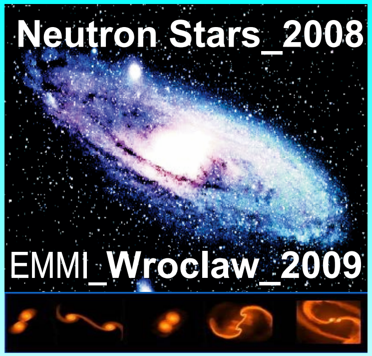


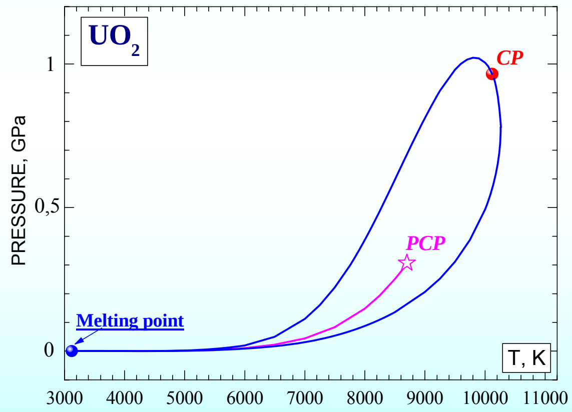
Critical Point and Onset of Deconfinement

JINR Dubna, Russia, August 2010

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Hypothetical Non-Congruence

of Quark-Hadron Phase Transition *and* Critical Point



Igor Iosilevskiy

Joint Institute for High Temperature (Russian Academy of Science)

Moscow Institute of Physics and Technology (State University)

arXiv:1005.4186v1

comp star

IHED RAS

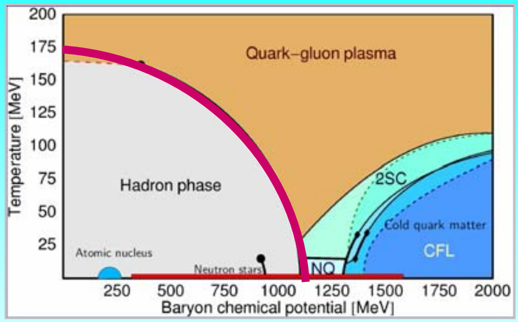
Extreme Matter Institute – EMMI

MIPT

EMMI

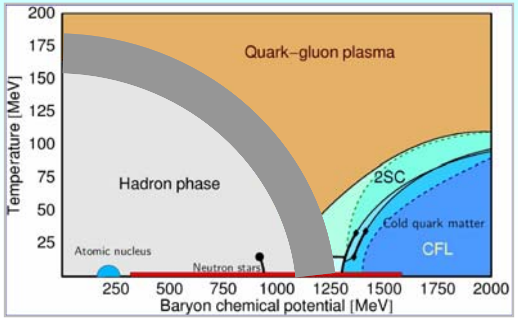
? ? ? ?

Coexistence of Macroscopic Phases



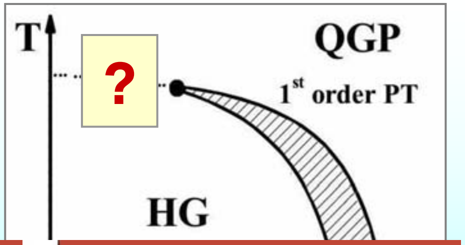
1st order // 1-D // End-point

1st order // 1-D // Unbounded *(no end-point)*

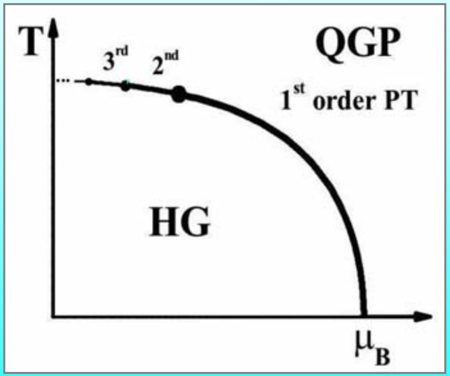


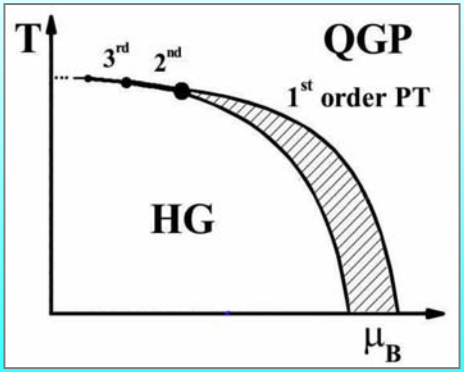
1st order // 2-D // No end-point *(stripe)*

1st order // 2-D // End-point

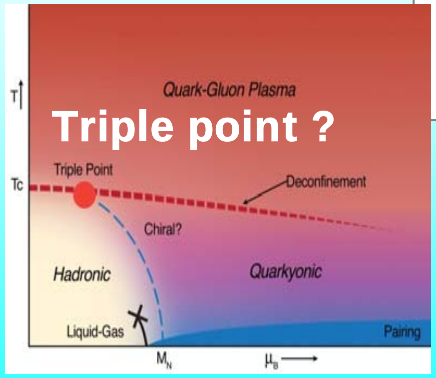


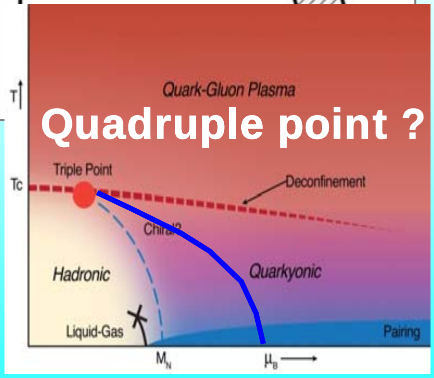
1st + 2nd + … // 1-D // 2-D // Several end-points





Mark Gorenstein (*Dubna-2006*)



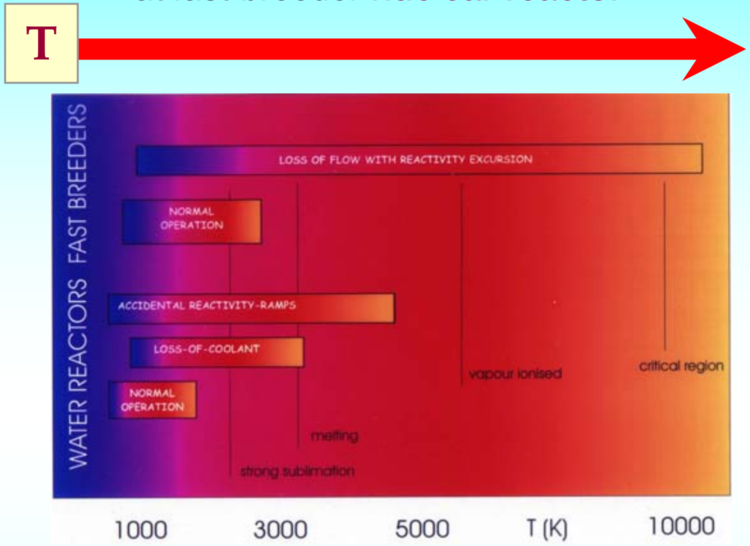


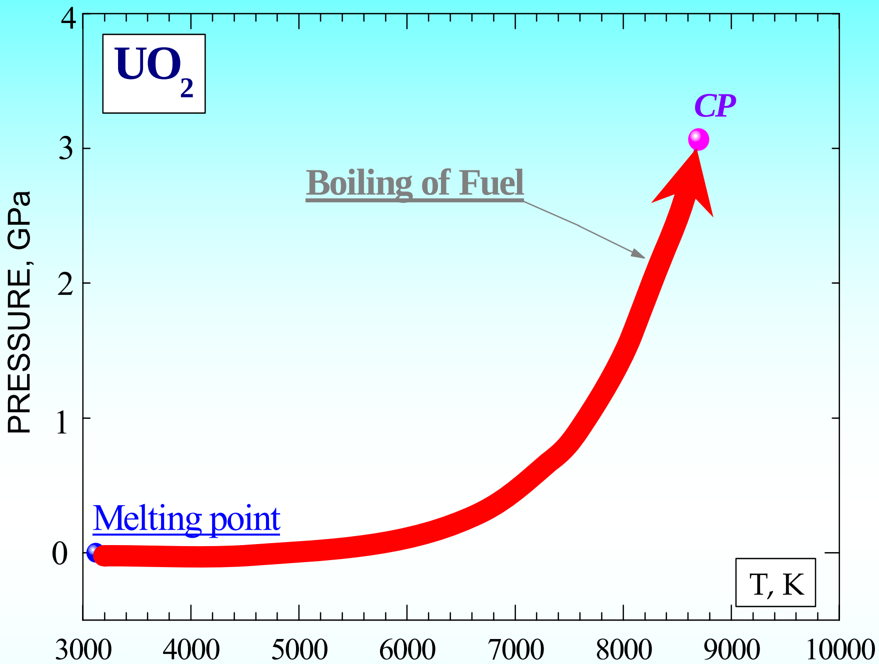
R. Pisarski, Wroclaw-2009 // L. McLerran Bad Honnef-2009

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)

Strong competition: Soviet Union ⇔ 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)

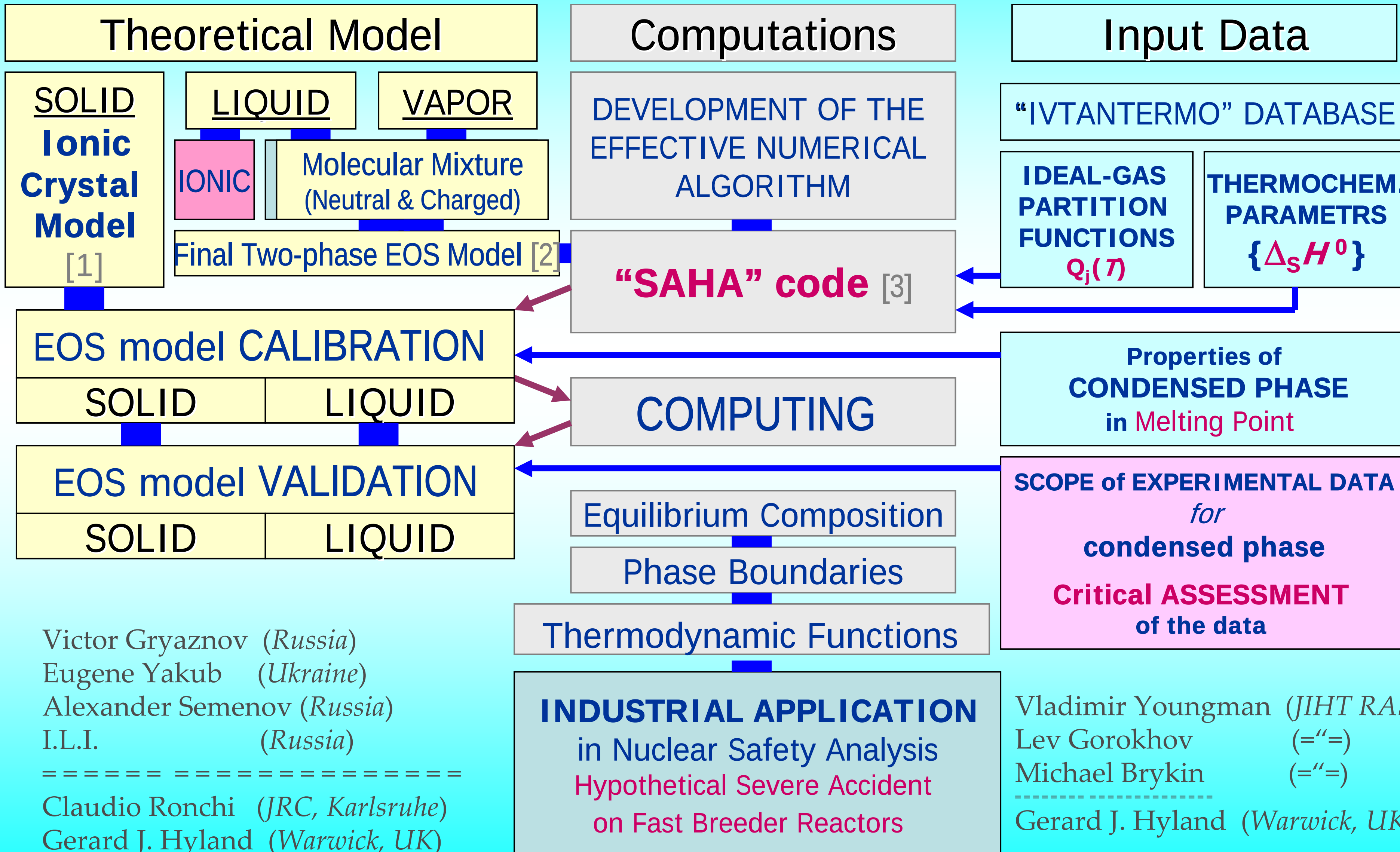
Two problems:

- Construction of Equation of State (EOS)

- Phase coexistence parameters calculation

INTAS Project (1995–2002)

Study of non-congruent evaporation in U-O system



Victor Gryaznov (*Russia*)
Eugene Yakub (*Ukraine*)
Alexander Semenov (*Russia*)
I.L.I. (*Russia*)
====== ===============
Claudio Ronchi (*JRC, Karlsruhe*)
Gerard J. Hyland (*Warwick, UK*)

Vladimir Youngman (*JIHT RAS*)
Lev Gorokhov (="=)
Michael Brykin (="=)
====================
Gerard J. Hyland (*Warwick, UK*)

Victor Gryaznov *&* I.I.

Quasi-chemical representation *for* liquid *and* vapour phases

Different EOS for coexisting phases

1

Ionic model (*Liquid*)

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

Multi-molecular model (*Vapour*)

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

No critical point **!**

Unique EOS for both coexisting phases

2

Combined ionic-molecular model

$U + O + O_2 + UO + UO_2 + UO_3 + U^{+} + UO^{+} + UO_2^{+} + O^{-} + UO_3^{-} + e^{-}$

Critical point exists **!**

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, (**2010**)

Quasi-chemical representation *for* liquid *and* vapour phases

Different EOS for coexisting phases

1

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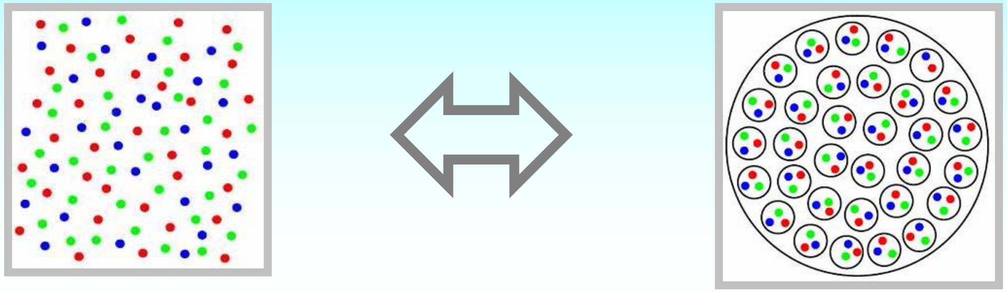
$U^{6+} + U^{5+} + U^{4+} + U^{3+} + O^{2-} + O^{-}$

Molecular model (*Vapour*)

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

No critical point **!**



Unique EOS for both coexisting phases

2

Combined ionic-molecular model

$U + O + O_2 + UO + UO_2 + UO_3 + U^{+} + UO^{+} + UO_2^{+} + O^{-} + UO_3^{-} + e^{-}$

Critical point exists **!**

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– Coulomb interaction between charged particles
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* Ronchi C., Iosilevskiy I., Yakub E. *Equation of State of Uranium Dioxide* / **Springer, Berlin,** (2004)

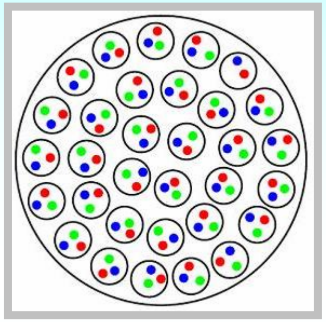
Quasi-chemical representation

("Chemical picture" - in plasma community)

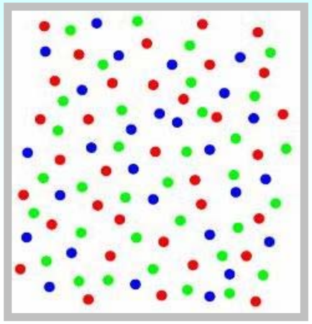
Strange (hybrid) stars

Different EOS for coexisting phases

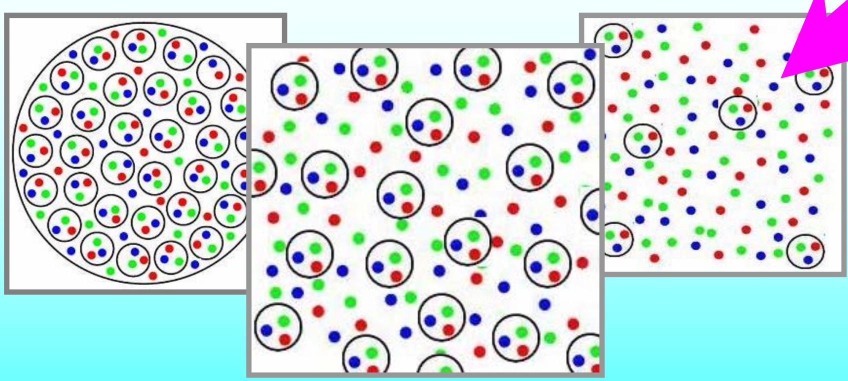
No critical point !



⇔



Unique EOS for coexisting phases



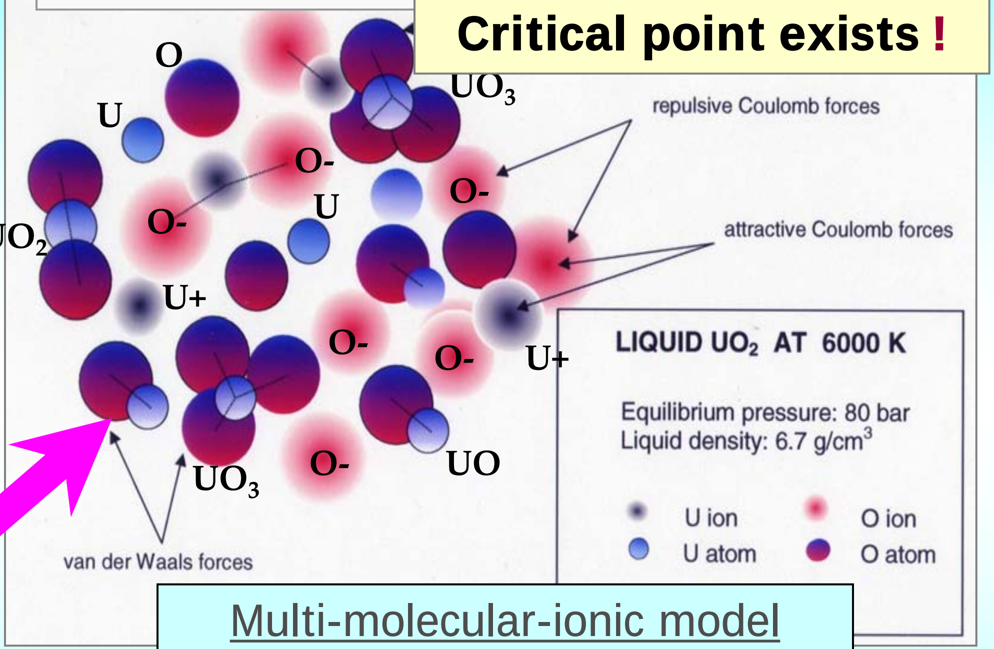
Critical point exists !

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**

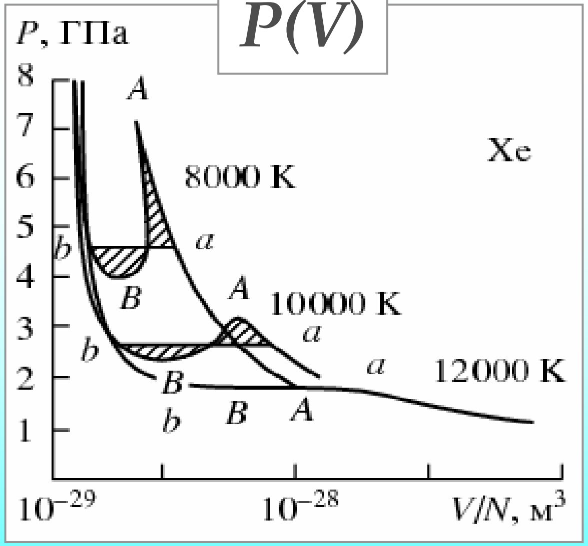
Phase coexistence parameters calculation

(standard approach)

Ordinary way:

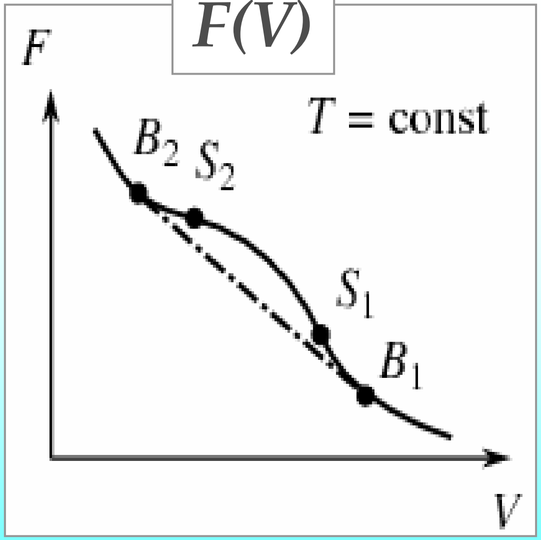
in pressure *P(V)* – **Maxwell (equal squares)** *or*
in free energy *F(V)* – "**Double tangent**"

P(V)



"Plasma" phase transition
(*in xenon*)

F(V)

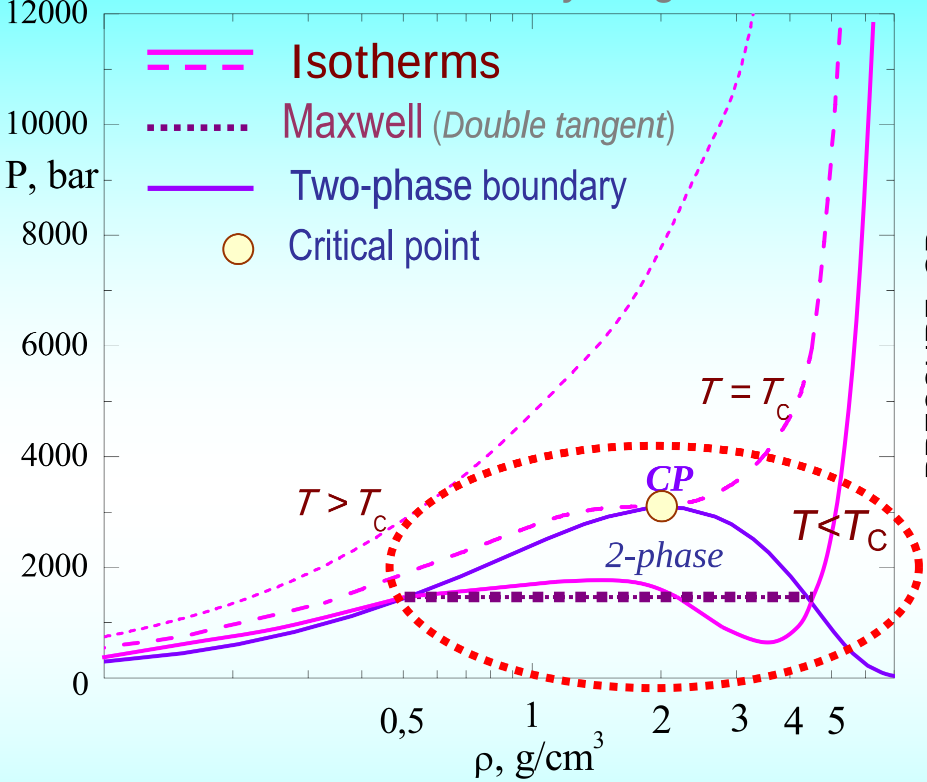


(*see for example:* Iosilevskiy I., *Encyclopedia on low-T plasmas. III-1,* **2000**, P.327-339); *III-1 (suppl)* **2004**, P.349-428)

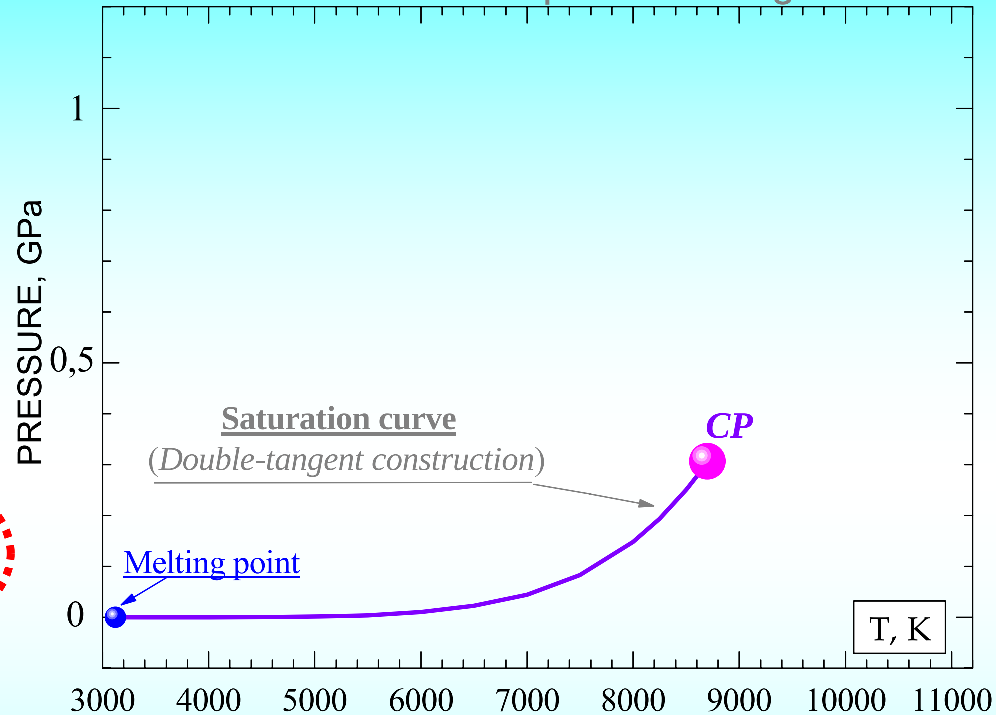
<u>**Standard**</u>

Forced-congruent evaporation in U-O system

Pressure - Density diagram



Pressure - Temperature diagram



- Stoichiometry of coexisting phases are equal: *Maxwell* $x' = x''$ — It should be instead $x' \neq x''$
- Van der Waals loops (at $T < T_c$) corrected via the "Double tangent construction"
- Standard phase equilibrium conditions:

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

  It should be (*Gibbs*)

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

- Standard critical point:

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

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

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

Bulk potential

Bulk potential

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

Particle Exchange
neutral species
(Gibbs)

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

Charged species

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

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

Equilibrium reactions
ab ⇔ a + b
(reduced number of basic units)

Uranium – Oxygen system

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

For example: Iosilevskiy I., *Encyclopedia of Low-T Plasmas. III-1 (suppl)* Moscow, **2004**

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

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

Bulk potential — Bulk potential

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

Particle Exchange
neutral species
(Gibbs)

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

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$$\mu_U'(P,T,x') = \mu_U''(P,T,x'')$$
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Charged species

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

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

$$\tilde{\mu}_1' = \tilde{\mu}_1''$$
$$\ldots\ldots\ldots\ldots$$
$$\tilde{\mu}_k' = \tilde{\mu}_k''$$

$\tilde{\mu}_k$

Non-local
Well-defined

NB! *Electro-chemical potentials are equal*

$$\tilde{\mu}_k' = \mu_k(P,T,x') + Z_k e\varphi' = \mu_k''(P,T,x'') + Z_k e\varphi'' = \tilde{\mu}_k''$$

NB! Potential drop at mean-phase interface in equilibrium Coulomb system

$$\Delta\varphi(T) = \varphi' - \varphi''$$

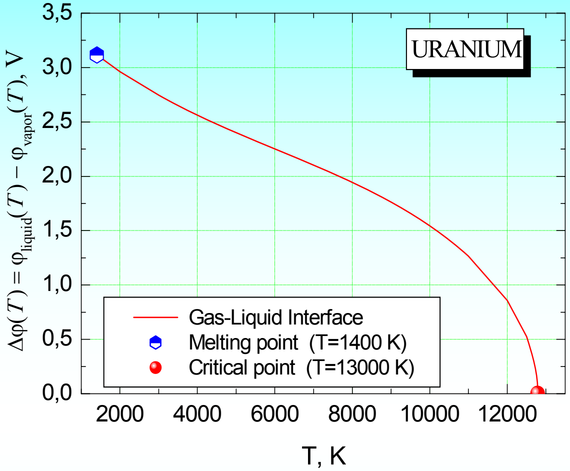
For example: Iosilevskiy I., *Encyclopedia of Low-T Pla*… 4

Electrostatics of phase boundaries in Coulomb systems

$$Z_i e\Delta\varphi = (\mu_i)_1 - (\mu_i)_2$$

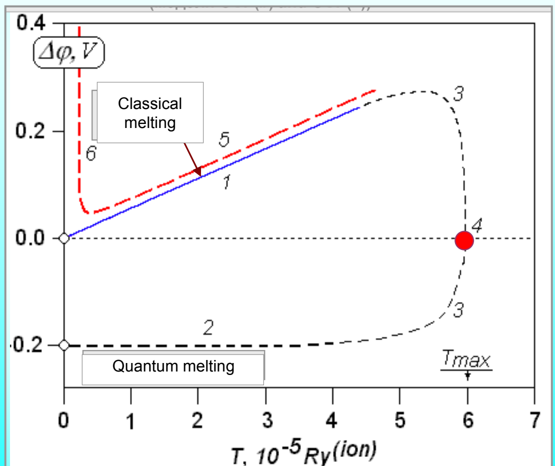
Terrestrial applications

Electrostatic (Galvani) potential



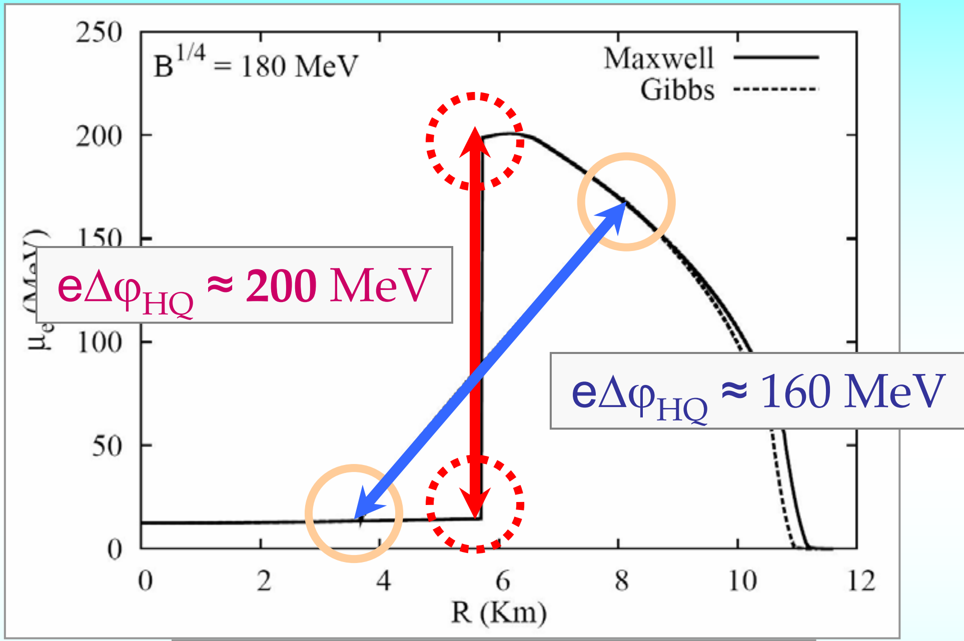
Iosilevskiy & Gryaznov, *J. Nucl. Mat.* (2005)

Electrostatic "portrait" of Wigner crystal in OCP



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

Quark-Hadron phase transition in NS



Bhattacharya A., Mishustin I., Greiner W., arXiv:0905.0352v1

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

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

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

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

Duality: Chemical ⇔ Electrochemical potentials

Electrochemical potential – well-defined, observable *but* **non-local !**

$$\tilde{\mu}_k(\mathbf{r}) \neq \tilde{\mu}_k\{P(\mathbf{r}), T(\mathbf{r}), x'(\mathbf{r})\}$$

Chemical potential – assumed *to be* **local, intuitively understandable**, *but* **have no correct definition** *in* **non-uniform Coulomb system**

Furtunately: **In macroscopic, uniform Coulomb system**

$$\tilde{\mu}_k = \mu_k\{P, T, x\} + Z_k e\varphi$$

φ – **average electrostatic (Galvani) potential**

(Gibbs – Guggenheim conditions)

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

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

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

Neutral species

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

$$\tilde{\mu}_1' = \tilde{\mu}_1''$$
$$\ldots\ldots\ldots\ldots$$
$$\tilde{\mu}_k' = \tilde{\mu}_k''$$

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

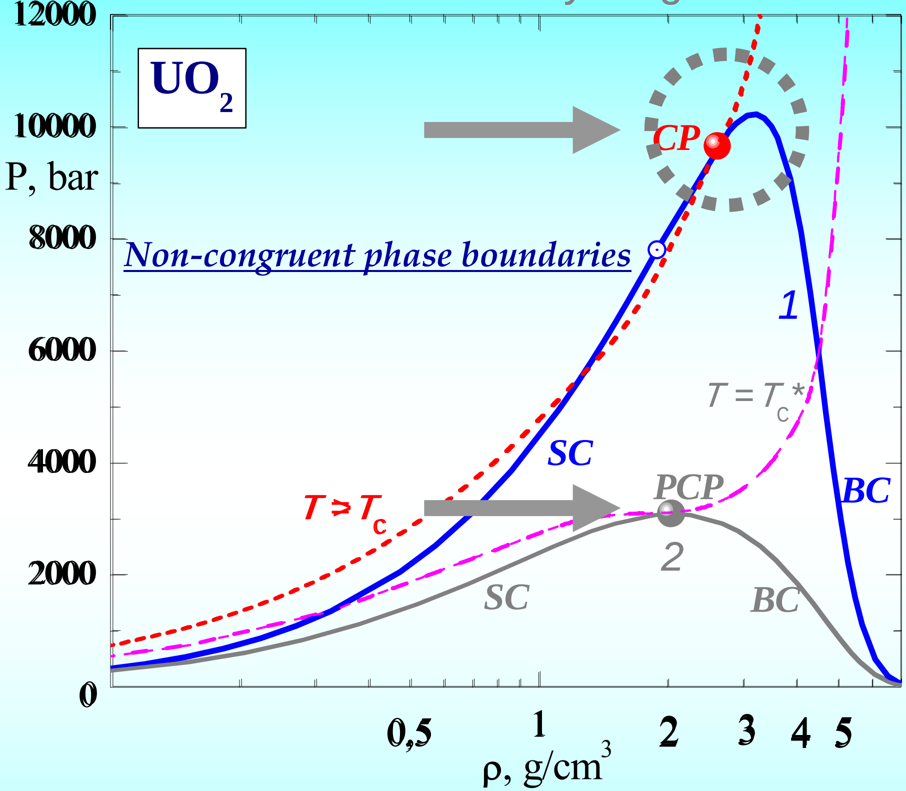
$$n_{U+} + n_{U++} + n_{UO2+} + n_{UO3+} = n_e + n_{O-} + n_{O2-} + n_{UO3-}$$

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

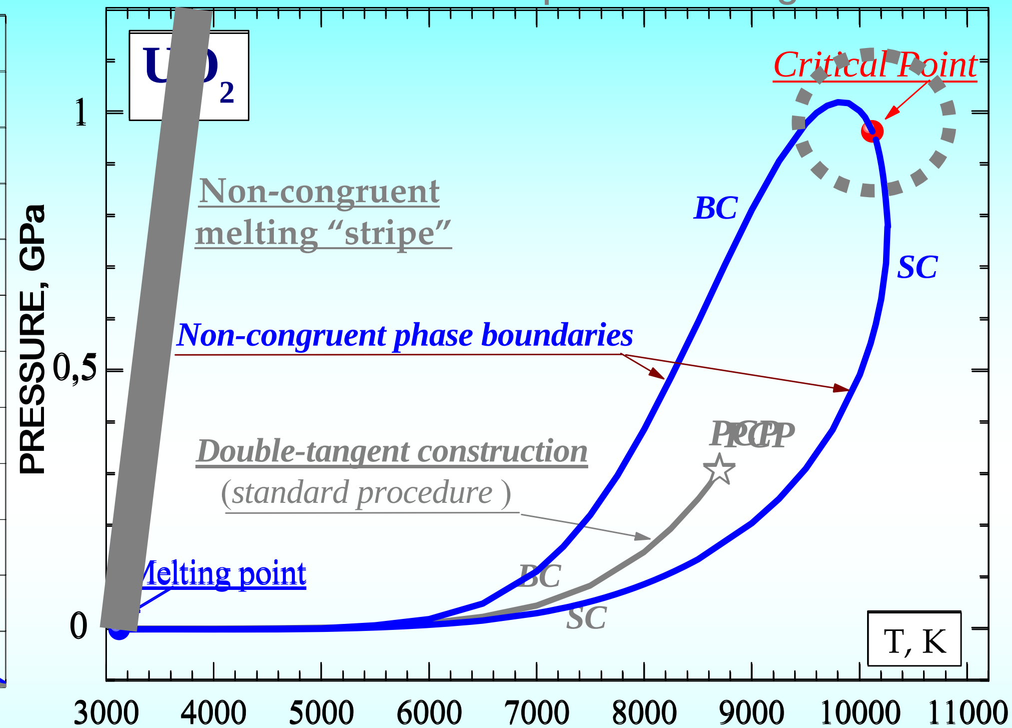
Non-congruent evaporation in U-O system

(*Gibbs - Guggenheim conditions*)

Pressure - Density Diagram



Pressure - Temperature Diagram



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

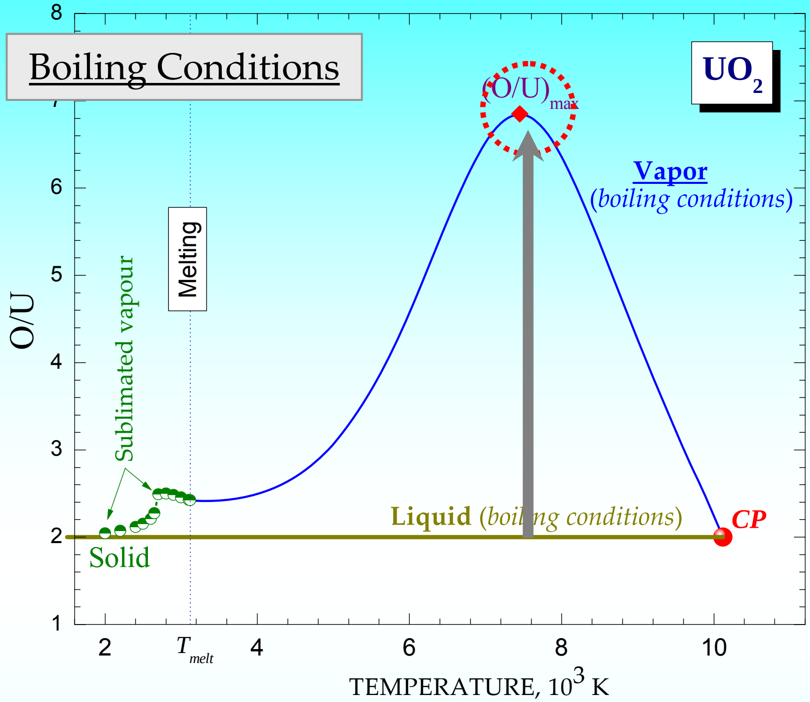
NB! **High pressure level** of non-congruent phase decomposition

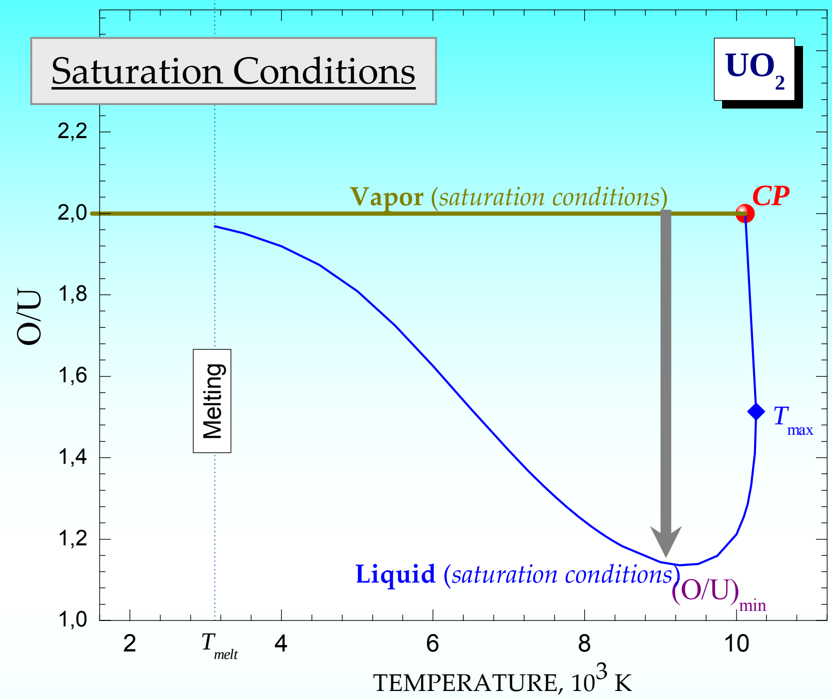
NB! **Critical point** should be of **non-standard** type: $(\partial P/\partial V)_T \neq 0$ $(\partial^2 P/\partial V^2)_T \neq 0$

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

No anomalous fluctuations of standard critical point **!**

Chemical Composition of Coexisting Phases

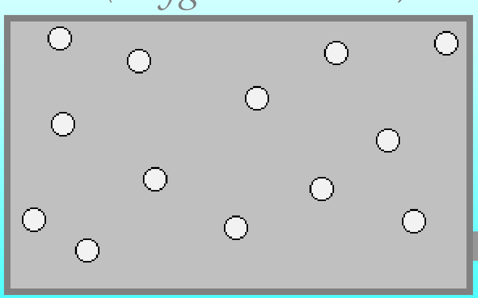


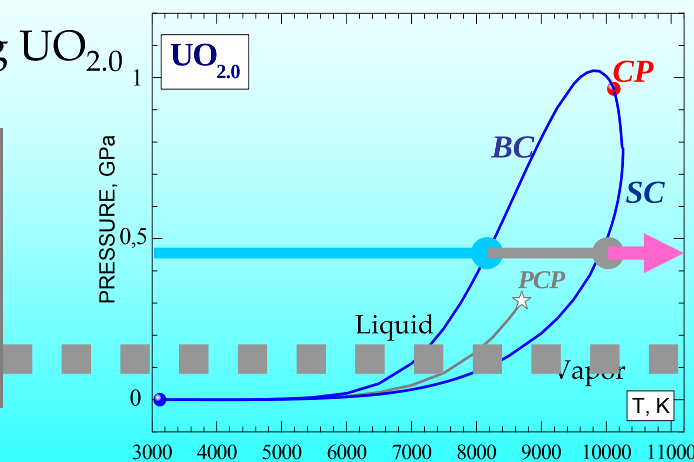


P = const

First vapor bubbles in boiling $UO_{2.0}$

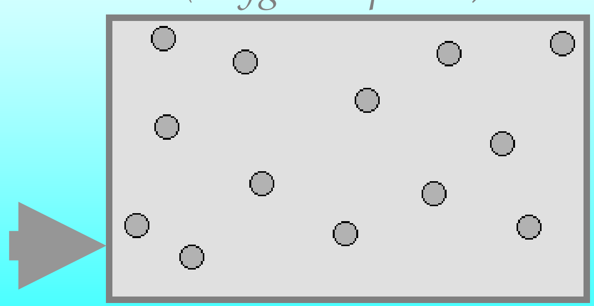
(oxygen enriched)





Last liquid drops in vapor $UO_{2.0}$

(oxygen depleted)

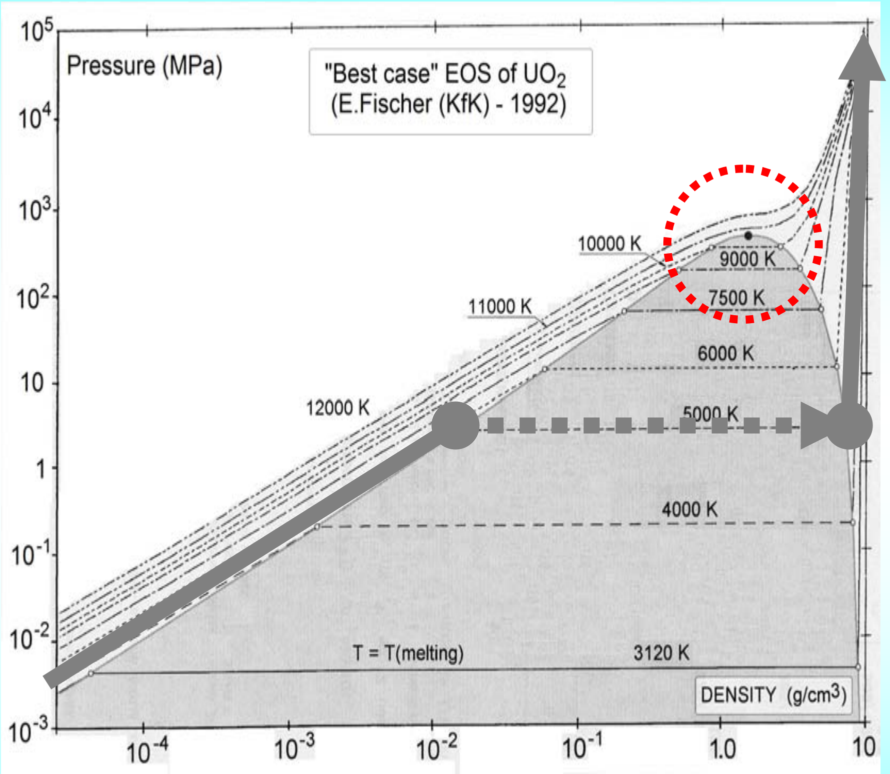


Liquid (O/U = 2.0) ⇔ Vapor (O/U > 2.0)

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

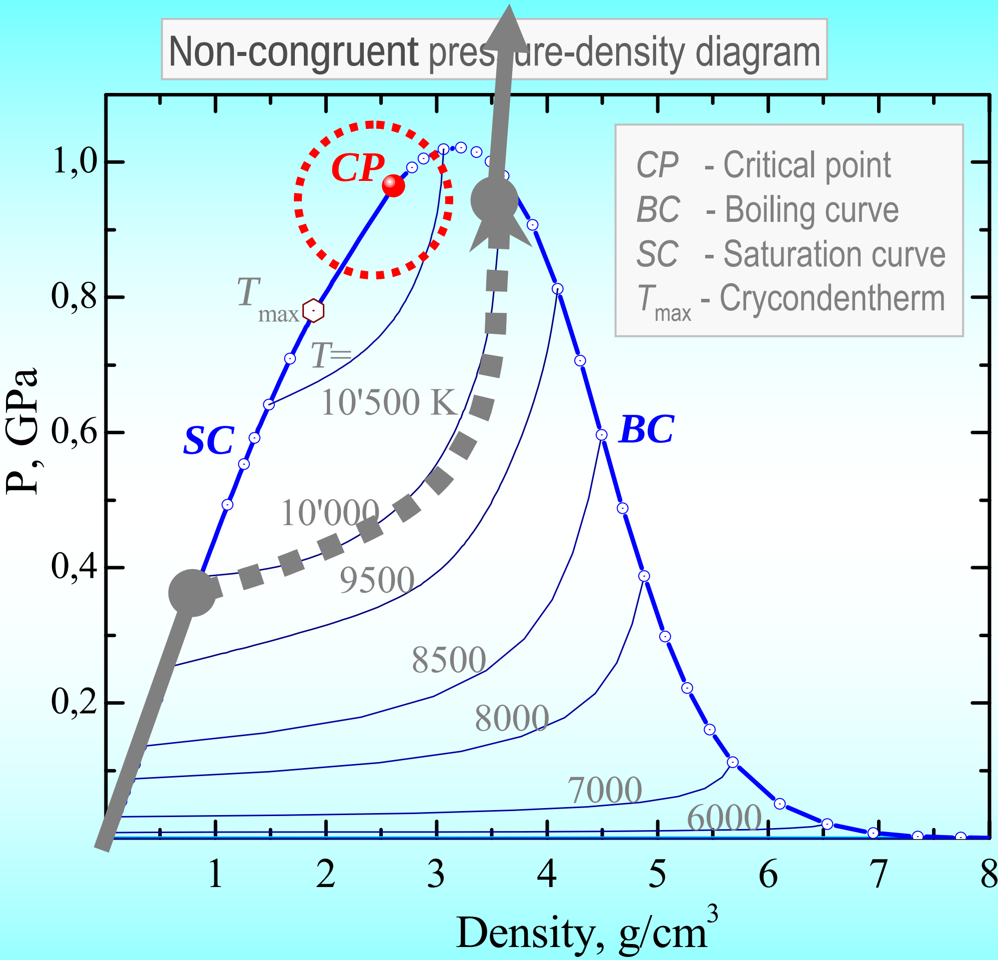
Isotherms in two-phase region

Standard pressure-density diagram



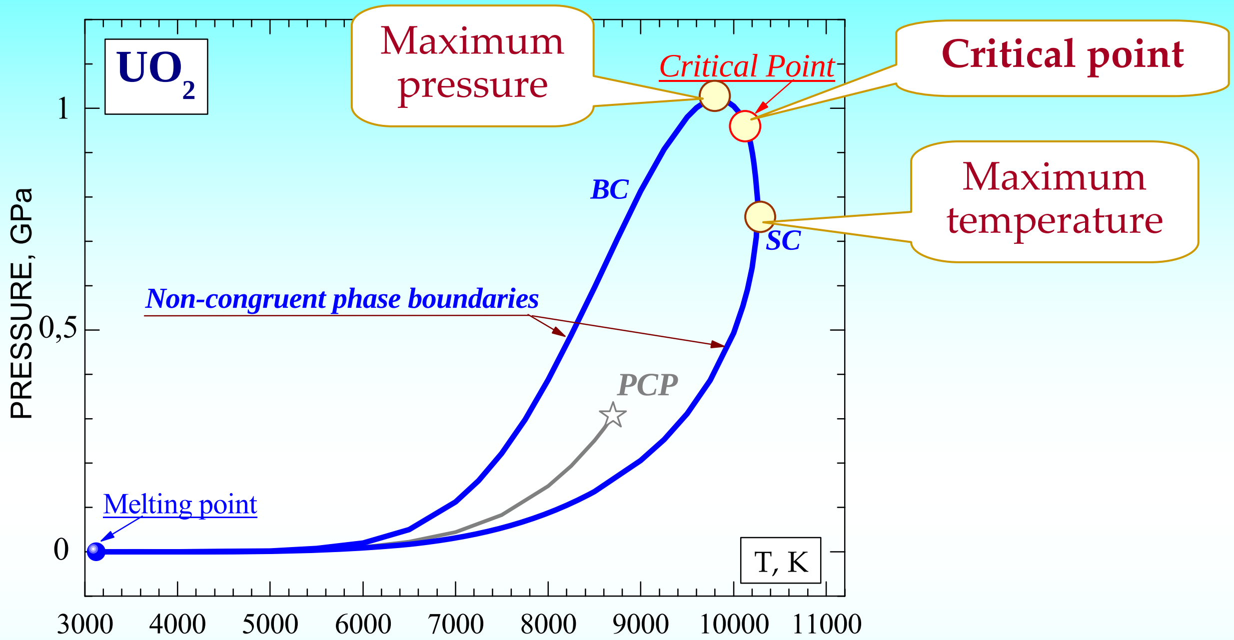
Fischer E.A. *J. Nucl. Sci. Eng.* (1989)

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 chemical potential extremum**
- **Critical point** *(thermodynamic singularity)*

are four different points !

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

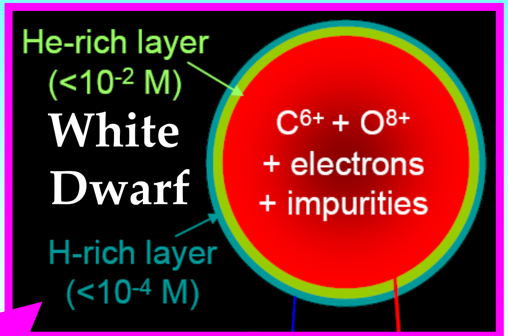
N-C Phase Transition Dynamics

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

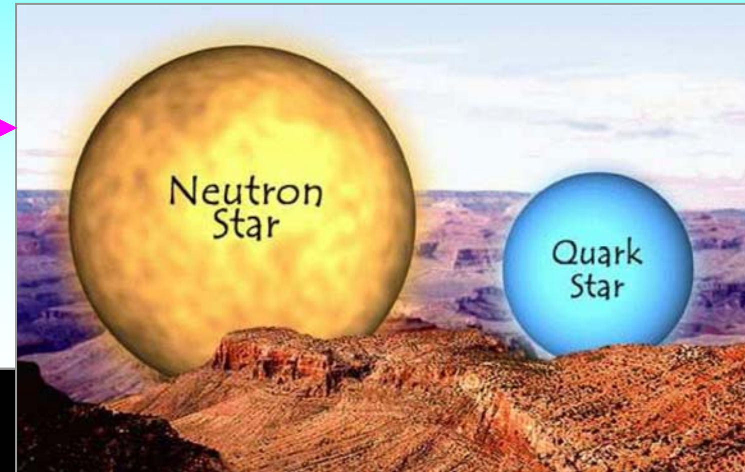
Hypothetical non-congruence *of* Quark-hadron PT *in* high-density matter

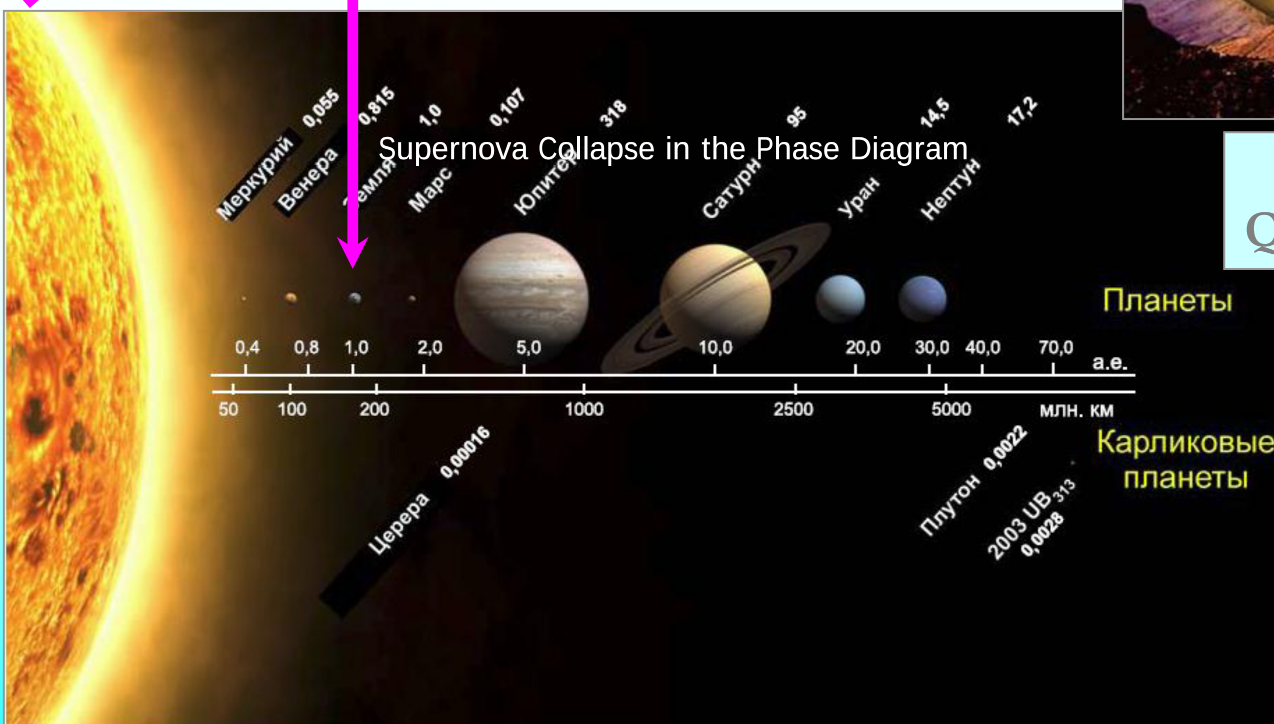
Compact stars

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

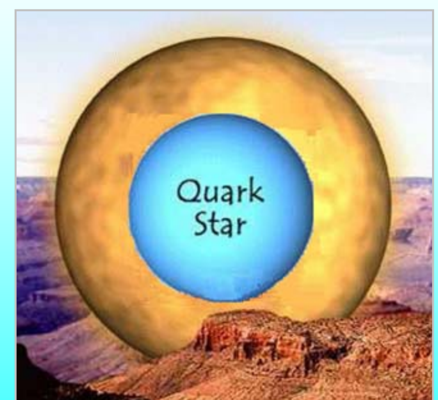


Neutron and “Strange” Stars





Hybrid Stars
Quark core + Hadron Crust

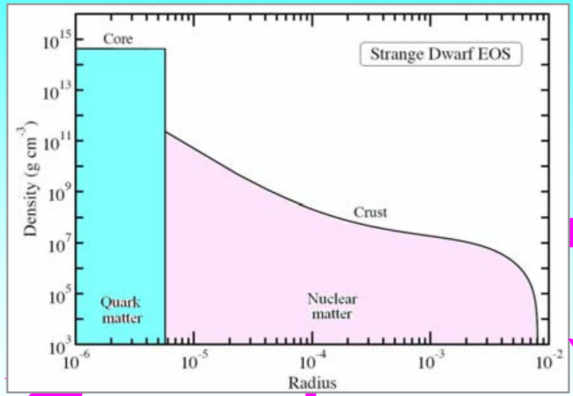


|← R ~ 10 km →|

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

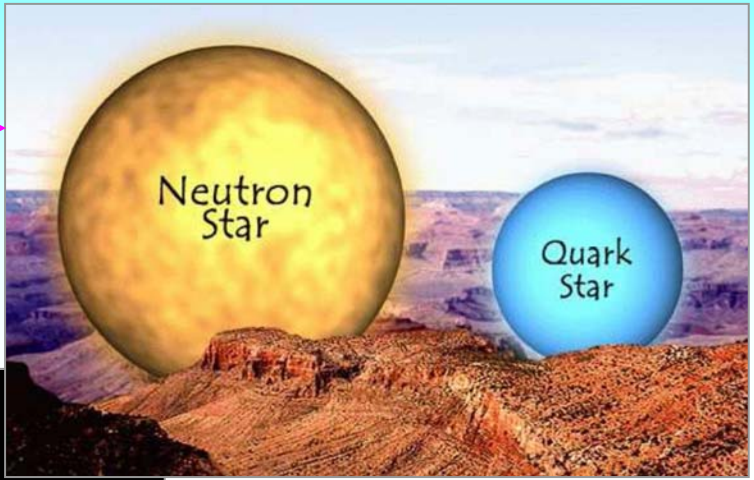
Compact stars

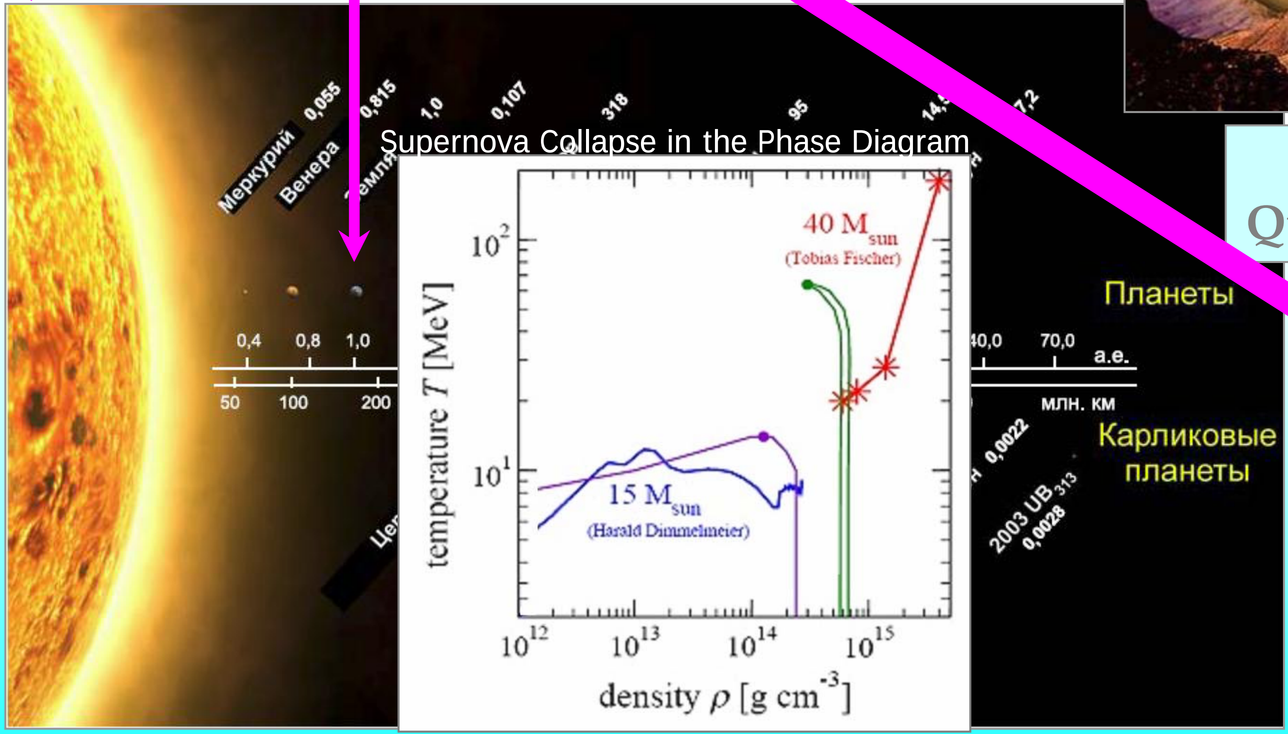
White dwarfs, Neutron stars, “Strange” (quark) stars, Hybrid stars



Hybrid WD
Mathews, Weber et al. 2006

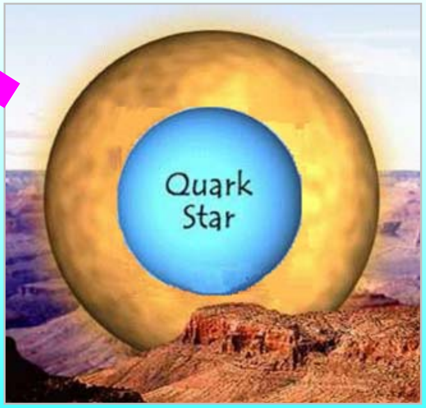
Neutron and “Strange” Stars





Hybrid Stars

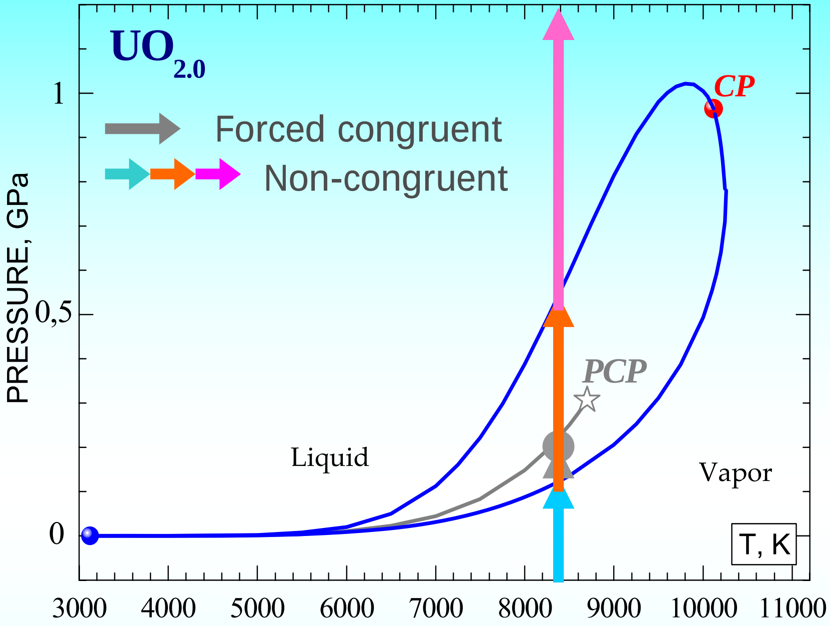
Quark core + Hadron Crust



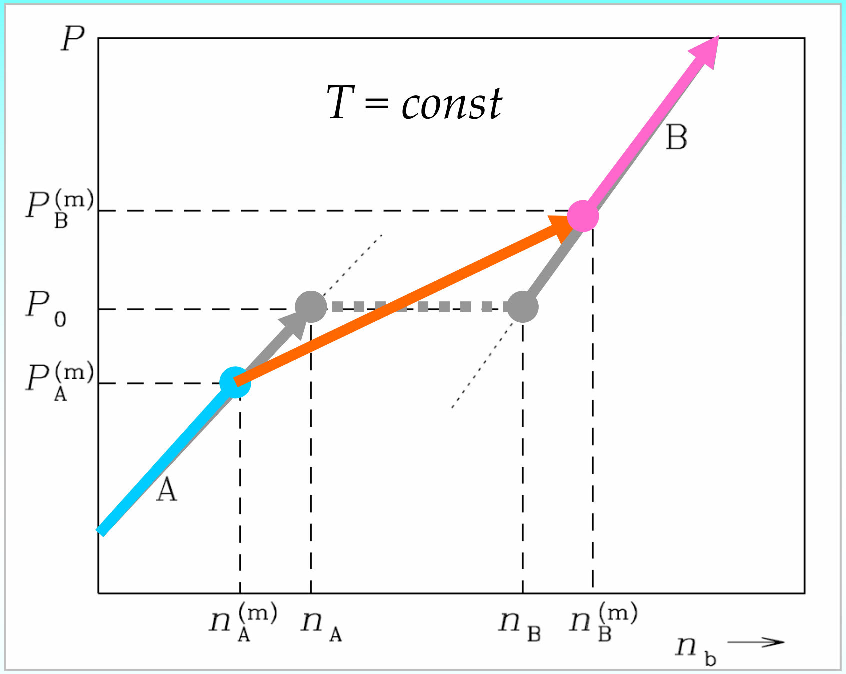
|← R ~ 10 km →|

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

Non-congruent phase transformation in two-phase region

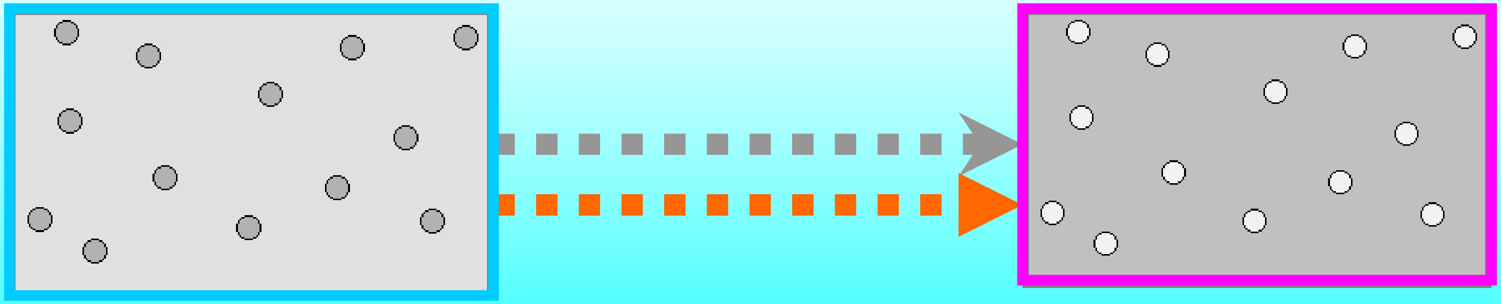


Phase Diagram *P-T* of Non-congruent Evaporation



First liquid droplets in saturated vapor

Last vapor bubbles in boiling liquid



Oxygen depleted liquid

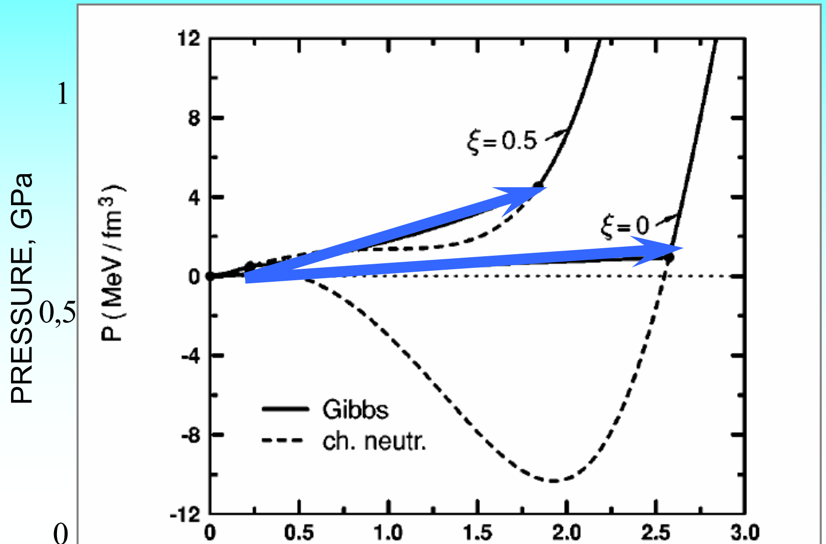
! *Different stoichiometry*!

Oxygen enriched vapor

! *Different stoichiometry*!

Hypothetical phase transitions in interior of compact stars:

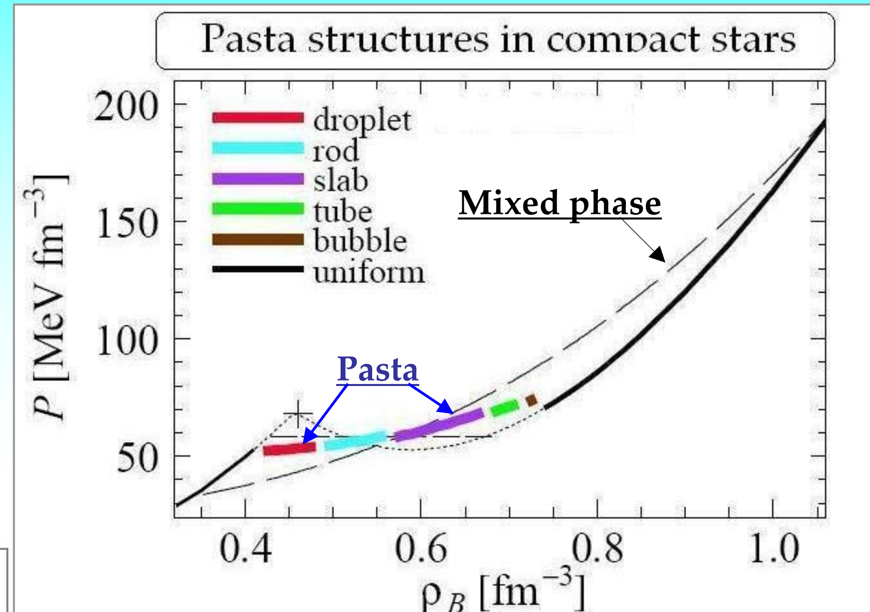
are they CONGRUENT or NON-CONGRUENT ?



PHYSICAL REVIEW D, VOLUME 64, 043005

Strange quark stars within the Nambu–Jona-Lasinio model

M. Hanauske,[1] L. M. Satarov,[1,2] I. N. Mishustin,[1,2,3] H. Stöcker,[1] and W. Greiner[1]
[1]*Institut für Theoretische Physik, J. W. Goethe–Universität, D-60054 Frankfurt, Germany*



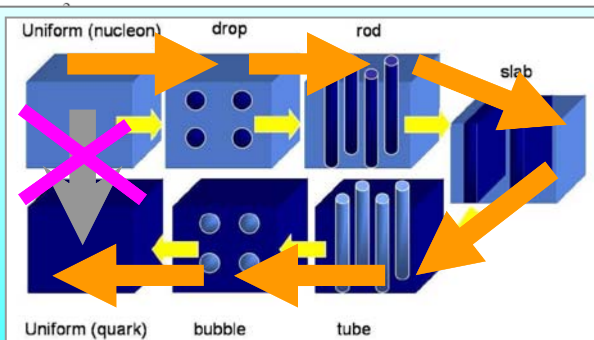
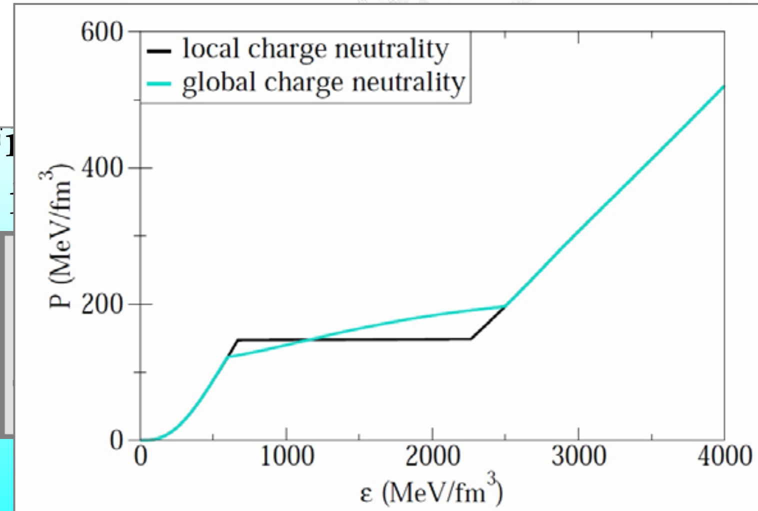


Figure 2: Schematic image of structured mixed phase.

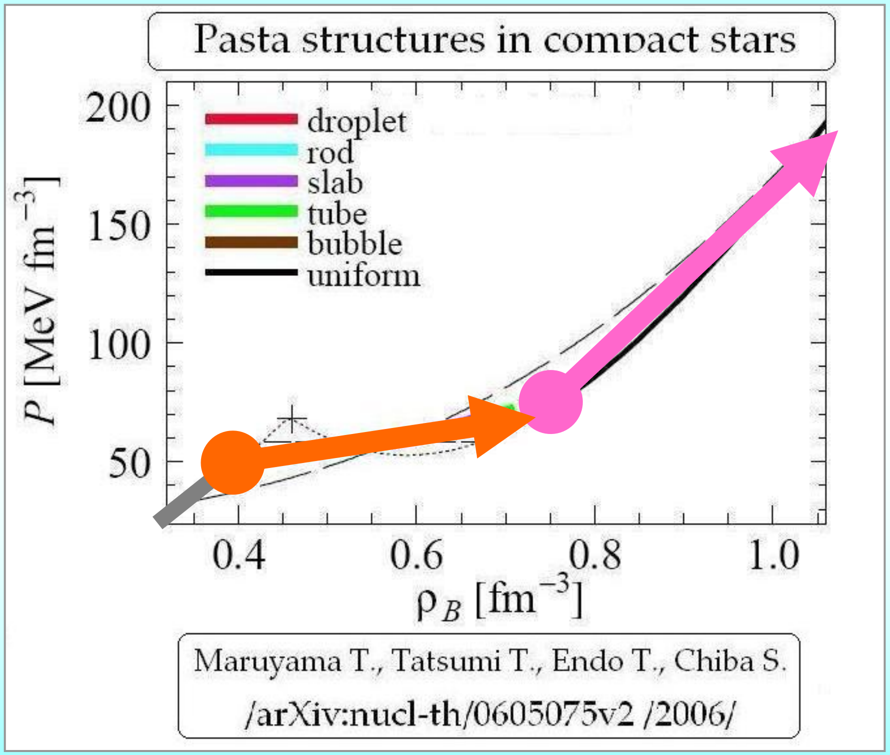
Endo T., Maruyama T., Chiba S., Tatsumi T. arXiv:astro-ph/0601017v1/ 2006 /

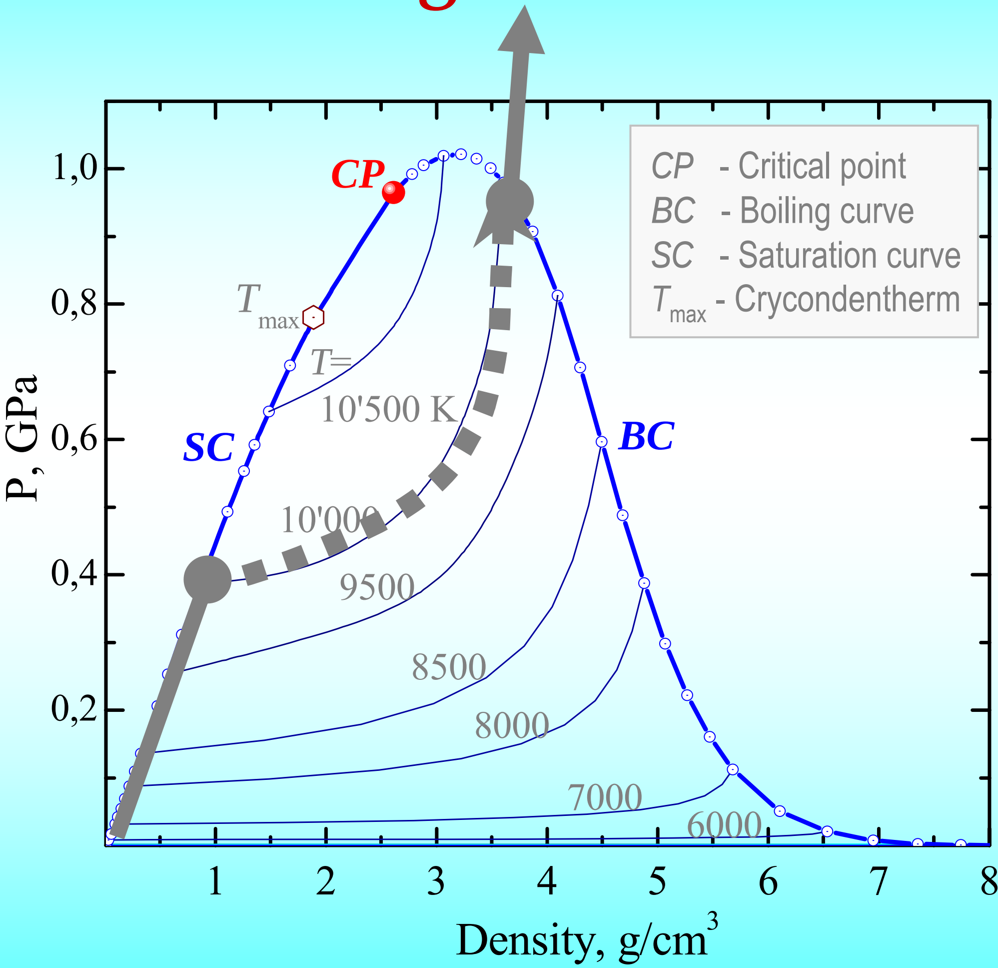


Equation of State for star matter at zero temperature

V.Dexheimer & S.Schramm, 2010

Quark-hadron phase transition via "mixed-phase" and "pasta" scenarios have the same features as non-congruent PT !

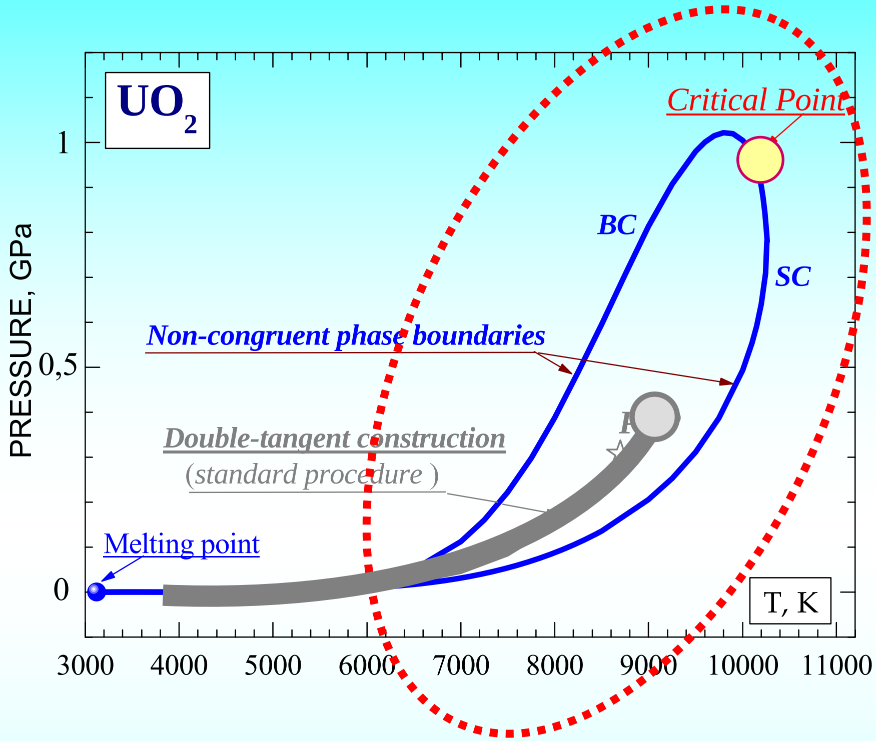




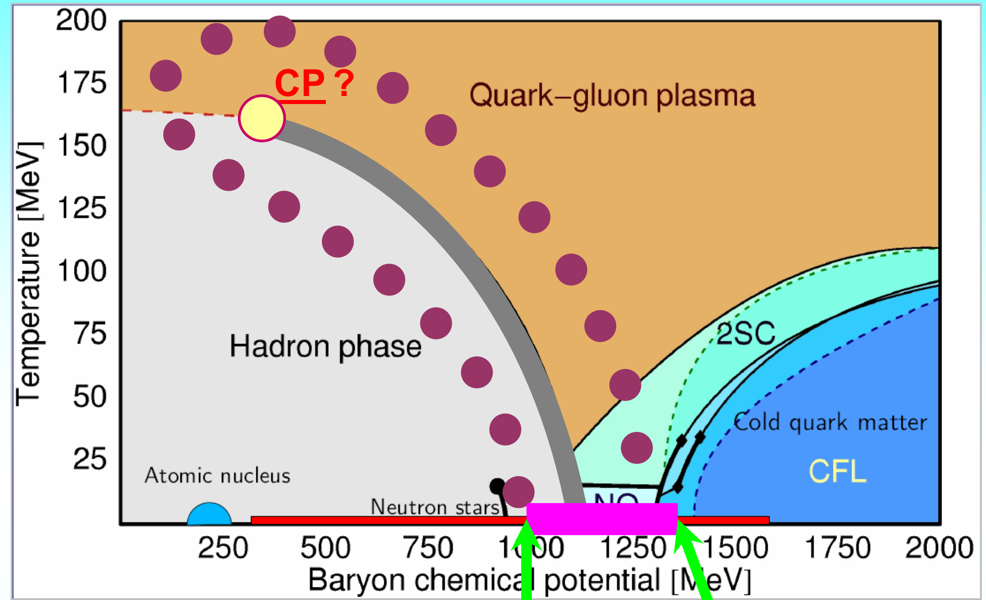
- **Isothermal** phase transition starts and finishes at ***different pressures***

Hypothetical phase transitions in ultra-dense matter:

are they CONGRUENT or NON-CONGRUENT ?



Phase diagram of quark-hadron matter

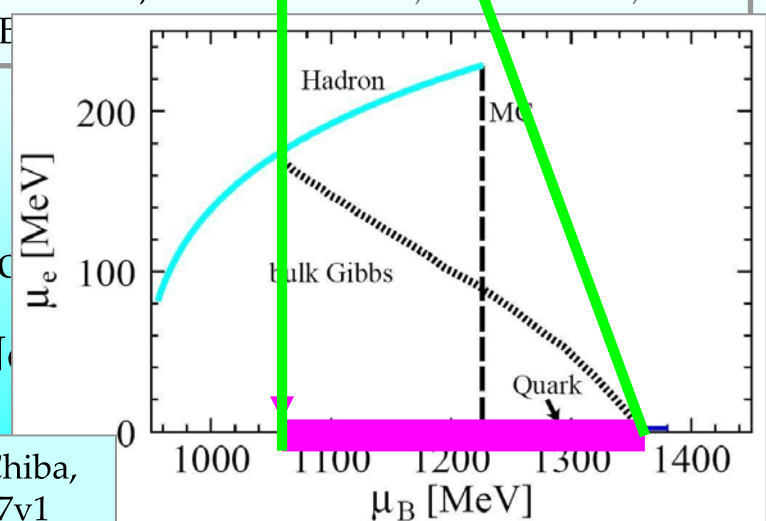


After Fridolin Weber, WEHS Seminar, Bad Honnef, 2006
After David B

?

- Fo

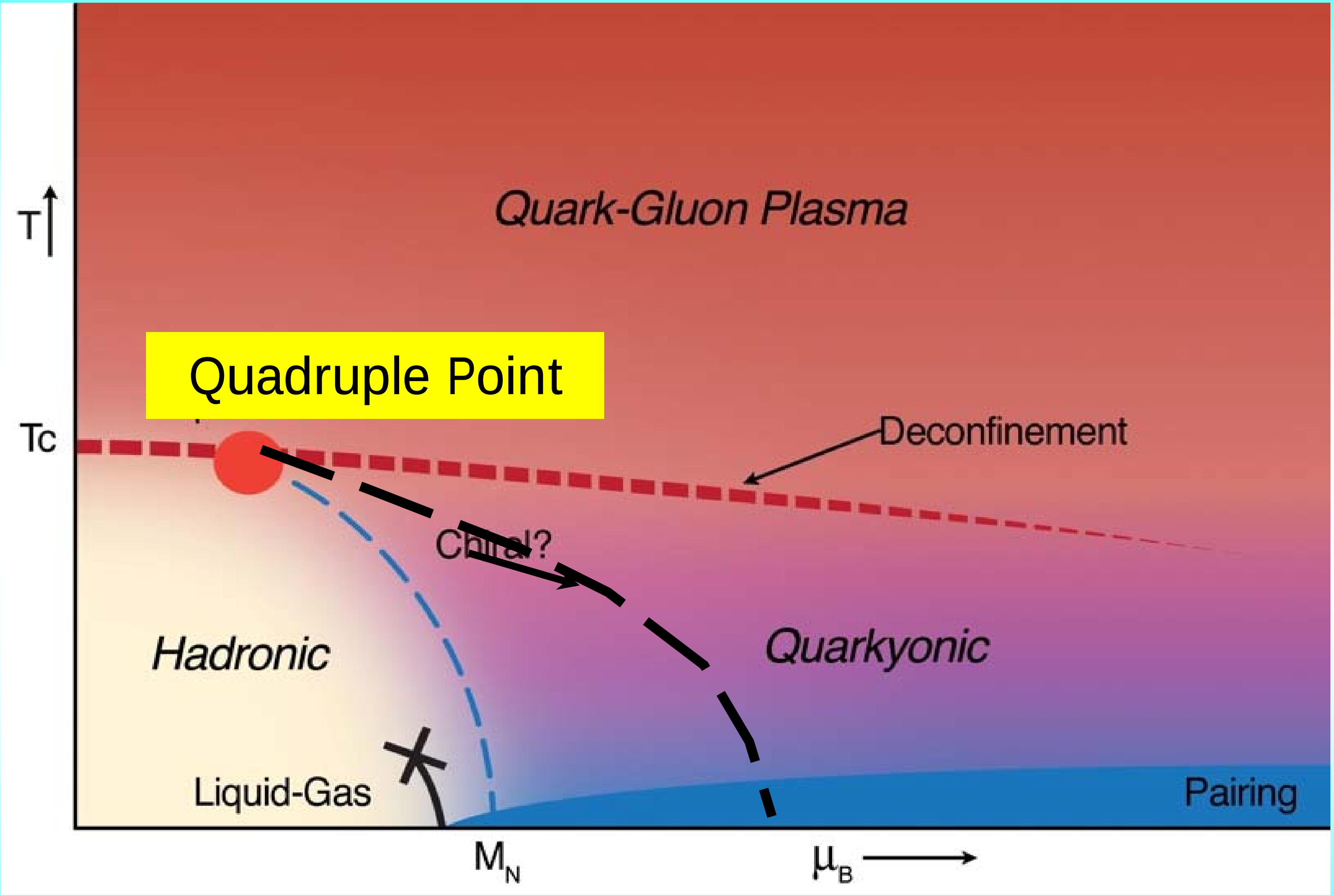
- N



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

Hypothetical phase transitions in ultra-dense matter:

are they CONGRUENT or NON-CONGRUENT ?

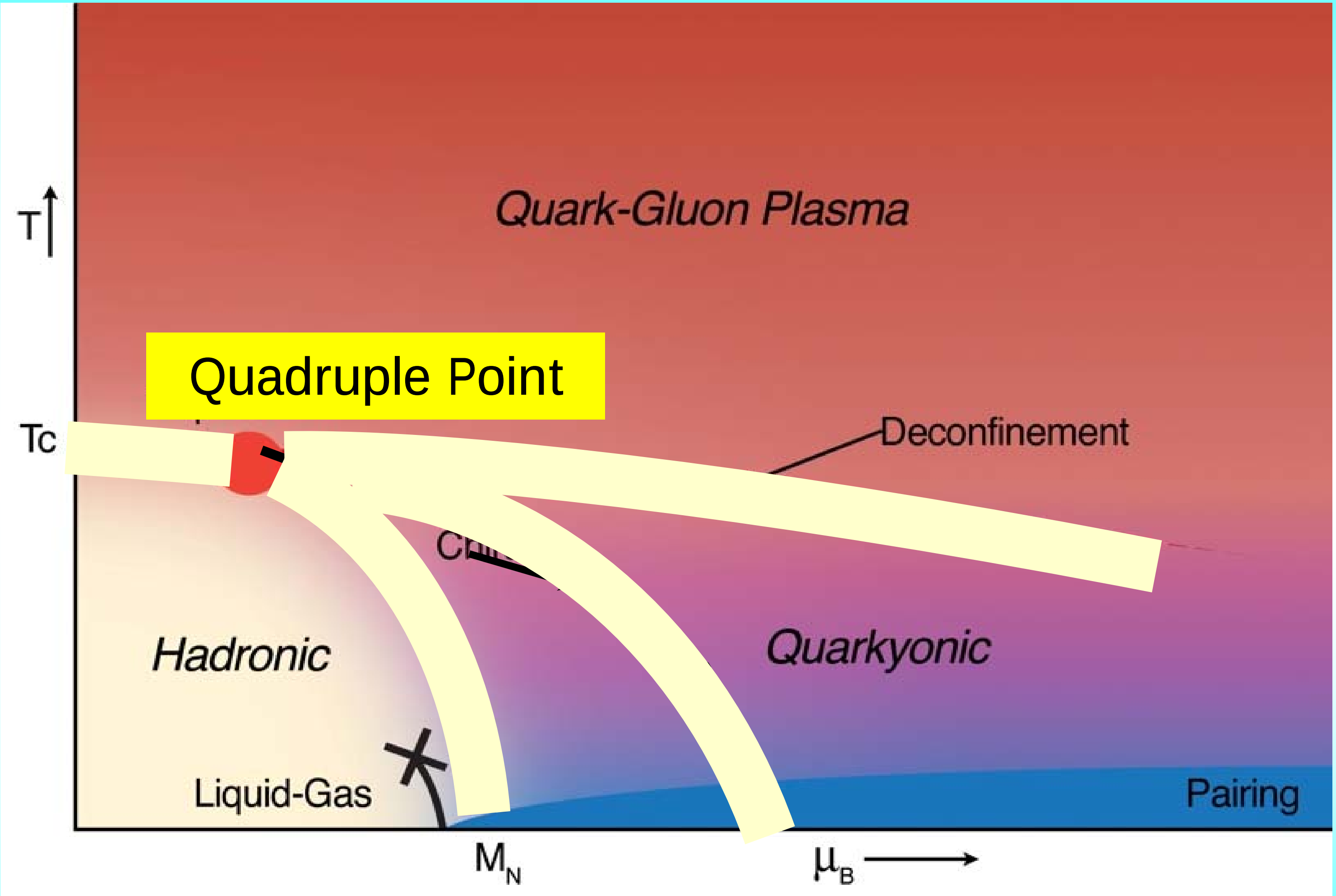


Hypothetical phase diagram with Triple or Quadruple Point

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

Hypothetical phase transitions in ultra-dense matter:

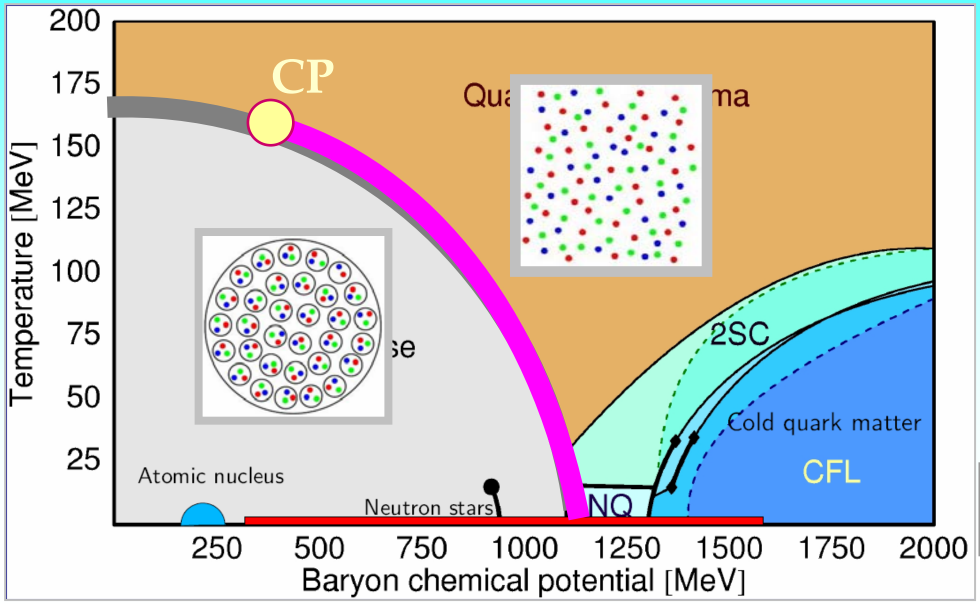
are they CONGRUENT or **NON-CONGRUENT ?**

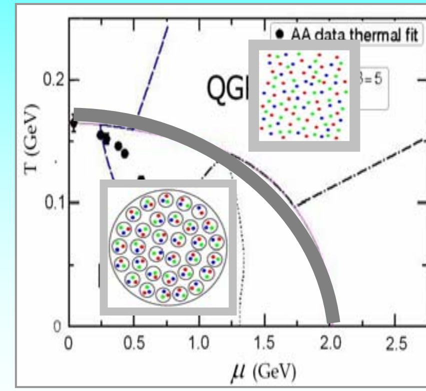


Hypothetical phase diagram with Triple or Quadruple Point

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

QHPT: Two macroscopic phases





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

(Gibbs-Guggenheim conditions)

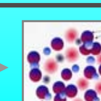
1-dimensional system $\{\mu_b\}$ → **Forced-congruent PT**

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

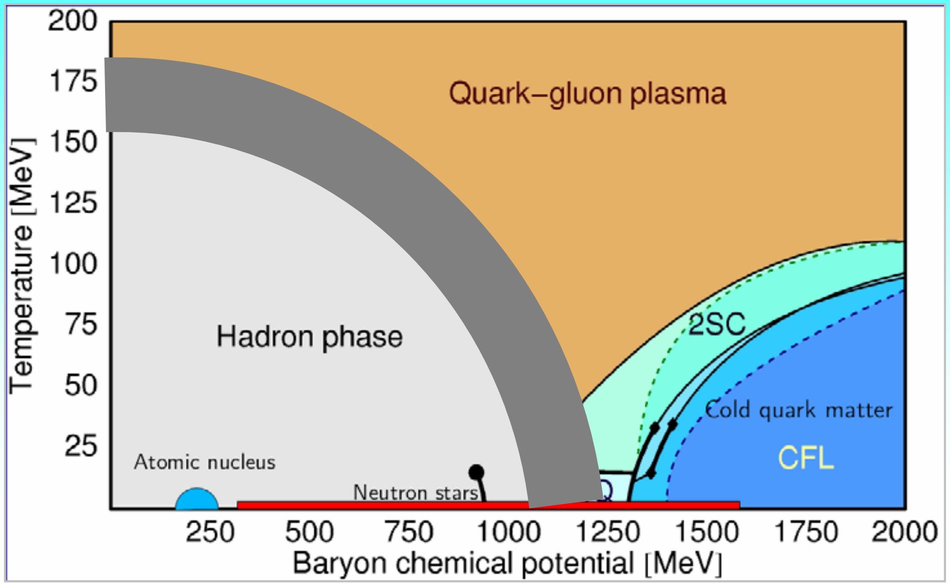
No critical point !

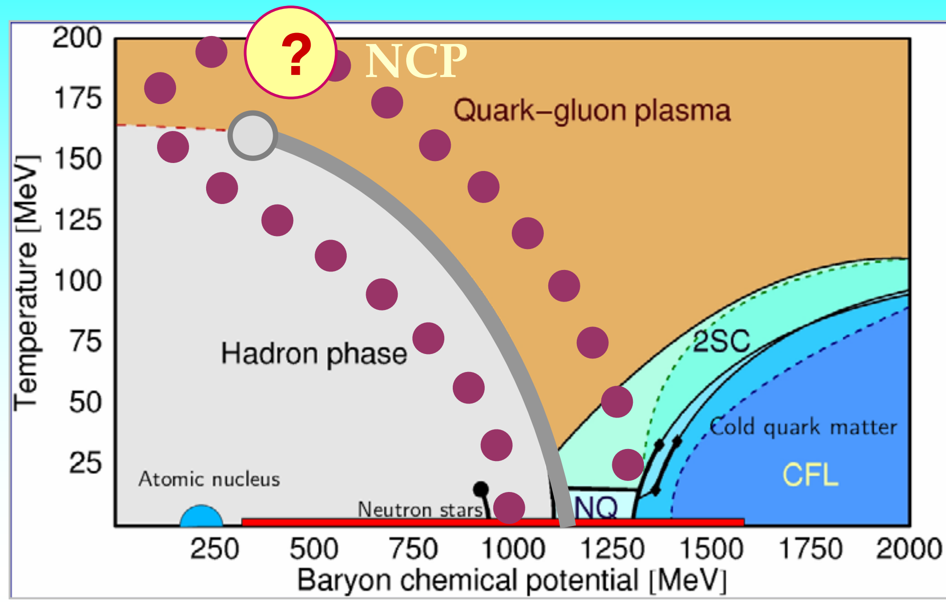
B Unique EOS *for* quark *and* hadron phases *(like in U-O)*

Critical point could exist !

 ↔ 

QHPT: Mixed phase scenario





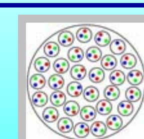
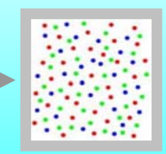
*(bulk **Gibbs** conditions for **all species**)*

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

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

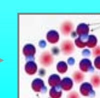
● *2-dimensional zone*

No critical point !

 ↔ 

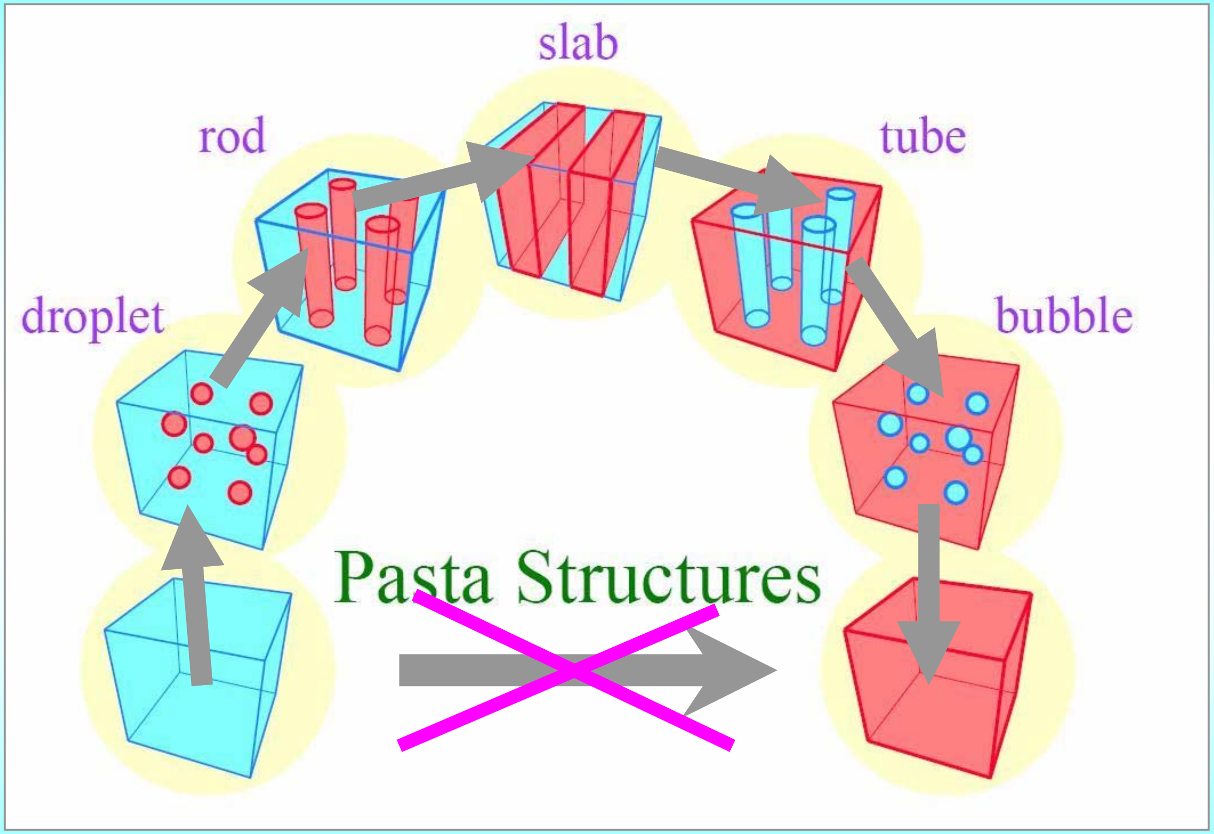
B **Unique EOS** *for* **quark** *and* **hadron phases** *(like in U-O)*

Non-congruent critical point could exist !

 ↔ 

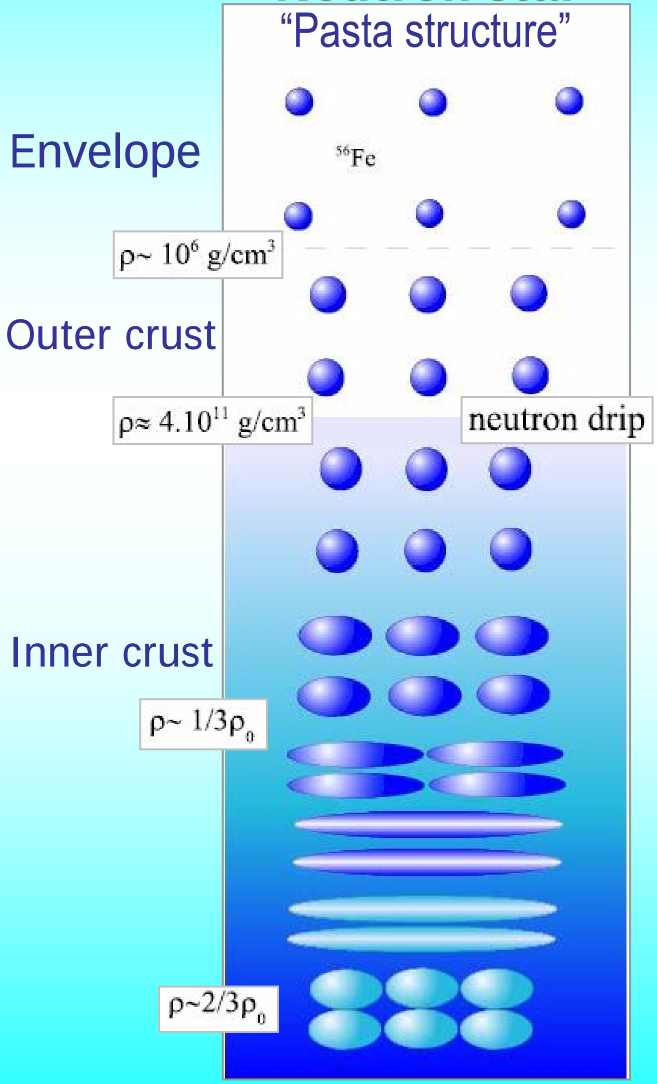
QHPT: Structured mixed phase concept ⇔ "pasta"

Wigner-Seitz "average cell" approximation



Maruyama T., Tatsumi T., Voskresenskiy D., Tanigava T., Chiba S.,
Phys.Rev. **C 72** (2005)
Nuclear pasta structures and charge screening effect

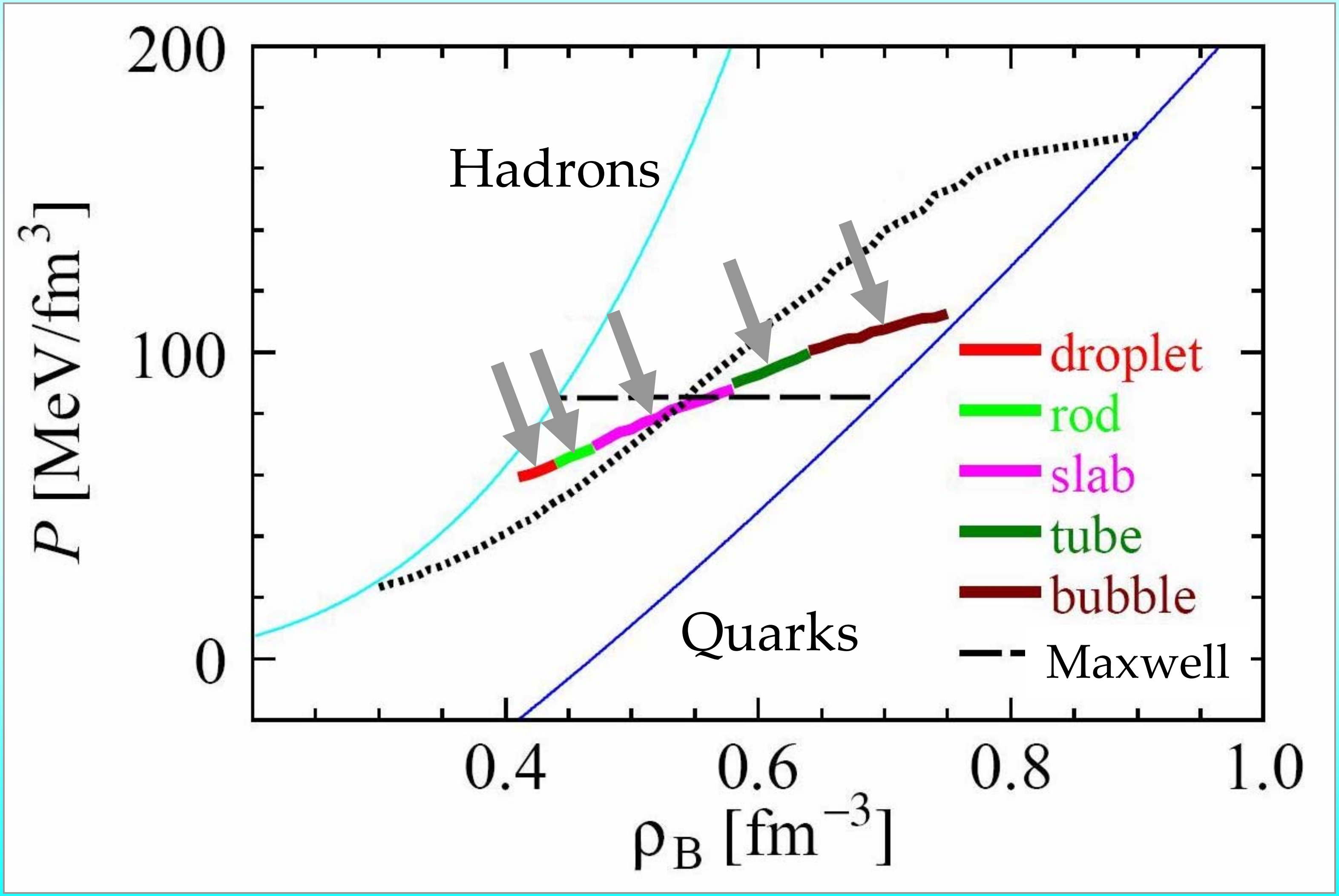
Neutron star



Structured Mixed Phase Scenario ⇔ "Pasta"

The sequence of seven (or more ?) phases !

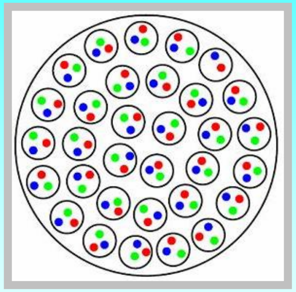
Uniform (nucleons) → **Drops** → **Rods** → **Slabs** → **Bubbles** → **Uniform** (quarks)



Basic question:

What is the nature of Q-H mixture:
is it **"solution"** *or* **charged "suspension"**
?

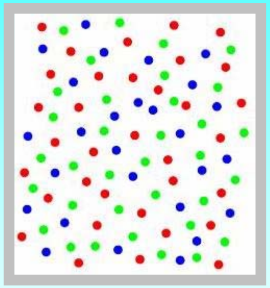
Standard Scenario



(suspension)

Different Equation of State
for two phases

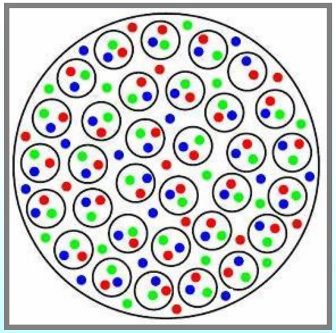
1st order phase transition
No critical point !



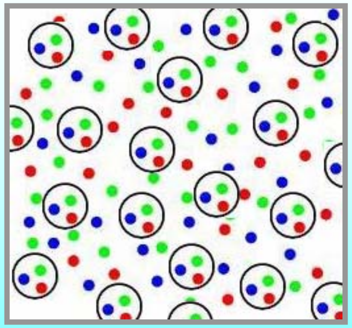
Pure hadronic phase
EOS_1

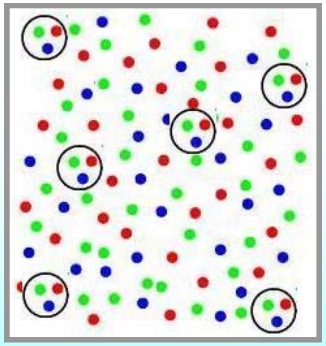
Pure quark phase
EOS_2

Non-Standard Scenario (*)



Unique Equation of State
for both phases





Weak solution of quarks
in hadronic "see" ?

1st order phase transition
Critical point exists !

Weak solution of hadrons
in quark "see" ?

Why not ?

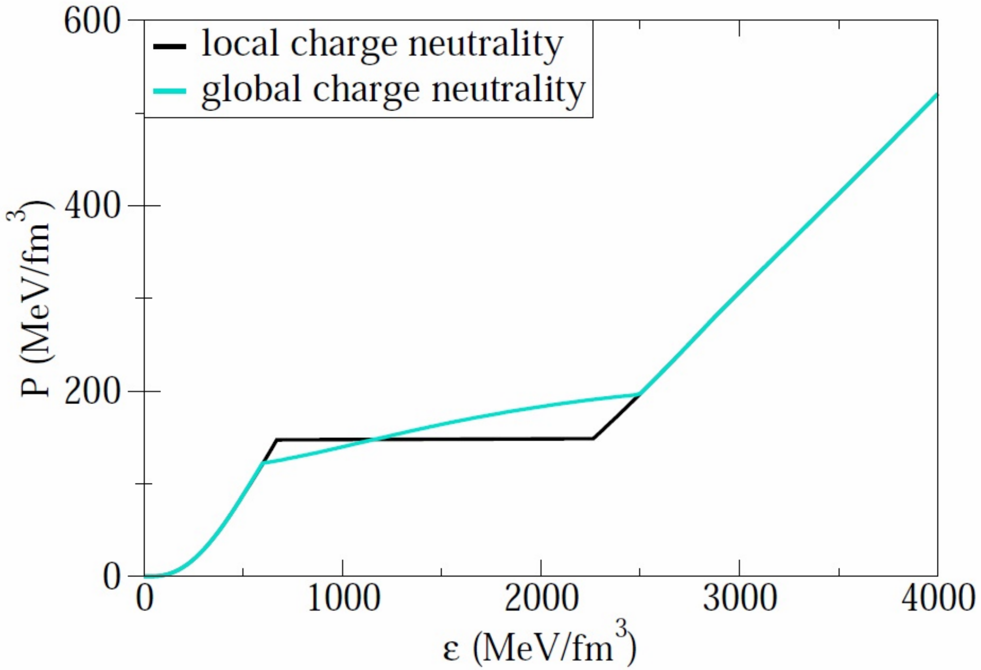
(*) – just like U-O system

Unique EOS *for* quark *and* hadron *phases*

Veronica Dexheimer & Stefan Schramm

A novel approach to model hybrid stars

arXiv:0901.1748v4

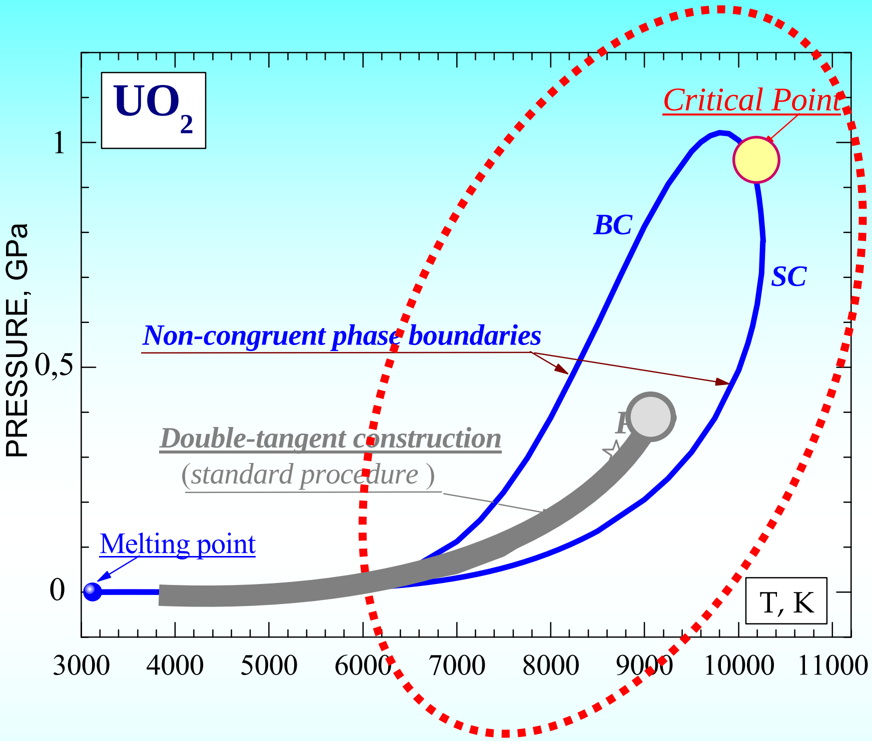


Equation of State for star matter at zero temperature

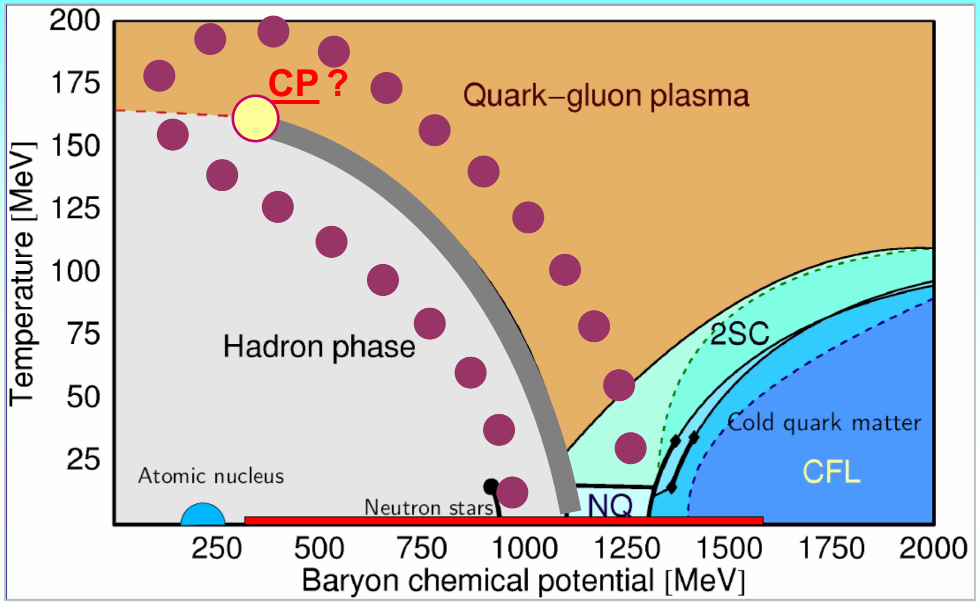
V.Dexheimer & S.Schramm, 2010

Hypothetical phase transitions in ultra-dense matter:

are they CONGRUENT or NON-CONGRUENT ?



Phase diagram of quark-hadron matter



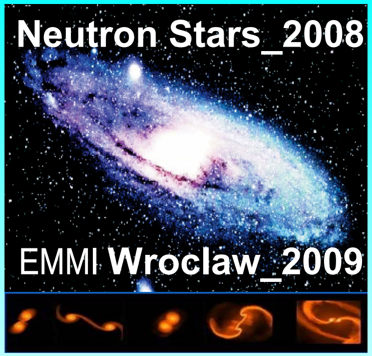
After **Fridolin Weber**, WEHS Seminar, Bad Honnef, 2006
After **David Blaschke**, WEHS Seminar, Bad Honnef, 2007

?

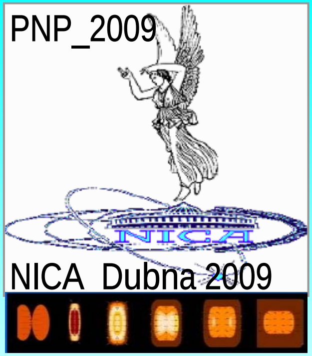
- Forced-congruent phase transition

- Non-congruent phase transition

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



Critical Point and Onset of Deconfinement
JINR Dubna, Russia, August 2010



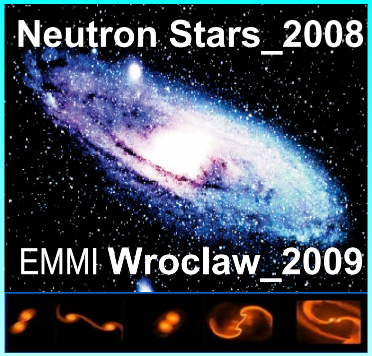
Conclusions *and* Perspectives

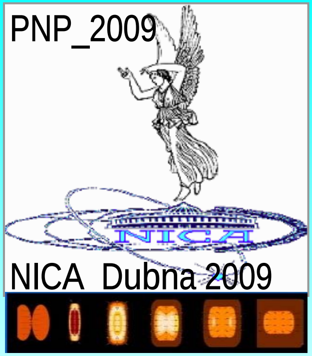
- **Non-congruent** phase transition is **general** phenomenon.

- **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)





Conclusions *and* Perspectives

- We have enough reason to expect **partial** or **total equivalence** of **quark-hadron phase transition** (QHPT) and **non-congruent phase transition** (NCPT)

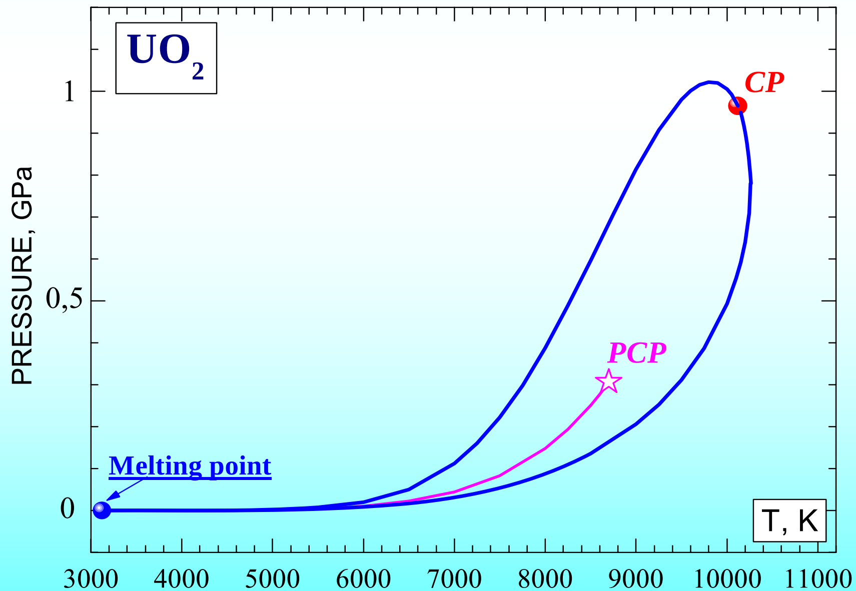
- **QHPT** as equilibrium of **macroscopic** phases is equivalent to **force-congruent** phase transition

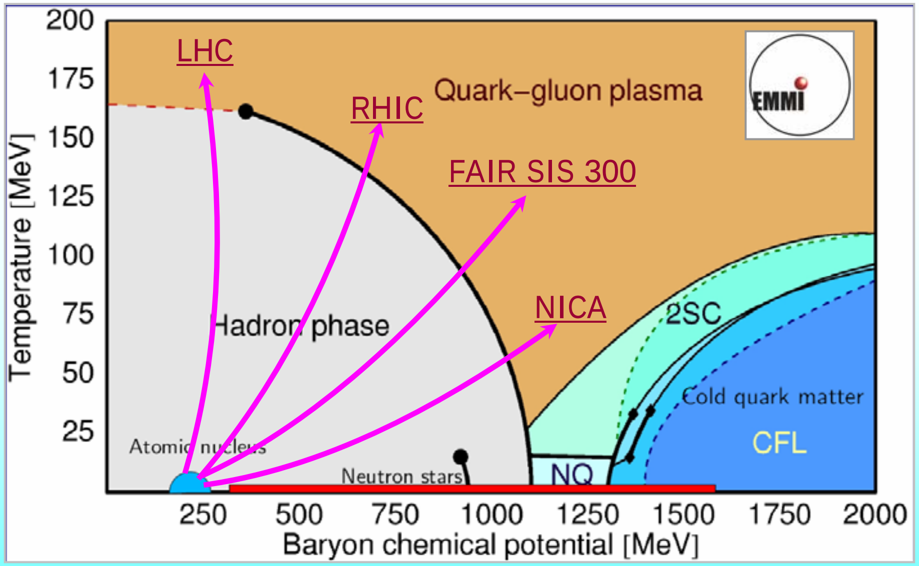
- **QHPT** under simple **mixed phase scenario** is equivalent to the **non-congruent** phase transition (in both variants: - with and without critical point)

- Equivalence of **NCPT** and **QHPT** under optimized **structured mixed phase** scenario (pasta) is **open question**

- Presence, location and properties of **Critical Point** in congruent or non-congruent variants of **QHPT** strongly depends on **basic assumption**: - What is the **nature** of **Quark-Hadron mixture** – **Solution** (“vodka” phase) or **Suspension** (“milk” phase)

Thank you!





Support: INTAS 93-66 // ISTC 3755 // CRDF № MO-011-0 // RFBR 06-08-01166,
RAS Scientific Program "Physics and Chemistry of Extreme States of Matter"
Extreme Matter Institute – EMMI

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)

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:
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