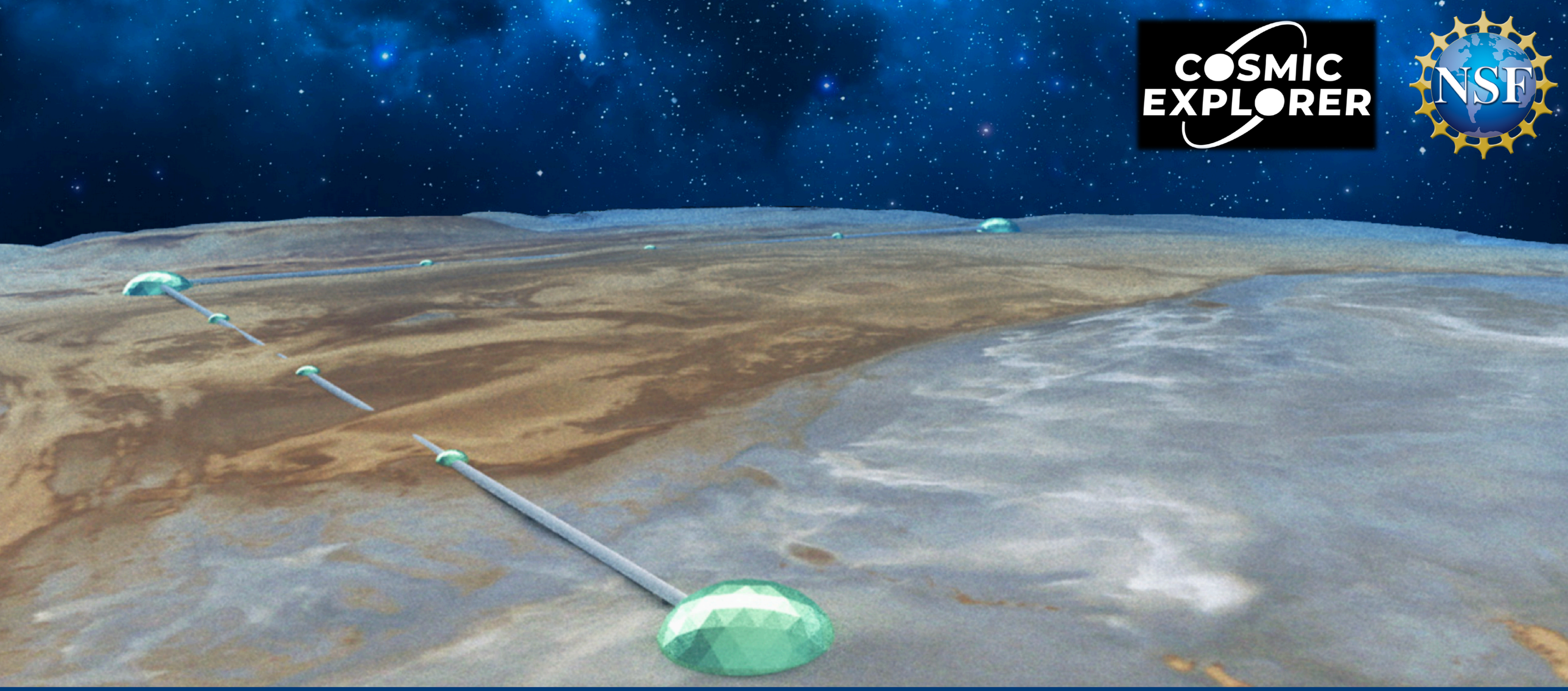


Cosmic Explorer Trade Study: Forecast for Future Gravitational-wave Networks

Ssohrab Borhanian (on behalf of the CE Project)

GWADW2021 — May 17, 2021

Cosmic Explorer Science Goals & Performance Metrics

1. **Black Holes and Neutron Stars throughout Cosmic Time**
    - Merger rates, mass/spin range limits, maximum observable redshifts for NS
2. **Dynamics of Dense Matter**
    - NS radius, ellipticity, EoS, central density/pressure, post-merger-signal
    - Critical parameters of hadron-quark phase transition
    - Number of sources with electromagnetic afterglows or GRBs
3. **Extreme Gravity and Fundamental Physics**
    - Graviton mass, PN parameter, exotic compact objects, primordial BHs
    - Hubble parameter, dark energy density/EoS, primordial background
    - Axion mass/cross section, stochastic backgrounds from cosmological phase transitions

Populations & Networks

- 2 populations: BNSs and BBHs
- 6 redshift bins: 250,000 injections & uniformly distributed in
  $z \in [0,0.5], [0.5,1], [1,2], [2,4], [4,10], [10,50]$
  - Merger rates:

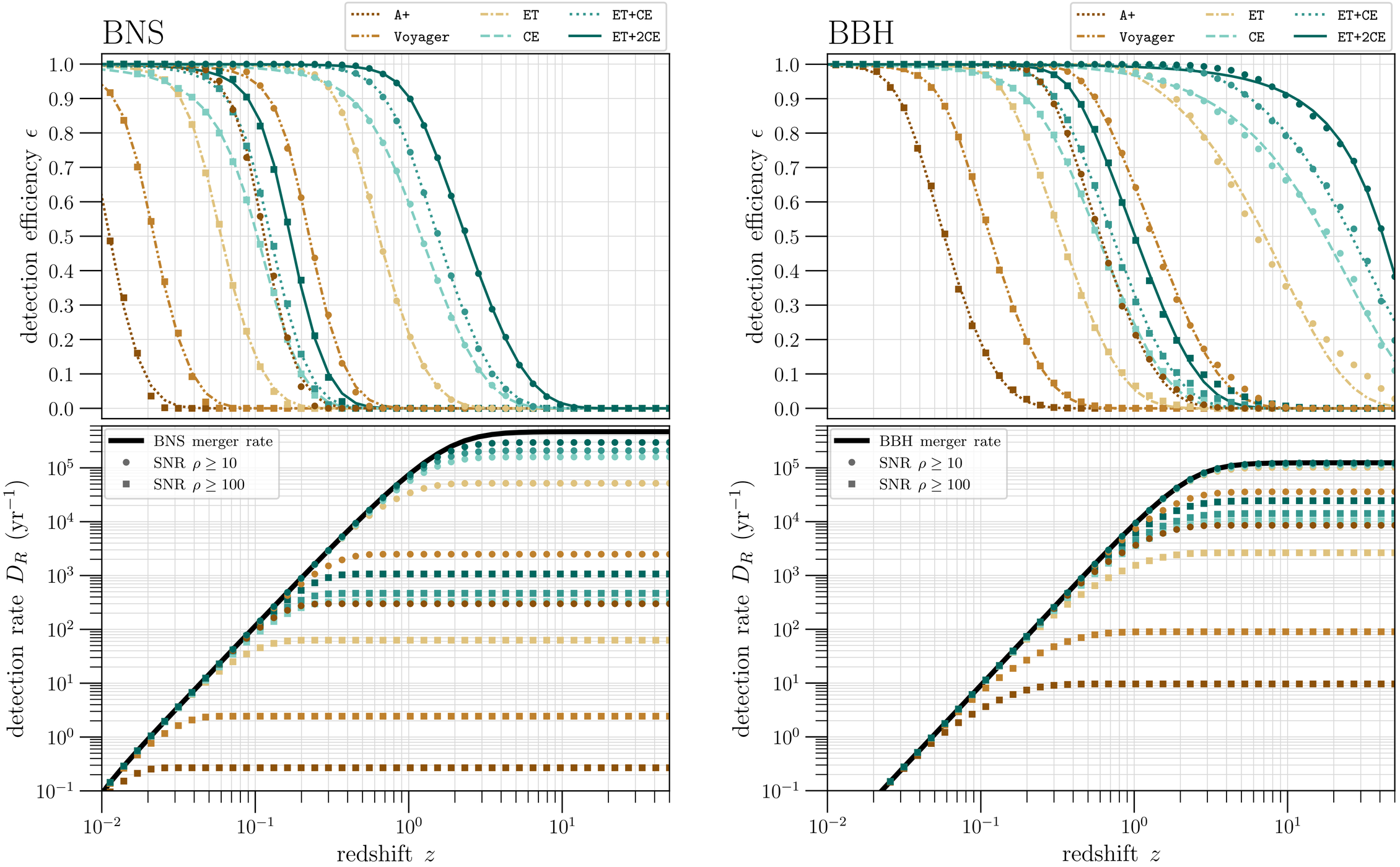
    $R_{\mathrm{BNS}} \approx 4.7 \times 10^{5}\,\mathrm{yr}^{-1}$

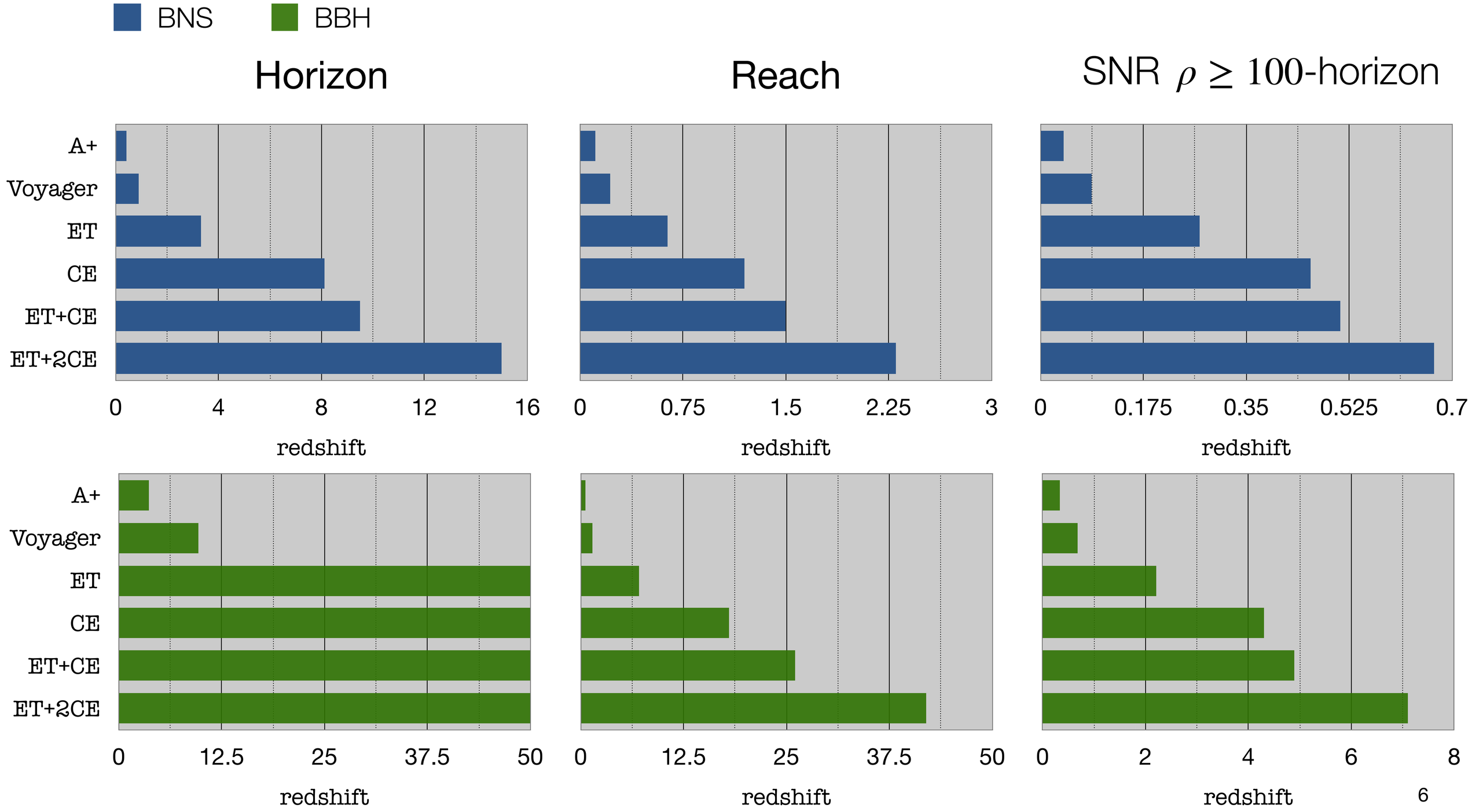
    $R_{\mathrm{BBH}} \approx 1.2 \times 10^{5}\,\mathrm{yr}^{-1}$
- Waveform models:
  - BNS: `IMRPhenomD_NRTidalv2`
  - BBH: `IMRPhenomHM`

- 6 Networks:
  - `A+` … HLVKI+
  - `Voyager` … VK+HLIvc
  - `ET` … HLKI+E
  - `CE` … VKI+Ca4c
  - `ET+CE` … KI+ECa4c
  - `ET+2CE` … ESa4cCa4c

Network Efficiency and Detection Rates

Redshift range: $z \in [0.02, 50]$

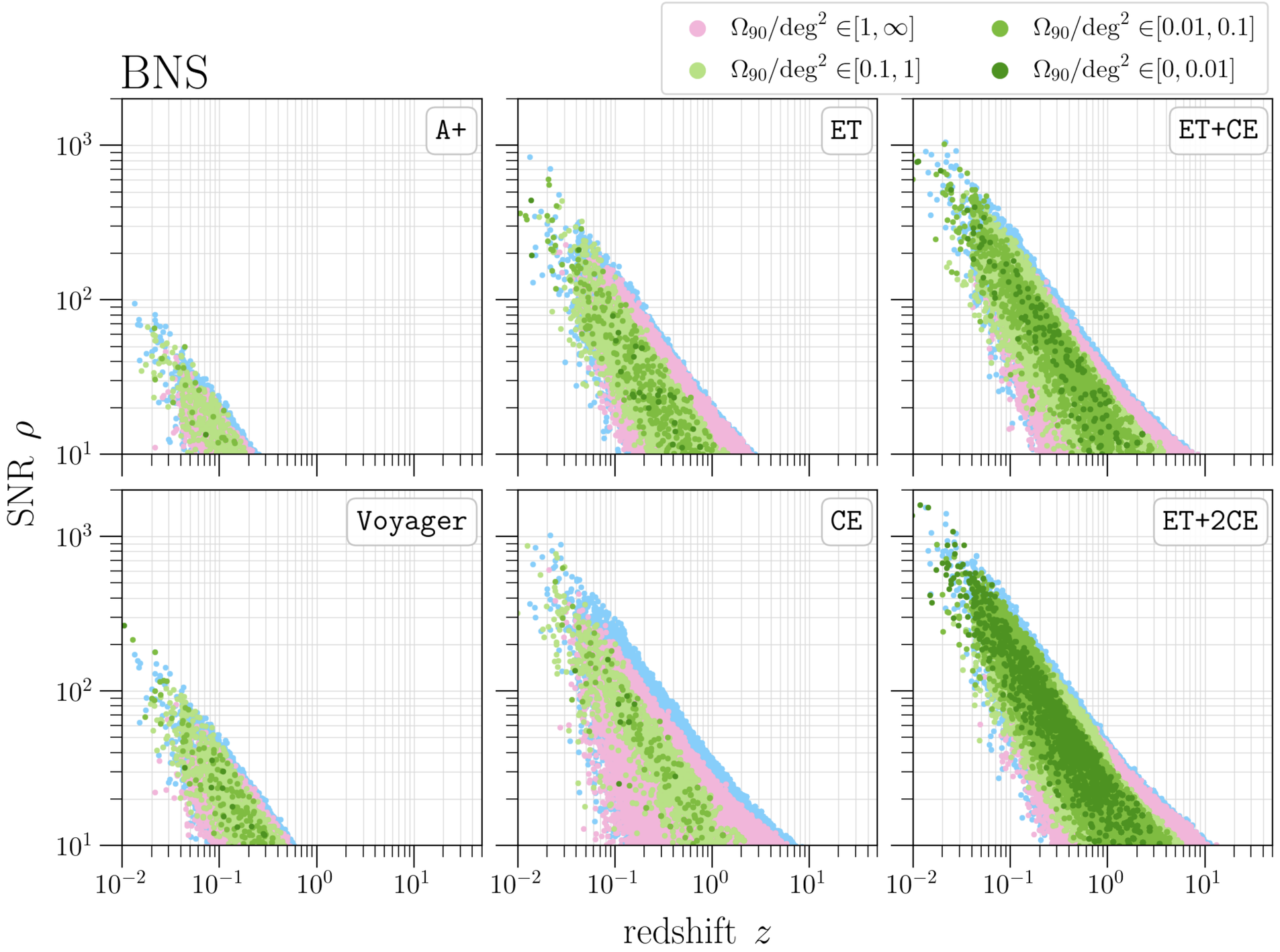

BNS
BBH
A+
Voyager
ET
CE
ET+CE
ET+2CE
detection efficiency ϵ
BNS merger rate
BBH merger rate
SNR $\rho \geq 10$
SNR $\rho \geq 100$
detection rate D_R (yr^{-1})
redshift z

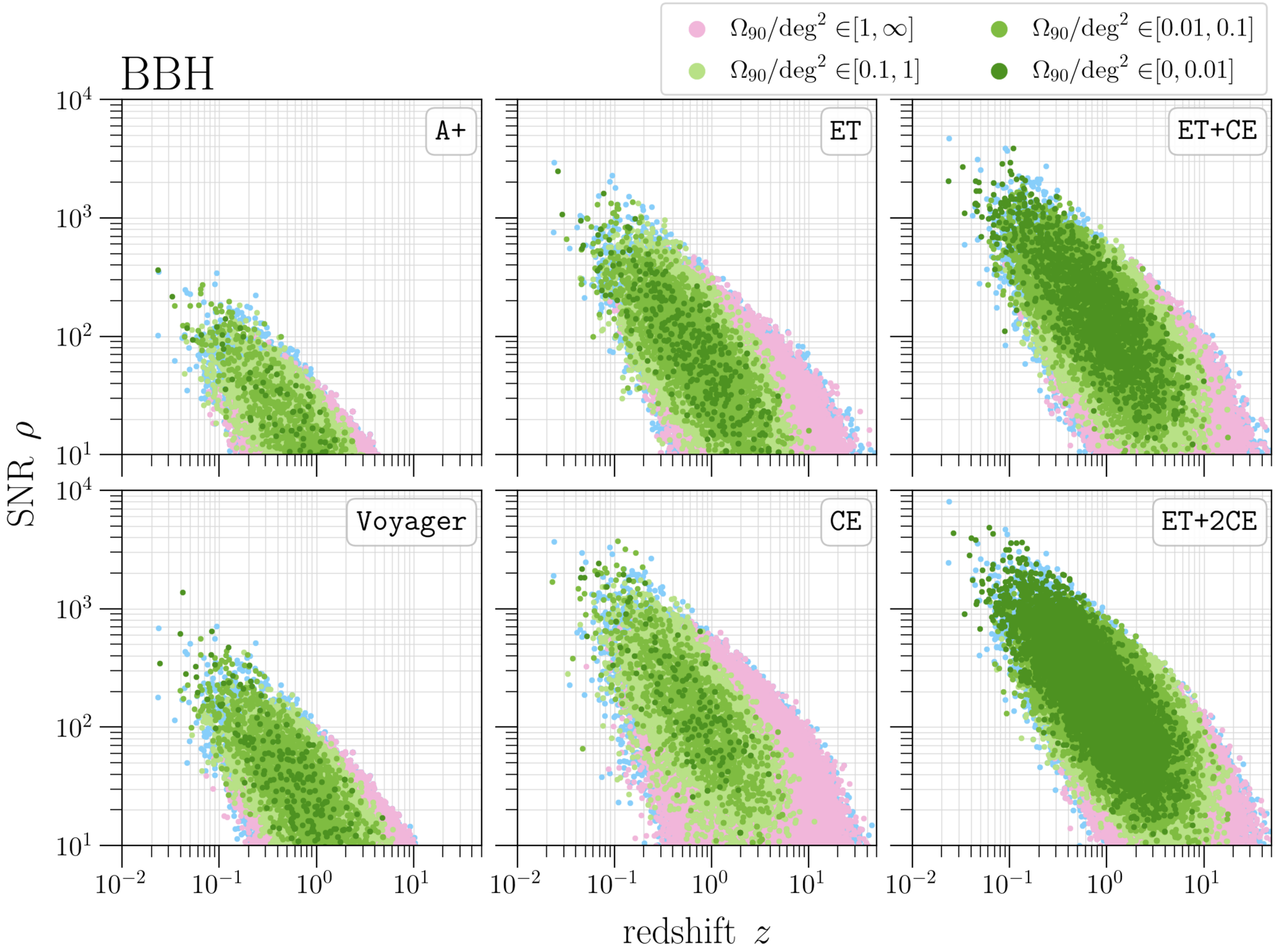

BNS
BBH
Horizon
Reach
SNR $\rho \geq 100$-horizon
A+
Voyager
ET
CE
ET+CE
ET+2CE
0
4
8
12
16
0
0.75
1.5
2.25
3
0
0.175
0.35
0.525
0.7
redshift
redshift
redshift
A+
Voyager
ET
CE
ET+CE
ET+2CE
0
12.5
25
37.5
50
0
12.5
25
37.5
50
0
2
4
6
8
redshift
redshift
redshift

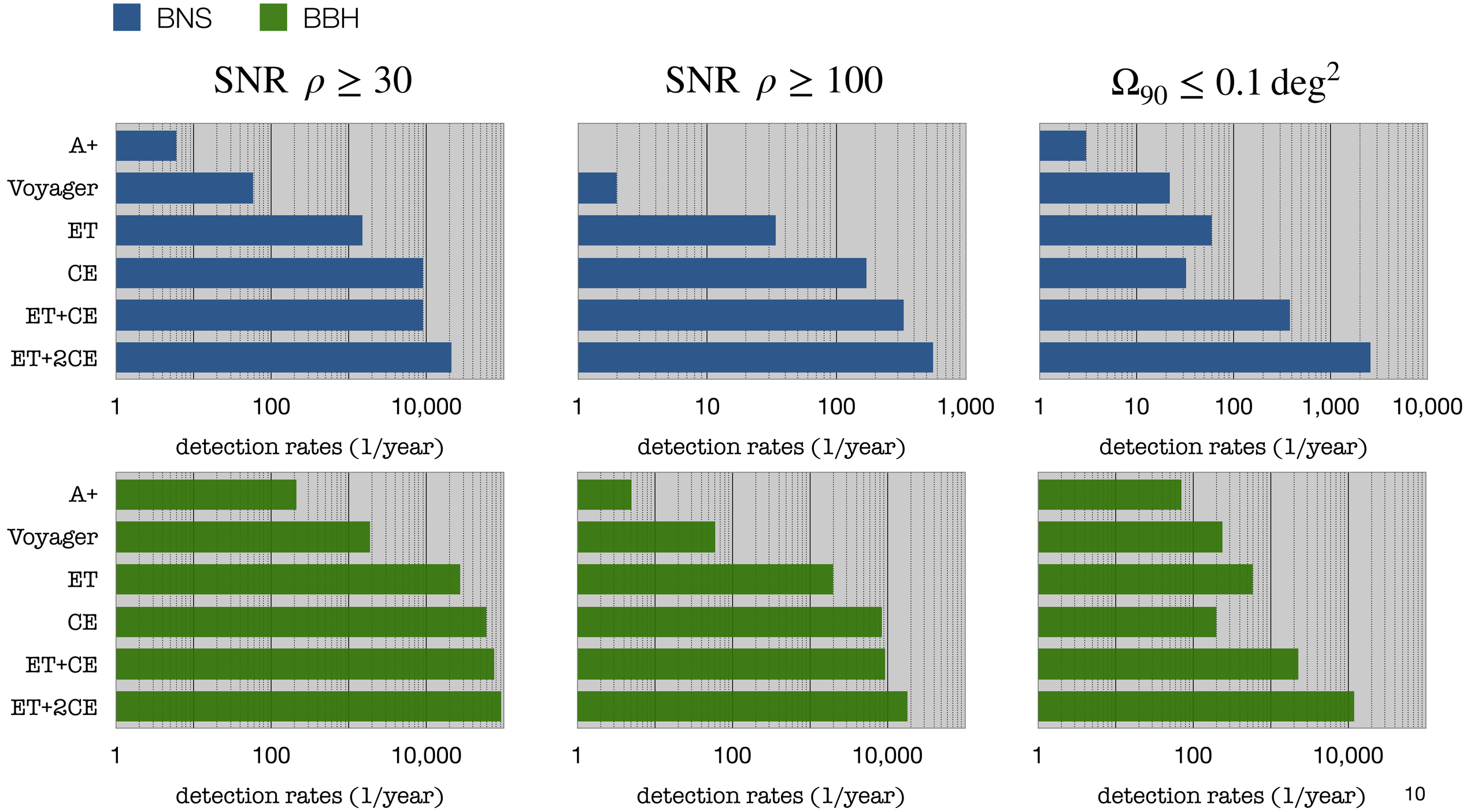
Visibility and Measurement Quality

Redshift z vs SNR ρ and sky area Ω_{90}

Redshift range: $z \in [0.02,50]$


BNS
$\Omega_{90}/\mathrm{deg}^2 \in [1, \infty]$
$\Omega_{90}/\mathrm{deg}^2 \in [0.1, 1]$
$\Omega_{90}/\mathrm{deg}^2 \in [0.01, 0.1]$
$\Omega_{90}/\mathrm{deg}^2 \in [0, 0.01]$
A+
ET
ET+CE
Voyager
CE
ET+2CE
SNR ρ
redshift z
10^1
10^2
10^3
10^{-2}
10^{-1}
10^0
10^1


BBH
$\Omega_{90}/\mathrm{deg}^2 \in [1, \infty]$
$\Omega_{90}/\mathrm{deg}^2 \in [0.1, 1]$
$\Omega_{90}/\mathrm{deg}^2 \in [0.01, 0.1]$
$\Omega_{90}/\mathrm{deg}^2 \in [0, 0.01]$
A+
ET
ET+CE
Voyager
CE
ET+2CE
SNR ρ
redshift z
10^4
10^3
10^2
10^1
10^{-2}
10^{-1}
10^0
10^1


BNS
BBH
SNR $\rho \geq 30$
SNR $\rho \geq 100$
$\Omega_{90} \leq 0.1\,\mathrm{deg}^2$
A+
Voyager
ET
CE
ET+CE
ET+2CE
1
100
10,000
10
1,000
detection rates (1/year)

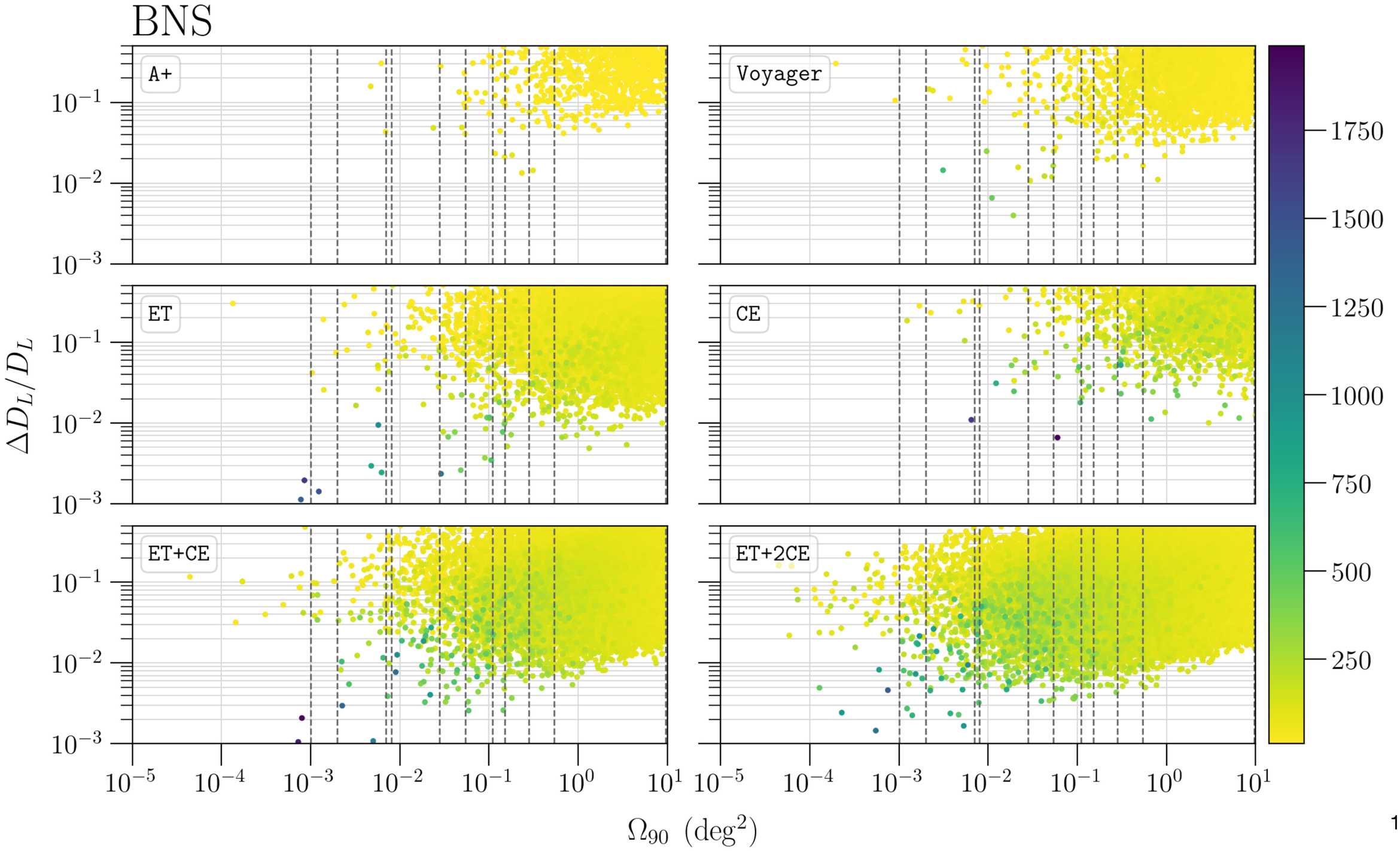
Enabling Multi-messenger Astronomy

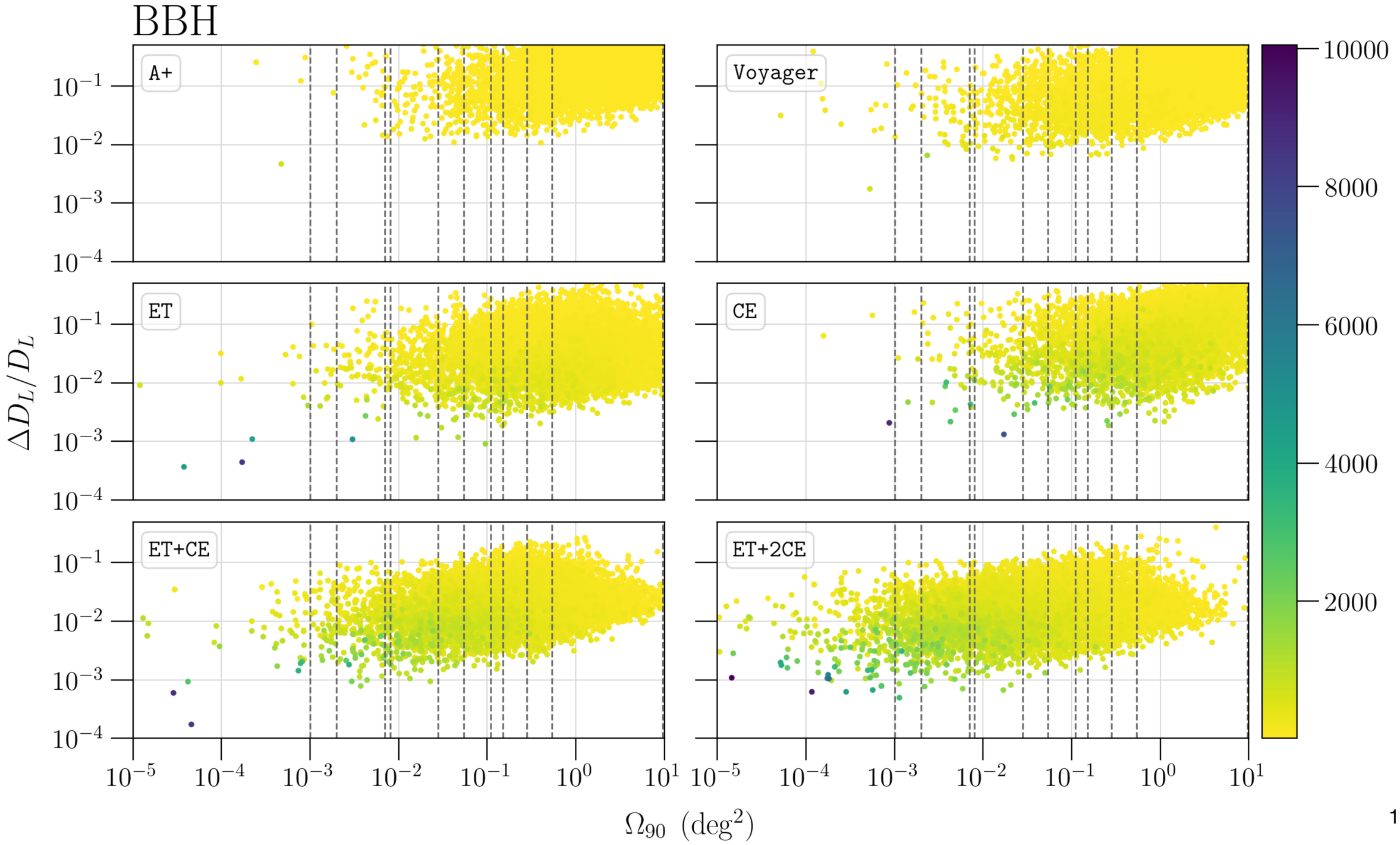
Sky area Ω_{90} vs distance estimation $\Delta D_L/D_L$ vs SNR ρ

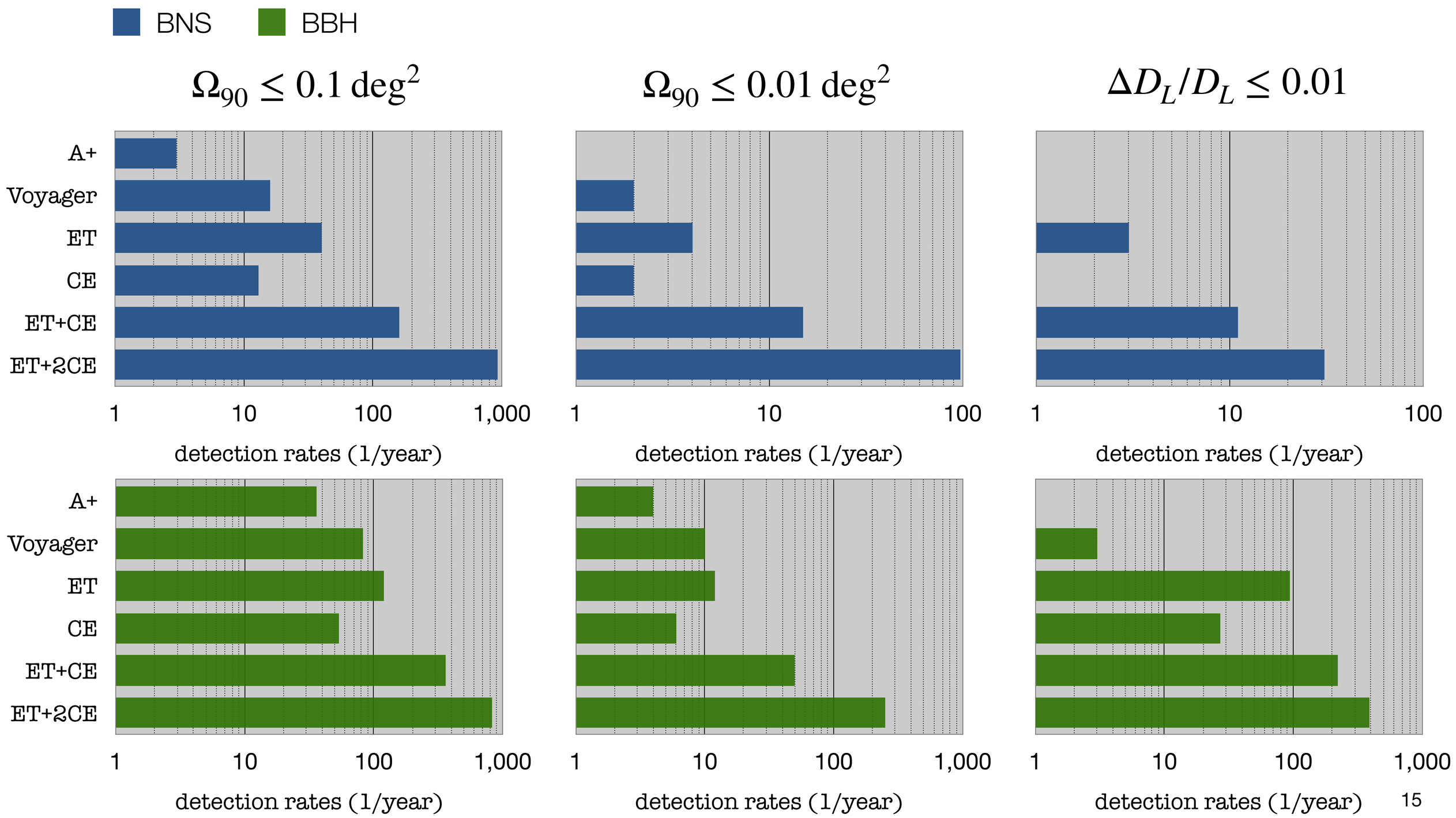
Redshift range: $z \in [0.02,0.5]$

Field-of-views for Electromagnetic Telescopes

EM telescope	FOV (deg^2)
Rubin Observatory	9.6
EUCLID	0.54
WFIRST	0.28
Chandra	0.15
20m–Telescope	0.11
Keck II	0.11
VLT	0.054
ELT	0.028
GMT	0.008
Swift–XRT	0.007
Lynx	0.007
HST–WFC3	0.002
Athena	0.001


BNS
A+
Voyager
ET
CE
ET+CE
ET+2CE
$\Delta D_L/D_L$
Ω_{90} (deg^2)
10^{-1}
10^{-2}
10^{-3}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
1750
1500
1250
1000
750
500
250

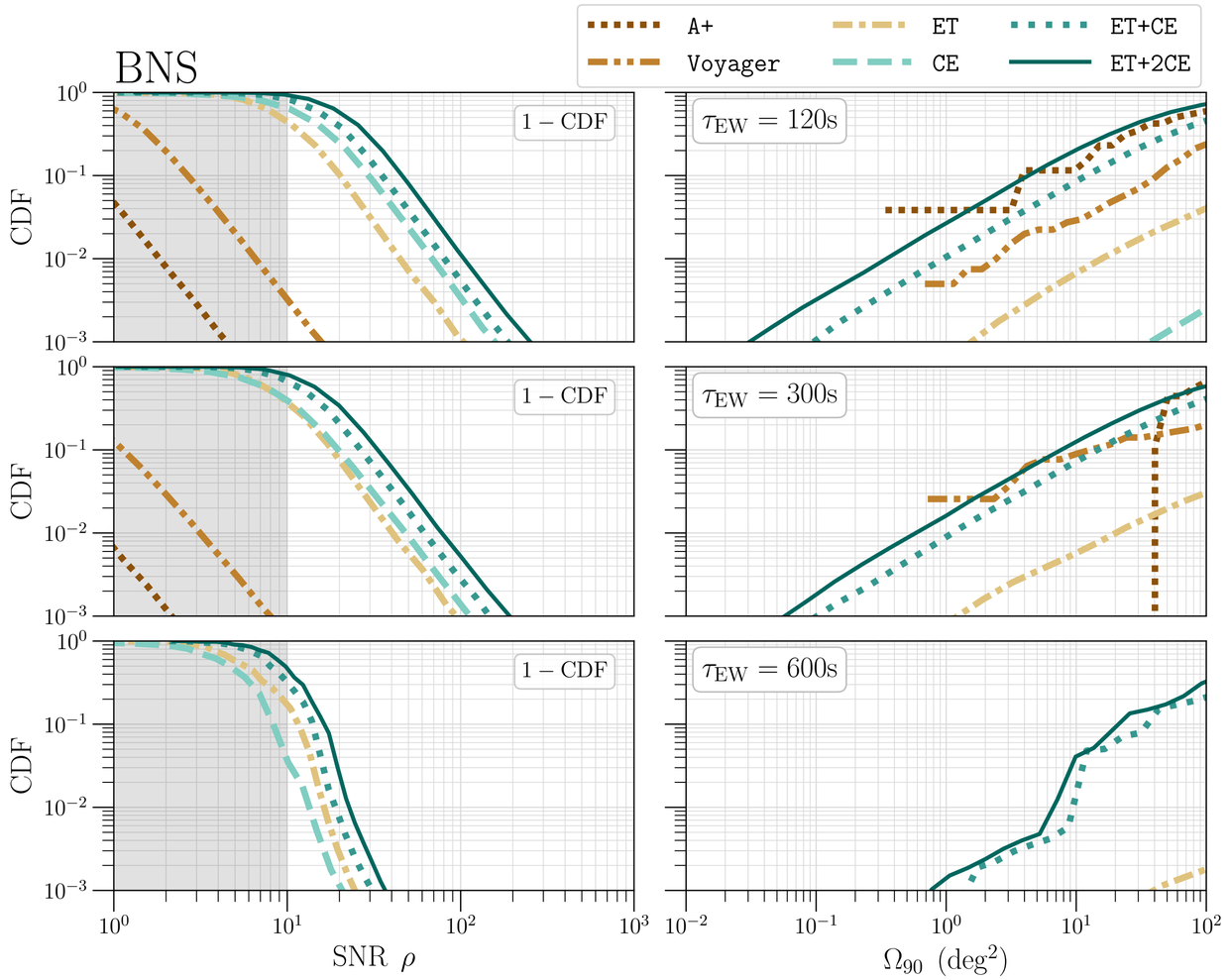

BBH
A+
Voyager
ET
CE
ET+CE
ET+2CE
$\Delta D_L/D_L$
Ω_{90} (deg^2)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{0}
10^{1}
10000
8000
6000
4000
2000


BNS
BBH
$\Omega_{90} \leq 0.1\,\mathrm{deg}^2$
$\Omega_{90} \leq 0.01\,\mathrm{deg}^2$
$\Delta D_L/D_L \leq 0.01$
A+
Voyager
ET
CE
ET+CE
ET+2CE
1
10
100
1,000
detection rates (1/year)

Enabling Multi-messenger Astronomy

Early Warning for BNS Signals

Redshift range: $z \in [0.02,05]$



EW time	$\tau_{\rm EW}$ = 120 s			$\tau_{\rm EW}$ = 300 s			$\tau_{\rm EW}$ = 600 s		
Ω_{90} (deg^2)	≤ 10	≤ 1	≤ 0.1	≤ 10	≤ 1	≤ 0.1	≤ 10	≤ 1	≤ 0.1
HLKI+E	40	4	1	27	4	1	0	0	0
VKI+C	2	0	0	1	0	0	0	0	0
KI+EC	890	100	9	540	73	8	54	1	0
ECS	2,100	250	34	1,100	160	15	250	7	0

detection rates (1/year)

EM telescope	FOV (deg^2)
Rubin Observatory	9.6
EUCLID	0.54
WFIRST	0.28
Chandra	0.15
20m–Telescope	0.11
Keck II	0.11
VLT	0.054
ELT	0.028
GMT	0.008
Swift–XRT	0.007
Lynx	0.007
HST–WFC3	0.002
Athena	0.001

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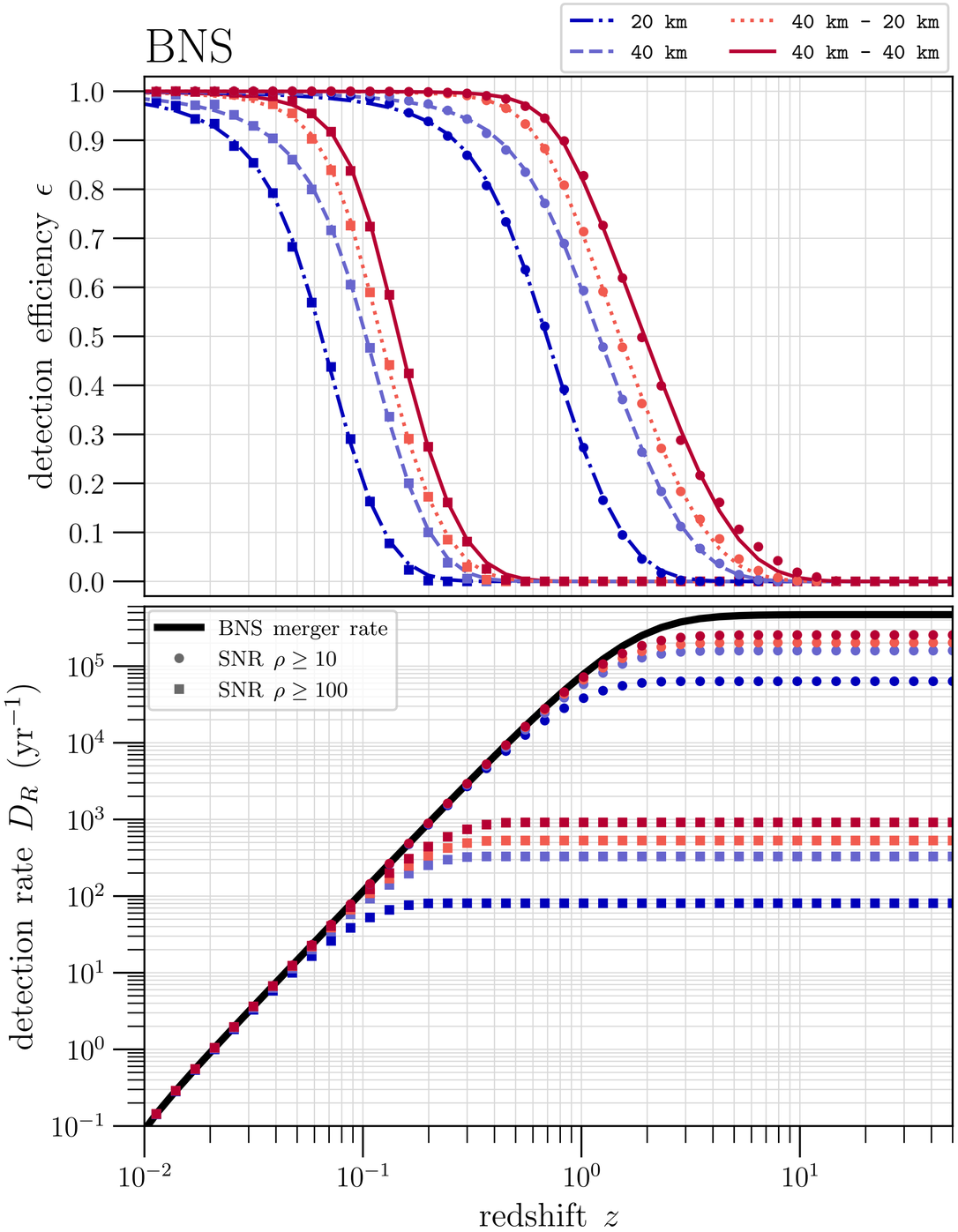
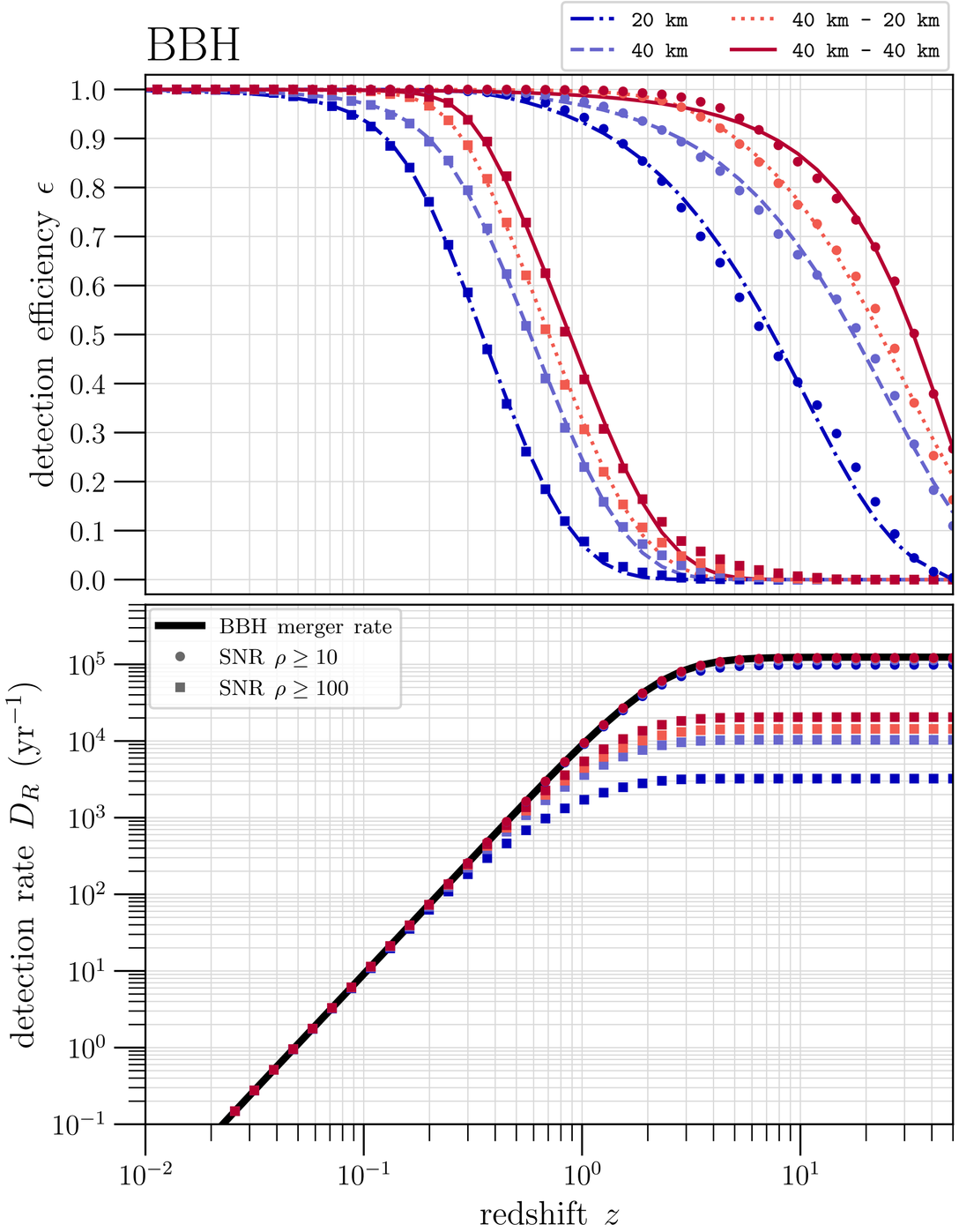
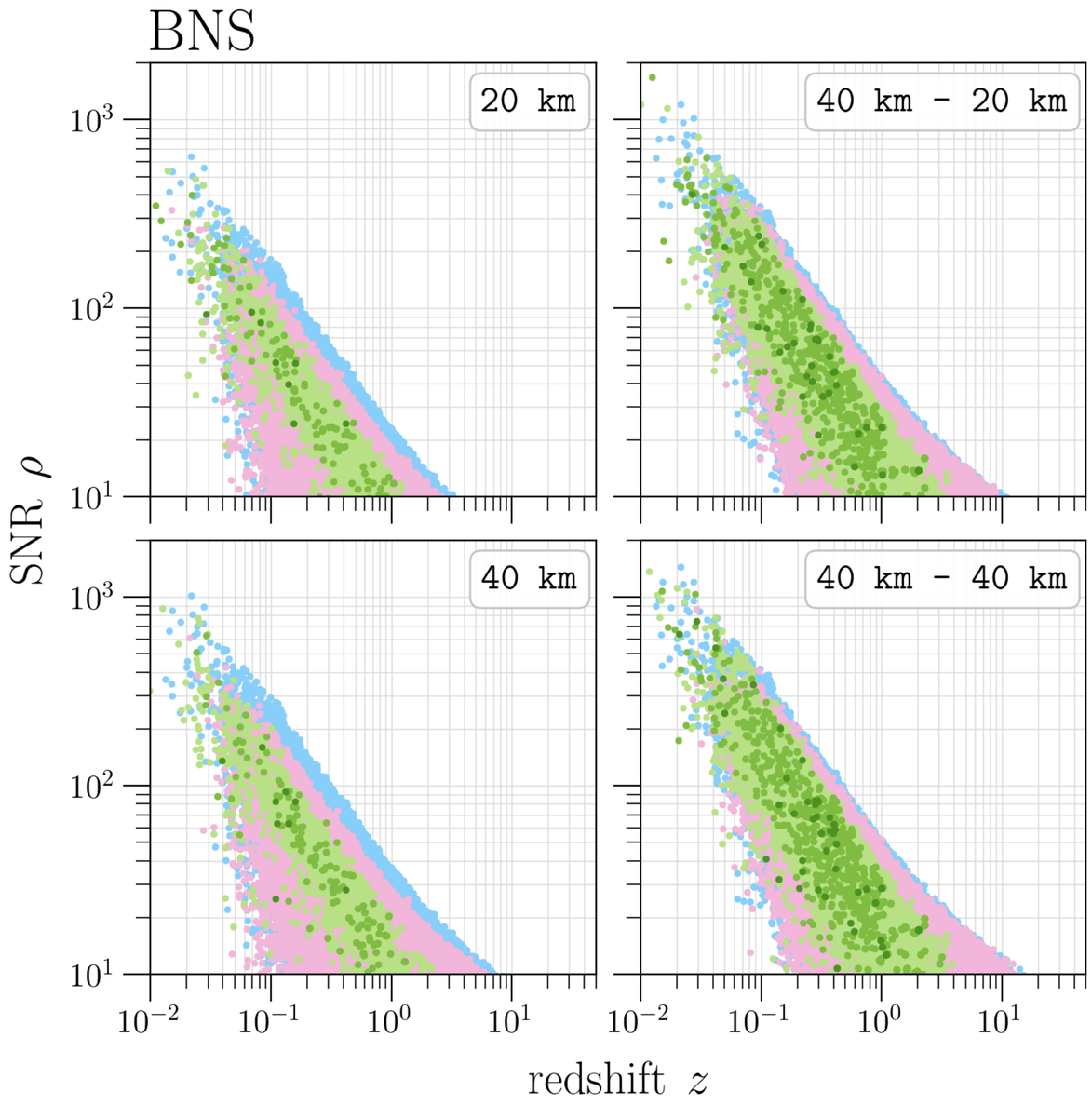
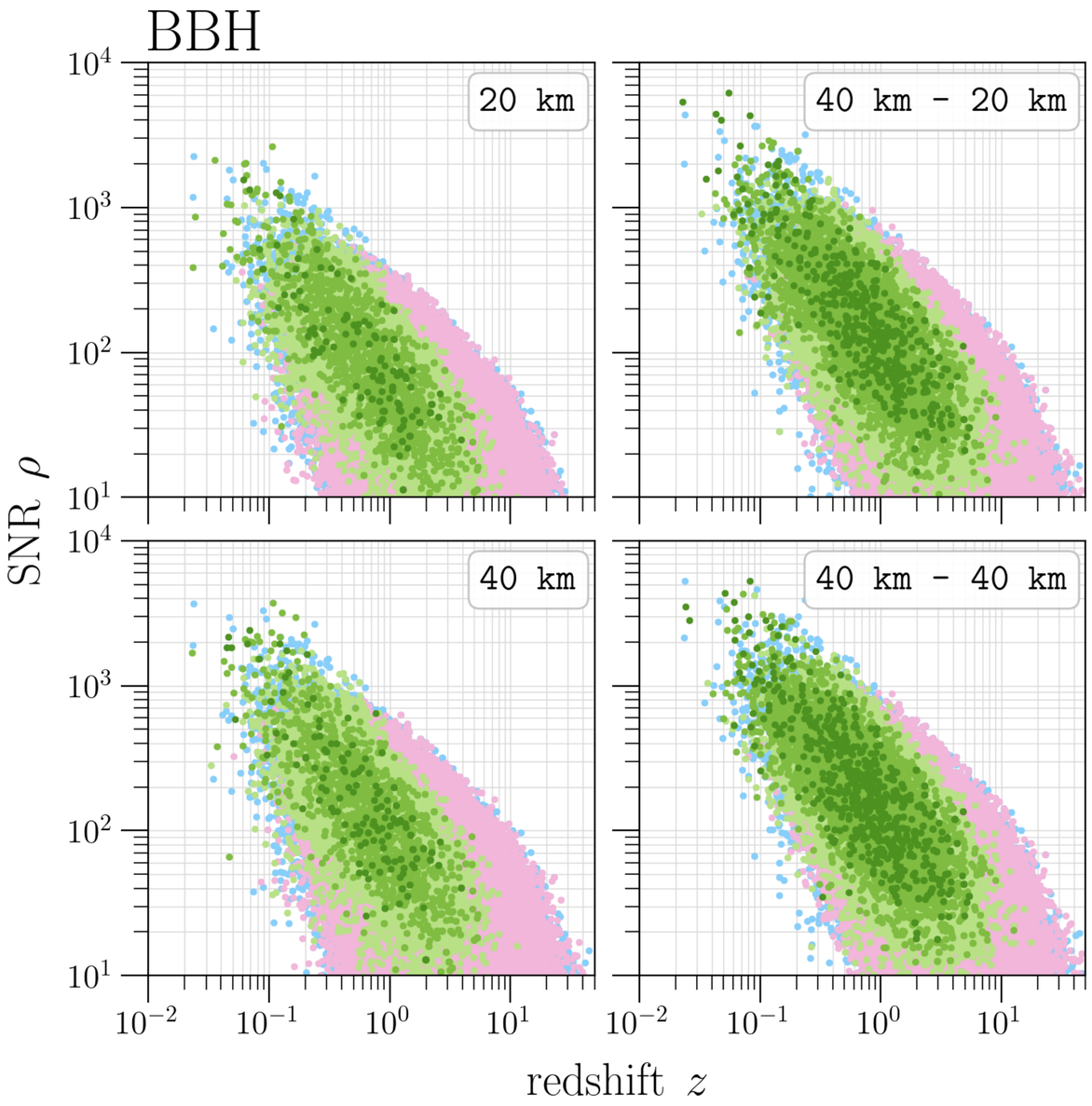
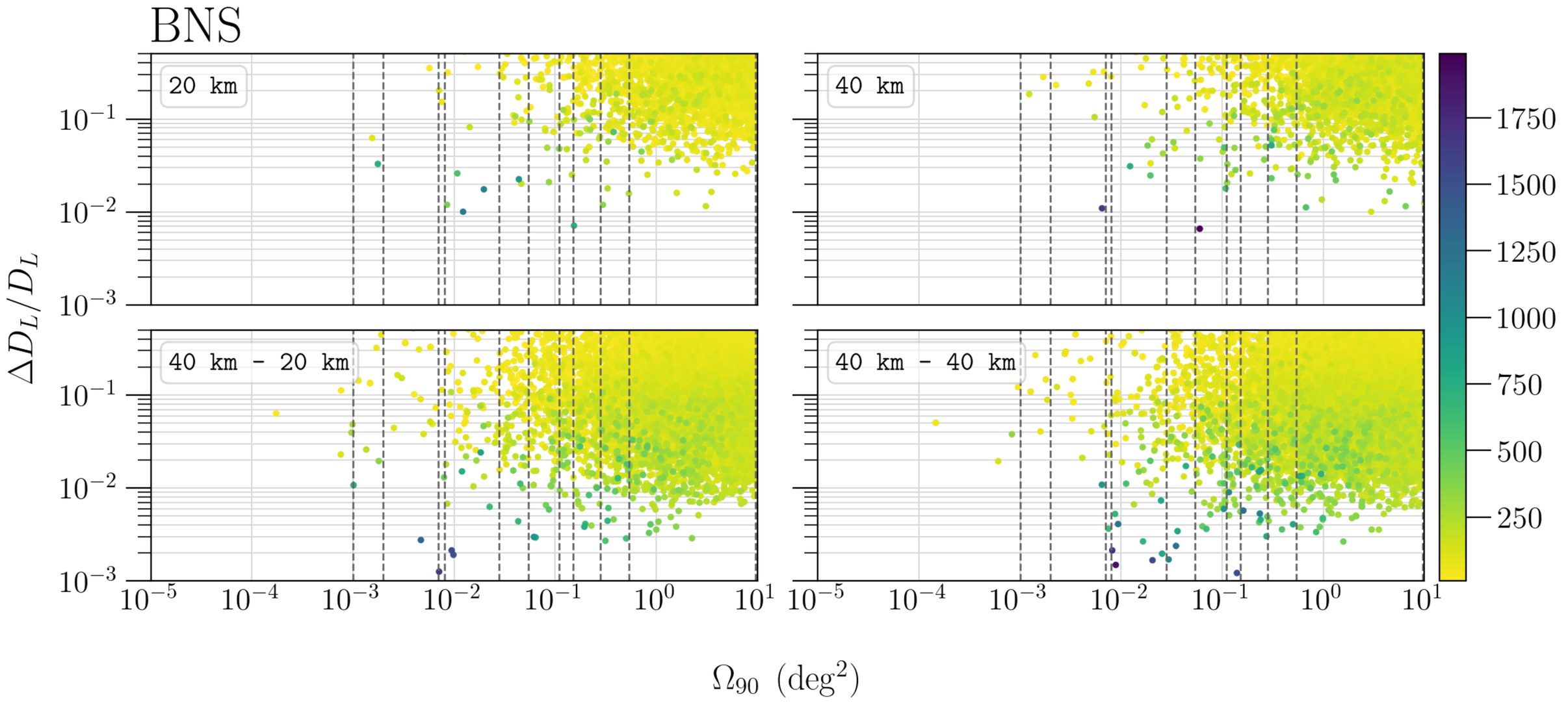
Extra Slides — Cosmic Explorer Configurations

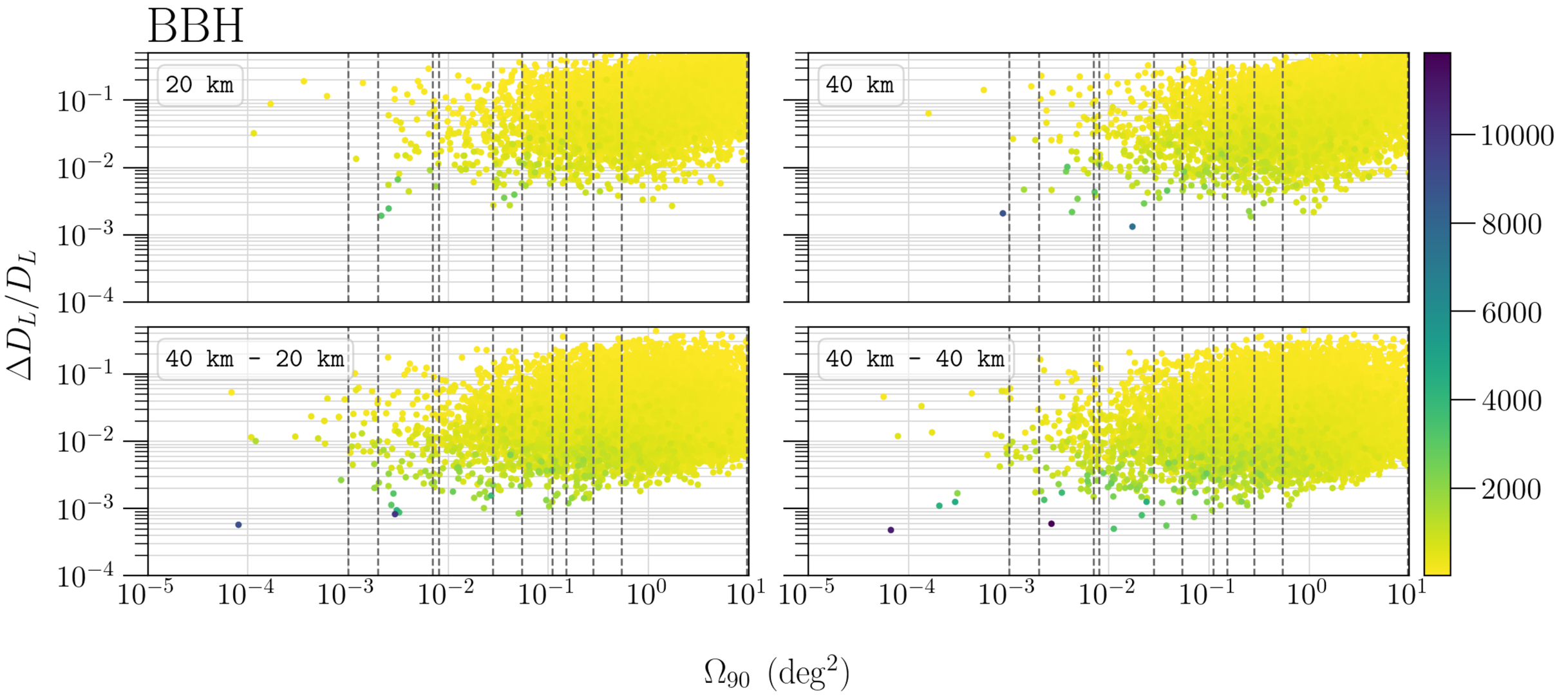

BNS
20 km
40 km
40 km - 20 km
40 km - 40 km
detection efficiency ϵ
BNS merger rate
SNR $\rho \geq 10$
SNR $\rho \geq 100$
detection rate D_R (yr^{-1})
redshift z

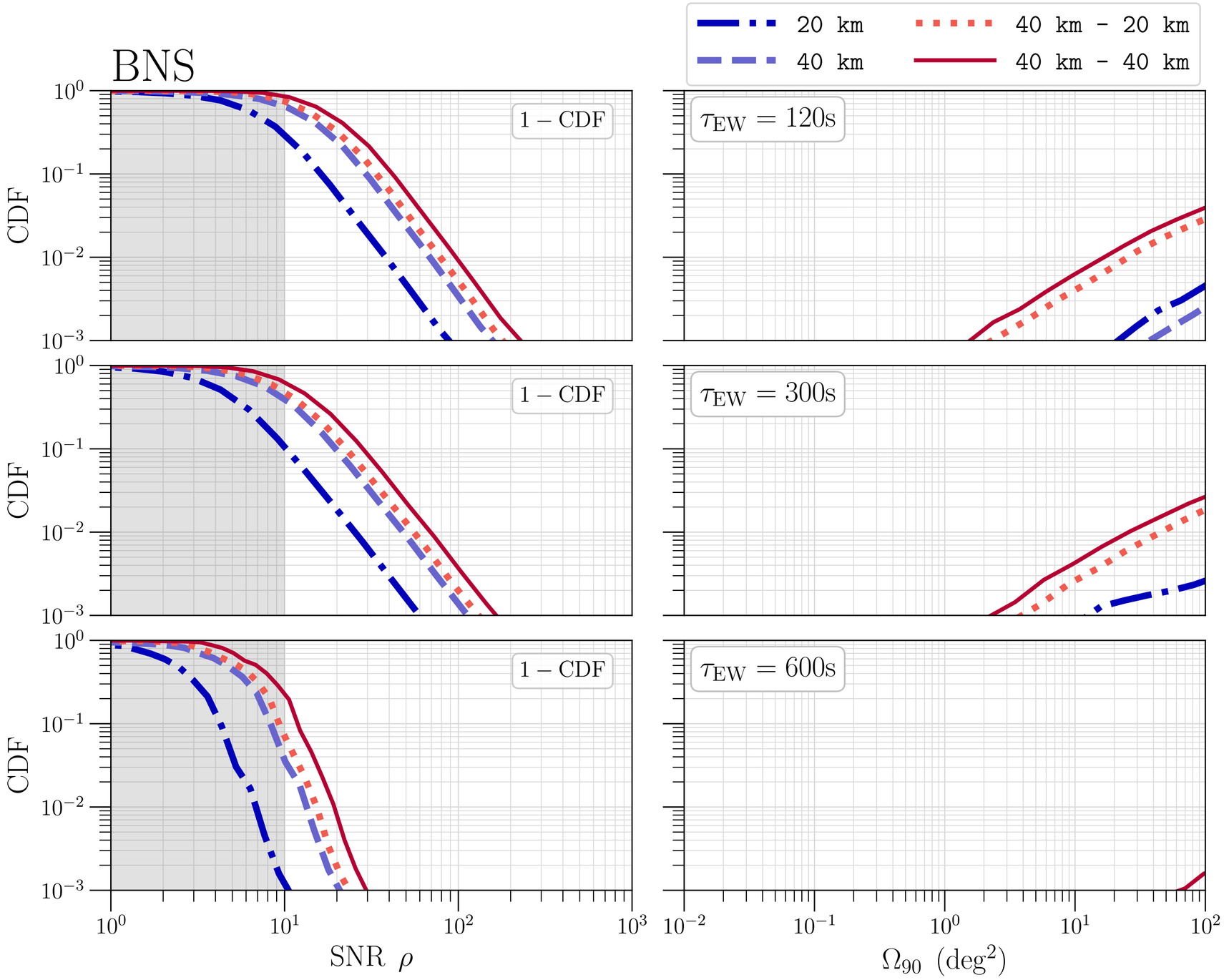

BBH
20 km
40 km
40 km - 20 km
40 km - 40 km
detection efficiency ϵ
BBH merger rate
SNR $\rho \geq 10$
SNR $\rho \geq 100$
detection rate D_R (yr^{-1})
redshift z


BNS
20 km
40 km - 20 km
40 km
40 km - 40 km
SNR ρ
redshift z


BBH
20 km
40 km - 20 km
40 km
40 km - 40 km
SNR ρ
redshift z


BNS
20 km
40 km
40 km - 20 km
40 km - 40 km
$\Delta D_L/D_L$
10^{-1}
10^{-2}
10^{-3}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Ω_{90} (deg^2)
1750
1500
1250
1000
750
500
250


BBH
20 km
40 km
40 km - 20 km
40 km - 40 km
$\Delta D_L/D_L$
Ω_{90} (deg^2)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{0}
10^{1}
10000
8000
6000
4000
2000


BNS
20 km
40 km
40 km - 20 km
40 km - 40 km
1 − CDF
CDF
$\tau_{\rm EW} = 120$s
$\tau_{\rm EW} = 300$s
$\tau_{\rm EW} = 600$s
SNR ρ
Ω_{90} (deg^2)