Future Observatories

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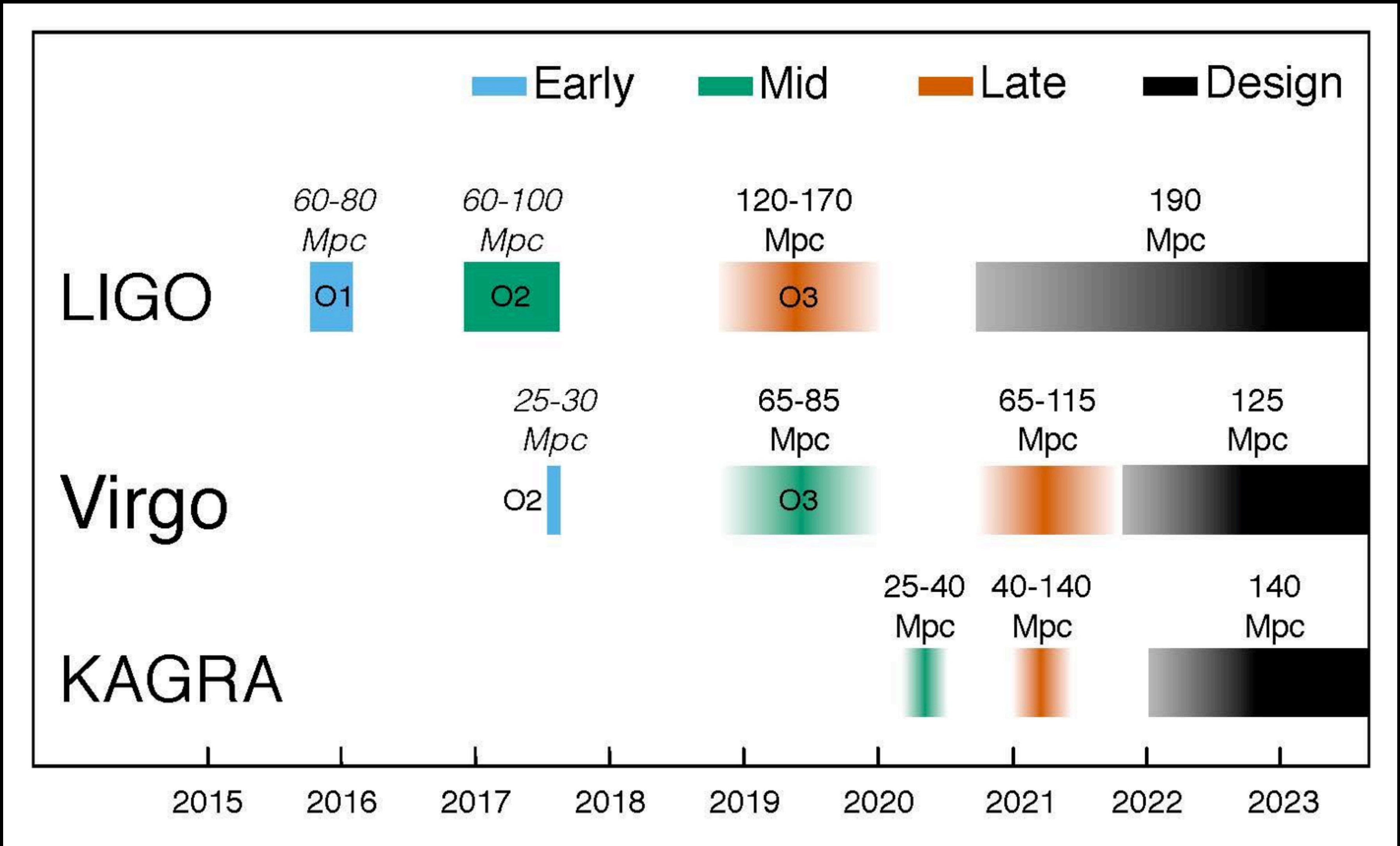
Chair: Lisa Barsotti (MIT)

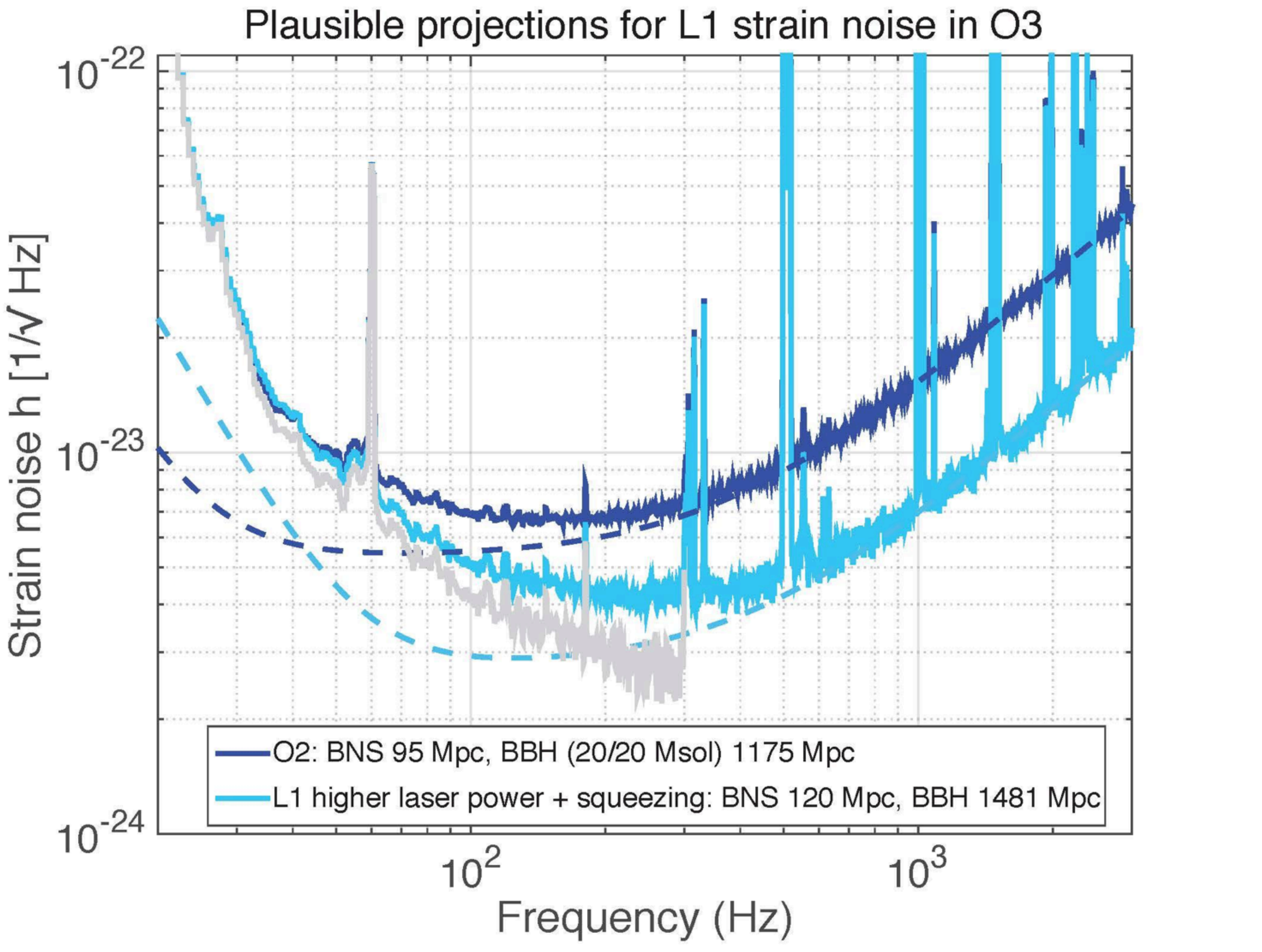
The GW world-wide network

- The present:
  - Advanced LIGO, Advanced Virgo: 2nd generation detectors (2G)
- The near future:
  - Kagra: 2G detector, pioneering 3G technologies
  - LIGO-INDIA
- The future:
  - Improved detectors in current facilities (A+, Voyager, …):
    - 3G technologies in 2G facilities = 2.5G
    - Length and shape constrained by existing facilities
  - New detectors in new facilities (3G)
    - Einstein Telescope concept, Cosmic Explorer concept

LIGO-VIRGO-KAGRA Observing plan

https://arxiv.org/abs/1304.0670




Plausible projections for L1 strain noise in O3
10^{-22}
10^{-23}
10^{-24}
Strain noise h [1/√Hz]
10^{2}
10^{3}
Frequency (Hz)
O2: BNS 95 Mpc, BBH (20/20 Msol) 1175 Mpc
L1 higher laser power + squeezing: BNS 120 Mpc, BBH 1481 Mpc

Can we build more sensitive detectors?
YES, we can.

- **More of the same, but even better**: more power, bigger/heavier masses, lower loss mirror coatings, better suspensions, …
- **New technologies**: squeezed light, alternative wavelengths + cryogenics, alternative optical configurations, ..

- **Make it longer:** take advantage of scaling of noises with arm length
- **Go Underground:** access low frequencies
- **New concepts:** triangular shape, xylophone, ..

ONLY FOR NEW FACILITIES

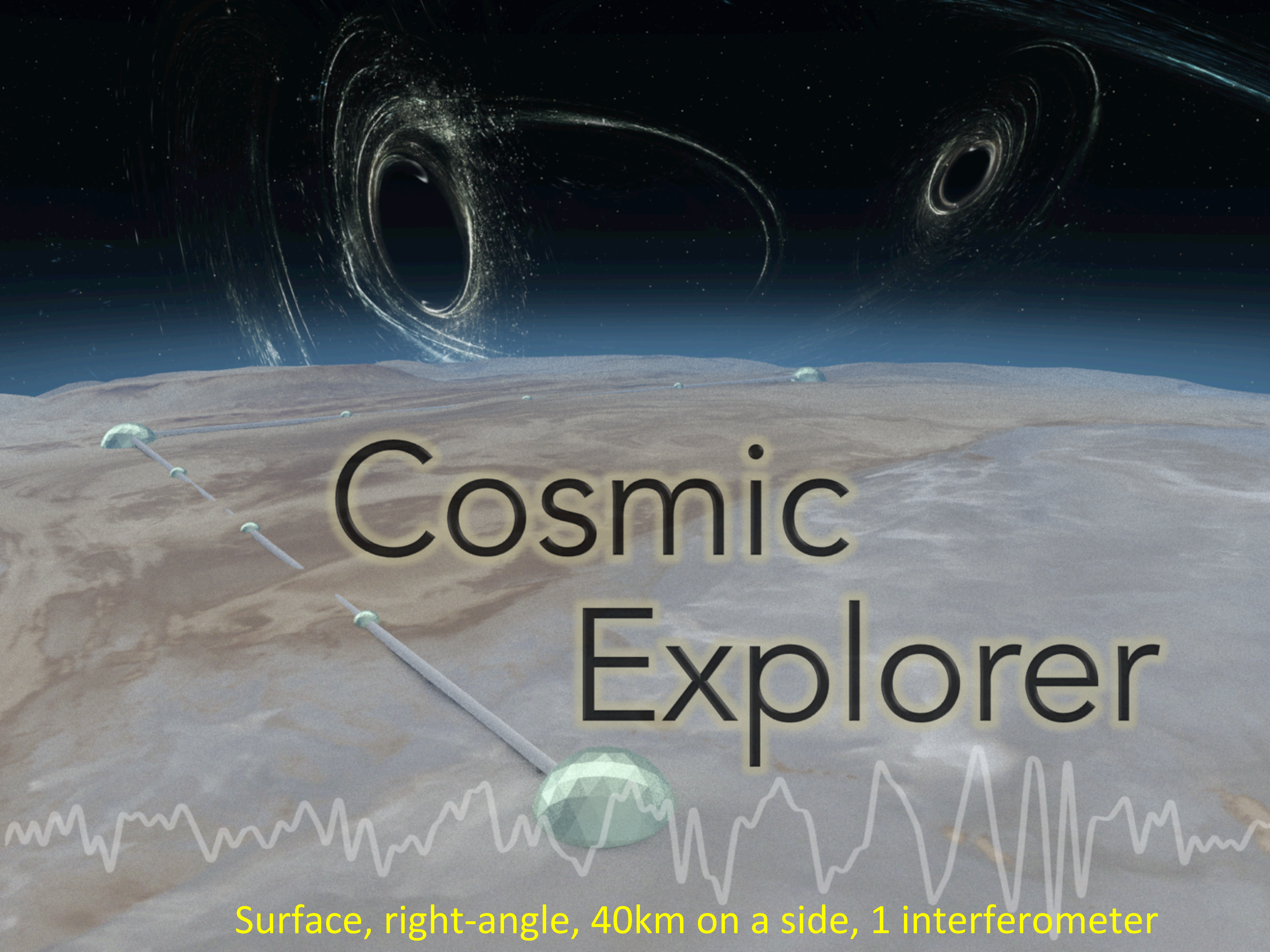
Vision beyond Advanced LIGO

- A+: near term improvement to Advanced LIGO
  - Lower mechanical loss mirror coatings, frequency dependent squeezing

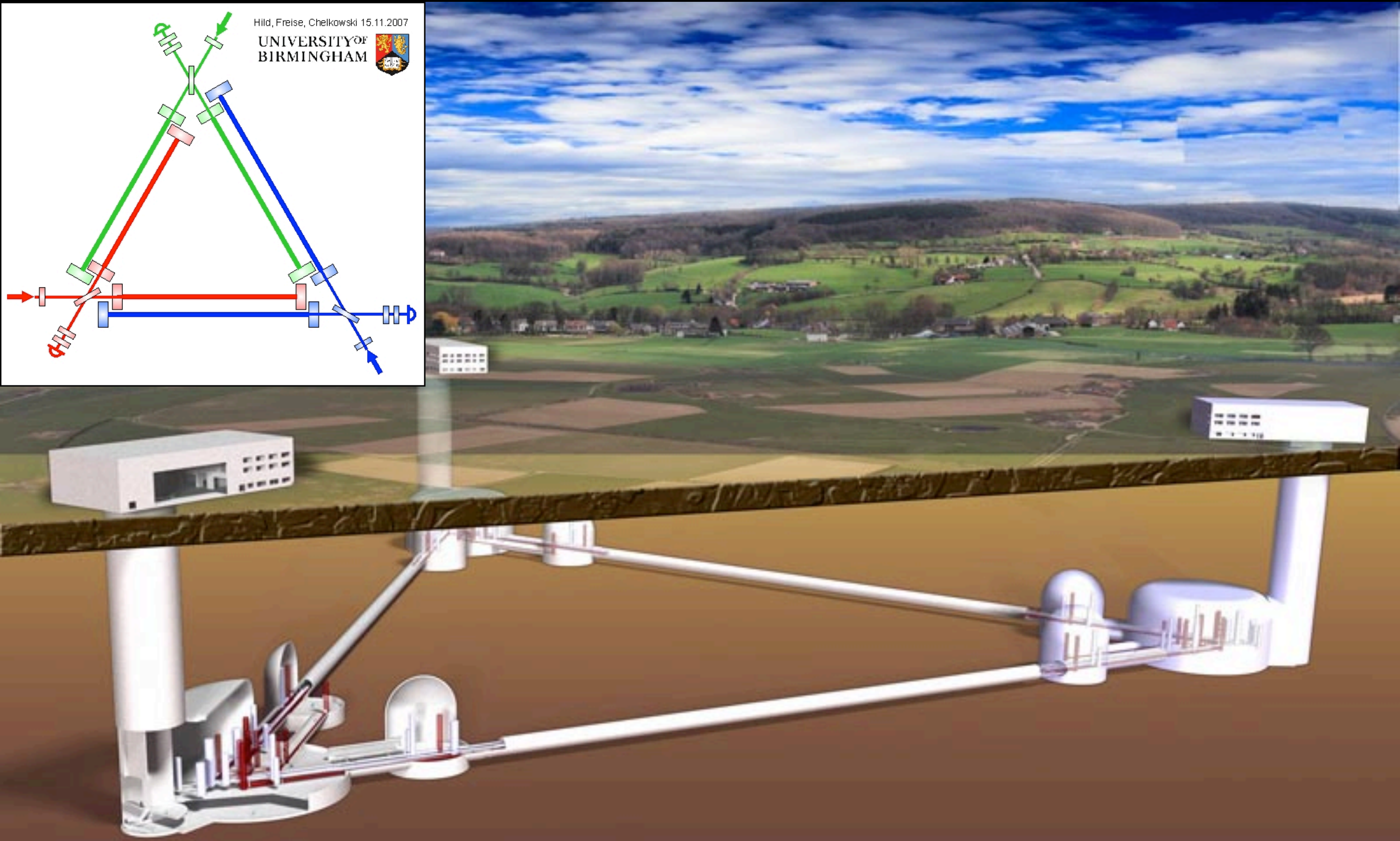
    ⇒ proposal to the NSF in preparation

    ⇒ could be operational by mid-22
- Voyager: same Advanced LIGO facility, possibly 2 um wavelength, modest cryogenics 120K,

    ⇒ world-wide R&D in progress

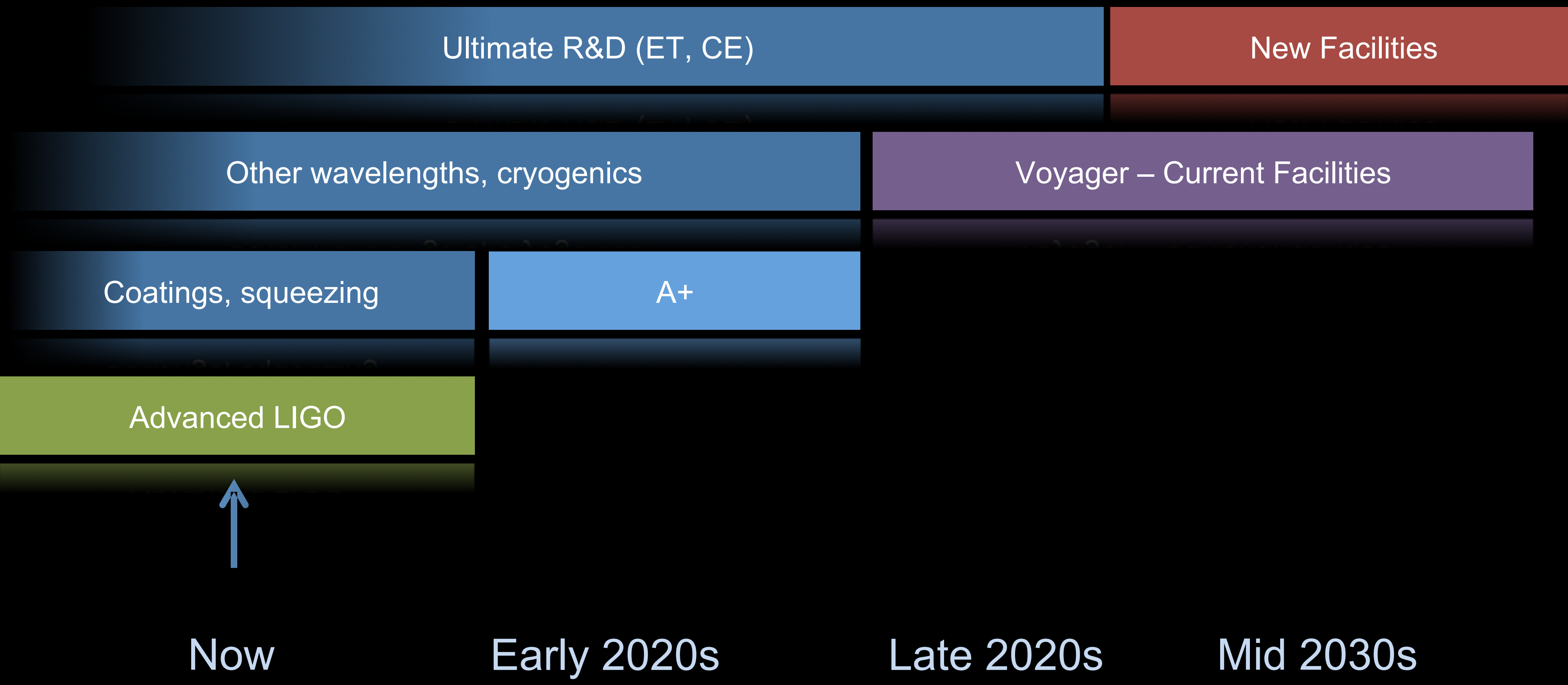

Cosmic
Explorer
Surface, right-angle, 40km on a side, 1 interferometer

Einstein Telescope

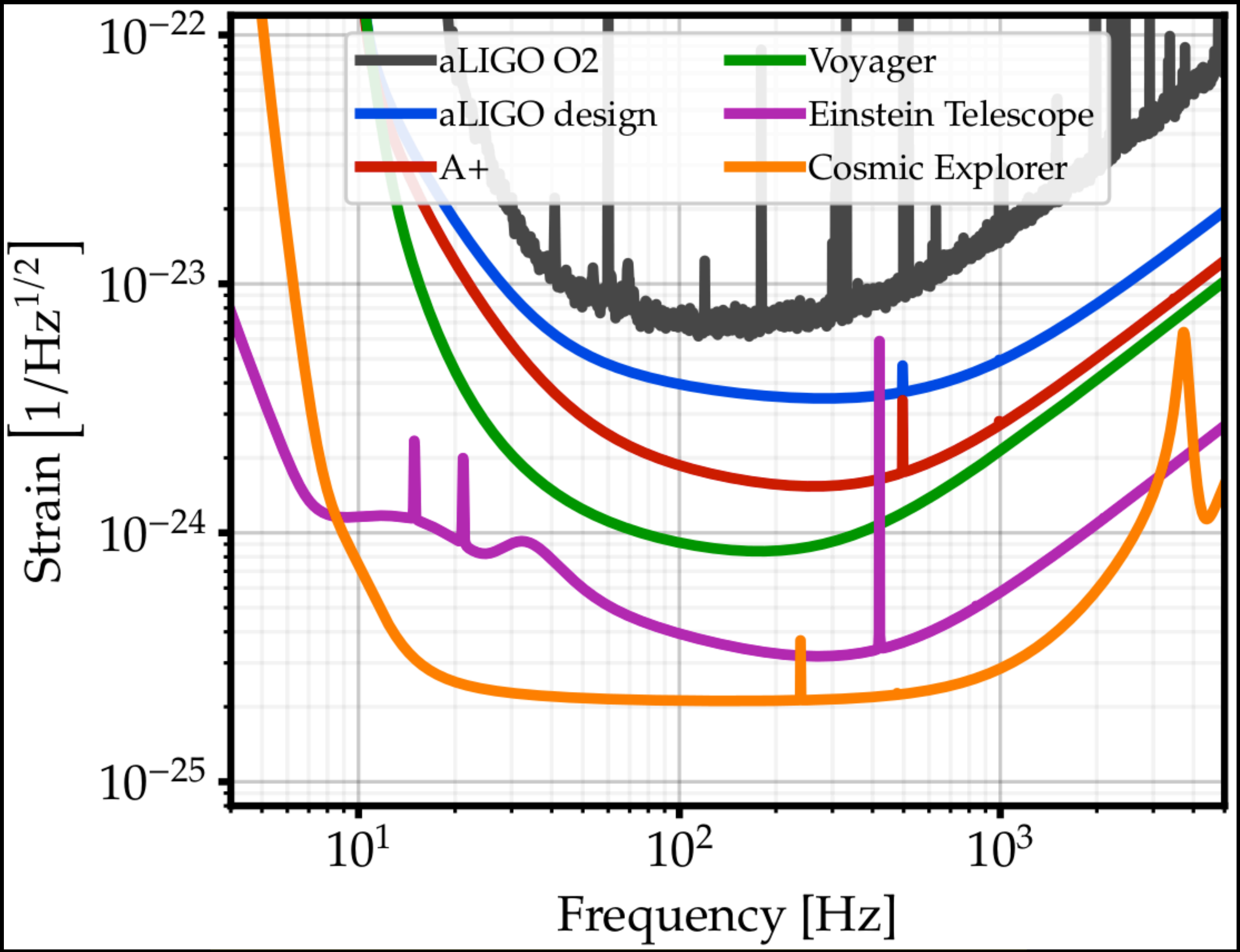


Underground, triangular, 10km on a side, 6 interferometers

Concept Roadmap



Example of curve progression



Uncontroversial goal of the future world-wide GW network: "maximize the science"

- BUT...what does it mean exactly?
- GWIC 3G https://gwic.ligo.org/3Gsubcomm/
- How can we condense the exciting physics that has been described here in a set of relevant metrics to inform the design of the future GW network?

Network Metrics

- How to measure the performance of a network of GW detectors?
  - BBH Range?
  - Median sky localization for BNS sources?
  - High frequency sensitivity?
- How do each of these metrics connect to our science goals?

Metrics: not so simple..

- For a given source, maximizing the number of events might not be what we want:
  - Is the science based on populations, or can we cherry pick the best events?
- Localization only important for close, bright events (don't need BNS localization for z>1)
- Cost (both for construction and operation) is a fundamental driver: how can we compare "cost-equivalent" configurations?

Some Science Targets

- Kilonova, Afterglow, … Multi-messenger physics with BNS events
- NS EOS, Merger and Nuclear Physics
- Testing-GR
- Hubble, Dark Energy, … H(z)
- Populations
  - Metal Production over Cosmic Time - BNS
  - Cosmic Dawn - POP III
  - Inflation - Primordial Black Holes
- Non CBC Sources (CCSN, Strings, …)

Some Science Targets

- Kilonova, Afterglow, … Multi-messenger physics with BNS events Low-z Localization
- NS EOS, Merger and Nuclear Physics kHz sensitivity
- Testing-GR CBC SNR GW Polarization
- Hubble, Dark Energy, … H(z) Low-z Localization kHz sensitivity CBC SNR
- Populations
  - Metal Production over Cosmic Time - BNS
  - Cosmic Dawn - POP III CBC SNR High-z Mass and Distance Estimation
  - Inflation - Primordial Black Holes
- Non CBC Sources (CCSN, Strings, …) kHz sensitivity

3G Mentality

- With 3G detectors we will have ~10^5 of events each year, mostly from z ~ 2 or 3
- Population based science won't need good sky localization
  - Mean and median values are meaningful
- Precision test will be done with the nearby high-SNR events
  - Only best ~10 events per year will be useful

Previous work on network design

Raffai+ 2013, Hu+ 2015:

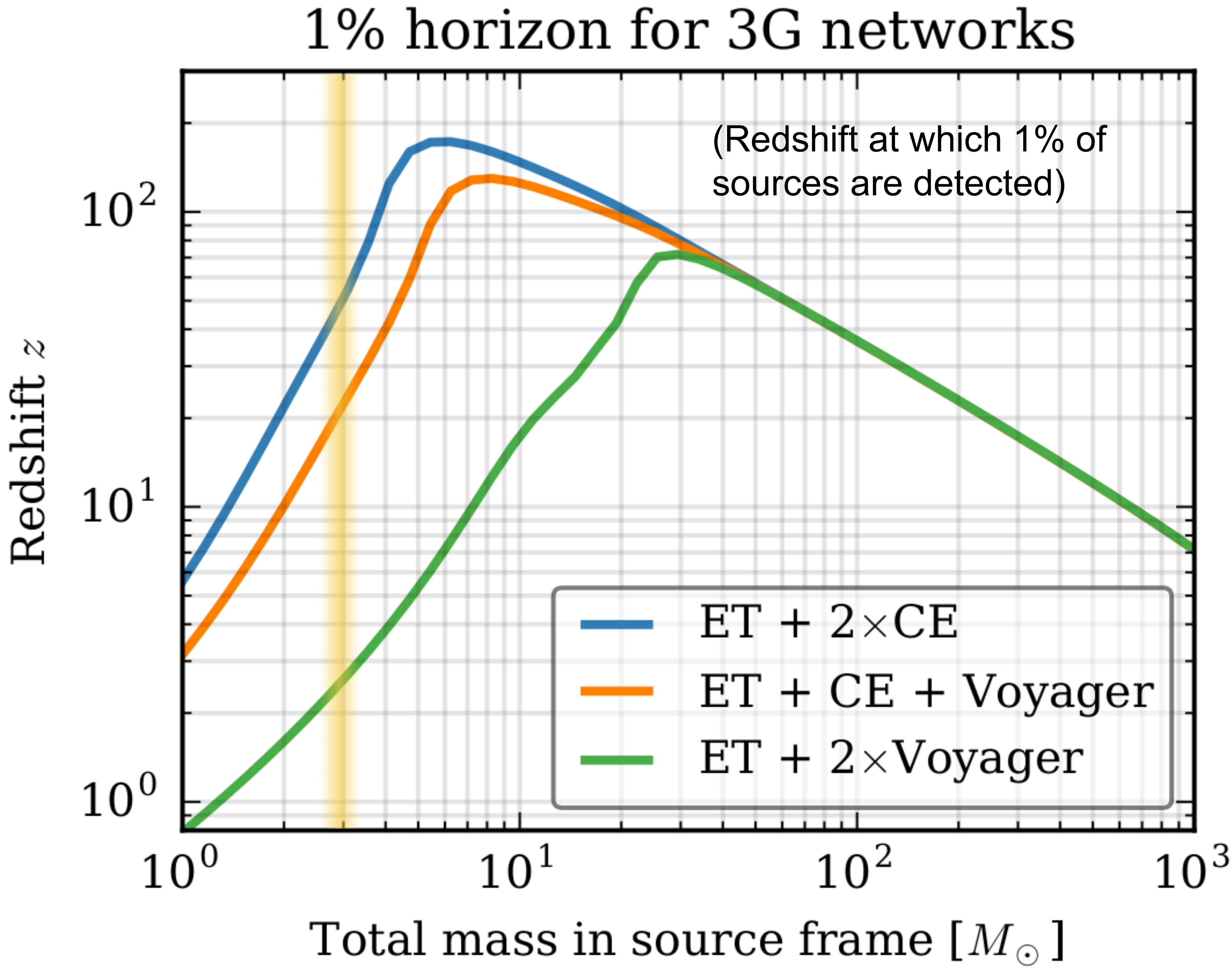
- Numerically optimize detector placement for 2G (aLIGO) and 3G (ET) networks
- Figures of merit: polarization sensitivity, sky localization, and chirp mass reconstruction

Vitale+ 2016:

- Evaluate CBC parameter estimation capabilities for 3G networks (CE, ET)

Mills+ 2017:

- Evaluate localization capabilities for 2G, 3G, and heterogeneous networks (Voyager, CE, ET)



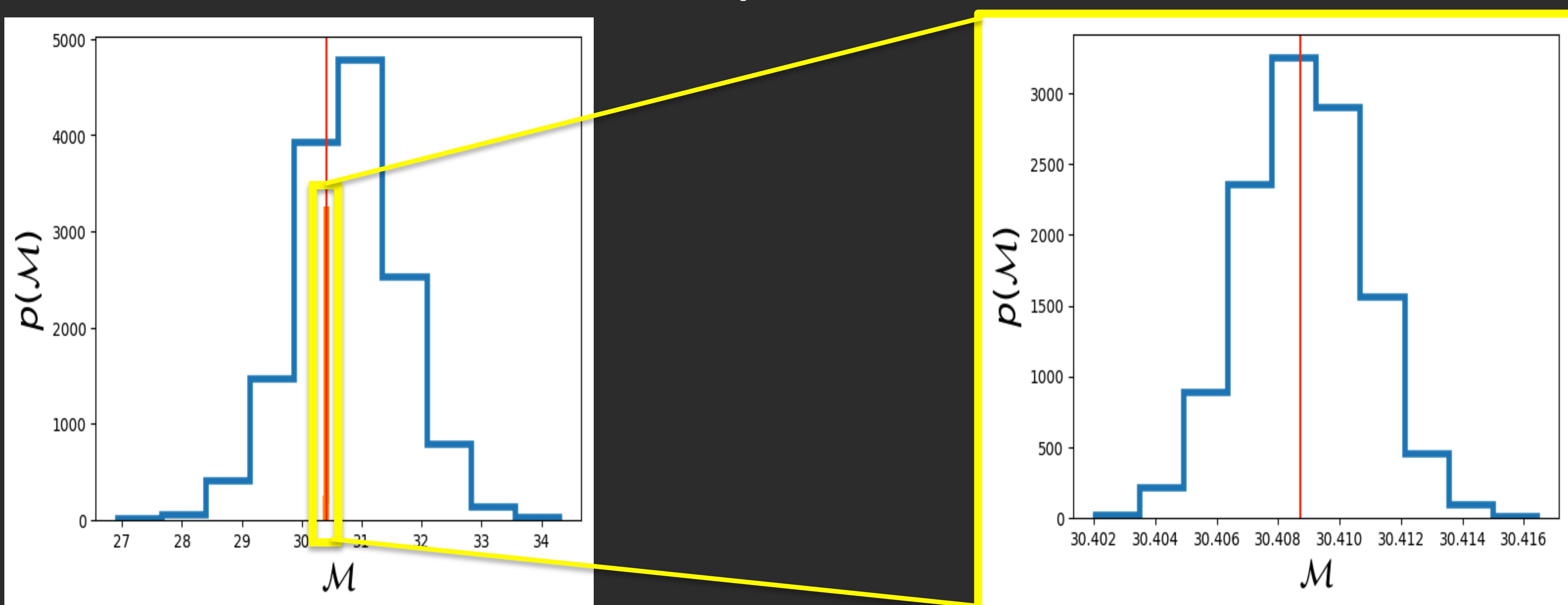
1% horizon for 3G networks
(Redshift at which 1% of
sources are detected)
Redshift z
10^0
10^1
10^2
10^3
Total mass in source frame $[M_\odot]$
ET + 2×CE
ET + CE + Voyager
ET + 2×Voyager

Rough Cost Estimation

- We have cost estimates based on LIGO, ET and LIGO-India experience and costing
- These are not accurate, since costs are inevitably driven by site specific factors and market prices which change with time, but they can be used as a means of making cost-based network optimizations
- We account for:
  - number of interferometers (1 xylophone ET detector is 2 ifos)
  - Ltube, Dtube = length of tube [km] with diameter Dtube [m]
  - Lsurface = length of surface grading [km] (80 for CE)
  - Lflat, Nflat = length and number of flat sections [km] (40, 2 for CE)
  - Ltunnel = lentgh of tunnel [km] (30 for ET)
  - Hdepth = depth of tunnel [m] (200 for ET)
  - Ncavern = major halls (3 for ET triangle)

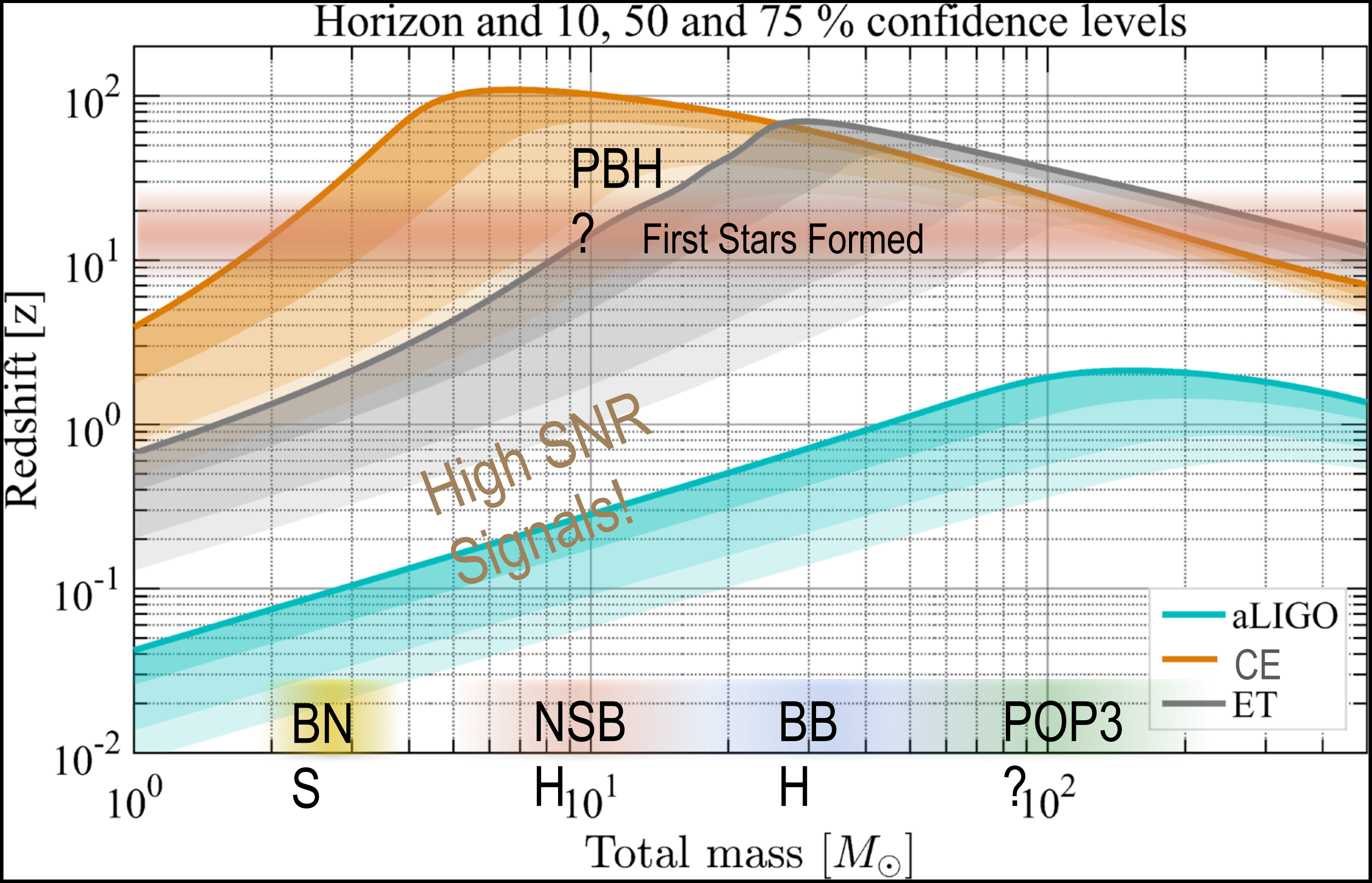
From Salvatore Vitale

- A GW150914-like event will have SNR~2000 in a Cosmic Explorer facility.
- How well can we do parameter estimation?



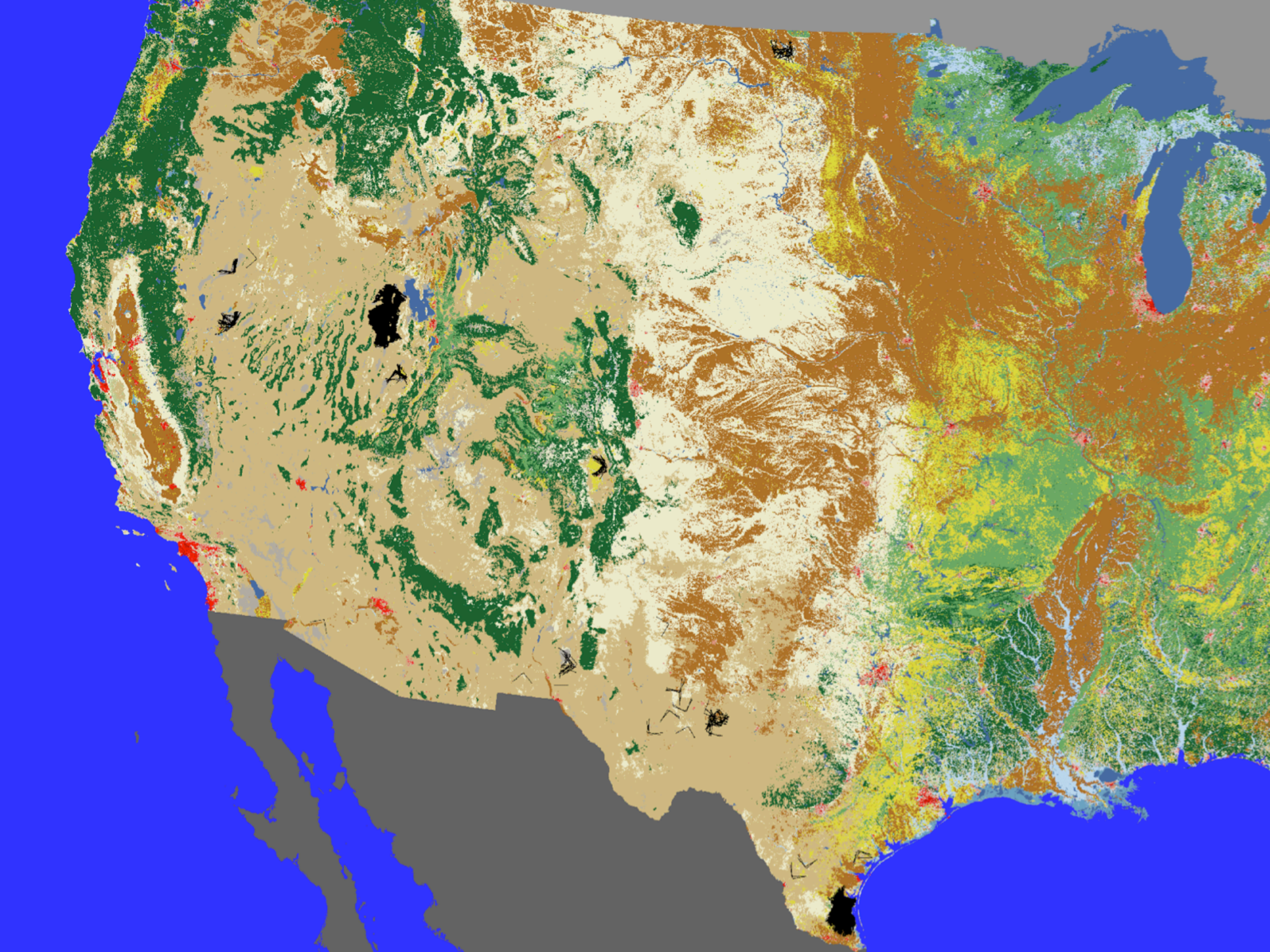
preliminary

BBH and BNS from the entire Universe!

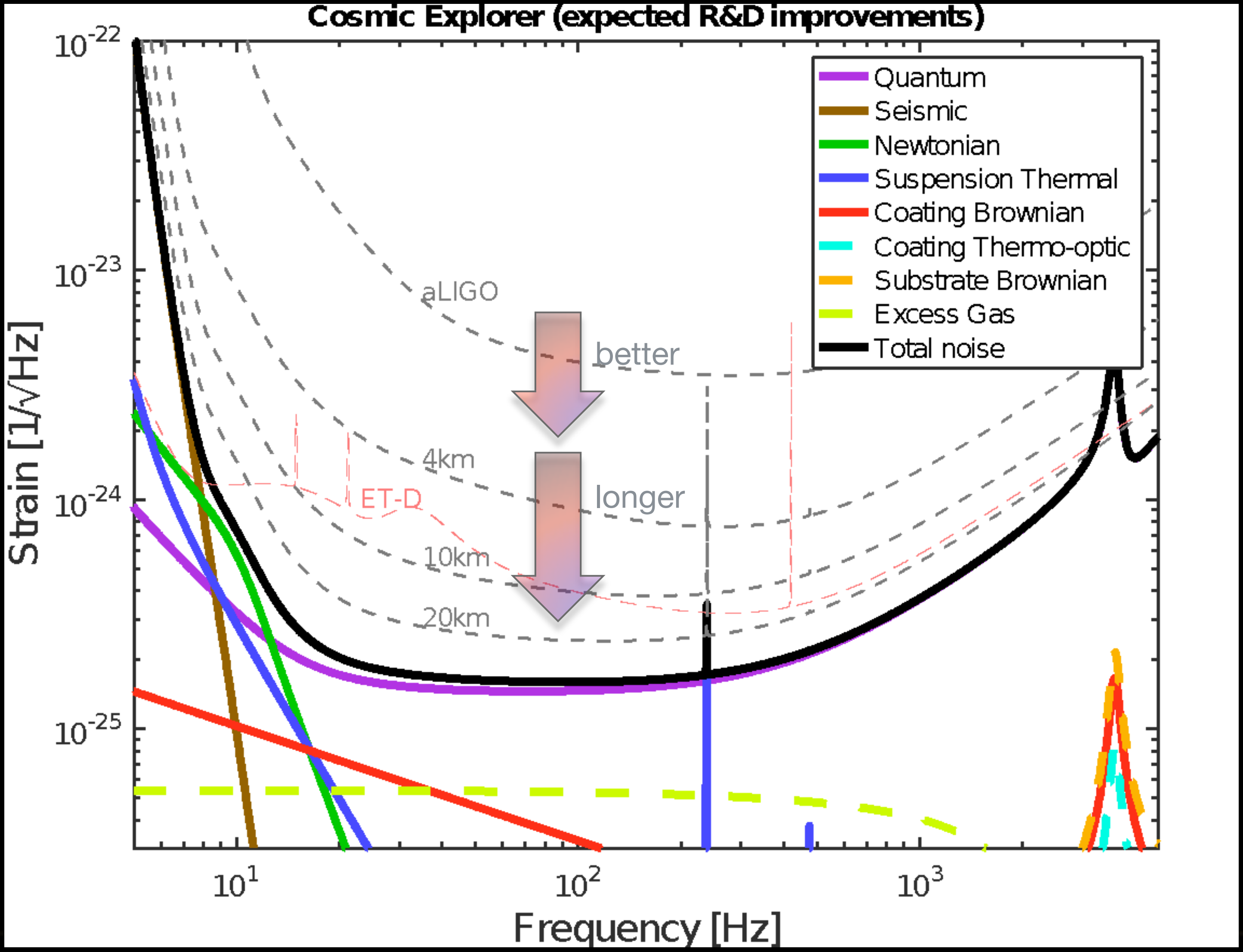


Parameter estimation for binary black holes with networks of third-generation gravitational-wave detectors.
Vitale, Evans (2017) PRD 95, 064052

Observing primordial gravitational waves below the binary-black-hole-produced stochastic background
Regimbau, Evans, …, Vitale, (2017) PRL 118, 151105

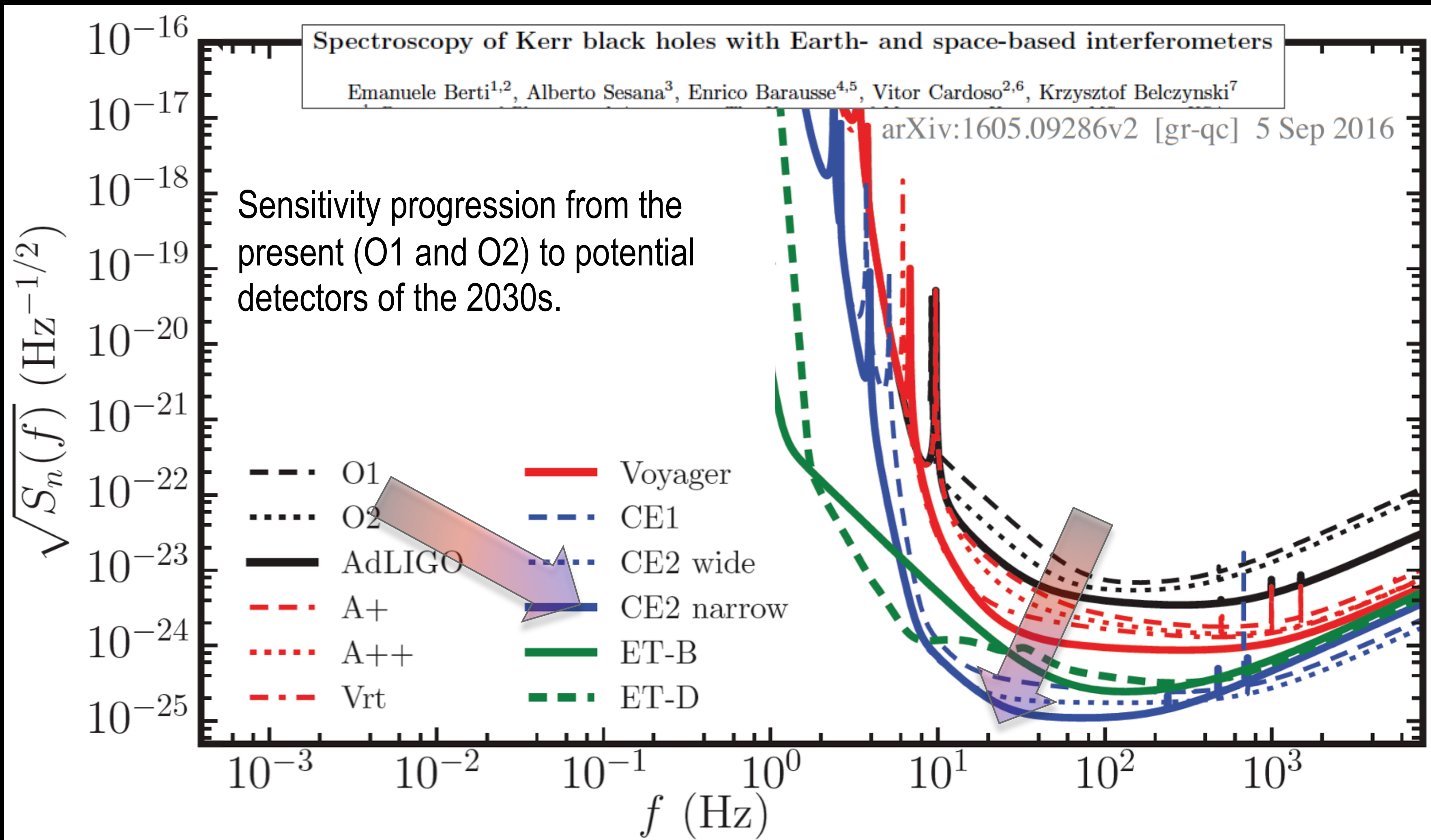


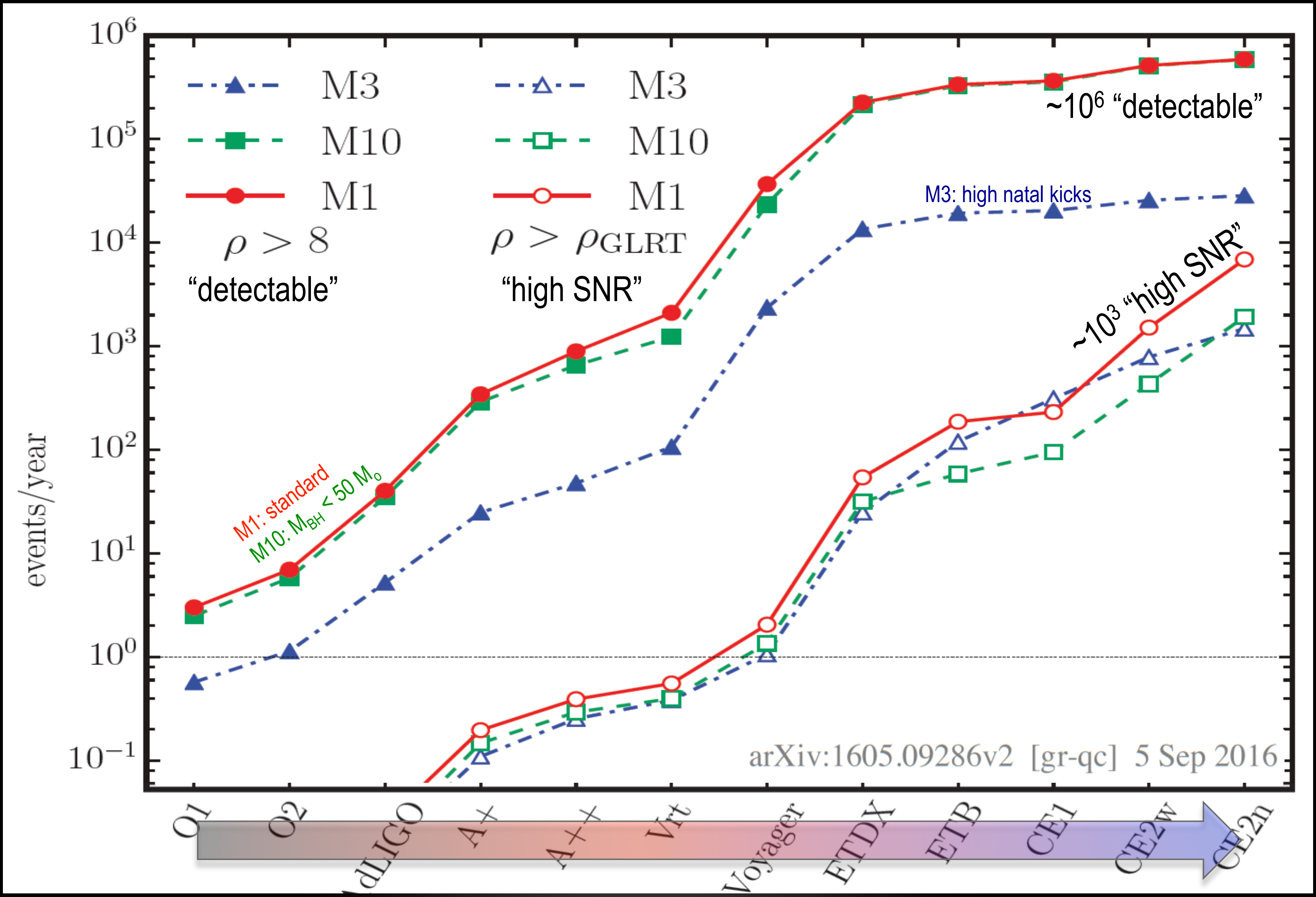
COSMIC EXPLORER:
a 40km facility with new coatings and squeezing



Exploring the sensitivity of next generation gravitational wave detectors (2017) CQG 34, 044001

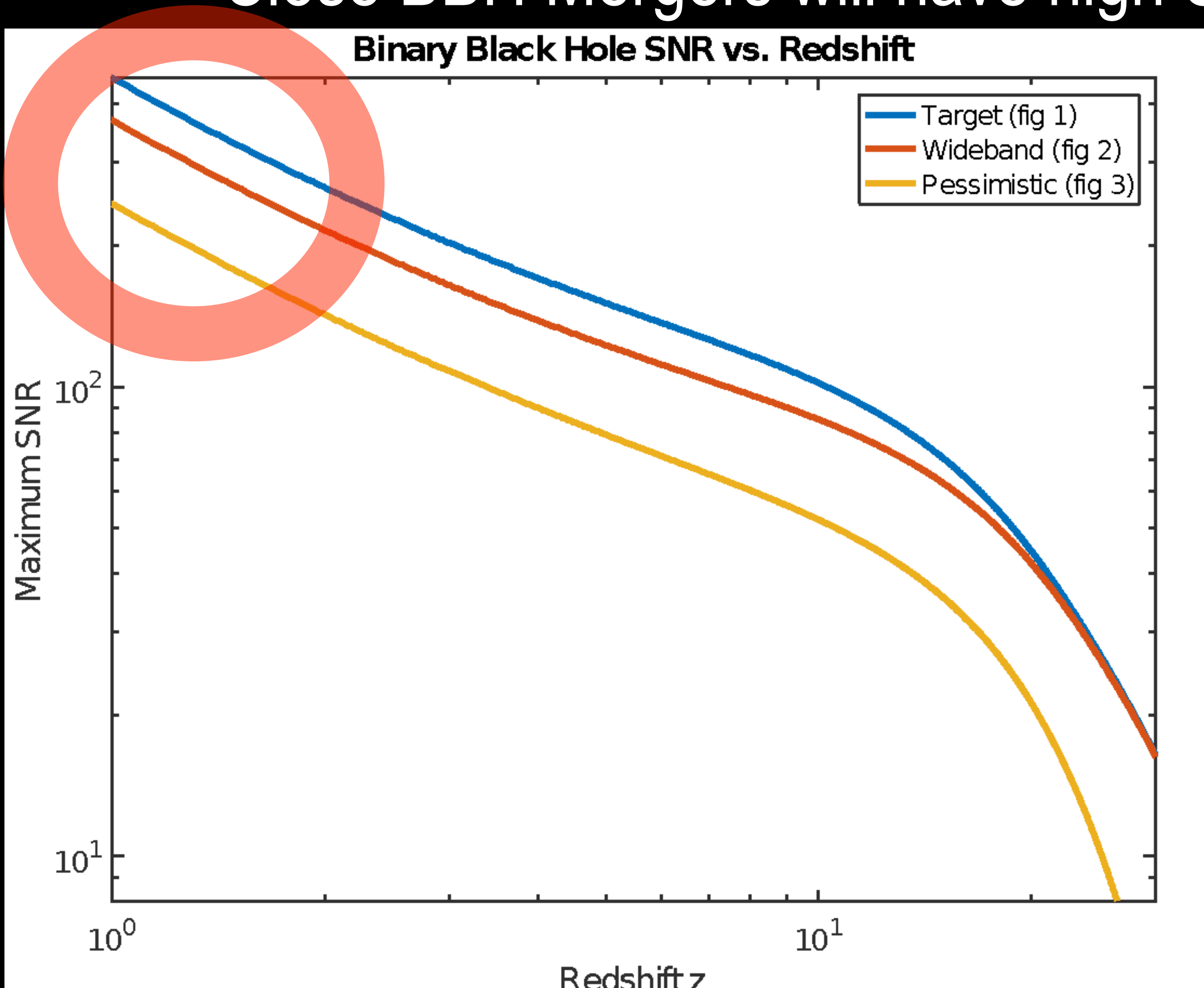
Over the next 20 years…





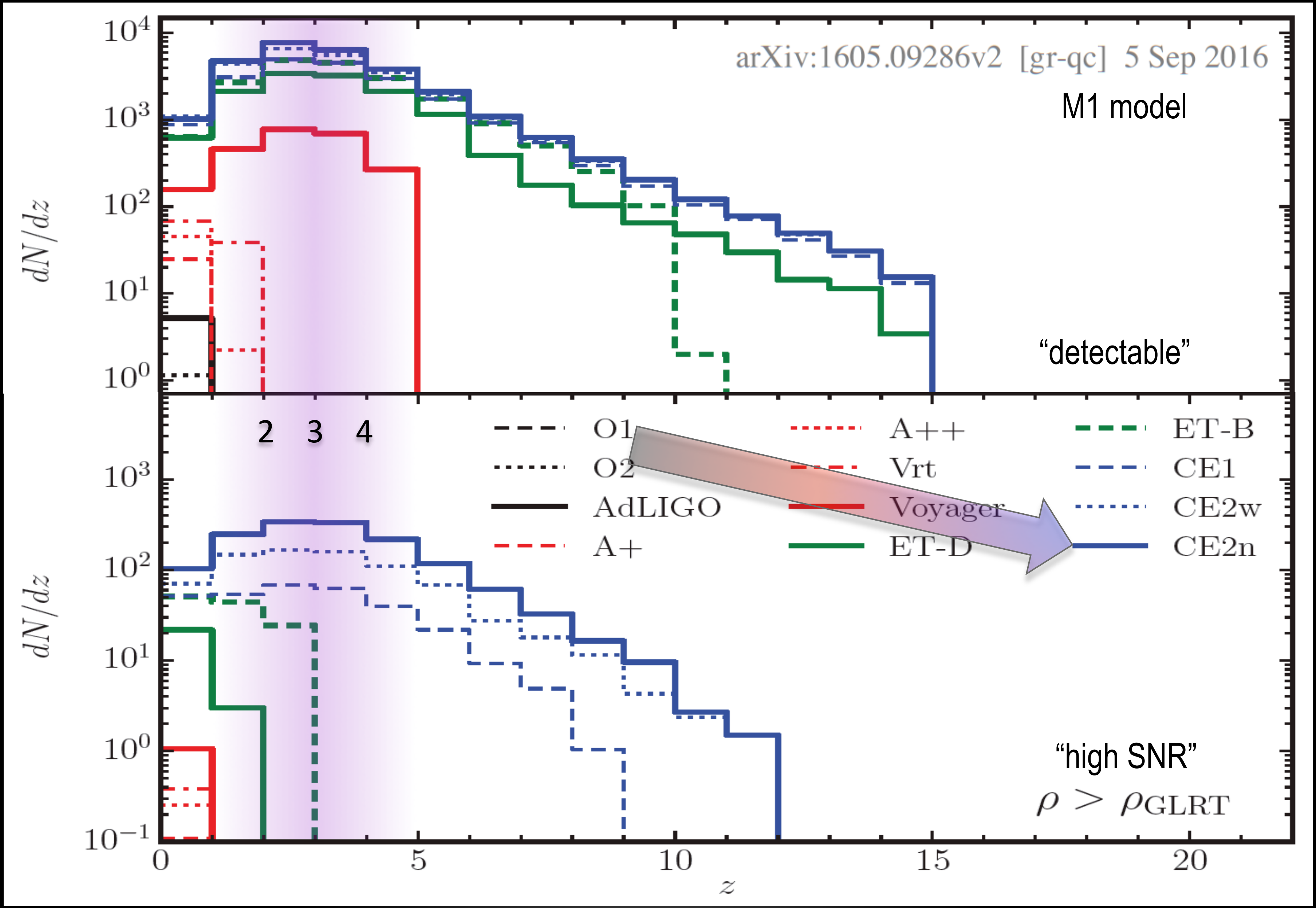
events/year
M3
M10
M1
$\rho > 8$
"detectable"
M3
M10
M1
$\rho > \rho_{GLRT}$
"high SNR"
~10^6 "detectable"
M3: high natal kicks
~10^3 "high SNR"
M1: standard
M10: M_{BH} < 50 M_o
arXiv:1605.09286v2 [gr-qc] 5 Sep 2016
O1
O2
AdLIGO
A+
A++
Vrt
Voyager
ETDX
ETB
CE1
CE2w
CE2n

Close BBH Mergers will have high SNR



Exploring the sensitivity of next generation gravitational wave detectors

CQG doi:10.1088/1361-6382/aa51f4


arXiv:1605.09286v2 [gr-qc] 5 Sep 2016
M1 model
"detectable"
"high SNR"
$\rho > \rho_{GLRT}$
dN/dz
z
2 3 4
O1
O2
AdLIGO
A+
A++
Vrt
Voyager
ET-D
ET-B
CE1
CE2w
CE2n

Hubble Constant (science goal weight? Not high?)

- Galaxy associations with localization volume
  - Requires localization of 10s of sources
  - Limited to low redshifts by galaxy catalogs
- Mass distribution
  - Just needs many sources
- BNS Spectroscopy
  - Needs high frequency sensitivity
- EM counterparts
  - Needs localization of local sources

BBH matter distribution vs. BAO