STANGENESS
IN
"NEUTRON" STARS

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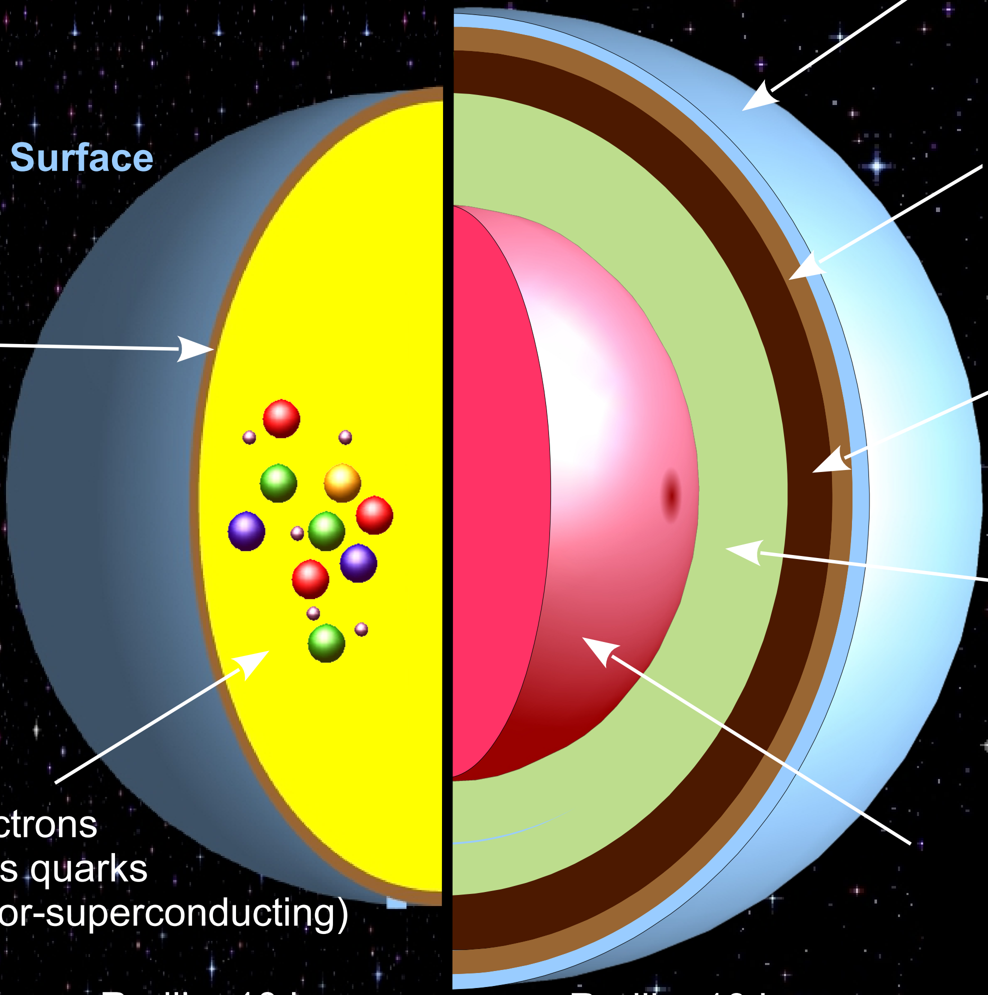
ExtreMe Matter Institute EMMI
Dense Baryonic Matter in the Cosmos and in the Laboratory
Tübingen University, Germany, October 11-12, 2012

Strange Quark Star

Neutron Star



Surface

Outer Crust

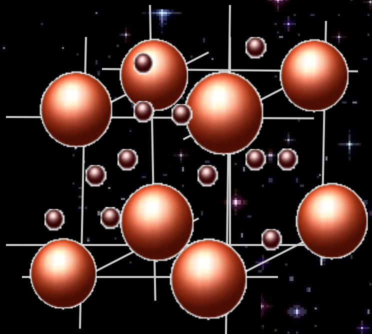
Core
- Electrons
- u,d,s quarks (color-superconducting)

Radii < 10 km

Radii > 10 km

Masses ~1 to 2 M_{sun}

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

Inner Core
- Neutrons
- Superconducting protons
- Electrons, muons
- Hyperons (Σ, Λ, Ξ)
- Deltas (Δ)
- Boson (π, K) condensates
- Deconfined (u,d,s) quarks / color-superconducting quark matter

F. Weber (SDSU, 2012)

OUTLINE

Neutron stars

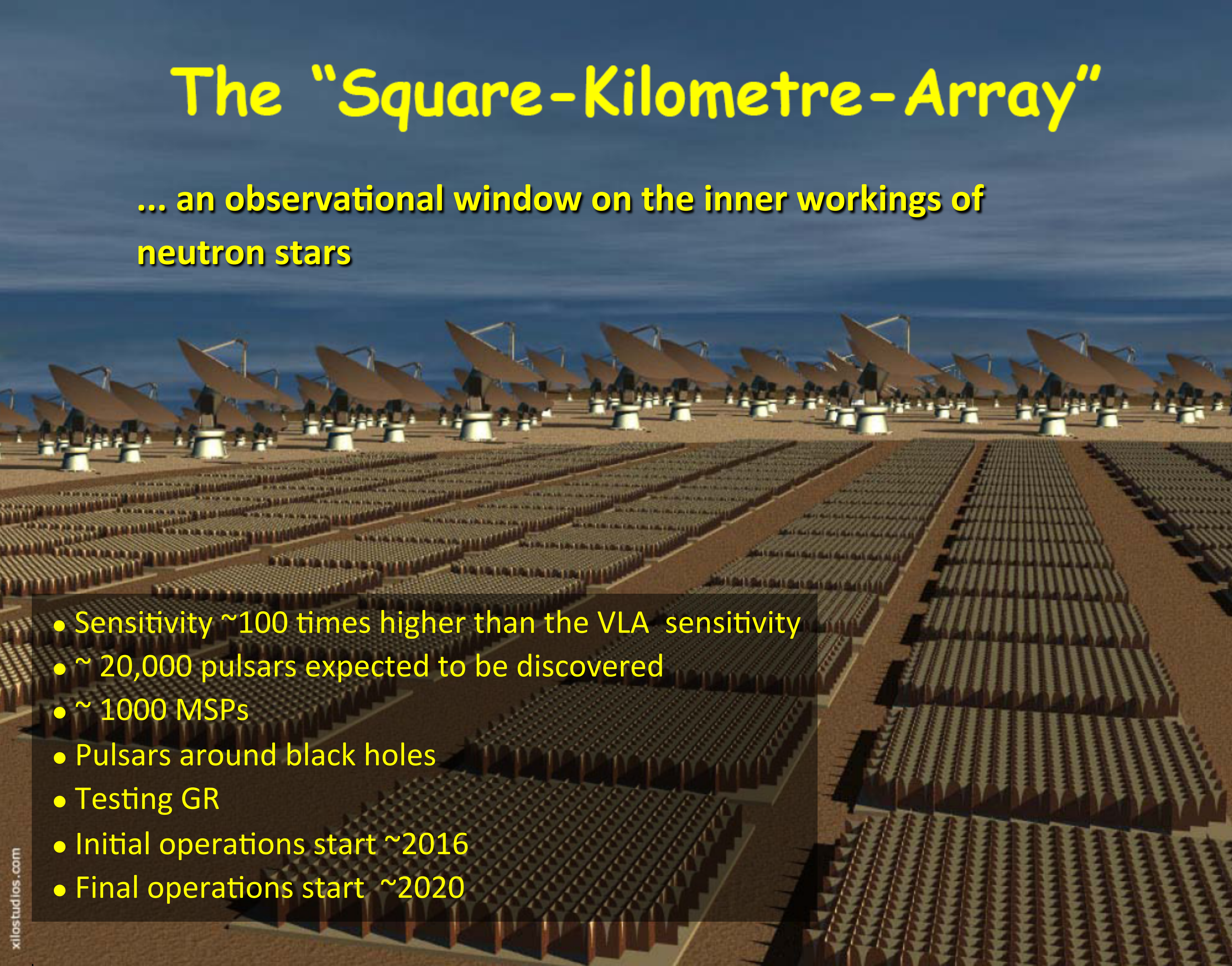
- **Hyperons**
  - ❑ Rotation-driven changes in particle composition
  - ❑ 2D cooling
- **Strange quarks – mixed phase of quarks and hadrons**
  - ❑ Quark matter in massive neutron stars
  - ❑ Geometric structures (Coulomb lattice)
  - ❑ Impact on thermal & transport properties

Strange quark stars

- **Ultra-high electric surface fields**
  - ❑ M-R relation
  - ❑ Strange dwarfs
  - ❑ Luminosity of electron-positron pairs
  - ❑ Differentially rotating electron seas
  - ❑ Electron seas may be oscillating
- **Meissner effect (vortex expulsion)**
- **Mass-shedding periods < 1 millisecond**

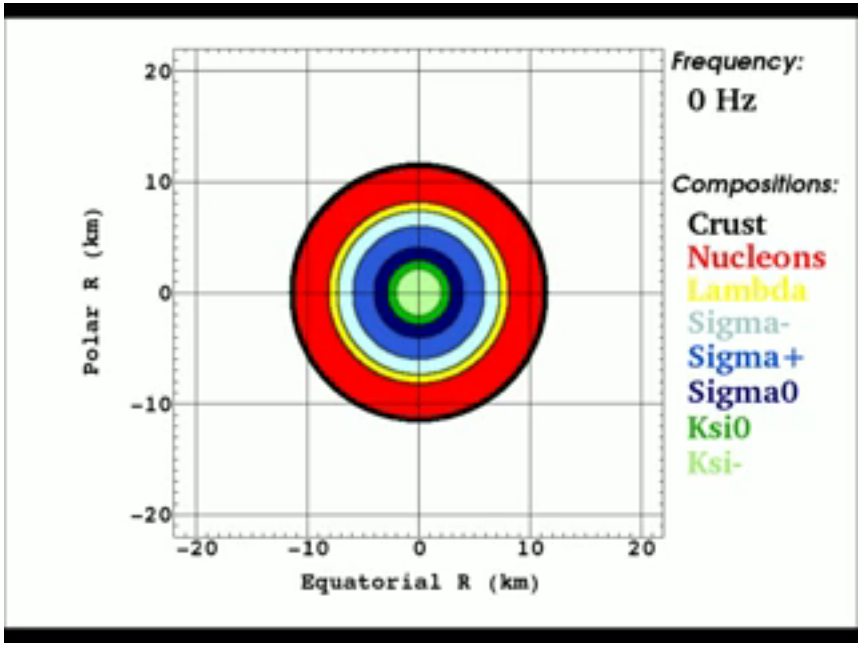
The “Square-Kilometre-Array”

... an observational window on the inner workings of neutron stars


xilostudios.com

- Sensitivity ~100 times higher than the VLA sensitivity
- ~ 20,000 pulsars expected to be discovered
- ~ 1000 MSPs
- Pulsars around black holes
- Testing GR
- Initial operations start ~2016
- Final operations start ~2020

Rotation-driven compositional changes inside of neutron stars

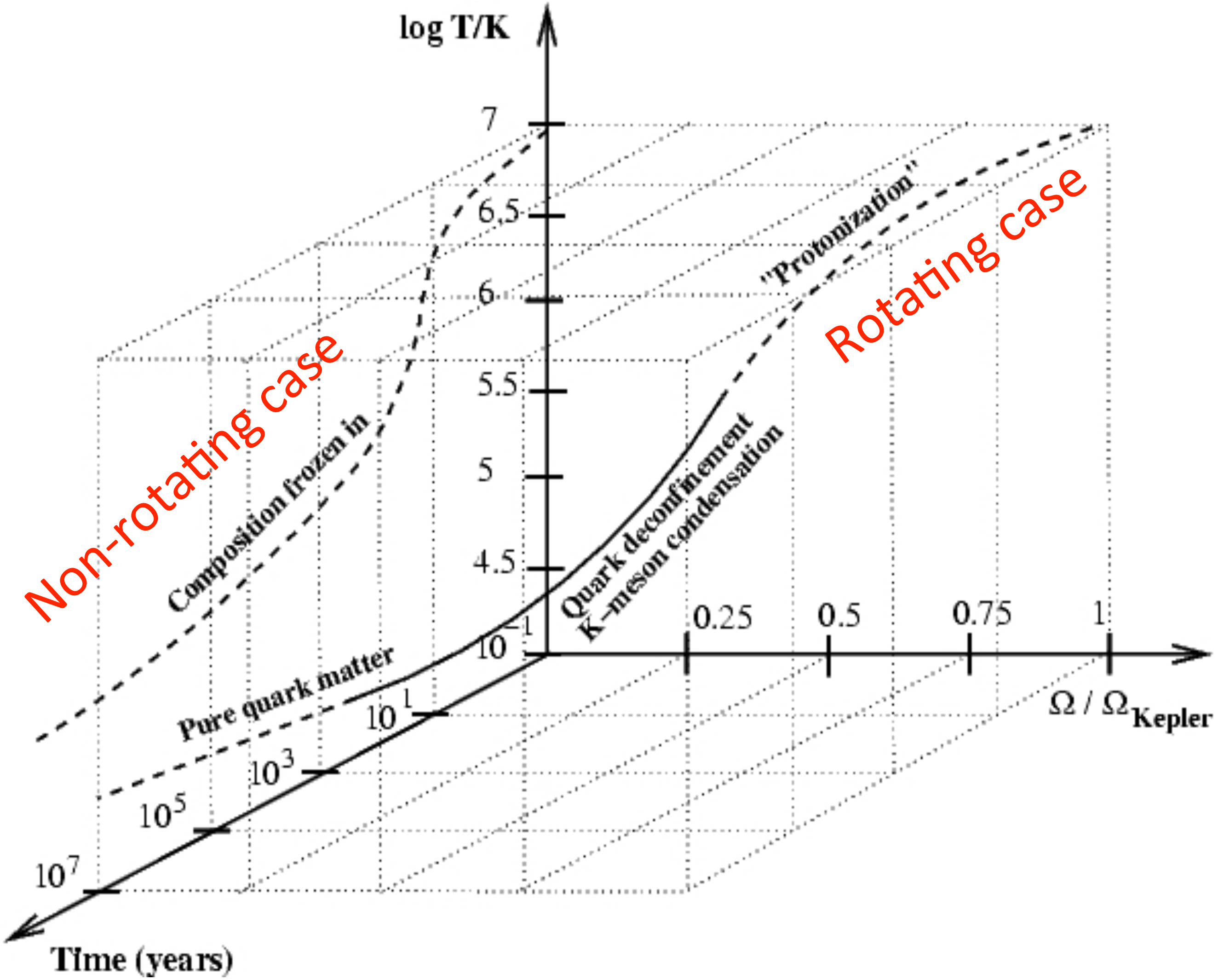


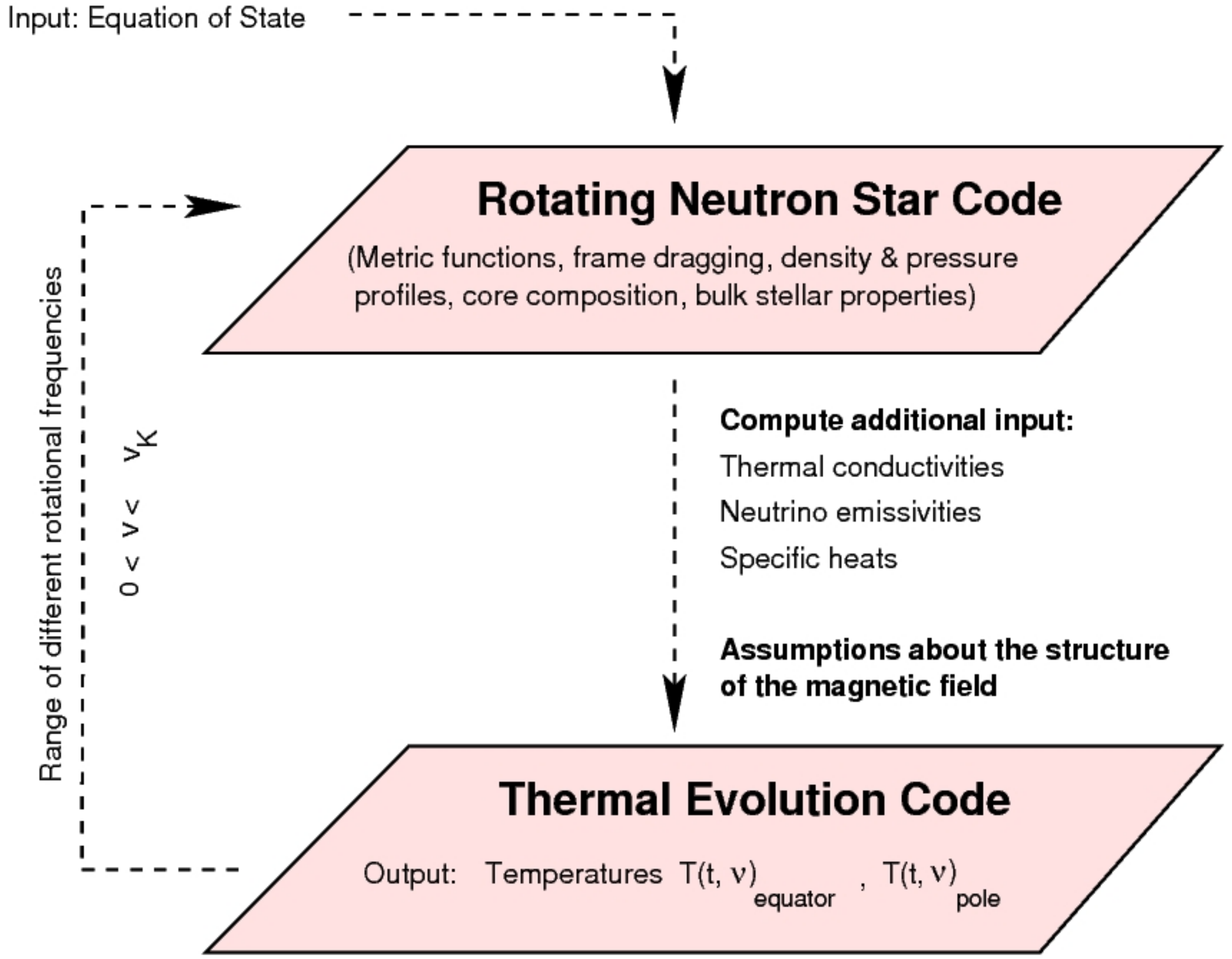
Jirina Stone (ORNL) & FW, 2012

Data: DDRMF (Hofmann, Keil, Lenske)

Thermal Evolution of Neutron Stars …

qualitative considerations





Input: Equation of State

Rotating Neutron Star Code

(Metric functions, frame dragging, density & pressure profiles, core composition, bulk stellar properties)

Compute additional input:

Thermal conductivities

Neutrino emissivities

Specific heats

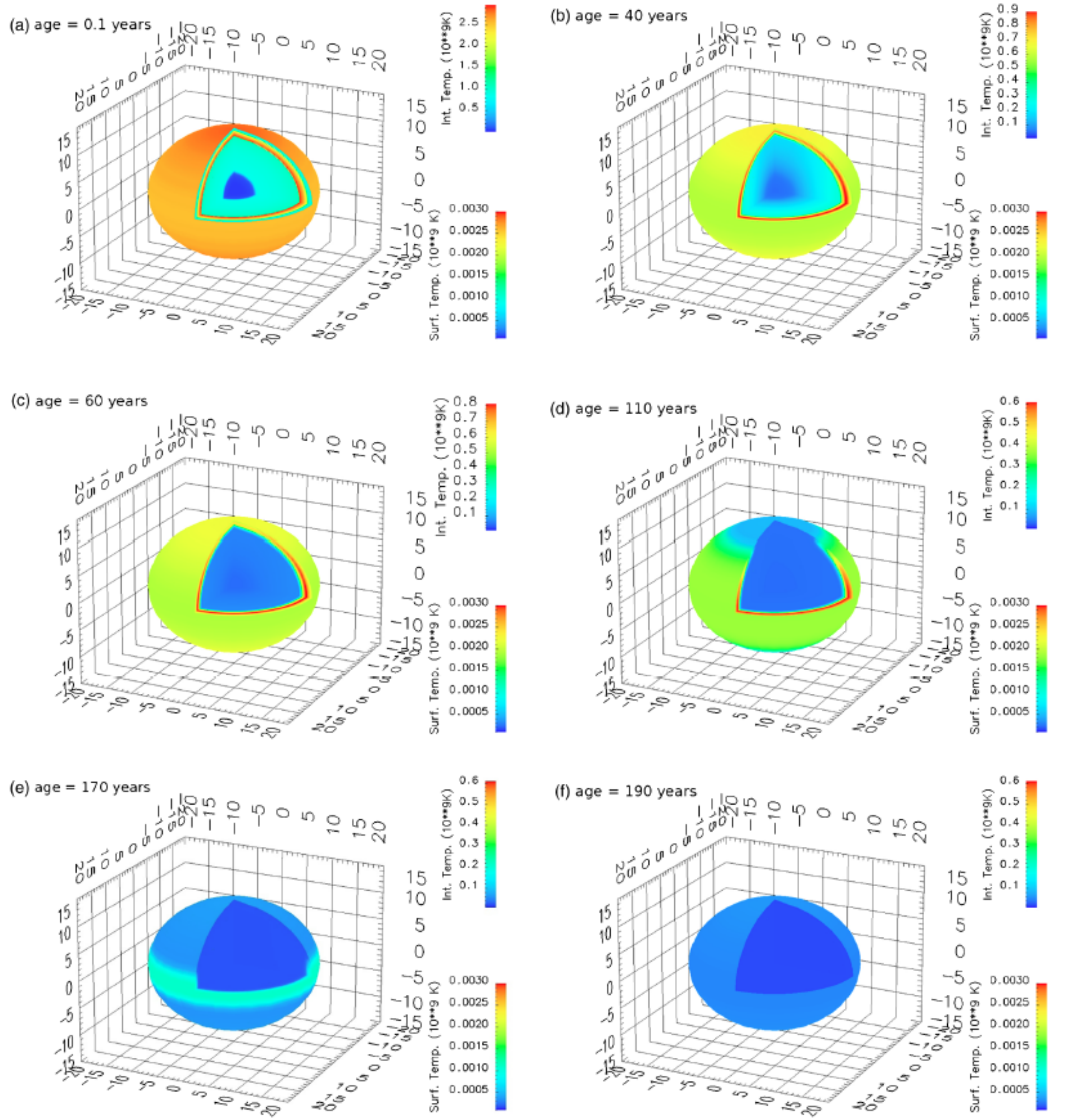
Assumptions about the structure of the magnetic field

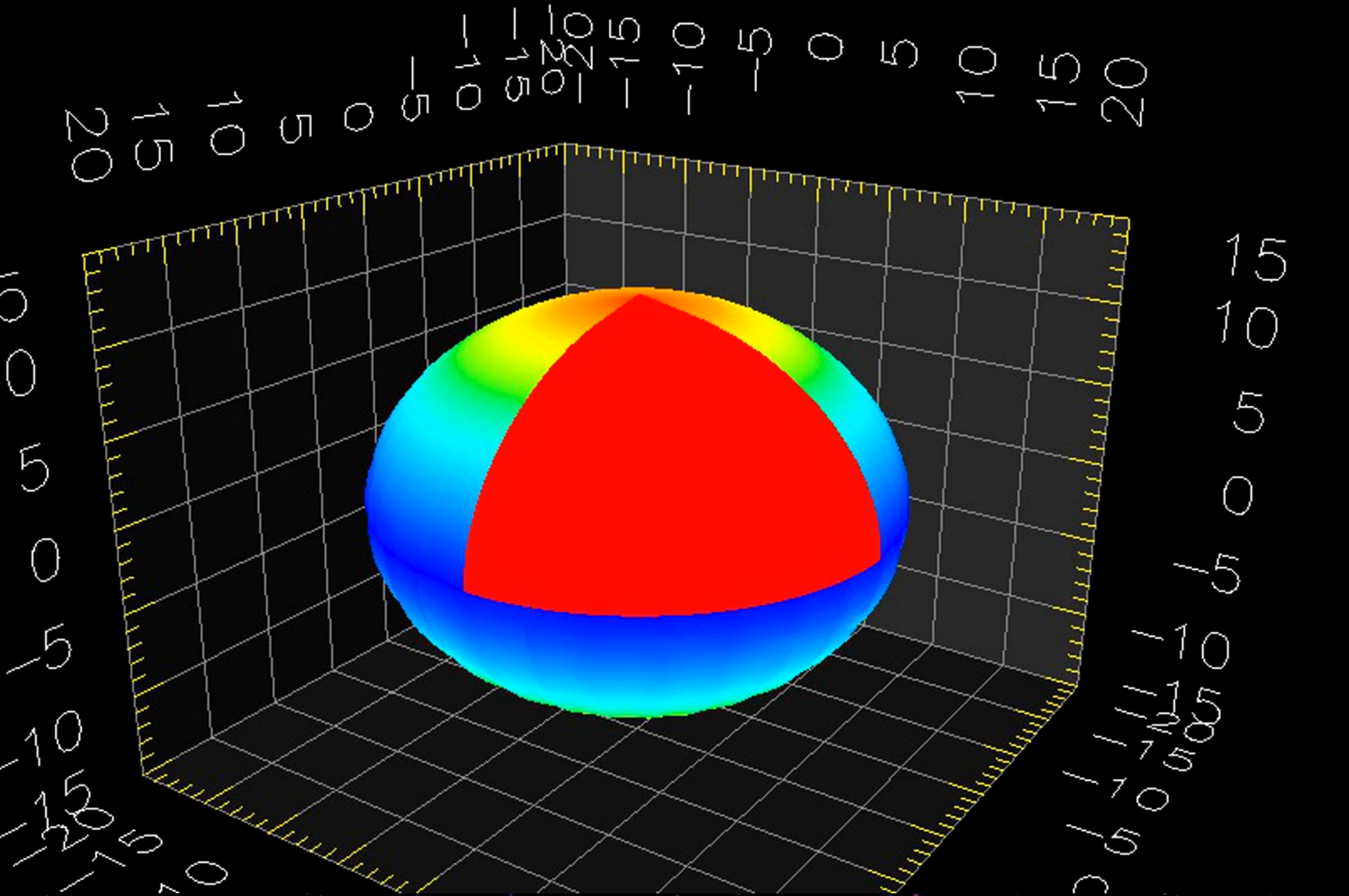
Range of different rotational frequencies

$0 < \nu < \nu_K$

Thermal Evolution Code

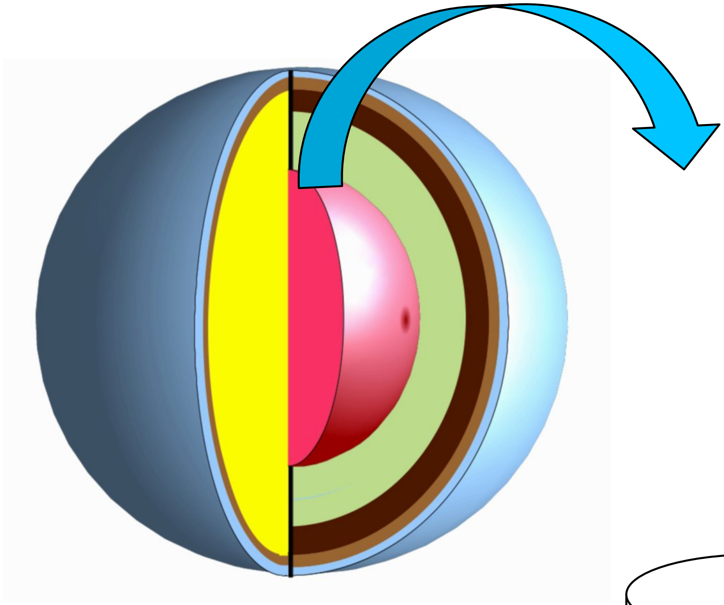
Output: Temperatures $T(t, \nu)_{\text{equator}}$, $T(t, \nu)_{\text{pole}}$


(a) age = 0.1 years
Int. Temp. (10**9K)
0.5
1.0
1.5
2.0
2.5
Surf. Temp. (10**9 K)
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
(b) age = 40 years
Int. Temp. (10**9K)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Surf. Temp. (10**9 K)
(c) age = 60 years
Int. Temp. (10**9K)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Surf. Temp. (10**9 K)
(d) age = 110 years
Int. Temp. (10**9K)
0.1
0.2
0.3
0.4
0.5
0.6
Surf. Temp. (10**9 K)
(e) age = 170 years
Int. Temp. (10**9K)
Surf. Temp. (10**9 K)
(f) age = 190 years
Int. Temp. (10**9K)
Surf. Temp. (10**9 K)
−20
−15
−10
−5
0
5
10
15
20

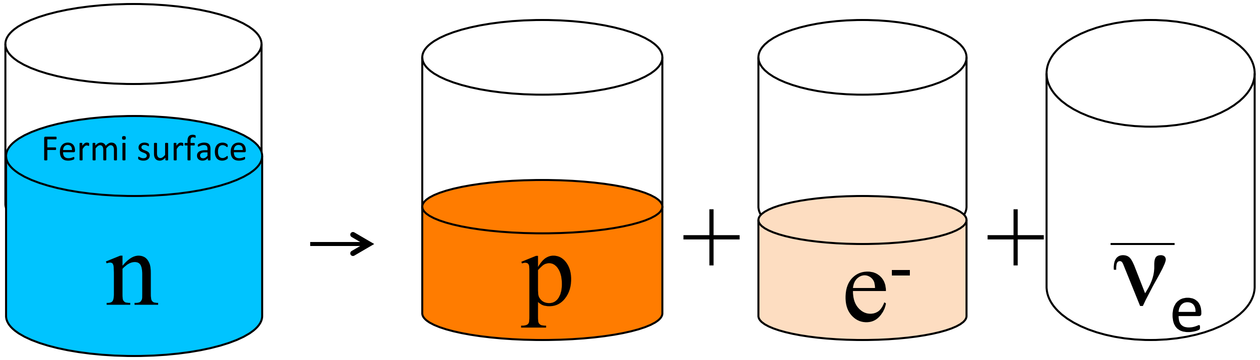


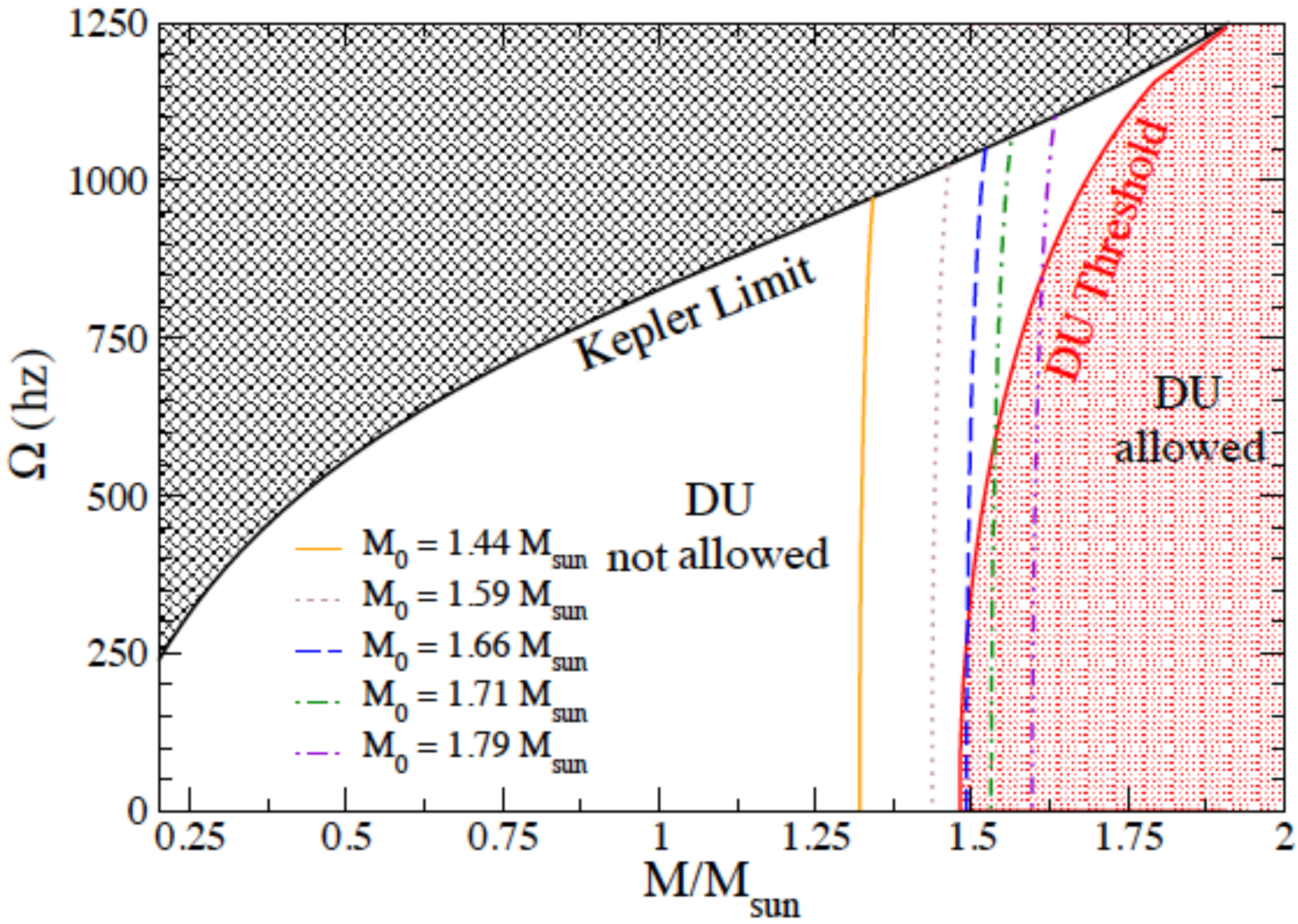
20
15
10
5
0
−5
−10
−15
−20
−20
−15
−10
−5
0
5
10
15
20
15
10
5
0
−5
−10
−15

Rotation-Driven Direct Urca Process in Stellar Core

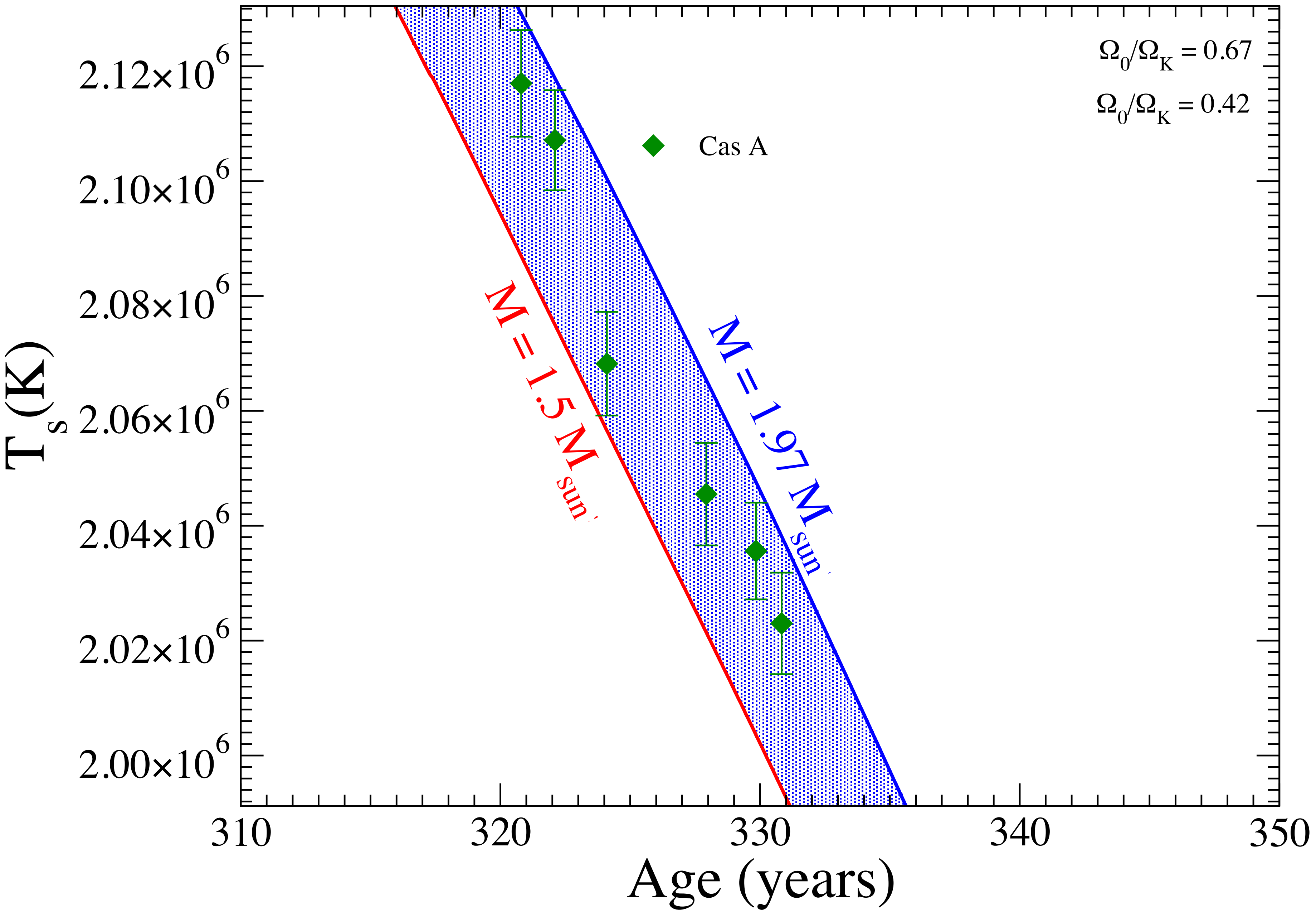


$$n \longrightarrow p + e^- + \bar{\nu}_e$$

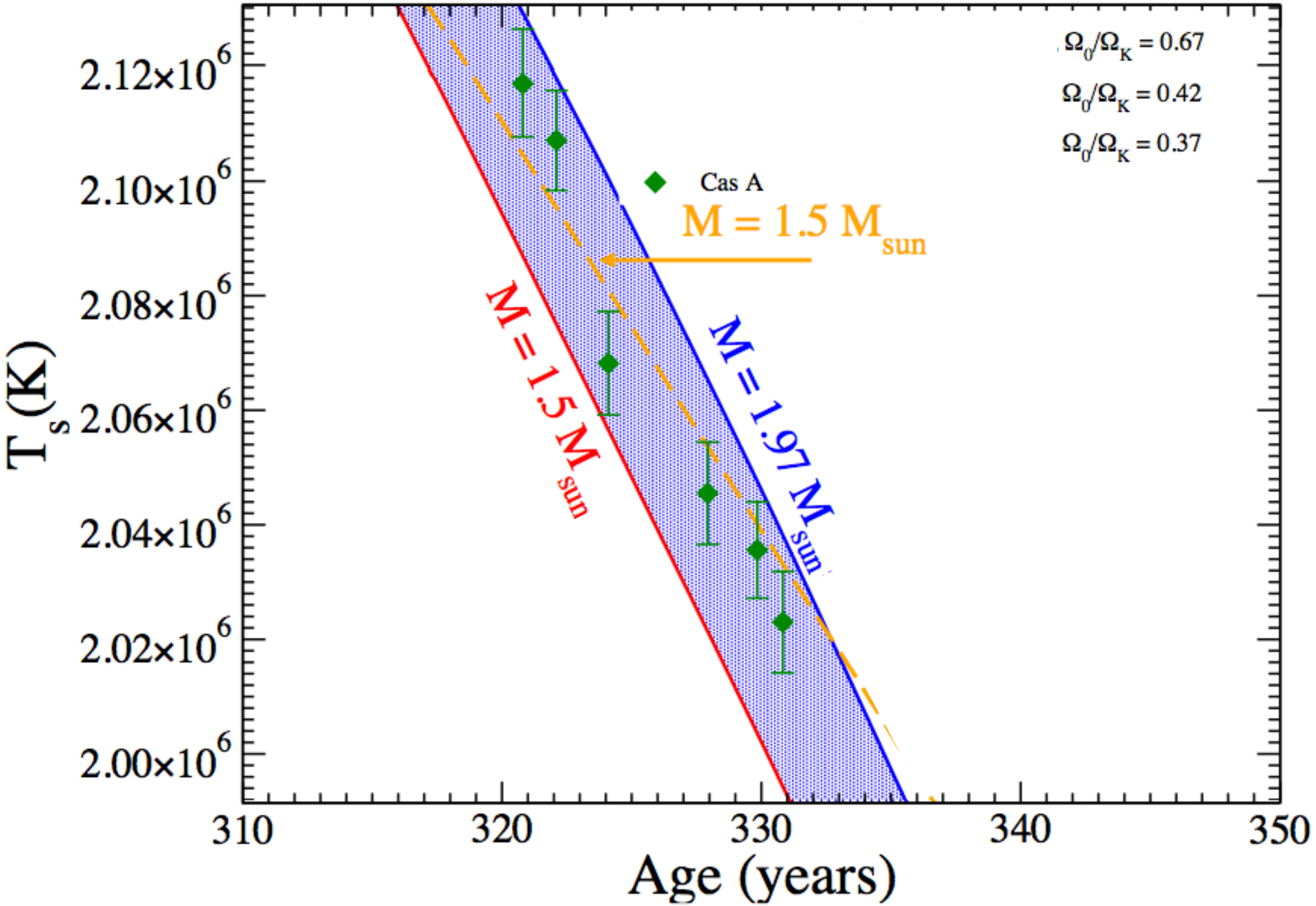




R. Negreiros, S. Schramm, FW (2012)

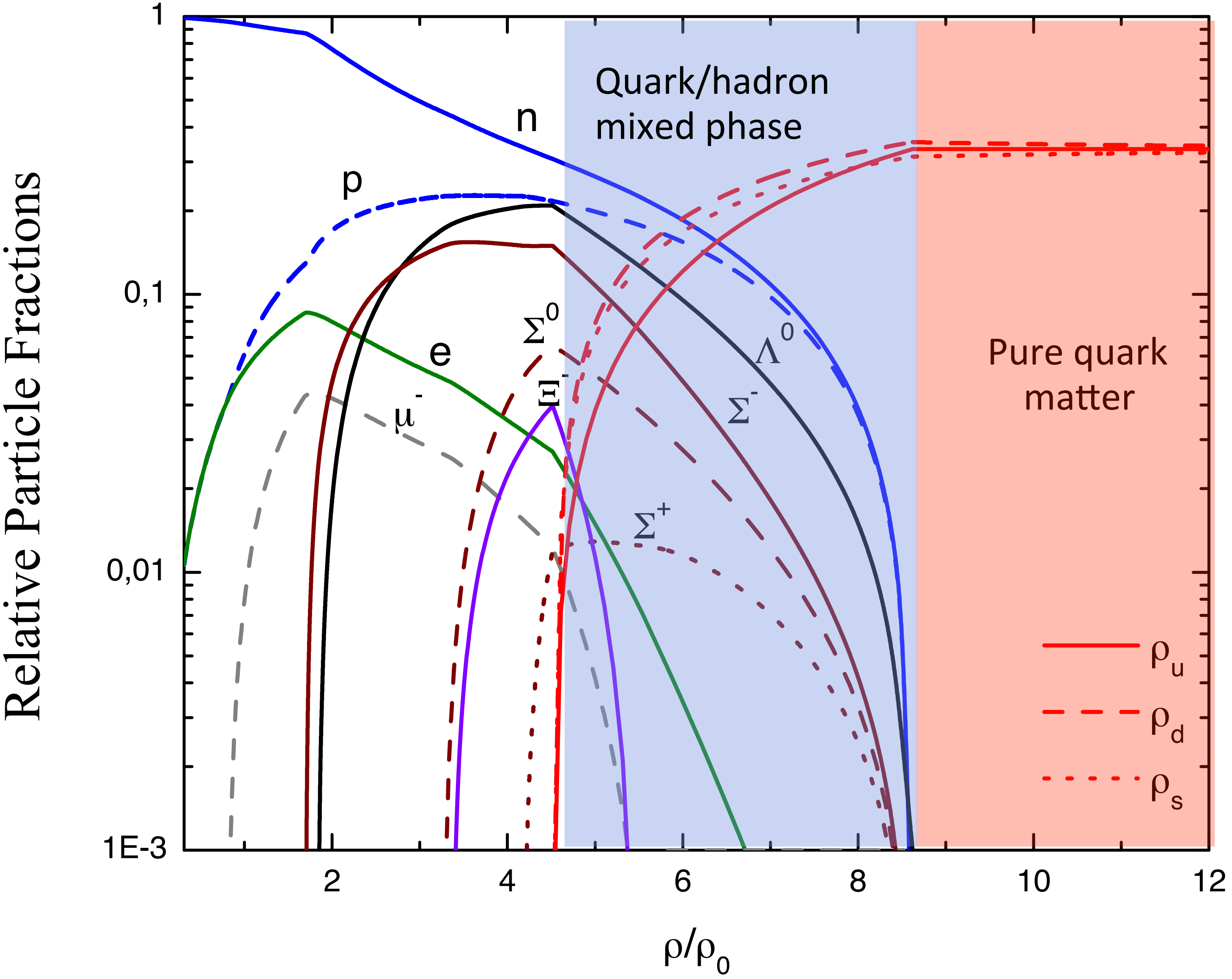


R. Negreiros, S. Schramm, FW (2012)

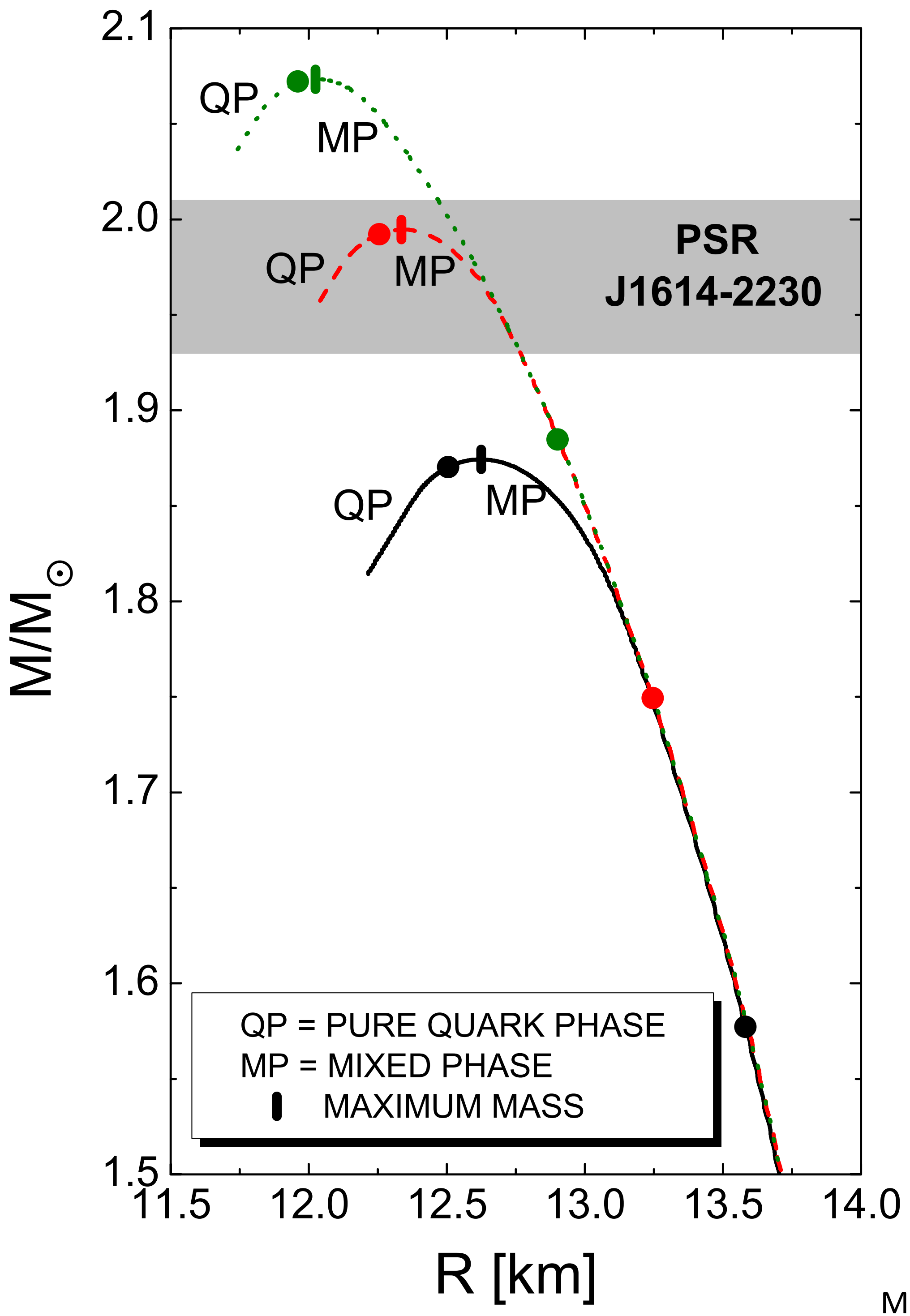

$\Omega_0/\Omega_K = 0.67$
$\Omega_0/\Omega_K = 0.42$
$\Omega_0/\Omega_K = 0.37$
Cas A
$M = 1.5\ M_{sun}$
$M = 1.5\ M_{sun}$
$M = 1.97\ M_{sun}$
T_s (K)
2.12×10^6
2.10×10^6
2.08×10^6
2.06×10^6
2.04×10^6
2.02×10^6
2.00×10^6
310
320
330
340
350
Age (years)

Quark Matter in Massive Neutron Stars?

Non-local SU(3) NJL with vector coupling



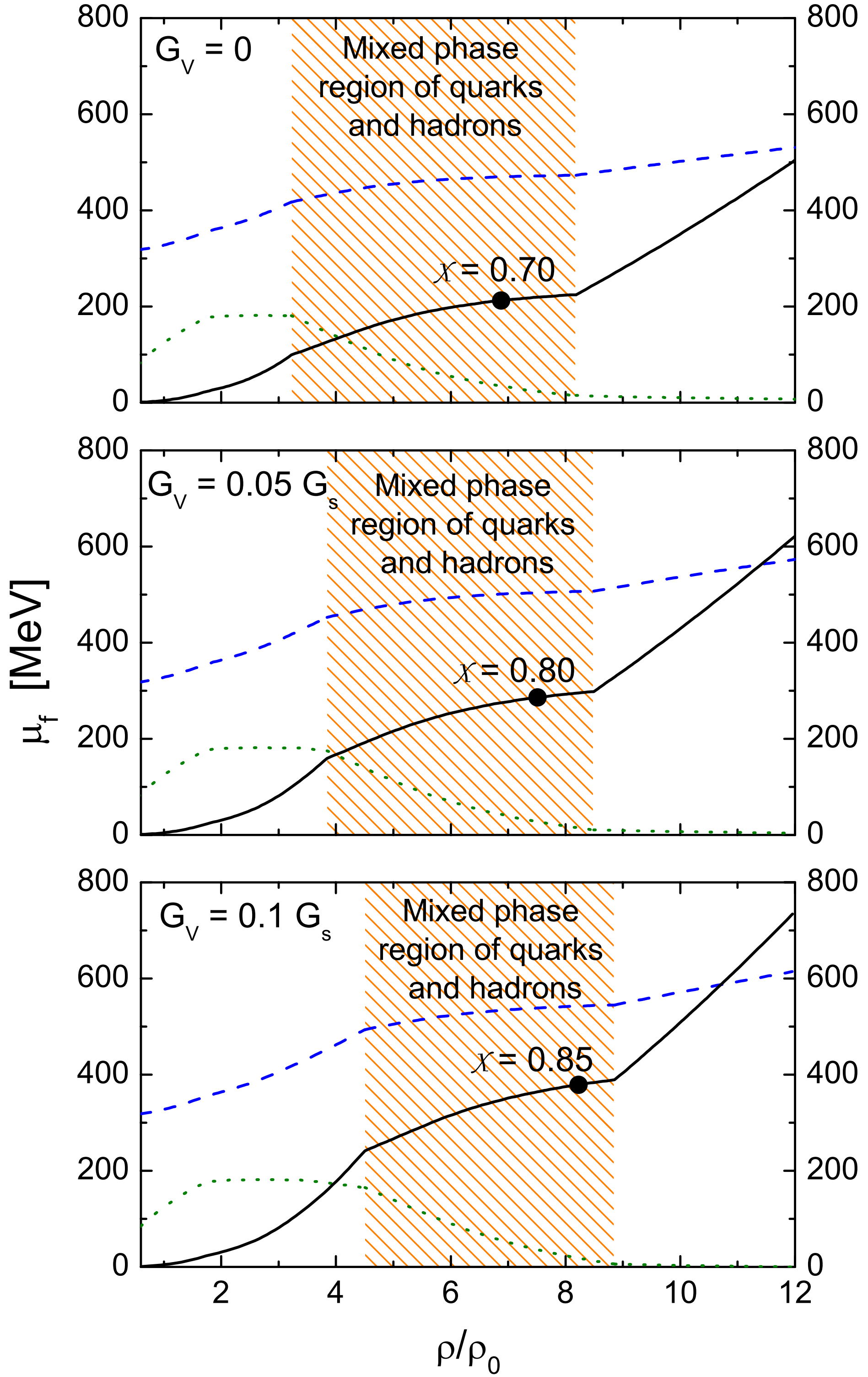
M. Orsaria, H. Rodrigues, FW (August, 2012)



Mass-Radius Relationship

EOS: non-local SU(3) NJL model with vector coupling

M. Orsaria, H. Rodrigues, FW, G. A. Contrera (October, 2012)



Equation of state (EOS): Non-local SU(3) NJL model with vector coupling

M. Orsaria, H. Rodrigues, FW, G. A. Contrera (October, 2012)

Geometrical Structures in Quark-Hadron Phase

…. N. K. Glendenning, PRD 46 (1992) 1274

- Impose global (rather than local) electric charge neutrality
- Relaxes the extreme isospin asymmetry of neutron star matter
  - ❑ Positively charged regions of nuclear matter
  - ❑ Negatively charged regions of quark matter
- Competition between Coulomb and surface energies in the mixed phase
- Mixed quark-hadron phase may develop geometrical

VOLUME 50, NUMBER 26 PHYSICAL REVIEW LETTERS 27 JUNE 1983

Structure of Matter below Nuclear Saturation Density

D. G. Ravenhall
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

and

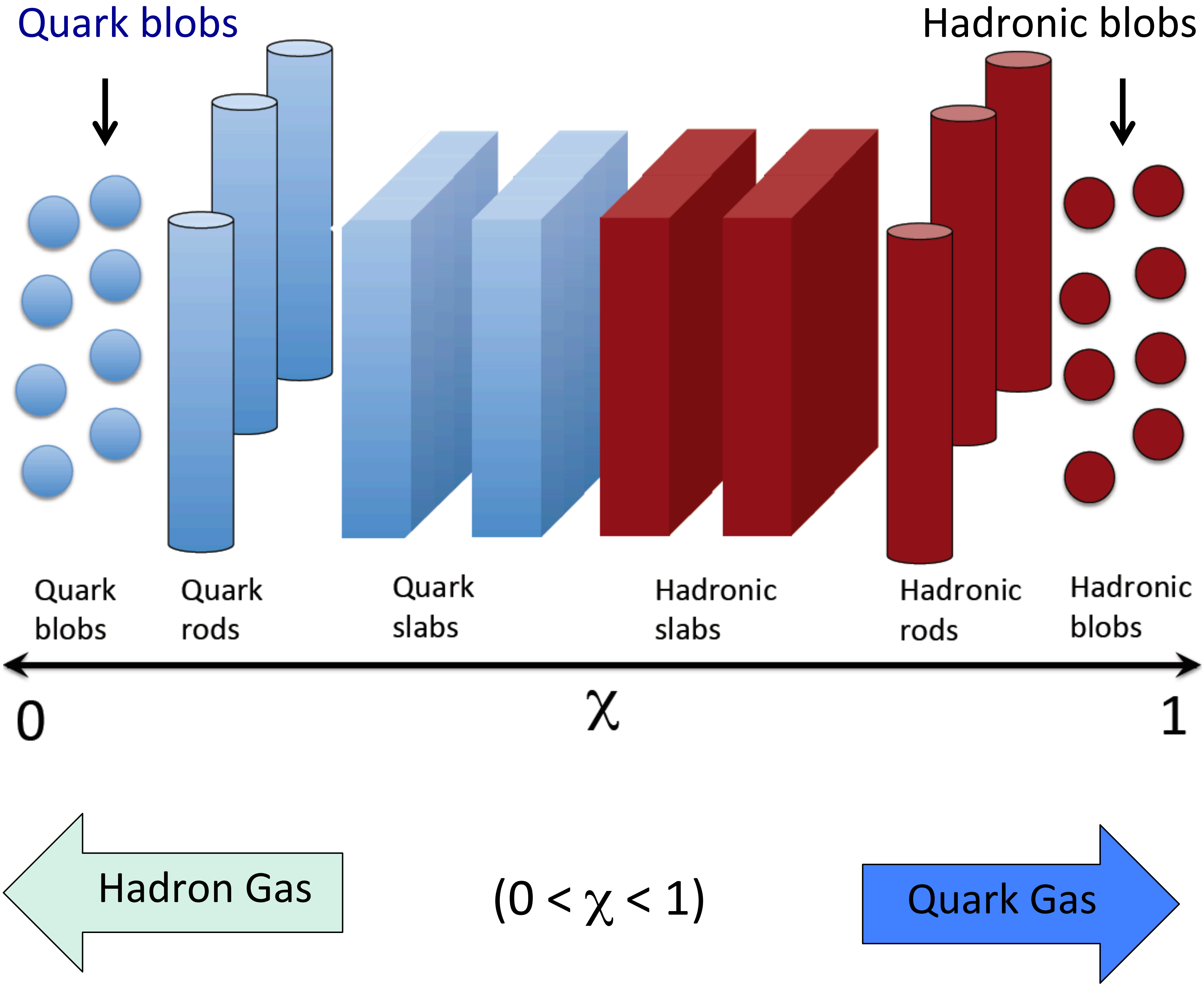
C. J. Pethick
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801,
and NORDITA, DK-2100 Copenhagen Ø, Denmark

and

J. R. Wilson
Lawrence Livermore National Laboratory, Livermore, California 94550

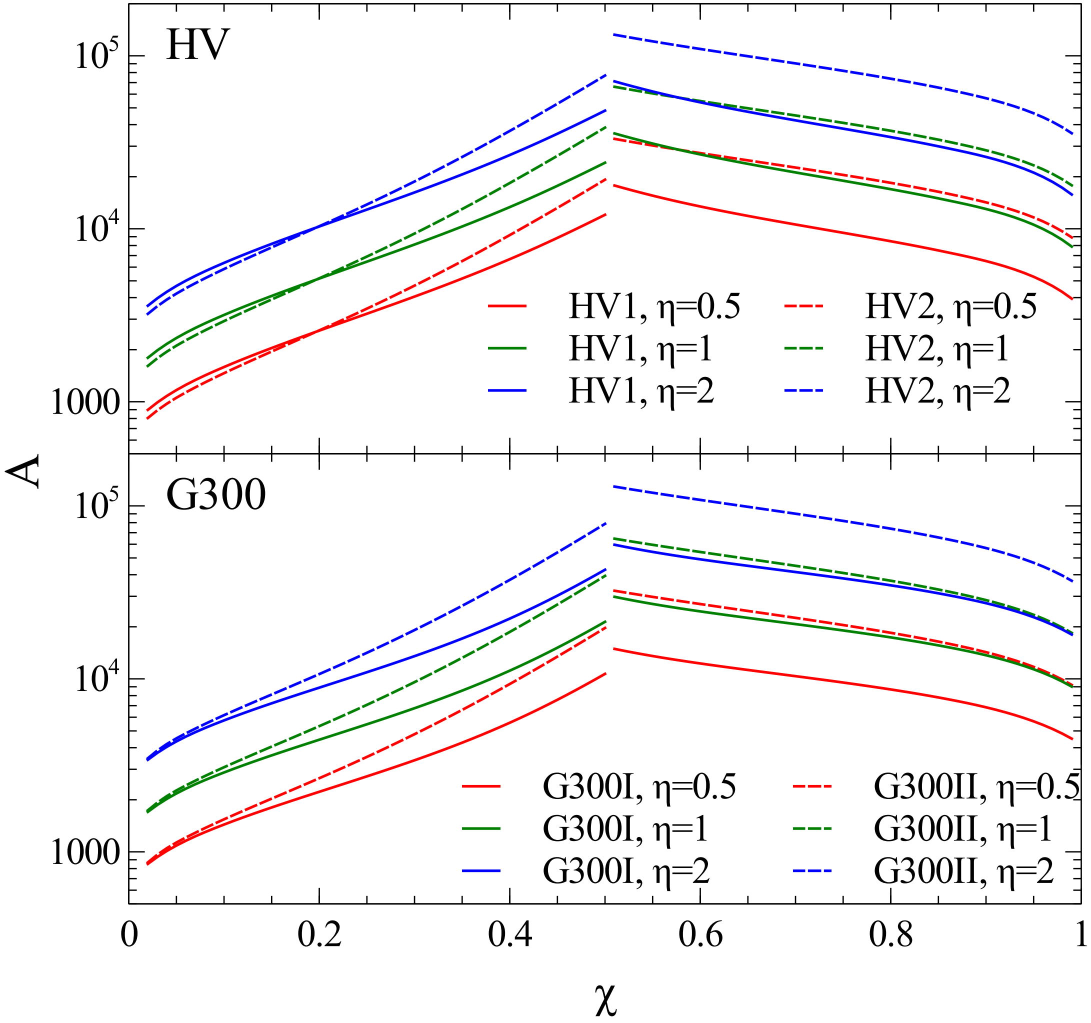
(Received 5 May 1983)

It is found that just below nuclear saturation density more stable forms of dense matter exist than the near-spherical nuclei or bubbles customarily assumed. Because of the large effect of the Coulomb lattice energy, cylindrical and planar geometries can occur, both as nuclei and as bubbles. It is suggested that in order to approximate more complicated kinds of short-range order, the dimensionality should be regarded as a continuous variable ranging from $d = 3$ (spheres) to $d = 1$ (planes). The dependence of d on density is illustrated, and its dependence on nuclear models discussed.



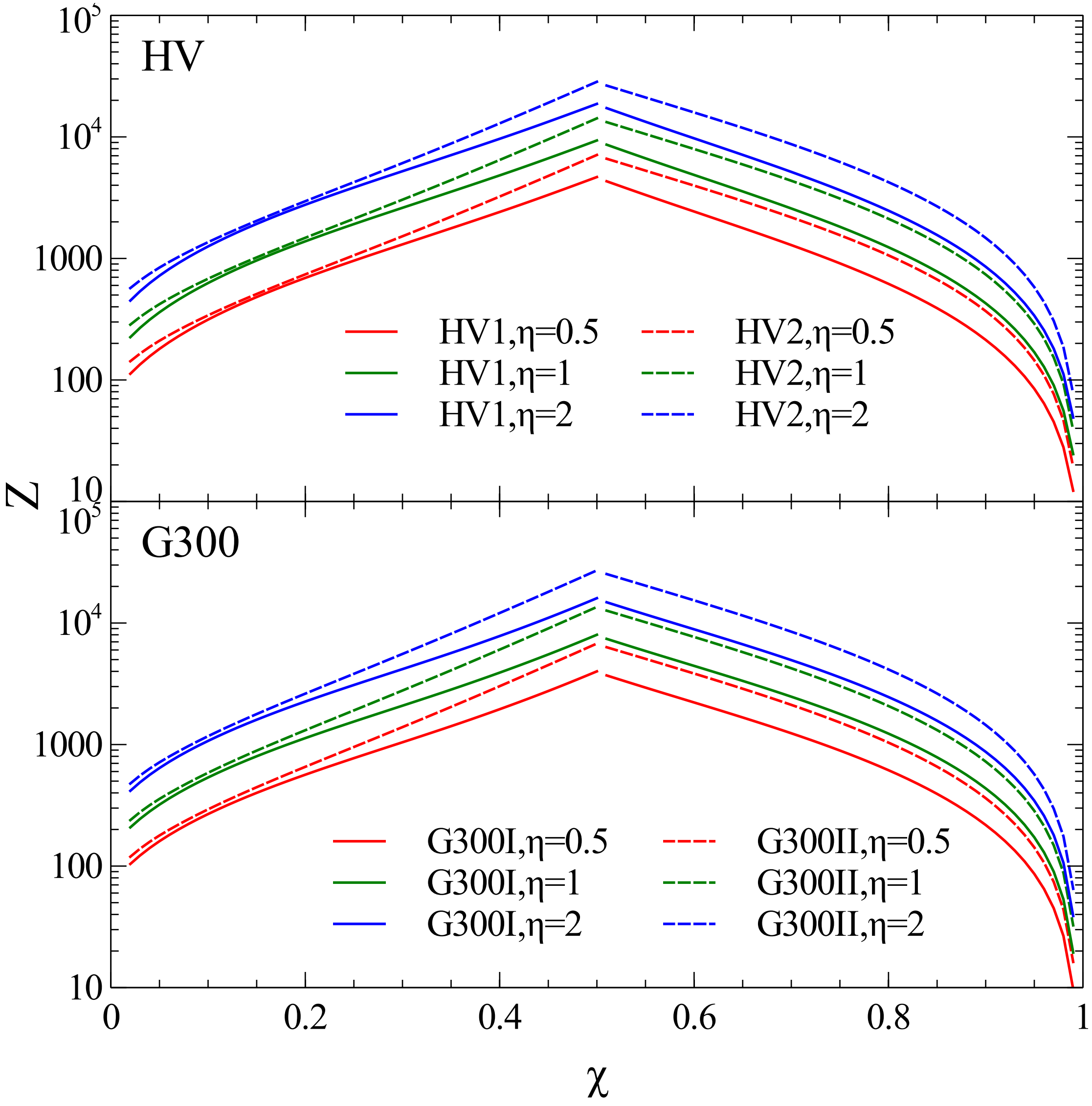
Impact on heat capacity, thermal conductivity, neutrino emissivity?

Mass number, A, of spherical blobs as a function of quark volume fraction, χ



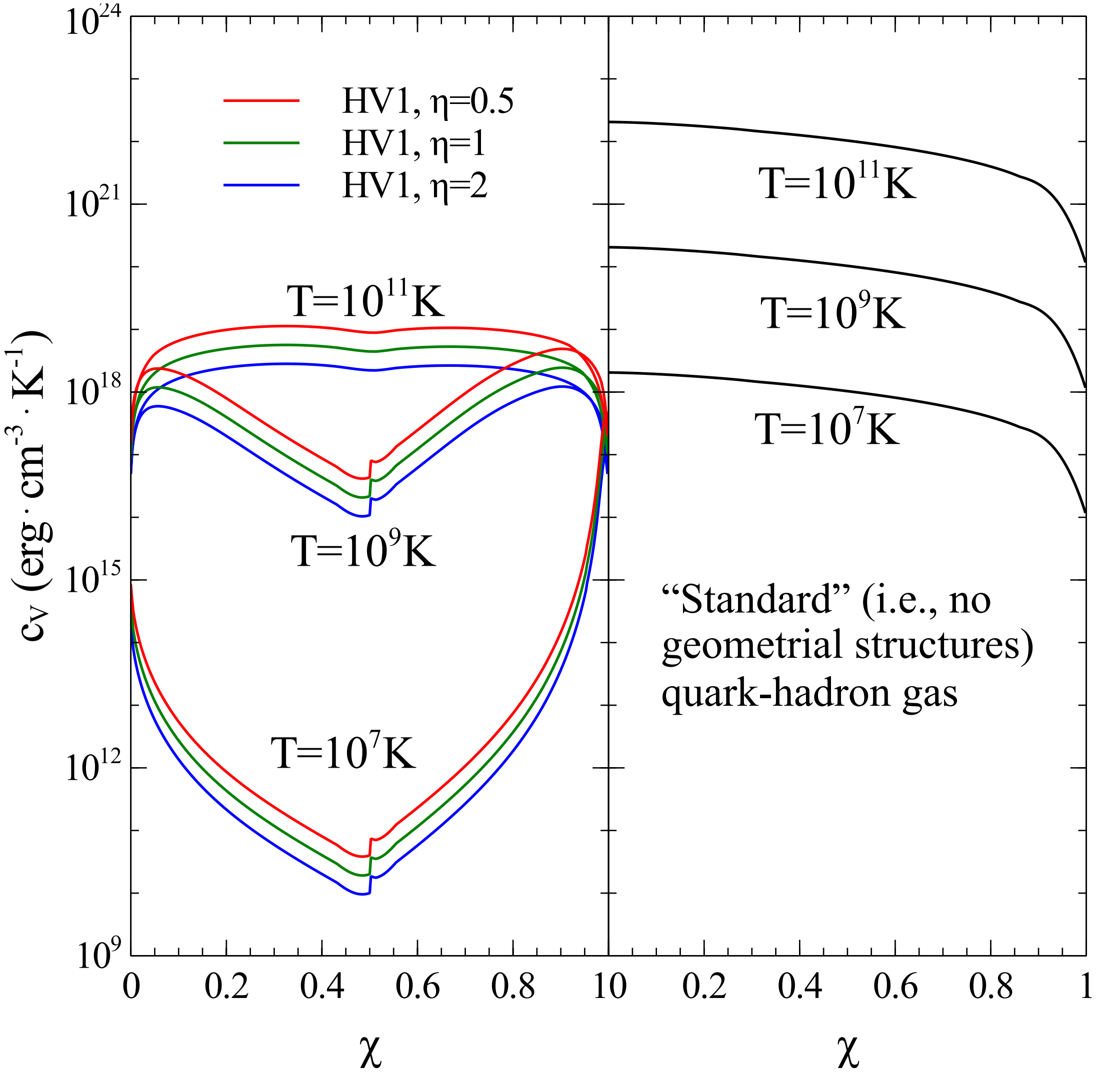
Xuesen Na, R. X. Xu & FW, arXiv:1208.5022v1 astro-ph.SR

Electric charge, Z, of spherical blobs as a function of quark volume fraction, χ



Xuesen Na, R. X. Xu & FW, arXiv:1208.5022v1 astro-ph.SR

Specific heat, c_v, of quark-hadron phase as a function of quark volume fraction, χ



Xuesen Na, R. X. Xu & FW, arXiv:1208.5022v1 astro-ph.SR

Modified URCA:

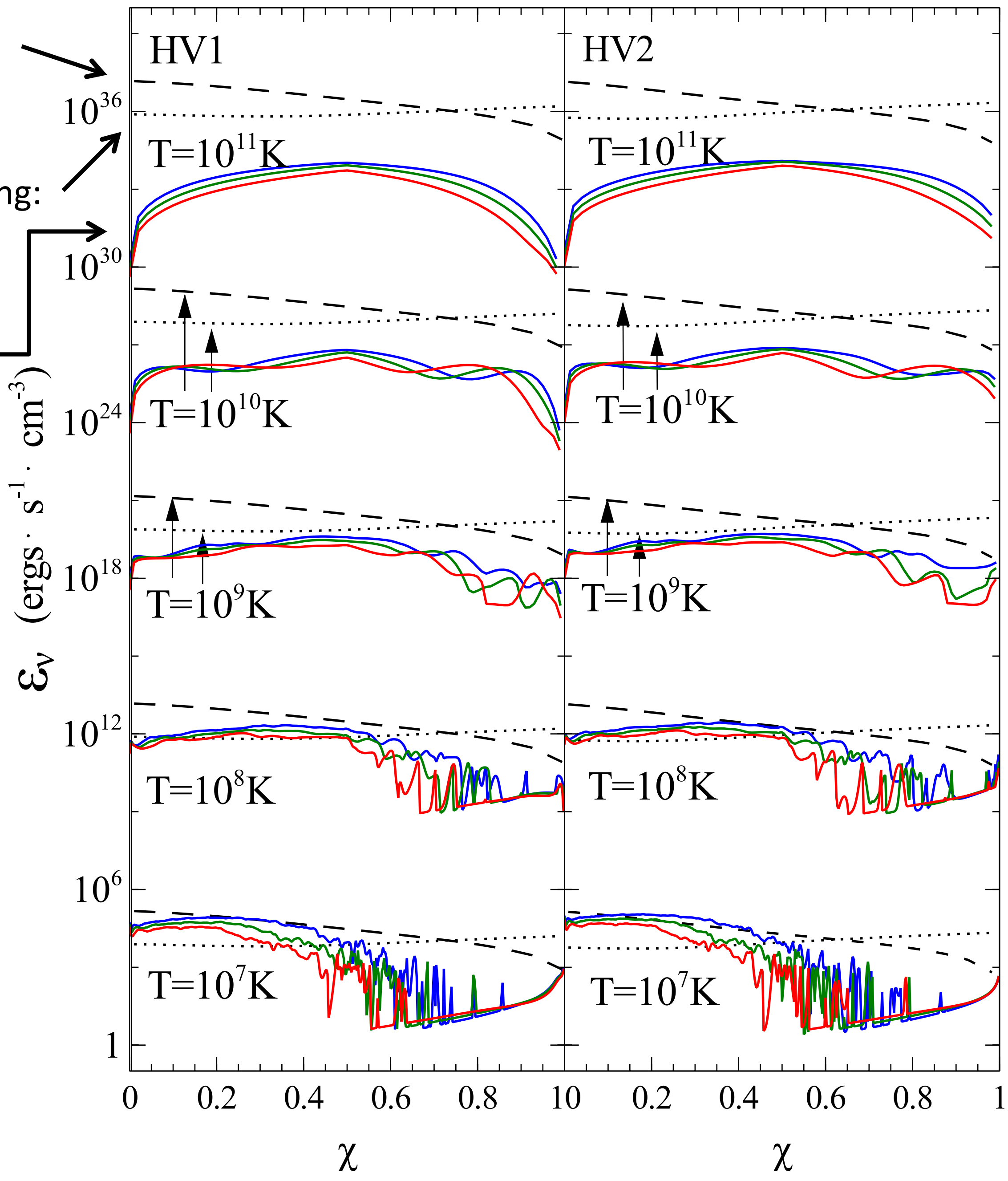
$n+n \rightarrow n+p+e+\nu$

Nucleon Bremsstrahlung:

$n+n \rightarrow n+n+\nu+\nu$

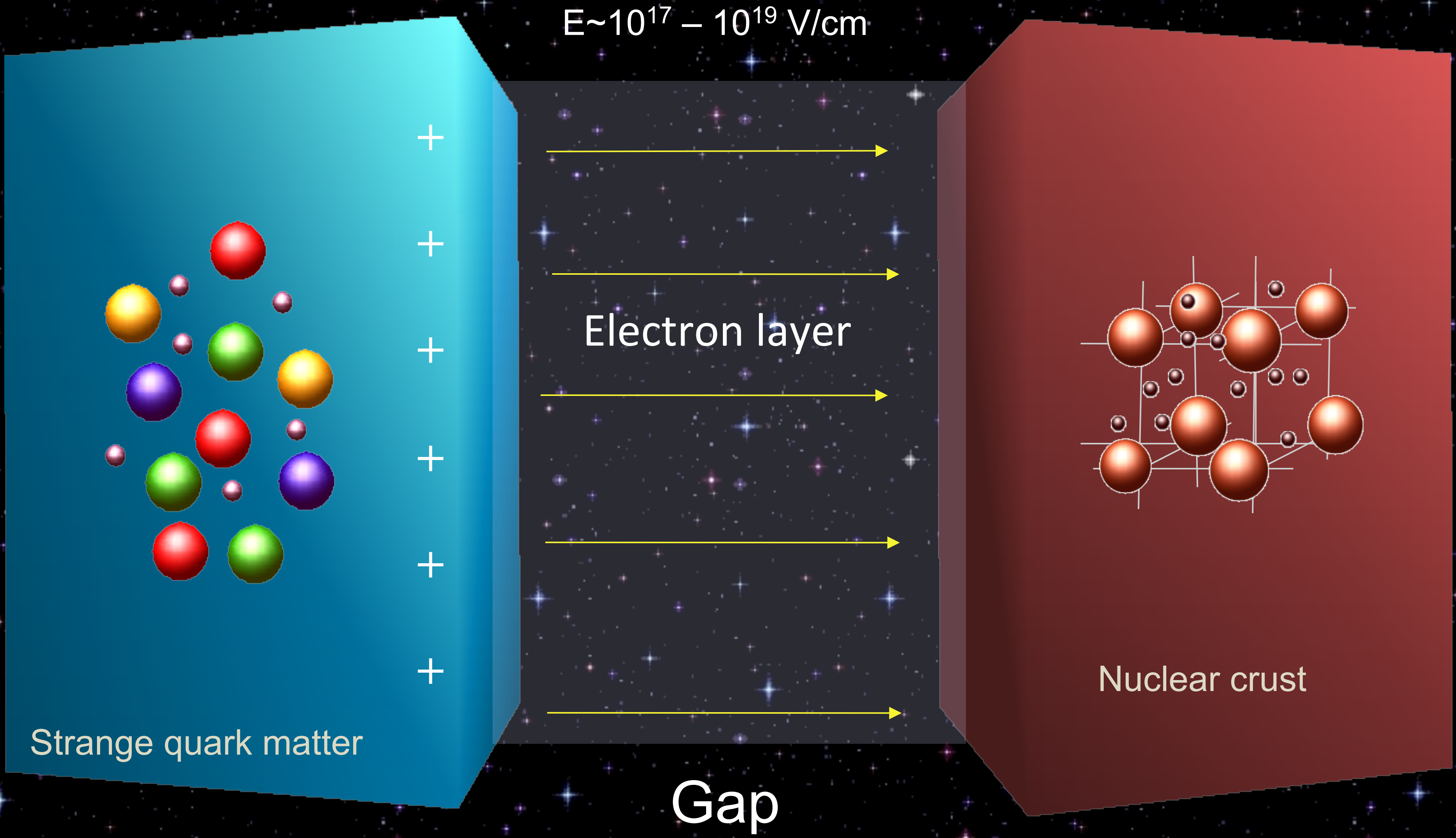
Electron-quark blob Bremsstrahlung:

$e+(Z,A) \rightarrow e+(Z,A)+\nu+\nu$

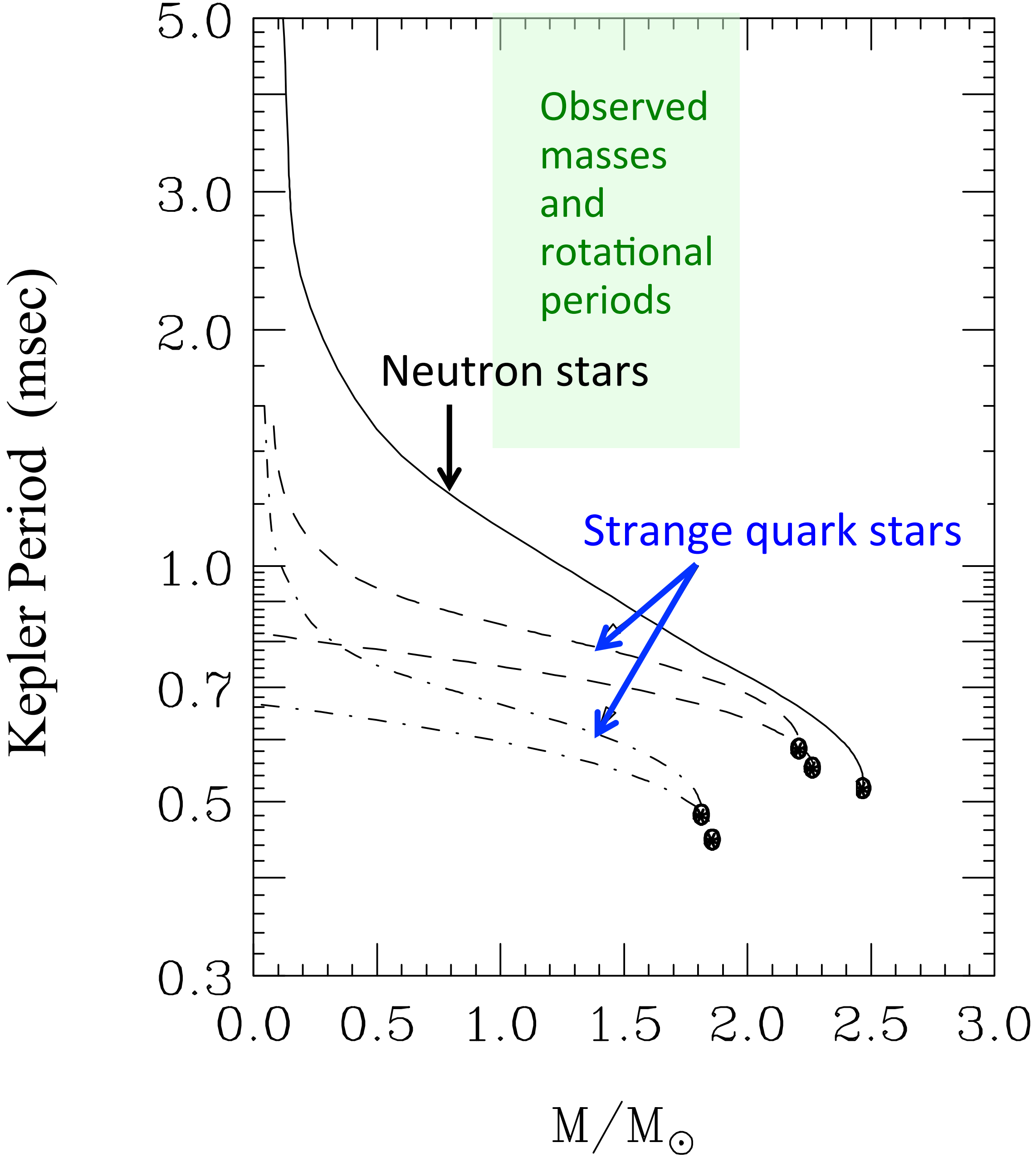


Xuesen Na, R. X. Xu & FW, arXiv:1208.5022v1 astro-ph.SR

Surface Properties of Strange Quark Matter



Rotation at Sub-Millisecond Periods



Tolman-Oppenheimer-Volkoff

Line element:

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

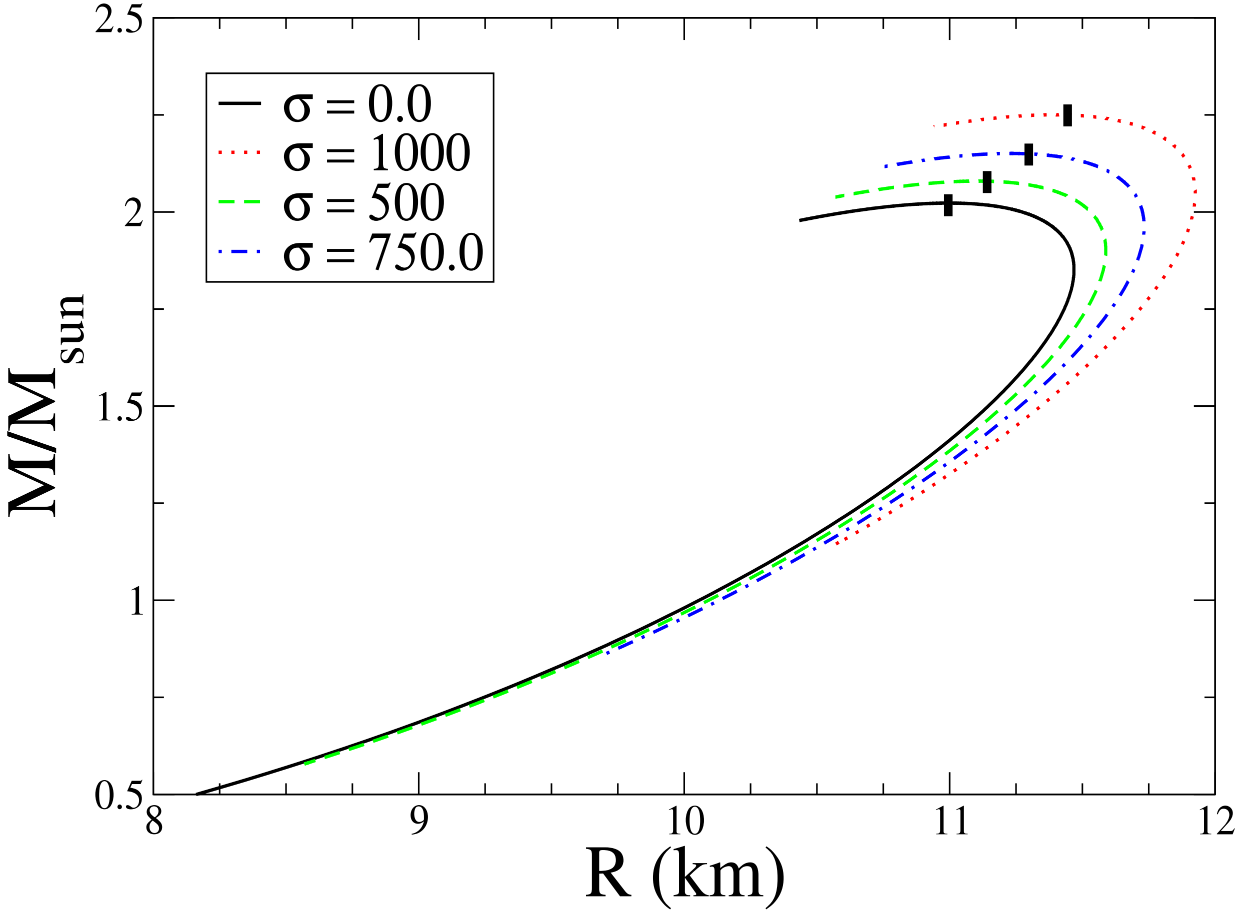
Einstein’s field equation:

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

Energy-momentum tensor: $T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu + g^{\mu\nu}P$

. . . describes an ideal fluid

Mass-Radius Relationship of Electrically Charged Quark Stars

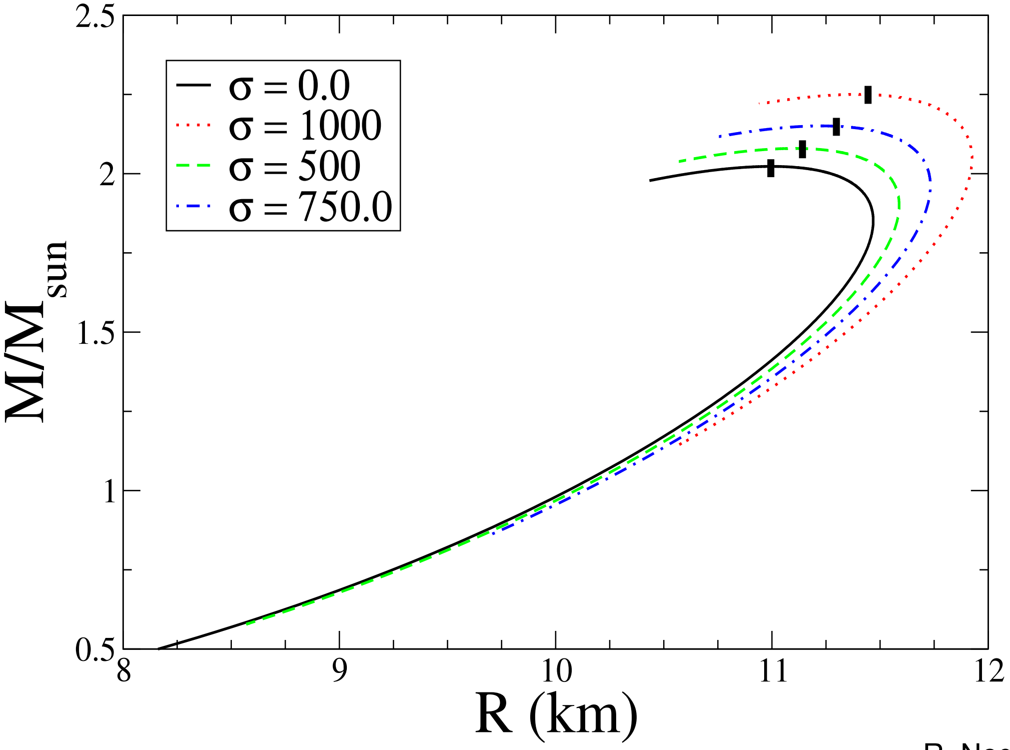


R. Negreiros, FW, M. Malheiro, V. Usov, PRD 80 (2009) 083006

Electrically Charged Quark Stars

Energy density of electric field is of same order as energy density of quark matter!

$$T_\nu{}^\mu = \underbrace{(P+\rho)u_\nu u^\mu + P\delta_\nu{}^\mu}_{\text{ideal fluid}} + \frac{1}{4\pi}\left(F^{\mu l}F_{\nu l} + \frac{1}{4\pi}\delta_\nu{}^\mu F_{kl}F^{kl}\right)$$



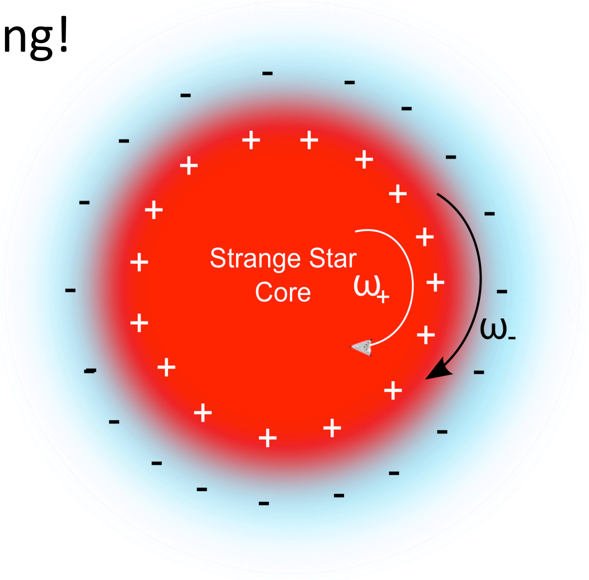
Gravitational mass Increases by up to 15%.

Radius increases by up to 5%.

R. Negreiros, FW, M. Malheiro, V. Usov, PRD 80 (2009) 083006

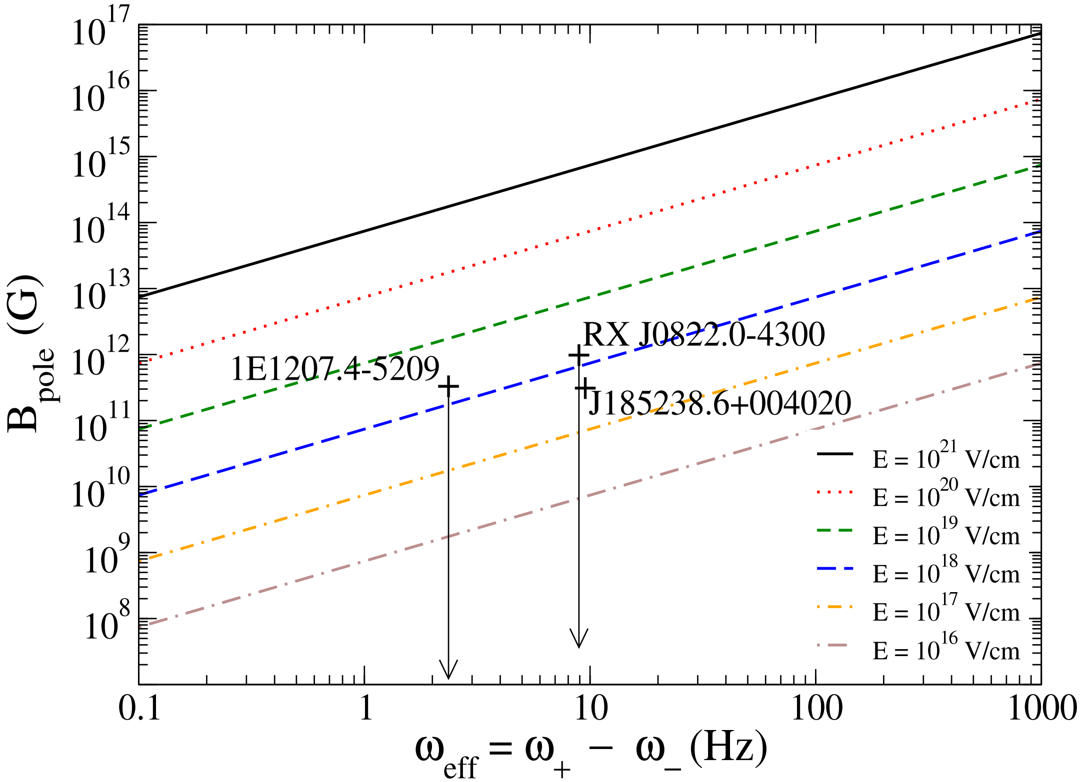
Electrically Charged Quark Stars (cont.)

Electron sphere may be differentially rotating!



$$I = \sigma(\omega_+ - \omega_-)$$

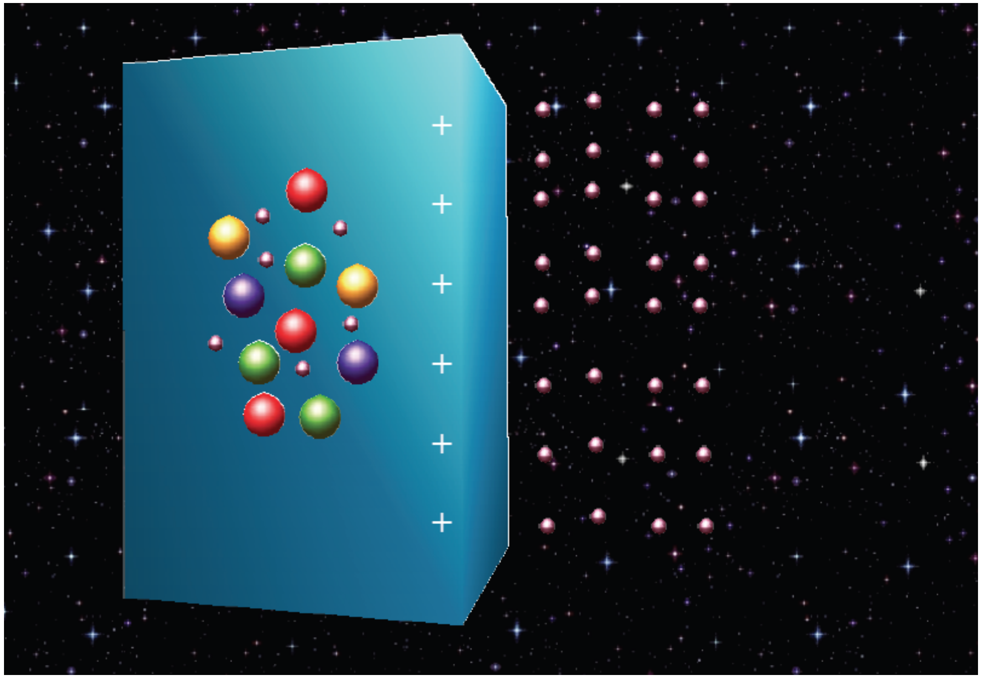
$$B = \mathrm{const}\ E\,(\omega_+ - \omega_-)\,R$$



Could explain observed magnetic fields of CCOs

R. Negreiros, I. Mishustin, S. Schramm, FW, PRD 82 (2010) 103010

Electron sea may perform global (hydrodynamical cyclotron) oscillations



Frequency spectrum calculated by R. X. Xu et al.*

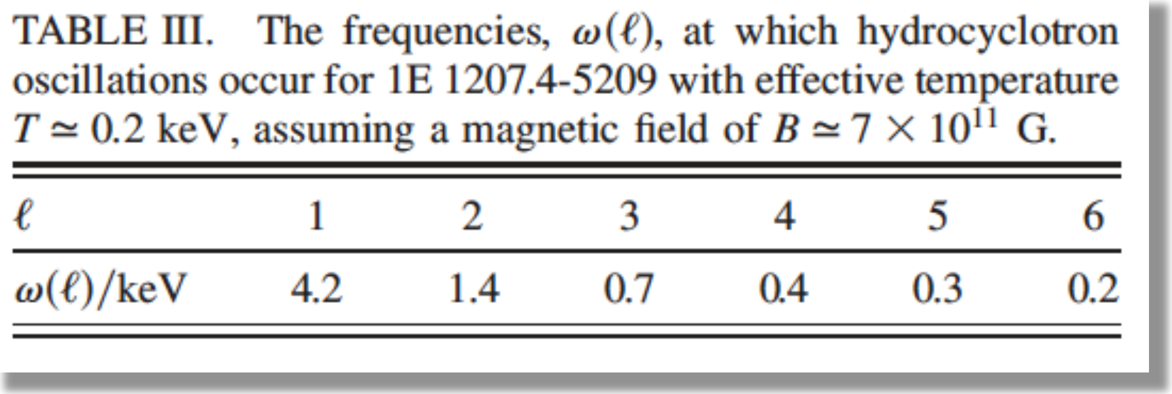
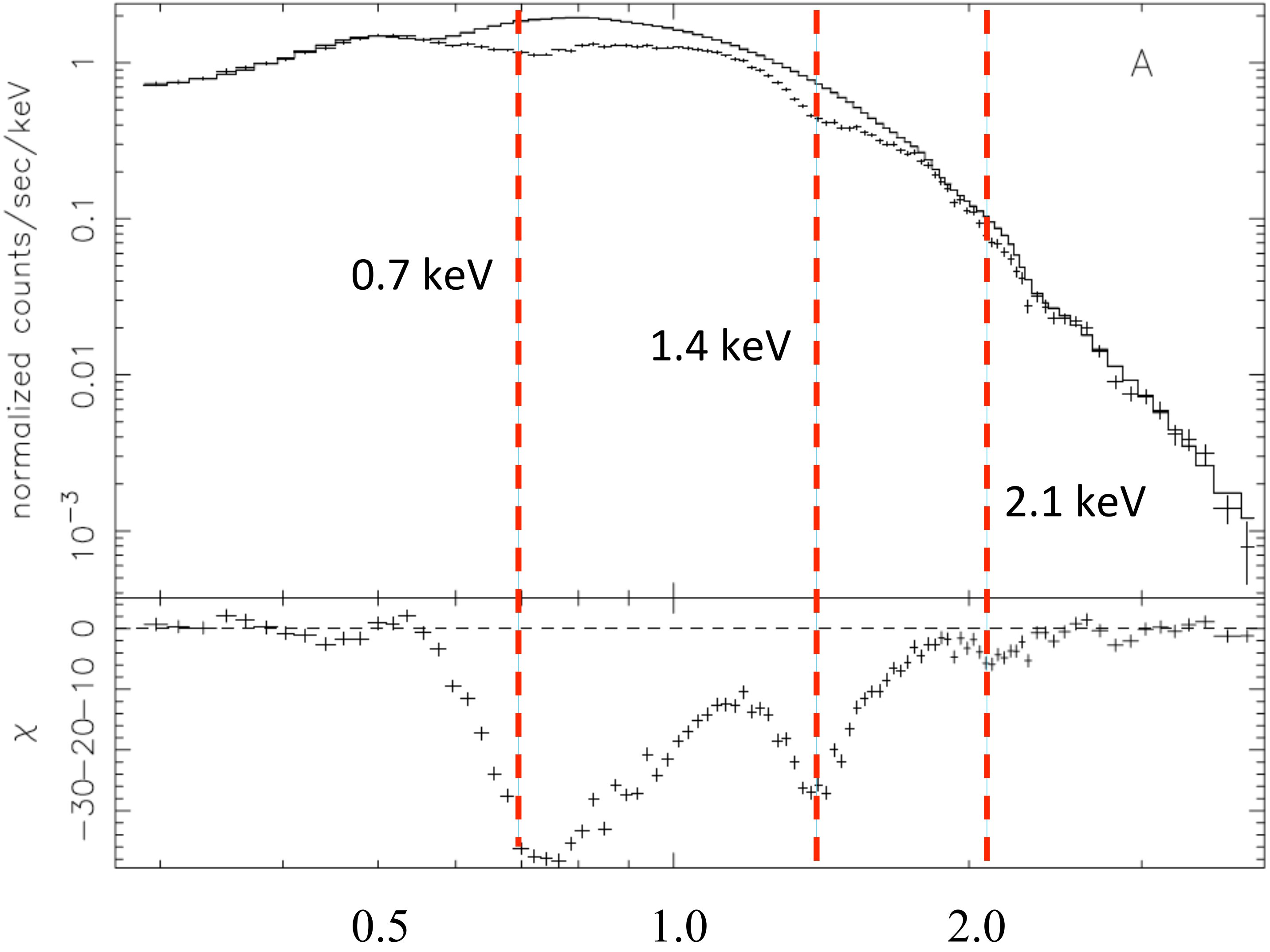


TABLE III. The frequencies, $\omega(\ell)$, at which hydrocyclotron oscillations occur for 1E 1207.4-5209 with effective temperature $T \simeq 0.2$ keV, assuming a magnetic field of $B \simeq 7 \times 10^{11}$ G.

ℓ	1	2	3	4	5	6
$\omega(\ell)$/keV	4.2	1.4	0.7	0.4	0.3	0.2

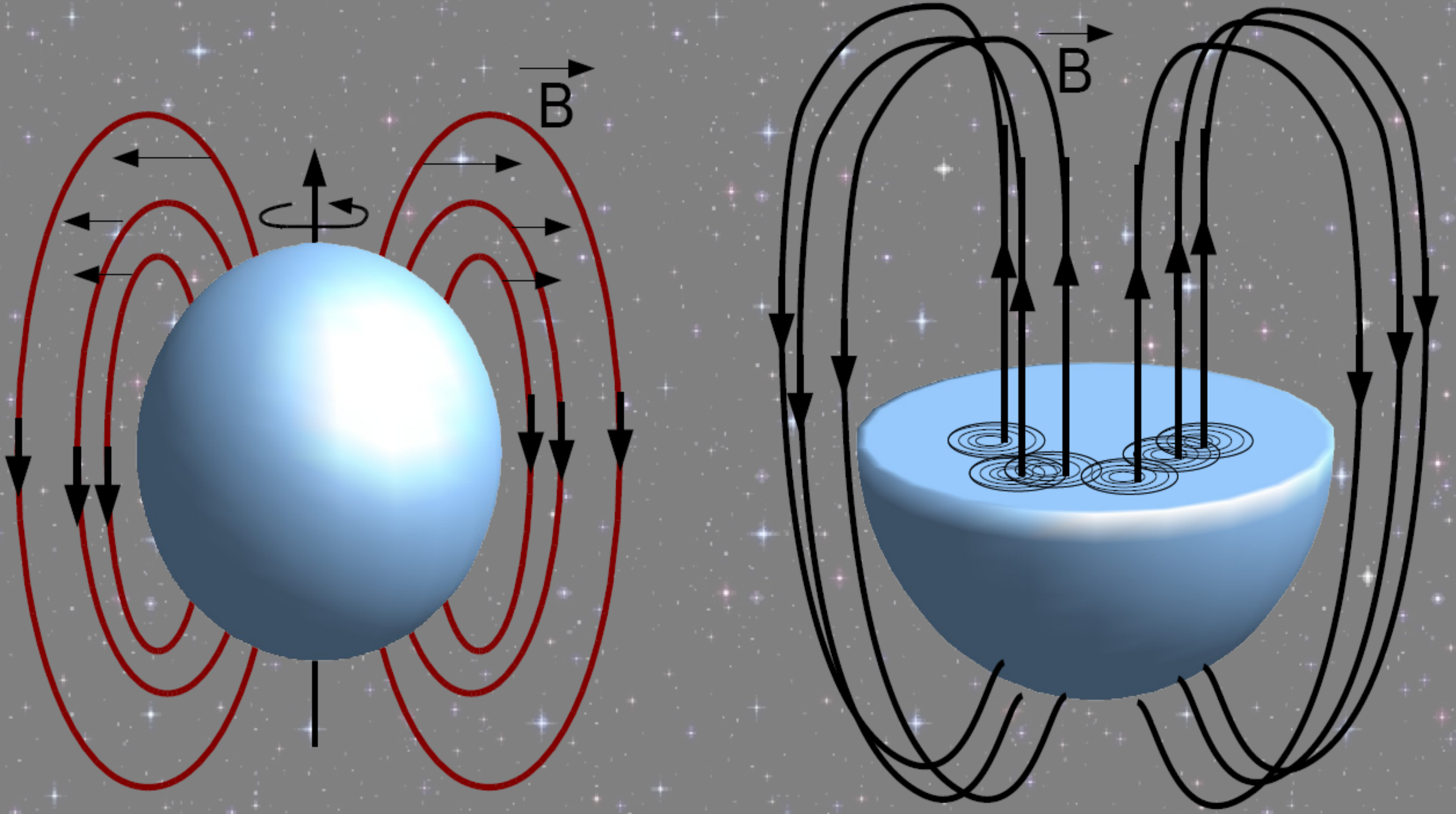
*R. X. Xu, Bastrukov, FW, Yu, Molodtsova, PRD 85 (2012) 023008

Absorption features in spectrum of 1E 1207.4-5209 at 0.7, 1.4 and 2.1 keV*



*G. F. Bignami, P. A. Caraveo, A. De Luca, & S. Mereghetti, Nature 423 (2003) 725

Meissner Effect in Quark Stars made of CFL Quark Matter



Vortex expulsion reheats the quark star

Image Credit: Rodrigo Negreiros

Equations of energy balance and thermal energy transport

$$\frac{\partial(le^{2\phi})}{\partial m} = -\frac{1}{\rho\sqrt{1-2m/r}}\left(\epsilon_\nu e^{2\phi} + c_v \frac{\partial(Te^{\phi})}{\partial t}\right)$$

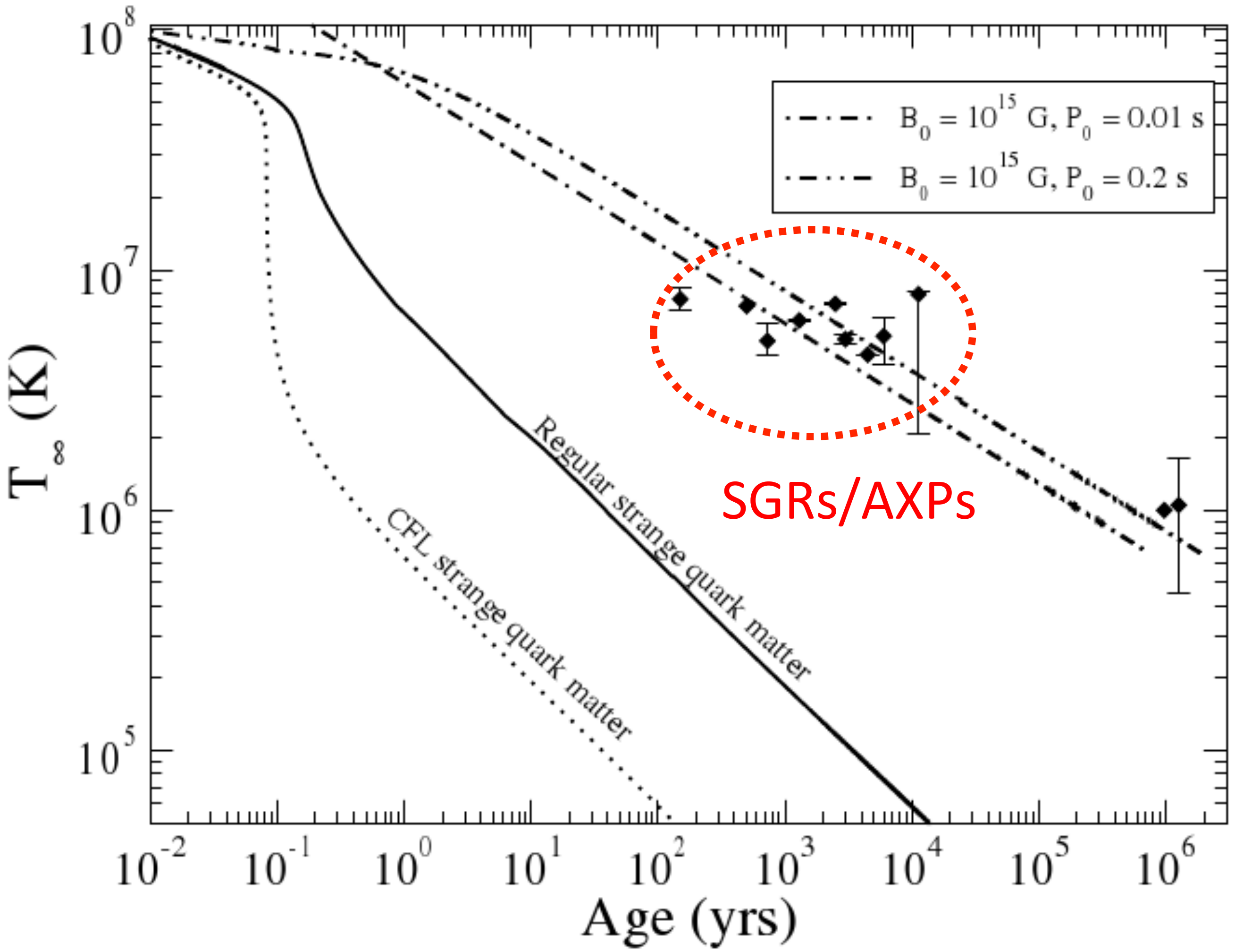
$$\frac{\partial(Te^{\phi})}{\partial m} = -\frac{le^{\phi}}{16\pi^2 r^4 \kappa \rho \sqrt{1-2m/r}}$$

Input: observed values for B_0 , P_0

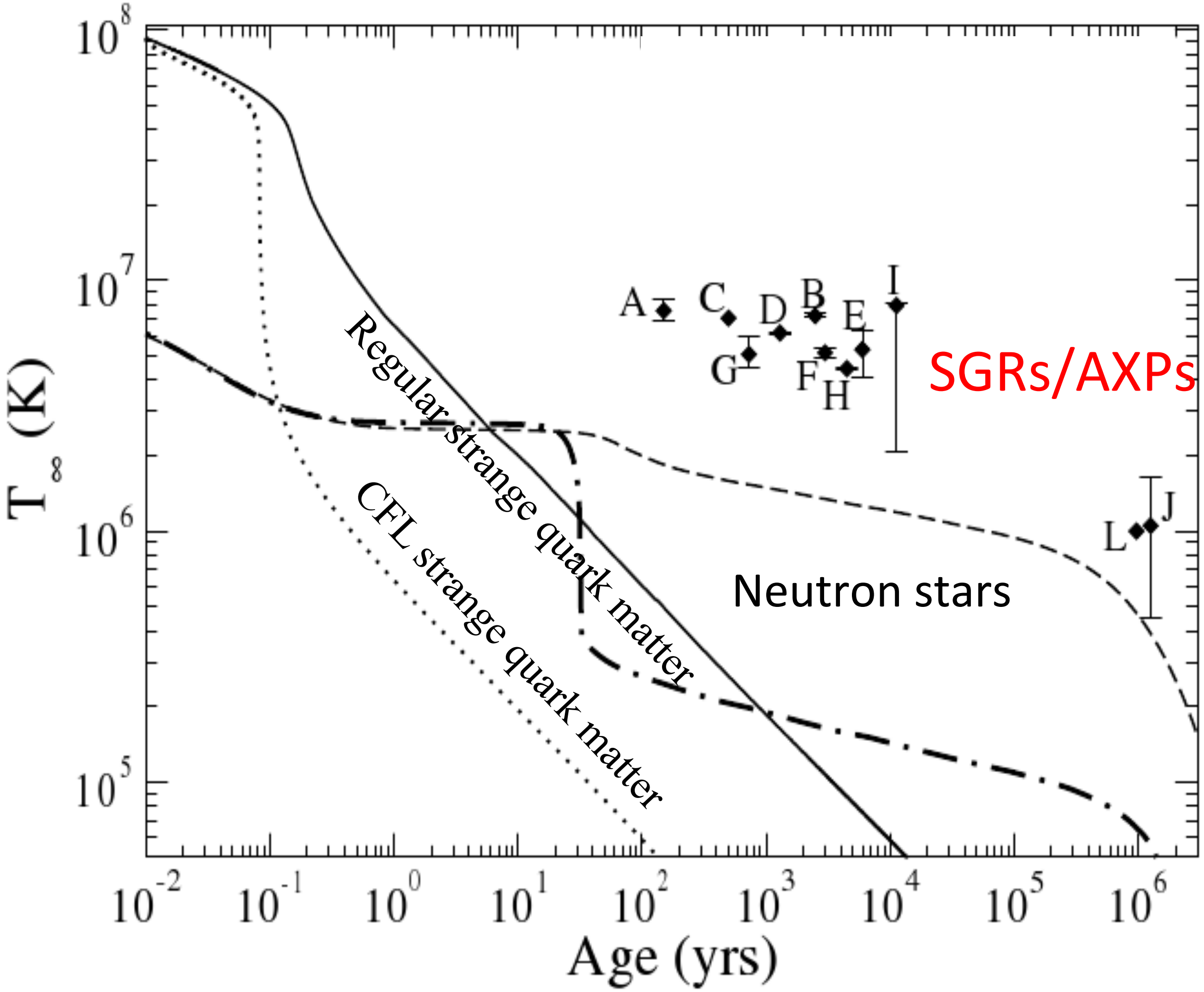
Output: $P(t)$, $dP(t)/dt$, $B(t)$, $T(t)$, $l(t)$

Negreiros, Niebergal, Ouyed, FW, PRD 81 (2010) 043005

Cooling of CFL Quark Stars via Vortex Expulsion



Negreiros, Niebergal, Ouyed, FW, PRD 81 (2010) 043005



Negreiros, Niebergal, Ouyed, FW, PRD 81 (2010) 043005

SUMMARY

- Spin-down/spin-up of neutron stars changes the core composition
- May cause phase transitions

Peculiar stellar properties/phenomena to watch out for:

- “Anomalies” in thermal evolution
- Backbending of isolated pulsars
- Braking indices
- Superfast rotation at < 1ms
- Unusually small objects (CCOs?)
- Unusually hot objects (SGRs, AGRs)
- Absorption features (XDIN, CCOs)