Probing high density physics in the gravitational wave astronomy era

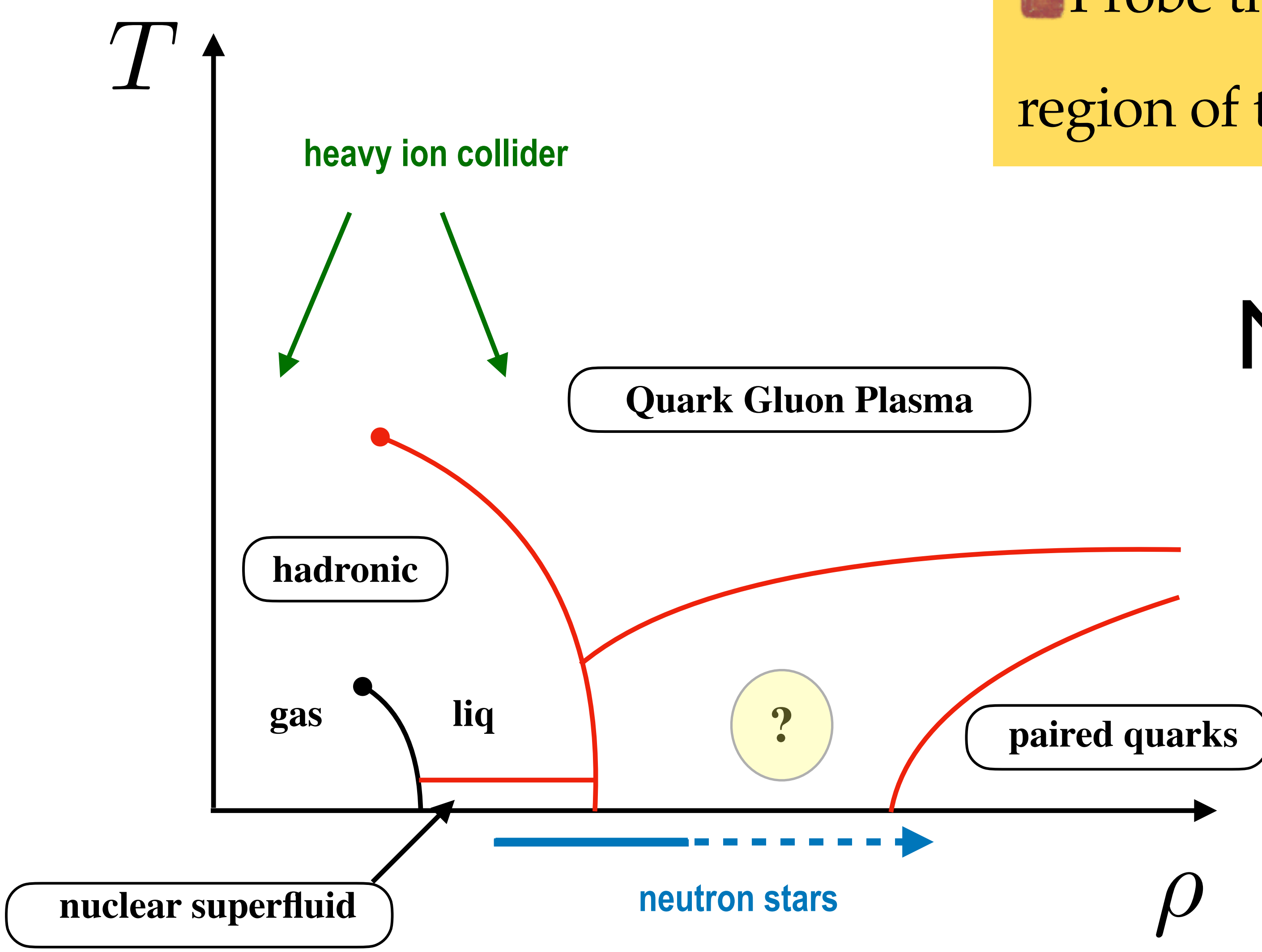
Brynmor Haskell

Polish Academy of Sciences
Nicolaus Copernicus Astronomical Center

LSC LIGO Scientific Collaboration
VIRGO

Neutron Stars - theoretical importance

What is the Equation of State of dense matter?



Probe the low-temperature high-density region of the QCD phase diagram!

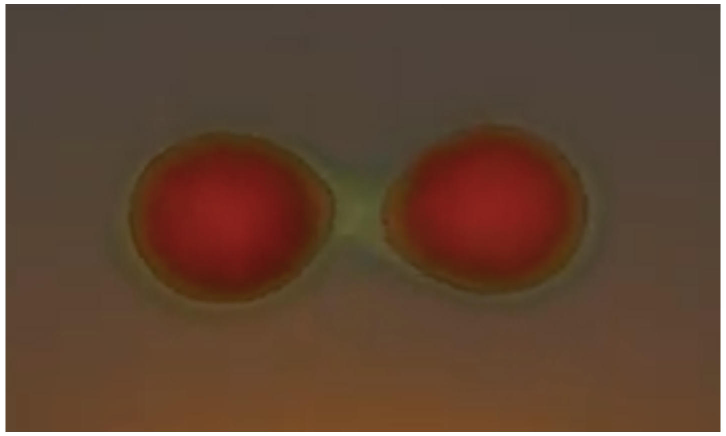
Neutron Stars are cold

$$T \approx 1 \ \ \mathrm{keV}$$

$$E_{\mathbf{Fermi}} \approx 50 \ \ \mathrm{MeV}$$

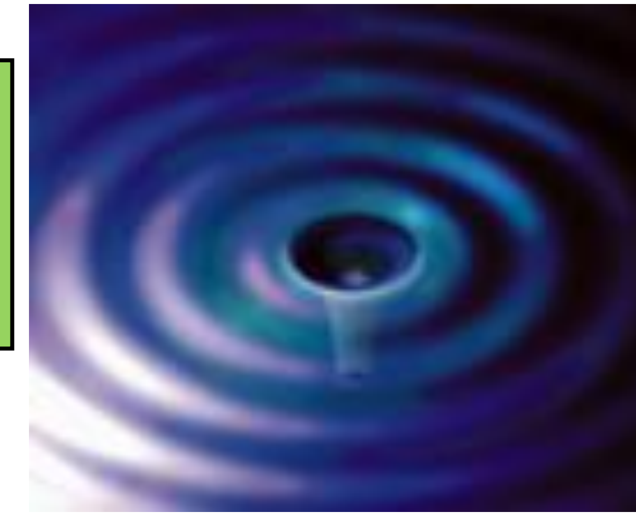
(see Haskell & Sedrakian 2018 for a review)

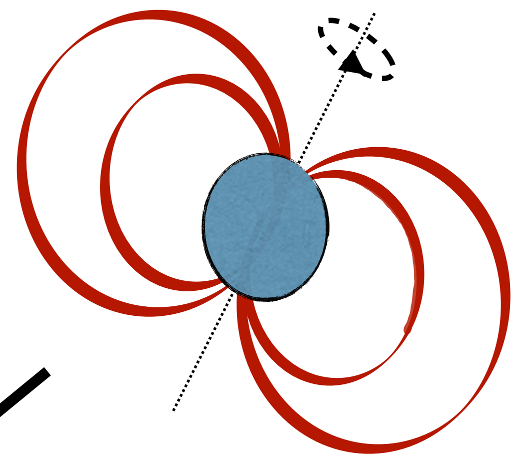
Neutron Stars - astrophysical laboratories

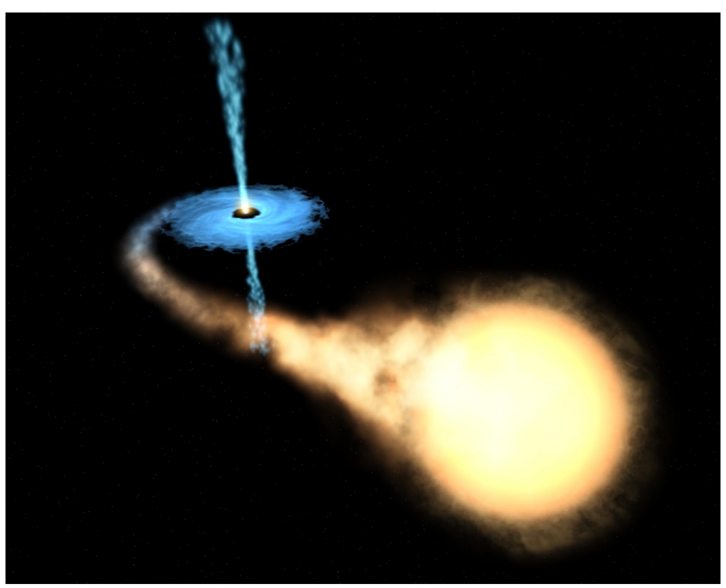


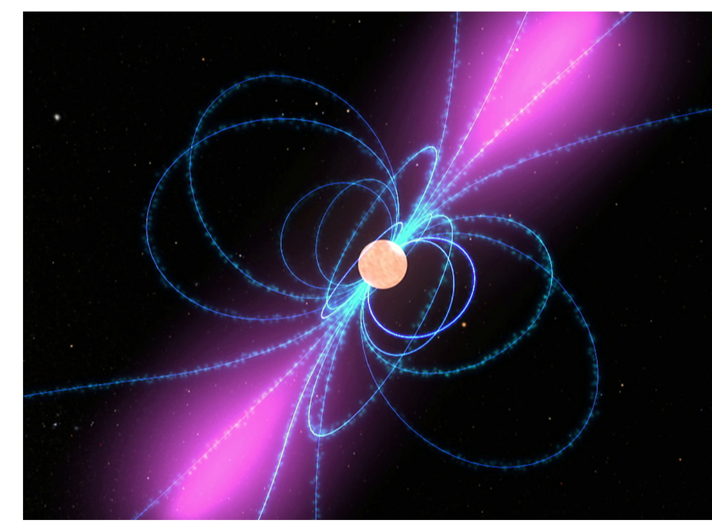
GW170817

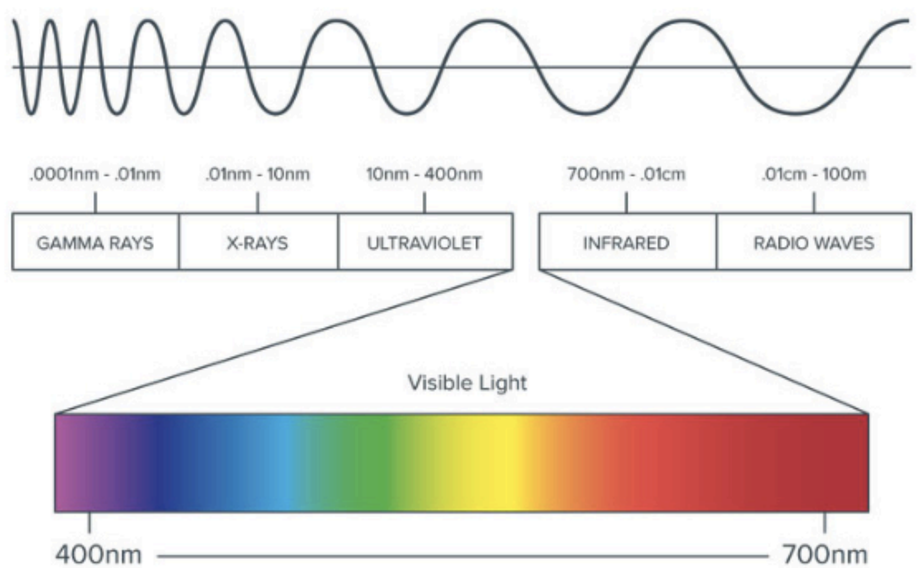
Gravitational waves







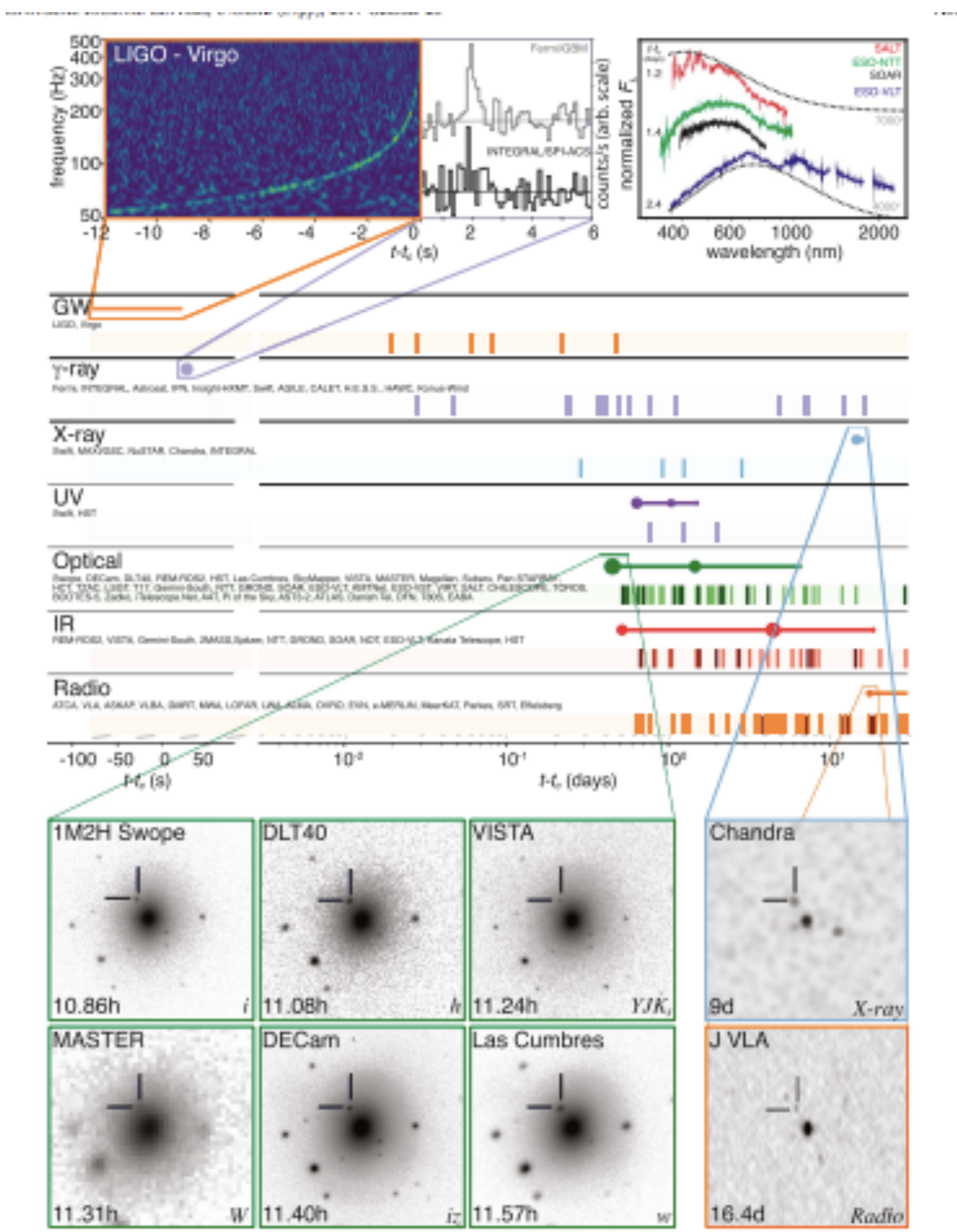


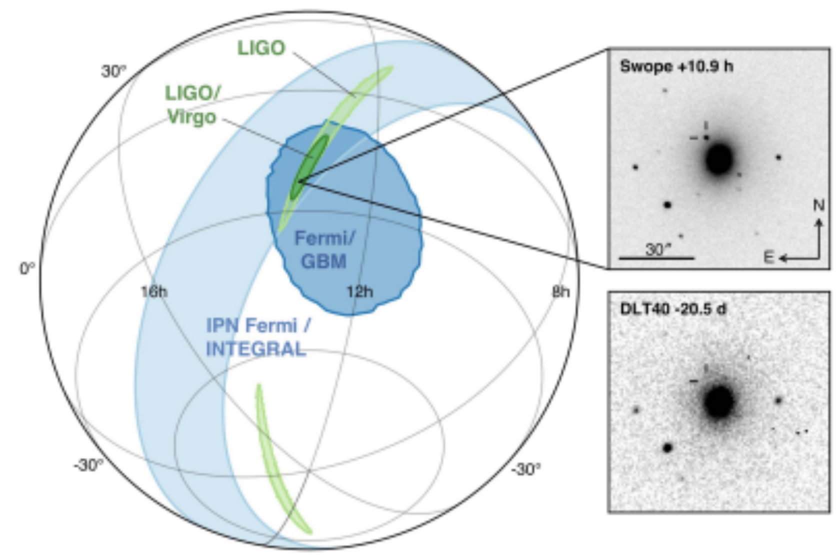


Neutrinos?

Electromagnetic waves

Observing NSs in gravitational waves





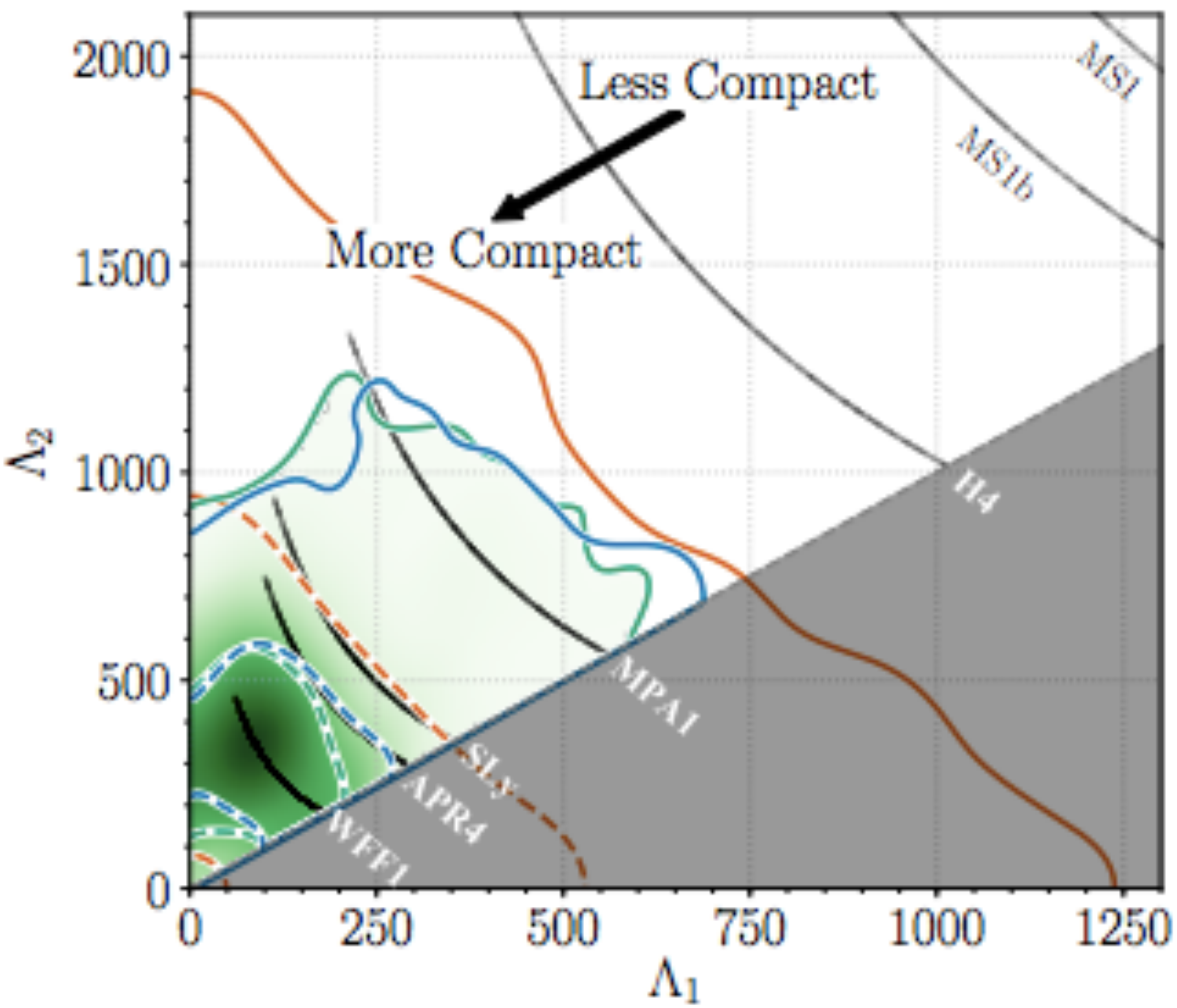
GW170817

(Abbott et al. 2017, ApJ Lett. 848, L12)

- NS-NS merger
- Confirmed by Multimessenger observations
- GRB detected - confirmation of models
- Kilonova emission detected, heavy element production models tested

Tidal deformability

- Higher order Post Newtonian (v/c) corrections can be measured, and constrain the tidal deformability of the stars



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(Abbott et al. 2017, PRL 119, 161101)

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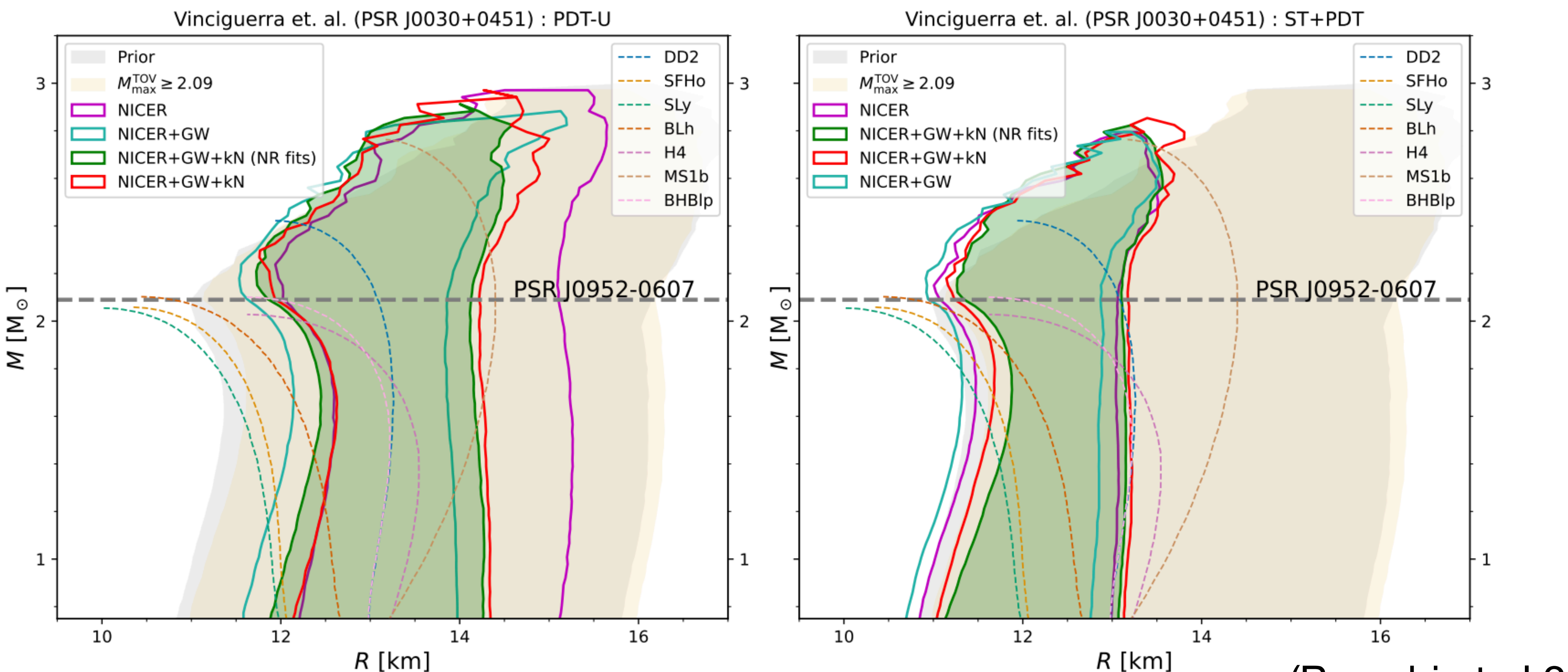
Multimessenger constraints - EOS of dense matter



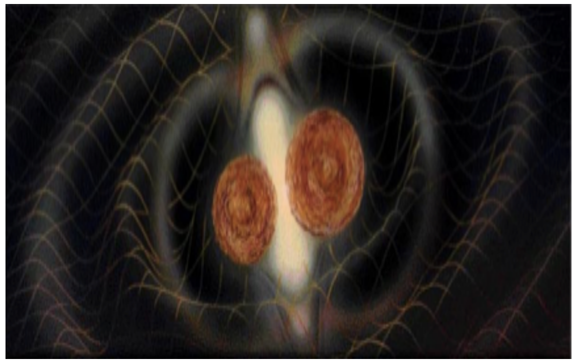
(Breschi et al 2024)

- Neutron star maximum mass (from binaries) → **Radio**
- Constraints on radii of some systems by NICER → **X-ray**
- Tidal deformability from binary mergers → **GWs**

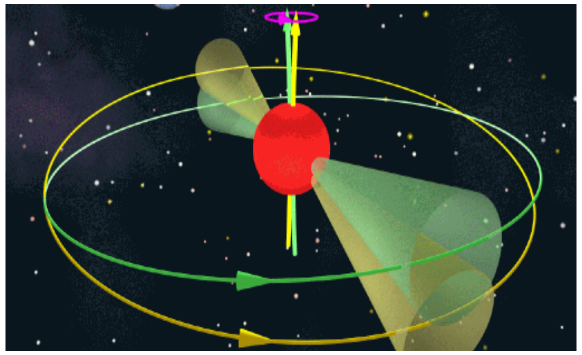
Constraints also from BH-NS binaries (Abac et al 2024)

Beyond binary coalescences…

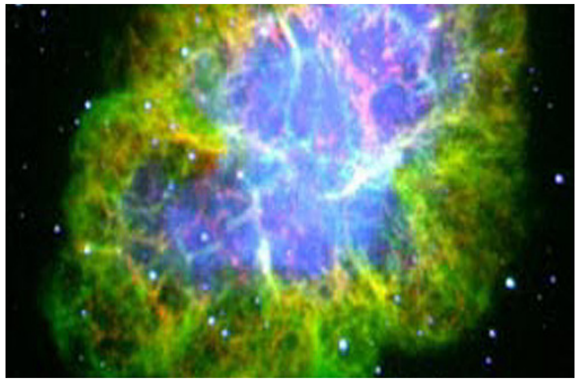
"chirps" (Compact binary inspirals)



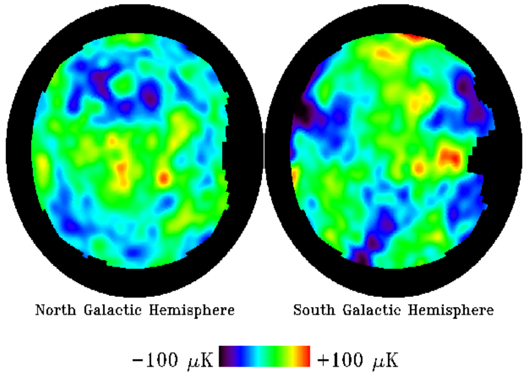
"continuous" (GW pulsars, asteroseismology)



"bursts" (Magnetar flares, Supernovae,…)

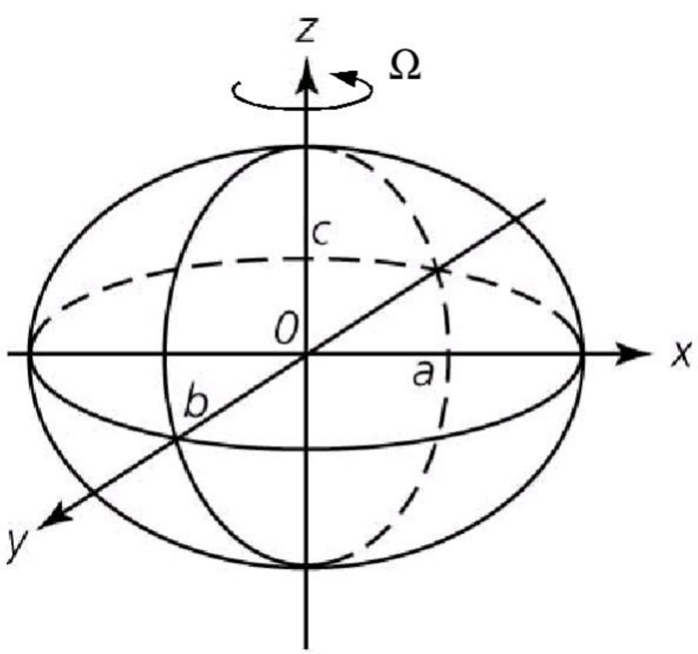


"stochastic" (Cosmological signals)



Emission mechanisms for isolated NSs

Mountains



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

- From theory

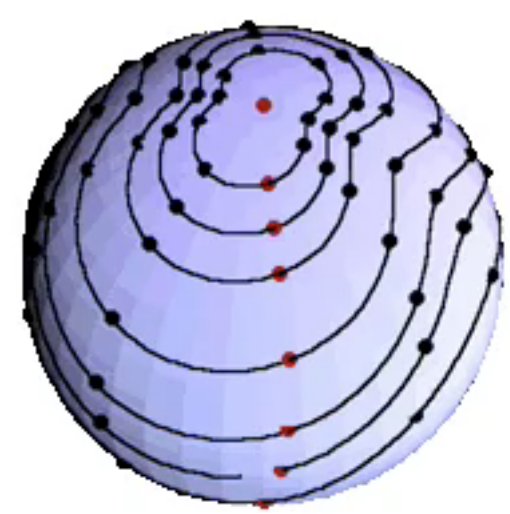
$$\epsilon_{\max} \approx 10^{-6} \left(\frac{\sigma_{br}}{10^{-2}} \right)$$

- …for an exotic cristalline core:

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

Modes of oscillation

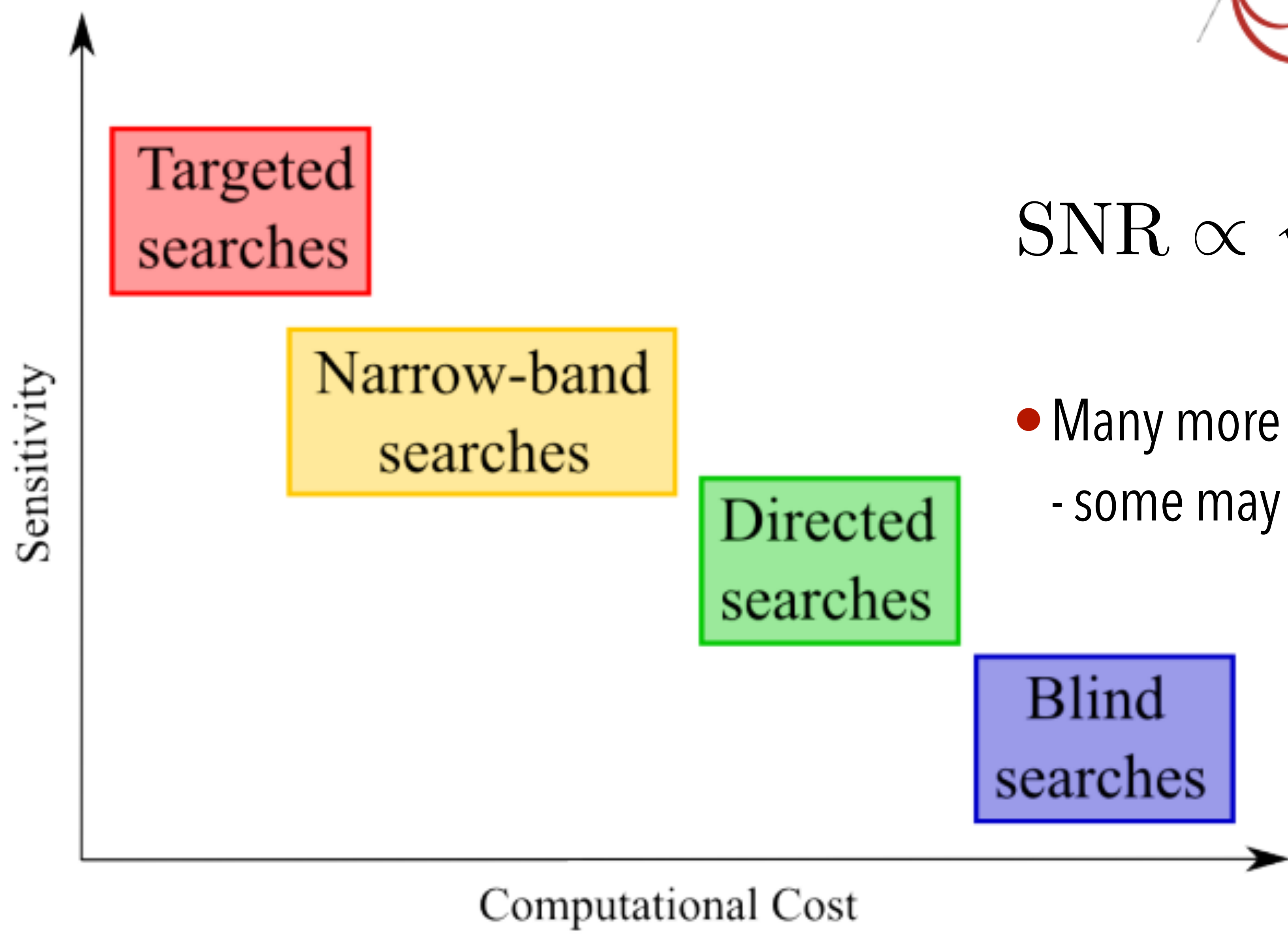
- Oscillations in the fluid couple to the gravitational field
- Main candidates **f** and **r** modes
- Emission at the mode frequency



(See BH & Schwenzer 2022 for a review)

CW searches

- Searches are computationally limited - the more one can restrict parameter space the deeper the search
- EM observations help obtain deeper searches
- Current GW searches sensitive to NS in our galaxy



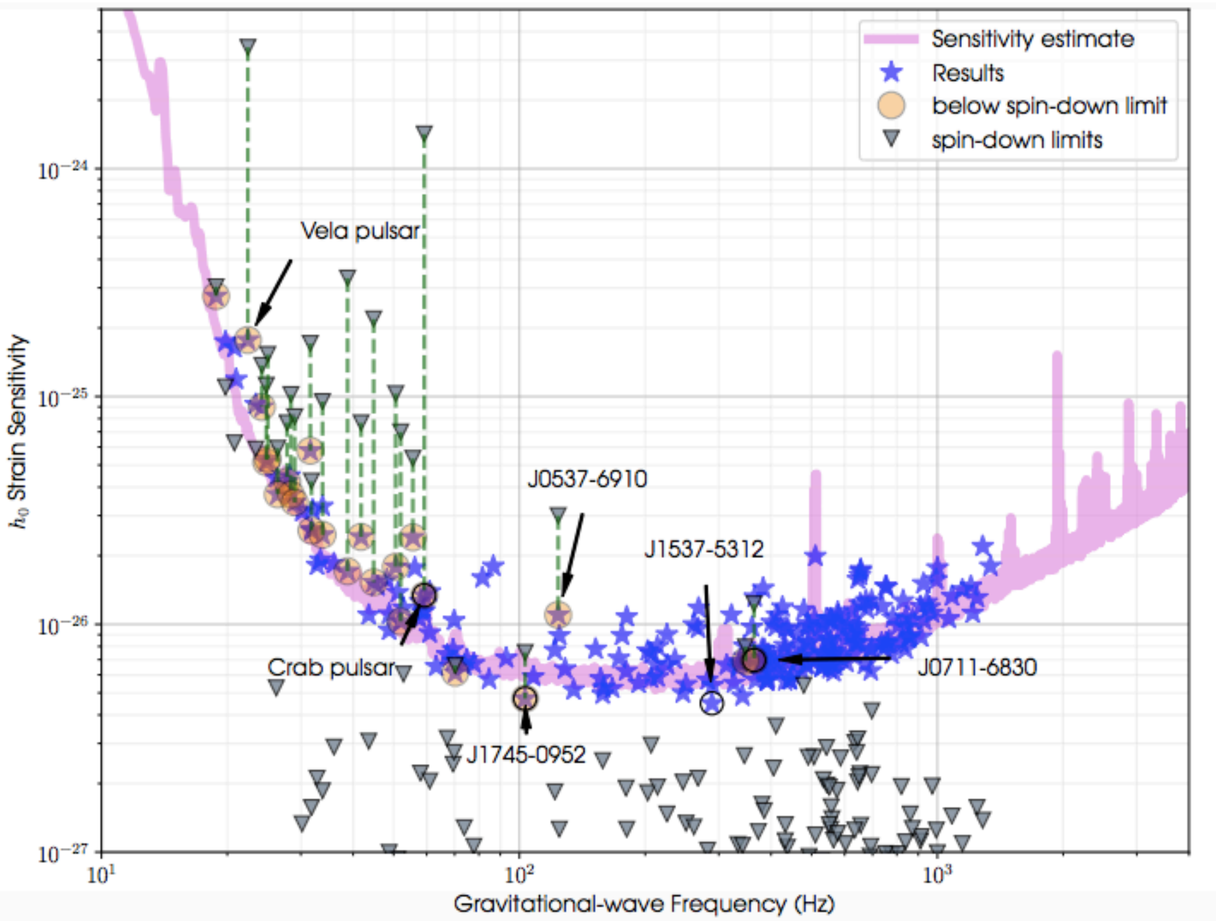
$$\mathrm{SNR} \propto \sqrt{T_{obs}}$$

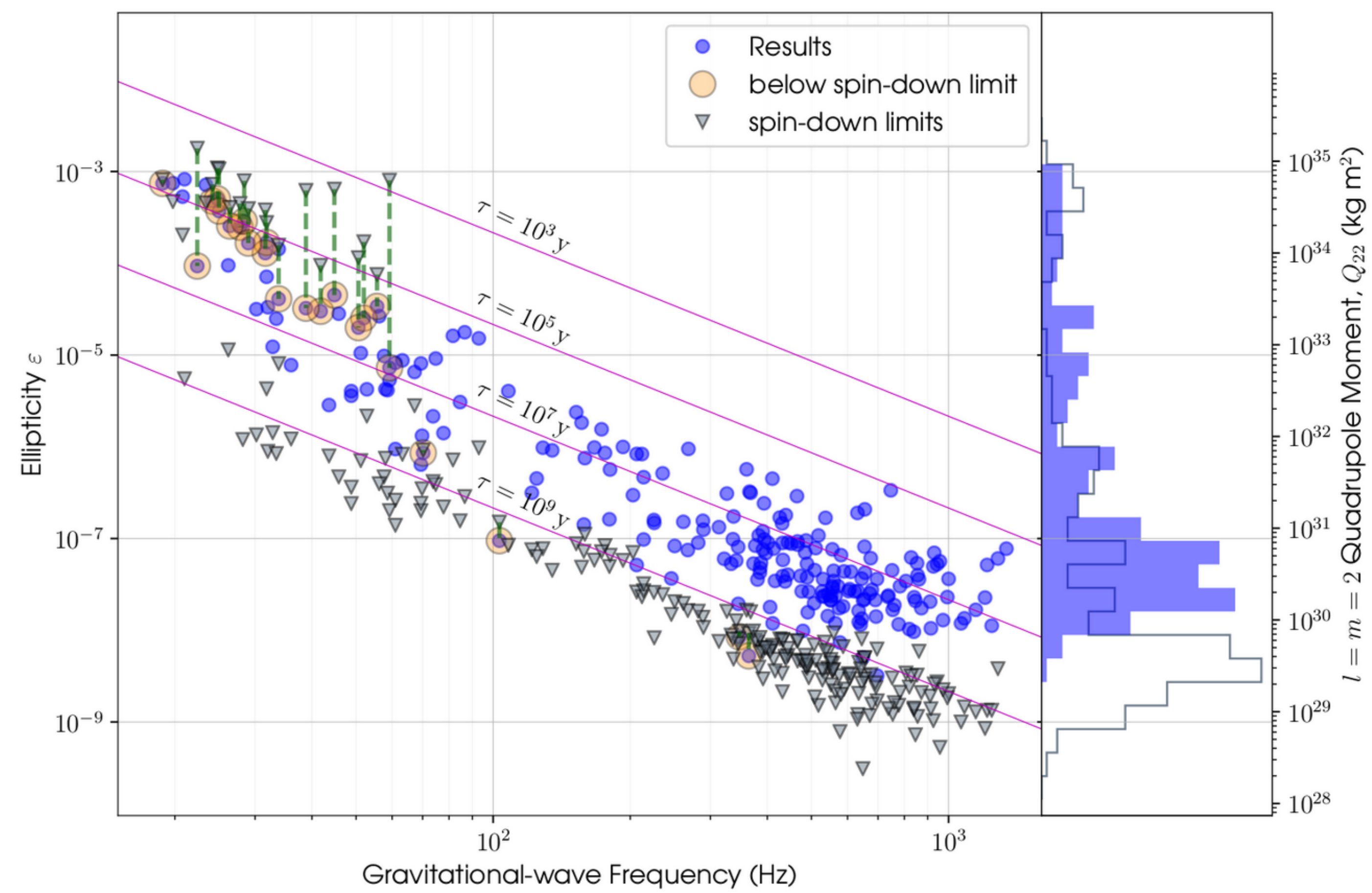
- Many more NS in our galaxy than those we see - some may be `gravitars'

Example: searching for known pulsars in O3

Abbott et al. ApJ 935, 1 (2022)

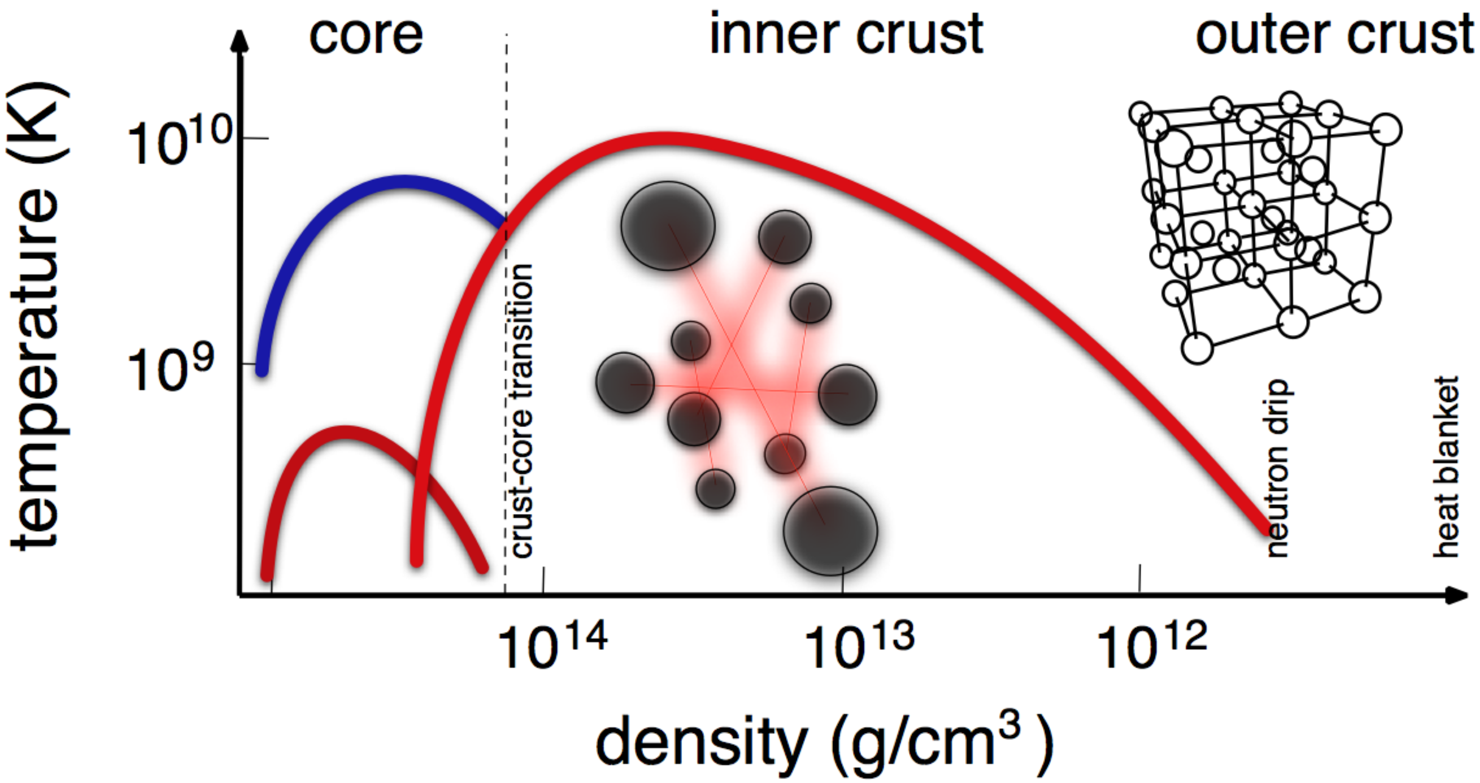
Abbott et al. Phys. Rev. D 105, 022002 (2022)

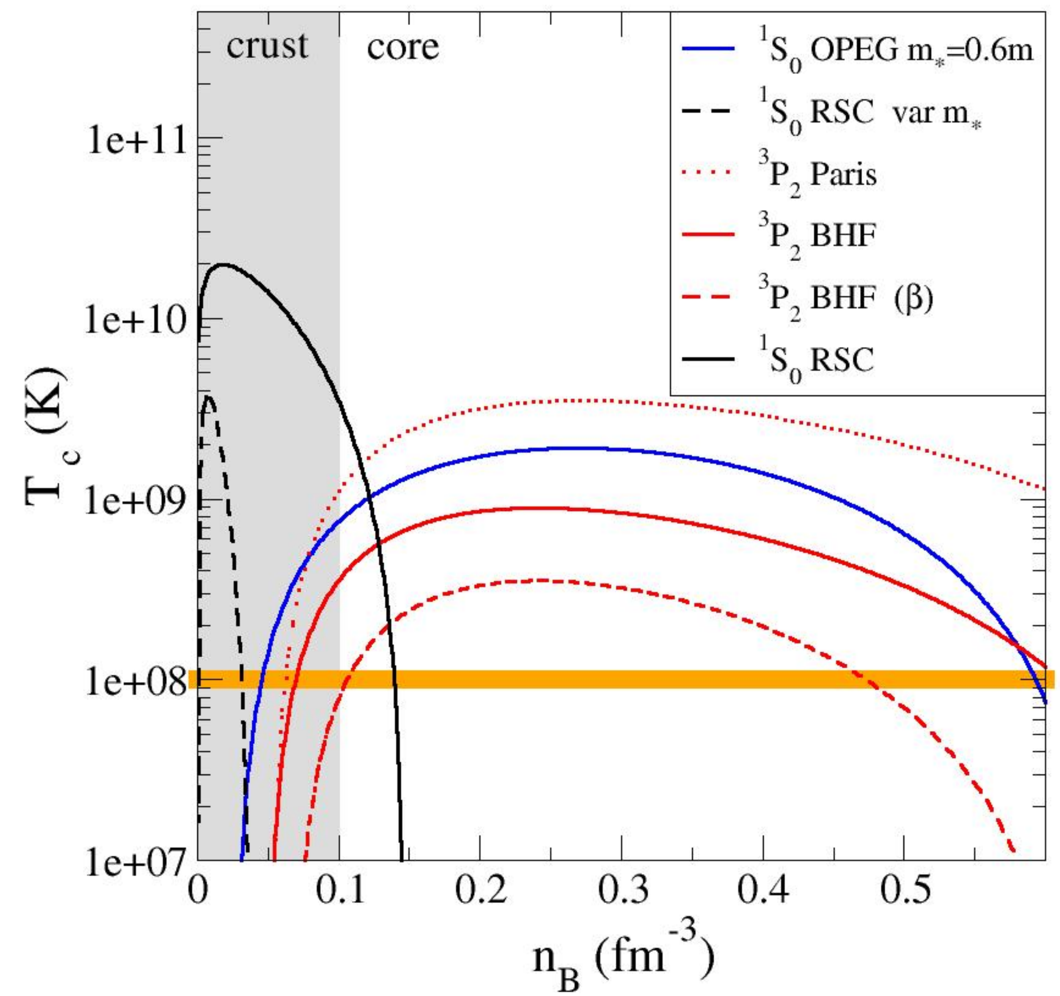




- No signal detected in current O3 searches, upper limits derived
- Energy emitted in GWs constrained for some pulsars
- Improvements in sensitivity needed to probe full range of models

Superfluids in neutron stars





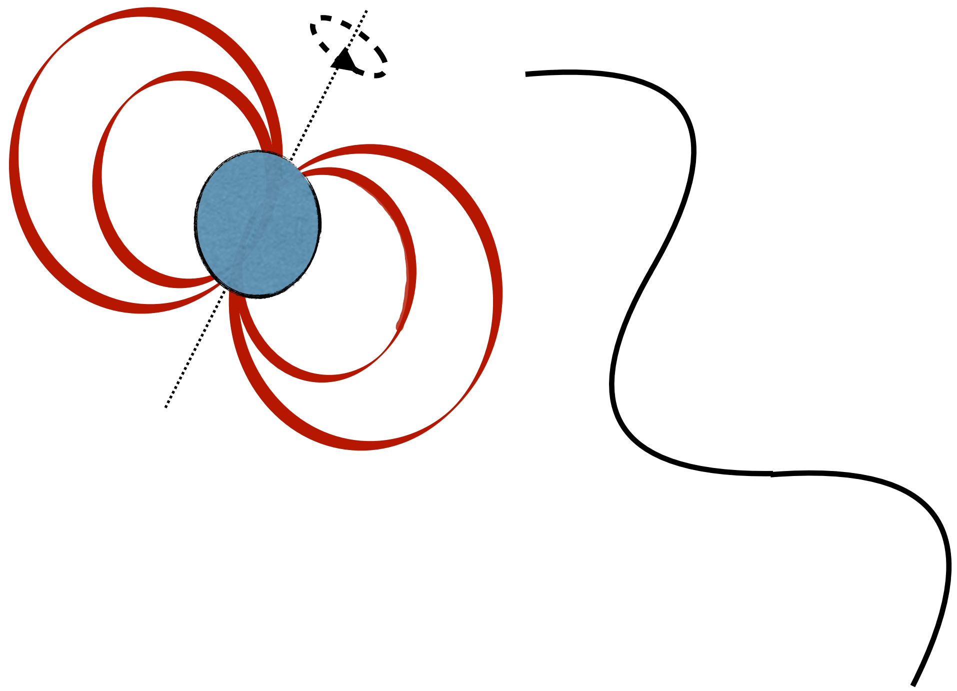
(courtesy of Nils Andersson)

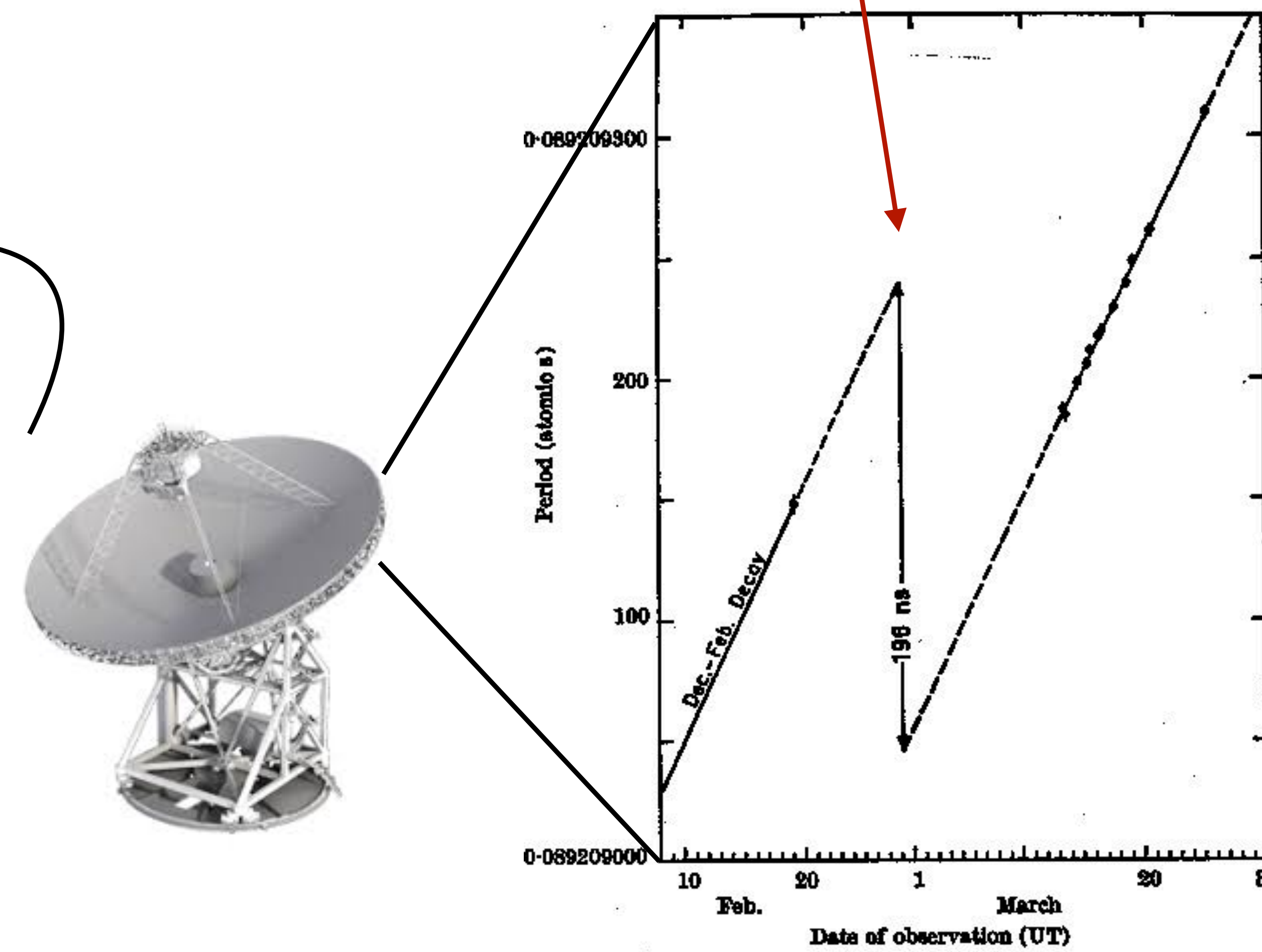
- Pairing calculations confirm that mature neutron stars are expected to be superfluid

(see Haskell & Sedrakian 2018 for a review)

Pulsar glitches: probing superfluids at high density

First Vela glitch 1969

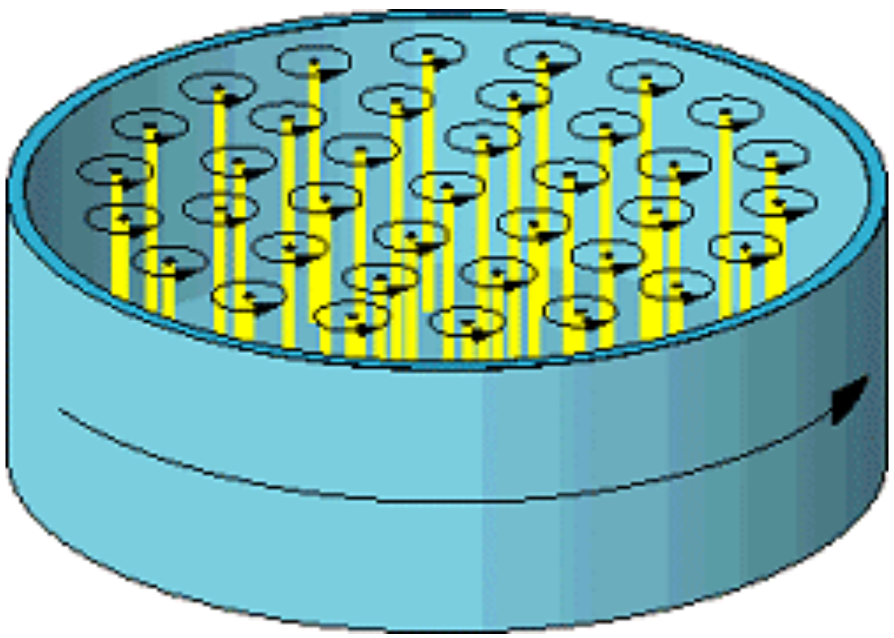




- Time of Arrival (TOA) registered for each pulse
- Pulsar spins down due to the emission of EM (and GW?) radiation

(see Antonopoulou, BH & Espinoza, 2022 for a review)

What is happening?



- Superfluids rotate by forming quantised vortices
- Vortex density determines spin : vortices must move out to spin down the fluid!

MoI of superfluid reservoir

Depends on Entrainment!

[Chamel 2012]

Observed

$$\Delta\Omega = \frac{I_n}{I_T}(\Omega_{\rm n} - \Omega_{\rm p})$$

Internal lag before the glitch

Depends on pinning force

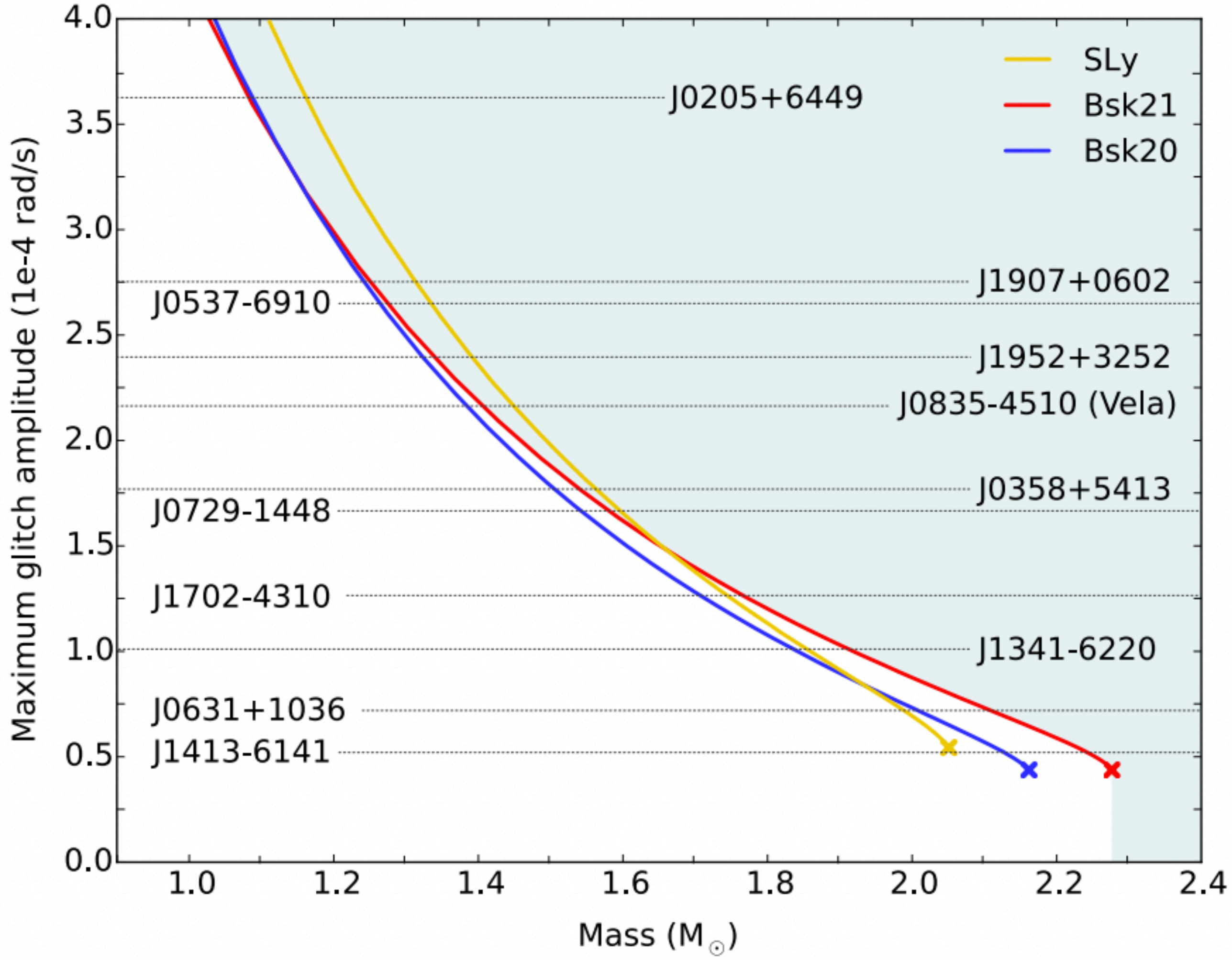
Magnus Force

$$\text{FREE} : \quad \boxed{\epsilon^{ijk}\hat{k}_j(v_k^{\rm v} - v_k^{\rm n})} + \mathcal{R}(v_p^i - v_{\rm v}^i) = 0$$

$$\text{PINNED} : \quad \epsilon^{ijk}\hat{k}_j(v_k^{\rm v} - v_k^{\rm n}) + F_{\rm p}^i = 0$$

Measuring masses

- From the angular momentum reservoir we can obtain an upper limit on the NS mass



- Need a model for the pinning force and superfluid gaps
- Results model dependent
- A mass measurement could constrain the gap model and EoS

[Pizzochero, Antonelli, BH & Seveso (2017)]
[Ho et al. (2015)]

GWs from pulsar glitches

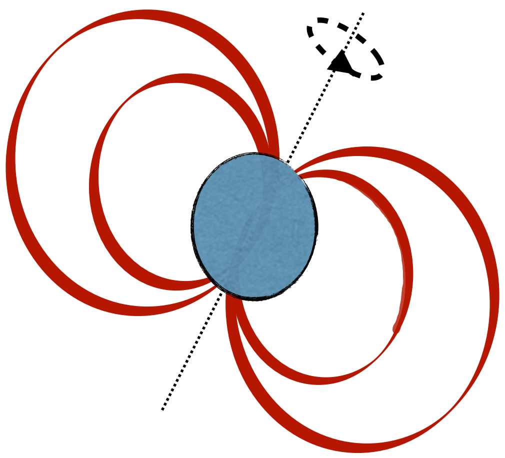
- GW signals possible, both bursts from the rise, and CWs from the post-glitch phase

  [For a review see BH & Jones (2024)]

- One of the most studied targets is the Vela pulsar: (PSR J0835–4510) - large glitches roughly every 3 years

- Searches for GWs carried out after the 2006 glitch (Abadie et al. 2011) and the 2016 glitch (Keitel et al. 2019). No signal was detected, constraints were placed

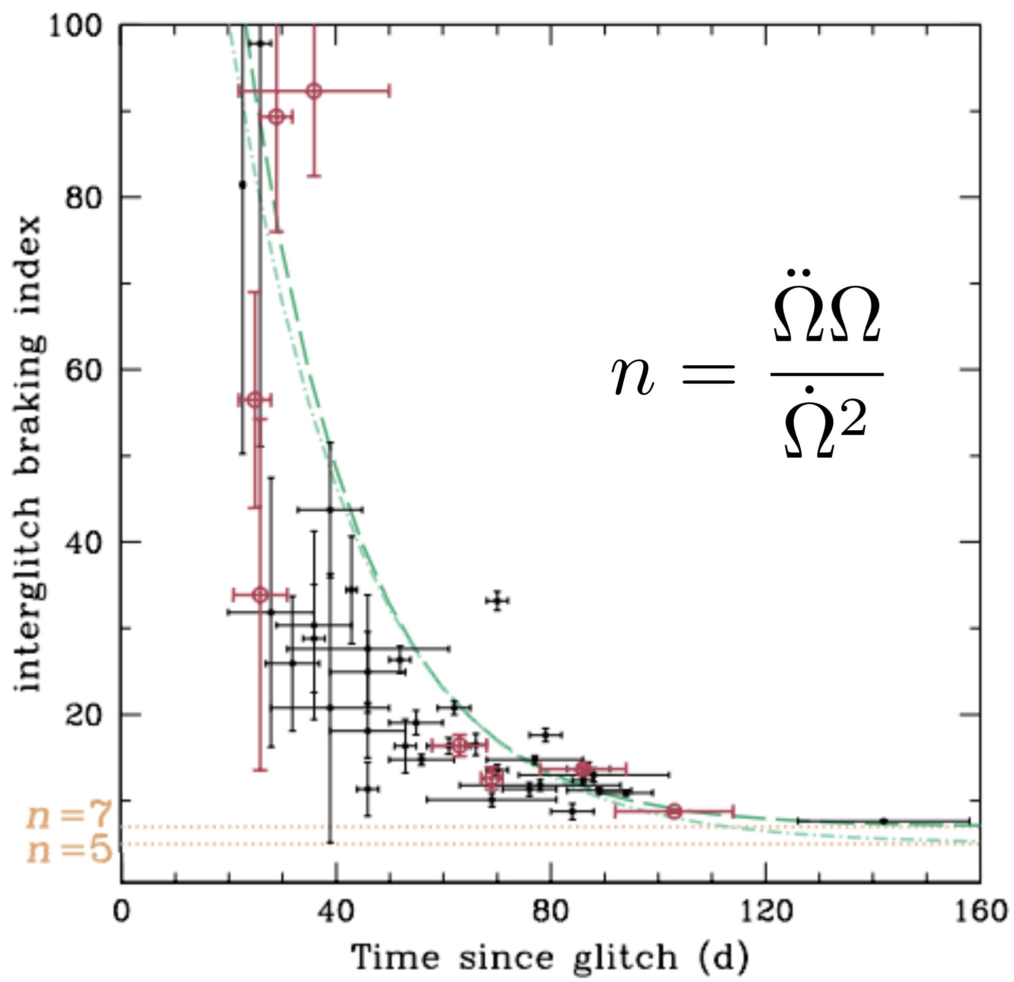
- The Vela has glitched this year, during the O4 run!



Newly born neutron stars - J0537-6910

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

$$\boxed{\dot{\Omega} \propto \Omega^n}$$



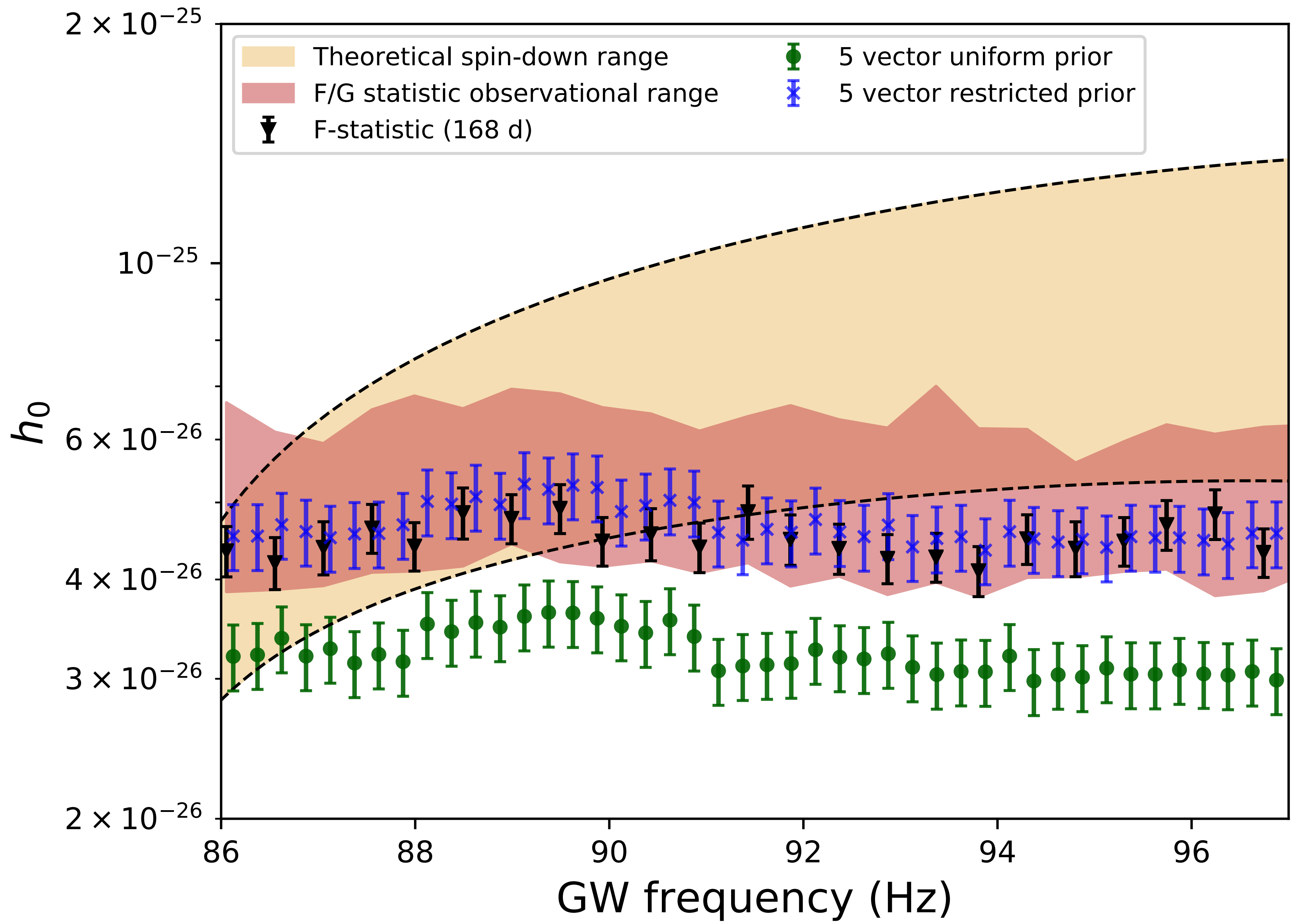
$$n = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$$

[from Abbott et al. ApJ Lett. 913, L27, (2021)]

- 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!

Results - Astrophysical constraints

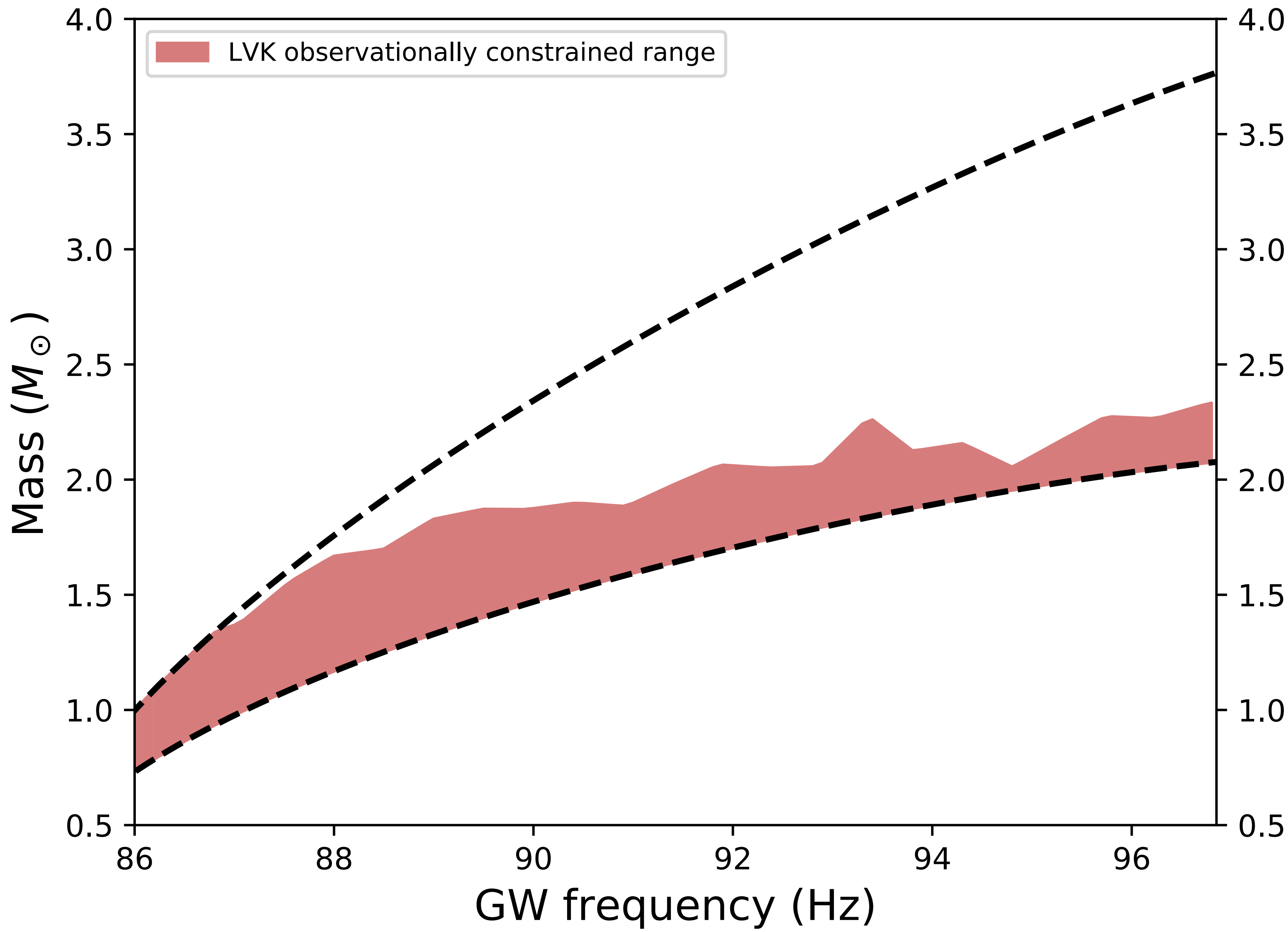
- The searches are digging well into the theoretical parameter space for the model, and below the spin-down limit! **Abbott et al. ApJ. 922, 71 (2021)**



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)



Conclusions

- Fourth observing run of the LVK (O4) is ongoing
- Future instruments planned (SKA, Athena, SVOM, IceCube-Gen2, Hyper-K, PINGU, ET, Cosmic Explorer, CTA, AugerPrime, eLISA…and more…)
- Compact binary coalescence detections are now commonplace - multi messenger observations are possible (also neutrino detection?)
- A CW detection is still elusive - but the sensitivity of the instruments allows to probe theoretically relevant parameter space. O4 ongoing, stay tuned!
- Terrestrial nuclear physics experiments can provide additional 'messengers'