Probing the Universe's expansion and the origin of compact object binaries with multi-messenger astronomy

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Seminario PLUS

U.S. Department of E

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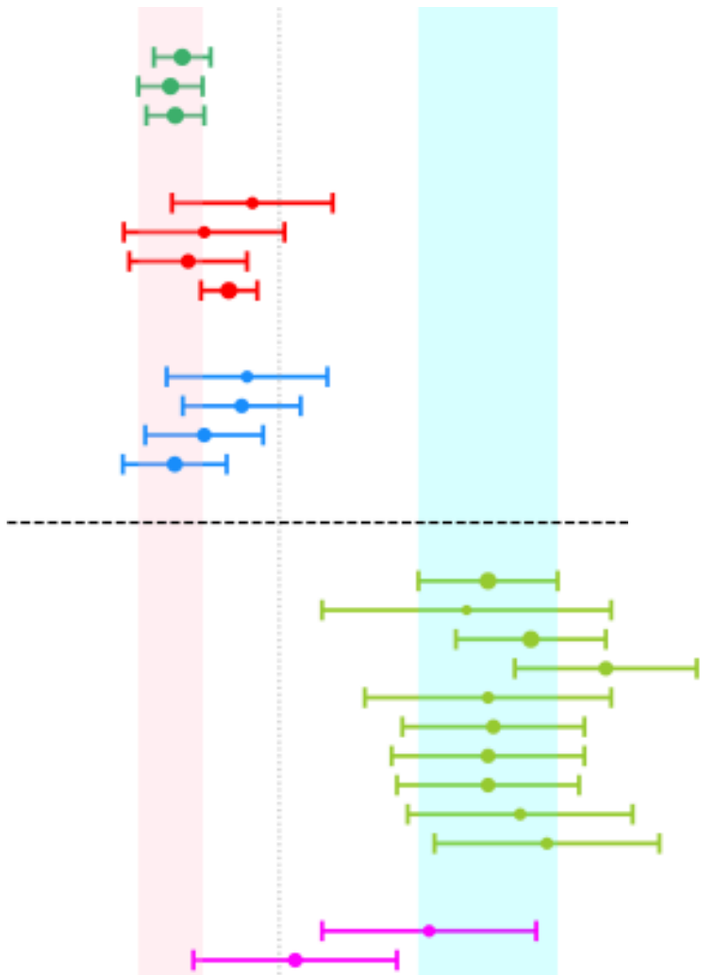
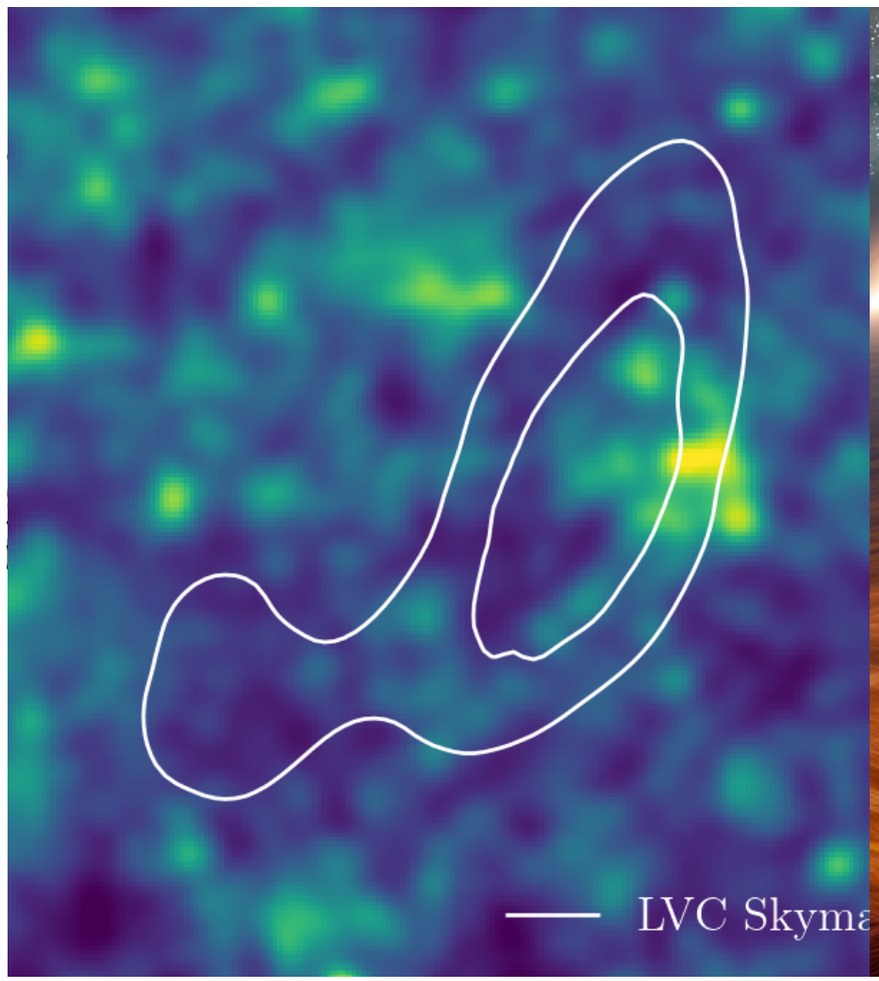
Introduction

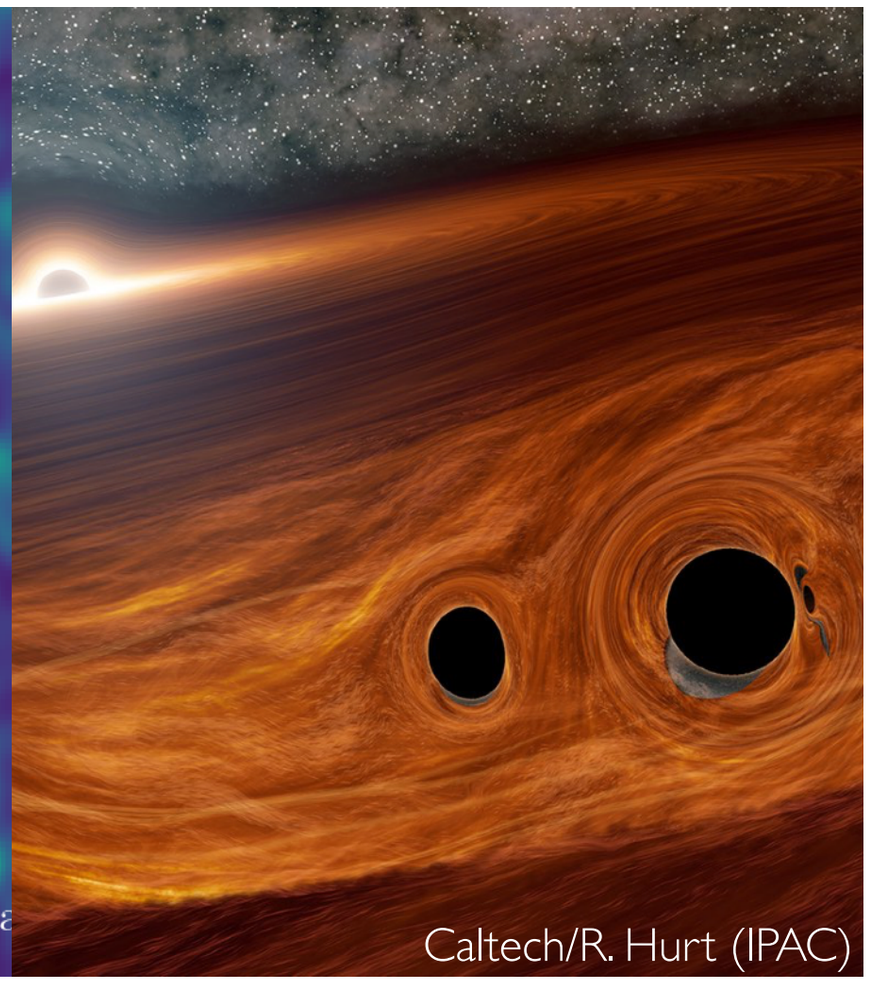


DES, DESI
GW sources
Hubble tension



GW Standard sirens

- Current measurements
- Prospects



Origin of GW binary black holes

The Dark Energy Survey (DES)

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

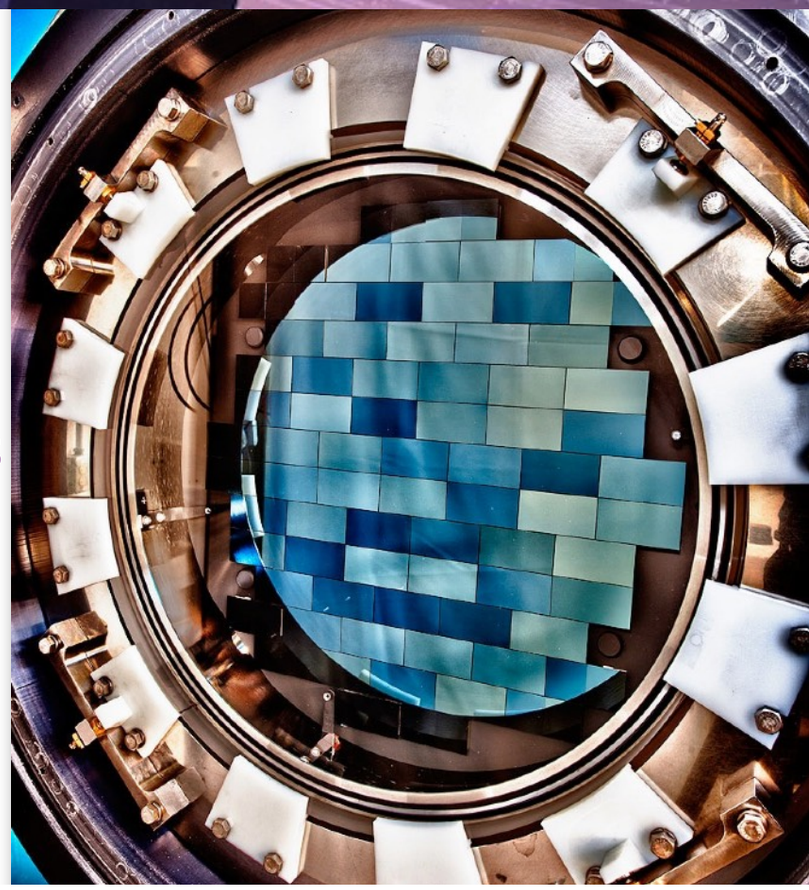
DES programs

Wide: 5000 sq deg *grizY*
Supernovae: 30 sq deg survey
Neutrinos: followup of Icecube events
Gravitational Waves - GW: followup of LIGO/Virgo events

DECam follow-up continues beyond DES

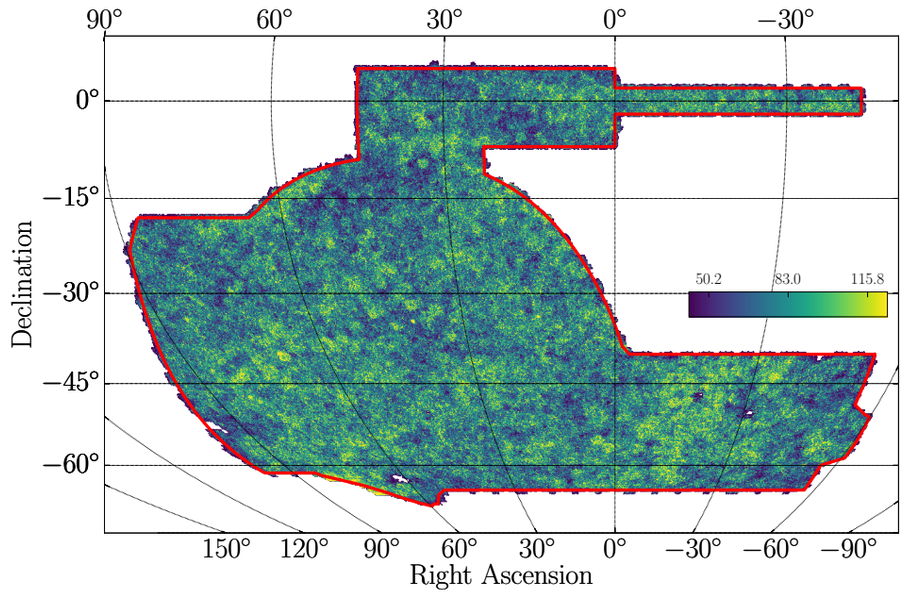
DECam

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)



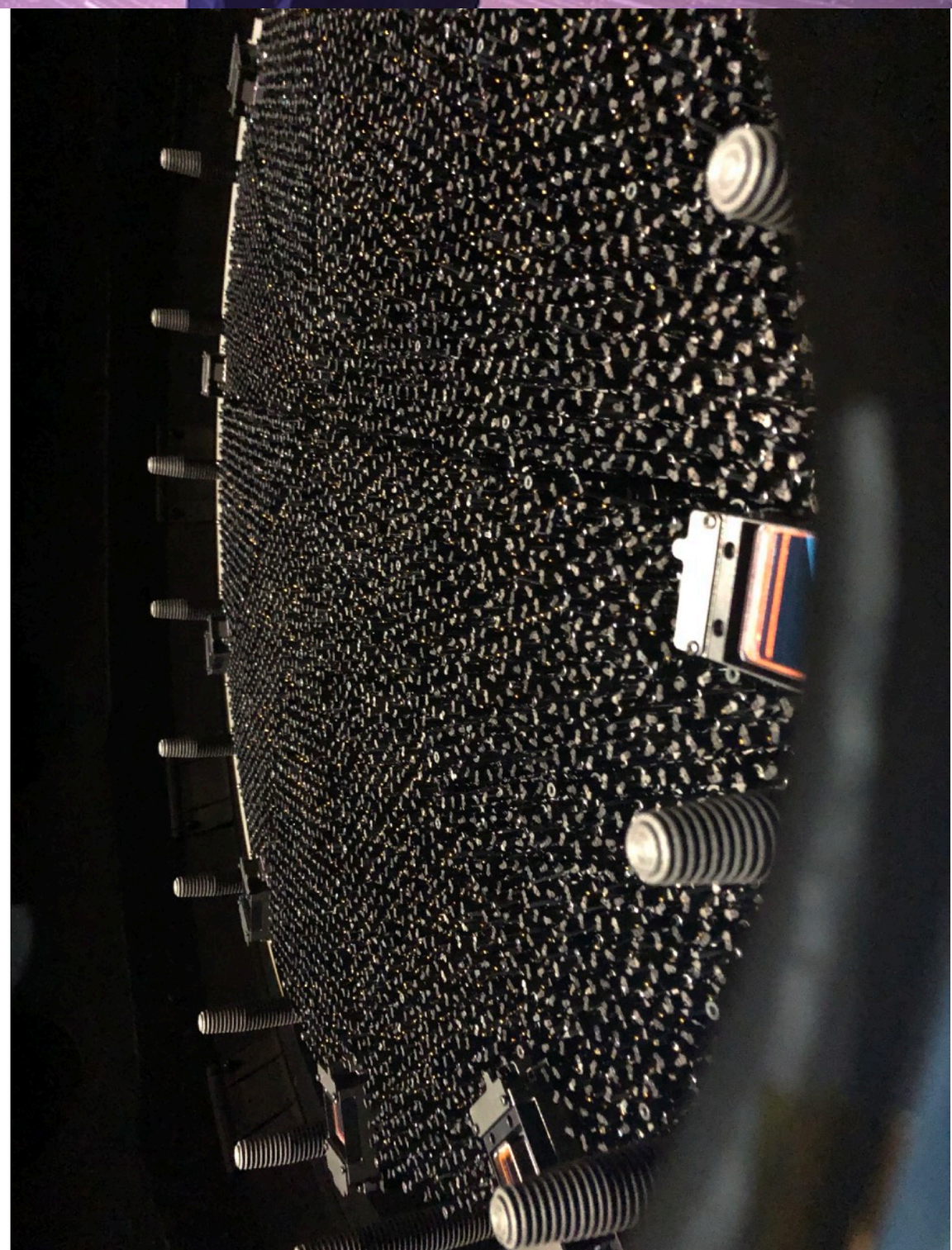
Public data

https://des.ncsa.illinois.edu/home
DR2 (Y6) - 600+M objects (*r*~24.4) + Y3 Gold **NEW!**



The Dark Energy Spectroscopic Instrument (DESI)

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



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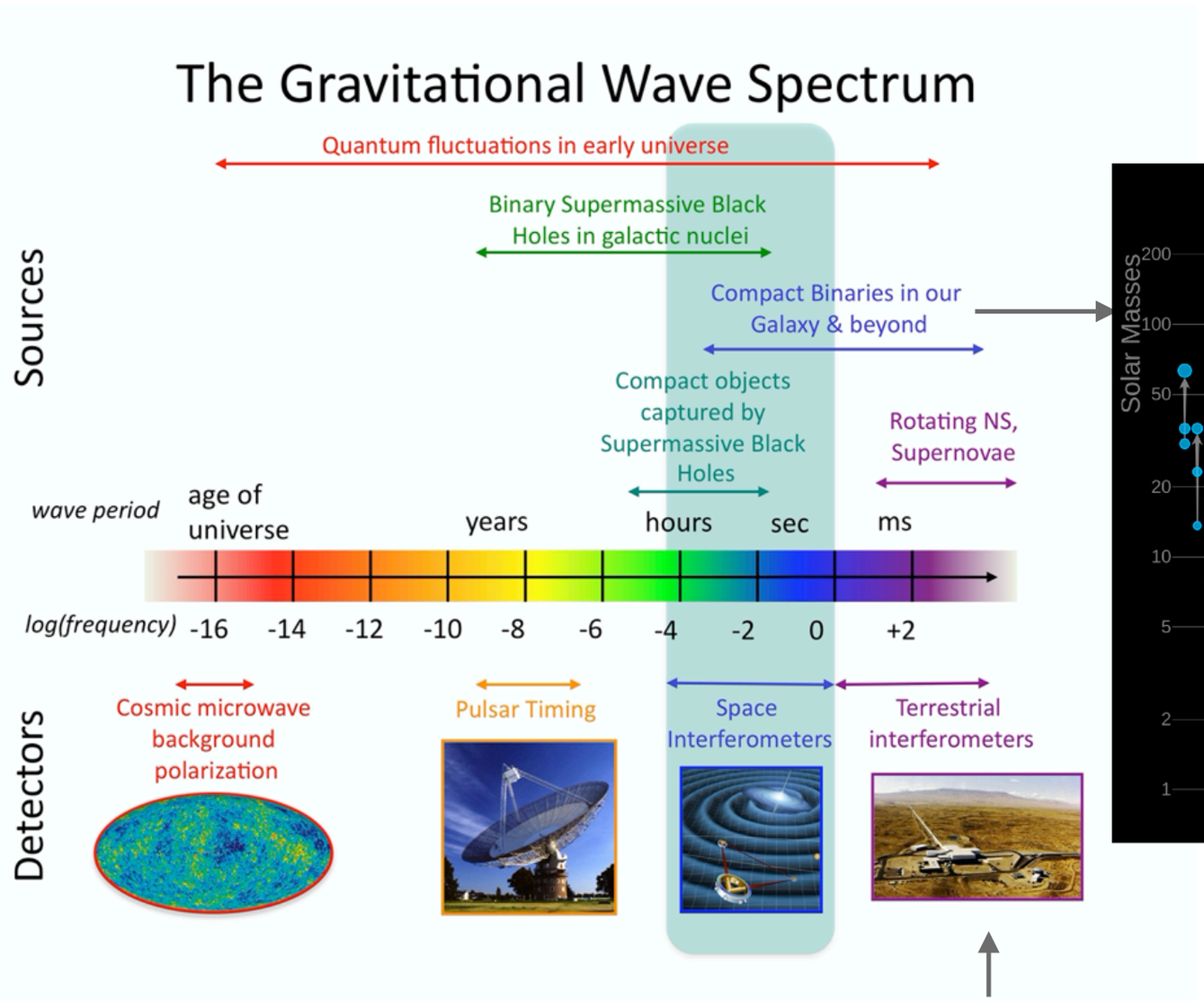
Dark Energy Spectroscopic Instrument (DESI) Creates Largest 3D Map of the Cosmos

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

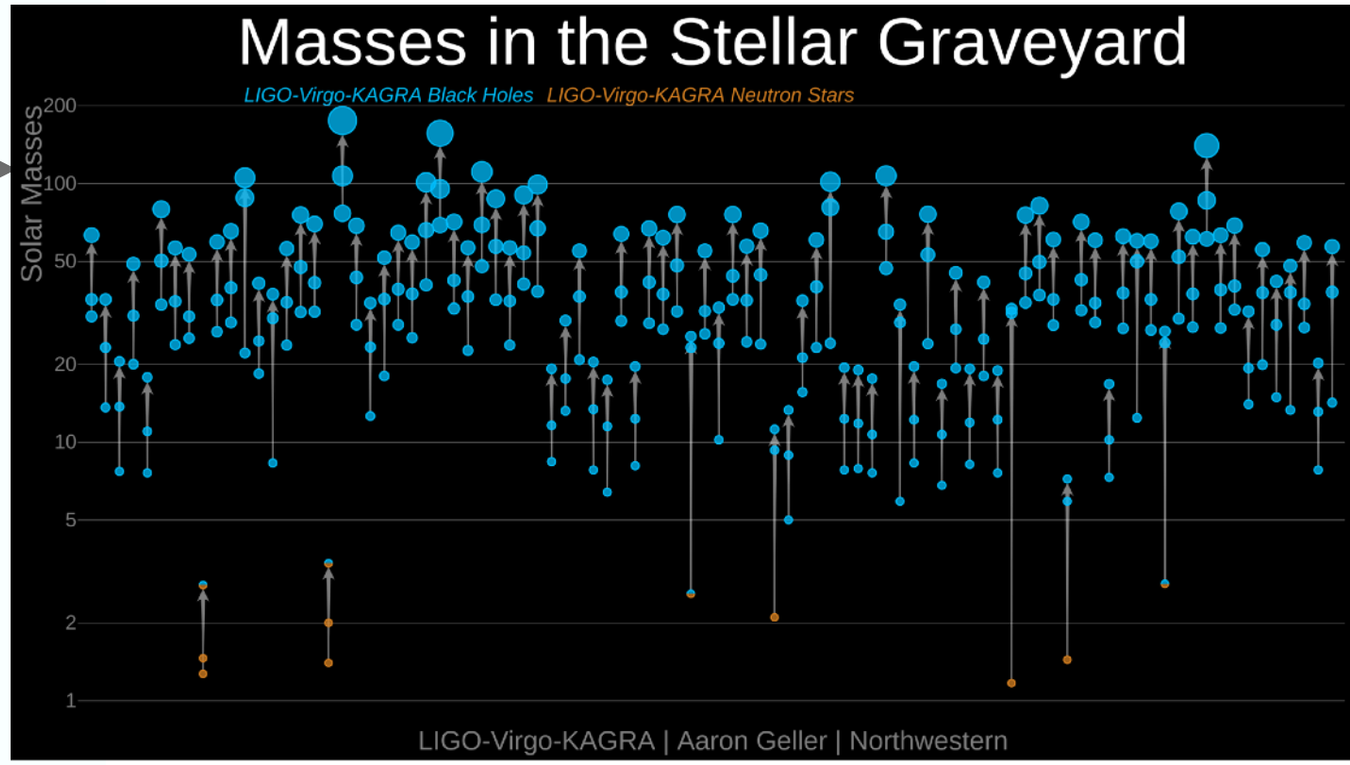
News Release Adam Becker (510) 424-2436 • **January 13, 2022**

GW sources



2G: LIGO/Virgo/KAGRA
3G (2030s): Einstein Telescope (ET; EU), Cosmic Explorer (CE; US)

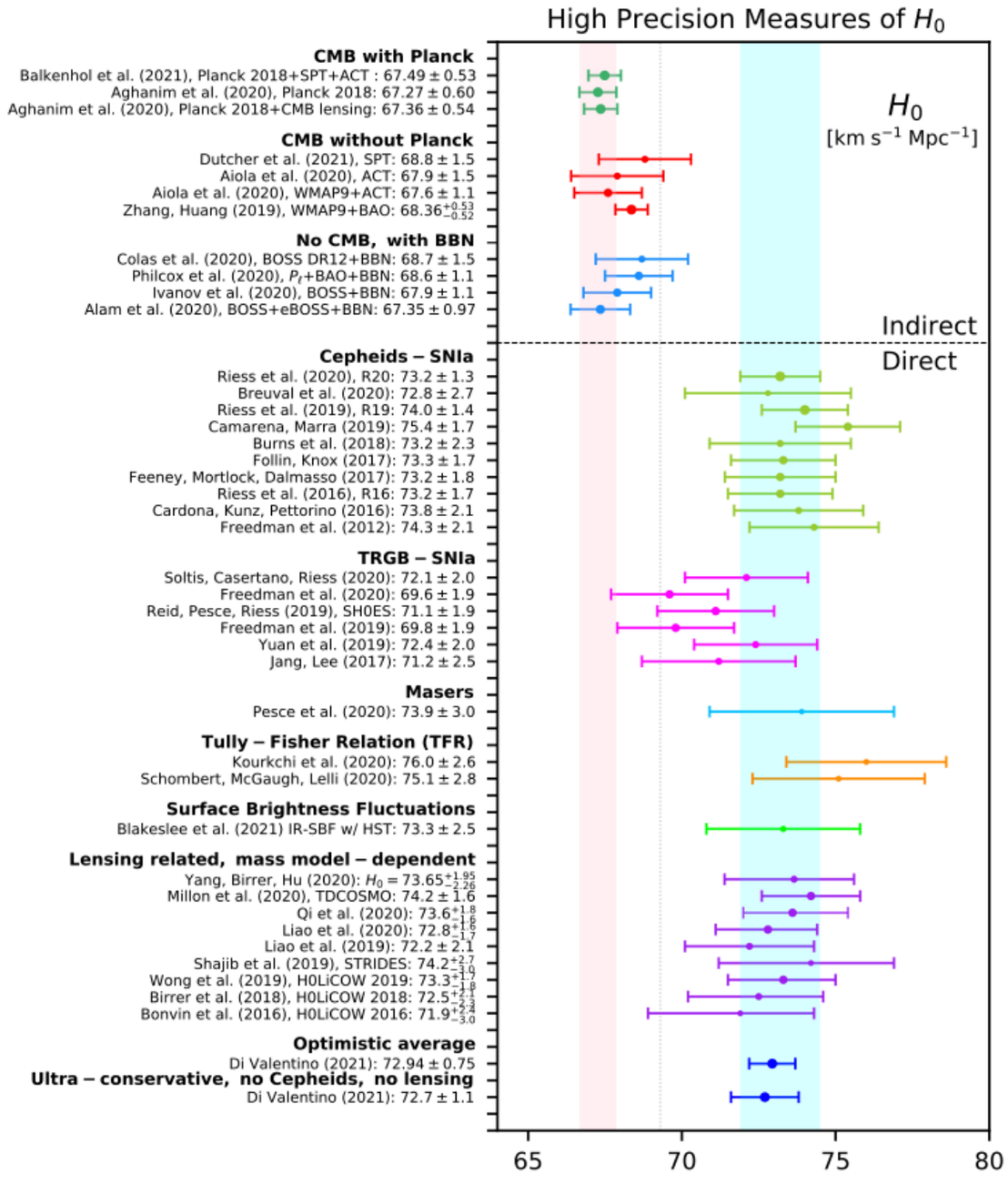
Gravitational wave Transient Catalog (GWTC-3):
LIGO/Virgo/KAGRA O1-O2-O3



BNS: binary neutron star
BBH: binary black hole
NSBH: Neutron star-black hole

Hubble constant tension

- Hubble constant 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

GW experiment

d_L

Standard Sirens

Schutz 1986

Holz & Hughes 2005

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GW experiment / d_L

EM experiment - host galaxy redshift / z

Standard Sirens

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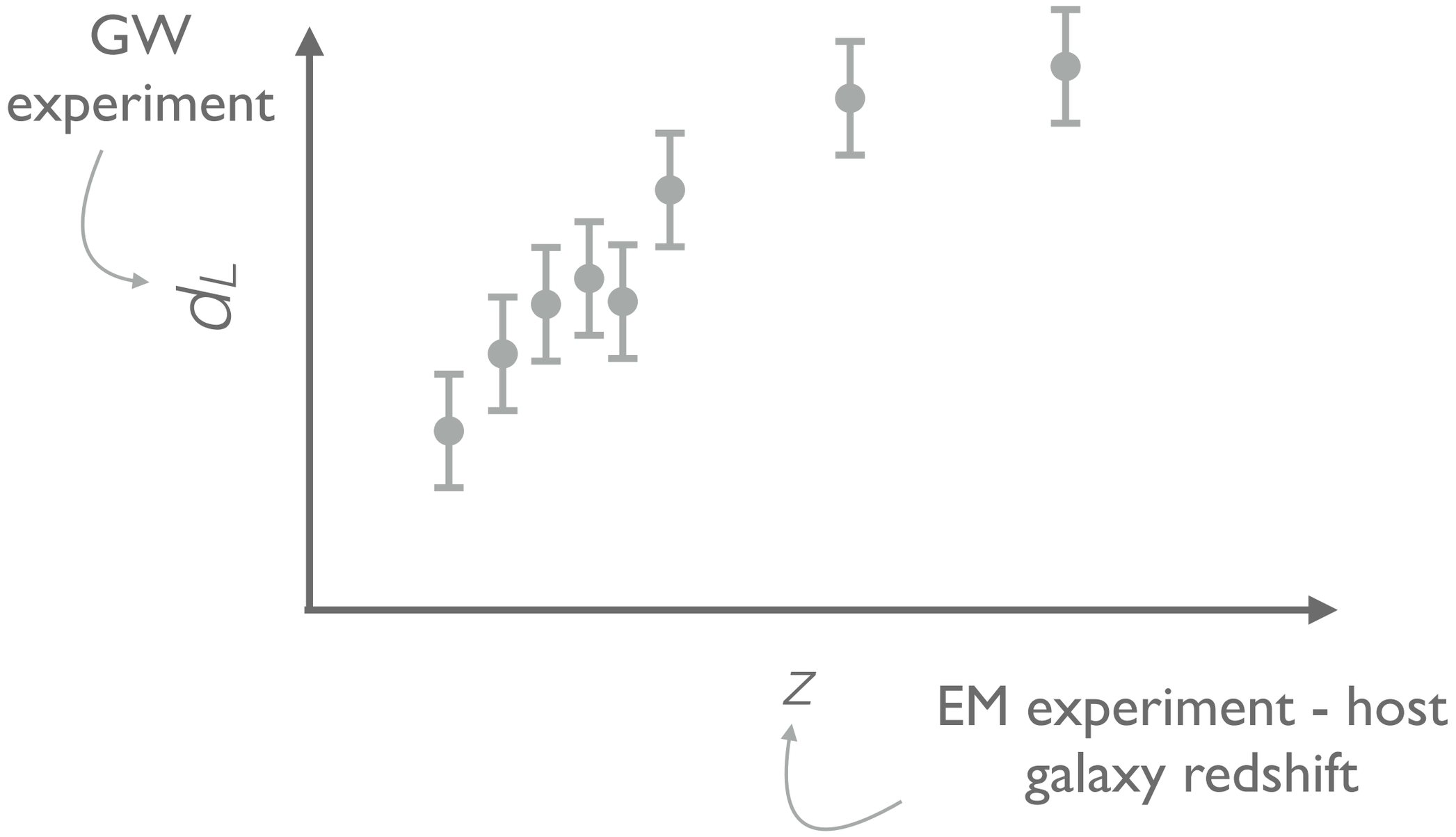

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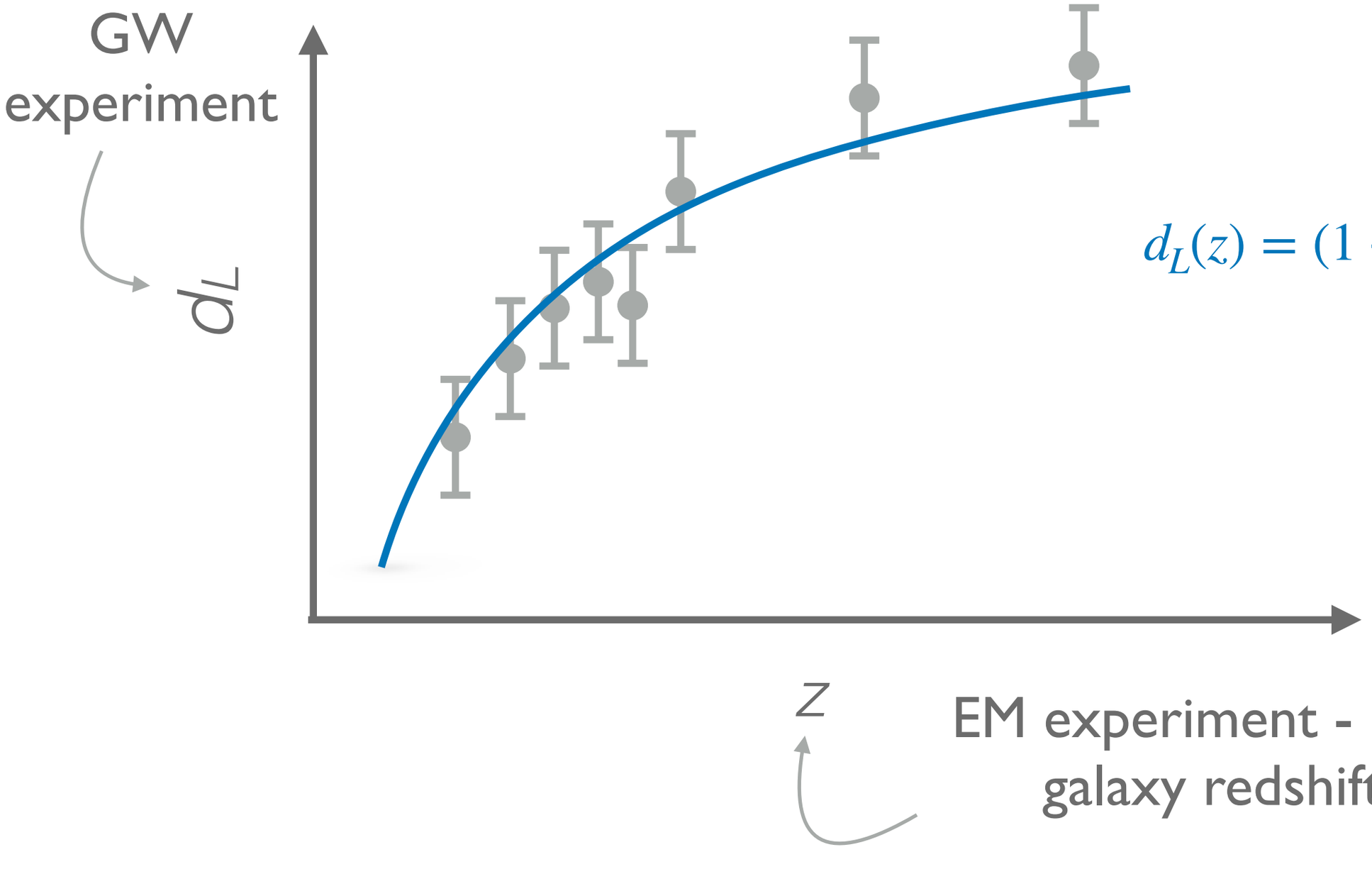

$$d_L(z) = (1+z)\int_0^z \frac{dz'}{H_0 E(z')}$$

Standard Sirens

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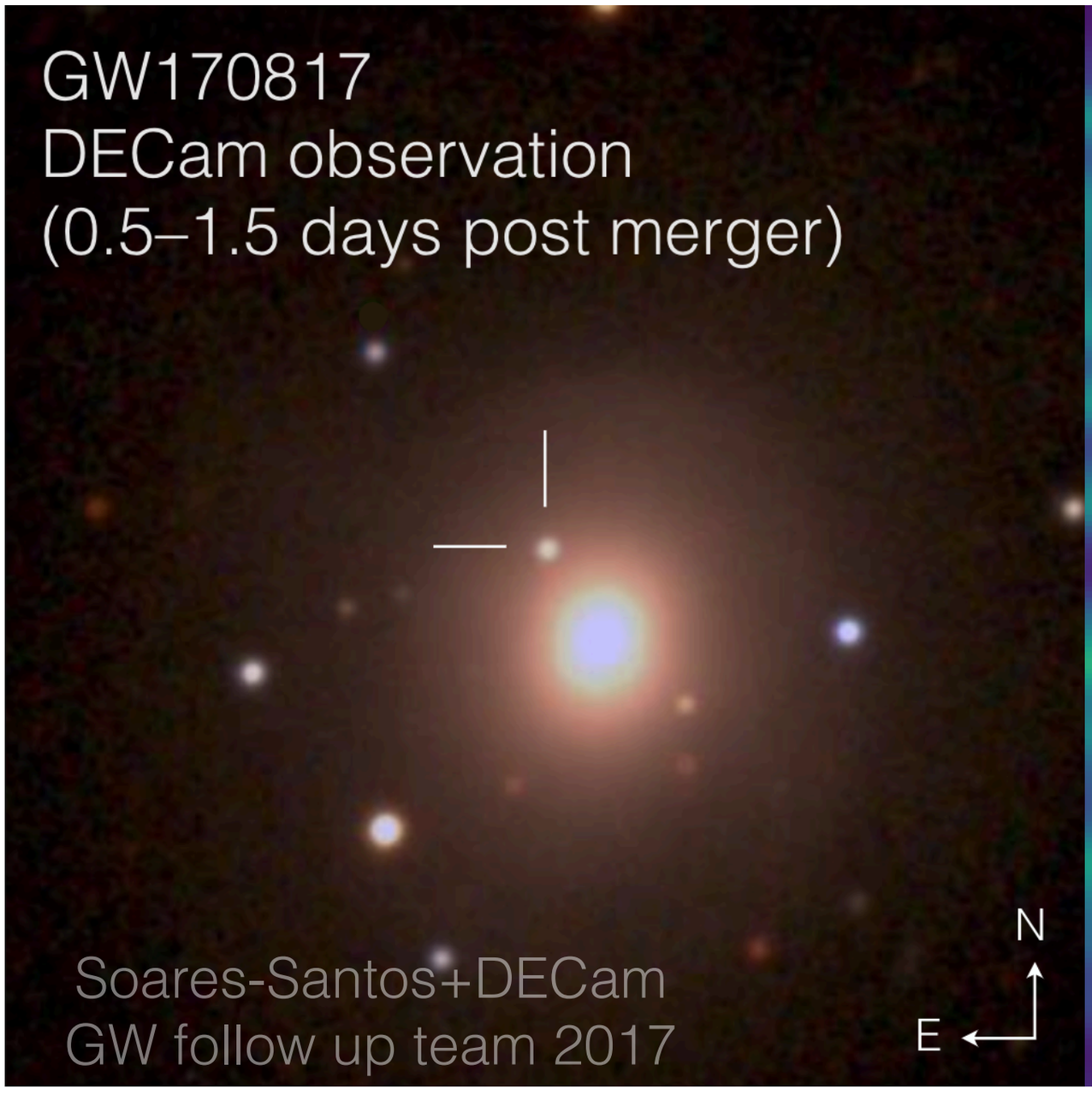
With EM counterpart (BNS/NSBH)



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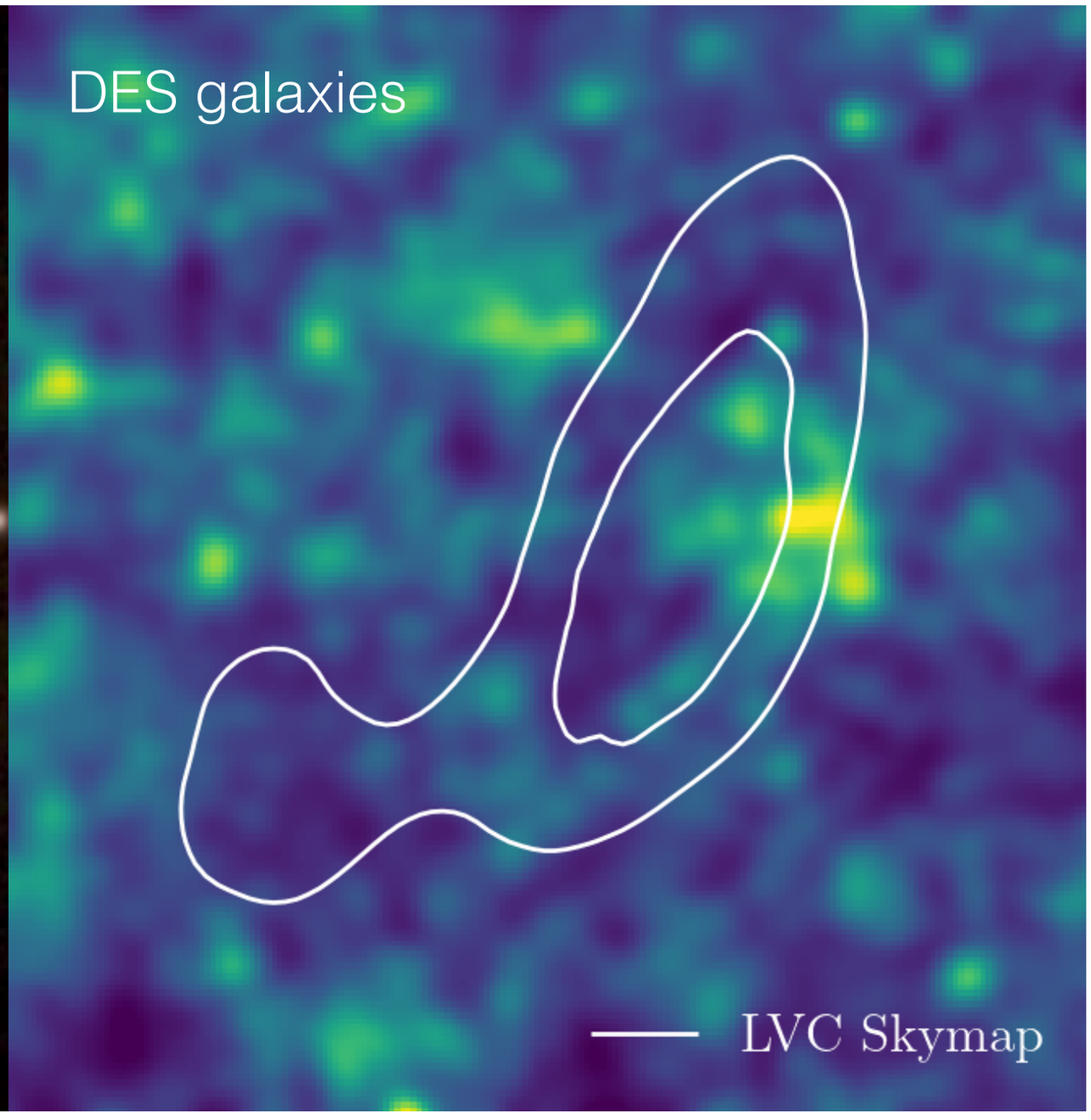

Bright standard sirens

Dark standard sirens / statistical method

Standard Sirens

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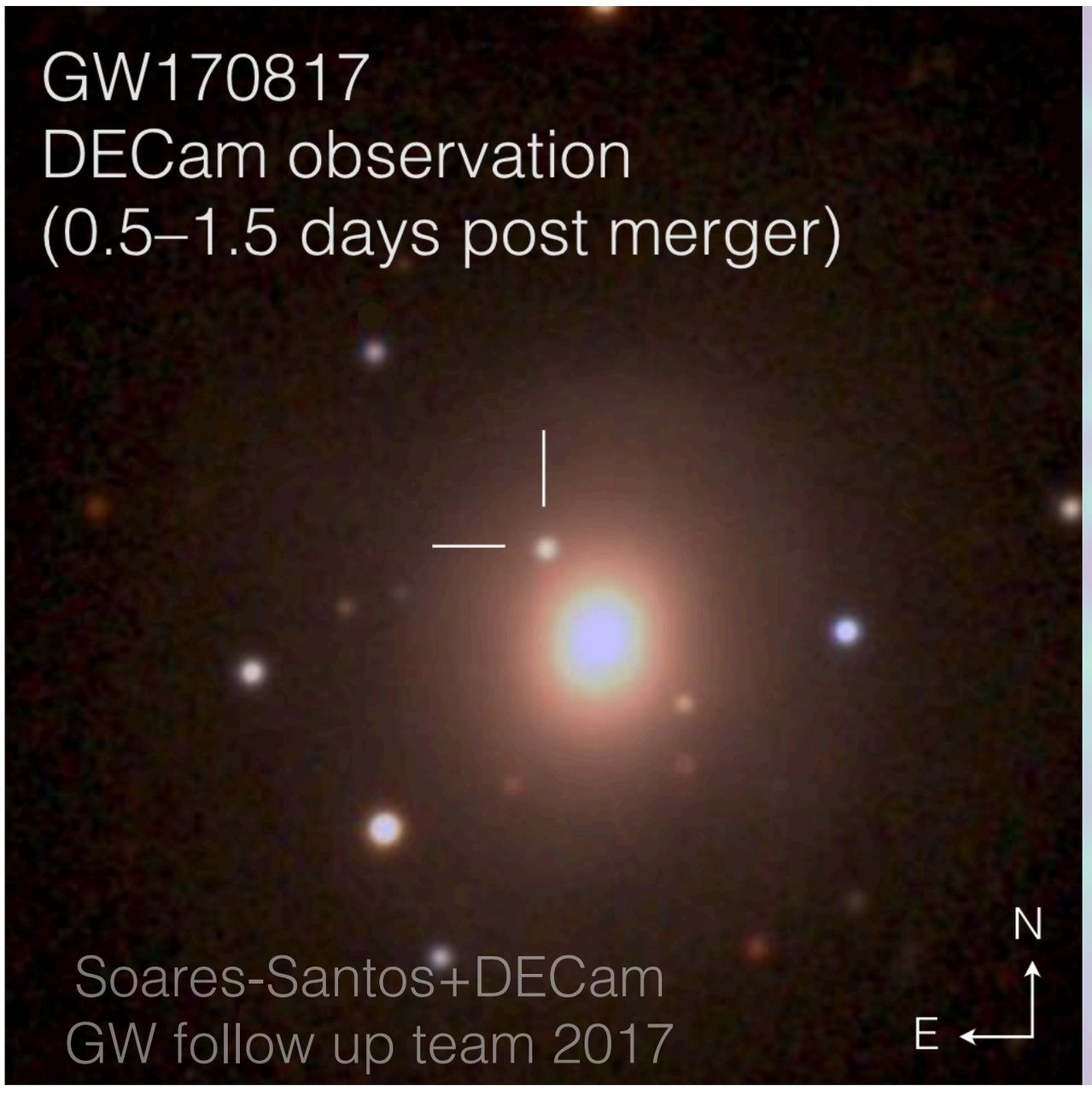
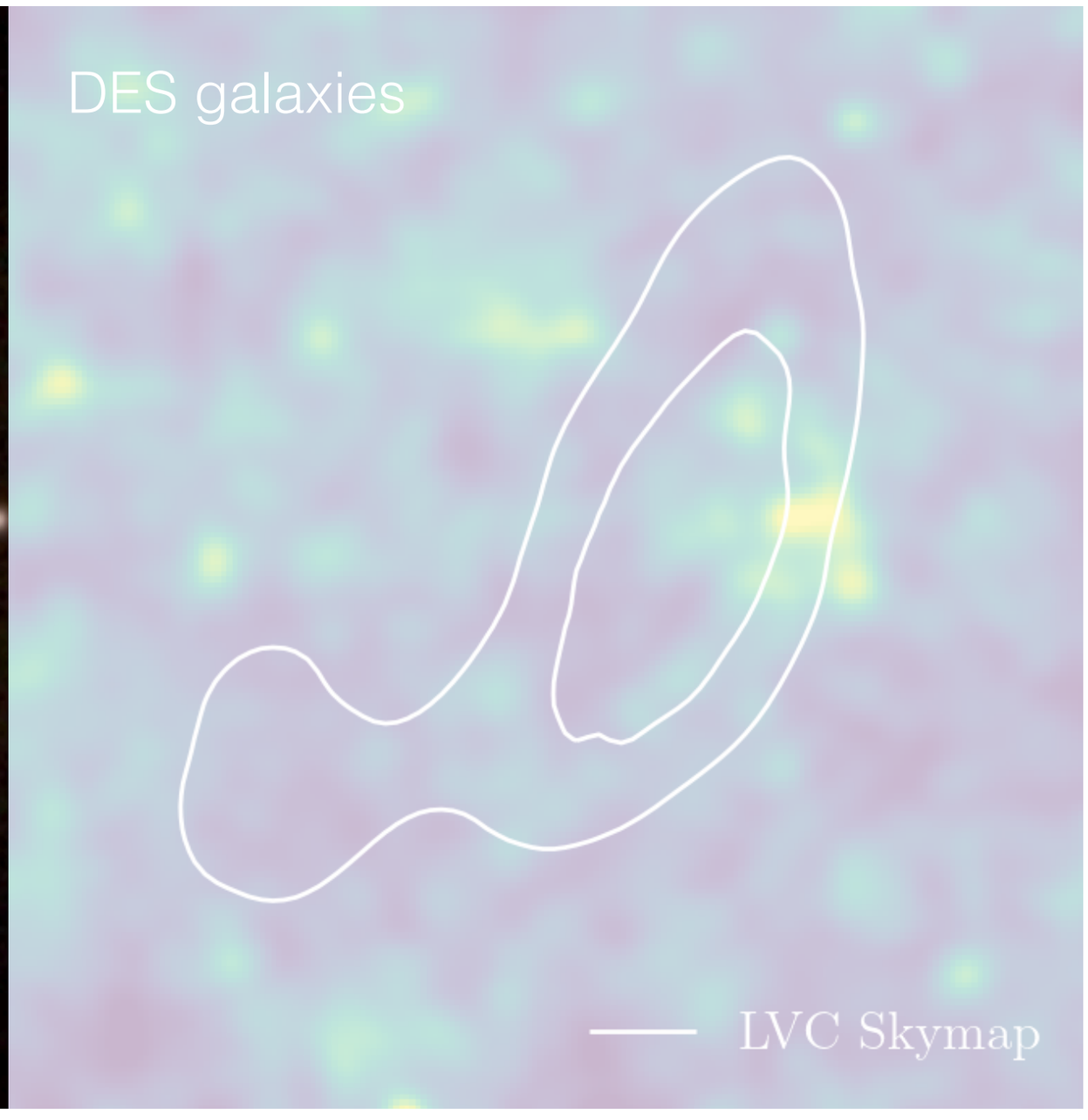
GW170817 - First GW from a BNS merger and first GW EM counterpart

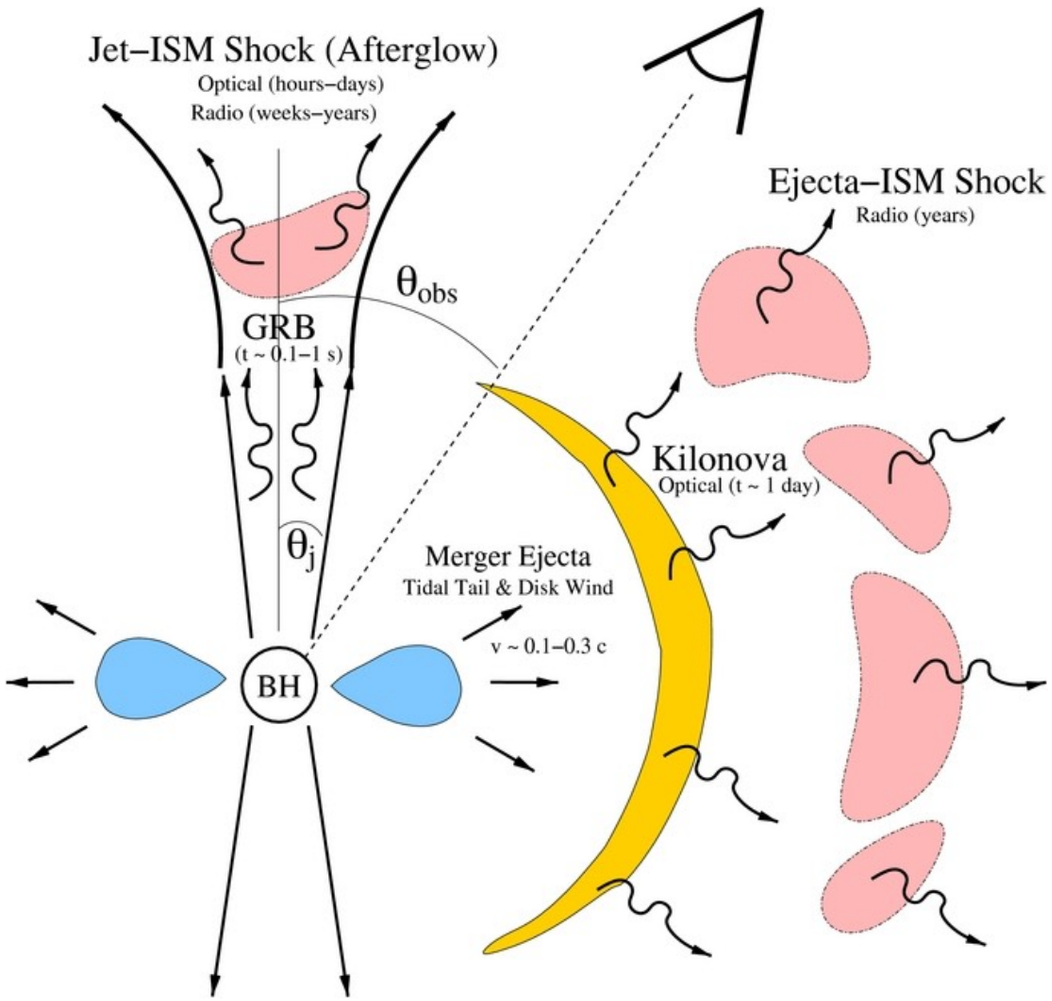




Bright standard sirens

Dark standard sirens / statistical method

Electromagnetic follow-up of GW binary neutron star mergers



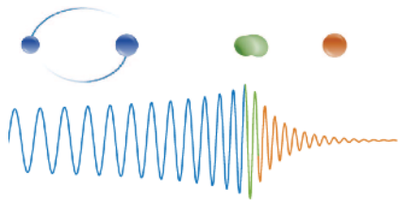
Metzger & Berger 2012

- **Relativistic jet** - gamma rays
- Ejecta from **kilonova** - UV/ optical/infrared
- **Afterglow** - X-rays, optical, radio

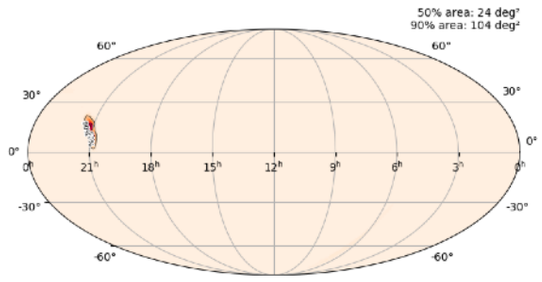
Kilonova: isotropic thermal transient powered by the radioactive decay of rapid neutron capture elements (Lattimer & Schramm 1974) synthetized in the merger ejecta
Most "promising" counterpart

Electromagnetic follow-up with DECam

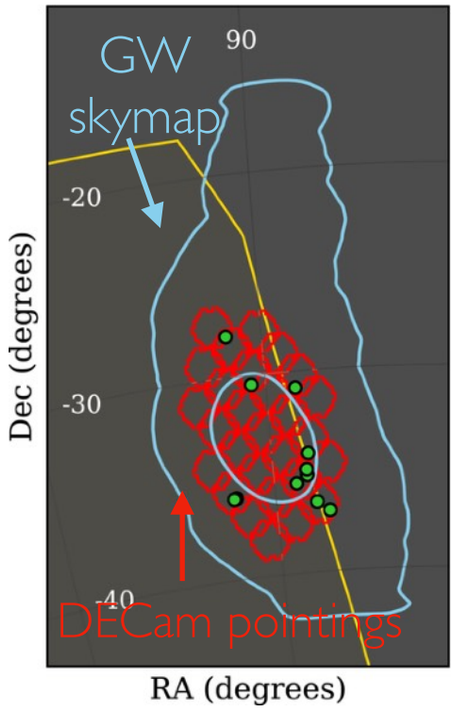
See: Herner+2020



GW event



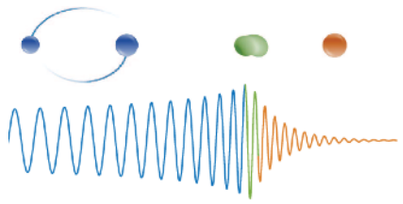
LIGO/Virgo/KAGRA send GW alert



Define strategy, observe

Electromagnetic follow-up with DECam

See: Herner+2020



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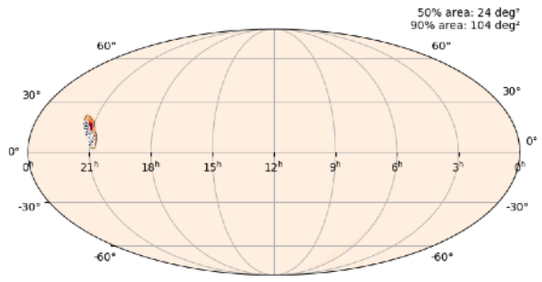

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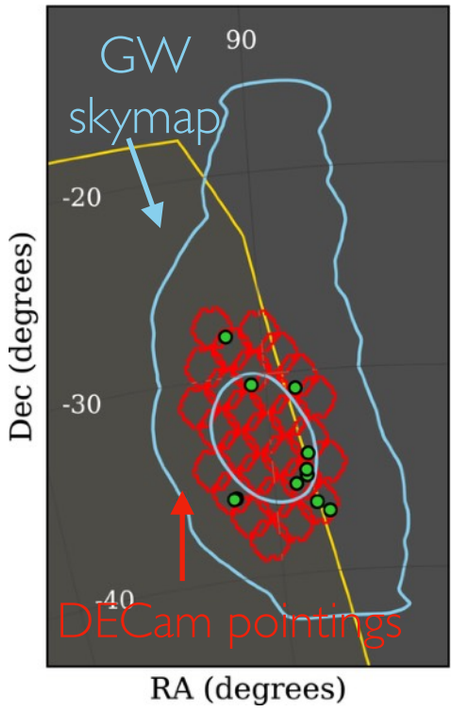

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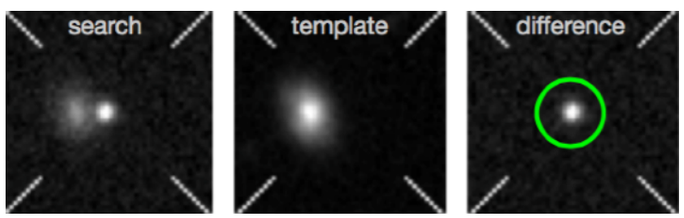
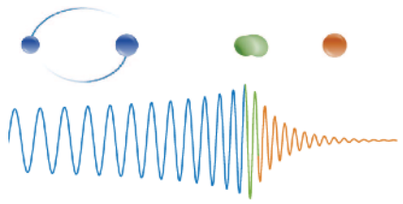


Find new astronomical transients

Electromagnetic follow-up with DECam

See: Herner+2020



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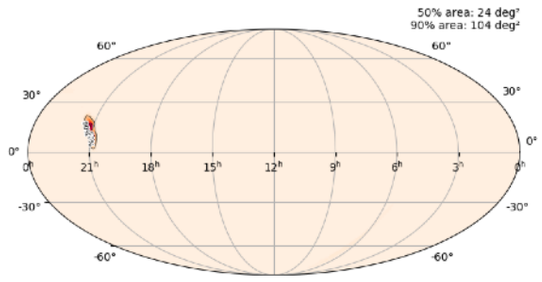

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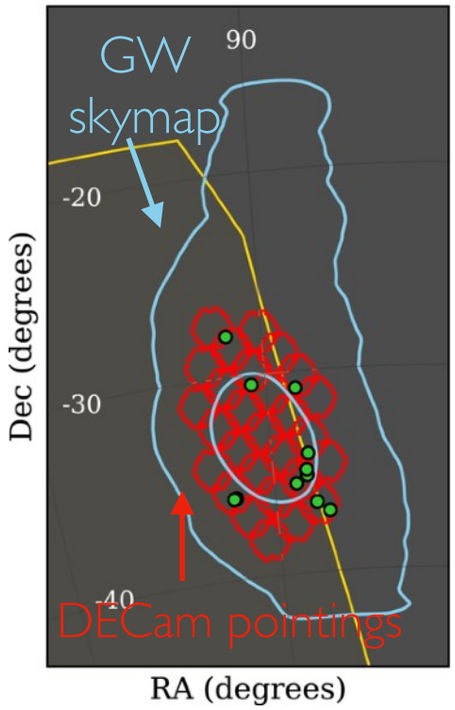

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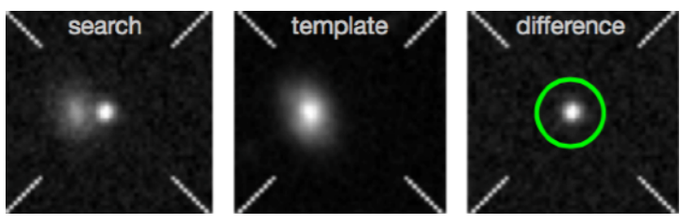


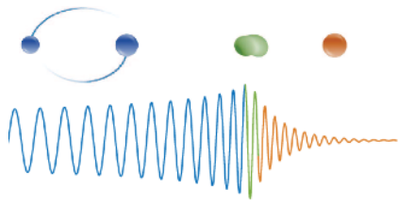
Find new astronomical transients

Post-processing (galaxy catalogs)

Often hundreds of candidates!

Electromagnetic follow-up with DECam

See: Herner+2020



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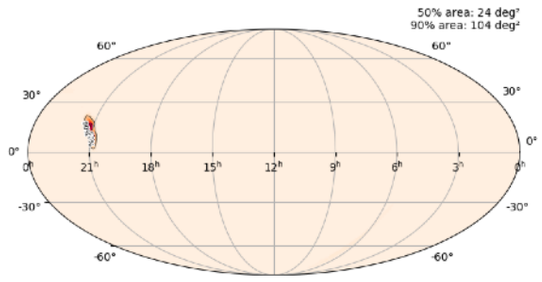

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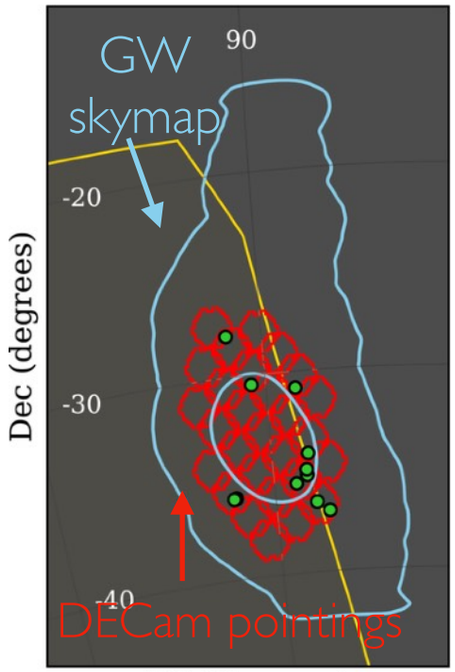

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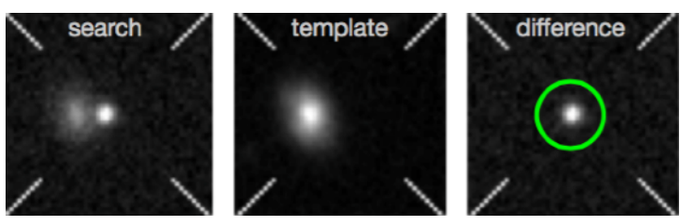

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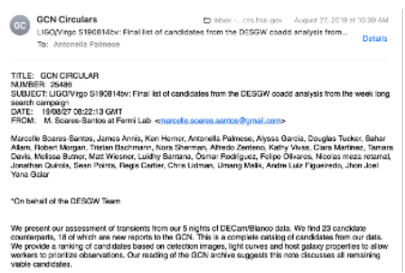
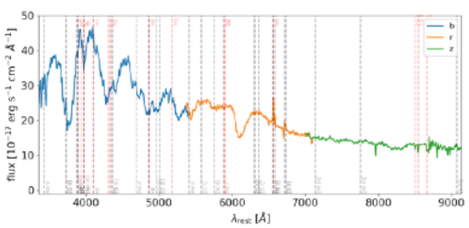


Public transient reports



Spectroscopic follow-up

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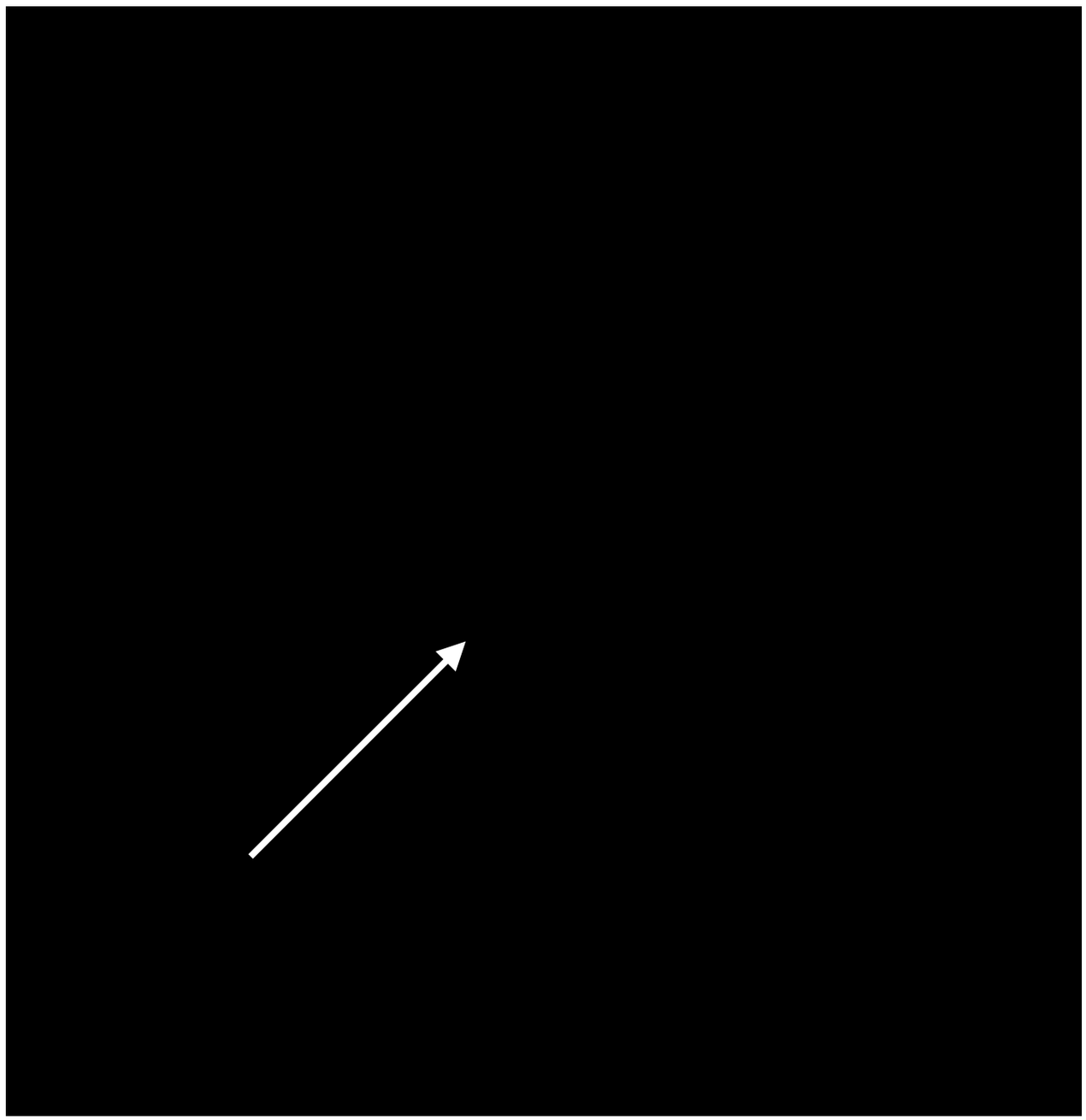
GW170817 with DECam

GW170817 - First GW from a BNS merger and first GW EM counterpart



DECam discovery:
Soares-Santos et al.
2017, ApJL 848, L16

All follow-up:
Abbott et al 2017
ApJL 848 L12

GW170817 with DECam

- Environment of astronomical transients (i.e. host galaxy) informs us about their progenitors and origin

AP+DES 2017, ApJL 849, L34

GW170817 with DECam

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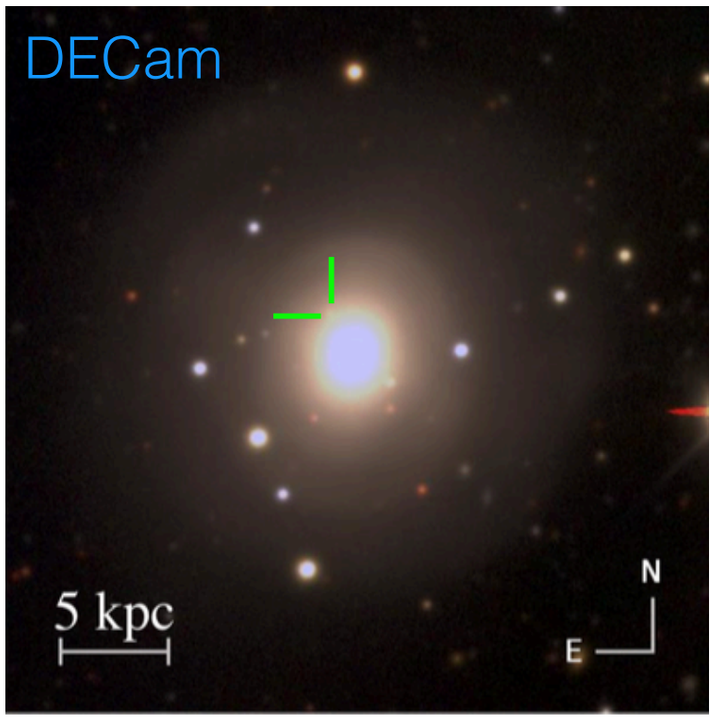
- Absence of recent star formation in GW170817 host



AP+DES 2017, ApJL 849, L34

GW170817 with DECam

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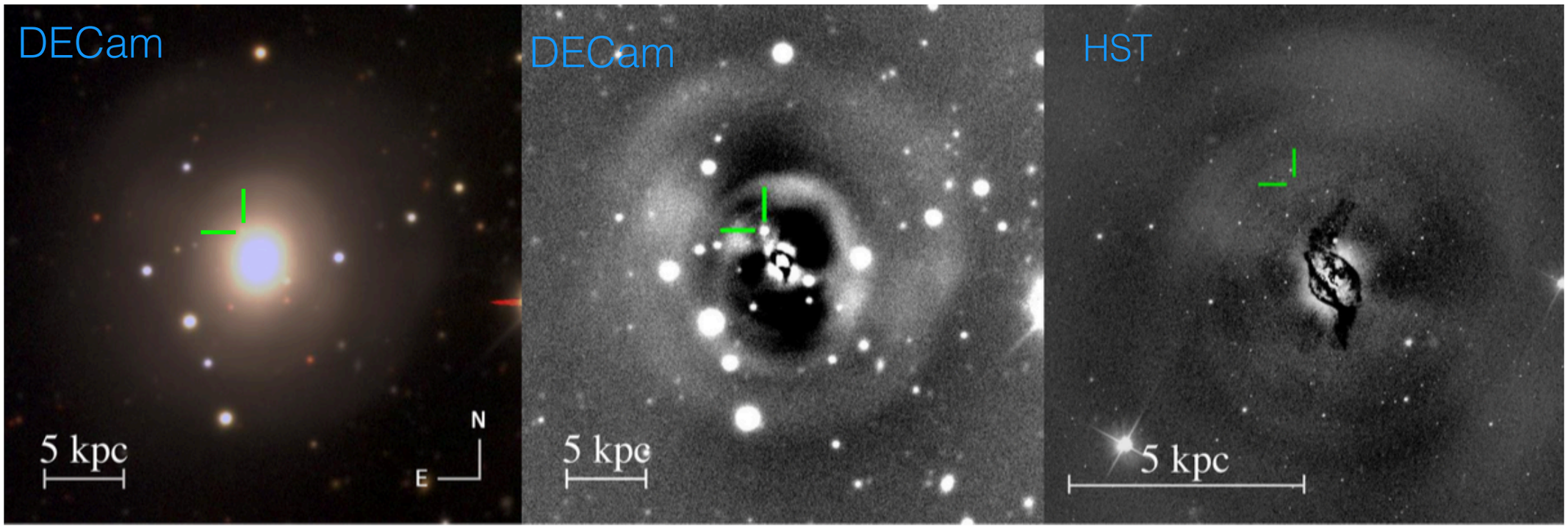
- Kilonova lies on a shell



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GW170817 with DECam

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- Shells form from infalling material from a galaxy merger

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

GW170817 with DECam

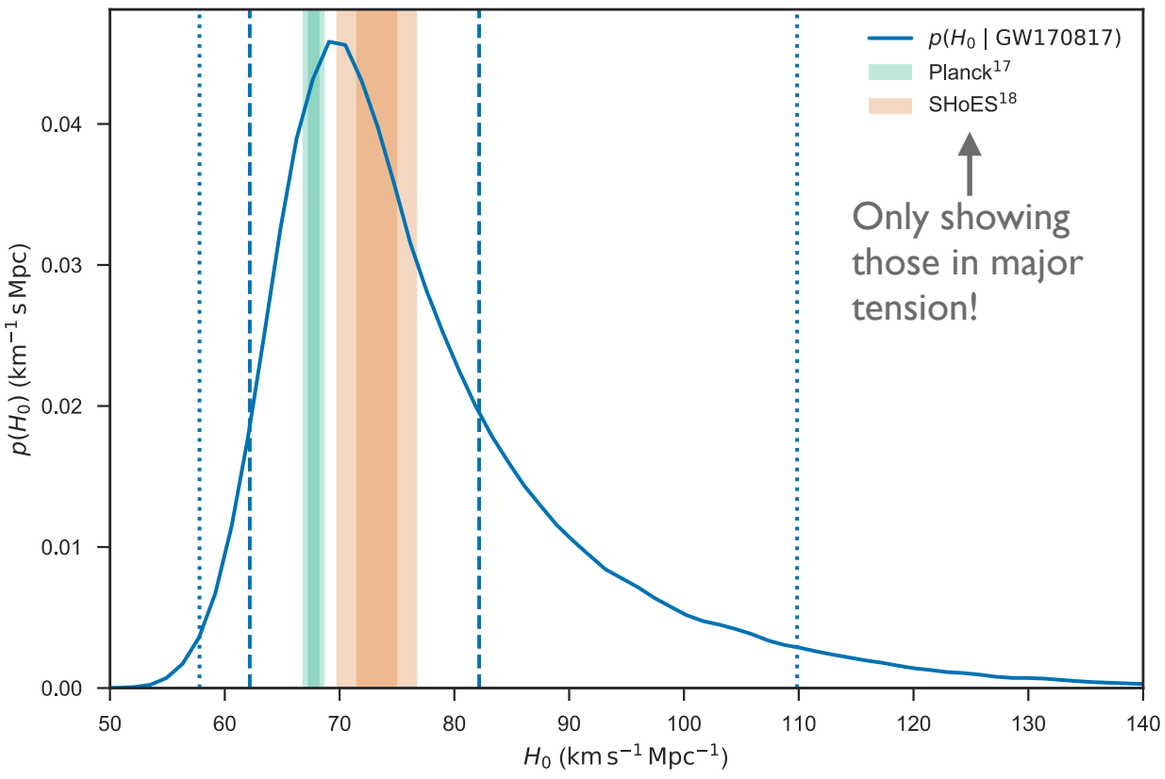
- Environment of astronomical transients (i.e. host galaxy) informs us about their progenitors and origin
- Absence of recent star formation in GW170817 host
- Kilonova lies on a shell
- Shells form from infalling material from a galaxy merger

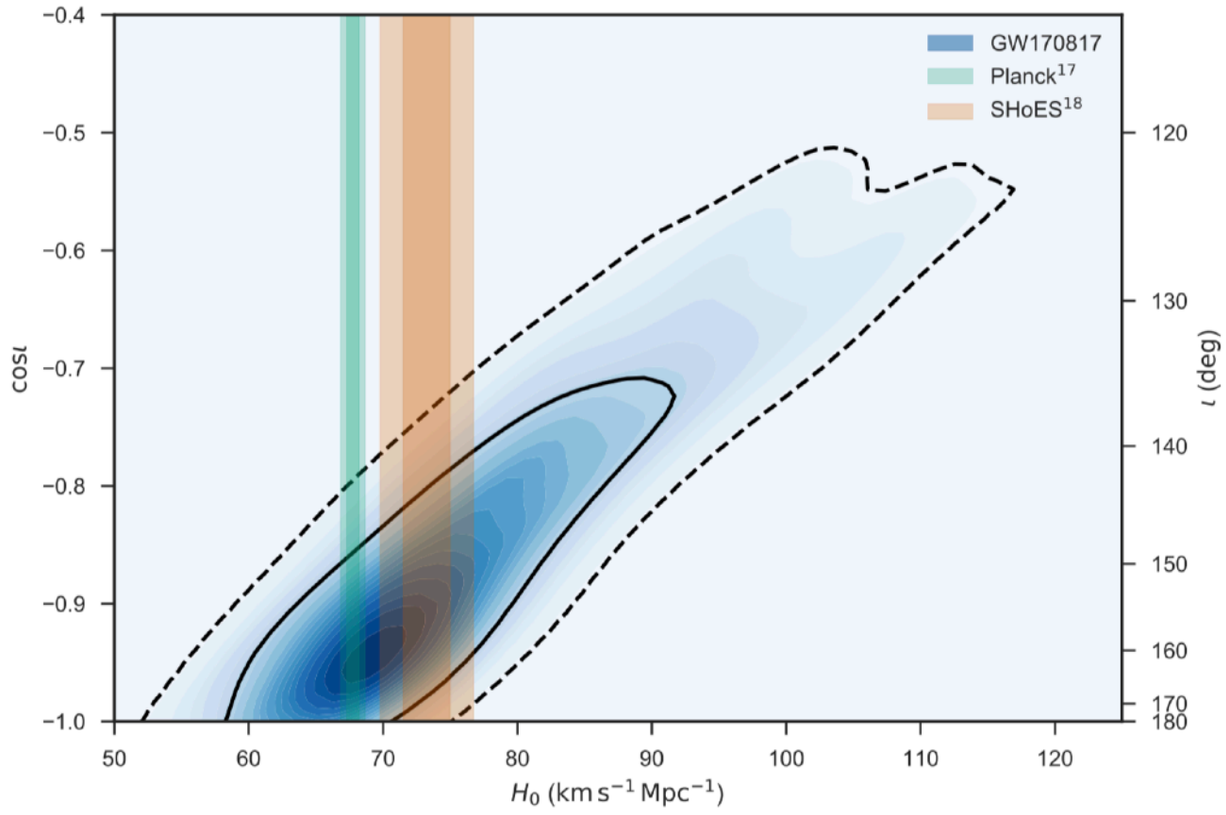
→ The binary may have been the result of enhanced dynamical interactions due to a galaxy merger ~300 Myr before, rather than a star formation event

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

GW170817 as a standard siren

LVC, 1M2H, DES+ 2017





- NGC 4993 (z~0.01)

$$H_0 = 70^{+12}_{-8}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

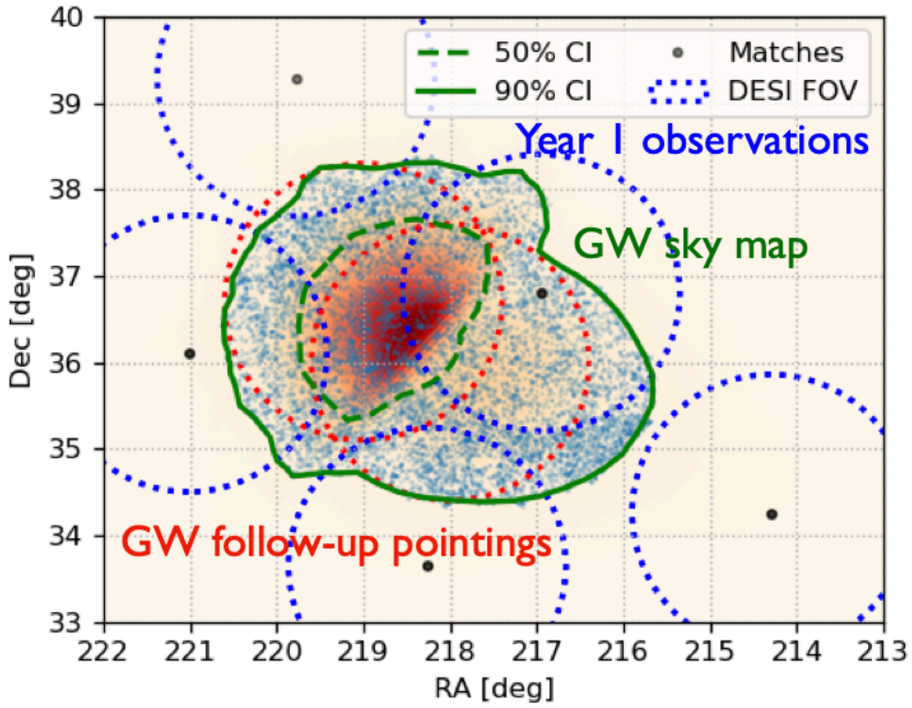
- **Ideal to solve the Hubble constant tension:**
  1. Self-calibrating: Independent of distance ladder
  2. Cosmological model independent

- Limitations:
  - ☆ Peculiar velocity (Nicolau+20, Howlett+20)
  - ☆ Inclination angle is correlated with *D*
- Can break degeneracy by constraining ι from EM
- Improve precision by factor 2-3 (Guidorzi+17,Hotokezaka+18)

Prospects & synergies with DESI

Preparing for next LIGO/Virgo/KAGRA observing run with more optical surveys, e.g. DESI:

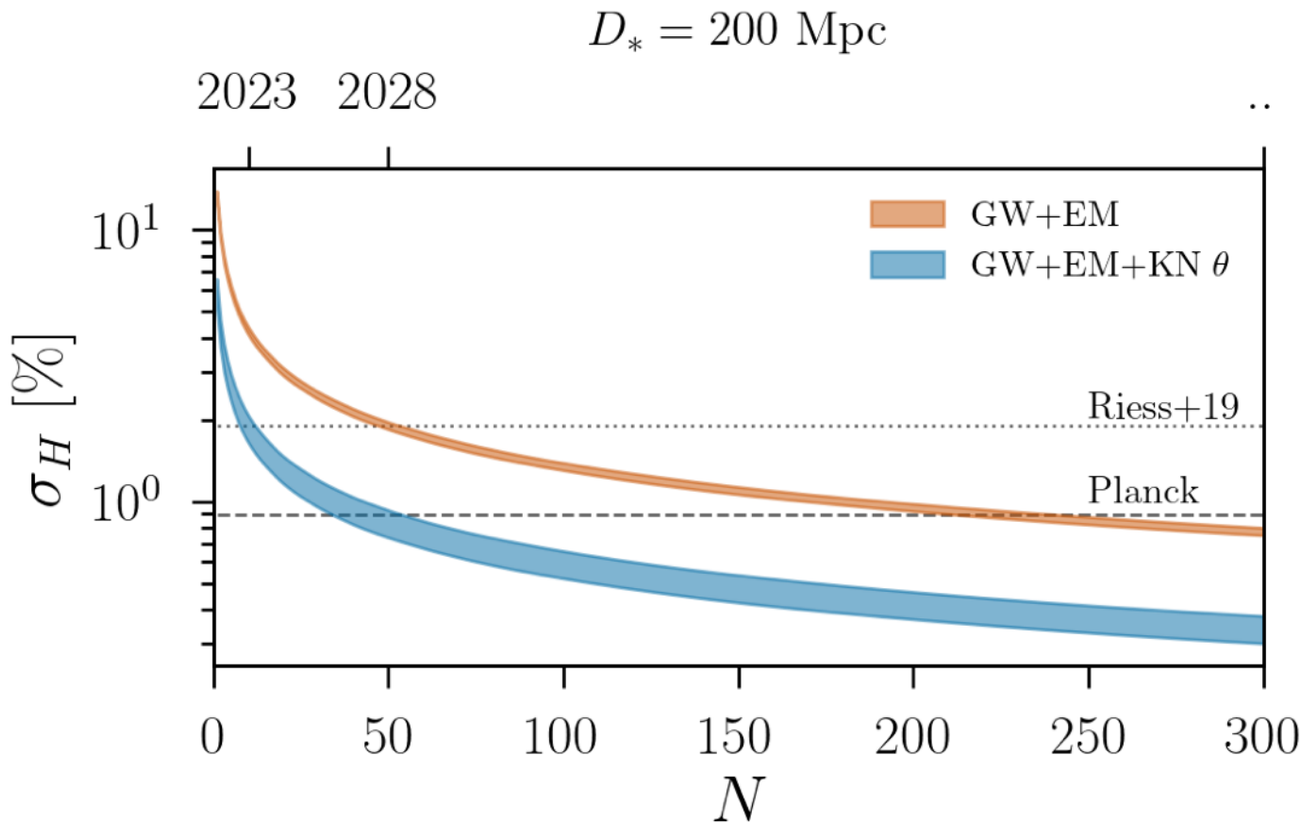
- **Quick classification of candidates (a main bottleneck)**
- Potential **host galaxies spectroscopic redshifts** for further follow-up analyses and cosmology



GW190412 follow-up - DESI Secondary Target Program: Multi-messenger observations (PI: AP)

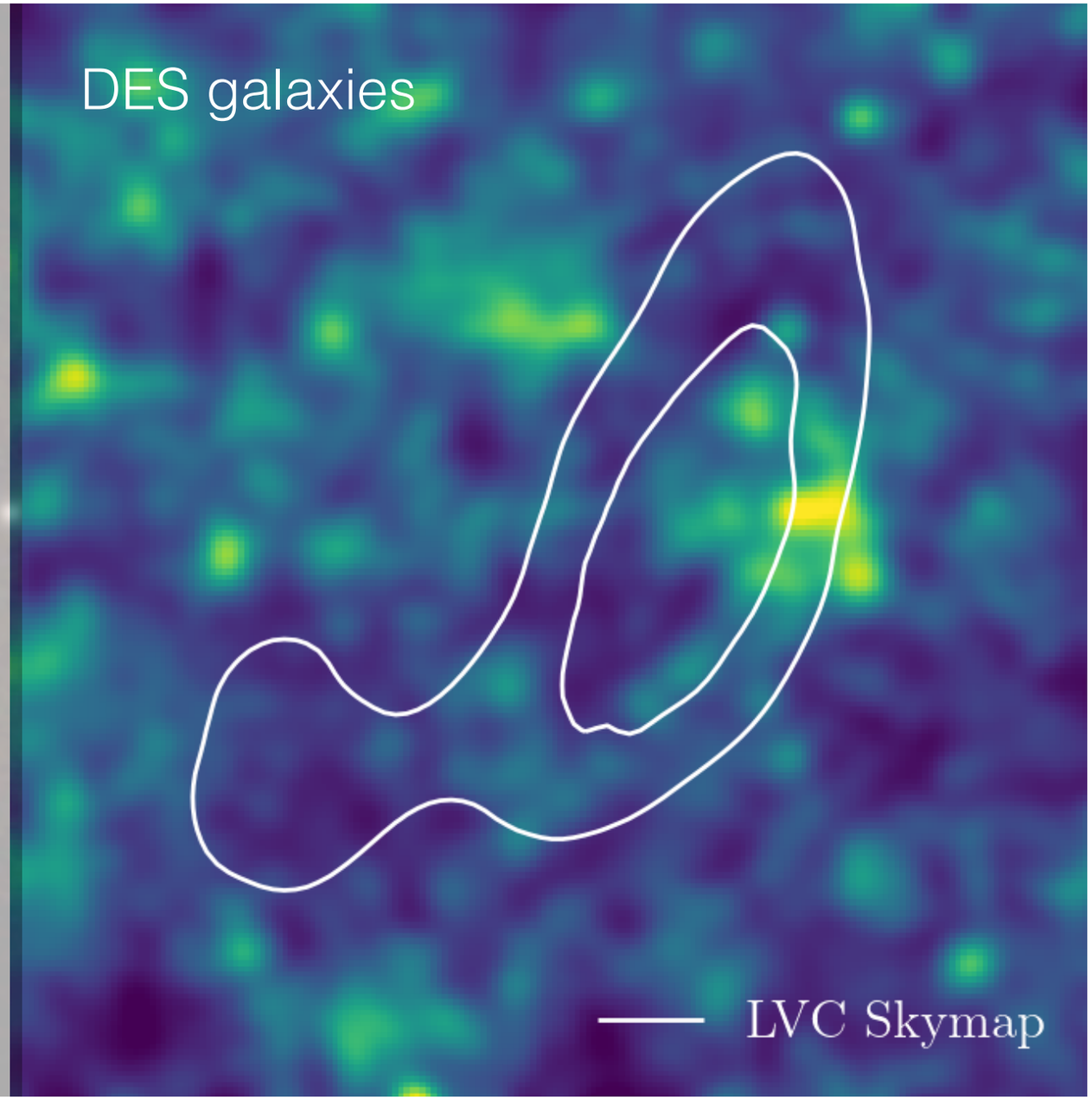
Prospects for bright sirens

~2% measurement w/ ~50 events, enough to understand H_0 tension (Chen+2018, Feeney+2019)



Adapted from **AP**+2019, arxiv: 1903.04730

Dark Standard Sirens

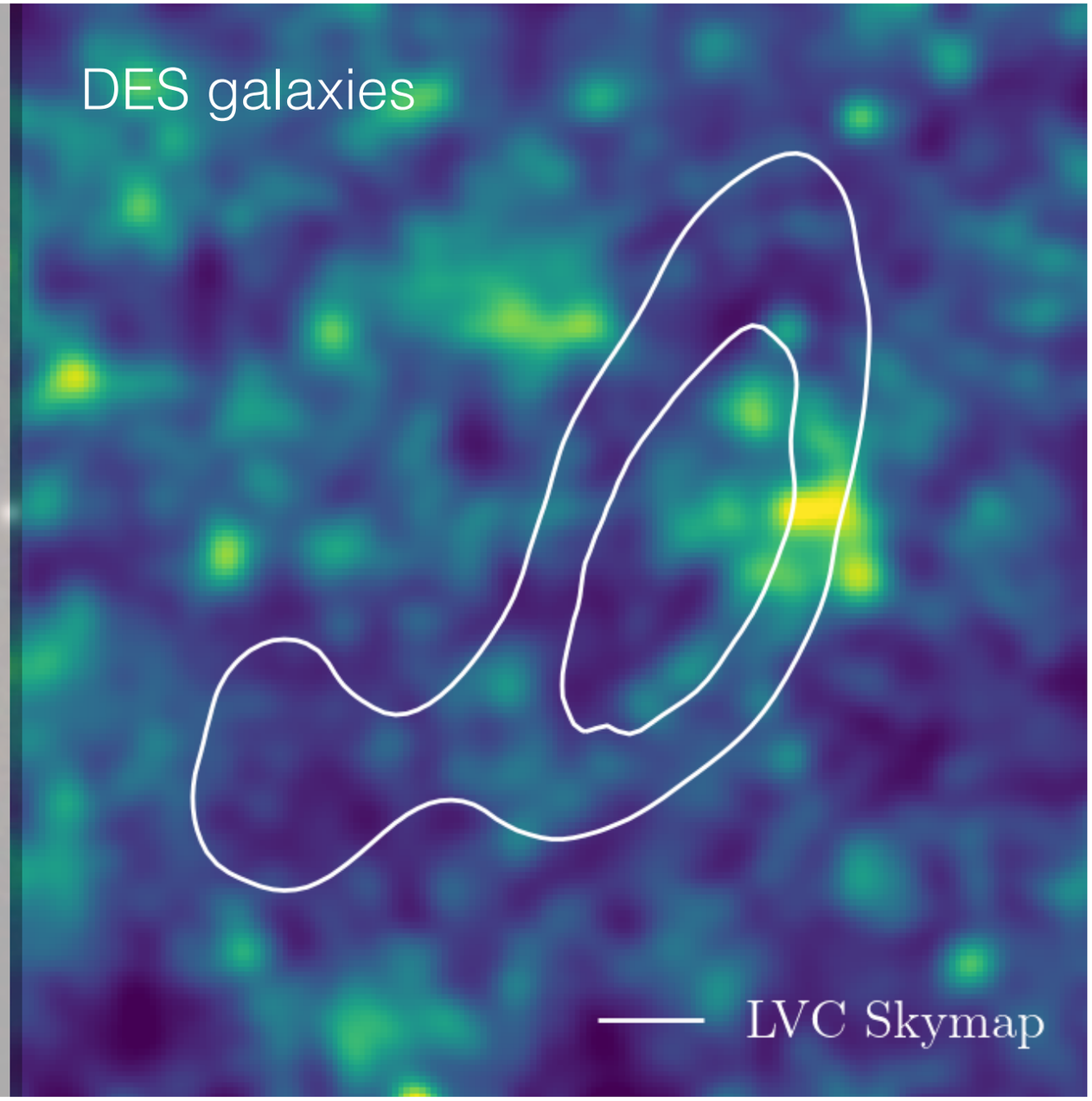


Dark Standard Sirens - **why?**

GW170817
DECam observation
(0.5–1.5 days post merger)

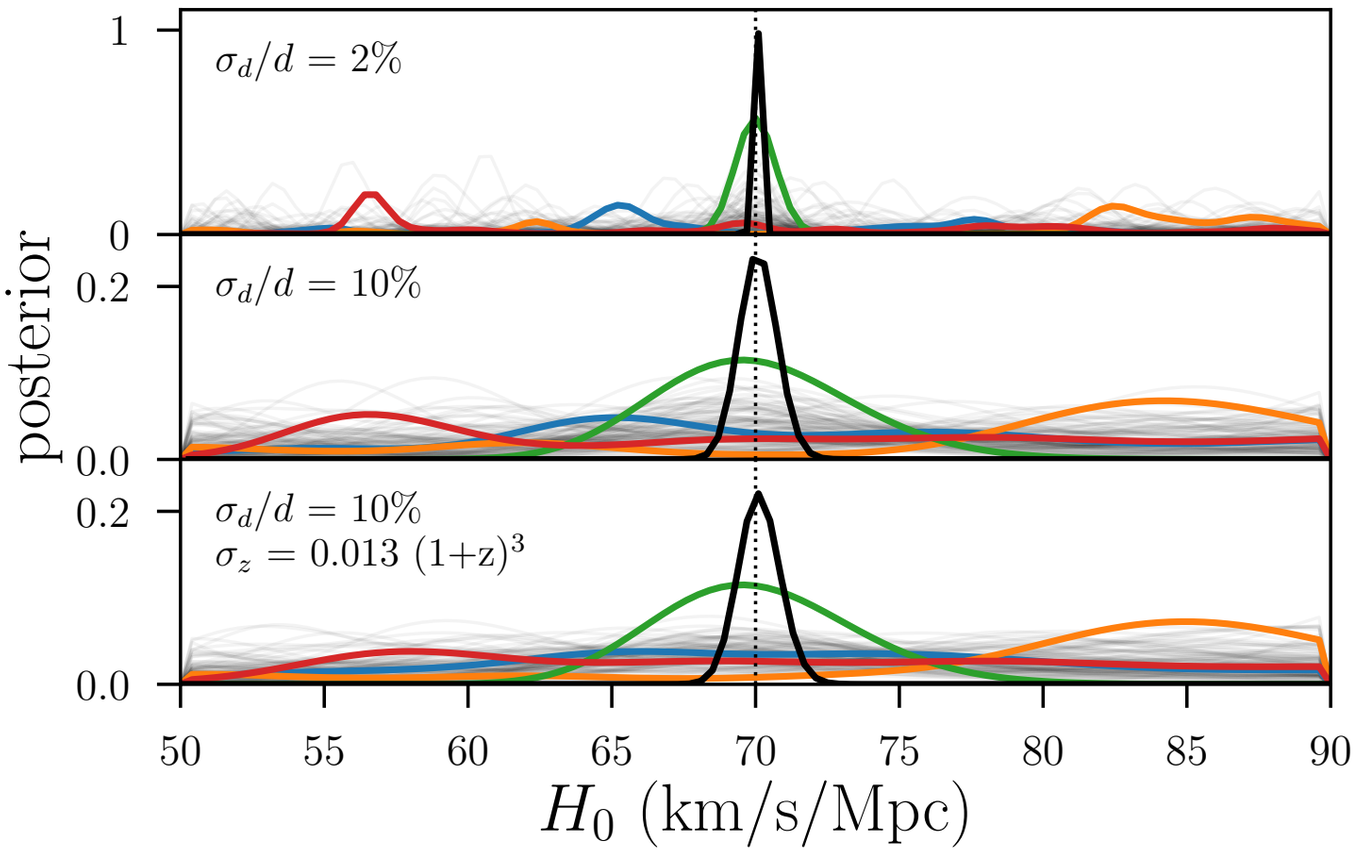
- Factor >10 more BBH events
- Will miss some EM counterparts to BNS and NSBH

Soares-Santos+DES 2017

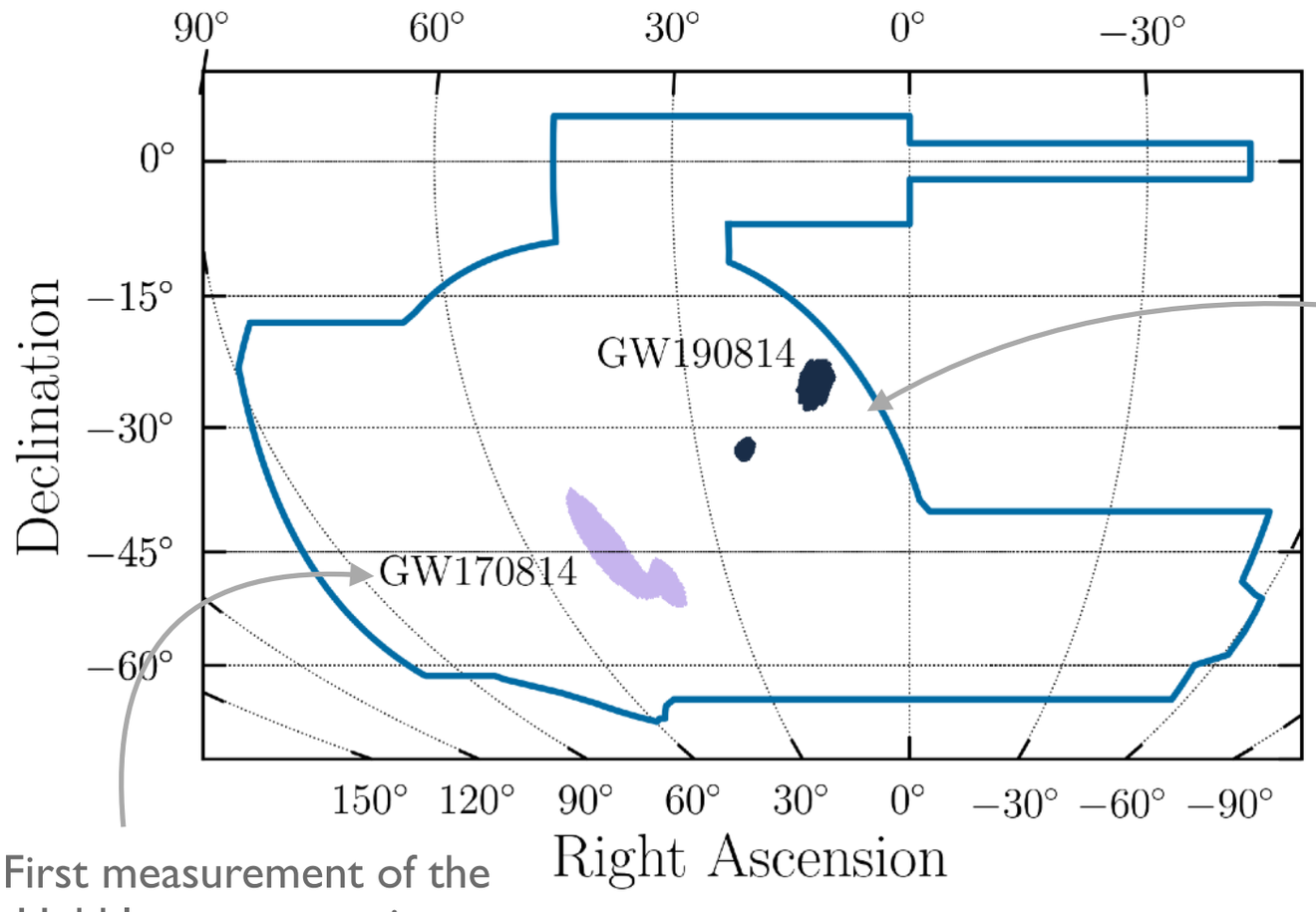


Dark standard sirens - simulations

- BCC galaxy simulations (DeRose et al. 2019, Wechsler et al. 2021)
- Simulated GW events in uniform comoving volume on a galaxy at *z* with H_0=70 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



LIGO/Virgo O3 Dark sirens with DES

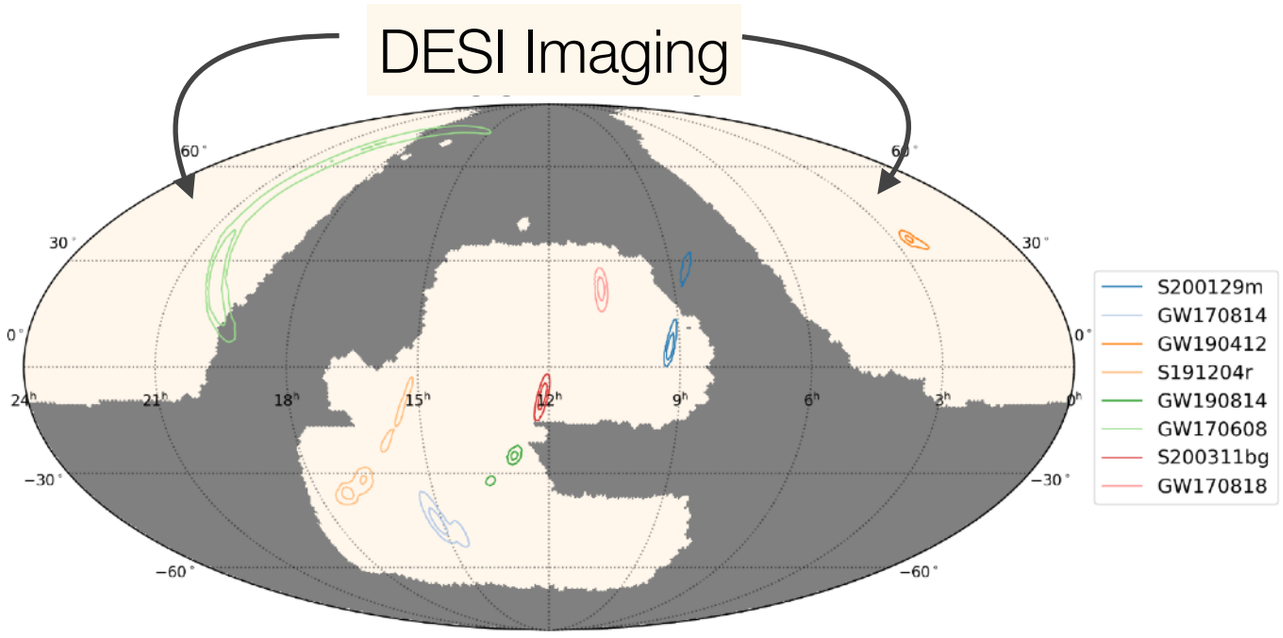


First measurement of the Hubble constant using a BBH
DES & LVC 2019,ApJL
(AP corresp.)
arxiv:1901.01540

- LIGO/Virgo O3: run in 2019-2020
- 50+ alerts, no convincing counterparts
  - GW190814 (Morgan+20, arxiv:2006.07385, Tucker+21)
  - S190510g (Garcia+20, arxiv:2007.00050)
- Focus on 2 best localized events
- **GW190814** (LVC 2020 arxiv:2006.12611) particularly interesting:
  - Lightest BH or heaviest NS ever discovered in a binary
  - Best localized dark siren
  - Improved d/localization from higher order modes
    - 18 sq deg
    - 241 ± 26 Mpc

AP+DES, 2020, ApJL arxiv:2006.14961

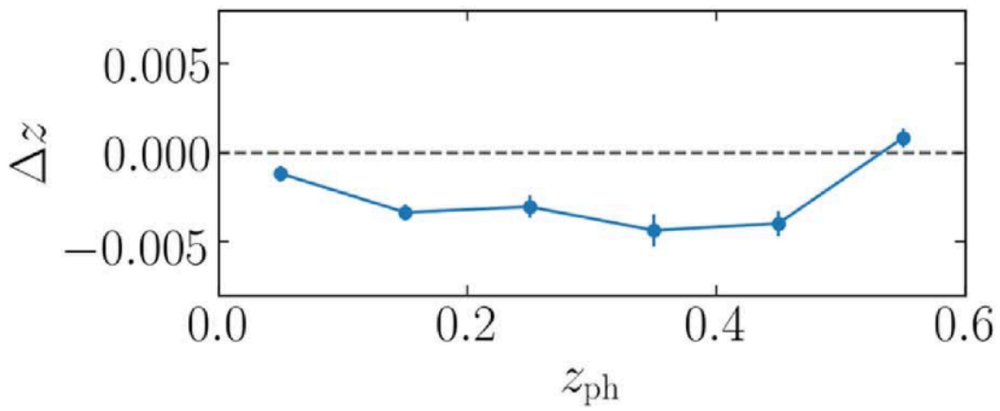
LIGO/Virgo O3 Dark sirens with DESI imaging

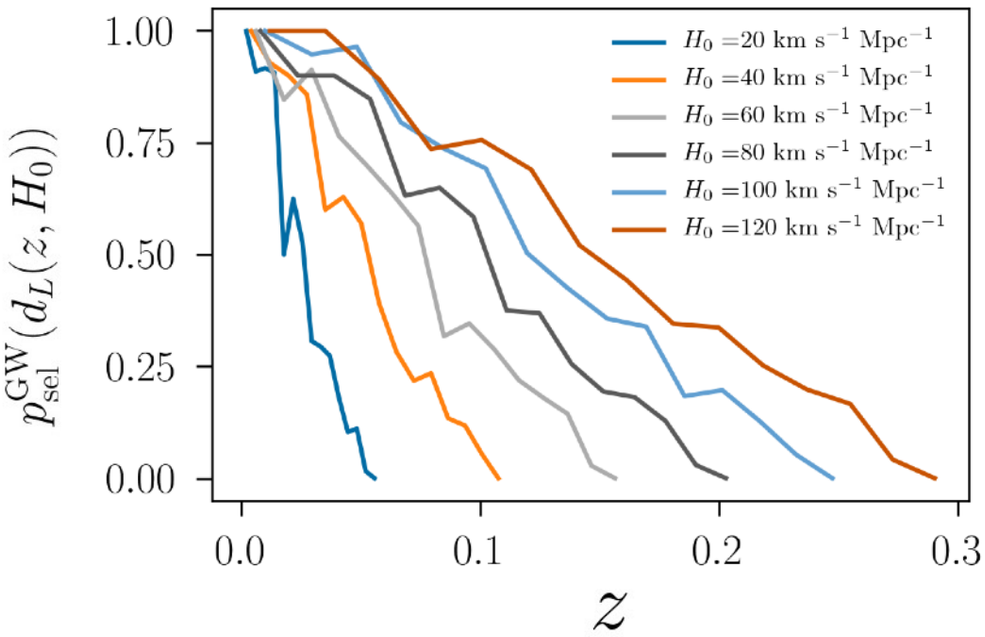


- Dark Energy Spectroscopic Instrument (DESI) imaging
- Well-localized events + high completeness galaxy catalog (DES+DESI imaging redshifts)
- Blinded analyses

AP+2021a arxiv:2111.06445

Dark siren systematics

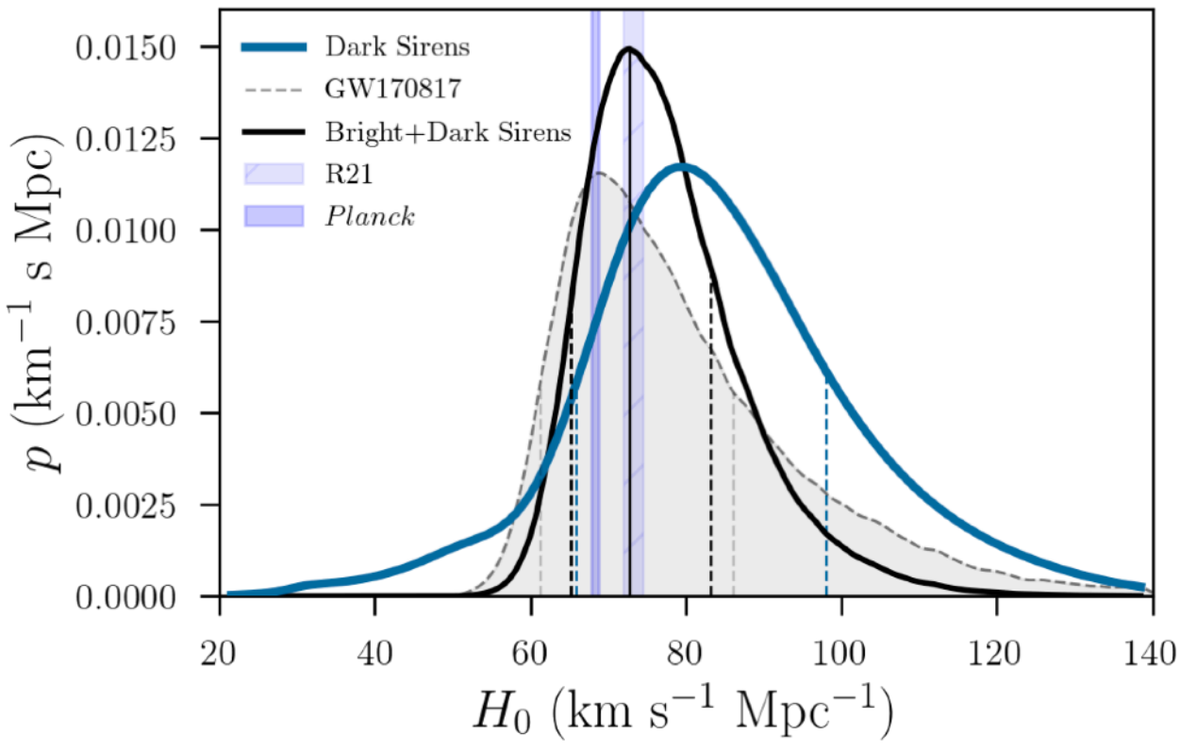




AP+2021a arxiv:2111.06445

- Systematics related to photometric redshifts: bias correction, full redshift PDF
- GW Selection effects
- Assumptions on BH mass functions (in particular LIGO, Virgo, KAGRA 2021 arxiv:2111.03604)
- Next: expectations from different BBH formation scenarios, marginalization over BH mass functions

Standard sirens w/ LIGO/Virgo O3 events



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

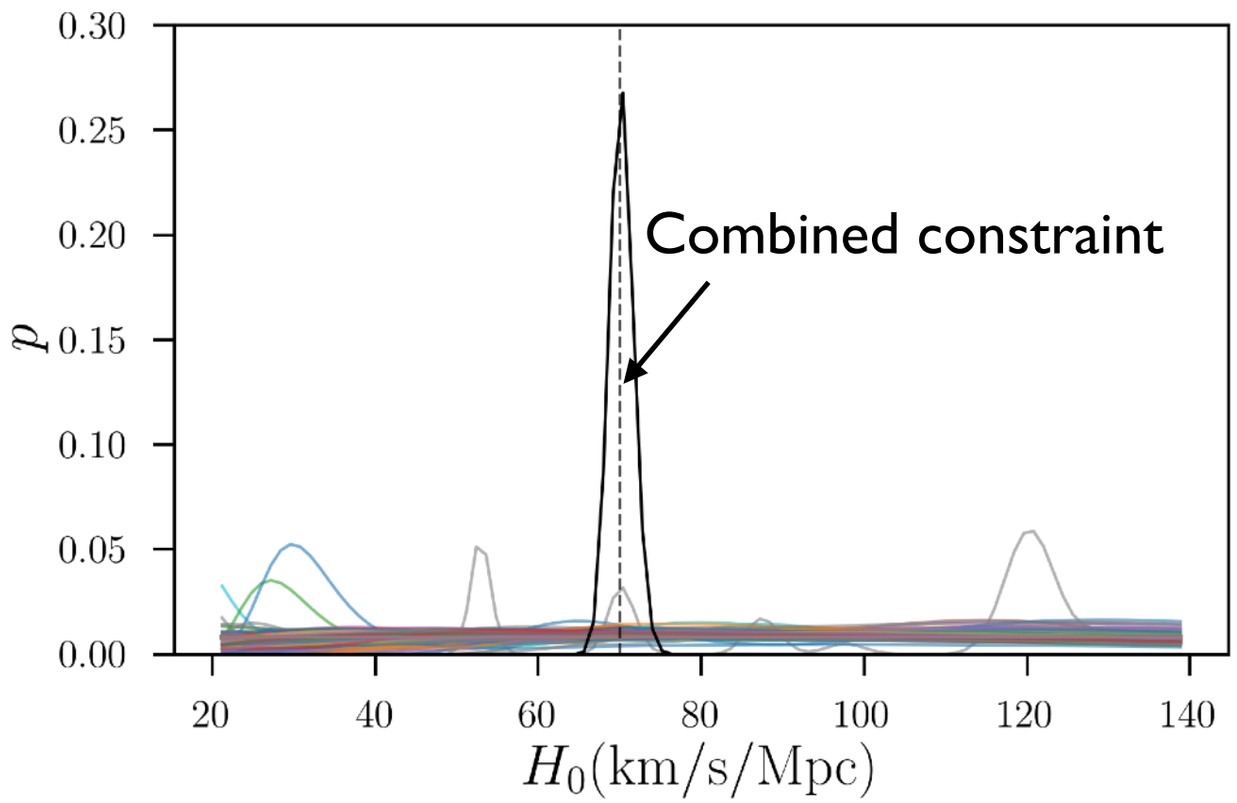
$$H_0 = 72.77^{+11.0}_{-7.55}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

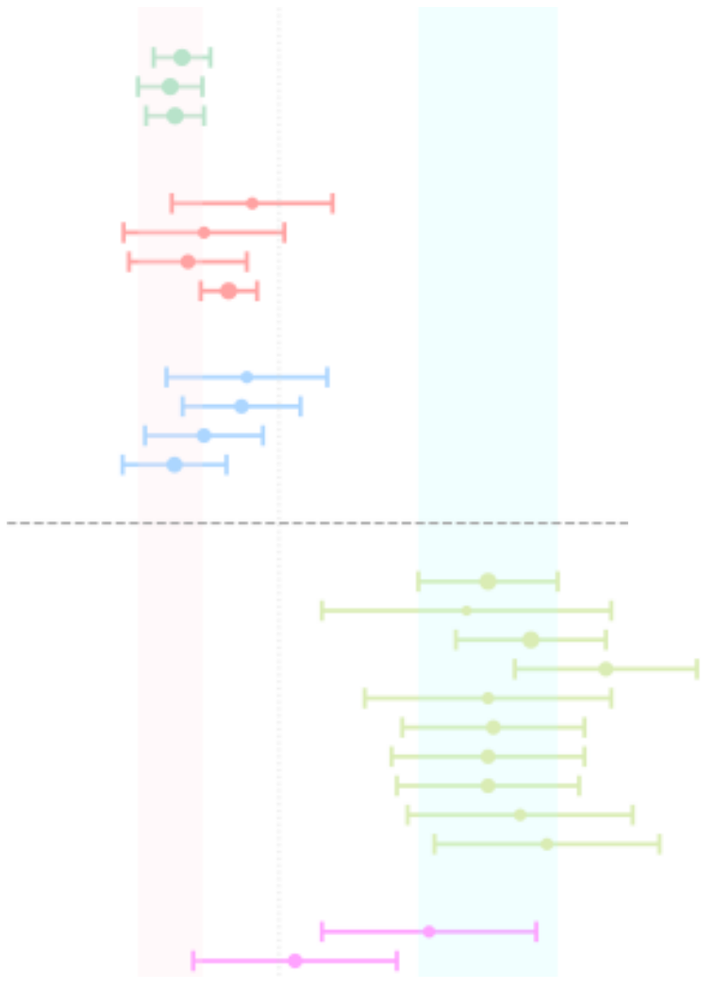
- Dark sirens provide **~30% improvement** to GW170817 precision
- Other work: LIGO, Virgo, KAGRA 2021 arxiv:2111.03604, in particular **GW-only** complementary method (Farr+2019)
- **Consistent with both early and late-time Universe *H₀*** measurements

AP+2021a arxiv:2111.06445

Prospects for dark sirens

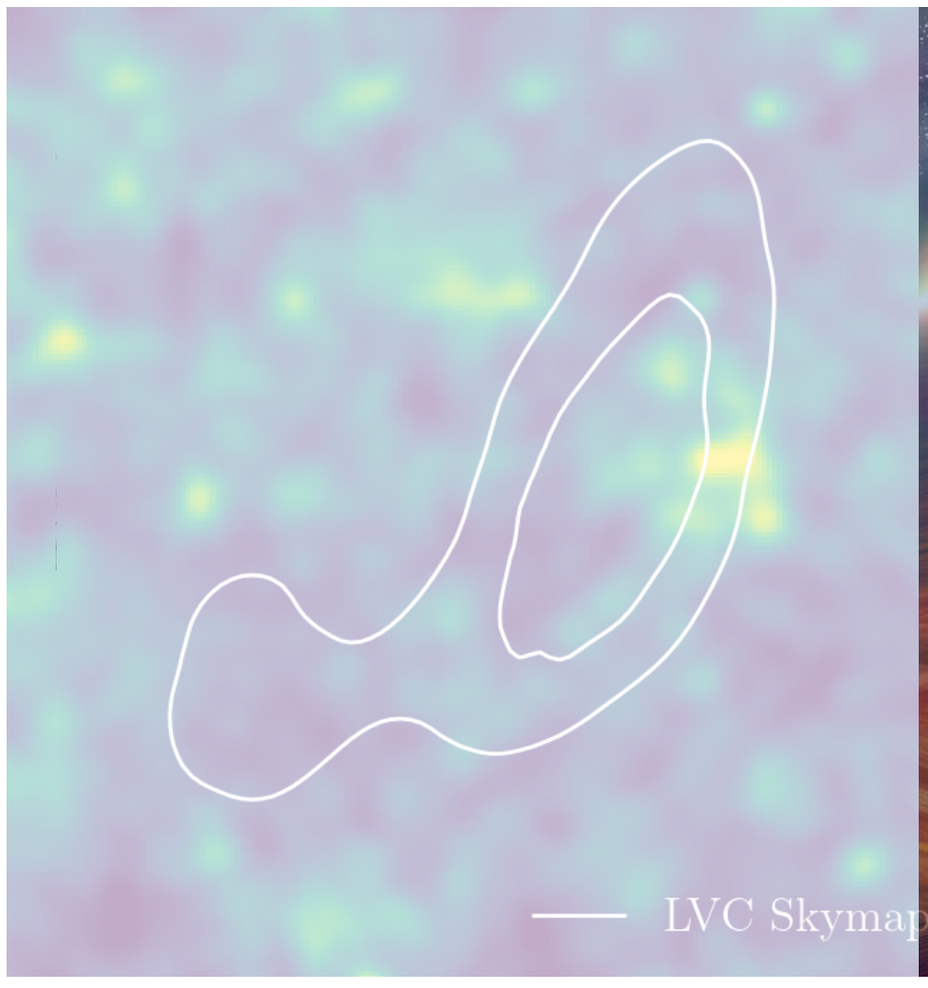
- **DES** galaxies + BBH mergers from LIGO/Virgo/KAGRA at design sensitivity
  - ~200 nearby detections
  - Down to **2% statistical precision** w/ "golden" events
  - Similar for Rubin **LSST** (>2024)
- **DESI**: 2% H_0 measurement w/ 5 year LIGO/Virgo/KAGRA (Diaz & Mukherjee 2021)
- Probe **origin of BBH** with cross-correlation of GW and galaxies





GW Standard sirens

- DES, DESI
- Current measurements
- Prospects



Peculiar velocities with GWs

- Prospects

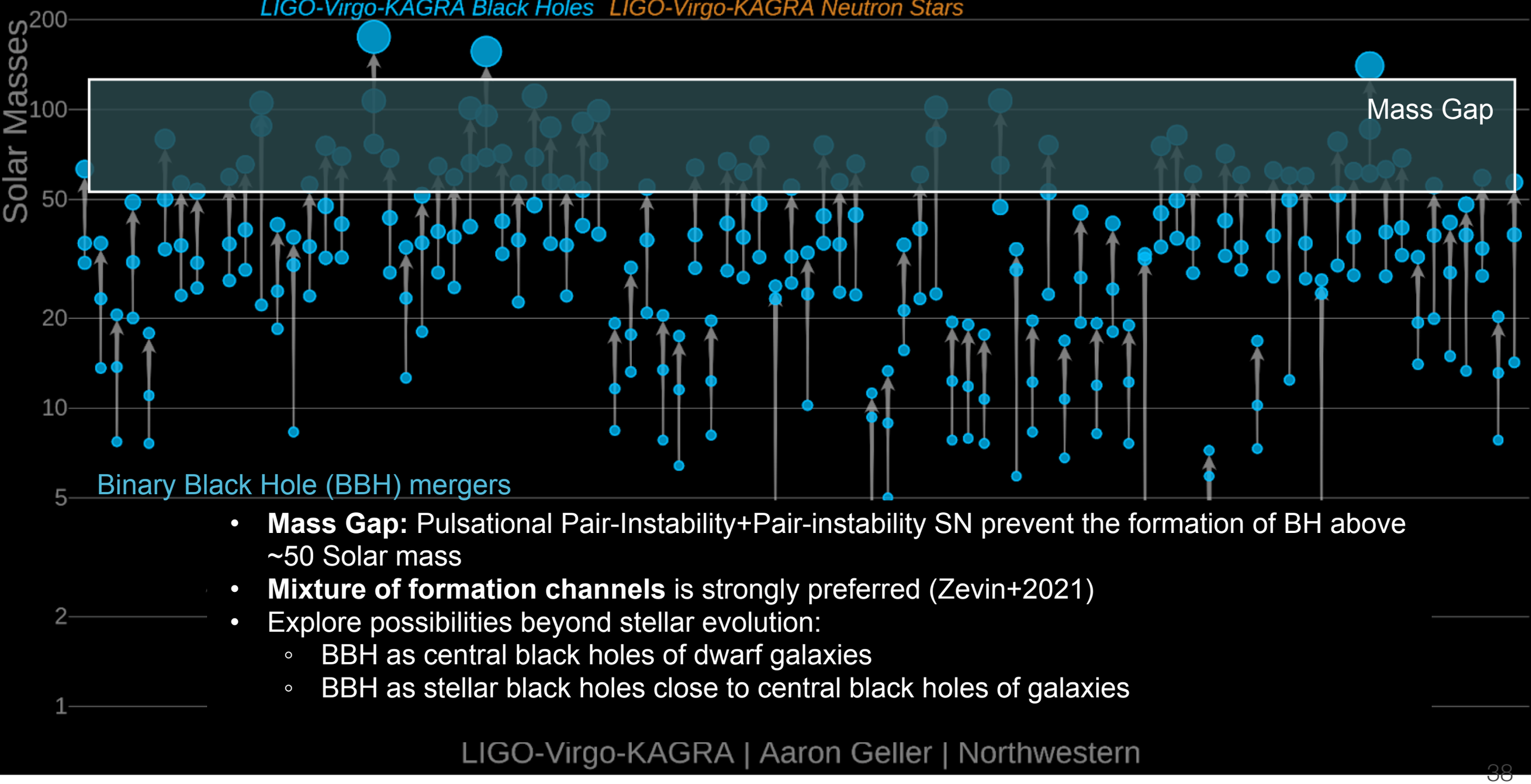
Origin of GW binary black holes

GW sources


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

GW sources

Masses in the Stellar Graveyard



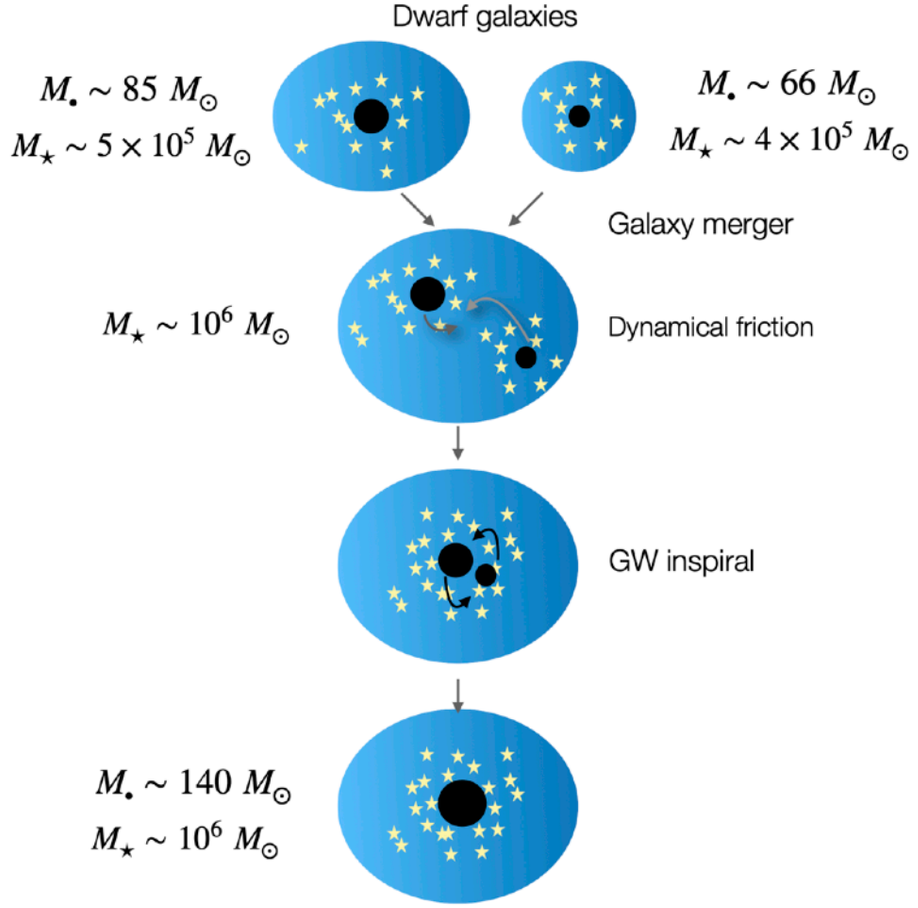
- **Mass Gap:** Pulsational Pair-Instability+Pair-instability SN prevent the formation of BH above ~50 Solar mass
- **Mixture of formation channels** is strongly preferred (Zevin+2021)
- Explore possibilities beyond stellar evolution:
  - BBH as central black holes of dwarf galaxies
  - BBH as stellar black holes close to central black holes of galaxies

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

BBHs from ultra-dwarf galaxies

Conselice, Bhatawdekar, AP & Hartley
2020, ApJ, arxiv:1907.05361

- **The massive stellar black holes detected by LIGO/Virgo could be the central black holes of ultra-dwarf galaxies (10^5-10^6 M_{sun})**
- New observational window into the formation of Supermassive BH

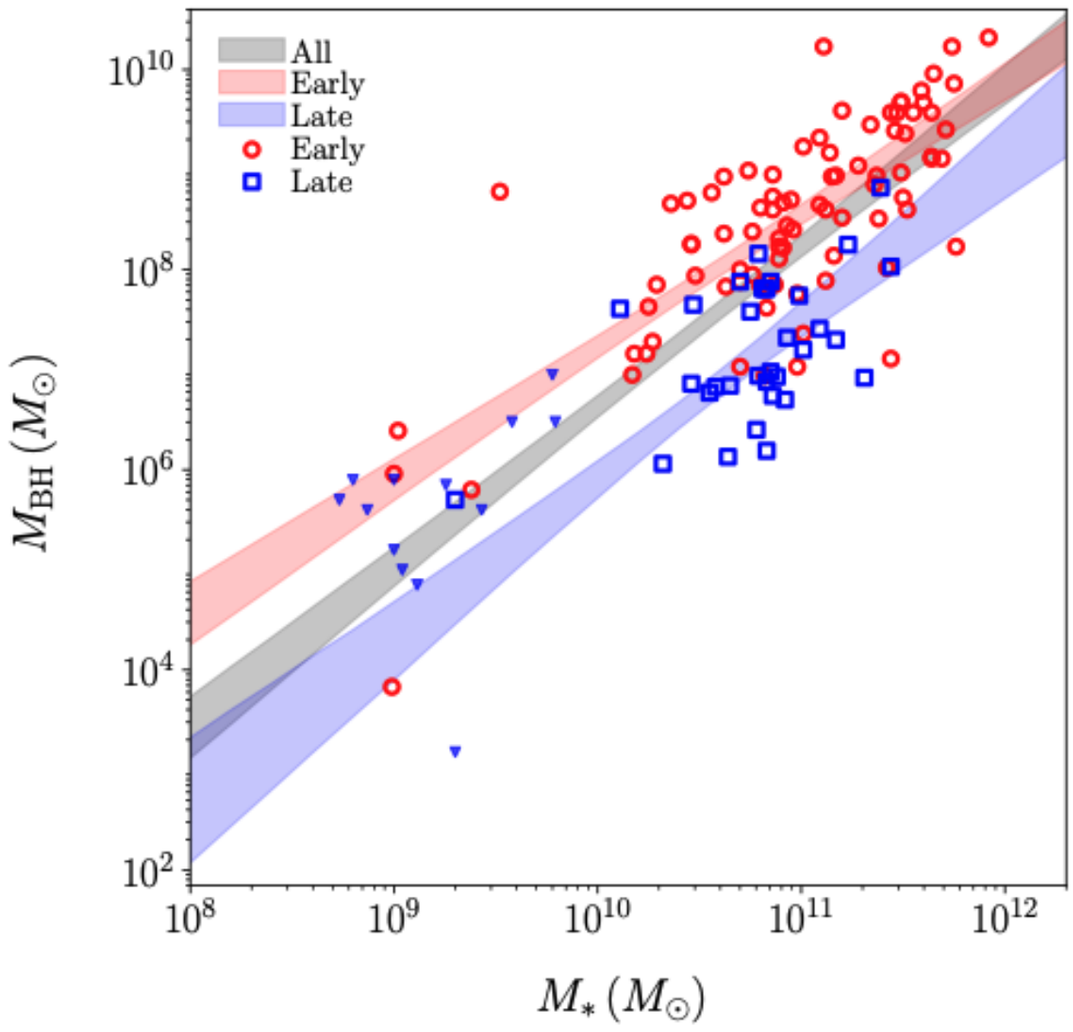


AP & Conselice, 2021, PRL, arXiv:2009.10688

How low can you go?

Known relation between mass of central black hole and galaxy stellar mass

Greene+2020, ARA&A



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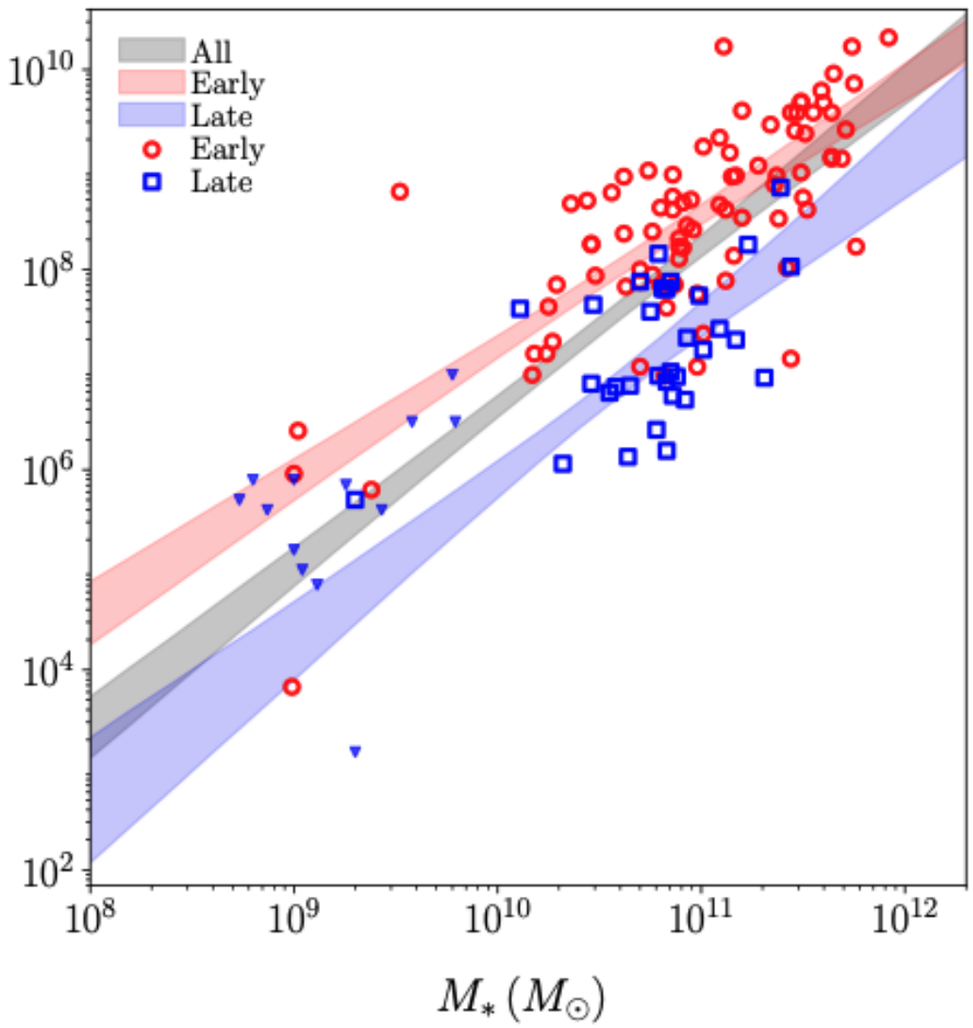
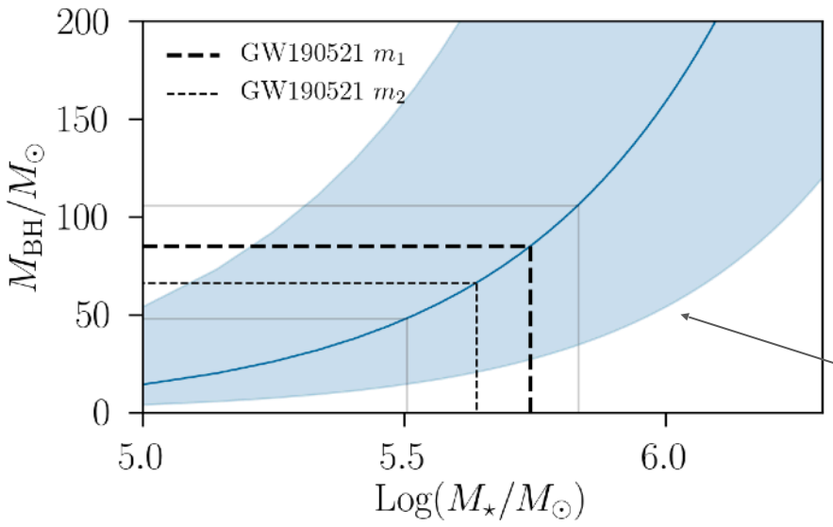
Known relation between mass of central black hole and galaxy stellar mass

Extend to lower mass:

Greene+2020, ARA&A





E.g. GW190521 (Abbott+2020 arxiv:2009.01075, 2009.01190) components mass in the mass gap

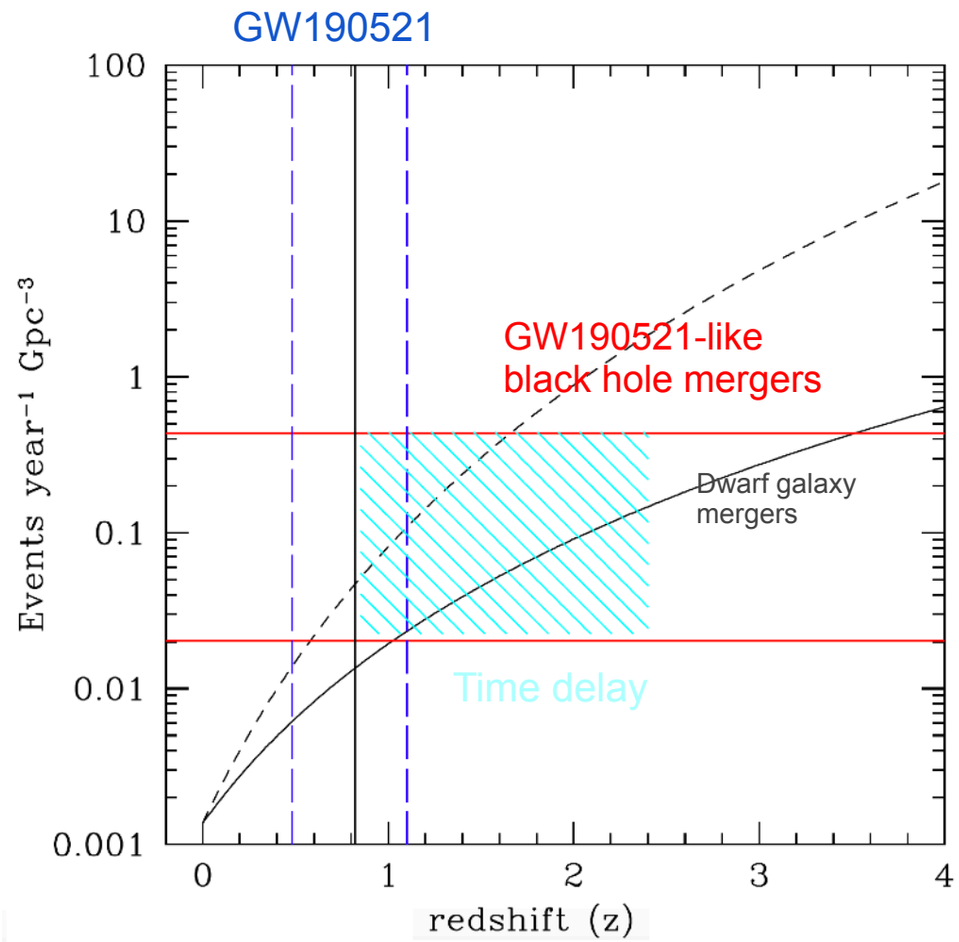
BBHs from ultra-dwarf galaxies

AP & Conselice, 2021, PRL, arXiv:2009.10688

Is the merger rate of dwarf galaxies ever high enough to explain the observed merger rate of black holes?

Yes, with **time delay** (time between galaxy to BH merger) ~4-5 Gyr

Dynamical friction could explain time scale



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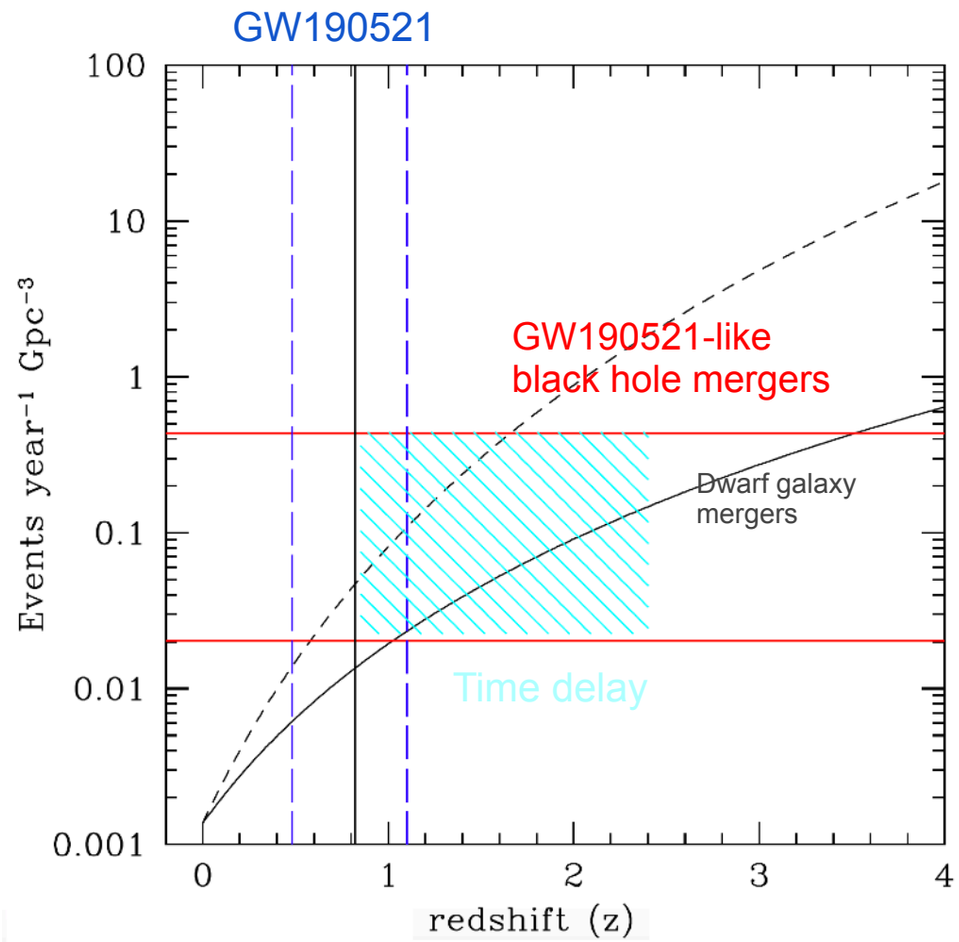
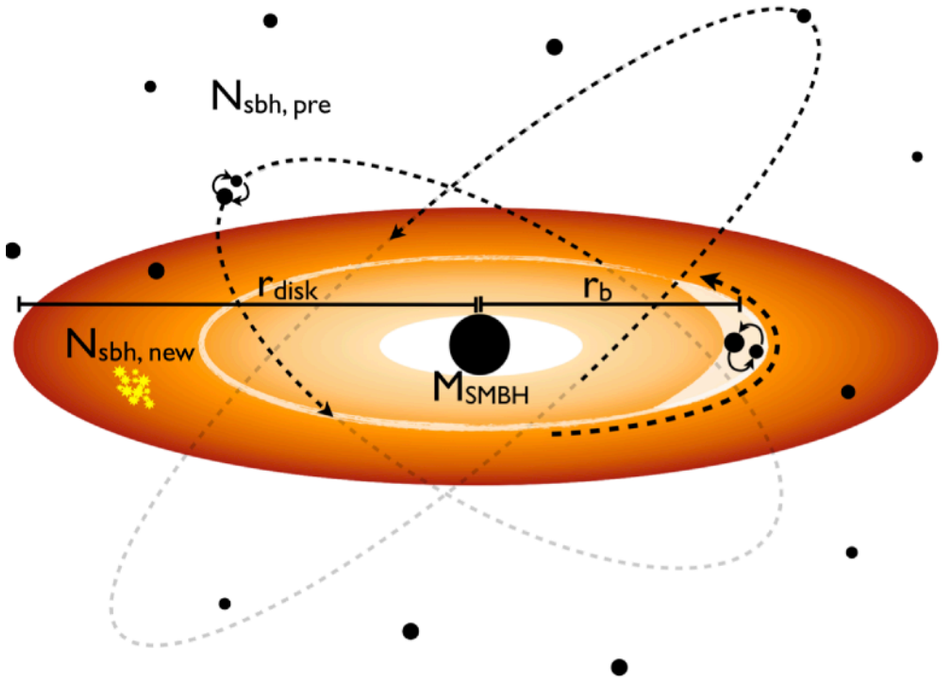


This formation scenario is plausible, more BBH detections, potentially very well localized and/or with EM counterparts, simulations, could confirm or rule out this scenario in the future.

Do LIGO/Virgo BBH produce Active Galactic Nuclei (AGN) flares?

- Ideal environment for formation of massive stellar black holes through repeated mergers of smaller BH in AGN disks
- Could give rise to EM counterpart (McKernan+12, Bartos+17)



Ford+2019 arxiv:1903.09529

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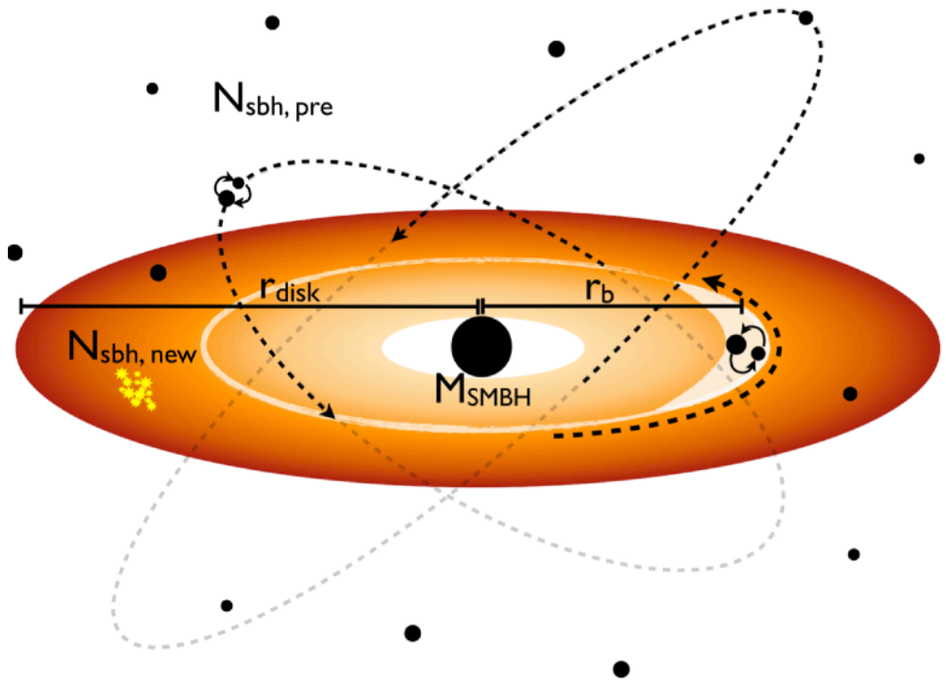
- AGN flare in coincidence with **GW190521** (ZTF, Graham+2020 arXiv:2006.14122)



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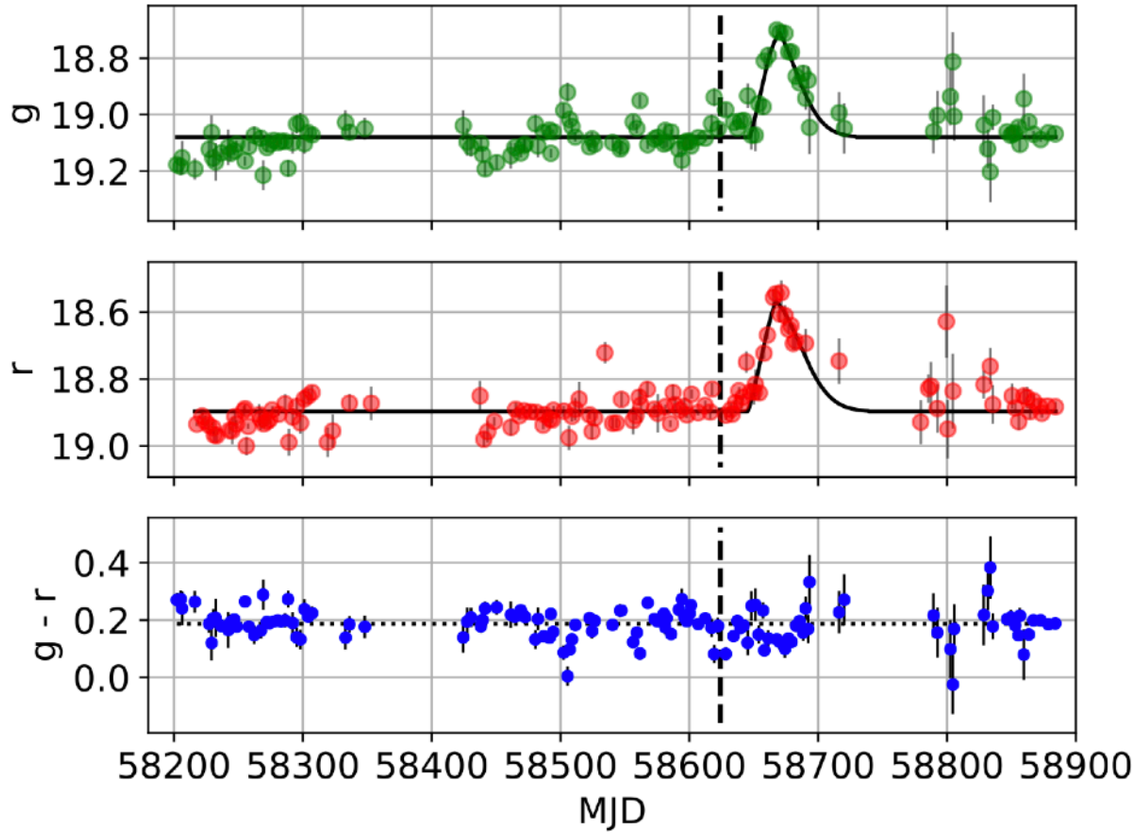


Graham+2020

Do LIGO/Virgo BBH produce AGN flares?

- **Case of GW190521**: 7400 Type I AGNs in 90% Volume result in **70% probability of chance coincidence** (large localization volume)
- Bayesian Formalism to establish confident association

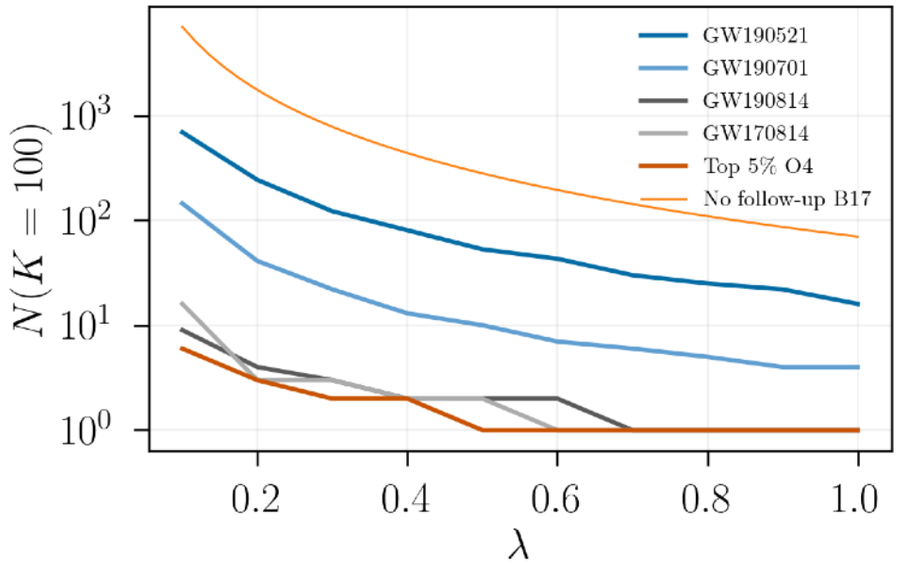
Fraction of BBH in AGN

$$\mathcal{L}_i \propto \prod_{j=1}^{k} \left[\lambda p(x_i^{\mathrm{GW}} \mid \Omega_{ij}^{\mathrm{AGN}}, z_{ij}^{\mathrm{AGN}}) p_0(\Omega_{ij}^{\mathrm{AGN}}, z_{ij}^{\mathrm{AGN}}) + R_B\left(\Omega_{ij}^{\mathrm{AGN}}, z_{ij}^{\mathrm{AGN}}\right)\right] e^{-\mu_i}$$

"Signal" AGN — "Background" AGNs

- Catalog of AGNs+follow-up+GWs: **confident association possible end of ~2023 if λ>0.1**

AP+2021b, ApJL arXiv:2103.16069

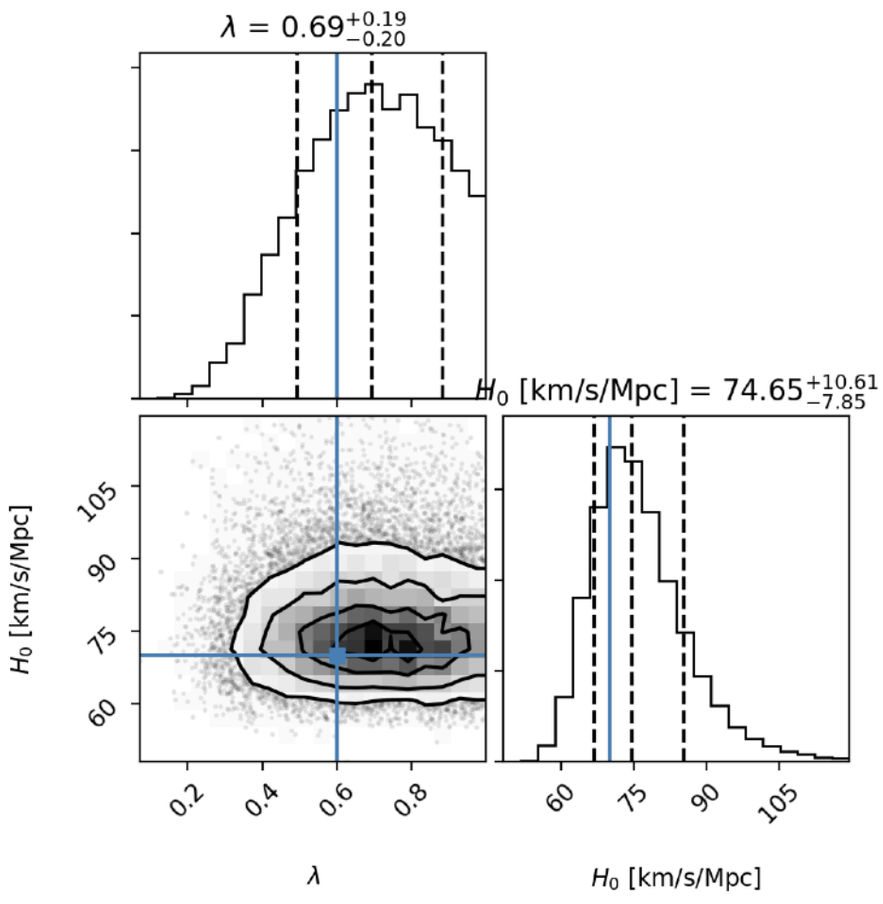


Fraction of BBH inducing AGN flare

Cosmology with AGN flares

AP+2021b,
ApJ arXiv:2103.16069

- Promising hybrid bright/dark standard siren
- Use same formalism to establish confident association **and** constrain cosmology
- LIGO/Virgo/KAGRA O4 Simulation, 10 "top 5%" BBH
- Planning for follow-up with DECam in 2023, Rubin LSST from following observing run



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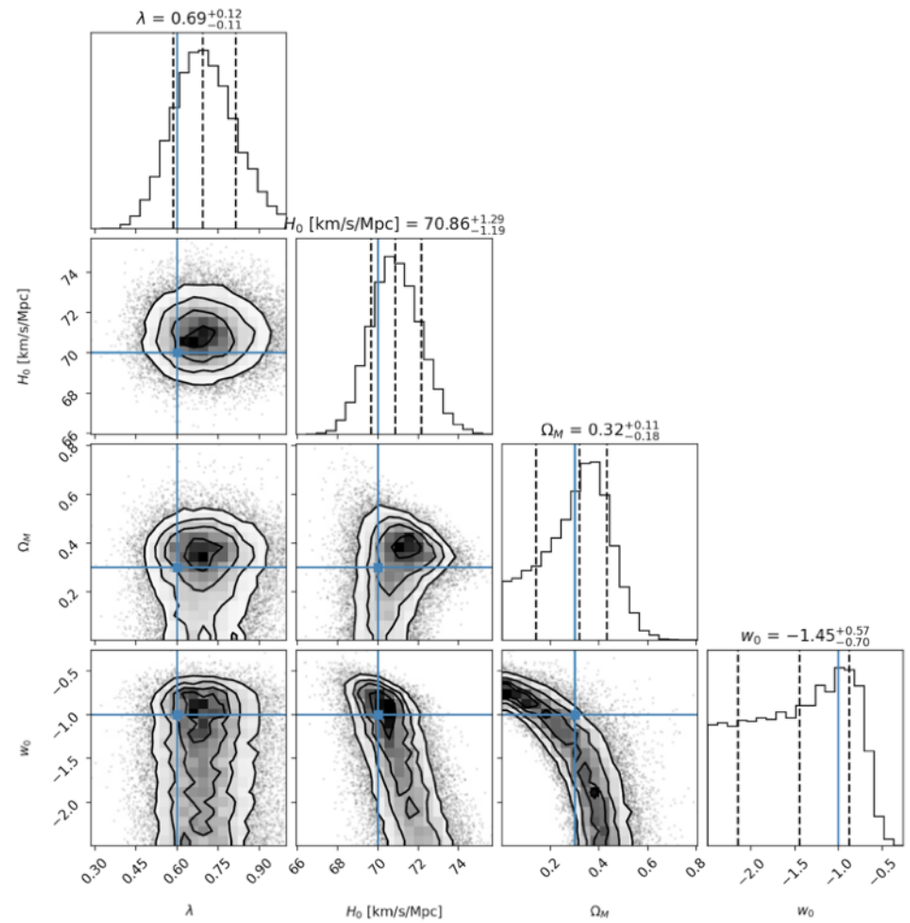

With C. Bom, in prep.

Conclusions

- **Synergies between GW experiments and both photometric/ spectroscopic sky surveys**
  - Counterparts discovery (ongoing preparation w/ DECam and DESI for O4 - March 2023)
  - Standard sirens - H_0 (+dark energy)
  - Peculiar velocities - $f\sigma_8, \gamma$
  - Origin of binaries - host galaxies, AGNs
- Even **without counterparts**
  - O3 dark sirens have an interesting impact on a combined standard siren H_0 constraint
  - LVK Design sensitivity + DES-like catalog: ~2-5% (stat.) with ~200 events
  - Cross-correlations of BBH+DESI galaxies/AGN/dwarf galaxy catalogs to probe nature of massive stellar BH

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

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

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