INNER CRUST OF NEUTRON STARS

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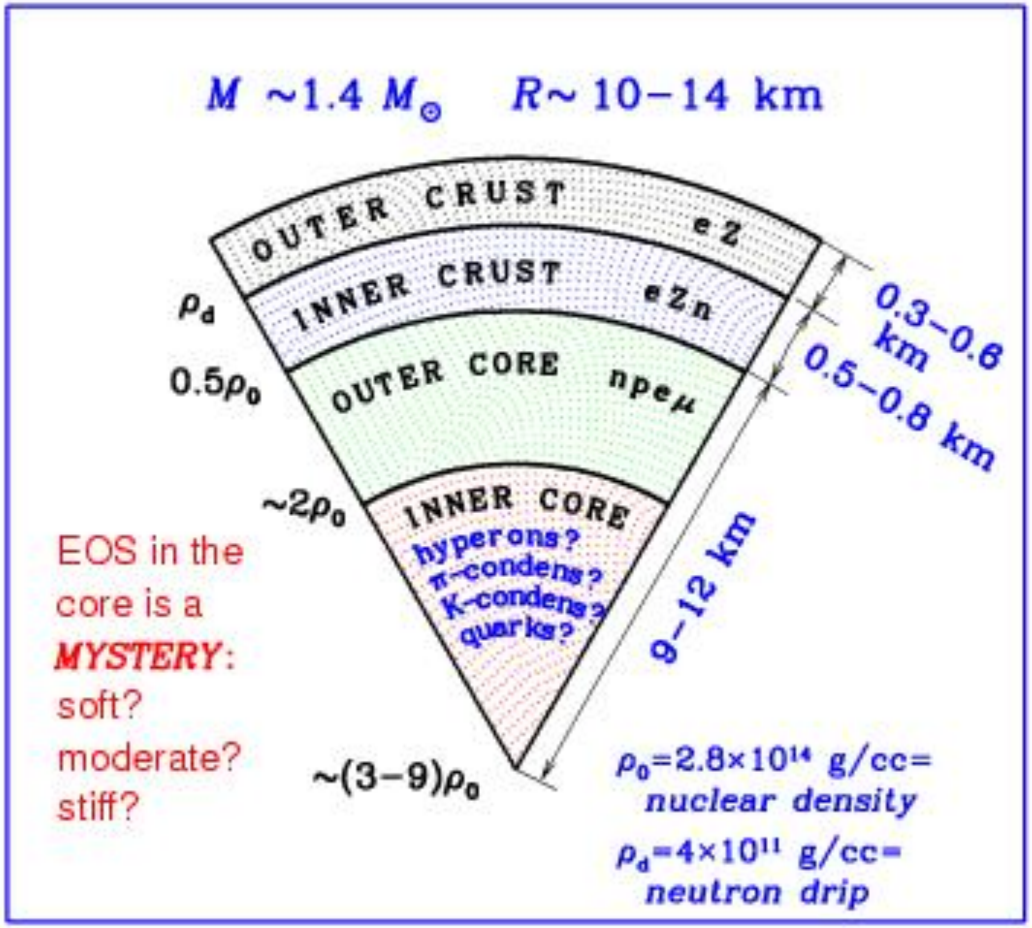
- Introduction
- Basic properties of inner crust
- Observational manifestations
- Conclusions

EMMI Workshop, October 12, 2012

INTRODUCTION: NEUTRON STARS. CORE AND CRUST

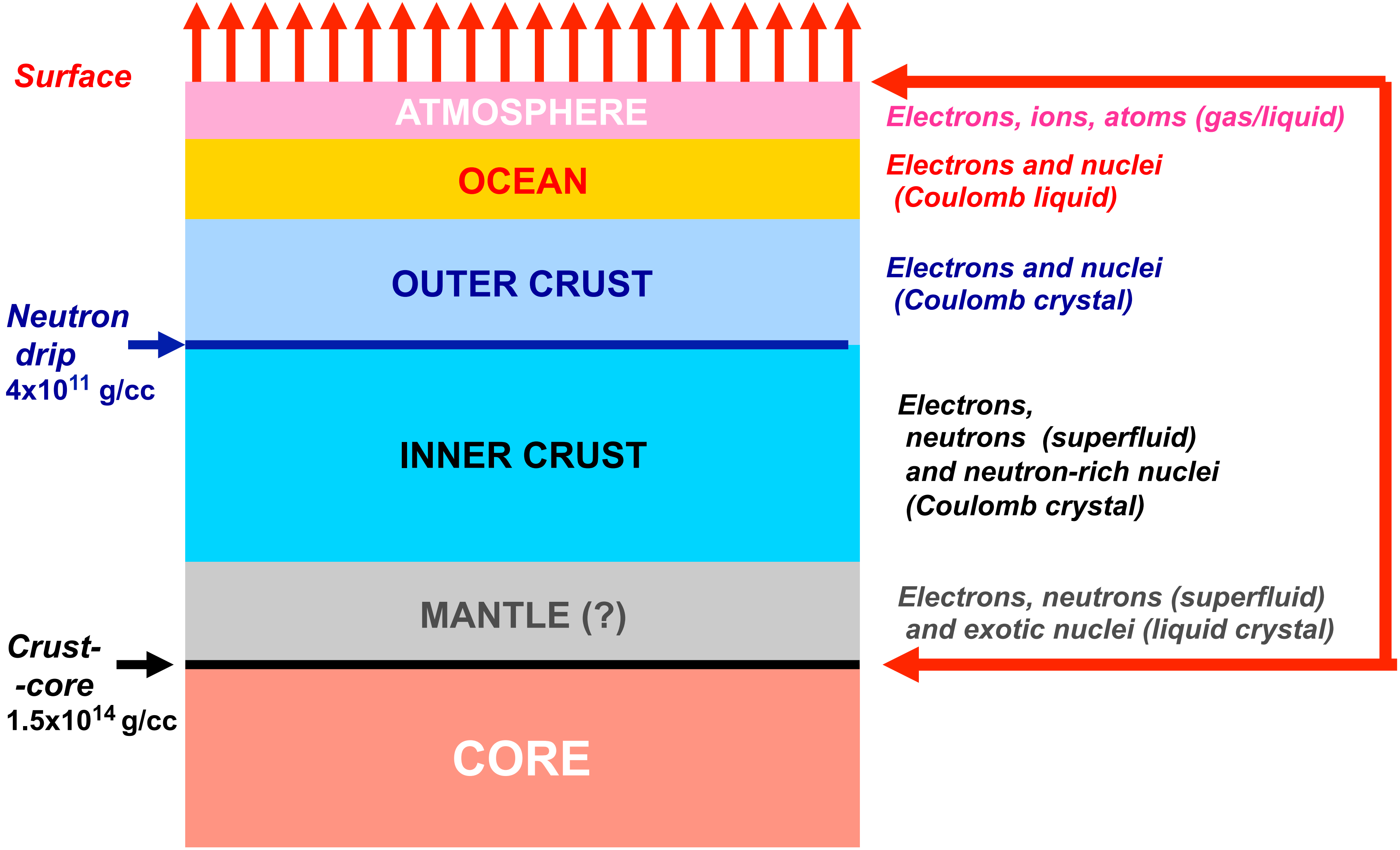
Neutron Star Mystery



Four main layers:

1. **Outer crust**
2. **Inner crust**
3. **Outer core**
4. **Inner core**

INTRODUCTION: NEUTRON STARS
Neutron Star Crust



Surface

ATMOSPHERE

Electrons, ions, atoms (gas/liquid)

OCEAN

Electrons and nuclei (Coulomb liquid)

OUTER CRUST

Electrons and nuclei (Coulomb crystal)

Neutron drip
$4\text{x}10^{11}$ g/cc

INNER CRUST

Electrons, neutrons (superfluid) and neutron-rich nuclei (Coulomb crystal)

MANTLE (?)

Electrons, neutrons (superfluid) and exotic nuclei (liquid crystal)

Crust--core
$1.5\text{x}10^{14}$ g/cc

CORE

INTRODUCTION
Core and crust

Core: *contains super-dense matter; the most interesting place for fundamental physics*

Crust: *shields the core; physics is more certain = transmitter of mystery physics to observers; necessary ingredient but less interesting*

This talk: *to clarify the importance of inner crust — microphysics and observables*

BASIC PROPERTIES OF INNER CRUST

Microphysics Needed

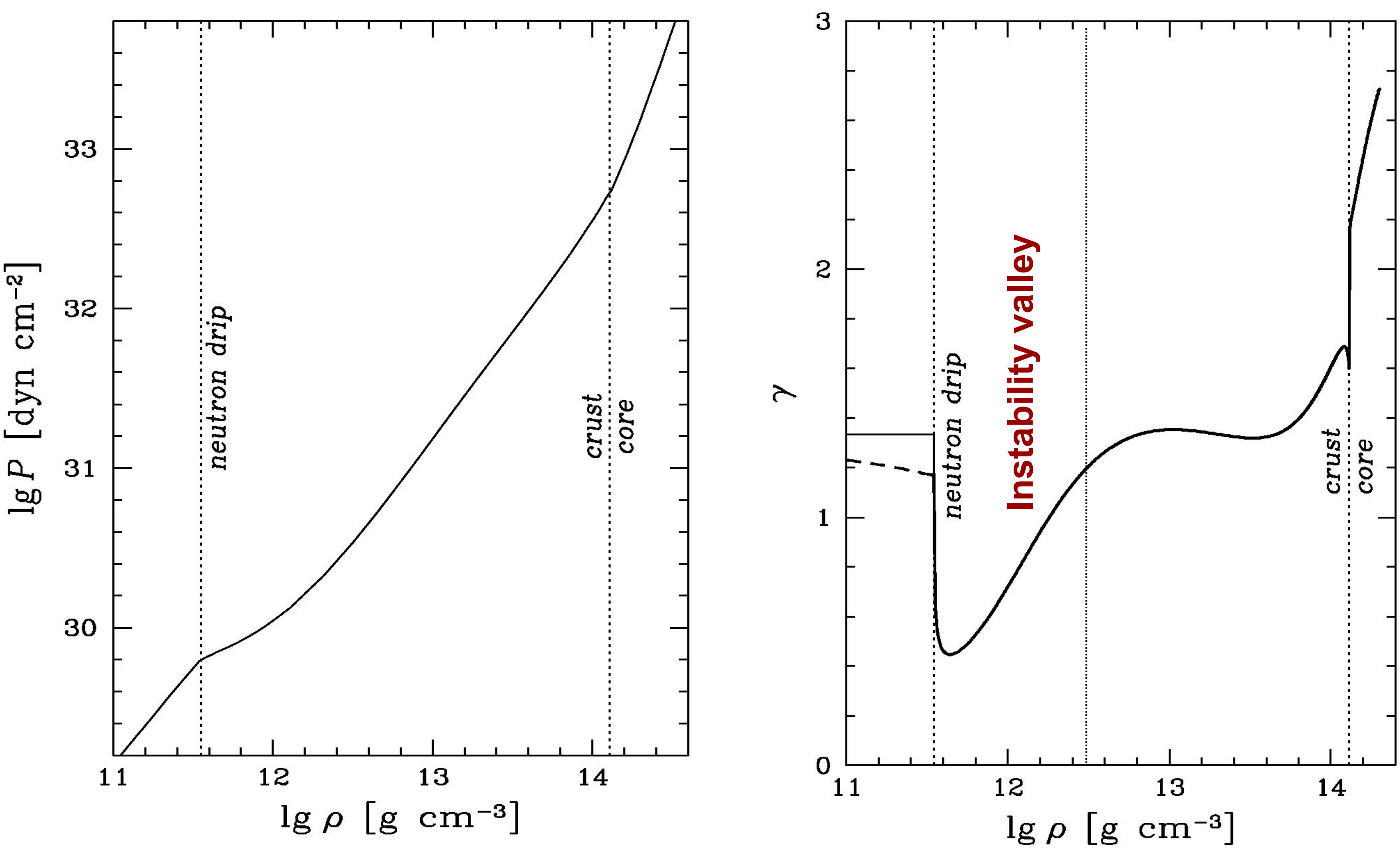
Thermodynamics	*EOS, heat cap,…*
Kinetics	*Conductivities, viscosities, diffusion coefficients*
Neutrinos	*Various mechanisms, beta processes*
Reactions	*Different types and regimes*
Superfluidity	*Hydrodynamics, entrainment, pinning,…*
Strong B-fields	*Effects on microphysics, numerical MHD*
Elastic properties	*Elastic moduli*

Theories involved:

- *Nuclear physics*
- *Weak interactions*
- *Coulomb interaction*
- *Transport*
- *Condensed matter*
- *Hydrodynamics + hydrostatic (MHD, SF)*
- *Nuclear burning, nucleosynthesis*
- *General Relativity*
- *Numerical modeling*

BASIC PROPERTIES OF INNER CRUST

EOS and adiabatic index

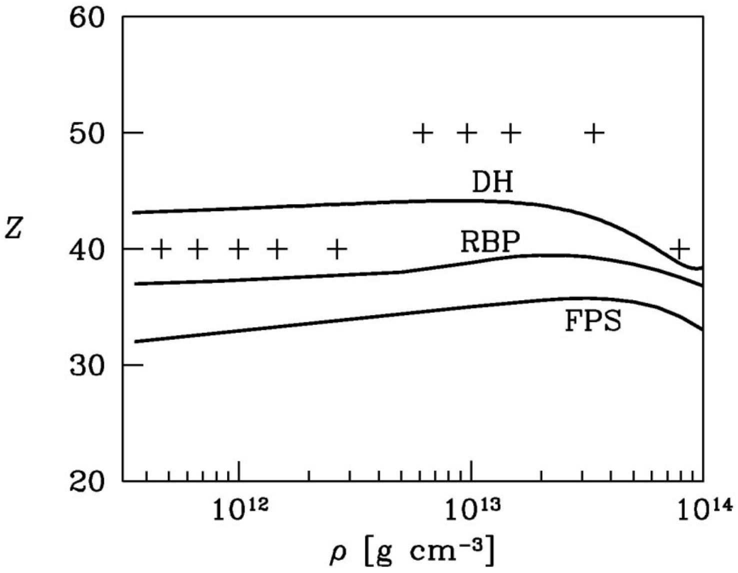


Sly EOS; Douchin & Haensel (2001)

Uncertainties of EOS in the crust do not greatly affect neutron star models

BASIC PROPERTIES OF INNER CRUST

Ground-state matter



DH: Douchin & Haensel (2000)
RBP: Ravenhall et al. (1971)
FPS: as quoted by Pethick & Ravenhall (1995)
Crosses: Negele & Vautherin (1973)

Negele & Vautherin (1973)

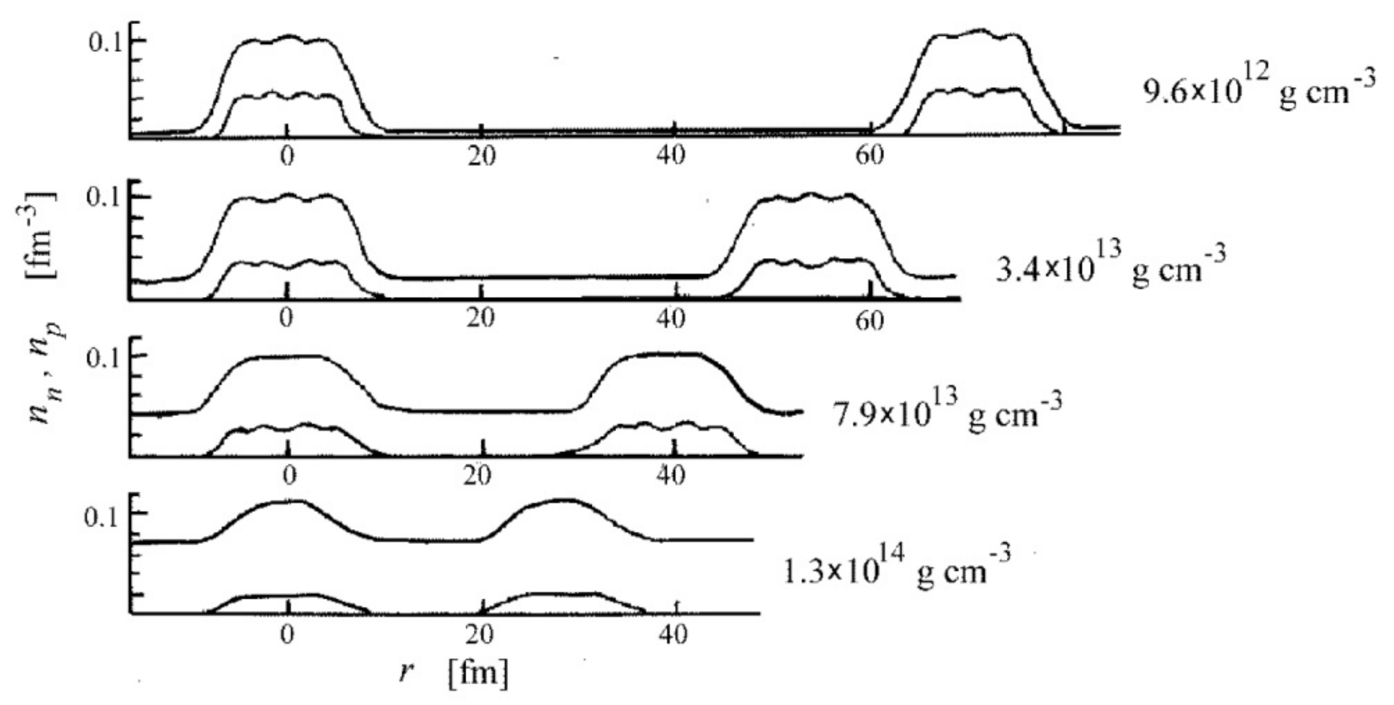
Max. density g/cc	*Z*	*A* (bound)	*A* (WS)	Nucleus
6.70e11	40	115	180	Zr
1.00e12	40	115	200	Zr
1.47e12	40	115	250	Zr
2.66e12	40	115	320	Zr
6.25e12	40	117	500	Zr
9.66e12	50	159	950	Sn
1.49e13	50	161	1100	Sn
3.41e13	50	164	1350	Sn
7.96e13	50	193	1800	Sn
1.32e14	40	183	1500	Zr
	32	232	982	Ge

In laboratory: A(Zr)=91, A(Sn)=119, A(Ge)=72

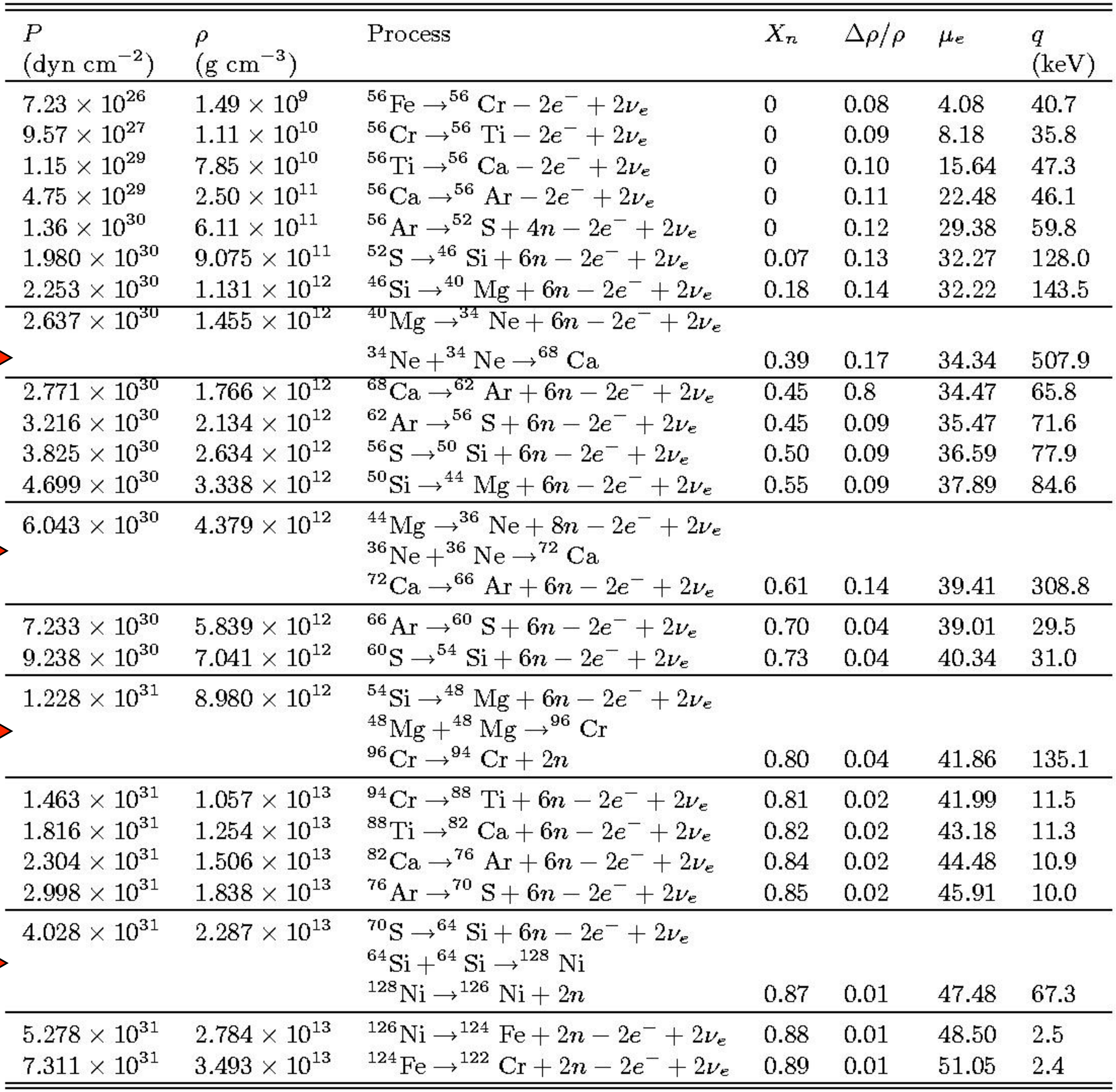
BASIC PROPERTIES OF INNER CRUST

Neutron and proton density profiles in ground-state matter

Negele & Vautherin (1973)



Accreted crust: Starting from ^{56}Fe (Haensel & Zdunik 2007)



P (dyn cm^{-2})	ρ (g cm^{-3})	Process	X_n	$\Delta\rho/\rho$	μ_e	q (keV)
7.23×10^{26}	1.49×10^{9}	$^{56}\mathrm{Fe} \to ^{56}\mathrm{Cr} - 2e^- + 2\nu_e$	0	0.08	4.08	40.7
9.57×10^{27}	1.11×10^{10}	$^{56}\mathrm{Cr} \to ^{56}\mathrm{Ti} - 2e^- + 2\nu_e$	0	0.09	8.18	35.8
1.15×10^{29}	7.85×10^{10}	$^{56}\mathrm{Ti} \to ^{56}\mathrm{Ca} - 2e^- + 2\nu_e$	0	0.10	15.64	47.3
4.75×10^{29}	2.50×10^{11}	$^{56}\mathrm{Ca} \to ^{56}\mathrm{Ar} - 2e^- + 2\nu_e$	0	0.11	22.48	46.1
1.36×10^{30}	6.11×10^{11}	$^{56}\mathrm{Ar} \to ^{52}\mathrm{S} + 4n - 2e^- + 2\nu_e$	0	0.12	29.38	59.8
1.980×10^{30}	9.075×10^{11}	$^{52}\mathrm{S} \to ^{46}\mathrm{Si} + 6n - 2e^- + 2\nu_e$	0.07	0.13	32.27	128.0
2.253×10^{30}	1.131×10^{12}	$^{46}\mathrm{Si} \to ^{40}\mathrm{Mg} + 6n - 2e^- + 2\nu_e$	0.18	0.14	32.22	143.5
2.637×10^{30}	1.455×10^{12}	$^{40}\mathrm{Mg} \to ^{34}\mathrm{Ne} + 6n - 2e^- + 2\nu_e$ $^{34}\mathrm{Ne} + ^{34}\mathrm{Ne} \to ^{68}\mathrm{Ca}$	0.39	0.17	34.34	507.9
2.771×10^{30}	1.766×10^{12}	$^{68}\mathrm{Ca} \to ^{62}\mathrm{Ar} + 6n - 2e^- + 2\nu_e$	0.45	0.8	34.47	65.8
3.216×10^{30}	2.134×10^{12}	$^{62}\mathrm{Ar} \to ^{56}\mathrm{S} + 6n - 2e^- + 2\nu_e$	0.45	0.09	35.47	71.6
3.825×10^{30}	2.634×10^{12}	$^{56}\mathrm{S} \to ^{50}\mathrm{Si} + 6n - 2e^- + 2\nu_e$	0.50	0.09	36.59	77.9
4.699×10^{30}	3.338×10^{12}	$^{50}\mathrm{Si} \to ^{44}\mathrm{Mg} + 6n - 2e^- + 2\nu_e$	0.55	0.09	37.89	84.6
6.043×10^{30}	4.379×10^{12}	$^{44}\mathrm{Mg} \to ^{36}\mathrm{Ne} + 8n - 2e^- + 2\nu_e$ $^{36}\mathrm{Ne} + ^{36}\mathrm{Ne} \to ^{72}\mathrm{Ca}$ $^{72}\mathrm{Ca} \to ^{66}\mathrm{Ar} + 6n - 2e^- + 2\nu_e$	0.61	0.14	39.41	308.8
7.233×10^{30}	5.839×10^{12}	$^{66}\mathrm{Ar} \to ^{60}\mathrm{S} + 6n - 2e^- + 2\nu_e$	0.70	0.04	39.01	29.5
9.238×10^{30}	7.041×10^{12}	$^{60}\mathrm{S} \to ^{54}\mathrm{Si} + 6n - 2e^- + 2\nu_e$	0.73	0.04	40.34	31.0
1.228×10^{31}	8.980×10^{12}	$^{54}\mathrm{Si} \to ^{48}\mathrm{Mg} + 6n - 2e^- + 2\nu_e$ $^{48}\mathrm{Mg} + ^{48}\mathrm{Mg} \to ^{96}\mathrm{Cr}$ $^{96}\mathrm{Cr} \to ^{94}\mathrm{Cr} + 2n$	0.80	0.04	41.86	135.1
1.463×10^{31}	1.057×10^{13}	$^{94}\mathrm{Cr} \to ^{88}\mathrm{Ti} + 6n - 2e^- + 2\nu_e$	0.81	0.02	41.99	11.5
1.816×10^{31}	1.254×10^{13}	$^{88}\mathrm{Ti} \to ^{82}\mathrm{Ca} + 6n - 2e^- + 2\nu_e$	0.82	0.02	43.18	11.3
2.304×10^{31}	1.506×10^{13}	$^{82}\mathrm{Ca} \to ^{76}\mathrm{Ar} + 6n - 2e^- + 2\nu_e$	0.84	0.02	44.48	10.9
2.998×10^{31}	1.838×10^{13}	$^{76}\mathrm{Ar} \to ^{70}\mathrm{S} + 6n - 2e^- + 2\nu_e$	0.85	0.02	45.91	10.0
4.028×10^{31}	2.287×10^{13}	$^{70}\mathrm{S} \to ^{64}\mathrm{Si} + 6n - 2e^- + 2\nu_e$ $^{64}\mathrm{Si} + ^{64}\mathrm{Si} \to ^{128}\mathrm{Ni}$ $^{128}\mathrm{Ni} \to ^{126}\mathrm{Ni} + 2n$	0.87	0.01	47.48	67.3
5.278×10^{31}	2.784×10^{13}	$^{126}\mathrm{Ni} \to ^{124}\mathrm{Fe} + 2n - 2e^- + 2\nu_e$	0.88	0.01	48.50	2.5
7.311×10^{31}	3.493×10^{13}	$^{124}\mathrm{Fe} \to ^{122}\mathrm{Cr} + 2n - 2e^- + 2\nu_e$	0.89	0.01	51.05	2.4

Pycnonuclear reactions

$Q_{\mathrm{TOT}} \approx 1.93$ MeV/N

BASIC PROPERTIES OF INNER CRUST

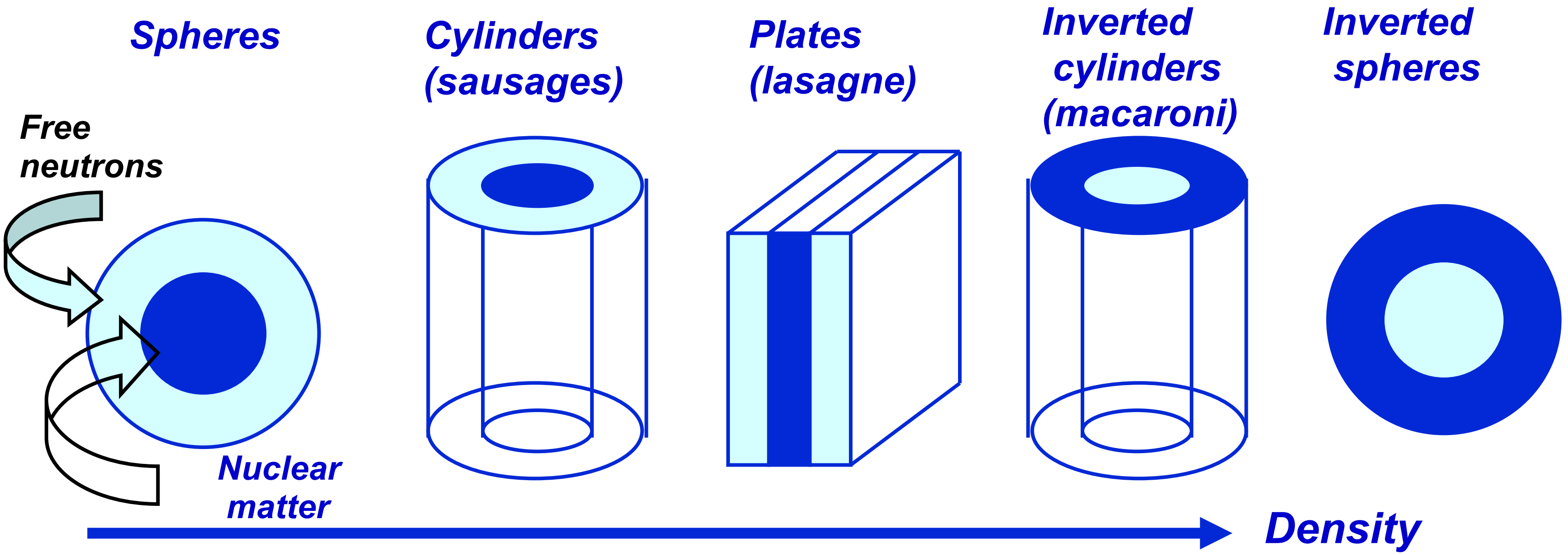
Tasty nuclear clusters

Density range: $10^{14}\ \text{g/cc} \le \rho \le 1.5\times10^{14}\ \text{g/cc}$

Width – a few hundred meters, significant fraction of crust mass

Ravenhall, Pethick, Wilson (1983)

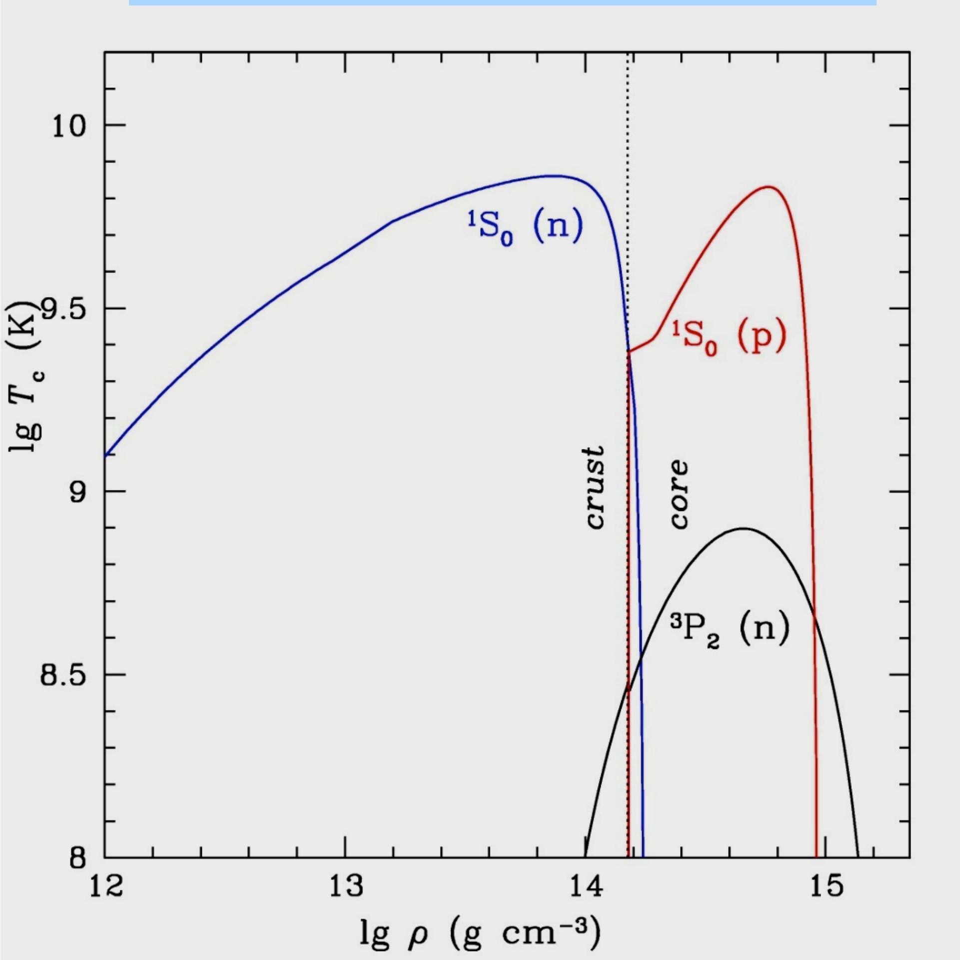
Atomic nuclei are almost dissolved into uniform nuclear matter. Coulomb and surface effects become most important. Some models of nuclear interaction predict a sequence of phase transitions to phases of non-spherical nuclear clusters.



BASIC PROPERTIES OF INNER CRUST

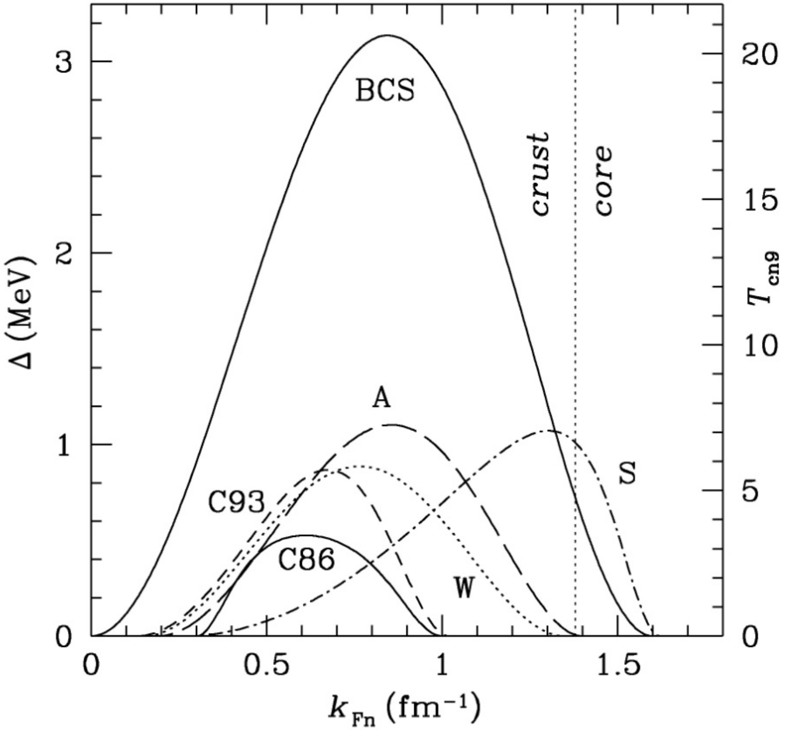
Superfluidity – Critical Temperatures

Density dependence of the gap



At high densities superfluidity disappears

$\Delta_0 \sim 1\ \text{MeV} \qquad T_c \sim 10^{10}\ \text{K}$



After Lombardo & Schulze (2001)

A=Ainsworth, Wambach, Pines (1989)

S=Schulze et al. (1996)

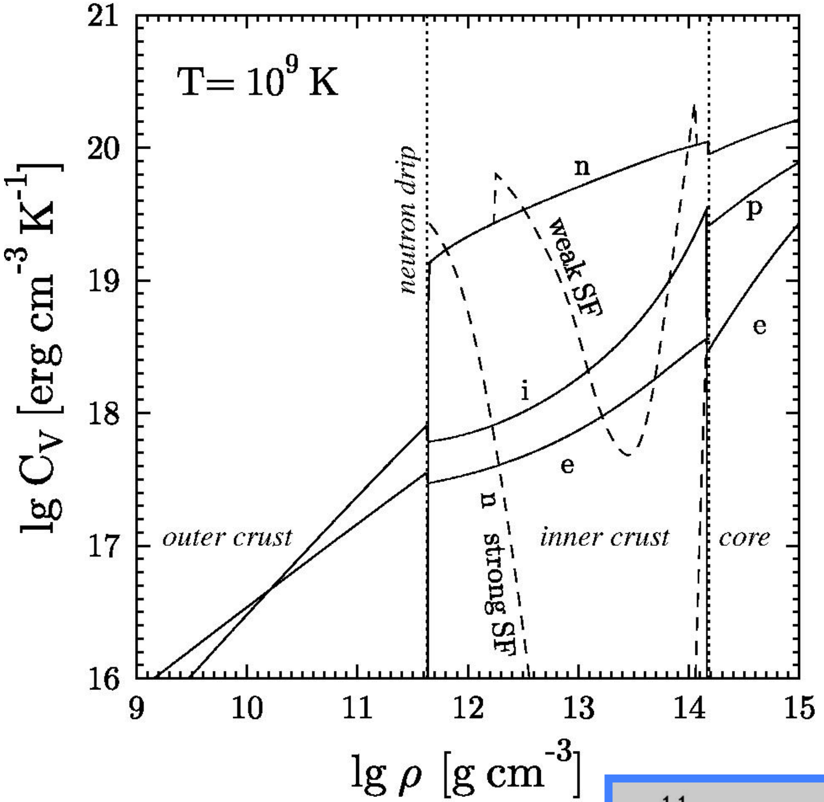
W=Wambach, Ainsworth, Pines (1993)

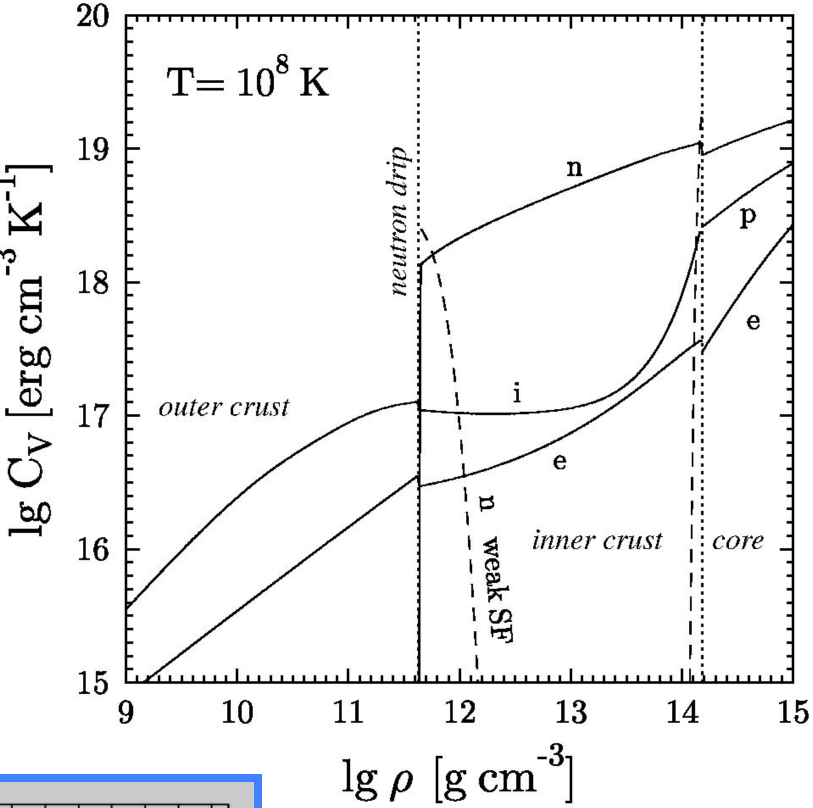
C86=Chen et al. (1986)

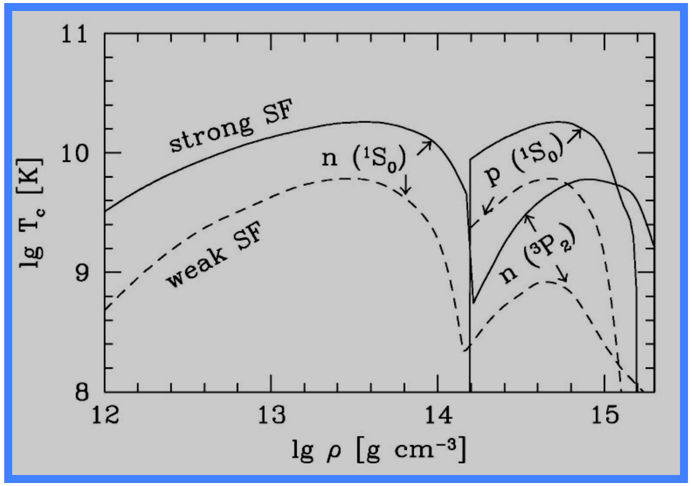
C93=Chen et al. (1993)

BASIC PROPERTIES OF INNER CRUST

Heat capacity throughout neutron star

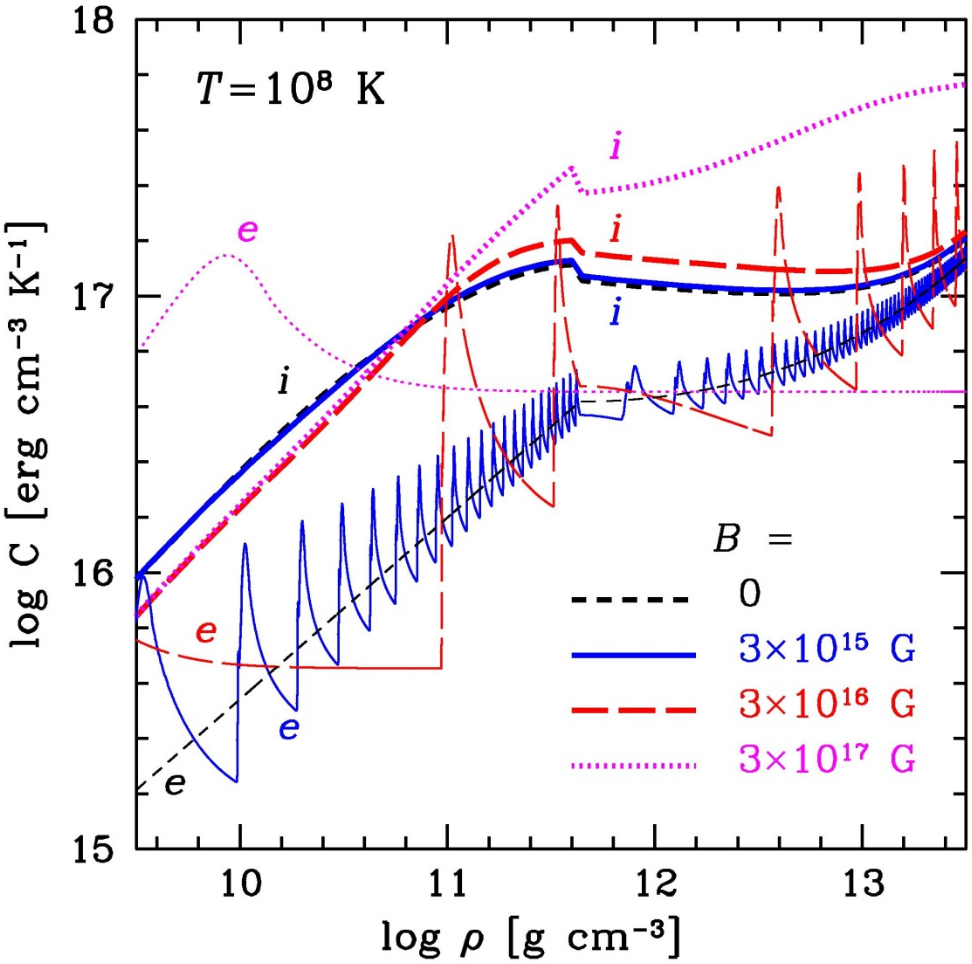






BASIC PROPERTIES OF INNER CRUST

Heat capacity of lattice and electrons in strong B-fields



BASIC PROPERTIES OF INNER CRUST
Transport Coefficients

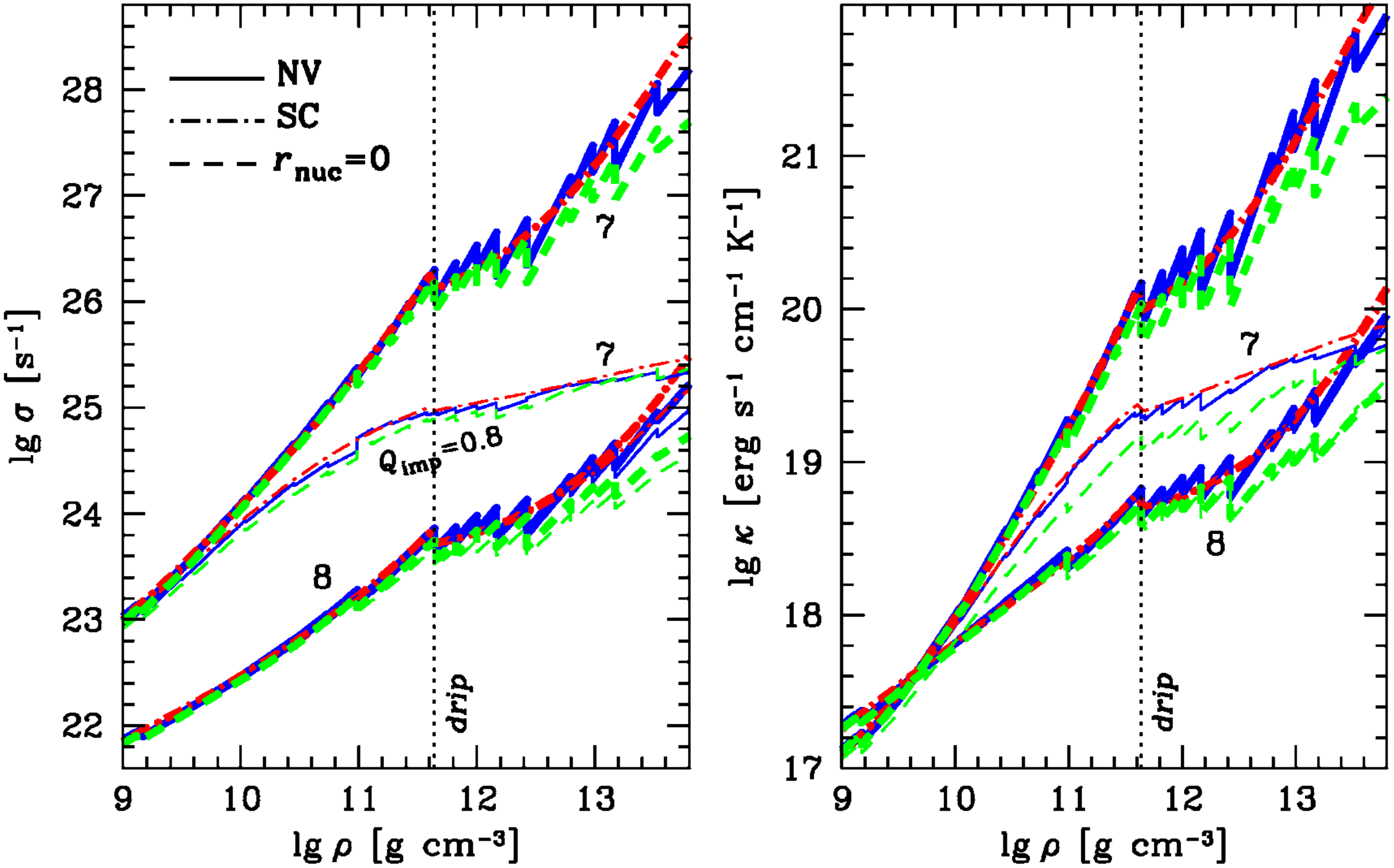
Transport of	Coefficient
Heat	*Thermal conductivity*
Charge	*Electric conductivity (resistivity)*
Heat and charge	*Thermopower*
Momentum	*Shear and bulk viscosity*
Particles	*Diffusion*

Carriers and Scatterers

Carriers	Scatterers
Electrons	*Ions (phonons), electrons*
Ions (phonons)	*Ions (phonons), electrons*
Neutrons	*Nuclei, phonons, neutrons*

KINETICS

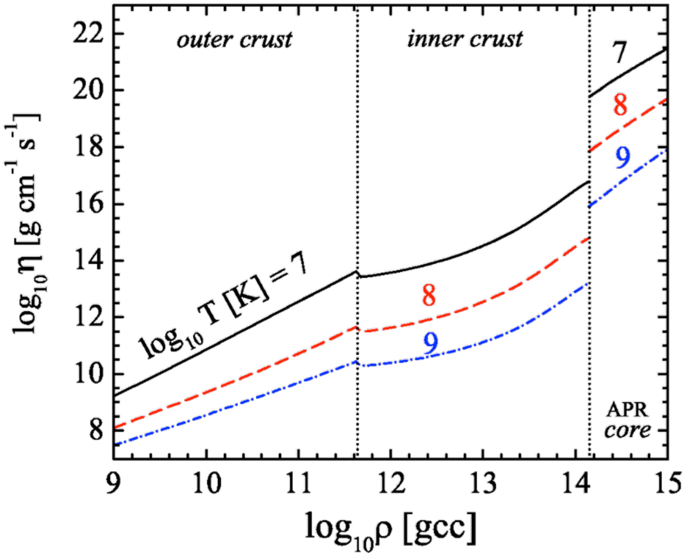
Electron Conduction in Inner and Outer Crust



Electric and and thermal conductivities of electrons in ground-state crust at lg T [K]=7 and 8. Dashed lines: point-like nuclei

Impurities are important at T well below 10^8 K

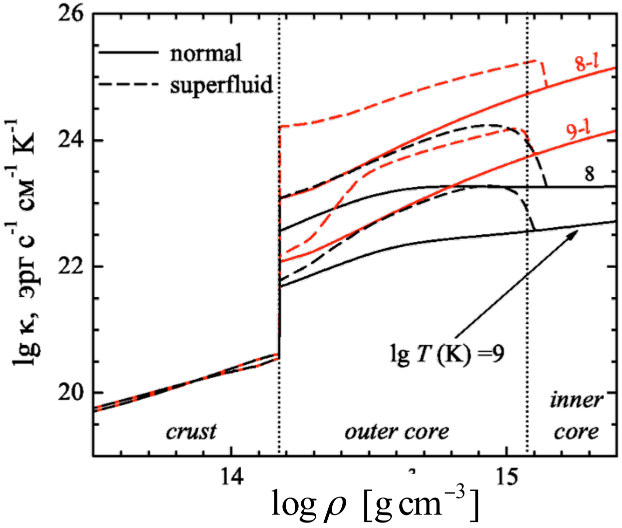
KINETICS
Crust as a special place



Chugunov and
Yakovlev (2005)

Shternin (2008)

Thanks to atomic nuclei,
crust is a special place:
(a) Heat conduction is slower
(b) Shear viscosity lower
(c) Electric resistivity higher
than in core



Shternin (2008)

NEUTRINO EMISSION OF NEUTRON STAR CRUST

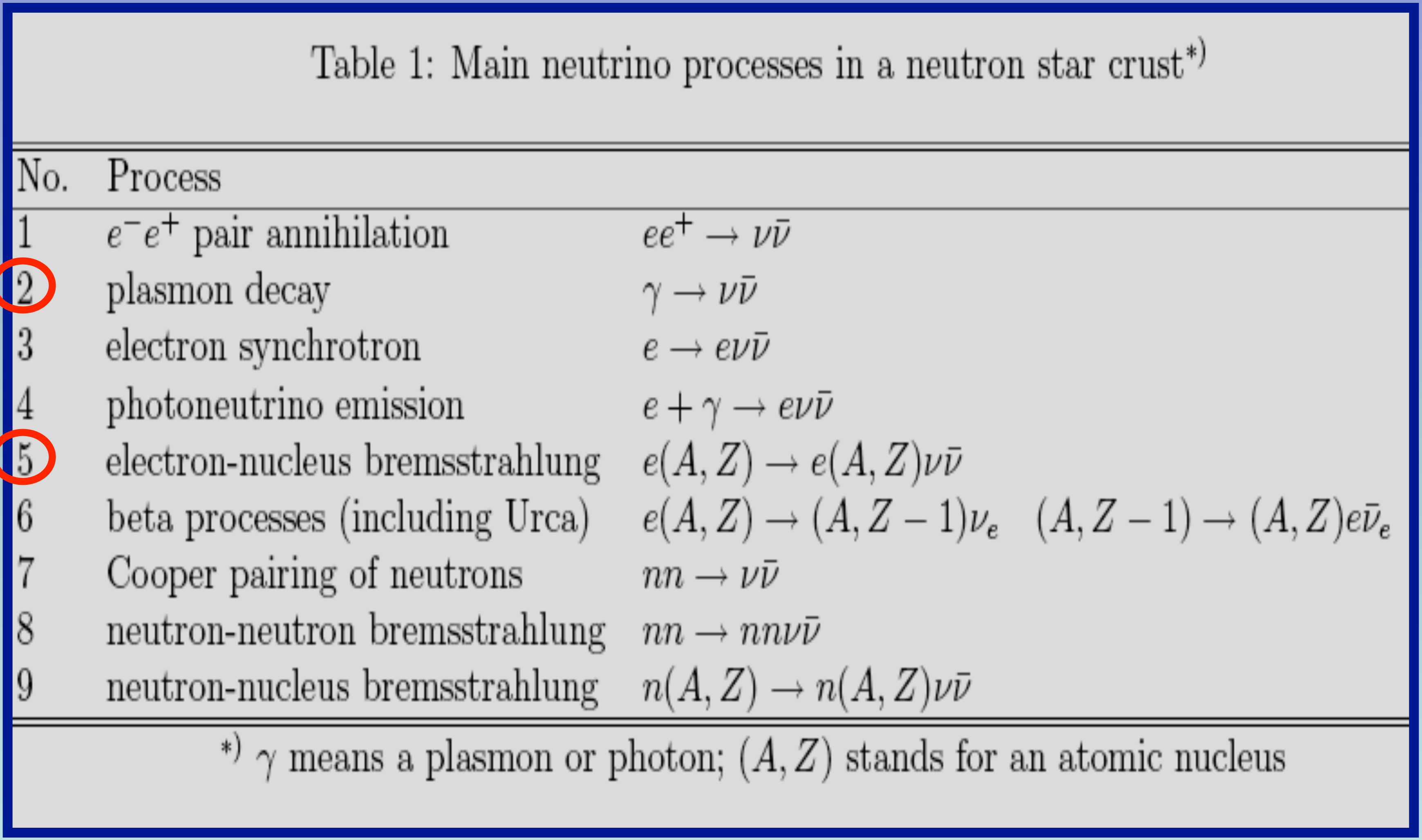


Table 1: Main neutrino processes in a neutron star crust*)

No.	Process	
1	e^-e^+ pair annihilation	$ee^+ \to \nu\bar{\nu}$
2	plasmon decay	$\gamma \to \nu\bar{\nu}$
3	electron synchrotron	$e \to e\nu\bar{\nu}$
4	photoneutrino emission	$e + \gamma \to e\nu\bar{\nu}$
5	electron-nucleus bremsstrahlung	$e(A, Z) \to e(A, Z)\nu\bar{\nu}$
6	beta processes (including Urca)	$e(A, Z) \to (A, Z-1)\nu_e \quad (A, Z-1) \to (A, Z)e\bar{\nu}_e$
7	Cooper pairing of neutrons	$nn \to \nu\bar{\nu}$
8	neutron-neutron bremsstrahlung	$nn \to nn\nu\bar{\nu}$
9	neutron-nucleus bremsstrahlung	$n(A, Z) \to n(A, Z)\nu\bar{\nu}$

*) γ means a plasmon or photon; (A, Z) stands for an atomic nucleus

NEUTRINO EMISSION OF NEUTRON STAR CRUST
Electron-nucleus bremsstrahlung emission

$$(A,Z)+e\rightarrow(A,Z)+e+\nu_e+\bar{\nu}_e$$

Kaminker, Pethick, Potekhin, Thorsson, Yakovlev (1999)

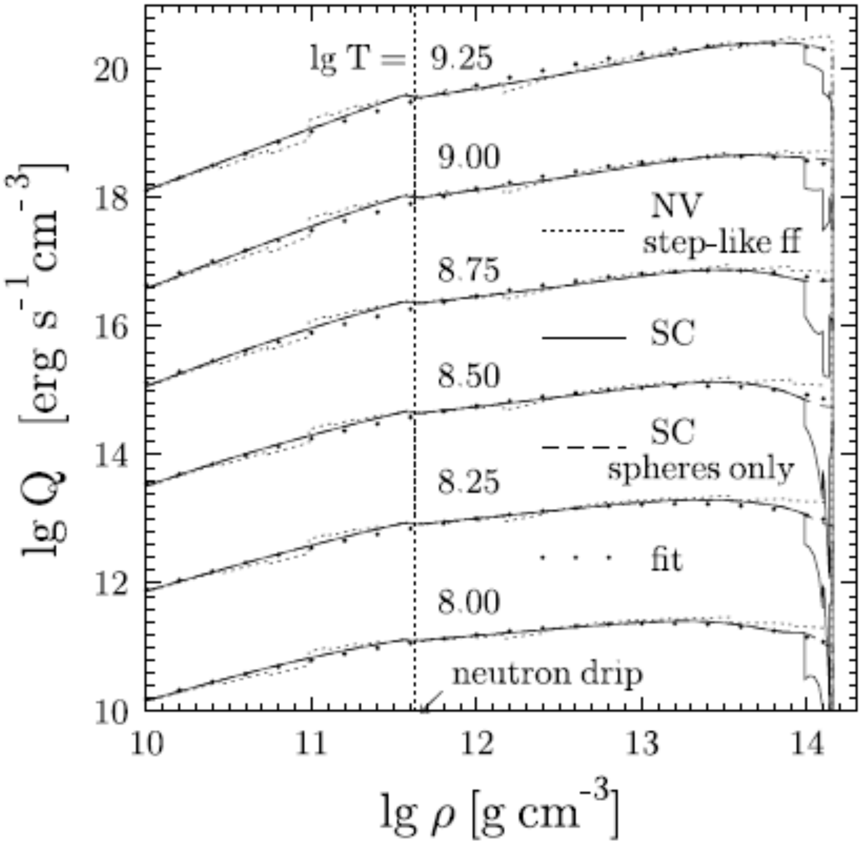


Fig. 11. Density dependence of the bremsstrahlung emissivity for the ground-state matter of the neutron-star crust at six temperatures T in the model by Negele & Vautherin (NV, dots) (1973) with the step-like form factor (ff), and in the SC model with the realistic form factor assuming either the nuclei are spherical to the crust bottom (dashes) or including non-spherical phases (solid lines). Filled circles show our fits (40) to dashed lines

NEUTRINO EMISSION OF NEUTRON STAR CRUST
Direct Urca process in the mantle

Gusakov, Yakovlev, Haensel, Gnedin (2004)

Direct Urca can also be opened in the inner crust,near crust-core interface, in funny phases of inverted (cylinders and inverted spheres) of nuclear clusters

There are free neutrons and protons there. They move in periodic potentials created by nuclear clusters. In this way nucleons acquire large quasi-momenta and satisfy momentum-conservation.

Direct Urca neutrino emissivity in a non-superfluid crust is 2—3 orders of magnitude higher than the emissivity of the modified Urca in the stellar core.

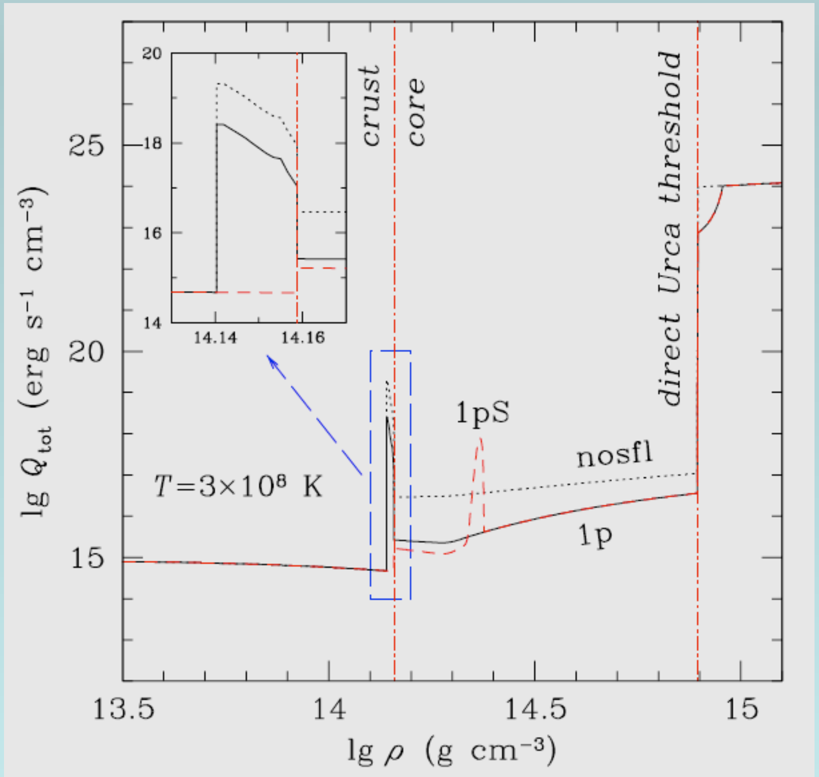
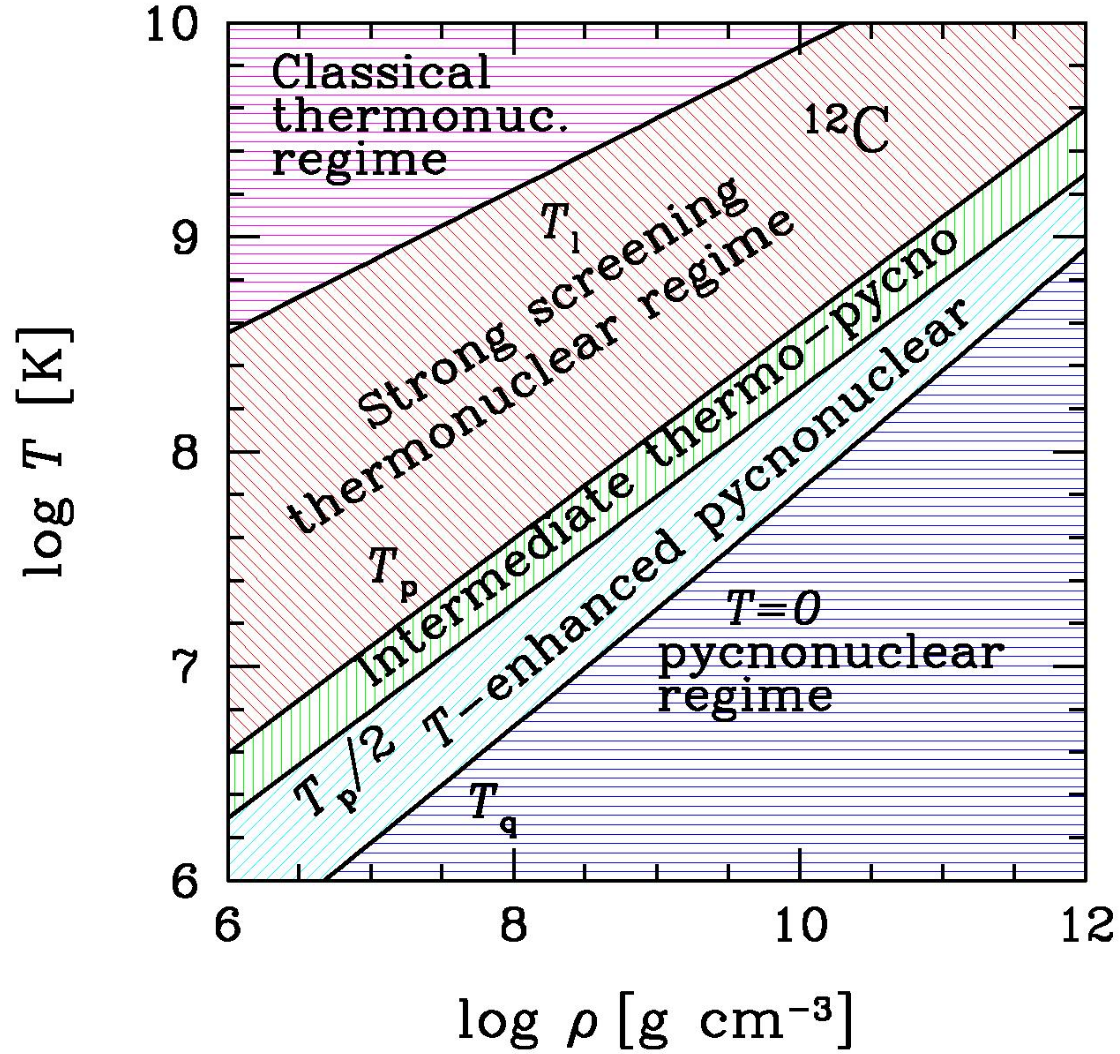


Fig. 2. Total neutrino emissivity versus density at $T = 3\times10^8$ K. The crust-core interface and the direct Urca threshold in the core are marked by dot-and-dashed lines. The peak near the core-crust interface shows the direct Urca process in the mantle (presented also in the insert). Dotted line: no nucleon superfluidity (nosfl); solid line: model 1p of proton superfluidity; dashed line: model 1p of proton superfluidity in the core and model S of neutron superfluidity in the crust (see the text). The neutron pairing 1nt is too weak to appear and affect the neutrino emission at the given T.

NUCLEAR BURNING IN INNER CRUST
Five regimes of nuclear burning

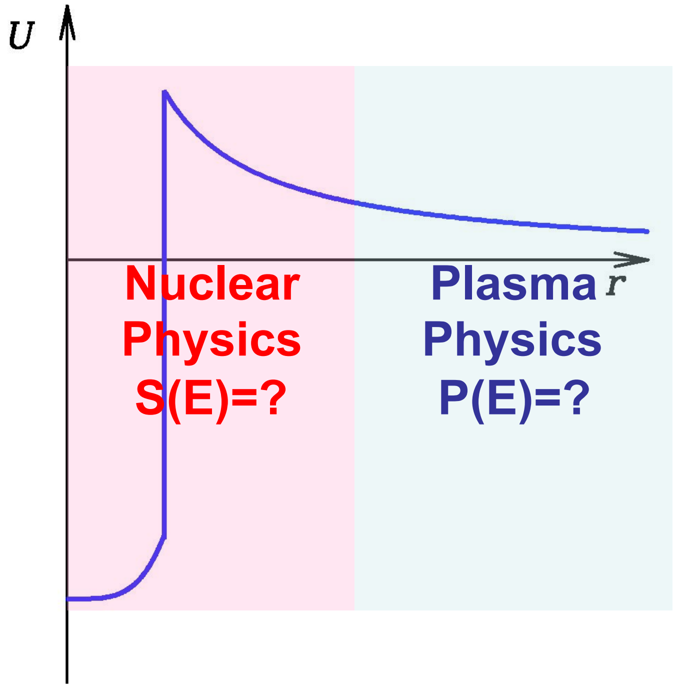
Coulomb plasma effects



NUCLEAR BURNING IN INNER CRUST

Pycnonuclear reactions

In NS inner crust: reactions are mostly pycnonuclear,
independent of temperature (T=0)

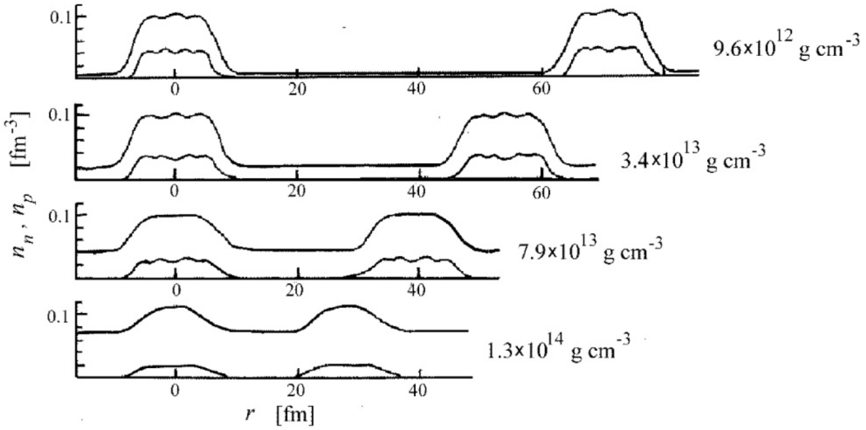


Nuclear Physics S(E)=?

Plasma Physics P(E)=?

Reaction cross section:

$$\sigma(E) = \frac{1}{E} \exp\left(-\frac{2\pi Z_1 Z_2 e^2}{\hbar v}\right) S(E)$$



In the inner crust (deep crustal heating): S(E) can be strongly affected by nuclear density profile in the nuclei and by free neutrons

MANIFESTATIONS OF INNER CRUST
List

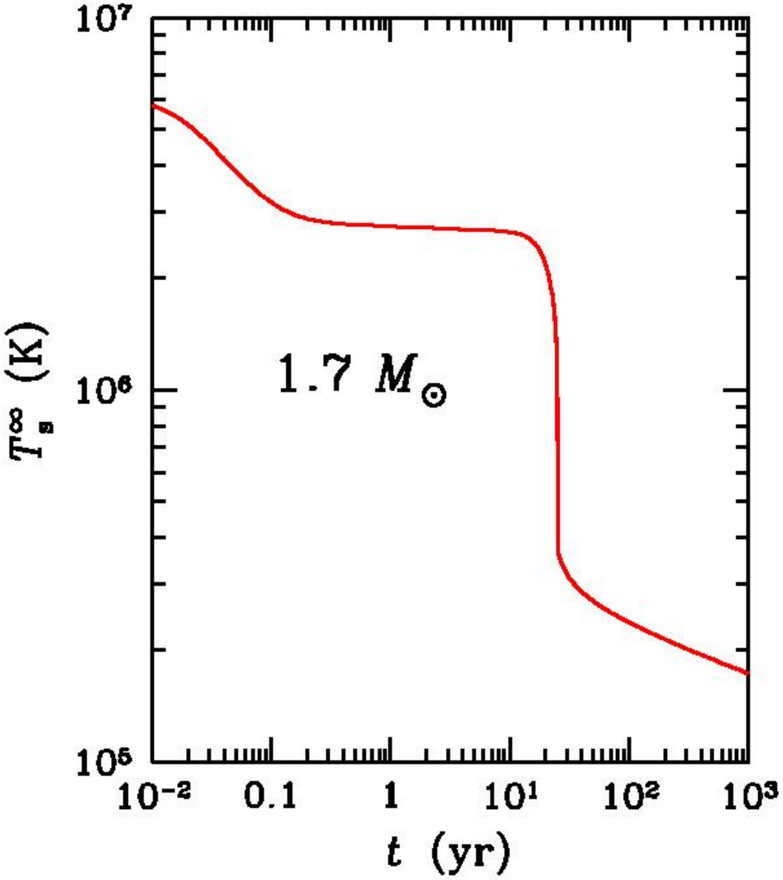
Not easy task.

Example: cooling isolated NSs after thermal relaxation – microphysics of inner crust is not needed

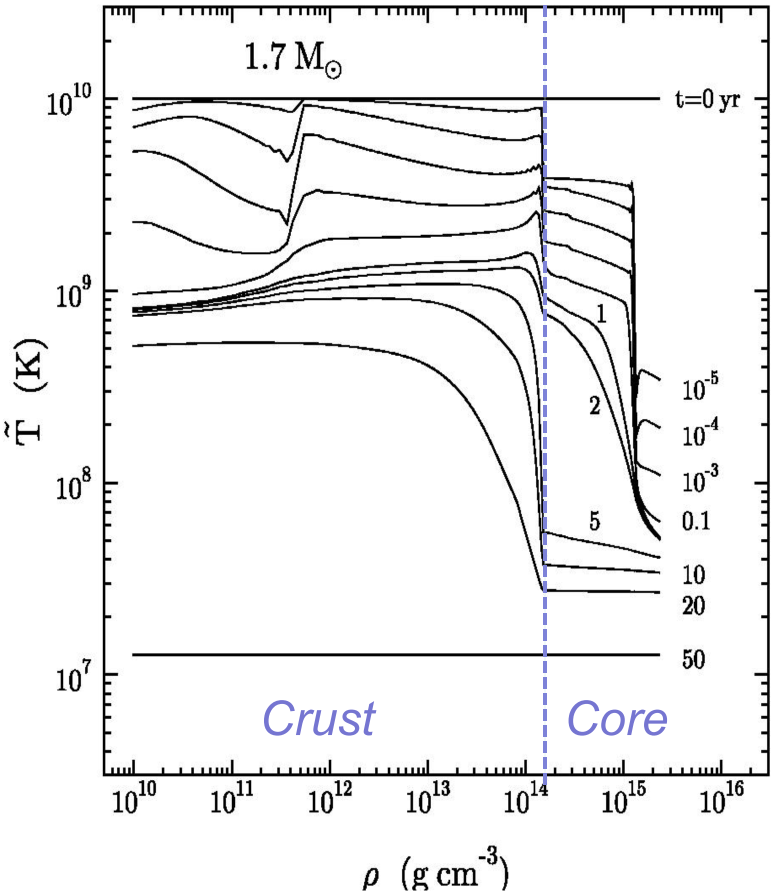
Effect	Objects	Microphysics
Thermal relaxation	***Young INSs, magnetars, quasi-persistent XRTs, superbursts***	***Transport, heat cap, neutrinos, SF***
Deep crustal heating	***Quasi-stationary and quasi-persistent XRTs***	***EOS of accreted crust, reactions***
Glitches, timing noise	***Pulsars***	***SF, pinning, nuclei***
B-filed evolution	***Pulsars, magnetars***	***Electric conductivity, thermomagnetic effects***
Seismology	***Magnetars, PSRs***	***Elastic properties, viscosity***

THERMAL RELAXATION IN COOLING NEUTRON STAR

Look from outside

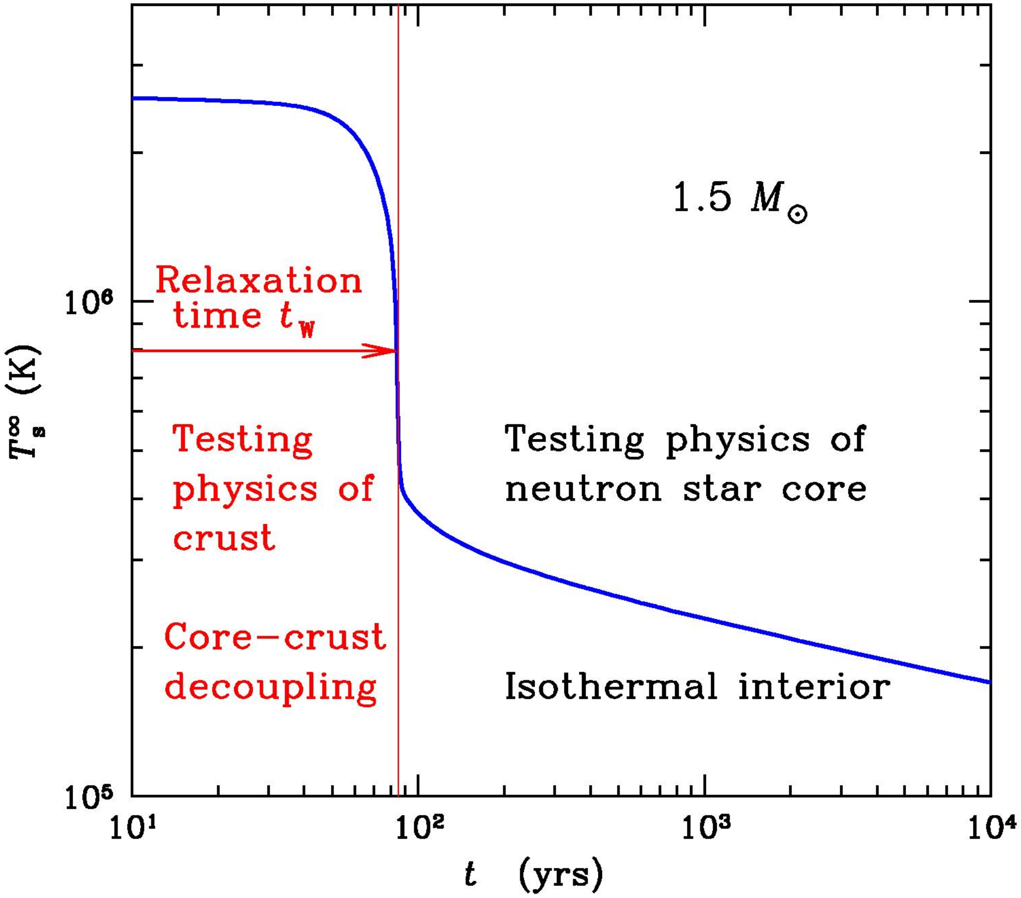


From inside



Gnedin et al. (2001)

THERMAL RELAXATION
The Relaxation Time



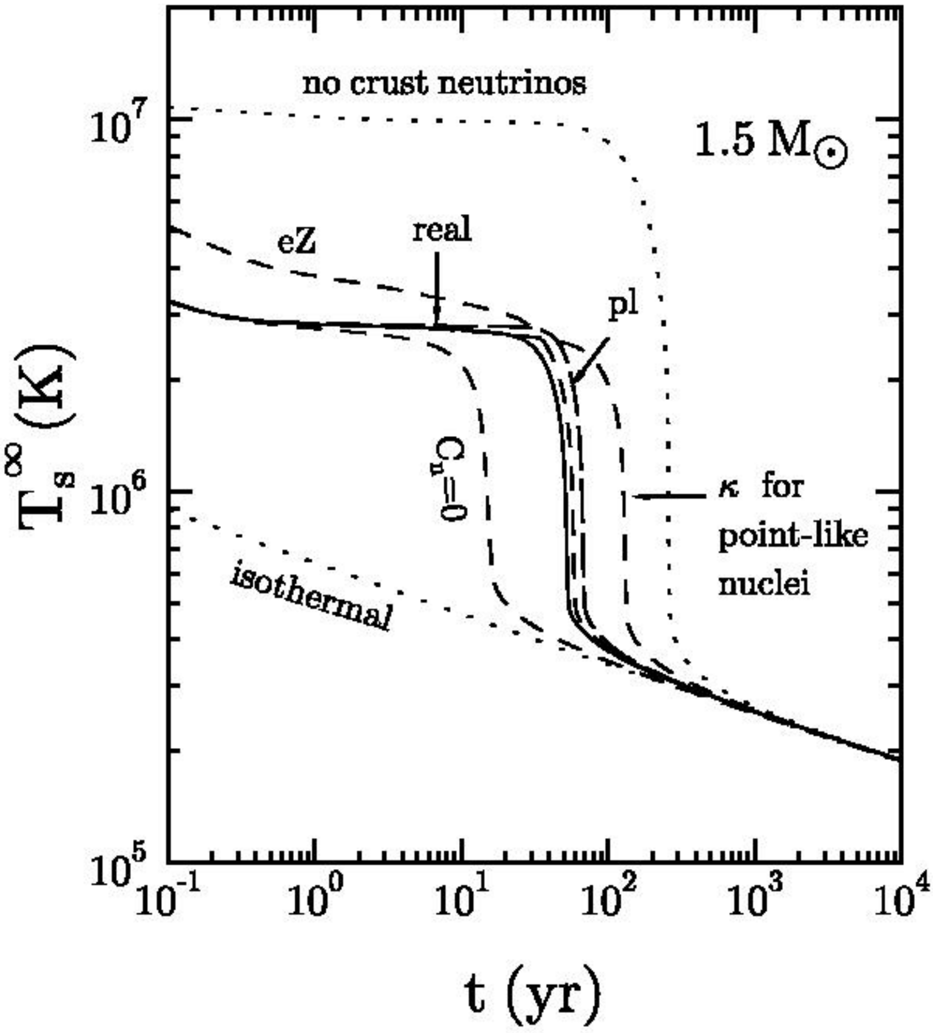
t_W=?

Nomoto, Tsuruta, ApJ 312, 711 (1987)

Lattimer, Van Riper, Prakash, Prakash, ApJ 425, 802 (1994)

Gnedin, Yakovlev, Potekhin MNRAS 325, 725 (2001)

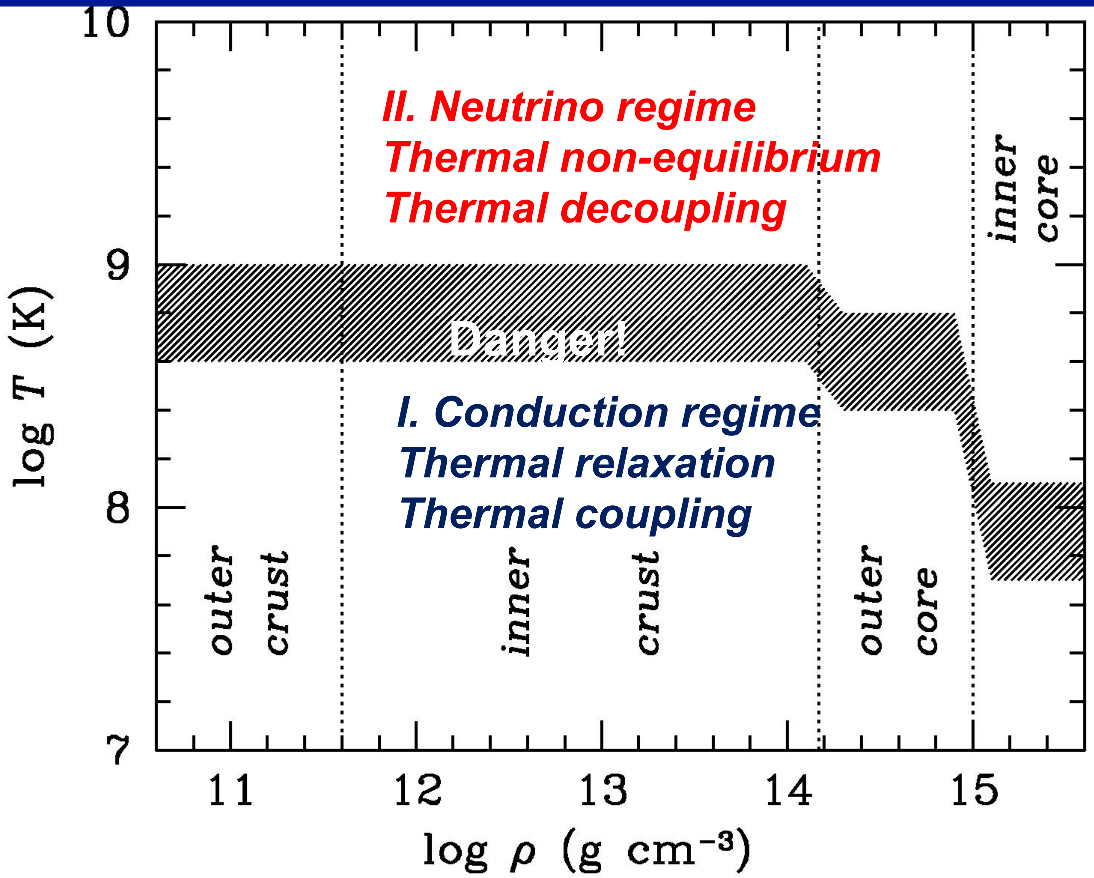
THERMAL RELAXATION
Relaxation Time of a Non-superfluid Star



Physics of crust	*t_W (years)*
Real	*51*
No crust neutrinos	*260*
Plasmon decay neutrinos in crust	*68*
No neutron heat capacity in crust	*15*
Thermal conductivity for point-like nuclei	*130*
Isothermal interior	*0*

Other physics:
Crust-core boundary
Thermal conductivity in the core

TWO THERMAL REGIMES



II. Neutrino regime
Thermal non-equilibrium
Thermal decoupling

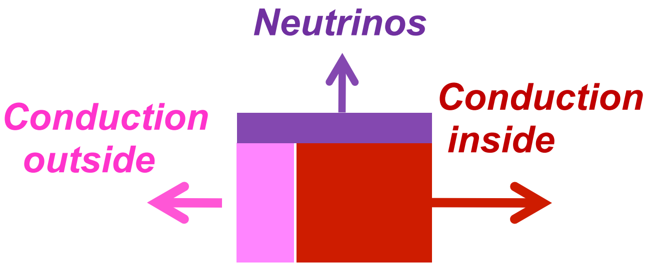
Danger!

I. Conduction regime
Thermal relaxation
Thermal coupling

1

$$T < 10^9 \text{ K}$$

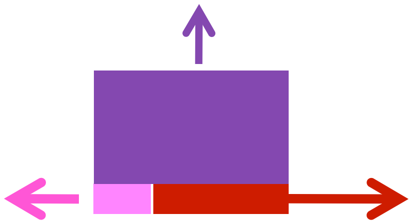
Regulated by thermal conduction



2

$$T > 10^9 \text{ K}$$

Regulated by neutrino emission



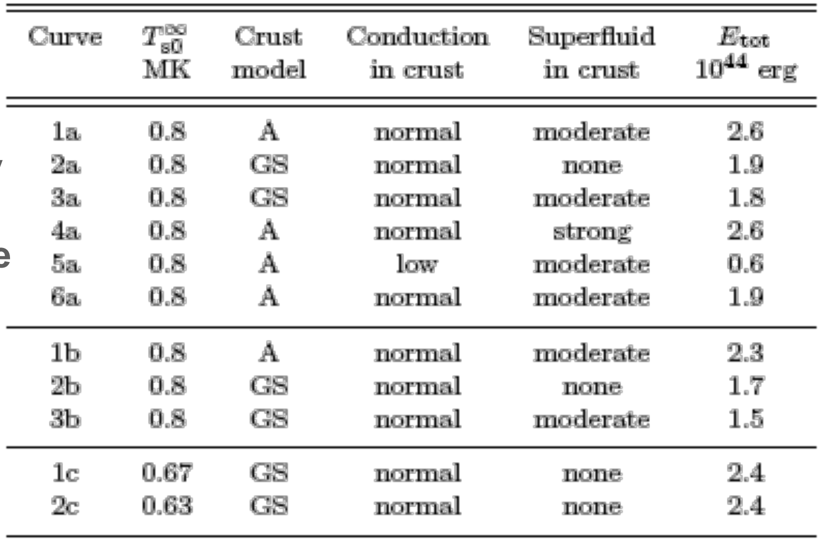
APPLICATIONS: Quasi-persistent XRTs
Modeling of Thermal Relaxation of KS 1731—260

1989=discovery (active)

12.5 yrs = active

Jan. 21, 2001 = last active

Feb. 7, 2001 = quiet



Curve	T_{s0}^{∞} MK	Crust model	Conduction in crust	Superfluid in crust	E_{tot} 10^{44} erg
1a	0.8	A	normal	moderate	2.6
2a	0.8	GS	normal	none	1.9
3a	0.8	GS	normal	moderate	1.8
4a	0.8	A	normal	strong	2.6
5a	0.8	A	low	moderate	0.6
6a	0.8	A	normal	moderate	1.9
1b	0.8	A	normal	moderate	2.3
2b	0.8	GS	normal	none	1.7
3b	0.8	GS	normal	moderate	1.5
1c	0.67	GS	normal	none	2.4
2c	0.63	GS	normal	none	2.4

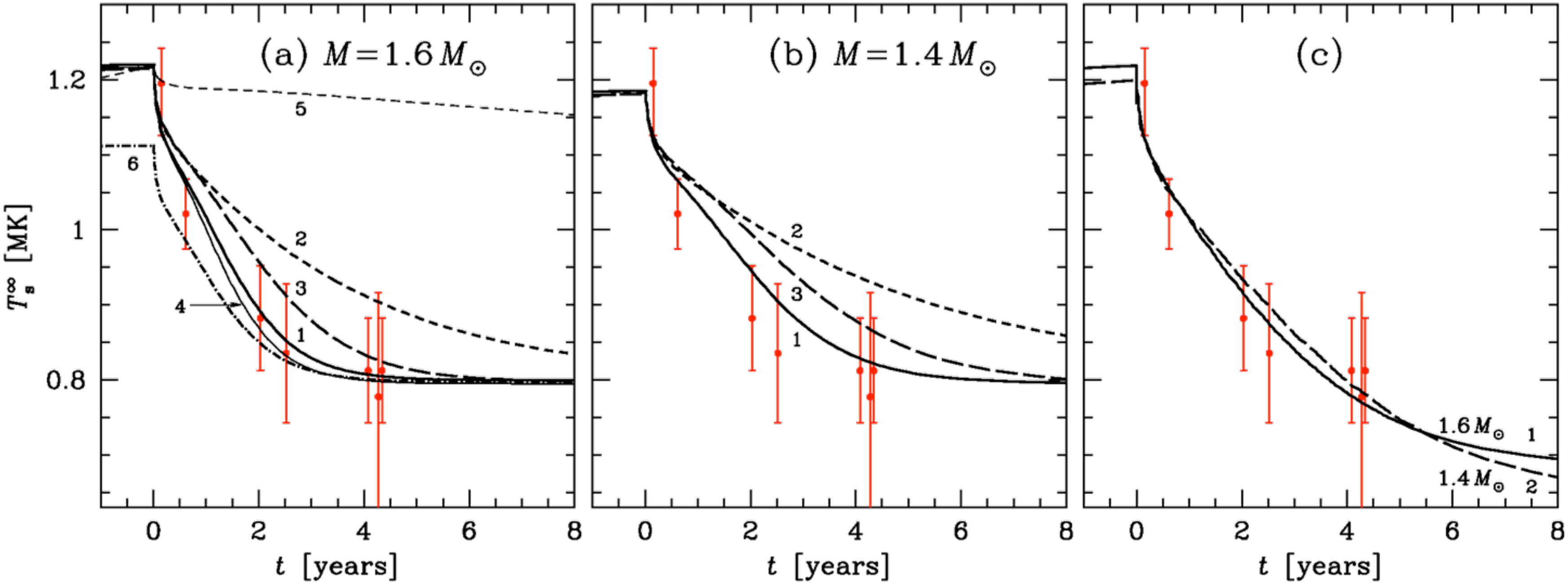
$$E_{tot} \leq 2.4 \cdot 10^{44} \, \mathrm{erg}$$

(a)– thinner crust – faster relaxation, one needs more energy

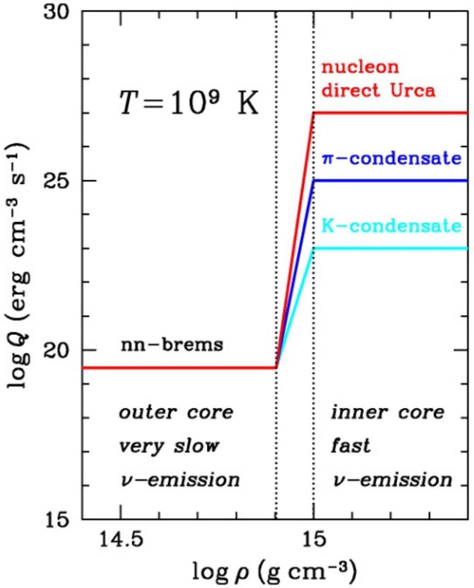
(b)– slower relaxation, but one needs less energy

(c) – crust-core relaxation has not achieved yet

Shternin et al. (2007)

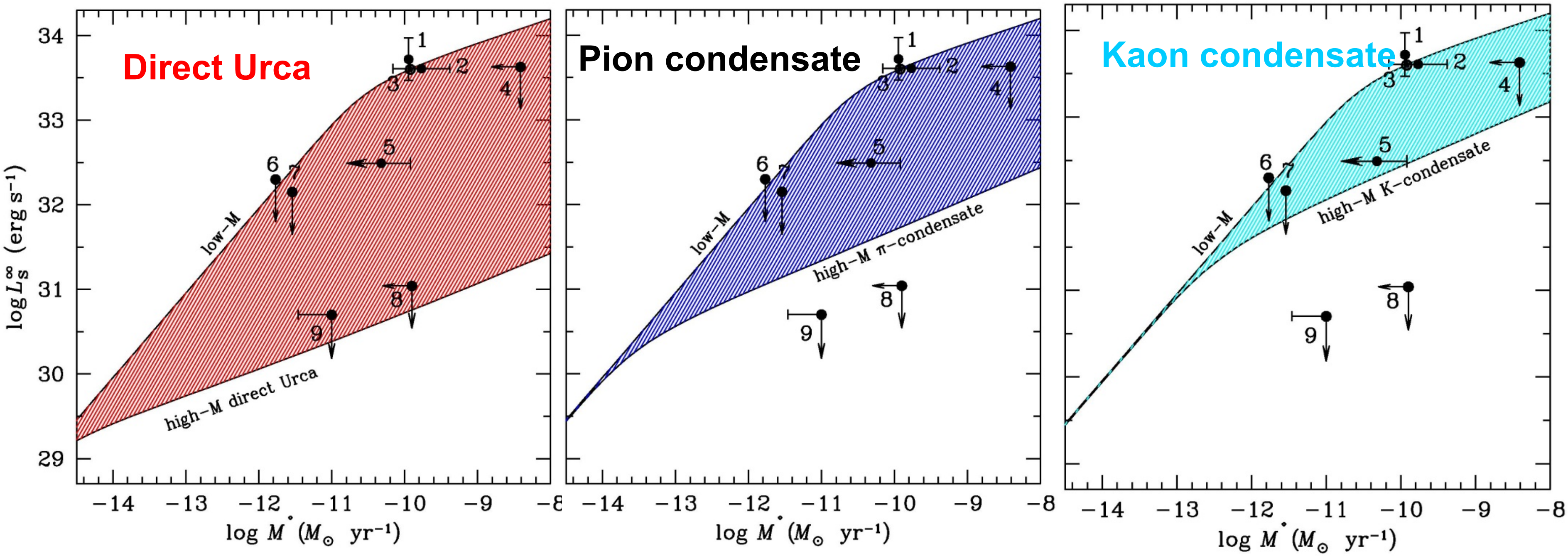


Quasi-stationary XRTs: Theory versus observations



1 **Aql X-1**
2 **4U 1608-522**
3 **RX J1709-2639**
4 **KS 1731-260**
5 **Cen X-4**
6 **SAX J1810.8-2609**
7 **XTE J2123-058**
8 **1H 1905+000**
9 **SAX 1808.4-3658**

Data collected by Kseniya Levenfish



CONCLUSIONS
Observed manifestations of inner crust

Observations	Indication of
Glitches	*Presence of SF*
Quasi-stationary XRTs	*Deep crustal heating* *Open direct Urca in the core*
Quasi-persistent XRTs	*Thermal conductivity in crust is not too low*
Magnetars	*B-field evolves and regulates magnetar activity*
Seismology	*Presence of crystalline crust*

CONCLUSIONS
Good and bad things

Good: (more or less) reliable

- *EOS*
- *Heat capacity of lattice and electrons*
- *Electron transport at not too low T*
- *Elastic properties*
- *Etc…*

Bad: (not very) reliable

- *SF: Tc, pinning, kinetics*
- *Heat capacity of neutrons*
- *Neutron transport*
- *Breaking strain*
- *Impure crust*
- *Multi-component accreted crust*
- *Etc*

We know much less than we should!