Color-magnetic “mountains” in neutron stars

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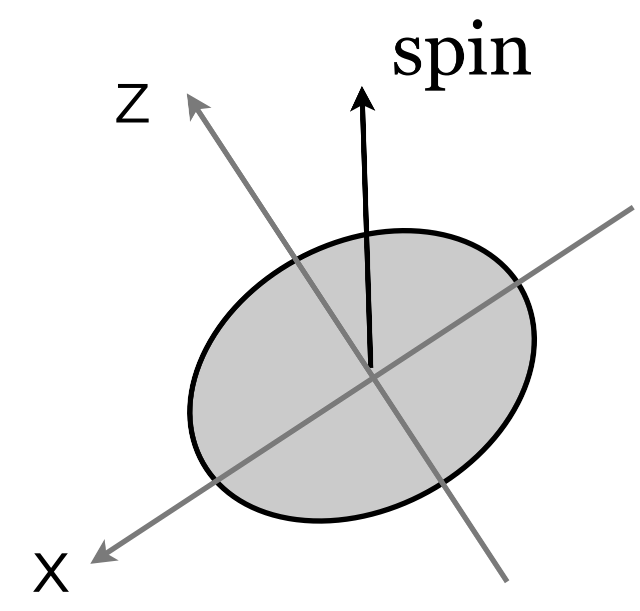
Prologue: GWs from a rotating ellipsoid

- A well known result: a rotating body with non-zero ellipticity is a source of gravitational waves.
- GW frequency: f, $2f$ (dominant)
- GW amplitude (for a source at distance D, and spin frequency f):



$$h_{\rm gw} = \frac{8G}{c^4}\left(\frac{2}{15}\right)^{1/2}\frac{\epsilon I\Omega^2}{D} \approx 10^{-28}\left(\frac{1\,{\rm kpc}}{D}\right)\left(\frac{f}{10\,{\rm Hz}}\right)^2\left(\frac{\epsilon}{10^{-6}}\right)$$

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

Building “mountains” in neutron stars

- The shape of neutron stars can depart from sphericity due to a number of reasons. Rotation is the most obvious one but this does not lead to GW emission.

- The magnetic field can also deform the star (originally proposed by Chandrasekhar & Fermi in 1953). For a generic configuration the system does emit GWs.

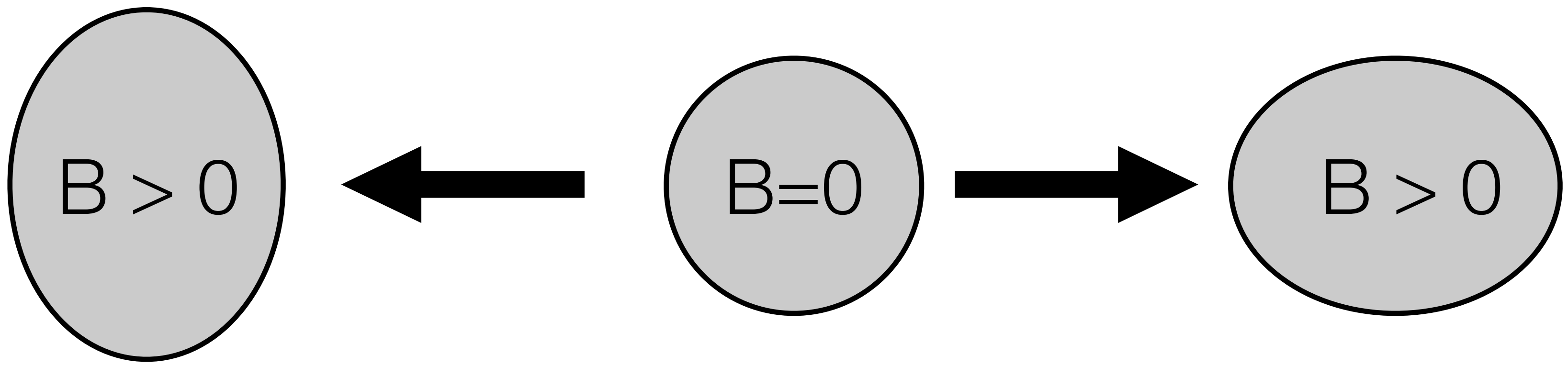


Figure not to scale!

- The deformation (ellipticity) is well approximated by the ratio of the volume-averaged magnetic energy to gravitational binding energy:

$$\epsilon \approx \frac{E_{\rm mag}}{E_{\rm grav}} \approx 10^{-12} \left(\frac{\bar{B}}{10^{12}\,{\rm G}} \right)^2$$

- Unfortunately, this is too small to be detectable ...

Superconductivity in neutron stars

- Proton pairing leads to **type II superconductivity** in the bulk of a typical neutron star core.

- The magnetic field penetrates the matter by forming **quantised vortices**.

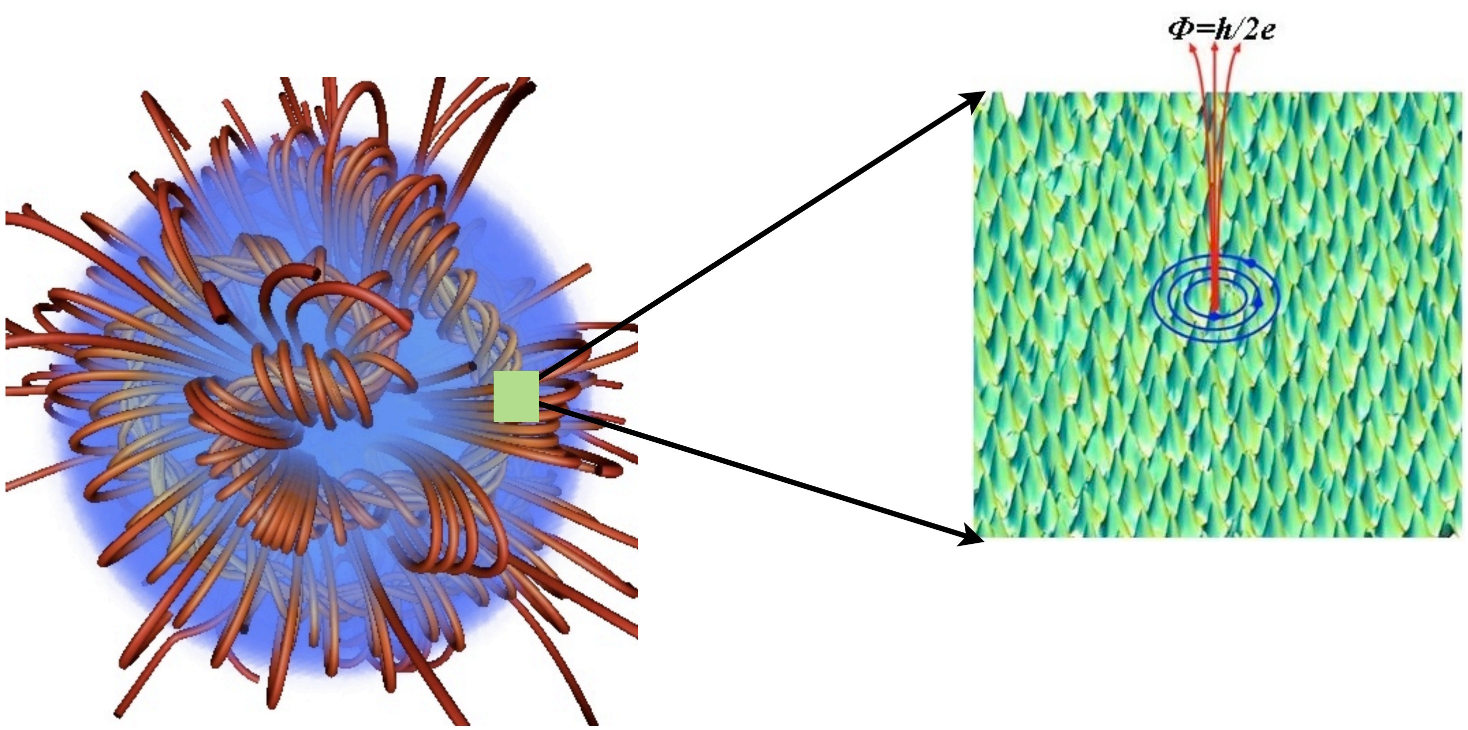


Figure credit : Braithwaite 2005

global B-field

$$B \approx N_{\rm p} \phi_0$$

$$\phi_0 = hc/2e$$

vortex area density

- A typical neutron star B-field is distributed into ~ 10^{30} proton vortices.

Magnetic mountains: with superconductivity

- Superconductivity amplifies the magnetic force by a factor ~ $H_{\rm c1}/B$ where the superconductivity critical field is given by:

$$H_{\rm c1} = \frac{4\pi\mathcal{E}_{\rm p}}{\phi_0} \approx 10^{15}\,{\rm G}$$

vortex energy/unit length

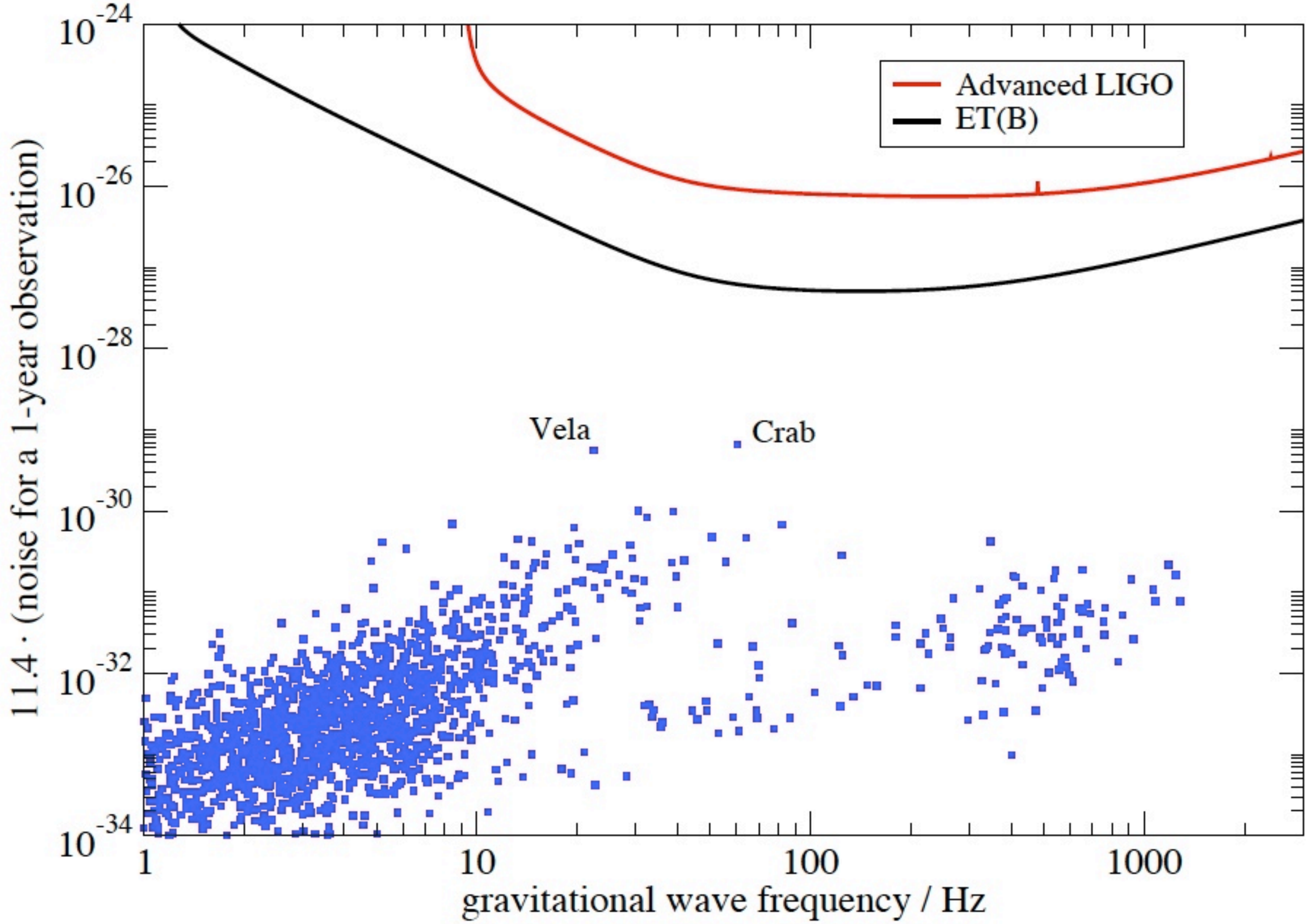
- The resulting magnetic "mountain" is much bigger than before:

$$\epsilon \approx \frac{\rm averaged\ vortex\ tension}{E_{\rm grav}} = \frac{N_{\rm p}\mathcal{E}_{\rm p}V_{\rm star}}{E_{\rm grav}} \longrightarrow \epsilon \approx 10^{-9}\left(\frac{\bar{B}}{10^{12}\,{\rm G}}\right)$$

- Is this detectable?

Detectability of magnetically-deformed NS

Despite the enhancing effect of superconductivity, the magnetically deformed neutron stars are still not detectable, unless we invoke an “abnormally” high interior B-field.



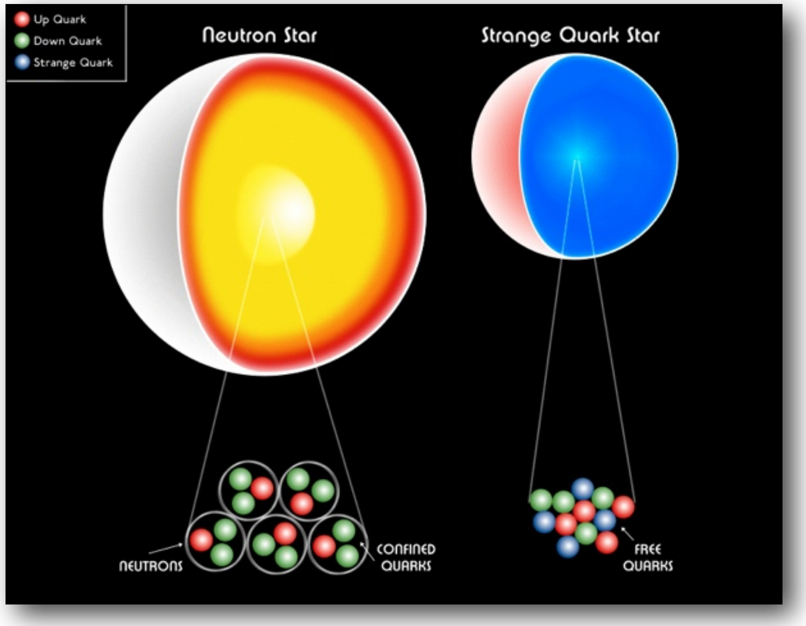
The quest for quark matter

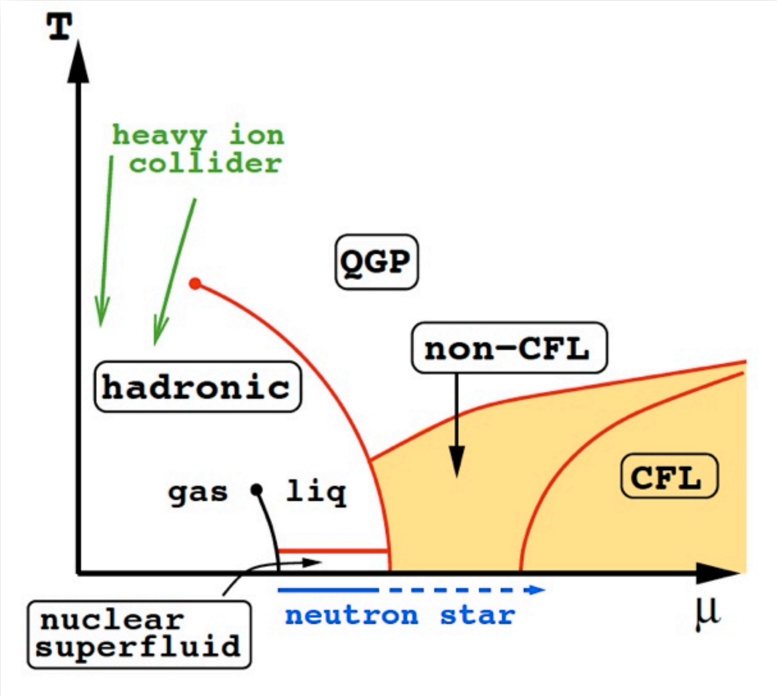
- The composition of matter at supra-nuclear densities is still a subject of debate. In fact, astrophysical observations of NS may be the only way to settle this issue.

- Are deconfined quarks the ground state of matter? This is a fundamental question that NS astrophysics may provide an answer for.

- This is not easy: the real systems can be hybrids with a quark inner core and an outer mantle of normal hadronic matter.

- Other strategies (observing surface properties, cooling, pulsation modes,) may not be effective here.

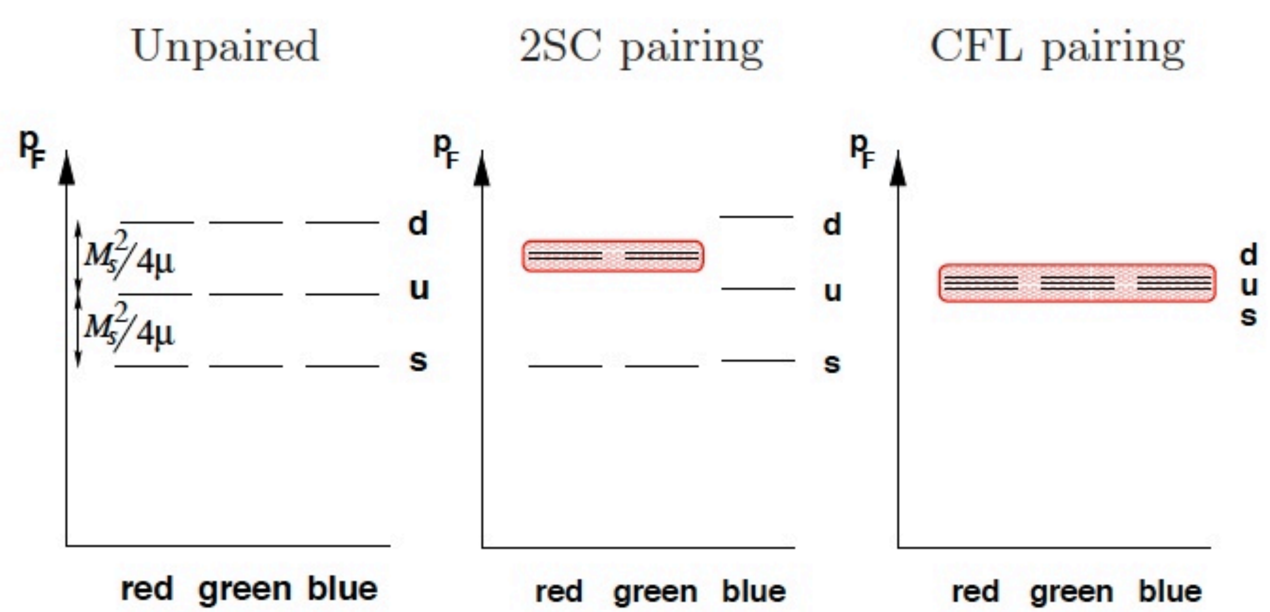




Alford et al. 2008

Quark *color* superconductivity

- In its stablest form, quark matter is a color superconductor, as a result of quark color/flavor pairing.
- 2SC phase: up and down quark pair.
- Color-flavor-locking (CFL) phase: all quarks pair. This is the most "popular" state in the literature.



Alford et al. 2008

- Comment: the recent discovery of a $2M_\odot$ neutron star strongly suggests color-superconductivity, *if* quark matter really exists in the interior of neutron stars (Özel et al. 2010).

Magnetic fields in quark matter

- What happens to a magnetic field penetrating a quark color superconductor?

- Magnetic and gluonic degrees of freedom get mixed up. Only one of the produced superpositions actually "feels" the ambient superconductivity:

$$\vec{B}_{\mathrm{X}} = \sin\chi\,\vec{B} + \cos\chi\,\vec{B}_8$$

magnetic ($\vec{B}$) gluonic ($\vec{B}_8$)

- Mixing angle: $\sin\chi \sim \frac{\text{QED coupling constant}}{\text{QCD coupling constant}} \ll 1$

- Comment: most of the magnetic field penetrates paramagnetically.

Color-magnetic mountains

- The X-field penetrates a 2SC/CFL superconductor by forming color-magnetic vortices (Iida & Baym 2002, Iida 2005, Alford & Sedrakian 2010).

- Each vortex carries ~ 1000 more energy than a proton vortex in "normal" superconductivity, while their numbers are comparable. The resulting deformation in the inner core is:

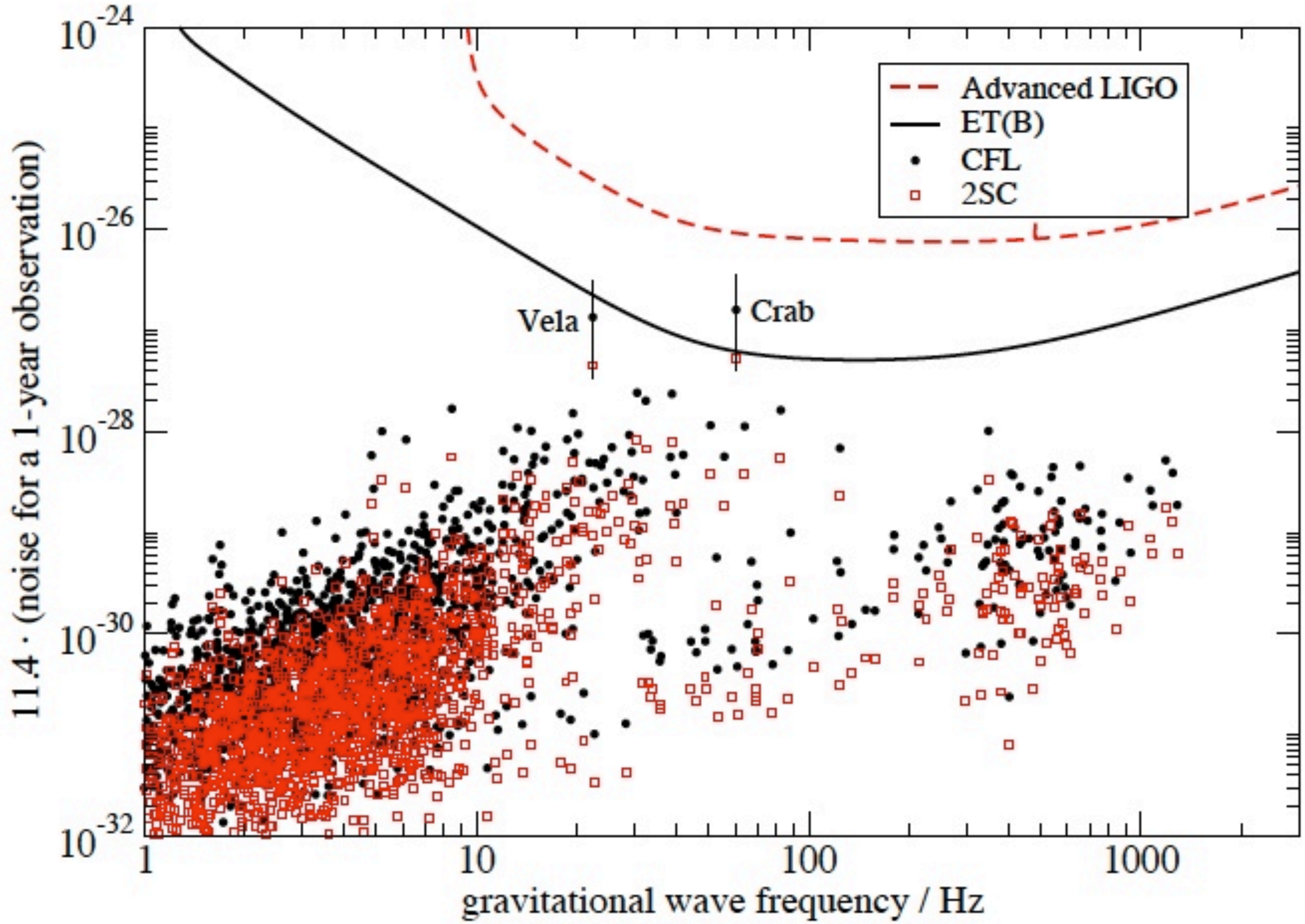
$$\epsilon_{\rm X} \approx \frac{N_{\rm X}\mathcal{E}_{\rm X}V_q}{3GM^2/(4R)} \longrightarrow \epsilon_{\rm X}^{\rm CFL} \approx 10^{-7}\left(\frac{\bar{B}}{10^{12}\,{\rm G}}\right)\left(\frac{V_q}{V_{\rm star}}\right)\left(\frac{\mu_q}{400\,{\rm MeV}}\right)^2$$

↓

- Our "canonical" stellar model is a n=1 polytrope, $M = 1.4\,M_\odot, \;\; R = 12\,{\rm km}$

- Quark core volume: $V_q = 0.5 V_{\rm star}$, interior magnetic field: $\bar{B} = 2B_{\rm surf}$

Color-magnetic mountains: detectability



[KG, Jones & Samuelsson 2012]

Another possibility: “buried” magnetic fields

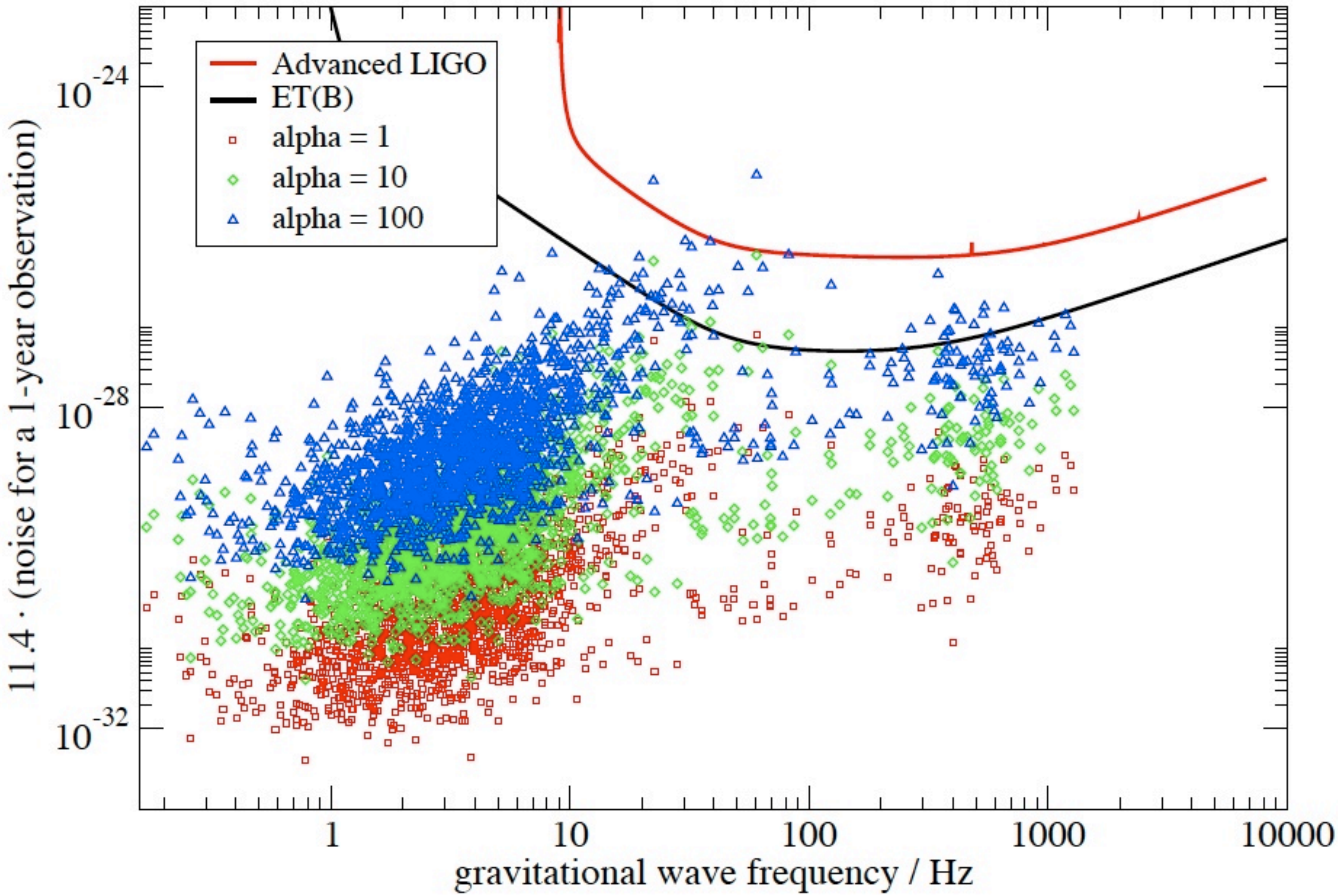
- The mountain size scales with the (volume-averaged) internal magnetic field B. Could this be much bigger than the surface dipole field (which is inferred from spindown)?

- This could naturally happen in recycled millisecond pulsars: these systems have passed a prolonged phase of accretion which spun them up. The accreted material may have also buried the surface field.

- Something similar may have taken place in young pulsars (like the Crab): this idea is invoked to explain the “anomalous” spin evolution (breaking index) in several of these systems.

- We repeat the previous calculation, using the parameter: $\alpha = \dfrac{\bar{B}}{B_{\rm surf}}$

Color-magnetic mountains: various alphas



Executive summary

- If deconfined quark matter is realized in neutron star cores then it is likely a color superconductor (CFL, 2SC, etc.)
- The presence of a magnetic field leads to the formation of color-magnetic vortices. Their volume-averaged tension makes the star non-axisymmetric and a potent source of GWs.
- Young radio pulsars (Crab, Vela) may be detectable by ET, provided they contain an appreciable quark matter inner core. CFL matter is the most favorable case.
- Recycled millisecond pulsars with buried strong buried magnetic fields may also be potentially detectable sources.