PRECISION COSMOLOGY WITH GRAVITATIONAL WAVE OBSERVATIONS

INTERSECTIONS IN PARTICLE AND NUCLEAR PHYSICS

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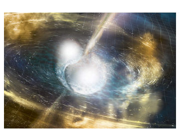
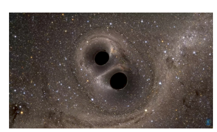




WHY ARE BLACK HOLE AND NEUTRON BINARY MERGERS STANDARD SIRENS?

Schutz: 1986

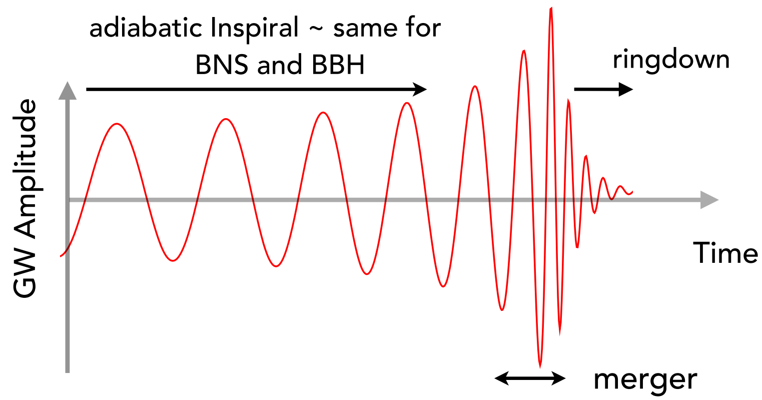
- A standard candle requires uncorrupt and unbiased measurement of apparent *F* and absolute luminosities *L* of a source:

$$F = \frac{L}{4\pi D_L^2}$$

  - Unbiased: we know the physical model "exactly"
    - General relativity is THE physical model
  - Uncorrupt: we know that nothing else (e.g. interactions other than gravity) corrupts the model
    - Black hole and neutron binaries evolve over hundreds of millions of years and they clear any debris in their vicinity long before they merge
- Similar to how sound waves distort the medium in which they travel, gravitational waves distort the spacetime itself
  - This analogy has led to the use of standard "sirens" instead of standard candles

GW APPARENT AND ABSOLUTE LUMINOSITIES

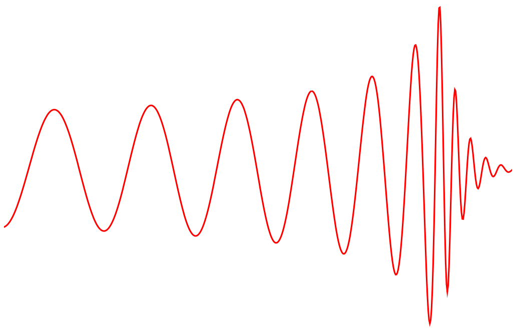
- Luminosities:
  - The measured strain amplitude: h=dL/L gives the apparent luminosity
  - the rate at which the frequency increases gives absolute luminosity
- Uncertainties in modeling (the instrument and the signals):
  - Instrument (amplitude and phase) calibration: currently at the level of 2-3% in amplitude and ~ 1 radian in phase
    - Currently these are smaller than the statistical uncertainty
  - Gravitational waves are detected and their parameters measured using matched filtering – waveform uncertainties could lead to systematic biases
    - Analytic models agree with numerical models to better than 1% in amplitude and fraction of a radian in phase
    - Modeling uncertainties are currently under control



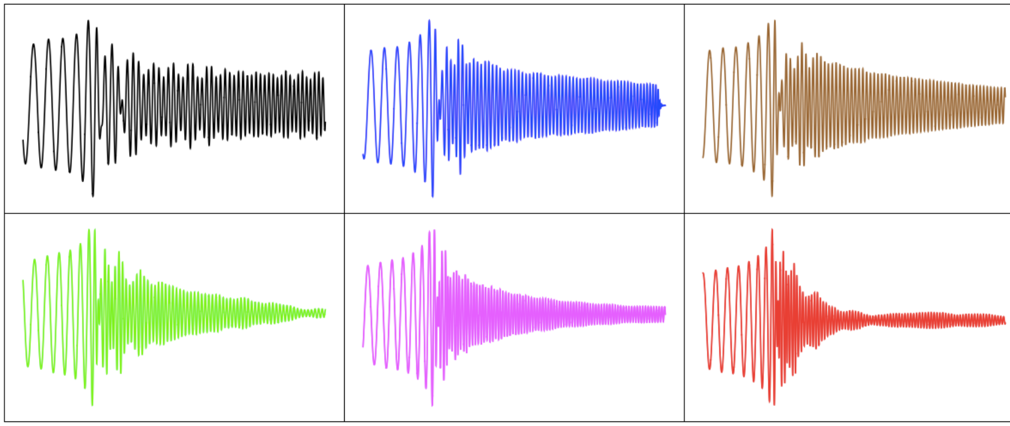
UNKNOWN PHYSICS:

- General relativity might not be the correct theory of gravity
    - Null tests of GR with GW data show no such evidence
- Black holes could be charged or on eccentric orbits
    - Both affect the dynamics very strongly and so far we don't see evidence for charge or eccentricity
- Neutron stars have matter:
    - Matter effects (static and dynamical tides) are important
    - They affect the waveform at late stages of inspiral and post-merger oscillations
    - The equation of state of dense matter in neutron star cores is unknown:
        - GW and X-ray measurements can determine the EOS
        - When EOS is determined neutron star binaries can also measure both luminosity distance and redshift

Binary Black Hole Mergers



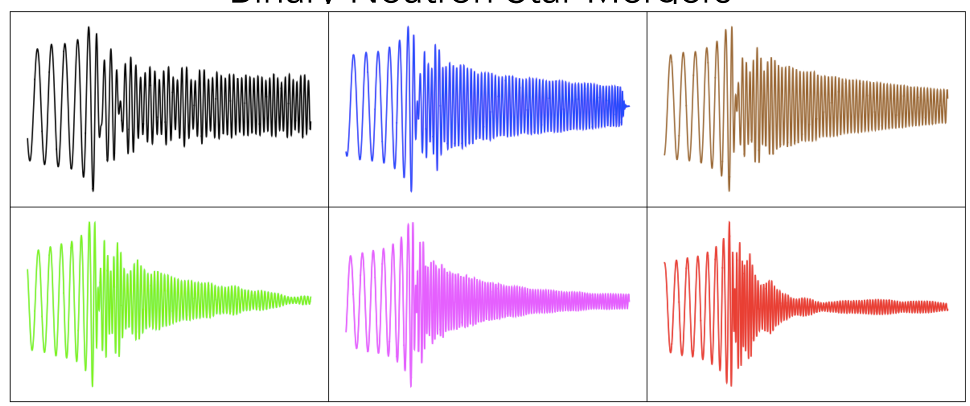
Binary Neutron Star Mergers



BREAKING THE MASS-REDSHIFT DEGENERACY WITH TIDES

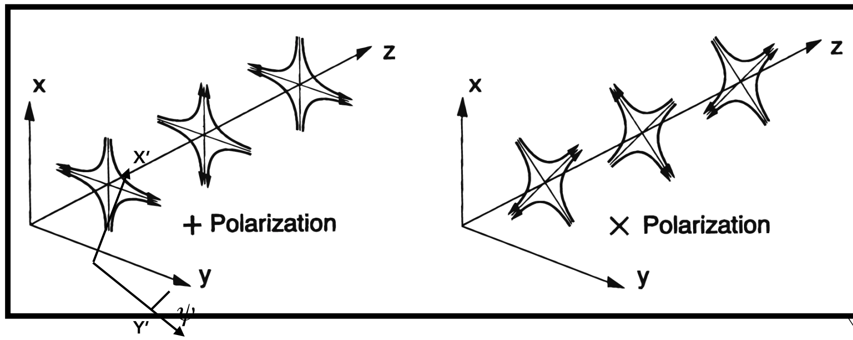
- GW observations can measure only redshifted mass
  - $M_{obs} = (1+z)\, M_{int}$
  - In GR and there is no mass scale and so black hole binaries cannot directly infer M_{int}
- Hadronic interactions impose a mass and length scale for neutron stars:
  - Neutron star masses are roughly in the 1–3 solar mass range
  - Tidal effects go as $(R/M_{int})^5$, where R is the radius of the neutron star
  - By measuring the tidal effects we can infer both M_{obs} and M_{int} and hence infer the redshift

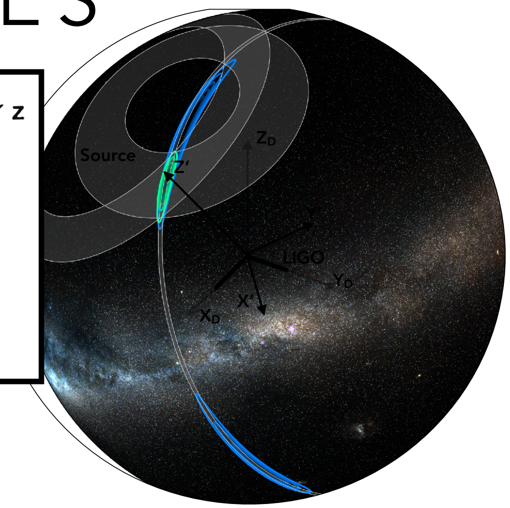
Binary Neutron Star Mergers

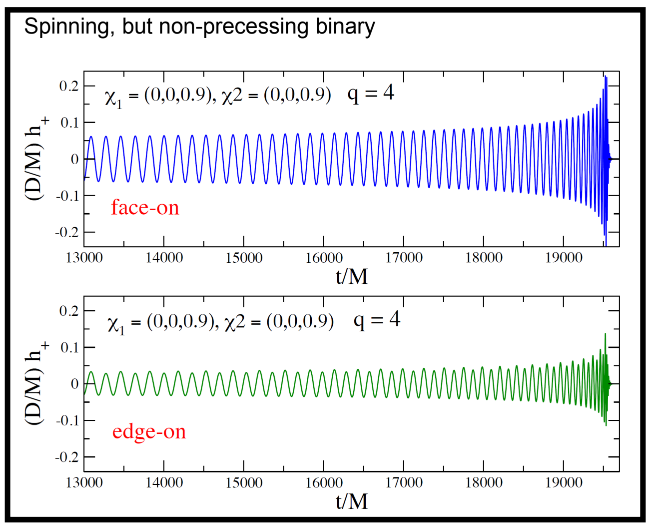


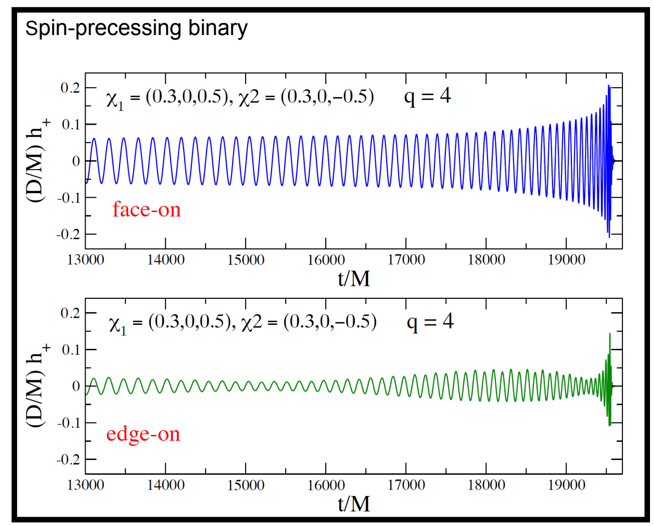
MEASURING SOURCE PROPERTIES

- for an arbitrary source must measure $(h_+, h_\times, \psi, \theta, \phi)$, equivalently, $(D_L, \iota, \psi, \theta, \phi)$
    - a single detector only measures a combination of h_+ and $h_\times$; need at least three non-collocated detectors to measure both
- the shape of the waveform contains information about the masses, spins, ~~eccentricity~~
    - matched filter the signal with a set of templates over the parameter space
- fiducial arrival time and overall phase of the signal
- in all 15 parameters assuming GR is correct



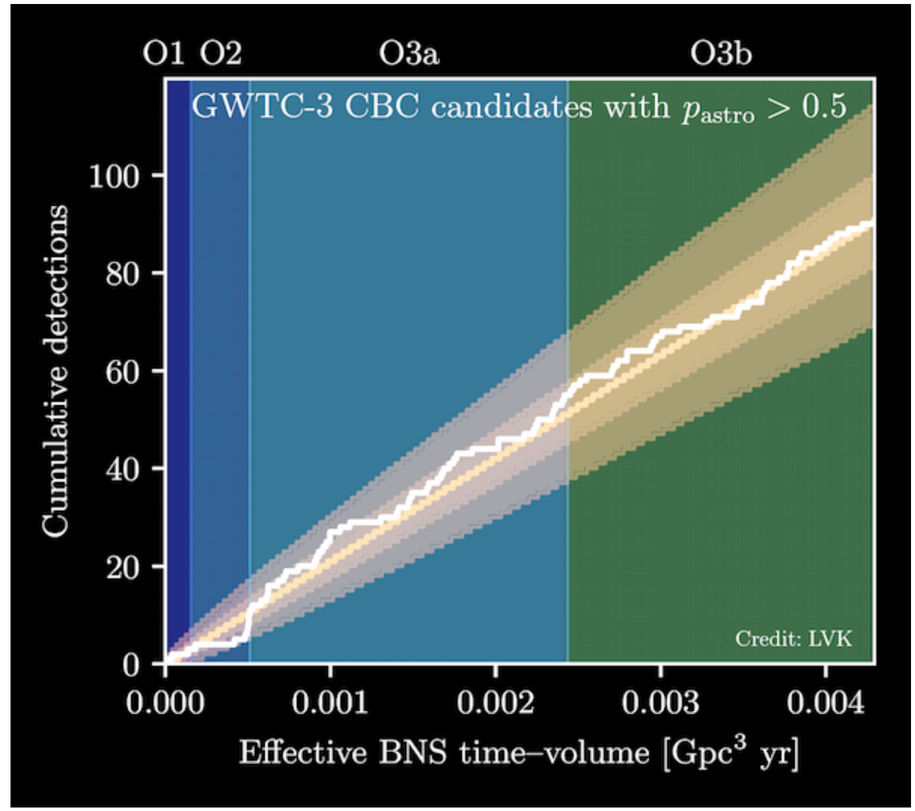






GRAVITATIONAL WAVE EVENT CATALOGS: GWTC-1 TO GWTC-3

- cumulative number of events
  - GWTC-1: 2015-2017, 11 events: 10 binary black holes (BBH) and 1 binary neutron star (BNS)
  - GWTC-2: 2015-2019: added 39 events, total number of events 50, 48 BBH, 2 BNS
  - GWTC-2.1 2015-2020: revisited the O3a analysis, 8 new candidates, but also dropped 3, total of 55 events.
- GWTC-3 adds a further 35 events from O3b
  - total number of events observed to date to 90
- 2 BNS events, 3 NS-BH events, 85 BBH events
  - 7 neutron stars, 2 mystery objects and 178 black holes



Reitze Plot

POPULATION PROPERTIES, BASED ON 76 EVENTS WITH FALSE ALARM RATE < 1 PER YEAR

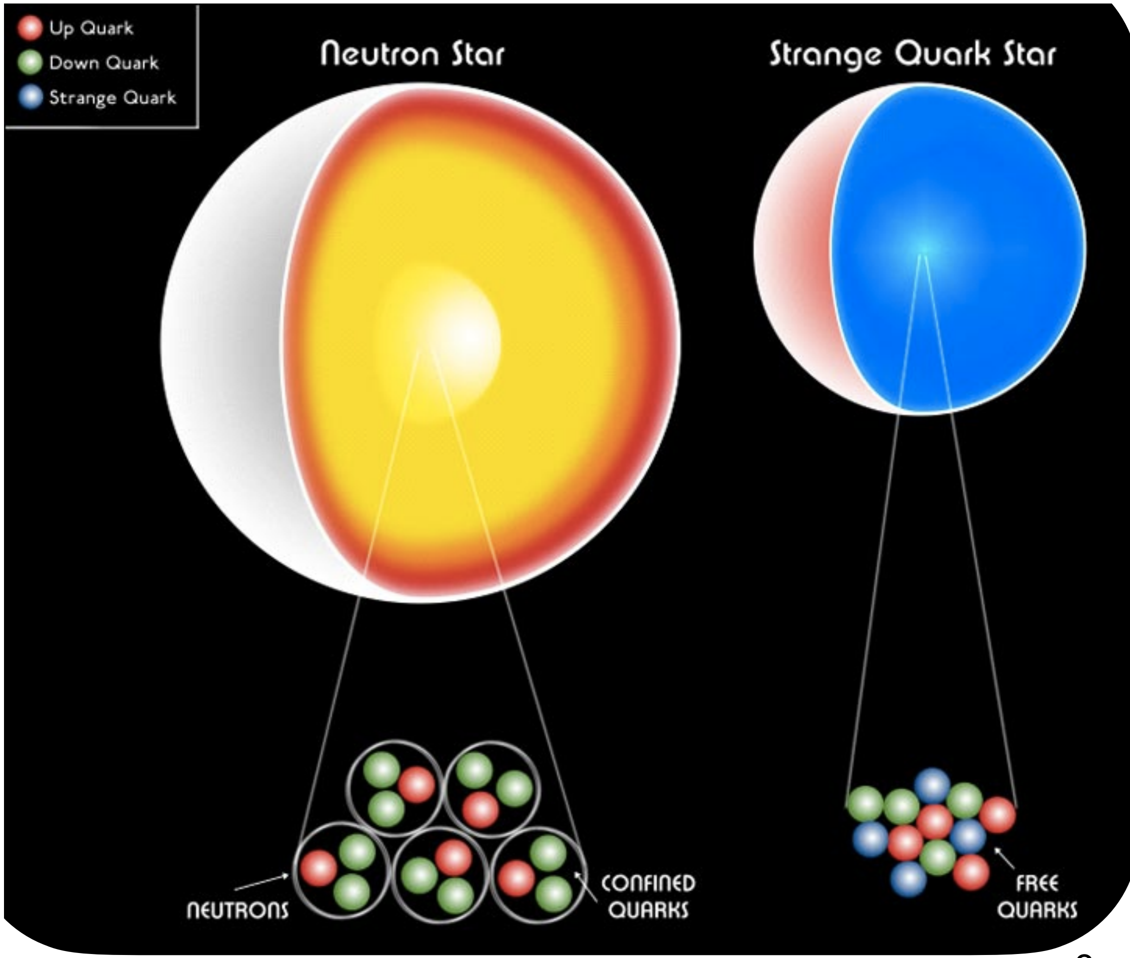
- what does the catalog contain:
  - 2 binary neutron star events
  - 72 confident binary black hole events
  - 2 neutron-star black hole candidate (one of which may be a binary black hole)
- rate at of mergers:
  - black hole binaries merge at the rate of ~ [17, 45] yr^{-1} Gpc^{-3}
  - neutron star binaries merge at the rate of : [13, 1900] yr^{-1} Gpc^{-3}
  - neutron star-black hole binaries merge at the rate of : [7.4, 320] yr^{-1} Gpc^{-3}
- mass spectrum peaks and gaps:
  - chirp mass peaks at 7.8 $M_\odot$ and 26.6 $M_\odot$ and a gap 10-20 $M_\odot$
  - there seems to be no suppression of the rate above 60 $M_\odot$

Chirp Mass

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

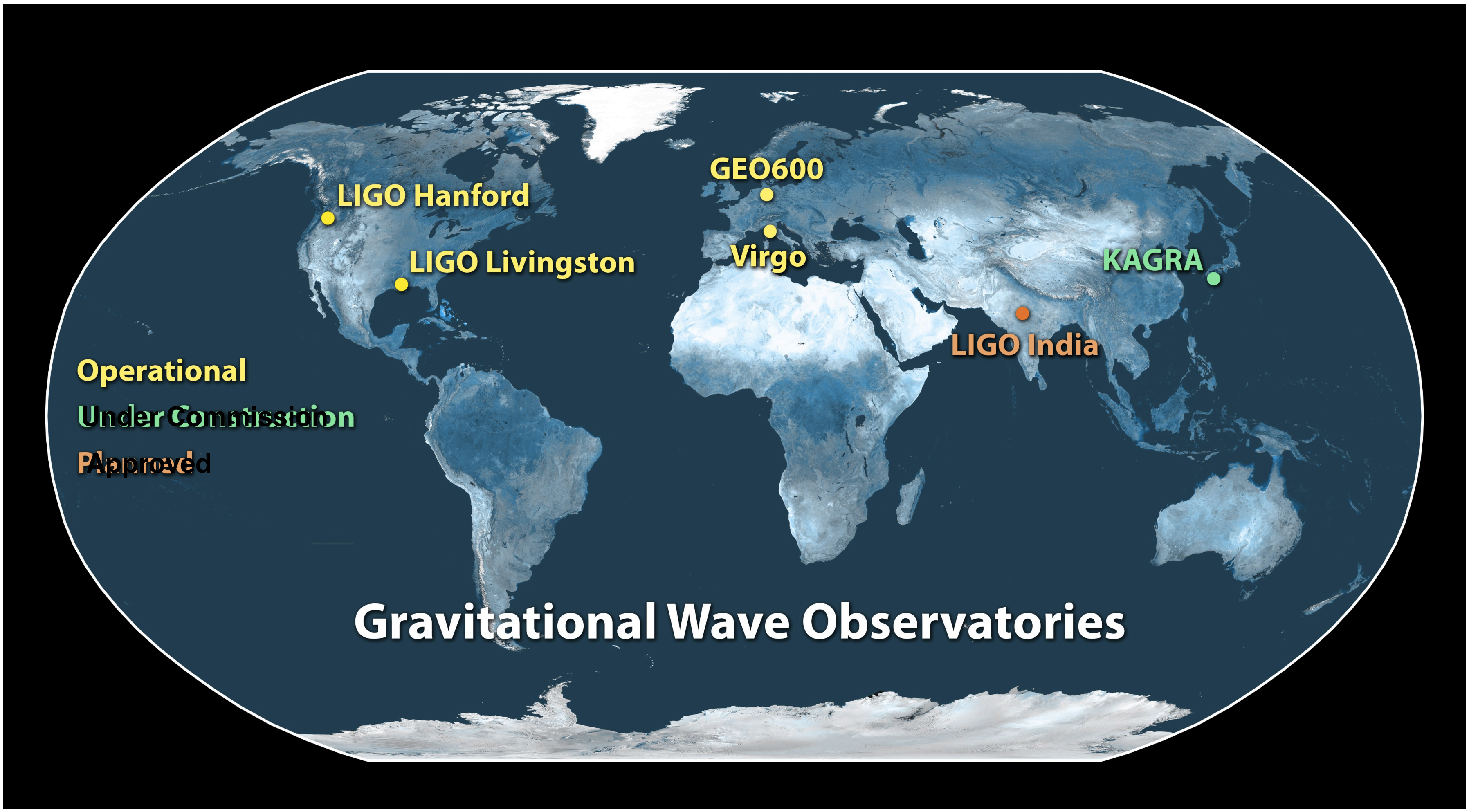
EQUATION OF STATE FROM MERGERS

- what is the equation of state of dense matter in neutron stars?
  - hadronic, strange matter, quark-gluon phase transition?
- how heavy can neutron stars be and how rapidly can they spin?



GLOBAL GROUND-BASED GRAVITATIONAL-WAVE DETECTOR NETWORK: 2010-2040+

LASER INTERFEROMETER GRAVITATIONAL WAVE DETECTORS



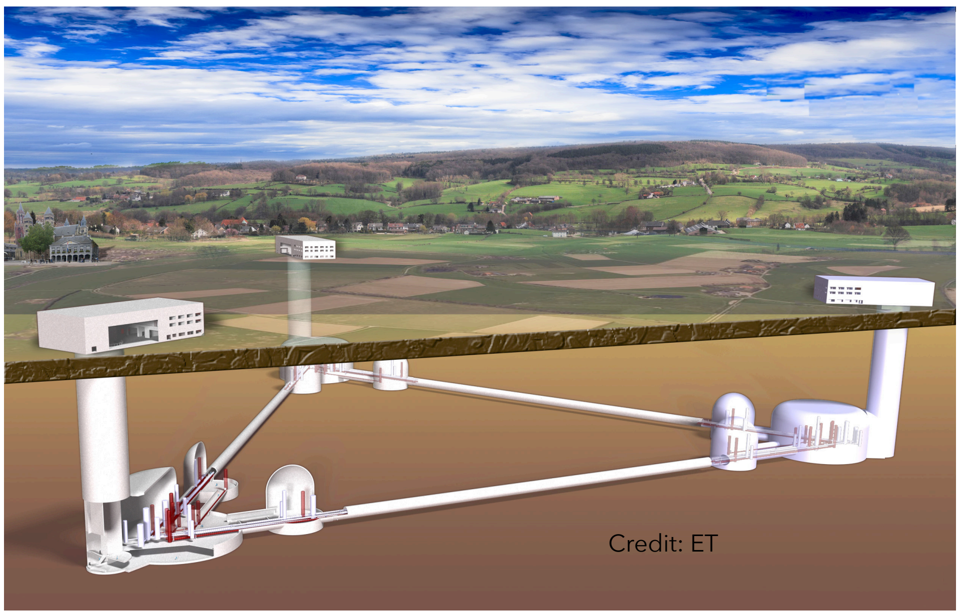
Credit: LIGO Hanford

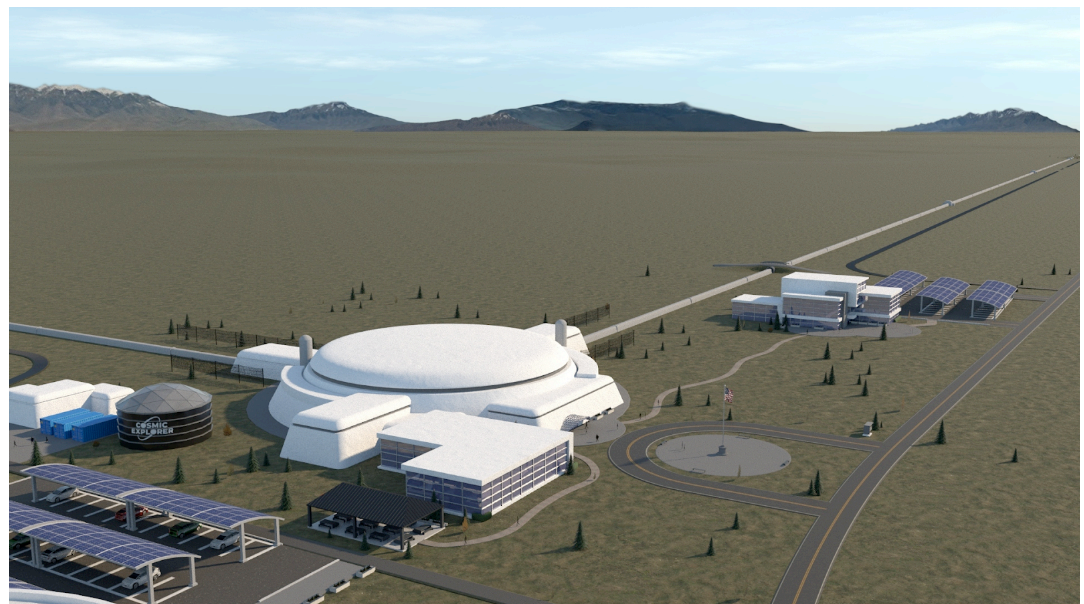
Credit: Virgo

LIGO INDIA

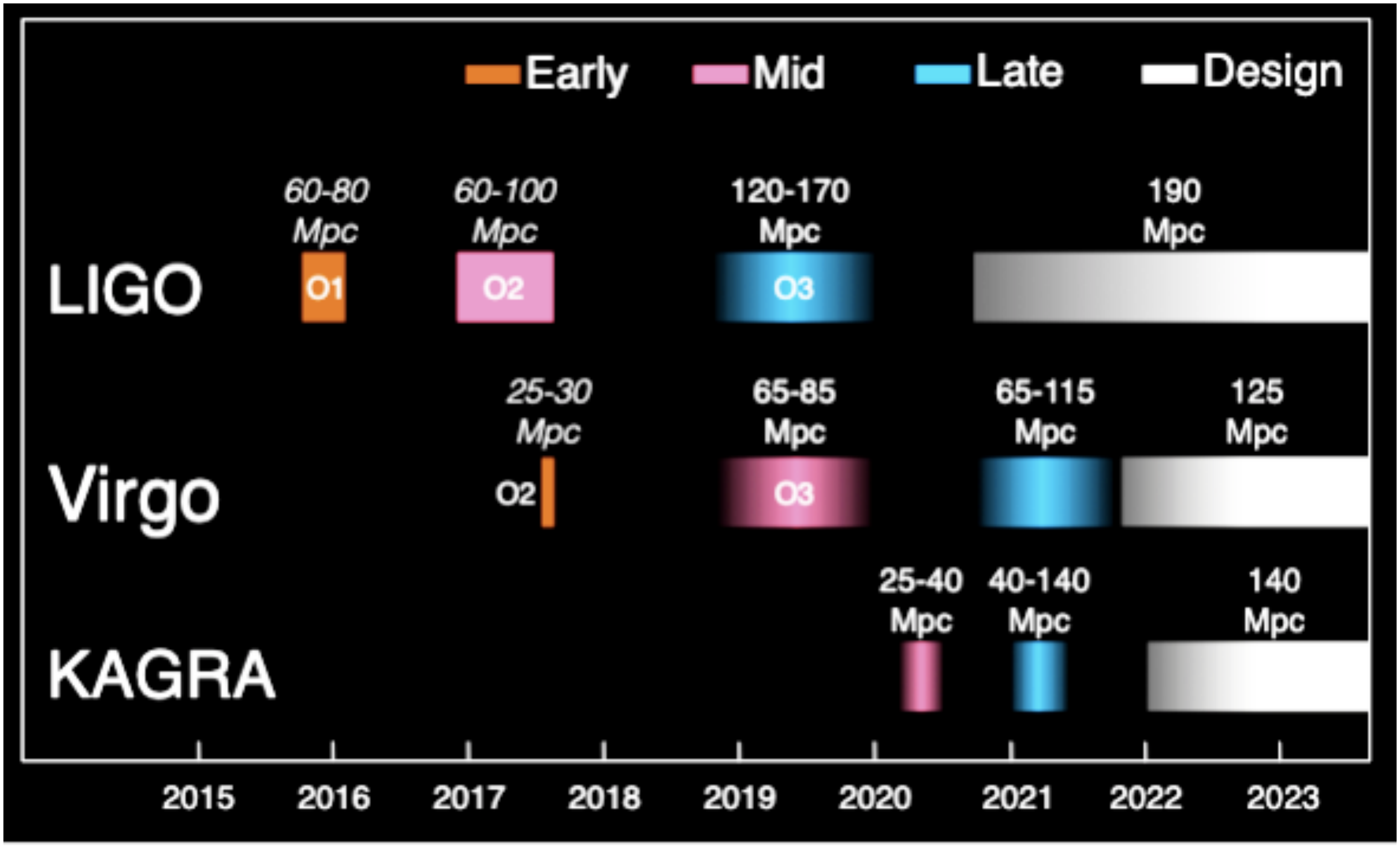
FUTURE GROUND-BASED GRAVITATIONAL-WAVE OBSERVATORIES

- Upgrades: LIGO-A+, Voyager
- Future Observatories
  - Einstein Telescope, Cosmic Explorer (often referred to as 3G or XG detectors)



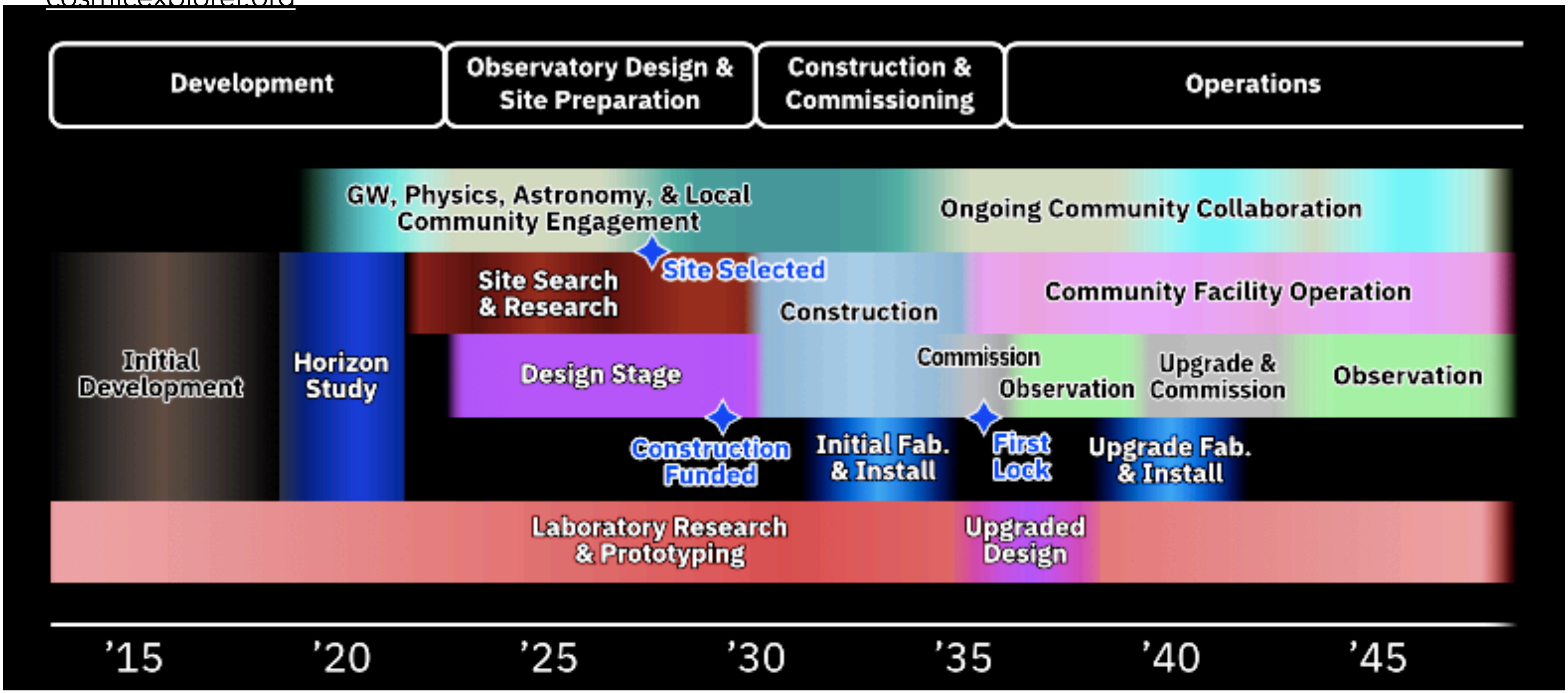


FUTURE RUNS AND SENSITIVITIES

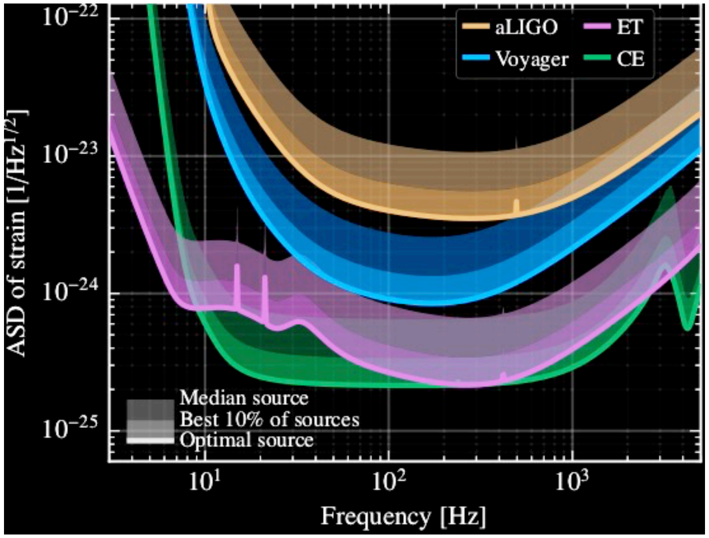


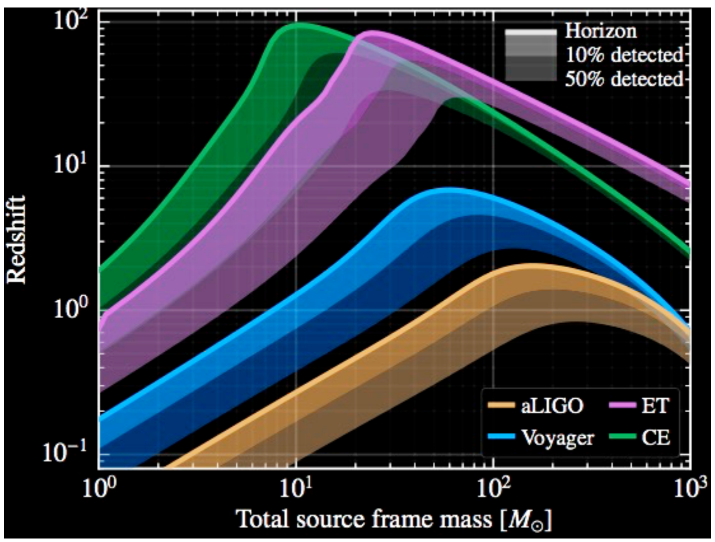
FUTURE RUNS AND SENSITIVITIES

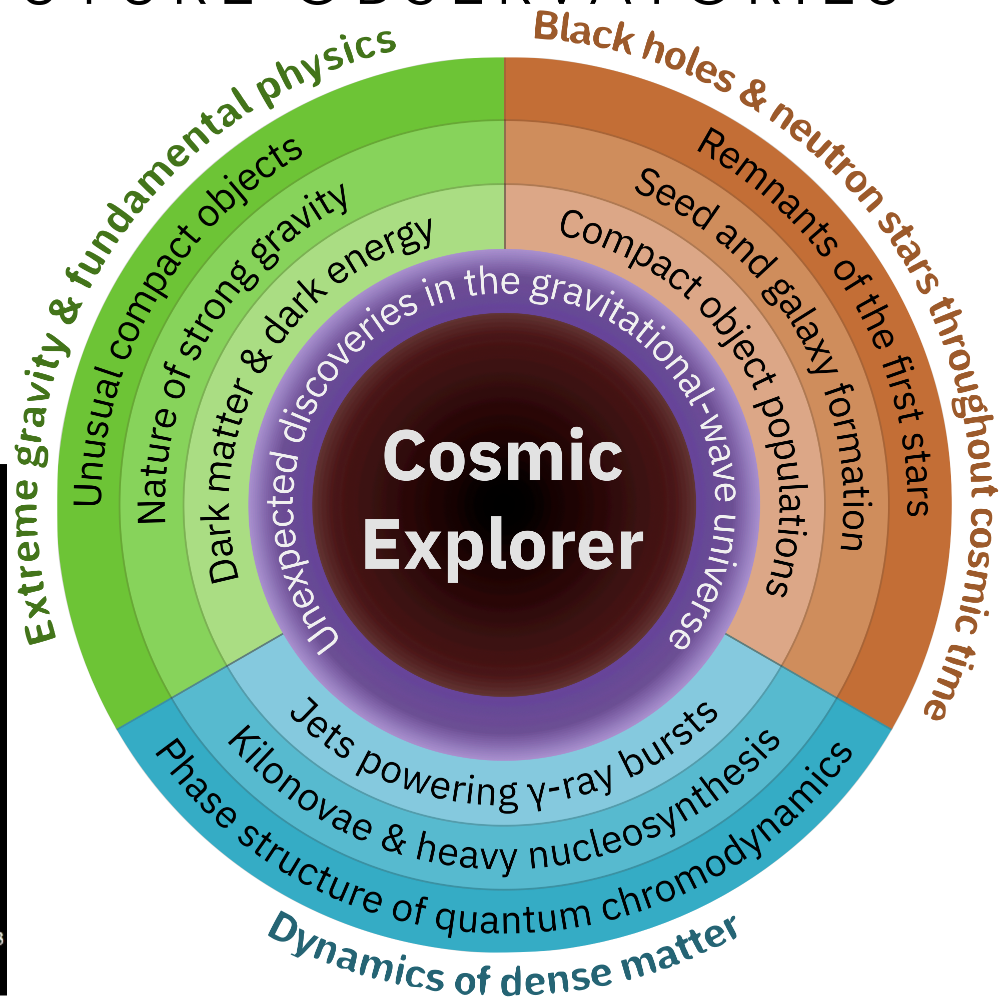
cosmicexplorer.org



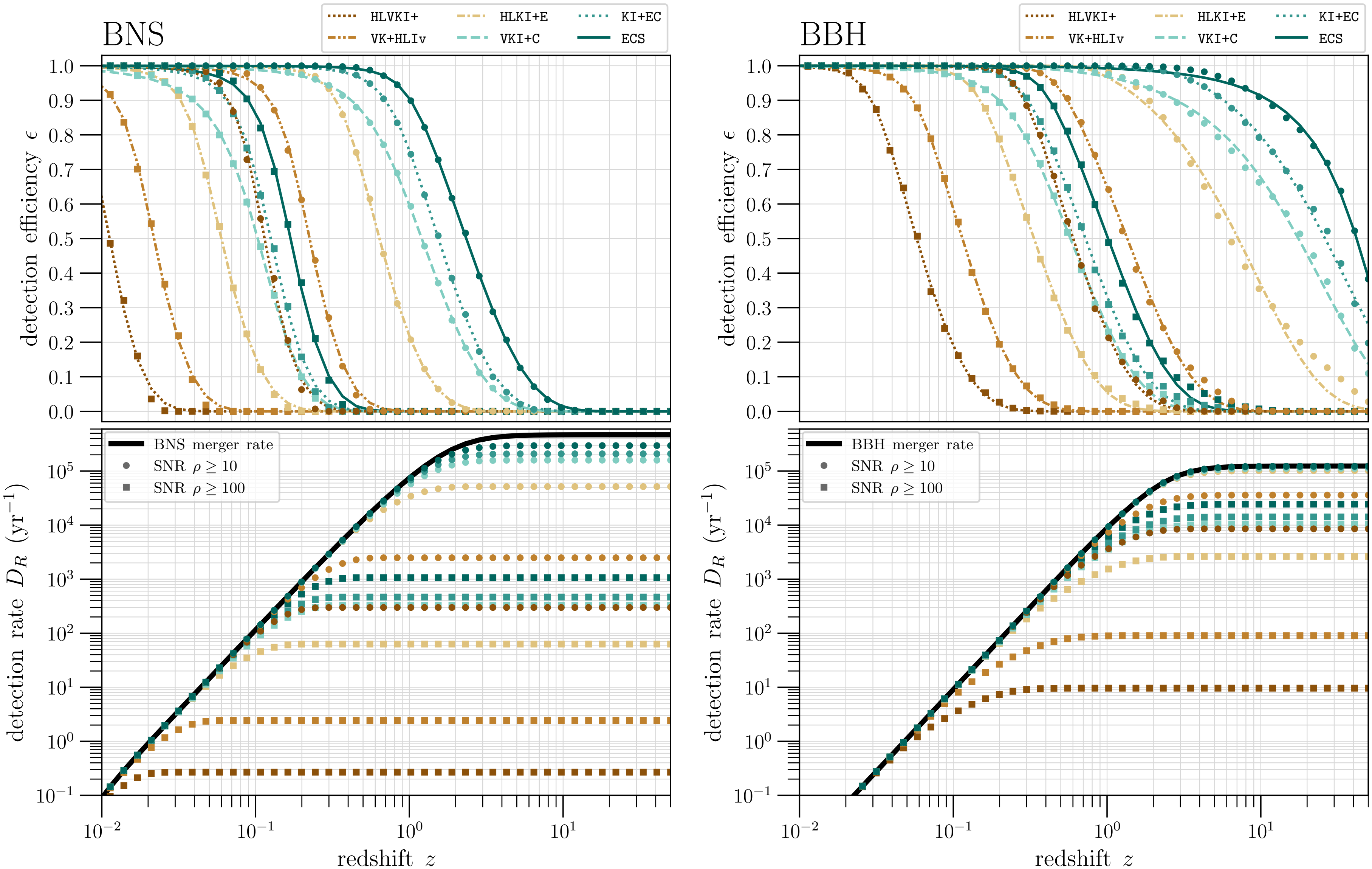
SENSITIVITY AND DISTANCE REACH OF FUTURE OBSERVATORIES

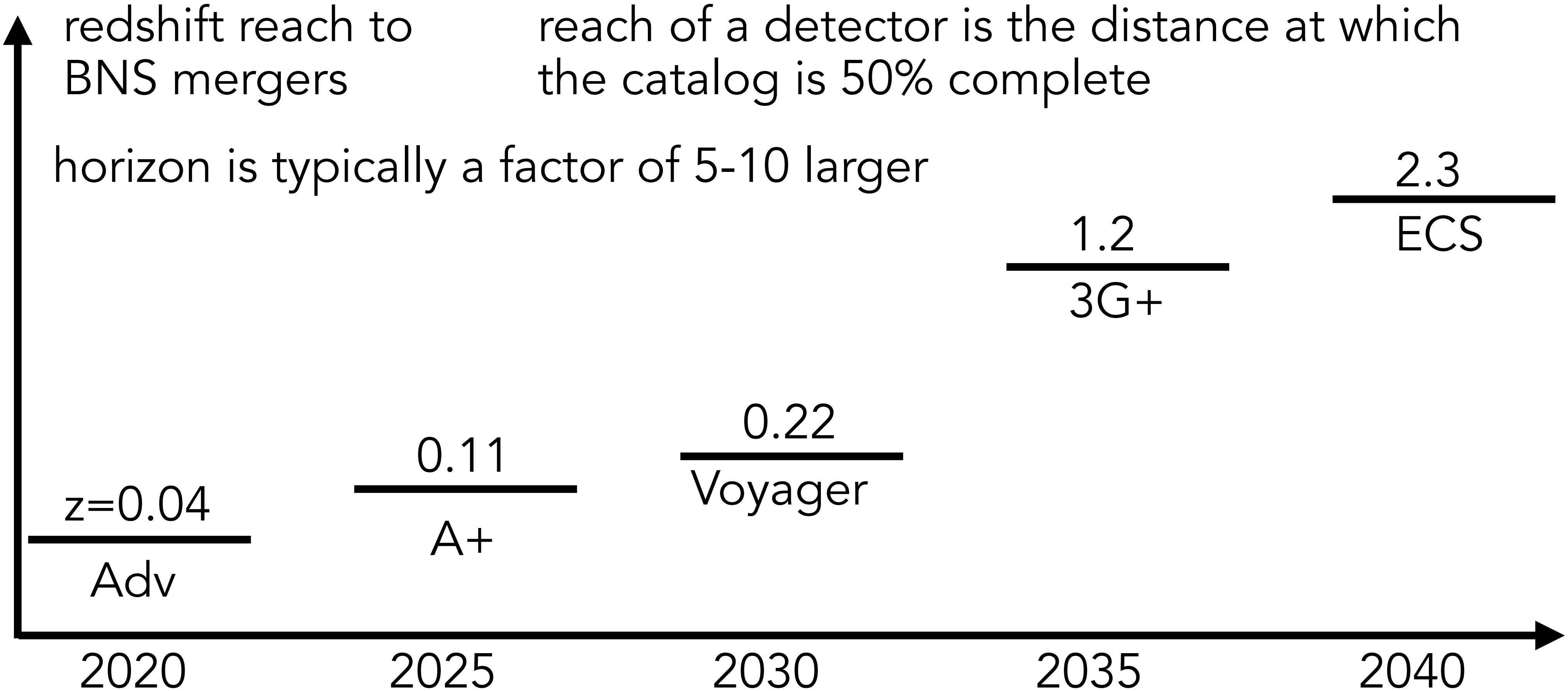




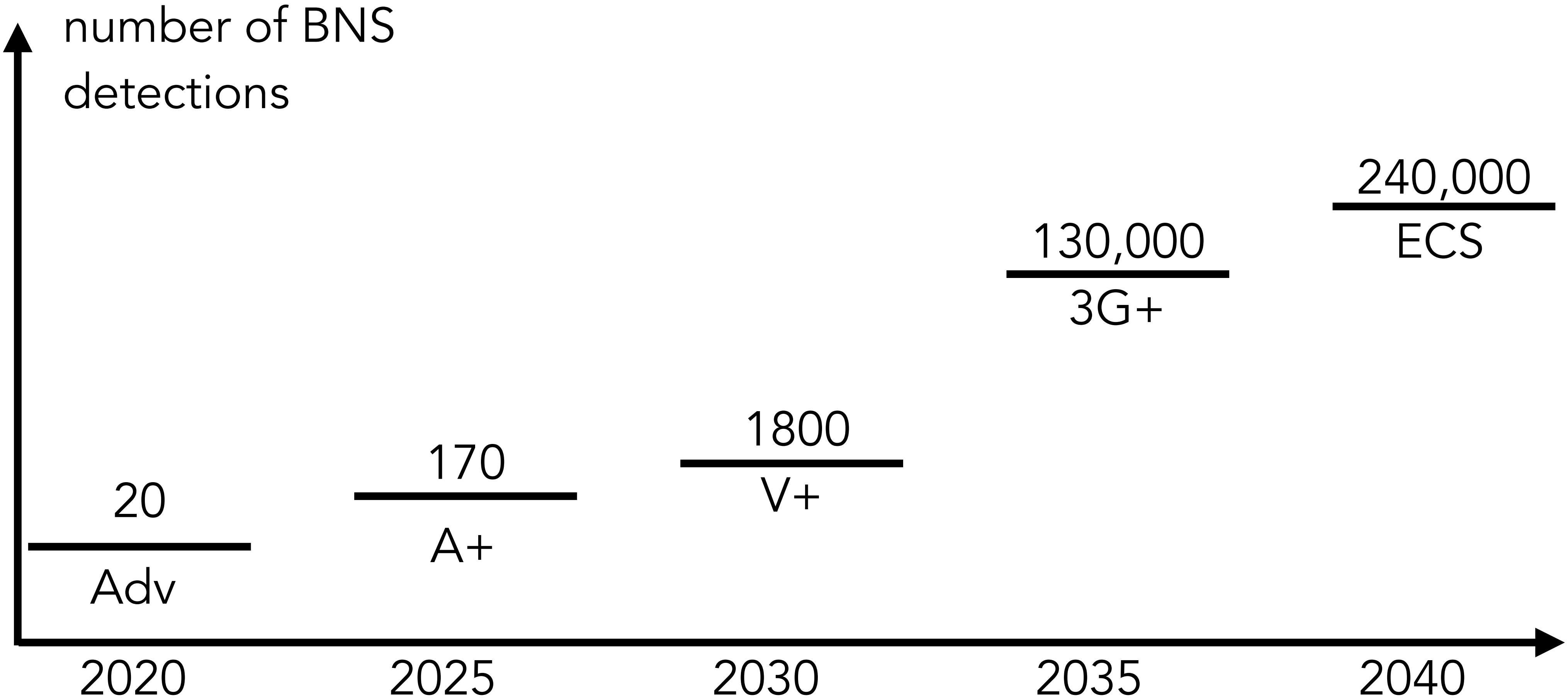


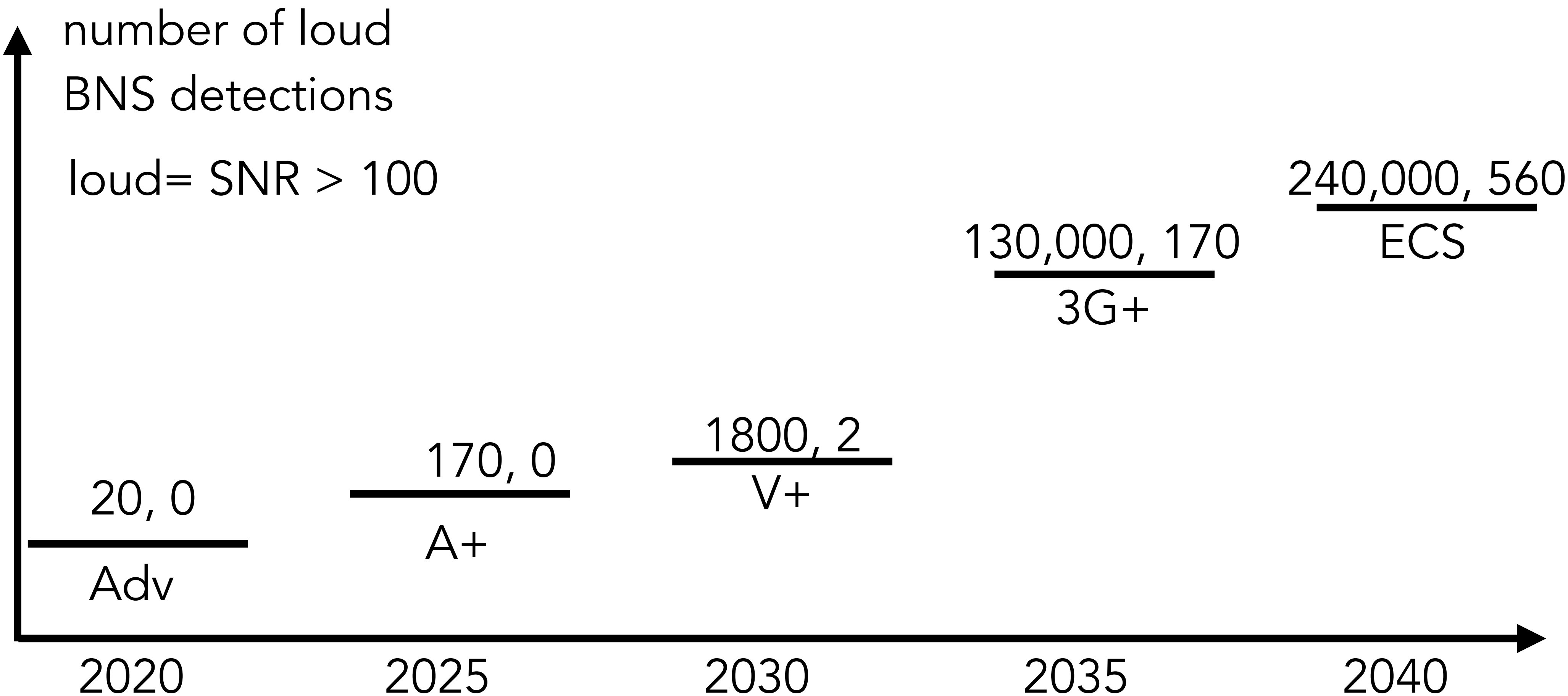
OBSERVING CAPABILITIES OF GW DETECTOR NETWORKS


BNS
HLVKI+
VK+HLIv
HLKI+E
VKI+C
KI+EC
ECS
detection efficiency ϵ
detection rate D_R (yr^{-1})
BNS merger rate
SNR $\rho \geq 10$
SNR $\rho \geq 100$
redshift z
BBH
BBH merger rate

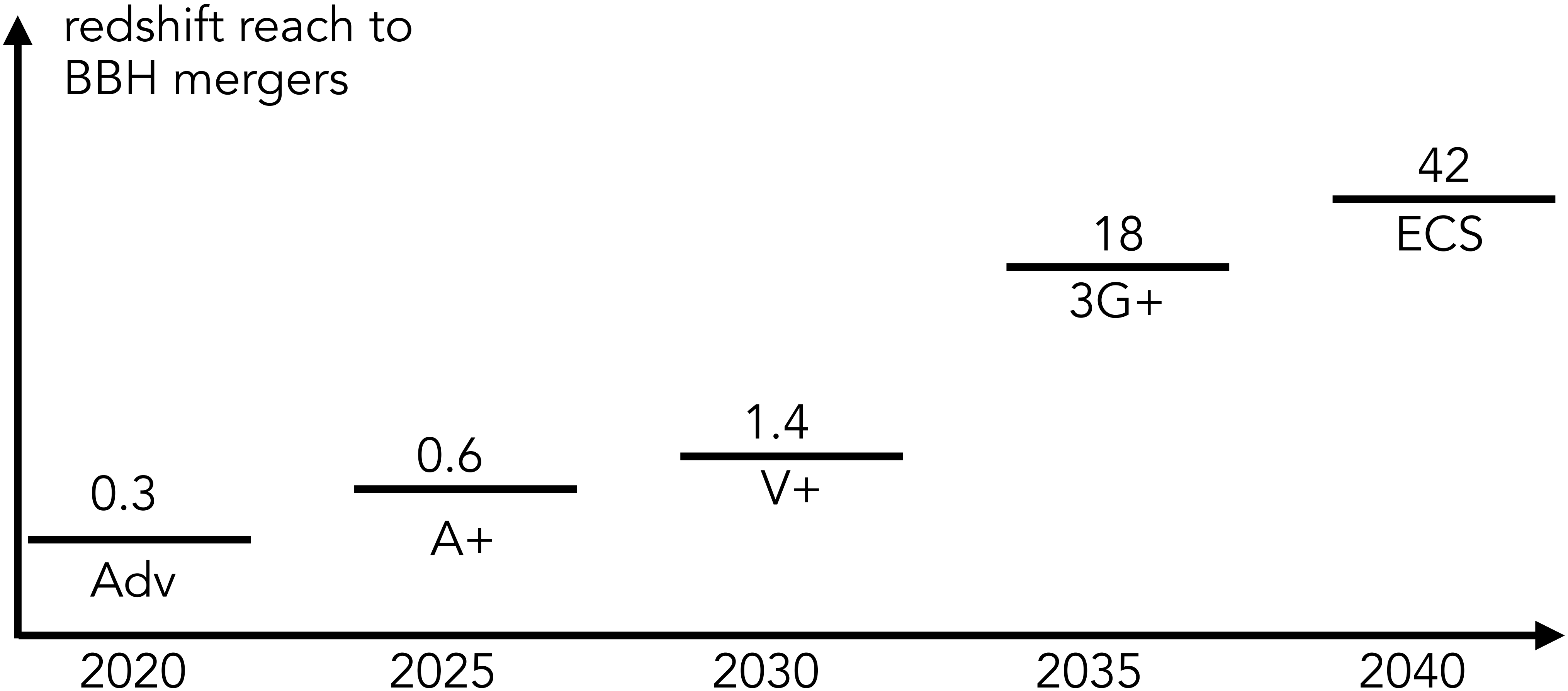


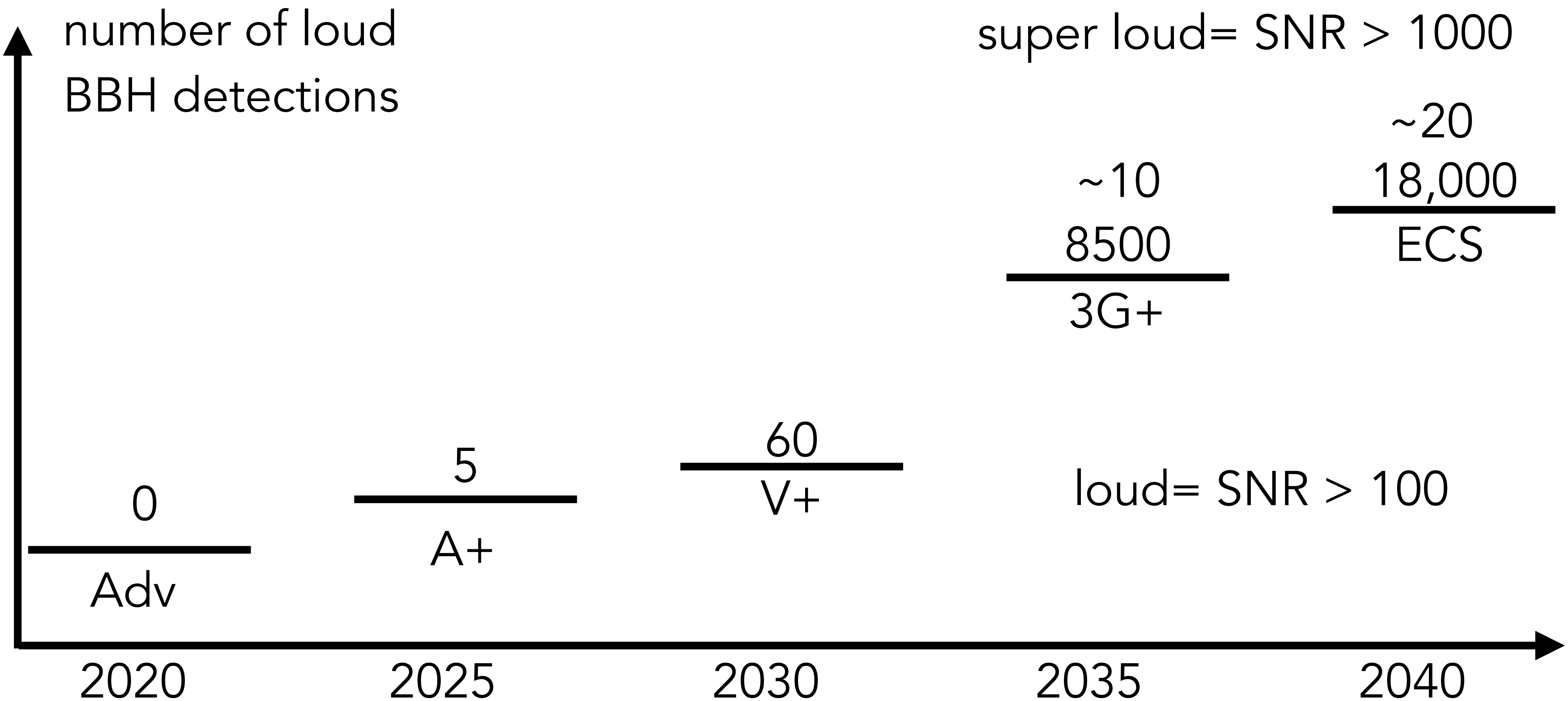
redshift reach to BNS mergers
reach of a detector is the distance at which the catalog is 50% complete
horizon is typically a factor of 5-10 larger
z=0.04
Adv
0.11
A+
0.22
Voyager
1.2
3G+
2.3
ECS
2020
2025
2030
2035
2040


number of BNS detections
240,000
ECS
130,000
3G+
1800
V+
170
A+
20
Adv
2020
2025
2030
2035
2040



number of loud
BNS detections
loud= SNR > 100
240,000, 560
ECS
130,000, 170
3G+
1800, 2
V+
170, 0
A+
20, 0
Adv
2020
2025
2030
2035
2040


redshift reach to
BBH mergers
0.3
Adv
0.6
A+
1.4
V+
18
3G+
42
ECS
2020
2025
2030
2035
2040


number of loud
BBH detections
super loud= SNR > 1000
~20
18,000
ECS
~10
8500
3G+
60
V+
5
A+
0
Adv
loud= SNR > 100
2020
2025
2030
2035
2040

Metric	Ω_{90} (deg^2)			$\Delta D_L/D_L$	
Quality	≤ 1	≤ 0.1	≤ 0.01	≤ 0.1	≤ 0.01
			BNS		
`HLVKI+`	6	1	0	19	1
`VK+HLIv`	19	1	0	130	1
`HLKI+E`	33	1	0	4,200	5
`VKI+C`	10	1	0	150	1
`KI+EC`	210	6	1	13,000	14
`ECS`	2,200	77	2	27,000	33
			BBH		
`HLVKI+`	110	4	0	600	0
`VK+HLIv`	310	12	0	3,600	3
`HLKI+E`	610	24	1	34,000	110
`VKI+C`	210	7	0	12,000	48
`KI+EC`	4,600	190	7	67,000	590
`ECS`	27,000	2,000	77	82,000	1,500

- Luminosity distance is measured “easily” from GW observations.
- How do we get the redshift?

Redshift

- EM counterpart
- Statistical host identification
- Cross correlation of GW and EM catalogs
- Features in the mass-spectrum of neutron stars and black holes
- Astrophysical distribution
- Tides in neutron stars

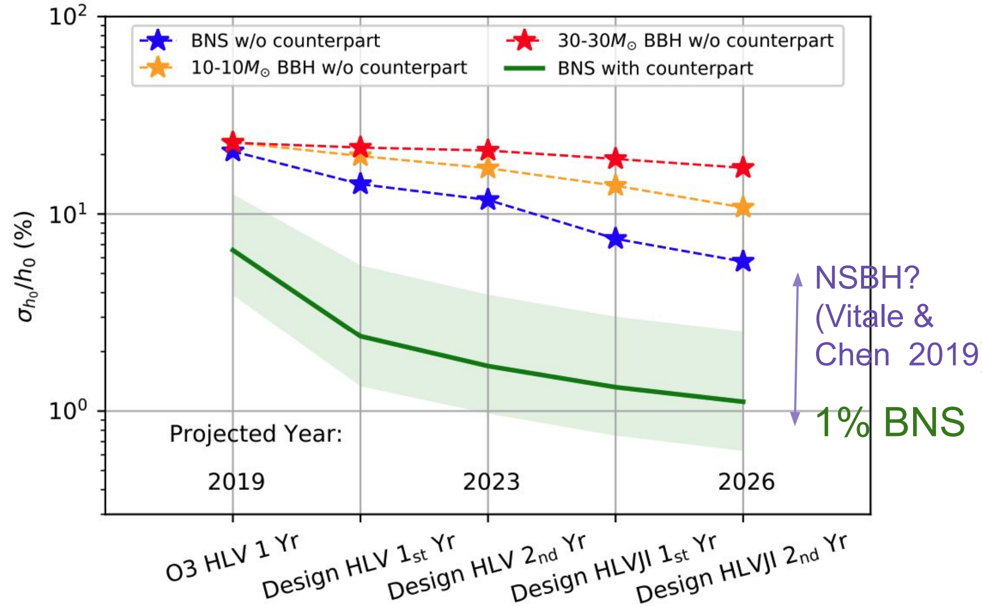
Counterpart cosmology

BNSs/fraction of NSBH expected to have EM counterparts at several wavelengths (GRB, KN - optical/IR, afterglow - X-ray/optical/radio..)

➔ Which counterpart will be the most promising for 3G cosmology?
  - GRBs and afterglows only detectable close to on axis (~<O(1%)). Helpful to constrain inc angle, but unlikely to be useful for 3G
  - KNe are ~isotropic, but faint and fading fast

BBH in AGN disks may also be promising (Bartos+17, McKernan+19)

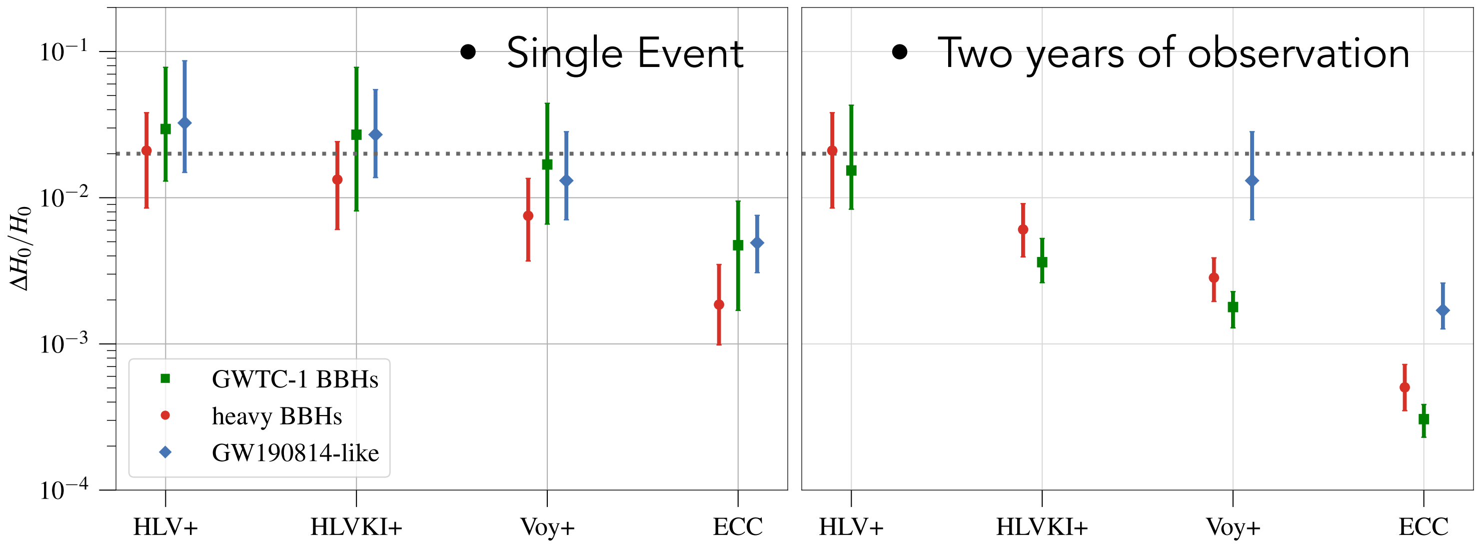
Chen, Fishbach, Holz 2018



Rare binary black holes can pin down the host galaxy with exquisite sky localization

- With A+ and Voyager Sensitivity there is 10% and 50% chance we will observe such rare events

- Next generation observatories guarantee hundreds of such identifications each year



Redshifts Without EM Observations (Mass Function Cosmology)

$$m_{\rm obs} = m\,(1+z)$$

Redshifts Without EM Observations (Mass Function Cosmology)

If I know this

$$m_{\rm obs} = m\,(1 + z)$$

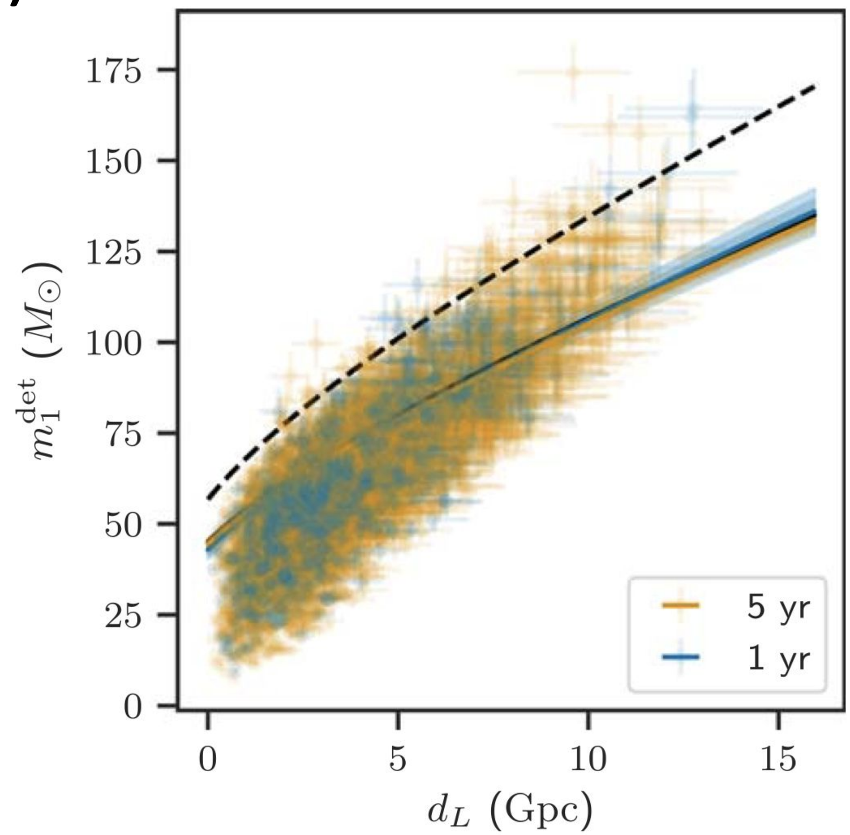
Redshifts Without EM Observations (Mass Function Cosmology)

If I know this

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

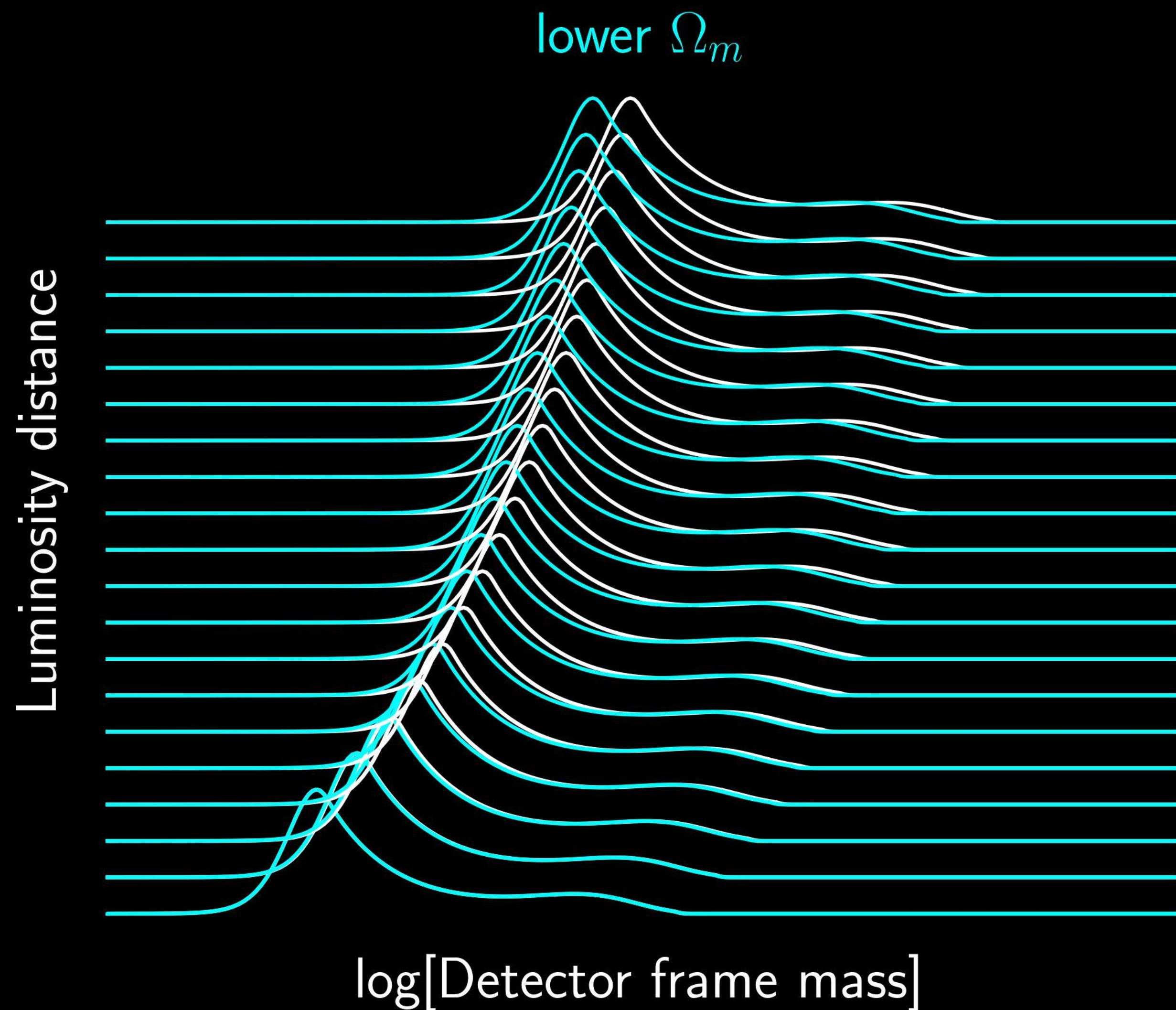
Then I can measure this.

Chernoff & Finn (1993)
Taylor & Gair (2012)
Ezquiaga & Holz (2022)



Farr, et al. (2019)

SPECTRAL SIRENS



[Chernoff&Finn'93]

[Taylor+'11]

[Farr+'19]

[Mastrogiovanni+'21]

[LVC Cosmo GWTC-3 '2

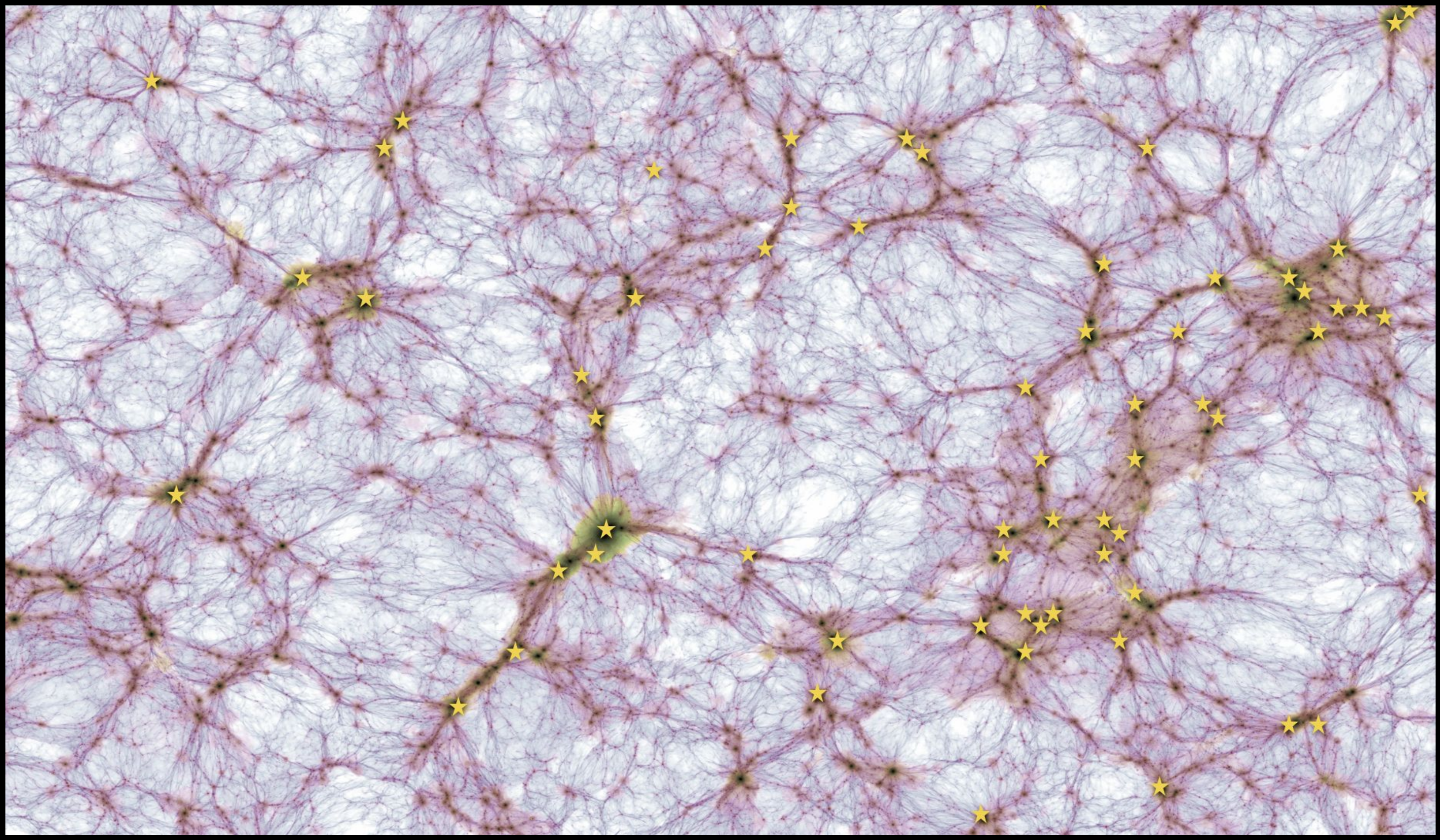
[You+'20]

[Ezquiaga&Holz'20]

[Ezquiaga&Holz'22]

Inferring redshift from dark compact objects using cross-correlation

Black holes will trace the underlying galaxies/dark matter distribution



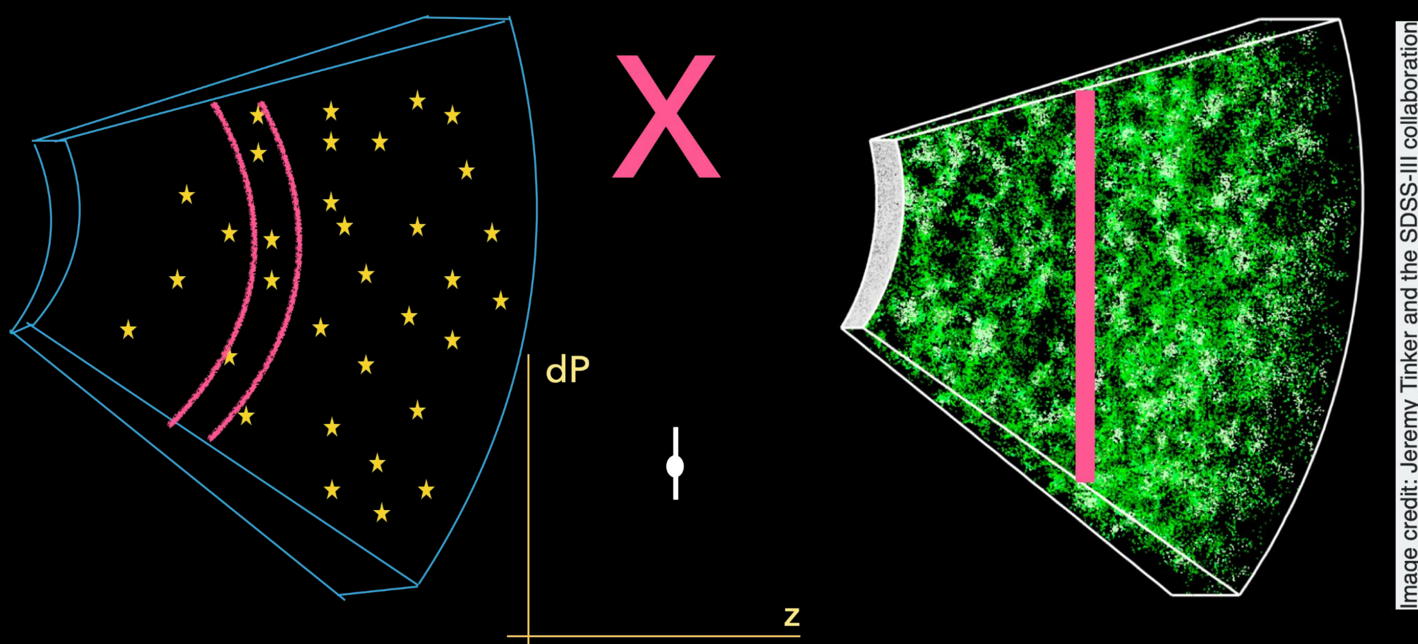
Oguri 2016,
Mukherjee+ 2018, 2019, 2020,2021
Calore+ 2020
Scelfo 2020
Bera+ 2020
Diaz+2021

Inferring redshift from dark compact objects using cross-correlation

Black holes will trace the underlying galaxies/dark matter distribution

$$dP = n_{GW} n_g (1 + \xi(r)) dV_{GW} dV_g$$

Mukherjee+ 2020



Dark sirens observed in luminosity distance space

Galaxy samples observed in redshift space

Oguri 2016,
Mukherjee+ 2018, 2019, 2020,2021
Calore+ 2020
Scelfo 2020
Bera+ 2020
Diaz+2021

- Cosmology Beyond H0

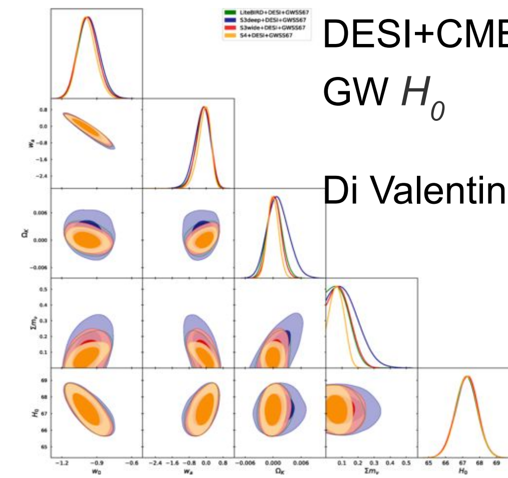
Very low-z cosmology with counterparts

Given how loud nearby BNS will be in 3G, can get precision H_0 measurements from few events. Let's assume it will be feasible to detect KNe out to z~0.3 in the 2030s.

Even if H_0 tension won't be interesting anymore in 2030s, percent-level H_0 measurements help break degeneracies from other probes for **beyond-LCDM** cosmologies (Di Valentino+19)

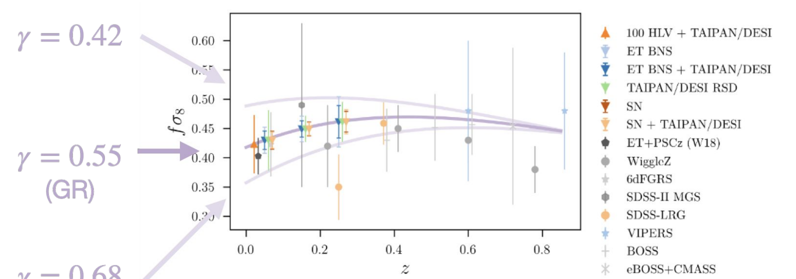
Sub-percent distance measurements in the very nearby universe will be unique to 3G observatories. They can be used to e.g. probe the **peculiar velocity field** and growth of structure (Palmese & Kim 21), **calibrate** SN distances (Gupta+19).

$\Lambda\mathrm{CDM} + \Omega_k + \Sigma m_\nu + w_0 + w_a$



DESI+CMB+1% GW H_0

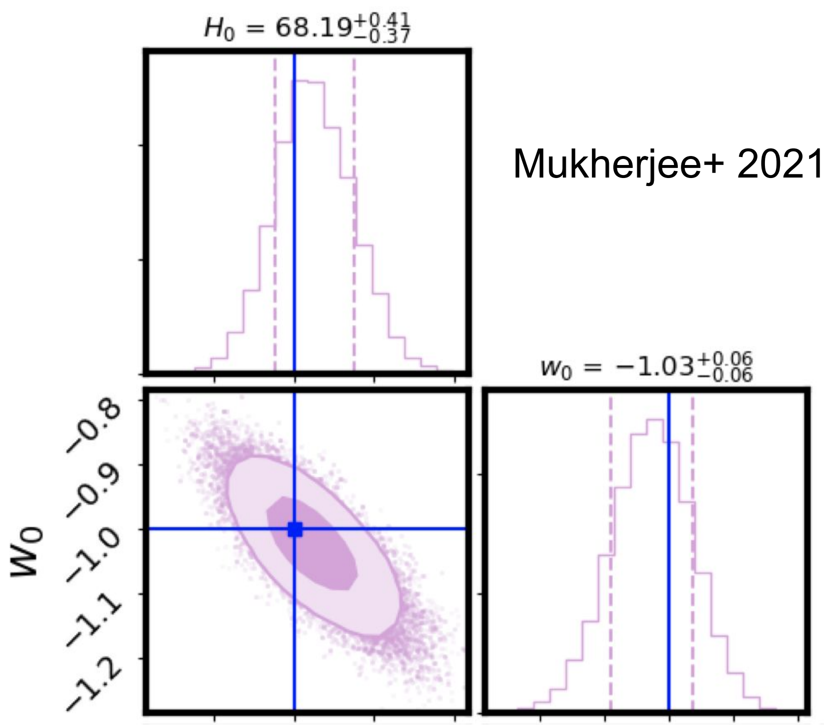
Di Valentino+19



3% precision on $f\sigma_8$, ~0.02 uncertainty on growth index γ with 3G (Palmese & Kim 21)

Dark Energy using dark sirens

- GW sources and galaxies will be spatially clustered —> **'This can give us redshift information' using cross-correlation**
- Numerous black holes to at low redshift, N^{1/2} reduction in error
- No 'Fundamental limitation' to measure luminosity distance
- Dark energy EoS measurement at sub-percent accuracy from 3G



Mukherjee+ 2021

GW DETECTORS ARE ALSO A DEEP PROBE OF FUNDAMENTAL PHYSICS

- Black hole horizons, quantum gravity, information paradox
  - black hole spectroscopy, multipolar structure, quantum modifications at horizon scales?
- Corrections to general relativity
  - additional fields, modifications of inspiral radiation
  - black hole uniqueness theorems violated: exotic compact objects?
- Probing dark matter
  - primordial black holes?, mini-charged dark matter, ultralight boson clouds, bosenovas, EM signatures?
- Gravitational-wave propagation and graviton mass
  - GW170817: constraints on Lorentz violation in the gravitational sector, Dispersion: graviton mass, extra dimensions, parity violation