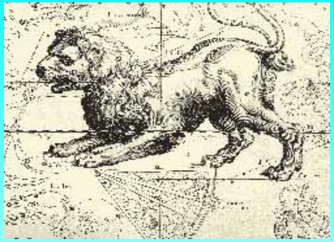
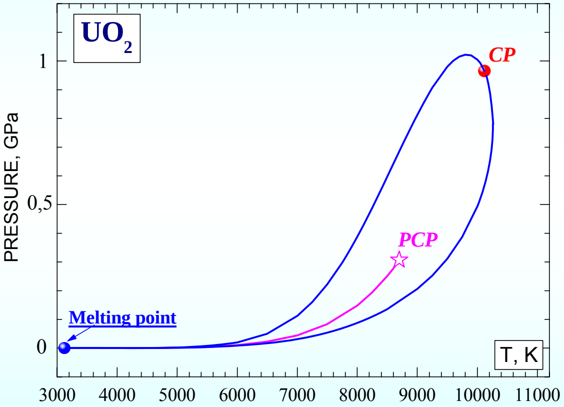
EMMI : Cosmic Matter in the Laboratory

Workshop, Wroclaw, July 9-11, 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

Non-Congruent phase transition – – what does it mean ?

Non-congruence – phase coexistence with *different chemical composition* !

Evident definition – in terrestrial applications

Non-evident – in interiors of compact stars

Non-evident – in ultra-high energy ion collisions products

The base

Non-Congruent Phase Transition in Uranium Dioxide

Hypothetical severe accident at fast-breeder nuclear reactor

Support
Vladimir Fortov (*Russia*)
Claudio Ronchi (*Germany*)
Boris Sharkov (*Russia*)
Dieter Hoffmann (*Germany*)

INTAS 93-66 // ISTC 2107 // CRDF MO-011

Research Programs of
Russian Academy of Science:

“Physics and Chemistry
of Extreme States of Matter”
and
“Physics of Compressed Matter
and Interiors of Planets”

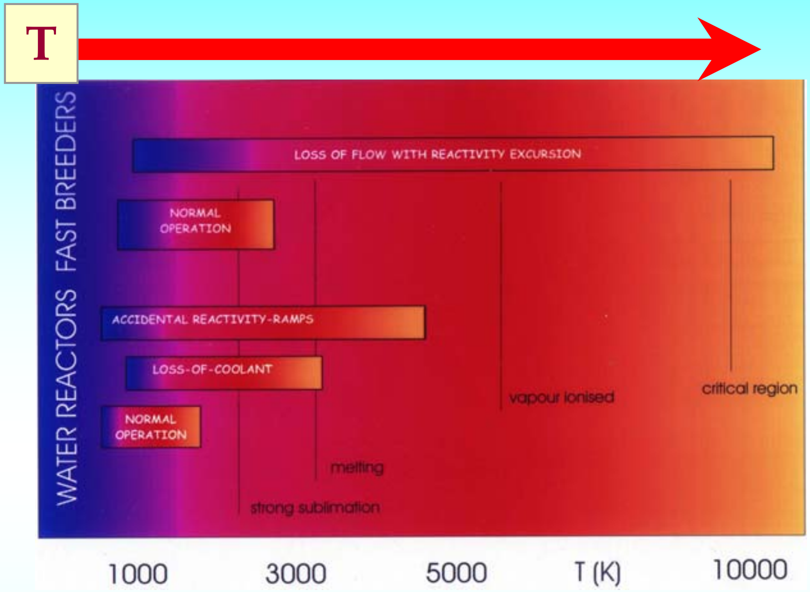
Cooperation
Victor Gryaznov (*Russia*)
Eugene Yakub (*Ukraine*)
Alexander Semenov (*Russia*)
Vladimir Youngman (=“=)
Lev Gorokhov (=“=)
Michael Brykin (=“=)
Andrew Basharin (=“=)
Michael Zhernokletov (=“=)
Michael Mochalov (=“=)
Temur Salikhov (*Uzbekistan*)

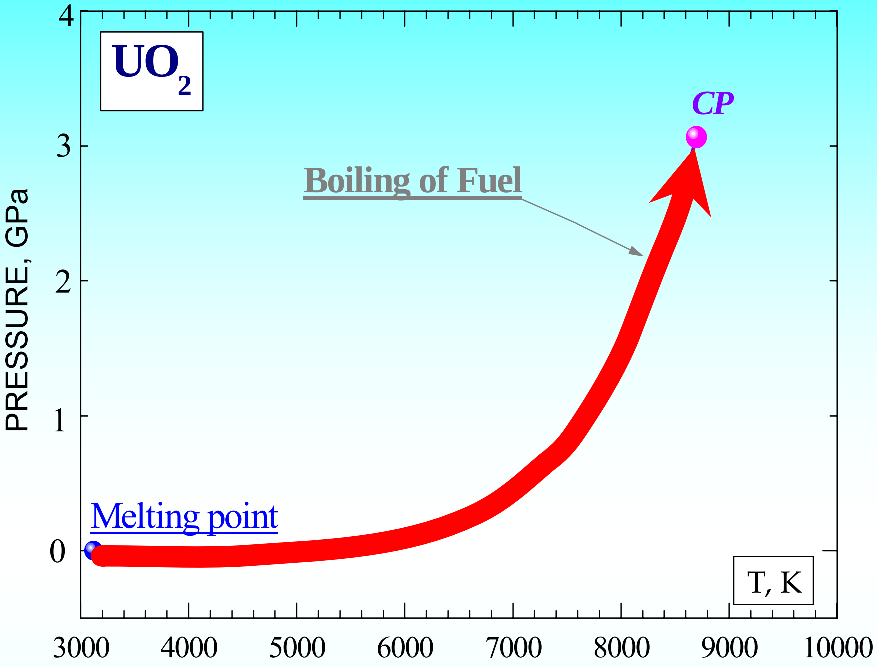
===============

Claudio Ronchi (*JRC, Karlsruhe*)
Gerard J. Hyland (*Warwick, UK*)

Non-Congruent Phase Transition in Uranium Dioxide

Expected temperature at hypothetical severe accident at fast-breeder nuclear reactor





INTAS Project (1995–2002)

Cooperation: **MIPT – IHED RAS – IPCP RAS – OSEU – MPEI** ⇔ **ITU** (JRC, Germany)

Project Coordinator – C. Ronchi (ITU, JRC) ⇔ Project Supervisor – V. Fortov

ISTC Project (2002–2005)

Cooperation: **MIPT – IHED RAS – IPCP RAS – ITEP – VNIIEF** ⇔ **GSI** (JRC, Germany)

Project Manager – B. Sharkov (ITEP, Moscow) ⇔ Project Science Supervisor – V. Fortov

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**)

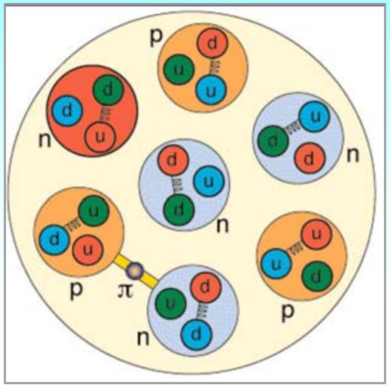
* Ronchi C., Iosilevskiy I., Yakub E. *Equation of State of Uranium Dioxide* / **Springer, Berlin,** (**2004**)

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

Quasi-chemical representation

(*"Chemical picture"*)

Neutron stars



u, d, s, p, n, e

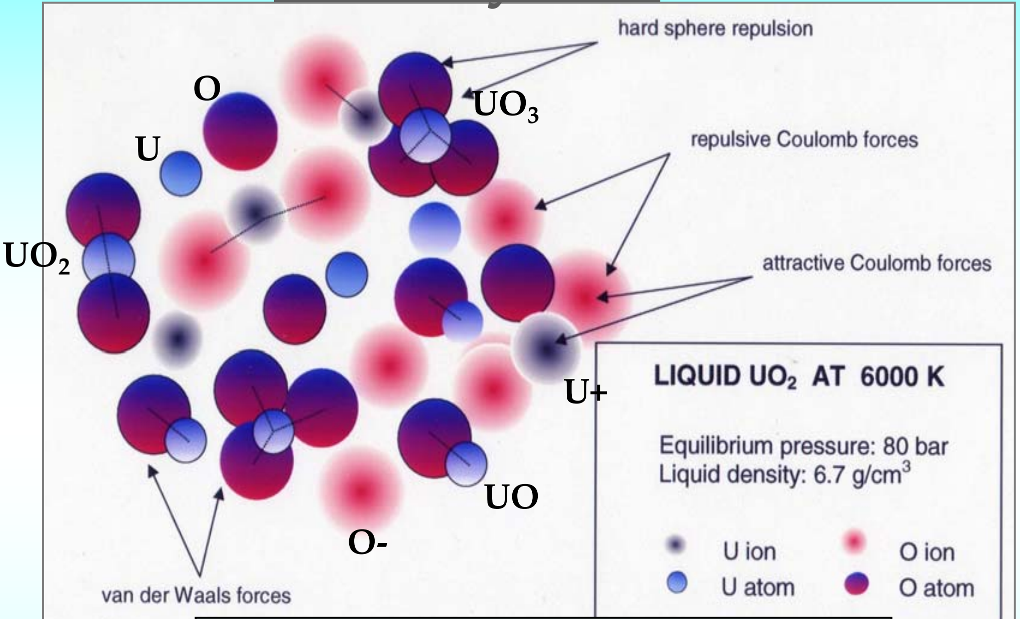
$\mu_u, \mu_d, \mu_s, \mu_p, \mu_n, \mu_e$

u + e ⇔ d
d ⇔ s
p + e ⇔ n
n ⇔ u + 2d
(p ⇔ 2u + d)

$$\mu_u + \mu_e = \mu_d,$$
$$\mu_d = \mu_s,$$
$$\mu_p + \mu_e = \mu_n \equiv \mu_B,$$
$$\mu_n = \mu_u + 2\mu_d,$$
$$(\mu_p = 2\mu_u + \mu_d).$$

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

U – O system



Multi-molecular model
(*Liquid & Gas*)
$U + O + O_2 + UO + UO_2 + UO_3$
$U^+ + UO^+ + UO_2^{\ +} + O^- + UO_3^{\ -} + e^-$

$U + 2O \Leftrightarrow UO_2$
$2O \Leftrightarrow O_2$
$U^+ + e \Leftrightarrow U$
$UO_3 + e \Leftrightarrow UO_3^-$
. . . . . .

$\mu_U + 2\mu_U = \mu_{UO2}$
$2\mu_O = \mu_{O2}$
$\mu_{U+} + \mu_e = \mu_U$
$\mu_{UO3} + \mu_e = \mu_{UO3-}$
. . . .

Phase coexistence parameters calculation

(***two approaches***)

***Ordinary way*:**

Maxwell ("equal squares") **construction**

{in unique two-phase pressure-density: $P(V)_T$ }

or

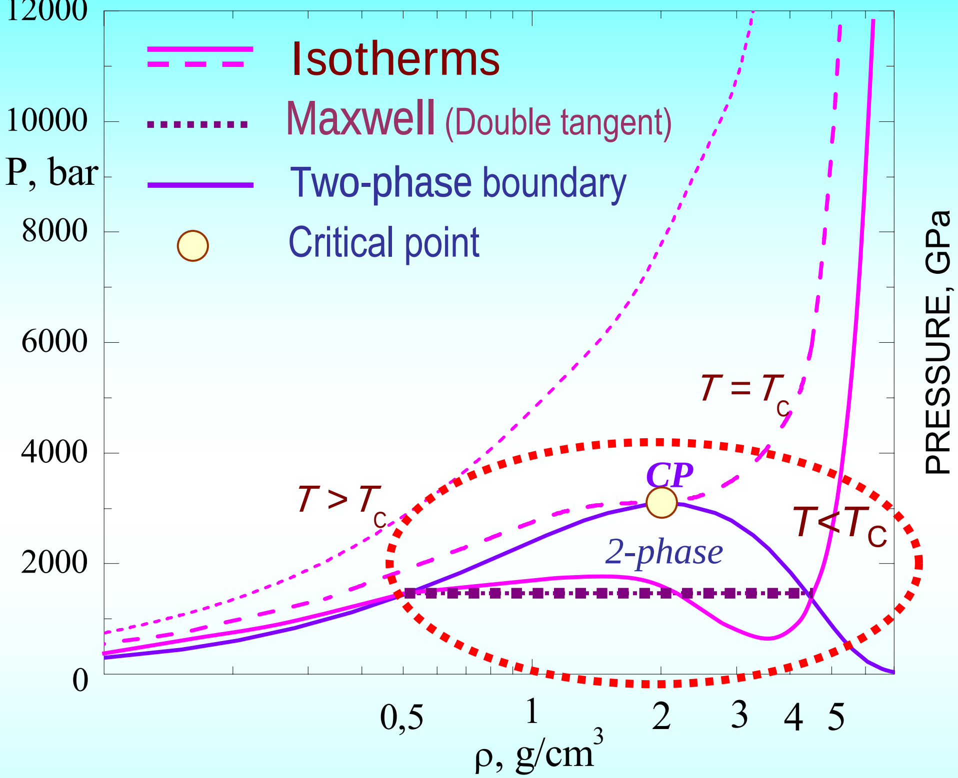
"Double tangent" construction

{in free energies of two phases: $F_1(V) \Leftrightarrow F_2(V)$ }

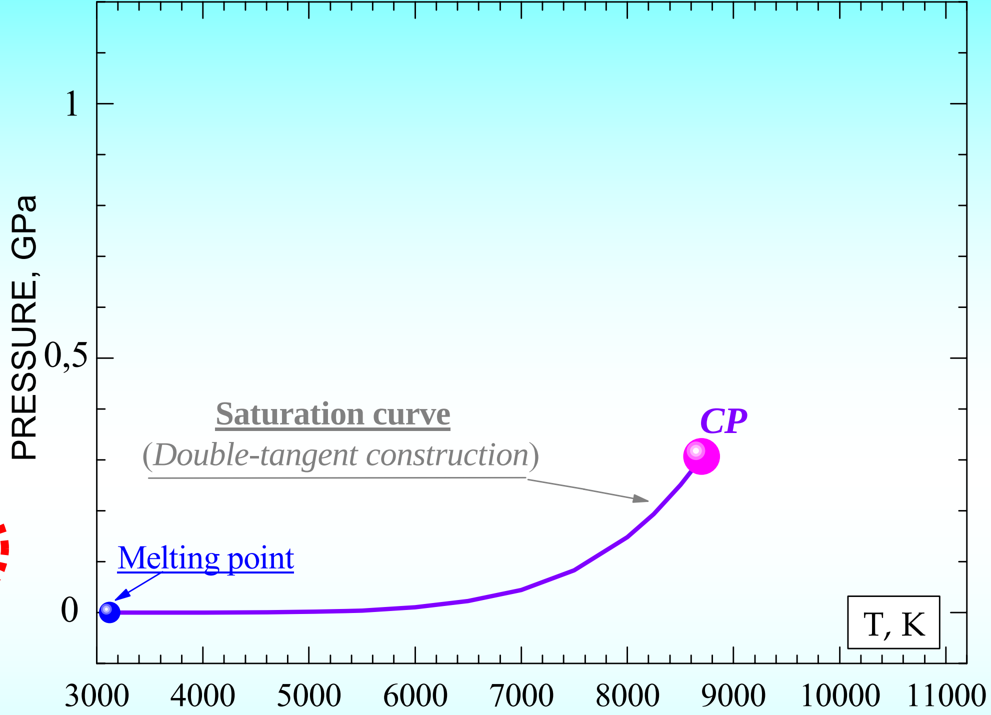
Standard

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:

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

- 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

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

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

(only to the partial one)

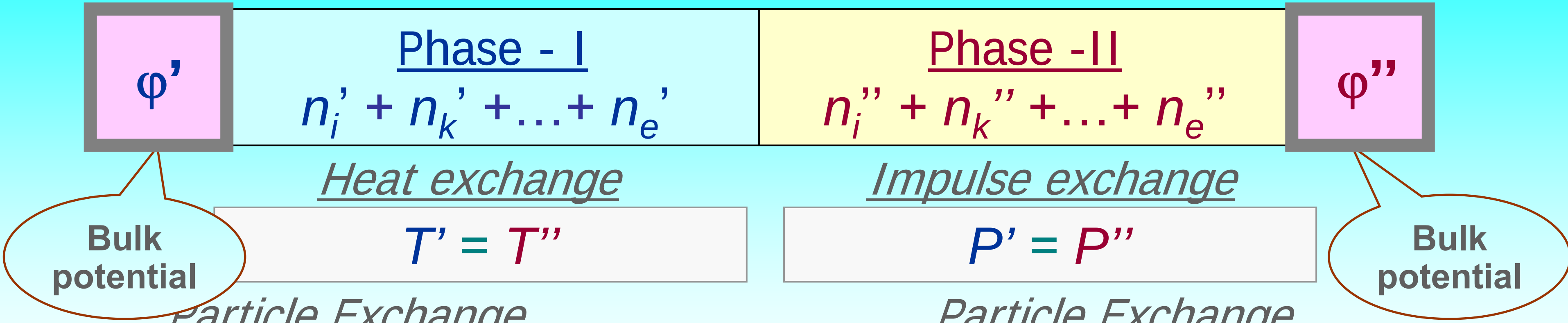
Maxwell approach

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

Correct approach:

- **Gibbs** (+ **Guggenheim**) **conditions**

Phase equilibrium conditions in reacting Coulomb system



φ’

Phase - I

$n_i' + n_k' + \ldots + n_e'$

Phase -II

$n_i'' + n_k'' + \ldots + n_e''$

φ’’

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

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

Potential drop at mean-phase interface
in equilibrium Coulomb system

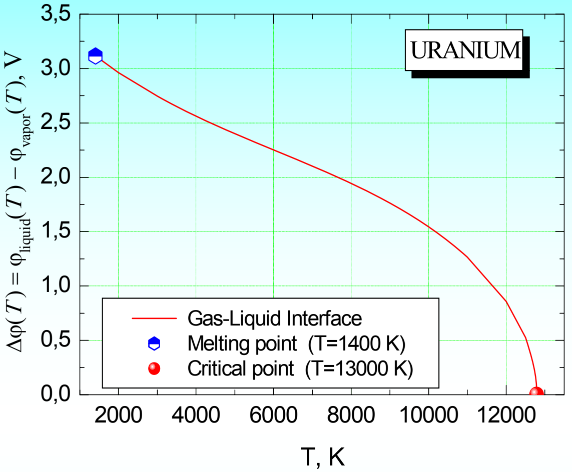
$$\mu_1'(P,T,x') = \mu_1''(P,T,x'') + Z_1 e\,\Delta\varphi(T)$$
$$\mu_2'(P,T,x') = \mu_2''(P,T,x'') + Z_2 e\,\Delta\varphi(T)$$
$$\ldots\ldots\ldots\ldots$$
$$\mu_e'(P,T,x') = \mu_e''(P,T,x'') - e\,\Delta\varphi(T)$$

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

Electrostatics of phase boundaries in Coulomb systems

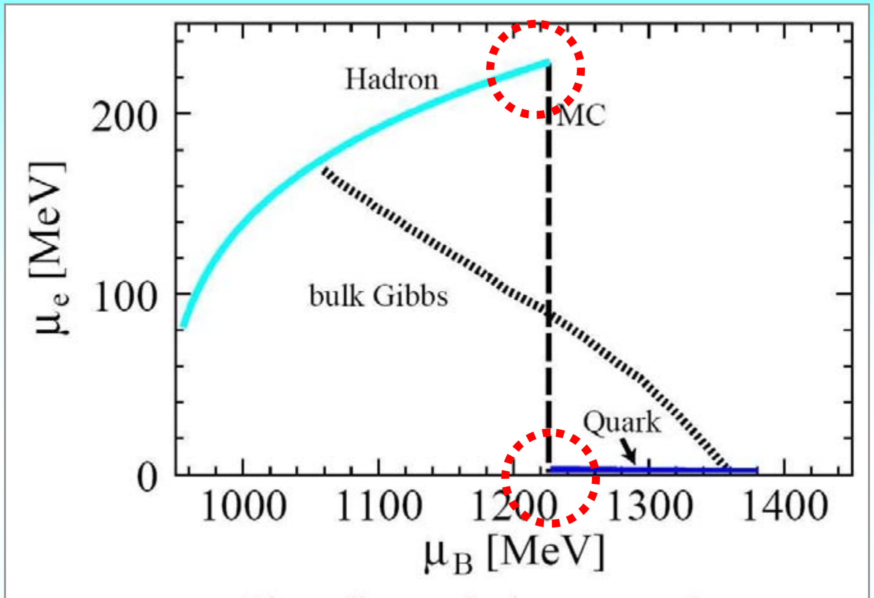
Terrestrial applications

Electrostatic (Galvani) potential



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

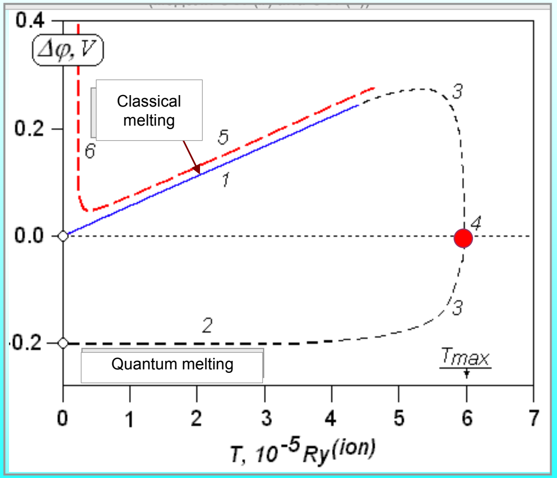
Quark-Hadron phase transition in NS



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

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

Electrostatic "portrait" of Wigner crystal in OCP



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

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

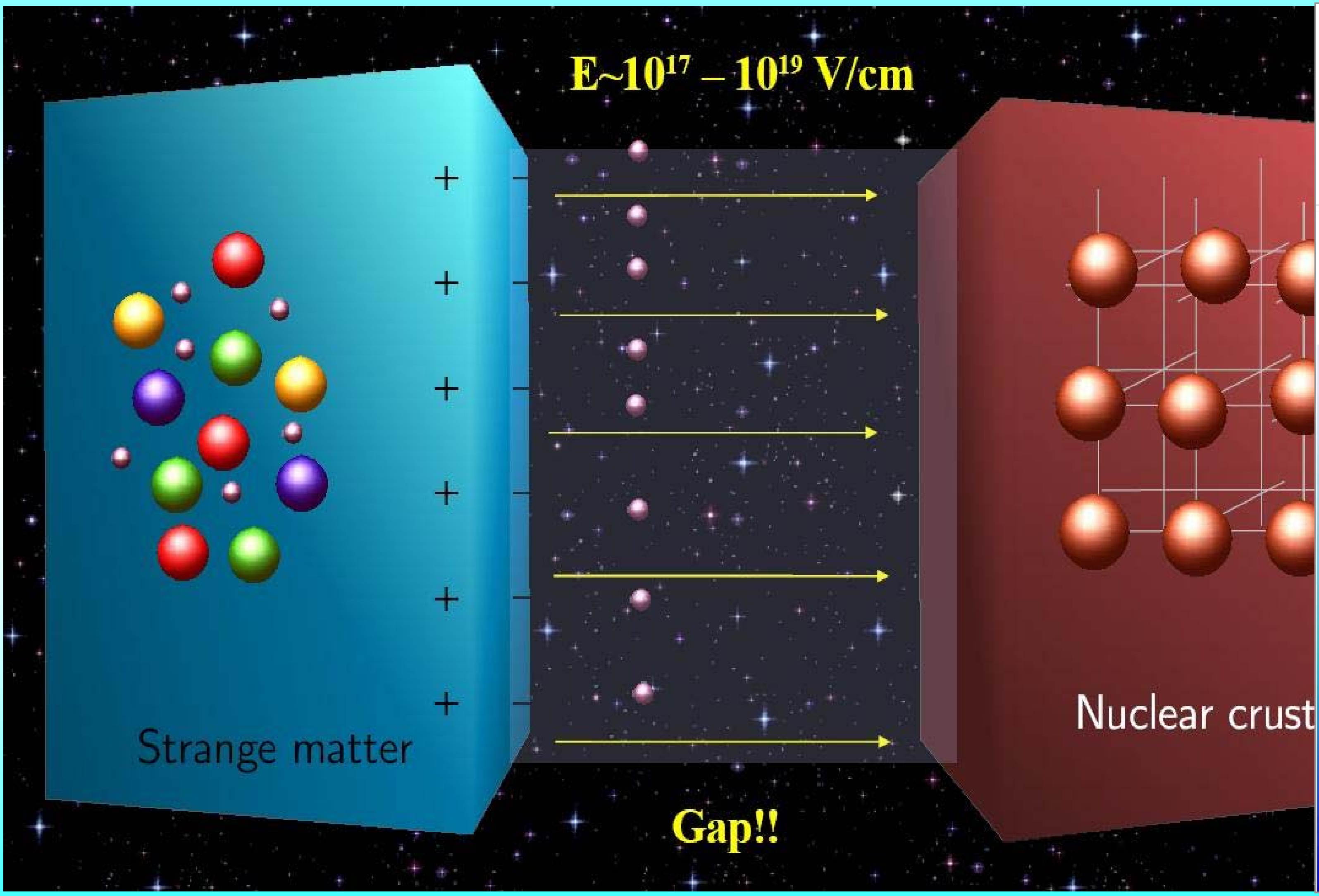
$$\mathbf{e\Delta\varphi_{HQ} \approx 200\ MeV}\ \ !$$

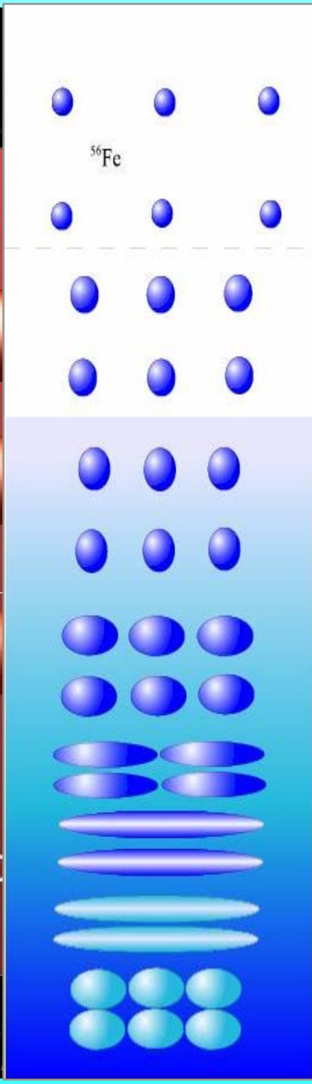
$$\delta_{HQ} \approx 10^3\ \text{fm} \ \rightarrow\ E \sim 10^{18}\ \text{V/cm}$$

For comparison: Alcock *et al.*, 1986: → $E \sim \mathbf{10^{17}}$ V/cm

Electrostatics of Quark-Hadron Interface

Nuclear Crust on Strange Mater





After **Fridolin Weber**, WEH Seminar, Bad Honnef, 2006

Gibbs - Guggenheim 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''

$T' = T''$

$P' = P''$

Neutral species

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

Charged species

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

Equilibrium reactions

$$\mu_{U} + \mu_{O} = \mu_{UO}$$
$$\mu_{UO} + \mu_{O} = \mu_{UO2}$$
$$\mu_{UO2} + \mu_{O} = \mu_{UO3}$$
$$\ldots\ldots\ldots\ldots$$
$$2\mu_{O} = \mu_{O2}$$
$$\ldots\ldots\ldots\ldots$$

Electroneutrality

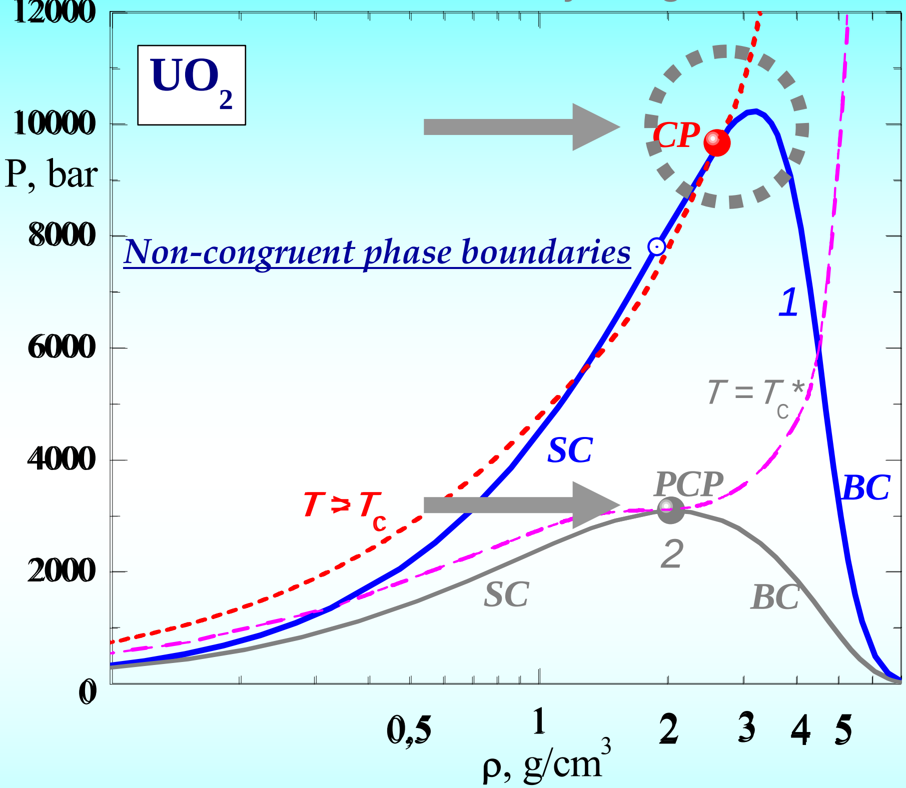
$$n_{U+} + n_{U++} + n_{UO2+} + n_{UO3+} = n_{e} + n_{O-} + n_{O2-} + n_{UO3-}$$

$$\mu_{U+} + \mu_{e} = \mu_{U} \qquad \mu_{UO3} + \mu_{e} = \mu_{UO3-}$$
$$\mu_{UO+} + \mu_{e} = \mu_{UO} \qquad \mu_{O} + \mu_{e} = \mu_{O-}$$
$$\mu_{UO2+} + \mu_{e} = \mu_{UO2} \qquad \ldots\ldots\ldots\ldots$$

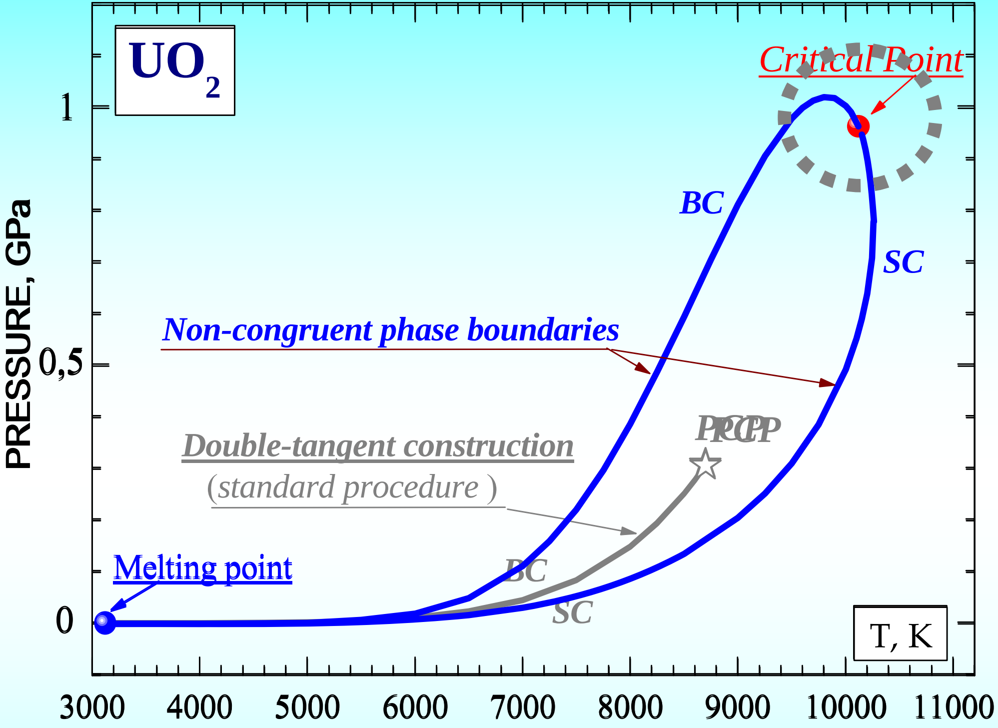
Non-congruent evaporation in U-O system

(*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

- Stoichiometry of coexisting phases are different: $x' \neq x''$

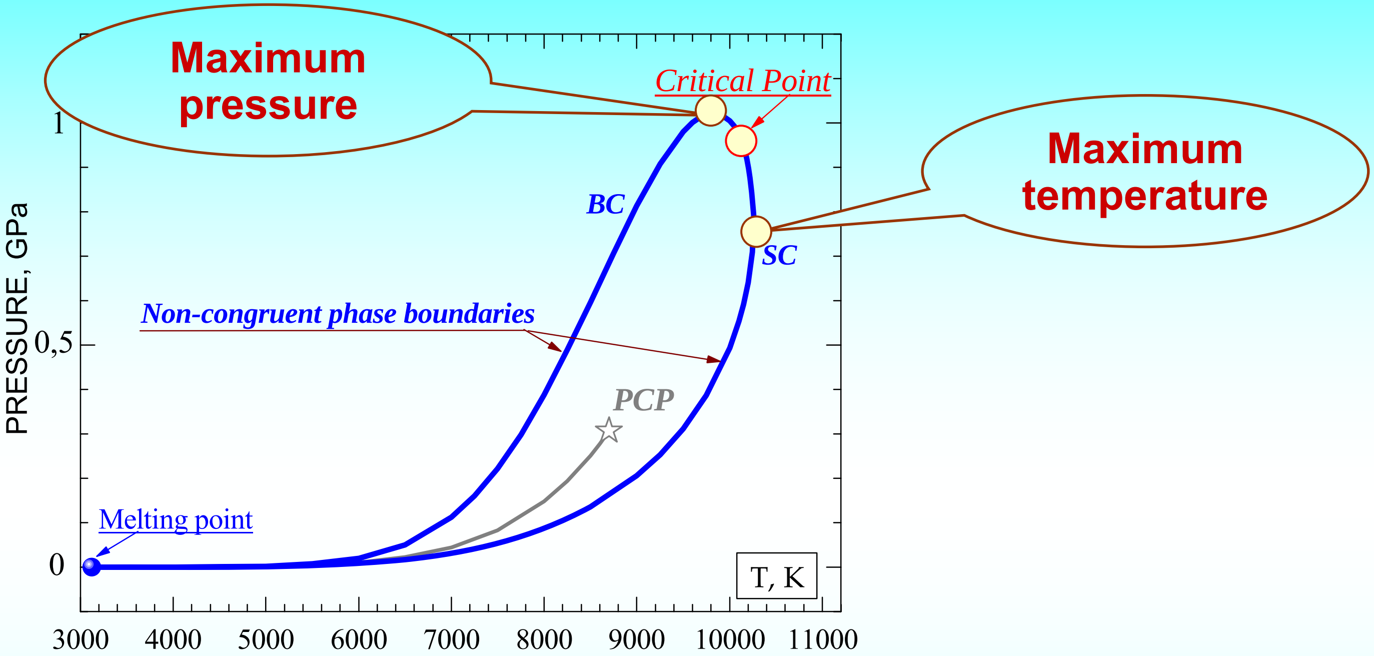
NB! **High pressure level** of non-congruent phase decomposition

- Total phase equilibrium conditions for mixture are valid instead of the

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 $\{||\partial \mu_i/\partial n_k||_T\}_{CP} = 0$

End-Points of Non-Congruent Phase Transition

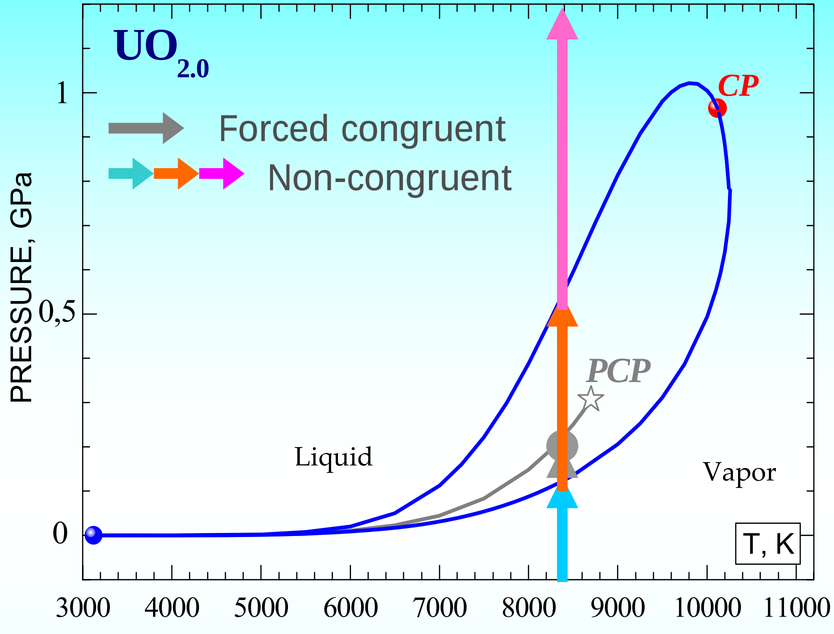


NB !

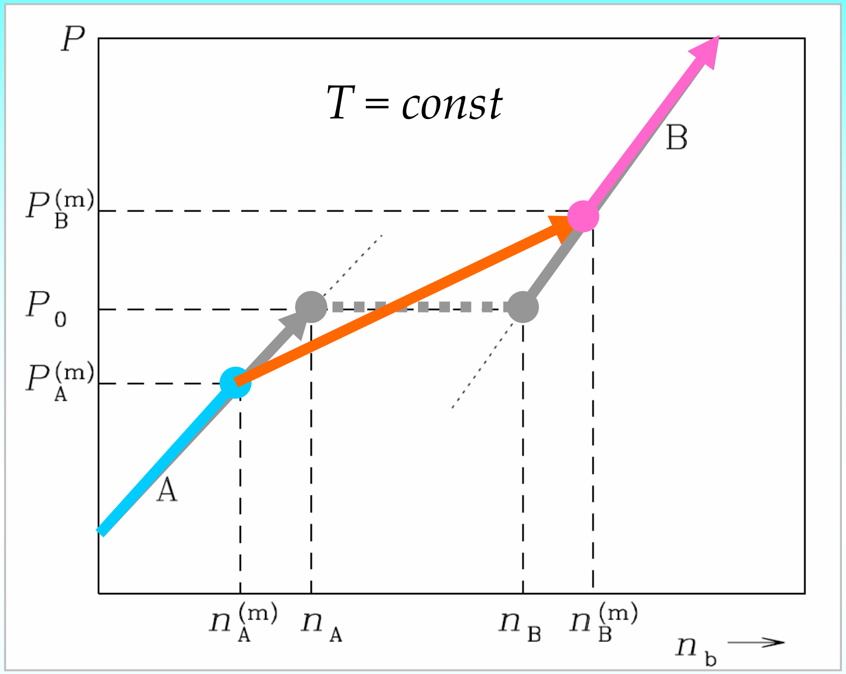
- Point of temperature maximum
- Point of pressure maximum
- Critical point

are three different points !

Non-congruent phase transformation in two-phase region

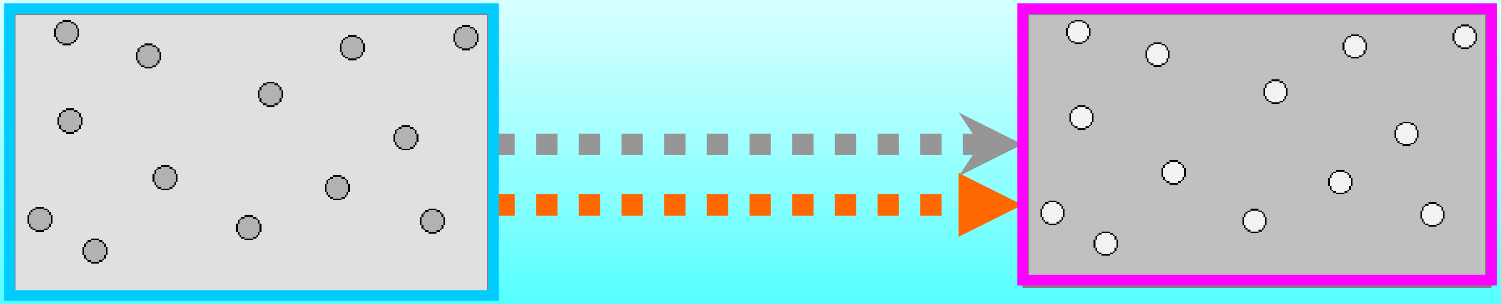


Phase Diagram *P-T* of Non-congruent Evaporation



First liquid droplets in saturated vapor

Last vapor bubbles in boiling liquid



Oxygen depleted liquid

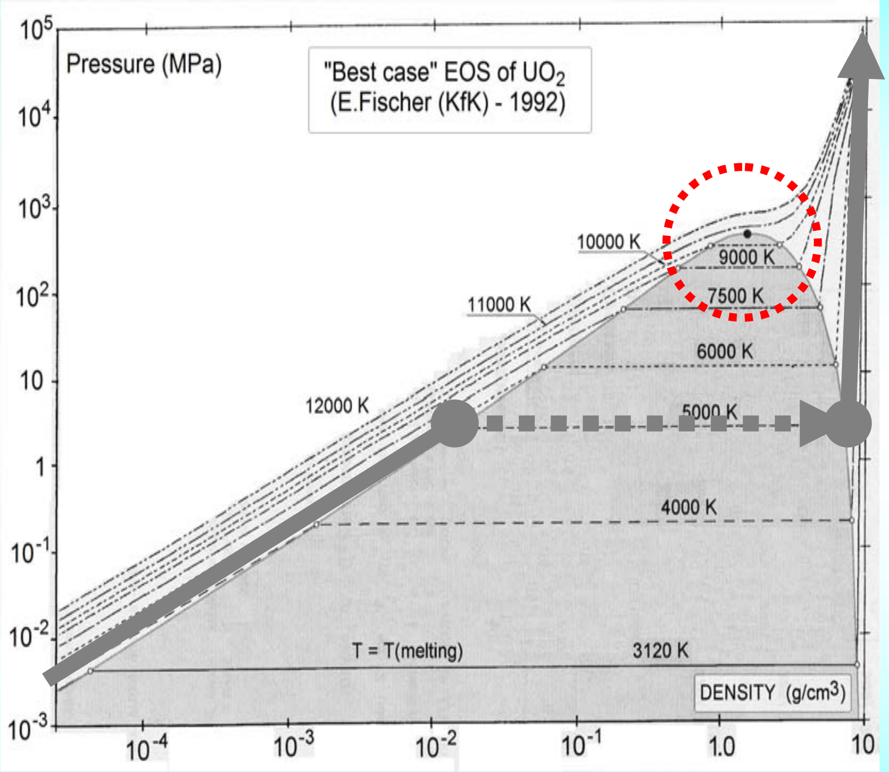
! *Different stoichiometry* !

Oxygen enriched vapor

! *Different stoichiometry* !

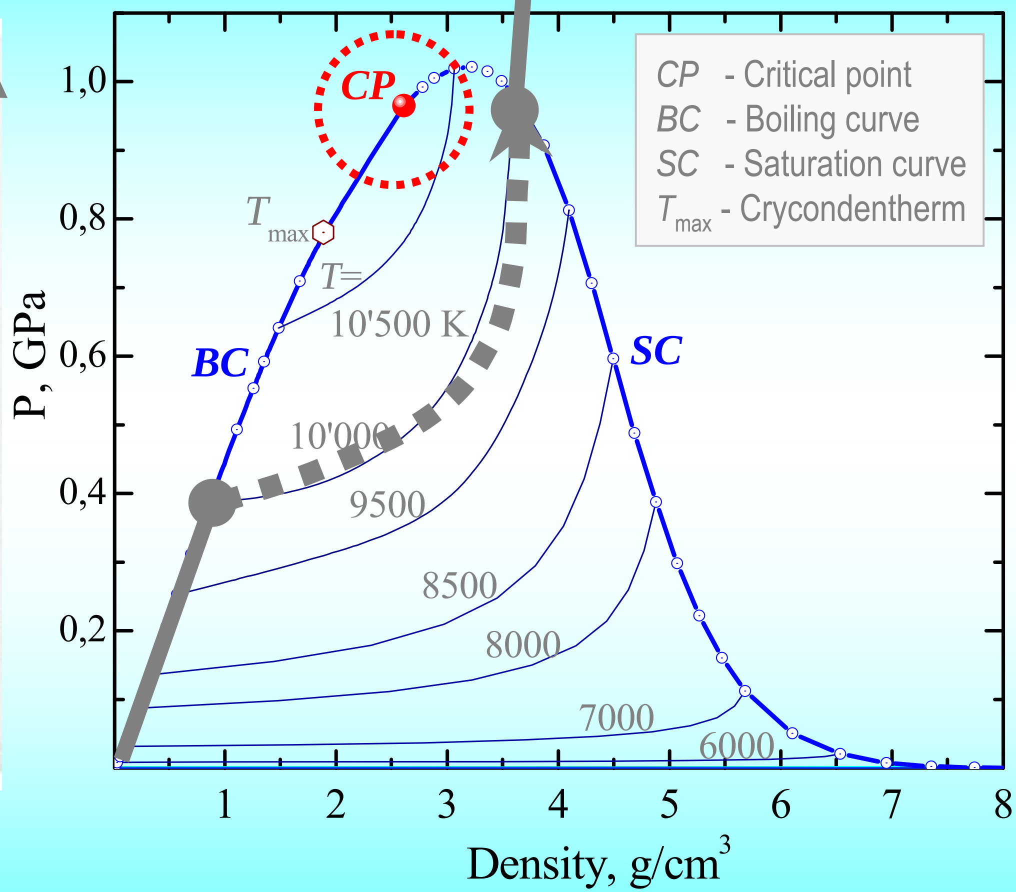
Isotherms in two-phase region

Standard pressure-density diagram



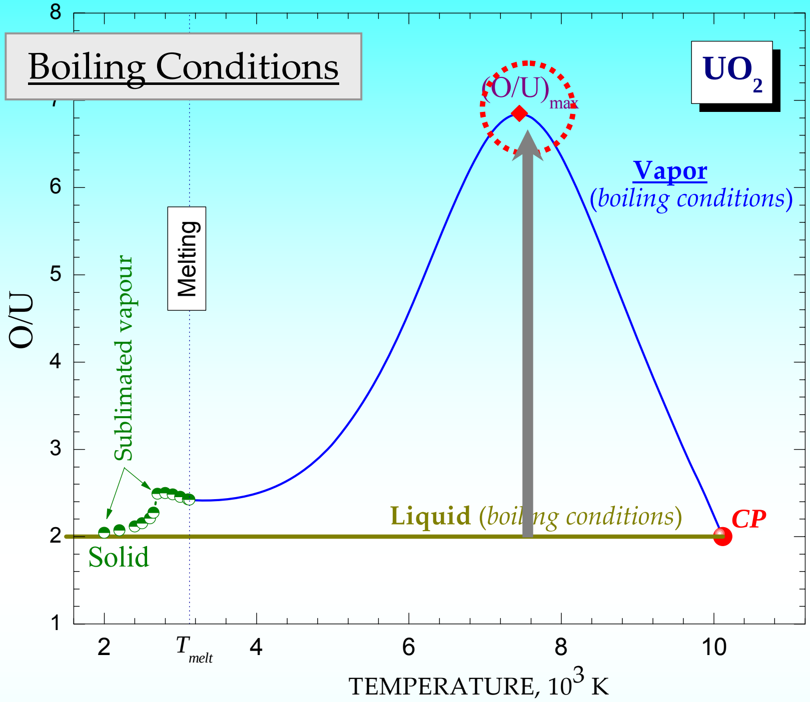
Fischer E.A. *J. Nucl. Sci. Eng.* (1989)

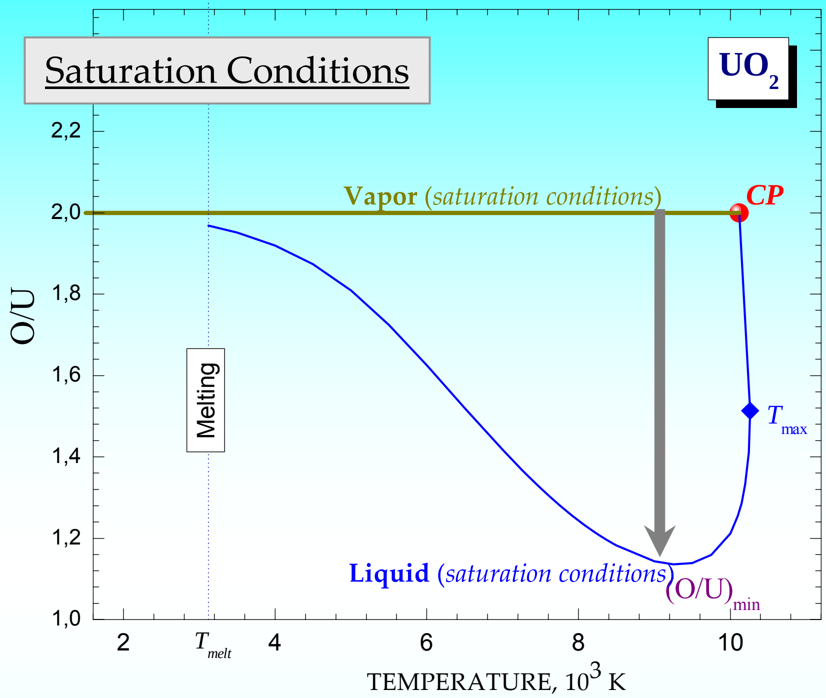
Non-congruent pressure-density diagram



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

Chemical composition at coexisting phases

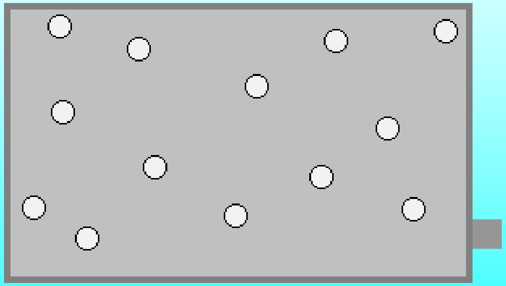


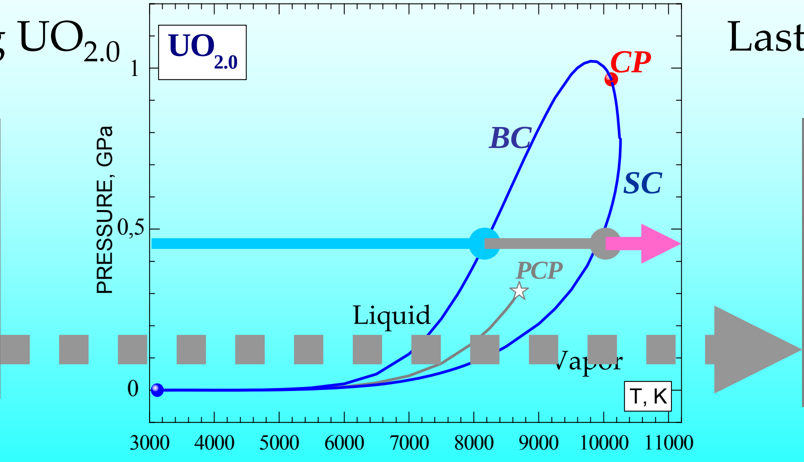


P = const

First vapor bubbles in boiling $UO_{2.0}$

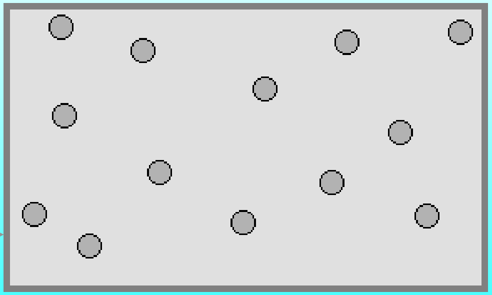
(oxygen enriched)





Last liquid drops in vapor $UO_{2.0}$

(oxygen depleted)

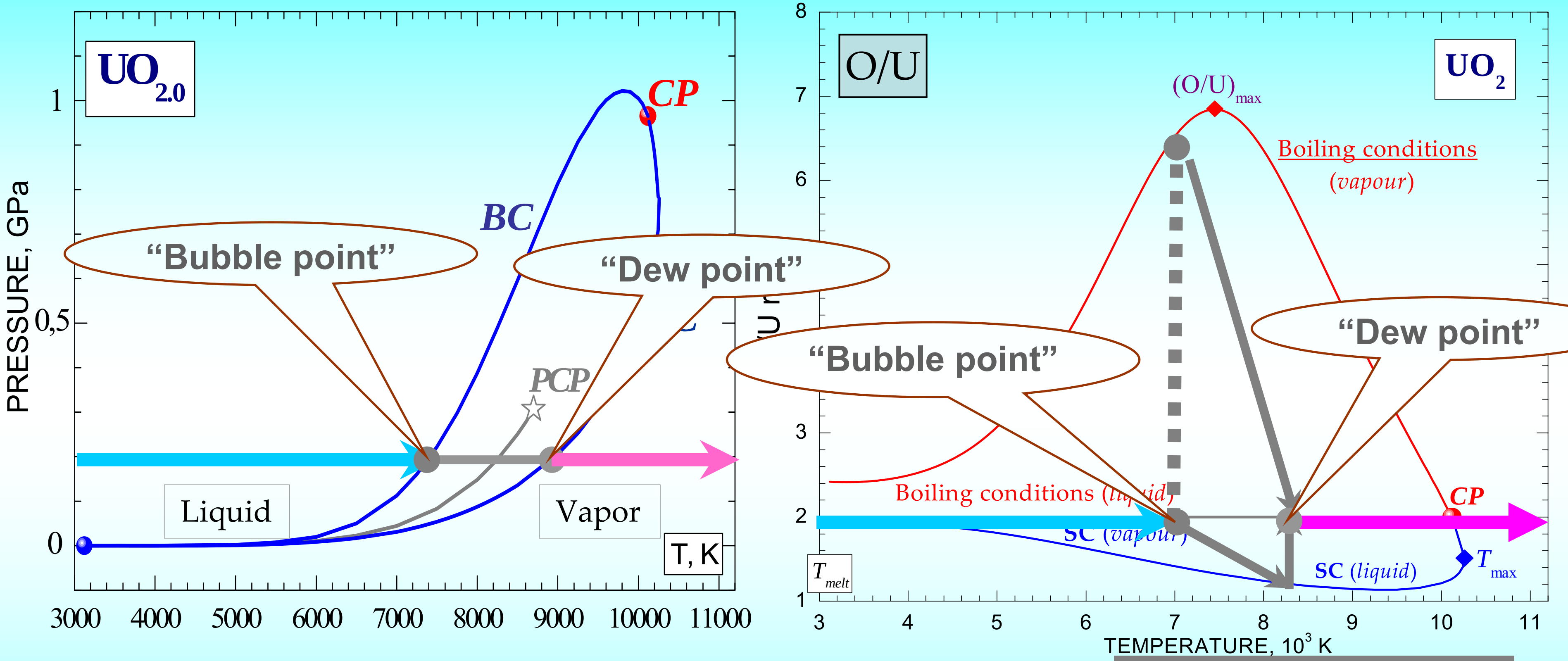


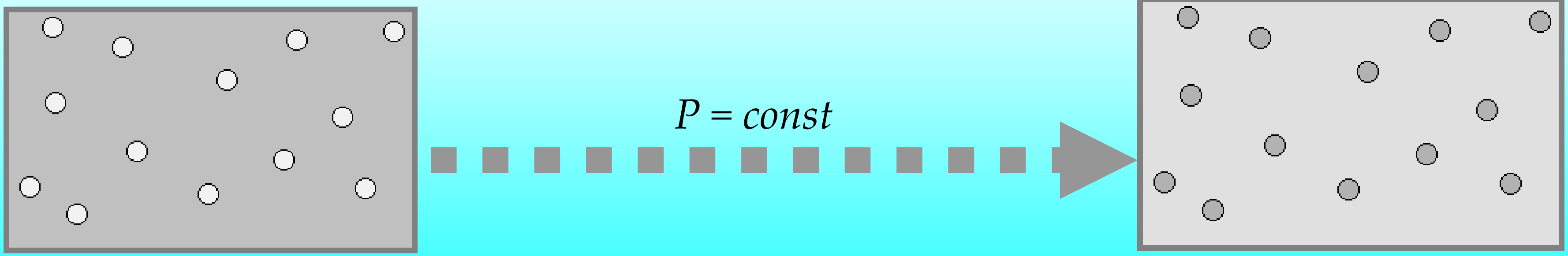
Liquid (O/U = 2.0) ⇔ Vapor (O/U > 2.0)

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

Non-congruent evaporation in U – O system

Isobaric transition through the two-phase region





First vapor bubbles in boiling $UO_{2.0}$
(oxygen enriched)

Last liquid drops in vapor $UO_{2.0}$
(oxygen depleted)

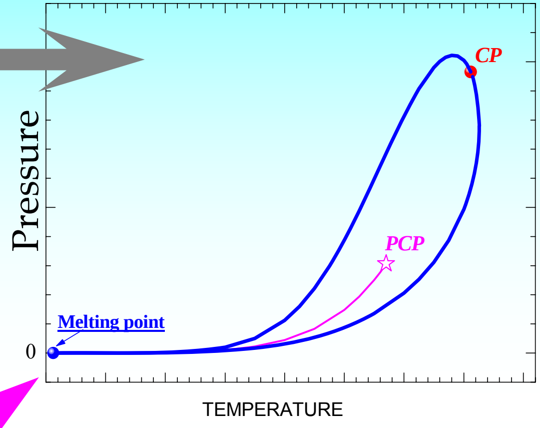
Non-congruence in general

Main issue for study of non-congruent evaporation in U–O system

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

Basic conclusion:

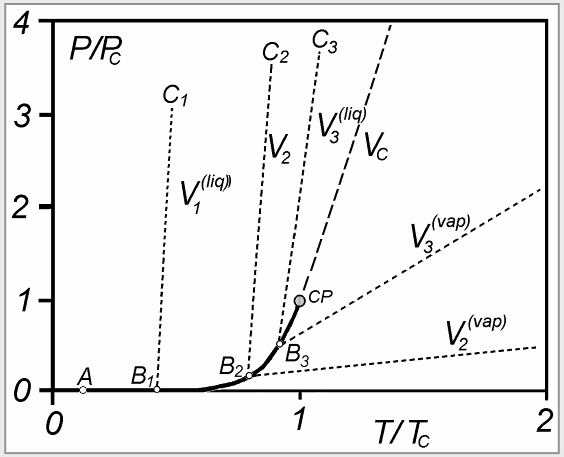
- Any phase transition in a system of **two** or **more** **chemical elements** must be **non-congruent**
- **Congruent** phase transition is **exception**



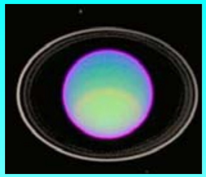
Evident contradiction

H_2O, CO_2, NH_3 . . . .

?

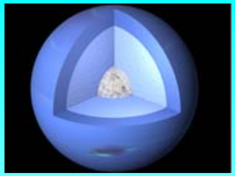


Non-congruence in H_2O etc... – what does it mean ?



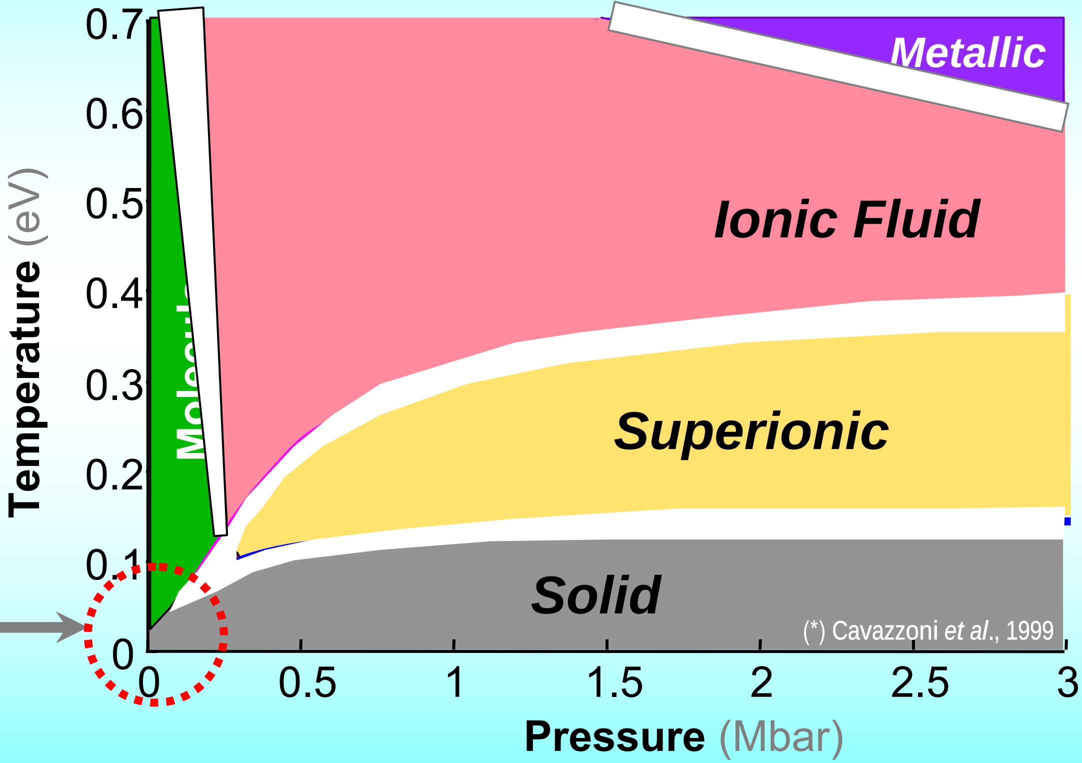
BASIC STATEMENT:

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

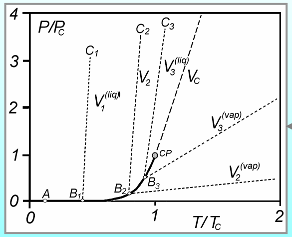


Neptune and “hot-water” extrasolar planet GJ436b

Water *(phase diagram)*



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

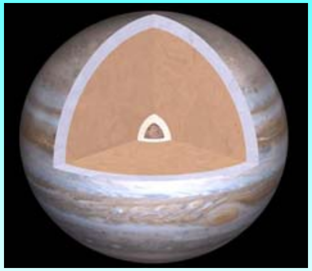
Cavazzoni, *et. al. Science (**1999**)*

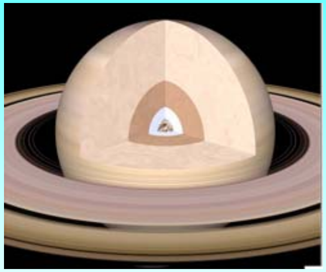
Mattsson & **Desjarlais** (*Sandia Lab.*): *High energy-density water: DFT/QMD simulations (**2007**)*

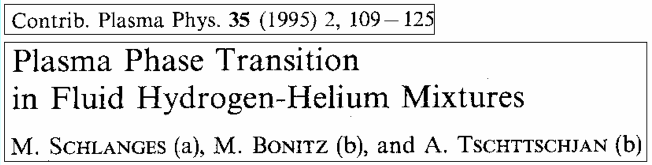
Any phase transition in *high-T_high-P* water must be *non-congruent*

Plasma Phase Transitions in H_2 + He plasma

(planetary science)



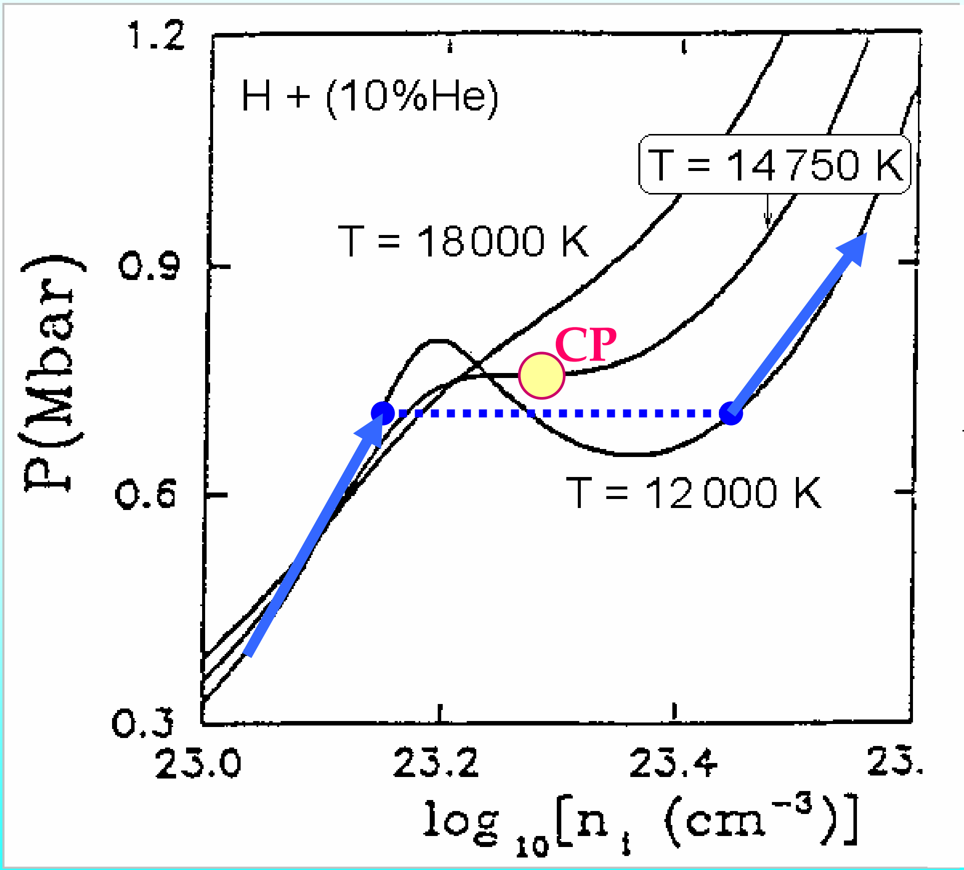


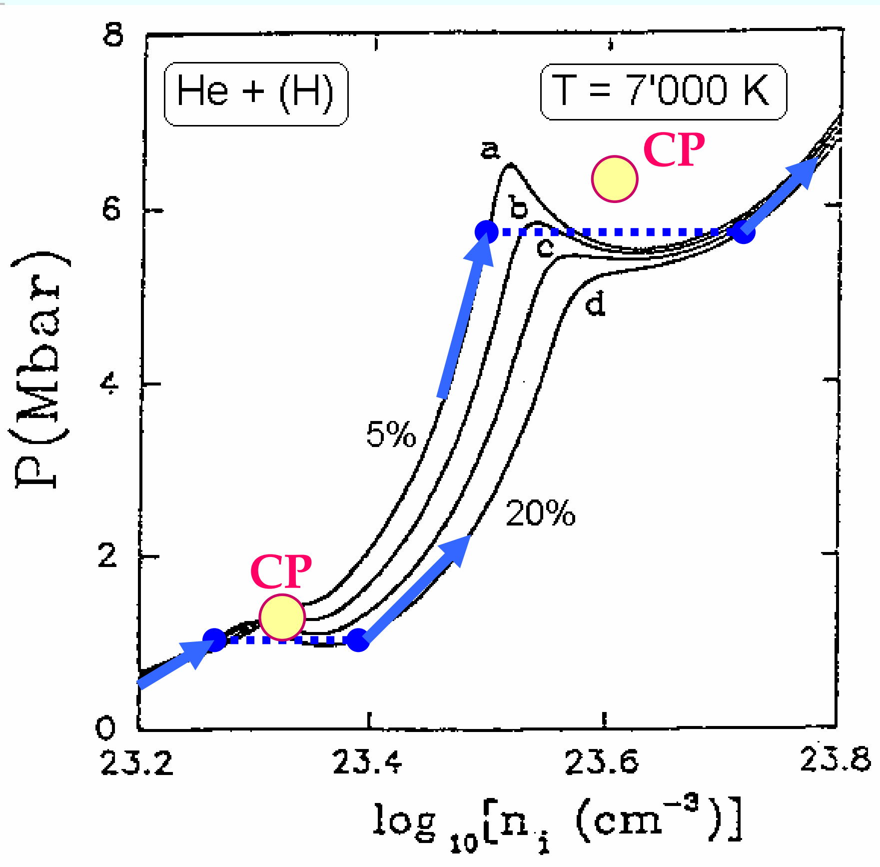


Contrib. Plasma Phys. 35 (1995) 2, 109 – 125

Plasma Phase Transition
in Fluid Hydrogen-Helium Mixtures

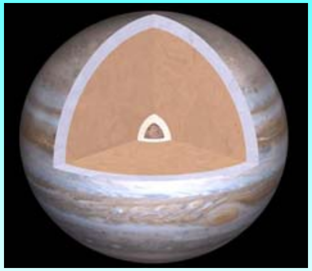
M. Schlanges (a), M. Bonitz (b), and A. Tschttschjan (b)

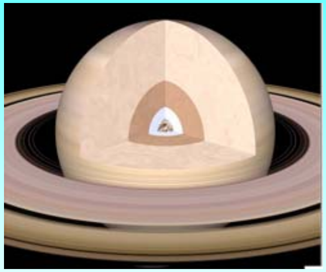




Plasma Phase Transitions in H_2 + He plasma

(*continued*)





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

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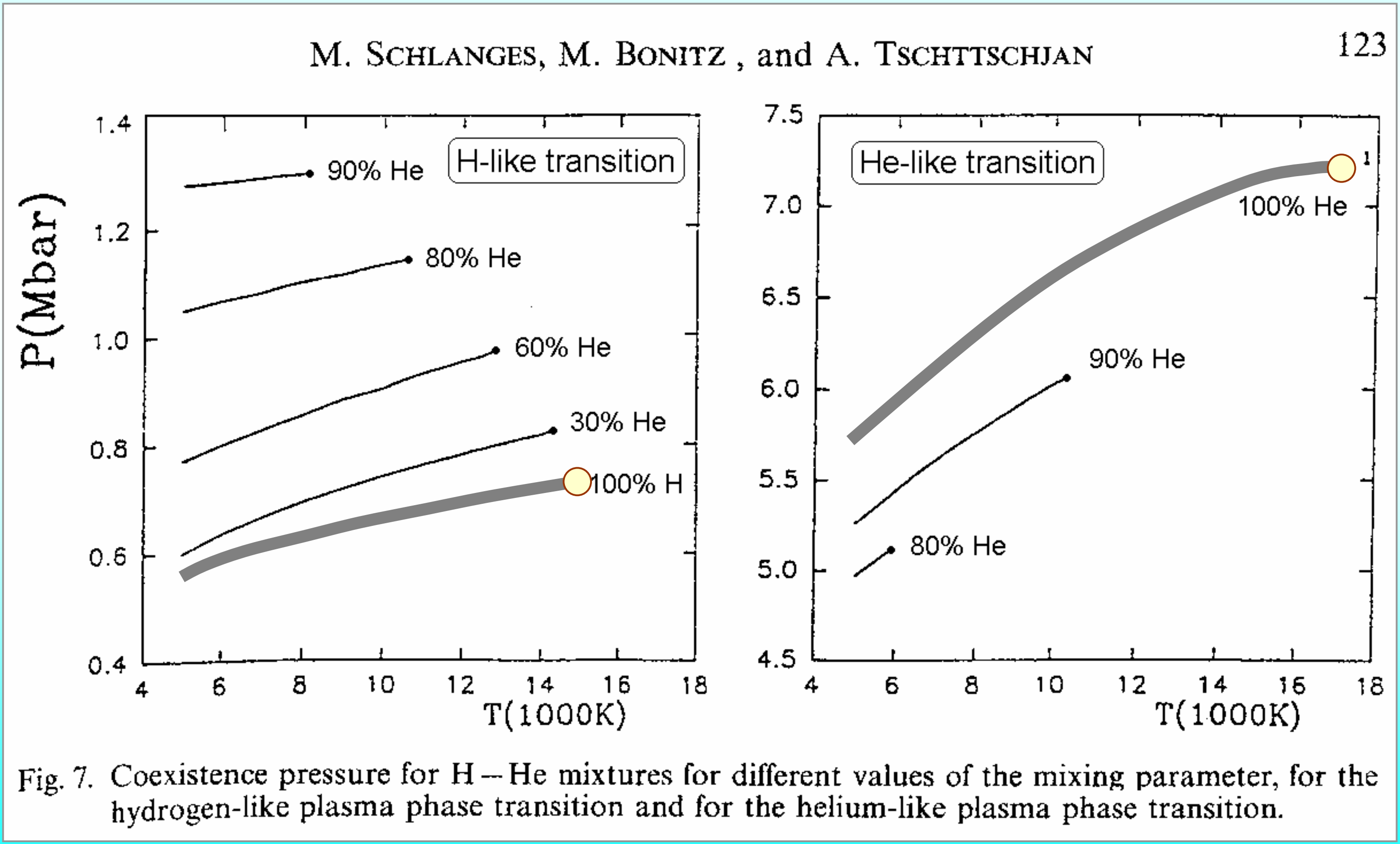
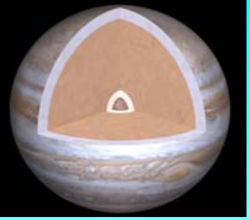


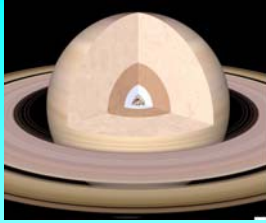
M. Schlanges, M. Bonitz, and A. Tschttschjan 123

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.



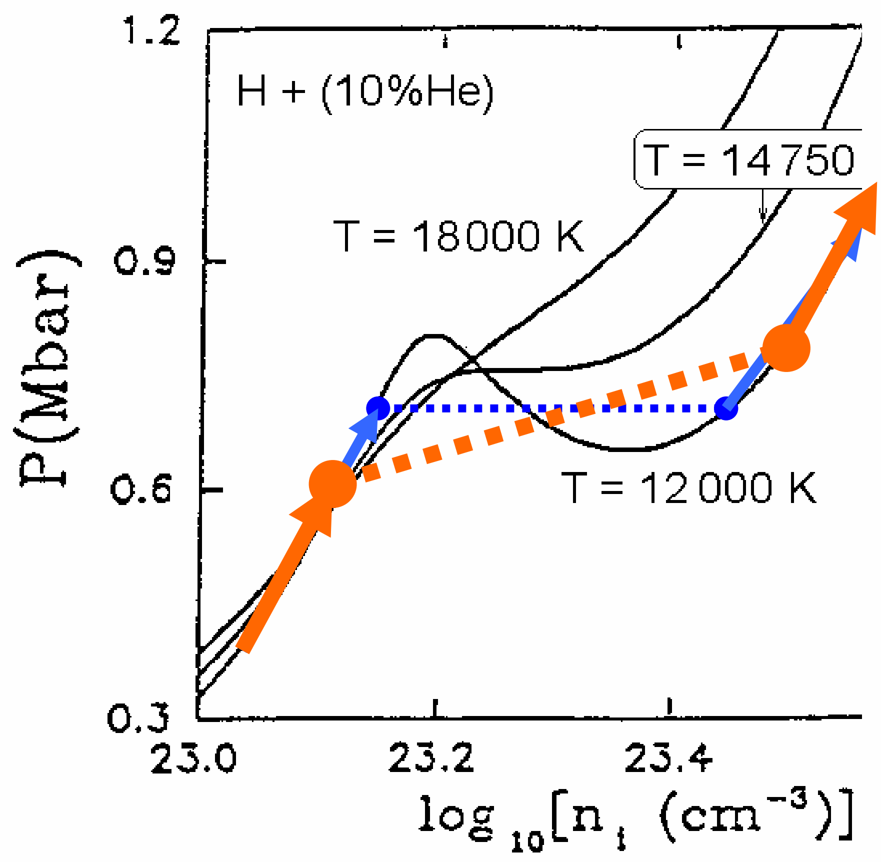
Thermodynamics of H_2 + He plasma

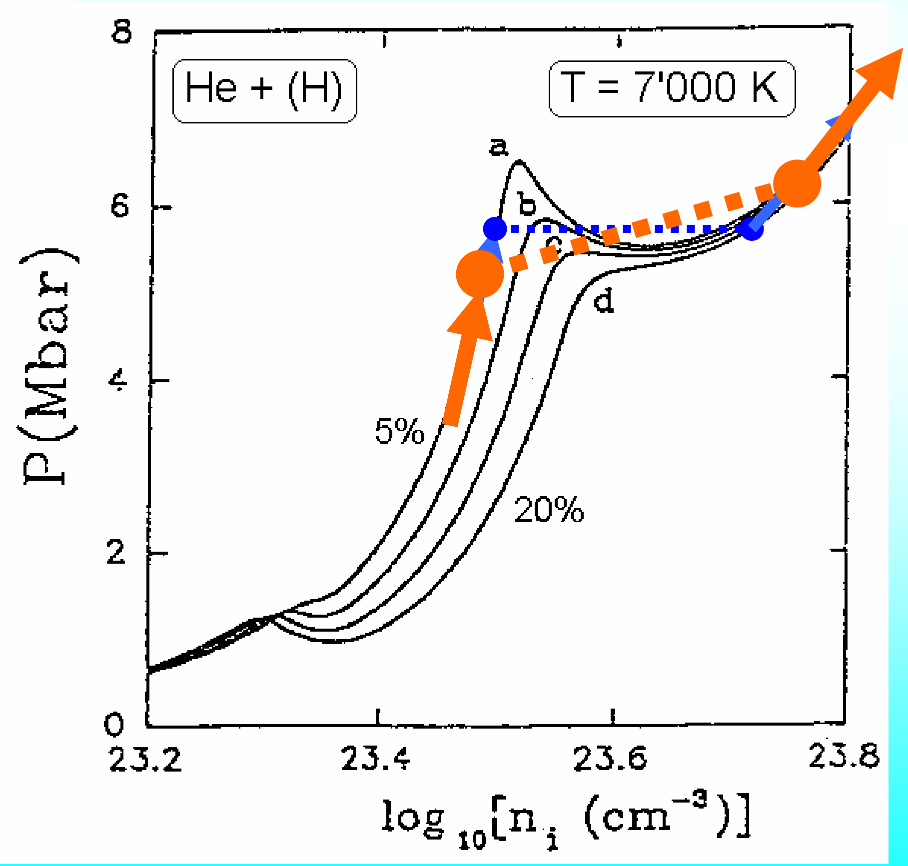
(planetary science)

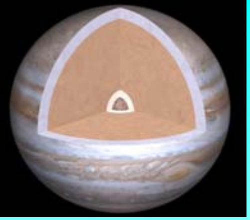


Congruent phase transition in the H_2+ He plasma

Non-Congruent phase transition in the H_2+ He plasma

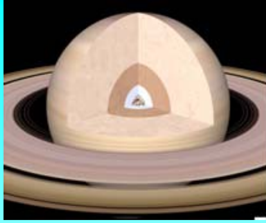


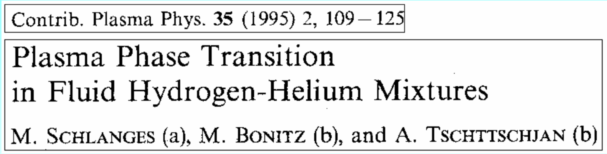




Thermodynamics of H_2 + He plasma

(*planetary science*)

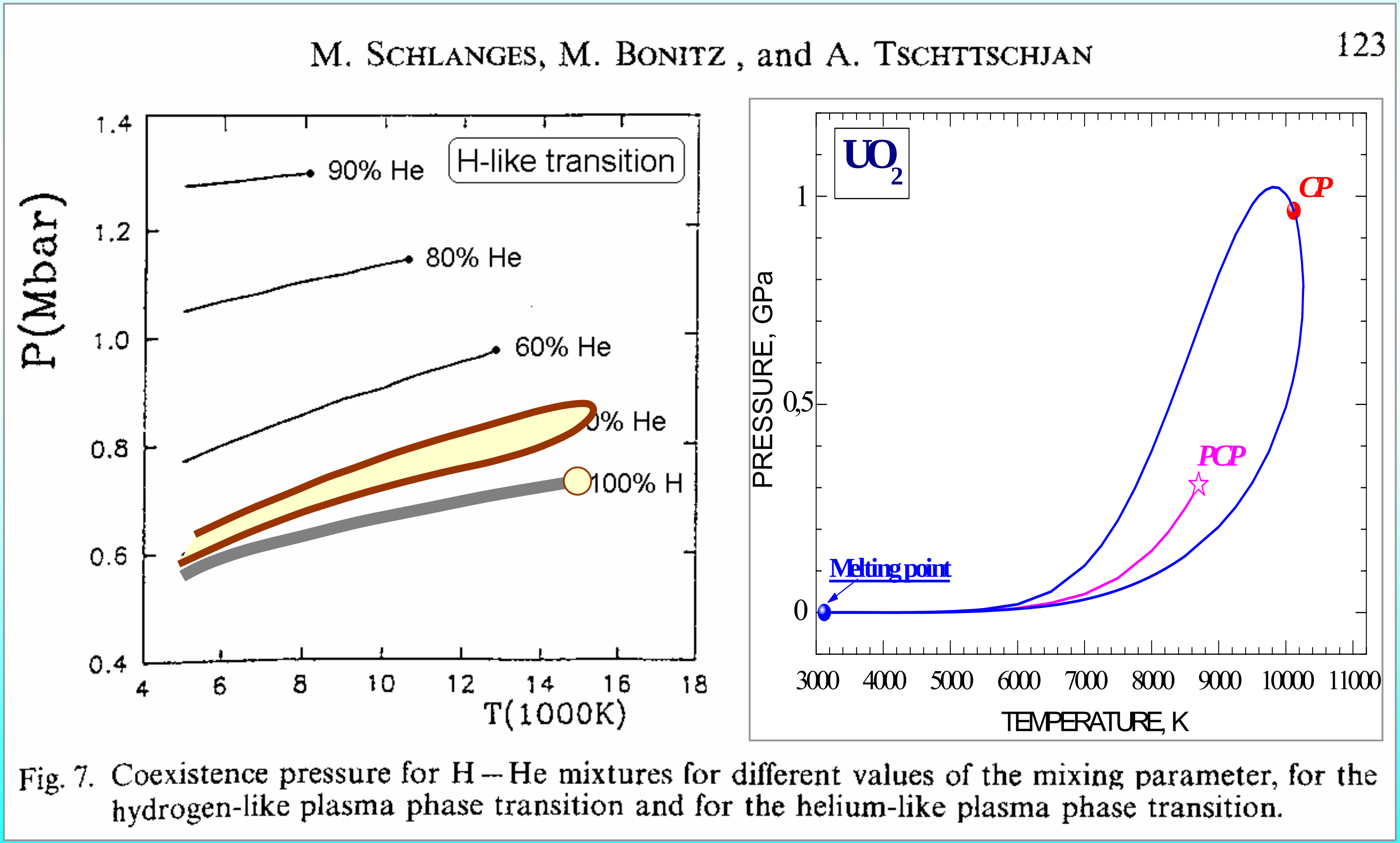




Contrib. Plasma Phys. **35** (1995) 2, 109 – 125

Plasma Phase Transition
in Fluid Hydrogen-Helium Mixtures

M. Schlanges (a), M. Bonitz (b), and A. Tschttschjan (b)



M. Schlanges, M. Bonitz, and A. Tschttschjan 123

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.

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

The question is:

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

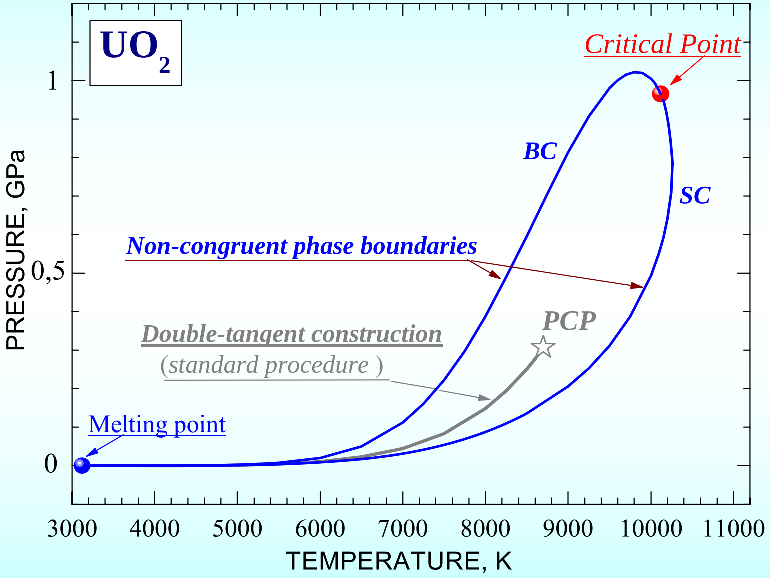
H_2 + He + H_2O + NH_3 + CH_4. . .

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

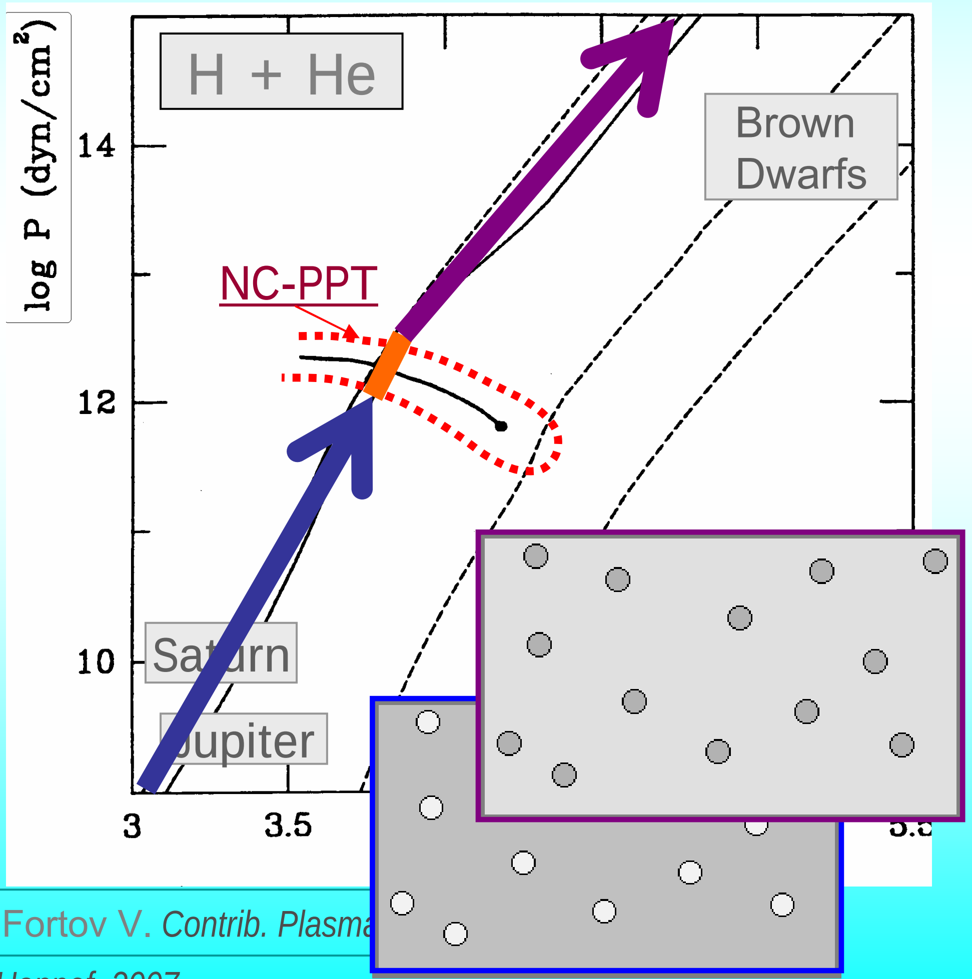
Typical composition in planetary science

Hypothetical non-congruent plasma phase transition in H_2 + He mixture in interiors of Jupiter and Saturn

Non-congruent phase transition in U–O system



Non-congruent PPT in H_2–He system (NC-PPT)



NB!

Two-phase region in H2/He must be non-conventional two-dimensional domain instead of one-dimensional curve

Iosilevskiy I., Gryaznov V., Yakub E., Ronchi C., Fortov V. *Contrib. Plasma*

Iosilevskiy - *PNP-12, Darmstadt-2006 // WEHS, Bad Honnef, 2007*

The question is:

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

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

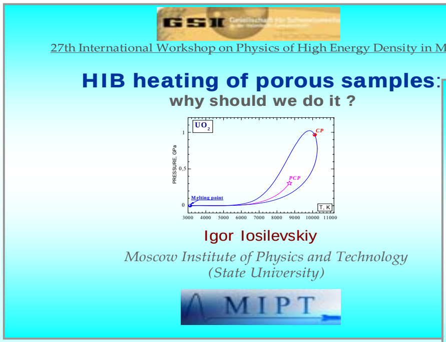
at $T \sim 1 - 20$ kK & $P \sim 1 - 10$ Mbar

We know almost nothing about it,
but we should know everything . . . .

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.

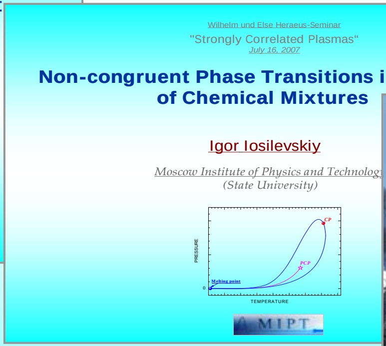


27th International Workshop on Physics of High Energy Density in Matter

HIB heating of porous samples:
why should we do it ?

Igor Iosilevskiy

Moscow Institute of Physics and Technology
(State University)



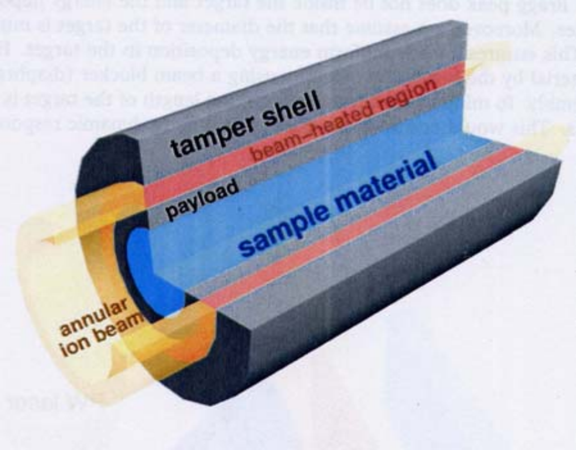
Wilhelm und Else Heraeus-Seminar
"Strongly Correlated Plasmas“
July 16, 2007

Non-congruent Phase Transitions in Plasmas of Chemical Mixtures

Igor Iosilevskiy

Moscow Institute of Physics and Technology
(State University)

LAPLAS



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

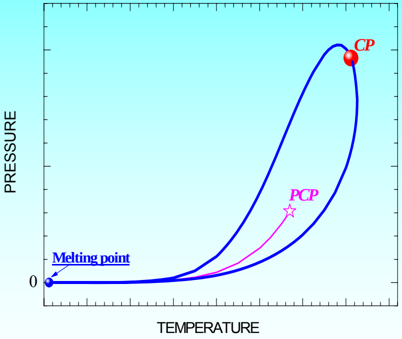
- **Heavy Ion Beam** volumetric heating is very promising tool for adiabatic compression of the **H_2 / He / H_2O / NH_3 / CH_4** mixture just under conditions of **Jovian** and **Extrasolar planets** and **Brown Dwarfs**.

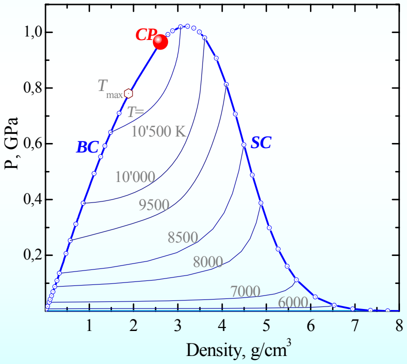
Hypothetical non-congruent phase transitions

(***short list***)

Terrestrial applications:

- ***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*)





Non-Congruence in Cosmic Matter:

- ***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)

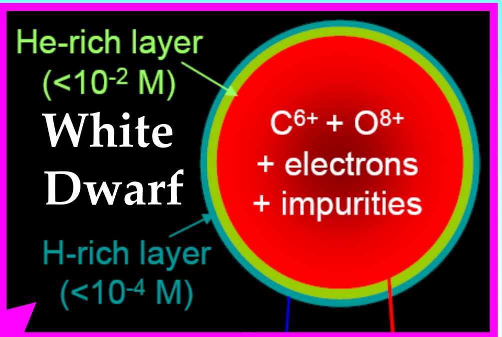
Non-congruence in exotic situations

(*discussion*)

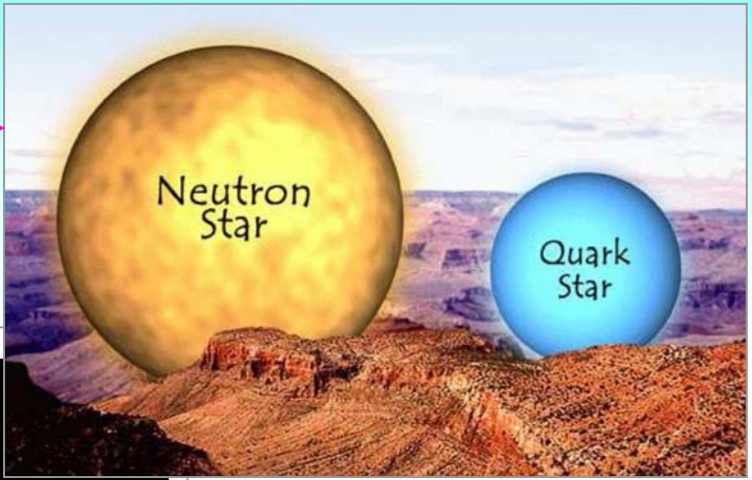
Non-congruence in compact stars

Compact stars

White dwarfs, *Neutron stars*, *“Strange” (quark) stars*, *Hybrid stars*



Neutron and “Strange” Stars



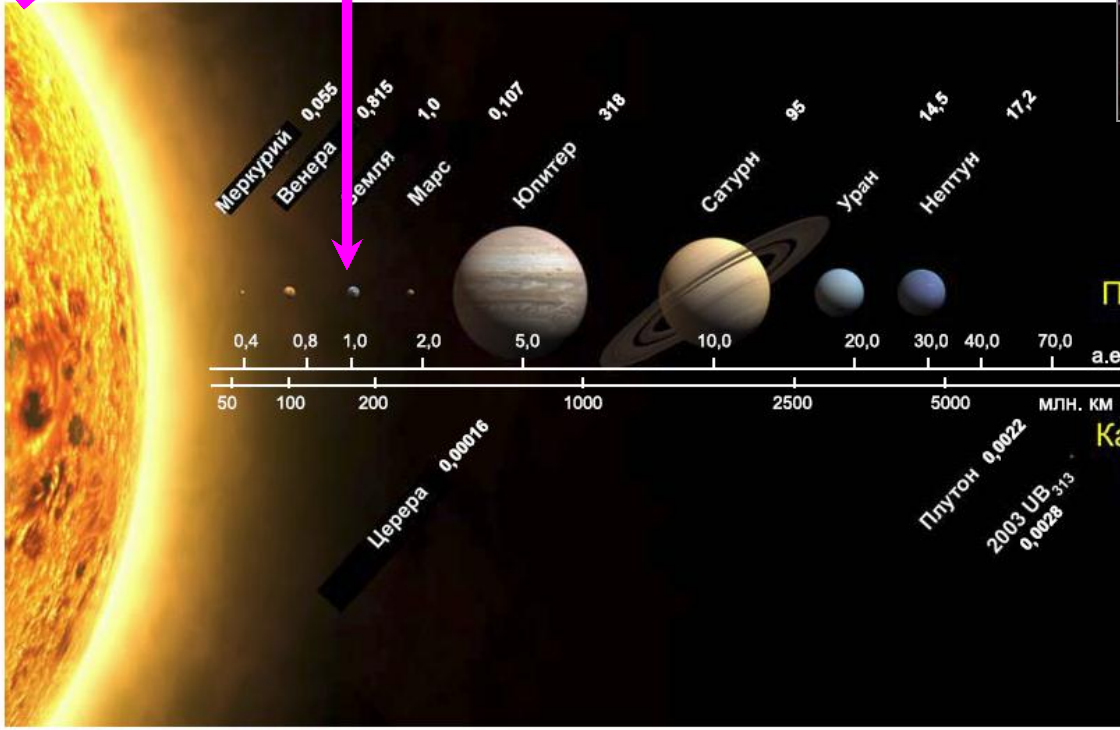
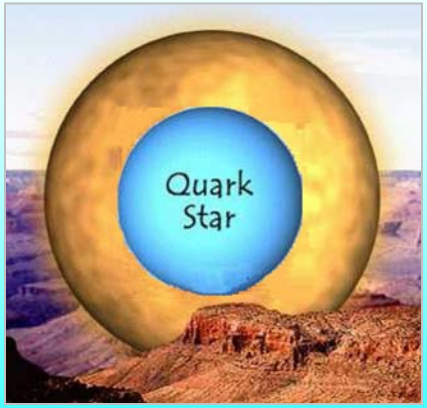


Рис. 65. Массы планет (в единицах массы Земли) и их среднее расстояние от Солнца [371]

Hybrid Stars

Quark core + Hadron Crust

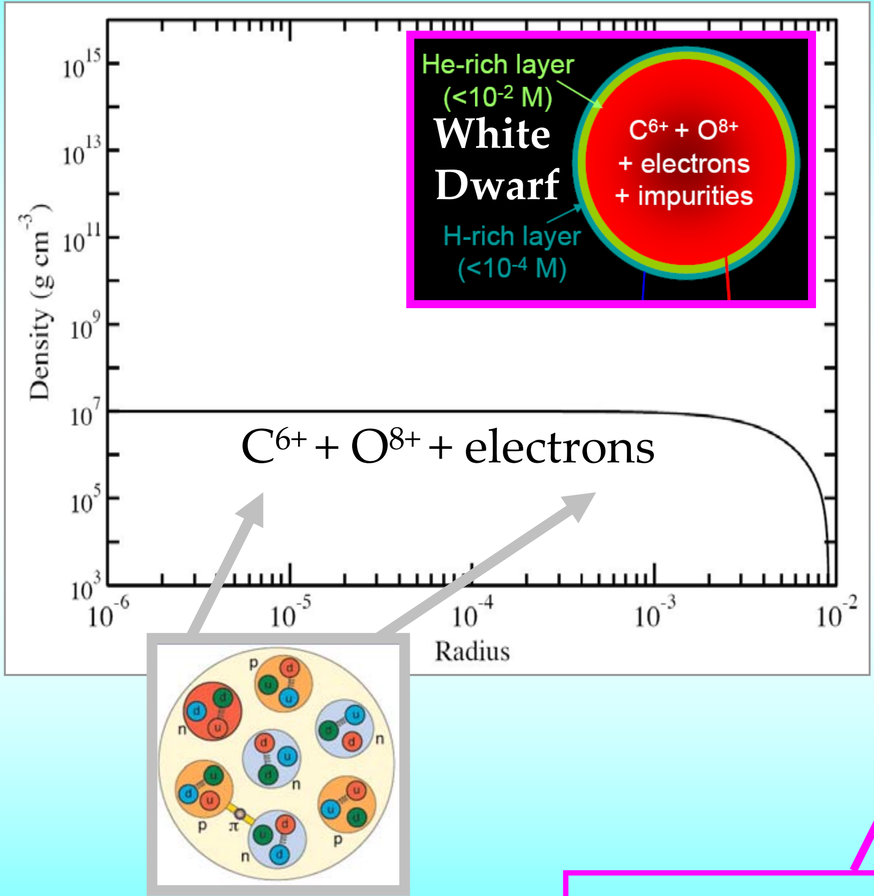


|← R ~ 10 km →|

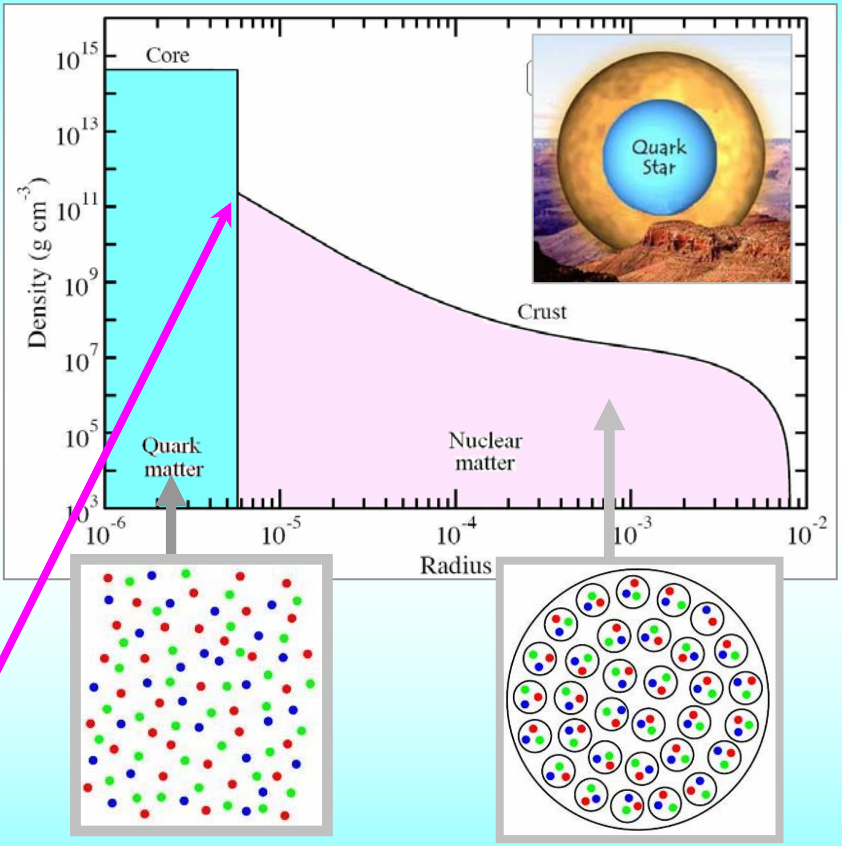
Hybrid ("strange") white dwarfs

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

Ordinary WD



Strange WD

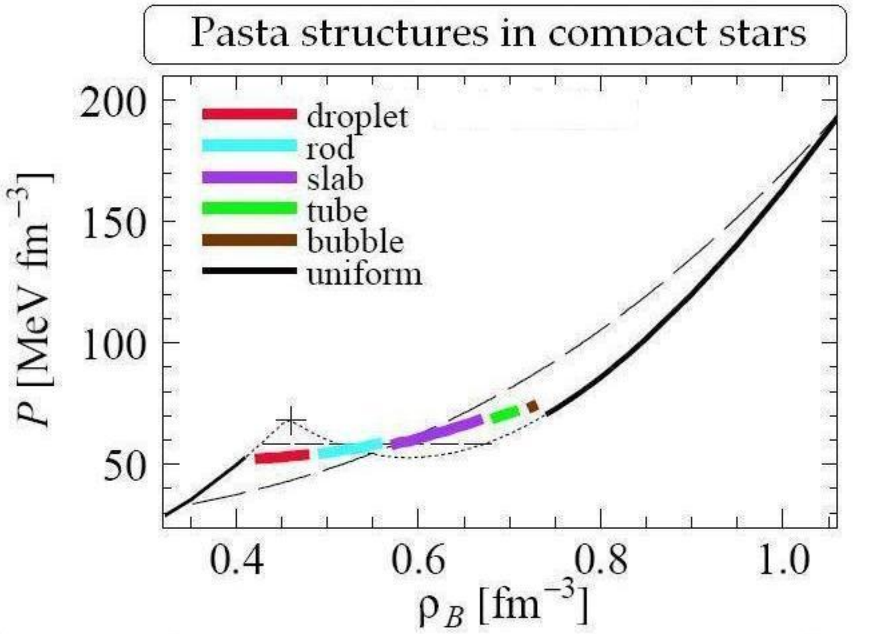


Phase transition ?

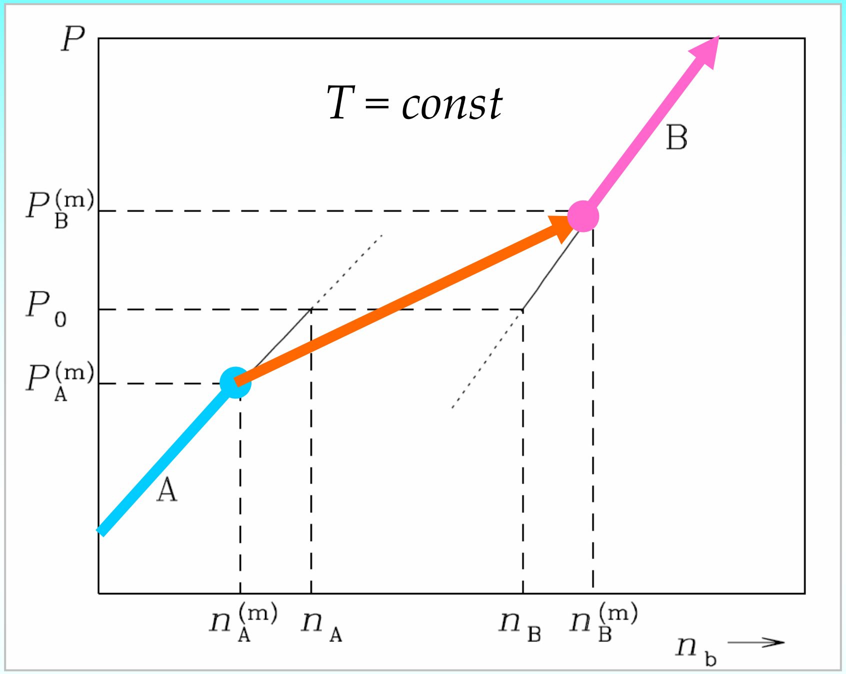
Jump-like ?

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/



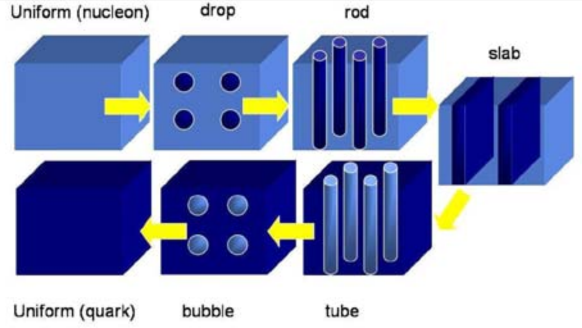
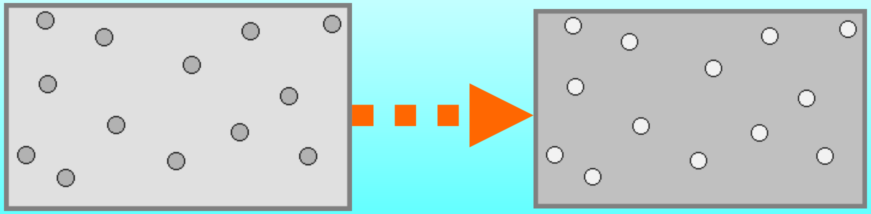


Figure 2: Schematic image of structured mixed phase.

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

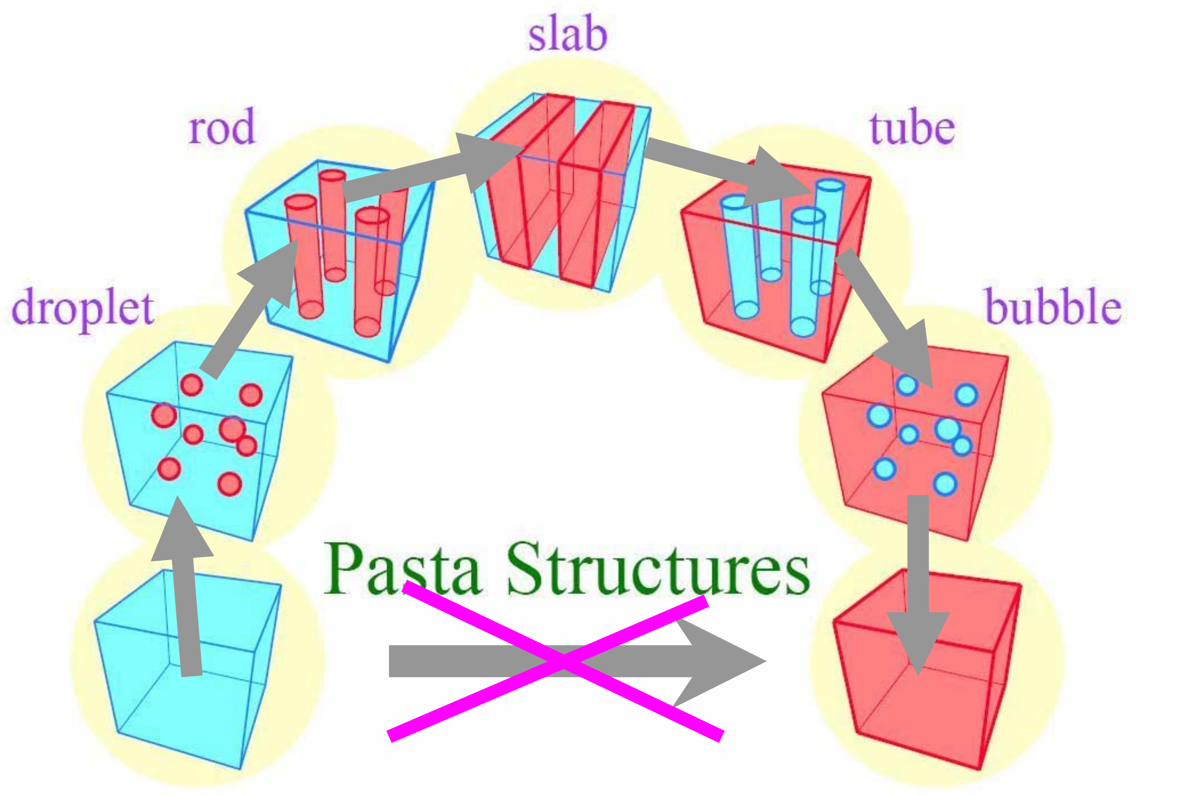
First quark droplets
in hadron matter



Last hadron bubbles
in quark matter

Non-congruence in exotic situations (mesoscopic scenario)

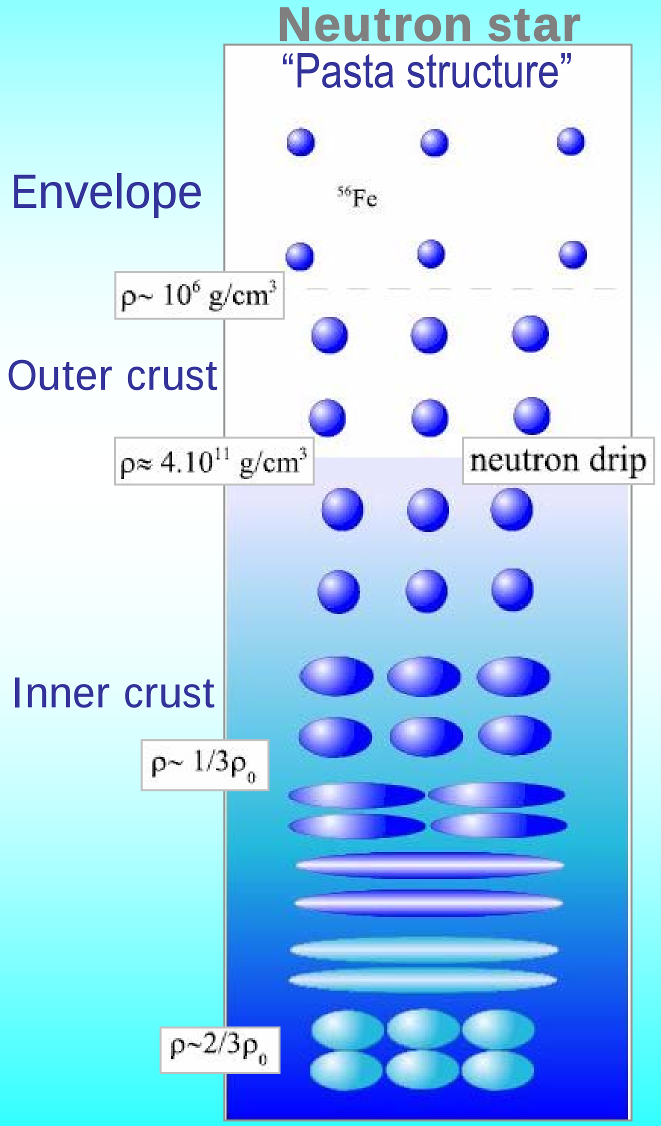
Structured Mixed Phase Concept ⇔ "Pasta"



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.

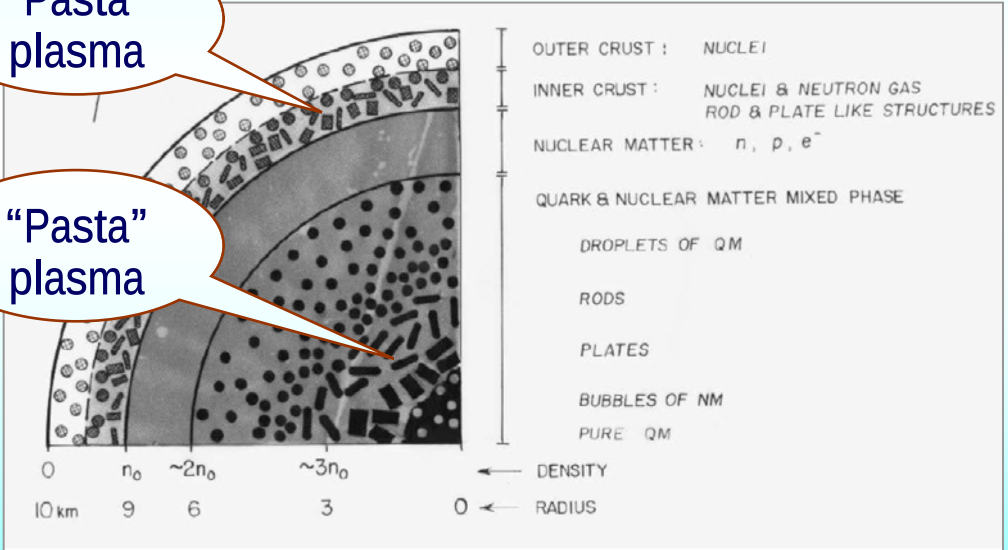


Structured Mixed Phase ⇔ "Pasta" plasma

'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



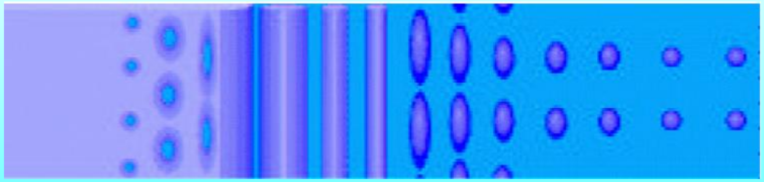
"Pasta" plasma

"Pasta" plasma

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**)

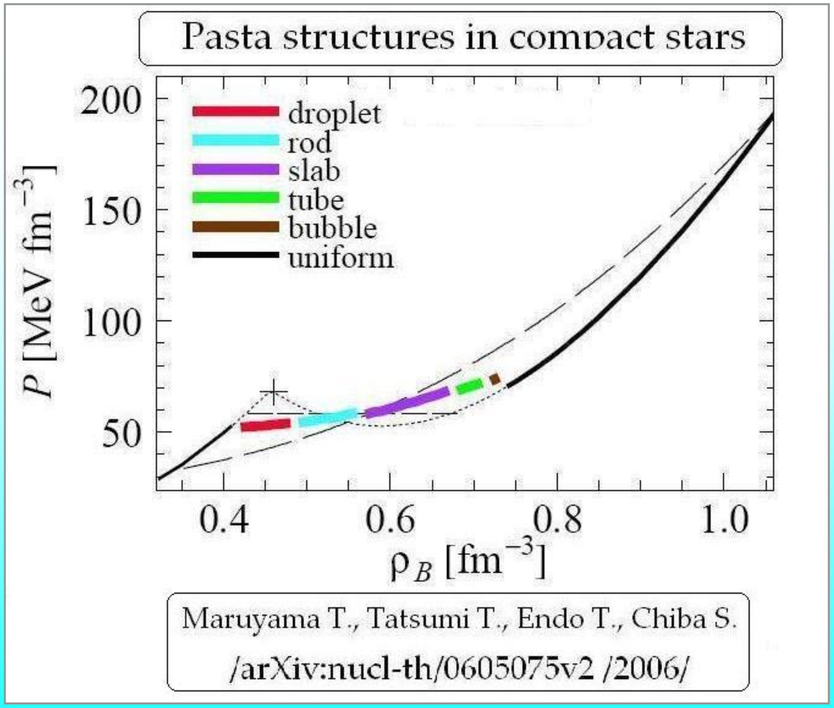


"Pasta" plasma:- *"Spaghetti" phase, "Lasagne" phase . . . . .*

Non-congruence in exotic situations

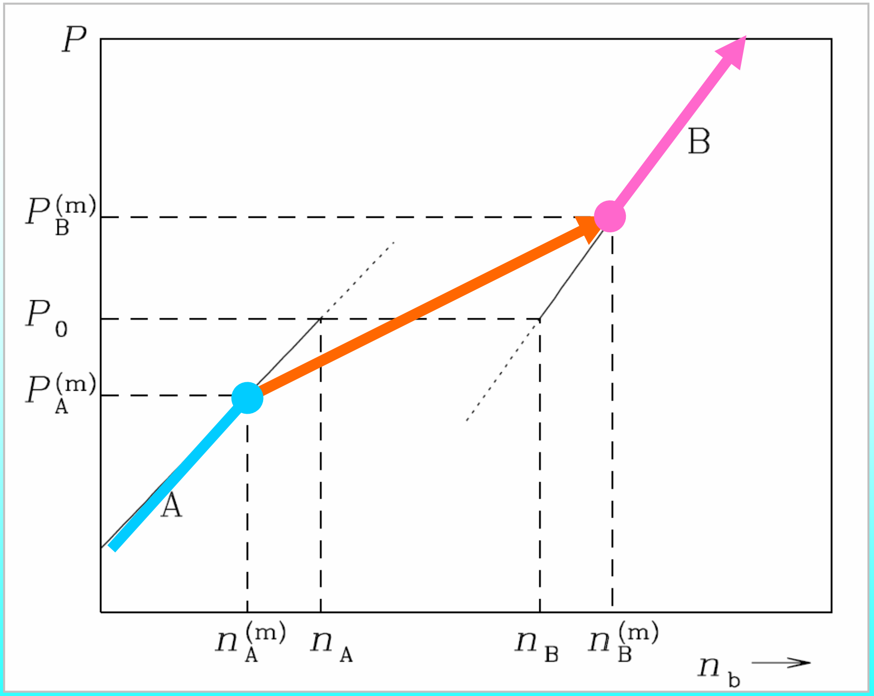
(*discussion*)

Quark-hadron phase transition via "mixed-phase" scenario has the features of non-congruent PT !



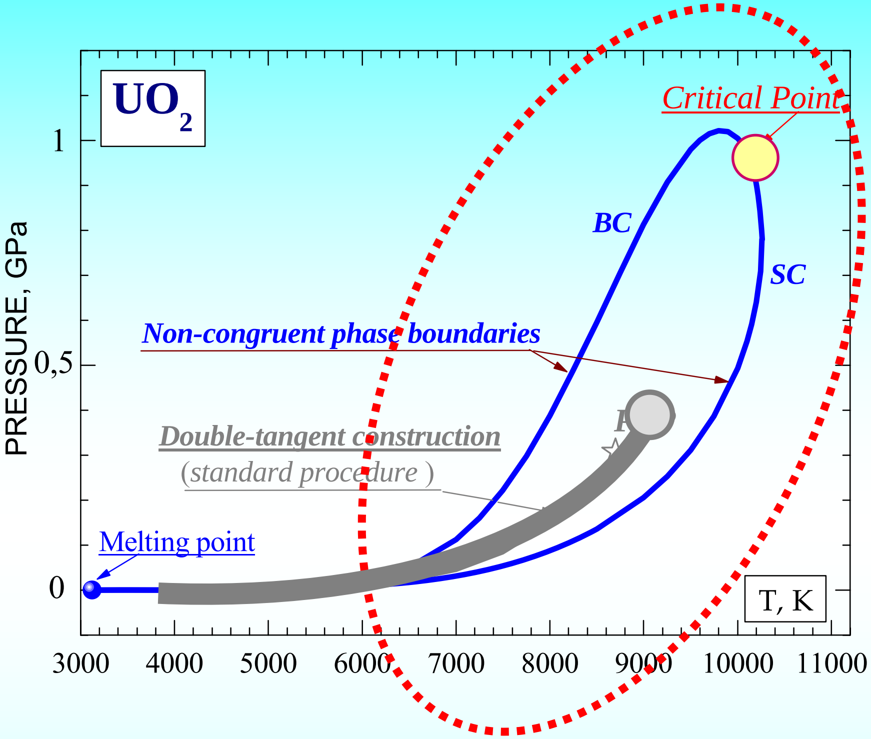
Pasta structures in compact stars

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

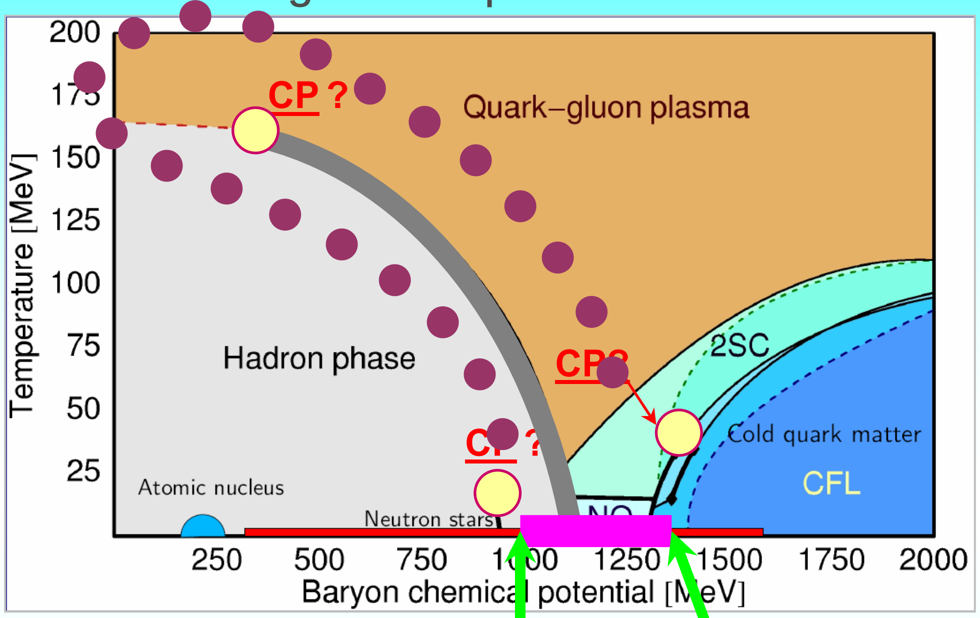


Hypothetical phase transitions in ultra-dense matter:

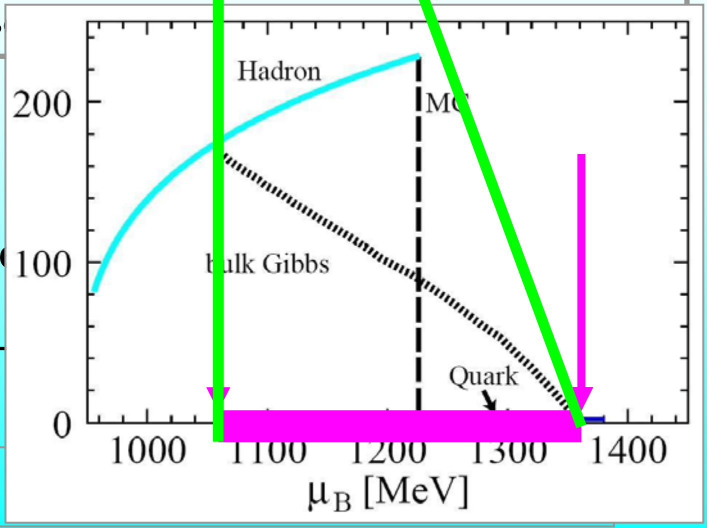
are they CONGRUENT or NON-CONGRUENT ?



Phase diagram of quark-hadron matter



After Fridolin Weber, WEHS Seminar, Bad Honnef, 2006
After David Blas



?

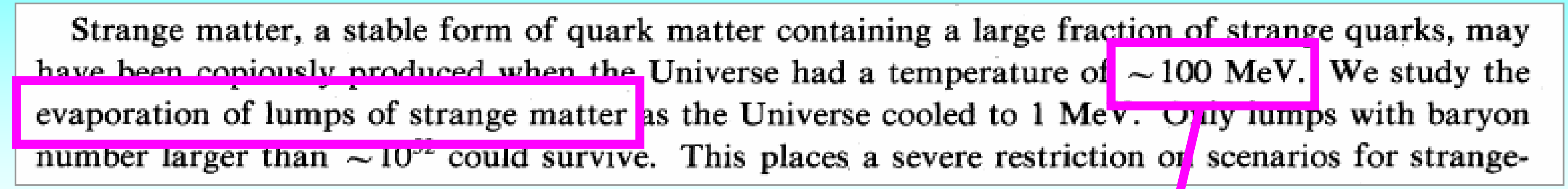
━━○ - Forc

▪ ▪ ▪ ▪ ▪ ▪ ▪ - Non-

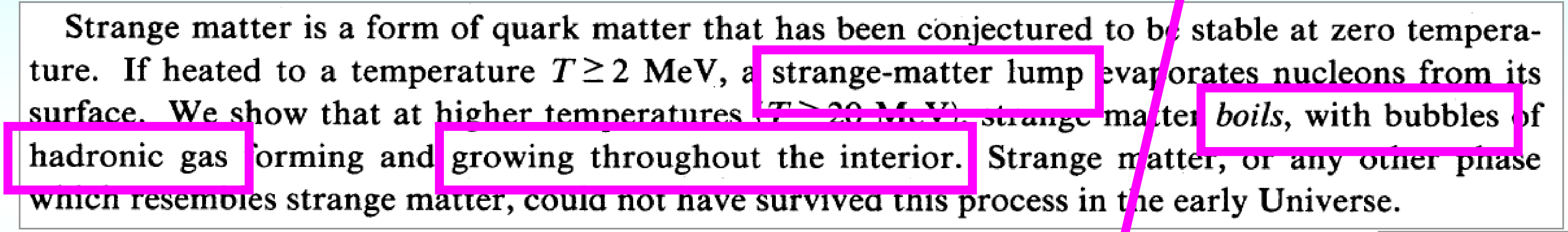
Evaporation of strange lumps in the early Universe

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

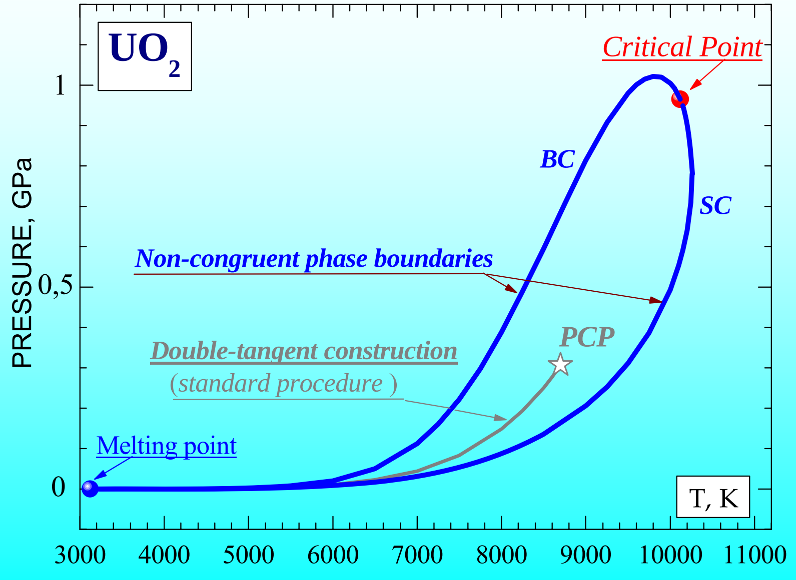
Alcock C., Olinto A. *(PRD, 1989)*

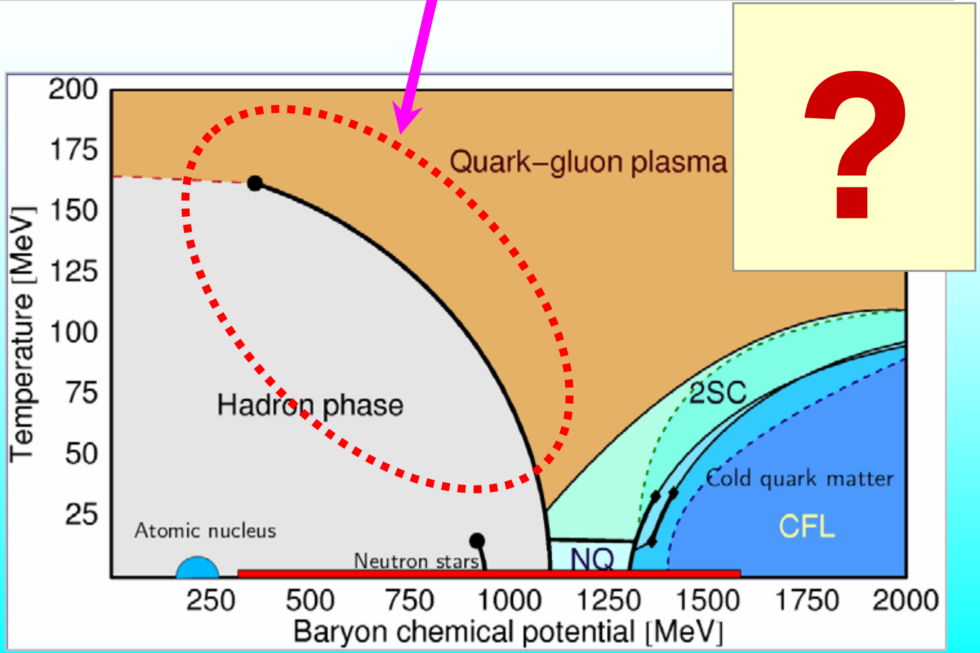


Strange matter, a stable form of quark matter containing a large fraction of strange quarks, may have been copiously produced when the Universe had a temperature of ~ 100 MeV. We study the evaporation of lumps of strange matter as the Universe cooled to 1 MeV. Only lumps with baryon number larger than $\sim 10^{52}$ 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 ($T > 20$ 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 ?

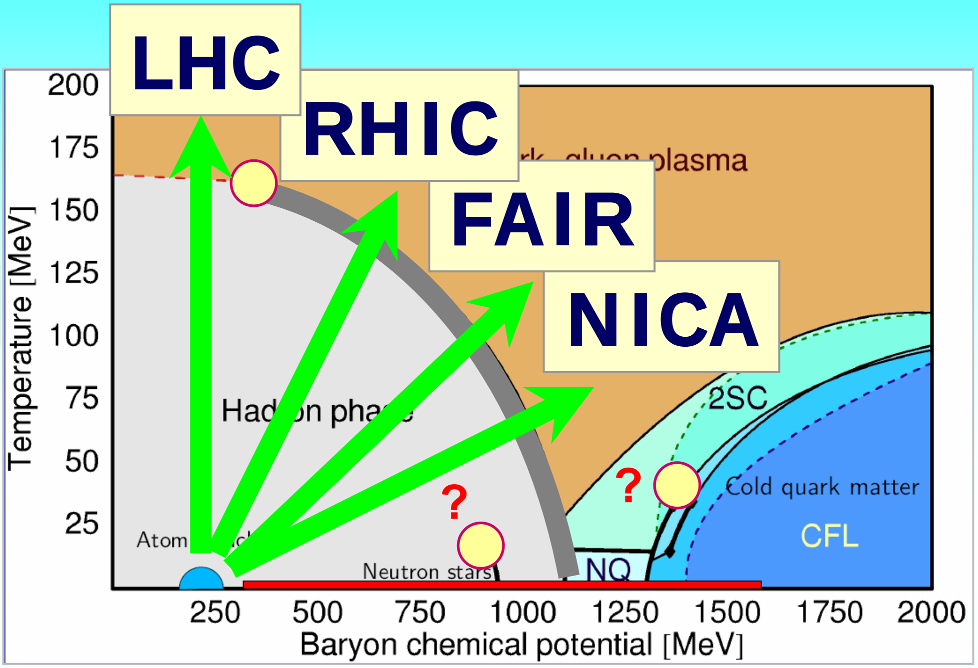
LHC – CERN

RHIC – Brookhaven

FAIR – Darmstadt

NICA – Dubna

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



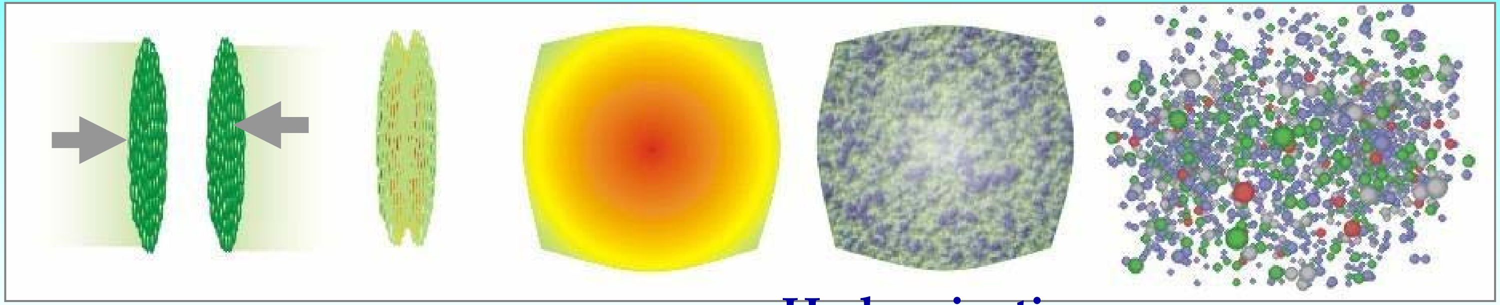
Quark-Hadron Phase Diagram

?

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

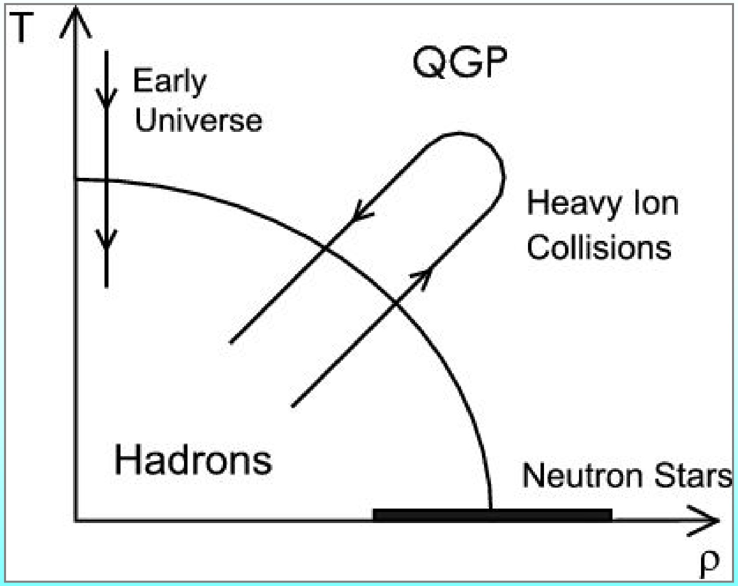
Iosilevskiy I. / Int. Workshop *“Physics of HEDM”*, JINR, Dubna, Russia, 2008

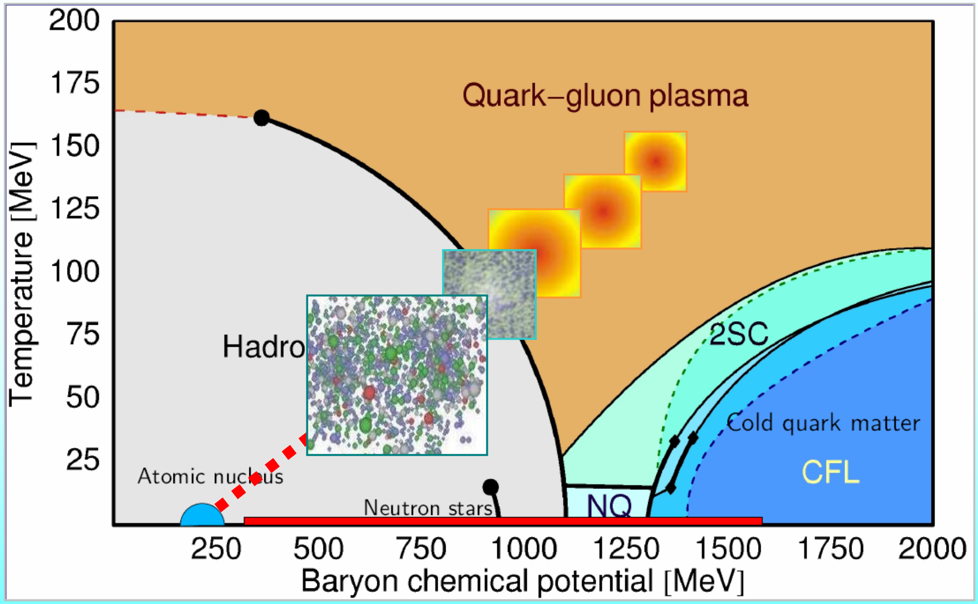
Non-congruence in high-energy collisions



Au + Au * **Thermalized Fireball** **Expansion** **Chemical & kinetic freeze-out**

Hadronization





After Markus H. Thoma, SCCS, Moscow, 2005

EMMI : *Cosmic Matter in the Laboratory*

Hydrodynamics of expanding fireball when it crosses quark-hadron phase boundary depends significantly from the fact – is this phase transition congruent or non-congruent !

The question is:

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

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

8, 2009 // Impact – October 2009

0 km/h ⬄ Impact plume ~ 50 km high

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

$SiO_2 + FeO + Al_2O_3 + CaO$

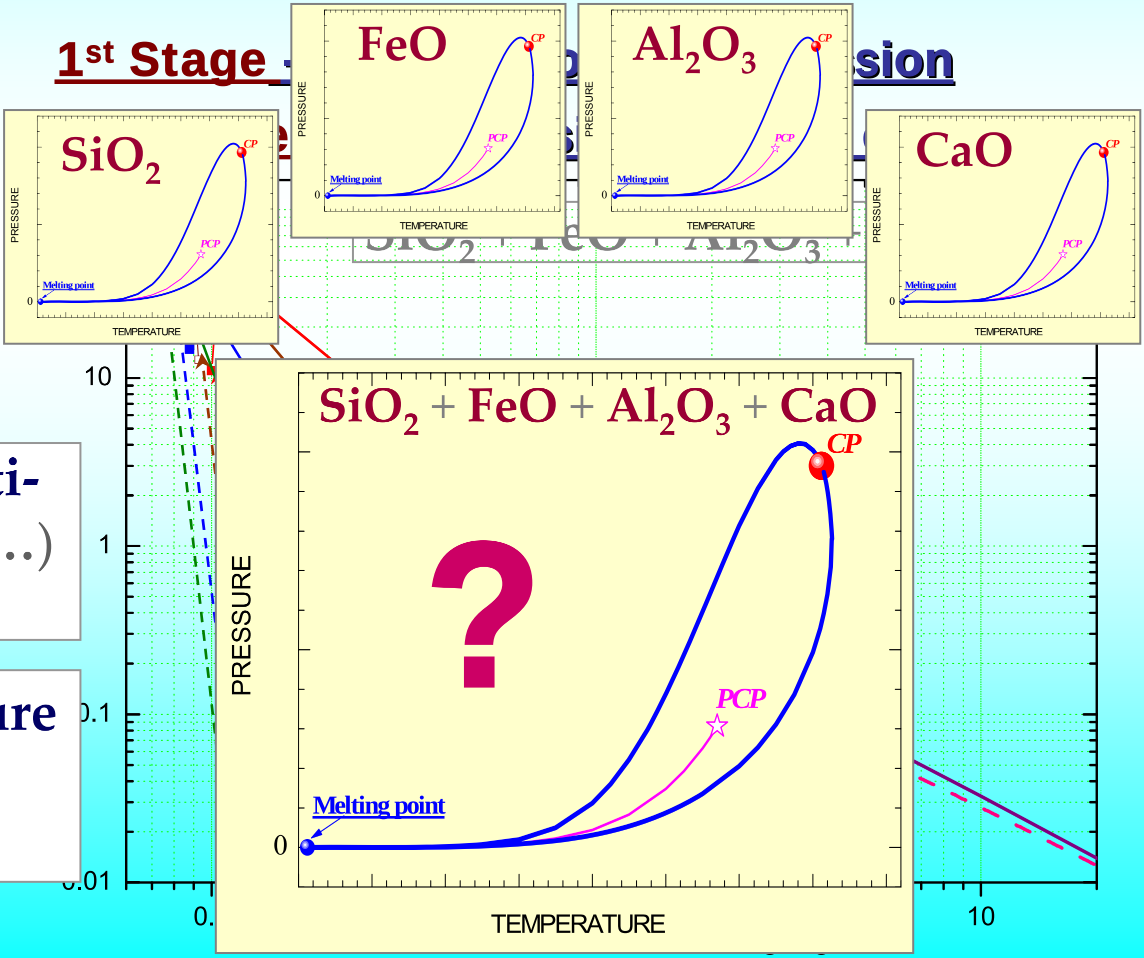
T ~ *eV* & *P* ~ *GPa*

The question is open

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 !



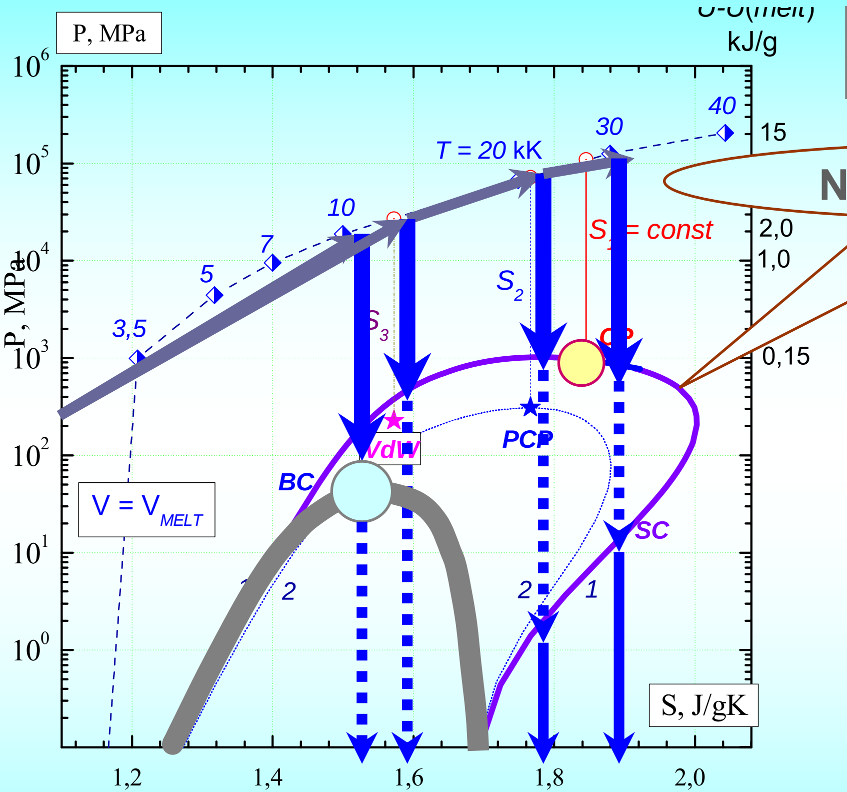
Features of isentropic release crossover of non-congruent phase transition boundary

ISTC: UO$_2$ isochoric heating under heavy ion beam irradiation

HIHEX

Heavy
Ion
Heating
and
EXpansion

P-S Diagram



Pressure - Entropy diagram of isochorically heated uranium diox
Microscopic Theory (Quasi-Chemical Representation)

Non-congruent PT

▬ - Standard 2-phase boundary of congruent PT

○ - Standard critical point

● - Critical point of non-congruent phase transition

“**Retrograde regime**” – typical scenario for transition through the two-phase region of **non-congruent** phase transformation

Conclusions *and* **Perspectives**

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

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

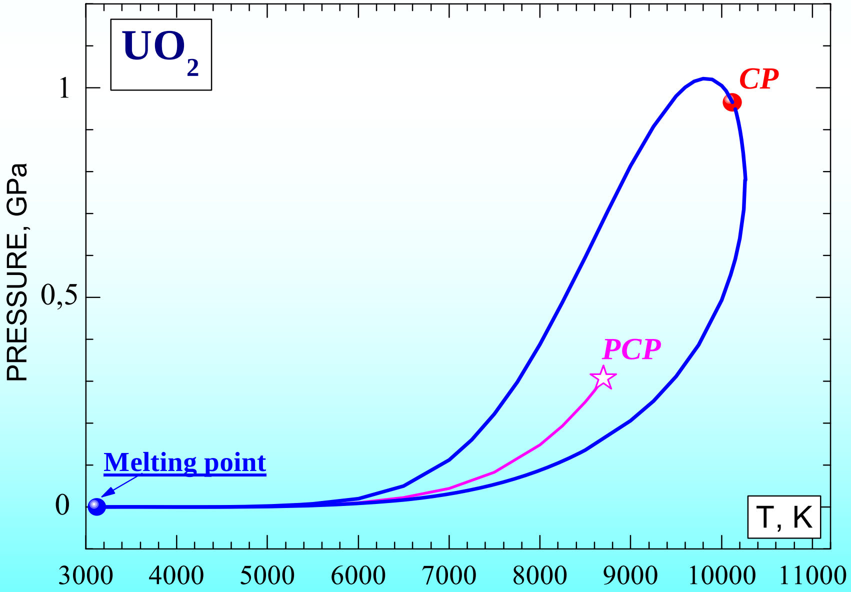
- **Non-congruent** phase transition is **interesting** phenomenon.

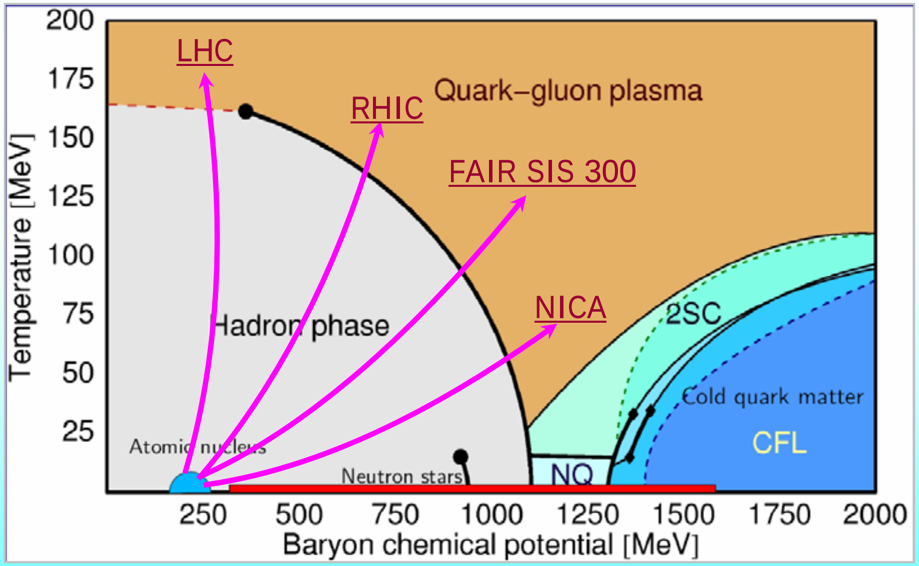
- It is **promising** to investigate non-congruent phase transitions **experimentally** in particular with **intense laser** and **heavy ion** heating

- 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.

Thank you!



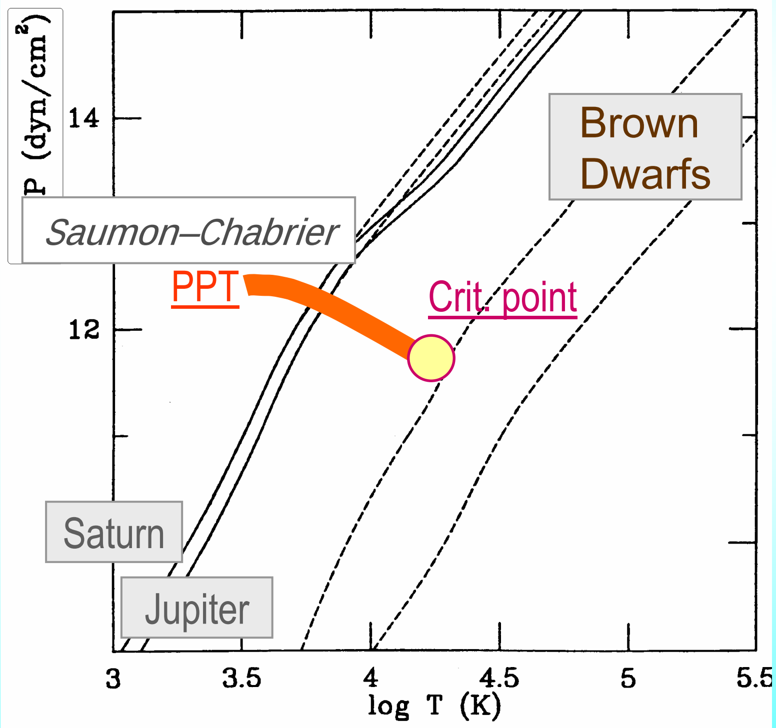


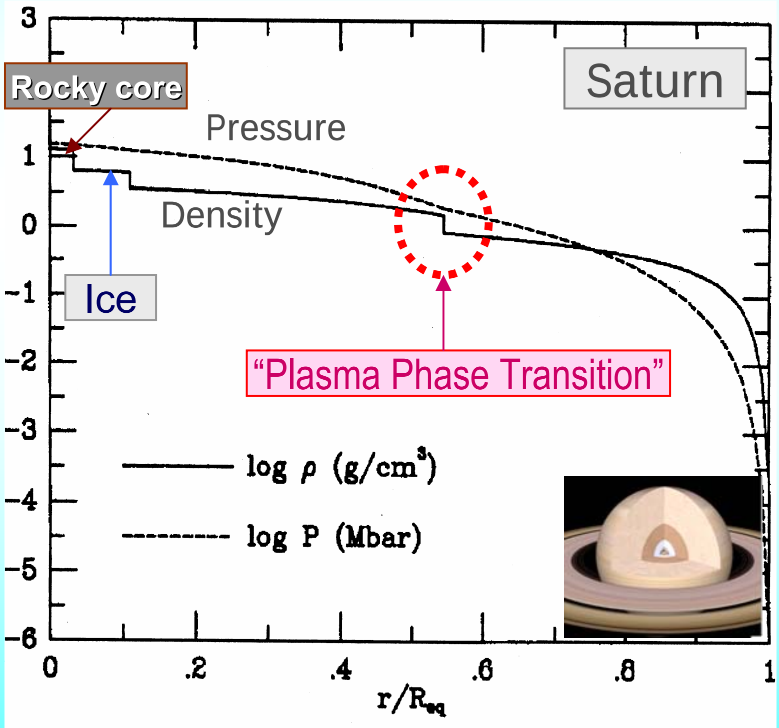
Support: INTAS 93-66 // ISTC 3755 // CRDF № MO-011-0 // RFBR 06-08-01166,
and by **RAS Scientific Programs**
“Physics and Chemistry of Extreme States of Matter” and “Physics of Compressed Matter and Interiors of Planets”

The end

Hypothetical phase transition in H_2/He mixture

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





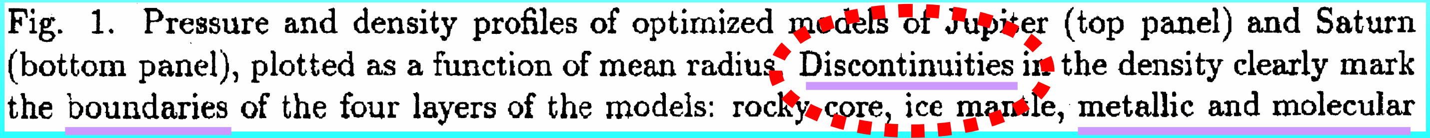
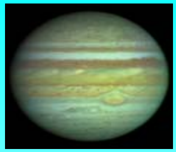


Fig. 1. Pressure and density profiles of optimized models of Jupiter (top panel) and Saturn (bottom panel), plotted as a function of mean radius. Discontinuities in the density clearly mark the boundaries of the four layers of the models: rocky core, ice mantle, metallic and molecular

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.

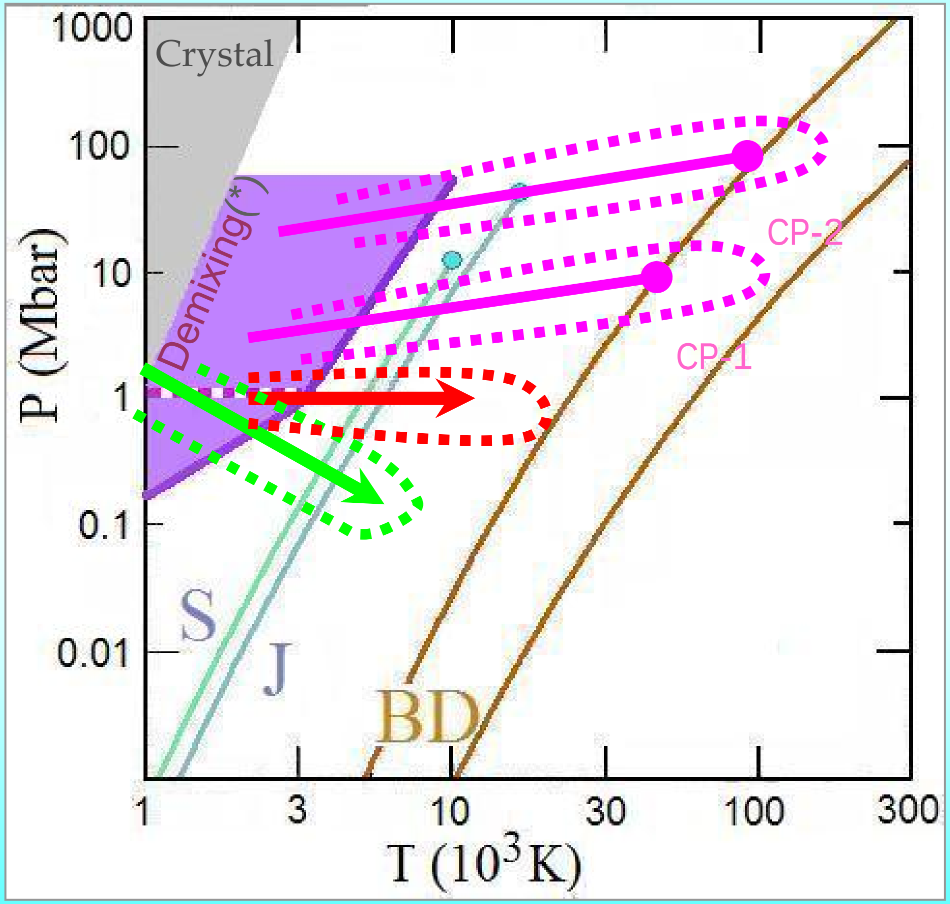
Dissociative Phase Transition in **H_2**
(*Scandolo S., Bonev S., Militzer B., Galli G.*)
⟶

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.) —●

H_2 + He

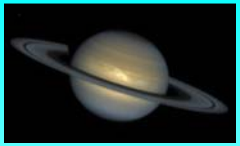


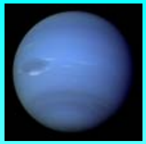
Presence of helium relax phase transition in hydrogen <> presence of hydrogen relax phase transition in helium

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

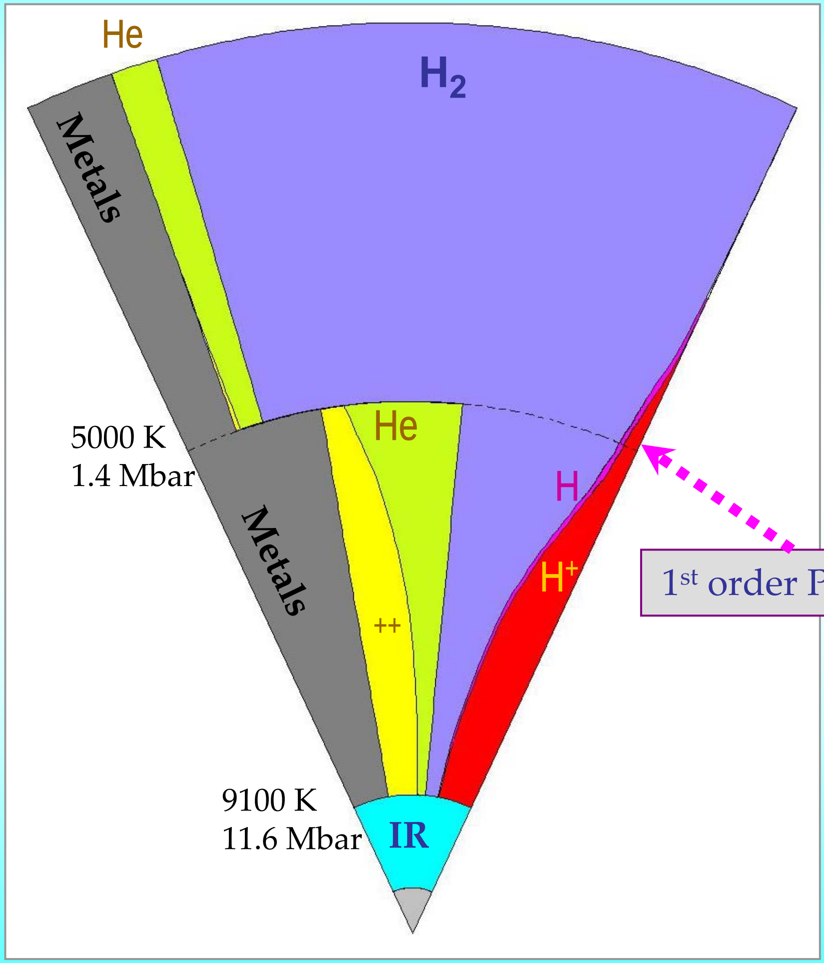
(*) **Pfaffenzeller** O. et al. *PRL* **74** (13) 2599 (1995)

Giant planets interior composition





Saturn interior composition
using SCVH-95_EOS

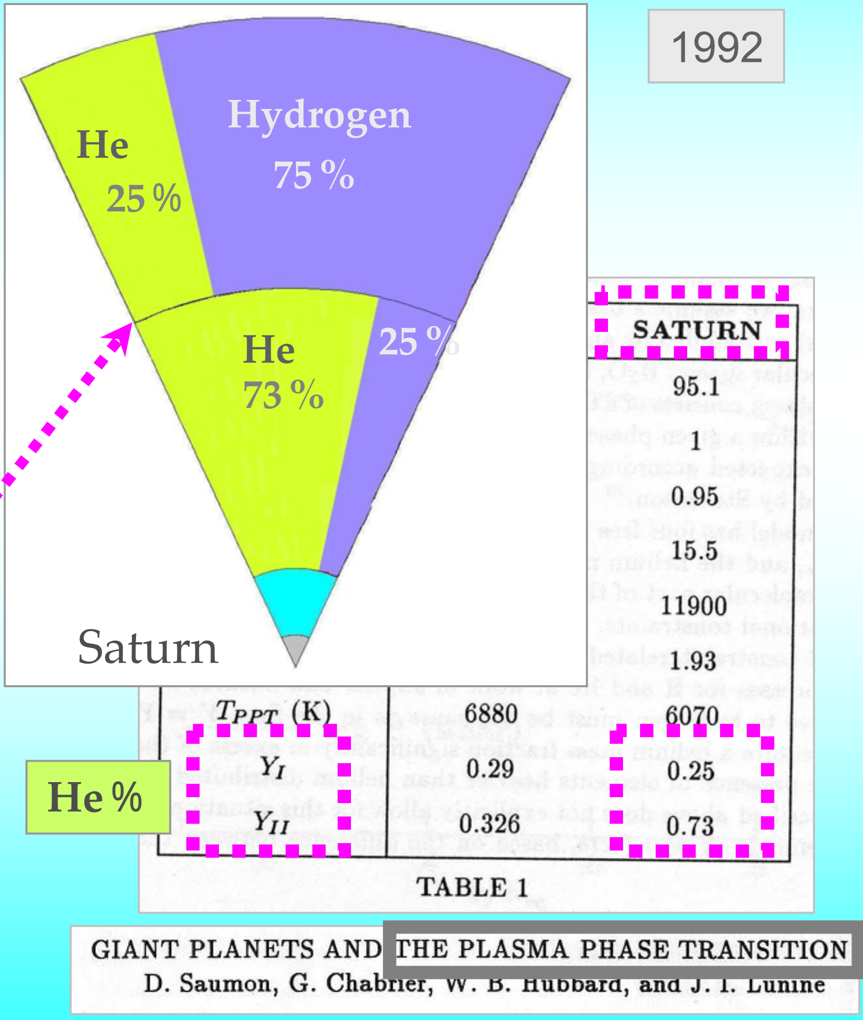


After N. Nettelmann, R. Redmer, et al., **PNP-12**, Darmstadt, 2006)

1st order PPT (?)

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

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

Five layers (!) model of Saturn's interior

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

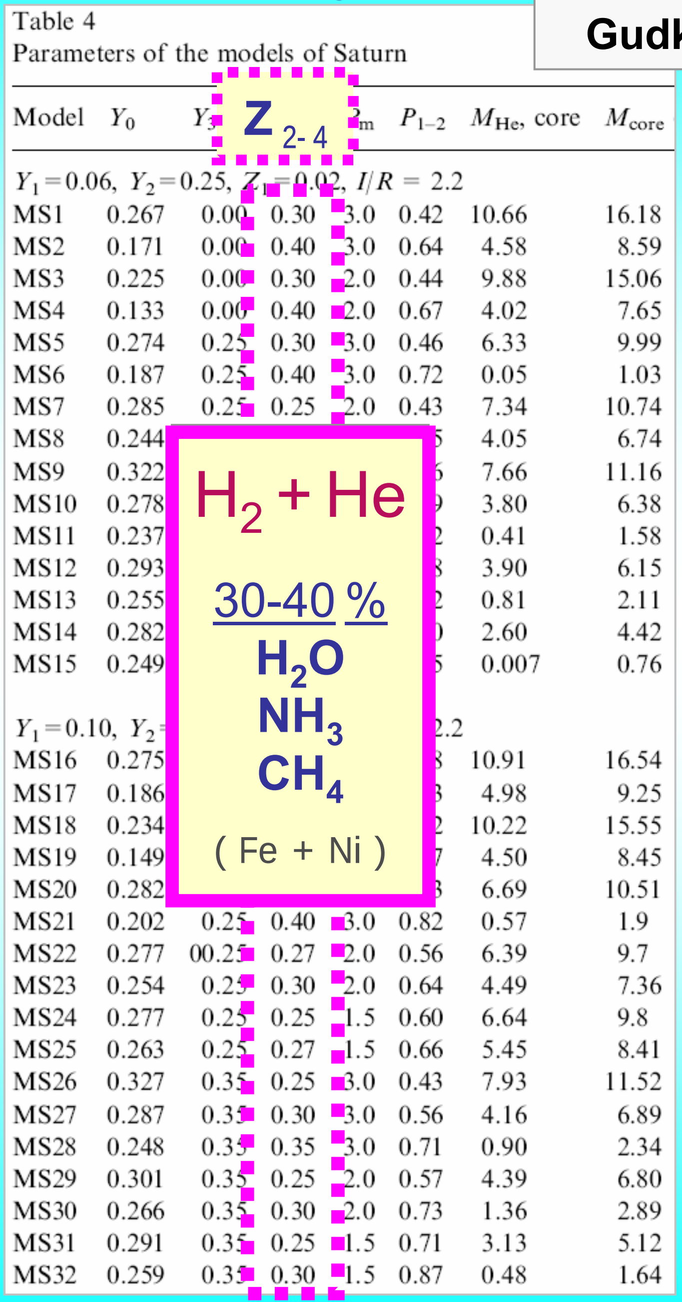


Table 4
Parameters of the models of Saturn

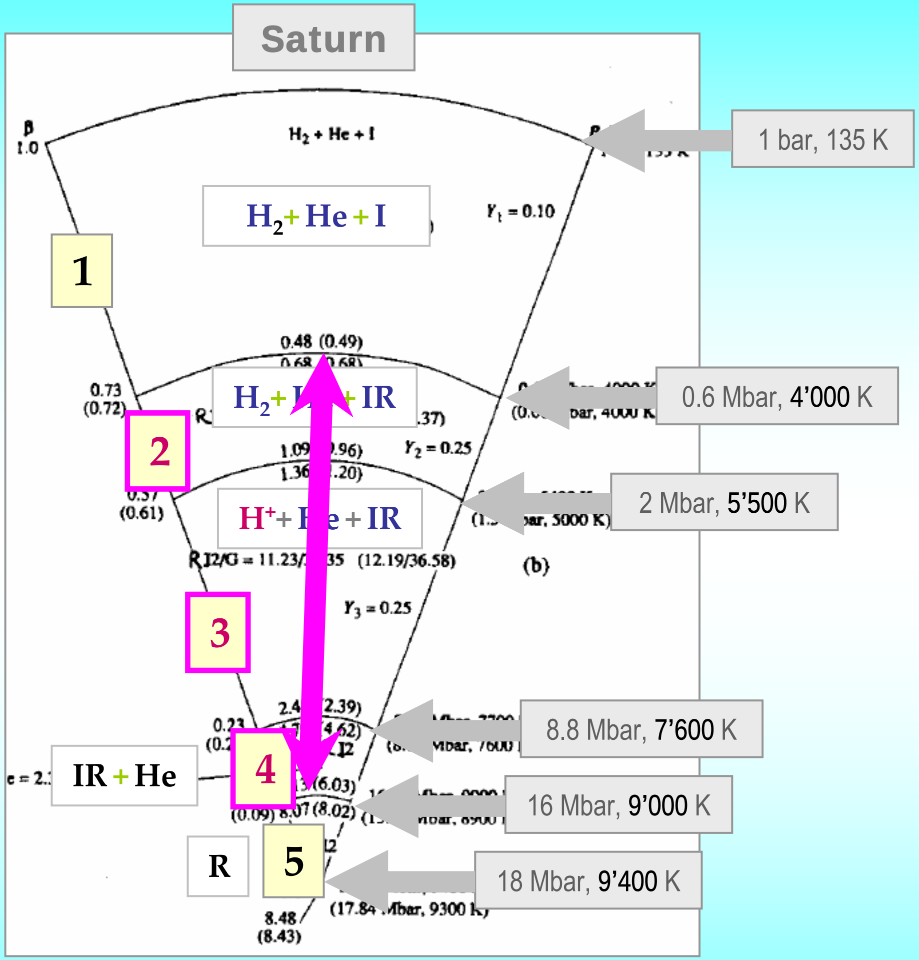
Model	Y_0	Y_3	Z_{2-4}	m	P_{1-2}	M_{He}, core	M_{core}
$Y_1=0.06,\ Y_2=0.25,\ Z_1=0.02,\ I/R = 2.2$							
MS1	0.267	0.00	0.30	3.0	0.42	10.66	16.18
MS2	0.171	0.00	0.40	3.0	0.64	4.58	8.59
MS3	0.225	0.00	0.30	2.0	0.44	9.88	15.06
MS4	0.133	0.00	0.40	2.0	0.67	4.02	7.65
MS5	0.274	0.25	0.30	3.0	0.46	6.33	9.99
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					4.05	6.74
MS9	0.322					7.66	11.16
MS10	0.278					3.80	6.38
MS11	0.237					0.41	1.58
MS12	0.293					3.90	6.15
MS13	0.255					0.81	2.11
MS14	0.282					2.60	4.42
MS15	0.249					0.007	0.76
$Y_1=0.10,\ Y_2=$ … 2.2							
MS16	0.275					10.91	16.54
MS17	0.186					4.98	9.25
MS18	0.234					10.22	15.55
MS19	0.149					4.50	8.45
MS20	0.282					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)

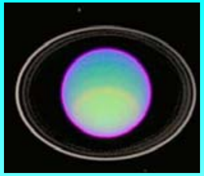
Saturn



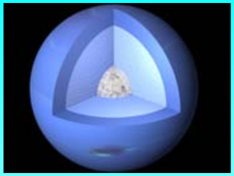
I = "Ices" (H_2O, NH_3, CH_4) **R** = Rocks + Fe + Ni

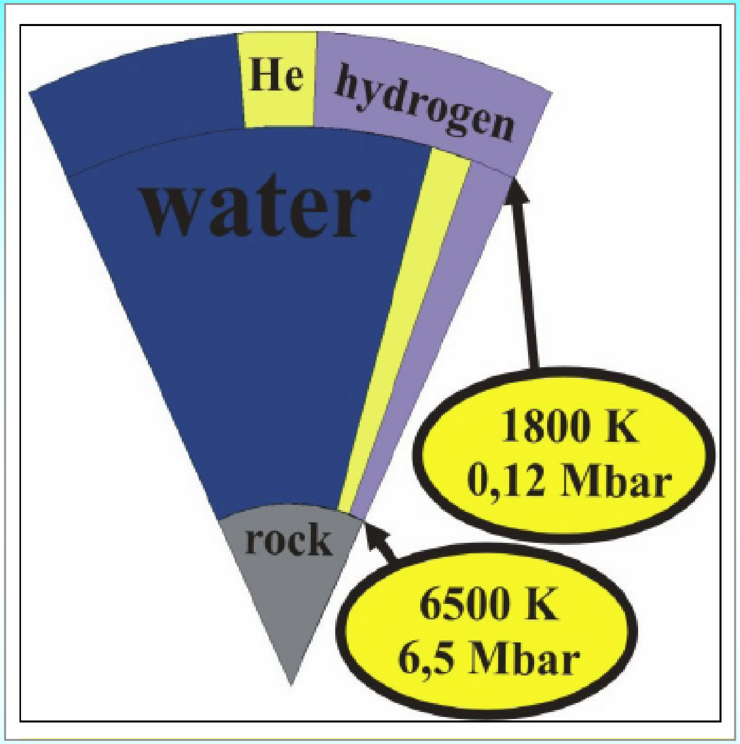
Y_i = mass fraction He

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)