Standard Siren cosmology

GW-MMADS

NSF

Antonella Palmese

23 July 2026

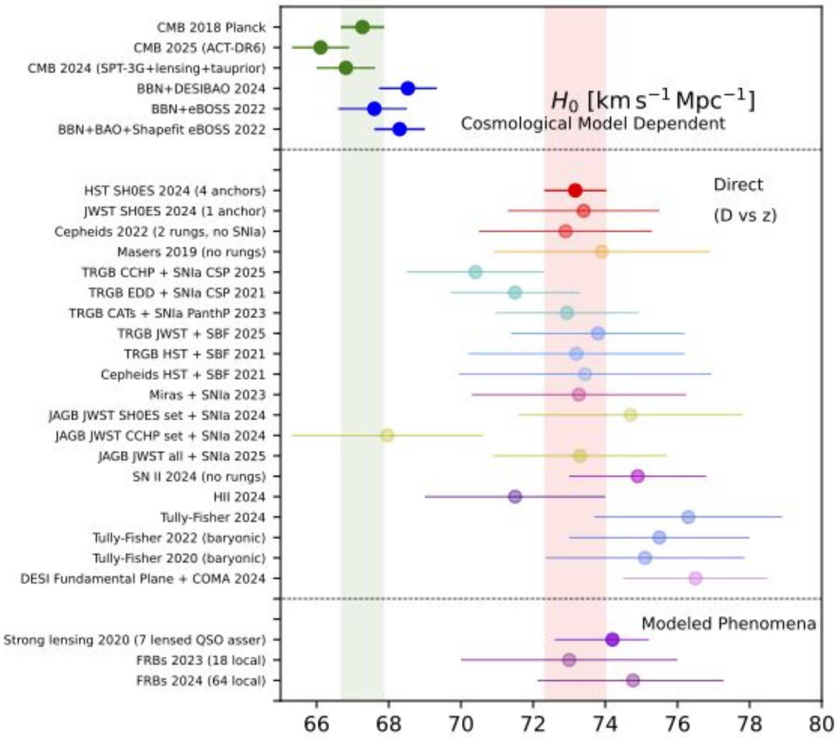
Exploring New Frontiers in Cosmology

GGI - Florence

McWilliams Center for
Cosmology & Astrophysics

Hubble tension

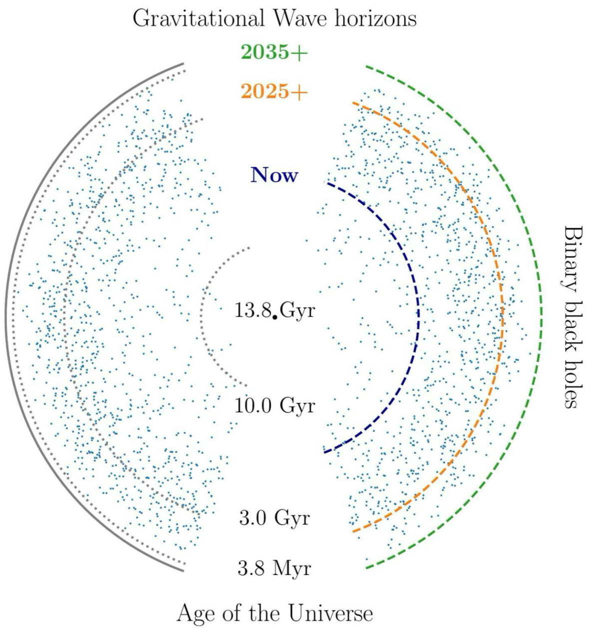
- **>4σ discrepancy** between early and late time Universe measurements
- Systematics or new physics?
- Need for an **independent measurement**. If from late Universe: ideally independent of distance ladder.



Di Valentino et al, +25

Standard Sirens are unique

1. Compact binaries merge at cosmological distances, and we will be able to observe them all the way to the first mergers
2. GWs travel unaltered through the Universe, except for gravitational lensing
3. GW wavelengths are of astrophysical scale
4. Signals are understood from first principles → distance measurement is too!

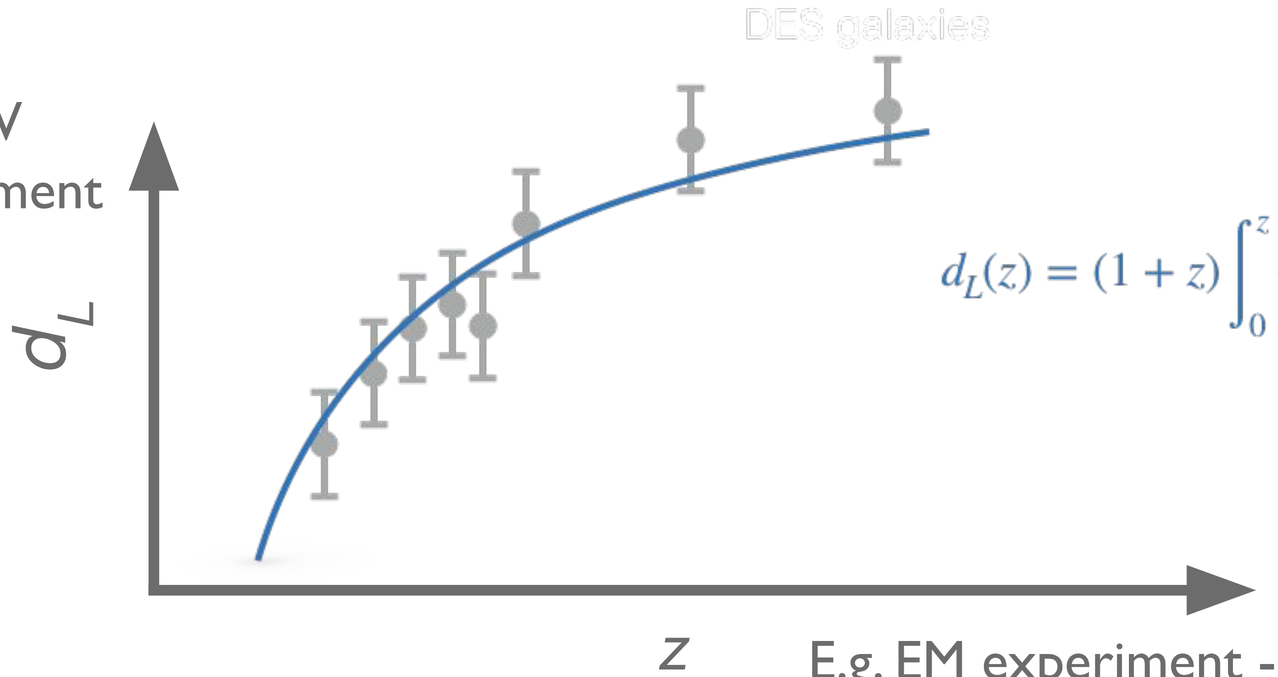


Chen, Ezquiaga & Gupta 2024

Standard Sirens

Schutz 1986
Holz & Hughes 2005
MacLeod & Hogan 2008
Nissanke+2010
Del Pozzo 2012...

GW experiment



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

E.g. EM experiment - host galaxy redshift

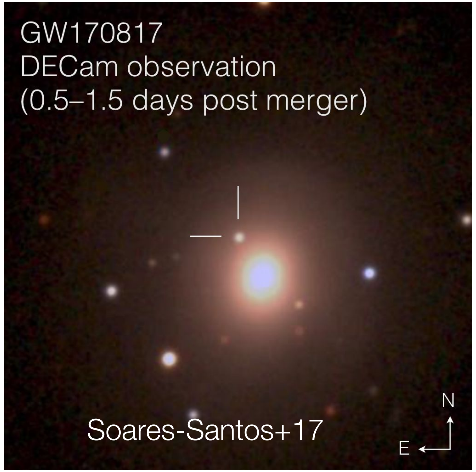
Standard Sirens

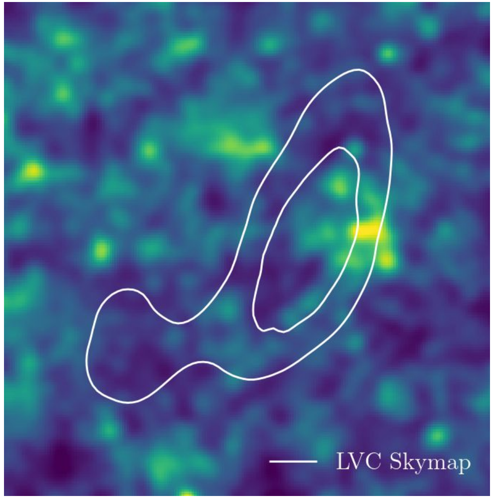
Schutz 1986
Holz & Hughes 2005
MacLeod & Hogan 2008
Nissanke+2010
Del Pozzo 2012...

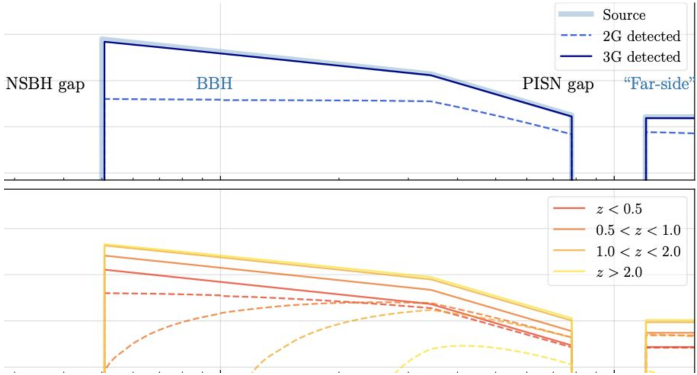
Bright
BNS/NSBH (+BBH?)

Dark (x galaxies)
BBH

Dark (GW alone)
All







Ezquiaga+22

Redshift from:

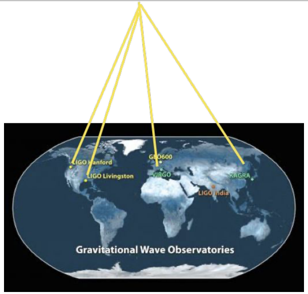
Host galaxy

Galaxies

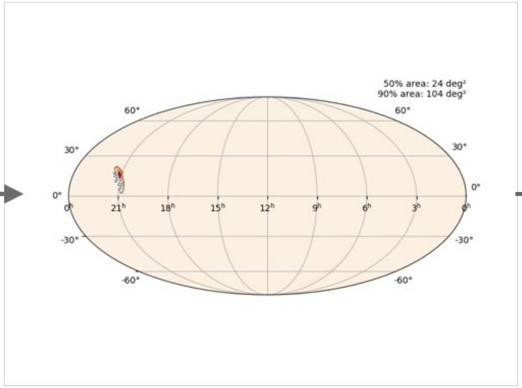
Redshifted mass

See AP & Mastrogiovanni (2026) arXiv:2502.00239 for a review

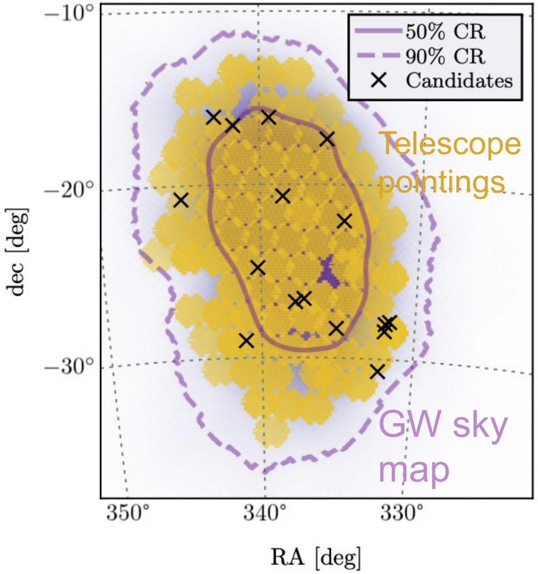
Gravitational waves and Electromagnetic follow-up



GW from merging neutron stars or black holes

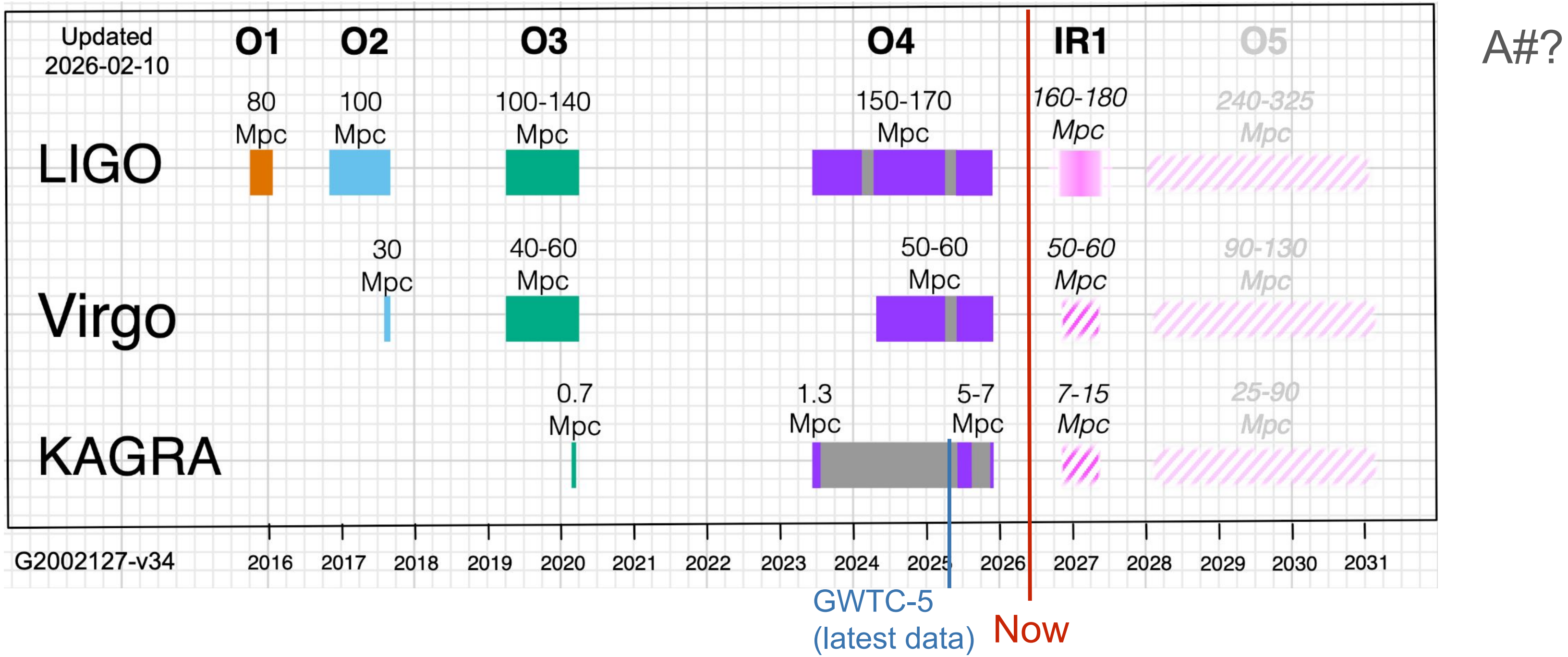


LIGO/Virgo/KAGRA send GW alert



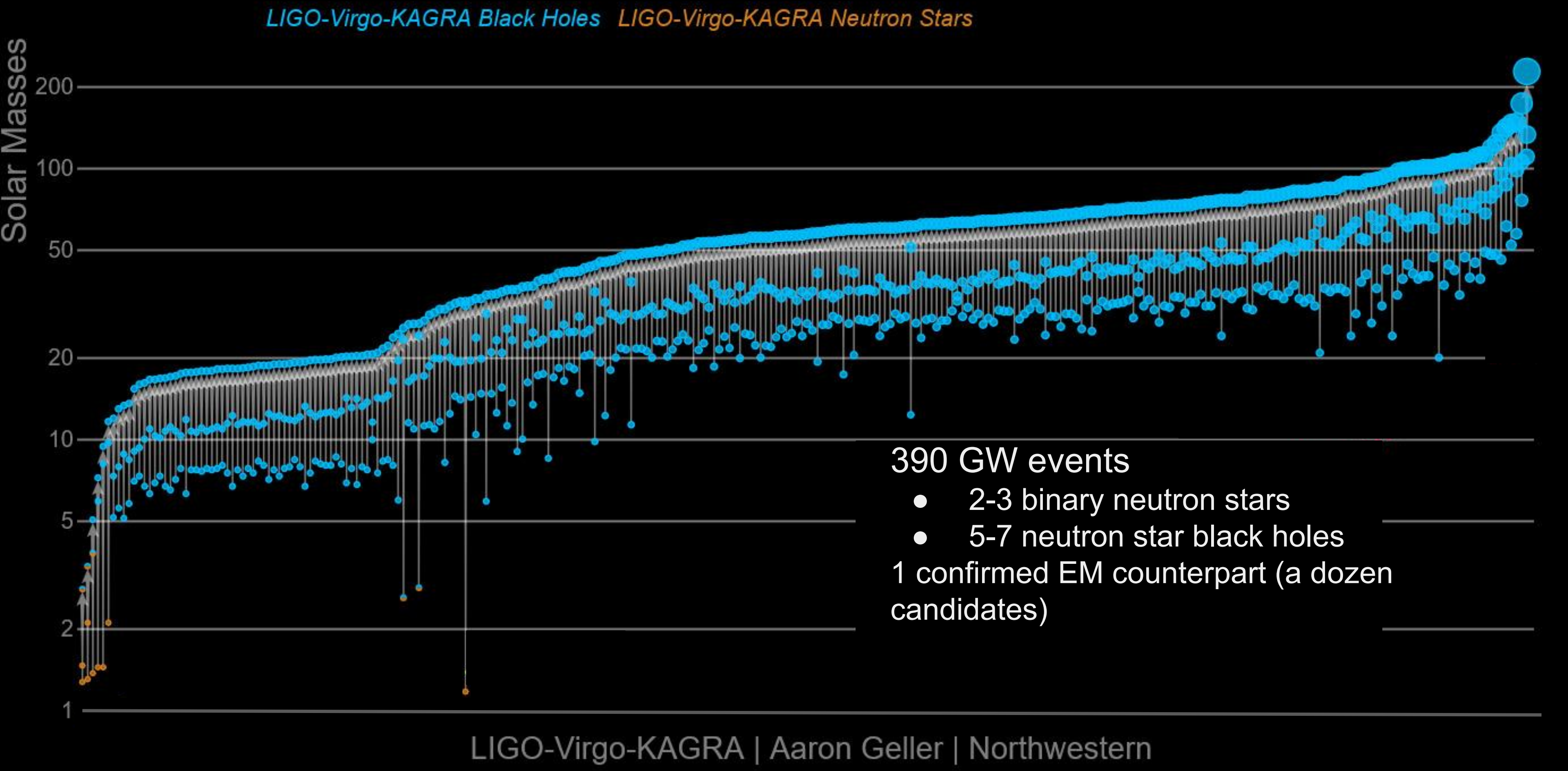
Telescope follow-up to identify electromagnetic (EM) counterpart: DECam, Rubin LSST, SALT, Gemini, HST, JWST…

Current generation GW detectors timeline



emfollow.docs.ligo.org

Masses in the Stellar Graveyard



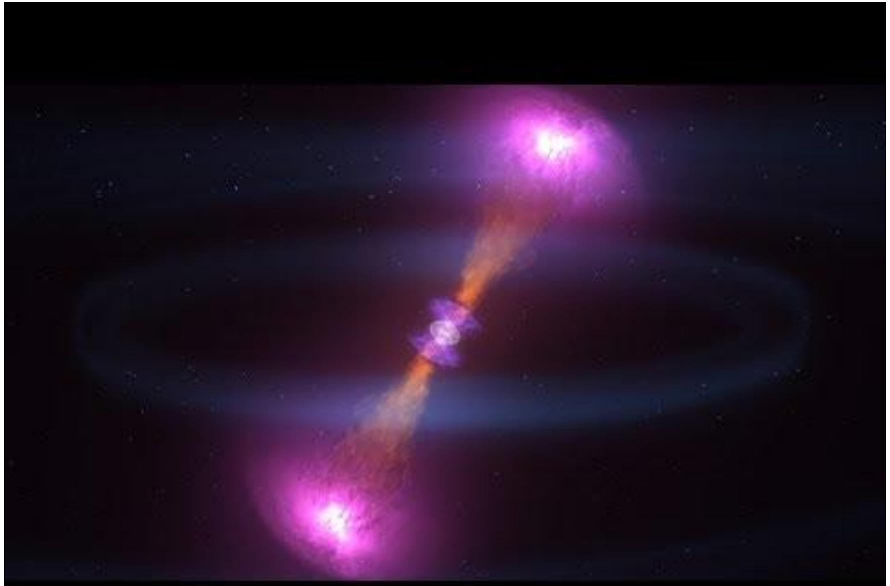
390 GW events

- 2-3 binary neutron stars
- 5-7 neutron star black holes

1 confirmed EM counterpart (a dozen candidates)

Binary neutron star mergers

Bright Standard Sirens - BNS counterpart

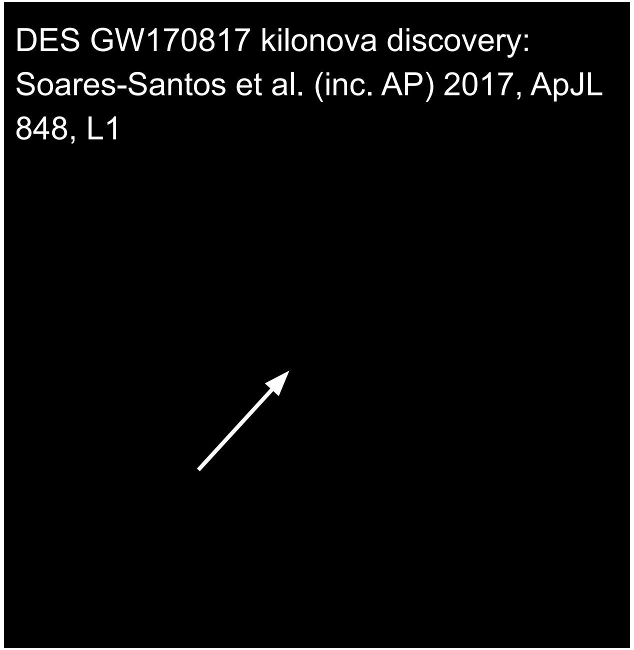


Credit: NASA's Goddard Space Flight Center/CI Lab

- **Relativistic jet** - gamma rays (magenta)
- Ejecta from **kilonova** - UV/optical/infrared (violet and white to red)
- **Afterglow** - X-rays, optical, radio

Bright Standard Sirens - BNS counterpart

GW170817 - First GW EM counterpart



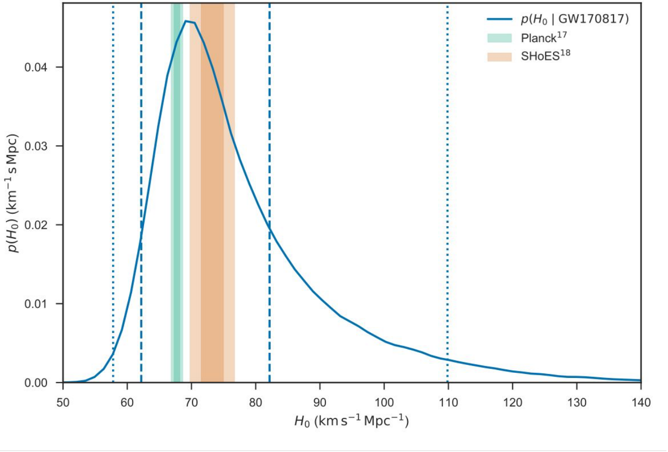
DES GW170817 kilonova discovery: Soares-Santos et al. (inc. AP) 2017, ApJL 848, L1

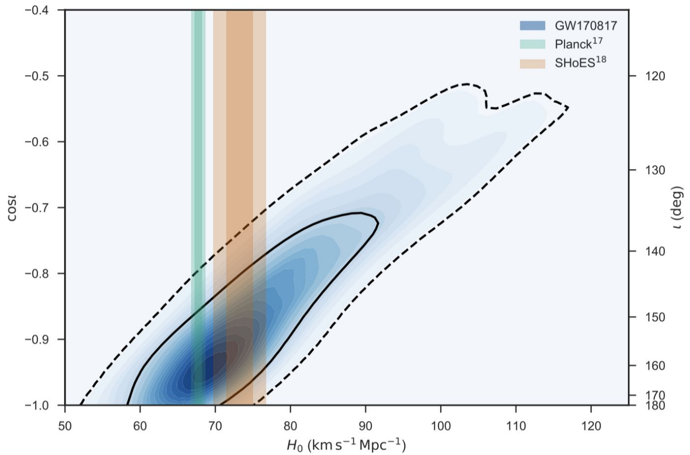
- **Relativistic jet** - gamma rays (magenta)
- Ejecta from **kilonova** - UV/optical/infrared (violet and white to red)
- **Afterglow** - X-rays, optical, radio

Kilonova: thermal transient powered by the radioactive decay of rapid neutron capture elements synthesized in the merger ejecta

GW170817 bright standard siren

LVC, EM partners+ 2017, Nature





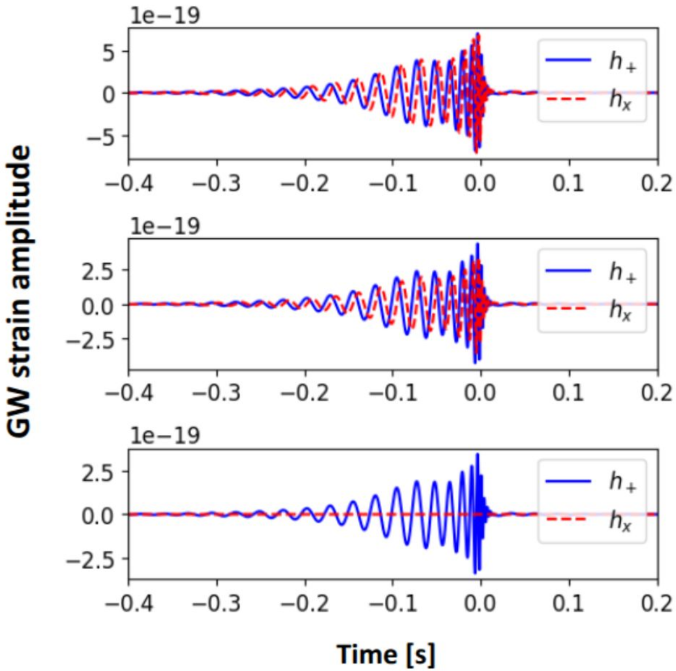
- NGC 4993 (z~0.01)

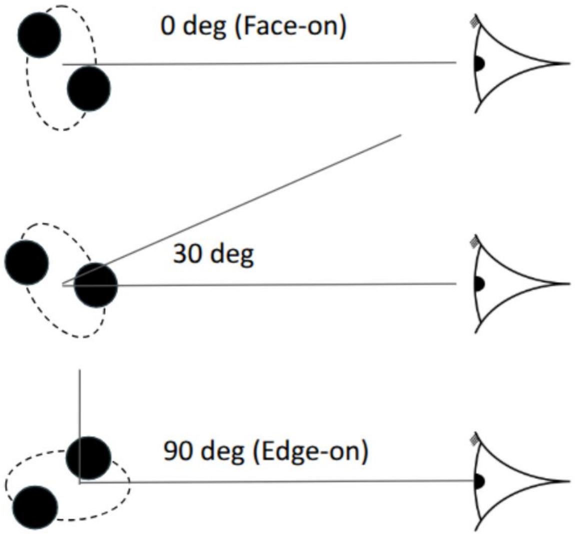
$$H_0 = 70^{+12}_{-8}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

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

- (Some) limitations:
  - Peculiar velocity
  - Inclination angle is correlated with luminosity distance

Standard sirens - viewing angle-distance degeneracy

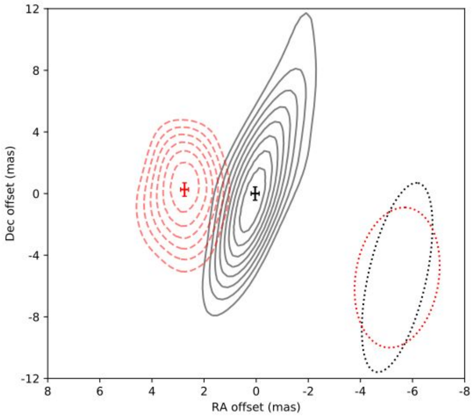


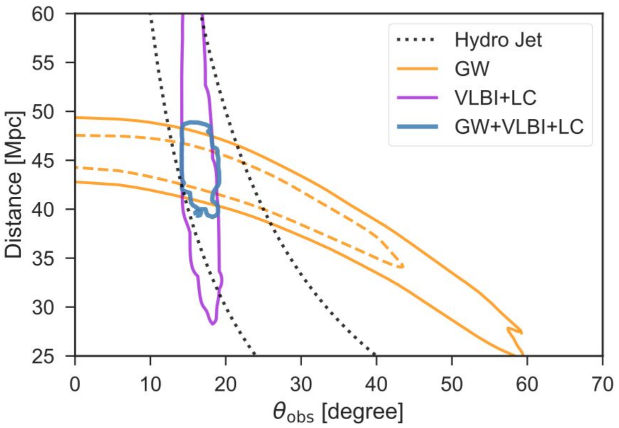


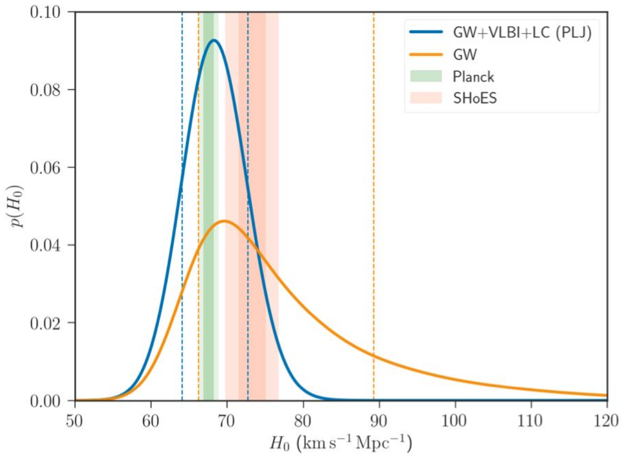
Credit: S. Mastrogiovanni

GW170817 bright standard siren - viewing angle

Break **distance-inclination degeneracy** by constraining viewing angle from EM observations





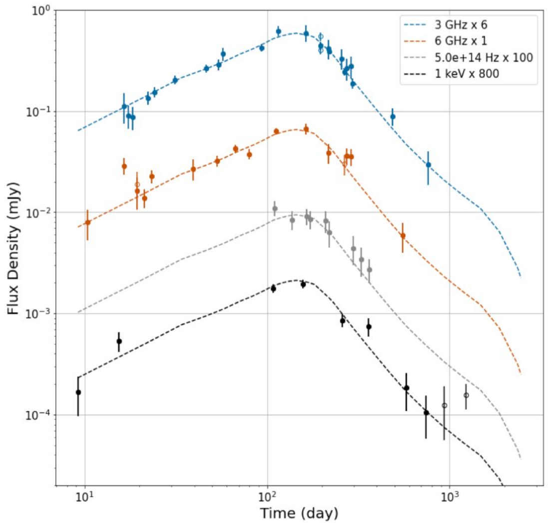


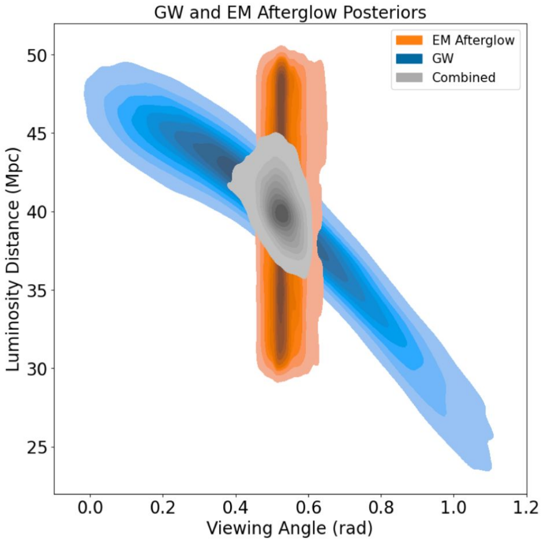
Mooley et al. 2018, Nature

Hotokezaka+2019, Nat. Ast.

GW170817 bright standard siren - viewing angle

- **GW170817 Afterglow at ~3.5 years**: including data beyond peak brightness
- Hydrodynamic simulation-based JetFit (Wu & MacFadyen 2018) to model the afterglow, consistently **from X-ray to radio**, with simulations from McDowell & MacFayden 2023





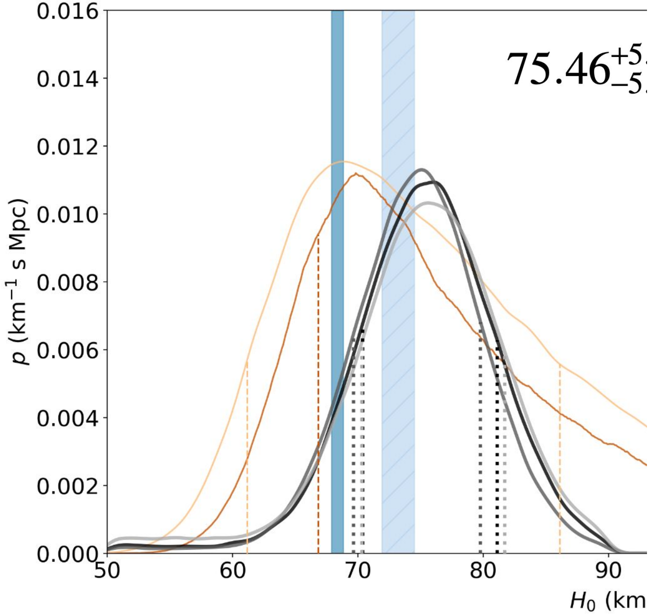
AP, Kaur, Hajela, Margutti, McDowell & MacFadyen 2024, PRD arXiv:2305.19914

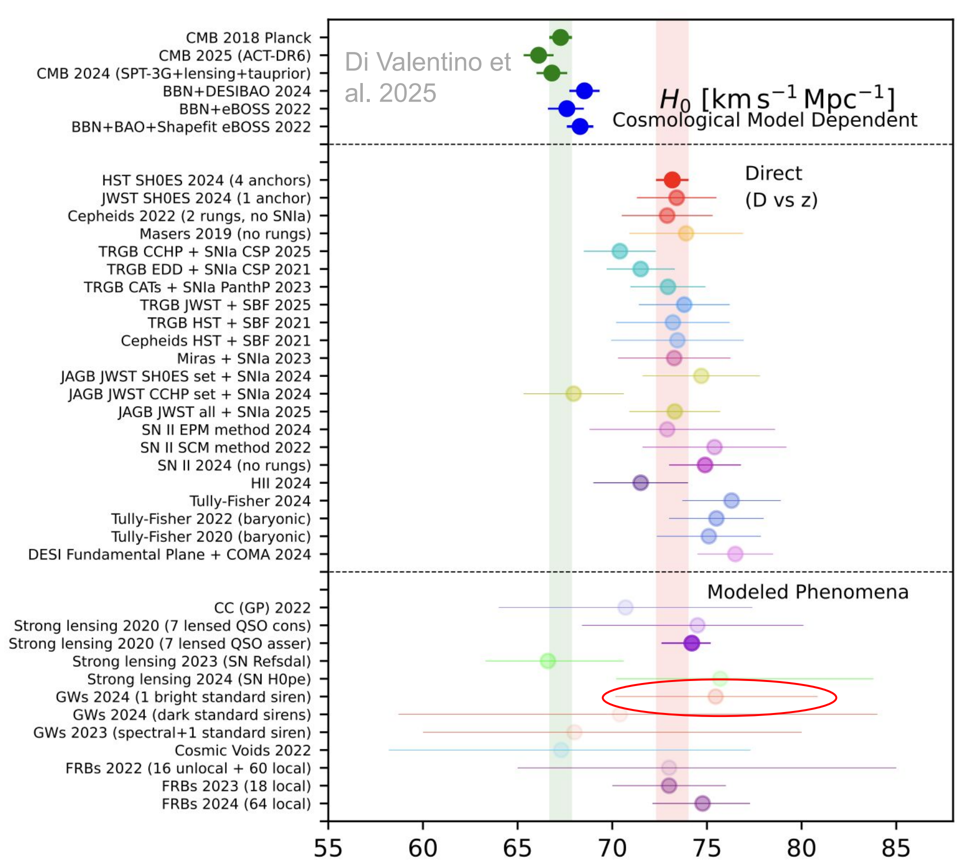
GW170817 bright standard siren

Joint GW-EM inference with host galaxy

Tests of the effect of assumptions on jet

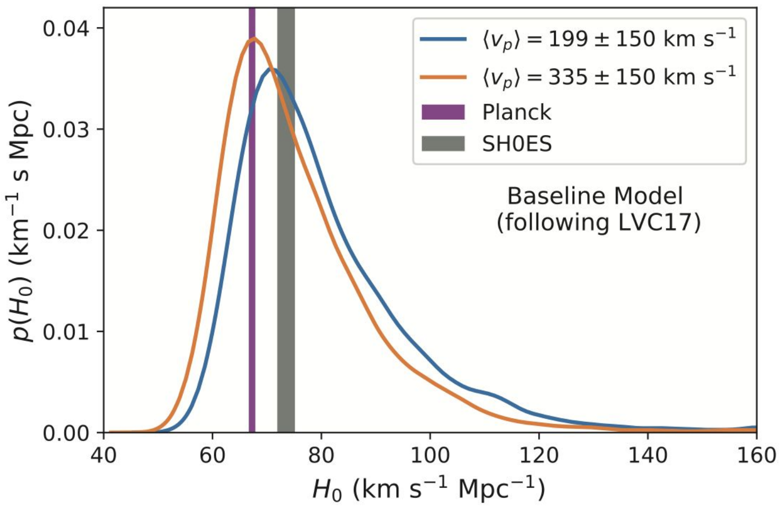
~7% H_0 precision measurement (vs 14



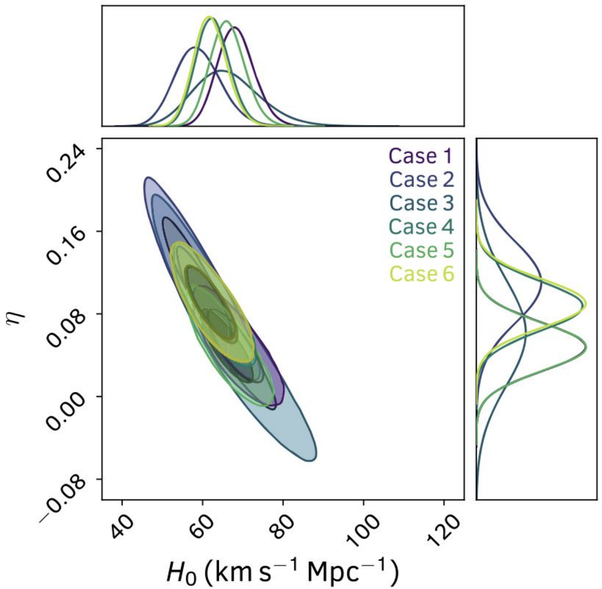


AP, Kaur, Hajela, Margutti, McDowell & MacFadyen 2024, PRD, arXiv:2305.19914

GW170817 bright standard siren - peculiar velocities



Nicoulau+ (2020)



Howlett & Davis (2020)

(Only 1-3 galaxies in group have peculiar velocity measurements)

See also:

Mukherjee+(2020)

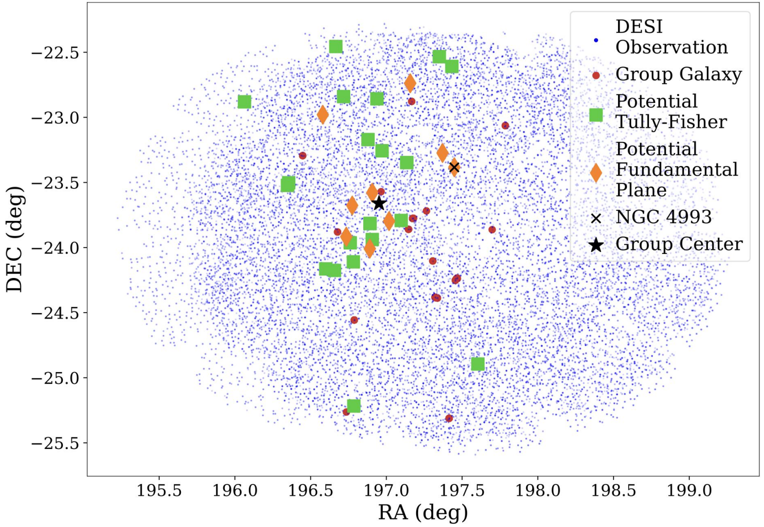
GW170817 as a bright standard siren - DESI

DESI observed 39 group galaxies

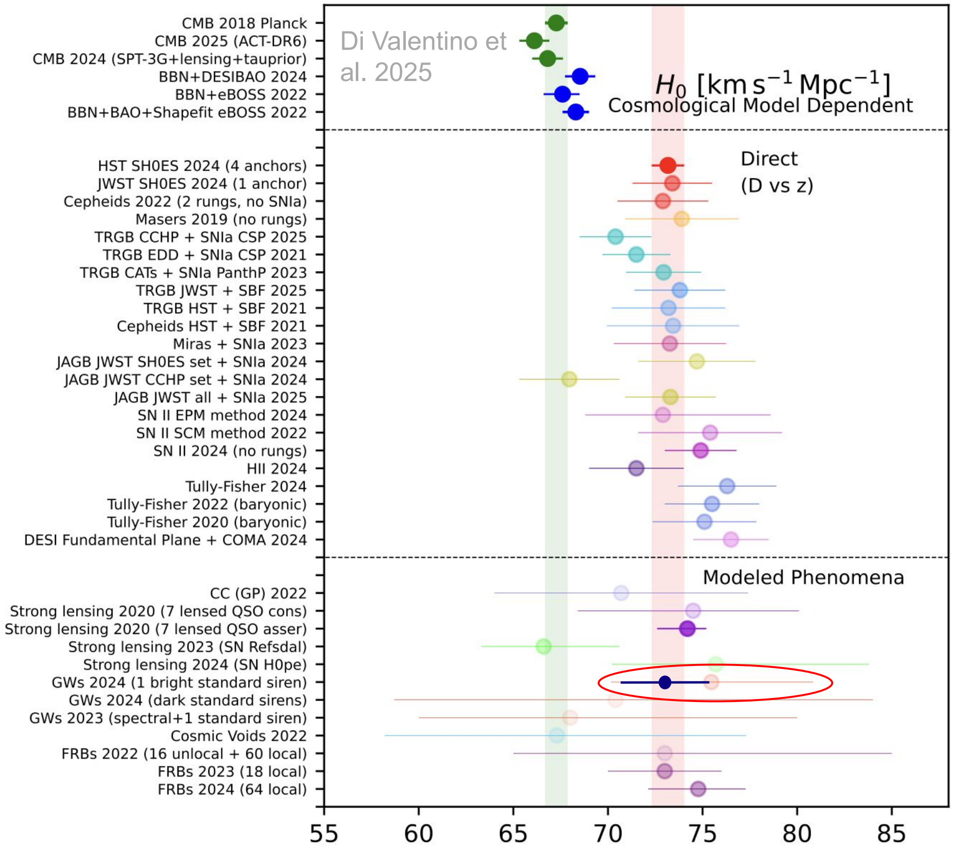
5-fold increase in number of peculiar velocity

DESI $H_0 = 70.9^{+6.4}_{-8.5}$ km s^{-1} Mpc^{-1}

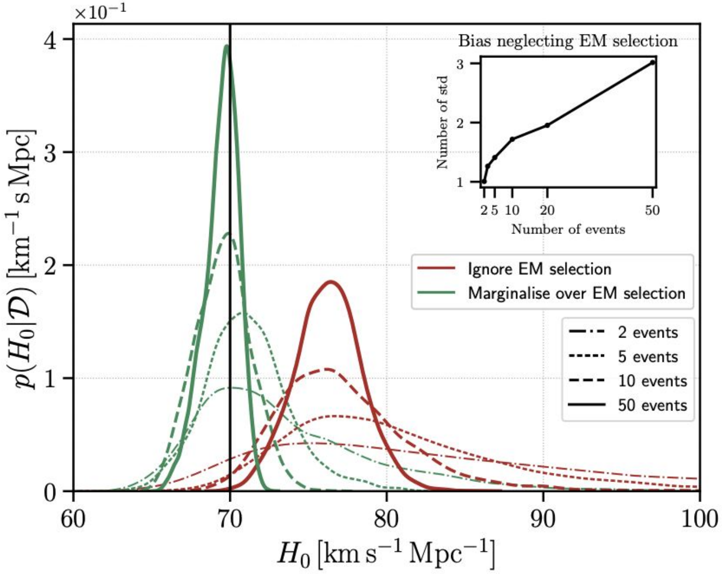
Surface Brightness Fluctuations $H_0 = 73.4$



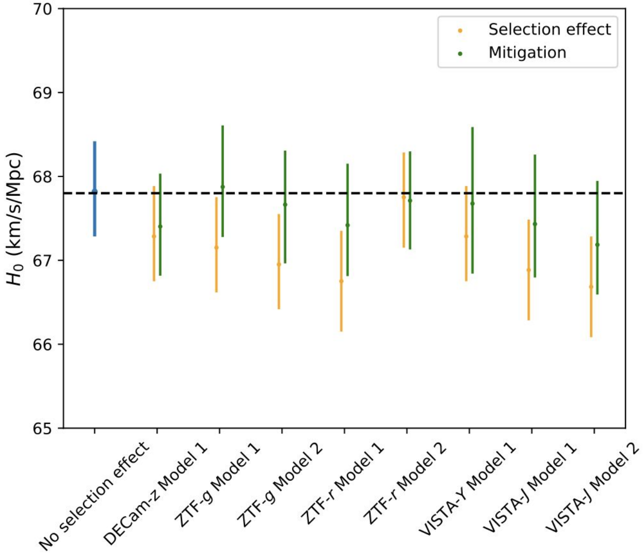
Amsellem, AP, et al. (DESI), 2026, ApJ,



Bright standard sirens - EM selection effects



Mancarella+2024, PRL

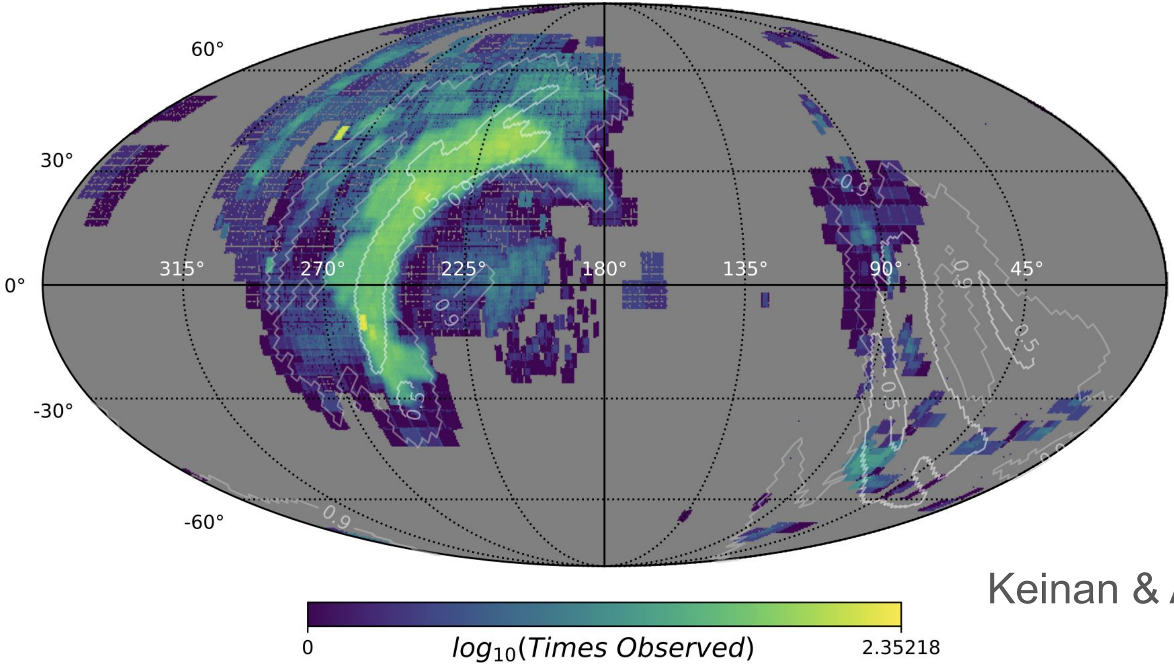


Chen+2024, PRL

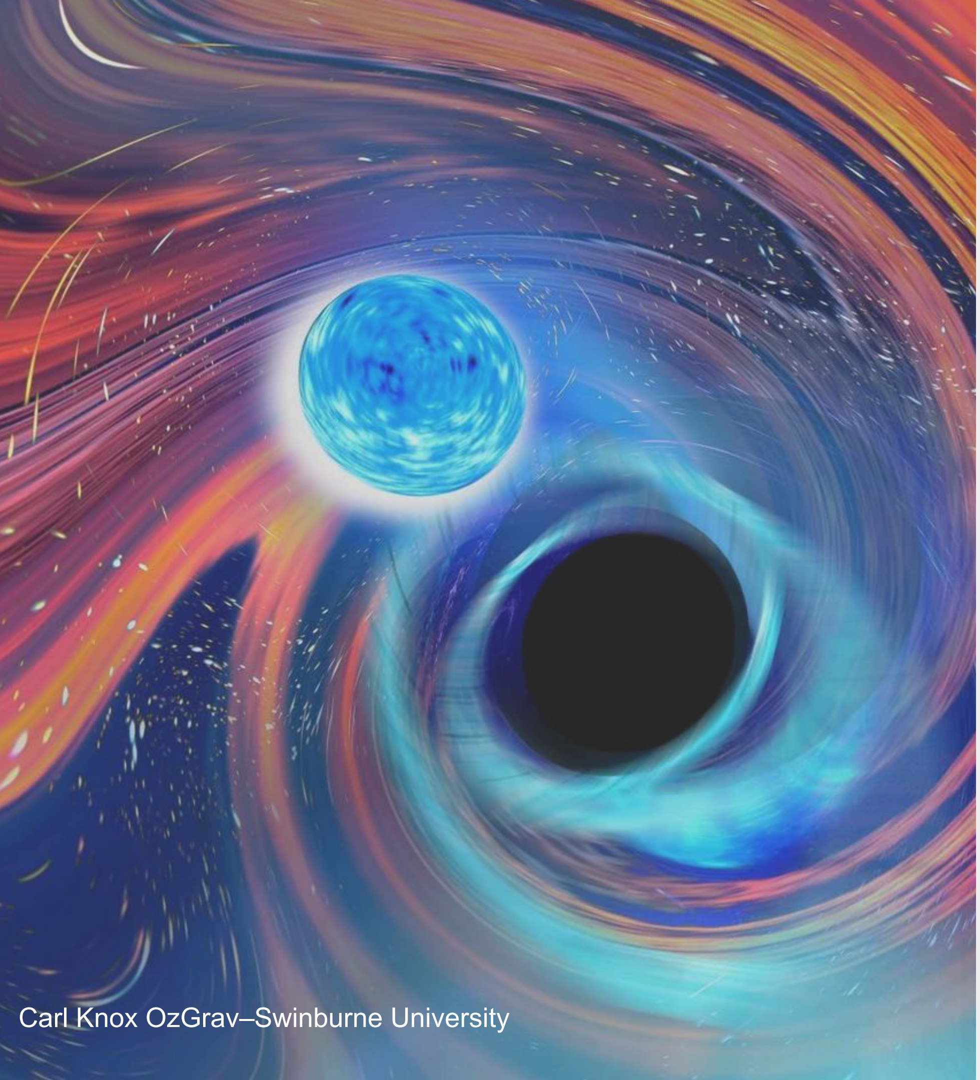
GW190425 - Optical observations

No EM counterpart found (e.g. Hosseinzadeh+2019, Coughlin+2019, Smartt+2024), but:

Single-detector detection (>7000 sq. deg. localization), and ~160 Mpc away, massive (small ejecta masses)



Keinan & Arcavi 2024

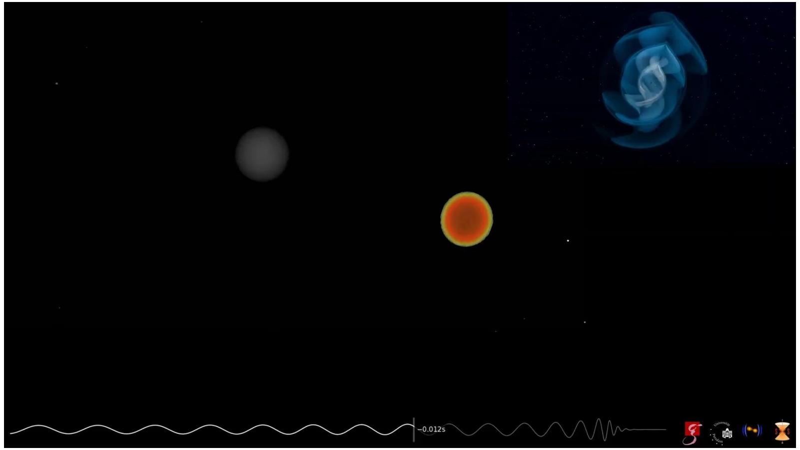

Carl Knox OzGrav–Swinburne University

Neutron star-black hole mergers

Neutron Star-black hole mergers - Simulations

EM Counterpart

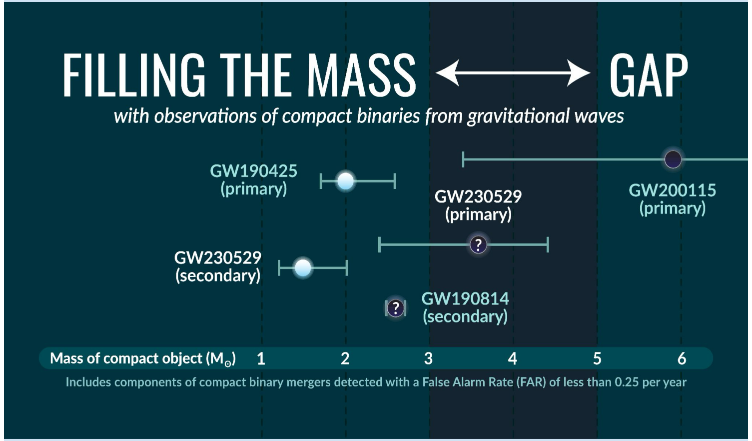
No EM Counterpart

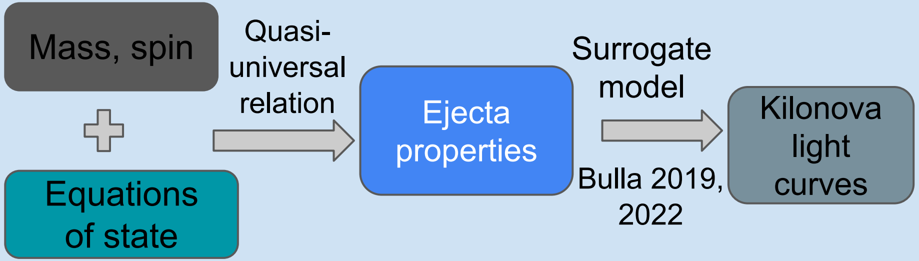


Kilonovae from mass-gap NSBH mergers

GW230529: likely NSBH merger with 2.5-4.5 M⊙ black hole (Abbott et al. 2024, ApJL, arXiv: 2404.04248)

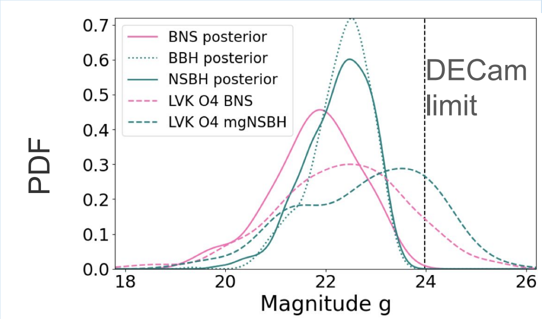
No EM counterpart detected





Kilonova production: 2-41% chance if NSBH

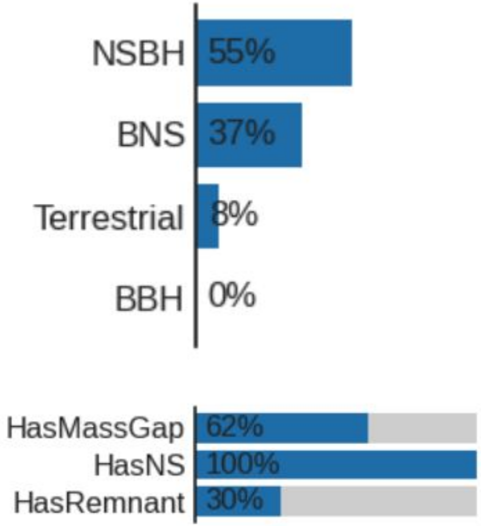
Kilonova detectability: High detectability in optical

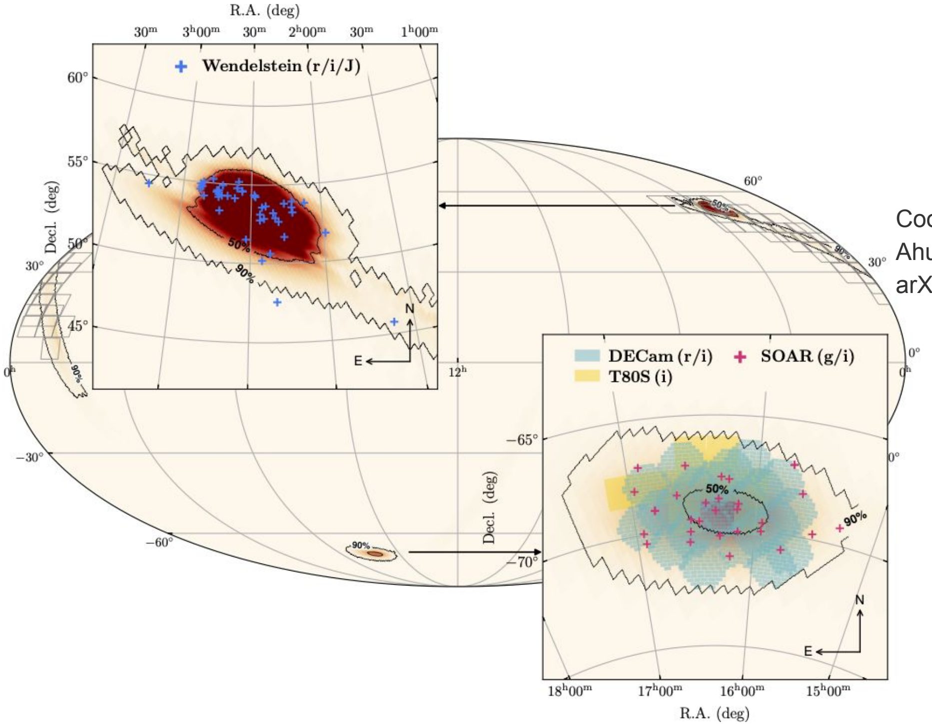


Kunnumkai, AP, Bulla, Dietrich, Farah & Pang, 2024, arXiv:2409.10651

S250206dm - Kilonova search

Hu, Cabrera, AP, et al., 2025 arXiv:2506.2262





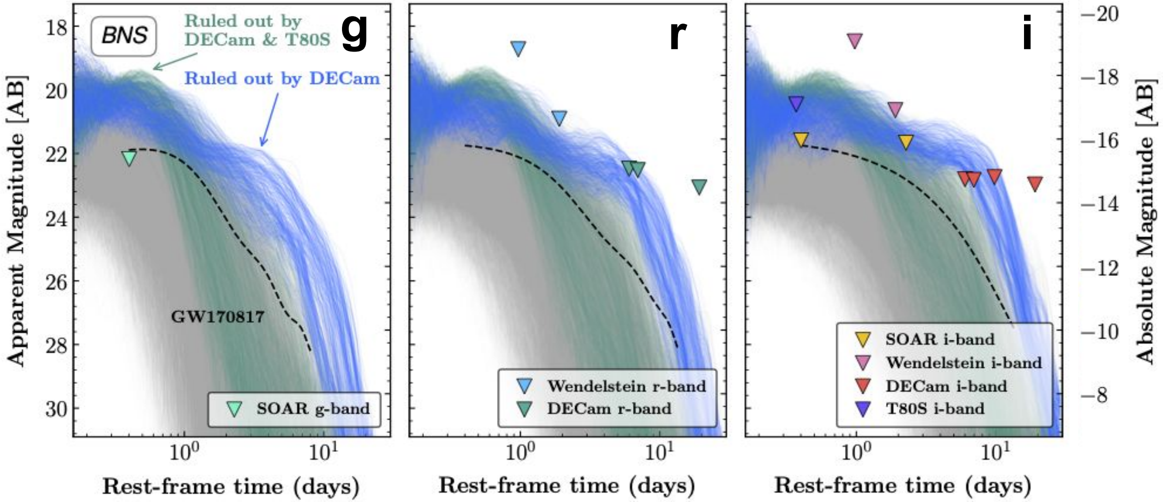
Coordinated with ZTF: Ahumada et al. 2025, arXiv:2507.003576

S250206dm - GW-MMADS DECam search

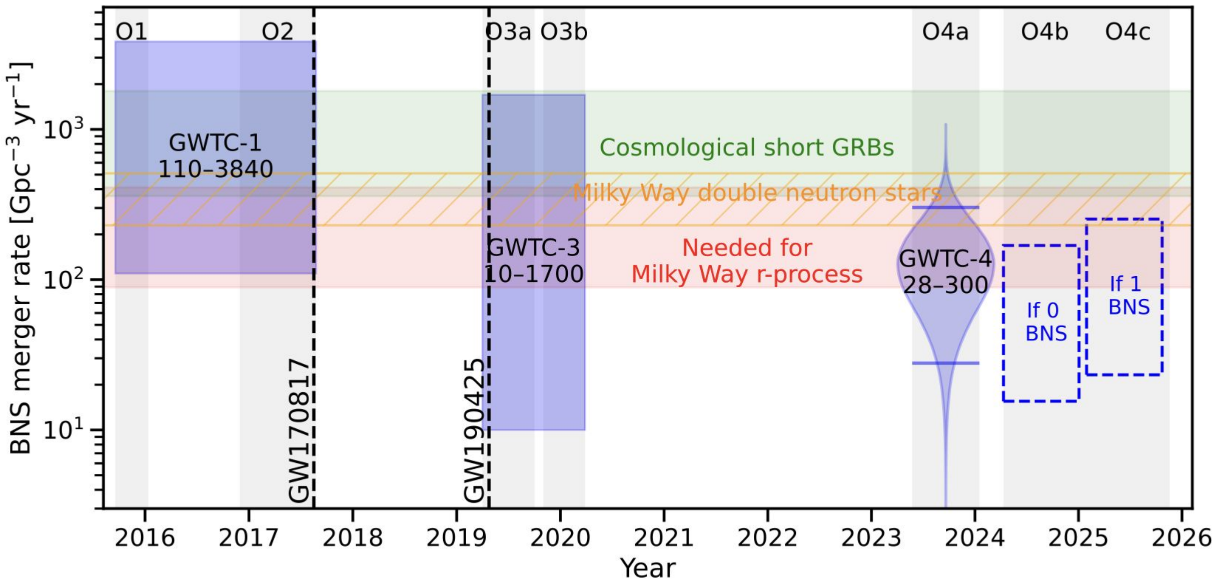
Hu, Cabrera, AP, et al., 2025 arXiv:2506.2262

Rule out **>40% kilonova models brighter/similar to GW170817** kilonova at **~320 Mpc**

If prompt observations were possible, we would have excluded >80% of all models (or found the counterpart!)



Where are the EM-bright neutron star mergers?



Fishbach et al. 2026

See Kunnumkai, AP, O'Connor, Farah, Magana-Hernandez 2026
arXiv:2604.05046

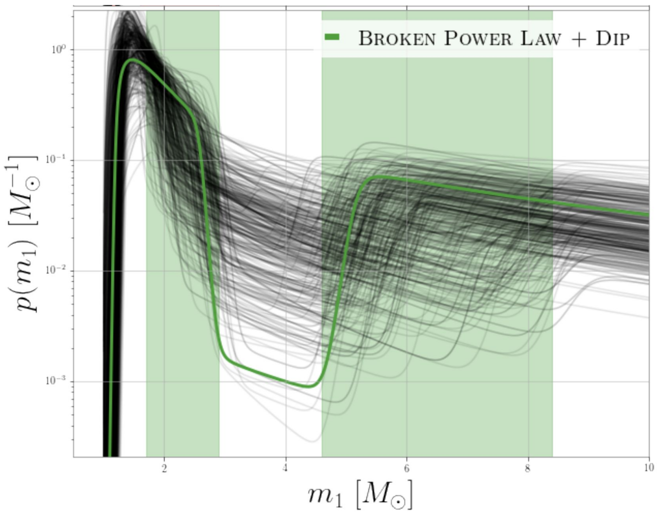
Multimessenger KN detection prospects

Simulate BNS+NSBH GW detections+KNe

Power law+dip+break model

BNS rates updated (rough estimate) based on no detections of BNS so far in O4

Produce lightcurves to inform follow-up campaigns



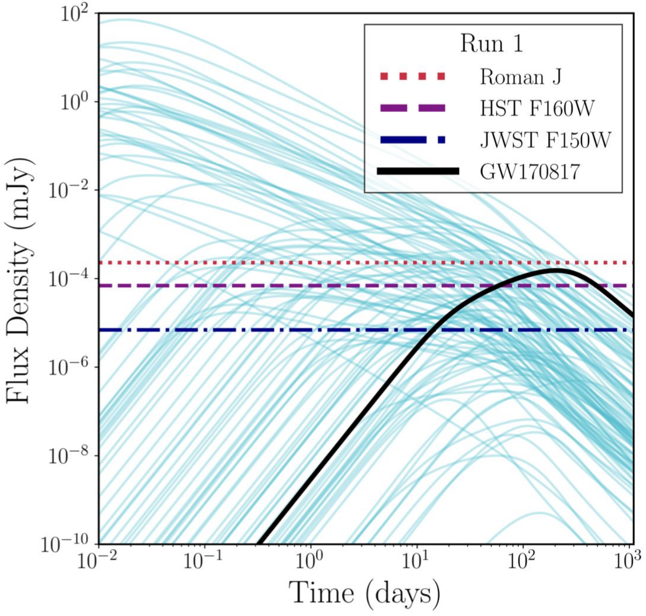
Farah+2022, ApJ; LVK 2024, ApJL

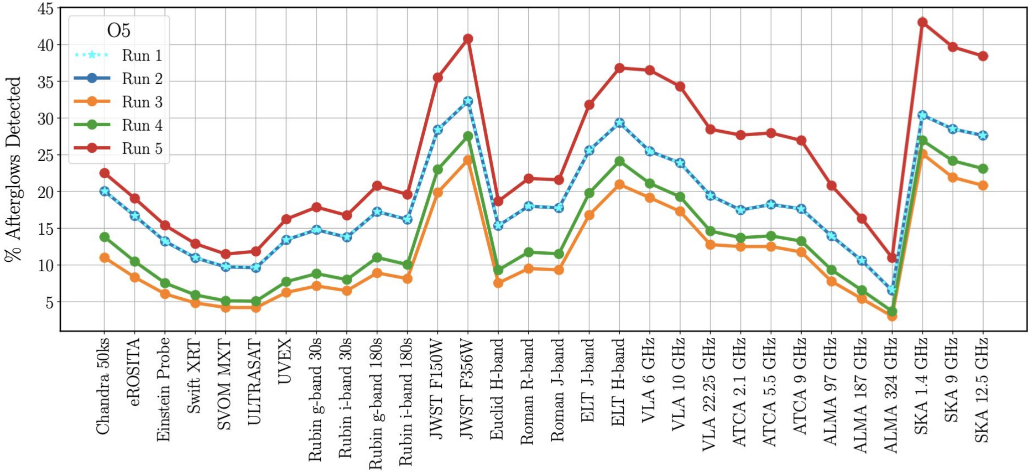
Run	Binary type	GW detection rate (yr^{-1})	KN detectability (yr^{-1})				
			Argus		Rubin		
			g	r	g	r	i
O5	BNS	$4.95^{+7.38}_{-3.76}$	$3.22^{+4.81}_{-2.45}$	$3.25^{+4.86}_{-2.48}$	$3.97^{+5.93}_{-3.02}$	$3.25^{+5.96}_{-2.48}$	$3.64^{+5.44}_{-2.77}$
	NSBH	$13.56^{+11.66}_{-7.58}$	$0.12^{+0.10}_{-0.07}$	$0.16^{+0.14}_{-0.09}$	$0.34^{+0.29}_{-0.19}$	$0.40^{+0.34}_{-0.22}$	$0.32^{+0.28}_{-0.18}$

Pretty much all
Mass gap

Kunnumkai, AP, Farah, Bulla, Dietrich, Pang, et al. 2025, ApJ arXiv:2411.13673

Multimessenger afterglow detections



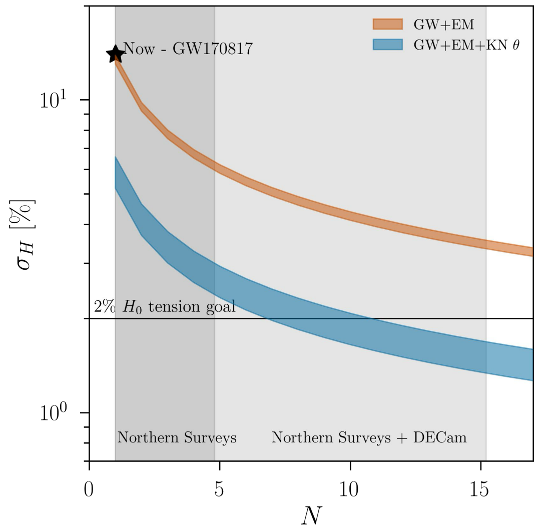


Kaur, O'Connor, AP & Kunnumkai 2024, arXiv:2410.10579

Bright Standard Sirens - Prospects

~2% measurement with ~50 events, enough to shed light on H_0 tension (Chen+2018, Feeney+2019), ~10 with viewing angle constraints

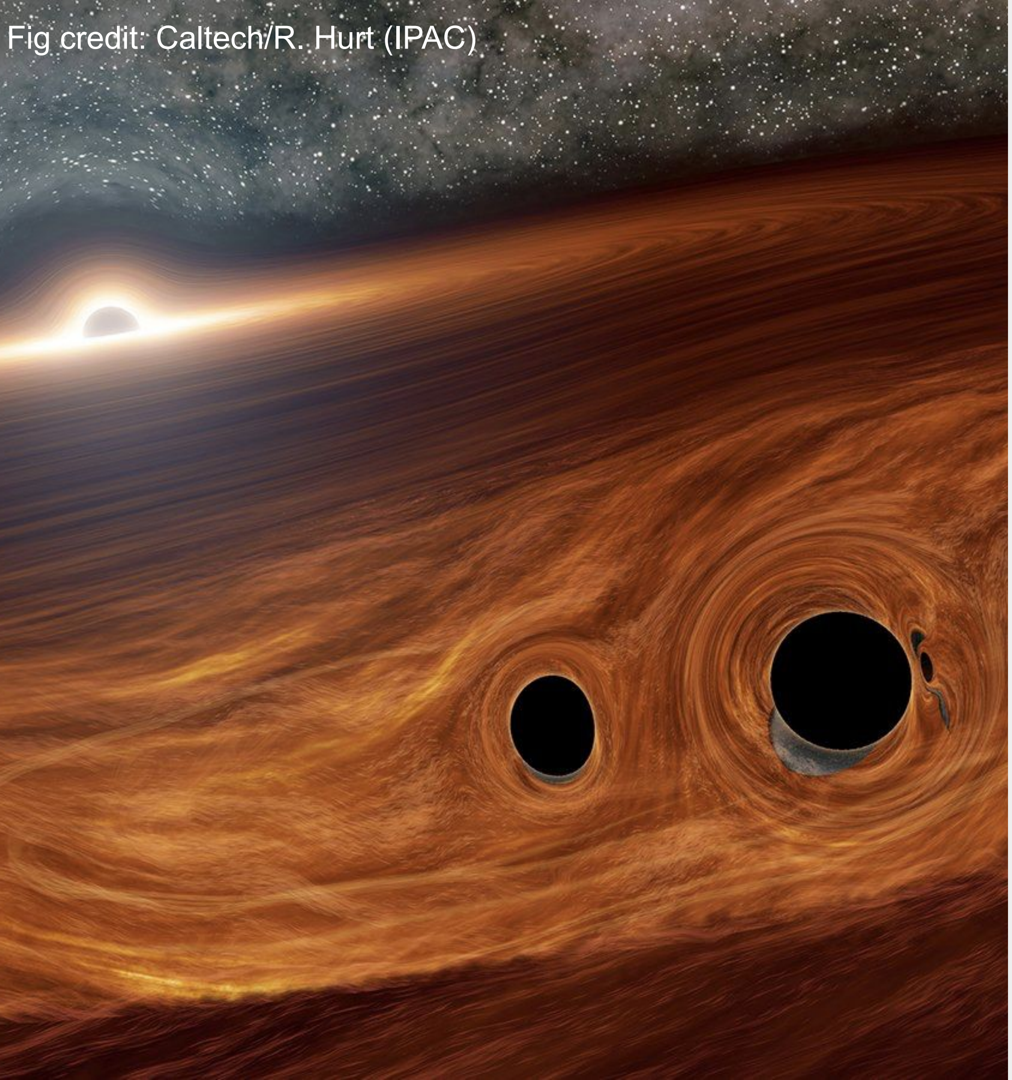
Need to wait for end of O5 (~2031) to reach ~2%



Adapted from AP+2019, arxiv:1903.04730

Potential sources of systematics/limitations:

- GW selection effects
- GW modeling (e.g. Kunert+2024)
- Peculiar velocity (nearby sources)
- Jet modeling (e.g. Gianfragna+2024), jet misalignment (Muller+2024)
- EM selection effects (e.g. Chen+ 2024, Mancarella+2024)

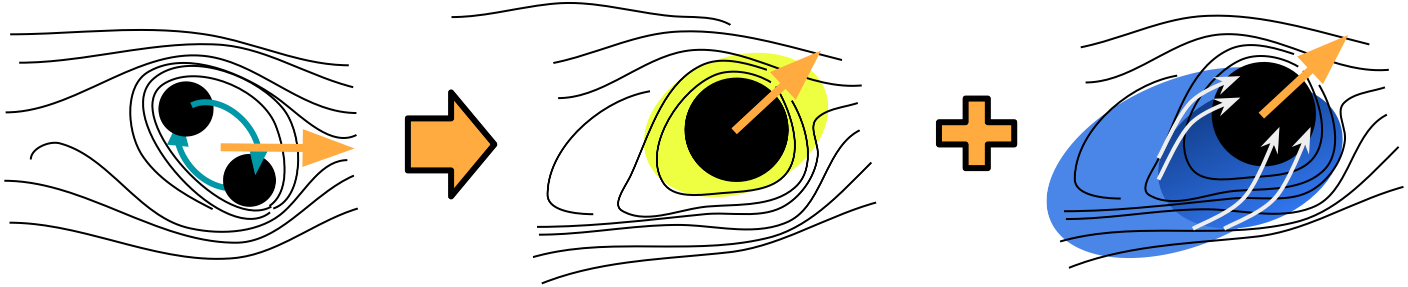


Binary black hole mergers

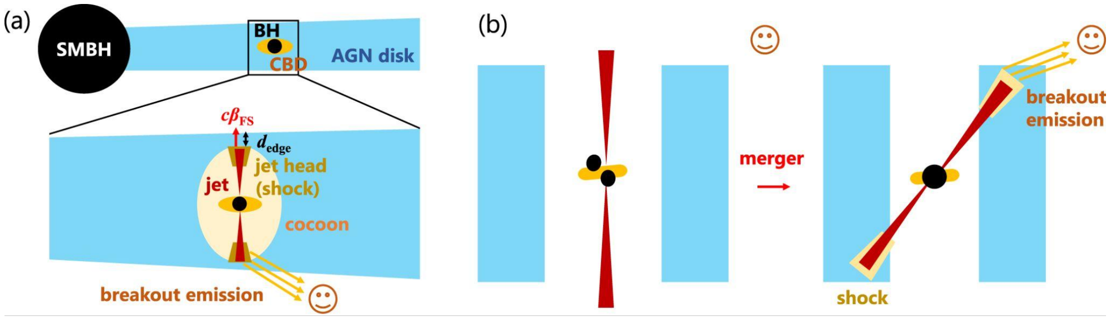
EM emission from BBH in AGN disks

See also Bartos+17

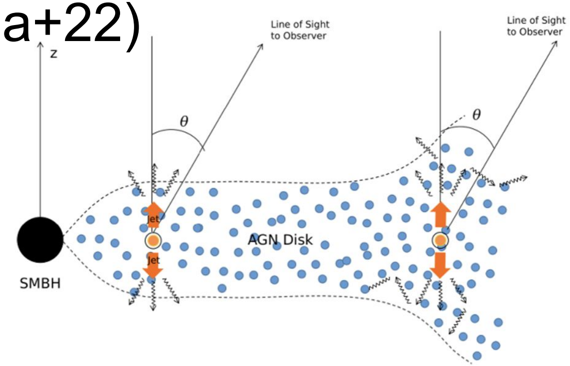
Ram-pressure stripping + Bondi tail (McKernan+19, Antoni+19)



Jet breakout, shock cooling (Tagawa+23, 24)

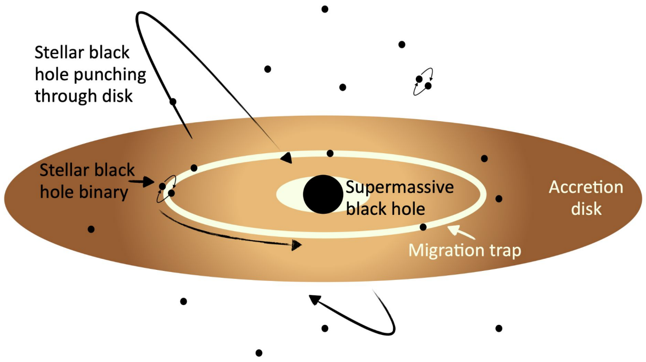


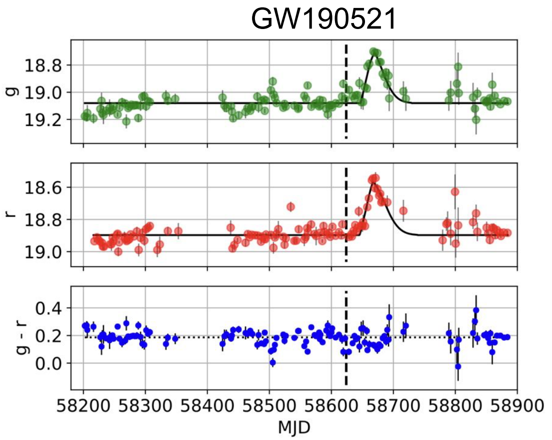
Jet afterglow (~Wang, Lazzati & Perna+22)



Do LIGO/Virgo/KAGRA BBH produce AGN flares?

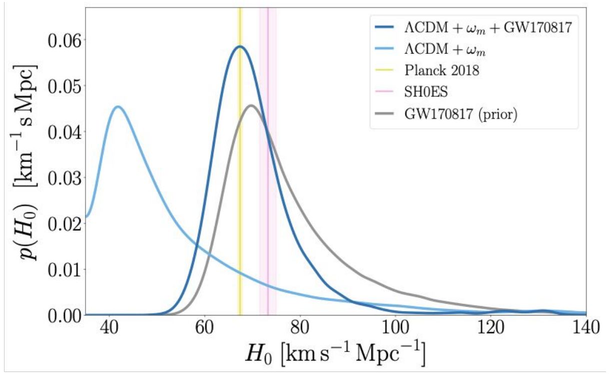
- Ideal environment for formation of massive stellar black holes through repeated mergers of smaller BH in AGN disks
- 7 AGN flare in coincidence with GW190521 (ZTF, Graham+2020, PRL arXiv:2006.14122), and other events (Graham et al 2023, ApJ, arXiv:2209.13004)



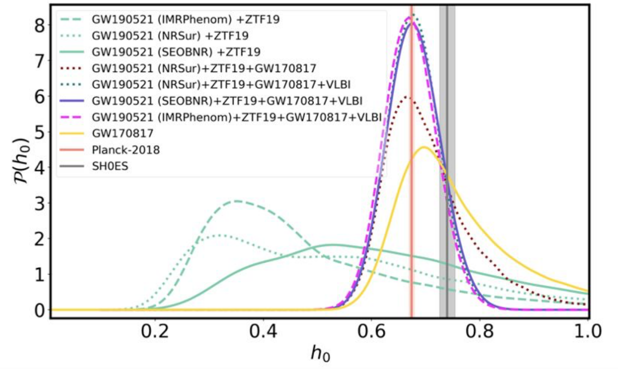


Graham+2020

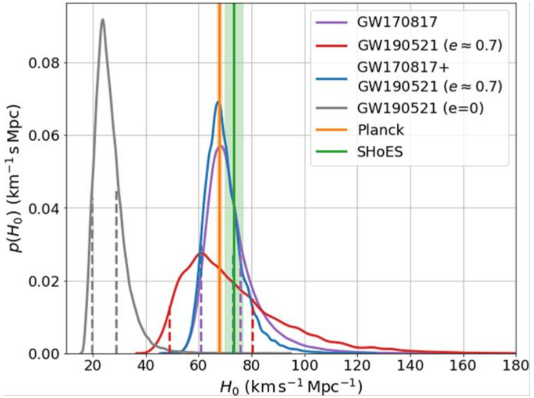
Cosmology with GW190521



Chen et al., MNRAS (2022)



Mukherjee et al., 2009.14199



Gayathri et al., ApJL (2021)

Chen+, MNRAS 2022

Mukherjee+ 2009.14199

Gayathri +, ApJL 2021

See also Alves et al. 2023, MNRAS arXiv:2009.13739

Rubin ToO

Rubin ToO: Andreoni, Margutti et al. arXiv:2411.04793

Total ToO time budget recommended for all the GW/MMA science cases

	GW case	Total time (hrs) - O5
	GW case	**Total time (hrs) - O5**
~5/year	BNS/NS-BH	240
	Lensed BNS	31
~7/year	BBH	11
	Unidentified GW	16
	Grand total	**298**

Table 4: Total Summary recommendation for GW MMA case during the LVK O5 run

Similar strategy implemented for the end of O4, currently working on IR1

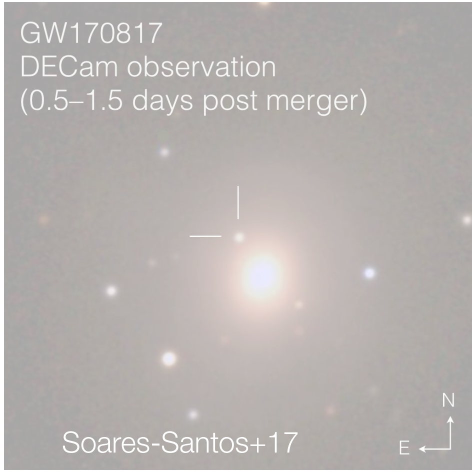
Standard Sirens

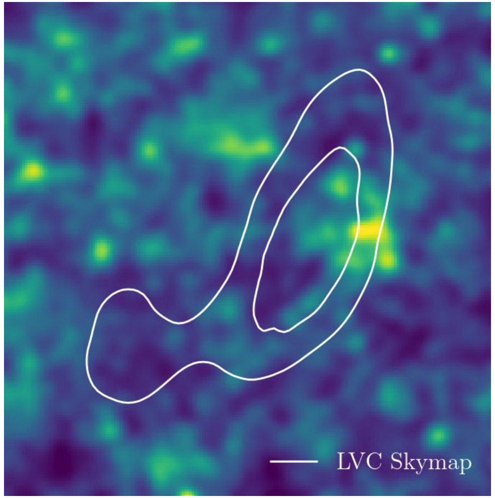
Schutz 1986
Holz & Hughes 2005
MacLeod & Hogan 2008
Nissanke+2010

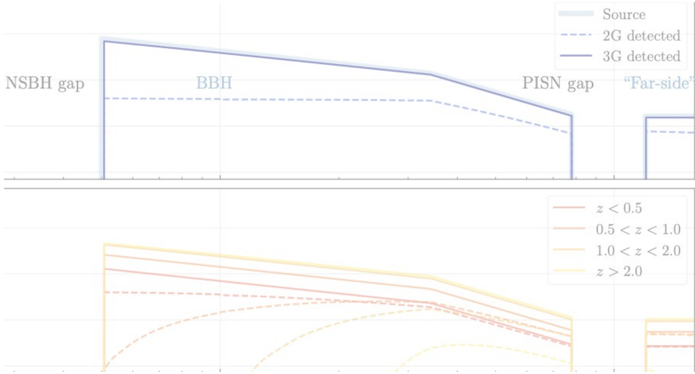
Bright
BNS/NSBH

Dark (x galaxies)
BBH/NSBH

Dark (GW alone)







Ezquiaga+22

Redshift from:

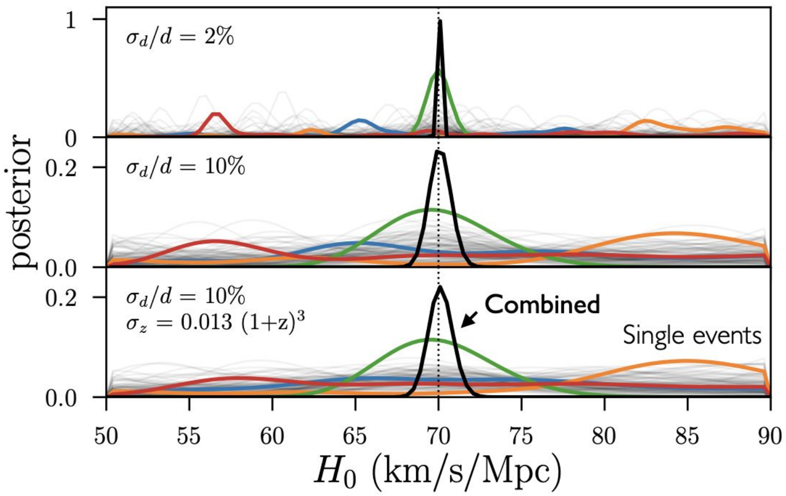
Host galaxy

Galaxies

Redshifted mass

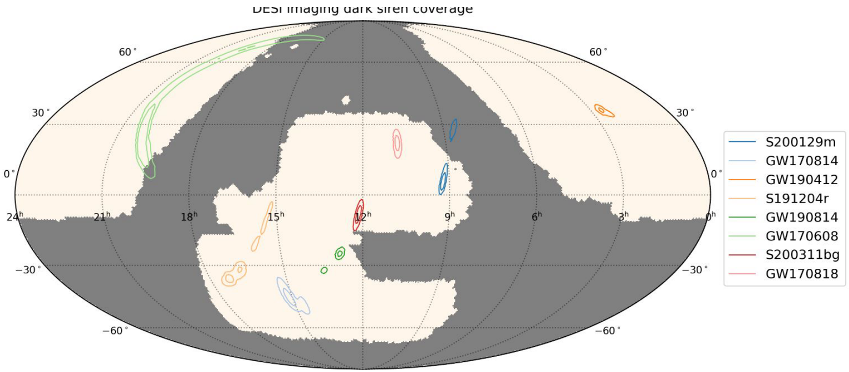
Dark sirens - simulations

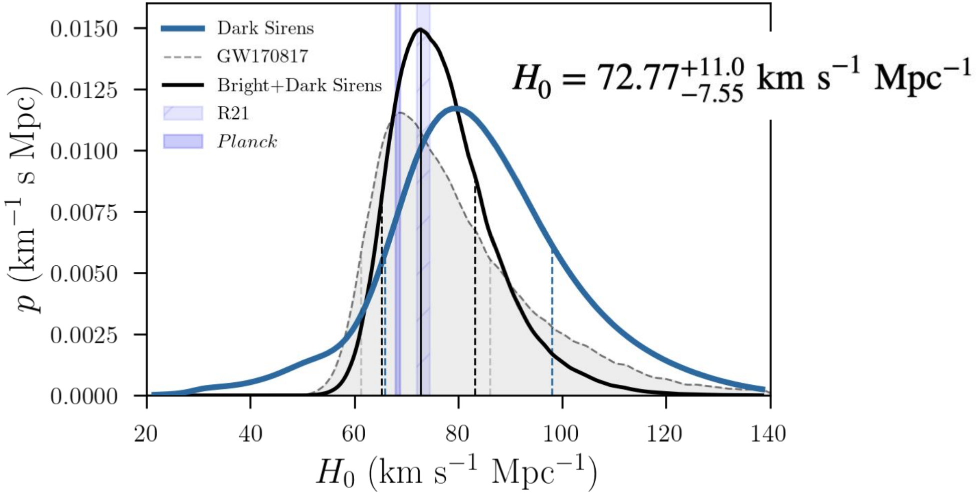
- Dark Energy Survey-like galaxy simulations (DeRose et al. 2019, Wechsler et al. 2021)
- Simulated GW events on a galaxy at *z* with H_0=70 km/s/Mpc
- **Single events**: posterior expected to have peaks corresponding to large scale structure along the line of sight
- **Peaks are broadened and blended** if d or z uncertainty increases.
- **Converge to the input value** of H_0 from combining enough events (O(100))



Dark sirens with LIGO/Virgo/KAGRA O3 events

See also LIGO, Virgo, KAGRA 2023, ApJ arxiv:2111.03604



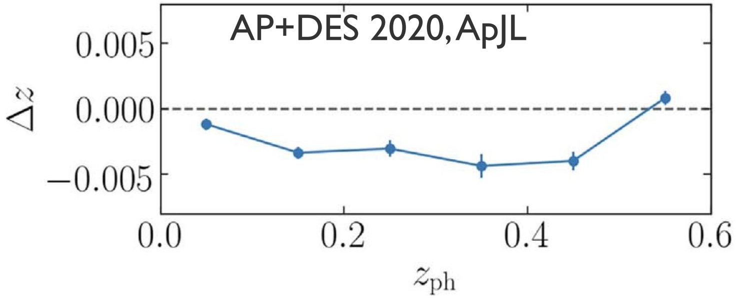


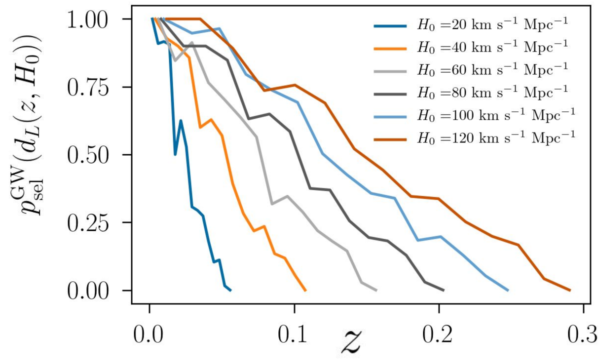
- **O3**: 50+ alerts, no high confidence counterparts
- Only consider **well-localized events + high completeness galaxy catalog** (**DESI** imaging)
- Less sensitive to populations assumptions than analyses with less complete catalogs, but smaller statistics
- Nearly 30% improvement to bright standard siren precision

AP, Bom, Mucesh, Hartley 2023, ApJ arxiv:2111.06445

Dark sirens systematics

- Systematics related to **photometric redshifts**: bias correction, full redshift PDF
- **GW Selection effects**
- **Galaxy catalog completeness** corrections (e.g. Fishbach+2019, Gray+2020)
- Expectations from **different BBH formation scenarios**
  - Some work on galaxy **weighing** Perna et al. 2024; Hanselman et al. 2025)

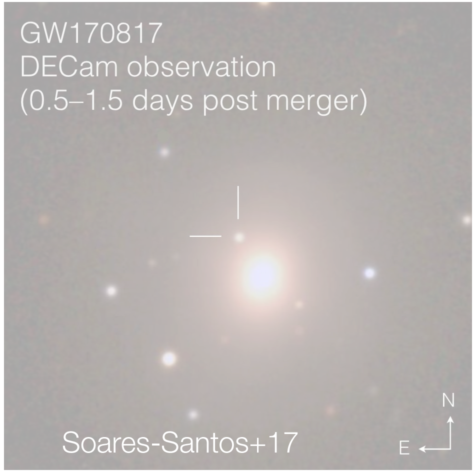




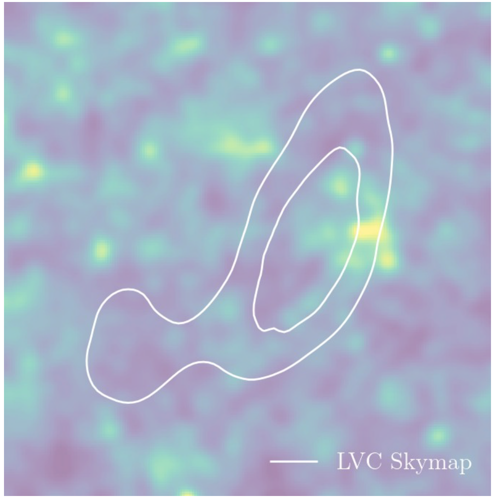
Standard Sirens

Schutz 1986
Holz & Hughes 2005
MacLeod & Hogan 2008
Nissanke+2010

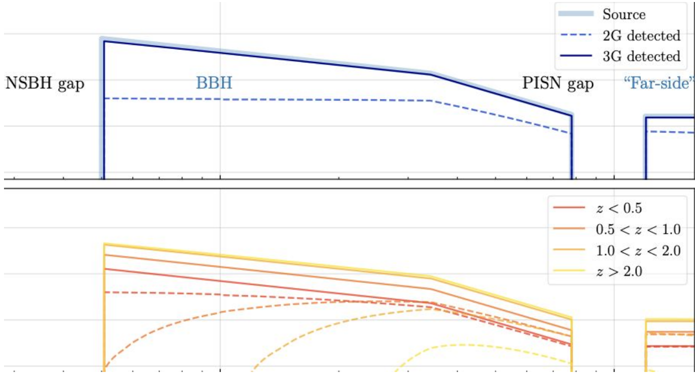
Bright
BNS/NSBH



Dark (x galaxies)
BBH/NSBH



Dark (GW alone)



Ezquiaga+22

Redshift from:

Host galaxy

Galaxies

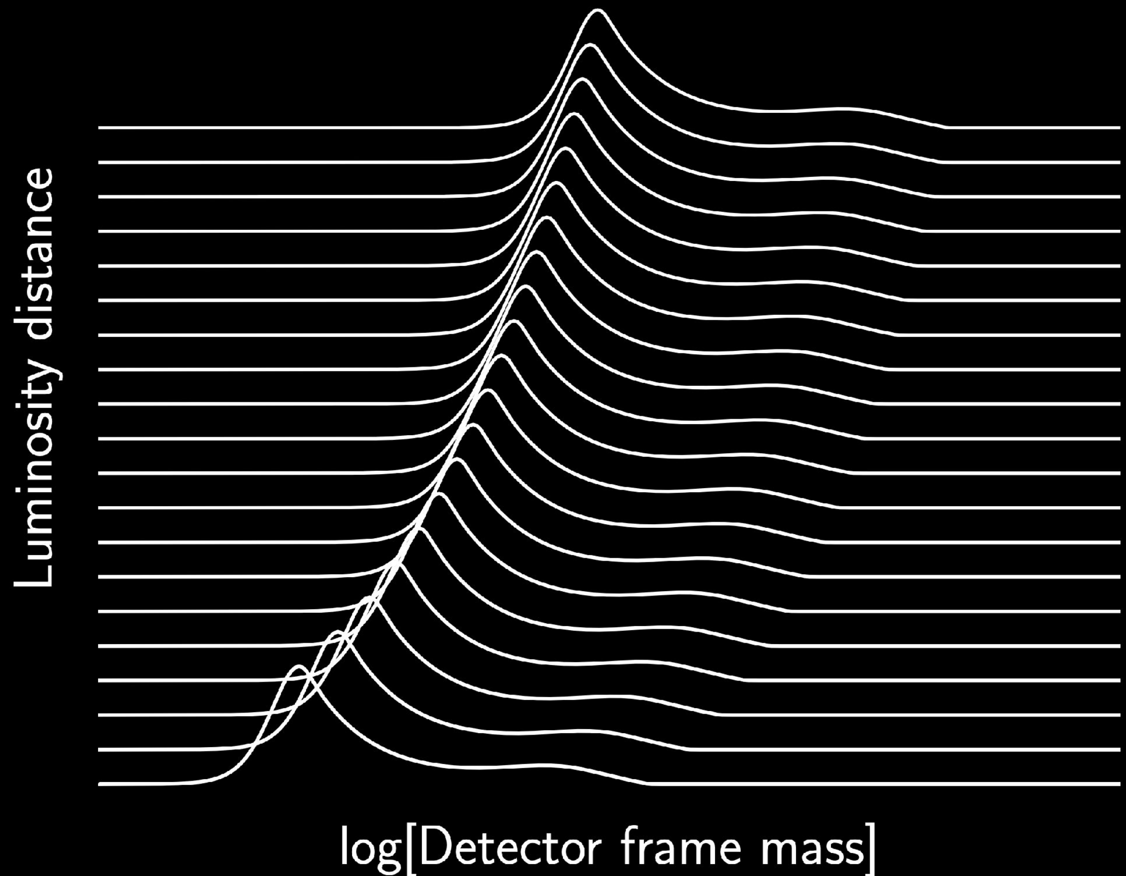
Redshifted mass

SPECTRAL SIRENS

$$\boxed{\{d_L(z), m_{\rm det} = (1+z)m\}}$$

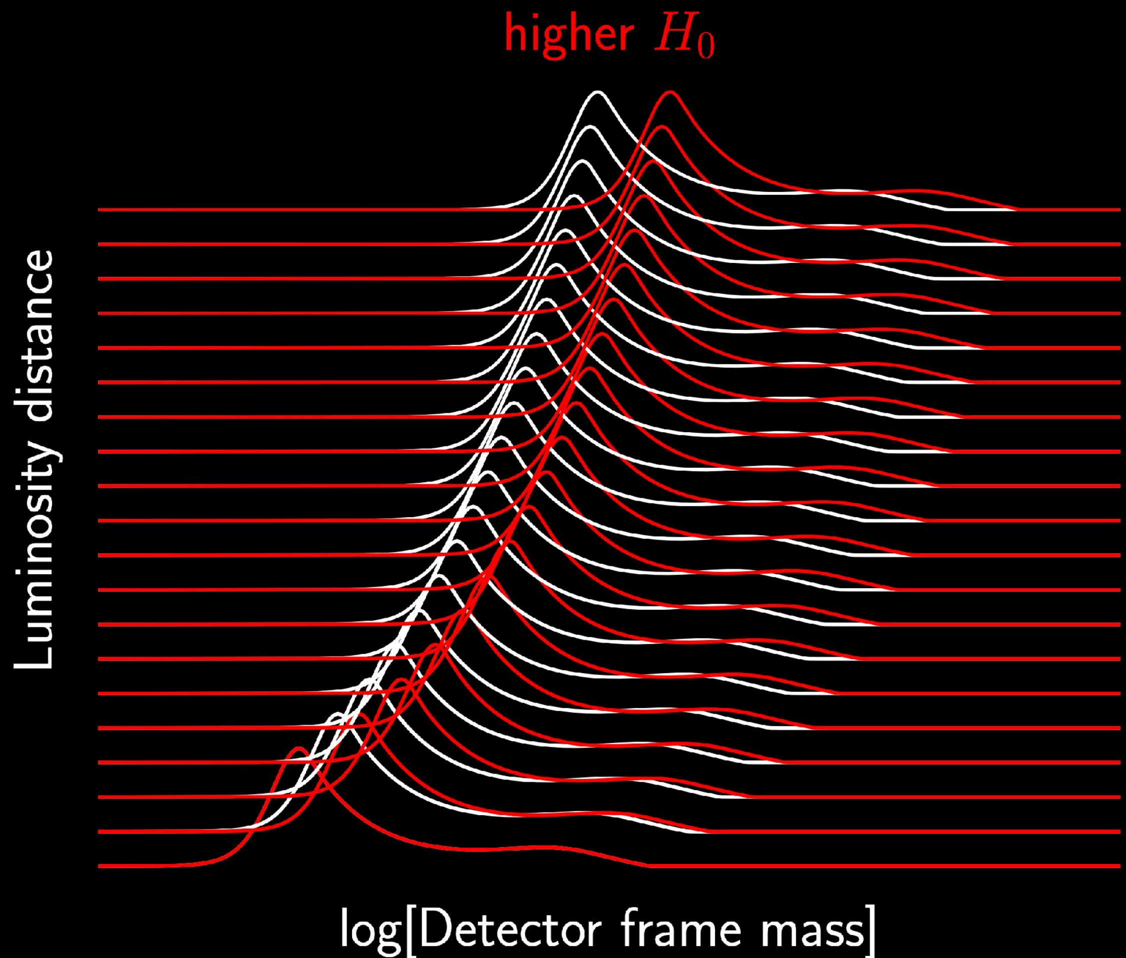
Credit: J. Ezquiaga

SPECTRAL SIRENS



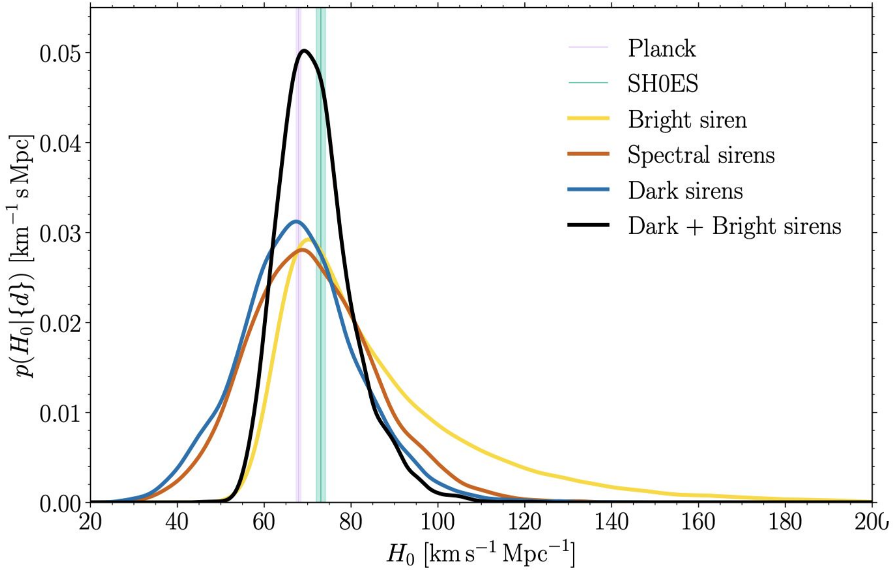
Credit: J. Ezquiaga

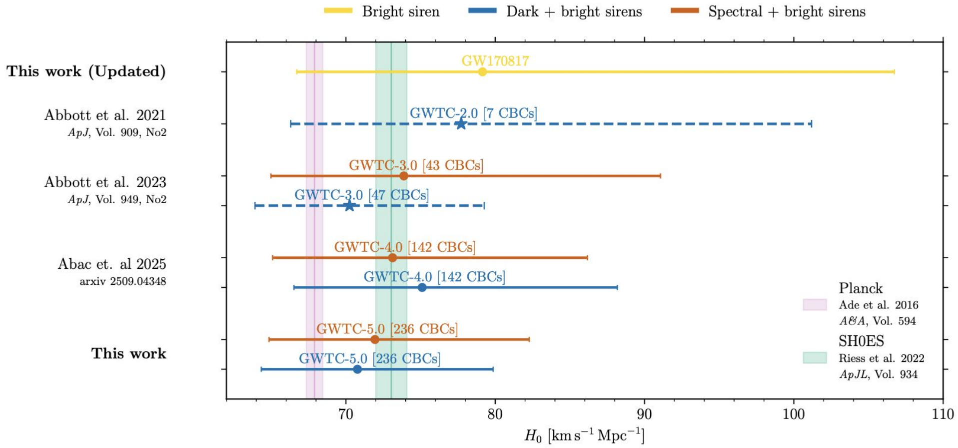
SPECTRAL SIRENS



Credit: J. Ezquiaga

Dark and spectral siren measurements with GWTC-5





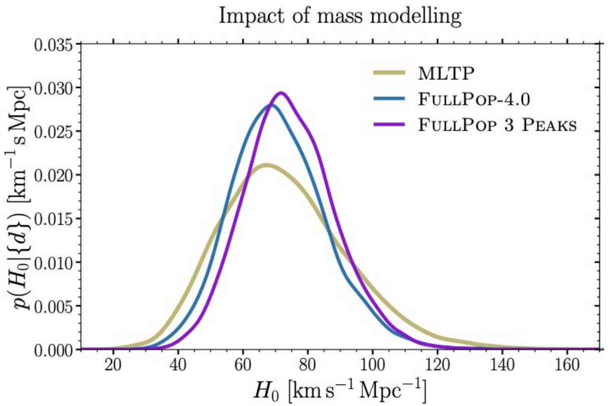
GLADE+ and DES galaxy catalogs

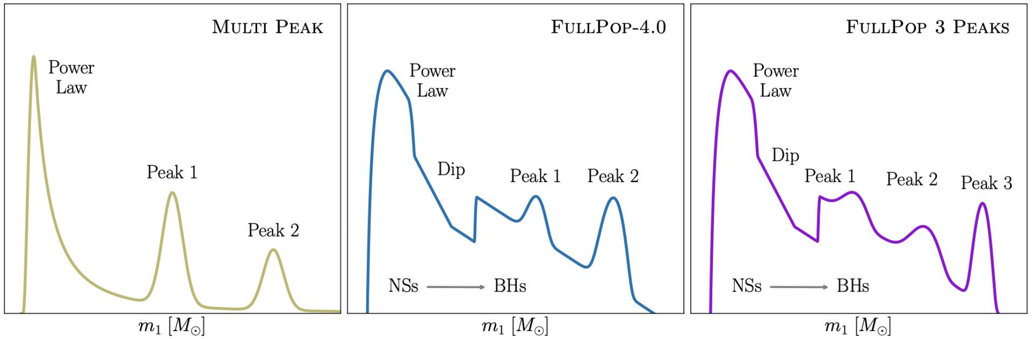
Marginalize over possible population

~26% precision improvement compared to GWTC-4 (up to O4a)

LVK 2026 https://arxiv.org/pdf/2605.27227

Dark and spectral siren measurements with GWTC-5

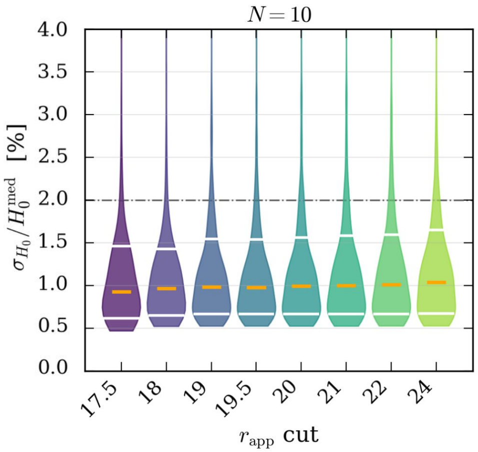


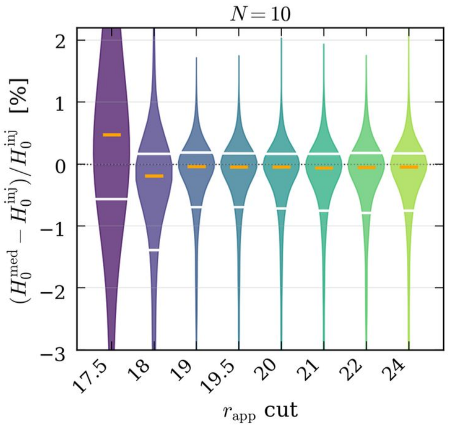


LVK 2026 https://arxiv.org/pdf/2605.27227

Dark siren prospects for current generation detectors

- Realistic O5 and A# black hole mergers simulation+Uchuu LSST-like cosmological simulation
- Top 10 A# events/year → 1-1.5% H_0 precision (achievable ~2030s?)
- Top 10 O5 events → 1-4% precision in O5
- DESI-like volume limited sample provides unbiased results
- Minimal impact of weighting scheme





Dang, Amsellem, Magaña-Hernandez, AP, Sathyaprakash 2026, arxiv:2607.17284

Conclusions

- **Standard sirens** are unique cosmological probes
- **2% H_0 precision needed** to provide insights on **Hubble tension**
  - ~10 bright standard sirens with EM viewing angle constraints
  - ~10 extremely well localized dark standard sirens
  - Possible by ~2032
- Standard sirens can measure **cosmological parameters beyond H_0**
- Different kinds of standard sirens are **complementary** and powerful when combined
- There is **a lot more** to learn from combining GW+EM observations: **modified gravity, neutron star equation of state** and **nuclear physics**, **origin of black holes and neutron stars**, the **formation of the heavy elements** in the Universe

Contact: palmese@cmu.edu - DES, DESI, LISA, Cosmic Explorer, Discovery Alliance, Rubin Observatory