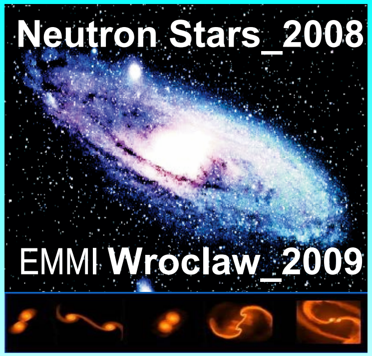
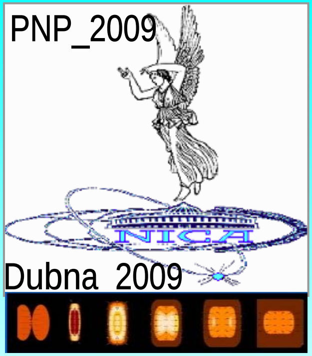
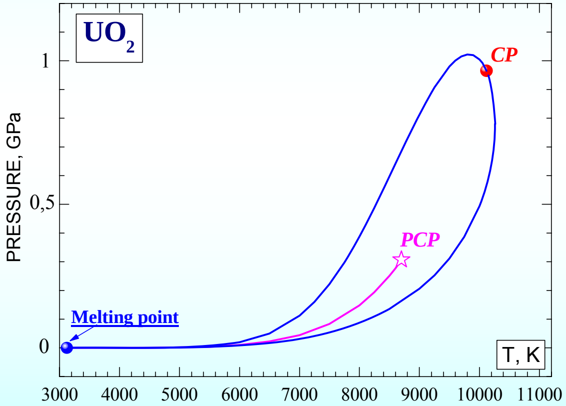


Hungarian Academy of Science
KFKI Institute for Particle and Nuclear Physics
Theoretical Physics Department, April, 2010



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)

The base:

- **Non-ideal plasma physics**
- **Developments of advanced nuclear reactor**

Main issue for EMMI:

- **The most general form of phase coexistence in *multy--component* systems is *non-congruent* phase transitions**

(in contrast to the phase transitions in ordinary one-component systems)

Non-congruent phase transition – *what does it mean*?

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

Evident definition – *in* terrestrial applications

Evident definition – *in* outer layers of compact stars

For example: Non-congruent crystallization in accreting layers of NS (C.Horowitz)

No nuclear transformations // **No** quark deconfinement

NB !

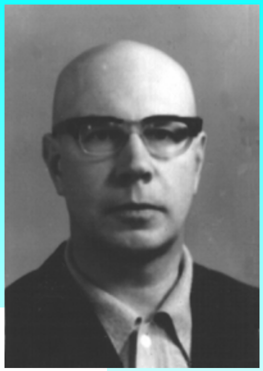
Non-evident – *in* interiors *of* compact stars

Non-evident – *in* products *of* HIC

Nuclear transformations // Quark deconfinement

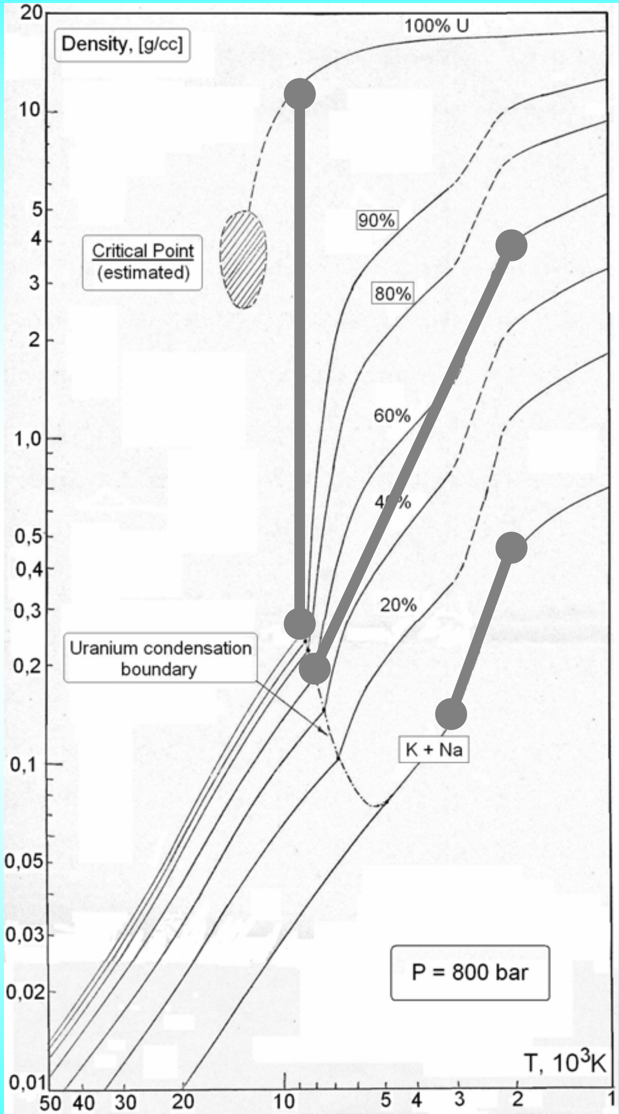
Thermodynamic dimensionality is the key parameter **!**

Developments of Gas-Core Nuclear Reactor

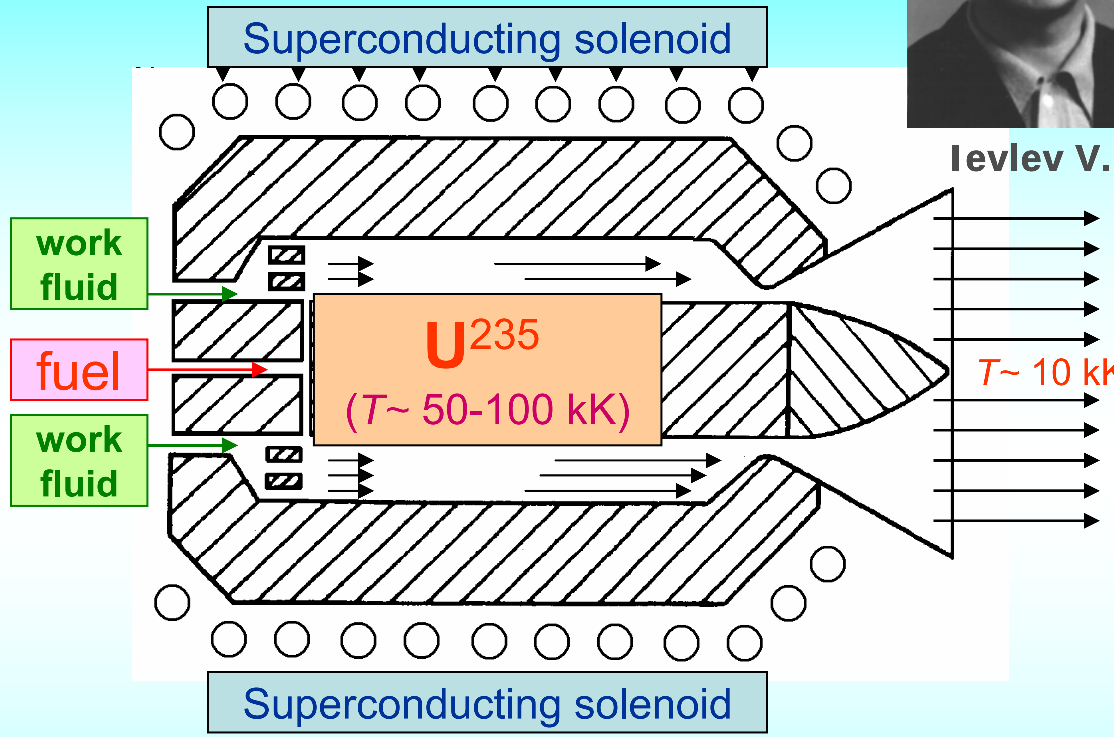


Ievlev V.M.

(1950-1980)



Phase diagram of mixture (U + K + Na)
Iosilevskiy et al. *ITPP Report*, 1972



High-temperature variant of GCNR

Ievlev V. *Bulletin of Russian Academy of Science* (Izvestia RAS), № **6**, (**1977**)

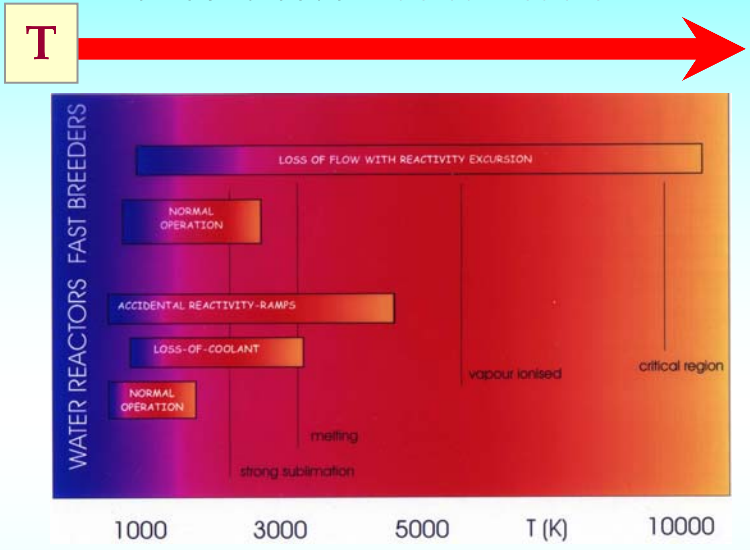
Gryaznov V, Iosilevskiy I, Fortov V, et al. "Thermophysics of gas-core nuclear reactor /Ed. V. Ievlev (**1980**) *(in Russian)*

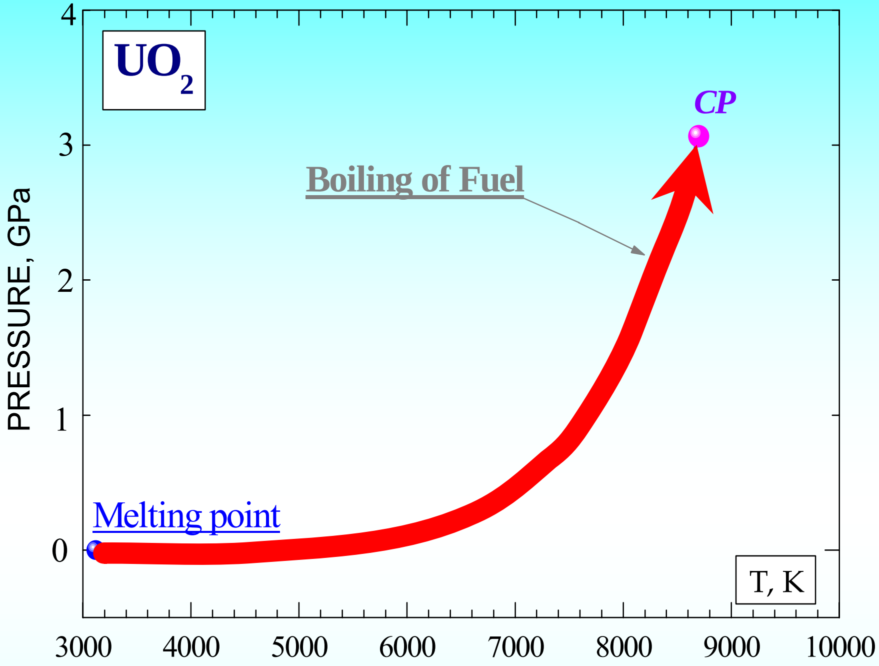
"Rocket engines and energy converters based on gas-core nuclear reactor", /Ed. A. Koroteev, "Mashinostroeniye" Publishing, Moscow, (2002), (in Russian)

The base

Non-congruent phase transition in uranium-bearing mixtures

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





Gas-Core Nuclear Reactor Project (1957–1980)

Competition: **Cosmic and Nuclear Agencies** (Soviet Union) ⇔ **Los Alamos** (United States)

Project Leader in Soviet Union – academician **Vitalii Ievlev** (RAS)

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

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

Managing, science *and* coordination: – V. Fortov (RAS, Moscow)/B. Sharkov (ITEP, Moscow) /C. Ronchi (ITU, JRC)

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

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

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

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

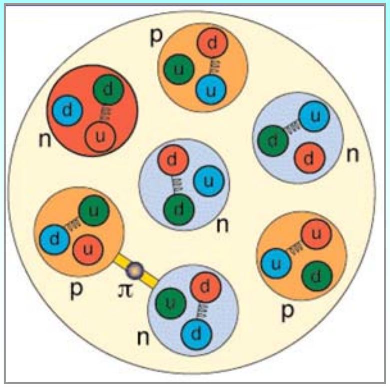
* Ronchi C., Iosilevskiy I., Yakub E. *Equation of State of Uranium Dioxide* / **Springer, Berlin,** (**2004**)

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

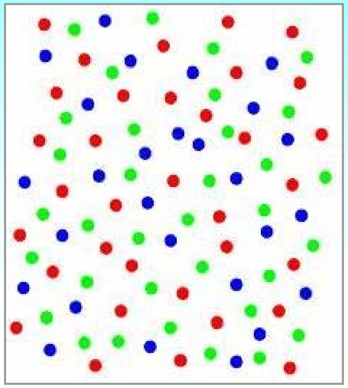
Quasi-chemical representation

(*"Chemical picture"*)

Strange (hybrid) stars



⇔



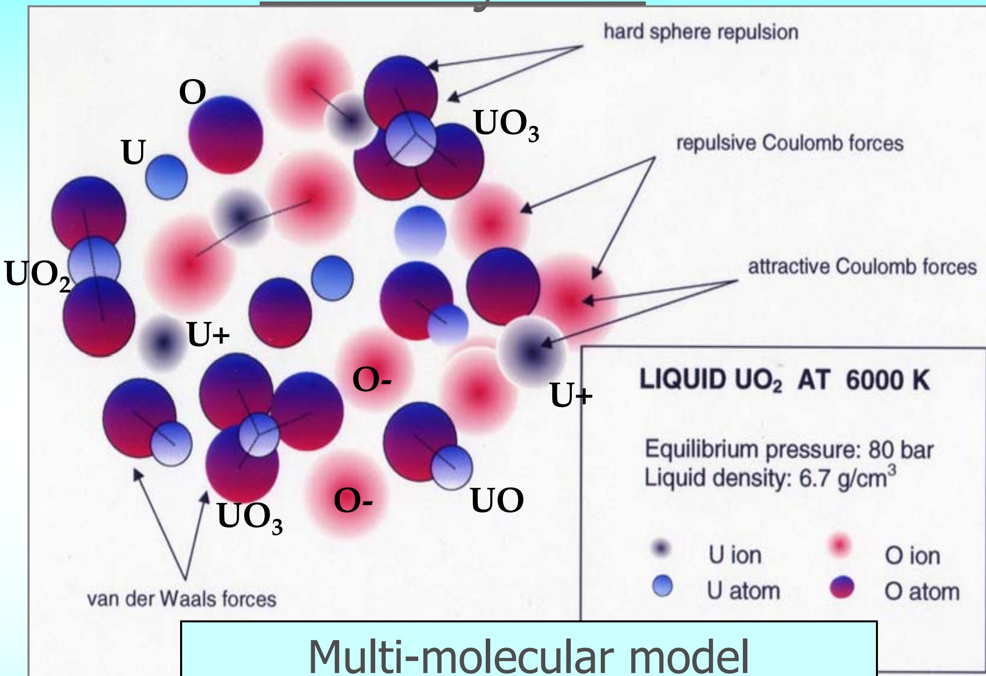
u, d, s, p, n, e	$\mu_u, \mu_d, \mu_s, \mu_p, \mu_n, \mu_e$

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 ⇔ UO_2
2O ⇔ O_2
U^+ + e ⇔ U
UO_3 + e ⇔ UO_3^-
. . . . . .

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

Two problems in phase transition calculation

- Construction of Equation of State (EOS)

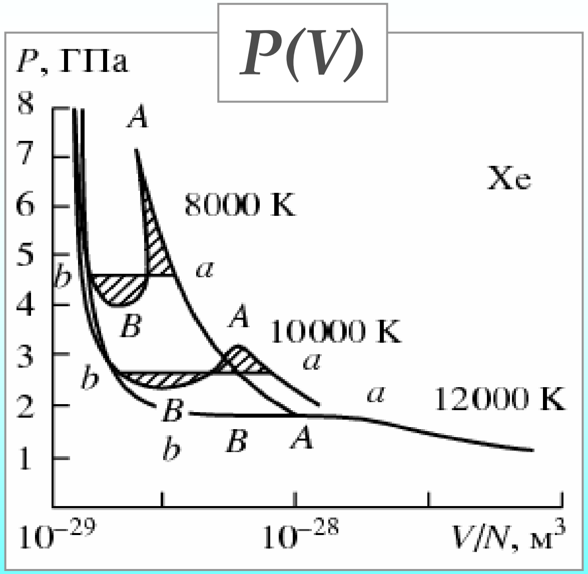
- **Phase coexistence parameters calculation**

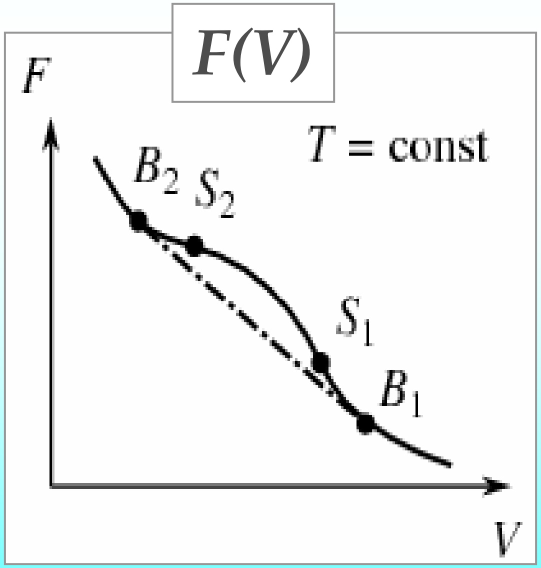
Phase coexistence parameters calculation

(standard approach)

Ordinary way:

in pressure *P(V)* – **Maxwell (equal squares)** *or*
in free energy *F(V)* – "**Double tangent**"



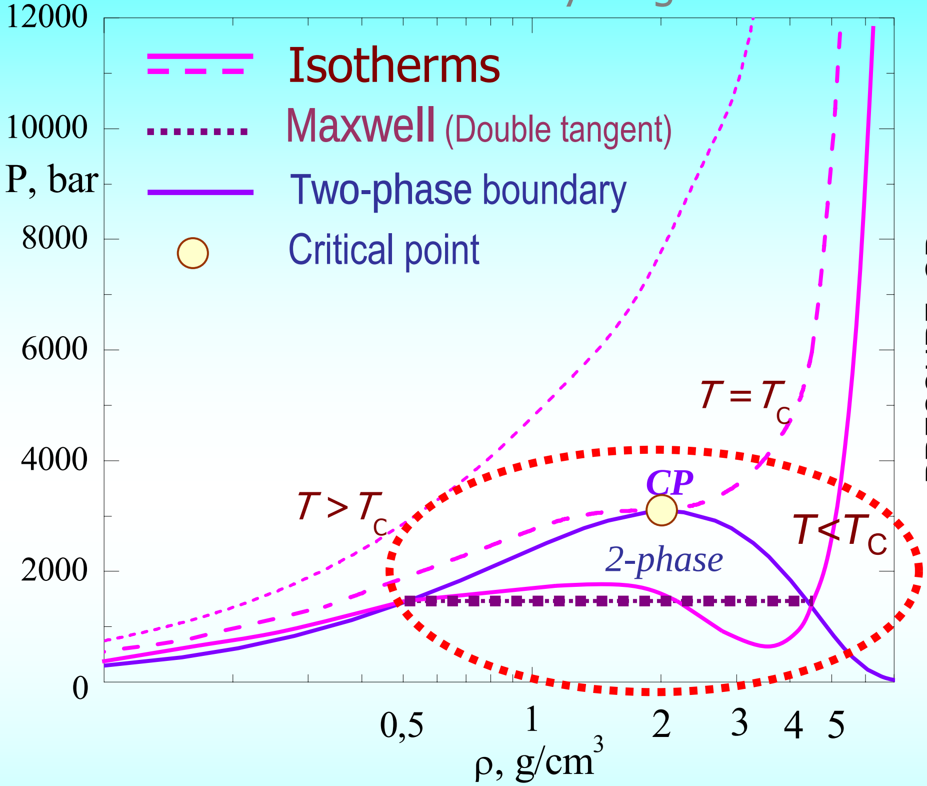


(*see for example:* Iosilevskiy I., *Encyclopedia on low-T plasmas*. *III-1,* **2000**, P.327-339); *III-1 (suppl)* **2004**, P.349-428)

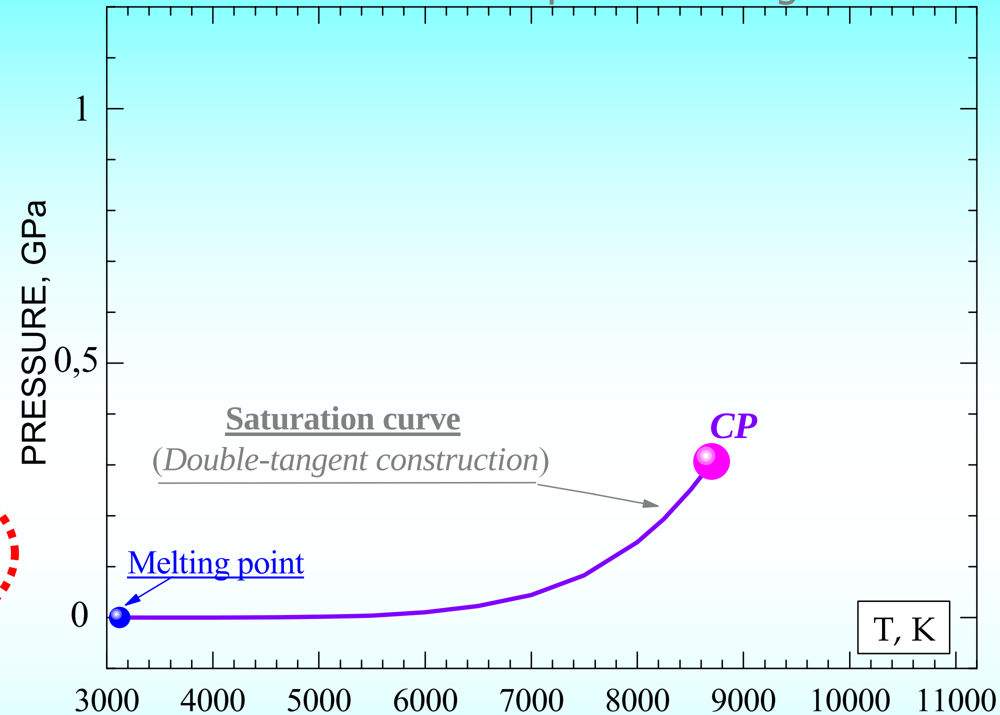
Standard

Forced-congruent evaporation in U-O system

Pressure - Density diagram



Pressure - Temperature diagram



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

It should be ***x' ≠ 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:

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

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

(only to the partial one)

Maxwell approach

- **is non-adequate for non-congruent phase transitions**

***Correct approach*:**

- **Gibbs (+ Guggenheim) conditions**

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

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

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

ab ⇔ a + b

(reduced number of basic units)

Uranium – Oxygen system

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

Particle Exchange
charged species

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

Electro-chemical potentials are equal

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

Potential drop at mean-phase interface in equilibrium Coulomb system

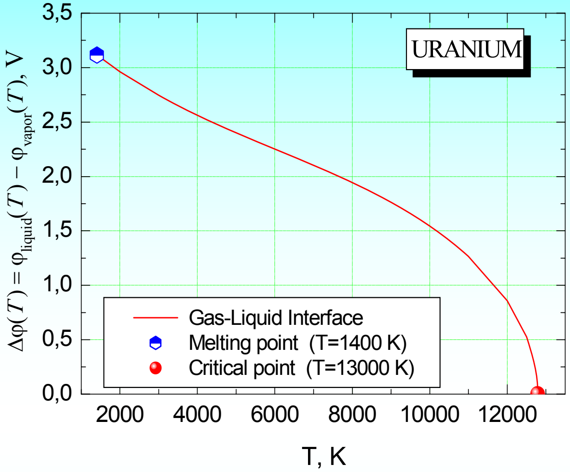
$$\mu_1'(P,T,x') = \mu_1''(P,T,x'') + Z_1 e\,\Delta\varphi(T)$$
$$\mu_2'(P,T,x') = \mu_2''(P,T,x'') + Z_2 e\,\Delta\varphi(T)$$
$$\ldots\ldots\ldots\ldots$$
$$\mu_e'(P,T,x') = \mu_e''(P,T,x'') - e\,\Delta\varphi(T)$$

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

Electrostatics of phase boundaries in Coulomb systems

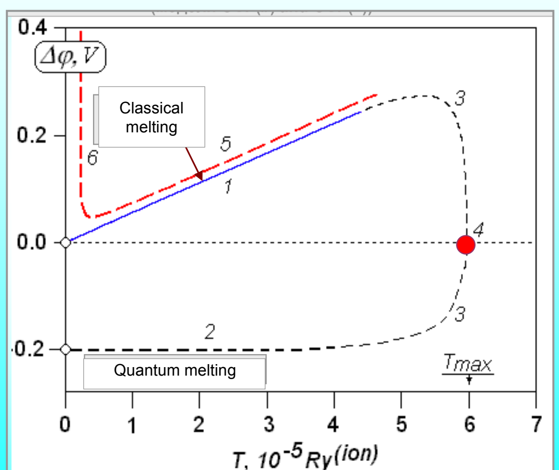
Terrestrial applications

Electrostatic (Galvani) potential



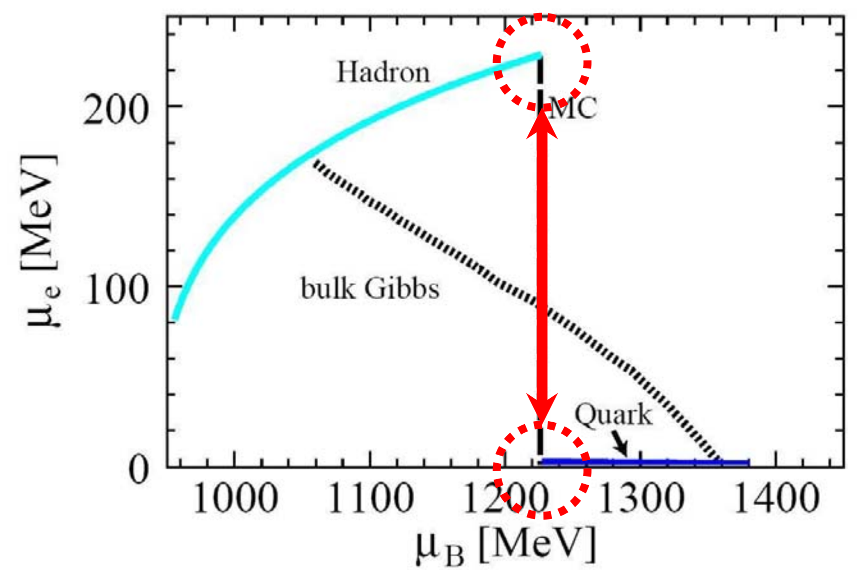
Iosilevskiy & Gryaznov, *J. Nucl. Mat.* (2005)

Electrostatic "portrait" of Wigner crystal in OCP



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

Quark-Hadron phase transition in NS



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

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

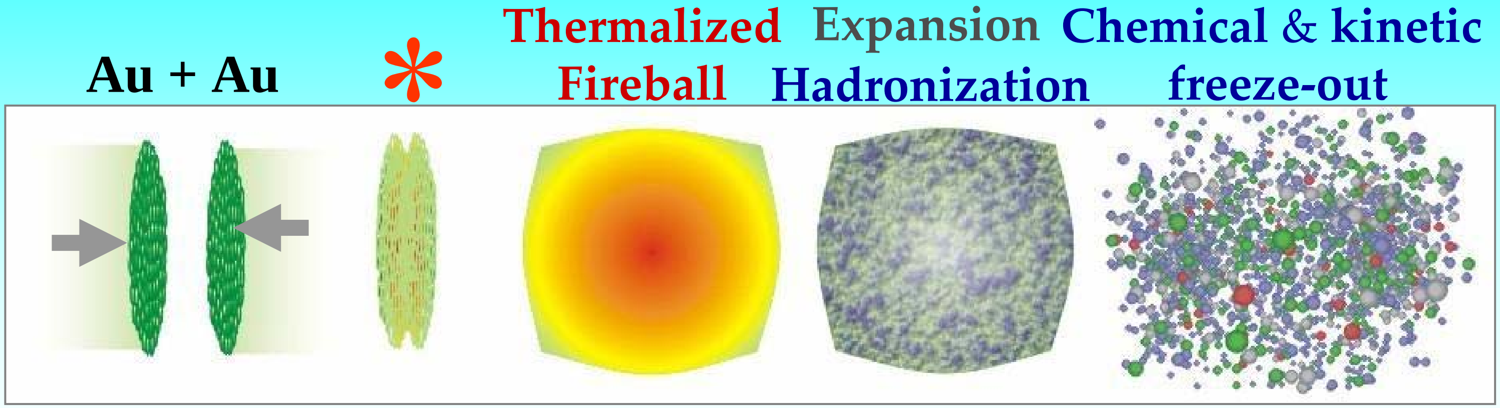
$$e\Delta\varphi_{HQ} = (\mu_e)_{\text{Hardron phaseb}} - (\mu_e)_{\text{Quark phase}}$$

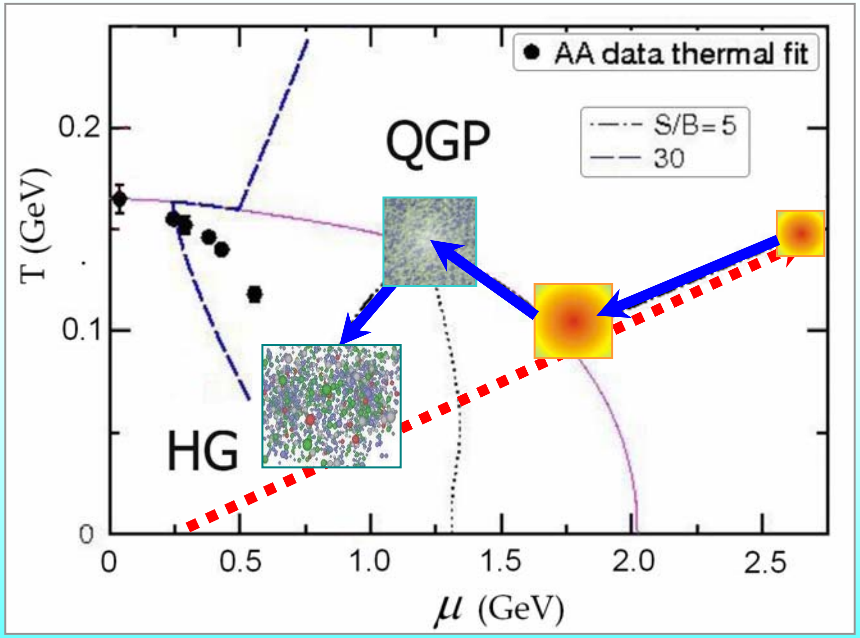
$$e\Delta\varphi_{HQ} \approx 200 \text{ MeV} \;\; !$$

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

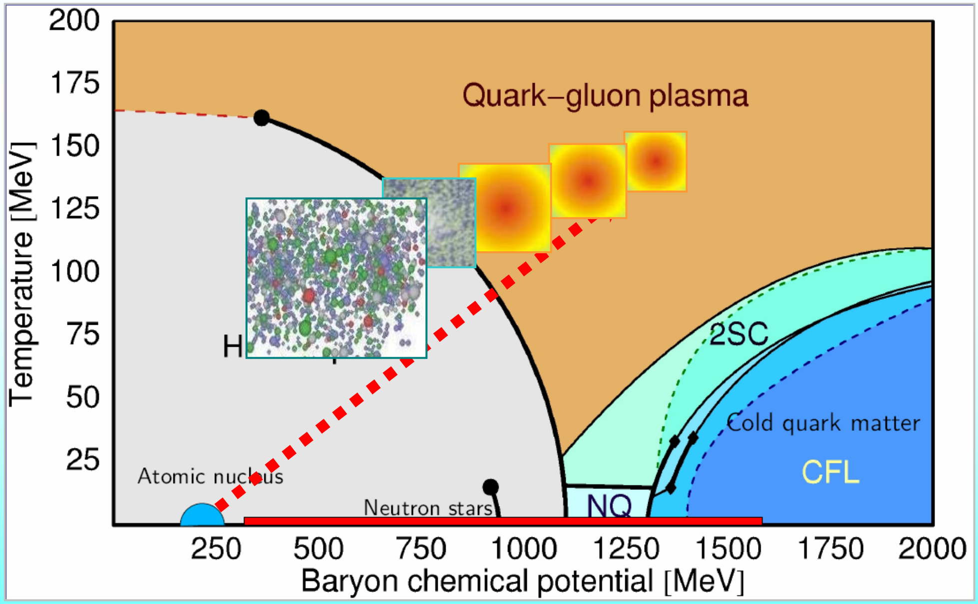
For comparison: Alcock *et al.*, 1986: $\rightarrow$ $E \sim 10^{17}$ V/cm

Impact *and* Fireball hydrodynamics *in* HIC





After L.Satarov, M.Dmitriev, I.Mishustin // 2009



After David Blaschke, WEHS Seminar, Bad Honnef, 2007

Phase equilibrium in reacting Coulomb system

(Gibbs – Guggenheim conditions)

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

$T' = T''$ $P' = P''$

Neutral species

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

Charged species

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

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

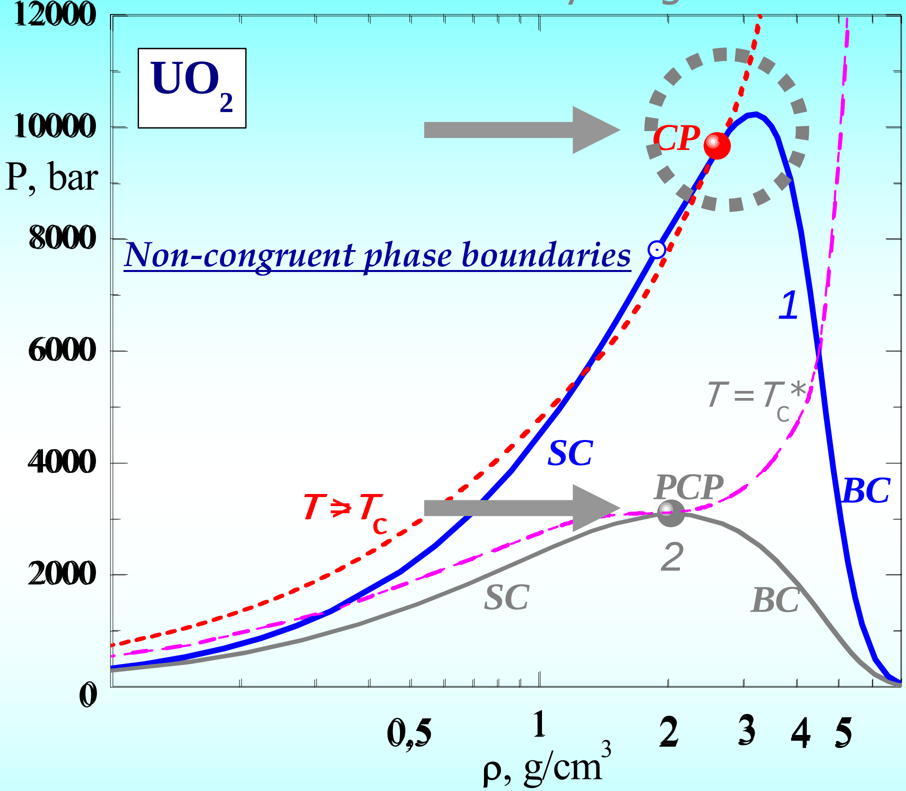
$$n_{U+} + n_{U++} + n_{UO2+} + n_{UO3+} = n_e + n_{O-} + n_{O2-} + n_{UO3-}$$

$$\mu_{U+} + \mu_e = \mu_U \qquad \mu_{UO3} + \mu_e = \mu_{UO3-}$$
$$\mu_{UO+} + \mu_e = \mu_{UO} \qquad \mu_O + \mu_e = \mu_{O-}$$
$$\mu_{UO2+} + \mu_e = \mu_{UO2} \qquad \ldots\ldots\ldots\ldots$$

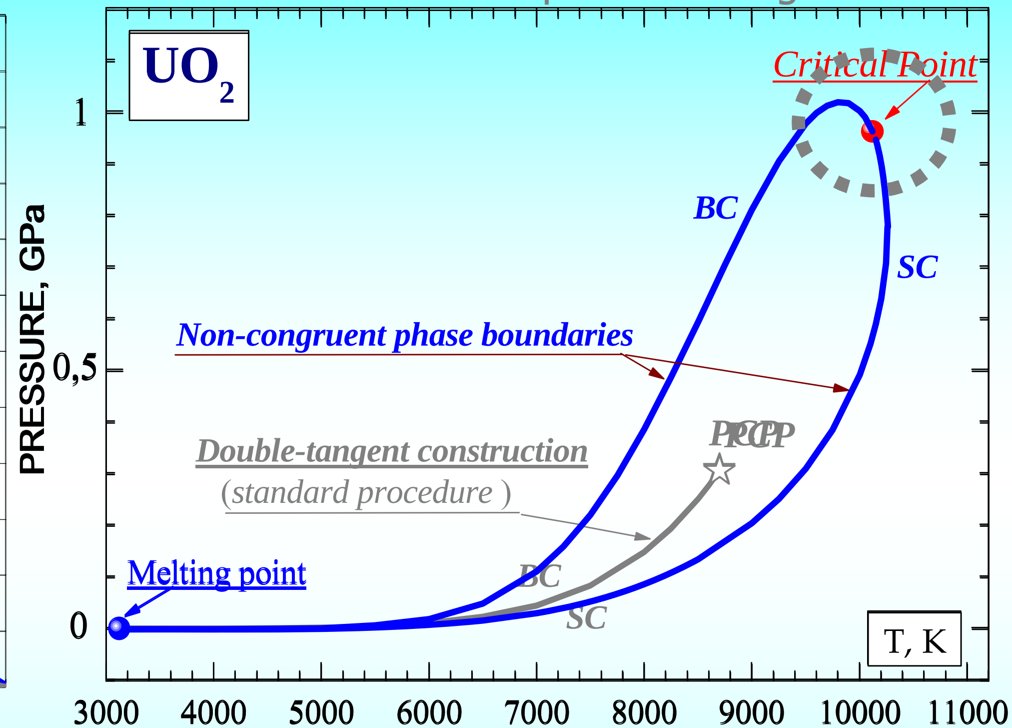
Non-congruent evaporation in U-O system

(*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

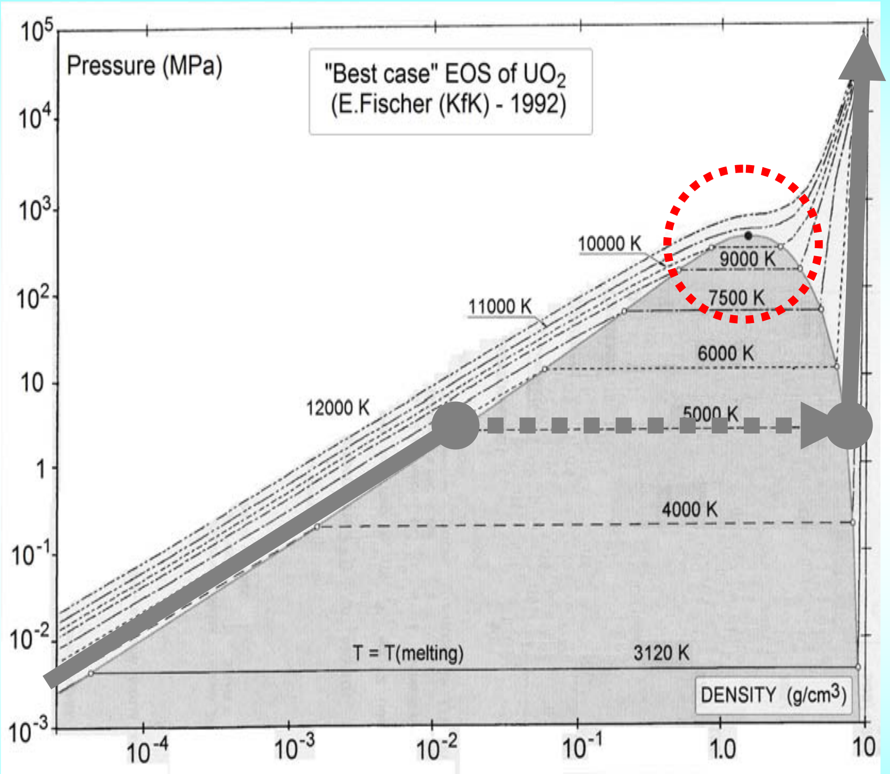
NB! **High pressure level** of non-congruent phase decomposition

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

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

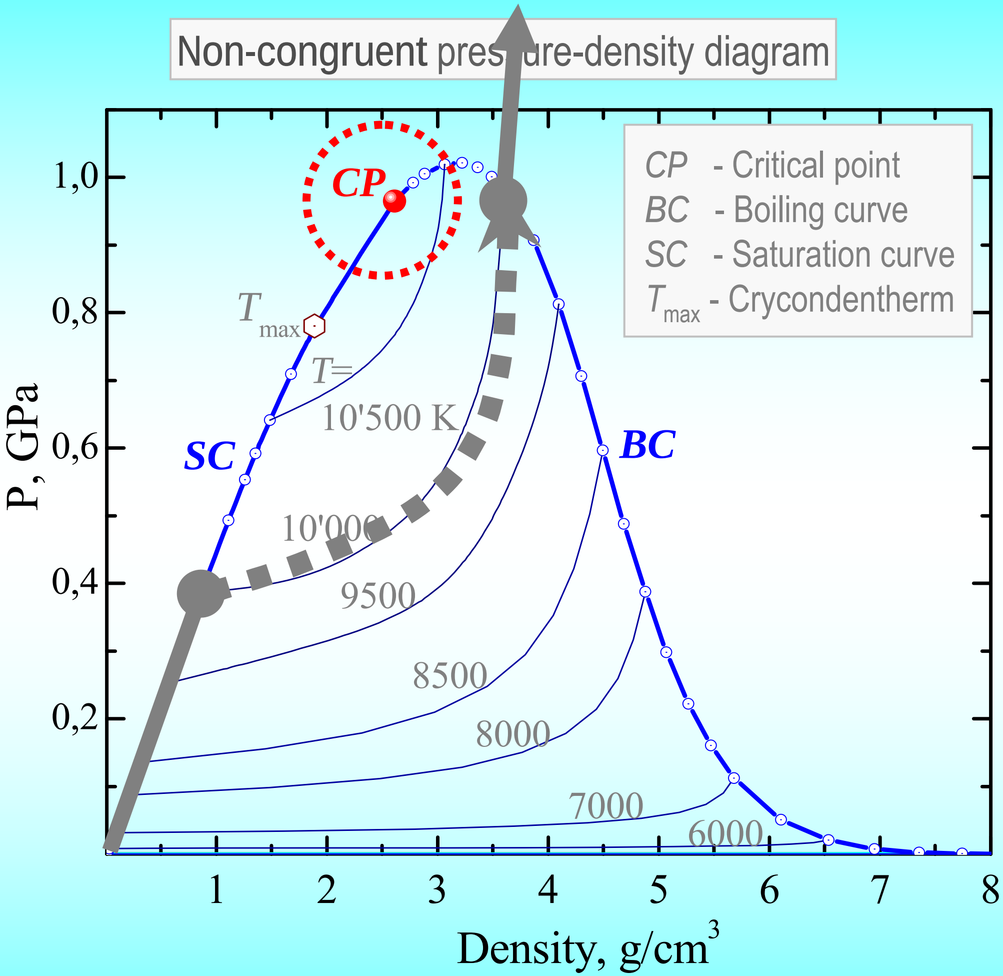
Isotherms in two-phase region

Standard pressure-density diagram



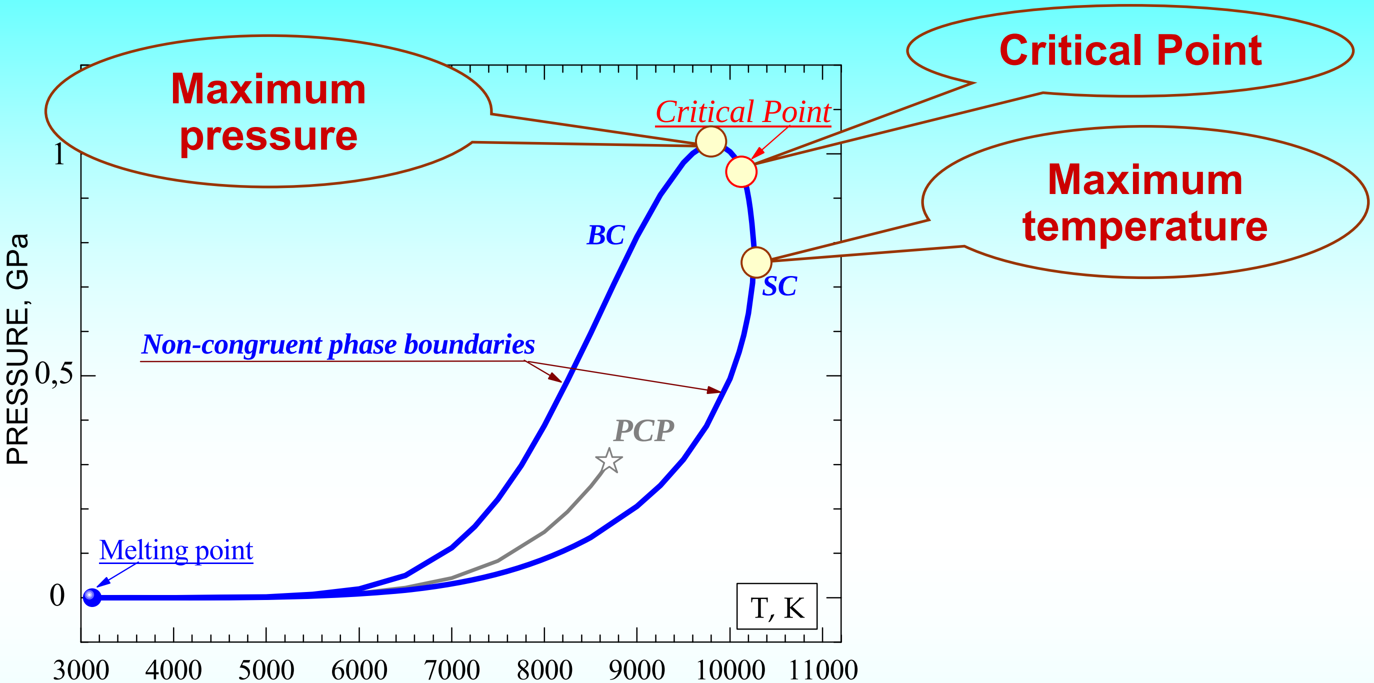
Fischer E.A. *J. Nucl. Sci. Eng.* (1989)

Non-congruent pressure-density diagram



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

End-Points of Non-Congruent Phase Transition

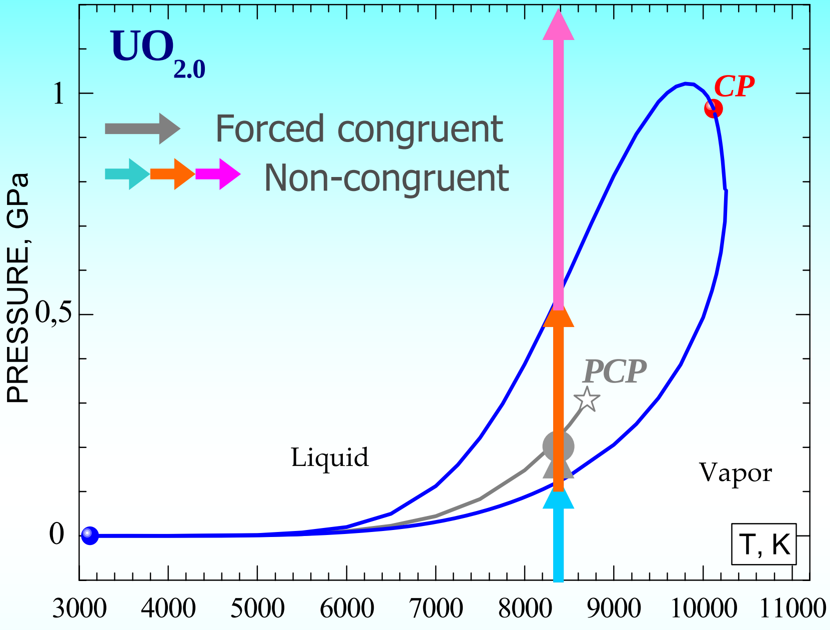


NB !

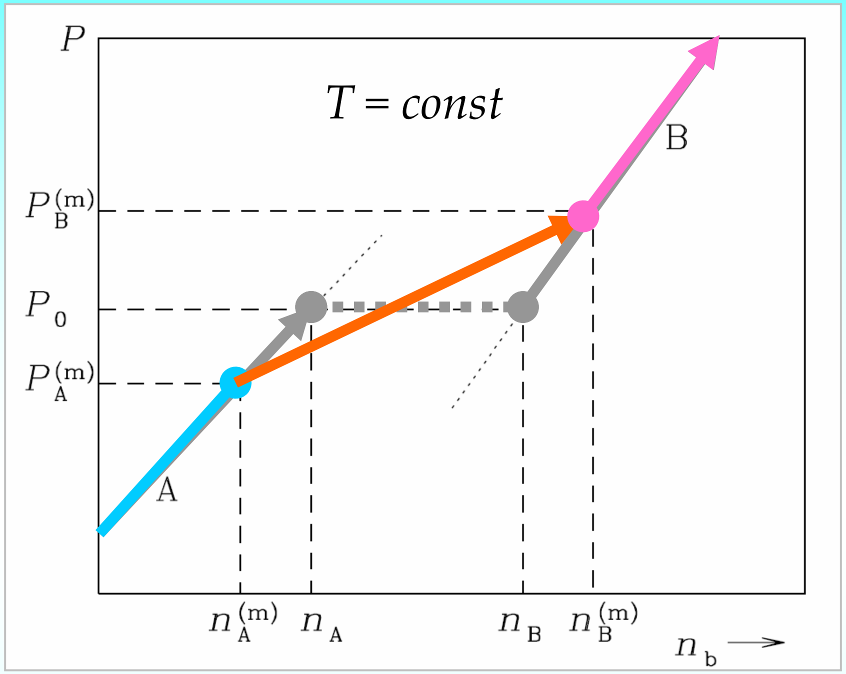
- **Point of temperature maximum**
- **Point of pressure maximum**
- **Point of chem. potential extremum**
- **Critical point** *(thermodynamic singularity)*

are four different points !

Non-congruent phase transformation in two-phase region

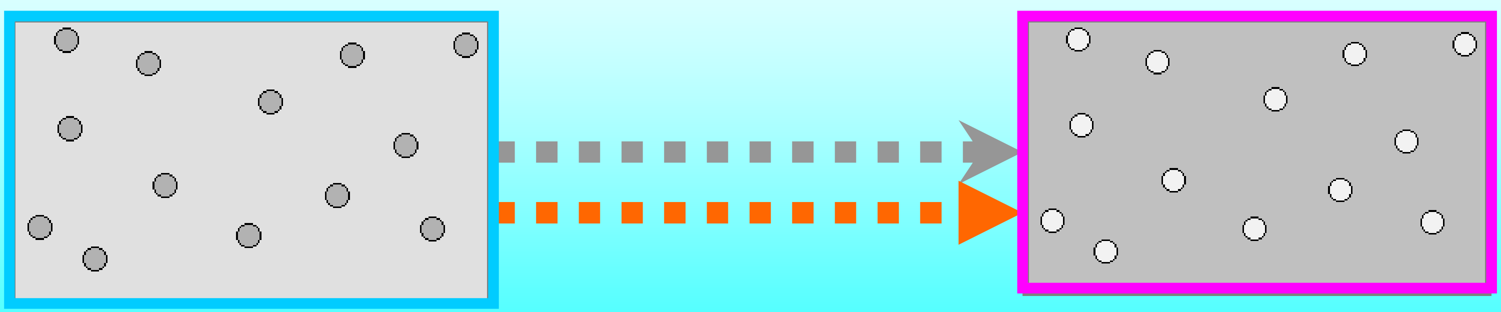


Phase Diagram *P-T* of Non-congruent Evaporation



First liquid droplets in saturated vapor

Last vapor bubbles in boiling liquid



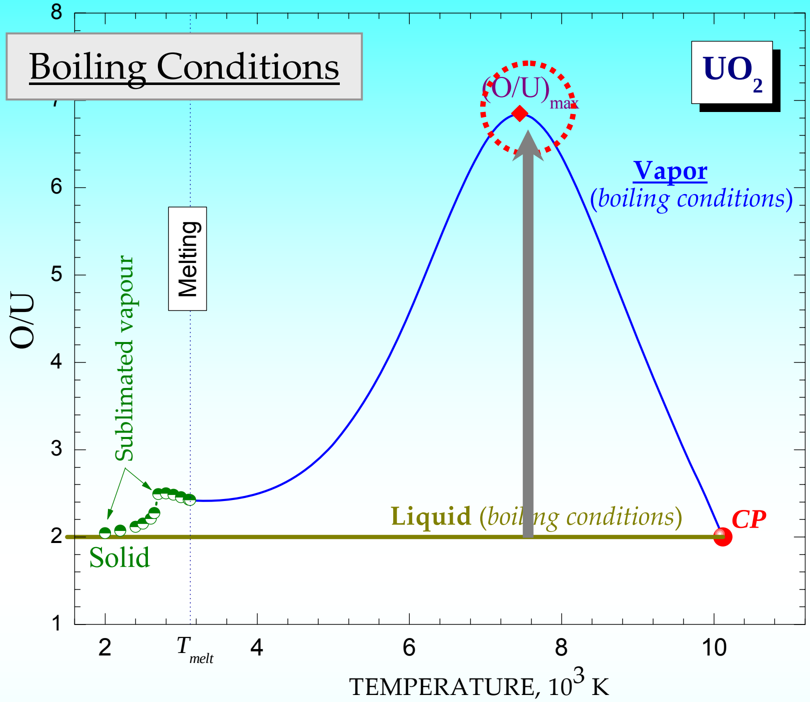
Oxygen depleted liquid

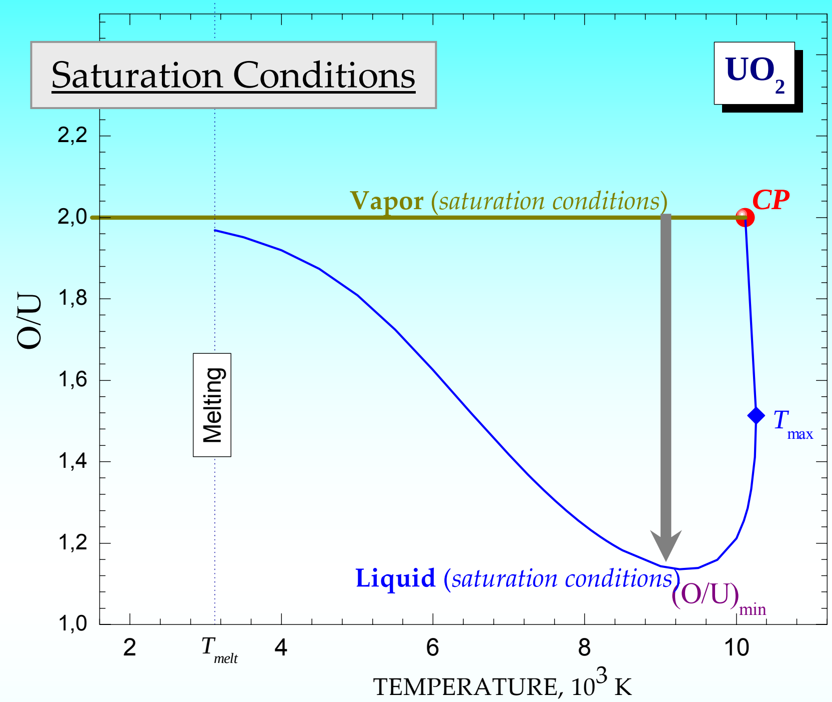
! *Different stoichiometry* !

Oxygen enriched vapor

! *Different stoichiometry* !

Chemical composition at coexisting phases

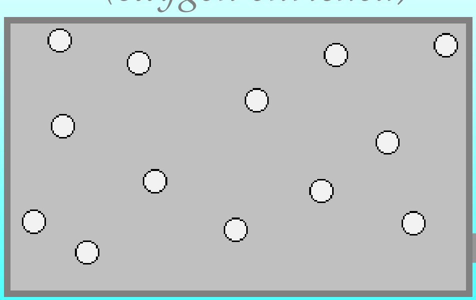


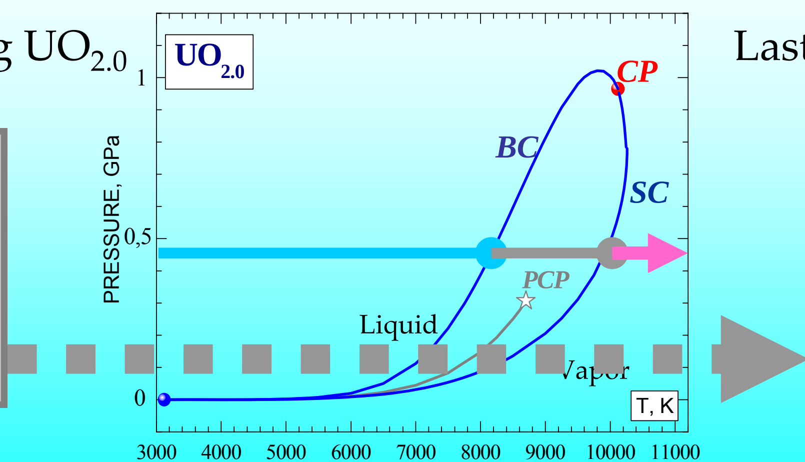


$P = const$

First vapor bubbles in boiling $UO_{2.0}$

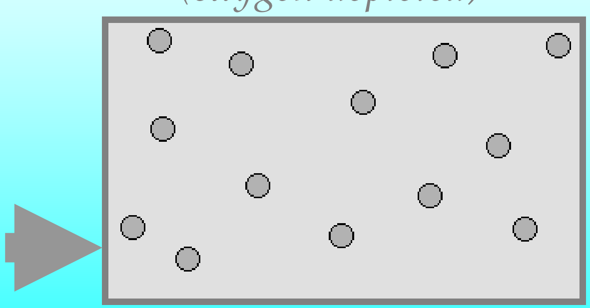
(oxygen enriched)





Last liquid drops in vapor $UO_{2.0}$

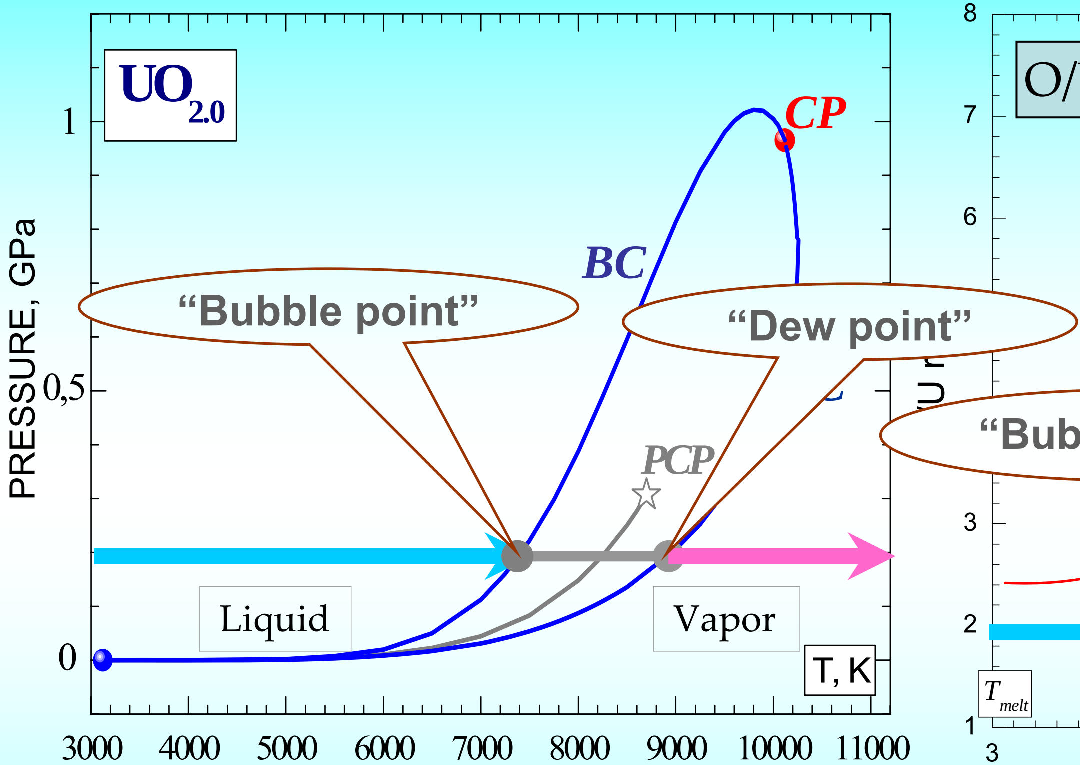
(oxygen depleted)

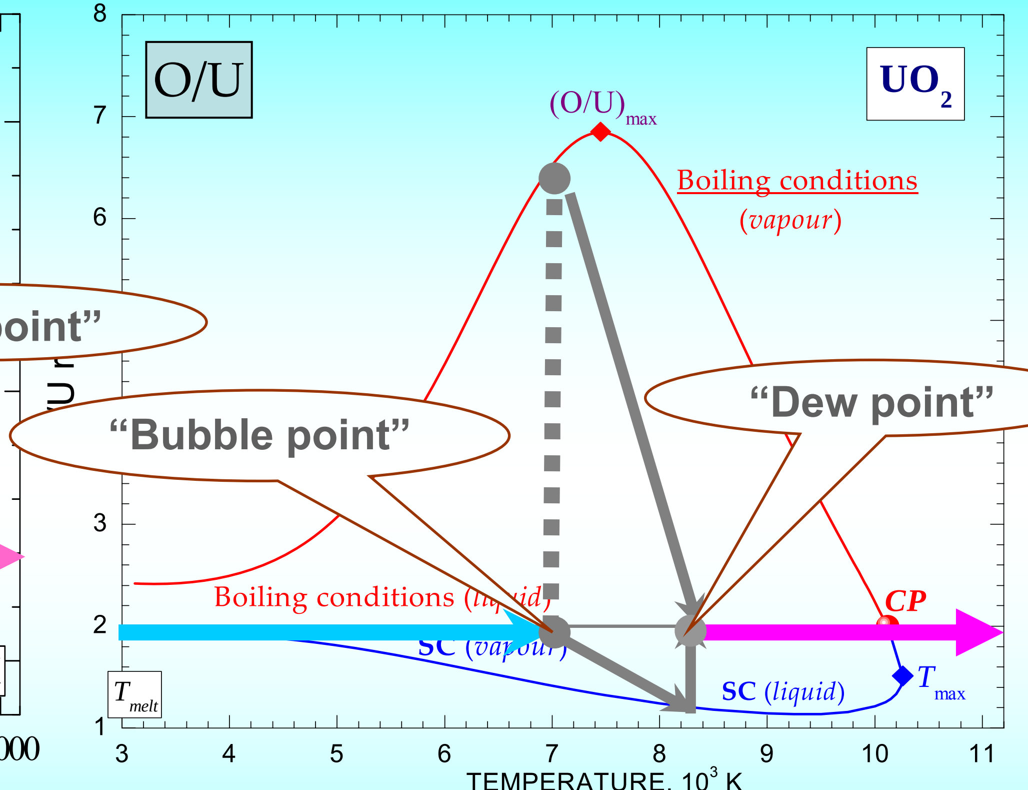


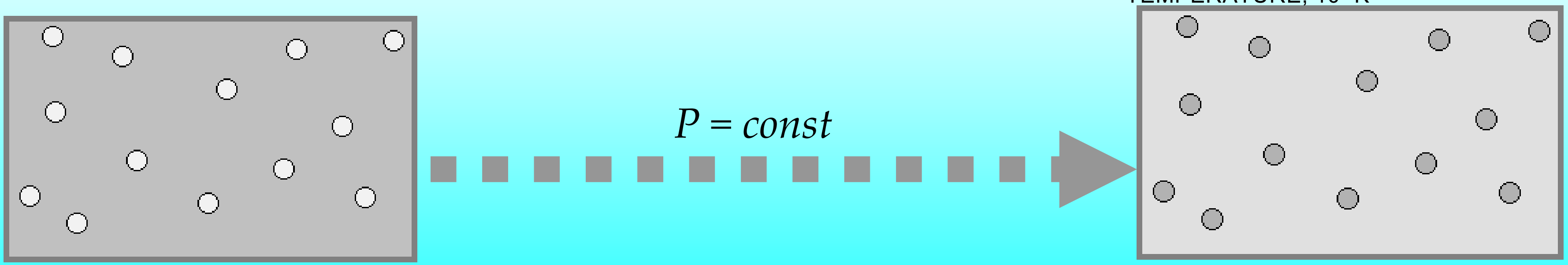
Liquid (O/U = 2.0) ⇔ Vapor (O/U > 2.0)

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

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)

N-C Phase Transition Thermodynamics

Two-phase region in intensive variables (*P-T, μ-T, μ-P*)

Two-phase region of non-congruent phase transition must be two-dimensional region (*instead of one-dimensional curve*)

Critical point

Critical point of non-congruent phase transition must be of non-standard type, i.e. $(\partial P/\partial V)_T \neq 0 \quad (\partial^2 P/\partial V^2)_T \neq 0$

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

N-C Phase Transition Dynamics

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

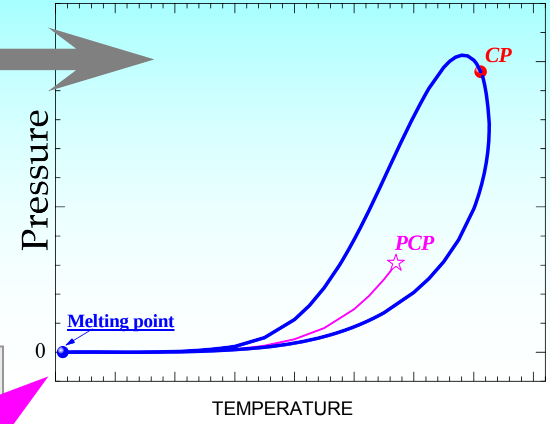
Non-congruence in general

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

Basic conclusion:

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

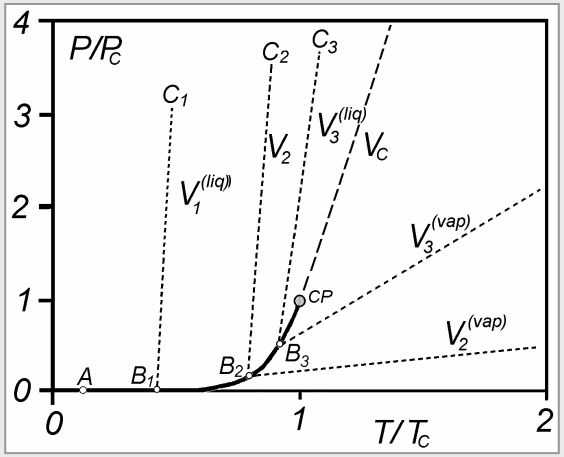
– **Congruent** phase transition is **exception**



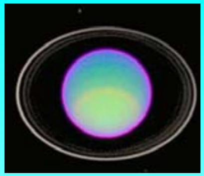
Evident contradiction

H_2O, CO_2, NH_3 . . . .

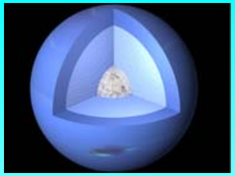
?



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

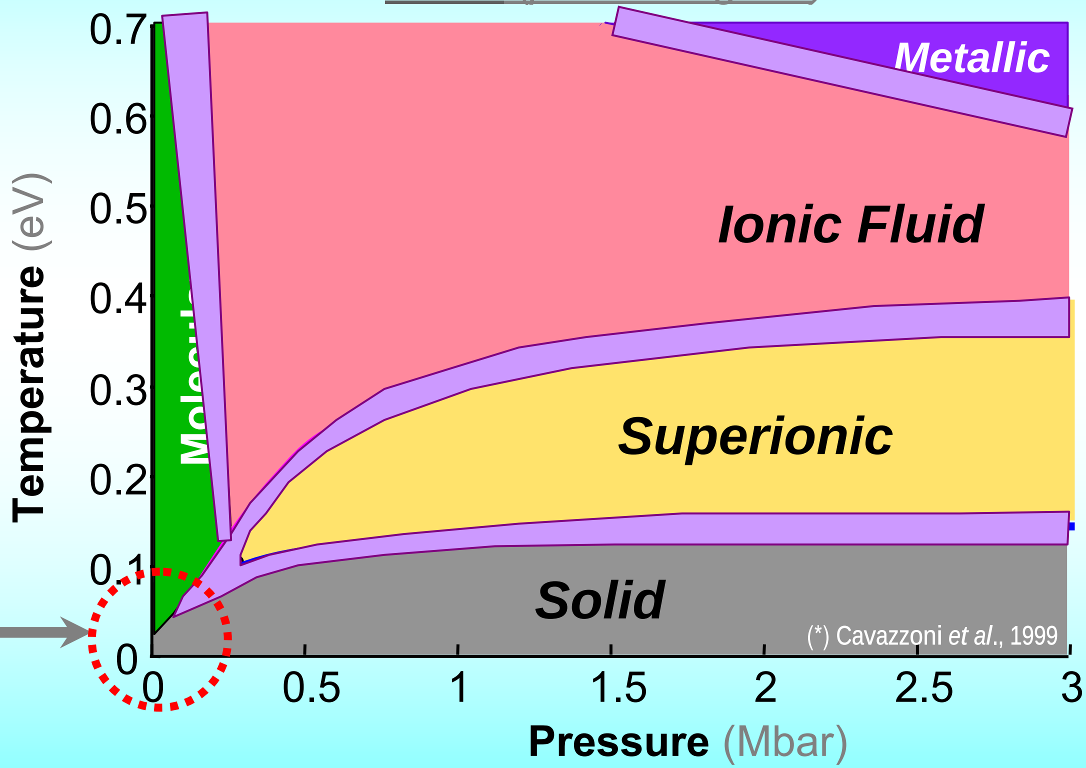


BASIC STATEMENT:
Any phase transition in a system of **two** or more **chemical elements** must be **non-congruent**

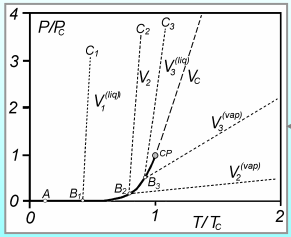


Neptune and “hot-water” extrasolar planet GJ436b

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*

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

<u>The question is:</u>

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

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

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

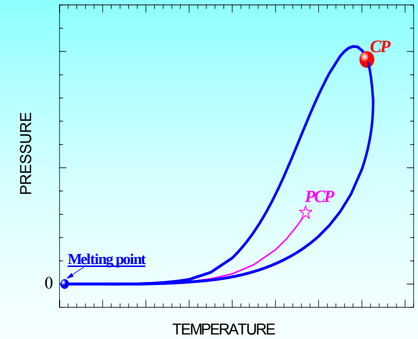
Typical composition in planetary science

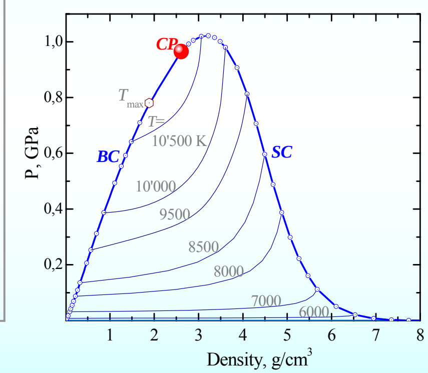
Hypothetical non-congruent phase transitions

(***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)*

The question is:

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

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

Launch – June 18, 2009 // Impact – 9 October 2009 12:30 a.m. !
Impact velocity ~ 9’000 km/h ⇔ Impact plume ~ 50 km high

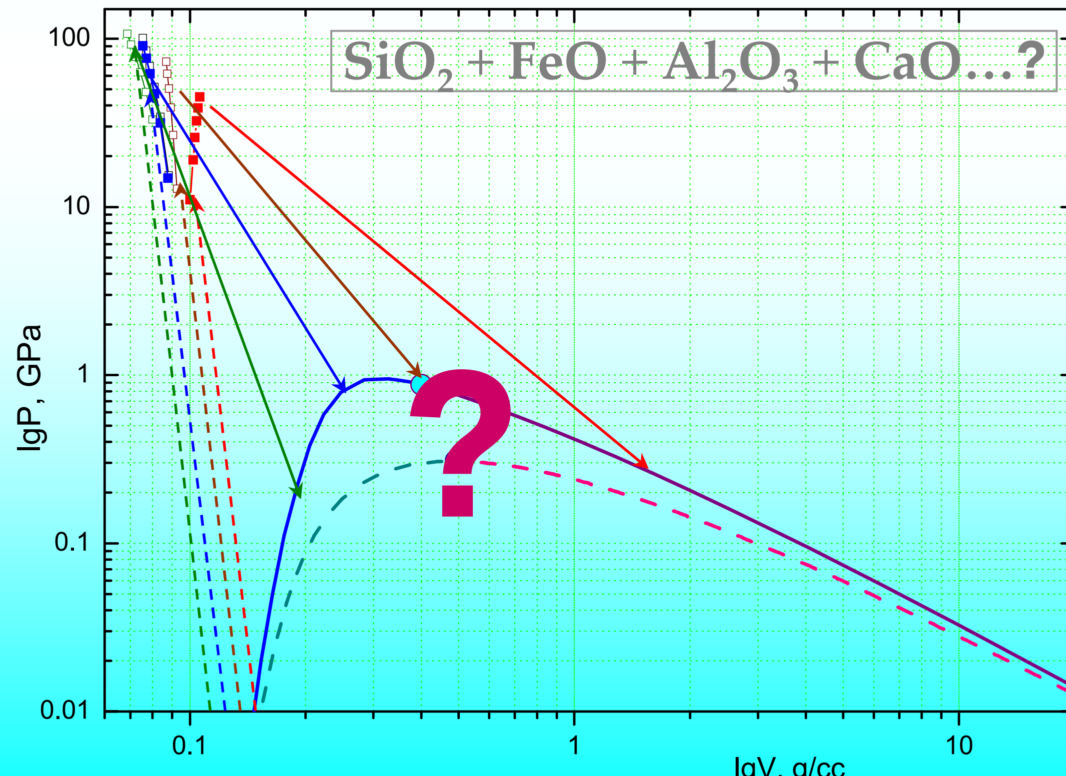
1st Stage – strong shock compression

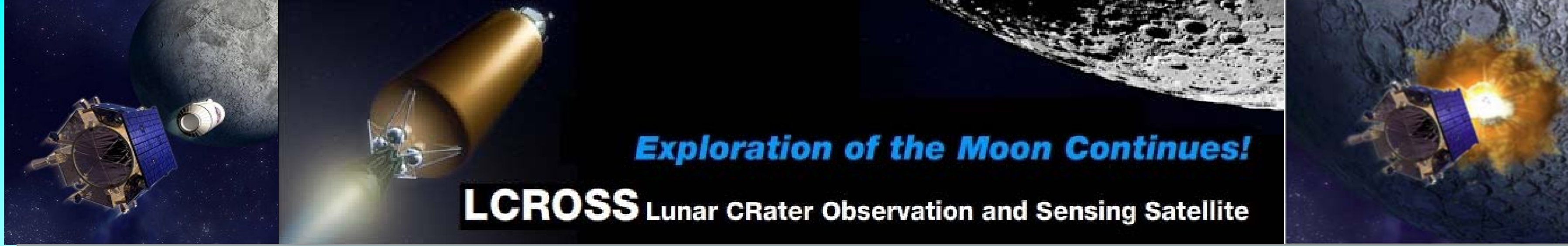
2nd Stage – free quasi-isentropic expansion

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





) // Impact – 9 October 2009 12:30 a.m. !

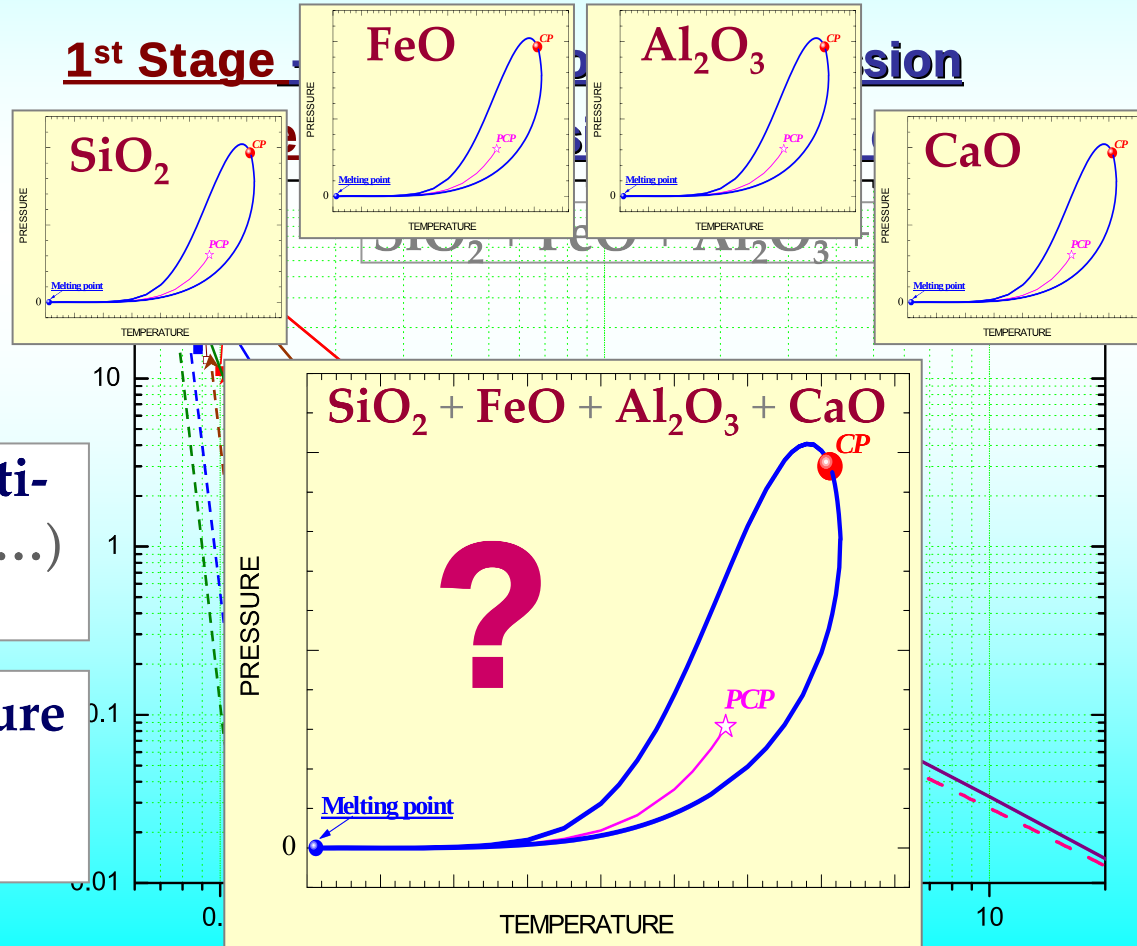
0 km/h ⇔ Impact plume ~ 50 km high

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

<u>The question is open</u>

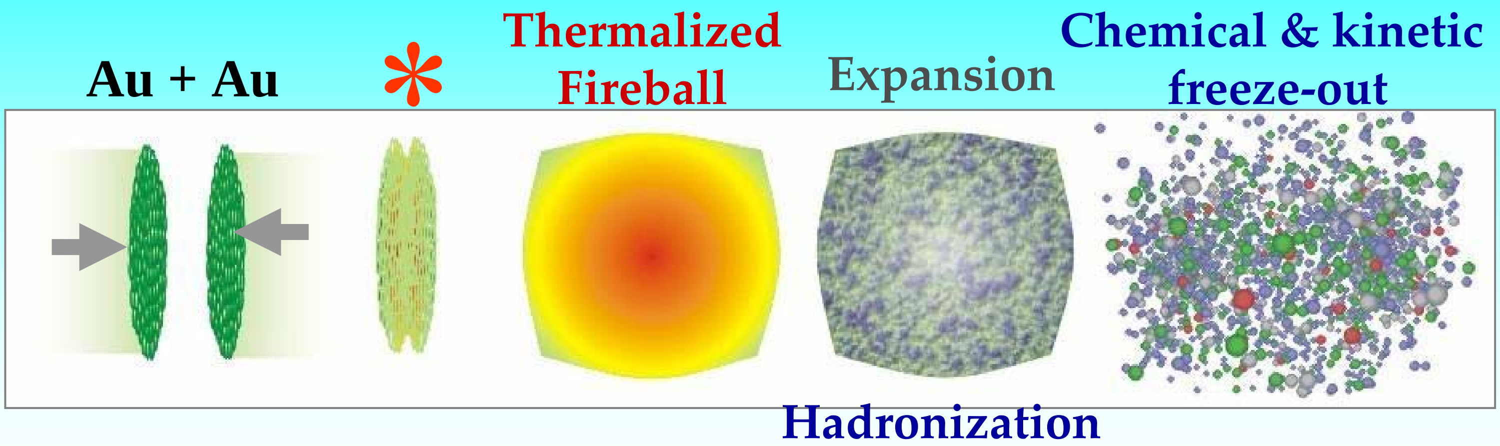


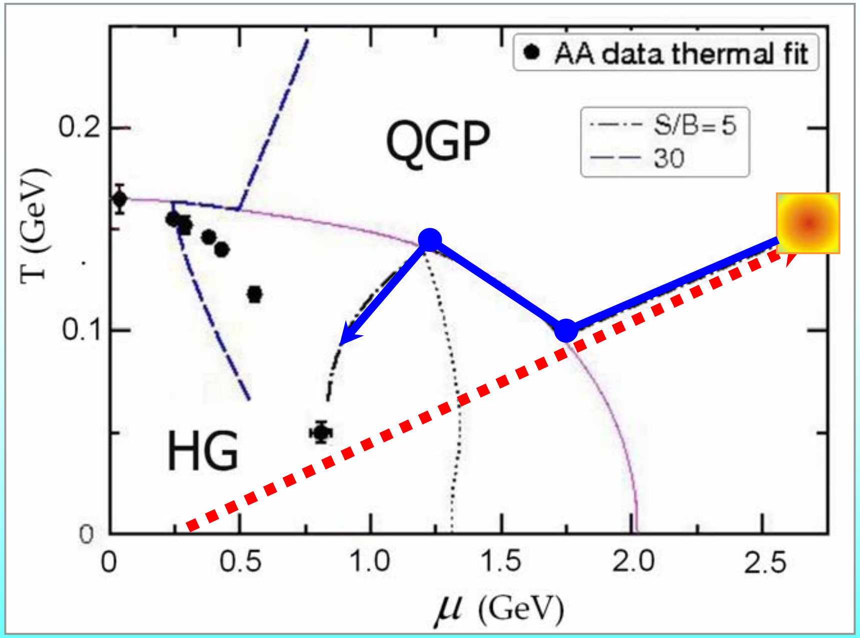
<u>NB</u> !

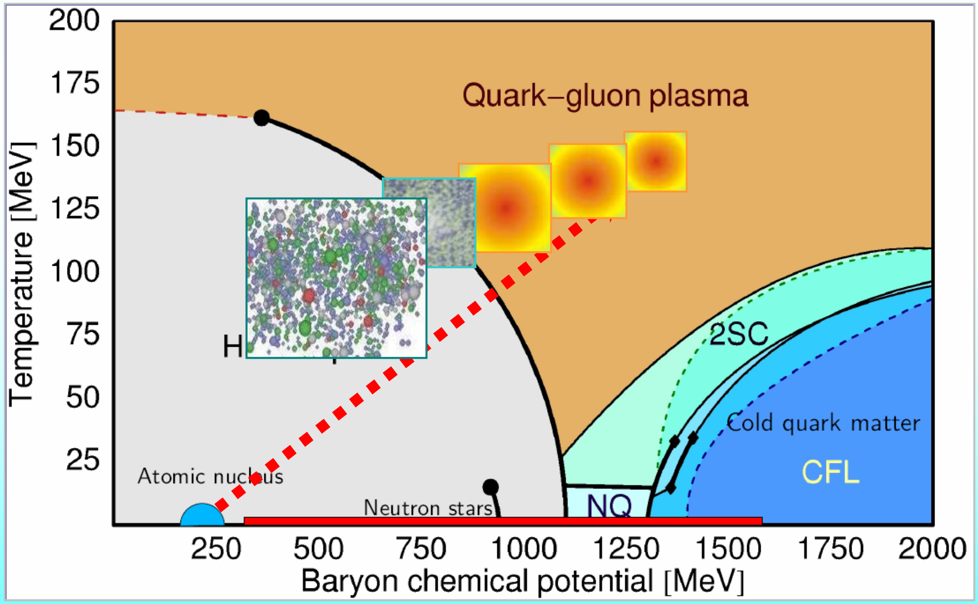
Phase transition in each constituent (SiO_2, FeO, Al_2O_3, CaO…) must be *non-congruent* !

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

Impact *and* Fireball hydrodynamics *in* HIC







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

After David Blaschke, WEHS Seminar, Bad Honnef, 2007

Hypothetical non-congruent phase transitions

(***short list***)

Terrestrial applications:

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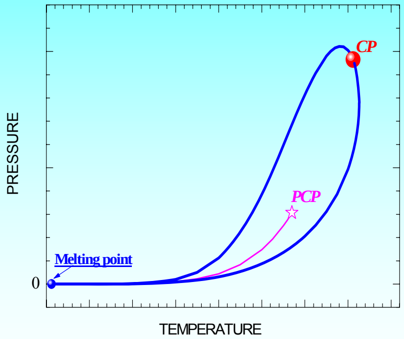
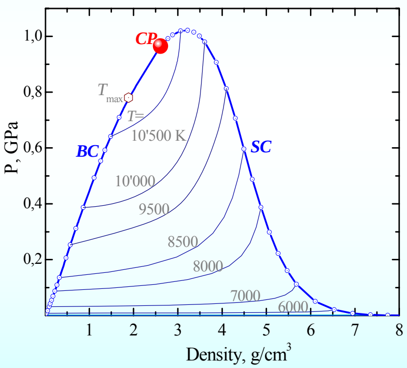
- ***"Dusty"** and **Colloid plasmas**:*
  (*Coulomb system of macro-ions +Z and micro-ions: +1, −1*)





Non-Congruence in Cosmic Matter:

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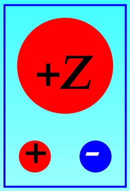
- ***Phase Transitions** in **"Strange" Stars*** (*quark-hadron transition … ets.*)

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

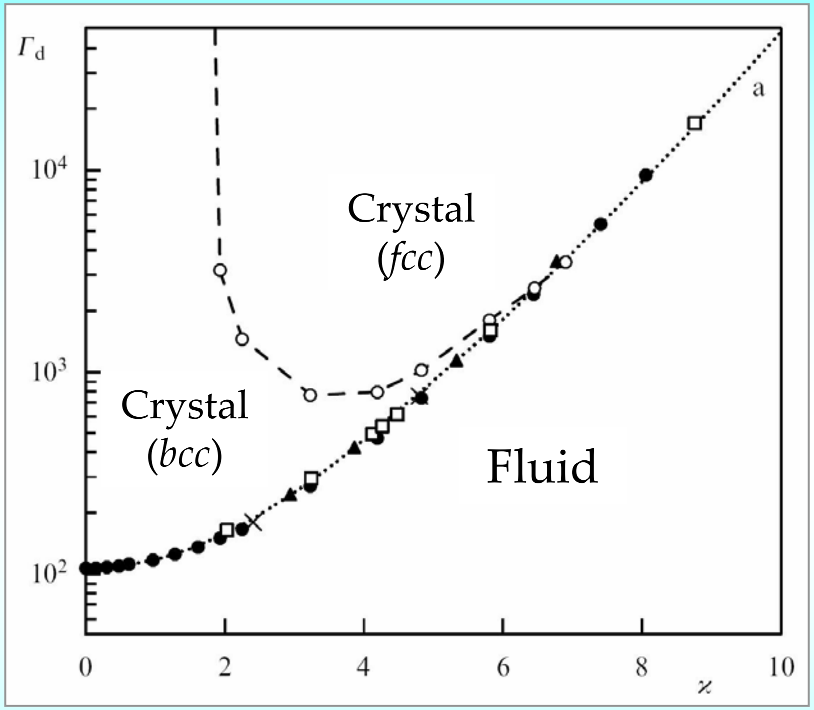
Non-congruence in complex (dusty) plasma ?



Primitive model

(non-Coulomb)

Hamaguchi S. et al., *Phys. Rev. E* **56**, 4671 (1997)



Phase Diagram in Yukawa system

(on rigid compensating background)

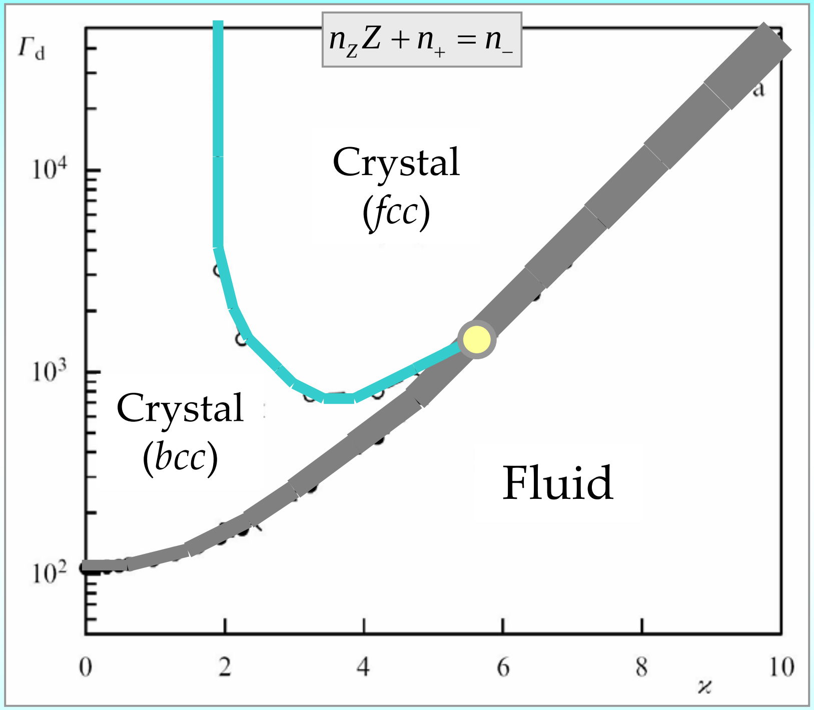
$$U(r) = \frac{Z^2 e^2}{r}\exp(-\kappa r)$$

No density gap!

All phase boundaries are one-dimensional curves.

More realistic model:

Macro-ions (+Z) + *micro-ions* (±1)



$$U_{ij}(r) = \frac{z_i z_j e^2}{r_{ij}}$$

$$\kappa^2 \equiv \frac{4\pi \sum n_i z_i^2 e^2}{kT}$$

Two-dimensional system

All phase transitions ***must be non-congruent***

(there must be density gap)

All phase boundaries are ***two-dimensional stripes***

(not curves!)

Non-congruence in exotic situations

Nuclear Defragmentation in High Energy Collisions

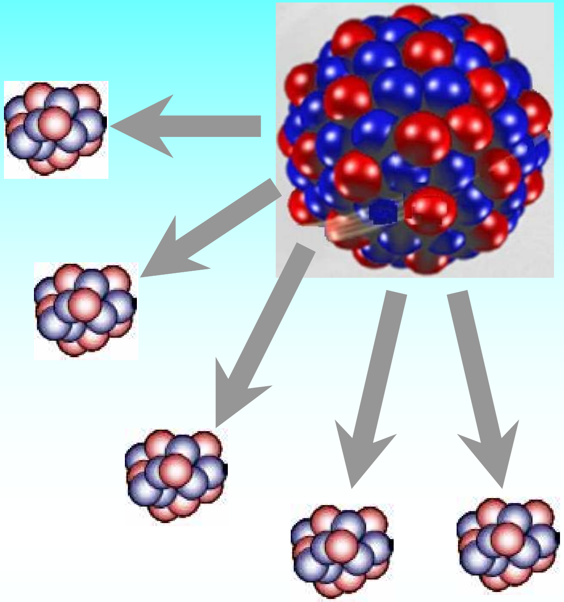
(*Berceley* ⇔ *GSI* ⇔ . . . . . .)

Constructing the phase diagram of finite neutral nuclear matter

arXiv: nucl-ex/0205004 v1 8 May 2002

J. B. Elliott[1], L. G. Moretto[1], L. Phair[1], G. J. Wozniak[1], S. Albergo[2], F. Bieser[1], F. P. Brady[3], Z. Caccia[2], D. A. Cebra[3], A. D. Chacon[4], J. L. Chance[3], Y. Choi[5], S. Costa[2], M. L. Gilkes[5], J. A. Hauger[5], A. S. Hirsch[5], E. L. Hjort[5], A. Insolia[2], M. Justice[6], D. Keane[6], J. C. Kintner[3], V. Lindenstruth[7], M. A. Lisa[1], H. S. Matis[1], M. McMahan[1], C. McParland[1], W. F. J. Müller[7], D. L. Olson[1], M. D. Partlan[3], N. T. Porile[5], R. Potenza[2], G. Rai[1], J. Rasmussen[1], H. G. Ritter[1], J. Romanski[2], J. L. Romero[3], G. V. Russo[2], H. Sann[7], R. P. Scharenberg[5], A. Scott[6], Y. Shao[6], B. K. Srivastava[5], T. J. M. Symons[1], M. Tincknell[5], C. Tuvé[2], S. Wang[6], P. Warren[5], H. H. Wieman[1],

[1] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*
[2] *Universitá di Catania and Istituto Nazionale di Fisica Nucleare-Sezione di Catania, 95129 Catania, Italy*
[3] *University of California, Davis, CA 95616*
[4] *Texas A&M University, College Station, TX 77843*
[5] *Purdue University, West Lafayette, IN 47907*
[6] *Kent State University, Kent, OH 44242*
[7] *GSI, D-64220 Darmstadt, Germany*
(June 15, 2006)



$_{197}\mathbf{Au}^{79}$

$E \sim 5$ AMev

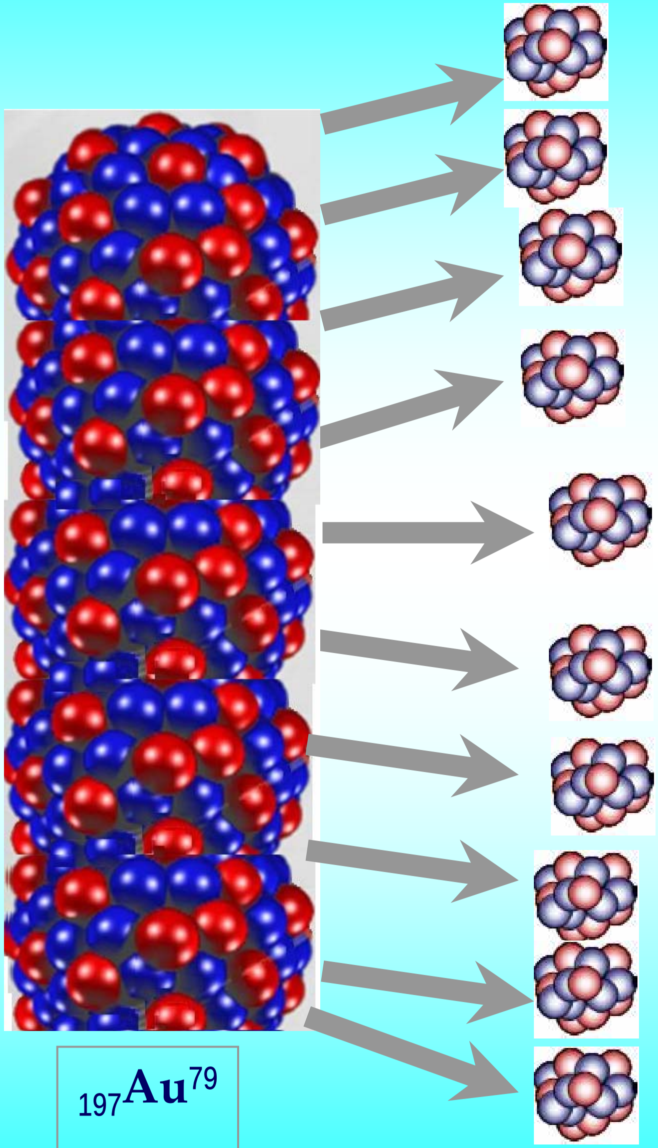
$Y = 0.67$

Elliott J.B., Moretto L.G. Phair L., Wozniak G.J., Bugaev K. *et al.*,
Phys. Rev. C (1999 - 2006) // *Nuclear Phys. A* (2001) // . . . . .
arXiv:nucl-th/0012037 // arXiv:hep-ph/0511180v1 2005 //
arXiv: nucl-ex/0205004 v1 // . . . . .

= = «» = =

Thermodynamics of Nuclear Multifragmentation
Phase Diagram of Nuclear Matter
Liquid to Vapor Phase Transition in Excited Nuclei
First-order Phase Transitions in Nuclei and other Mesoscopic Systems
Nuclear Decay and the Liquid-Vapor Phase Transition: A Physical Picture
. . . .

Nuclear Multifragmentation in High Energy Collisions



$_{197}$**Au**^{79}

$Y = 0.67$

Basic idea:

- equivalence of collision products ensemble to:

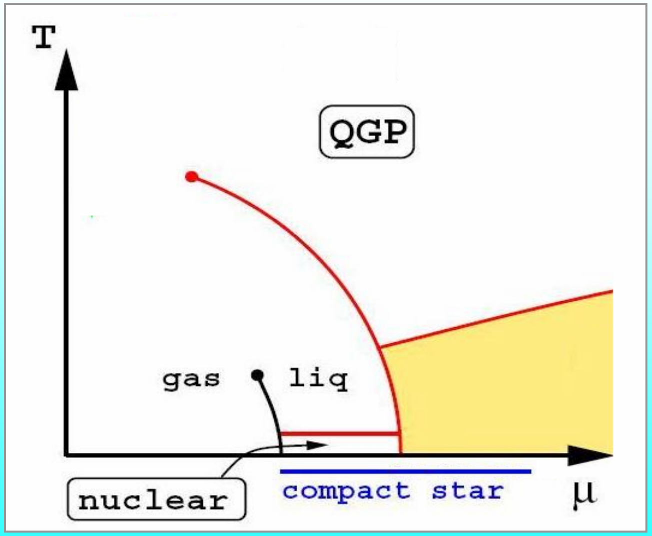
Hypothetical phase coexistence

of *infinite* nuclear liquid ("caviar")

and

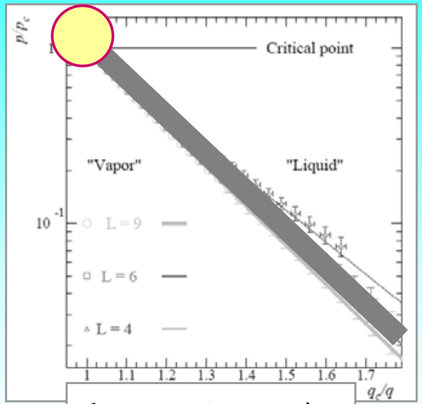
"vapor" of de-fragmentation *clusters*

$$N_0(A, Z) \Leftrightarrow \{N_i(A_i, Z_i)\}$$



"Gas-Liquid" coexistence in nuclear collision products

It proved to be possible to define equivalents of ***pressure***, ***temperature*** and ***density***



$\ln P = A - B/T$

Experimental P-T data were matched by ***one-dimensional curve P (T)*** and ***Standard Van der Waals cupola*** (ρ - T)

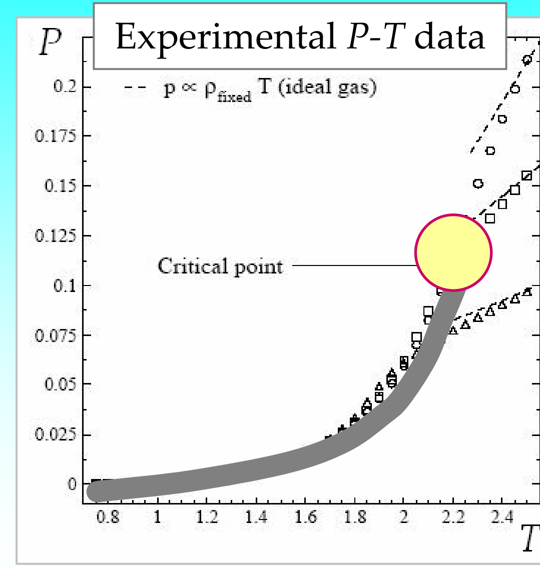


FIG. 2: Pressure p as a function temperature T.

This "Saturation Curve" P-T proved to be ***linear*** in ***Arrenius*** coordinates: $\ln P \Leftrightarrow 1/T$

- Standard "saturation curve" $\{P_S$-$T_S\}$
- Standard Van der Waals cupola (ρ - T)
- Standard Critical Point

This ***Van der Waals cupola*** (ρ - T) proved to be matched by ***Guggenheim's*** equations: $\rho\ (T)$

(Guggenheim's eqn.)

$$\frac{\rho_{l,v}}{\rho_c} = 1 + b_1\left(1 - \frac{T}{T_c}\right) \pm b_2\left(1 - \frac{T}{T_c}\right)^{\beta}$$

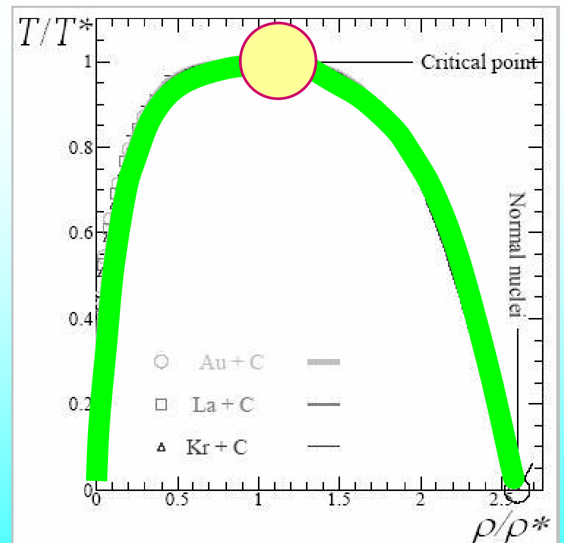
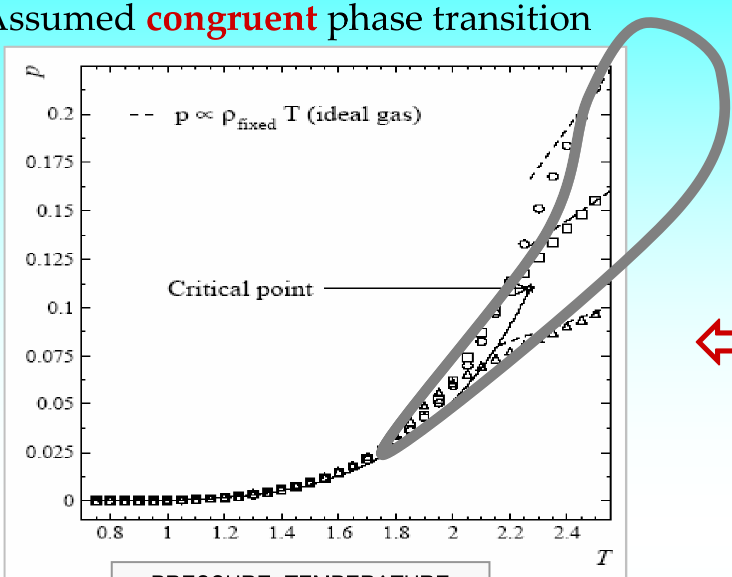


FIG. 6. The points are calculations performed at the excitation energies below the critical point and the lines are a fit to and reflection of Guggenheim's equation.

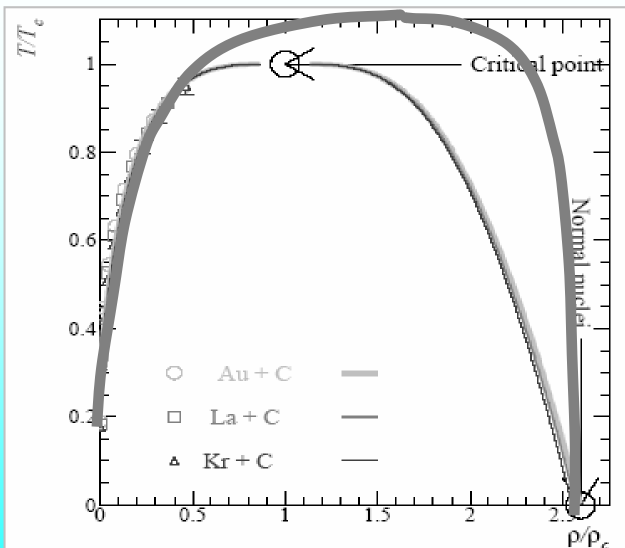
arXiv:nucl-ex/0205004 v1 8 May 2002

Hypothetical phase coexistence in multi-fragmentation of nuclear matter: is it CONGRUENT or NON-CONGRUENT ?

Assumed **congruent** phase transition



PRESSURE -TEMPERATURE

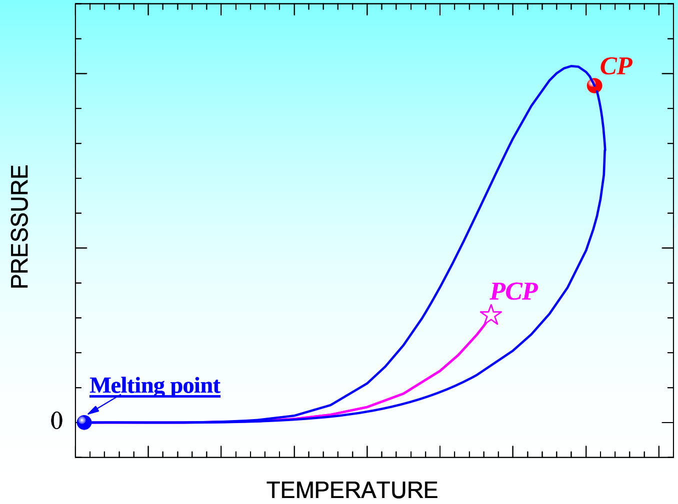


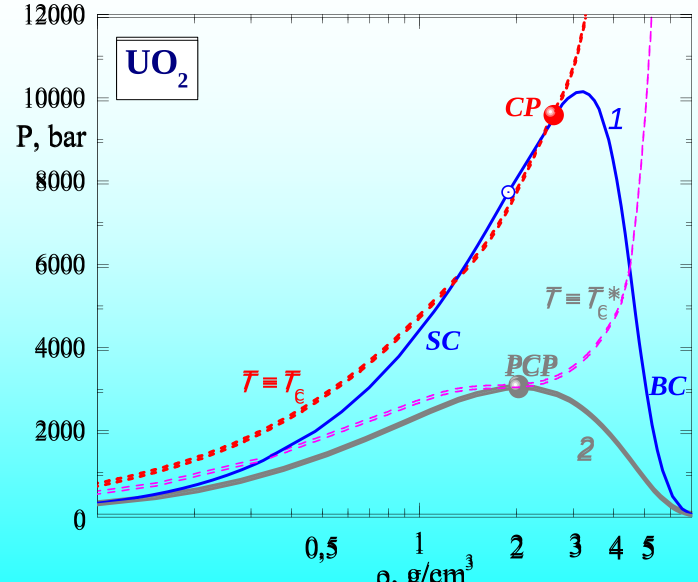
DENSITY -TEMPERATURE

⇔

⇔

Non-congruent phase transition





$_{197}\mathbf{Au}^{79}$

$Y = 0.67$

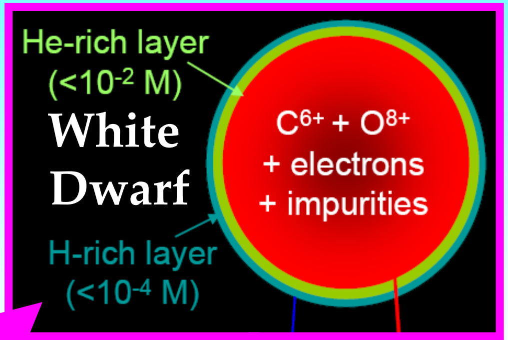
Non-congruence in exotic situations

(*discussion*)

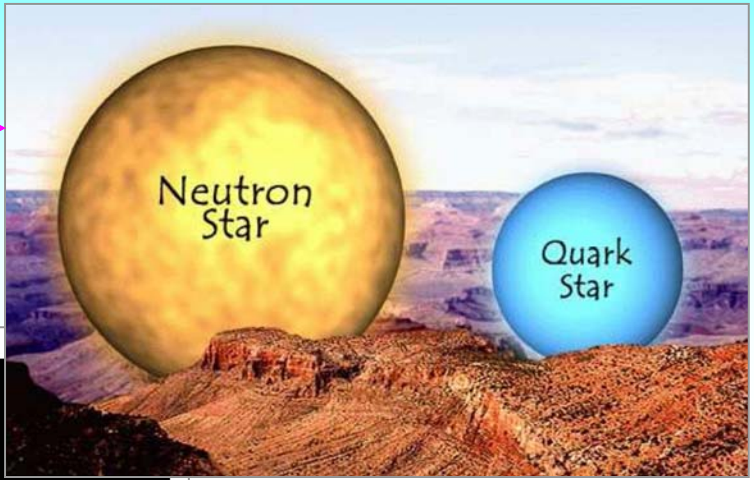
Non-congruence in compact stars and supernova explosion

Compact stars

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



Neutron and “Strange” Stars



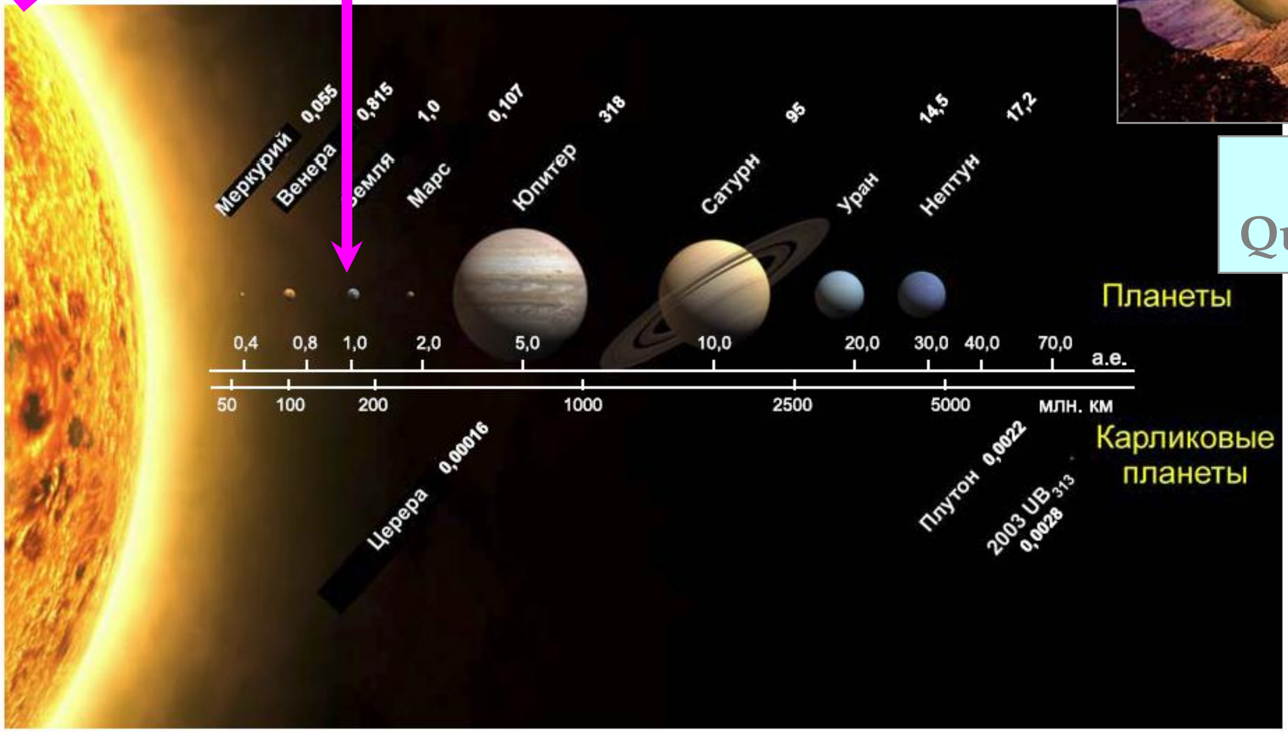
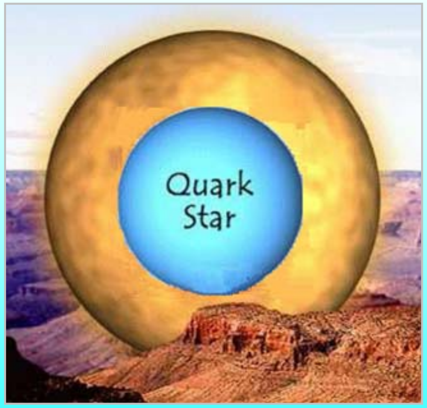


Рис. 65. Массы планет (в единицах массы Земли) и их среднее расстояние от Солнца [371]

Hybrid Stars

Quark core + Hadron Crust

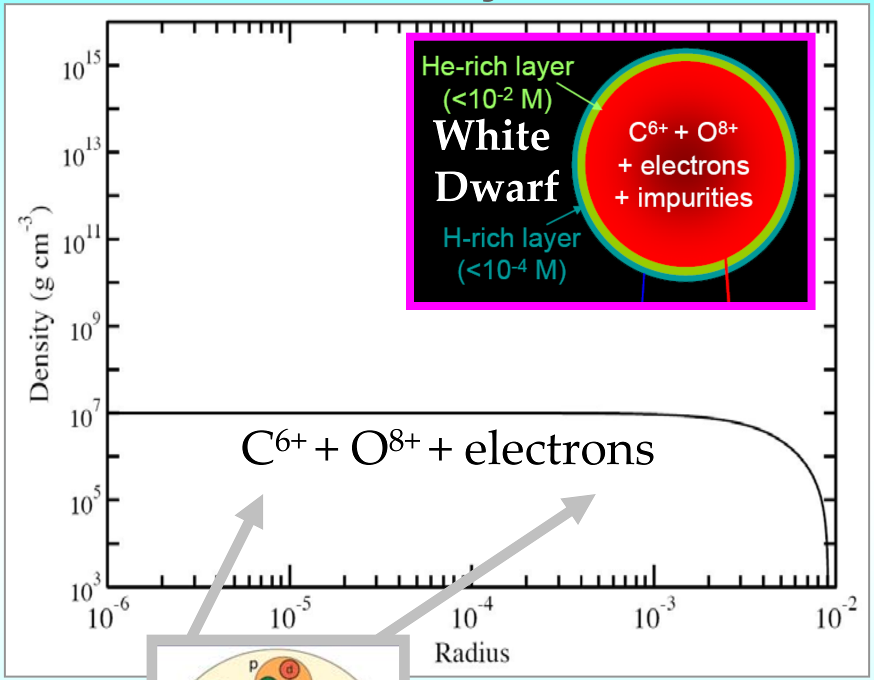


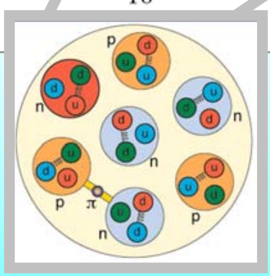
|← R ~ 10 km →|

Hybrid ("strange") white dwarfs

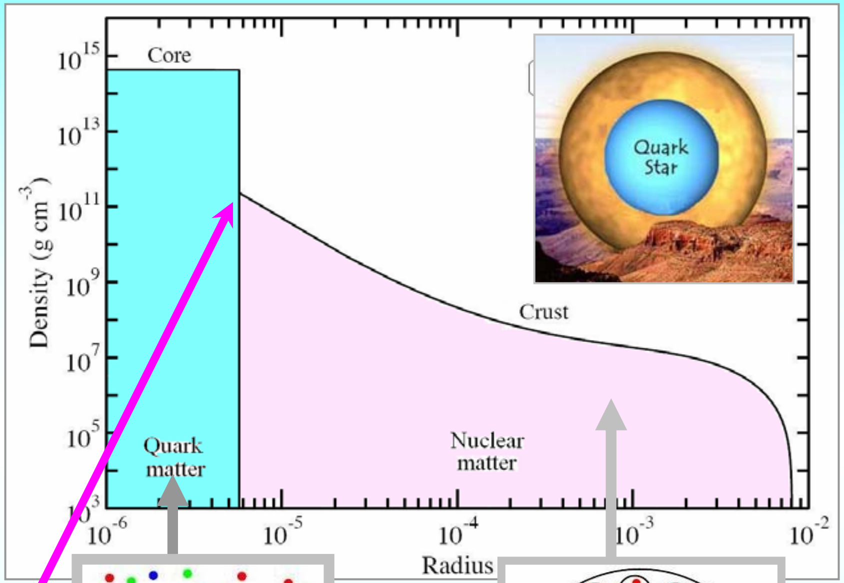
Mathews G., Weber F. et al. *J. Phys. G*, 32, (2006) - *White dwarfs with strange-matter cores*

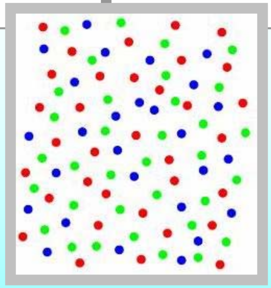
Ordinary WD

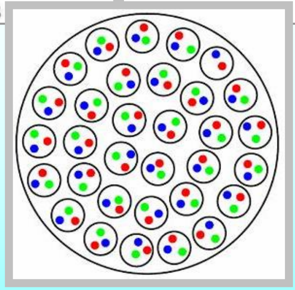




Strange WD







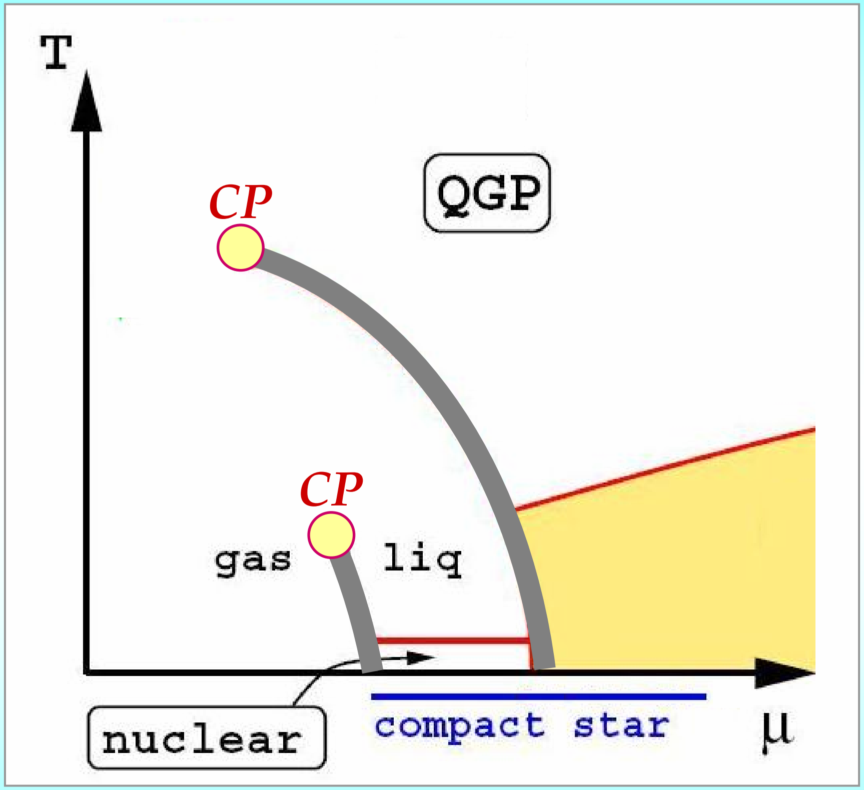
Phase transition ?

Jump-like ?

or ***Extended ?***

Hypothetical non-congruence
for phase transitions *in* high density matter

(*discussion*)

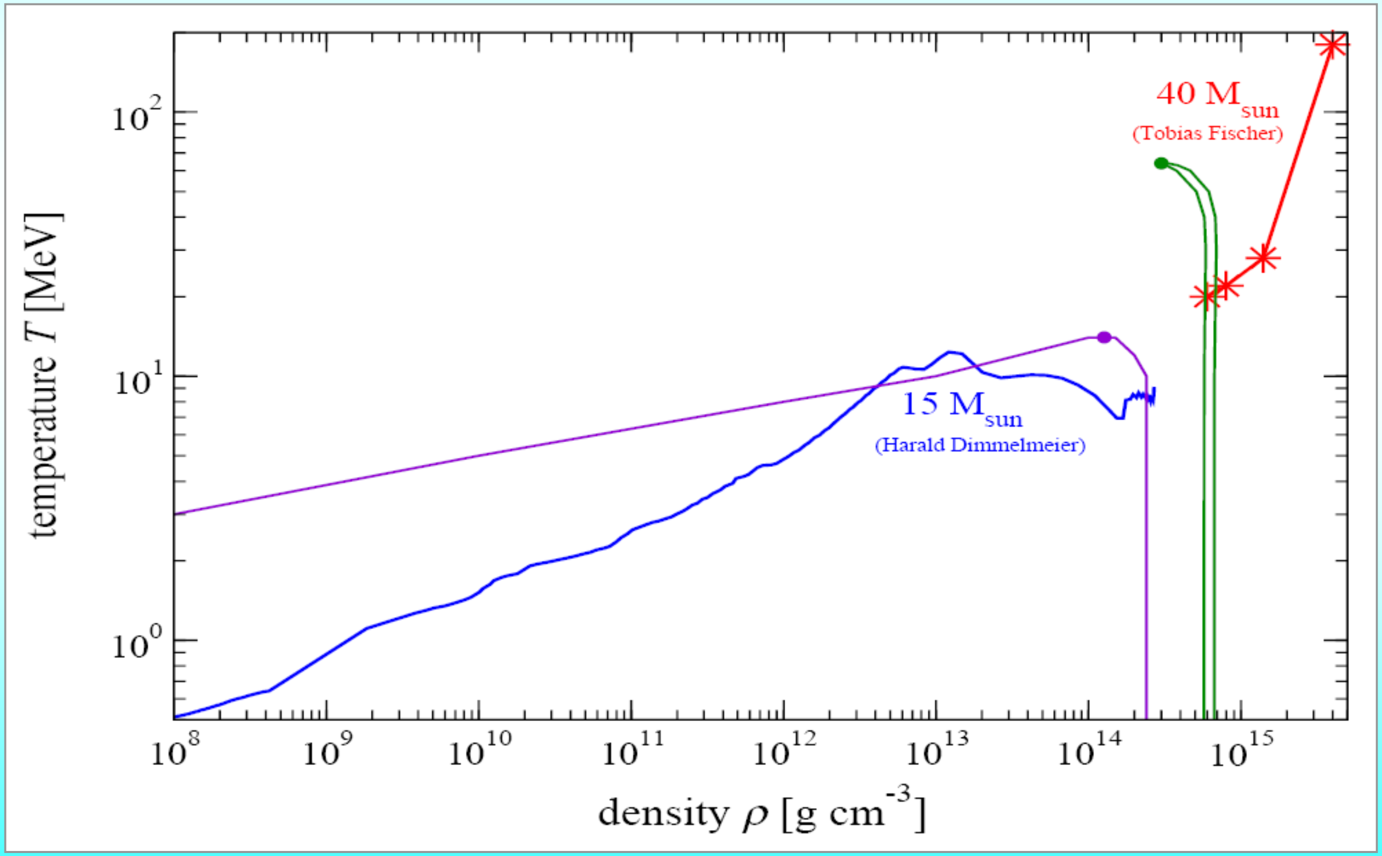


- "Gas-Liquid" phase transitions
- Quark-Hadron phase transitions

Non-congruence in exotic situations

(*discussion*)

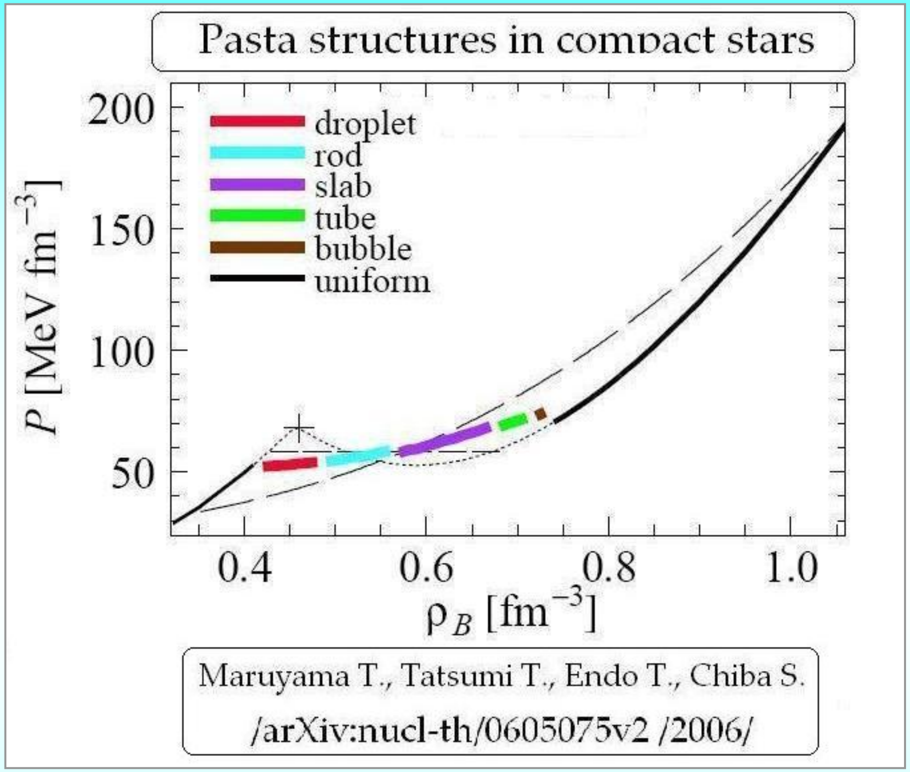
Supernova Collapse in the Phase Diagram

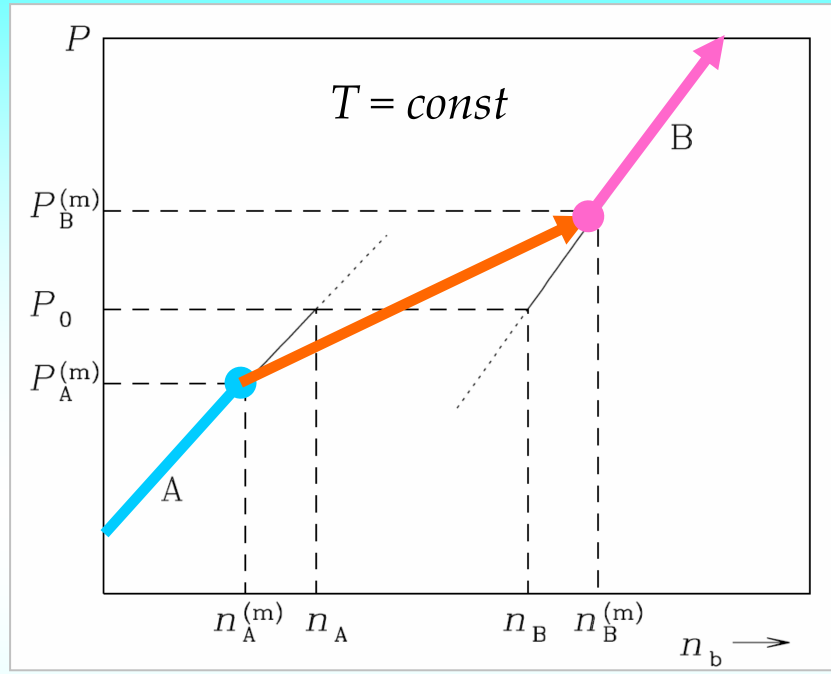


(*after D.Blaschke, "Extreme Matter", Elbrus-2010*)

Hypothetical phase transitions in interior of compact stars:

are they CONGRUENT or NON-CONGRUENT ?





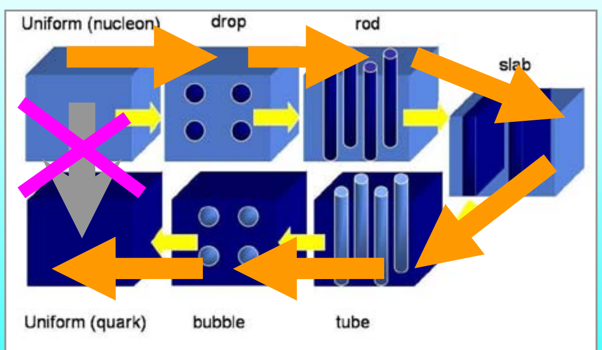
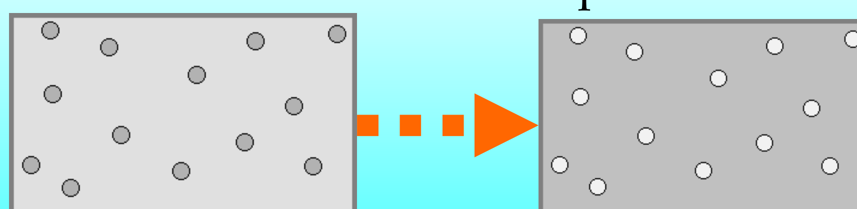


Figure 2: Schematic image of structured mixed phase.

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

First quark droplets in hadron matter

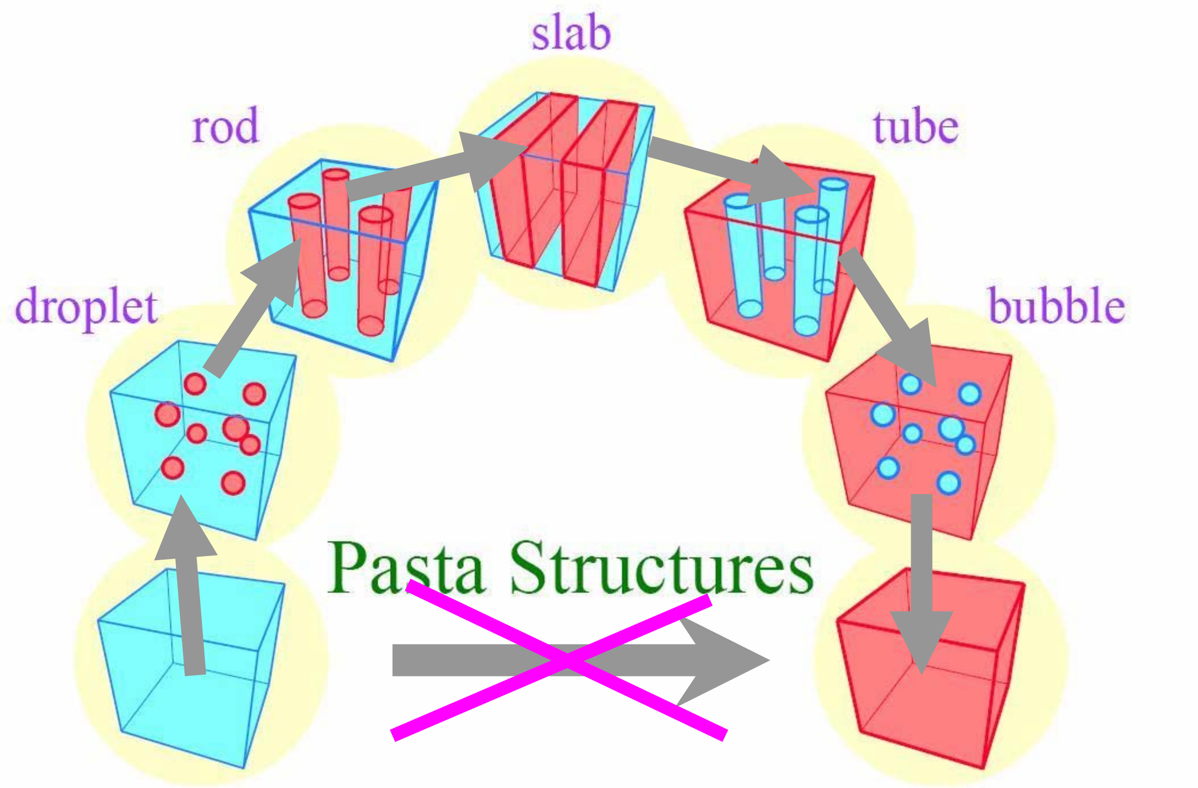
Last hadron bubbles in quark matter



"Dew" point

"Bubble" point

Structured Mixed Phase Concept ⇔ "Pasta"

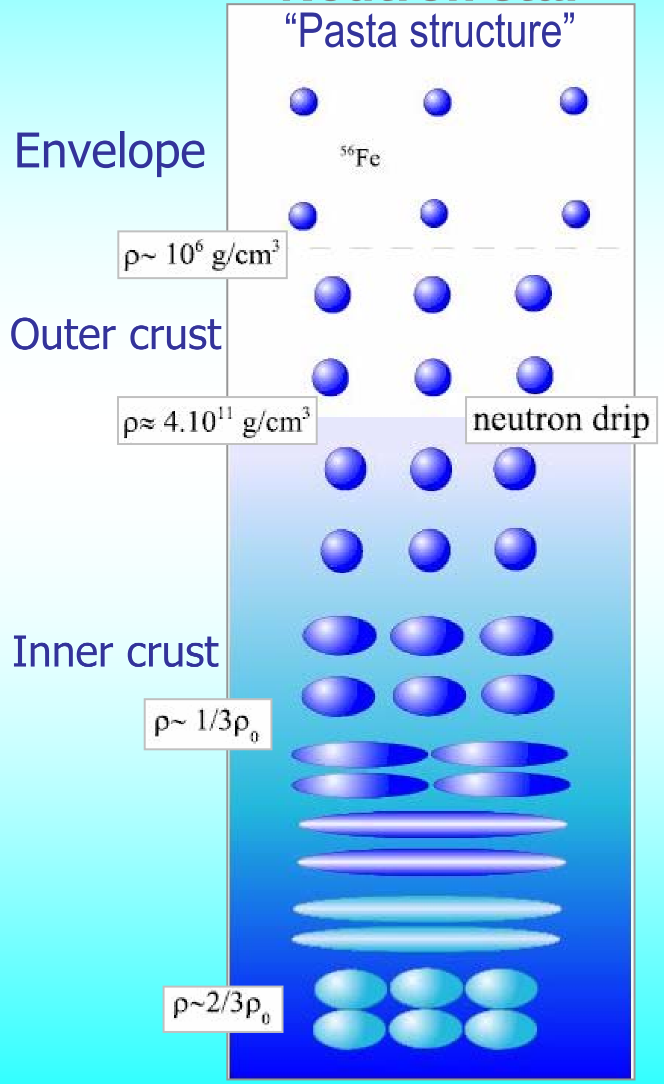


Schematic picture of pasta structures. Phase transition from blue phase (left-bottom) to red phase (right-bottom) is considered.

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

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

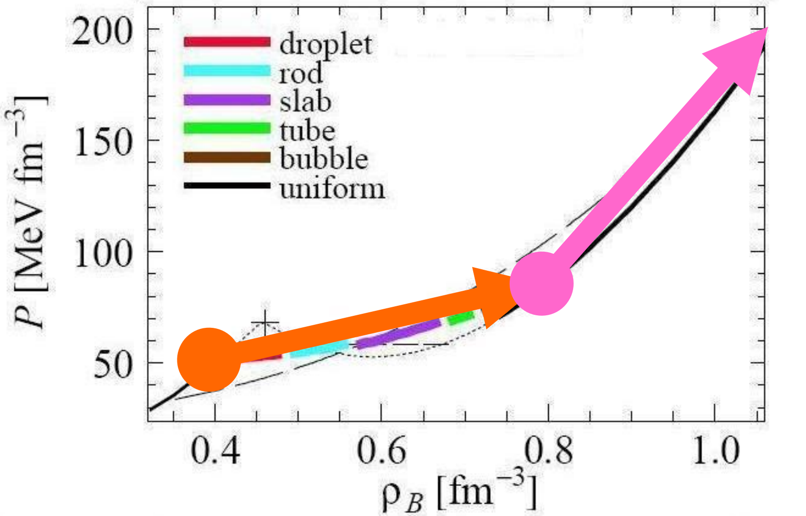
Neutron star



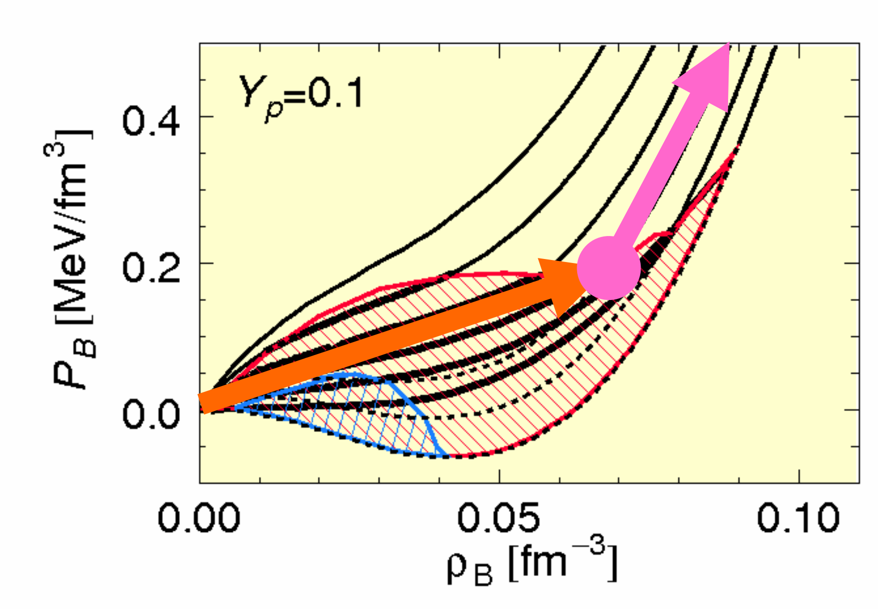
Non-congruence in exotic situations

(*discussion*)

Quark-Hadron *and* **Gas-Liquid**
phase transitions via "mixed-phase" scenario
have the same features as non-congruent PT !



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

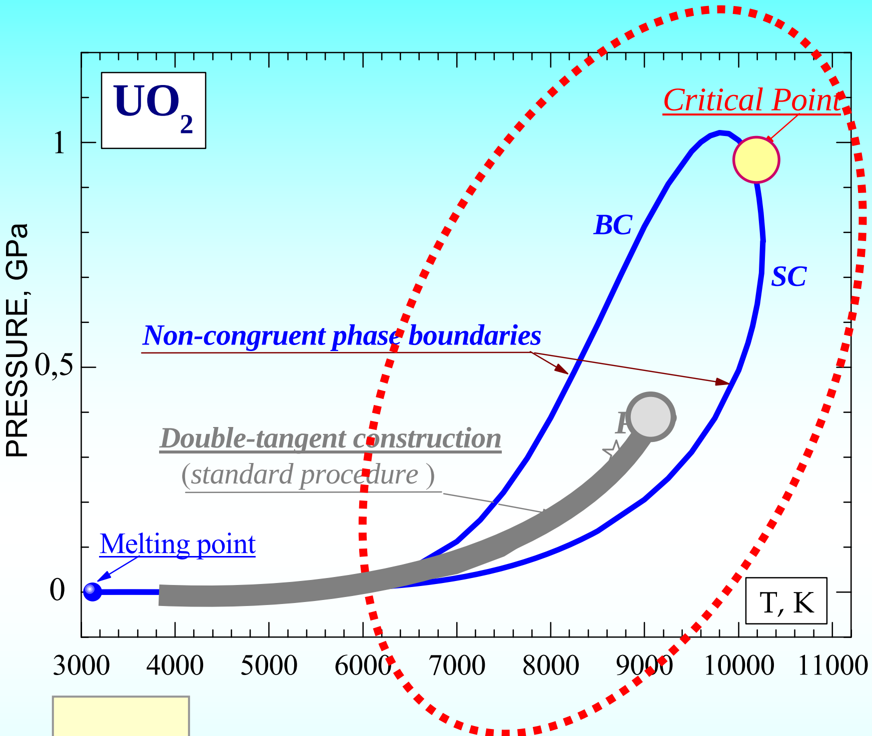


Mixed phase scenario
in non-symmetric nuclear matter

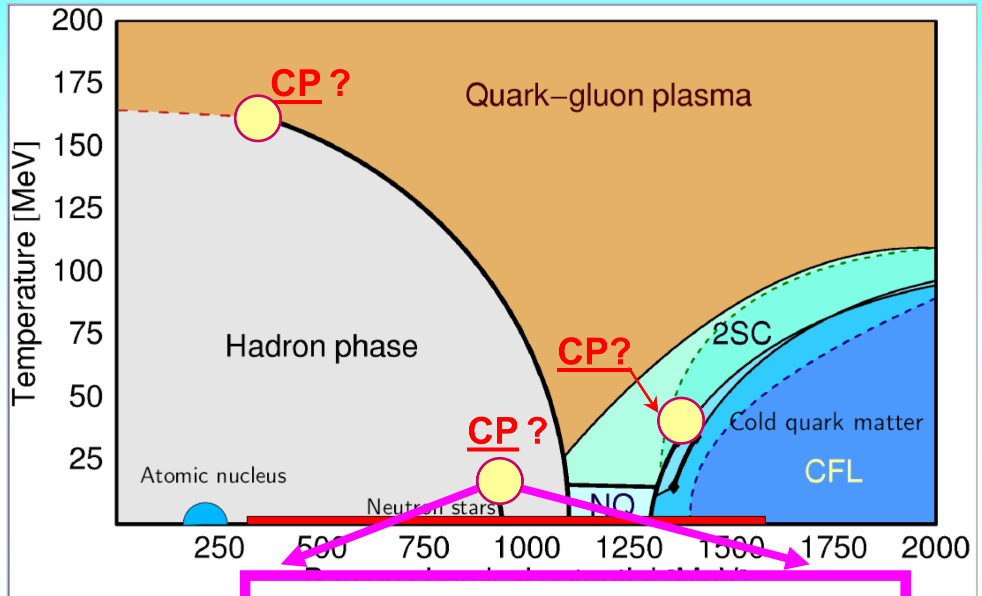
T. Maruyama et al. *FAIR-Russia School, Moscow, 2009*

Hypothetical phase transitions in ultra-dense matter:

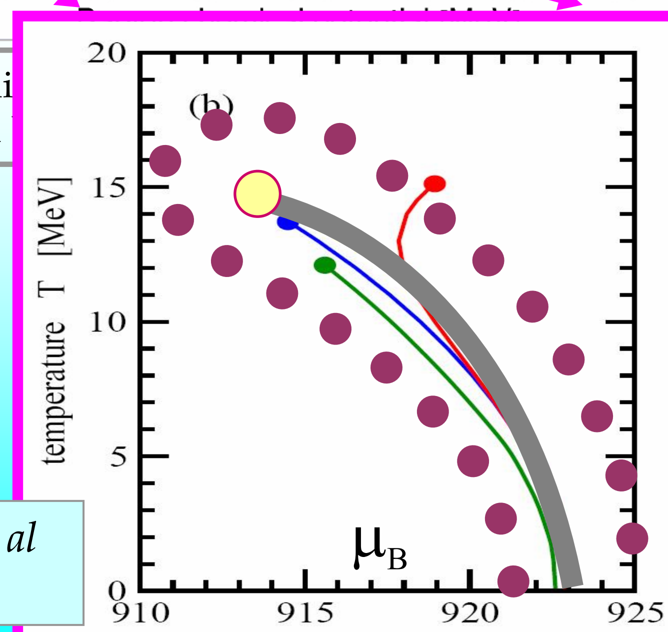
are they CONGRUENT or NON-CONGRUENT ?



Phase diagram of quark-hadron matter



After Fridoli... 006
After David ... 007



?

- Forced-congruent phase transition

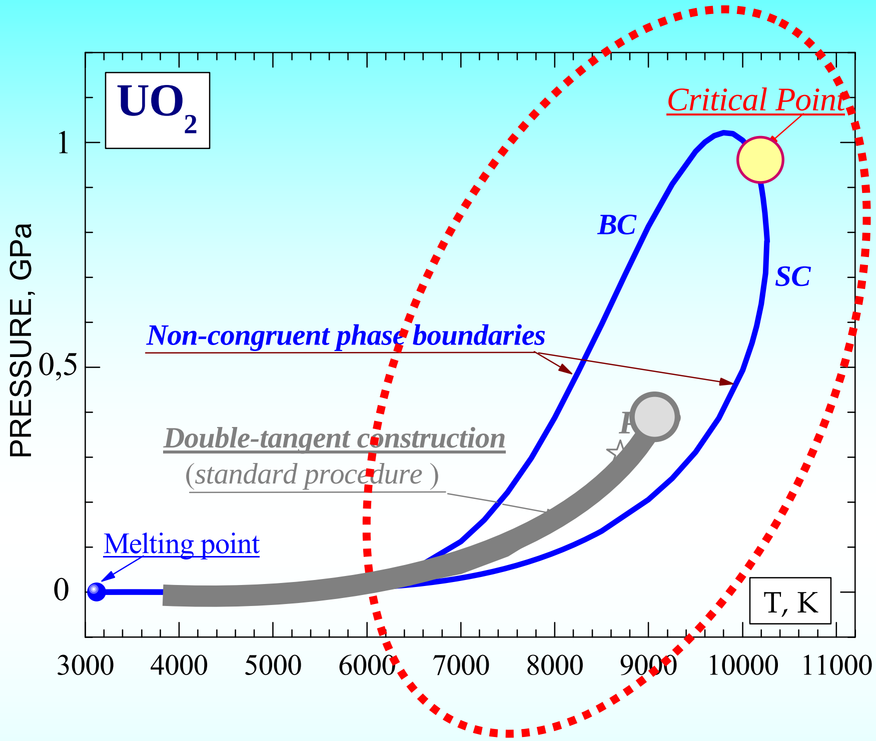
- Non-congruent phase transition

S. Typel, G. Roepke, D. Blaschke *et al*
/ arXiv:0908.2344v1/2009

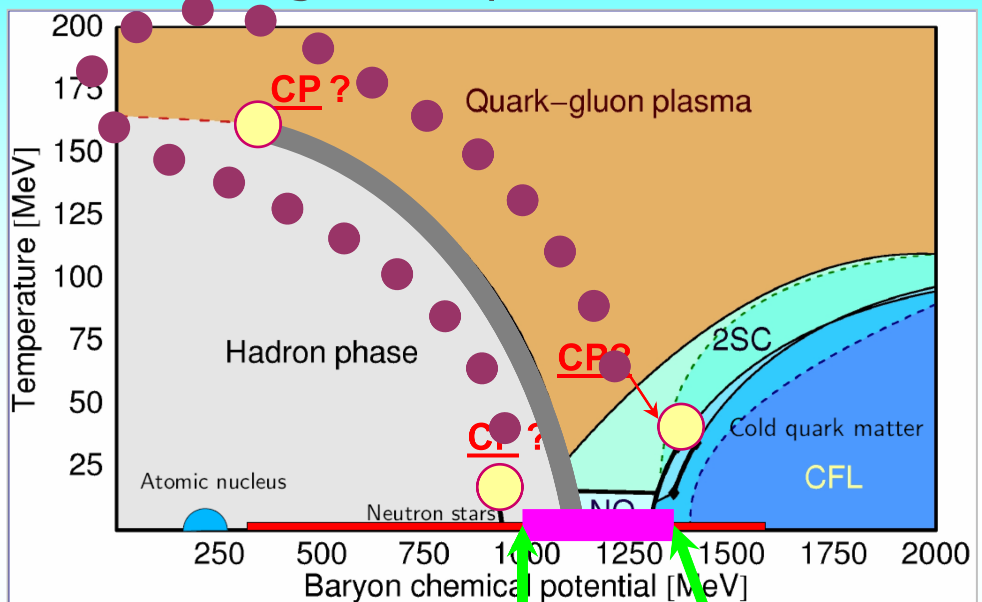
Iosilevskiy I. /

Hypothetical phase transitions in ultra-dense matter:

are they CONGRUENT or NON-CONGRUENT ?



Phase diagram of quark-hadron matter



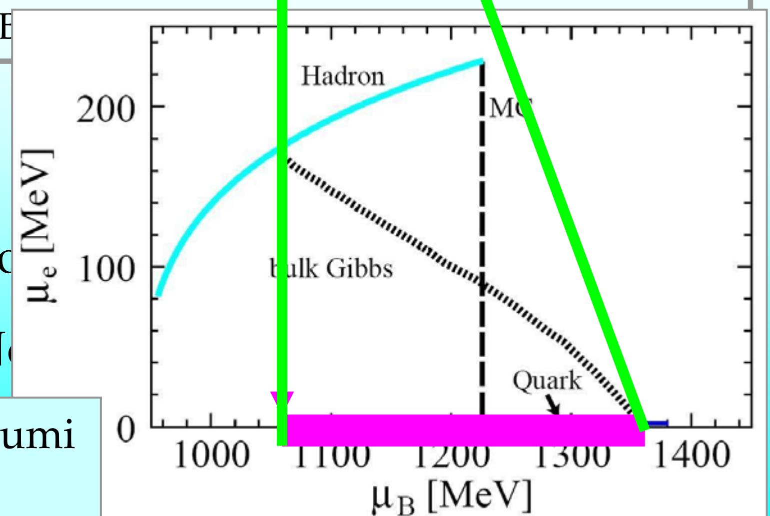
After Fridolin Weber, WEHS Seminar, Bad Honnef, 2006

After David B

?

- Fo

- N

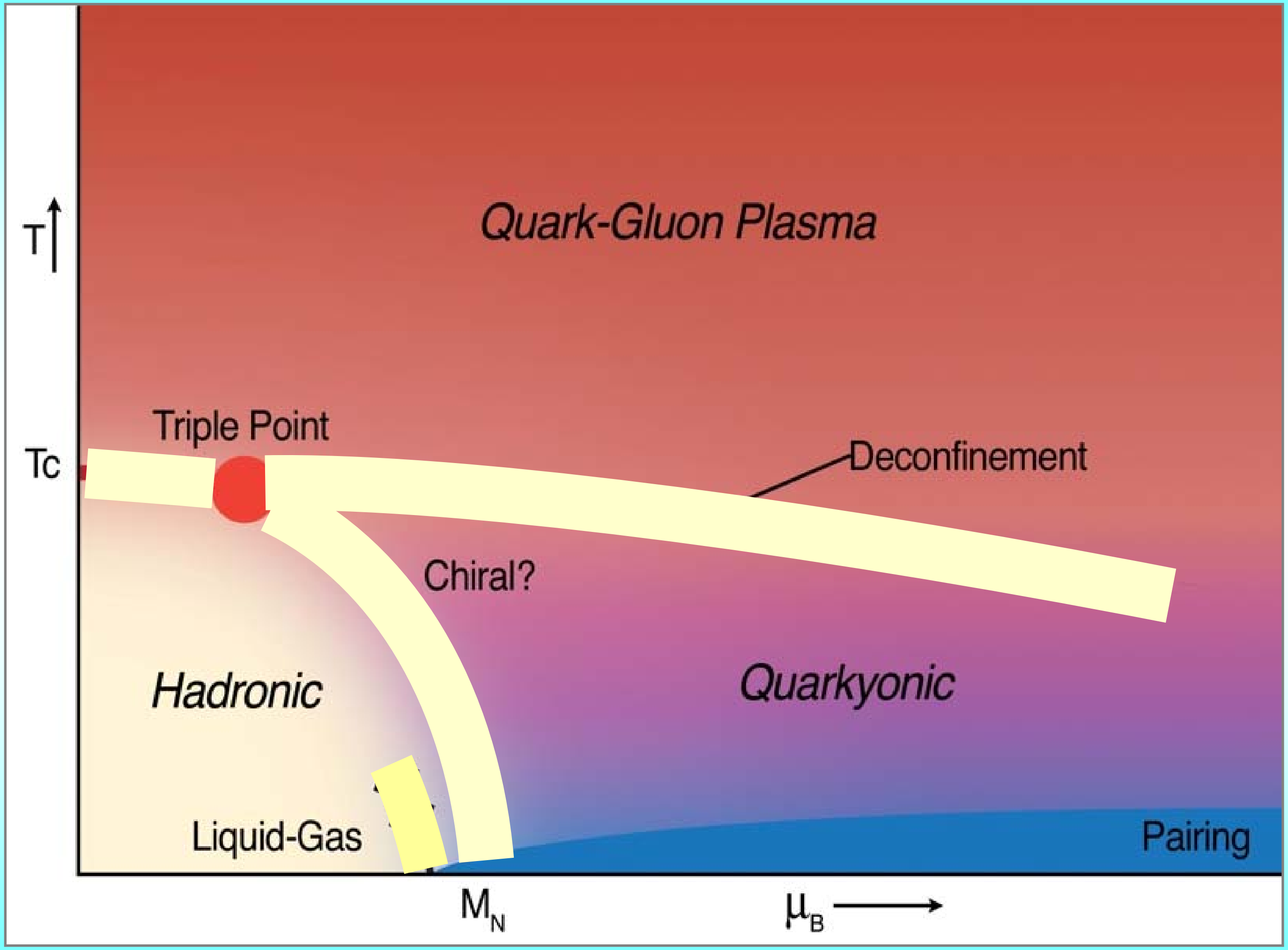


T. Endo, T. Maruyama, S. Chiba, T. Tatsumi / arXiv:0601017v1/2006

Iosilevskiy

Hypothetical phase transitions in ultra-dense matter:

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

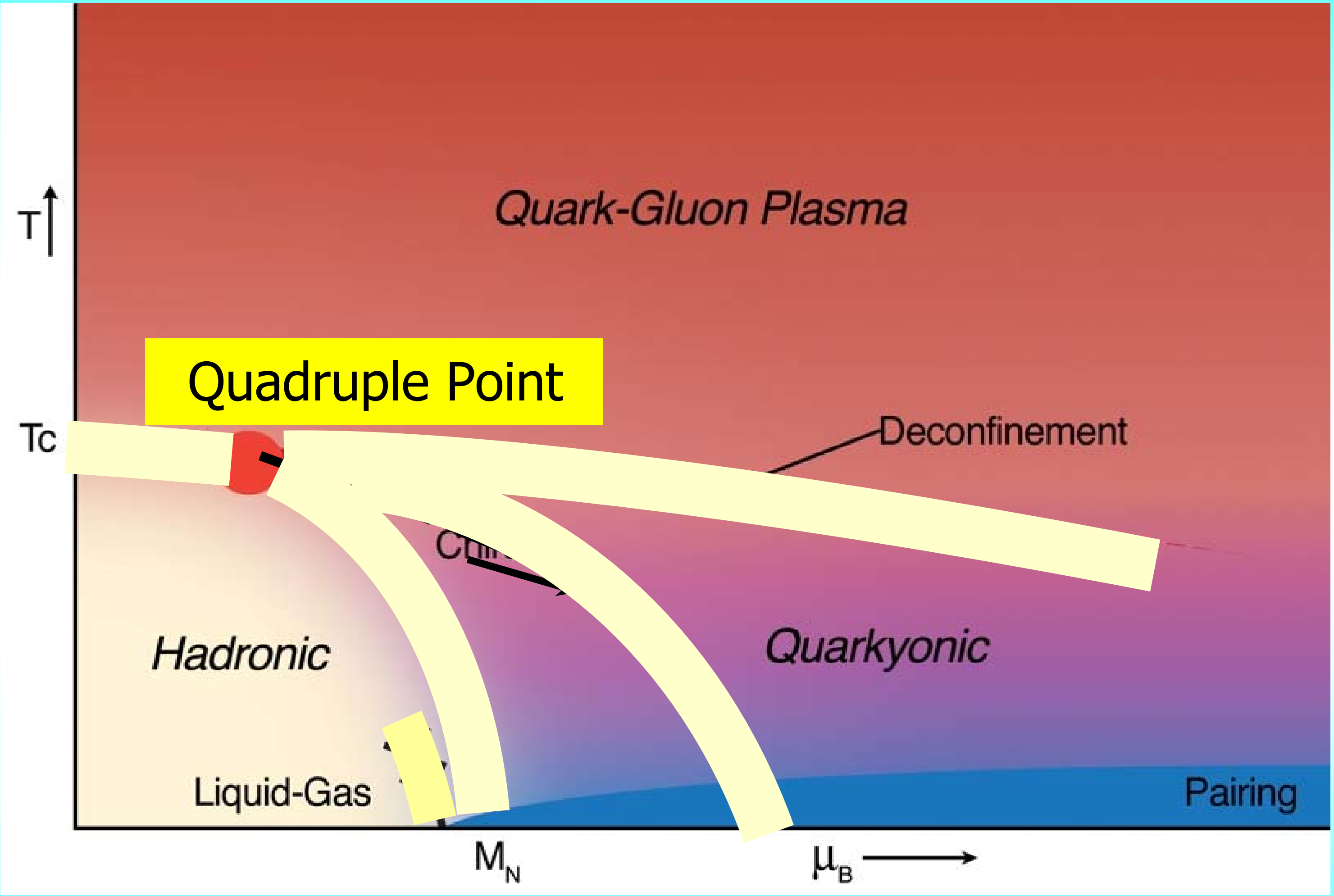


Hypothetical phase diagram with Triple Point

after R. Pisarski, EMMI Workshop, Wroclaw, July 2009

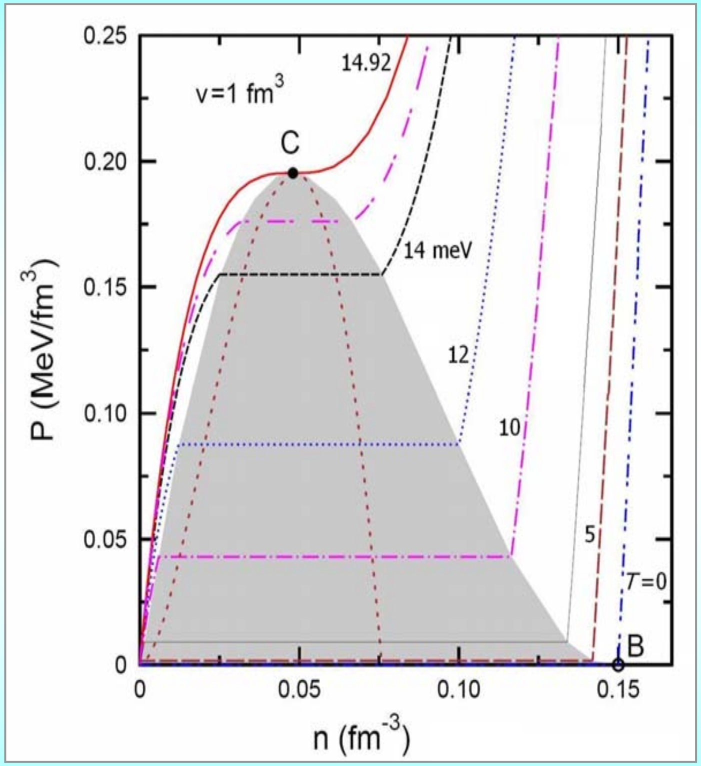
Hypothetical phase transitions in ultra-dense matter:

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



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

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



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

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

Macroscopic phases

No electrons
No Coulomb effects

(1) **Ensemble**: $p + n + N(A,Z)$ | **Equilibrium**: $N(A,Z) = Zp + (A - Z)n$

(2) **Ensemble**: $p + n + N(A,Z) + e$ | **Equilibrium**: $N(A,Z) = Zp + (A - Z)n$ // *electroneutrality*

(3) **Ensemble**: $p + n + N(A,Z) + e$ | **Equilibrium**: $N(A,Z) = Zp + (A - Z)n$ // ***β – equilibrium***

Mixed phase scenario

No surface effects

1 2 3

Structured mixed phase scenario

With surface effects | *With Coulomb effects*

1 2 3

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

Macroscopic phases

No electrons
No Coulomb effects

(1) **Ensemble**: $p + n + N(A,Z)$ | **Equilibrium**: $N(A,Z) = Zp + (A - Z)n$

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

(2) **Ensemble**: $p + n + N(A,Z) + e$ | **Equilibrium**: $N(A,Z) = Zp + (A - Z)n$ // *electroneutrality*

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

(3) **Ensemble**: $p + n + N(A,Z) + e$ | **Equilibrium**: $N(A,Z) = Zp + (A - Z)n$ // $\boldsymbol{\beta}$ **– equilibrium**

1-dimensional system $\{p = e\}$ → **Forced-congruent PT** — **GGC**

NB !

Independently on symmetry (Y)

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

Macroscopic phases

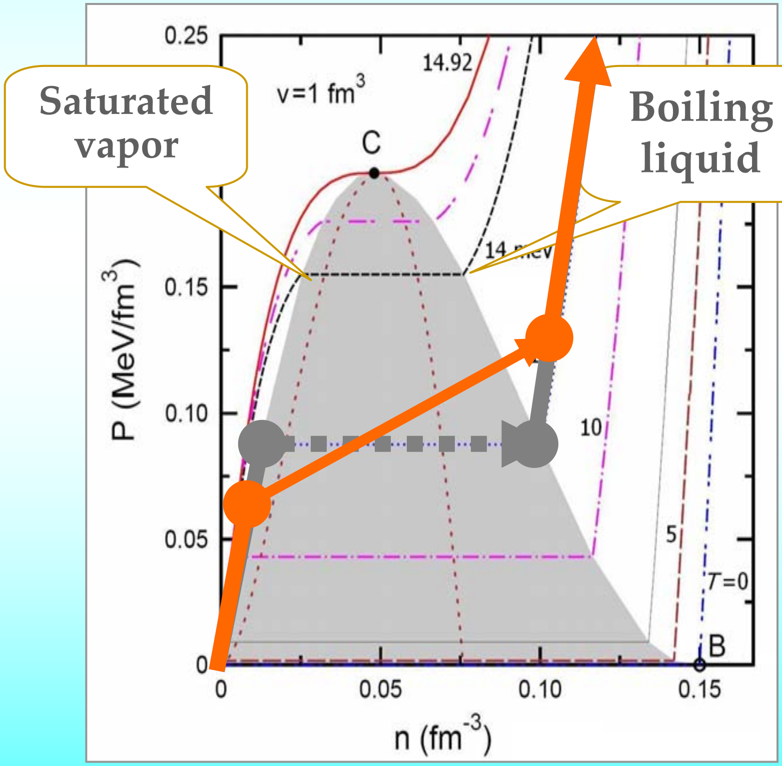
(1) **Ensemble:** $p + n + N(A,Z)$ | **Equilibrium:** $N(A,Z) = Zp + (A - Z)n$

No electrons
No Coulomb effects

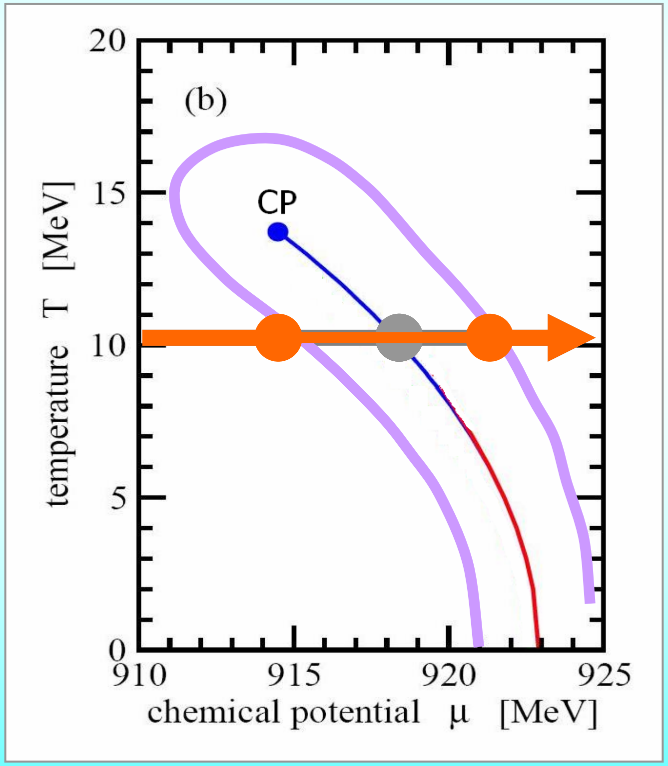
2-dimensional system $\{p+n\}$ → **Non-congruent PT**

Gibbs

?



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



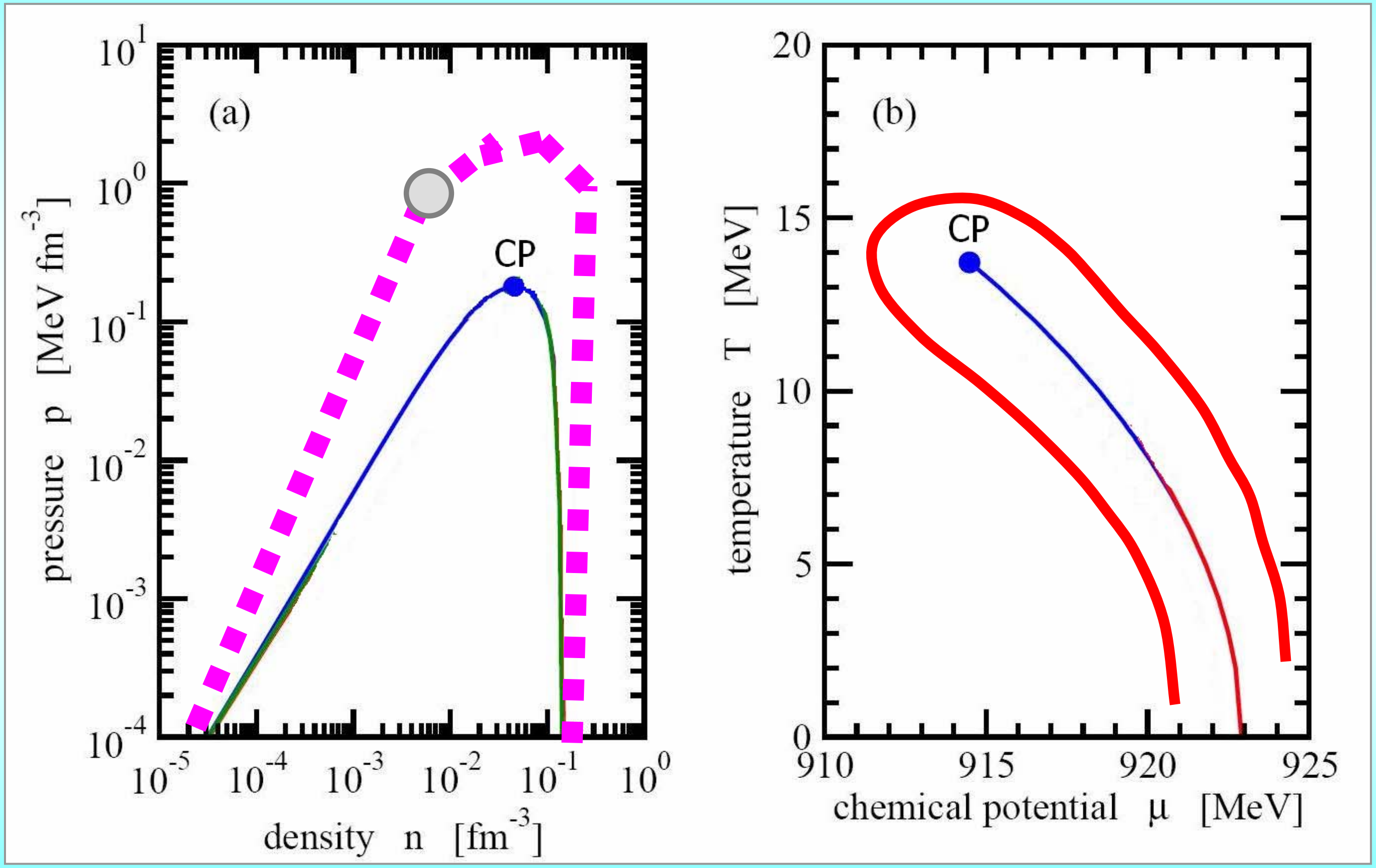
S. Typel, G. Roepke, D. Blaschke *et al.*
Phys. Rev. C, **81** (2010)

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

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

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

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

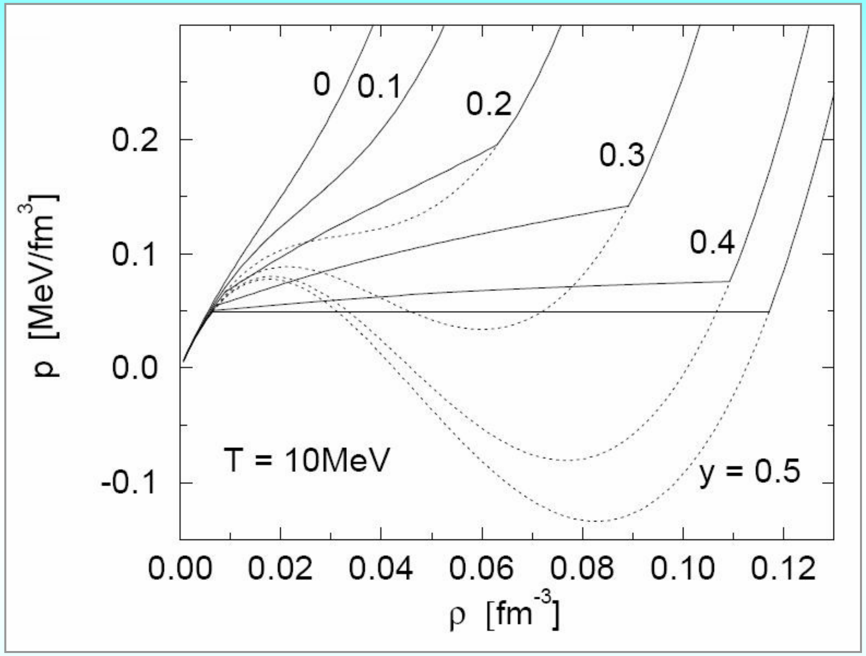


Phase diagram of (neutral) **non-symmetric** *p-n-N(A,Z)* nuclear matter with light clusters

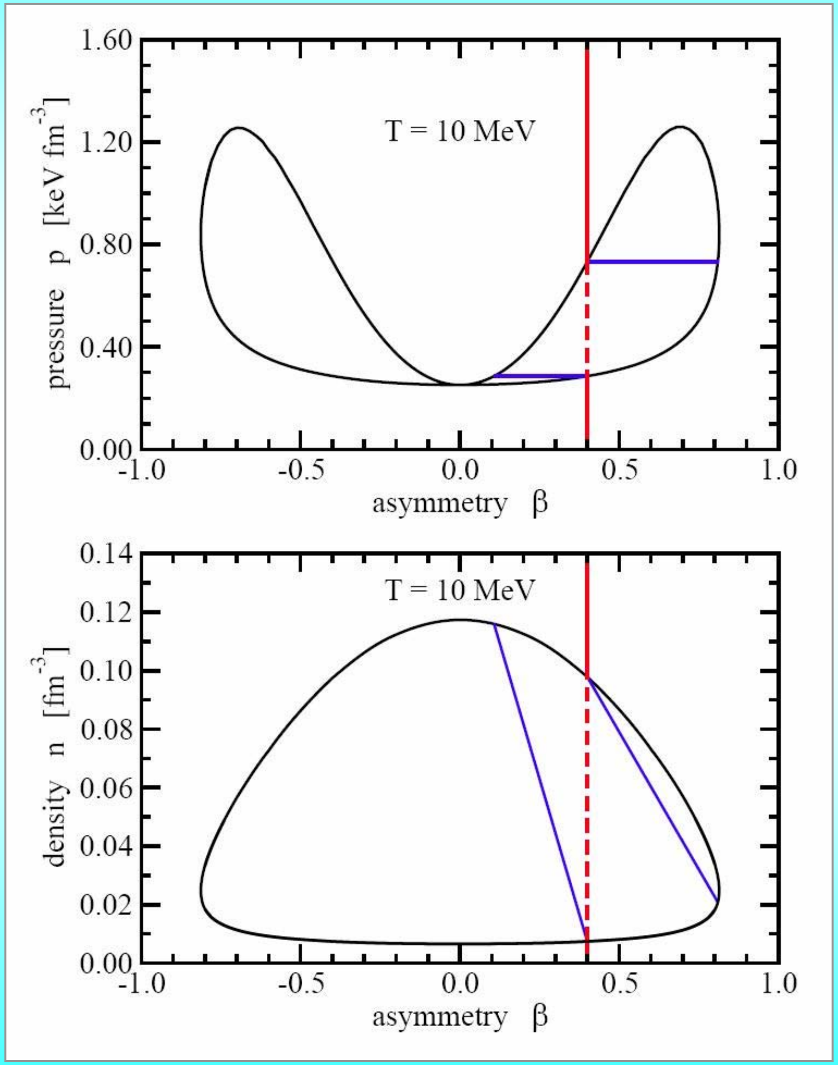
Muller H., Serot B., *Phys. Rev. C,* **52,** 2072 (1995)

Non-congruence in exotic situations

(*discussion*)

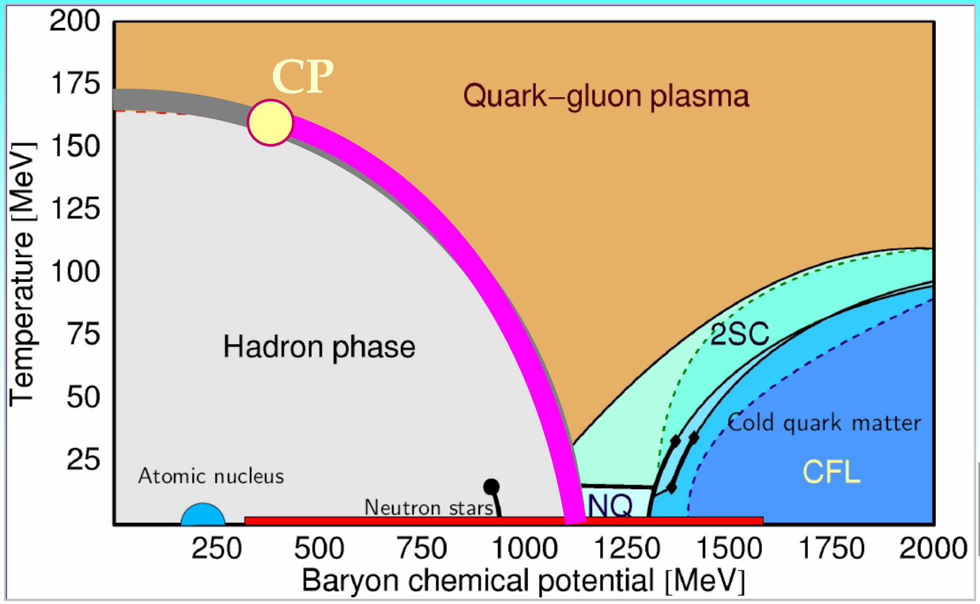


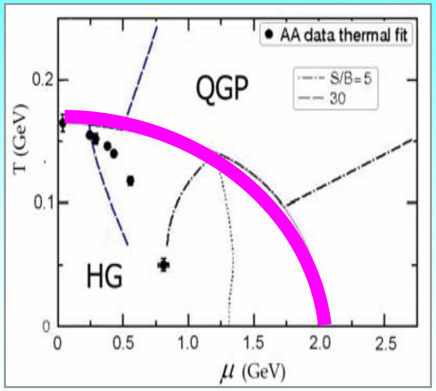
Muller H., Serot B., *Phys. Rev. C,* **52,** 2072 (1995)
nucl-th/9505013



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

Quark-Hadron PT *in* ultra-high-density matter





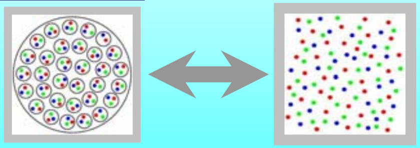
L.Satarov, M.Dmitriev, I.Mishustin
Phys. At. Nucl. (2009)

Macroscopic phases *(Gibbs-Guggenheim conditions)*

1-dimensional system $\{\mu_b\}$ → **Forced-congruent PT**

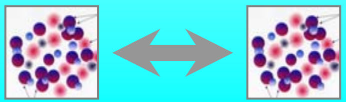
A *Separate EOS-s for quark and hadron phases*

No critical point !

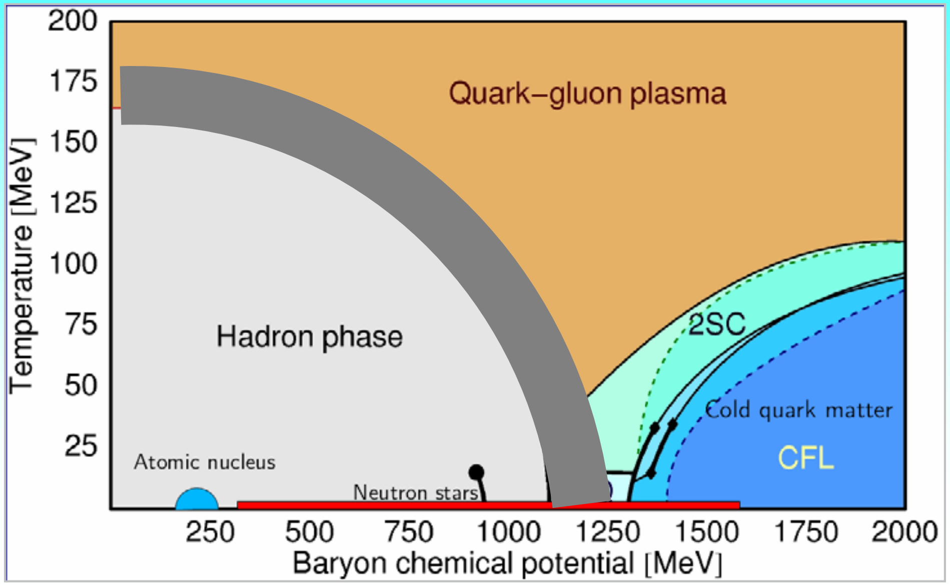


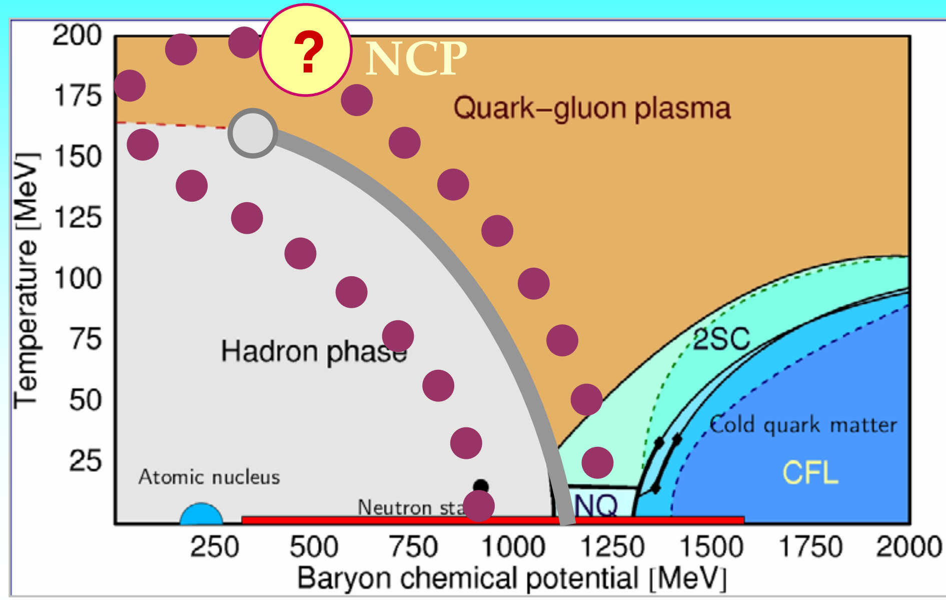
B *Unique EOS for quark and hadron phases* *(like in U-O)*

Critical point could exist !



Quark-Hadron PT *in* ultra-high-density matter



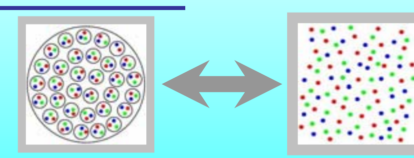


Mixed Phase (Gibbs-conditions for all species)

2-dimensional system $\{\mu_b, \mu_e\}$ → **Non-congruent PT**

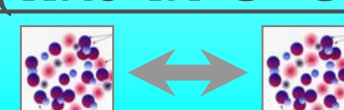
A *Separate EOS-s for quark and hadron phases –*
– 2-dim. zone in PT

No critical point !

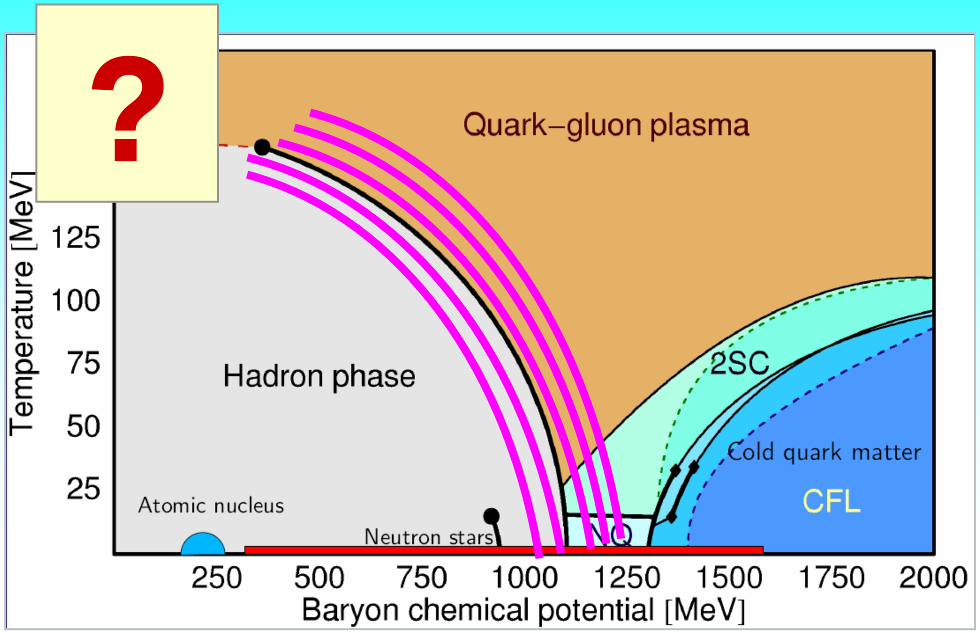


B *Unique EOS for quark and hadron phases (like in U-O)*

Non-congruent critical point could exist !



Quark-Hadron PT *in* ultra-high-density matter



Structured Mixed Phase Scenario

highly dispersive mixture for mini-fragments of both phases with optimal form, size and charge

[*for example*: Maruyama T., Tatsumi T., Voskresenskiy D., Tanigava T., Chiba S., *Phys. Rev.* C (2005)]

The question is open !

It looks as if we deal with not one, but several mini-phase transitions

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

Hypothetical phase transitions in ultra-dense matter

are they <u>CONGRUENT</u> or <u>NON-CONGRUENT</u> ?

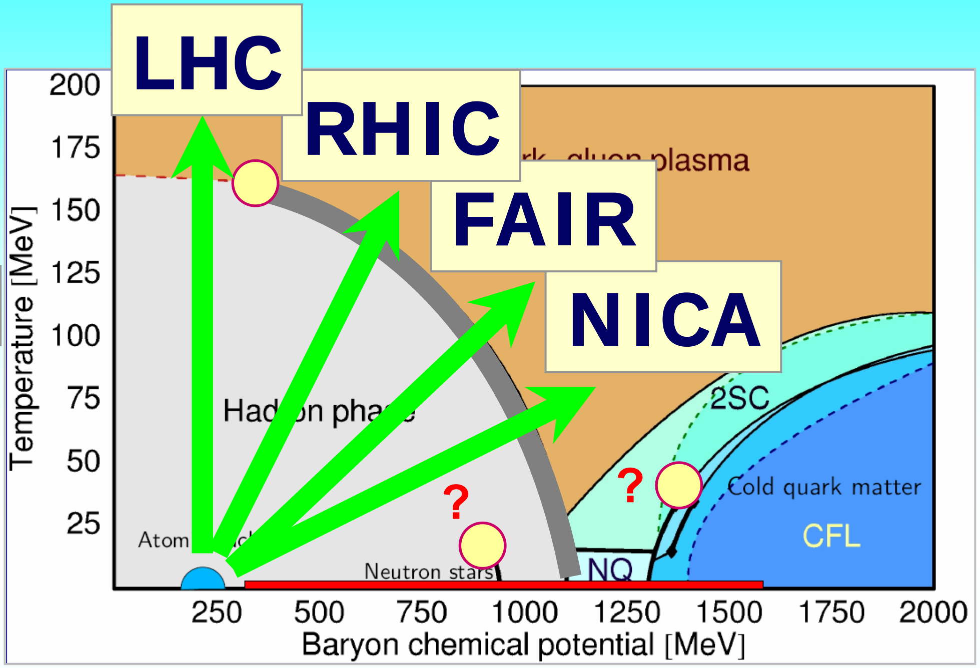
LHC – Cern

RHIC – Brookhaven

FAIR – Darmstadt

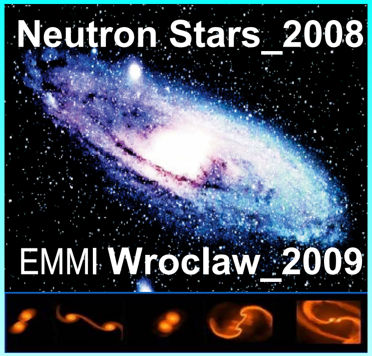
NICA – Dubna

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



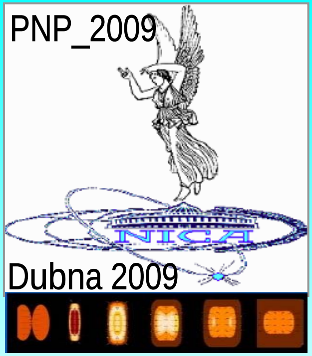
Quark-Hadron Phase Diagram

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



KFKI Institute for Particle and Nuclear Physics

Theoretical Physics Department, April, 2010



Conclusions *and* Perspectives

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

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

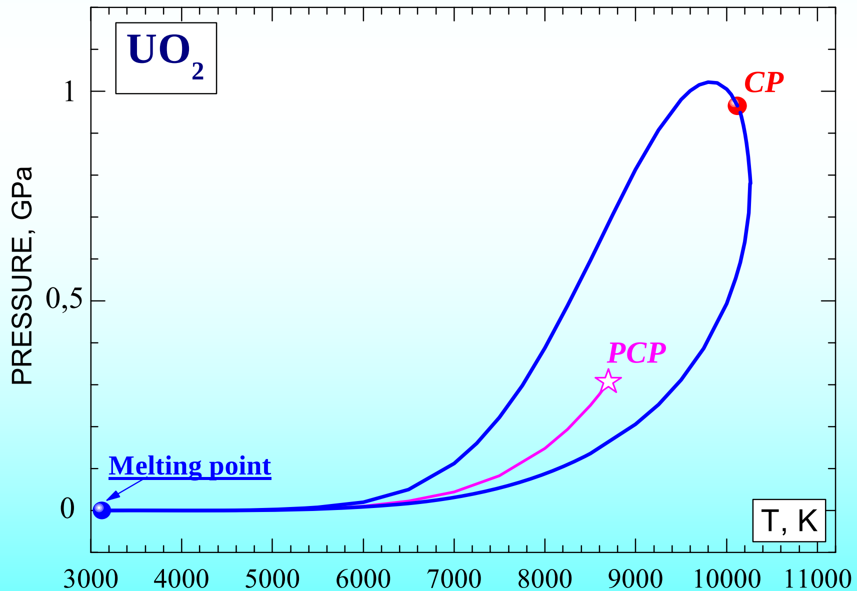
- If one takes into account hypothetical **non-congruence** of **phase transitions** in **cosmic matter** objects (*planets, compact stars, supernova etc.*) he should **revise** totally the **scenario** of all **phase transformations** in these objects.

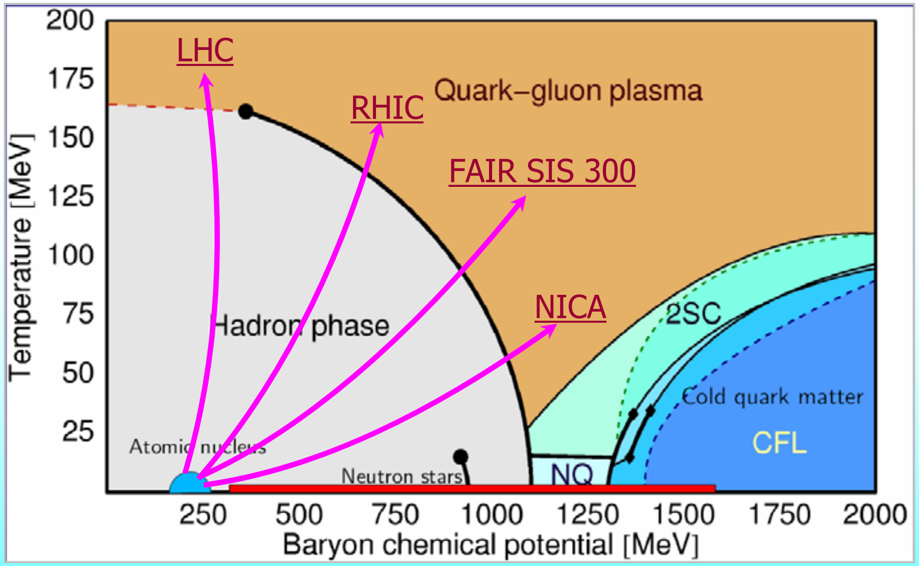
- We have good enough reason to expect **anomalous** features for **hydrodynamics** of isentropic **expansion** for **QGP fireball** when thermodynamic trajectory **crosses** the **Q-H phase boundary** (congruent or non-congruent)

- We have good enough reason to expect **anomalous** features for **hydrodynamics** of **expansion** and **compression** for **supernova** when thermodynamic trajectory **crosses** the **G-L phase boundary** (congruent or non-congruent)

Non-congruent phase transitions *in* cosmic matter *and* laboratory

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”

There will be enough challenges
to keep us all happily occupied for years to come.

Hugh Van Horn (1990)
(Phase Transitions in Dense Astrophysical Plasmas)

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

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Russian Academy of Science:

"Physics *and* Chemistry
of Extreme States *of* Matter"

MIPT Research & Educational Center
"High Energy Density Physics"

Cooperation
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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 // CRDF MO-011