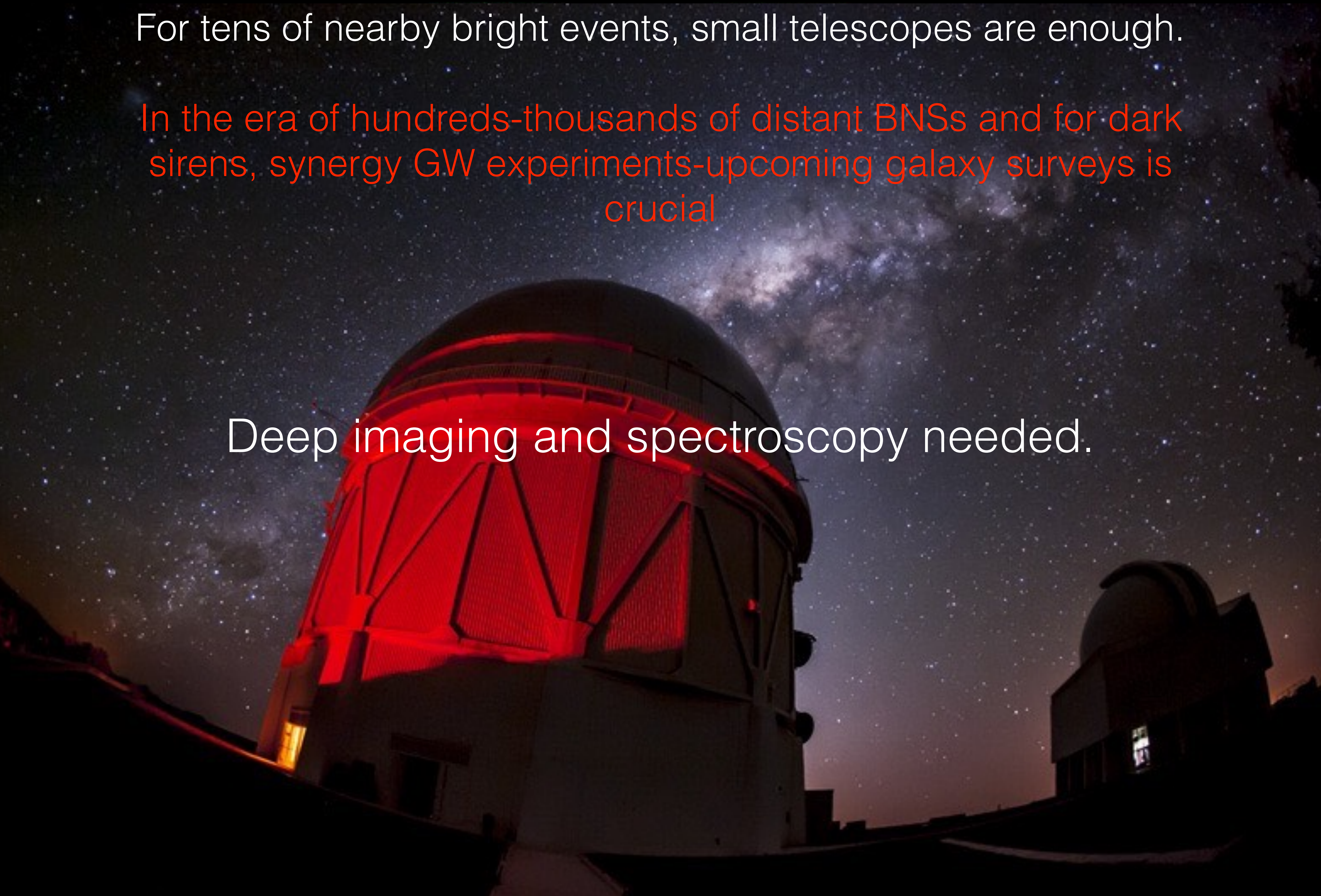
Alternative: assume isolated binary + SFH ⟶ constrain time delay (Blanchard+2017)

<u>**Larger statistics of GW hosts will shed light on formation channels of GW sources**</u>

Palmese+DES (2017) arxiv:1710.06748

For tens of nearby bright events, small telescopes are enough.

In the era of hundreds-thousands of distant BNSs and for dark sirens, synergy GW experiments-upcoming galaxy surveys is crucial



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Deep imaging and spectroscopy needed.

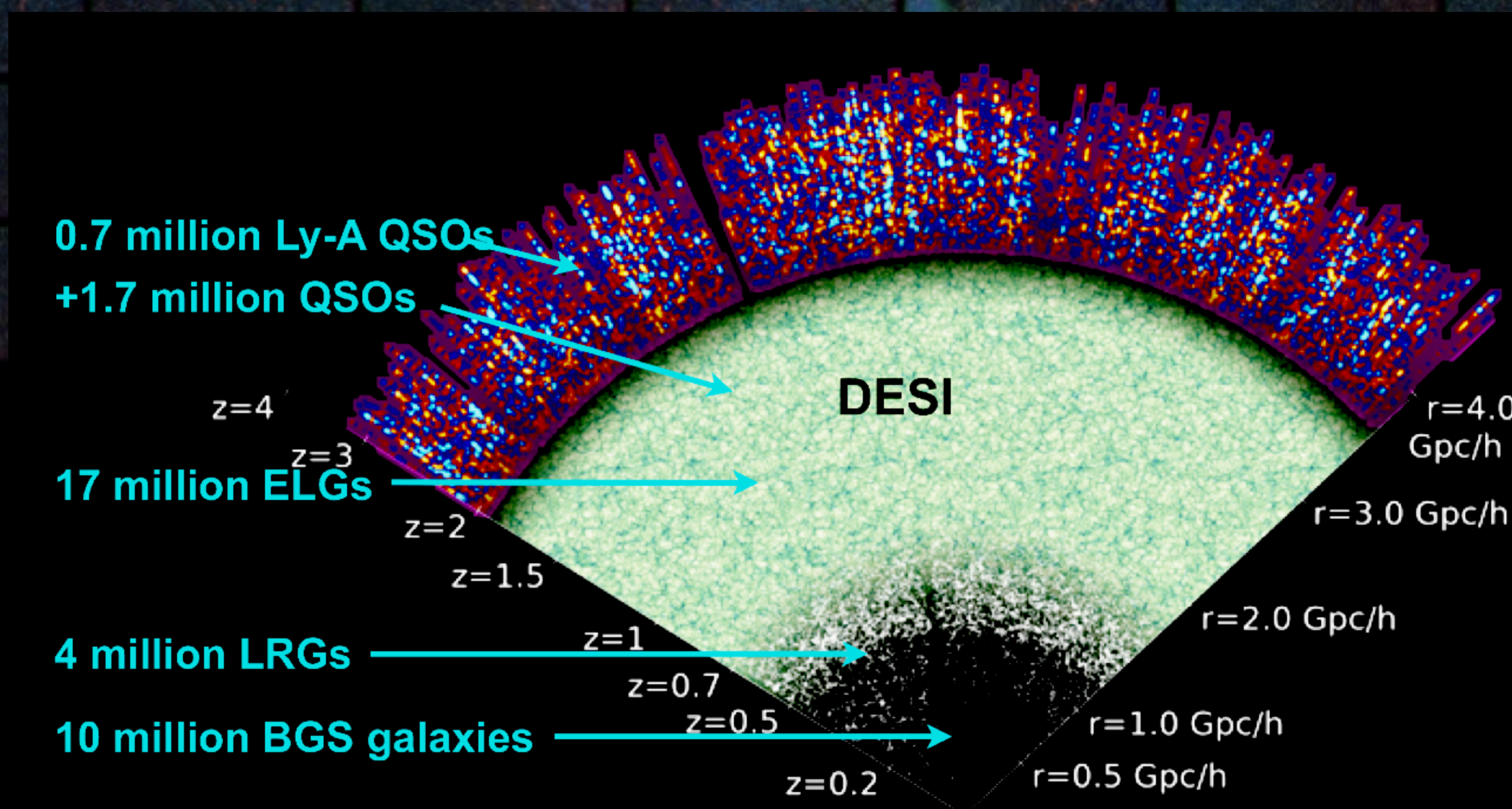
DESI (Wide field spec surveys - Taipan, 4MOST, SDSSV)

Dark Energy Spectroscopic Instrument

- 5000 fibers spectrograph at Kitt Peak (AZ)
- ~7 sq. deg. FoV
- 5 years, first light 2019

The Bright Galaxy Survey (BGS)

- 14,000 sq deg
- Magnitude limited (r=19.5) out to z~0.4 (median 0.2)
- Great host galaxy catalog for GW science



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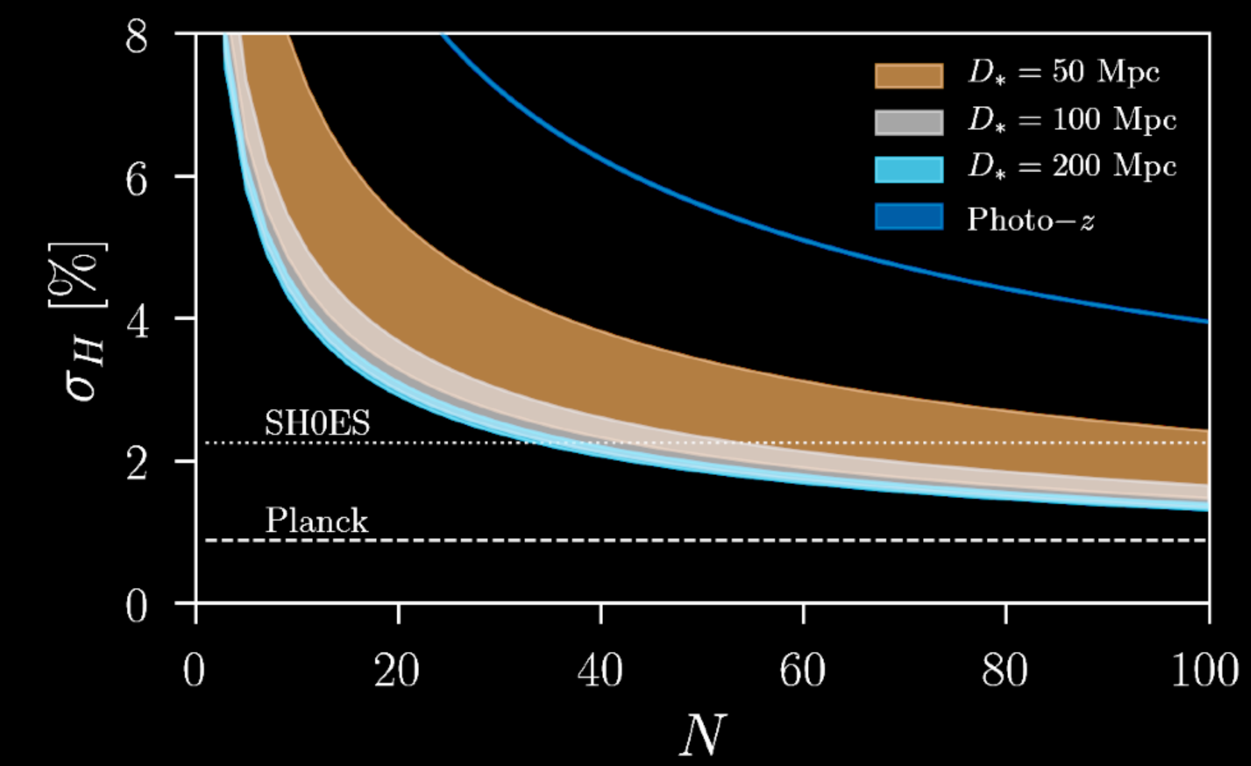
Prospects for standard sirens:

- **Bright sirens**:
  Quick counterpart classification
  Galaxy redshift and peculiar velocities

$$\sigma_H \simeq \frac{1}{D}\sqrt{c^2\sigma_z^2 + \sigma_v^2 + H_0^2\sigma_D^2}$$

- **Dark sirens**:
  Photo-z systematics suppressed



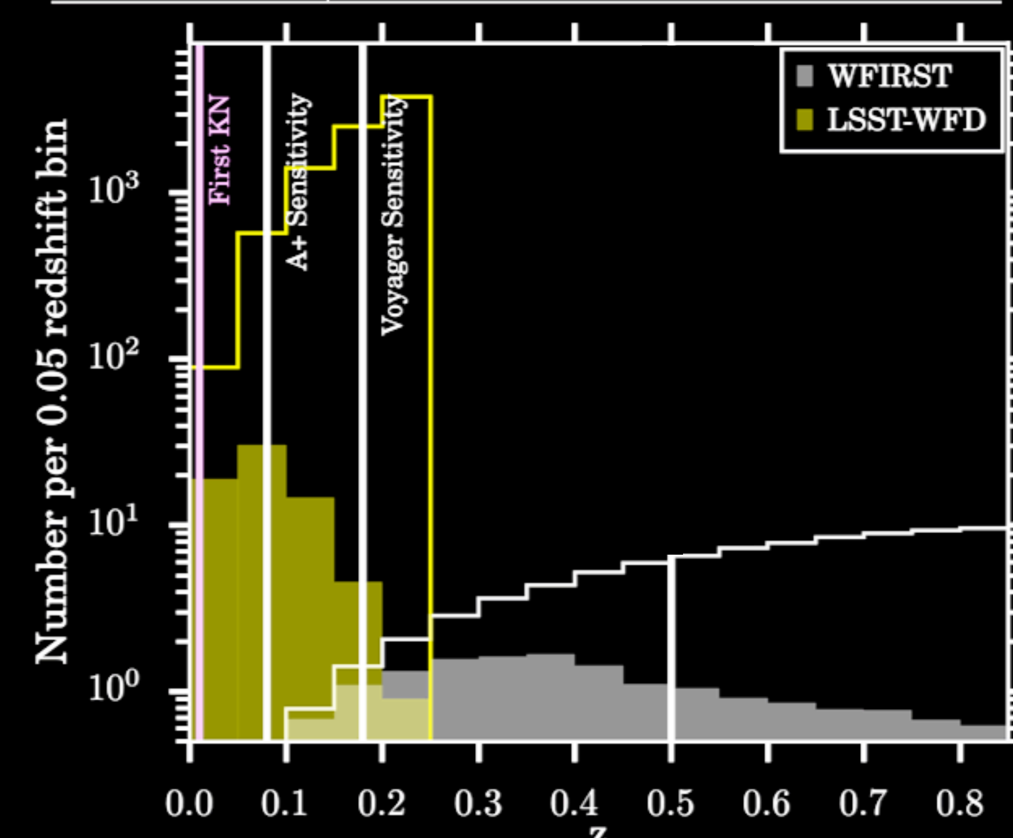
Palmese+2019, arxiv:1903.04730

LSST & other imaging surveys

- 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

Expected number of KNe found in each sample.

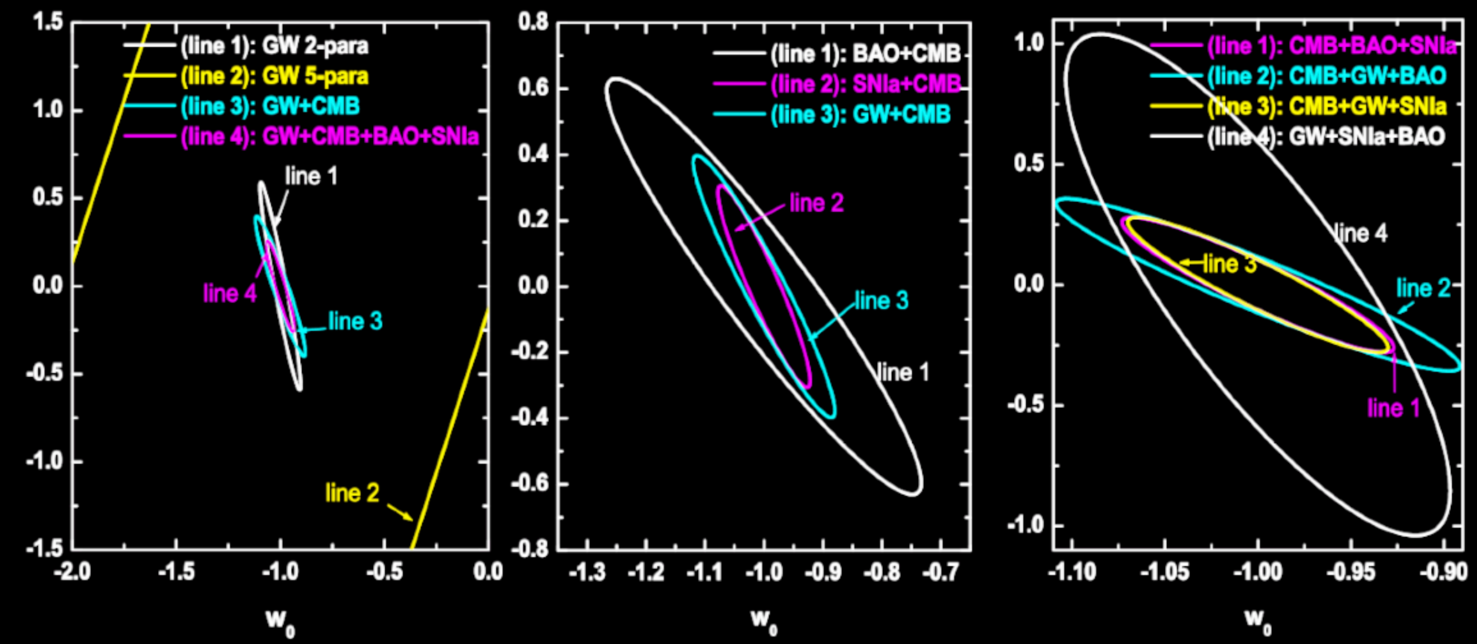
Survey	# KNe[a]	Survey Years	KN Redshift Range
SDSS	0.13	2	0.02 – 0.05
SNLS	0.11	4	0.05 – 0.20
PS1	0.22	4	0.03 – 0.11
DES	0.26	5	0.05 – 0.20
ASAS-SN	< 0.001	3	—
SMT	0.001	5	0.01 – 0.01
ATLAS	8.3	5	0.01 – 0.03
ZTF	10.6	5	0.01 – 0.04
LSST WFD	69	10	0.02 – 0.25
LSST DDF	5.5	10	0.05 – 0.25
WFIRST	16.0	2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



Scolnic+DES 2017

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)



Zhao+11

Conclusions

- Current GW detectors +current/near future galaxy surveys have the potential to help understanding:
  - ⋆ H_0 tension
  - ⋆ LCDM extensions (indirectly)
- 3G: Dark Energy

- Improved localization volume will be crucial for cosmology with 3G, potentially allowing interesting dark siren cosmology constraints

To dos:

- More uniformly sampled, complete, **galaxy catalogs** for dark siren cosmology & follow-up
- **Forecasts** for 3G + galaxy surveys
- **Impact** on target selection + GW follow-up for 2030s DE experiments (DESI2, LSST spectroscopy…)

Back-up slides

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

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

Selection effects

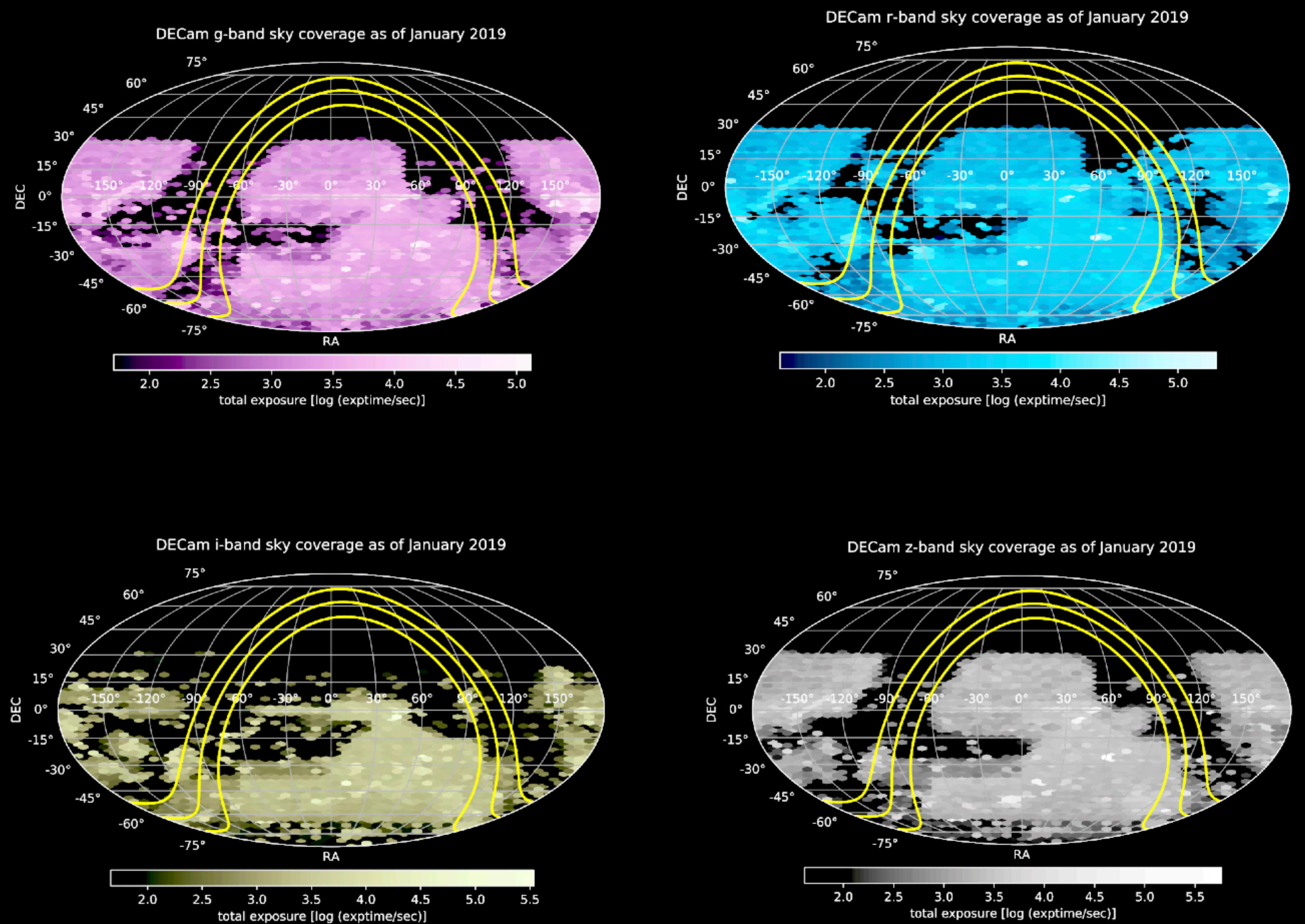
LIGO/Virgo Skymap

DES photo-zs

Del Pozzo 2012
Chen, Fishbach & Holz (2018)

BLISS+DELVE PI: Drlica-Wagner

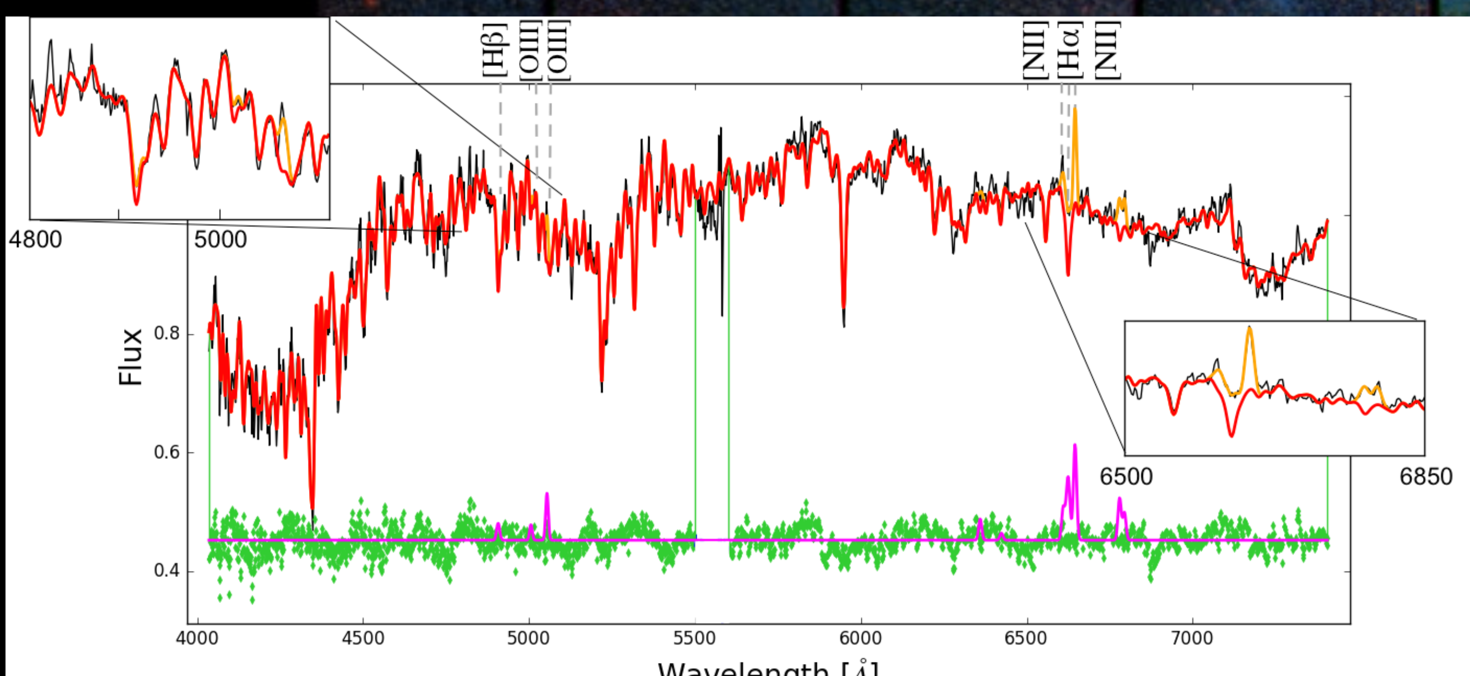
While we wait for LSST…

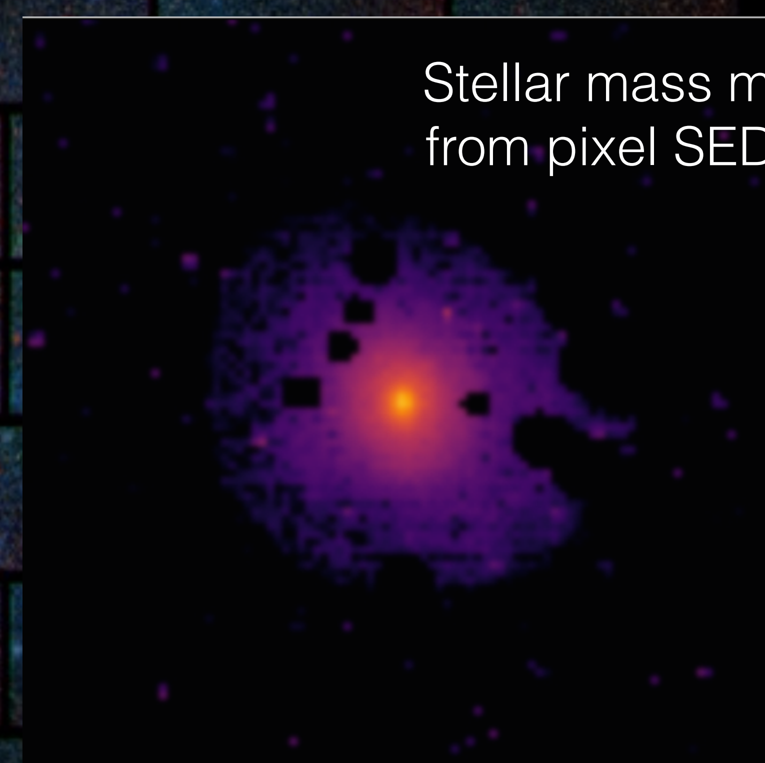


- ★ Important for:
  - Template images
  - Complete galaxy catalogs
- ★ + Pan-STARRS in the North

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

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

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

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

Fraction of NS in BNS

Delay time

Vangioni et al. 2016

- Assume SMF + cosmic SFR density:

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

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

Palmese et al. (2017) arxiv:1710.06748