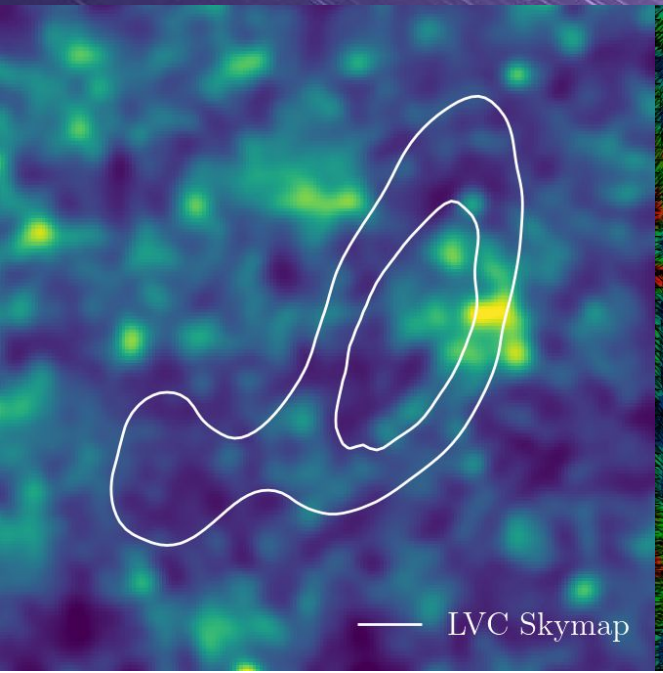
Standard Sirens

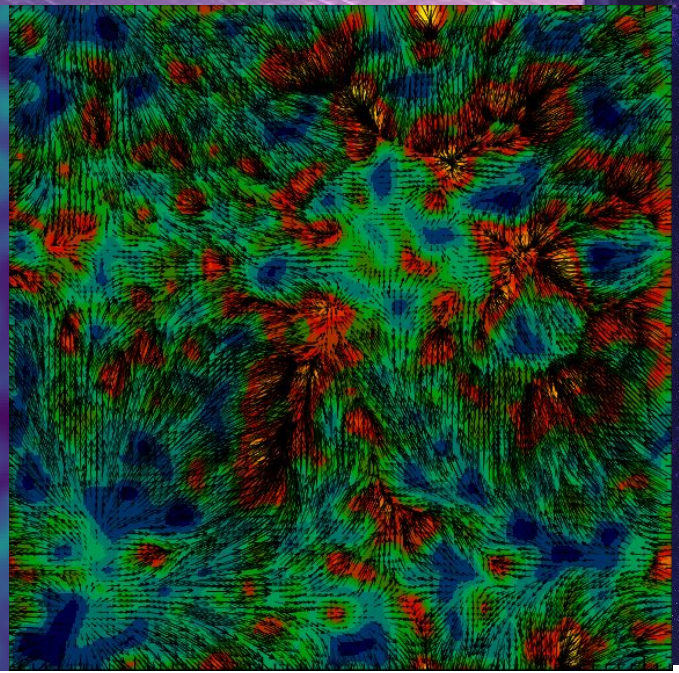
Antonella Palmese
NASA Einstein Fellow

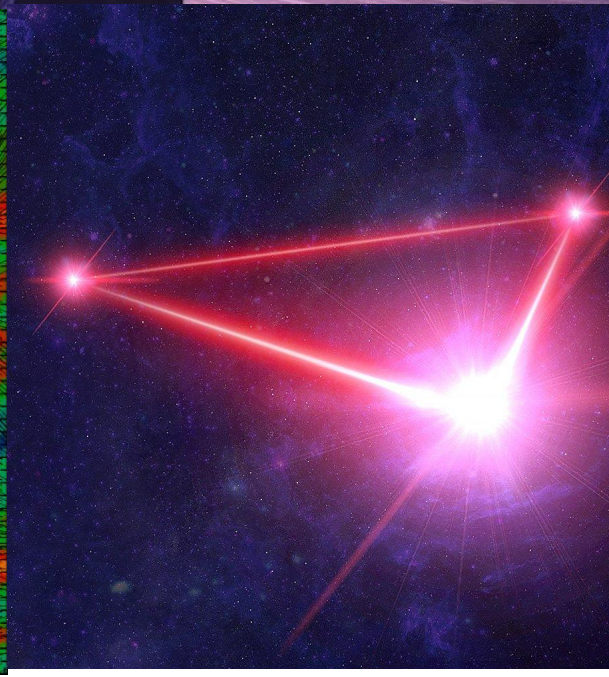
19 Nov 2021

Cosmology Intertwined Snowmass Workshop

Introduction







Gravitational Wave (GW) Standard sirens

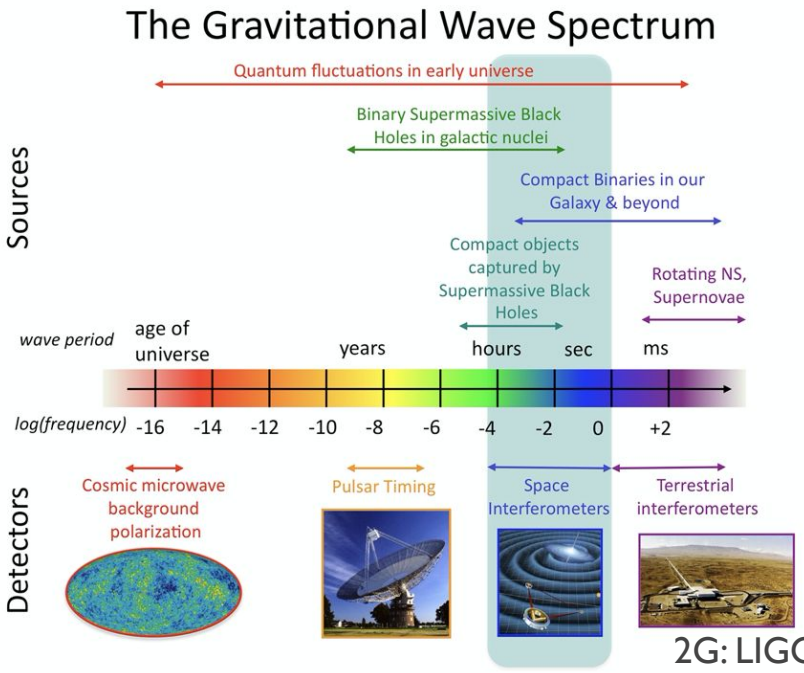
- Current measurements w/ LVK

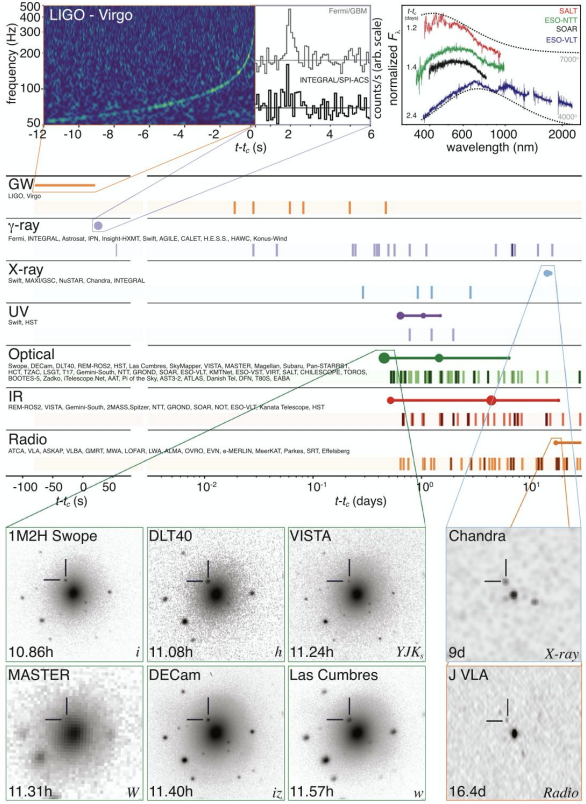
GW Standard sirens

- Future prospects w/ LVK and 3G

LISA standard sirens

Multi-messenger Multi-Band





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

LISA (2030s)

Abbott et al 2017

Standard Sirens

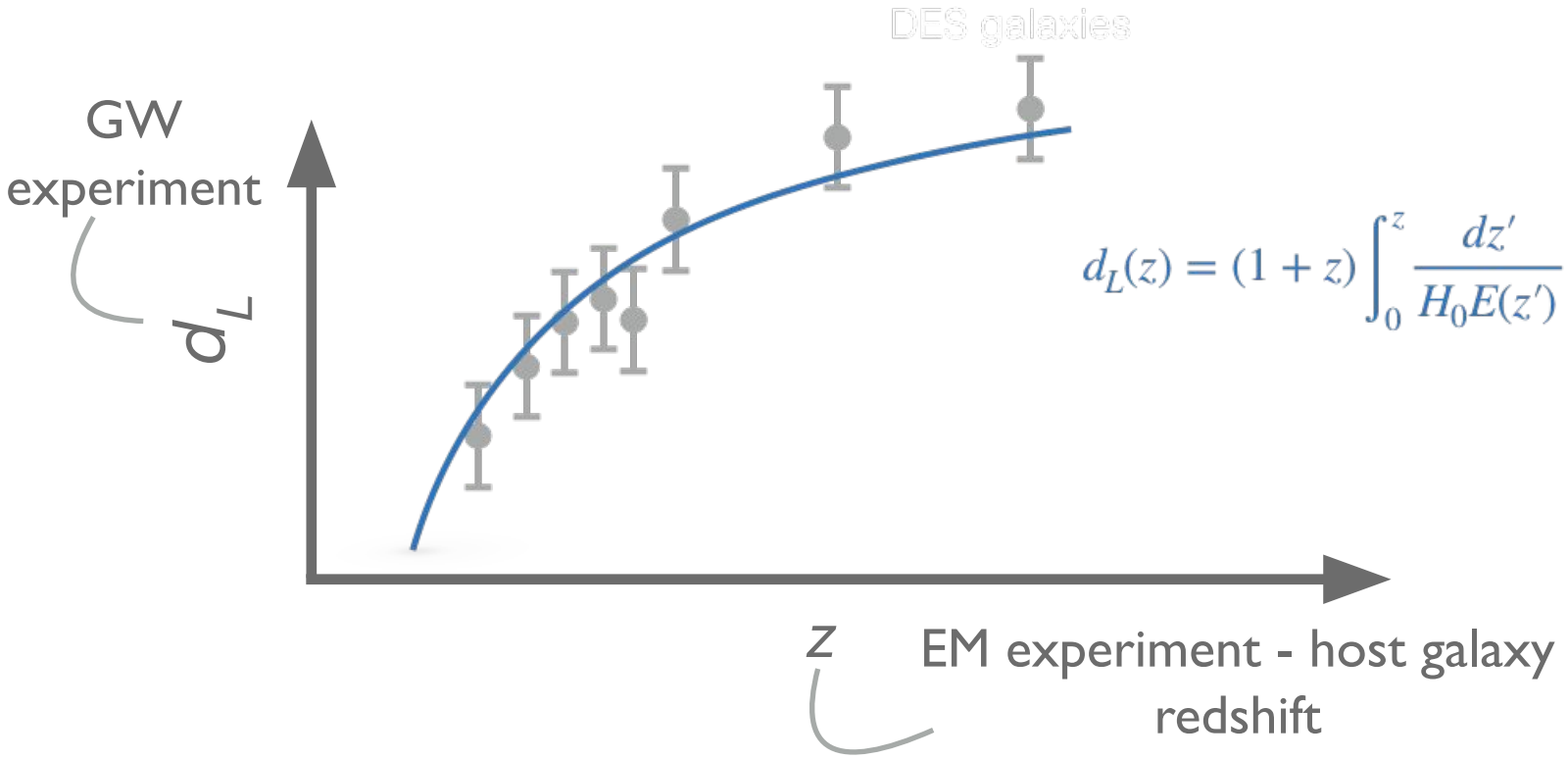
Schutz 1986

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

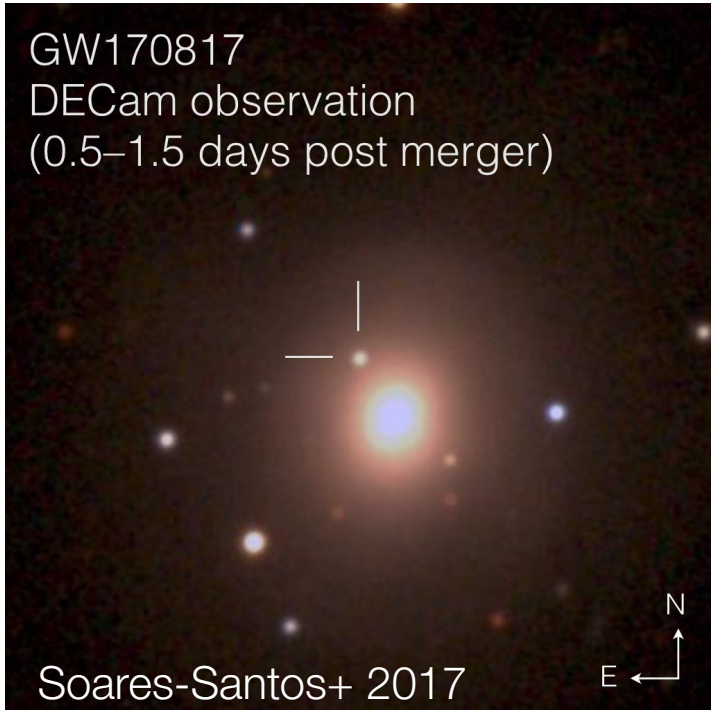
Holz & Hughes 2005

MacLeod & Hogan 2008

Nissanke+2010

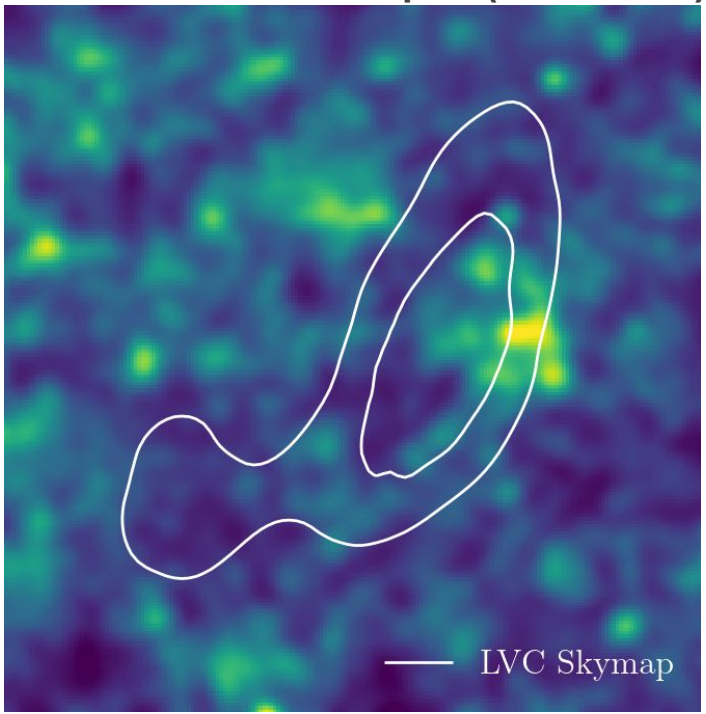
Del Pozzo 2012...

With EM counterpart (BNS/NSBH)



Bright standard sirens

Without EM counterpart (BBH/NSBH)



Dark standard sirens

Standard Sirens

Schutz 1986

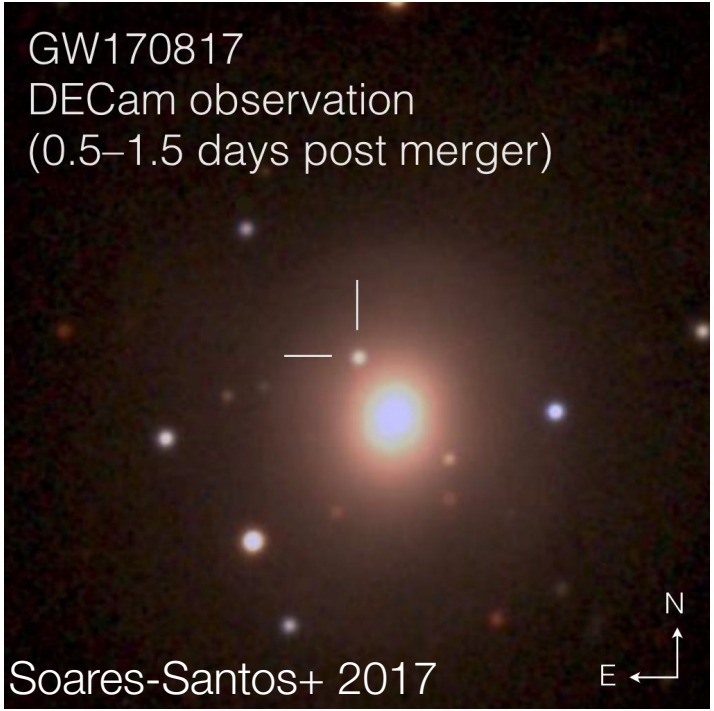
Holz & Hughes 2005

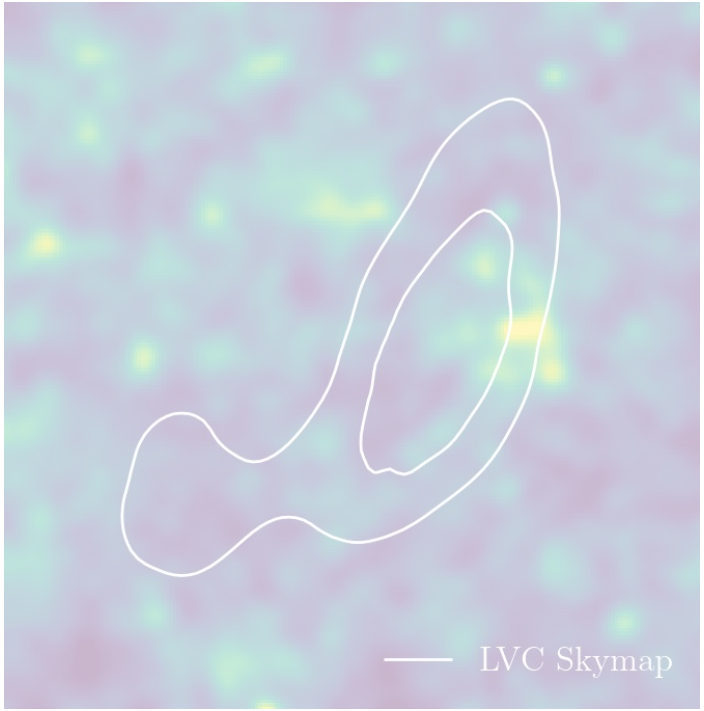
MacLeod & Hogan 2008

Nissanke+2010

Del Pozzo 2012...

GW170817 - First GW from a BNS merger and first (and last!) GW EM counterpart

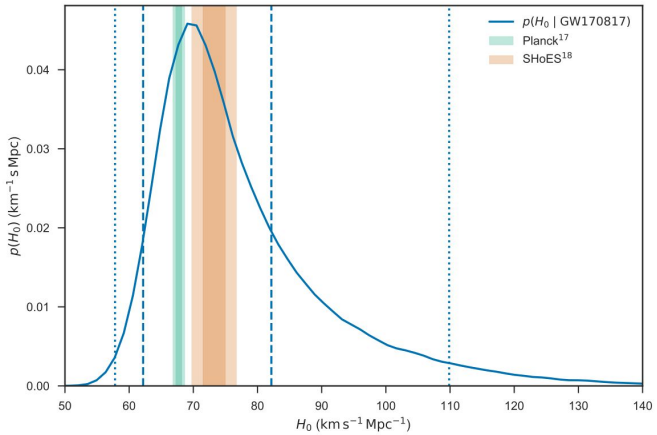


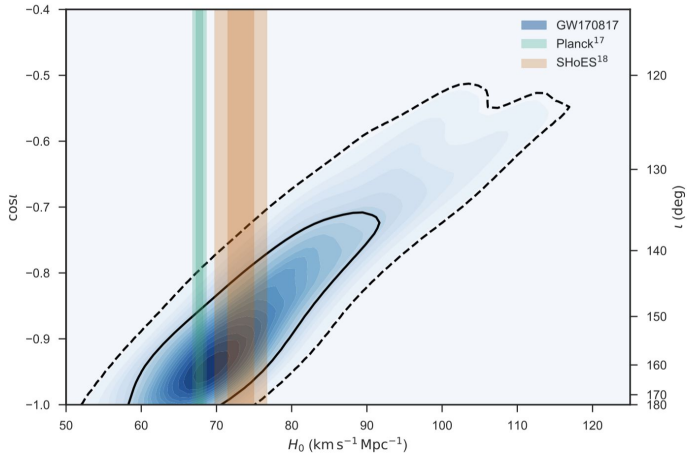


Bright standard sirens

GW170817 as a standard siren

LVC, EM partners+ 2017





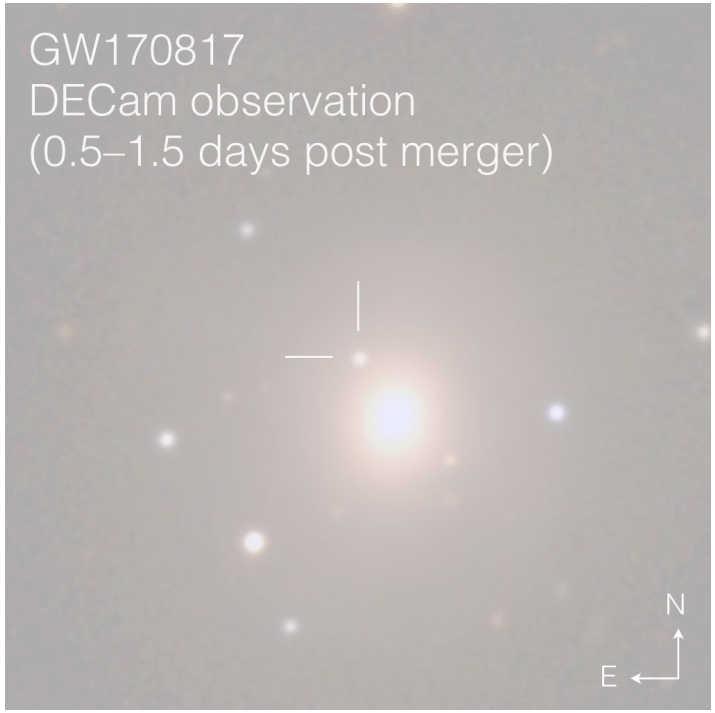
- NGC 4993 (z~0.01)

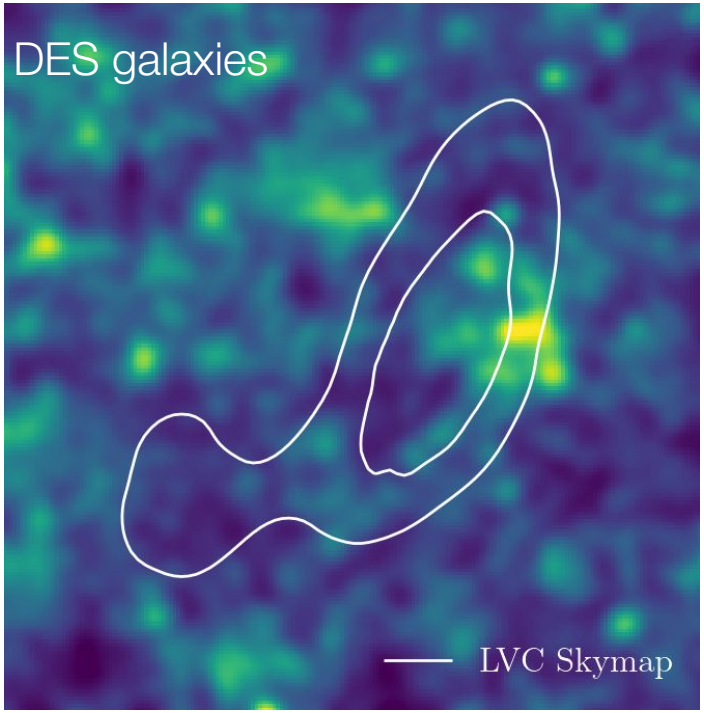
$$H_0 = 70^{+12}_{-8}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

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

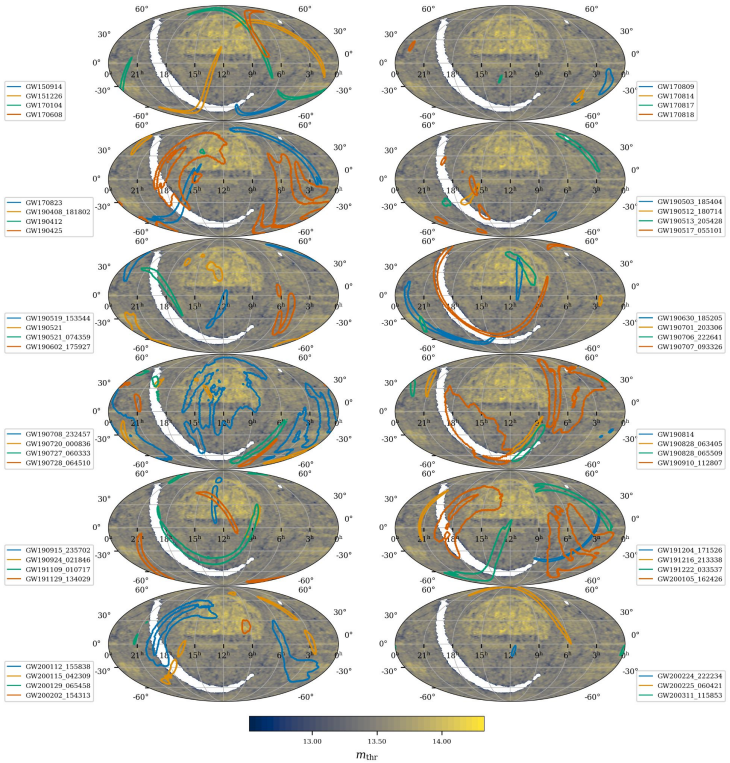
- Limitations:
  - Peculiar velocity (Nicolau+19, Howlett+19)
  - Inclination angle is correlated with *D*
- **Can break degeneracy by constraining ι from EM**
- Improve precision by factor 2-3 (Guidorzi+17,Hotokezaka+18)

Dark Standard Sirens





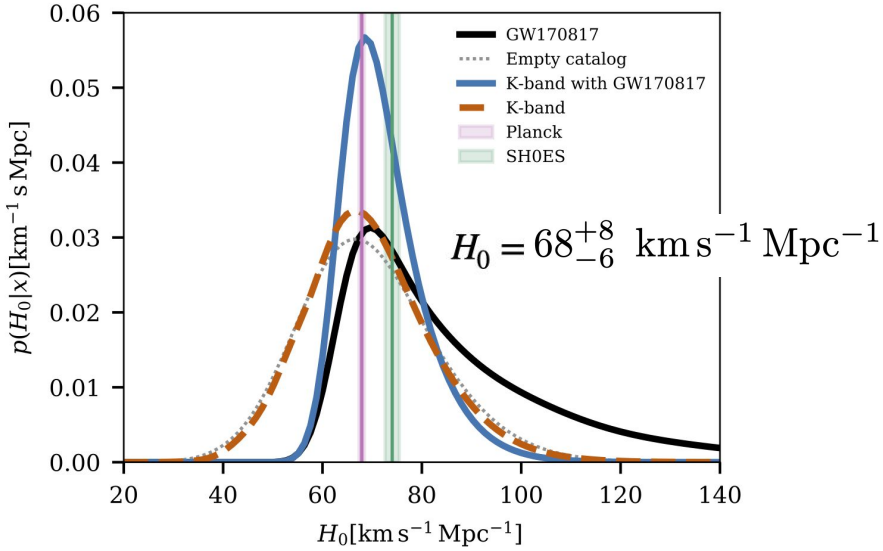
Dark sirens w/ LIGO/Virgo/KAGRA O3 events

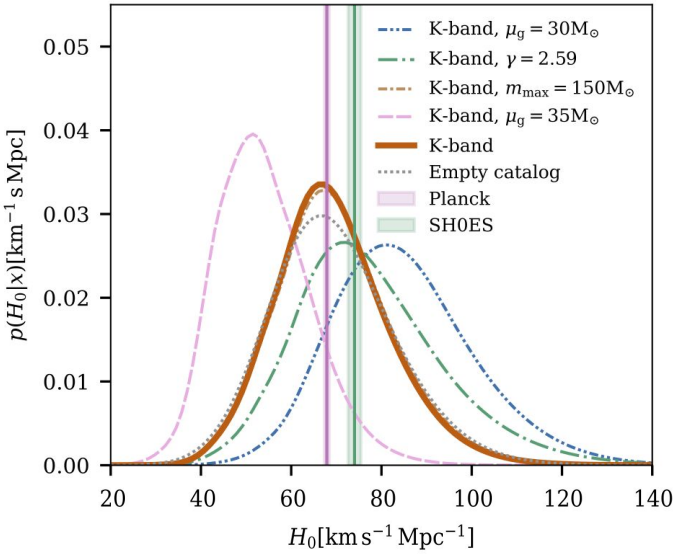


- 50+ alerts, no convincing counterparts
- 47 sources from GWTC-3: 42(+1) Binary Black Holes (BBH), 2 Binary Neutron Stars (BNS), 2 Neutron Star Black Holes (NSBH) (Abbott+2021 arxiv:2111.03606)
- GLADE+ galaxy catalog (Dálya+2018, 2021)

LIGO, Virgo, KAGRA 2021 arxiv:2111.03604

Dark sirens w/ LIGO/Virgo/KAGRA O3 events

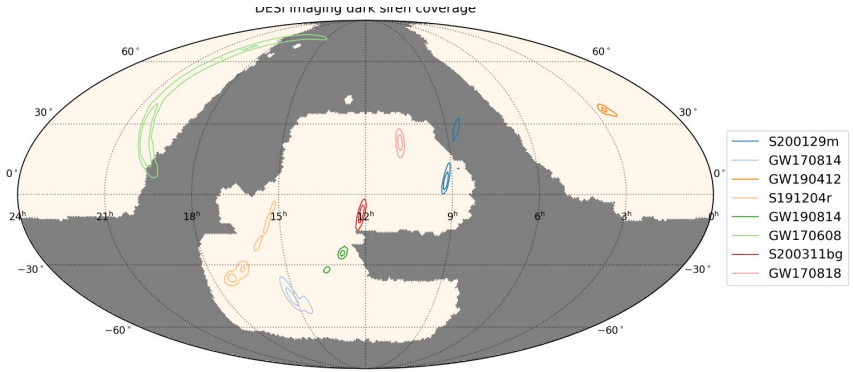


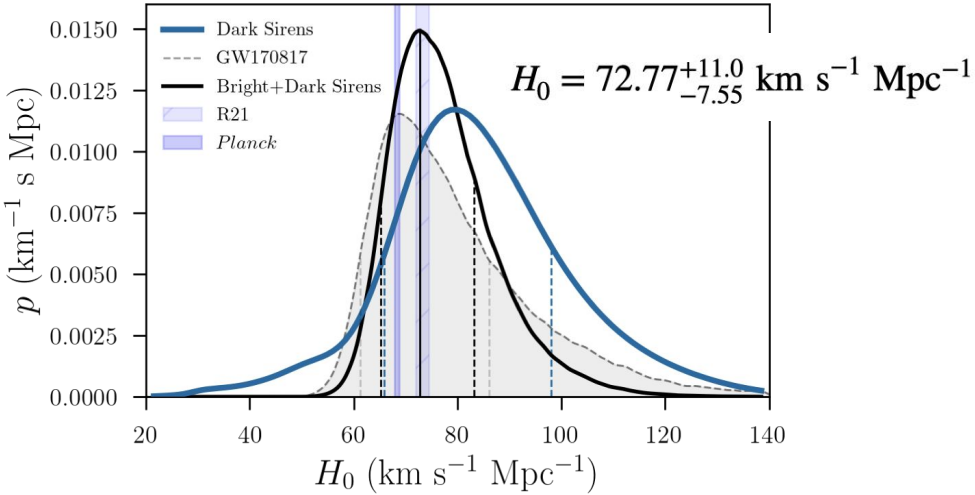


- 40% improvement compared to O2
- Dependence on assumptions about the BBH mass distribution

LIGO, Virgo, KAGRA 2021 arxiv:2111.03604

Dark sirens w/ LIGO/Virgo/KAGRA O3 events



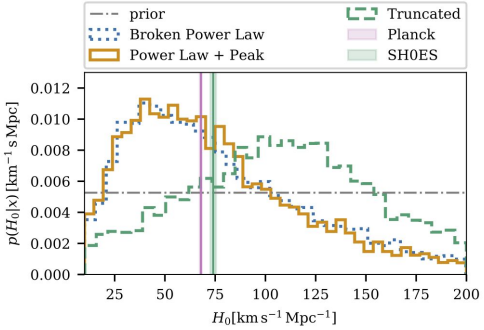


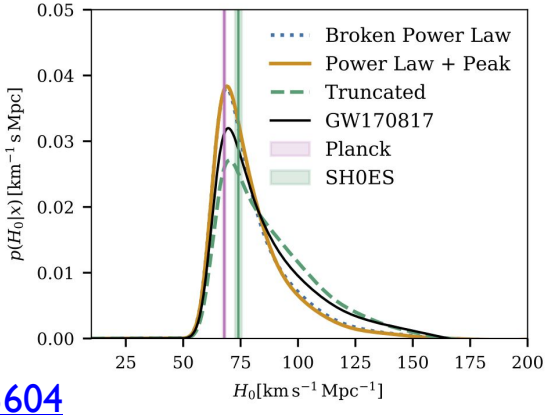
- Only consider well-localized events + high completeness galaxy catalog (DESI imaging)
- Less sensitive to populations assumptions, but smaller statistics
- Close to 30% improvement to bright standard siren precision
- ~2-5% statistical precision from dark sirens with ~200 nearby events from LIGO/Virgo at design sensitivity

Palmese, Bom, Mucesh, Hartley 2021 arxiv:2111.06445

GW-only Standard Sirens

- Break mass-z degeneracy
- Assume Pair-Instability SN cutoff
- 3% H(z) constraint at z=0.8 after 5 years (Farr+2019)





LIGO, Virgo, KAGRA 2021 arxiv:2111.03604

Remarks on current measurements

No standard siren measurement currently provides insight about the Hubble tension (but future measurements will)

All the dark siren measurements presented are cosmological model dependent

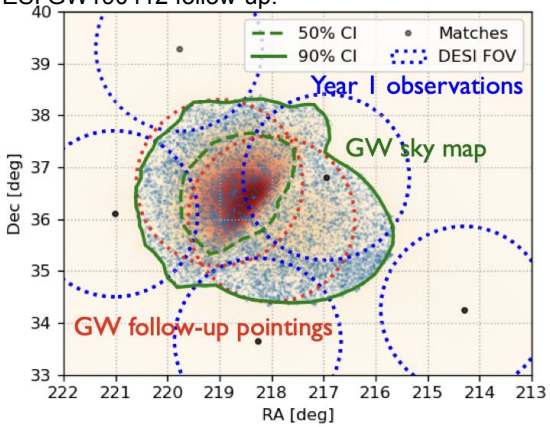
If focus is to understand Hubble tension: ideal to invest on finding BNS/NSBH counterparts

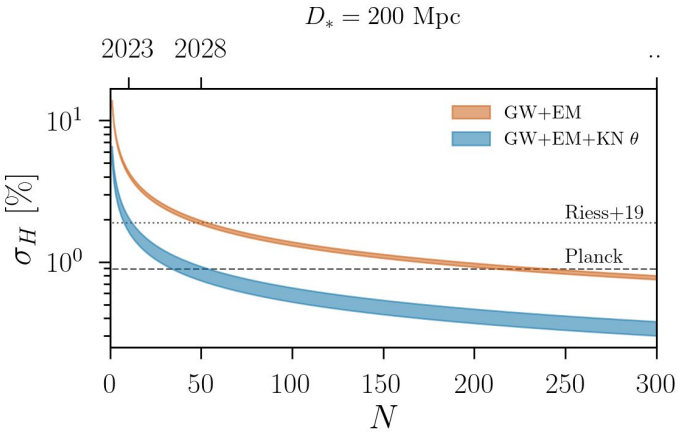
Synergies with wide field multi-object spectroscopy

Synergies between wide-field photometric & spectroscopic surveys for GW follow up

- Quick classification
- Potential host galaxies redshifts for follow-up and cosmology
- **Bright sirens:**
    - **~2%** measurement w/ ~50 events, enough to solve H_0 tension (Chen+2018, Feeney+2019)
    - Peculiar velocity field: 2-3% $f\sigma_8$ measurement w/ 3G (Palmese & Kim 2021)
- **Dark sirens:** Cross-correlation of dark sirens 2% H_0 measurement w/ 5 year LVK+DESI (Diaz & Mukherjee 2021)

DESI GW190412 follow-up:

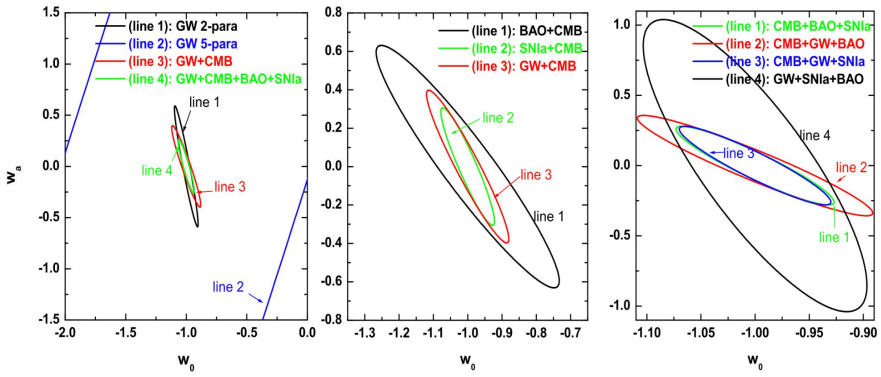




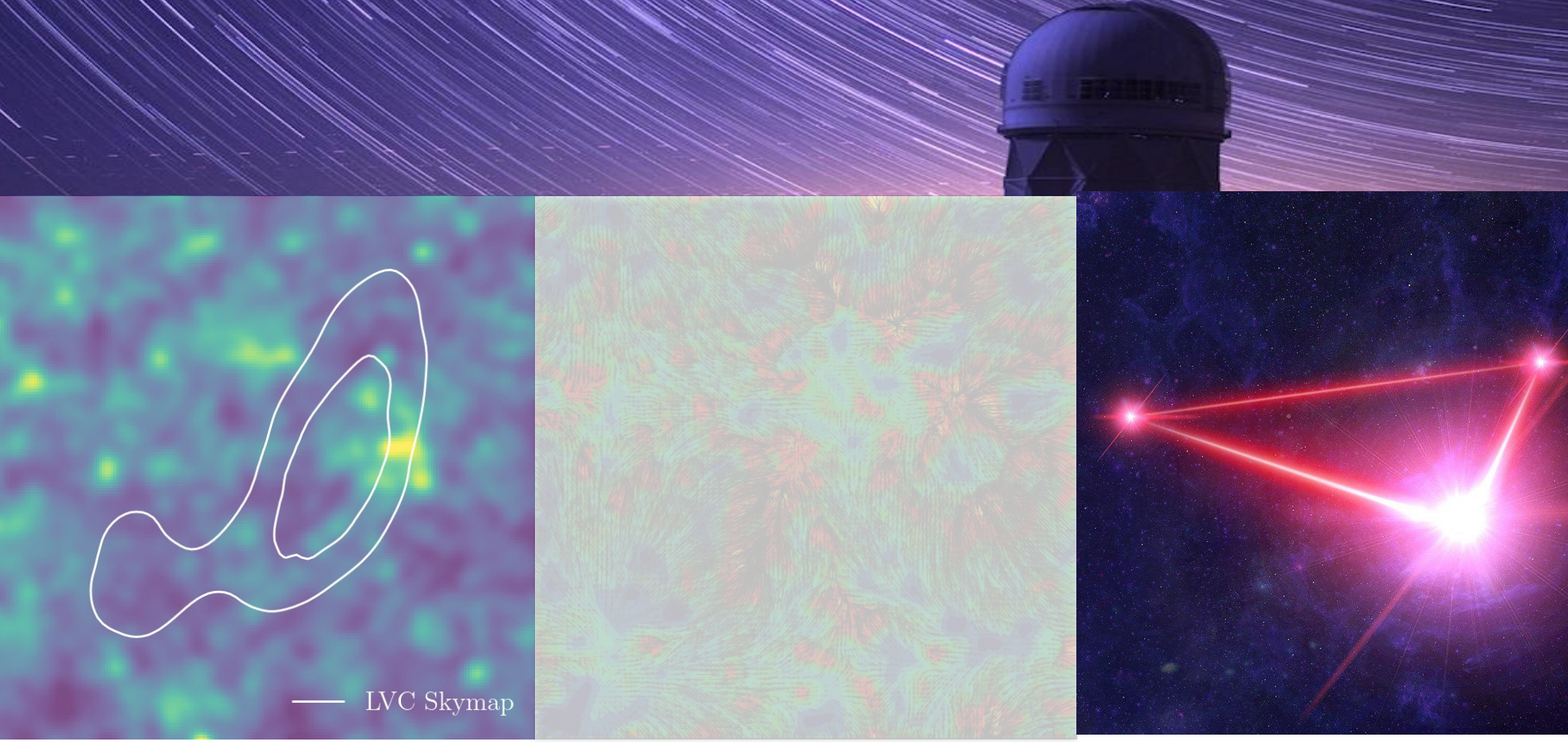
AP+ Astro2020 whitepaper 2019, arxiv: 1903.04730
Also see Morgan+LoI

Prospects for 3G

- Huge increase in detection rates: 10^5-10^6 BNS per year
- Sensitivity to cosmological parameters beyond H_0 because of higher D reach
- **ET + sGRB**: ~1000 events. Can **improve with KNe or mass distribution assumptions**
- 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 competitive DE constraints (in particular Taylor & Gair 2012, w/o EM counterparts)



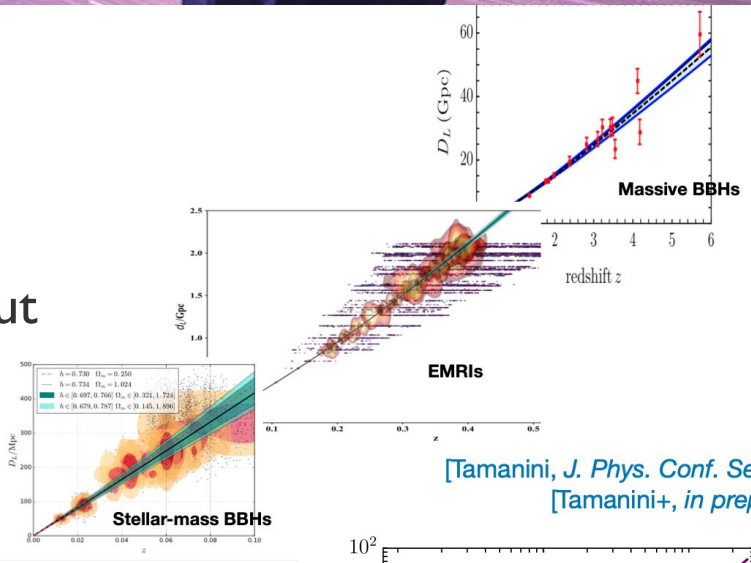
Zhao+2011



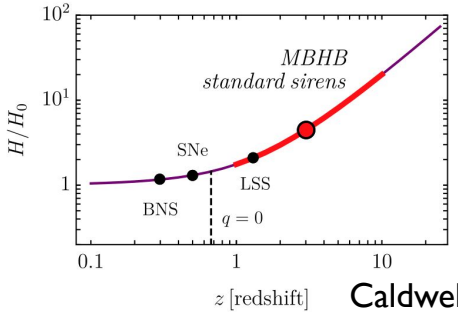
LISA standard sirens

LISA (Laser Interferometer Space Antenna)

- ESA/NASA space mission
- To be launched with Athena (2032)
- StS sources:
  - Massive Black Holes (bright or dark) out to z<10 Tamanini+16,LISA CosmoWG 2019
  - Extreme mass ratio inspirals (EMRI; expected dark) MacLeod & Hogan 2018, Babak+2017, Laghi+21
  - Stellar black holes (expected dark): few % precision on H0 Kyutoku & Seto 2017, Del Pozzo+ 2018



[Tamanini, *J. Phys. Conf. Ser.* (2017)]
[Tamanini+, *in prep.* (2020)]



Caldwell+2019

Conclusions for Cosmology Intertwined

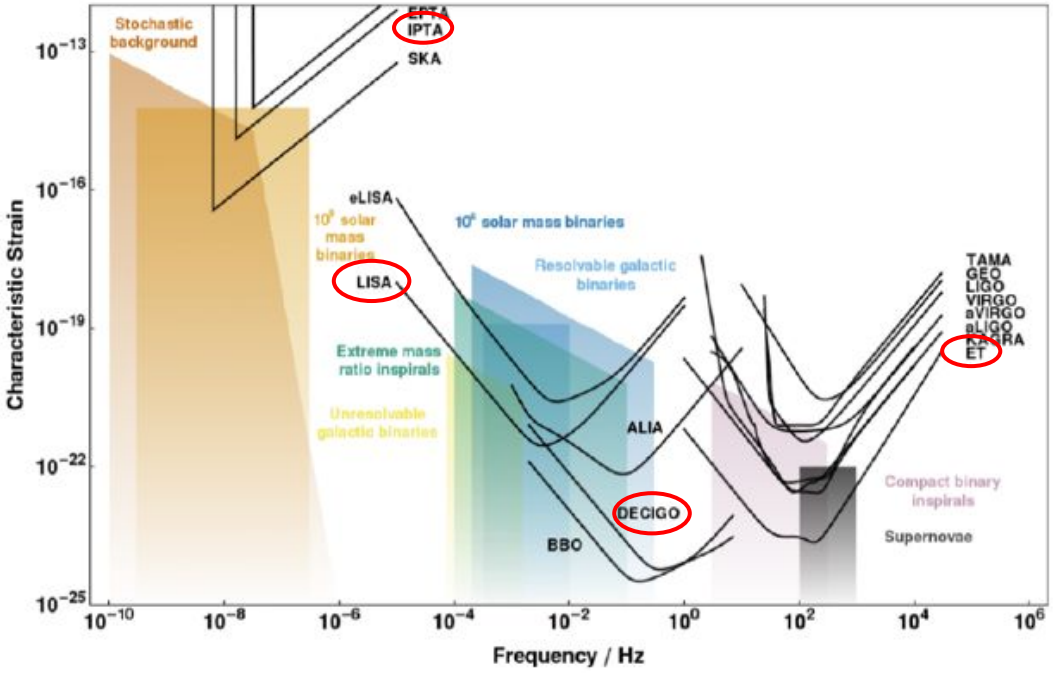
1. **If understanding Hubble tension is a main goal, we should focus on EM counterpart identification**
2. 2% H0 measurement will be possible within the next decade
3. **Need for multi-band multi-messenger coordination across experiments, and for dedicated follow-up programs**
   - **GW experiments:**
     - **ET + CE** for ideal standard siren measurements (localization & distance precision needed for precise StS measurements), will also enable measurements of growth of structure
     - LISA will be able to reach redshifts beyond current late-time Universe DE experiments

   - **EM experiments:**
     - **Programs dedicated to GW follow-up**, esp. KNe: wide FoV (~few-10 deg^2) photometry e.g. LSST, ZTF, LS4 (Nugent+ LoI) multi-object spectroscopy (DESI-II (Dawson+LoI)? MSE?)
     - If to constrain better inclination angle, need precise photometry (maybe from space) and/or radio
     - Influence **galaxy survey target selection** to include potential hosts

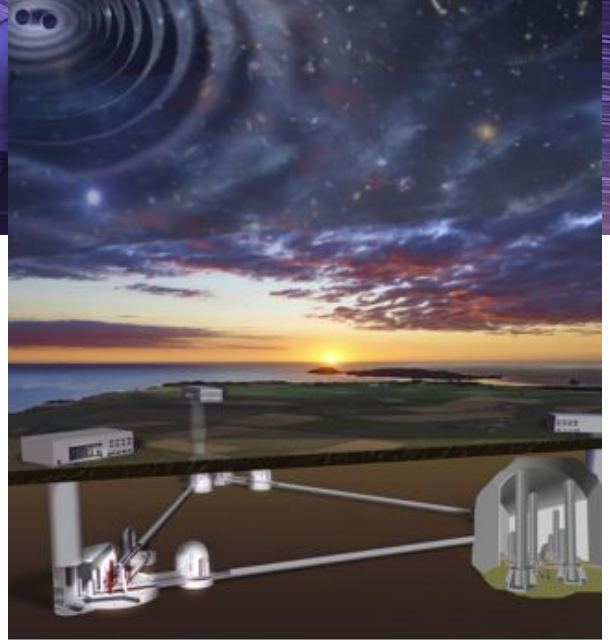
Back-up slides

GW detectors

- Now:
  - 2G (2nd generation): LIGO/Virgo/KAGRA (LVK)
  - IPTA
  - Holometer
- Next decade:
  - 2G A+
  - 3G (3rd generation): Einstein Telescope (ET; EU), Cosmic Explorer (CE; US)
  - LISA (ESA/NASA)
  - DECIGO (Japan)
  - IPTA
  - Lunar GW Observatory?



Cosmic Explorer/Einstein Telescope (2030s)



- Huge increase in detection rates:
  - 10^5-10^6 BNS per year
- Much higher SNR for mergers in 2G band
- Many mergers (~10k/year) with 1 sq. deg. localization

Combination of CE+ET (or 2+ detectors configurations) improves:

- localization
- distance uncertainty
- early warnings

Peculiar velocities (PV)

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

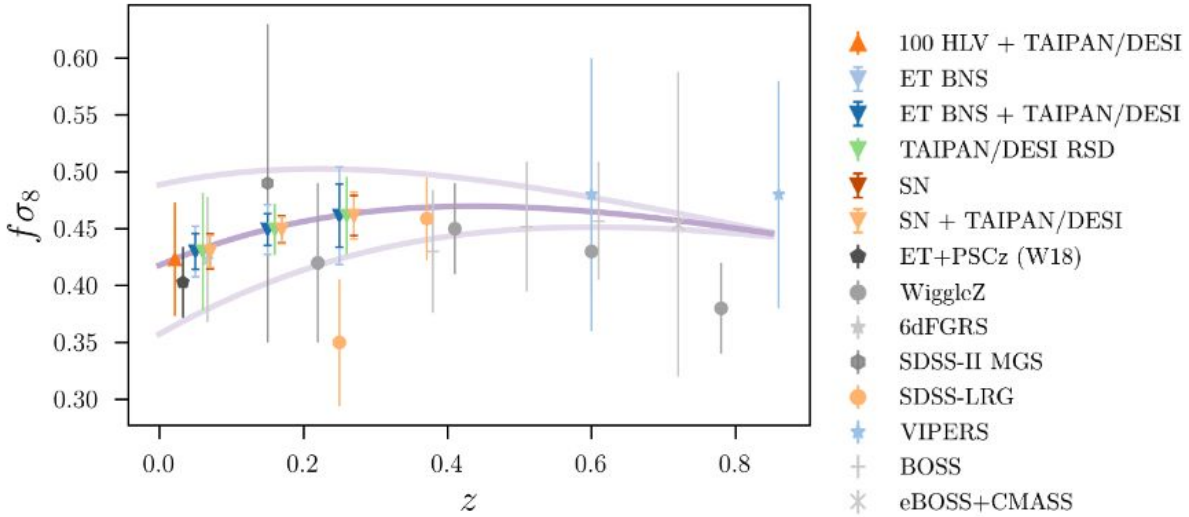
$$fD = \Omega_M^{\gamma} \exp\left(\int_a^1 \Omega_M^{\gamma} d\ln a\right)$$

Growth rate

Linear growth factor

Linder 2005

Growth of structure

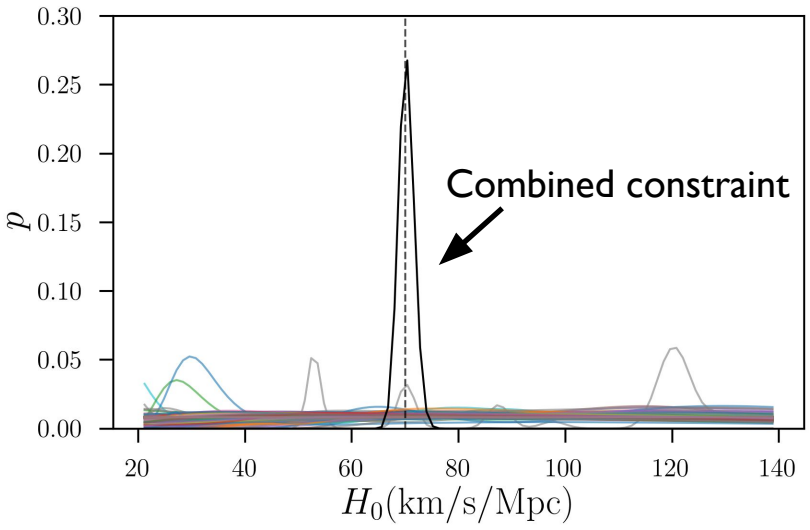


- Fix growth index
- 3% precision on with 3G + galaxy survey (10 yr ET, 5 yr 3 detectors)

AP & Kim 2021, PRD, arxiv:2005.04325

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

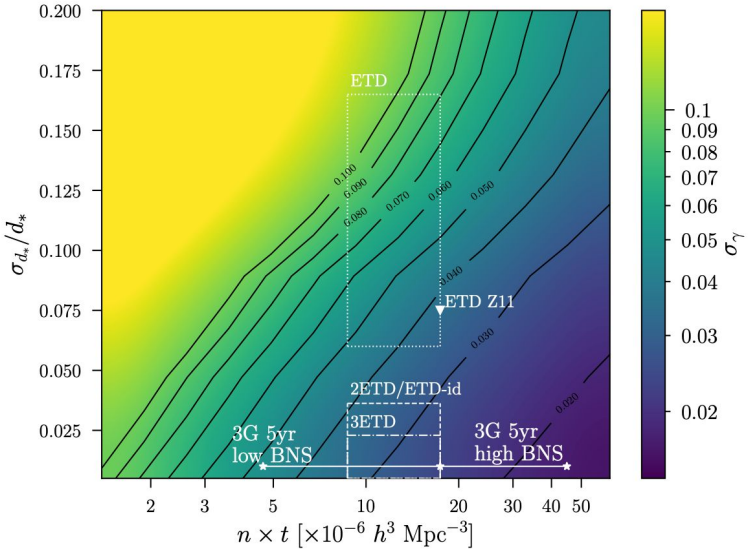


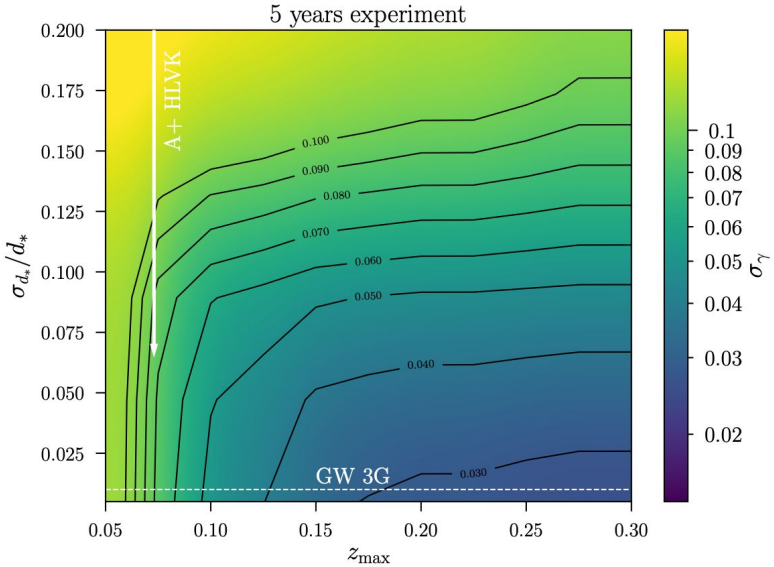
Probes of interest for GW cosmology

- **Dark Energy & Cosmological Parameters**
  - StSs
  - PVs
  - BAO & LSS Cross-correlations for bias and cosmological parameters
- **Modified Gravity**
  - GW vs photons arrival time
  - Luminosity distance vs dGW
- **Dark Matter**
  - Superradiance - probe DM candidates bosonic fields (axions, dark photons)
  - Gravitational lensing of gravitational waves
  - PBH, exotic compact objects

Also consider: NS equation of state un-modeled sources and new discoveries, galaxy formation and galaxy evolution w/ LISA

Growth index





- Let growth index vary
- From GW+hosts only
- If galaxy overdensities from galaxy survey are added: 0.02-0.03

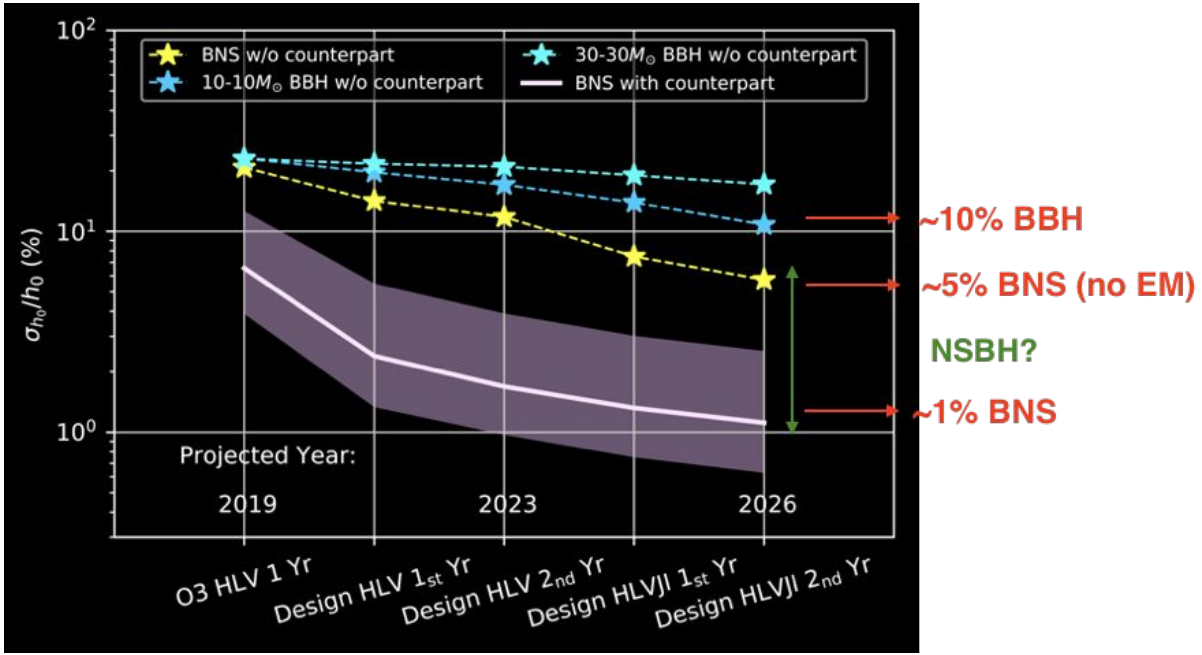
AP & Kim 2020 arxiv:2005.04325

Discussion

- Focus on low-z (z<0.5) photoz and spectroscopy for this decade
- Build on host galaxy catalogs to enable follow-up, identification, standard sirens measurememt
- When will we stop looking for EM counterparts to BNS?
  - 3G will see BNSs out to z~2. We can't see KNe out there. So galaxy catalog focus will still be at z<0.5.
  - At that point, only dark sirens, or GW-only StS methods.
  - If localization is 1 sq. Deg what useful facilities do we have? What would we need if it's more?
- What instrumentation could DOE bring to GW missions?
- Black hole -galaxy-halo connection
  - Should we take into account these stellar black holes in simulations of LSS?
- LSS connection and complementarity with galaxy surveys

Bright vs dark sirens in 2G (to be updated...)

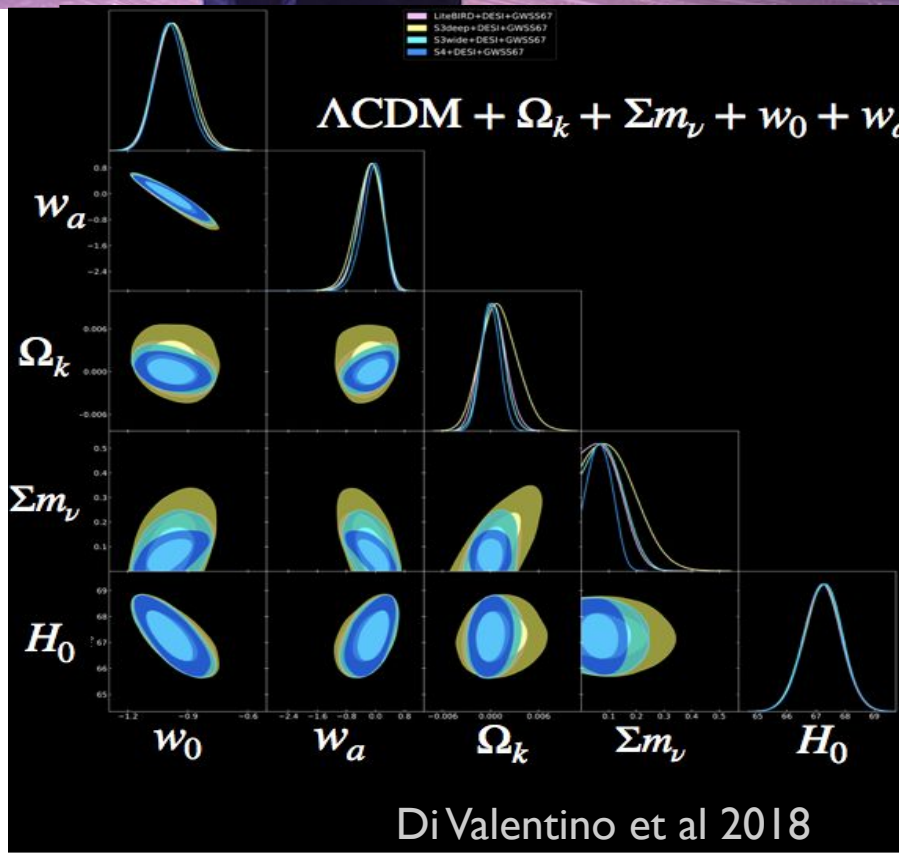
- **NSBHs** can provide competitive constraints, if rate >1/10 BNS (Vitale & Chen 2019)



Chen, Fishbach & Holz 2018

Impact on full cosmology

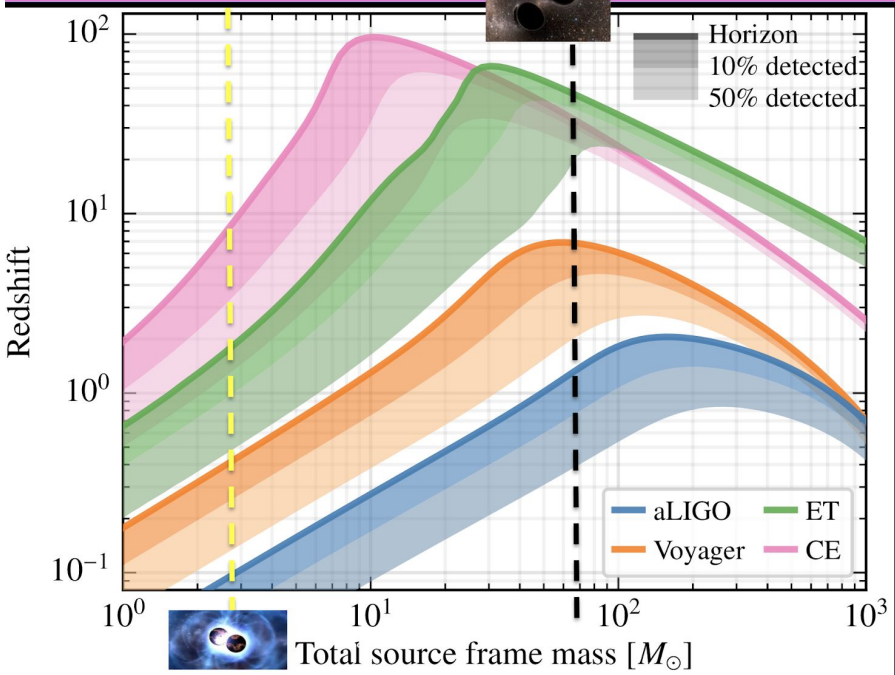
- Combining upcoming GW H_0 constraints + CMB S4 + BAO significantly **improves constraints beyond LCDM**
- **Breaks geometrical degeneracies** between parameters from CMB
- Factor 1.6-2.8 improvement on dynamical DE parameters

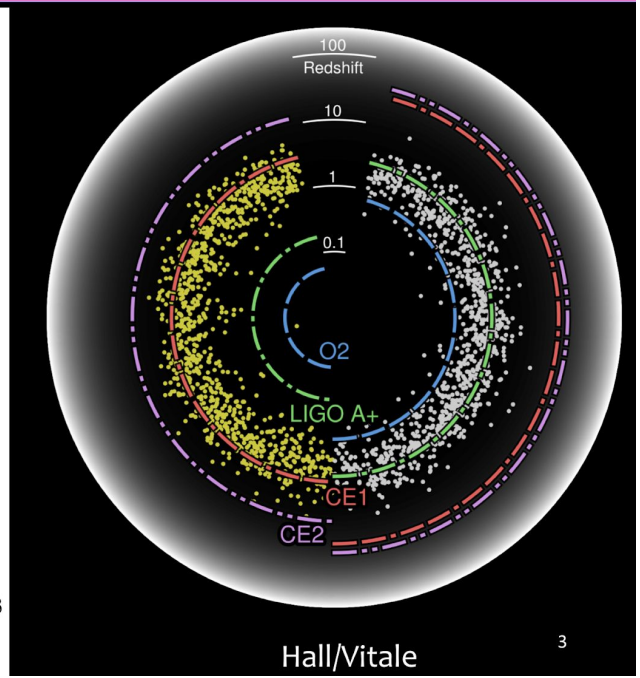


Di Valentino et al 2018

Cosmic Explorer/Einstein Telescope horizon

credit E. Hall, J. Miller





Fermilab Holometer

The Holometer is intended to be the world's most sensitive laser interferometer, surpassing the sensitivity of the GEO600 and LIGO systems, and theoretically able to detect **holographic fluctuations in spacetime.**[1][2][3]

According to the director of the project, the Holometer should be capable of detecting fluctuations in the light of a single attometer, meeting or exceeding the sensitivity required to detect the smallest units in the universe called Planck units.[1] Fermilab states: "Everyone is familiar these days with the blurry and pixelated images, or noisy sound transmission, associated with poor internet bandwidth. The Holometer seeks to detect the equivalent blurriness or noise in reality itself, associated with the ultimate frequency limit imposed by nature."[2]

(Wikipedia)

https://holometer.fnal.gov