Rotochemical heating in hybrid stars

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Problems of theoretical physics, BITP

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Outline

- Neutron stars properties
- Thermodynamic equilibrium
- Rotochemical heating

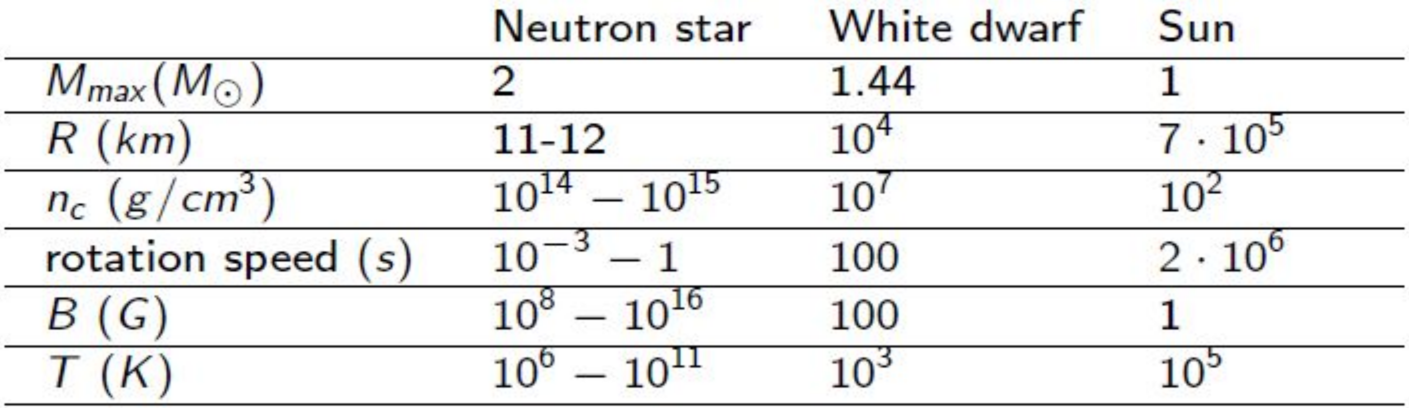
1.

Neutron stars properties

Neutron stars properties

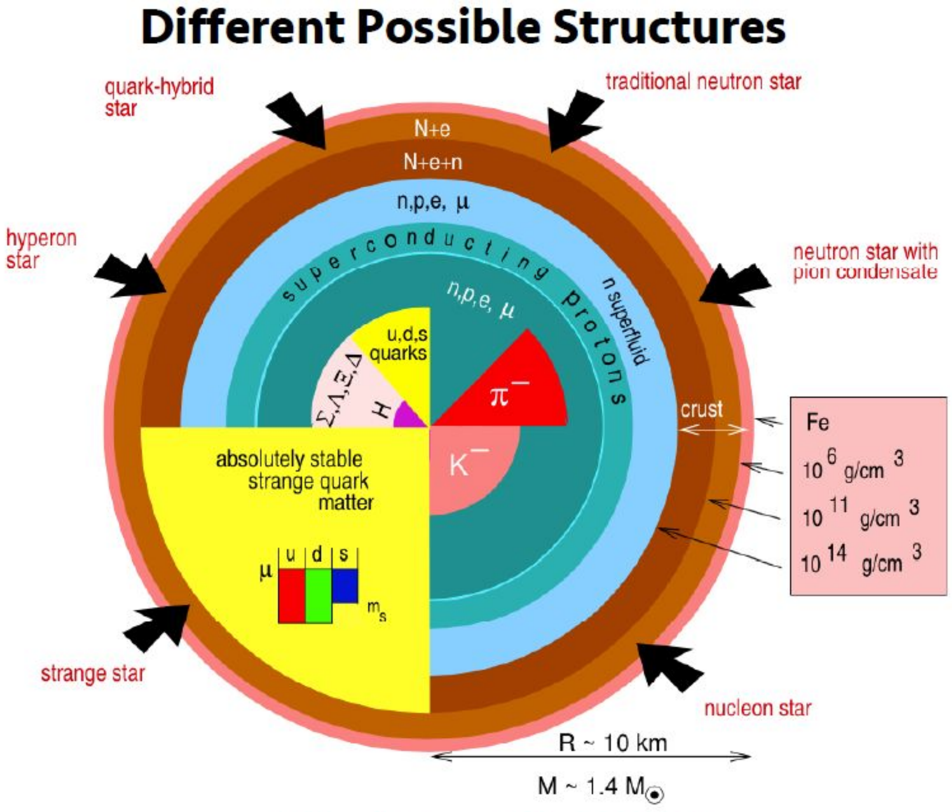
Extreme matter

- Extreme properties among all known observable objects
  - Great for exotic matter search!
- Most related data is unobservable
  - Not so great then?



	Neutron star	White dwarf	Sun
$M_{max}(M_\odot)$	2	1.44	1
R (km)	11-12	10^4	$7 \cdot 10^5$
n_c (g/cm^3)	$10^{14} - 10^{15}$	10^7	10^2
rotation speed (s)	$10^{-3} - 1$	100	$2 \cdot 10^6$
B (G)	$10^8 - 10^{16}$	100	1
T (K)	$10^6 - 10^{11}$	10^3	10^5

Neutron stars properties

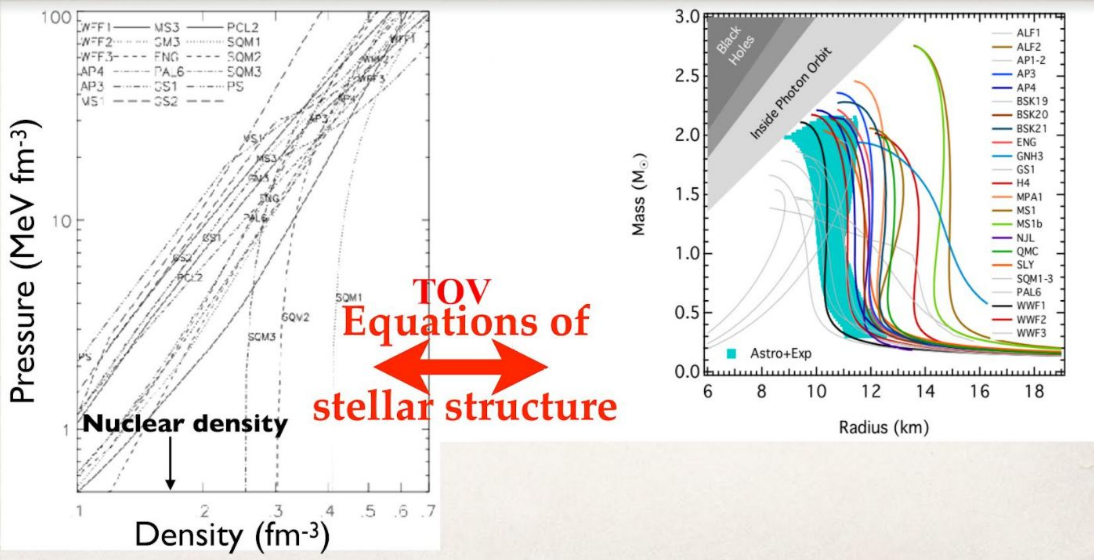


[Weber, J. Phys. G **27**, 465 (2001)]

Inner structure models

As for now almost none models can be excluded from consideration! But we could really benefit from that..

Neutron stars properties



Lattimer and Prakash 2001

TOV eq. (relativ. hydro):

$$\frac{dP}{dr} = -\frac{G}{r^2}\left(\rho + \frac{P}{c^2}\right)\left(m + 4\pi r^3 \frac{P}{c^2}\right)\left(1 - \frac{2Gm}{c^2 r}\right)^{-1}$$

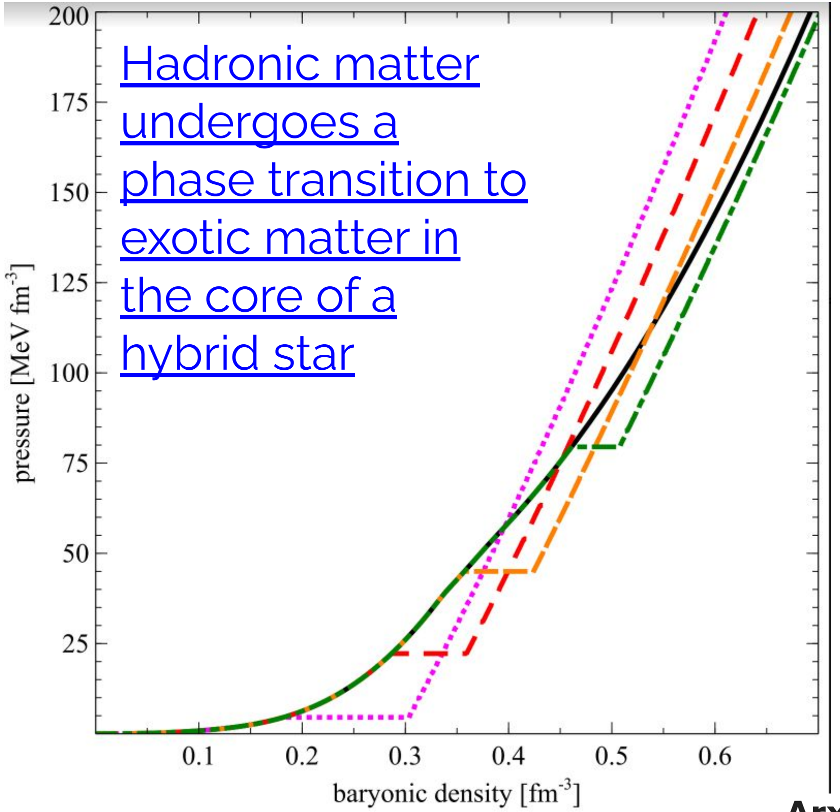
EoS

Continuous nuclear matter
+ hydrostatic equilibrium
=> Results based on
Equation of State P(ρ) only

Nuclear phenomenology ultimate goal <= find the most descriptive nuclear EoS.

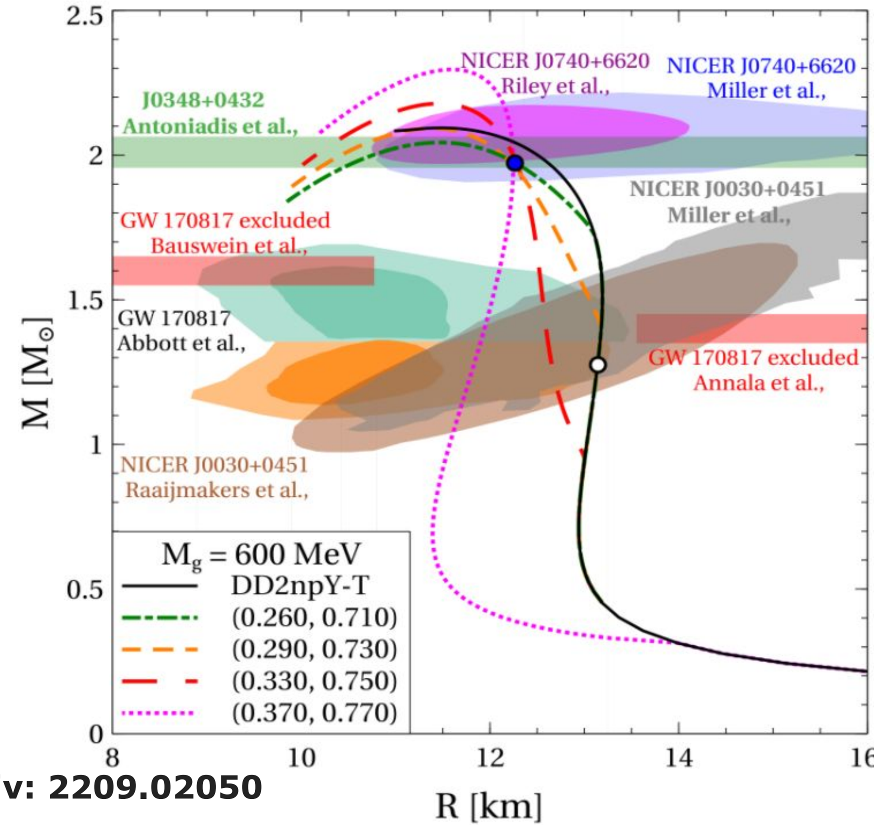
Can neutron star research help?

Neutron stars properties



Hadronic matter undergoes a phase transition to exotic matter in the core of a hybrid star

Hybrid EoS



Arxiv: 2209.02050

2.

Thermodynamic equilibrium

Thermodynamic equilibrium

Equilibrium of phases

It makes sense to apply hybrid EoS to neutron stars since we expect more than one matter phase within it (QCD prediction!)

At phase boundary, phases coexist in equilibrium:

- Thermal: no heat flow $T_h = T_{exot}$
- Dynamical: pressure is equalized $p_h = p_{exot}$
- Chemical: no charge flow $\mu_h = \mu_{exot}$

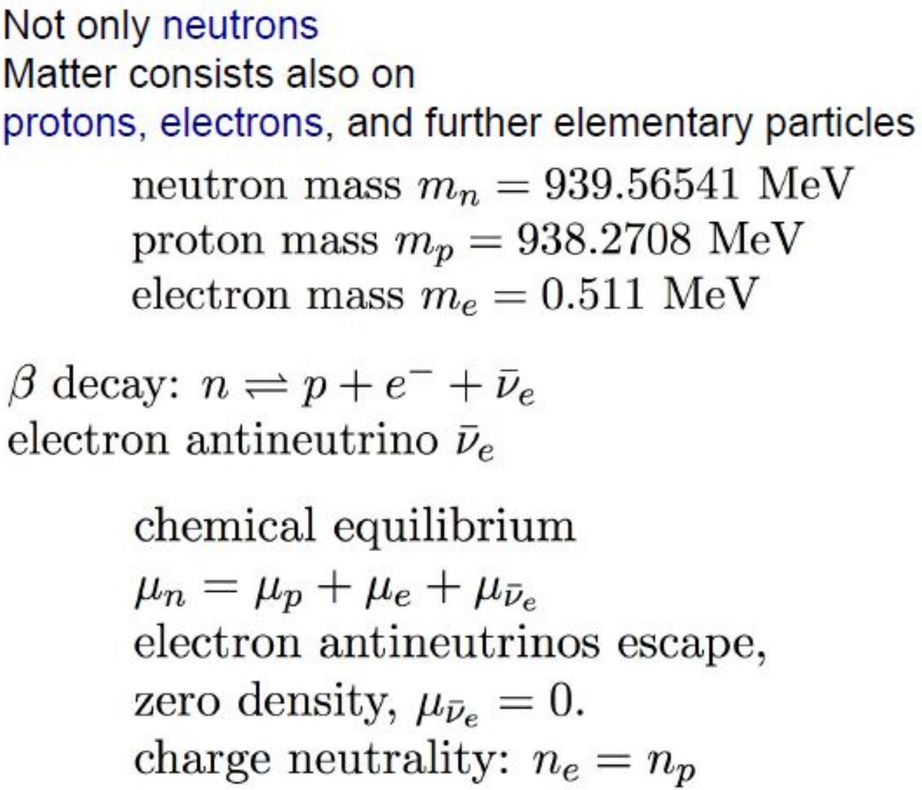
We also apply additional physical constraints, including

- Local/Global charge neutrality $\sum_i n_i q_i = 0$
- Beta equilibrium $n \rightleftharpoons p + e^- + \bar{\nu}_e$

Even with these requirements, there are multiple ways to impose a phase transition in equilibrium!

Thermodynamic equilibrium

Equilibrium of phases



Not only neutrons
Matter consists also on
protons, electrons, and further elementary particles

neutron mass $m_n = 939.56541$ MeV
proton mass $m_p = 938.2708$ MeV
electron mass $m_e = 0.511$ MeV

β decay: $n \rightleftharpoons p + e^- + \bar{\nu}_e$
electron antineutrino $\bar{\nu}_e$

chemical equilibrium
$\mu_n = \mu_p + \mu_e + \mu_{\bar{\nu}_e}$
electron antineutrinos escape,
zero density, $\mu_{\bar{\nu}_e} = 0$.
charge neutrality: $n_e = n_p$

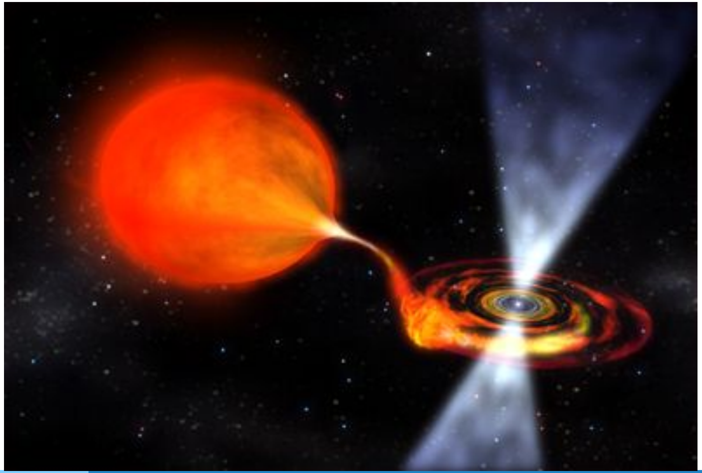
3.

Rotochemical heating

Rotochemical heating

Quasi-equilibrium

- Millisecond pulsars (MSP, rapidly rotating neutron stars) deviate from chemical equilibrium due to fast rotation
- Results in enhanced neutrino emission and heat generation – “rotochemical heating”
- Especially notable for old neutron stars



Very important since it allows to constraint physical models, if spin characteristics and surface temperature are known

Rotochemical heating

For stars in quasi-equilibrium (MSP), the final temperature mostly depends on rotochemical heating!

Temperature evolution

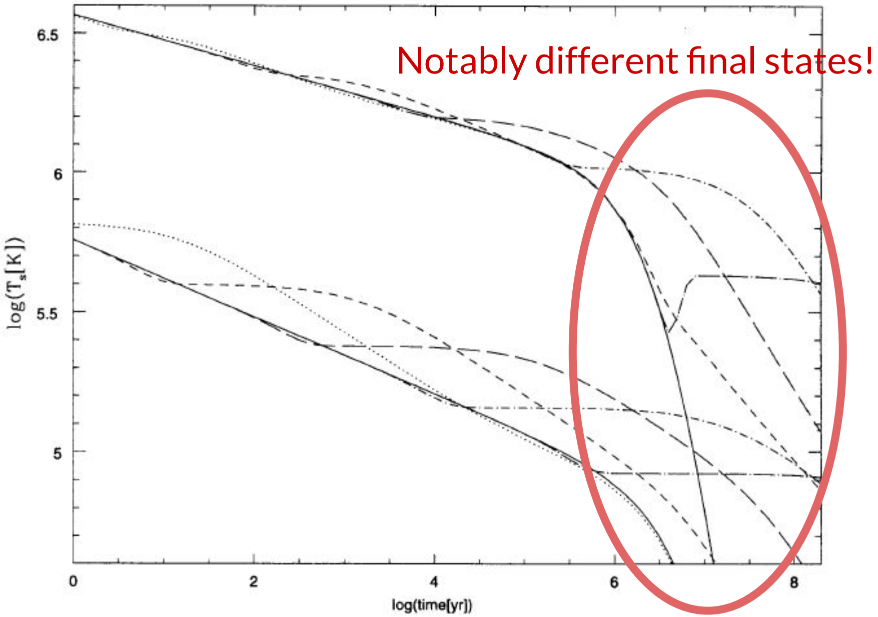


FIG. 2.—Effective surface temperature as a function of time for stars with direct (*lower curves*) and modified (*upper curves*) Urca reactions, with no heating (*solid lines*) or spin-down heating with magnetic field strengths $B = 10^{12}$ G (*dotted lines*), 10^{11} G (*short-dashed lines*), 10^{10} G (*long-dashed lines*), 10^9 G (*short-dashed–dotted line*), and 10^8 G (*long-dashed–dotted line*). The initial spin period is taken to be 1 ms.

Reisenegger 1995

Rotochemical heating

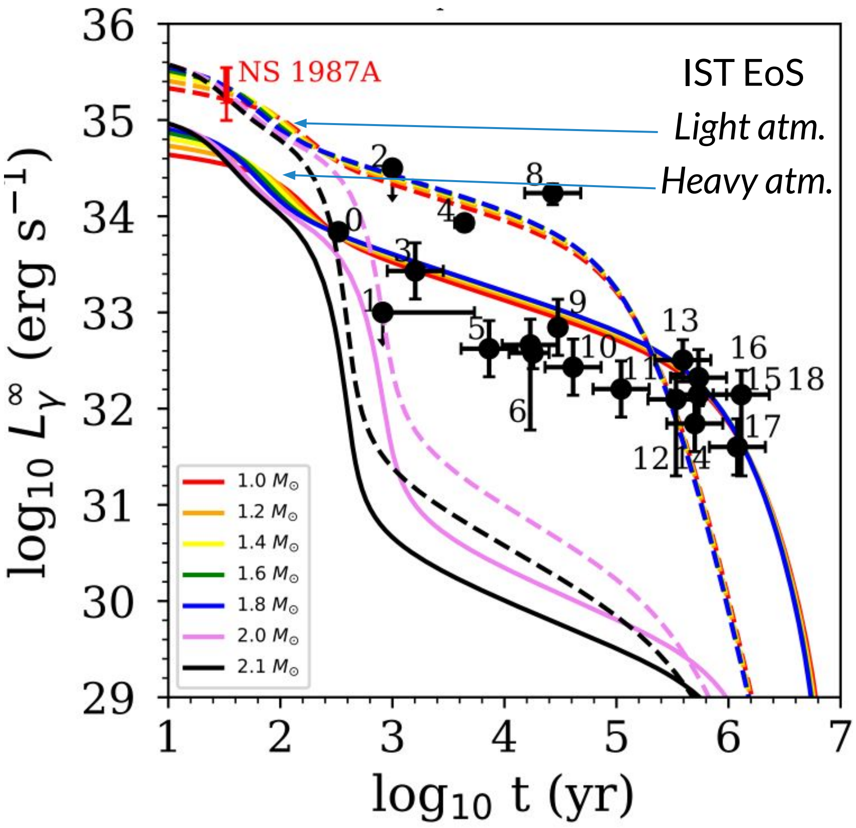
Thermal balance:

$$C\frac{dT^\infty}{dt} = -L_\nu^\infty - L_\gamma^\infty + L_H^\infty$$

- Heat loss due to neutrino/gamma emission
- **Heat acquirement due to spin-down energy release with each beta decay**

$$\eta_{npe} = \mu_p + \mu_e - \mu_n \neq 0$$

Heating source



Heat evolution

IST EoS

Light atm.

Heavy atm.

Rotochemical heating

Impact

A rotating rate of MSP decrease -> the centrifugal force decrease -> NS continuously contracts -> it perturbs the local number density of each particle species away from equilibrium -> timescale of beta decay is much longer than that of the NS contraction -> beta equilibrium cannot be maintained

Coefficient coming from EoS

$$\eta_\ell^\infty \simeq W_{np\ell}(\Omega(t)^2 - \Omega(0)^2)$$, where

$$\Omega(t) = \frac{2\pi}{\sqrt{P_0^2 + 2P\dot{P}t}}$$

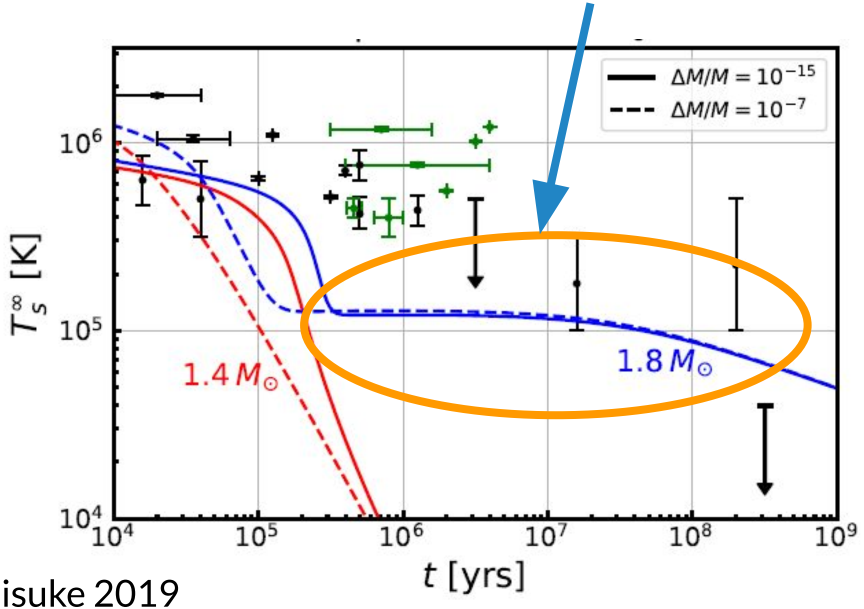
initial

period

Mostly notable for MSP!

Imbalance is linked directly to the heating term

Very gradual temperature loss



Yanagi Keisuke 2019

Conclusions

- Compact stars may have a quark-gluon plasma or other exotics in their core, but we have not much options how to verify its EoS
  - Rotochemical heating to the help
- Millisecond pulsars are especially interesting in this context as their spin-down power remains high long enough for this state to be reached with a substantial luminosity
- We plan to study the effect of this heating mechanism on the thermal evolution of hybrid millisecond pulsars with quark core, considering that both phases, i.e. hadron and quark matter, departured from beta equilibrium
- Our preliminary results show that the effect of rotochemical heating is very significant and gives apparent modifications of the surface temperature of hybrid stars, which could be probed with the present and ongoing x-ray telescopes

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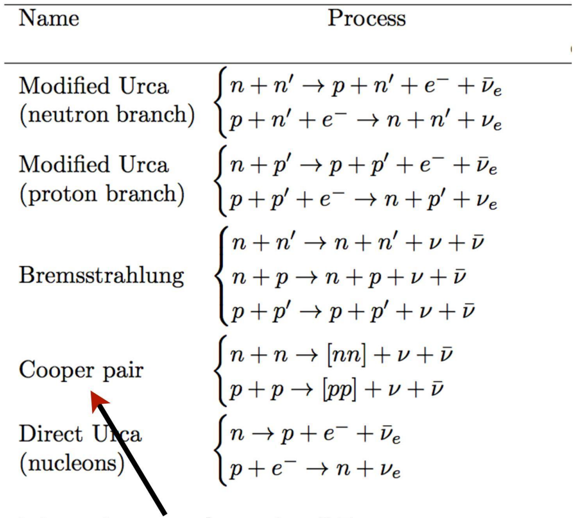
Backup

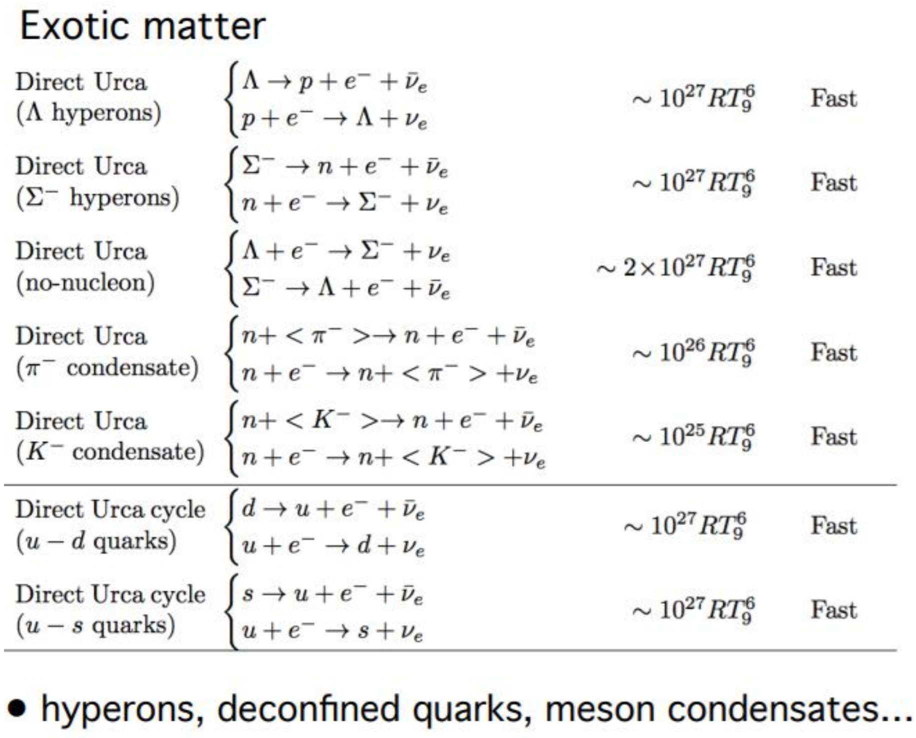
Processes in different phases

Neutrino Emission



Name	Process
Modified Urca (neutron branch)	$\begin{cases} n + n' \to p + n' + e^- + \bar{\nu}_e \\ p + n' + e^- \to n + n' + \nu_e \end{cases}$
Modified Urca (proton branch)	$\begin{cases} n + p' \to p + p' + e^- + \bar{\nu}_e \\ p + p' + e^- \to n + p' + \nu_e \end{cases}$
Bremsstrahlung	$\begin{cases} n + n' \to n + n' + \nu + \bar{\nu} \\ n + p \to n + p + \nu + \bar{\nu} \\ p + p' \to p + p' + \nu + \bar{\nu} \end{cases}$
Cooper pair	$\begin{cases} n + n \to [nn] + \nu + \bar{\nu} \\ p + p \to [pp] + \nu + \bar{\nu} \end{cases}$
Direct Urca (nucleons)	$\begin{cases} n \to p + e^- + \bar{\nu}_e \\ p + e^- \to n + \nu_e \end{cases}$

Pairing in nucleonic SF: suppresses Urca processes but triggers PBF neutrino emission



Exotic matter

Direct Urca (Λ hyperons)	$\begin{cases} \Lambda \to p + e^- + \bar{\nu}_e \\ p + e^- \to \Lambda + \nu_e \end{cases}$	$\sim 10^{27} R T_9^6$	Fast
Direct Urca (Σ^- hyperons)	$\begin{cases} \Sigma^- \to n + e^- + \bar{\nu}_e \\ n + e^- \to \Sigma^- + \nu_e \end{cases}$	$\sim 10^{27} R T_9^6$	Fast
Direct Urca (no-nucleon)	$\begin{cases} \Lambda + e^- \to \Sigma^- + \nu_e \\ \Sigma^- \to \Lambda + e^- + \bar{\nu}_e \end{cases}$	$\sim 2 \times 10^{27} R T_9^6$	Fast
Direct Urca (π^- condensate)	$\begin{cases} n + <\pi^-> \to n + e^- + \bar{\nu}_e \\ n + e^- \to n + <\pi^-> + \nu_e \end{cases}$	$\sim 10^{26} R T_9^6$	Fast
Direct Urca (K^- condensate)	$\begin{cases} n + <K^-> \to n + e^- + \bar{\nu}_e \\ n + e^- \to n + <K^-> + \nu_e \end{cases}$	$\sim 10^{25} R T_9^6$	Fast
Direct Urca cycle ($u - d$ quarks)	$\begin{cases} d \to u + e^- + \bar{\nu}_e \\ u + e^- \to d + \nu_e \end{cases}$	$\sim 10^{27} R T_9^6$	Fast
Direct Urca cycle ($u - s$ quarks)	$\begin{cases} s \to u + e^- + \bar{\nu}_e \\ u + e^- \to s + \nu_e \end{cases}$	$\sim 10^{27} R T_9^6$	Fast

- hyperons, deconfined quarks, meson condensates...

P-Pdot diagram