Color Superconductivity and Exotic matter in Neutron stars

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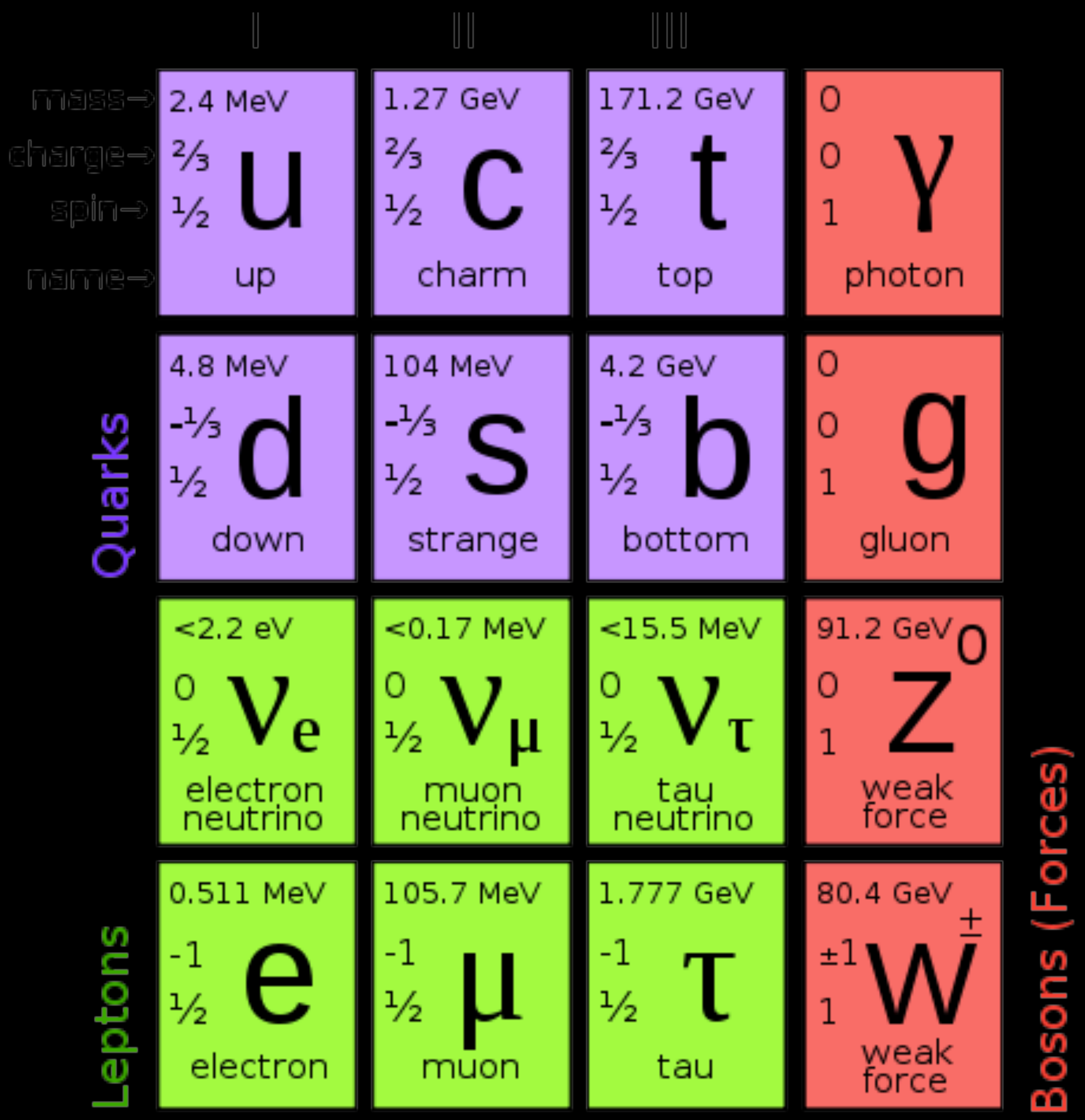
QCD

The theory describing the interactions between quarks and gluons



		I	II	III	Bosons (Forces)
Quarks	mass→ charge→ spin→ name→	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top	0 0 1 γ photon
		4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom	0 0 1 g gluon
Leptons		<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 weak force
		0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ weak force

Asymptotic Freedom

The force between quarks goes to zero at asymptoticly short distances (very large energy scales).

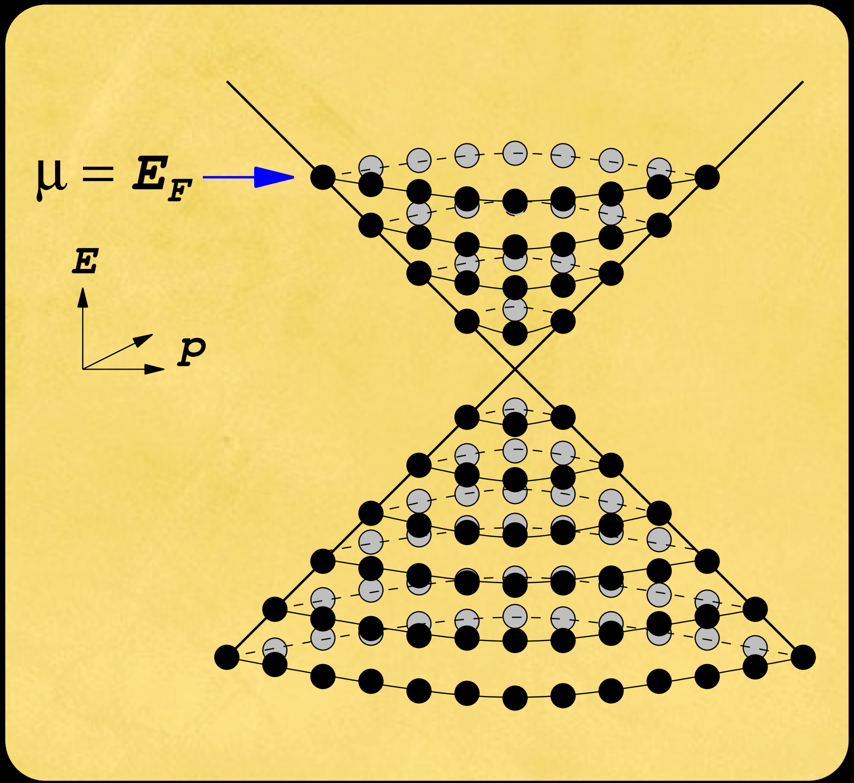
Confinement

Quarks are confined inside baryons and mesons.

BCS Theory

No interaction → Adding or subtracting particles or holes near the fermi surface would cost zero free energy.

In the presence of an attractive potential, no matter how weak, cooper pairs will form.



$$F = E - \mu N$$

Color Superconductivity

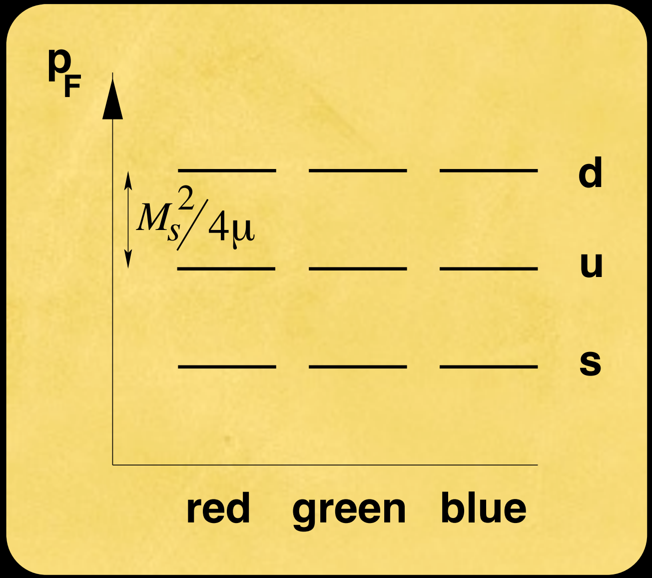
Barrois and Frautschi 1977
Bailin and Love 1979

In QCD the "color Coulomb" interaction is attractive between quarks whose color wave function is antisymmetric.

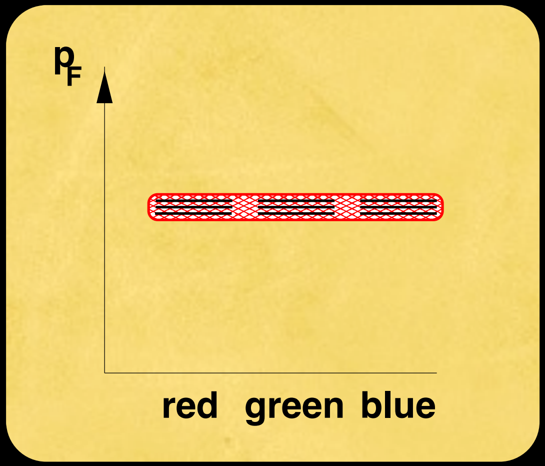
Asymptotic freedom + BCS theory $\longrightarrow$ Color Superconductivity

Matter at sufficiently large densities and low temperatures is a color superconductor, which is a degenerate Fermi gas of quarks with a condensate of Cooper pairs near the Fermi surface.

Unpaired quarks



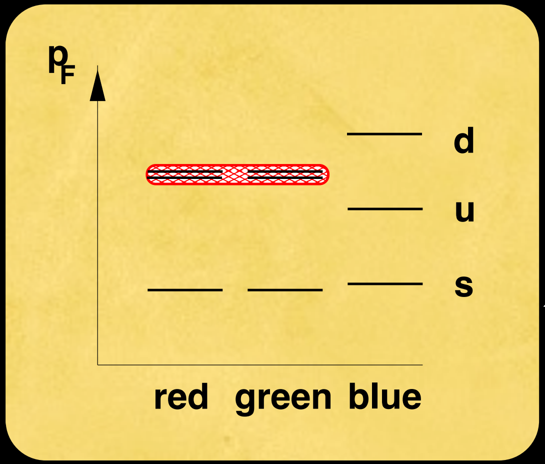
CFL



Highest densities
Color-flavor-locked
phase favored

All quarks are gapped.

2SC



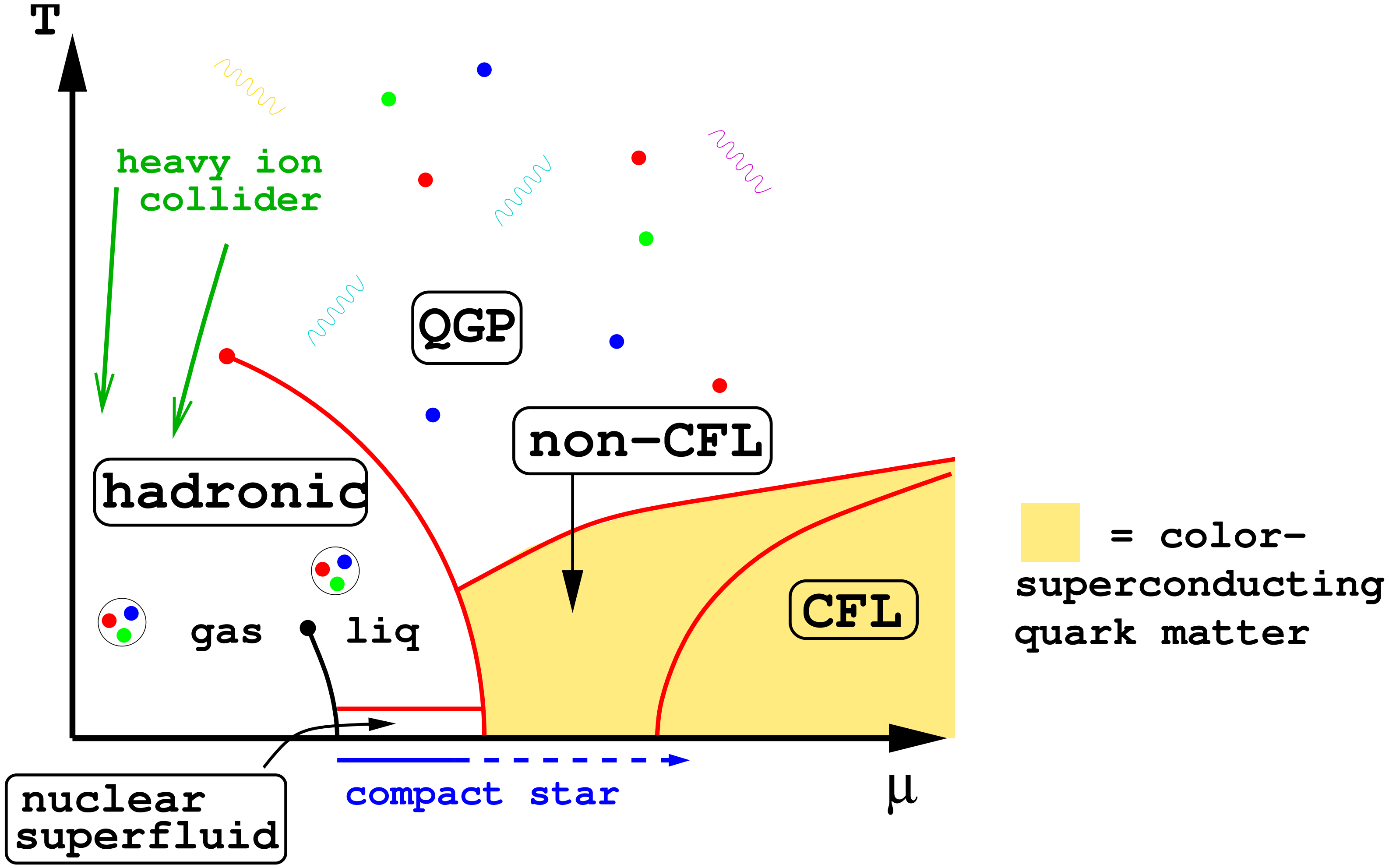
Intermediate densities
Quarks of two colors
and two flavors (ones with
the most phase space near their
Fermi surface) pair.

CFL-K0

“Switching on” strange quark mass
→ modifying the CFL pairing by
inducing a flavor rotation of the
condensate Kaon condensation

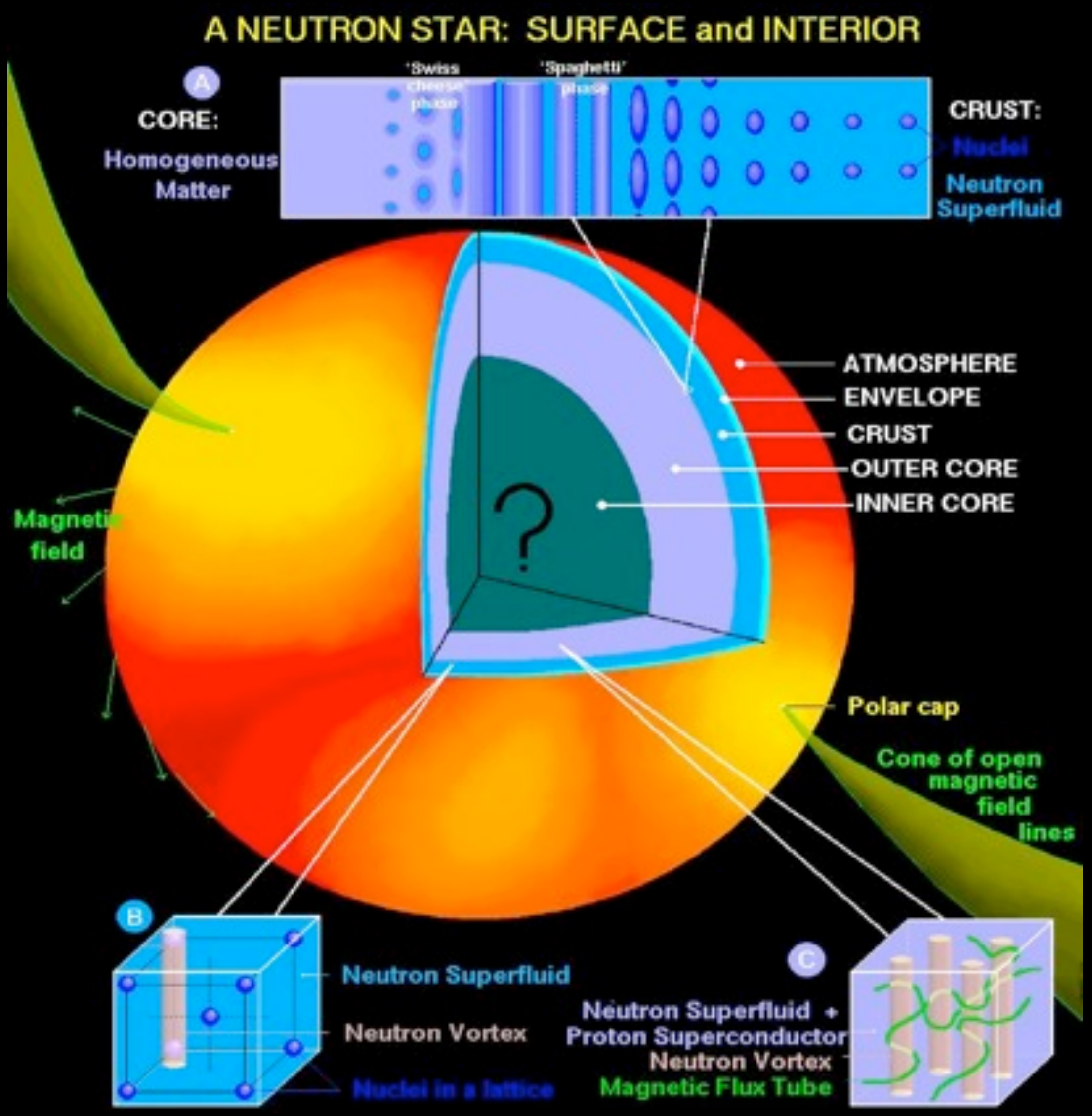
K0 meson carries negative
strangeness → Relieves the
stress on the CFL phase

Conjectured QCD phase diagram



Compact Stars

The only “laboratory” for the study of color-superconductivity



Mass ~ $1.4M_\odot$
Radius ~ O(10 km)
Density > $\rho_{nuclear}$
Initial temp ~ 30 MeV

Signatures of quark matter in compact stars

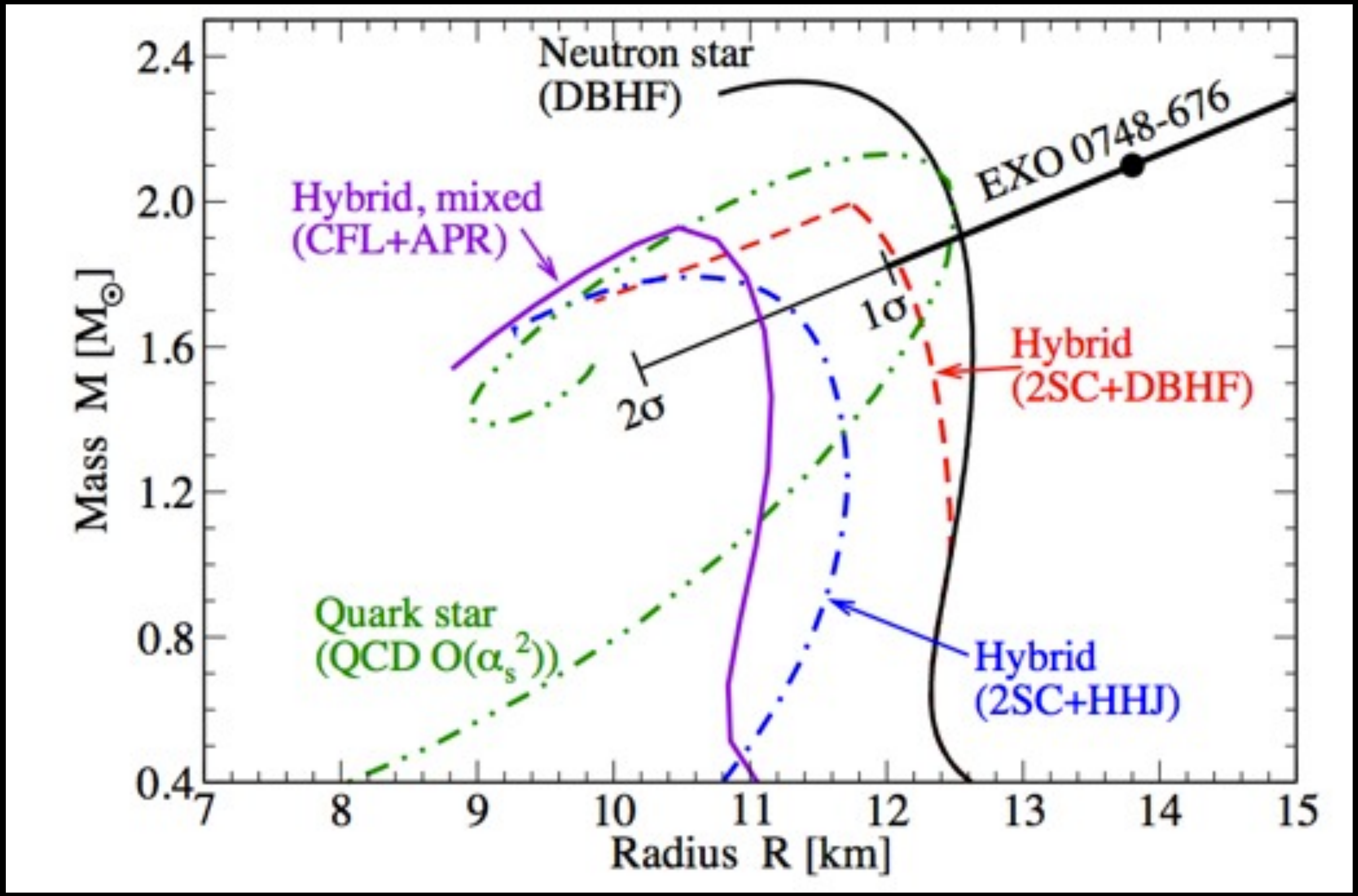
- Pairing energy affects Equation of state.
  Mass-Radius
- Gaps in quark spectra and Goldstone bosons affect
  Transport properties: emissivity, heat capacity, viscosity (shear, bulk), conductivity (electrical, thermal), . . .

Computing thermodynamical and transport properties of different phases ⇒ Predicting the behavior of the star with a quark matter core in the respective phase

Comparing these predictions with the actual astrophysical observations ⇒ Mapping the phases of QCD at high densities.

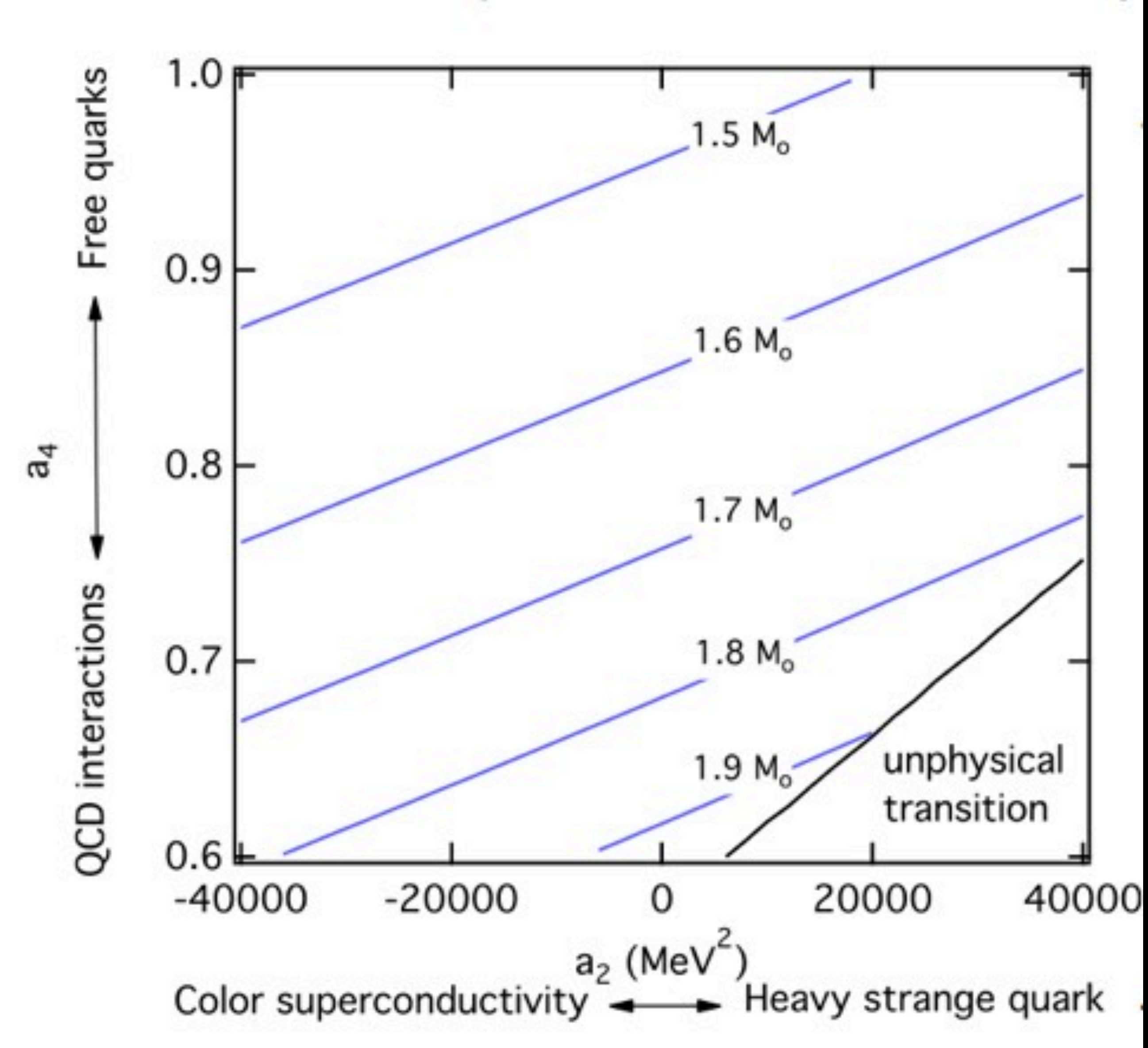
Can a neutron star contain quark matter?

The appearance of new degrees of freedom at and above the nuclear saturation density, such as quarks, hyperons, or bosons, softens the equation of state and lowers the maximum mass of the star.



Alford et. al.
arXiv:astro-ph/0606524

Recent measurement of a 2 M⊙ star (Demorest et. al. arXiv:1010.5788).



$$P(\mu) \sim a_4\mu^4 - a_2\mu^2 - B_{eff}$$

$$a_4 = \frac{3}{4\pi^2}(1-c)$$

$$a_2 = \frac{3}{4\pi^2}(M_s^2 - 4\Delta^2)$$

Fixing B_{eff} so that the transition from nuclear matter to quark matter occurs when $n = 1.5n_{sat}$

The maximum neutron star mass as a function of two parameters of quark matter EOS

Özel et.al. arXiv:1010.5790
Alford et. al. nucl-th/0411016

Cooling

All forms of dense matter are good heat conductors $\longrightarrow$

Neutron star interiors are isothermal $\longrightarrow$

Cooling is dominated by properties of the phase which has highest neutrino emissivity and highest specific heat

$$C\frac{dT}{dt} = -\epsilon_\nu + \epsilon_h$$

Neutrino emissivity in dense matter:

- Direct Urca: $\epsilon \propto T^6$
  - Unpaired quarks
  - Baryonic matter containing hyperons
  - Pion or kaon condensed nuclear matter
  - Ordinary nuclear matter at sufficiently high densities where x_p>0.1

- Modified Urca: $\epsilon \propto T^8$

- CFL quark matter: $\epsilon \propto T^{15}$

$C_{CFL} \propto T^3$ → Total emissivity and specific heat are both dominated by the contribution of outer layers

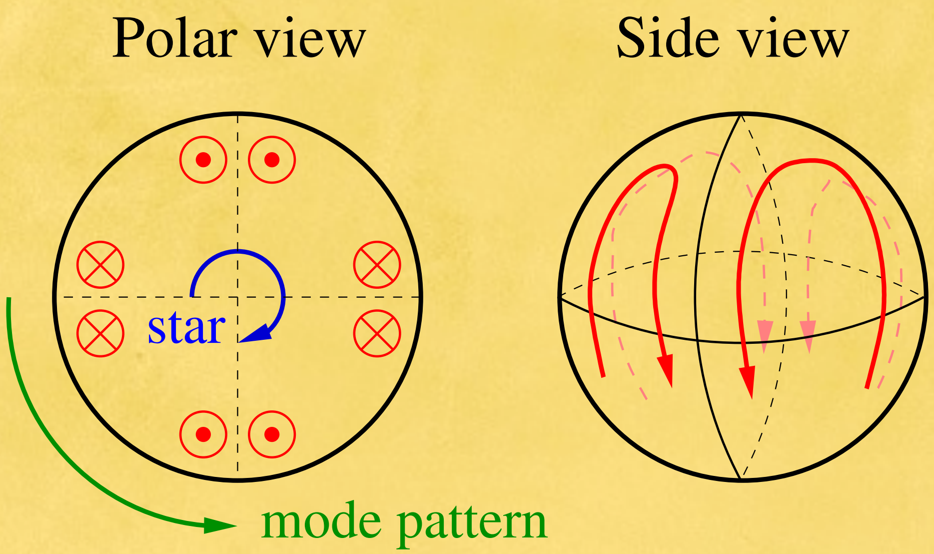
$C \propto T$ in all other phases of dense matter

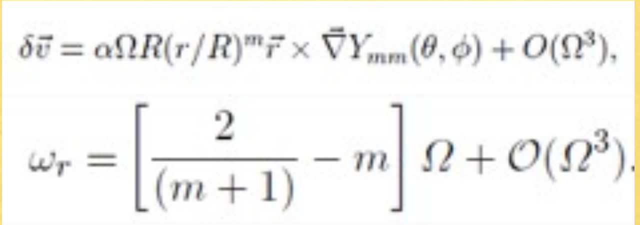
r-modes in neutron stars

A bulk flow in a rotating star that couples to gravitational radiation and radiates away energy and angular momentum of the star in the form of gravitational waves.

- grow unstabl by emission of gravitational radiation
- spin down the star within months
- fast rotating stars are observed!
- There must be some damping mechanism

Bulk and Shear Viscosity





$$\delta\vec{v} = \alpha\Omega R(r/R)^m \vec{r} \times \vec{\nabla} Y_{mm}(\theta,\phi) + O(\Omega^3),$$

$$\omega_r = \left[\frac{2}{(m+1)} - m\right]\Omega + \mathcal{O}(\Omega^3).$$

The amplitude of the r-mode evolves as $e^{i\omega t - \frac{t}{\tau}}$.

$$\frac{1}{\tau} = \frac{-1}{|\tau_{GR}|} + \frac{1}{\tau_S} + \frac{1}{\tau_B}$$

The fastest process dominates!

- R–mode is unstable as long as its growth time is shorter than the damping time due to the viscosity, i.e. when the damping timescale τ is negative.
- Bulk viscosity timescale is given by:

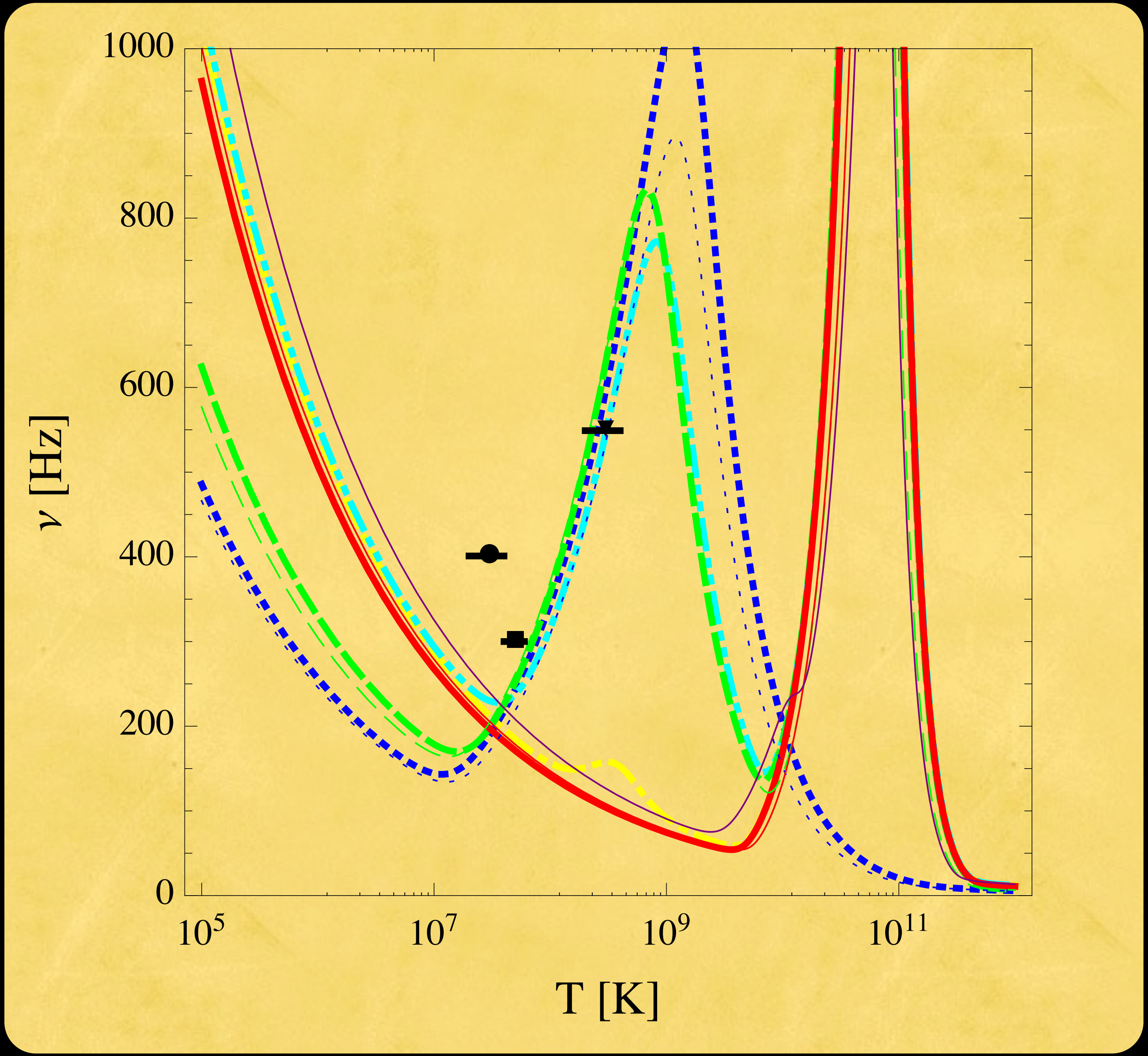
$$\frac{1}{\tau_B} \approx \frac{(\omega + m\Omega)^2}{2\tilde{E}} \int \zeta\,(\delta n/n) \left|\frac{\delta n}{n}\right|^2 d^3x$$

$\tilde{E}$: Energy of the mode
ζ : Bulk viscosity
ω : Oscillation frequency
Ω : Rotation frequency of the star
$\frac{\delta n}{n}$: Density fluctuation amplitude

$$m = 2$$

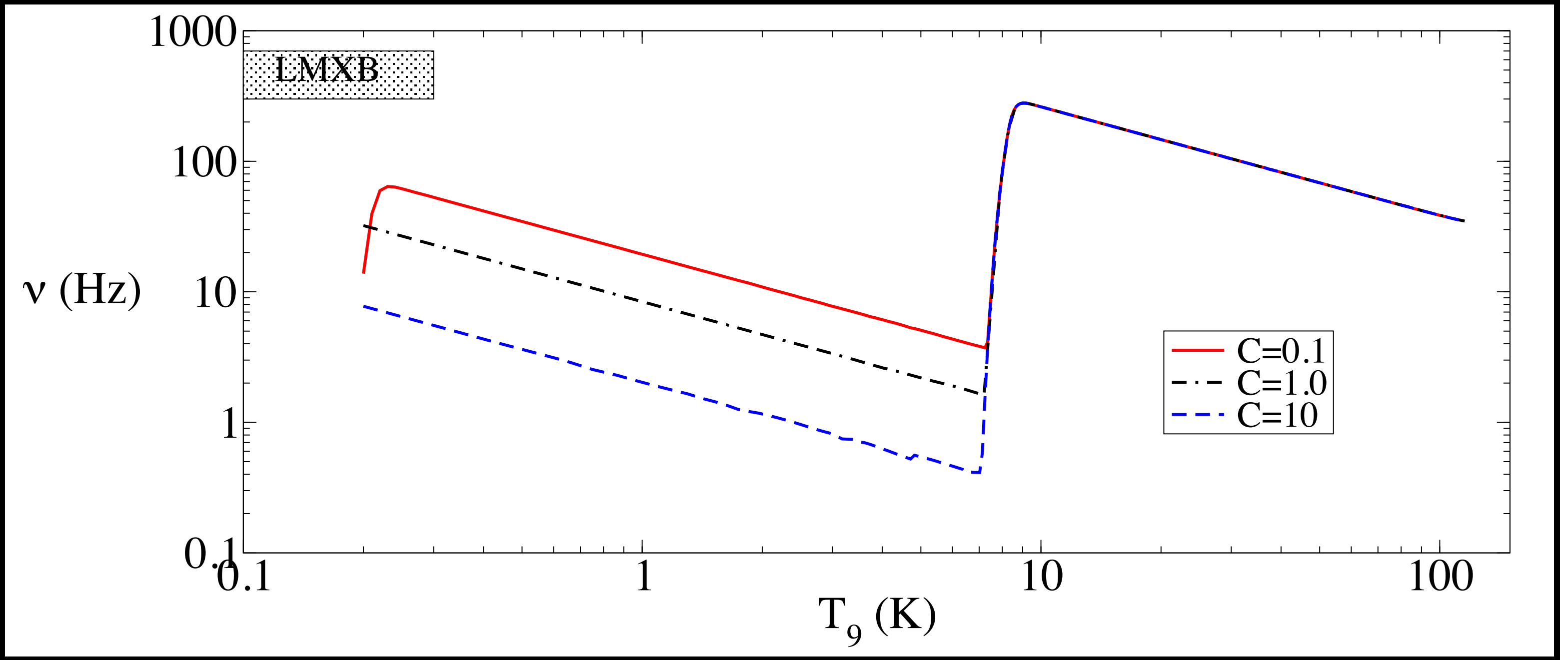
$$\frac{\delta n}{n} \propto \alpha$$

r-mode instability window for strange quark, hadronic and hybrid stars



Alford et. al. **arXiv:1012.4883**

The critical frequency vs. temperature for CFL-K0 phase



G. Rupak, P. Jaikumar, arXiv1005.4161, 2010

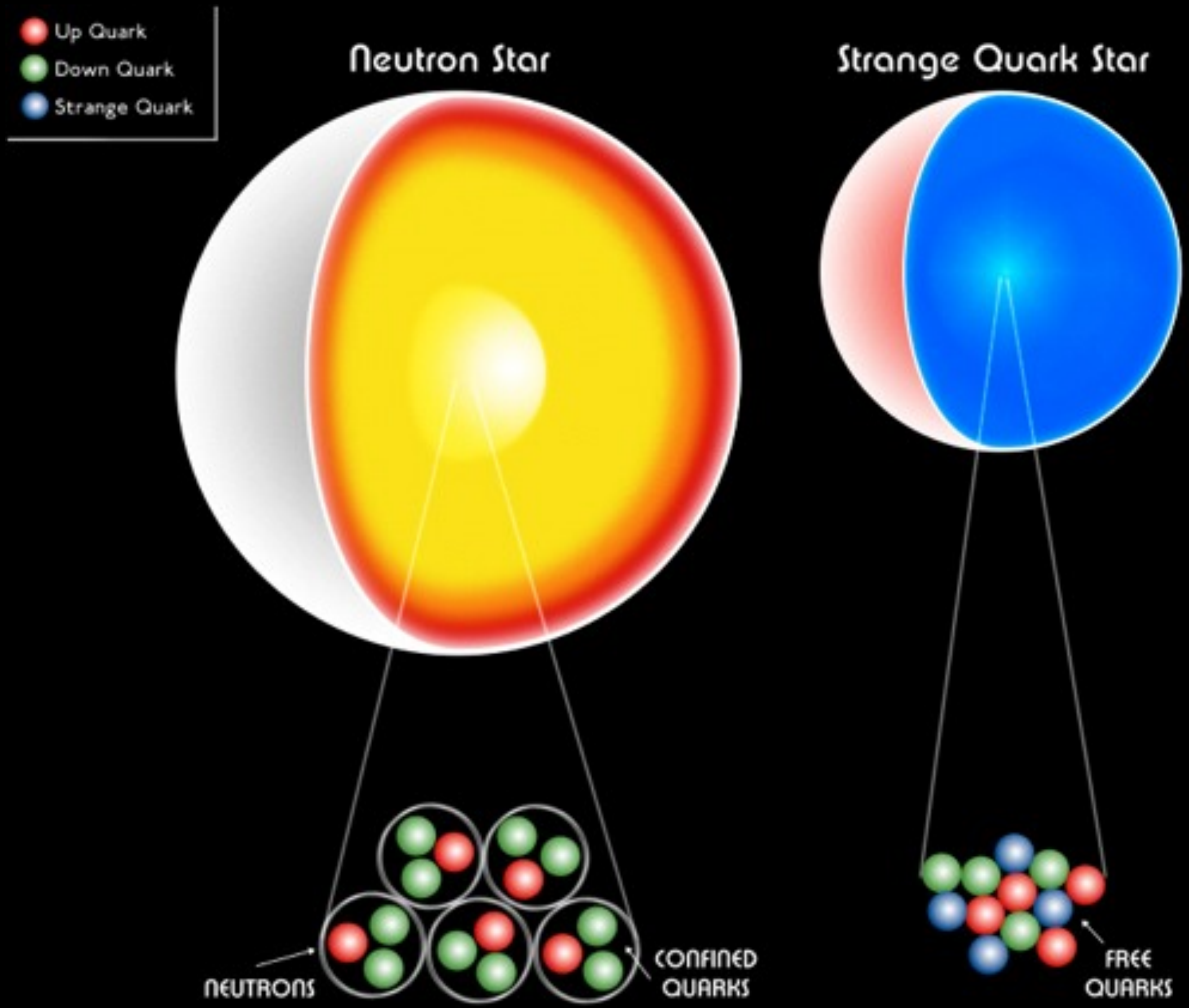
A pure quark star in the CFL or CFL-K0 phase is ruled out by observed LMXB spin rates.

Conclusion

- Phases between CFL and hadronic matter are unknown

- By computing transport properties of different phases and comparing the effect of them on the behavior of the star with the astrophysical observations, one can confirm or rule out the presence of different phases in the star.

Thank You!



Up Quark
Down Quark
Strange Quark
Neutron Star
Strange Quark Star
NEUTRONS
CONFINED QUARKS
FREE QUARKS