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Recent continuous wave searches and their astrophysical implications

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on behalf of the LIGO-Virgo-KAGRA Collaboration

AGENDA

1 BACKGROUND

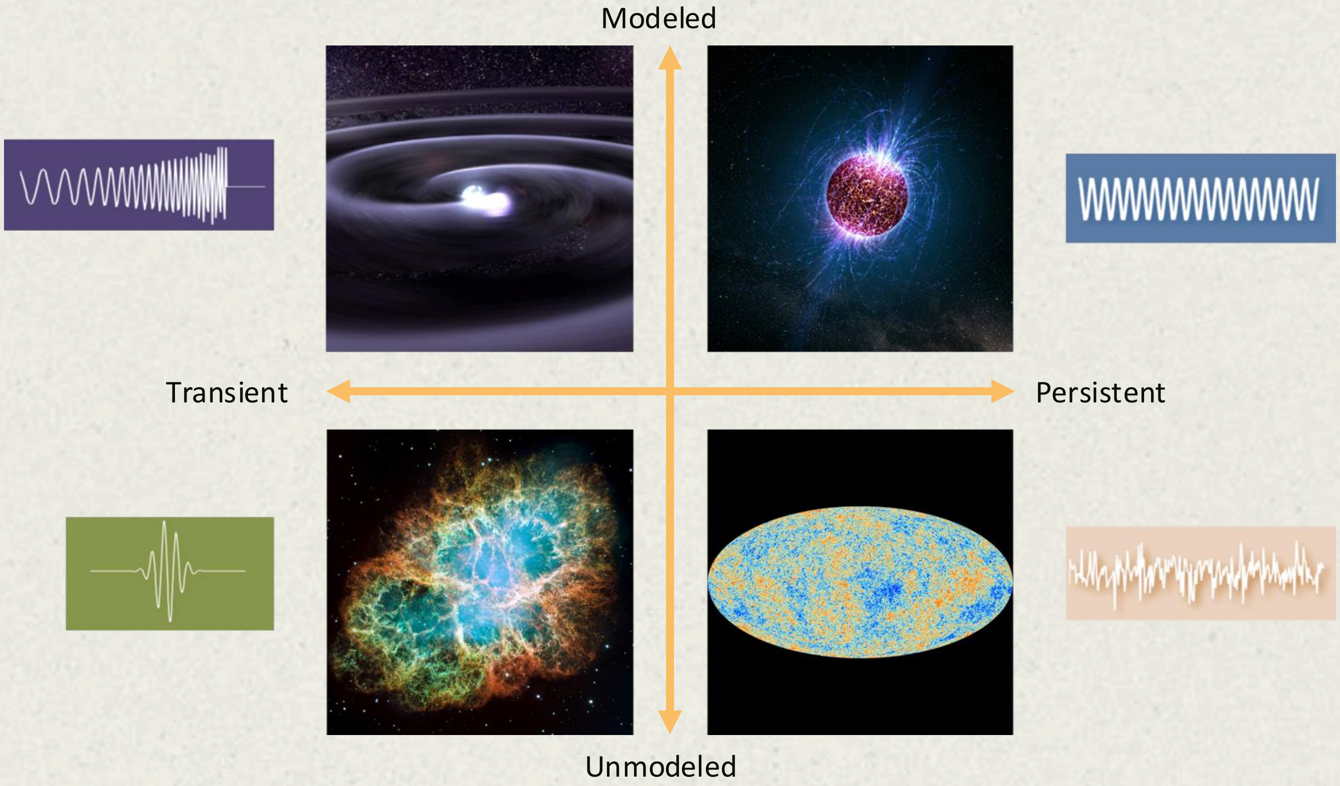
2 CW SEARCHES

3 DM SEARCHES

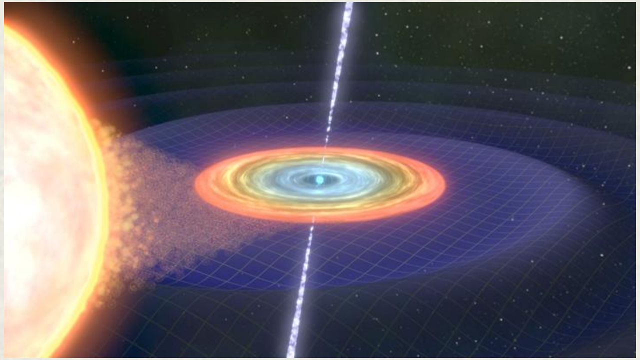
BACKGROUND

1.

SOURCES OF GRAVITATIONAL WAVES



CWS FROM NEUTRON STARS



Source: Mark Myers, OzGrav-Swinburne

$f_{GW} = 2f_{rotation}$

- Non-axisymmetric deformation due to elastic stresses or magnetic field
  - Imagine a "tiny mountains" on the surface
  - Signal is weak but persistent
- Free precession around the rotation axis

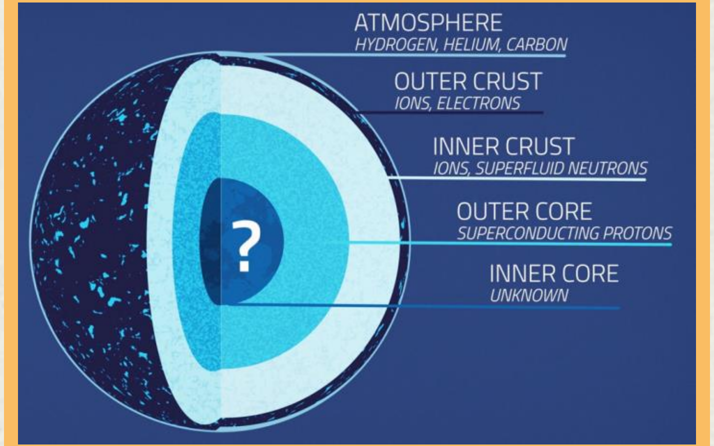
$f_{GW} \sim f_{rotation} + f_{precession}$

$f_{GW} \sim 2f_{rotation} + 2f_{precession}$

$f_{GW} \sim \frac{4}{3} f_{rotation}$

- r-modes
  - Long-lasting oscillations in the fluid that makes up most of the star
  - A fluid wave travelling around the star and driven by the Coriolis force due to rotation
- Deformation due to matter accretion in a binary system
  - Torque-balance equilibrium

$f_{GW} \sim 2f_{rotation}$

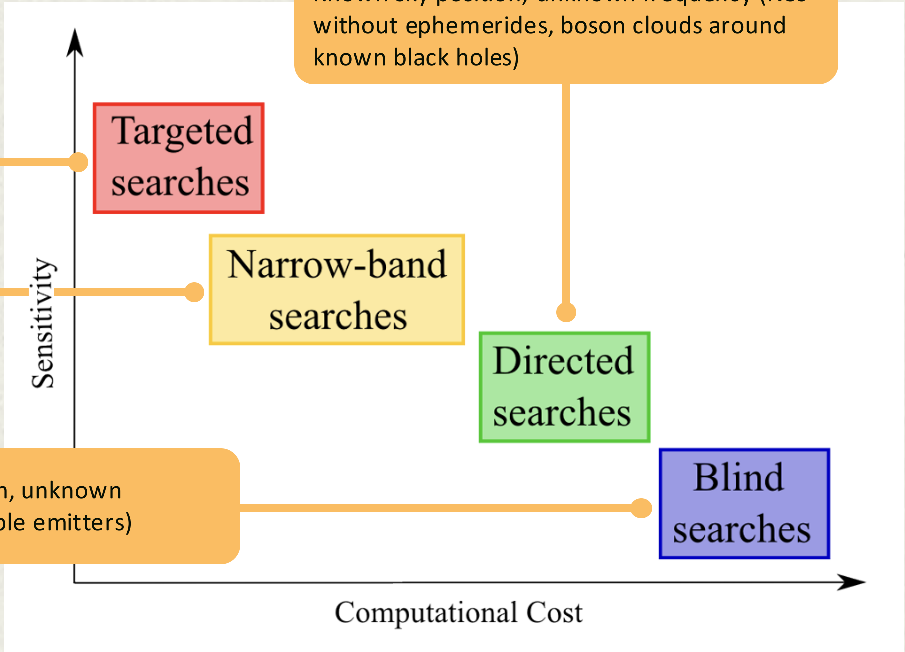


Source: NASA's Goddard Space Flight Center/Conceptual Image Lab

WHAT CAN WE LEARN?

- Nuclear equation of state → exotic states of matter?
- Neutron star properties, e.g., mass, spin, ellipticity
- Multi-messenger studies, e.g., mass and magnetic field structure inferred from relative phase of GW/EM
- Tests of General Relativity

TYPES OF CW SEARCHES



Known sky position, phase-locked to EM signal (known pulsars)

Known sky position, relaxed coupling between GW & EM signals (known pulsars)

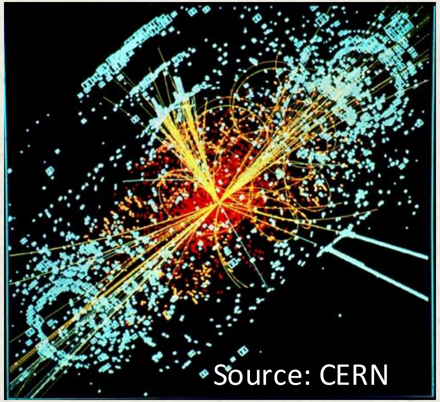
Known sky position, unknown frequency (NSs without ephemerides, boson clouds around known black holes)

Unknown sky position, unknown frequency (any possible emitters)

Source: Sieniawska & Bejger

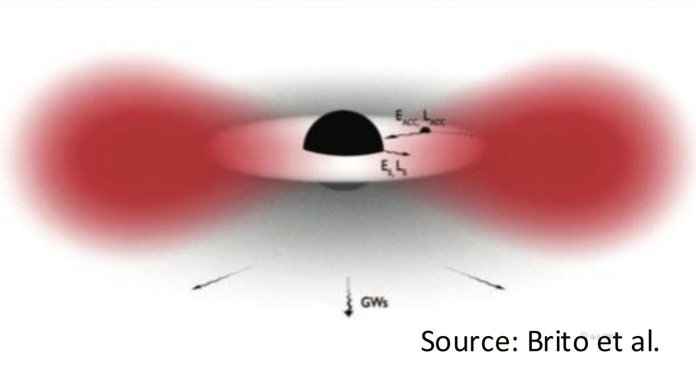
CWS FROM DARK MATTER

- Direct interaction: DM particles
  - May couple to ordinary matter in interferometer test masses, causing an oscillatory force that effects the length of the arm cavities
  - The signal, though not a GW, would look similar to a CW in the data



Source: CERN

- Detection through GWs: Ultralight boson clouds
  - May form bound states with rotating black holes through the superradiance phenomenon, growing into macroscopic clouds
  - Clouds dissipate over time through pseudo-CW radiation



Source: Brito et al.

LVK O3 CW SEARCHES

Phys. Rev. D 110, 042001 (2024)

Astrophys. J. Lett. 941, L30 (2022)

Phys. Rev. D 106, 042003 (2022)

Phys. Rev. D 106, 062002 (2022)

Phys. Rev. D 106, 102008 (2022)

Astrophys. J. 932, 133 (2022)

Phys. Rev. D 105, 082005 (2022)

Phys. Rev. D 105, 102001 (2022)

Astrophys. J. 935, 1 (2022)

Phys. Rev. D 105, 022002 (2022)

Phys. Rev. D 104, 082004 (2021)

Phys. Rev. D 105, 063030 (2022)

Astrophys. J. 921, 80 (2021)

Astrophys. J. 922, 71 (2021)

Astrophys. J. Lett. 913, L27 (2021)

Phys. Rev. D 103, 064017 (2021)

Astrophys. J. Lett. 902, L21 (2020)

I will discuss a small selection of these in the next slides.

Some recent reviews for a comprehensive guide:

Piccinni, Galaxies 10(3) (2022)

Riles, Living Reviews in Relativity 26, 3 (2023)

Wette, Astroparticle Physics 153 (2023) 102880

CW SEARCHES

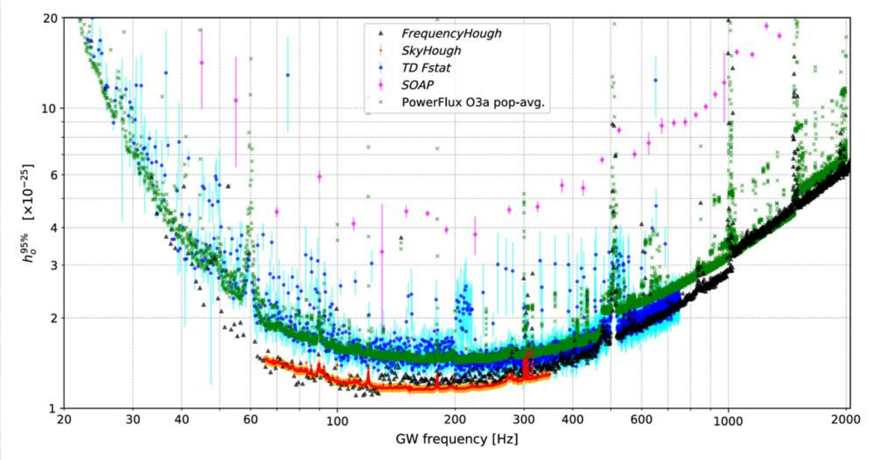
2.

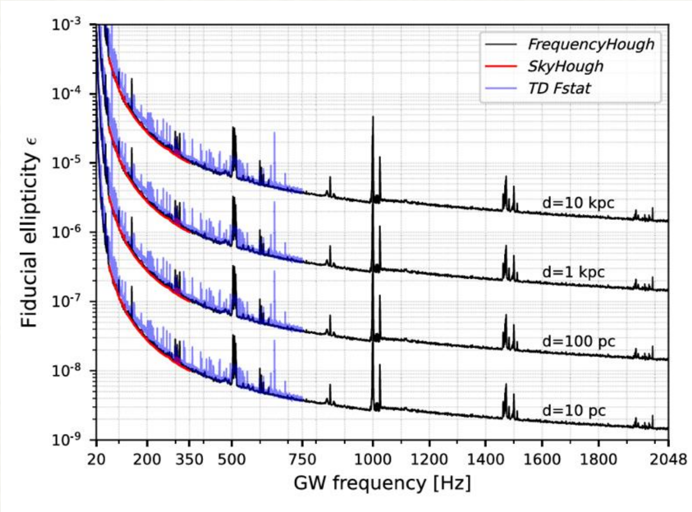
BLIND SEARCH: ISOLATED NEUTRON STARS

- Searched 20-2000 Hz band
- Most sensitive all-sky search to date for CWs in the given parameter space
- Other searches outside LVK, e.g., deeper search done by AEI over a more focused parameter space (B. Steltner *et al* 2023 ApJ 952 55)

$$\epsilon = \frac{c^4}{4\pi^2 G}\frac{h_0 d}{I_{zz} f^2}$$

- Upper limits are good enough to begin to probe the ellipticity range $10^{-7} - 10^{-6}$, which is predicted for young stars



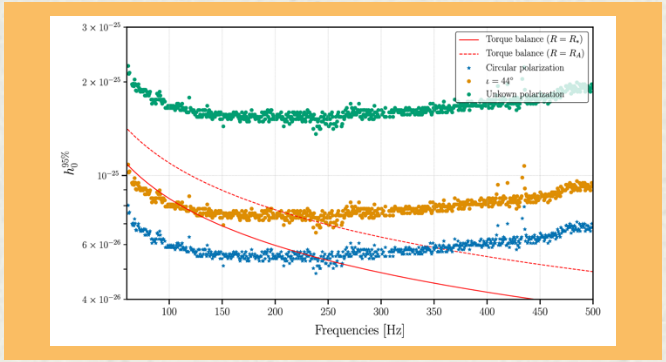


DIRECTED SEARCH: SCORPIUS X-1

- Scorpius X-1 is the most X-ray-luminous low-mass X-ray binary

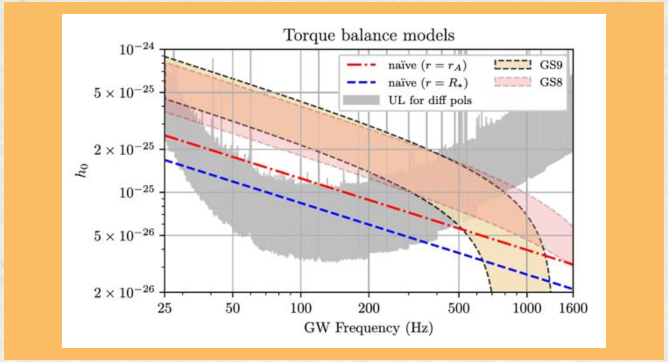
[1] O3 HL, Phys. Rev. D 106, 062002 (2022)

- Searched 60–500 Hz band
- Used a hidden Markov model search method to allow for spin wandering



[2] O3 HL, Astrophys. J. Lett. 941, L30 (2022)

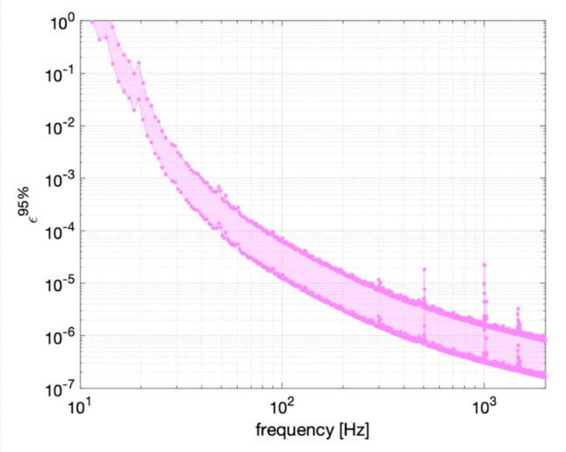
- Searched 25–1600 Hz band
- Used the model-based Cross-correlation search method

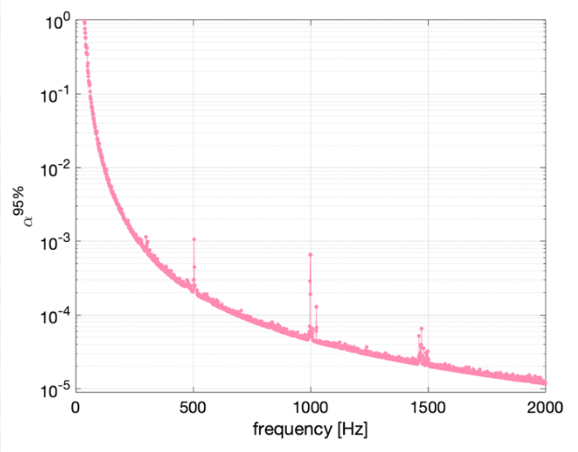


- Sensitivity of both searches is good enough to begin to probe possible models of torque balance equilibrium.

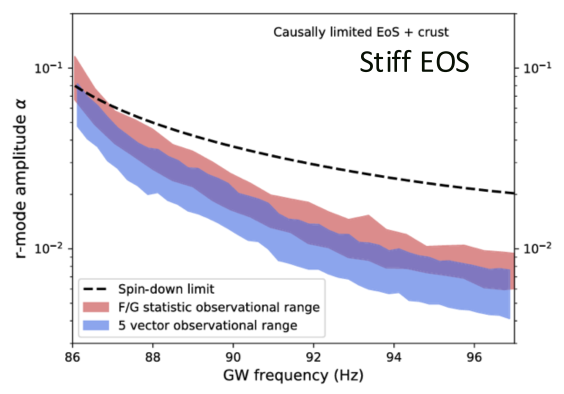
DIRECTED SEARCH: GALACTIC CENTER

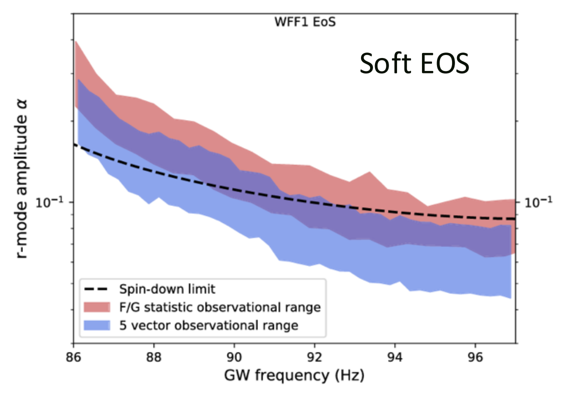
- There is compelling evidence for a large population of neutron stars in the Galactic Center
- Searched 10–2000 Hz band
- No significant detection → upper limits are significantly more constraining than those reported in previous searches
- Constraints placed on the fiducial neutron star ellipticity, r-mode amplitude, and on boson mass within certain ranges





TARGETED SEARCH: KNOWN PULSAR





- PSRJ0537–6910 → young energetic X-ray pulsar, most frequent glitcher known
- Evidence that the spin-down of the pulsar may be driven by GW emission due to unstable r-mode oscillations
- Searched 86–97 Hz band and used timing ephemeris obtained from NICER data
- Assuming r-mode-driven spin-down, unlikely to have stiff EOS because upper limits have already surpassed this limit

DARK MATTER SEARCHES

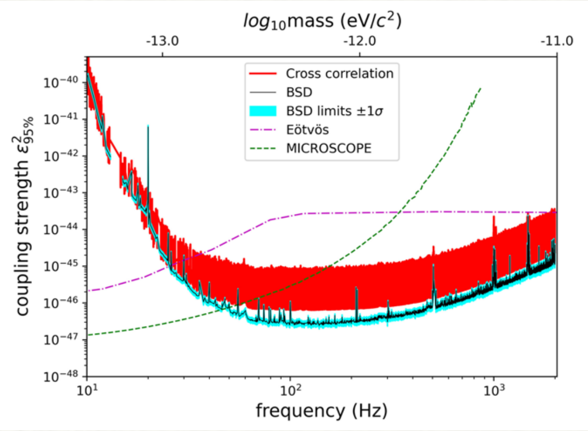
3.

* Andrew Miller will give more info during his talk Thursday at 11:40 am

DIRECT INTERACTION: DARK PHOTONS

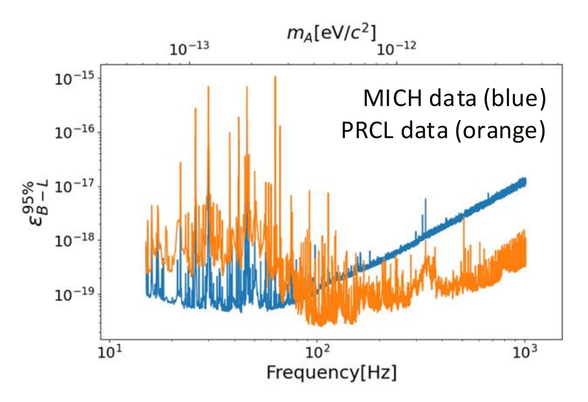
[1] O3 HLV, Phys. Rev. D 105, 063030 (2022) + Phys. Rev. D 109, 089902 (2024) (LIGO-Virgo)

- Upper limits in this search improve upon those obtained in other direct dark matter searches by a factor of ~2 at high frequencies boson masses $\sim[2-4] \times 10^{-13}$ eV



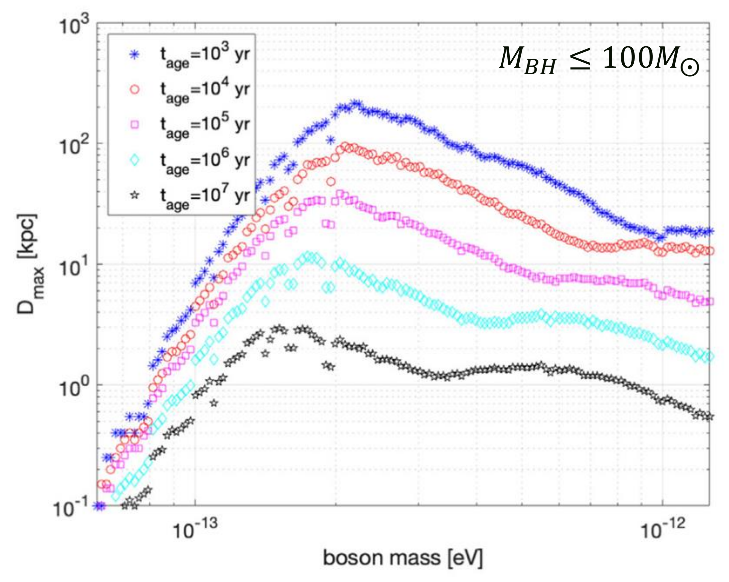
[2] O3GK K, Phys. Rev. D 110, 042001 (2024) (KAGRA)

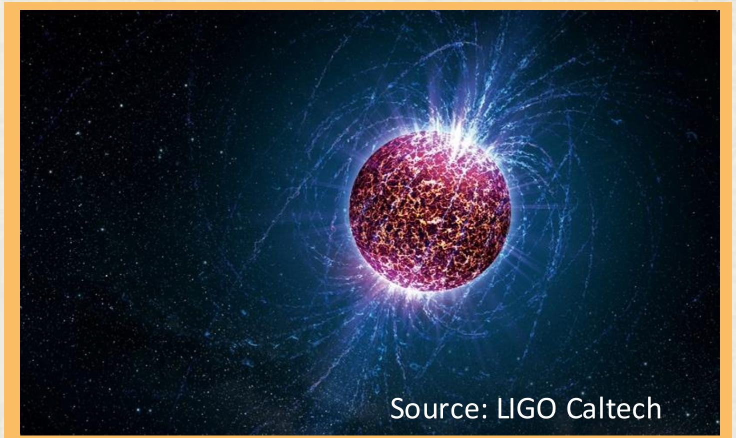
- Mirrors are not all made from the same material → each material would react differently to the DM, enhancing a potential signal
- Upper limits in this study are weaker than previous published limits by orders of magnitude → KAGRA's sensitivity is not optimized, measurement duration too short
- Primarily useful as a demonstration of the pipeline



DETECTION VIA GWS: SCALAR BOSONS

- First tailored all-sky search for long-duration, quasimonochromatic GW signals emitted by scalar boson clouds around spinning black holes
- Searched 20 – 610 Hz band
- Scalar boson clouds younger than 1000 years made up of bosons with masses $\sim[10^{-13}, 10^{-12}]$ eV are not likely to exist in our Galaxy
- Results are complementary with direct interaction studies





SUMMARY

- Potential sources of CW radiation we look for today include spinning neutron stars and particle dark matter
- Search methods and techniques continue to improve and can be tailored to a particular source, balancing computational efficiency with sensitivity
- Although no confident CW detection yet, beginning to probe physically interesting regions
- O4 analyses using more sensitive data are underway → new and exciting results to come!

QUESTIONS?