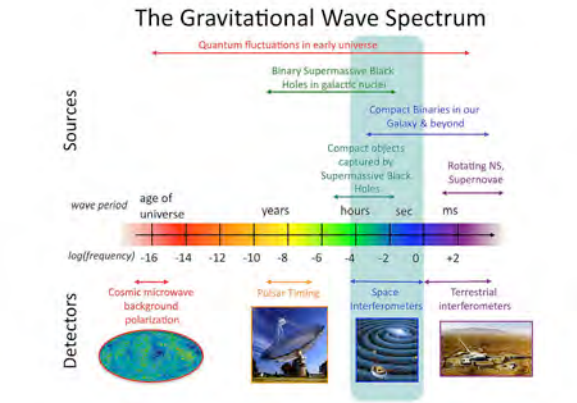
Exploring Gravitational Wave Effects on Hydrogen Radio Spectral Lines

Hyperfine Shifts and Rydberg-Line Broadening

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The Gravitational-Wave Spectrum

An unexplored frontier above ∼10 kHz



Credit: NASA Goddard Space Flight Center

Key point: Current detectors cover nHz–kHz, but sensitivity collapses above 10 kHz.

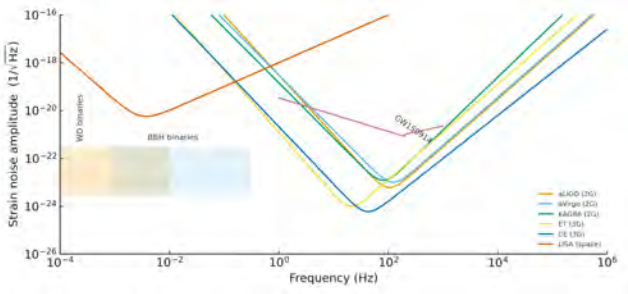
- No broadband sensitivity in MHz–GHz.
- Interferometers cannot respond to HF tidal motion.

Hydrogen spectroscopy operates in this band.

Why High-Frequency GWs Are Hard to Detect

Technical barriers beyond the audio band

- **Interferometer limitations**
  - — Test masses cannot follow MHz–GHz tides.
  - — Shot noise dominates at high frequency.
- **Mechanical filtering**
  - — Suspensions act as low-pass filters.
  - — Seismic isolation ineffective above kHz.
- **Existing HF concepts are ultra-narrowband**
  - — BAW, cavities, magnon systems: $\Delta f/f \ll 1$.
  - — Hard to scan MHz–GHz range.



Motivation: Hydrogen naturally emits in this band ⇒ natural broadband probe.

Opportunities in the High-Frequency Frontier

New-physics sources in the MHz–GHz band

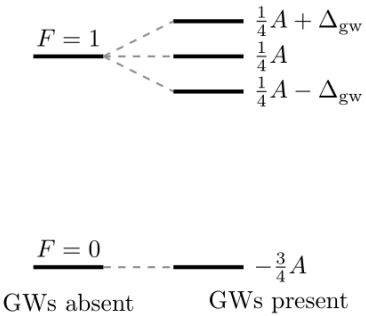
- Natural HF emitters in beyond-SM scenarios:
  - primordial black-hole (PBH) binaries
  - axion/light-scalar clouds (superradiance)
  - cosmic-string cusps and kinks
  - preheating and high-energy phase transitions
- Signals often **monochromatic or narrowband**.
- Frequencies overlap with **hydrogen RRLs**.

→ Suggests spectroscopy as an alternative path to HF GW detection.

Hydrogen as a Probe of Spacetime

Two radio channels of interest

- **21-cm hyperfine** ultra-precise, but GW response $\Delta\nu/\nu \sim 10^{-35}$ negligible
- **Rydberg transitions (RRLs)**
  - abundant in ISM recombination zones
  - frequencies: 0.1–100 GHz
  - sensitive to GW tidal terms: n^4 (shift), n^7 (broadening)



Rydberg Atoms and Radio Recombination Lines

Why high-n hydrogen matters

- Rydberg atoms: $n \sim 50$–1000, radius $\propto n^2$, long-lived in low-density ISM.
- Form naturally in:
  - H II regions, WIM
  - galactic-center clouds
  - extragalactic star-forming regions
- RRLs = $\Delta n = 1, 2, 3$ transitions extremely narrow, stable lines in the MHz–GHz band.
- Observed with VLA, ALMA, GBT, LOFAR, ASKAP, MeerKAT.

Gravitational-Wave Effects on Rydberg RRLs

Large atomic size strong tidal response

- Quadrupolar GW coupling:

$$H = H_{\rm Bohr} + H_{\rm gw}, \quad H_{\rm gw} \sim \tfrac{\mu}{4}\ddot{h}_{jk}x^j x^k$$

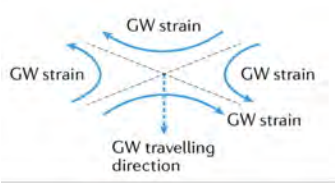
- Rydberg matrix elements: $\langle x^2 \rangle \propto n^4$
- Energy shift:

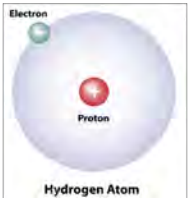
$$\boxed{\delta E \propto n^4 \omega_{\rm gw}^2 h}$$

- Line broadening:

$$\boxed{\left(\frac{\Delta\nu}{\nu}\right)_{\rm gw} \sim n^7 \omega_{\rm gw}^2 h}$$

- **High-n ($n \gtrsim 300$) RRLs maximize GW visibility.**





Astrophysical Broadening of RRLs

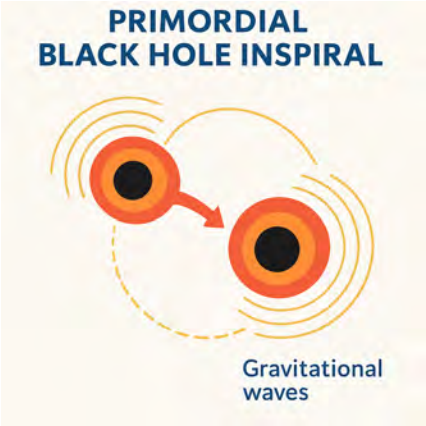
When can GW effects compete?

- Contributions to linewidth:
  - radiative width (small)
  - blackbody stimulation
  - collisions (environment-dependent)
  - **Doppler/turbulence (dominant)**
- In cold, diffuse ISM: high-*n* RRLs may reach regime where GW broadening is comparable.

Primordial Black-Hole Binaries

A physically motivated MHz–GHz GW source

- PBH masses: 10^{-6}–$10^{-3}\,M_{\odot}$
- Inspiral emission peaks in MHz–GHz band
- Overlaps naturally with RRL frequency range
- Under optimistic ISM conditions:
  GW-induced broadening may be marginally detectable



Key Takeaways

- The MHz–GHz band is a major blind spot in GW astronomy.
- Rydberg RRLs lie naturally in this band and are highly GW-sensitive.
- Strong scalings:

$$n^4 \text{ (energy shift)} \qquad n^7 \text{ (linewidth)}$$

- PBH binaries provide concrete HF sources.

These results are theoretical; detection remains challenging due to turbulence and environmental broadening.

Wanwieng (2025), Phys. Rev. D 112, 044061