Searches for Continuous Waves: current status and future prospects

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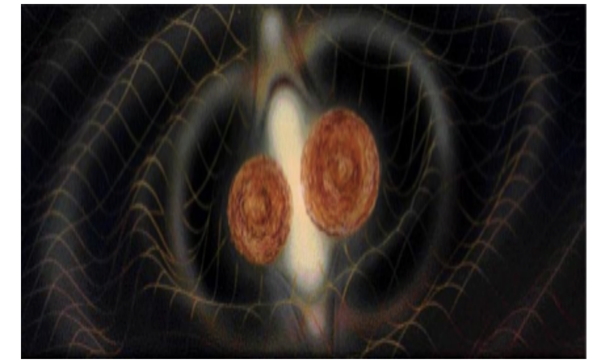
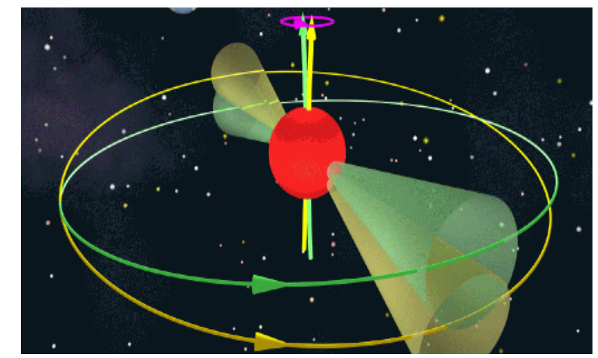
Gravitational wave signal types

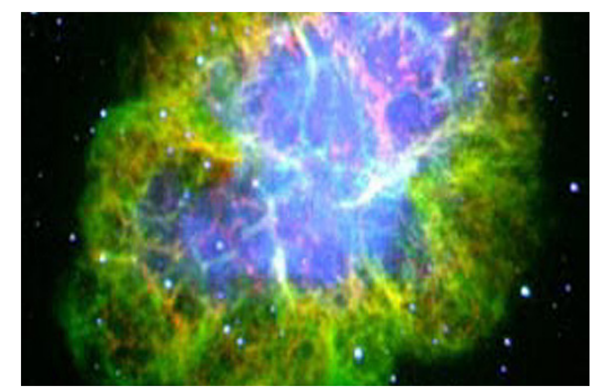
"chirps" ✓ **(Compact binary inspirals)**



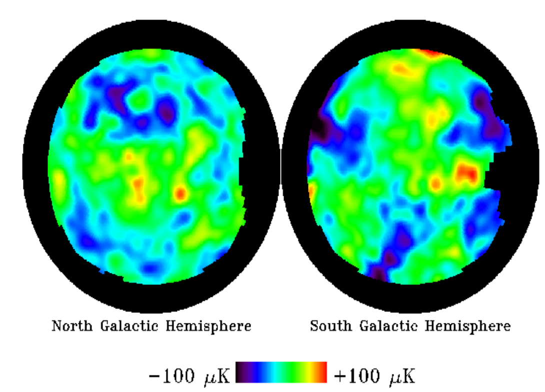
"continuous" **(GW pulsars, asteroseismology)**



"bursts" **(Magnetar flares, Supernovae,...)**

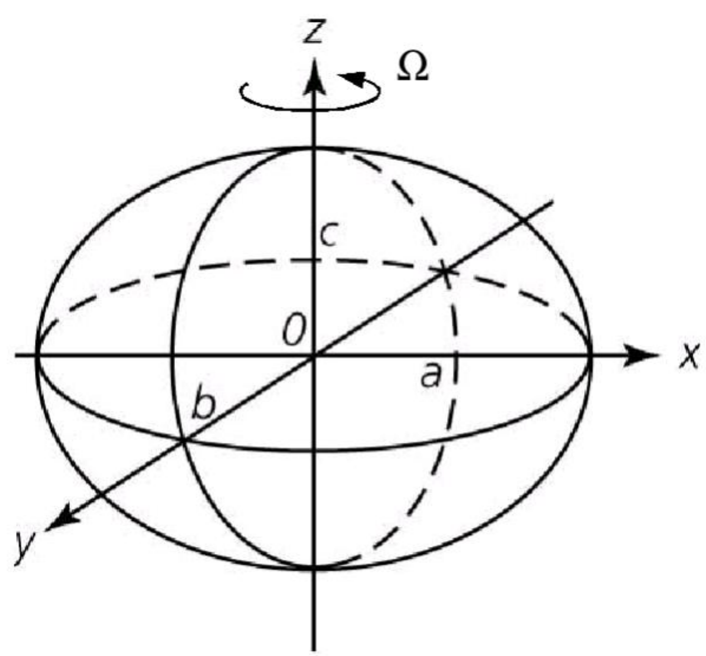


"stochastic" **(Cosmological signals)**



Emission mechanisms for isolated NSs

Mountains



$$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

- Emission at 2Ω and possibly Ω

Modes of oscillation

- Oscillations in the fluid couple to the gravitational field
- Main candidates **f** and **r** modes
- Emission at the mode frequency

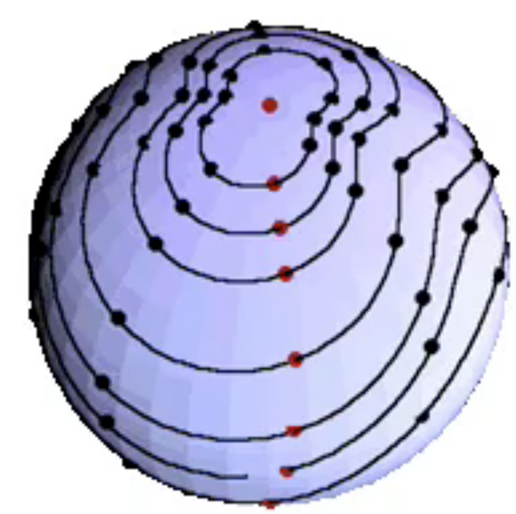
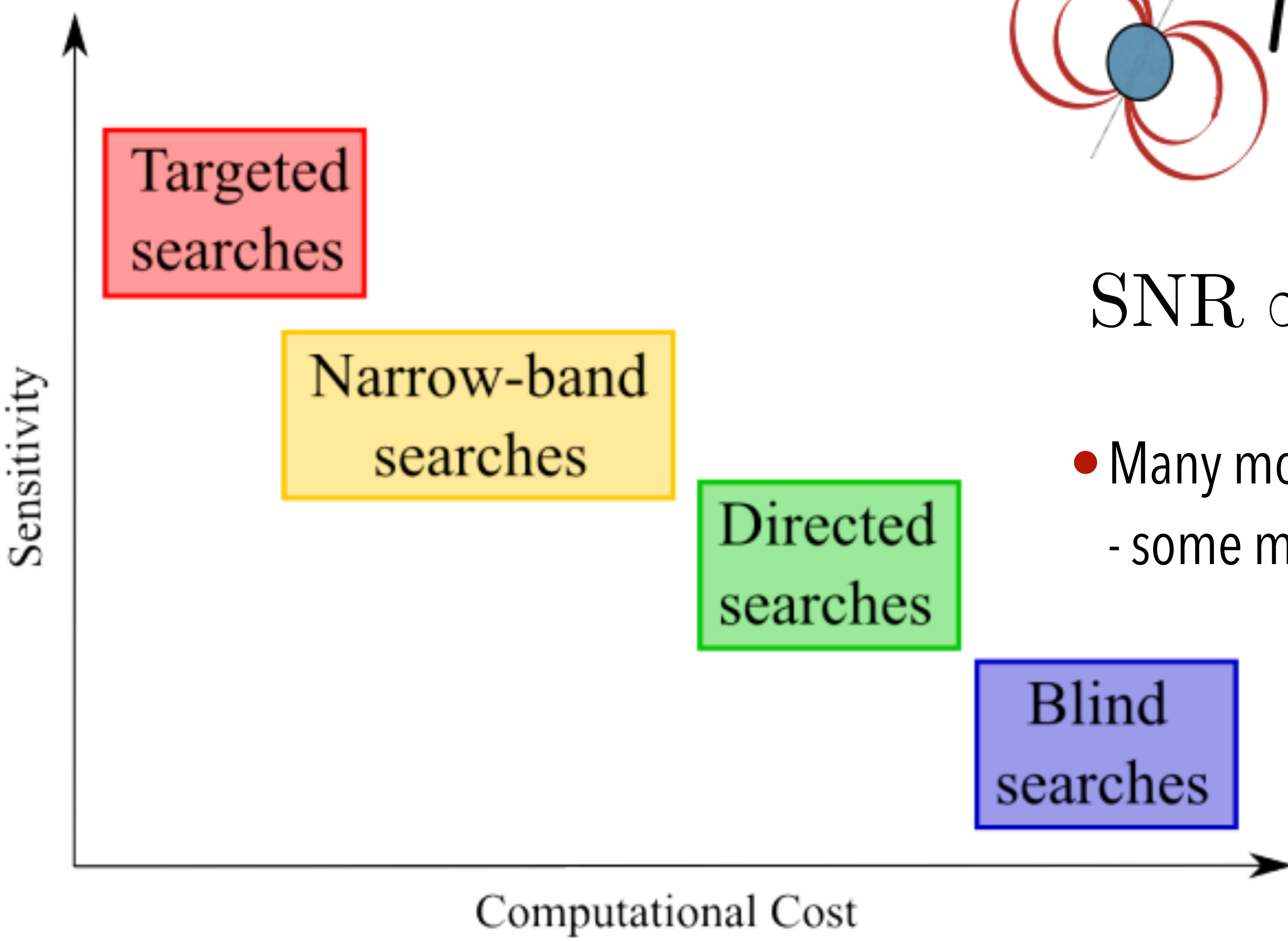


Figure: C. Hanna and B. Owen

Continuous Wave (CW) searches

- Searches are computationally limited - the more we can restrict parameter space the deeper the search
- We are sensitive to Neutron Stars (NSs) in our galaxy

$$\mathrm{SNR} \propto \sqrt{T_{obs}}$$



- Many more NS in our galaxy than those we see
  - some may be `gravitars'

(Sieniawska & Bejger 2019)

How large an ellipticity do we expect?

- We can obtain a spin-down upper limit from those we see

$$h_0^{\rm sd} = \left(\frac{5}{2}\frac{GI_{zz}|\dot{f}_{\rm rot}|}{c^3 d^2 f_{\rm rot}}\right)^{1/2} \qquad \epsilon_{\rm sd} = \sqrt{\frac{5c^5}{512 G I_{zz}}\frac{|\dot{f}_{\rm rot}|}{f_{\rm rot}^5}}$$

e.g. Crab pulsar
$\epsilon \approx 7 \times 10^{-4}$

- Theory can tell us how large a mountain can get before breaking the crust

$$\epsilon_{\rm max} \approx 10^{-6}\left(\frac{\sigma_{br}}{10^{-2}}\right)$$

Molecular dynamics simulations $\longrightarrow \sigma_{br} \approx 10^{-1}$

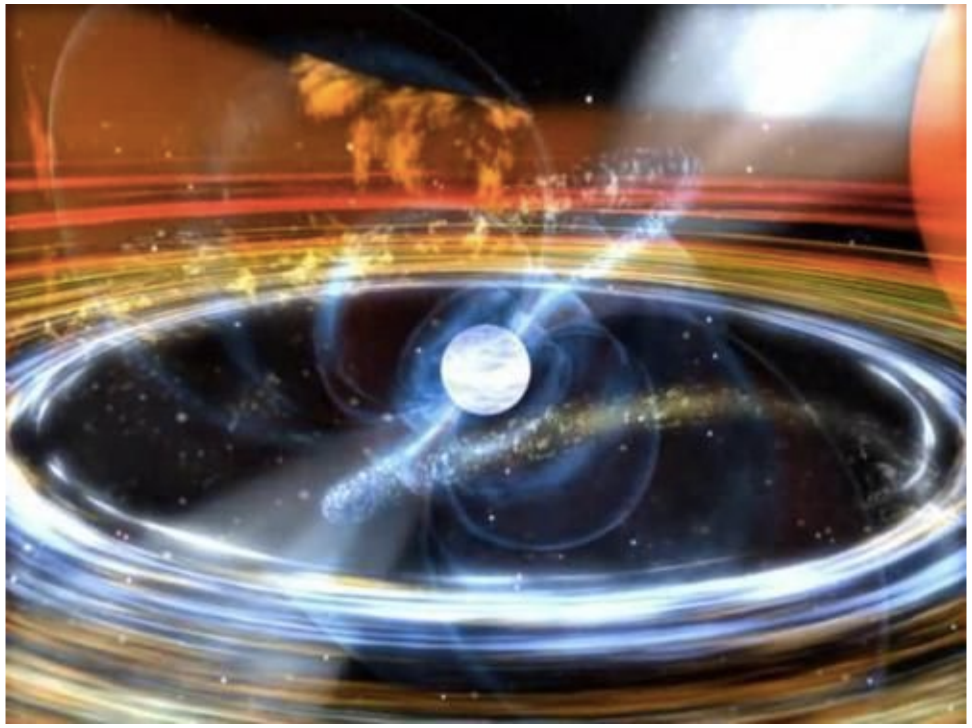
- …or the core if it's in a cristalline state

$$\epsilon_{\rm max} \approx 10^{-4}$$

For a review see:
Haskell & Schwenzer 2022
(Handbook of GW Astronomy)
arXiv: 2104.03137

- We are sensitive to signals from NSs in the galaxy

Old NSs - accreting NSs in LMXBs



Fastest Neutron Star: 716 Hz

[Chakrabarty et al 2003, Patruno 2010, Papitto et al. 2014, Patruno, BH and Andersson. 2017]

- Spin up halted well before breakup frequency

  (Theoretical lower limit on max breakup f ~1200 Hz - **BH et al. 2018**)

- Disk/magnetosphere interaction?

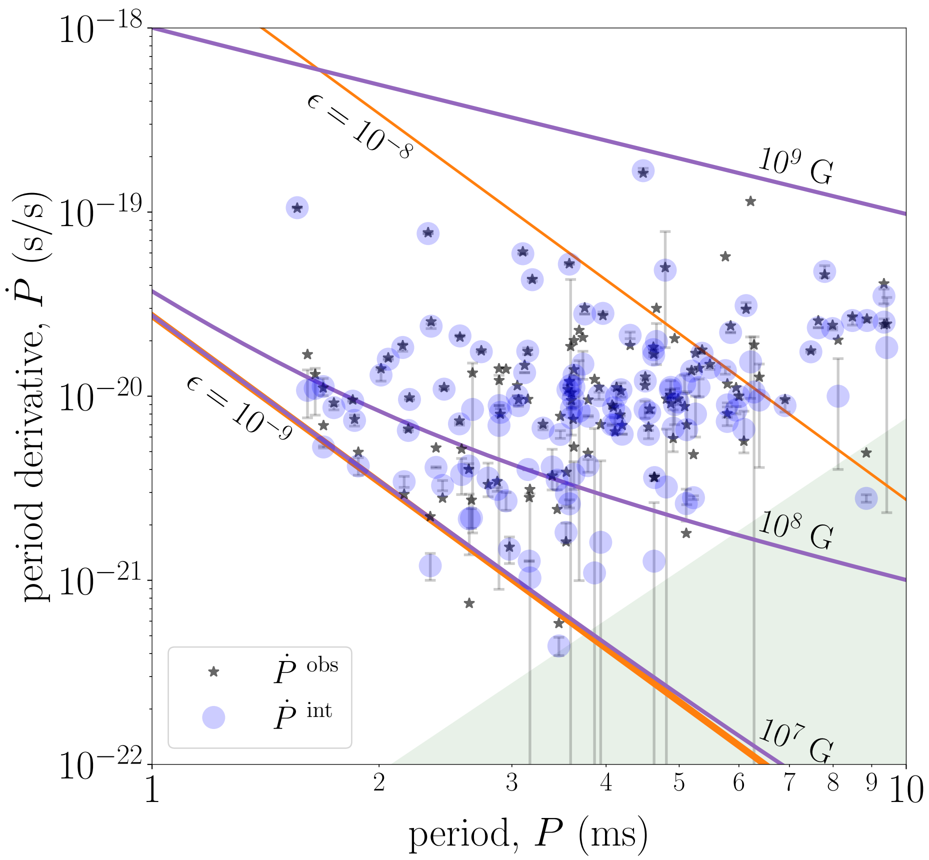
  [White & Zhang 1997, Andersson, Glampedakis, BH & Watts 2006, BH & Patruno 2011, Patruno, D'Angelo & BH 2012, D'Angelo 2016, Bhattacharya & Chakrabarty 2017]

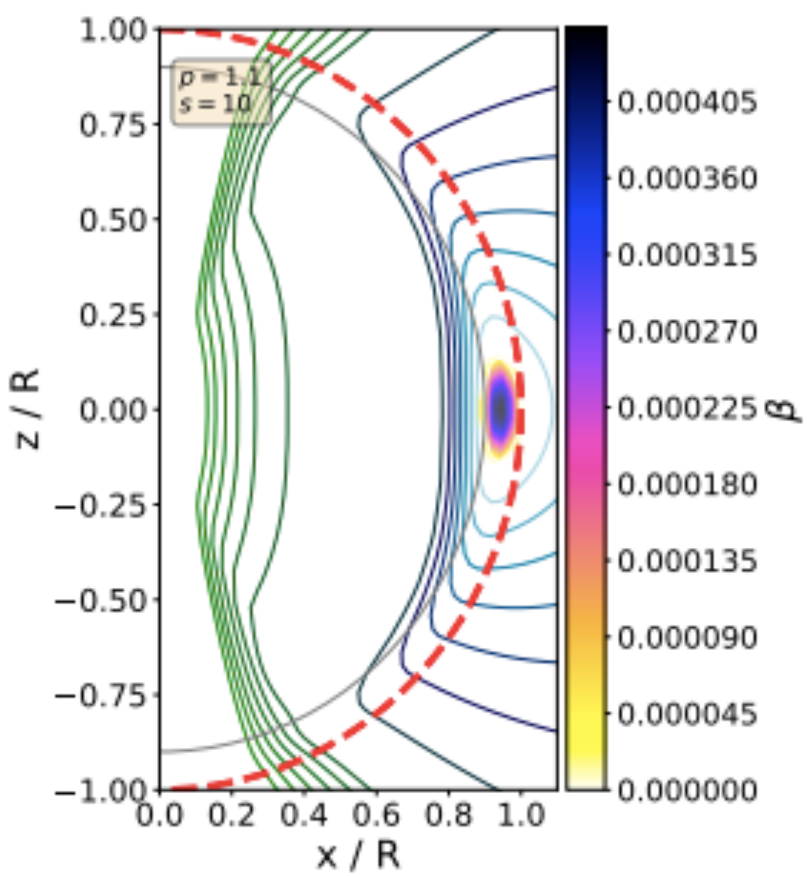
- GWs!: "mountains", unstable modes, magnetic deformations

$$\epsilon \approx 10^{-7}$$

[Bildsten 1998, Andersson 1998, Cutler 2002, BH et al. 06, BH et al. 08, Payne & Melatos 05]

Minimum ellipticity





- Evidence for a cutoff in the P-Pdot diagram

(Woan, Pitkin, BH, Jones & Lasky 2018)

(BH & Patruno 2017)

- Buried magnetic field in type II superconductor?

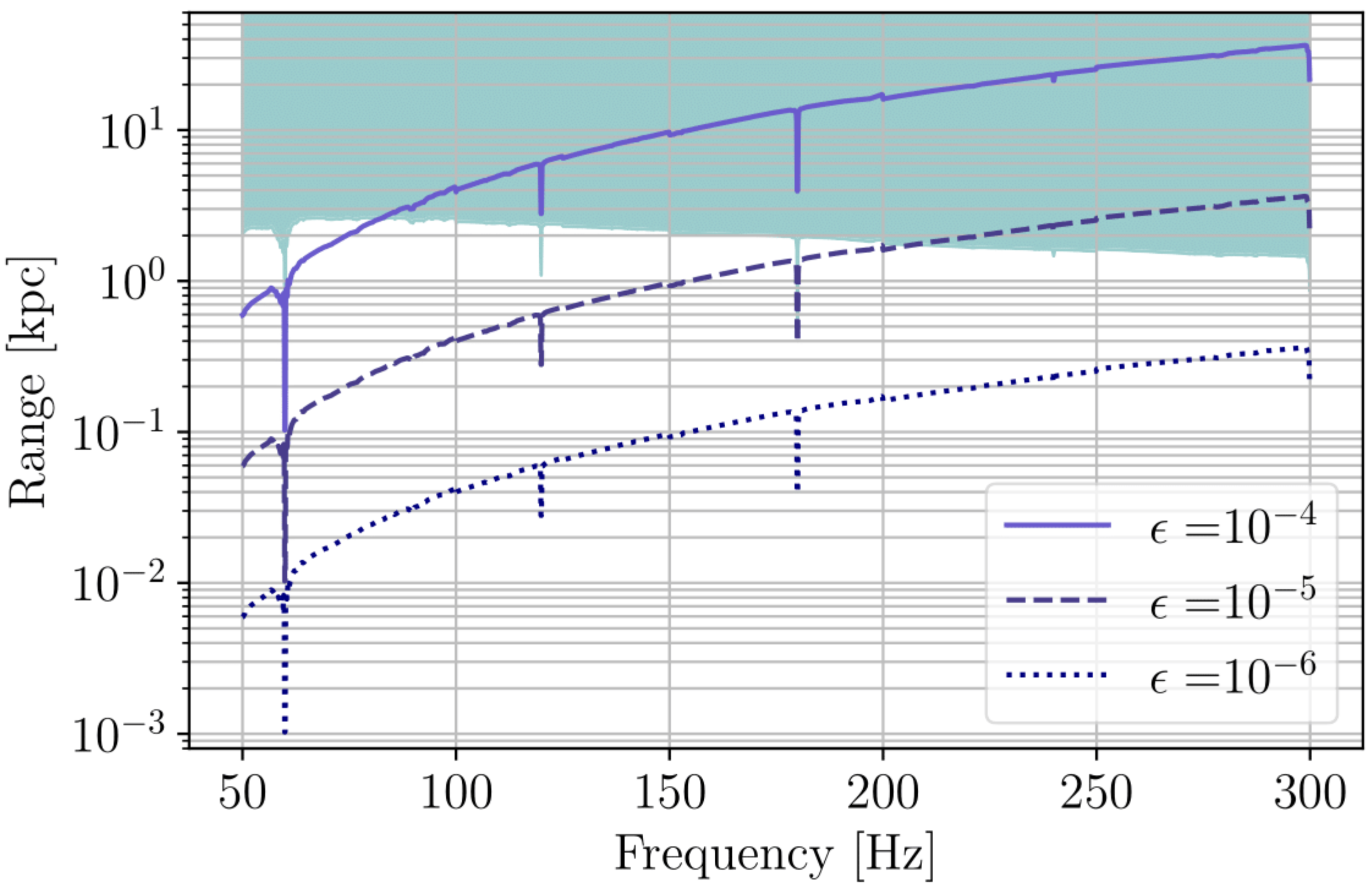
$$\epsilon \approx 10^{-9}$$

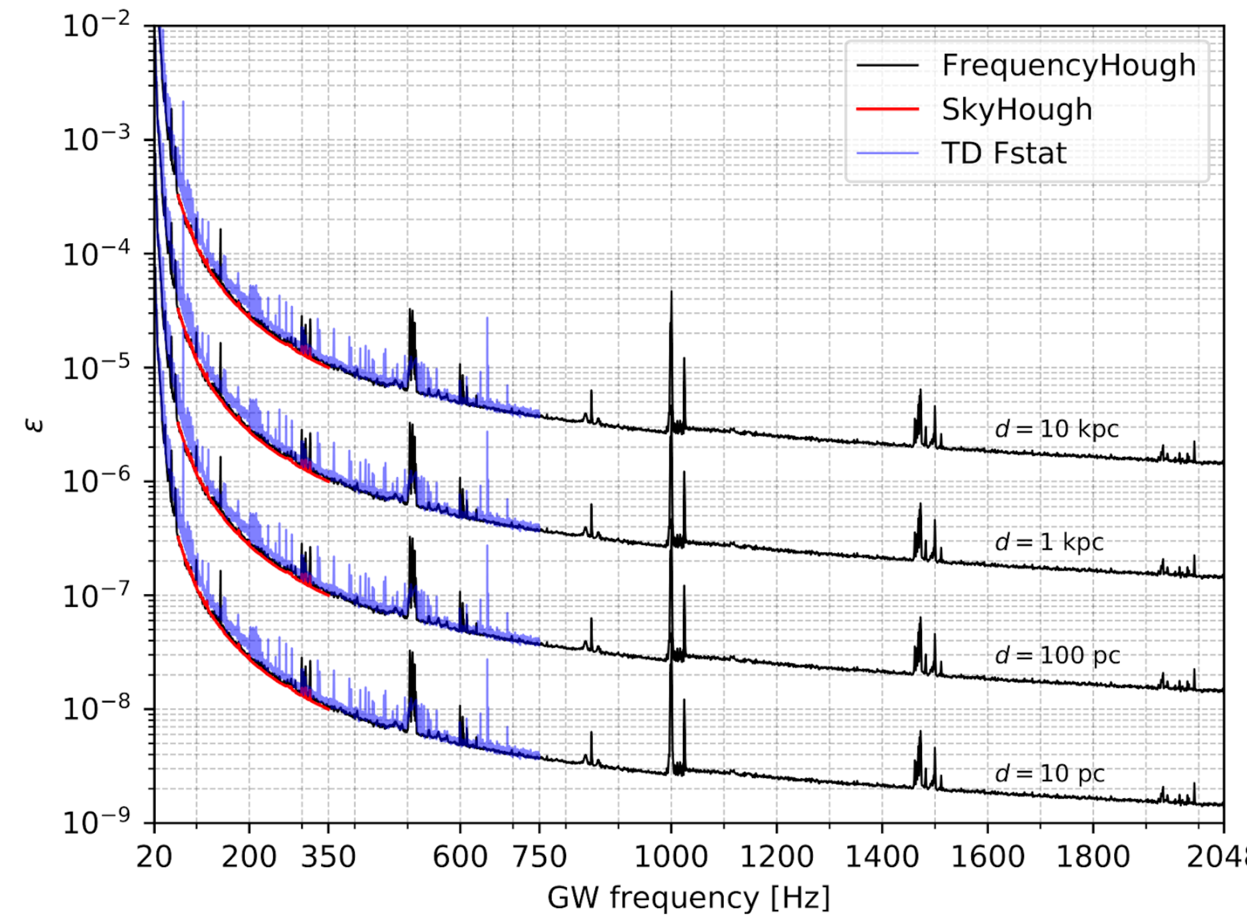
(Lander 2013, Sur and BH 2021)

- Deformations expected also in young NSs (up to $\epsilon \approx 10^{-6}$)

(Suvorov et al. 2016)

Searching for unknown sources: examples





- Probing NS in the galaxy
- Starting to probe exotic Equations of State (EoS)
- Future advanced detectors can probe realistic Equations of State (EoS)

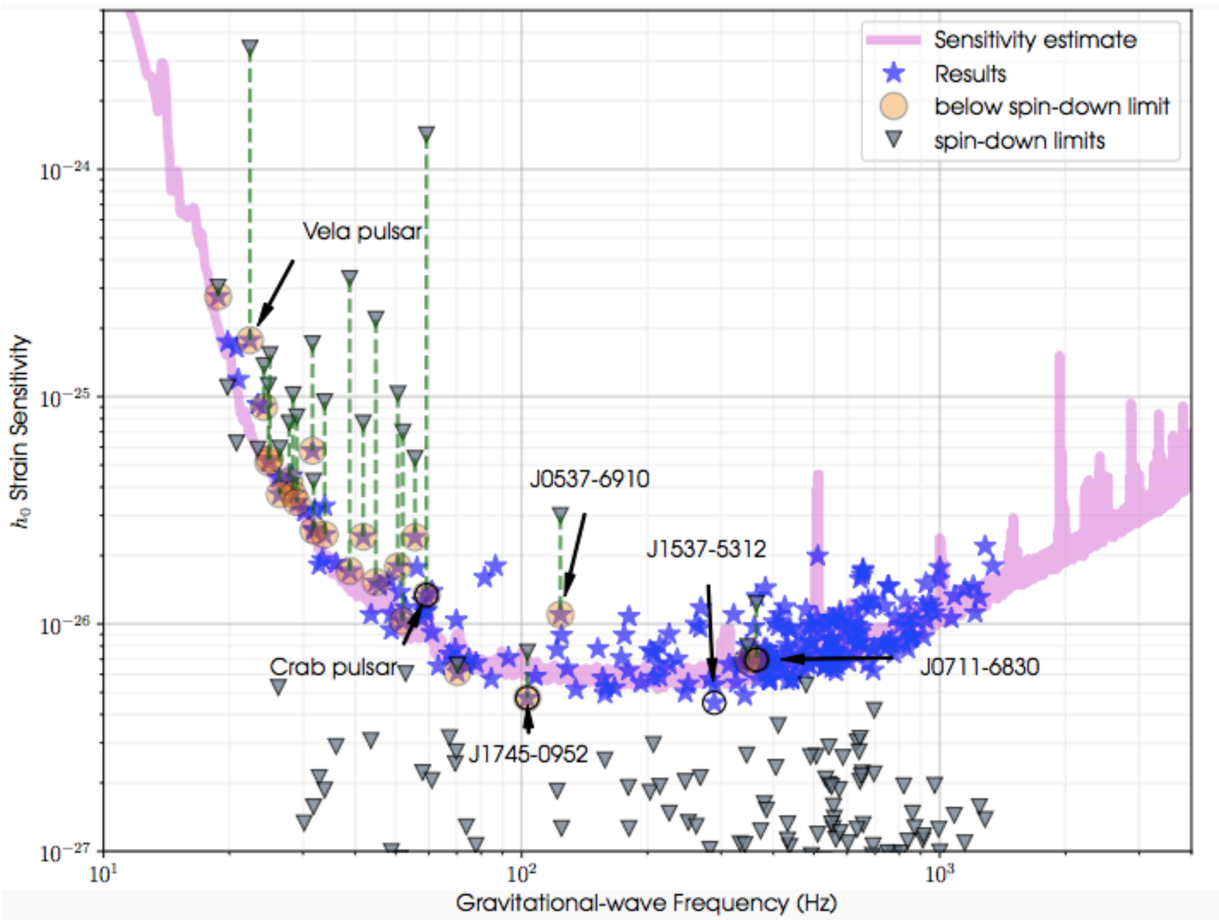
Abbott et al. Phys. Rev. D 103, 064017 (2021)

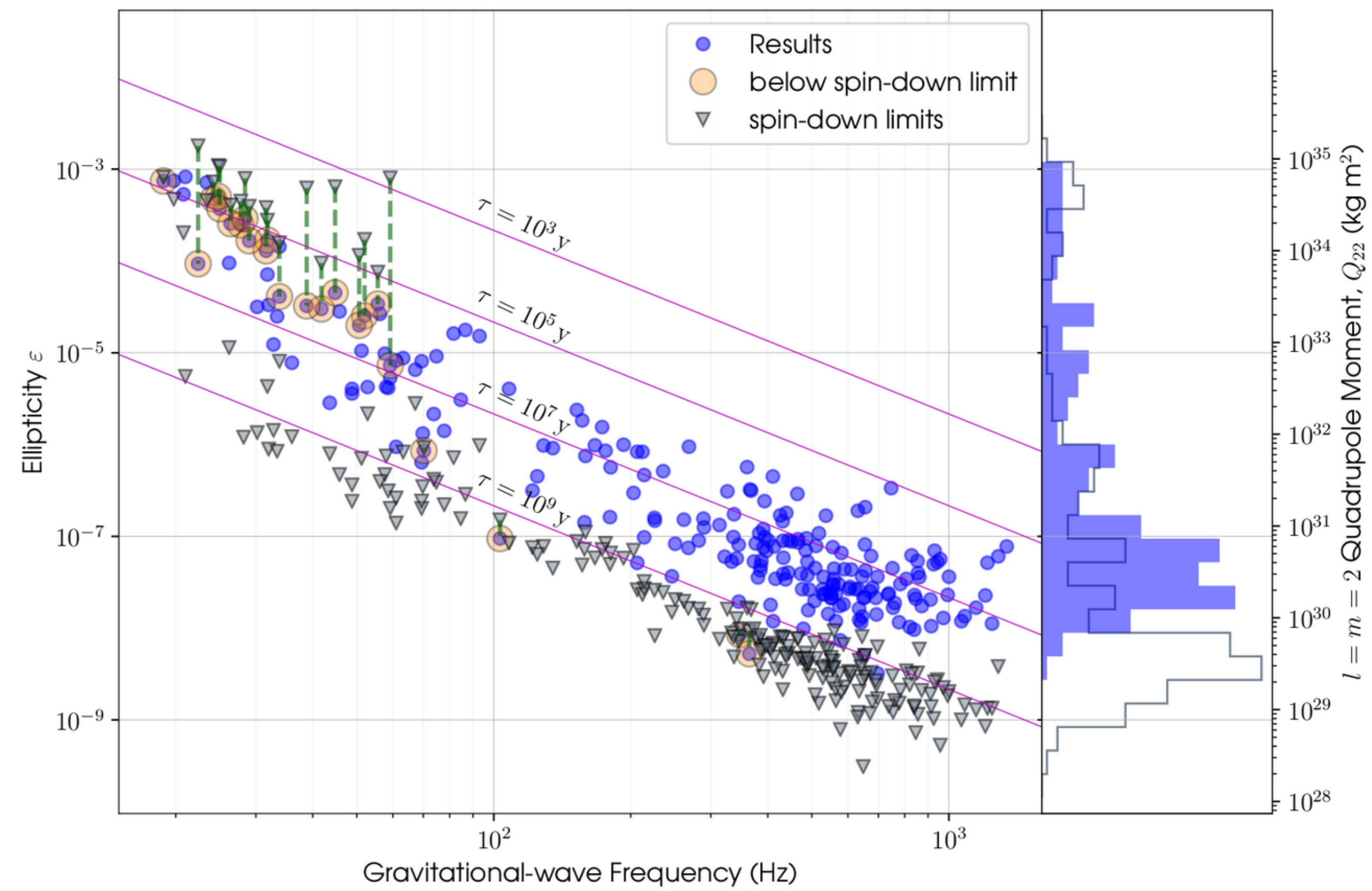
Abbott et al. 2022, arXiv:2201.00697

Searching for known sources: examples

Abbott et al. (2022), arXiv: 2111.13106 (accepted by ApJ)

Abbott et al. Phys. Rev. D 105, 022002 (2022) *(X-ray pulsars)*

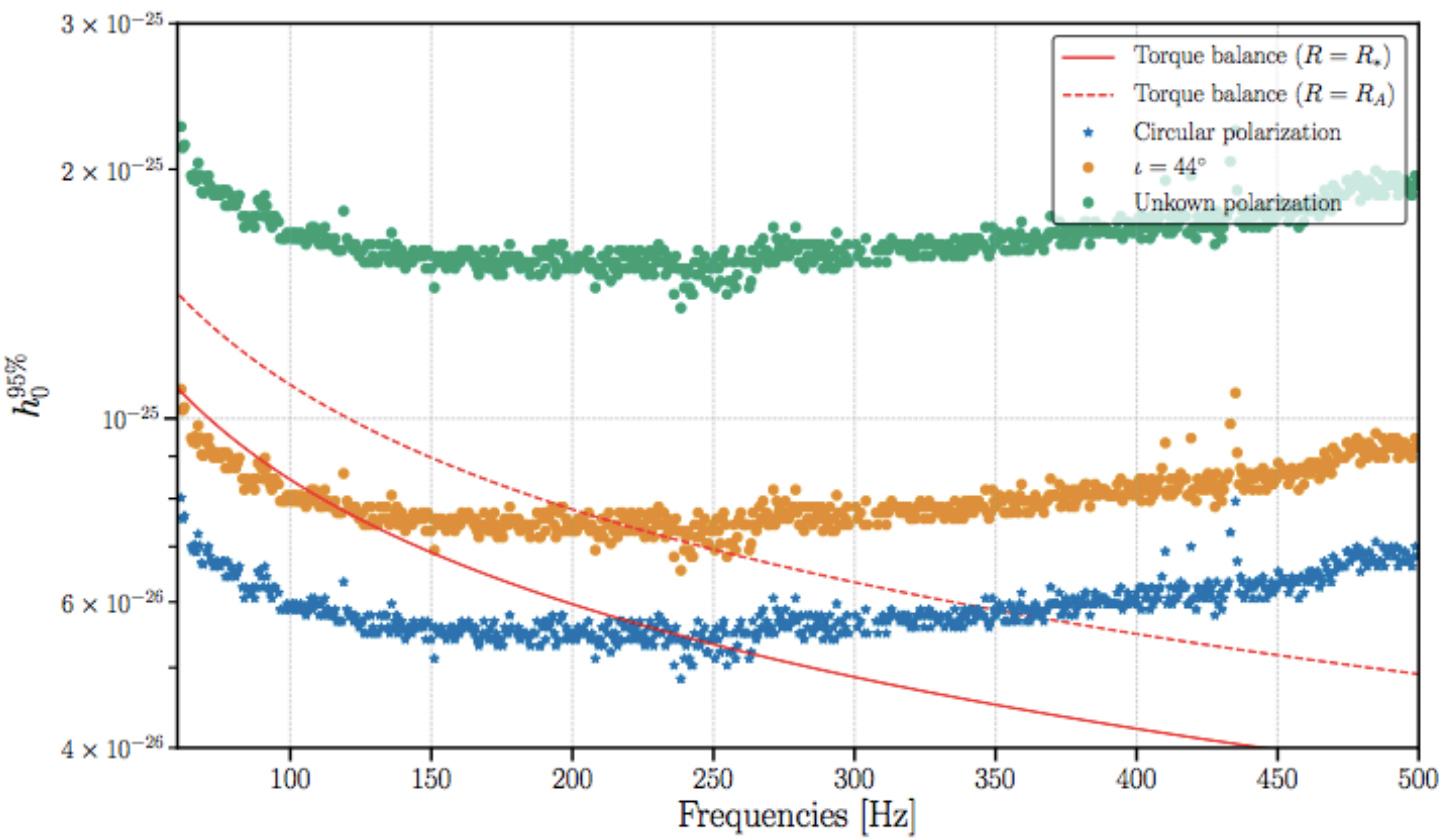




- Energy emitted in GWs constrained at lower frequency
- Improvements needed to probe realistic models of deformation due to Hall evolution in the crust

Targeted search: probing spin-equilibrium

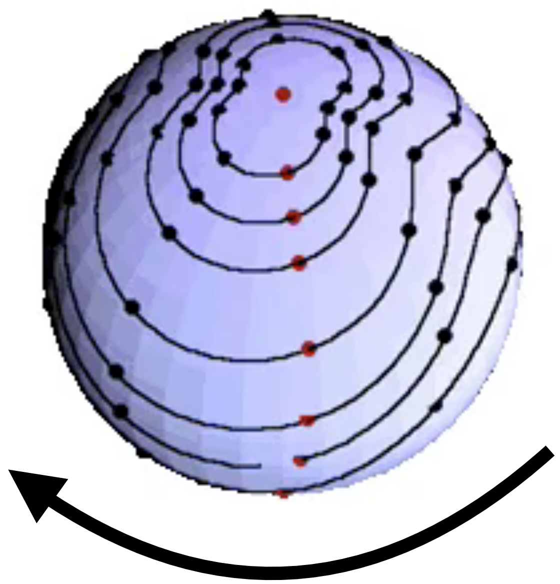
- Scorpius X-1 is the most X-ray luminous LMXB
- No pulsations detected…spin unknown
- Search carried out allowing for spin wandering, deeper search in progress



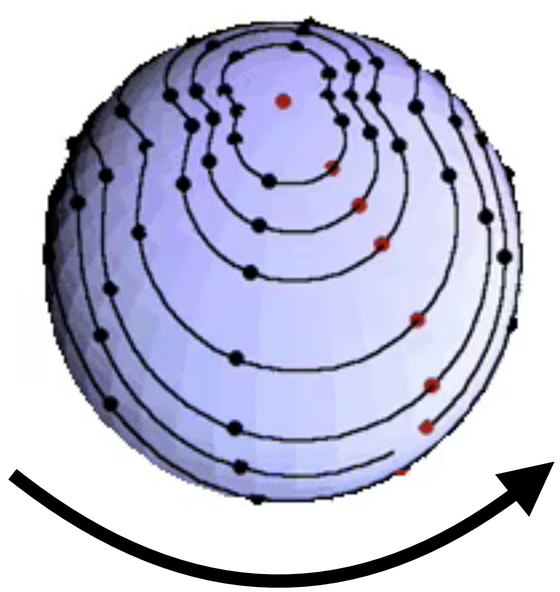
Abbott et al., arXiv:2201.10104 (2022)

The r-mode instability

(Animation by Ben Owen)



Rotating observer



Inertial observer

How do young, hot and rapidly rotating NSs spin down?

GW emission? [Andersson et al. 1999, Alford & Schwenzer 2014]

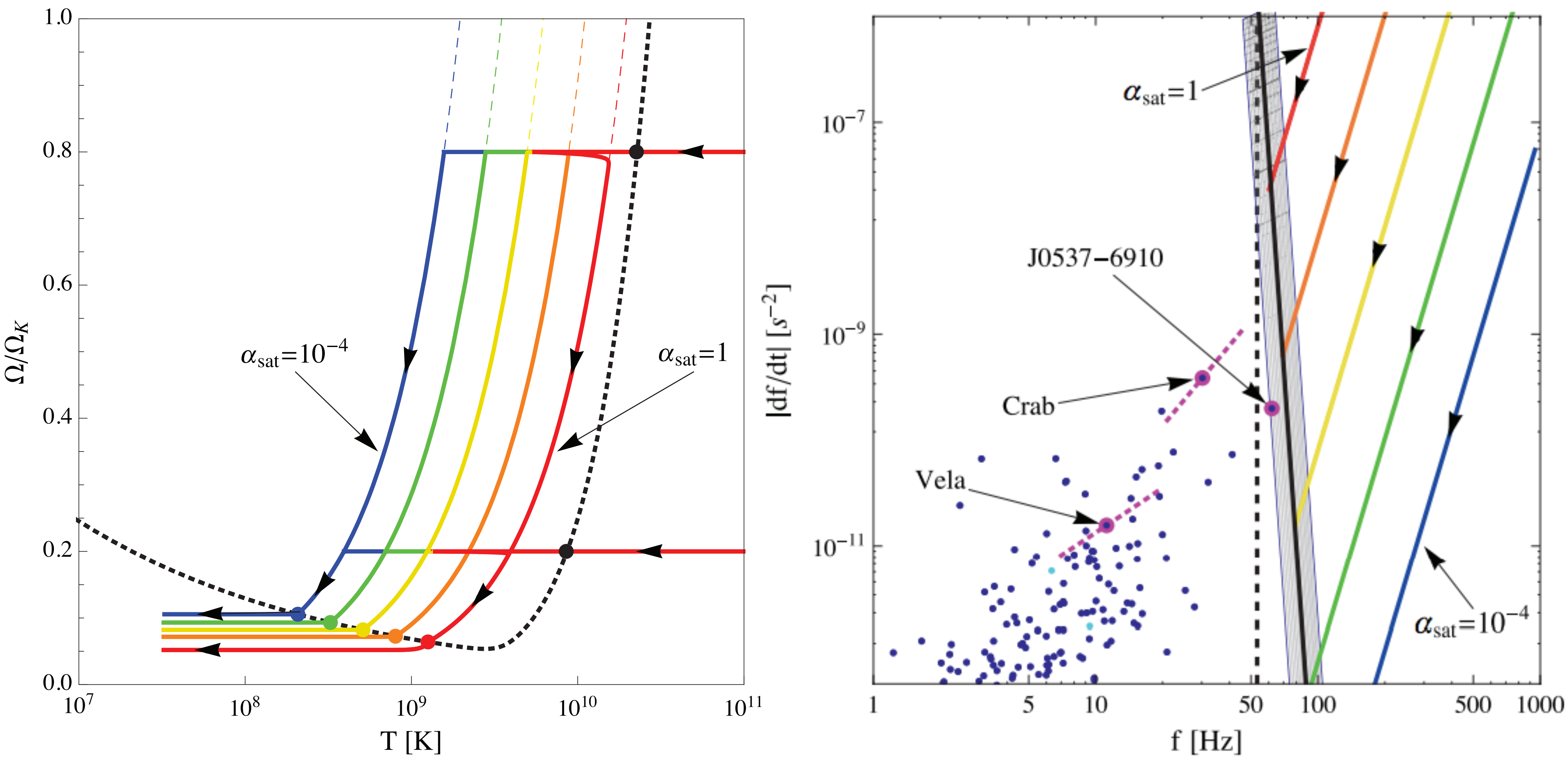
The r-mode instability could be responsible

- r-mode unstable to GW emission
- Emission at $\omega \approx \frac{4}{3}\Omega$
- Viscosity damps the mode except in a window of temperatures and frequencies

[Andersson 1998, Friedman & Morsink 1998]

Newly born NSs

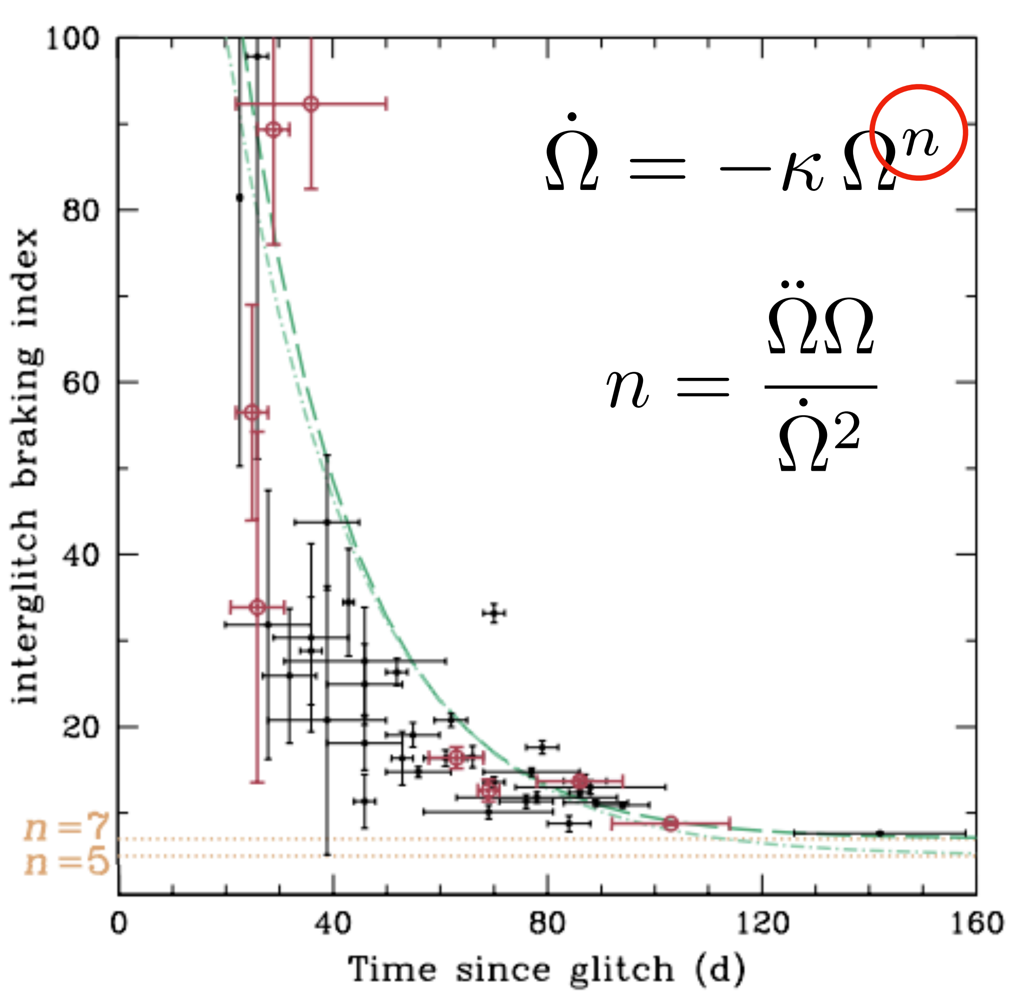
- r-modes may spin down young NS to the current pulsar periods
  [Andersson et al. 1999, Alford & Schwenzer 2014]



[from Alford & Schwenzer 2014]

Newly born NSs

- **Andersson et al. (2018), Ferdman et al. (2018)** studied n between glitches
- far from glitches there is evidence for n=7 ⟶ constant amplitude r-mode
- a similar conclusions by **Ho et al. (2020)** with NICER data



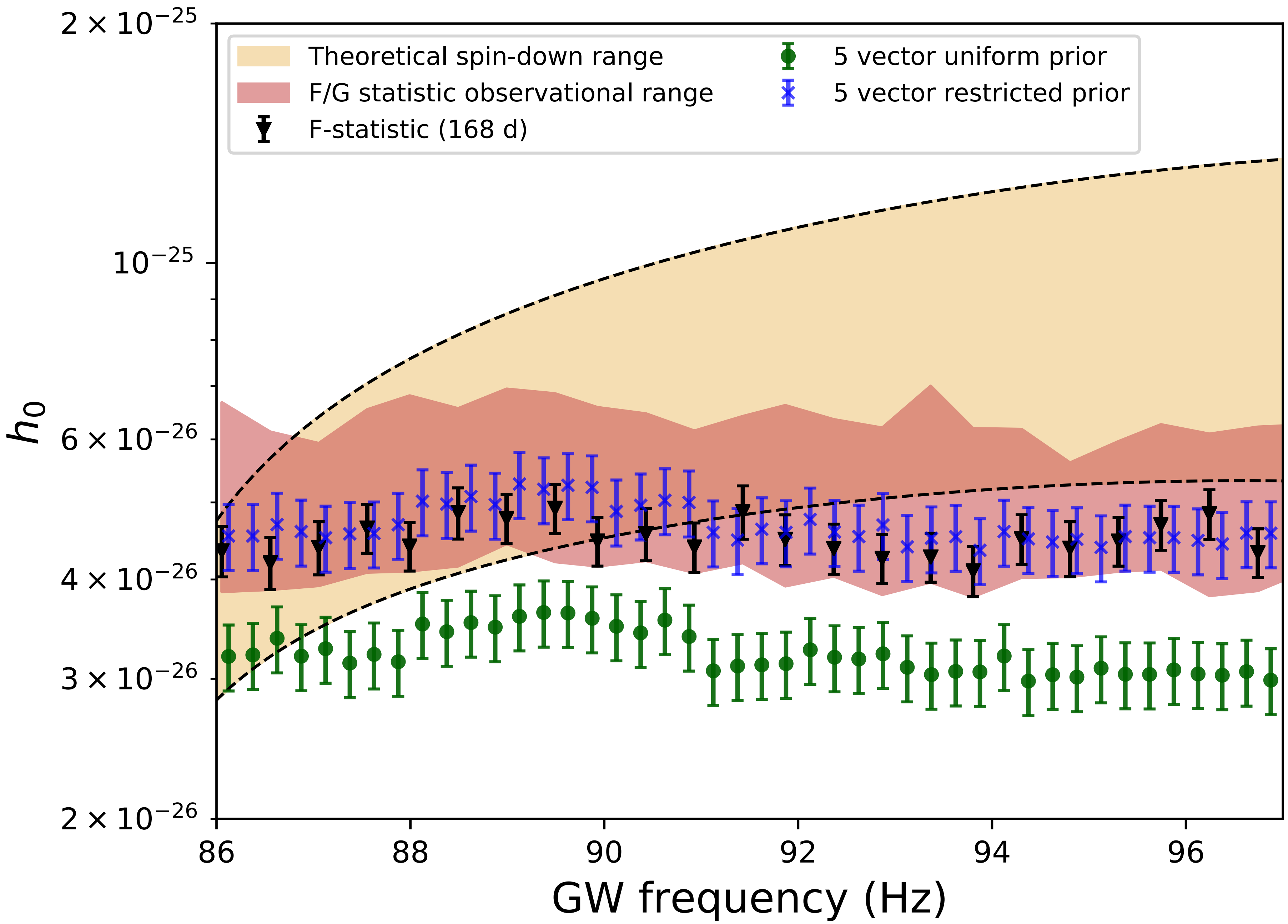
[from Abbott et al. 2020]

- First searches in GW data from O1 and O2 **(Fesik & Papa 2020)** were not quite sensitive enough…new search with O3 data probes this scenario!
- Search for emission from mountains constrains n=5 emission to less than 14% of the energy budget

Abbott et al., ApJL. 913, L27 (2021)

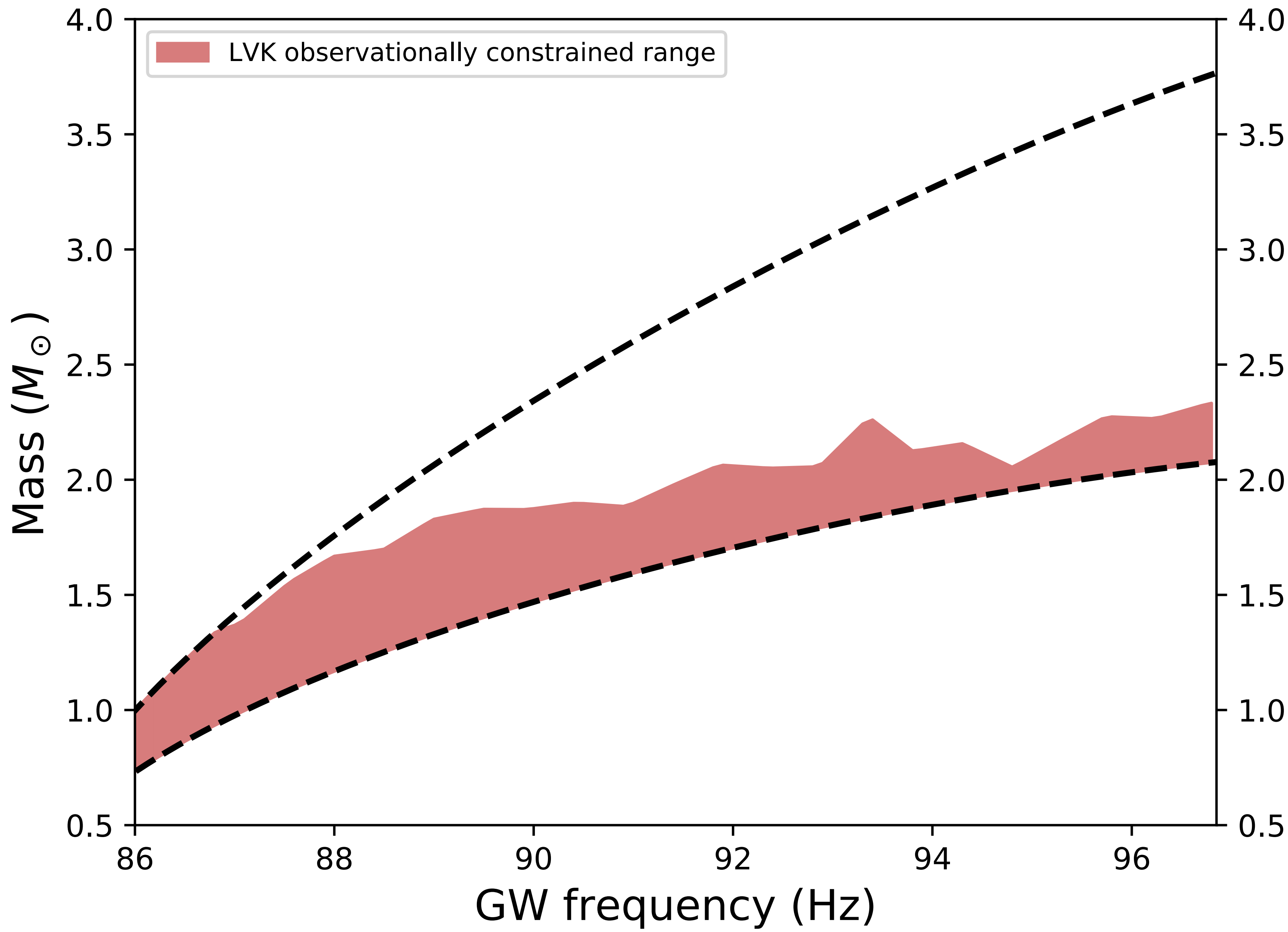
Results - Astrophysical constraints

- The O3 searches are digging well into the theoretical parameter space for the model, and below the spin-down limit! **Abbott et al., ApJ. 922, 71 (2021)**



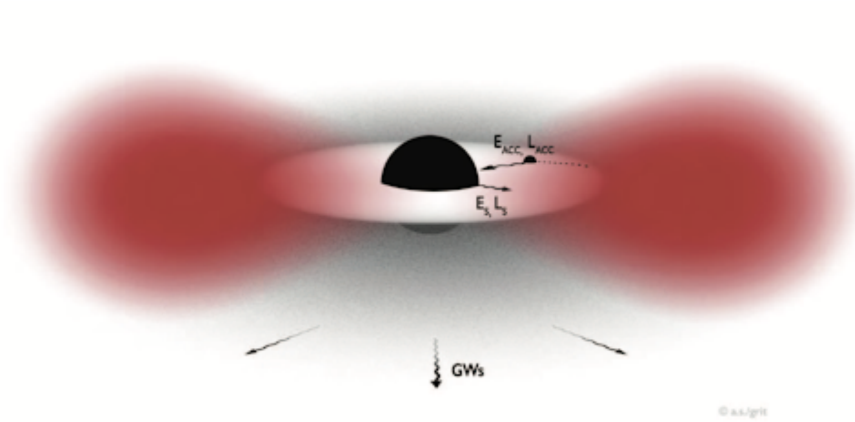
Results - Astrophysical constraints

- We constrain the range of masses and EoS consistent with r-mode emission leading to the observed n=7 braking index **Abbott et al., ApJ. 922, 71 (2021)**



Beyond NSs: dark matter searches

- CW searches can probe astrophysical signals due to dark matter candidates
- One example are clouds of ultralight bosons around rotating BHs

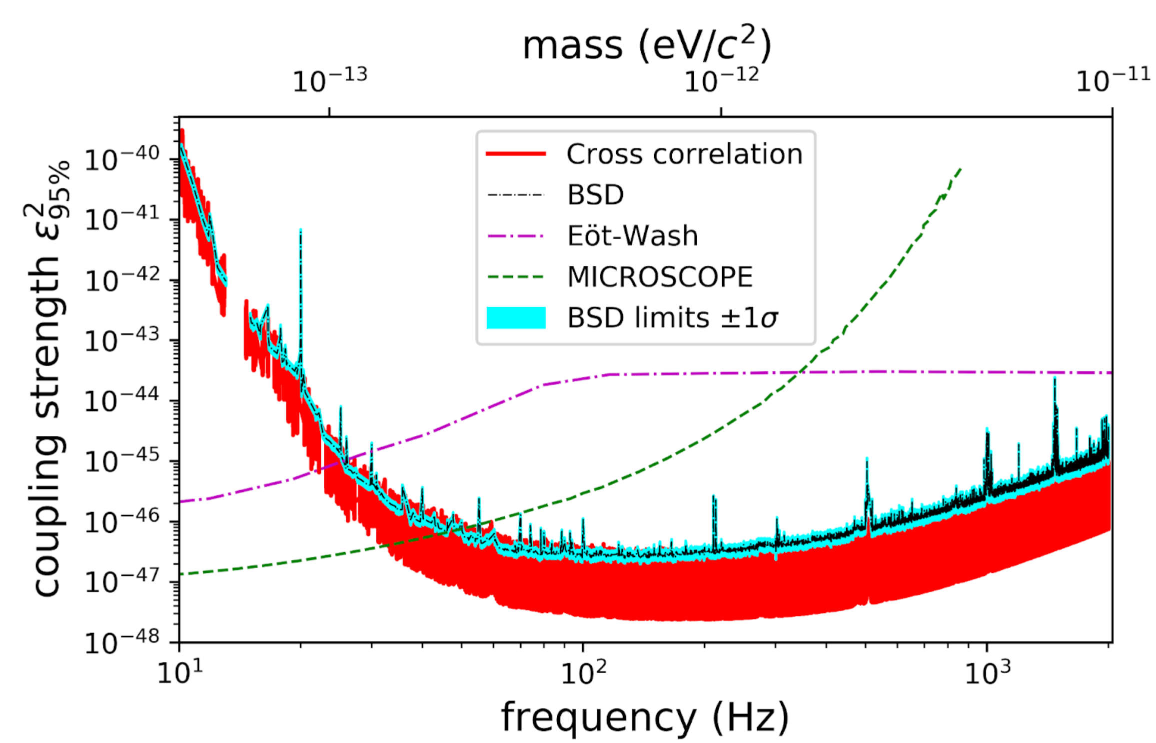


Abbott et al., Phys. Rev. D **105**, 102001 (2022)

- Also sensitive to binaries of planetary mass primordial BHs

- Dark matter particles can interact with the detector (e.g. ultralight vector particles - dark photons can couple to photons)
- Competitive with other experiments

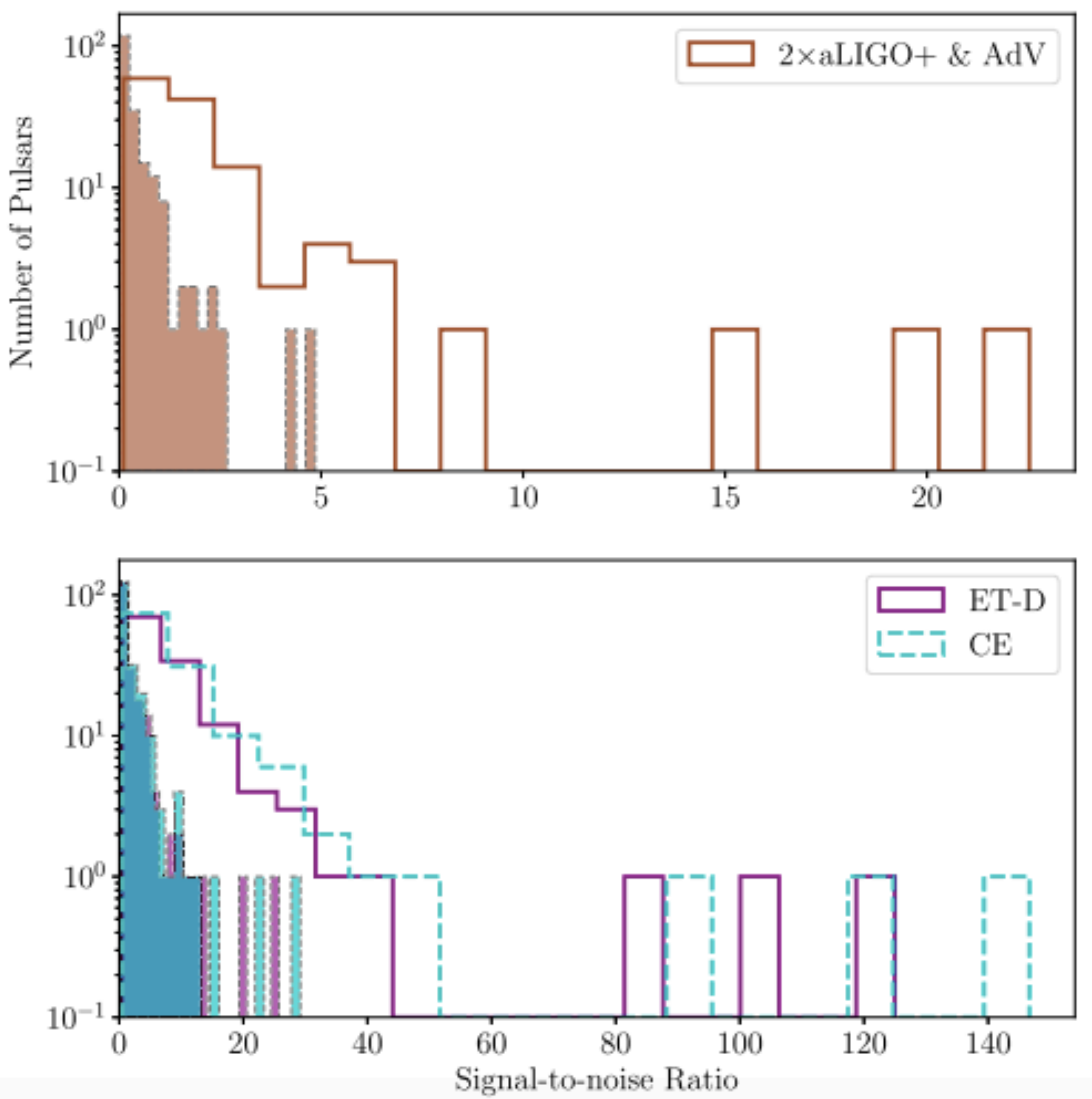
Abbott et al., Phys. Rev. D **105**, 063030 (2022)



Future constraints

- Einstein Telescope (ET) and LIGO Cosmic Explorer can probe much deeper, e.g. allowing to test realistic ellipticities, but also search e.g. for a <u>minimum</u> ellipticity in the population of pulsars

(Woan, Pitkin, BH, Jones & Lasky 2018)



- <u>How do we understand what we are seeing?</u>

$$n = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$$ **(n=5 mountain, n=7 r-mode)**

- EM counterparts (cyclotron lines for magnetic mountains, flux variations for compositional mountains) (BH et al. 2015)

Conclusions

- Compact binary coalescence detections are now commonplace - GW astronomy of these source has begun, allowing also for NS EoS constraints.

- A CW detection is still elusive - but our sensitivity is now starting to probe theoretically relevant parameter space. We look forward to O4.

- Theoretical work needed on models, to extract astrophysical parameters and fundamental physics constraints from the data in the next runs and prepare for ET.