Precision Cosmology with Advanced and 3G Detectors: Prospects and Challenges

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Cosmology

- Cosmography
  - Build the cosmic distance ladder, strengthen existing calibrations at high z
  - Measure the Hubble parameter, dark matter and dark energy densities, dark energy EoS w, variation of w with z
- Black hole seeds
  - Black hole seeds could be intermediate mass black holes
  - Might explore hierarchical growth of central engines of black holes
- Dipole anisotropy in the Hubble parameter
  - The Hubble parameter will be "slightly" different in different directions due to the local flow of our galaxy
- Anisotropic cosmologies
  - In an anisotropic Universe the distribution of *H* on the sky should show residual quadrupole and higher-order anisotropies
- Primordial gravitational waves
  - Quantum fluctuations in the early Universe could produce a stochastic b/g
- Production of GW during early Universe phase transitions
  - Phase transitions, pre-heating, re-heating, etc., could produce detectable stochastic GW

New Developments: In a nutshell

- Compact binary coalescences could be used to measure both the luminosity distance and redshift their host galaxies
  - Three different methods explored so far
    - post-Newtonian tidal effect
    - statistical approach based on the narrow distribution of neutron star masses
    - merger dynamics that contains information about the intrinsic mass of the neutron star
- Low frequency sensitivity is critical to observing intermediate mass black hole binaries
  - Black holes of 10-1000 solar masses might be seeds of supermassive black holes at galactic nuclei
  - Observing them at high redshifts would require good low-frequency sensitivity
- Detector networks are useful in completeness of a survey
  - More detectors does not necessarily mean deeper surveys but bigger networks have greater completeness

Precision Cosmology: Requirements

- By PC (*Precision Cosmology*) we assume accurate measurement of dark energy EoS, given that every other cosmological parameter is known.
  - Measurements that are worse than other dedicated DE missions are not attractive and cannot be chosen to be a primary objective of a GW science goal.
- What do we need for PC:
  - Requirement if the number of observed sources is ~ few (<10)
    - Accurate measurement of *luminosity distance* - fractional error in distance should be at the level of 0.1-1%
    - Identification of the host galaxy - sky localisation to within 1 sq degree
    - Correct for weak lensing bias in luminosity distance at the level of 0.5% (currently thought to be impossible)
  - Requirement if the number of observed sources is large (>100):
    - Distance accuracies to within 30%
    - Identification of candidate host galaxies to within 10 sq degrees
  - Requirement if the number of observed sources is very large (~1000)
    - Distance accuracies to within 50%
    - No need for EM identification but

Established Fact: Inspiralling Binaries are Standard Sirens

- Gravitational wave observations of compact binary coalescences measure both the apparent and absolute luminosity of a source
  - The amplitude of the strain we measure gives us the apparent luminosity
  - The rate at which the frequency of our signals increase depend solely on the intrinsic luminosity
- It is therefore possible to measure the distance to a compact binary source
- Compact binary inspirals are self-calibrating standard sirens

The importance of a detector network

- The strain amplitude contains a number of unknown angles which must be determined to extract the relevant parameters

$$h = \frac{4\mathcal{M}}{D}\left[\pi\mathcal{M}f(t)\right]^{2/3}\cos\left[\int_0^t f(t')\,\mathrm{d}t'\right]$$

$$\frac{df}{dt} = \frac{96\,\mathcal{M}^{5/3}}{5\pi}(\pi f)^{11/3} \Rightarrow \mathcal{M} = \left(\frac{5\pi\,\dot{f}}{96}\right)^{3/5}(\pi f)^{-11/5}$$

- We would know h at any given time as well as frequency derivative, this helps in measuring *D*
- But *D* is the *effective distance* containing source position, polarisation and its orientation and the distance to the source
- The angles must all be measured to infer *D* and this where the source of large errors is

What do we actually measure?

- We really only measure
  - the redshifted distance = luminosity distance

$$D_{\rm L} = D(1+z)$$

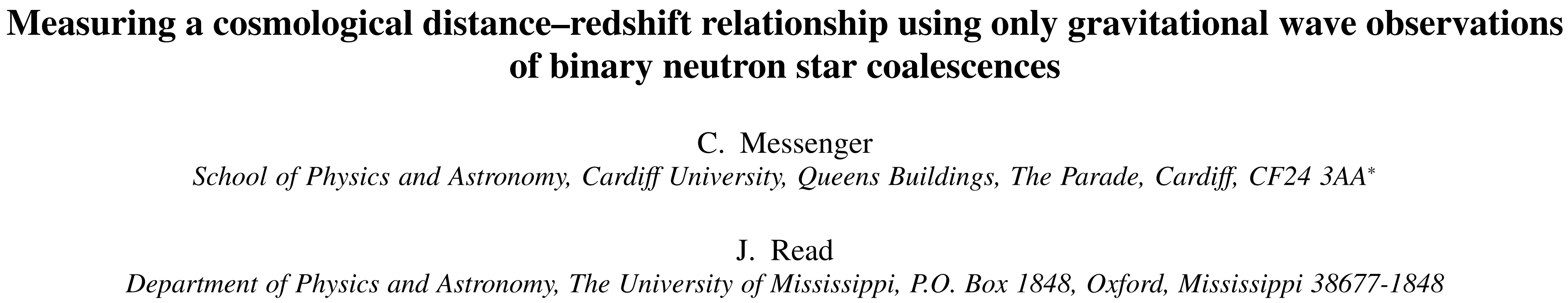
  - blueshifted chirp mass $\mathcal{M}(1+z)$

- This means we cannot measure the source's redshift without EM identification
  - at least that is what we thought until recently ...
- If we can somehow measure the intrinsic mass of the source then we can resolve the redshift-source mass degeneracy

Details of the calculation

$$\mathrm{Flux} = \frac{1}{4\pi D^2}\frac{dE_{Obs}}{dt_{\mathrm{Obs}}} = \frac{1}{4\pi(1+z)^2 D^2}\frac{dE_{\mathrm{Int}}}{dt_{\mathrm{Int}}}$$

$$\begin{aligned}
\frac{df_{\mathrm{obs}}}{dt_{\mathrm{obs}}} &= \frac{1}{(1+z)^2}\frac{df_{\mathrm{int}}}{dt_{\mathrm{int}}} \\
&= \frac{1}{(1+z)^2}\frac{96{\mathcal{M}_{\mathrm{int}}}^{5/3}}{5\pi}(\pi f_{\mathrm{int}})^{11/3} \\
&= \frac{96(1+z){\mathcal{M}_{\mathrm{int}}}^{5/3}}{5\pi}(\pi f_{\mathrm{obs}})^{11/3} \\
&= \frac{96{\mathcal{M}_{\mathrm{obs}}}^{5/3}}{5\pi}(\pi f_{\mathrm{obs}})^{11/3} \\
\mathcal{M}_{\mathrm{obs}} &= (1+z)\mathcal{M}_{\mathrm{int}}
\end{aligned}$$



Measuring a cosmological distance–redshift relationship using only gravitational wave observations of binary neutron star coalescences

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J. Read
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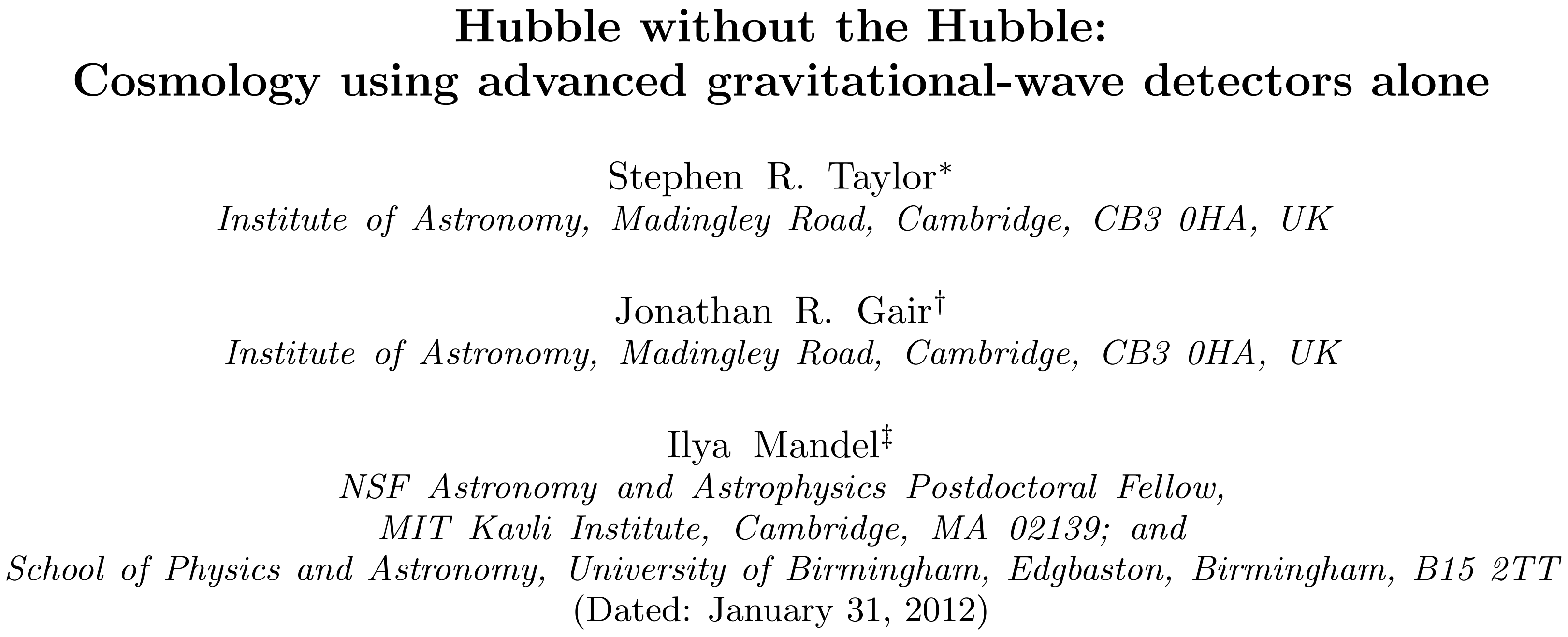

Hubble without the Hubble: Cosmology using advanced gravitational-wave detectors alone

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(Dated: January 31, 2012)

Messenger-Read Method: Make use of the post-Newtonian Tidal Term

K. G. Arun, B. R. Iyer, B. S. Sathyaprakash, and P. A. Sundararajan, Phys. Rev. D, **71**, 084008 (2005), arXiv:gr-qc/0411146.

$$\Psi_{PP}(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\eta x^{5/2}} \sum_{k=0}^{N} \alpha_k x^{k/2}$$

T. Hinderer, B. D. Lackey, R. N. Lang, and J. S. Read, Phys. Rev. D, **81**, 123016 (2010), arXiv:0911.3535 [astro-ph.HE].

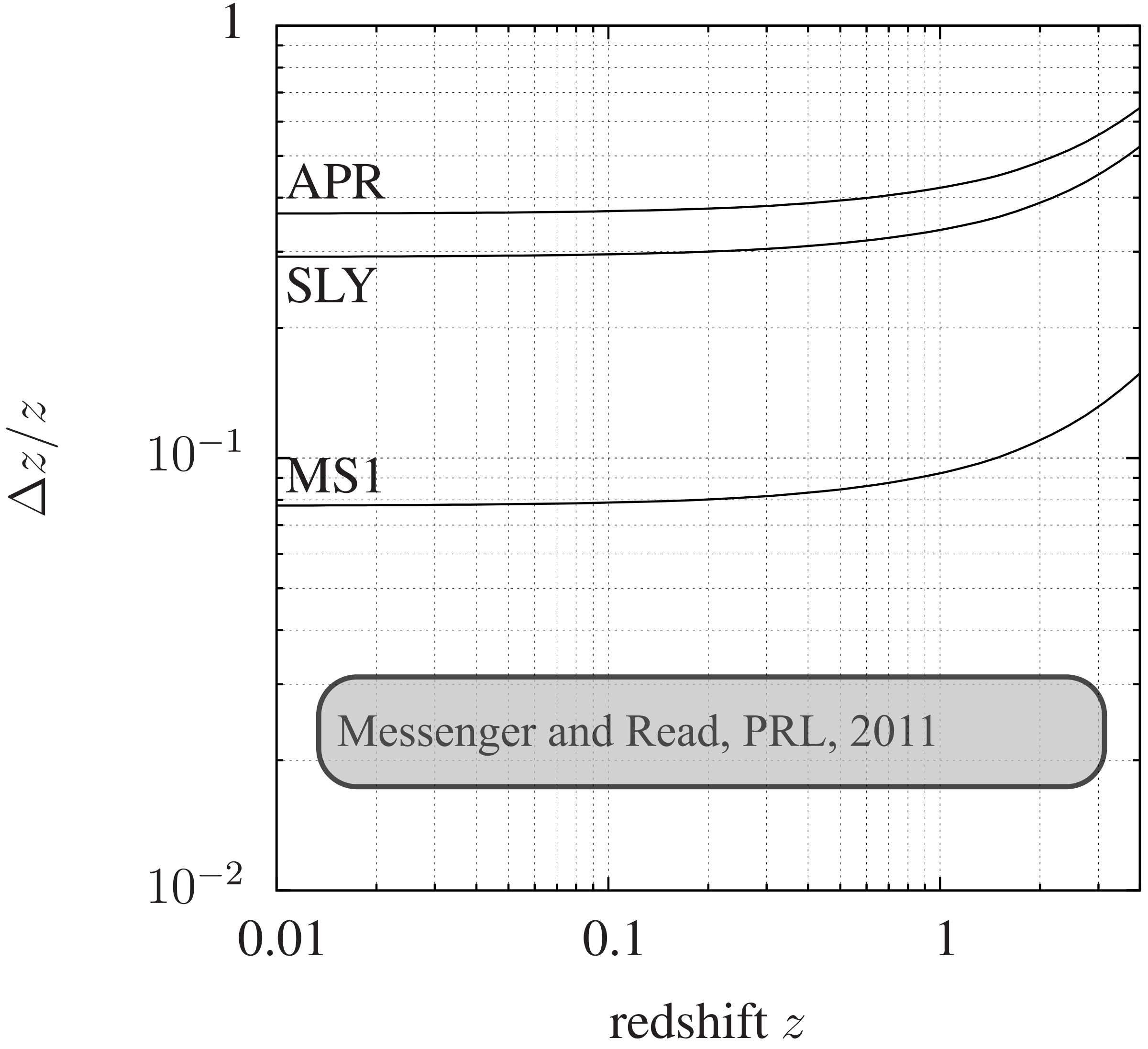
$$\Psi^{\mathrm{tidal}}(f) = \sum_{a=1,2} \frac{3\lambda_a}{128\eta} \left[-\frac{24}{\chi_a}\left(1 + \frac{11\eta}{\chi_a}\right)\frac{x^{5/2}}{M^5} \right. \qquad (3)$$

$$\left. - \frac{5}{28\chi_a}\left(3179 - 919\chi_a - 2286\chi_a^2 + 260\chi_a^3\right)\frac{x^{7/2}}{M^5} \right]$$

$$x = (\pi M f)^{2/3}$$

$$\lambda = (2/3) R_{\mathrm{ns}}^5 k_2$$

Measurement accuracy of source redshift



Messenger and Read, PRL, 2011

Cosmology with the lights off:

Taylor, Gair, Mandel 2011, 2012

Distribution of Chirp Mass

$$\mathcal{M} \sim N(\mu_c, \sigma_c^2),$$

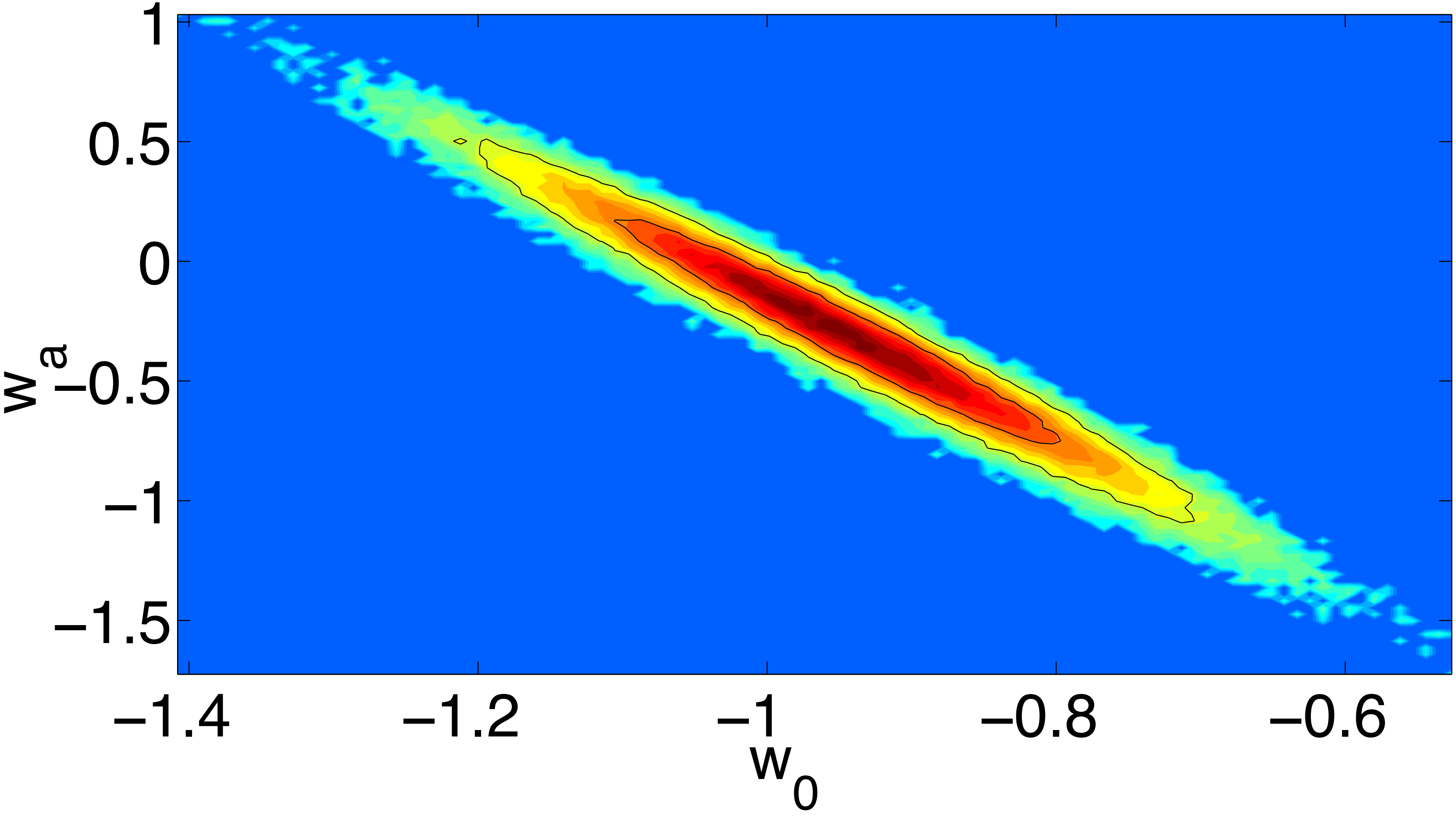
$$\mu_c \approx 2(0.25)^{3/5}\mu_{\rm NS}, \quad \sigma_c \approx \sqrt{2}(0.25)^{3/5}\sigma_{\rm NS},$$

$$\mu_{\rm NS} \in [1.0, 1.5]M_\odot, \; \sigma_{\rm NS} \in [0, 0.3]M_\odot$$

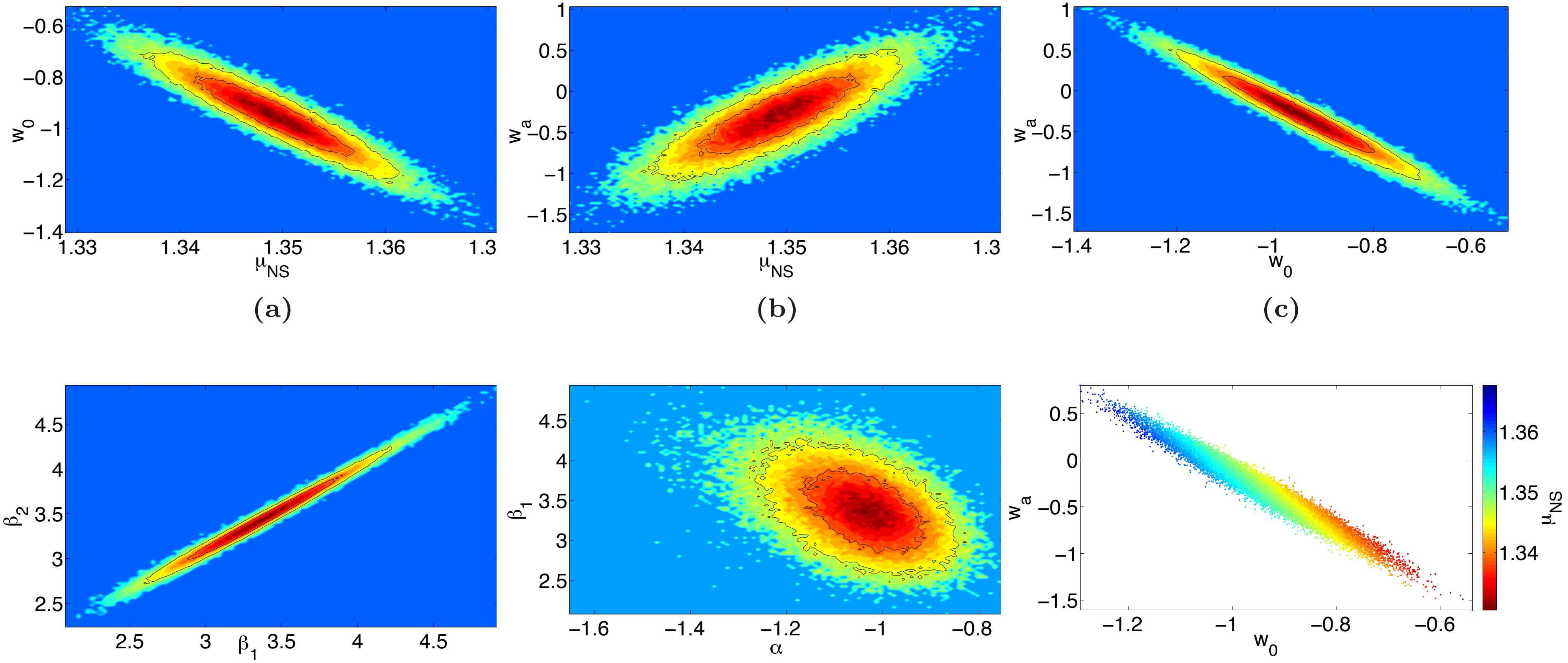
$$w(a) = w_0 + w_a(1-a),$$

$$w(z) = w_0 + w_a\left(\frac{z}{1+z}\right).$$

Measuring dark energy EoS and its variation with redshift



Two-D posterior Distributions



(a) (b) (c)

(d) (e) (f)

Measurement accuracy of dark energy EoS parameters

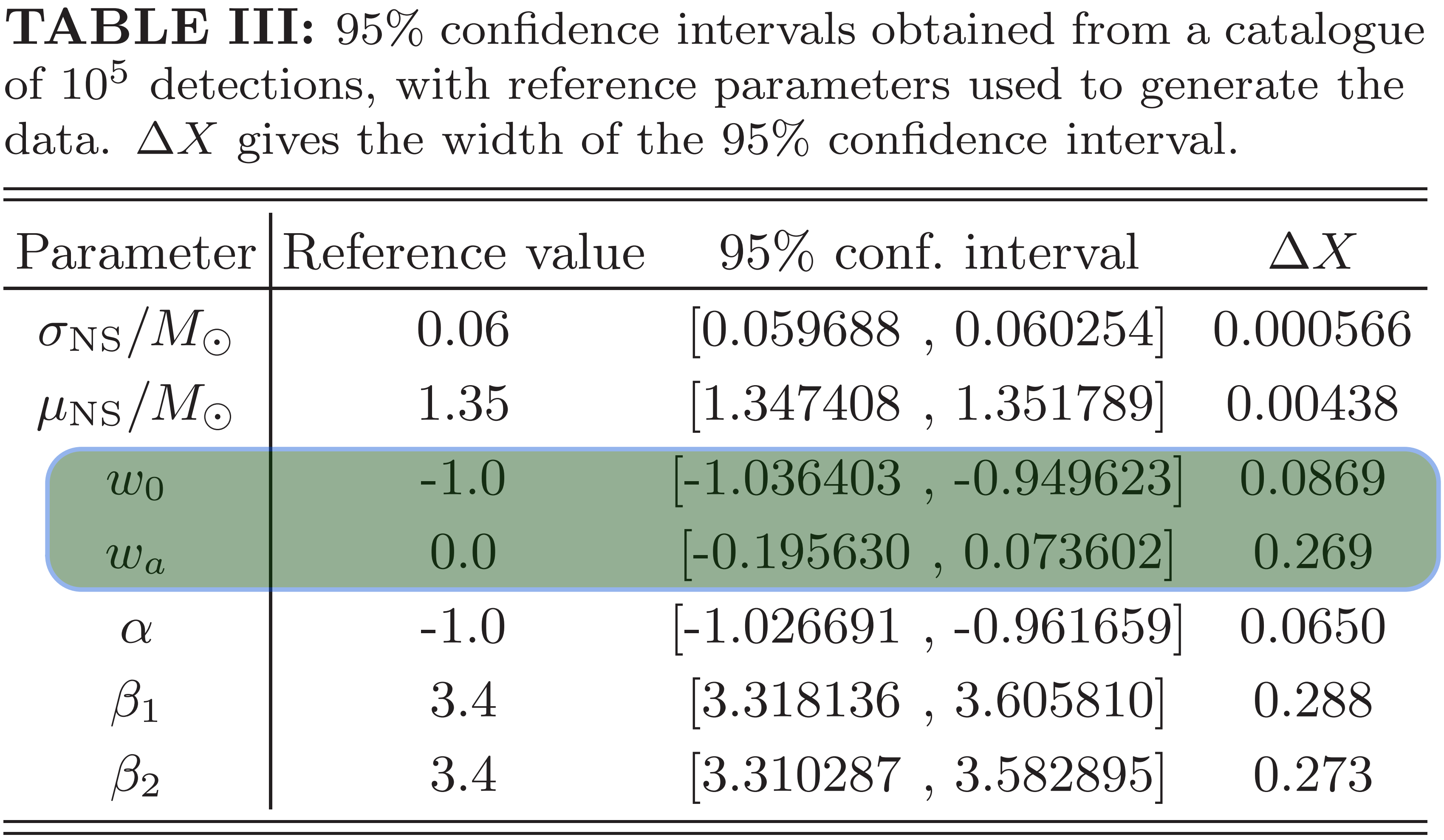
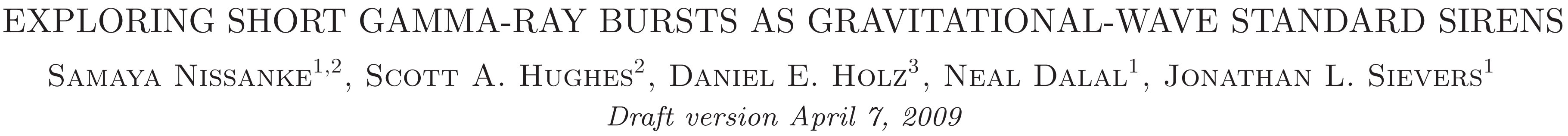


TABLE III: 95% confidence intervals obtained from a catalogue of 10^5 detections, with reference parameters used to generate the data. ΔX gives the width of the 95% confidence interval.

Parameter	Reference value	95% conf. interval	ΔX
$\sigma_{\rm NS}/M_\odot$	0.06	[0.059688 , 0.060254]	0.000566
$\mu_{\rm NS}/M_\odot$	1.35	[1.347408 , 1.351789]	0.00438
w_0	-1.0	[-1.036403 , -0.949623]	0.0869
w_a	0.0	[-0.195630 , 0.073602]	0.269
α	-1.0	[-1.026691 , -0.961659]	0.0650
β_1	3.4	[3.318136 , 3.605810]	0.288
β_2	3.4	[3.310287 , 3.582895]	0.273

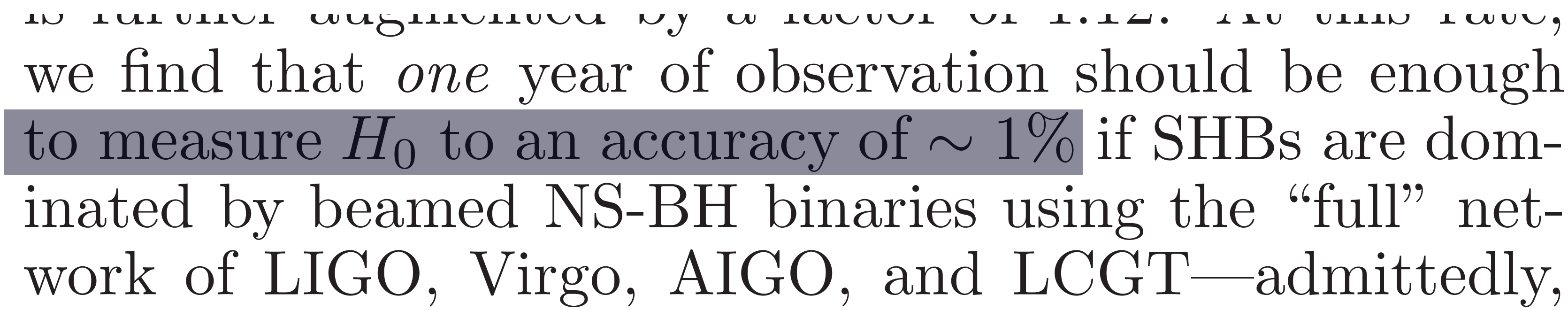
Hubble Constant from Advanced Detectors



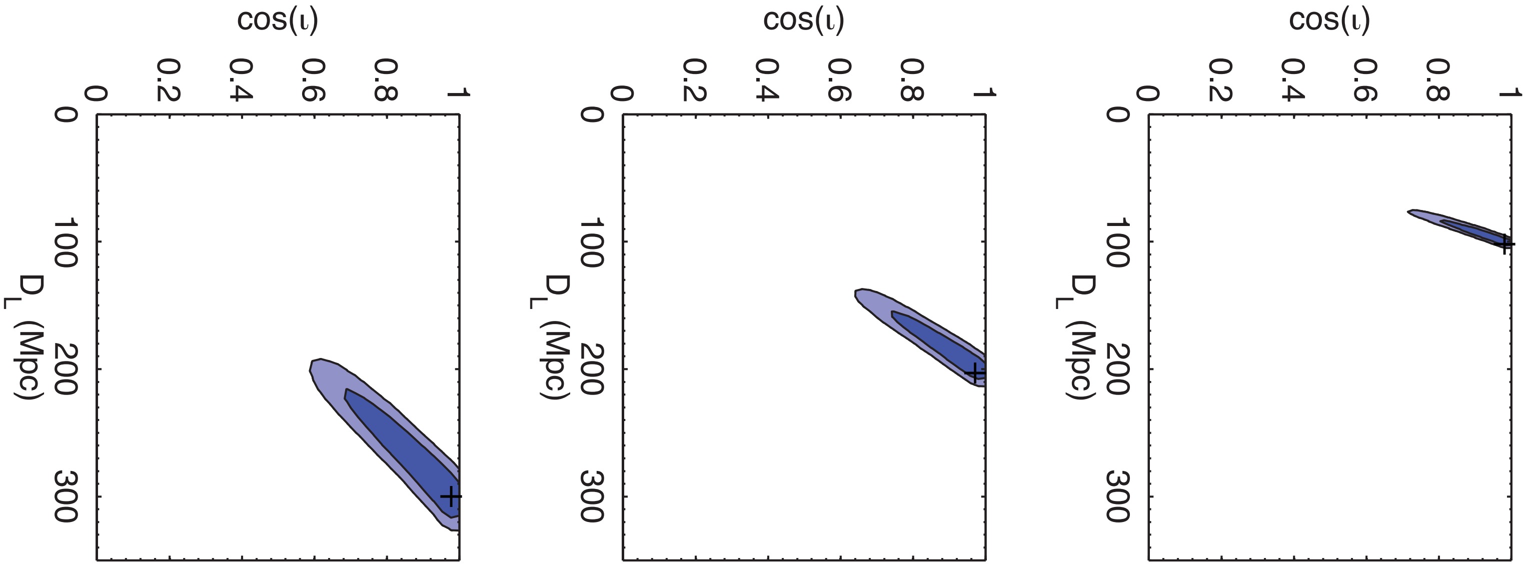
EXPLORING SHORT GAMMA-RAY BURSTS AS GRAVITATIONAL-WAVE STANDARD SIRENS

Samaya Nissanke[1,2], Scott A. Hughes[2], Daniel E. Holz[3], Neal Dalal[1], Jonathan L. Sievers[1]

Draft version April 7, 2009



we find that *one* year of observation should be enough to measure H_0 to an accuracy of $\sim 1\%$ if SHBs are dominated by beamed NS-BH binaries using the "full" network of LIGO, Virgo, AIGO, and LCGT—admittedly,

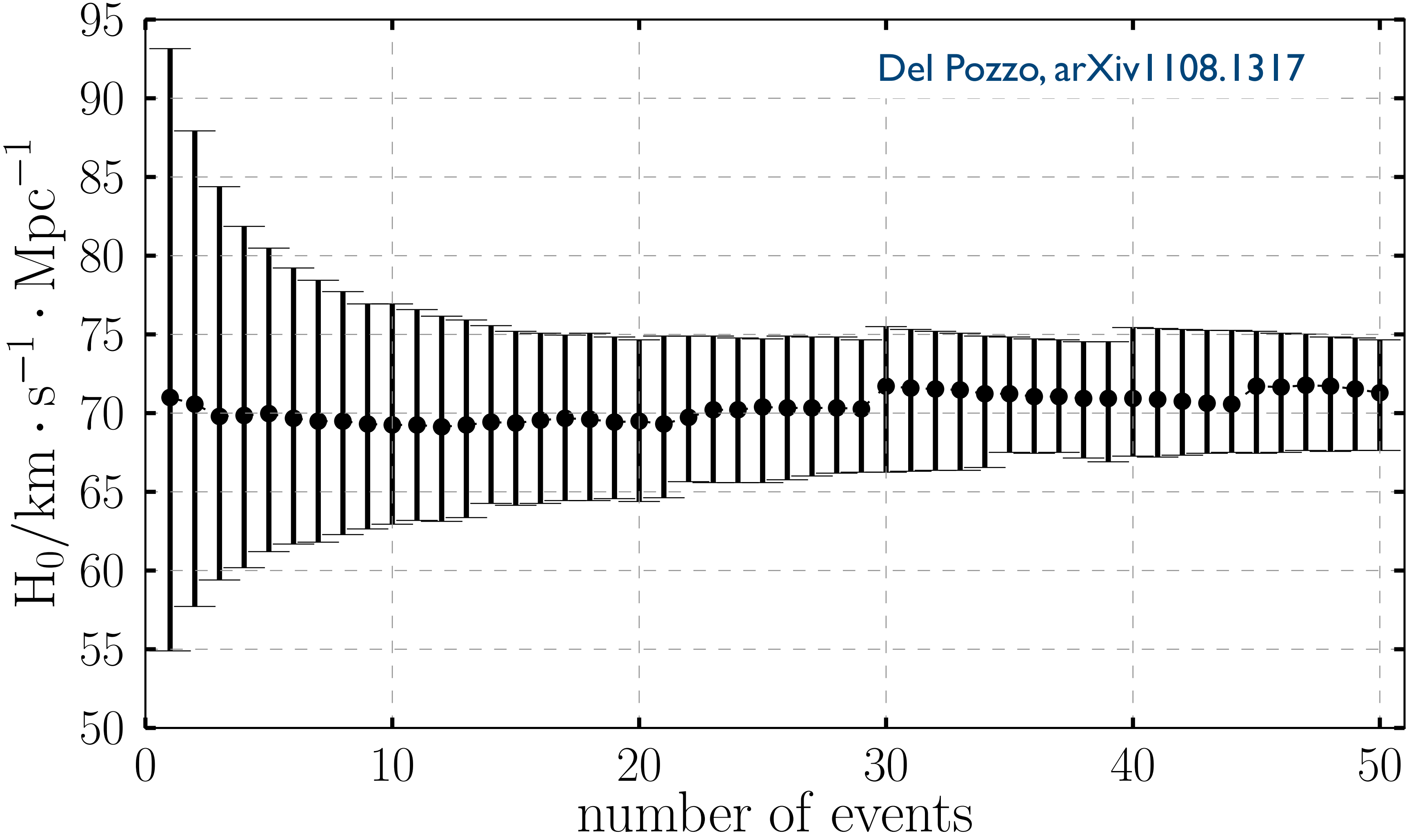


Hubble Constant from Advanced Detectors without EM counterparts

Del Pozzo, arXiv1108.1317

- 25 events:
  - H_0= 69 ± 3 km s^{-1} Mpc^{-1} (~4% at 95% confidence)
- 50 events:
  - H_0= 69 ± 2 km s^{-1} Mpc^{-1} (~3% at 95% confidence)
- WMAP7+BAO+SnIa (Komatsu et al.,2011):
  - H_0= 70.2 ± 1.4 km s^{-1} Mpc^{-1} (~2% at 68% confidence)

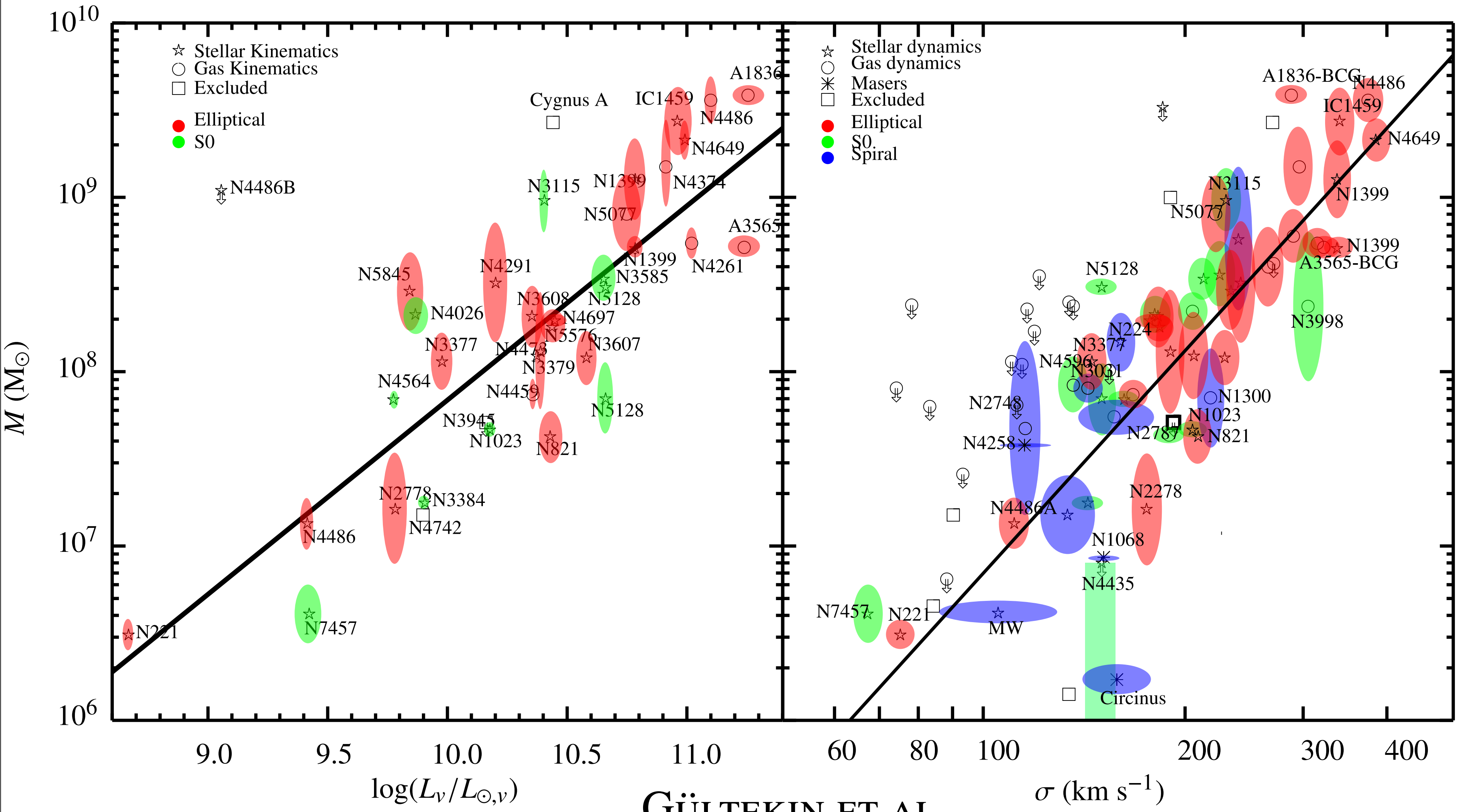
Error in H_0 with Catalogue Size



Searching for Intermediate Mass Black Hole Binaries

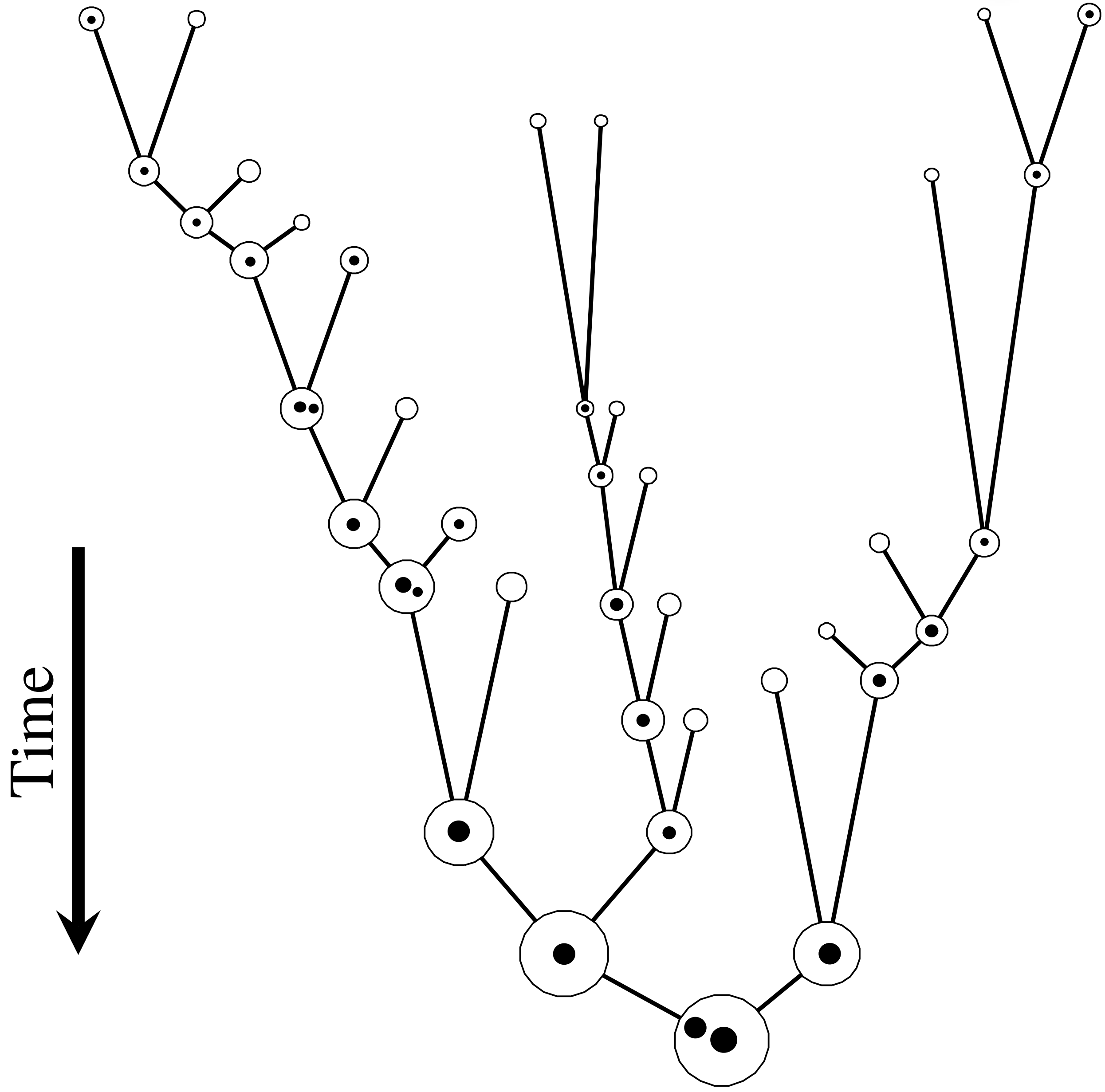
Importance of the low-frequency sensitivity

BH mass correlated with Galaxy luminosity and bulge mass

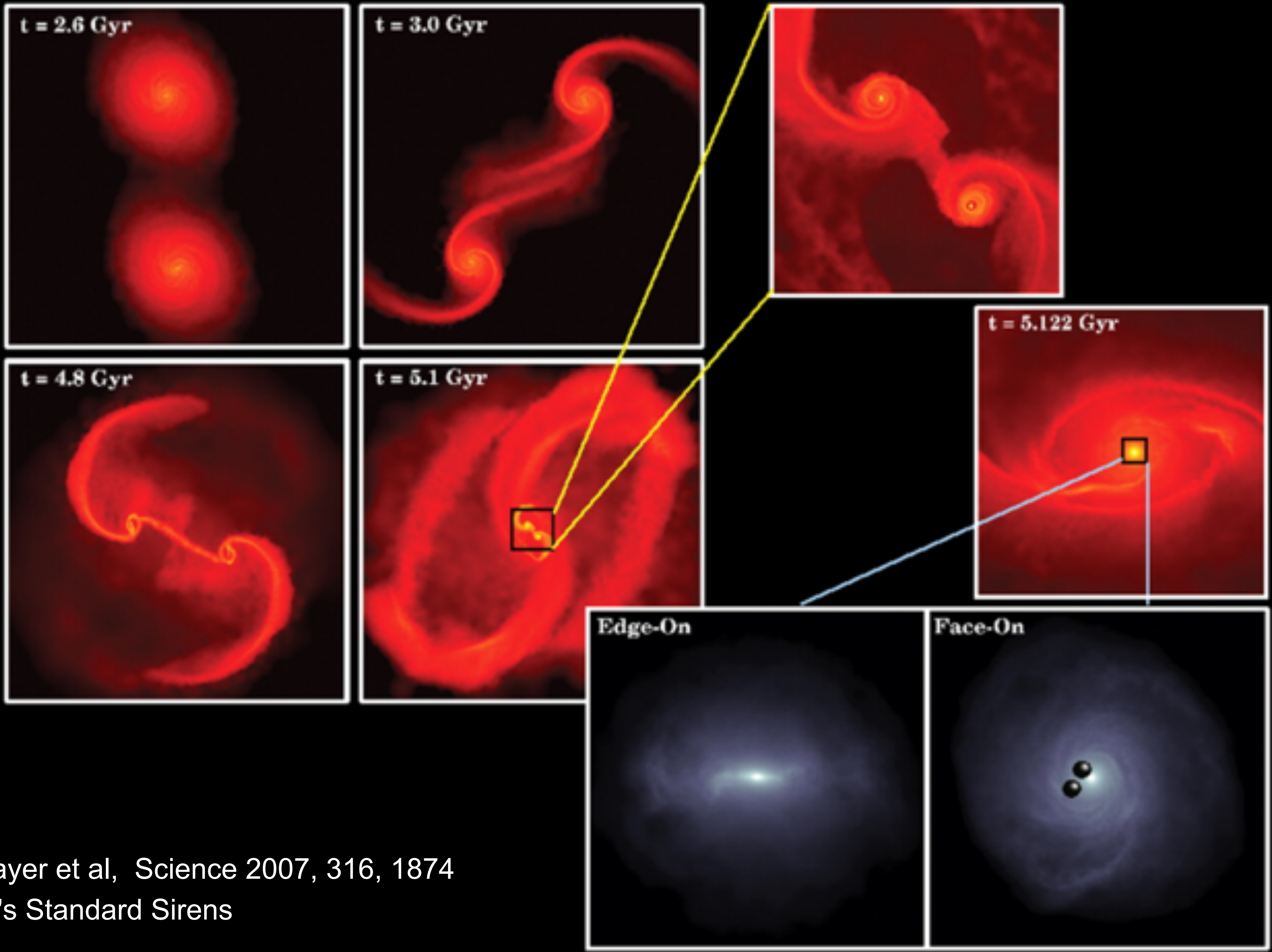


GÜLTEKIN ET AL.

Merger Tree Simulations Predict Frequent Mergers



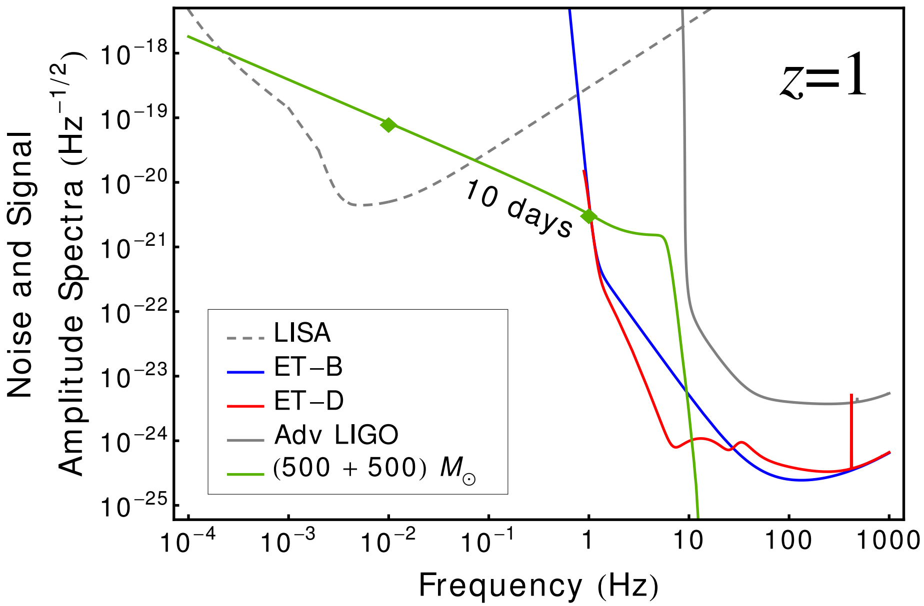
BHs grow by merger

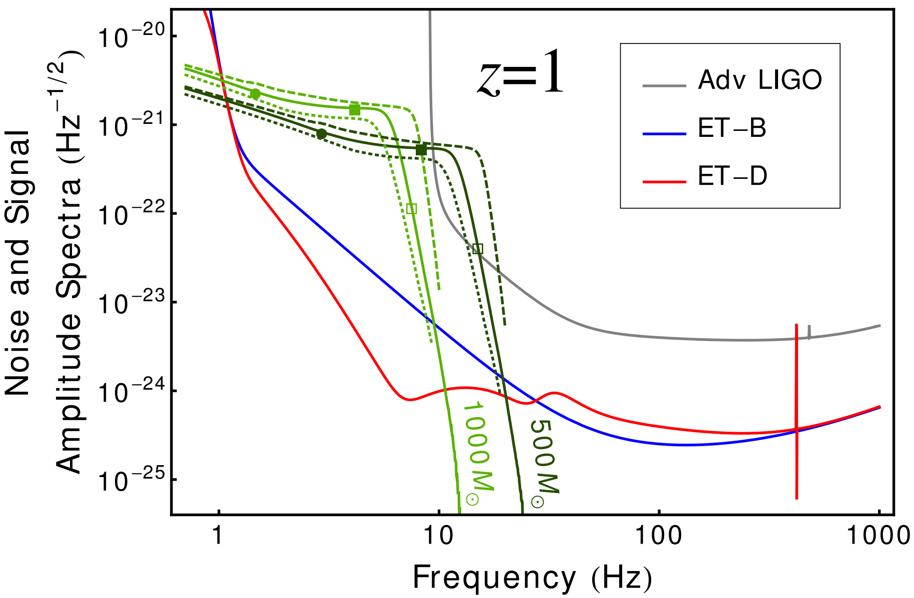


Mayer et al, Science 2007, 316, 1874

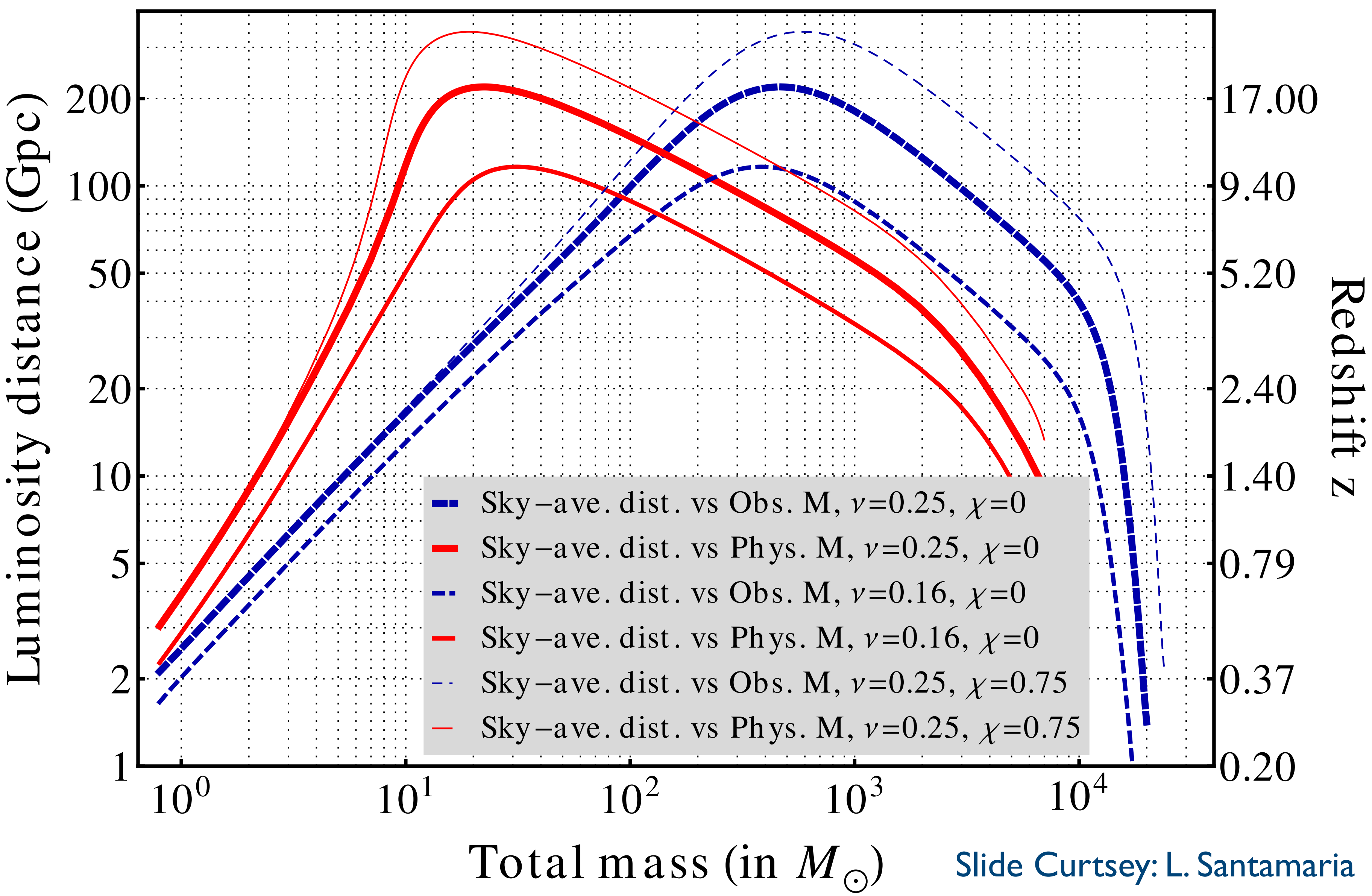
ET can Observe Intermediate-mass Black Hole Binaries, Some of them in Coincidence with NGO/eLISA

- Ultra-luminous X-ray sources might be hosting black holes of mass one thousand solar masses
- 100 solar mass black holes could be seeds of galaxy formation
- ET could observe black hole populations at different red-shifts and resolve questions about black hole demographics



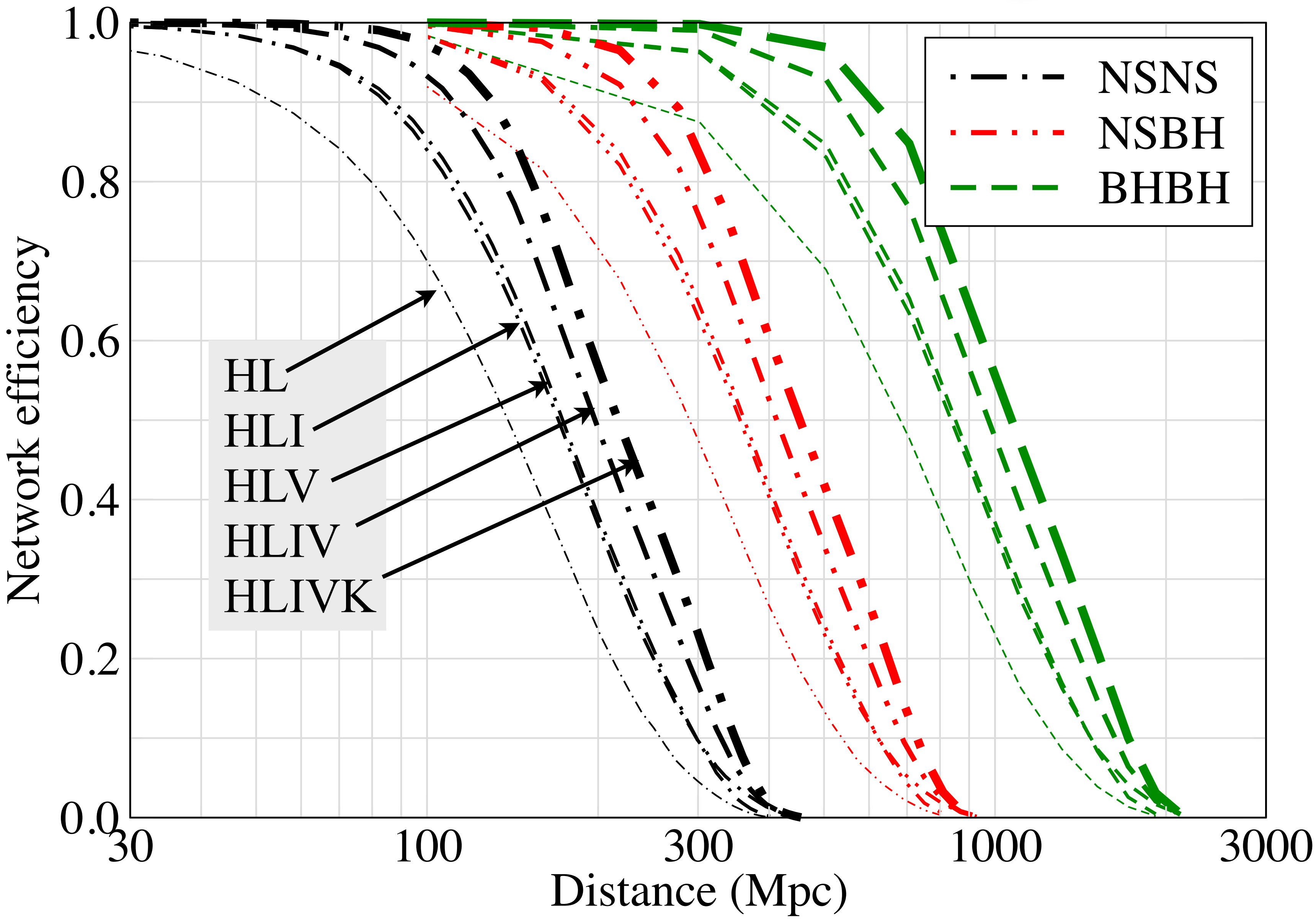


ET Distance Reach for Compact Binary Mergers

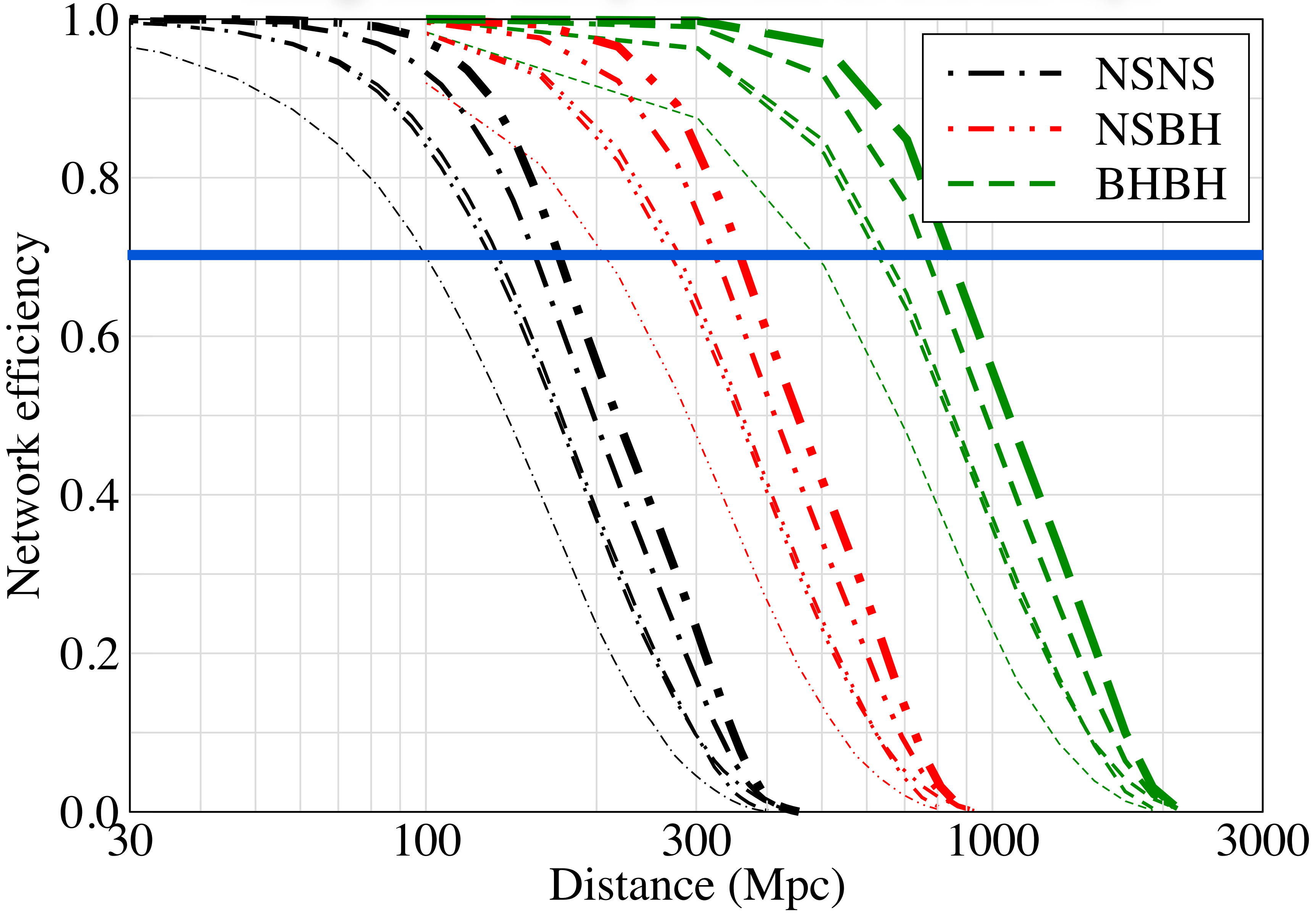


Slide Curtsey: L. Santamaria

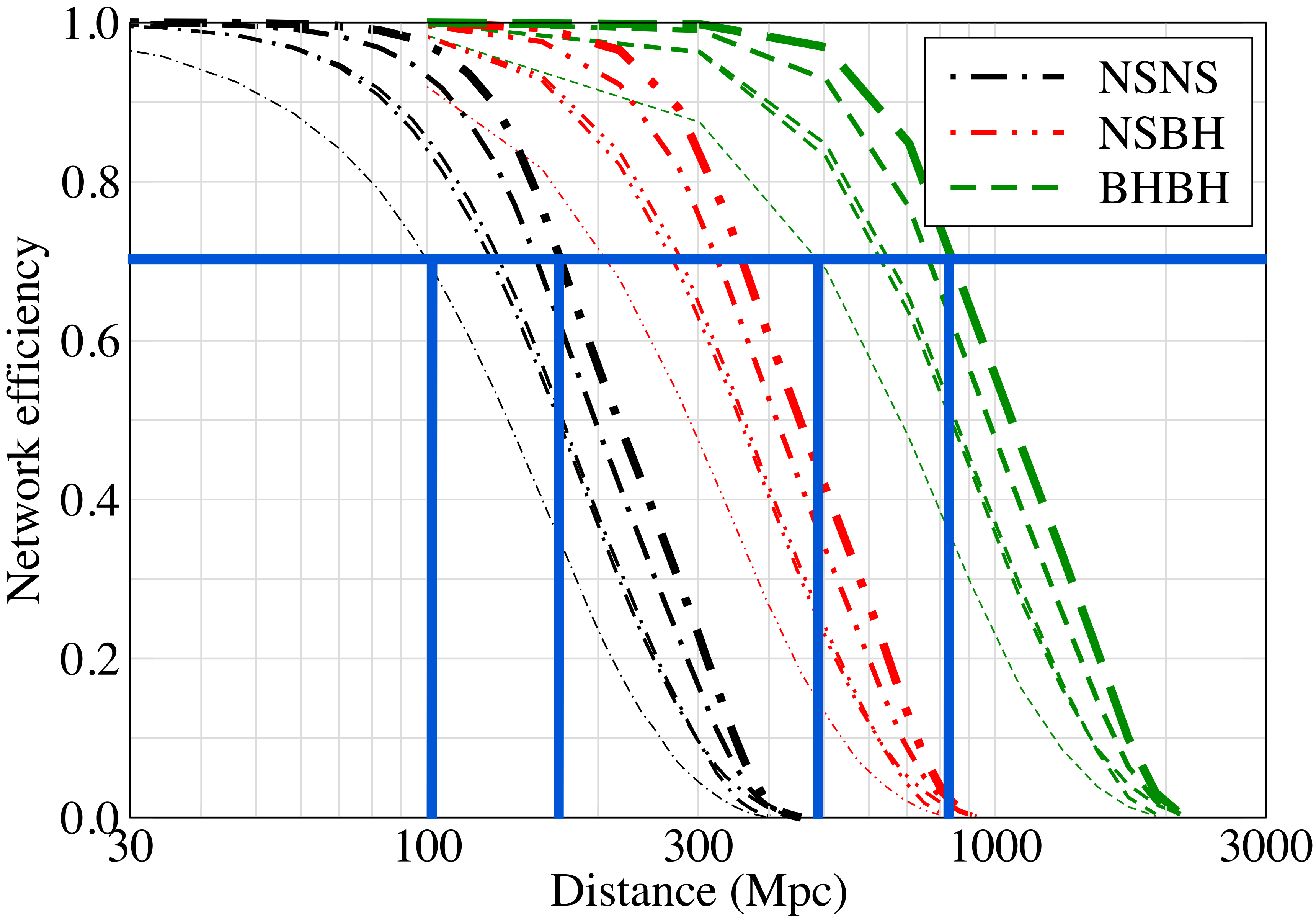
Network Efficiency



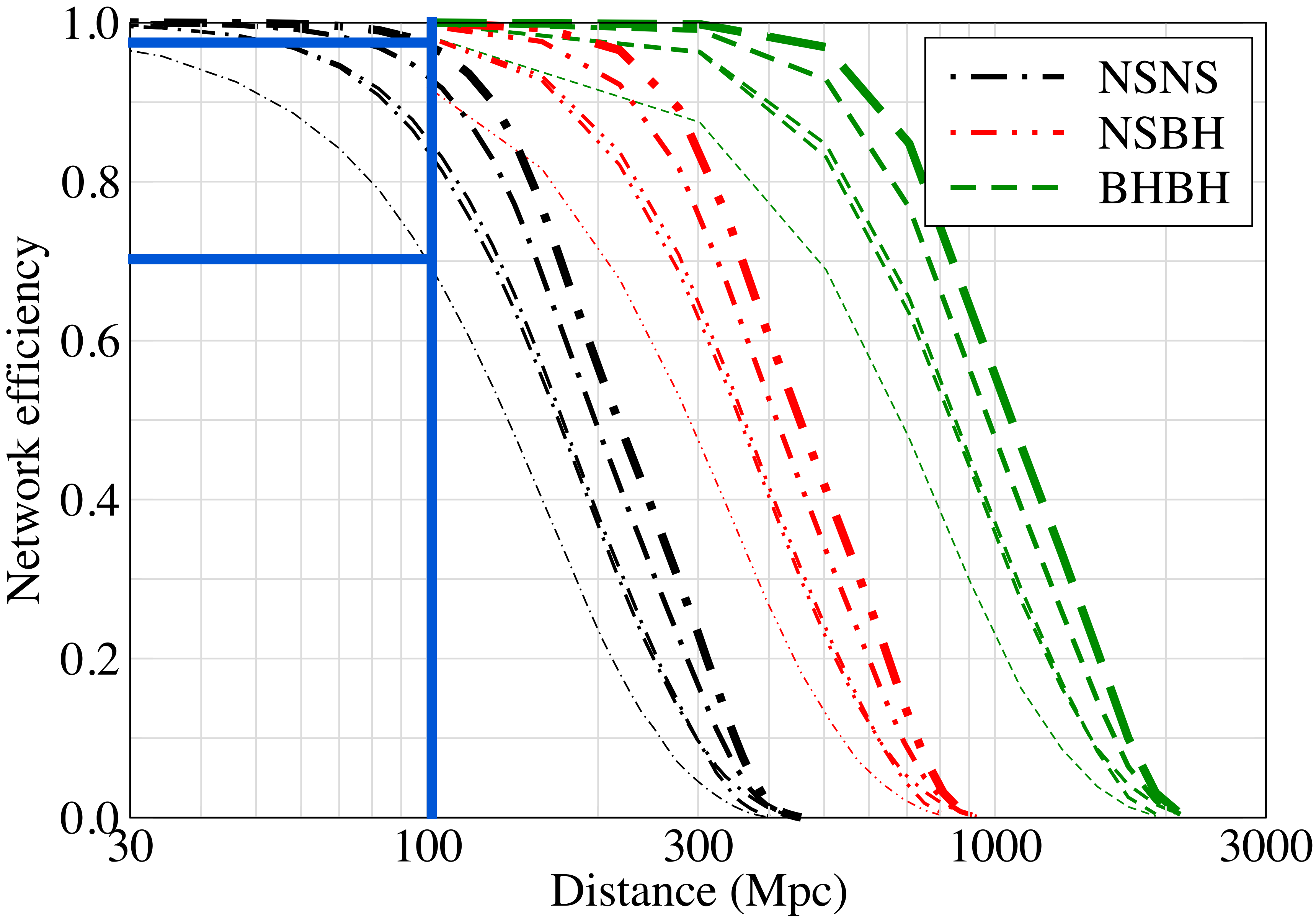
More detectors in a network does not mean deeper searches; but greater completeness of the surveys



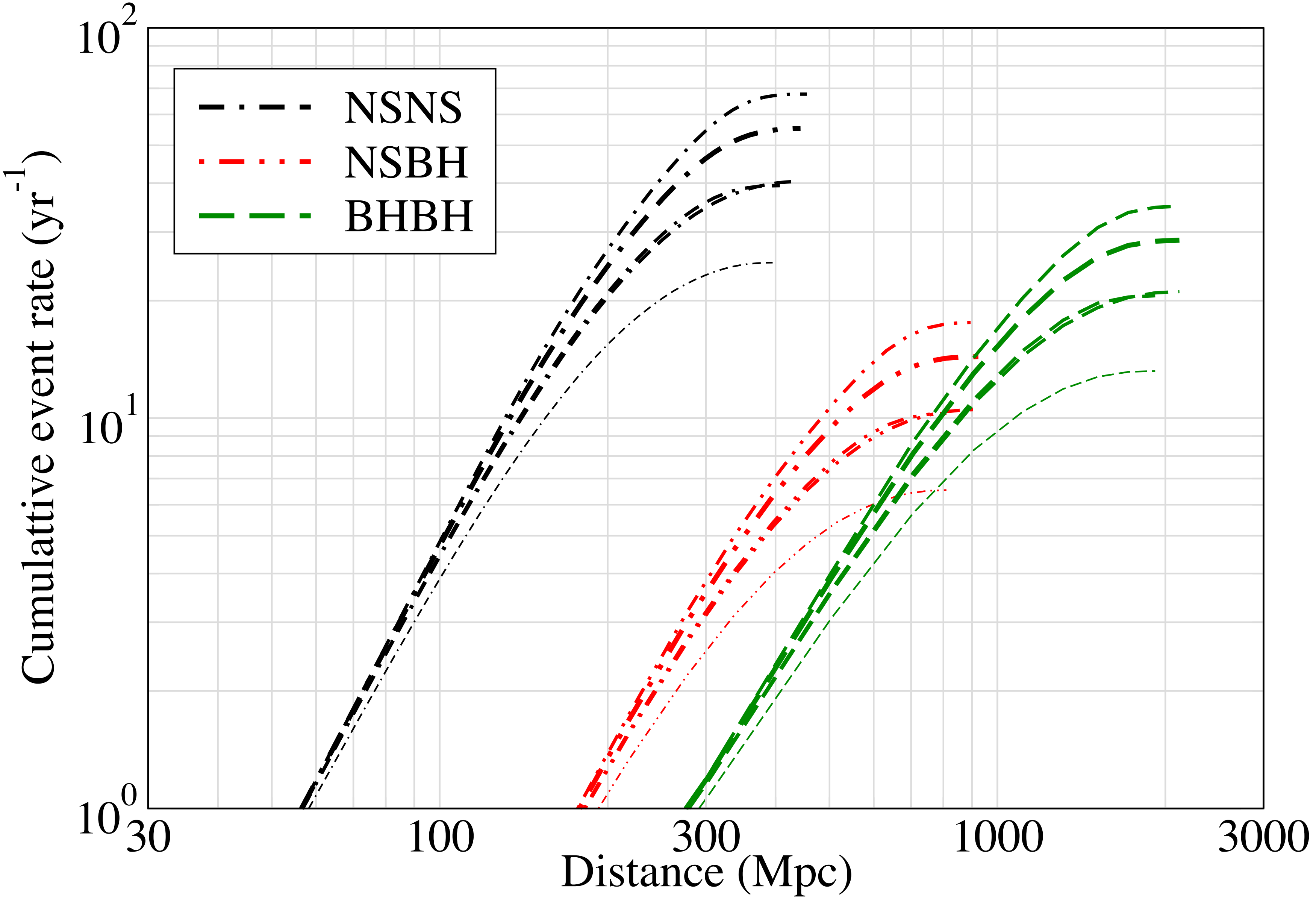
Reach of advanced networks at given completeness



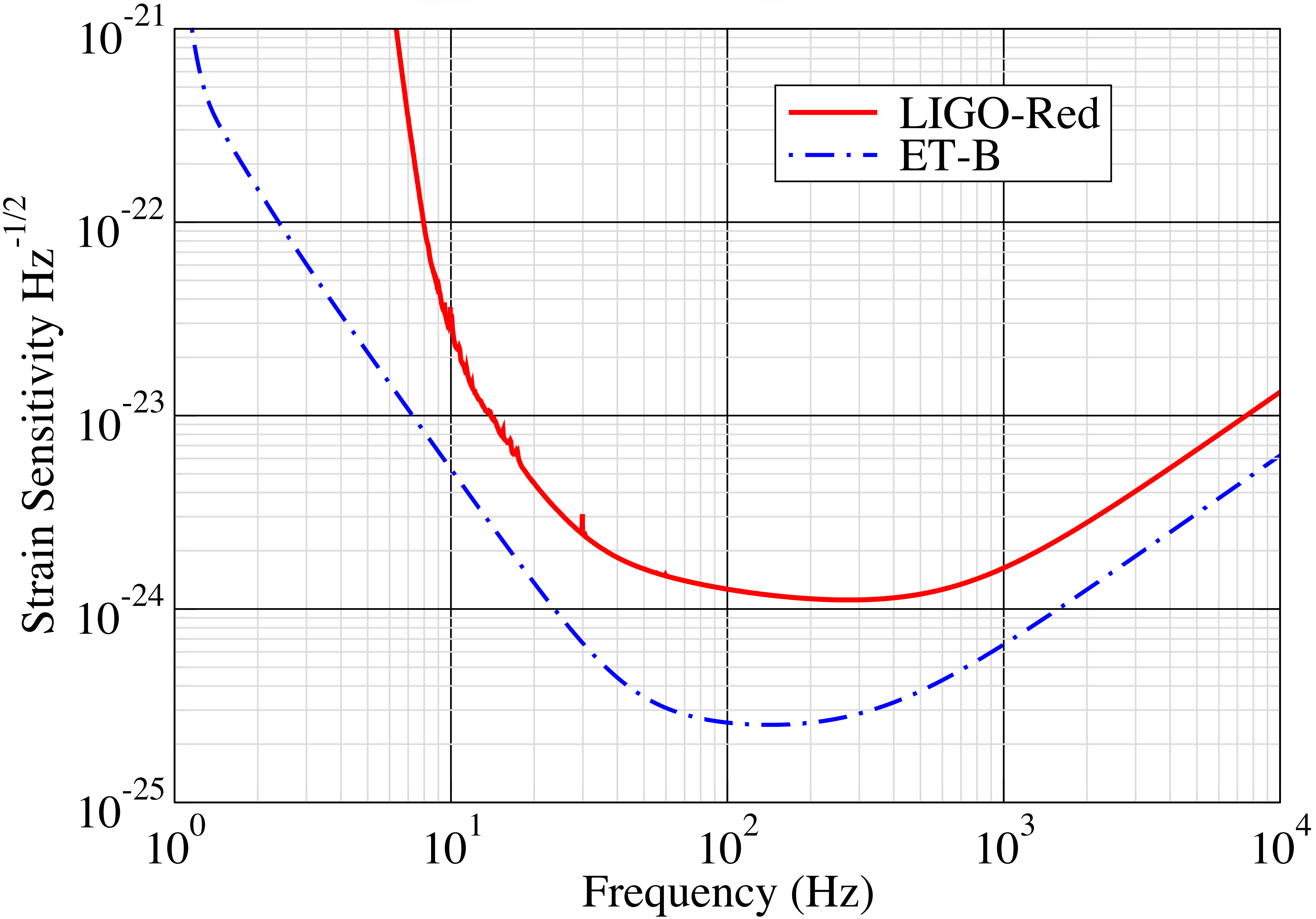
Completeness within a given distance



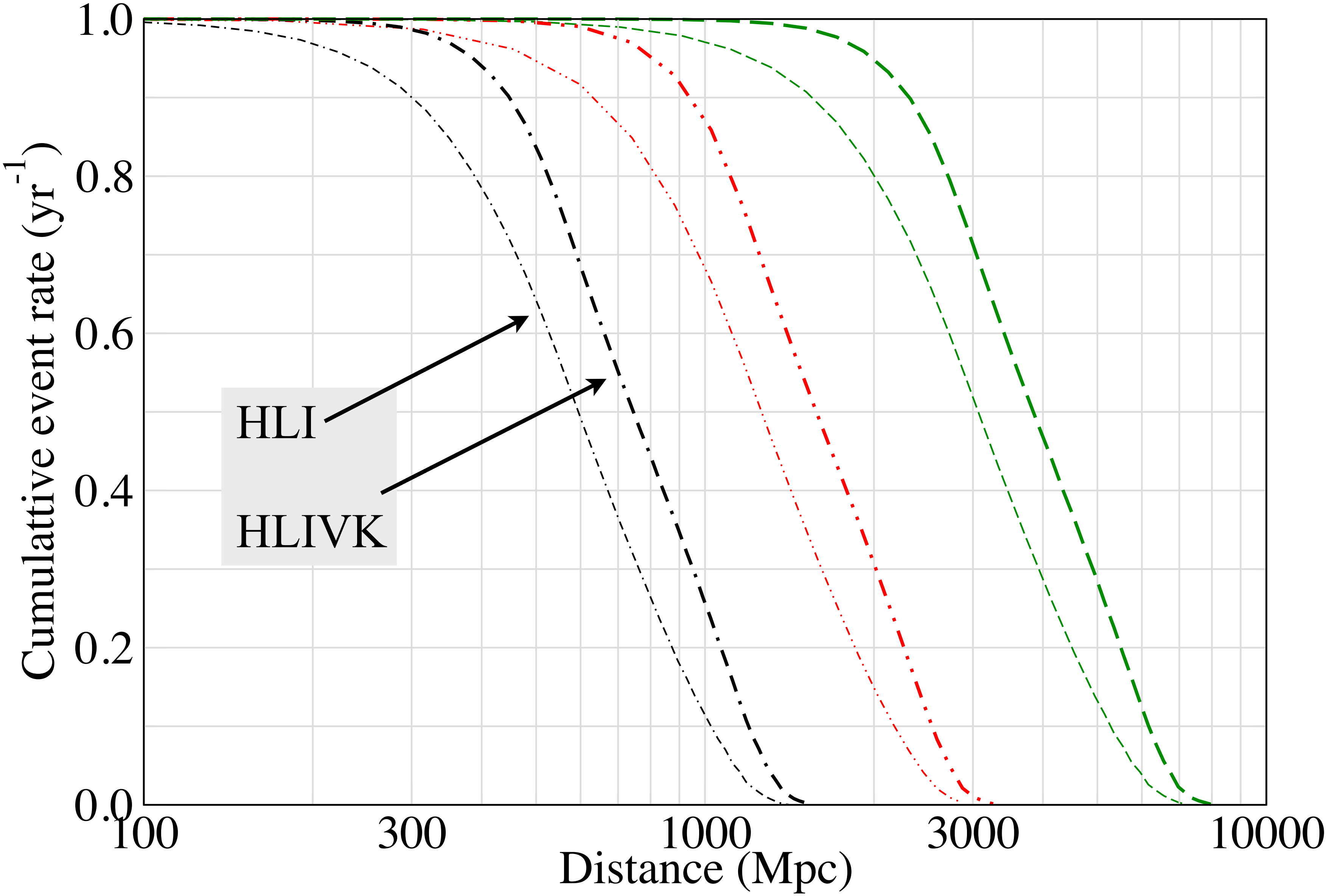
Number of events in advanced detectors



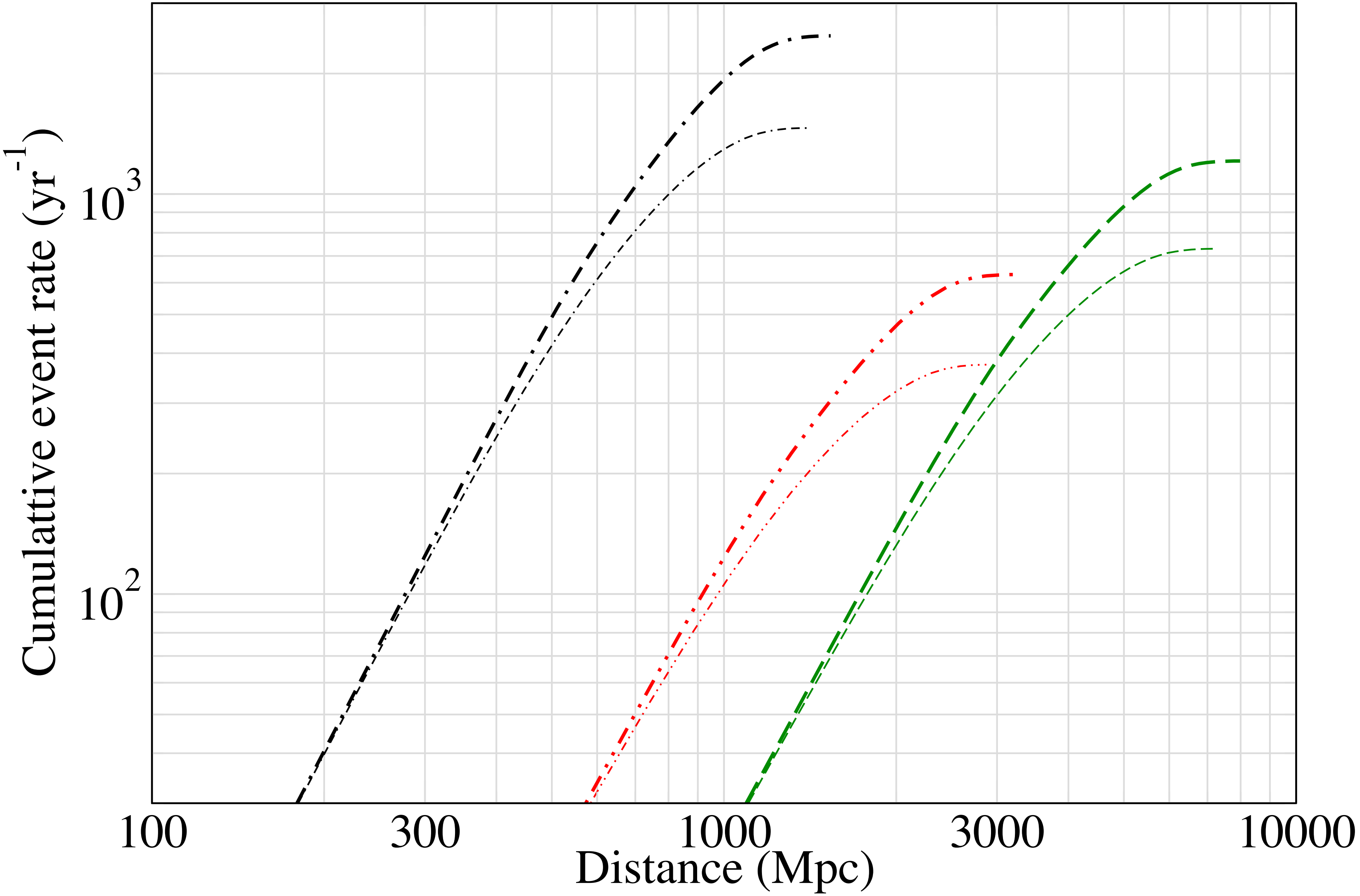
Cosmology with improved aLIGO



Completeness of LIGO-Red a given distance



Number of events in LIGO-Red detectors



Summary

- Gravitational wave detectors can potentially impact
  - Fundamental Physics
    - Is the nature of gravitational radiation as predicted by Einstein?
    - Is Einstein theory the correct theory of gravity?
    - Are black holes in nature black holes of GR?
    - Are there naked singularities?
  - Astrophysics
    - What is the nature of gravitational collapse?
    - What is the origin of gamma ray bursts?
    - What is the structure of neutron stars and other compact objects?
  - Cosmology
    - How did massive black holes at galactic nuclei form and evolve?
    - What is dark energy?
    - What phase transitions took place in the early Universe?
    - What were the physical conditions at the big bang?