Strangeon star oscillations and quasi-periodic oscillations (QPOs) during magnetar giant flares

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Outline

- Observations - quasi-periodic oscillations (QPOs)
- Global torsional oscillation of SS
- Interface mode of ocean-crust
- Comparison with the quark star (QS)
- Summary

Observations - quasi-periodic oscillations (QPOs)

(1) QPOs in giant flares

(I) SGR 1806-20 (2004): 18, 26, 30, 92 150, 625, 1840 Hz

(II) SGR 1900+14 (1998): 28, 53, 84, 155 Hz

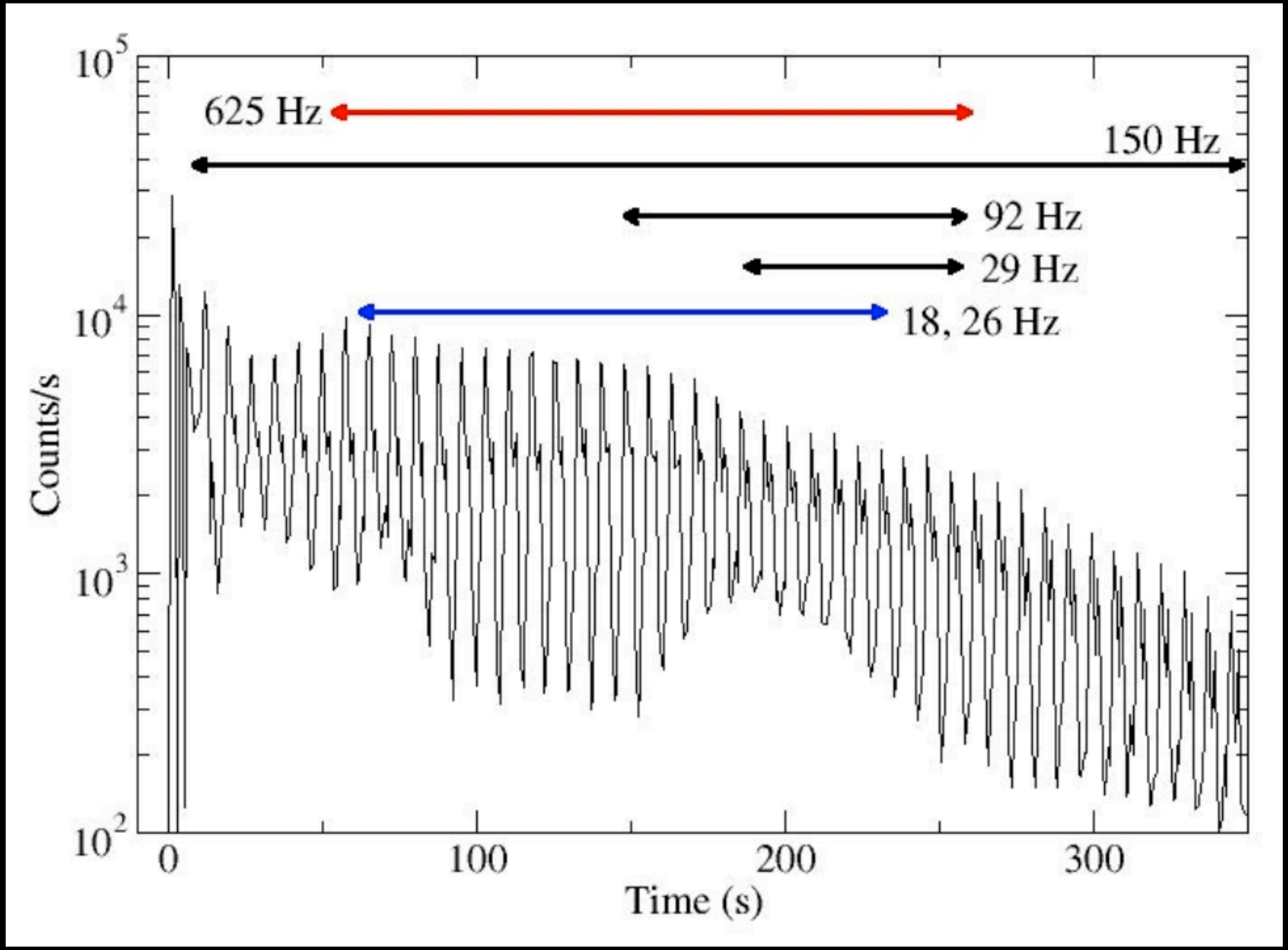
Israel et al., 2005; Strohmayer and Watts, 2005; Watts and Strohmayer, 2006, ……

(2) QPOs in normal bursts

SGR J1550-5418: 93, 127, 260 Hz

……

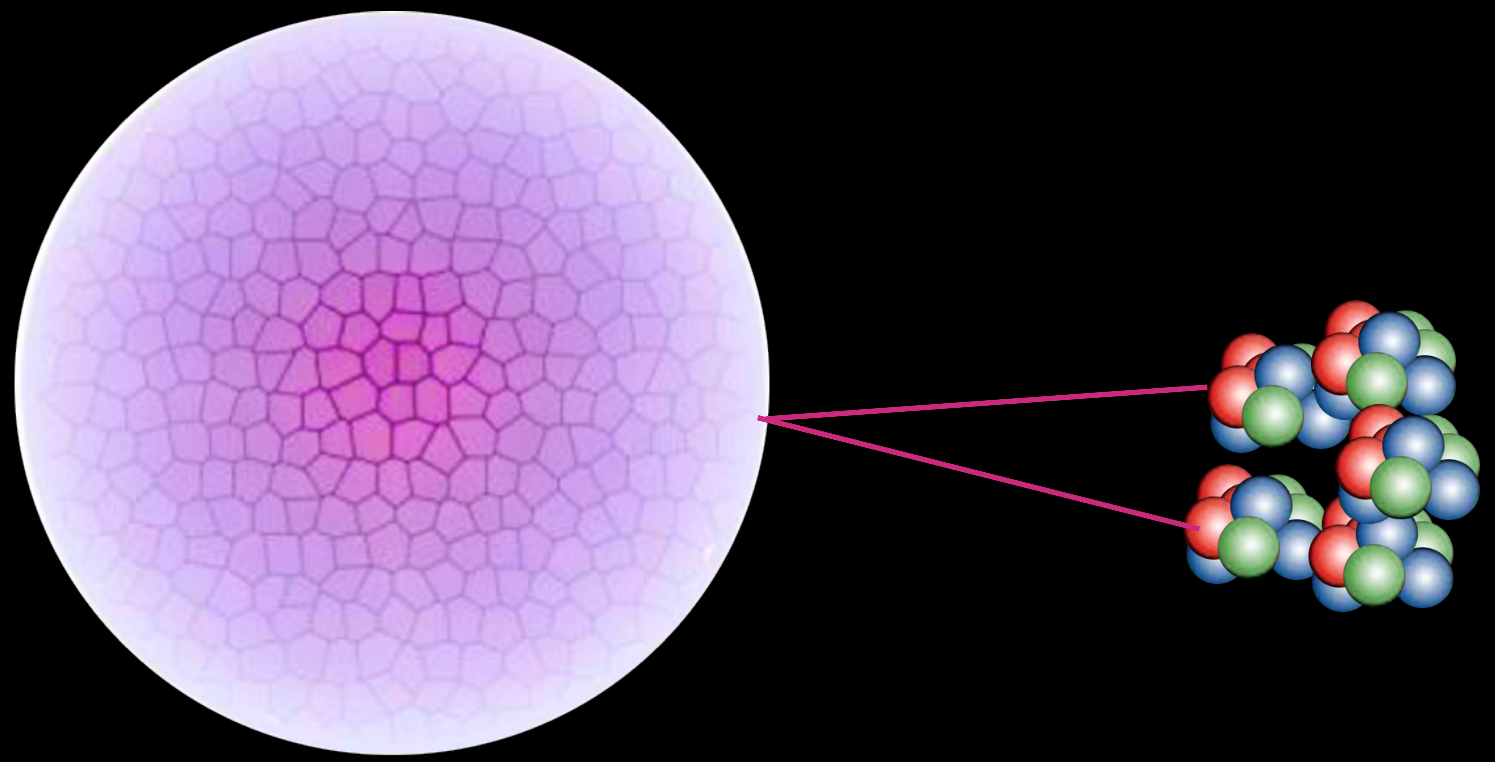
SGR 1806-20



Credit: Watts and Strohmayer, 2006

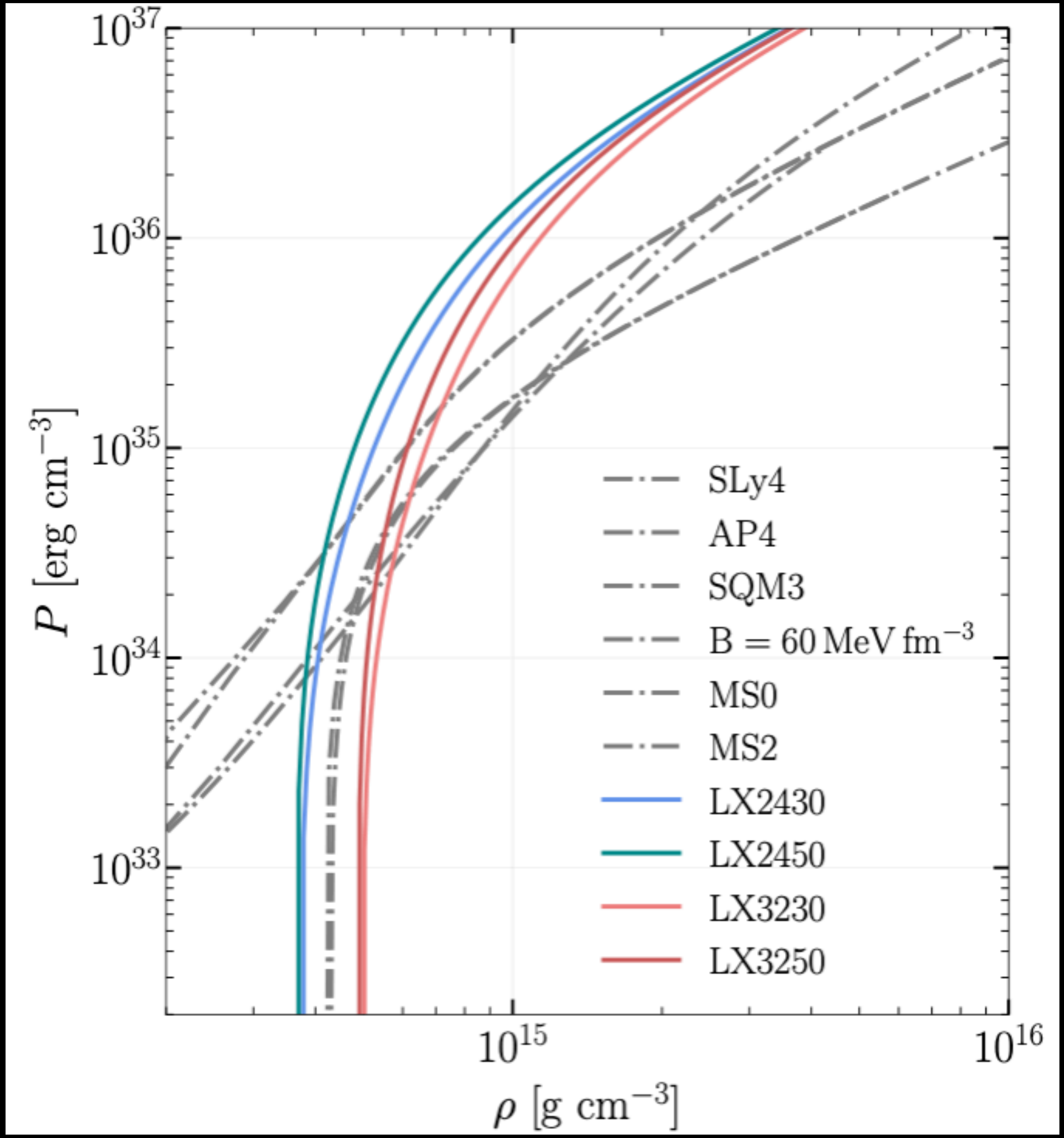
Xu’s conjecture: quarks could be clustered or localized. Strangeon stars (SSs)

Strangeons (quark clusters)



Xu, ApJL, 2003; Lai & Xu, MNRAS, 2009;
Gao et al., MNRAS, 2022; Li et al., MNRAS, 2023

μ is the constant



Torsional oscillations of SSs

$$Y'' + \left(\frac{4}{r} + \Phi' - \Lambda' + \frac{\mu'}{\mu}\right) Y' + \left[\frac{\rho + P}{\mu}\omega^2 \mathrm{e}^{-2\Phi} - \frac{(\ell + 2)(\ell - 1)}{r^2}\right] \mathrm{e}^{2\Lambda} Y = 0$$

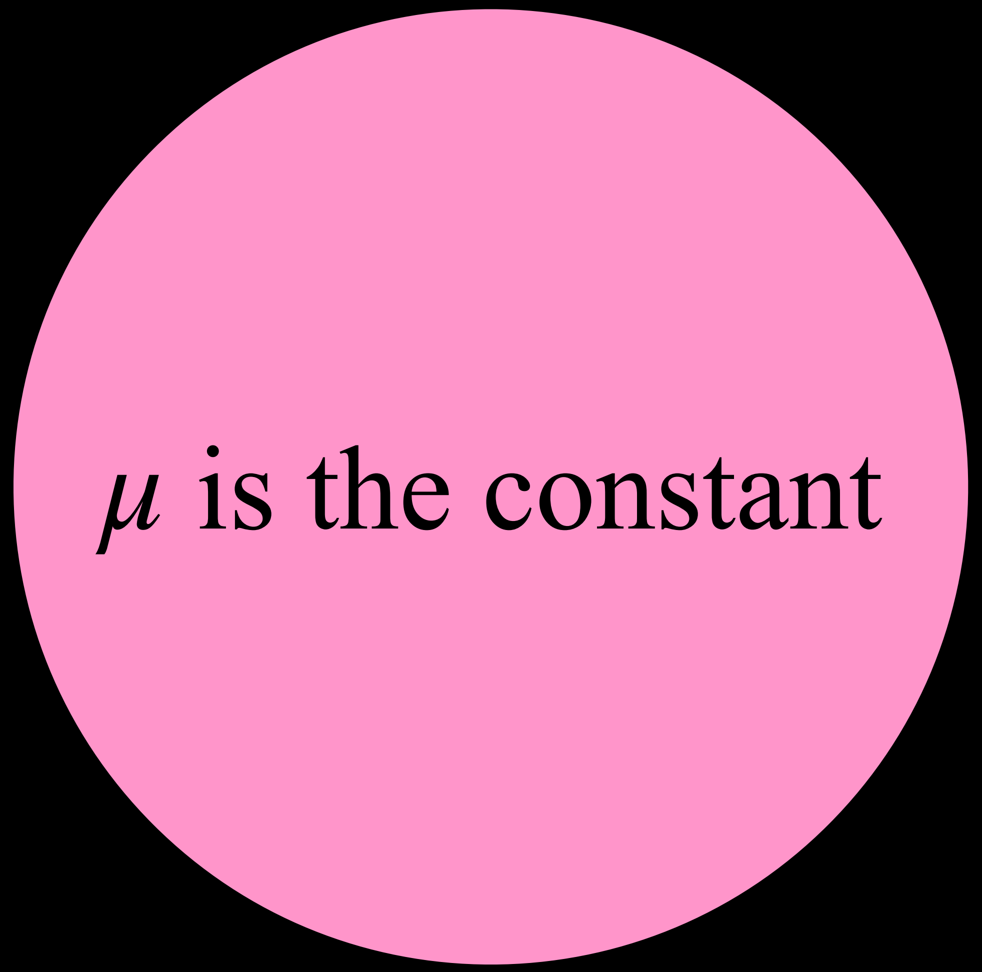
(1) No magnetic field

(2) Eigenvalue problem

(3) We need some parameters:

M and R of strangeon star
(Lennard-Jones potential)

$\mu = 4 \times 10^{32}\,\mathrm{erg\,cm^{-3}}$ Xu, 2003



strangeon star

The frequency of the n = 0, l = 2 mode is 198 Hz

The frequency of the n = 1, l = 2 mode is 448 Hz

The frequency of the n = 6, l = 3 mode is 1821 Hz

Attributing to the large shear modulus of SSs, our results explain well the high-frequency QPOs ($\gtrsim$ 150 Hz)

Interface mode of the ocean-crust

Such an ocean layer could have a width in the range of $\sim 10 - 50\,\mathrm{m}$, with density and temperature in the range of $10^6 - 10^9\,\mathrm{g\,cm^{-3}}$ and $10^8 - 10^9\,K$, respectively

Piro and Bildsten, 2005

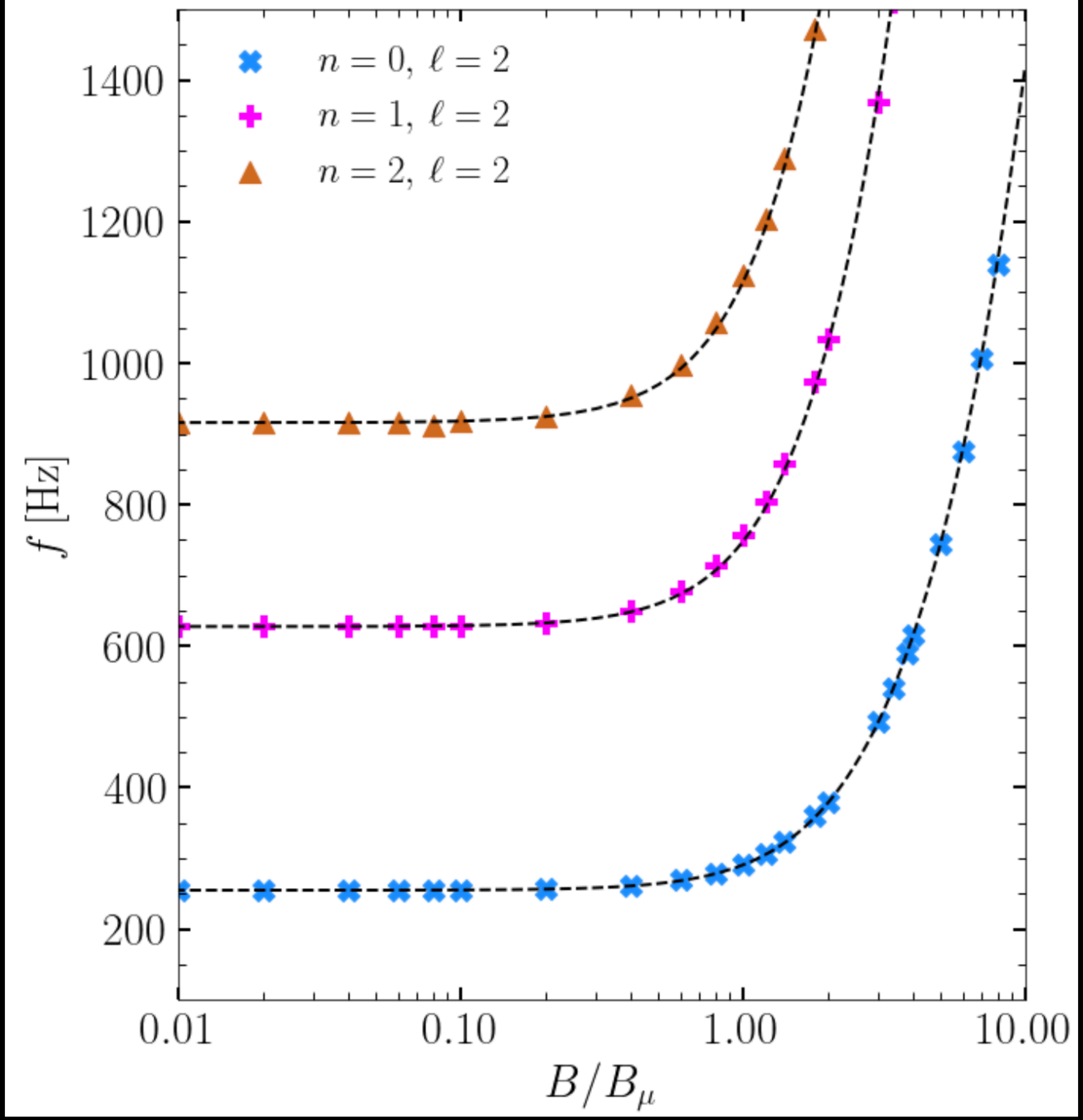
$$f = 16.5\,\mathrm{Hz}\left(\frac{\Gamma}{173}\right)^{1/2}\left(\frac{T_8}{4}\right)^{1/2}\times\left(\frac{64}{A}\right)^{1/2}\left(\frac{10\,\mathrm{km}}{R}\right)\left[\frac{\ell(\ell+1)}{2}\right]^{1/2}$$

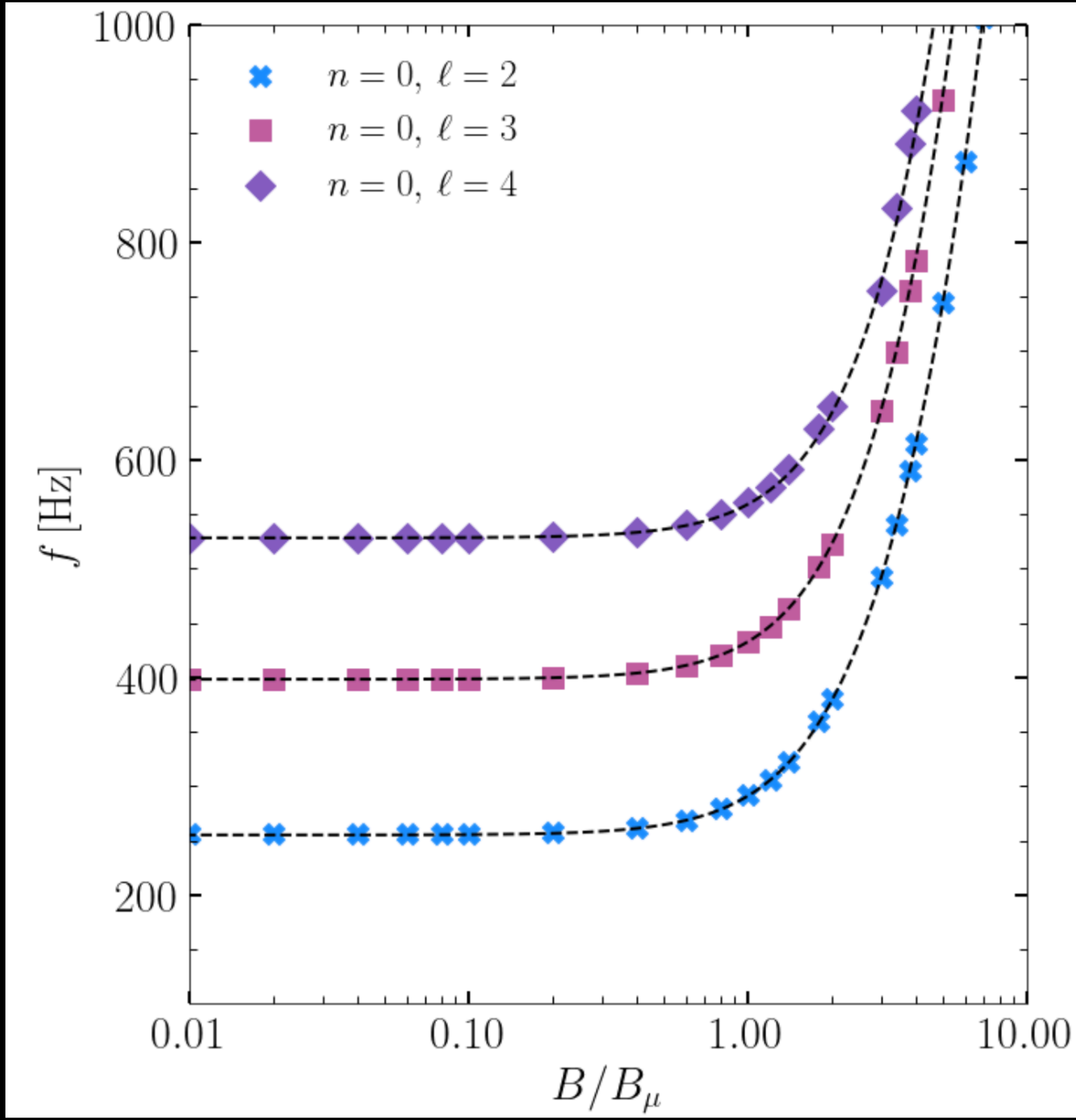
$$\Gamma \equiv \frac{(Ze)^2}{ak_{\mathrm{B}}T} = \frac{127}{T_8/4}\left(\frac{Z}{30}\right)^2\left(\frac{64}{A}\right)^{1/3}\left(\frac{\rho}{10^9\,\mathrm{g\,cm^{-3}}}\right)^{1/3} \qquad T_8 \equiv T/10^8\mathrm{K}$$

The low-frequency QPOs ($\lesssim 150\mathrm{Hz}$) can also be interpreted when the ocean-crust interface modes are included

Effect of the magnetic field

The typical magnetic field strength is defined as $B_\mu \equiv (4\pi\mu)^{1/2} = 4 \times 10^{16}\,\mathrm{G}$

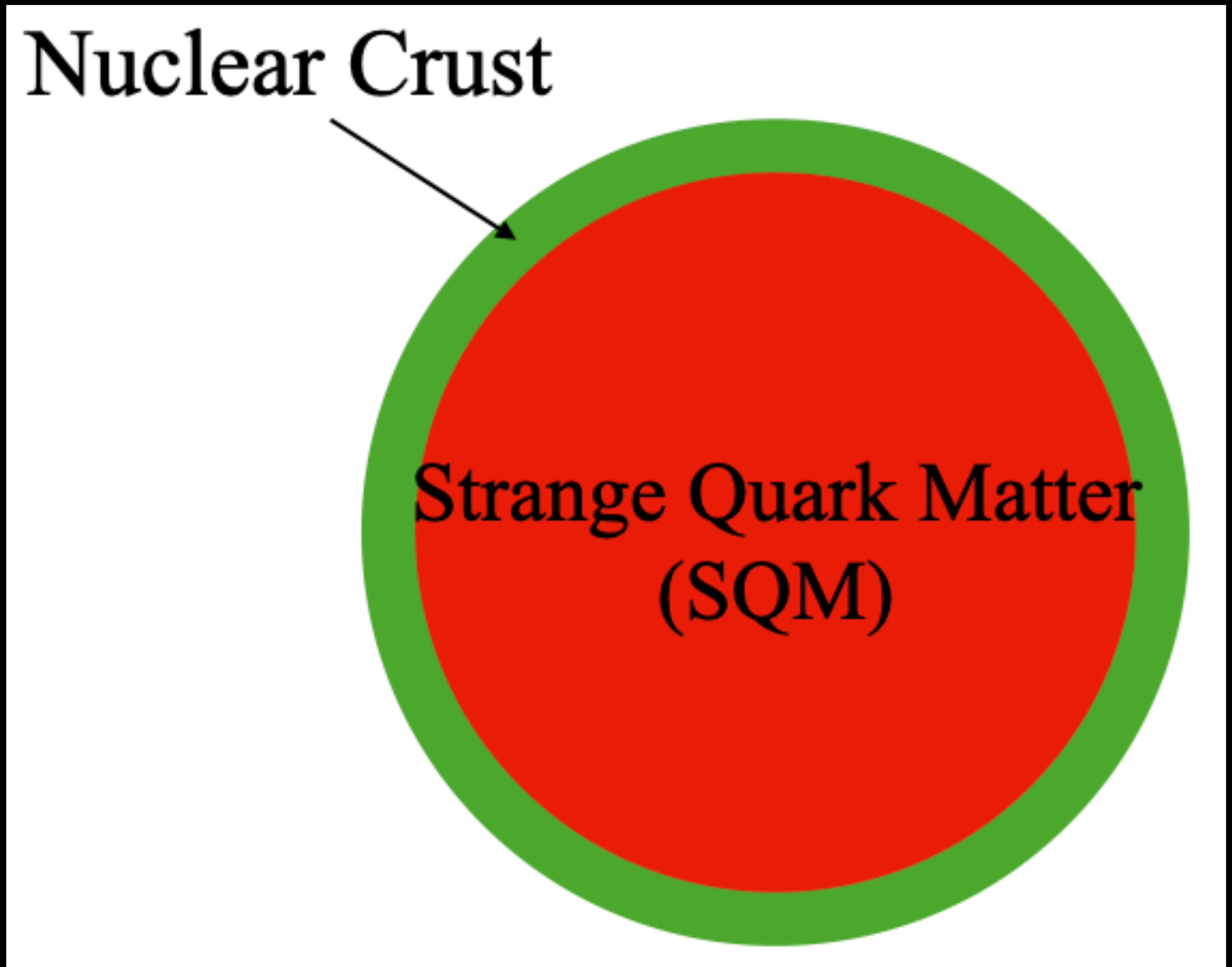




Comparison with the QSs

(I) Thin nuclear crust

Alcock, Farhi & Olinto, 1986

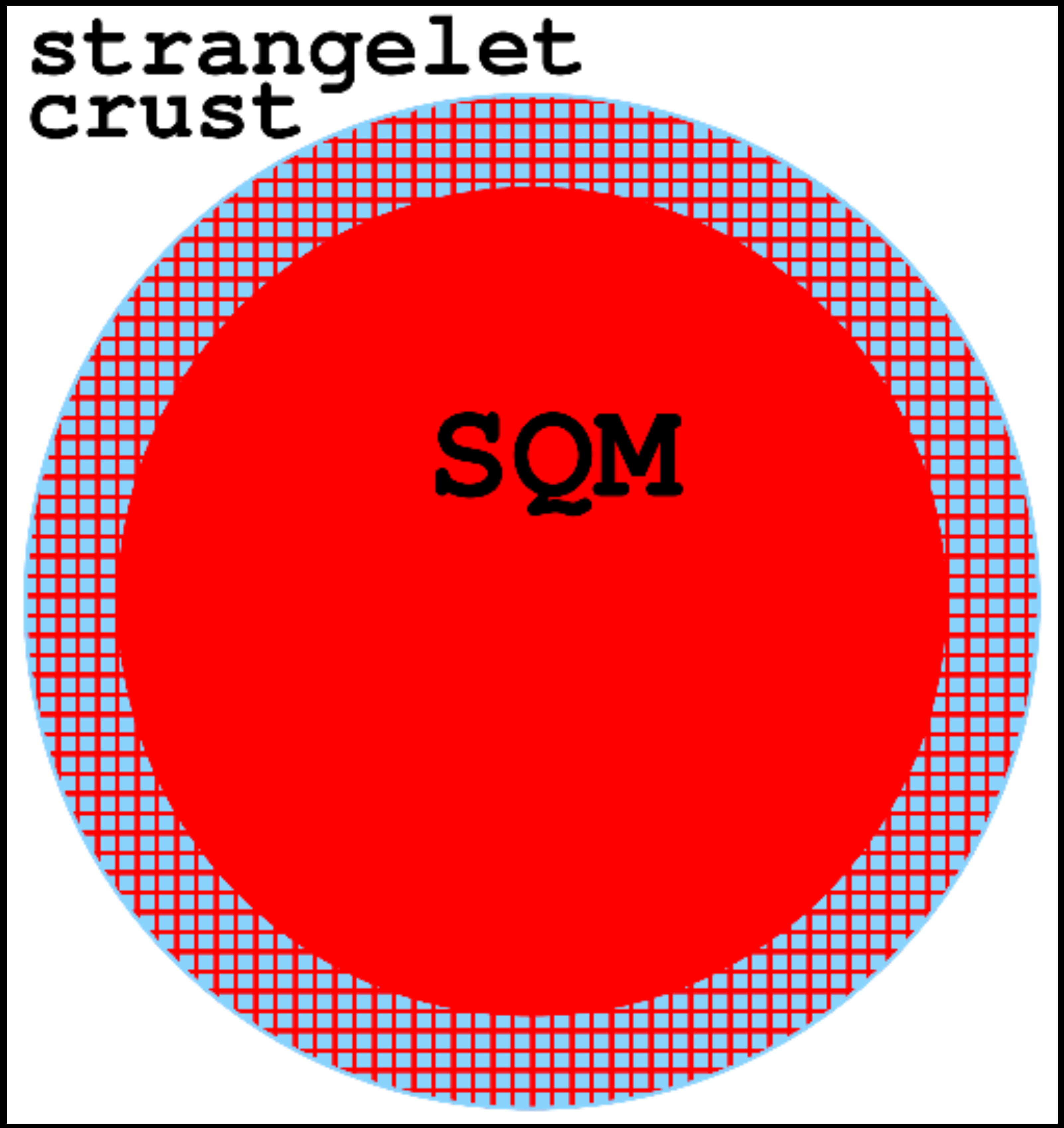


The crust density extends down to neutron drip density: BPS EOS

Baym, Pethick, and Sutherland, 1971

(II) Strange nugget crust

Jaikumar et al., 2006



Credit: Alford, 2008

Alfven and shear speed for QSs

Nuclear crust and strange nugget crust

Jaikumar et al., 2006

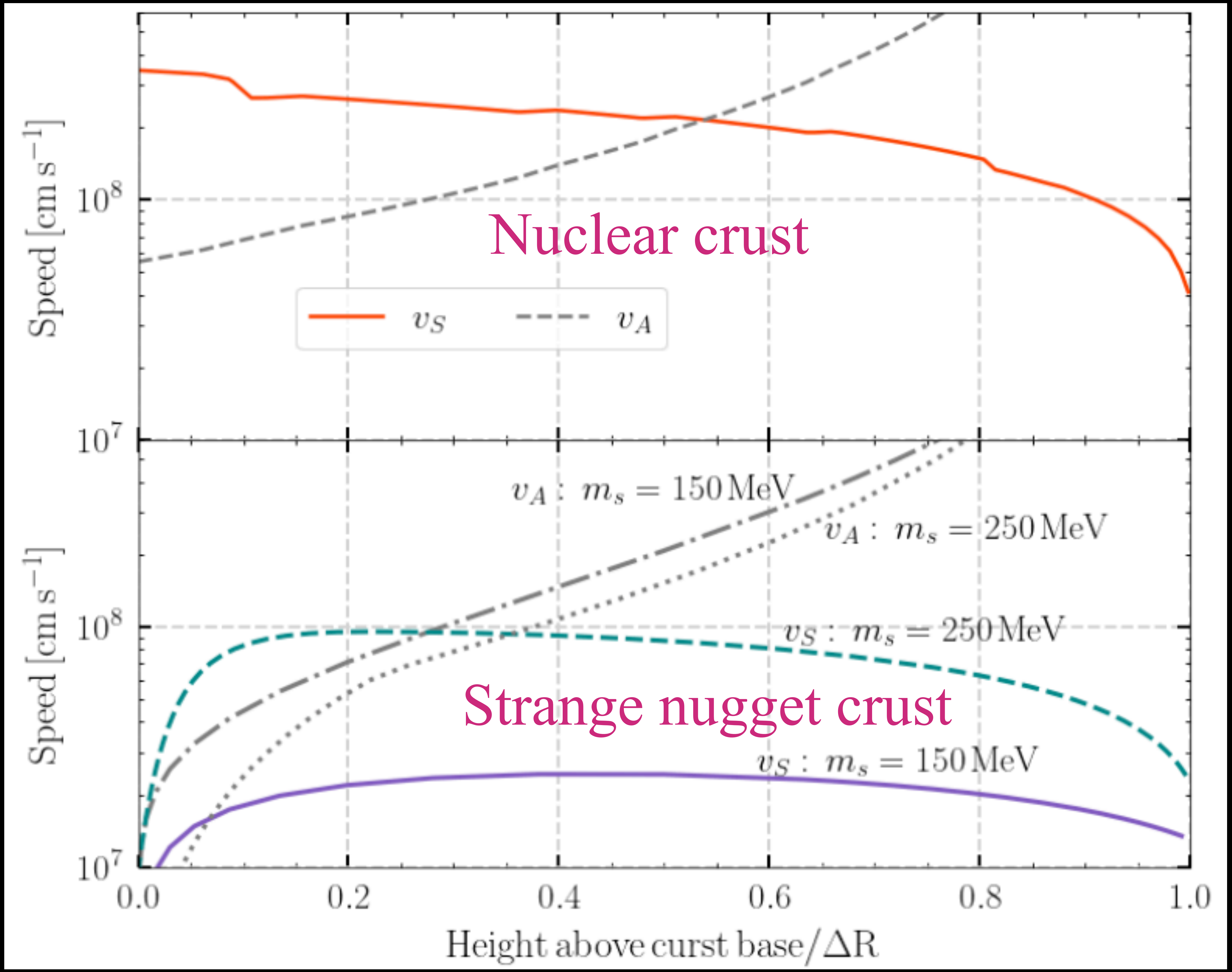
Watts and Reddy, 2007

Alfven speed: $v_A = B/(4\pi\rho)^{1/2}$

Shear speed: $v_S = (\mu/\rho)^{1/2}$

(a) Shear speed is lower in the nugget crust than in the thin nuclear model

(b) Shear modulus and shear speed sensibility depend on the strange quark mass m_s



Effect of the magnetic field

Thin nuclear crust:

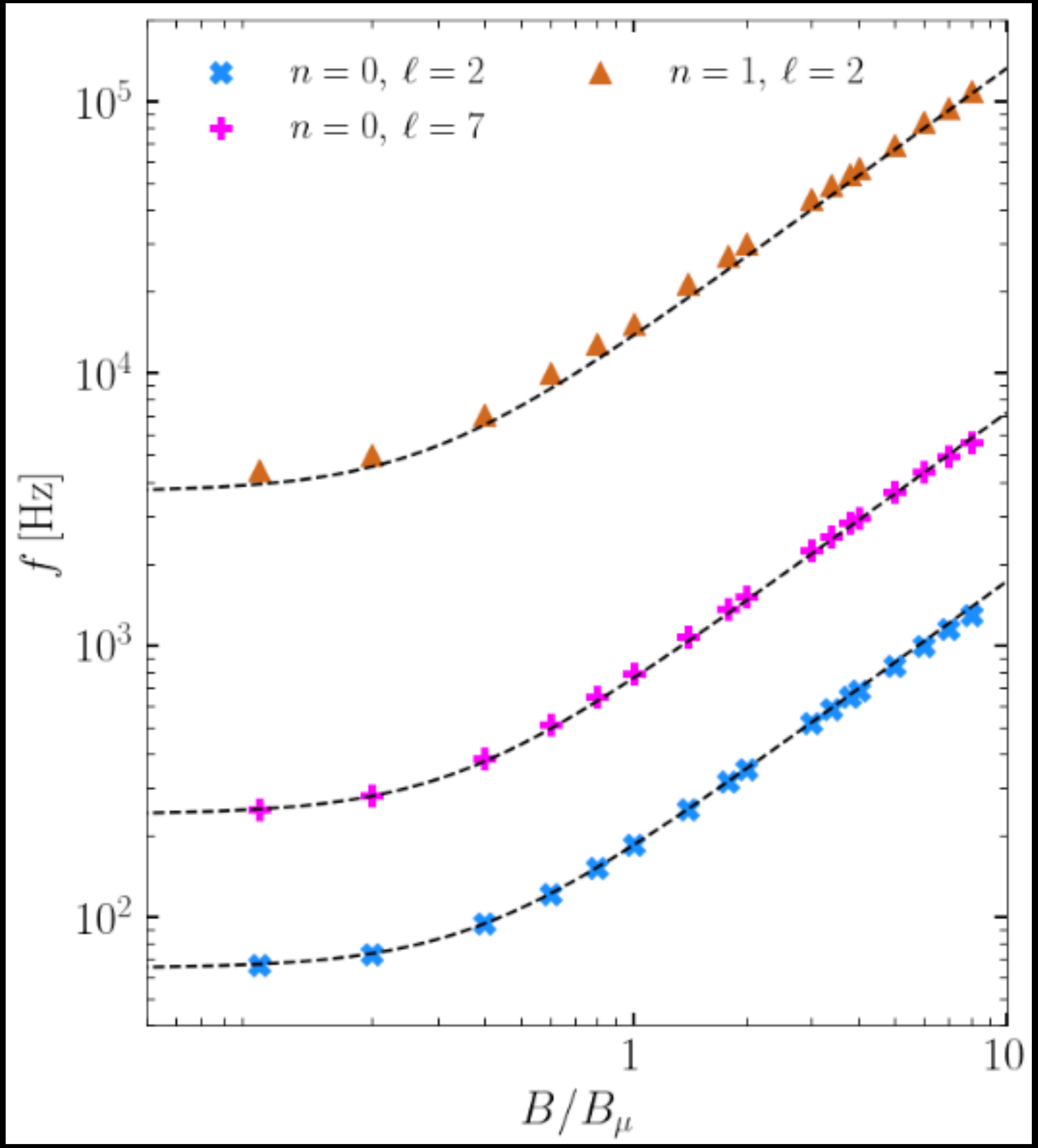
Bag constant = 60 MeV fm^{-3}

Crust thichness = 315 m

$$\frac{{}_\ell f_n}{{}_\ell f_n^{(0)}} \approx \left[1 + {}_\ell\alpha_n \left(\frac{B}{B_\mu}\right)^2\right]^{1/2}$$

$B_\mu = 1 \times 10^{14}\,\mathrm{G}$

Fundamental mode can be fit if mass is large, but overtone frequencies are far too high



Effect of the magnetic field

Strange nugget crust

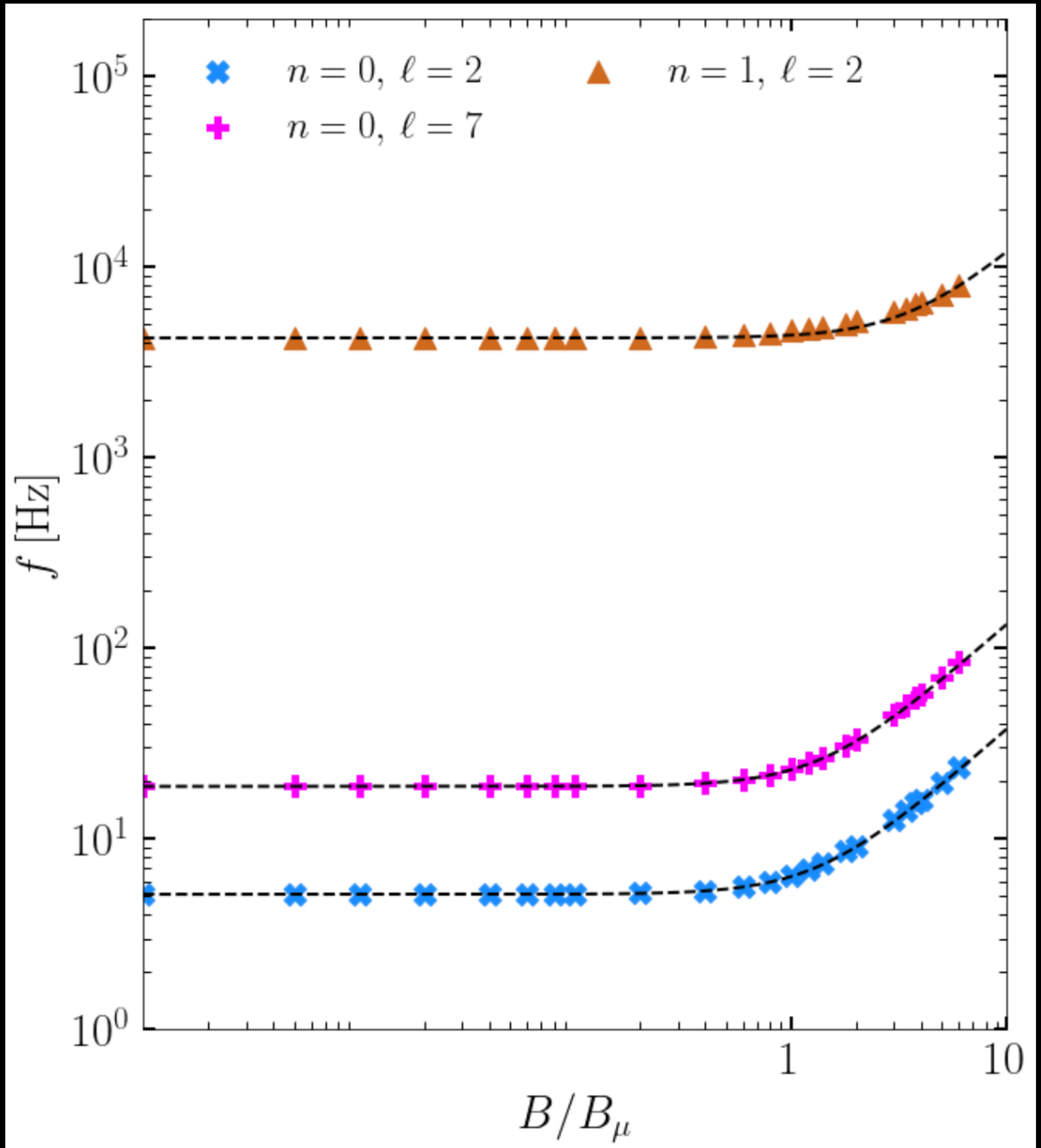
Quark mass $m_s = 150\,\text{MeV}$ Crust thichness = 40 m

$B_\mu = 4 \times 10^{11}\,\text{G}$

$$\frac{{}_\ell f_n}{{}_\ell f_n^{(0)}} \approx \left[1 + {}_\ell\alpha_n \left(\frac{B}{B_\mu}\right)^2\right]^{1/2}$$

(1) The frequency of the n = 0, l = 2 mode is 5.16 Hz

(2) There is no model that would permit a fundamental in the range 28–30 Hz



Despite additional uncertainty in parameters, cannot fit overtone unless magnetic field is an order of magnitude smaller than expected

Summary

(1) Interface mode to explain low-frequency QPOs between a few tens of Hz and up to 150 Hz

(2) Global toroidal oscillation to explain the high-frequency QPOs above 150 Hz

(3) The frequencies of toroidal shear modes in QSs crusts have serious difficulty explaining the QPO frequencies observed

Thank you for your attention!