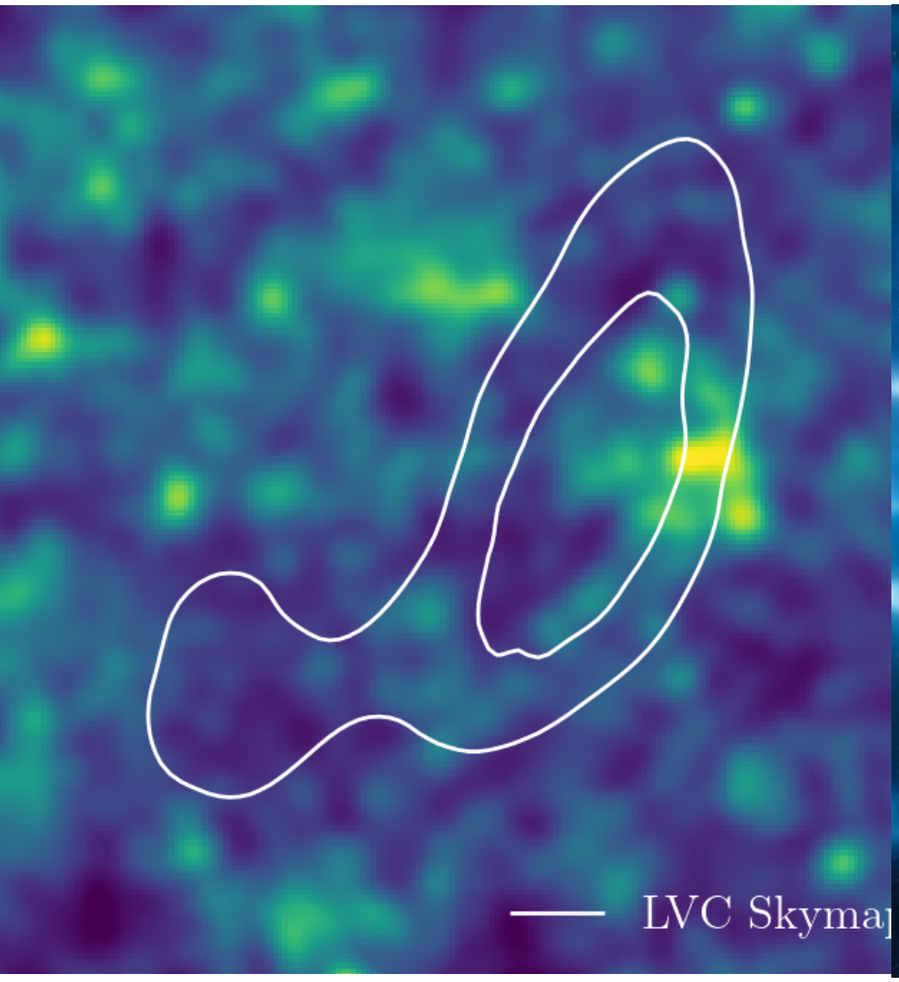
Multi-messenger studies with DESI

Antonella Palmese
NASA Einstein Fellow
UC Berkeley

9 July 2022
ICHEP Bologna

Outline



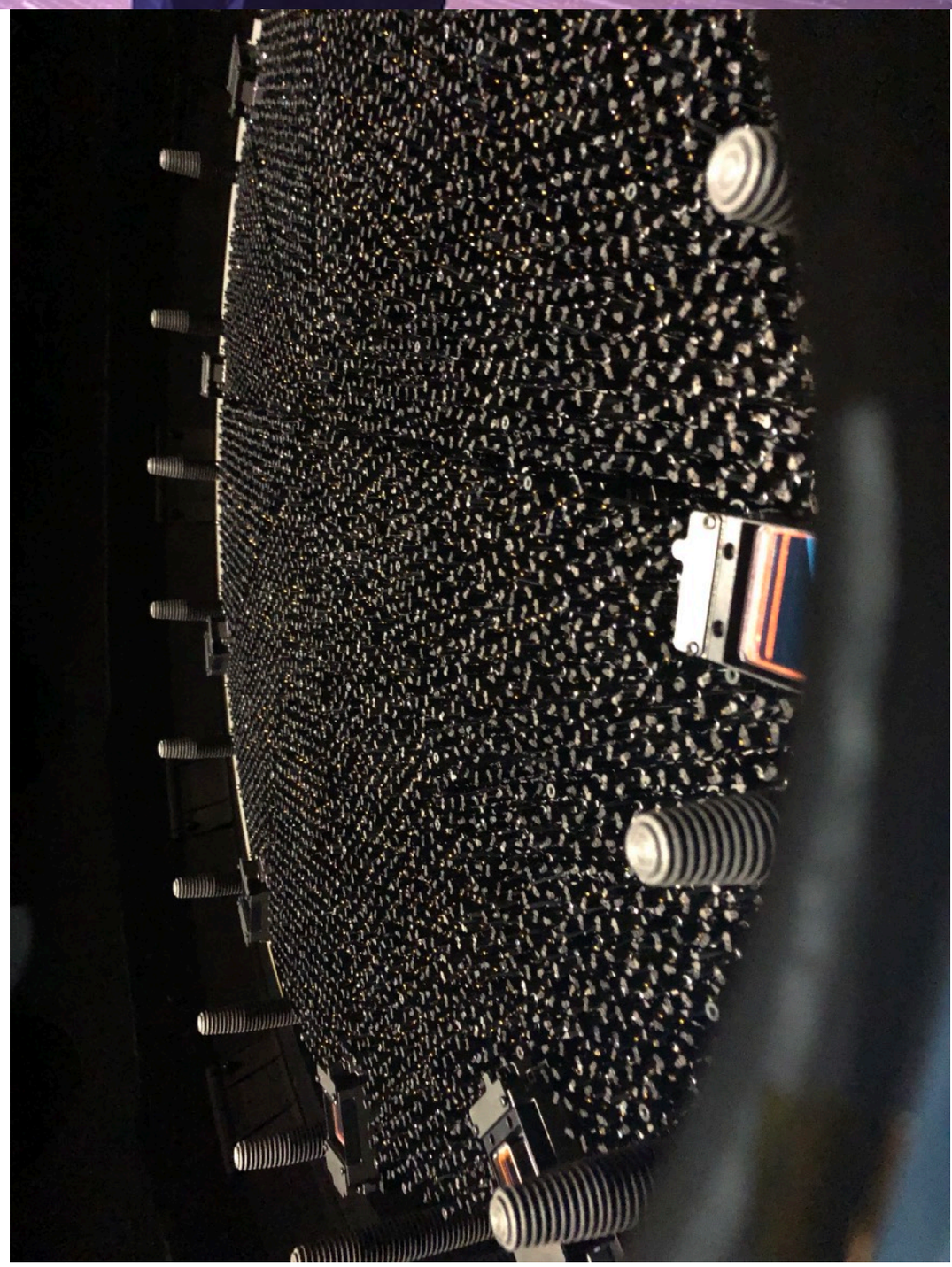
-DESI
-Hubble tension
-Gravitational Wave (GW) Dark Standard sirens

Multi-messenger follow-up with DESI

DESIRT

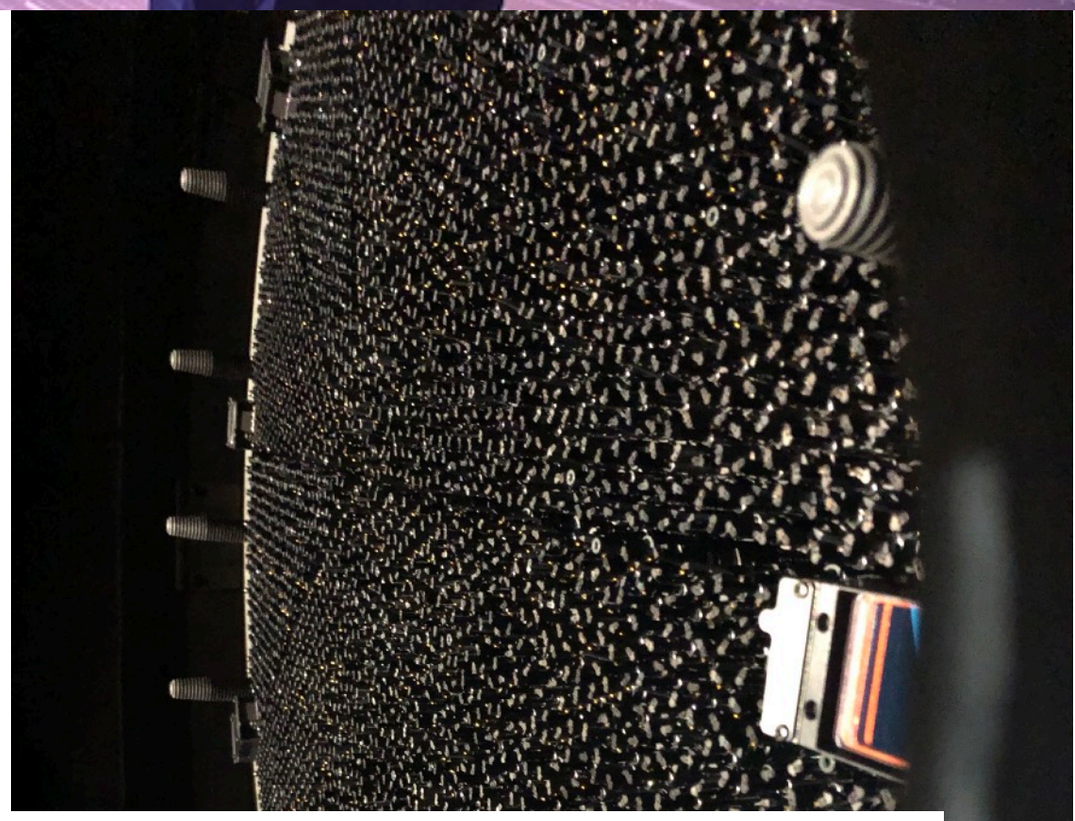
The Dark Energy Spectroscopic Instrument (DESI)

- **5000-fiber** optical-NIR **spectrograph** on Kitt Peak Mayall 4m Telescope (AZ)
- **~8 deg² FoV**
- **Stage-IV** BAO/RSD DE experiment
- >30M galaxy redshifts (lots of potential GW host galaxies)
- Sky area: **14,000 sq. deg.**
- **DESI imaging** - DESI Legacy Survey: photometry to define targets (grz+WISE)
- **DESI started taking data early 2020, now finishing Year 1**



The Dark Energy Spectroscopic Instrument (DESI)

- **5000-fiber** optical-NIR **spectrograph** on Kitt Peak Mayall 4m Telescope (AZ)
- **~8 deg² FoV**
- **Stage-IV** BAO/RSD DE experiment
- >30M galaxy redshifts (lots of potential GW host galaxies)
- Sky area: **14,000 sq. deg**



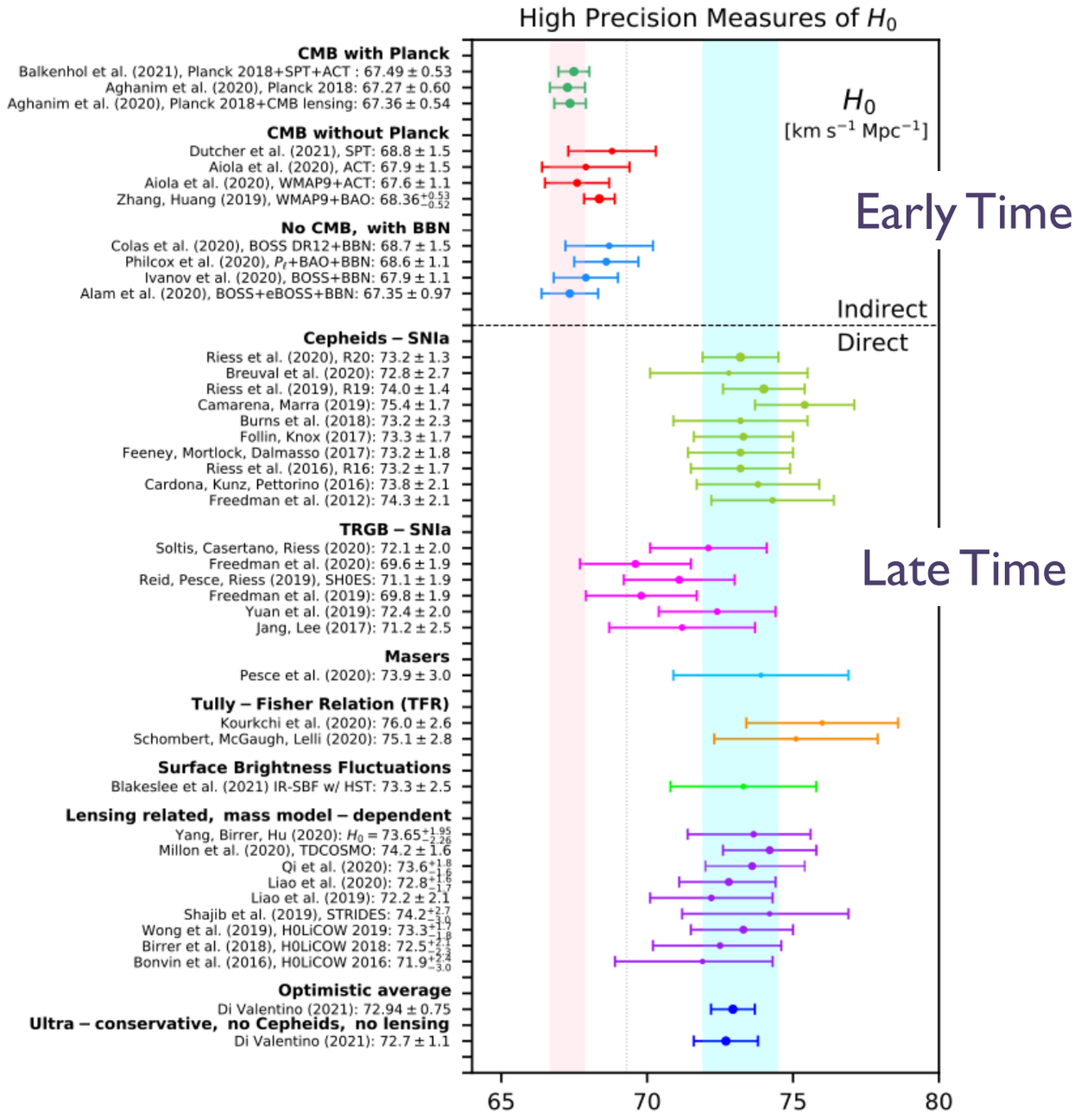
Dark Energy Spectroscopic Instrument (DESI) Creates Largest 3D Map of the Cosmos

DESI has already mapped out more galaxies than all previous 3D surveys combined — and it's just getting started

News Release Adam Becker (510) 424-2436 • **January 13, 2022**

Hubble constant tension

- H_0 tells us about the rate of expansion of the Universe
- **>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**.



Di Valentino+21

Standard Sirens

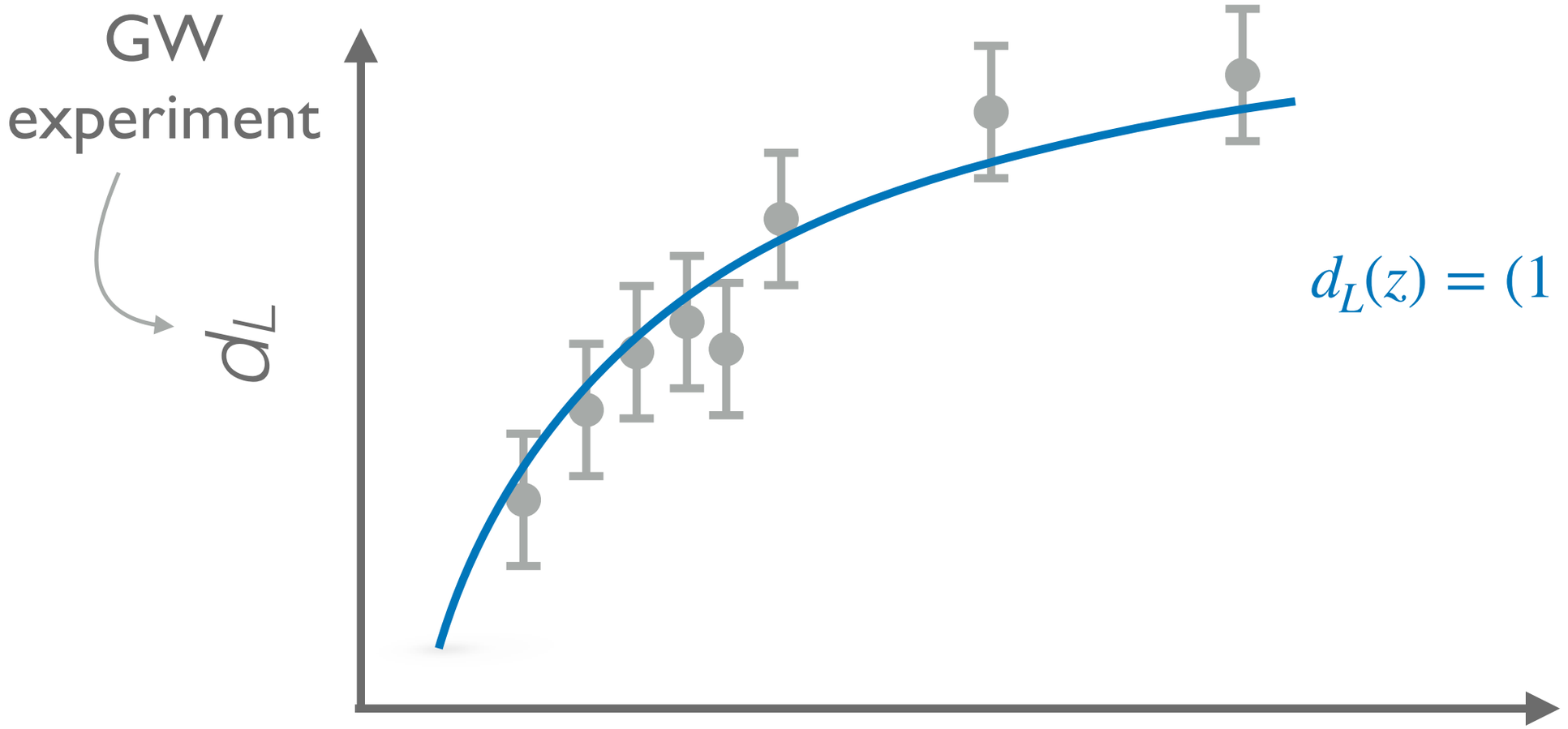
Schutz 1986

Holz & Hughes 2005

MacLeod & Hogan 2008

Nissanke+2010

Del Pozzo 2012



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

Standard Sirens

Schutz 1986

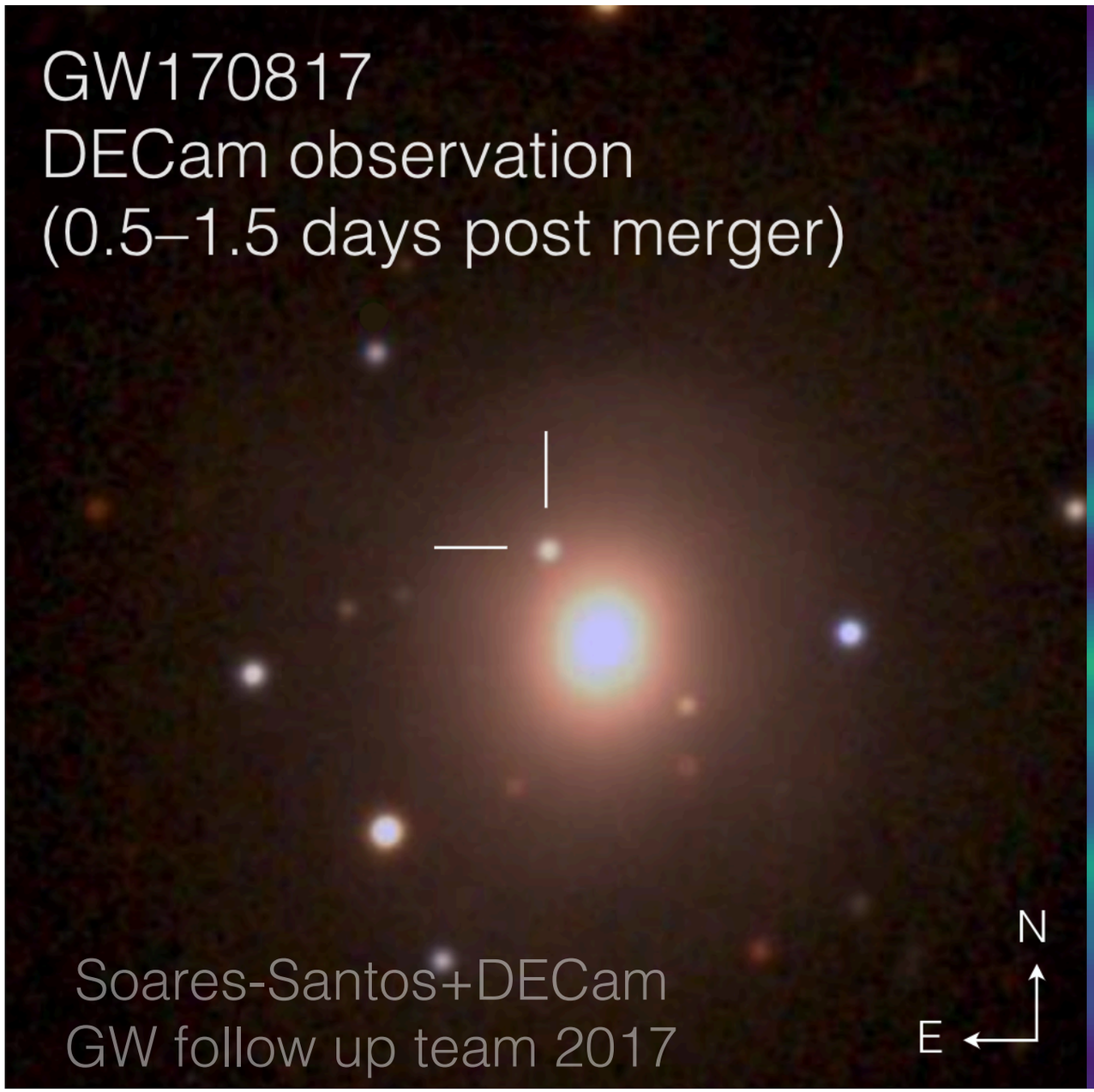
Holz & Hughes 2005

MacLeod & Hogan 2008

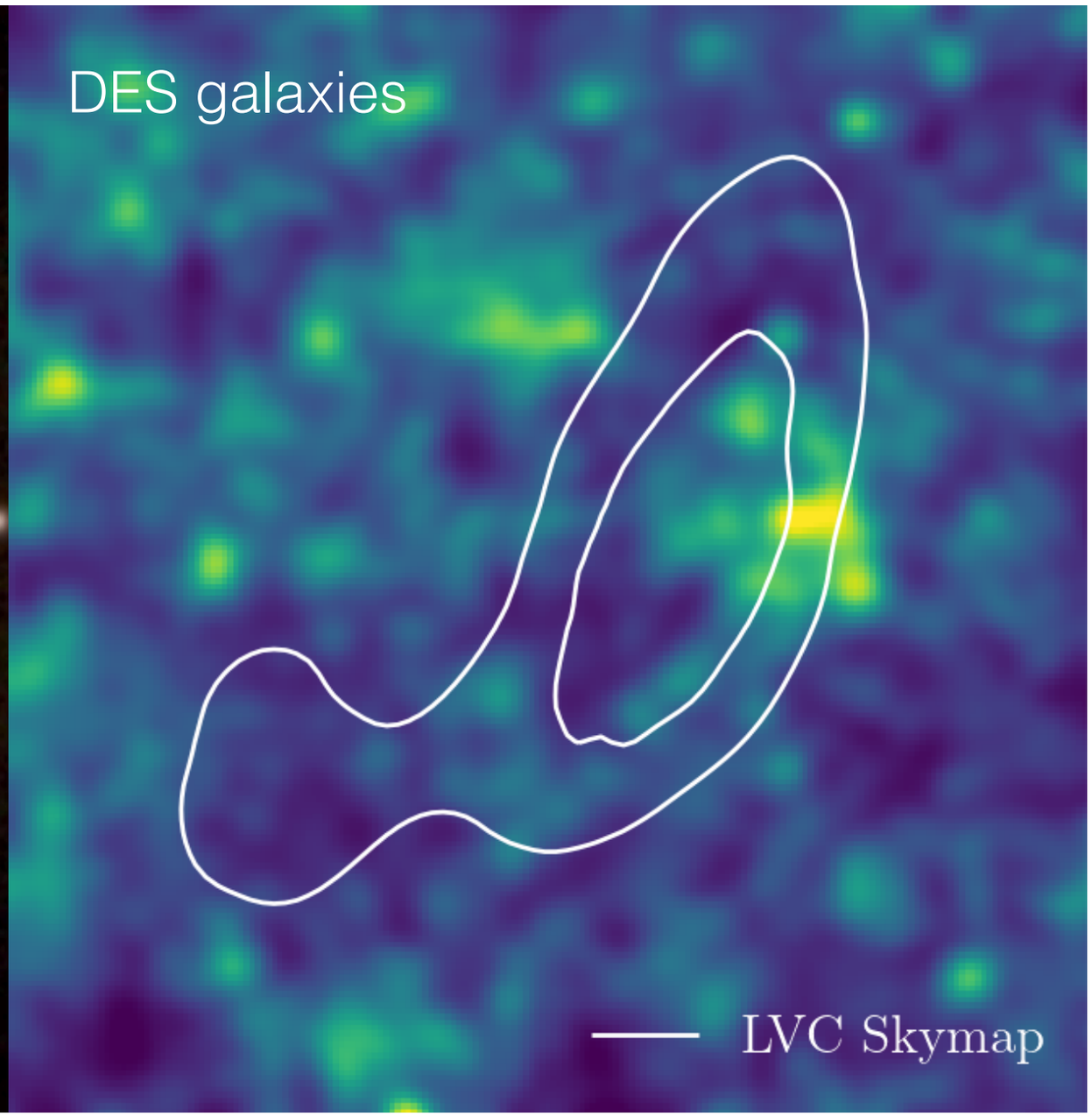
Nissanke+2010

Del Pozzo 2012

With EM counterpart (BNS/NSBH)



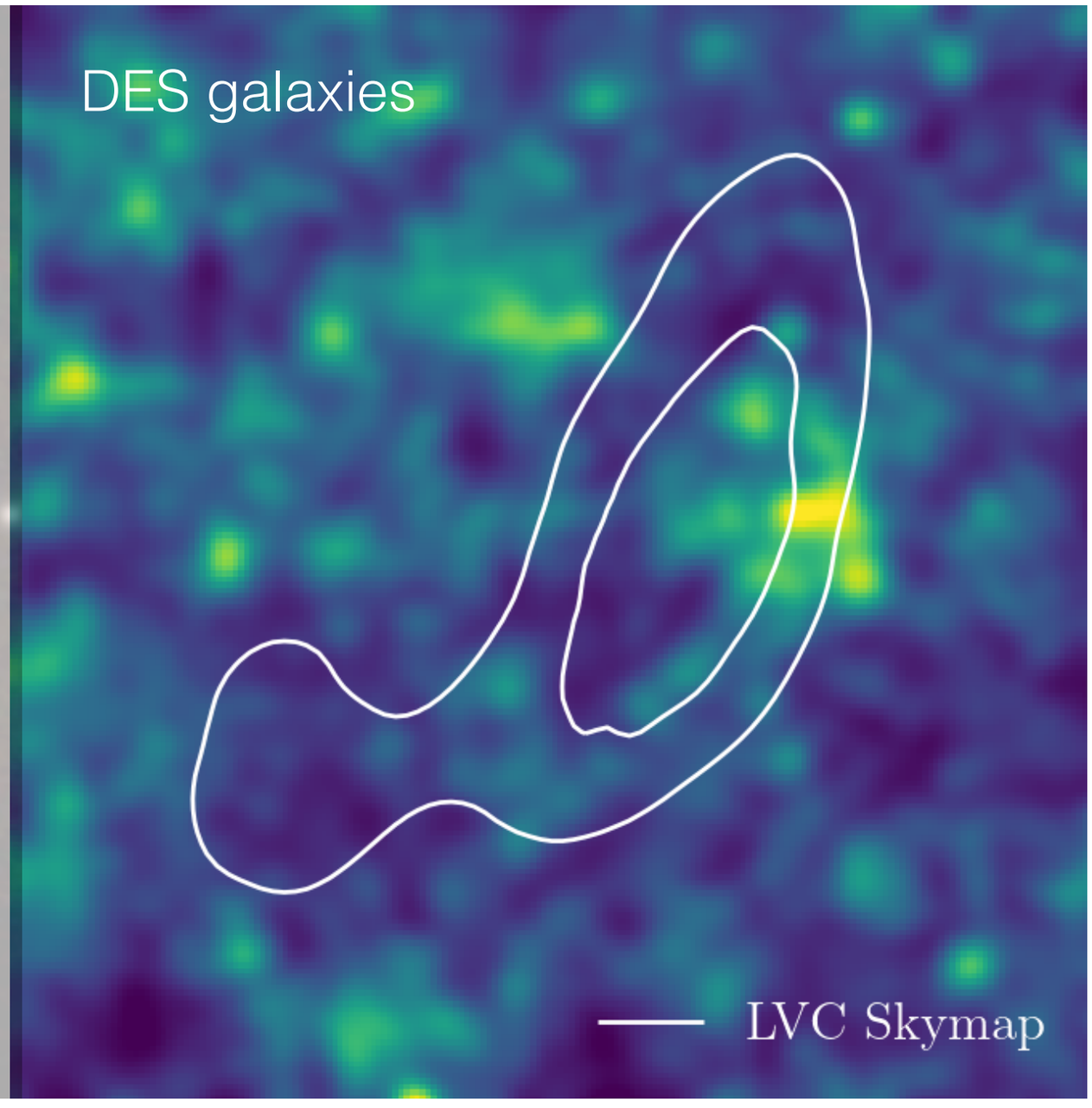
Without EM counterpart (BBH/NSBH)



Bright standard sirens

Dark standard sirens

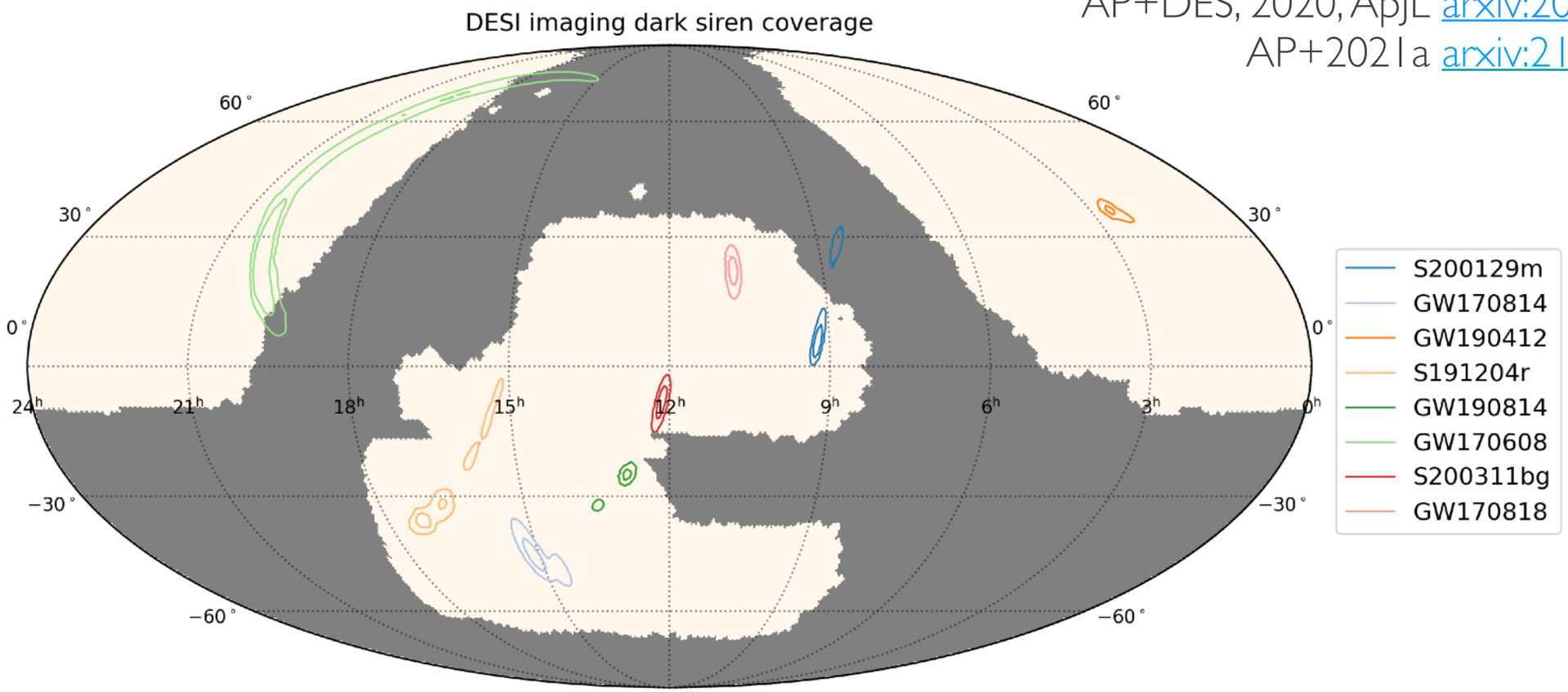
Dark Standard Sirens



Dark standard sirens

Dark sirens with LIGO/Virgo+DESI data

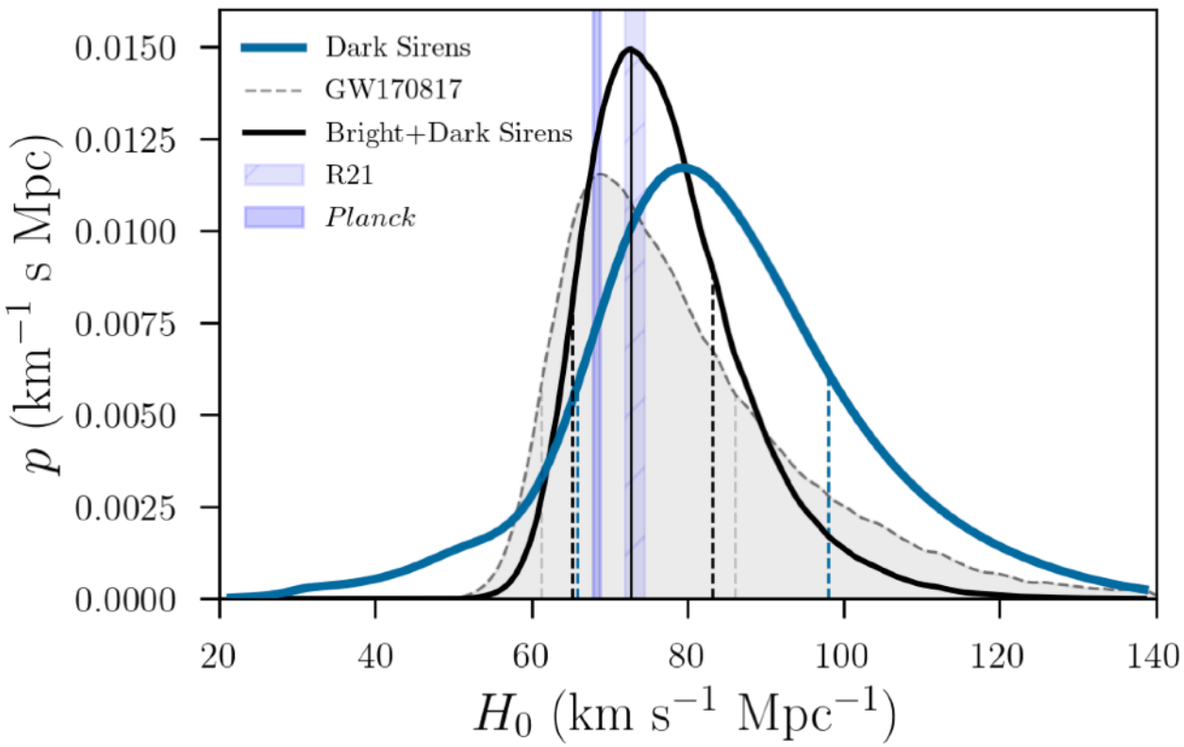
DES & LVC 2019, ApJL (AP corresp.) arxiv:1901.01540
AP+DES, 2020, ApJL arxiv:2006.14961
AP+2021a arxiv:2111.06445



- ~90 GW events from LIGO/Virgo, 1 with confident counterpart association
- Only consider well-localized events + high completeness galaxy catalog (DESI imaging)
- **Photometric** redshifts (Zhou+20) validation
- **Selection** based on comoving volume, selection effects corrected for using binary black hole simulations

Dark siren results

DES & LVC 2019, ApJL (AP corresp.) arxiv:1901.01540
AP+DES, 2020, ApJL arxiv:2006.14961
AP+2021a arxiv:2111.06445



- **Bright** (w/ peculiar velocity treatment) **+ dark** standard sirens:

$$H_0 = 72.77^{+11.0}_{-7.55}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

- Dark sirens provide **~30% improvement** to GW170817 H_0 precision
- Other work: LIGO, Virgo, KAGRA 2021 arxiv:2111.03604, in particular **GW-only** complementary method (Farr+2019)
- **Consistent with both early and late-time Universe H_0** measurements
- ~200 nearby detection at design sensitivity needed to reach ~2% from dark siren alone

Outline

DESI
Hubble tension
Gravitational Wave (GW)
Dark Standard sirens

Multi-messenger follow-up with DESI

DESIRT

GW follow-up with DESI

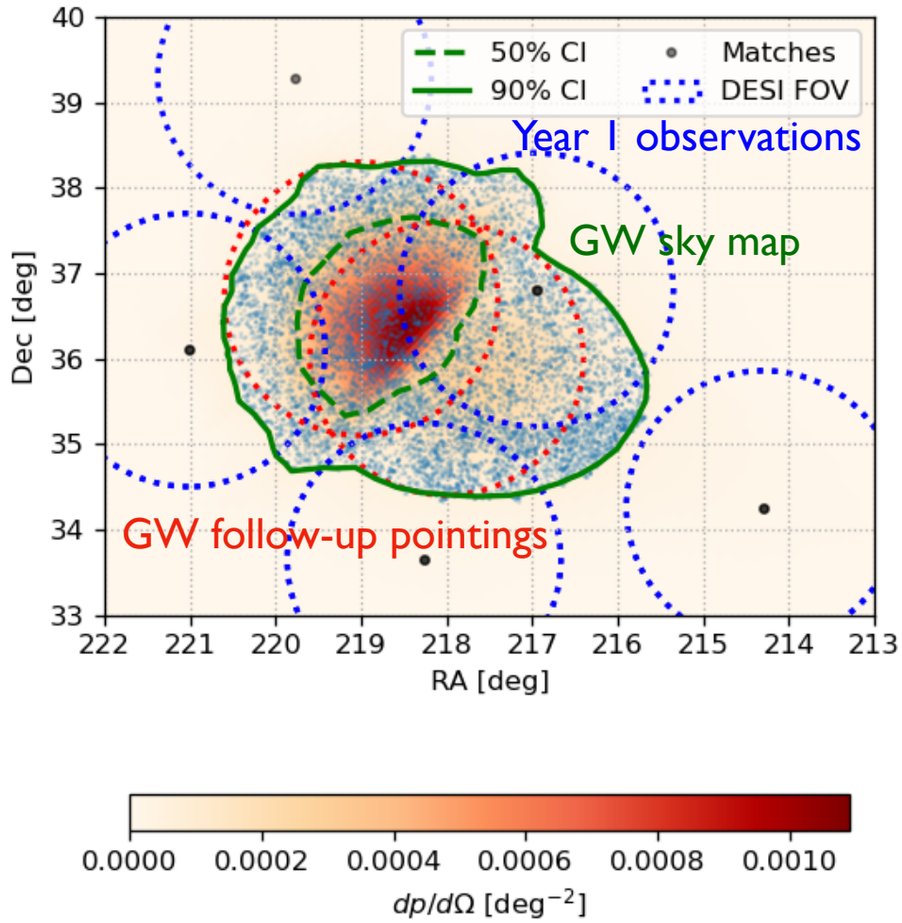
AP+2019, arxiv:1903.04730

DESI can play an important role in GW follow-up

- **Quick classification of candidates (a main bottleneck)**
- Potential **host galaxies spectroscopic redshifts** for follow-up and cosmology

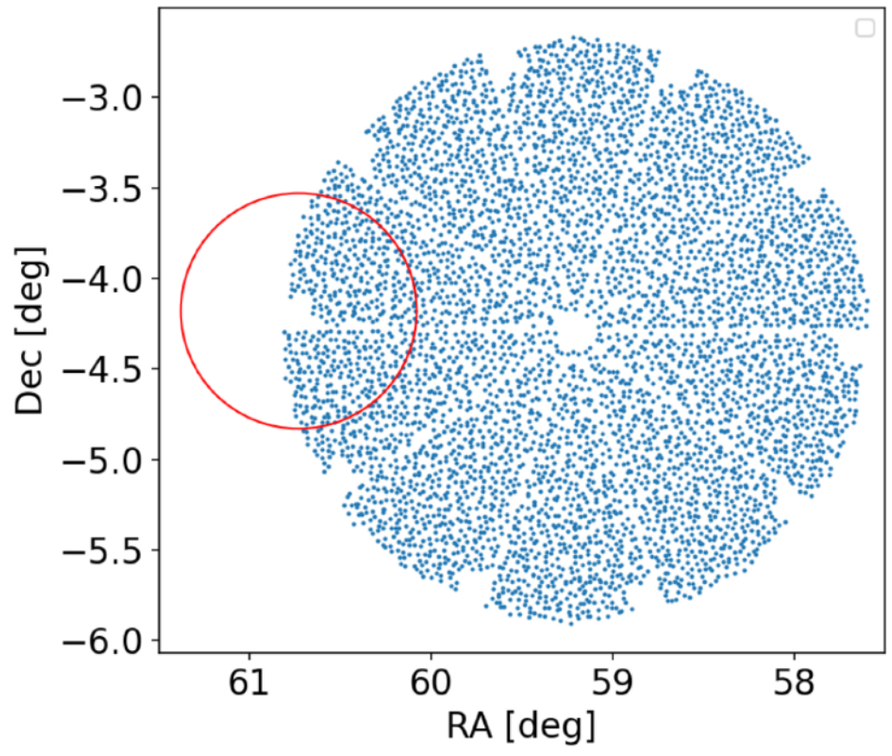
Archival **GW190412 follow-up** successfully performed **- DESI Multi-messenger secondary target program** (PI:AP)

Disruptive mode - possibly few per year

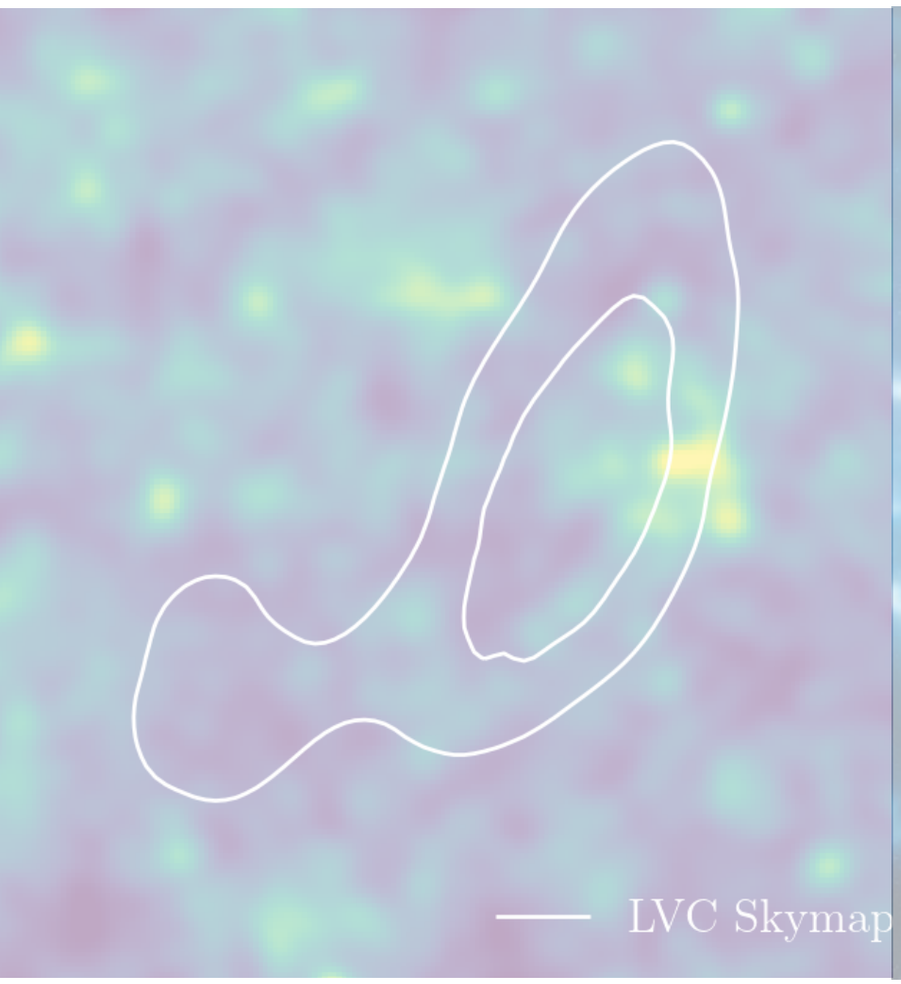


IceCube follow-up with DESI

- While LIGO/Virgo are off, we follow up IceCube high energy neutrinos in a similar fashion
- Main sources of IceCube high-E neutrinos still unclear
- **Core-collapse** (CC) **Supernovae** (SNe), **Tidal Disruption Events** potential sources
- Followed up **IC210922A** in ~24 h
- No transient detections: AP+2021 https://gcn.gsfc.nasa.gov/gcn3/30923.gcn3
- **Non-disruptive** mode

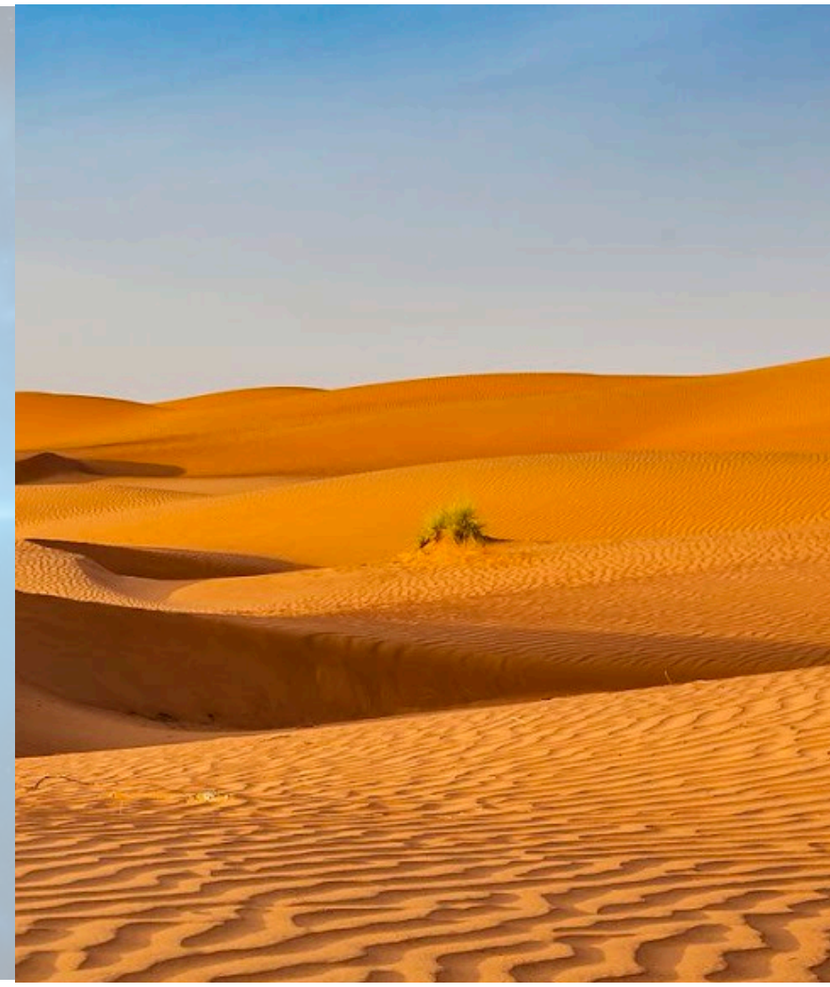


Outline



DESI
Hubble tension
Gravitational Wave (GW)
Dark Standard sirens

Multi-messenger follow-up with DESI



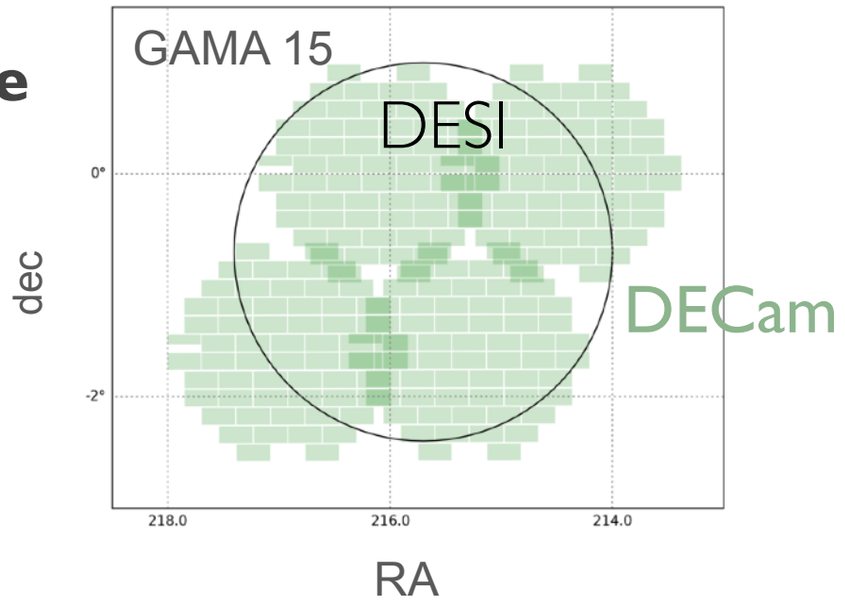
DESIRT

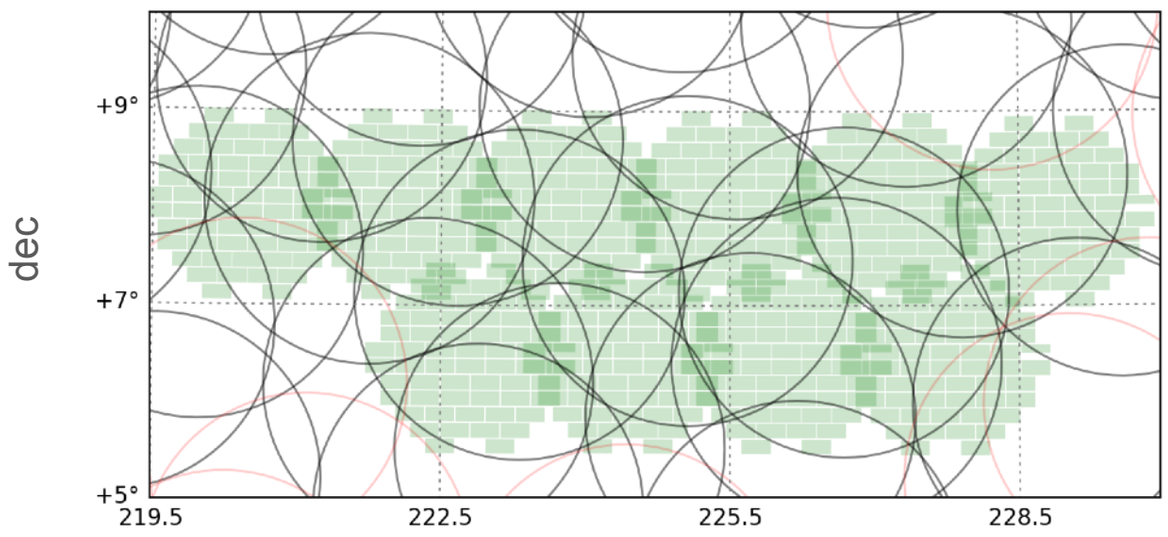
DESIRT: DECam observations of Intermediate Redshift Transients

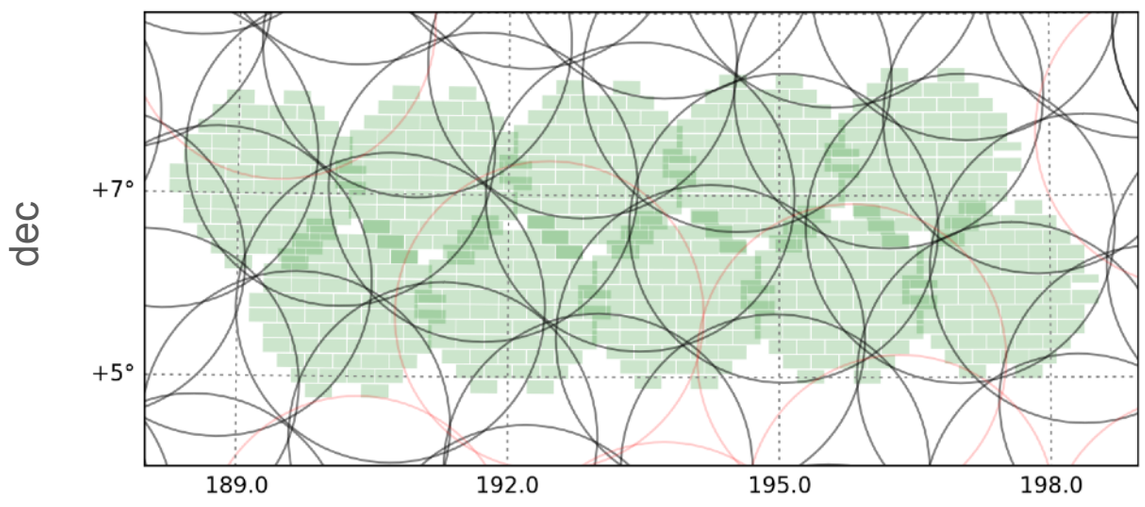
PI: AP & Wang

- **Dark Energy Camera** (DECam) *grz+g* observations
- Filling a gap between deep fields (e.g. DESSN) and shallower large surveys (e.g. ZTF)
- Getting transients and hosts **spectra for "free" + spare fibers** by observing DESI fields - precursor of Rubin LSST+DESI/DESI-II
- ~100 sq deg. every ~3-4 nights (21A, 22A, 22B)
- g,r,z ~23.6, 23.6, 22.8 5sigma depth
- Public alerts:
  - TNS: Bot sent 355 public alerts in 2021A
  - Broker alerts from 2022: https://decat-webap.lbl.gov/
- **Data public immediately**

AP+2022, TNS







Conclusions

- **Synergies between GW experiments and spectroscopic sky surveys**
  - Counterparts discovery (also true for IceCube neutrinos): **preparing for follow-up during LIGO/Virgo/KAGRA O4** run (2023)
  - Standard sirens - H_0 (+dark energy)
    - ~50 events w/ counterparts needed to reach 2% precision
    - Origin of binaries - host galaxies
- Even **without counterparts**
  - Dark sirens can provide significant improvement on a combined standard siren H_0 constraint
  - LVK Design sensitivity + DESI-like catalog: ~2-5% (stat.) with ~200 well-localized events
- Stay tuned for new DESI results
- Come speak to me about **DESIRT** if interested!

Contact: palmese@berkeley.edu - DES, DESI, LISA palmese

DARK ENERGY SPECTROSCOPIC INSTRUMENT

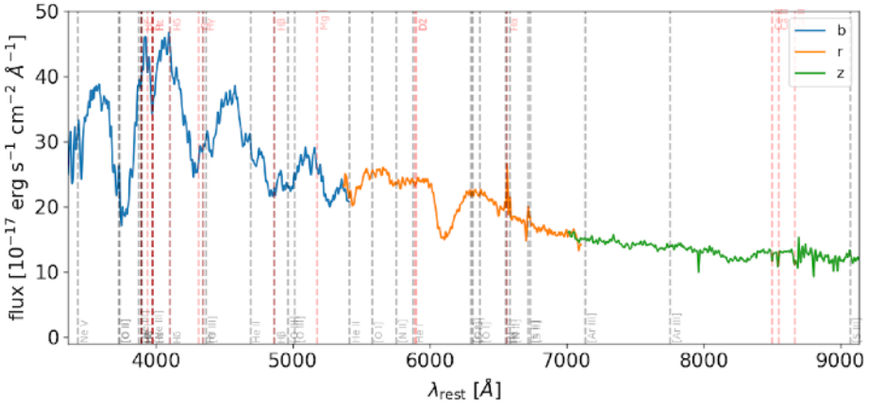
U.S. Department of Energy Office of Science

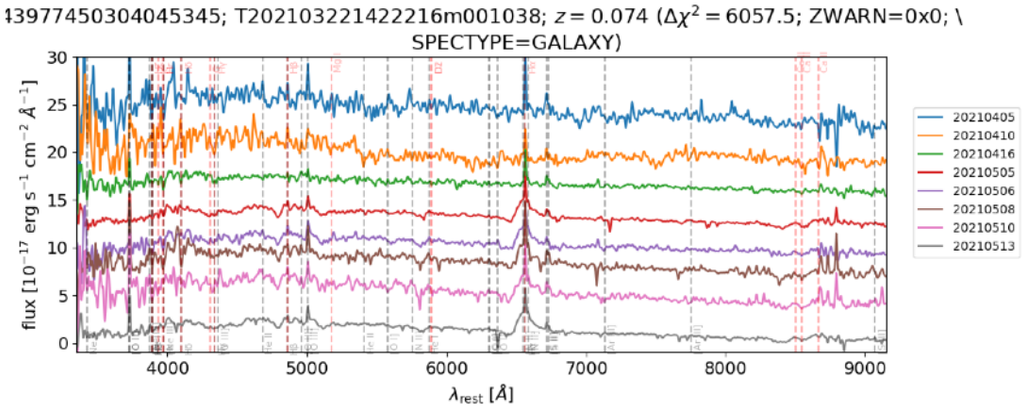
Thanks to our sponsors and
69 Participating Institutions!

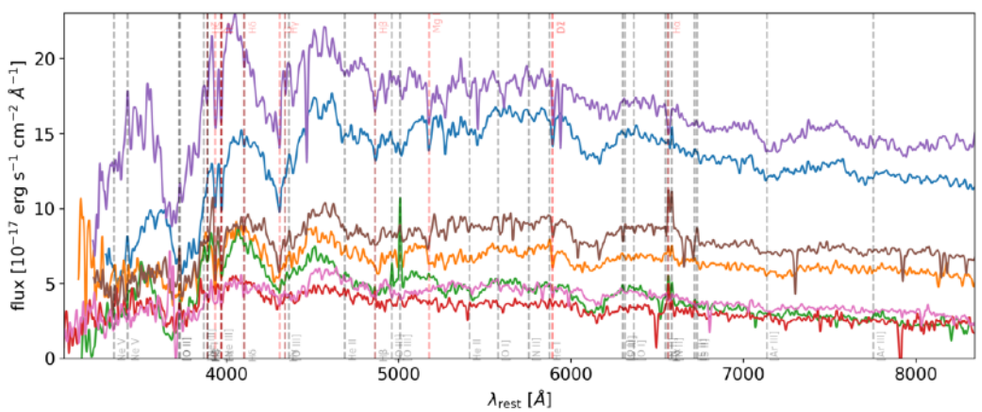
Discovering transients in DESI

Automatic daily Machine Learning transient classification pipeline searching all DESI spectra for supernovae and kilonovae in host galaxy emission

- Thousands of candidates identified from few months of SV+Year1, O(100) confirmed by imaging
- DESI spectra of SN Ia and CC SN serendipitously discovered







Peculiar Velocities with gravitational waves

Image credit: Planck 2015 arxiv:1504.03339 - Central Galaxy Catalog PV field

Peculiar velocities (PV)

Kaiser 1987

Strauss & Willick 1995

Gordon et al. 2007

….

- Galaxies' Peculiar Velocities: **motions on top of cosmological expansion**
- Follow inhomogeneous clustering of structures and the laws of gravity
- PV field probes large scale structure and its growth, and gravity
- One possibility is to use galaxies with **distance measurement** (e.g. FP, SNe Ia)
- Use GW BNS from 3G GW detectors - forecast
- We use PV power spectrum, overdensities power spectrum, and their cross-correlation

Power Spectra depend on:

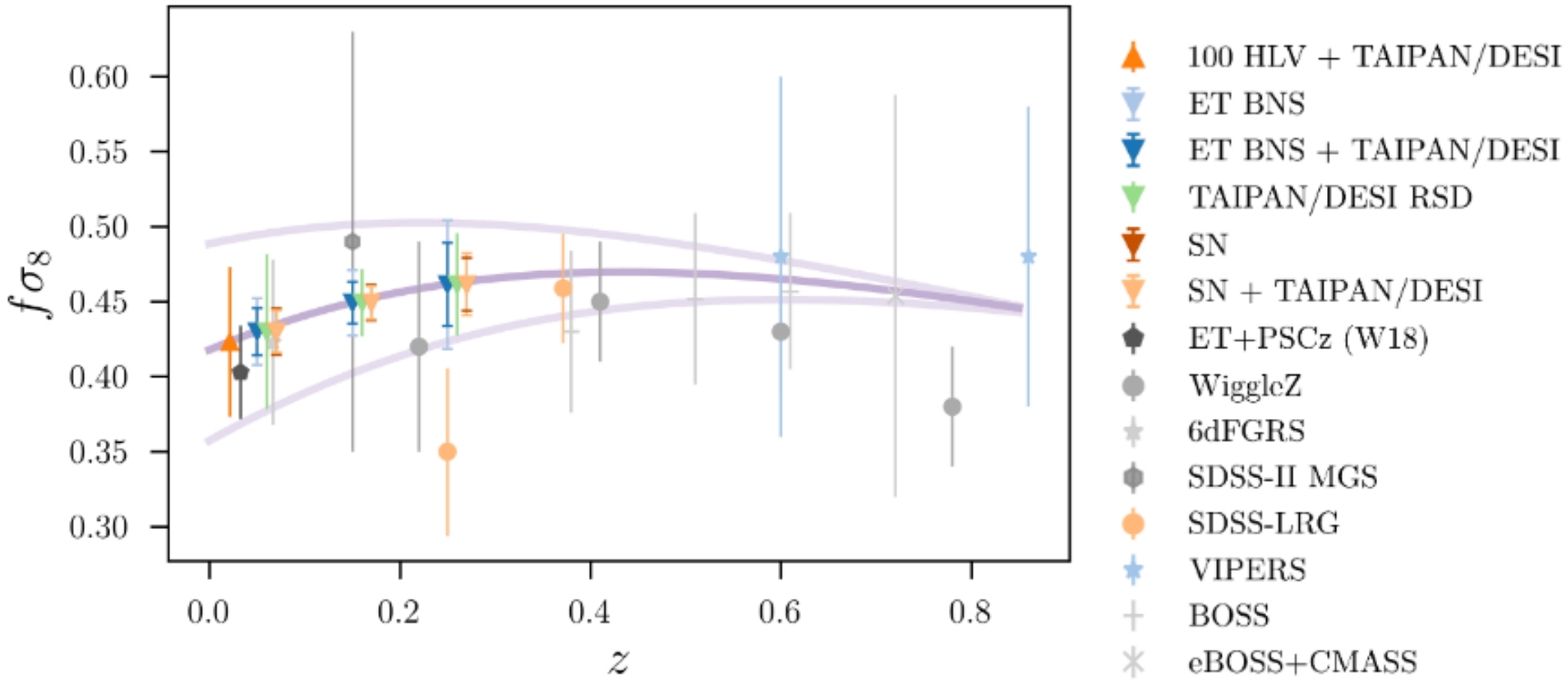
Growth index
Depends on gravity

$$fD = \Omega_M^{\gamma} \exp\left(\int_a^1 \Omega_M^{\gamma} d\ln a\right)$$

Growth rate **Linear growth factor**

Linder 2005

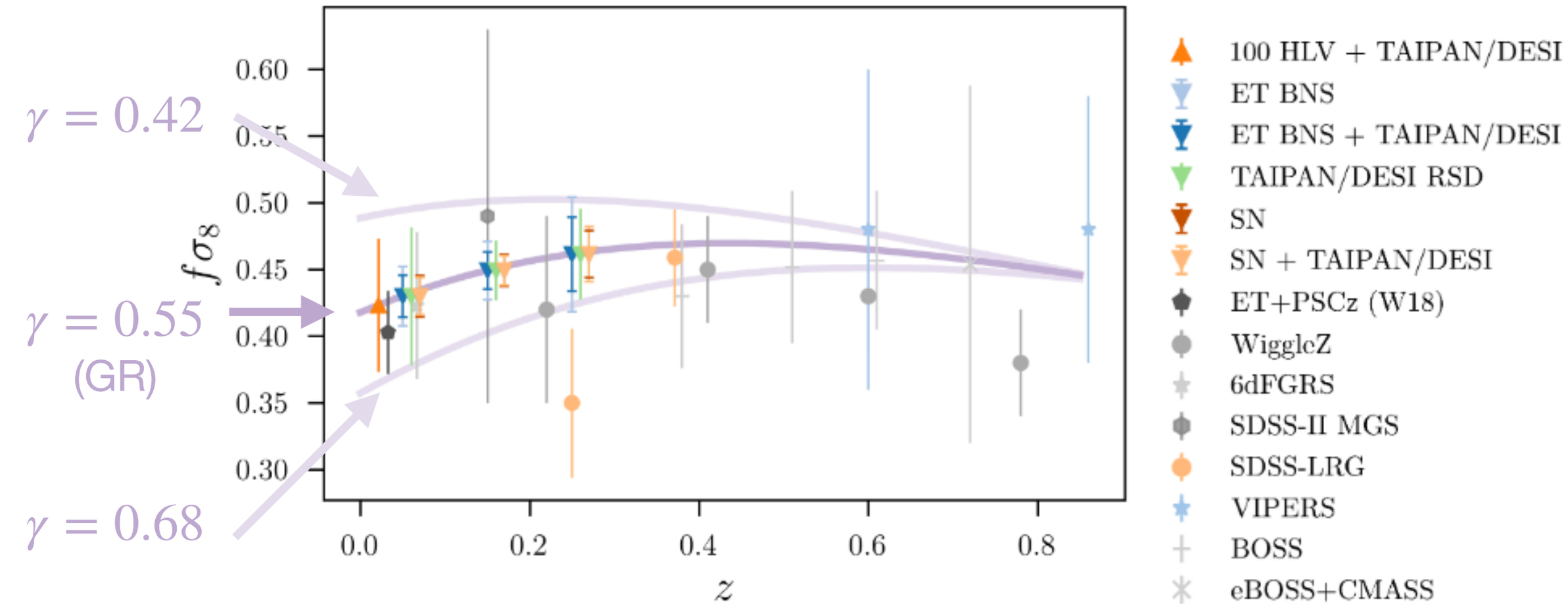
Growth of structure



- Fix $\gamma = 0.55$
- 3% precision on $f\sigma_8$ with 3G + galaxy survey (10 yr ET, 5 yr 3 detectors)

AP & Kim 2021, PRD, arxiv:2005.04325

Growth of structure



- Varying growth index $\sigma_\gamma \sim 0.02 - 0.03$

AP & Kim 2021, PRD, arxiv:2005.04325

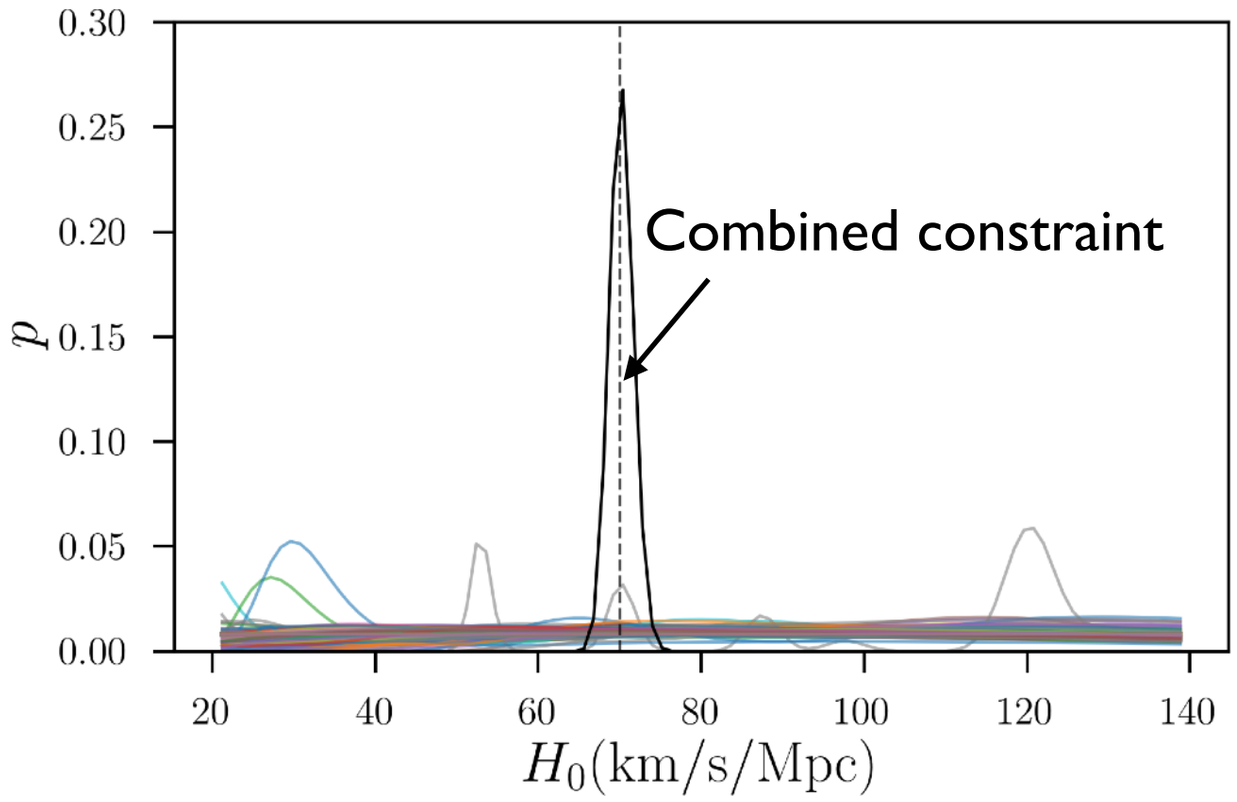
Conclusions

- **Synergies between GW experiments and spectroscopic sky surveys**
  - Counterparts discovery (also true for IceCube neutrinos): **preparing for follow-up during LIGO/Virgo/KAGRA O4** run (2023)
  - Standard sirens - H_0 (+dark energy)
  - Peculiar velocities - $f\sigma_8, \gamma$
  - Origin of binaries - host galaxies
- Even **without counterparts**
  - Dark sirens can provide significant improvement on a combined standard siren H_0 constraint
  - LVK Design sensitivity + DESI-like catalog: ~2-5% (stat.) with ~200 well-localized events
- Come speak to me about **DESIRT** if interested!

Contact: palmese@berkeley.edu - DES, DESI, LISA palmese

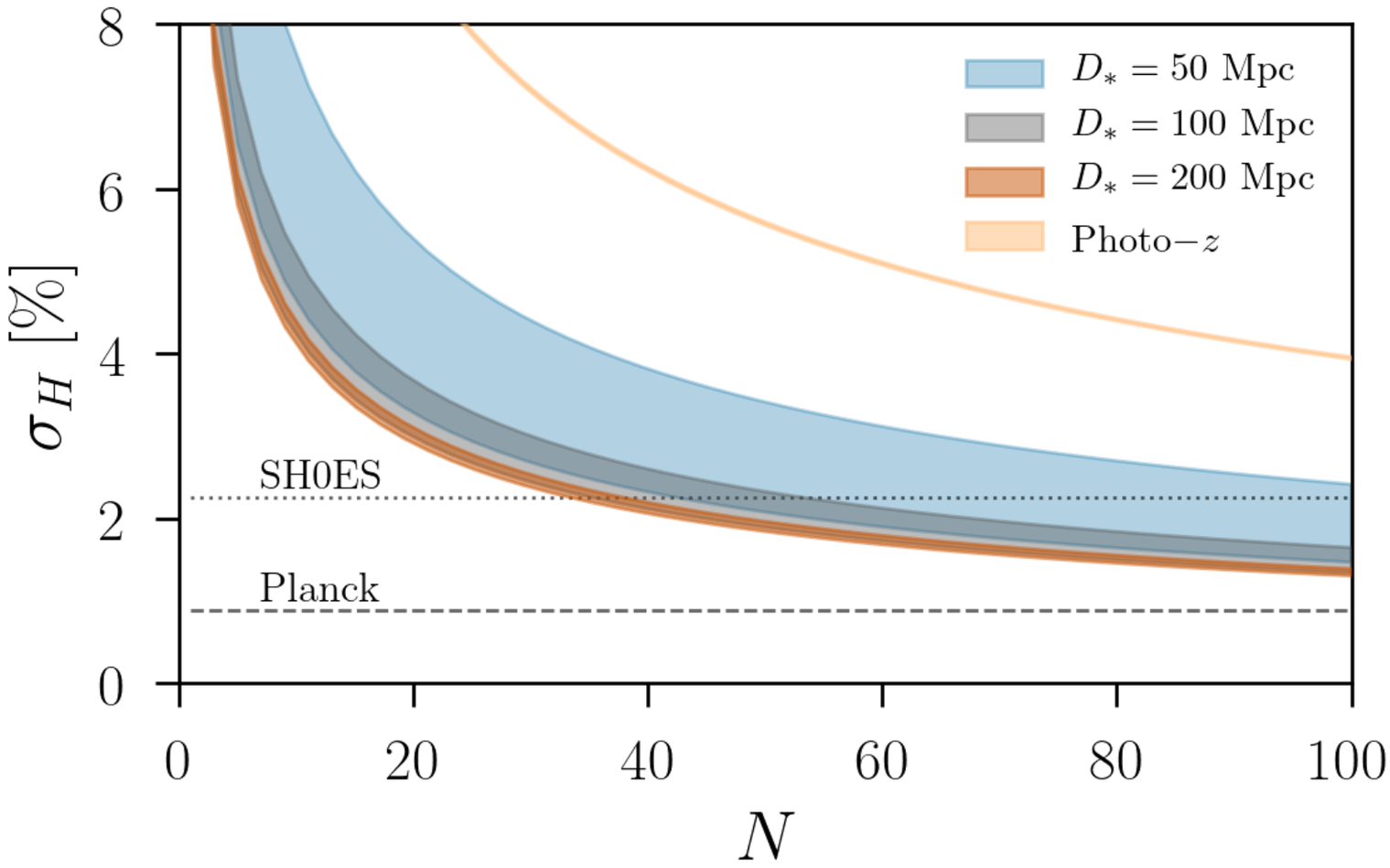
Prospects for LIGO/Virgo at design sensitivity

- Inject BBH mergers on DES galaxies+localize for HLV at design sensitivity (LALSuite+BAYESTAR)
- ~200 detections up to 900 Mpc
- **5%** statistical precision with a DES-like catalog
- Down to **2%** w/ "golden" events (interesting to shed light on Hubble tension)



Bright Standard Sirens with DESI

- DESI can help with quick classification, **host galaxy redshifts and peculiar velocities**
- **~2%** measurement in ~5 years: enough to solve H_0 tension - **Chen, Fishbach & Holz 2018**

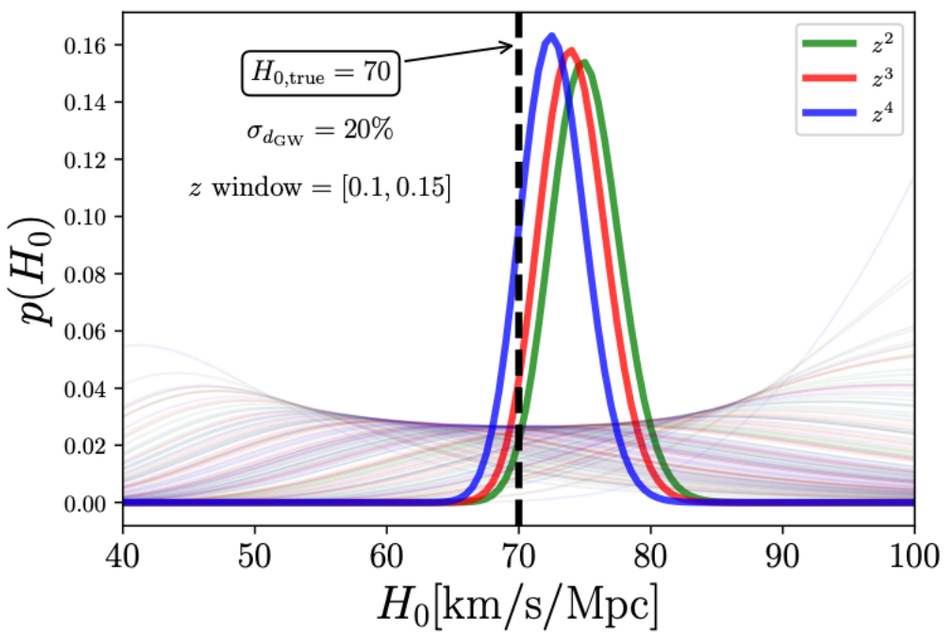


AP+DESI time-domain 2019, arxiv: 1903.04730

Challenges

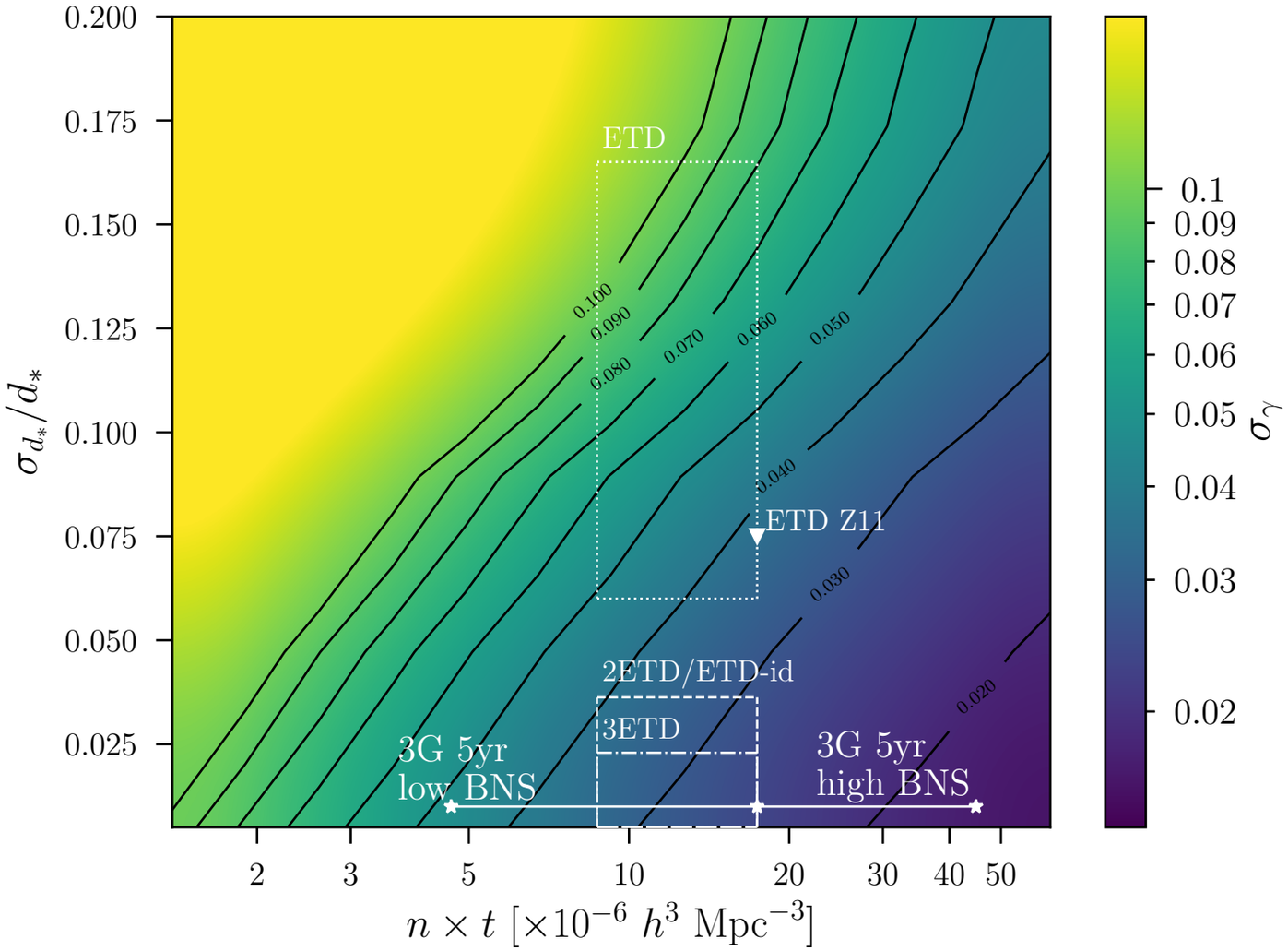
Now we are ready to combine all of our GW and EM information by convolving Eq. (2) with the photo-z distribution $p(z)$ to give us the likelihood $p(d_{\rm GW}, d_{\rm EM}|H_0)$. A simple application of Bayes' theorem then gives us the Bayesian posterior on H_0,

$$p(H_0|d_{\rm GW}, d_{\rm EM}) \propto \frac{\int p(d_{\rm GW}|d_{\rm L}(z, H_0))p(z)\mathrm{d}z}{\int p(z)\mathrm{d}z}. \qquad (6)$$



https://ui.adsabs.harvard.edu/abs/2021arXiv211200241T/abstract

Growth index γ



- Let γ vary
- From GW+hosts only
- If galaxy overdensities from survey are added: $\sigma_\gamma \sim 0.02 - 0.03$

AP & Kim 2021, PRD, arxiv:2005.04325