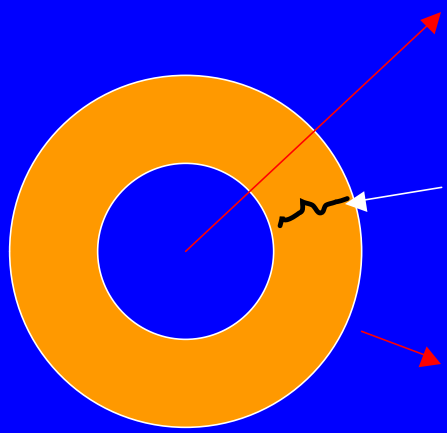
Cooling of neutron stars



Neutrino generation in core

Heat transport in “blanket”

Radiation from surface

(+ heating processes)

URCA process:

$$n \rightarrow p + e^- + \bar{\nu}$$
$$e^- + p \rightarrow n + \nu$$

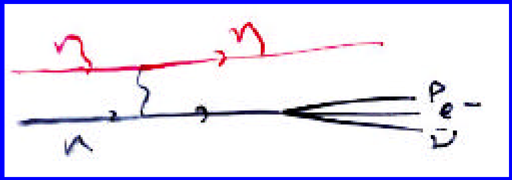
Neutrinos leave star carrying energy and entropy away

For proton fraction < 11-14% can't satisfy energy and momentum conservation, since $p_f\,(n) >> p_f\,(p) = p_f\,(e)$

Modified URCA process

Process works if excess momentum is transfered to a bystander nucleon

$$n + n \rightarrow p + e^- + \bar{\nu} + n$$
$$e^- + p + n \rightarrow n + \nu + n$$



Cooling time $\boxed{\tau_{\text{mod URCA}} \text{ » } (1\ \text{yr})/T_9^{\,6}}$

(where $T_9 = T/10^9$ K)

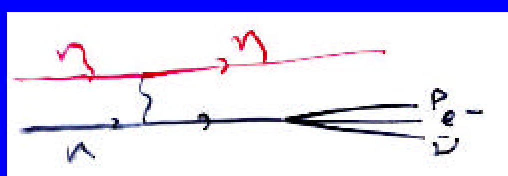
Cooling rates in degenerate matter

Pauli principle limits initial particles and final states that can participate in process. Reduction of rate by factor » T/T_f for each degenerate initial and final particle.

One additional factor of T for final neutrino.

$n \to p + e^- + \bar{\nu}$
$e^- + p \to n + \nu$

Rate » $T\,(T/\mu_n)(T/\mu_e)^2$ » T^4

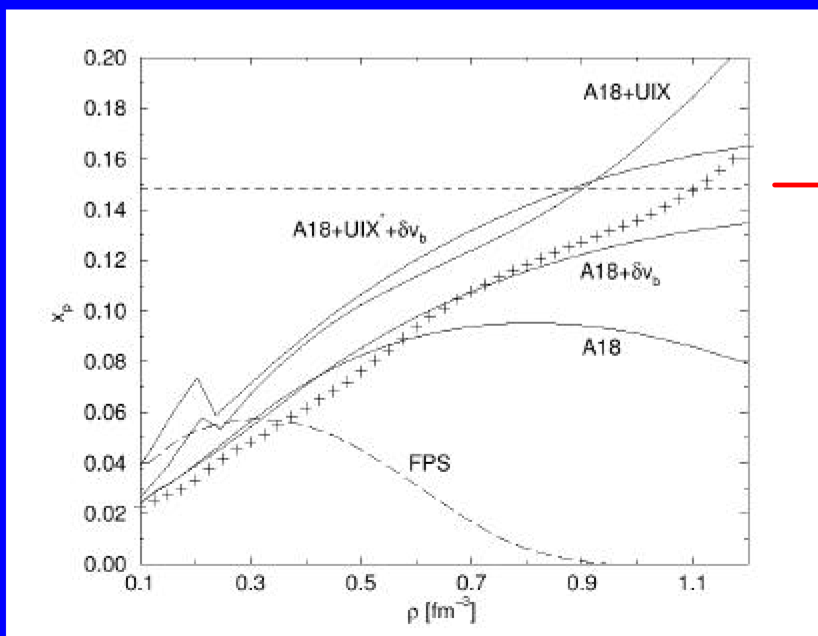


Rate » $T\,(T/\mu_n)^3(T/\mu_e)^2$ » T^6

Direct URCA process

$n \to p + e^- + \bar{\nu}$
$e^- + p \to n + \nu$

For large proton fraction can have direct URCA:
Nuclear symmetry energy not sufficiently certain to rule it out in inner core



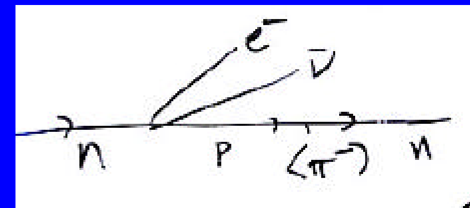
direct URCA

Proton fraction $x_p = n_p/(n_p+n_n)$ in matter in beta equilibrium

$\tau_{\text{direct URCA}} \sim 1\ \text{min}/T_9^4$

URCA in exotic phases faster than modified URCA

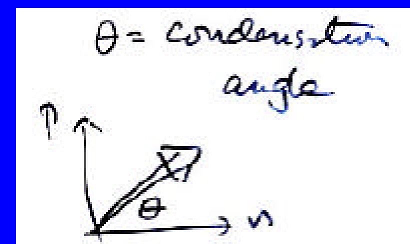
Pion condensed phase



$n \rightarrow p + e^- + \bar{\nu}$

$p + \langle\pi\rangle \rightarrow n$

Bragg scattering of n by pion field transfers needed momentum



τ_π » (1 min)/$\theta^2\ T_9^{\,4}$

Kaon condensed phase, similar

τ_K » 300 τ_π

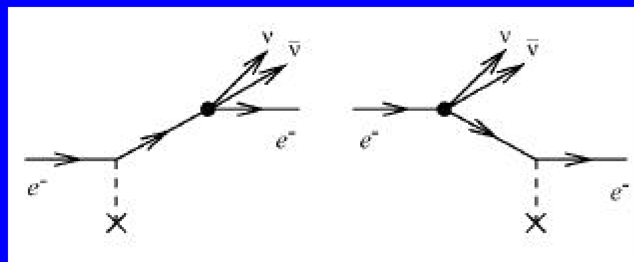
Quark matter: relativistic kinematics with interactions allows phase space for direct process

$d \rightarrow u + e^- + \bar{\nu}$

$e^- + u \rightarrow d + \nu$

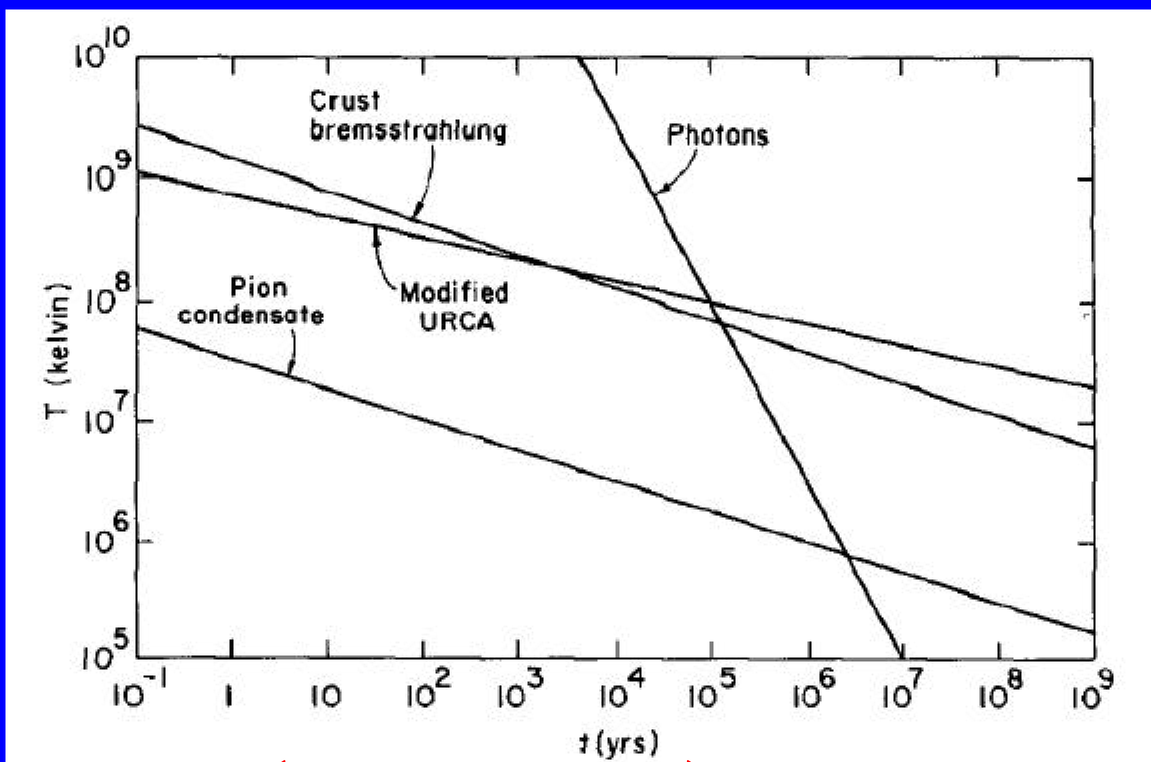
τ_{QM} » τ_π

Crust bremsstrahlung produces neutrino- antineutrino pairs



Rates very sensitive to solid state band effects in crust

$\tau_{CB} \gg T^6$

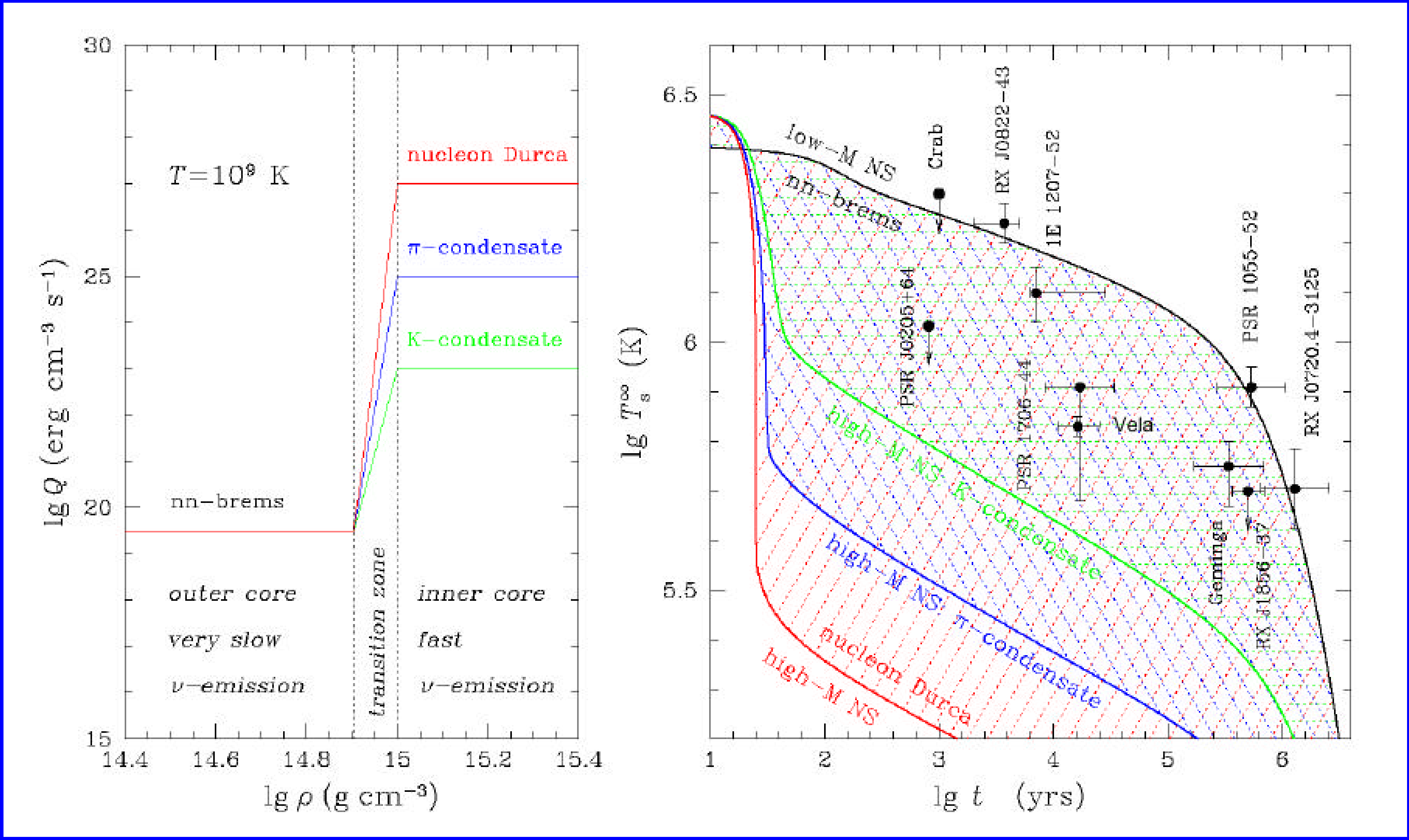


Schematic of neutron star interior temperature for separate cooling processes

core neutrinos

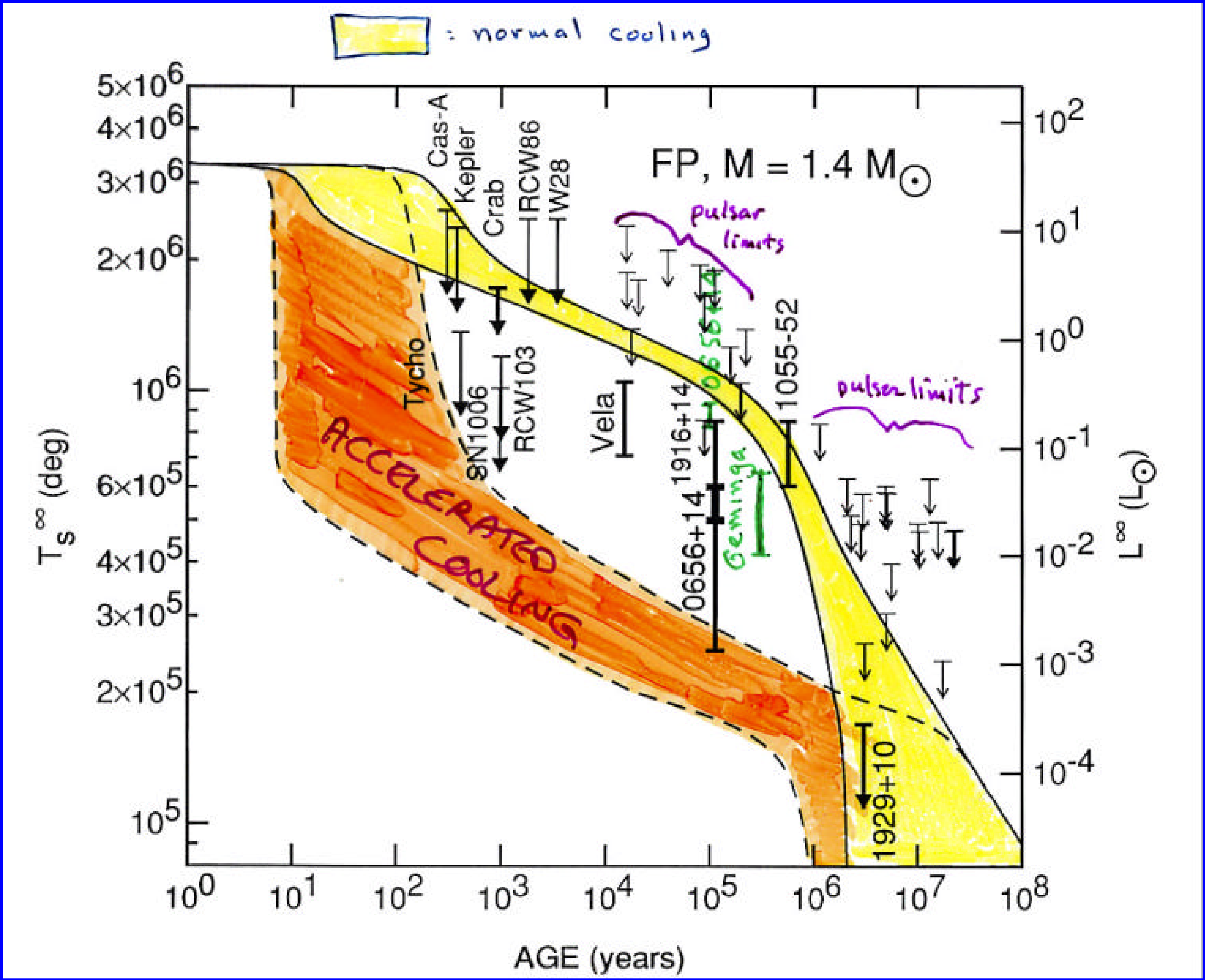
surface photons

Accelerated cooling of neutron stars by exotic interiors



Yakovlev and Pethick. Ann. Rev. Astr. Astrophys. 2004

Accelerated cooling by exotic interior, for 1.4M– star



X-ray luminosity of neutron stars in supernova remnants

D.L. Kaplan et al., ApJS 153, 269 (2004)

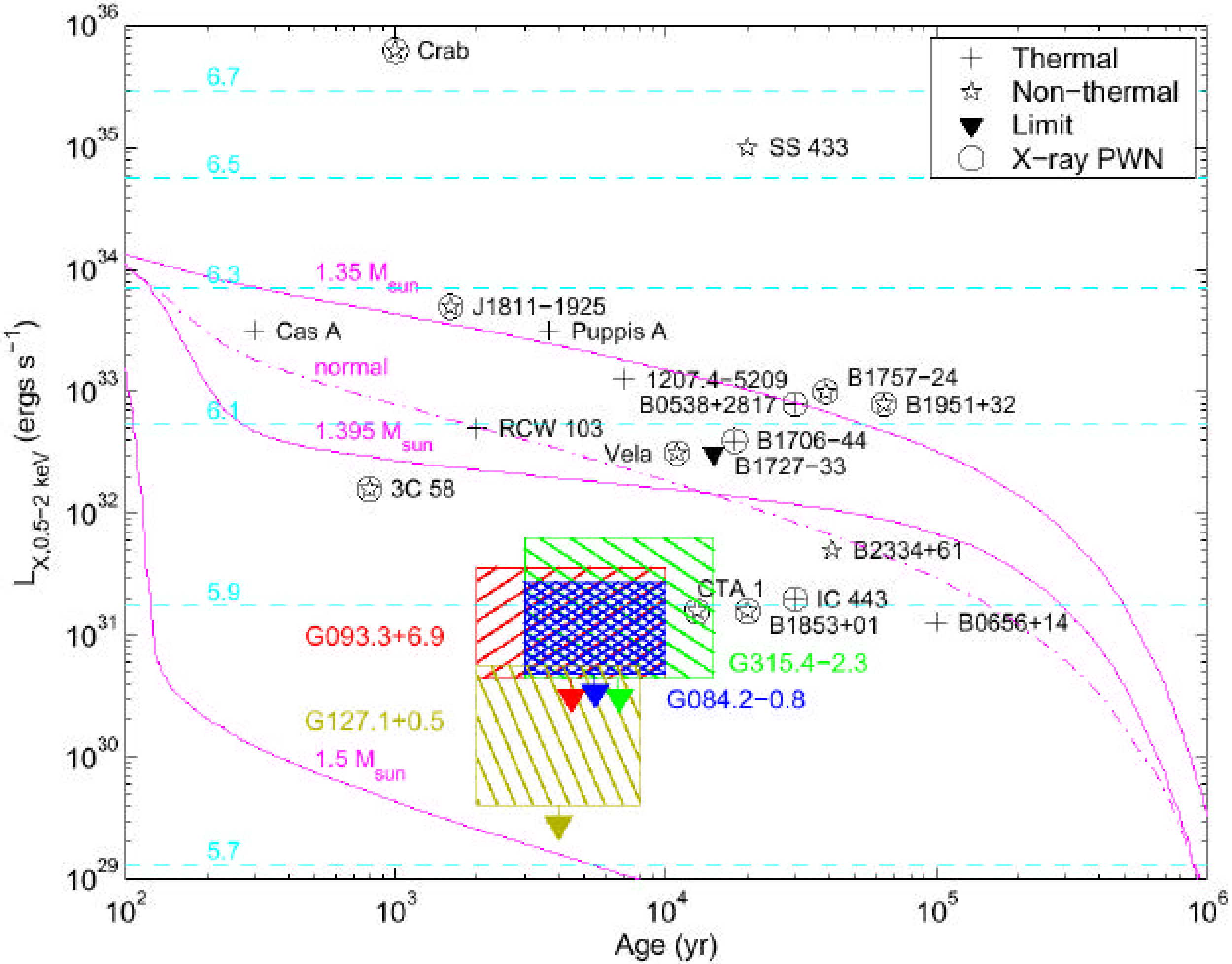
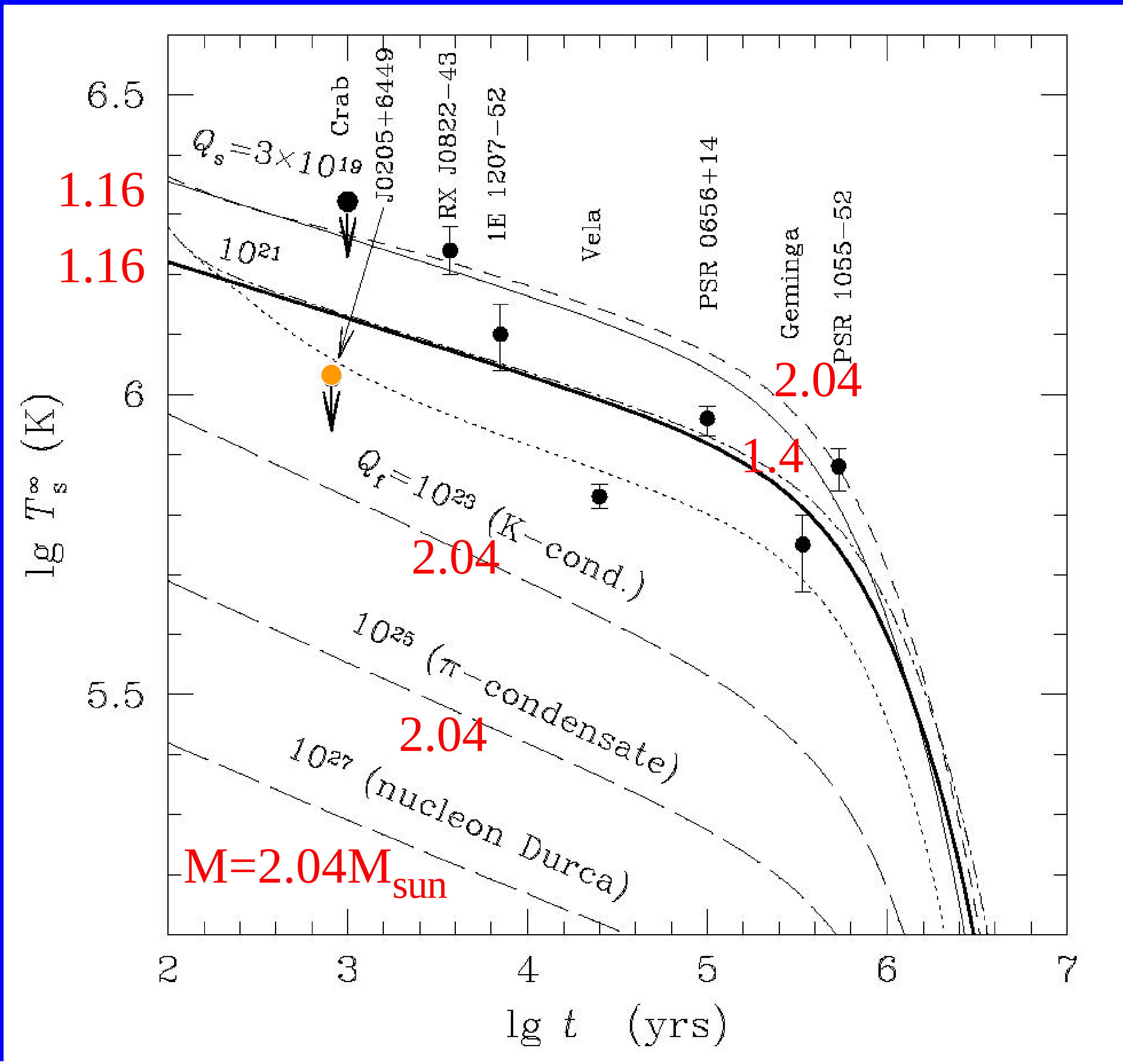


FIG. 37.— X-ray luminosities (0.5–2 keV) as a function of age for neutron stars in SNRs from Table 2. Sources whose emission is primarily thermal are indicated with plus symbols, those whose emission is primarily non-thermal are indicated with stars, and those with only limits are indicated with triangles. The sources that have X-ray PWNe, which are typically > 10 times the X-ray luminosity of the neutron stars themselves, are circled. We also plot the limits to blackbody emission from sources in SNRs G093.3+6.9 (red hatched region), G315.4_2.3 (green hatched region), G084.2+0.8 (blue cross-hatched region), and G127.1+0.5 (gold hatched region). A 30% uncertainty in the distance has been added to the range of luminosities given in Table 18 (i.e. we have taken the Type I limits with a 30% larger distance and the Type II limits with a 30% smaller distance, to give the widest probable range of luminosities), and the likely range of ages is also shown. The cooling curves are the 1p proton superfluid models from Yakovlev et al. (2003) (solid lines, with mass as labeled) and the normal (i.e., non-superfluid) $M = 1.35\,M_\odot$ model (dot-dashed line), assuming blackbody spectra and $R_\infty = 10$ km. These curves are meant to be illustrative of general cooling trends, and should not be interpreted as detailed predictions. The horizontal lines show the luminosity produced by blackbodies with $R_\infty = 10$ km and $\log T_\infty$ (K) as indicated. Faster cooling than the curves is possible, due either to the presence of exotic particles in the NS core or to the full onset of direct Urca cooling for a heavier NS (e.g., Yakovlev et al. 2002b).

Dependence on mass (RED) and neutrino cooling rates (Q)



1.4M–

2.04M–

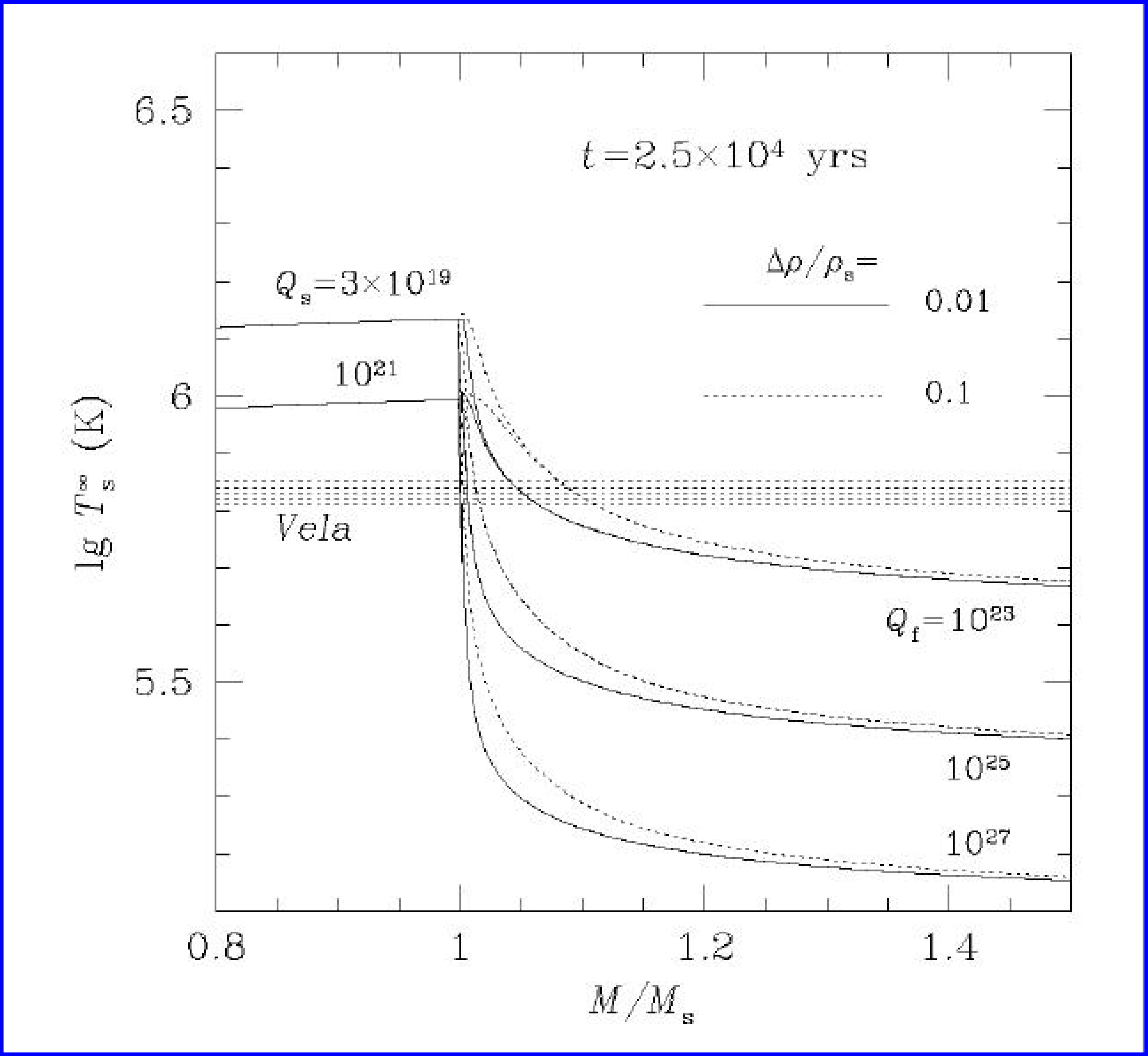
p pairing

n pairing

Haensel & Yakovlev, A&A 407, 2003

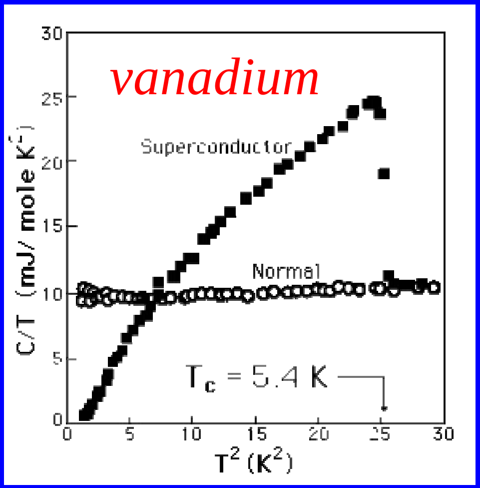
Cooling after 25,000 years: cf. Vela

Haensel & Yakovlev, A&A 407, 2003



Effects of superfluidity in interior

Specific heat of matter enhanced just below T_c and exponentially suppressed at $T \ll T_c$:



=> slower cooling just below T_c, and much faster at $T \ll T_c$

Neutrino processes suppressed by energy gap in nucleon quasiparticle spectrum: $E = ((p^2/2m - \mu)^2 + \Delta^2)^{1/2} + \mu$

With and without proton superconductivity

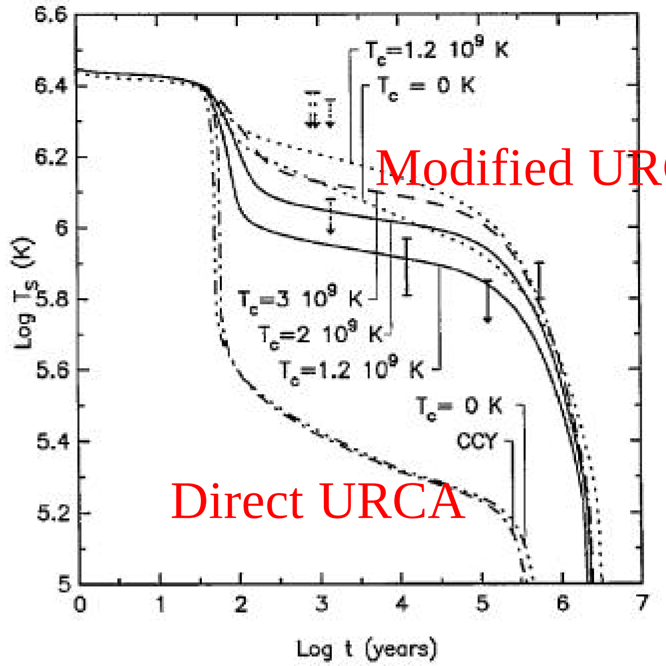


FIG. 3.—Effect of proton superfluidity on direct Urca cooling. Cooling curves for a 1.4 $M_\odot$ direct Urca star using various assumptions about the proton $^1S_0$ gap are shown. The dash-dot curve uses the proton gap found by Chao et al. (1972). The dashed curve and the two solid curves have been computed using density-independent critical temperature for proton $^1S_0$ superfluidity as labeled. The dotted curves show the cooling of a 1.3 $M_\odot$ star without direct Urca, with and without proton pairing for comparison.

With and without neutron superfluidity

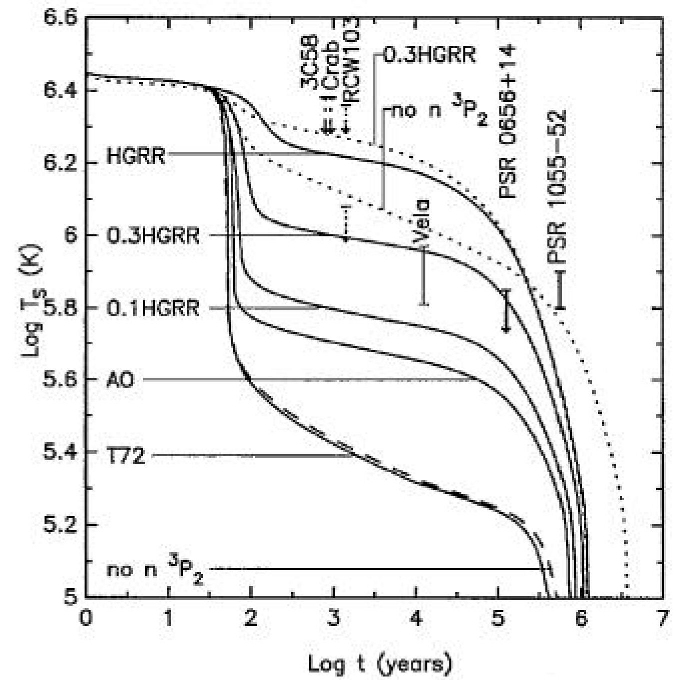
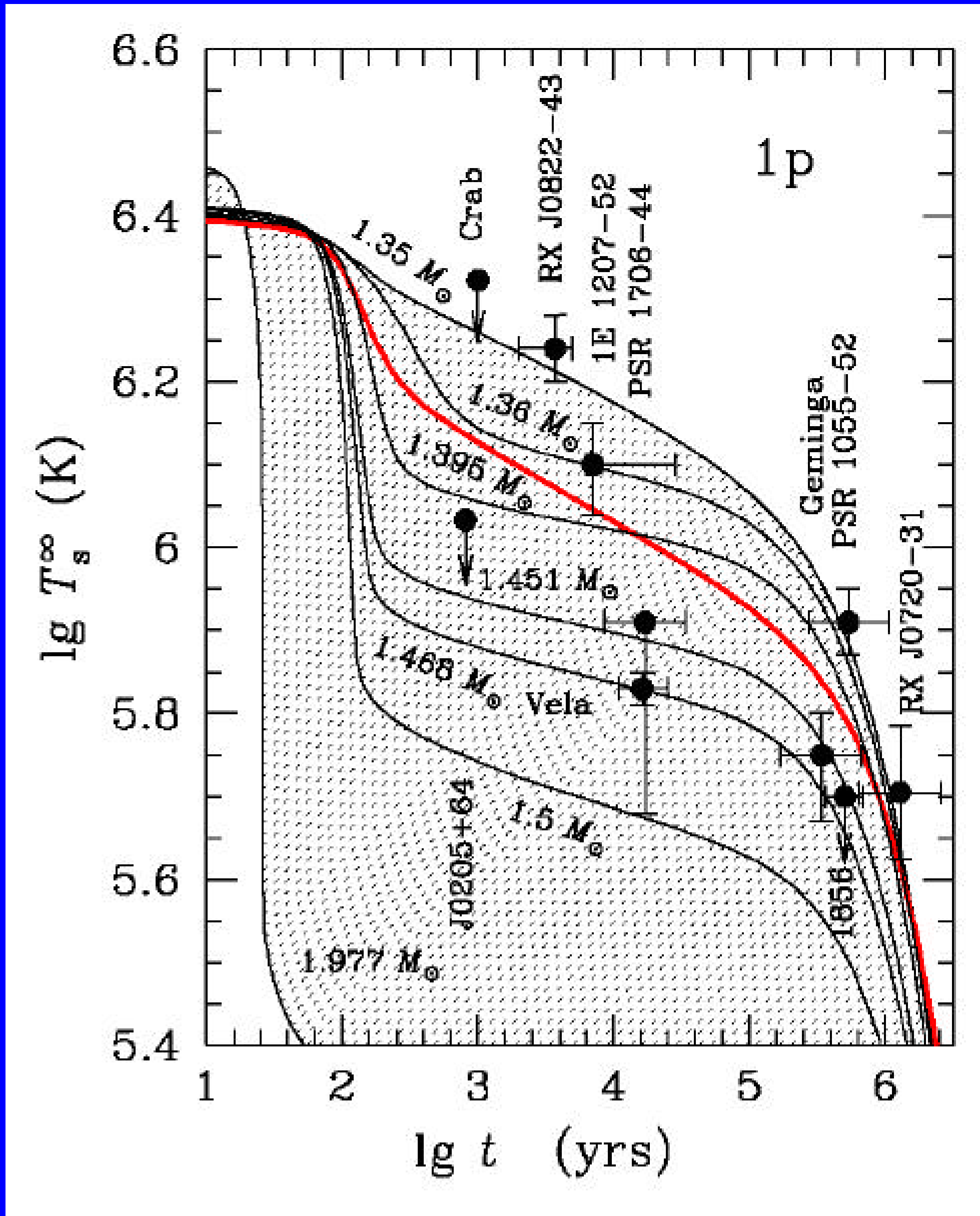


FIG. 2.—Effect of neutron superfluidity on the direct Urca cooling. Cooling curves for a 1.4 $M_\odot$ direct Urca star using various calculations of the neutron $^3P_2$ gap are shown in the solid curves. The labels are defined in the text. The dashed curve has no neutron $^3P_2$ superfluidity. The dotted curves show the cooling of a 1.3 $M_\odot$ star without direct Urca, with and without neutron $^3P_2$ pairing for comparison. The sources of the plotted data are given in the text.

M= 1.4 M–

Page and Applegate, Ap. J. Lett. 394 (1992)



Yakovlev and Pethick. Ann. Rev. Astr. Astrophys. 2004

Effects of magnetic fields

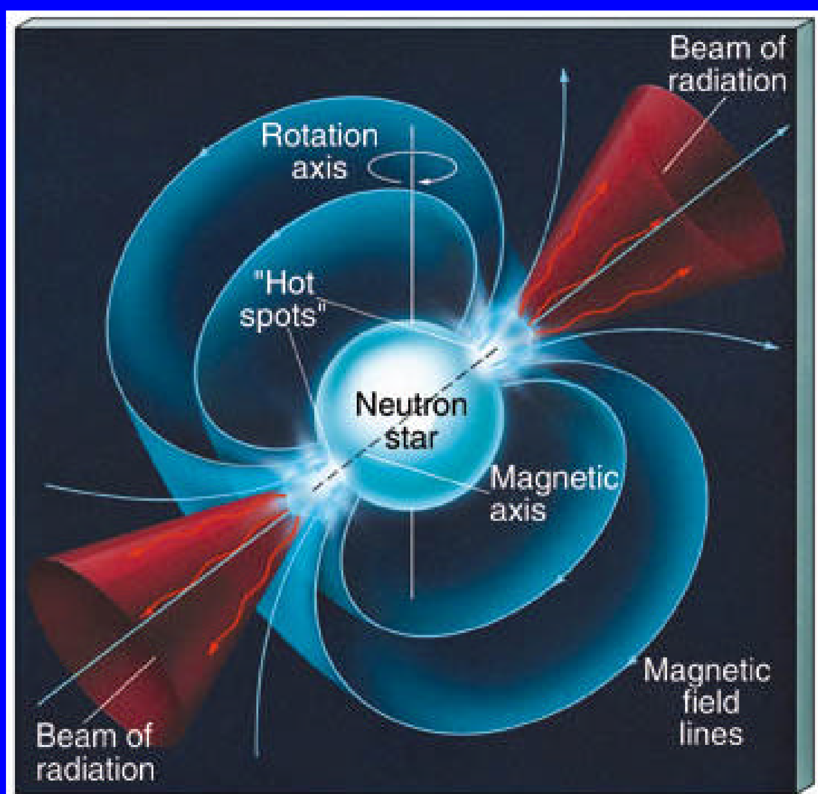
Photon emissivity » $(\omega/\omega_c)^2$ for polarization ? B.

ω_c = eB/mc = e^- cyclotron frequency

Raises surface temperature.

Surface emission not black body!

Effects of magnetosphere surrounding star.



Deducing surface temperatures and radii of neutron stars from detected x-ray luminosity non-trivial.