Oscillations of superfluid neutron stars

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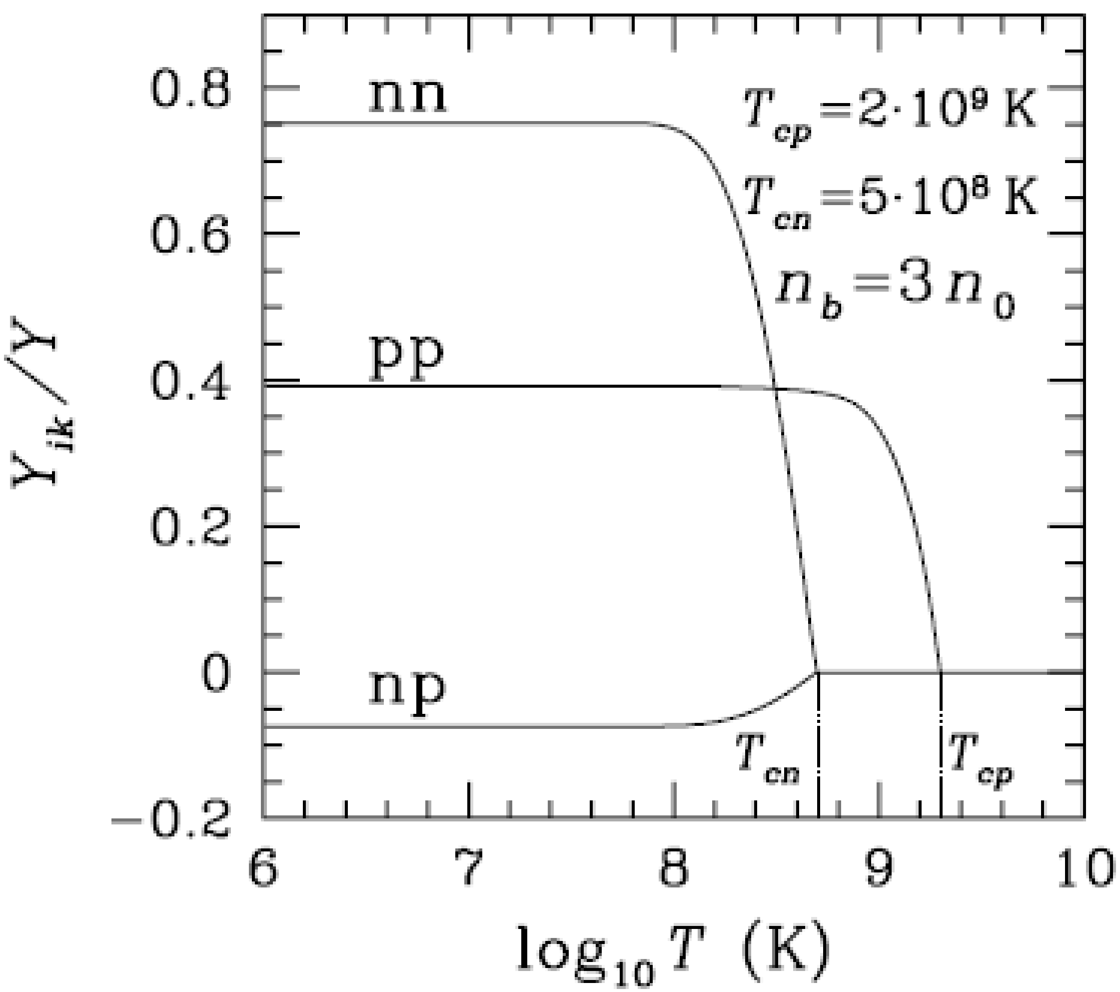
Superfluidity at $T \neq 0$

$$j^{\mu}_{(i)} = n_i u^{\mu} + Y_{ik} w^{\mu}_{(k)}$$

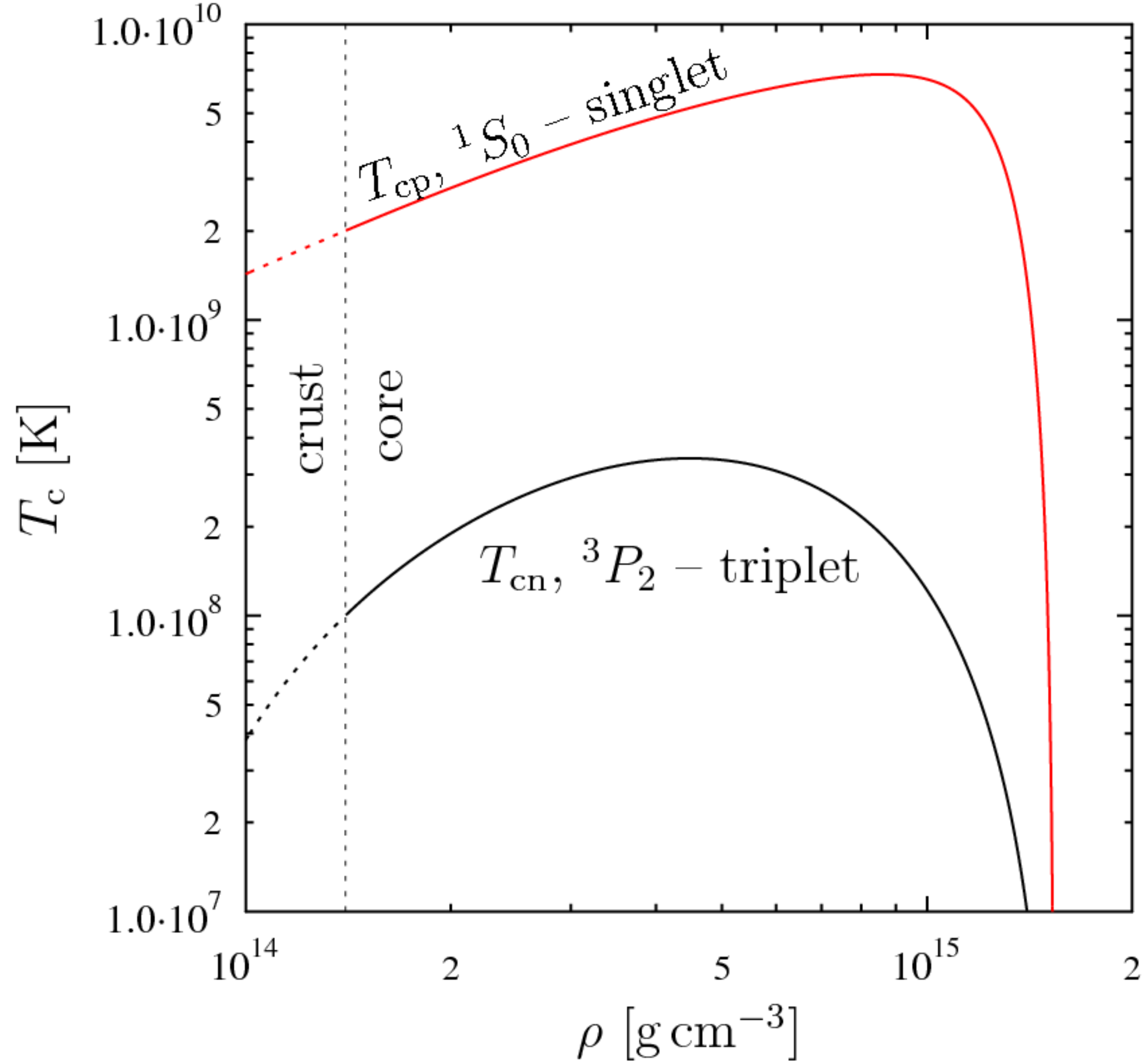


Strong temperature dependence

Temperature dependent pulsations!

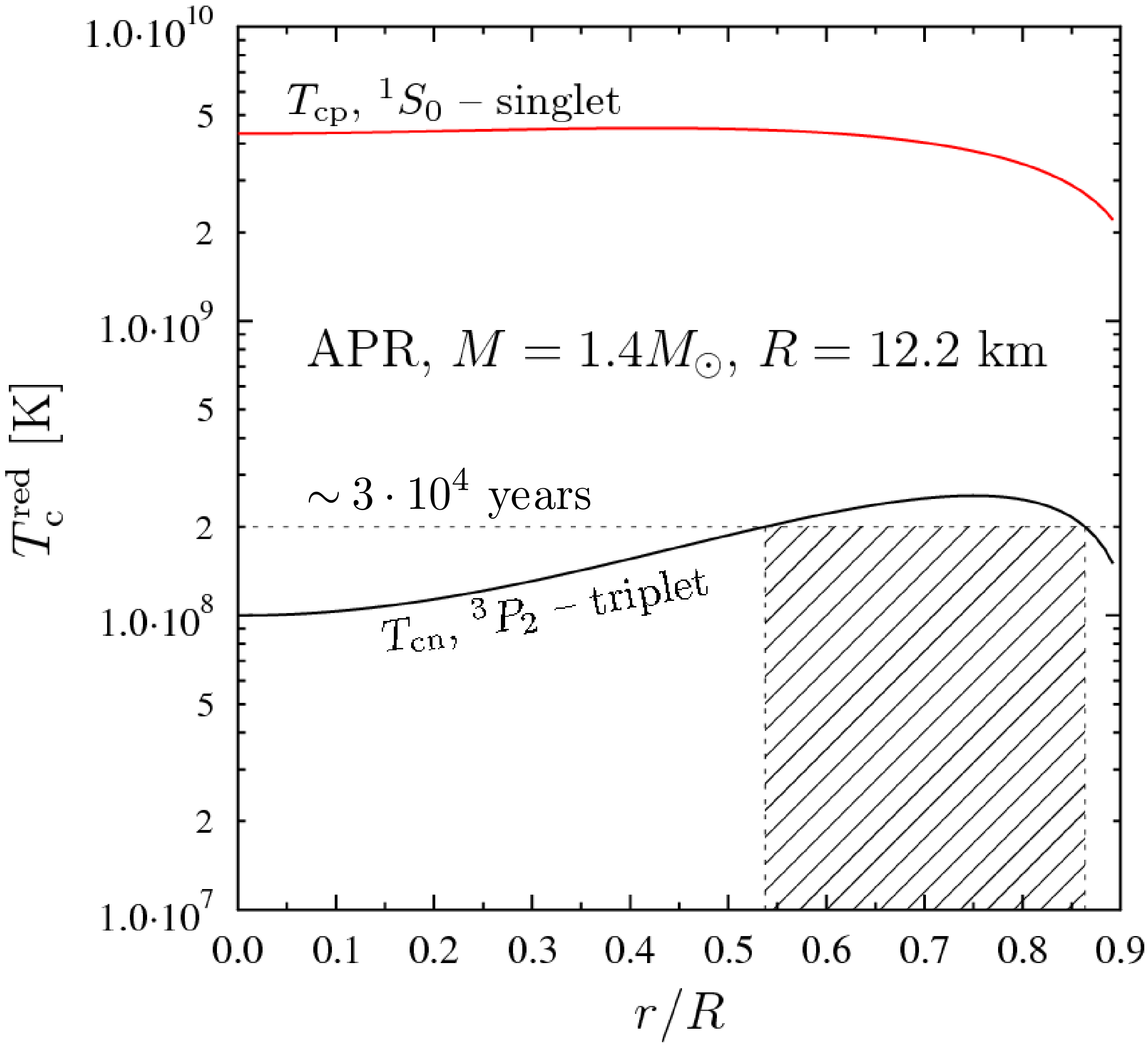
From Gusakov, Kantor, Haensel (2009), PRC 80, 015803

Superfluidity in NS cores

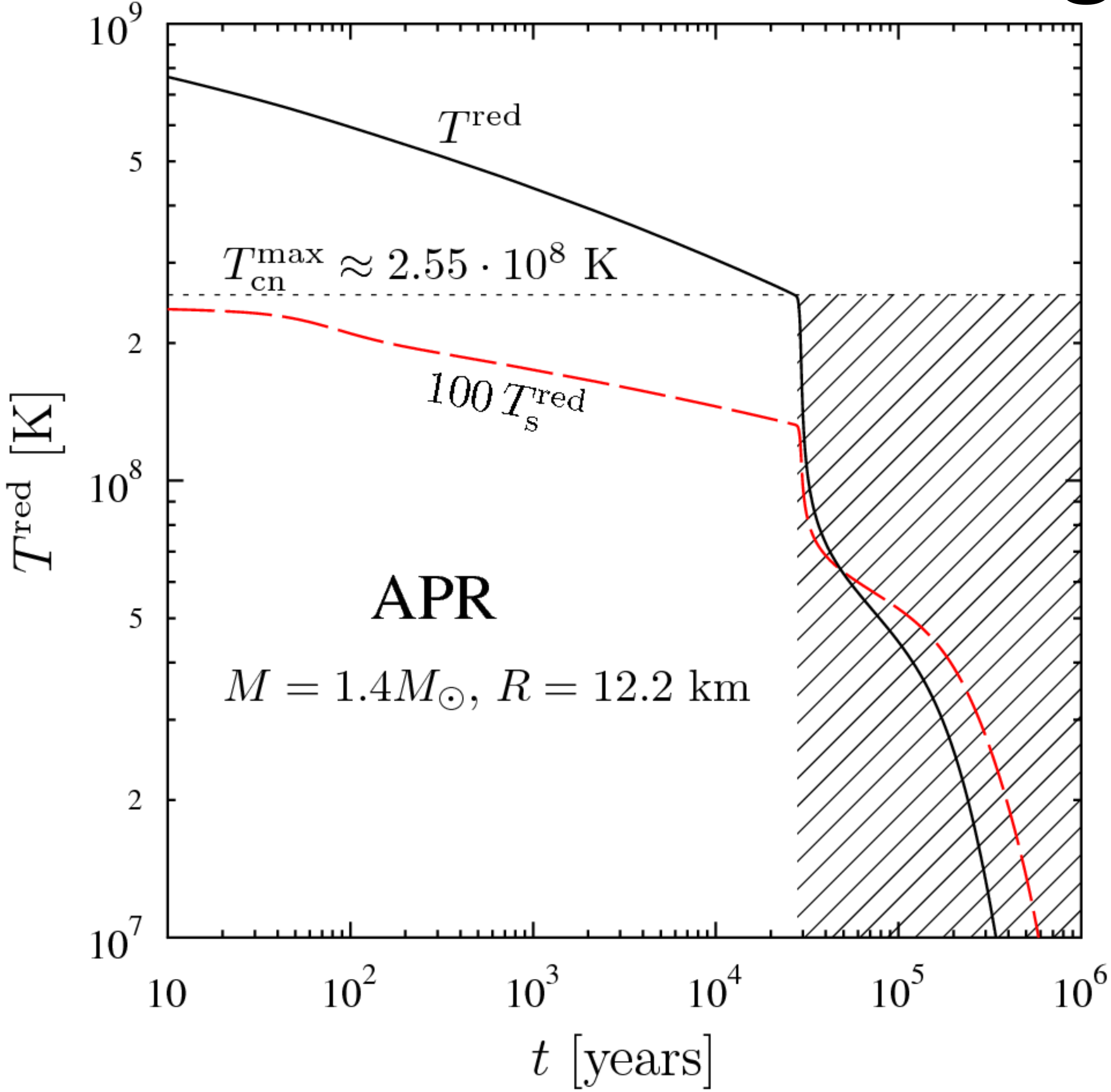


The model by Kaminker, Yakovlev, Gnedin (2002), A&A **383**, 1076

Critical temperature vs radius



Neutron star cooling



Decoupling of superfluid and normal modes

Talk by M.E. Gusakov, E.M. Kantor arXiv:1007.2752

$$s \equiv \frac{n_{e0}}{n_{b0}} \frac{\partial P/\partial n_{e0}}{\partial P/\partial n_{b0}} \ll 1$$

$$j^{\mu}_{(\mathrm{b})} = n_{\mathrm{b}} u^{\mu} + Y_{\mathrm{n}k} w^{\mu}_{(k)}$$

Modes

Normal

$$\delta j^{\mu}_{(\mathrm{b})} \sim n_{\mathrm{b}} \delta u^{\mu} \qquad \frac{Y_{\mathrm{n}k} w^{\mu}_{(k)}}{n_{\mathrm{b}} \delta u^{\mu}} \sim 1$$

Frequencies and $\delta j^{\mu}_{(\mathrm{b})}$ are the same as for normal star

Superfluid $\delta j^{\mu}_{(\mathrm{b})} \ll n_{\mathrm{b}} u^{\mu}$

$$\delta j^{\mu}_{n} \neq 0, \; \delta u^{\mu} \neq 0$$

Equation for superfluid modes

$$\delta\mu'' + \left(\frac{h'}{h} - \lambda' + \frac{2}{r}\right)\delta\mu' - \mathrm{e}^{\lambda}\left[\frac{l(l+1)}{r^2} + \mathrm{e}^{-\nu/2}\,\frac{\omega^2}{h}\,\left(\frac{\partial\delta\mu}{\partial n_{\mathrm{e}}}\right)^{-1}\right]\delta\mu = 0$$

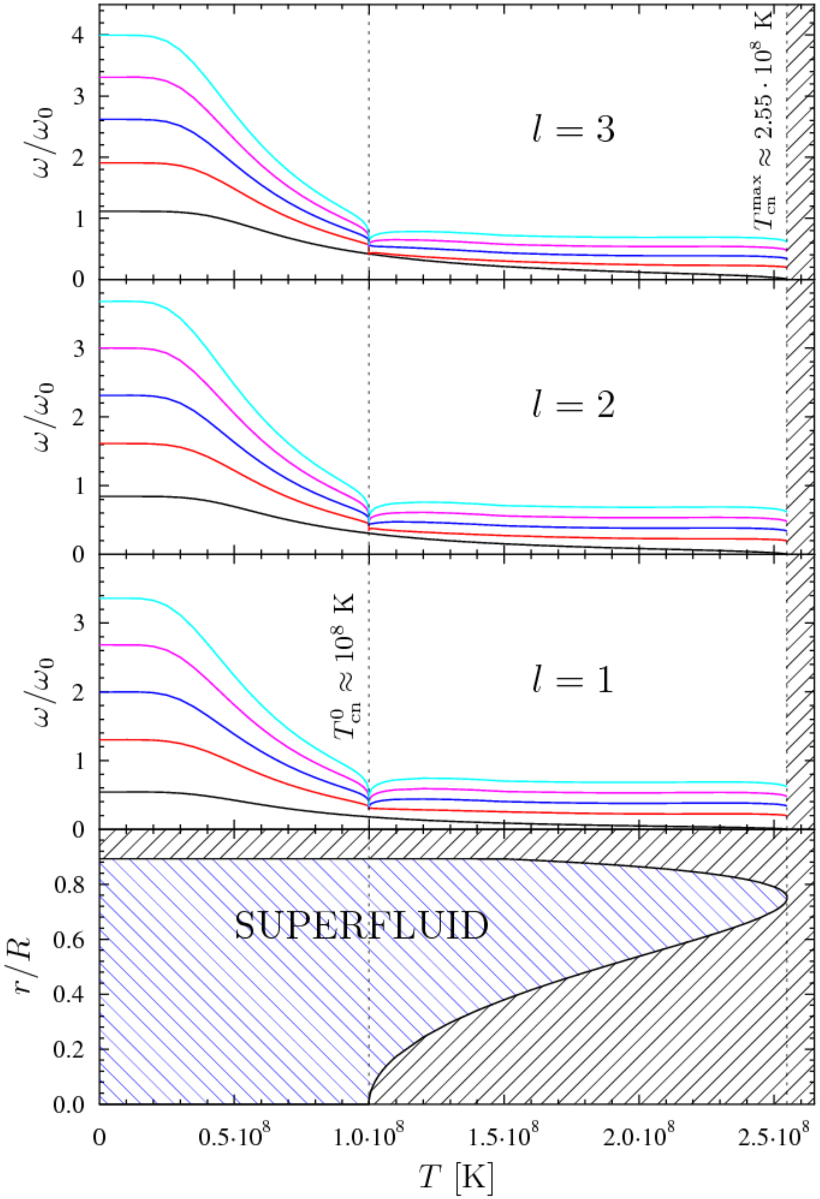
$$\delta\mu = \mu_n - \mu_p - \mu_e$$

Microphysics

$$h = \mathrm{e}^{\nu/2}\,\frac{n_{\mathrm{e}}^2}{y n_{\mathrm{b}}\mu_{\mathrm{n}}}$$

$$y = \frac{n_{\mathrm{b}} Y_{\mathrm{pp}}}{\mu_{\mathrm{n}}\,\left(Y_{\mathrm{nn}}Y_{\mathrm{pp}} - Y_{\mathrm{np}}Y_{\mathrm{pn}}\right)} - 1$$

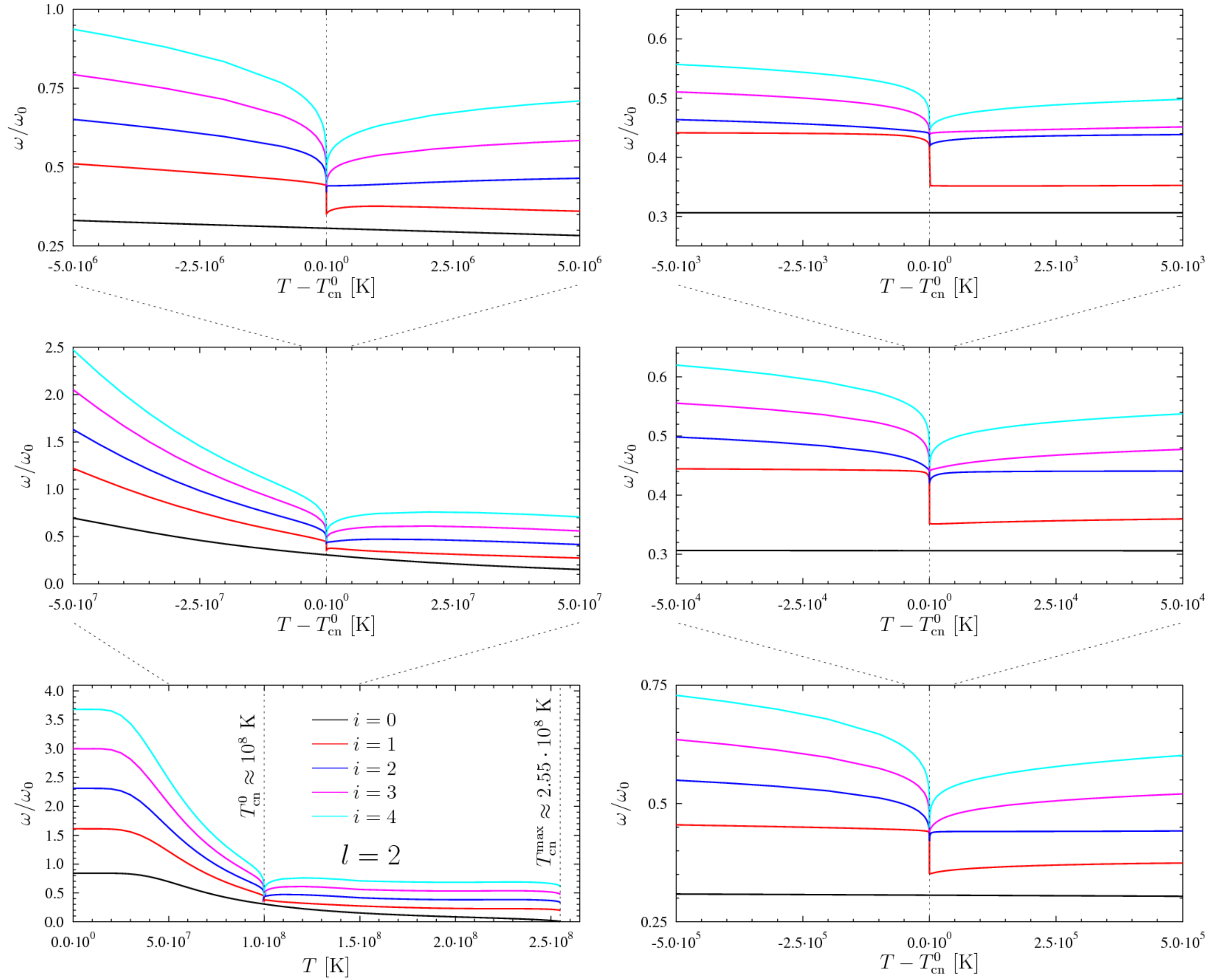
Oscillation spectrum vs T



$$\omega_0 = c/R$$

- Frequencies are very sensitive to the variation of temperature
- Frequencies depend not only on the superfluid region, but also on the temperature at this region

Oscillation spectrum vs T



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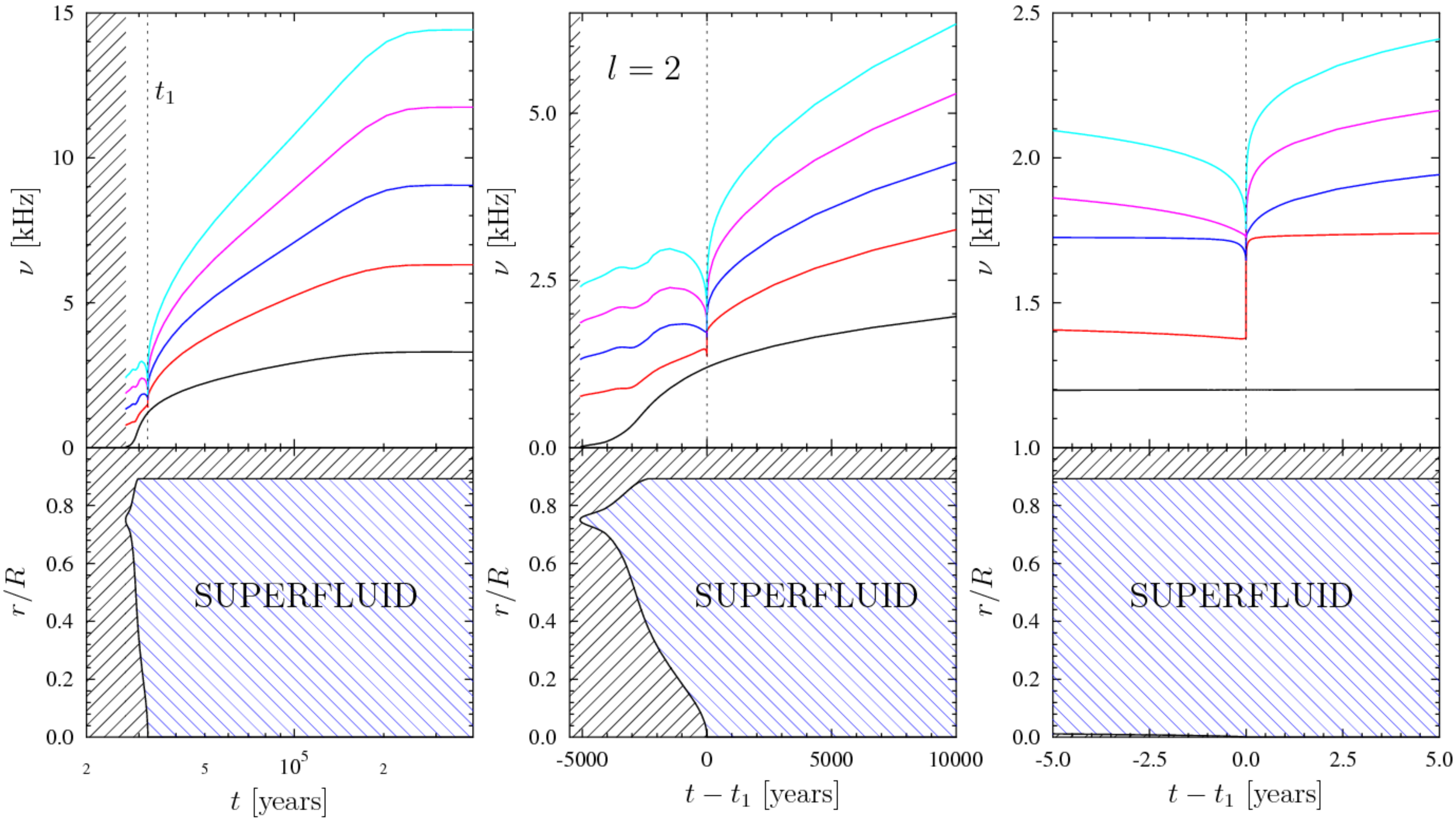
Evolution of spectrum



Damping of superfluid modes

Zero order in s

$\delta u^{\mu} \neq 0$ → Shear viscosity damping

$\delta \mu \neq 0$ → Bulk viscosity damping

$\delta g^{\mu\nu} = 0$ → No gravitational waves

Next order perturbations

$\delta g^{\mu\nu} \propto s$ → Coupling with gravitational waves is strongly ($\sim s^2 \sim 10^{-3}$) suppressed

Future perspectives of the decoupling approach

Normal modes

- Frequencies and $j^{\mu}_{(\mathrm{b})}$ can be calculated using the code designed to calculate pulsations of normal stars.
- The normal velocity u^{μ} and $w^{\mu}_{(\mathrm{k})}$ can be easily extracted from $j^{\mu}_{(\mathrm{b})}$ with help of superfluid equation.
- The damping rates can be calculated, since u^{μ} and $w^{\mu}_{(\mathrm{k})}$ are known

Superfluid modes

- Calculation of the gravitational waves from superfluid modes is a simple task, if one has a code calculating pulsations of a normal star
- Next order perturbation theory can be easily developed

Results and conclusions

Oscillations of redrealistic superfluid neutron stars are studied. We dont simplify microphysics and apply:

- **realistic equation of state (APR)**
- **realistic density dependent models of critical temperatures**

We demonstrate that:

- The superfluid pulsations strongly depend on temperature
- The temperature dependence caused not only by variation of superfluid region, but also by the properties of the matter
- Temporal evolution of superfluid spectrum is fast
- The superfluid modes are dumped by viscosity in zero order in s
- The emission of gravitational waves is supressed by a factor of $s^2 \lesssim 10^{-3}$