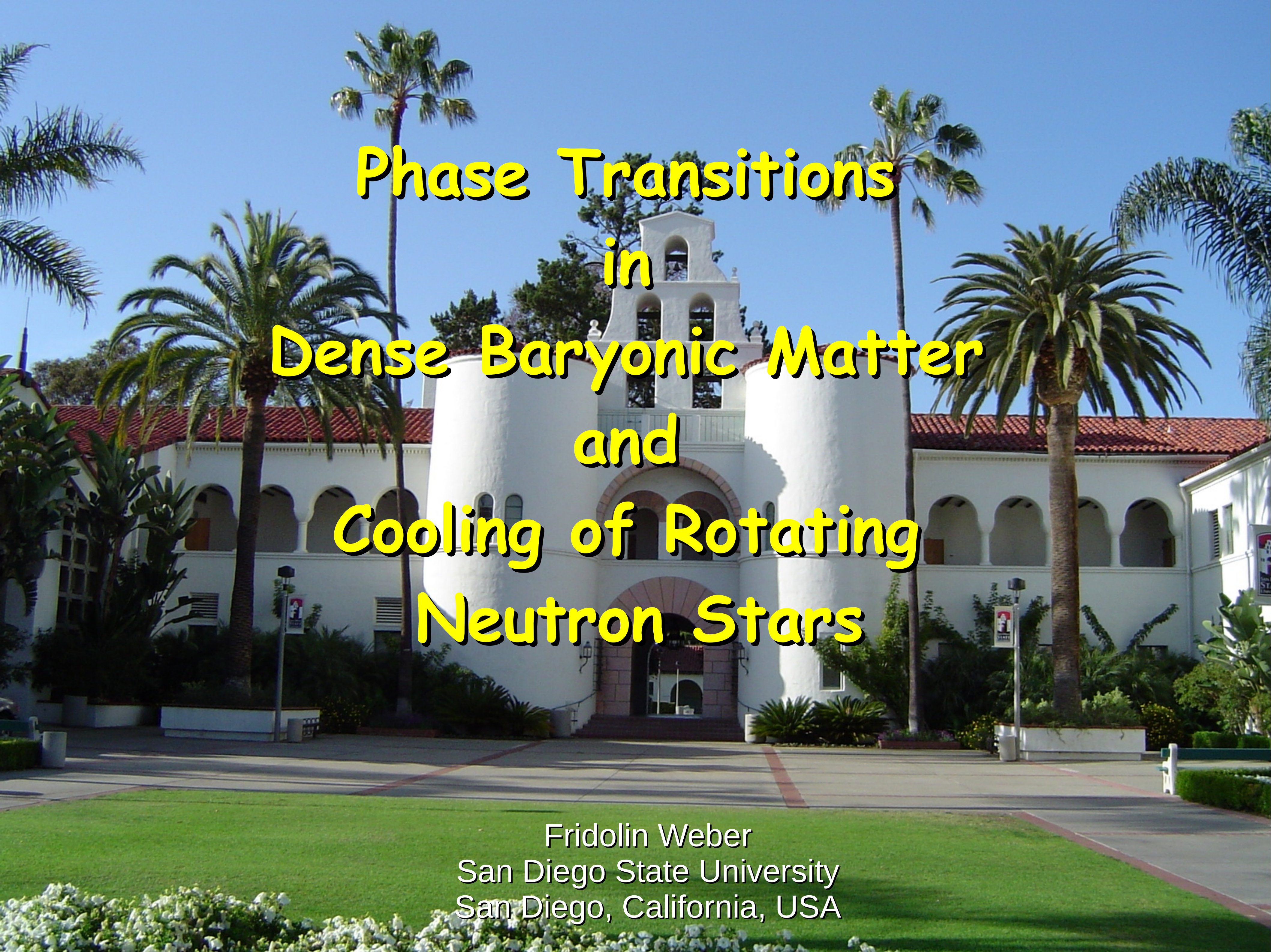


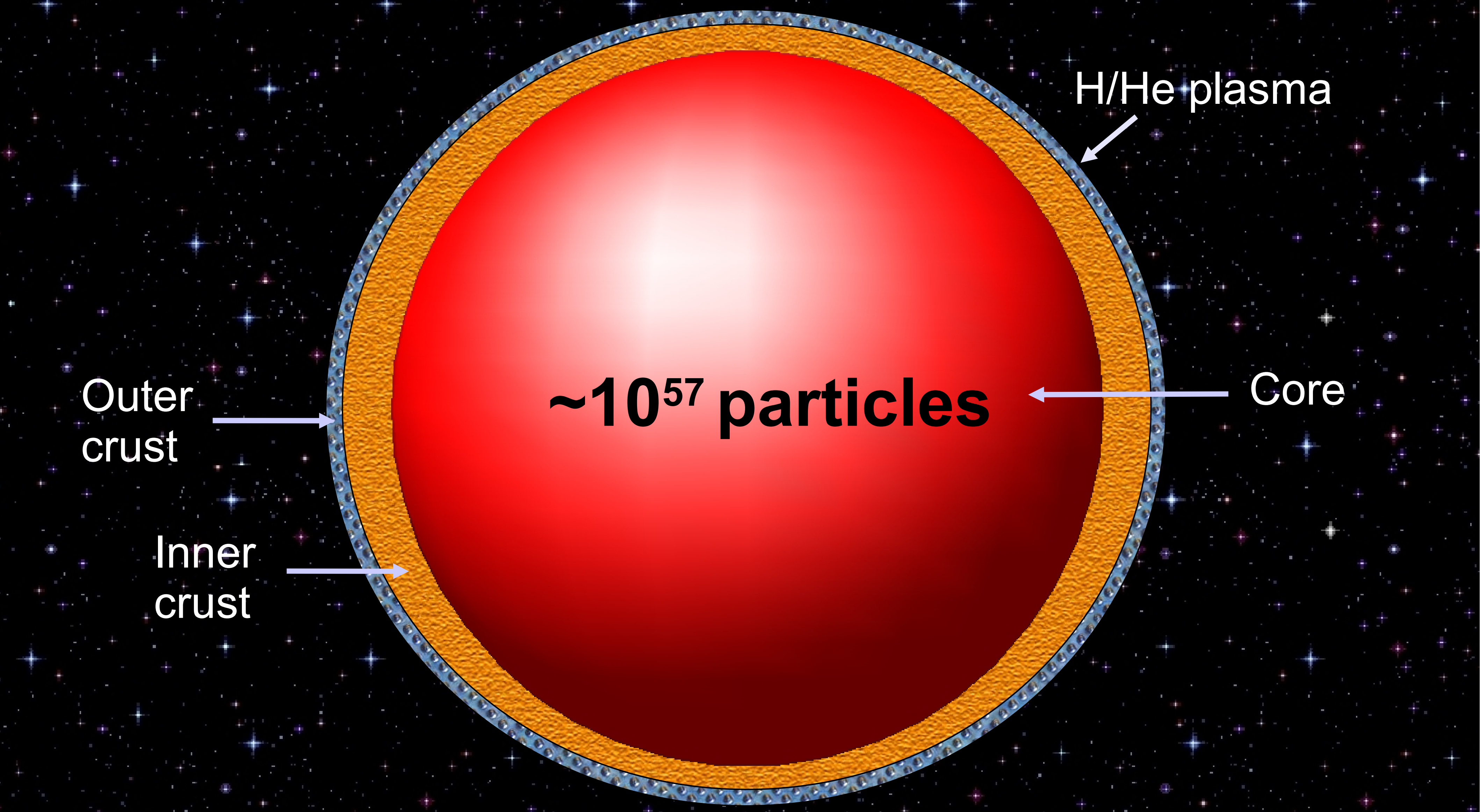
Phase Transitions in Dense Baryonic Matter and Cooling of Rotating Neutron Stars

Fridolin Weber
San Diego State University
San Diego, California, USA

Outline

- A few general remarks on "neutron" stars
- Rotation-driven changes
  - Re-population of matter
  - Phase transitions
- Cooling of rotating compact stars in GR
- Internal Heating
  - CFL matter in neutron stars?
  - Pycnonuclear reactions (strange quark matter nuggets)
- Summary

Structure of “Neutron” Stars



M~ 1 to 2 M_{sun}, R~10 km

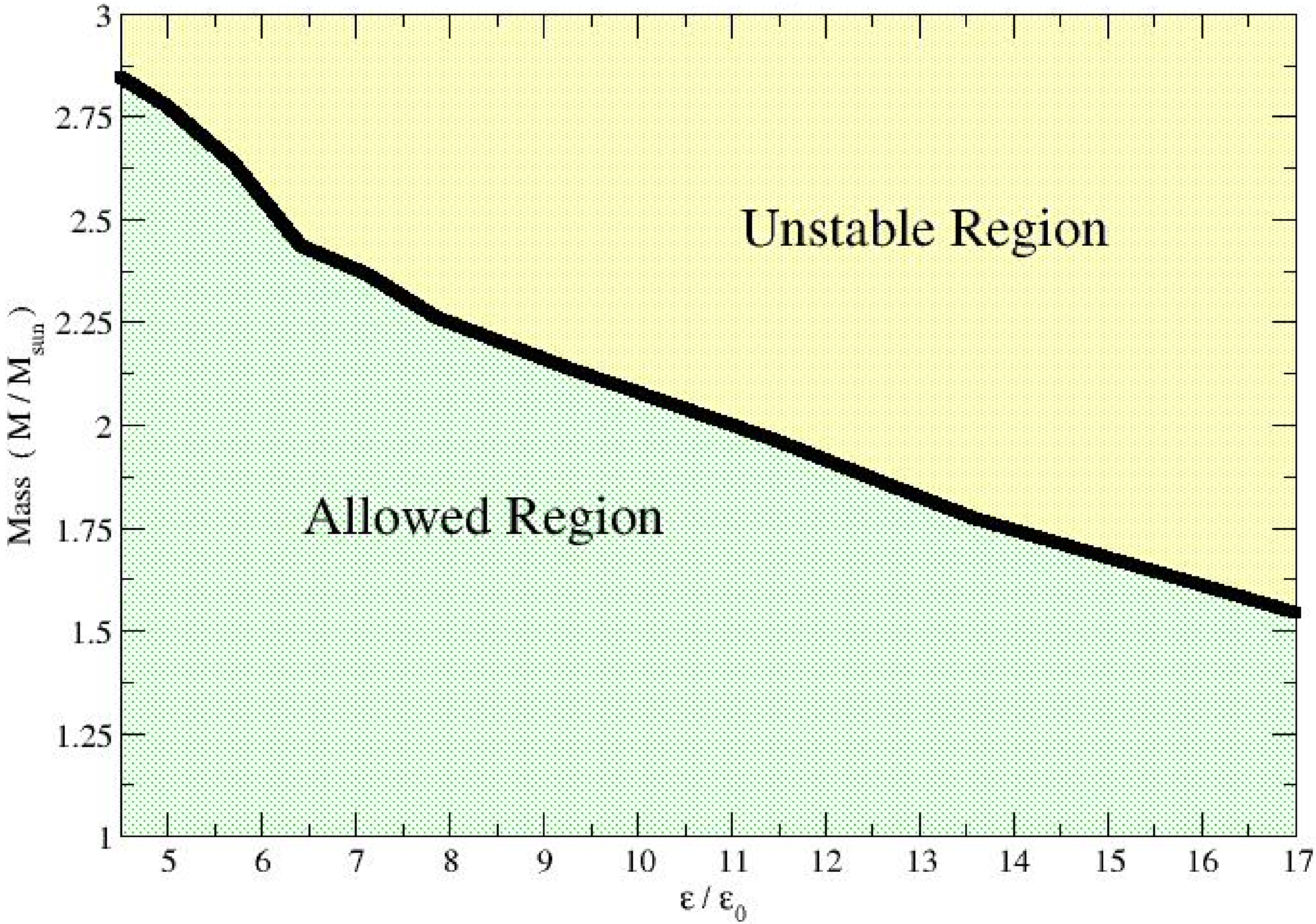
How dense? Room for "Exotica"

Perform variational study

Key assumptions:

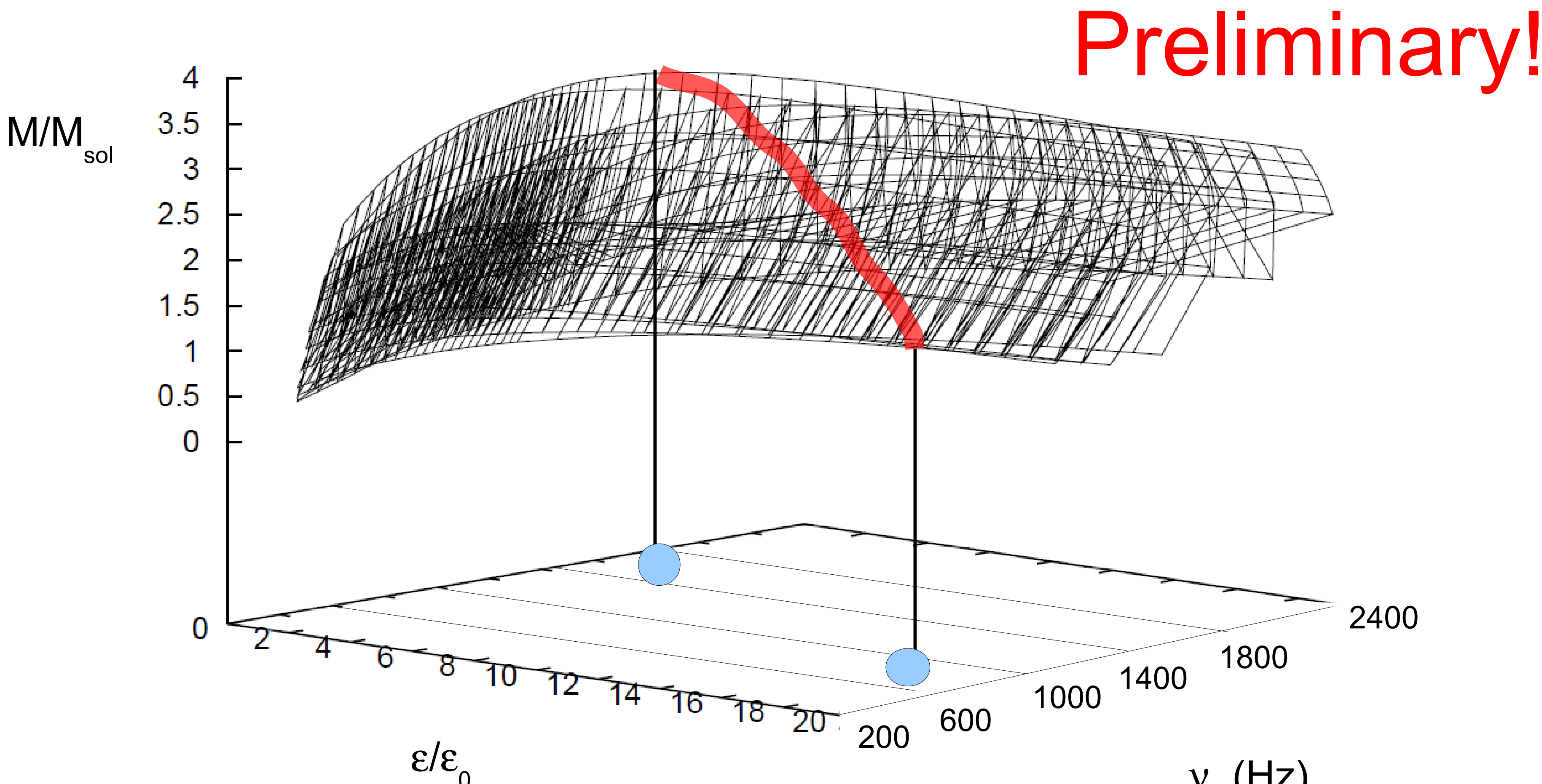
- Einstein's theory of GR is correct
- Know EoS up to $\sim 10^{13}$ g/cm^3
- Microscopic stability
- Causality

Maximum Central Densities of Neutron Stars



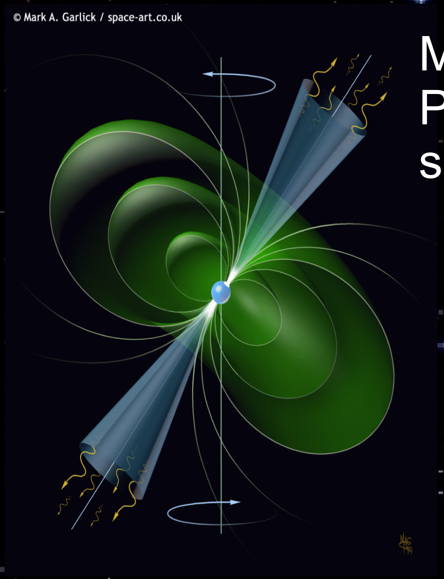
Oliver Hamil, SDSU, 2009

Maximum Central Densities of Neutron Stars



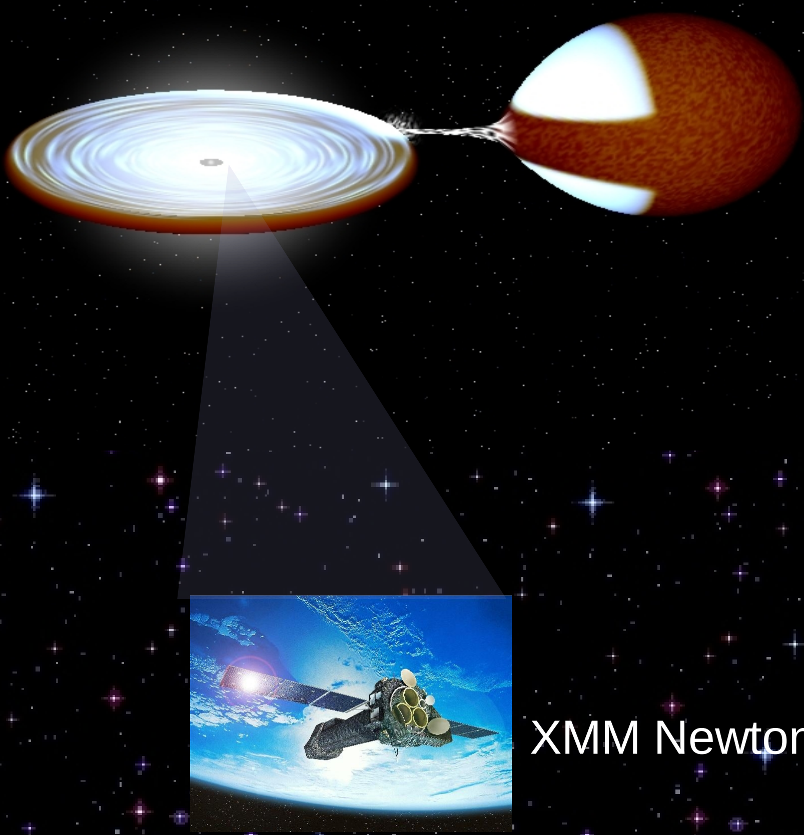
Oliver Hamil, SDSU, 2009

Magnetars:
unusually
hot

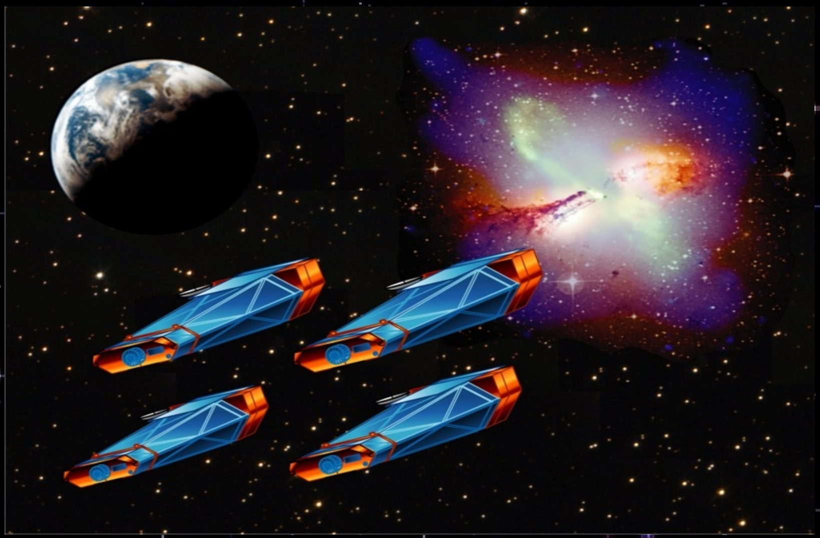


Millisecond
Pulsars:
spinning-down

Neutron stars in LMXBs:
accretion of matter,
being spun up

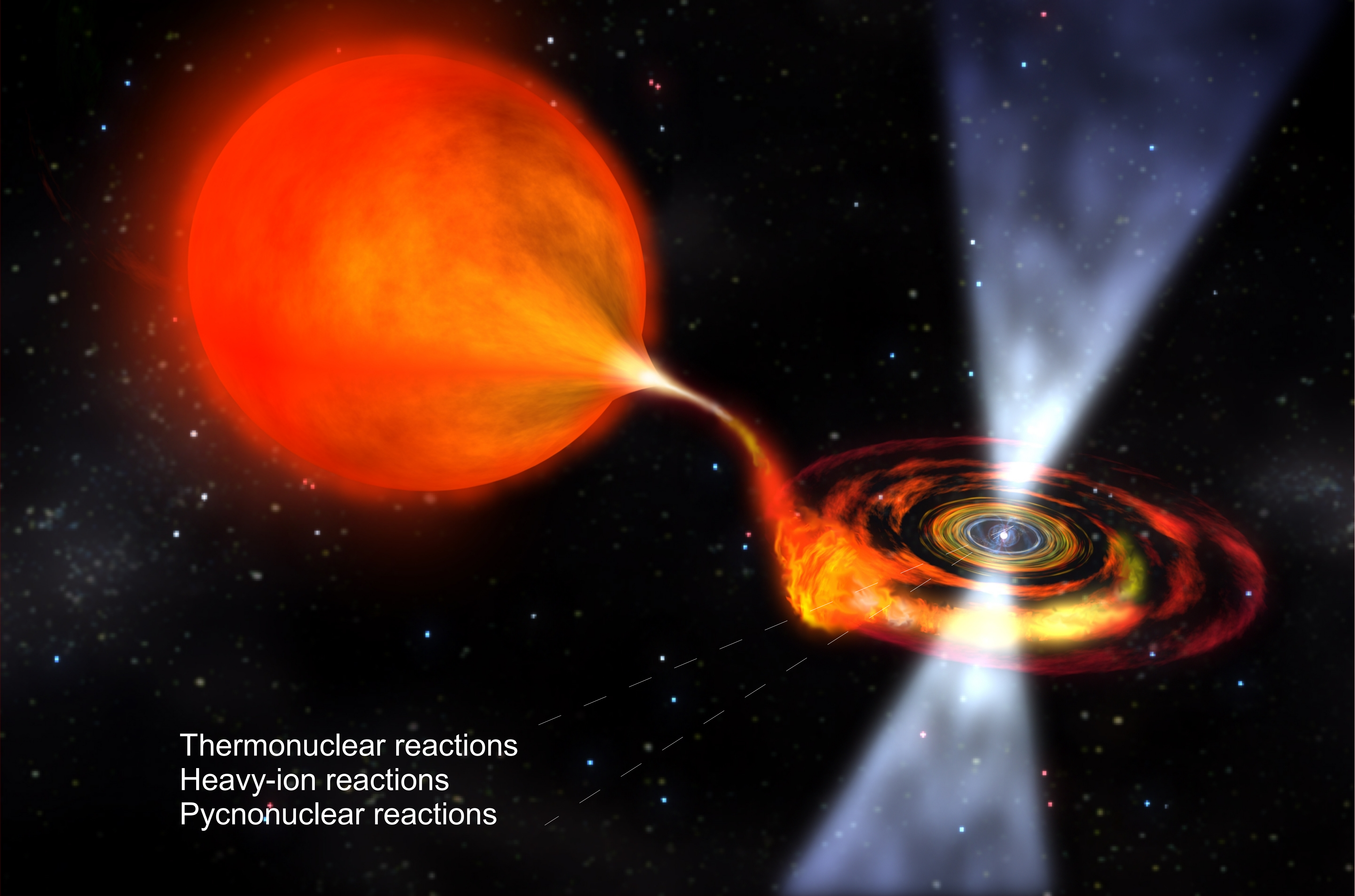


XMM Newton

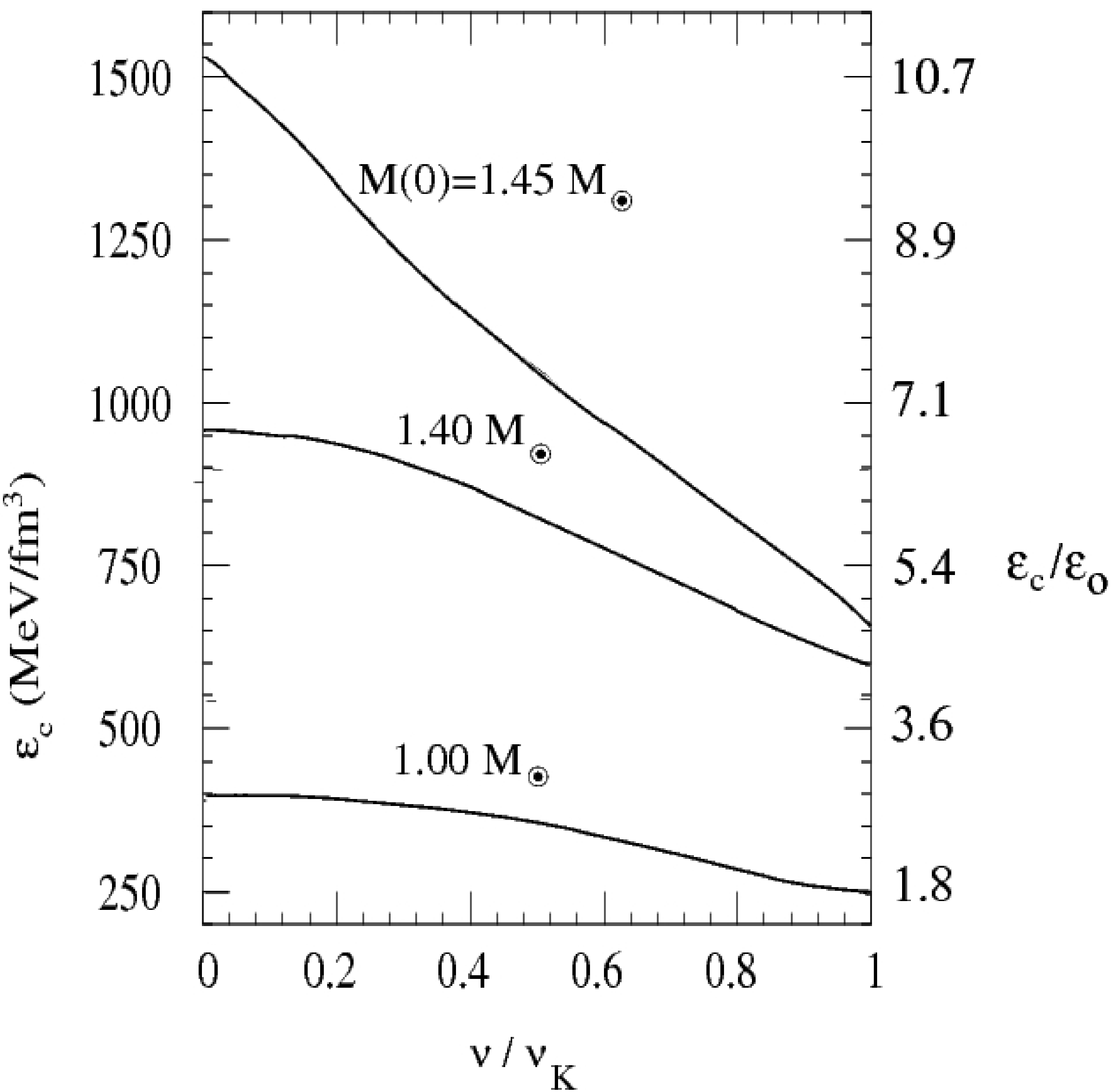


IXO (Constellation X)

Neutron Stars in LMXBs

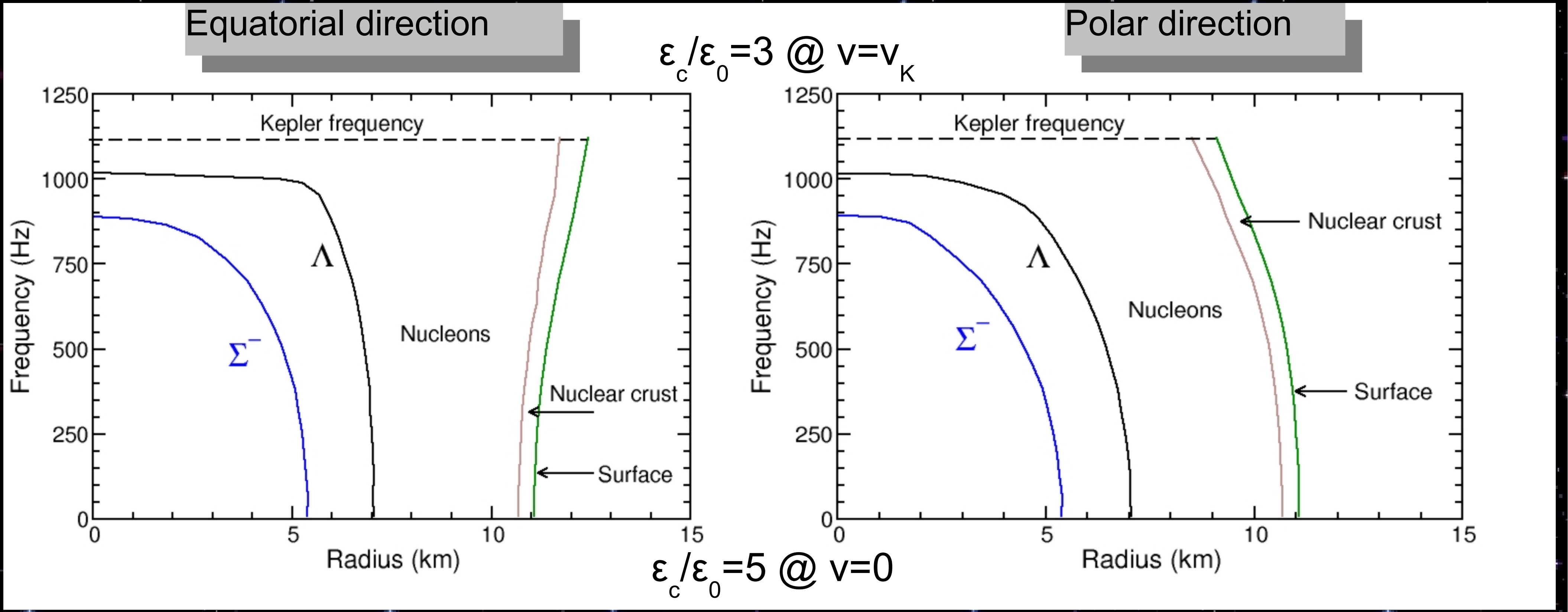


Rotation-Driven Changes inside Compact Stars



1500
1250
1000
750
500
250
10.7
8.9
7.1
5.4
3.6
1.8
M(0)=1.45 M⊙
1.40 M⊙
1.00 M⊙
εc (MeV/fm3)
εc/εo
0
0.2
0.4
0.6
0.8
1
ν / νK

Model Composition of a $M=1.4\ M_{sun}$ Neutron Star



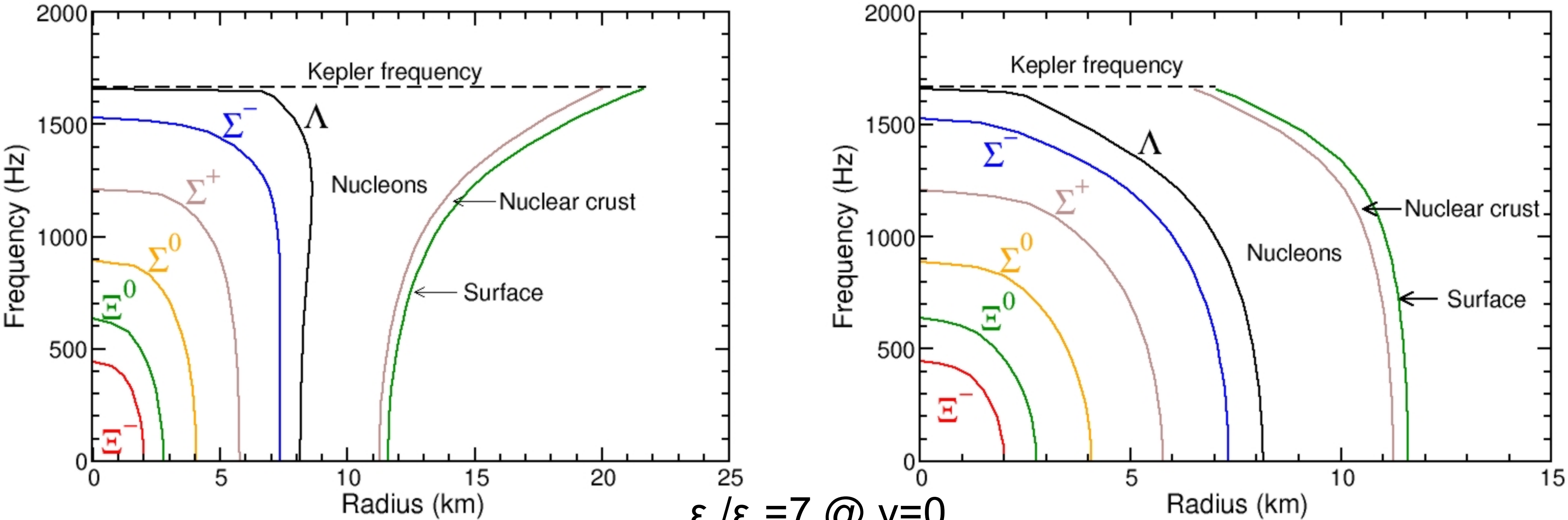
Equation of state:
Hofmann, Keil, Lenske.
PRC 64 (2001) 034314

Model Composition of a M=1.7 M_{sun} Neutron Star

Equatorial direction

$\varepsilon_c/\varepsilon_0=3$ @ $v=v_K$

Polar direction



$\varepsilon_c/\varepsilon_0=7$ @ $v=0$

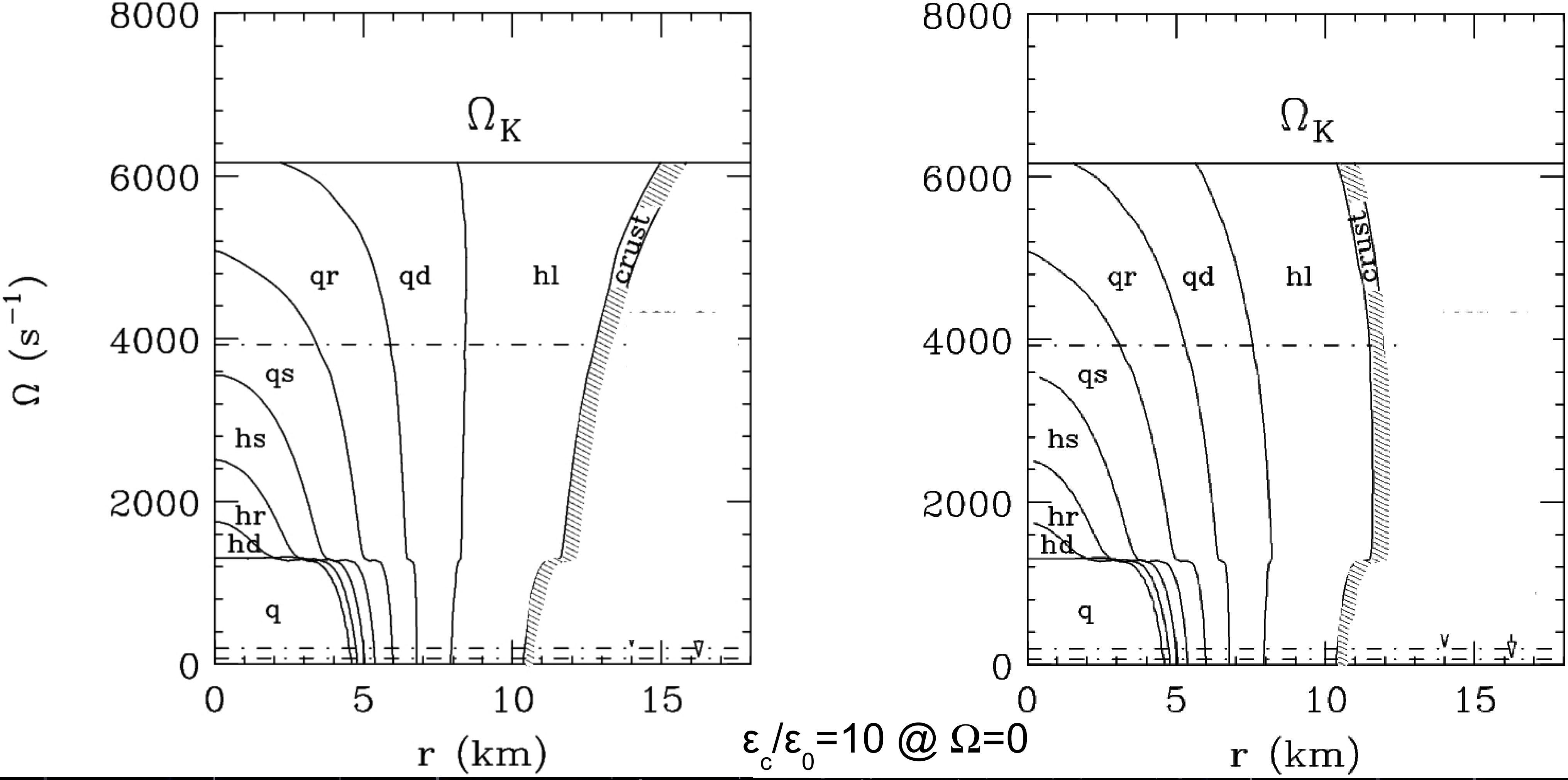
Equation of state:
Hofmann, Keil, Lenske.
PRC 64 (2001) 034314

Model Quark-Hadron Composition of Neutron Stars

Equatorial direction

Polar direction

$\varepsilon_c/\varepsilon_0=4$ @ $\Omega=\Omega_K$



$\varepsilon_c/\varepsilon_0=10$ @ $\Omega=0$

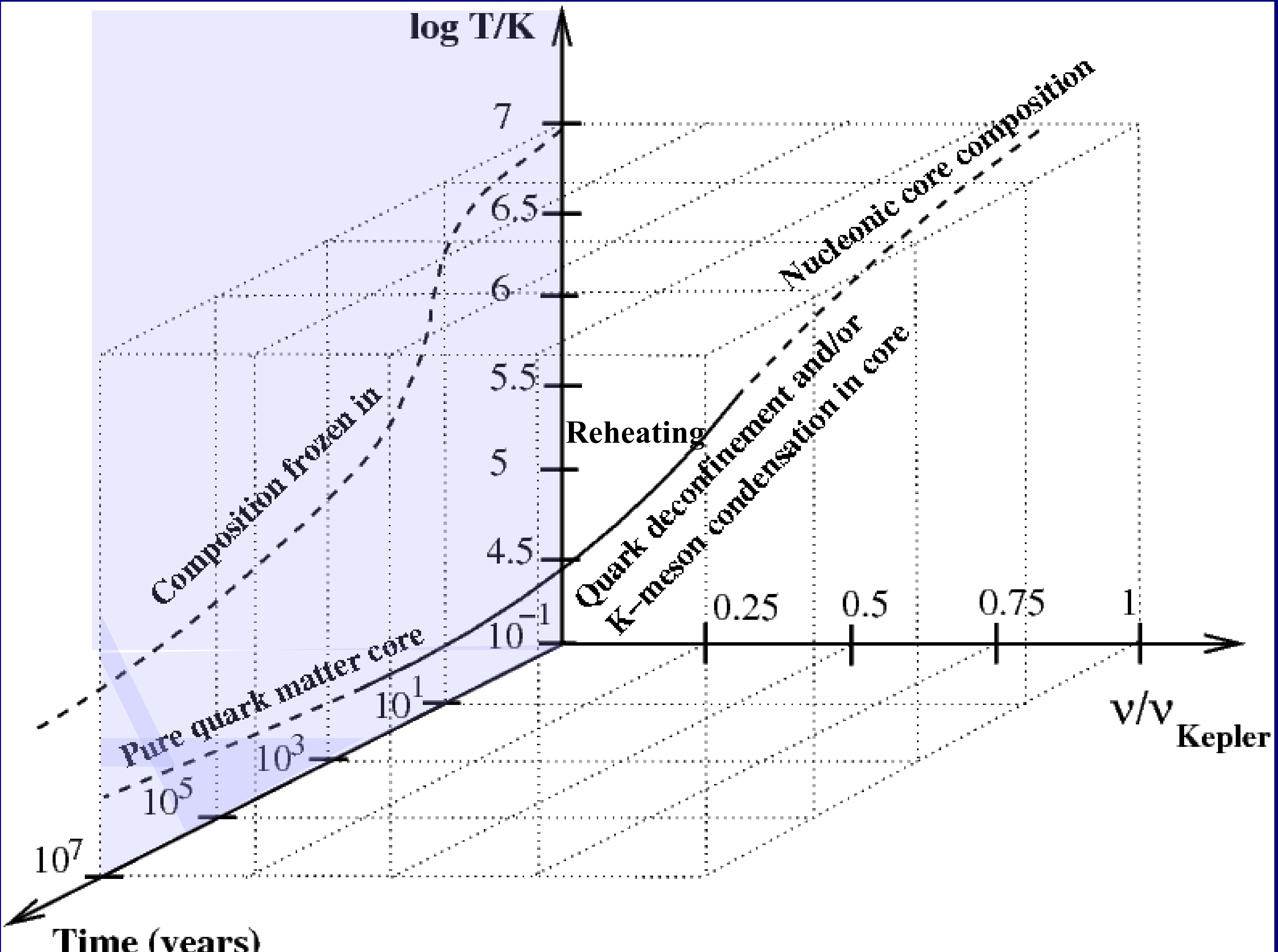
Cooling of Rotating Compact Stars in GR

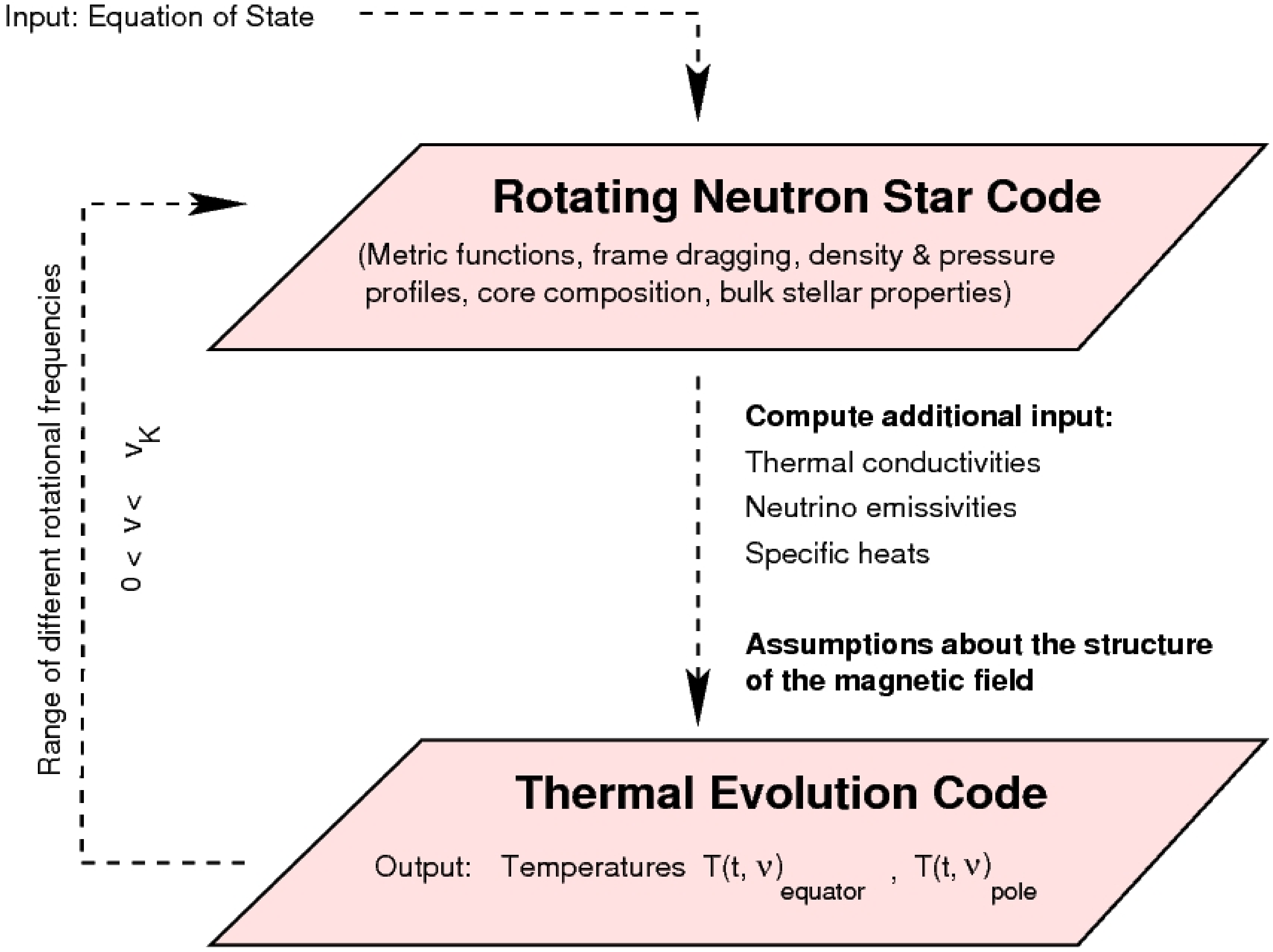
Neutron Star Cooling I

Modified Urca:	$n+n \rightarrow n+p+e+\nu$	slow
	$p+n \rightarrow p+p+e+\nu$	slow
Direct Urca:	$n \rightarrow p+e+\nu$	fast
Bremsstrahlung:	$n+n \rightarrow n+n+\nu+\nu$	slow
π^- condensate	$n+\langle \pi^- \rangle \rightarrow n+e+\nu$	fast
K^- condensate	$n+\langle K^- \rangle \rightarrow n+e+\nu$	fast
Cooper pair formations:	$n+n \rightarrow [nn] + \nu+\nu$	slow

Neutron Star Cooling II

Modified Urca:	$Q+u+e \rightarrow Q+d+\nu$ $Q+u+e \rightarrow Q+s+\nu$	slow
Direct Urca:	$d \rightarrow u+e+\nu$ $s \rightarrow u+e+\nu$	fast
Bremsstrahlung:	$Q_1+Q_2 \rightarrow Q_1+Q_2+\nu+\nu$	slow
Cooper pair formations:	$u+u \rightarrow [uu] + \nu+\nu$ $d+d \rightarrow [dd] + \nu+\nu$ $s+s \rightarrow [ss] + \nu+\nu$	slow

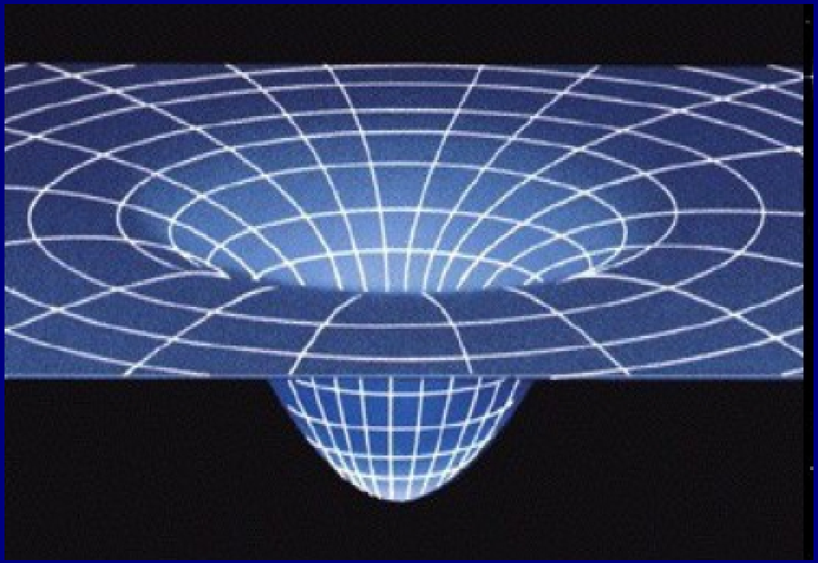

log T/K
7
6.5
6
5.5
5
4.5
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}
Time (years)
0.25
0.5
0.75
1
ν/ν_{Kepler}
Reheating
Composition frozen in
Pure quark matter core
Nucleonic core composition
Quark deconfinement and/or
K–meson condensation in core


Input: Equation of State
Rotating Neutron Star Code
(Metric functions, frame dragging, density & pressure profiles, core composition, bulk stellar properties)
Range of different rotational frequencies
0 < ν < ν_K
Compute additional input:
Thermal conductivities
Neutrino emissivities
Specific heats
Assumptions about the structure of the magnetic field
Thermal Evolution Code
Output: Temperatures T(t, ν)_equator , T(t, ν)_pole

Einstein's Field Equations for Rotating Compact Objects

- Metric: $ds^2 = -\, e^{2\nu}\, dt^2 + e^{2(\alpha+\beta)}\, r^2 \sin^2\theta\, (d\varphi - N^\varphi\, dt)^2 + e^{2(\alpha-\beta)}\, (dr^2 + r^2\, d\theta^2)$

- Christoffel symbols:
  $\Gamma^\sigma_{\mu\nu} = g^{\sigma\lambda} (\partial_\nu g_{\mu\lambda} + \partial_\mu g_{\nu\lambda} - \partial_\lambda g_{\mu\nu}) / 2$



- Riemann tensor:
  $R^\tau_{\mu\nu\sigma} = \partial_\nu \Gamma^\tau_{\mu\sigma} - \partial_\sigma \Gamma^\tau_{\mu\nu} + \Gamma^\kappa_{\mu\sigma} \Gamma^\tau_{\kappa\nu} - \Gamma^\kappa_{\mu\nu} \Gamma^\tau_{\kappa\sigma}$

- Ricci tensor: $R_{\mu\nu} = R^\tau_{\mu\sigma\nu}\, g^\sigma_\tau$

- Scalar curvature: $R = R_{\mu\nu}\, g^{\mu\nu}$

- Rotational frequency: $\Omega_K = r^{-1}\, e^{\nu-\alpha-\beta}\, U_K + N^\varphi$

→ **Stellar properties: M, R_p, R_{eq}, I, z, Ω_K, ω, ε, ρ, κ, ν, C**

Non-Rotating Case

$$\frac{dP}{dr} = -\frac{\epsilon(1+P/\epsilon)\,m(1+4\pi P r^3/m - \Lambda r^3/3m)}{r^2(1-2m/r-\Lambda r^2/3)}$$

Stellar Cooling Equation

$$\partial_t \tilde{T} = -\frac{1}{\Gamma^2} e^{2\nu} \frac{\epsilon}{C_V} - r \sin\theta \, U e^{\nu+\gamma-\xi} \frac{1}{C_V} \left(\partial_r \Omega + \frac{1}{r} \partial_\theta \Omega \right)$$

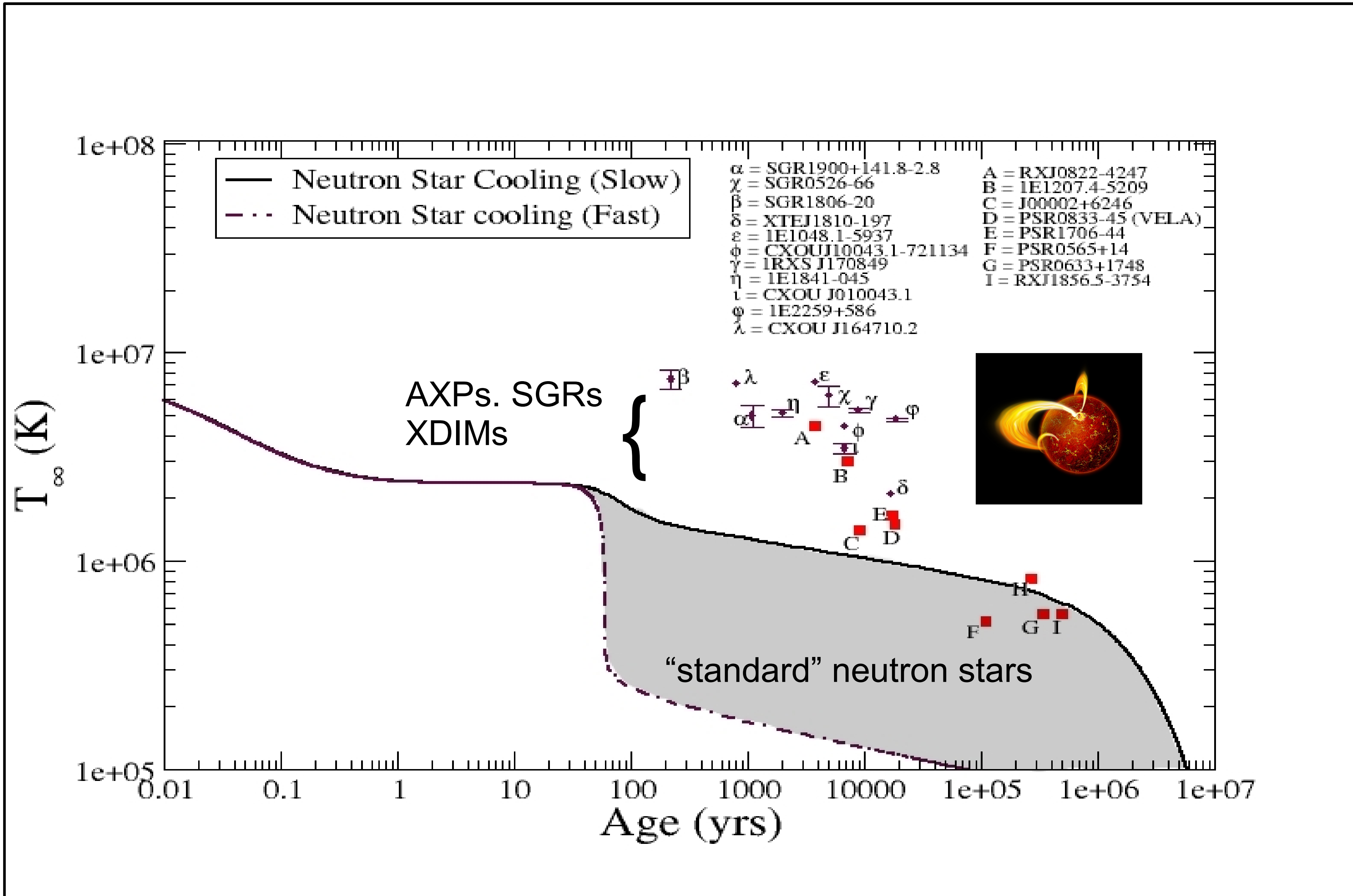
$$+ \frac{1}{r^2 \sin\theta} \frac{1}{\Gamma} e^{3\nu-\gamma-2\xi} \frac{1}{C_V} \left(\partial_r \left(r^2 \kappa \sin\theta \, e^{\gamma} \left(\partial_r \tilde{T} + \Gamma^2 U e^{-2\nu+\gamma} \tilde{T} \partial_r \Omega \right) \right) \right.$$

$$\left. + \frac{1}{r^2} \partial_\theta \left(r^2 \kappa \sin\theta \, e^{\gamma} \left(\partial_\theta \tilde{T} + \Gamma^2 U e^{-2\nu+\gamma} \tilde{T} \partial_\theta \Omega \right) \right) \right)$$

to be combined with stellar rotation code.

First attempt: see M. Stejner, F. Weber, J. Madsen, ApJ 694 (2009) 1019

Neutron Star Cooling Curves



Rodrigo Negreiros, SDSU, 2009

Internal Heating

- Quark-hadron phase transition
- Re-population
- Reheating via vortex expulsion
- Pycnonuclear reactions

Reheating via Vortex Expulsion

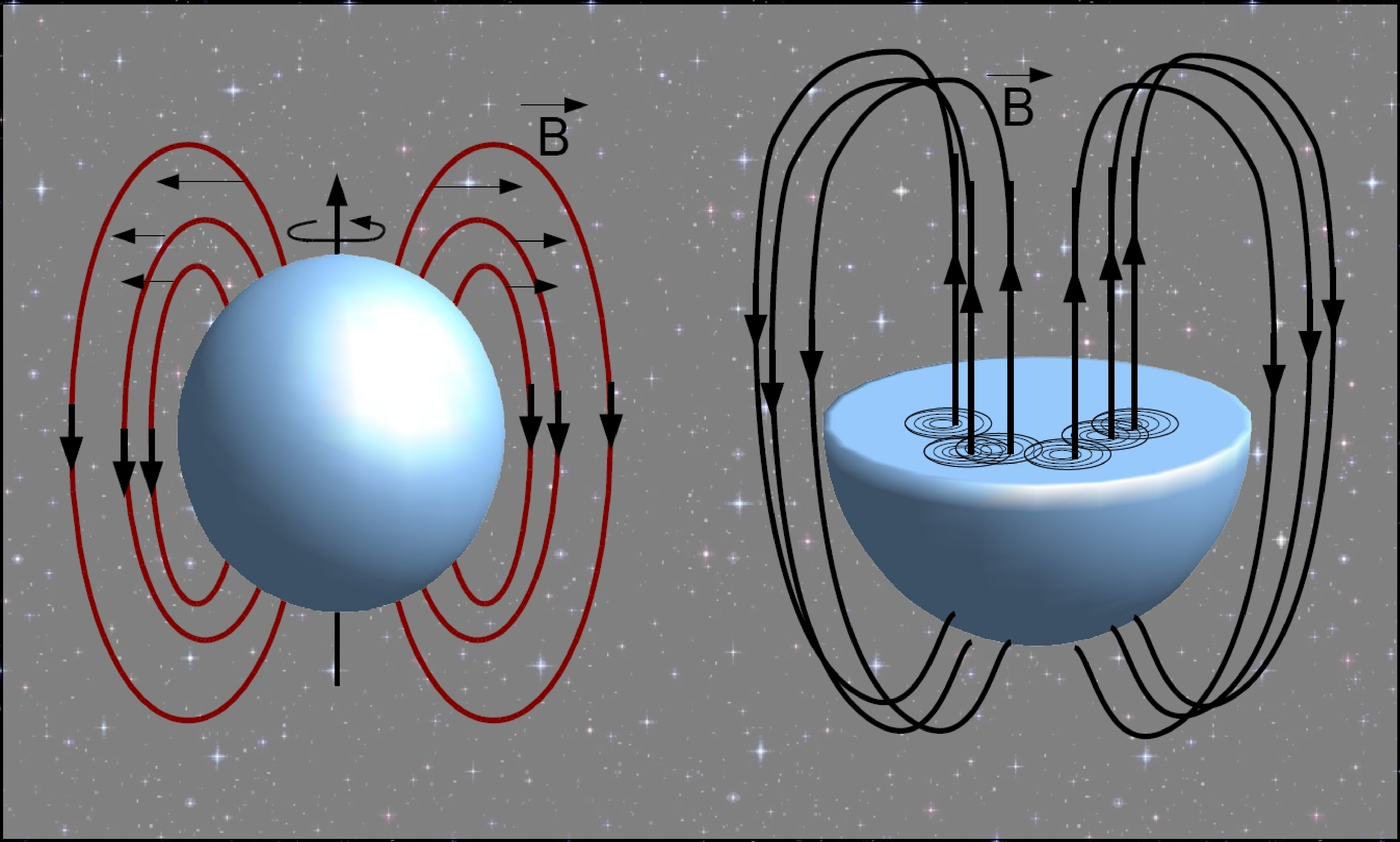
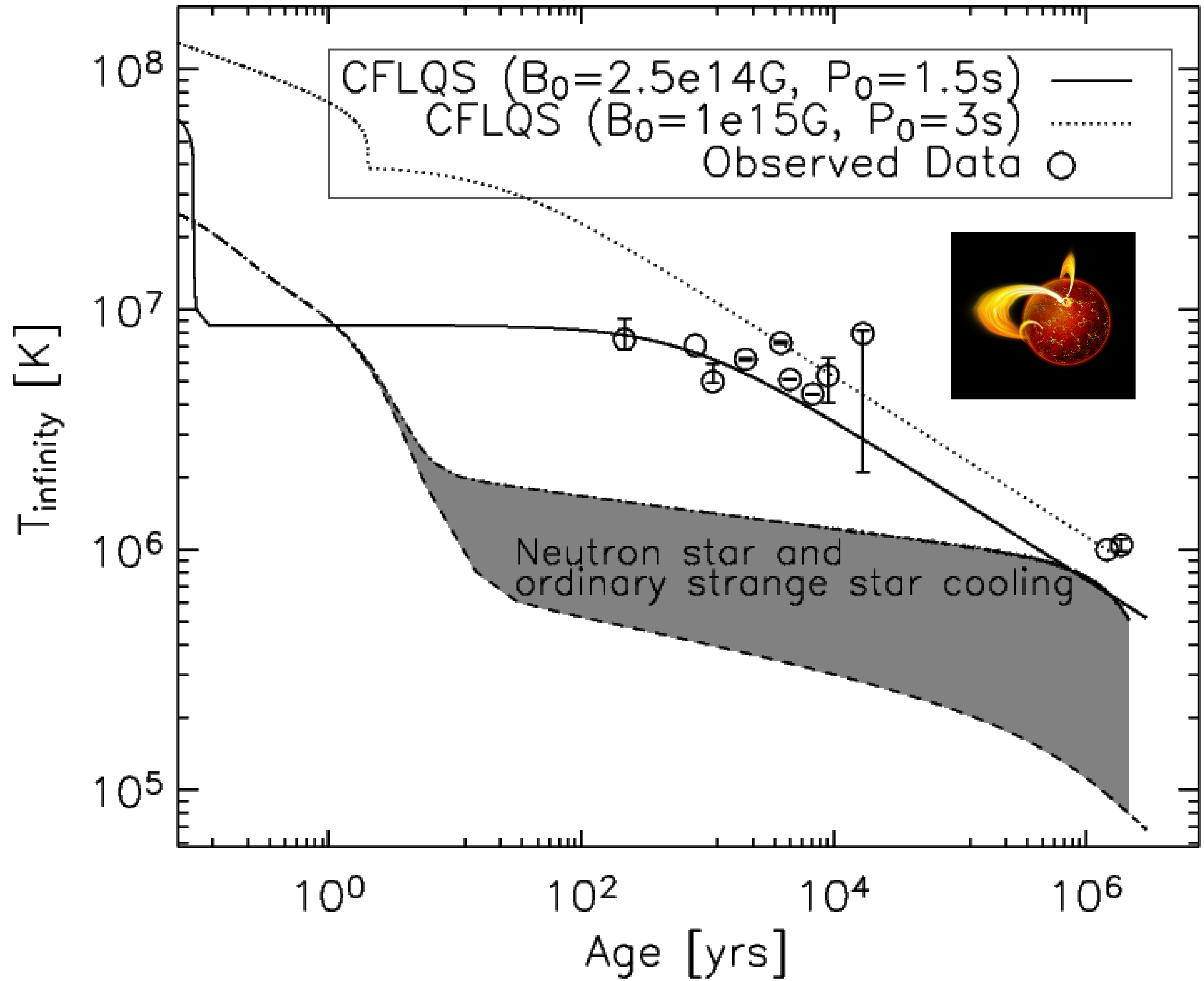
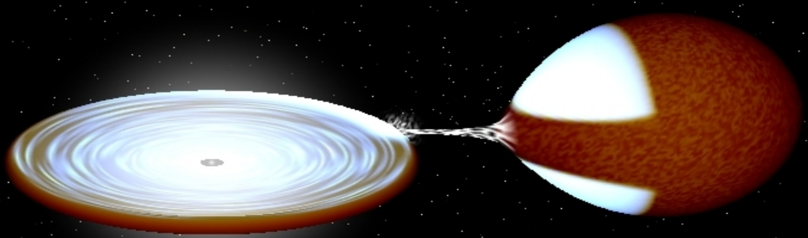


Image Credit: Rodrigo Negreiros

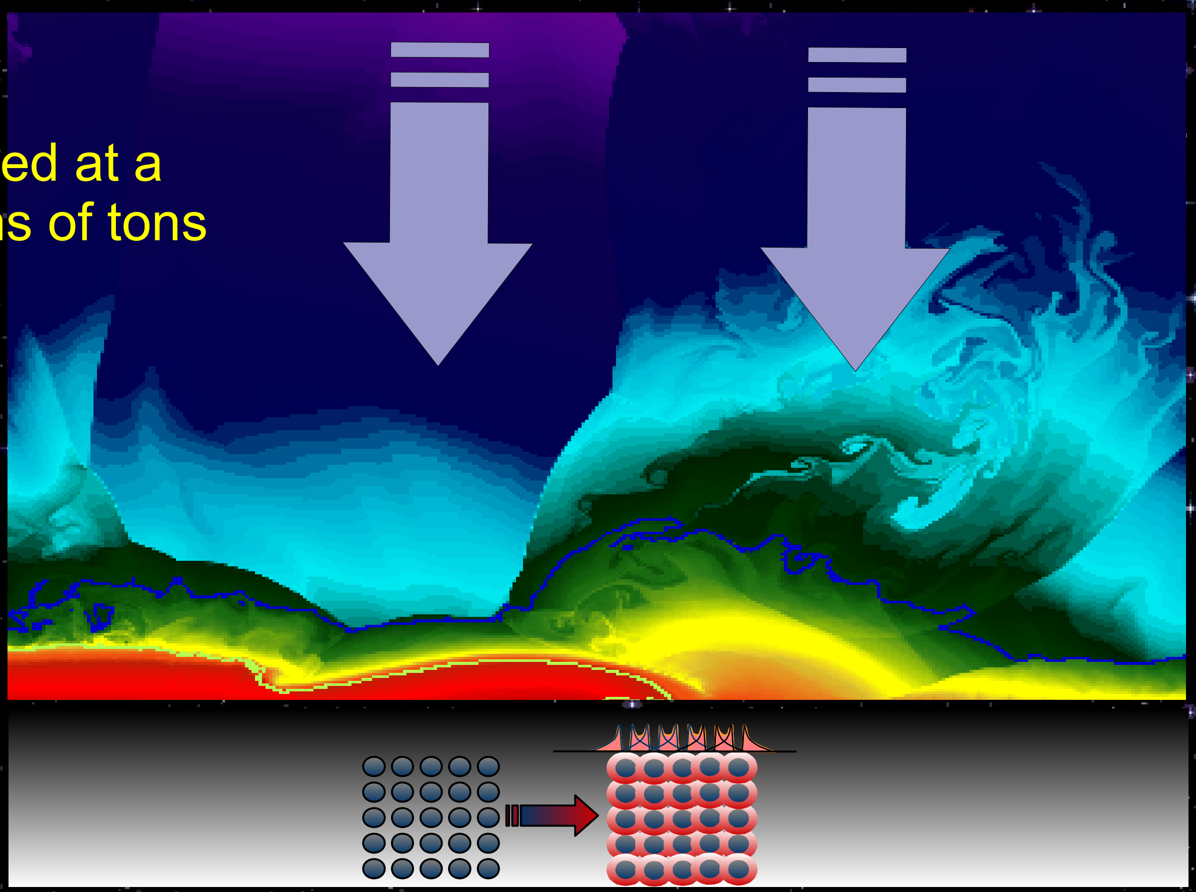


B. Niebergal, R. Ouyed, R. Negreiros, F. Weber, 2009

Neutron Star Surface and Crust



Matter accreted at a rate of millions of tons per second!

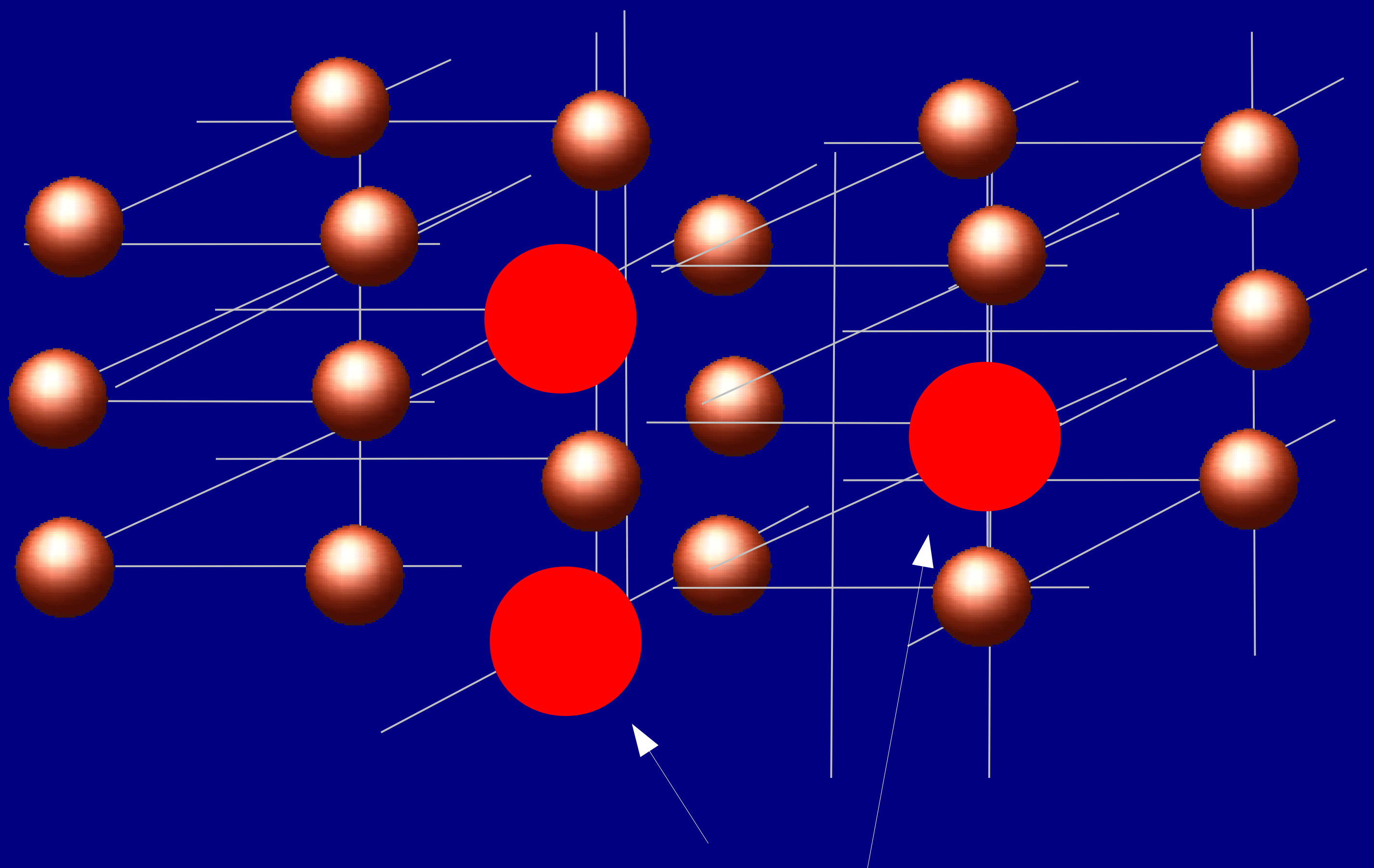


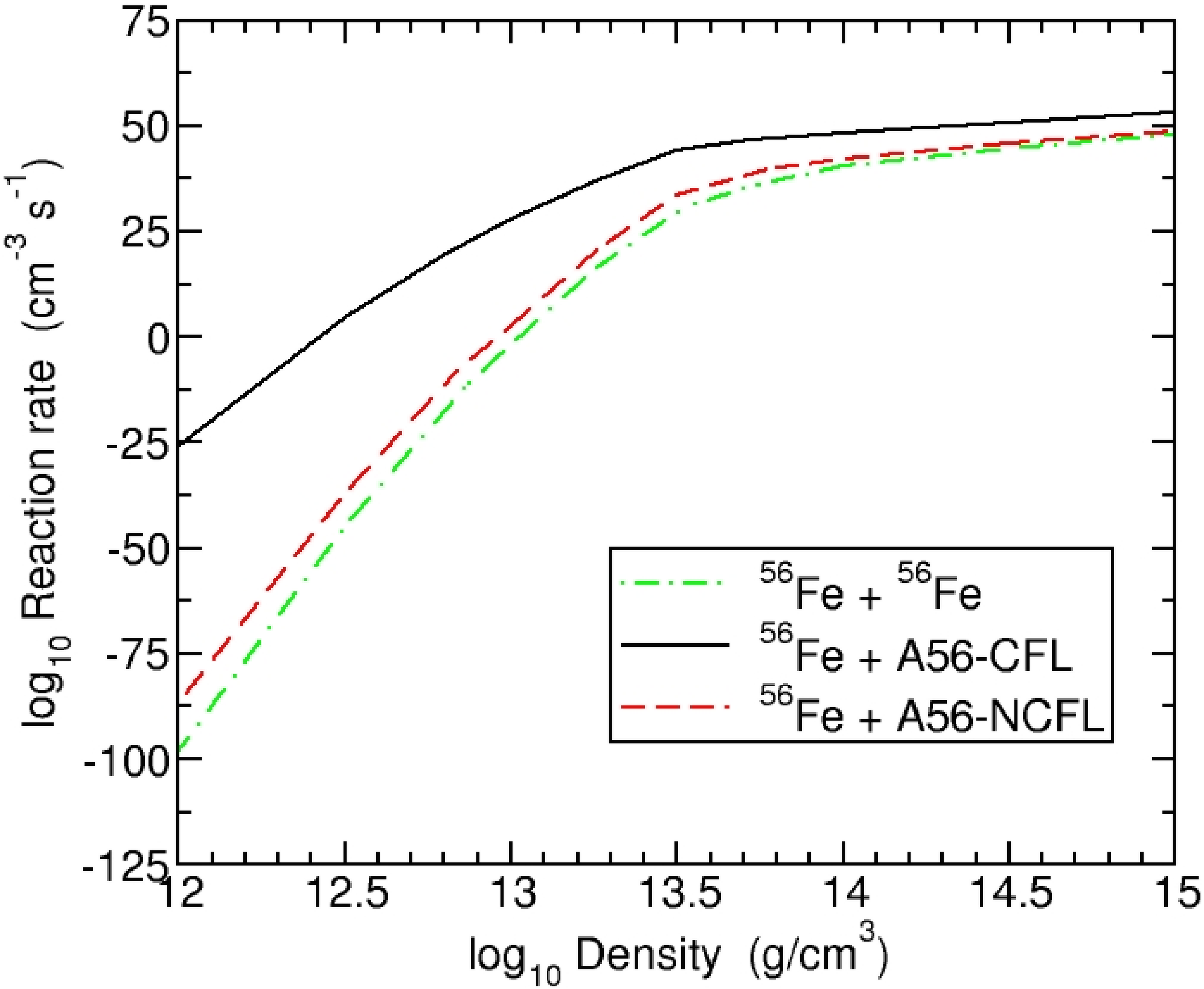
Thermonuclear reactions

Neutron star crust

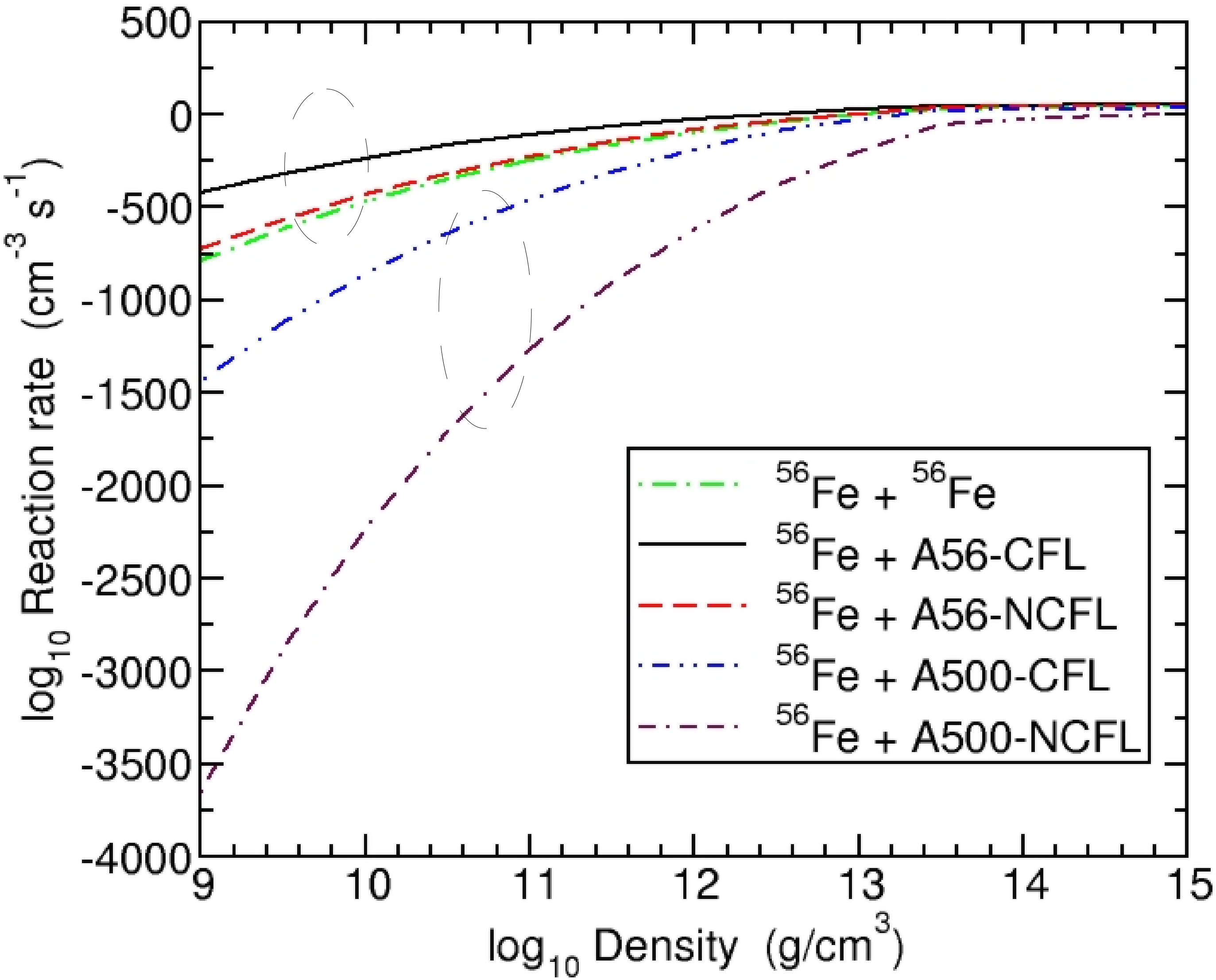
Pycnonuclear reactions

Pycnonuclear Reactions in Crusts of Neutron Stars





B. Golf, J. Hellmers, F. Weber, to appear in PRC (2009)



B. Golf, J. Hellmers, F. Weber, to appear in PRC (2009)

Summary

- MSPs and LMXBs

  Experience strong rotation-driven changes in core composition

  Internal heat release and reheating

- LMXBs

  Pycnonuclear reactions

  Reaction rates strongly modified by presence of strange quark matter nuggets

- SGRs, AXPs:

  Made of CFL quark matter?

  Challenges ahead:

    Very strong magnetic fields

    Anisotropic heat transport

    Heat conductivity becomes a tensor