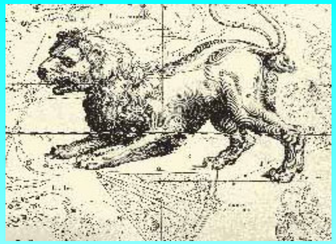
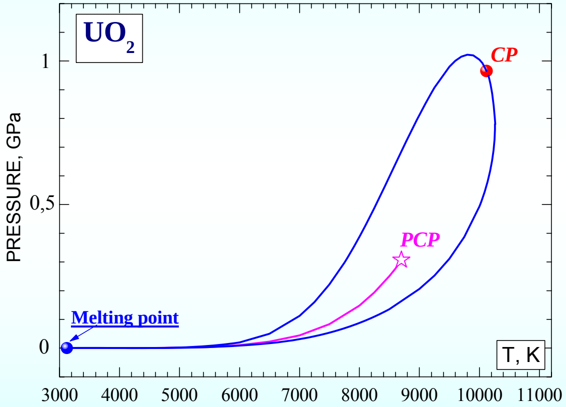


EMMI : Cosmic Matter in the Laboratory

Workshop, Moscow, RAS, May 14-15, 2009

Non-congruent Phase Transitions

in Cosmic Matter *and* Laboratory



Igor Iosilevskiy

Joint Institute for High Temperature (Russian Academy of Science)
Moscow Institute of Physics and Technology (State University)

IHED RAS
MIPT

Elemental Abundance in Solar and Extrasolar Planets

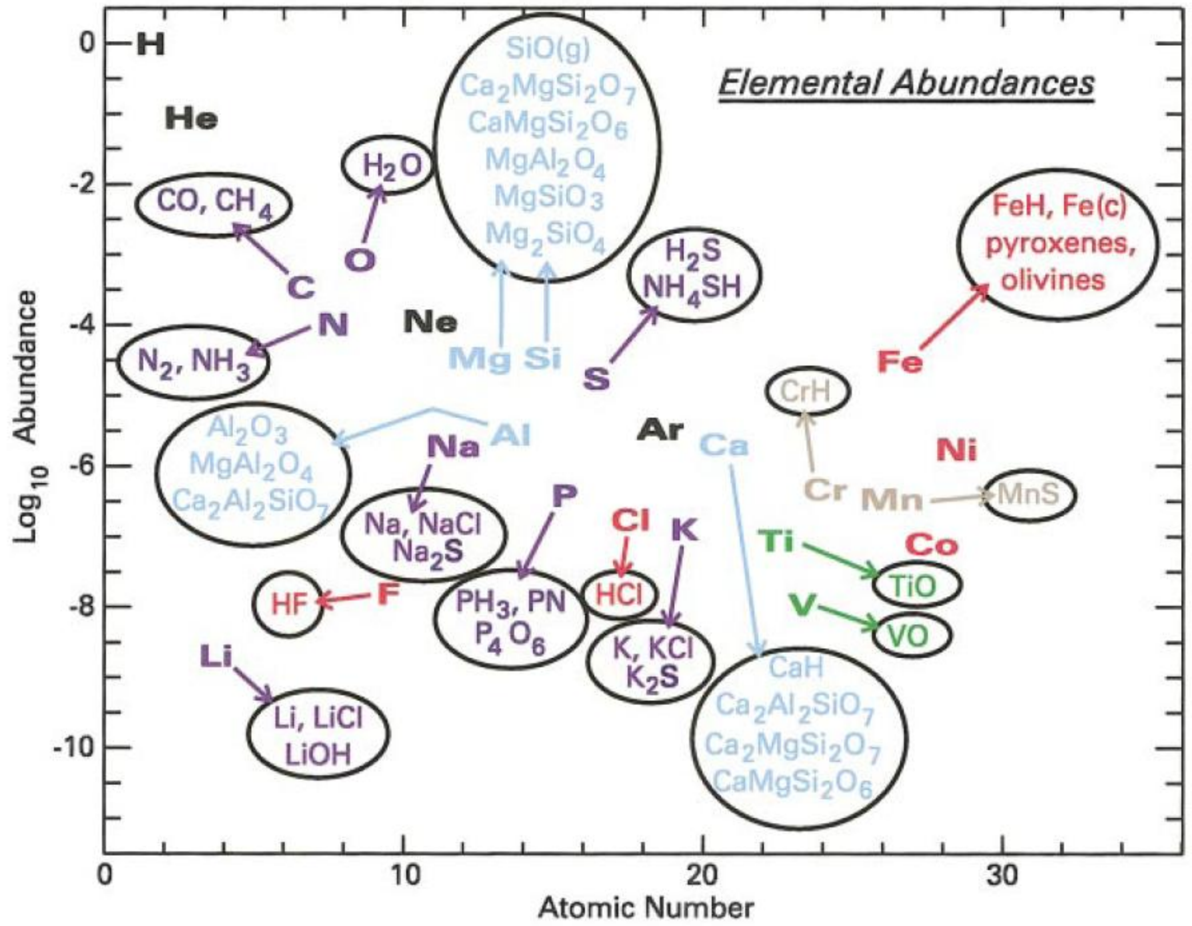


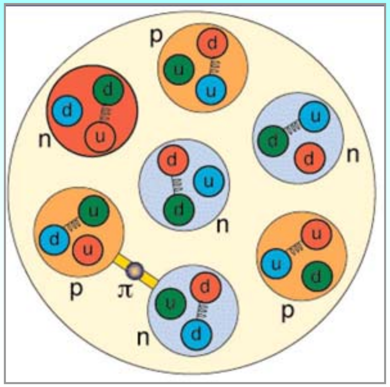
FIG. 10. A plot of the abundance of the elements vs atomic number. The position of the element name indicates its elemental abundance according to Anders and Grevesse (1989); see Table II. The balloons contain representative associated molecules/atoms/condensates of importance in brown dwarf and giant planet atmospheres. See Sec. V in text for discussion [Color].

Burrows A., Hubbard W.B., Lunine J.L. and Liebert J. *Rev. Mod. Phys.* 73, 719 (2001) *The theory of brown dwarfs and extrasolar giant planets*

Quasi-chemical representation

(*“Chemical picture”*)

Neutron stars



u, d, s, p, n, e	$\mu_u, \mu_d, \mu_s, \mu_p, \mu_n, \mu_e$

$u + e \Leftrightarrow d$

$d \Leftrightarrow s$

$p + e \Leftrightarrow n$

$n \Leftrightarrow u + 2d$

$(p \Leftrightarrow 2u + d)$

$$\mu_u + \mu_e = \mu_d,$$

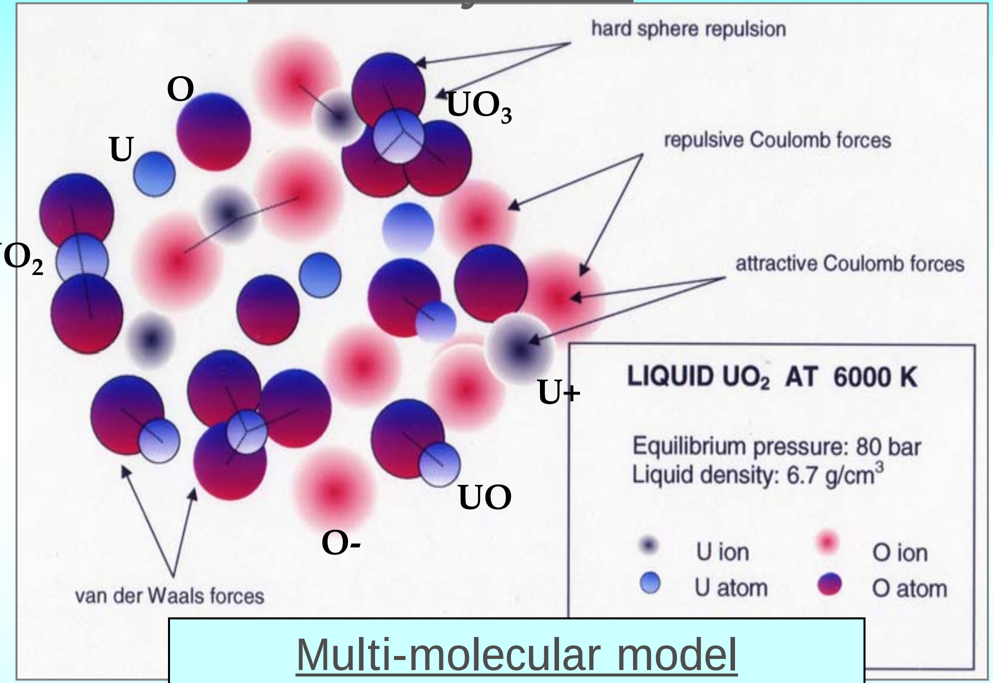
$$\mu_d = \mu_s,$$

$$\mu_p + \mu_e = \mu_n \equiv \mu_B,$$

$$\mu_n = \mu_u + 2\mu_d,$$

$$(\mu_p = 2\mu_u + \mu_d)\,.$$

U – O system



Multi-molecular model

(*Liquid & Gas*)

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

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

$U + 2O \Leftrightarrow UO_2$

$2O \Leftrightarrow O_2$

$U^+ + e \Leftrightarrow U$

$UO_3 + e \Leftrightarrow UO_3^-$

. . . . . .

$\mu_U + 2\mu_U = \mu_{UO2}$

$2\mu_O = \mu_{O2}$

$\mu_{U+} + \mu_e = \mu_U$

$\mu_{UO3} + \mu_e = \mu_{UO3-}$

. . . .

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

astro-ph/0601017v1/ 2006 /

Two problems in phase transition calculation

- Construction of Equation of State (EOS)
- Phase coexistence parameters calculation

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- $\sigma(T)$; $\varepsilon(T)$}

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

* Iosilevski 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,** (**2003**)

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

* Iosilevskiy I., Son E., Fortov V. *Thermophysics of non-ideal plasmas*. MIPT (2000); FIZMATLIT, (2009)

Phase coexistence parameters calculation

(*two approaches*)

Ordinary way:

Maxwell ("equal squares")

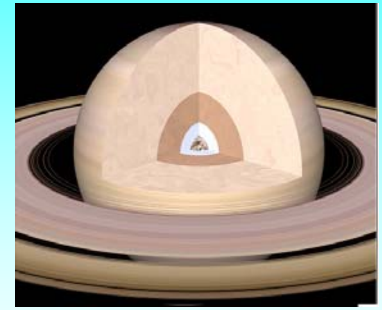
or **"Double tangent"** {in $F(V)$} **construction**

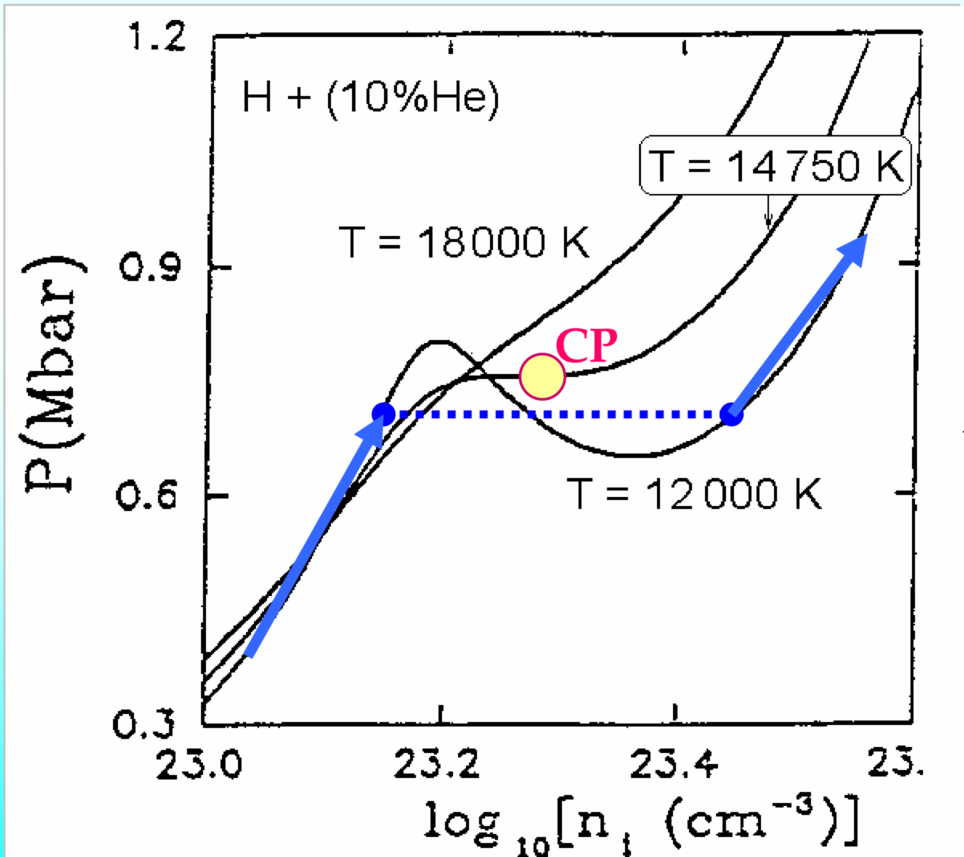
Plasma Phase Transitions in H_2 + He plasma

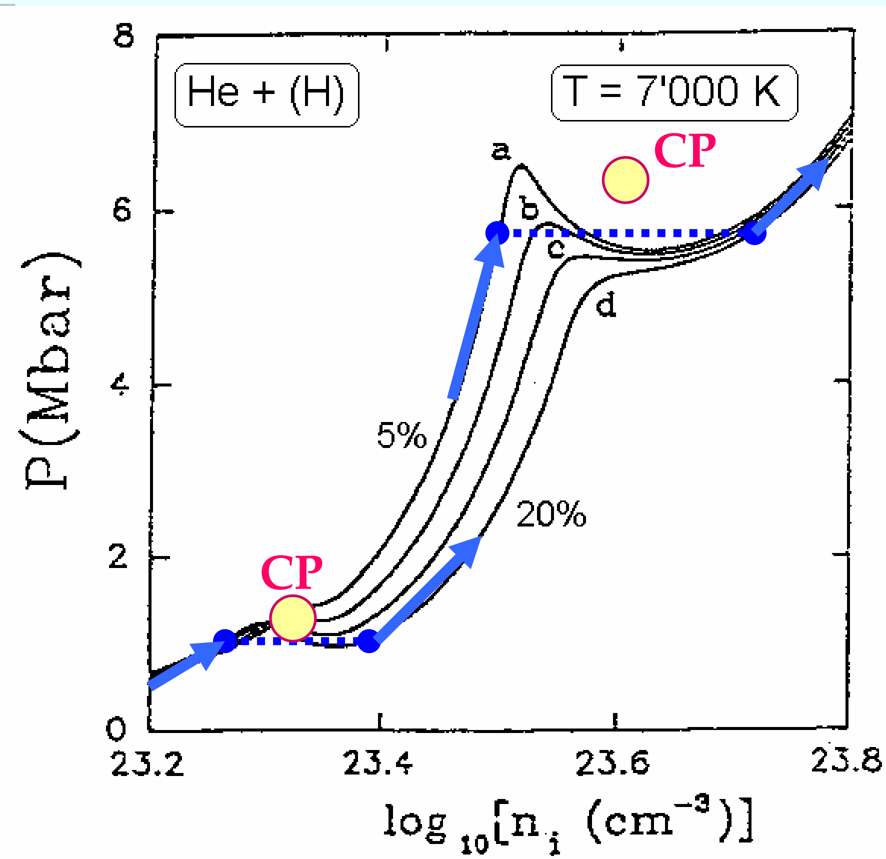
Contrib. Plasma Phys. 35 (1995) 2, 109 – 125

Plasma Phase Transition
in Fluid Hydrogen-Helium Mixtures

M. SCHLANGES (a), M. BONITZ (b), and A. TSCHTTSCHJAN (b)







Thermodynamics of H_2 + He plasma

(continued)

Contrib. Plasma Phys. 35 (1995) 2, 109 – 125

Plasma Phase Transition
in Fluid Hydrogen-Helium Mixtures

M. SCHLANGES (a), M. BONITZ (b), and A. TSCHTTSCHJAN (b)

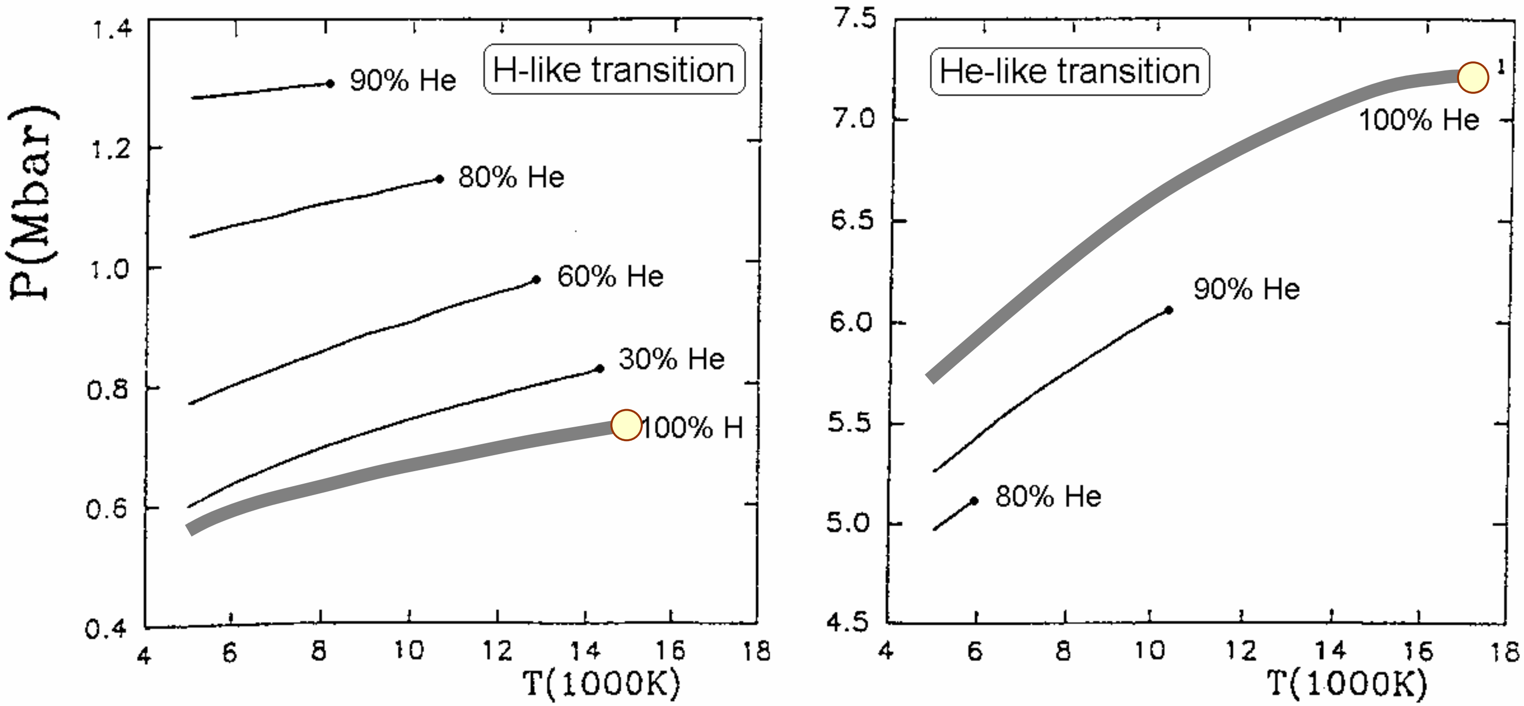
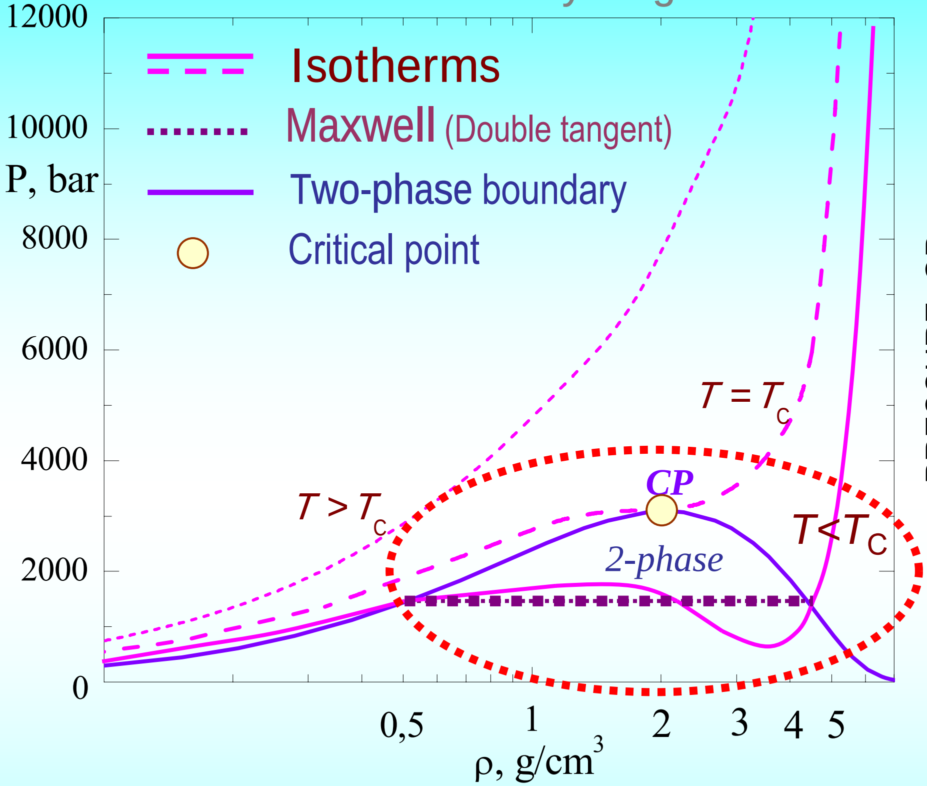


Fig. 7. Coexistence pressure for H – He mixtures for different values of the mixing parameter, for the hydrogen-like plasma phase transition and for the helium-like plasma phase transition.

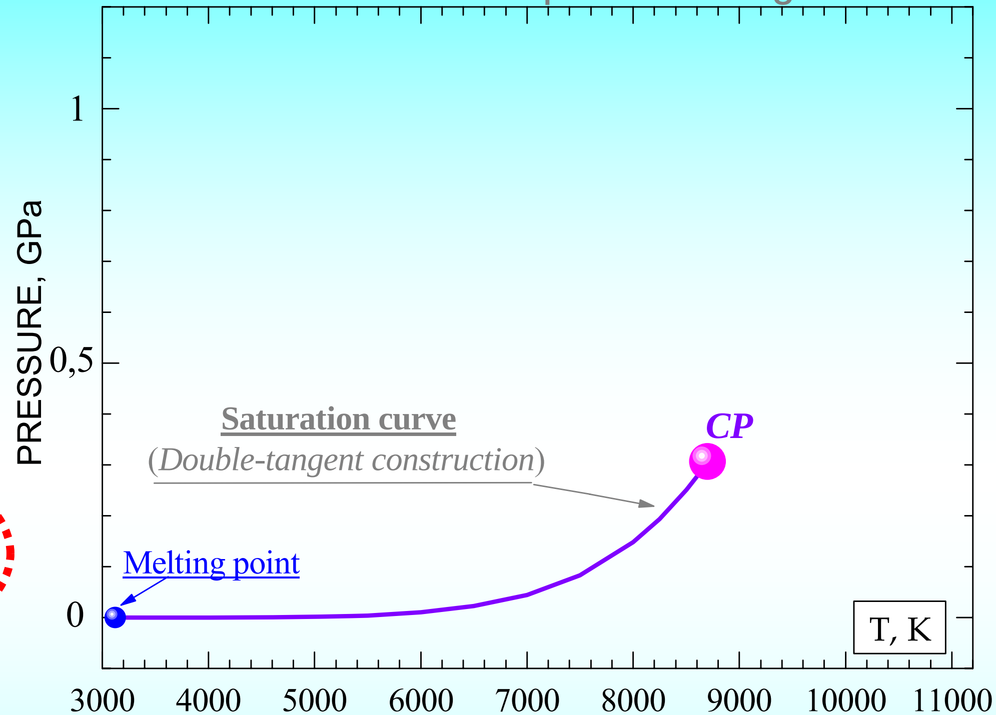
Standard

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:

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

- Standard critical point:

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

It should be

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

Congruent evaporation in U-O system *does not* correspond to the *total equilibrium*

(only to the partial one)

Maxwell approach

- **should be rejected as non-adequate**

Correct approach:

- **Gibbs (+ Guggenheim) conditions**

Phase equilibrium conditions in reacting Coulomb system

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

Bulk potential

Bulk potential

Heat exchange

$T' = T''$

Impulse exchange

$P' = P''$

Particle Exchange
neutral species

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

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

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

Particle Exchange
charged species

NB! - Chemical potentials of charged species are not equal (*Guggenheim, 1929*)

Electro-chemical potentials are equal

$$\mu_i' + Z_i e\,\varphi' = \mu_i'' + Z_i e\,\varphi'' \quad \Leftrightarrow \quad \Delta\varphi(T)$$

Potential drop at mean-phase interface
in equilibrium Coulomb system

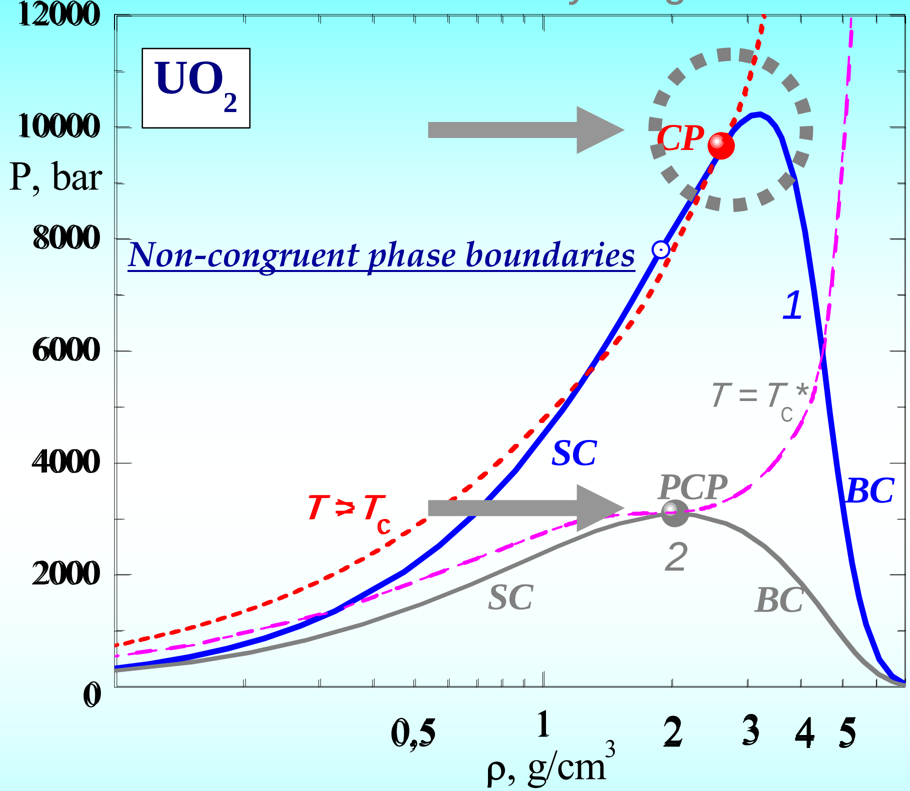
$$\mu_1'(P,T,x') = \mu_1''(P,T,x'') + Z_1 e\,\Delta\varphi(T)$$
$$\mu_2'(P,T,x') = \mu_2''(P,T,x'') + Z_2 e\,\Delta\varphi(T)$$
$$\ldots\ldots\ldots\ldots$$
$$\mu_e'(P,T,x') = \mu_e''(P,T,x'') - e\,\Delta\varphi(T)$$

(*see for example:* Iosilevskiy I., *Encyclopedia on low-T plasmas. III-1 (suppl)* **2004**, P.349-428)

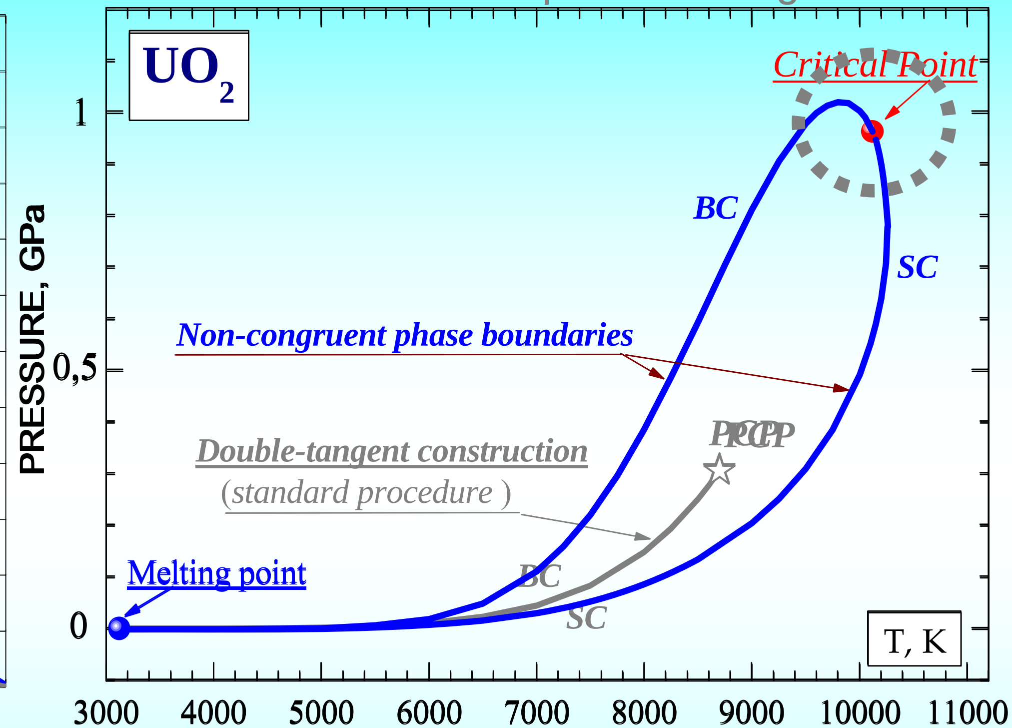
Non-congruent evaporation in U-O system

(*Gibbs - Guggenheim conditions*)

Pressure - Density Diagram



Pressure - Temperature Diagram



1 – Non-congruent (total) equilibrium

2 – Forced-congruent (partial) equilibrium

BC – Boiling liquid conditions

SC – Saturated vapor conditions

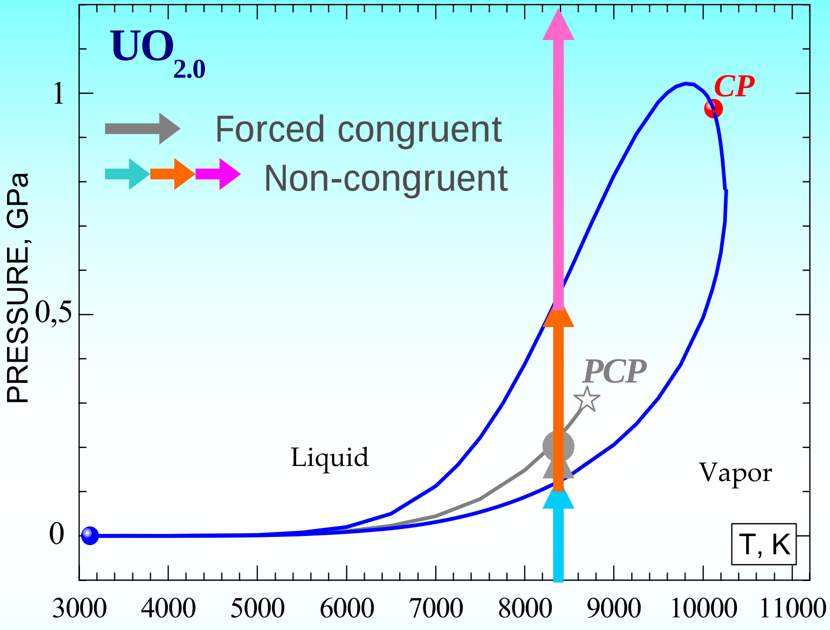
NB! **2-dimensional two-phase region** instead of standard *P-T* saturation curve

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

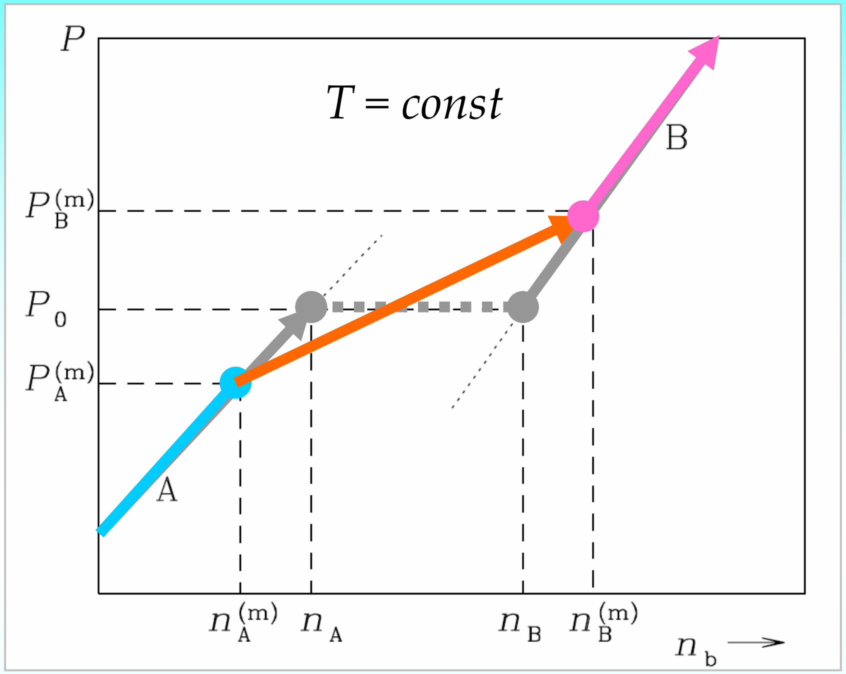
NB! **Critical point** should be of **non-standard** type: $(\partial P/\partial V)_T \neq 0$ $(\partial^2 P/\partial V^2)_T \neq 0$

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

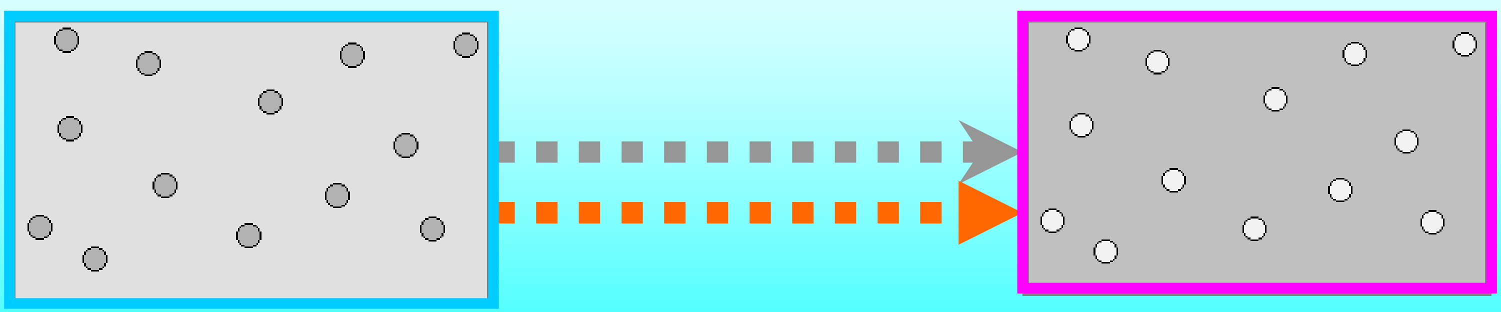


Phase Diagram *P-T* of Non-congruent Evaporation



First liquid droplets in saturated vapor

Last vapor bubbles in boiling liquid



Oxygen depleted liquid

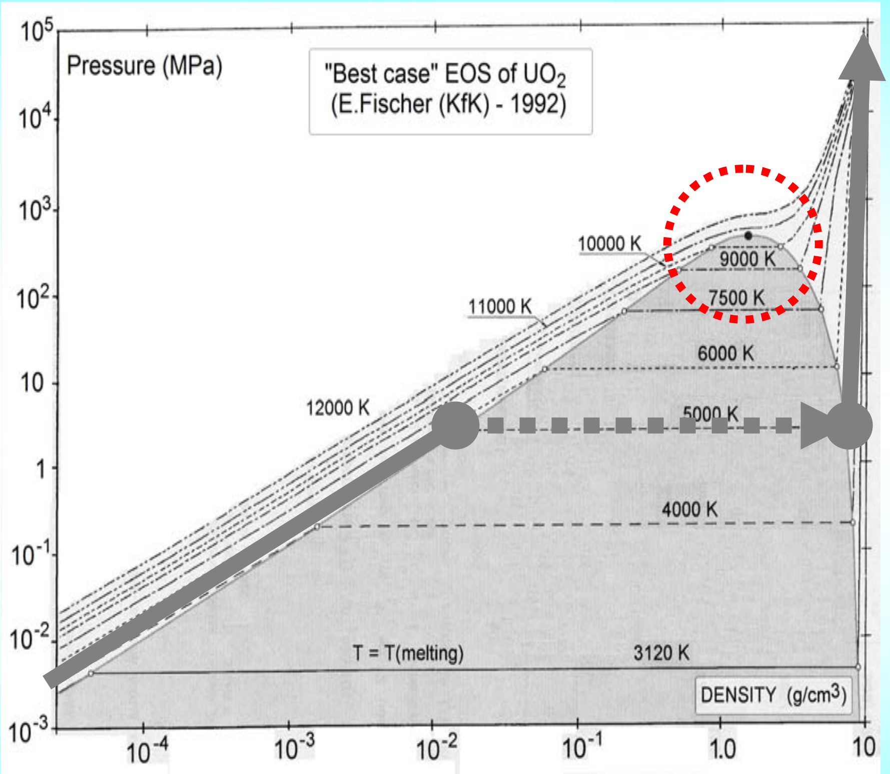
! *Different stoichiometry* !

Oxygen enriched vapor

! *Different stoichiometry* !

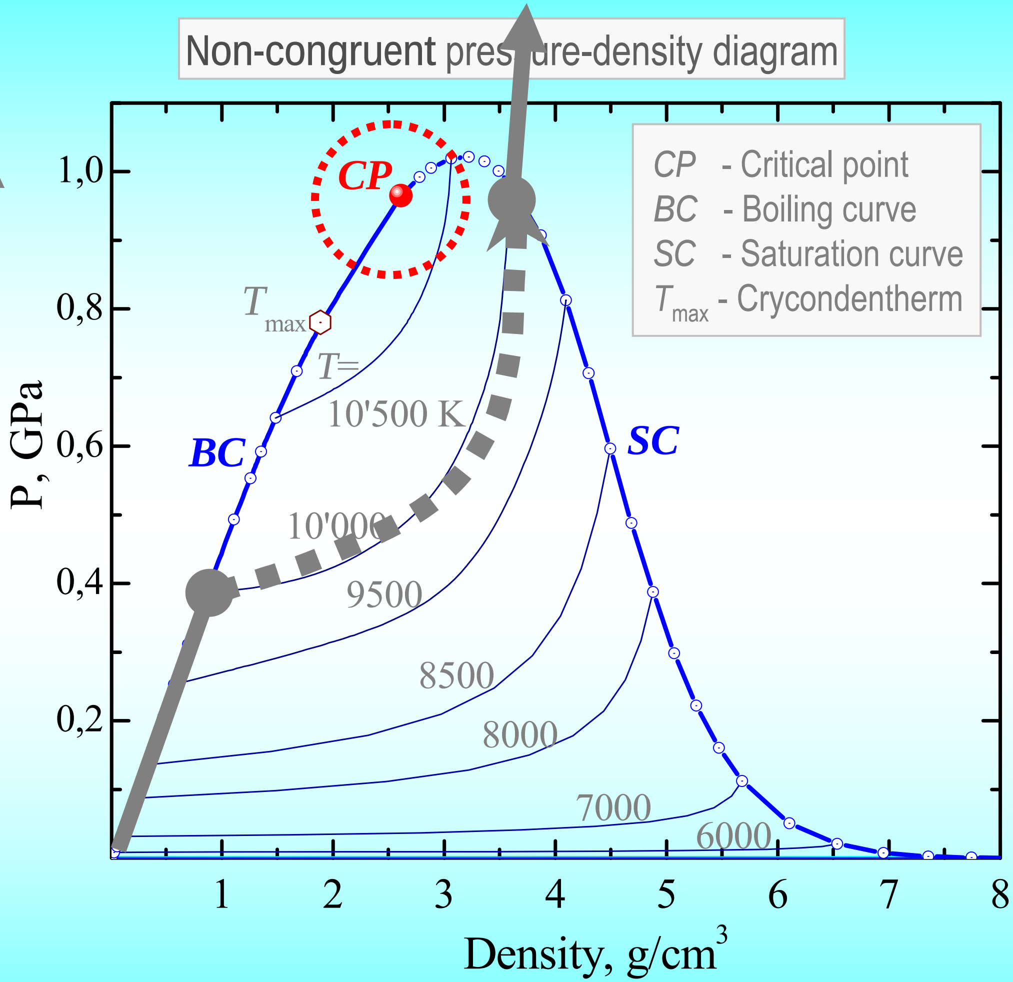
Isotherms in two-phase region

Standard pressure-density diagram



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

Non-congruent pressure-density diagram



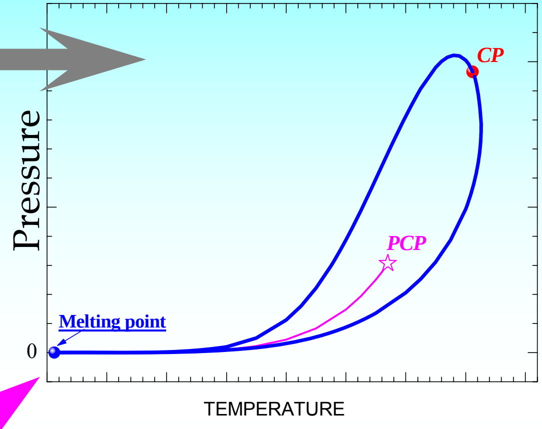
- **Isothermal** phase transition starts and finishes at ***different pressures***
- **Isobaric** phase transition starts and finishes at ***different temperatures***

Non-congruence in general

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

Basic conclusion:

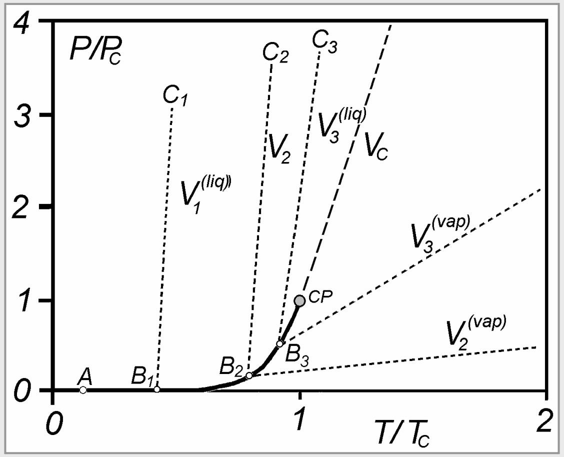
- Any phase transition in a system of **two** or **more** **chemical elements** must be **non-congruent**
- **Congruent** phase transition is **exception**



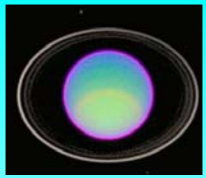
Evident contradiction

H_2O, CO_2, NH_3 . . . .

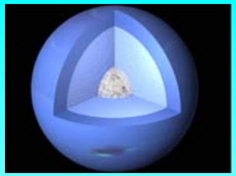
?



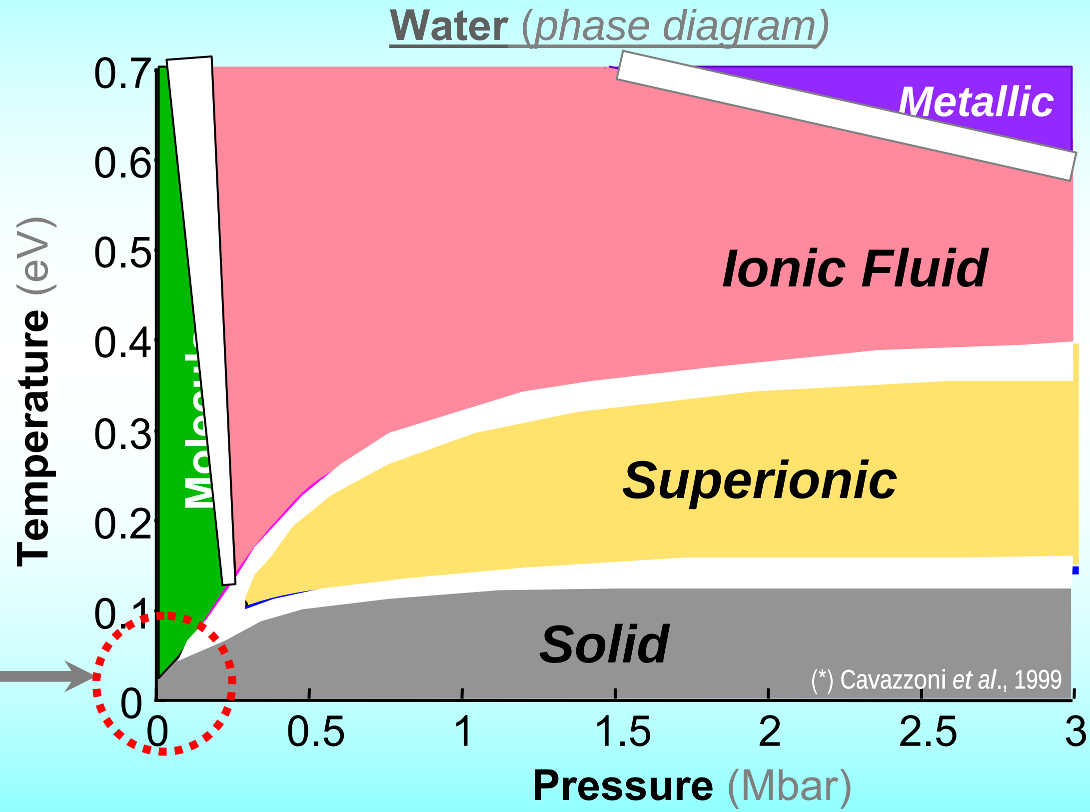
Non-congruence in H_2O etc... – what does it mean ?



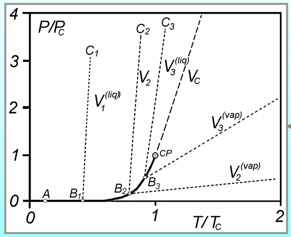
BASIC STATEMENT:
Any phase transition in a system of **two** or more **chemical elements** must be **non-congruent**



Neptune and **“hot-water” extrasolar planet** GJ436b



Room conditions



Star: - Gliese 436 (RD)
$M \sim 22\, M_O$
$R \sim 4\, R_O$
$\Delta T \sim 2{,}6$ days (!)
$T_{surface} \sim 500$ K
Main comp-t. – H_2O
= «» =
(*Discovered* – 2007)

Ab initio calculations
Cavazzoni, *et. al. Science* (***1999***)
Mattsson & **Desjarlais** (*Sandia Lab.*): *High energy-density water: DFT/QMD simulations* (***2007***)

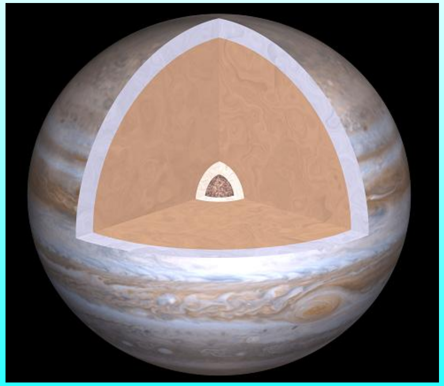
Any phase transition in *high-T_high-P* water must be *non-congruent*

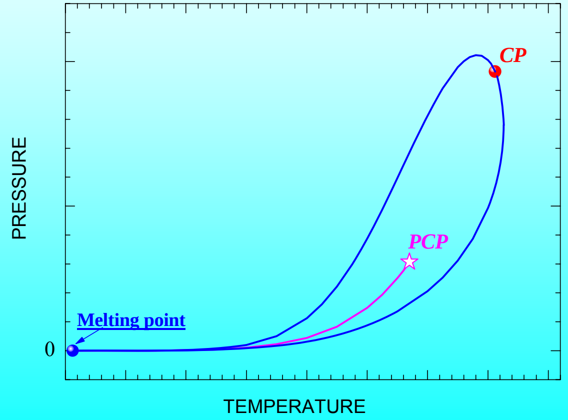
Non-congruent of phase transition in U-O system – – is it an exception or a general rule ?

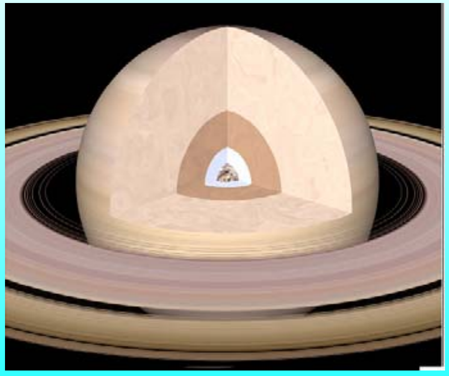
Basic conclusion

- 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*** *. . .*





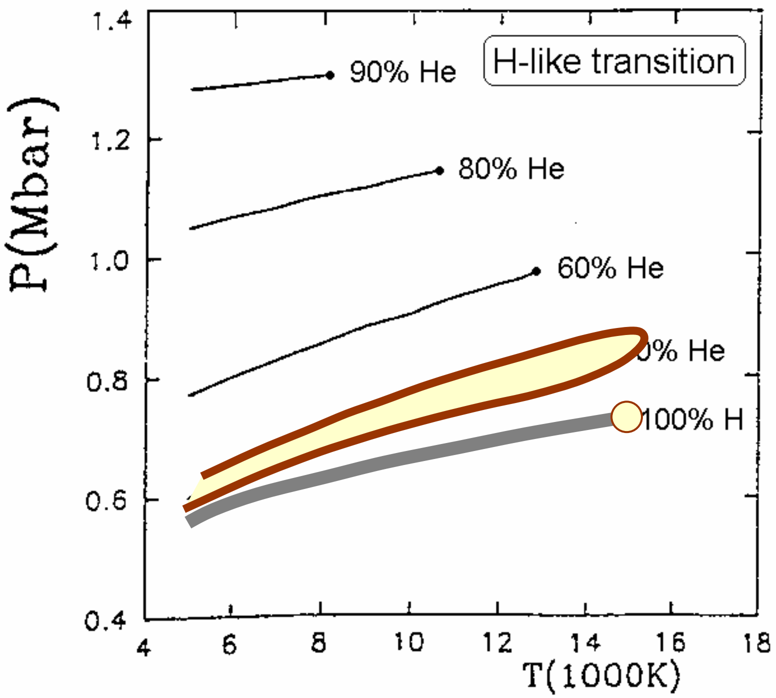


Thermodynamics of H_2 + He plasma (*continued*)

Contrib. Plasma Phys. 35 (1995) 2, 109 – 125

Plasma Phase Transition in Fluid Hydrogen-Helium Mixtures

M. SCHLANGES (a), M. BONITZ (b), and A. TSCHTTSCHJAN (b)



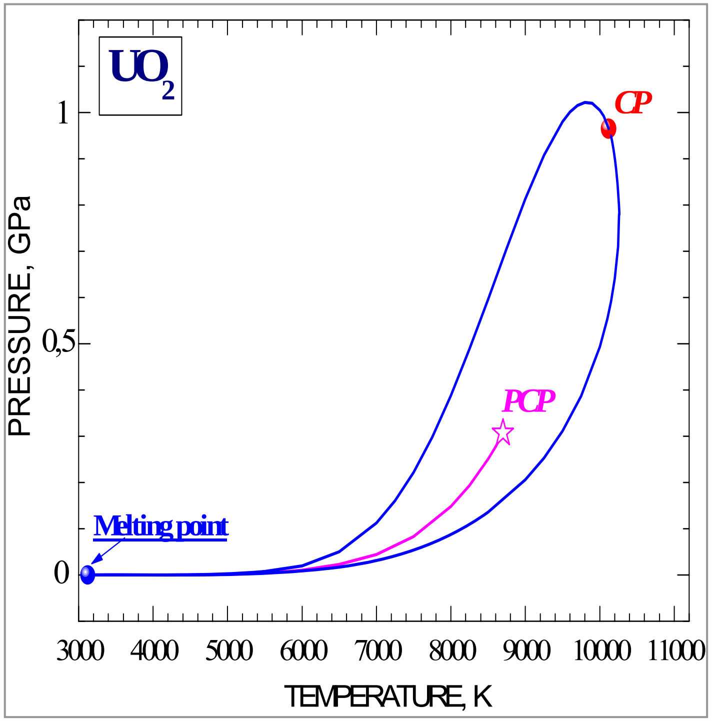


Fig. 7. Coexistence pressure for H – He mixtures for different values of the mixing parameter, for the hydrogen-like plasma phase transition and for the helium-like plasma phase transition.

Thermodynamics of H_2 + He plasma

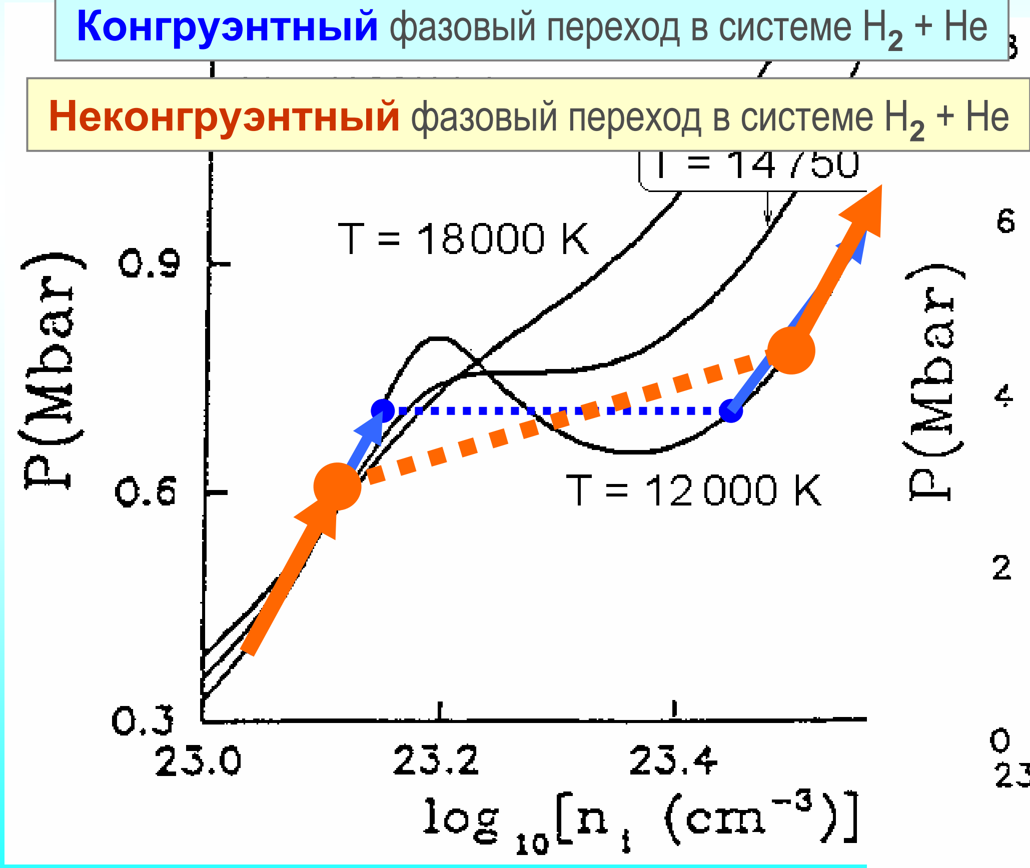
Contrib. Plasma Phys. 35 (1995) 2, 109 – 125

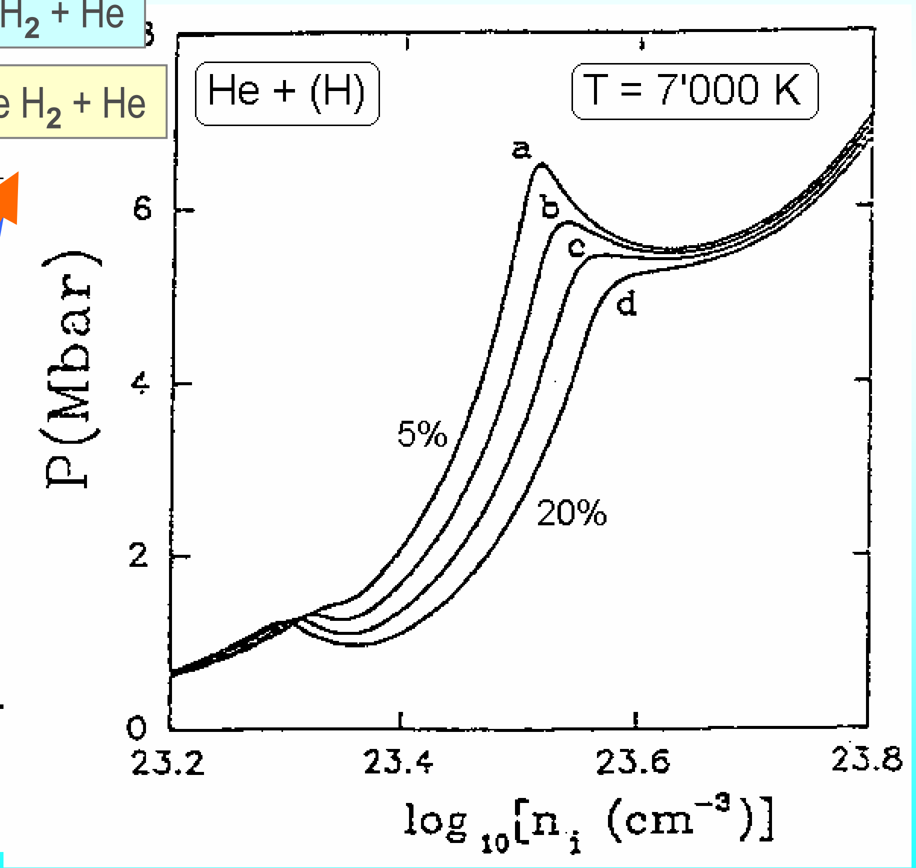
Plasma Phase Transition in Fluid Hydrogen-Helium Mixtures

M. SCHLANGES (a), M. BONITZ (b), and A. TSCHTTSCHJAN (b)

Конгруэнтный фазовый переход в системе H_2 + He

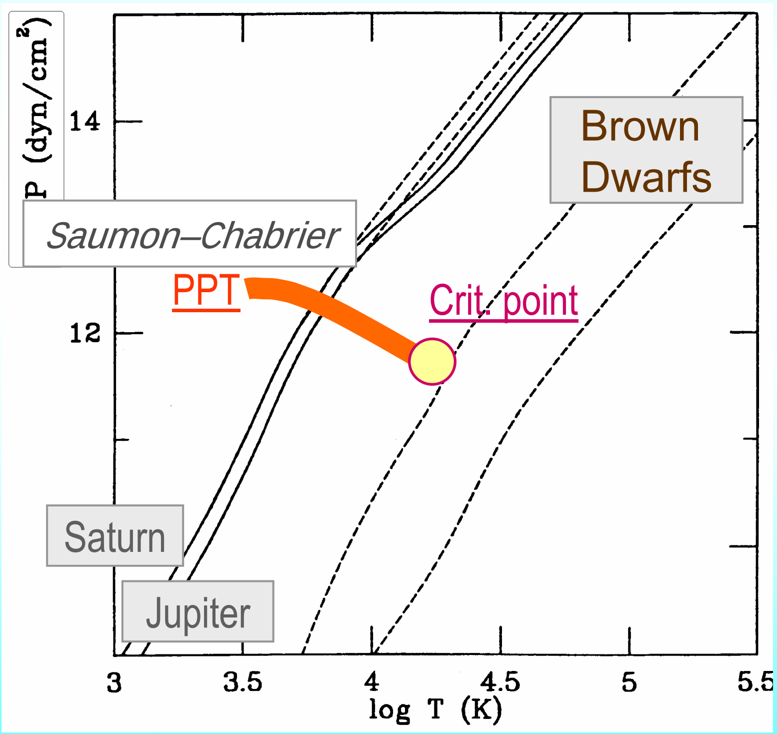
Неконгруэнтный фазовый переход в системе H_2 + He

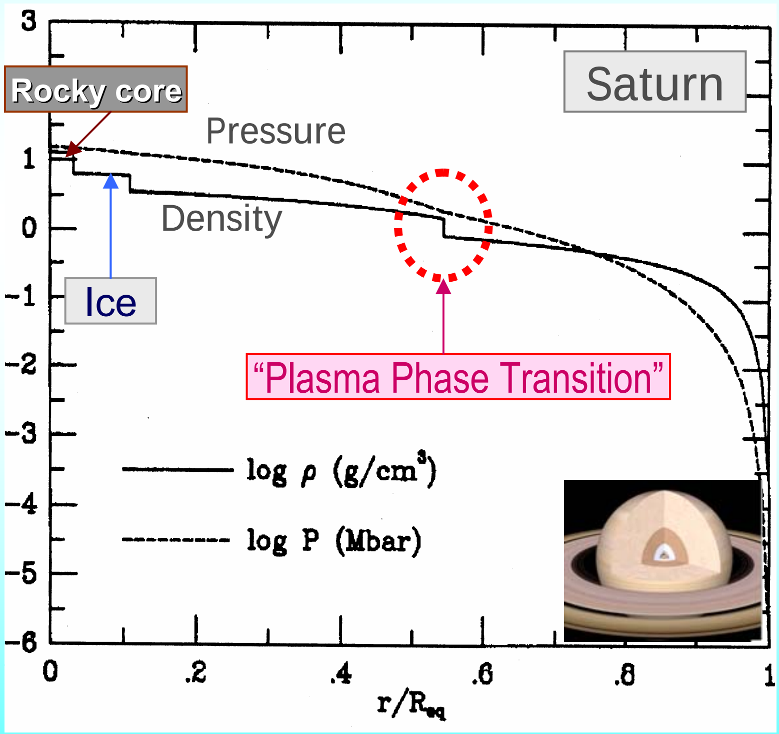




Hypothetical phase transition in H_2/He mixture

after Chabrier G., Saumon D., Hubbard W., Lunine J. (SCCS-1992, Rochester)





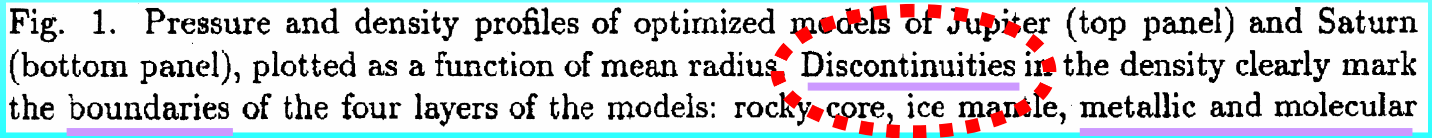
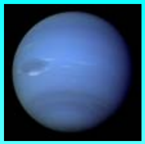
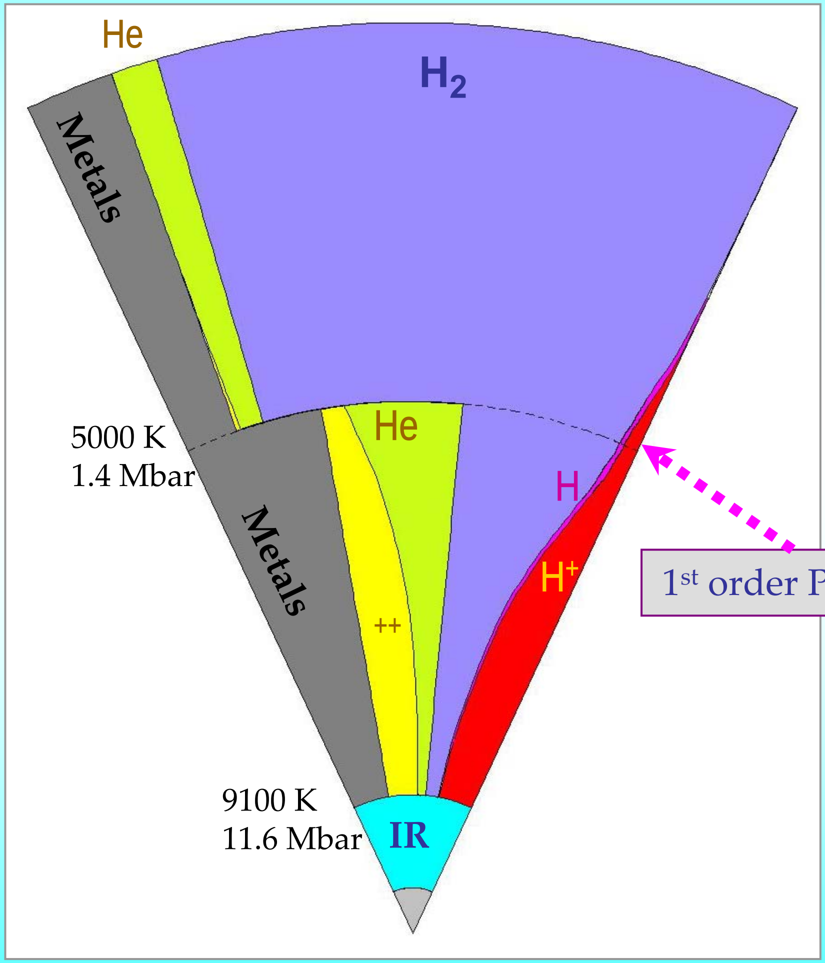


Fig. 1. Pressure and density profiles of optimized models of Jupiter (top panel) and Saturn (bottom panel), plotted as a function of mean radius. Discontinuities in the density clearly mark the boundaries of the four layers of the models: rocky core, ice mantle, metallic and molecular

Giant planets interior composition



Saturn interior composition
using SCVH-95_EOS

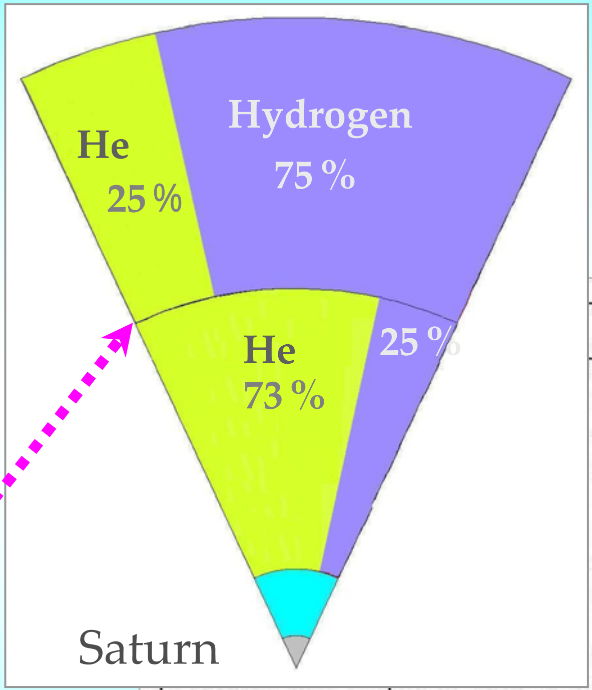


1st order PPT (?)

After N. Nettelmann, R. Redmer, et al., **PNP-12**, Darmstadt, 2006)

Optimized models of Jupiter and Saturn
(D. Saumon, G. Chabrier , W. Hubbard, J. Lunine)

1992



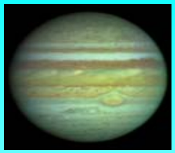
		SATURN
		95.1
		1
		0.95
		15.5
		11900
		1.93
T_{PPT} (K)	6880	6070
Y_I	0.29	0.25
Y_{II}	0.326	0.73

TABLE 1

He %

GIANT PLANETS AND THE PLASMA PHASE TRANSITION
D. Saumon, G. Chabrier, W. B. Hubbard, and J. I. Lunine

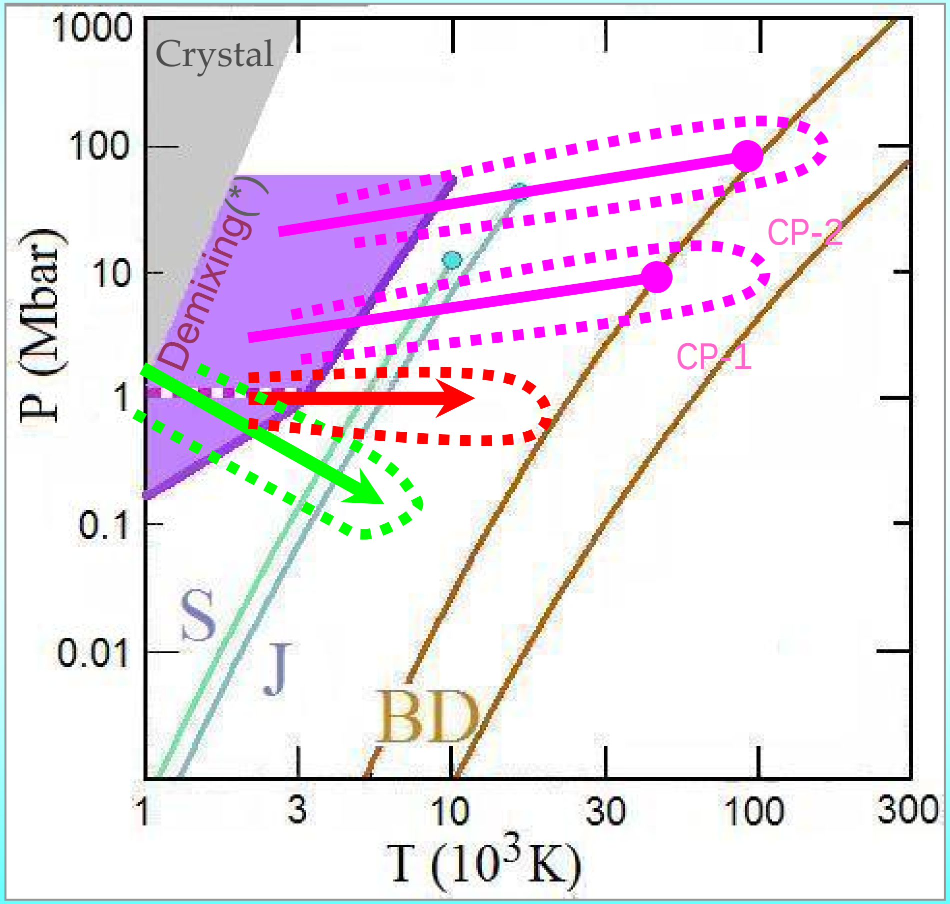
Hypothetical phase transitions in interiors of GP-s and BD-s via "additivity approximation"



(optimistic)

Phase diagram of H_2/He mixture in frames of "additivity approximation" is **superposition** of *P*-*T* phase diagrams for pure hydrogen and helium.

H_2 + He



Dissociative Phase Transition in H_2
(*Scandolo S., Bonev S., Militzer B., Galli G.*)

Plasma Phase Transition in H
(Ebeling et al.)

1st Plasma Phase Transition in He
(Ebeling et al.)

2nd Plasma Phase Transition in He^+
(Ebeling et al.)

Presence of helium relax phase transition in hydrogen <> presence of hydrogen relax phase transition in helium

Schlanges M., Bonitz M, Tschetschjan A. *Contrib. Plasma Phys.* **35** 109 (1995)

(*) **Pfaffenzeller** O. et al. *PRL* **74** (13) 2599 (1995)

Phase diagram in simple mixture H_2 + He could be complicated due to non-congruence

<u>The question is:</u>

What kind of phase transition one can expect in high-*T* high-*P* complex plasma ?

$H_2 + He + H_2O + NH_3 + CH_4 \ldots$

at $T \sim 1 - 20$ kK & $P \sim 1 - 10$ Mbar

Typical composition in planetary science

Five layers (!) model of Saturn's interior

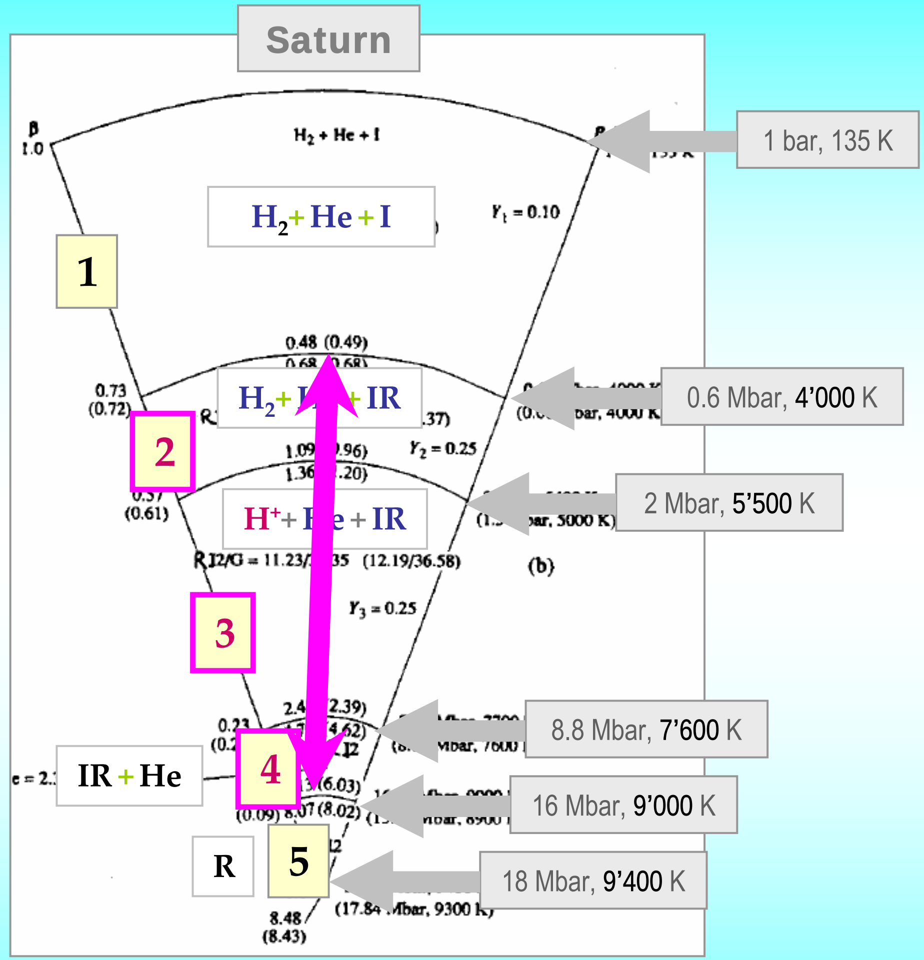
Gudkova T. & Zharkov V. *Planetary and Space Science 47 (1999)* **(1999)**

Table 4
Parameters of the models of Saturn

Model	Y_0	Y_3	Z_{2-4}	[illegible]	P_{1-2}	M_{He}, core	M_{core}
$Y_1 = 0.06$, $Y_2 = 0.25$, $Z_1 = 0.02$, $I/R = 2.2$							
MS1	0.267	0.00	0.30	3.0	0.42	10.66	16.18
MS2	0.171	0.00	0.40	3.0	0.64	4.58	8.59
MS3	0.225	0.00	0.30	2.0	0.44	9.88	15.06
MS4	0.133	0.00	0.40	2.0	0.67	4.02	7.65
MS5	0.274	0.25	0.30	3.0	0.46	6.33	9.99
MS6	0.187	0.25	0.40	3.0	0.72	0.05	1.03
MS7	0.285	0.25	0.25	2.0	0.43	7.34	10.74
MS8	0.244	[illegible]	[illegible]	[illegible]	[illegible]	4.05	6.74
MS9	0.322	[illegible]	[illegible]	[illegible]	[illegible]	7.66	11.16
MS10	0.278	[illegible]	[illegible]	[illegible]	[illegible]	3.80	6.38
MS11	0.237	[illegible]	[illegible]	[illegible]	[illegible]	0.41	1.58
MS12	0.293	[illegible]	[illegible]	[illegible]	[illegible]	3.90	6.15
MS13	0.255	[illegible]	[illegible]	[illegible]	[illegible]	0.81	2.11
MS14	0.282	[illegible]	[illegible]	[illegible]	[illegible]	2.60	4.42
MS15	0.249	[illegible]	[illegible]	[illegible]	[illegible]	0.007	0.76
$Y_1 = 0.10$, Y_2 = [illegible] 2.2							
MS16	0.275	[illegible]	[illegible]	[illegible]	[illegible]	10.91	16.54
MS17	0.186	[illegible]	[illegible]	[illegible]	[illegible]	4.98	9.25
MS18	0.234	[illegible]	[illegible]	[illegible]	[illegible]	10.22	15.55
MS19	0.149	[illegible]	[illegible]	[illegible]	[illegible]	4.50	8.45
MS20	0.282	[illegible]	[illegible]	[illegible]	[illegible]	6.69	10.51
MS21	0.202	0.25	0.40	3.0	0.82	0.57	1.9
MS22	0.277	00.25	0.27	2.0	0.56	6.39	9.7
MS23	0.254	0.25	0.30	2.0	0.64	4.49	7.36
MS24	0.277	0.25	0.25	1.5	0.60	6.64	9.8
MS25	0.263	0.25	0.27	1.5	0.66	5.45	8.41
MS26	0.327	0.35	0.25	3.0	0.43	7.93	11.52
MS27	0.287	0.35	0.30	3.0	0.56	4.16	6.89
MS28	0.248	0.35	0.35	3.0	0.71	0.90	2.34
MS29	0.301	0.35	0.25	2.0	0.57	4.39	6.80
MS30	0.266	0.35	0.30	2.0	0.73	1.36	2.89
MS31	0.291	0.35	0.25	1.5	0.71	3.13	5.12
MS32	0.259	0.35	0.30	1.5	0.87	0.48	1.64

$H_2 + He$

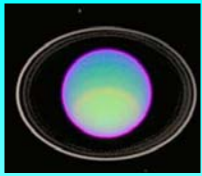
30-40 %
H_2O
NH_3
CH_4
(Fe + Ni)



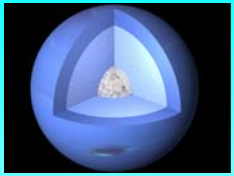
I = "Ices" (H_2O, NH_3, CH_4) **R** = Rocks + Fe + Ni

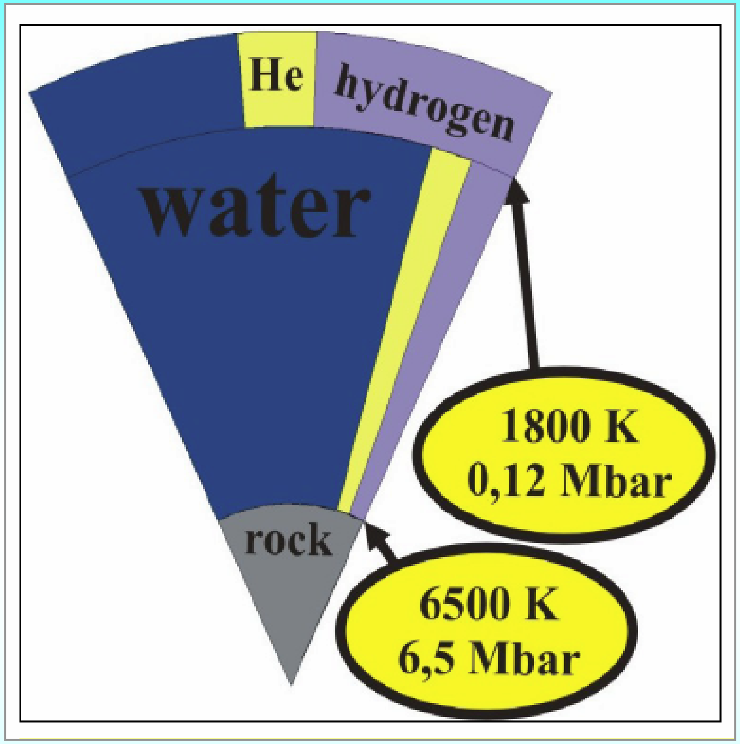
Y_i = mass fraction He

Z_i = mass fraction (H_2O, NH_3, CH_4 + Fe + Ni)



H_2O, CH_4, NH_3 in giant planets





Neptune

After N.Nettelmann, R.Redmer *et al.* (2007)

Chemical composition of Neptune [1]:
- 56% water
- 36% methane
- 8% ammonia

W. Hubbard. *Science*, **214** (1981)

"Hot-water" extrasolar planet GJ436b

GJ436b
Star: - Gliese 436 (RD)
$M \sim 22M_O$
$R \sim 4R_O$
$\Delta T \sim 2{,}6$ days (!)
$T_{Surf.} \sim 500$ K
Main Comp. – H_2O
= «» =
(*Discovered in* 2007)

Phase diagram in simple mixture H_2 + He may be very complicated due to non-congruence

The question is:

What kind of phase transition one can expect in high-T high-P complex plasma ?

H_2 + He + H_2O + NH_3 + CH_4. . .

at **T ~ 1 – 20 kK & P ~ 1 – 10 Mbar**

Typical composition in planetary science

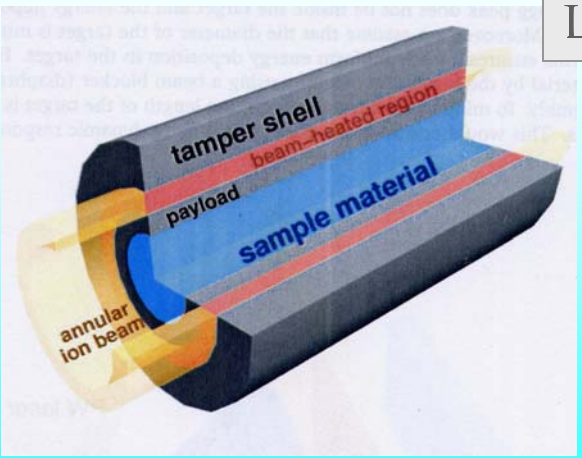
Conclusions *and* perspectives

- Non-congruence of phase transitions in **H_2 / He** mixture can 'provoke' to the **H⇔He** separation in interiors of *Jovian* and *Extrasolar* planets and *Brown Dwarfs*.

- New experiments are desirable for study of discussed *non-congruence* for phase transition in **H_2 / He / H_2O / NH_3 / CH_4** / mixture.

- **Heavy Ion Beam** volumetric heating is very promising tool for adiabatic compression of the **H_2 / He / H_2O / NH_3 / CH_4** mixture just under conditions of **Jovian** and **Extrasolar planets** and **Brown Dwarfs**.

LAPLAS



HEDgeHOB — *High Energy Density Matter Generated by Heavy Ion Beams*

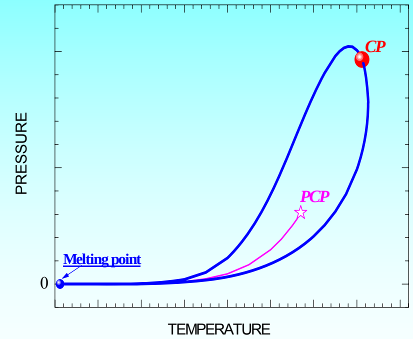
Non-congruence in general

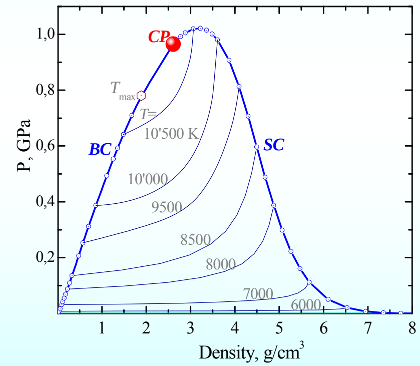
Hypothetical non-congruent phase transitions

(*__short list__* *- Swedish buffet*)

<u>Terrestrial applications</u>:

- ***Uranium**- and **Plutonium**-bearing compounds:*
  - ***UO_2**, **PuO_2** , **UC**, **UN**, ... ets.,*
- ***Metallic alloys**:* (*Li-K-Na,...etc.*)
- ***Oxides**:* (*SiO_2...etc.*)
- ***Hydrides** of metals* (*LiH,... etc.*)
- ***Ionic liquids** and **molten salts**:*
  - *alkali halides* (*NaCl, ... etc.*), *ammonium halides* (*NH_4Cl ... etc.*)
- ***"Dusty"** and **Colloid plasmas**:*
  (*Coulomb system of macro-ions +Z and micro-ions: +1, –1*)





<u>Non-Congruence in Cosmic Matter</u>:

- ***Plasma Phase Transitions** in mixture:* **H_2/ He /H_20 / NH_3 / CH_4**
  *in **Giant Planets, Brown Dwarfs** and **Extra-Solar Planets**,*
- ***Phase Transitions** in **White Dwarfs**,*
- ***Phase Transitions** in **Neutron Stars**,*
- ***Phase Transitions** in **"Strange" Stars*** (*quark-hadron transition ... ets.*)

Iosilevskiy I. / Int. Congress on Plasma Physics / Fukuoka, Japan, 2008 (*J. of Plasma and Fusion Research*, 2009)

The question is:

What kind of phase transition one can expect in high-*T*_high-*P* complex plasma ?

$SiO_2 + FeO + Al_2O_3 + CaO + \ldots$

...ch – June 2, 2009

...km/h ⇔ Impact plume ~ 50 km high

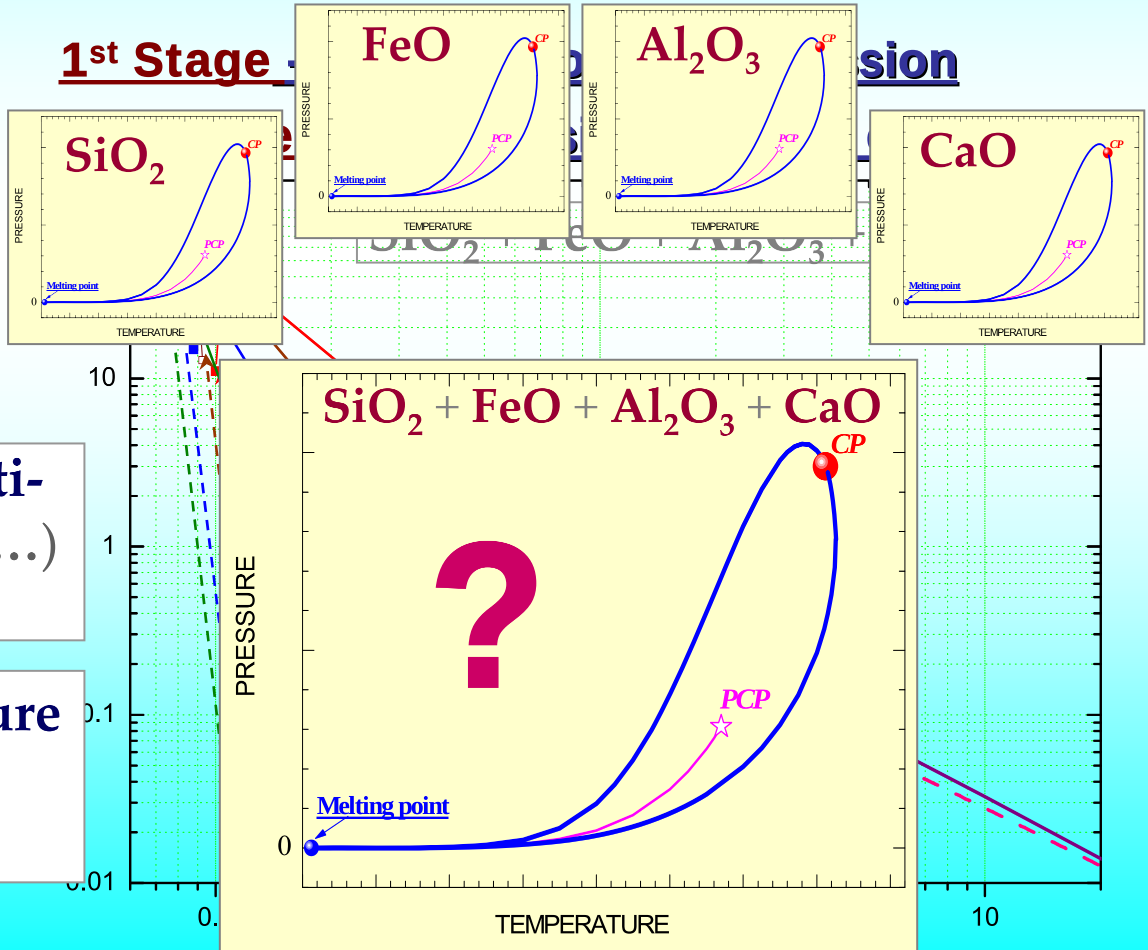
What kind of phase transition one can expect in high-*T*_high-*P* complex plasma?

$SiO_2 + FeO + Al_2O_3 + CaO$

T ~ *eV* & *P* ~ *GPa*

The question is open

1st Stage ... sion



NB !

Phase transition in each constituent (SiO_2, FeO, Al_2O_3, CaO…) must be *non-congruent* !

Phase transitions in the mixture must be *non-congruent* moreover !

Conclusions *and* perspectives

- **Non-congruence** of phase transitions in SiO_2 + FeO + Al_2O_3 + CaO (+ H_2O) mixture can 'provoke' to the **Si** ⇔ **O** ⇔ **Fe** ⇔ **Al** ⇔ **Ca** (+ H_2O) () separation in the *high-T_high-P* **impact plume** of *Lunar ground* in **LCROSS** experiment.

- New experiments are desirable for study of discussed *non-congruence* for phase transition in SiO_2 + FeO + Al_2O_3 + CaO mixture.

- **Heavy Ion Beam** heating is very promising tool for isochoric compression *and* adiabatic release of the SiO_2 / FeO / Al_2O_3 / CaO mixture just under conditions of **LCROSS** experiment.

- **Surface Laser Heating** (PHELIX) is very promising tool for non-congruent evaporation *and* expansion in the SiO_2 / FeO / Al_2O_3 / CaO mixture just under conditions of **LCROSS** experiment.

HIHEX

PHELIX

High-Temperature evaporation in SiO_2 - is it congruent or not ?

Fast Optical Discharge Propagation through Optical Fibres under kW-Range Laser Radiation

I.A. Bufetov(1), A.A. Frolov(1), V.P. Efremov(2), M.Ya.Schelev(3), V.I.Lozovoi(3), V.E. Fortov(2), E.M. Dianov(1).
1 : Fiber Optics Research Center at the A.M. Prokhorov General Physics Institute, RAS
38 Vavilov Street, 119991 Moscow, Russia, iabuf@fo.gpi.ru
2: Institute for High Energy Density, RAS, efremov@ihed.ras.ru, 3: A.M.Prokhorov General Physics Institute, RAS

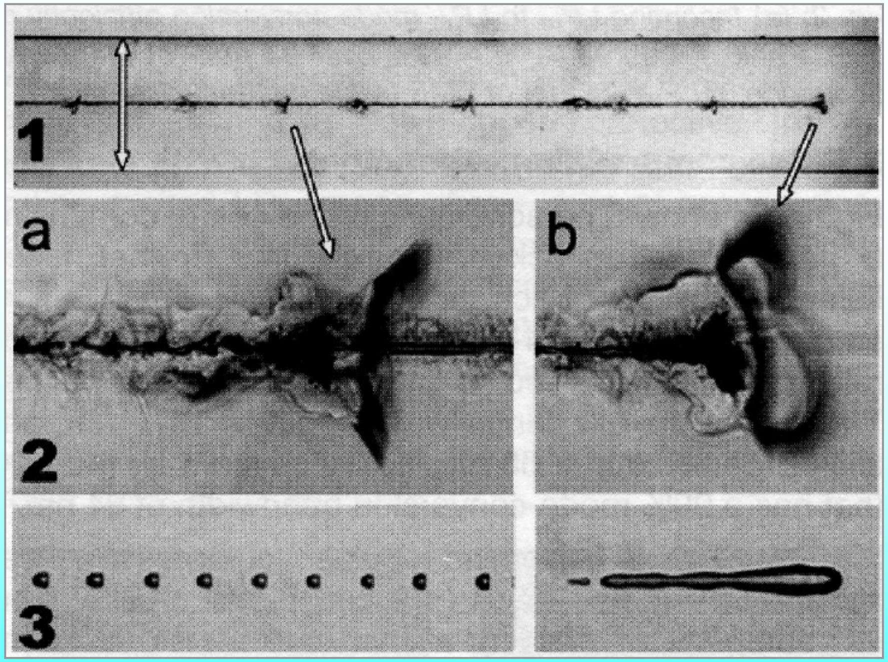
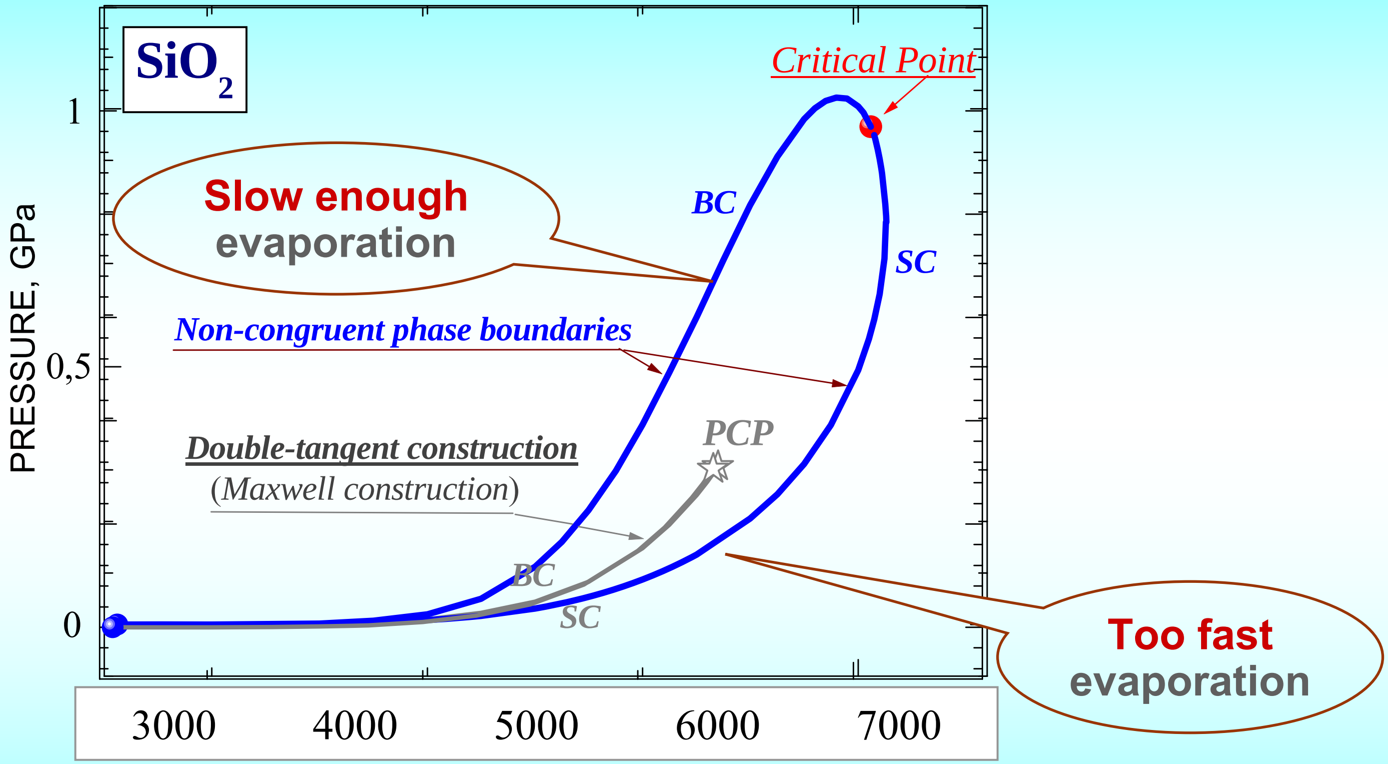


Fig.1. Pictures of F2 fibre after OD propagation. 1–damaged core of the fibre after fast OD propagation. The double-sided arrow indicates 600μm diameter of the fibre. 2–damages of the fibre core on an enlarged scale (the vertical dimension of the frame is 100μm): 2a–region of intermediate stop of OD, 2b–final stop point of fast OD. 3–for comparison: damaged fibre core after slow OD propagation: 3a–at the distance of 1mm from the stop point, 3b– stop point of the slow OD after laser beam cut off by mechanical shutter. The scale is the same as for part 2. In all frames the laser radiation propagated from right to left.

High-Temperature evaporation in SiO_2 - is it congruent or not ?



Parameters of non-congruent evaporation in SiO_2 *strongly depend* on the *rapidity* of phase transformation !

Non-congruence in exotic situations

(*discussion*)

3

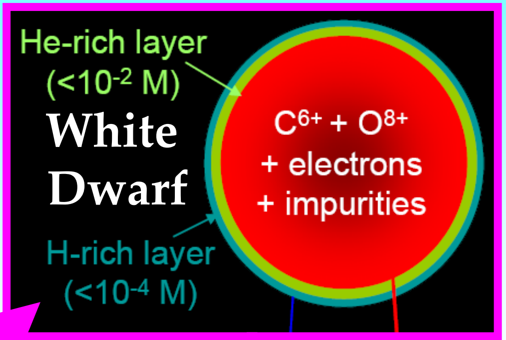
Non-congruence in exotic situations

(*discussion*)

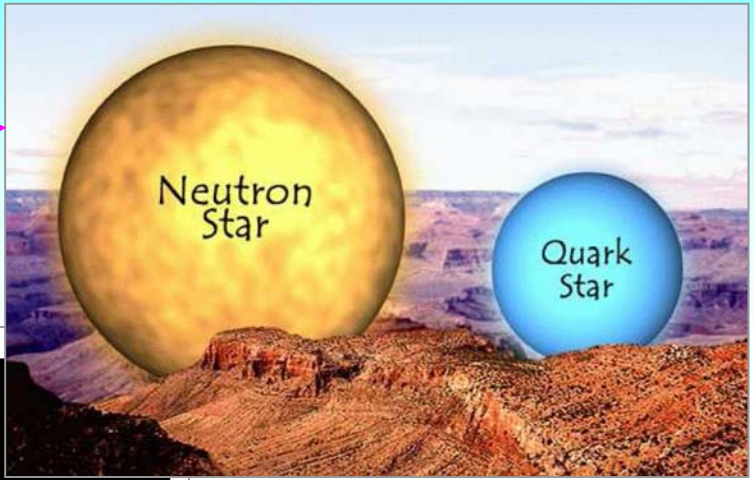
Non-congruence in compact stars

Compact stars

White dwarfs, Neutron stars, "Strange" (quark) stars, Hybrid stars



Neutron and "Strange" Stars



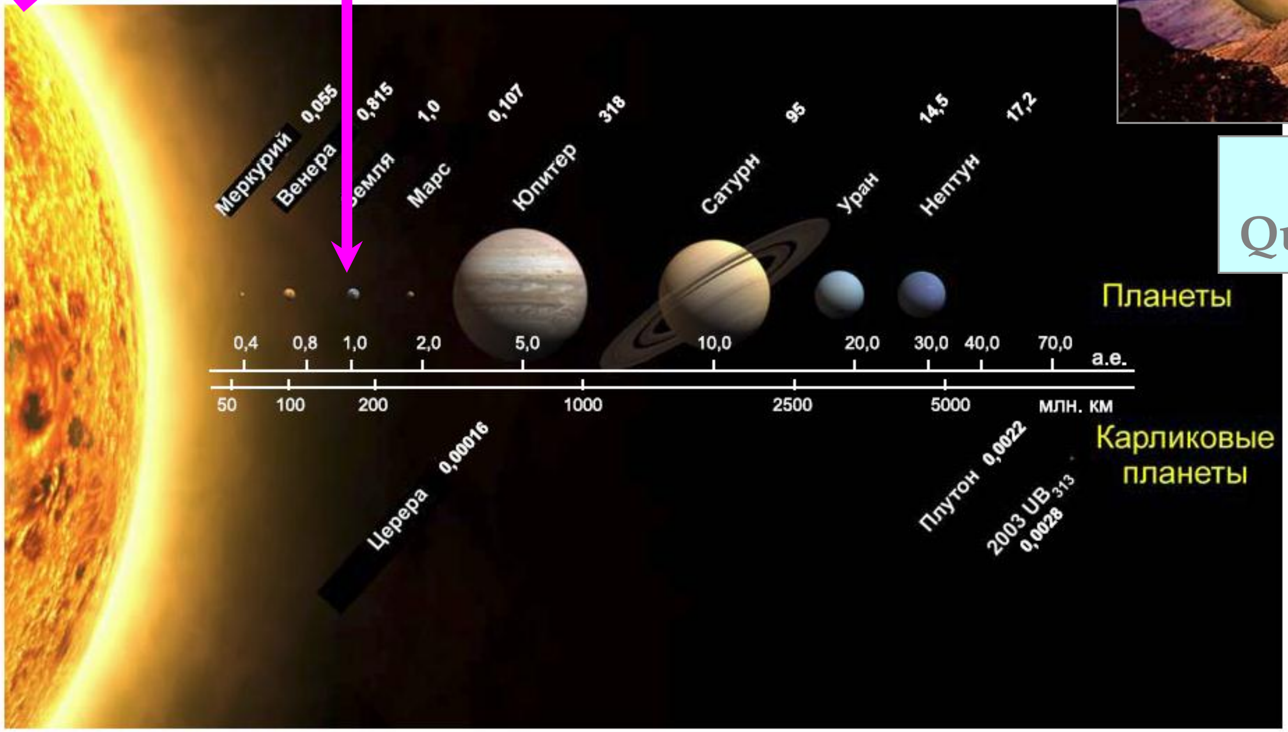
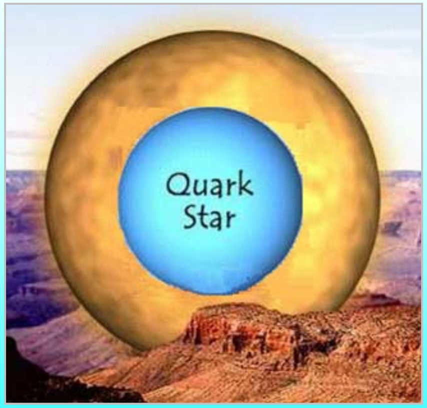


Рис. 65. Массы планет (в единицах массы Земли) и их среднее расстояние от Солнца [371]

Hybrid Stars

Quark core + Hadron Crust

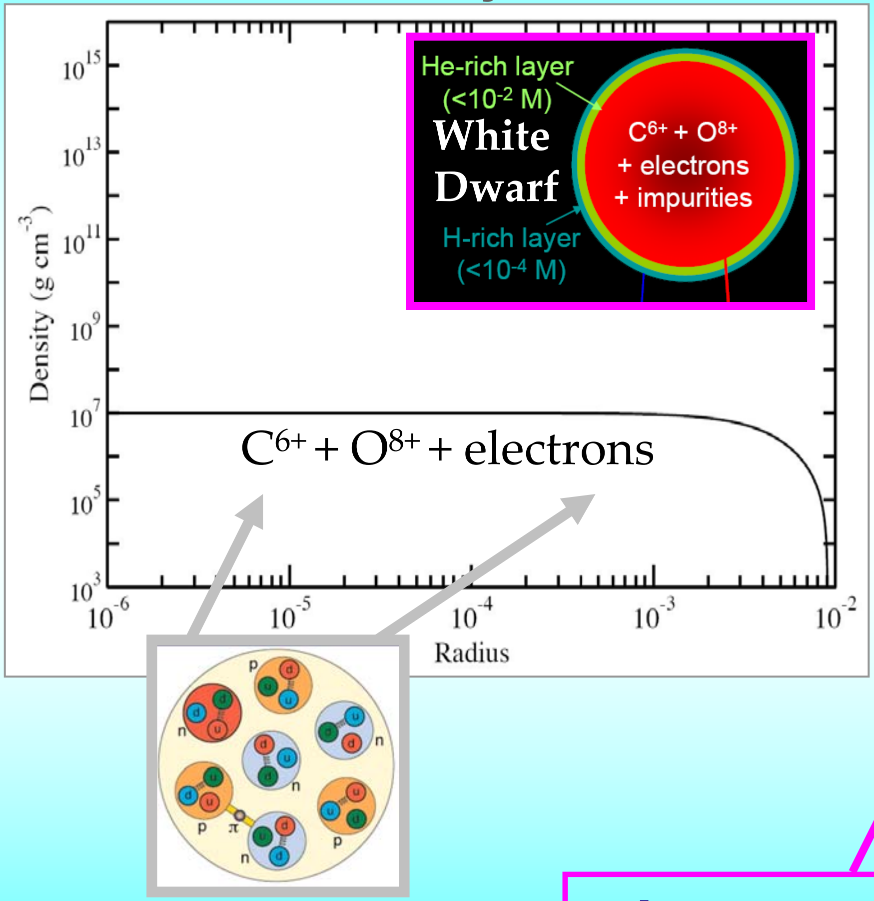


|← R ~ 10 km →|

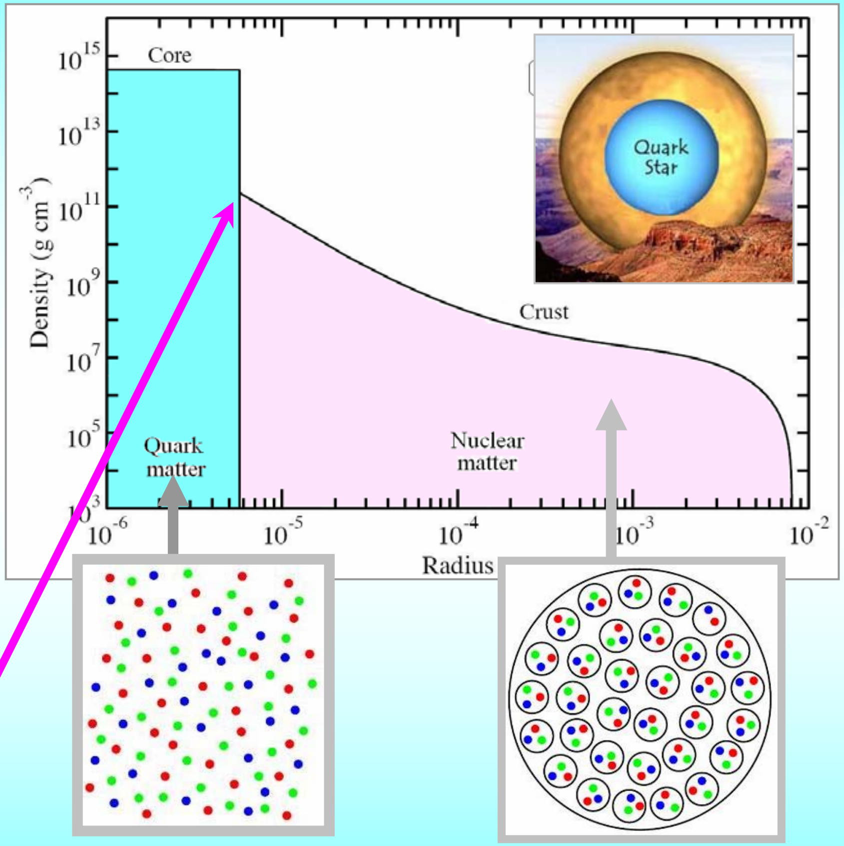
Hybrid ("strange") white dwarfs

Mathews G., Weber F. et al. *J. Phys. G*, 32, (2006) - *White dwarfs with strange-matter cores*

Ordinary WD



Strange WD



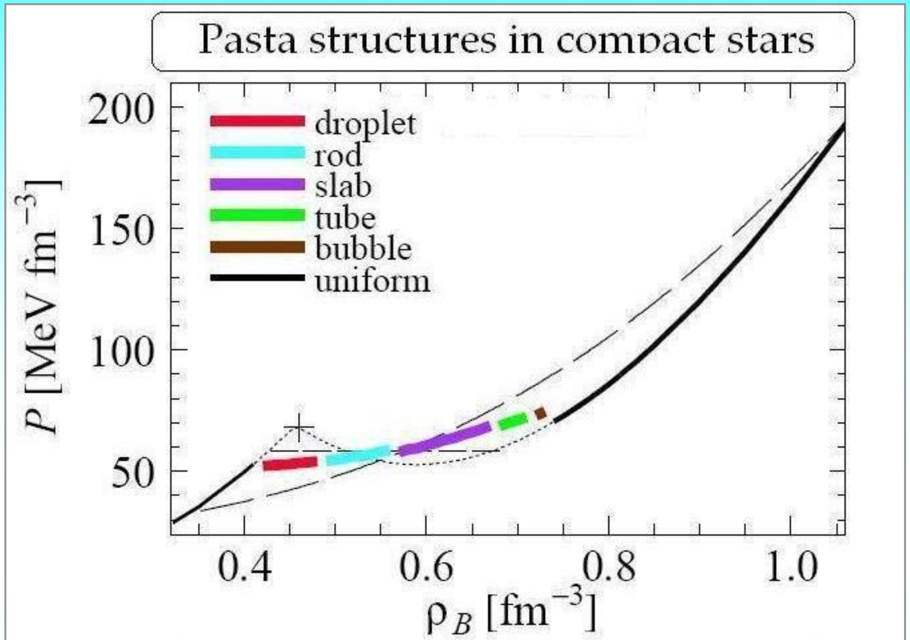
Phase transition?

Jump-like ?

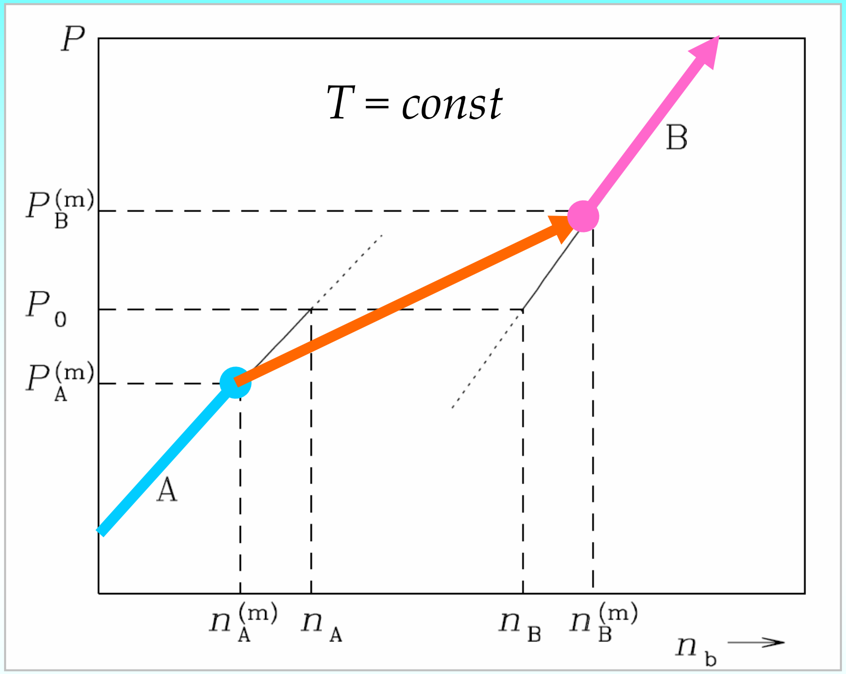
or ***Extended ?***

Hypothetical phase transitions in interior of compact stars:

are they CONGRUENT or NON-CONGRUENT ?



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



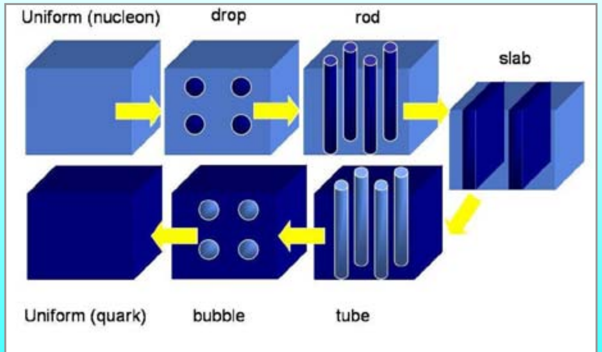
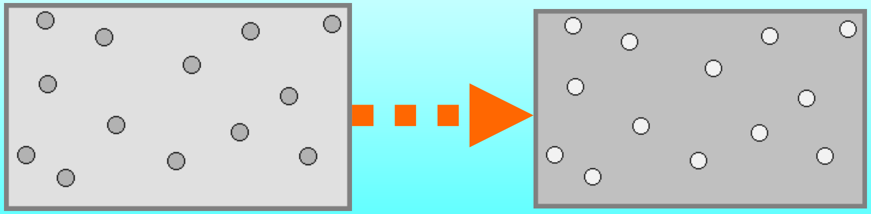


Figure 2: Schematic image of structured mixed phase.

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

First quark droplets in hadron matter

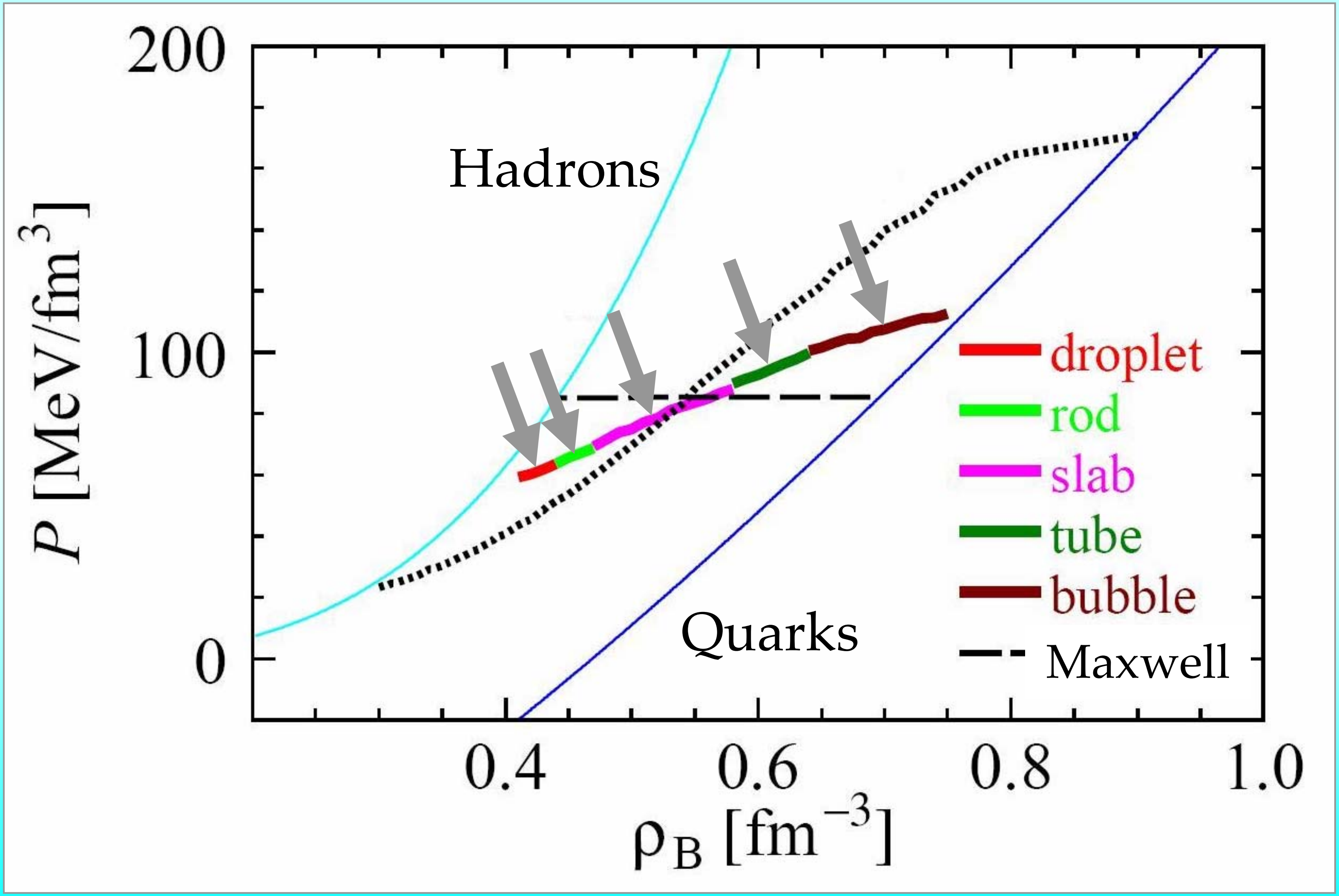


Last hadron bubbles in quark matter

Structured Mixed Phase Concept ⇔ "Pasta"

The sequence of five (or more ?) phase transitions !

Uniform (nucleons) → **Drops** → **Rods** → **Slabs** → **Bubbles** → **Uniform** (quarks)



Structured Mixed Phase ⇔ "Pasta" plasma

'Pasta' plasma – hadron-quark phase transition in interior of neutron stars
('Mixed phase' of Glendenning *et al*. 1992)

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

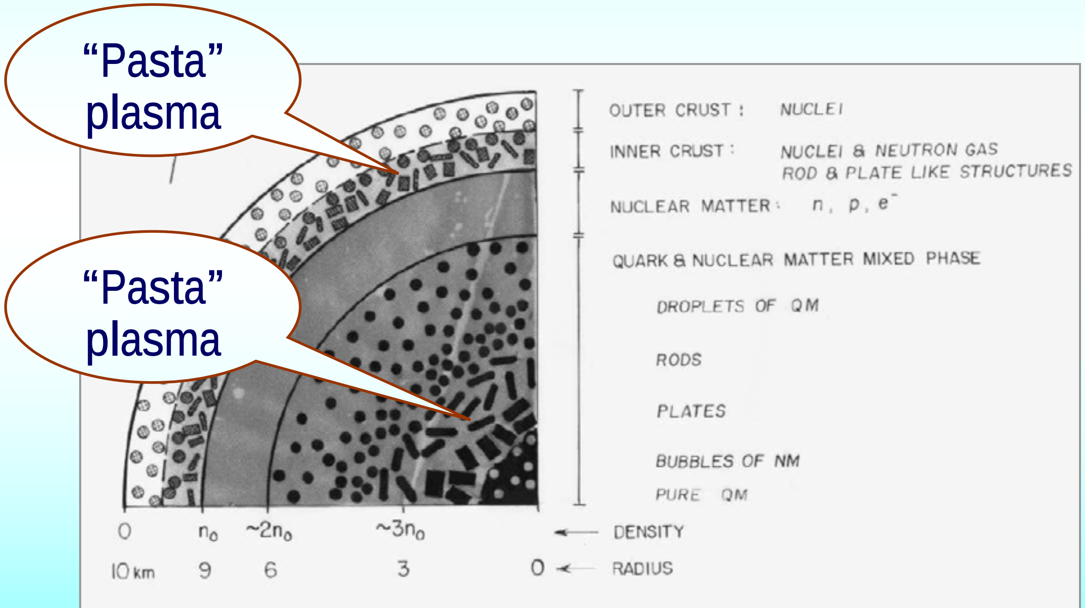
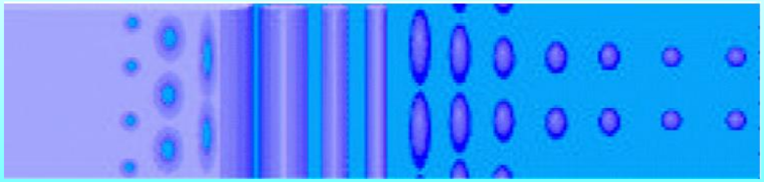


Fig. 1. Nuclear and quark matter tructures in a $\sim 1.4 M_\odot$ neutron star. Typical sizes of structures are $\sim 10^{-14} m$ but have been scaled up to be seen.

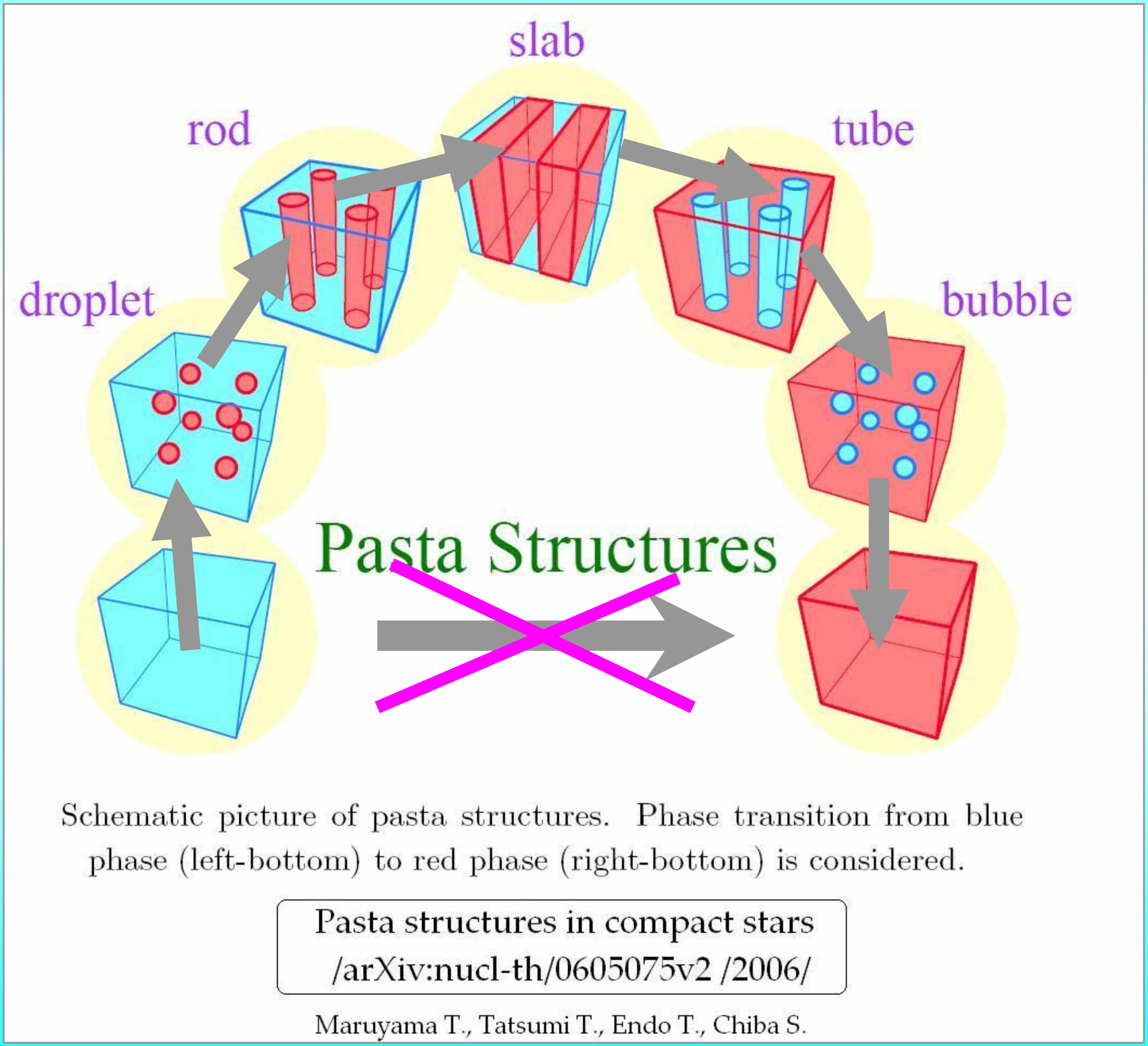
Heiselberg *and* Hjorth-Jensen
Phase Transitions in Neutron Stars
arXiv:astro-ph/9802028v1 (1998)

T.Maruyama, T.Tatsumi, T.Endo, S.Chiba
Pasta structures in compact stars
arXiv:nucl-th/0605075v2 31 (**2006**)



"Pasta" plasma:- *"Spaghetti" phase, "Lasagne" phase* . . . . .

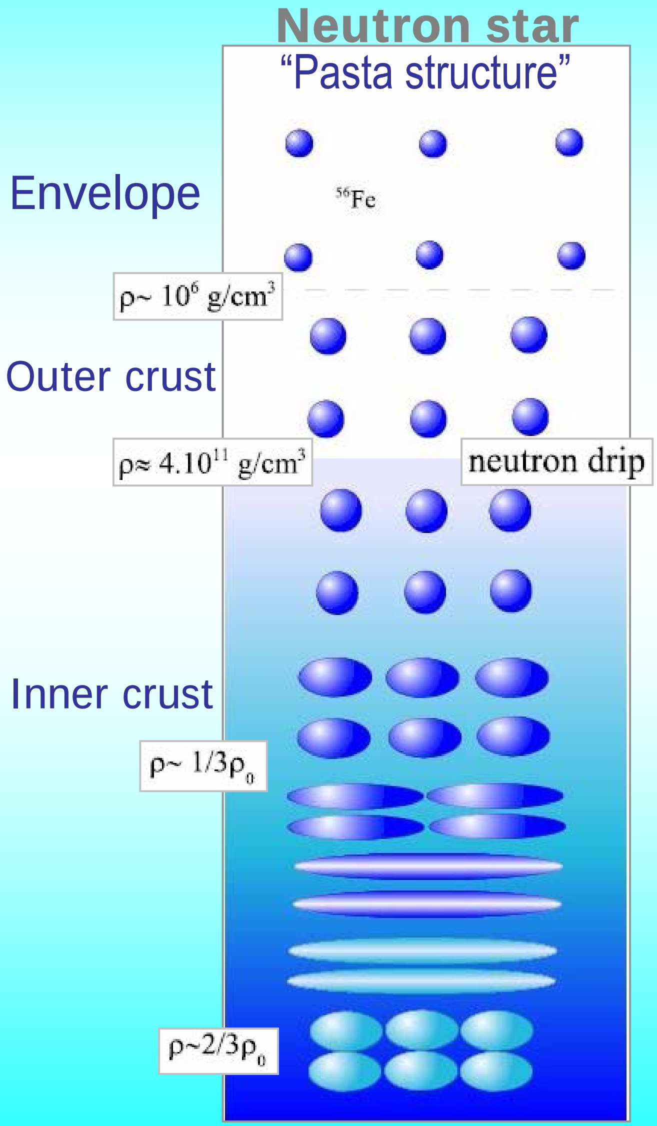
Structured Mixed Phase Concept ⇔ "Pasta"



Schematic picture of pasta structures. Phase transition from blue phase (left-bottom) to red phase (right-bottom) is considered.

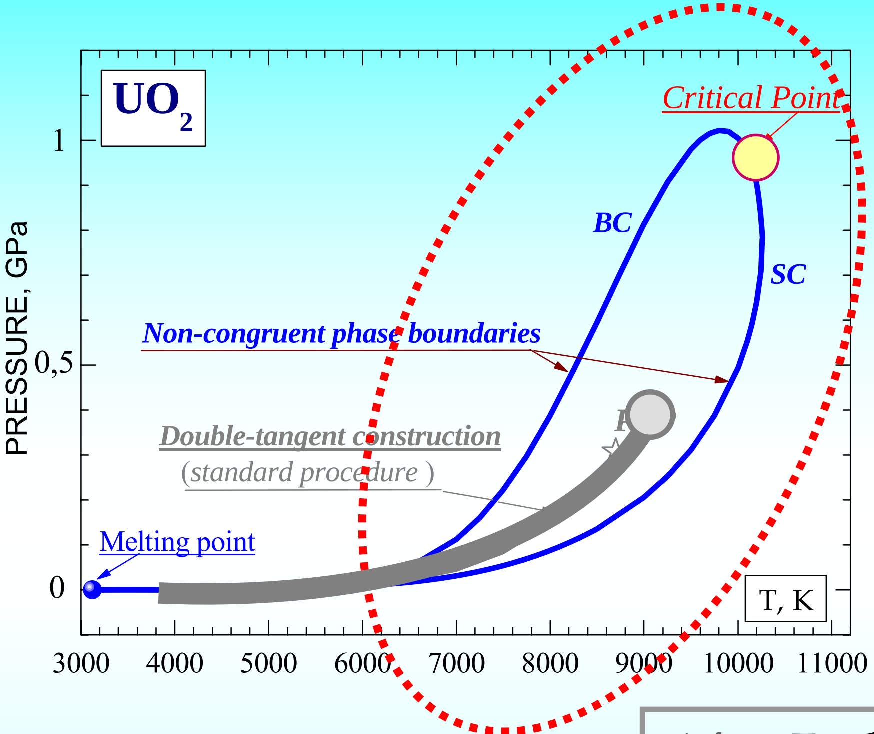
Pasta structures in compact stars /arXiv:nucl-th/0605075v2 /2006/

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

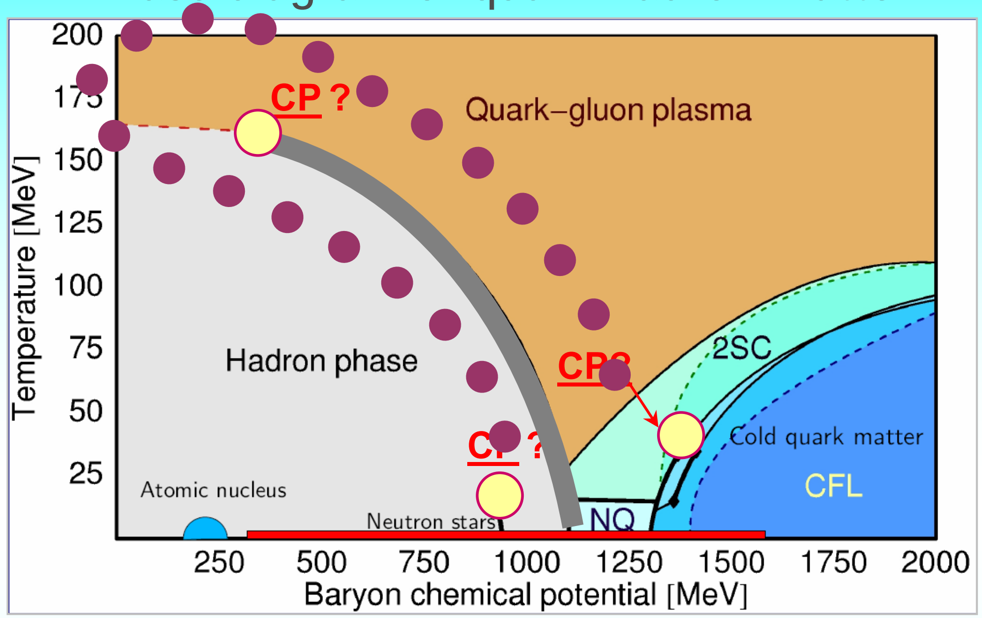


Hypothetical phase transitions in ultra-dense matter:

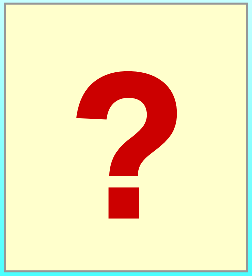
are they CONGRUENT or NON-CONGRUENT ?

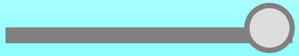


Phase diagram of quark-hadron matter



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



 - Forced-congruent phase transition

 - Non-congruent phase transition

Iosilevskiy I. / Int. Conference ***"Physics of Neutron Stars"***, St.-Pb. Russia, 2008

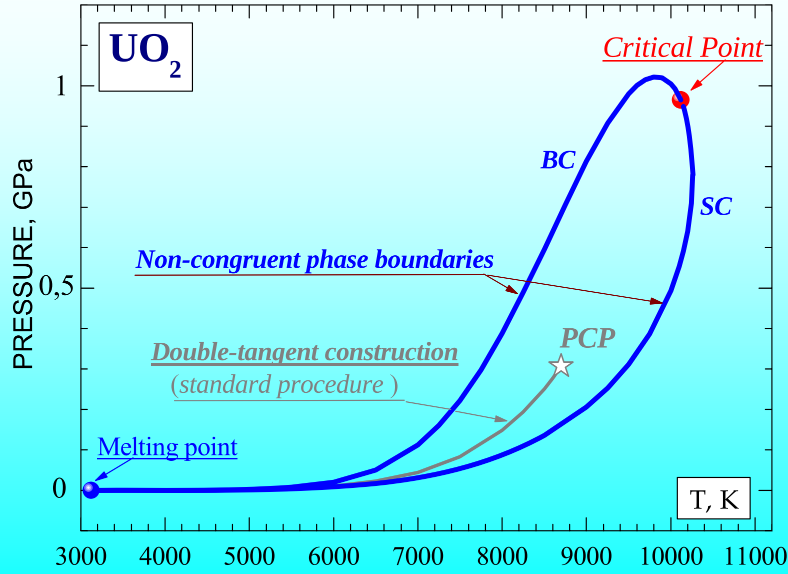
Evaporation of strange matter in the early Universe

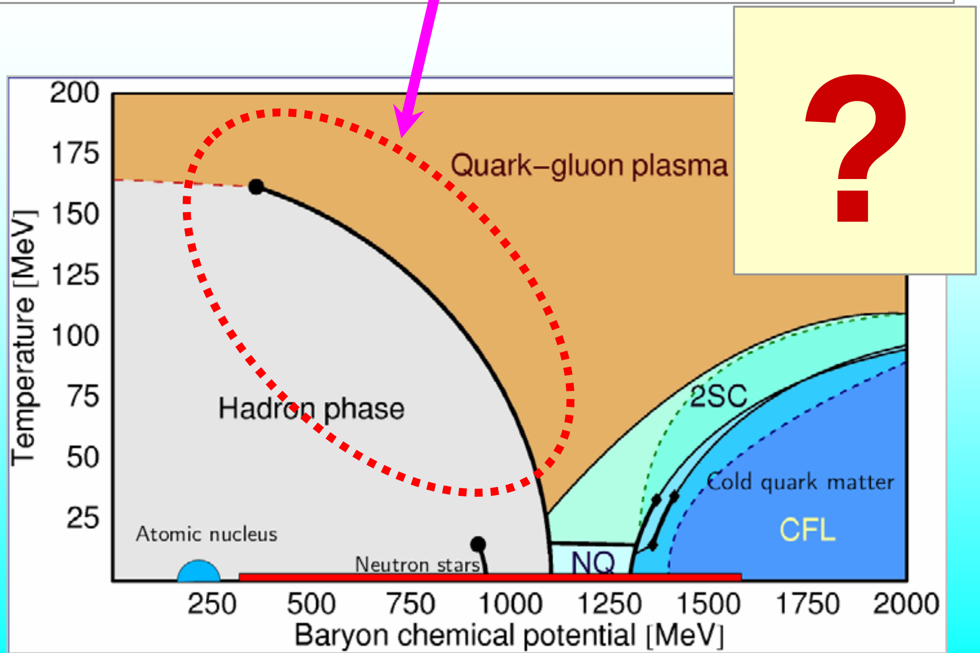
Alcock C., Farhi E. *(PRD, 1985)*

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 ultra-dense matter

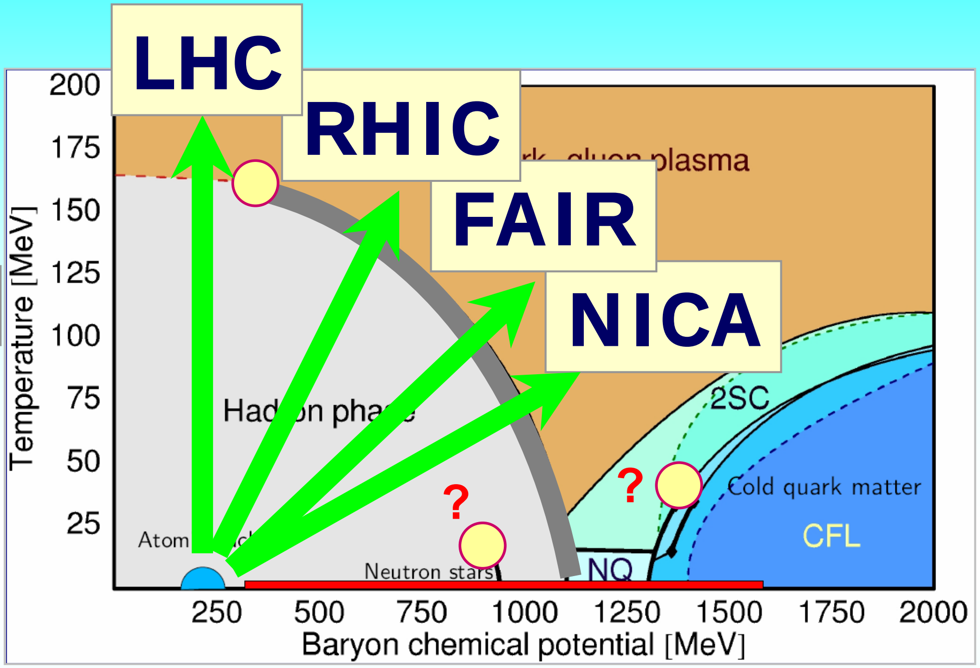
are they CONGRUENT or NON-CONGRUENT ?

LHC – CERN

RHIC – Brookhaven

FAIR – Darmstadt

NICA – Dubna



Nuclotron **I**on **C**ollider f**A**cility
JINR, Dubna

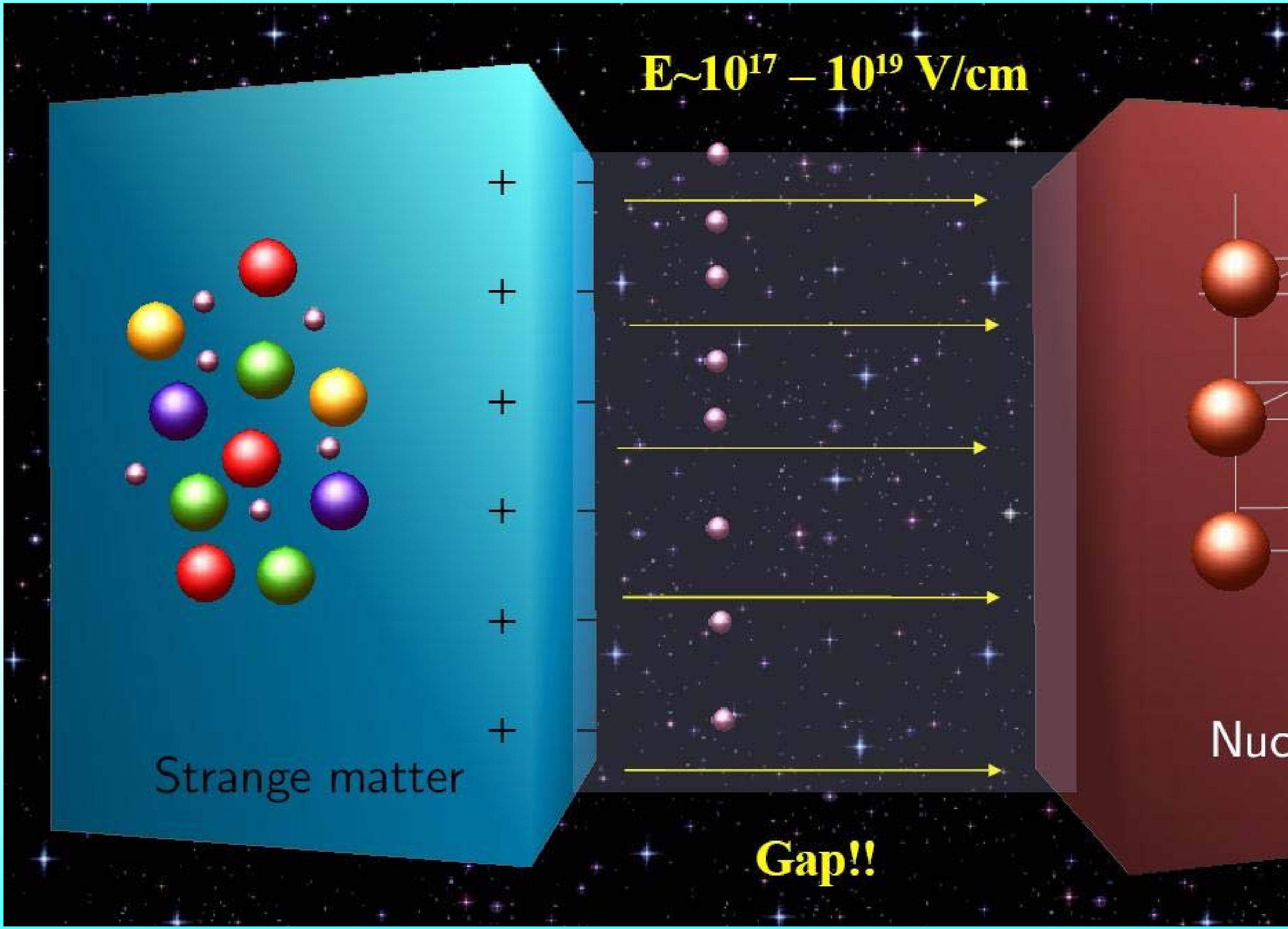
Quark-Hadron Phase Diagram

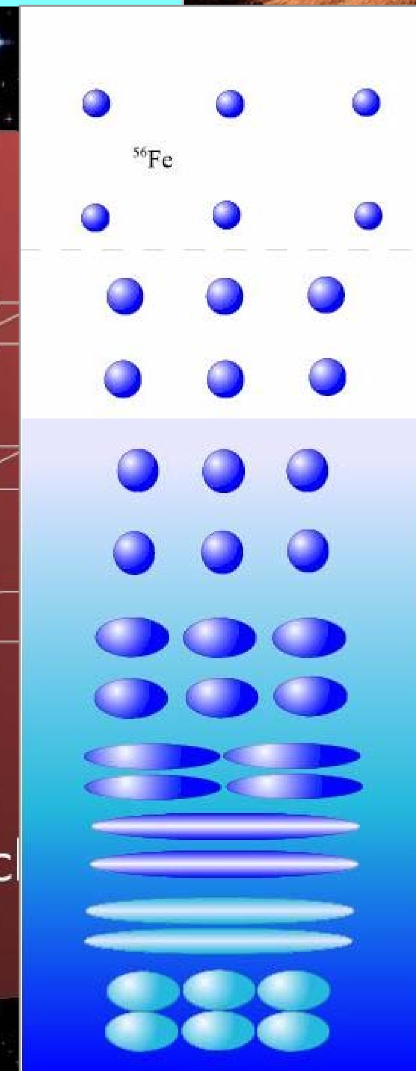
The problem of non-congruence for the Quark-Hadron phase transition is relevant !

Iosilevskiy I. / Int. Workshop *"Physics of HEDM"*, JINR, Dubna, Russia, 2008

Electrostatics of Quark-Hadron Interface

Nuclear Crust on Strange Mater





After Fridolin Weber, WEH Seminar, Bad Honnef, 2006

Conclusions *and* Perspectives

- **Non-congruent** phase transition is **general** phenomenon.

- **Non-congruent** phase transition is **universal** phenomenon.

- **Non-congruent** phase transition is **interesting** phenomenon.

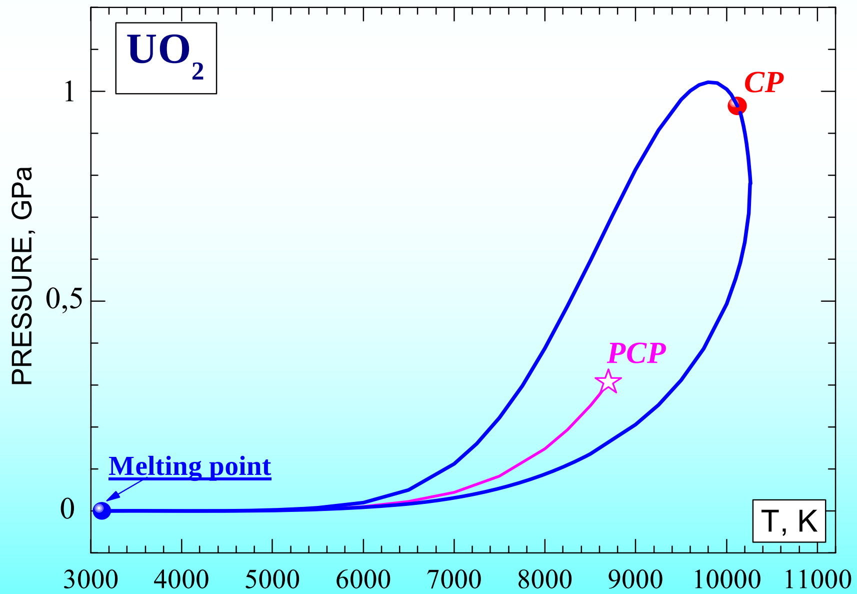
- It is **promising** to investigate non-congruent phase transitions **experimentally** in particular with **intense laser** and **heavy ion** heating

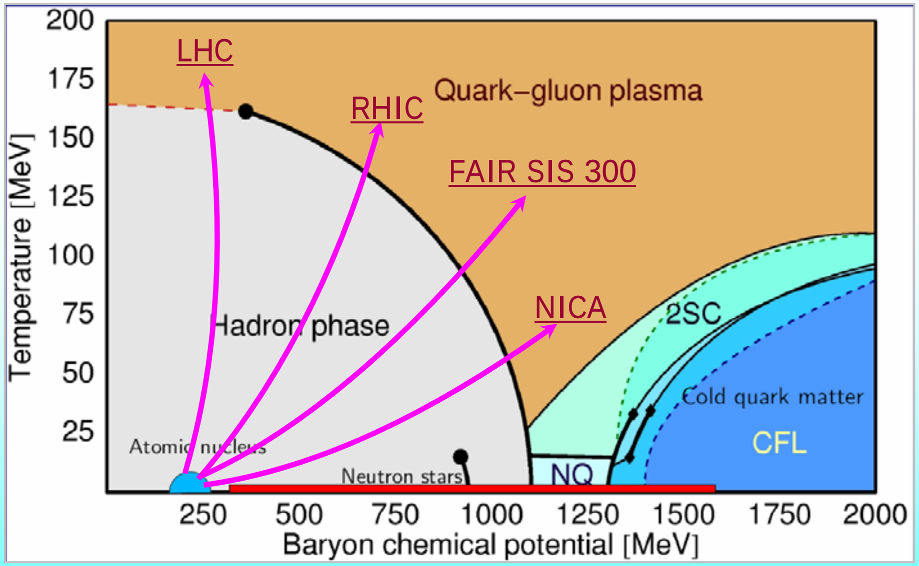
- It is **promising** to investigate non-congruent phase transitions in **direct numerical simulations** (“numerical experiment”) DFT_MD, PIMC, WP_MD…

- If one takes into account hypothetical **non-congruence** of **phase transitions** in **cosmic matter** objects (*planets, compact stars etc.*) he should **revise** totally the **scenario** of all **phase transformations** in these objects.

Non-Congruent Phase Transitions *in* Cosmic Matter *and* Laboratory

Thank you!





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