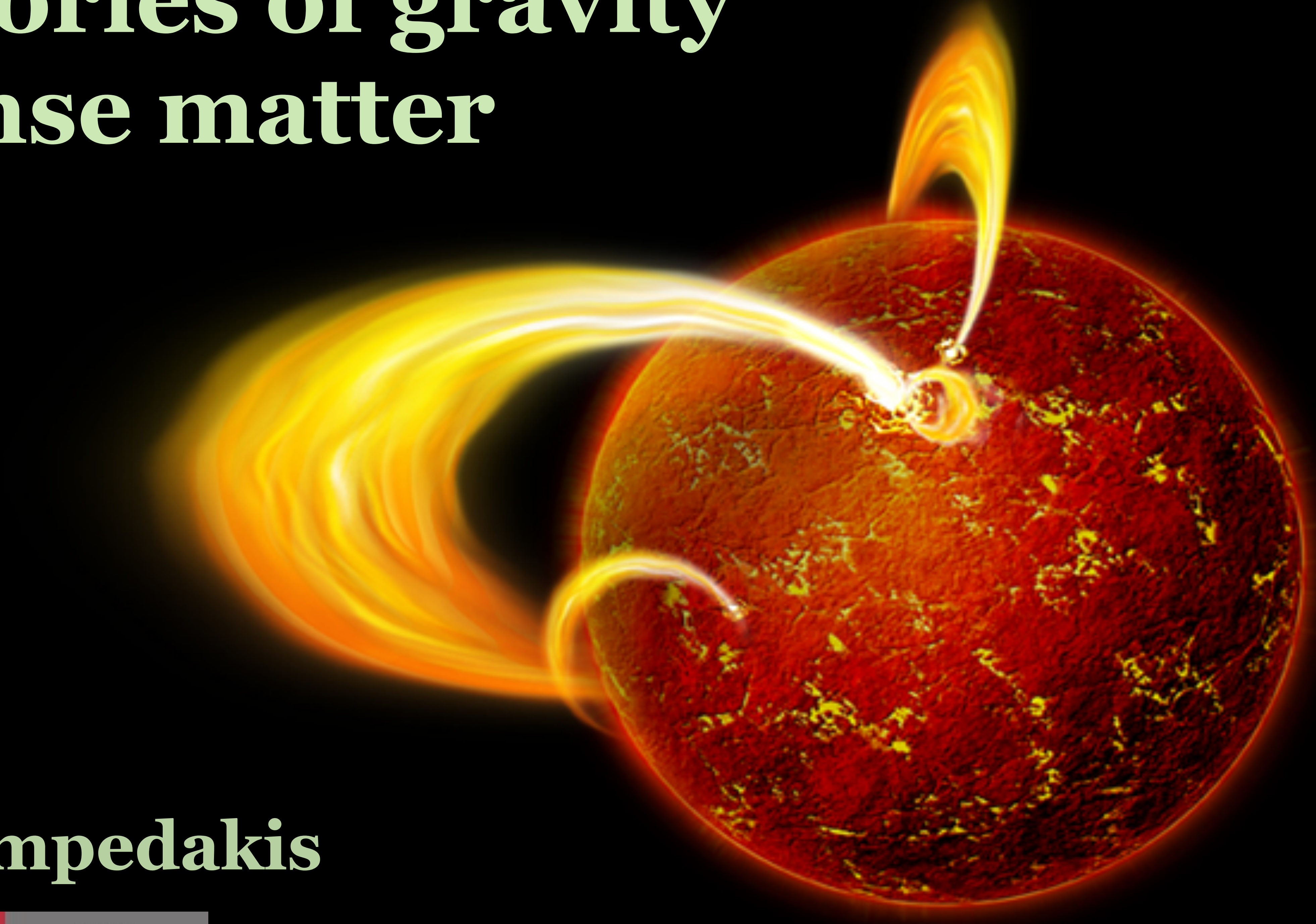
Neutron stars: cosmic laboratories of gravity and dense matter



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This talk

- We highlight some recent progress in key topics of neutron star (astro)-physics:

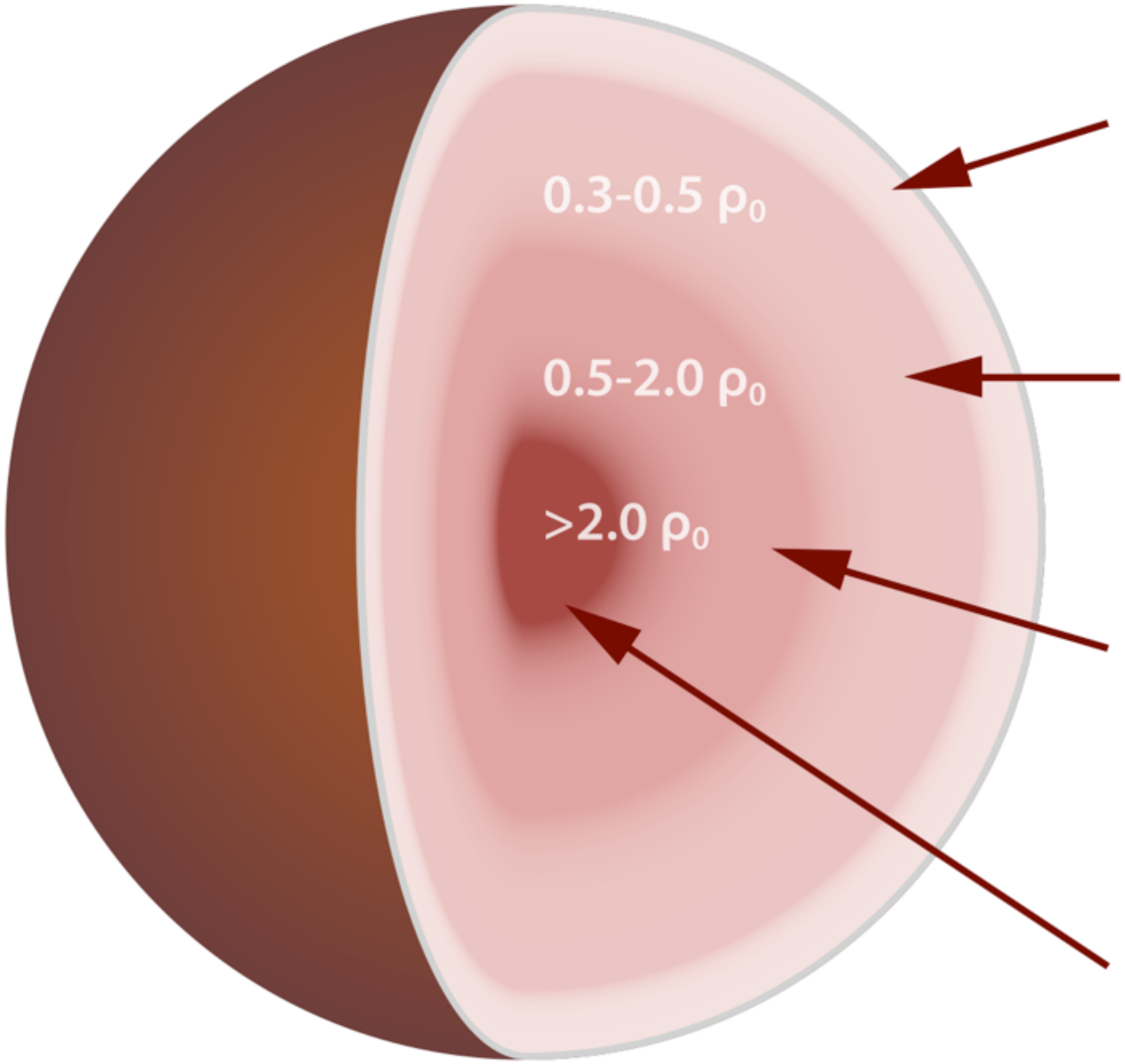
✓ Superfluidity: pulsar glitches.

✓ Gravitational waves: emission from neutron star “mountains”.

✓ Oscillations: the gravitational wave-driven r-mode instability.

Dissecting a neutron (or is it quark?) star

$$\rho_0 = 2.8 \times 10^{14}\,\mathrm{gr/cm^3}$$



outer crust 0.3-0.5 km

ions, electrons

inner crust 1-2 km

electrons, neutrons, nuclei

superfluidity, “pasta” phases

outer core ~ 9 km

neutron-proton Fermi liquid

few % electron Fermi gas

superfluidity, superconductivity

inner core 0-3 km

quark gluon plasma?

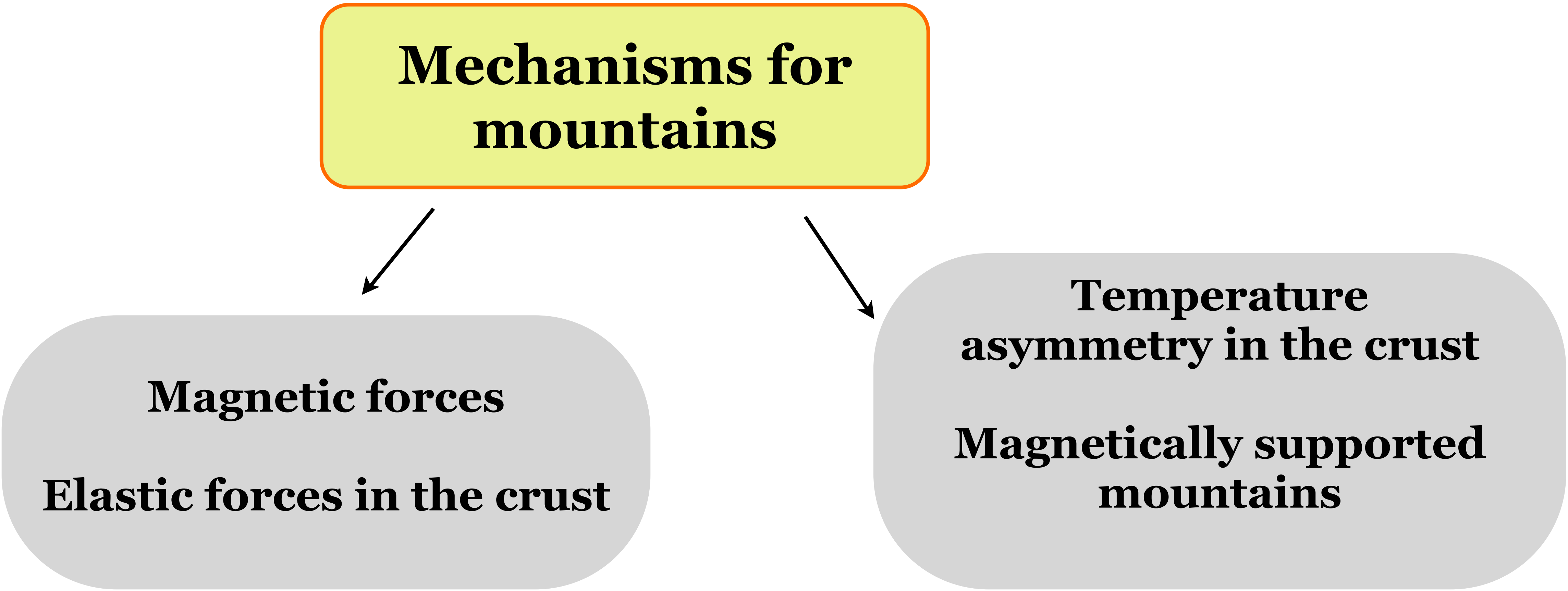
color superconductivity?

Neutron star mountains

“Mountains” in neutron stars

- Any mechanism leading to a ***non-axisymmetric mass quadrupole*** is interesting for GW emission!
  (note: in this regard the rotational deformation is irrelevant).

- The “mountain” may be “buried” in the stellar interior.



Mechanisms for mountains

Magnetic forces

Elastic forces in the crust

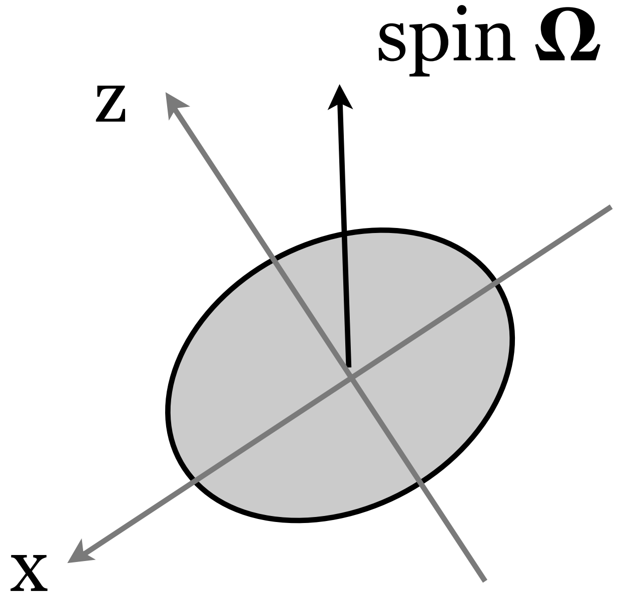
Temperature asymmetry in the crust

Magnetically supported mountains

Accreting neutron stars only

GWs from a rotating ellipsoid

- A textbook result: a rotating body with non-zero ellipticity (=quadrupole moment) is emits GWs if the symmetry axis is misaligned with the spin axis.



- **GW frequency:** $2 f_{\rm spin}$ (under certain circumstances $f_{\rm spin}$ can also appear).
- **GW amplitude** (for a source at distance D):

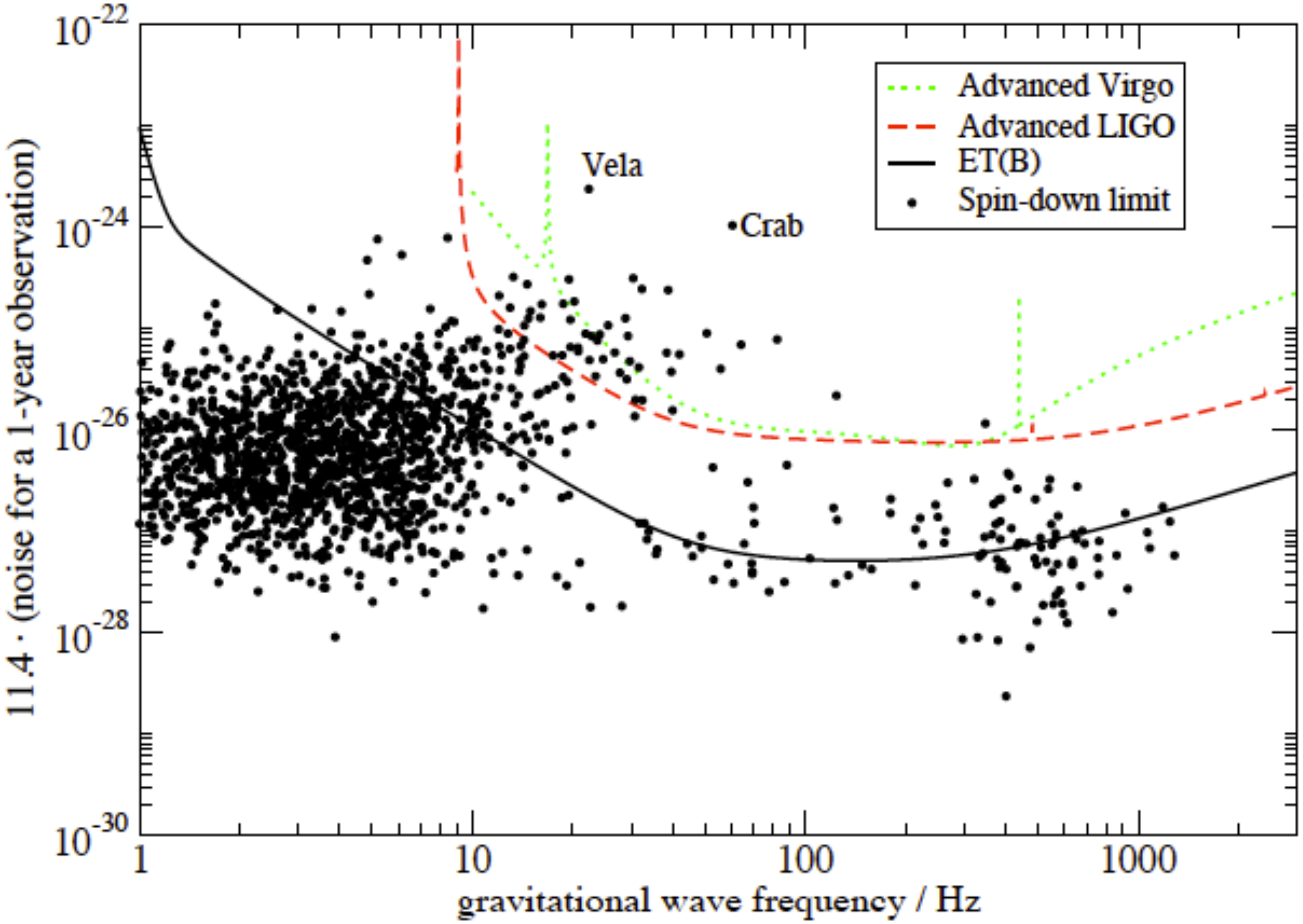
$$h_{\rm gw} \approx \frac{G}{c^4 D} \epsilon I_{\rm zz} \Omega^2 \approx 10^{-28} \left(\frac{1\,{\rm kpc}}{D} \right) \left(\frac{f_{\rm spin}}{10\,{\rm Hz}} \right)^2 \left(\frac{\epsilon}{10^{-6}} \right)$$

stellar ellipticity: $\epsilon = (I_{\rm xx} - I_{\rm zz})/I_{\rm zz}$

Fast spinning systems strongly favored for detection!

Spin-down upper limits

- It is assumed a 100% conversion of the kinetic spin-down energy into GWs.
- The **no-detection of GWs** places an upper limit on the size of the ellipticity, and this becomes interesting if is comparable to the theoretical predictions.



Spin-down upper limits

- In fact, LIGO/Virgo no-detections have already “beaten” the spin-down limit for two pulsars [Aasi et al. 2014].

- **Crab pulsar**:

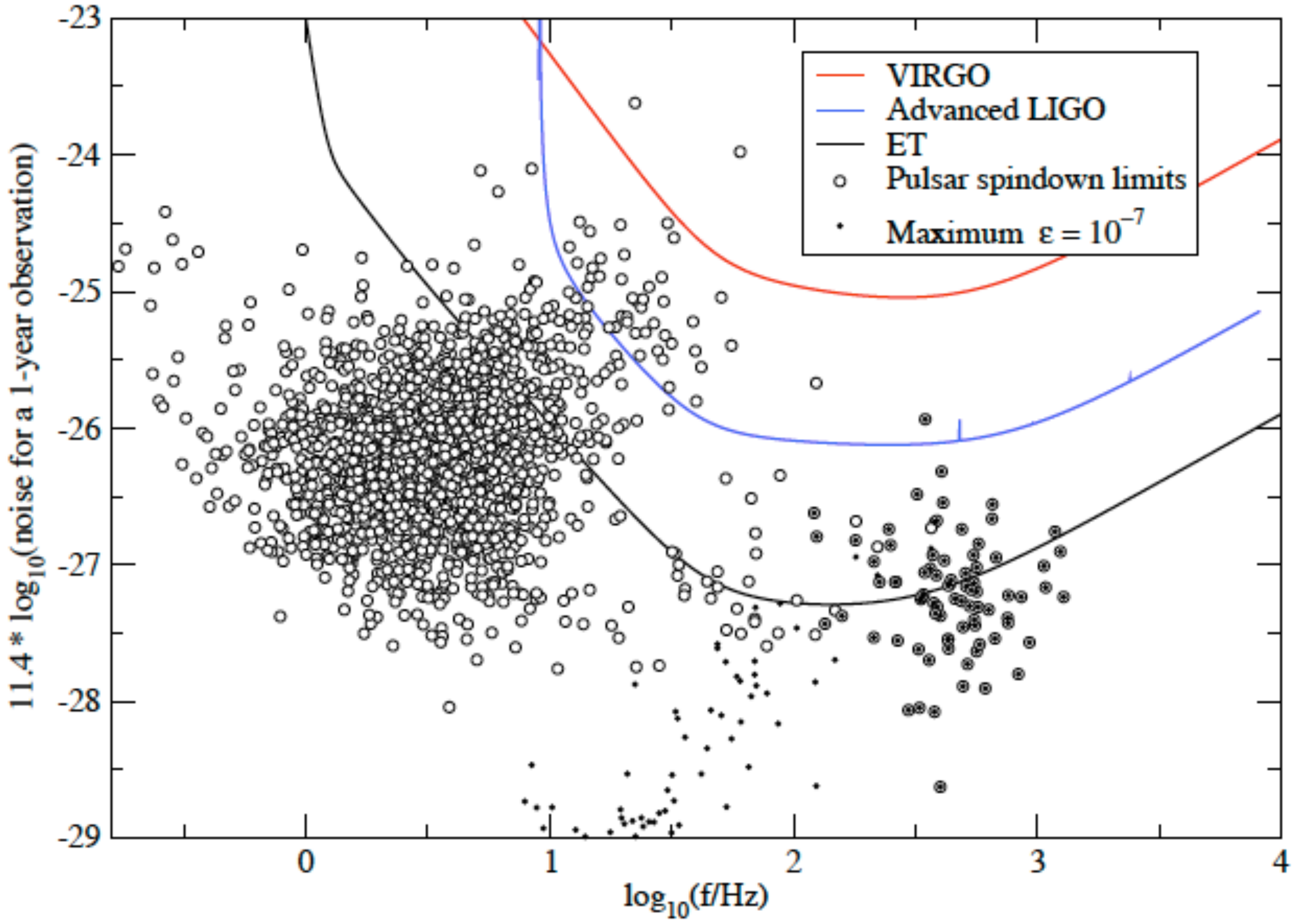
$$\frac{\text{energy in GWs}}{\text{spin-down energy}} \leq 1\% \qquad \longrightarrow \qquad \epsilon \lesssim 10^{-4}$$

- **Vela pulsar**:

$$\frac{\text{energy in GWs}}{\text{spin-down energy}} \leq 10\% \qquad \longrightarrow \qquad \epsilon \lesssim 6 \times 10^{-4}$$

- The data are already becoming theoretically interesting.

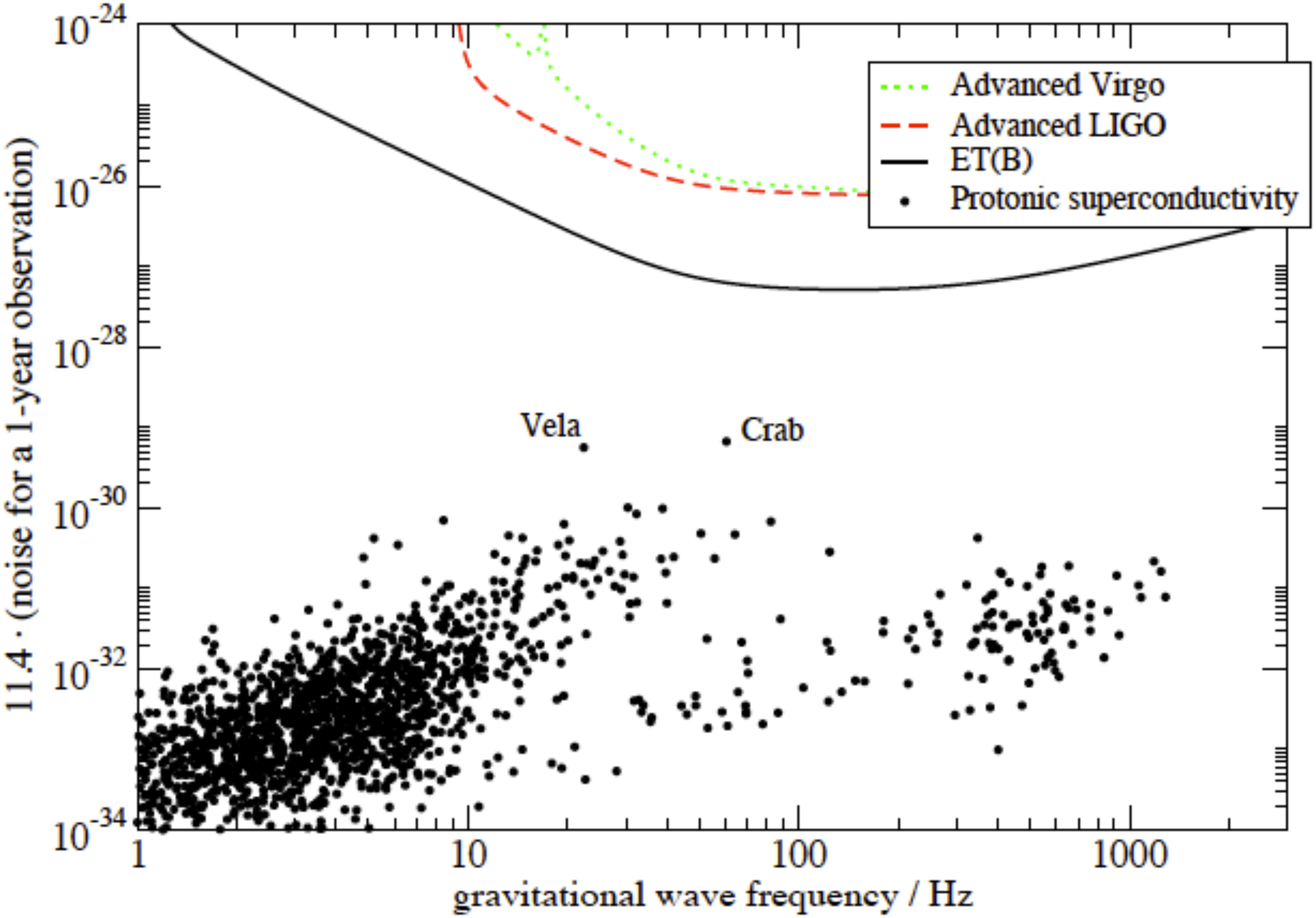
Mountains: GW detectability



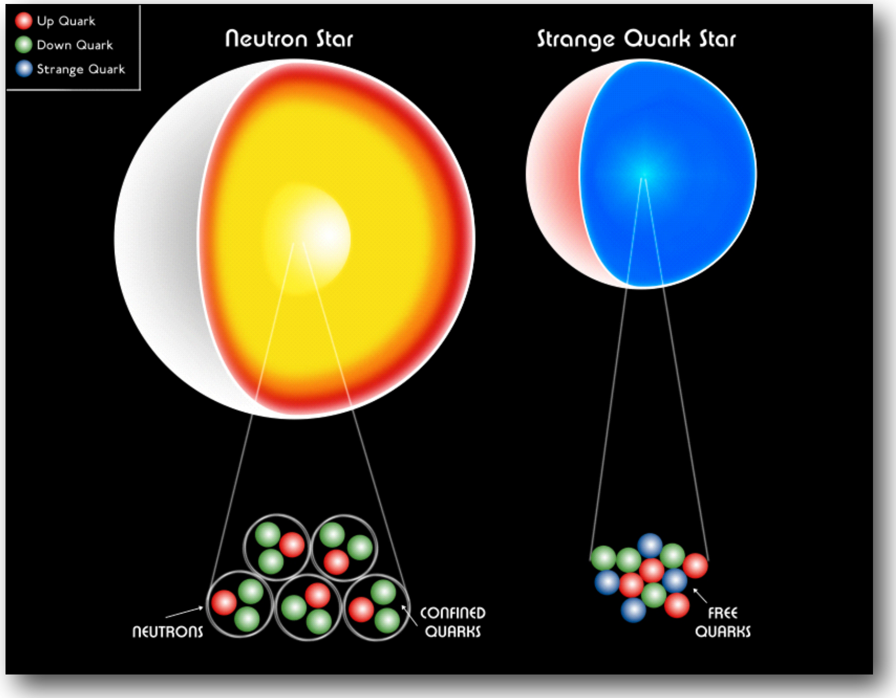
assumed ellipticity: $\epsilon = 10^{-7}$

[Andersson et al. 2011]

Magnetic mountains: detectability



Quark stars: color-magnetic mountains



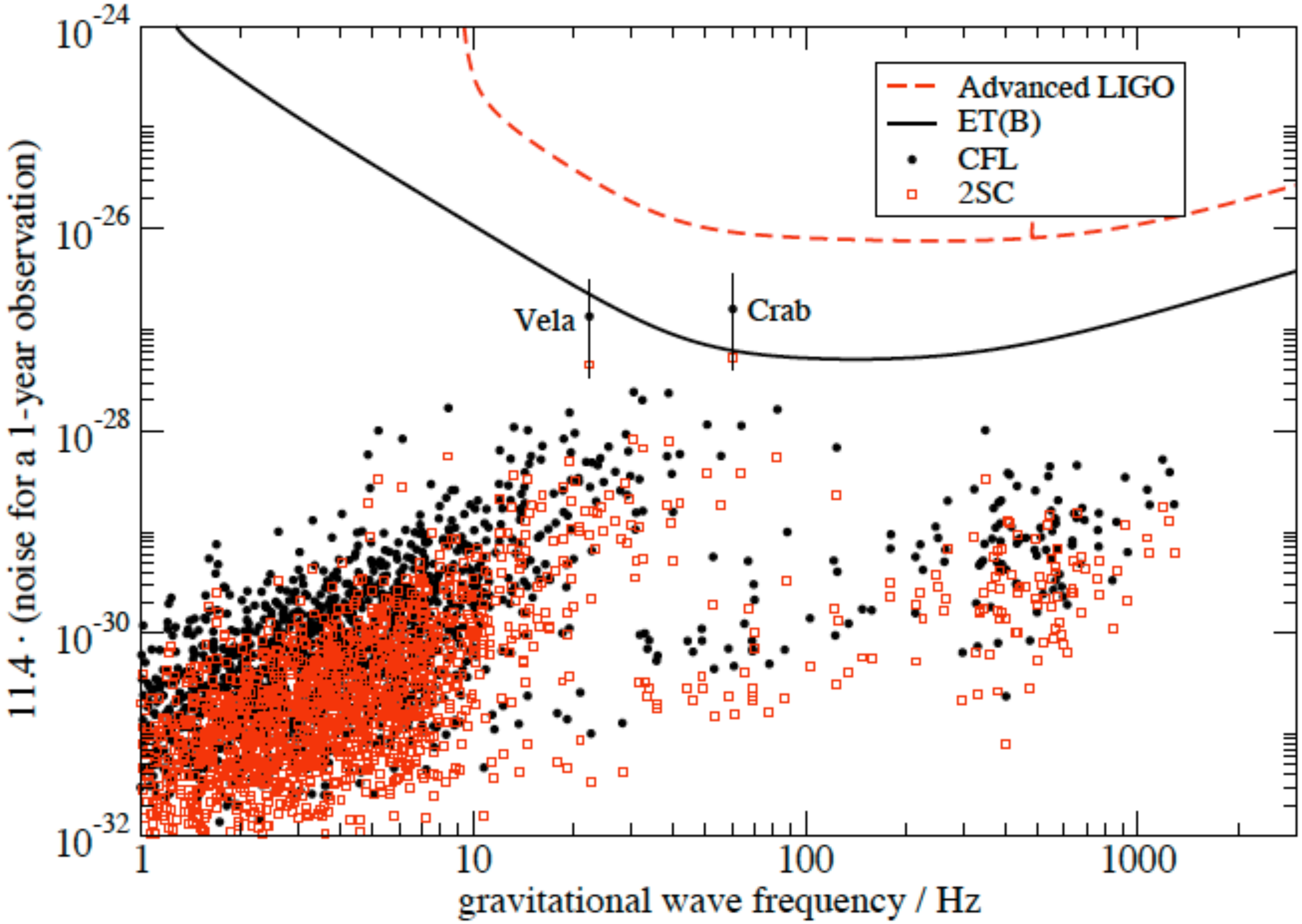
- **What is the ground state of matter?**

- Neutron stars may have quark cores, in a state of color-superconductivity (e.g. 2SC, CFL phases)

- The magnetic field penetrating such exotic phases becomes "color-magnetic" and the magnetic force can be amplified by about a factor ~ 1000.

- The resulting color-magnetic deformation is amplified by the same factor with respect to ordinary neutron star matter for the same B-field.

Color-magnetic mountains: detectability



The figure assumes

$$B_{\text{int}} = B_{\text{surf}}$$

but the interior field could be markedly stronger than the surface dipole.

[KG, Jones & Samuelsson 2012]

Neutron star superfluidity

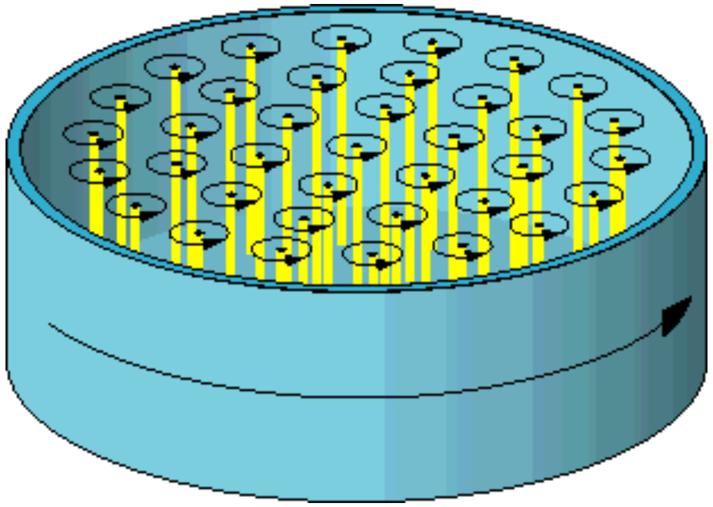
Neutron star superfluidity

- Since mature neutron stars are “cold” Fermi systems ($T \sim 10^8$ K << $T_{\text{Fermi}} = 10^{12}$K) they **should be either solid or superfluid**.

- Theory:
  Since the 1950’s, nuclear physics calculations indicate “BCS-like” Cooper-pairing for neutrons and protons.

- Neutron stars are the hottest (and largest) superfluid systems!

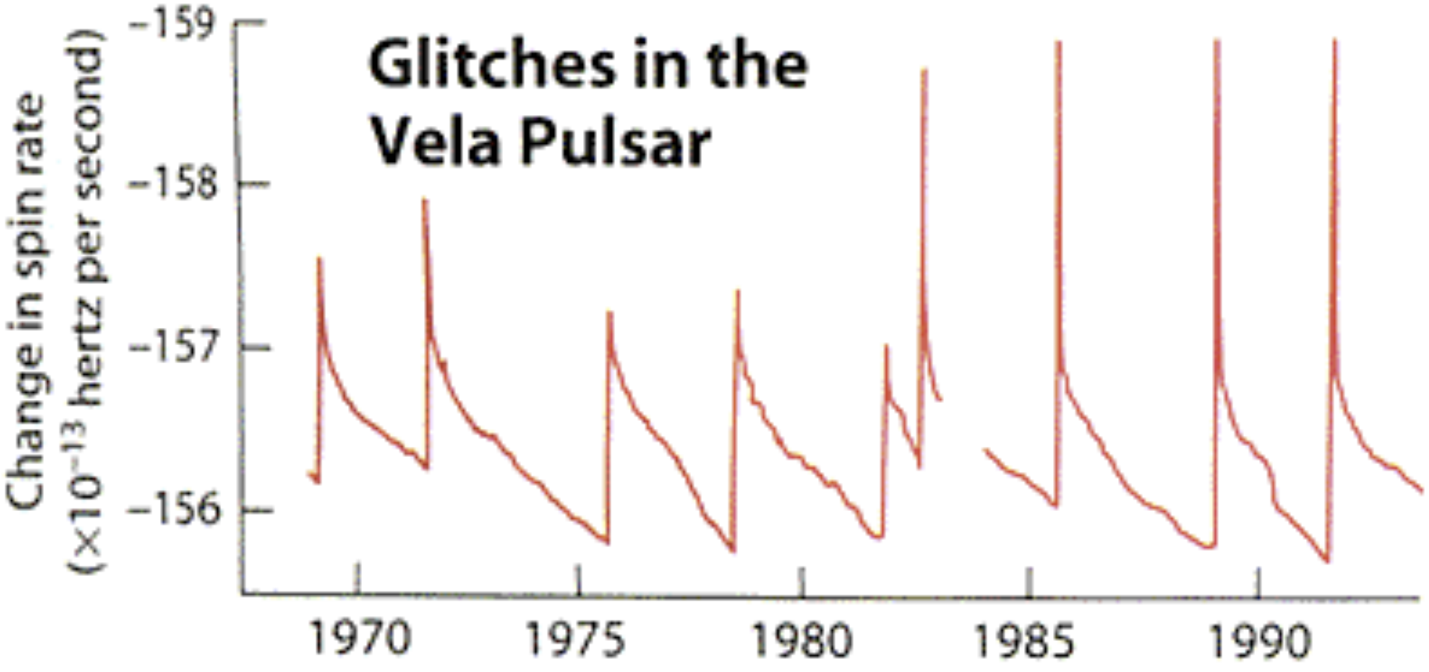
- The superfluid rotates by establishing an array of quantised vortices.



Pulsar glitches

- Glitches: sudden spin-up events punctuating the slow pulsar spin-down.

- The first neutron star seen to glitch was Vela, back in 1969. Vela has proven to be the most prolific and regular "glitcher". Nowadays > 100 glitching systems.



range of glitch amplitude:

$$\frac{\delta\Omega}{\Omega} \sim 10^{-9} - 10^{-5}$$

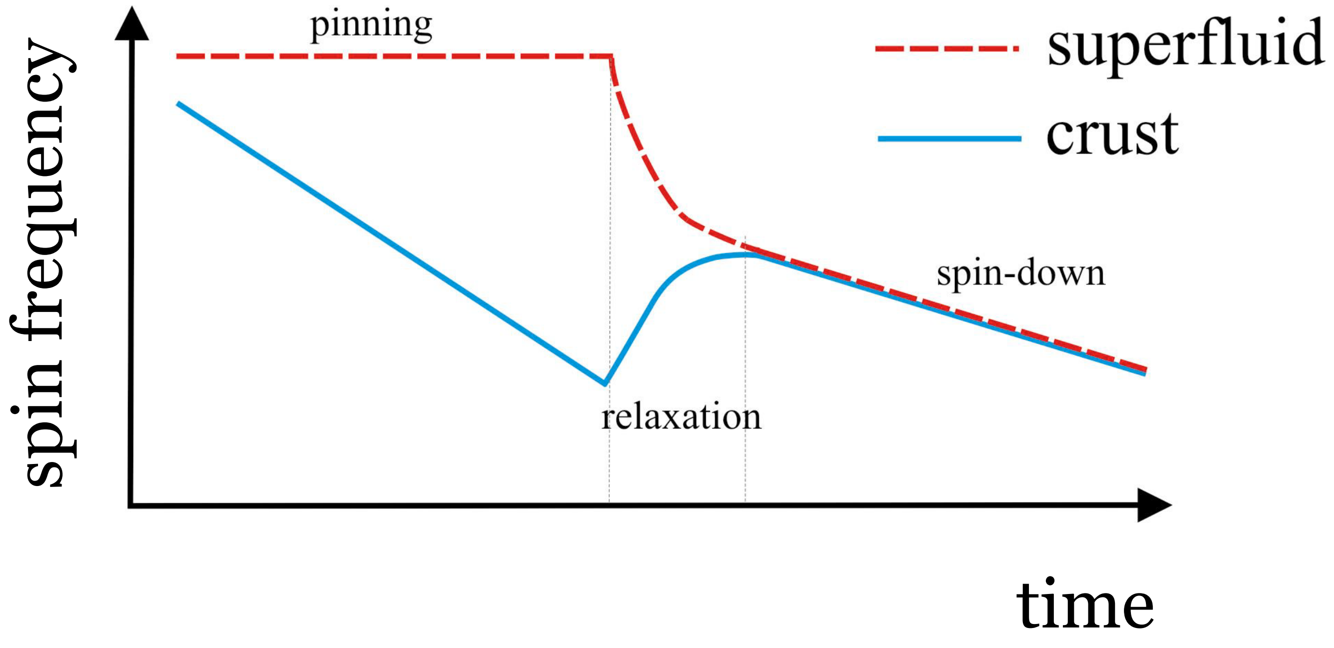
- **Since no such phenomenon has ever been observed in other celestial bodies, we should expect that glitches have something to do with the specific properties of neutron stars.**

Glitches: the standard model

- The star comprises "superfluid" and "normal" fluid components.

- The normal component is electromagnetically spun down.

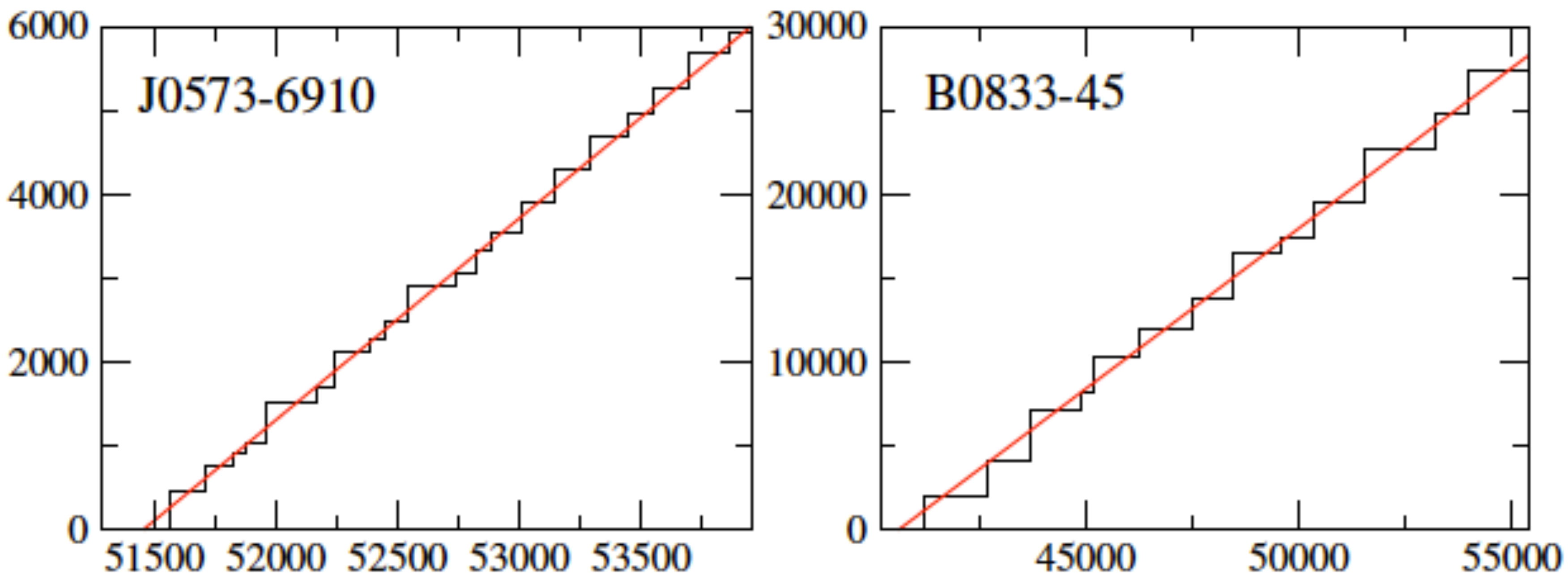
- The superfluid's spin frequency may decrease slower (or at all) if the neutron vortices are efficiently "pinned" onto another stellar component (e.g. the crustal lattice).



- Once a critical spin-lag has been reached, a global vortex unpinning occurs and the superfluid spins down transferring angular momentum to the normal component.

How much superfluid?

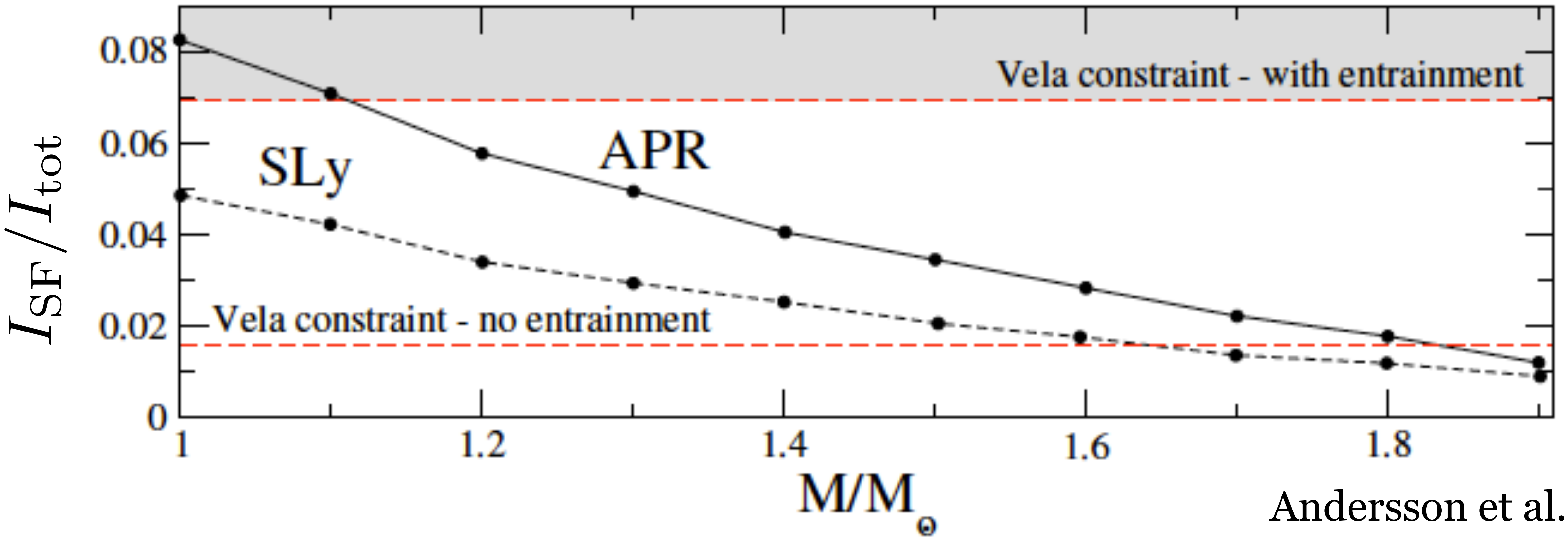
- The remarkable glitch regularity in systems like Vela is a strong indication of a **superfluid reservoir that is fully spent and replenished periodically.**
- The inferred moment of inertia fraction $I_{\rm SF}/I_{\rm tot} \sim 1-2\%$ involved in glitches is comparable to the amount of neutron superfluid expected in the crust.
- This has been taken as evidence of a **superfluid reservoir located in the crust.** Also, the crust can provide the required pinning sites for the vortices.



The crust is not enough

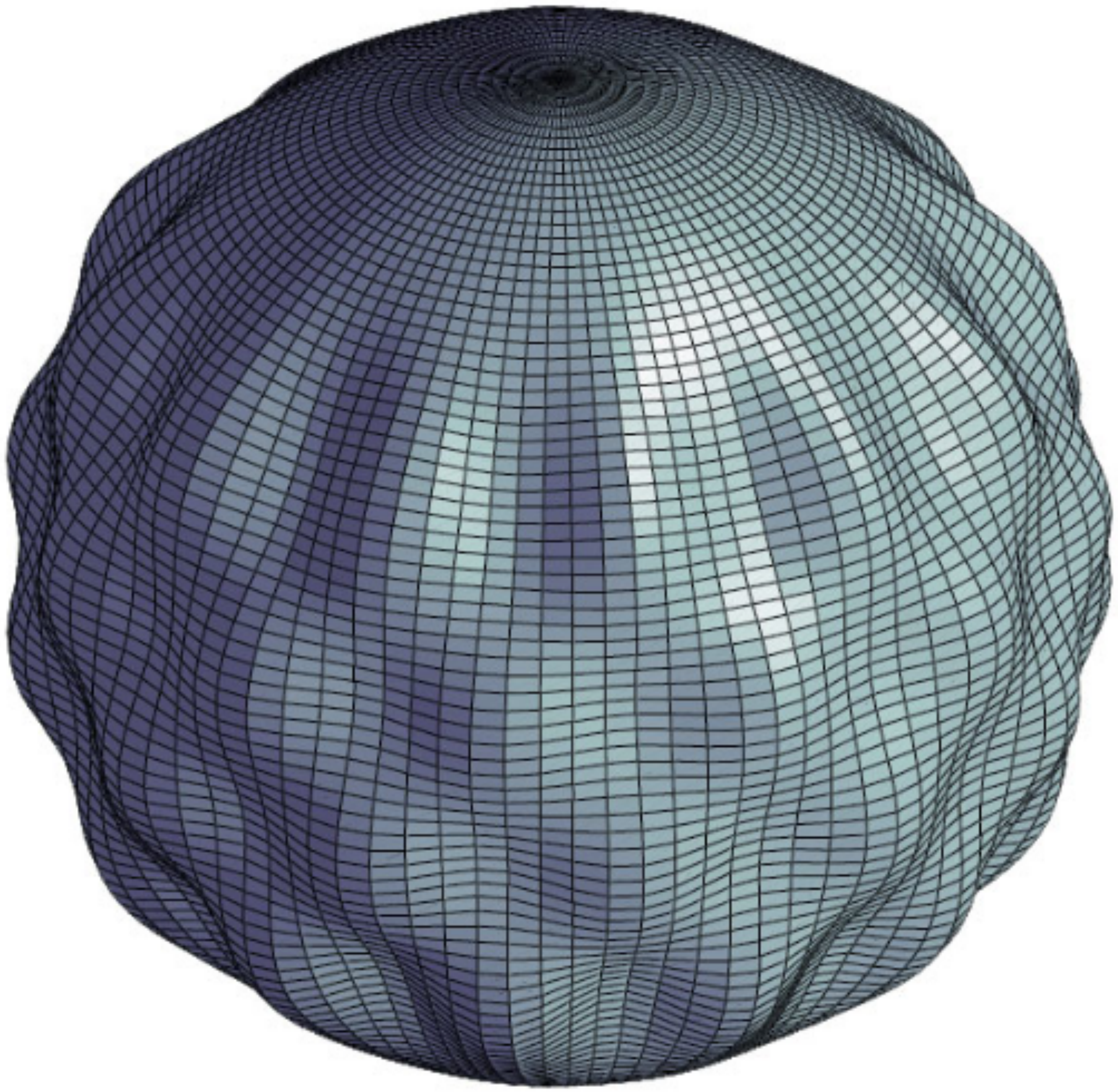
- **How robust is this conclusion?**
  As first suggested by Chamel & Carter (2006), the liquid Fermi physics of the crust (entrainment) reduces the superfluid's mobility and moment of inertia.

- Unless the stellar mass is quite low, the crust is unlikely to contain enough SF that could drive large glitches.



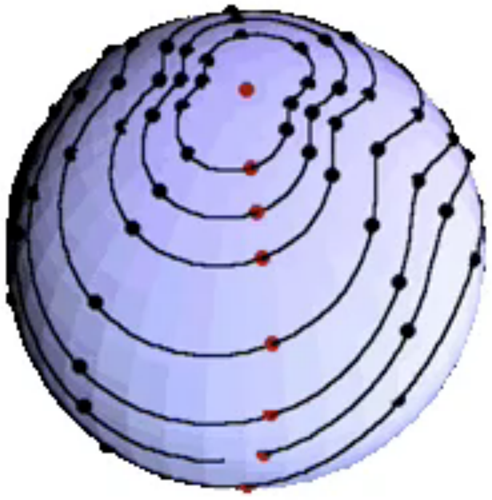
Andersson et al. 2012

The r-mode instability

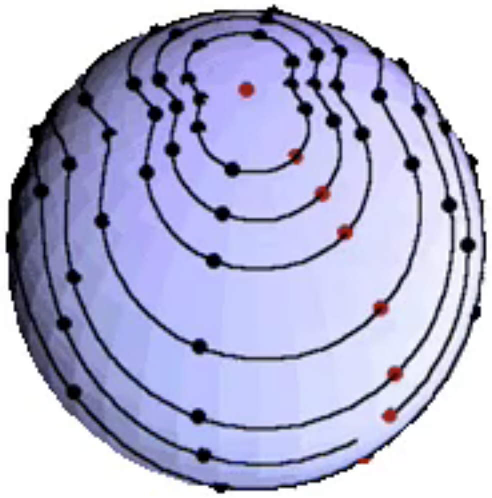


The r-mode instability

- The r-modes is a special class of **inertial waves**, characterised by nearly horizontal fluid motion.
- r-modes may be driven unstable **by the emission of GWs** via the **CFS mechanism**: this involves the reverse-dragging of the mode by the rotating background.
- The r-mode GW radiation is special in the sense that it is dominated by the **current multipole.**
- The $\ell = m = 2$ r-mode is the most unstable one, with a growth timescale of ~ 1 min.
- **GW frequency:** $f_{\rm gw} = f_{\rm mode} \approx \dfrac{4}{3} f_{\rm spin}$



corotating frame



inertial frame

Figure credit: Hanna & Owen

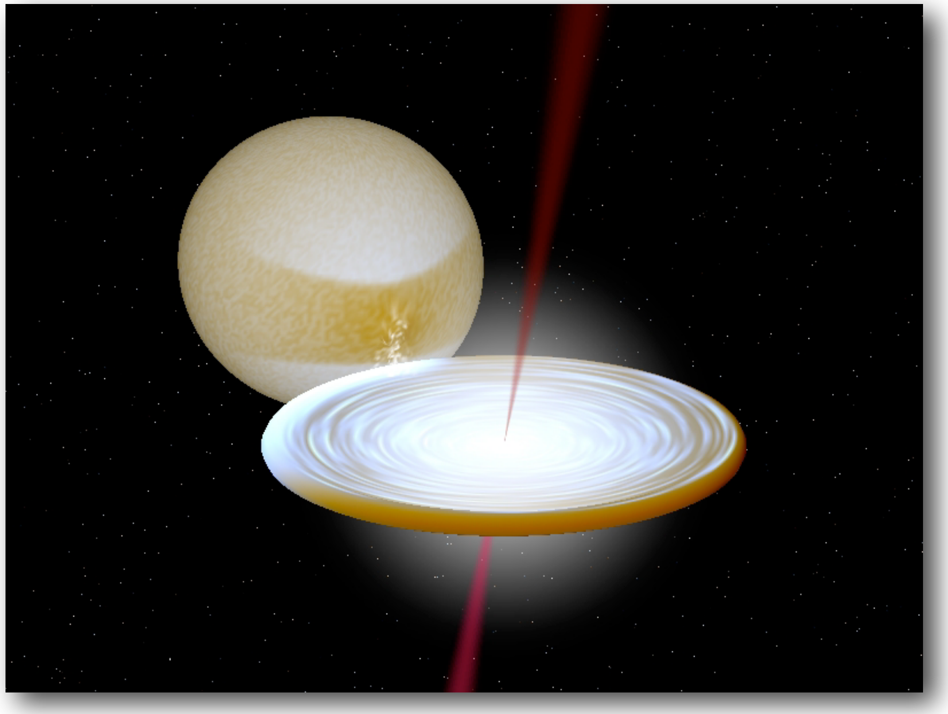
Context: spin equilibrium in LMXBs

- LMXB spin distribution:

$$200\,\mathrm{Hz} \lesssim f_{\mathrm{spin}} \lesssim 600\,\mathrm{Hz}$$

- This is well below the mass-shedding limit:

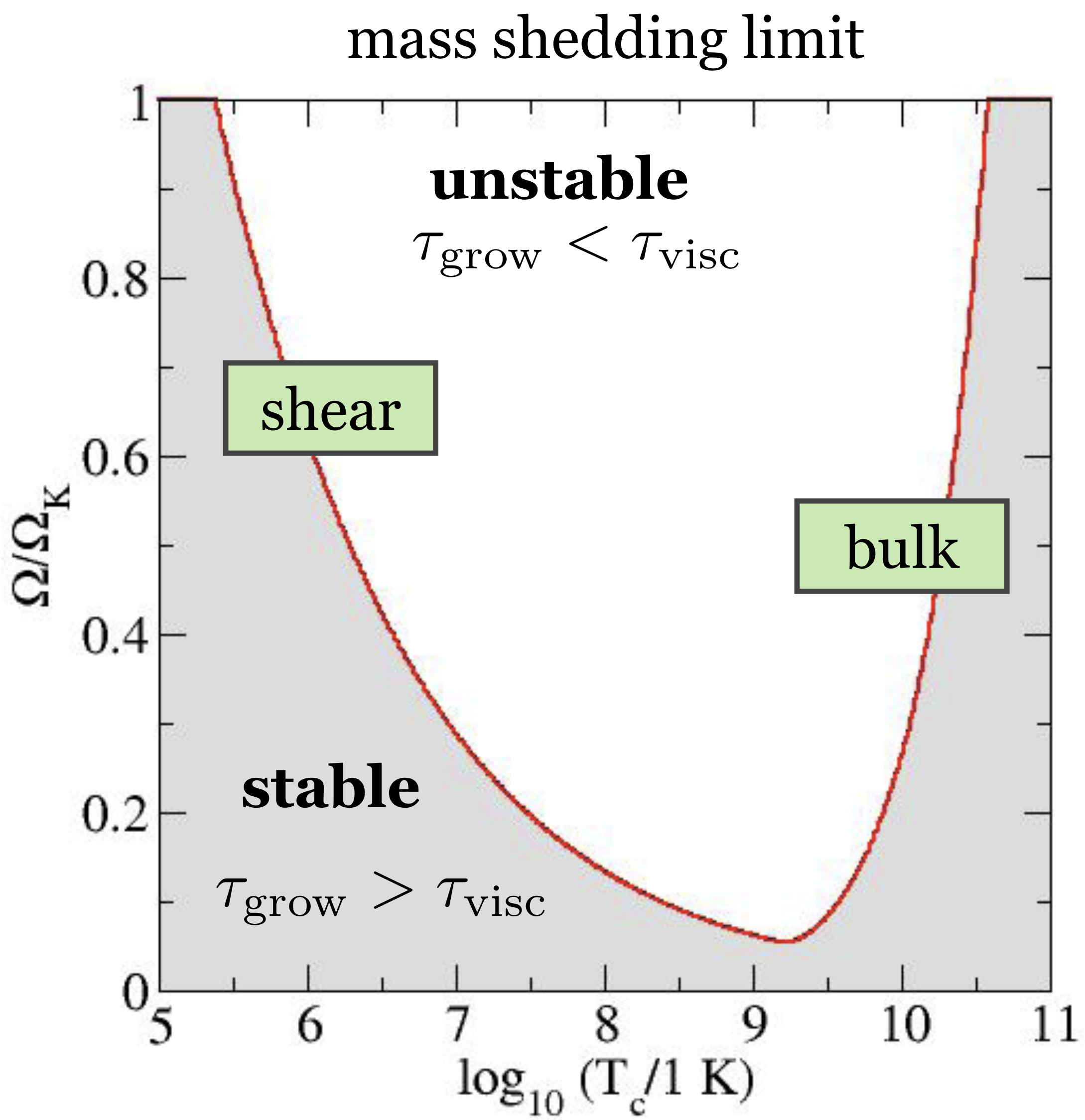
$$f_{\mathrm{spin}} \ll f_{\mathrm{Kepler}} \sim 1.5\,\mathrm{kHz}$$



- Accretion lasts $\sim 10^7$ yr, Kepler limit should be reached.
- **Some process seems to halt the spin-up.**
- **Unstable r-modes could be at work.**

The r-mode instability window

- The r-mode instability is active for any rotation but can be damped by viscous processes.
- The **spin-temperature instability window** is “large” but depends on uncertain core-physics.
- **A “minimal” model** accounts for damping due to shear (particle collisions) and bulk viscosity (β-equilibrium reactions).



r-mode paradox?

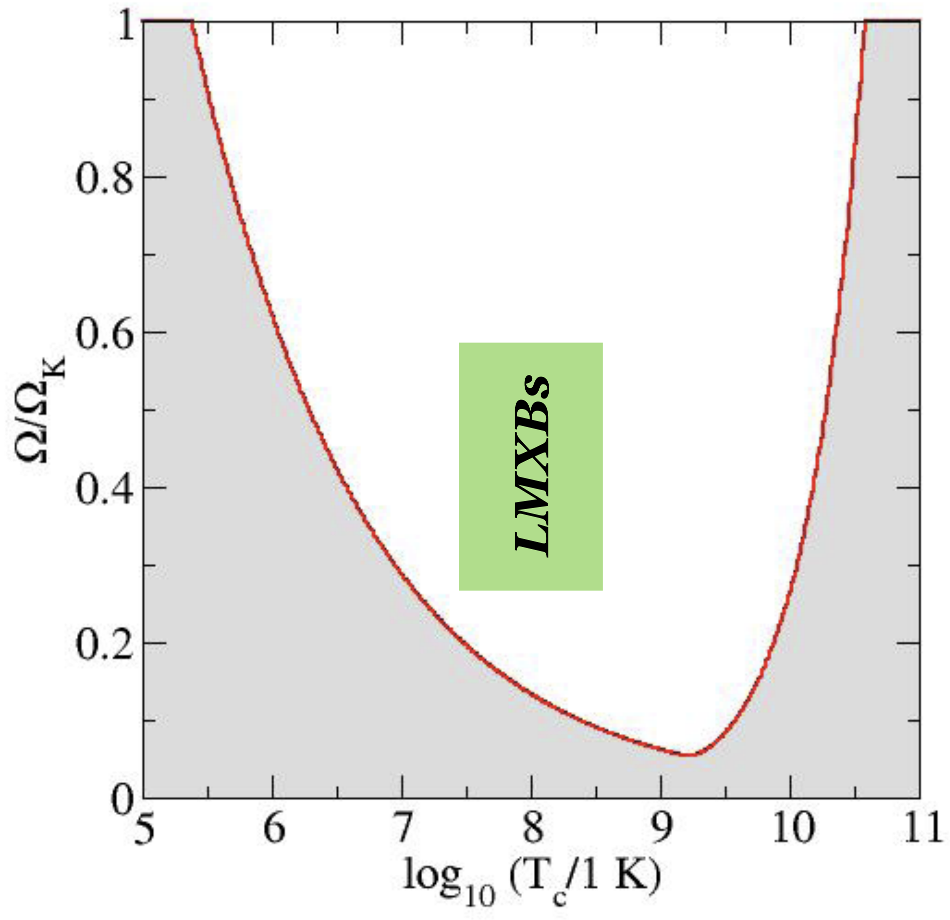
- Several LMXBs (and perhaps some MSPs) reside well inside the “minimal” instability window.

- These systems should experience r-mode-driven evolution and a GW spin-down torque.

- … but this is not what observations suggest. Possible resolutions:

✓ **Additional damping** (e.g. friction at the crust-core boundary, exotica in the core, …).

✓ r-mode amplitude **much smaller** than current theoretical predictions.



The role of the neutron star crust

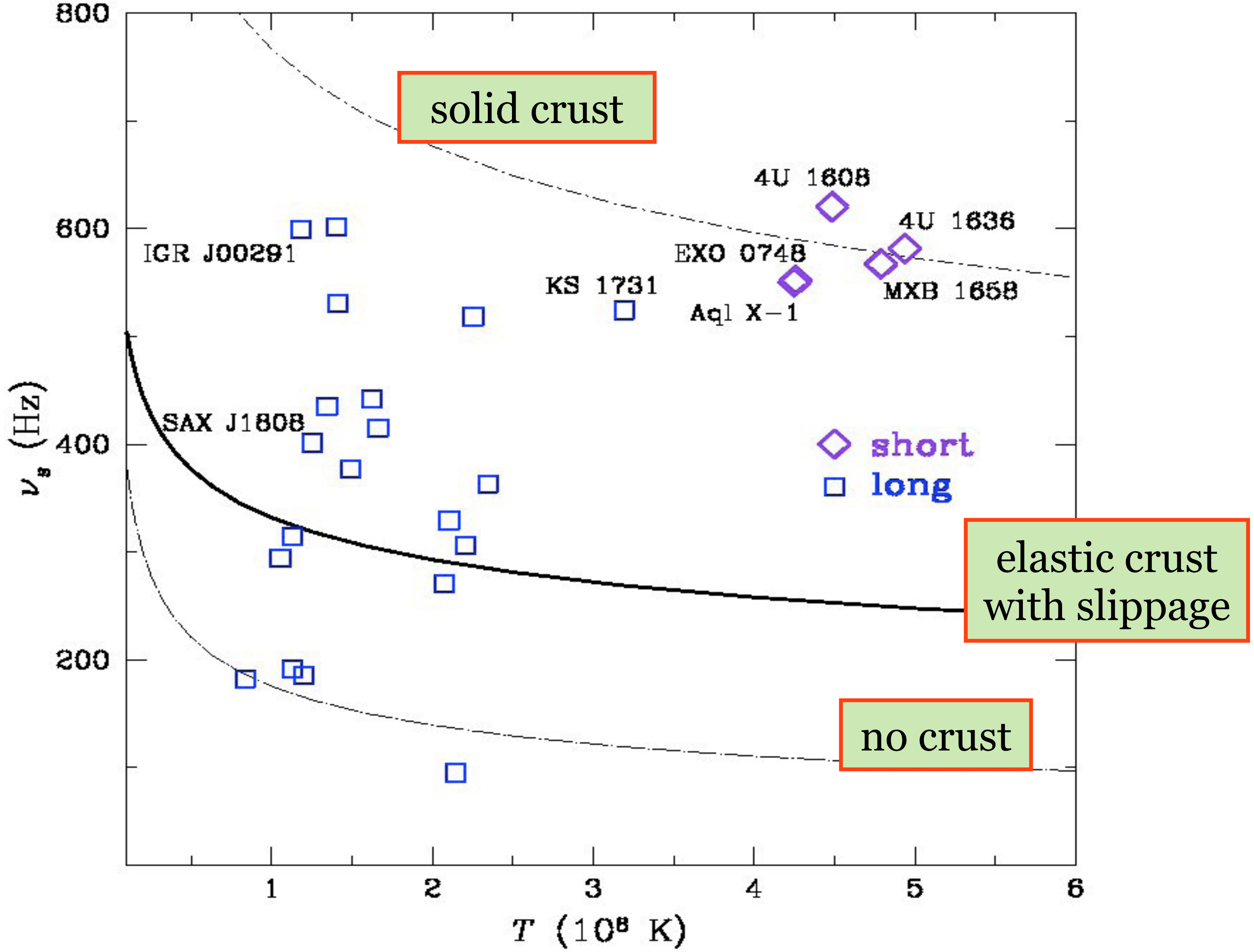
- **r-mode damping could be easily dominated by the viscous “rubbing” at the base of the crust (Ekman boundary layer).**

- The crust is more like a jelly than solid: the resulting crust-core “slippage” reduces damping.

- Resonances between the r-mode and torsional crustal modes may also play a key role.

- The magnetic field coupling between the crust and the core could modify the Ekman layer and boost dissipation.

r-mode window: “theory vs observations”



[Ho, Andersson & Haskell 2011]

Outlook

- Observations (photons and soon GWs) already place constraints on neutron star structure.

- Prospects for probing the ground state of matter and large-scale superfluidity.