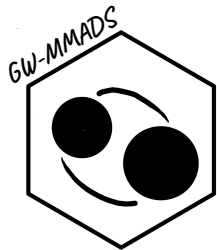


Carnegie Mellon University

Gravitational wave cosmology



Antonella Palmese

July 2026

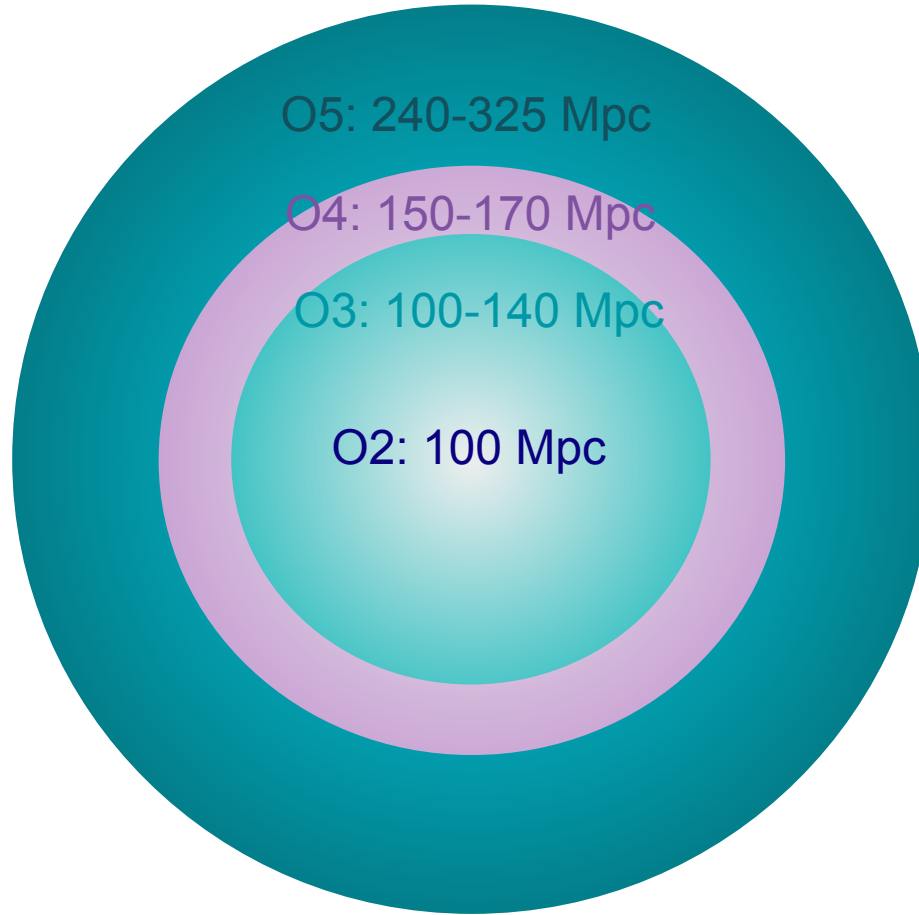
Exploring New Frontiers in Cosmology

GGI - Florence



McWilliams Center for
Cosmology & Astrophysics

BNS Merger
Horizon

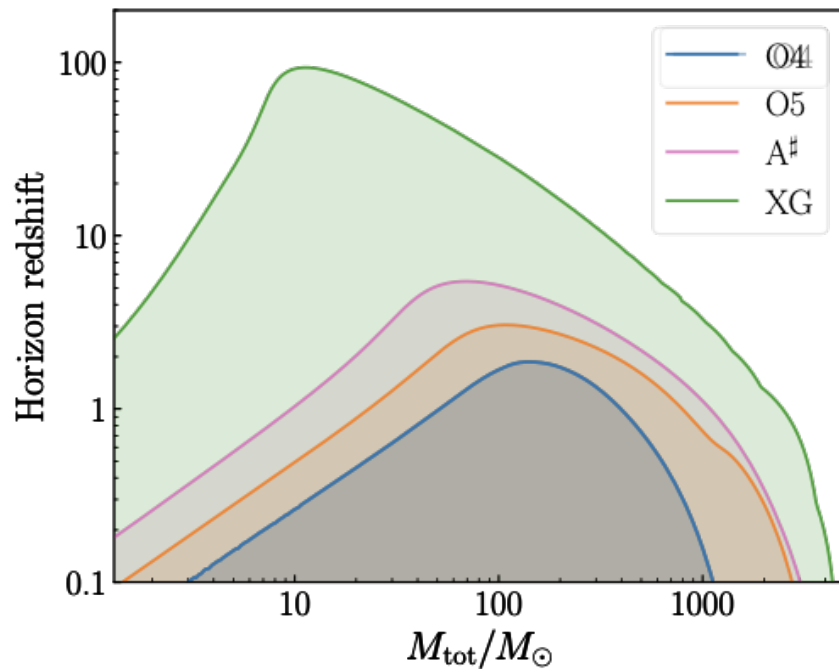
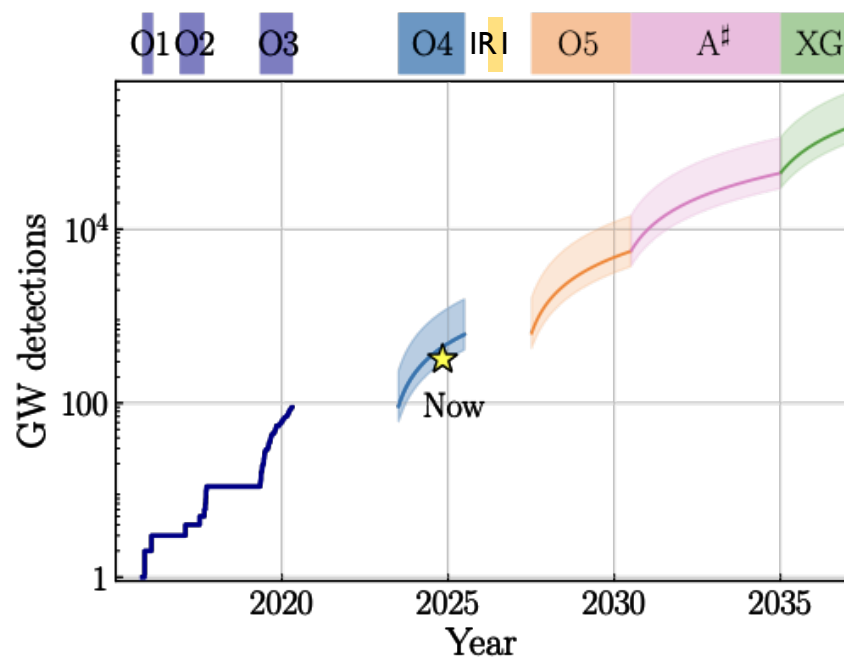


O5 vs O2: > 1
order of mag
more volume

Acronyms: BNS - binary neutron star, BBH - Binary Black Hole, LVK -
LIGO Virgo KAGRA

LIGO BNS range, single detector SNR>8
<https://emfollow.docs.ligo.org/userguide/capabilities.html>

Future prospects



Please log in to view full database contents.

LIGO/Virgo/KAGRA Public Alerts

- More details about public alerts are provided in the [LIGO/Virgo/KAGRA Alerts User Guide](#).
- Retractions are marked in **red**. Retraction means that the candidate was manually vetted and is no longer considered a candidate of interest.
- Less-significant events are marked in **grey**, and are not manually vetted. Consult the [LVK Alerts User Guide](#) for more information on significance in O4.
- Less-significant events are not shown by default. Press "**Show All Public Events**" to show significant and less-significant events.

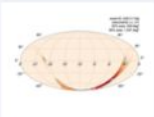
O4 Significant Detection Candidates: **254** (283 Total - 29 Retracted)

O4 Low Significance Detection Candidates: **5136** (Total)

Show All Public Events

Page 1 of 19. [next](#) [last](#) »

SORT: EVENT ID (A-Z) ▾

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S251117dq	BBH (>99%)	Yes	Nov. 17, 2025 21:38:33 UTC	GCN Circular Query Notices VOE		1 per 5.4005e+06 years	

Slack bot: <https://github.com/scimma/slackbot>



Gravitational Wave Events

LIGO/Virgo/KAGRA GCN alerts

Open

132 RATINGS

4.8

★★★★★

AGE RATING

4+

Years

CATEGORY



Education

DEVELOPER



Peter K

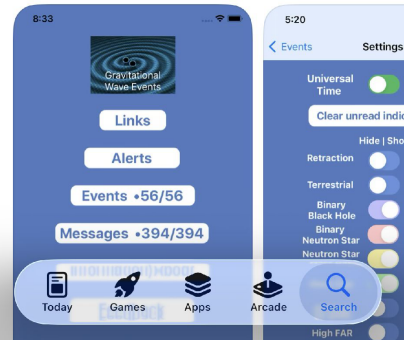
What's New >

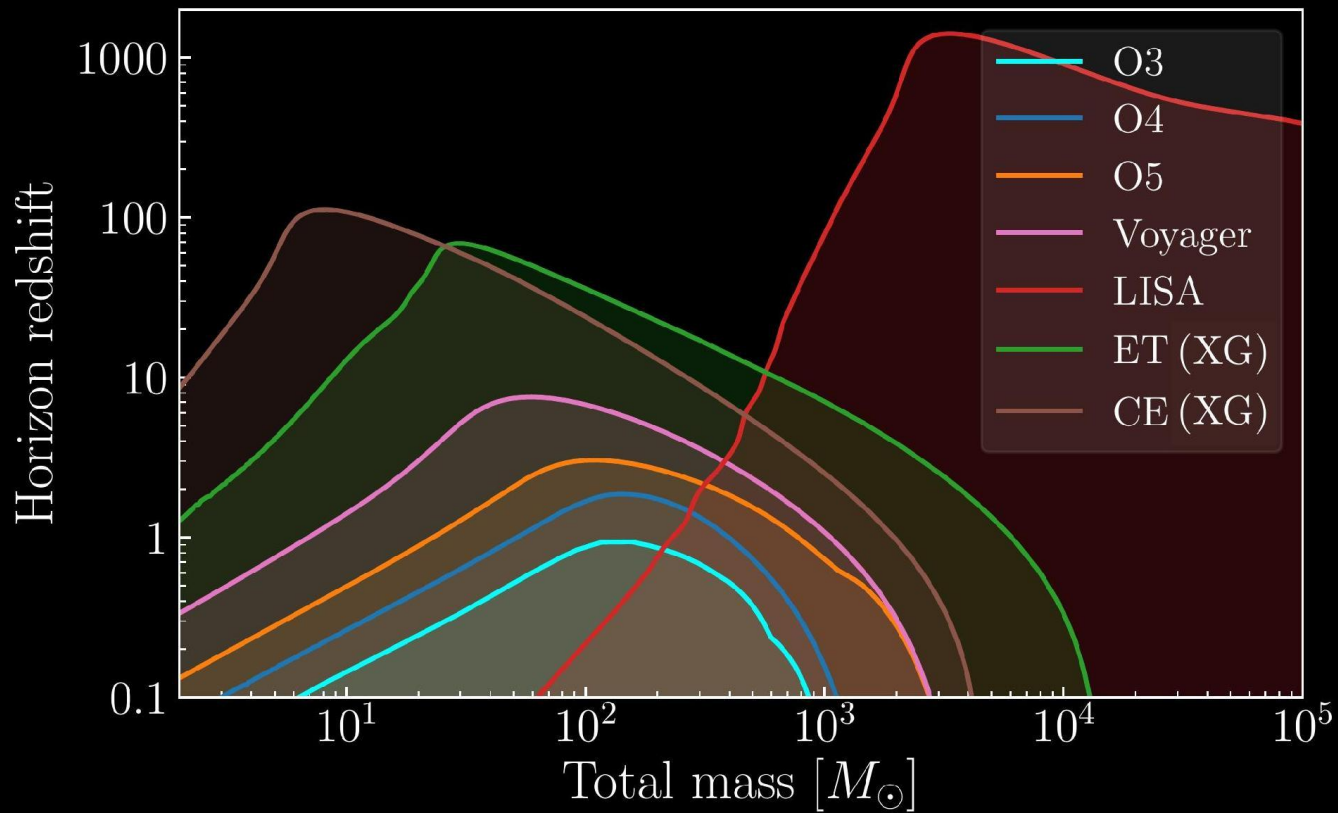
Version 2.2.2

3d ago

Updated for visual features of iOS26.

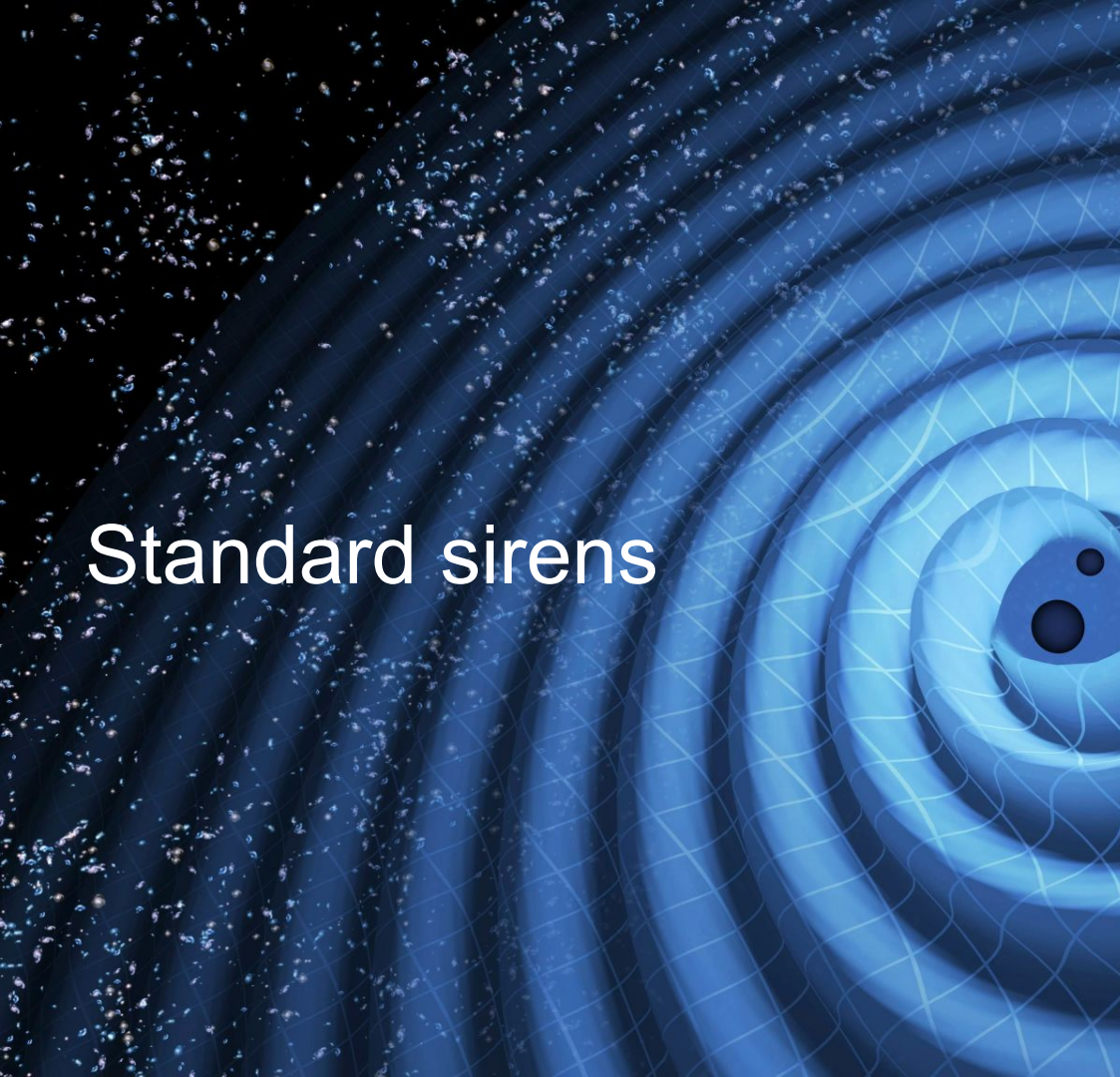
Preview





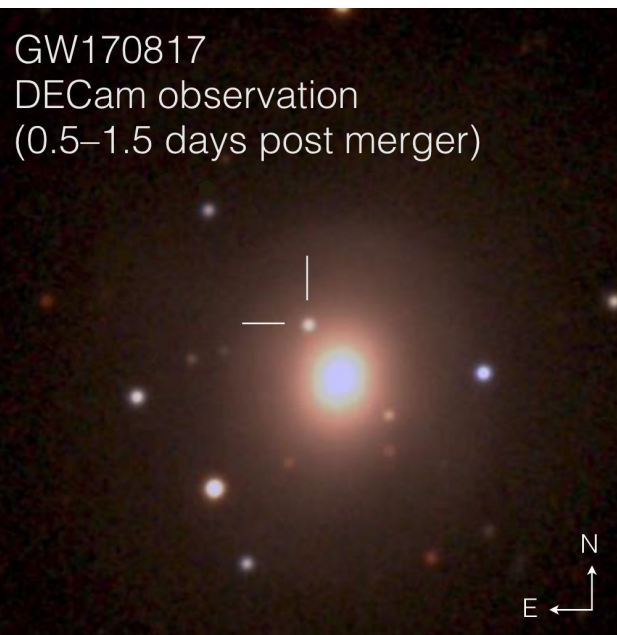
2. Key takeaways

- Gravitational waves detectors are describes by their *noise* and *antenna pattern* function
- The *optimal signal to noise* is given when the filter matches the signal
- Data stream can be *matched filtered* using a template bank. An event is found when it cannot be explained by noise background
- Once an event is detected, we can infer the parameters. This is a *15D* parameter space
- Almost *400* significant events since the first observation. *Many* more to come in the *future*!

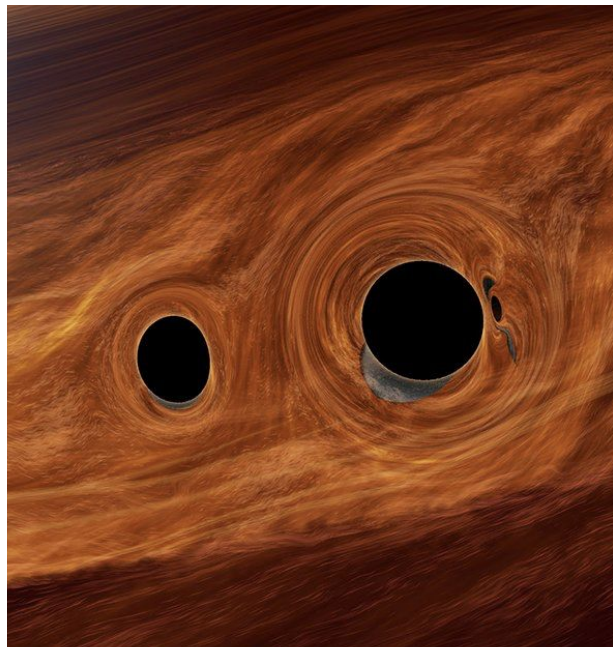


Standard sirens

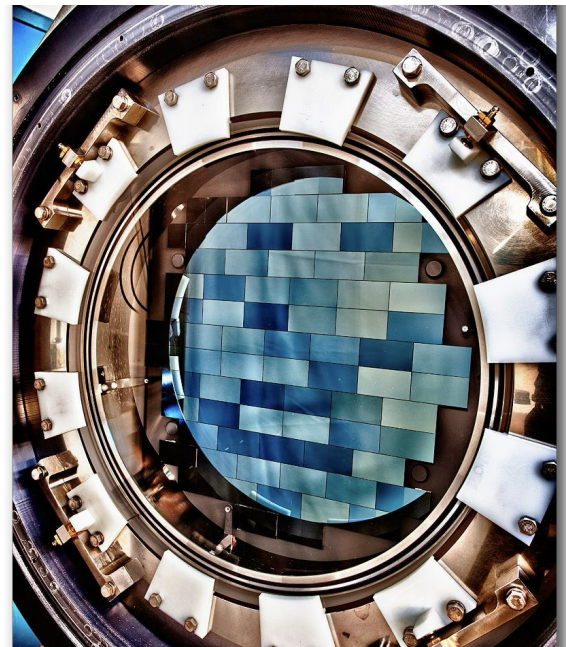
Outline



Standard sirens and neutron star mergers



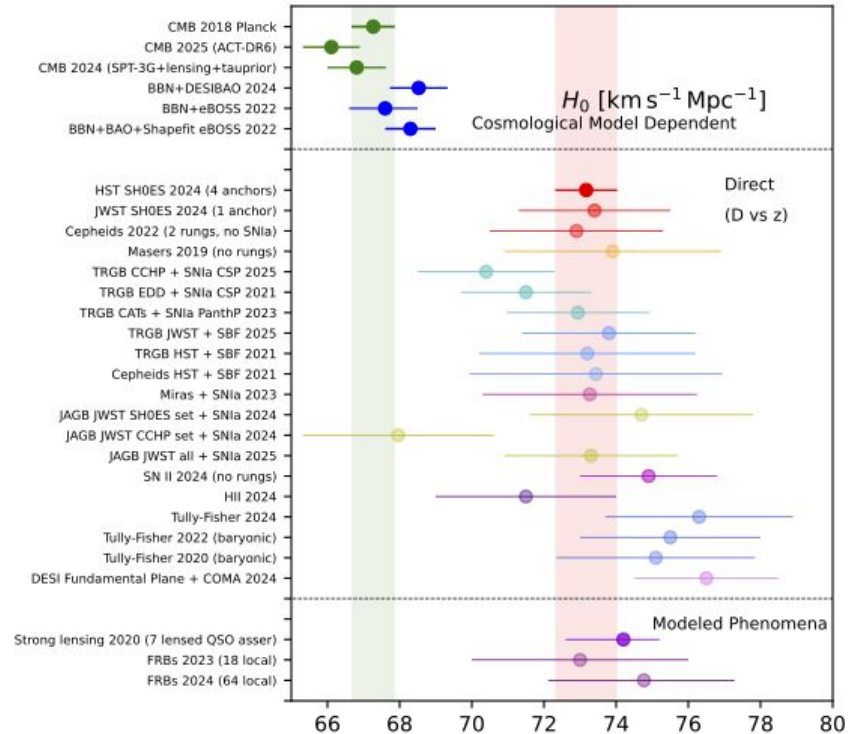
Binary Black Holes



GW follow-up

Hubble tension

- **$>4\sigma$ 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 et al, +25

Standard Sirens

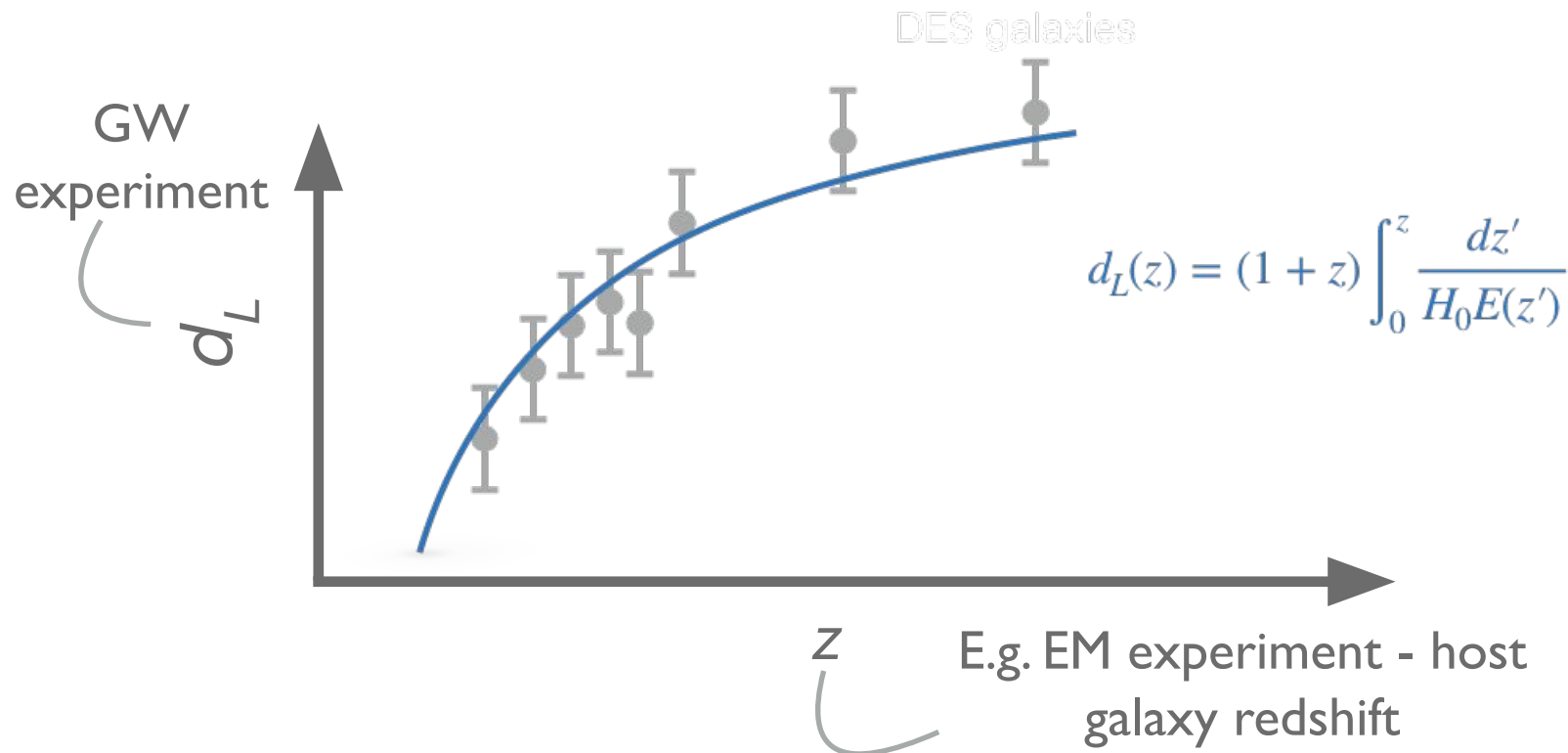
Schutz 1986

Holz & Hughes 2005

Nissanke+2010

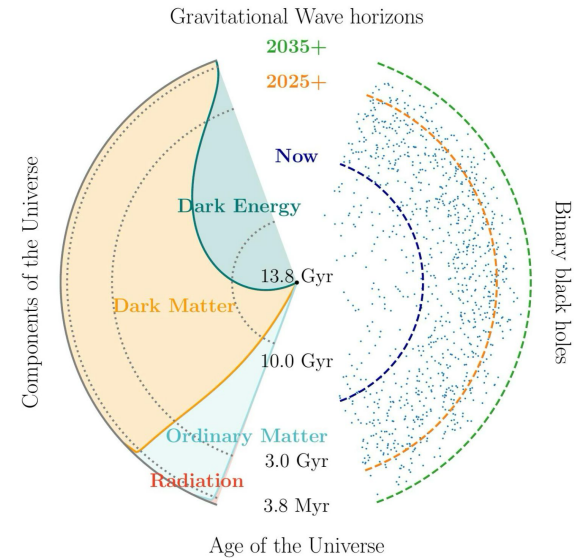
MacLeod & Hogan 2008

Del Pozzo 2012...



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. Signals are understood **from first principles** -> distance measurement is too!
3. GWs **travel unaltered** through the Universe, except for gravitational lensing
4. GW wavelengths are of **astrophysical scale**



Standard Sirens

Schutz 1986

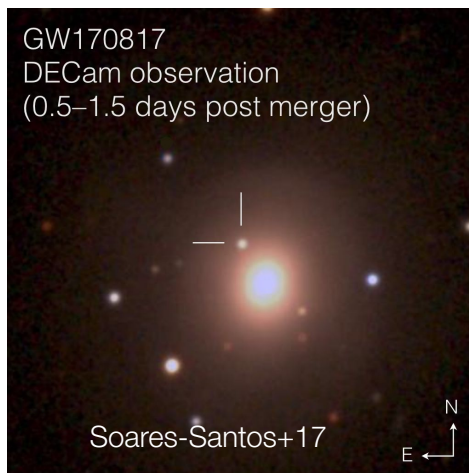
Holz & Hughes 2005

Nissanke+2010

MacLeod & Hogan 2008

Del Pozzo 2012...

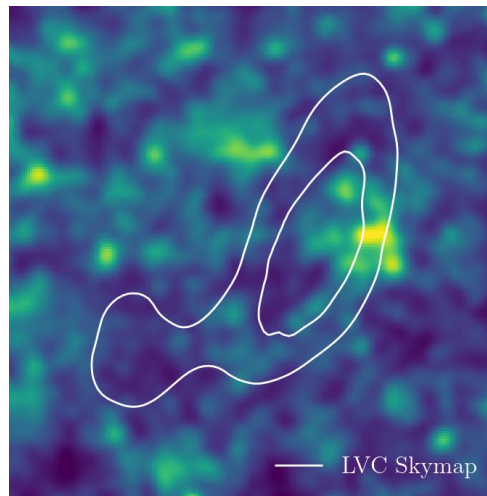
Bright
BNS/NSBH (+BBH?)



Redshift from:

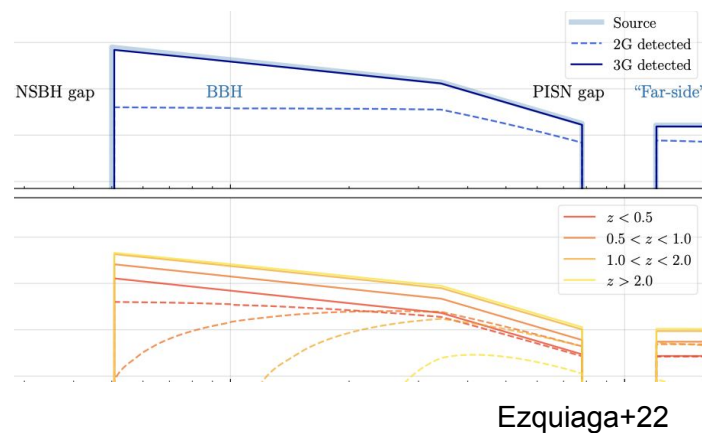
Host galaxy

Dark (x galaxies)
BBH



Galaxies

Dark (GW alone)
All



Redshifted mass

See AP & Mastrogiovanni (2025) arXiv:2502.00239 for a review¹²

Standard siren bets

Join by Web PollEv.com/antonellapal851



Which will reach the 2% H0 precision first?

Bright sirens



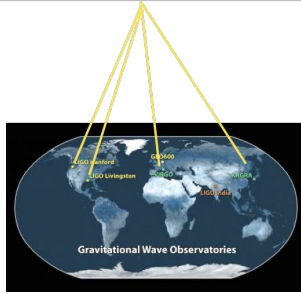
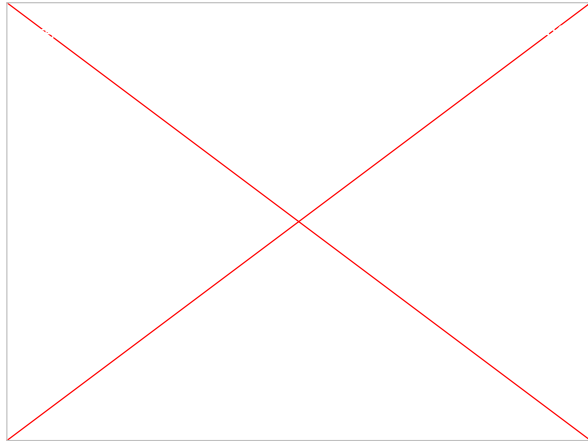
Dark sirens (galaxy catalogs)



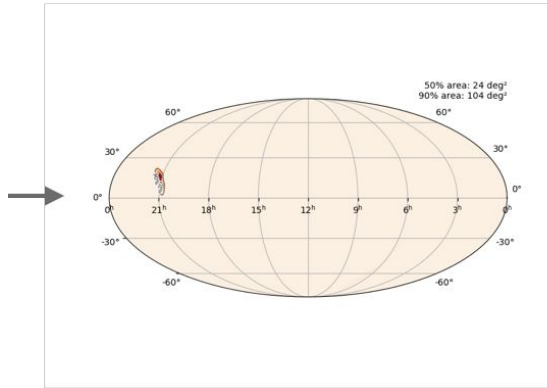
Spectral sirens



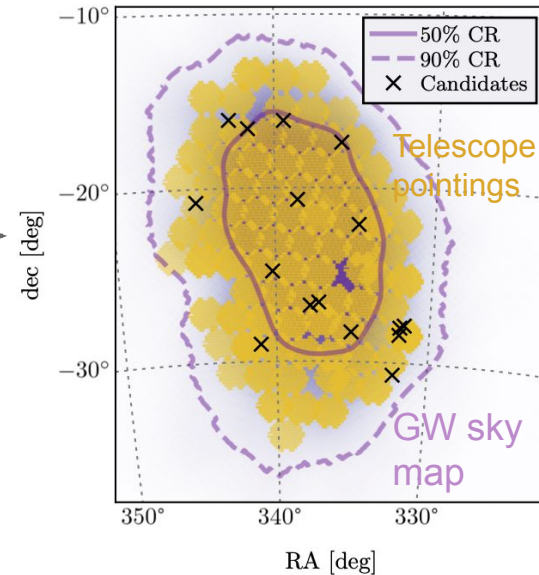
Gravitational waves and Electromagnetic follow-up



GW from merging neutron stars or black holes



LIGO/Virgo/KAGRA send
GW alert

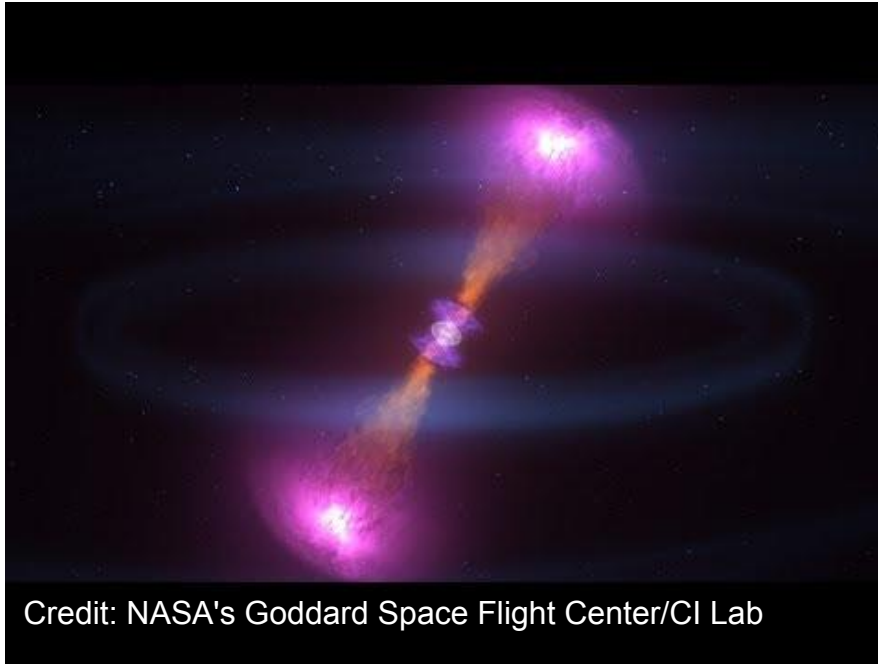


Telescope follow-up to identify
electromagnetic (EM) counterpart:
DECam, Rubin LSST, SALT,
Gemini, HST, JWST...



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

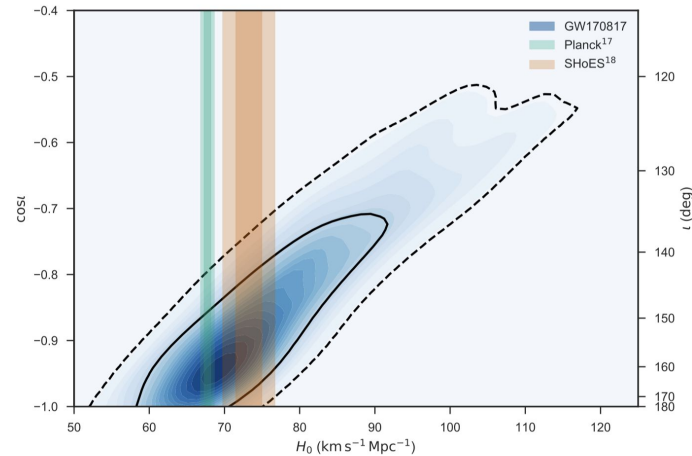
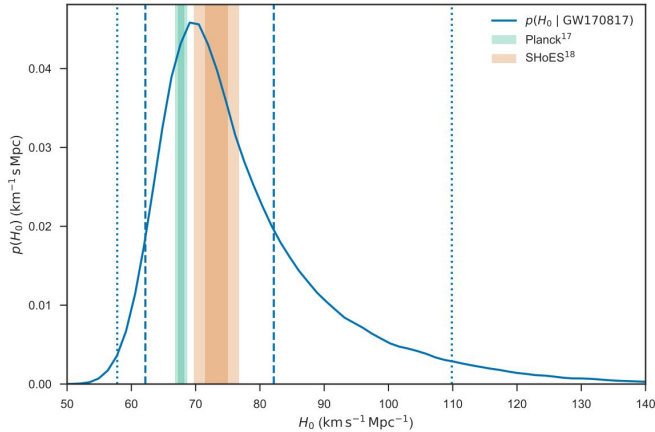


- **Relativistic jet** - gamma rays (magenta)
- Ejecta from **kilonova** - UV/optical/infrared (violet and white to red)
- **Afterglow** - X-rays, optical, radio

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 ($z \sim 0.01$)

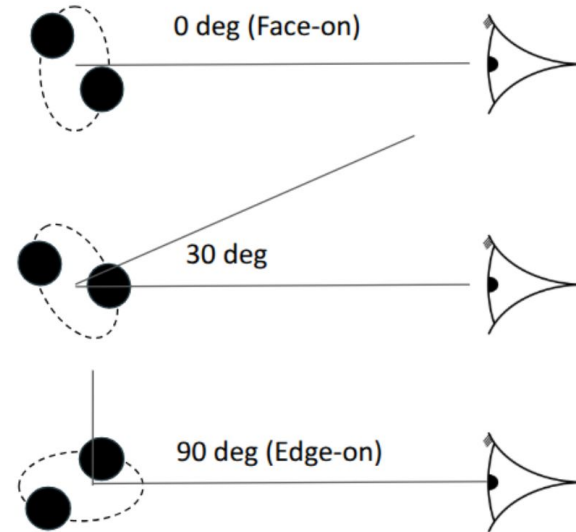
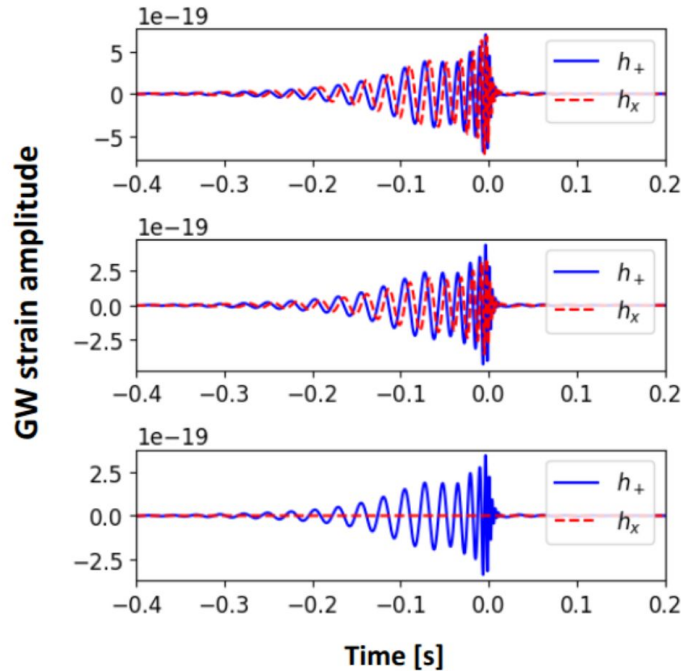
$$H_0 = 70_{-8}^{+12} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

- **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

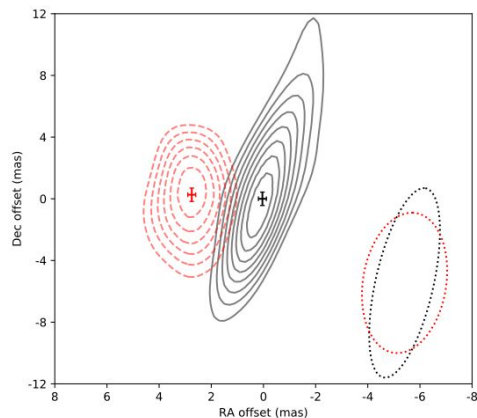
Standard sirens - viewing angle-distance degeneracy



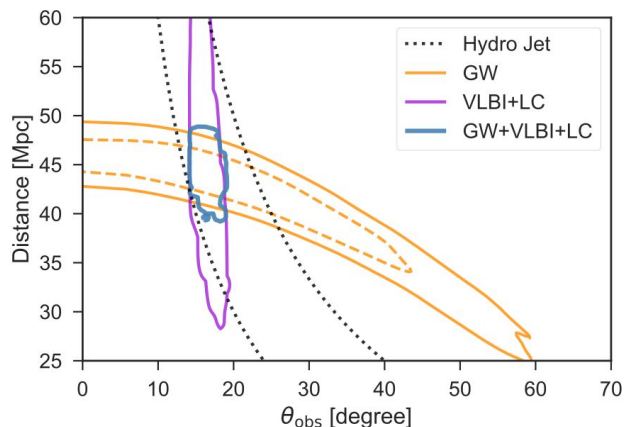
Credit: S. Mastrogiovanni

GW170817 bright standard siren - viewing angle

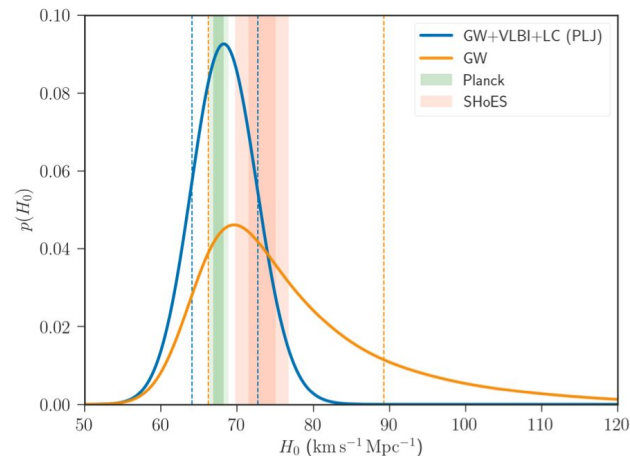
Break **distance-inclination degeneracy** by constraining viewing angle from EM observations



Mooley et al. 2018, Nature

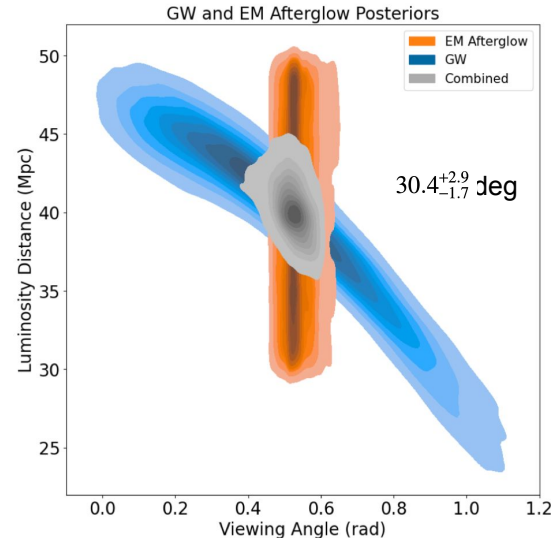
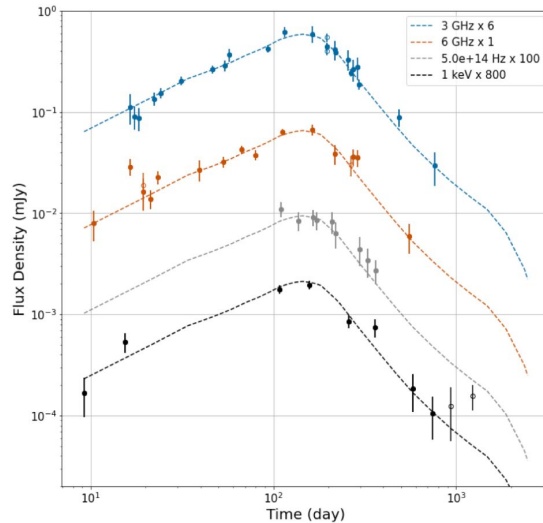


Hotokezaka+2019, Nat. Ast.



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

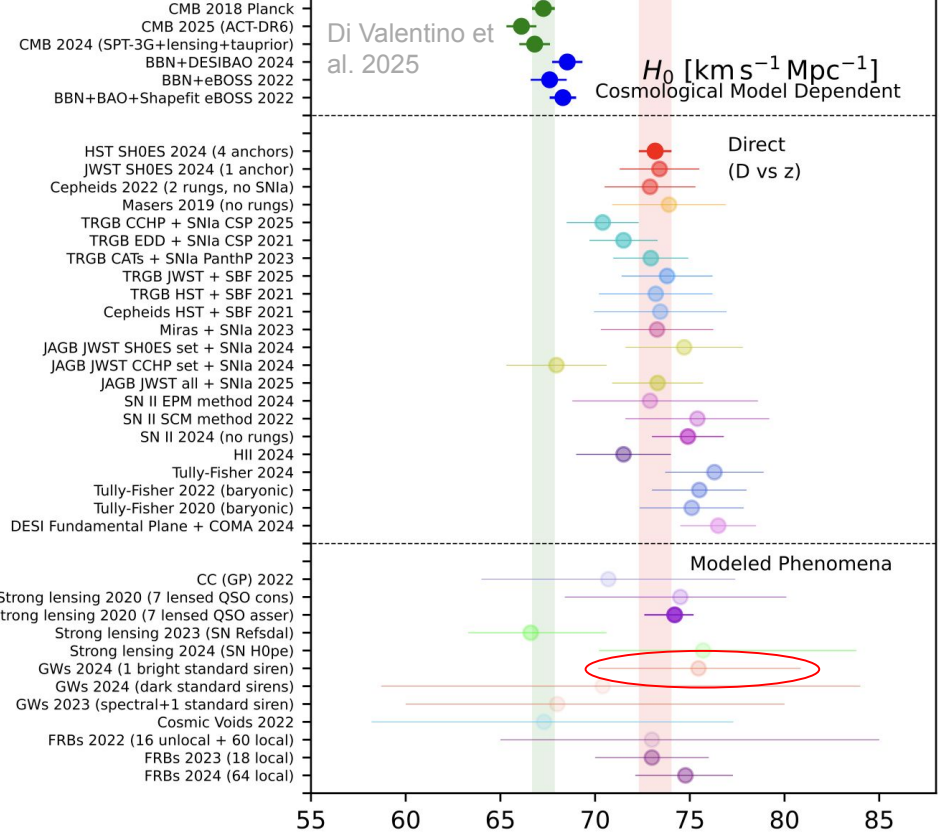
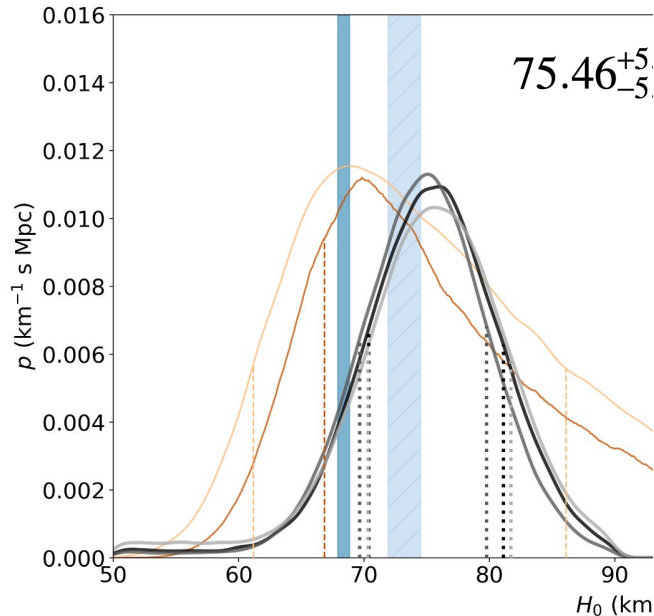


GW170817 bright standard siren

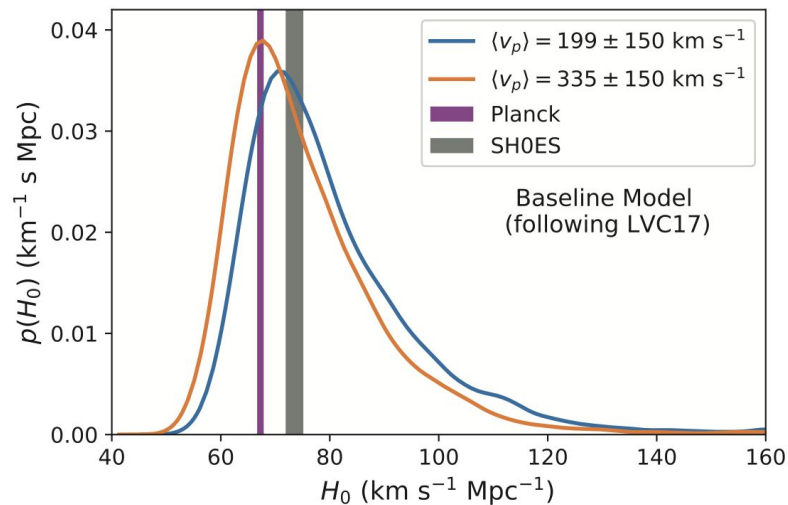
Joint GW-EM inference with host galaxy

Tests of the effect of assumptions on jet

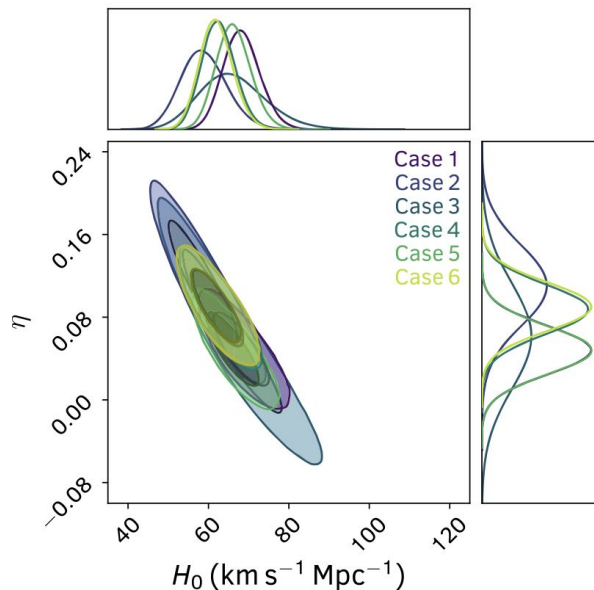
~7% H_0 precision measurement (vs 14'



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) 26

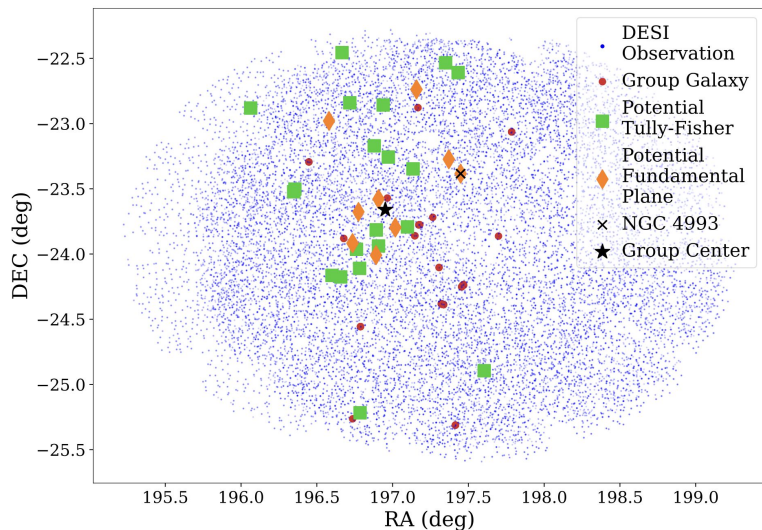
GW170817 as a bright standard siren - DESI

DESI observed 39 group galaxies

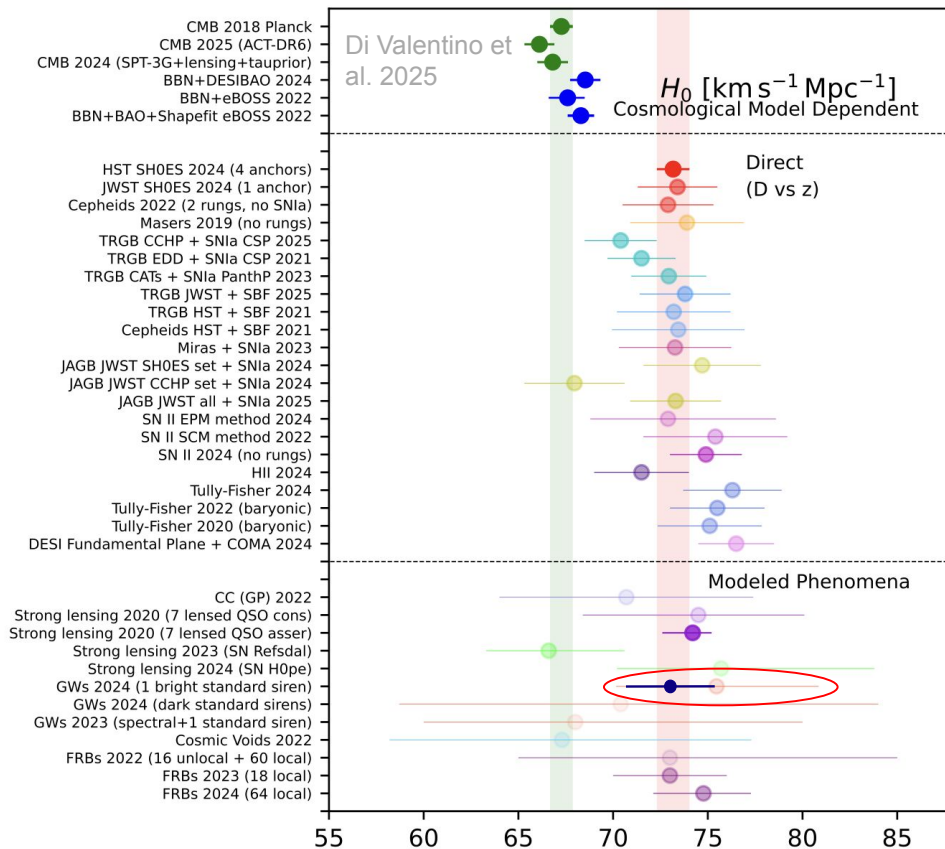
5-fold increase in number of peculiar velocity

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

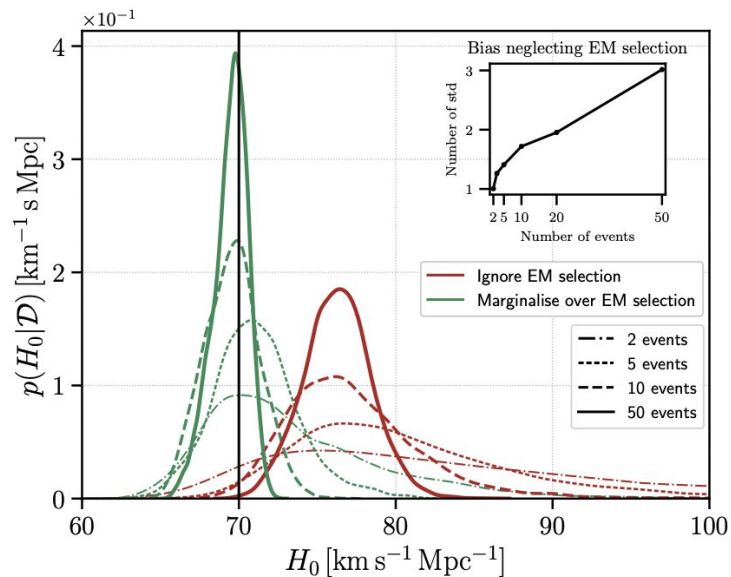
$$\text{Surface Brightness Fluctuations } H_0 = 73.4^{+5.5}_{-5.5}$$



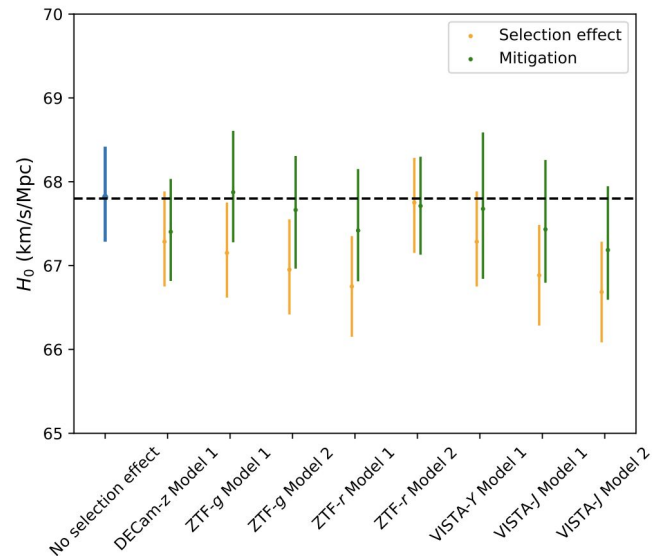
Amsellem, AP, et al. (DESI), 2026, ApJ,



Bright standard sirens - EM selection effects



Mancarella+2024, PRL

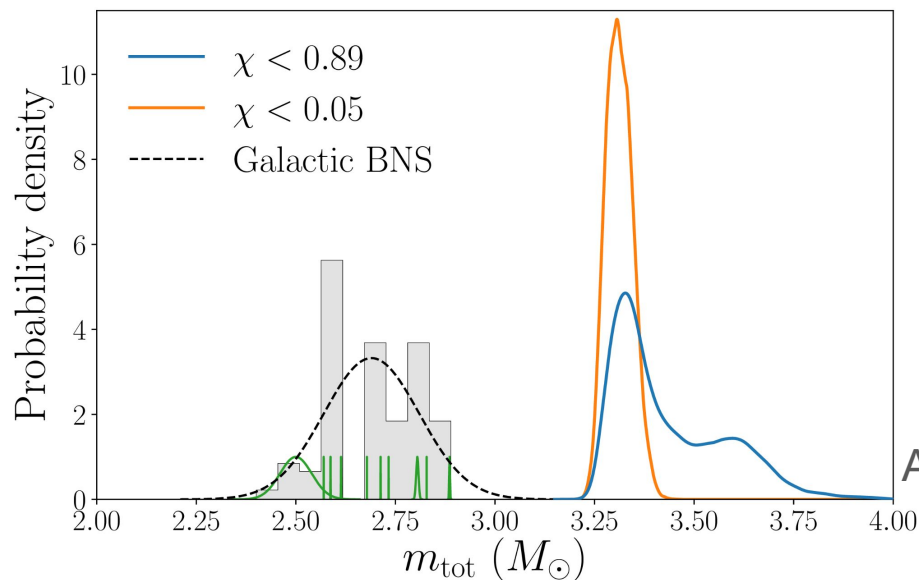


Chen+2024, PRL

GW190425

Binary Neutron star merger with total mass $3.4^{+0.3}_{-0.1}M_{\odot}$ (5σ away from Galactic BNS mean)

Likely promptly collapsed to a black hole (96% probability)

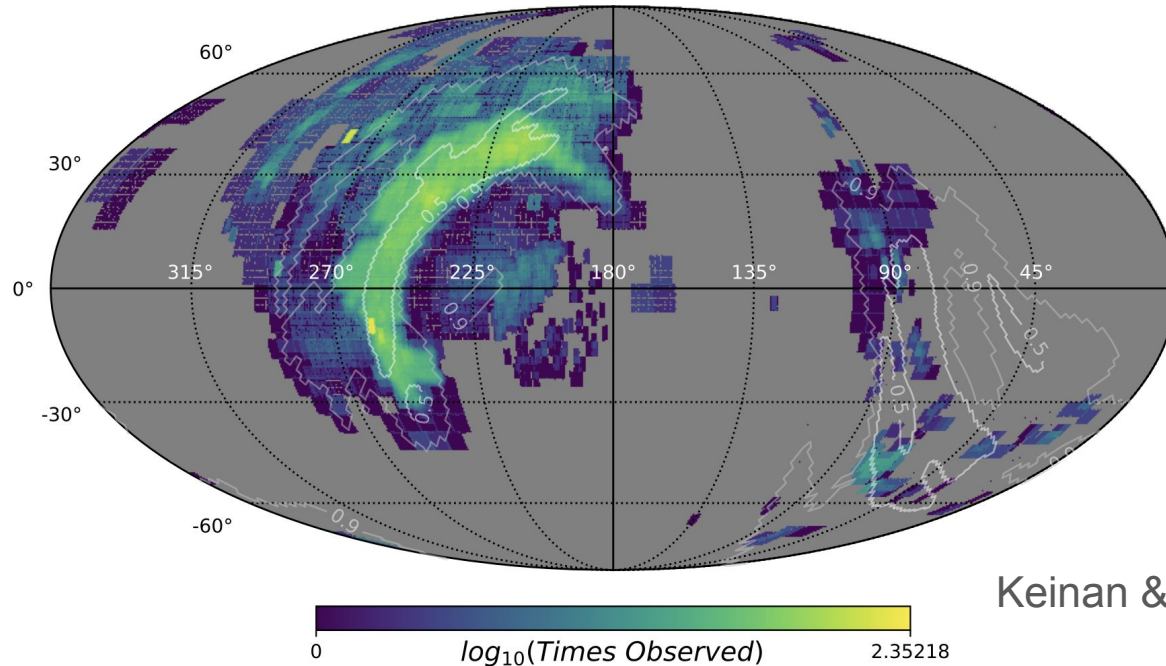


Abbott et al. 2020, ApJL

Optical observations

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

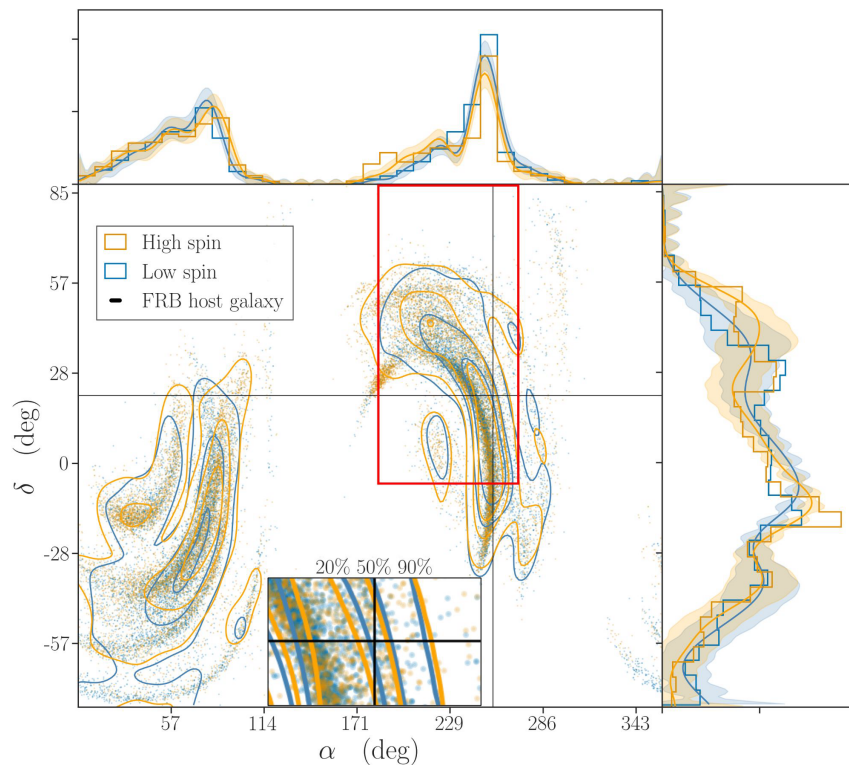
Single-detector detection (>7000 sq. deg. localization), and ~ 160 Mpc away, massive (small ejecta masses)



Keinan & Arcavi 2024

GW190425 - FRB 20190425A

- FRB 20190425A within 2.5h of GW190425
- **Host galaxy** (UGC10667; Panther+2022, Bhardwaj+2024) within 90% CI area
- Association at **2.8σ level** (Moroianu+2023)
- **Blitzar** scenario: merger may have led to the formation of highly spinning SMNS FRB at collapse (Moroianu+2023; Zhang+2023)



GW190425 - FRB 20190425A - inclination

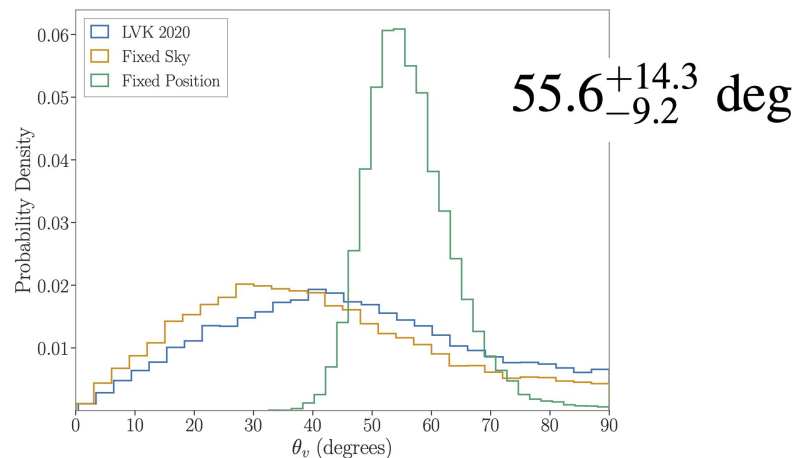
Rerun Parameter Estimation fixing galaxy position and z

Break distance-inclination angle degeneracy

Viewing angle > 30 deg at 99.99% CI

Jet could lead to **reduction of ejecta density** leading to FRB detection (Zhang 2014), not an option in this case

Kilonova **dynamical and wind ejecta** are expected



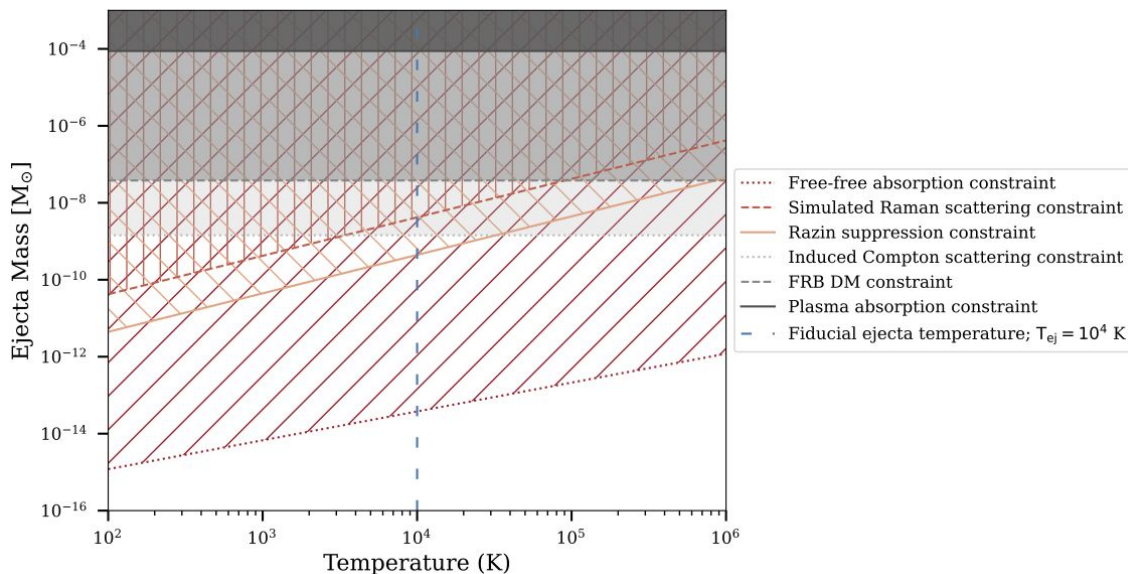
GW190425 - FRB 20190425A: emission constraints

What is the maximum ejecta mass required to enable FRB signal propagation at 400 MHz?

Estimate ejecta electron number density and derive maximum ejecta mass

Problems:

- need stiff EOS to have a SMNS but a soft EOS to produce less ejecta mass
- Prompt collapse probability >88% in all cases
- Posterior odds association ~5 (Magaña Hernandez+ 2024, ApJL)





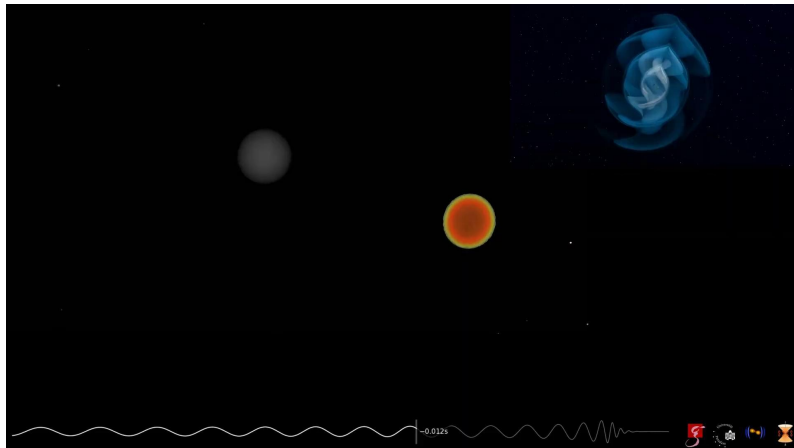
Neutron star-black hole mergers

Neutron Star-black hole mergers - Simulations

EM Counterpart



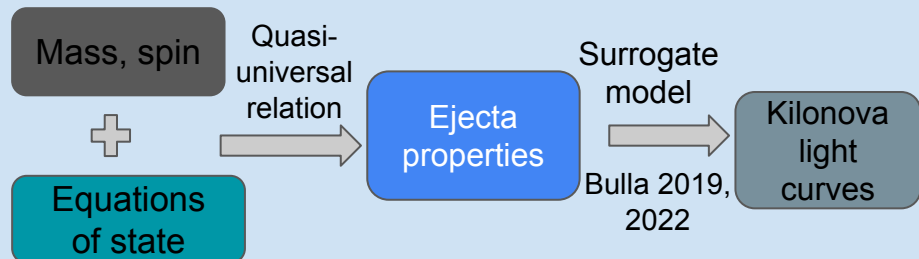
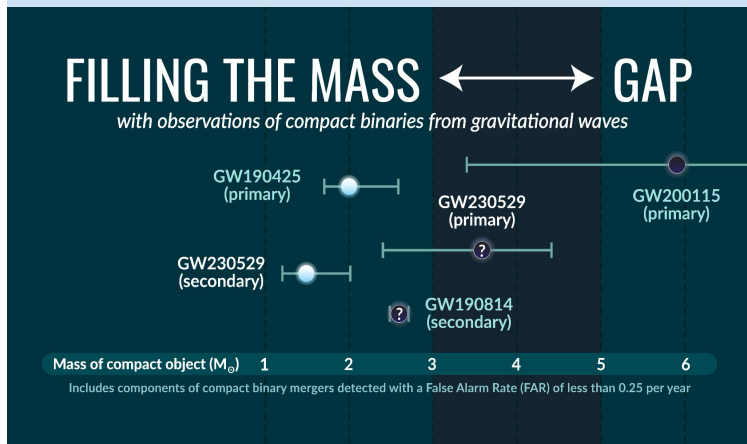
No EM Counterpart



Kilonovae from mass-gap NSBH mergers

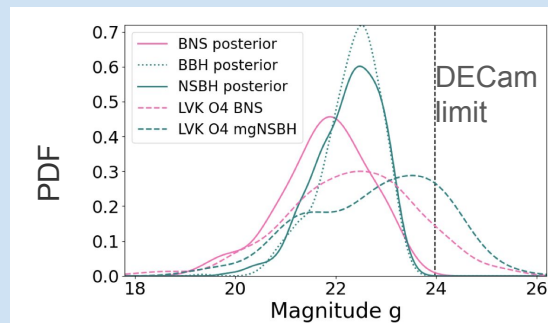
GW230529: likely NSBH merger with 2.5-4.5 $M_{\odot}$ black hole (Abbott et al. 2024, ApJL, arXiv: 2404.04248)

No EM counterpart detected



Kilonova production: 2-41% chance if NSBH

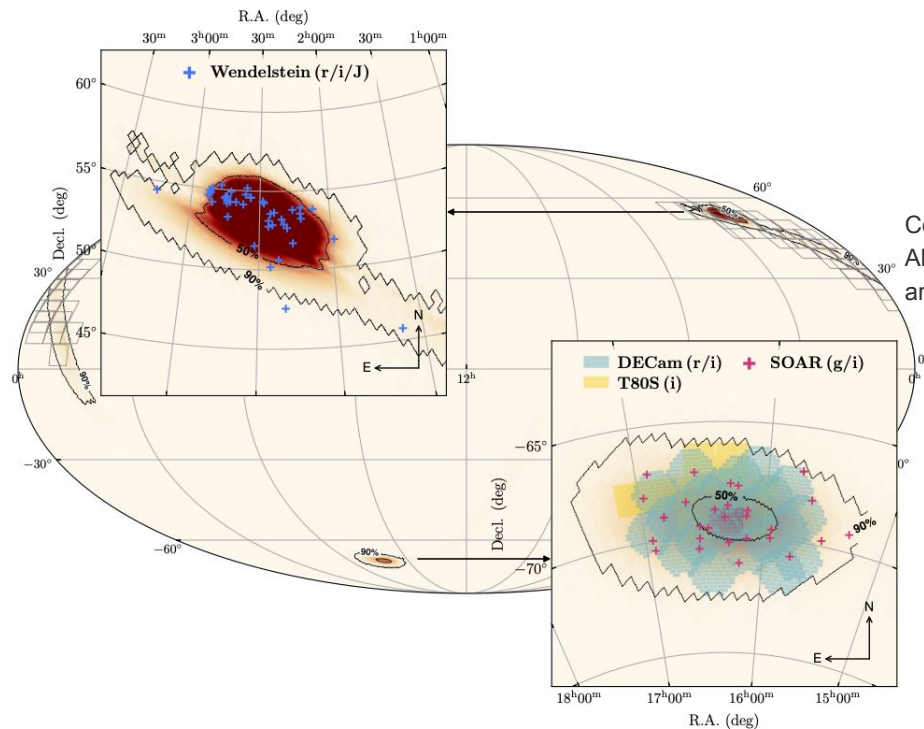
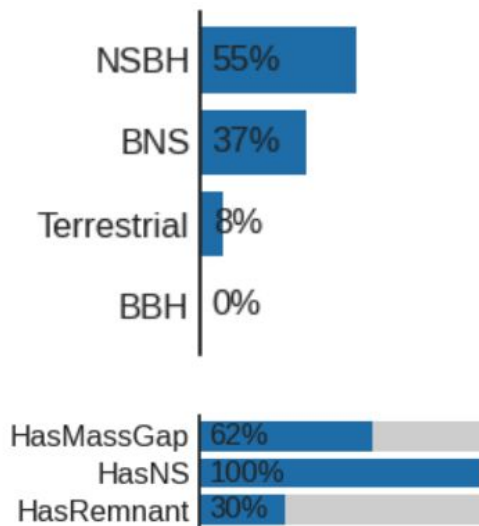
Kilonova detectability: High detectability in optical



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

S250206dm - Kilonova search

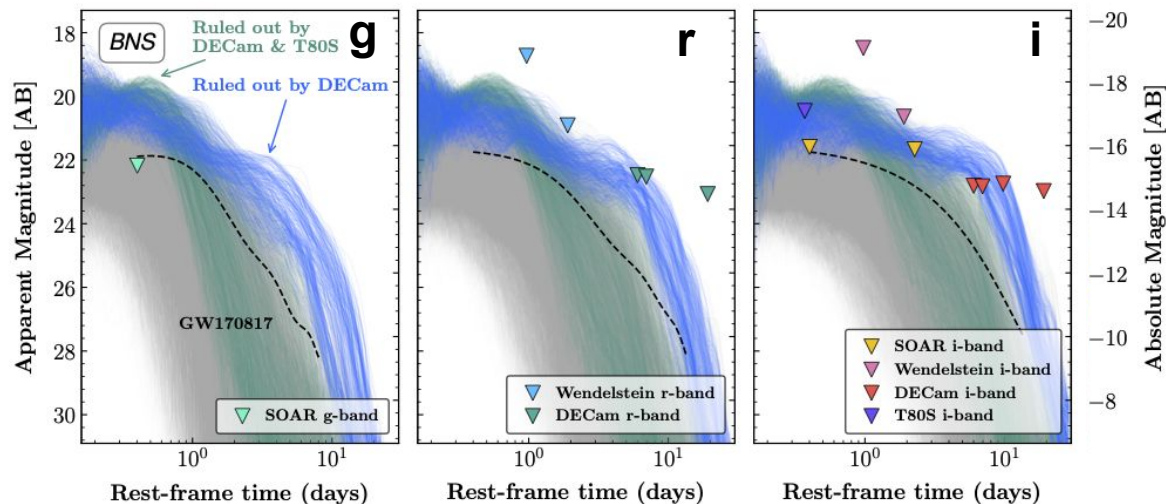
Hu, Cabrera, AP, et al.,
2025 arXiv:2506.2262



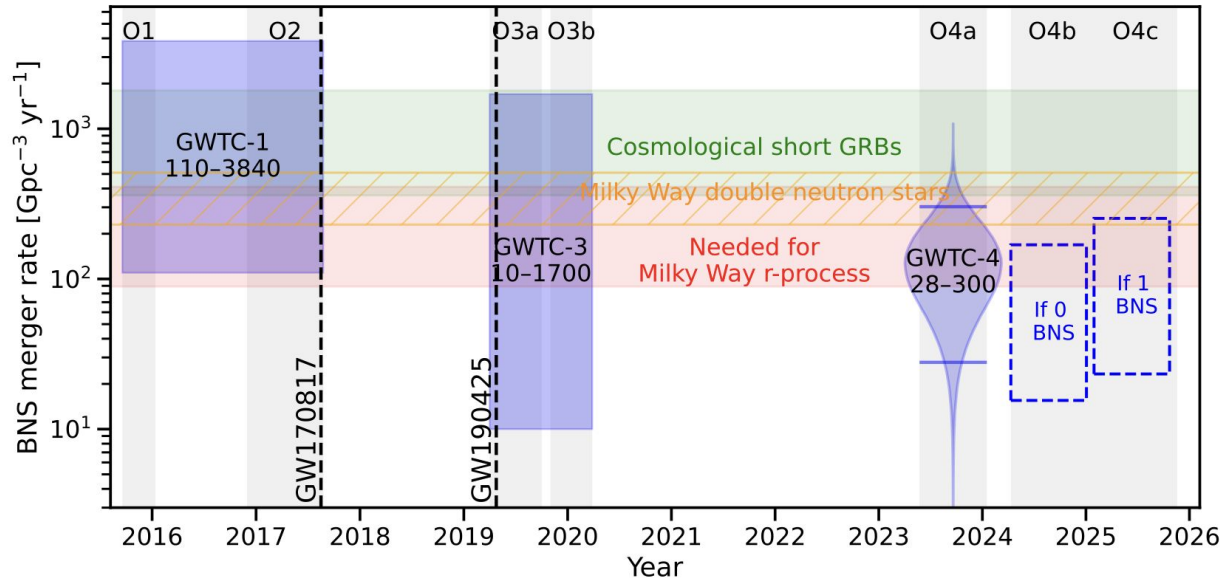
Coordinated with ZTF:
Ahumada et al. 2025,
arXiv:2507.003576

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?

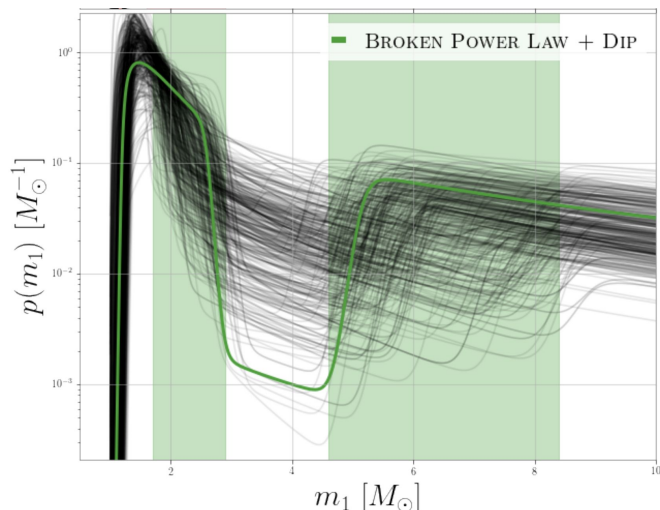


Fishbach et al. 2026

Multimessenger KN detection prospects

Simulate BNS+NSBH GW detections+KNe

Power law+dip+break model



Farah+2022, ApJ; LVK 2024, ApJL

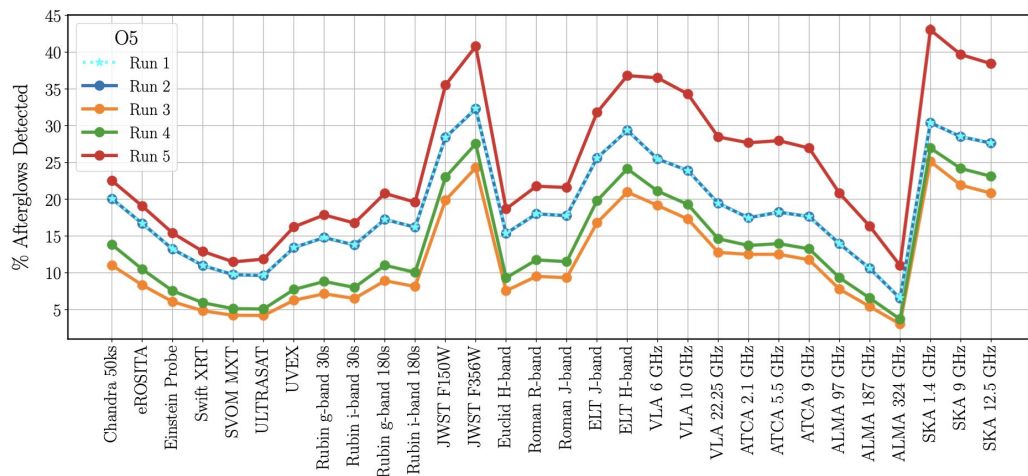
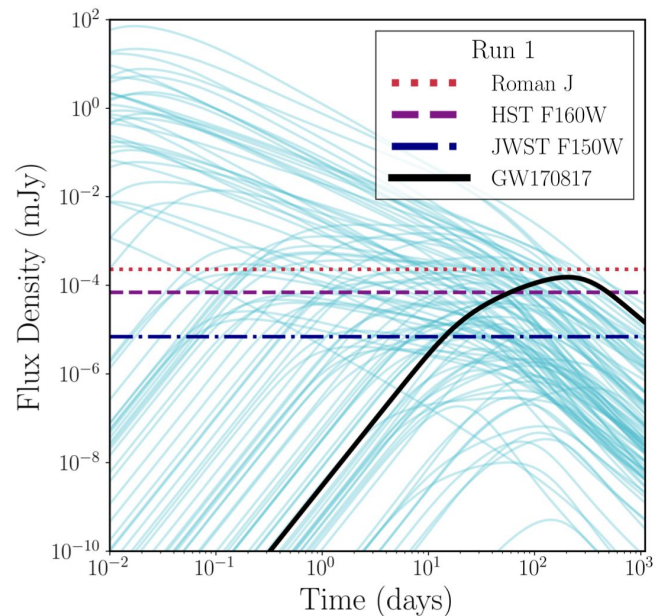
BNS rates updated (rough estimate) based on no detections of BNS so far in O4

Produce lightcurves to inform follow-up campaigns

Run	Binary type	GW detection rate (yr ⁻¹)	KN detectability (yr ⁻¹)				
			Argus		Rubin		
			<i>g</i>	<i>r</i>	<i>g</i>	<i>r</i>	<i>i</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

Multimessenger afterglow detections

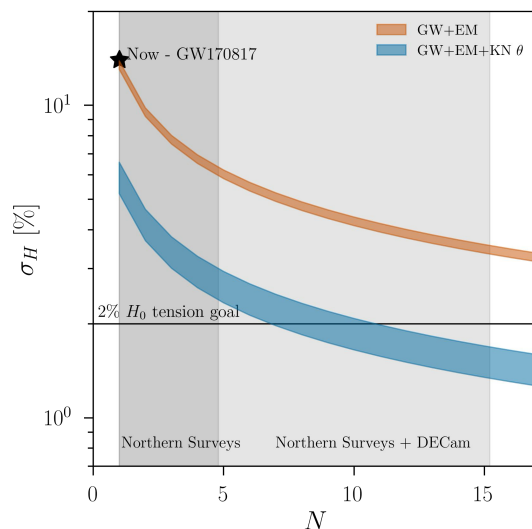


Kaur, O'Connor, AP & Kunnumkai 2024, arXiv:2410.10579

Bright Standard Sirens - Prospects

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

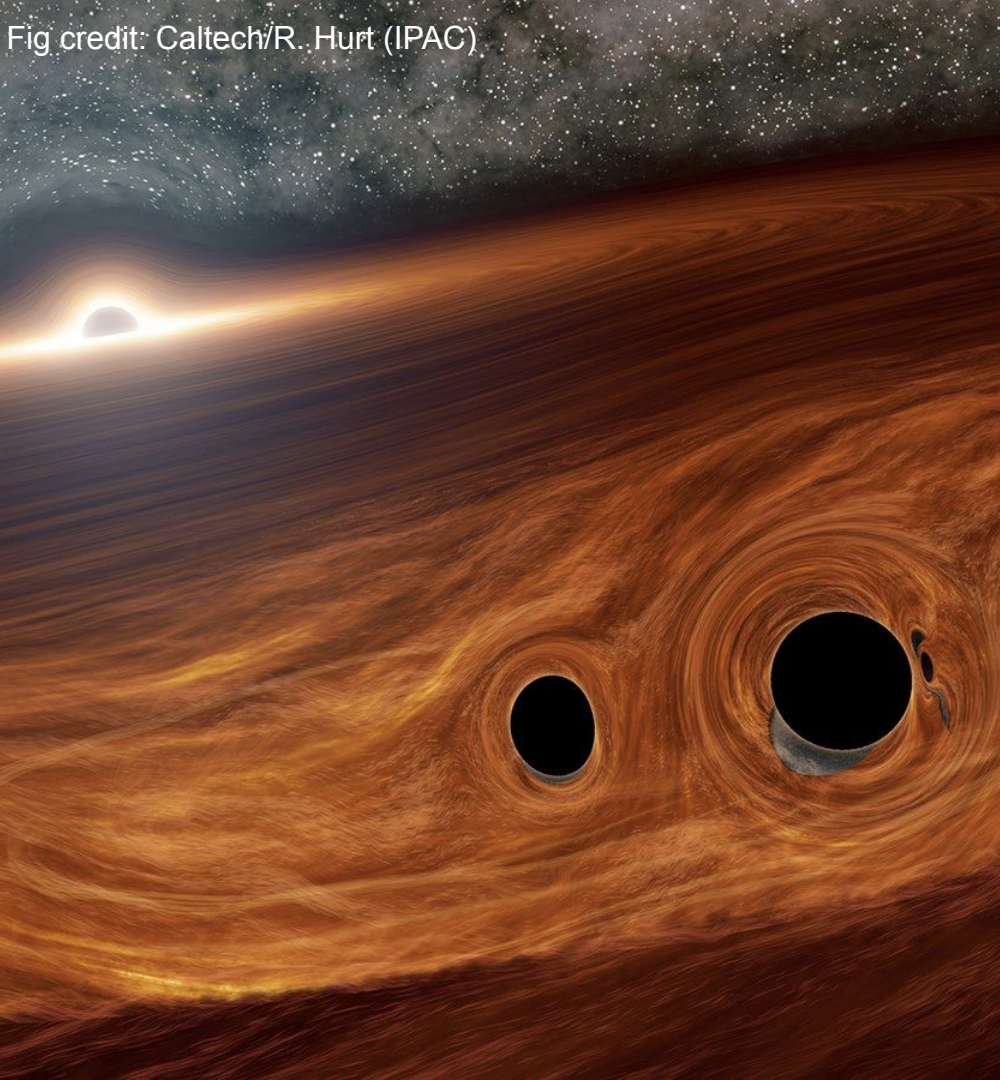
Need to wait for O5 (>2028) to reach ~2%



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)

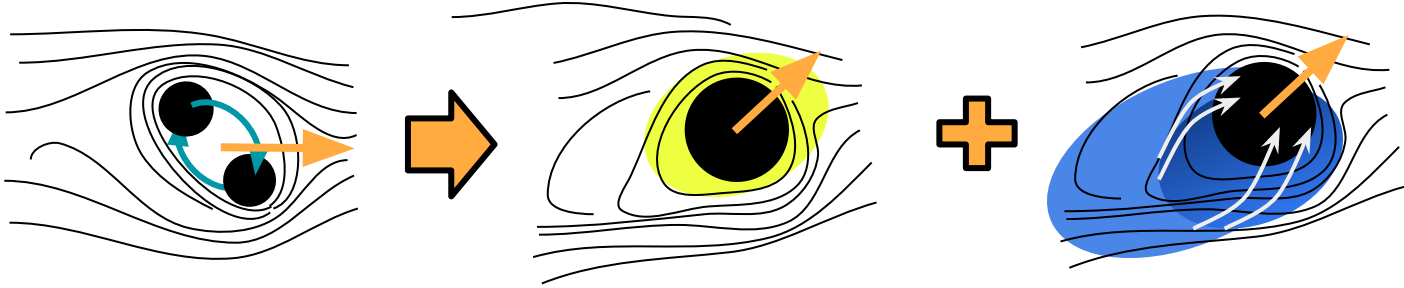


Binary black hole mergers

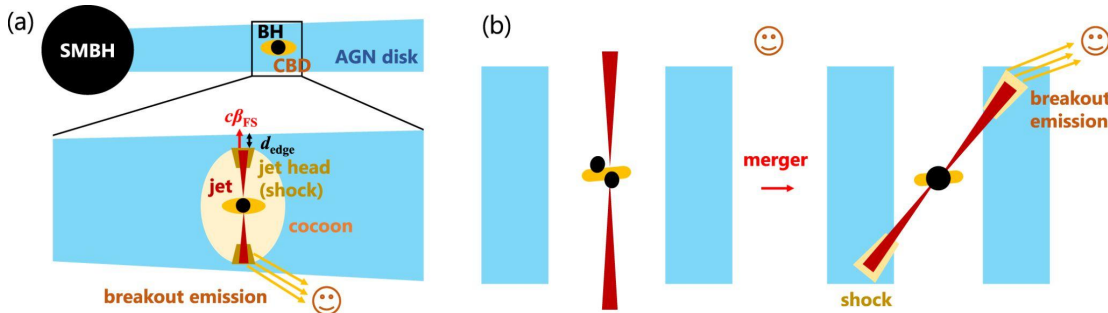
EM emission from BBH in AGN disks

See also Bartos+17

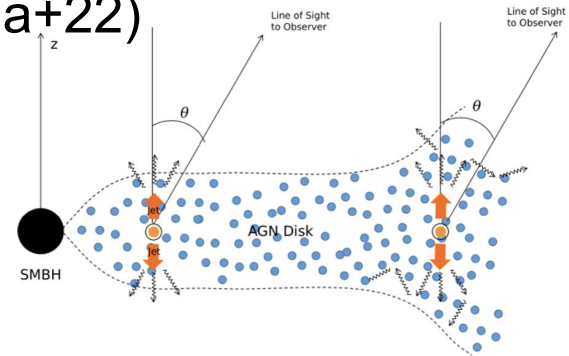
Ram-pressure stripping + Bondi tail (McKernan+19, Antoni+19)



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



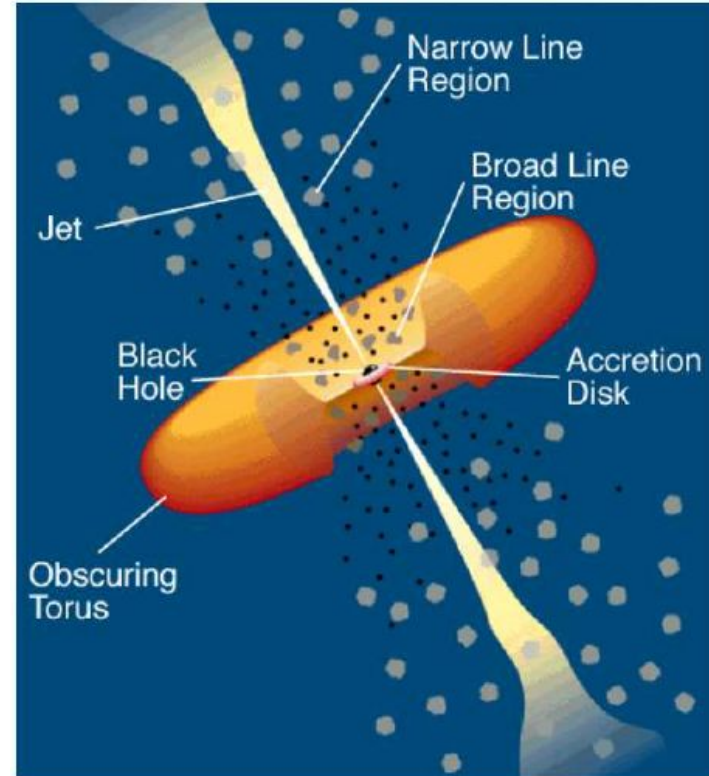
Jet afterglow ($\sim$ Wang, Lazzati & Perna+22)



BBH Multimessenger emission

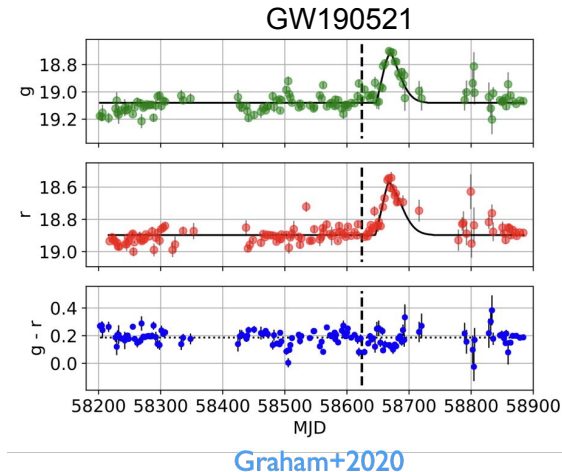
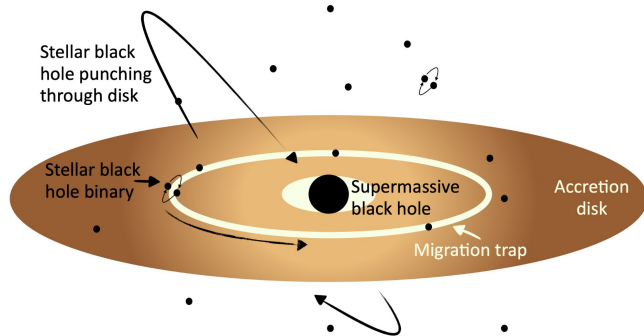
Asymmetric broad line emission for off-center source (McKernan+2019)

Urry and Padovani (1995)



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)



Do LIGO/Virgo/KAGRA BBH produce AGN flares?

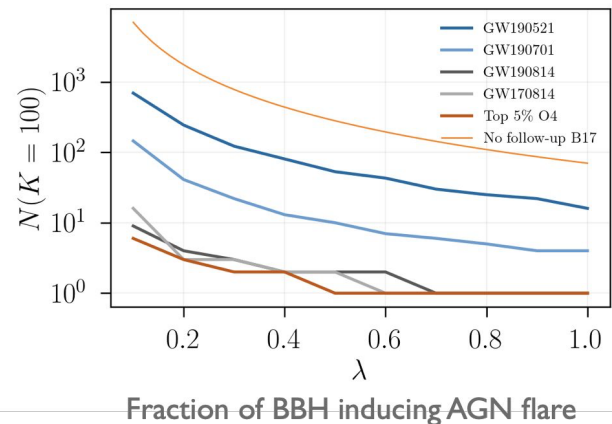
Case of **GW190521**: Using Structure Functions and AGN Luminosity Functions: 7400 Type I AGNs in 90% Volume result in 70% probability of chance coincidence (large localization volume).

Is a BBH-AGN confident association possible in presence of a background once a *population* of flares and GW BBH detections is available?

Fraction of BBH in AGN

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

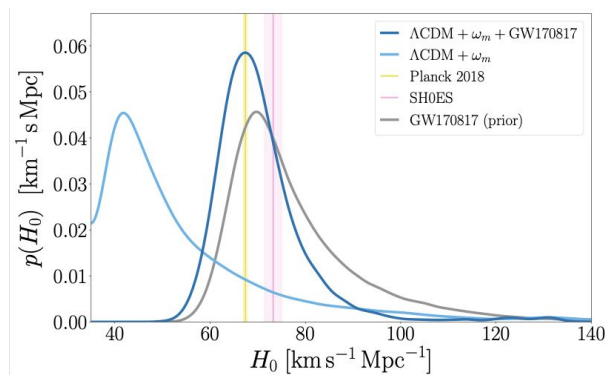
“Signal” AGN “Background” AGNs



LVK at design sensitivity: confident association possible with ~10 follow up campaigns of best localized/most massive events if $\lambda > 0.1$

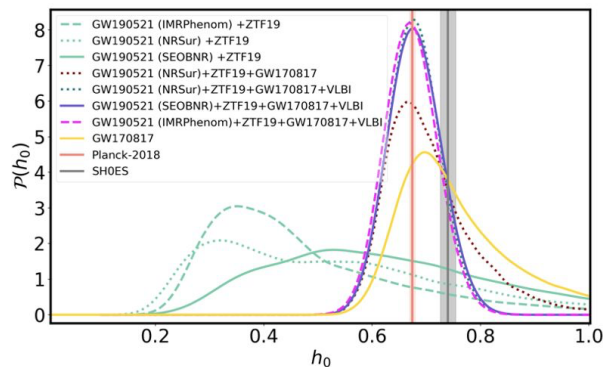
AP, Fishbach, Burke, Liu, Annis 2021,
ApJL, arXiv:2103.16069

Cosmology with GW190521



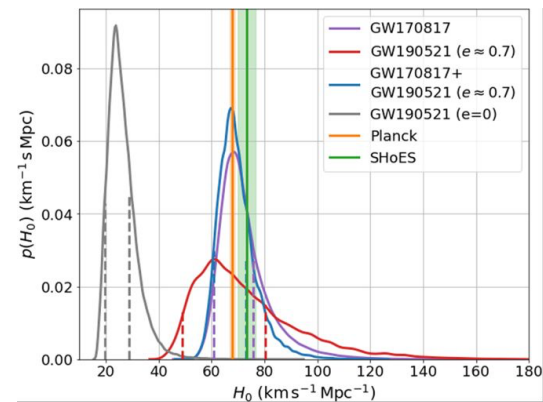
Chen et al., MNRAS (2022)

Chen+, MNRAS 2022



Mukherjee et al., 2009.14199

Mukherjee+ 2009.14199



Gayathri et al., ApJL (2021)

Gayathri +, ApJL 2021

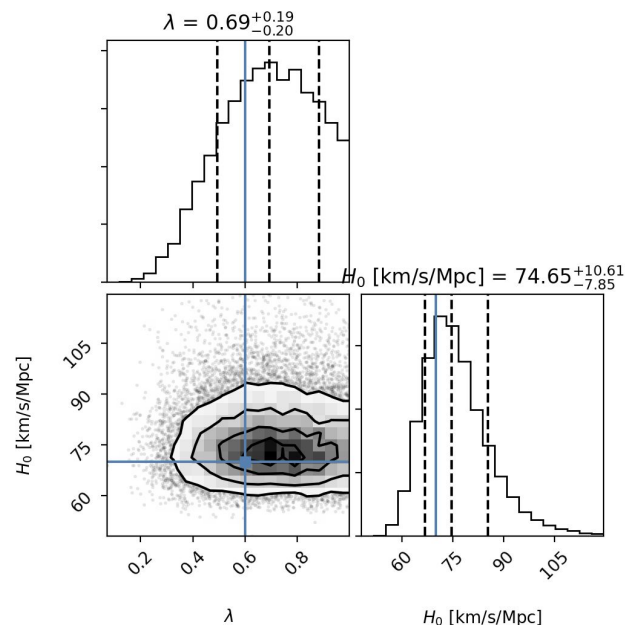
See also Alves et al. 2023, MNRAS arXiv:2009.13739

Cosmology with LIGO/Virgo/KAGRA BBH and AGN

- “Hybrid” bright/dark standard siren
- Use same formalism to establish confident association **and** constrain cosmology

Cosmological parameters

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



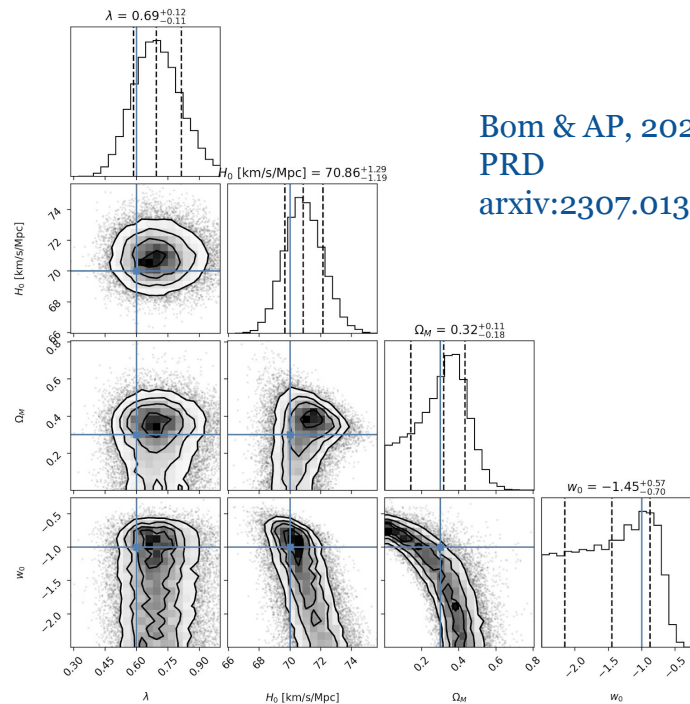
AP, Fishbach, Burke, Liu, Annis 2021,
ApJL, arXiv:2103.16069

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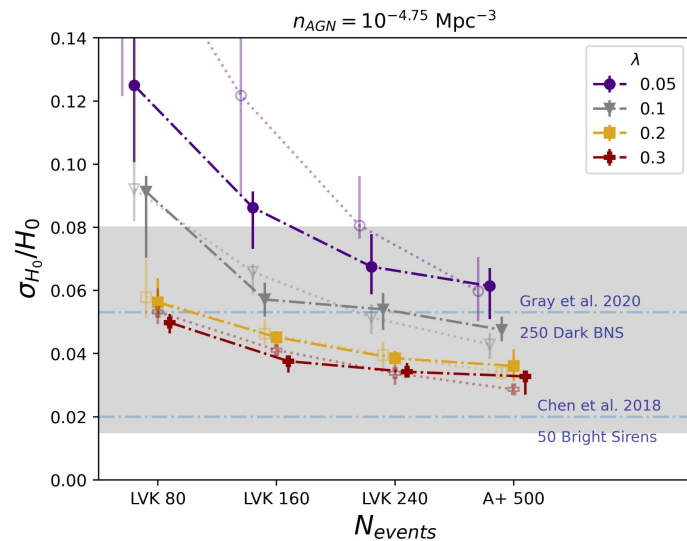
Bom & AP, 2024,
PRD
arxiv:2307.01330

Prospects for O5 and beyond

20-80% of LVK BBH may be from AGN channel (Ford & McKernan 2021, MNRAS arXiv:2109.03212, Gayathri et al. 2021,2023, ApJL arXiv:2104.10253), scaled for unobscured AGNs

Consider different AGN number densities and flare probabilities

Competitive with other standard siren methods (for H_0): 2-6% in ~ 1 year O5 (A+)



Bom & AP, 2024,
PRD
arxiv:2307.01330

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
~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



Subsolar mass mergers

Standard Sirens

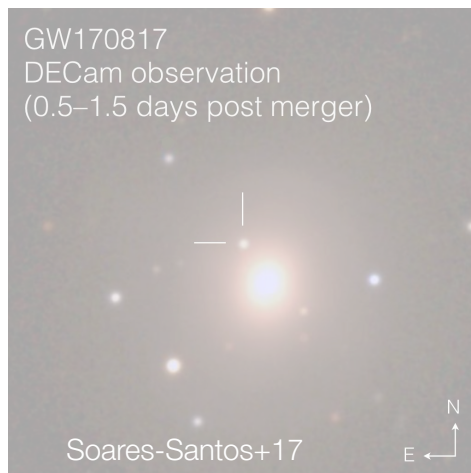
Schütz 1986

Holz & Hughes 2005

MacLeod & Hogan 2008

Nissanke+2010

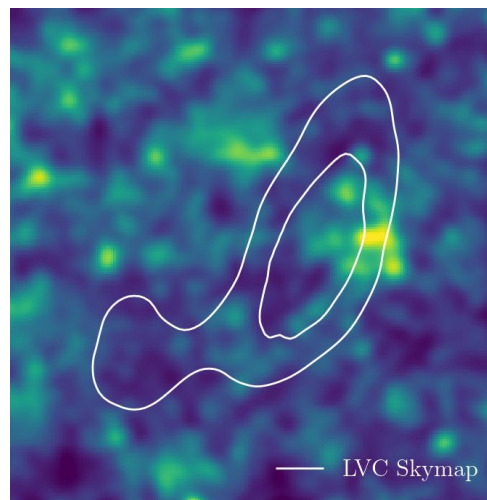
Bright
BNS/NSBH



Redshift from:

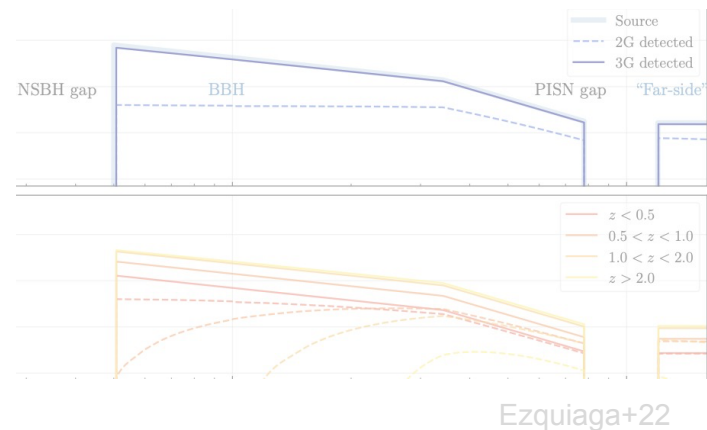
Host galaxy

Dark (x galaxies)
BBH/NSBH



Galaxies

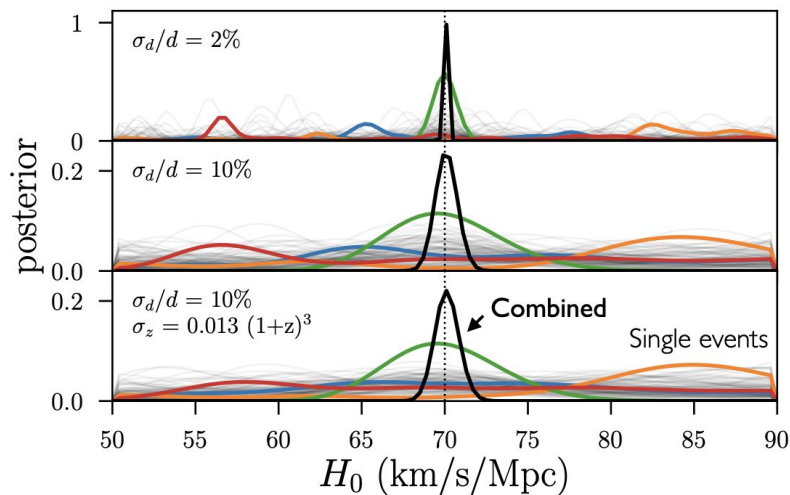
Dark (GW alone)



Redshifted mass

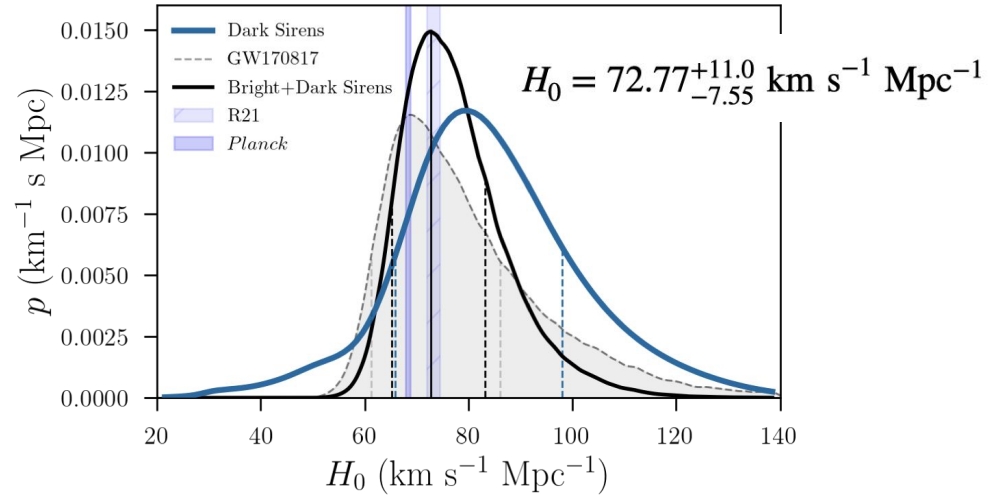
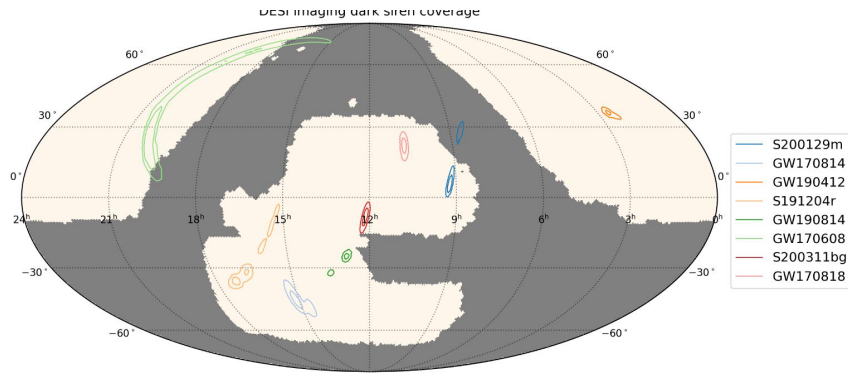
Dark sirens - simulations

- 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

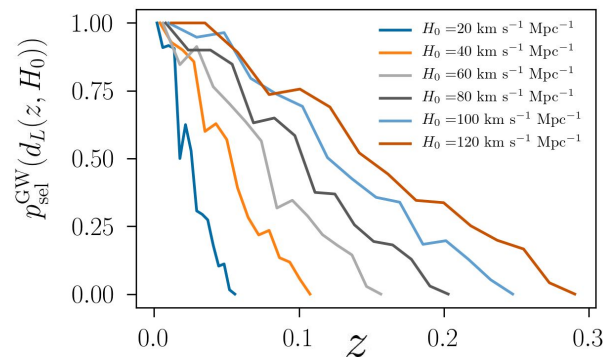
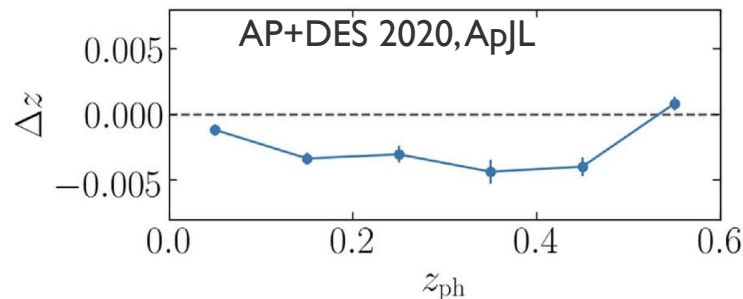
See also LIGO, Virgo,
KAGRA 2023, ApJ
arxiv:2111.03604



- **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

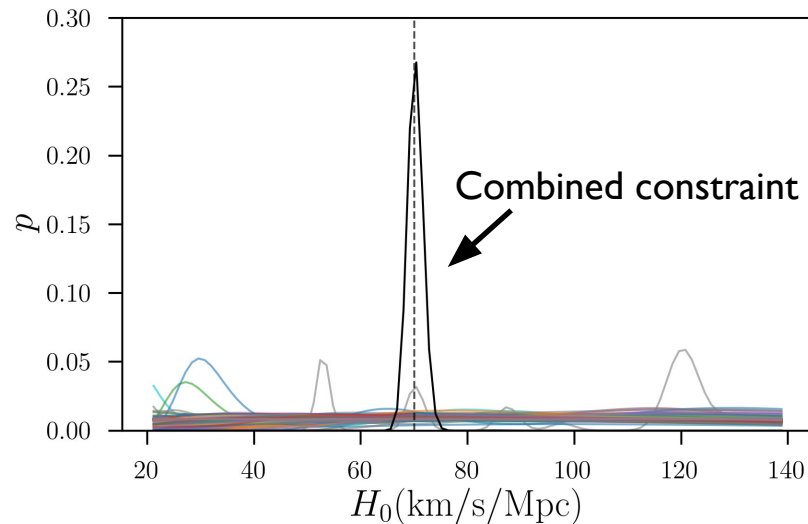
Dark sirens systematics

- Systematics related to **photometric redshifts**: bias correction, full redshift PDF (Stay tuned for more results with DESI spectroscopy!)
- **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)

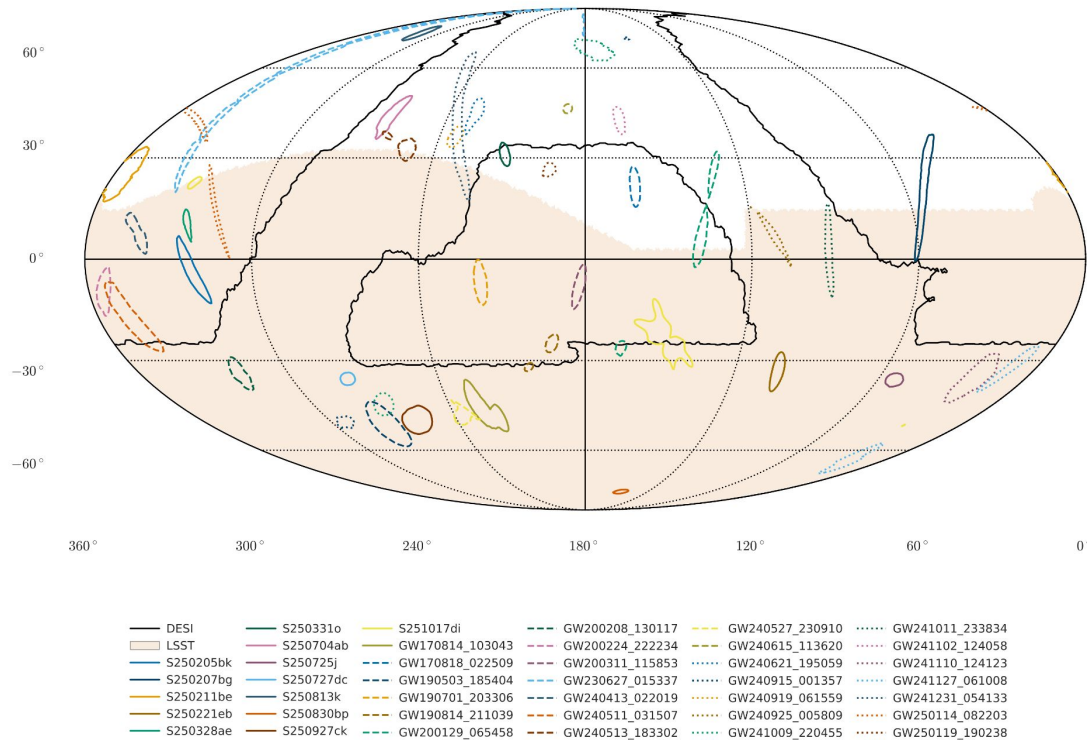


Prospects for LIGO/Virgo

- Inject BBH mergers on DES galaxies+localize for HLV at design sensitivity
- ~200 detections up to 900 Mpc
- **2-5%** statistical precision with a DES-like catalog



Current well-localized dark sirens



Standard Sirens

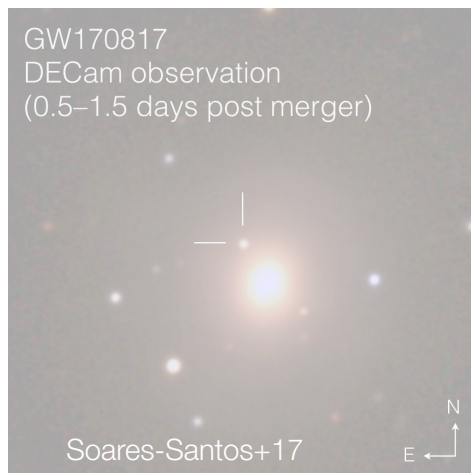
Schütz 1986

Holz & Hughes 2005

MacLeod & Hogan 2008

Nissanke+2010

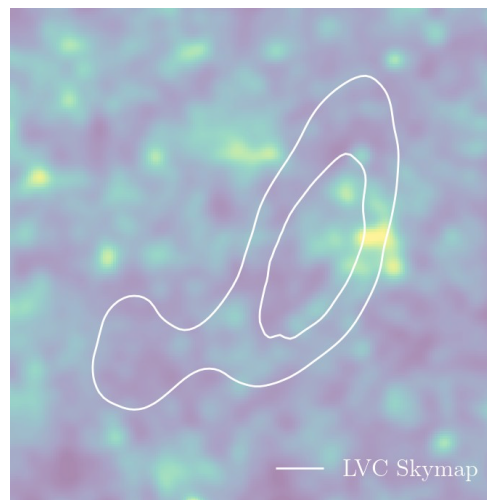
Bright
BNS/NSBH



Redshift from:

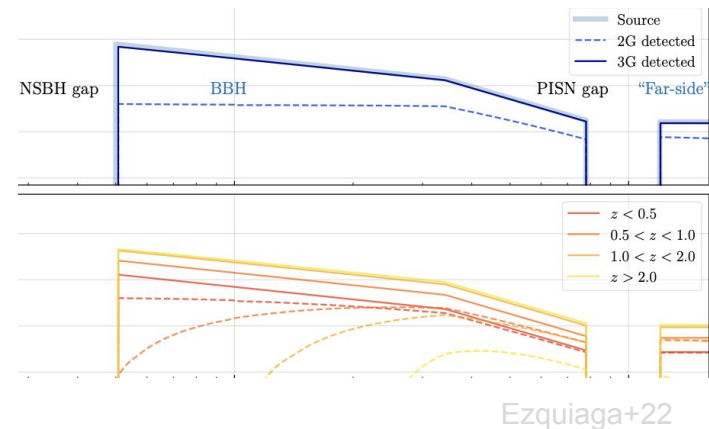
Host galaxy

Dark (x galaxies)
BBH/NSBH



Galaxies

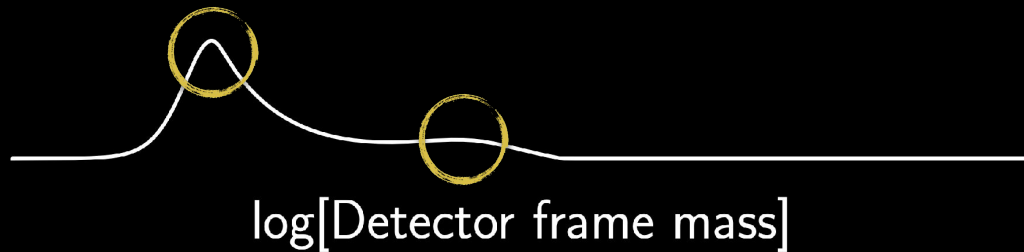
Dark (GW alone)



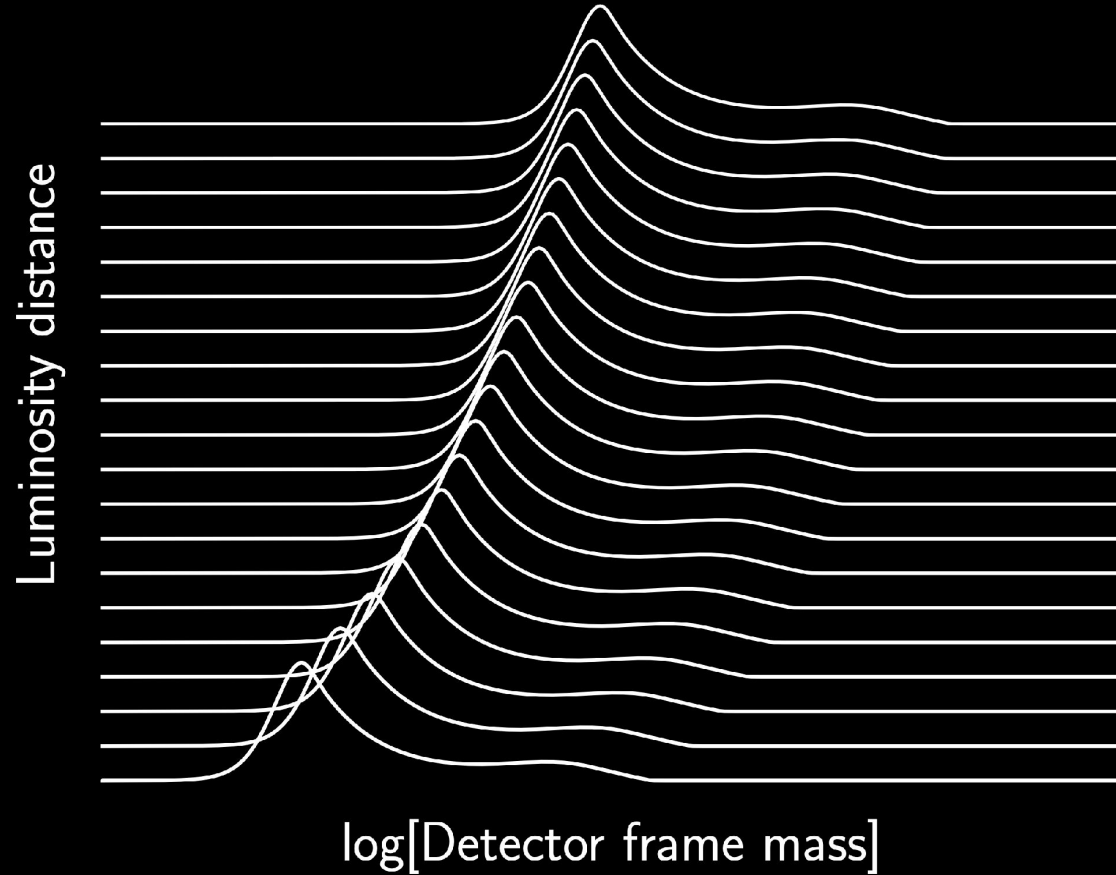
Redshifted mass

SPECTRAL SIRENS

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

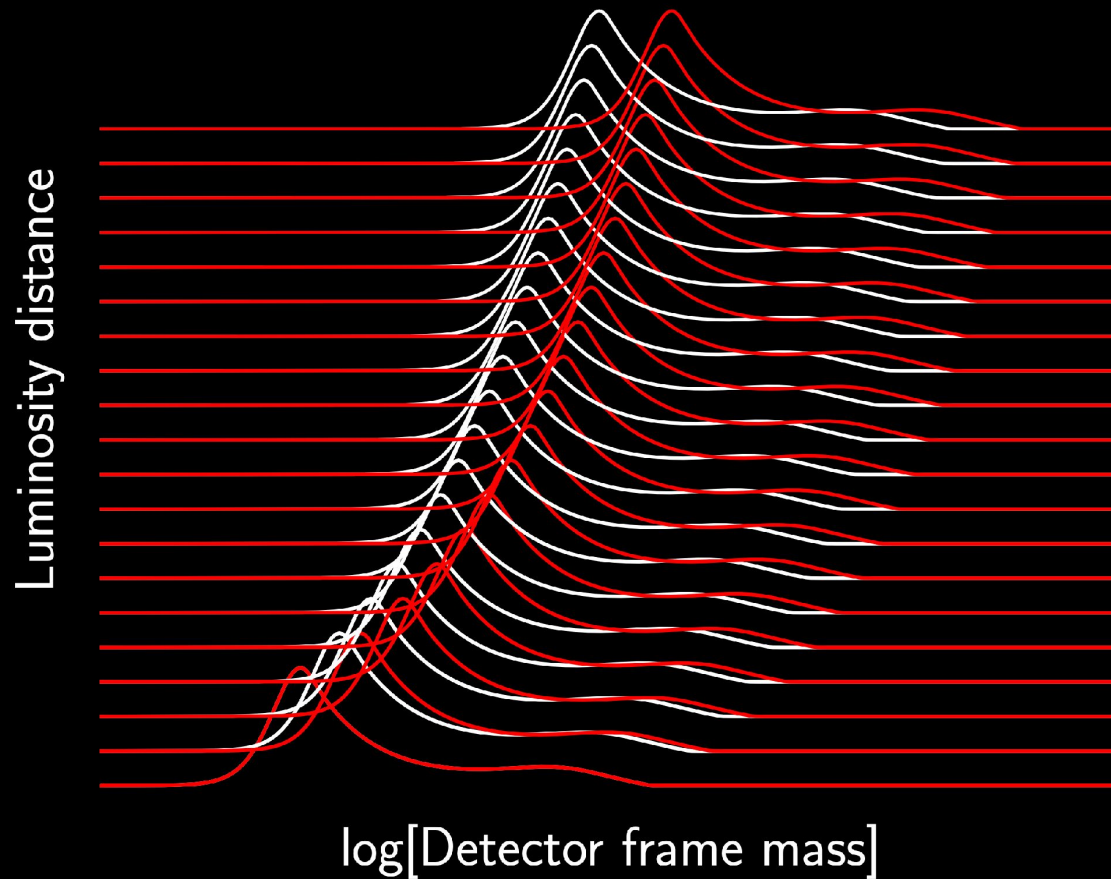


SPECTRAL SIRENS



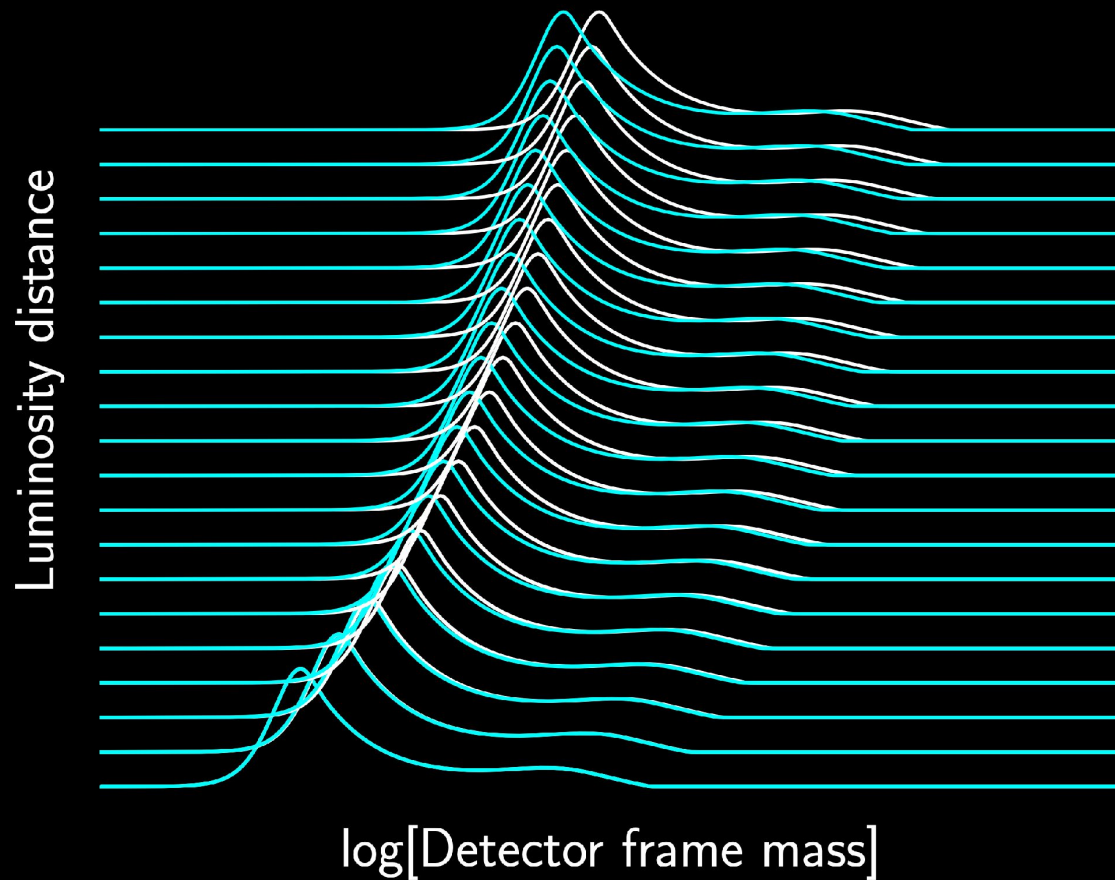
SPECTRAL SIRENS

higher H_0



SPECTRAL SIRENS

lower Ω_m



All compact binaries are standard sirens, no electromagnetic information is necessary



Ezquiaga & Holz; *Spectral sirens: Cosmology from full mass distribution of compact binaries* (PRL'22, [arXiv 2202.08240](#))

[Chernoff&Finn'93]

[Roy+'24]

[Farr+'19]

[Mastrogiovanni+'21]

[Ezquiaga&Holz'20]

[Taylor+'11]

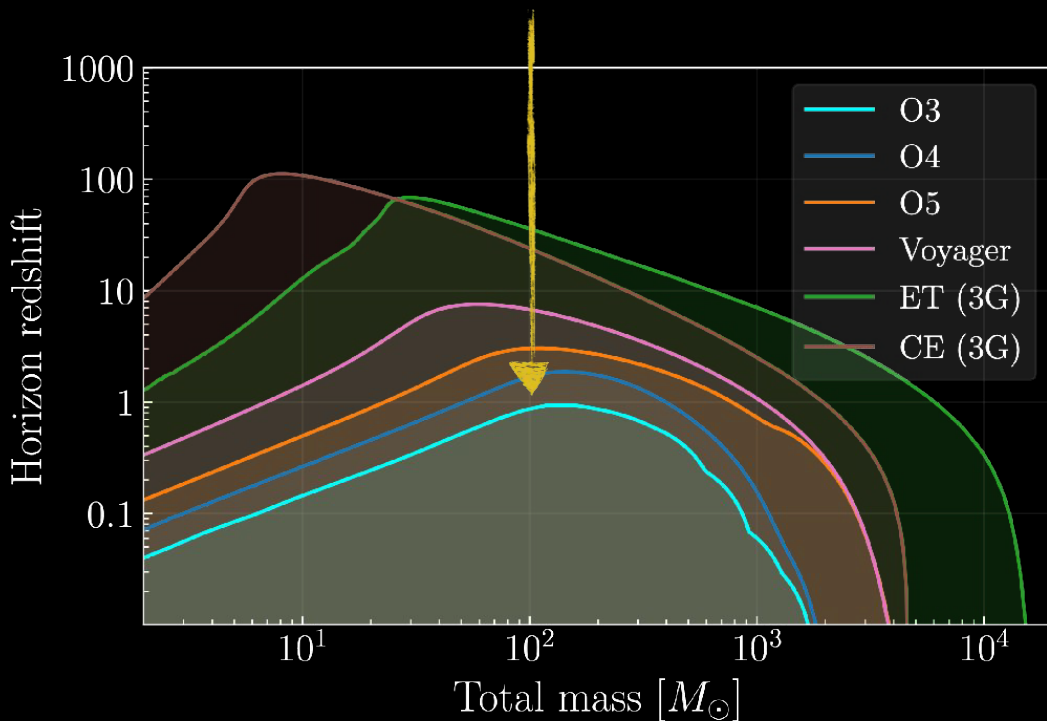
[Mali&Esscik'24]

[You+'20]

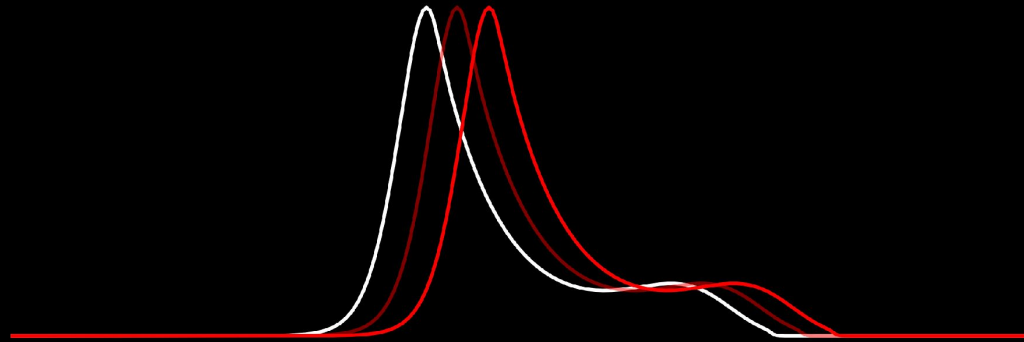
[LVC Cosmo GWTC-3 '21]....

All compact binaries are spectral sirens, no electromagnetic information is necessary

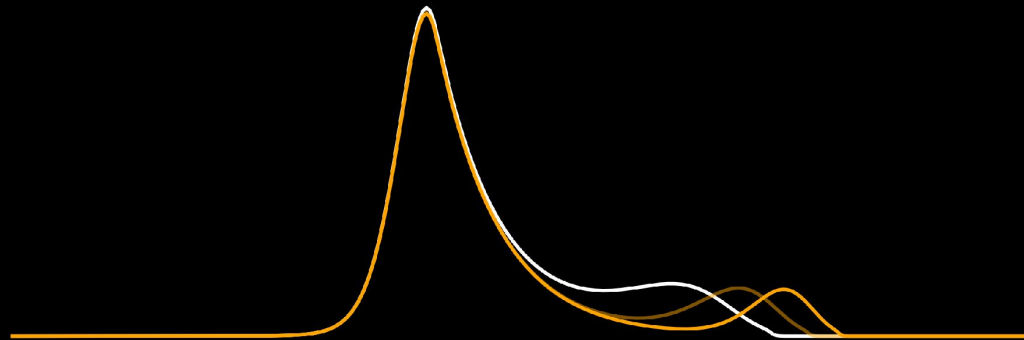
Currently, binary black holes most promising



Cosmology



Astrophysics



$\log[\text{Detector frame mass}]$

Standard siren inference

Hierarchical Bayesian inference in presence of selection effects and measurement uncertainties - modified Poisson process (Mandel+2019)

Likelihood of obtaining N_{obs} observations, each described by some parameters θ , in a GW data collection $\{x\}$, for non overlapping signals, for a given observing time T_{obs} :

$$\begin{aligned}\mathcal{L}(\{x\}|\Lambda) &\propto e^{-N_{\text{exp}}(\Lambda)} \prod_{i=1}^{N_{\text{obs}}} \int \mathcal{L}(x_i|\theta) \frac{dN}{dtd\theta}(\Lambda) dt d\theta \\ &\propto e^{-N_{\text{exp}}(\Lambda)} \prod_{i=1}^{N_{\text{obs}}} T_{\text{obs}} \int \mathcal{L}(x_i|\theta) \frac{dN}{dtd\theta}(\Lambda) d\theta.\end{aligned}\quad \mathcal{L}(x|\Lambda) \propto \prod_{i=1}^{N_{\text{obs}}} \frac{\int \mathcal{L}(x_i|\theta) p_{\text{pop}}(\theta|\Lambda) d\theta}{\int p_{\text{det}}(\theta) p_{\text{pop}}(\theta|\Lambda) d\theta}.$$

Focus on parameters of interest and move to source frame with a cosmology:

$$\mathcal{L}(x|\Lambda) \propto \prod_{i=1}^{N_{\text{obs}}} \frac{\int \mathcal{L}(x_i|z, \mathbf{m}, \cos \iota, \mathbf{\Omega}, H_0) p_{\text{pop}}(z, \mathbf{m}, \cos \iota, \mathbf{\Omega}|\Lambda) dz d\mathbf{m} d\cos \iota d\mathbf{\Omega}}{\int p_{\text{det}}(z, \mathbf{m}, \cos \iota, \mathbf{\Omega}, H_0) p_{\text{pop}}(z, \mathbf{m}, \cos \iota, \mathbf{\Omega}|\Lambda) dz d\mathbf{m} d\cos \iota d\mathbf{\Omega}}.$$

Explicitly model: the population distribution of CBCs in the source frame

$$p_{\text{pop}}(z, \mathbf{m}, \cos \iota, \mathbf{\Omega}|\Lambda) = p_{\text{pop}}(z|\Lambda) p_{\text{pop}}(\mathbf{m}|\Lambda) p_{\text{pop}}(\cos \iota|\Lambda) p_{\text{pop}}(\mathbf{\Omega}|\Lambda).$$

Standard siren inference - galaxy catalog (dark sirens)

Defining a population distribution conditioned on galaxy catalog CAT:

$$p_{\text{pop}}(z, \mathbf{m}, \cos \iota, \mathbf{\Omega} | \mathbf{\Lambda}, \text{CAT}) = p_{\text{pop}}(z, \mathbf{\Omega} | \text{CAT}, \mathbf{\Lambda}) p_{\text{pop}}(\mathbf{m} | \mathbf{\Lambda}) p_{\text{pop}}(\cos \iota | \mathbf{\Lambda}).$$

$$p_{\text{pop}}(z, \mathbf{\Omega} | \text{CAT}, \mathbf{\Lambda}) \propto \int \delta(z - z_g) p_{\text{gal}}(z_g, \mathbf{\Omega}, \zeta | \text{CAT}) p_{\text{host}}(\zeta, z_g | \mathbf{\Lambda}) d\zeta dz_g.$$

$$p_{\text{pop}}(z, \mathbf{\Omega} | \text{CAT}, \mathbf{\Lambda}) = f(z, \mathbf{\Omega}) p_{\text{pop}}(z, \mathbf{\Omega} | \text{CAT}, \mathbf{\Lambda}) + [1 - f(z, \mathbf{\Omega})] p_{\text{pop}}(z | \mathbf{\Lambda}) p_{\text{pop}}(\mathbf{\Omega} | \mathbf{\Lambda}),$$

$$f(z, \mathbf{\Omega}) = \frac{\int_{M_{\text{thr}}(z, \mathbf{\Omega})}^{\infty} \text{Sch}(M, z) p_{\text{host}}(M, z | \mathbf{\Lambda}) dM}{\int_{M_{\text{faint}}}^{\infty} \text{Sch}(M, z) p_{\text{host}}(M, z | \mathbf{\Lambda}) dM},$$

Standard siren inference - bright sirens

$$\mathcal{L}(x|\Lambda) \propto \prod_{i=1}^{N_{\text{obs}}} \frac{\int \mathcal{L}(x_i|z, \mathbf{m}, \cos \iota, \mathbf{\Omega}, H_0) \mathcal{L}_{\text{EM}}(y_i|z, \cos \iota, \mathbf{\Omega}) p_{\text{pop}}(z, \mathbf{m}, \cos \iota, \mathbf{\Omega}|\Lambda) dz d\mathbf{m} d\cos \iota d\mathbf{\Omega}}{\int p_{\text{det}}^{\text{GW+EM}}(z, \mathbf{m}, \cos \iota, \mathbf{\Omega}, H_0) p_{\text{pop}}(z, \mathbf{m}, \cos \iota, \mathbf{\Omega}|\Lambda) dz d\mathbf{m} d\cos \iota d\mathbf{\Omega}}.$$

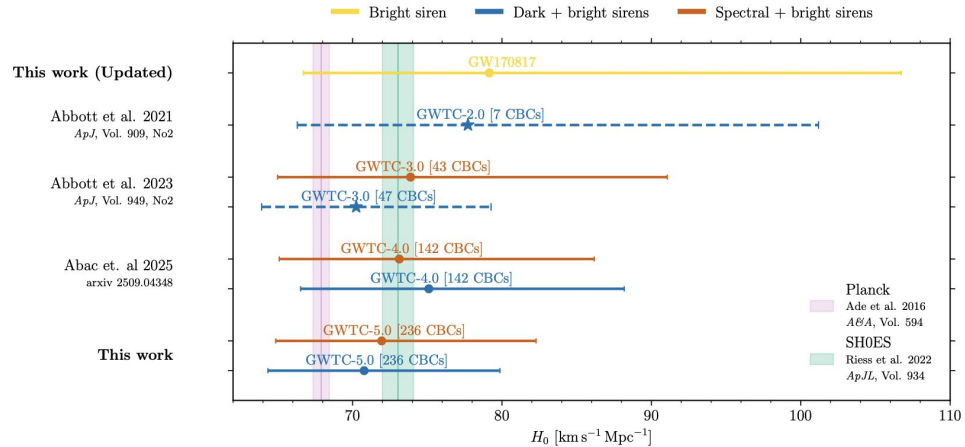
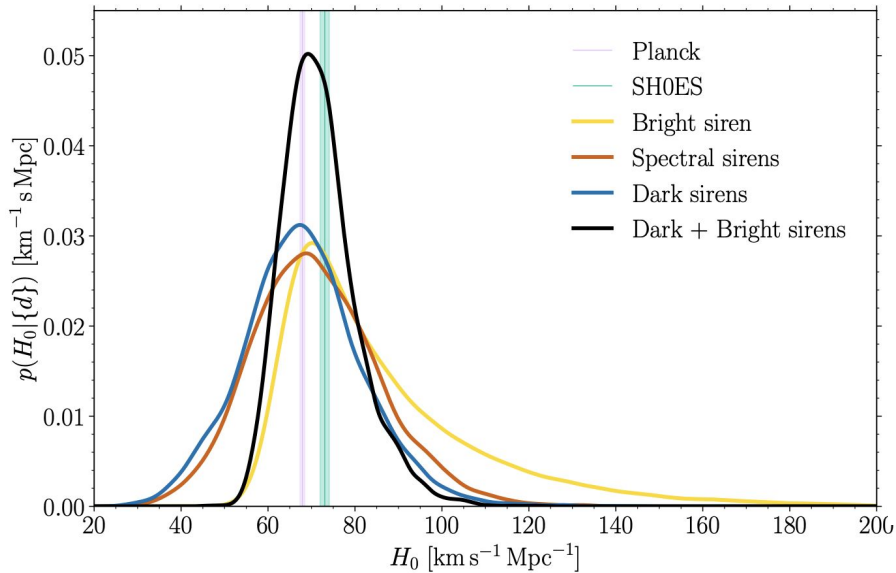
Eq. can simplify:

the redshift is perfectly known, the source frame mass distribution will not introduce any reference

Assume most limiting selection for detection is given by GW detectors

$$\mathcal{L}(x|\Lambda) \propto \prod_{i=1}^{N_{\text{obs}}} \frac{\mathcal{L}(x_i|d_L(z_s, H_0))}{H_0^3}.$$

Dark and spectral siren measurements with GWTC-5

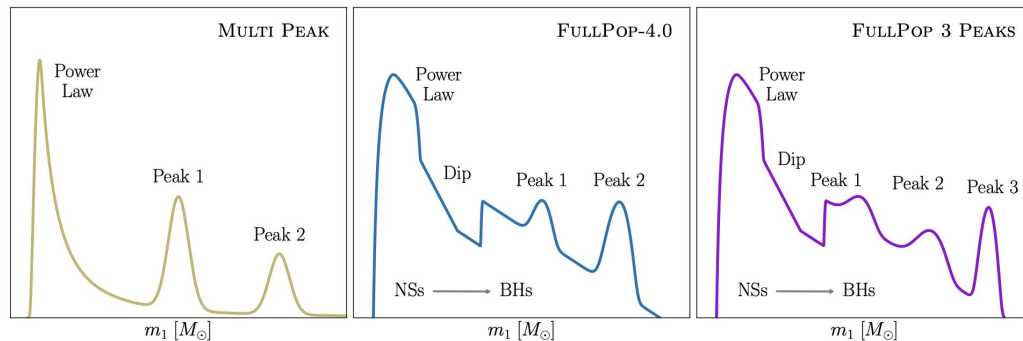
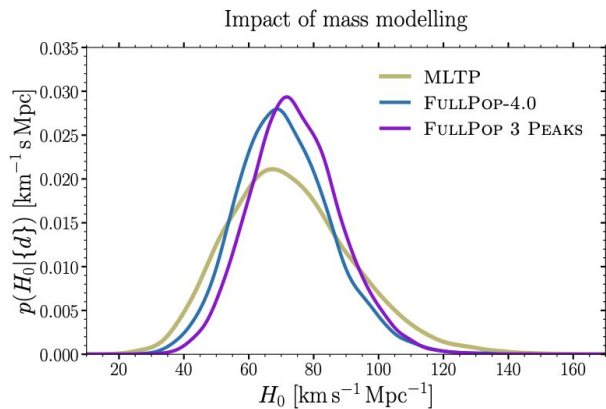


GLADE+ and DES galaxy catalogs

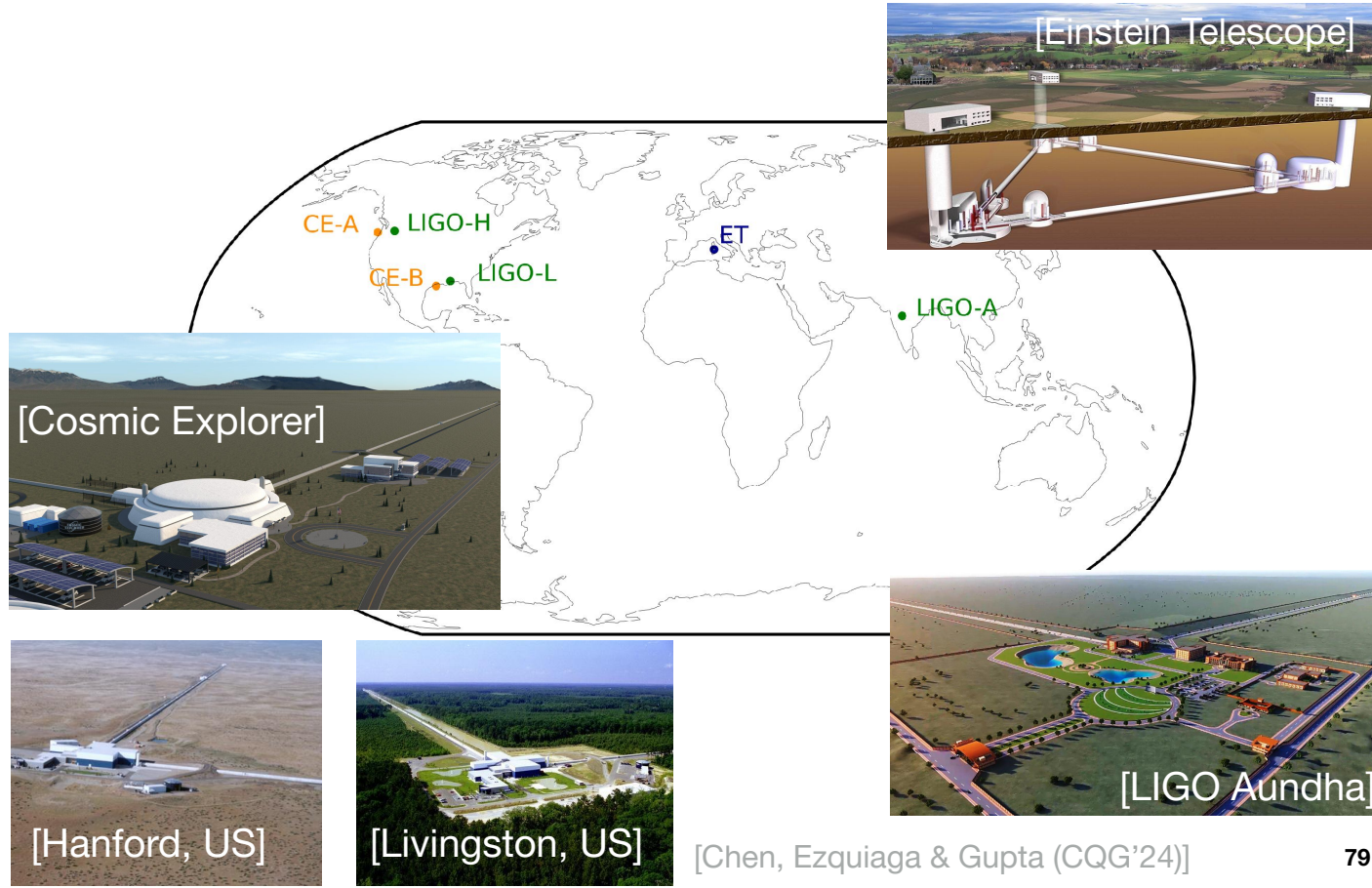
Marginalize over possible population

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

Dark and spectral siren measurements with GWTC-5

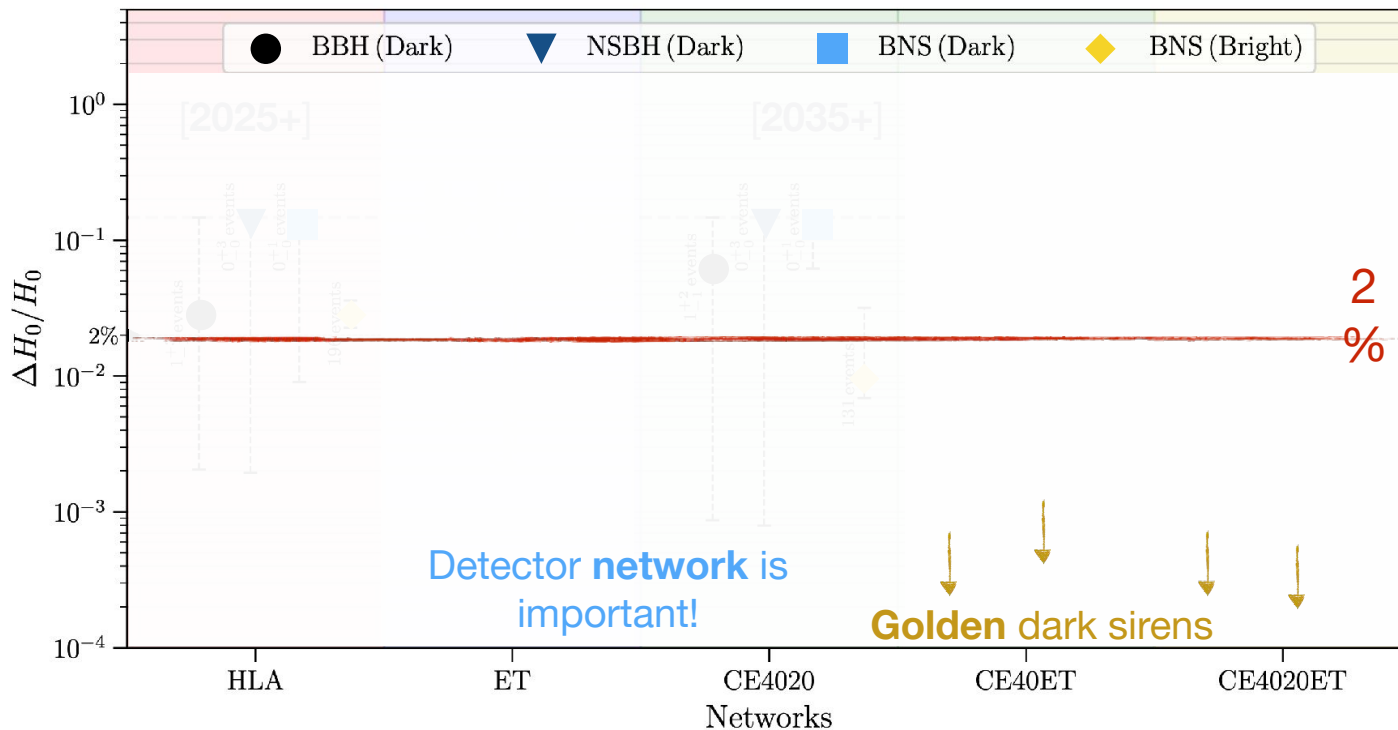


Standard sirens: *forecasts*



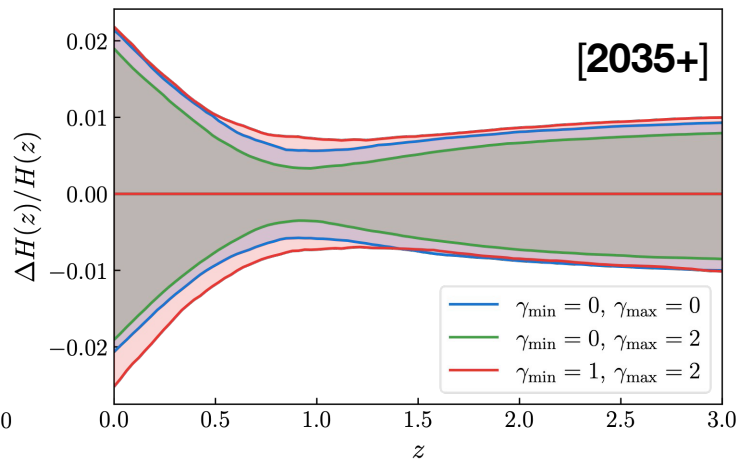
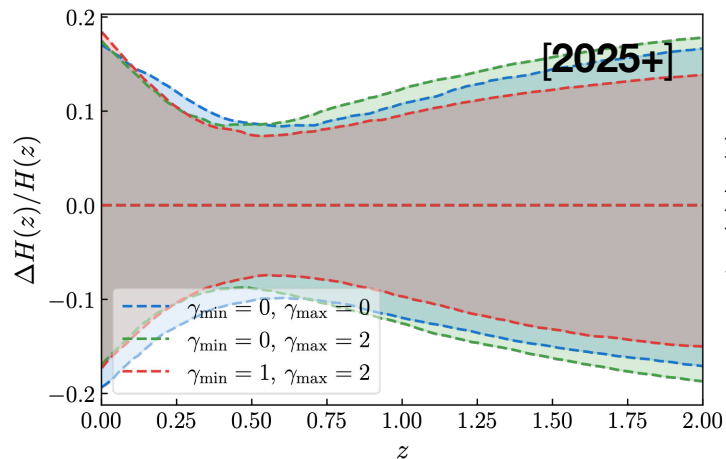
Bright and dark sirens H_0

H: Hanford (US)
L: Livingston (US)
A: Aundha (India)
ET: Einstein Telescope (EU)
CE: Cosmic Explorer (US)



Spectral sirens: *forecasts*

[BBHs between NSBH and PISN gap]



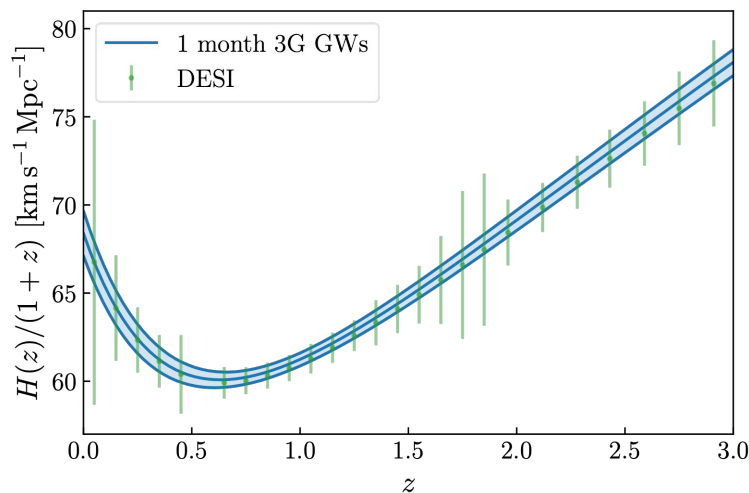
2G: <10% within 1 year at approx. $z=0.7$

XG: Sub-percent within 1 month. High-redshift!

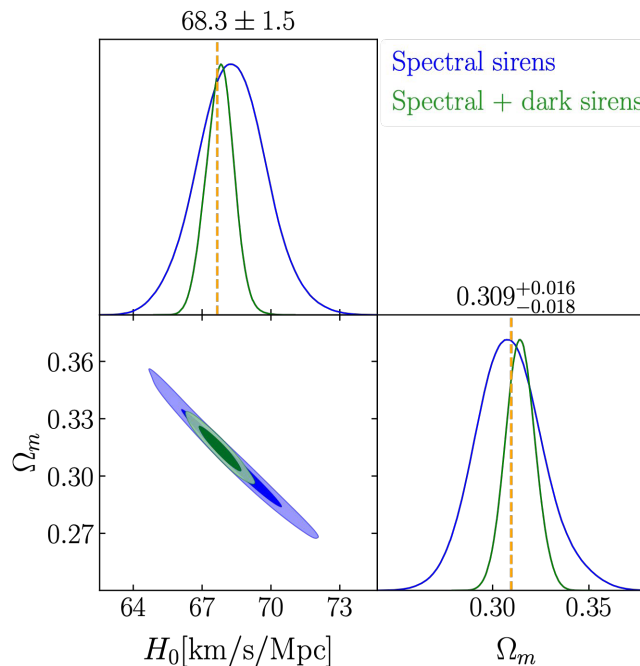
Expansion rate at high redshift $H(z)$

Combining sirens **sub-percent** precision across cosmic history!

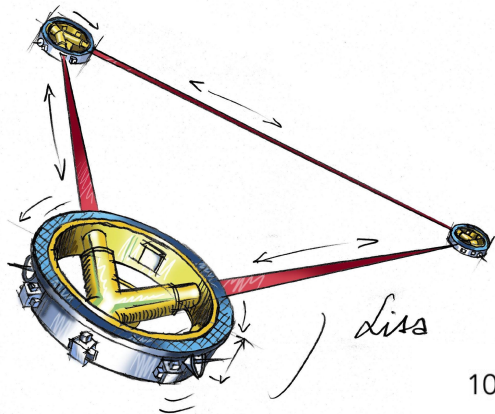
Spectral sirens are competitive
with cosmic surveys



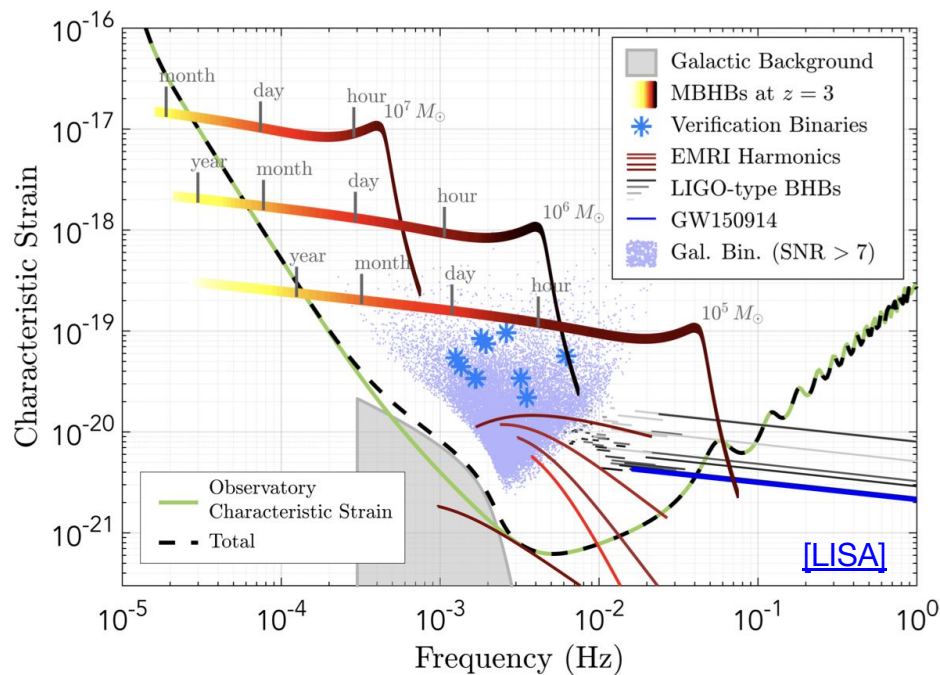
[Ezquiaga & Holz (PRL'22)]



[Chen, Ezquiaga & Gupta (CQG'24)]

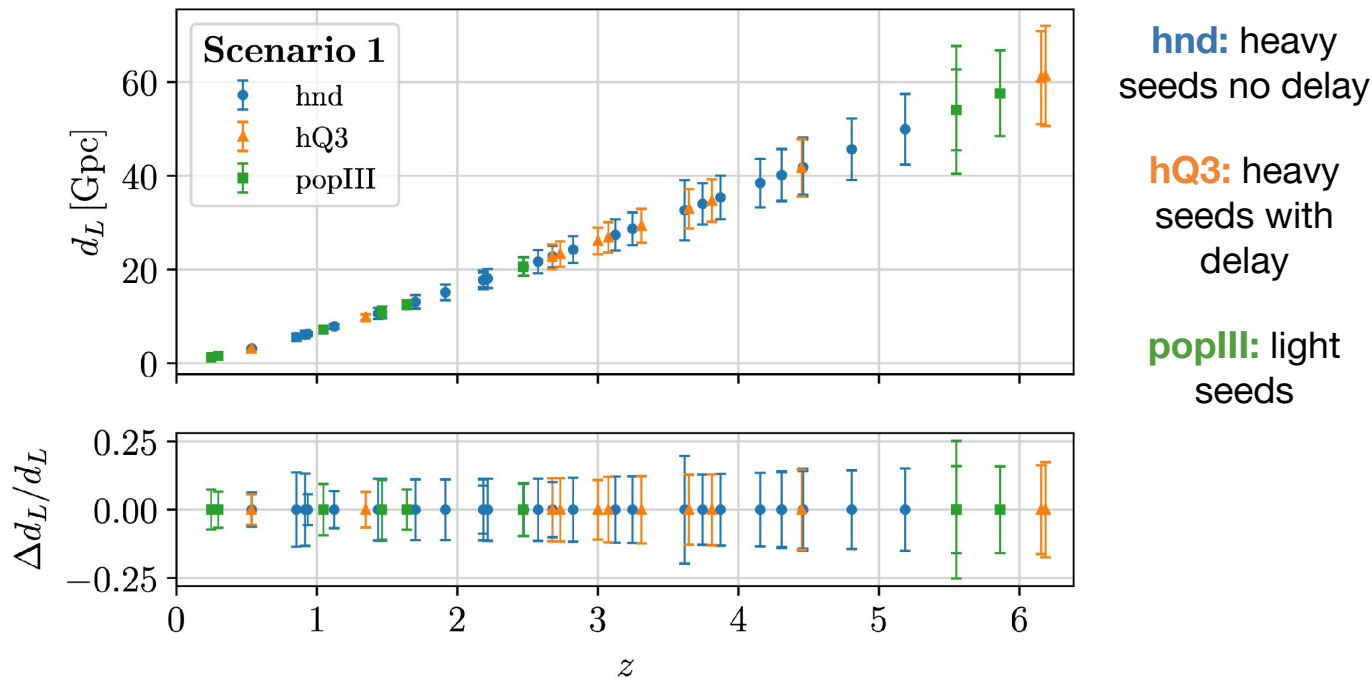


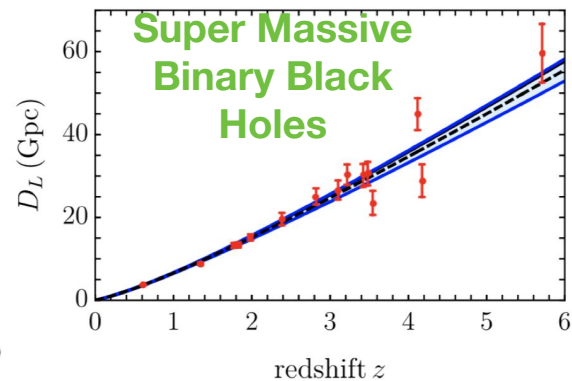
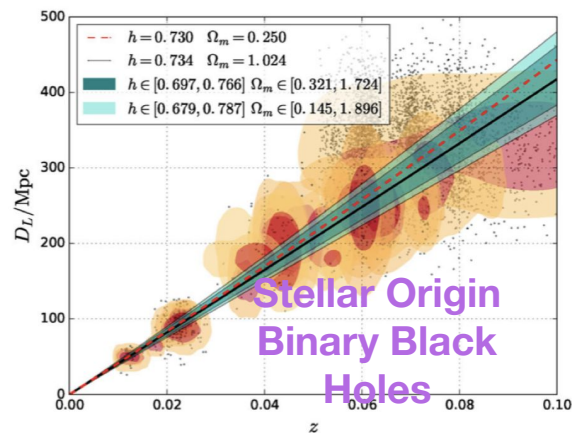
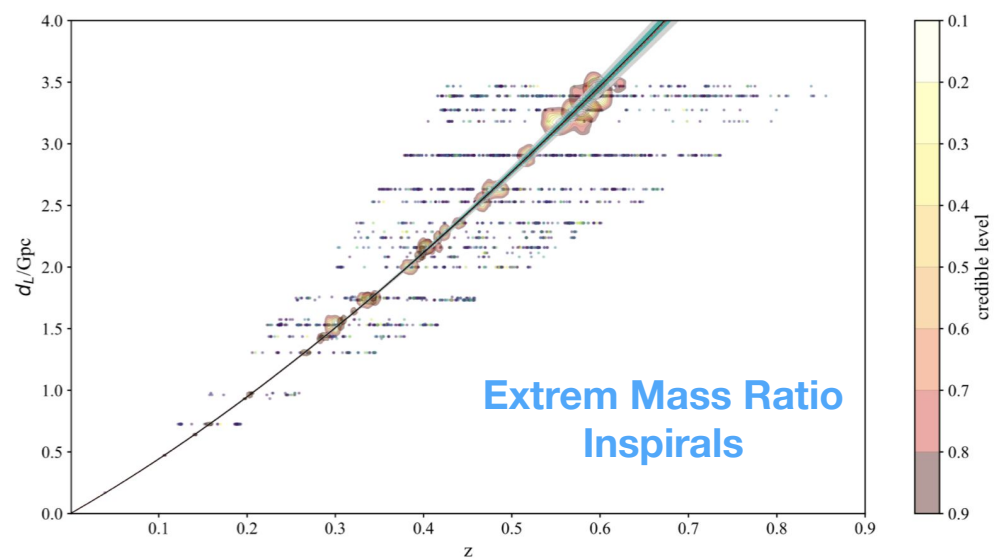
LISA's perspective



LISA forecasts: massive BBHs

[approx. 10-30 **bright sirens** (4 yrs)]





Conclusions

- **Standard sirens** are special cosmological probes
- **2% H_0 precision needed** to provide insights on **Hubble tension**
 - A dozen bright standard sirens with EM viewing angle constraints
 - A few hundreds well localized dark standard sirens
 - Possible by ~2032
- **$H(z)$** constraints will also be interesting!
- **Growth of structure** can also be probed with XG (AP & Kim 2021)
- Different kinds of standard sirens are **complementary** and powerful when combined
- There is **a lot more** to learn from combining GW observations and sky surveys: multimessenger observations also provide insight on the **neutron star equation of state** and **nuclear physics**, **origin of black holes and neutron stars**, the **formation of the heavy elements** in the Universe