ELECTROMAGNETIC SIGNALS FROM BARE STRANGE STARS

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Mannarelli *et al.* **arXiv:1403.0128**

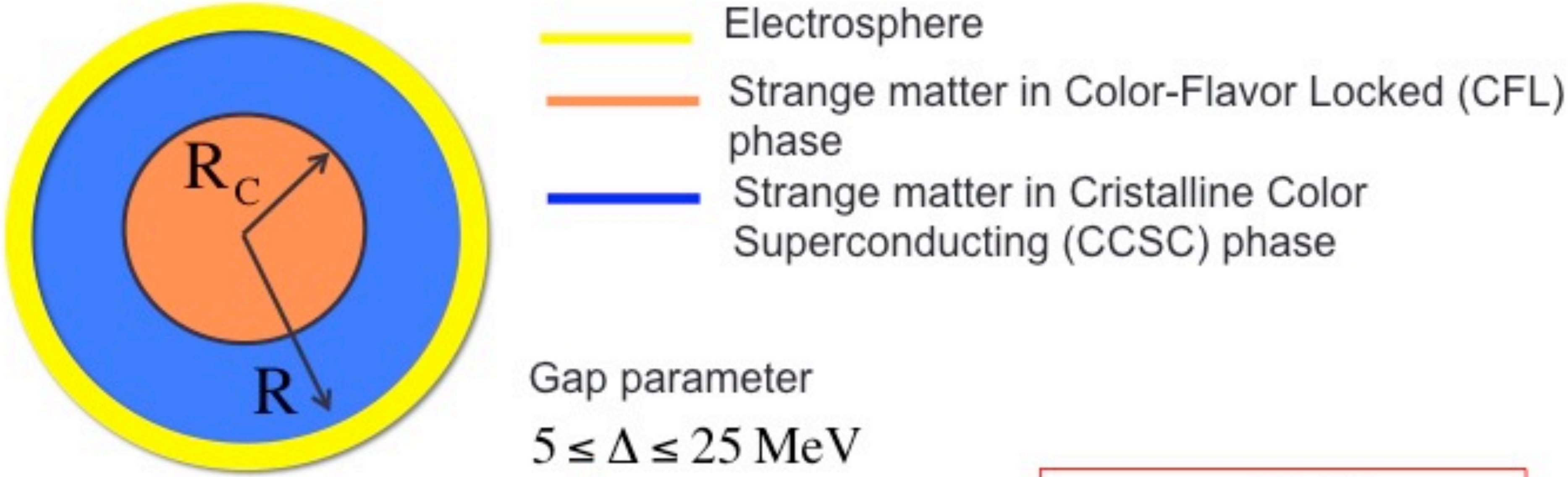
"The Structure and Signals of Neutron Stars, from Birth to Death"
Florence 24-28 March 2014

Outline

- Star Structure
- Charge Distributions
- Torsional Oscillations
- Emitted EM Power
- Prediction vs Observations

Structure

Spherically symmetric nonrotating star



Gap parameter

$$5 \le \Delta \le 25\ \mathrm{MeV}$$

$$\nu_0 = 2.47\ \frac{\mathrm{MeV}}{\mathrm{fm}^3} >> \nu_{NS}$$

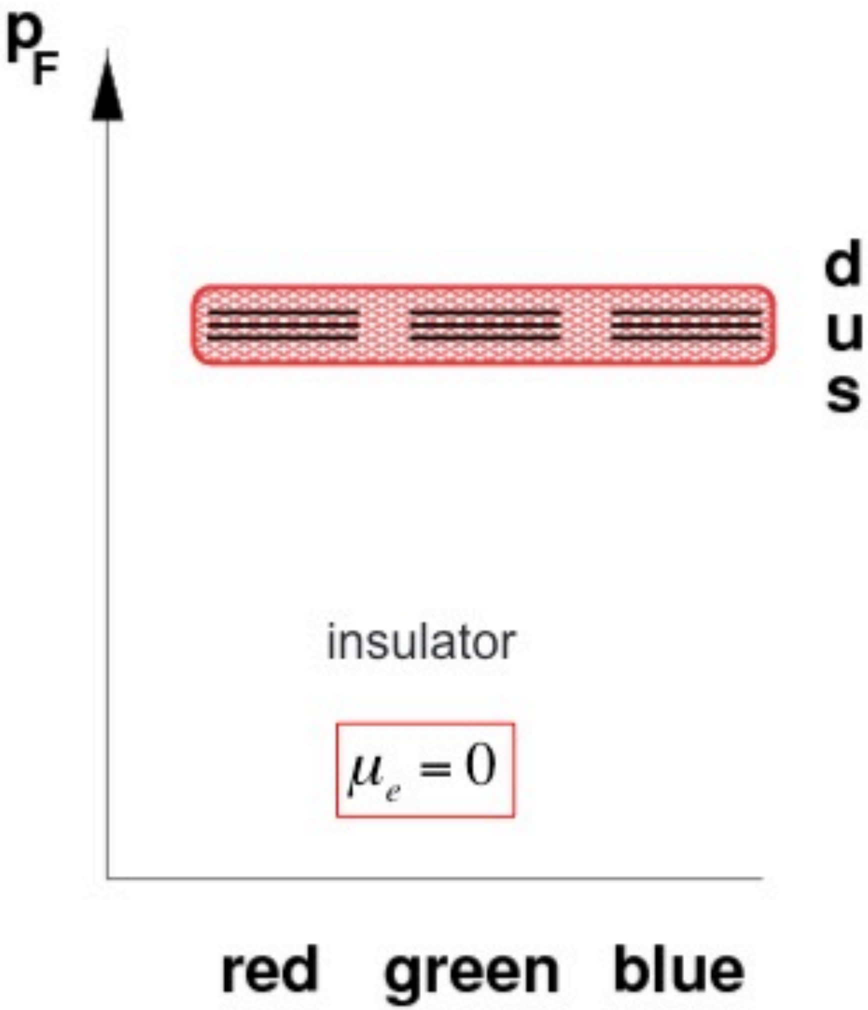
Shear Modulus of CCSC phase

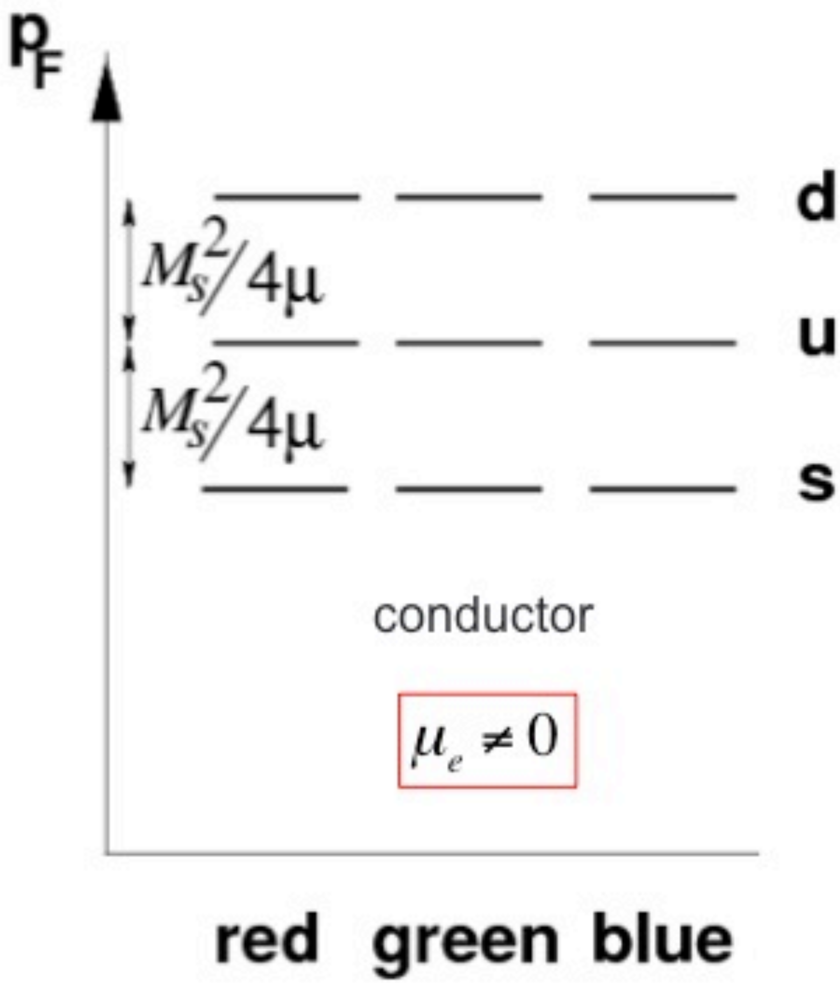
$$\nu \approx \nu_0 \left(\frac{\Delta}{10\ \mathrm{MeV}}\right)^2 \left(\frac{\mu}{400\ \mathrm{MeV}}\right)^2$$

Mannarelli *et al.* PRD 76(2007)

Anglani *et al.* arXiv:1302.4264

CFL vs CCSC





Alford, Nucl.Phys. A830 (2009)

Equilibrium Configurations

We solved the TOV equations for two estreme sets of EOS parameters

$$\Omega_{\rm QM} = -\frac{3}{4\pi^2} a_4 \mu^4 + \frac{3}{4\pi^2} a_2 \mu^2 + B_{\rm eff}$$

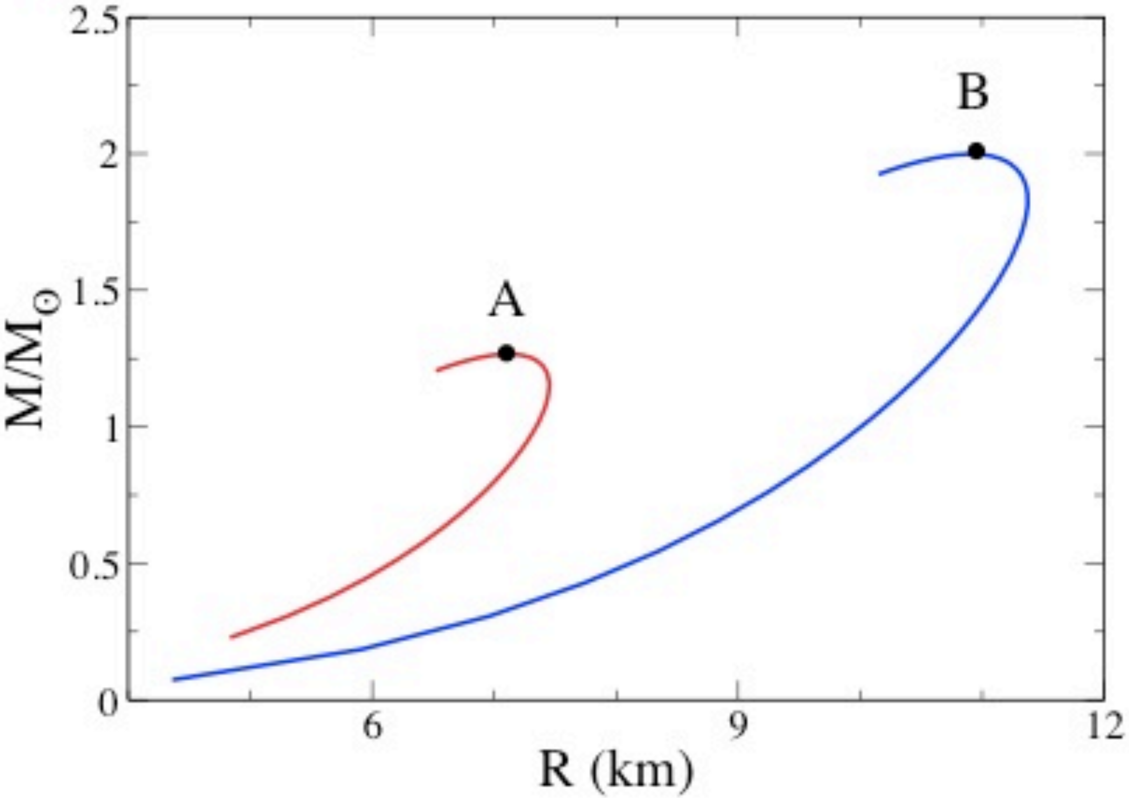
Alford *et al.* Astrophys.J.629 (2005)

$A)\ \mathrm{M} = 1.27\mathrm{M}_\Theta \quad \mathrm{R} \cong 7.1\,\mathrm{km}$

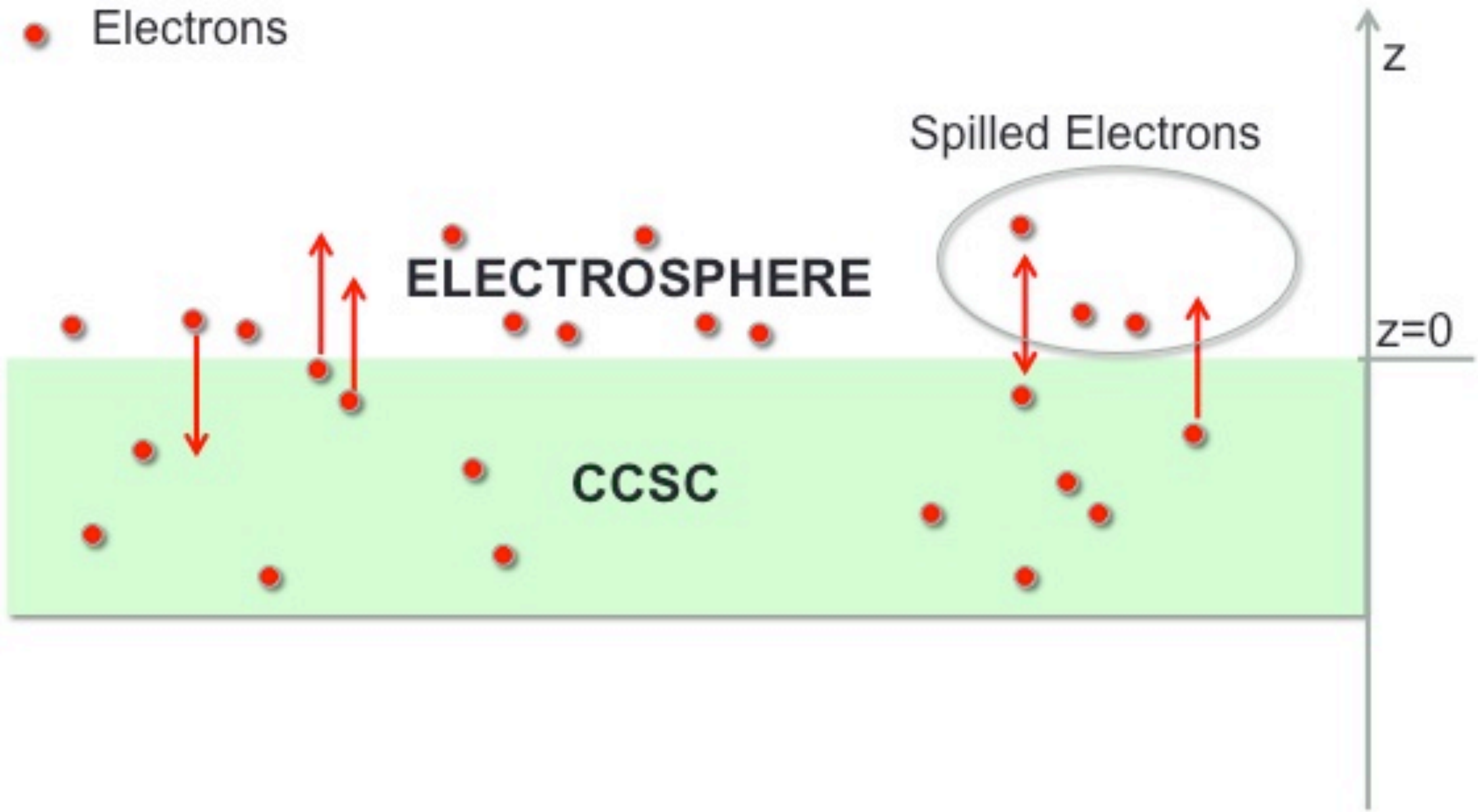
$\rho_C \cong 5 \cdot 10^{15}\,\mathrm{g} \cdot \mathrm{cm}^{-3}$

$B)\ \mathrm{M} = 2\ \mathrm{M}_\Theta \quad \mathrm{R} \cong 10.9\,\mathrm{km}$

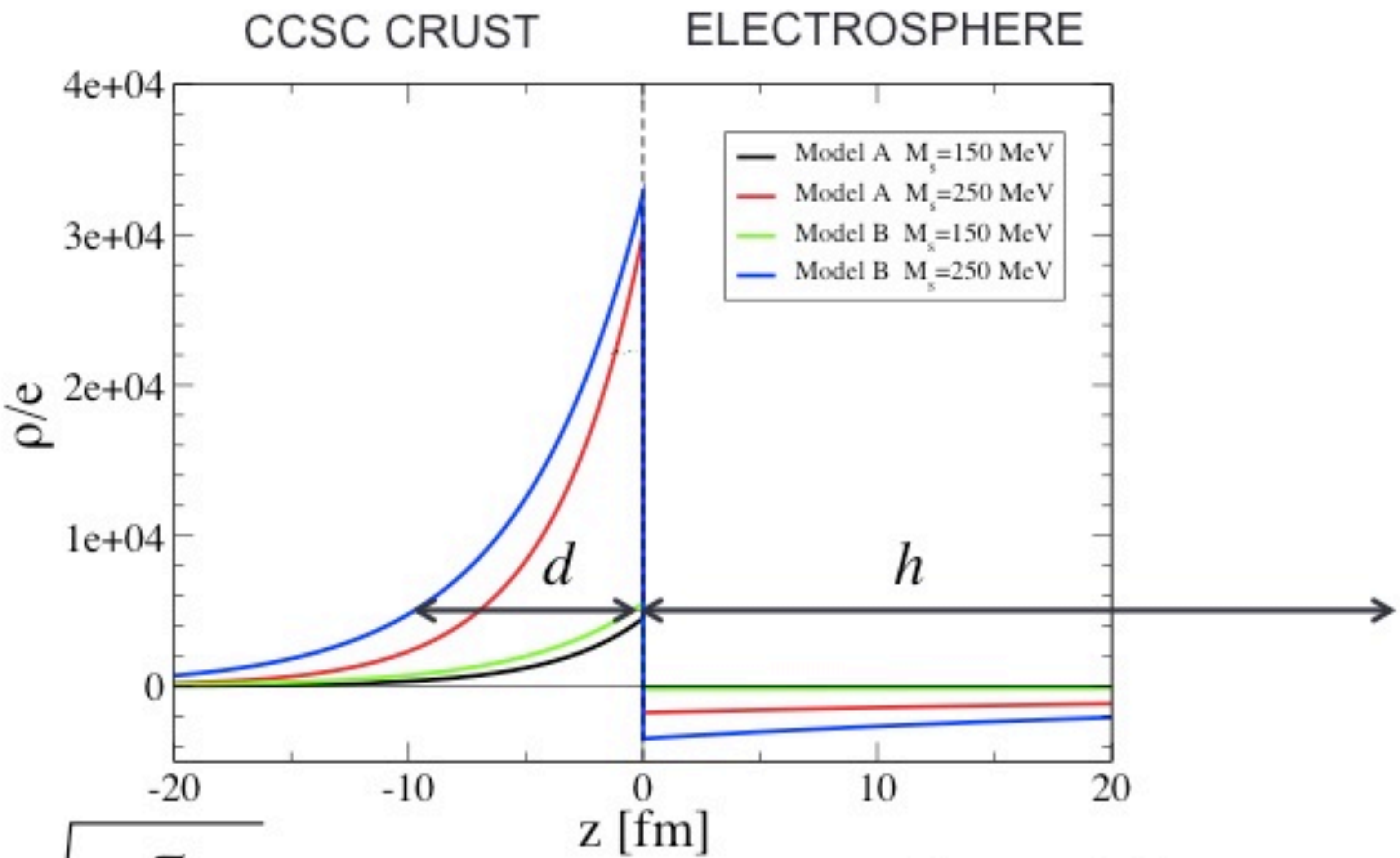
$\rho_C \cong 2 \cdot 10^{15}\,\mathrm{g} \cdot \mathrm{cm}^{-3}$



Charge Distribution



Charge Distribution



$$d = \sqrt{\frac{\pi}{8\alpha_{em}\mu^2}} \approx 5\text{fm}$$

$$h \propto \left(M_s^2 / \mu\right)^{-1} \approx 100\text{fm}$$

Positive Charge Distribution

Net charge inside the CCSC crust

$$\sum_i Q_i n_i(z) = b e^{z/d} \quad z \le 0$$

Debye screening length approximately given by the free Fermi gas

Model	μ_R (MeV)	M_s (MeV)	d (fm)	b (MeV^3)	V_0 (MeV)
A	387	150	3.8	4.5×10^3	14.2
A	387	250	3.9	3.0×10^4	37.4
B	302	150	4.9	5.5×10^3	17.8
B	302	250	3.3	5.2×10^4	46.9

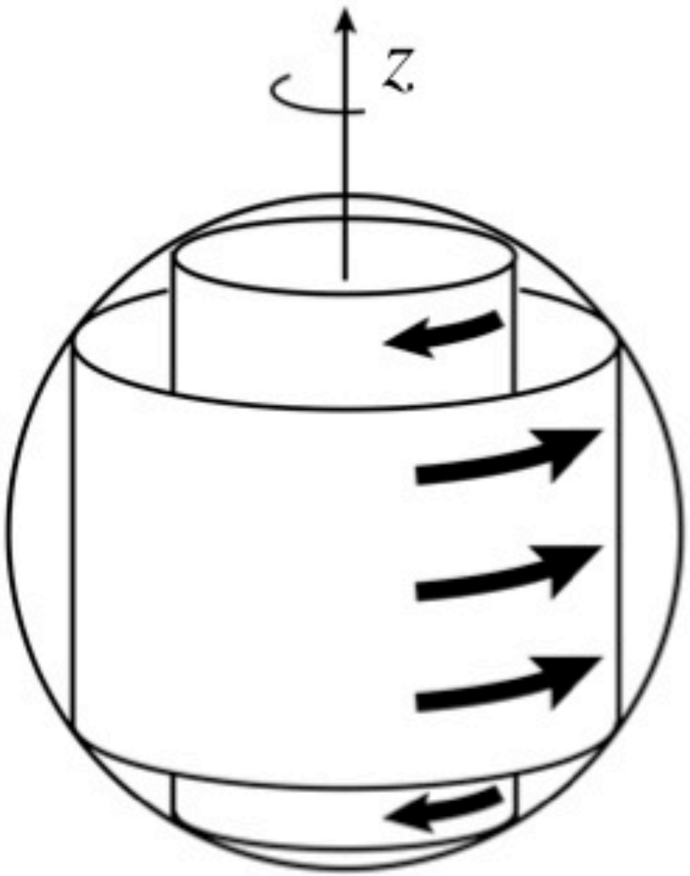
The total positive charge Weakly depends on the Star Model A or B

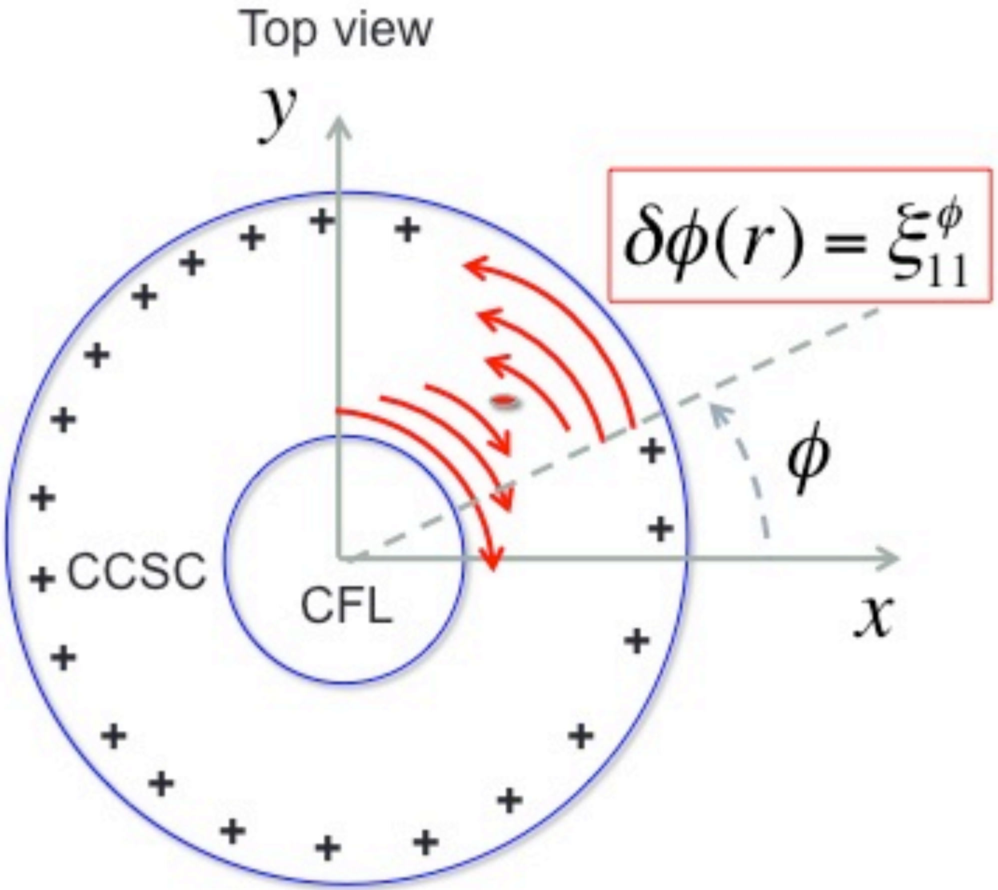
$$Q^+ \cong 10^4 \, \frac{\text{MeV}}{\text{fm}^3}$$

Depends on the Mass of the Strange quark

$$\text{M}_s \uparrow \Rightarrow n_e(z) \uparrow$$

Torsional Perturbation l=1 n=1





Frequency of the first mode

Only 1 component of the displacement

$$\delta\phi(r) = \xi_{11}^{\phi} = \frac{W_{11}(r)}{r} e^{i\omega_{11}t}$$

$$\rho_0 = 10^{15} \frac{g}{cm^3}$$

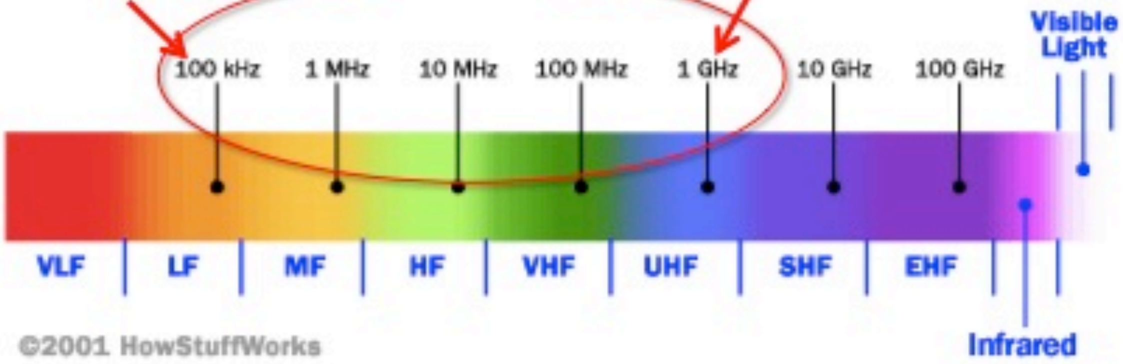
Frequency of the Mode

$$\omega_{11} \cong 0.06 \left(\frac{\nu}{\nu_0}\right)^{1/2} \left(\frac{1\text{km}}{D}\right)\left(\frac{\rho_0}{\rho_R}\right)^{1/2} \text{MHz}$$

Thickness of the CCSC crust

$\mathrm{D} \approx \mathrm{km}$ $\mathrm{D} \approx \mathrm{cm}$

RADIO FREQUENCY SPECTRUM



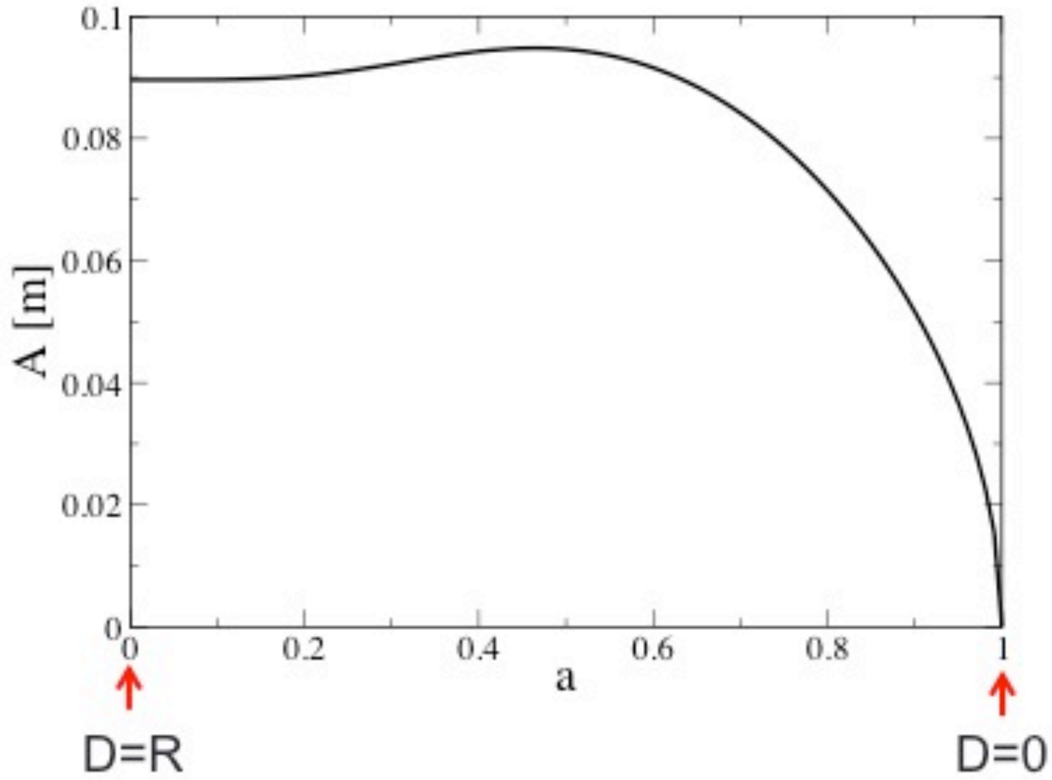
Amplitude of the Oscillation

$$\xi_{11}^{\phi} = \frac{W_{11}(r)}{r} e^{i\omega_{11} t}$$

A fraction of the energy of a glitch excites the l = 1, n = 1 mode

$$\alpha E_{\text{glitch}} = \frac{\rho_R}{2} \int \left|\delta u_{11}\right|^2 dV$$

$$\delta u_{11} = i\omega_{11}\xi_{11}$$



$$W_{11}(R) = A(a)\left(\frac{\nu}{\nu_0}\right)^{-1/2}\left(\frac{R}{10\text{km}}\right)^{-1/2}\left(\frac{\alpha E_{\text{glitch}}}{E_{\text{glitch}}^{\text{Vela}}}\right)^{1/2} \qquad E_{\text{glitch}}^{Vela} = 2.7 \cdot 10^{42}\,\text{erg}$$

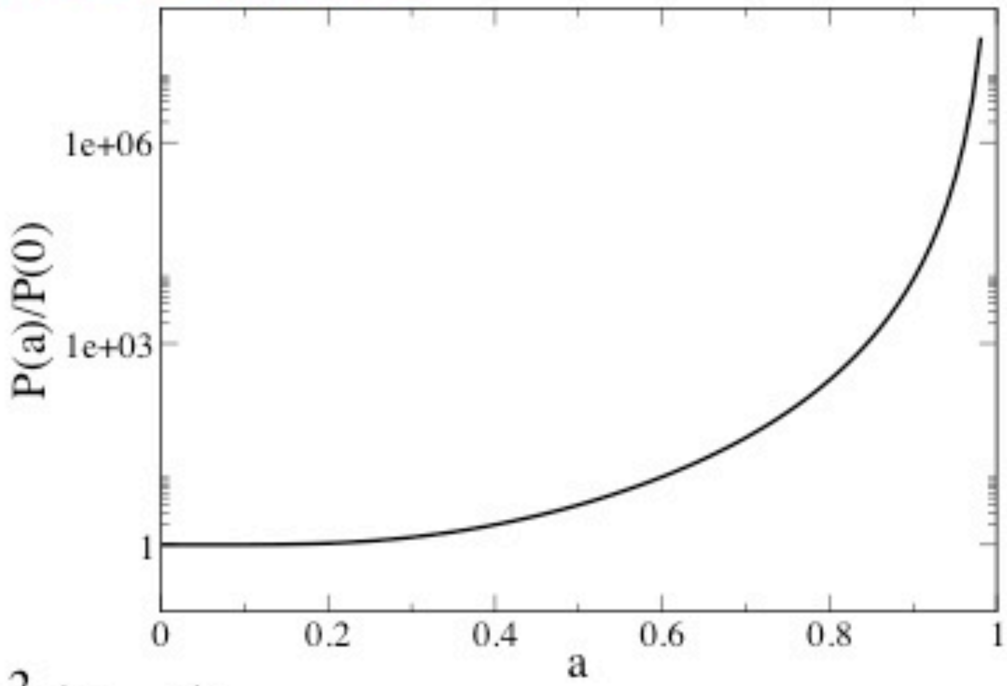
Oscillating Magnetic Dipole

Charge Current density

$$\delta J = e \sum_i Q_i n_i(r) \delta u_{11}$$

Far Field approximation $r >> R$

Coherent emission $c/\omega >> R$



$$P \propto \left(\omega_{11} R\right)^6 W_{11}(R)^2 Q_+^2 \sin^2(\omega_{11} t)$$

Time needed to emitt all the energy of the excited mode

$$T \cong \frac{\alpha E_{glitch}}{P}$$

Prediction vs Observations

- No periodicity
- Radio Frequency Band
- High Emitted Power
- Short Duration

$\omega \cong 60$ kHz ↑

$P \cong 10^{46}$ erg/s ↑

$T = 10^{-4}$ s ↓

$D \cong 1$km ↓

- Only frequencies ≥ GHz

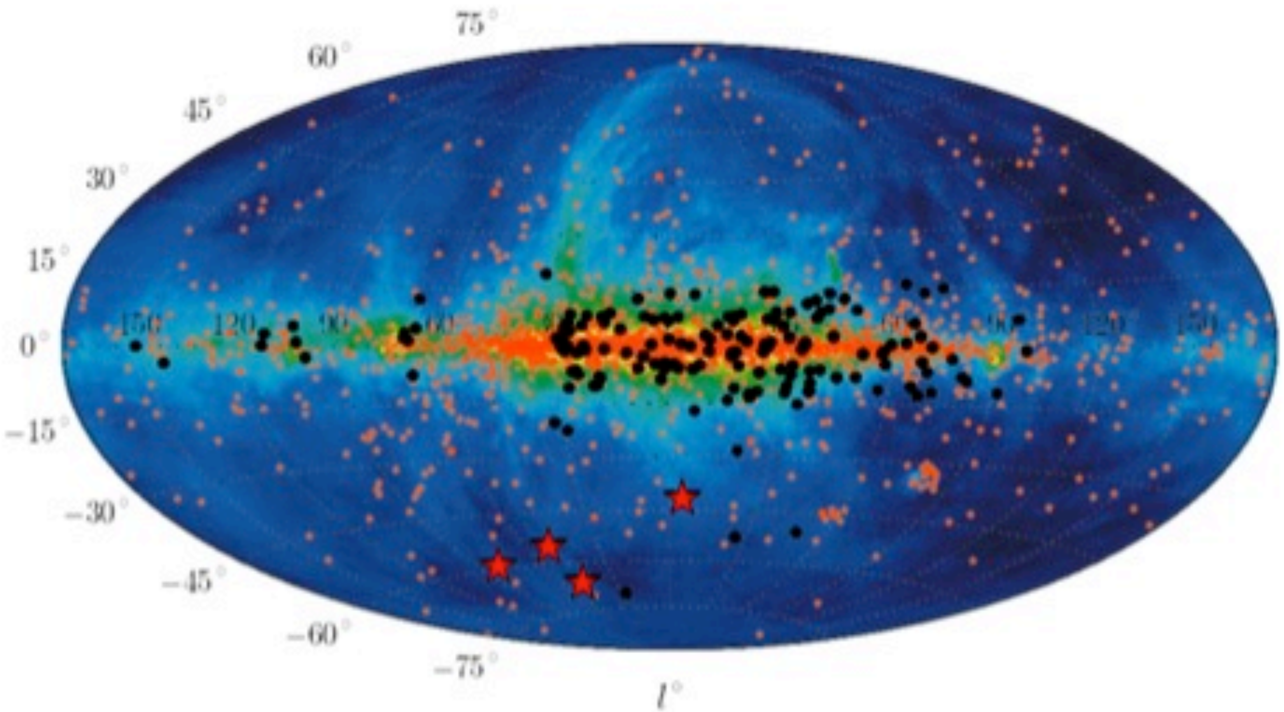
(Parkes 64 meter radio telescope)

Bandwidth of 400 MHz centered at 1.382 GHz

FAST RADIO BURSTS

D. Thornton, et al., Science, vol. 341, no. 6141, 2013

"detection of four nonrepeating radio transient events with millisecond duration at a distance of about 3.2 Gpc and extimated power of $P \leq 10^{49}$ erg/s



Open Questions

- The EM emission for higher frequency?
- What is the role of the electrosphere? 1 order of magnitude suppression by Thomson scattering
- What happens with a large background Magnetic field?
- What for higher modes (l=2)?
- ???

Assumptions

$$m_e \cong m_u \cong m_d \cong 0$$

$$\mu_i(z) = \mu_i - eQ_i\phi(z)$$

Local Weak equilibrium

$$\mu_u(z) + \mu_e(z) = \mu_d(z)$$

$$\mu_d(z) = \mu_s(z)$$

Poisson Equation

$$\frac{d^2\phi}{dz^2} = e\sum_i Q_i n_i(z)$$

Boundary Conditions

$$n_e(+\infty) = 0$$

$$n_q(-\infty) - n_e(-\infty) = 0$$

$$\frac{d\phi}{dz}(0^-) = \frac{d\phi}{dz}(0^+)$$

CFL

Internal dof

$$n_i(z) = C_i \frac{k_{F,i}(z)^3}{3\pi^2}$$

$$k_{F,i}(z) = \sqrt{\mu_i(z)^2 - m_i^2}$$

CCSC phase

Electrons

Shear Modulus in CCSC

- This large value of the shear modulus is due to the fact that the typical energy density associated with the oscillations of the condensate modulation is μ^2 Δ^2 , where Δ is determined by the strong interaction in the antitriplet channel. Instead, in conventional neutron star the associated energy is at the electromagnetic scale.

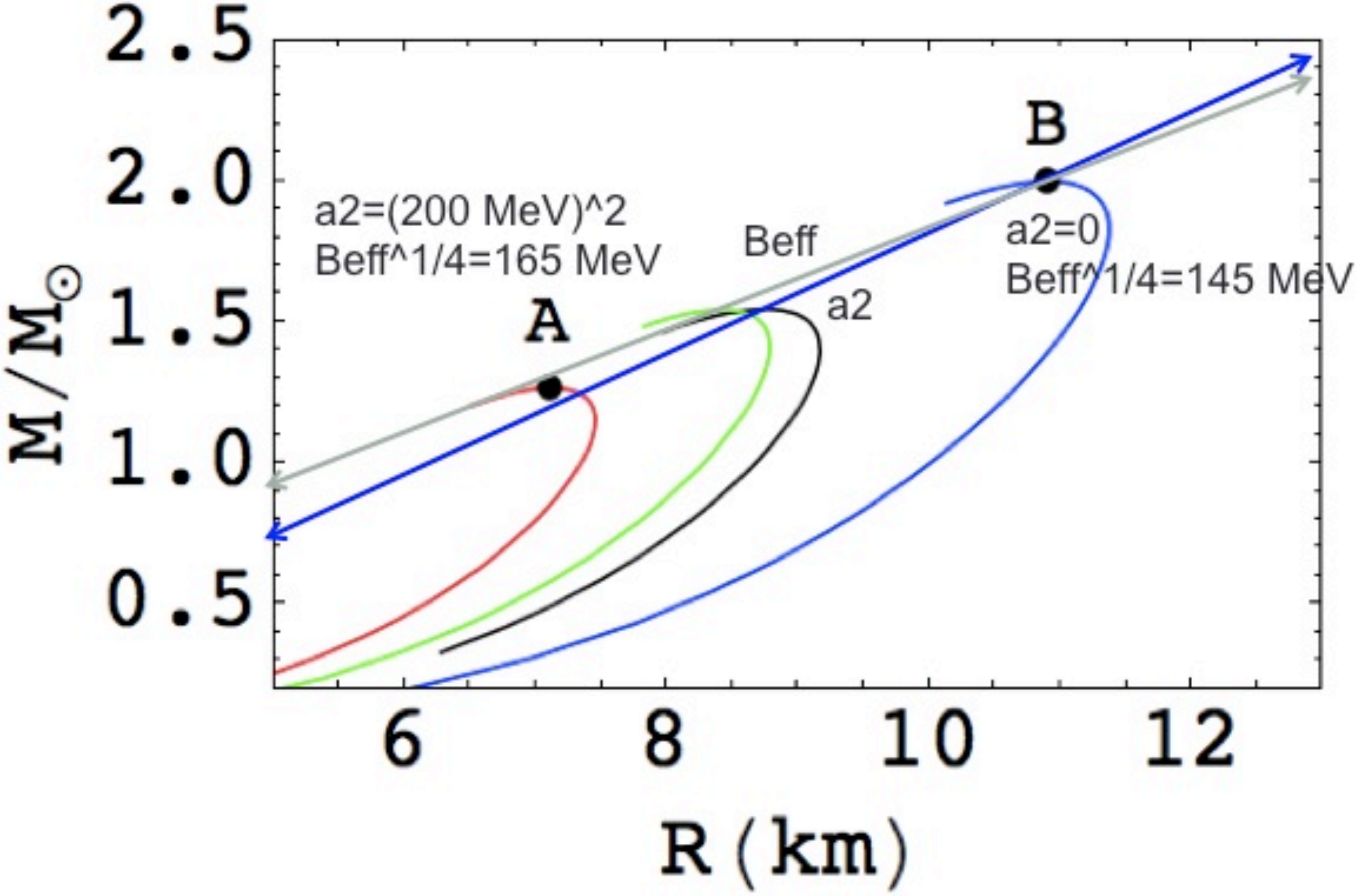
$$\mu_d(z) = \mu_s(z) = \mu + \frac{1}{3}V(z)$$

$$\mu_u(z) = \mu - \frac{2}{3}V(z)$$

$$V(z) = \mu_e(z) = \mu_e - e\phi(z)$$

$$\frac{d^2V}{dz^2} = -\frac{4\alpha}{3\pi}\sum_i Q_i C_i k_i^3(z)$$

$$\varepsilon = 3P + 4B_{\mathrm{eff}} + \frac{3}{2\pi^2} a_2 B_{\mathrm{eff}}$$



Torsional Perturbation l=1 n=1