PHYSICS OF NEUTRON STARS

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Facets of Strong-Interaction Physics, January 15-21, 2012
Hirschegg, Austria

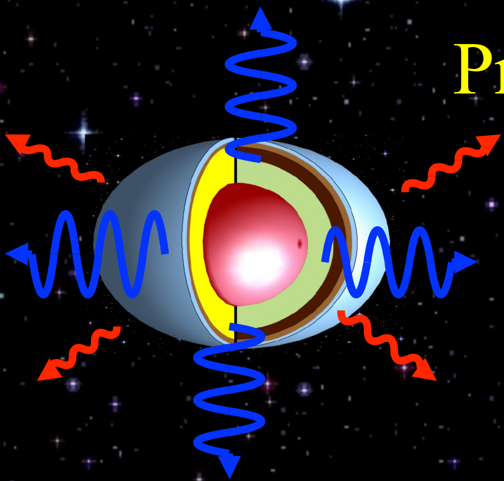
Outline

- Neutron star basics
- Structure and composition
- Rotation in General Relativity
- Phase transitions driven by rotation
- Cooling (2D simulations)
- Summary

SN Ib, Ic, SN II

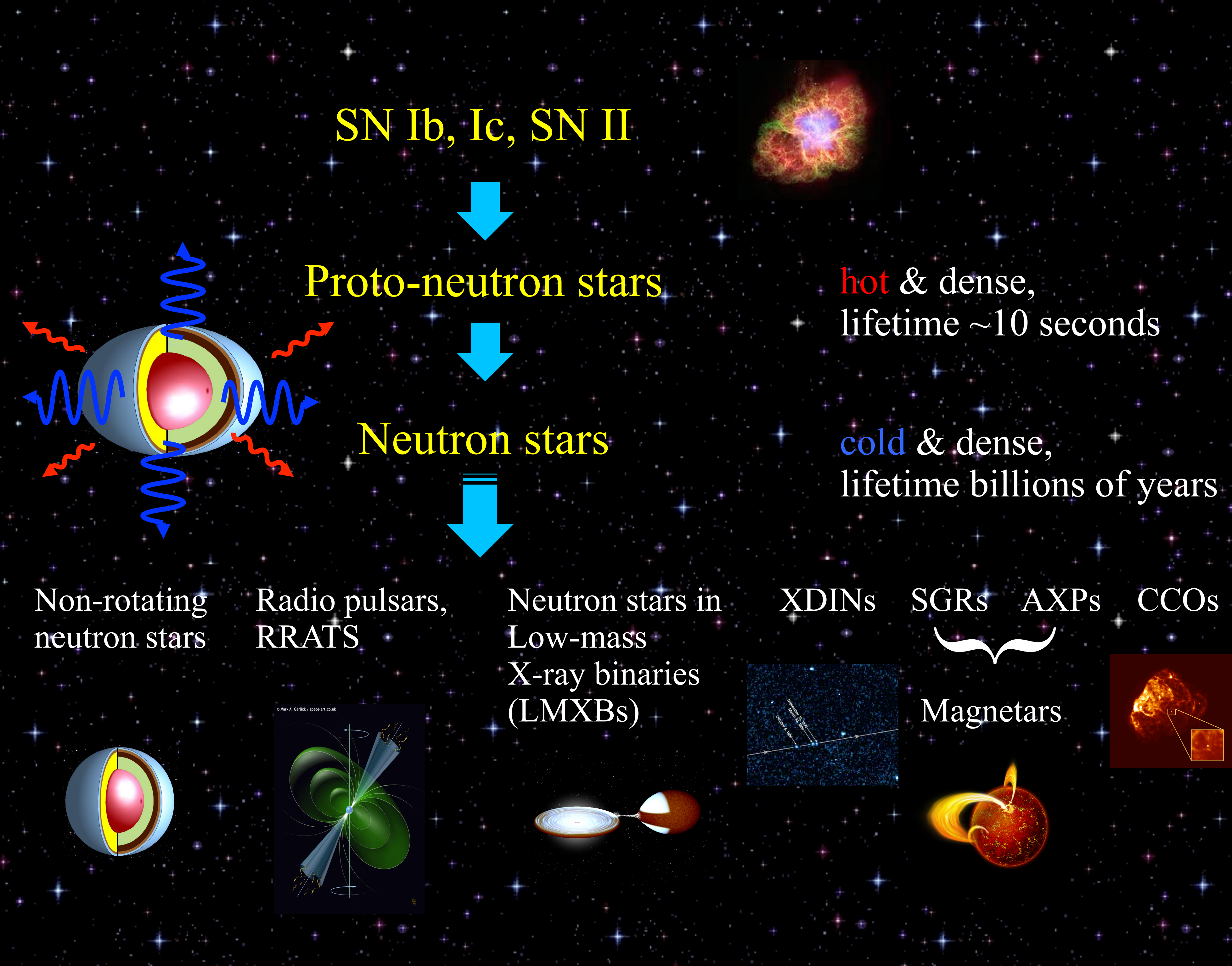
Proto-neutron stars

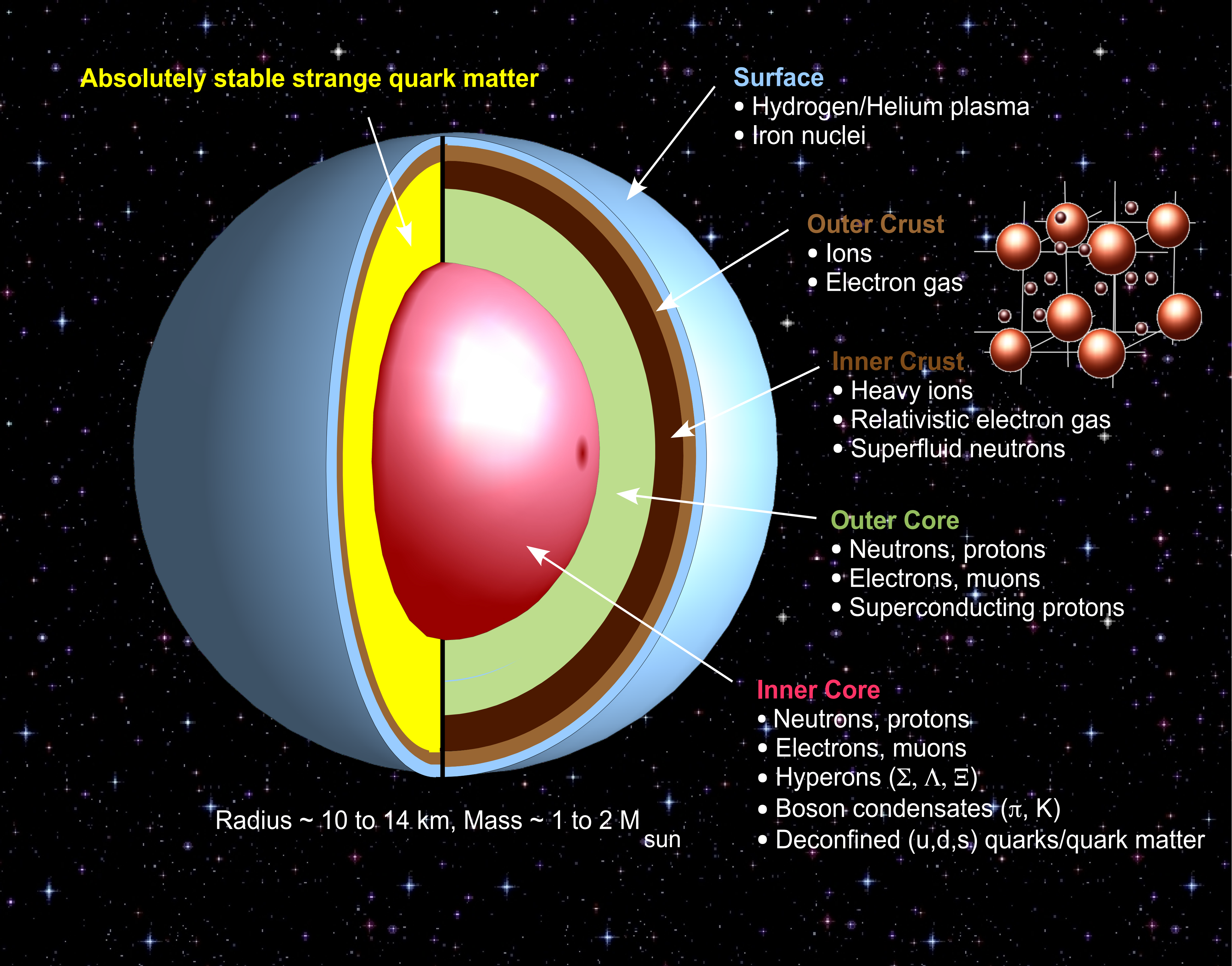
Neutron stars



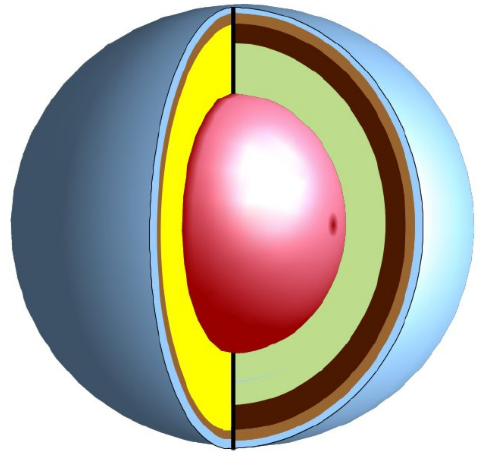
hot & dense,
lifetime ~10 seconds

cold & dense,
lifetime billions of years


SN Ib, Ic, SN II
Proto-neutron stars
hot & dense,
lifetime ~10 seconds
Neutron stars
cold & dense,
lifetime billions of years
Non-rotating neutron stars
Radio pulsars, RRATS
Neutron stars in Low-mass X-ray binaries (LMXBs)
XDINs
SGRs
AXPs
CCOs
Magnetars


Absolutely stable strange quark matter
Surface
• Hydrogen/Helium plasma
• Iron nuclei
Outer Crust
• Ions
• Electron gas
Inner Crust
• Heavy ions
• Relativistic electron gas
• Superfluid neutrons
Outer Core
• Neutrons, protons
• Electrons, muons
• Superconducting protons
Inner Core
• Neutrons, protons
• Electrons, muons
• Hyperons (Σ, Λ, Ξ)
• Boson condensates (π, K)
• Deconfined (u,d,s) quarks/quark matter
Radius ~ 10 to 14 km, Mass ~ 1 to 2 M_{sun}

Core Composition



- **Baryons:** $\Sigma, \Lambda, \Xi, \Delta$

  Ambartsumyan & Saakyan, 1960

- **Boson condensates:** π^-, K^-

  Brown & Weise, 1976
  Kaplan & Nelson, 1986; Politzer & Wise, 1991; Brown et al, 1992
  Waas, Rho, Weise 1997

- **Quarks: u, d, s,** c, t, b

  Ivanenko & Kurdgelaidze, 1965
  Fritzsch, Gell-Mann & Leutwyler, 1973
  Collins & Perry, 1975
  Baym & Chin; Keister & Kisslinger, 1976
  Chapline & Nauenberg, 1977

Two conserved charges (Glendenning 1992)

$$P_H(\mu^e, \mu^n) = P_Q(\mu^e, \mu^n) \Rightarrow \rho > 2 - 3\rho_0$$

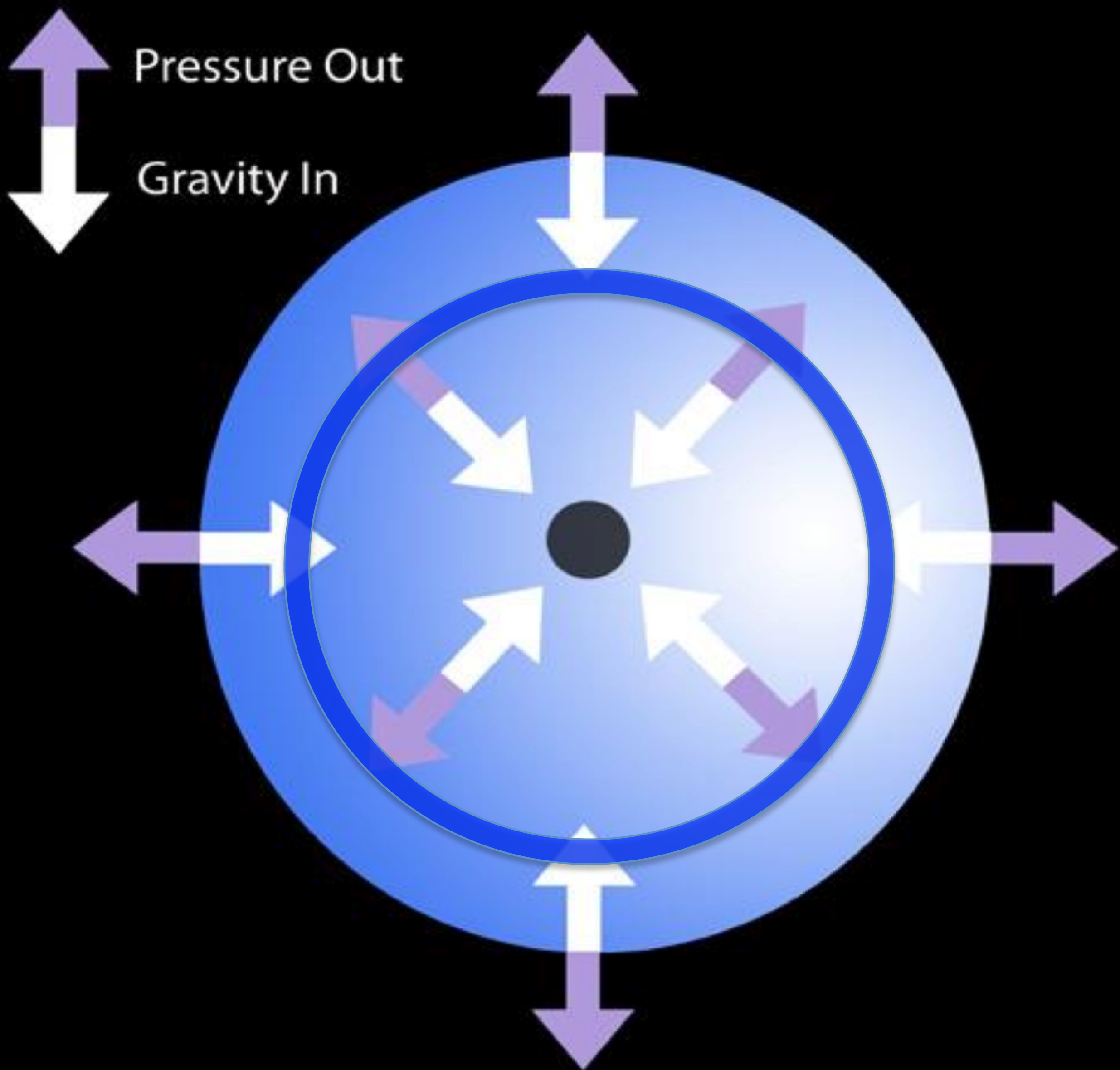
Possible existence of:

- Mixed phase of quarks and hadrons
- Quark drops, quark rods, quark slabs
- Pure quark matter in cores of neutron stars

Discovery of color superconductivity
Alford, Rajagopal, Wilczek (1998);
Rapp, Shuryak, Schaefer, Velkovsky (1998)

CFL, 2SC, gCFL, LOFF, …

Modeling Neutron Stars



Tolman-Oppenheimer-Volkoff (1939)

$$ds^2 = -e^{2\Phi(r)}\,dt^2 + e^{2\Lambda(r)}\,dr^2 + r^2\,d\theta^2 + r^2\sin^2\theta\,d\phi^2$$

$$R^{\mu\nu} - \frac{1}{2}g^{\mu\nu}R = 8\pi T^{\mu\nu}\,, \qquad T^{\mu\nu}{}_{;\mu} = 0$$

$$\Uparrow$$

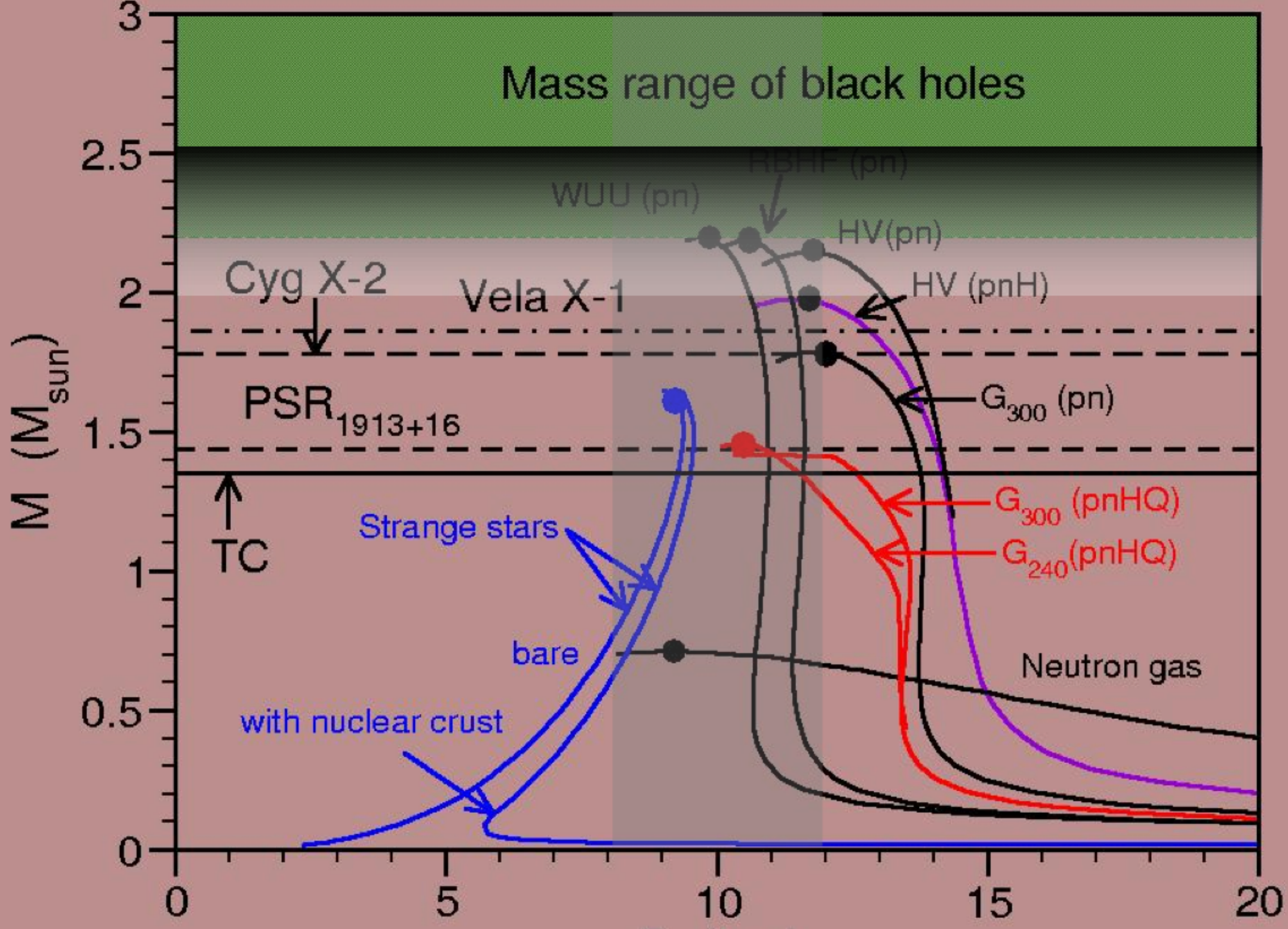
$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu + g^{\mu\nu}P$$

Input: equation of state

$$\frac{dp}{dr} = -\frac{\epsilon\,(1 + P/\epsilon)\;m\;(1 + 4\pi P r^3/m)}{r^2\,(1 - 2m/r)}\,, \qquad m = 4\pi\int_0^r dr\,r^2\,\epsilon$$

Note: $\dfrac{dp}{dr} < 0$

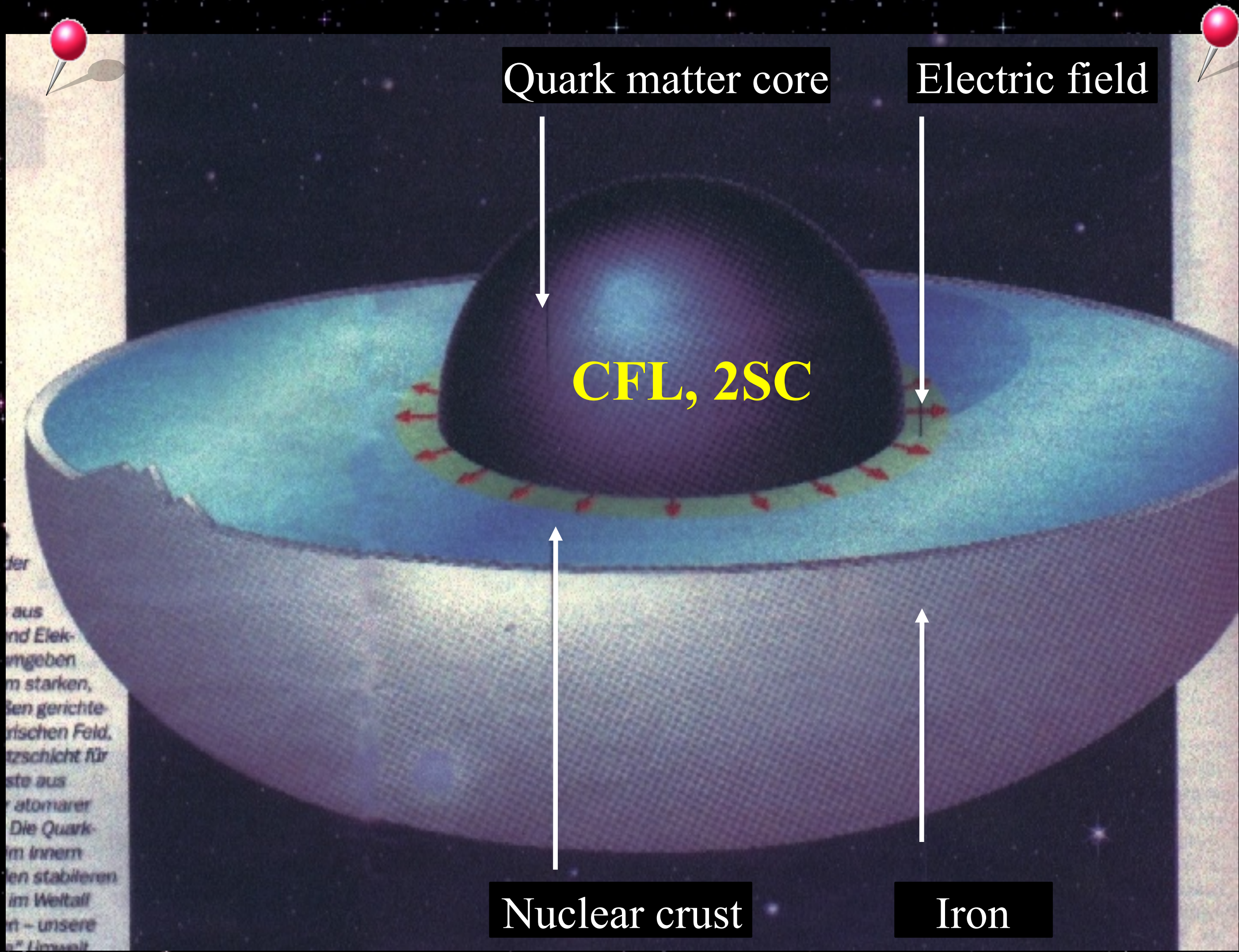
Mass-Radius Relationship of Neutron Stars and Quark Stars



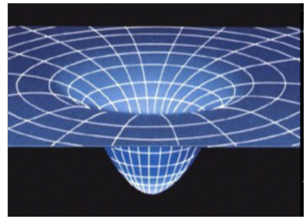
Strange (quark) stars

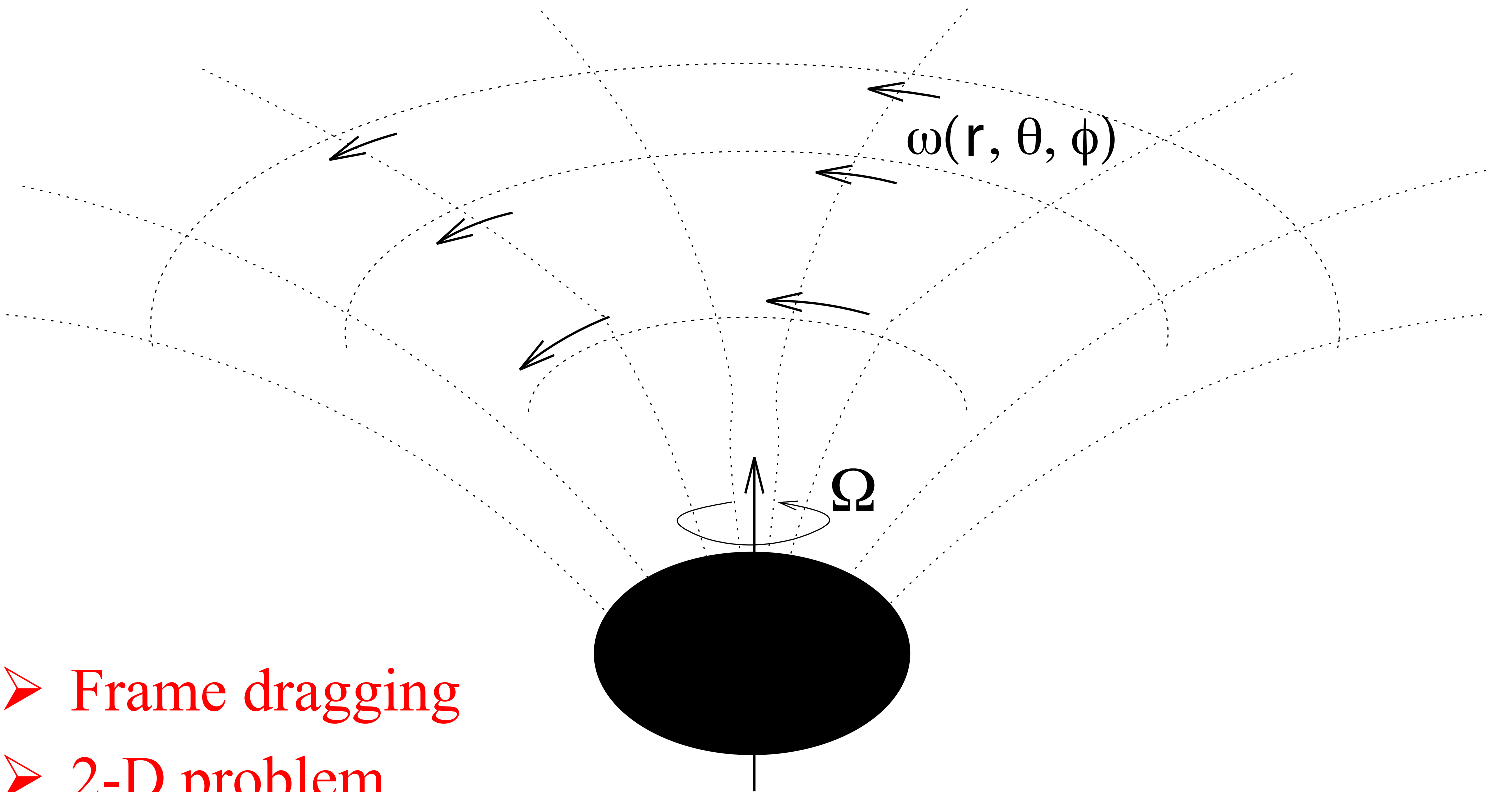
Neutron stars

Strange Quark Stars with Crust



Rotation in General Relativity





- Frame dragging
- 2-D problem

Rotating Neutron Stars in General Relativity

$$ds^2 = -e^{2\nu} dt^2 + e^{2\phi}(d\varphi - N^{\varphi} dt)^2 + e^{2\omega}(dr^2 + r^2 d\theta^2)$$

$$R^{\mu\nu} - \frac{1}{2} g^{\mu\nu} R = 8\,\pi\, T^{\mu\nu}$$

Input: equation of state

$$T^{\mu\nu}{}_{;\nu} = q^{\mu}$$

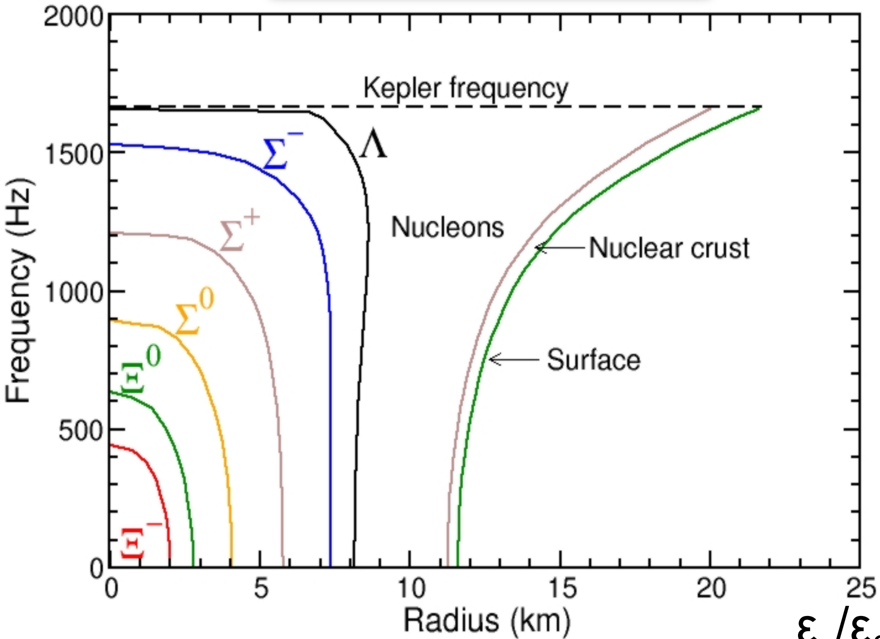
$0 \leq \nu \leq \nu_K$ Kepler (mass shedding) frequency

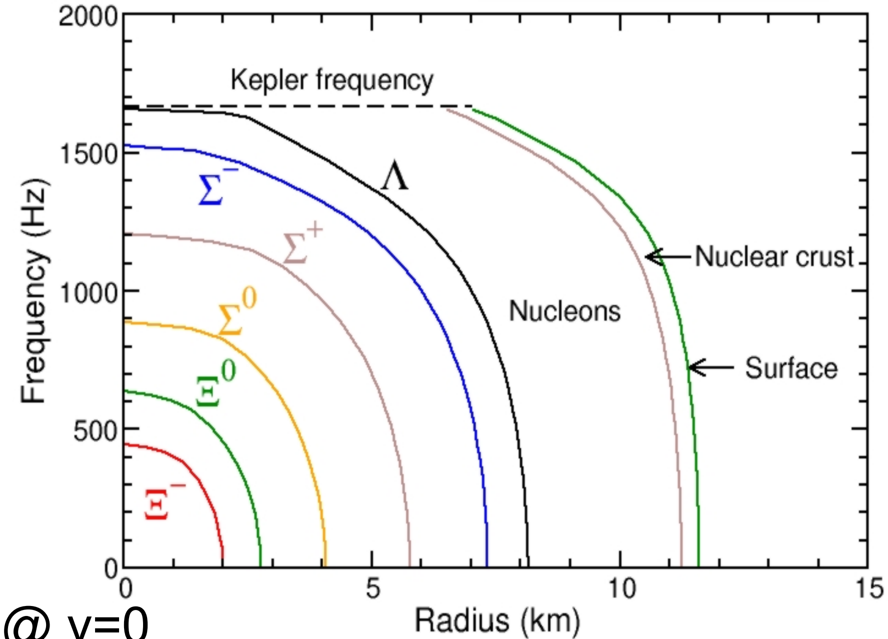
Model Composition of a M=1.7 M_{sun} Neutron Star

Equatorial direction

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

Polar direction

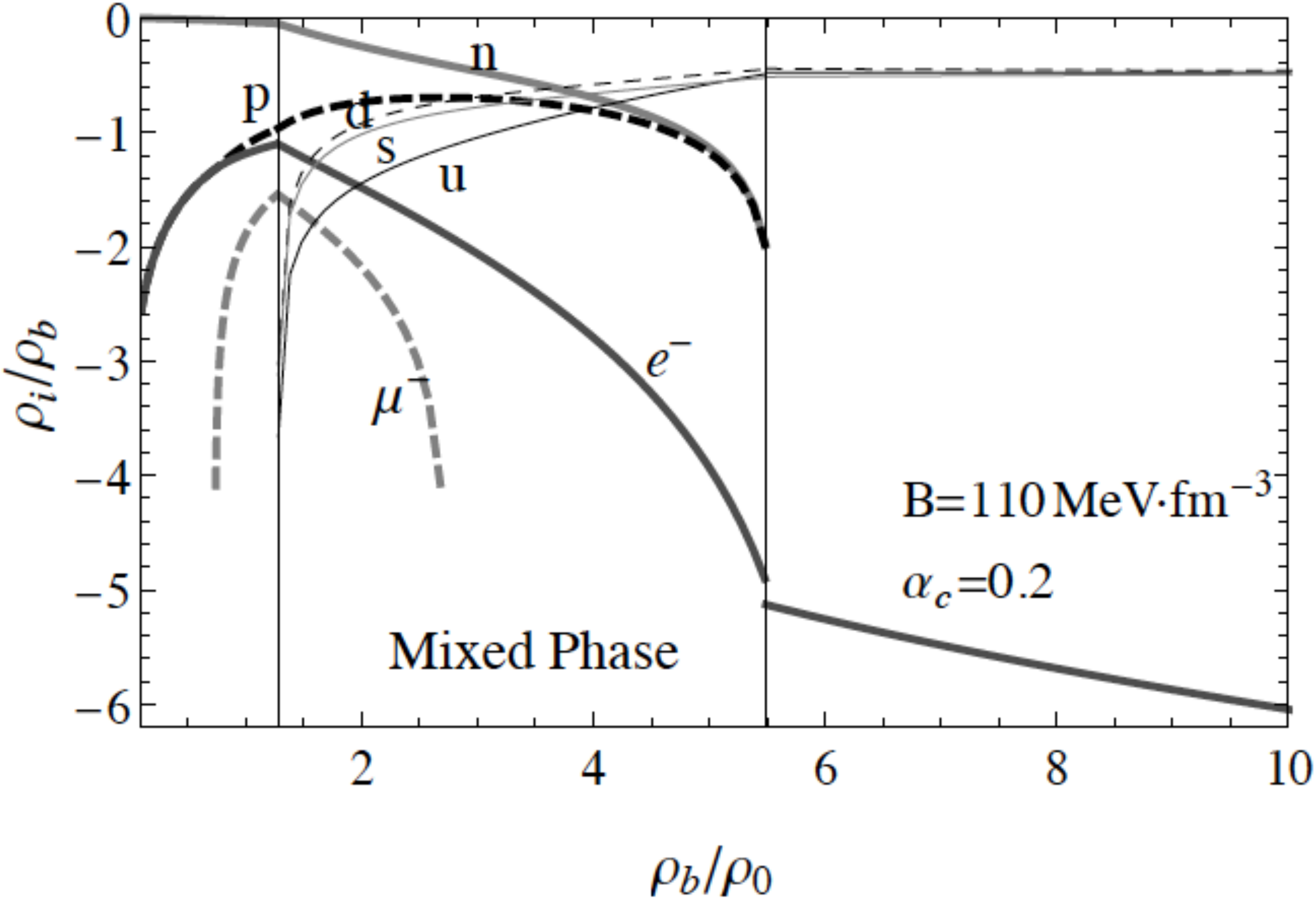




$\varepsilon_c/\varepsilon_0=7$ @ $v=0$

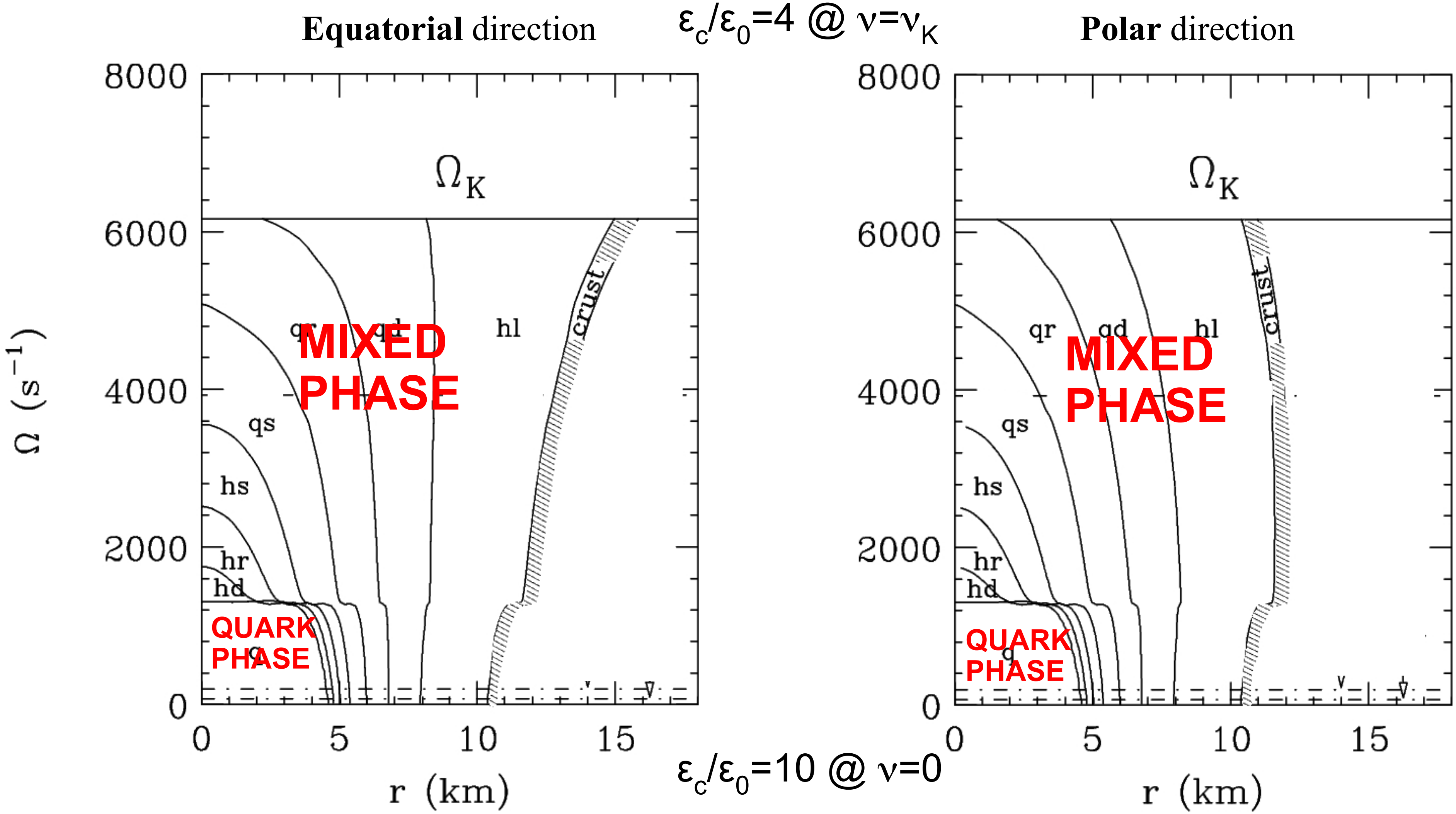
Rosenfield, (SDSU, 2008); Equation of state: DDRMF, Hofmann, Keil, Lenske.

Sample Quark-Hadron Composition



Xuesen Na, R. X. Xu & FW (2012)

Model Quark-Hadron Composition of 1.45 M_{sun} Neutron Star



Moment of inertia:

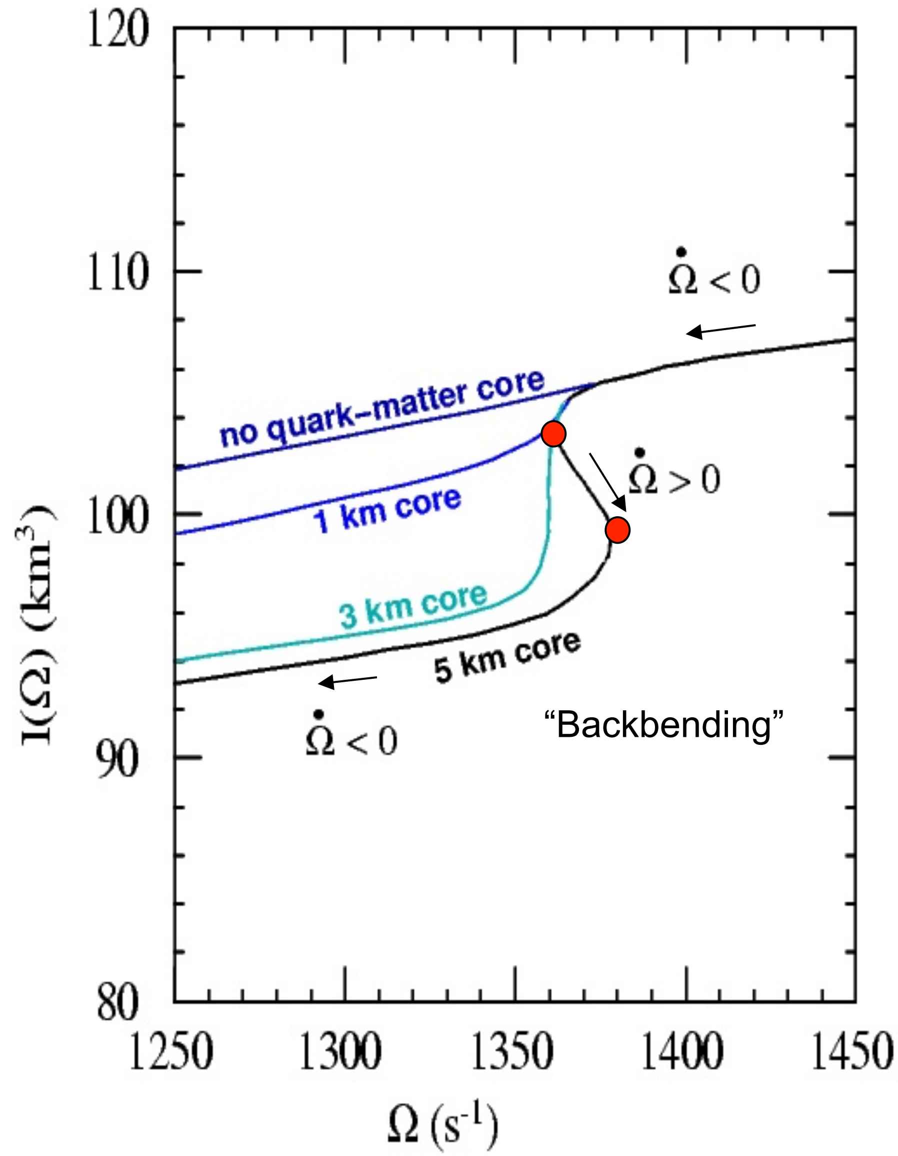
$$I = \frac{1}{\Omega} \int dr\, d\theta\, d\phi\, T_{\phi}{}^{t} \sqrt{-g}$$

Braking index (n) of a pulsar:

$$n = 3 - \frac{I''\Omega^2 + 3I'\Omega}{I'\Omega + 2I}$$

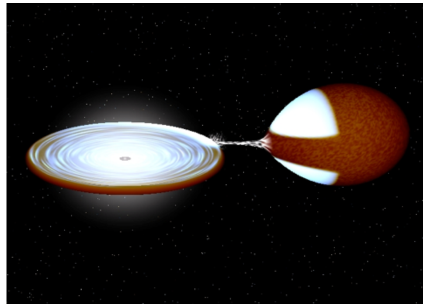
Signals of quark deconfinment:

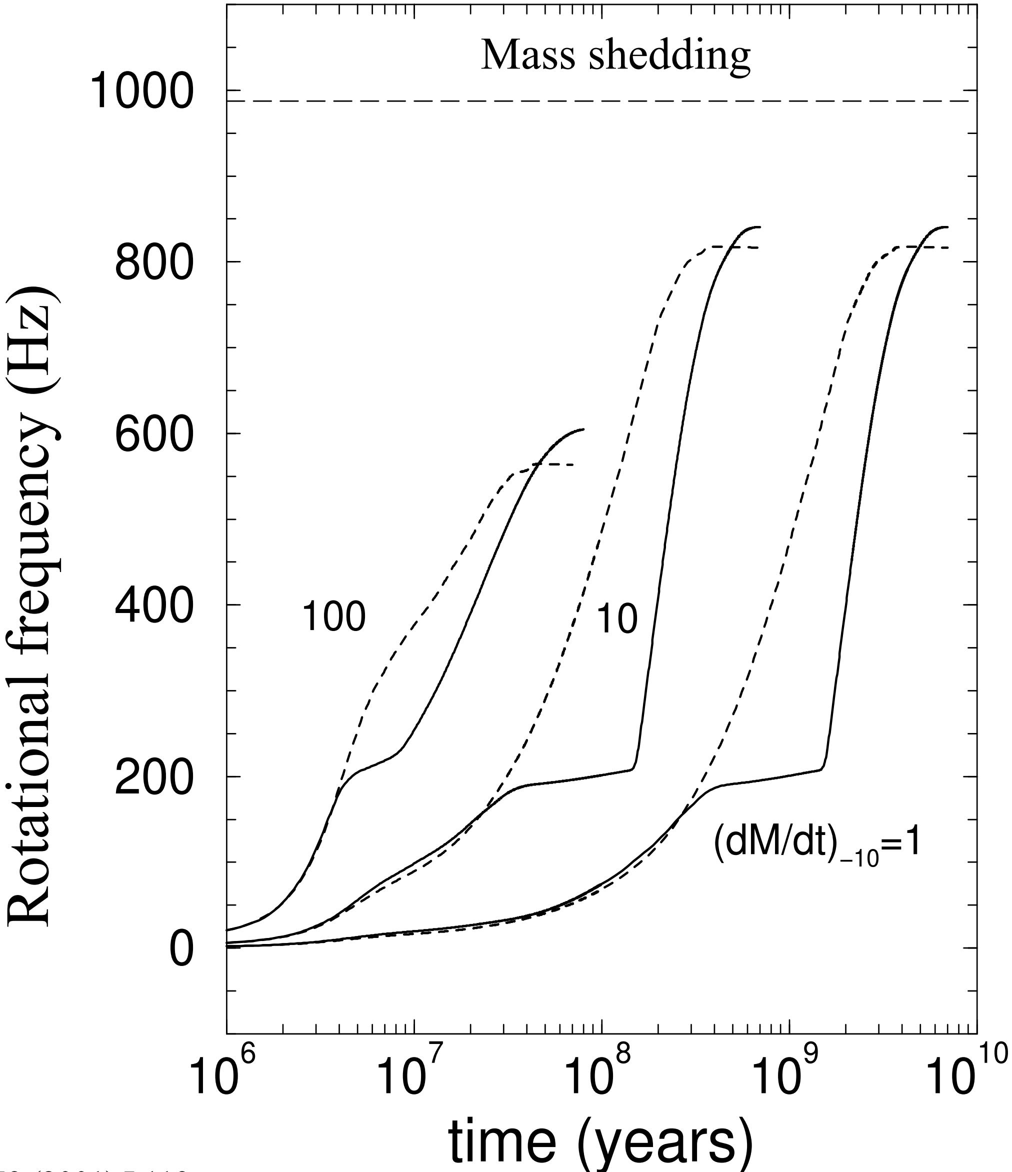
- Braking indices of pulsars $-\infty < n < +\infty$
- Spin-up of isolated rotating neutron stars



Glendenning, Pei, FW, PRL 79 (1997) 1603
Chubarian, Grigorian, Poghosyan, Blaschke A&A 357 (2000)
FW, Prog. Nucl. Part. Phys. 54 (2005) 193

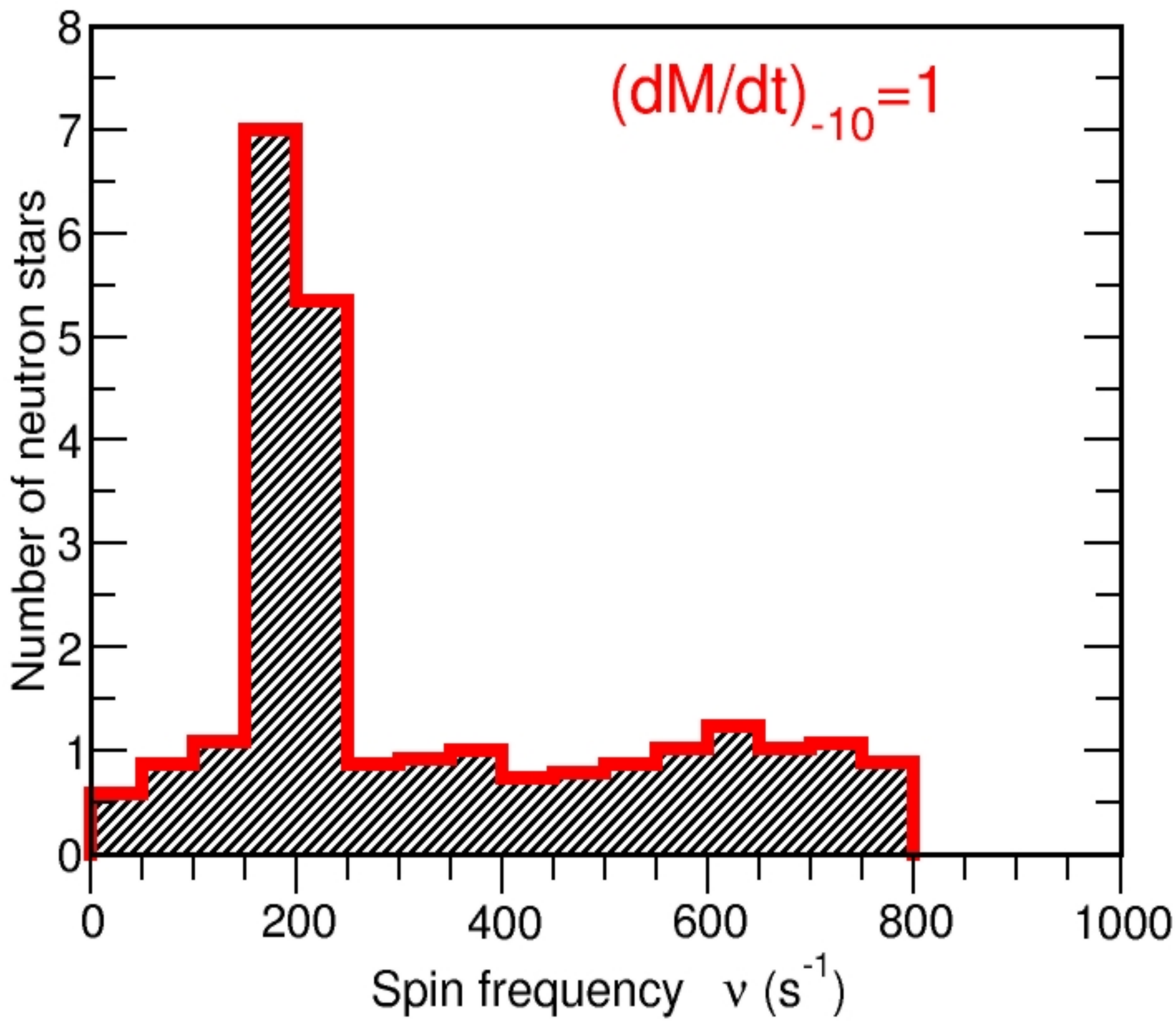
Possible Signal of Quark re-confinement in X-ray Neutron Stars





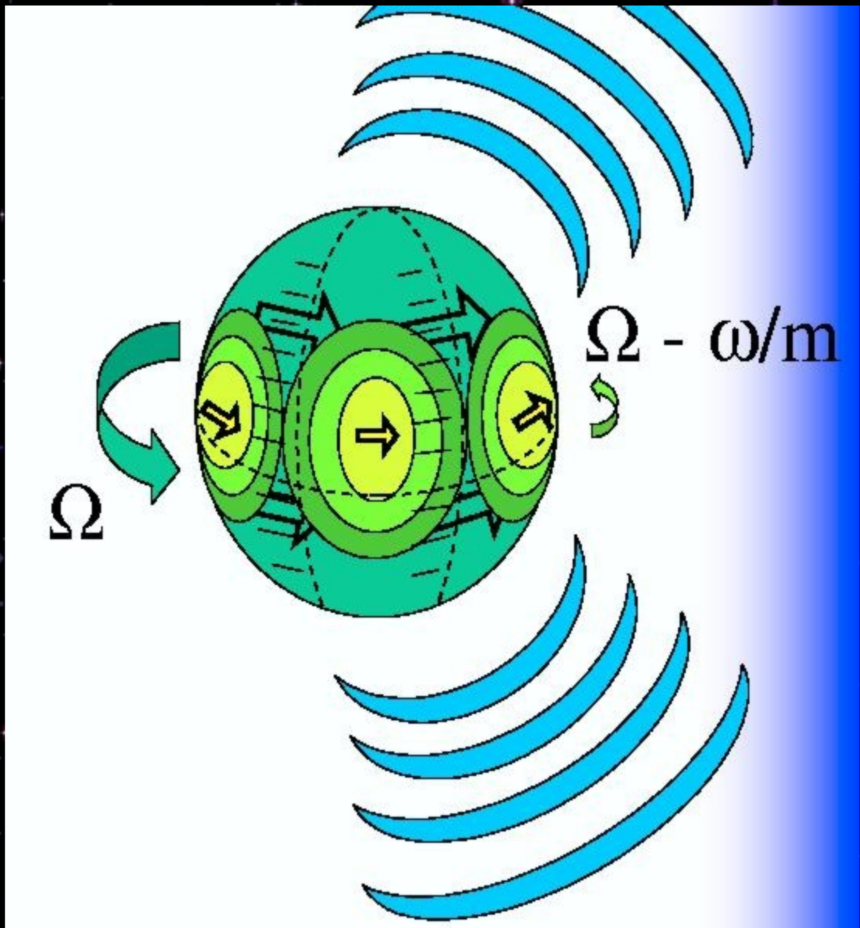
Glendenning & FW, ApJ 559 (2001) L119

Pile-up of neutron star spin frequencies caused by quark re-confinement



Glendenning & FW, ApJ 559 (2001) L119

Gravitational-Radiation Reaction Driven Instabilities ...

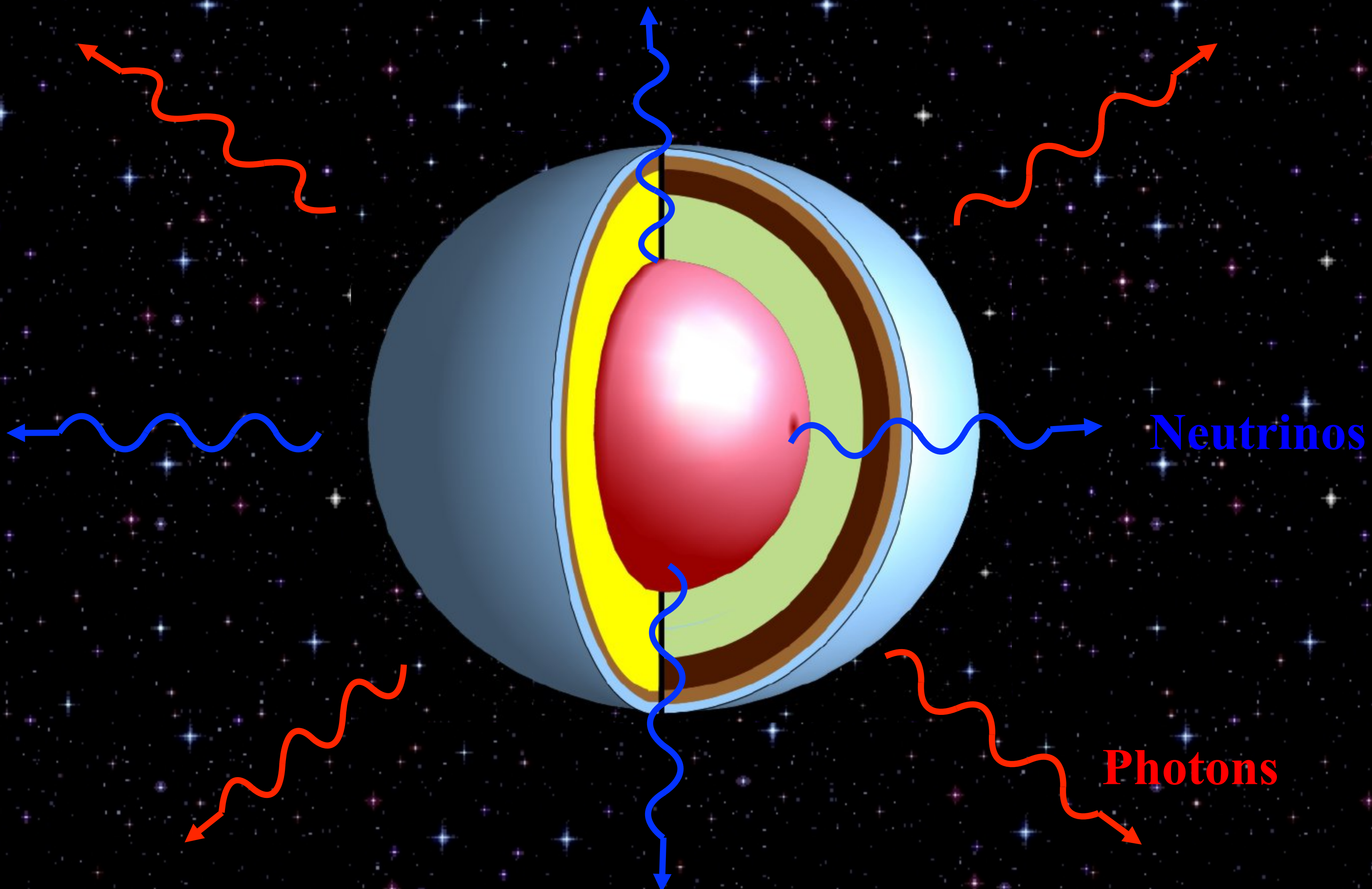


Rotating compact star emitting gravitational radiation

Driven by rotation at $v > v_{critical}$

Damped by
- Shear viscosity
- Bulk viscosity

Thermal Evolution of Neutron Stars



Neutron Star Cooling I

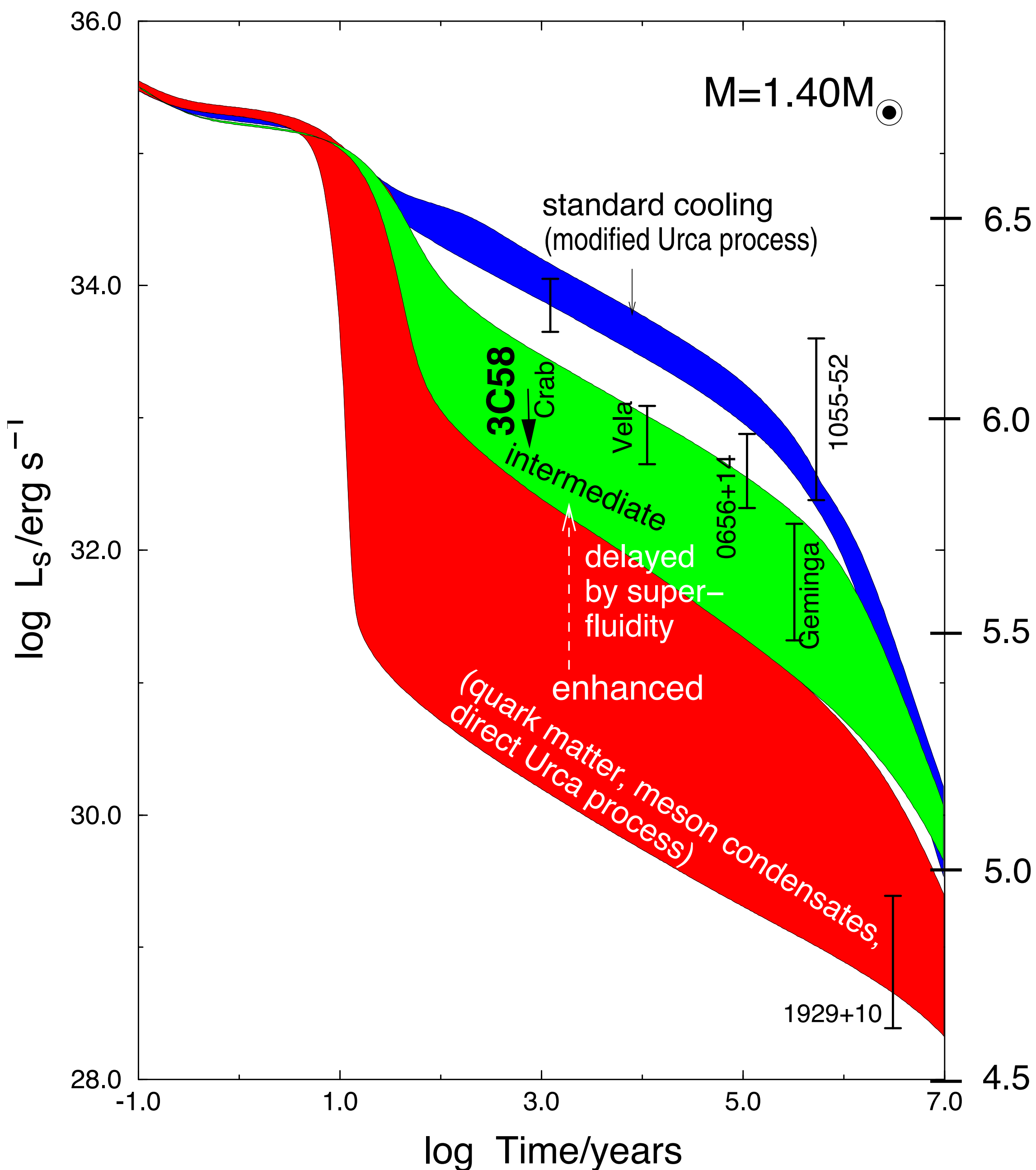
Modified Urca:	$n+n \rightarrow n+p+e+\nu$	slow
	$p+n \rightarrow p+p+e+\nu$	slow
Direct Urca:	$n \rightarrow p+e+\nu$	fast
Bremsstrahlung:	$n+n \rightarrow n+n+\nu+\nu$	slow
π^- condensate	$n+\langle \pi^- \rangle \rightarrow n+e+\nu$	fast
K^- condensate	$n+\langle K^- \rangle \rightarrow n+e+\nu$	fast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

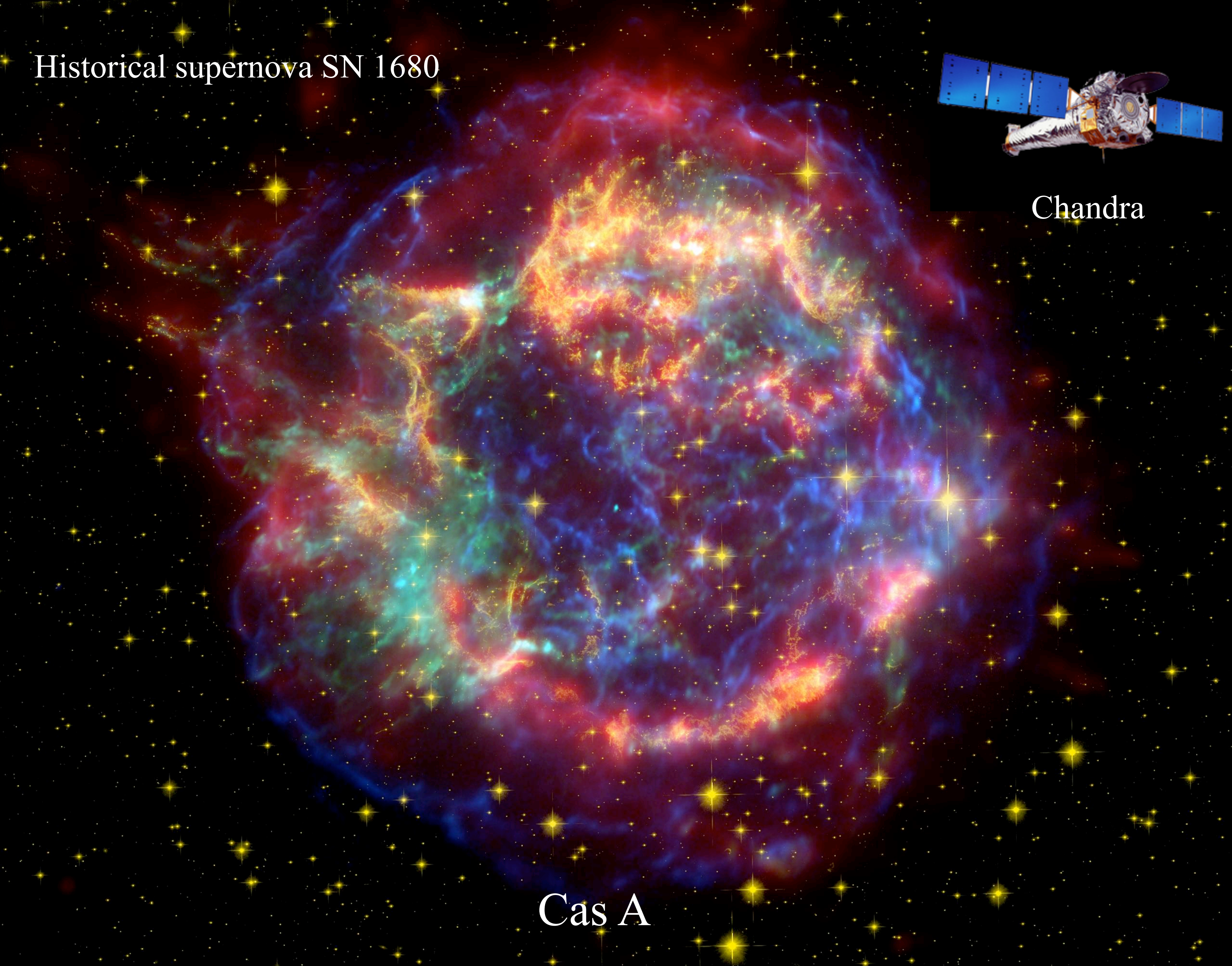
Neutron Star Cooling II

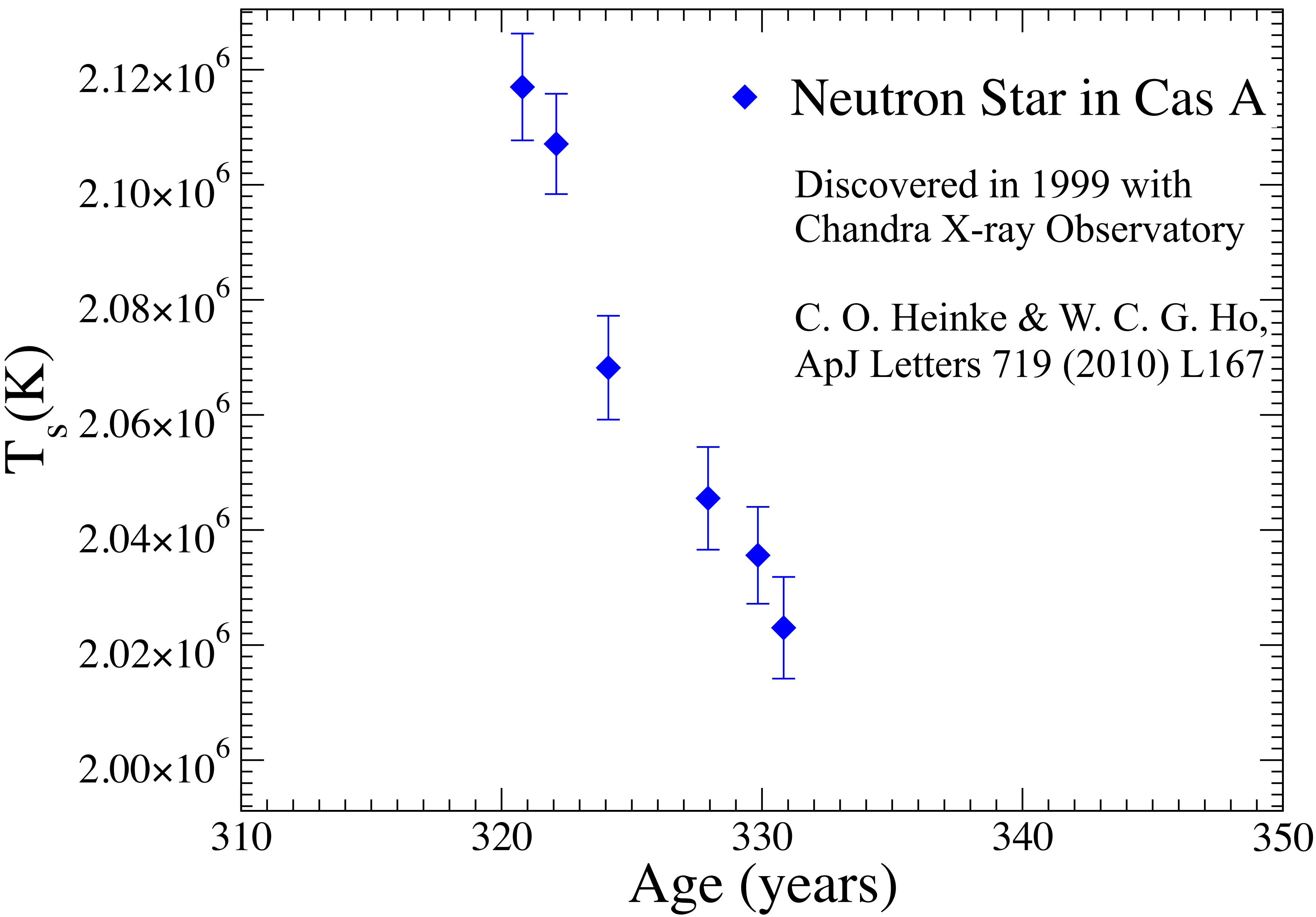
Modified Urca:	$Q+u+e \rightarrow Q+d+\nu$ $Q+u+e \rightarrow Q+s+\nu$	slow
Direct Urca:	$d \rightarrow u+e+\nu$ $s \rightarrow u+e+\nu$	fast
Bremsstrahlung:	$Q_1+Q_2 \rightarrow Q_1+Q_2+\nu+\nu$	slow
Cooper pair formations:	$u+u \rightarrow [uu] + \nu+\nu$ $d+d \rightarrow [dd] + \nu+\nu$ $s+s \rightarrow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

FW, Prog. Part. Nucl. Phys 54 (2005) 193
D. Page, U. Geppert, FW, NPA 777 (2006) 497

Neutron Star Cooling




Historical supernova SN 1680
Chandra
Cas A


Neutron Star in Cas A
Discovered in 1999 with
Chandra X-ray Observatory
C. O. Heinke & W. C. G. Ho,
ApJ Letters 719 (2010) L167
2.12×10^6
2.10×10^6
2.08×10^6
2.06×10^6
2.04×10^6
2.02×10^6
2.00×10^6
T_s (K)
310
320
330
340
350
Age (years)

Selected for a Viewpoint in *Physics*
PRL **106,** 081101 (2011) PHYSICAL REVIEW LETTERS week ending 25 FEBRUARY 2011

Rapid Cooling of the Neutron Star in Cassiopeia A Triggered by Neutron Superfluidity in Dense Matter

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(Received 29 November 2010; published 22 February 2011)

We propose that the observed cooling of the neutron star in Cassiopeia A is due to enhanced neutrino emission from the recent onset of the breaking and formation of neutron Cooper pairs in the $^3P_2$ channel. We find that the critical temperature for this superfluid transition is $\simeq 0.5 \times 10^9$ K. The observed rapidity of the cooling implies that protons were already in a superconducting state with a larger critical temperature. This is the first direct evidence that superfluidity and superconductivity occur at supranuclear densities within neutron stars. Our prediction that this cooling will continue for several decades at the present rate can be tested by continuous monitoring of this neutron star.

See also D. Yakovlev et al., MNRAS 411 (2011) 1977

Alternative explanations …

On the Cooling of the Neutron Star in Cassiopeia A

D. Blaschke,[1,2] H. Grigorian,[3] D. N. Voskresensky,[4,5] and F. Weber[6]

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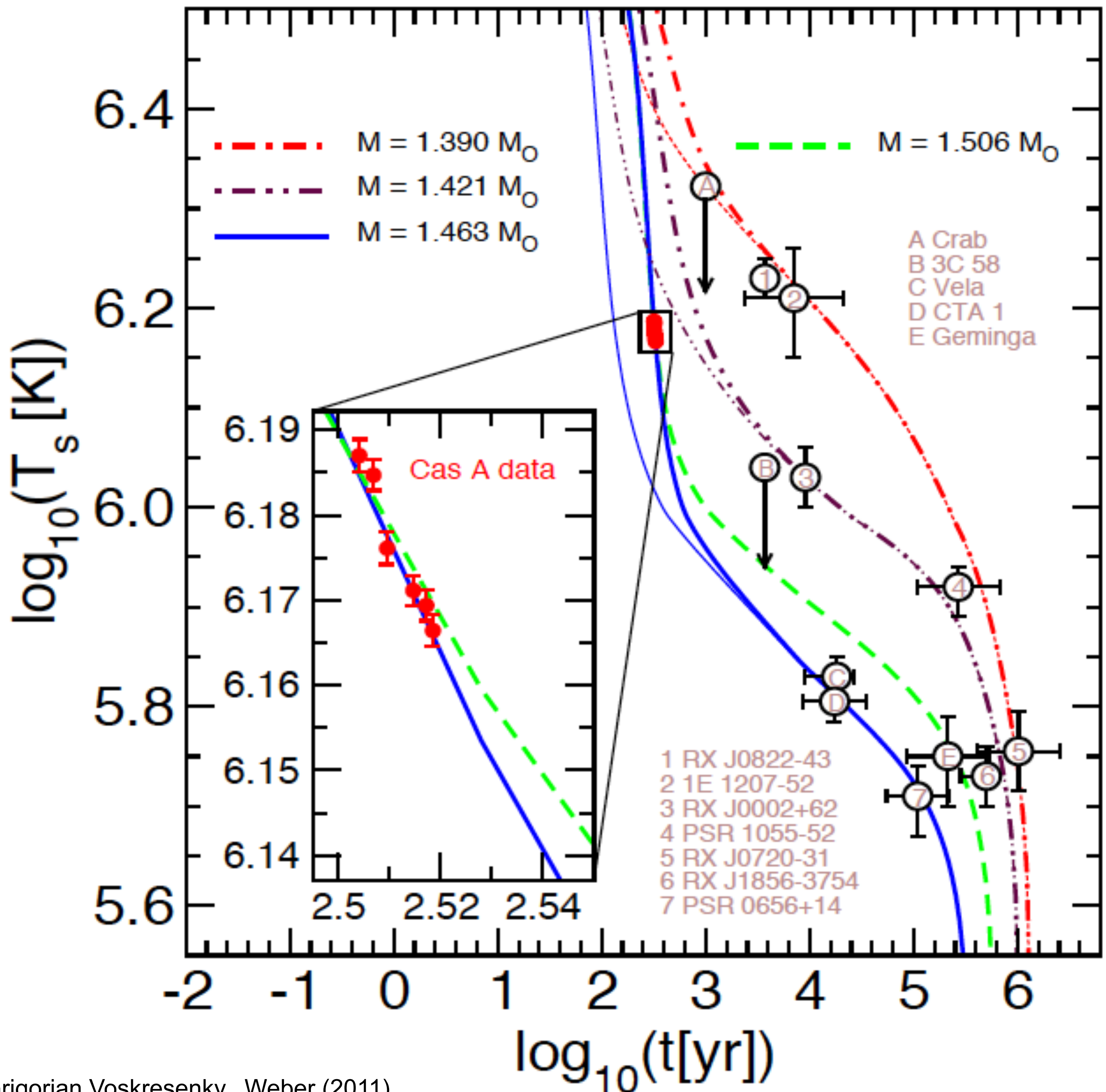
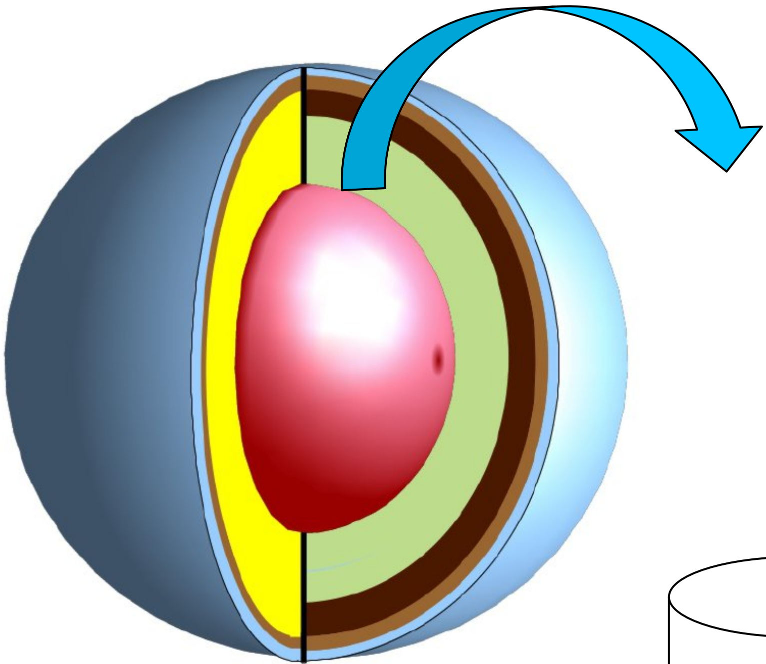
We demonstrate that the high-quality cooling data observed for the young neutron star in the supernova remnant Cassiopeia A over the past 10 years–as well as all other reliably known temperature data of neutron stars–can be comfortably explained within the ”nuclear medium cooling” scenario. The cooling rates of this scenario account for medium-modified one-pion exchange in dense matter and polarization effects in the pair-breaking formations of superfluid neutrons and protons. Crucial for the successful description of the observed data is a substantial reduction of the thermal conductivity, resulting from a suppression of both the electron and nucleon contributions to it by medium effects. In a few more decades of continued monitoring of Cassiopeia A, the observed data may allow one to put additional constraints on the efficiency of different cooling processes in neutron stars.

submitted to PRC (2011)



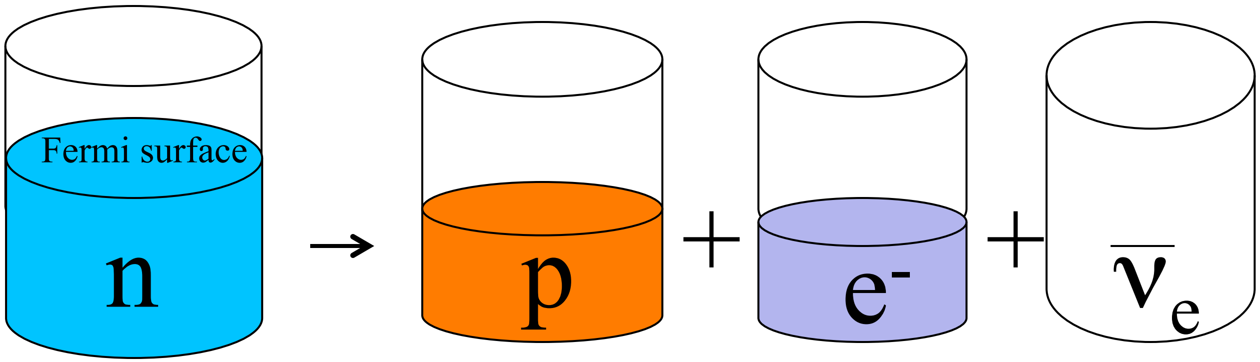
Blaschke, Grigorian,Voskresenky, Weber (2011)

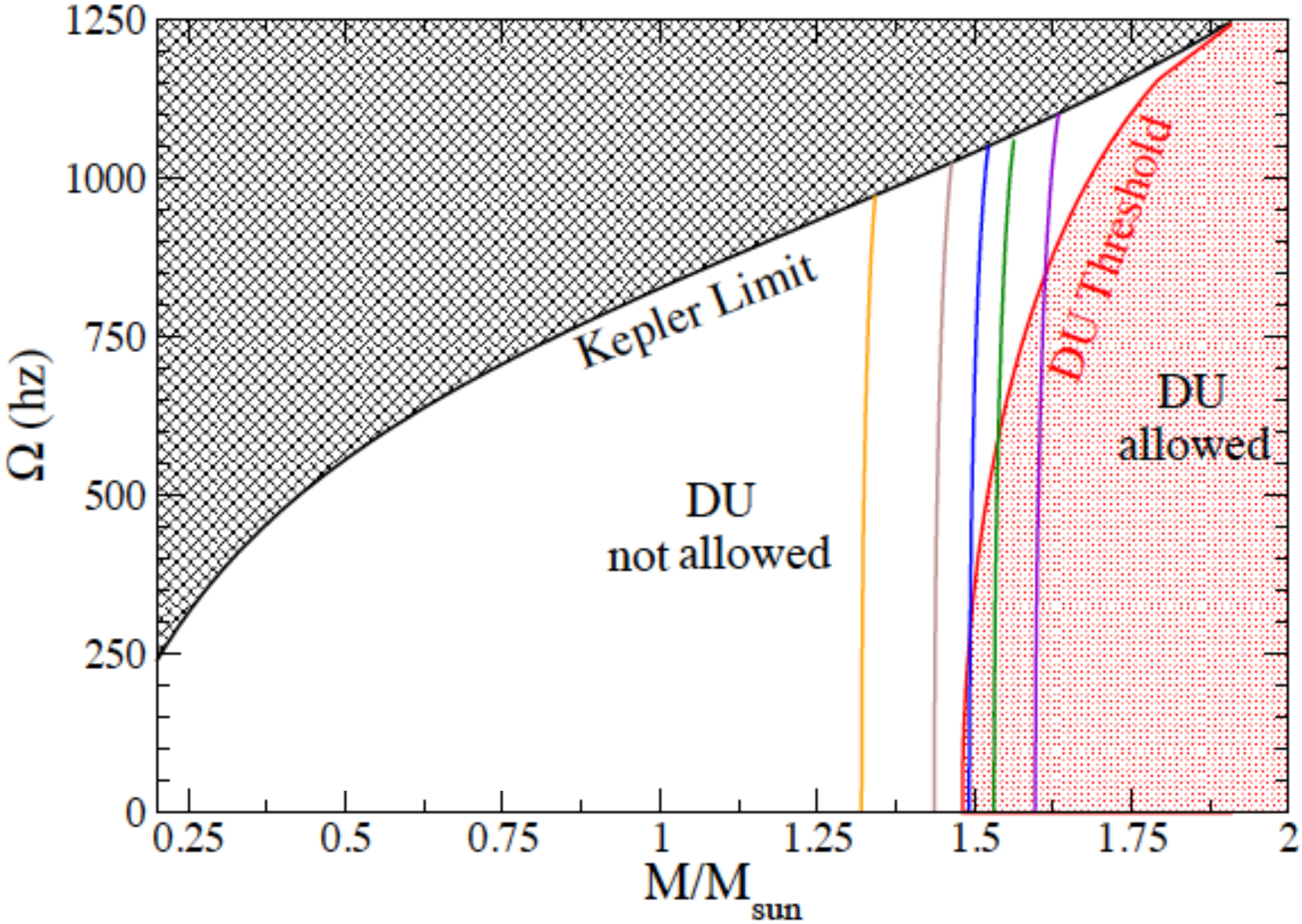
Neutrino-Emitting Particle Reactions inside of Neutron Stars . . .



Direct Urca Process

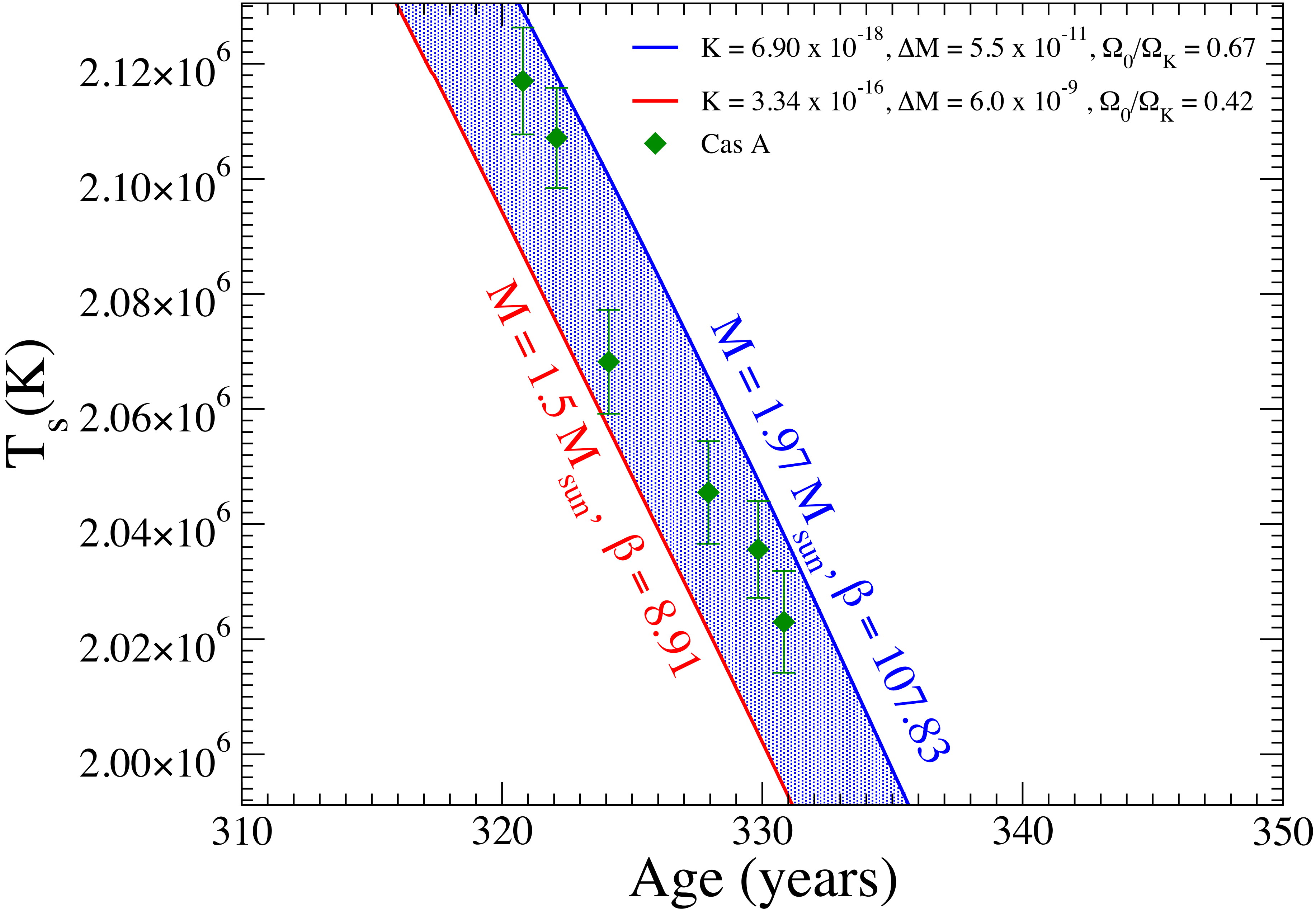
$$n \longrightarrow p + e^- + \bar{\nu}_e$$





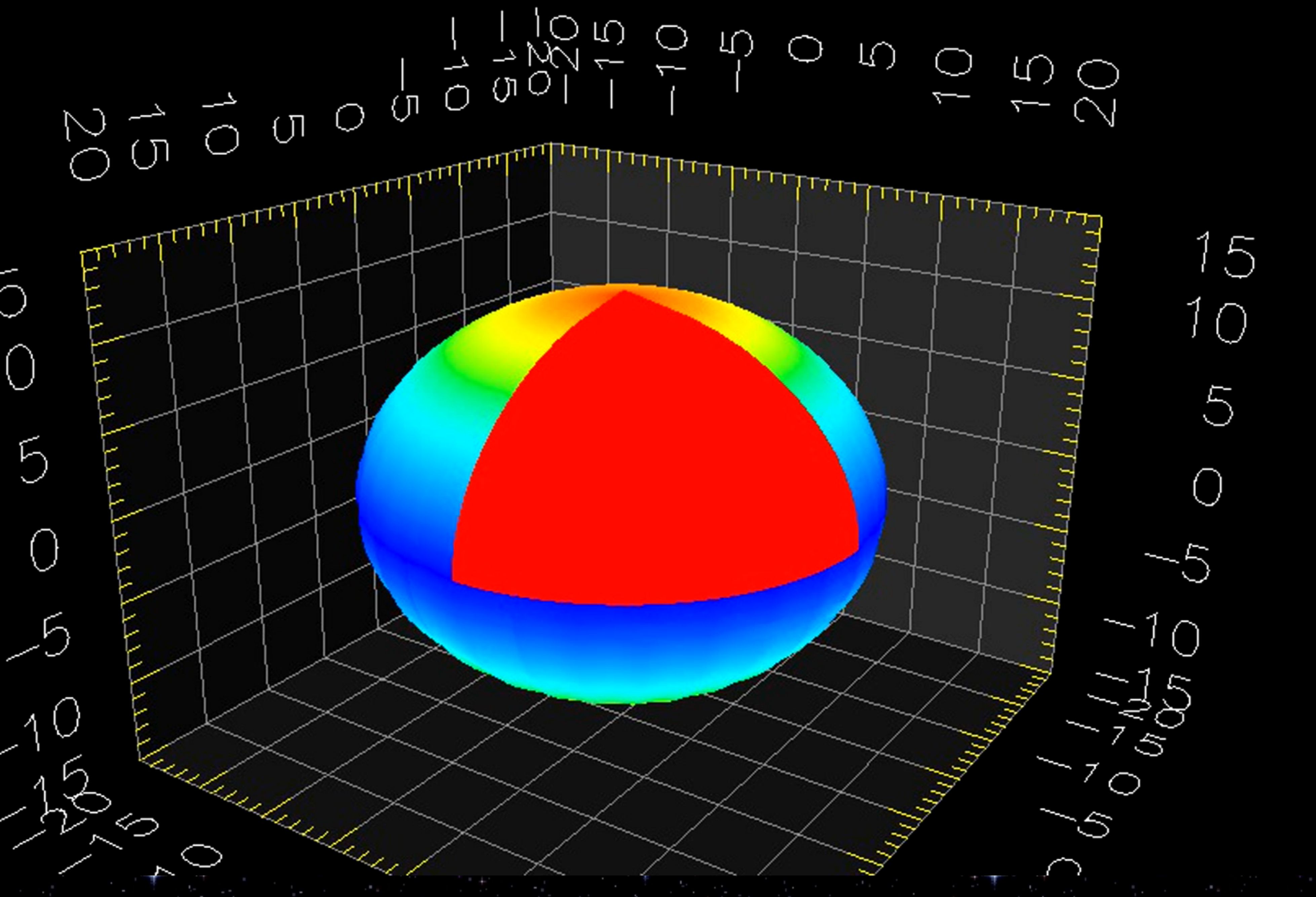
1250
1000
750
500
250
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
Ω (hz)
M/M sun
Kepler Limit
DU Threshold
DU
allowed
DU
not allowed

R. Negreiros, S. Schramm, FW (2011)



(submitted for publication)

Movie showing the 2-D cooling of a rotating neutron star produced by Rodrigo Negreiros, FIAS



Summary

Research on compact stars and relativistic astrophysical phenomena is on its way of providing solid information about the properties of highly compressed baryonic matter and its associated phase diagram.

- Exotica in heavy neutron stars (~2 M_{sun}) possible
- iMSPs & LMXBs ideal objects to look for phase transitions
- Information about properties of compressed baryonic matter from thermal evolution of NSs
- Need more observed data … (SkA $\longrightarrow$ ~20,000 new pulsars)