Neutron vs. Quark Stars

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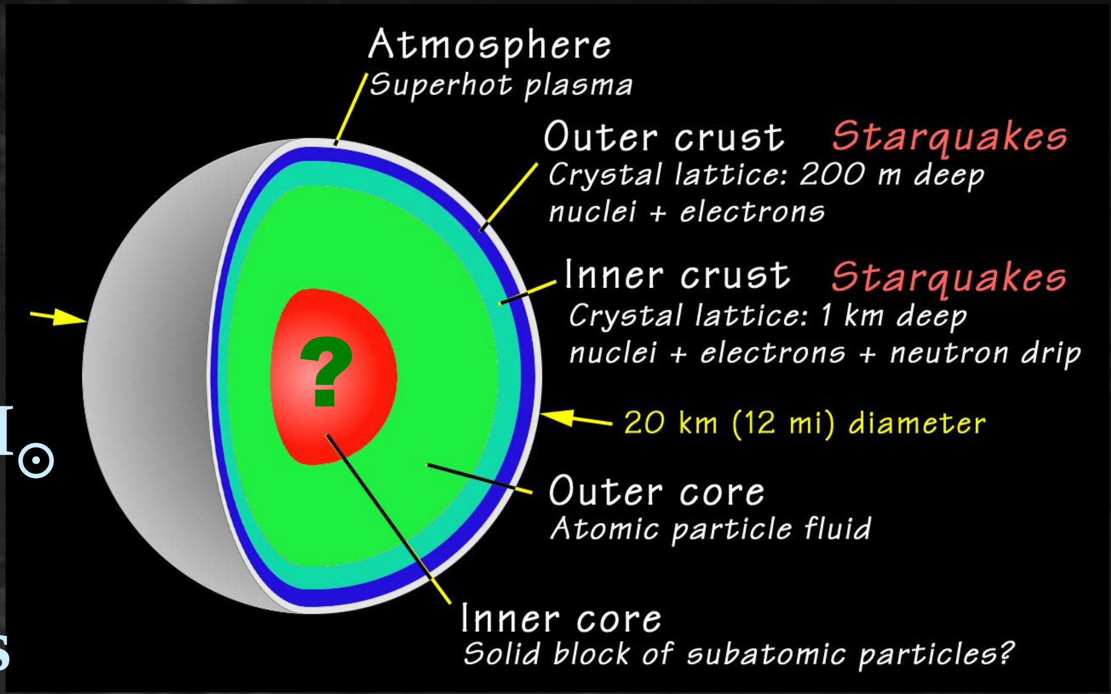
Neutron stars



- **Radius:**

  $R \simeq 10$ km

- **Mass:**

  $1.25 M_\odot \lesssim M \lesssim 2 M_\odot$

- **Period:**

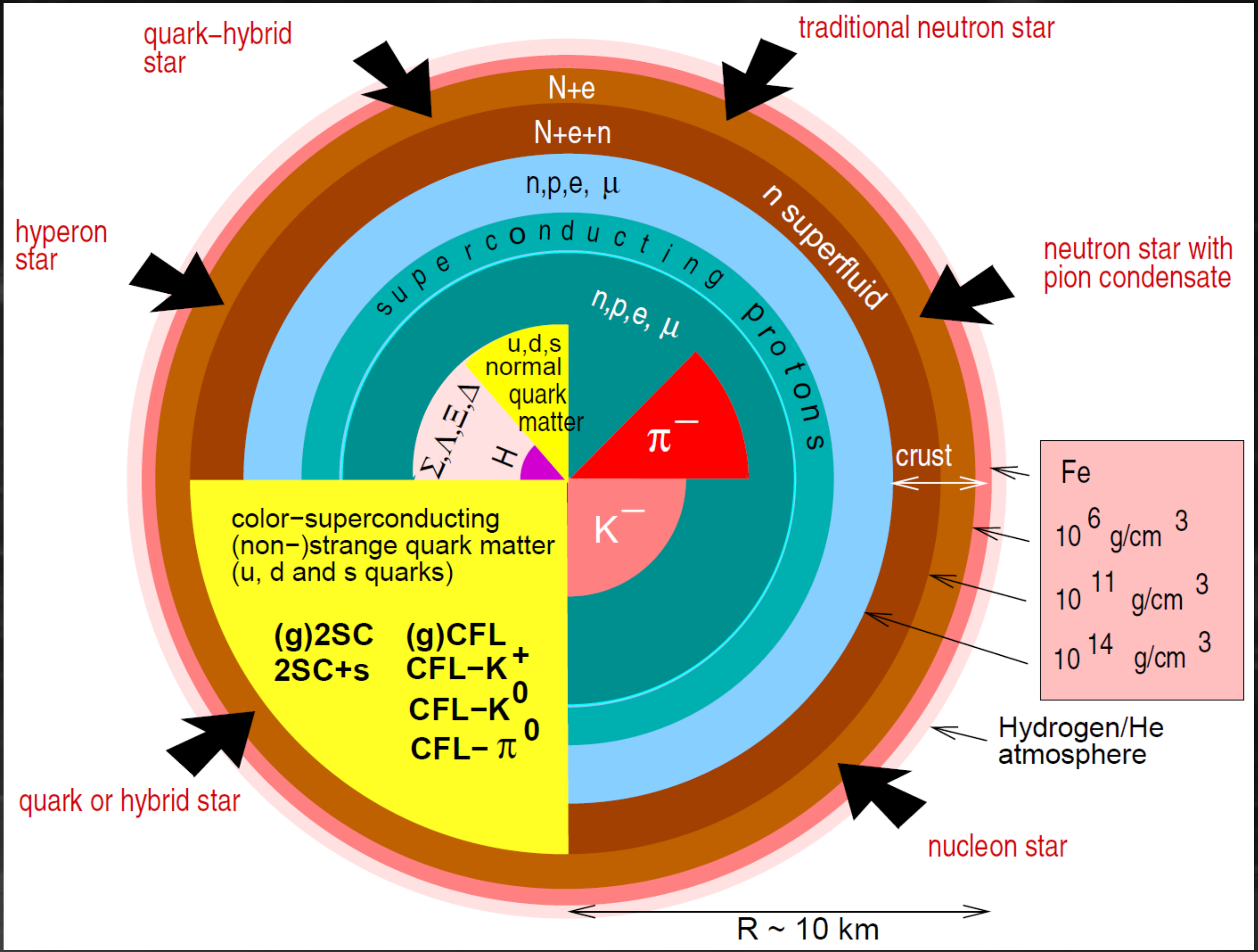
  $1.6\ \mathrm{ms} \lesssim P \lesssim 12\ \mathrm{s}$

- **Surface magnetic field:**

  $10^8\ \mathrm{G} \lesssim B \lesssim 10^{14}\ \mathrm{G}$

- **Core temperature:** $10\ \mathrm{keV} \lesssim T \lesssim 10\ \mathrm{MeV}$

Dense matter at the core



[adapted from F. Weber, Prog. Part. Nucl. Phys. **54** (2005) 193]

Extremely dense matter

Nuclear matter → quark matter

- **Asymptotic freedom:**

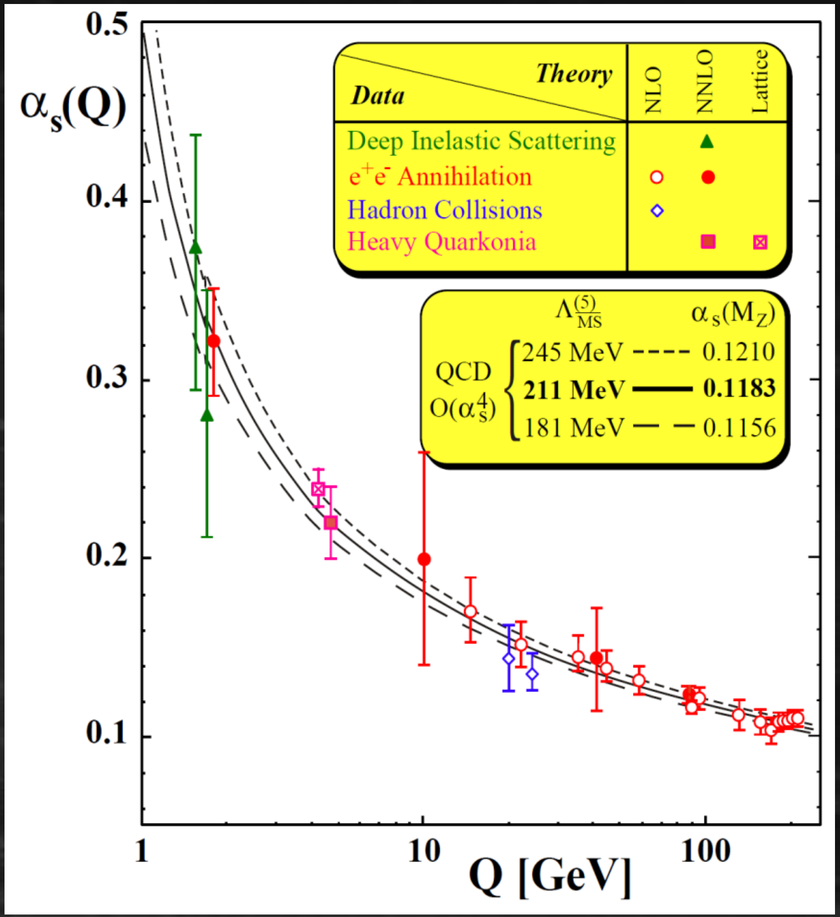
  $\alpha_s(\mu) \ll 1$ when $\mu \gg \Lambda_{QCD}$

  [Gross & Wilczek, 1973; Politzer,1973]

- **High density quark matter is weakly interacting**

  [Collins & Perry, 1975]

- **Note:** **realistic densities in stars are not large enough…**



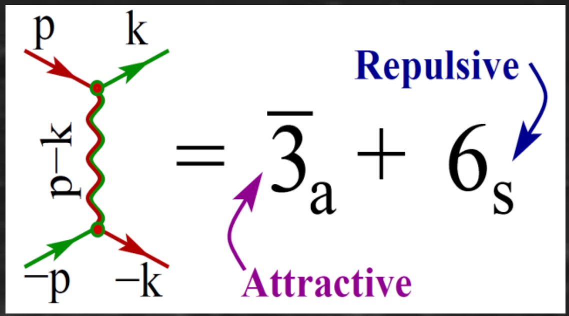
$$\rho \lesssim 10\rho_0 \text{ where } \rho_0 \simeq 0.15\ \text{fm}^{-3} \Longrightarrow \mu \lesssim 0.5\ \text{GeV} \Longrightarrow \alpha_s(\mu) \gtrsim 1$$

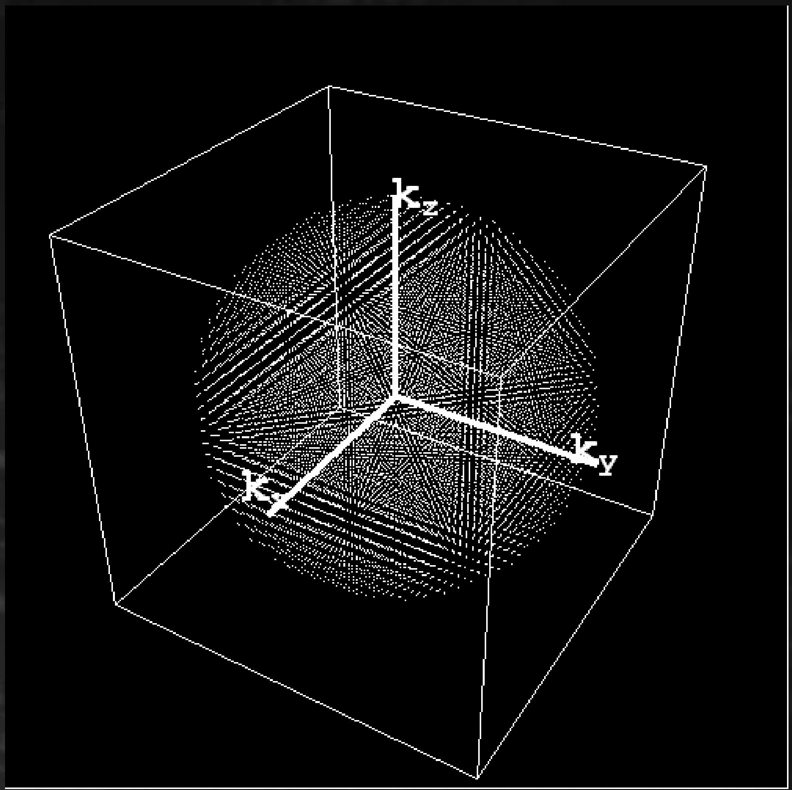
Ground state of dense matter

- Quarks are fermions (s=½)

- Free quarks occupy all states with $k \leq k_F$

- Real quarks interact

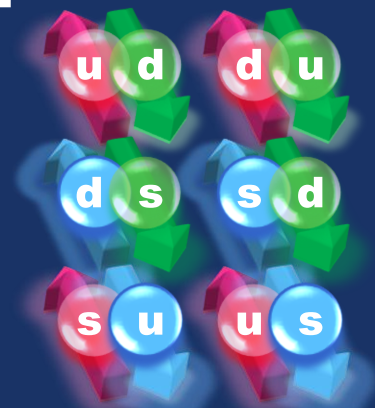




Because of the Cooper theorem, such a degenerate quark system is unstable

The ground state is a (color) superconductor

Many color superconductors

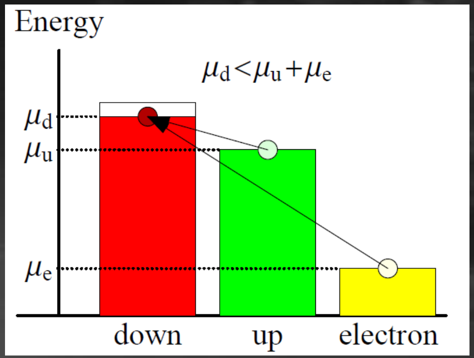
<table>
<tr><th colspan="2">1 quark flavor (spin-1)
(e.g., only up)</th><th>2 quark flavors
(up & down)</th><th>3 quark flavors
(up, down & strange)</th></tr>
<tr><td>CSL</td><td></td><td rowspan="3">2SC
</td><td rowspan="3">CFL
</td></tr>
<tr><td>Planar</td><td></td></tr>
<tr><td>A/Polar</td><td></td></tr>
<tr><td colspan="2">Meissner effect: Yes</td><td>Meissner effect: No</td><td>Meissner effect: No</td></tr>
<tr><td colspan="2">Superfluidity: Yes</td><td>Superfluidity: No</td><td>Superfluidity: Yes</td></tr>
</table>

- **The actual composition of quark matter depends on its density: q_i is present if $\mu_i > m_i$**
- **For $\mu \lesssim 0.5$ GeV, c-, b- and t-quarks have no chance**

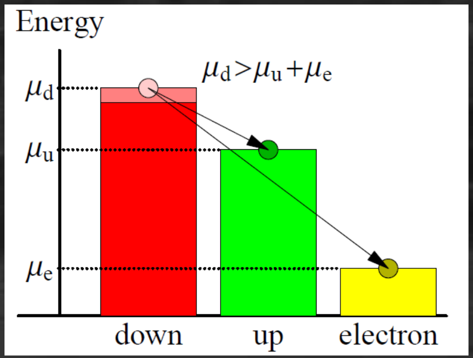
Color superconductivity in stellar matter

- **Stellar matter is**
  - **(i) neutral (to avoid large Coulomb energy price,** $E_{Coulomb} \propto n_Q^2 R^5 \gg M_\odot c^2$**)**
  - **(ii) in β-equilibrium:** $\mu_d = \mu_u + \mu_e = \mu_s$

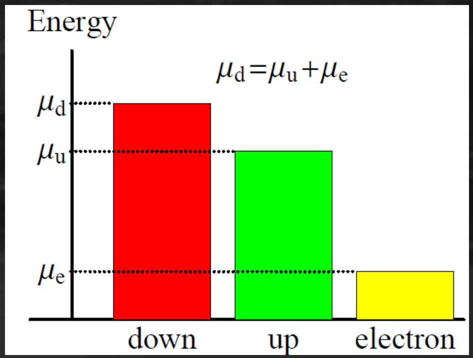
Too few d-quarks



Too many d-quarks



β-equilibrium



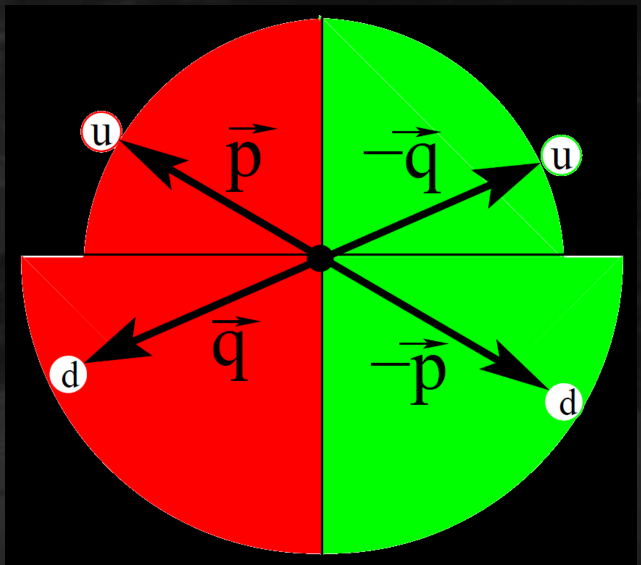
Unconventional Cooper pairing in stellar matter

- **Bottom line:** Fermi momenta of all quarks are different: $p_{F,u} \neq p_{F,d} \neq p_{F,s}$

(note that $p_{F,u} \approx \mu_u$, $p_{F,d} \approx \mu_d$ & $p_{F,s} = \sqrt{\mu_s^2 - m_s^2}$)

Thus, Cooper pairing is "stressed" by the mismatch, $\delta p_F \neq 0$

What happens then?



Gapless phases (2 flavors)

[I.S. & M. Huang, Phys. Lett. **564** (2003) 205; Nucl. Phys. **729** (2003) 835.]

Strength of pairing (Δ_0) vs. mismatch ($\delta\mu$)

1. Weak coupling

$$\Delta_0 \lesssim \delta\mu$$

$\Longrightarrow$ normal quark matter phase

2. Strong coupling

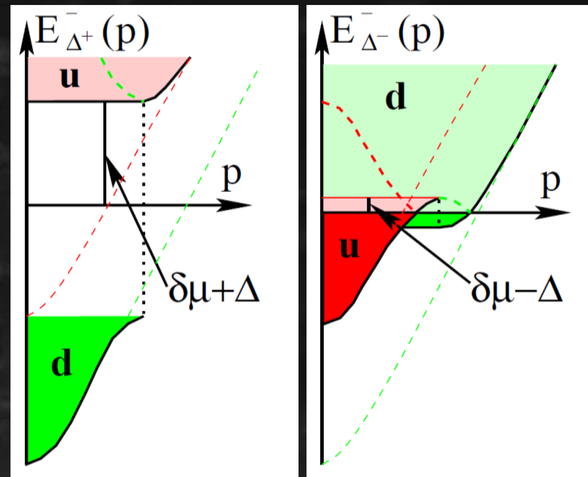
$$\Delta_0 \gtrsim 2\,\delta\mu$$

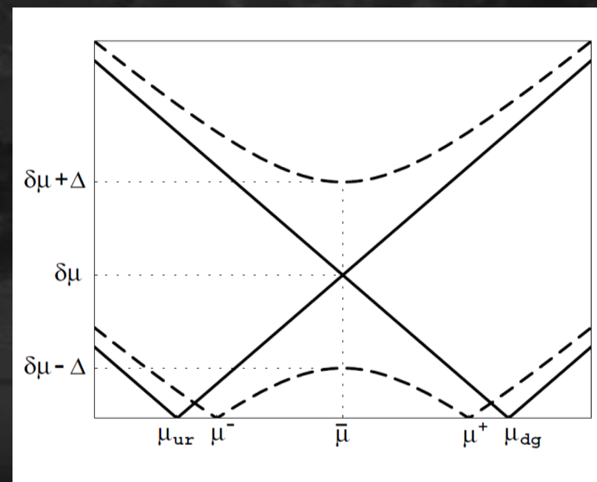
$\Longrightarrow$ "usual" superconducting phase

3. Intermediate strength

$$\delta\mu \lesssim \Delta_0 \lesssim 2\,\delta\mu$$

$\Longrightarrow$ **gapless** superconducting phase





"No-go" theorem

- **Stressed pairing is unavoidable**

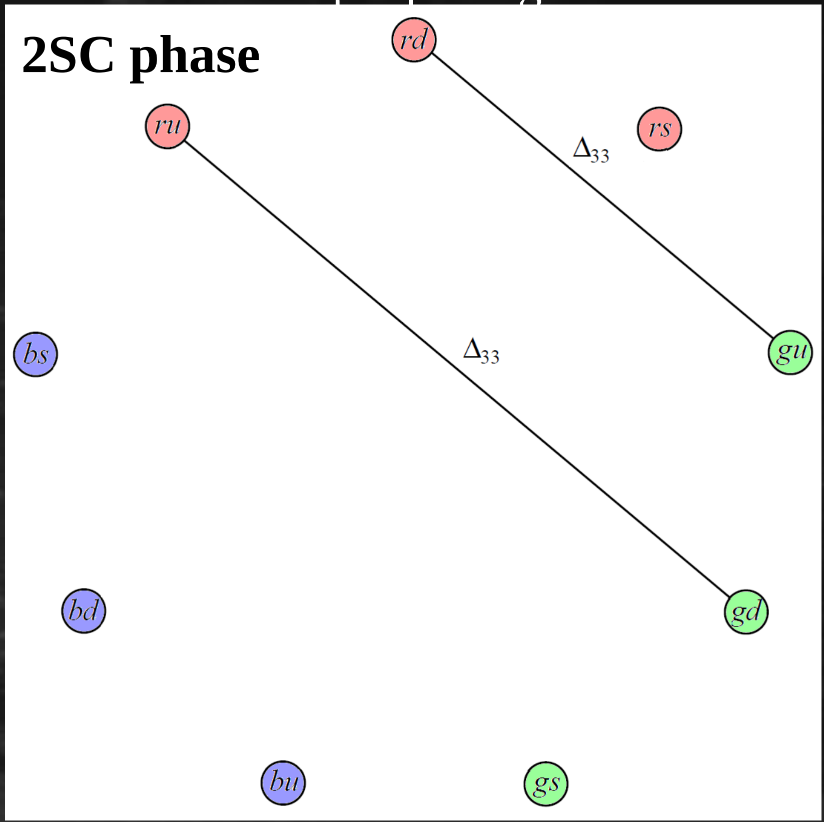
  [Schmitt & Rajagopal, PRD **73** (2006) 045003]

- **Using graph theory, 511 pairing patterns (including all 148 inequivalent ones) were analyzed**

- **None of them is stress-free**

- **So, what does it mean?**

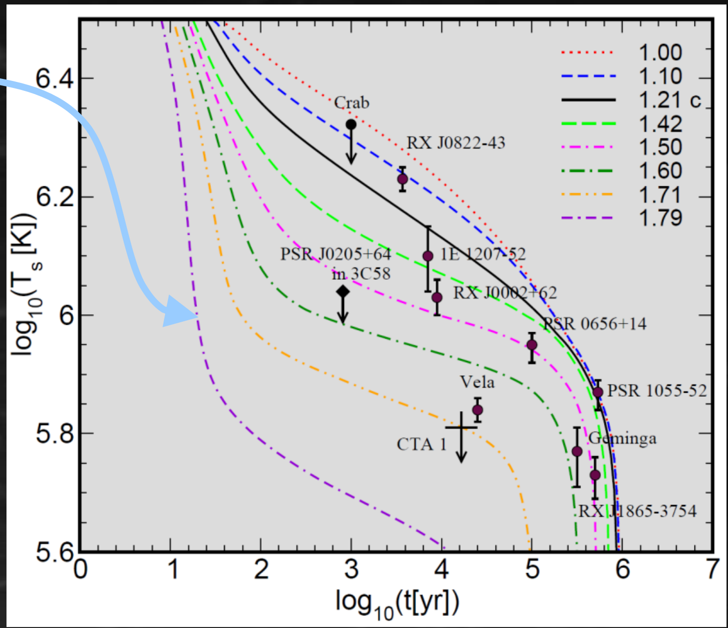
Each line in the graph represents an allowed Cooper pairing channel



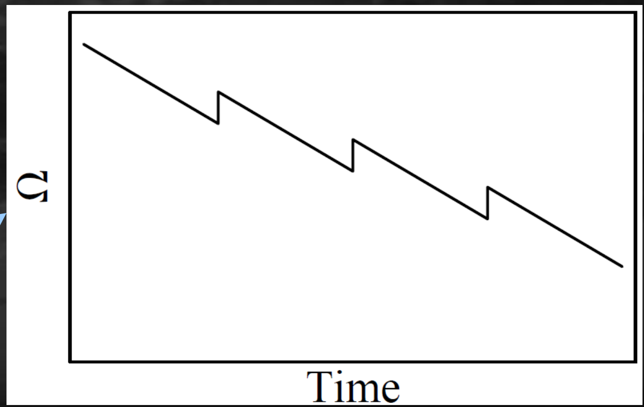
[adapted from Schmitt & Rajagopal, Phys. Rev. D **73** (2006) 045003]

Observational data as a tool

1. Neutron star cooling
2. Stellar “glitches”
3. Gravitational waves & r-mode instability
4. Magnetic properties
5. Transient signals from protoneutron stars
6. ...



[Blaschke et al, Phys.Rev.C**71** (2005) 045801]



Future direction: Transport

- **Conductivities**

[I.S. & Ellis, PRC **66** (2002) 015802; *ibid.* **67** (2003) 048801]

  - **Heat**
  - **Electric**

- **Viscosities**

[Manuel et al, JHEP **0509** (2005) 76]
[Sa'd et al, PRD**75** (2007) 065016], [Alford & Schmitt, JPG **34** (2007) 67],
[Dong et al, astro-ph/0701104], [Alford et al, nucl-th/0701067]

  - **Bulk**
  - **Shear**

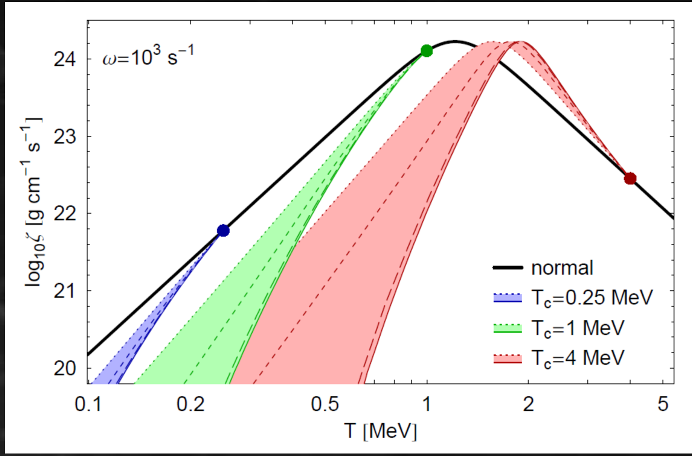
- **Mean free paths**

[Carter & Reddy, PRD **62** (200) 103002],
[Kundu & Reddy, PRC **70** (2004) 055803], …

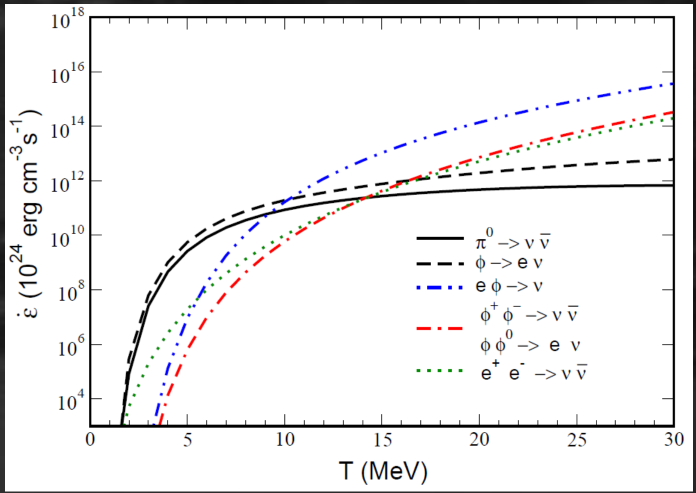
  - **Neutrinos**
  - **Photons**

- **Emission rates**

[Jaikumar et al, PRD 66 (2002) 063003],
[Reddy et al, NPA 714 (2003) 337],
[Schmitt et al, PRD 73 (2006) 034012], …



[Sad, I.S. & Rischke, PRD **75** (2007) 065016]

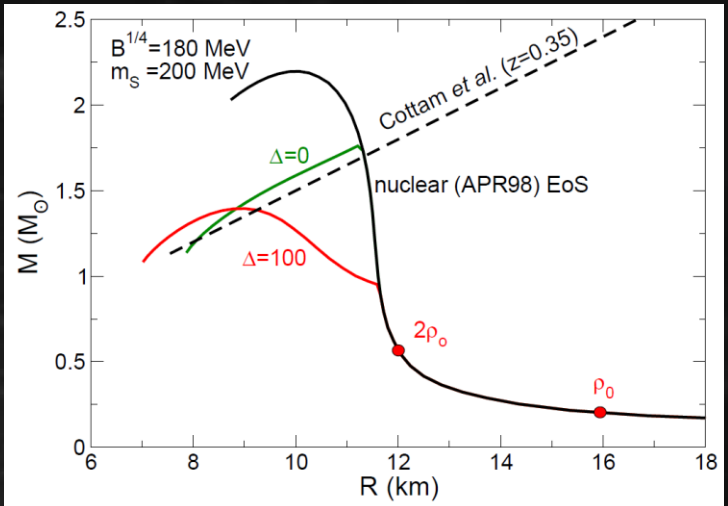


[from Reddy et al, NPA 714 (2003) 337]

Future direction: Thermodynamics

- **Equation of state**
  - Pressure
  - Energy density

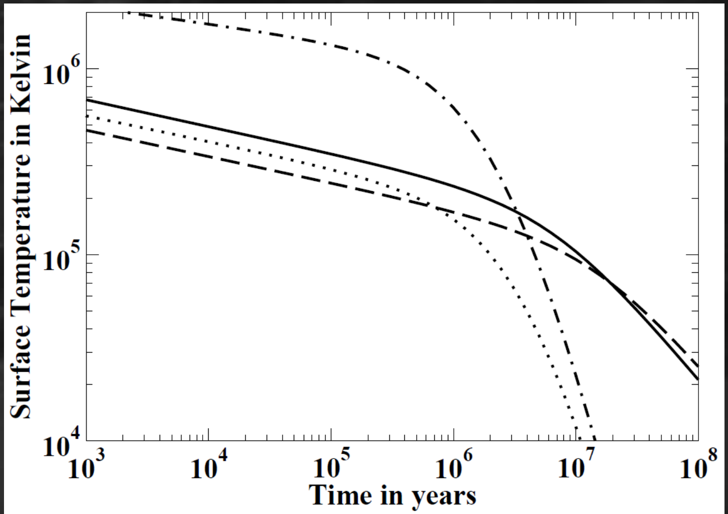
[Lugones & Horvath, PRD **66** (2002) 074017],
[Alford & Reddy, PRD **67** (2003) 074024],
[Baldo et al, 562 (2003) 163],
[Banik & Bandyopadhyay, PRD **67** (2003) 123003], …



- **Specific heat**

[Alford et al, PRD **71** (2005) 114011], …

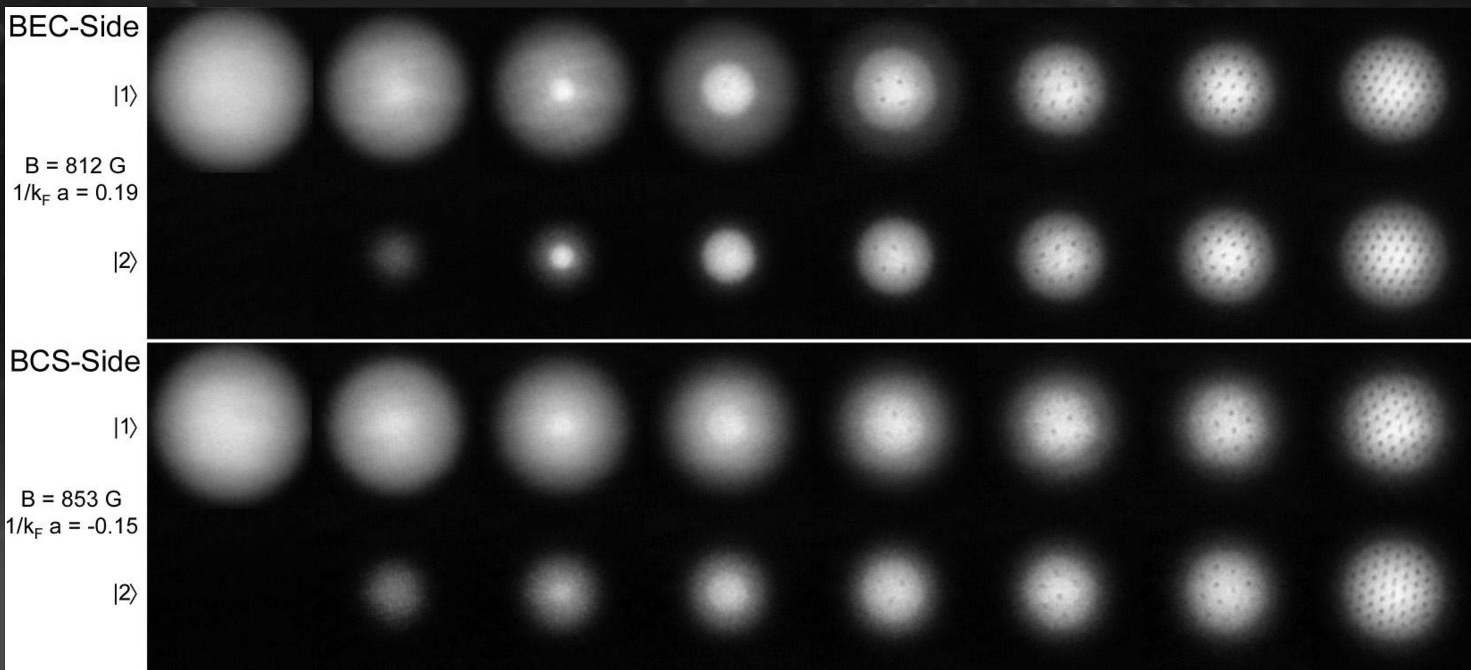
  - Important for cooling
  - Sensitive to gapless modes



Detour: Atomic systems

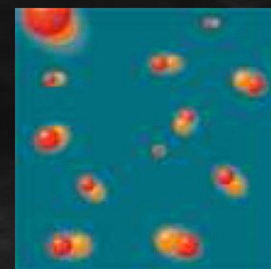
- **Dense quark matter may be modeled in a tabletop experiment (using cold gas of ^{6}Li or ^{40}K atoms)**

[Zwierlein et. al.,, Science 311 (2006), 492], [Partridge et. al.,, Science 311 (2006) 503]



[from the web page of Ketterle's group]

BEC pairs



BCS pairs

Current research directions

- Weak processes in various phases of dense quark matter
- Systematic study of transport properties of quark matter
- The study of quark matter in strong external fields
- Analysis of the observational data and search for signatures of new states of matter
- Development of non-perturbative techniques for studying quark matter
- High temperature quark matter (RHIC & LHC)
- Cross-disciplinary insight into quark dynamics (e.g., from physics of cold atoms, graphene, high-T_c superconductivity, etc.)

Summary

- Deconfined quark matter is likely to exist in stars
- β-equilibrium plays and important role in shaping the ground state
- Such matter is an unconventional color superconductor
- Phase structure of dense matter is very rich
- Observational data may help to shed light on the phase diagram

Thank you