東北大學
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Forecast for cosmological parameter estimation in the era of the third-generation gravitational wave detectors

Shang-Jie Jin (金上捷)

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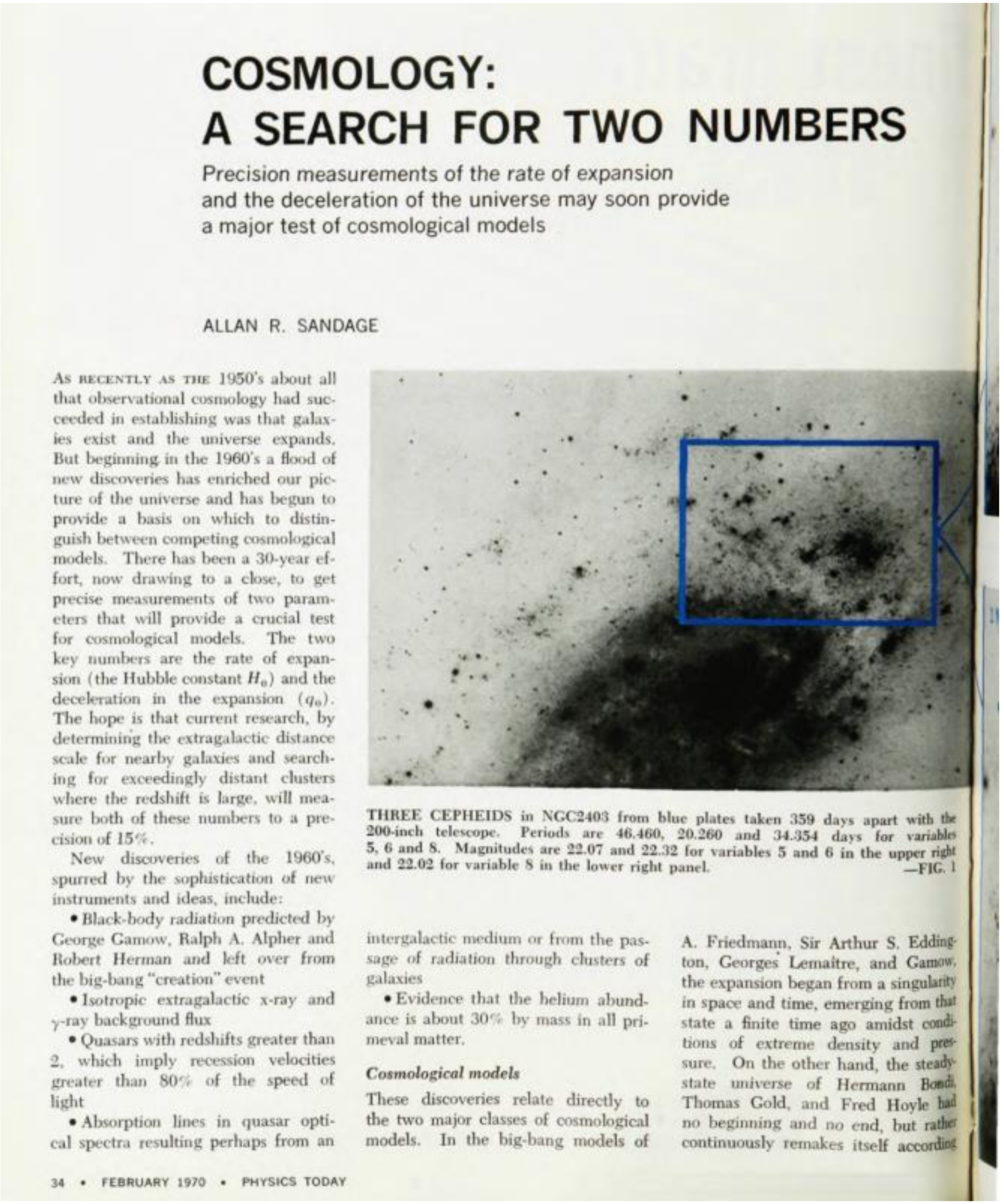
Based on 2001.05393, 2106.01859, 2202.11882, 2204.04689

21 cm Cosmology Workshop 2023 & Tianlai Collaboration Meeting
China•Shenyang 2023.7.19

Two important numbers



COSMOLOGY: A SEARCH FOR TWO NUMBERS

Precision measurements of the rate of expansion
and the deceleration of the universe may soon provide
a major test of cosmological models

ALLAN R. SANDAGE

As recently as the 1950's about all that observational cosmology had succeeded in establishing was that galaxies exist and the universe expands. But beginning in the 1960's a flood of new discoveries has enriched our picture of the universe and has begun to provide a basis on which to distinguish between competing cosmological models. There has been a 30-year effort, now drawing to a close, to get precise measurements of two parameters that will provide a crucial test for cosmological models. The two key numbers are the rate of expansion (the Hubble constant H_0) and the deceleration in the expansion (q_0). The hope is that current research, by determining the extragalactic distance scale for nearby galaxies and searching for exceedingly distant clusters where the redshift is large, will measure both of these numbers to a precision of 15%.

New discoveries of the 1960's, spurred by the sophistication of new instruments and ideas, include:

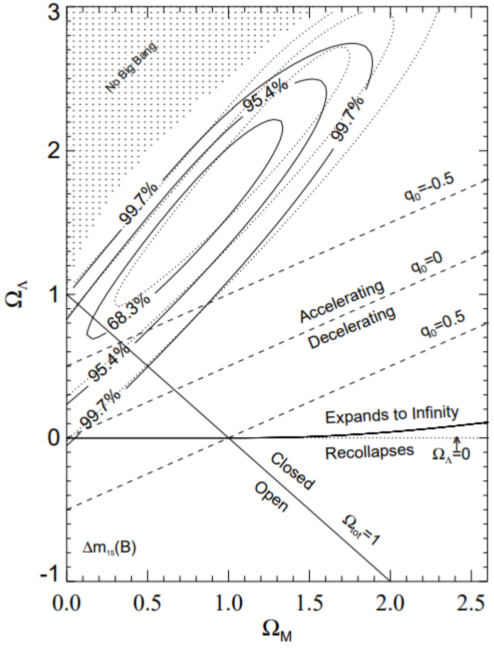
- Black-body radiation predicted by George Gamow, Ralph A. Alpher and Robert Herman and left over from the big-bang "creation" event
- Isotropic extragalactic x-ray and γ-ray background flux
- Quasars with redshifts greater than 2, which imply recession velocities greater than 80% of the speed of light
- Absorption lines in quasar optical spectra resulting perhaps from an intergalactic medium or from the passage of radiation through clusters of galaxies
- Evidence that the helium abundance is about 30% by mass in all primeval matter.

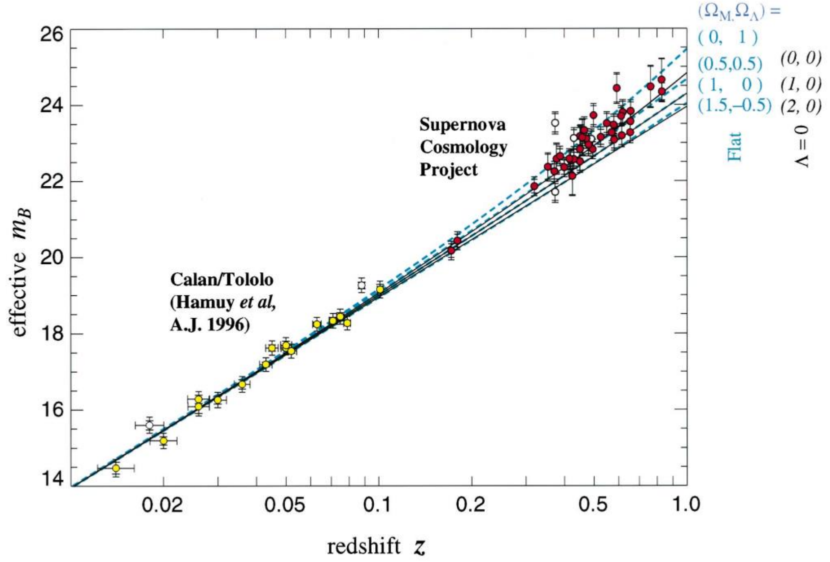
THREE CEPHEIDS in NGC2403 from blue plates taken 359 days apart with the 200-inch telescope. Periods are 46.460, 20.260 and 34.354 days for variables 5, 6 and 8. Magnitudes are 22.07 and 22.32 for variables 5 and 6 in the upper right and 22.02 for variable 8 in the lower right panel. —FIG. 1

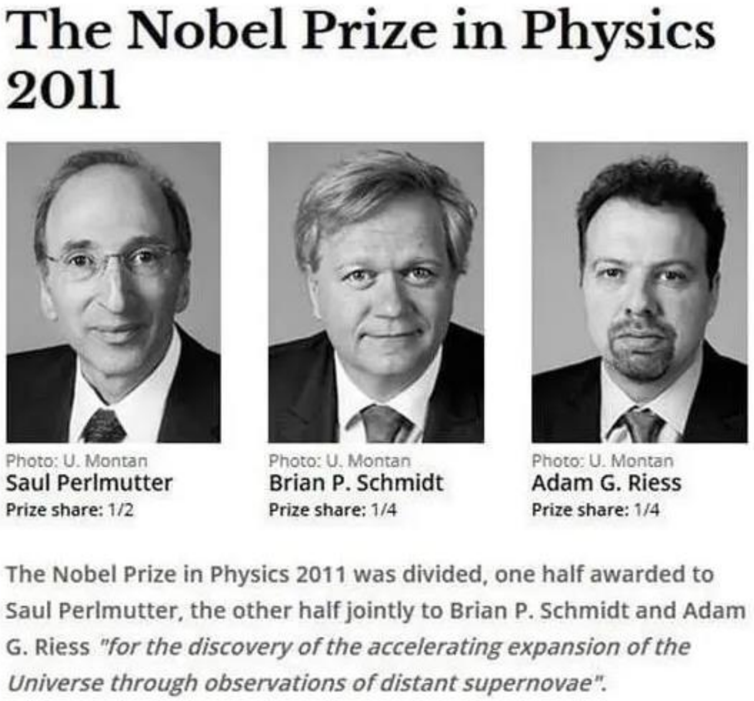
Cosmological models

These discoveries relate directly to the two major classes of cosmological models. In the big-bang models of A. Friedmann, Sir Arthur S. Eddington, Georges Lemaitre, and Gamow, the expansion began from a singularity in space and time, emerging from that state a finite time ago amidst conditions of extreme density and pressure. On the other hand, the steady-state universe of Hermann Bondi, Thomas Gold, and Fred Hoyle had no beginning and no end, but rather continuously remakes itself according

34 • FEBRUARY 1970 • PHYSICS TODAY







The Nobel Prize in Physics 2011

Photo: U. Montan
Saul Perlmutter
Prize share: 1/2

Photo: U. Montan
Brian P. Schmidt
Prize share: 1/4

Photo: U. Montan
Adam G. Riess
Prize share: 1/4

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae".*

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

Adam G. Riess,[1] Alexei V. Filippenko,[1] Peter Challis,[2] Alejandro Clocchiatti,[3] Alan Diercks,[4]
Peter M. Garnavich,[2] Ron L. Gilliland,[5] Craig J. Hogan,[4] Saurabh Jha,[2] Robert P. Kirshner,[2]
B. Leibundgut,[6] M. M. Phillips,[7] David Reiss,[4] Brian P. Schmidt,[8,9] Robert A. Schommer,[7]
R. Chris Smith,[7,10] J. Spyromilio,[6] Christopher Stubbs,[4]
Nicholas B. Suntzeff,[7] and John Tonry[11]
Received 1998 March 13; revised 1998 May 6

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. Perlmutter,[1] G. Aldering, G. Goldhaber,[1] R. A. Knop, P. Nugent, P. G. Castro,[2] S. Deustua, S. Fabbro,[3]
A. Goobar,[4] D. E. Groom, I. M. Hook,[5] A. G. Kim,[1,6] M. Y. Kim, J. C. Lee,[7] N. J. Nunes,[2] R. Pain,[3]
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C. Lidman
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R. S. Ellis, M. Irwin, and R. G. McMahon
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P. Ruiz-Lapuente
Department of Astronomy, University of Barcelona, Barcelona, Spain
N. Walton
Isaac Newton Group, La Palma, Spain
B. Schaefer
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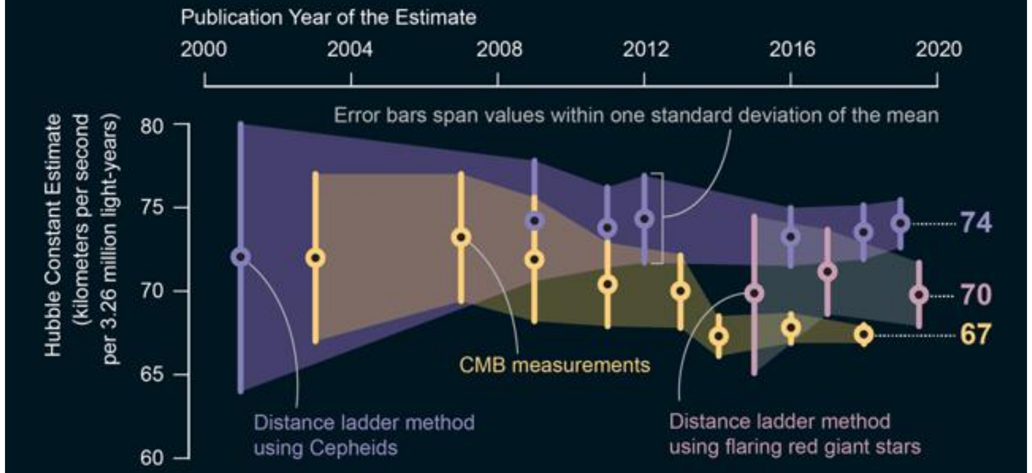
B. J. Boyle
Anglo-Australian Observatory, Sydney, Australia
A. V Filippenko and T. Matheson
Department of Astronomy, University of California, Berkeley, CA
A. S. Fruchter and N. Panagia[9]
Space Telescope Science Institute, Baltimore, MD
H. J. M. Newberg
Fermi National Laboratory, Batavia, IL
and
W. J. Couch
University of New South Wales, Sydney, Australia
(The Supernova Cosmology Project)
Received 1998 September 8; accepted 1998 December 17

Sandage, Physics Today 23 (1970) 34
Riess, Astron. J. 116 (1998) 1009
Perlmutter, Astrophys. J. 517 (1999) 565

Hubble tension

DIVERGING RESULTS

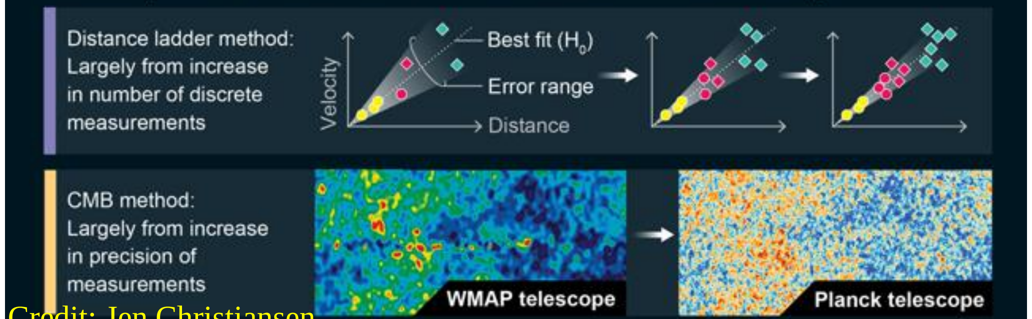
The CMB-based, early universe value for H_0 is 67 (in units of kilometers per second per 3.26 million light-years). The Cepheid-based, late universe value is 74. A new alternative to Cepheids—red giant stars that flare with a known intrinsic brightness—only complicated the tension. They indicated an H_0 of about 70—a value that is midway between the other two, with no overlap of error ranges.



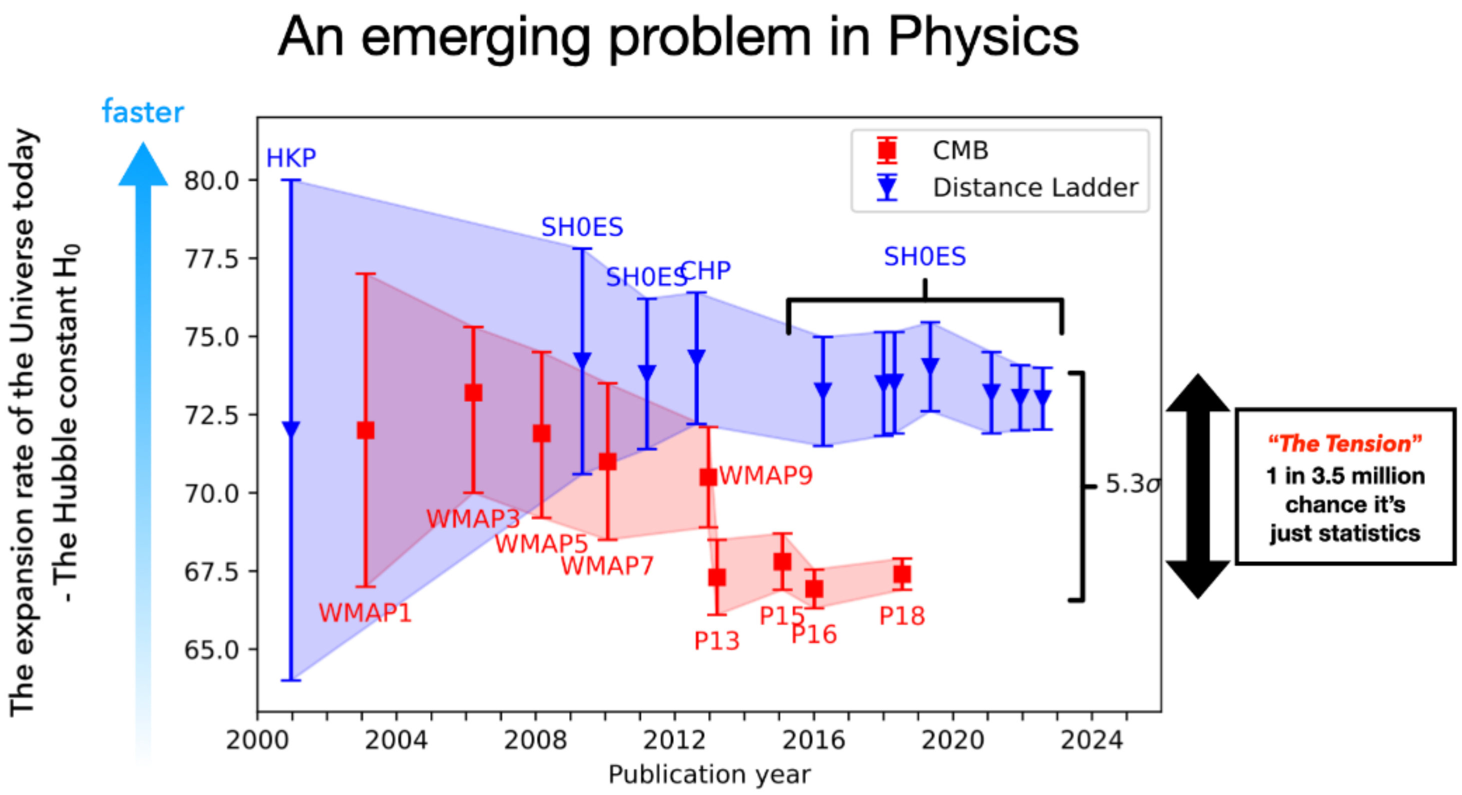
TOWARD A MORE PERFECT UNION—OR NEW PHYSICS

Astronomers and cosmologists alike are working to increase the precision of their respective estimates of H_0, progressively reducing uncertainties and possible errors in hopes their results may eventually overlap. Larger telescopes are gazing deeper into the cosmos, measuring Cepheids ever farther from Earth, and the CMB-mapping Planck satellite has dramatically improved on the measurements of its predecessor, the Wilkinson Microwave Anisotropy Probe (WMAP). If, however, the discrepancy endures, profound revisions to our cosmological models may be required.

Increased precision of Hubble constant calculations over time



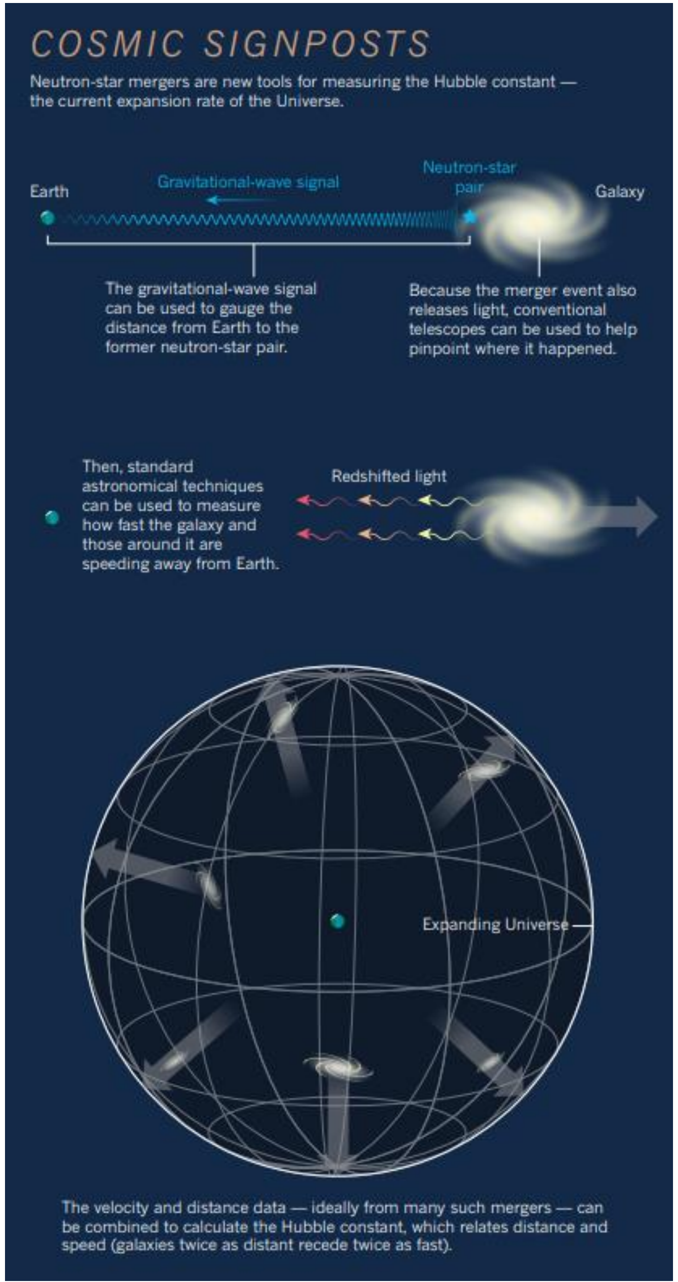
Credit: Jen Christiansen


An emerging problem in Physics

Credit: D'arcy Kenworthy

67 or 74 ?

Gravitational wave standard siren



COSMIC SIGNPOSTS

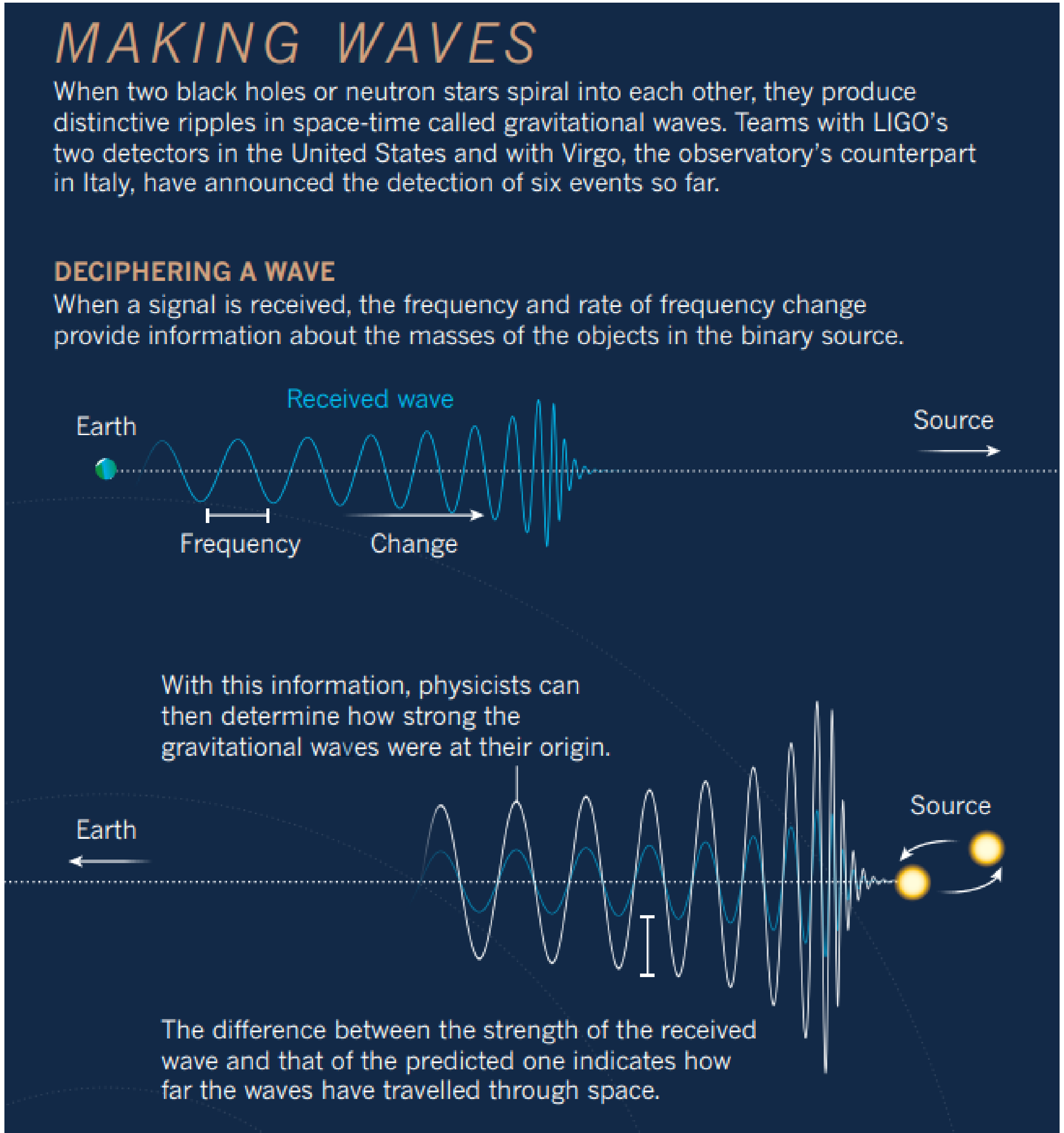
Neutron-star mergers are new tools for measuring the Hubble constant — the current expansion rate of the Universe.

The gravitational-wave signal can be used to gauge the distance from Earth to the former neutron-star pair.

Because the merger event also releases light, conventional telescopes can be used to help pinpoint where it happened.

Then, standard astronomical techniques can be used to measure how fast the galaxy and those around it are speeding away from Earth.

The velocity and distance data — ideally from many such mergers — can be combined to calculate the Hubble constant, which relates distance and speed (galaxies twice as distant recede twice as fast).



MAKING WAVES

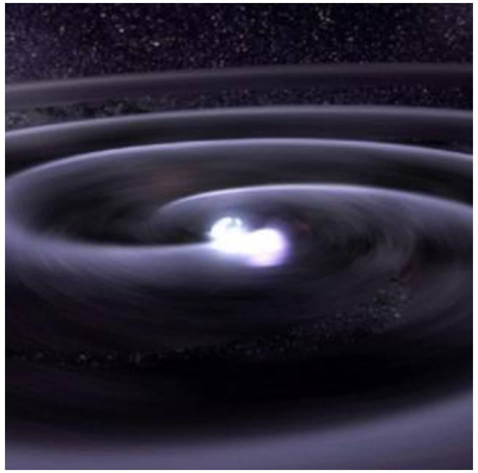
When two black holes or neutron stars spiral into each other, they produce distinctive ripples in space-time called gravitational waves. Teams with LIGO's two detectors in the United States and with Virgo, the observatory's counterpart in Italy, have announced the detection of six events so far.

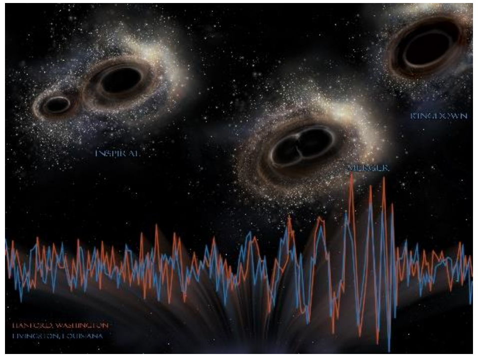
DECIPHERING A WAVE

When a signal is received, the frequency and rate of frequency change provide information about the masses of the objects in the binary source.

With this information, physicists can then determine how strong the gravitational waves were at their origin.

The difference between the strength of the received wave and that of the predicted one indicates how far the waves have travelled through space.



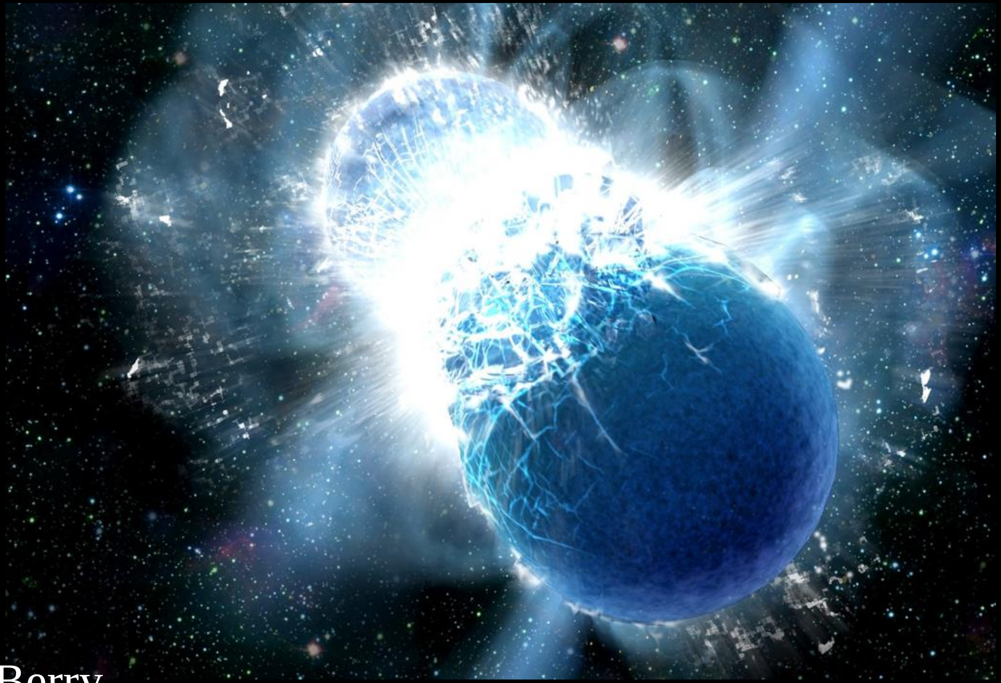


Schutz, Nature 323 (1986) 310
Holz & Hughes, Astrophys. J. 629 (2005) 15
Castelvecchi,Nature 556 (2018) 7
700, 164-168

GW standard siren cosmology

Bright sirens

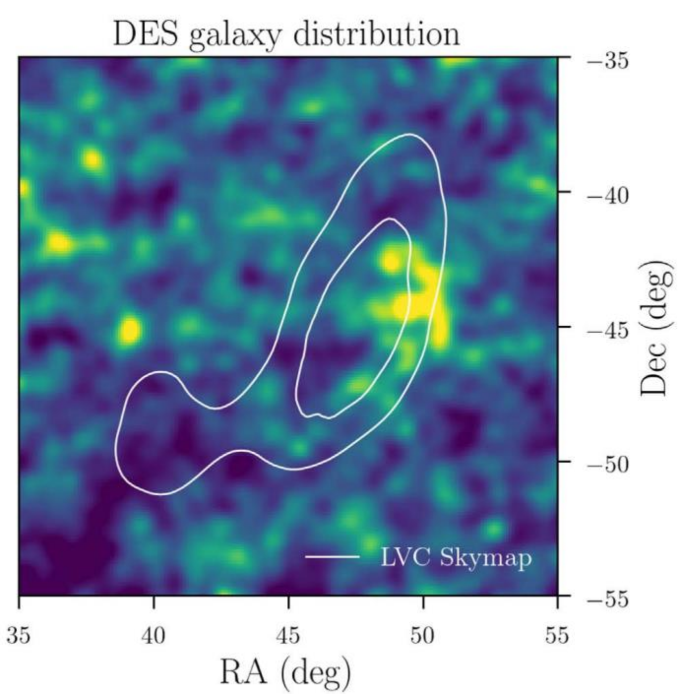
- Redshift from electromagnetic counterparts
- Need binary neutron star mergers



Credit: Dana Berry

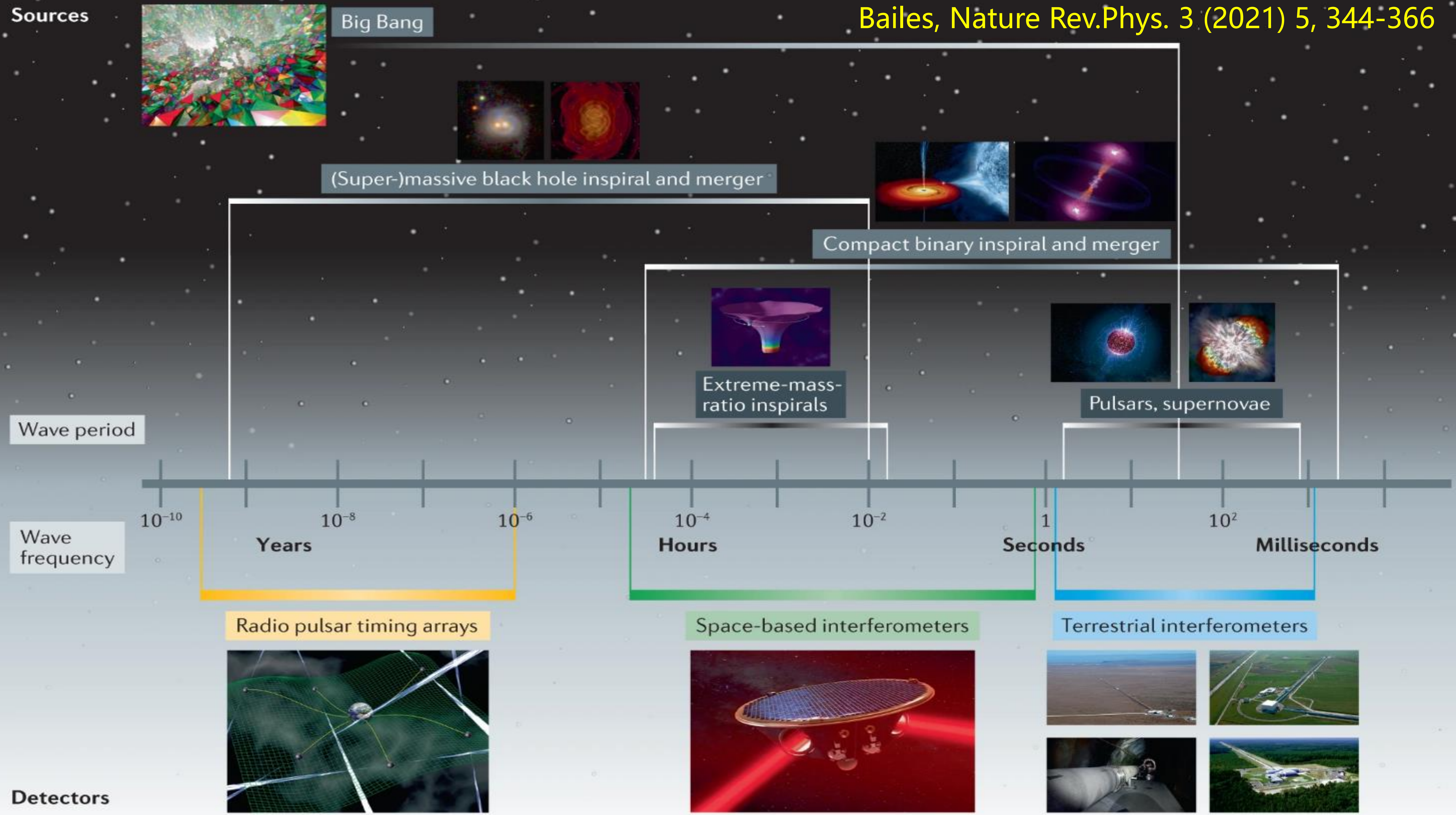
Dark sirens

- Statistically infer z from galaxies from localization volume
- Need good localization and complete galaxy catalog



Credit: DES

Bailes, Nature Rev.Phys. 3 (2021) 5, 344-366



Sources

Big Bang

(Super-)massive black hole inspiral and merger

Compact binary inspiral and merger

Extreme-mass-ratio inspirals

Pulsars, supernovae

Wave period

Wave frequency

10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}

Years **Hours** **Seconds** **Milliseconds**

Radio pulsar timing arrays

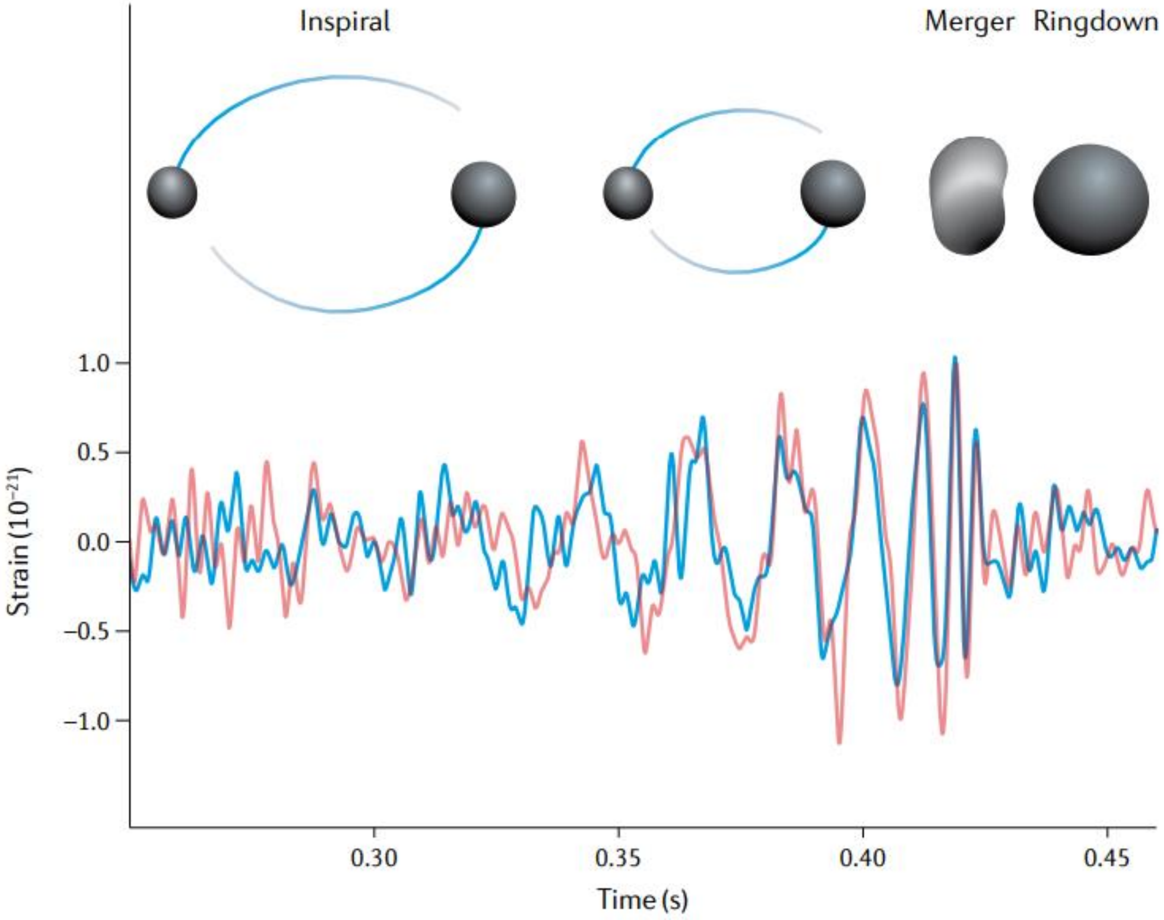
Space-based interferometers

Terrestrial interferometers

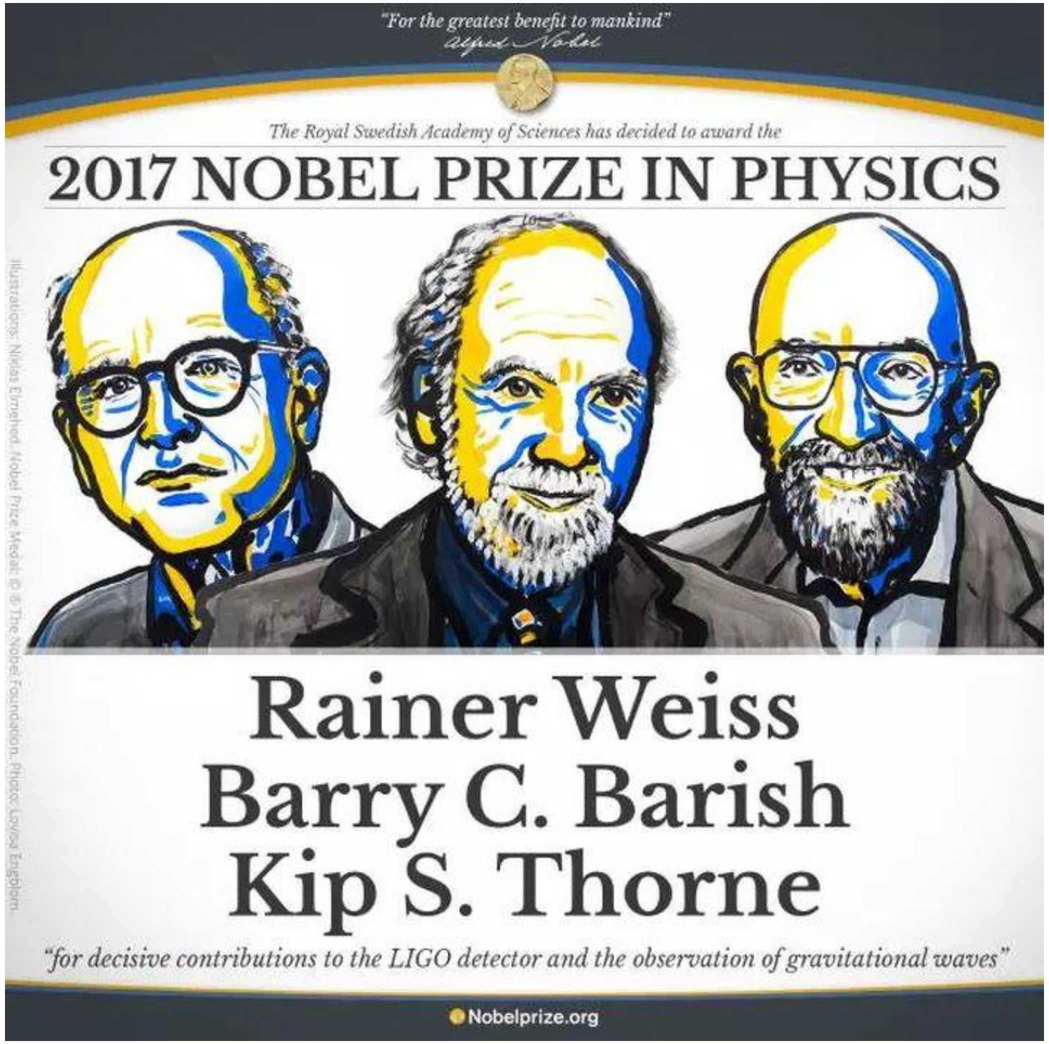
Detectors

GW150914: observation of GW from a binary black hole merger

Open the era of GW astronomy



Bailes, Nature Rev.Phys. 3 (2021) 5, 344-366



"For the greatest benefit to mankind"

Alfred Nobel

The Royal Swedish Academy of Sciences has decided to award the

2017 NOBEL PRIZE IN PHYSICS

to

Rainer Weiss

Barry C. Barish

Kip S. Thorne

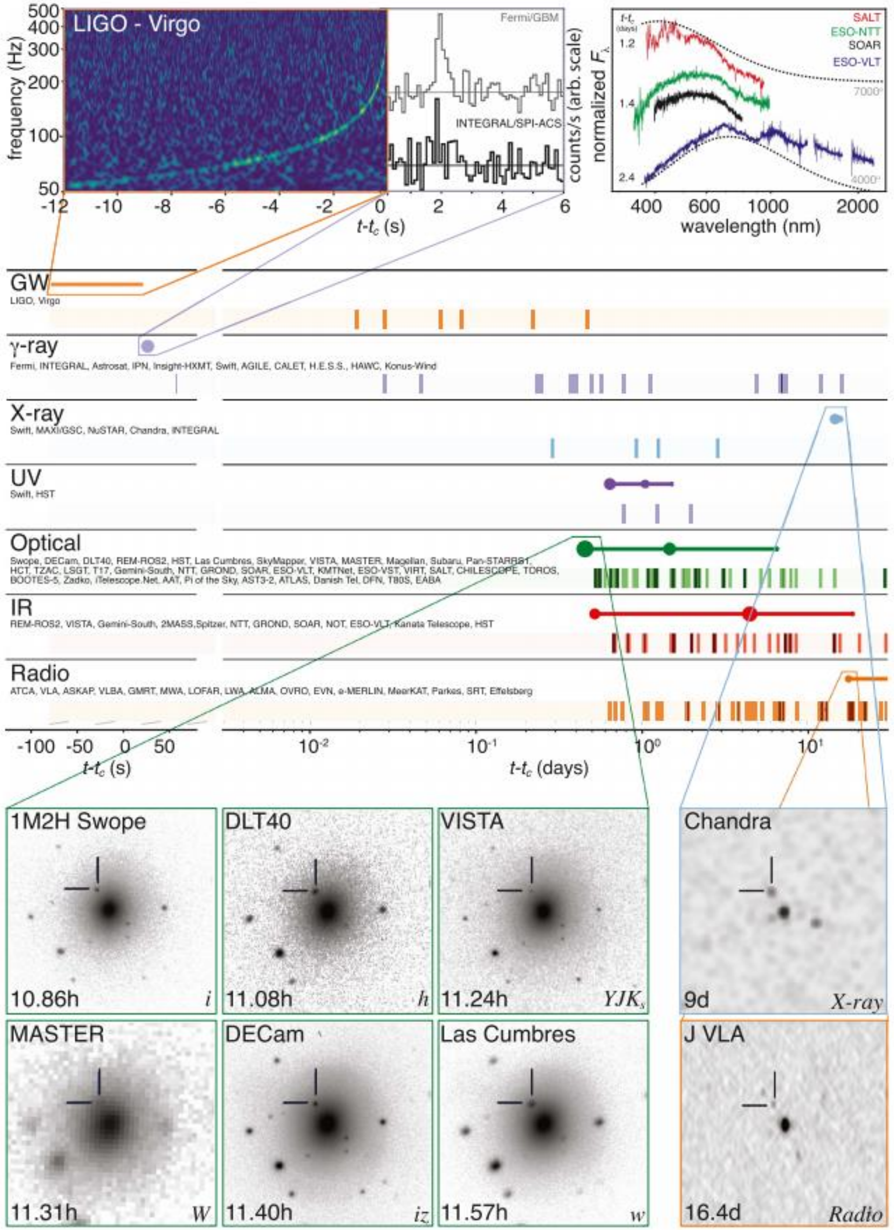
"for decisive contributions to the LIGO detector and the observation of gravitational waves"

Nobelprize.org

Illustrations: Niklas Elmehed. Nobel Prize Medal: © ® The Nobel Foundation. Photo: Lovisa Engblom.

GW150914: the first observed GW

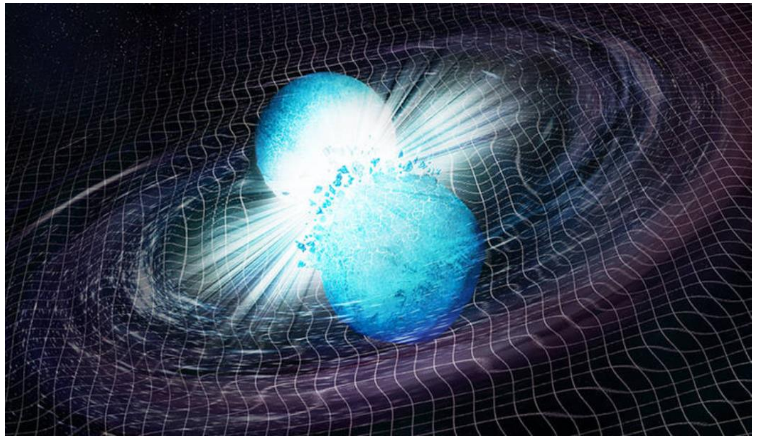
GW170817: observation of GW from a binary neutron star merger

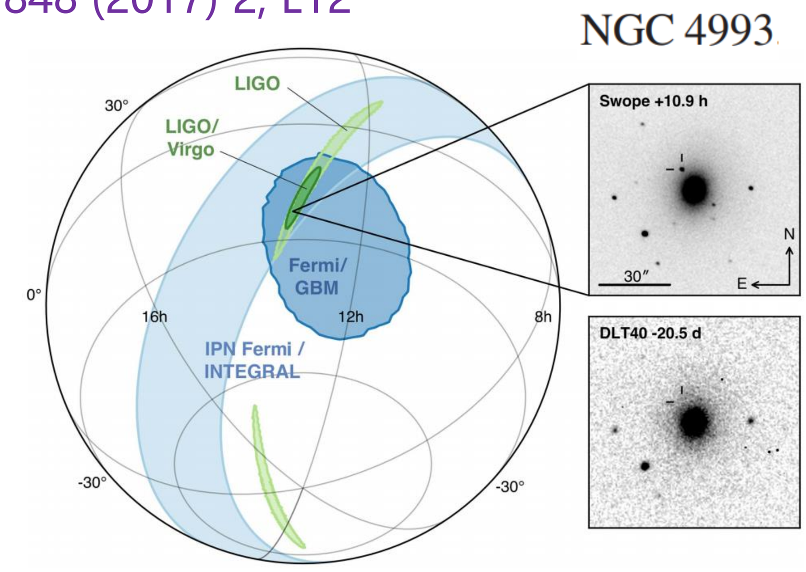


GW170817: Multi-messenger observation

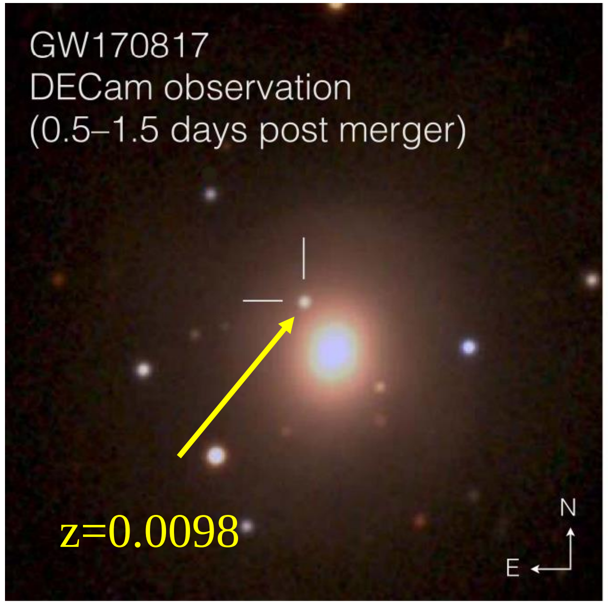
- ✓ Gravitational wave
- ✓ γ-ray
- ✓ Optical, UV, IR, Radio

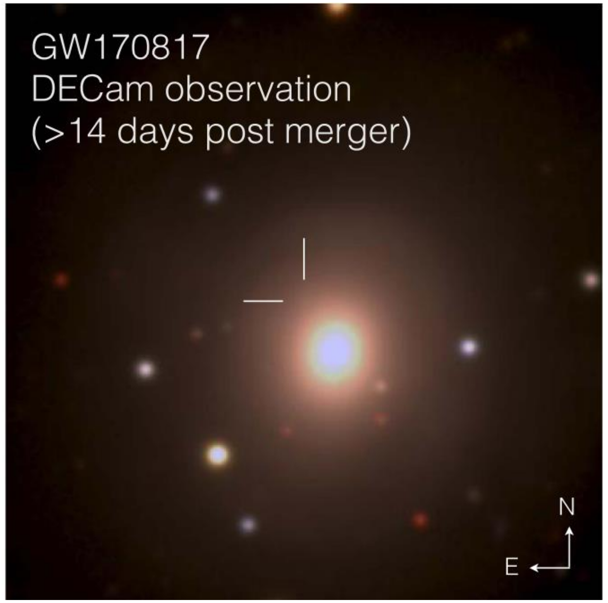
B. P. Abbott, et al. Astrophys.J.Lett. 848 (2017) 2, L12

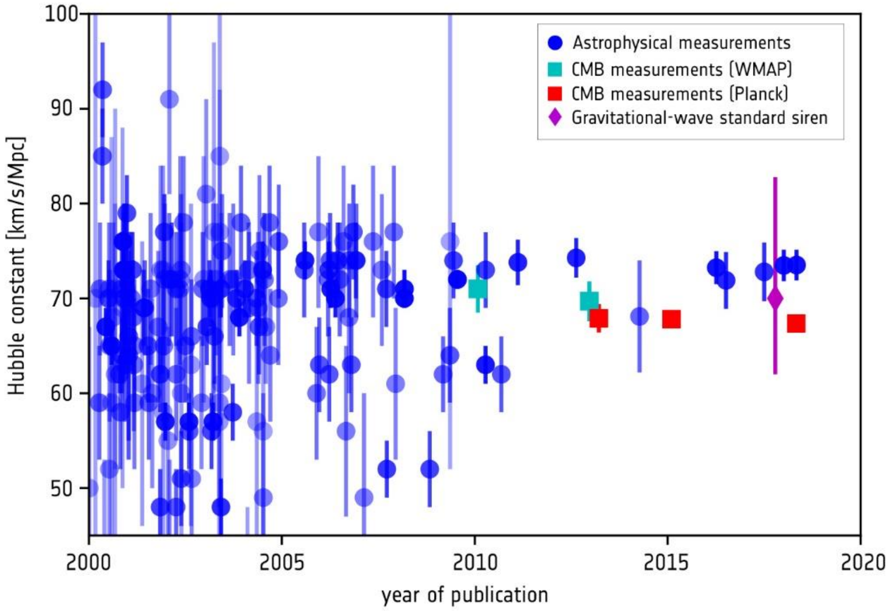




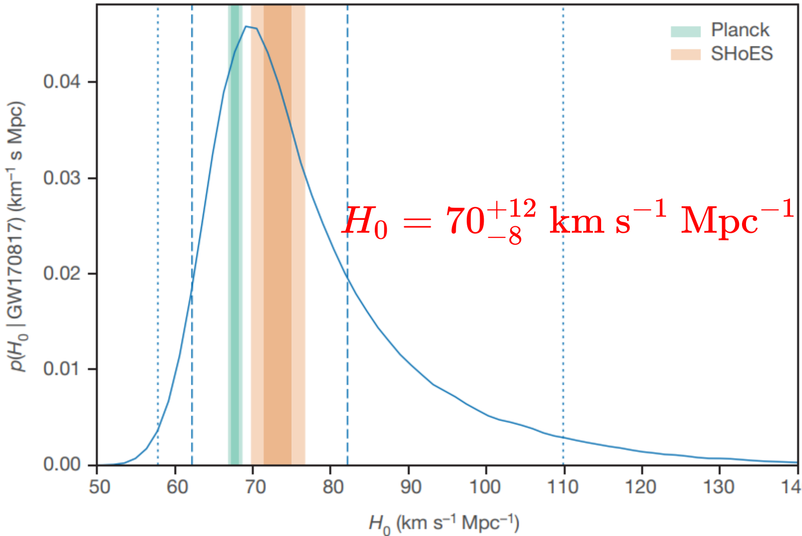
GW bright sirens







From LIGO-Virgo: $d_L = 43^{+2.9}_{-6.9}$ Mpc

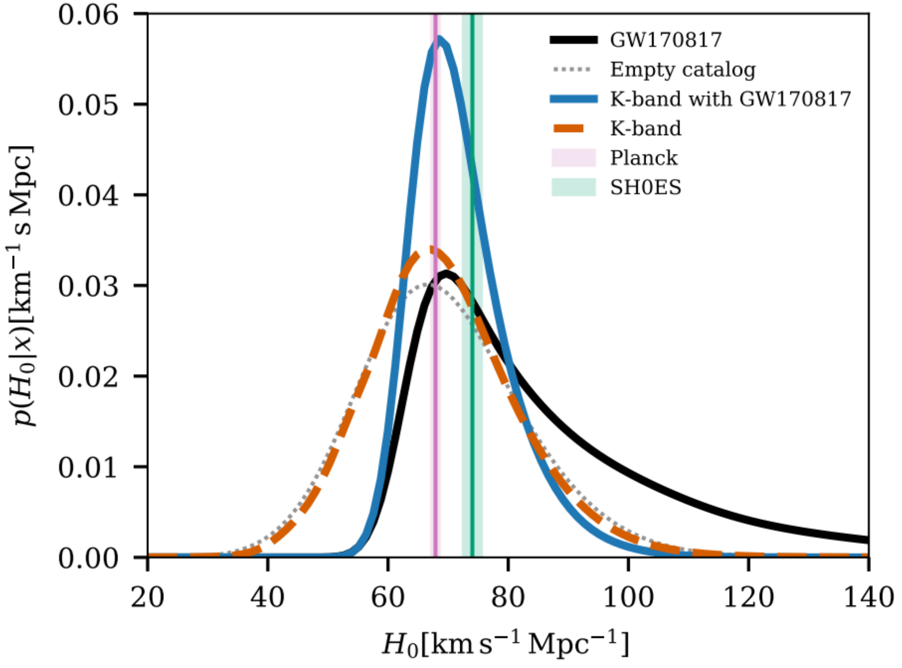


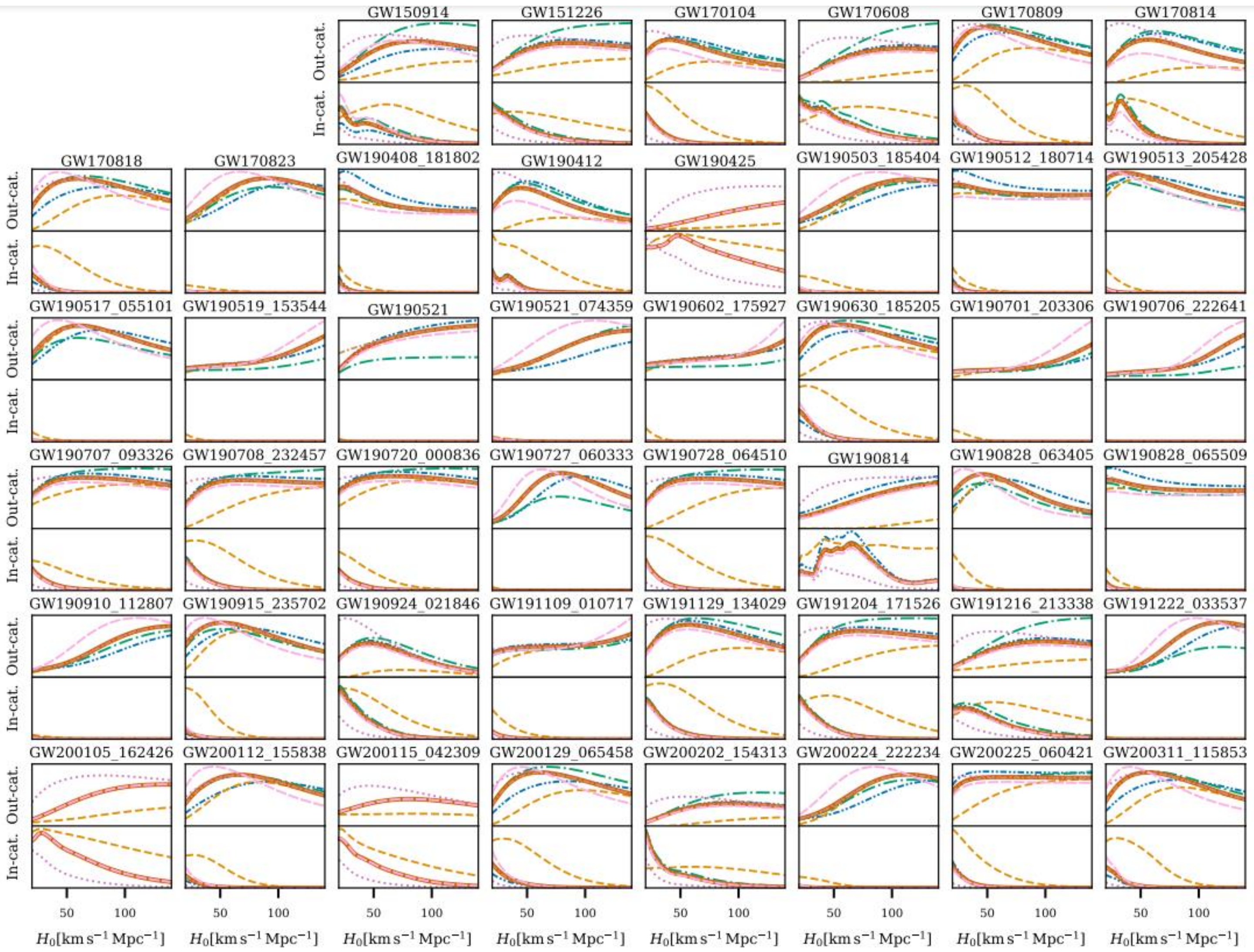
- ➢ Only one data point, constraint precision of H_0 is about 14%
- ➢ H_0: 2% precision (50 similar data points, $15\%/\sqrt{N}$)

M. Soares-Santos et al. Astrophys.J.Lett. 848 (2017) 2, L16

B.P. Abbott et al. Nature 551, 85 (2017)

GW dark sirens





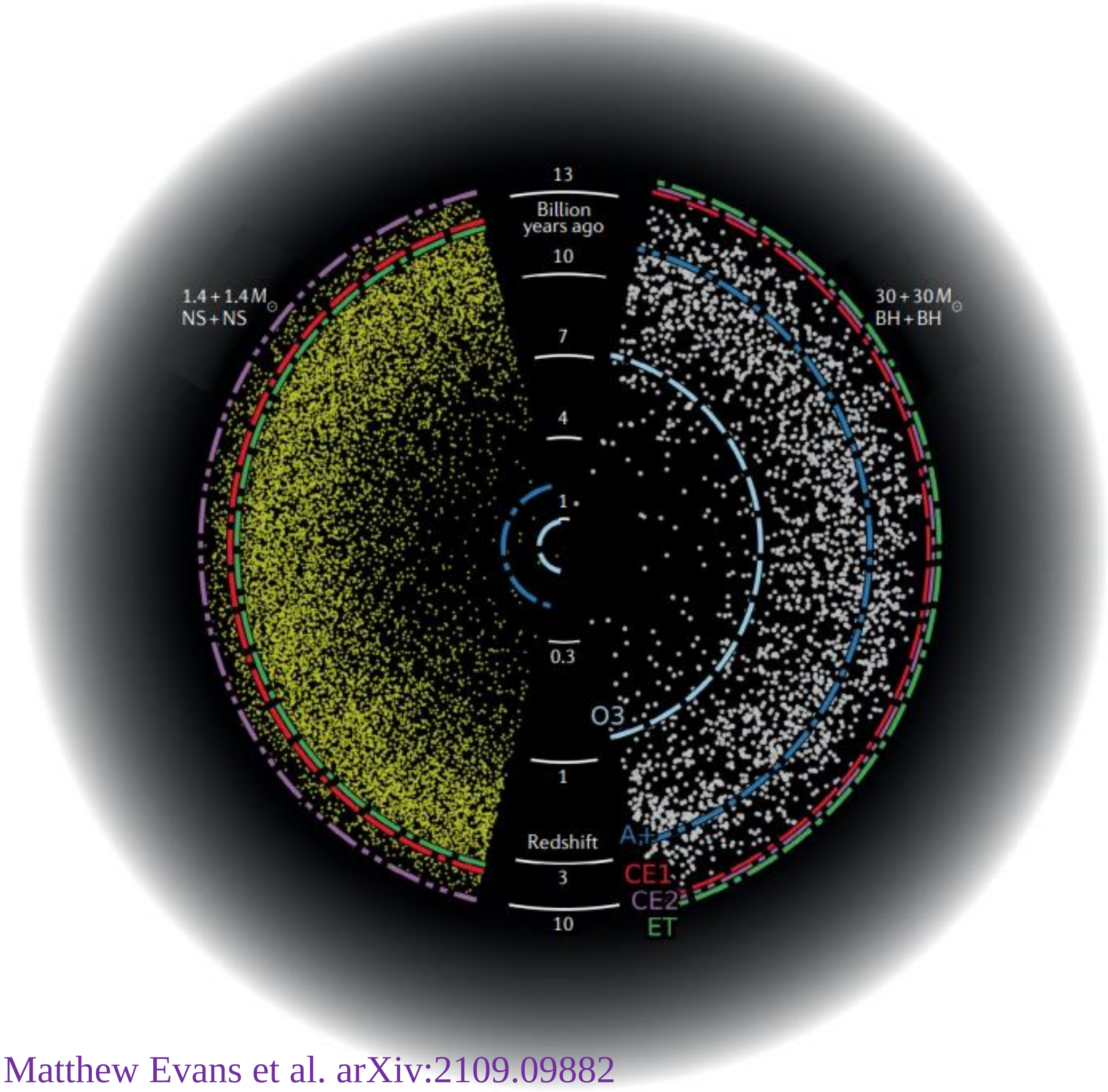
Dark siren alone: $H_0 = 67^{+13}_{-12}\ \mathrm{km\ s^{-1} Mpc^{-1}}$

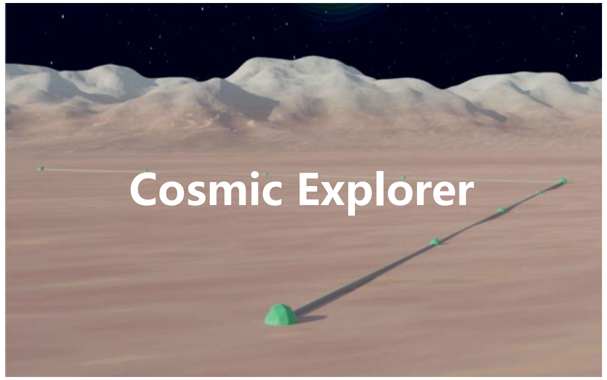
Combined with GW170817:
$H_0 = 68^{+8}_{-6}\ \mathrm{km\ s^{-1} Mpc^{-1}}$

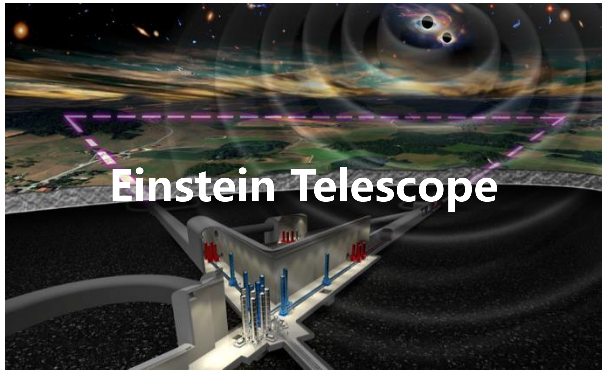
- 47 events with SNR>11
- GW events combined with GLADE+ catalog

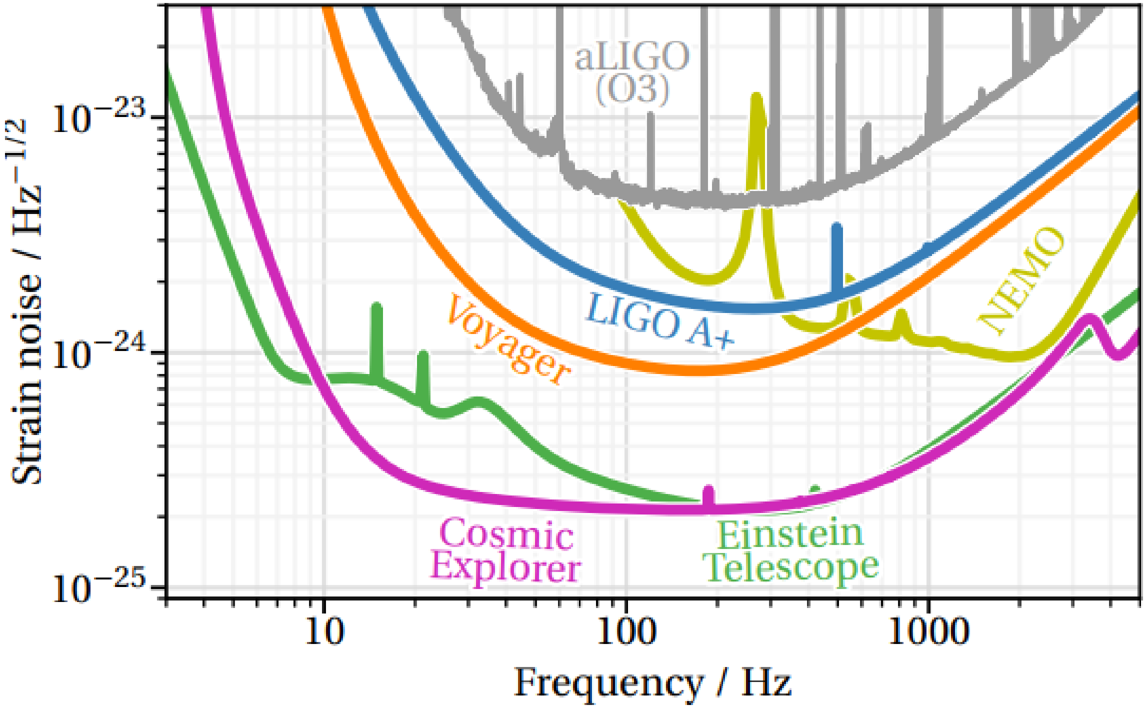
R. Abbott et al. arXiv: 2111.03604

The third-generation ground-based GW detectors



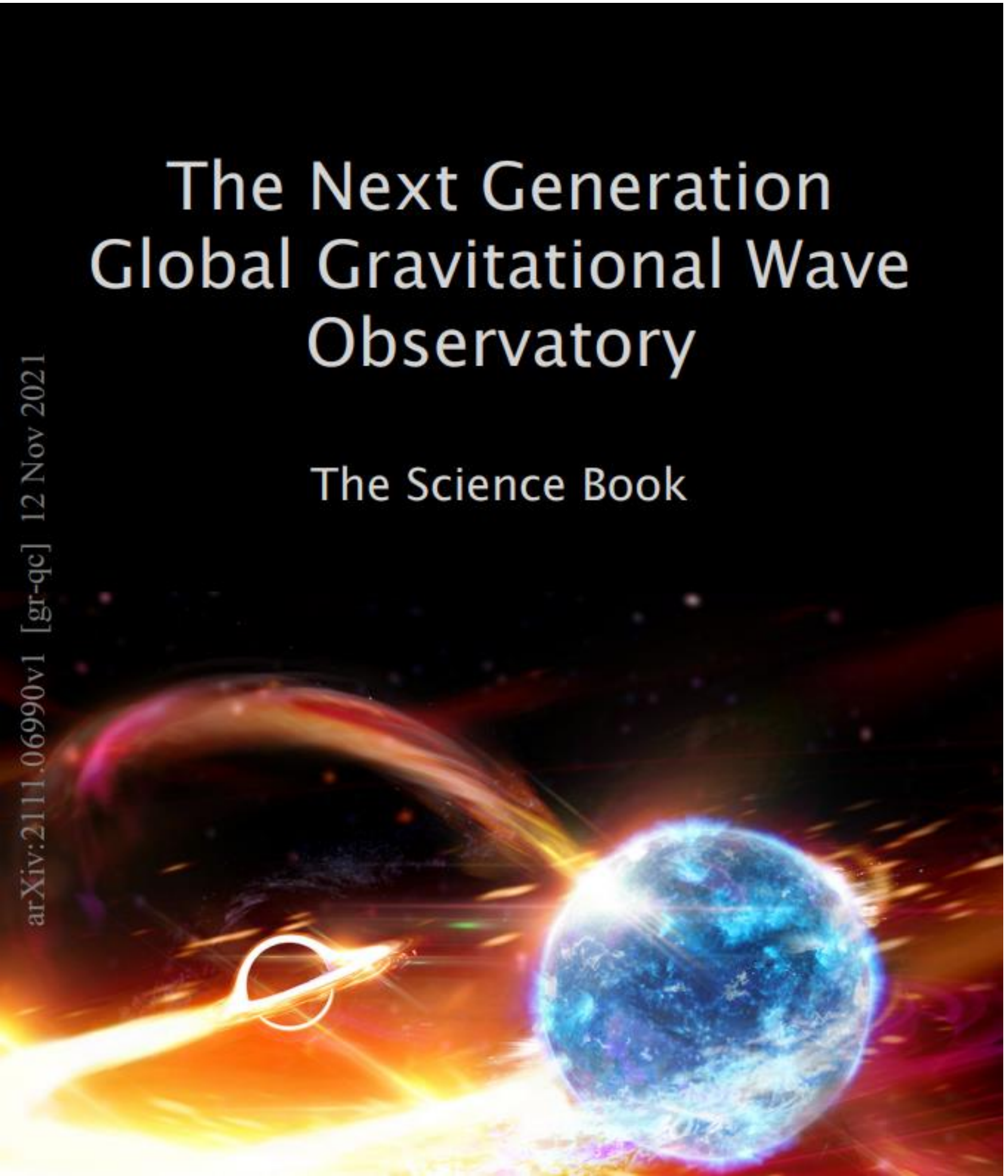






Matthew Evans et al. arXiv:2109.09882

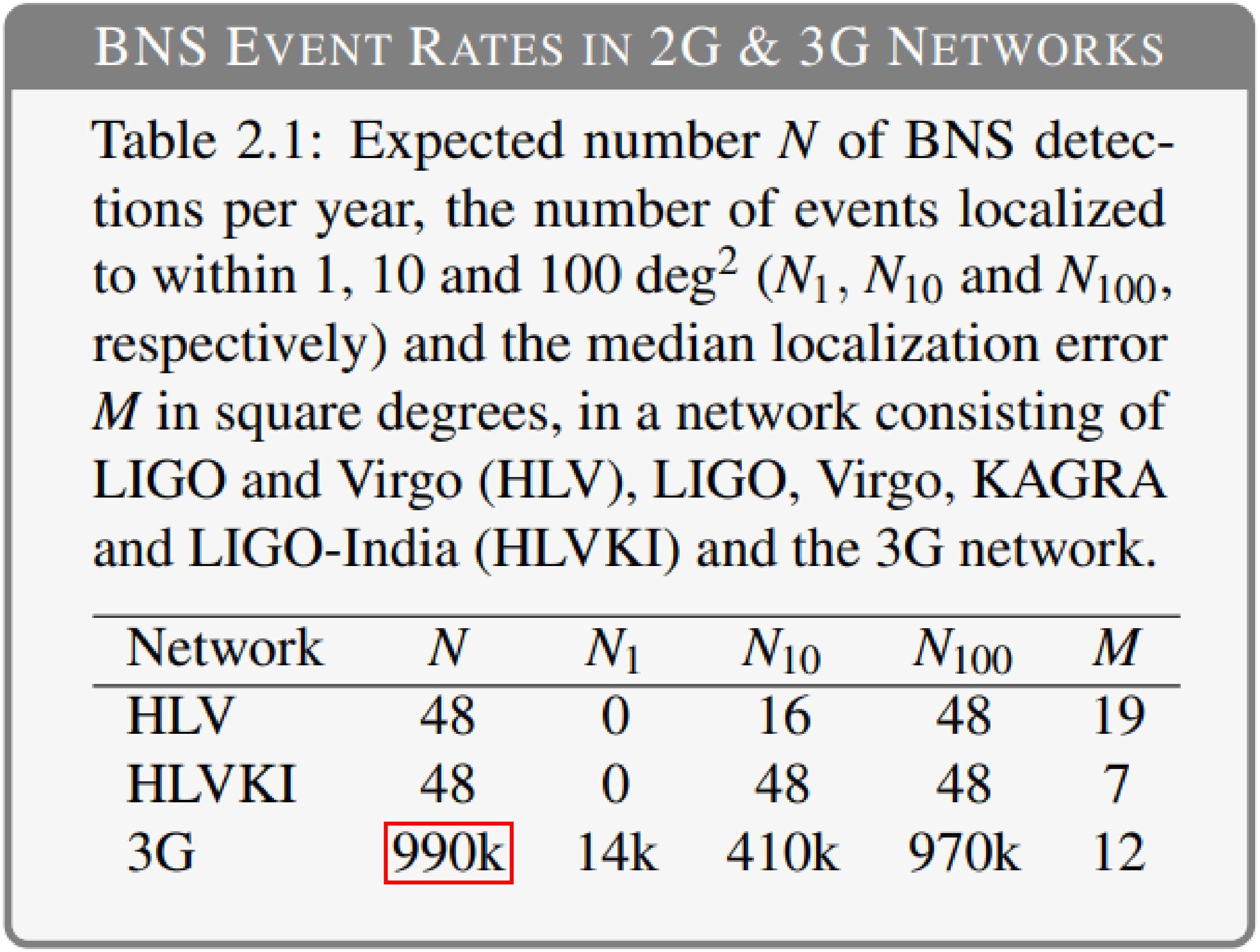
The third-generation ground-based GW detectors



The Next Generation Global Gravitational Wave Observatory

The Science Book

arXiv:2111.06990v1 [gr-qc] 12 Nov 2021



BNS EVENT RATES IN 2G & 3G NETWORKS

Table 2.1: Expected number N of BNS detections per year, the number of events localized to within 1, 10 and 100 deg^2 (N_1, N_{10} and N_{100}, respectively) and the median localization error M in square degrees, in a network consisting of LIGO and Virgo (HLV), LIGO, Virgo, KAGRA and LIGO-India (HLVKI) and the 3G network.

Network	N	N_1	N_{10}	N_{100}	M
HLV	48	0	16	48	19
HLVKI	48	0	48	48	7
3G	990k	14k	410k	970k	12

Vicky Kalogera et al.arXiv:2111.06990

Multi-messenger observation rates of the 3G GW detectors

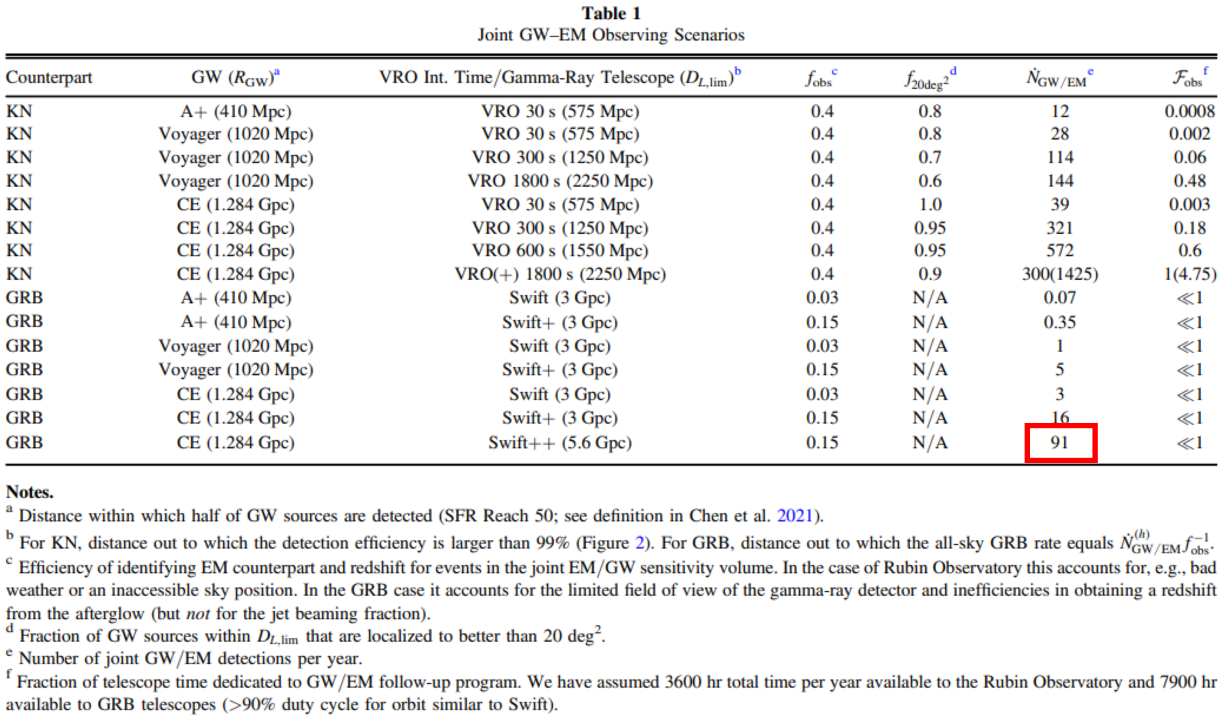


Table 1
Joint GW–EM Observing Scenarios

Counterpart	GW ($R_{\rm GW}$)[a]	VRO Int. Time/Gamma-Ray Telescope ($D_{L,\rm lim}$)[b]	$f_{\rm obs}$[c]	$f_{20\rm deg^2}$[d]	$\dot{N}_{\rm GW/EM}$[e]	$\mathcal{F}_{\rm obs}$[f]
KN	A+ (410 Mpc)	VRO 30 s (575 Mpc)	0.4	0.8	12	0.0008
KN	Voyager (1020 Mpc)	VRO 30 s (575 Mpc)	0.4	0.8	28	0.002
KN	Voyager (1020 Mpc)	VRO 300 s (1250 Mpc)	0.4	0.7	114	0.06
KN	Voyager (1020 Mpc)	VRO 1800 s (2250 Mpc)	0.4	0.6	144	0.48
KN	CE (1.284 Gpc)	VRO 30 s (575 Mpc)	0.4	1.0	39	0.003
KN	CE (1.284 Gpc)	VRO 300 s (1250 Mpc)	0.4	0.95	321	0.18
KN	CE (1.284 Gpc)	VRO 600 s (1550 Mpc)	0.4	0.95	572	0.6
KN	CE (1.284 Gpc)	VRO(+) 1800 s (2250 Mpc)	0.4	0.9	300(1425)	1(4.75)
GRB	A+ (410 Mpc)	Swift (3 Gpc)	0.03	N/A	0.07	$\ll$1
GRB	A+ (410 Mpc)	Swift+ (3 Gpc)	0.15	N/A	0.35	$\ll$1
GRB	Voyager (1020 Mpc)	Swift (3 Gpc)	0.03	N/A	1	$\ll$1
GRB	Voyager (1020 Mpc)	Swift+ (3 Gpc)	0.15	N/A	5	$\ll$1
GRB	CE (1.284 Gpc)	Swift (3 Gpc)	0.03	N/A	3	$\ll$1
GRB	CE (1.284 Gpc)	Swift+ (3 Gpc)	0.15	N/A	16	$\ll$1
GRB	CE (1.284 Gpc)	Swift++ (5.6 Gpc)	0.15	N/A	91	$\ll$1

Notes.

[a] Distance within which half of GW sources are detected (SFR Reach 50; see definition in Chen et al. 2021).

[b] For KN, distance out to which the detection efficiency is larger than 99% (Figure 2). For GRB, distance out to which the all-sky GRB rate equals $\dot{N}^{(h)}_{\rm GW/EM} f^{-1}_{\rm obs}$.

[c] Efficiency of identifying EM counterpart and redshift for events in the joint EM/GW sensitivity volume. In the case of Rubin Observatory this accounts for, e.g., bad weather or an inaccessible sky position. In the GRB case it accounts for the limited field of view of the gamma-ray detector and inefficiencies in obtaining a redshift from the afterglow (but *not* for the jet beaming fraction).

[d] Fraction of GW sources within $D_{L,\rm lim}$ that are localized to better than 20 deg^2.

[e] Number of joint GW/EM detections per year.

[f] Fraction of telescope time dedicated to GW/EM follow-up program. We have assumed 3600 hr total time per year available to the Rubin Observatory and 7900 hr available to GRB telescopes (>90% duty cycle for orbit similar to Swift).

- **~100 joint GW-EM events per year**
- **Only 0.1% of BNS merger events could detect the EM counterparts**
- **We simulate 1000 GW standard sirens based on 10-year observation**

Hsin-Yu Chen et al. Astrophys.J.Lett. 908 (2021) 1, L4
Jiming Yu et al. Astrophys.J. 916 (2021) 1, 54

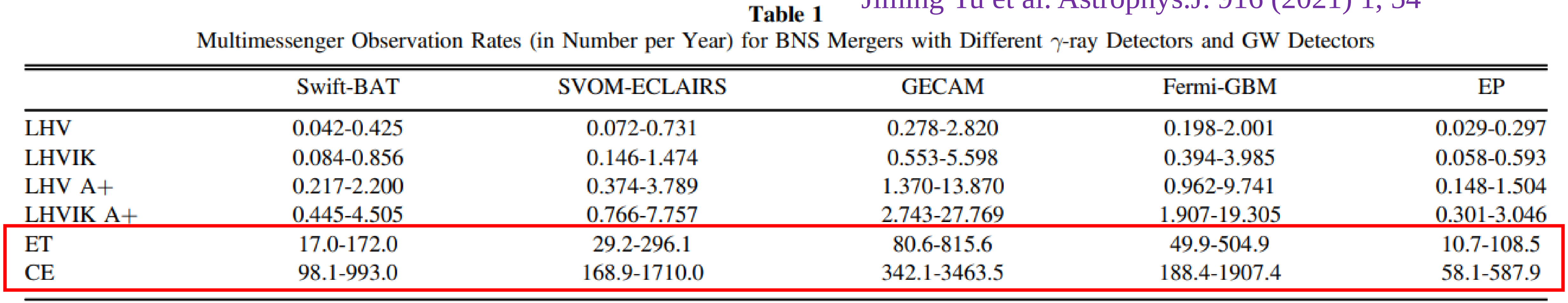


Table 1
Multimessenger Observation Rates (in Number per Year) for BNS Mergers with Different γ-ray Detectors and GW Detectors

	Swift-BAT	SVOM-ECLAIRS	GECAM	Fermi-GBM	EP
LHV	0.042-0.425	0.072-0.731	0.278-2.820	0.198-2.001	0.029-0.297
LHVIK	0.084-0.856	0.146-1.474	0.553-5.598	0.394-3.985	0.058-0.593
LHV A+	0.217-2.200	0.374-3.789	1.370-13.870	0.962-9.741	0.148-1.504
LHVIK A+	0.445-4.505	0.766-7.757	2.743-27.769	1.907-19.305	0.301-3.046
ET	17.0-172.0	29.2-296.1	80.6-815.6	49.9-504.9	10.7-108.5
CE	98.1-993.0	168.9-1710.0	342.1-3463.5	188.4-1907.4	58.1-587.9

Simulation of GW bright sirens from CE and ET

Reshift distribution: $P(z) \propto \frac{4\pi d_C^2(z)R(z)}{H(z)(1+z)}$

$$R(z)=\begin{cases}1+2z, & z\leq 1,\\ \frac{3}{4}(5-z), & 1<z<5,\\ 0, & z\geq 5.\end{cases}$$

GW waveform: $\tilde{h}(f)=\mathcal{A}f^{-7/6}\exp[i(2\pi f t_0-\pi/4+2\Psi(f/2)-\varphi_{(2.0)})],$

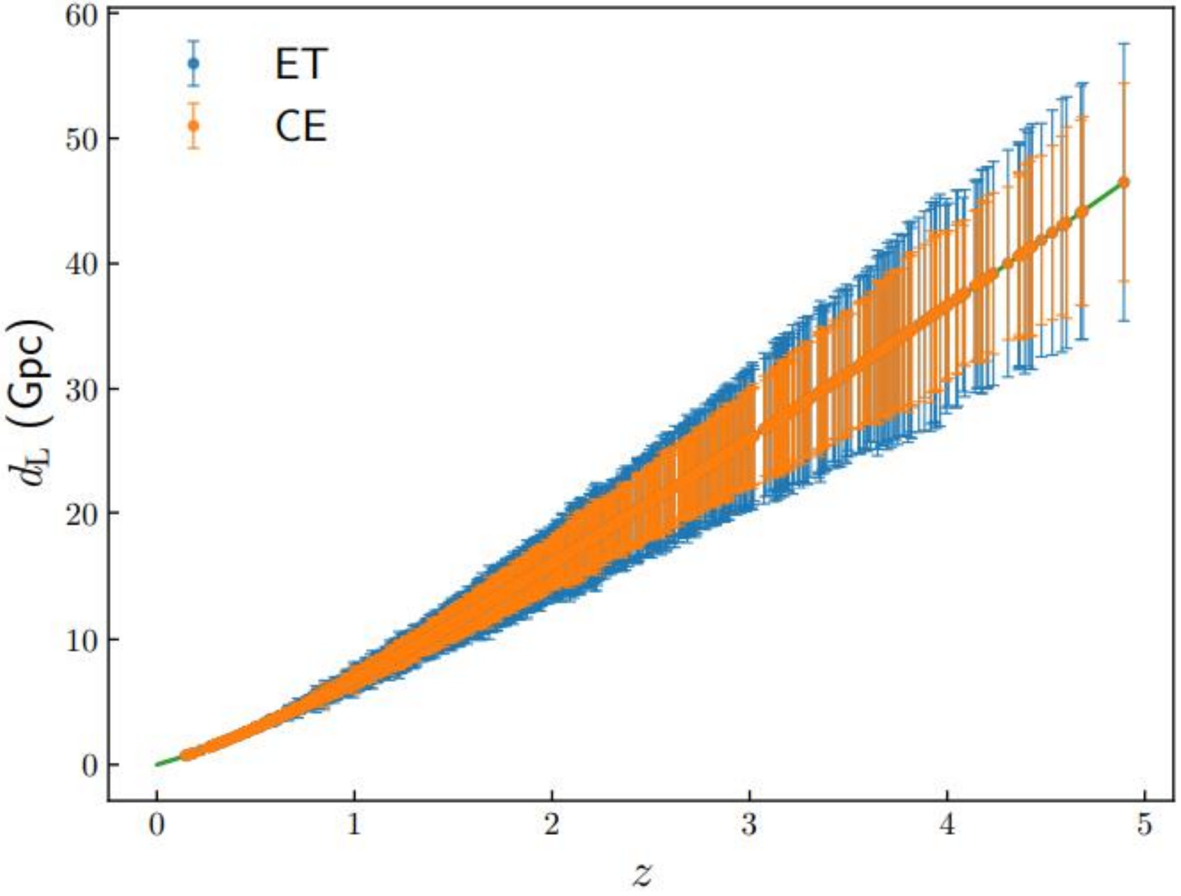
$$\mathcal{A}=\frac{1}{d_L}\sqrt{F_+^2(1+\cos^2(\iota))^2+4F_\times^2\cos^2(\iota)}\sqrt{5\pi/96}\pi^{-7/6}\mathcal{M}_c^{5/6},$$

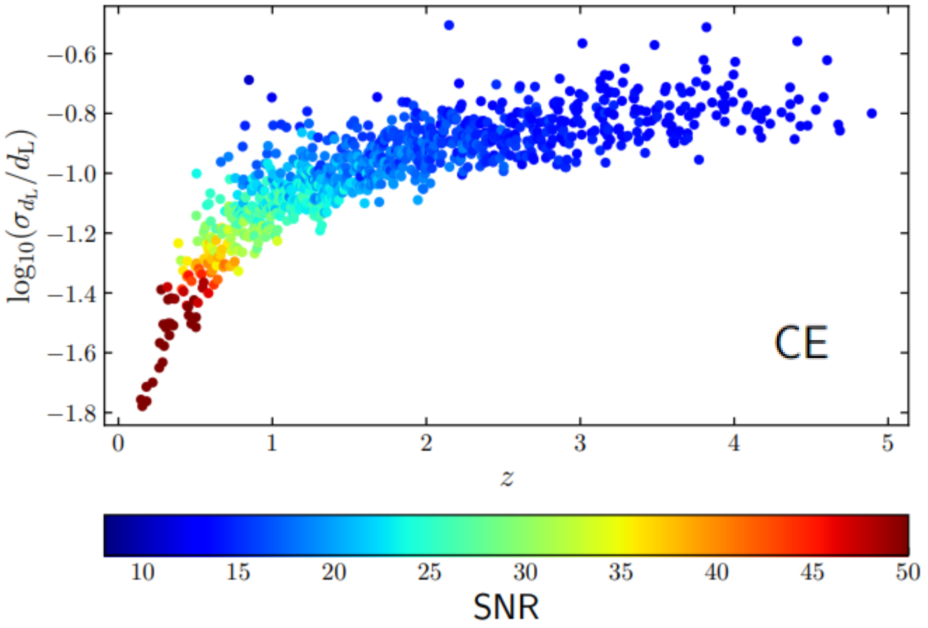
Fisher matrix: $F_{ij}=\left(\frac{\partial\tilde{\boldsymbol{h}}}{\partial\theta_i}\middle|\frac{\partial\tilde{\boldsymbol{h}}}{\partial\theta_j}\right)=\sum_{k=1}^{N}\left(\frac{\partial\tilde{h}_k}{\partial\theta_i}\middle|\frac{\partial\tilde{h}_k}{\partial\theta_j}\right)$ $\quad \tilde{\boldsymbol{h}}=\left[\tilde{h}_1,\tilde{h}_2,\cdots,\tilde{h}_k,\cdots,\tilde{h}_N\right]$

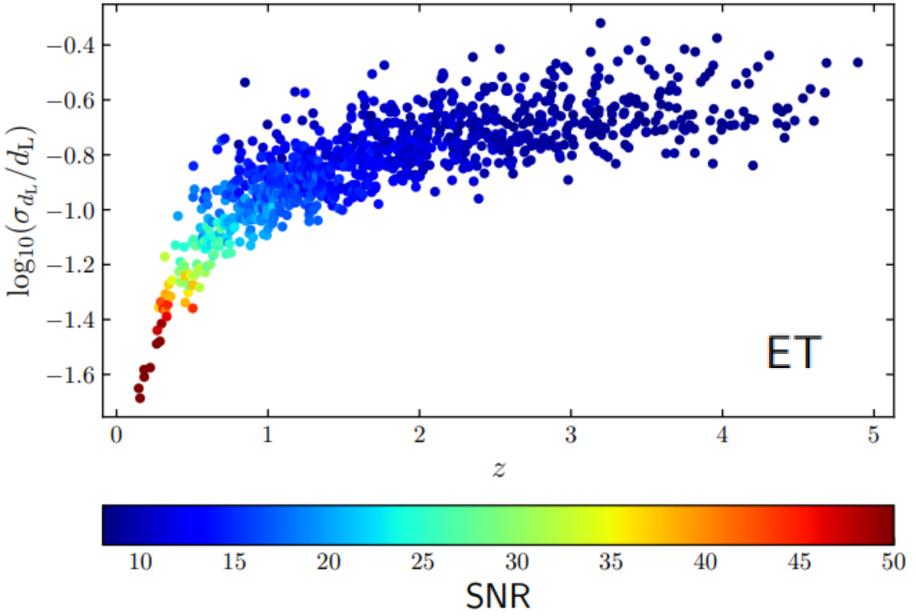
$$(\tilde{\boldsymbol{h}}|\tilde{\boldsymbol{h}})=\sum_{k=1}^{N}(\tilde{h}_k|\tilde{h}_k)=\sum_{k=1}^{N}4\mathrm{Re}\int_{f_{\mathrm{lower}}}^{f_{\mathrm{upper}}}\frac{\tilde{h}_k(f)\tilde{h}_k^*(f)}{S_{\mathrm{n},k}(f)}\mathrm{d}f,$$

Error of luminosity distance: $(\sigma_{d_{\mathrm{L}}})^2=(\sigma_{d_{\mathrm{L}}}^{\mathrm{inst}})^2+(\sigma_{d_{\mathrm{L}}}^{\mathrm{lens}})^2+(\sigma_{d_{\mathrm{L}}}^{\mathrm{pv}})^2$ $\quad \Delta\theta_i=\sqrt{(F^{-1})_{ii}},$ $\quad \sigma_{d_{\mathrm{L}}}^{\mathrm{inst}}=\Delta\theta_1$

GW standard sirens from CE and ET

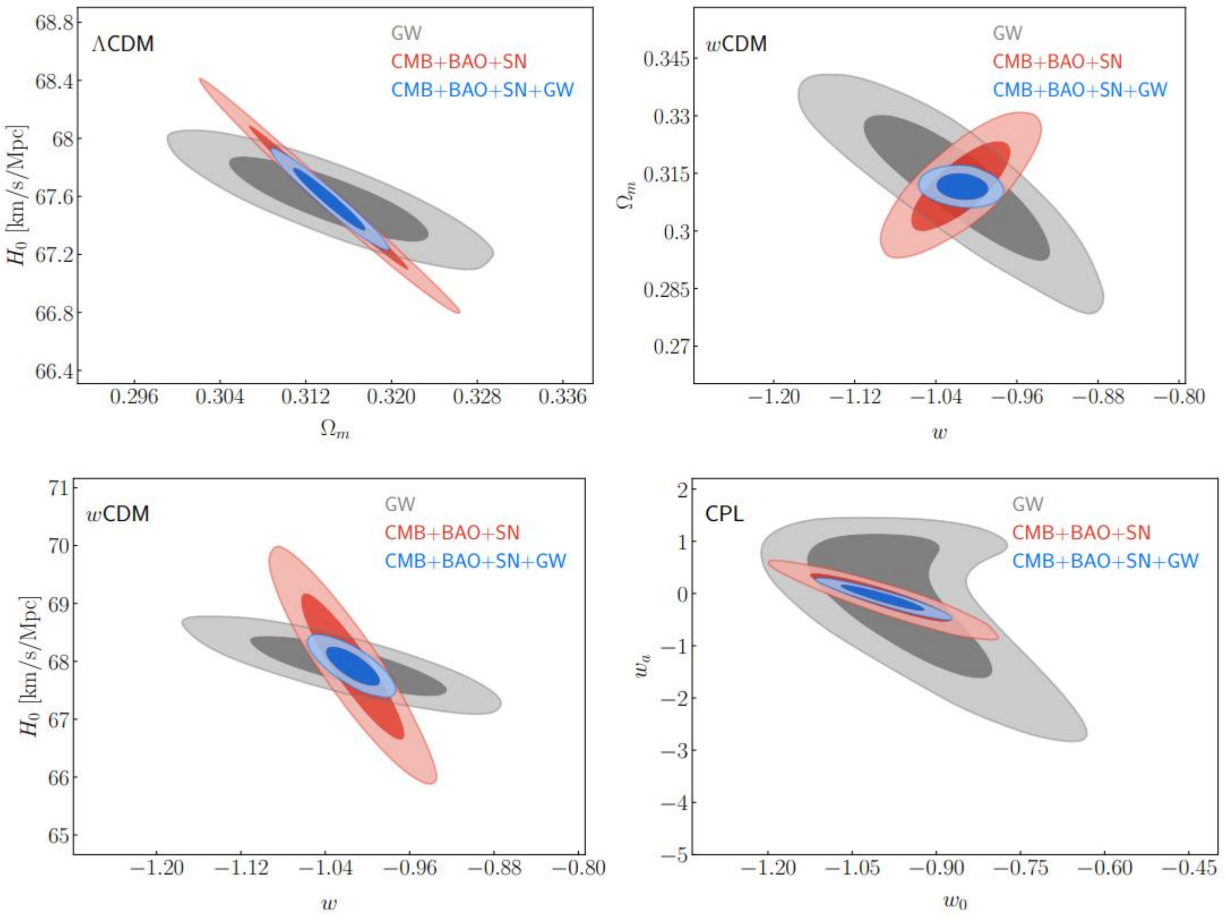


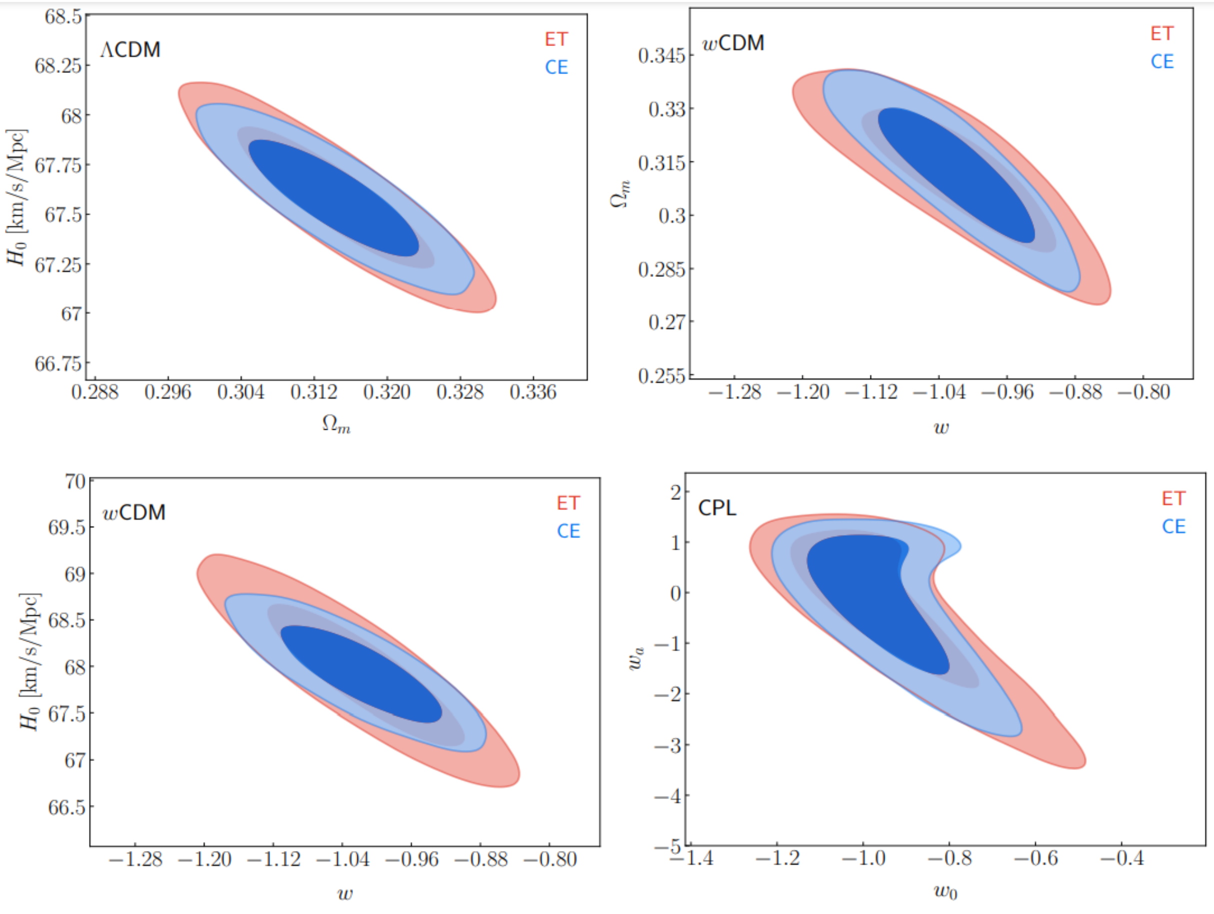




Jin, Zhu, Wang, Li, Zhang, & XZ, Commun. Theor. Phys. 74 (2022) 105404

Forecast for cosmological parameter estimation from CE

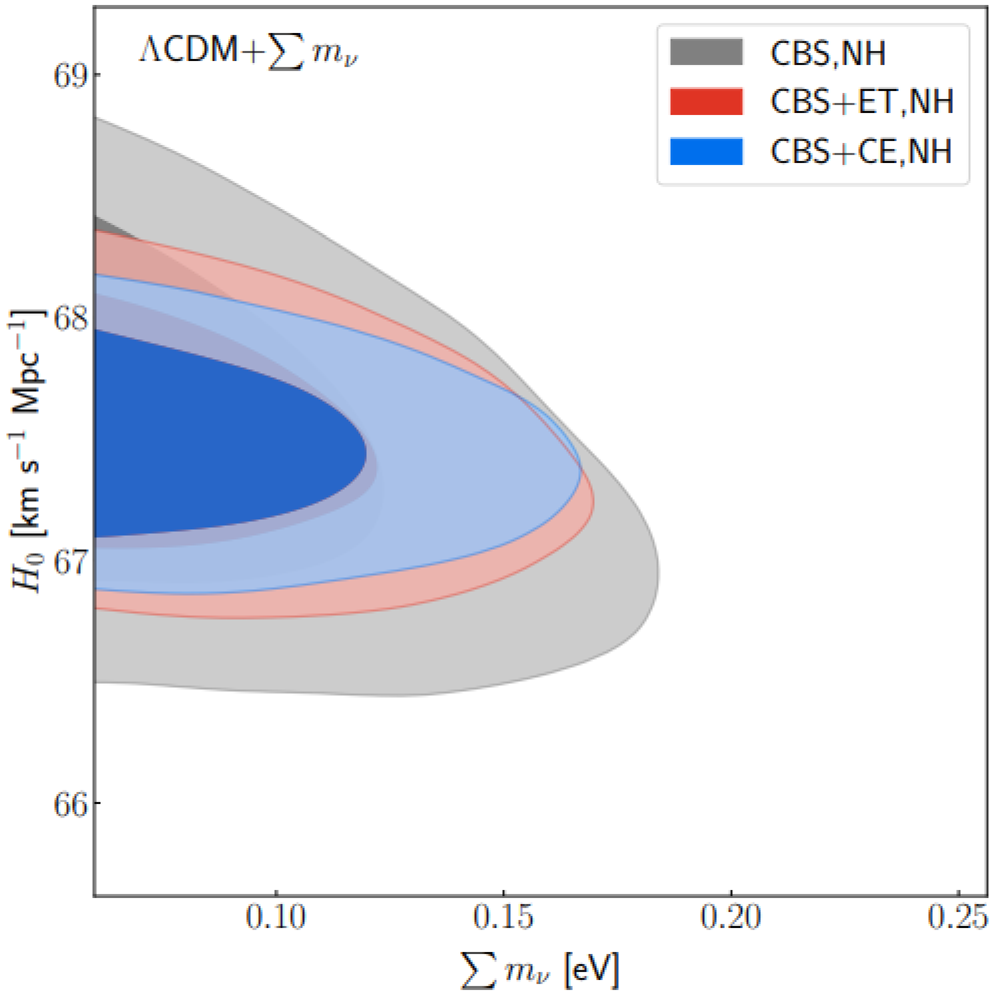


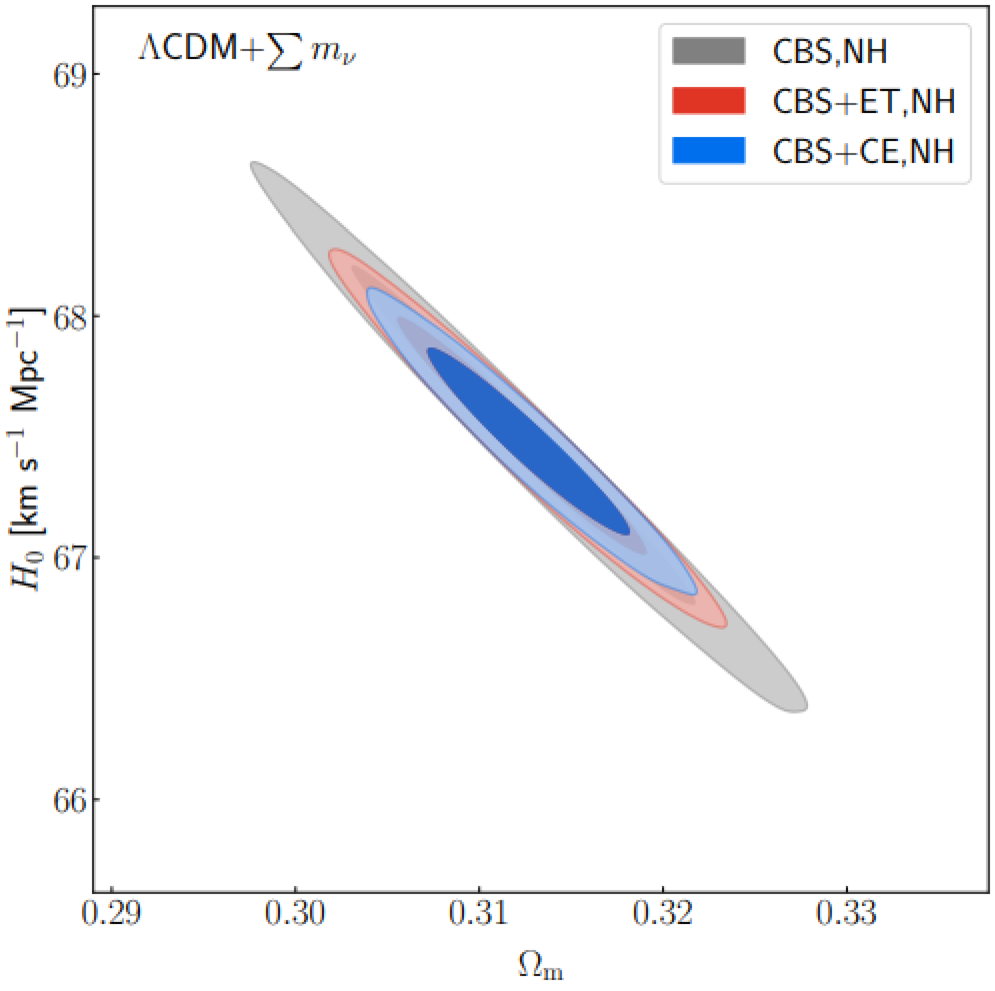


- **GW could break the parameter degeneracies generated by EM observations**
- **The ability of CE to constrain cosmological parameters is better than that of ET**

Jin, He, Xu, Zhang, & XZ, JCAP 03(2020) 051

Impacts on weighing neutrinos

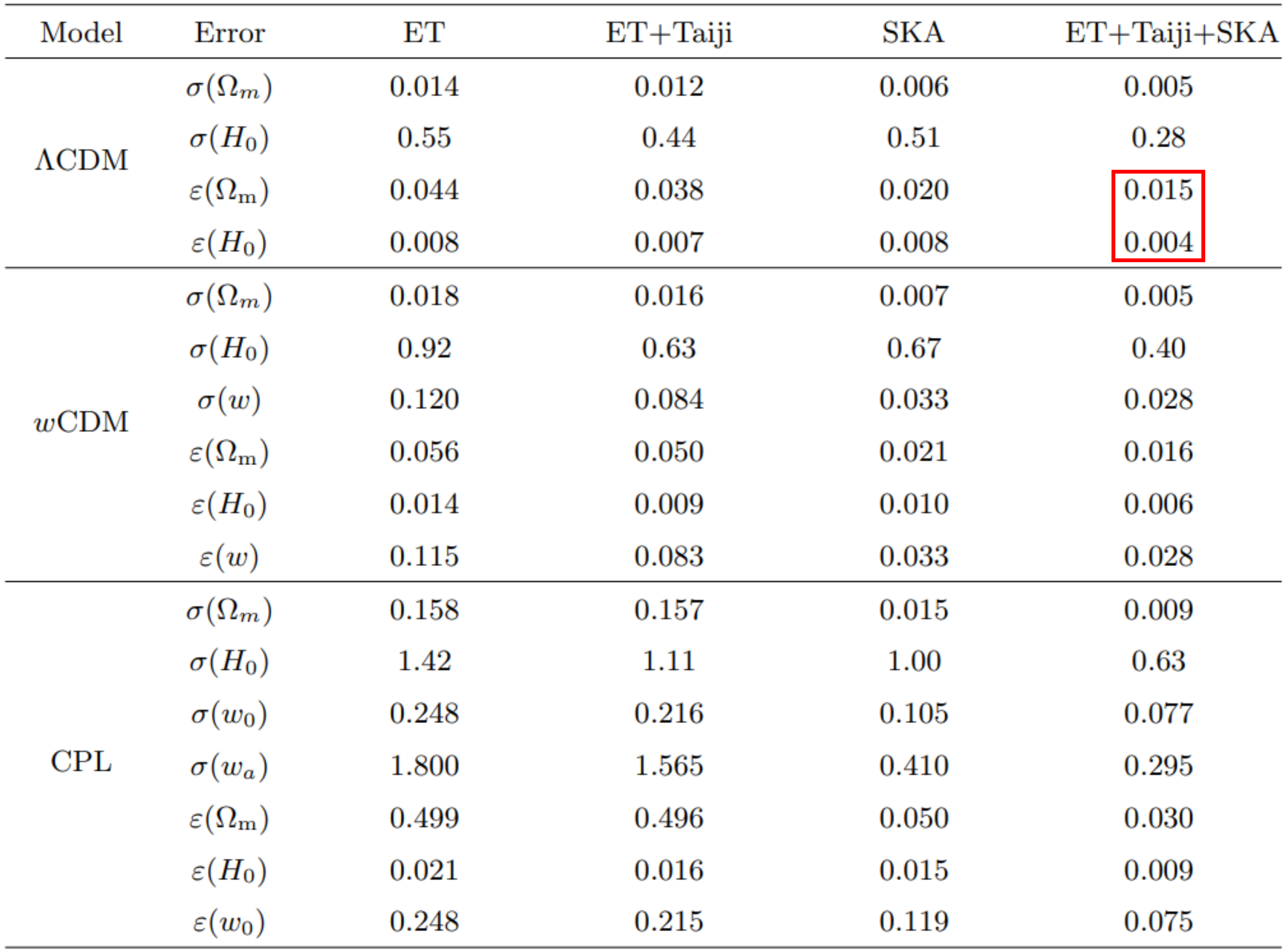




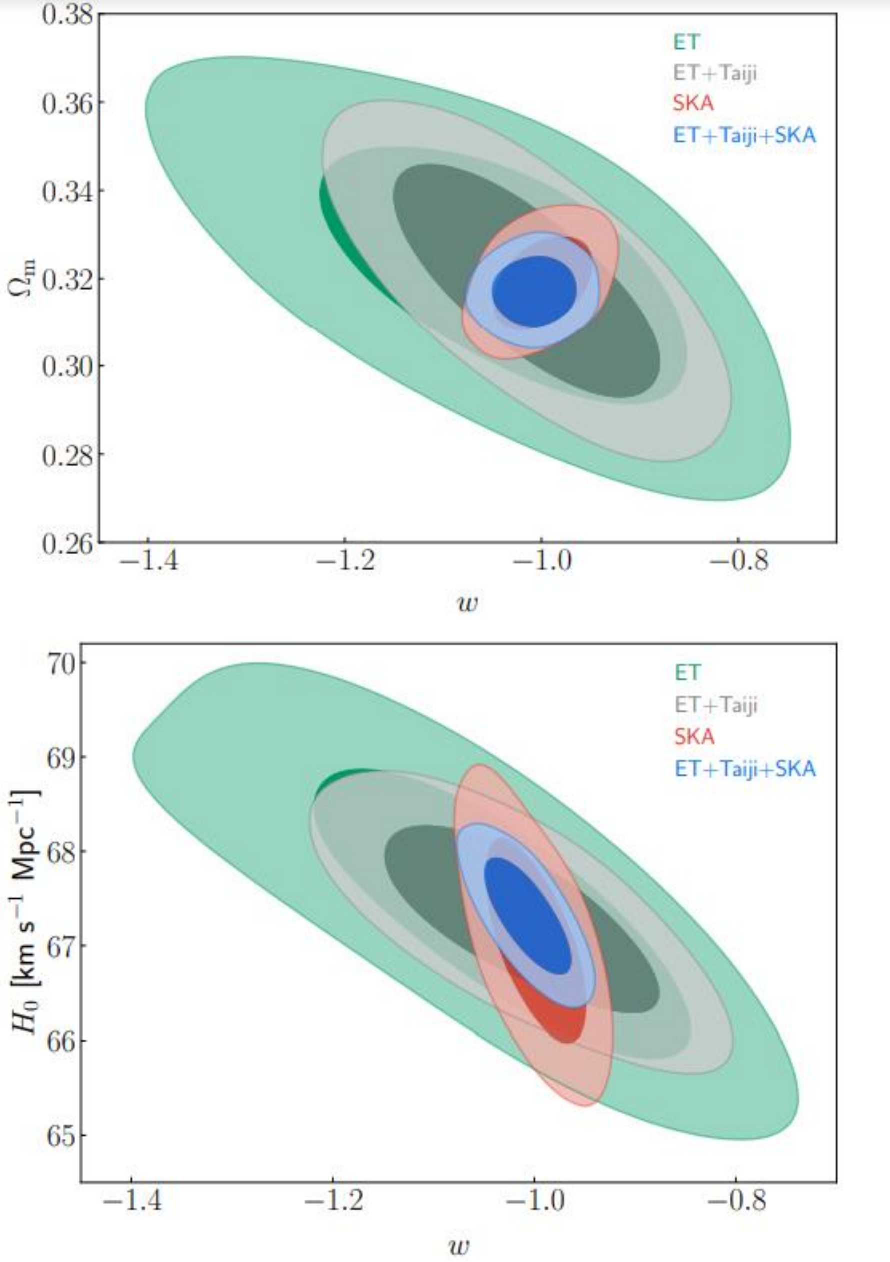
- **GW could slightly improve the upper limit of neutrino mass**

Jin, Zhu, Wang, Li, Zhang, & XZ, Commun. Theor. Phys. 74 (2022) 105404

Synergy between GW and 21 cm intensity mapping



Model	Error	ET	ET+Taiji	SKA	ET+Taiji+SKA
ΛCDM	$\sigma(\Omega_m)$	0.014	0.012	0.006	0.005
	$\sigma(H_0)$	0.55	0.44	0.51	0.28
	$\varepsilon(\Omega_{\rm m})$	0.044	0.038	0.020	0.015
	$\varepsilon(H_0)$	0.008	0.007	0.008	0.004
wCDM	$\sigma(\Omega_m)$	0.018	0.016	0.007	0.005
	$\sigma(H_0)$	0.92	0.63	0.67	0.40
	$\sigma(w)$	0.120	0.084	0.033	0.028
	$\varepsilon(\Omega_{\rm m})$	0.056	0.050	0.021	0.016
	$\varepsilon(H_0)$	0.014	0.009	0.010	0.006
	$\varepsilon(w)$	0.115	0.083	0.033	0.028
CPL	$\sigma(\Omega_m)$	0.158	0.157	0.015	0.009
	$\sigma(H_0)$	1.42	1.11	1.00	0.63
	$\sigma(w_0)$	0.248	0.216	0.105	0.077
	$\sigma(w_a)$	1.800	1.565	0.410	0.295
	$\varepsilon(\Omega_{\rm m})$	0.499	0.496	0.050	0.030
	$\varepsilon(H_0)$	0.021	0.016	0.015	0.009
	$\varepsilon(w_0)$	0.248	0.215	0.119	0.075



- **GW and 21 cm IM could break the cosmological parameter degeneracies**

Jin, Wang, Wu, Zhang, & XZ, Phys.Rev.D 104 (2021) 10, 103507

Summary

- GW could break the parameter degeneracies generated by the EM observations
- The ability of CE to constrain cosmological parameters is better than that of ET
- Synergy between GW and 21 cm intensity mapping could provide a precise late-universe cosmological probe
- It is worth expecting to explore the nature of dark energy and precisely measure the Hubble constant in the era of the third-generation ground-based GW detectors

Thank you!

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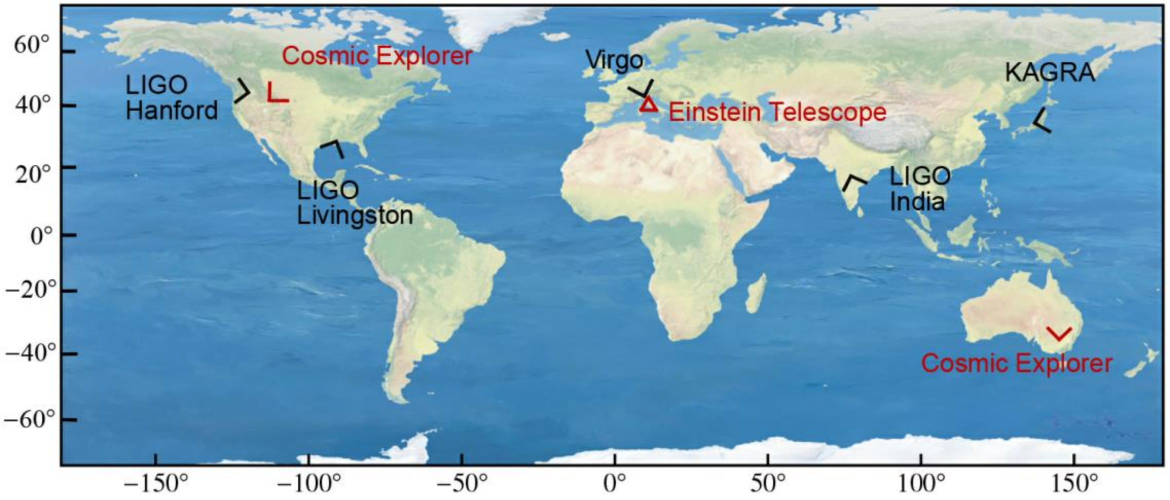
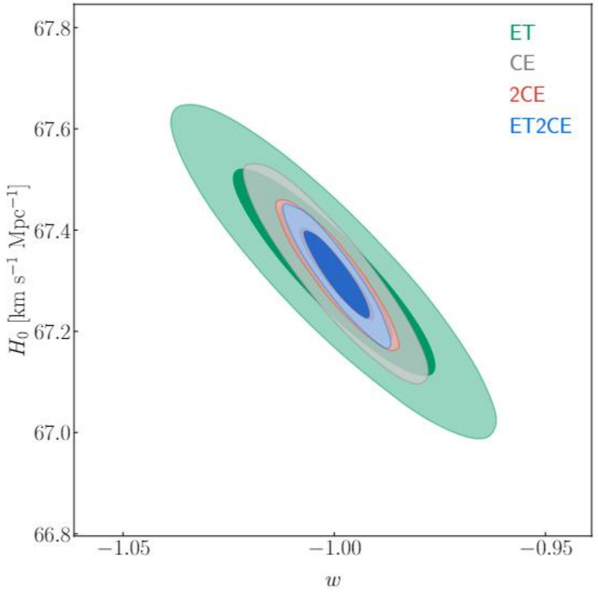
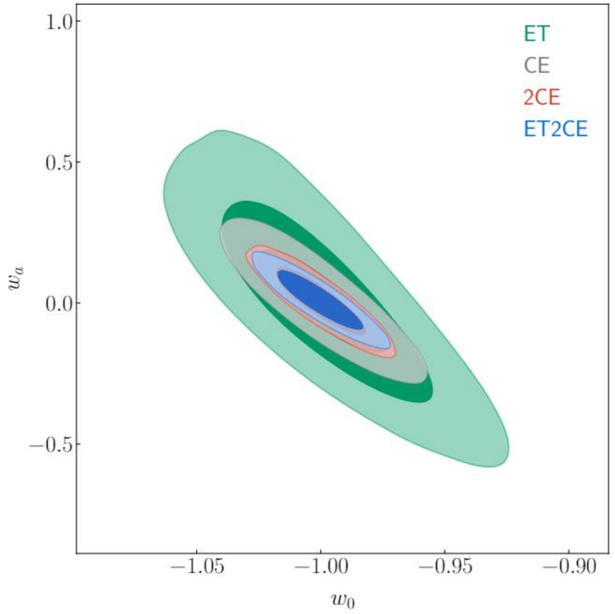
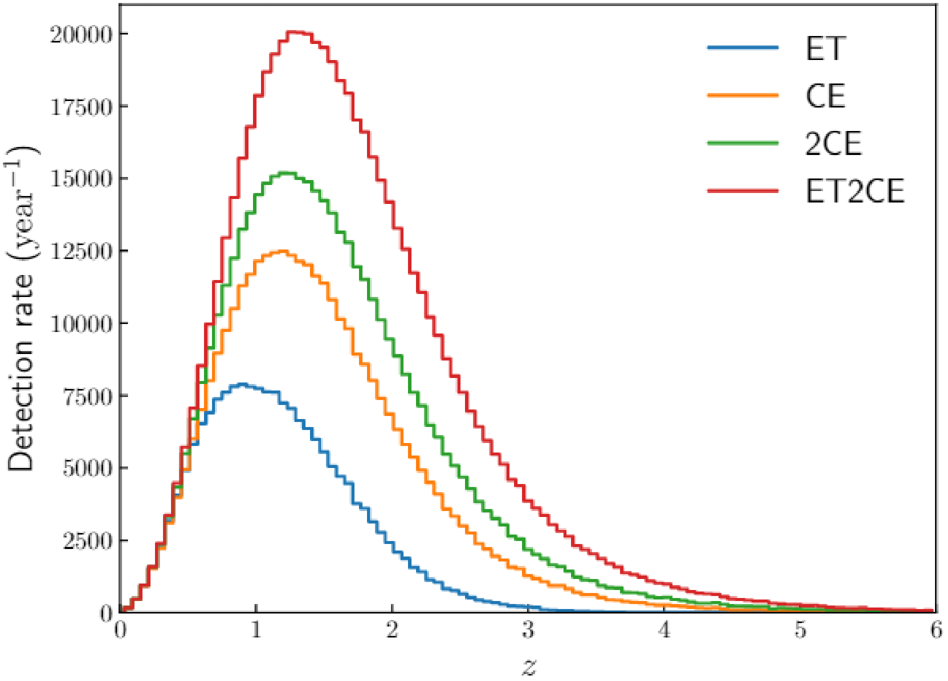
Dark sirens: tidal deformations of binary neutron star mergers









- Giving a fiducial EoS of neutron star, the measurements of the additional tidal deformation phase could break the degeneracy between mass and redshift
- Using only GW observations could obtain the relation between distance and redshift
- Hubble constant and dark energy could be precisely measured using only GW dark sirens

Jin, Li, Zhang, & XZ, arXiv: 2202.11882