Asymmetric neutrino emission in quark matter and pulsar kicks

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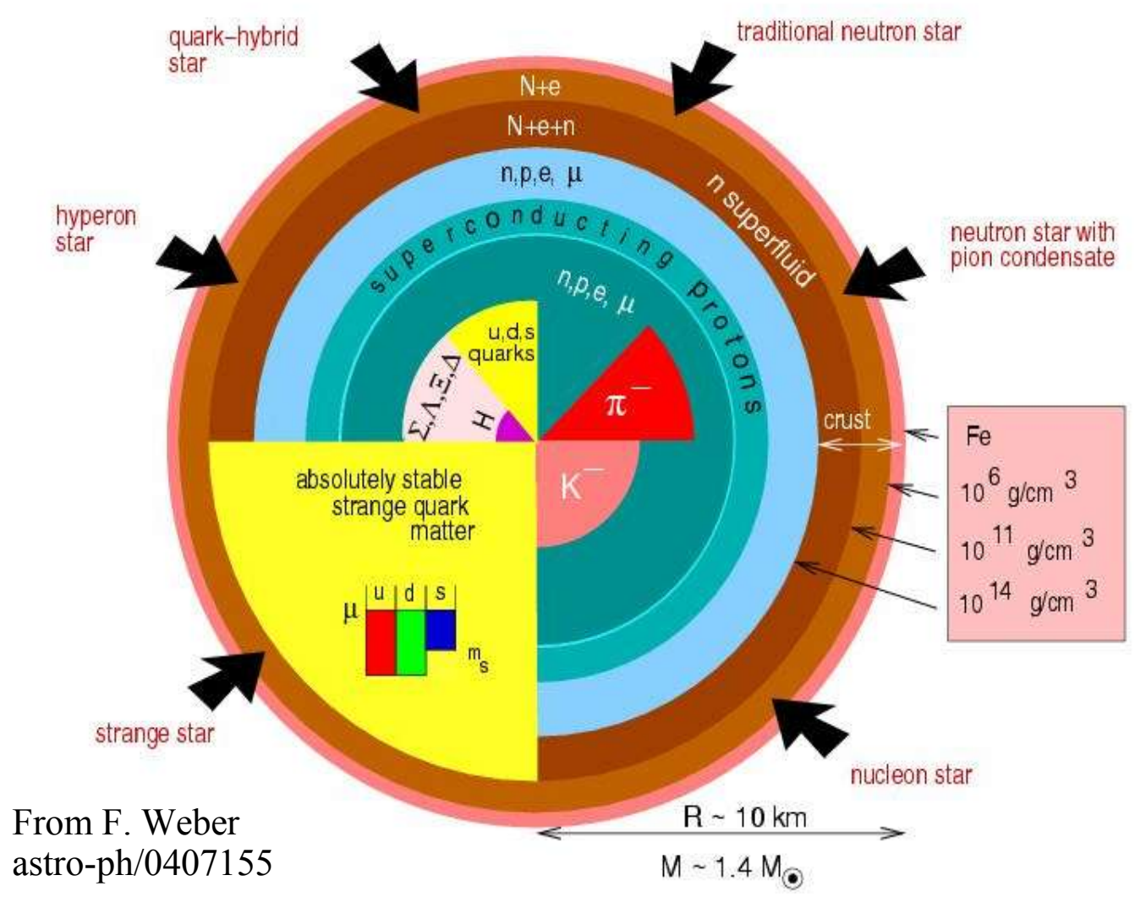

From F. Weber
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Neutron Stars

Neutron stars are born in supernova explosions of stars with masses 8 $M_{sun} < M < 20\ M_{sun}$ due to their gravitational collapse at the end of their life. In the center the stellar iron-core collapses to nuclear density producing a large amount of neutrinos by electron capture. As the nuclear equation of state is very stiff, the inner core rebounds and drives a shock wave in the falling outer core. While the shock wave propagates through the outer core it again produces neutrinos by electron capture. The shock reverses the fall and ejects the stellar envelope leaving behind a proto-neutron star, which then cools by thermal neutrino emission from a temperature around 50 MeV down to ca. 0.5 MeV, creating an object of ~1.4 – 2 M_{sun} and R ~10 km – the neutron star.
The gravitational binding energy which is released in the collapse is about ~ $3*10^{53}$ erg. The kinetic energy of the shock wave is of the order 10^{51} erg, leaving ~ 99% of the binding energy to be carried off by neutrinos and anti-neutrinos. Depending on the equation of state a neutron star can contain quark matter in the core (hybrid model) or even consist entirely of strange quark matter (strange star). As the quarks are present in three different flavors there is a rich variety of different phases.

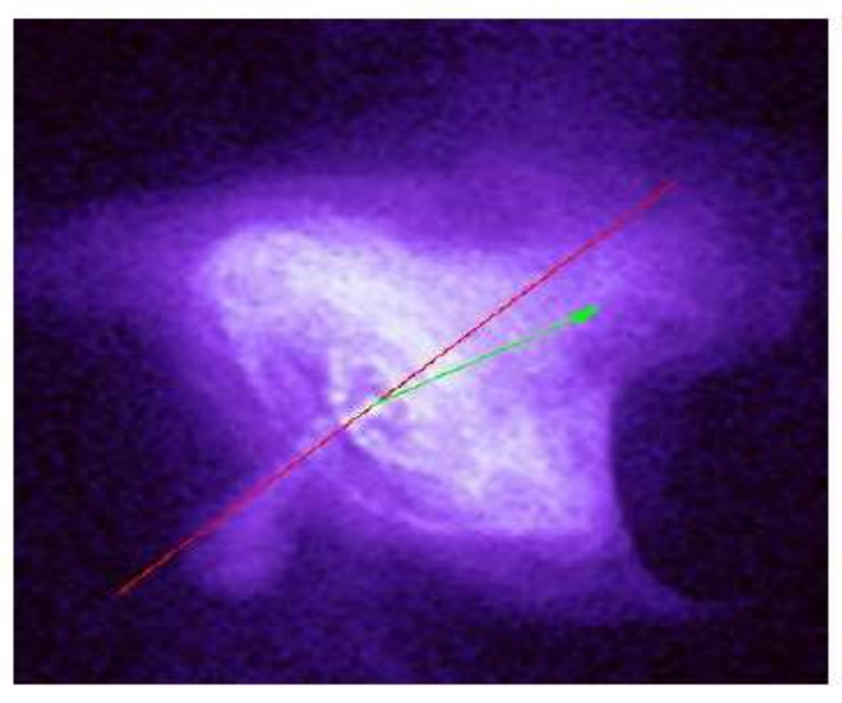
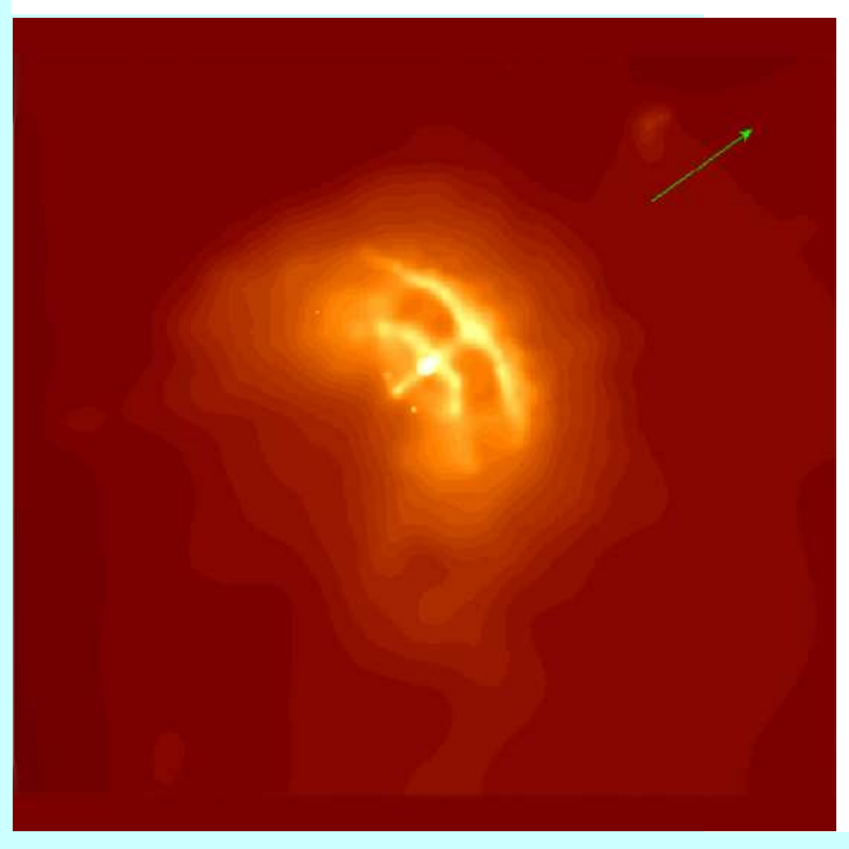


Figure 1: The Crab nebula as seen by *Chandra*. The red line indicates the line of mirror symmetry and the green arrow shows the proper motion of the pulsar as determined by Caraveo & Mignani (1999). Image credit: NASA/CXC/ASU/J. Hester et al.



Pulsar kicks – Observation

Pulsars are rapidly rotating, highly magnetized neutron stars and observable due to charged particles, which are accelerated out along the magnetic field lines and emit electromagnetic radiation. The magnetic field is generally not aligned with the rotational axis and rotates with the pulsar creating a so called Lighthouse effect. Observations show very high pulsar space velocities between 100 – 1600 km/s (Hobbs), whereas their progenitors move with just ~10-50 km/s, raising the question about the origin of the high pulsar velocities denoted generally as pulsar kicks. Though measurements of space velocities often have large error bars the highest directly measured velocity for a pulsar is 1083(+103/-90) km/s (B1508+55, Chatterjee et al.). Another interesting fact is the alignment between the velocity vector and the rotational axis (Johnston et al., Brisken and Romani) of the Crab, the Vela pulsar and PSR B0656+14 giving strong indication for a connection between the pulsar kick direction and the rotational axis and the magnetic field, respectively.

A neutron star which moves with a velocity of 1000 km/s has a kinetic energy of ~10^{49} erg, that is just a small asymmetry in the neutrino emission would be sufficient to accelerate the neutron star to the observed high velocities

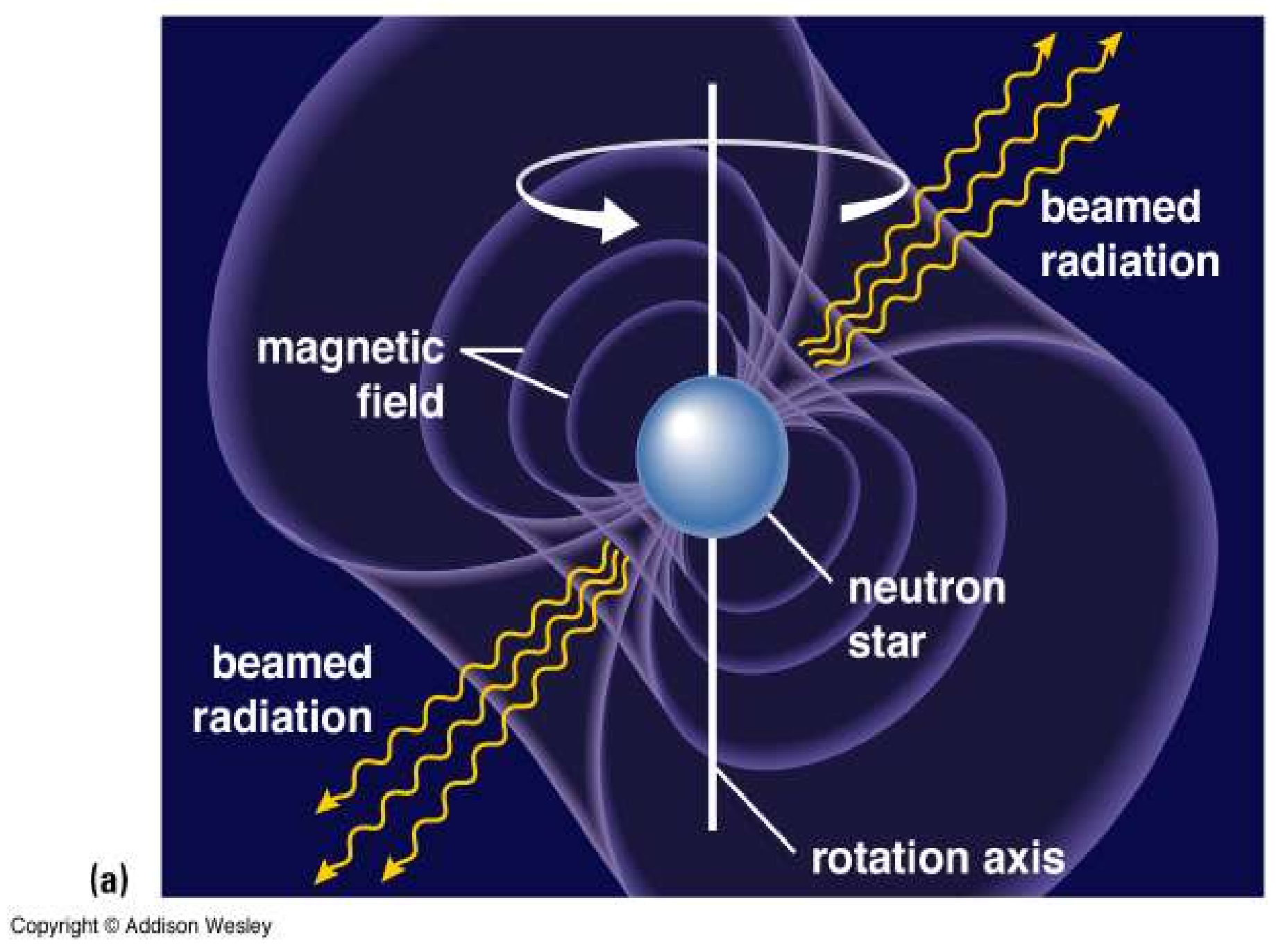
Pulsar kicks by anisotropic neutrino emission

For the first $10^5 - 10^6$ years neutron stars cool by neutrino emission from the so called Urca process (beta decay and inverse beta decay) which can be applied to nucleon matter as well as quark matter The largest neutrino emissivity can be found for the direct Urca process in quark matter

$$d \to u + e^- + \bar{\nu}_e, \quad u + e^- \to \nu_e + d$$

A strong magnetic field (~$10^{16} - 10^{17}$ Gauss) can polarize the neutrino-emission in one direction and therefore cause a pulsar kick. Though the observed magnetic fields on the surface of pulsars are in the range of 10^{12} Gauss a much larger magnetic fields can be reached in the core, where it forces the electrons in the lowest Landau Level polarizing their spin and accordingly the neutrino spin as well as the momentum due to parity violation.
The spin-polarized neutrinos propagate along the magnetic field axis in one direction and work as a propulsion mechanism for the neutron star.
If neutrinos are produced in a statistical and thermal equilibrium they can loose their polarization due to high interaction rates (no-go-theorem, Vilenkin)

To check whether this mechanism for pulsar kicks driven by a magnetic field works three questions need to be answered:
1) What magnetic field strengths are required to fully polarize the electrons?
2) Is the neutrino energy high enough to accelerate the neutron star?
3) Is the mean free path of the neutrinos large enough to leave the star without interacting with the medium?



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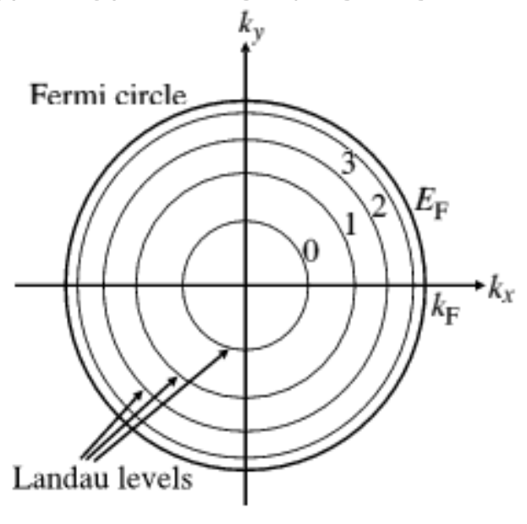
Polarization of electrons - Landau Levels



Electrons in an external magnetic field move on orbits orthogonal to the direction of the magnetic field with a radius

$$r = v_t \frac{m_e c}{eB}$$

For a high magnetic field the energy states of an electron in an external magnetic field are quantized and become relativistic (cyclotron energy becomes comparable to the electron rest mass energy):

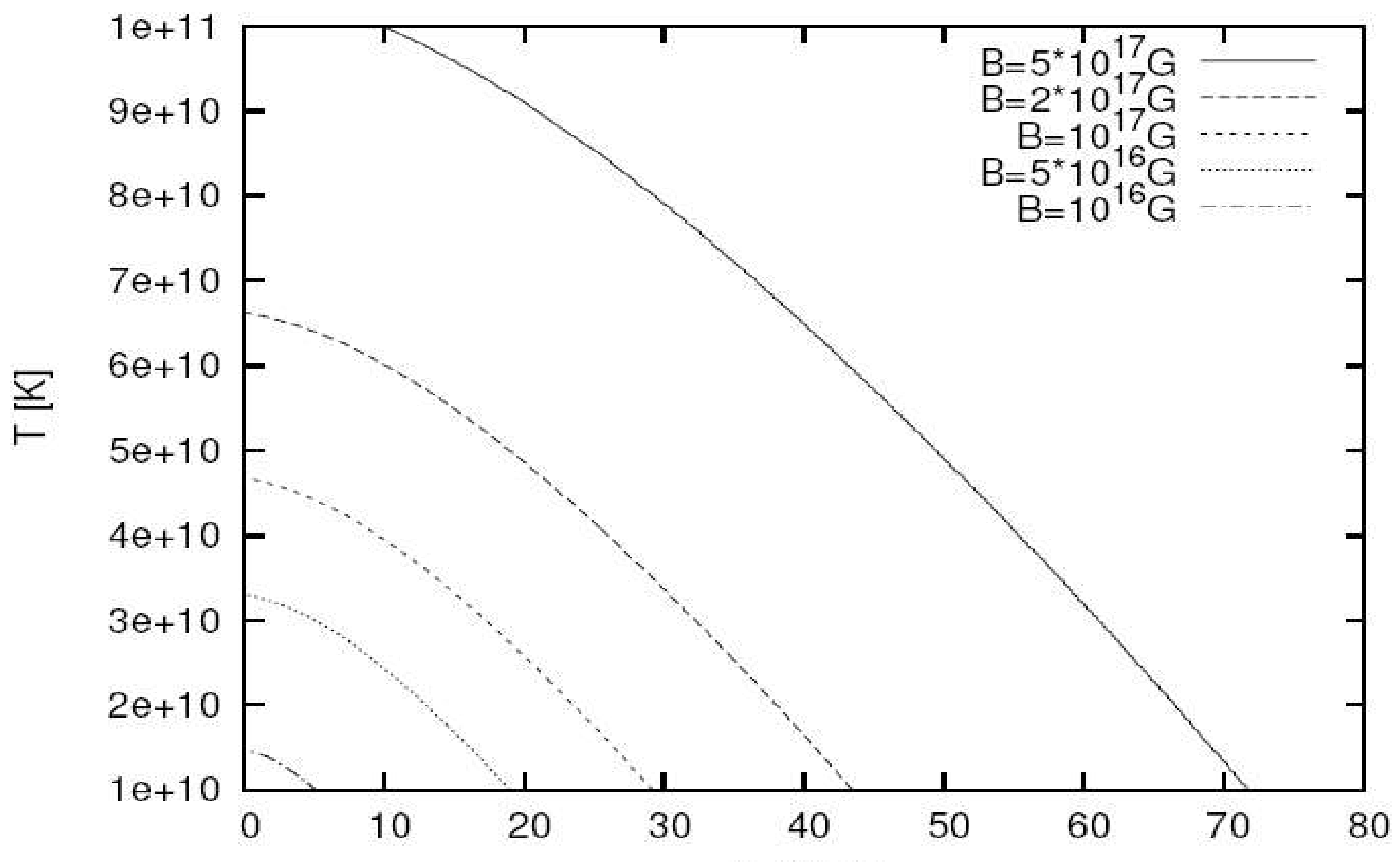
$$E_n^2 = m^2 + p_z^2 + 2eBn = m^2 + p_z^2 + 2eB(\nu + \frac{1}{2} + s)$$

ν .. quantum number of the Landau Level n
s .. electron spin with s= ½ and s = - ½
eB(2ν +1+2s) .. Energy of bound cyclic electron motion in the plane

Lowest Landau Level n = 0 has just s = - ½ for electrons
→ spin polarization of electrons in the lowest Landau Level.
Electron density in absence of magnetic field changes

$$n = \int \frac{g}{(2\pi)^3} f\, d^3 p \to \frac{geB}{(2\pi)^2} \sum_{\nu=0}^{\nu_{max}} \int f\, d\, p_z$$

where g is degeneracy factor and $f = \left(e^{(E-\mu)/T} + 1\right)^{-1}$ is the distribution function.
The electron polarization is defined by $\chi = \frac{n_- - n_+}{n_- + n_+}$



Constraints on T and μ_e for $\chi=1$

Kick Velocities

Heat capacity $C_q = 9\mu_q^2 T\left(1 - \frac{2\alpha_s}{\pi}\right) = A\mu_q^2 T$

Neutrino luminosity for direct Urca process with quarks

$$L = \frac{4}{3}\pi R^3 \epsilon_{q\beta}$$

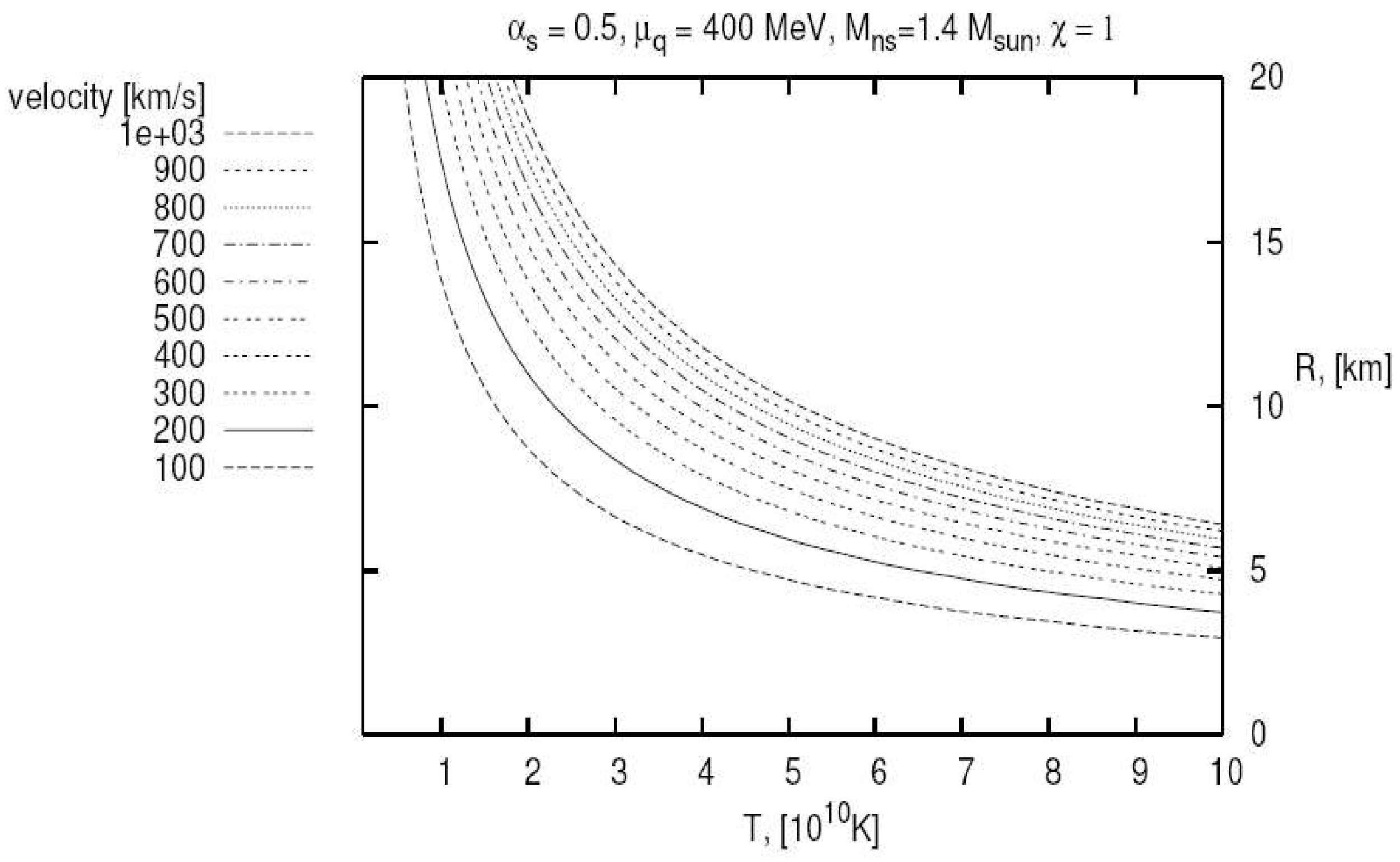
The relation between heat capacity and neutrino luminosity is

$$C_q\, dT = -\epsilon_{q\beta}\, dt$$

The velocity can be determined with $dv = \frac{\chi L}{M_{ns}} dt \to dv = \frac{4}{3}\pi R^3 \epsilon_{q\beta} \frac{\chi}{M_{ns}} \left(\frac{-C_q}{\epsilon_{q\beta}}\right) dT$

$$\to v = \frac{2}{3}\pi R^3 \frac{\chi}{M_{ns}} A\mu_q^2 T_0^2 \sim 24*10^{-5} \frac{km}{s} \left(\frac{\mu_q}{MeV}\right)^2 \left(\frac{T_0}{10^{10} K}\right)^2 \left(\frac{R}{10\,km}\right)^3 \frac{1.4 M_{sun}}{M_{ns}}$$

$$\to v \sim 38 \frac{km}{s} \left(\frac{T_0}{10^{10} K}\right)^2 \quad for\ \mu_q = 400\, MeV$$



Kick velocities of ~1000km/s for a realistic quark phase radius (~10 km) can be reached with T~$5*10^{10}$K and electron chemical potential μ ~ 20 MeV for magnetic field strengths B~$2*10^{17}$ G.

Neutrino mean free paths

Neutrino mean free paths in the interior of the neutron star are defined by absorption and scattering in quark as well as neutron matter. For interactions with quarks for

$$E_\nu = 3T, \quad \mu_q = 400\, MeV, \quad \alpha_s = 0.5, \quad \mu_e = 10\, MeV$$

they are given by (Iwamoto):

$$l_{scat} = 5\pi^3 \left(1 + \frac{2\alpha_s}{3\pi}\right)^2 \left((C_{Vd}^2 + C_{Ad}^2 + C_{Vu}^2 + C_{Au}^2)\mu_q^2 G_F^2 E_\nu^3\right)^{-1} \sim 92\, km \left(\frac{MeV}{T}\right)^3$$

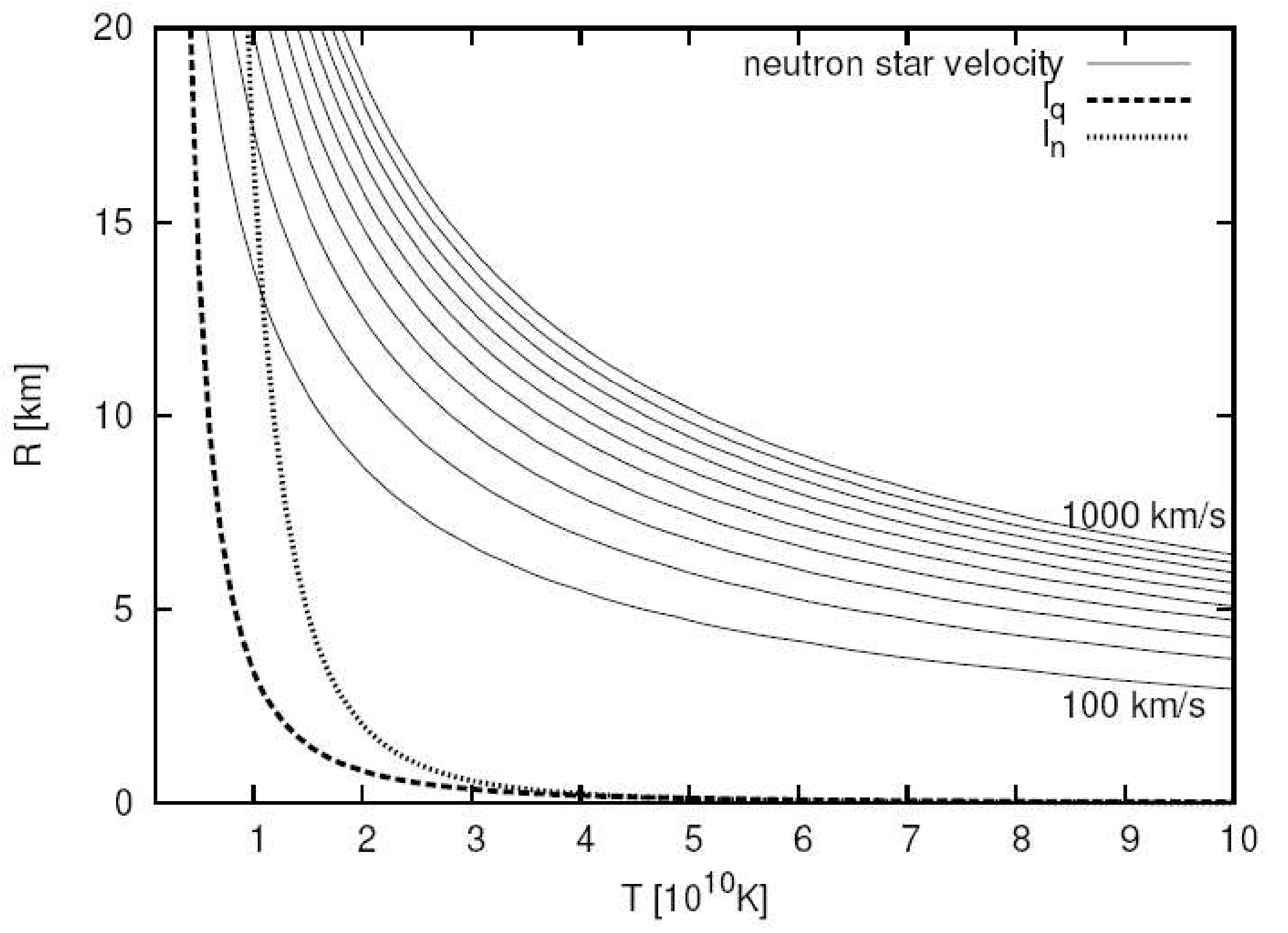
$$l_{abs}(E_\nu, T) = \left(16 G_F^2 \alpha_s \cos\theta_c^2 \mu_q^2 \mu_e\right)^{-1} \pi^4 \left(1 + \frac{2\alpha_s}{3\pi}\right)^2 \left(\frac{E_\nu^2 + (\pi T)^2}{1 + e^{-E_\nu/T}}\right)^{-1} \sim 25\, km \frac{MeV^3}{T^2 \mu_e}$$

In neutron matter the mean free paths of neutrinos are (Iwamoto) :

$$l_{abs} = \left(\left(\frac{3 n_n}{\pi^7}\right)^{1/3} 4(1 + 3g_A^2) G_F^2 m_n E_\nu^2 T\right)^{-1} \sim 17\, km \left(\frac{MeV}{T}\right)^3$$

$$l_{scat} = 4.5*10^6 \left(\frac{n_0}{n_b}\right)^{2/3} \left(\frac{10\, MeV}{T}\right)^4 \left(\left(\frac{E_\nu}{T}\right)^4 + 10\pi^2 \left(\frac{E_\nu}{T}\right)^2 + 9\pi^4\right)^{-1} cm \sim 244\, km \left(\frac{MeV}{T}\right)^4$$

with C_{Vi} Vector and axial current coupling constants, $g_A = 1.25$ and the weak coupling constant $G_F = 1.435*10^{-49}\, erg\, cm^3$



Problem: neutrino mean free paths are too small causing them to interact with the medium on their way to the surface → neutrinos isotropize → loss of polarization!

Possible solution for small mean free paths

The neutrino-quark interaction is exponentially suppressed in the color flavor locked (CFL) quark phase with the factor ~ exp(-Δ(T)/T), for T < T_c

The gap Δ also suppresses the heat capacity of quark matter with

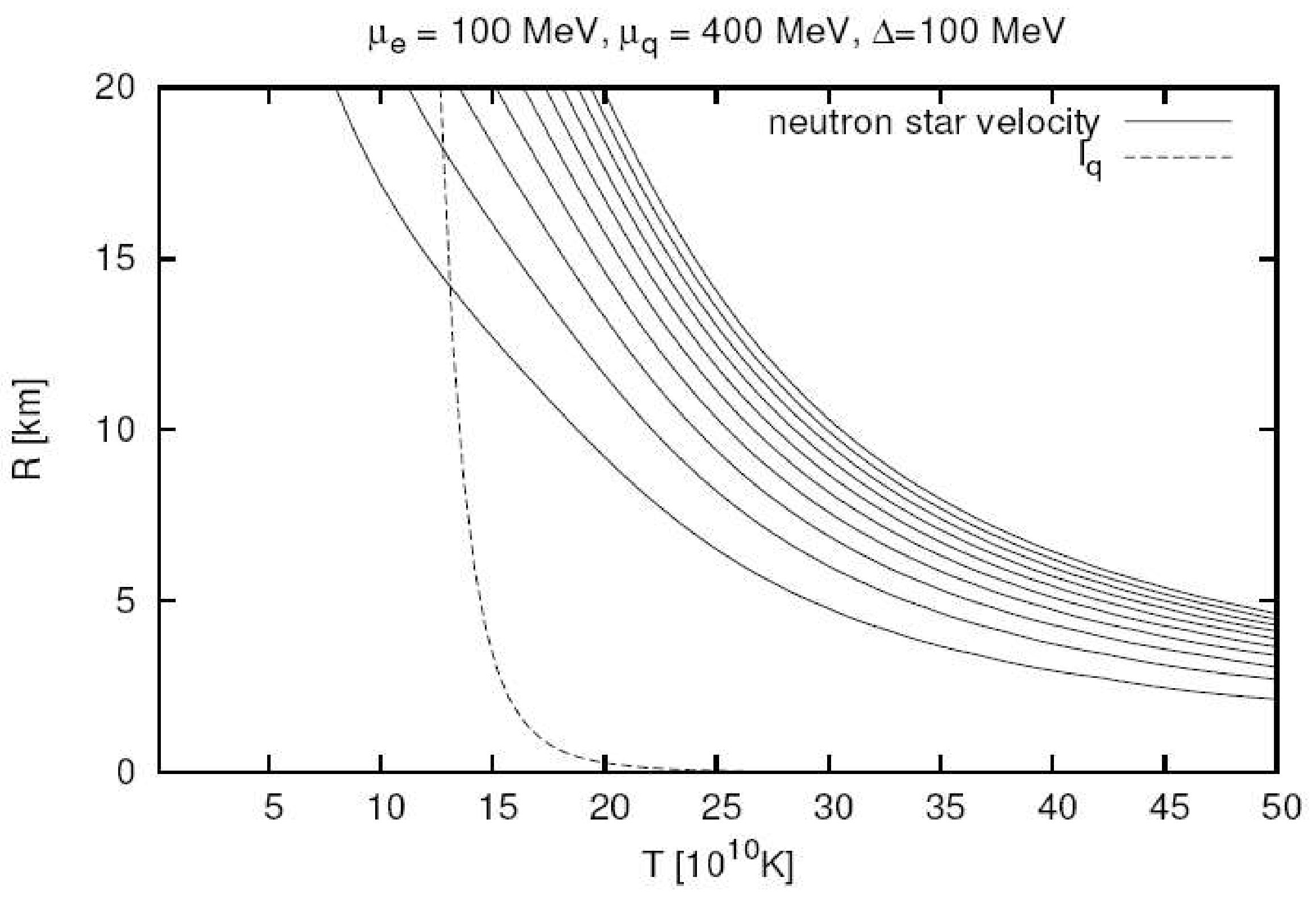
$$C_q = A\mu_q^2 T e^{-\Delta/T}$$

that is the electron heat capacity

$$C_e = \frac{\mu_e^2 T}{2} + \frac{7\pi^2 T^3}{30}$$

becomes important for the neutron star's velocity.

$$\to v = \frac{2}{3}\pi R^3 \frac{\chi}{M_{ns}} \left(\left(\frac{\mu_e^2}{2} + \frac{7\pi^2 T^2}{60}\right) T^2 + A\mu_q^2 e^{-\Delta/T} T^2\right)$$



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