Hyperons, Neutron Stars and Supernovae

Jürgen Schaffner-Bielich

Institut für Theoretische Physik

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

SFB-TR Proposal Meeting 2015
GSI, Juli 22, 2015

PROJEKTTRÄGER FÜR DAS
Bundesministerium für Bildung und Forschung

comp star

HIC for FAIR
Helmholtz International Center

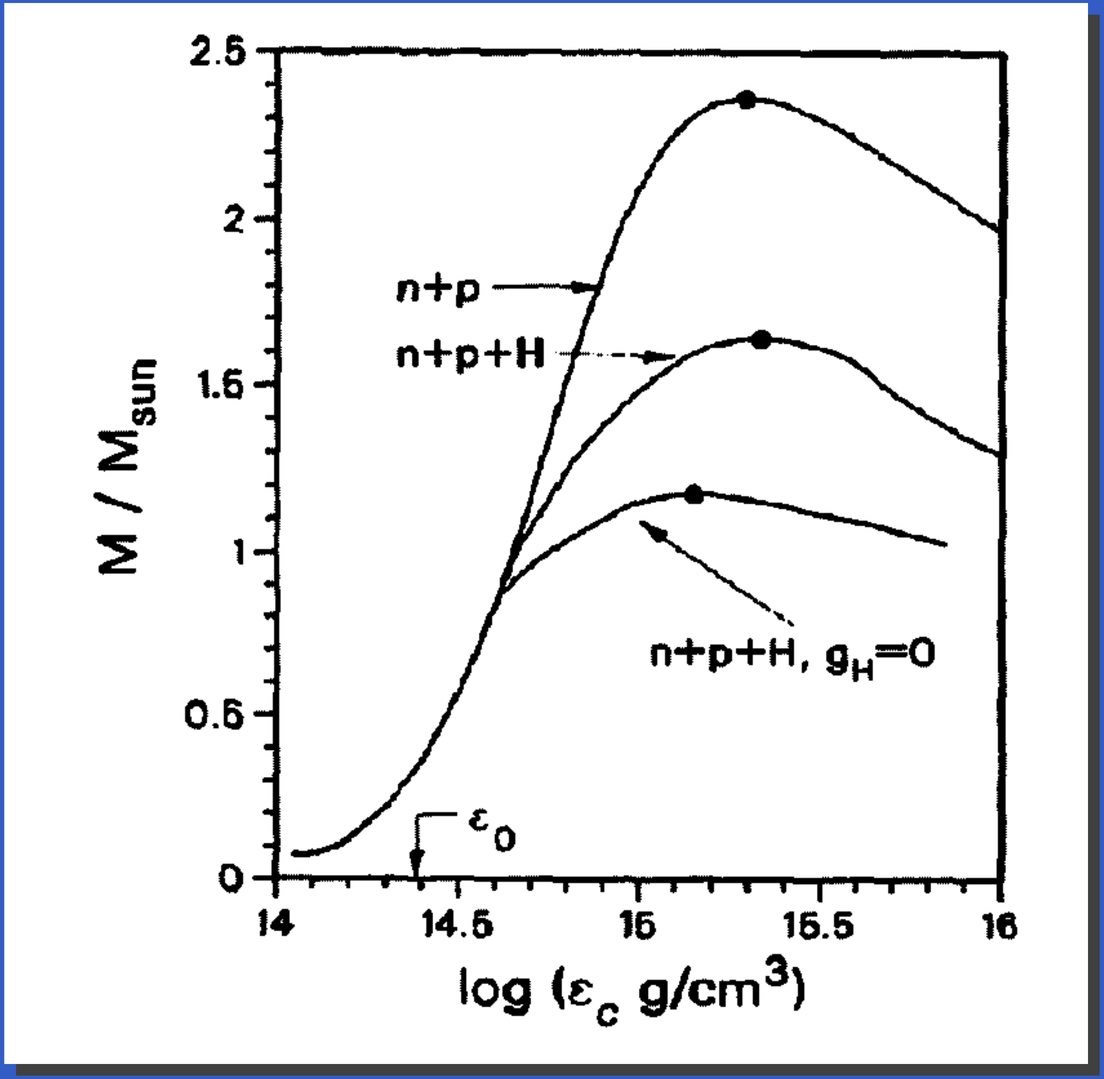
HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

Outline

- Masses of neutron stars: controlled by three-body force involving hyperons
- Neutron star cooling: fast cooling with hyperons
- Gravitational wave emission from rotating neutron stars: stabilized with nonmesonic weak processes involving hyperons
- Supernova matter: presence of hyperons can trigger the phase transition to quark matter

Masses of Neutron Stars

Impact of hyperons on the maximum mass of neutron stars



(Glendenning and Moszkowski 1991)

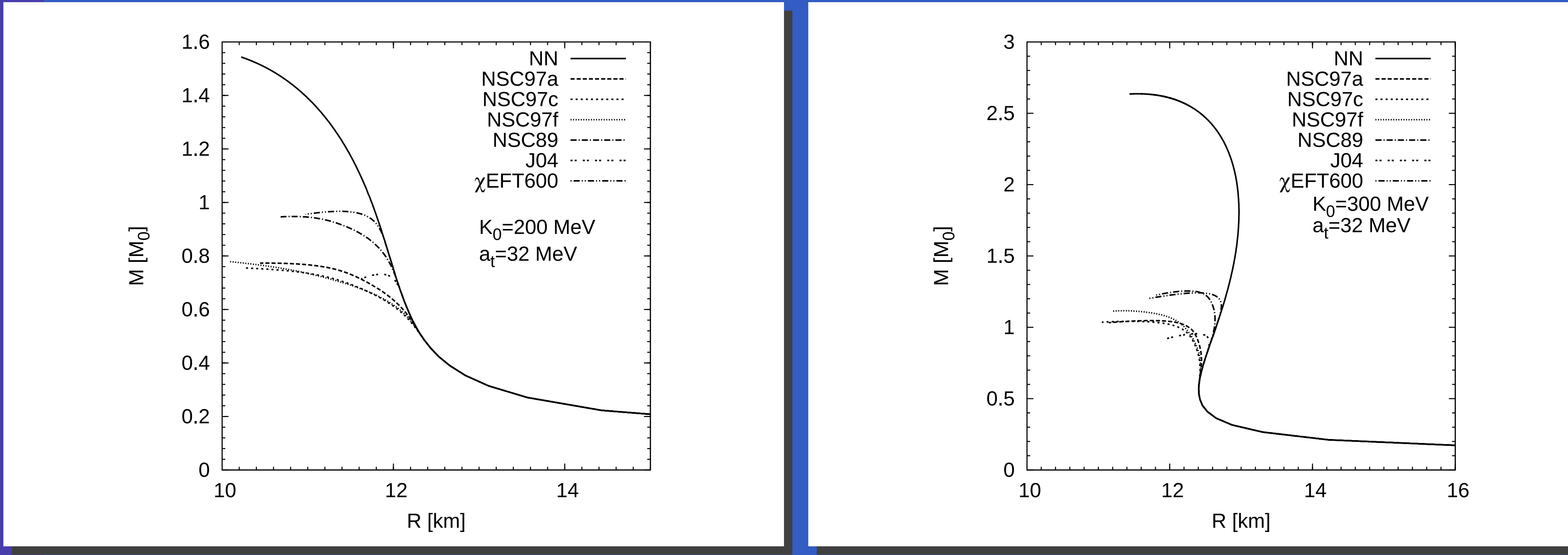
- neutron star with nucleons and leptons only: $M \approx 2.3 M_\odot$
- substantial decrease of the maximum mass due to hyperons!
- maximum mass for "giant hypernuclei": $M \approx 1.7 M_\odot$
- noninteracting hyperons result in a too low mass: $M < 1.4 M_\odot$!

Maximum mass and modern many-body approaches

modern many-body calculations
(using Nijmegen soft-core YN potential)

- Vidana et al. (2000): $M_{\rm max} = 1.47 M_\odot$ (NN and YN interactions), $M_{\rm max} = 1.34 M_\odot$ (NN, NY, YY interactions)
- Baldo et al. (2000): $M_{\rm max} = 1.26 M_\odot$ (including three-body nucleon interaction)
- Schulze et al. (2006): $M_{\rm max} < 1.4 M_\odot$
- Djapo et al. (2008): $M_{\rm max} < 1.4 M_\odot$
- too soft EoS, too low masses!
- missing three-body force for hyperons (YNN, YYN, YYY): neutron stars can not live without it!
- more input needed from hypernuclear physics!

Mass-radius relation with $V_{\mathrm{low\ k}}$ potential



(Djapo, Schäfer, Wambach 2008)

- RG approach with $V_{\mathrm{low\ k}}$ potential from various models
- presence of hyperons substantially reduces the maximum mass
- in contradiction with pulsar data: $M_{\max} < 1.44 M_\odot$

Neutron star cooling with hyperons

Cooling processes with neutrinos

modified URCA process (slow):

$$N + p + e^- \rightarrow N + n + \nu_e \qquad N + n \rightarrow N + p + e^- + \bar{\nu}_e$$

direct URCA process (fast):

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

can only proceed for $p_F^p + p_F^e \geq p_F^n$! Charge neutrality implies:

$$n_p = n_e \hookrightarrow p_F^p = p_F^e \hookrightarrow 2p_F^p = p_F^n \hookrightarrow n_p/n \geq 1/9$$

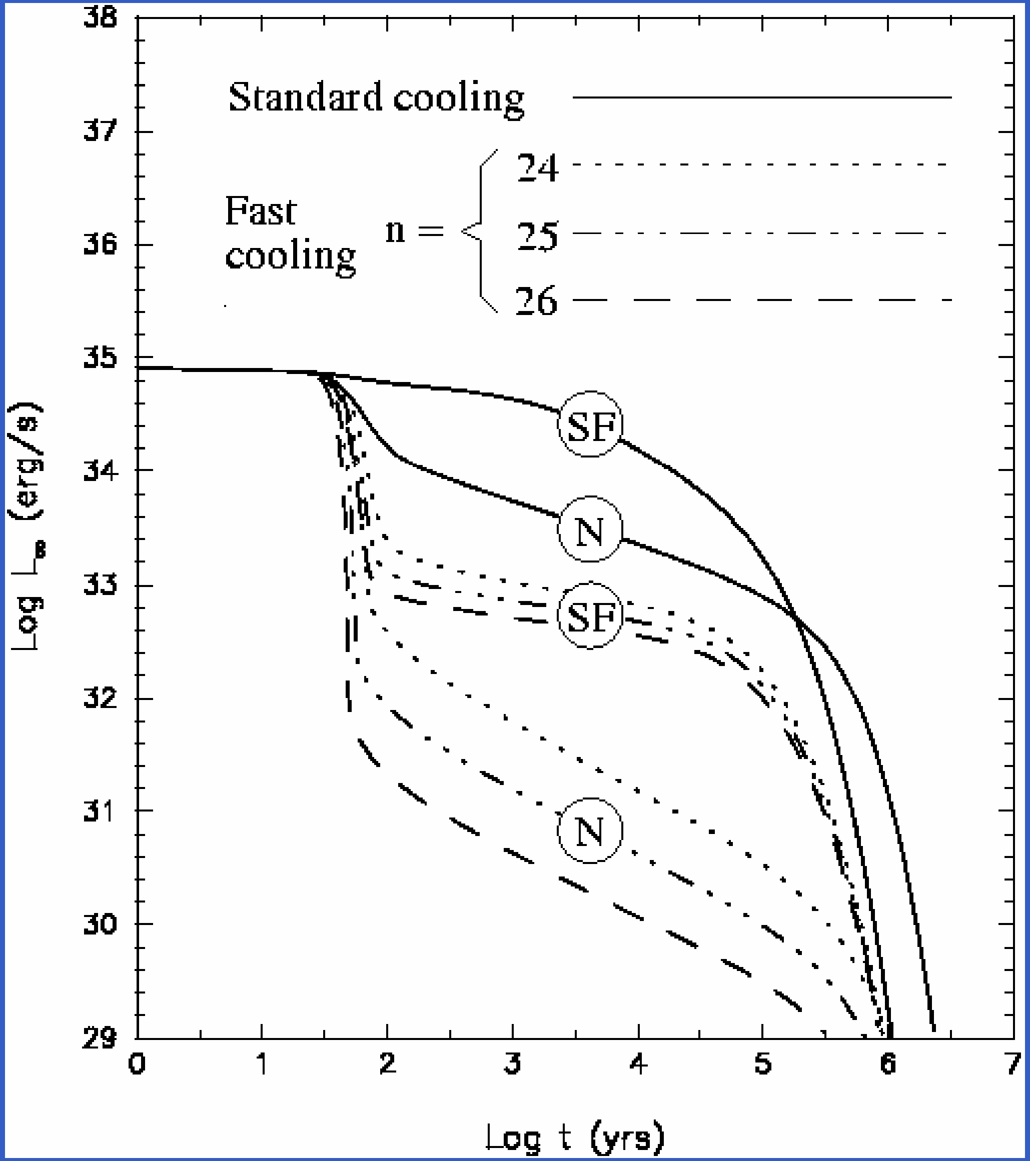
nucleon URCA only for large proton fractions, but hyperon URCA process:

$$\Lambda \rightarrow p + e^- + \bar{\nu}_e \quad , \quad \Sigma^- \rightarrow n + e^- + \bar{\nu}_e \quad , \quad \ldots$$

happens immediately when hyperons are present!

only suppressed by hyperon pairing gaps!

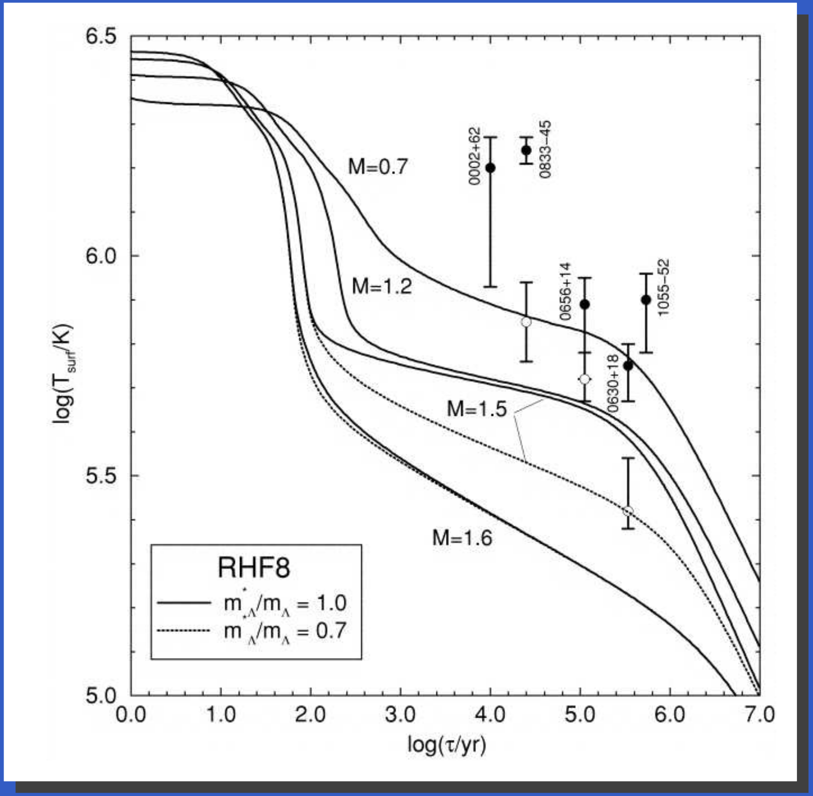
Basic cooling of neutron stars (Page and Reddy (2006))



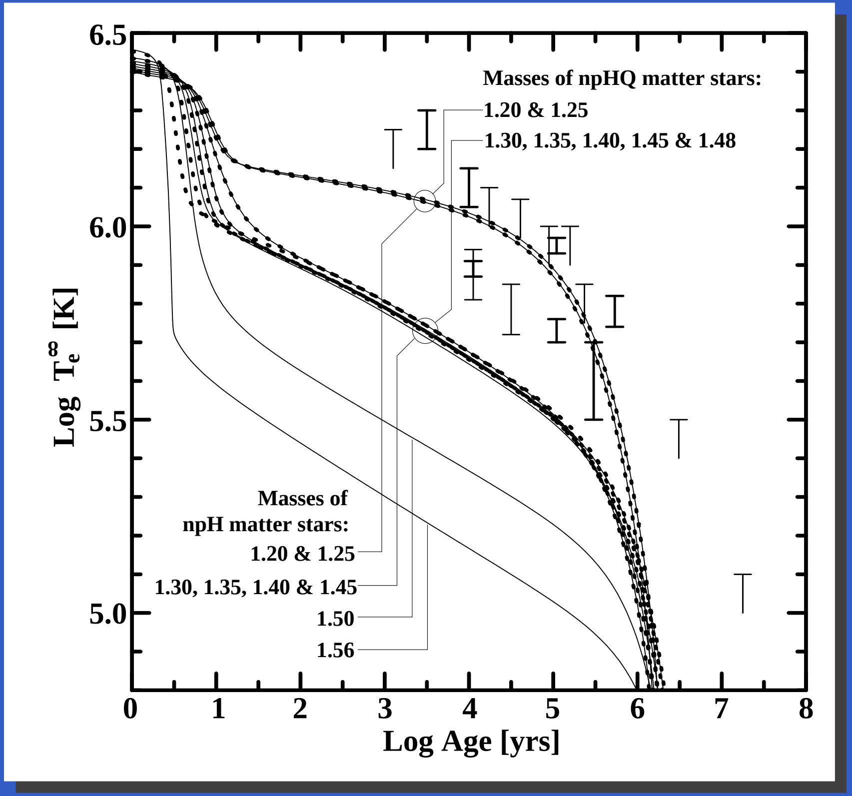
- slow standard cooling via the modified URCA process versus fast neutrino cooling (emissivities of $\epsilon_\nu = 10^n \times T_9^6 \text{ erg cm}^{-3} \text{ s}^{-1}$)
- normal neutron matter: N, superfluid neutron matter: SF
- fast cooling due to ’exotic’ processes as nucleon direct URCA or kaon condensation

Cooling with hyperons: fast cooling and hyperon gaps

(Schaab, JSB, Balberg 1998)



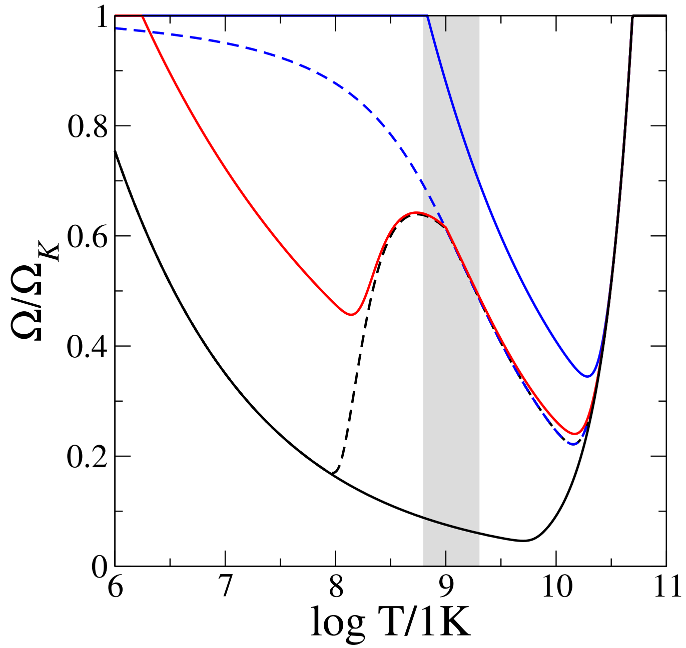
(Page, Lattimer, Prakash, Steiner 2000)



- slow cooling for low mass neutron stars
- fast cooling for heavier ones due to direct nucleon URCA
- hyperon cooling suppressed by pairing gaps (left) and unsuppressed (right)
- two-body YY interactions as input needed!
- pairing of Σ hyperons and cooling: Vidana and Tolos (2004)

Gravitational wave emission from rotating neutron stars

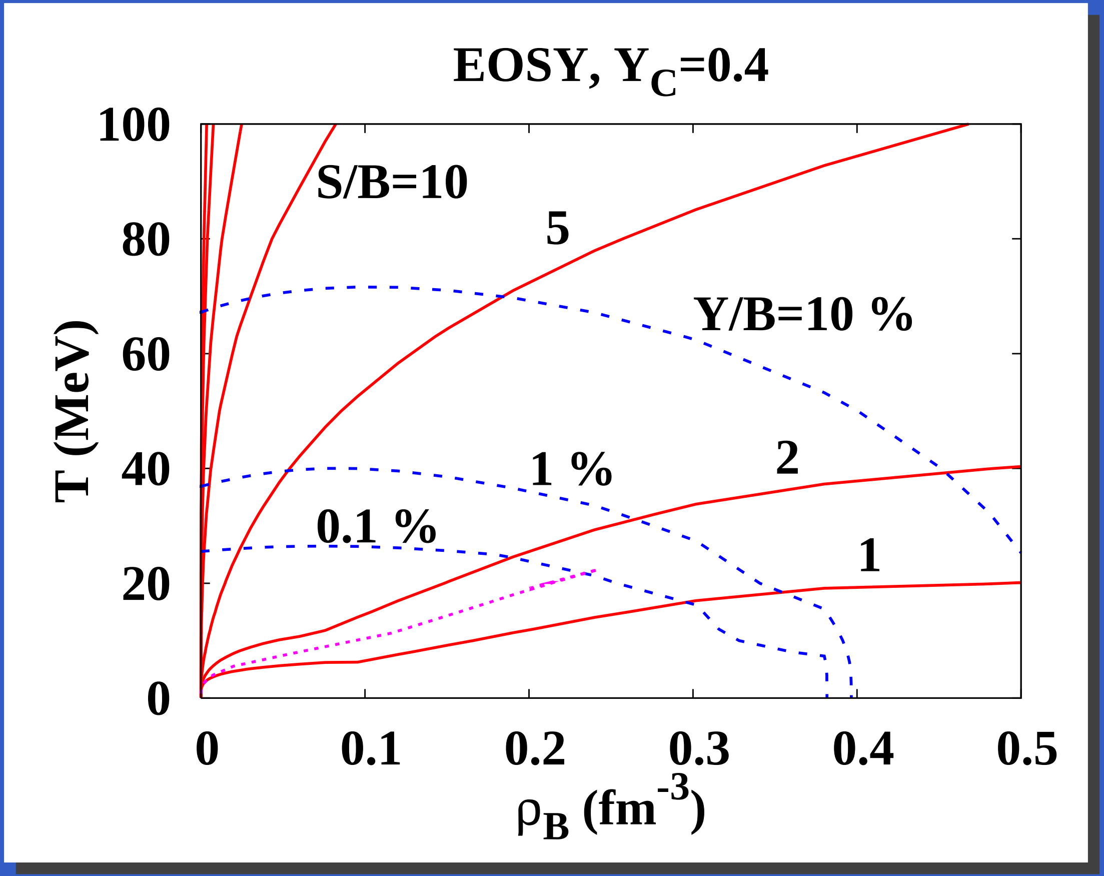
R-mode instability for rotating neutron stars



- oscillations brings the matter out of β-equilibrium
- dominating effect to restore equilibrium: weak nonmesonic processes $NN \leftrightarrow \Lambda N$ and $NN \leftrightarrow \Sigma N$
- substantial increase of the stability window (blue line)
- depends crucially on hyperon superfluidity (dashed lines)

Core-Collapse Supernovae, Neutron Star Merger and Hyperons

Strangeness in Supernova Matter: Hyperons



C. Ishizuka, A. Ohnishi, K. Tsubakihara, K. Sumiyoshi, S. Yamada 2008

- supernova matter for $Y_c = 0.4$ with constant entropy/baryon ratio S/B
- hyperon fraction at bounce $T \sim 20$ MeV: about 0.1%
- thermally produced strangeness, hyperons are in β-equilibrium!

Summary

Hypernuclear physics has a substantial impact on neutron star properties!

- Two-body YN interaction: controls composition and cooling
  $\Longrightarrow$ hyperons are most likely the first exotic phase to appear in the core
  $\Longrightarrow$ hyperons can cool neutron stars rapidly (hyperon gaps!)
- Three-body YNN and YYN force: controls the maximum mass
  $\Longrightarrow$ low maximum masses below $1.4M_\odot$ without three-body force
- Nonmesonic weak nonmesonic reactions with hyperons
  $\Longrightarrow$ damps the r-mode instability of rotating neutron stars (pulsars) and their gravitational wave emission
- YN potentials control amount of strangeness present supernova matter
  $\Longrightarrow$ presence of hyperons trigger the phase transition to quark matter