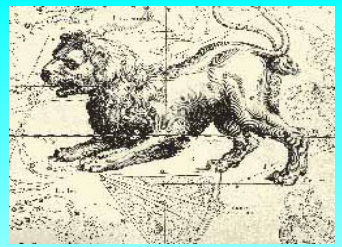
Seminar for young scientists

Physics of high energy density in matter

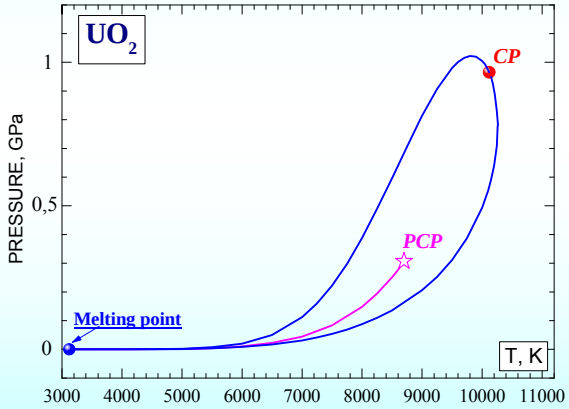
FAIR-Russia Research Centre,

Moscow, 21-22 November 2011



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

Content

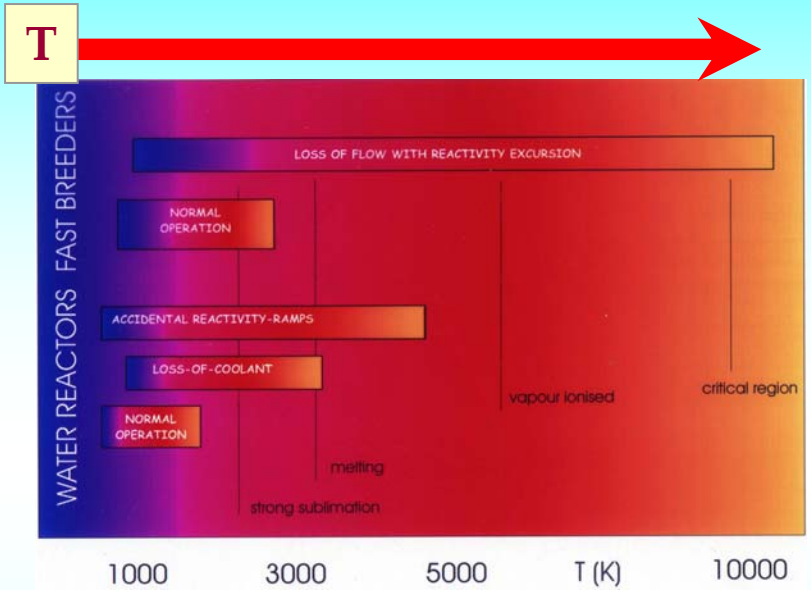
Non-congruence in general
The base: Non-congruent phase transition in U-O system
Non-congruence in terrestrial and planetary applications
Non-congruence in exotic situations (compact stars)
Summary

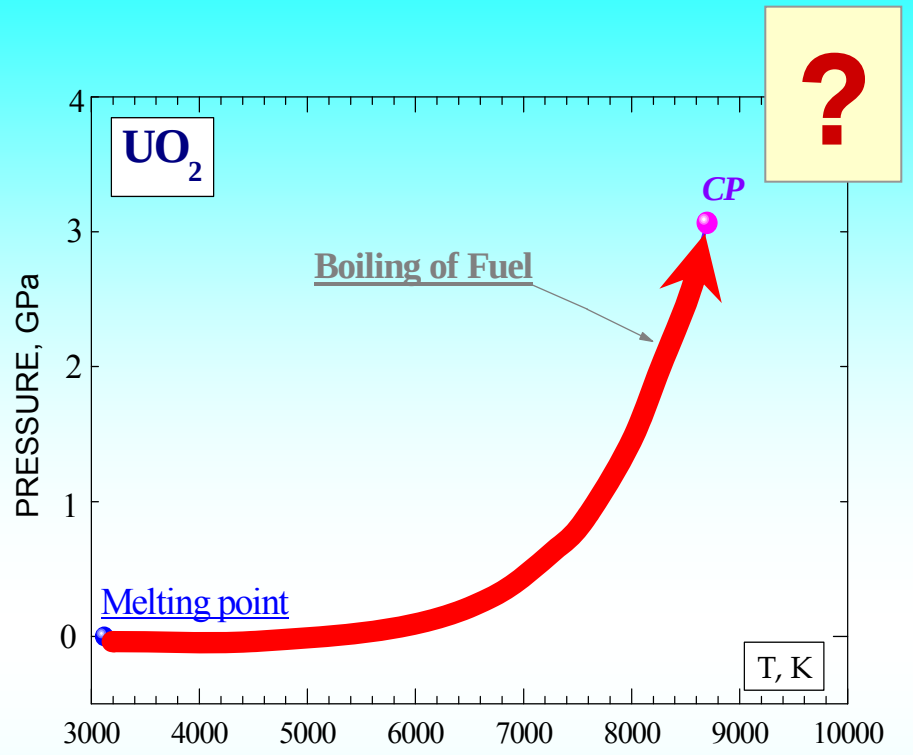
The base

Non-congruent phase transitions in chemically reacting U-O plasma

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 stages

- Construction of Equation of State (EOS)

- Phase coexistence parameters calculation

Quasi-chemical representation

(*"Chemical picture"*)

Multi-molecular model

(*Liquid & Gas*)

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

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

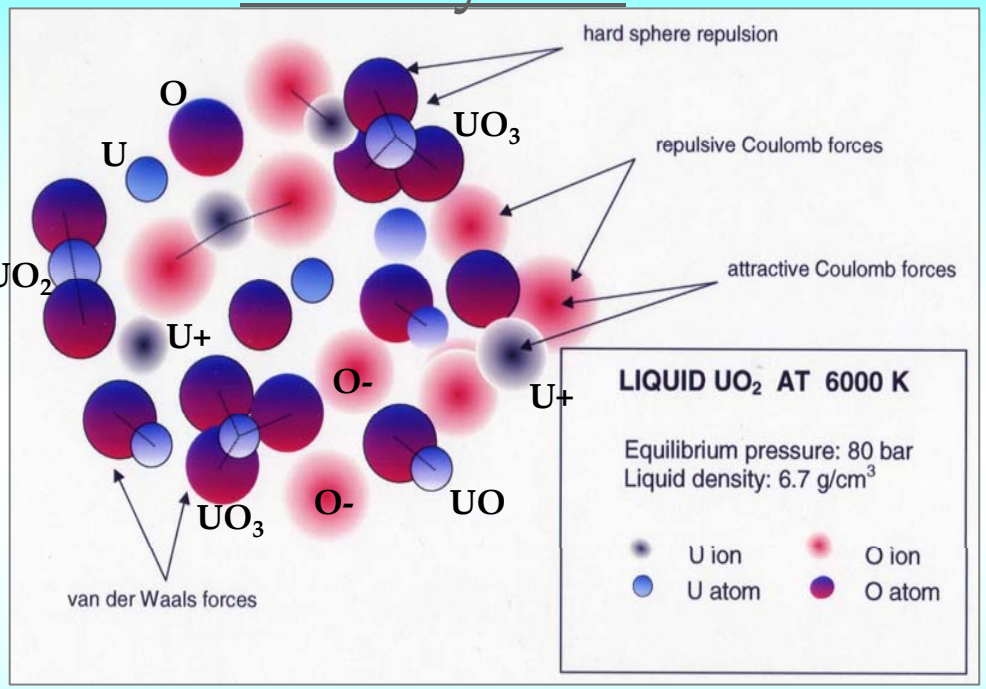
Interactions: (*Pseudopotential components*)

- 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
- Modified Thermodynamic Perturbation Theory

U – O system



* I.L.I., Yakub E., Hyland G., Ronchi C. *Trans. Amer. Nucl. Soc.* **81 (1999)** // *Int. Journ. Thermophysics* **22 (2001)**

* I.L.I., Gryaznov V., Yakub E., Ronchi C., Fortov V. *Contrib. Plasma Phys.* **43**, (**2003**)

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

* I.L.I., Gryaznov V., Semenov A.M., Yakub E., Fortov V. Ronchi C., Hyland G., *High Temperature* **48**, (**2010**)

* I.L.I., Son E., Fortov V. *Thermophysics of non-ideal plasmas.* MIPT (**2000**); FIZMATLIT, (**2011**)

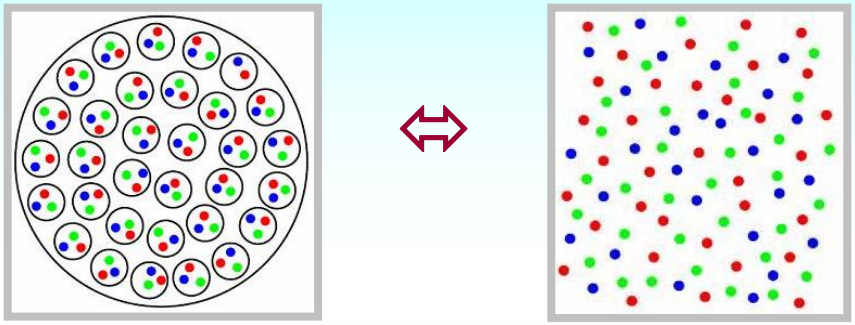
Quasi-chemical representation

("Chemical picture" - in plasma community)

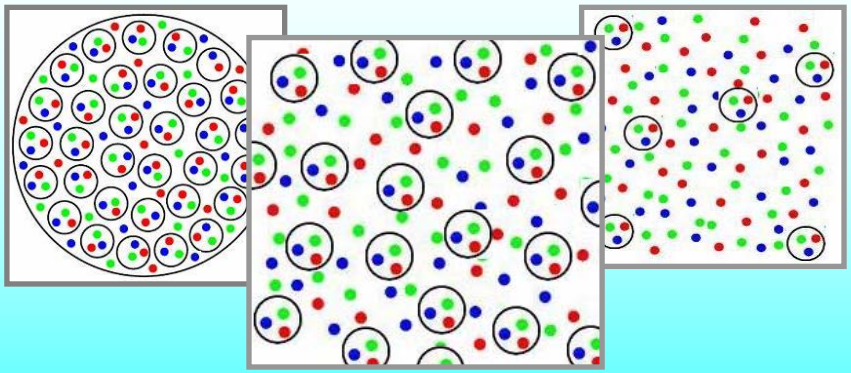
Strange (hybrid) stars

Different EOS for coexisting phases

No critical point !



Unique EOS for coexisting phases



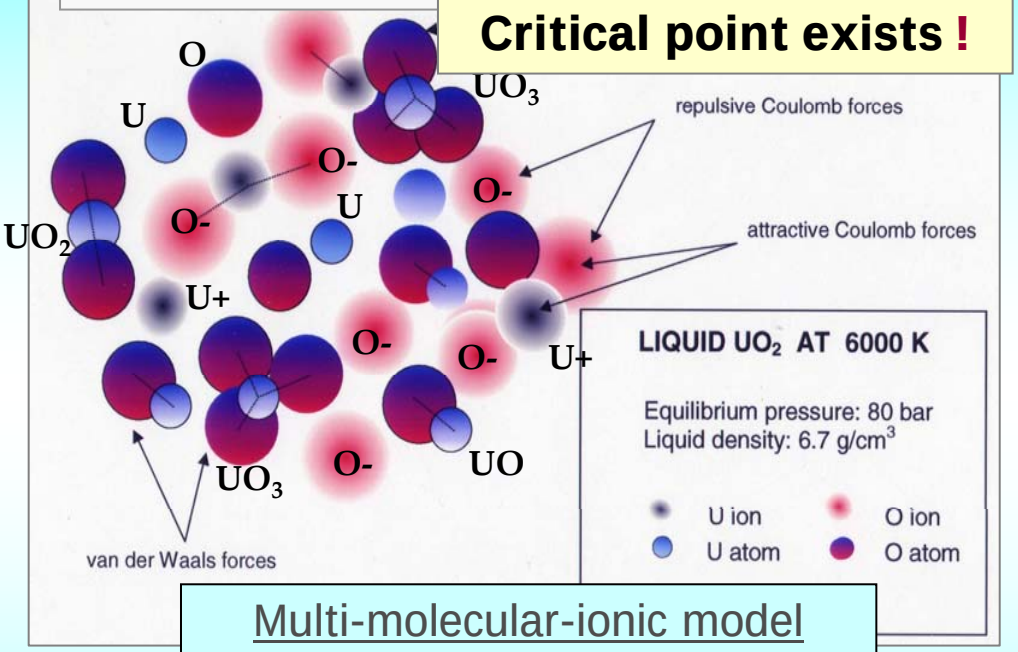
Critical point exists !

Why not ?

U – O system

Unique EOS for coexisting phases

Critical point exists !



Multi-molecular-ionic model

(*Liquid & Gas*)

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

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

$UO_2 \Leftrightarrow U + 2O$

$O_2 \Leftrightarrow 2O$

$U \Leftrightarrow U^+ + e$

$UO_3 + e \Leftrightarrow UO_3^-$

.....

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

$\mu_{O2} = 2\mu_O$

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

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

.....

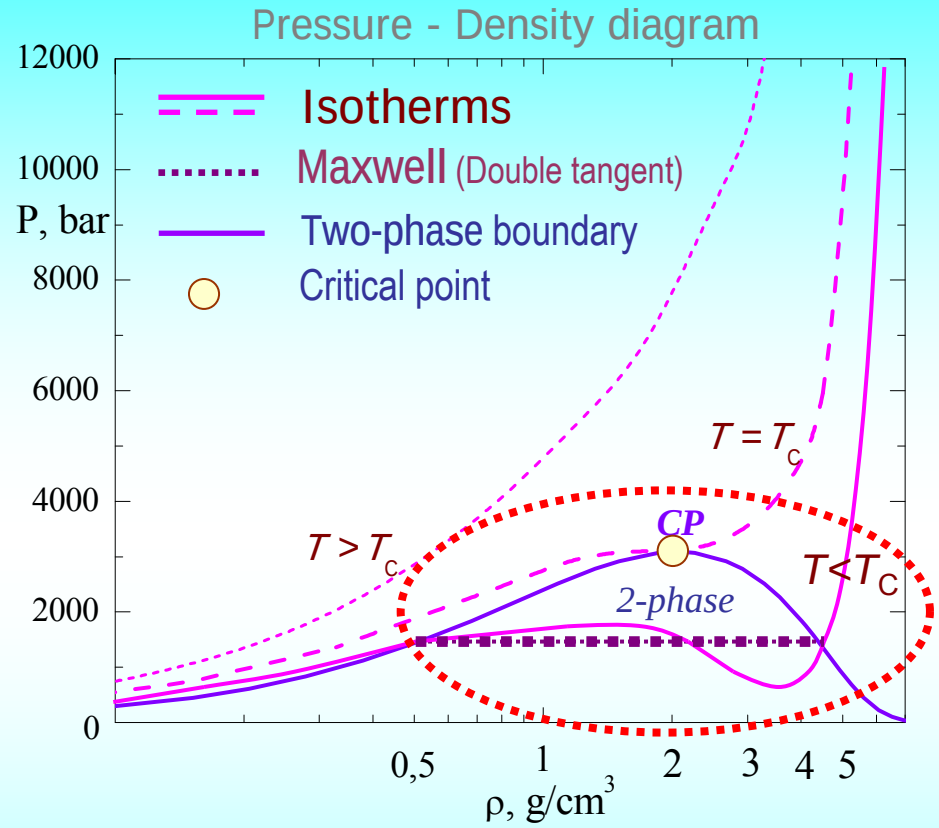
Two problems in phase transition calculation

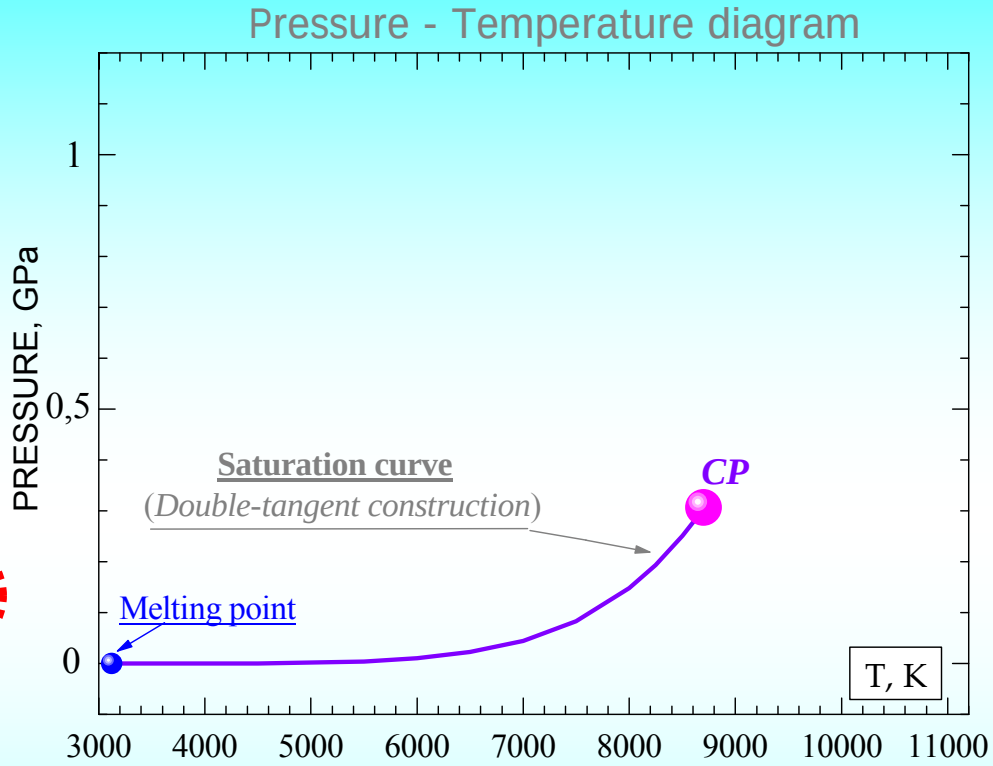
- Construction of Equation of State (EOS)

- **Phase coexistence parameters calculation**

Standard

Congruent evaporation in U-O system





- Stoichiometry of coexisting phases are equal: $x' = x''$
- Van der Waals loops (at $T < T_c$) corrected via the "double tangent construction"
- Standard phase equilibrium conditions:

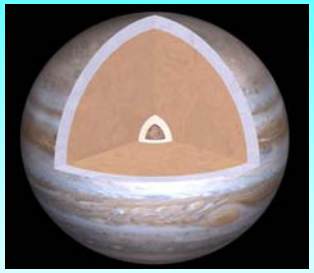
$$P' = P'' \quad // \quad T' = T'' \quad // \quad G'(P,T,x) = G''(P,T,x)$$

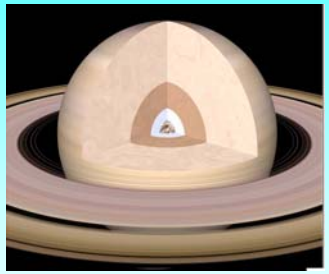
- Standard critical point:

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

Plasma Phase Transitions in H_2 + He plasma

(*planetary science*)

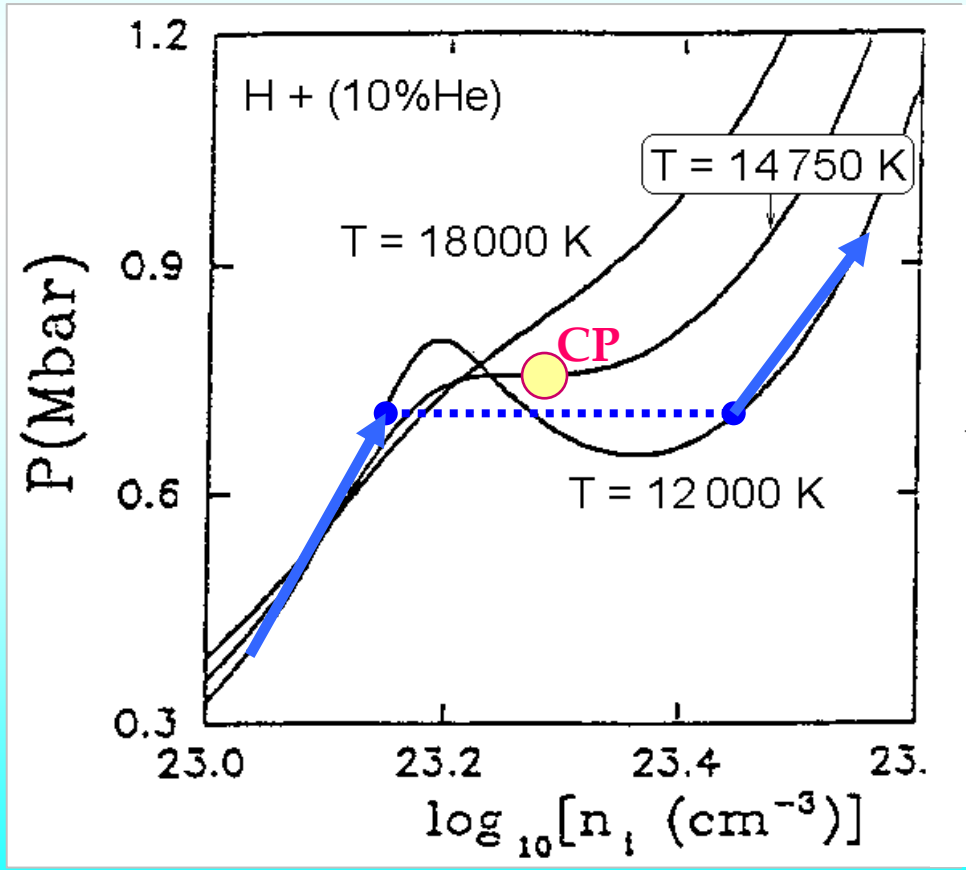


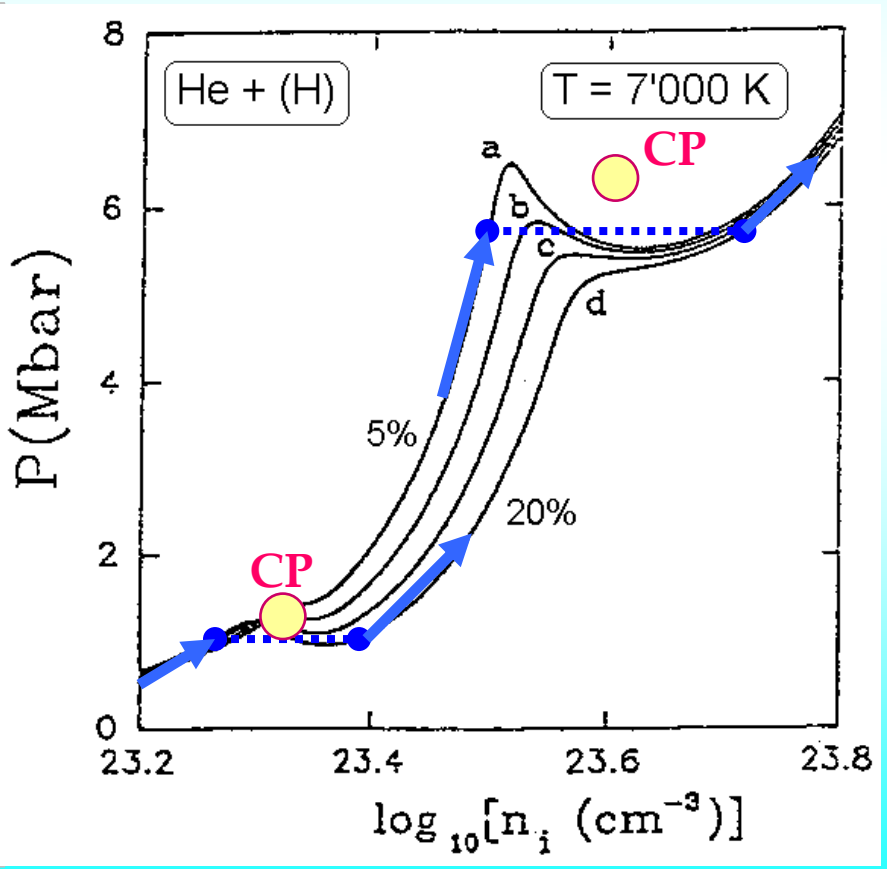


Contrib. Plasma Phys. **35** (1995) 2, 109 – 125

Plasma Phase Transition
in Fluid Hydrogen-Helium Mixtures

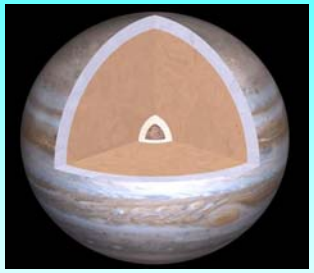
M. SCHLANGES (a), M. BONITZ (b), and A. TSCHTTSCHJAN (b)





Plasma Phase Transitions in H_2 + He plasma

(*continued*)



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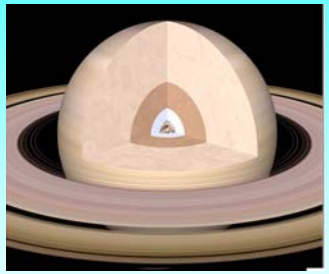


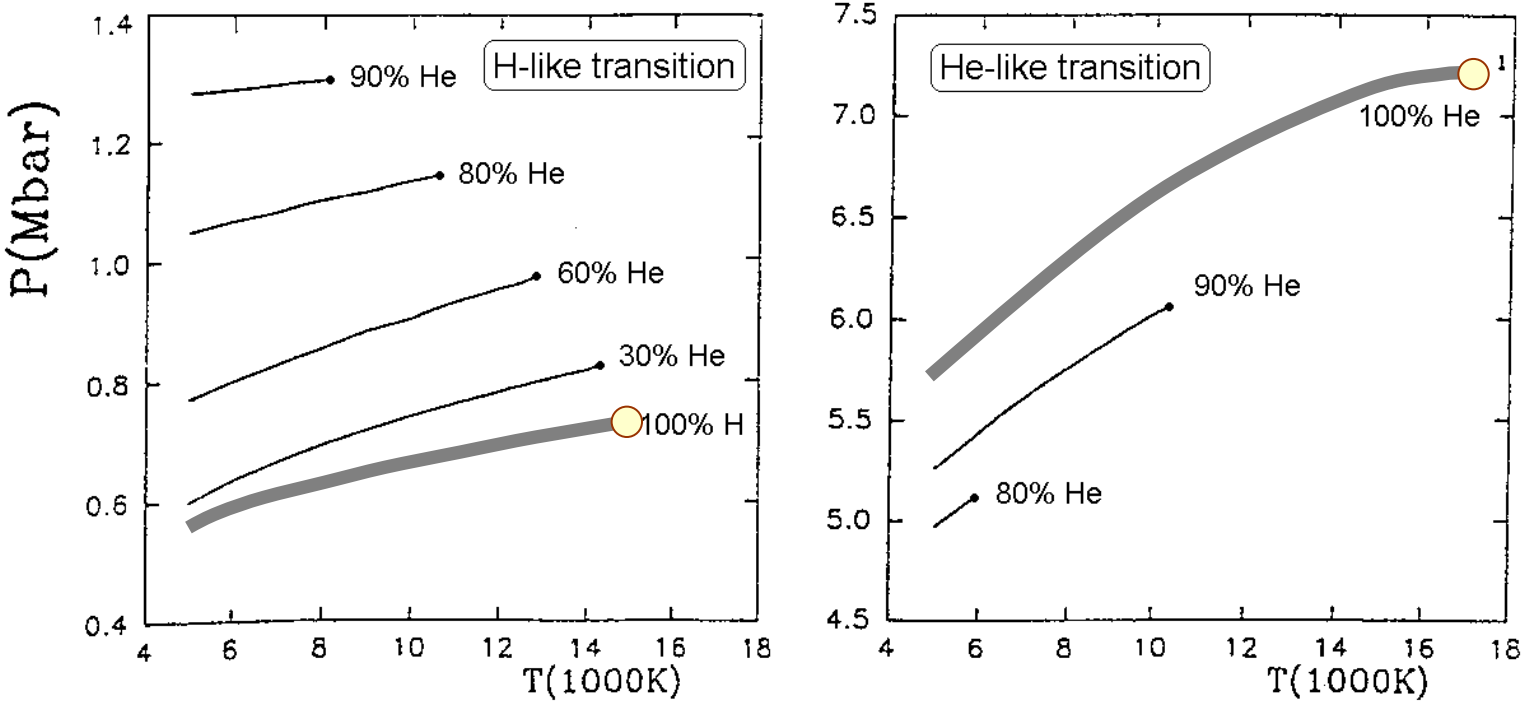
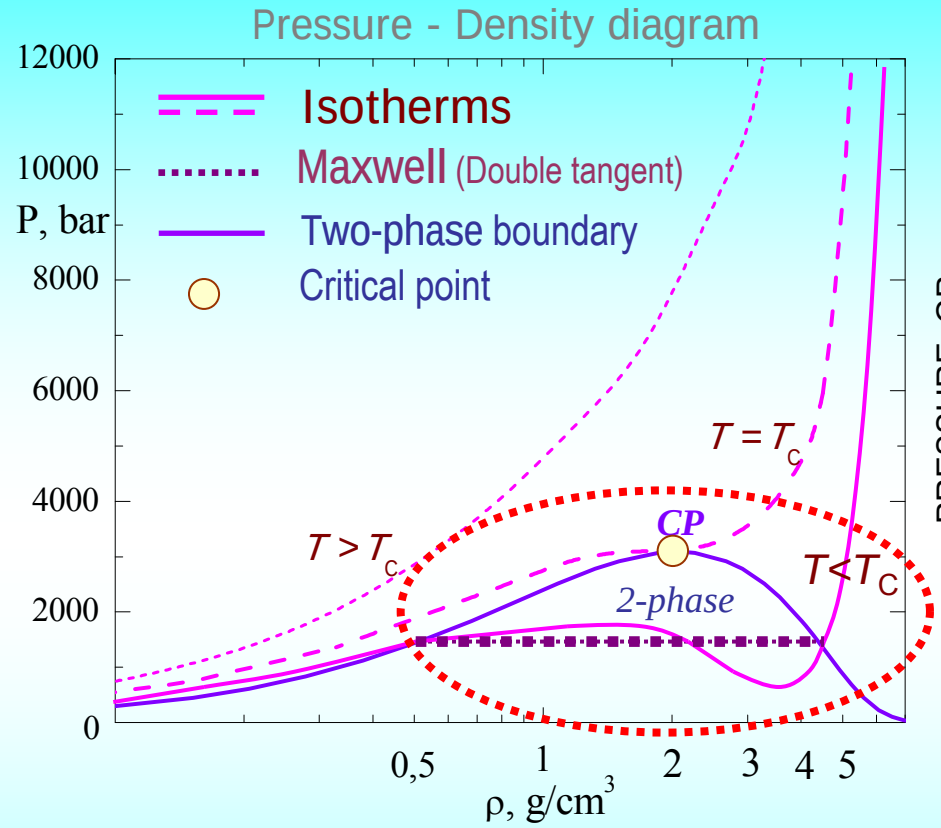
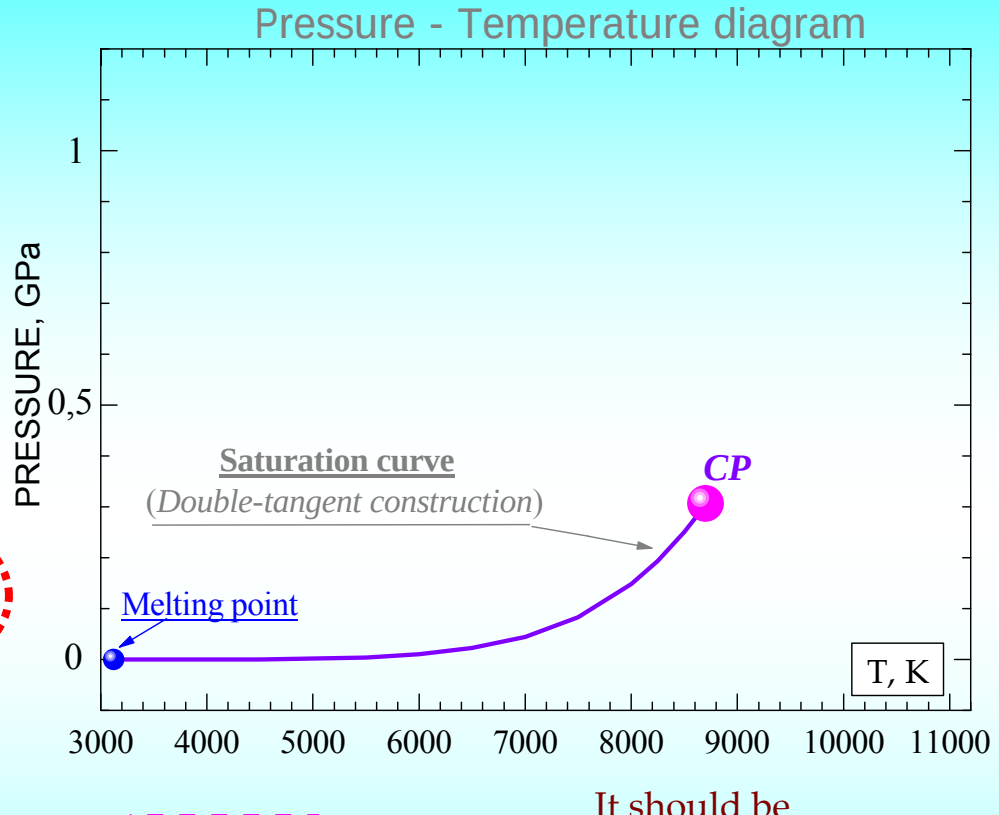


Fig. 7. Coexistence pressure for H – He mixtures for different values of the mixing parameter, for the hydrogen-like plasma phase transition and for the helium-like plasma phase transition.

Standard

Congruent evaporation in U-O system





- 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:

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

It should be

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

- Standard critical point:

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

Phase equilibrium in reacting Coulomb system
(Gibbs – Guggenheim conditions)

φ'	Phase - I $n_1' + n_2' + \ldots + n_k'$	$\Leftrightarrow$	Phase -II $n_1'' + n_2'' + \ldots + n_k''$	φ''

Bulk potential

Bulk potential

Heat exchange

$$T' = T''$$

Impulse exchange

$$P' = P''$$

Particle Exchange neutral species

(Gibbs)

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

Particle Exchange charged species

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

Electro-chemical potentials are equal

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

Galvani potential

Potential drop at mean-phase interface in equilibrium Coulomb system

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

Equilibrium reactions

ab ⇔ a + b

(reduced number of basic units)

Uranium – Oxygen system

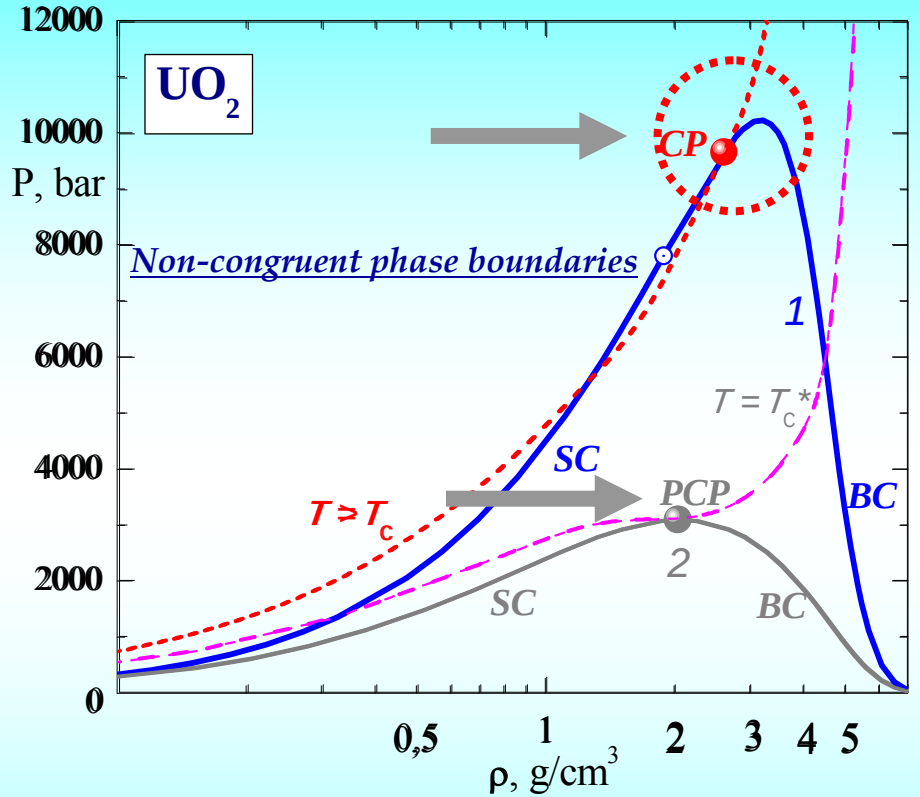
$$\mu_U'(P,T,x') = \mu_U''(P,T,x'')$$
$$\mu_O'(P,T,x') = \mu_O''(P,T,x'')$$

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

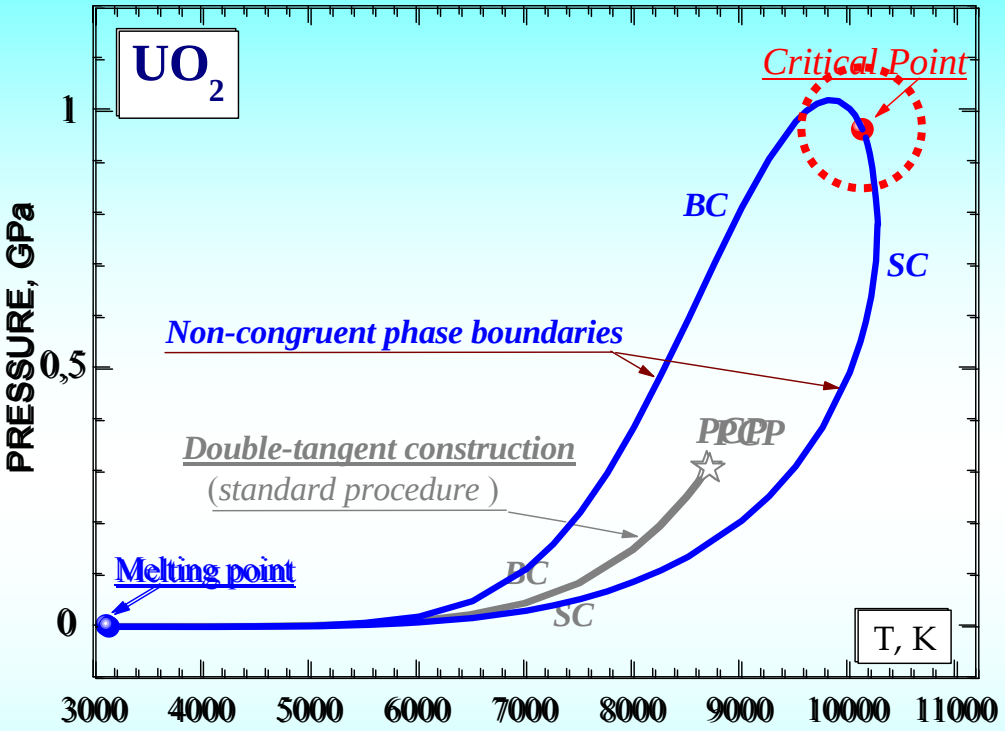
Non-congruent evaporation in U-O system

(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

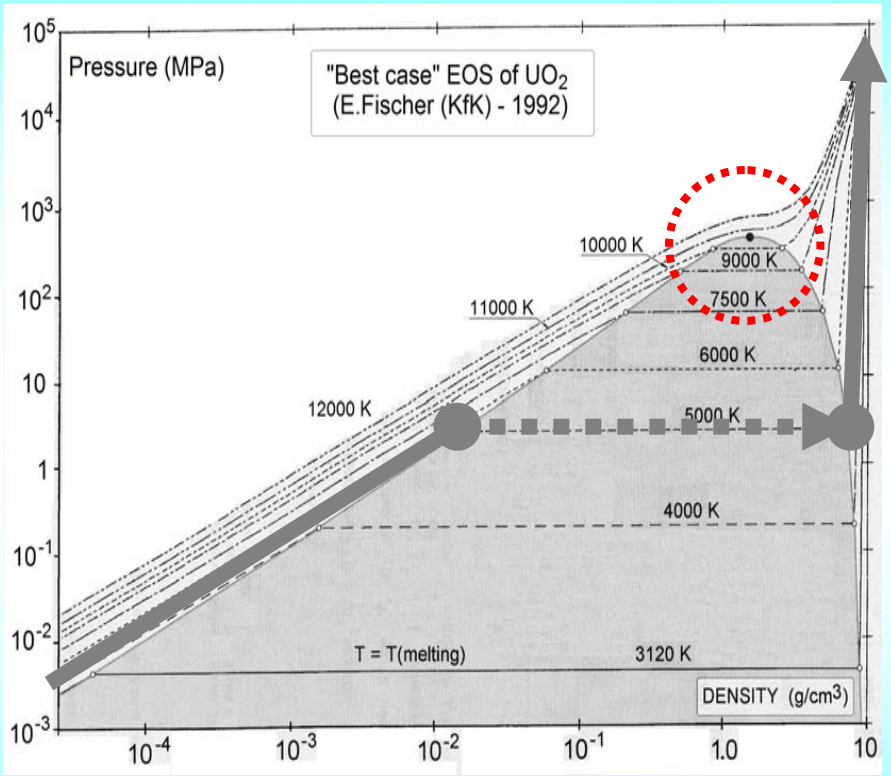
NB! **High pressure level** of non-congruent phase decomposition

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

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

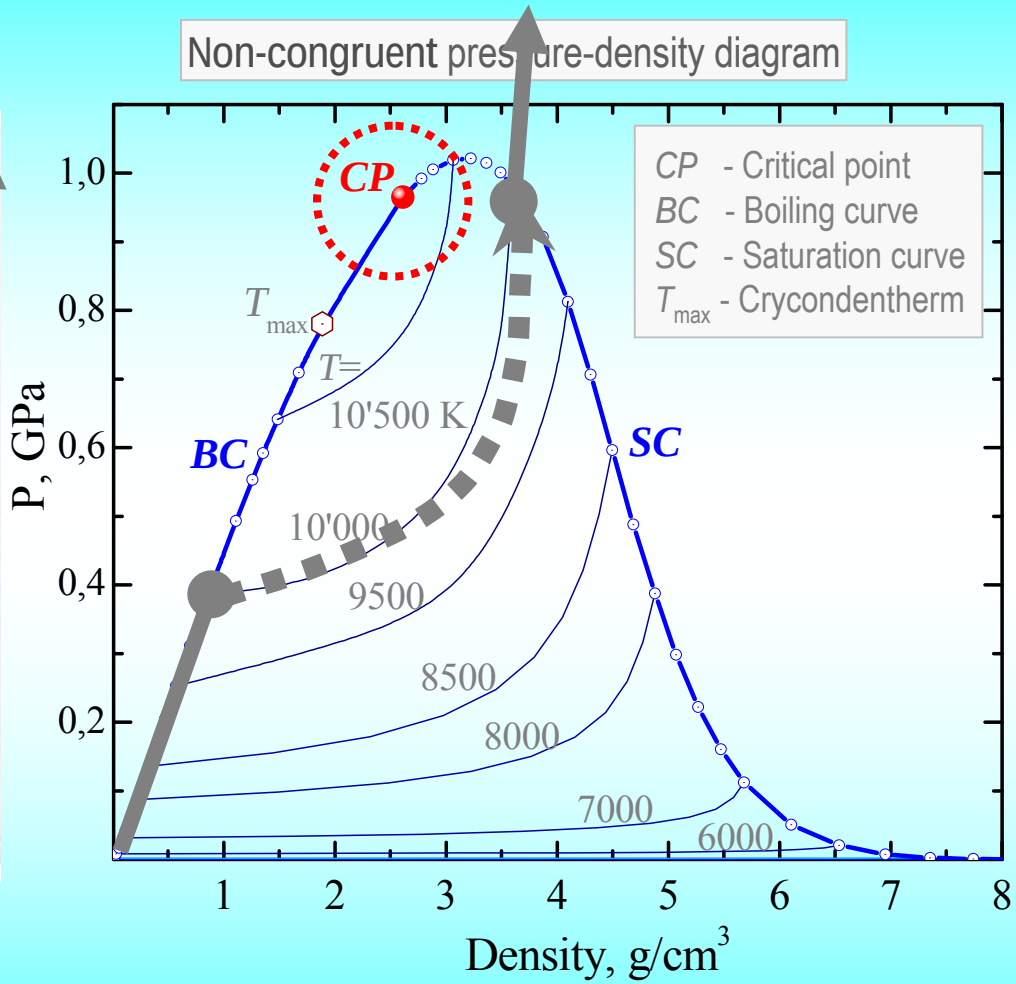
Isotherms in two-phase region

Standard pressure-density diagram

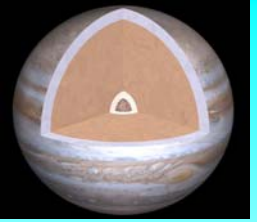


Fischer E.A. *J. Nucl. Sci. Eng.* (1989)

Non-congruent pressure-density diagram

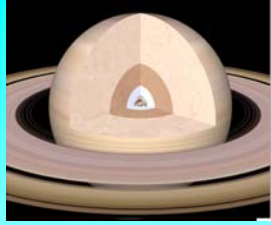


- **Isothermal** phase transition starts and finishes at ***different pressures***
- **Isobaric** phase transition starts and finishes at ***different temperatures***



Thermodynamics of H_2 + He plasma

(*planetary science*)



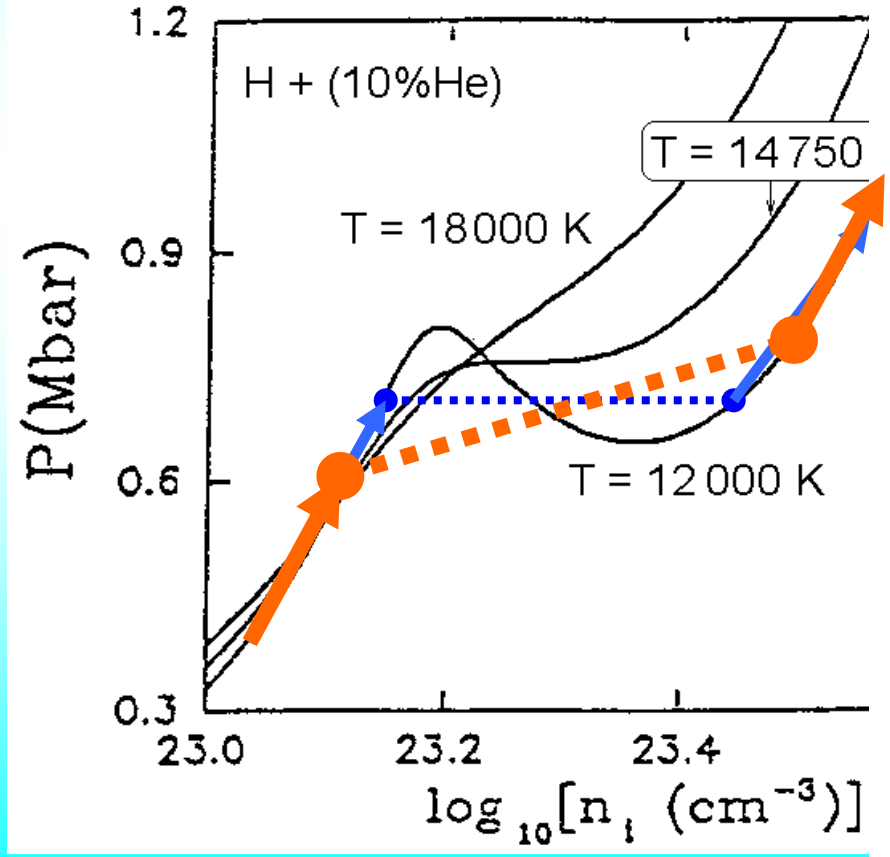
Forced-Congruent phase transition in H_2+ He plasma (*calculated*)

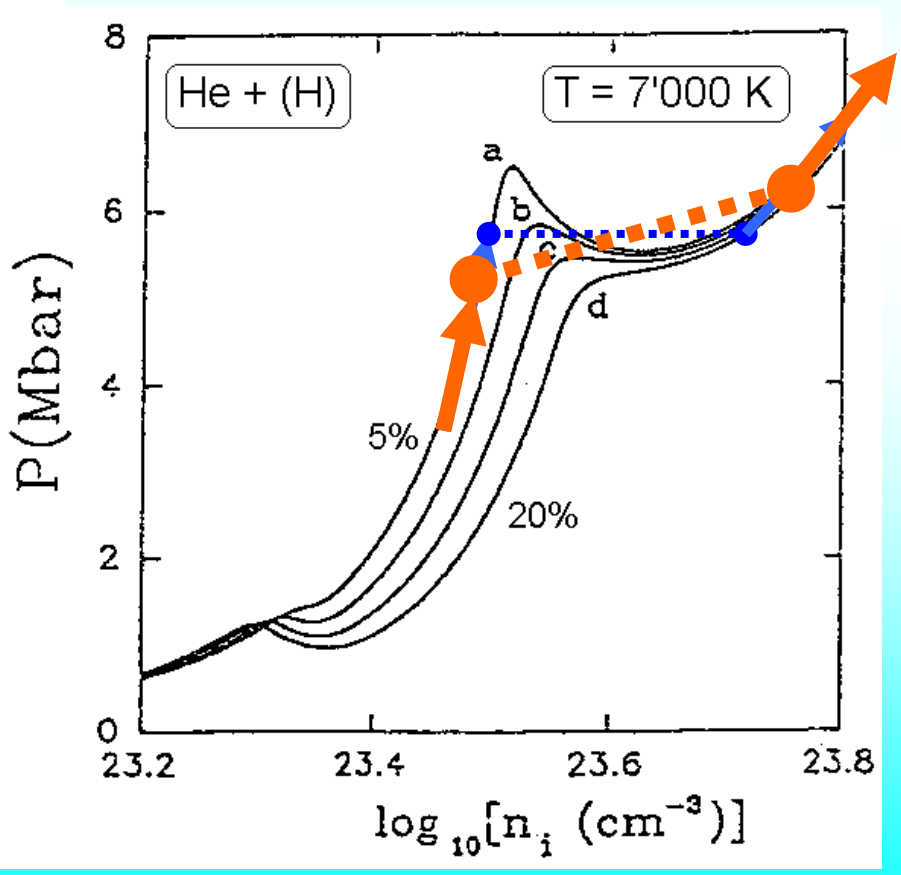
Contrib. Plasma Phys. **35** (1995) 2, 109 – 125

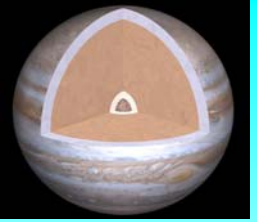
Plasma Phase Transition
in Fluid Hydrogen-Helium Mixtures

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

Non-Congruent phase transition in H_2+ He plasma (*must be instead* **!**)

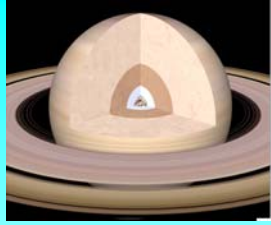






Thermodynamics of H_2 + He plasma

(*planetary science*)



Non-Congruent phase transition in H_2+ He plasma (*must be!*)

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

Plasma Phase Transition
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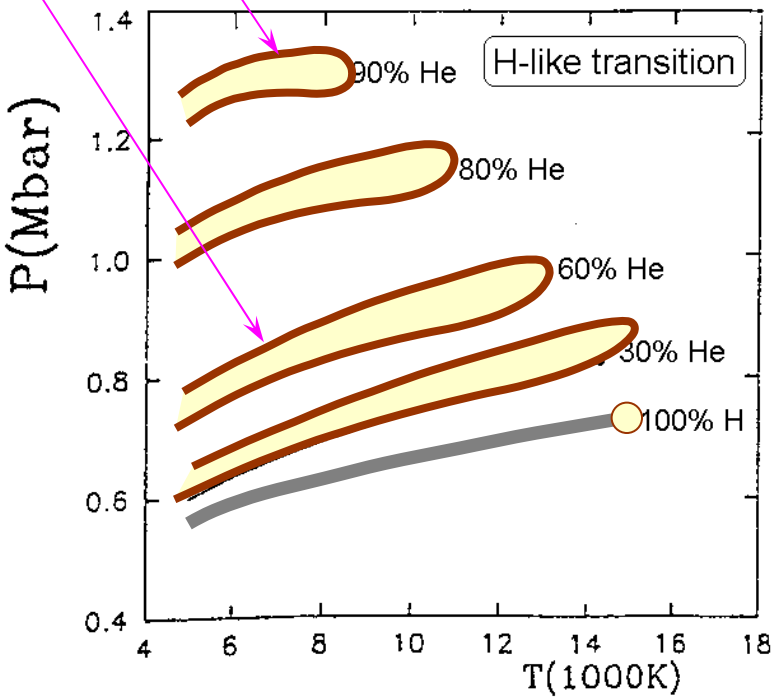


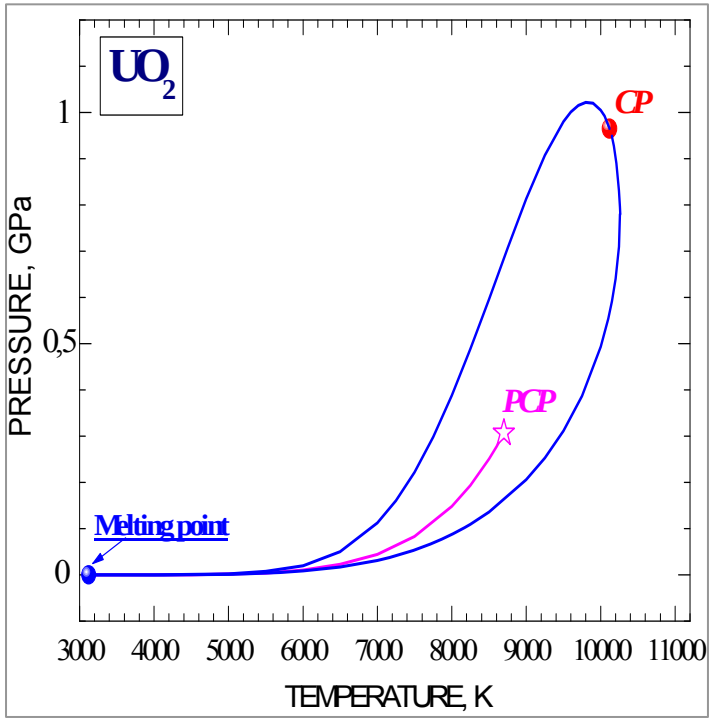


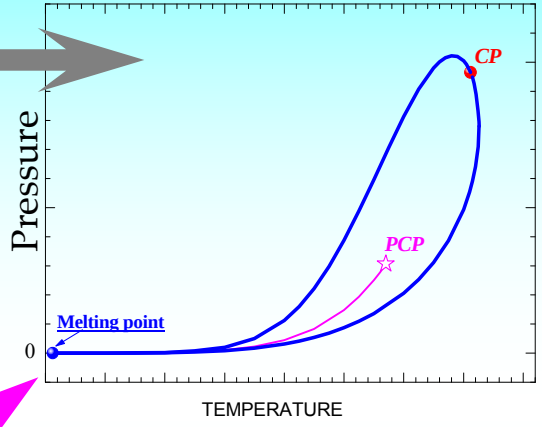
Fig. 7. Coexistence pressure for H – He mixtures for different values of the mixing parameter, for the hydrogen-like plasma phase transition and for the helium-like plasma phase transition.

Main issue from 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:

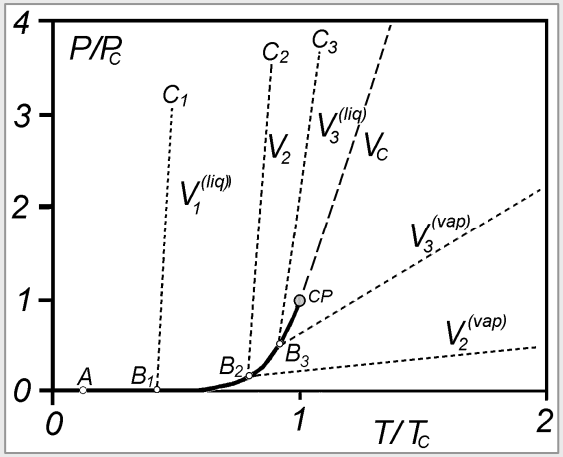
- Any phase transition in a system of **two** or **more chemical elements** must be **non-congruent**
- **Congruent** phase transition is **exception**



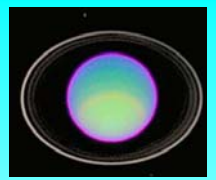
Evident contradiction

H_2O, CO_2, NH_3 . . . .

?

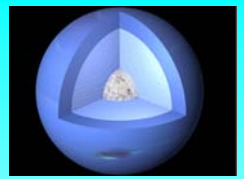


Non-congruence in H_2O etc... – what does it mean ?



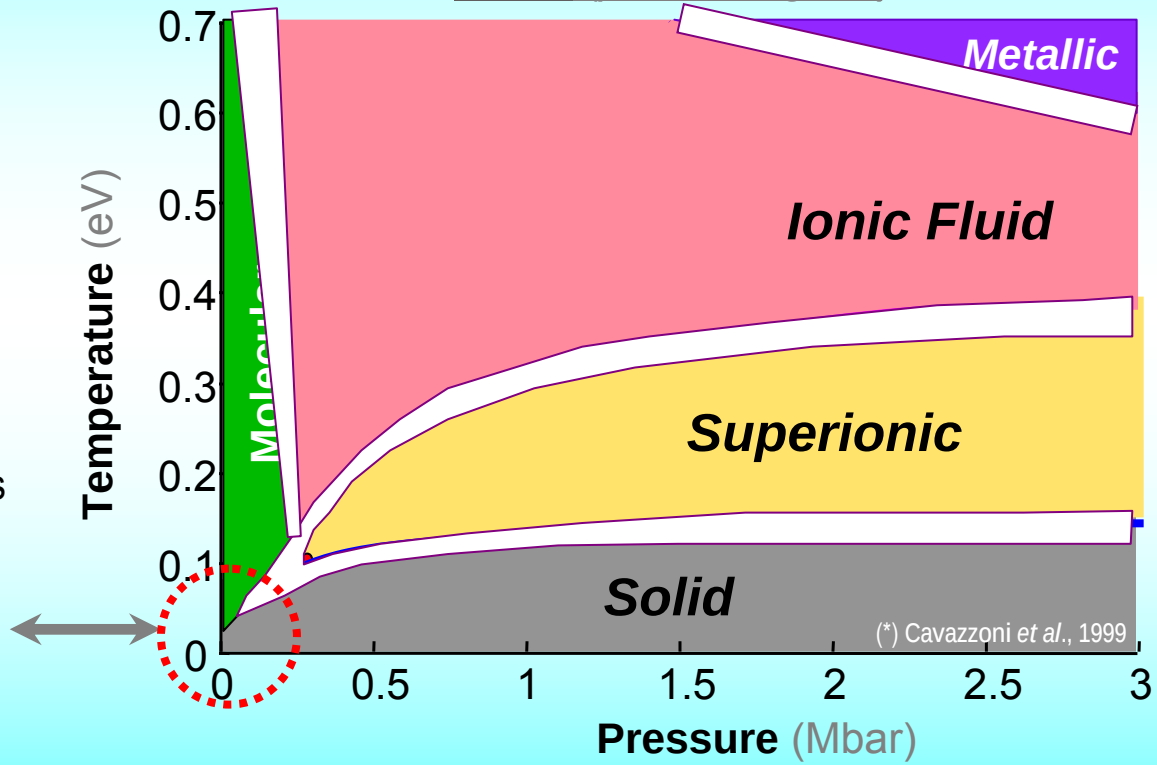
BASIC STATEMENT:

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

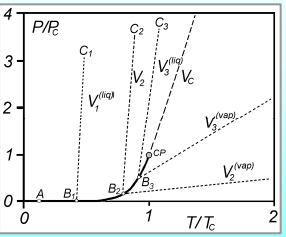


Neptune and "hot-water" extrasolar planets

Water (*phase diagram*)



Room conditions



GJ436b

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

= «» =

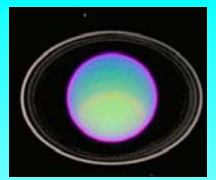
(*Discovered* – 2007)

Ab initio calculations

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

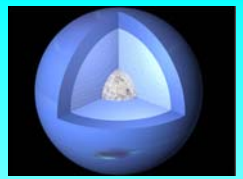
Mattsson & **Desjarlais** (*Sandia Lab.*): *High energy-density water: DFT/QMD simulations* (***2007***)

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



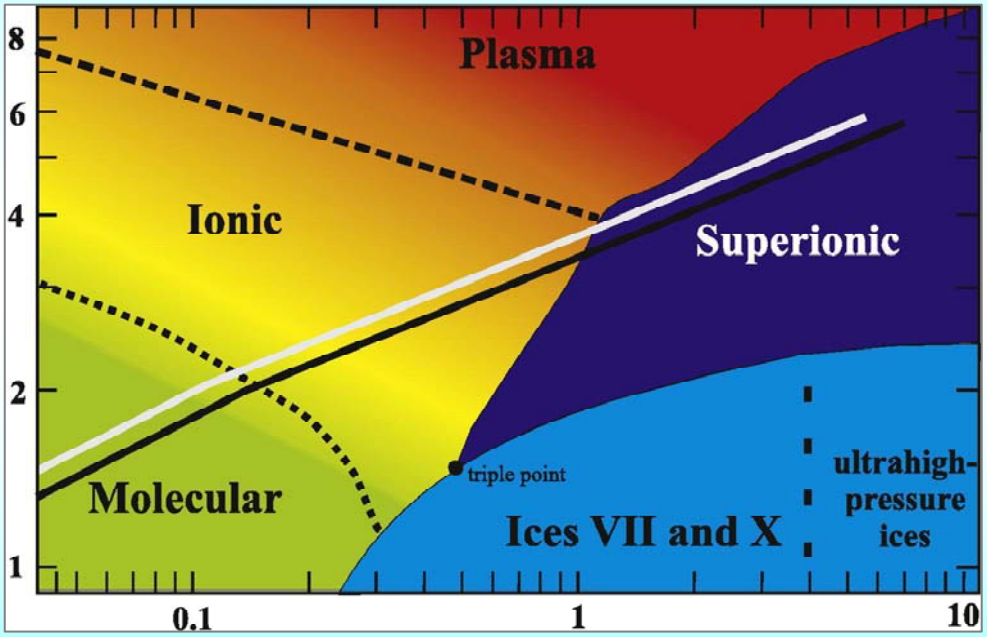
BASIC STATEMENT:

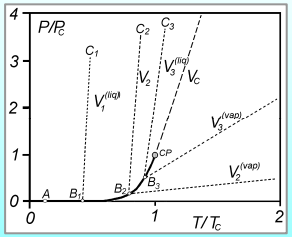
Any phase transition in a system of **two or more chemical elements** must be **non-congruent**



Neptune and "hot-water" extrasolar planets

Water (*phase diagram - 2011*)





GJ436b

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

= «» =

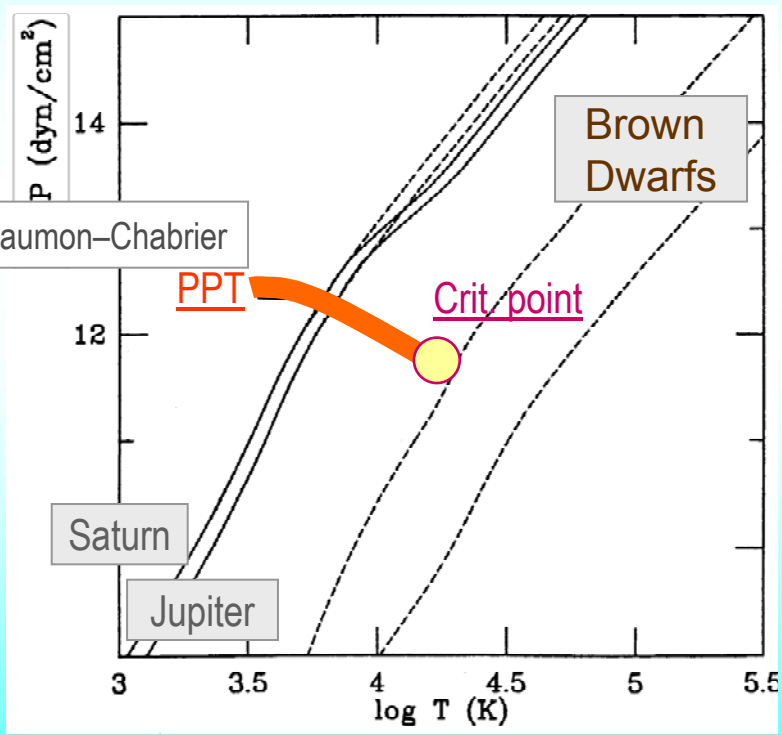
(*Discovered* – 2007)

Ab initio calculations

R.Redmer, T.Mattsson, N.Nettelman, M.French, *Icarus* ***(2011)***

Hypothetical phase transitions in H_2/He mixture

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



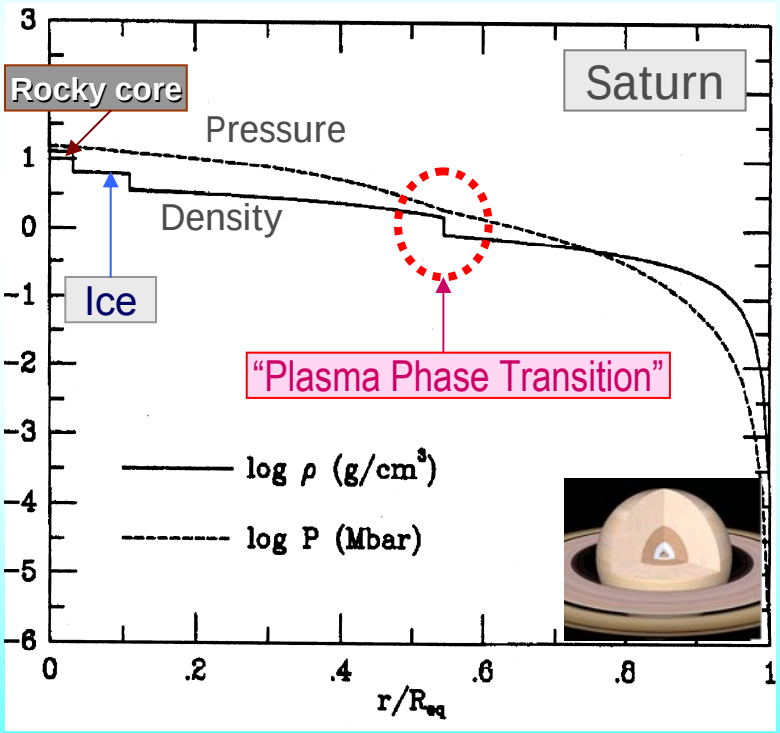


Fig. 1. Pressure and density profiles of optimized models of Jupiter (top panel) and Saturn (bottom panel), plotted as a function of mean radius. Discontinuities in the density clearly mark the boundaries of the four layers of the models: rocky core, ice mantle, metallic and molecular

Hypothetical phase transitions in H_2/He mixture

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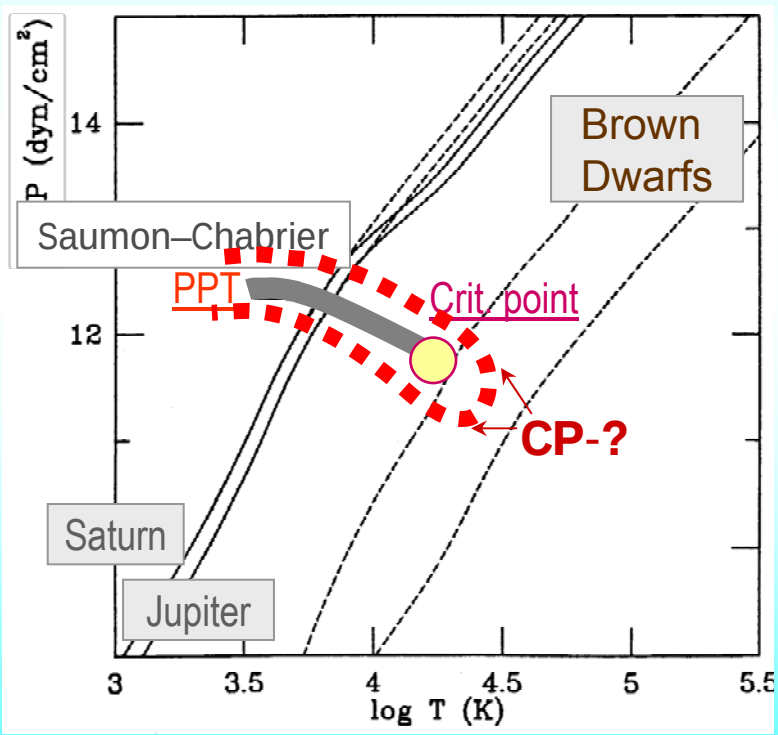


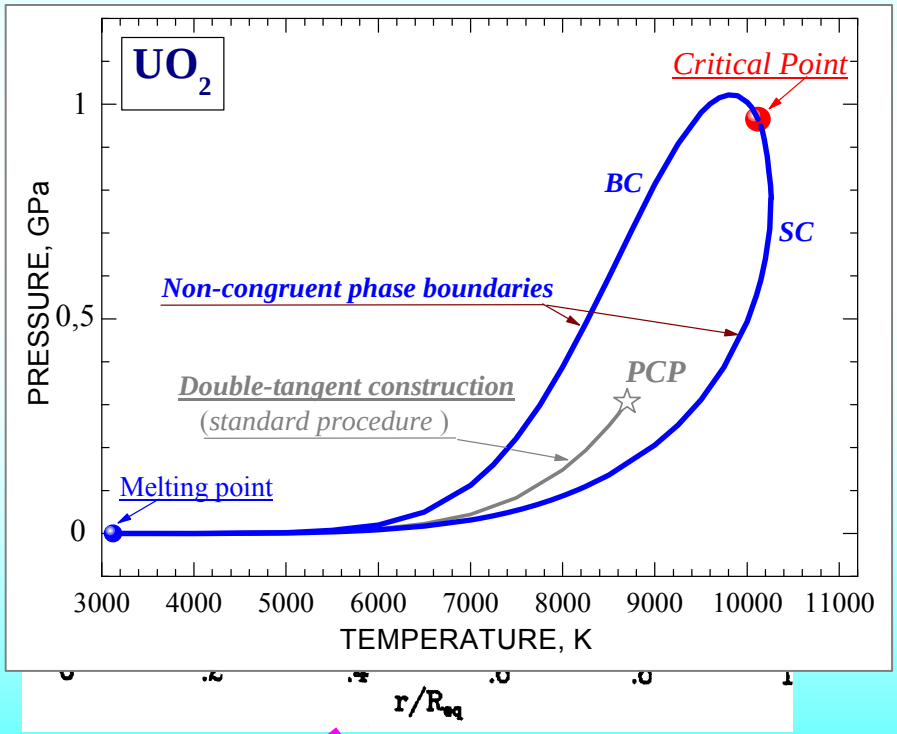


Fig. 1. Pressure and density profiles of optimized models of Jupiter (top panel) and Saturn (bottom panel), plotted as a function of mean radius. Discontinuities in the density clearly mark the boundaries of the four layers of the models: rocky core, ice mantle, metallic and molecular

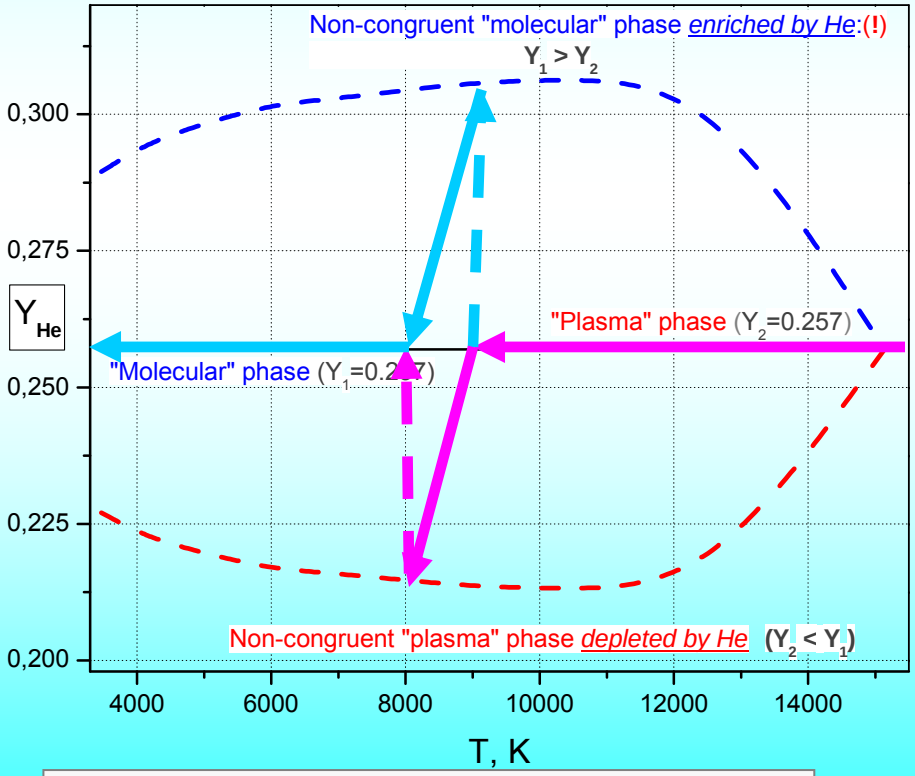
Estimated non-congruence for plasma phase transition in H_2/He mixture of Jupiter and Saturn

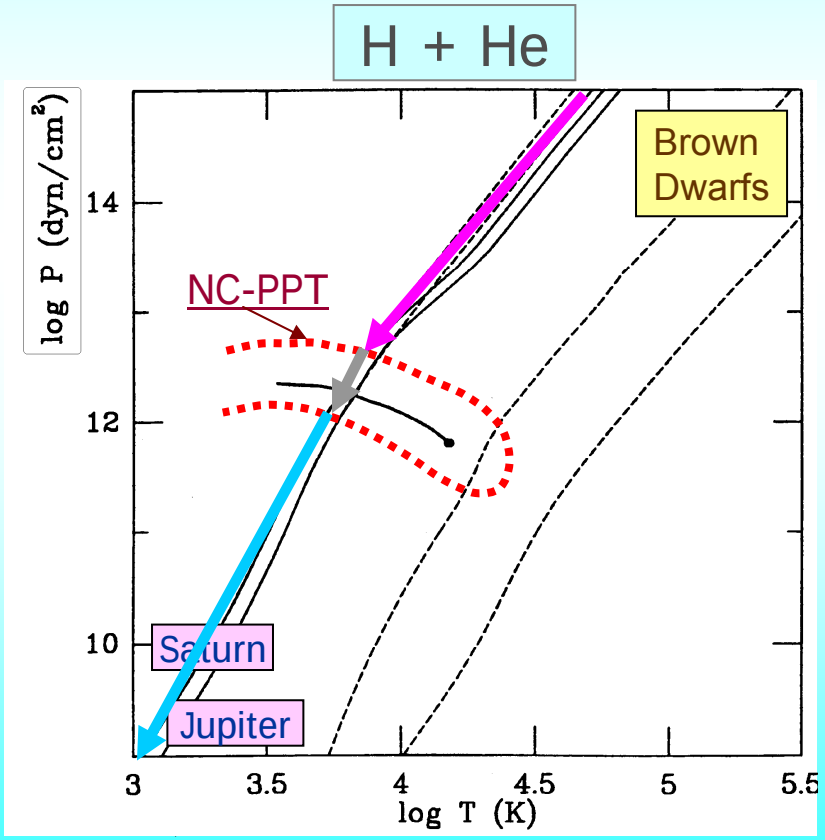
(with Artem Ukrainets)

(*PPT-variant of Saumon, Chabrier and Van Horn – 1995*)

Assumptions:

- Helium is not ionized.
- Atomic helium interacts with neutral hydrogen species only (H_2 and H).
- Interaction of atomic helium with charged species are low and repulsive.





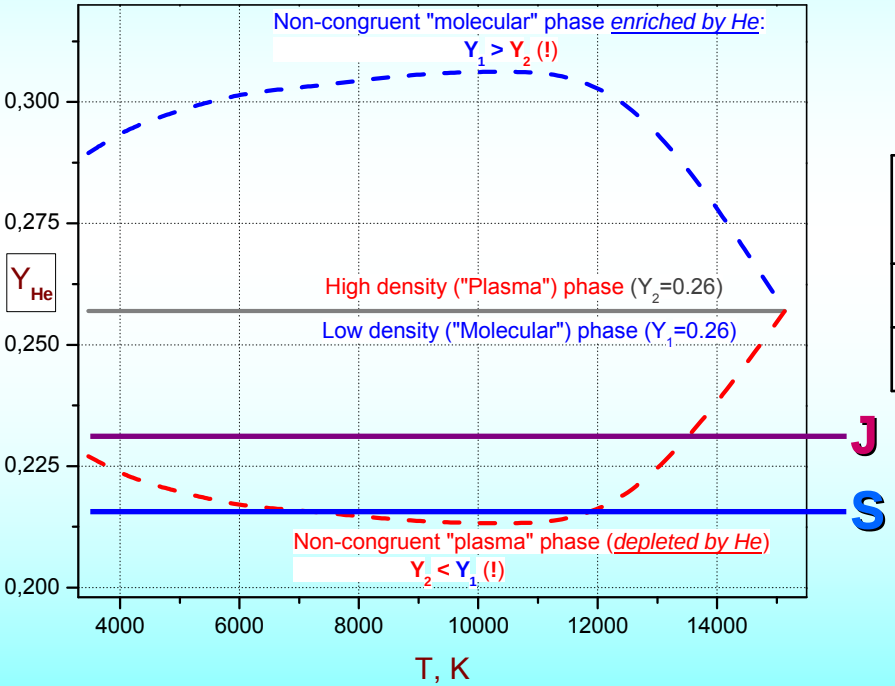
A. Ukrainets & I. Iosilevskiy
in "*Physics of matter under extreme conditions*",
Ed. V.Fortov, Moscow, IPCP (2005) 116. (*in Russ.*)

Estimated non-congruence for the plasma phase transition in H_2/He mixture of Jupiter and Saturn

(*PPT-variant of Saumon, Chabrier and Van Horn – 1995*)

Question:

- Is the estimated helium enrichment (depletion) negligible or noticeable? (or may be even significant ?)



Phase Separation in Giant Planets:

Jonathan J. FORTNEY, William B. HUBBARD

Icarus, 164 (1) 2003

Atmospheric elemental abundances in Jupiter and Saturn

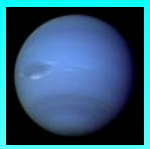
(*mass fractions*)

Element	SOLAR	JUPITER *Galileo*	SATURN *Voyager*	SATURN **revised**
H	0.736	0.742	0.92	0.76
He	0.**249**	0.**231** ± 0.04	**0.06** ± 0.05	0.**215** ± 0.035

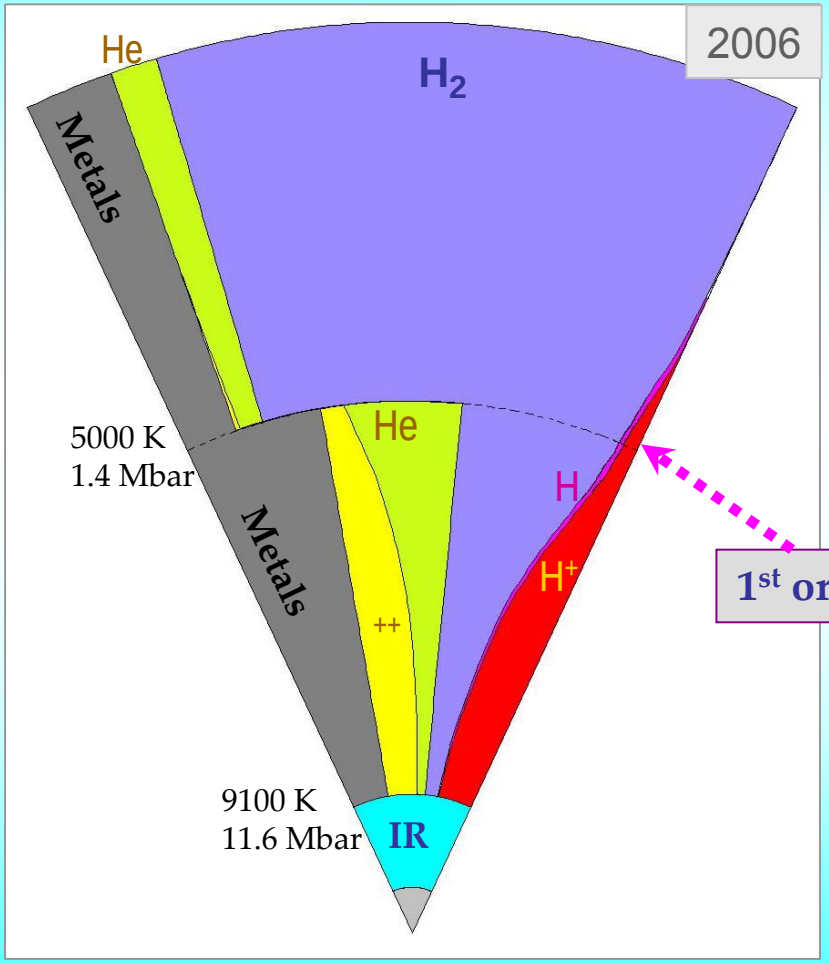
* Provided estimation of the non-congruence for PPT in version of Saumon and Chabrier approves full-size calculation of this effect.

* The same is true for all other variants of predicted hypothetical phase transitions in pure hydrogen and helium when they being transformed into H2/He mixture.

Giant planets interior composition



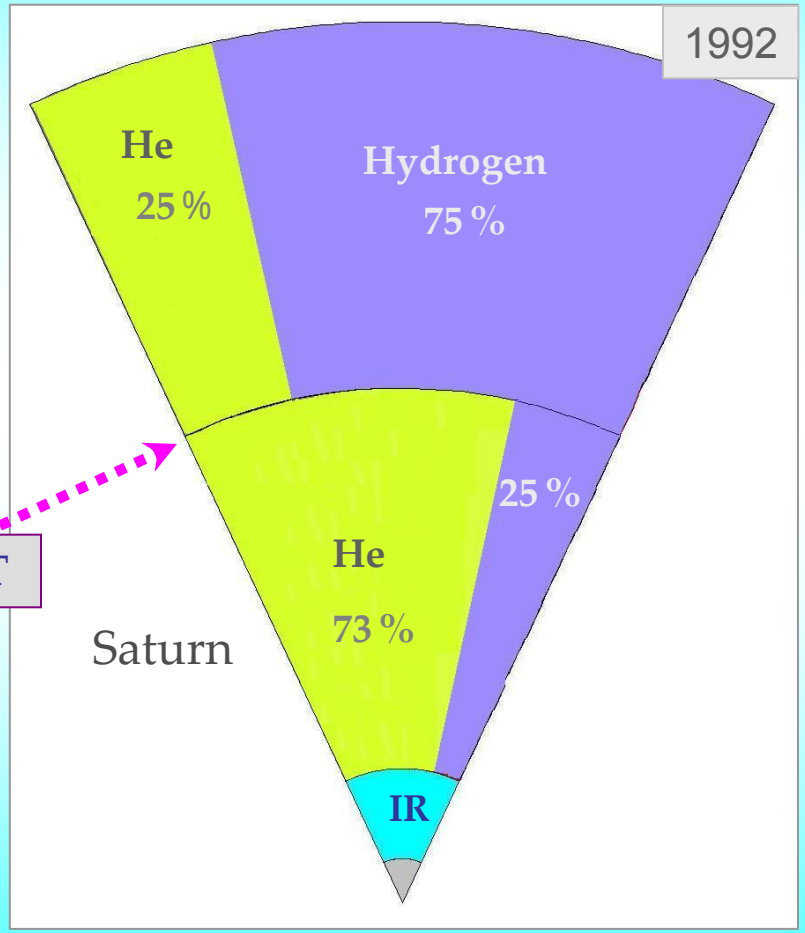
Saturn interior composition



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*)



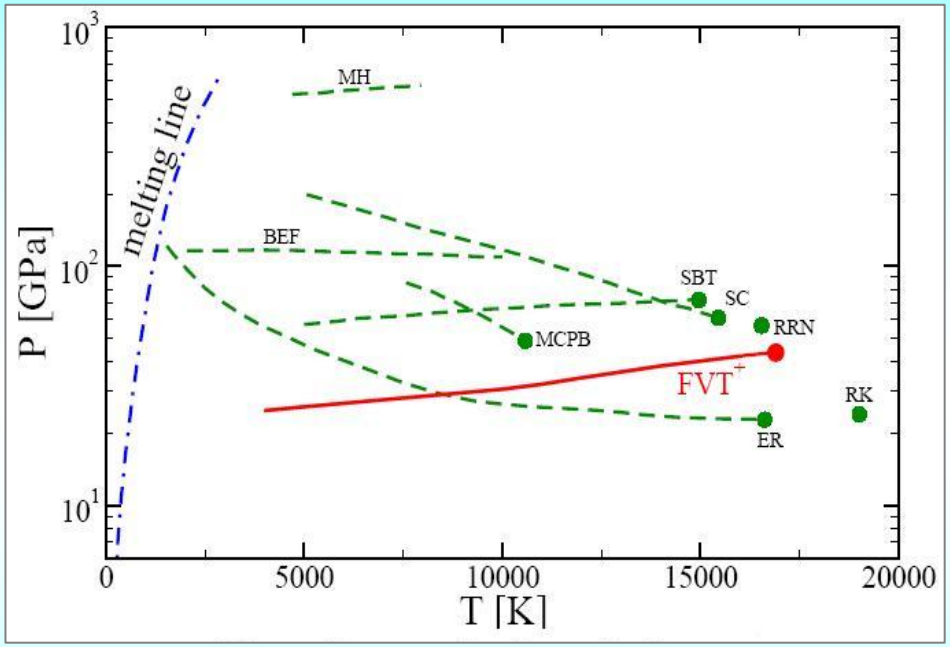
1st order PPT

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

Предсказания плазменных фазовых переходов

Модельные подходы (1970 – 2007)

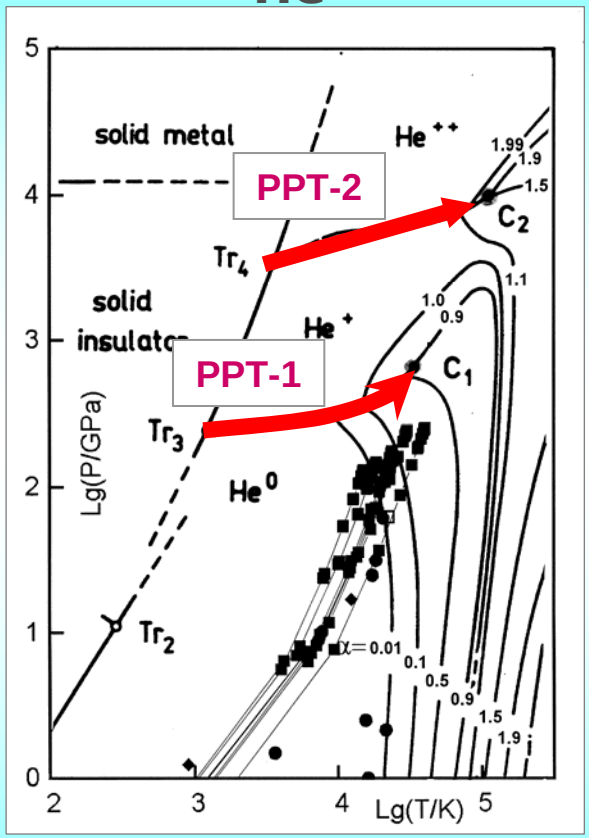
H



Варианты границ плазменного фазового перехода в водороде
(модельные подходы 1970 - 2007)

Holst B., Nettelmann N., Redmer R.,
Contrib. Plasma Phys. **47**, (**2007**)

He



Два раздельных плазменных перехода в гелии
(на 1й и 2й ионизации)

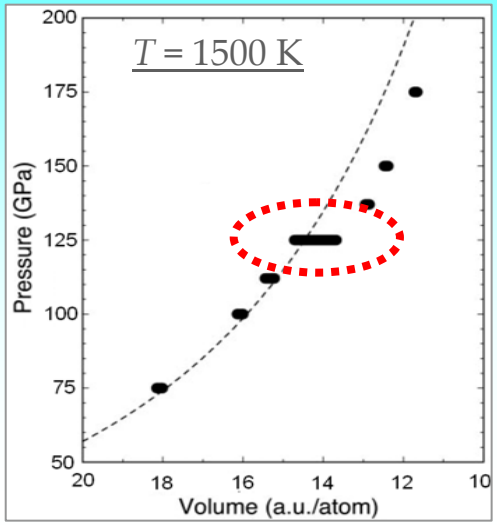
Ebeling, Foerster *et al.* (1991)

Ландау Л.Д. Зельдович Я.Б. *ЖЭТФ* **14** 32 (1944)

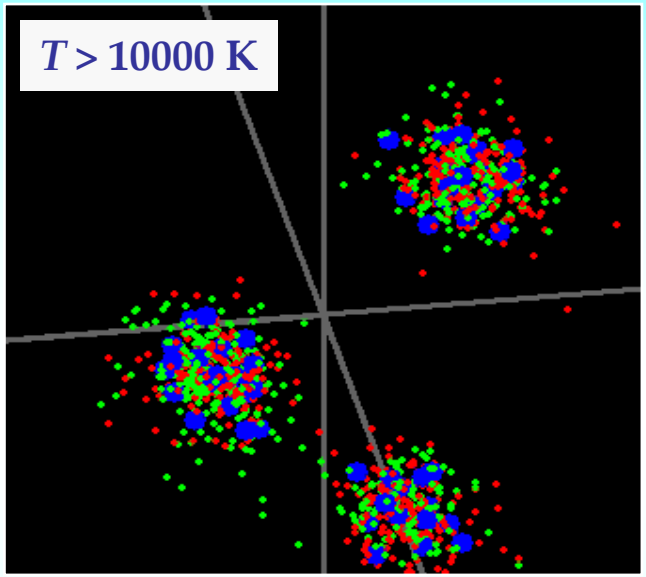
Норман Г.Э., Старостин А.Н. *ТВТ* (1968 - 1970)

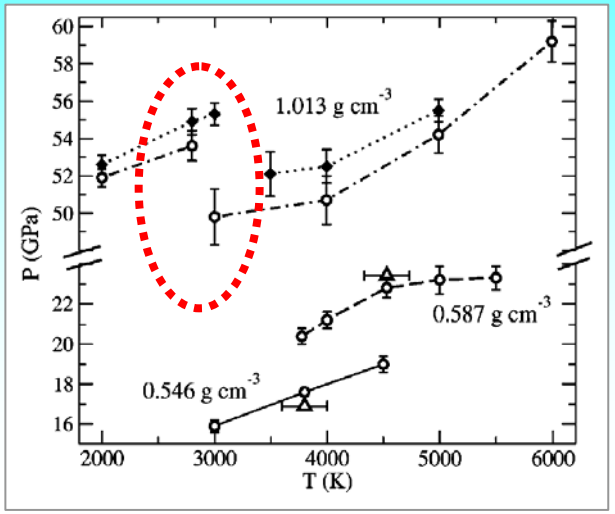
Фазовый переход в плазме водорода уверенно предсказывается различными вариантами первопринципных подходов

Quantum Numerical Simulations

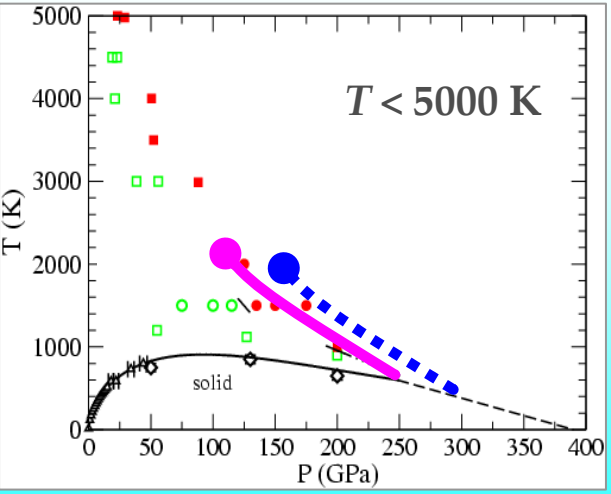


DFT + MD / Scandolo (2003)





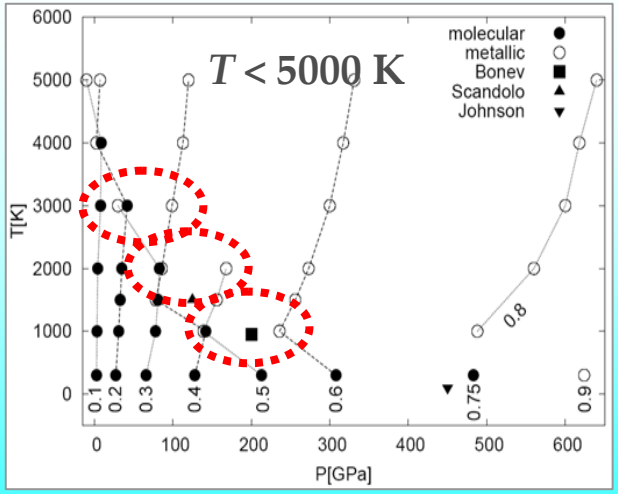
DFT + MD / Bonev, Militzer, Galli (2004)



DFT + MD / Bonev, Militzer, Galli.

Phase Transition in Hydrogen Plasma
V.Filinov, V.Fortov, M.Bonits, P.Levashov
Письма ЖЭТФ **74** (2001)
Phys. Lett. **A 274** (2000)
= «» =
Path Integral Monte-Carlo

DFT + MD / Morales M. *et al.* (**2010**)/
Lorenzen W. *et al. PRB* (**2010**)



Wave-Packets + MD
Erlangen University, ***Phys.Rev.E*** (**2007**)

Theoretical predictions of "dissociative" fluid-fluid phase transition in liquid hydrogen

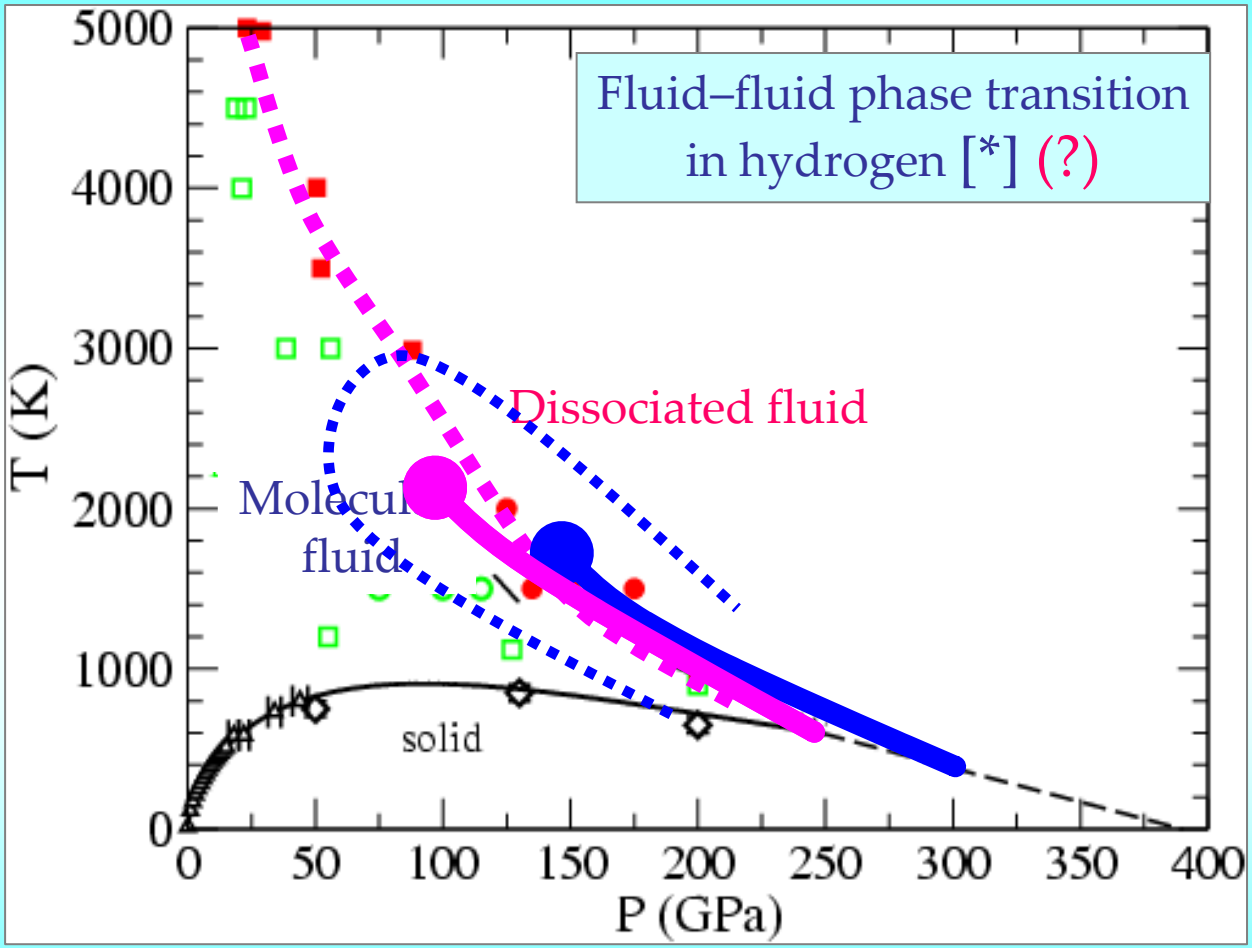


Figure from:
Giulia Galli,
SCCS-2005,
Moscow

Morales *et al*, 2010

Lorenzen *et al*, 2010

H + He

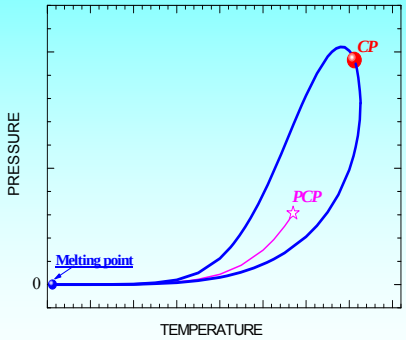
DFT/MD: Scandolo S. *PNAS* **100**, (2003) // Bonev S., Militzer B., Galli G. *PRB* **69** (2004)
WPMD : Jakob B. *et al. PRE* (2007) // **DFT/MD**: Morales M. *et al. PNAS* **107**, (2010)/
DFT/MD: Lorenzen W. *et al. PRB* (2010)

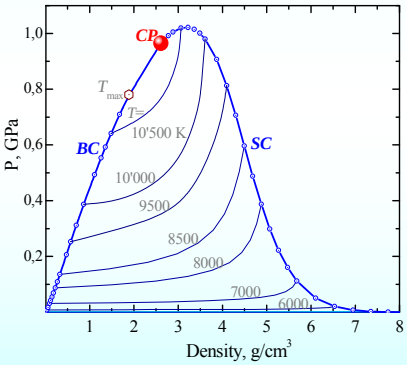
Hypothetical non-congruent phase transitions

(***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*** *and* ***Dissociative Phase Transitions*** *in mixtures:* 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.*)

The question is:

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

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

Natural and artificial bombarding of lunar surface

Launch – April 24, 2009
Impact velocity ~ 9'000 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

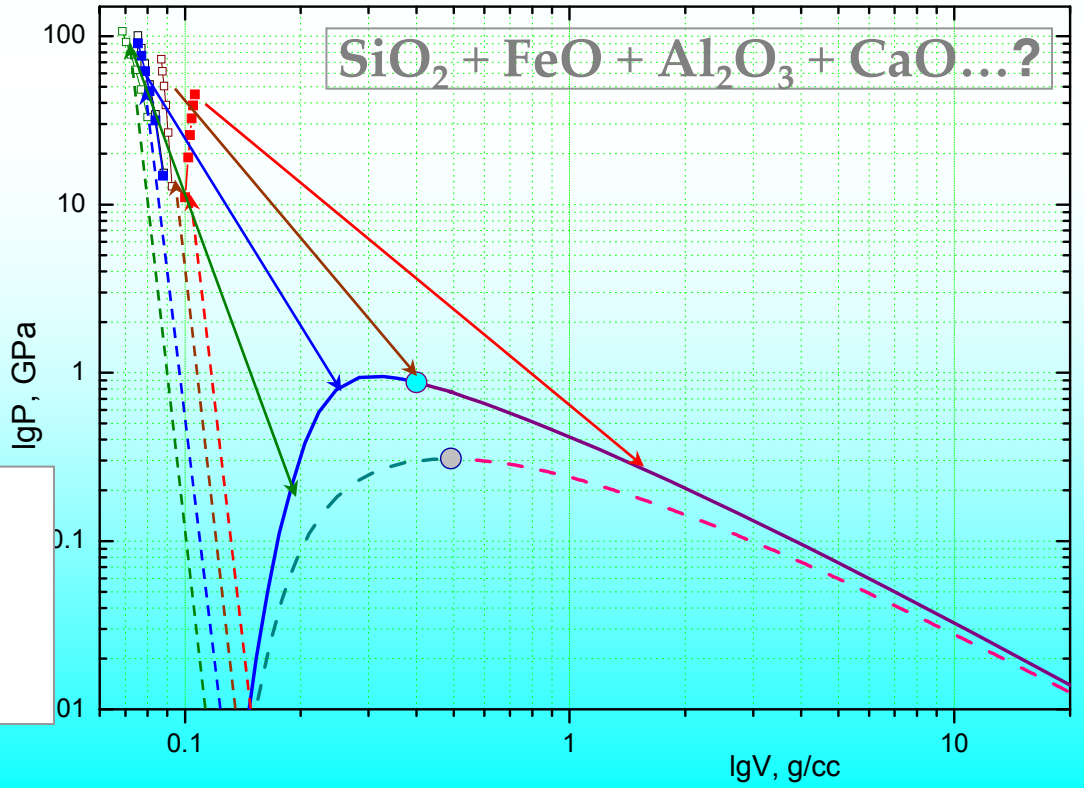
The question is open

NB !

Any phase transition in such mixture must be *non-congruent*

1st Stage – strong shock compression

2nd Stage – free quasi-isentropic expansion



, 2009 // Impact – 9 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

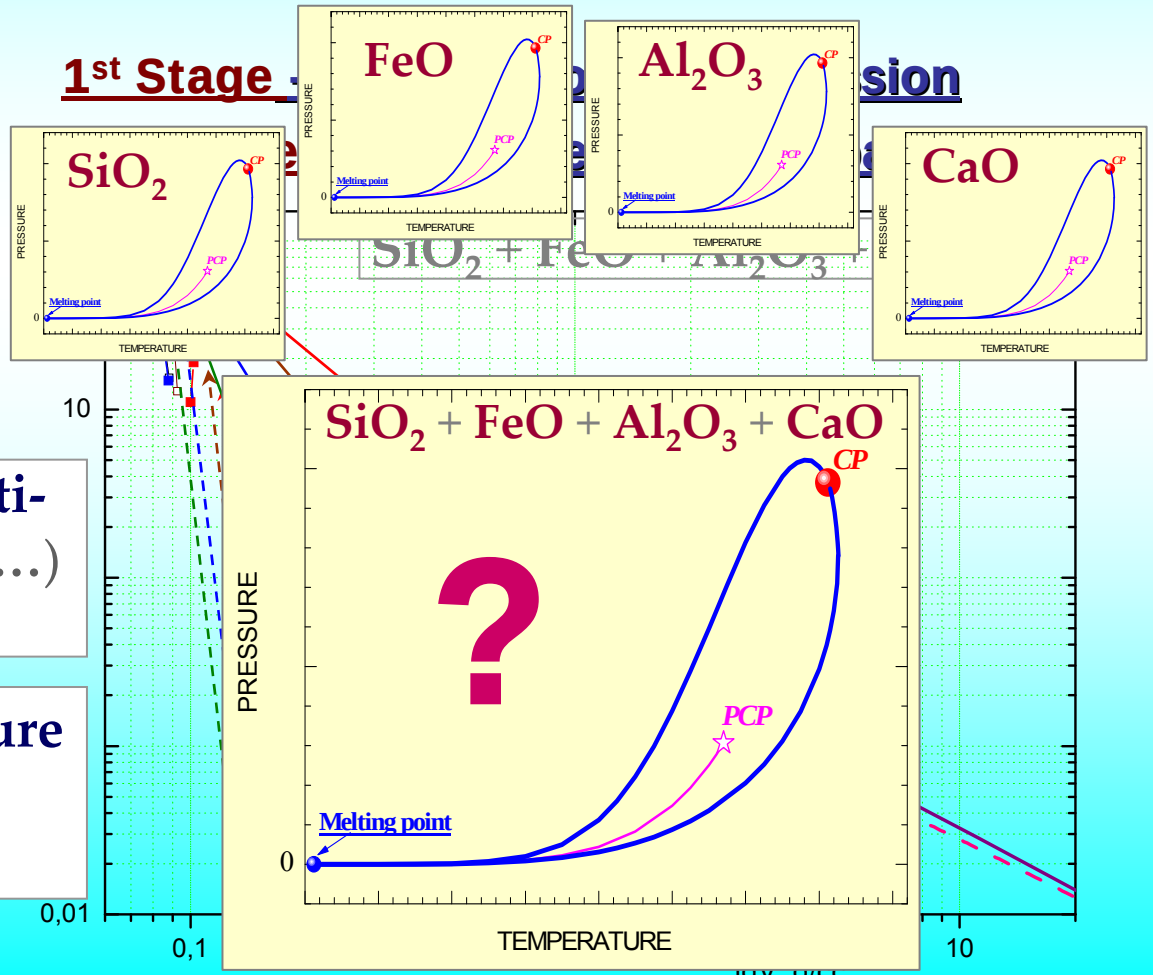
The question is open

NB !

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

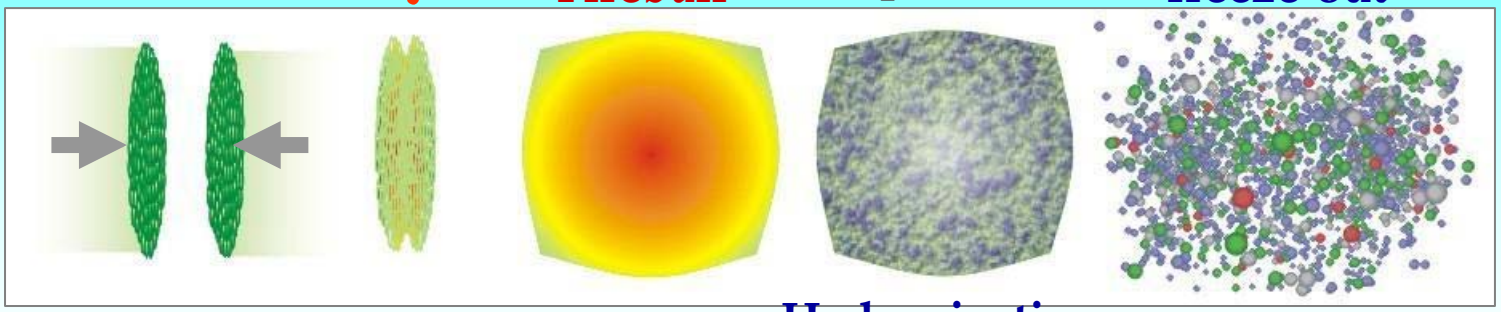
Phase transitions in the mixture must be *non-congruent* moreover !

1st Stage ... sion

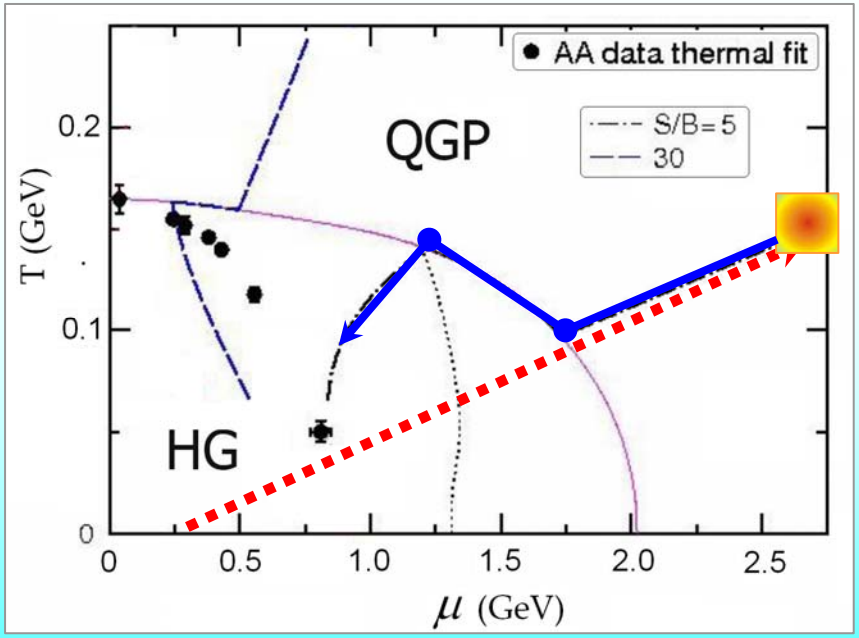


Impact *and* fireball hydrodynamics *in* HIC

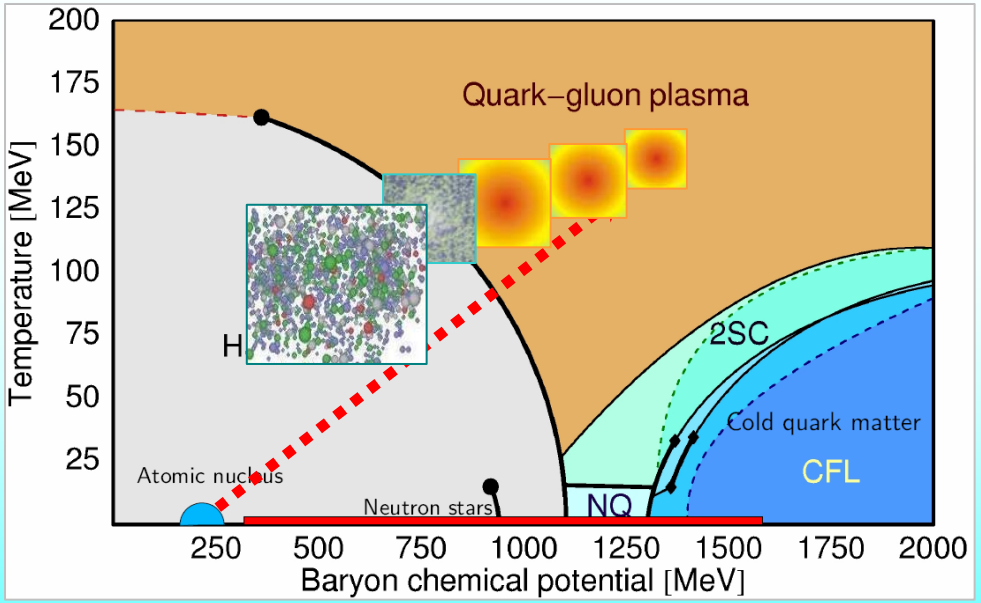
Au + Au * **Thermalized Fireball** **Expansion** **Chemical & kinetic freeze-out**



Hadronization



L.Satarov, M.Dmitriev, I.Mishustin //arXiv: 0901.1430v1



After David Blaschke, WEHS Seminar, Bad Honnef, 2007

Hypothetical non-congruent phase transitions
(*short list*)

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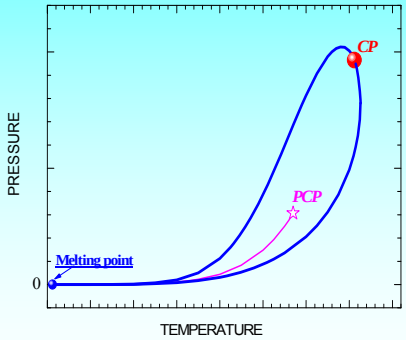
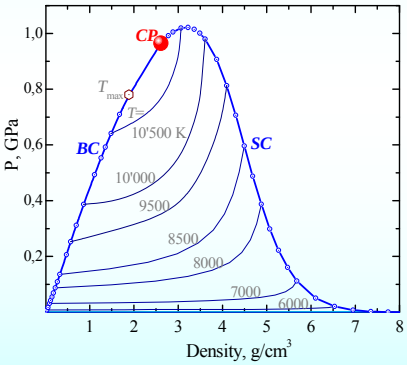
- ***"Dusty"*** *and* ***Colloid plasmas***:
  (*Coulomb system of macro-ions +Z and micro-ions: +1, –1*)





Non-Congruence in Cosmic Matter:

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- ***Phase Transitions*** *in* ***White Dwarfs,***
- ***Phase Transitions*** *in* ***Neutron Stars,***
- ***Phase Transitions*** *in* ***"Strange" Stars*** (*quark-hadron transition … ets.*)

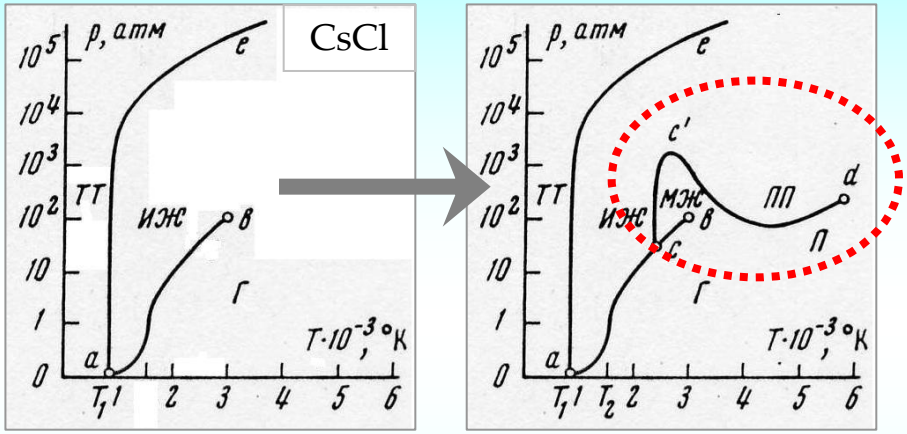
Non-congruence *of* hypothetical "plasma phase transition" *in* molten salts

Zeigarnik V, Kobzev G., Kurilenkov Yu., Norman G. *High Temp.* 10 (1972)

Ordinary phase transitions

\+ Plasma phase transition

P



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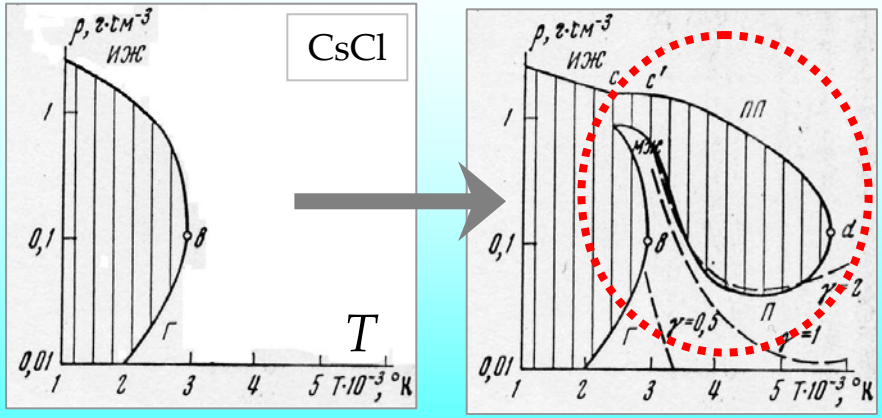
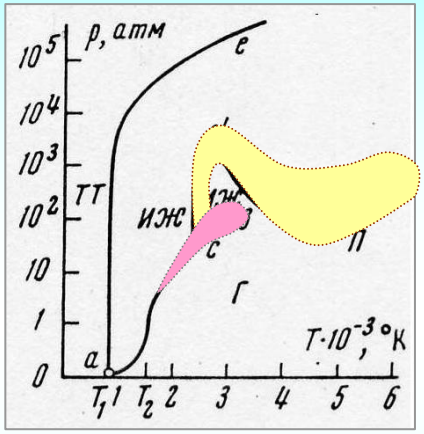


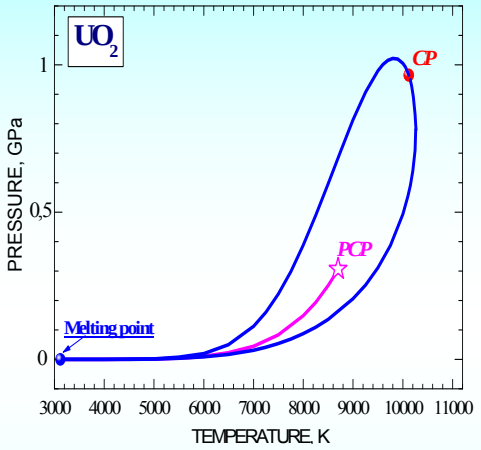
Рис. 1. Диаграмма состояния P — T для CsCl

a, b, c, d — тройные и критические точки; однородные фазы: ТТ — твердое тело; Г — газ, ИЖ — ионная жидкость; МЖ — молекулярная жидкость; П — плазма, ПП — плотная плазма. T_1 — температура плавления;

Basic conclusion:

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





The ordinary gas-liquid phase transition in CsCl must be **non-congruent** –

Hypothetical "plasma phase transition" in CsCl must be **non-congruent** even more -

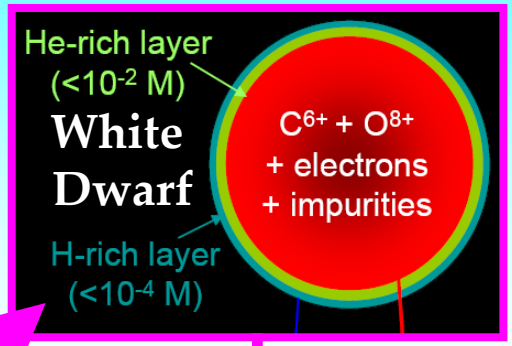
Non-congruence in exotic situations

(*discussion*)

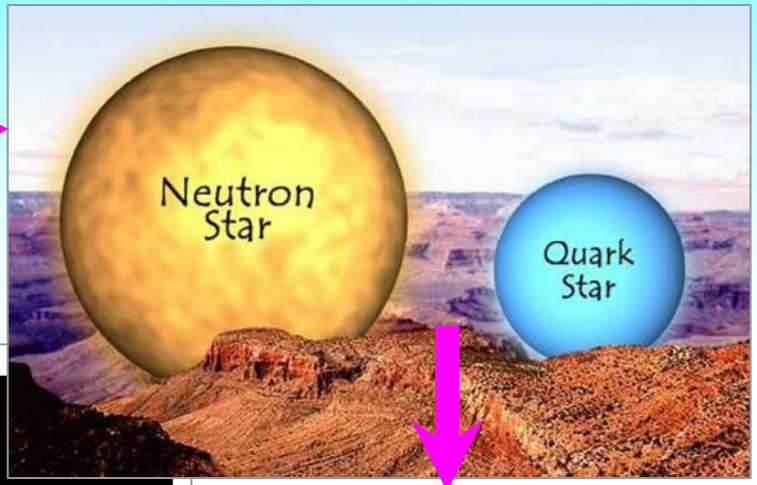
Non-congruence *in* compact stars *and* supernova explosions

Compact stars

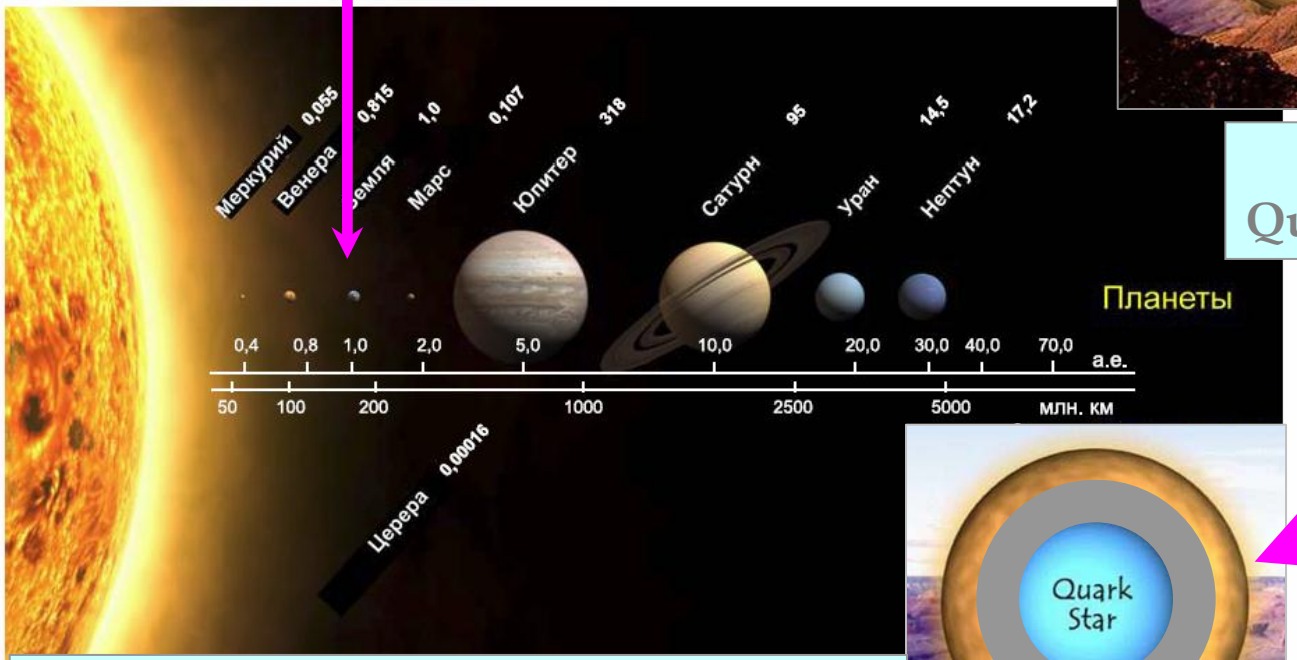
White dwarfs, *Neutron stars*, *"Strange" (quark) stars*, *Hybrid stars*



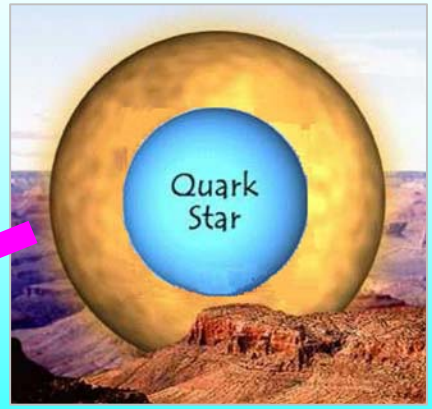
Neutron *and* "Strange" Stars



Hybrid Stars
Quark core + Hadron crust



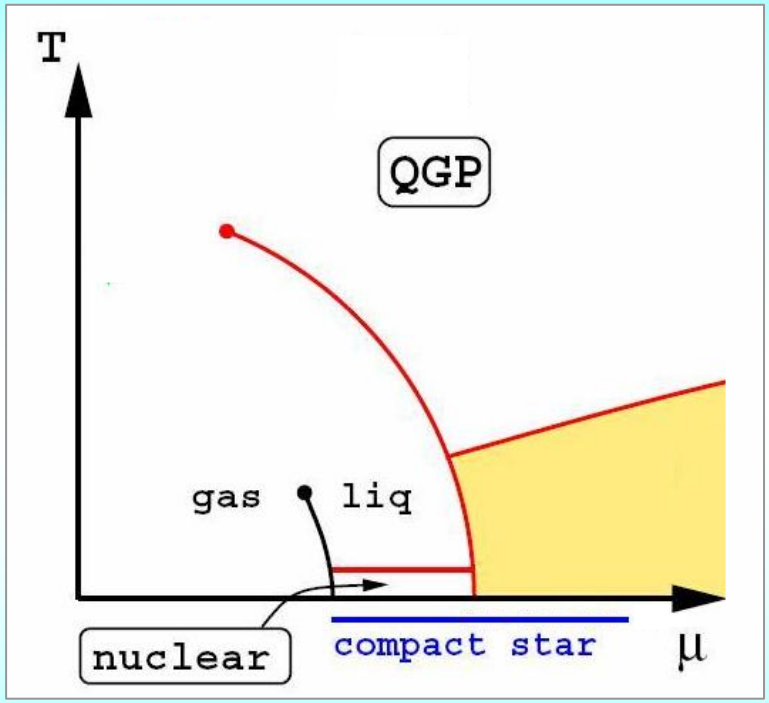
Hybrid Stars - II
Quark core + Hadron crust + **Mixed phase**



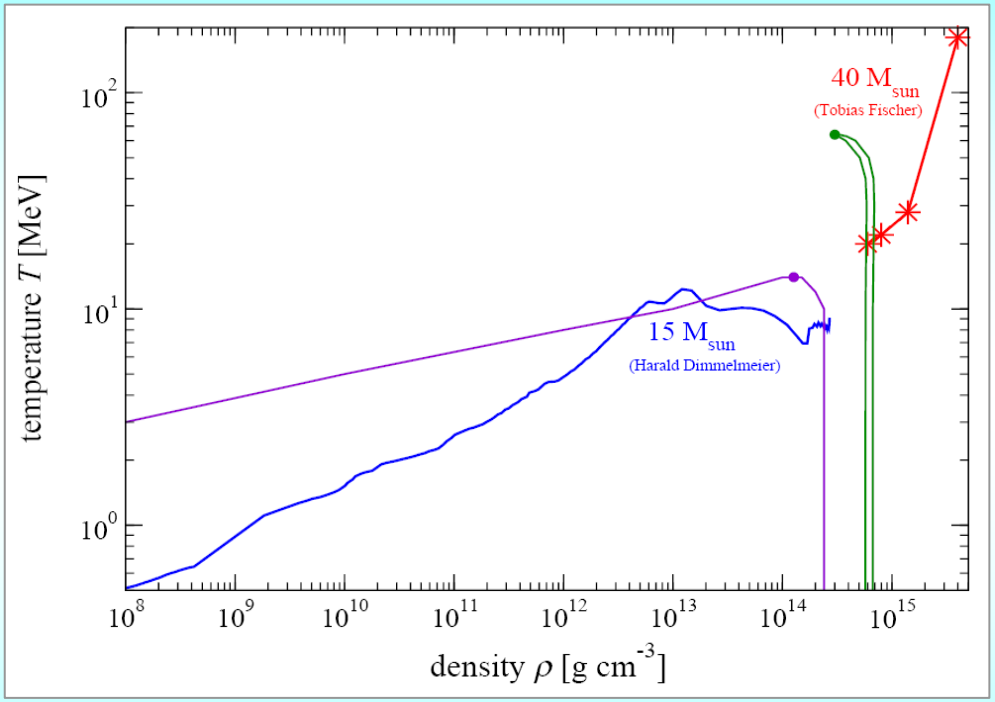
$|\leftarrow R \sim 10\ \text{km} \rightarrow|$

Hypothetical non-congruence in compact stars and supernova explosions

Phase Diagram



Supernova Collapse in the Phase Diagram



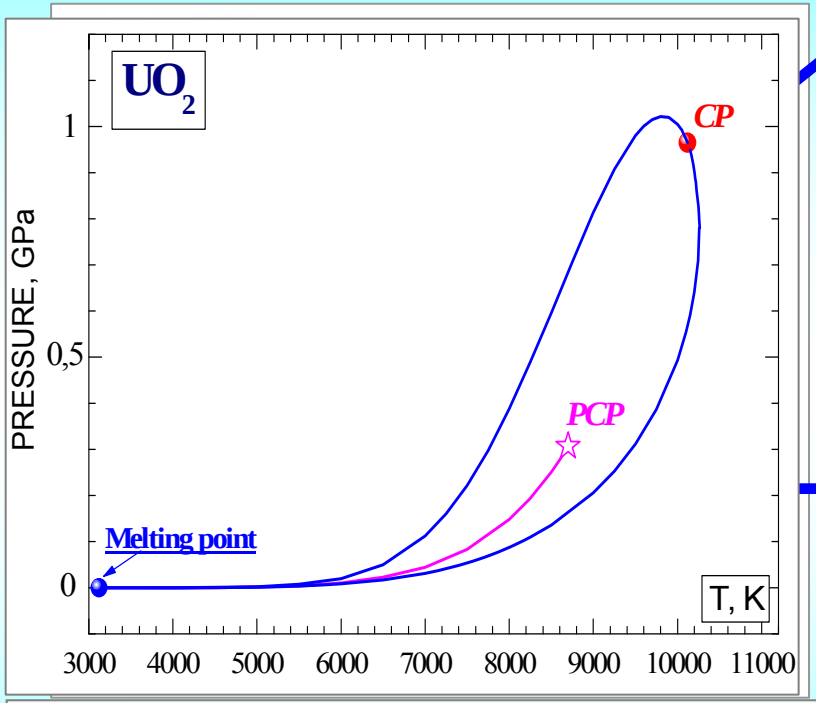
(*after D.Blaschke, "Extreme Matter", Elbrus-2010*)

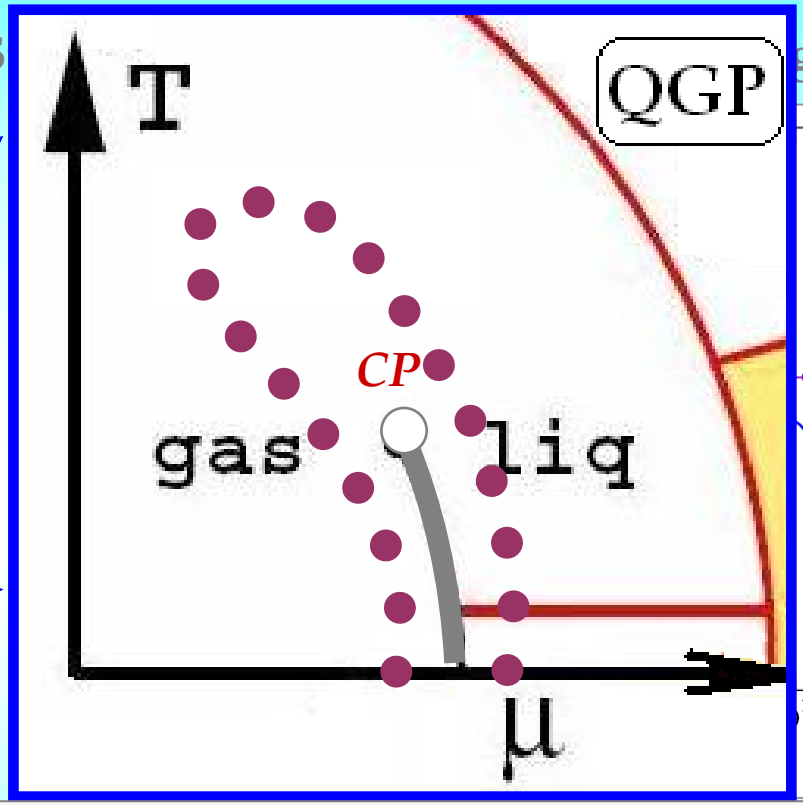
- "Gas-Liquid" phase transitions
- Quark-Hadron phase transitions

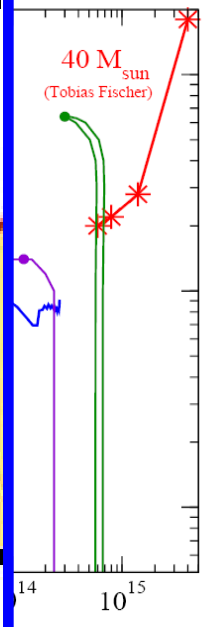
(*discussion*)

Hypothetical non-congruence in compact stars and supernova explosions

Phase Diagram







"Gas-liquid" PT *in* "low-density" nuclear matter

Ensemble: $p + n + N(A,Z)$

Equilibrium: $N(A,Z) = Zp + (A - Z)n$

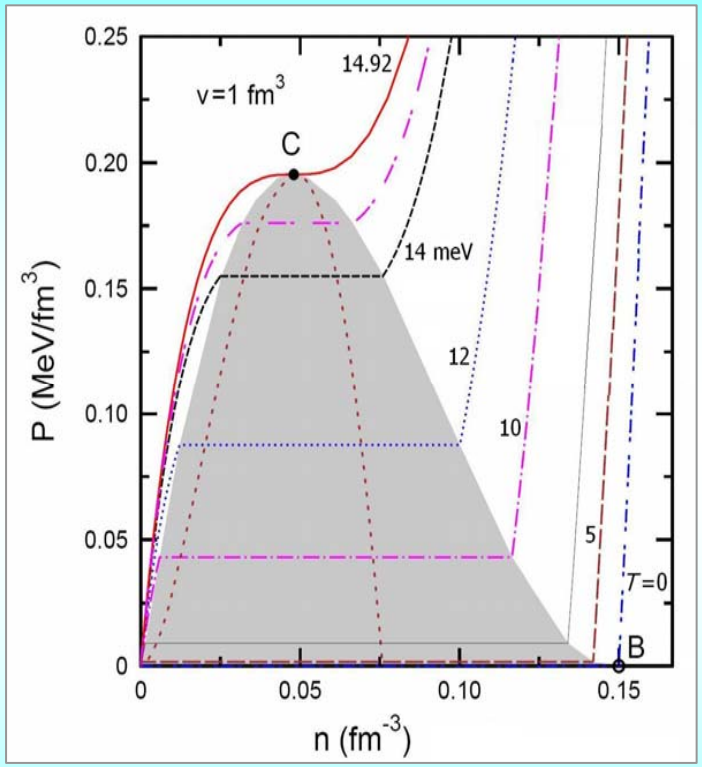
No electrons
No Coulomb effects

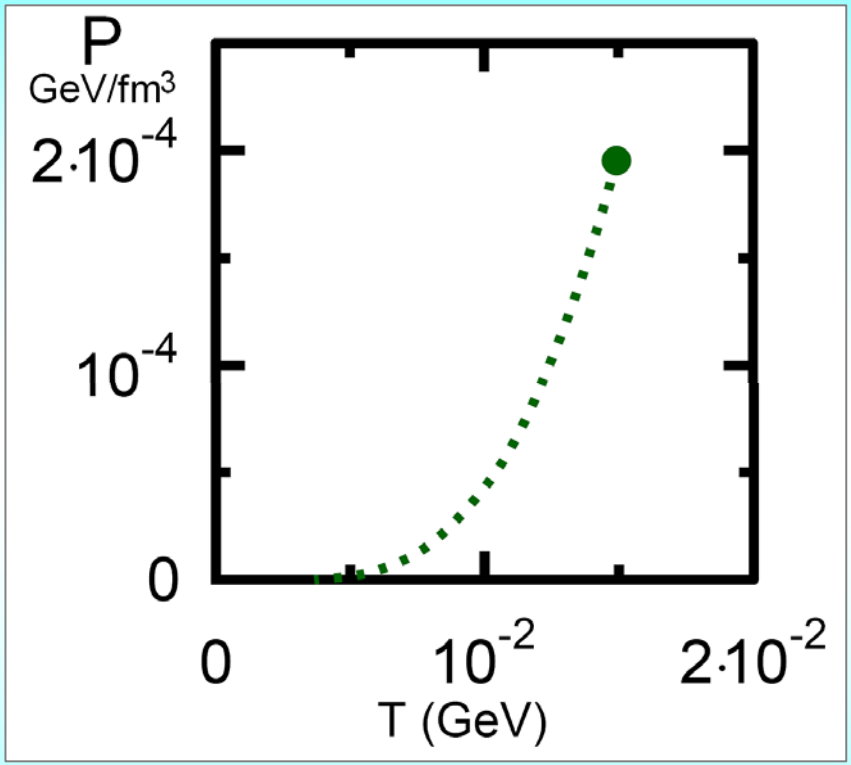
2-dimensional system $\{p+n\}$ → **Non-congruent PT**

(*discussion*)

“Gas-liquid” PT *in* “low-density” nuclear matter

Phase diagram of symmetric *p-n-N(A,Z)* nuclear matter





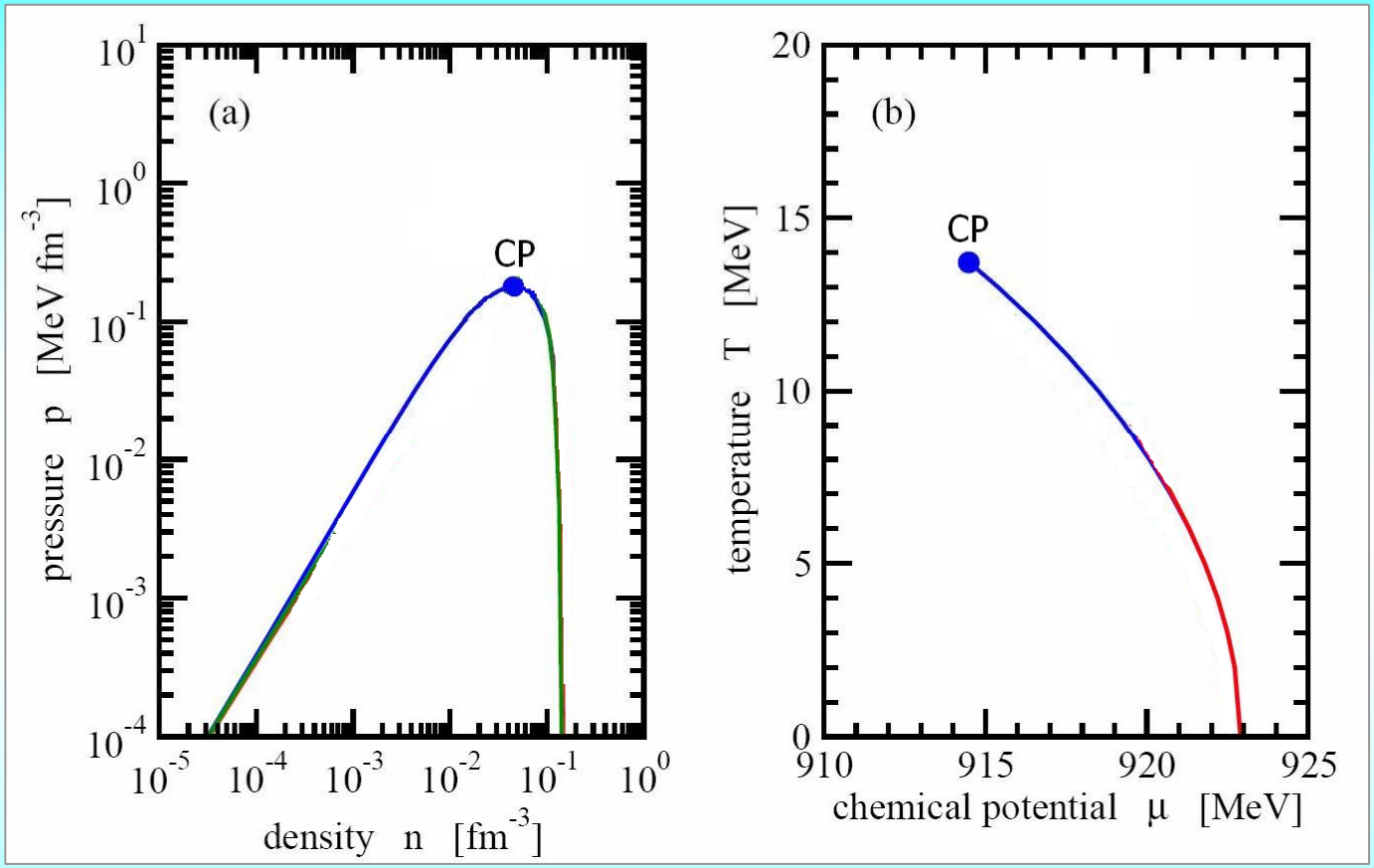
Satarov L., Dmitriev M., Mishustin I.
Phys. At. Nucl. (2009)

Evident contradiction

Calculated phase transitions are of ordinary VdW type (congruent) **!**

“Gas-liquid” PT *in* “low-density” nuclear matter

(*discussion*)



S. Typel, G. Roepke, D. Blaschke *et al. Phys. Rev. C,* **81** (2010)

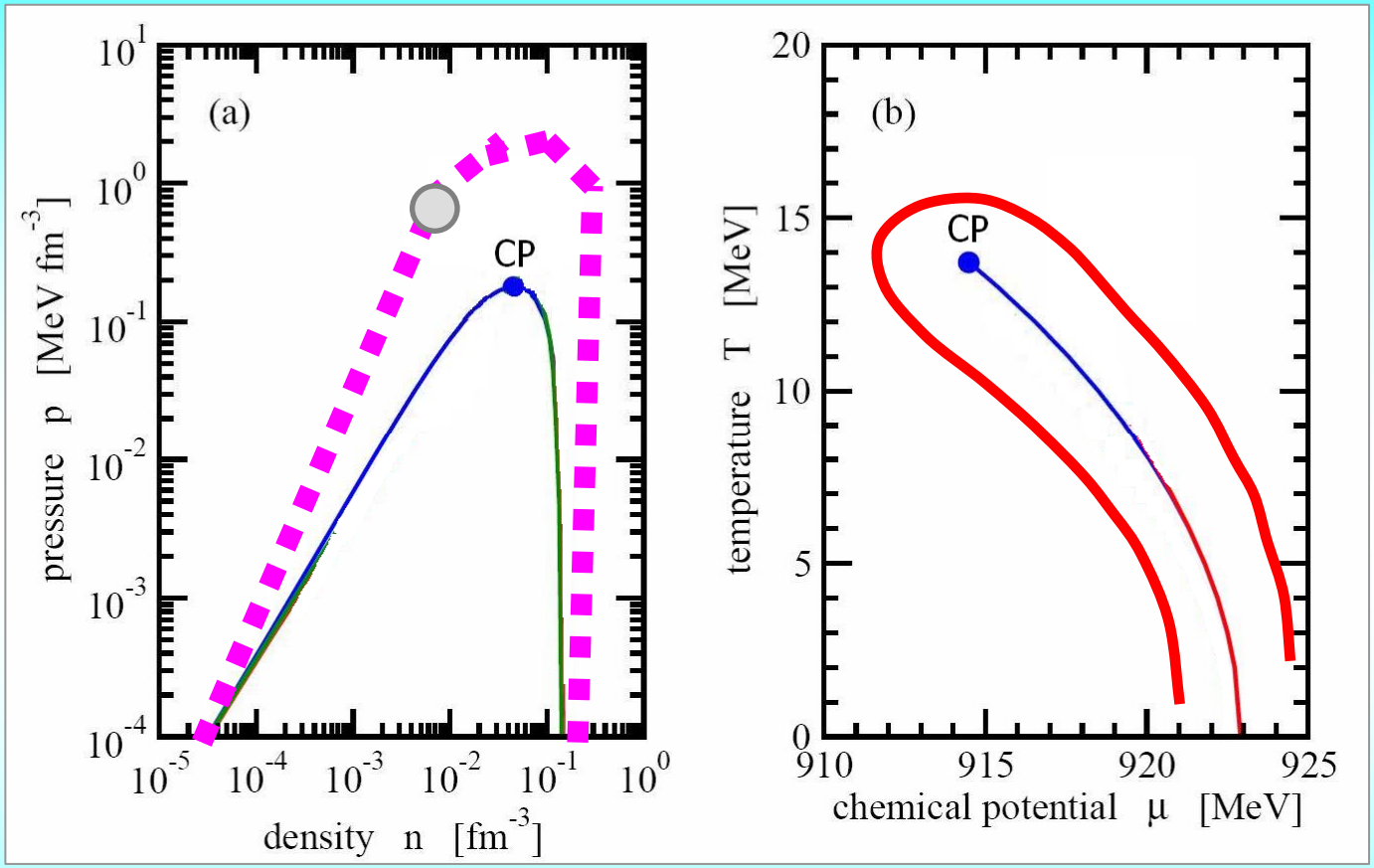
Evident contradiction

Calculated phase transitions are of ordinary VdW type (congruent) **!**

“Gas-liquid” PT *in* “low-density” nuclear matter

(*discussion*)

?



S. Typel, G. Roepke, D. Blaschke *et al. Phys. Rev. C,* **81** (2010)

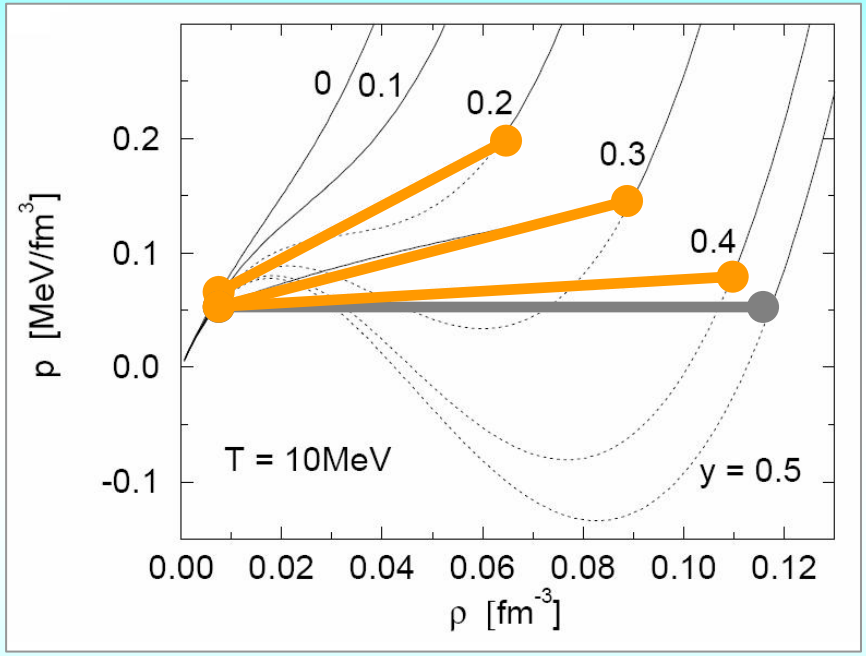
Phase transition in **symmetric** *p-n-N(A,Z)* nuclear matter is **congruent**

Aseotropic composition

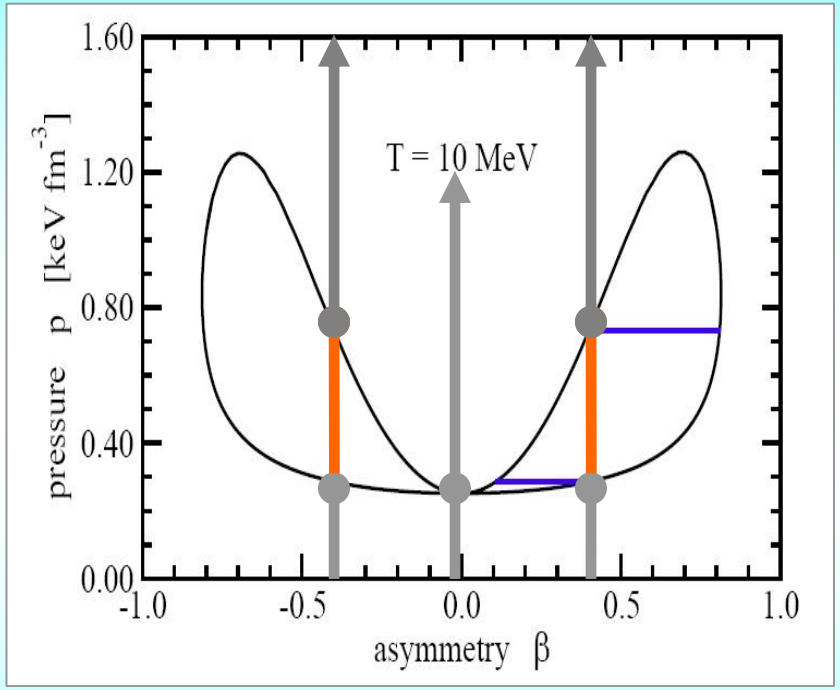
“Gas-liquid” PT *in* “low-density” nuclear matter

(*discussion*)

Phase transition in **non-symmetric** *p-n-N(A,Z)* nuclear matter is **non-congruent !**



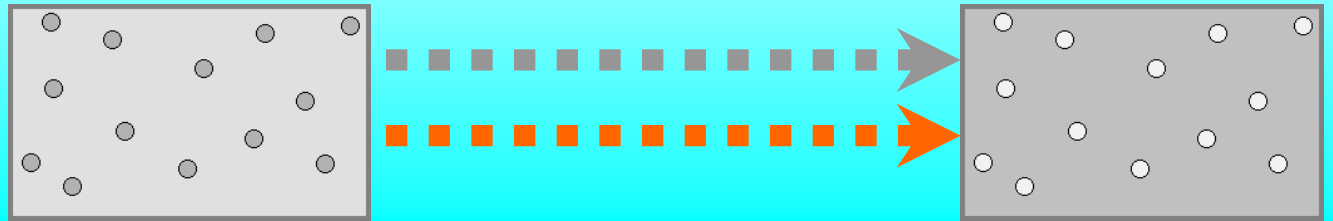
Muller H., Serot B., *Phys. Rev. C* **52** (1995)
nucl-th/9505013



(*after* ***S. Typel,*** *HIC for FAIR, Prerow-****2009***)

“Dew” point

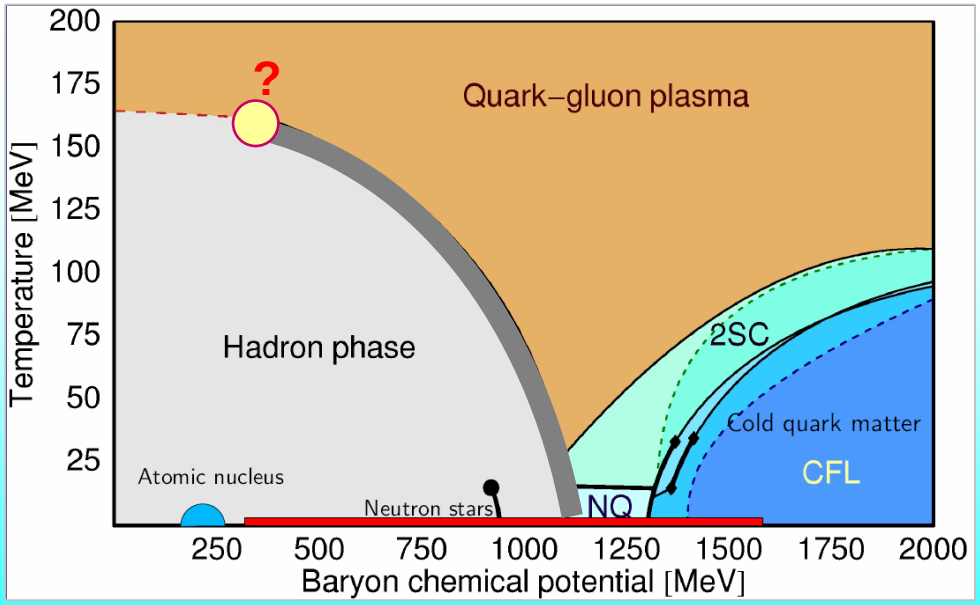
“Bubble” point



Non-congruence *in* compact stars

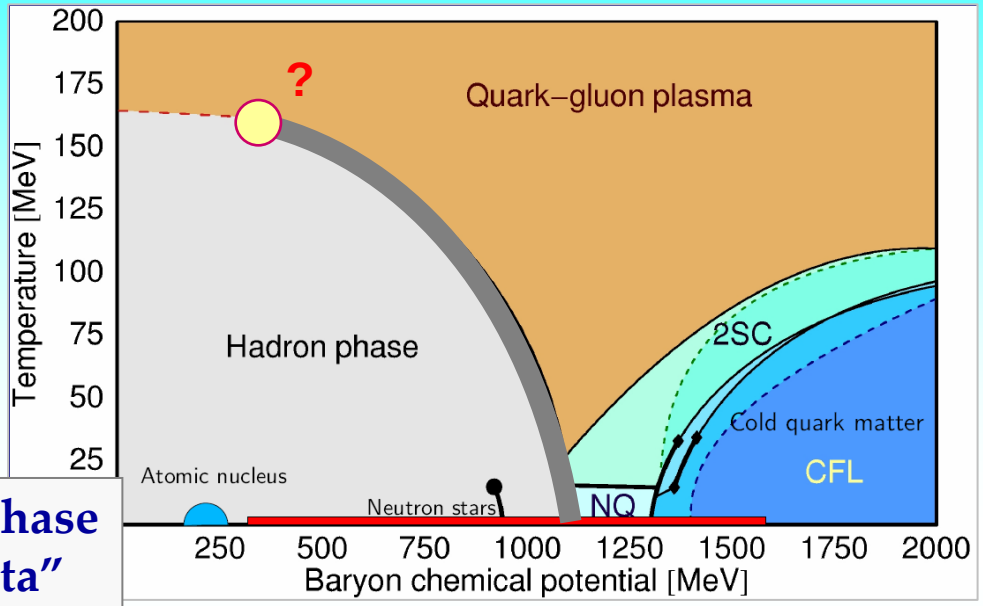
(*discussion*)

Quark-hadron phase transition



Hypothetical quark-hadron phase transition

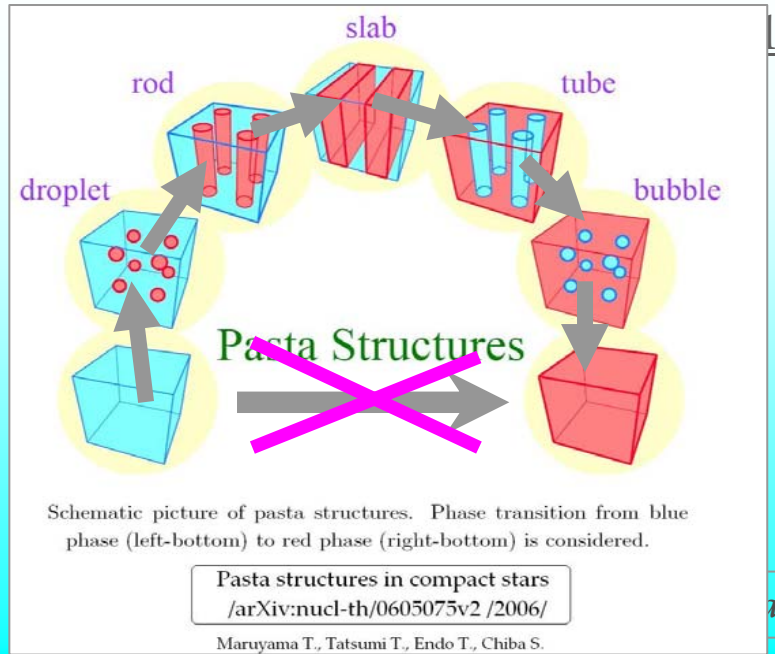
is it CONGRUENT *or* NON-CONGRUENT ?



Sequence of five
(or more ?)
mini-phase transitions !

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

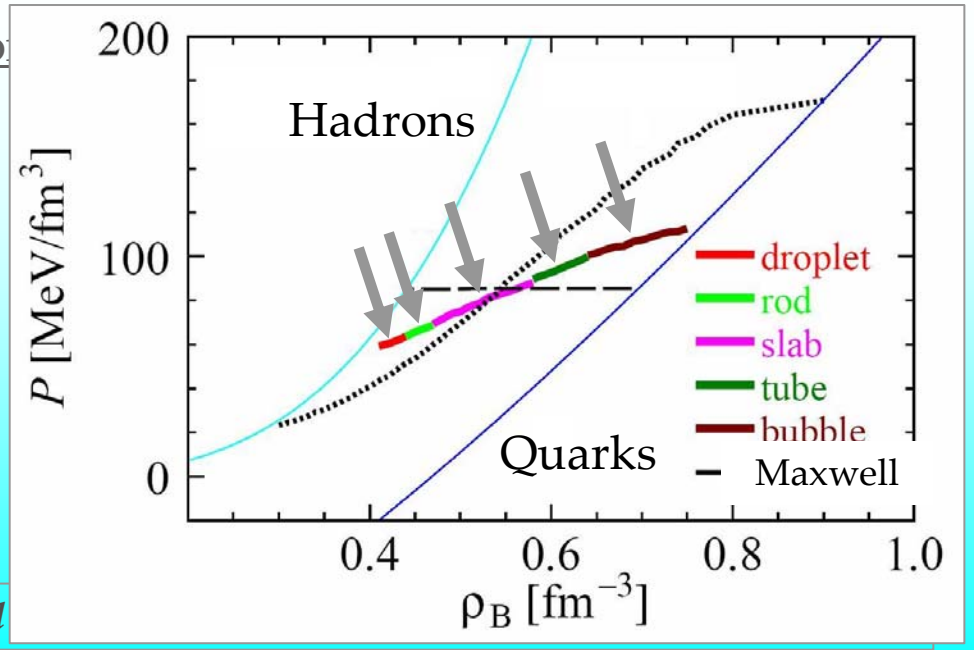
Structured Mixed Phase
Concept ⇔ "Pasta"



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

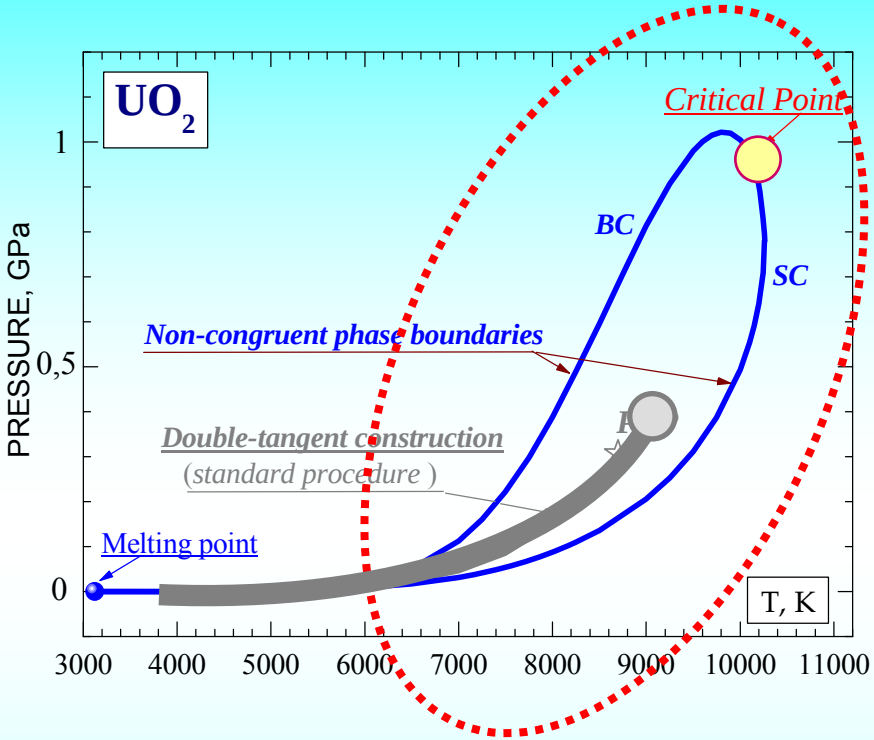
Pasta structures in compact stars
/arXiv:nucl-th/0605075v2 /2006/

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

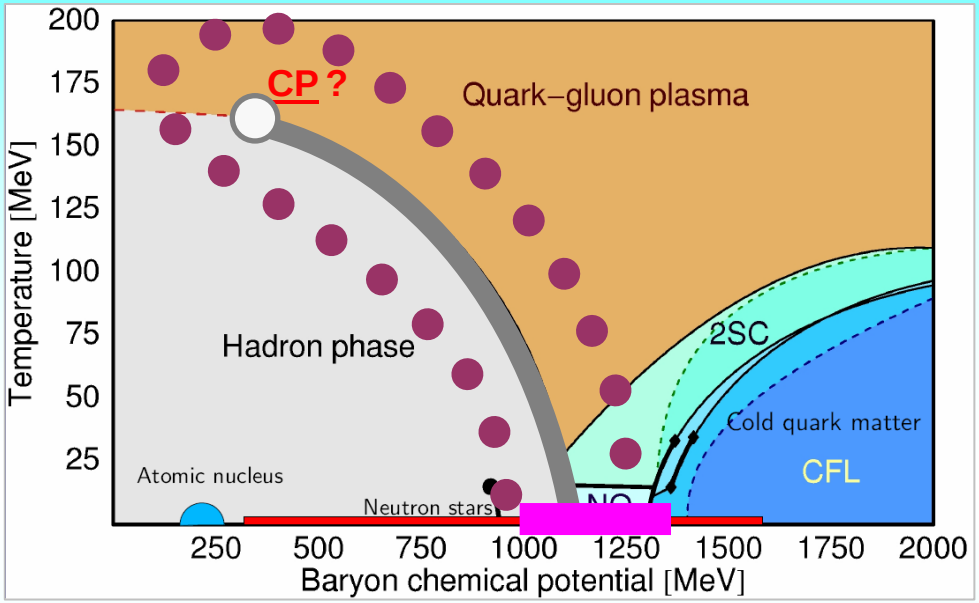


Hypothetical phase transitions in ultra-dense matter:

are they CONGRUENT or NON-CONGRUENT ?



Phase diagram of quark-hadron matter



?

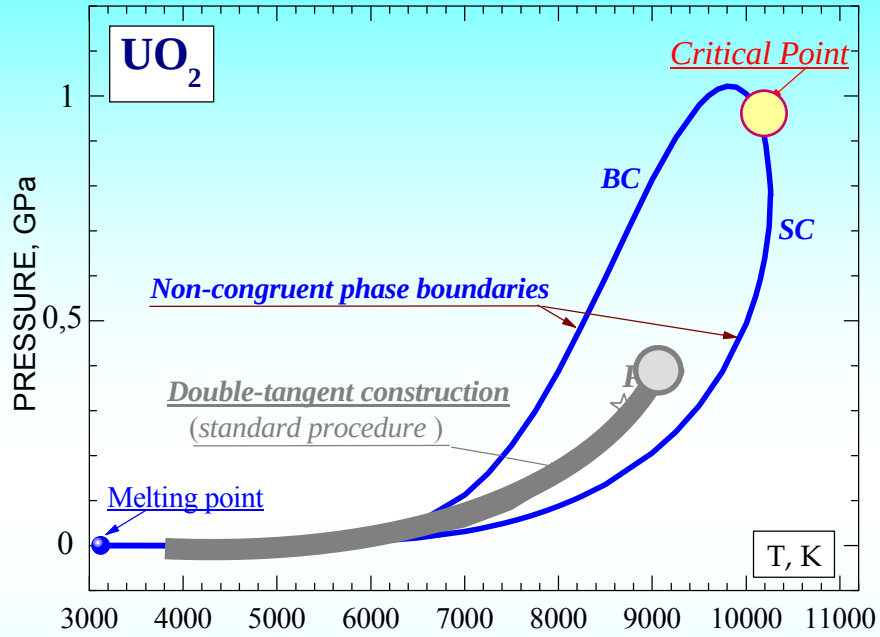
- Forced-congruent phase transition

- Non-congruent phase transition

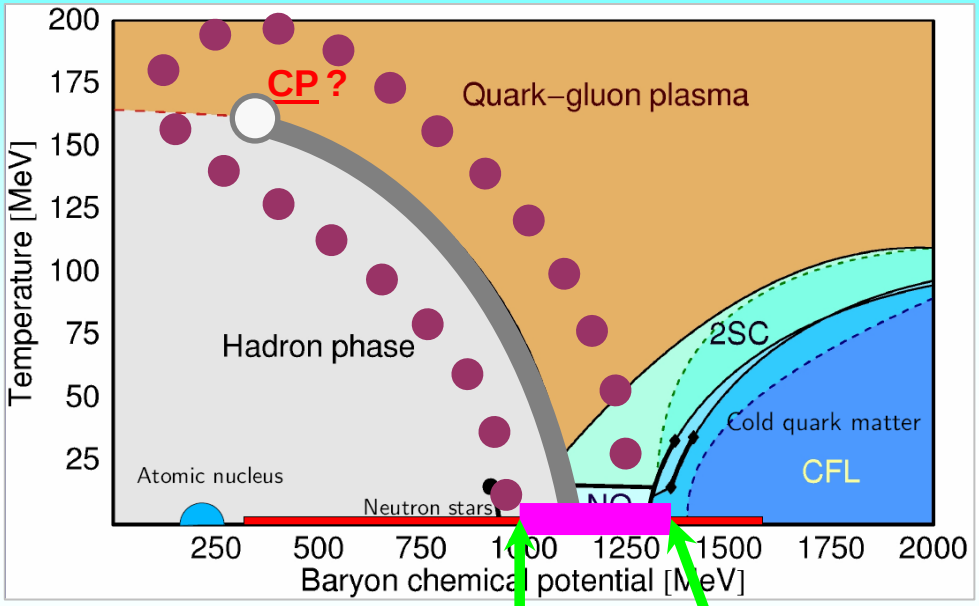
I.Iosilevskiy: "*Physics of Neutron Stars*", St.-Pb. Russia, 2008 // EMMI-Workshop_Max Born Symposium, Wroclaw, 2009 // arXiv:1005.4192

Hypothetical phase transitions in ultra-dense matter:

are they CONGRUENT or NON-CONGRUENT ?

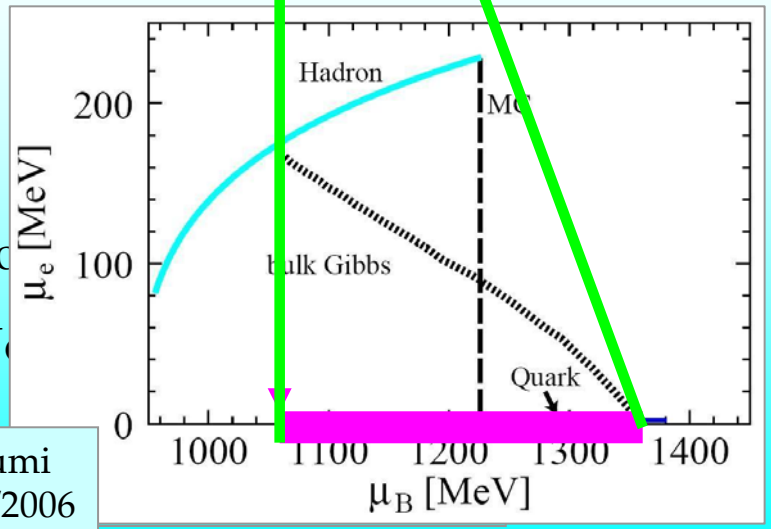


Phase diagram of quark-hadron matter



NB !

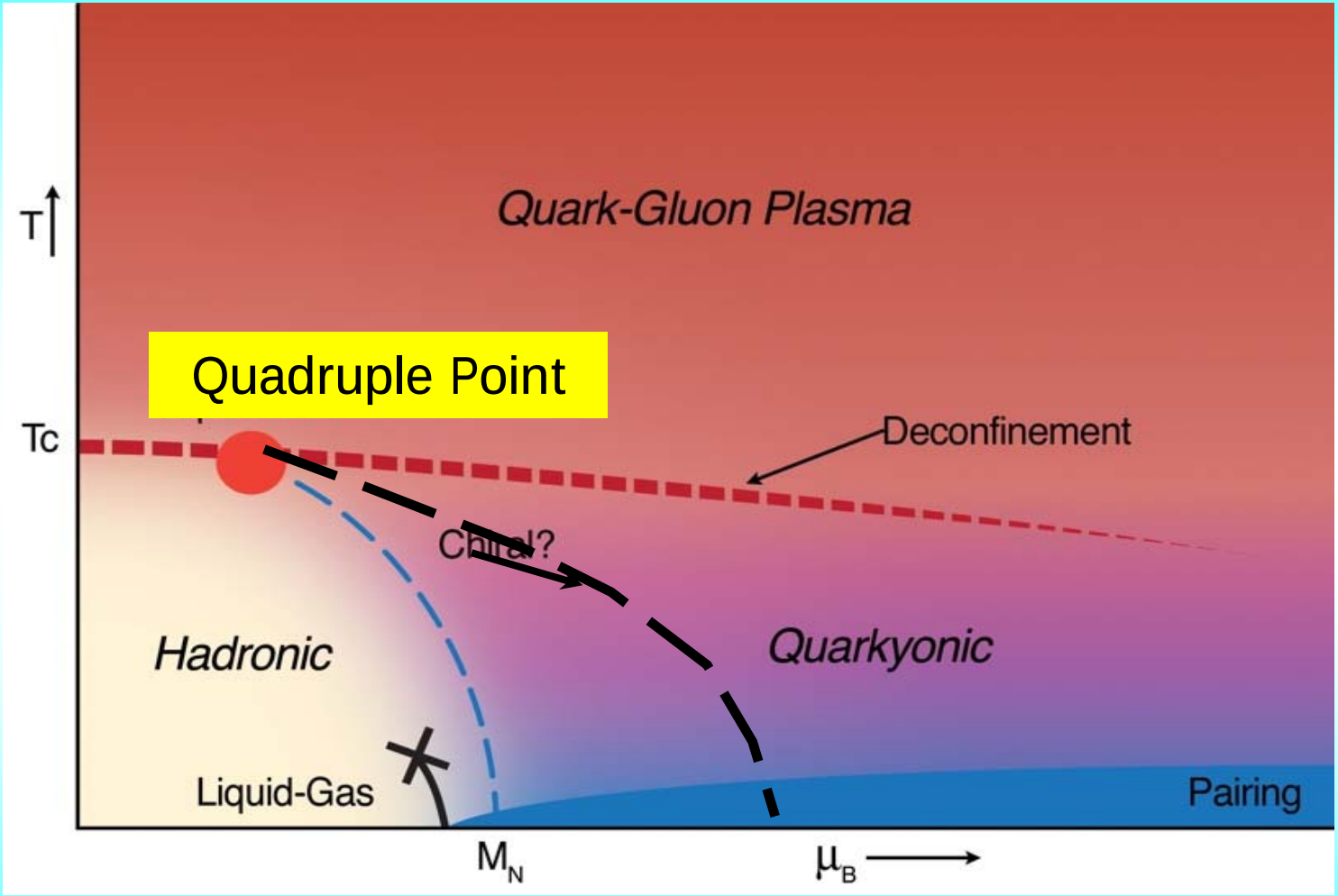
Supposed gap in chemical potential in **Non-Congruent** scenario for phase transition is in agreement with “mixed phase” calculations at $T = 0$!



T. Endo, T. Maruyama, S. Chiba, T. Tatsumi
(*mixed phase calculations* / arXiv:0601017v1/2006

Hypothetical phase transitions in ultra-dense matter:

are they CONGRUENT or NON-CONGRUENT ?

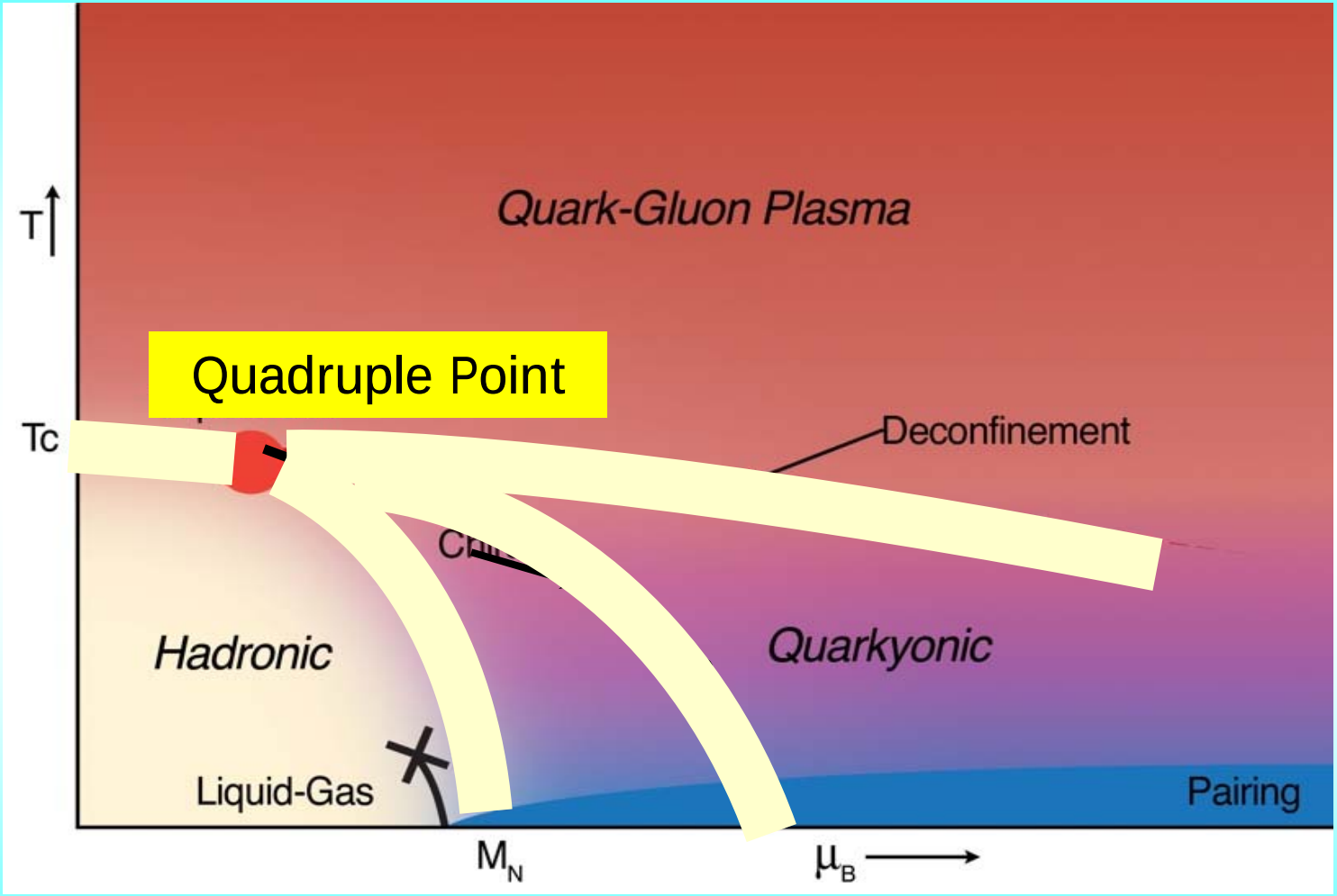


Hypothetical phase diagram with Triple or Quadruple Point

R. Pisarski & L. McLerran : EMMI-Wroclaw /2009/, QCD-Bad Honnef /2010/

Hypothetical phase transitions in ultra-dense matter:

are they CONGRUENT or **NON-CONGRUENT ?**



What is this – **Triple** and **Quadruple** points in **Non-Congruent** phase transition **?**

I.Iosilevskiy: EMMI-Wroclaw /2009/, QCD-Bad Honnef /2010/

Hypothetical phase transitions in ultra-dense matter

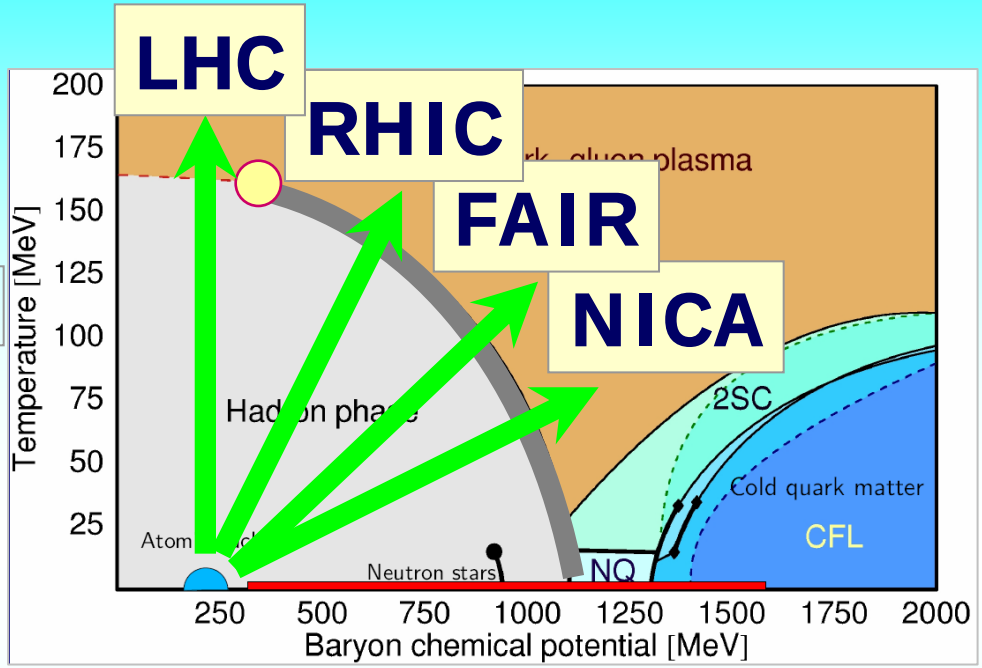
are they CONGRUENT or NON-CONGRUENT ?

LHC – CERN

RHIC – Brookhaven

FAIR – Darmstadt

NICA – Dubna

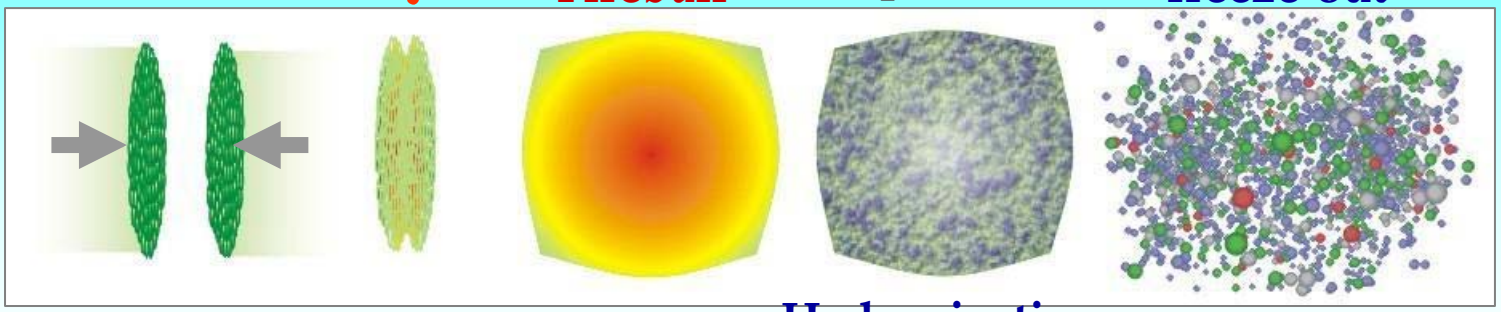


Quark-Hadron Phase Diagram

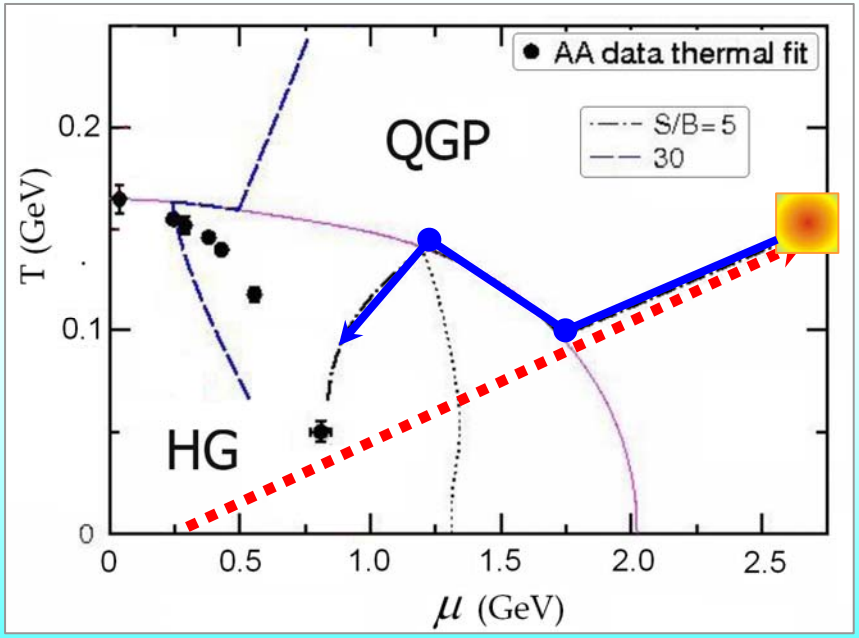
The problem of non-congruence for Quark-Hadron phase transition is relevant to physics of super-colliders !

Impact *and* fireball hydrodynamics *in* HIC

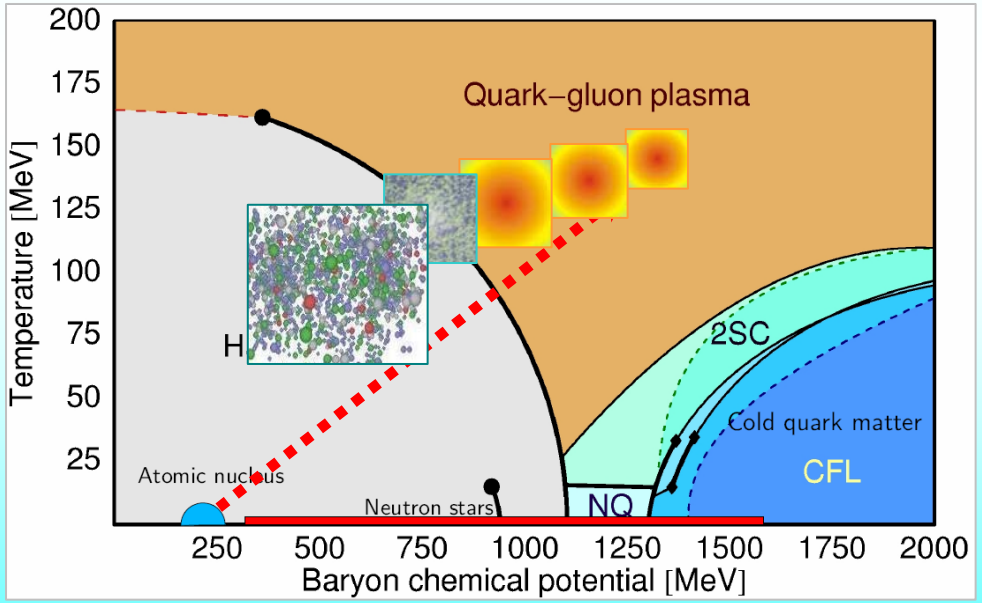
Au + Au * Thermalized Fireball Expansion Chemical & kinetic freeze-out



Hadronization



L.Satarov, M.Dmitriev, I.Mishustin //arXiv: 0901.1430v1



Isentropic expansion of "QGP-Fireball" (*schematic*) /Iosilevskiy: EMMI Workshop, Wroclaw, 2009/

Conclusions *and* Perspectives

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

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

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

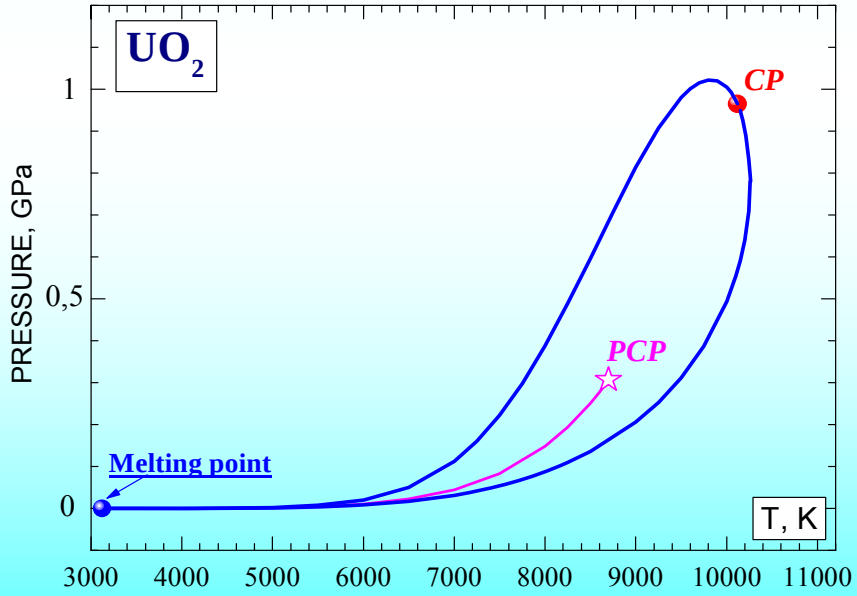
- It is **promising** to investigate non-congruent phase transitions **experimentally**. in particular with **intense laser** and **heavy ion** heating

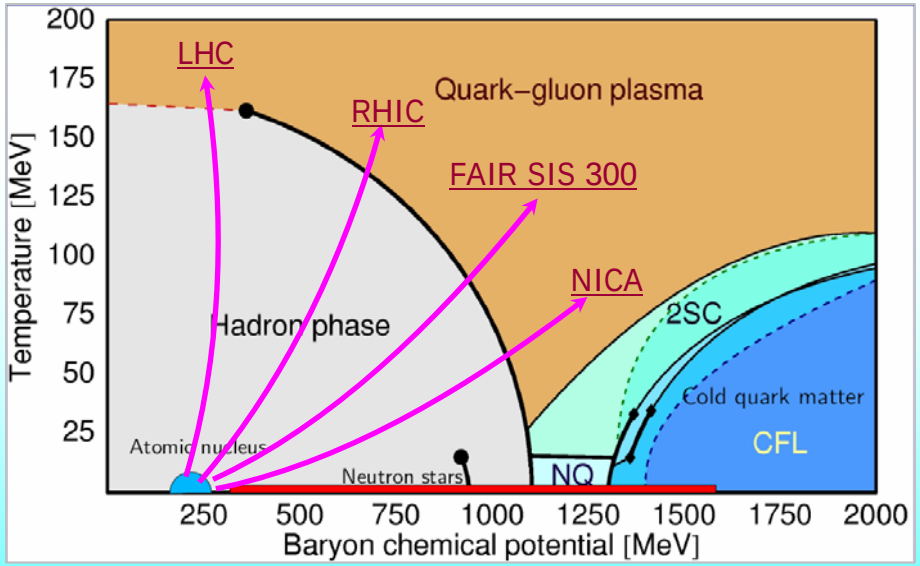
- It is **promising** to investigate non-congruent phase transitions in **direct numerical simulations** ("numerical experiment") DFT/MD, PIMC, WP/MD…

- If one takes into account hypothetical **non-congruence** of **phase transitions** in **astrophysical** 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!





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

Acknowledgements

Support

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

RAS Scientific Program:
"Physics *and* Chemistry
of Extreme States *of* Matter"

MIPT Research & Educational Center
"High Energy Density Physics"

Extreme Matter Institute - EMMI

Collaboration (INTAS 1995-2002):
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*)

INTAS 93-66 // ISTC 2107, 3755 // CRDF MO-011