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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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

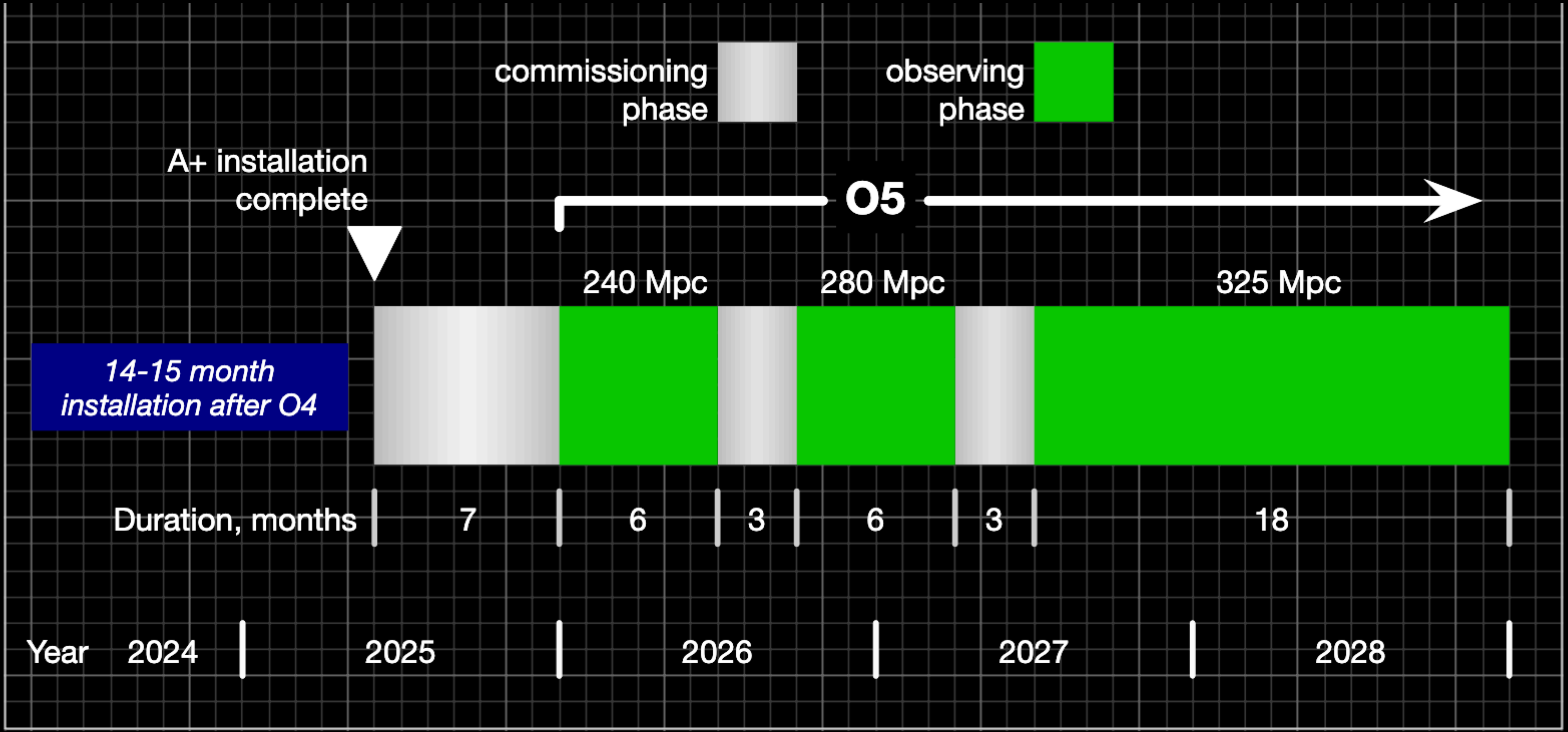
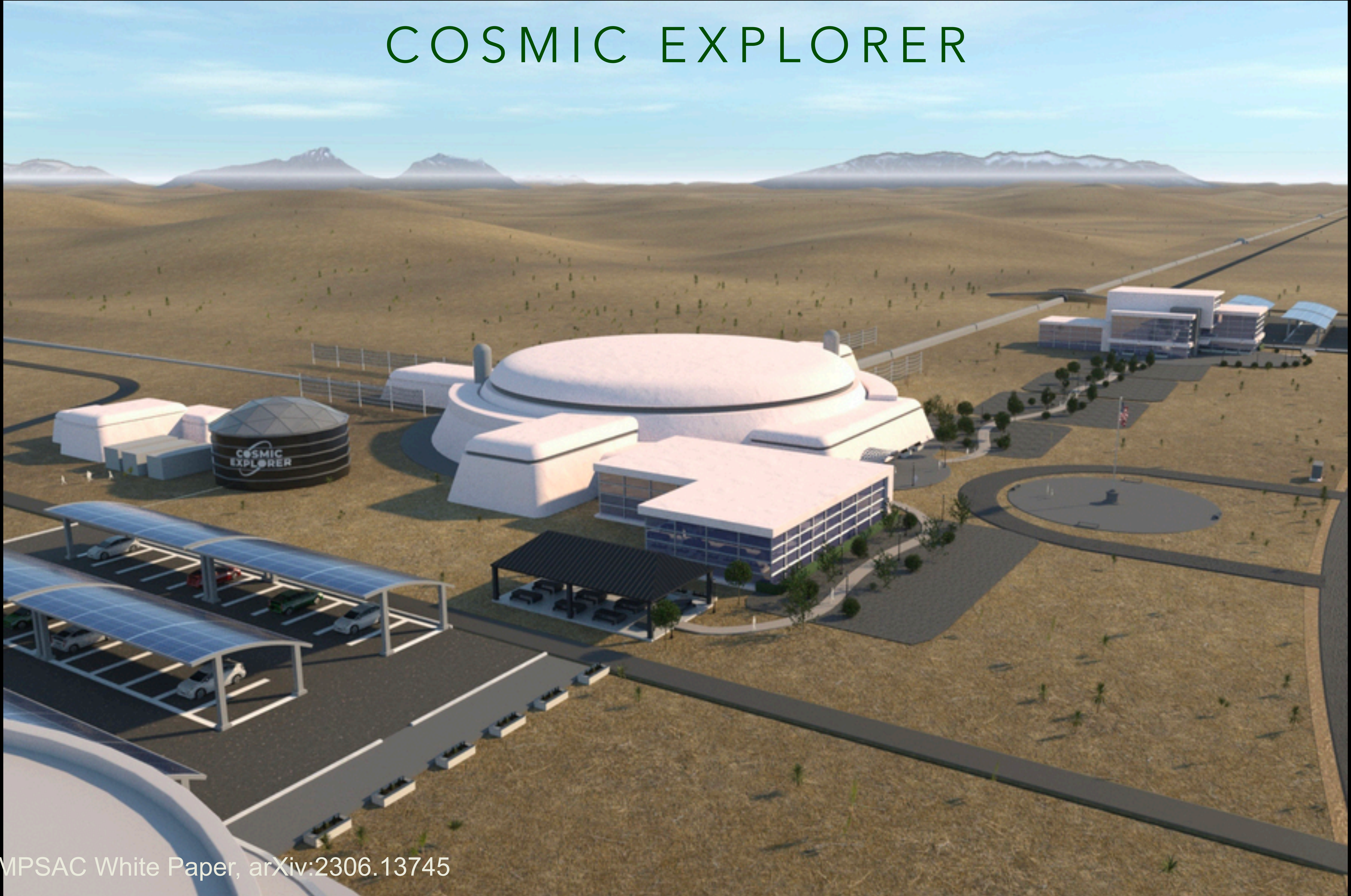


Figure 3: Proposed O5 timeline, with O5 ending at the end of 2028.

LIGO INDIA


Einstein
Telescope

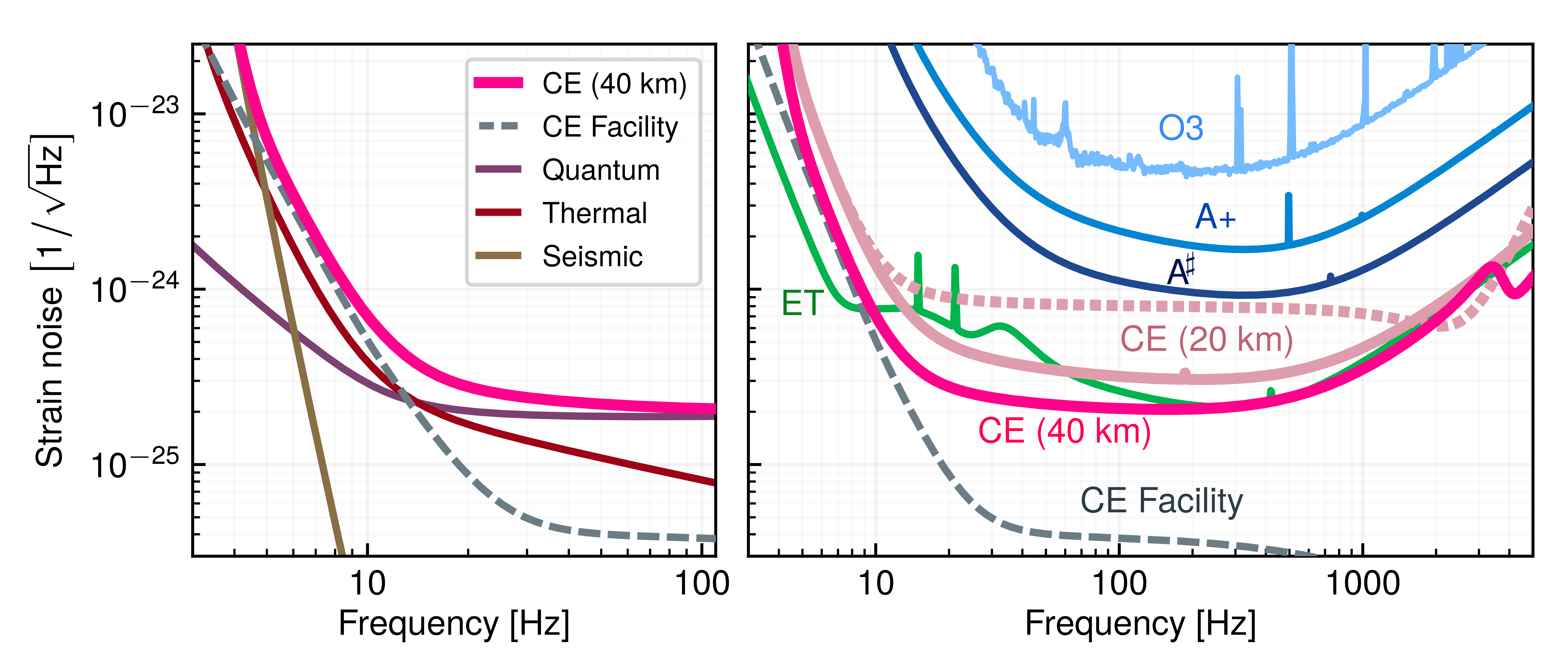
COSMIC EXPLORER



Evans+, MPSAC White Paper, arXiv:2306.13745

A# AND XG NETWORKS

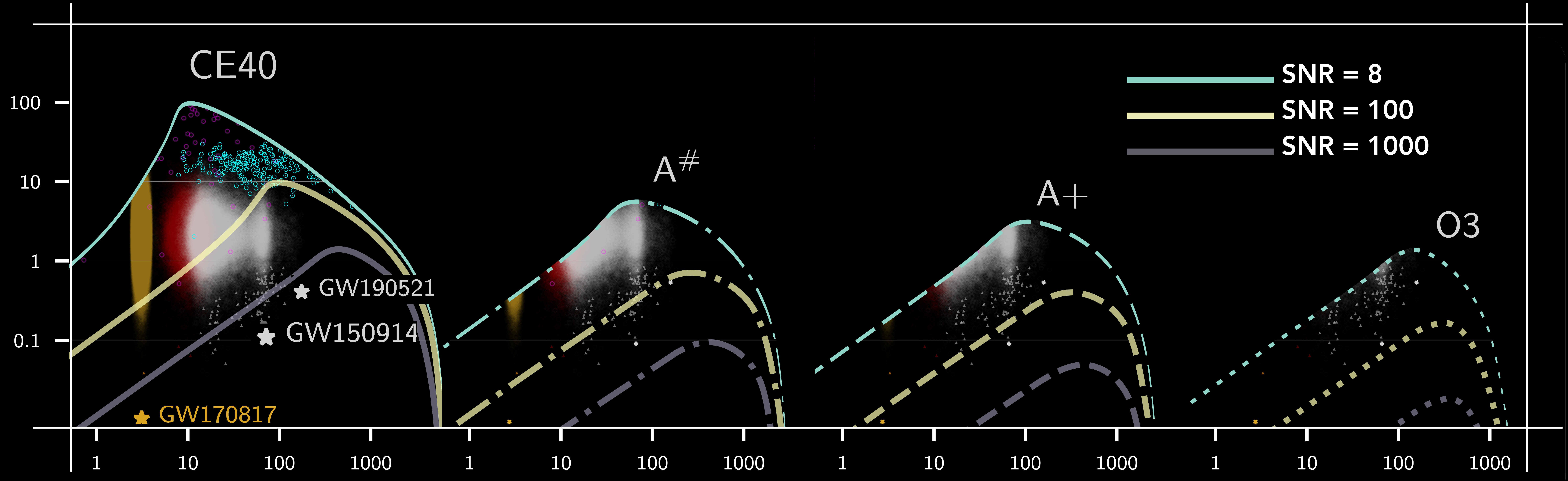
- HLA: LIGO Hanford, Livingston and India in A# (or Voyager) configuration
- CE40LA: CE40 together with LIGO Livingston and LIGO India in A# configuration
- CE4020ET: Two Cosmic Explorer detectors, one 40 km, another 20 km with ET



Evans+, MPSAC White Paper, arXiv:2306.13745

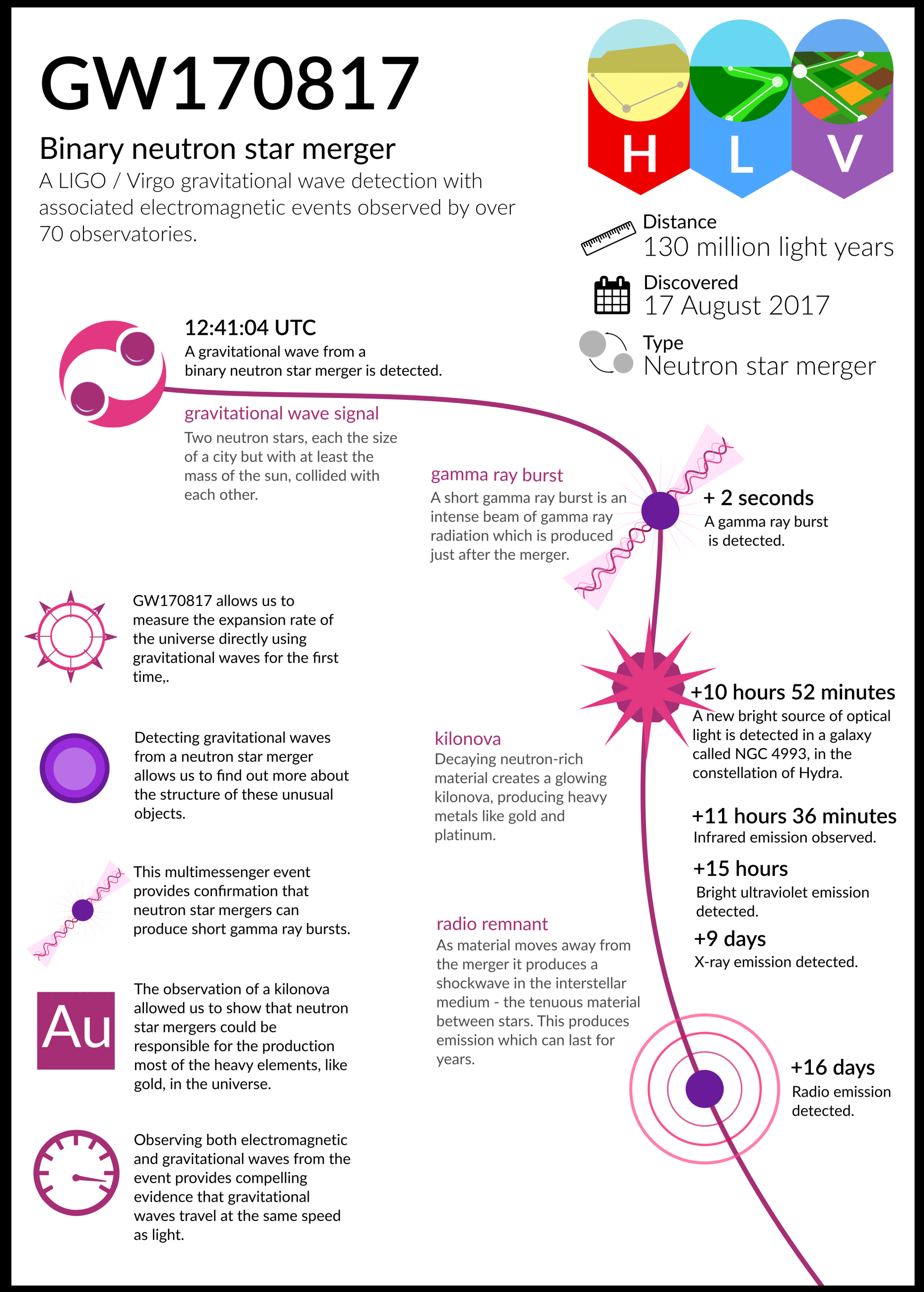
COMPARATIVE REACH: FROM O3 TO XG

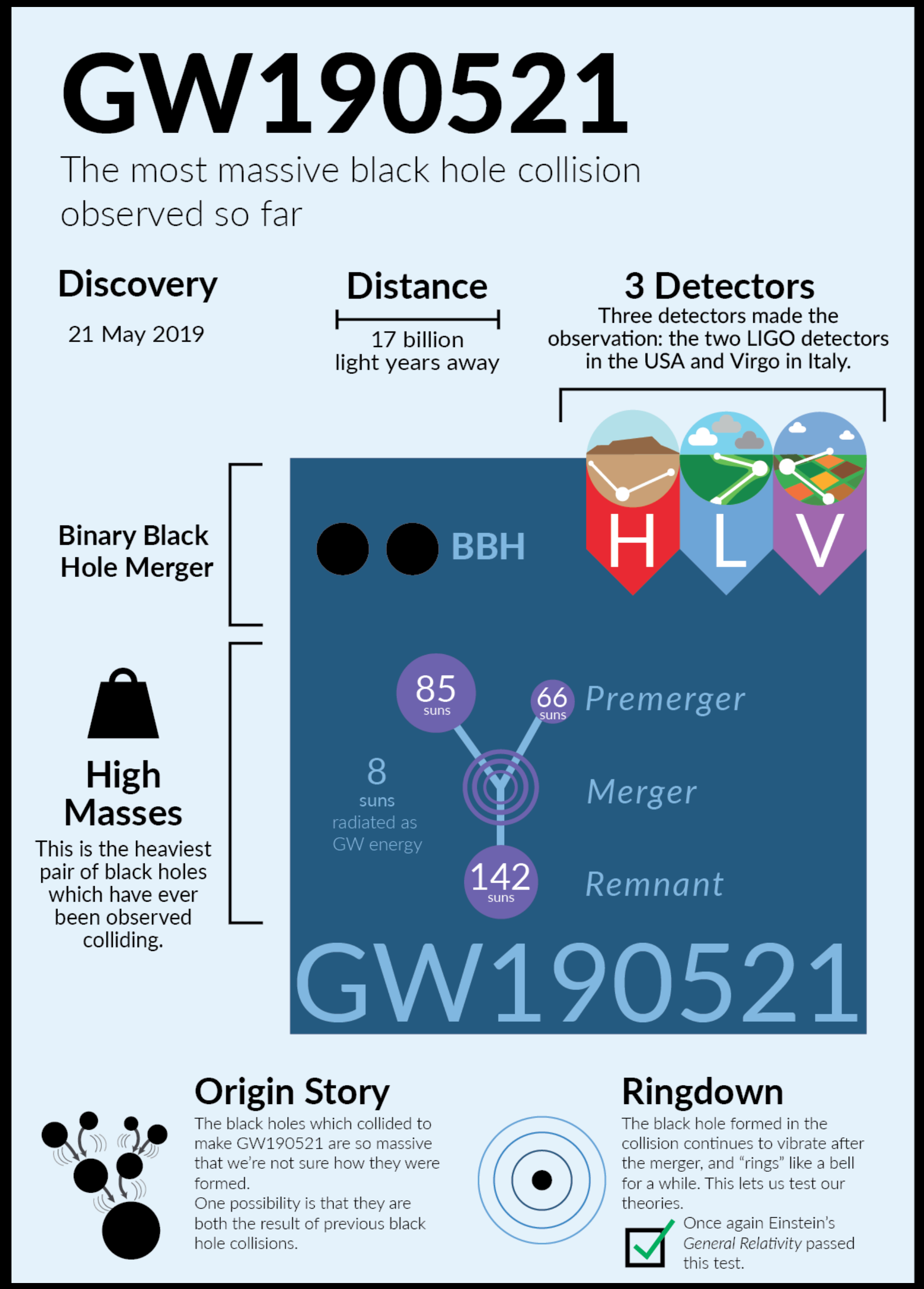
redshift v total mass

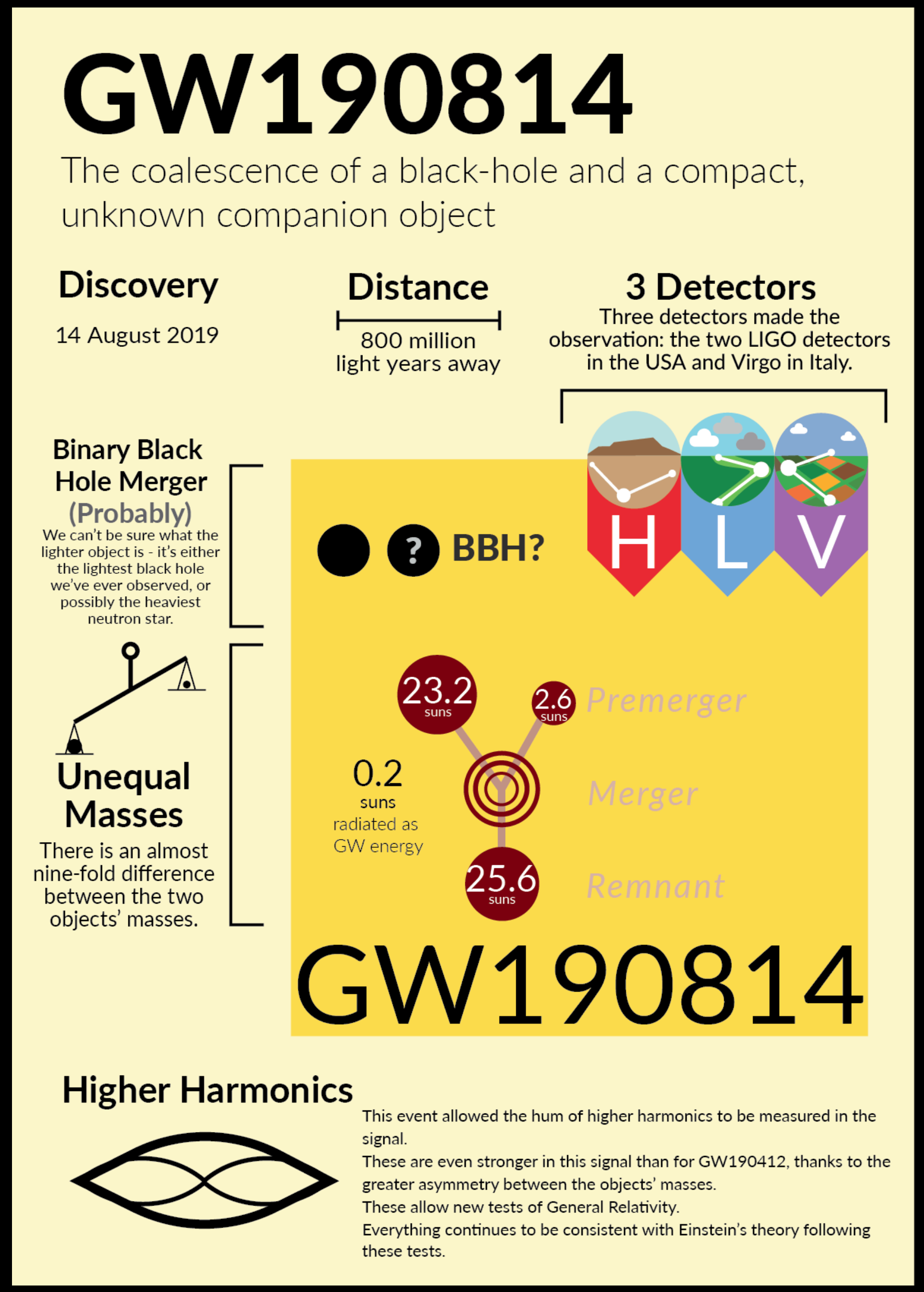


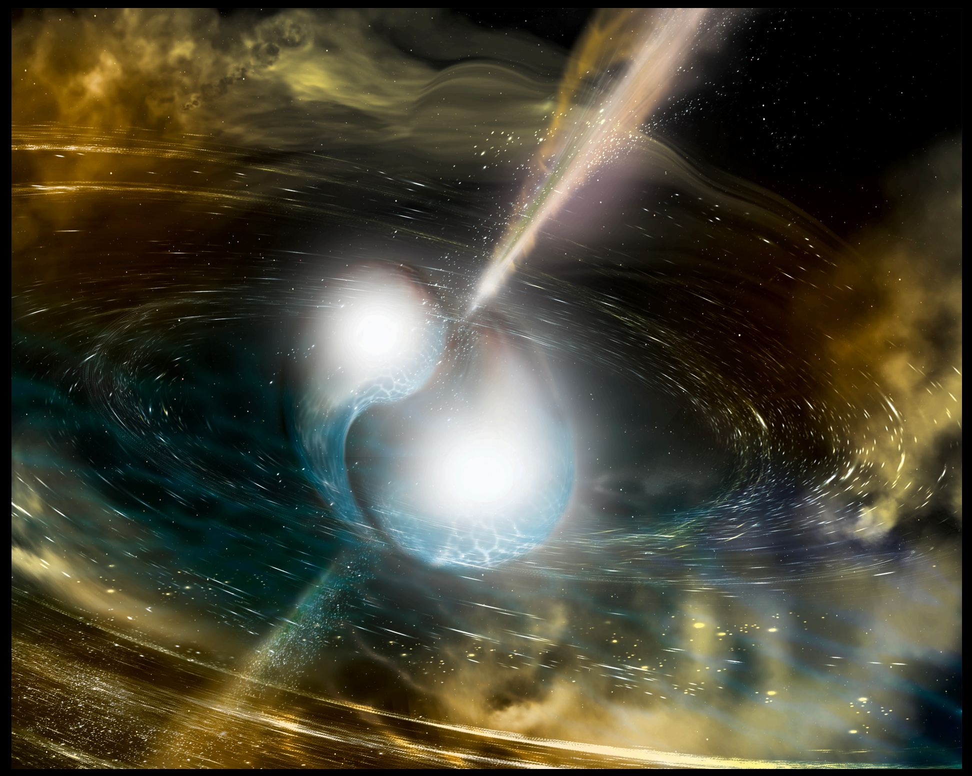
Evans+, MPSAC White Paper, arXiv:2306.13745

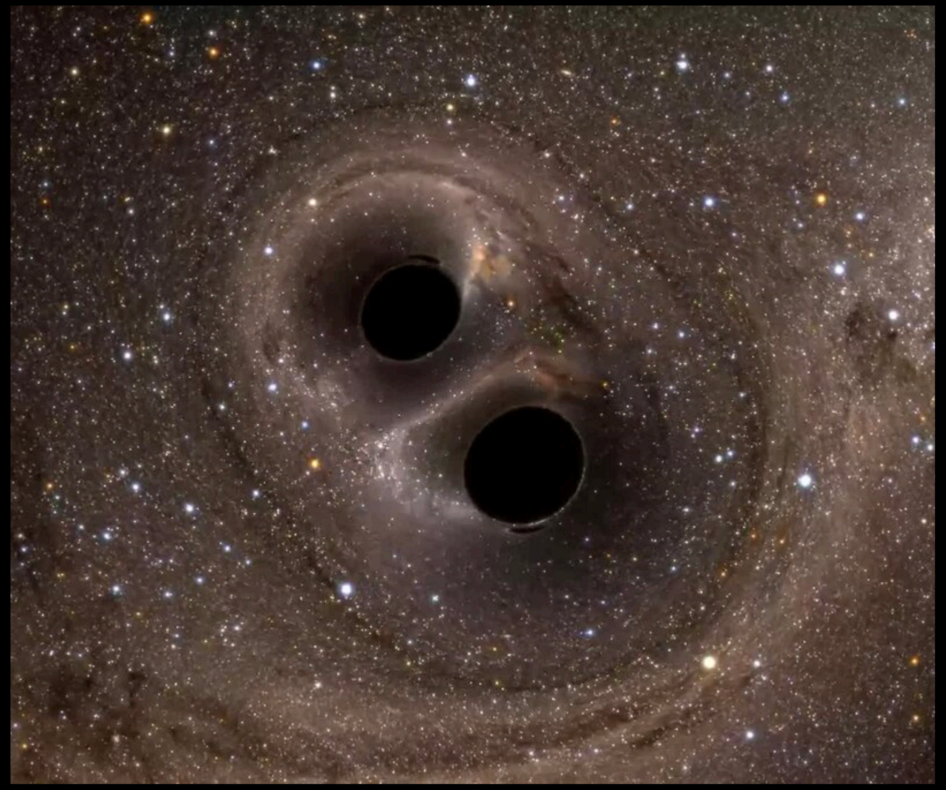
EXCEPTIONAL EVENTS IN A# AND CE

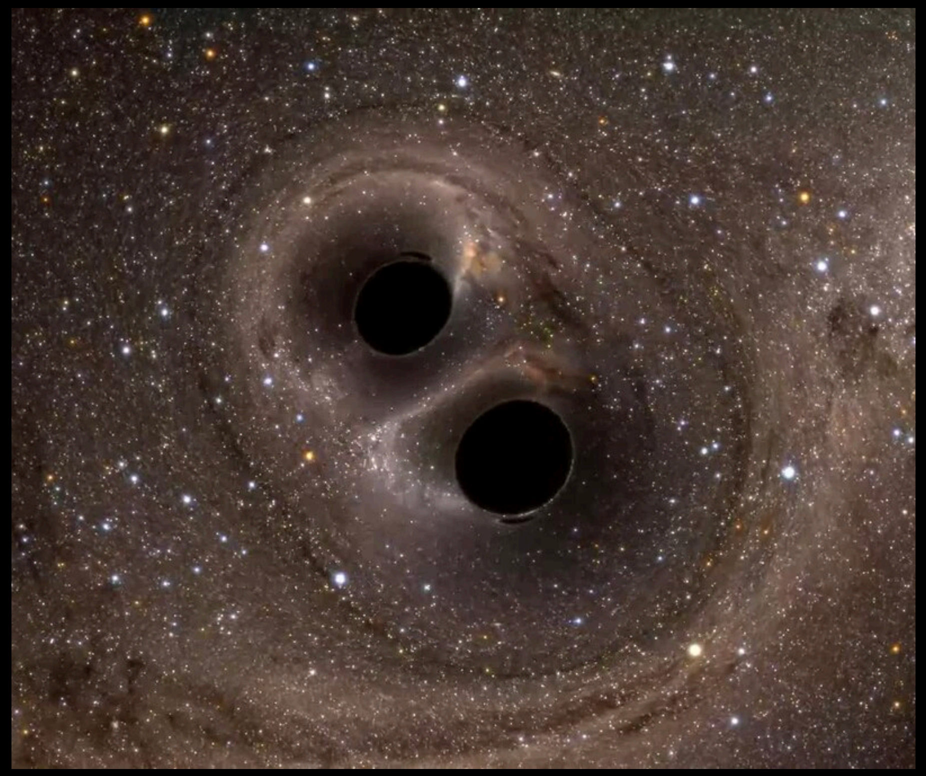


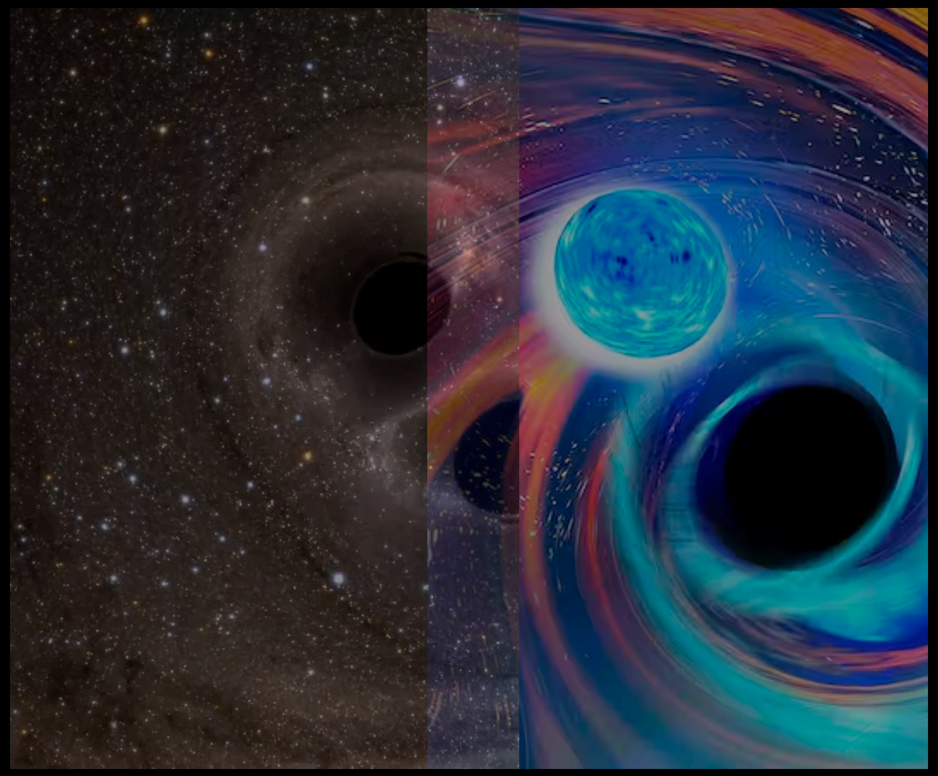


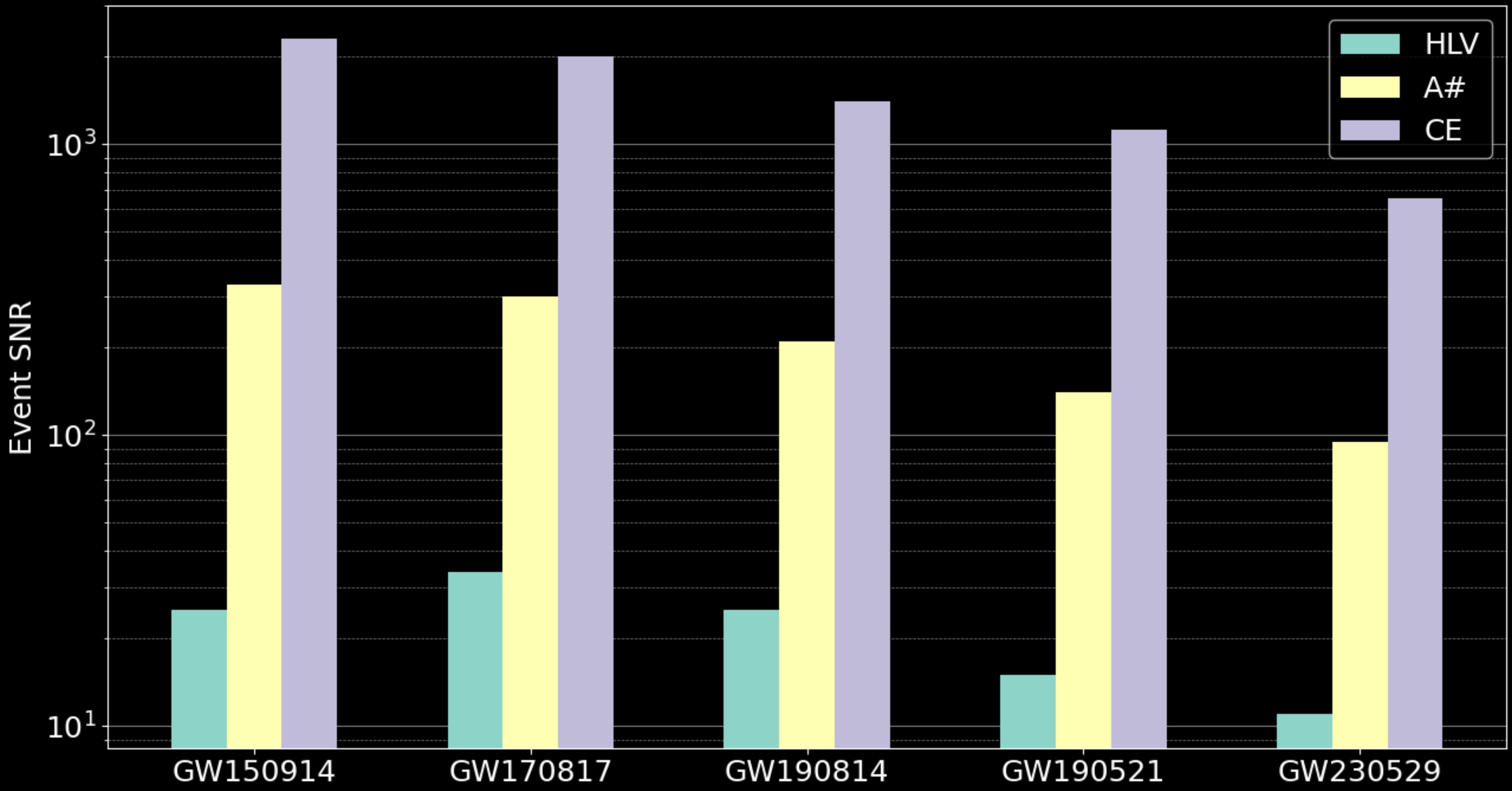






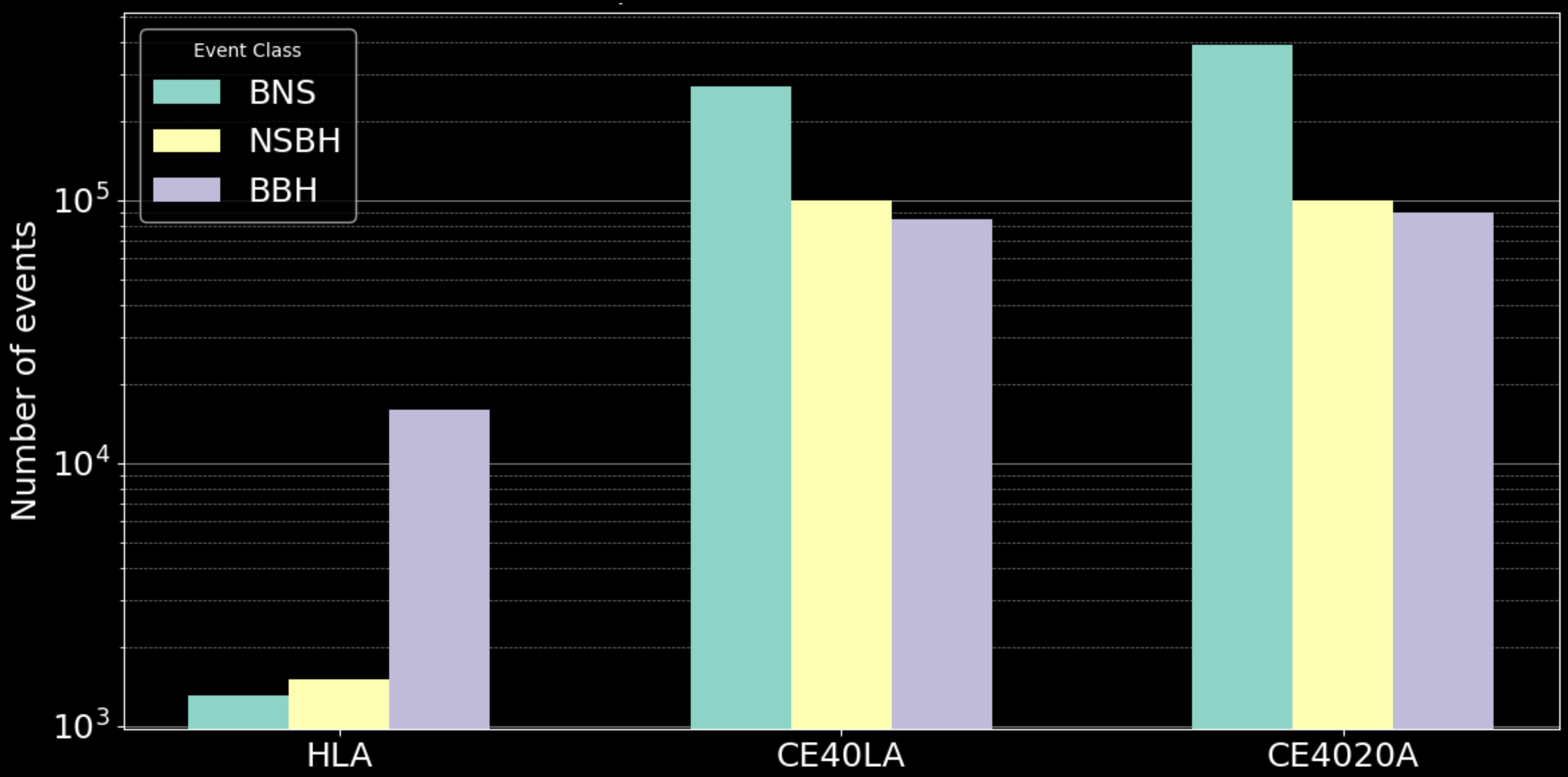




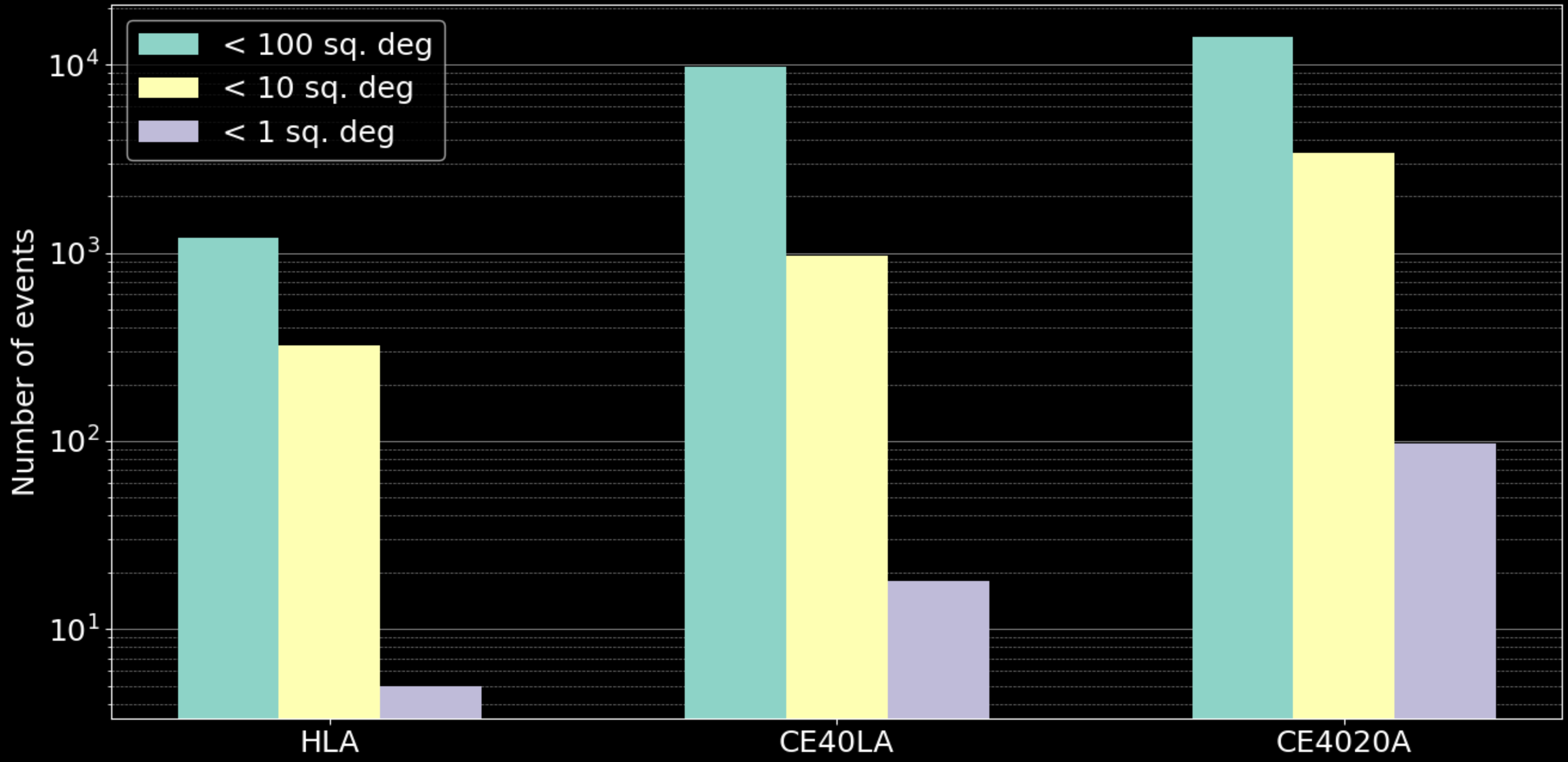


HLV
A#
CE
Event SNR
10^3
10^2
10^1
GW150914
GW170817
GW190814
GW190521
GW230529

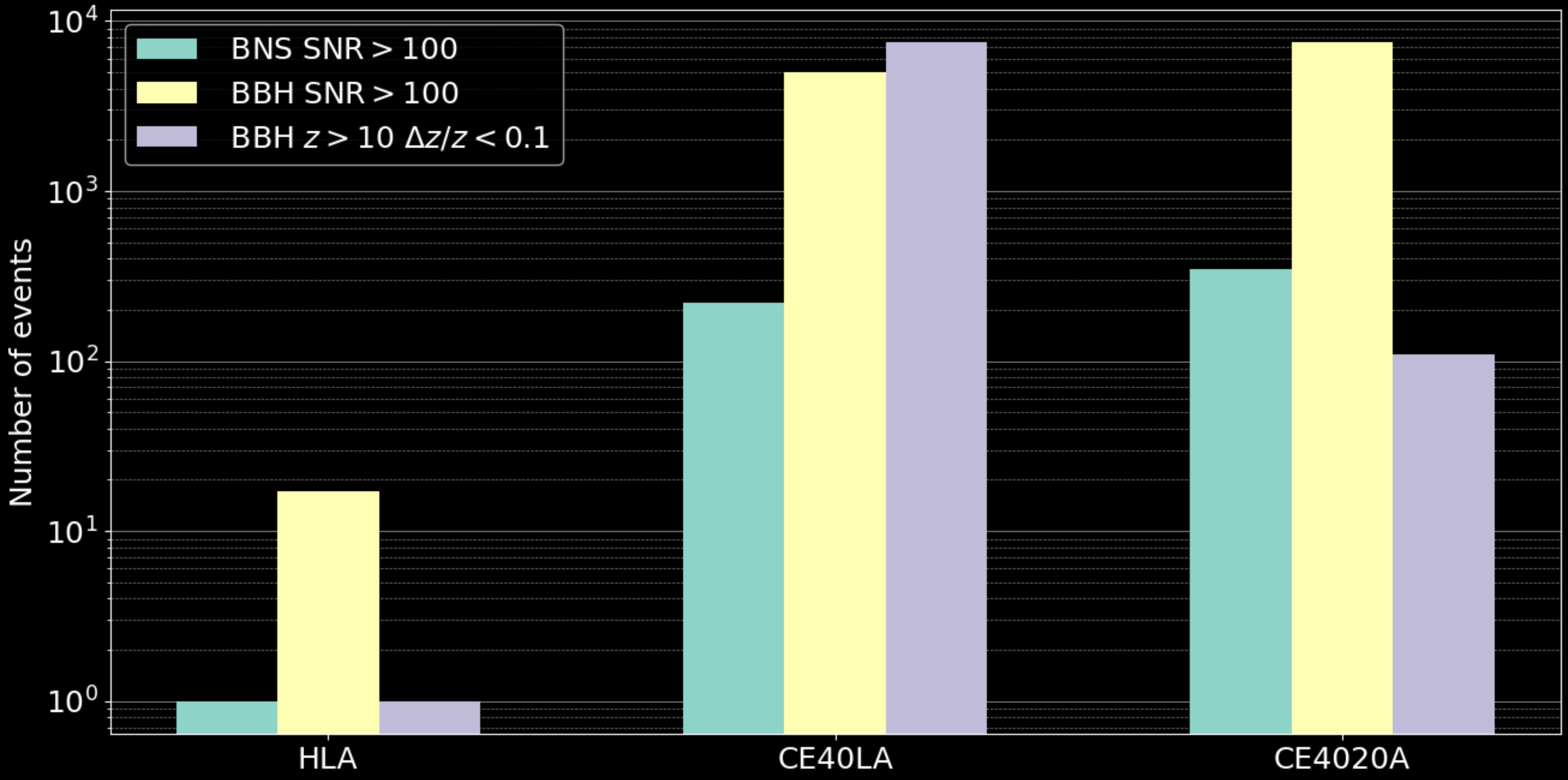
ANNUAL DETECTIONS



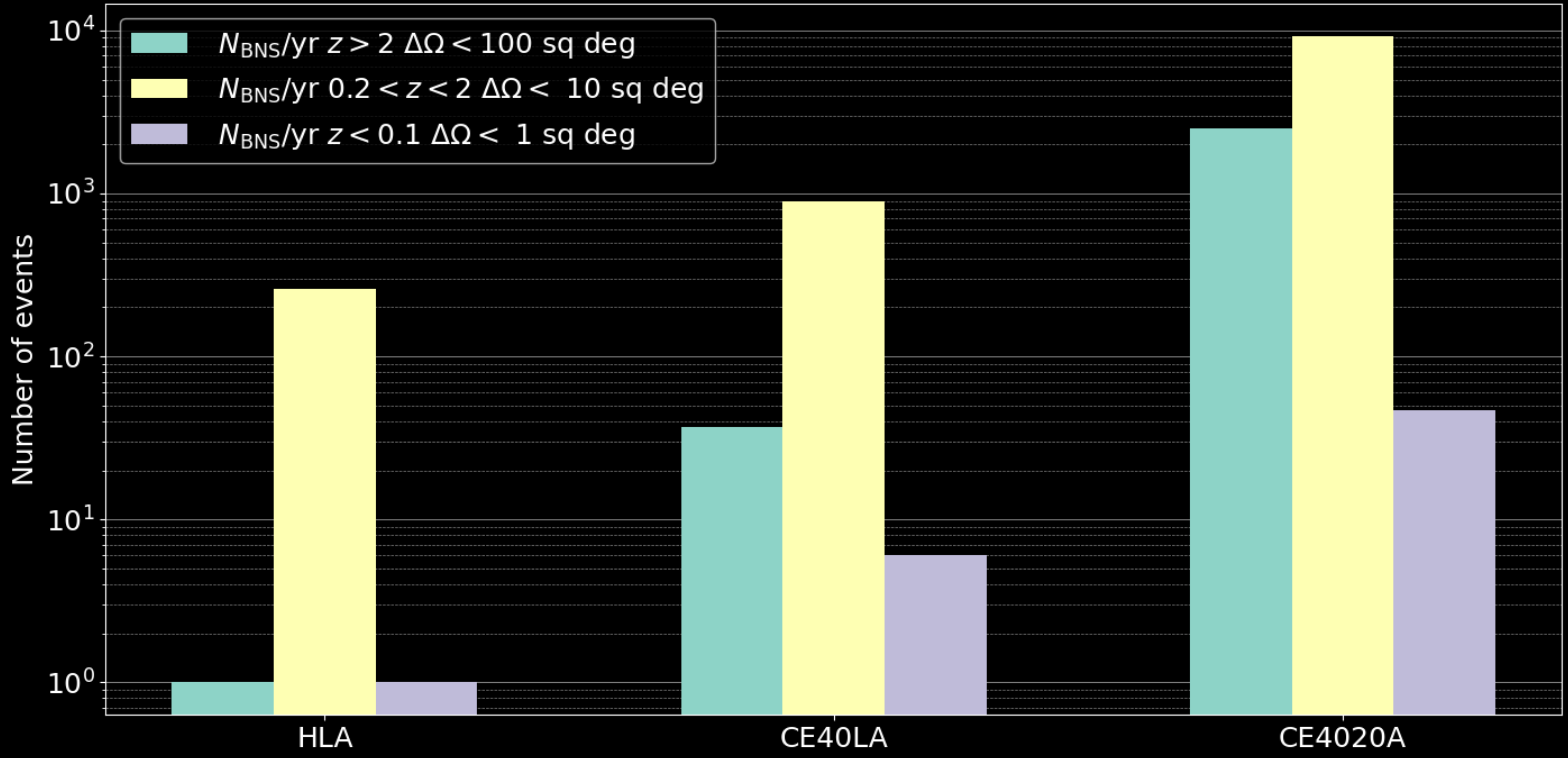
WELL-LOCALIZED BNS SOURCES



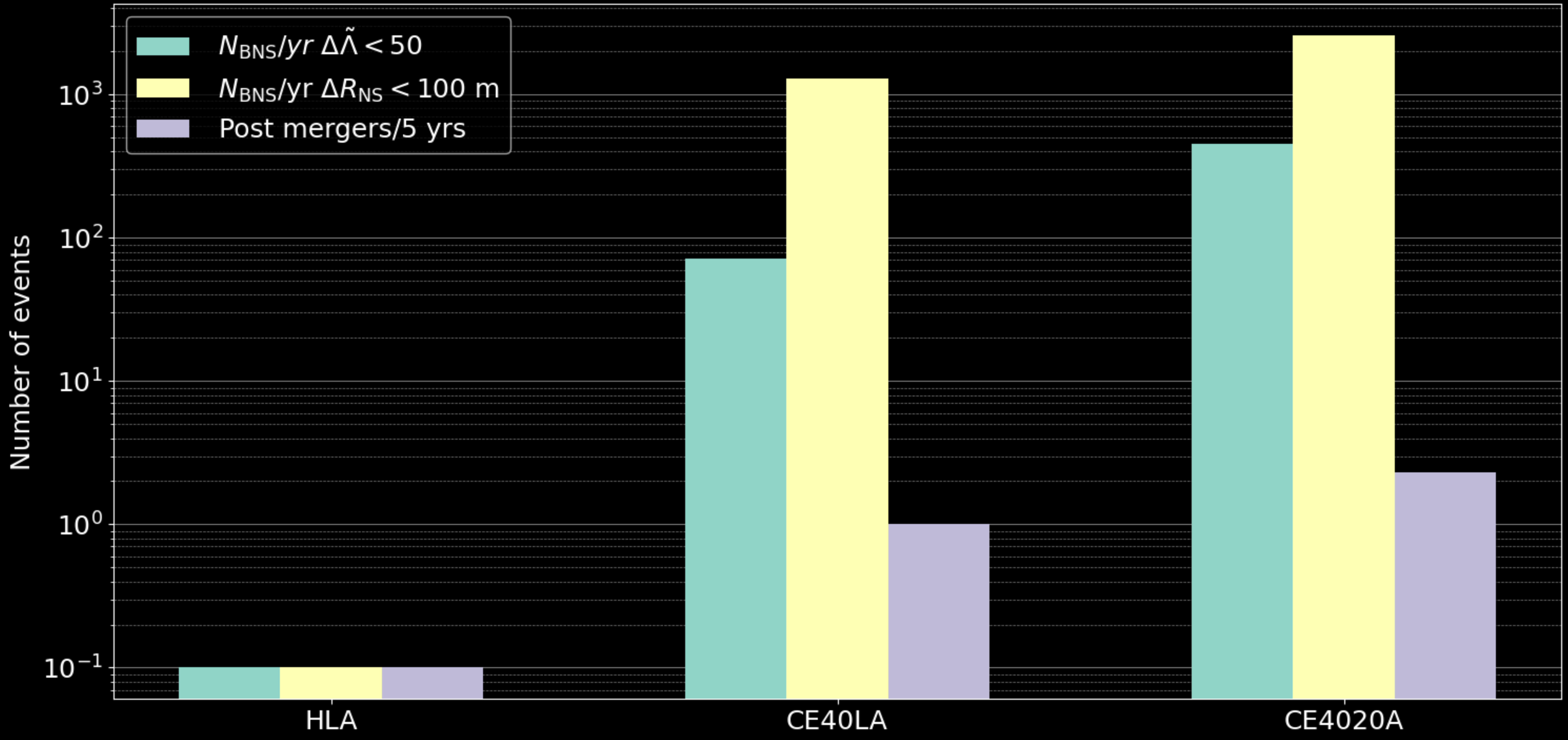
HIGH FIDELITY EVENTS



ASTROPHYSICS OF ULTRA-RELATIVISTIC SOURCES



DENSE MATTER EQUATION OF STATE



CONSTRAINING NEUTRON STAR MASS-RADIUS RELATIONSHIP

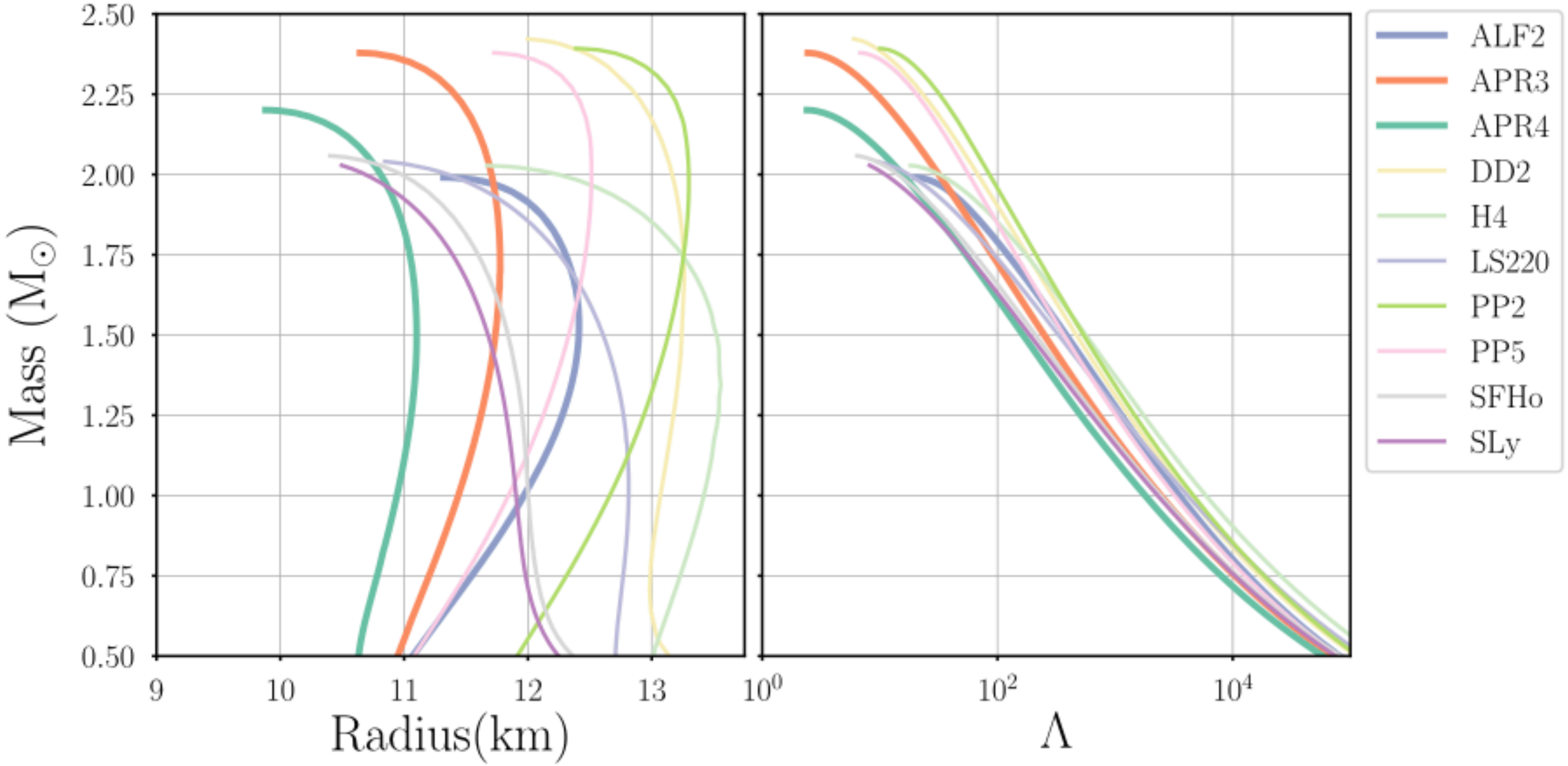
Use Universal Relations to Resolve Individual Tidal Deformabilities

Huxford+ PRD 109 (2024) 10, 103035; Kashyap+ PRD 106 (2022) 12, 123001; Khadkikar+ in preparation

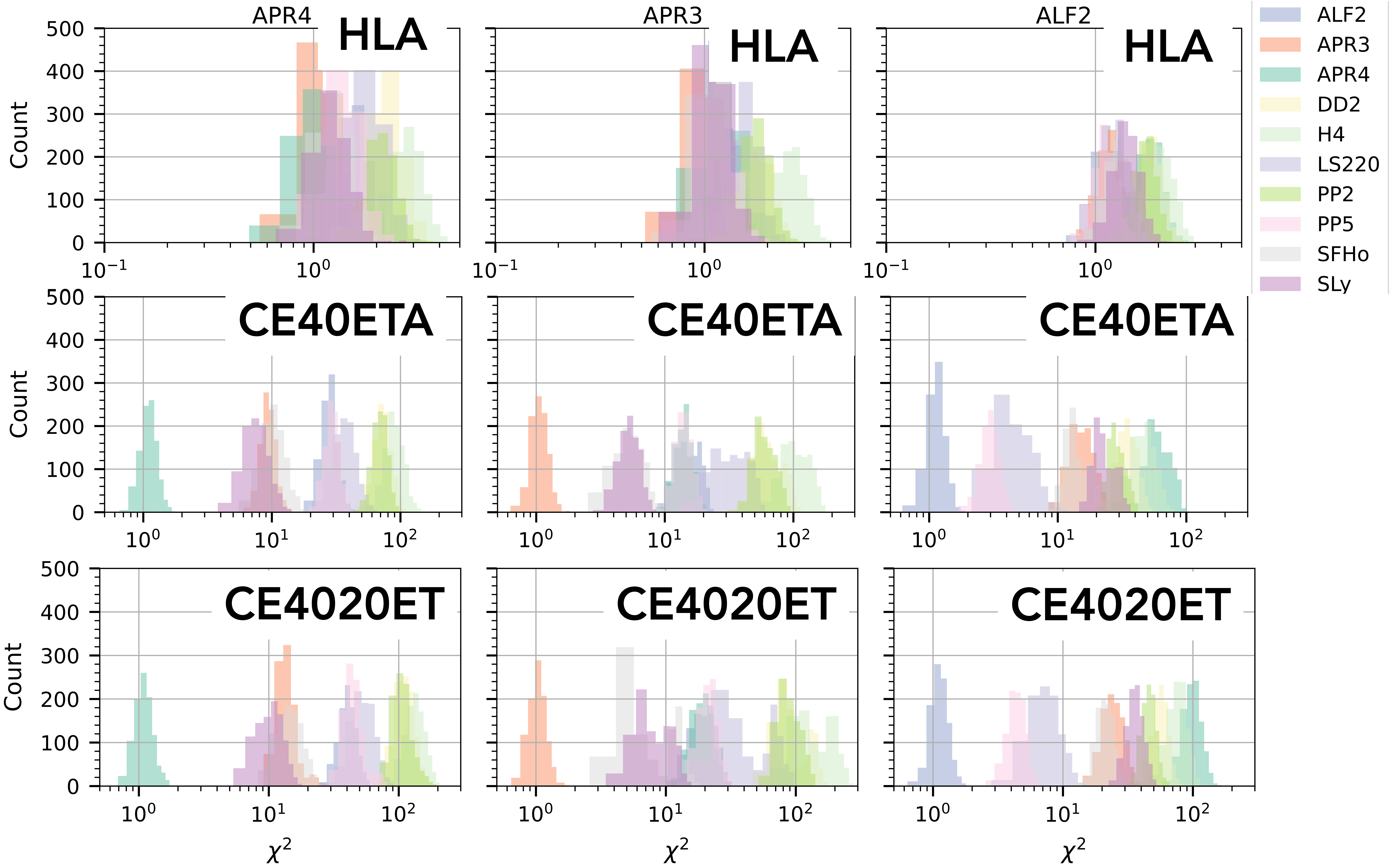
STRATEGY TO EVALUATE CAPABILITIES OF XG OBSERVATORIES

- 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



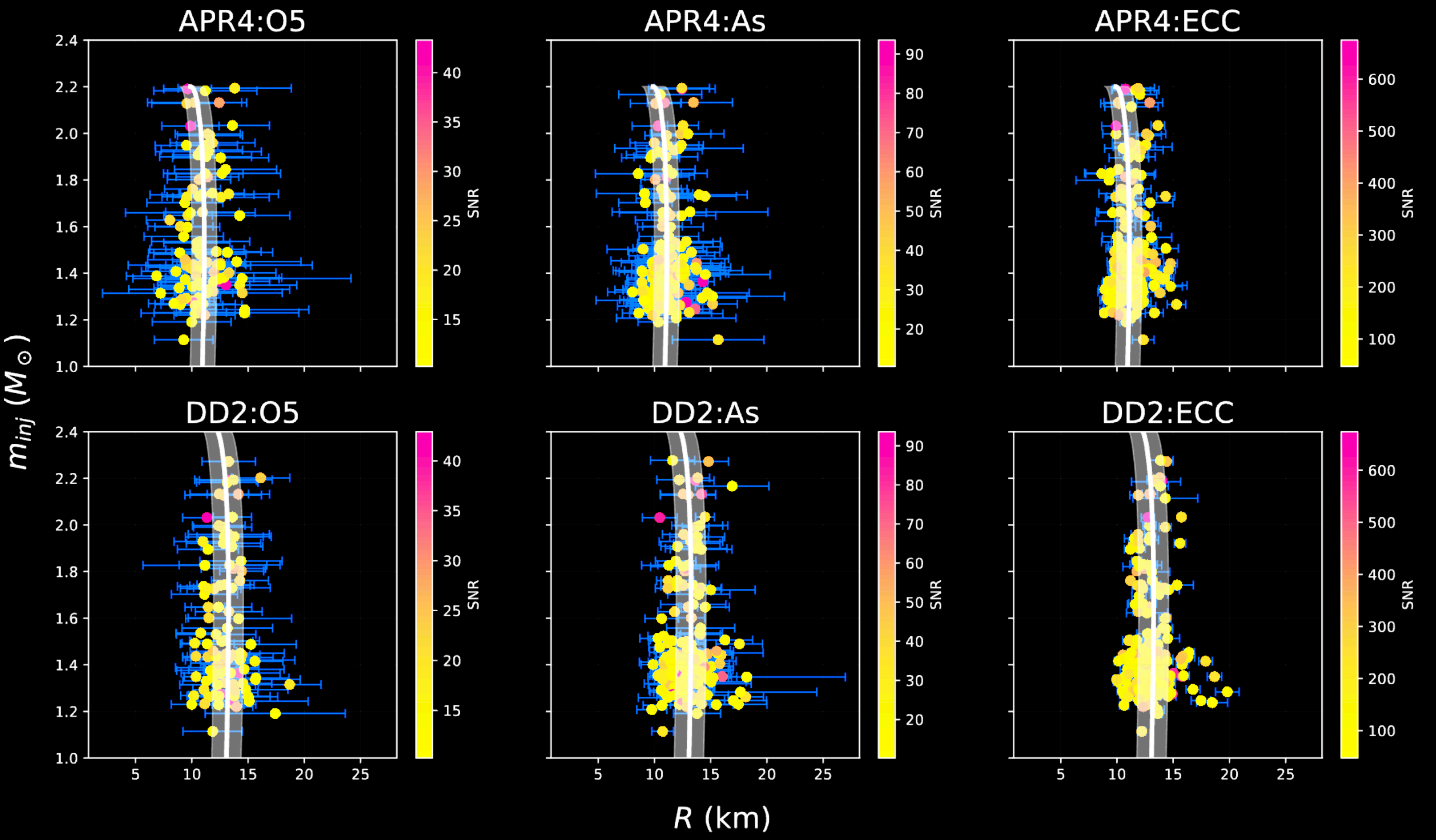
RELATIVE PERFORMANCE OF NETWORKS



APR4
HLA
APR3
HLA
ALF2
HLA
CE40ETA
CE40ETA
CE40ETA
CE4020ET
CE4020ET
CE4020ET
Count
Count
Count
χ^2
χ^2
χ^2
ALF2
APR3
APR4
DD2
H4
LS220
PP2
PP5
SFHo
SLy

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 ~ two orders of magnitude better than where we are now.

CONSTRAIN PROPERTIES OF WIMP DARK MATTER

Black Holes Have Zero Tidal Deformability

Singh+ PRD 107 (2023) 8, 083037

DARK MATTER INDUCED IMPLOSION OF NEUTRON STARS

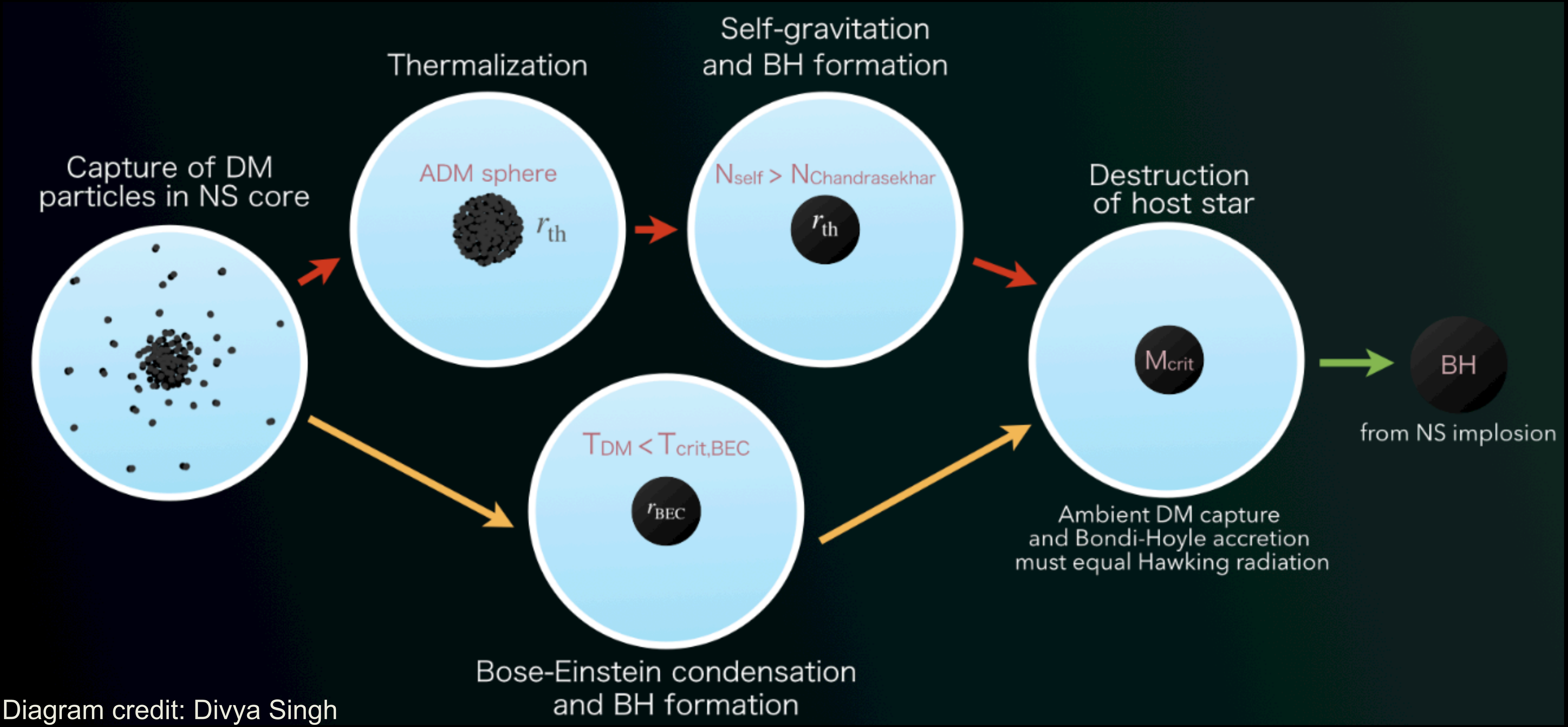


Diagram credit: Divya Singh

Merger rate density

Relative abundances

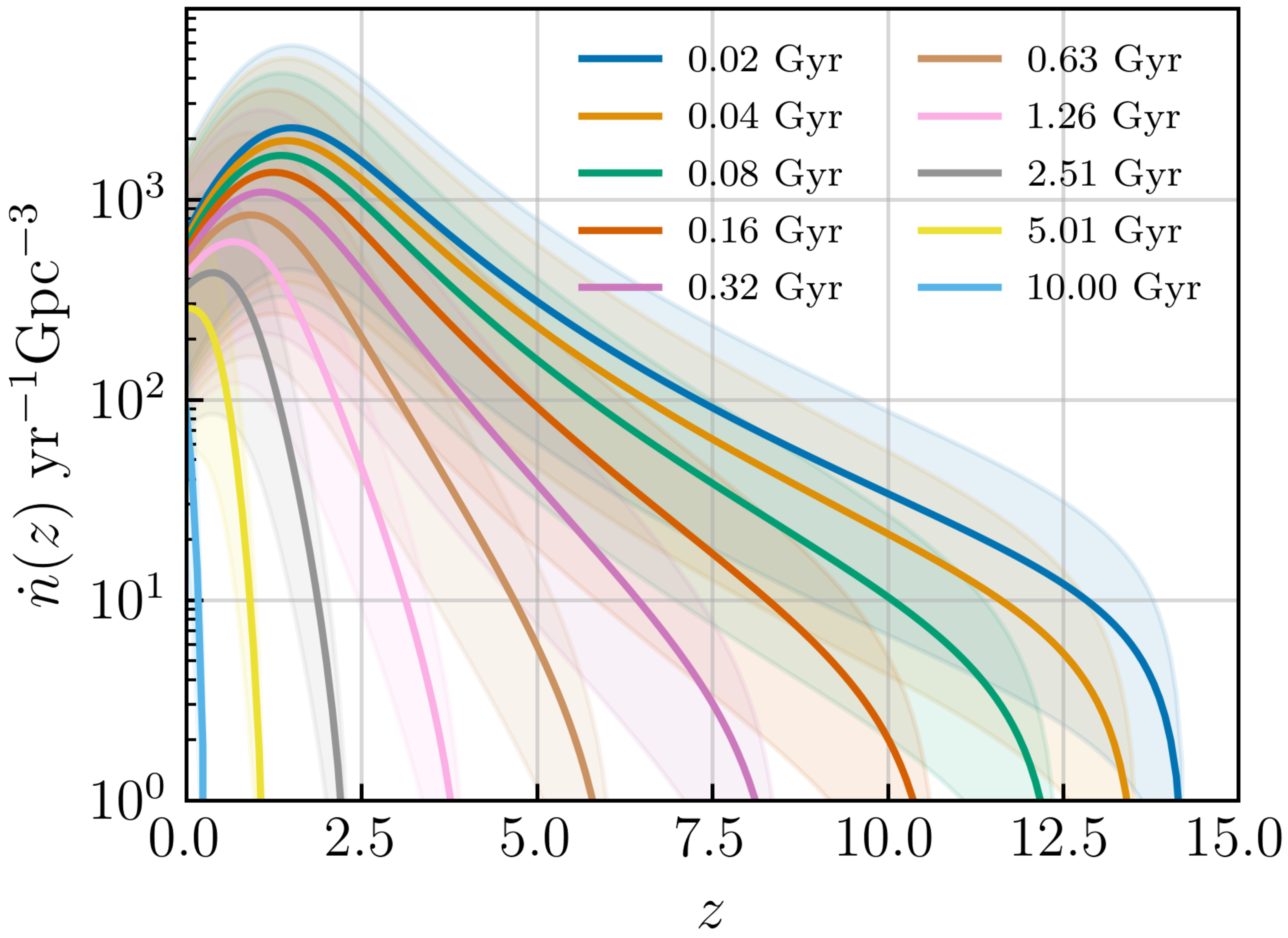
$$\dot{n}(z) = A \int_{t_d^{\min}}^{t_d^{\max}} \psi(z_f(z, t_d))\mathscr{P}(t_d)\, dt_d$$

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

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

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

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



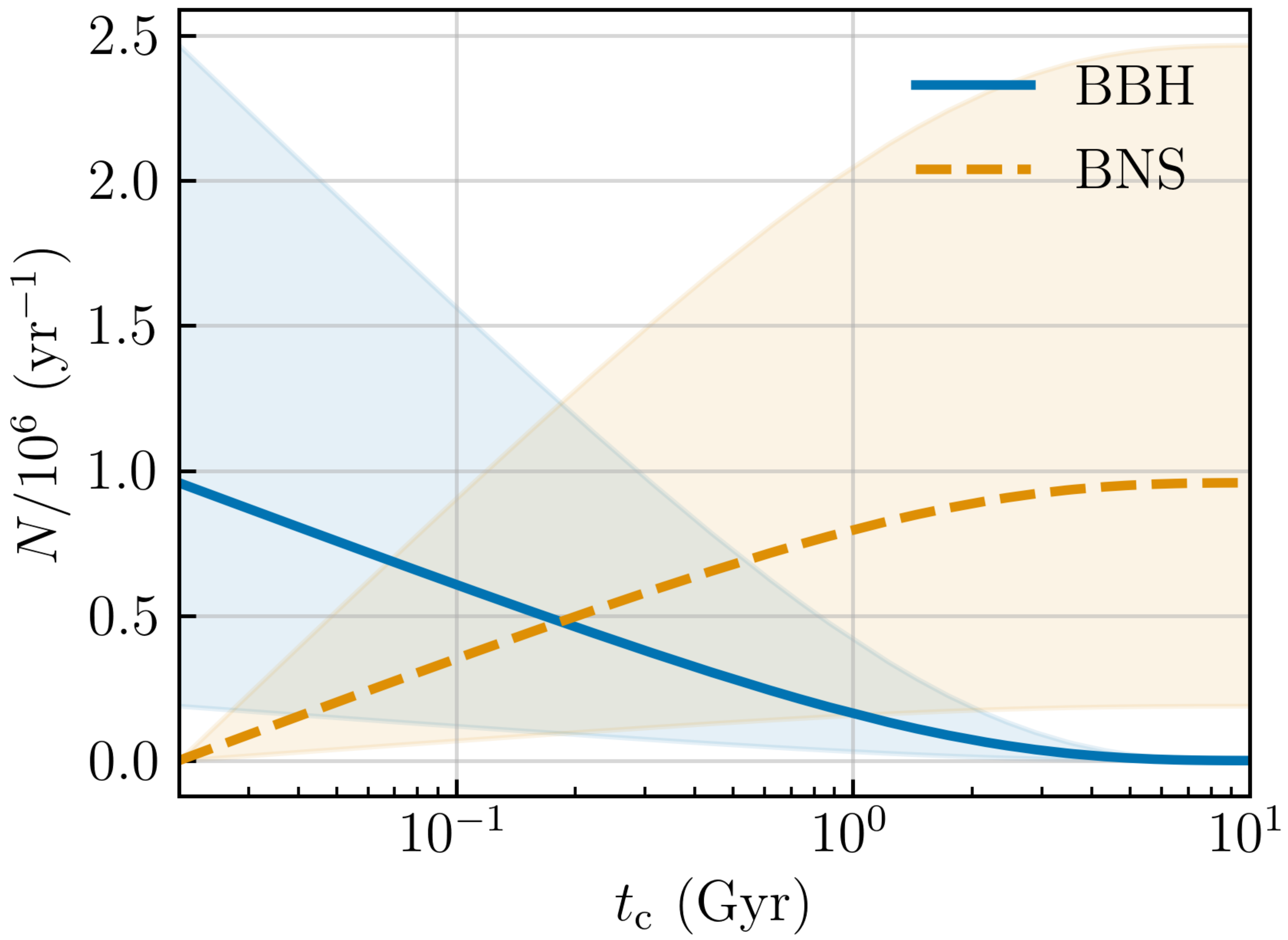
Total merger rate

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 ~ 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,** $\tilde{\Lambda}$
  - $\tilde{\Lambda}_{\mathrm{BBH}} = 0$
  - $\tilde{\Lambda}_{\mathrm{BNS}} > 0$

Measuring $\tilde{\Lambda}$
Methods

- Fisher Matrix approach to estimate the errors on measured $\tilde{\Lambda}$ using GWBench.
- BBH population with $m1,\ m2 \in [1M_\odot,\ 2M_\odot]$ 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

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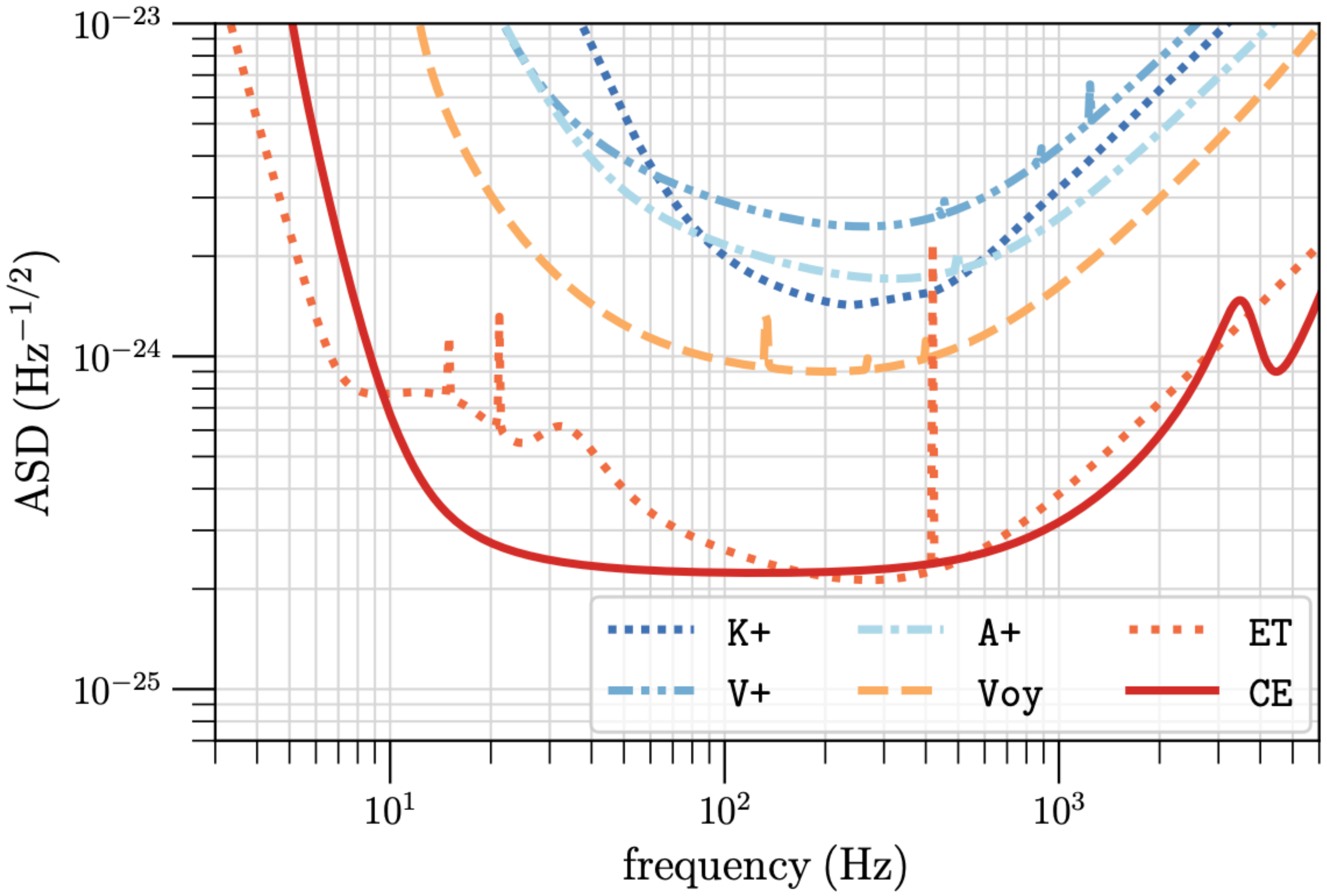


Measurement of $\tilde{\Lambda}$

Detectability and differentiability

Measurement of $\tilde{\Lambda}$

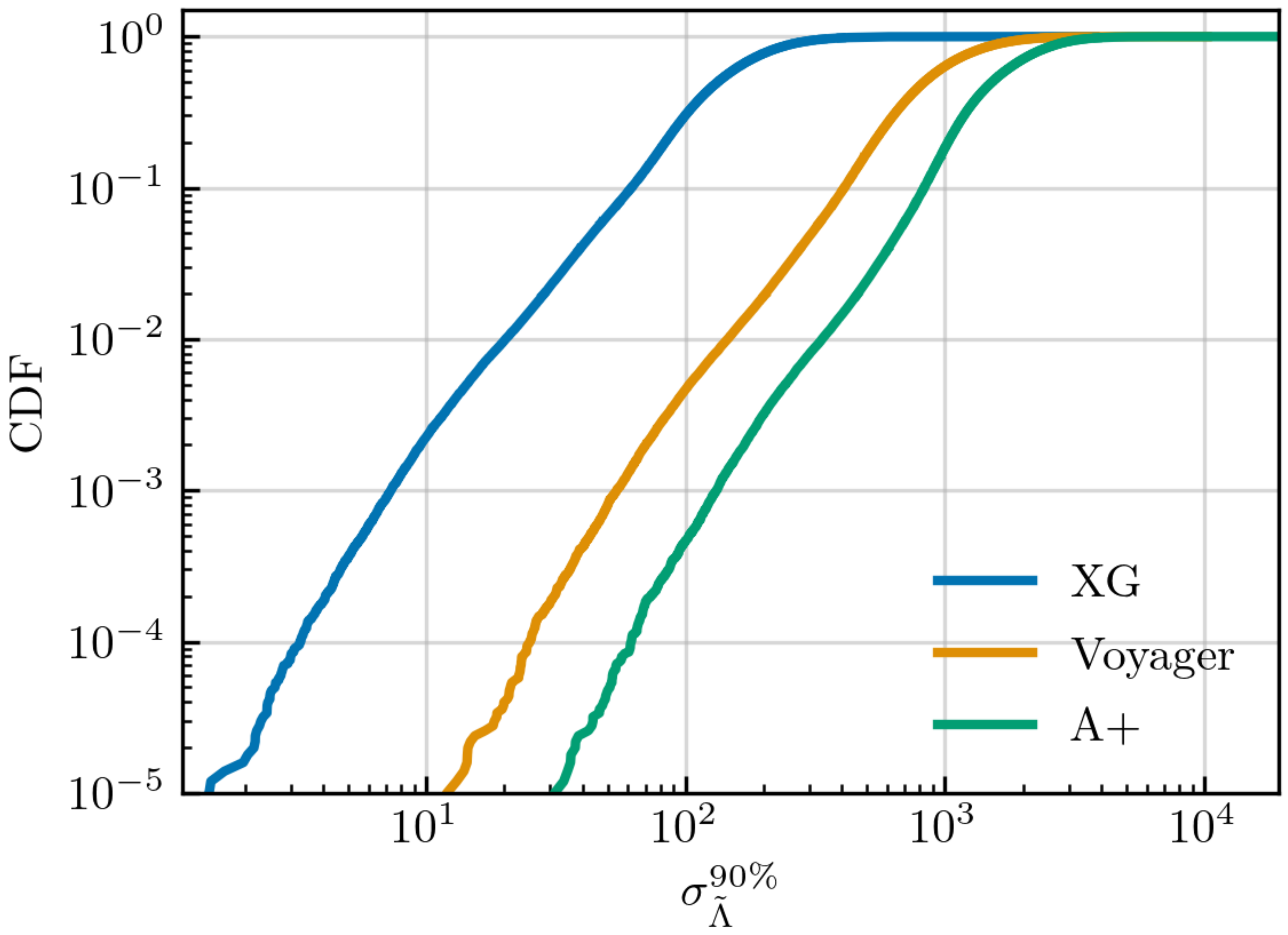
Differentiability

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 $\sigma_{\tilde{\Lambda}}^{90\%} < 20$.

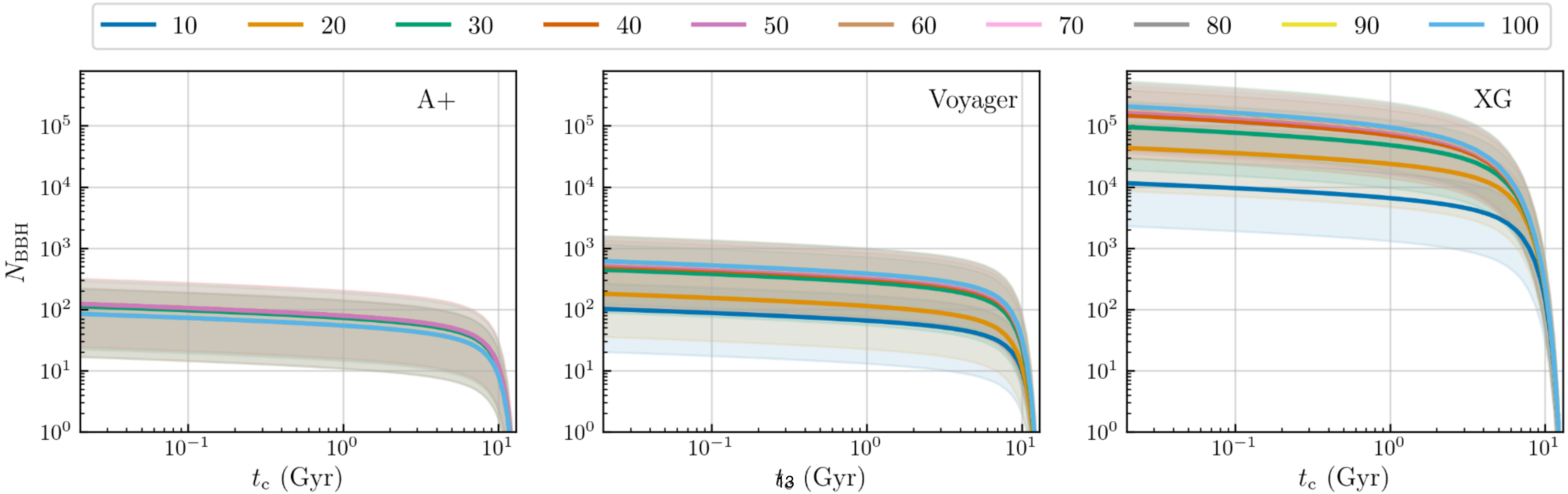


Observed Merger rate

Including detestability and differentiability in total merger rate

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

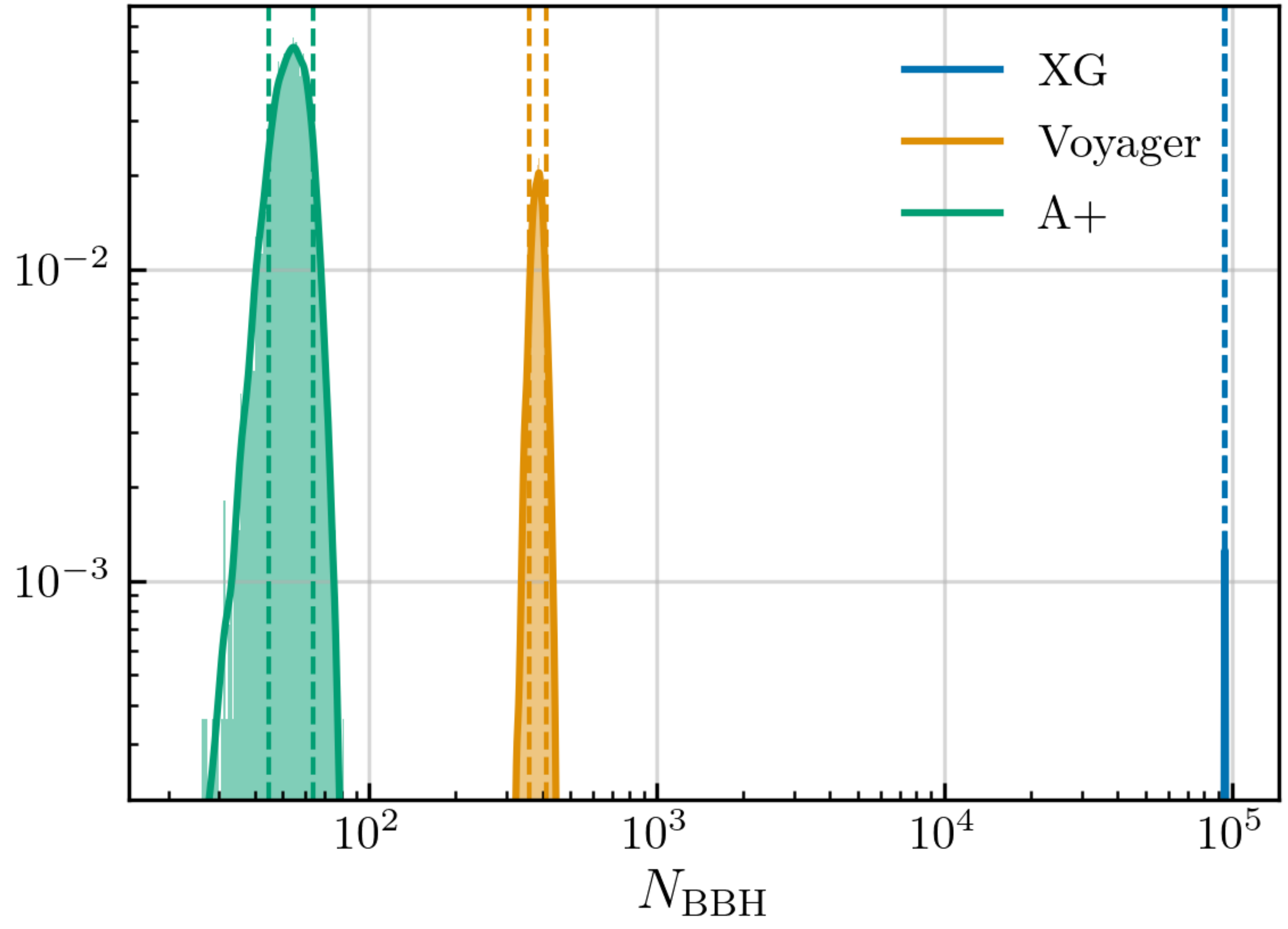
$$\rho_T = 10,\ T_{\rm obs} = 5{\rm yrs}$$



Inference of collapse time

Illustrative example

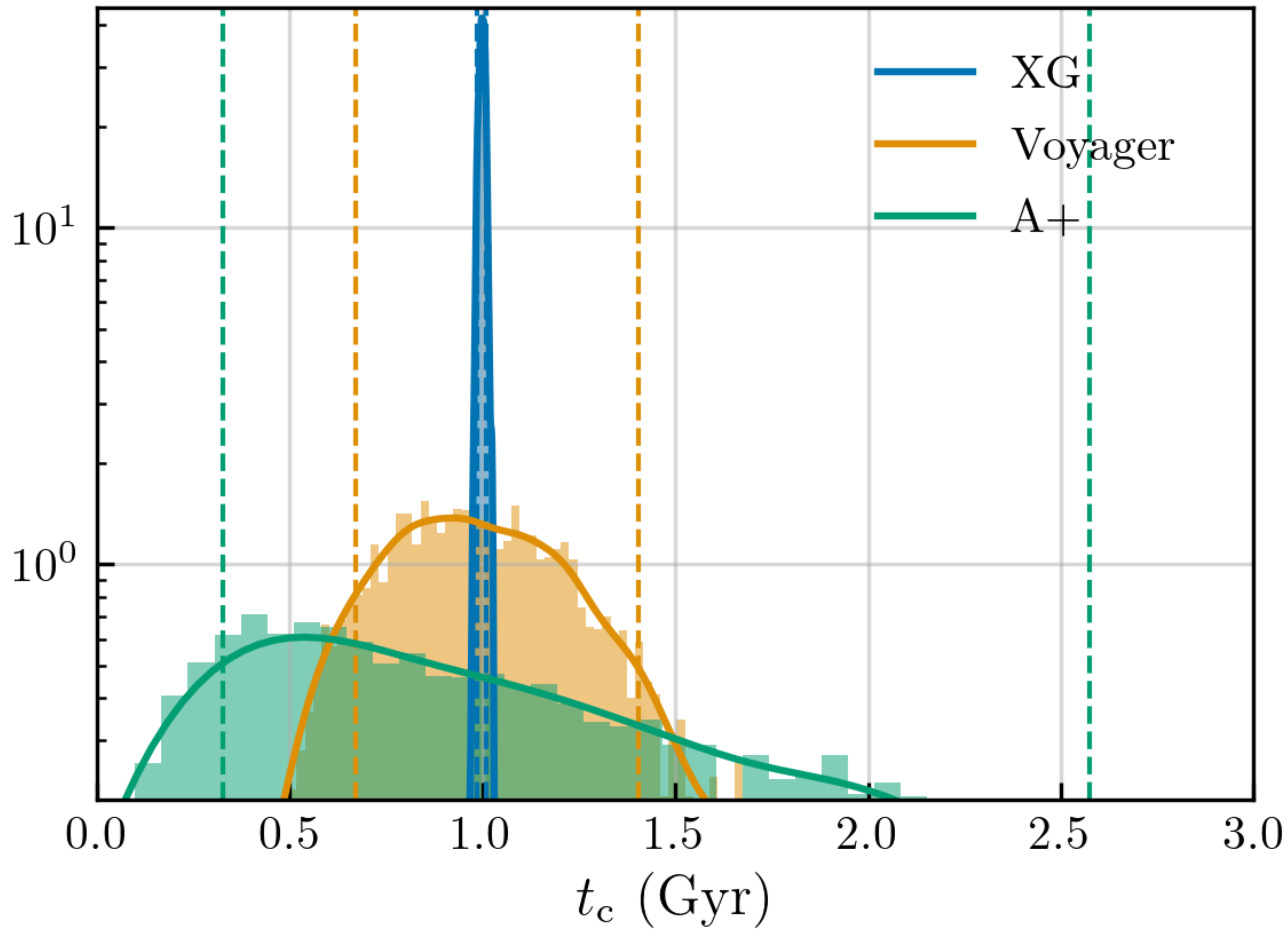
- Distribution of observed number of BBH merger computed for a fiducial collapse time, $t_c = 1\text{Gyr}$.
- As expected, the number of observable events is multiple orders of magnitude higher for XG, with smaller relative errors.



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 —> 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.