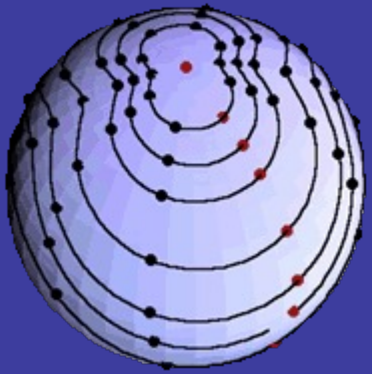
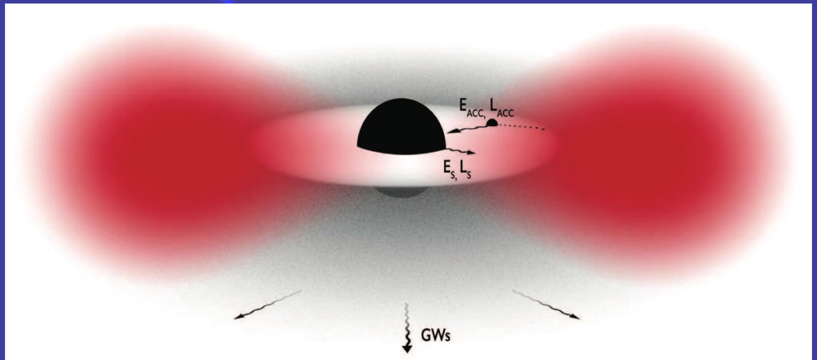
Continuous Gravitational Waves – What Can Cosmic Explorer Find?

NASA



B. Owen



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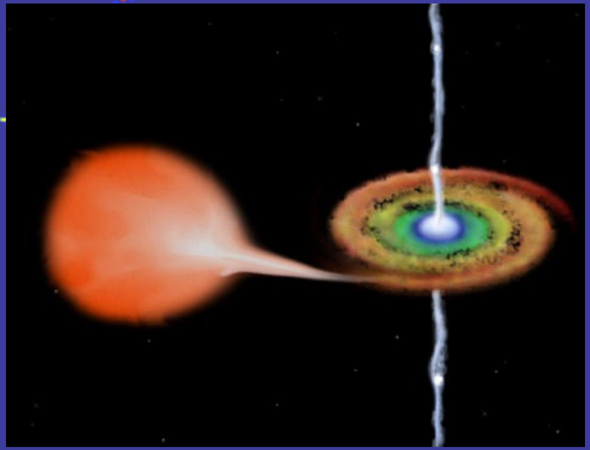

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Possible sources of continuous waves (CW)

Conventional:

Fast-spinning galactic neutron stars with residual non-axisymmetry

- Crustal deformation from cooling / spindown
- Buried magnetic field energy
- r-modes (quadrupolar mass currents)
- "Mountain" driven by accretion from a companion

Strange quark stars with solid cores

Exotic sources:

Black hole superradiance from condensed ultralight bosons ("cloud")

- Scalars (*e.g.*, QCD axions)
- Vectors (*e.g.*, dark photons)

Ultralight primordial binary black holes

References in K. Riles – Liv. Rev. Rel. 26, 3 (2023)

Search limits often interpreted via equatorial ellipticity ε_{equat}

Radiation generated by quadrupolar mass movements: ($I_{\mu\nu}$ = quadrupole tensor, r = source distance)

$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}\left[I_{\mu\nu}\right] \qquad \varepsilon_{\text{equat}} = \frac{|I_{xx} - I_{yy}|}{I_{zz}}$$

→ No GW from axisymmetric object rotating about symmetry axis (ε = 0)

Expected strain amplitude h ($f_{GW} = 2 \bullet f_{Rot}$):

Scaling

$$h = 1.1\times10^{-24}\left[\frac{kpc}{r}\right]\left[\frac{f_{GW}}{kHz}\right]^2\left[\frac{\varepsilon}{10^{-6}}\right]\left[\frac{I_{zz}}{10^{38}\ \text{kg}\cdot\text{m}^2}\right]$$

Maximum ε value: ~10^{-5}

N.K. Johnson-McDaniel & B.J. Owen, PRD 88 (2013) 044004

Equating "measured" rotational energy loss (from measured period increase and reasonable moment of inertia) to GW emission gives: (gravitar extreme for known pulsars)

$$h_{SD} = 2.5\times10^{-25}\left[\frac{kpc}{d}\right]\sqrt{\left[\frac{1kHz}{f_{\text{GW}}}\right]\left[\frac{-df_{\text{GW}}/dt}{10^{-10}\ Hz/s}\right]\left[\frac{I}{10^{45}\ g\cdot cm^2}\right]}$$

Example:

Crab → $h_{SD} = 1.4 \times 10^{-24}$

(d=2 kpc, f_{GW} = 59.5 Hz, $df_{GW}/dt = -7.4\times10^{-10}$ Hz/s)

Plausible ellipticity ε_{equat} values

Simple scaling argument:

Magnetic energy / Gravitational energy

[D.I. Jones, CQG 19, 1255 (2002)]

$$\epsilon \sim \frac{B^2 R^3}{GM^2/R} \sim 10^{-12}\left(\frac{B}{10^{12}\,\mathrm{G}}\right)^2$$

Toroidal field due to superfluid protons in interior:

[C. Cutler, PRD 66, 084025 (2002)]

$$\epsilon \sim 10^{-9}\left(\frac{B}{10^{12}\,\mathrm{G}}\right)$$

Mechanical strain limits:

(μ = shear modulus, ΔR = crust thickness)

[D.I. Jones, CQG 19, 1255 (2002)]

$$\epsilon_{\mathrm{max}} \sim \frac{\mu R^2 \Delta R}{GM^2/R} u_{\mathrm{break}} \equiv b u_{\mathrm{break}} = 10^{-6}\left(\frac{b}{10^{-5}}\right)\left(\frac{u_{\mathrm{break}}}{0.1}\right)$$

Empirical observation: milli-second pulsar spin-downs consistent with <u>minimum</u> ellipticity of ~10^{-9} [G. Woan et al, ApJL 863, L40 (2018)]

***Summary from D.I. Jones & K. Riles – arXiv:2403.02066**

Three broad categories of CW searches have dominated analyses to date*:

Targeted searches for known pulsars using radio / X-ray / γ-ray ephemerides

→ Exact phase tracking over O(years) – low trials factor (3 methods)

→ Variation ("narrowband") allows for EM/GW $\Delta f \sim O(10^{-3}) f_{EM}$

Computationally cheap and most sensitive

Directed searches for known sources / locations (unknown / poorly known frequencies)

- Isolated and binary sources treated separately
- Fully coherent searches over days/weeks
- Semi-coherent searches over full data runs

Computationally demanding

Focus on these extremes in the following

All-sky searches for unknown sources

- Isolated and binary sources treated separately (binary esp. challenging)
- Semi-coherent searches over full data runs

Computationally formidable!!! …and much less sensitive ☹

***Recent review of CW searches: K. Riles – Liv. Rev. Rel. 26, 3 (2023)**

Sensitivity assumptions used in the following graphs

Targeted search sensitivity:

$$h_{95\%} = 11\,[S_h]^{1/2} \,/\, [N_{detector} \times T_{obs}]^{1/2}$$

All-sky search sensitivity:

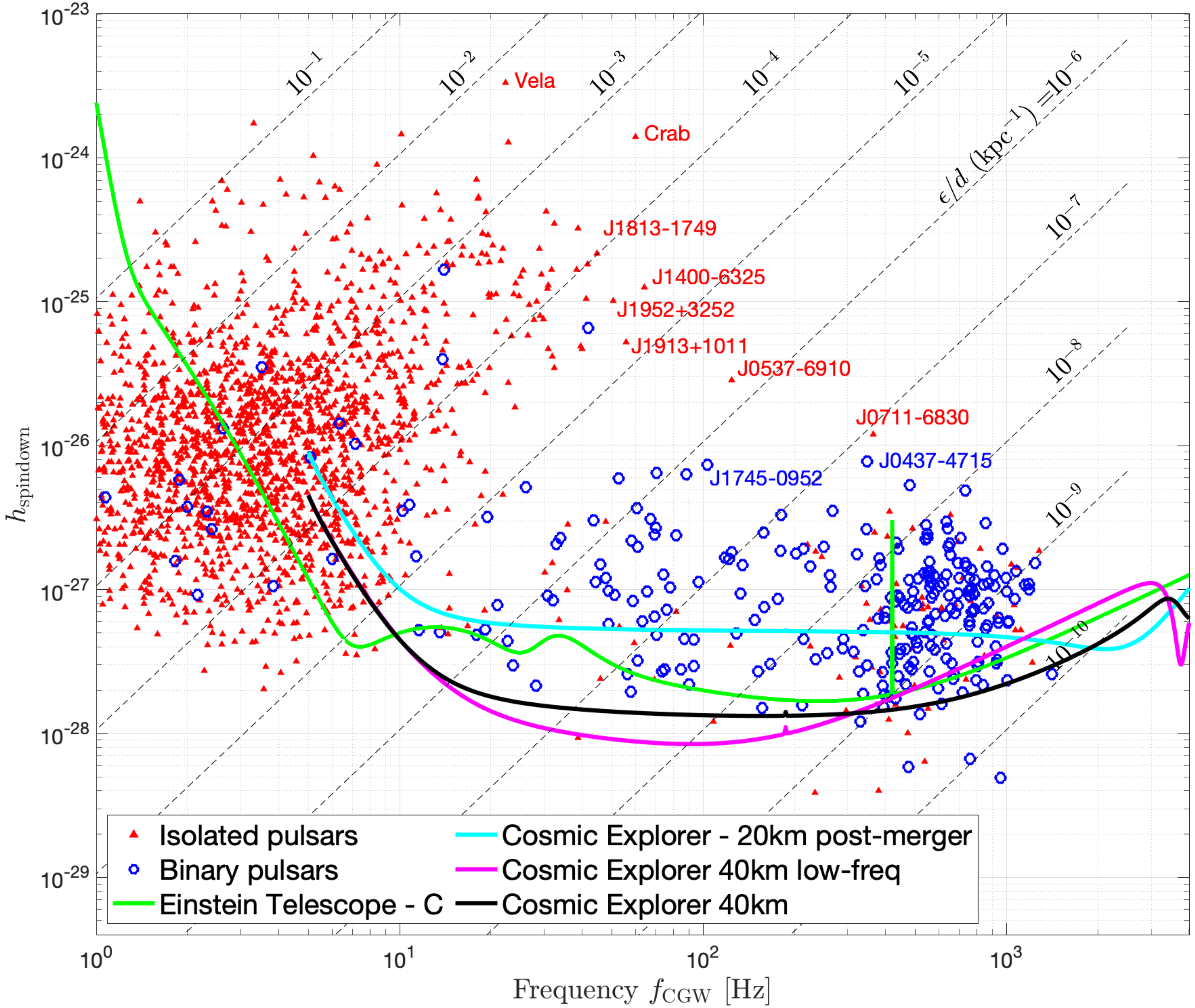
$$h_{95\%} = [S_h]^{1/2} / [50\ \mathrm{Hz}^{-1/2}]$$

Observation time: T_{obs} **= 5 years** (100% duty factor)

Number of detectors:

Einstein Telescope (ET-C) – $N_{detector} = 3$

Cosmic Explorer (40 km) – $N_{detector} = 2$



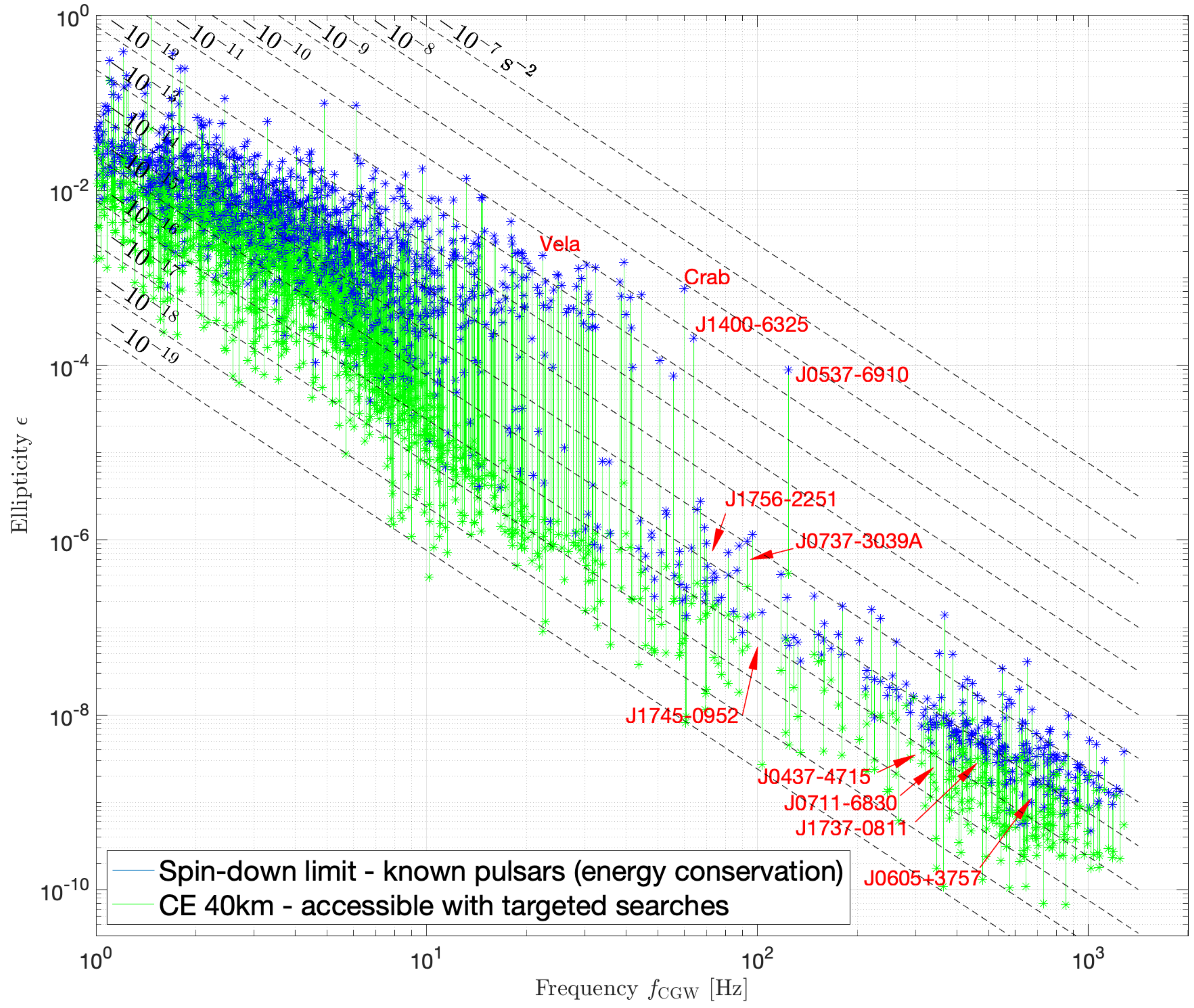
Population of known pulsars with GW frequencies > 1 Hz

Graph shows spin-down strain limits (energy conservation) and nominal targeted-search sensitivities for ET and different CE scenarios (gravitar extreme)

Binary systems dominate at high frequencies (“recycled” millisecond pulsars)

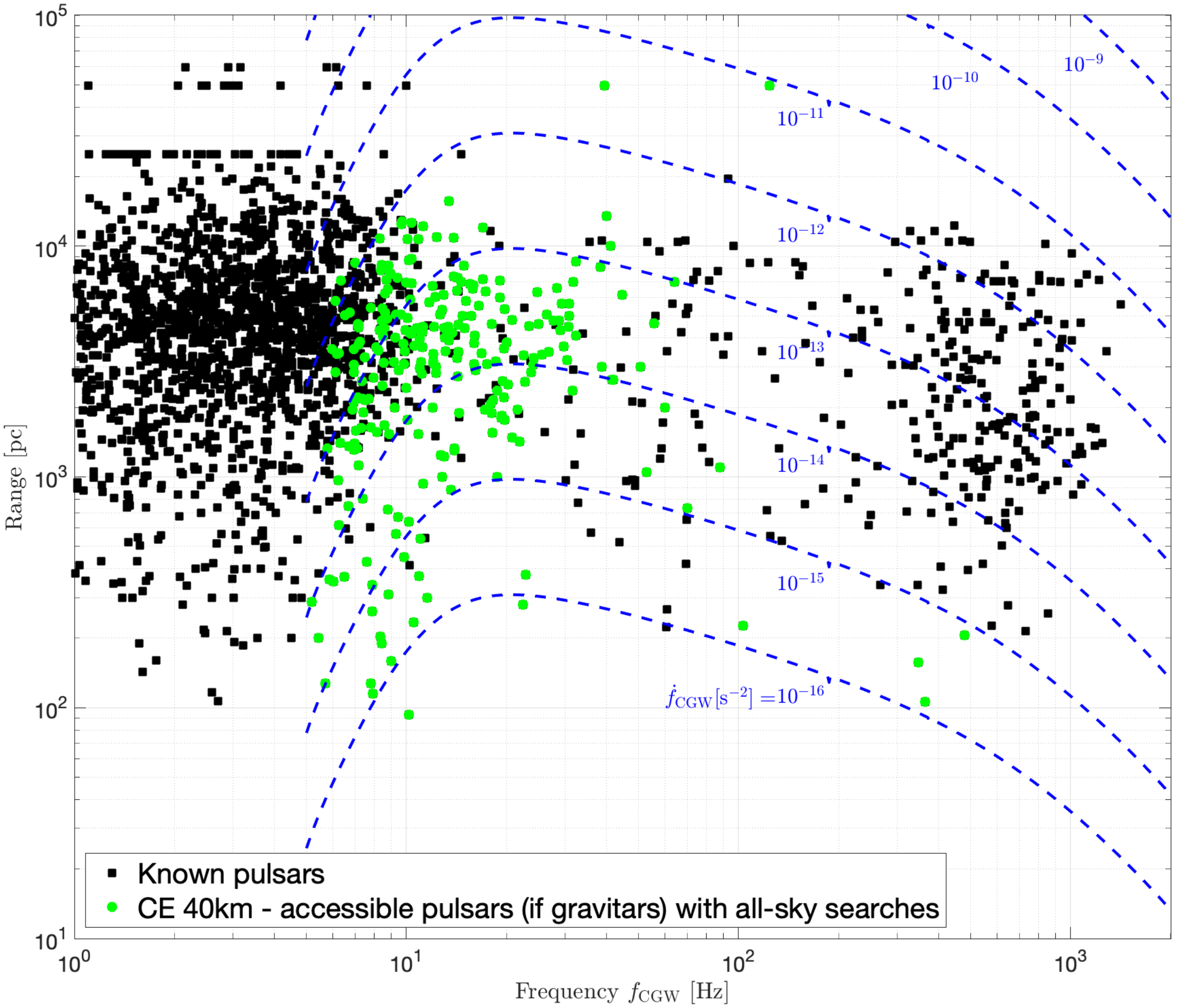
Dashed lines mark fixed ratios of ellipticity / distance

Population of known pulsars with GW frequencies > 1 Hz



Graph shows ellipticity limits (energy conservation) and range of accessible ellipticities with CE (40 km) using targeted searches

Dashed lines mark corresponding first frequency derivatives (gravitar extreme)



Population of known pulsars with GW frequencies > 1 Hz

Dashed curves show ranges (pc) for all-sky searches for different maximum frequency derivatives.

Green squares show known pulsars accessible with CE (40 km) (gravitar extreme)

What can be learned from a CW discovery?

A truly continuous-wave signal can be followed indefinitely

- Correlating GW and electromagnetic signals:
  - Stellar inclination / polarization straightforward to extract from CGWs
  - Ideal: EM pulsations detected (*a priori* or *a posteriori*) in multiple bands
  - Other possible EM-derived observables:
    - Source distance
    - Mass (in a binary system or X-ray emitting)
    - Radius (X-ray emitting)
    - Spectrum, including effective temperature
  - Another handle on NS EoS / dynamics (including glitch mechanisms)

→ **Potentially splendid multi-messenger source once detected**

- Demanding GR tests from long-duration tracking (one detector suffices)

  [see, e.g, M. Isi et al., PRD 91, 082002 (2015); P. Verma, Univ. 7, 351 (2021)]