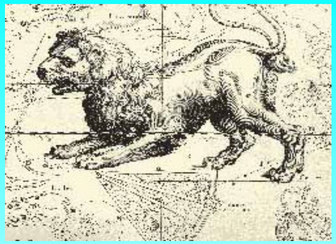
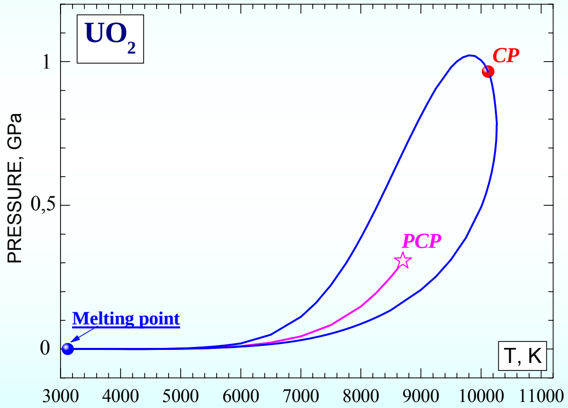
Physics of Neutron Stars

St. Petersburg, June 2008



Phase Transitions in Neutron Stars.

Are they non-congruent?



Igor Iosilevskiy

Moscow Institute of Physics and Technology

(State University)

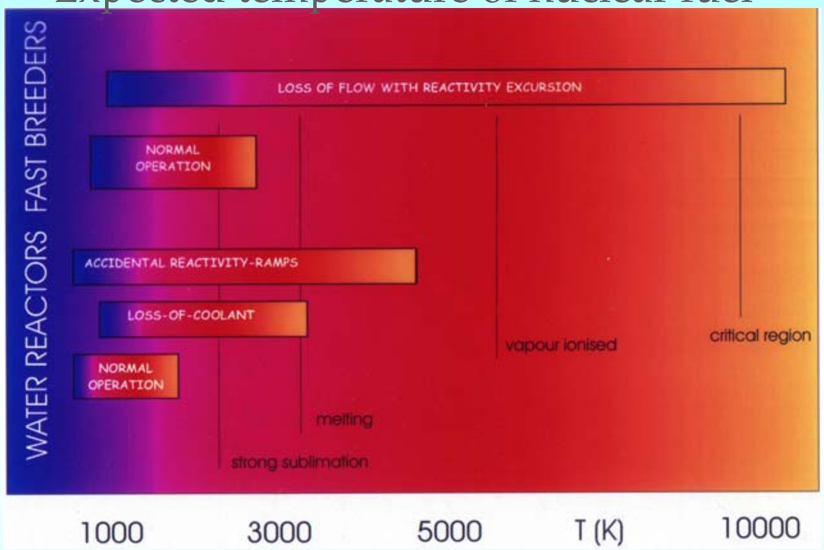
MIPT

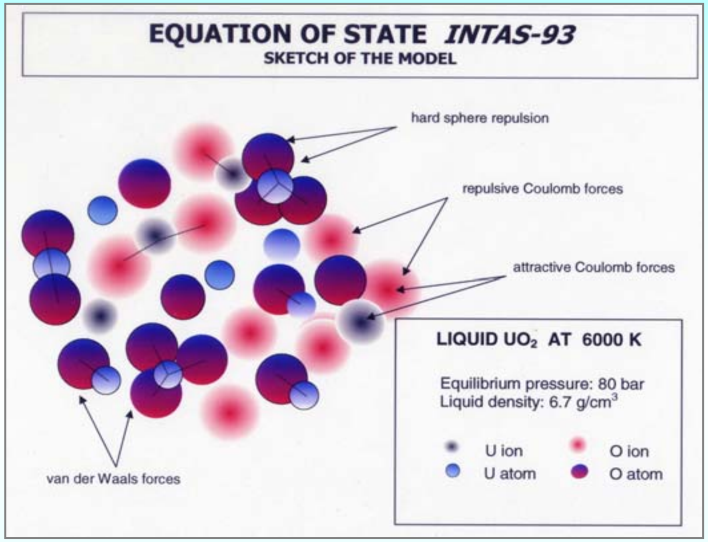
The base

Non-Congruent Phase Transition in Uranium Dioxide

Hypothetical severe accident at fast breeder nuclear reactor

Expected temperature of nuclear fuel





INTAS Project (1995-2002) – ISTC Project (2003–2005)

Cooperation: **MIPT - IHED RAS - IPCP RAS - OSEU**(Ukraine) - **MPEI - ITEP – VNIIEF** (Sarov) ⇔ **ITU** (JRC, Karlsruhe) ⇔ **GSI** (Darmstadt)

Project managers: - *V. Fortov, B. Sharkov* ⇔ Project coordinator: - *C. Ronchi*

Non-congruent phase transition in uranium dioxide

INTAS Project (1995–2002) – ISTC Project (2003–2005)

Sketch of theoretical approach

Quasi-chemical representation for liquid & gaseous phases

Ionic model

(*Liquid*)

$U^{6+} + U^{5+} + U^{4+} + U^{3+} + O^{2-} + O^{-}$

Multi-molecular model

(*Liquid & Gas*)

$U + O + O_2 + UO + UO_2 + UO_3$

$U^{+} + UO^{+} + UO_2^{+} + O^{-} + UO_3^{-} + e^{-}$

Interactions: (*Pseudopotential components*)

– Intensive short-range repulsion
– Coulomb interaction between charged particles
– Short-range effective attraction between all particles

Interaction corrections: (*Modified for mixtures*)

– Hard-sphere mixture with varying diameters
– Modified Mean Spherical Approximation (MSAE+DHSE)
– Modified Thermodynamic Perturbation Theory {TPT- $\sigma(T)$; $\varepsilon(T)$}

* Iosilevskiy I., Yakub E., Hyland G., Ronchi C. *Trans. Amer. Nuclear Soc.* **81,** 122 **(1999)**

* Iosilevskiy I., Yakub E., Hyland G., Ronchi C. *Int. Journal of Thermophysics* **22** 1253 **(2001)**

* Iosilevskiy I., Gryaznov V., Yakub E., Ronchi C., Fortov V. *Contrib. Plasma Phys*. **43**, N 5-6 316 (**2003**)

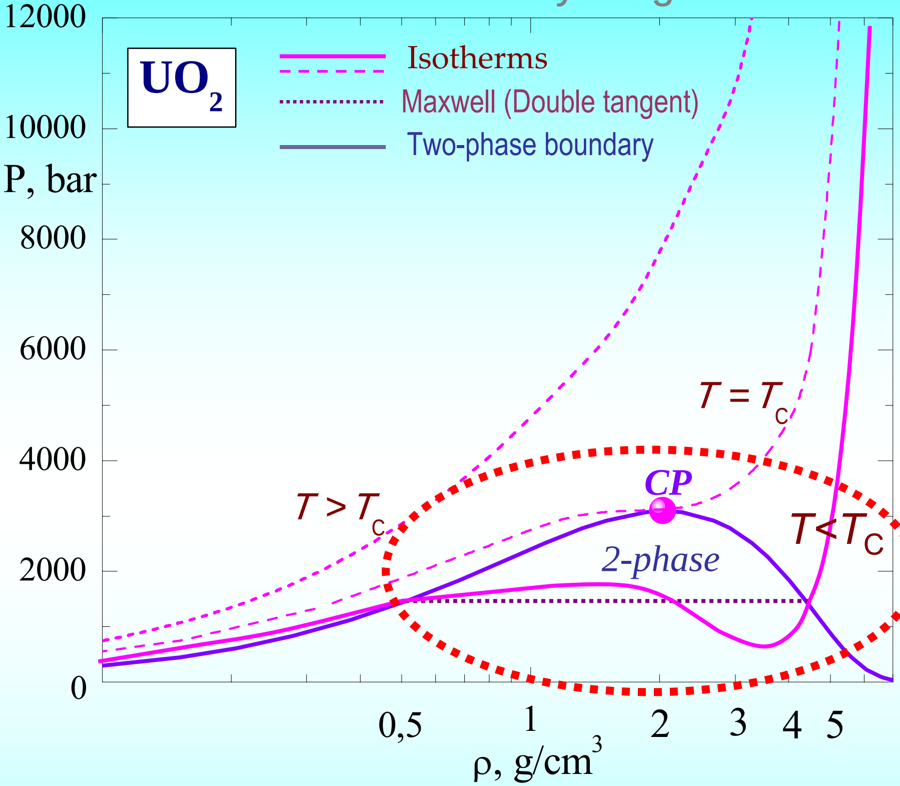
* Ronchi C., Iosilevskiy I., Yakub E. *Equation of State of Uranium Dioxide* / **Springer, Berlin,** (**2004**)

* Iosilevskiy I., Krasnikov Yu., Son E., Fortov V. *Thermophysics of non-ideal plasmas*. MIPT (2000); FIZMATLIT, (2008) /in press/

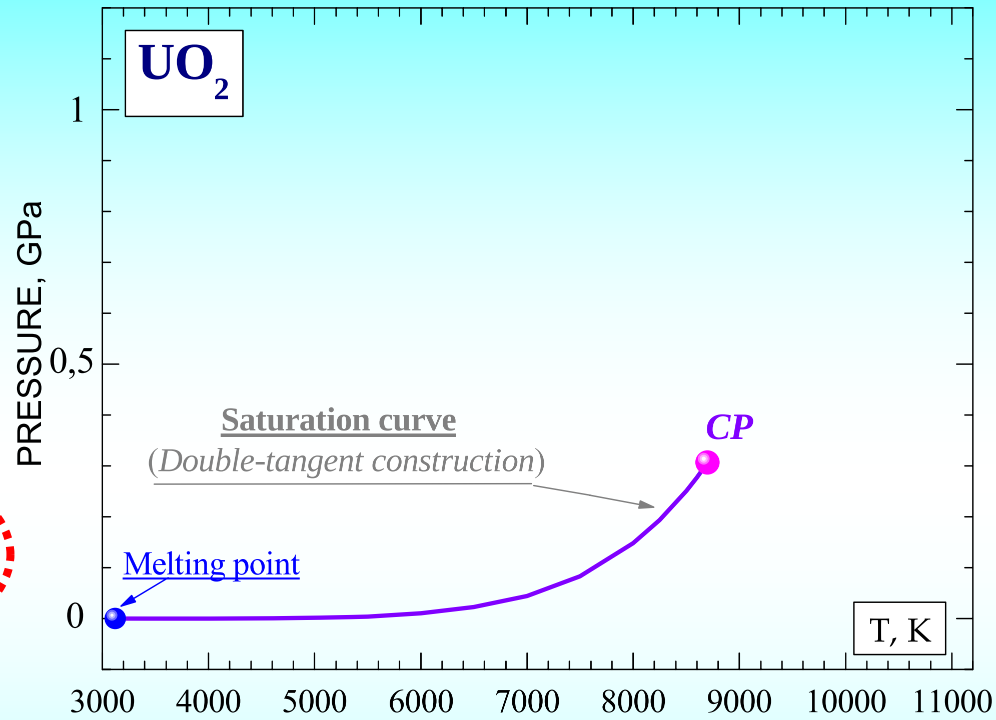
<u>**Standard**</u>

Forced-congruent evaporation in U-O system

Pressure - Density Diagram



Pressure - Temperature Diagram



- Stoichiometry of coexisting phases are equal: $x' = x''$

It should be

$x' \neq x''$

- Van der Waals loops (at $T < T_c$) corrected via the "double tangent construction"
- Standard phase equilibrium conditions:

$P' = P''$ // $T' = T''$ // $G'(P,T,x) = G''(P,T,x)$

- Standard critical point:

$(\partial P/\partial V)_T = 0$ // $(\partial^2 P/\partial V^2)_T = 0$ // $(\partial^3 P/\partial V^3)_T <$

It should be

$\mu_1'(P,T,x') = \mu_1''(P,T,x'')$
$\mu_2'(P,T,x') = \mu_2''(P,T,x'')$
. . . .
$\mu_k'(P,T,x') = \mu_k''(P,T,x'')$

Phase equilibrium conditions in reacting Coulomb system

φ'	Phase - I $n_i' + n_k' + \ldots + n_e'$	Phase -II $n_i'' + n_k'' + \ldots + n_e''$	φ''

Heat exchange

$$T' = T''$$

Impulse exchange

$$P' = P''$$

Particle Exchange

Neutral species

$$\mu_1'(P,T,x') = \mu_1''(P,T,x'')$$
$$\mu_2'(P,T,x') = \mu_2''(P,T,x'')$$
$$\ldots\ldots\ldots\ldots\ldots$$
$$\mu_k'(P,T,x') = \mu_k''(P,T,x'')$$

Equilibrium reactions

(reduced number of basic units)

$$\mu_a'(P,T,x') = \mu_a''(P,T,x'')$$
$$\mu_b'(P,T,x') = \mu_b''(P,T,x'')$$

Uranium – Oxygen system

$$\mu_U'(P,T,x') = \mu_U''(P,T,x'')$$
$$\mu_O'(P,T,x') = \mu_O''(P,T,x'')$$

! *Basic units in NS: – baryons and electrons* **!**

Charged species

NB! - Chemical potentials of charged species are not equal

Electro-chemical potentials are equal

$$\mu_i' + Z_i e\,\varphi' = \mu_i'' + Z_i e\,\varphi''$$

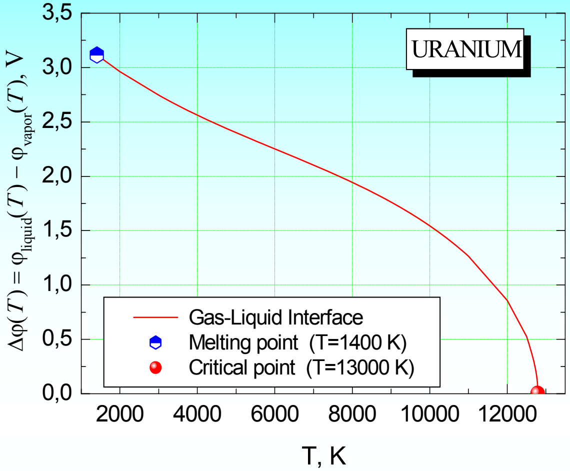
Potential drop at any mean-phase interface in equilibrium Coulomb system

$$\mu_1'(P,T,x') = \mu_1''(P,T,x'') + \Delta\varphi\, Z_1 e$$
$$\mu_2'(P,T,x') = \mu_2''(P,T,x'') + \Delta\varphi\, Z_2 e$$
$$\ldots\ldots\ldots\ldots\ldots$$
$$\mu_e'(P,T,x') = \mu_e''(P,T,x'') - \Delta\varphi\, e$$

Electrostatics of Phase Boundaries in Coulomb Systems

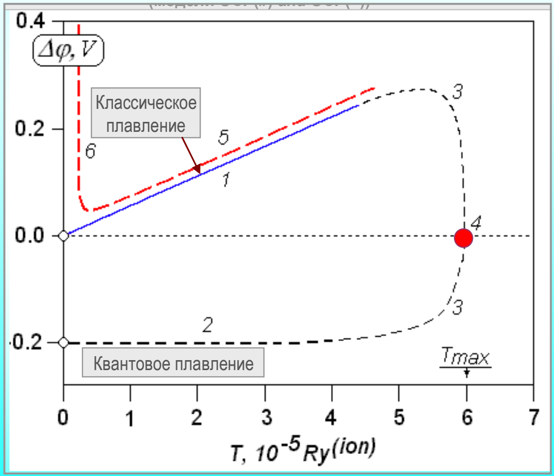
Terrestrial applications

Electrostatic (Galvani) potential



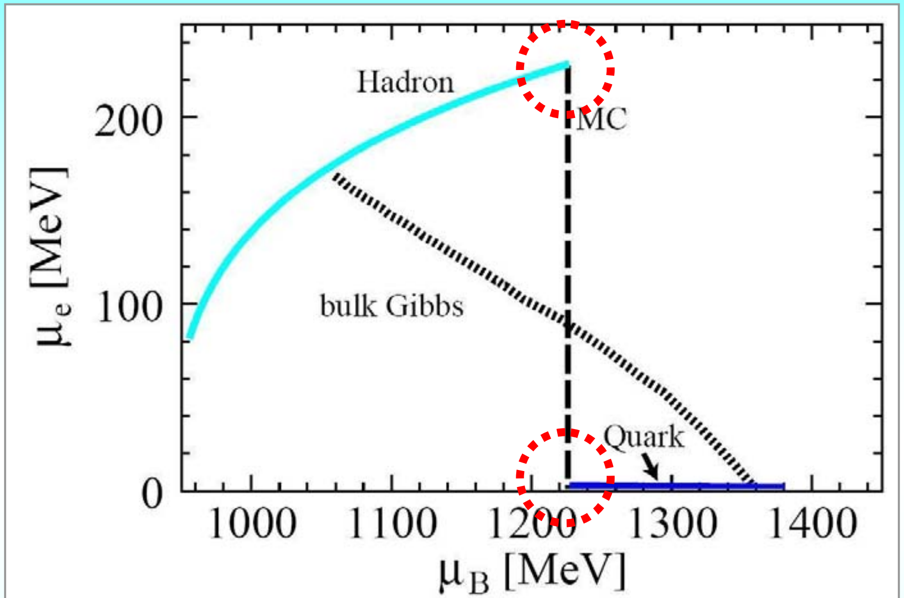
Iosilevski & Gryaznov, *J.Nucl.Mat.* (2005)

Electrostatic "portrait" of Wigner crystal in OCP



Iosilevski & Chigvintsev, *J. Physique* (2000)

Quark-hadron phase transition in NS



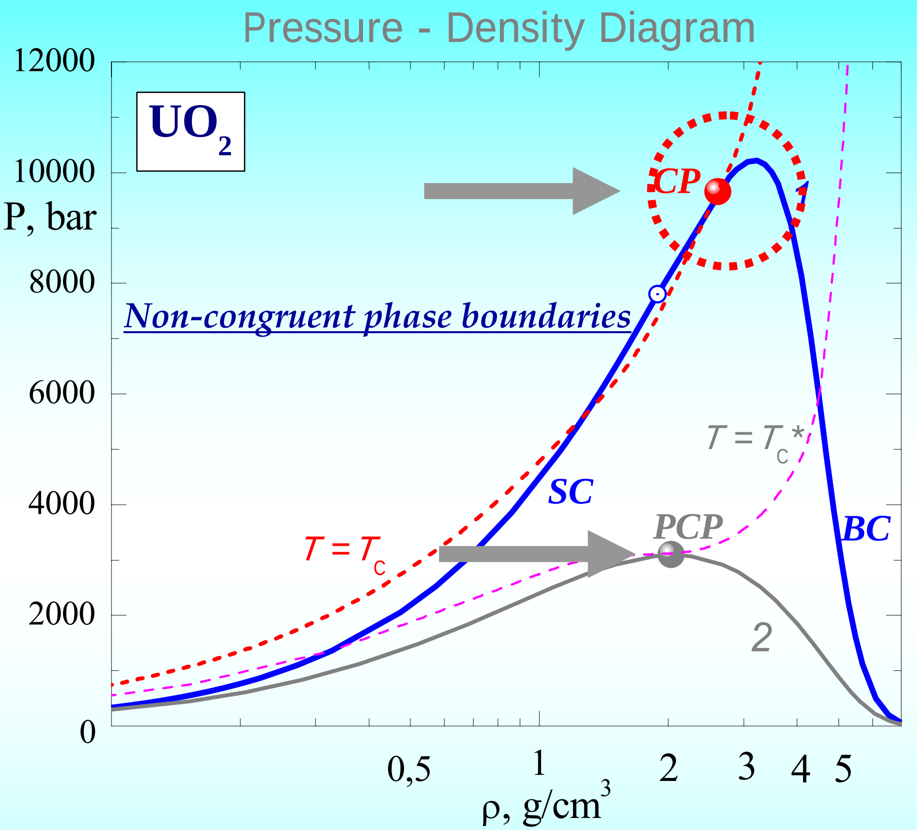
Phase diagram in the $\mu_B - \mu_e$ plane.

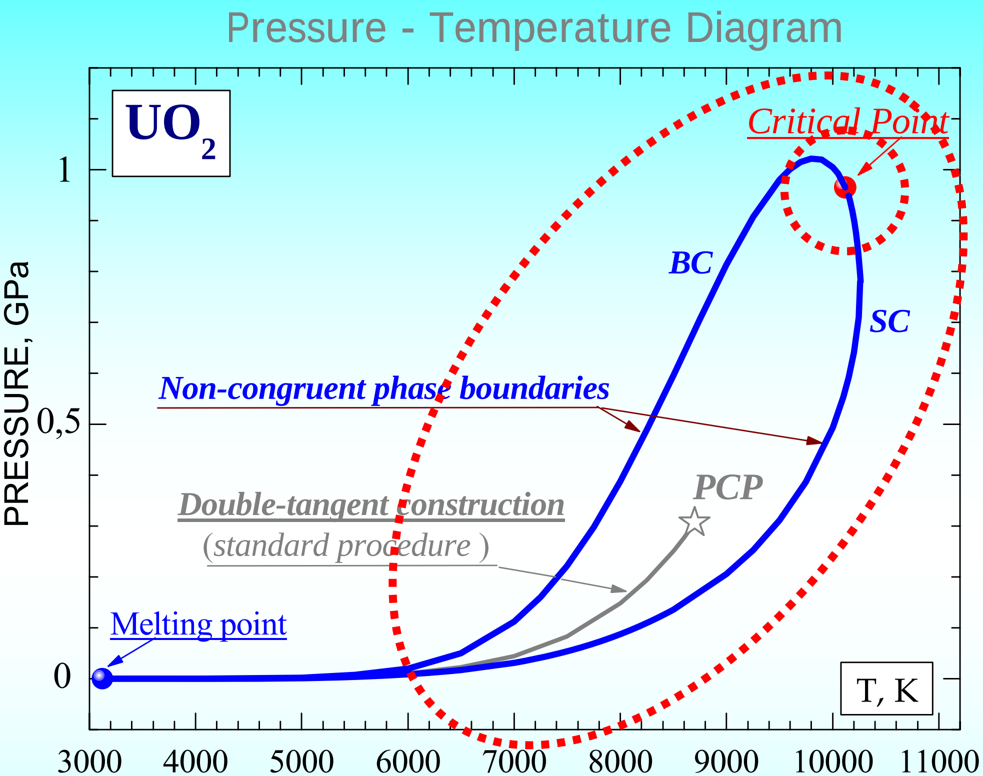
Endo T., Maruyama T., Chiba S., Tatsumi T.
arXiv:astro-ph/0601017v1/ 2006 /

$$e\Delta\varphi_{HQ} = (\mu_e)_{\text{Hadron phase}} - (\mu_e)_{\text{Quark phase}}$$

$$e\Delta\varphi_{HQ} \approx 200\ \text{MeV}$$ **!**

Non-congruent evaporation in U-O system





1 – Non-congruent (total) equilibrium
2 – Forced-congruent (partial) equilibrium

BC – Boiling (liquid) conditions
SC – Saturated (vapor) conditions

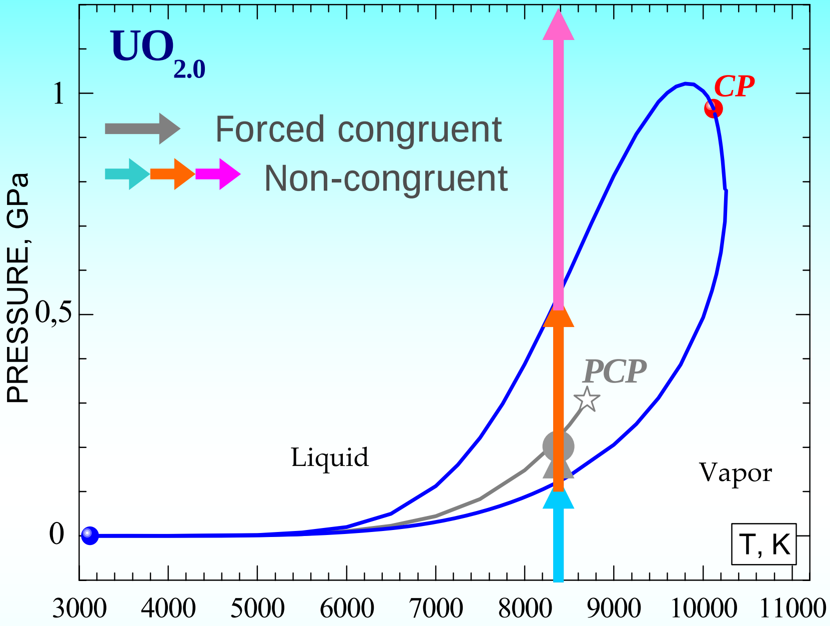
NB! **2-dimensional** two-phase **region** instead of standard *P-T* **saturation curve**

NB! **High pressure level** of non-congruent phase decomposition

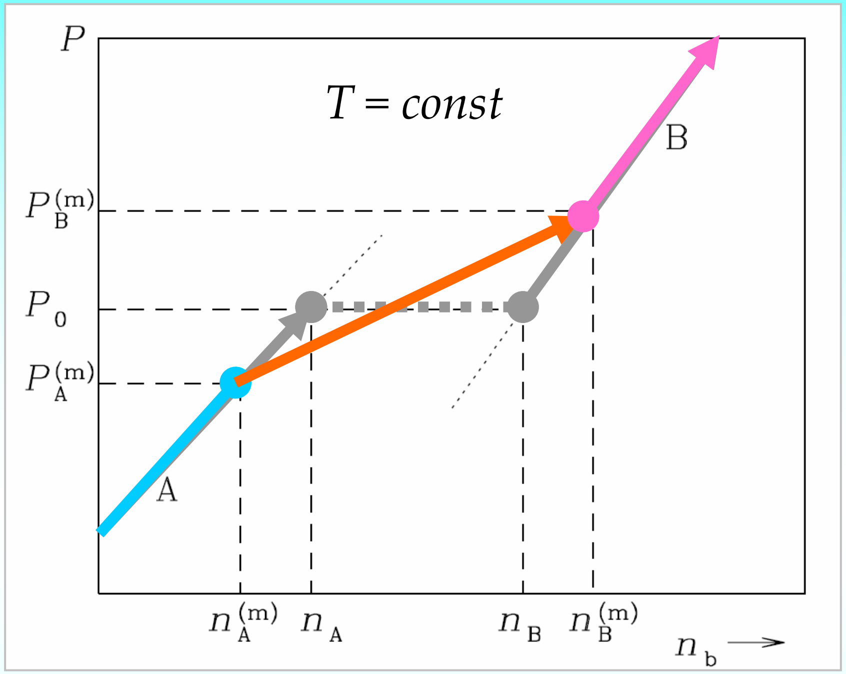
NB! **Critical point** should be of **non-standard** type: $(\partial P/\partial V)_T \neq 0$ $(\partial^2 P/\partial V^2)_T \neq 0$

It should be instead: $(O/U)_{liquid} = (O/U)_{vapor}$ and $\{\|\partial \mu_i / \partial n_k\|_T\}_{CP} = 0$

Non-congruent phase transformation in two-phase region

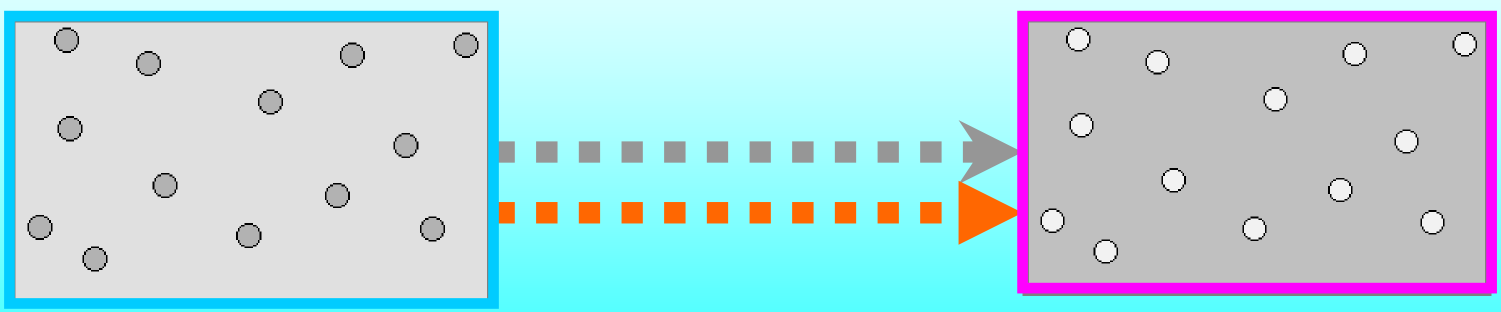


Phase Diagram *P-T* of Non-congruent Evaporation



First liquid droplets in saturated vapor

Small vapor bubbles in boiling liquid



Oxygen depleted liquid!

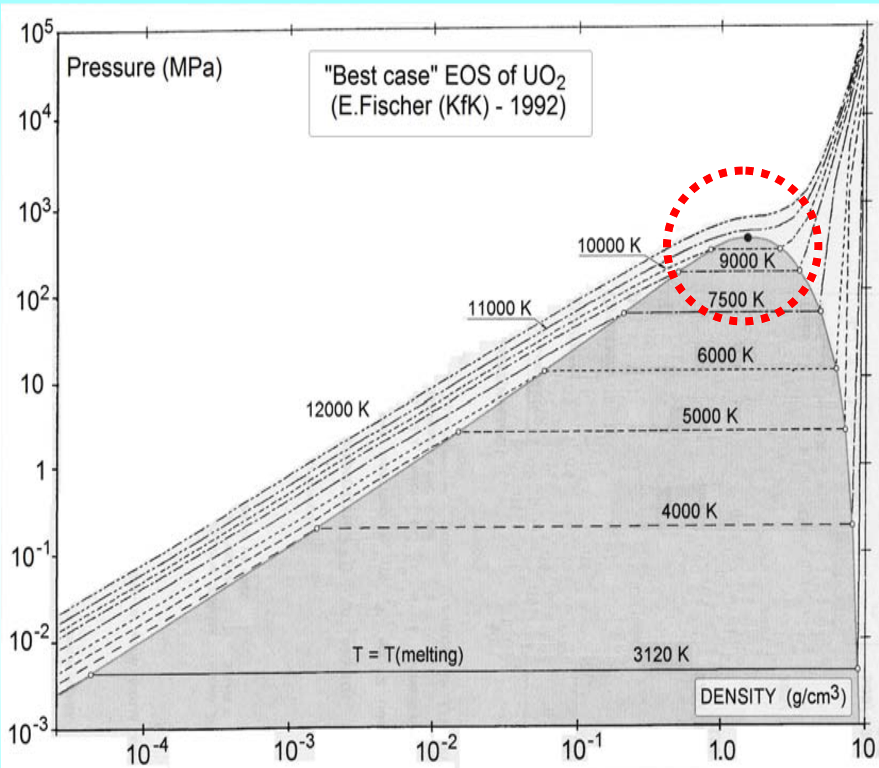
***Different stoichiometry*!**

Oxygen enriched vapor

! *Different stoichiometry*!

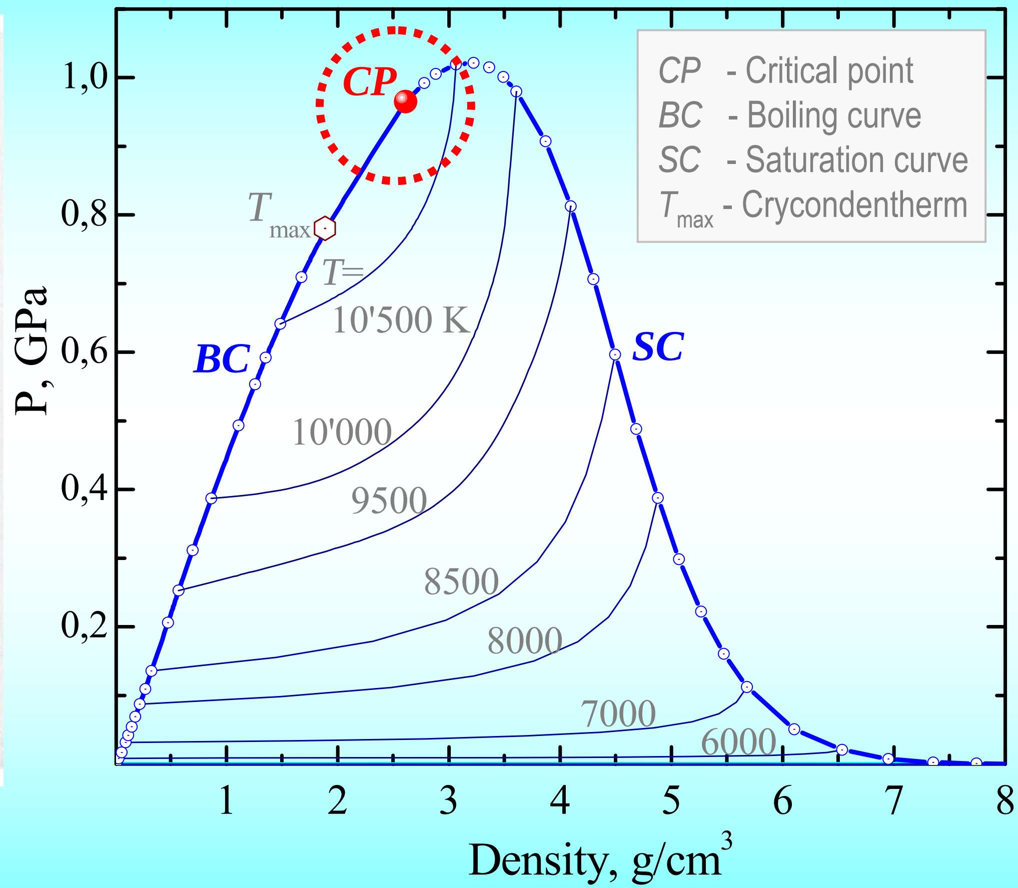
Isotherms in two-phase region

Standard pressure-density diagram



Fischer E.A. *J. Nucl. Sci. Eng.* (1989)

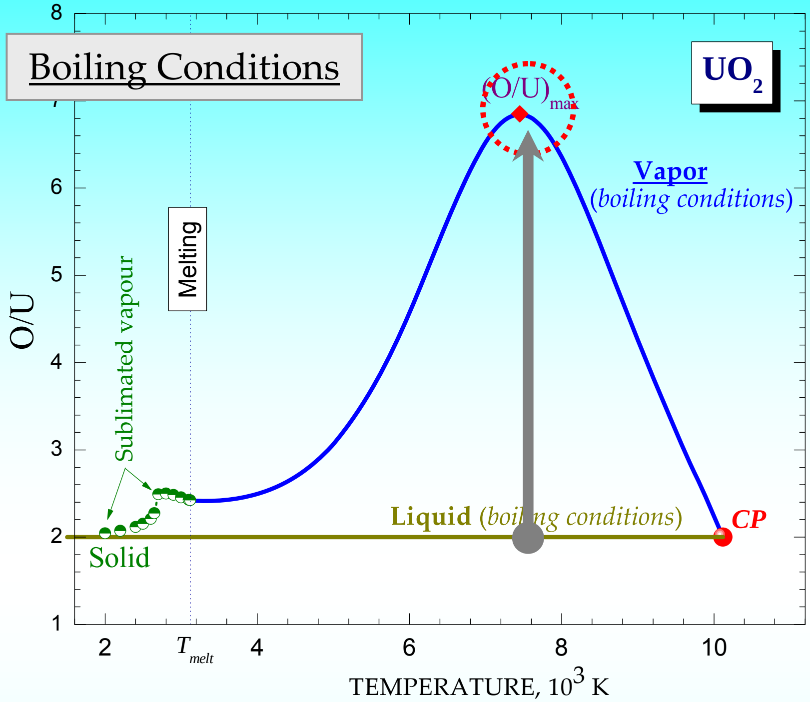
Non-congruent pressure-density diagram

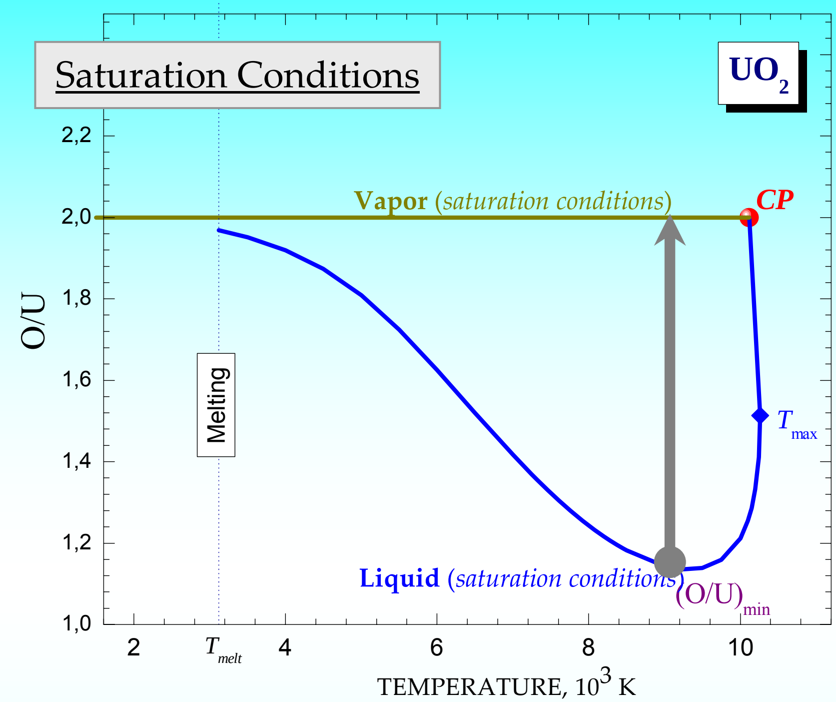


- **Isothermal** phase transition starts and finishes at ***different pressures***

- **Isobaric** phase transition starts and finishes at ***different temperatures***

Chemical composition of coexisting phases

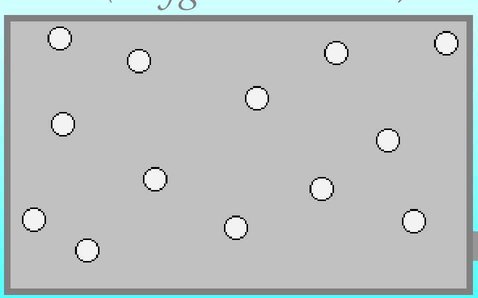


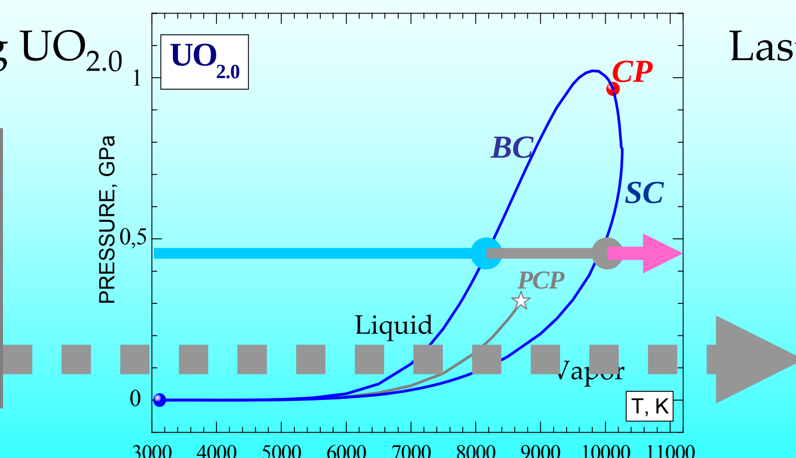


$P = const$

First vapor bubbles in boiling $UO_{2.0}$

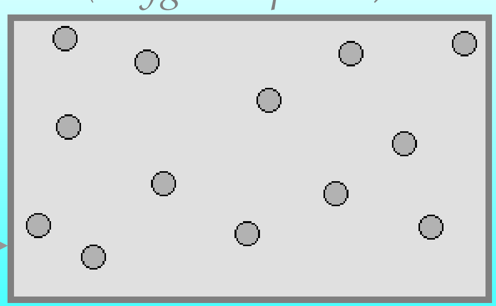
(oxygen enriched)





Last liquid drops in vapor $UO_{2.0}$

(oxygen depleted)



Liquid (O/U = 2.0) ⇔ Vapor (O/U > 2.0)

Vapor (O/U = 2.0) ⇔ Liquid (O/U < 2.0)

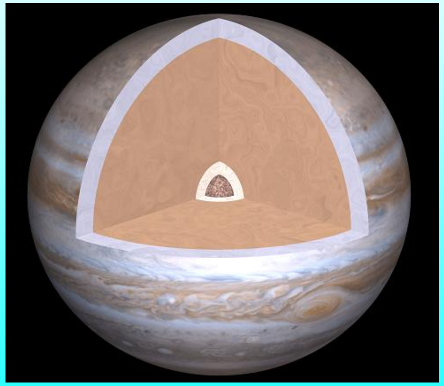
Non-congruence of phase transition in U-O system – – is it an exception or a general rule ?

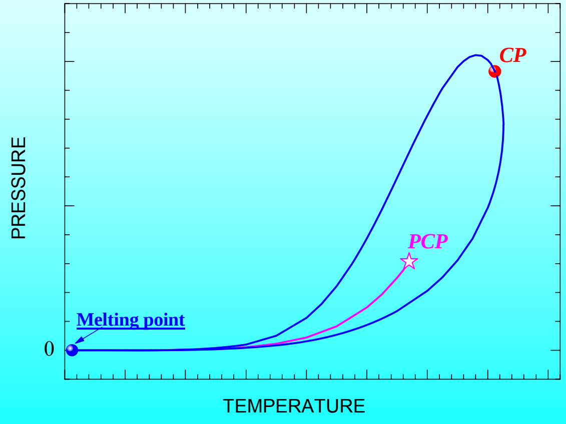
Basic conclusion

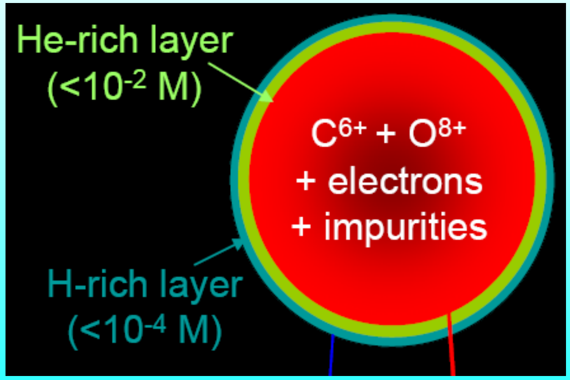
- Any phase transition in a system of **two** or **more chemical elements** must be **non-congruent**
- **Congruent** phase transition is **exception**

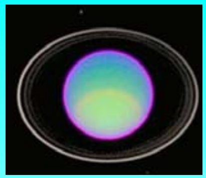
Hypothetical example of non-congruent phase transition

- ***Plasma Phase Transition*** *in* **H_2/He** *mixture in* ***Jupiter, Saturn, Brown Dwarfs*** *and* ***Extra-Solar Planets*** *. . .*
- ***Coulomb crystallization*** *in* **C^{6+}/O^{8+}/He^{4+}** *mixture in* ***White Dwarfs*** *and in multi-nuclear* ***envelope*** *of* ***Neutron Stars***
- ***Quark-hadron phase transition*** *in* ***interiors*** *of* ***Strange Stars***



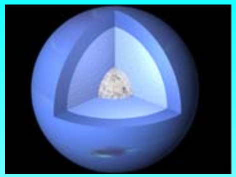






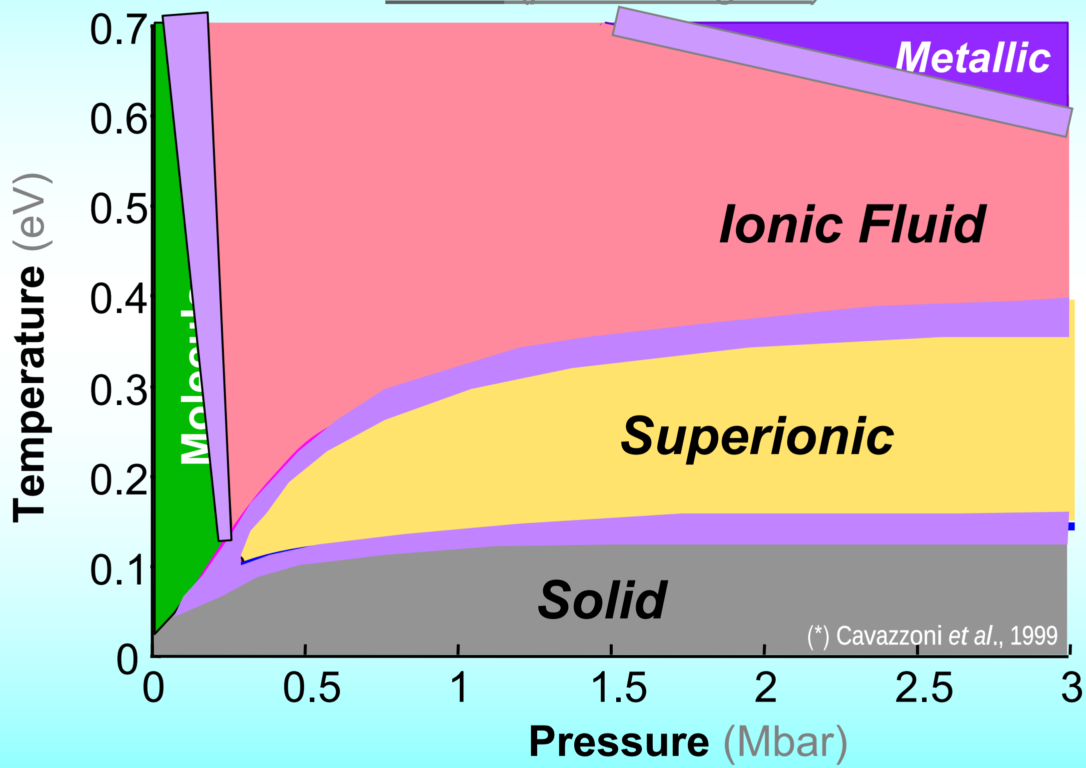
BASIC STATEMENT:

Any phase transition in a system of **two or more chemical elements** must be **non-congruent**



Neptune and "Hot-water" extrasolar planet GJ436b

Water *(phase diagram)*



GJ436b

Star: - Gliese 436 (RD)

$M \sim 22 M_O$

$R \sim 4 R_O$

$\Delta T \sim 2{,}6$ days (!)

$T_{Surf.} \sim 500$ K

Main Comp. – H_2O

= «» =

(*Discovered* – 2007)

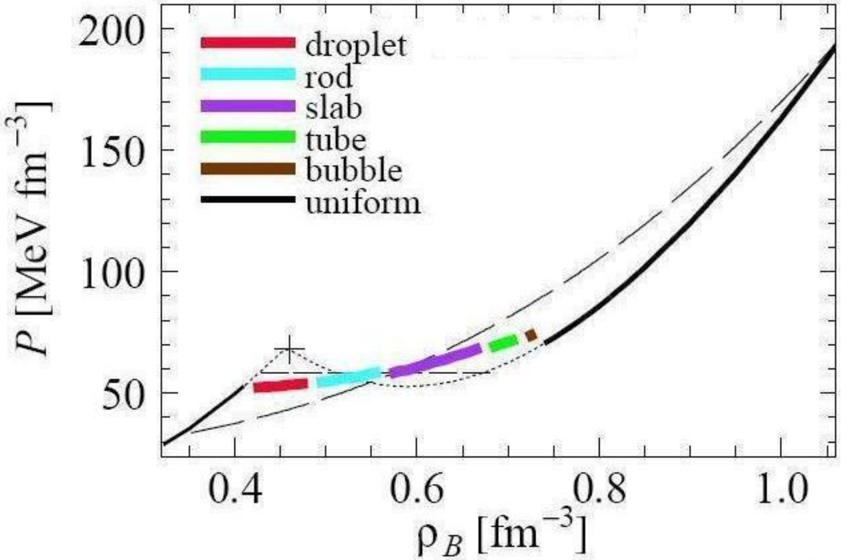
T. Mattsson & M. Desjarlais (*Sandia Lab.*): *High energy-density water: DFT – simulations*
PNP-12, 2006, Darmstadt, Germany // WEHS-workshop 2007, Bad Honnef, Germany,

Any phase transition in high-*T*_high-*P* water *must be non-congruent*

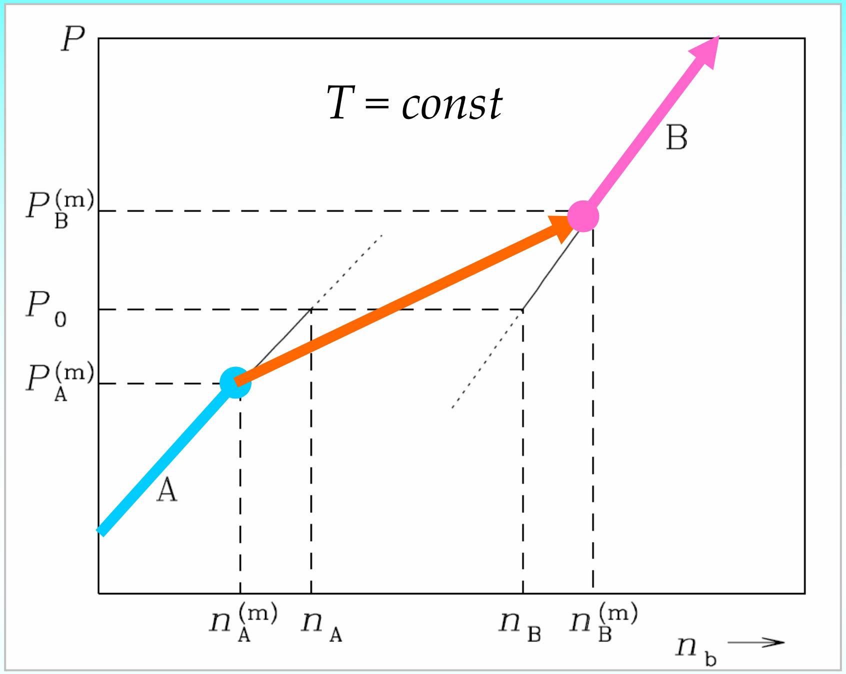
Hypothetical phase transitions in interior of neutron stars:

are they CONGRUENT or NON-CONGRUENT ?

Pasta structures in compact stars



Maruyama T., Tatsumi T., Endo T., Chiba S.
/arXiv:nucl-th/0605075v2 /2006/



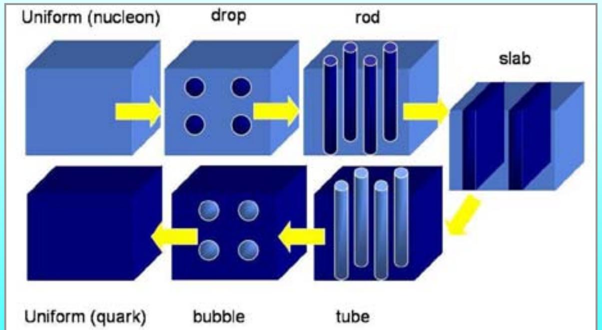
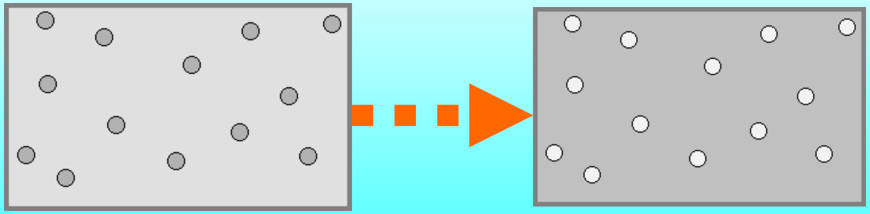


Figure 2: Schematic image of structured mixed phase.

Endo T., Maruyama T., Chiba S., Tatsumi T.
arXiv:astro-ph/0601017v1/ 2006 /

First quark droplets in hadron matter



Last hadron bubbles in quark matter

Structured Mixed Phase ⇔ 'Pasta' plasma

'Pasta' plasma – hadron-quark phase transition in interior of neutron stars
('Mixed phase' of Glendenning *et al.*)

- Charged quark droplets (rods, slabs) in equilibrium hadron matter
- Charged hadron droplets (rods, slabs) in equilibrium quark matter

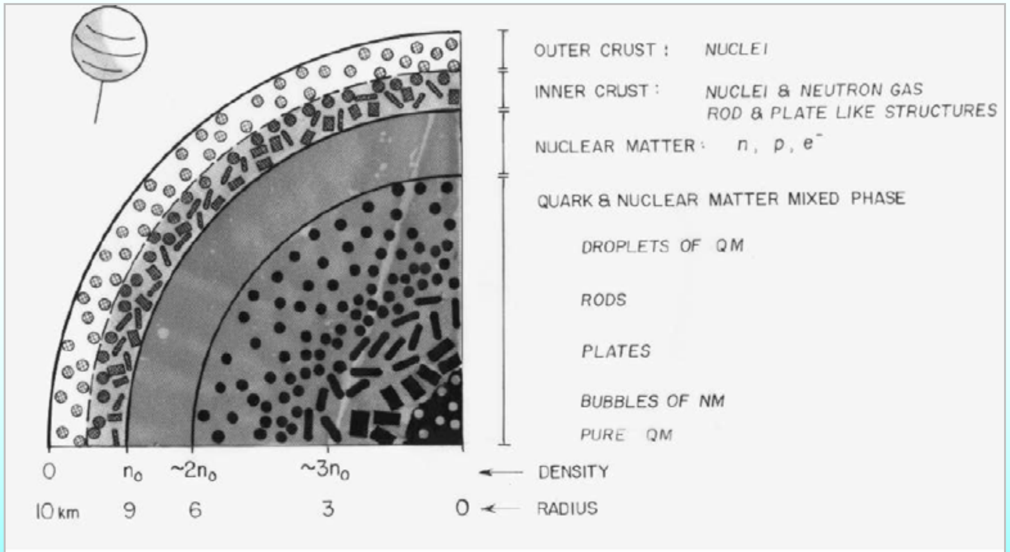


Fig. 1. Nuclear and quark matter tructures in a $\sim 1.4 M_\odot$ neutron star. Typical sizes of structures are $\sim 10^{-14} m$ but have been scaled up to be seen.

Heiselberg and Hjorth-Jensen
Phase Transitions in Neutron Stars
arXiv:astro-ph/9802028v1 (1998)

T.Maruyama, T.Tatsumi, T.Endo, S.Chiba

Pasta structures in compact stars
arXiv:nucl-th/0605075v2 31 (2006)

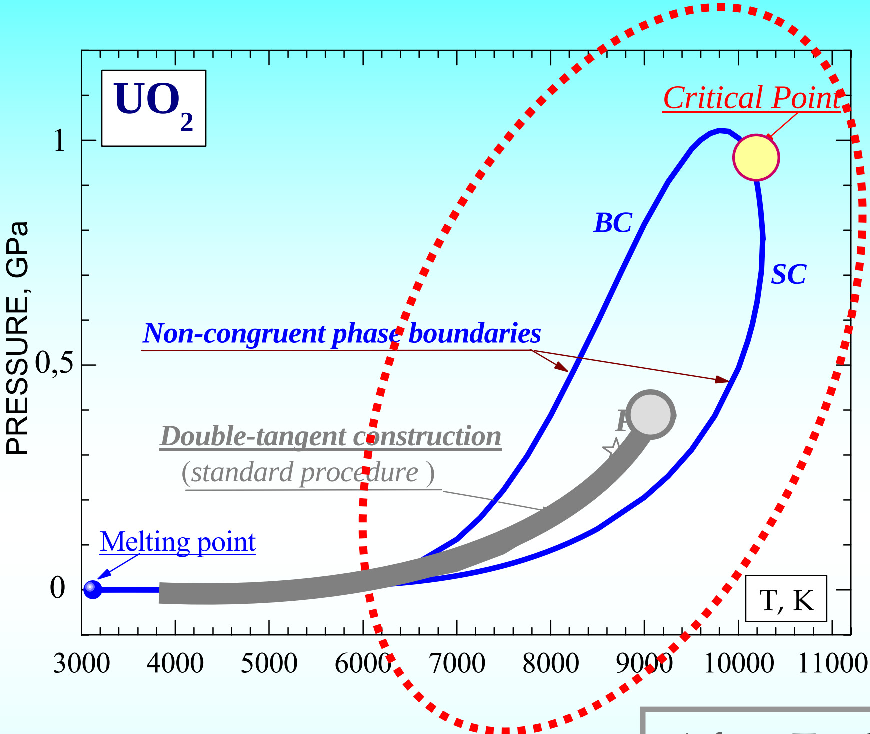
Structured Mixed Phase Transitions – are they congruent or not ?

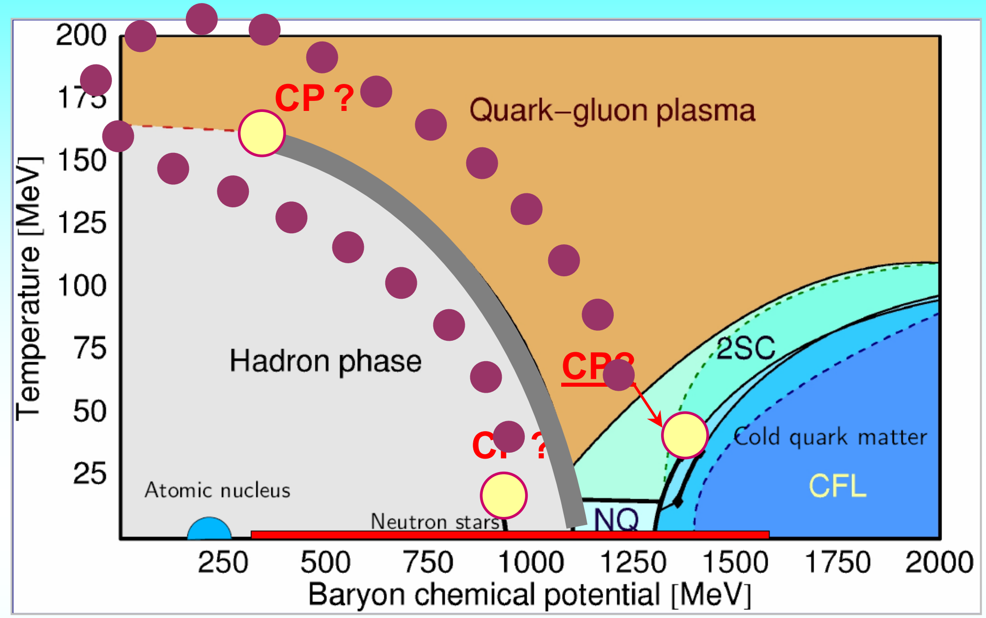
Что пользы нам в неконгруэнтности кроме замены терминологии?

What's the use of talking about non-congruence besides terminology changing ?

Hypothetical phase transitions in interior of neutron stars:

are they CONGRUENT or NON-CONGRUENT ?





After **Fridolin Weber**, WEHS Seminar, Bad Honnef, 2006
After **David Blaschke**, WEHS Seminar, Bad Honnef, 2007

?

- Forced-congruent phase transition

- Non-congruent phase transition

А так ли важна структура фазовых превращений в NS при высоких температурах?

What's a matter of high-temperature phase transformations in NS ?

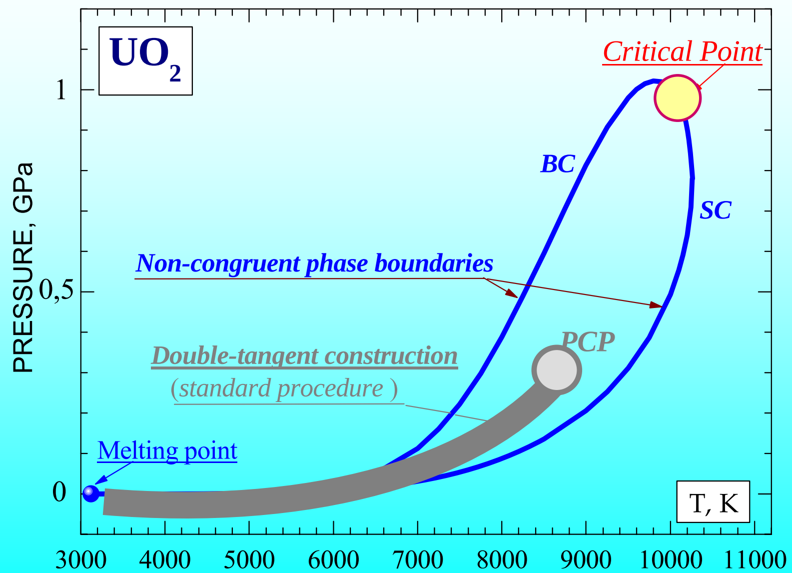
Evaporation of strange matter in the early Universe

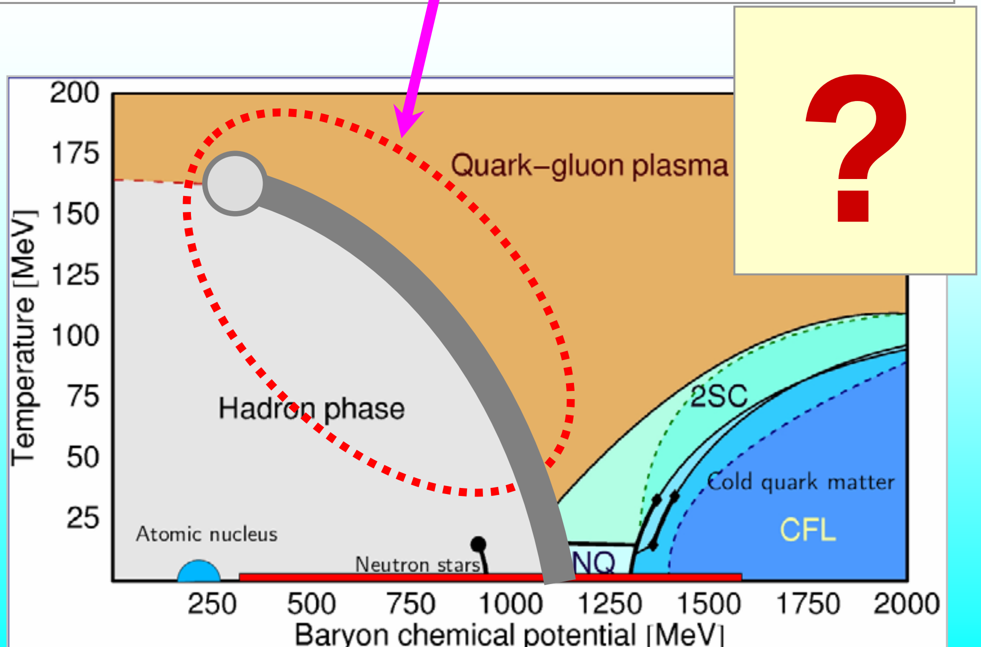
Alcock C., Farhi E. *(PRD, 1985)*

Alcock C., Olinto A. *(PRD, 1989)*

Strange matter, a stable form of quark matter containing a large fraction of strange quarks, may have been copiously produced when the Universe had a temperature of ~ 100 MeV. We study the evaporation of lumps of strange matter as the Universe cooled to 1 MeV. Only lumps with baryon number larger than $\sim 10^{52}$ could survive. This places a severe restriction on scenarios for strange-

Strange matter is a form of quark matter that has been conjectured to be stable at zero temperature. If heated to a temperature $T \geq 2$ MeV, a strange-matter lump evaporates nucleons from its surface. We show that at higher temperatures ($T \gtrsim 20$ MeV), strange matter *boils*, with bubbles of hadronic gas forming and growing throughout the interior. Strange matter, or any other phase which resembles strange matter, could not have survived this process in the early Universe.





Hypothetical phase transitions in interior of neutron stars:

are they CONGRUENT or NON-CONGRUENT ?

Главный вопрос:

– каков сценарий фазовых превращений в NS при высоких температурах?

Main point:

– Phase transformations in NS at high temperature?

2

Basic feature of non-congruent phase transition dynamics

Parameters of non-congruent phase transformation strongly depend on rapidity of the transition.

Main point – competition between thermal conductivity and diffusion

- There are two limiting regimes of transformation:
  - **Slow**, totally equilibrium transformation ("Global" equilibrium mode)
  - **Fast**, partially equilibrium transformation without change of stoichiometry (Forced-congruent mode - FCM)

- Terrestrial applications:
  - ***Evaporation*** *under the intensive* ***surface heating*** *(**laser**, **electron** or **ion beam** etc.)*

?

What's scenario of non-congruent phase transitions in NS and WD

- "Slow" crystallization in WD looks like Global Equilibrium Mode.

- "Fast" crystallization in NS looks like Forced-congruent Mode.

Evaporation of strange matter in the early Universe

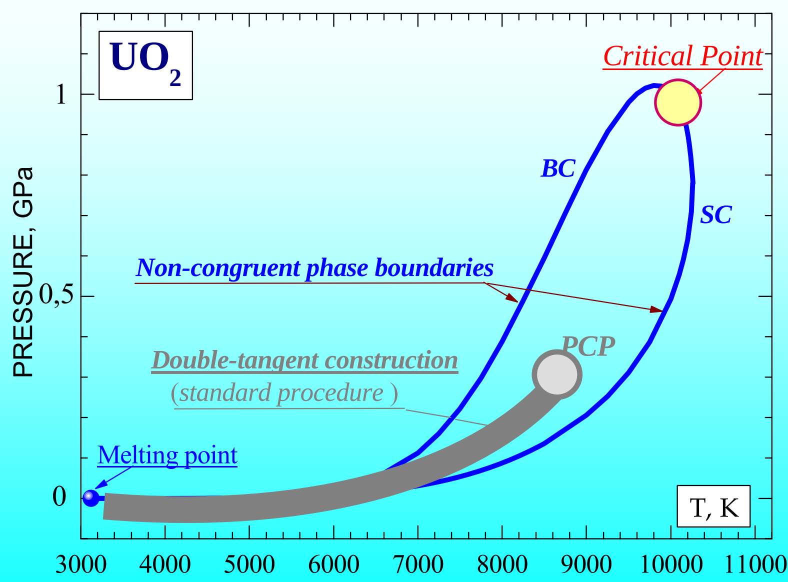
Alcock C., Farhi E. *(PRD, 1985)*

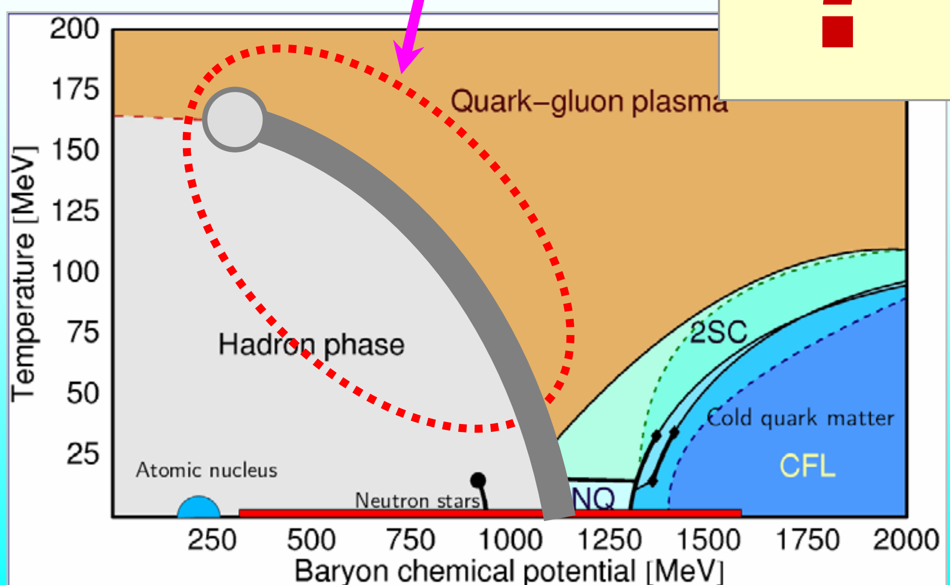
Alcock C., Olinto A. *(PRD, 1989)*

What's scenario of hypothetical non-congruent boiling up (*foam*) of strange matter lumps in early Universe

surface. We show that at higher temperatures ... strange matter *boils*, with bubbles of hadronic gas forming and growing throughout the interior. Strange matter, or any ... which resembles strange matter, could not have survived this process in the early Univers...

?





Crystallization on C/O mixture in White Dwarf

Phase diagram in C/O mixture

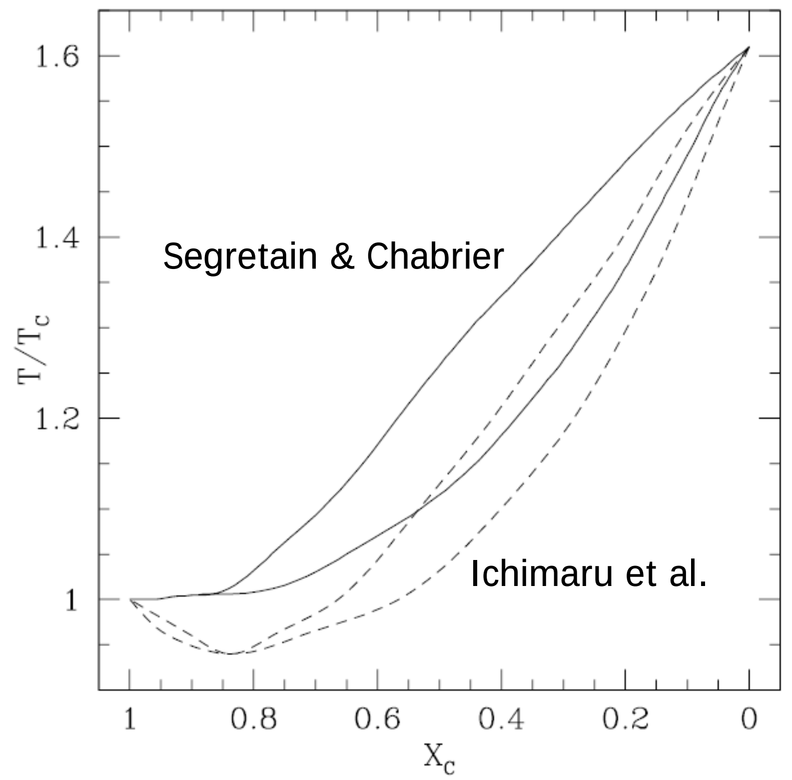


FIG. 1.—Phase diagrams for a C/O mixture as computed by Ichimaru et al. (1988, *dashed line*) and Segretain & Chabrier (1993, *solid line*), where

Phase diagram in C/O mixture

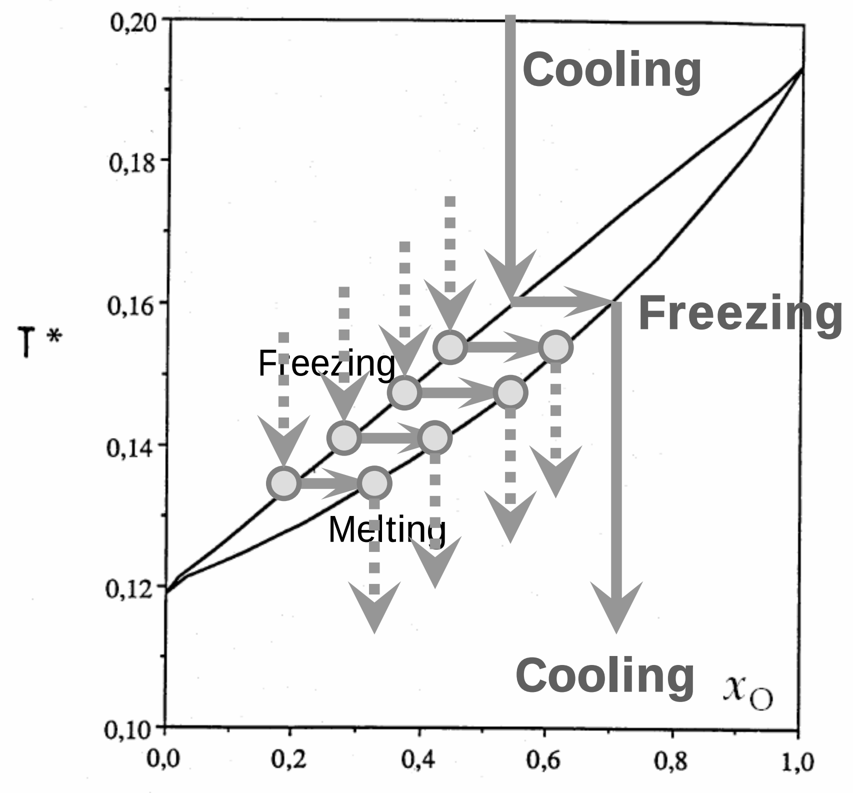


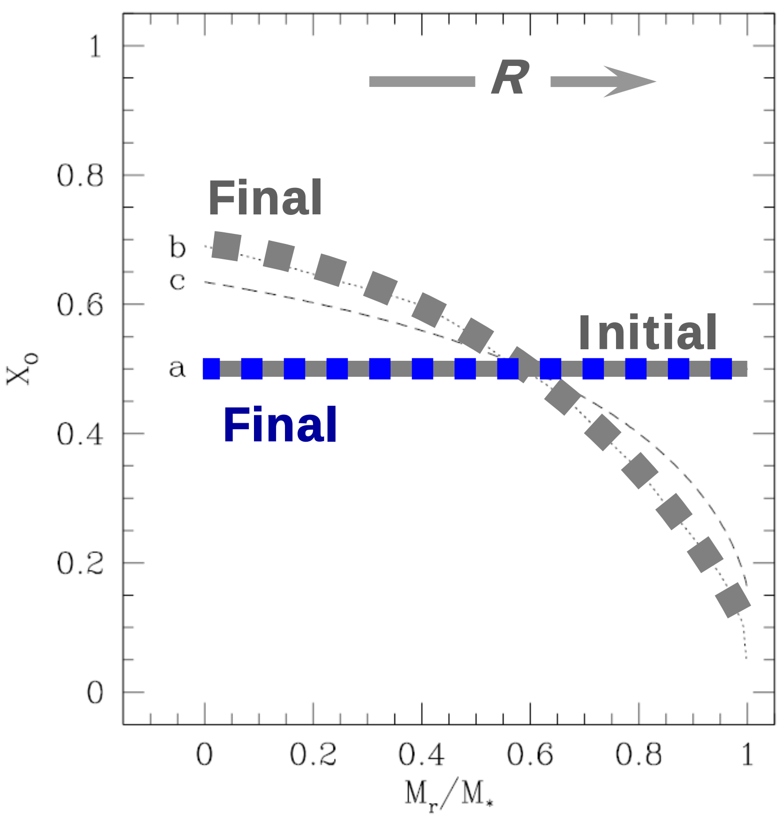
Fig. 1. Phase diagram of the carbon-oxygen mixture at constant electronic pressure. $T^* = 1/\Gamma$ is the reduced temperature,

J.Barrat, J.P.Hansen, R.Mochkovich (1988)

"Slow" crystallization in WD looks like *Global Equilibrium Mode*

Crystallization on C/O mixture in White Dwarf

Oxygen profile in WD



a) – initial
b) – final (Ichimaru)
b) – final (Segretain & Chabrier)

Phase diagram in C/O mixture

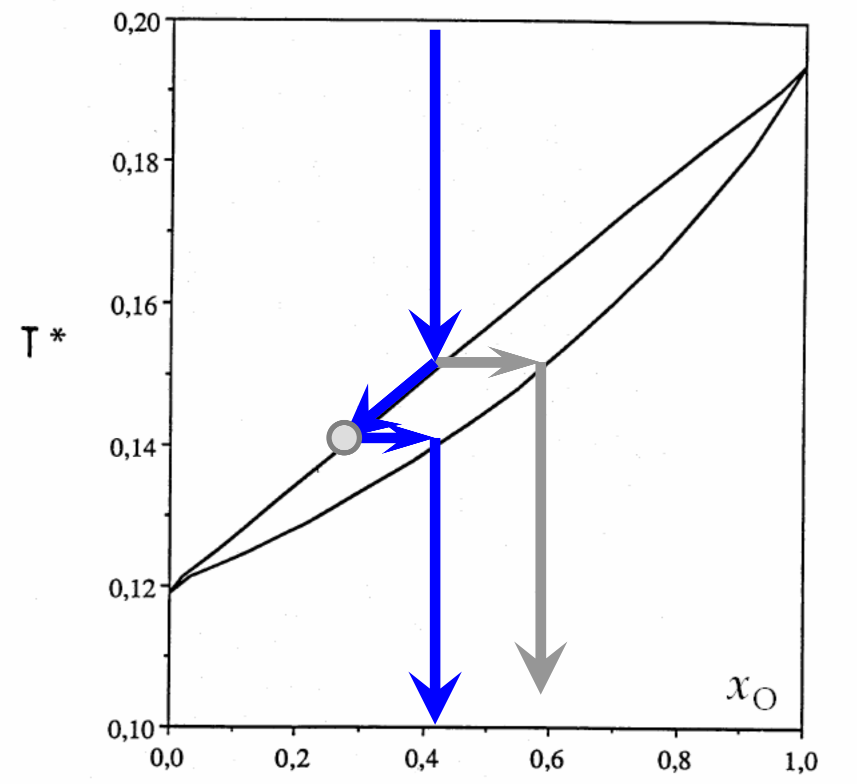


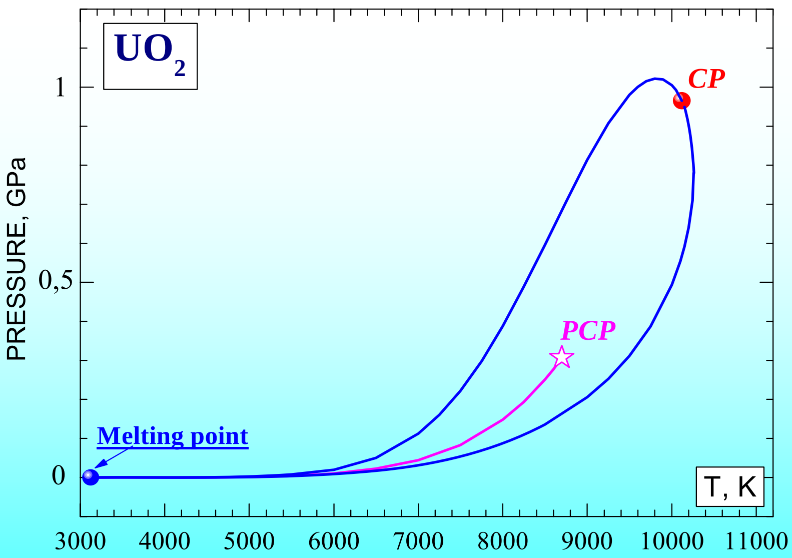
Fig. 1. Phase diagram of the carbon-oxygen mixture at constant electronic pressure. $T^* = 1/\Gamma$ is the reduced temperature,

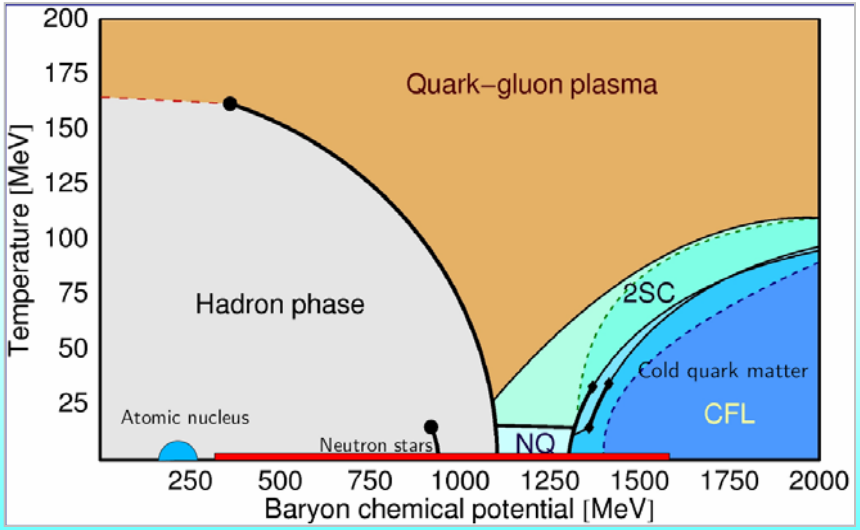
J.Barrat, J.P.Hansen, R.Mochkovich (1988)

"Fast" crystallization in NS looks like *Forced-Congruent Mode*

Conclusion

If one takes into account hypothetical **non-congruence** of **phase transitions** in neutron stars he should **revise** totally the **scenario** of all the phase transformations in NS





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