THE FUTURE OF GW ASTRONOMY

PATRICIA SCHMIDT

GEMMA2 @ ROME
SEPTEMBER 19, 2024

OUTLINE

- Where are we now
- Prospects for the nearish future: Post-O5 science
- Science with 3G detectors
- NEMO - a dedicated high-frequency detector
- A new frontier: LISA

Disclaimer:

By no means a complete overview but rather a selection of science examples

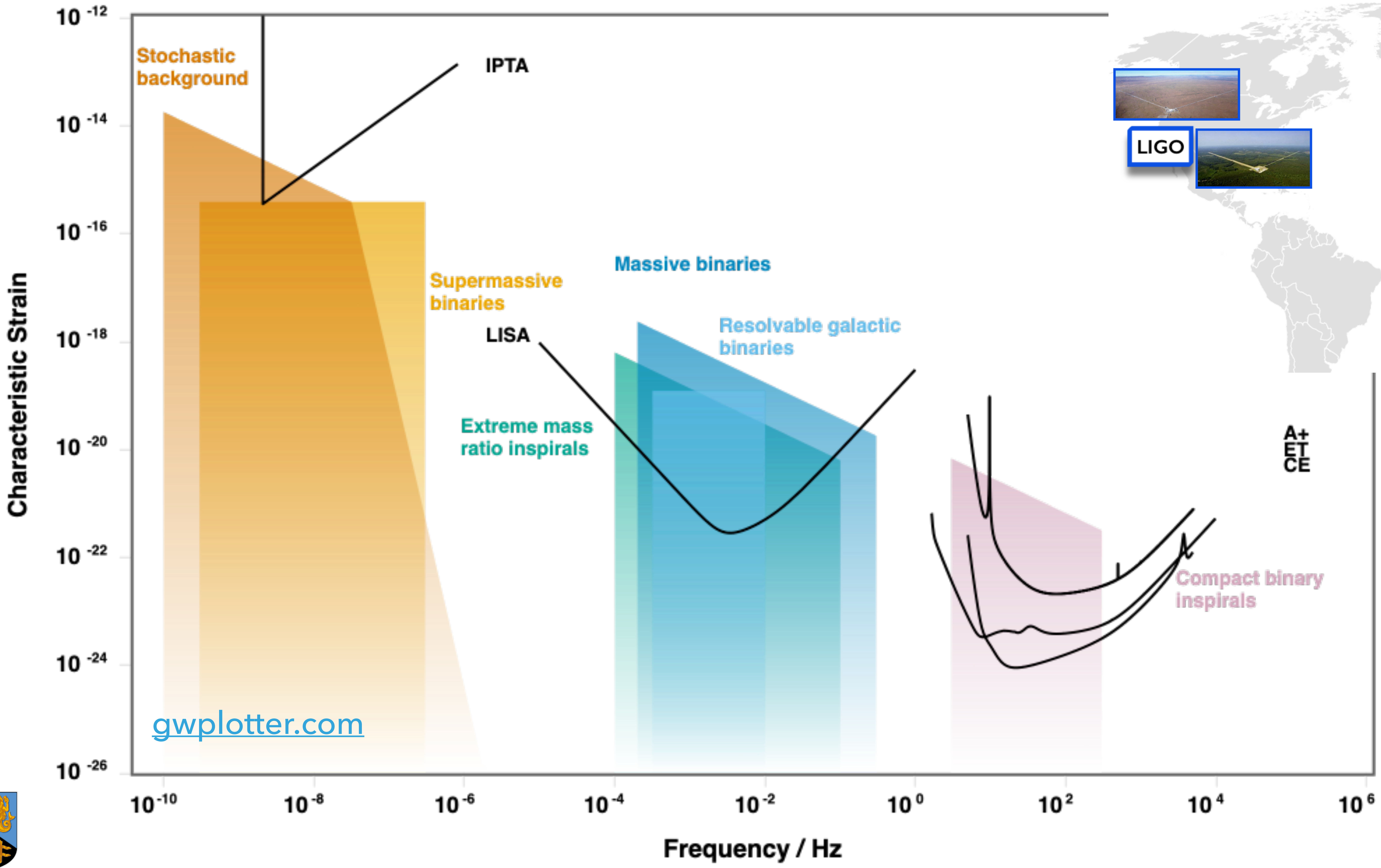
Heavy personal bias towards compact binaries

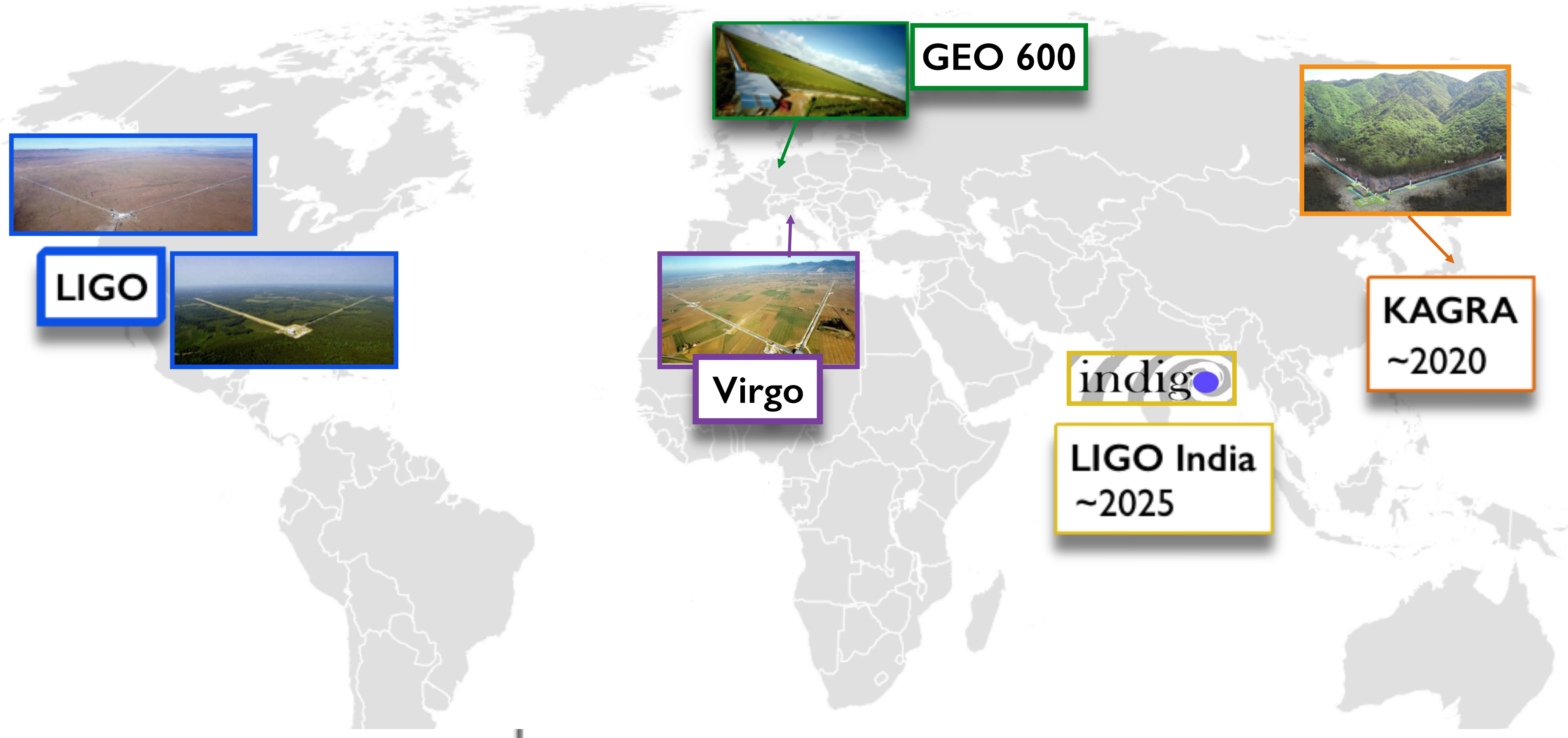
I am a LIGO member

SCIENCE CASE REFERENCES

- LSC Post-O5 report, Fritschel et al. (inc. PS): https://dcc.ligo.org/LIGO-T2200287/public
- CE Horizon Study, Evans et al.: https://doi.org/10.48550/arXiv.2109.09882
- Cosmic Explorer: A submission to the NSF MPSAC ngGW Subcommittee, Evans et al.: https://dcc.cosmicexplorer.org/public/0163/P2300018/003/CE_WP_v3.pdf
- COBA study, Branchesi et al.: https://iopscience.iop.org/article/10.1088/1475-7516/2023/07/068
- CE Trade Study, Gupta et al.: https://doi.org/10.48550/arXiv.2307.10421
- NEMO, Ackley et al.: https://doi.org/10.1017/pasa.2020.39
- LISA Science Definition Report, ESA: https://www.cosmos.esa.int/documents/15452792/15452811/LISA_DEFINITION_STUDY_REPORT_ESA-SCI-DIR-RP-002_Public+%281%29.pdf

OBSERVATORY LANDSCAPE





Masses in the Stellar Graveyard

SOME THINGS WE HAVE LEARNED SO FAR

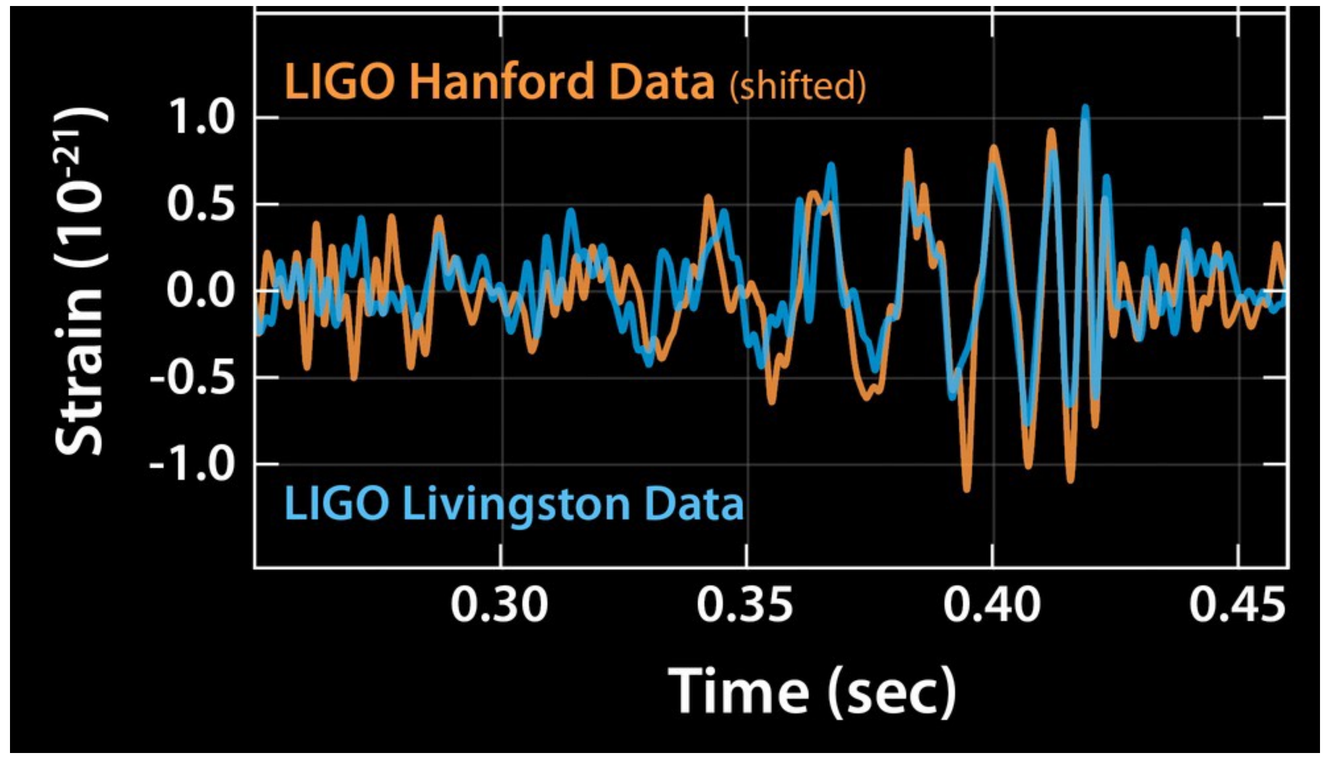
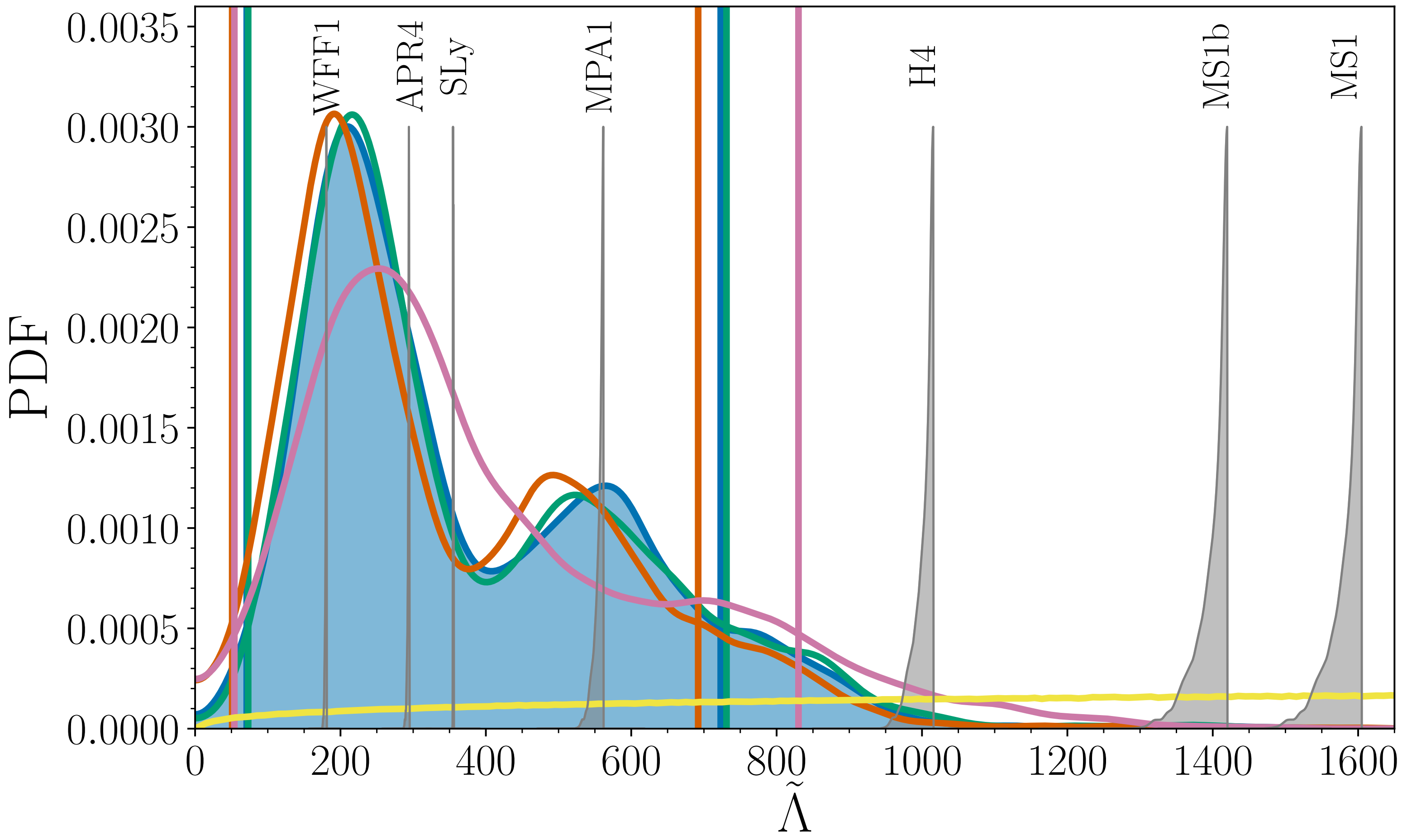
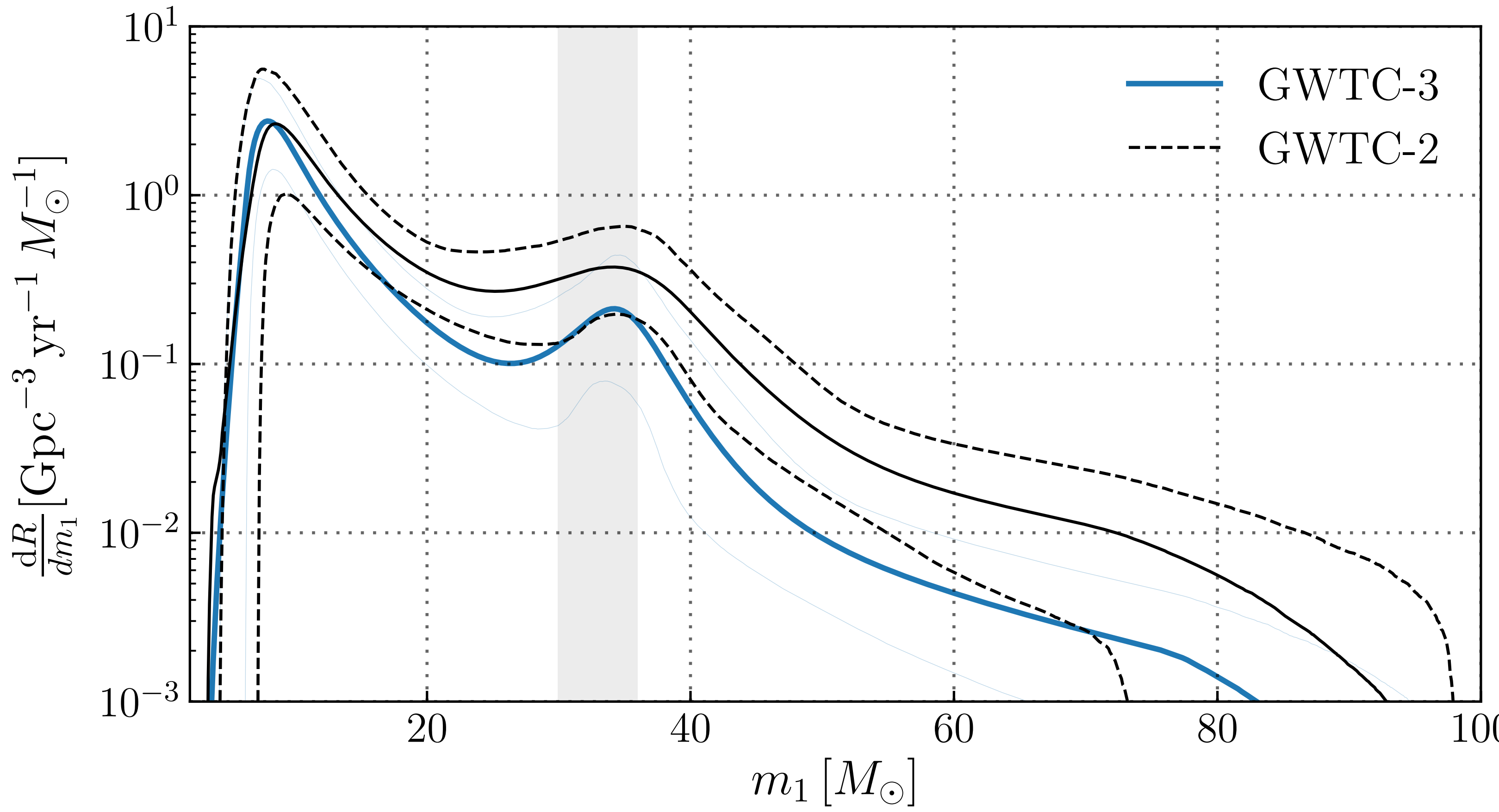


Image Credit: Caltech/MIT/LIGO Lab.

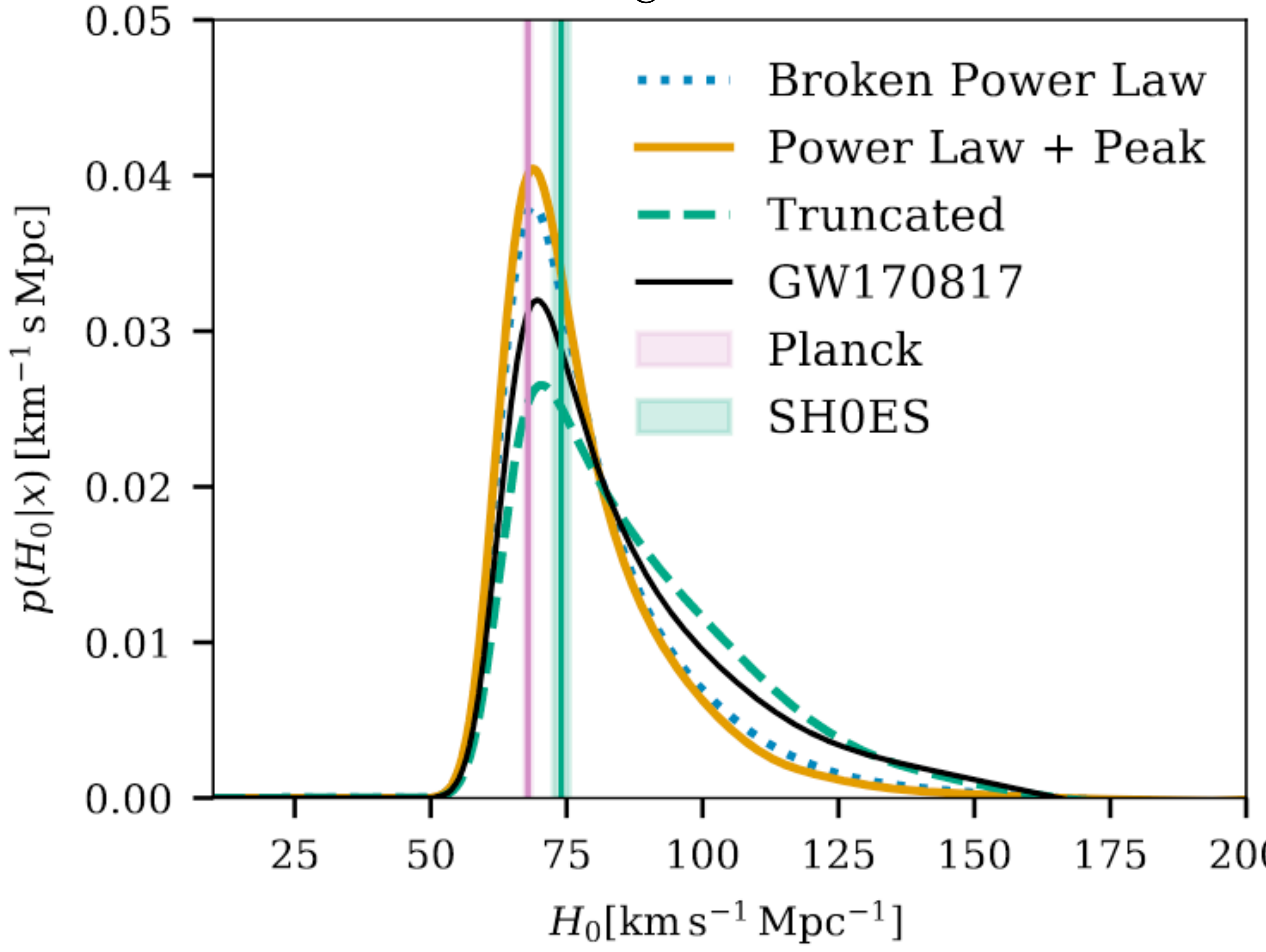


[LVC, PRX 9, 031040 (2019)]

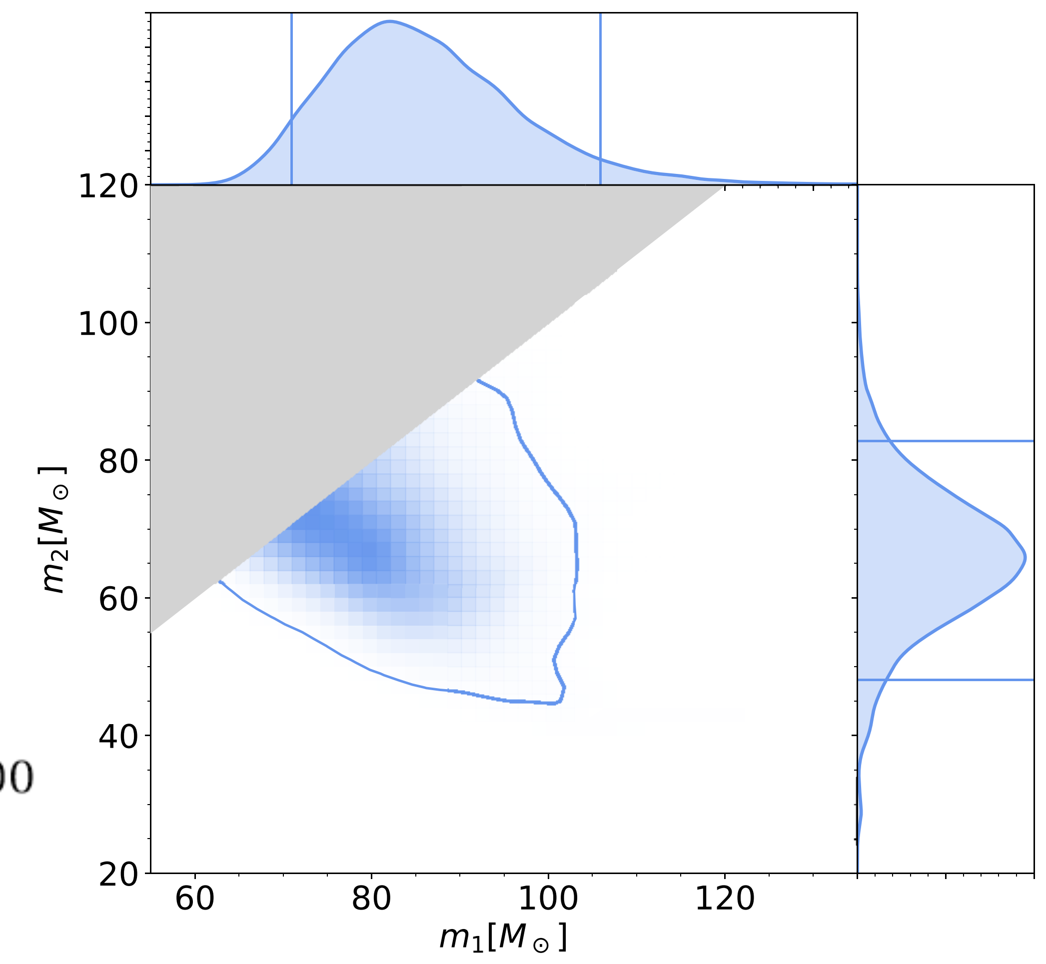


[LVK, arXiv 2111.03634 (2021)]

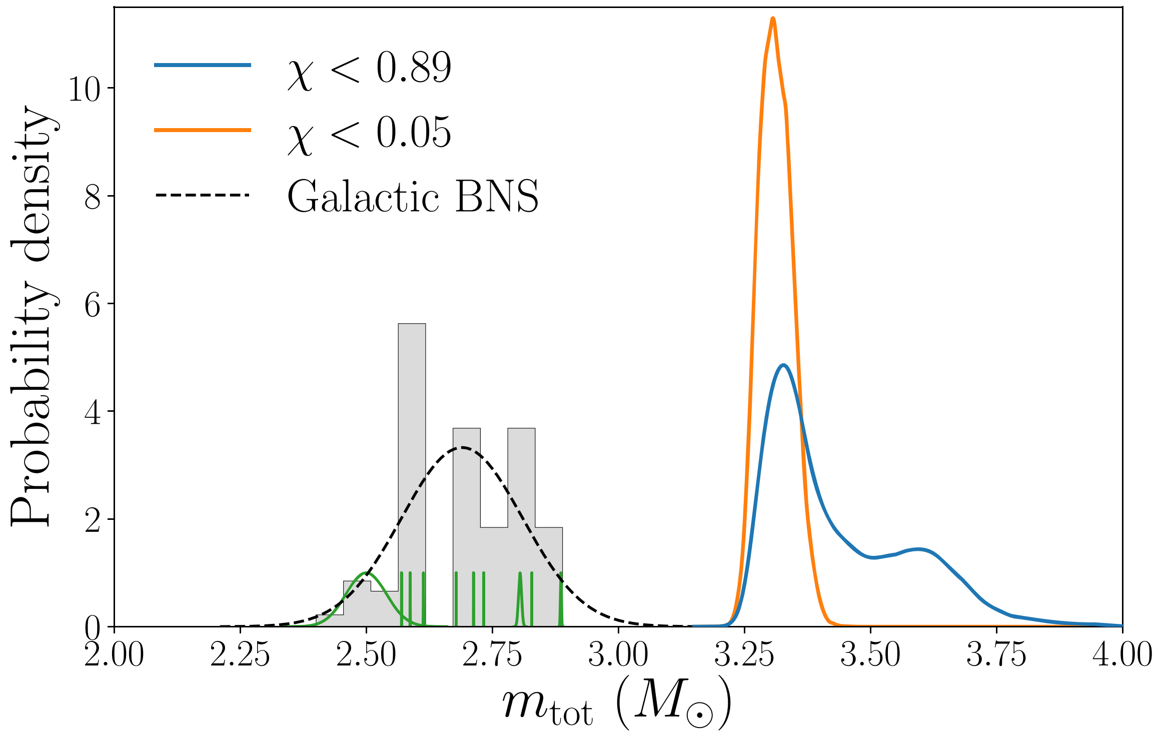
$$H_0 = 68^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$



[LVK, arXiv:2111.03604]

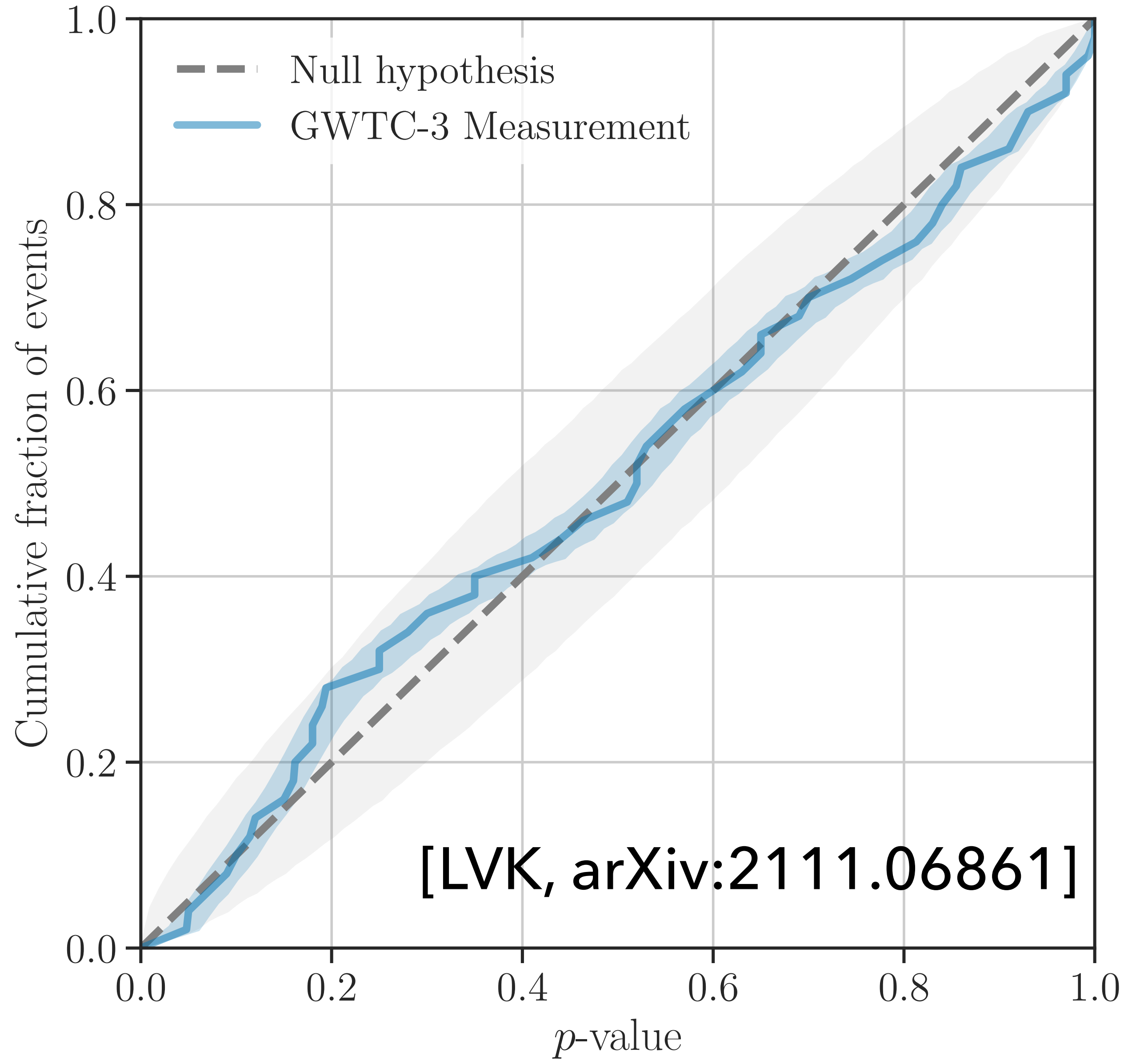


[LVK, PRL 125, 101102 (2020)]



[LVK, ApJ L 892:L3 (2020)]

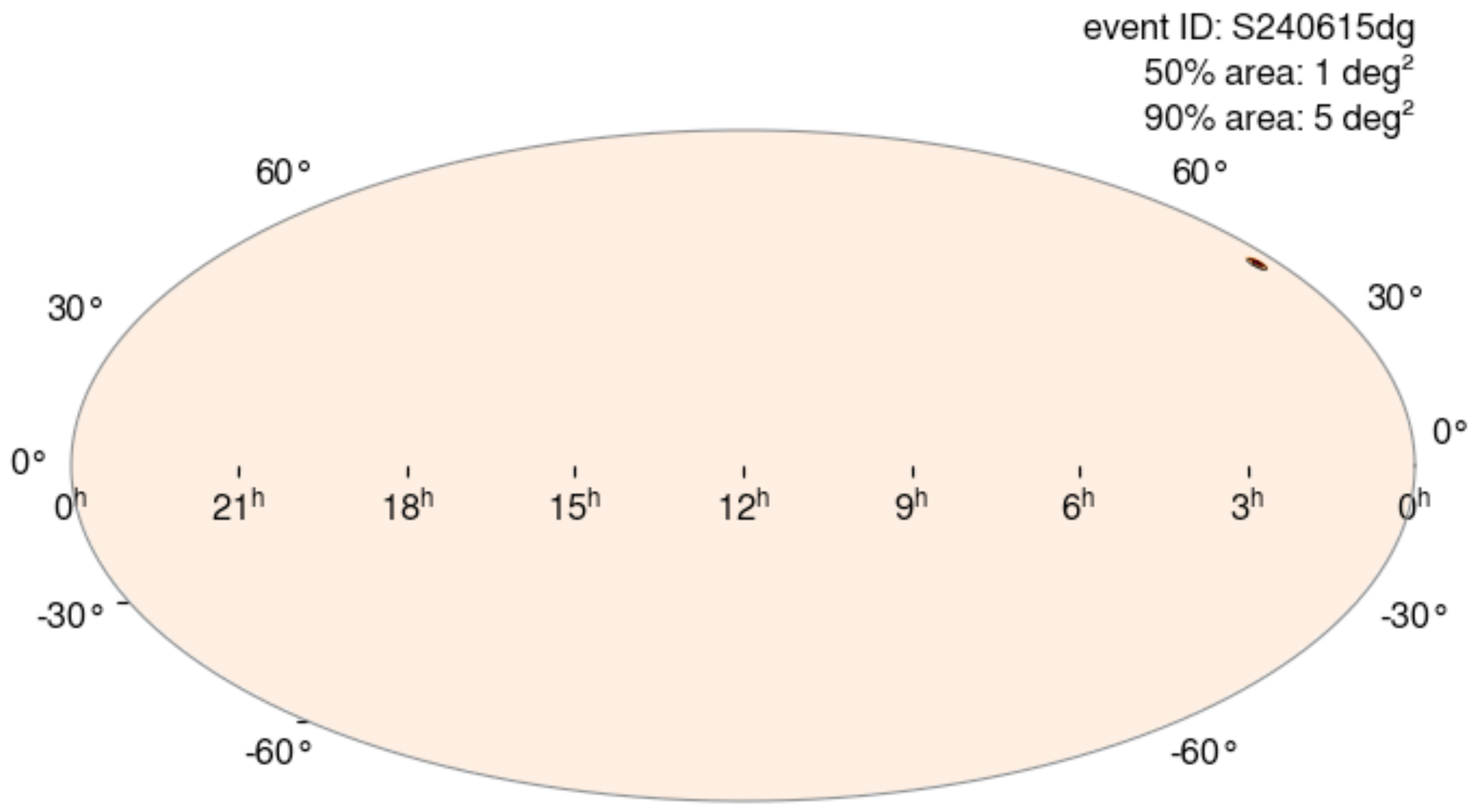
$$m_g \leq 1.27 \times 10^{-23}\,\mathrm{eV/c^2}$$

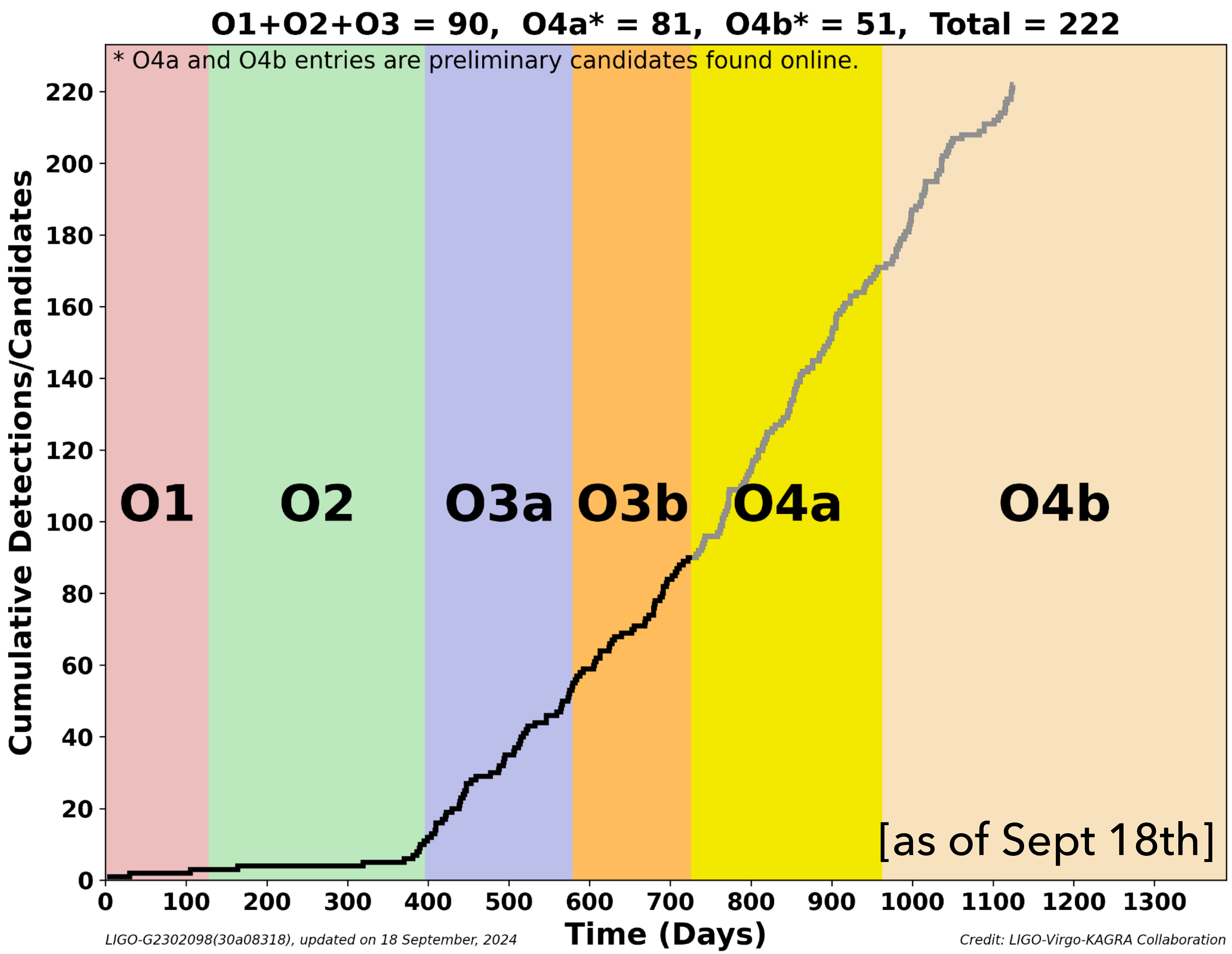


[LVK, arXiv:2111.06861]

FOURTH OBSERVING RUN

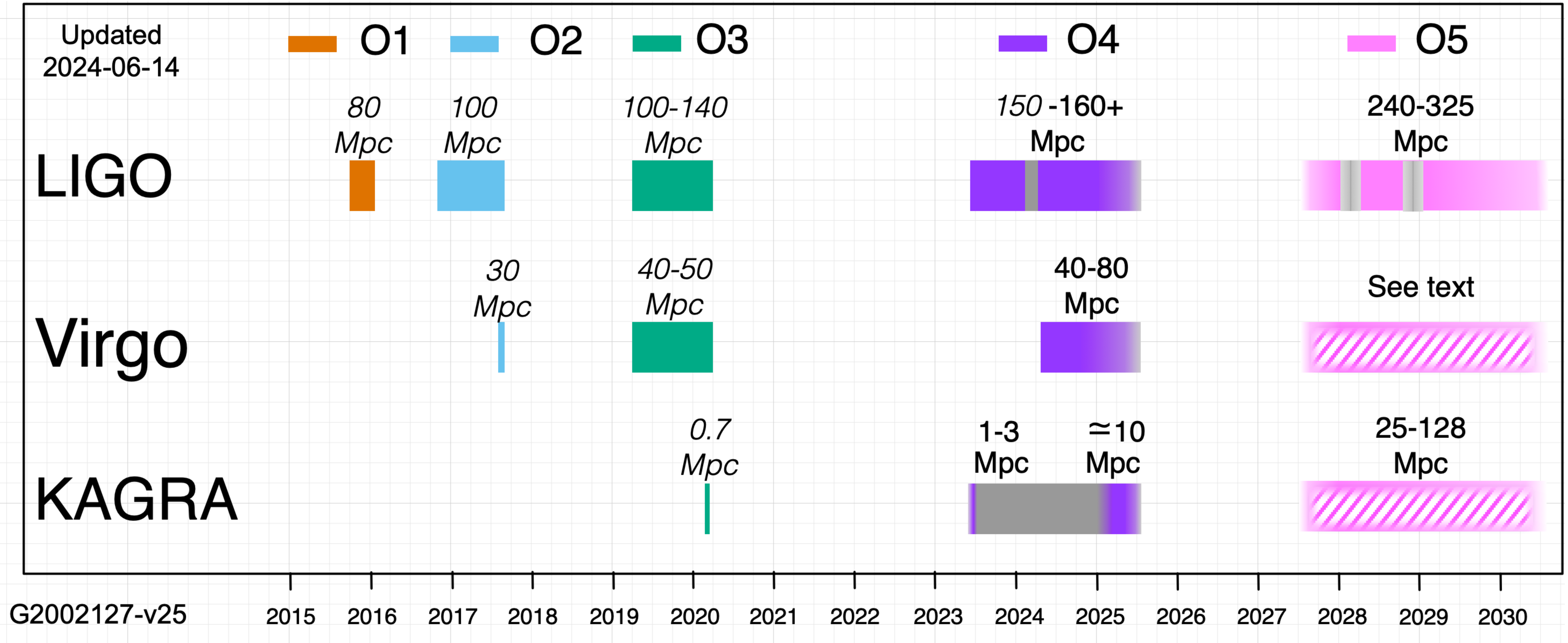
- As of Sept 18th @ 11.45 CEST:
  - **132 significant detection candidates**
  - 2389 low-significance detection candidates
- Binary detection rate:
  - **~a few events per week**
- Public alerts now also for
  - Low-significance triggers
  - Early warning





RUN EXTENSION & O5

- **O4 extended until June 9th, 2025**



See https://observing.docs.ligo.org/plan/

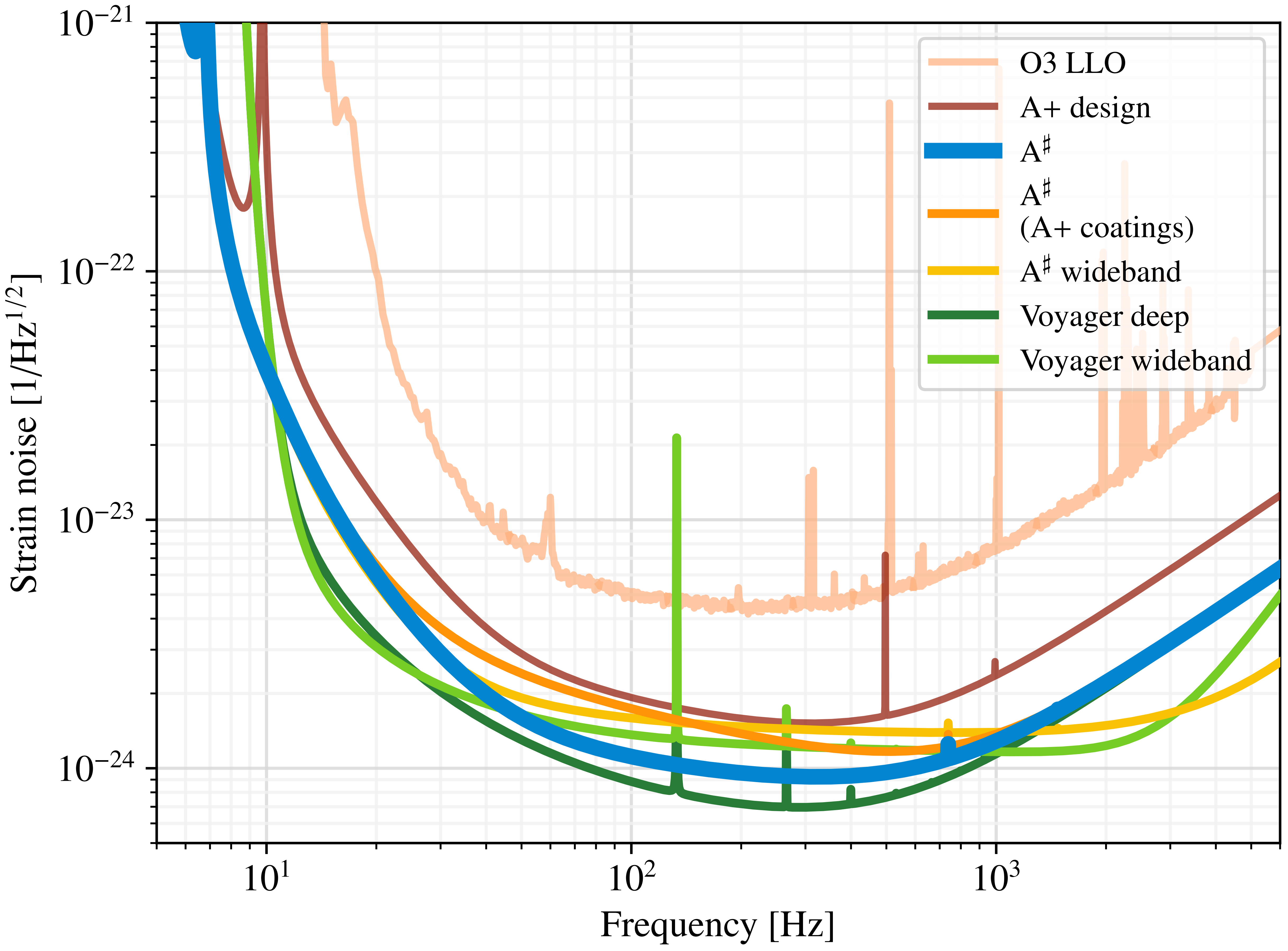
Virgo target sensitivity and entry date for O5 are currently being assessed

[See talk by G. Losurdo]

POST O5

- **LIGO Aundha Observatory** (LAO) to be constructed in India
  - To be run as part of LIGO in the ~2030s
- **A#** – a *possible* targeted upgrade to the existing LIGO facilities
  - LSC Post-O5 study group chaired by Peter Fritschel (inc. PS)
  - Report: https://dcc.ligo.org/LIGO-T2200287/public]
  - A **factor 2 improvement in sensitivity** (larger test masses, improved seismic isolation & mirror coatings, higher laser power, etc.)
  - Pathfinder for next-gen technology
- Similar upgrade proposal for Virgo (**V_nEXT**)

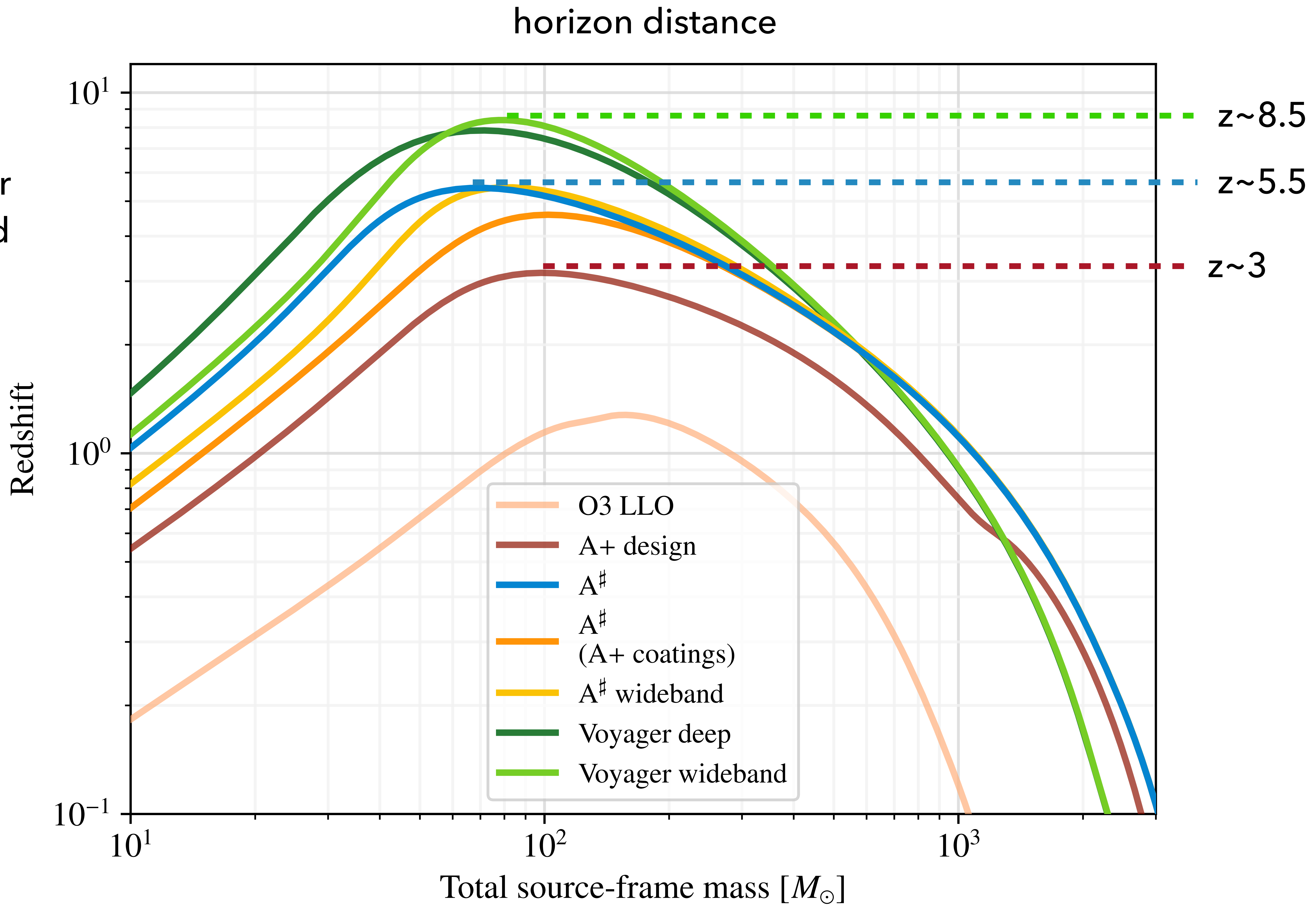
Sensitivity curves



[Post-O5 report]

REACHING FURTHER

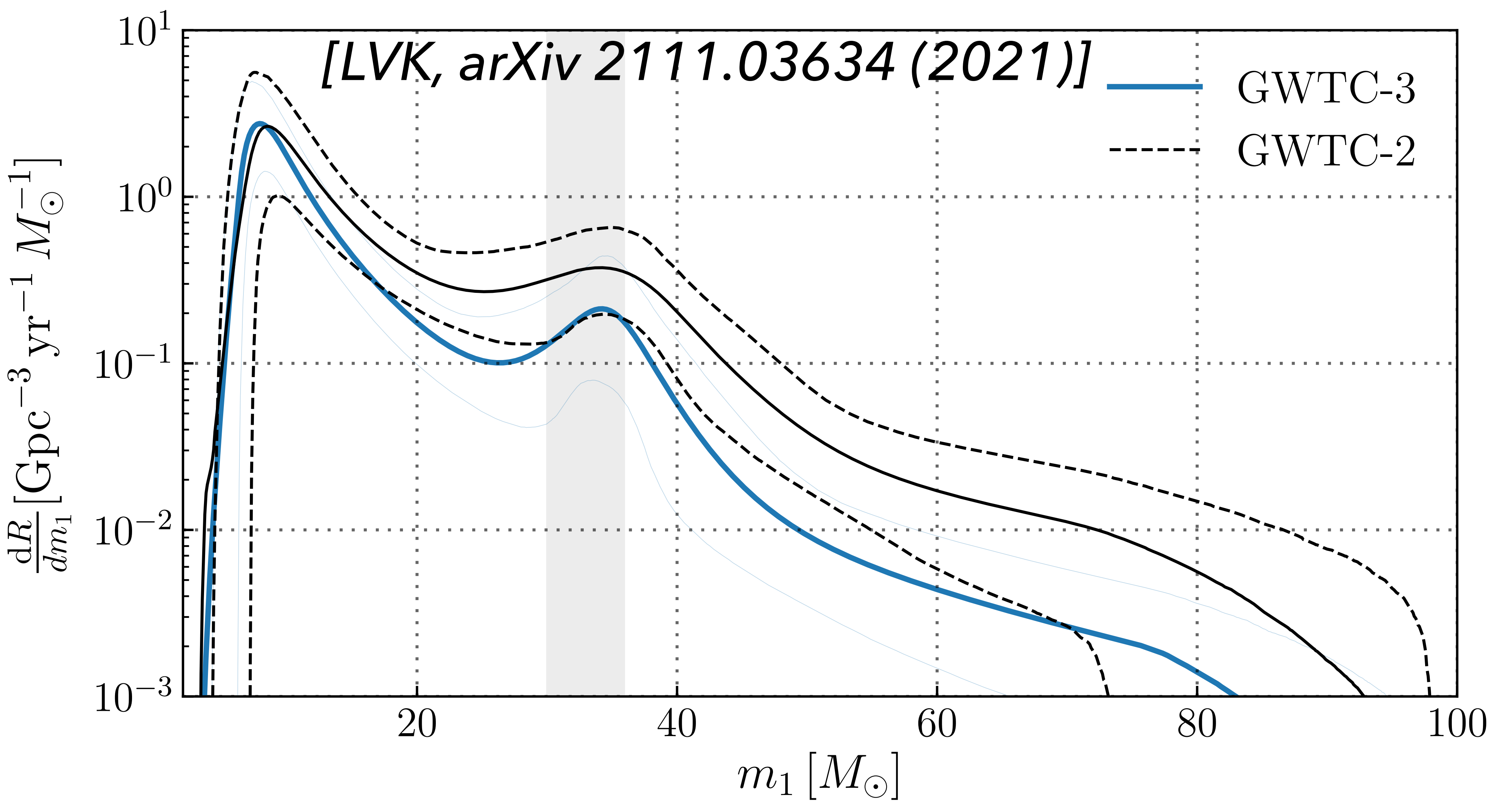
Farthest possible detections: Horizon for optimally oriented and located equal-mass binaries



[Post-O5 report]

POST O5 – DETECTIONS

- H#L#V+ network, 70% duty cycle
- O3 binary merger rates (note: assumed to be non-evolving):
  - BBH: 16-61 $Gpc^{-3}yr^{-1}$
  - BNS: 10-1700 $Gpc^{-3}yr^{-1}$
  - NSBH: 7.8 - 140 $Gpc^{-3}yr^{-1}$



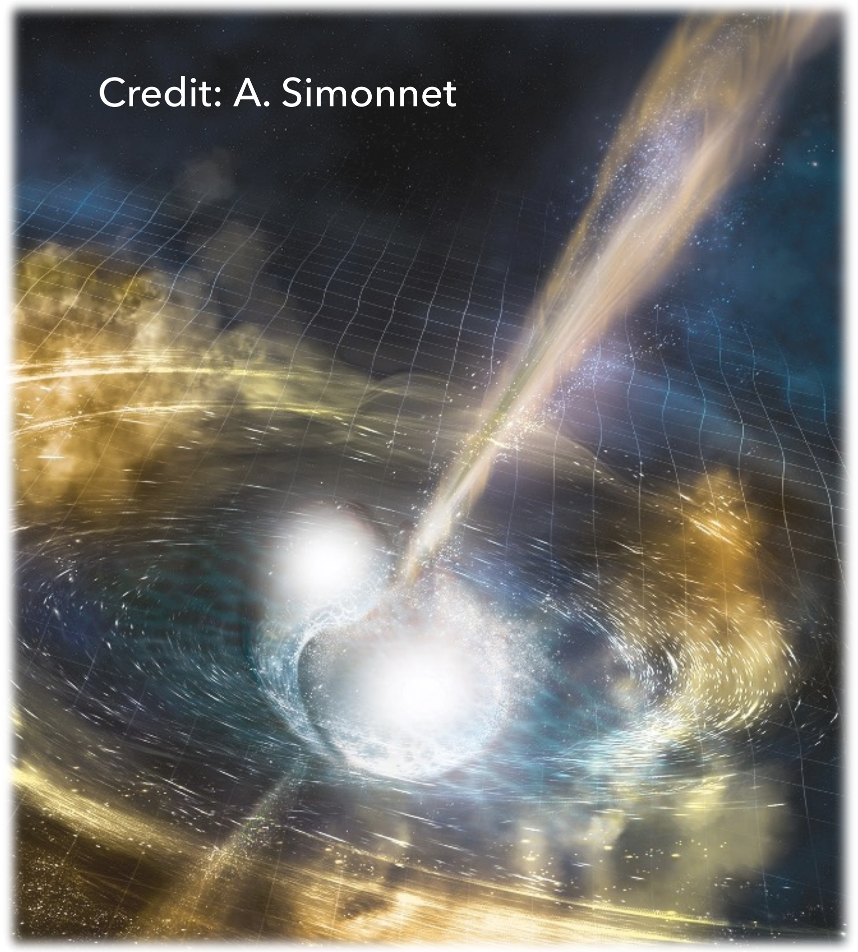
Configuration	Annual Detections BNS	NSBH	BBH
A+	135^{+172}_{-78}	24^{+34}_{-16}	740^{+940}_{-420}
A$^\sharp$	630^{+790}_{-350}	100^{+128}_{-58}	2100^{+2600}_{-1100}
A$^\sharp$ (A+ coatings)	260^{+320}_{-140}	45^{+60}_{-27}	1150^{+1450}_{-640}
A$^\sharp$ Wideband (A+ coatings)	200^{+250}_{-110}	40^{+54}_{-25}	970^{+1220}_{-540}
Voyager Deep	1280^{+1610}_{-710}	190^{+240}_{-110}	3100^{+3900}_{-1700}
Voyager Wideband	730^{+920}_{-410}	129^{+165}_{-74}	2300^{+2900}_{-1300}

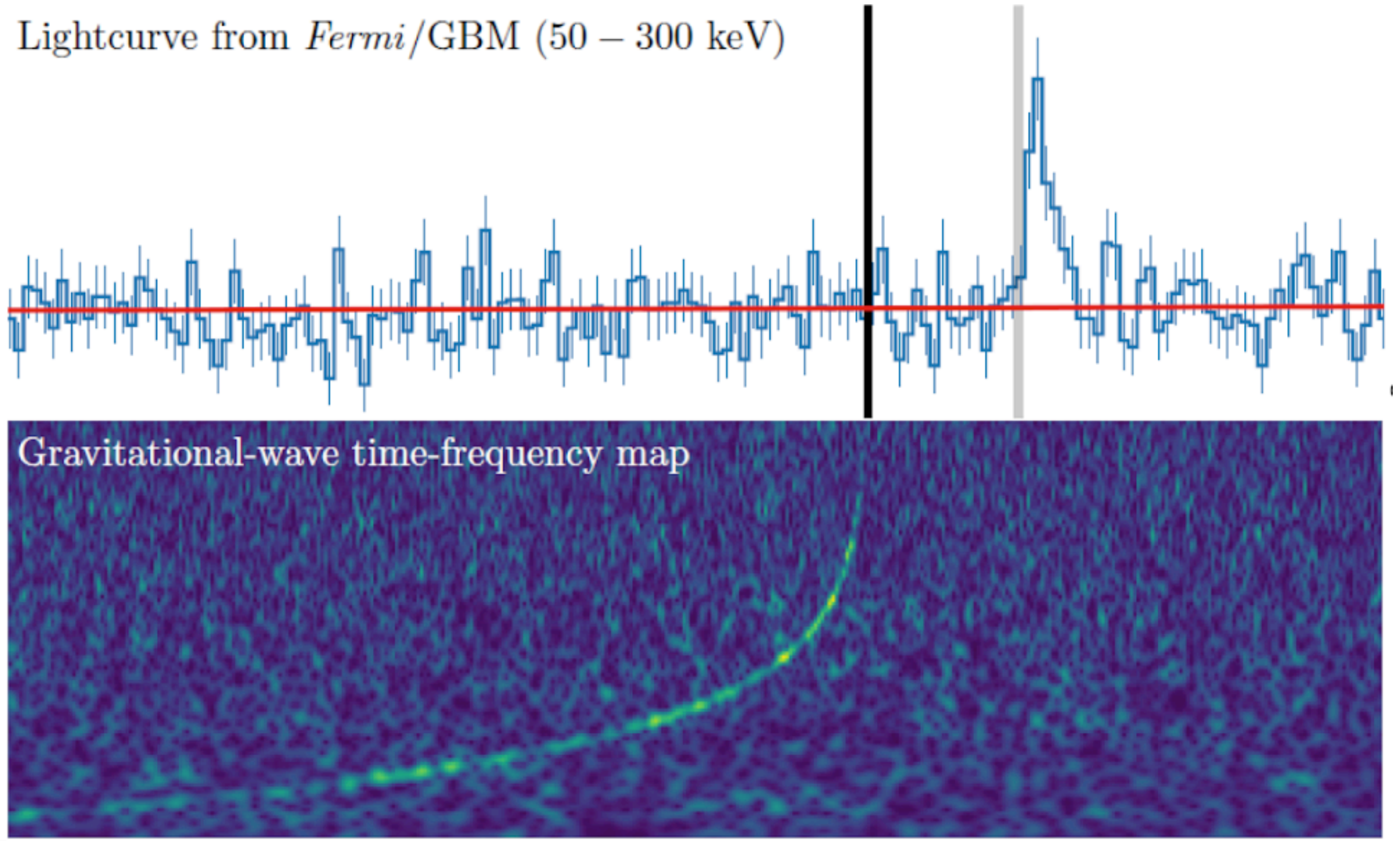
Catalogues of this size across a range of redshifts will allow for **detailed analyses** of the astrophysical population:

- Mass distributions incl. substructures
- Spin distributions
- Branching ratio for different formation scenarios

[Post-O5 report]

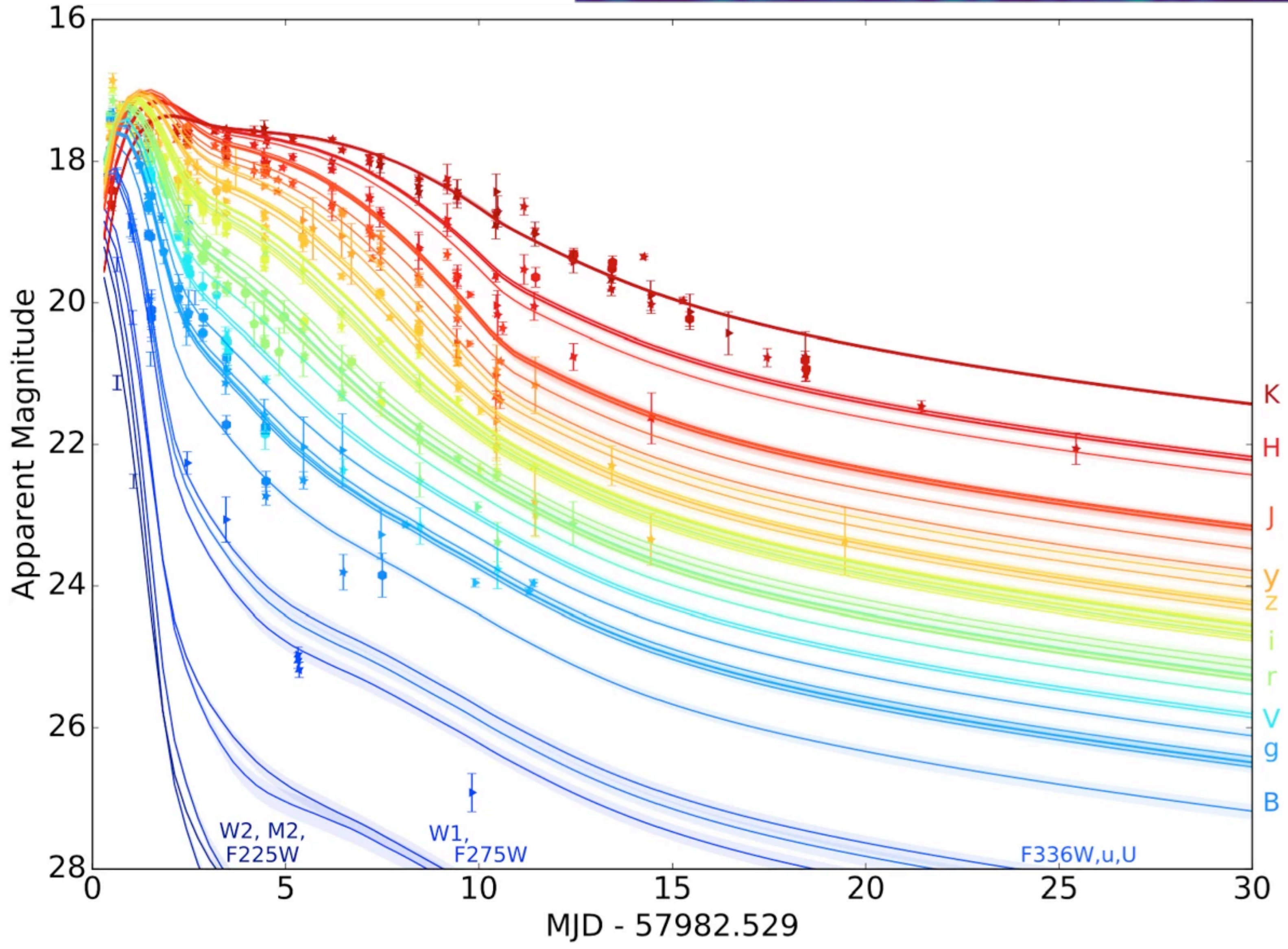
POST-O5 & MMA PROSPECTS





Early warning:

Configuration	BNS Range [Mpc]	t_{early} [min]
O3 LLO	130	0.3
A+ design	350	2.7
$A^\sharp$ (A+ coatings)	440	6.1
$A^\sharp$	600	6.2
$A^\sharp$ wideband	490	6.8
Voyager deep	780	9.0
Voyager wideband	630	9.3

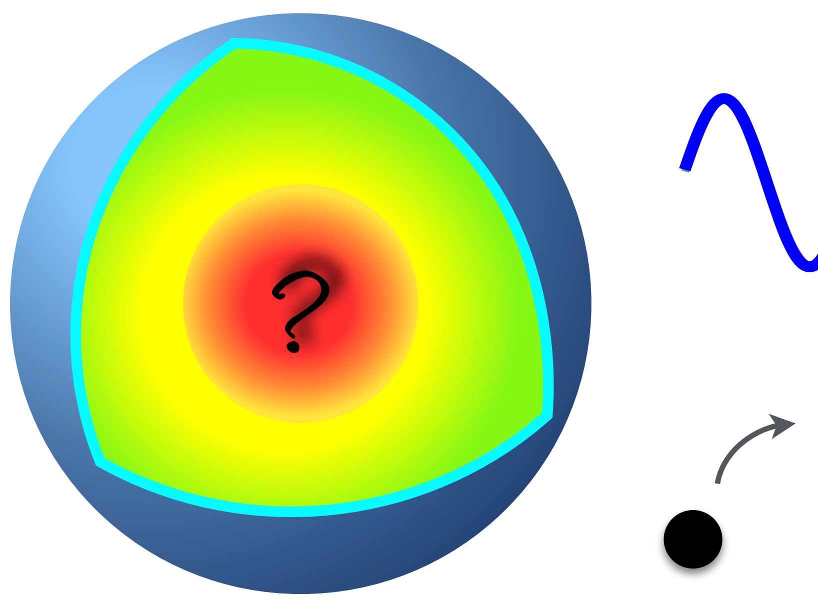


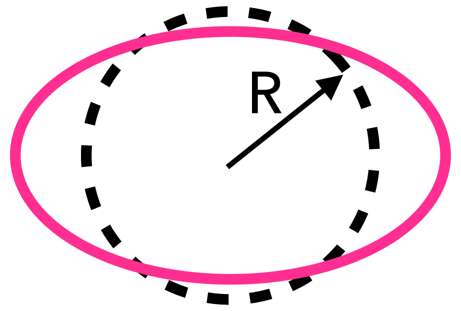
Villar+, Astrophys.J.Lett. 851 (2017) 1, L21

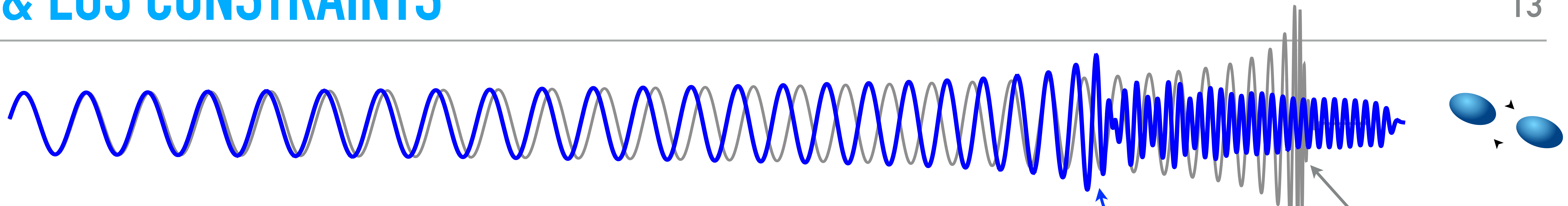
- Greatly enhanced prospects for **joint multi-messenger observations**
  - Prompt EM emission
  - Potential precursor EM signals
- Average sky area O(10s) deg^2 for an A# + Virgo_nEXT detector network
- Percent-level H_0 measurement with bright sirens

[Post-O5 report]

POST-O5 & EOS CONSTRAINTS



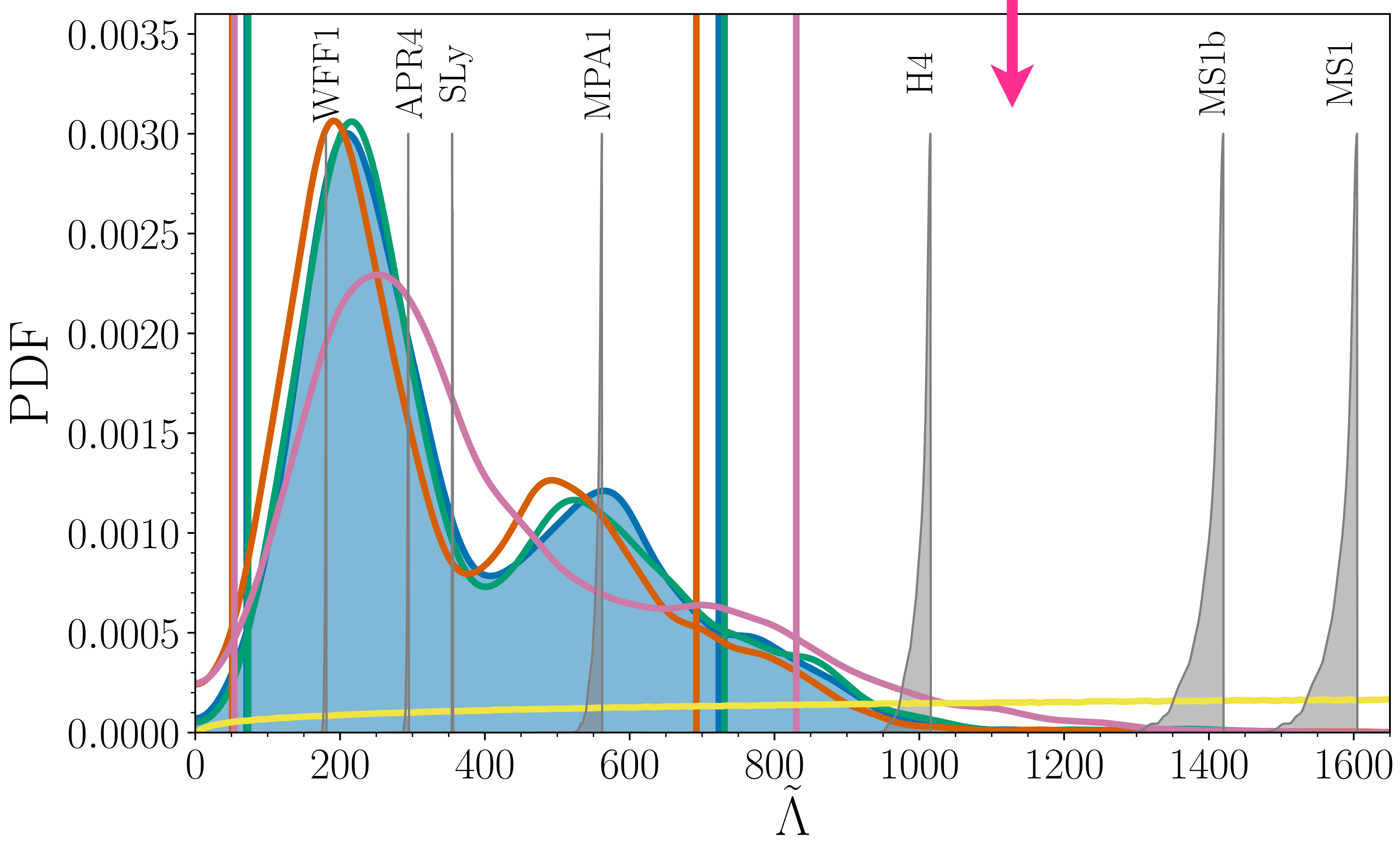




$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1+m_2)^5}$$

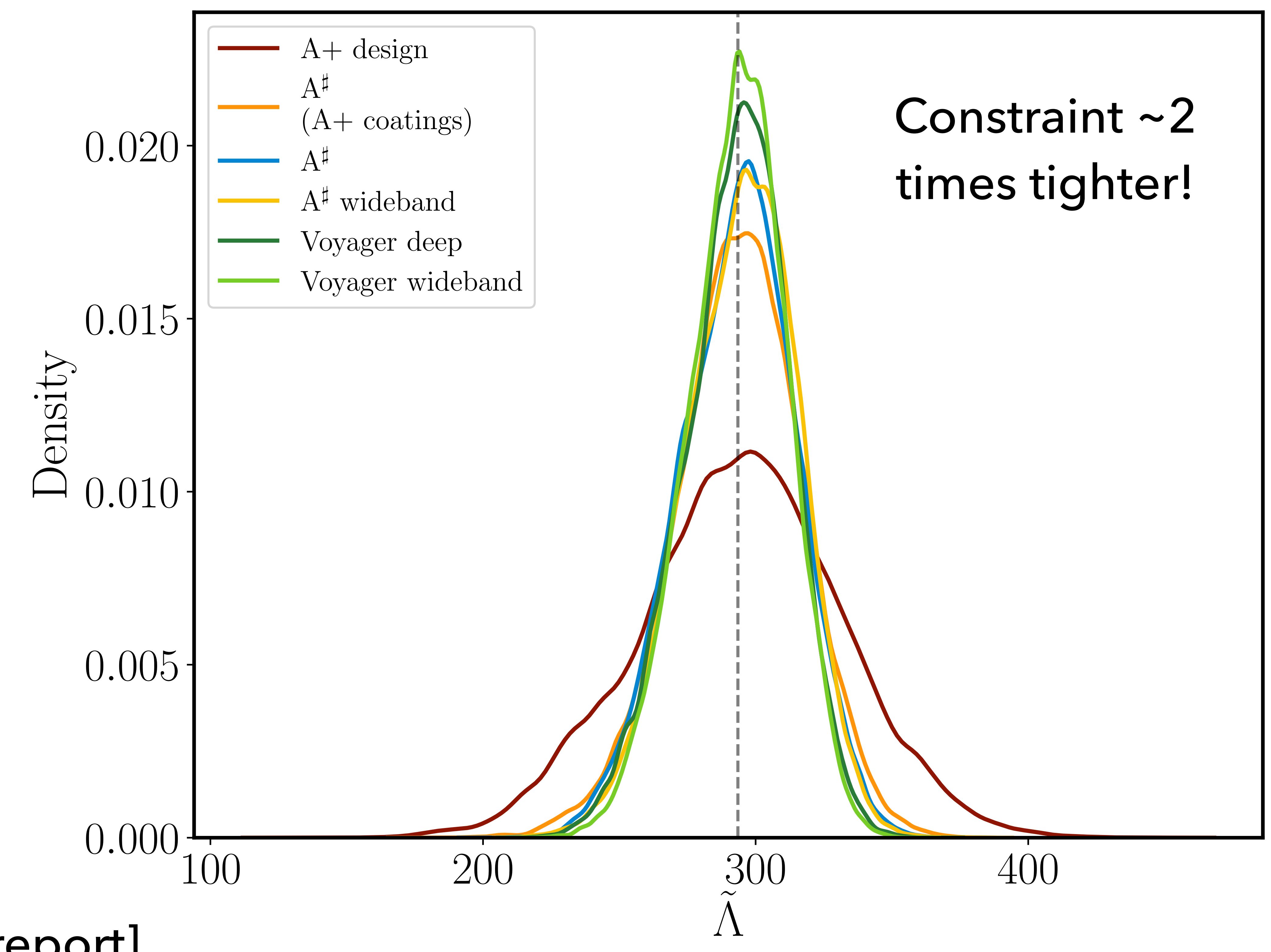
equation of state

GW170817



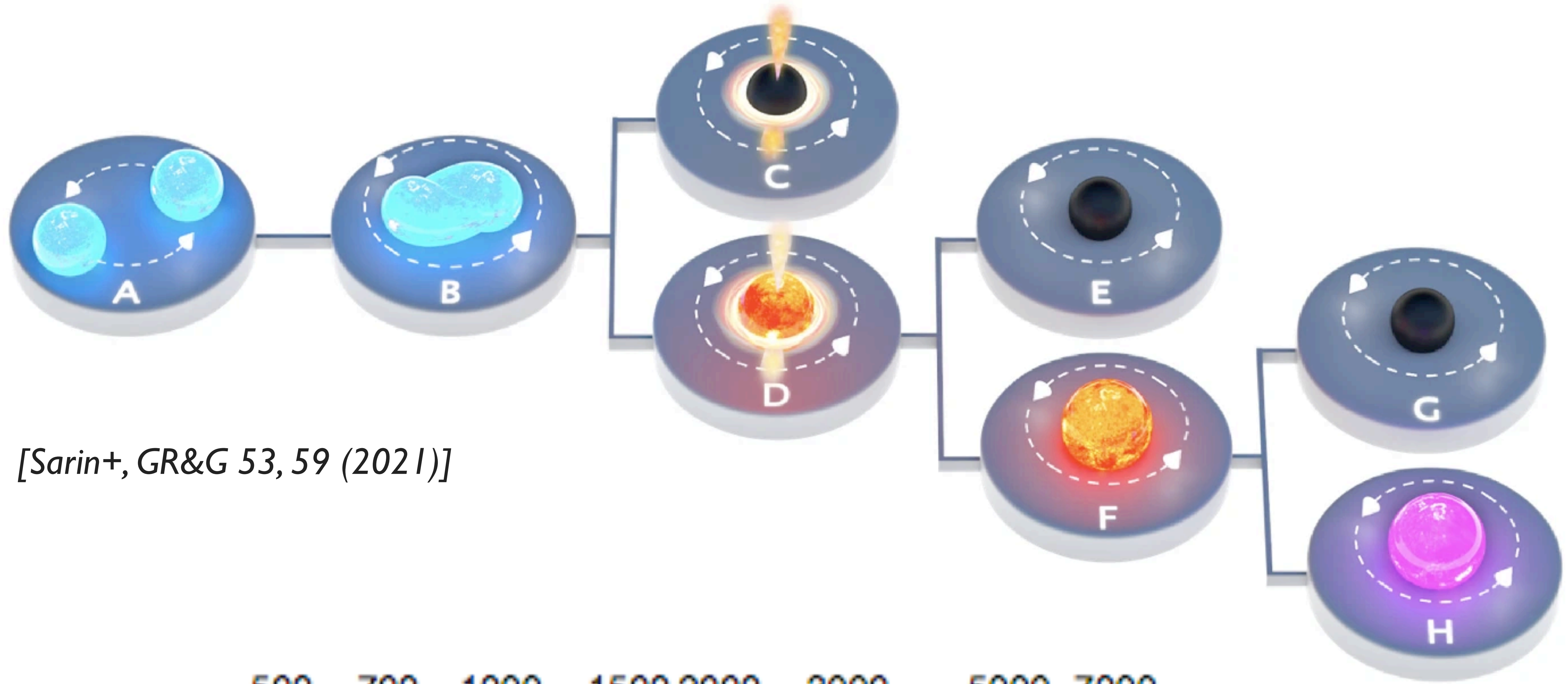
[LVC - Abbott et al., PRX (9) 2019]

GW170817-like BNS at 100 Mpc



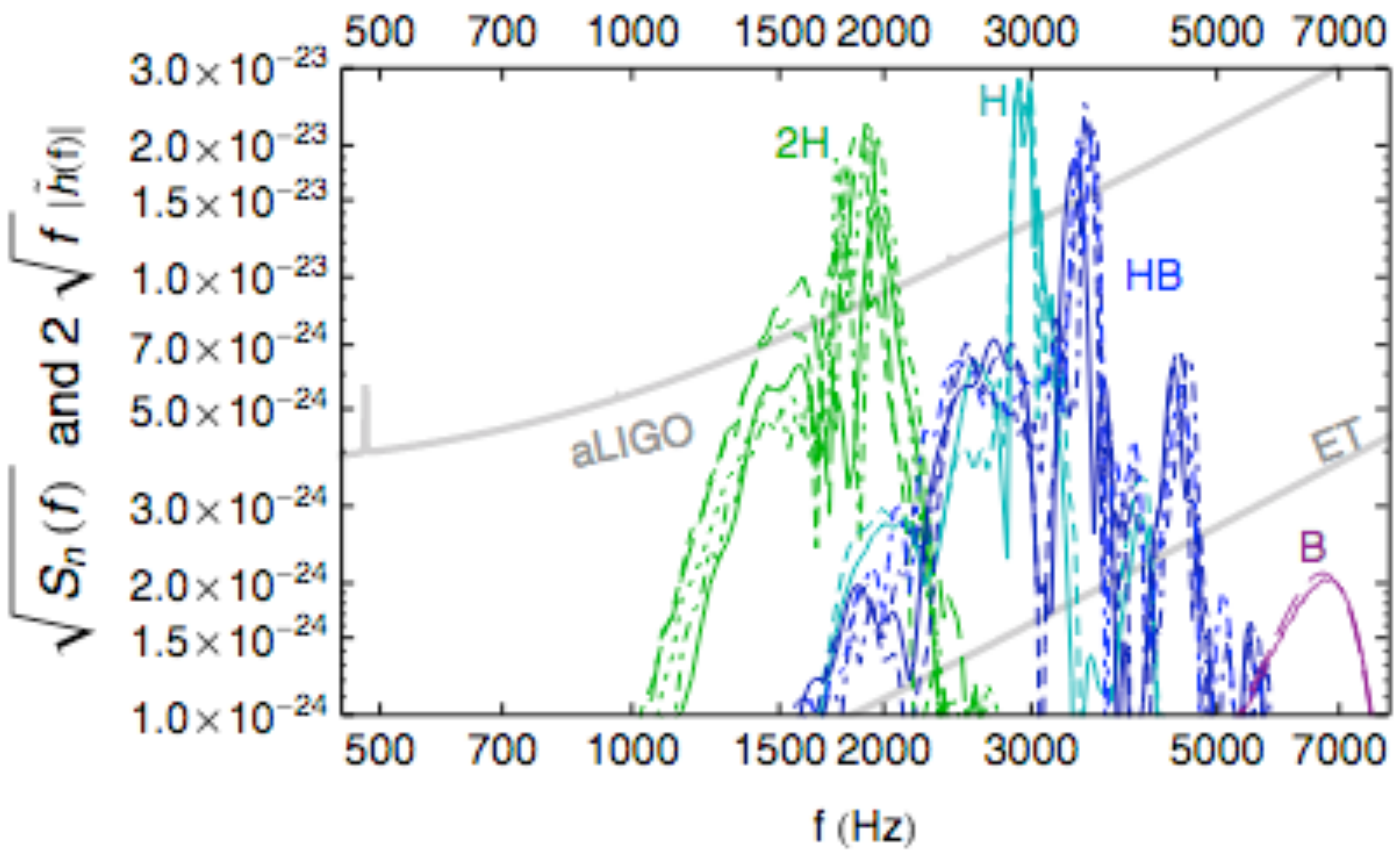
[Post-O5 report]

POST-O5 & THE POST-MERGER



[Sarin+, GR&G 53, 59 (2021)]

- Nature of the remnant
- Hot equation of state
- Phase transitions



[Read+, PRD 88, 044042 (2013)]

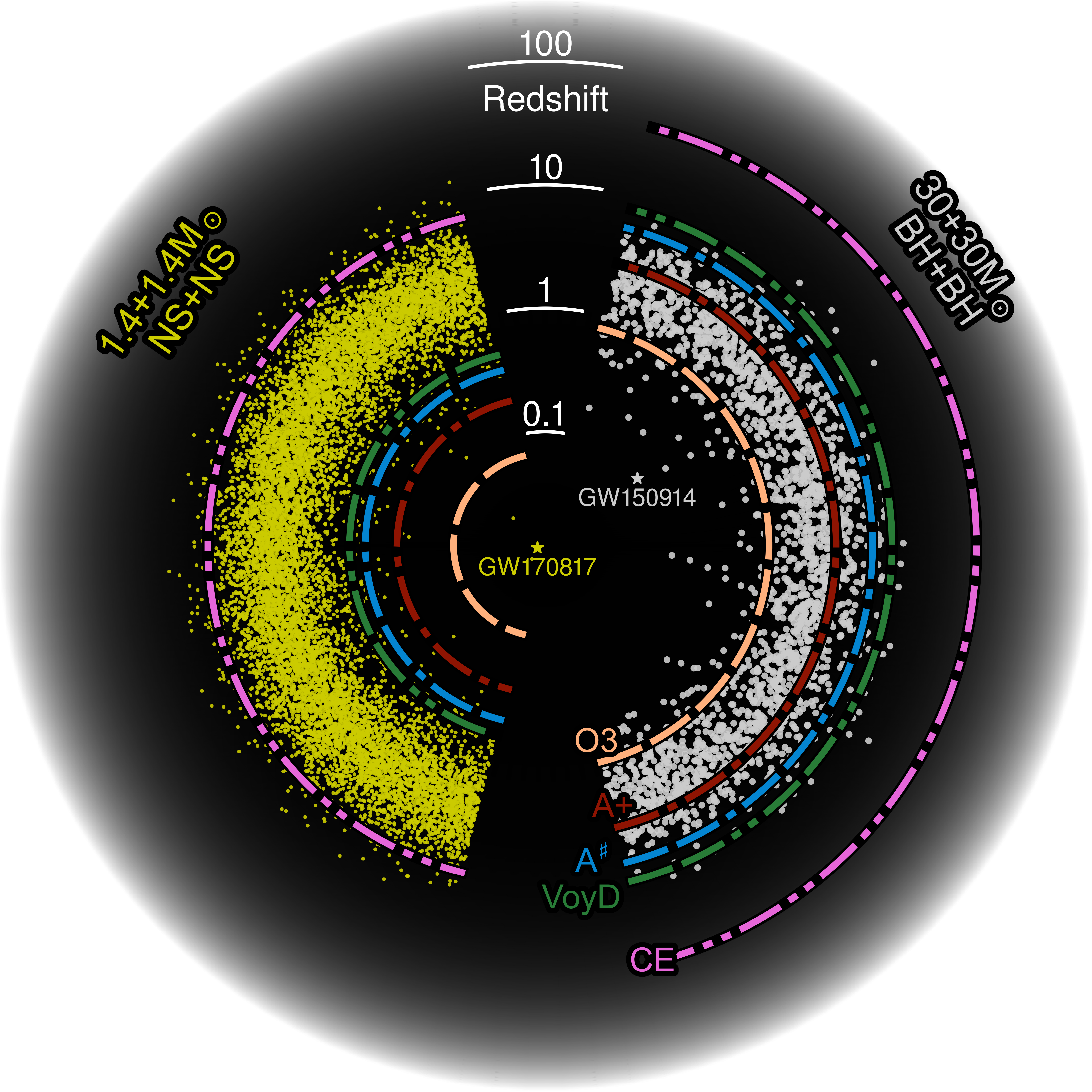
SNR of an optimally oriented BNS at 100 Mpc:

Configuration	BNS Range [Mpc]	$\rho_{\rm pm}^{(10)}$	$\rho_{\rm pm}^{(\rm max)}$
O3 LLO	130	0.4	0.6
A+ design	350	1.4	2.0
A$^\sharp$ (A+ coatings)	440	2.7	3.4
A$^\sharp$	600	2.7	3.7
A$^\sharp$ wideband	490	4.8	5.6
Voyager deep	780	2.8	4.1
Voyager wideband	630	5.2	5.9

[Post-O5 report]

SOME THINGS WE CAN'T LEARN …YET

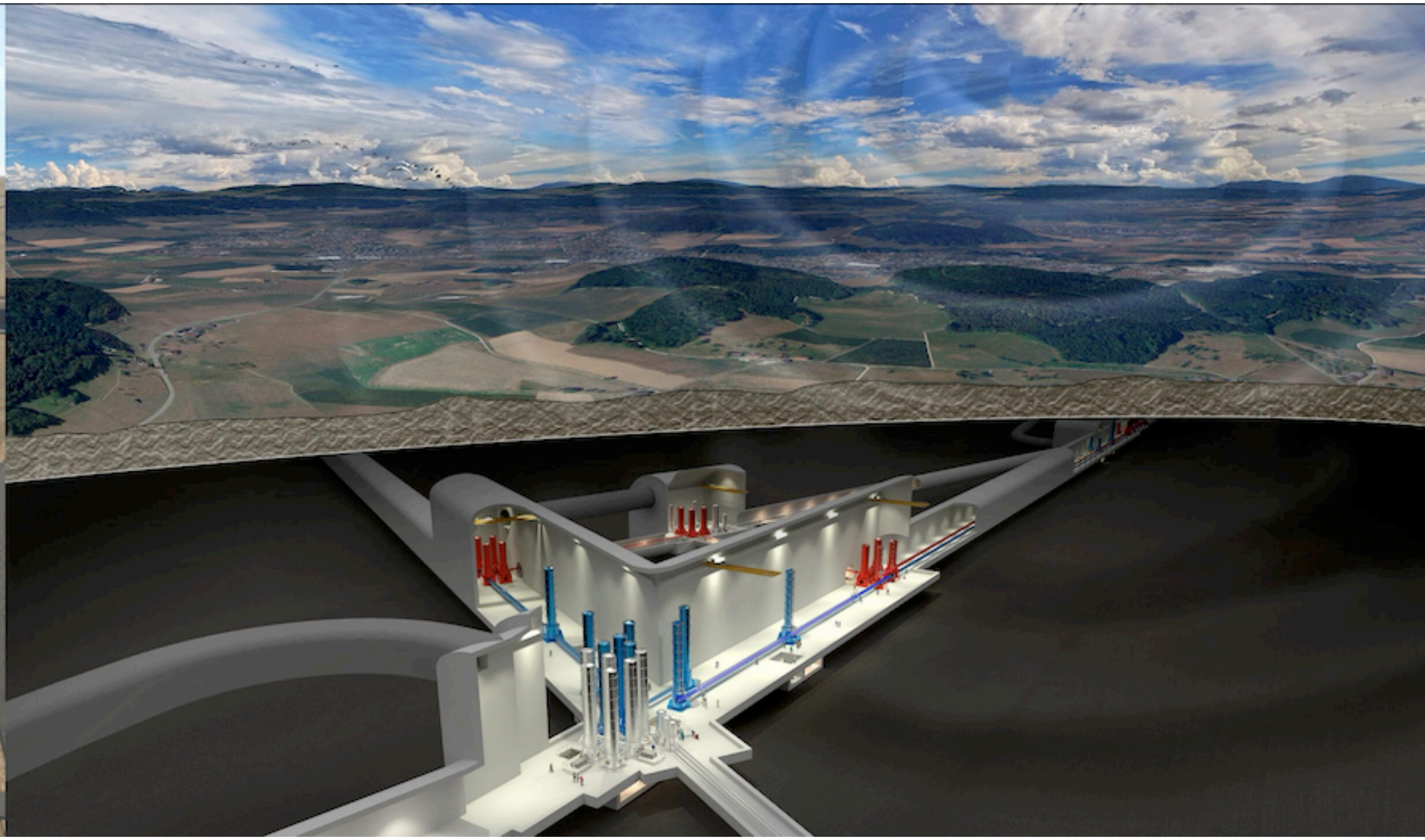
- Binary neutron star mergers beyond the very local universe
- Precise measurement of the nuclear equation of state
- Observing the fate of neutron star collisions
- Precision tests of the Kerrness of black holes
- Observing the GW memory
- BBH mergers in the high redshift universe
- Cosmological GW background
- …



THE NEXT GENERATION OF GROUND-BASED GW DETECTORS

Cosmic Explorer (CE)

Einstein Telescope (ET)

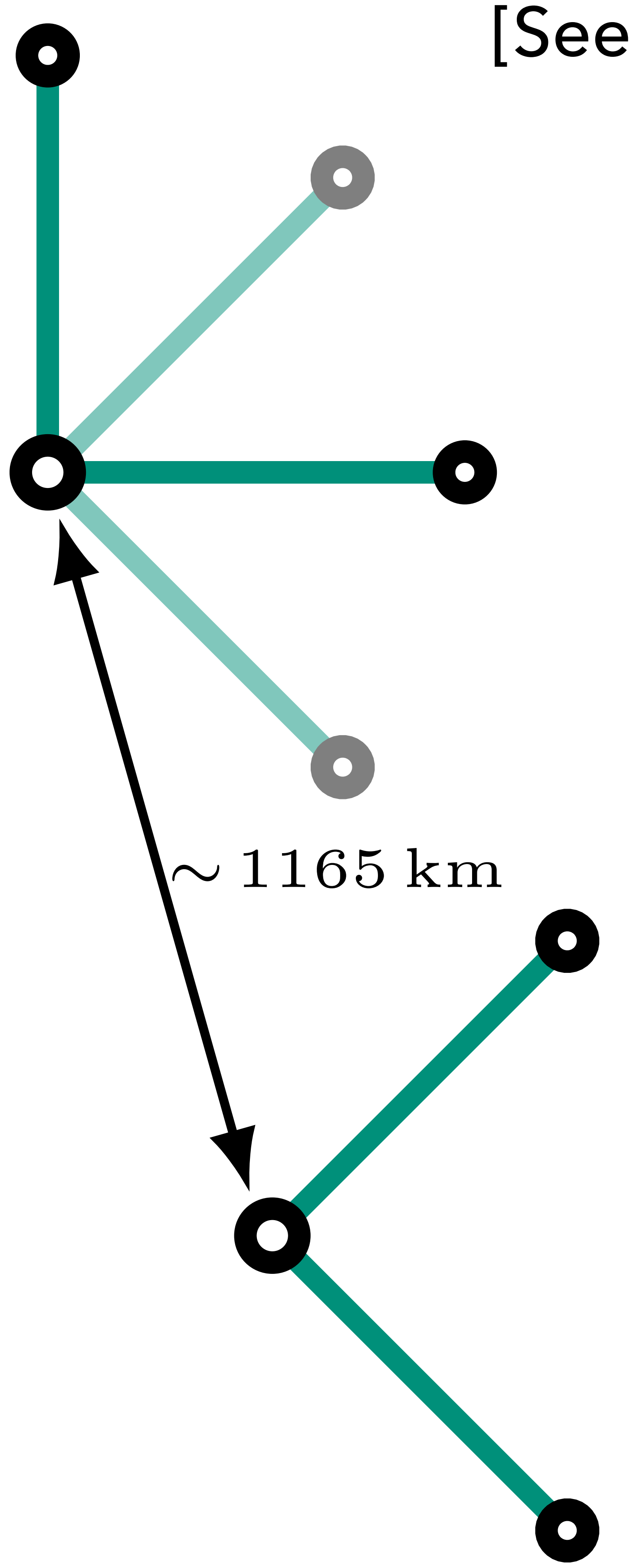


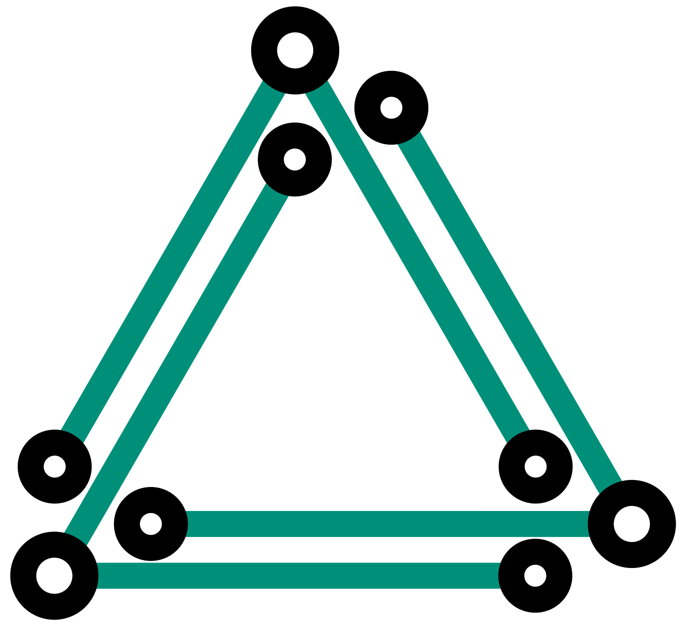
Artists' impressions of the Cosmic Explorer (left) and Einstein Telescope (right) projects. Cosmic Explorer credits: A. Nguyen, V. Kitchen, E. Anaya, California State University Fullerton / Einstein Telescope credits: M. Kraan, Nikhef

EINSTEIN TELESCOPE

- Reference design: 10km triangular "xylophone" configuration with cryogenic cooling (ET-D)
- Alternative: 2 15km L-shaped detectors

[See talk by L. Naticchione for more details]

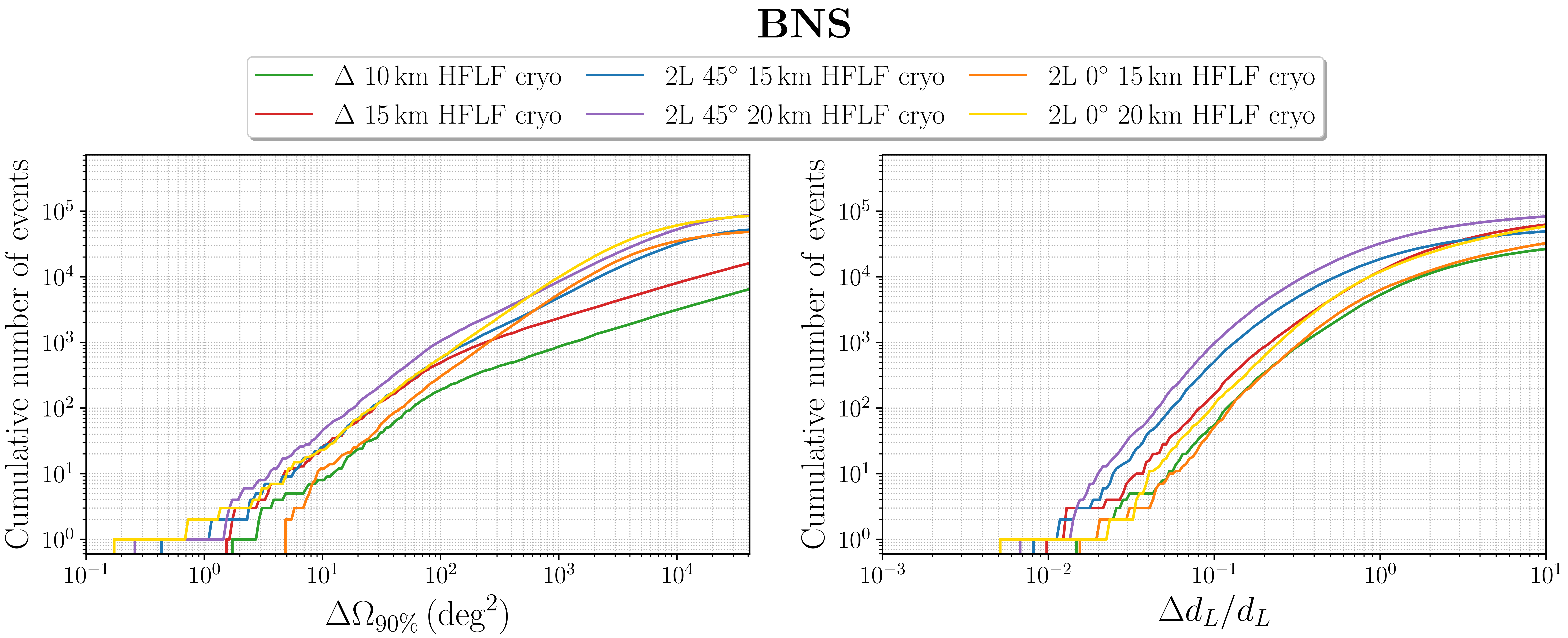




reference design

GEOMETRY IMPACTS MEASUREMENT ACCURACY

- Example: BNS localisation

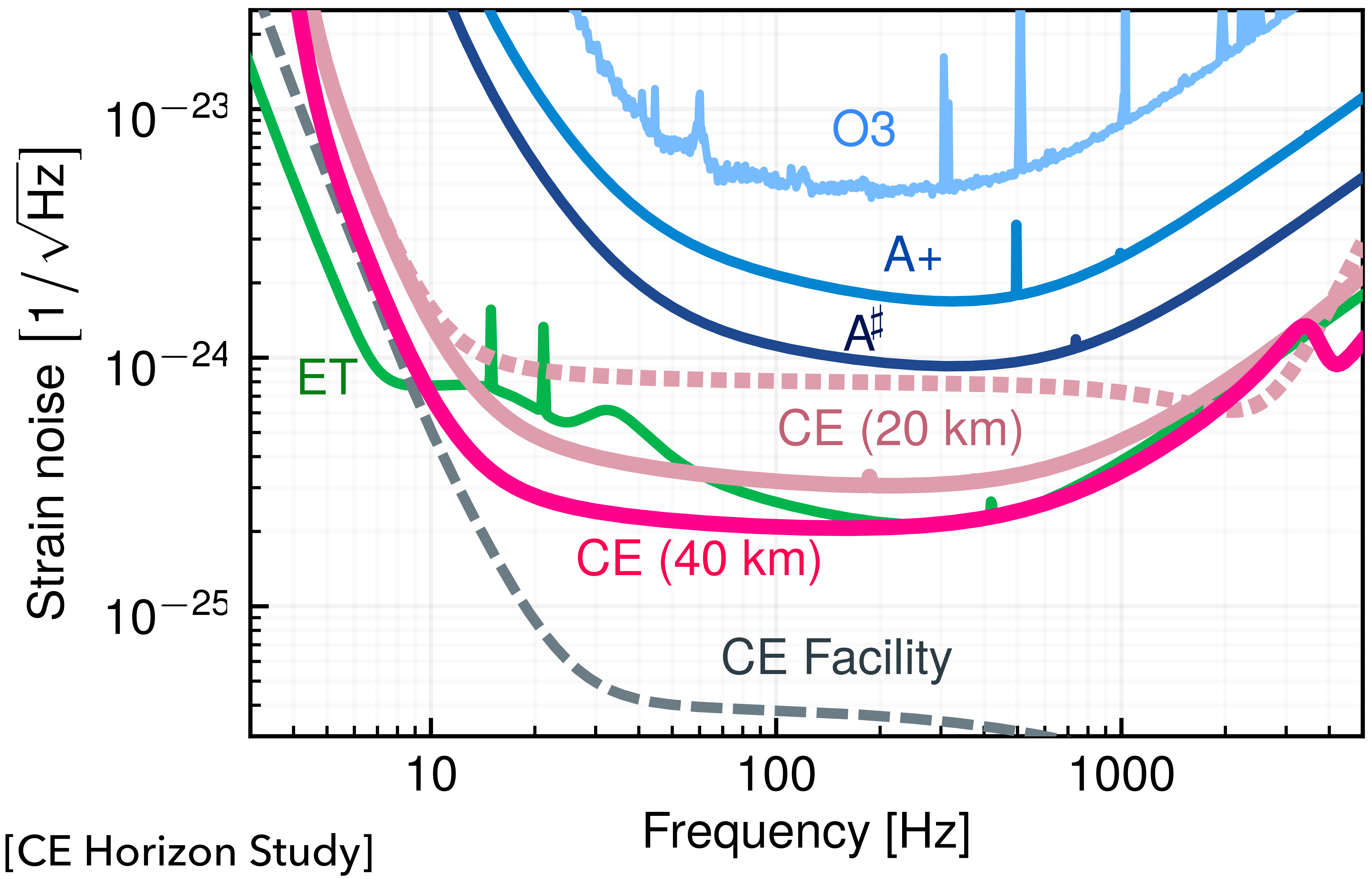


[COBA study]

COSMIC EXPLORER

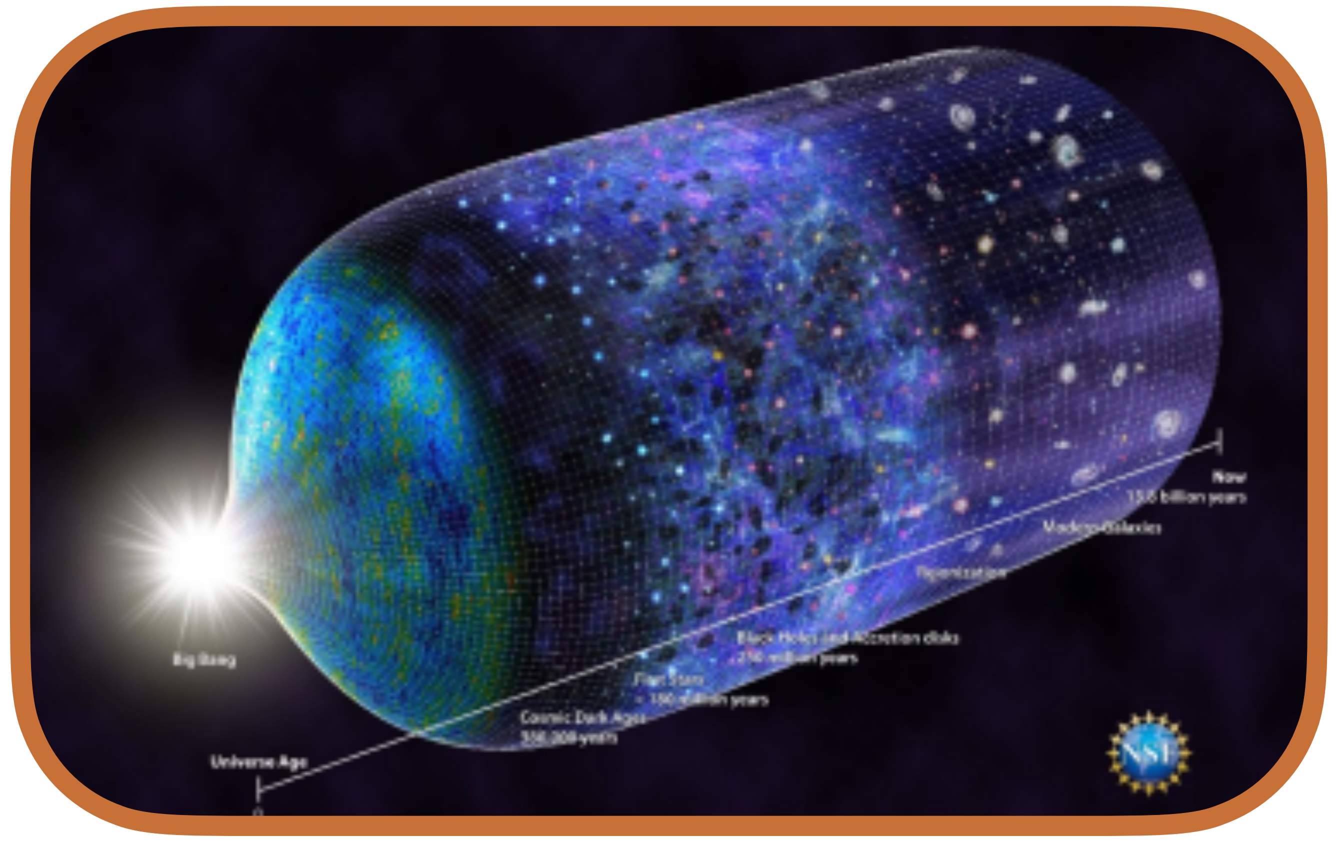
- Reference design: 2 L-shaped detectors with 20km and 40km
- An order of magnitude strain improvement
  - Equivalent to an order of magnitude increase in the diameter of a telescope

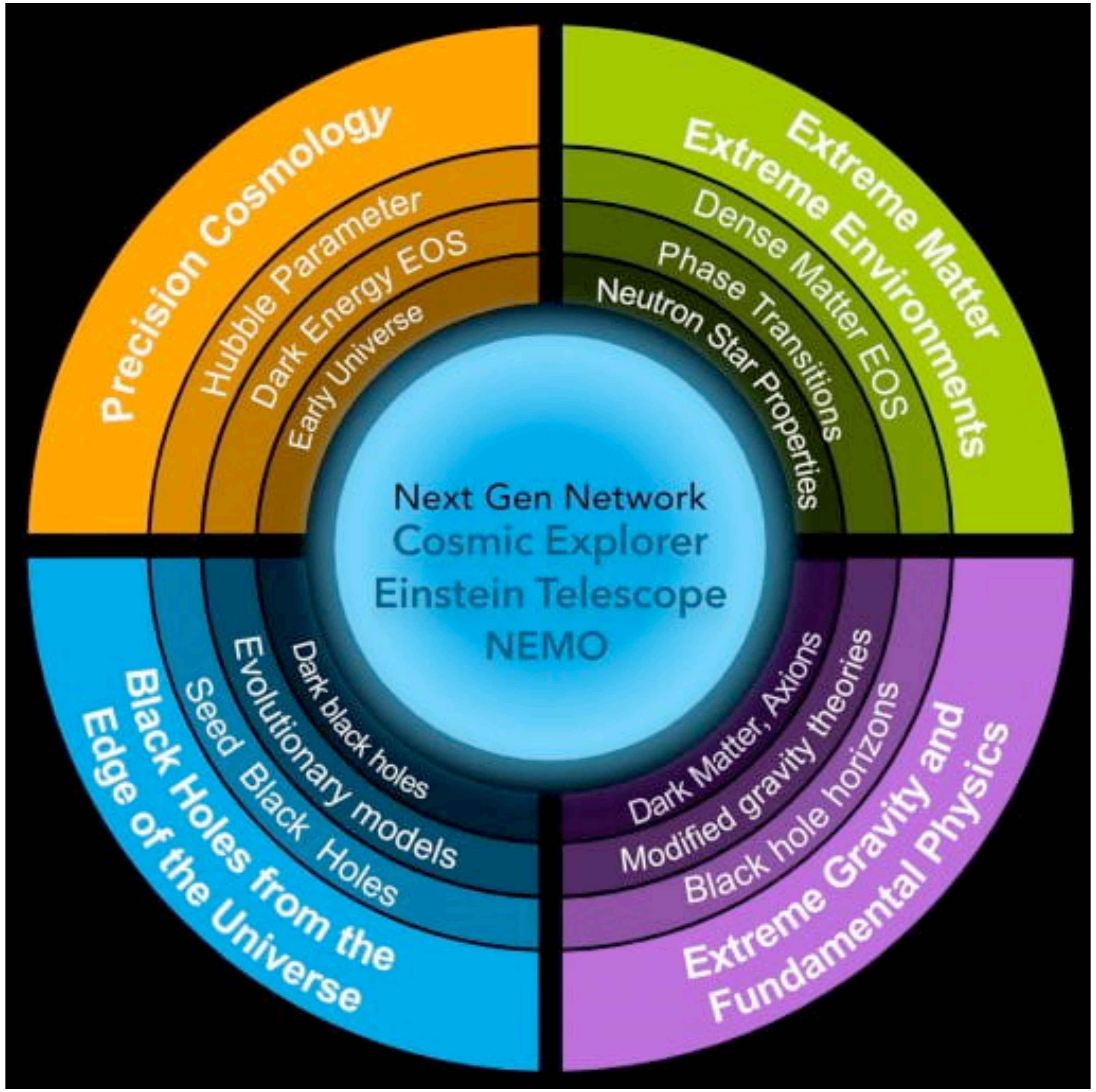
Design parameter	A+	$A^\sharp$	CE
Arm length	4 km	4 km	20 km, 40 km
Arm power	750 kW	1.5 MW	1.5 MW
Squeezing level	6 dB	10 dB	10 dB
Test mass mass	40 kg	100 kg	320 kg
Test mass coatings	A+	A+/2	A+
Suspension length	1.6 m	1.6 m	4 m
Newtonian mitigation	0 dB	6 dB	20 dB

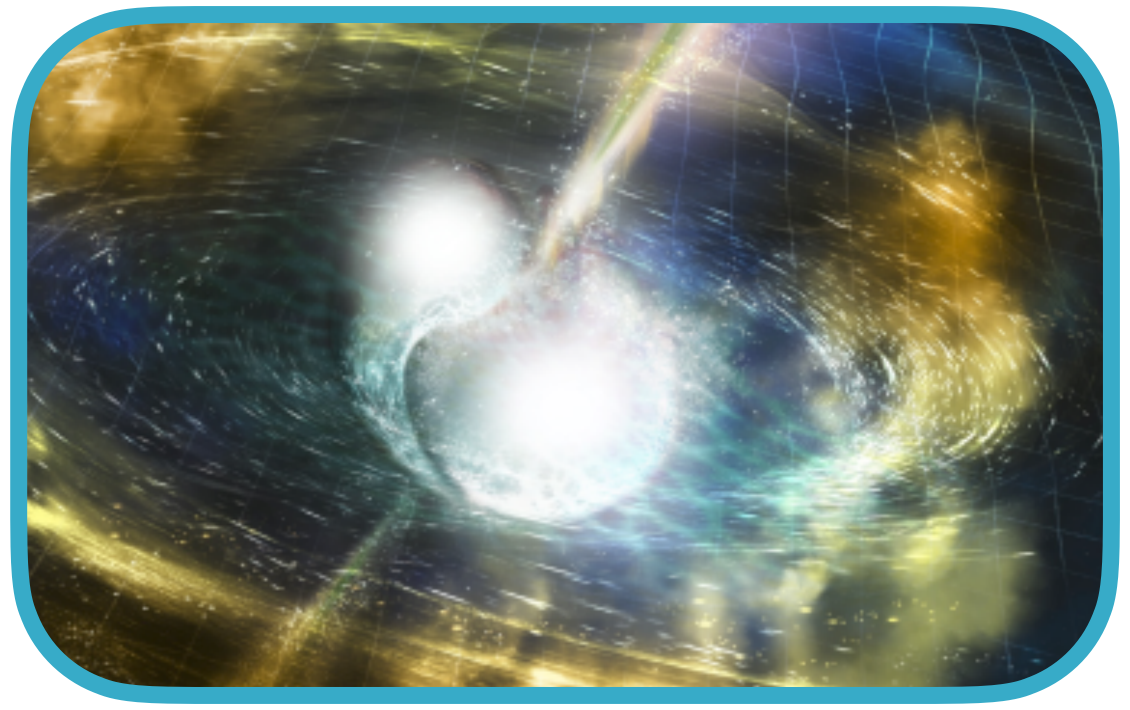


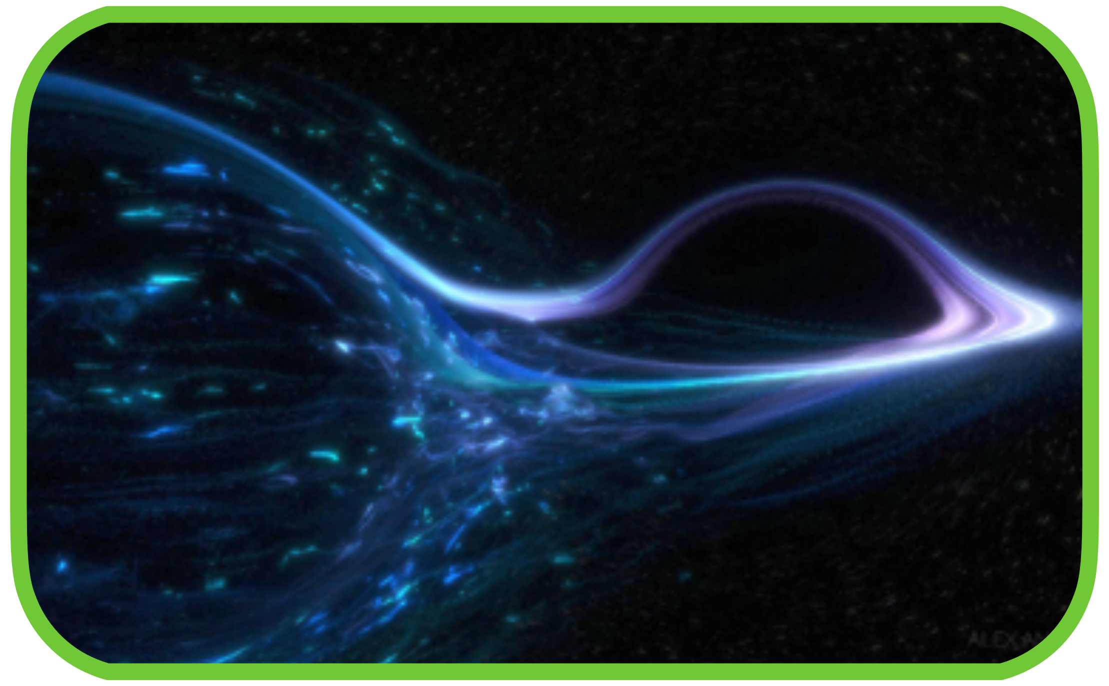
[CE Horizon Study]

KEY SCIENCE OBJECTIVES



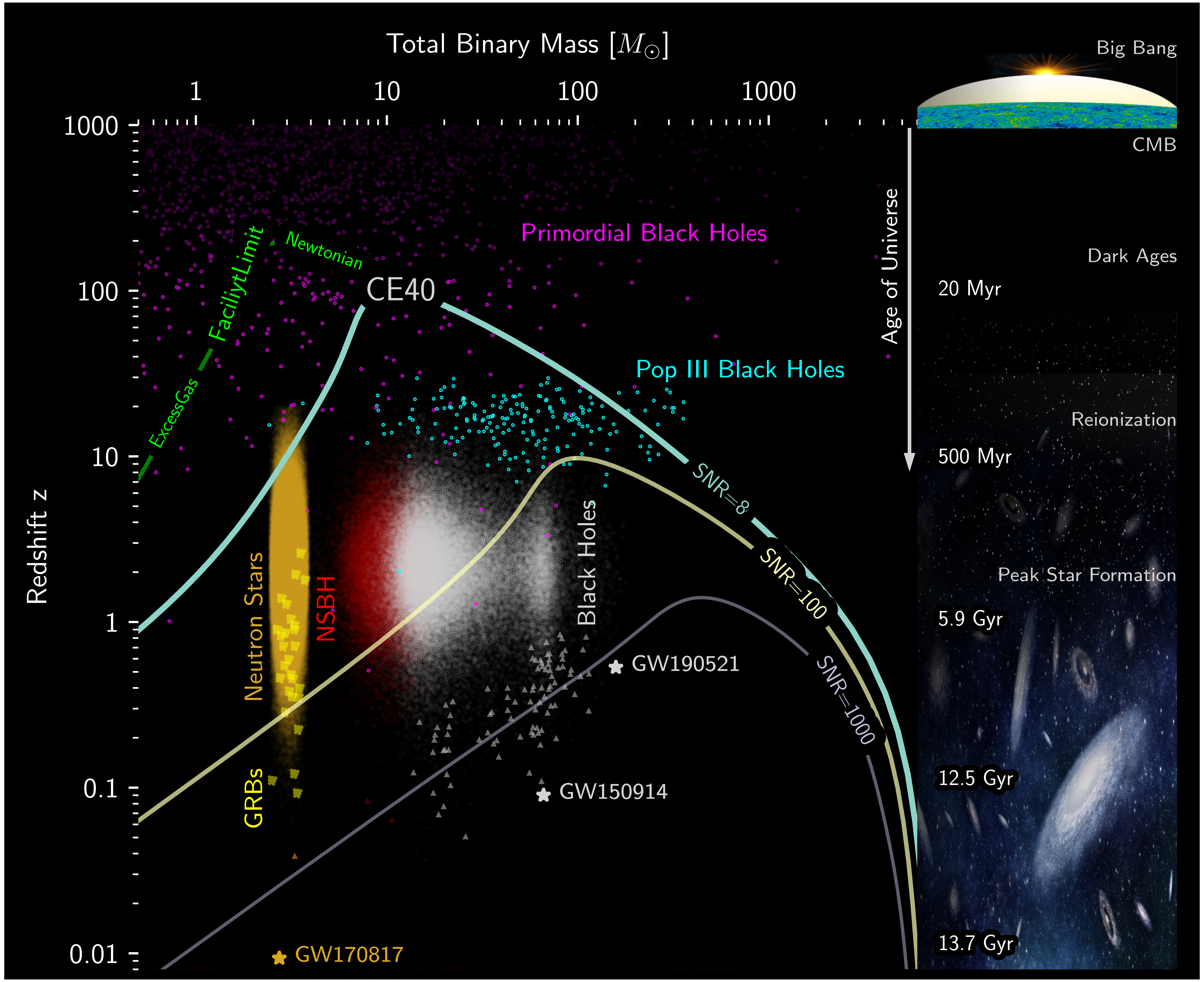


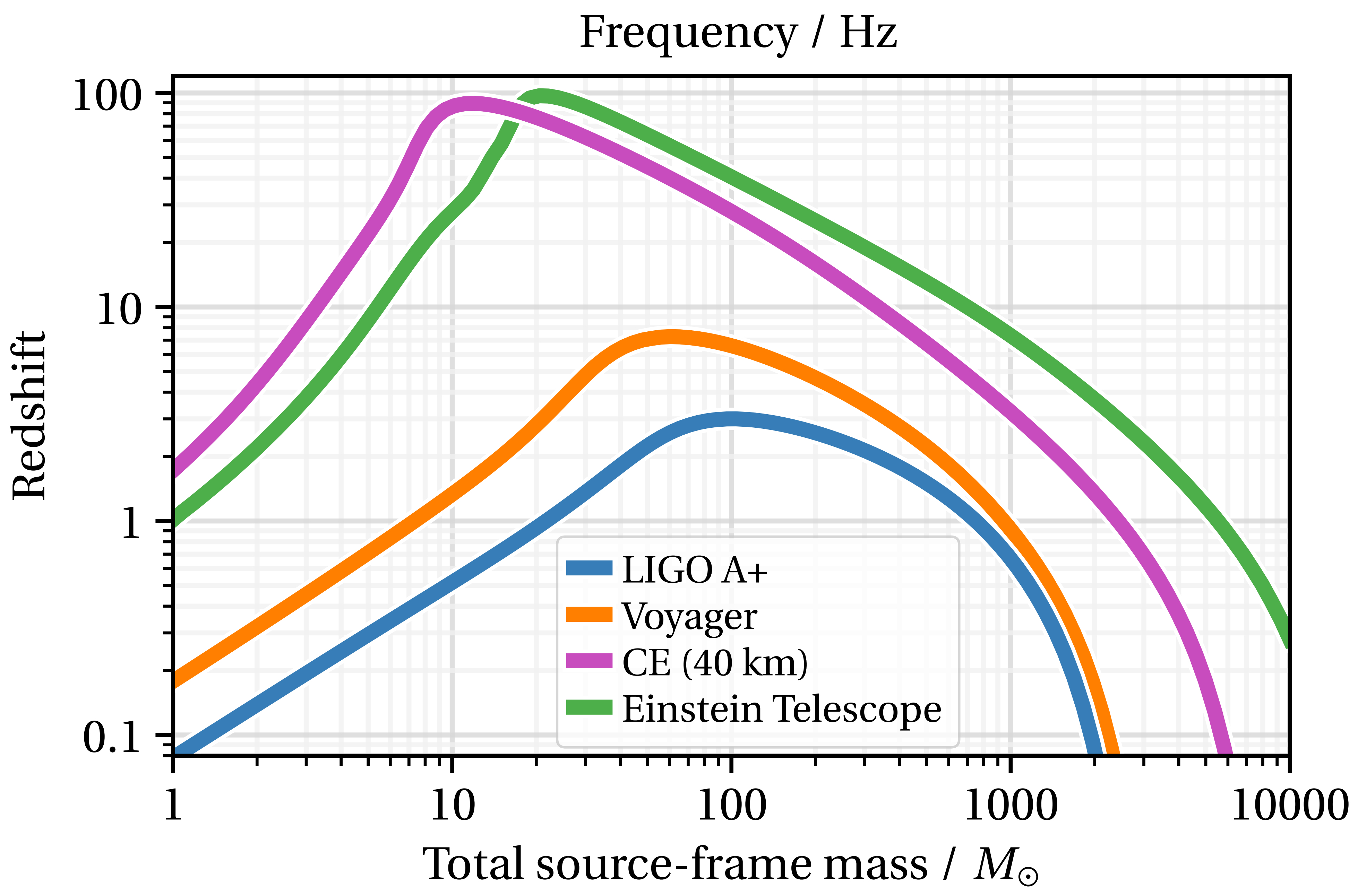




[CE Horizon Study, ET Science case]

BLACK HOLES & NEUTRON STARS THROUGH COSMIC TIME

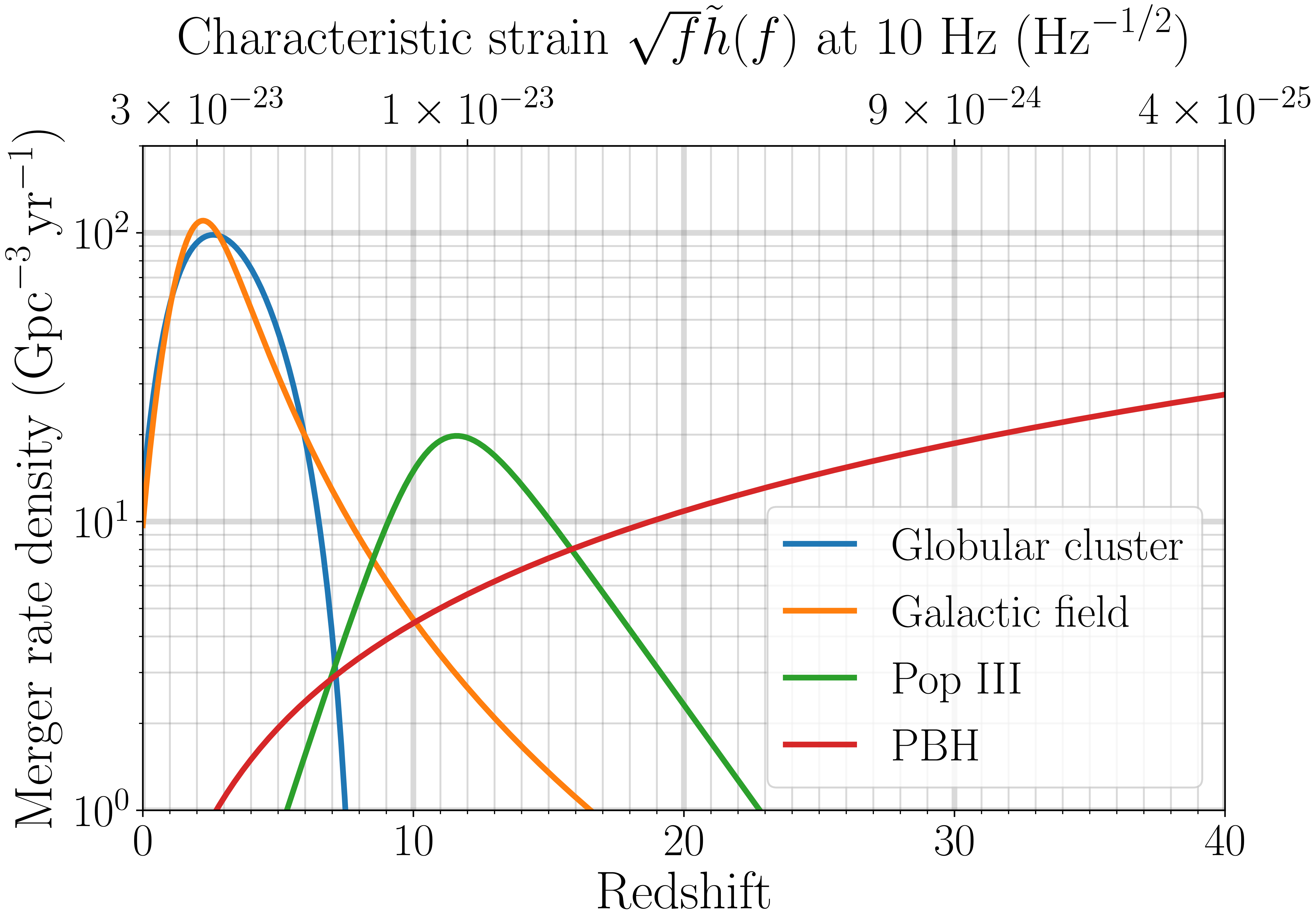




[CE Horizon Study/MPSAC]

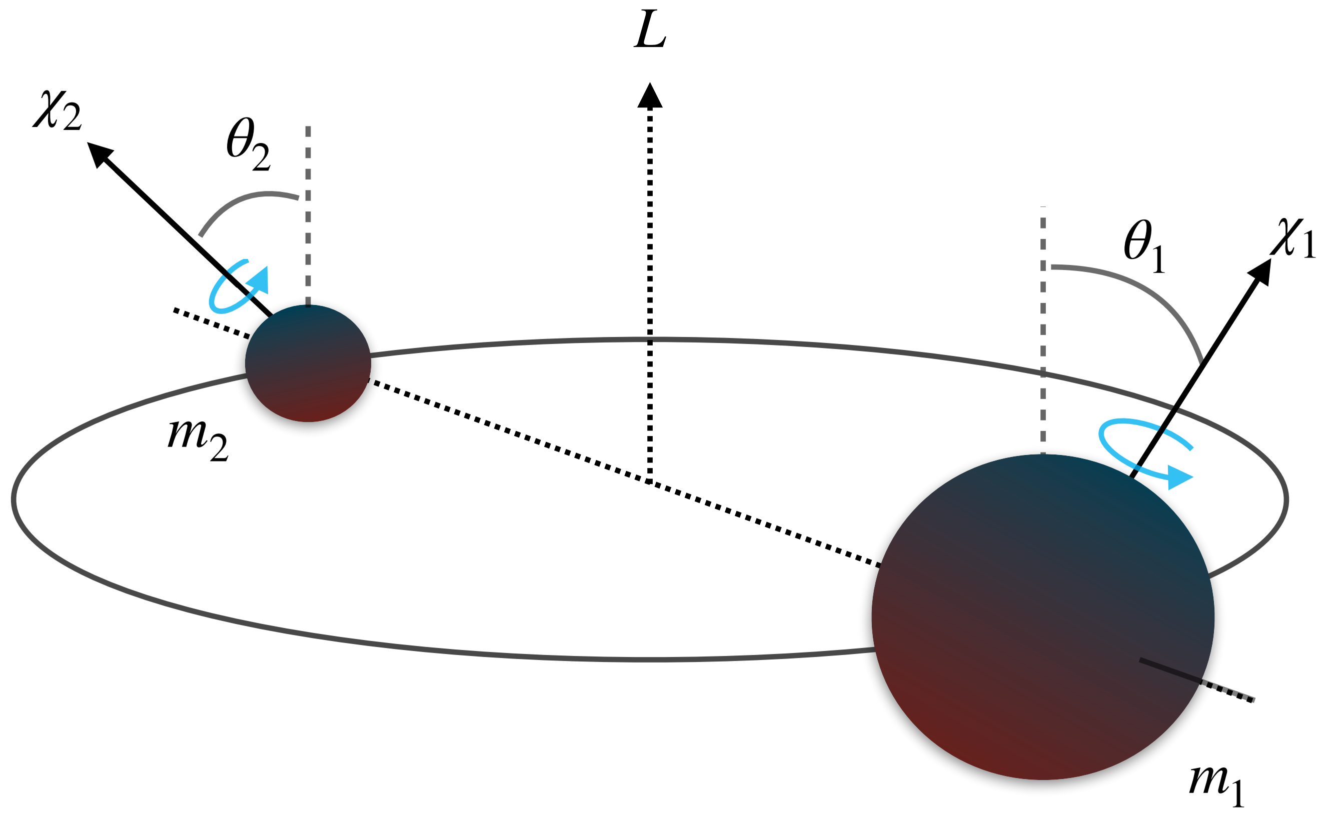
BLACK HOLES & NEUTRON STARS THROUGH COSMIC TIME

- **Access to the high-z universe**
- Remnants of Population III stars
- Seed black holes & hierarchical growth of supermassive black holes
- Evolution of the merger rate as a function of time
- Low-frequency performance is crucial
- Accurate localisation (sky & distance) is key
  - Requires 2 3G detectors due to mass-redshift degeneracy

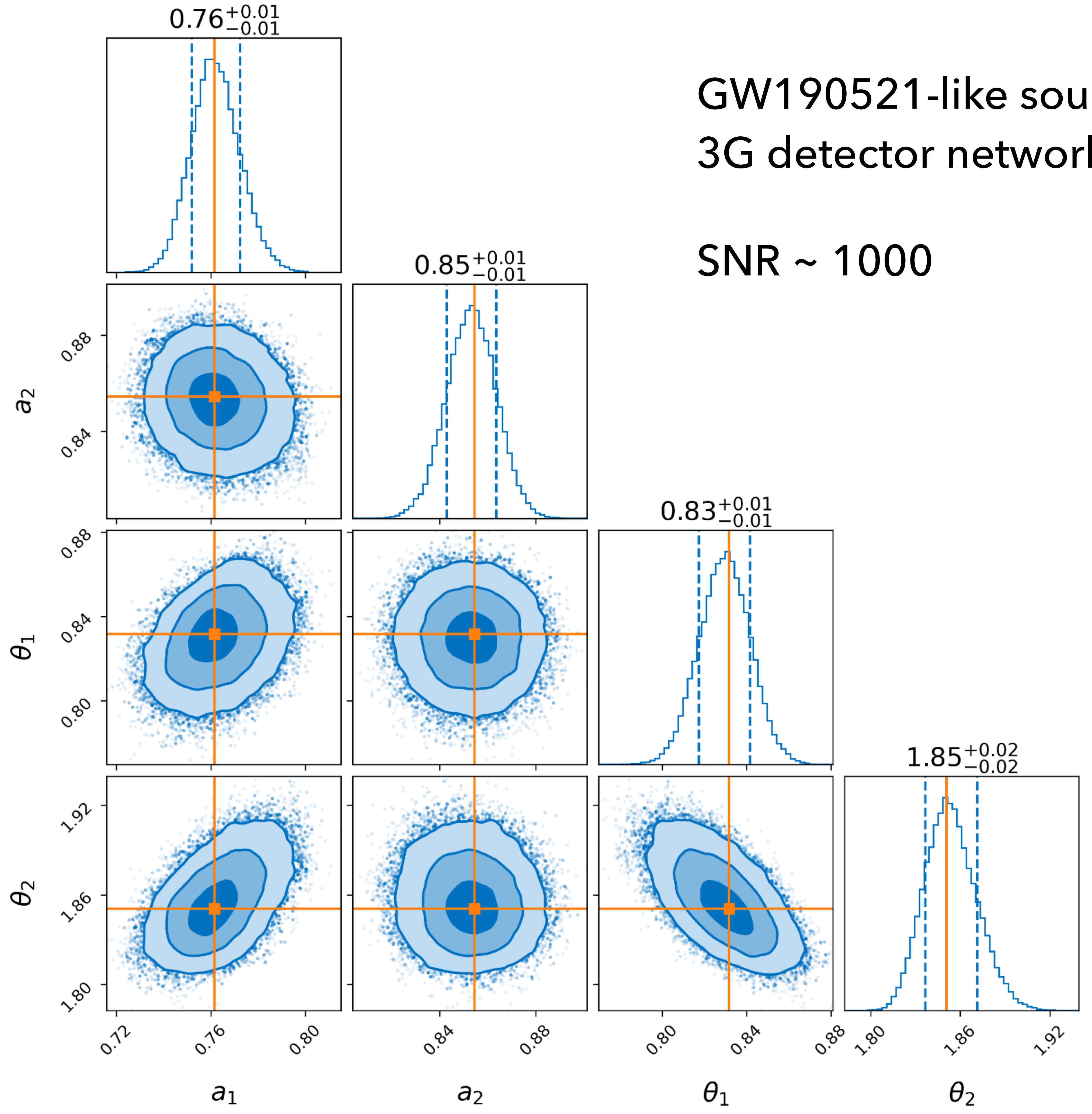


[CE Horizon Study]

BLACK HOLES & NEUTRON STARS THROUGH COSMIC TIME



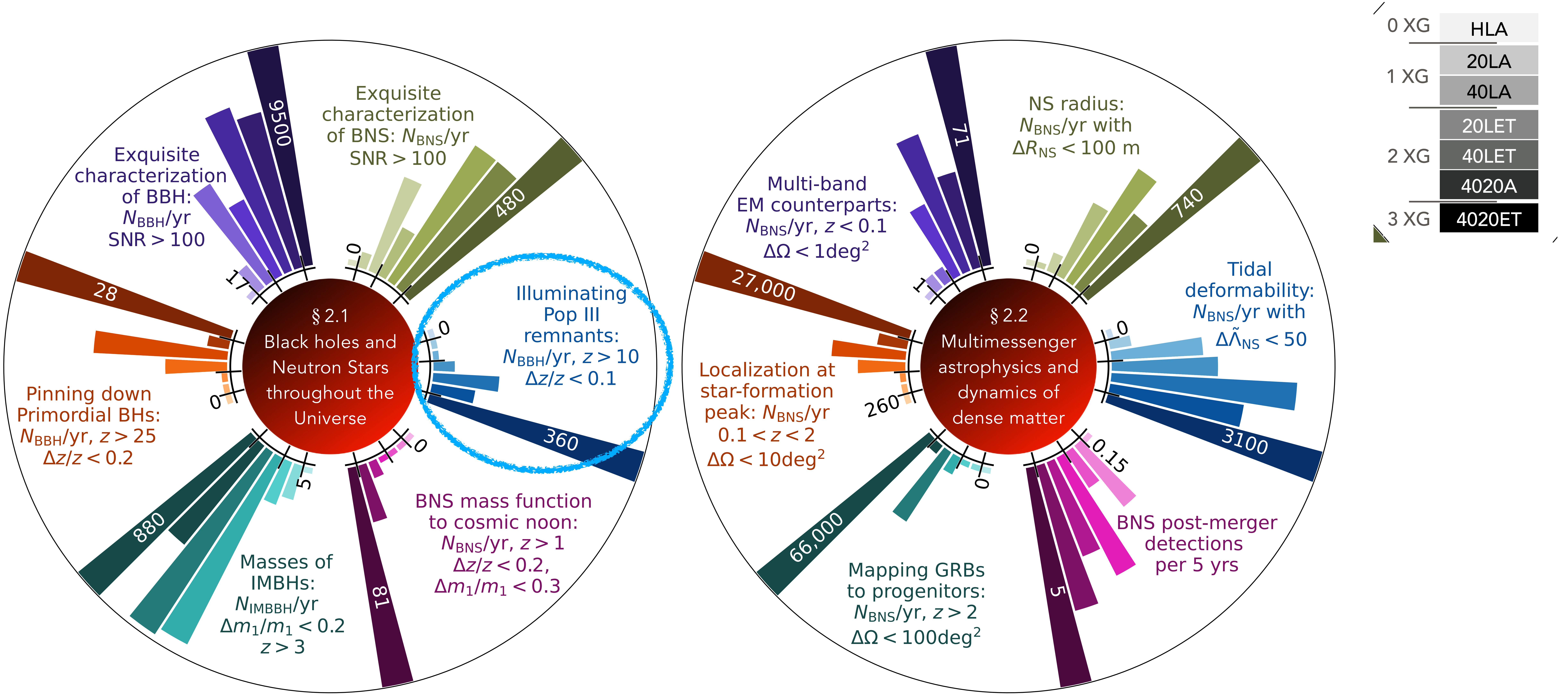
- Precision measurement of BH properties
  - Degree-level precision of spin tilts
  - Percent-level measurement of individual spin magnitudes
- Implications for astrophysics, populations and formation scenarios



GW190521-like source in 3G detector network

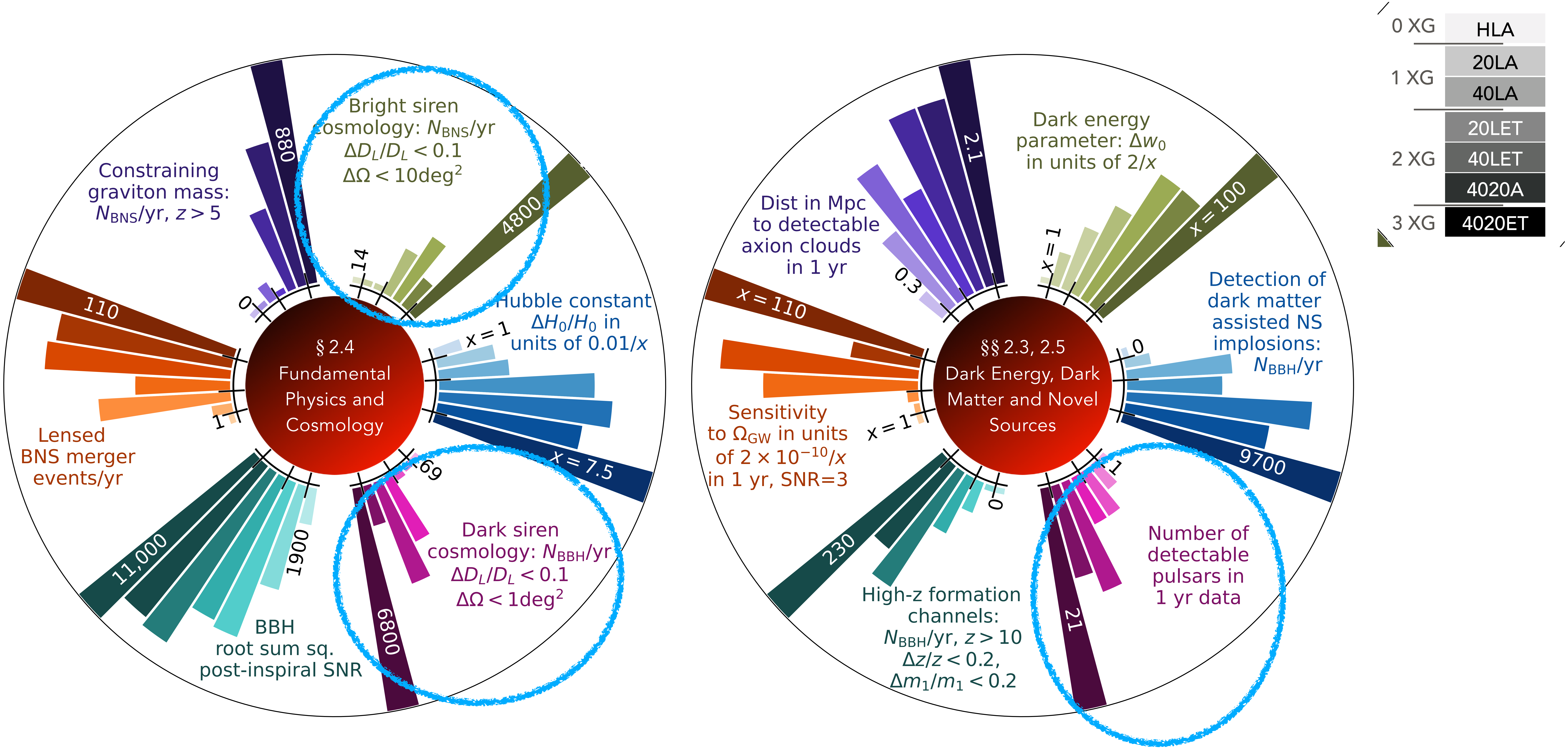
SNR ~ 1000

[Klein+ inc. PS, arXiv:2204.03423]



§ 2.1 Black holes and Neutron Stars throughout the Universe
Exquisite characterization of BBH: N_{BBH}/yr SNR > 100
9500
17
Exquisite characterization of BNS: N_{BNS}/yr SNR > 100
480
0
Illuminating Pop III remnants: N_{BBH}/yr, $z > 10$ $\Delta z/z < 0.1$
360
0
BNS mass function to cosmic noon: N_{BNS}/yr, $z > 1$ $\Delta z/z < 0.2$, $\Delta m_1/m_1 < 0.3$
81
0
Masses of IMBHs: N_{IMBBH}/yr $\Delta m_1/m_1 < 0.2$ $z > 3$
880
5
Pinning down Primordial BHs: N_{BBH}/yr, $z > 25$ $\Delta z/z < 0.2$
28
0
§ 2.2 Multimessenger astrophysics and dynamics of dense matter
NS radius: N_{BNS}/yr with $\Delta R_{NS} < 100$ m
740
0
Multi-band EM counterparts: N_{BNS}/yr, $z < 0.1$ $\Delta\Omega < 1\mathrm{deg}^2$
71
1
Tidal deformability: N_{BNS}/yr with $\Delta\tilde{\Lambda}_{NS} < 50$
3100
0
BNS post-merger detections per 5 yrs
5
0.15
Mapping GRBs to progenitors: N_{BNS}/yr, $z > 2$ $\Delta\Omega < 100\mathrm{deg}^2$
66,000
0
Localization at star-formation peak: N_{BNS}/yr $0.1 < z < 2$ $\Delta\Omega < 10\mathrm{deg}^2$
27,000
260
0 XG HLA
1 XG 20LA 40LA
2 XG 20LET 40LET 4020A
3 XG 4020ET

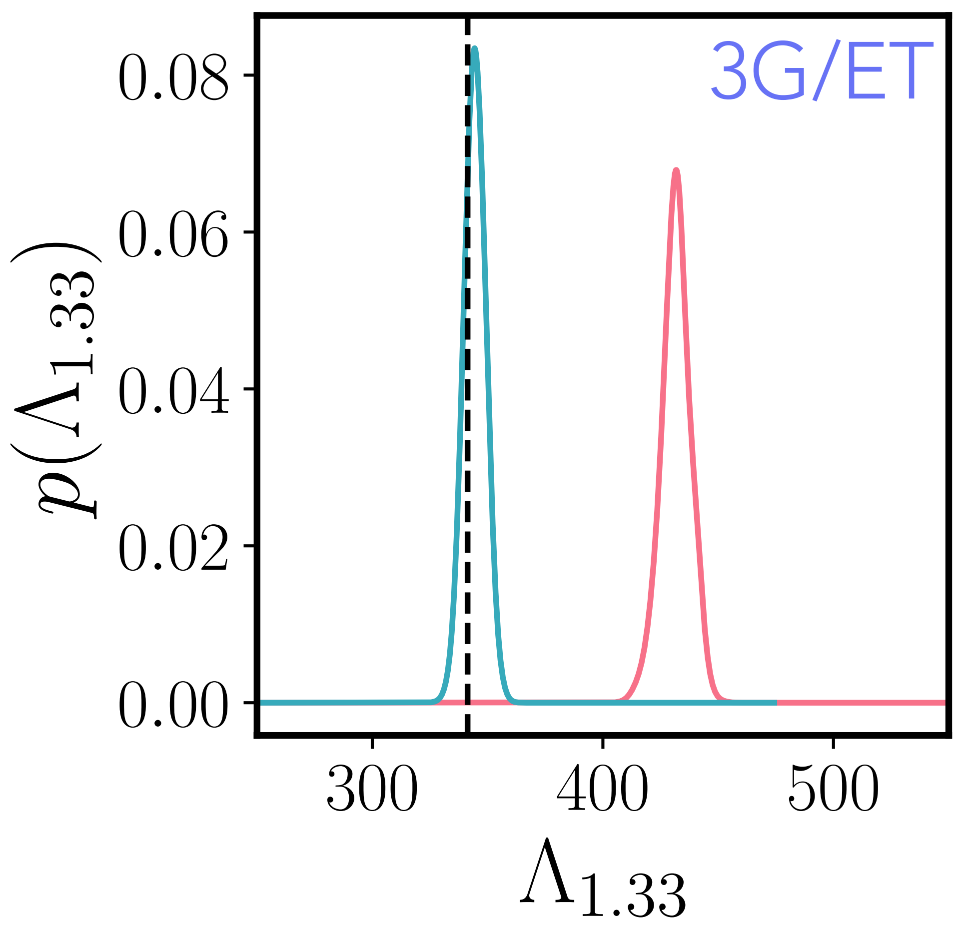
[MPSAC]


0 XG
HLA
1 XG
20LA
40LA
2 XG
20LET
40LET
4020A
3 XG
4020ET
§ 2.4
Fundamental
Physics and
Cosmology
Bright siren
cosmology: N_{BNS}/yr
$\Delta D_L/D_L < 0.1$
$\Delta\Omega < 10\text{deg}^2$
Constraining
graviton mass:
N_{BNS}/yr, $z > 5$
Hubble constant
$\Delta H_0/H_0$ in
units of 0.01/x
Lensed
BNS merger
events/yr
BBH
root sum sq.
post-inspiral SNR
Dark siren
cosmology: N_{BBH}/yr
$\Delta D_L/D_L < 0.1$
$\Delta\Omega < 1\text{deg}^2$
880
14
4800
0
110
1
$x = 1$
$x = 7.5$
69
6800
1900
11,000
§§ 2.3, 2.5
Dark Energy, Dark
Matter and Novel
Sources
Dark energy
parameter: Δw_0
in units of 2/x
Dist in Mpc
to detectable
axion clouds
in 1 yr
Detection of
dark matter
assisted NS
implosions:
N_{BBH}/yr
Sensitivity
to Ω_{GW} in units
of $2 \times 10^{-10}/x$
in 1 yr, SNR=3
High-z formation
channels:
N_{BBH}/yr, $z > 10$
$\Delta z/z < 0.2$,
$\Delta m_1/m_1 < 0.2$
Number of
detectable
pulsars in
1 yr data
2.1
0.3
$x = 1$
$x = 100$
$x = 110$
$x = 1$
0
9700
1
21
0
230

[MPSAC]

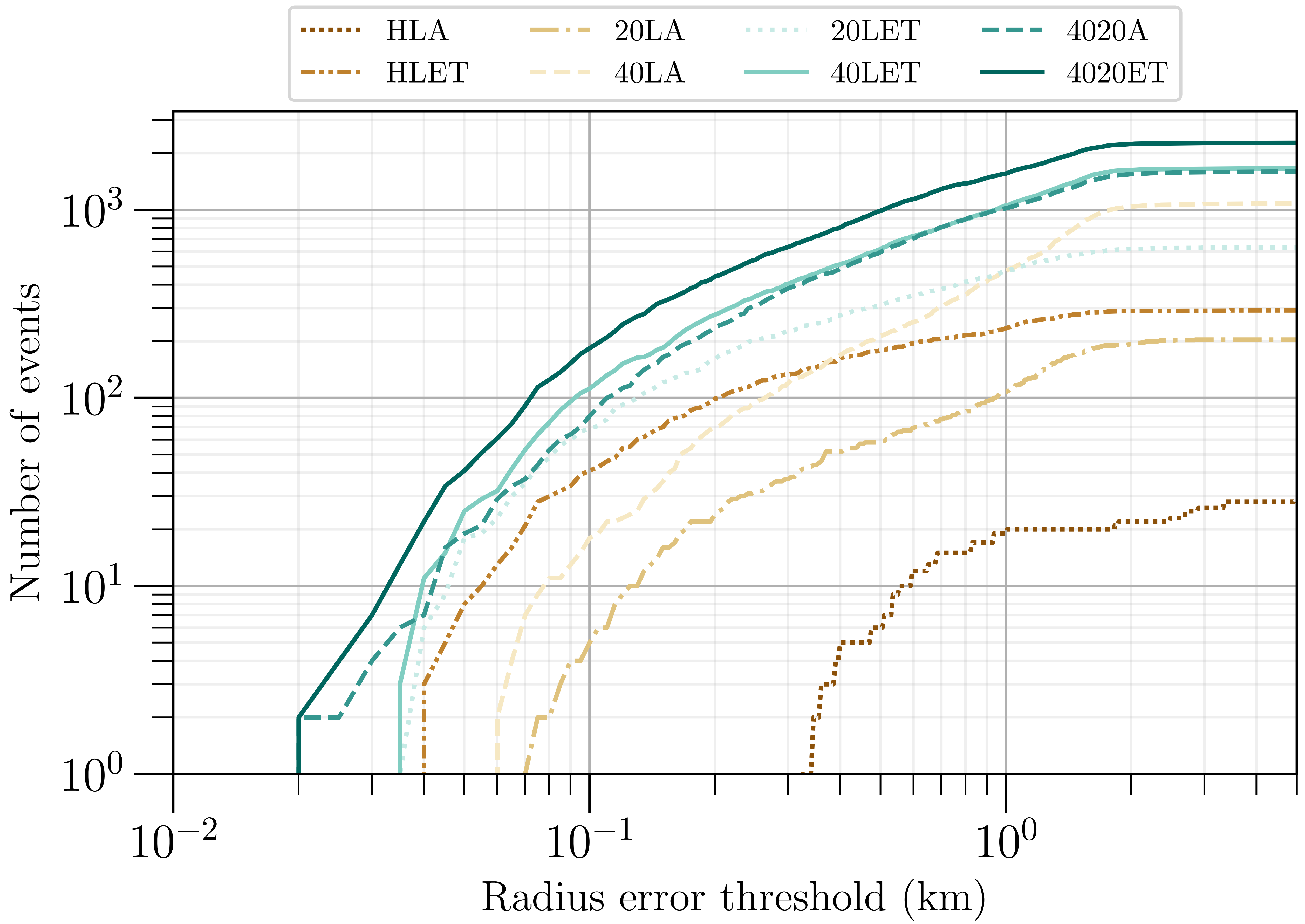
DYNAMICS OF DENSE MATTER

- Error on neutron star radius < 100m for O(10-100) of detections
- **On the population level: ~10m**



Caution: Systematics matter!

[Pratten+ inc. PS, PRL]

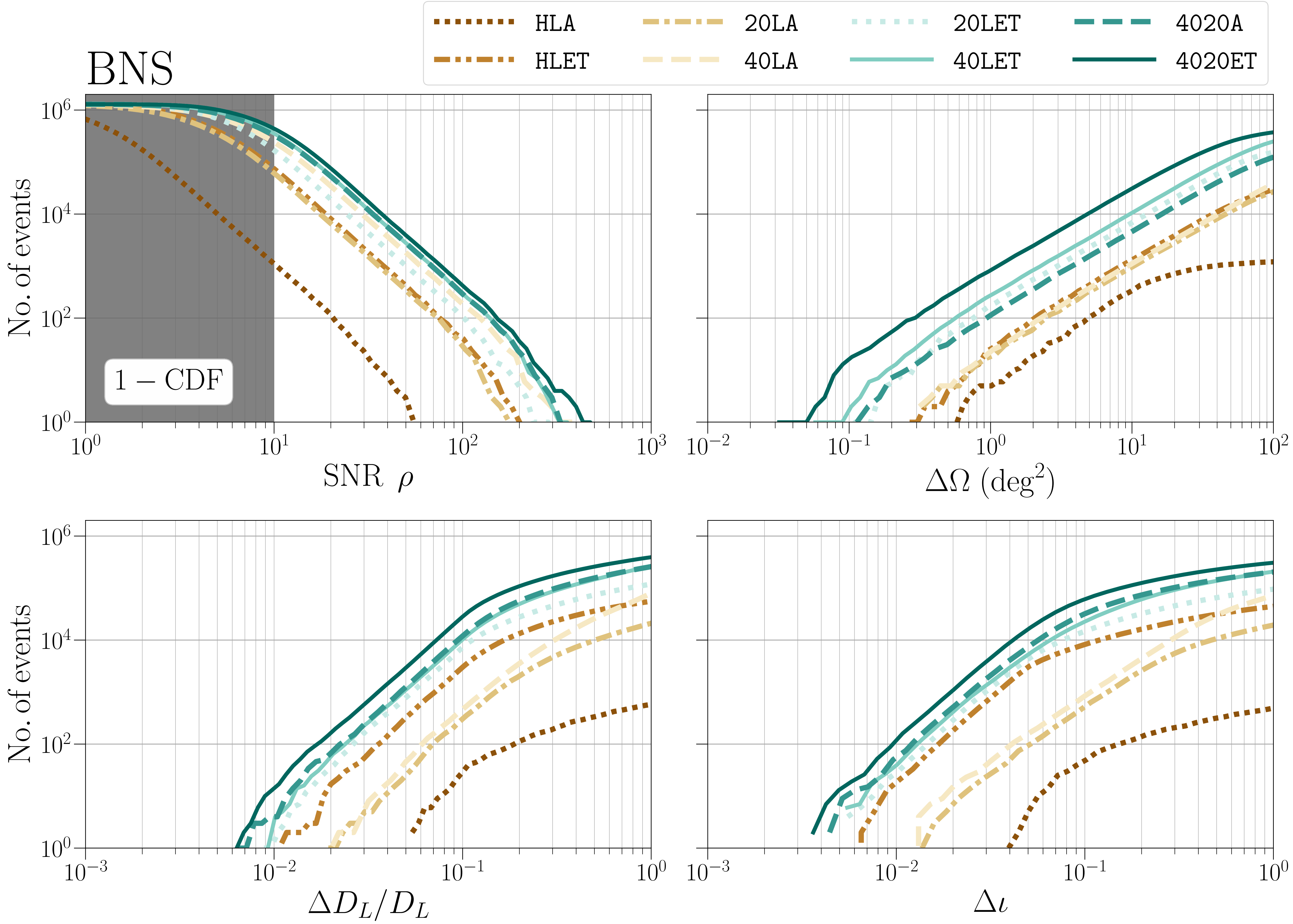


[CE Trade Study]

- Detection of ~1 BNS post-merger per year
  - High frequency performance is crucial
- Supernova detection in Milky Way or satellite galaxy (caution: low rate) [Gossan+]

MULTI-MESSENGER ASTRONOMY

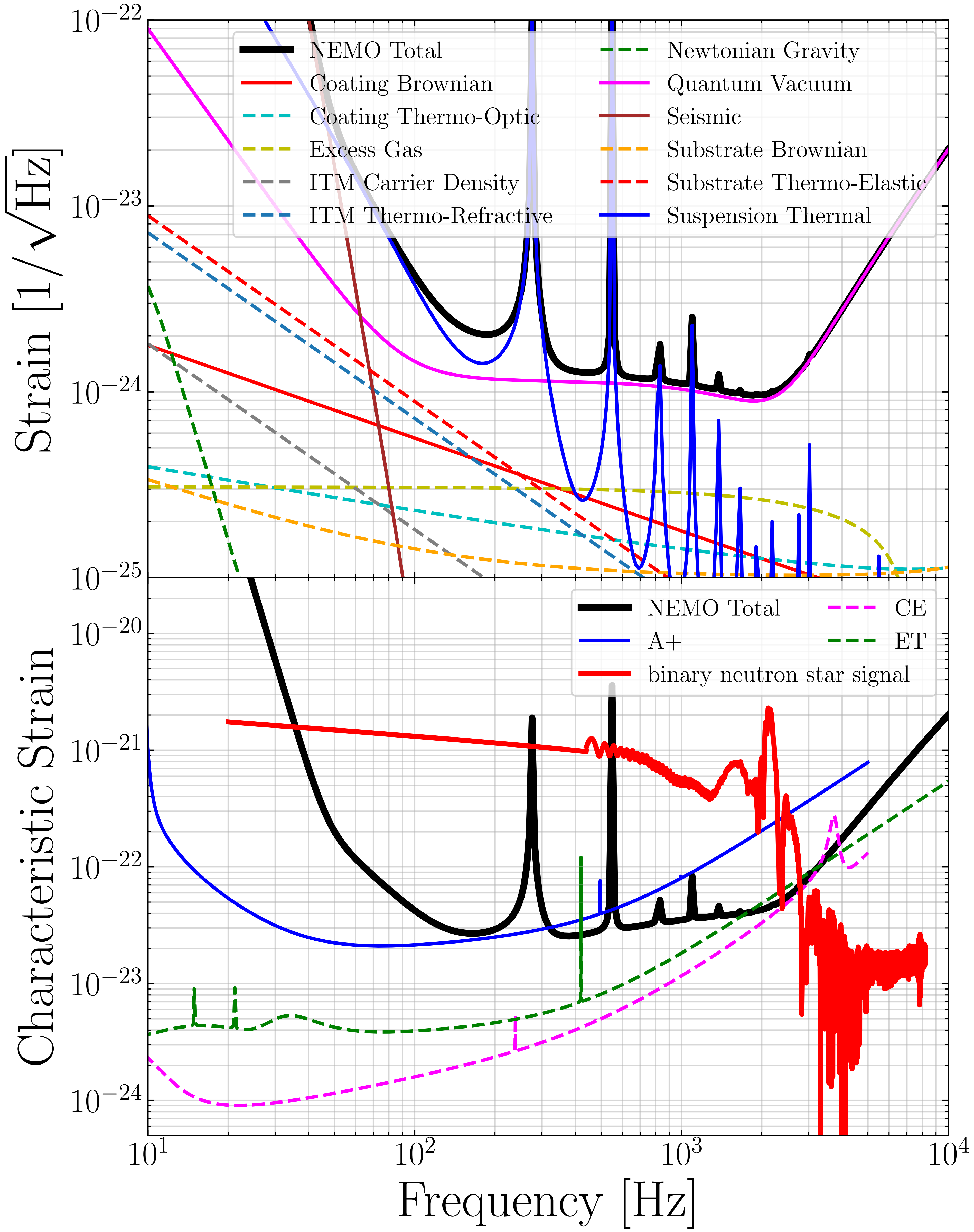
- BNS detections out to the **peak of the SFR (z~2)**
  - Map GRB progenitors
  - Measure delay times
- 1 3G detector in the network increases the annual BNS detection rate by O(100)
- 2 3G detectors allow for the localisation of BNS to O(10deg²)
  - Almost all BNS & NSBH up to z=0.5 localised to within 100deg²
  - O(100) events with $\Delta\Omega \leq 1\mathrm{deg}^2$: kilonova detection



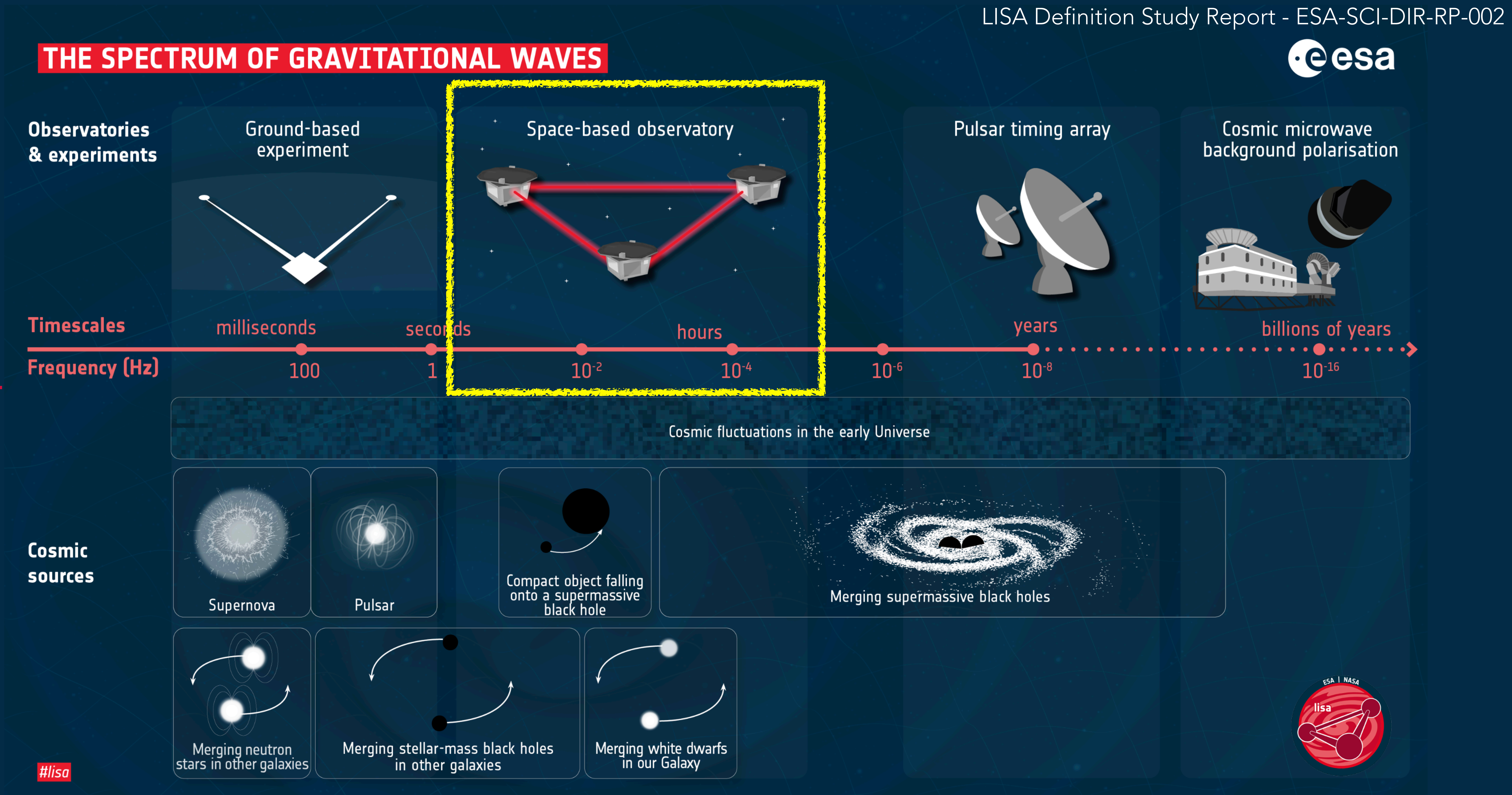
[CE Trade Study]

A SCIENCE CASE FOR 2–4 KHZ

- NEMO = neutron star extreme matter observatory
  - Australian proposal
  - Design concept optimised for to study nuclear matter in neutron star mergers
  - 4km L-shape
  - Above 1kHz - comparable sensitivity to ET/CE
  - Characteristic peak frequency (f_2) can be constrained to within 10s of Hz

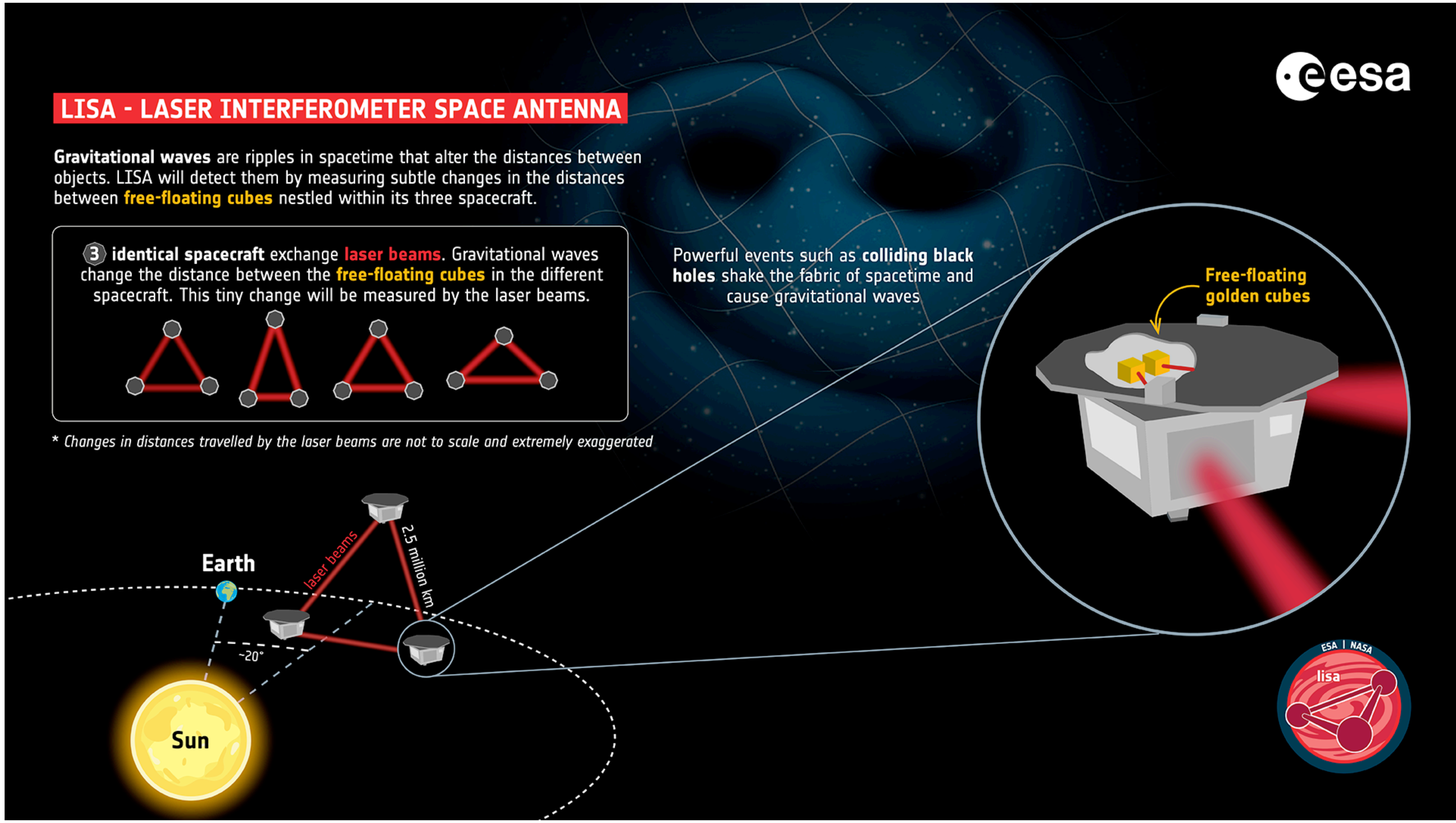


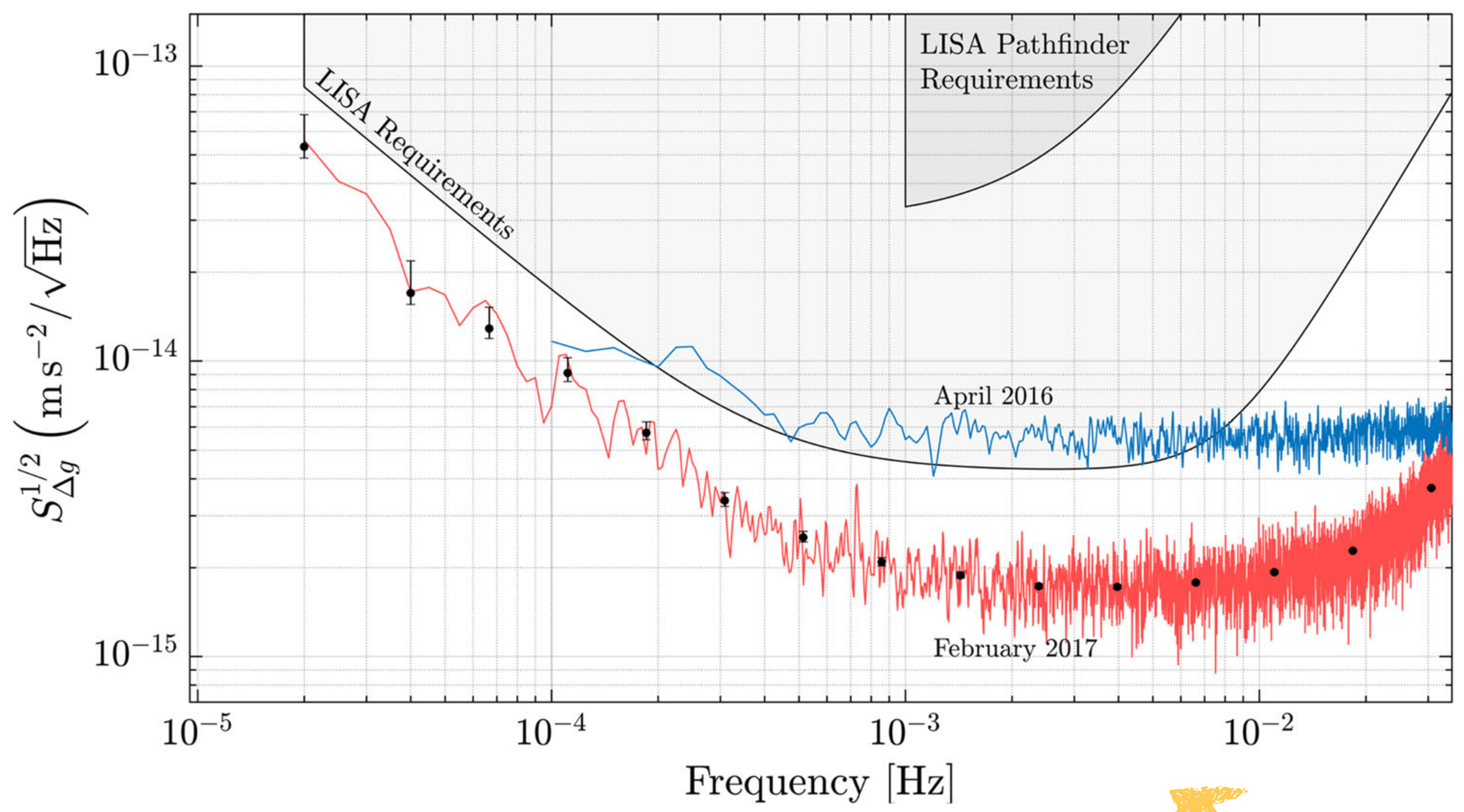
[NEMO]


LISA Definition Study Report - ESA-SCI-DIR-RP-002
THE SPECTRUM OF GRAVITATIONAL WAVES
esa
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10-2
10-4
10-6
10-8
10-16
Cosmic fluctuations in the early Universe
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
#lisa
ESA | NASA
lisa

INTO SPACE: LISA

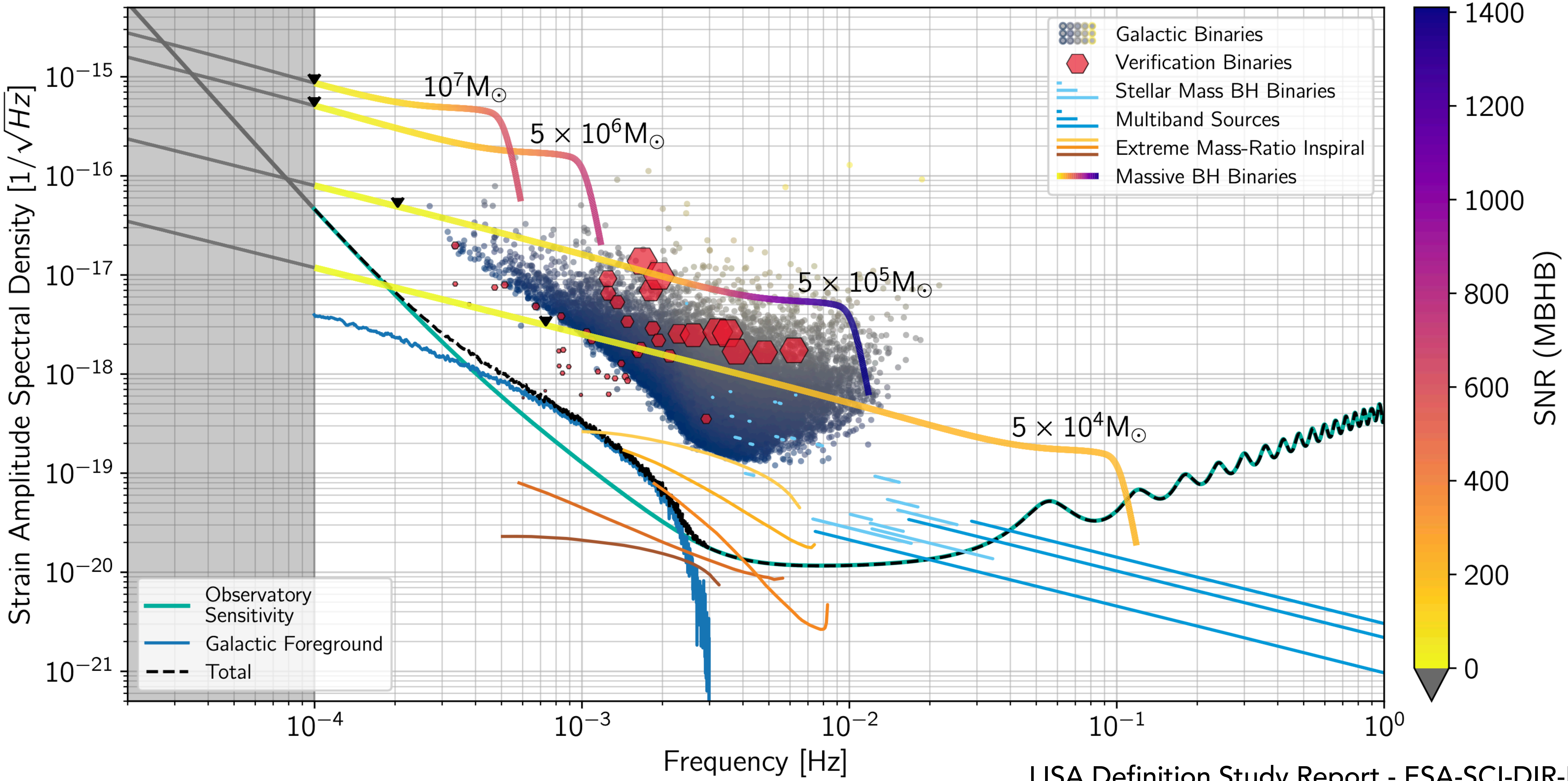
- ESA-led space-based mission
  - Adopted in January 2024
  - Now in implementation phase
  - Planned launch: ~2035
  - Range: 0.1mHz - 1Hz
  - Duration: at least 4 years





Successful demonstration of realisation of freely falling test masses and low-frequency sensitivity with LISA Pathfinder mission [Armano et al. PRL]

SOURCES


Strain Amplitude Spectral Density [1/√Hz]
Frequency [Hz]
SNR (MBHB)
10^7 M☉
5 × 10^6 M☉
5 × 10^5 M☉
5 × 10^4 M☉
Galactic Binaries
Verification Binaries
Stellar Mass BH Binaries
Multiband Sources
Extreme Mass-Ratio Inspiral
Massive BH Binaries
Observatory Sensitivity
Galactic Foreground
Total

KEY SCIENCE GOALS

Observing the **growth & merger history** of massive black holes throughout the Universe

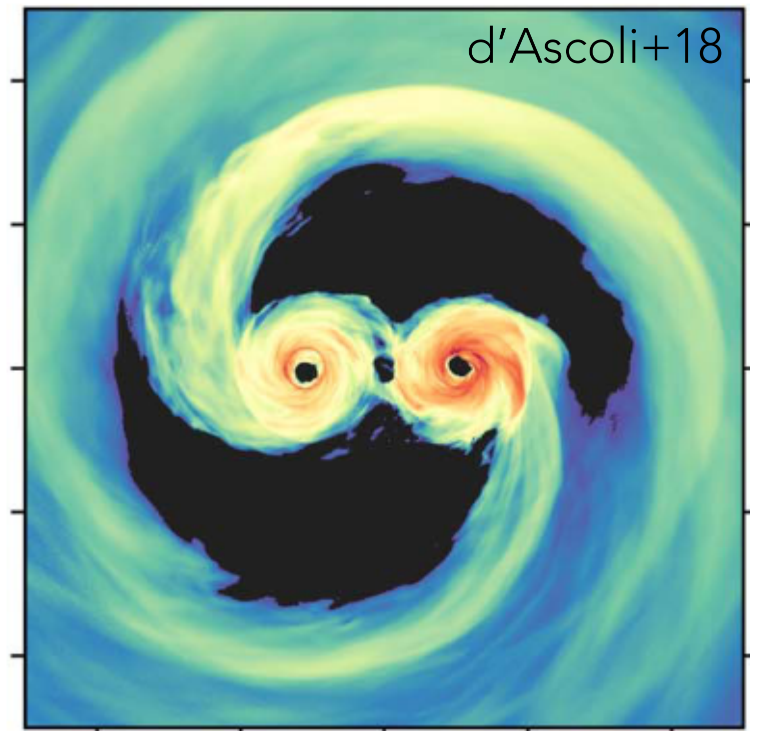
Understanding the dynamics & characteristics of the **environments** surrounding black holes

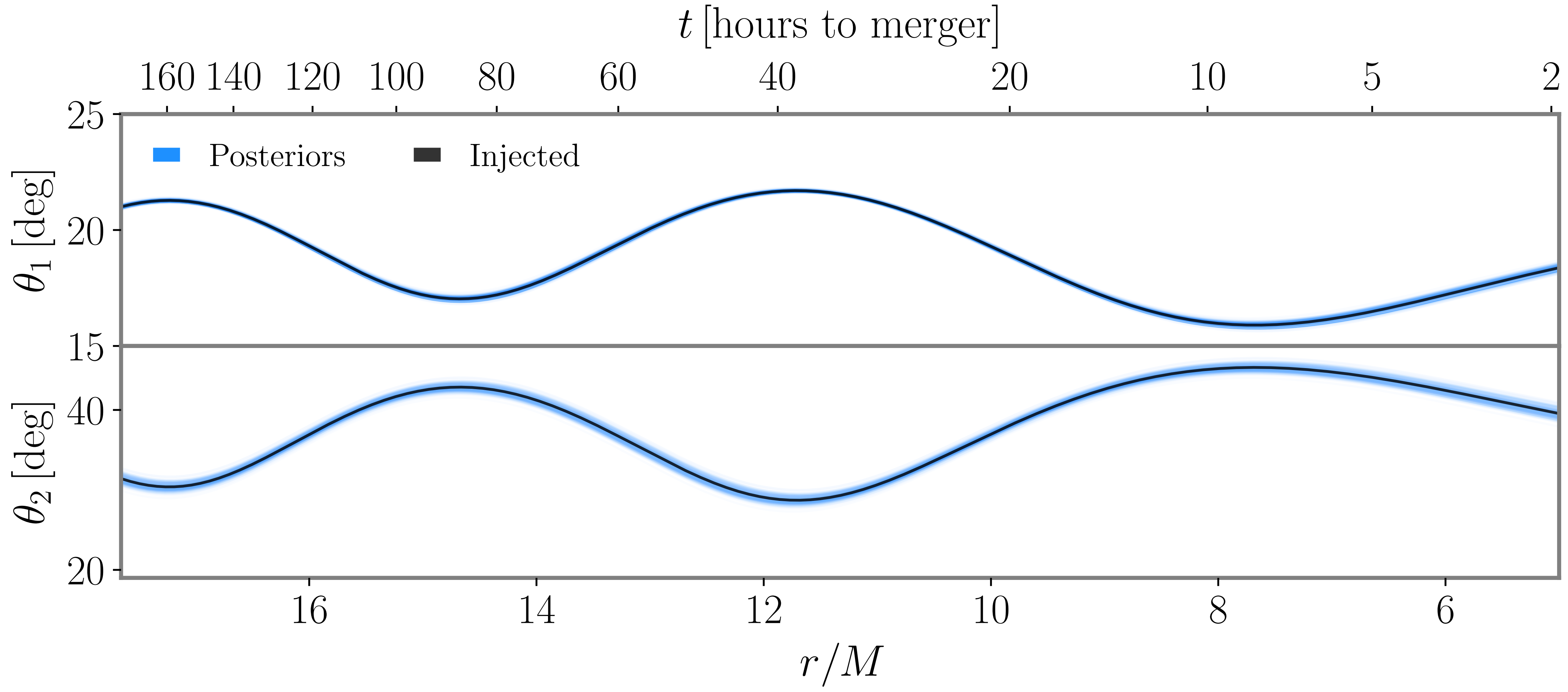
Precisely mapping thousands of **double compact objects** (DCOs) in the Milky Way

Probing the early universe via **primordial GWs** from the time of inflation

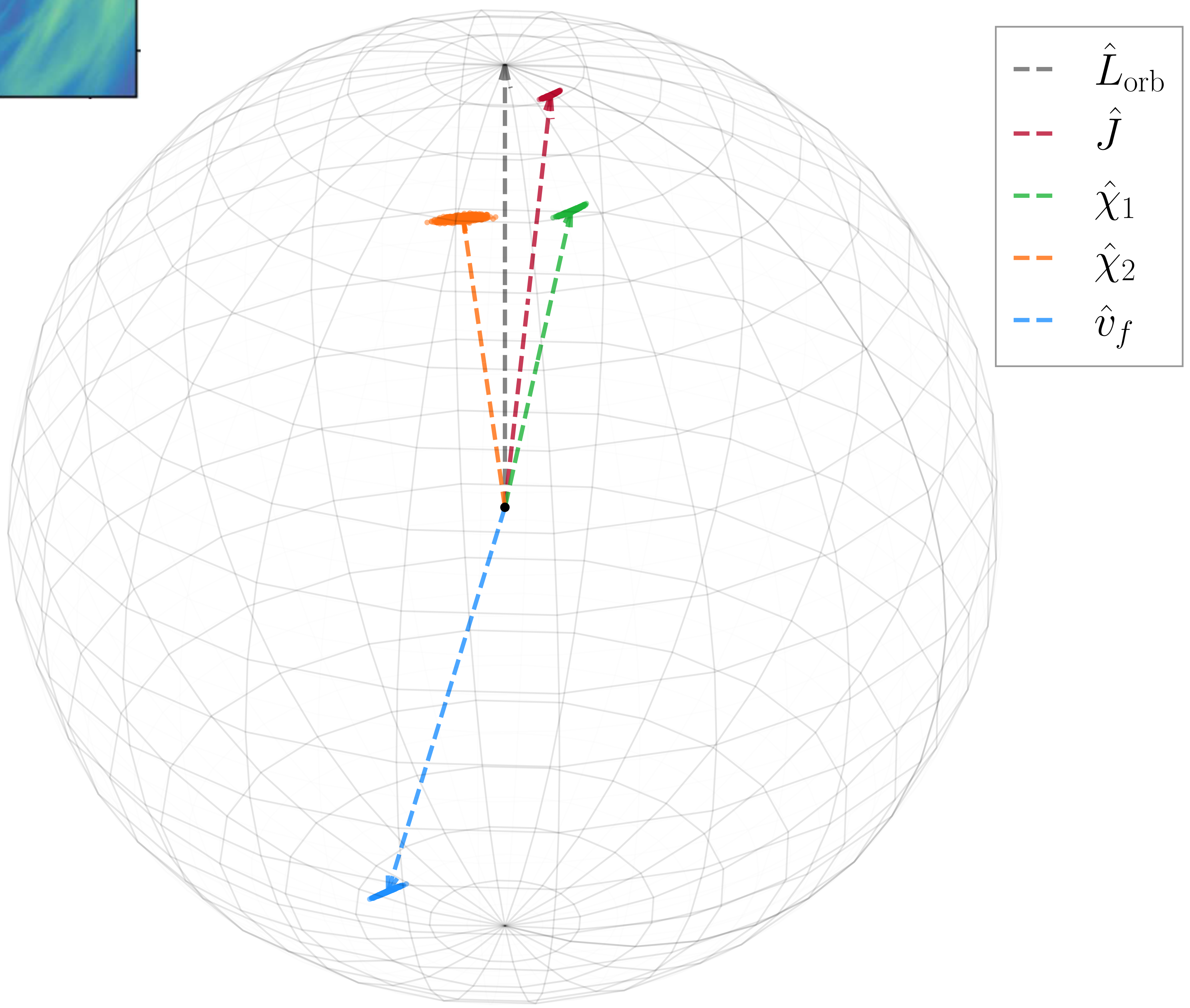
EM BRIGHT MBHB MERGERS?

- Expect MBHB in gaseous environments
  - Distinct pre- and post-merger EM signals
  - BH spins are key tracers of environmental interactions
- Exquisite sky localisation for EM follow-up
  - Synergies with X-ray/optical/radio





Track spin evolution at sub-degree accuracy through merger



Determine merger geometry with high precision

[Pratten, PS+, PRD (2023)]

SUMMARY

- Proposal for upgrades to the current LIGO and Virgo facilities (A#, V_nEXT)
- Mature plans for LIGO Aundha Observatory (formerly LIGO India)

- 3G detector network with CE and ET will enable:
  - Detailed study of the high-z BBH population
  - Measurement of neutron star radii to within 10m (CAUTION: systematics!)
  - Measurement BH spins to degree-level precision (CAUTION: systematics!)
  - BNS localisation with $\Delta\Omega \leq 1\mathrm{deg}^2$ for hundreds of events per year (MMA!!)
  - New discoveries!

- Design concept for high-frequency detector to observe BNS post-merger

- LISA adopted by ESA to launch ~2035
  - Opens a new GW window
  - Probes of BH growth & merger environments