Continuous Gravitational Waves from Supermassive Black Hole Binaries



Richárd Tamás Varga[1], Emma Kun[2,3], László Árpád Gergely[1,4]

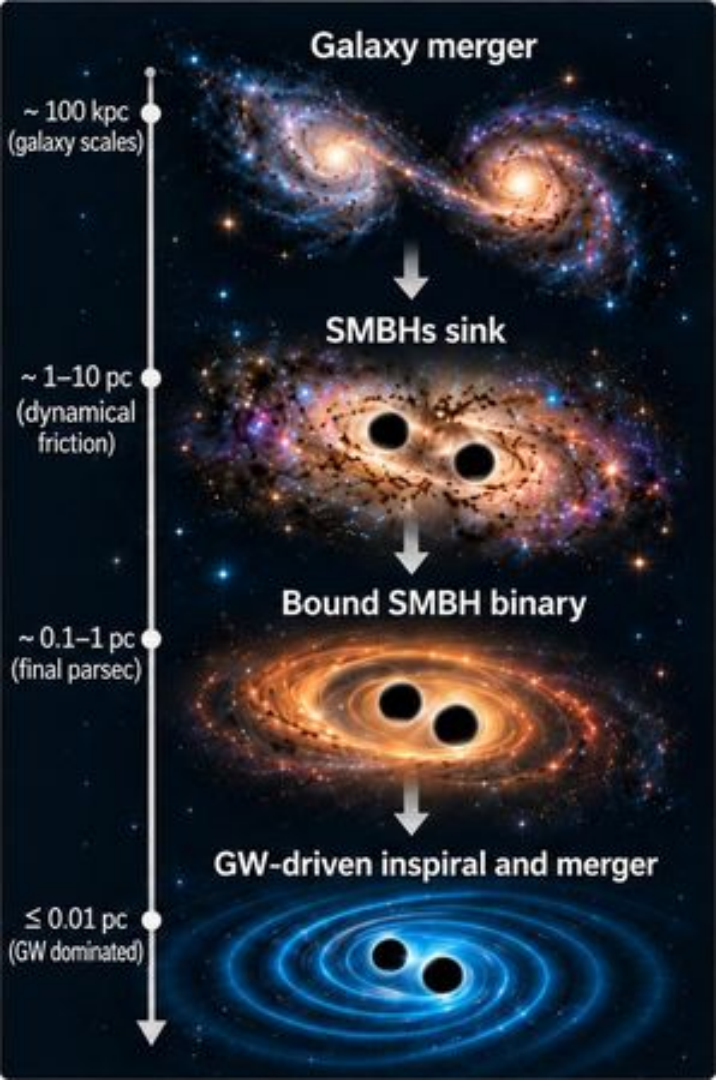
Meeting of Young Astronomers and Astrophysicists
FIKUT NEXTGEN

05 November 2026
HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

[1]Department of Theoretical Physics, University of Szeged, Hungary
[2]Institute for Theoretical Physics IV, Ruhr University Bochum
[3]Astronomical Institute, Ruhr University Bochum
[4]Department of Theoretical Physics, HUN-REN Wigner RCP

Outline

- Supermassive Black Hole Binaries
- Observations
- Gravitational radiation
- Gravitational wave spectrum
- Pulsar Timing Arrays
- Current Continuous Wave upper limits
- Square Kilometre Array



Supermassive Black Hole Binaries

- galaxies grow hierarchically
  - small galaxies merge to form larger ones
- dynamical friction
  - central SMBHs of merging galaxies move closer together
  - gravitational interactions with surrounding stars and gas
  - efficient at large separations (≥ 1 pc)
- become gravitationally bound

- final parsec problem
  - gravitational emission alone is too weak
  - inspiral time: ~10^{10}–10^{11} yr
  - additional dynamical mechanisms are required

Observations

- Electromagnetic measurements
  - direct imaging
  - jet kinematics
  - spectroscopy
  - Spectral Energy Distribution
  - time-domain photometry
- Gravitational radiation
  - binaries emit Gravitational Waves
  - low-frequency ⟷ long-period
  - **Pulsar Timing Array (PTA)**
  - Laser Interferometer Space Antenna (LISA)

➢ EM observations identify potential SMBHBs

➢ physical parameters from EM (z, P, M, q) → GW parameters (f, h)

➢ targeted search for GWs

➢ multi-messenger counterpart would validate the SMBHB candidates

Gravitational radiation

- orbiting binaries emit quadrupole radiation
- carries away energy and angular momentum

shrinking separation

increasing frequency

$$\frac{df}{dt} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}$$

<< nHz/yr

quasi-Keplerian orbit

circularize eccentric orbits

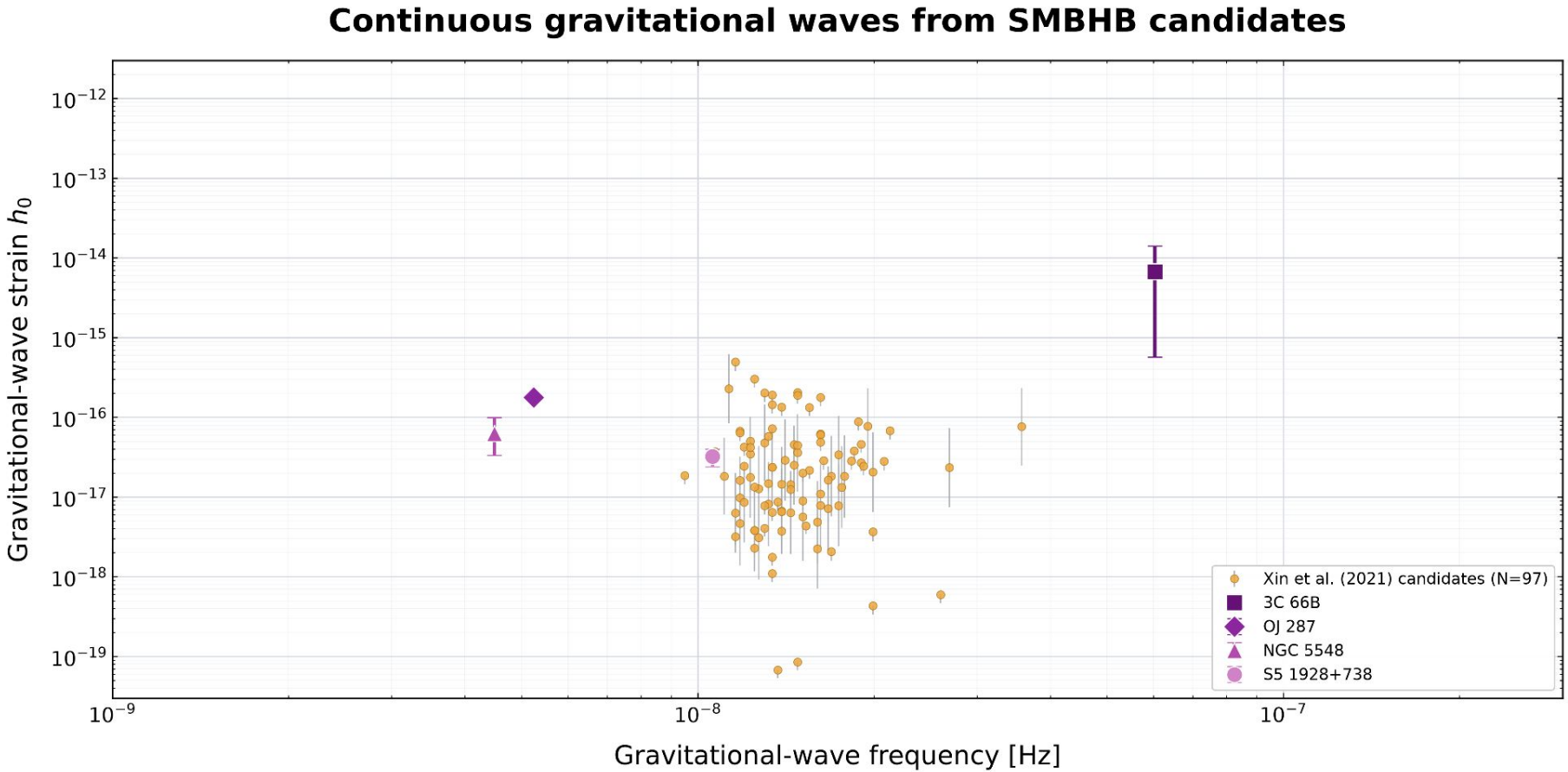
$$f_{\rm GW} = \frac{1}{\pi}\sqrt{\frac{GM}{a^3}}$$

P ~ yr → f ~ nHz

$$h_0 = \frac{2(G\mathcal{M}_z)^{5/3}}{c^4 D_L}(\pi f_{\rm GW})^{2/3}$$

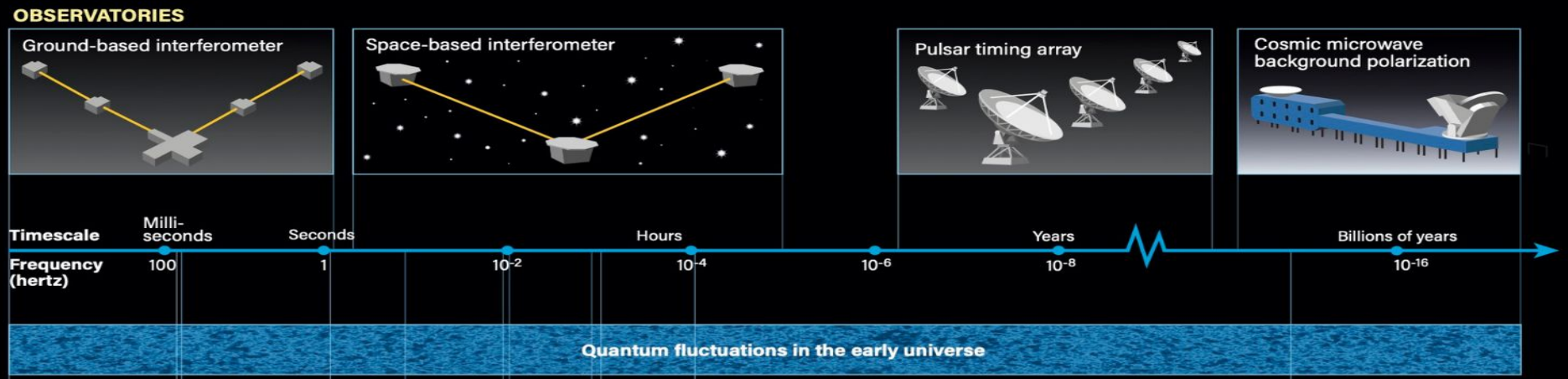
$$h_0 \simeq 9.45\times10^{-15}\left(\frac{\mathcal{M}_z}{10^9 M_\odot}\right)^{5/3}\left(\frac{100\,\mathrm{Mpc}}{D_L}\right)\left(\frac{1\,\mathrm{yr}}{P_{\rm obs}}\right)^{2/3}$$

continuous, quasi-monochromatic GW

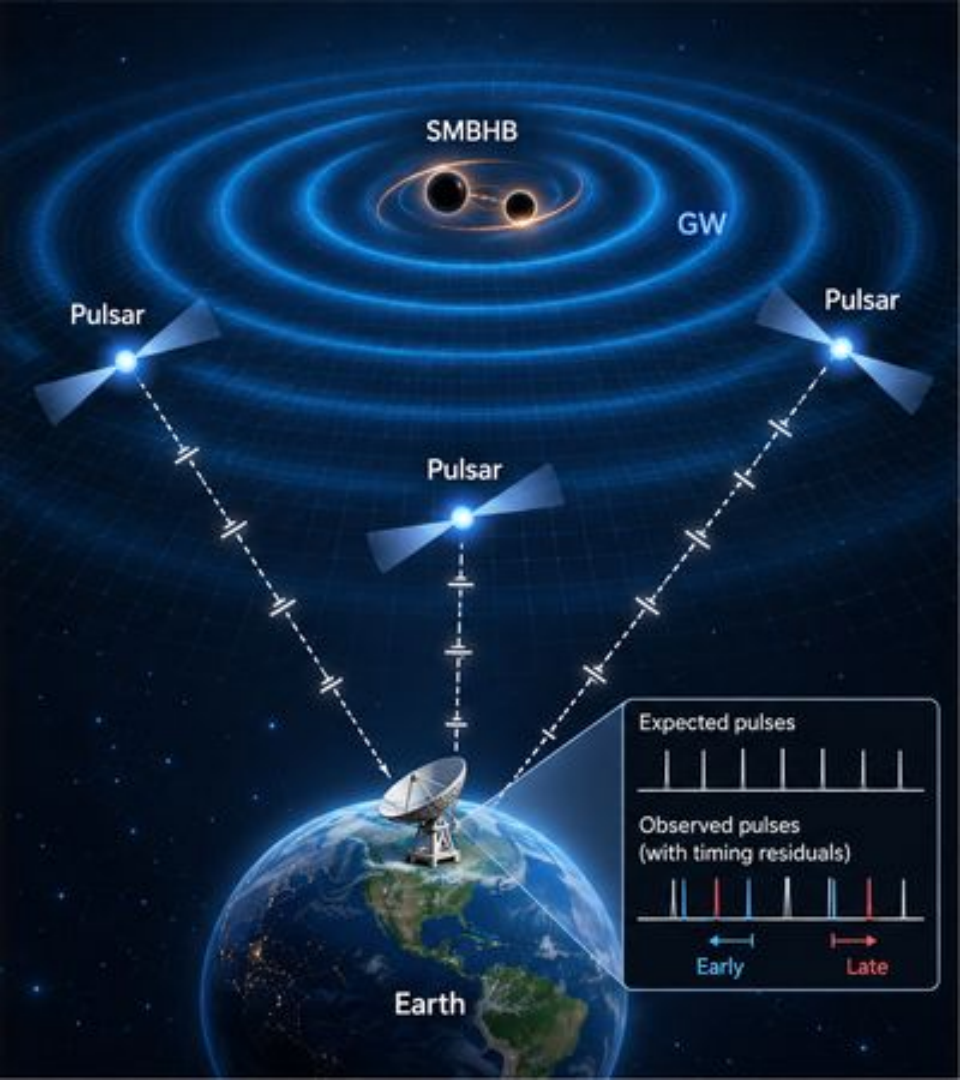


Zhu, Cui & Thrane (2019)
Kun et al. (2023)
Xin, Mingarelli & Hazboun (2021)

THE GRAVITATIONAL-WAVE SPECTRUM



https://www.astronomy.com/

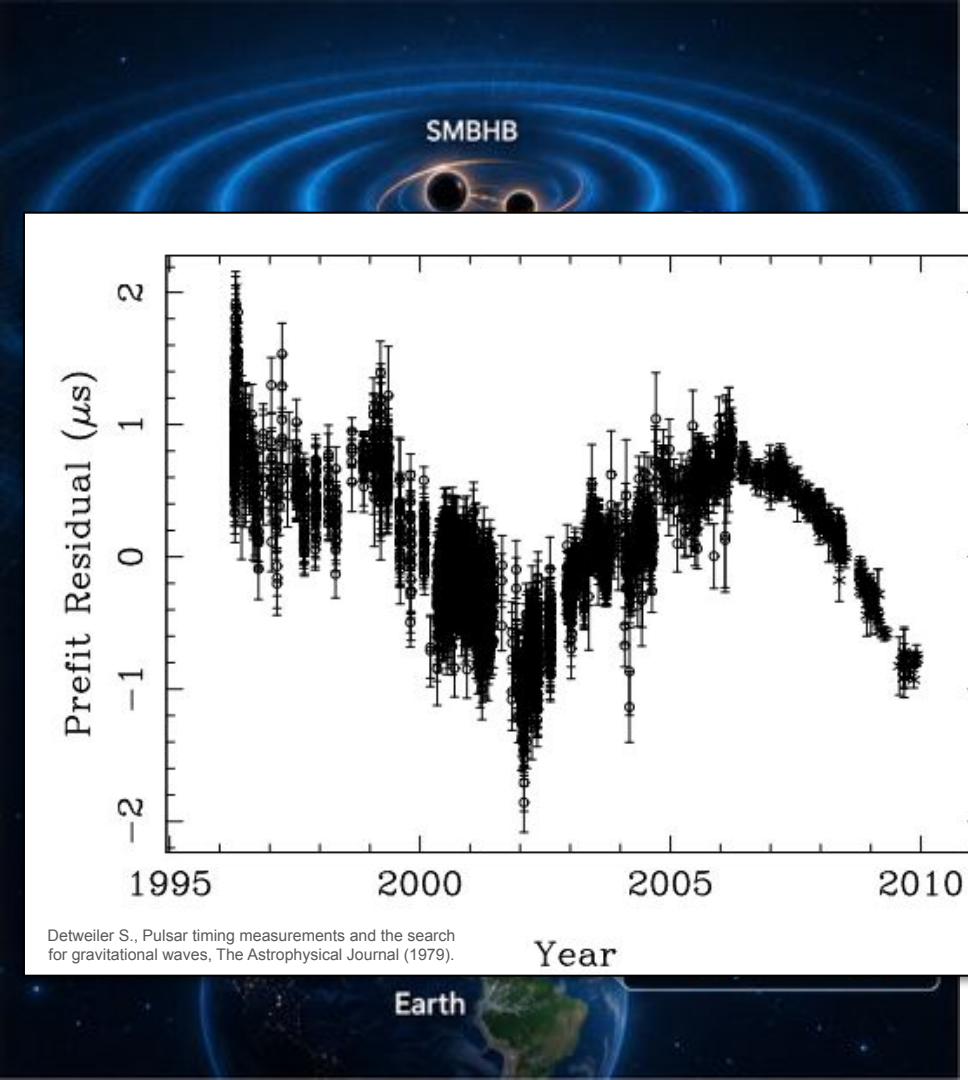


Pulsar Timing Array (PTA)

- ★ galaxy-scale GW detector
  - arm: Earth-pulsar baseline
- ★ MSPs are extremely stable clocks
  - measuring times of arrival (TOAs)

- ★ GW passes the baseline
  - spacetime distortion
  - TOAs shift from their expected value
    - timing residuals

GW frequency, strain



Pulsar Timing Array (PTA)

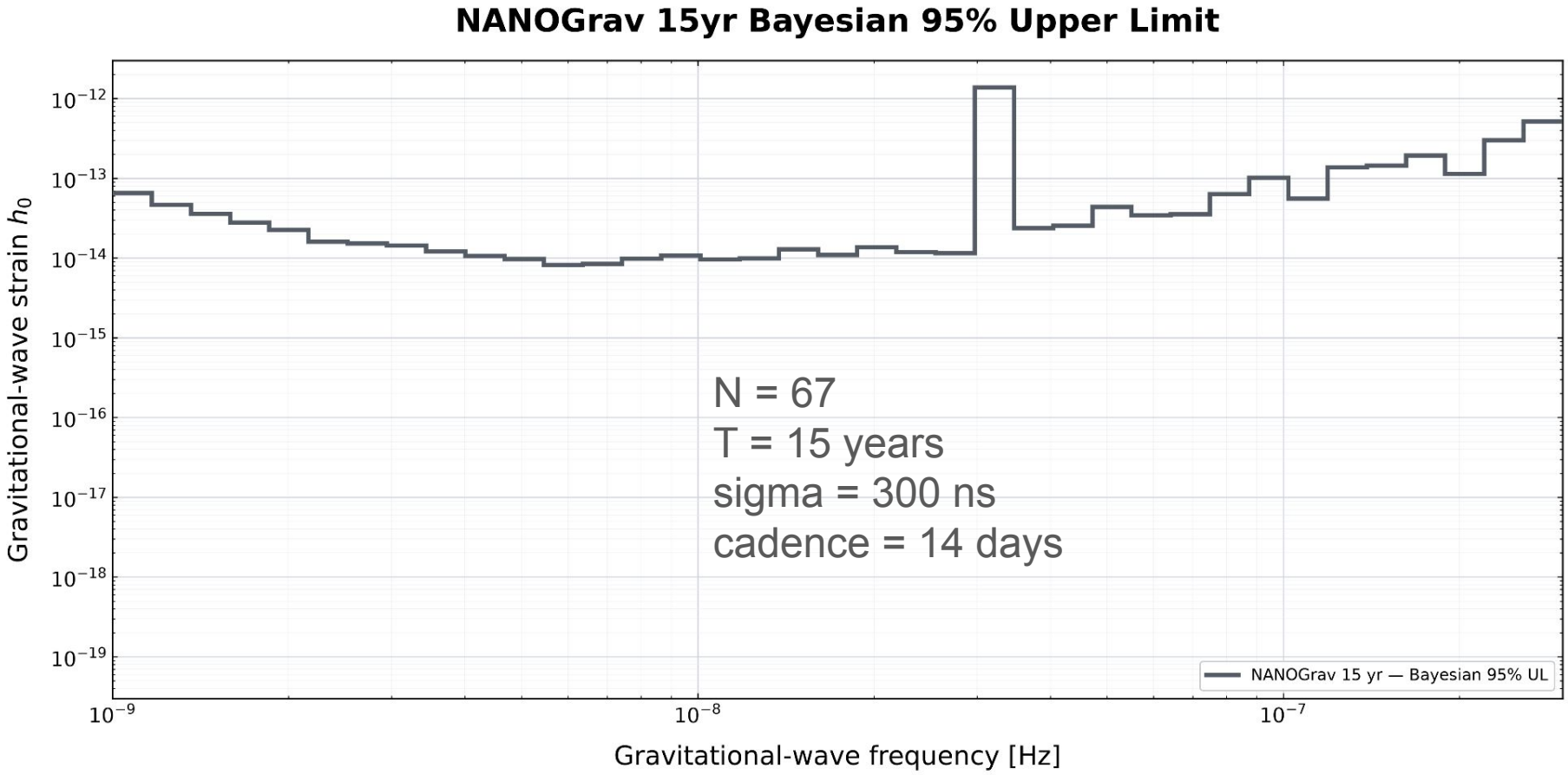
Detweiler S., Pulsar timing measurements and the search for gravitational waves, The Astrophysical Journal (1979).

galaxy-scale GW detector
- arm: Earth-pulsar baseline

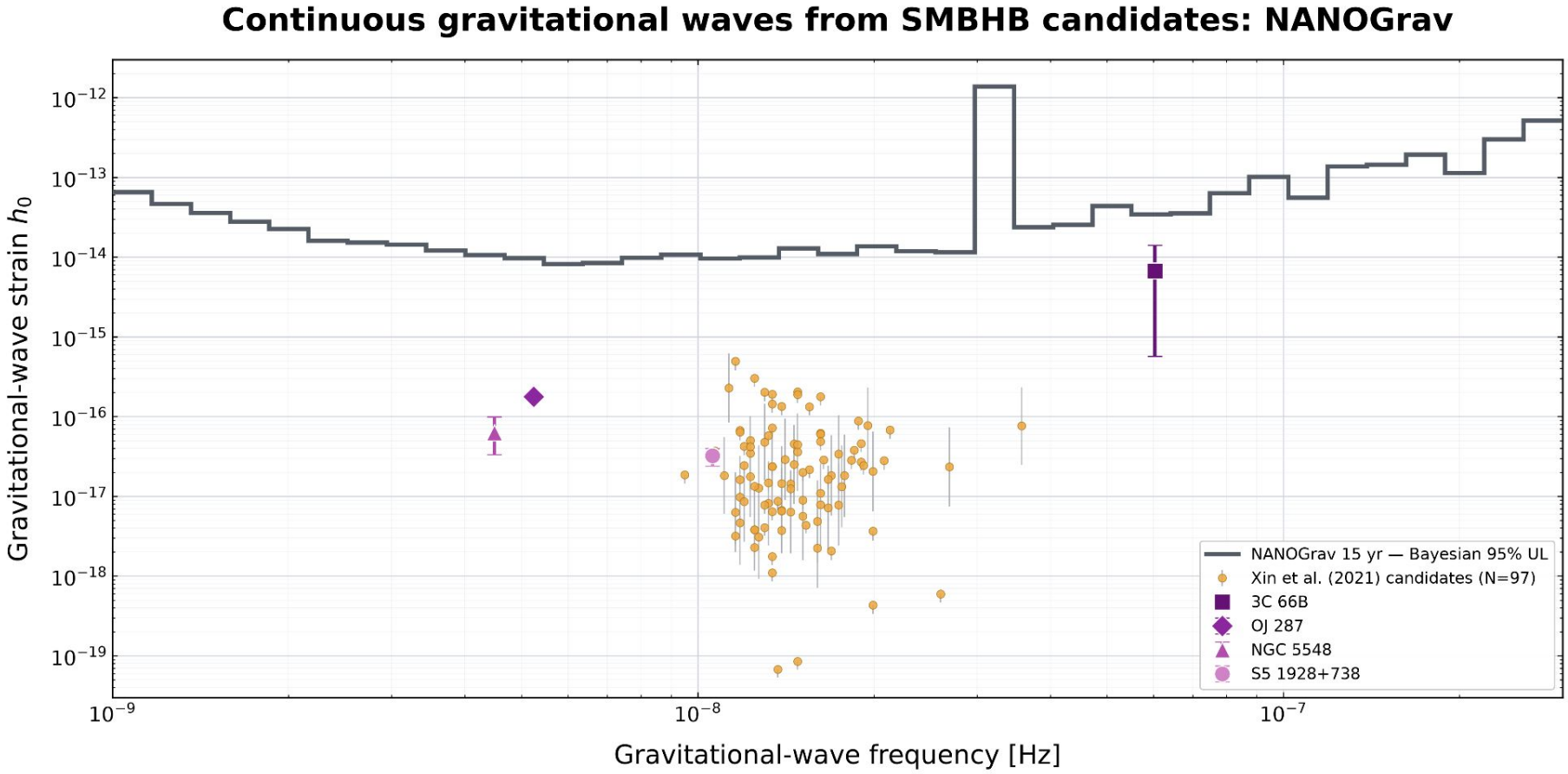
MSPs are extremely stable clocks
- measuring Timing Of Arrivals

GW passes the baseline
- spacetime distortion
- TOAs shift from their expected value
  - timing residuals

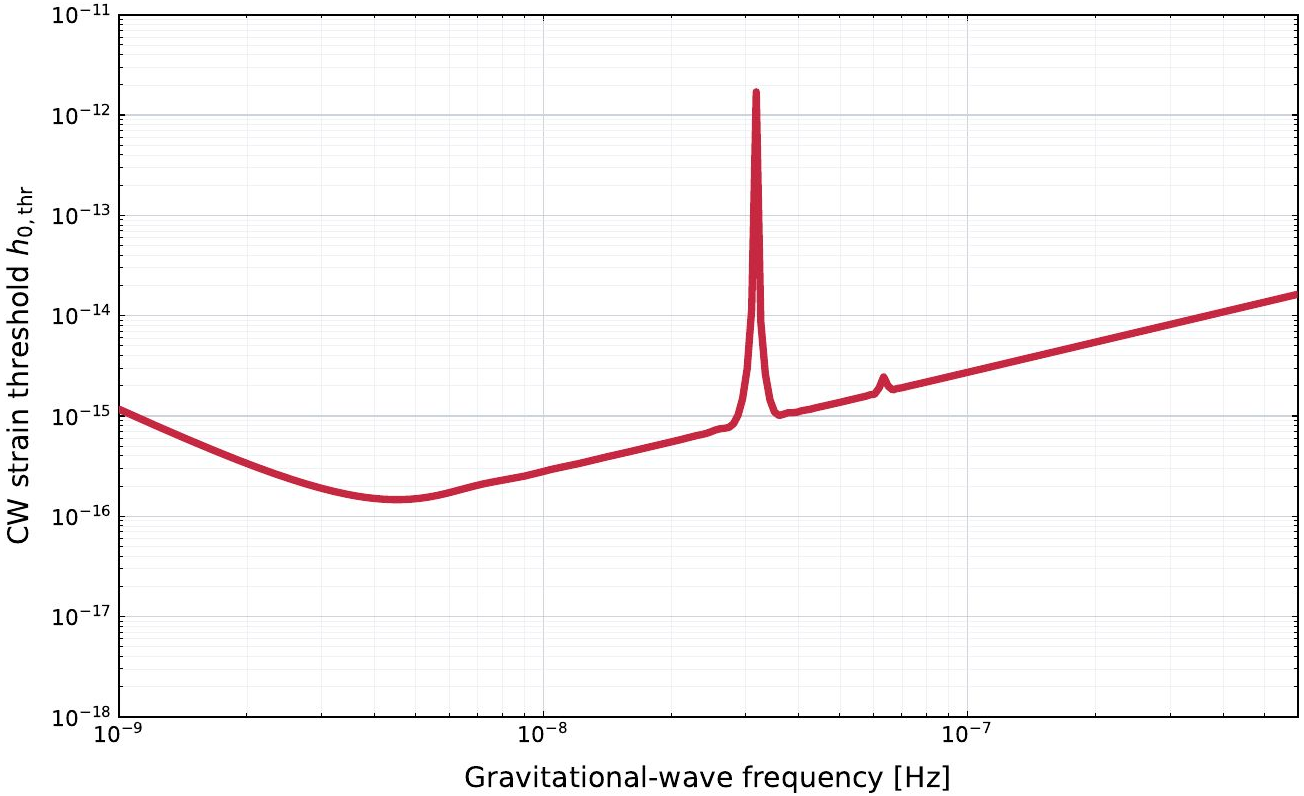
GW frequency, strain



Agazie et al. (2023)


Continuous gravitational waves from SMBHB candidates: NANOGrav
Gravitational-wave strain h_0
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-9}
10^{-8}
10^{-7}
Gravitational-wave frequency [Hz]
NANOGrav 15 yr — Bayesian 95% UL
Xin et al. (2021) candidates (N=97)
3C 66B
OJ 287
NGC 5548
S5 1928+738

IMPROVING PTA CONTINUOUS-WAVE SENSITIVITY



$N = 100$

$\sigma_{\mathrm{TOA}} = 50$ ns

$T = 10$ yr

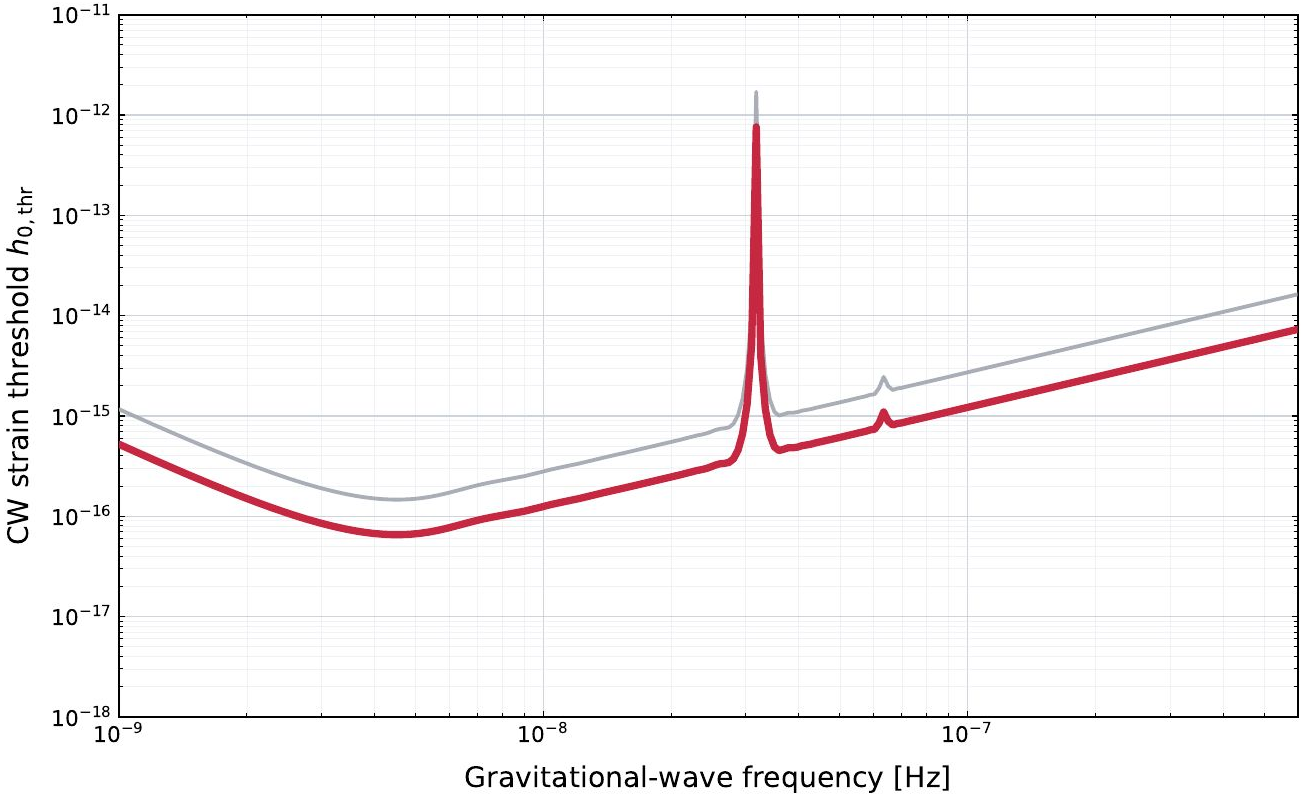
Baseline configuration

PTA CONFIGURATIONS

100 / 50 ns / 10 yr

Hasasia | Sky-averaged Earth-term CW forecast | White noise only | S/N = 5 | Cadence = 0.02 yr

IMPROVING PTA CONTINUOUS-WAVE SENSITIVITY



$N = 500$

$\sigma_{\mathrm{TOA}} = 50$ ns

$T = 10$ yr

More pulsars: 100 → 500

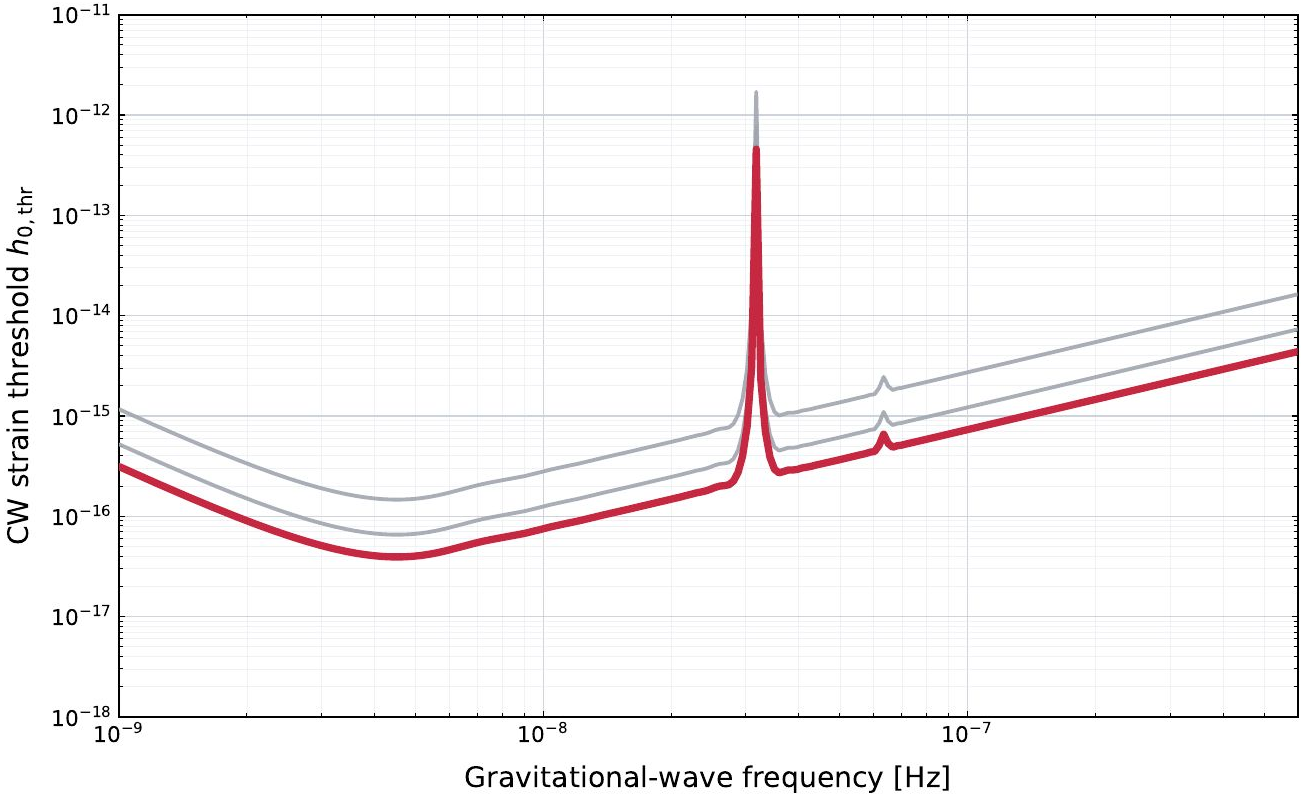
PTA CONFIGURATIONS

100 / 50 ns / 10 yr

500 / 50 ns / 10 yr

Hasasia | Sky-averaged Earth-term CW forecast | White noise only | S/N = 5 | Cadence = 0.02 yr

IMPROVING PTA CONTINUOUS-WAVE SENSITIVITY



$N = 500$

$\sigma_{\mathrm{TOA}} = 30$ ns

$T = 10$ yr

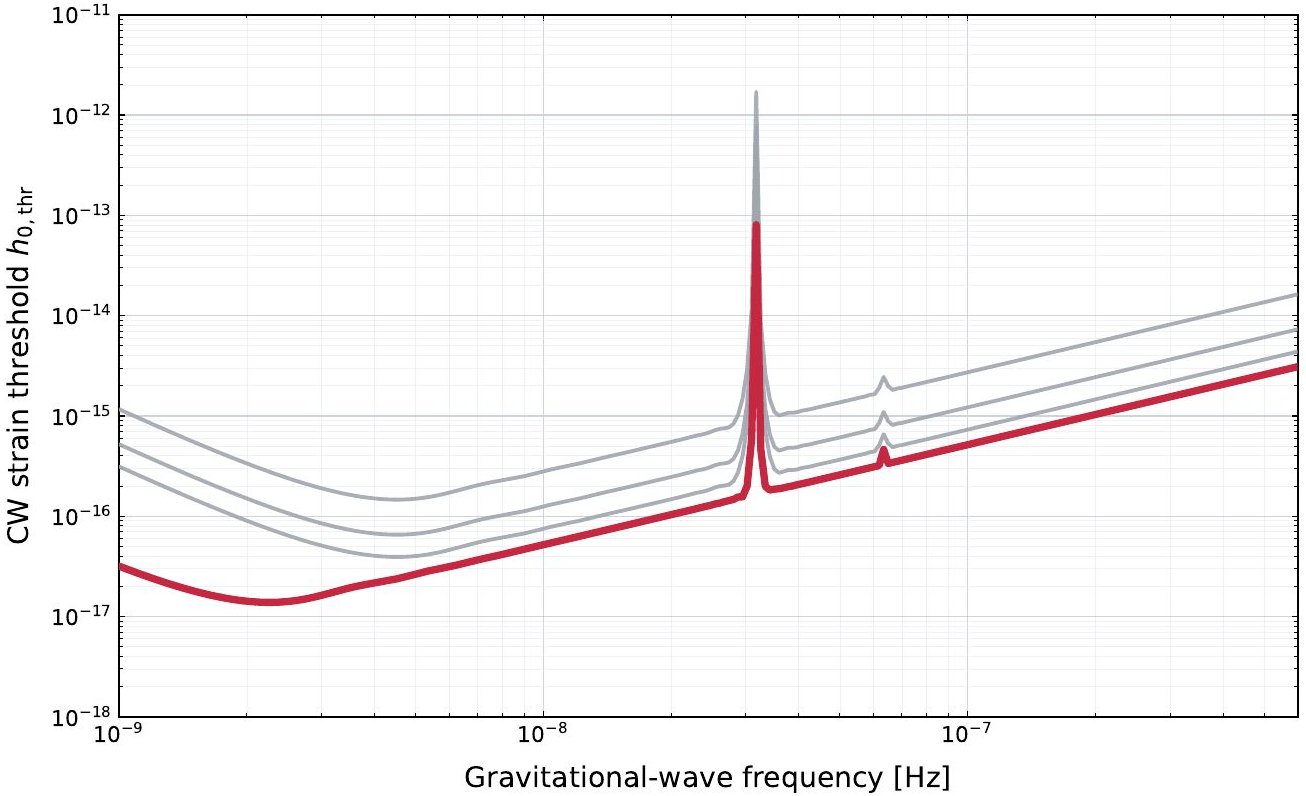
Better timing: 50 → 30 ns

PTA CONFIGURATIONS

- 100 / 50 ns / 10 yr
- 500 / 50 ns / 10 yr
- **500 / 30 ns / 10 yr**

Hasasia | Sky-averaged Earth-term CW forecast | White noise only | S/N = 5 | Cadence = 0.02 yr

IMPROVING PTA CONTINUOUS-WAVE SENSITIVITY



$N = 500$

$\sigma_{\mathrm{TOA}} = 30$ ns

$T = 20$ yr

Longer observations: 10 → 20 yr

PTA CONFIGURATIONS

- 100 / 50 ns / 10 yr
- 500 / 50 ns / 10 yr
- 500 / 30 ns / 10 yr
- **500 / 30 ns / 20 yr**

Hasasia | Sky-averaged Earth-term CW forecast | White noise only | S/N = 5 | Cadence = 0.02 yr

Hazboun, Romano & Smith (2019)



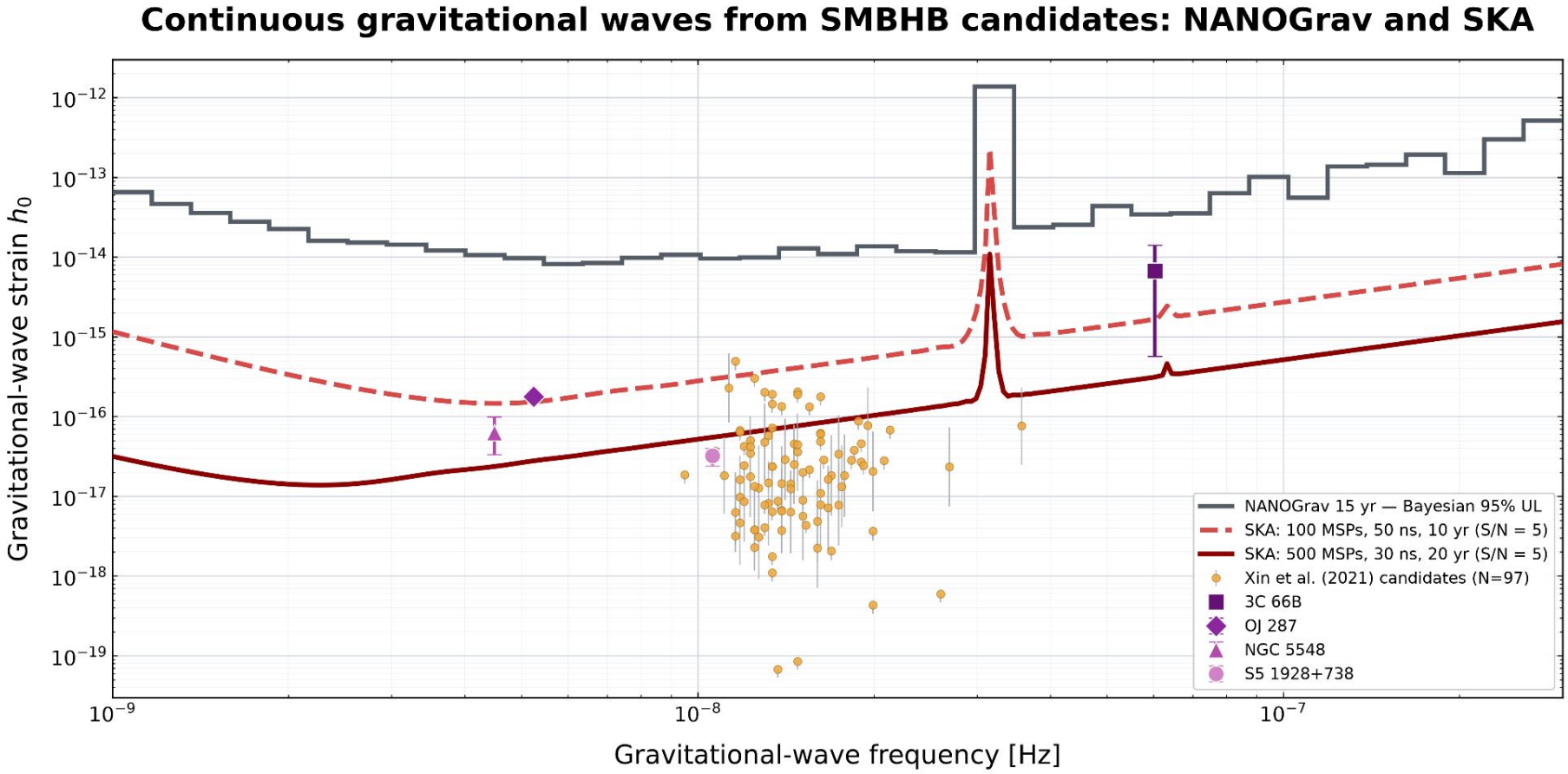


Square Kilometre Array (SKA)

- Larger collecting area
  - ➢ higher S/N
- Number of pulsars **> 100**
- Timing precision **< 100 ns**
  - ➢ higher GW sensitivity
- Observing cadence: 1 - 2 weeks
- Timespan **> 10 yr**
  - ➢ access to lower GW frequencies

- Goal: Detection and characterization of individual SMBHBs

SKA Observatory (2026)


Continuous gravitational waves from SMBHB candidates: NANOGrav and SKA
Gravitational-wave strain h_0
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-9}
10^{-8}
10^{-7}
Gravitational-wave frequency [Hz]
NANOGrav 15 yr — Bayesian 95% UL
SKA: 100 MSPs, 50 ns, 10 yr (S/N = 5)
SKA: 500 MSPs, 30 ns, 20 yr (S/N = 5)
Xin et al. (2021) candidates (N=97)
3C 66B
OJ 287
NGC 5548
S5 1928+738

Future prospects for PTA GW detection

- Multimessenger astronomy
  - Combine EM and GW observations to identify and characterize SMBHBs
- Final parsec problem
  - Test how SMBH binaries reach the GW-driven inspiral phase
- SMBH and galaxy evolution
  - Understand BH growth, galaxy mergers, and binary dynamics
- Cosmology
  - Potential independent measurements of the Hubble constant using GW standard sirens

Thank you for your attention!

References

Agazie et al. (2023)
NANOGrav 15 yr: Observations and Timing of 68 MSPs.
ApJL 951, L9
doi:10.3847/2041-8213/acda9a

Agazie et al. (2023)
NANOGrav 15 yr: Evidence for a GW Background.
ApJL 951, L8
doi:10.3847/2041-8213/acdac6

Agazie et al. (2023)
Bayesian Limits on GWs from Individual SMBHBs.
ApJL 951, L50
doi:10.3847/2041-8213/ace18a

Agarwal et al. (2026)
NANOGrav 15 yr: Targeted Searches for SMBHBs.
ApJL 998, L11
arXiv:2508.16534

Xin, Mingarelli & Hazboun (2021)
Multimessenger PTA Constraints on SMBHBs.
ApJ 915, 97
doi:10.3847/1538-4357/ac01c5

Moore, Taylor & Gair (2015)
Estimating the Sensitivity of Pulsar Timing Arrays.
Class. Quantum Grav. 32, 055004

Zhu, Cui & Thrane (2019)
The Minimum and Maximum Gravitational-wave Background from Supermassive Binary Black Holes.
MNRAS 482, 2588–2596
doi:10.1093/mnras/sty2849

Shannon et al. (2025)
The SKAO Pulsar Timing Array.
doi:10.33232/001c.154243

SKA Observatory (2026)
Official SKA-Mid and SKA-Low specifications.
skao.int/en/explore/telescopes

Kun et al. (2023)
VLBI model of the S5 1928+738 binary candidate.
MNRAS 526, 4698

Foustoul et al. (2025)
Catalogue of milli-parsec SMBHB candidates.
arXiv:2505.06656

Peters (1964)
Gravitational Radiation and Two-Body Motion.
Phys. Rev. 136, B1224

Hazboun, Romano & Smith (2019)
Realistic Sensitivity Curves for Pulsar Timing Arrays.
Phys. Rev. D 100, 104028
doi:10.1103/PhysRevD.100.104028

Hazboun, Romano & Smith (2019)
Hasasia: A Python Package for Pulsar Timing Array Sensitivity Curves.
JOSS 4, 1775
doi:10.21105/joss.01775

Bécsy, Cornish & Digman (2022)
Fast Bayesian Analysis of Individual Binaries in Pulsar Timing Array Data.
Phys. Rev. D 105, 122003
doi:10.1103/PhysRevD.105.122003