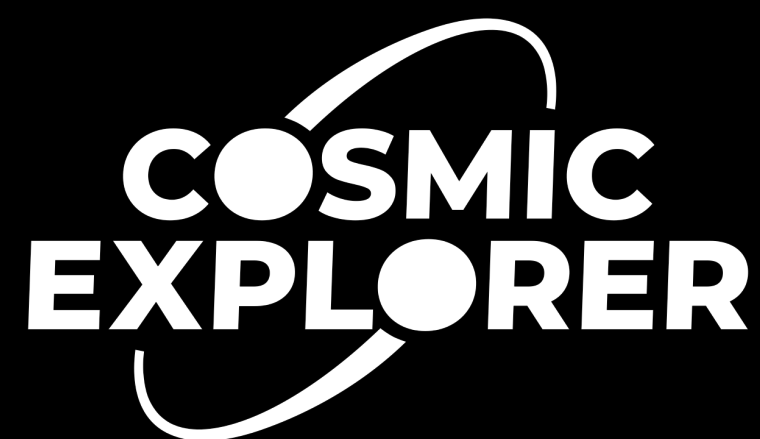


CHARACTERIZING NEUTRON STARS WITH XG DETECTORS: FROM A# TO CE AND ET

INT-24-89W EOS MEASUREMENTS WITH NEXT-GENERATION GRAVITATIONAL-WAVE
DETECTORS

AUGUST 26-SEPTEMBER 6, 2024

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Pennsylvania State University



OVERVIEW

- How well can we constrain neutron star radius from a population of events?
- How well can we constrain the presence of WIMP dark matter in neutron star cores?
- Brief introduction to evolution of sensitivity of GW detectors over the next decade+

THE NEXT DECADE AND BEYOND

CONTEXT

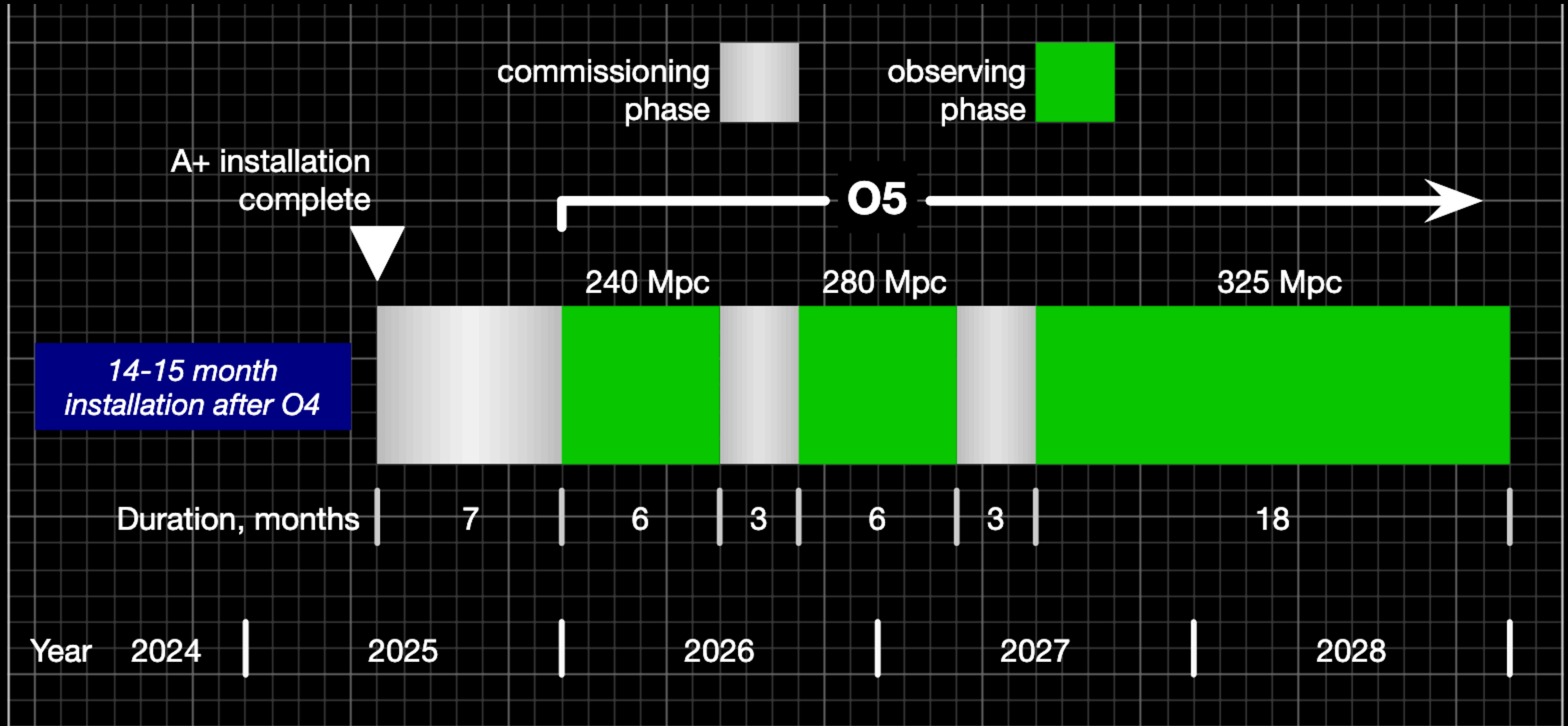
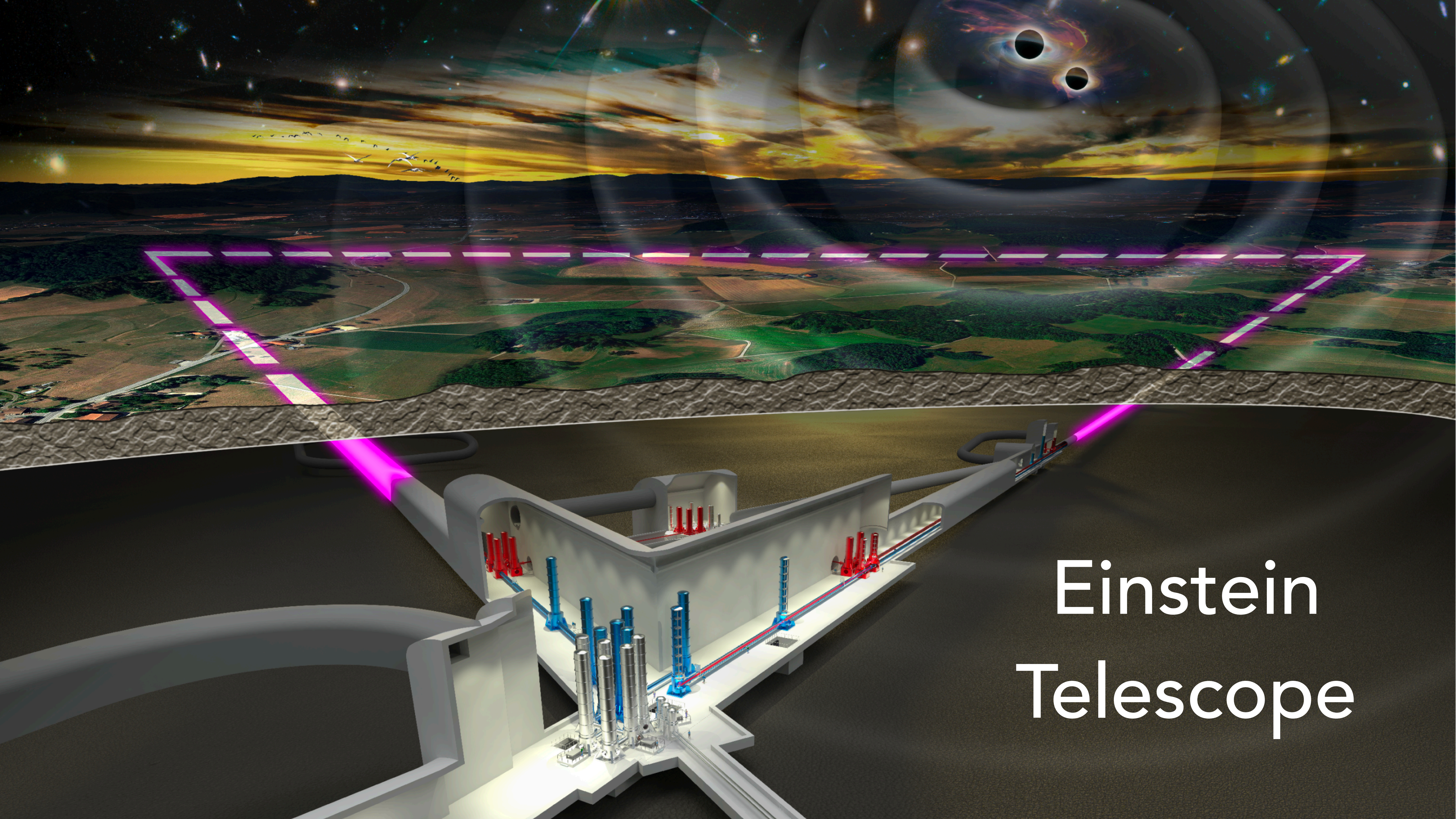


Figure 3: Proposed O5 timeline, with O5 ending at the end of 2028.

LIGO INDIA





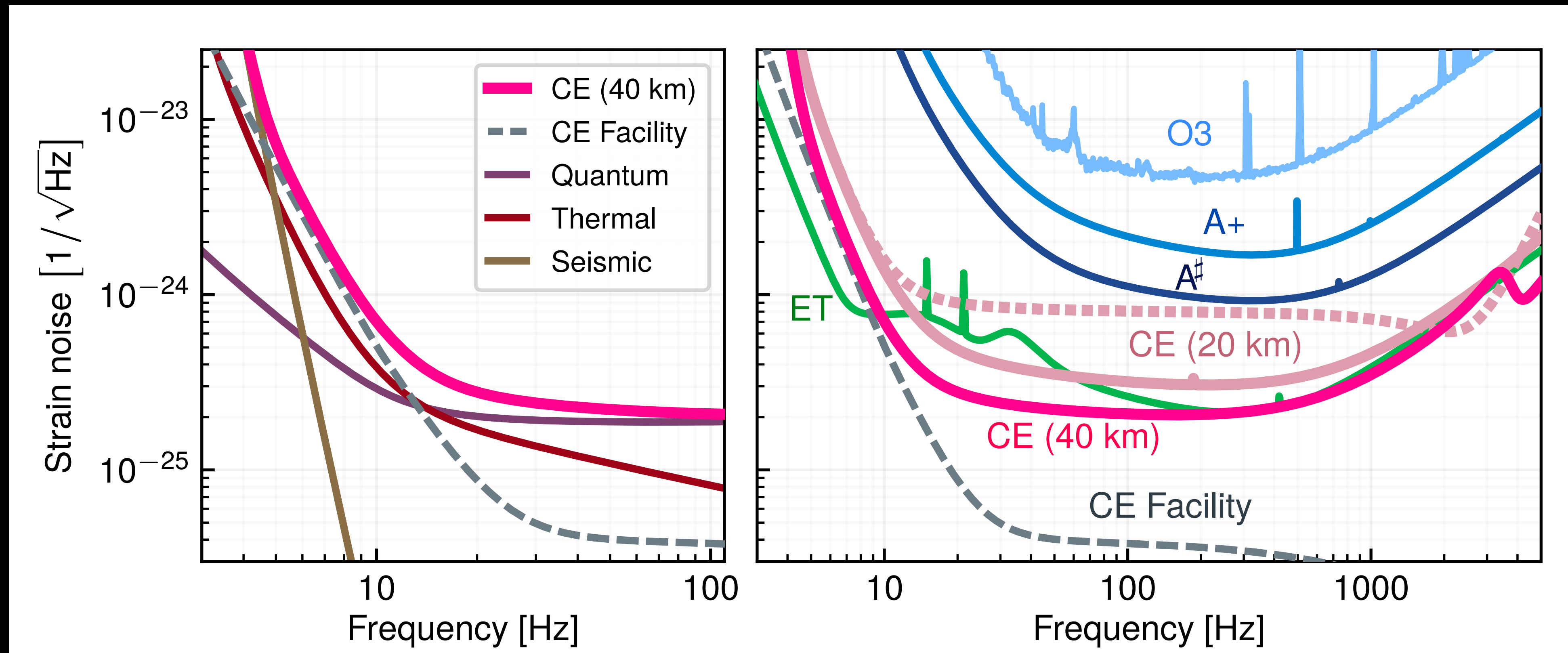
Einstein
Telescope

COSMIC EXPLORER



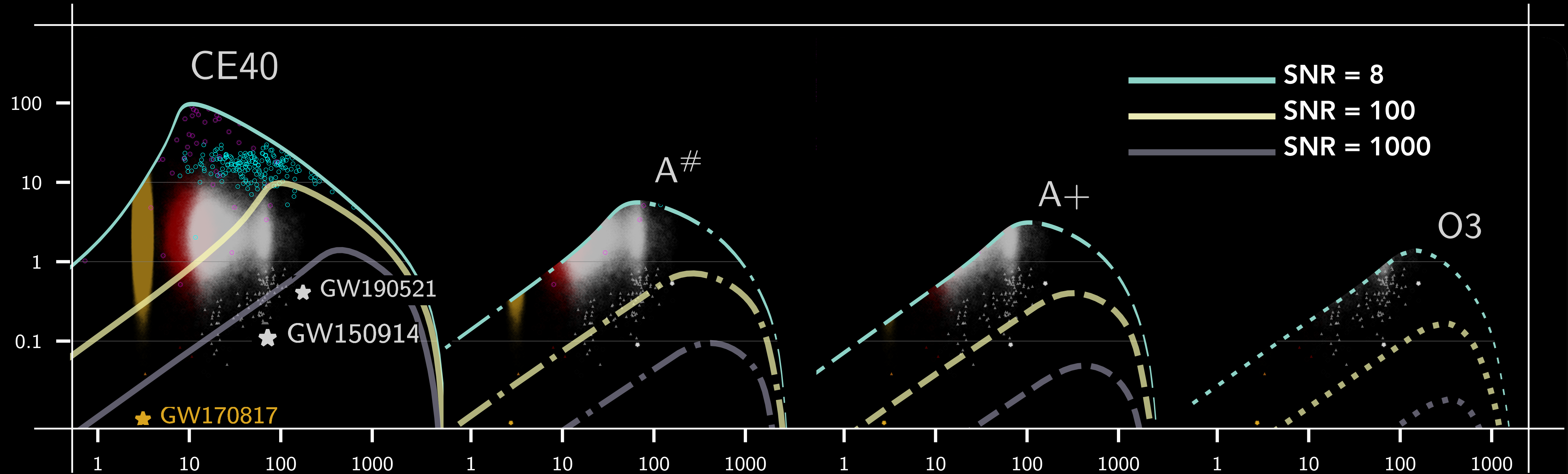
A# AND XG NETWORKS

- **HLA**: LIGO Hanford, Livingston and India in A# (or Voyager) configuration
- **CE40LA**: CE40 together with LIGO Livingston and LIGO India in A# configuration
- **CE4020ET**: Two Cosmic Explorer detectors, one 40 km, another 20 km with ET



COMPARATIVE REACH: FROM O3 TO XG

redshift v total mass



EXCEPTIONAL EVENTS IN A# AND CE

GW170817

Binary neutron star merger

A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.

Distance
130 million light years

Discovered
17 August 2017

Type
Neutron star merger

12:41:04 UTC
A gravitational wave from a binary neutron star merger is detected.

gravitational wave signal
Two neutron stars, each the size of a city but with at least the mass of the sun, collided with each other.

gamma ray burst
A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.

+ 2 seconds
A gamma ray burst is detected.

+10 hours 52 minutes
A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

+11 hours 36 minutes
Infrared emission observed.

+15 hours
Bright ultraviolet emission detected.

+9 days
X-ray emission detected.

+16 days
Radio emission detected.

kilonova
Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

radio remnant
As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.

Au
The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production most of the heavy elements, like gold, in the universe.

Observing both electromagnetic and gravitational waves from the event provides compelling evidence that gravitational waves travel at the same speed as light.

GW150914: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP); BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1	duration from 30 Hz	~ 200 ms
source type	black hole (BH) binary	# cycles from 30 Hz	~10
date	14 Sept 2015	peak GW strain	1×10^{-21}
time	09:50:45 UTC	peak displacement of interferometers arms	± 0.002 fm
likely distance	0.75 to 1.9 Gly	frequency/wavelength at peak GW strain	150 Hz, 2000 km
redshift	0.054 to 0.136	peak speed of BHs	~ 0.6 c
signal-to-noise ratio	24	peak GW luminosity	3.6×10^{56} erg s ⁻¹
false alarm prob.	< 1 in 5 million	radiated GW energy	2.5-3.5 M _☉
false alarm rate	< 1 in 200,000 yr	remnant ringdown freq.	~ 250 Hz
Source Masses	M_☉	remnant damping time	~ 4 ms
total mass	60 to 70	remnant size, area	180 km, 3.5×10^5 km ²
primary BH	32 to 41	consistent with general relativity?	passes all tests performed
secondary BH	25 to 33	graviton mass bound	< 1.2×10^{-22} eV
remnant BH	58 to 67	coalescence rate of binary black holes	2 to 400 Gpc ⁻³ yr ⁻¹
mass ratio	0.6 to 1	online trigger latency	~ 3 min
primary BH spin	< 0.7	# offline analysis pipelines	5
secondary BH spin	< 0.9	CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
remnant BH spin	0.57 to 0.72	papers on Feb 11, 2016	13
signal arrival time delay	arrived in L1 7 ms before H1	# researchers	~1000, 80 institutions in 15 countries
likely sky position	Southern Hemisphere		
likely orientation resolved to	face-on/off ~600 sq. deg.		

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds.
Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear= 9.46×10^{12} km; Mpc=mega parsec= 3.2 million lightyear, Gpc=10³ Mpc, fm=femtometer= 10^{-15} m, M_☉=1 solar mass= 2×10^{30} kg

GW190521

The most massive black hole collision observed so far

Discovery
21 May 2019

Distance
17 billion light years away

3 Detectors
Three detectors made the observation: the two LIGO detectors in the USA and Virgo in Italy.

Binary Black Hole Merger

High Masses
This is the heaviest pair of black holes which have ever been observed colliding.

Origin Story
The black holes which collided to make GW190521 are so massive that we're not sure how they were formed. One possibility is that they are both the result of previous black hole collisions.

Ringdown
The black hole formed in the collision continues to vibrate after the merger, and "rings" like a bell for a while. This lets us test our theories. Once again Einstein's General Relativity passed this test.

Merger Statistics:
85 suns radiated as GW energy
66 suns radiated as GW energy
142 suns radiated as GW energy

Premerger: 85 suns, 66 suns
Merger: 142 suns
Remnant: 142 suns

GW190814

The coalescence of a black-hole and a compact, unknown companion object

Discovery
14 August 2019

Distance
800 million light years away

3 Detectors
Three detectors made the observation: the two LIGO detectors in the USA and Virgo in Italy.

Binary Black Hole Merger (Probably)
We can't be sure what the lighter object is - it's either the lightest black hole we've ever observed, or possibly the heaviest neutron star.

Unequal Masses
There is an almost nine-fold difference between the two objects' masses.

Higher Harmonics
This event allowed the hum of higher harmonics to be measured in the signal. These are even stronger in this signal than for GW190412, thanks to the greater asymmetry between the objects' masses. These allow new tests of General Relativity. Everything continues to be consistent with Einstein's theory following these tests.

Merger Statistics:
23.2 suns radiated as GW energy
2.6 suns radiated as GW energy
25.6 suns radiated as GW energy

Premerger: 23.2 suns, 2.6 suns
Merger: 25.6 suns
Remnant: 25.6 suns

Get to know GW230529

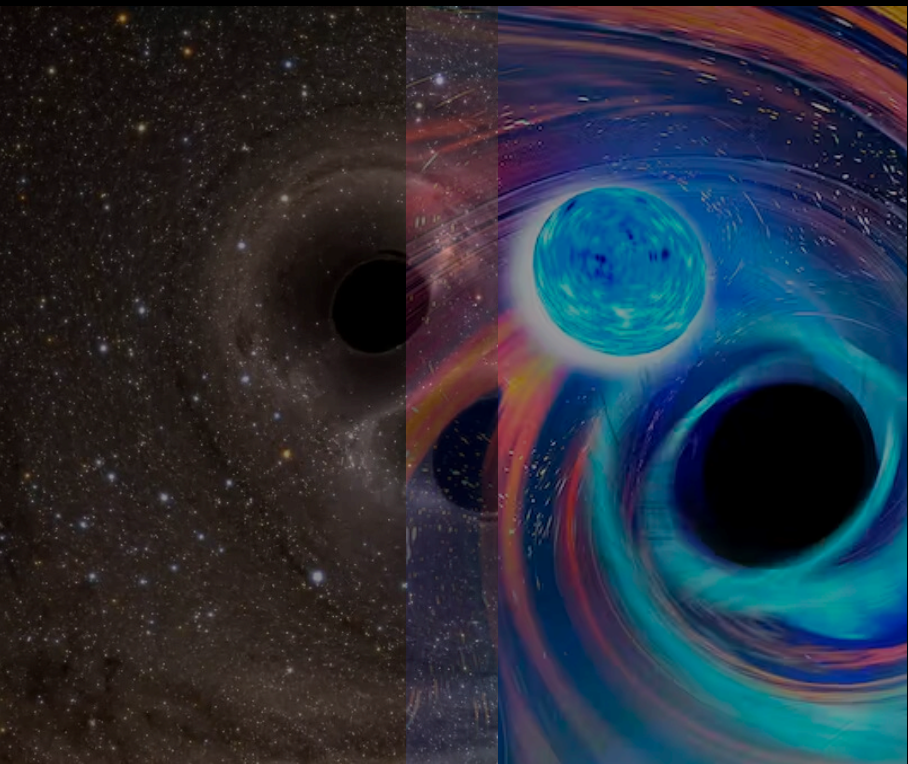
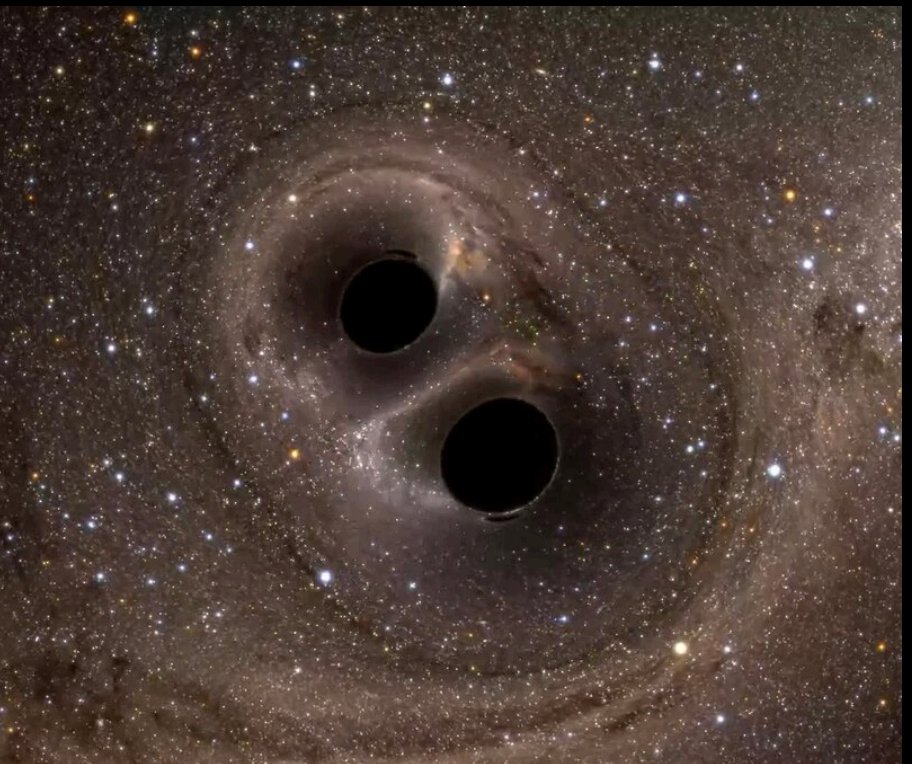
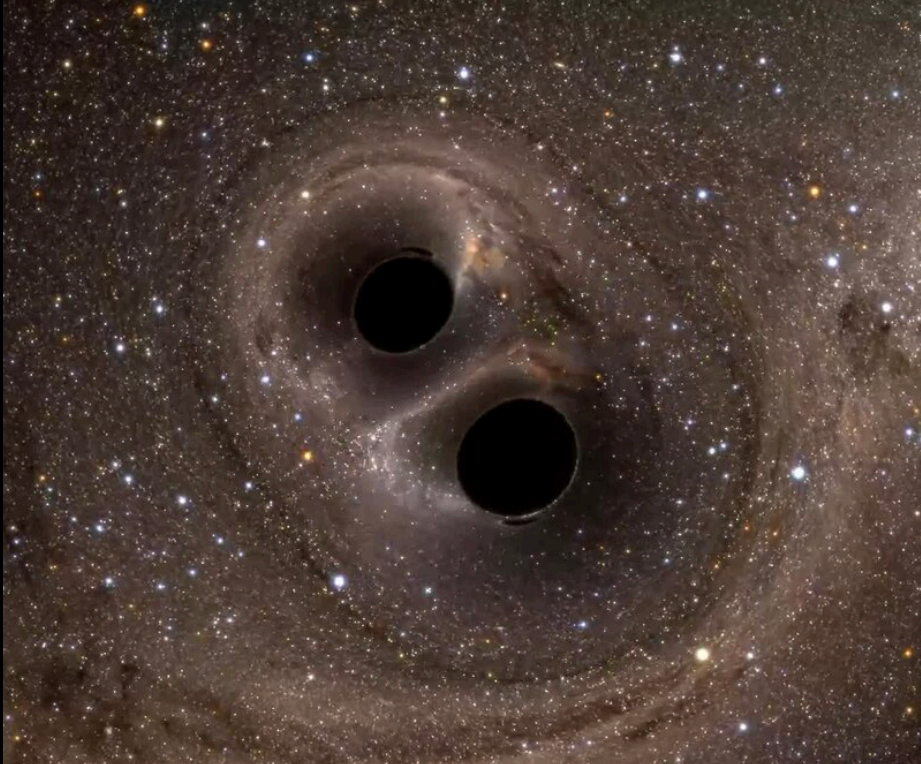
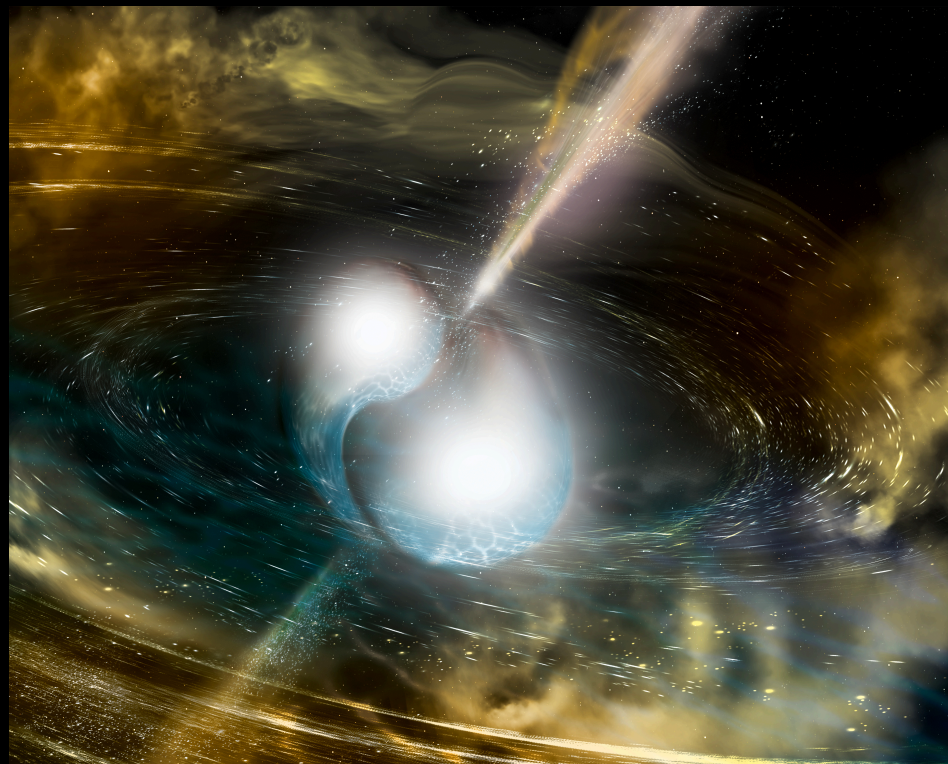
Full name GW230529_181500

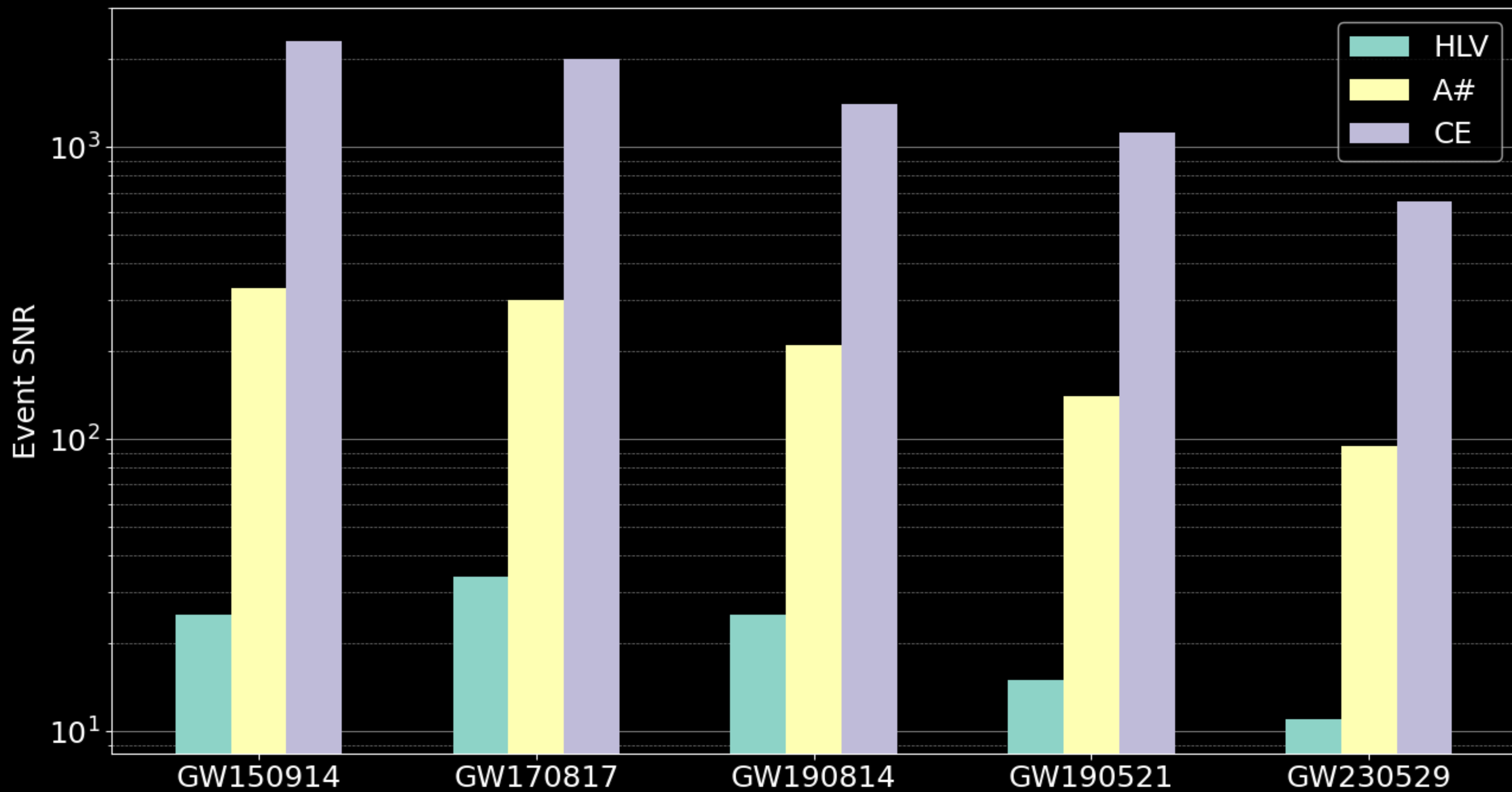
Discovered on 29 May 2023 at 18h15 UT

most likely a merger between a Neutron Star & Black Hole (NSBH)

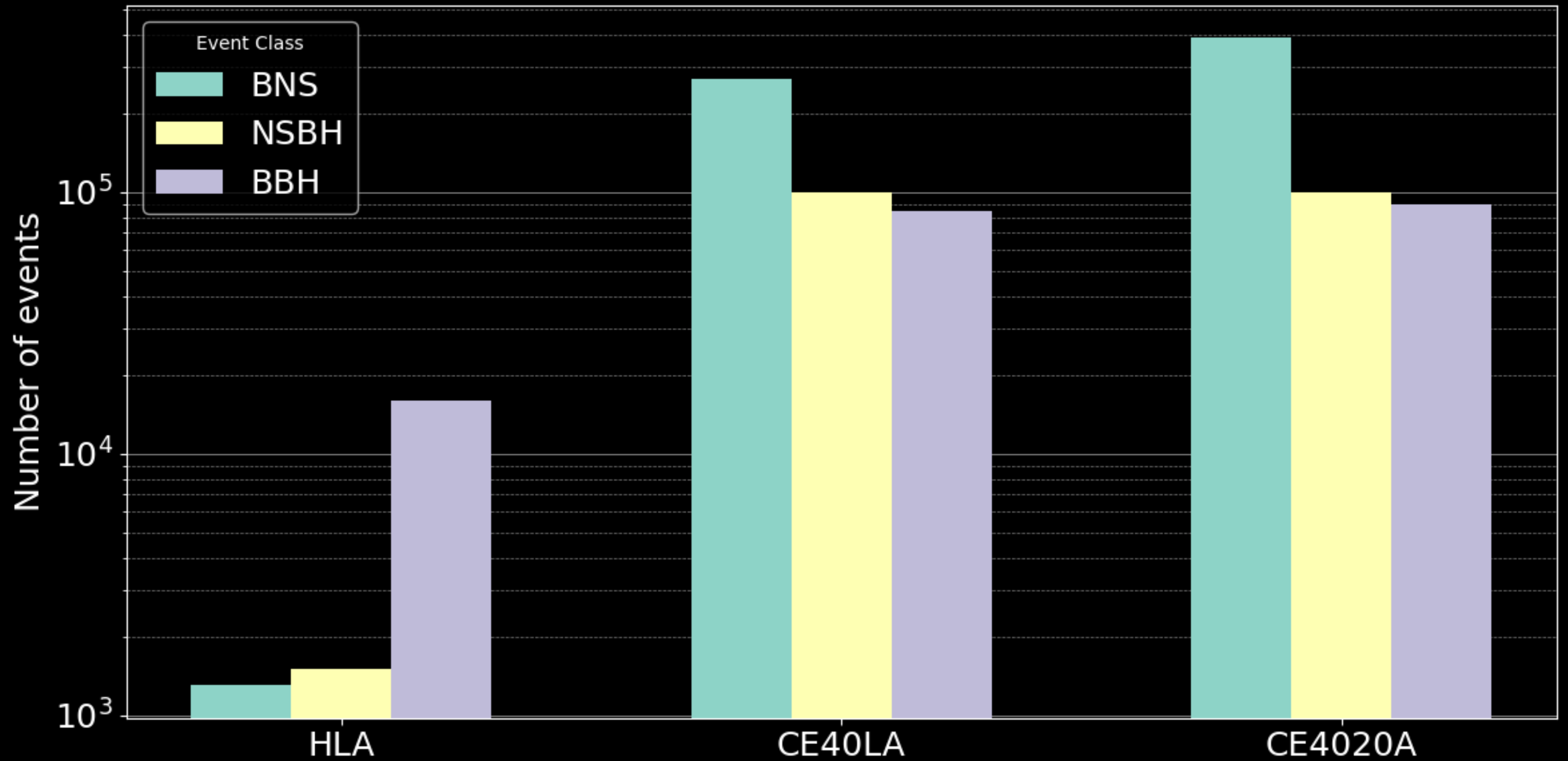
~1.4 M_☉ ~3.6 M_☉

Most symmetric NSBH event so far
more likely than prior GW NSBHs to have the neutron star ripped apart by the black hole

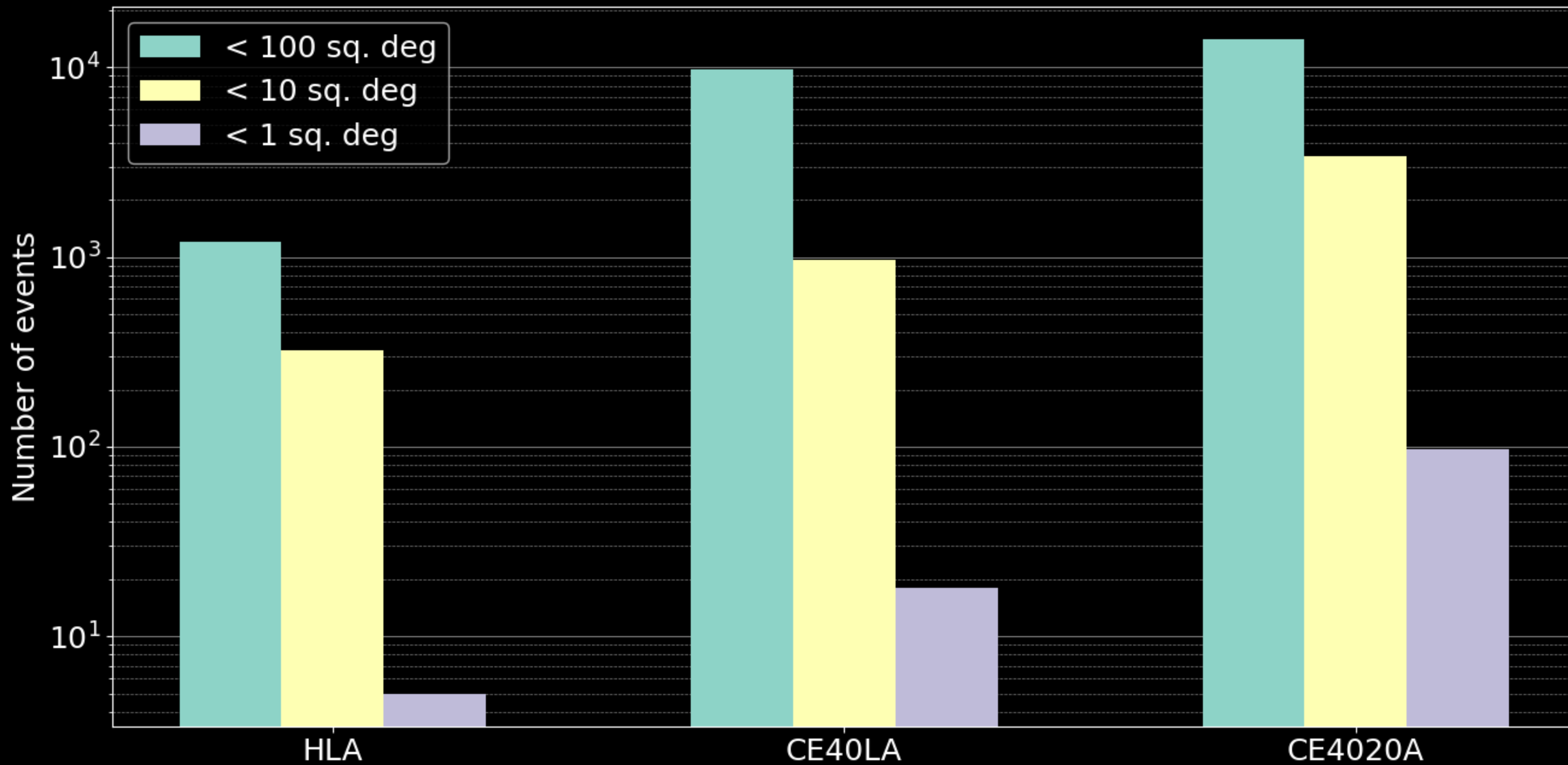




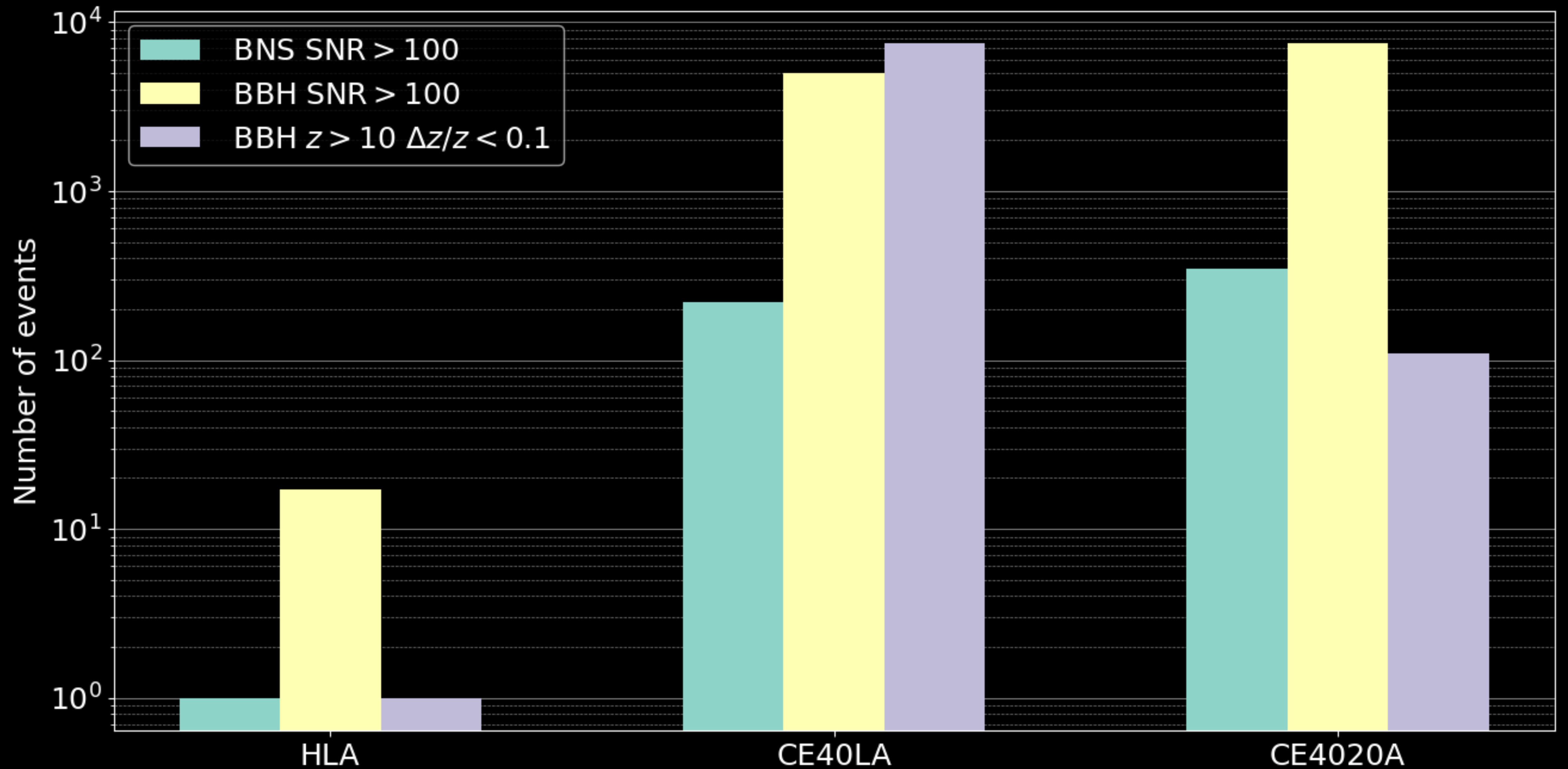
ANNUAL DETECTIONS



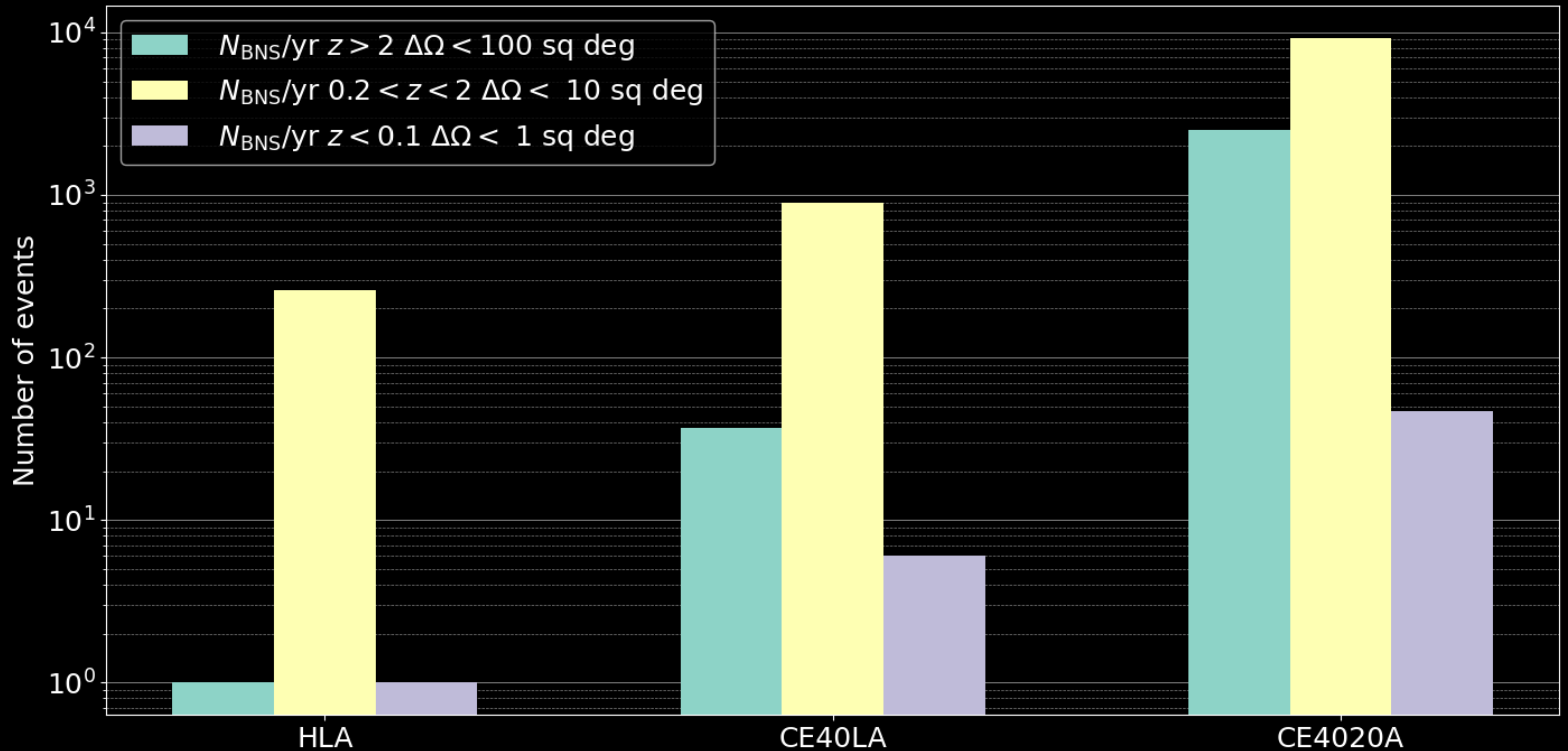
WELL-LOCALIZED BNS SOURCES



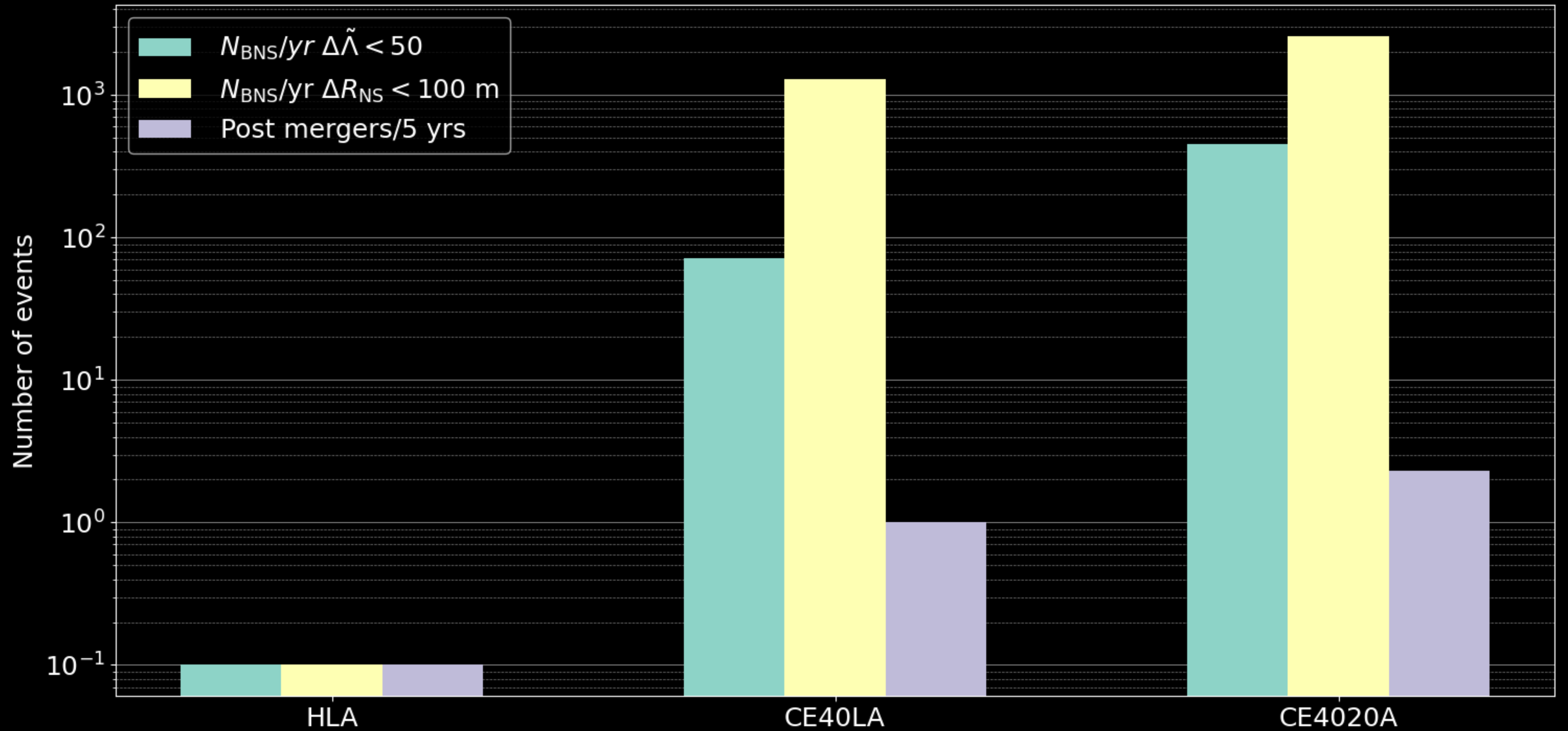
HIGH FIDELITY EVENTS



ASTROPHYSICS OF ULTRA-RELATIVISTIC SOURCES



DENSE MATTER EQUATION OF STATE



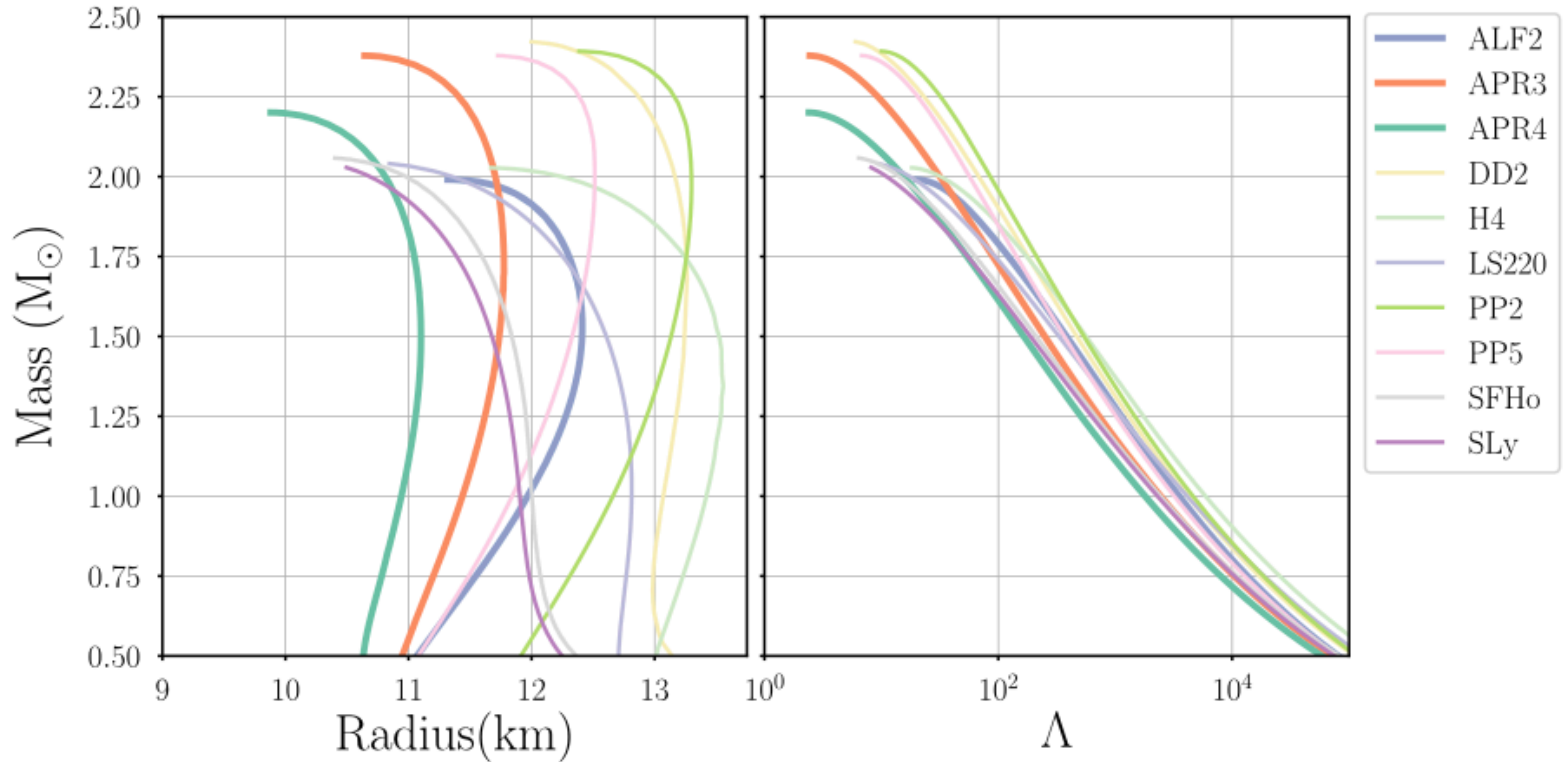
CONSTRAINING NEUTRON STAR MASS-RADIUS RELATIONSHIP

Use Universal Relations to Resolve Individual Tidal
Deformabilities

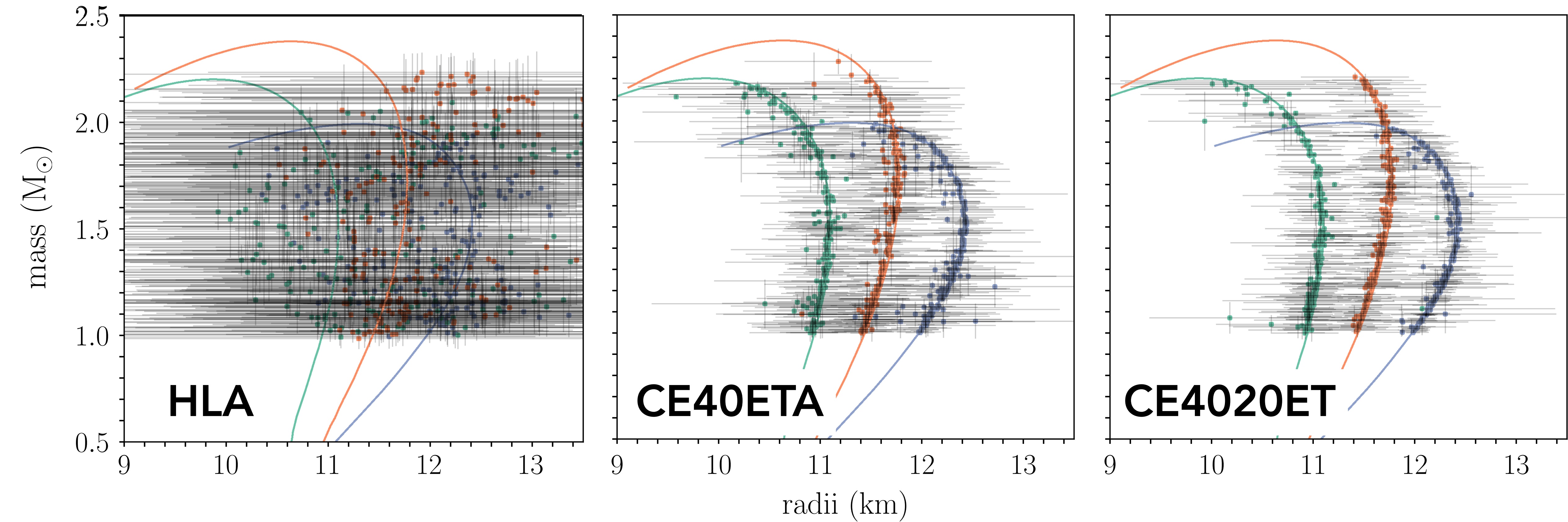
STRATEGY TO EVALUATE CAPABILITIES OF XG OBSERVATORIES

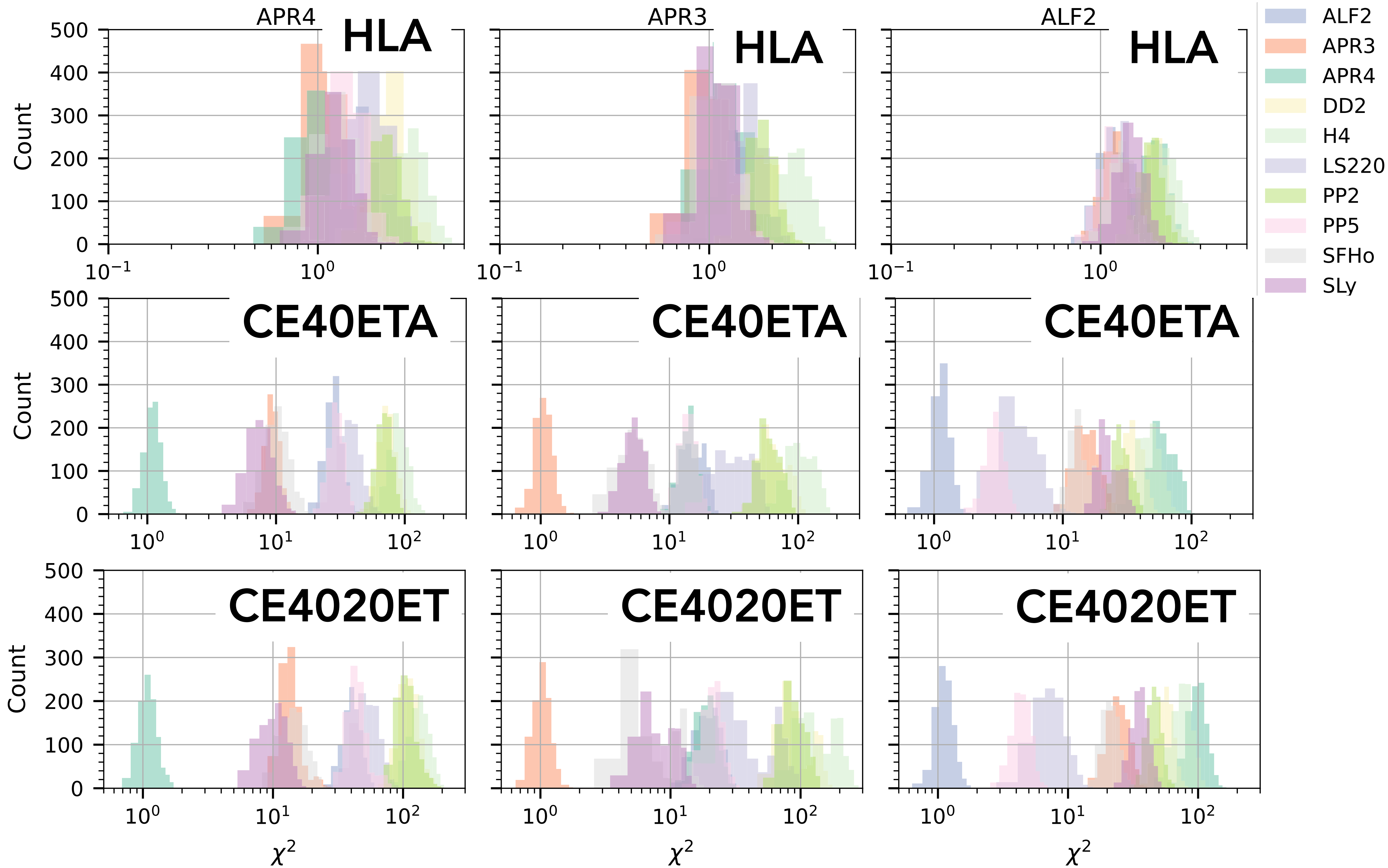
- Use Fisher matrix to evaluate the measurement capabilities of different networks
 - Bayesian inference is too expensive for the full population
- Consider a an observation period of 10 years to capture statistical variation in the number of events observed with high SNRs
 - This will provide uncertainties in number of events, etc., over a one year period
- Spot check Fisher calculations with Bayesian inference runs
 - Check the uncertainty in mass-radius measurements (and hence EoS) for about 100 events expected to be observed within z of 0.1 in one year
 - This was done to validate the large scale Fisher studies

INJECTIONS PERFORMED ALF2, APR3, APR4

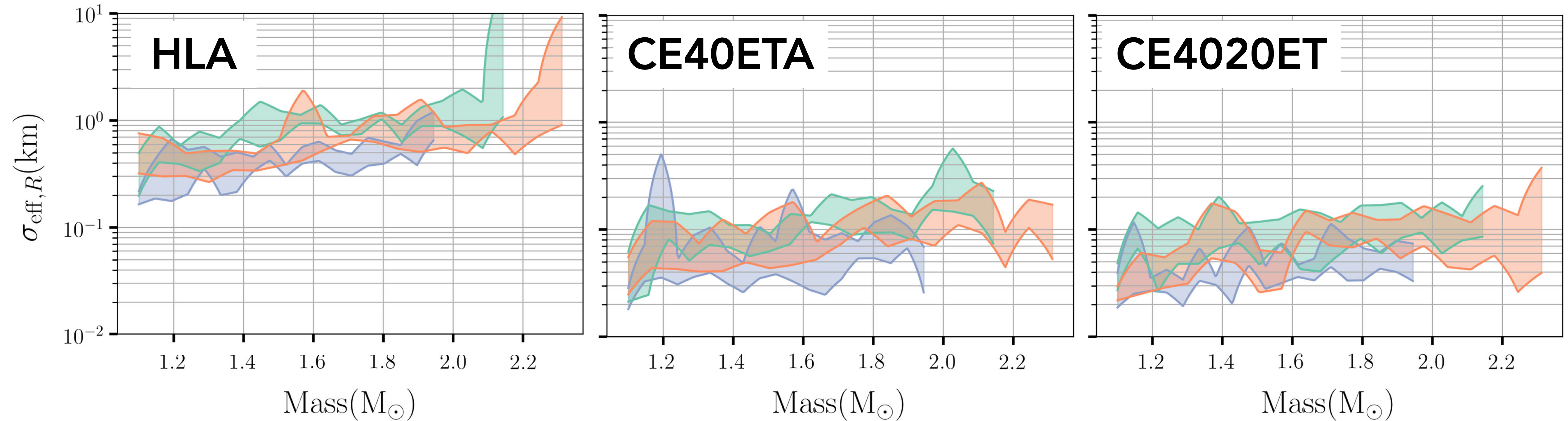


RELATIVE PERFORMANCE OF NETWORKS

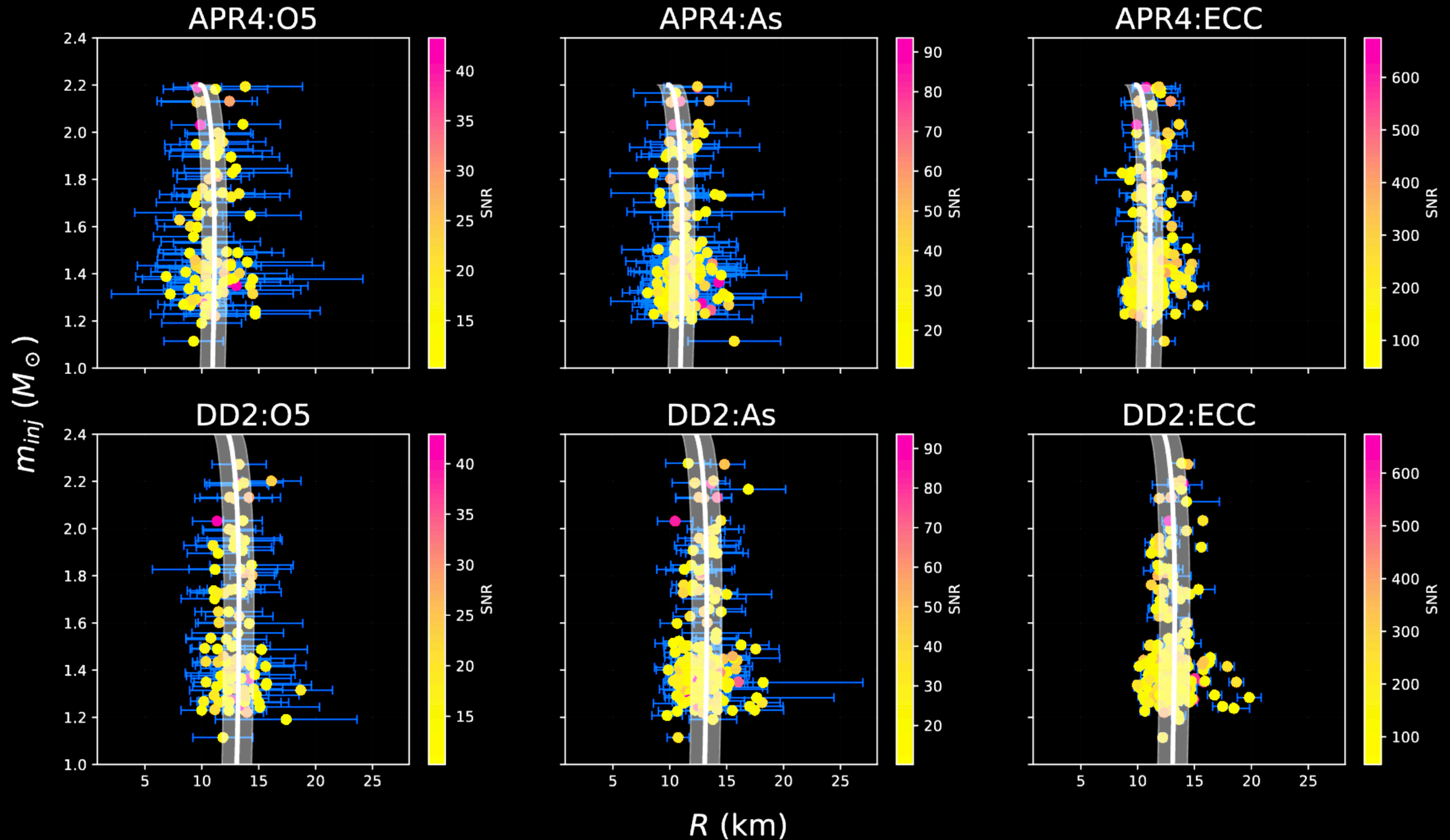




MEASUREMENT ACCURACY OF RADIUS AS A FUNCTION OF NEUTRON STAR MASS



MEASUREMENT ACCURACY OF NS RADIUS



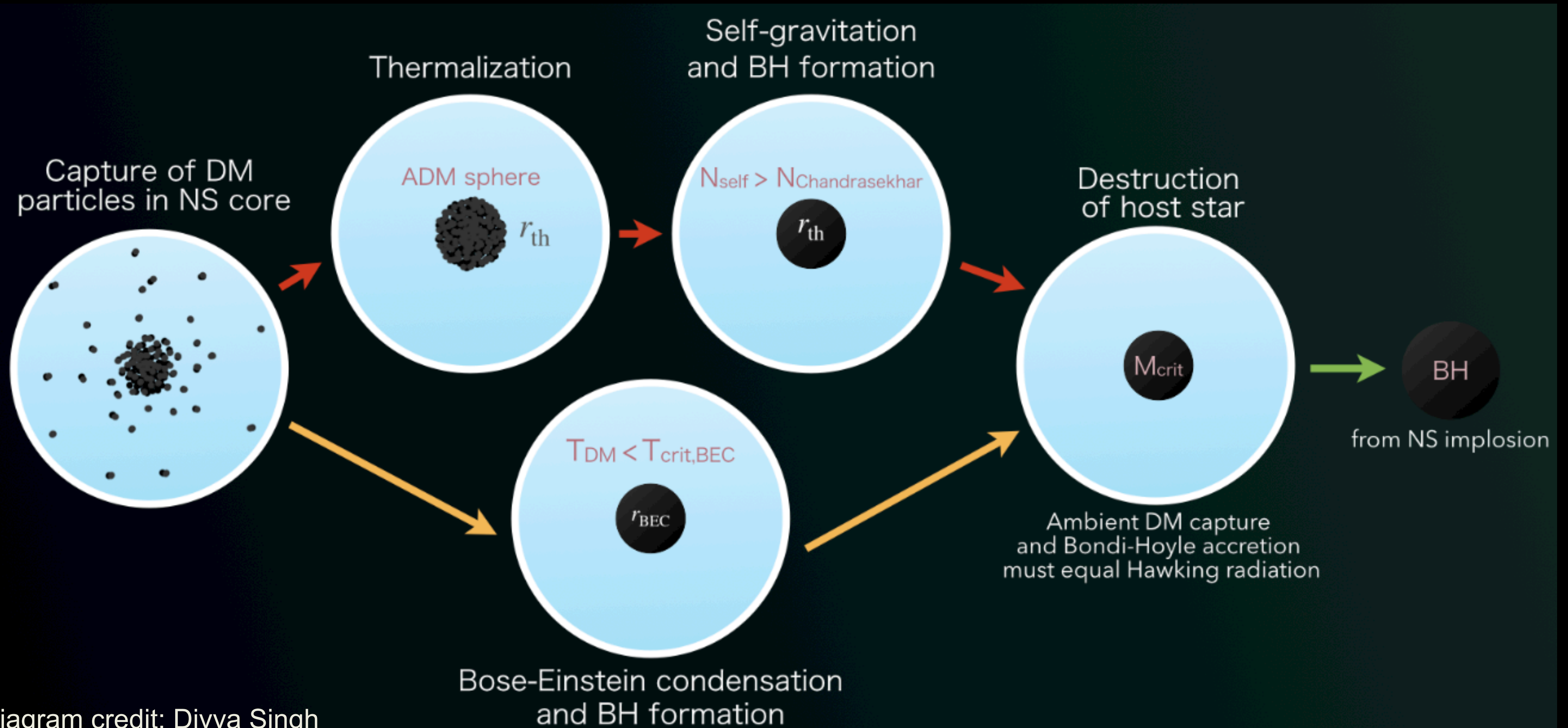
CHALLENGES

- What are the appropriate priors for luminosity distance and inclination angle?
- Are waveform systematics under control and mismatches less than 1 part in 10,000?
- Require instrument amplitude and phase calibration uncertainties to be \sim two orders of magnitude better than where we are now.

CONSTRAIN PROPERTIES OF WIMP DARK MATTER

Black Holes Have Zero Tidal Deformability

DARK MATTER INDUCED IMPLOSION OF NEUTRON STARS



Merger rate density

Relative abundances

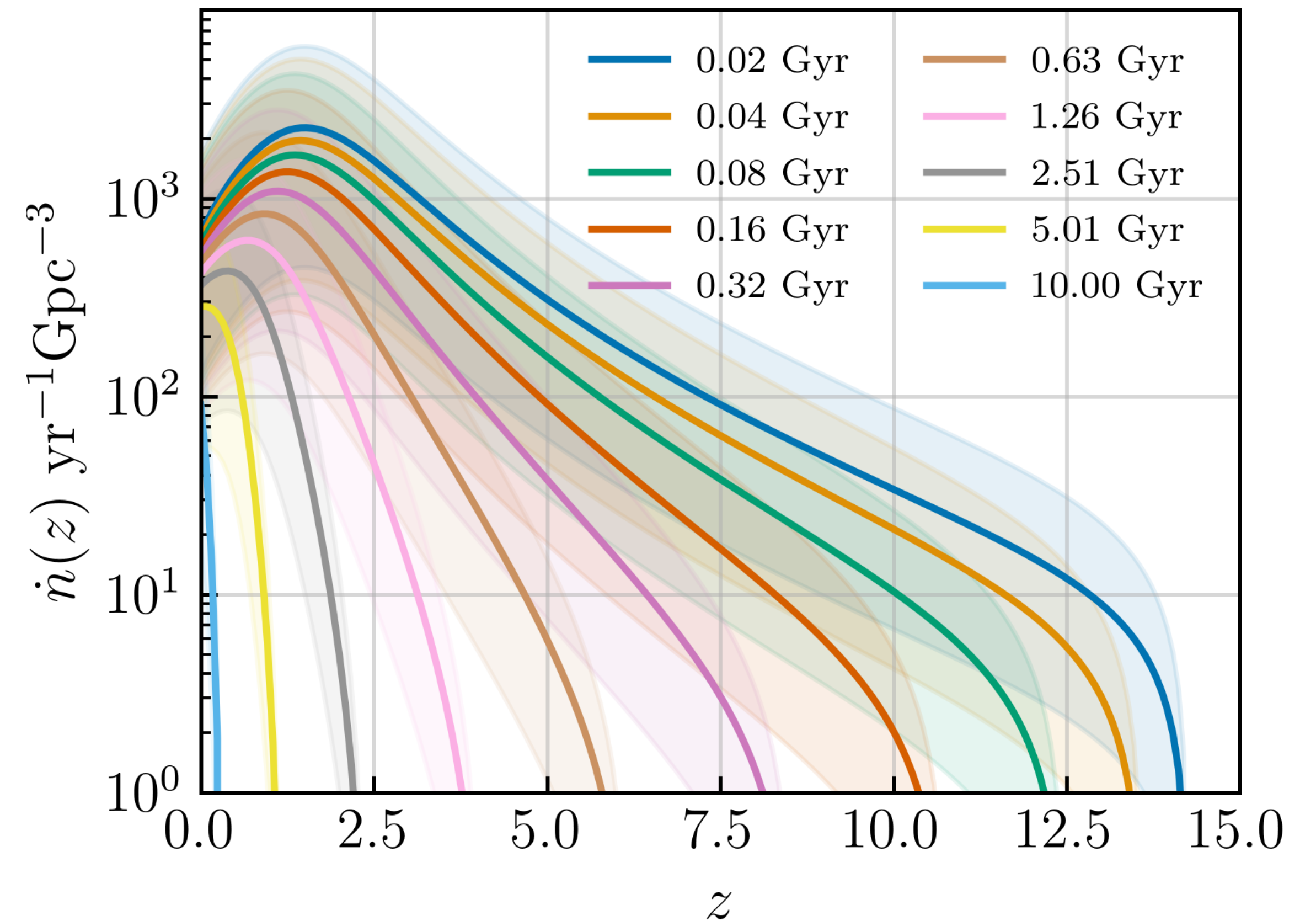
$$\dot{n}(z) = A \int_{t_d^{\min}}^{t_d^{\max}} \psi(z_f(z, t_d)) \mathcal{P}(t_d) dt_d$$

$$\dot{n}(z)_{\text{BNS}} = A \int_{t_d^{\min}}^{t_c} \psi(z_f(z, t_d)) \mathcal{P}(t_d) dt_d$$

$$\dot{n}(z)_{\text{BBH}} = A \int_{t_c}^{t_d^{\max}} \psi(z_f(z, t_d)) \mathcal{P}(t_d) dt_d$$

Error bands are from the uncertainty in the observed local rate density,
 $130 \leq R_0 \leq 1700 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (GWTC-3 Populations paper).

Merger rate density for BBH is a function of the collapse time. Higher collapse time implies more BNS and vice versa.



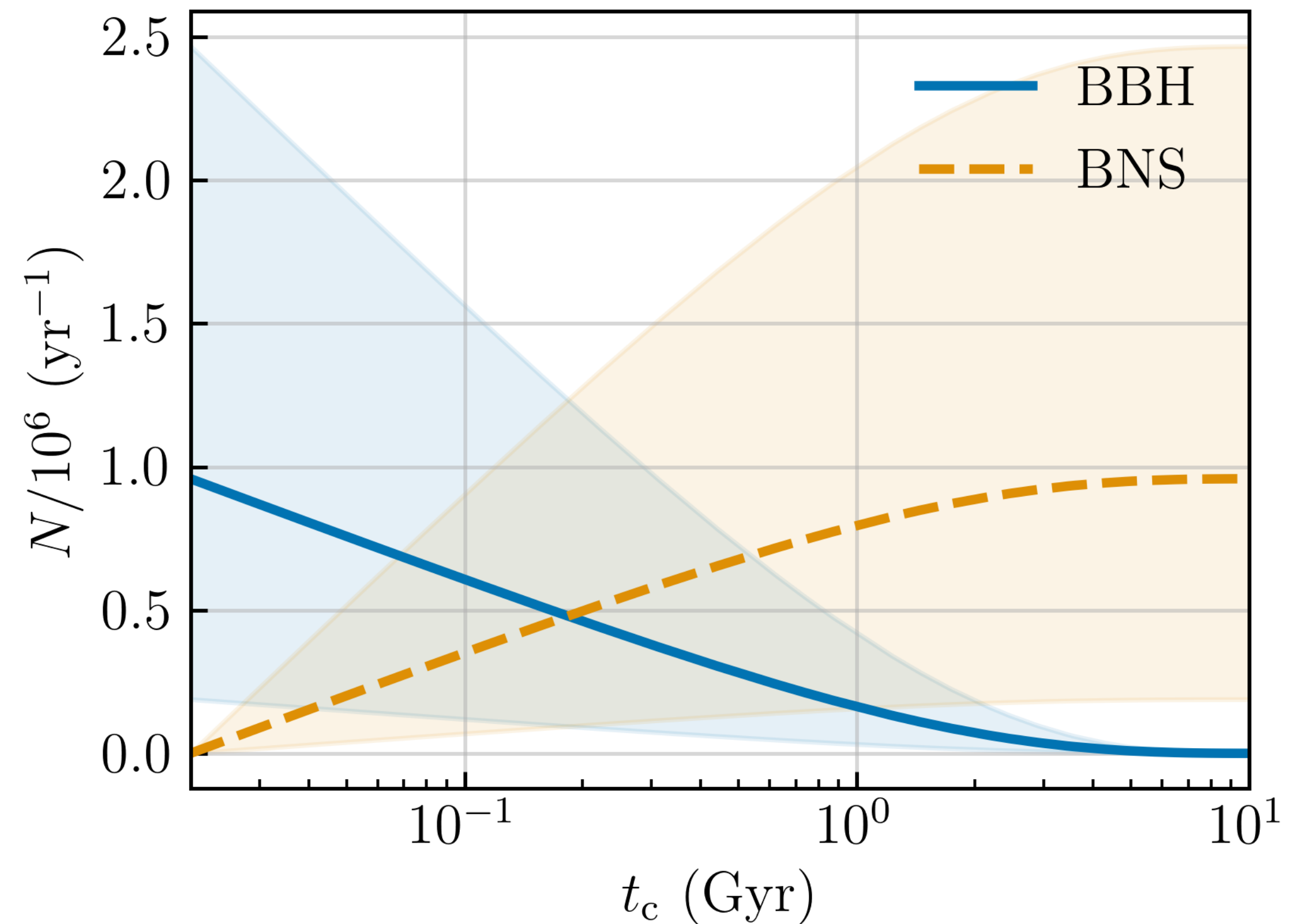
Total merger rate

Relative abundances

The merger rate within redshift z observed locally, at $z=0$.

$$\dot{N} = \int_0^z \frac{\dot{n}(z')}{1+z'} \frac{dV_c}{dz'} dz'$$

The total merger rate derived from integrating the merger rate densities over redshift is also a function of collapse time. Higher collapse time implies more number of BNS mergers and vice versa.



Population of interest

Differentiating between BBH and BNS

BBH with component masses similar to NS masses $\sim 1-2 M_{\odot}$.

The relative abundance of BNS to BBH depends on the collapse time of NS to BH.

How do we differentiate between these binary systems?

- Electromagnetic counterparts
- **Effective tidal deformability parameter, $\tilde{\Lambda}$**
 - $\tilde{\Lambda}_{\text{BBH}} = 0$
 - $\tilde{\Lambda}_{\text{BNS}} > 0$

Measuring $\tilde{\Lambda}$

Methods

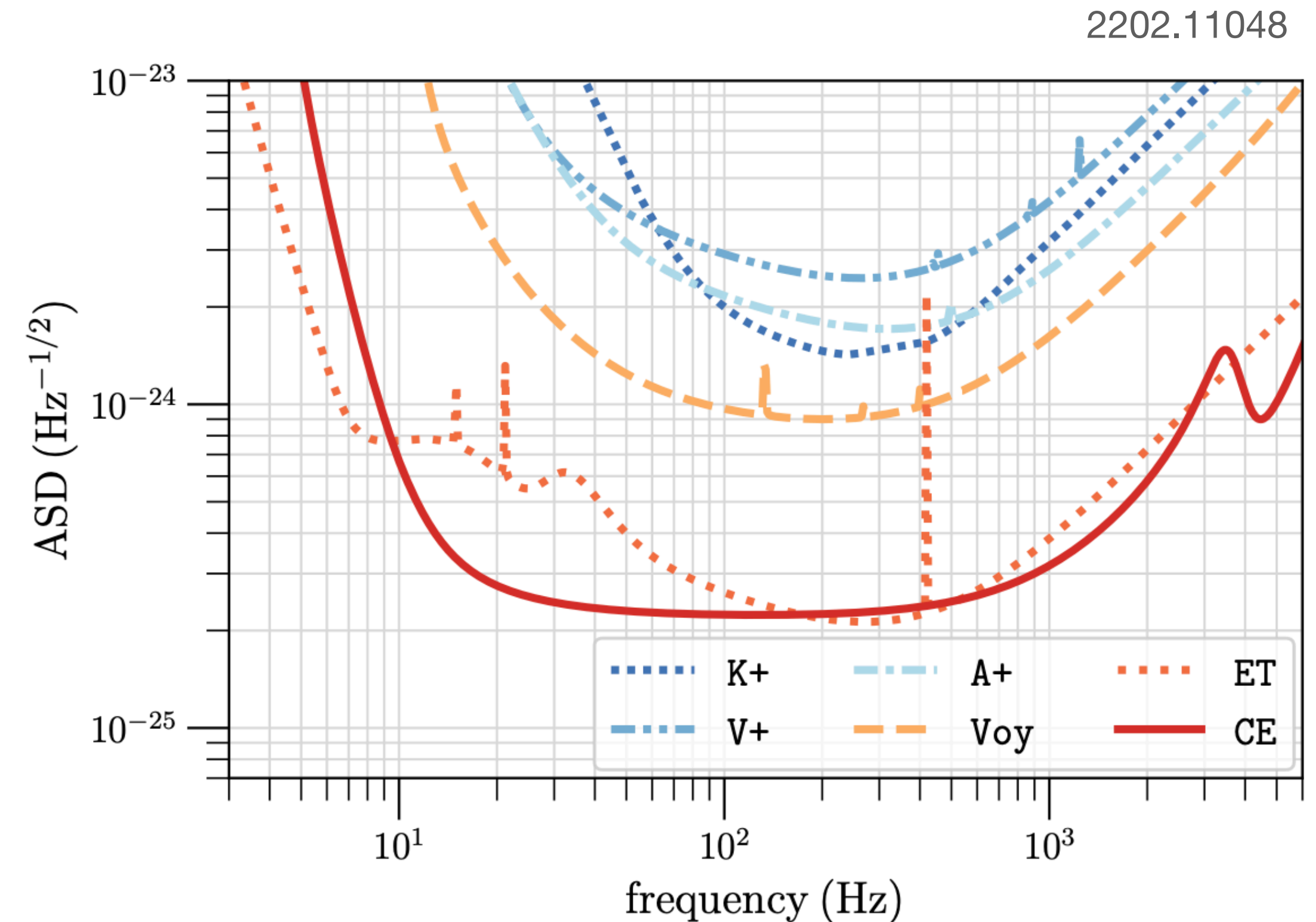
- Fisher Matrix approach to estimate the errors on measured $\tilde{\Lambda}$ using GWBench.
- BBH population with $m_1, m_2 \in [1M_\odot, 2M_\odot]$ upto a redshift of 10.

Component mass, m_1 and m_2	$[1, 2] M_\odot$
Tidal Parameters ^a , Λ_1 and Λ_2	2.0
Effective tidal parameter, $\tilde{\Lambda}$	$(6q^2 + q + 6)\Lambda_1/(13q)$
Right ascension, α	$[0, 2\pi)$
Declination, δ	$[-\pi/2, \pi/2]$
Inclination, ι	$[0, \pi]$
Polarization, ψ	$[0, 2\pi]$
Redshift, z	$[0, 10]$

Measurement of $\tilde{\Lambda}$

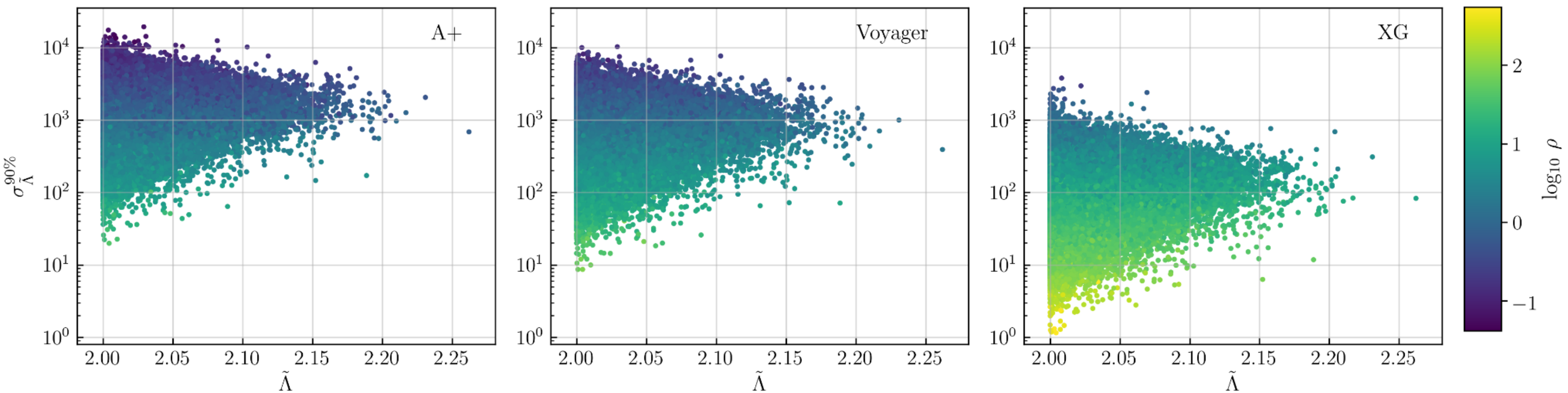
Detector Networks

- **A+** : LIGO-Hanford, LIGO-Livingston, Virgo, KAGRA and LIGO-Aundh at A+ sensitivity
- **Voyager**: The Voyager network consists of LIGO-Hanford, LIGO-Livingston and LIGO-Aundh at Voyager sensitivity, with Virgo and KAGRA at A+ sensitivities.
- **XG**: the XG network includes the Einstein Telescope, one Cosmic Explorer in the US, and another Cosmic Explorer in Australia



Measurement of $\tilde{\Lambda}$

Detectability and differentiability



Measurement of $\tilde{\Lambda}$

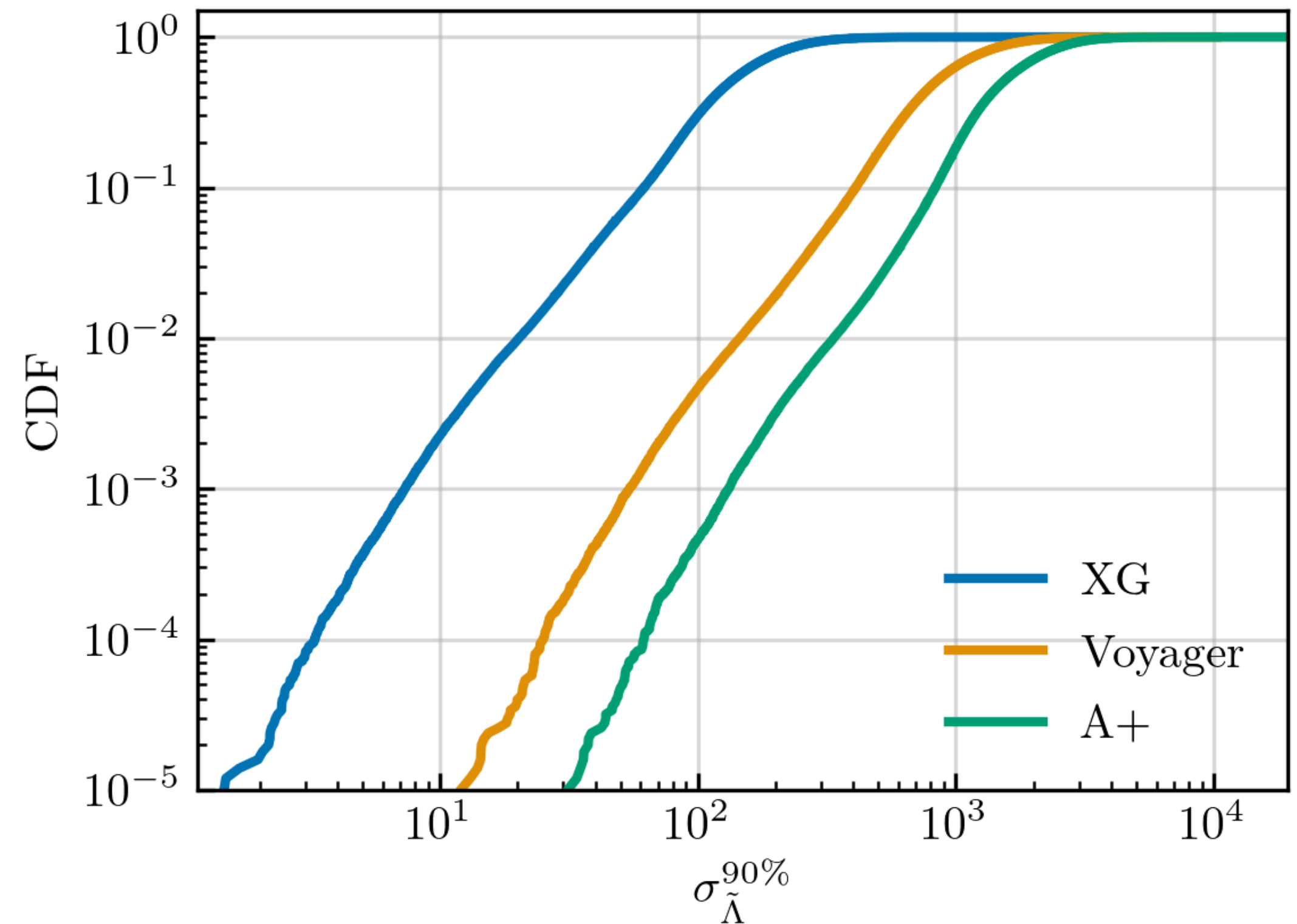
Differentiability

At an assumed threshold of $\sigma_{\tilde{\Lambda}}^{90\%} = 100$, fraction of events that can be confidently classified as BBH

- A+ : 0.05%
- Voyager : 0.5%
- XG : 30%

XG can measure $\tilde{\Lambda}$ to an accuracy of ~ 200 for $>90\%$ sources.

Only XG measures $\tilde{\Lambda}$ to better than $\sigma_{\tilde{\Lambda}}^{90\%} < 20$.

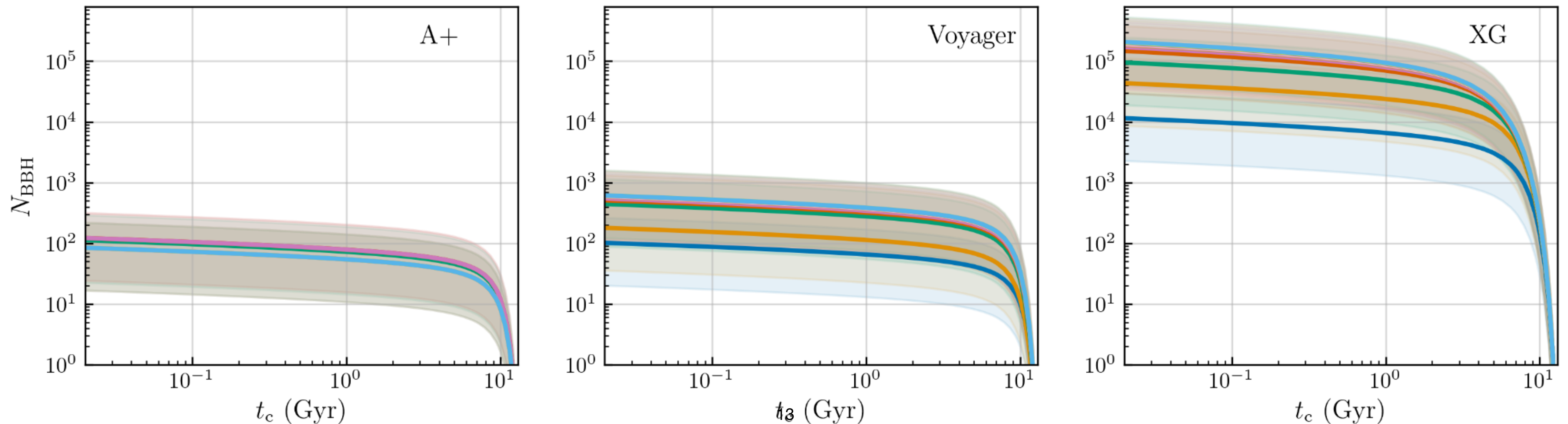


Observed Merger rate

Including detestability and differentiability in total merger rate

$$\dot{N}_{\text{obs}} = \int_0^z \frac{\dot{n}(z')}{1+z'} \frac{dV_c}{dz'} \epsilon(z') dz', \quad \epsilon(z) = \frac{1}{N} \sum_{i=1}^N \Pi\left(\frac{\rho}{\rho_T} - 1 \mid z\right) \Pi\left(\frac{\sigma_{\tilde{\Lambda}_T}}{\sigma_{\tilde{\Lambda}}} - 1 \mid z\right)$$

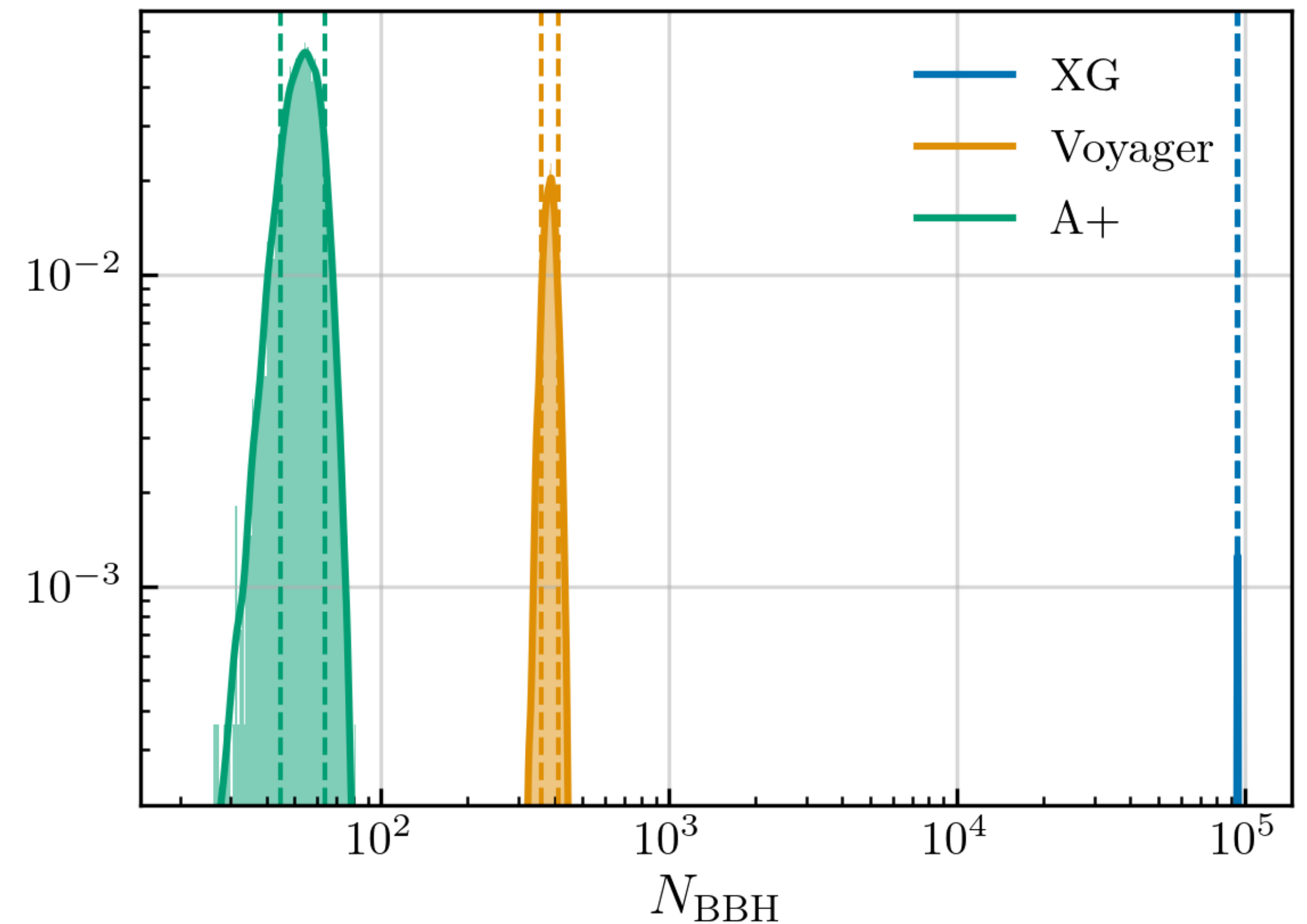
$$\rho_T = 10, \quad T_{\text{obs}} = 5 \text{ yrs}$$



Inference of collapse time

Illustrative example

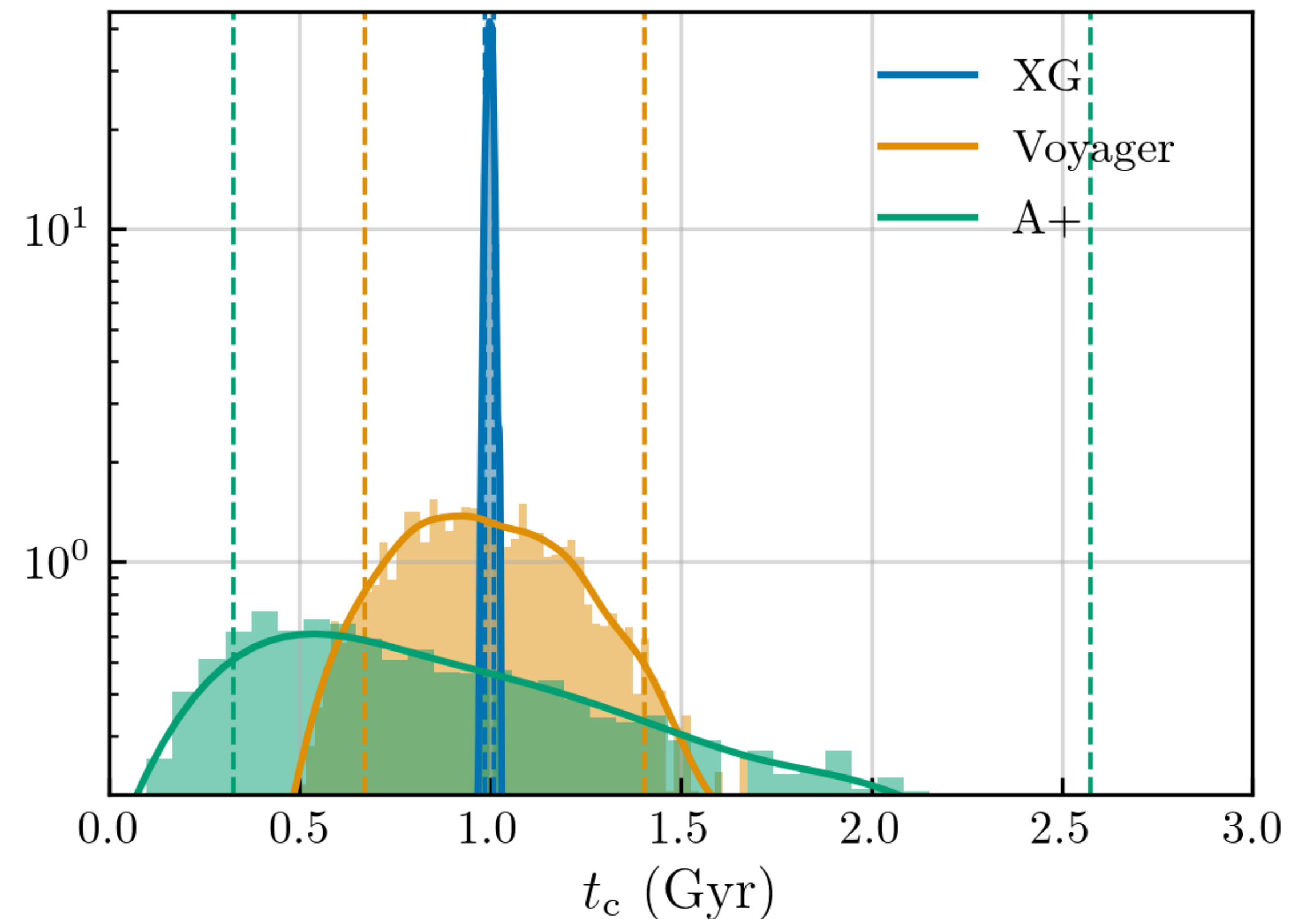
- Distribution of observed number of BBH merger computed for a fiducial collapse time, $t_c = 1\text{Gyr}$.
- As expected, the number of observable events is multiple orders of magnitude higher for XG, with smaller relative errors.



Inference of collapse time

Illustrative example

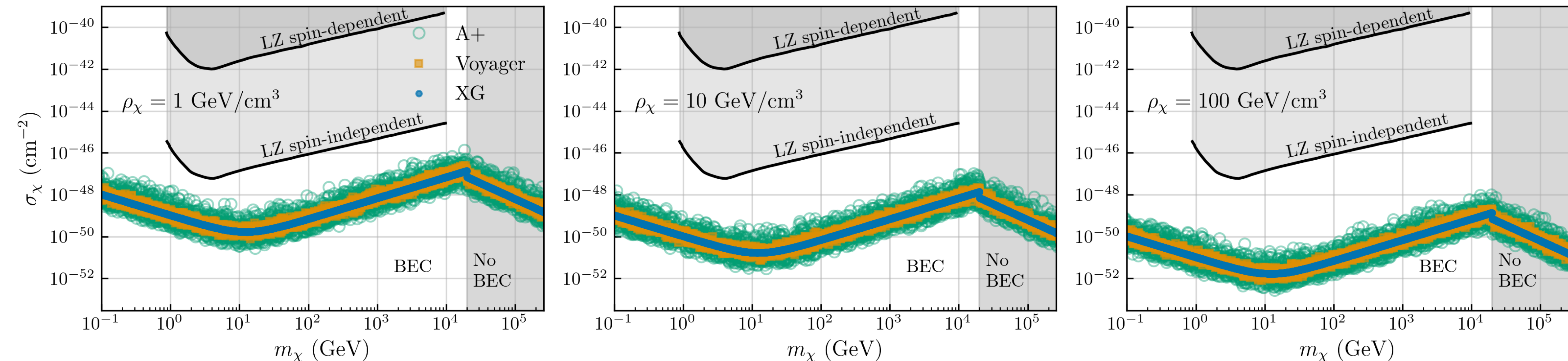
- Use interpolation to determine collapse time from observed N_{BBH} .
- The larger fraction of systems that can be clearly identified as BBH helps in placing a tighter constraint on the collapse time.
- ***This inference is DM model agnostic.***



Limits on dark matter properties

Constraints on mass, m_χ and scattering cross-section, σ_χ

- The larger fraction of systems that can be clearly identified as BBH helps in placing a tighter constraint on the collapse time \rightarrow tighter constraints on dark matter mass and scattering cross-section.
- Tighter limits for regions with higher ambient dark matter density.
- Competitive with LZ limits over the entire range of m_χ .



To summarize

- Combination of measurements from GW observations with particle properties of DM, especially in the WIMP mass range, through the observation (or lack thereof) of a novel population of BBHs in the BNS mass range.
- XG detectors would definitely be able to observe such a population if it exists due to higher sensitivities and the accuracy in the measurement of the effective tidal deformability parameter.
- Constrain or rule out models of DM that allow for such a formation scenario for BBH with GW observations.
- Exciting science case for XG GW detectors!

CHALLENGES

- Neutron stars are contaminated by dark matter particles but don't necessarily collapse to black holes.
- Could bias the inference of nuclear EOS.
- Distribution of tidal deformability will be unusual and inexplicable and this could be a hint of the contamination.
- How do we infer DM properties if neutron stars are just contaminated and their EOS is simply modified?
- More theoretical and data analysis work is needed to resolve these issues.