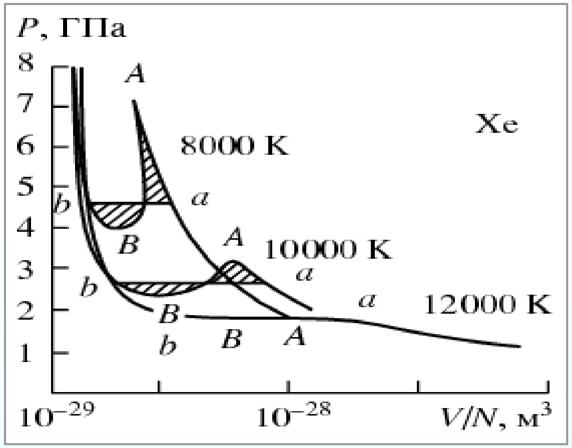
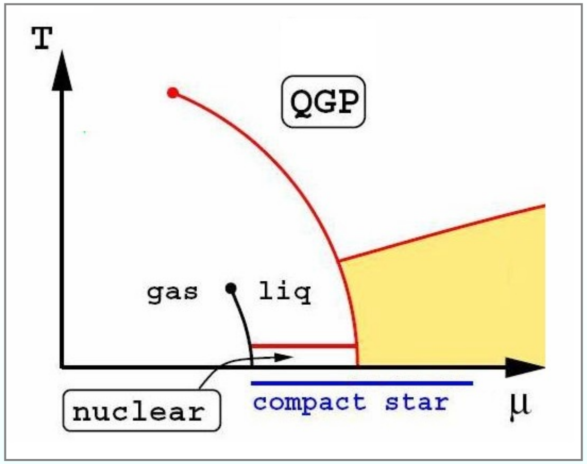
Helmholtz International Summer School
Nuclear Theory and Astrophysical Applications
*Dubna, Russia, July **2017***

Enhalpic *and* Entropic Phase Transitions

& *anomalous thermodynamics of high energy density matter*





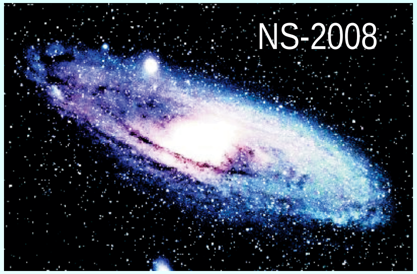
Igor Iosilevskiy

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

arXiv:1005.4186v1

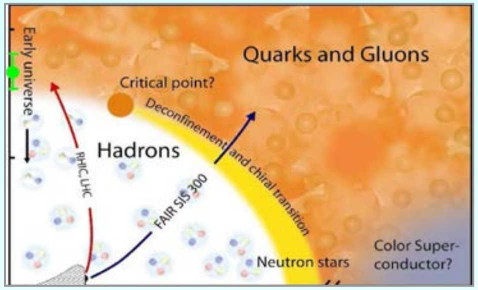
arXiv:1401.5481 IHED RAS MIPT arXiv:1504.0585

comp star



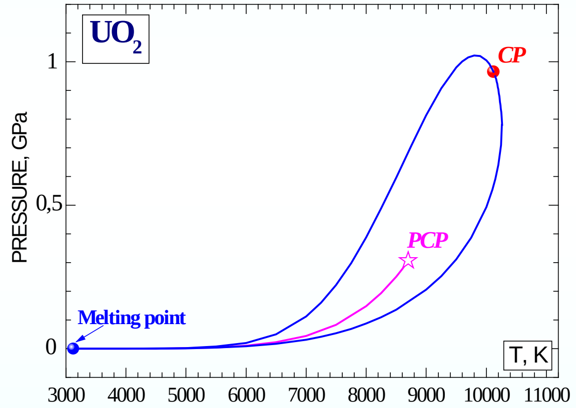
DIAS-TH: Dubna International Advanced School of Theoretical Physics
Helmholtz International Summer School
2008
Dense Matter in
Heavy Ion Collisions and Astrophysics

2008



Non-Congruent Phase Transitions

in High Energy Density Matter



Igor Iosilevskiy

Moscow Institute of Physics and Technology
(State University)

MIPT

Content (*PT – phase transition*)

- Motivation
- Enthalpic and Entropic PTs. Terminology.
- Historical comments
- Entropic PT – what does it mean ?
- Pressure delocalization of bound complexes – key driving mechanism.
- Entropic PTs via 1st principle approaches
- Anomalous thermodynamics within and nearby the boundaries of entropic phase transitions

Illustrations: Entropic phase transitions in hydrogen and nitrogen plasmas

- Summary and outlook

The main point

Proposal:

Additional subdivision *(classification)* **of all 1^{st}-order phase transitions (PT) into two subclasses – enthalpic and entropic PTs**

The term enthalpic PT – does not exist !

The term entropic PT – is used already for rather delicate structural PTs *(Daan Frenkel et al)*

NB!

I propose to use these terms in general context

Entropic Phase Transitions

?

Entropic Phase Separation in Polymer-Microemulsion Networks

A. Zilman, J. Kieffer, F. Molino, G. Porte, and S. A. Safran

Phys. Rev. Lett. **91**, (2003)

We study theoretically a model system of a transient network of **microemulsion droplets connected** by telechelic **polymers** and explain recent experimental findings. Despite the absence of any specific interactions between either the droplets or polymer chains, we predict that as the number of polymers per drop is increased, the system undergoes a first-order phase separation into a dense, highly connected phase, in equilibrium with dilute droplets, decorated by polymer loops. The phase transition is purely entropic and is driven by the interplay between the translational entropy of the drops and the configurational entropy of the polymer connections between them. Because it is dominated by entropic effects, the phase behavior of the system is extremely and is independent of the detailed properties of either polymers or drops.

Entropic Phase Transitions

?

Entropy-driven phase transitions in Hard-body systems

Daan Frenkel

Physica A, **263**, (1999)

We study theoretically a model system of hard-body particles . . . . .

$F = U - TS$

$U \equiv 0$

$F = - TS$

Freezing in the Hard-sphere system is *enthalpy-driven* transition !

$G = H - TS$

$\Delta V < 0$

$\Delta H = - T\Delta S \leq 0$

Journal of Modern Physics, **7 (2016)**

Entropic and Enthalpic First-Order Phase Transitions in Strongly Interacting Matter

F. Wunderlich, R. Yaresko, B. Kämpfer
Helmholtz-Zentrum, Institut für Strahlenphysik, Dresden, Germany
Institut für Theoretische Physik, TU Dresden, Germany

Published 29 April 2016

FAIR, NICA, LHC…

Physical Review D, **94 (2016)**

A Hot Third Family of Compact Stars and the Possibility of Core-collapse Supernova Explosions

Hempel M., Heinimann O., Yudin A., Iosilevskiy I., Liebendoerfer M., Thielemann F-K.,
Basel University, Switzerland; Joint Institute for High Temperature, Russia;
Institute for Experimental and Theoretical Physics, Russia

Published, December 2016

Astrophysics

Motivation - I

The wide world *of* phase transitions *in* high energy density matter

There are many phase transitions which differ significantly from the well-known gas-liquid PT of VdW-type

What should we classify when we meet unexplored phase transition -?

1st *or* **2nd order ?**

Isostructural *or* **non-isostructural ?**

Congruent *or* **non-congruent ?**

Enthalpic *or* **entropic ?**

Do we use **Coulomb-less approximation** *or* we take into account all consequences *of* **long-range nature** *of* **Coulomb** interaction **?**

Scenario *of* **phase transformation** *in* **two-phase region** –

– **Macro-** *or* **Mesoscopic ?**

Phase transitions *in* high energy density matter

Enthalpic *vs* **Entropic**

?

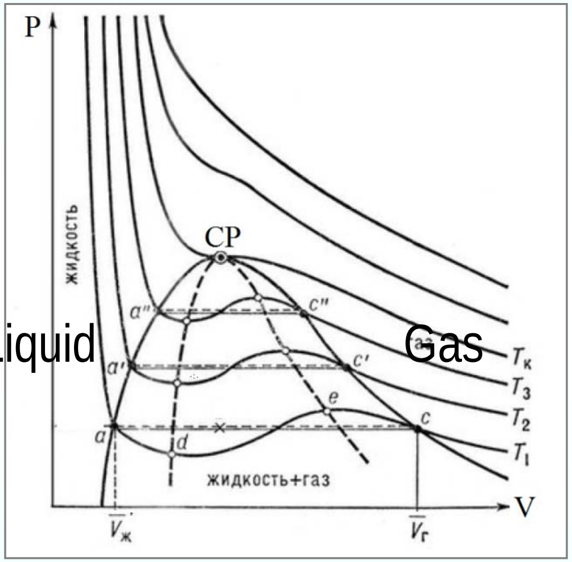
The main subject of our interest

Isostructural 1st-order entropic fluid-fluid phase transitions

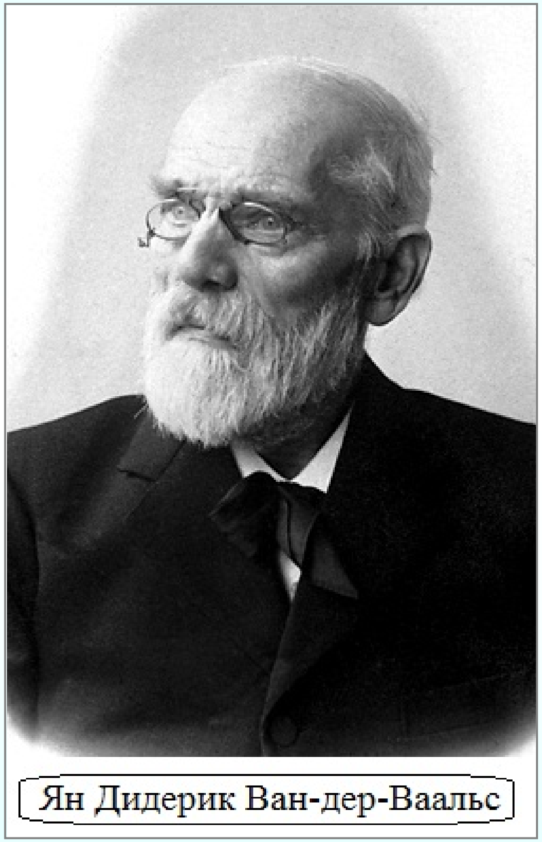
Historical comments

Van der Waals model *of* gas-liquid phase transition

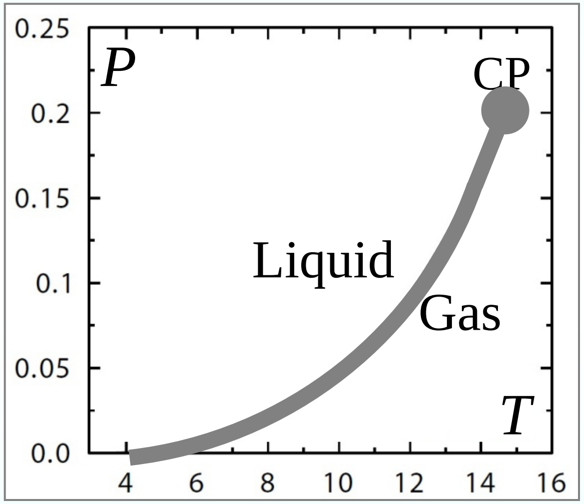
$$(P + a\rho^2)(1 - \rho b) = \rho T,$$



Two-phase region
Binodals, Spinodals
Critical Point
VdW-loops at iso-T
Two metastable zones
Unstable state region
Etc . . . . . .



Johannes D. **Van der Waals**
(1837 – **1923**)
On the Continuity of the Gaseous and Liquid States,
Ph.D. Diss. Leiden, **1873**

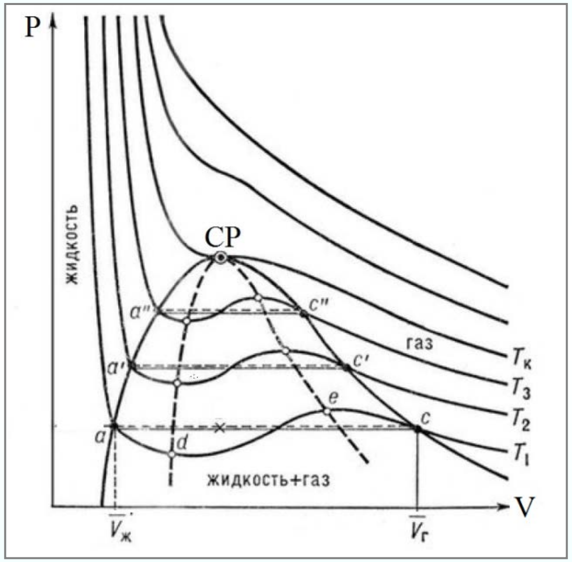


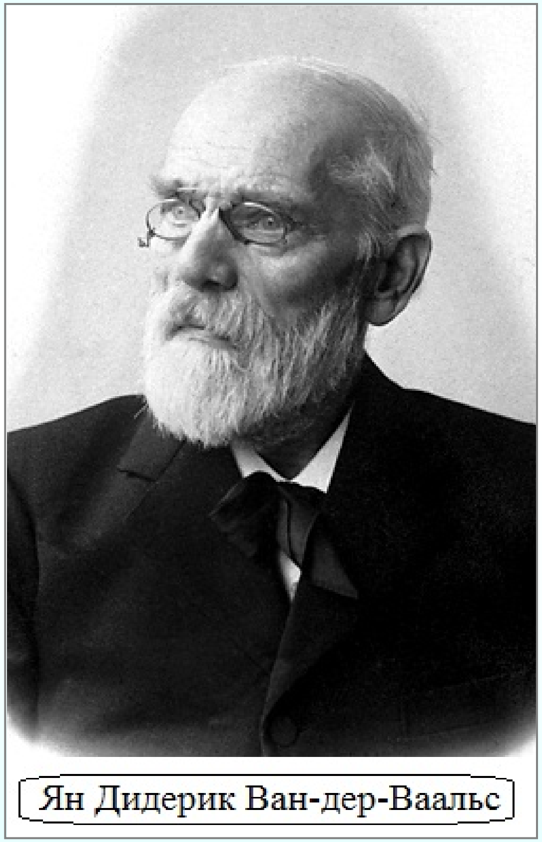
Saturation Curve . . .

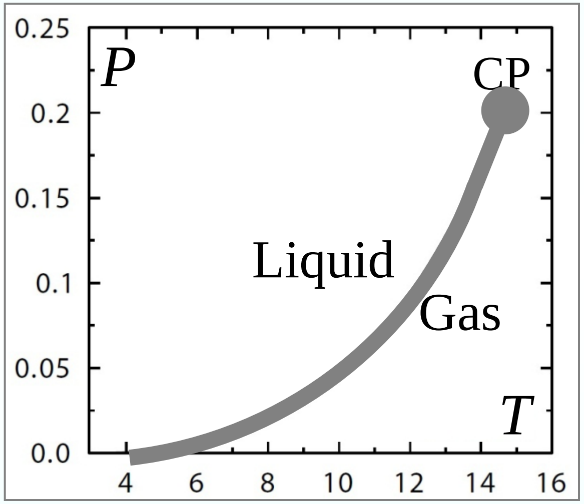
144 years

VdW - typical "enthalpic" phase transition !

$$(P + a\rho^2)(1 - \rho b) = \rho T,$$



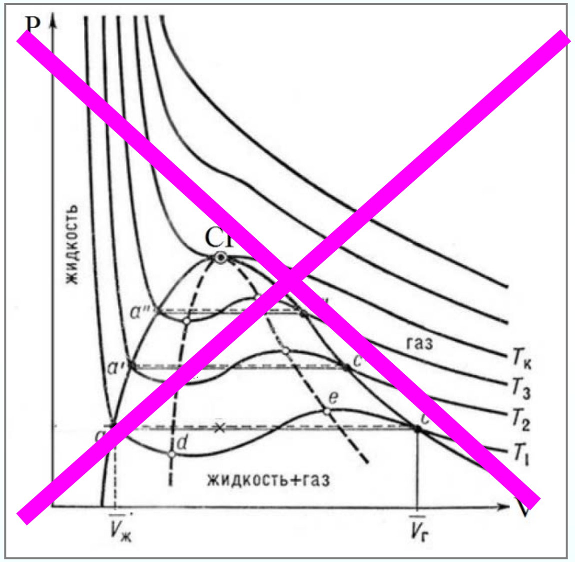


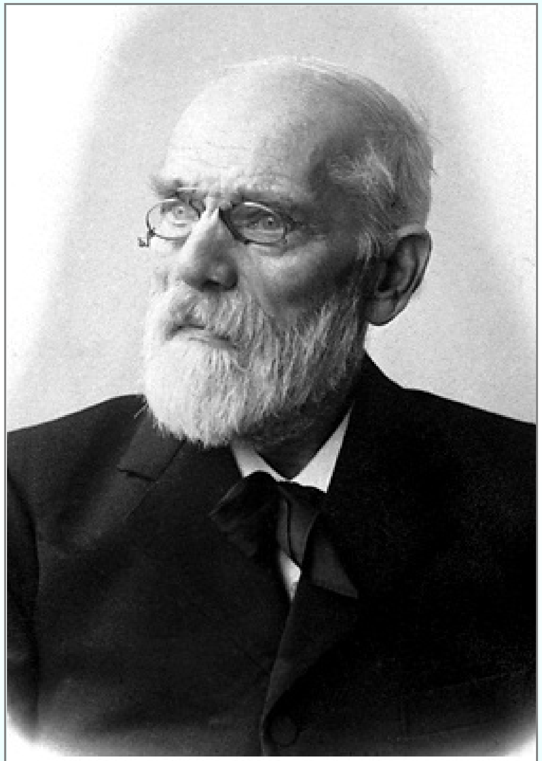


Johannes D. **Van der Waals**
(1837 – **1923**)
On the Continuity of the Gaseous and Liquid States,
Ph.D. Diss. Leiden, **1873**

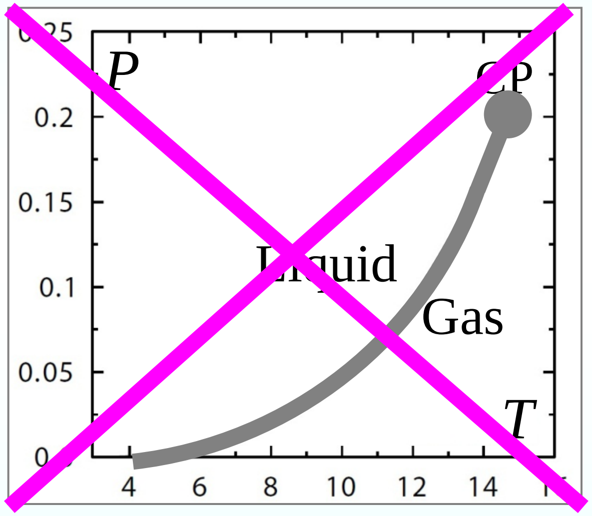
And what about typical "entropic" phase transition ?

$$(P + a\rho^2)(1 - \rho b) = \rho T,$$





Ян Дидерик Ван-дер-Ваальс



Two-phase region - **diff.**
Binodals, Spinodals - **diff.**
Critical Point - **diff.**
VdW-loops at iso-T - **diff.**
Two metastable zones - diff.
Unstable state region- **diff.**
Etc . . . . . .

Debye – Hückel non-ideality correction

The simplest model of Coulomb nonideality (DHLL)

Debye and Hückel, *Phys. Zeitschr.*, **24**, 8, 1923.

Peter Debye

Erich Hückel

(1923)

94 years

$$\frac{P}{nkT} = 1 - \frac{\Gamma_D}{6} + \ldots$$

NB!

$$\Gamma_D = 4 \qquad \left(\frac{\partial P}{\partial V}\right)_T = 0$$

$$\Gamma_D > 6 \quad \Leftrightarrow \quad P < 0 \ \ !$$

$$\boldsymbol{\Gamma_D \equiv Z^2 e^2 / kT r_D}$$

Phase transitions *in* high energy density matter

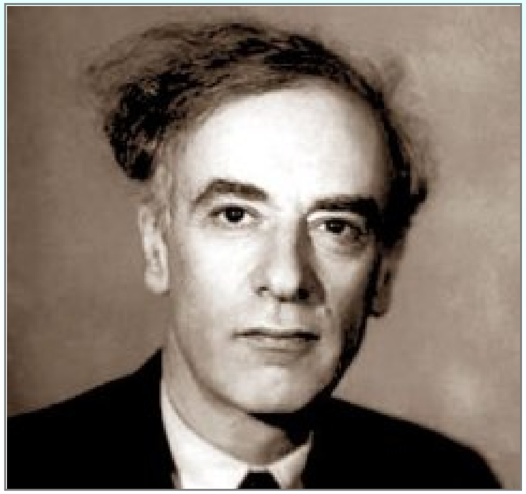
Ionization-driven (“*plasma*”) phase transition

is it Enthalpic *or* Entropic

?

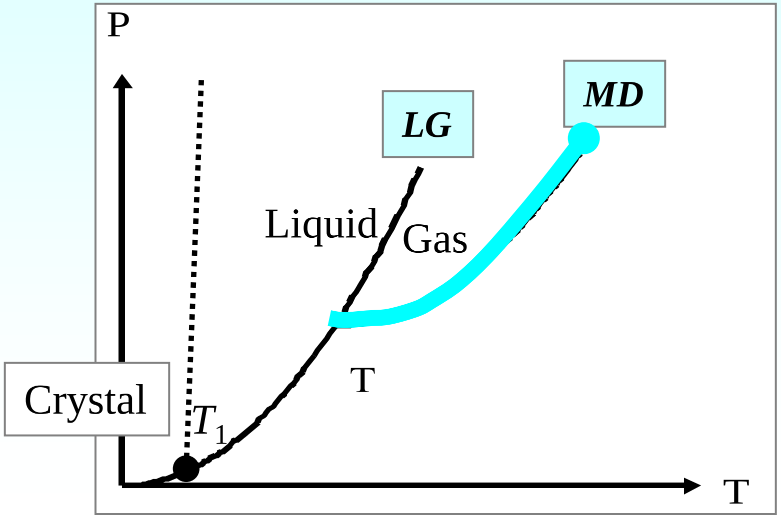
Hypothetical 1st order phase transition "insulator-conductor" *in* metals

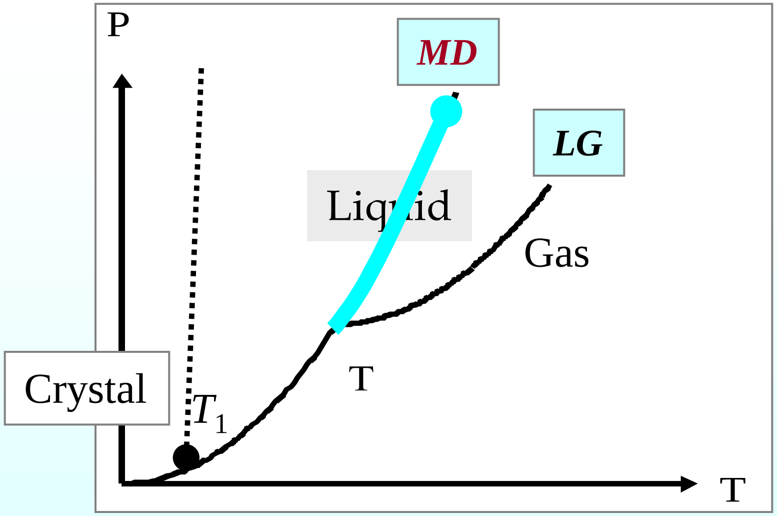
(1943)



Lev Landau

Yakov Zeldovich





74 years

Landau L.D., Zeldovich Ya.B., *Acta Physico-Chimica URSS*, 18, (**1943**)
On the relation between the liquid and the gaseous states of metals

Phase transitions *in* high energy density matter

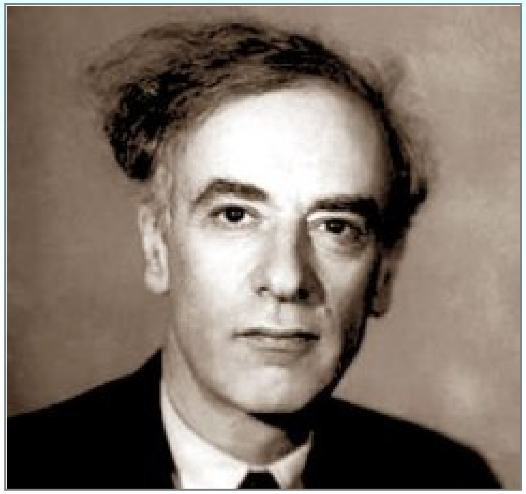
"Pressure ionization"-driven phase transition in compressed metal vapors

- is it Enthalpic *or* Entropic

?

Hypothetical 1st order phase transition "insulator-conductor" *in* metals

(1943)



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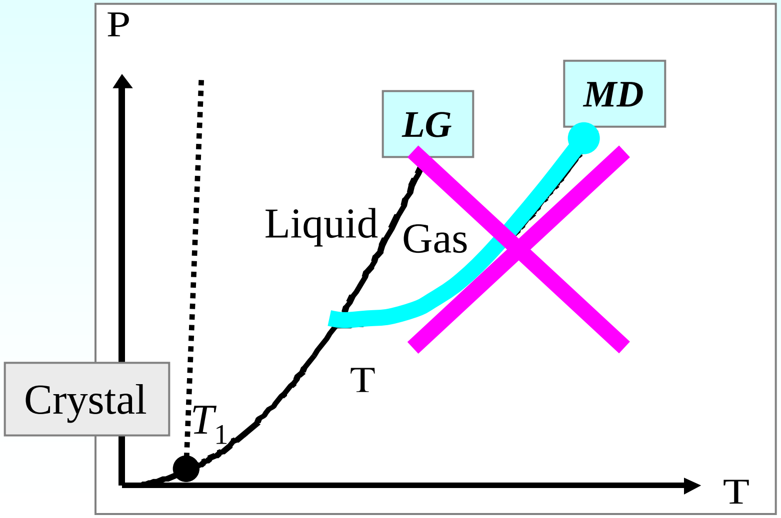
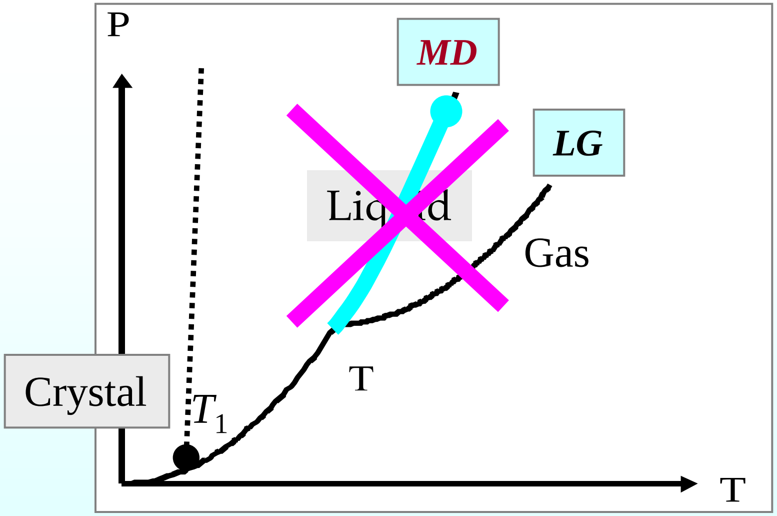




Landau L.D., Zeldovich Ya.B., *Acta Physico-Chimica URSS*, 18, (**1943**)
On the relation between the liquid and the gaseous states of metals

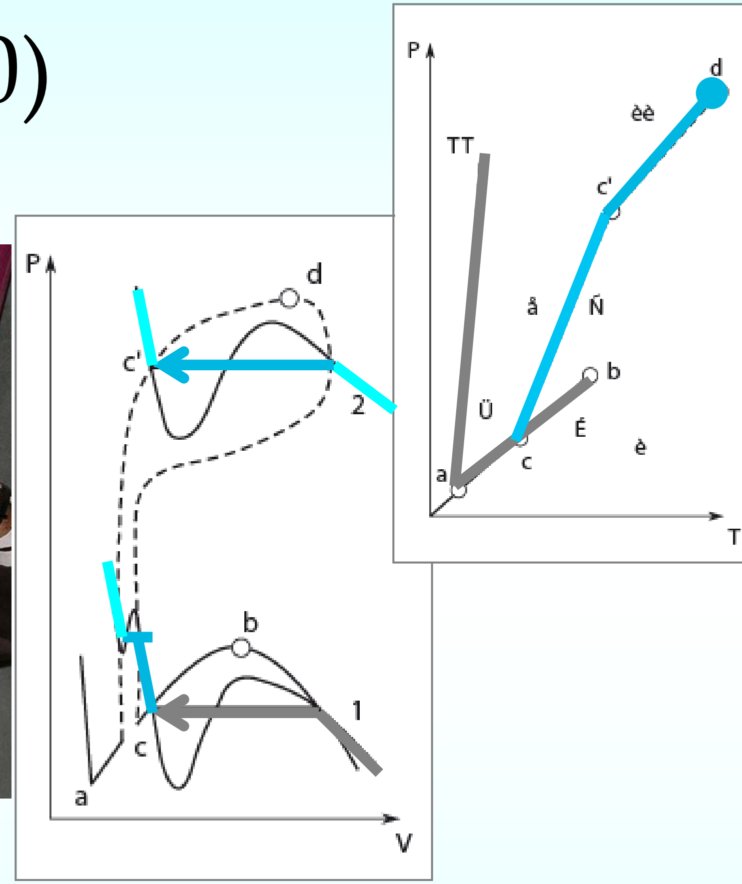
“Plasma” phase transitions theory

(Coulomb attraction + quantum repulsion)

(1968-1970)

Andrew Starostin

Henry Norman



~ 50 years

Norman H., Starostin A. *High Temperature*, **6**, (1968)
Plasma phase transitions

See also: Ebeling W., Kraeft W.D., Kremp D. *Theory of Bound States and Ionization Equilibrium in Plasmas* (Akademic–Verlag, Berlin, 1976 / МИР, Москва, 1979)

Phase transitions *in* high energy density matter

Ionization-driven (“*plasma*”) phase transition

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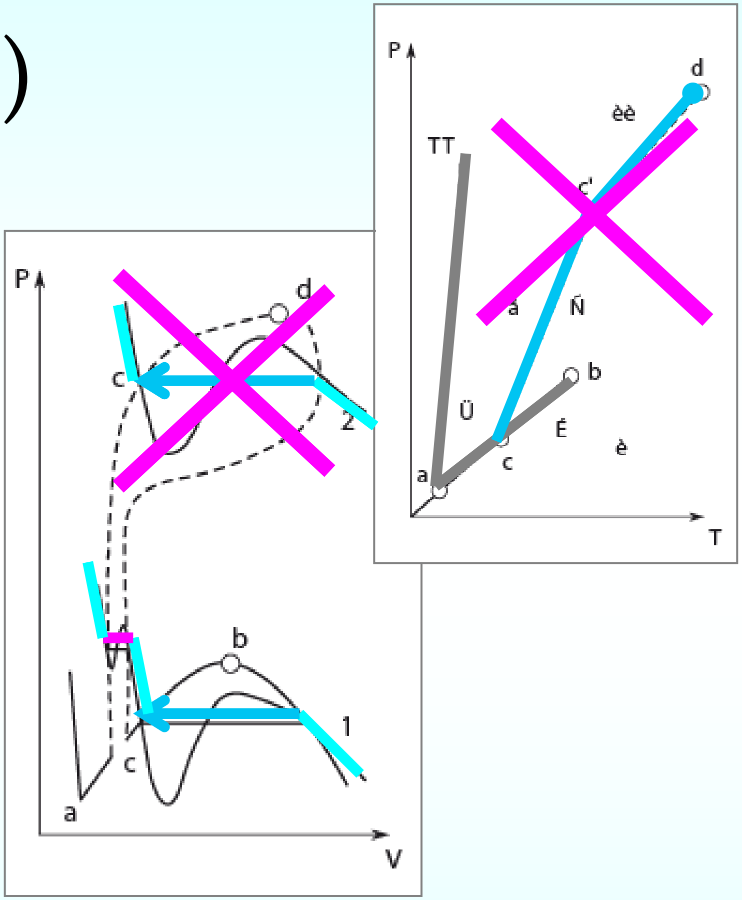


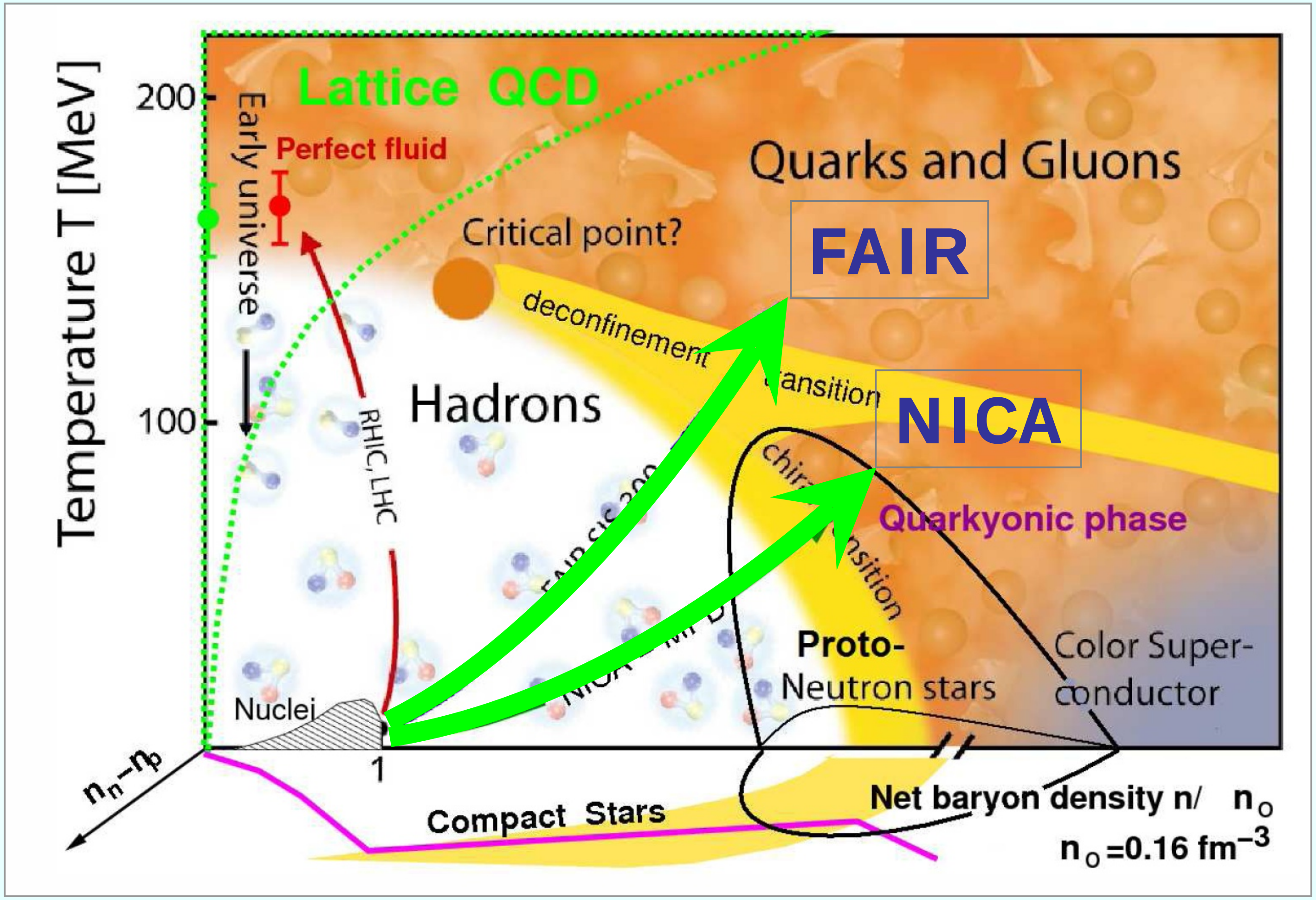
Norman H., Starostin A. *High Temperature*, **6**, (1968)
Plasma phase transitions

See also: Ebeling W., Kraeft W.D., Kremp D. *Theory of Bound States and Ionization Equilibrium in Plasmas* (Akademic–Verlag, Berlin, 1976 / МИР, Москва, 1979)

Motivation - II

Motivation

Phase diagram *of* matter *in* ultra-high energy *and* density

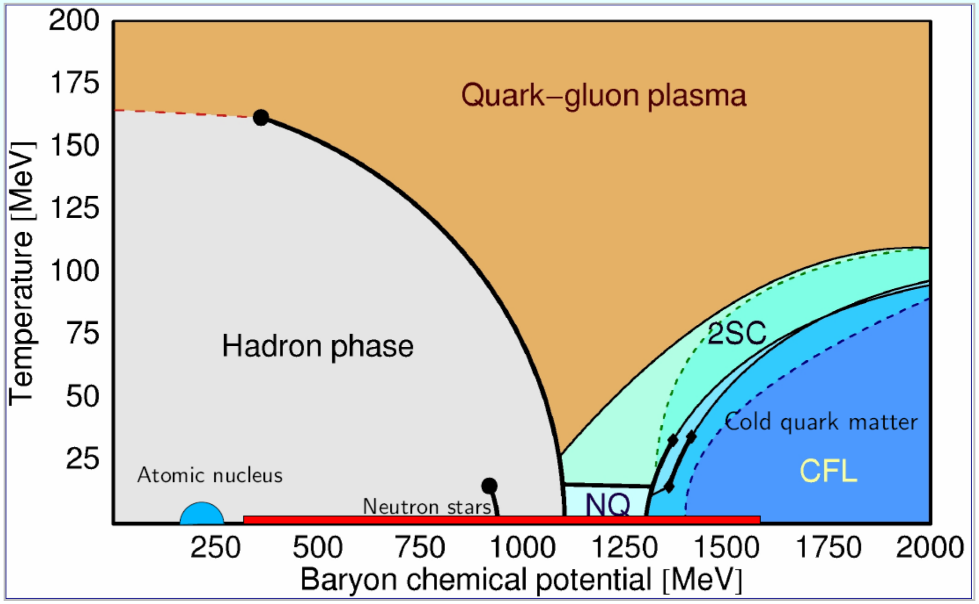


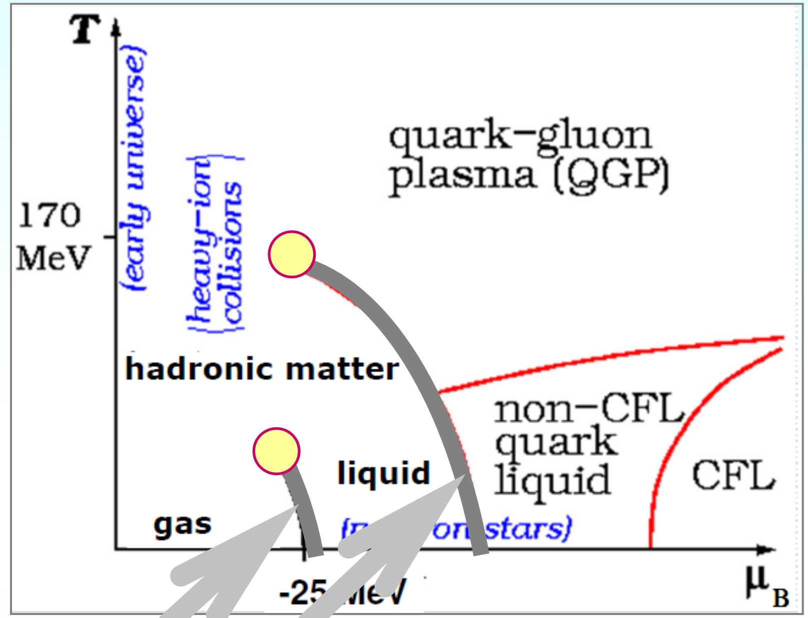
NICA White Book

After David Blaschke, *NICA Workshop, Dubna,* 2009

Phase diagram of matter in ultra-high energy and density

(*schematic*)





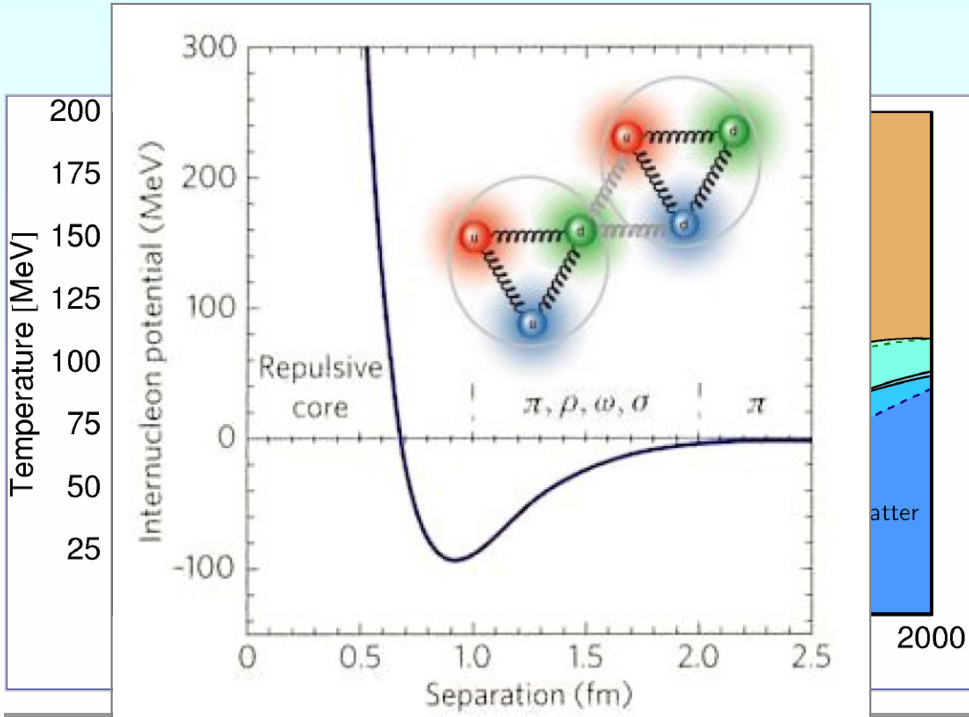
After **Fridolin Weber**, WEHS Seminar, Bad Honnef, 2006
After **David Blaschke**, WEHS Seminar, Bad Honnef, 2007
……………………………………………………..

Source: WIKIPEDIA

"Gas-liquid" phase transition in Coulombless system {*p,n,N(A,Z)*}
/ **GLPT** /

Quark-Hadron phase transition
/ **QHPT** /

Phase diagram of matter in ultra-high energy and density

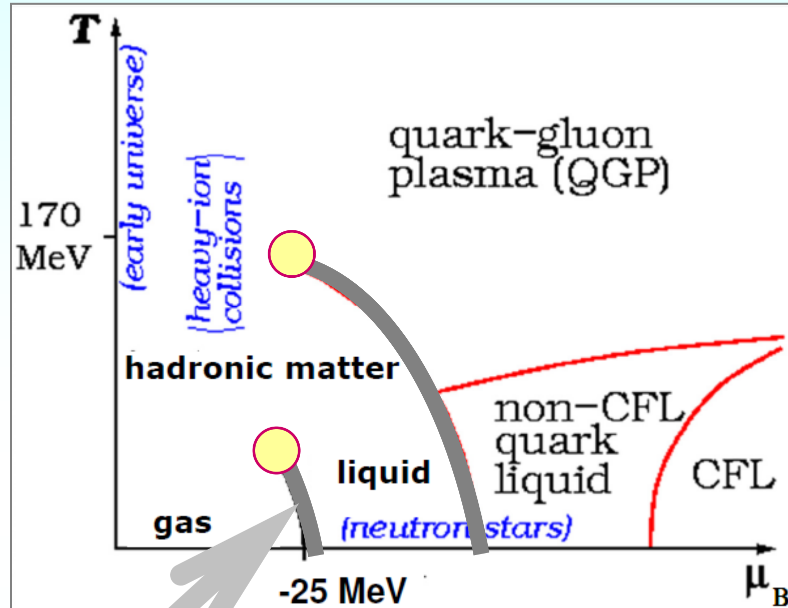


Internucleon potential (MeV)

Micaela Oertel
NewComsptar School, Barcelona, September,2014

After … , 2006
After … , 2007

(*schematic*)



Source: WIKIPEDIA

“Gas-liquid” phase transition in Coulombless system { *p,n,N(A,Z)* }
/ GLPT /

Quark-Hadron phase transition
/ QHPT /

Direct numerical simulation in simplified model

Horowitz C., Pérez-García M.A., et al. *Phys. Rev. C*, **69**, (2004)

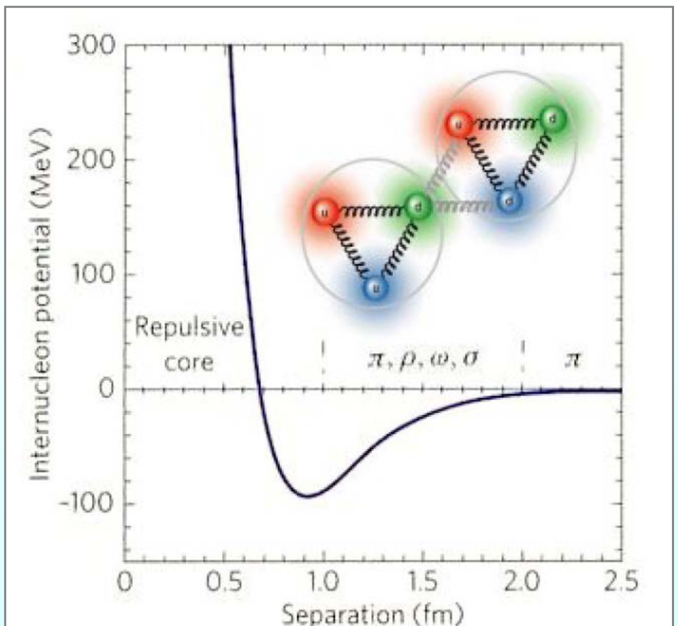
$$V_{tot} = \sum_{i<j} V(i,j) \ ,$$

$$V(i,j) = a e^{-r_{ij}^2/\Lambda} + \left[b + c\tau_z(i)\tau_z(j) \right] e^{-r_{ij}^2/2\Lambda} + V_{\mathrm{c}}(i,j)$$

$\tau_z(j) = 1$ - protons

$\tau_z(j) = -1$ - neutrons

V_c - Coulomb



“Pasta”

Direct numerical simulation in simplified model

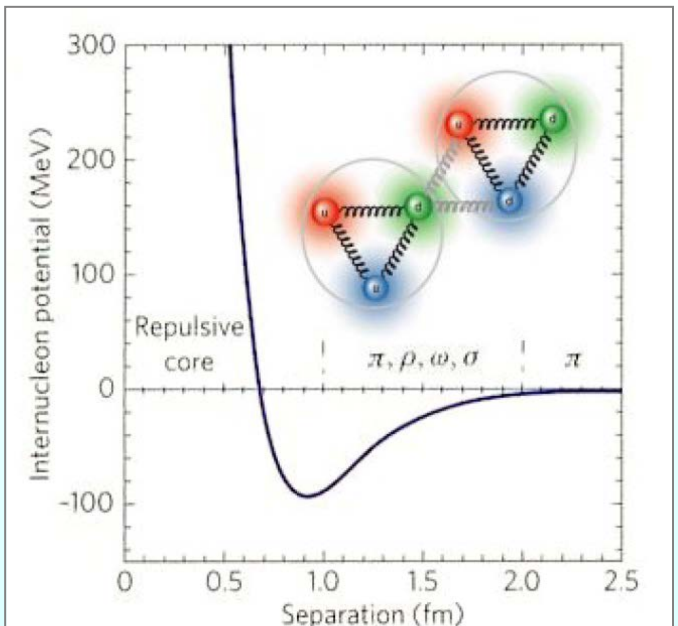
Horowitz C., Pérez-García M.A., et al. *Phys. Rev. C*, **69**, (2004)

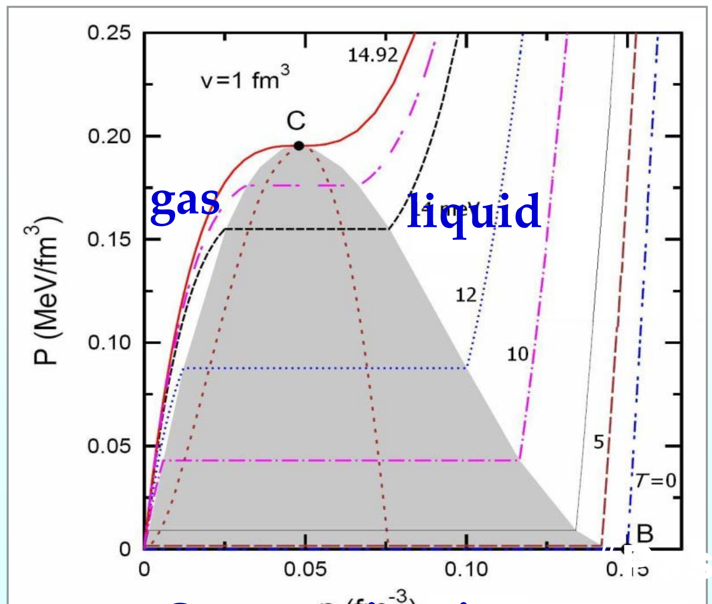
$$V_{tot} = \sum_{i<j} V(i,j)\ ,$$

$$V(i,j) = a e^{-r_{ij}^2/\Lambda} + \Big[b + c\tau_z(i)\tau_z(j)\Big] e^{-r_{ij}^2/2\Lambda}$$

Coulombless approximation

$\tau_z(j) = 1$ - protons $\tau_z(j) = -1$ - neutrons V_c





Symmetric mixture

Asymmetric mix.

Non-congruent phase transition

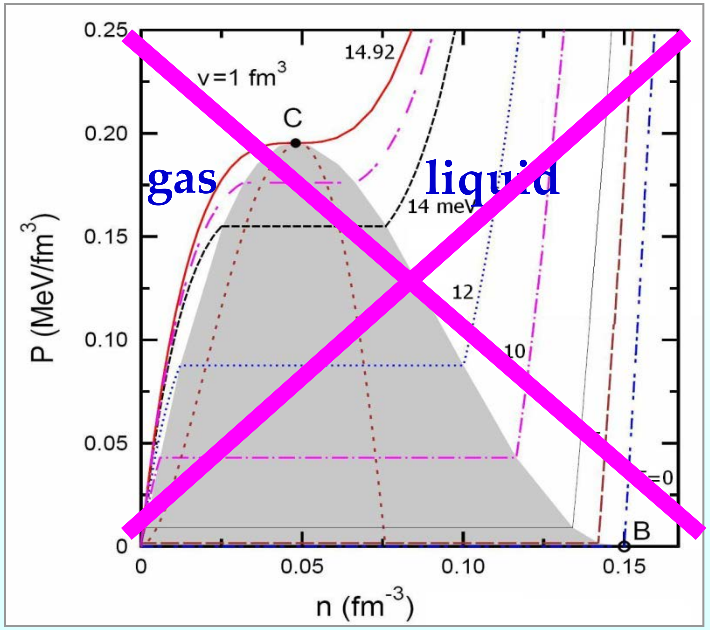
Direct numerical simulation in simplified model

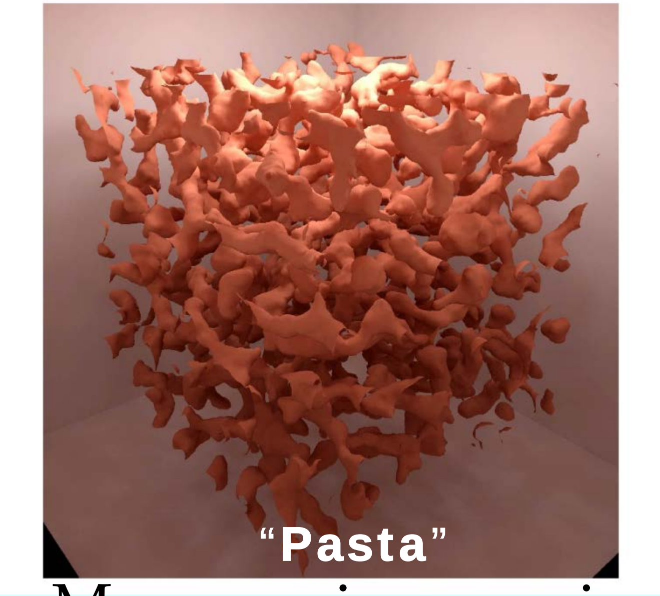
Horowitz C., Pérez-García M.A., et al. *Phys. Rev. C*, **69**, (2004)

$$V_{tot} = \sum_{i<j} V(i,j) \ ,$$

$$V(i,j) = a e^{-r_{ij}^2/\Lambda} + \left[b + c\tau_z(i)\tau_z(j)\right] e^{-r_{ij}^2/2\Lambda} + V_c(i,j)$$

$\tau_z(j) = 1$ - protons $\tau_z(j) = -1$ - neutrons V_c - Coulomb

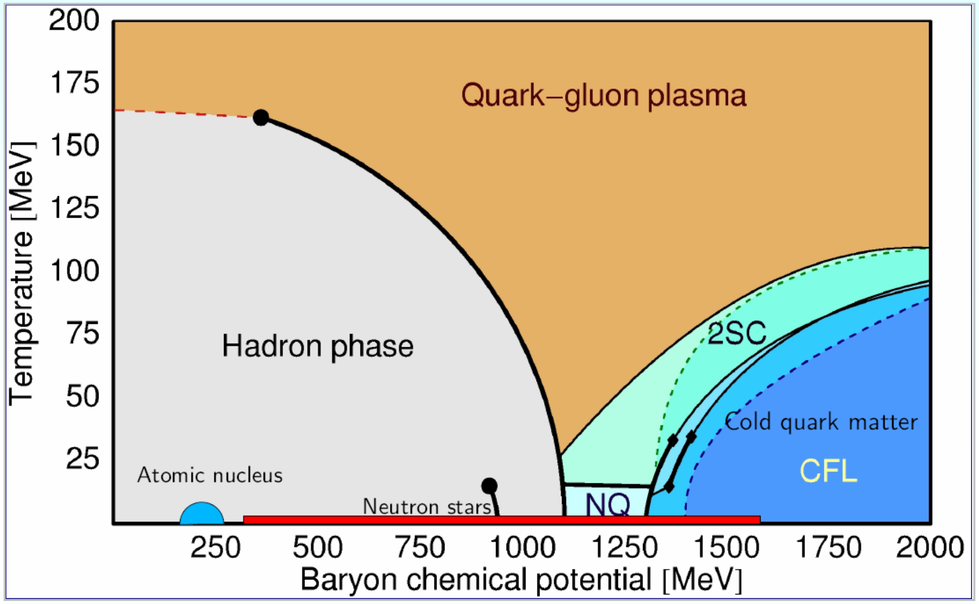


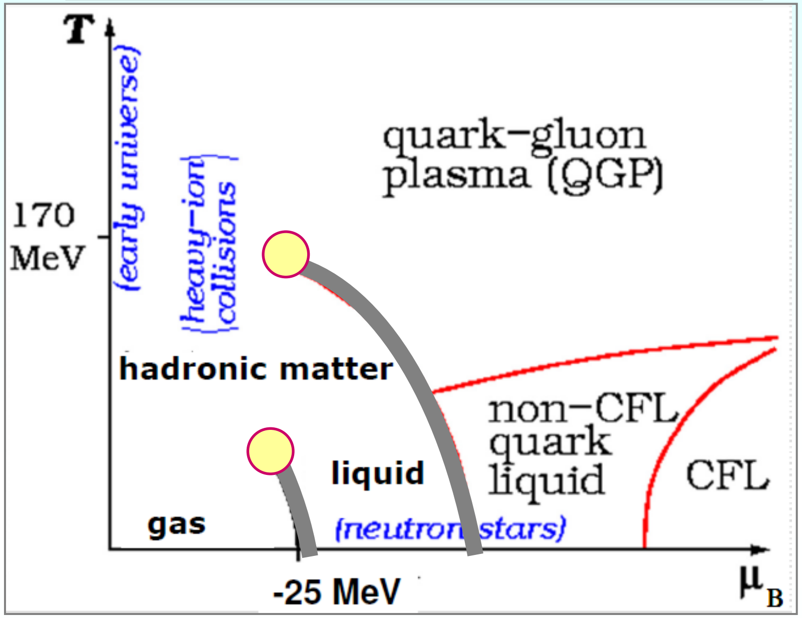


Mesoscopic scenario

Phase diagram of matter in ultra-high energy and density

(*schematic*)





After David Blaschke, WEHS Seminar, Bad Honnef, 2007
……………………………………………………..

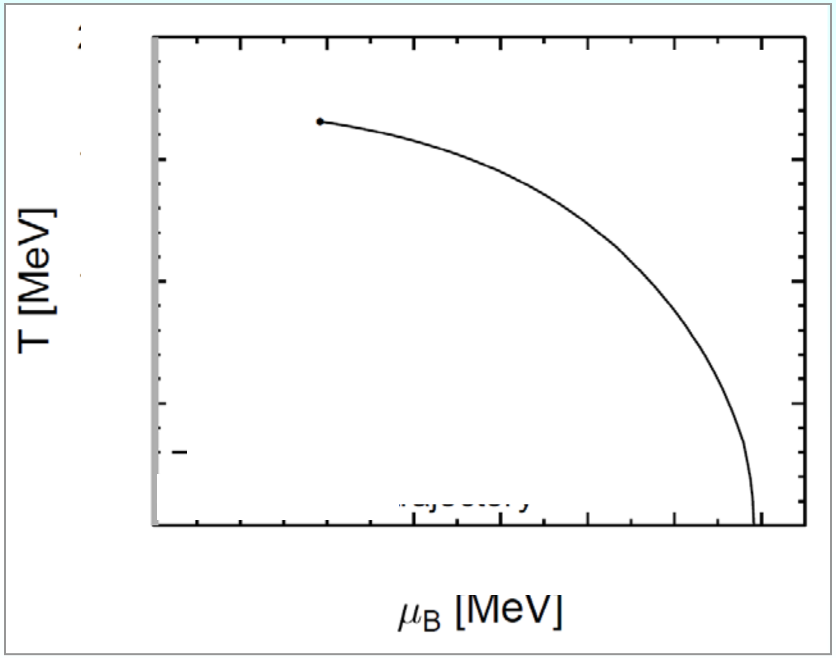
Source: WIKIPEDIA

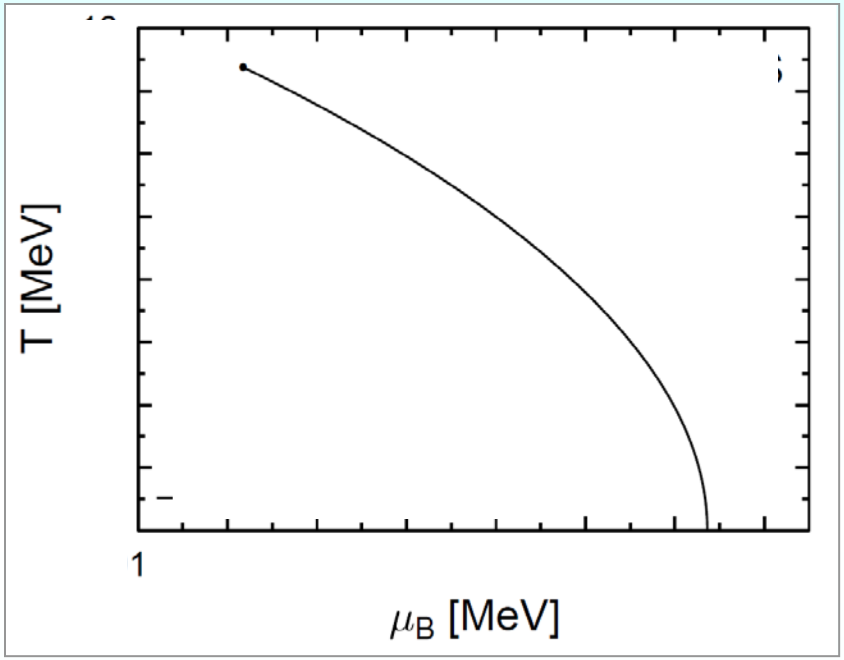
"Gas-liquid" phase transition in Coulombless system {*p,n,N(A,Z)*}
/ GLPT /

Quark-Hadron phase transition
/ QHPT /

T-μ phase diagram *for* symmetric GLPT *and* QHPT

Coulombless approximation





Non-congruence of the nuclear liquid-gas and the deconfinement phase transitions
Matthias Hempel, Veronica Dexheimer, Stefan Schramm, Igor Iosilevskiy
(Phys. Rev. C, **88**, 2013*)*

arXiv:1504.058050

NB!

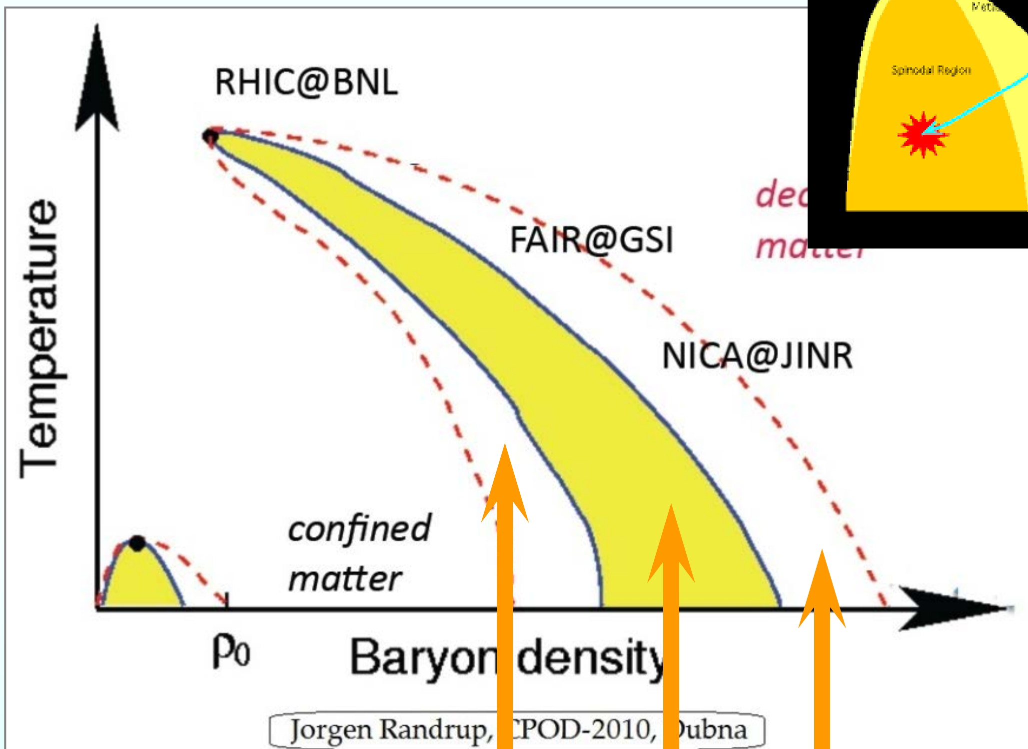
One could not distinguish GLPT vs. **QHPT** in T- μ plane

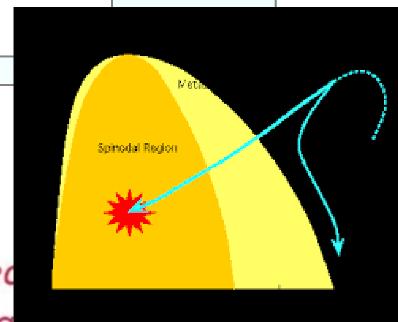
Gas-liquid *and* Quark-hadron phase transitions are often considered as similar

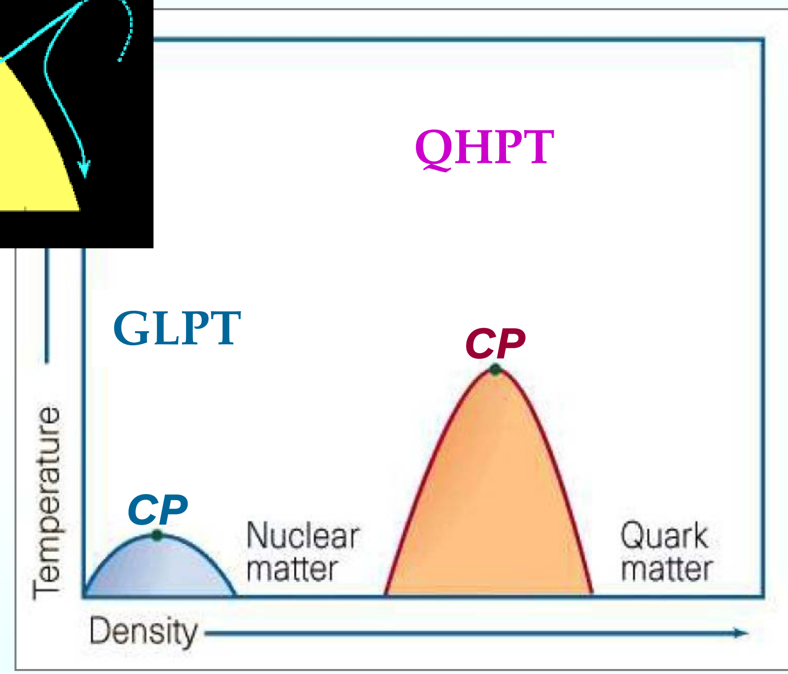
Jorgen Randrup

"Critical Point and Onset of Deconfinement"
Dubna, Russia, 2009

"Critical Point and Onset of Deconfinement"
Napa, USA, 2013







J. Steinheimer & J. Randrup, *CPOD*-2013

Metastable

Spinodal region

Metastable

Jorgen Randrup

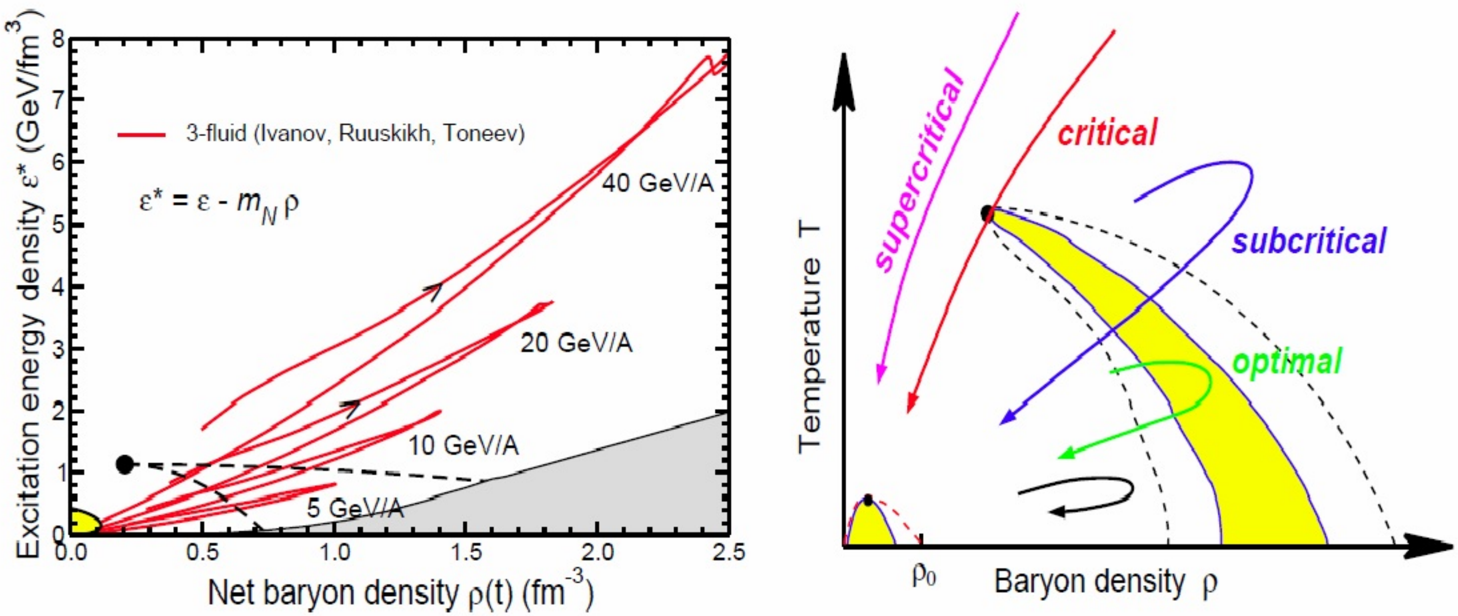
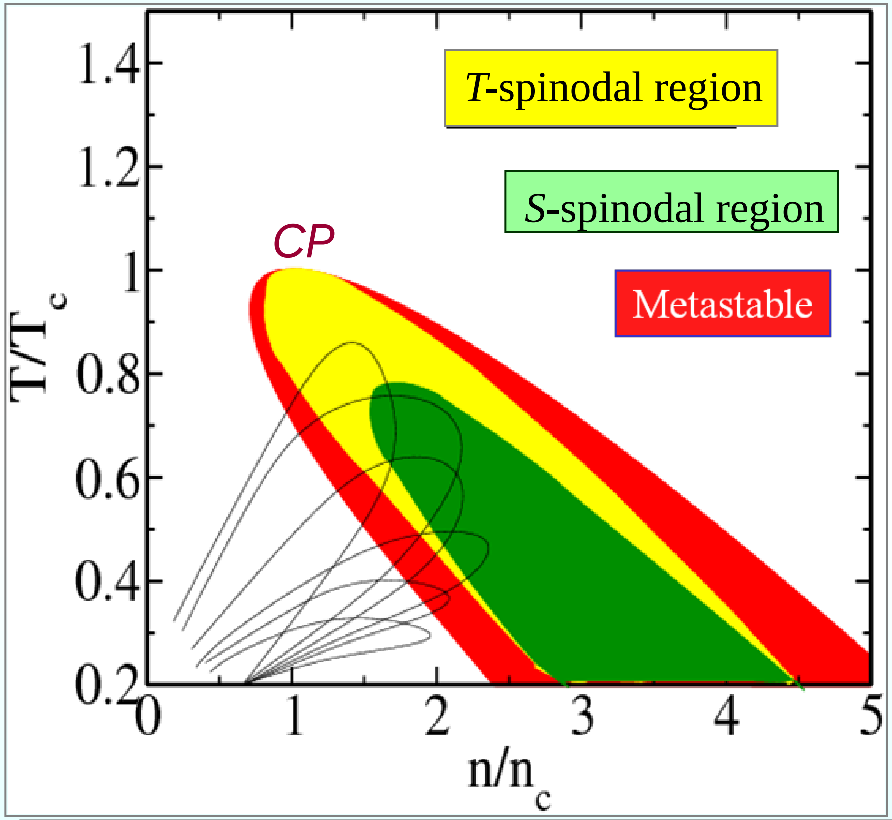


Figure 4: Dynamical phase trajectories. *Left:* Time evolution of the mechanical phase point $(\rho(t), \varepsilon^*(t))$ extracted at the center of a head-on gold-gold collision as calculated in the 3-fluid model (from Ref. [4]). *Right:* Sketch of the associated generic features as a sweep is made in the collision energy.

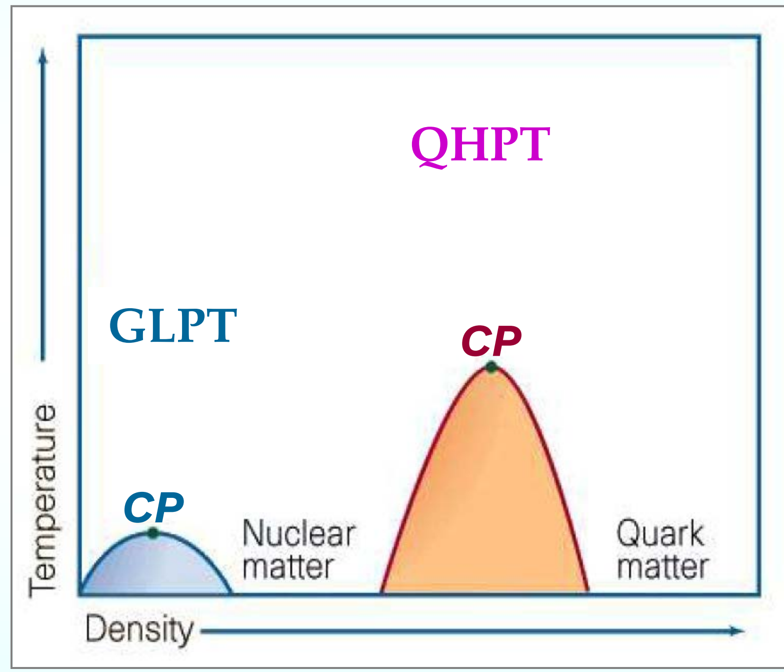
Dubna, Russia, 2009

Dense QCD Phases in Heavy Ion Collisions and Supernovae,
11 October, 2009



Vladimir Skokov (GSI, Darmstadt)

Jan Steinheimer & J. Randrup, *CPOD*-2013

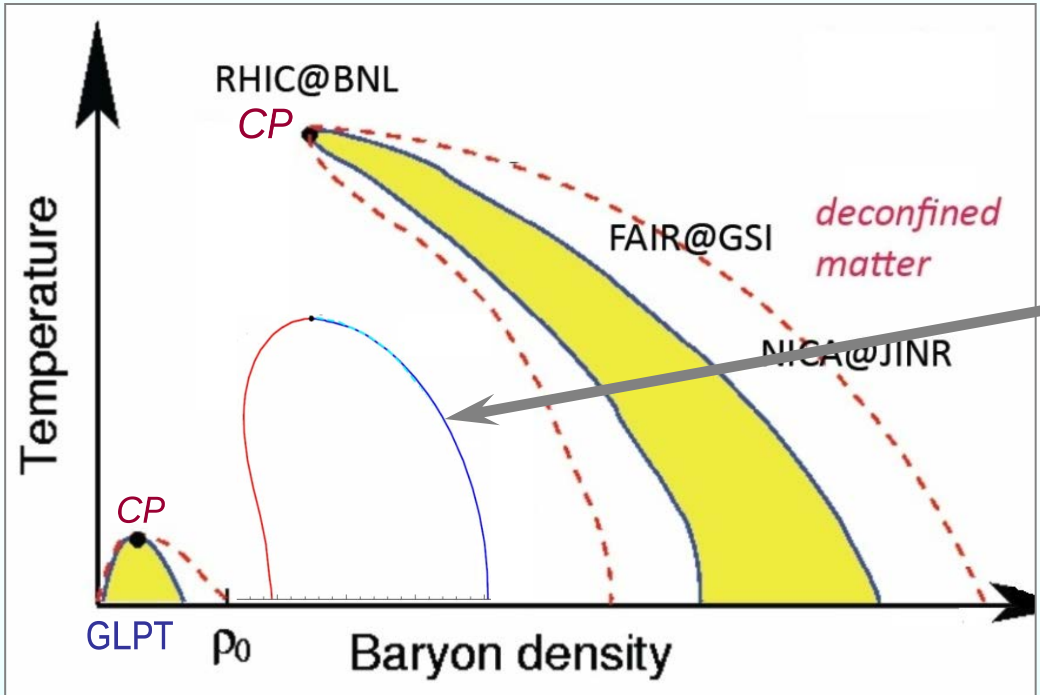


QHPT is expected naturally as a little bit bending VdW-like PT

Gas–liquid, Hadron–Δ-meson *and* Quark–hadron phase transitions are often considered as similar

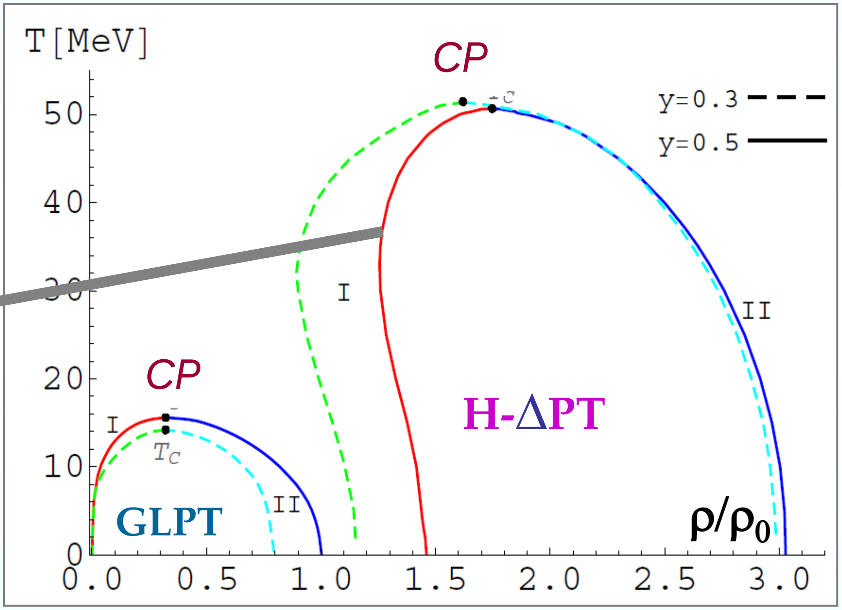
Prerow 2009

"Critical Point and Onset of Deconfinement"
Dubna, Russia, 2009



Jorgen Randrup, CPOD-2010, Dubna

Phase diagram of the liquid-gas and the nucleon-Δ matter phase transition

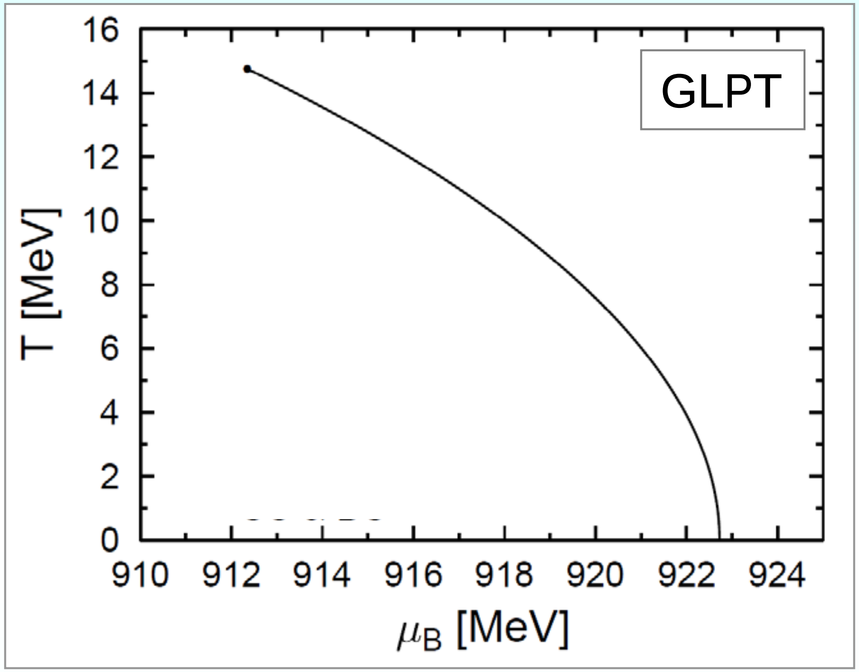


Lavagno A., Drago A., Pagliara G., Pigato D.
J. of Phys. **527** (2014)
Thermodynamic instability *in nuclear matter and in* ***compact stars***

What type of this new phase transition: - enthalpic or entropic?

GLPT *and* QHPT look *like* equivalent *in* T-μ phase diagram

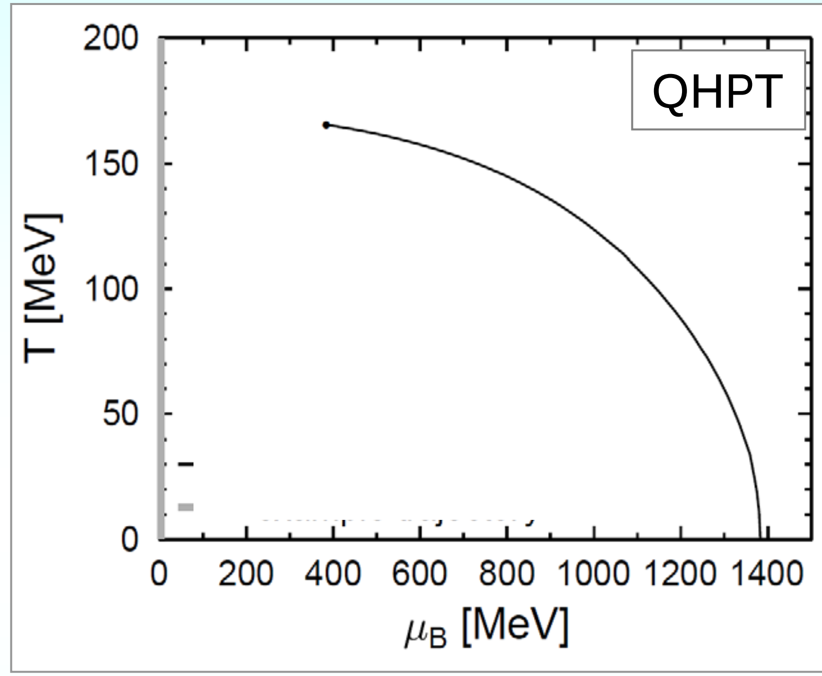
(symmetric case)



FSUGold (*Matthias Hempel (*)*)

Gas-liquid PT {$p,n,N(A,Z)$}

? =



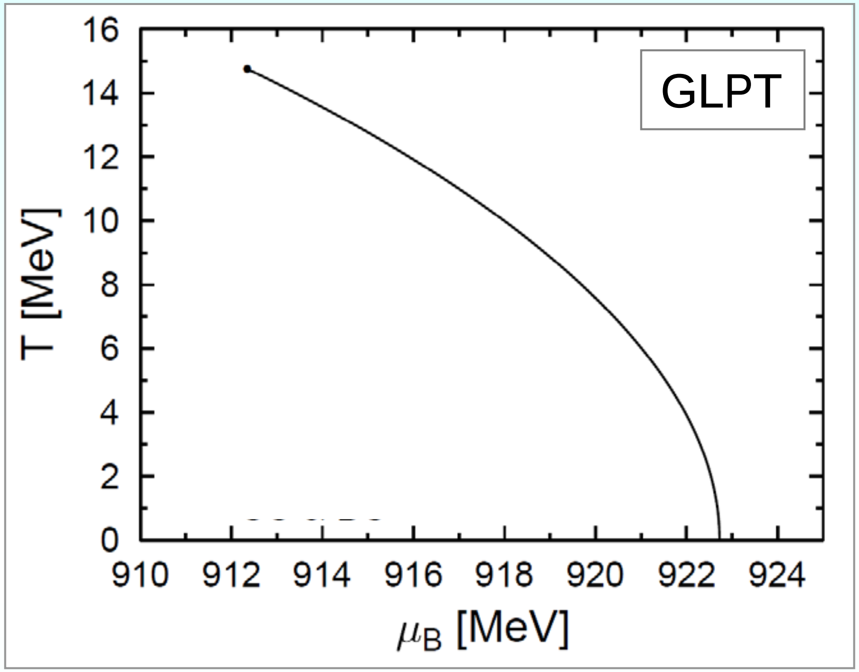
SU(3) model (*V. Dexheimer & S. Schramm (*)*)

Quark-hadron PT

(*) M. Hempel, V. Dexheimer, S. Schramm *and* I. Iosilevskiy // (*Phys. Rev.* C **88**, (2013)

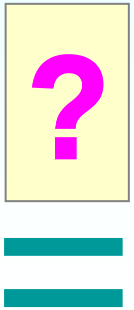
GLPT *and* QHPT look *like* equivalent *in* T-μ phase diagram

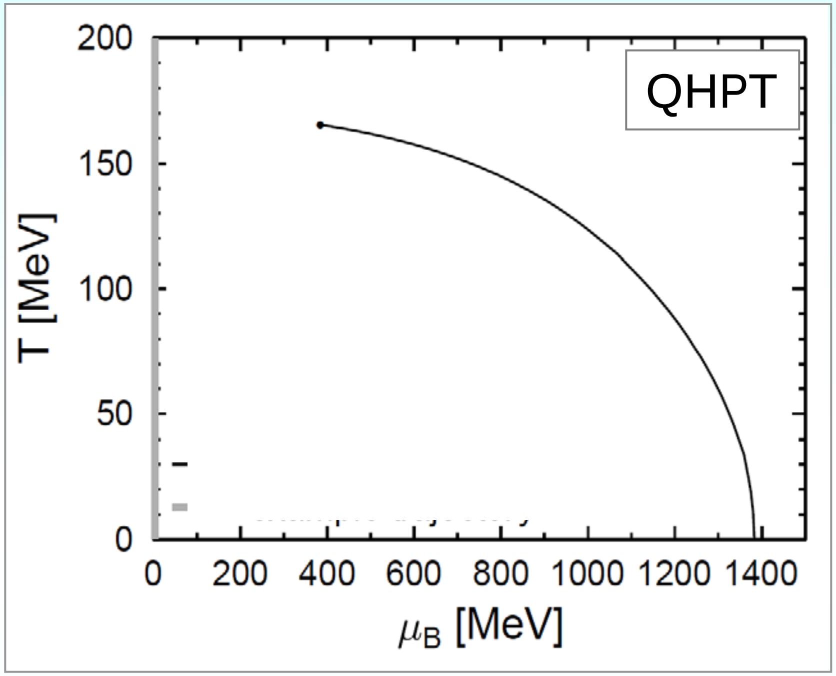
(symmetric case)



FSUGold (*Matthias Hempel (*)*)

Gas-liquid PT {$p,n,N(A,Z)$}





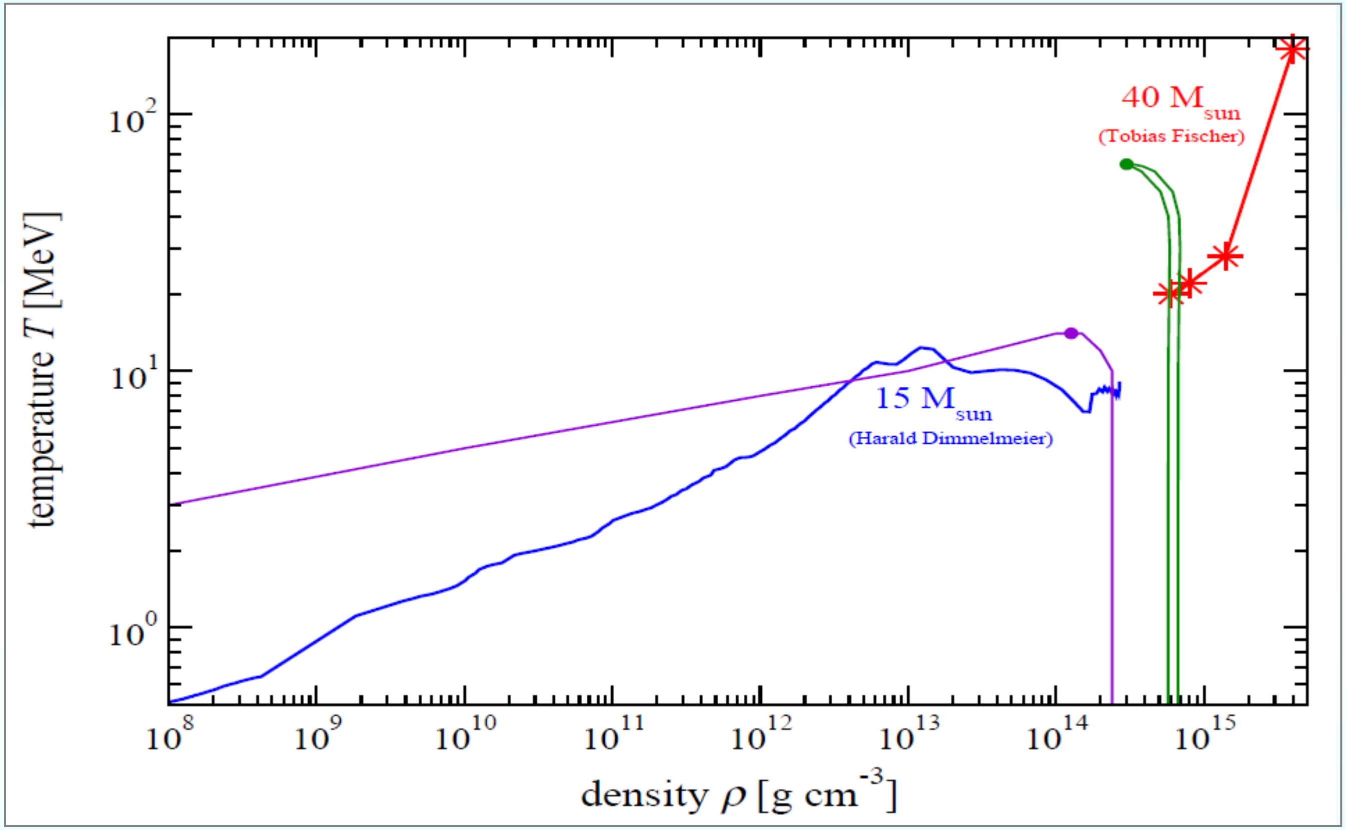
SU(3) model (*V. Dexheimer & S. Schramm (*)*)

Quark-hadron PT

(*) M. Hempel, V. Dexheimer, S. Schramm *and* I. Iosilevskiy // (*Phys. Rev.* C **88**, (2013)

No ! **Enthalpic PT** ≠ **Entropic PT**

Supernova Collapse in the Phase Diagram (III)



David Blaschke, *"Extreme State of Matter"*, *Elbrus-2010*

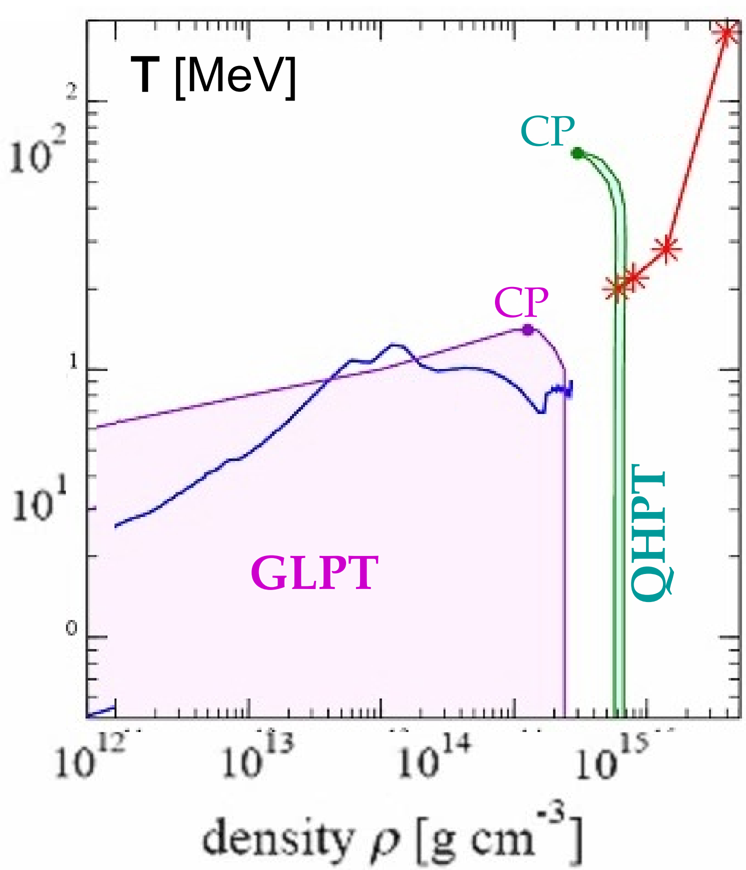
Supernova trajectories are taken from: Harald Dimmelmeier *and* Tobias Fischer

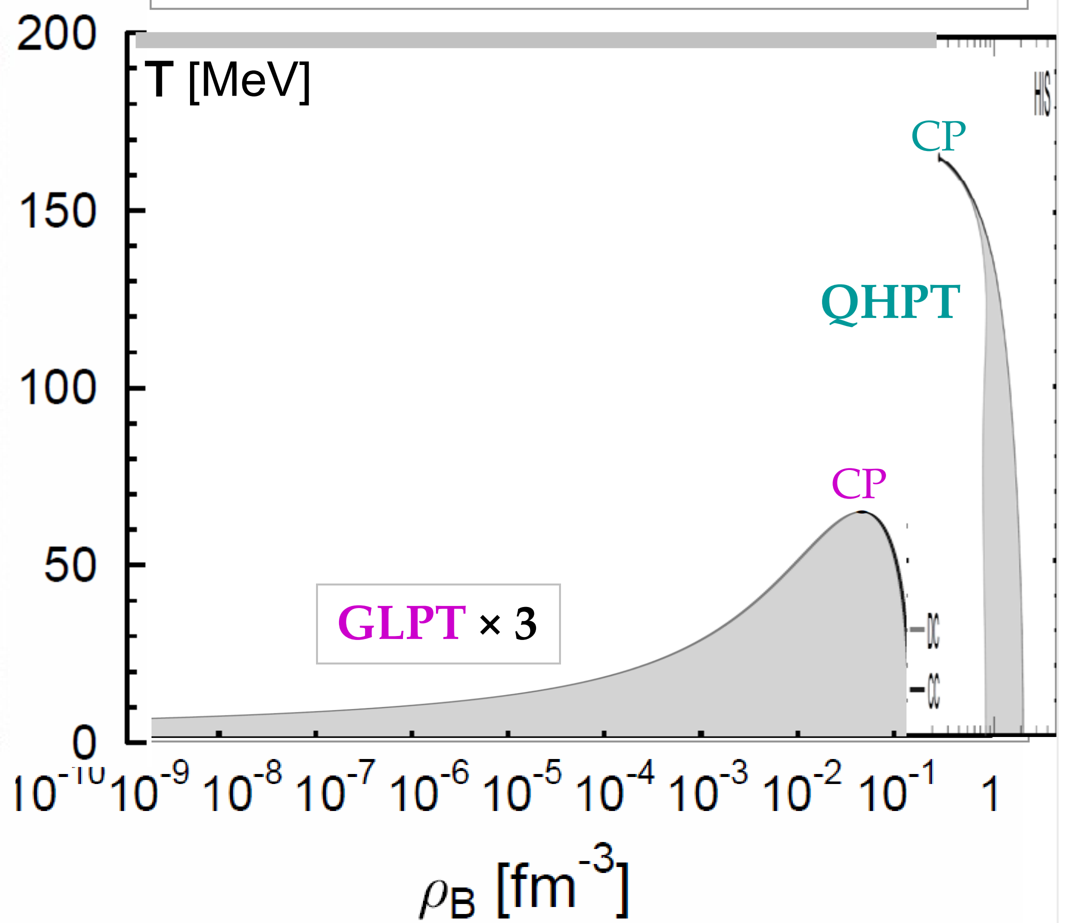
Gas-Liquid Phase Ttransition:
- G. Roepke et al., *Nucl.Phys.*A **399** (**1983**)

Quark-Hadron Phase Transition:
- D. Blaschke, T. Klaehn, F. Weber , "*Compact Star constraints on the EOS*", Lecture Notes in Physics, **814**, Springer (2011)

T - ρ phase diagram *of* symmetric Coulombless GLPT *and* QHPT

M. Hempel, V. Dexheimer, S. Schramm, I. Iosilevskiy
Phys. Rev. C **88** (2013)





after David Blaschke *et al.*
Acta Phys. Pol. Supp. **3** (2010)
GLPT - G.Roepke *et al.*. *Nucl.Ph.* (1983)
QHPT - D.Blaschke, T.Klaehn, F.Weber…(2011)
SN path calcs: - Tobias Fisher

FSUGold (*Matthias Hempel*)	SU(3) model (*Veronica Dexheimer*)
GLPT	**QHPT**

arXiv:1302.2835

Phase transitions *in* high energy density matter

Enthalpic *vs* **Entropic**

?

Enthalpic *and* entropic phase transitions *in* nuclear matter *and in* electromagnetic plasma

PT under isothermal compression

GLPT	⇔	$\Delta H < 0$	⇔	GLPT
QHPT	⇔	$-T\Delta S < 0$	⇔	PPT

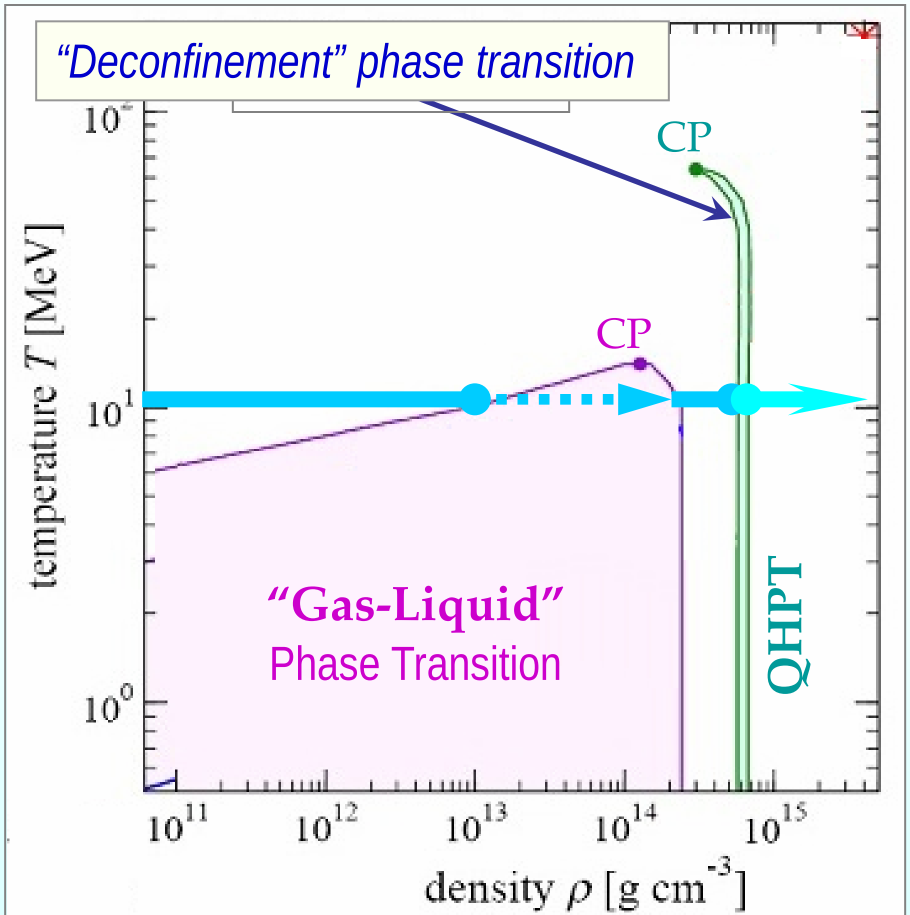
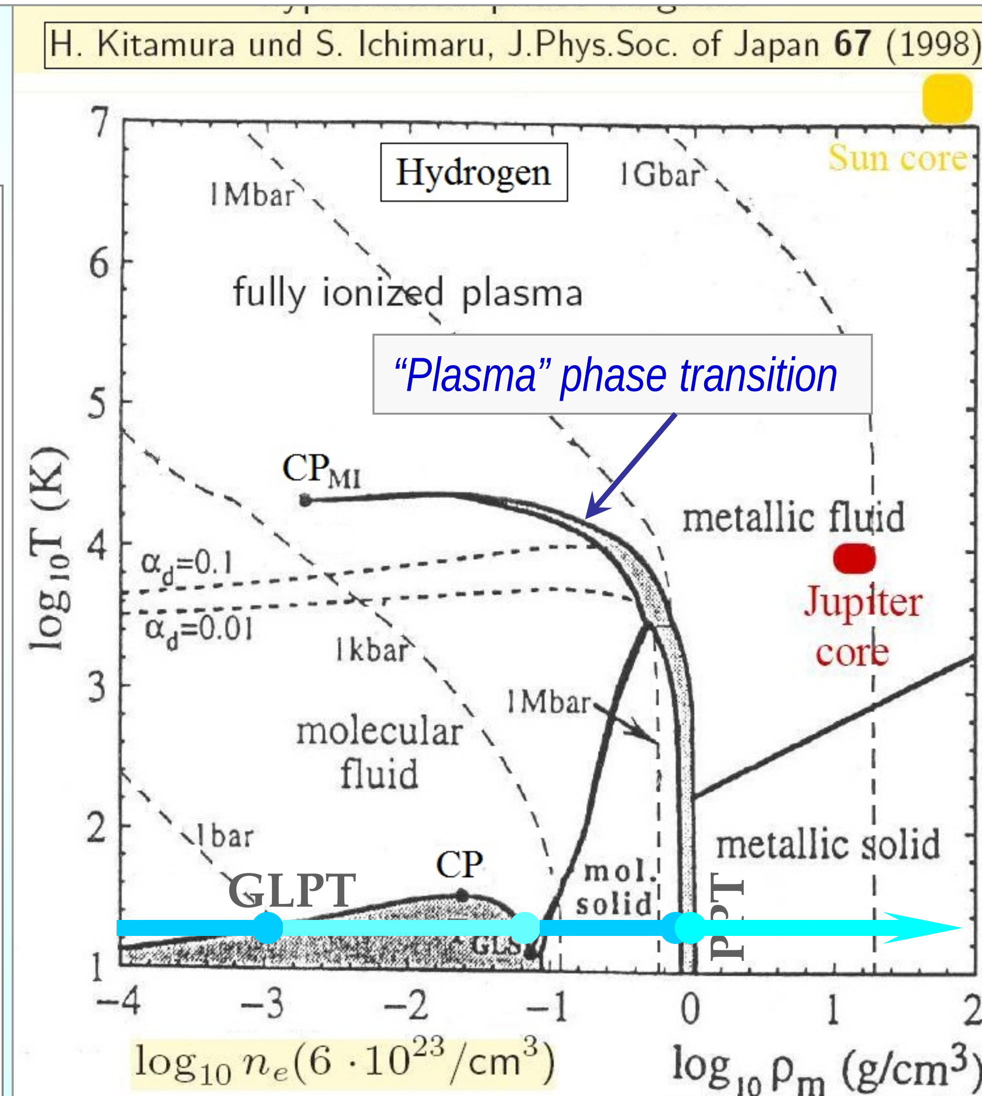
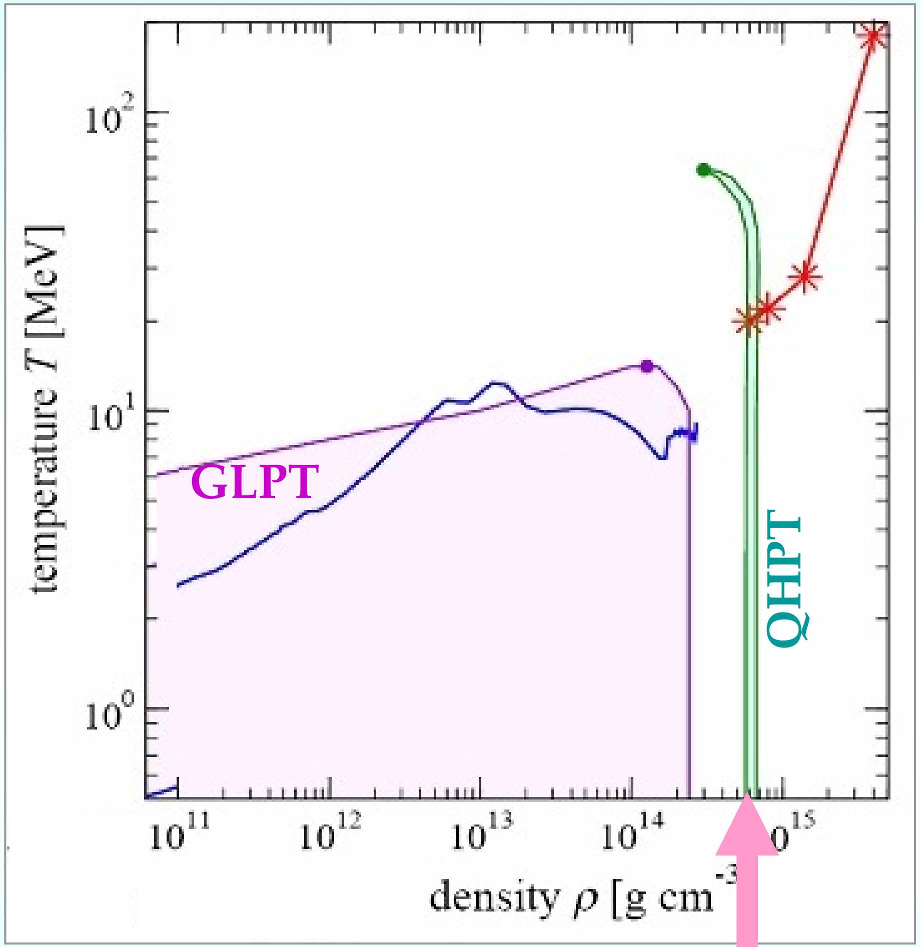


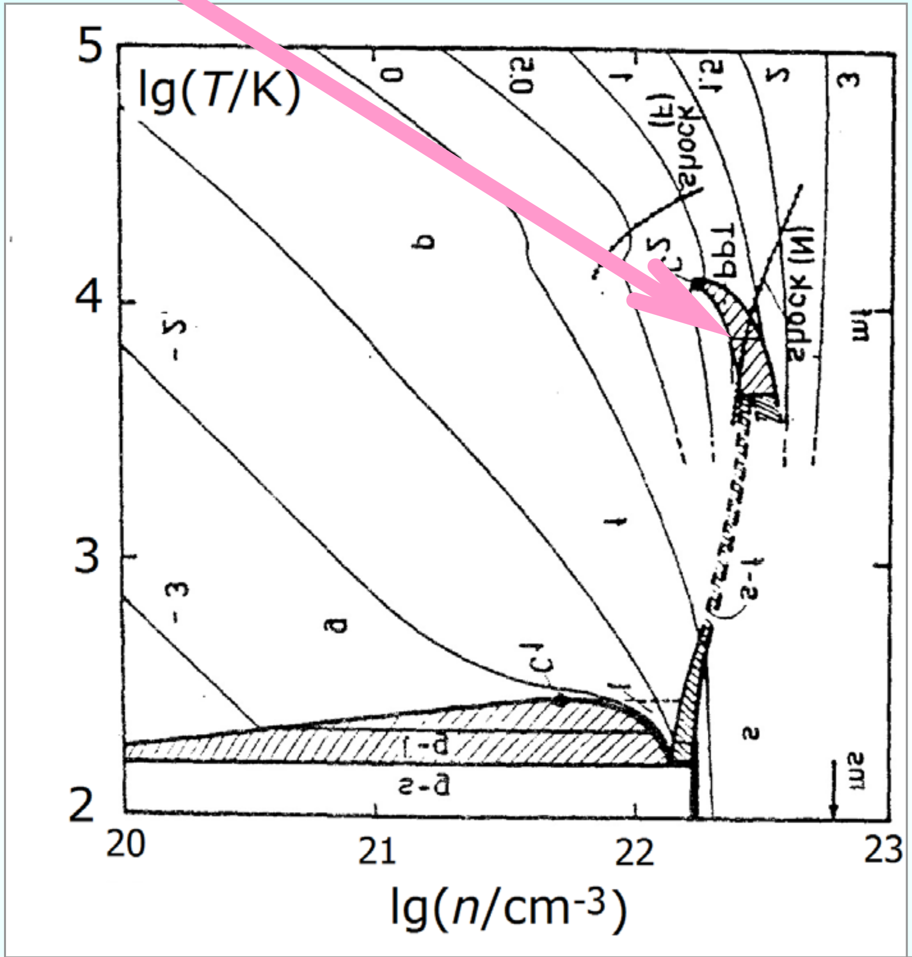
Figure after David Blaschke

Hypothetical "Plasma" phase transition (PPT) in hydrogen



Gas-liquid *and* **ionization-driven** phase transitions *in* xenon





Dienemann H, Clemens G, Kraeft W. D. *Annalen der Physik* 7, (**1980**)

Gas-liquid *and* **deconfinement-driven** PT *in* dense nuclear matter

General: "**Delocalization-driven**" PT-s *in* matter *of* **extreme state**

Basic point

Most of **entropic 1st-order fluid-fluid phase transitions** are "**driven**" by **forced decay** (*delocalization under compression)* of some kind of **bound complexes** :

= = = «» = = =

("*pressure" ionization, "pressure" dissociation….*

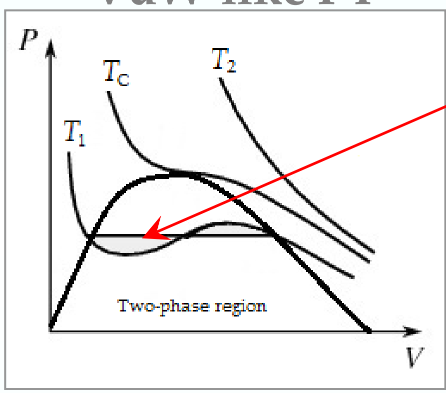
…"pressure" quark deconfinement" …*etc*)

Phase transitions: **Enthalpic** *or* **Entropic ?**

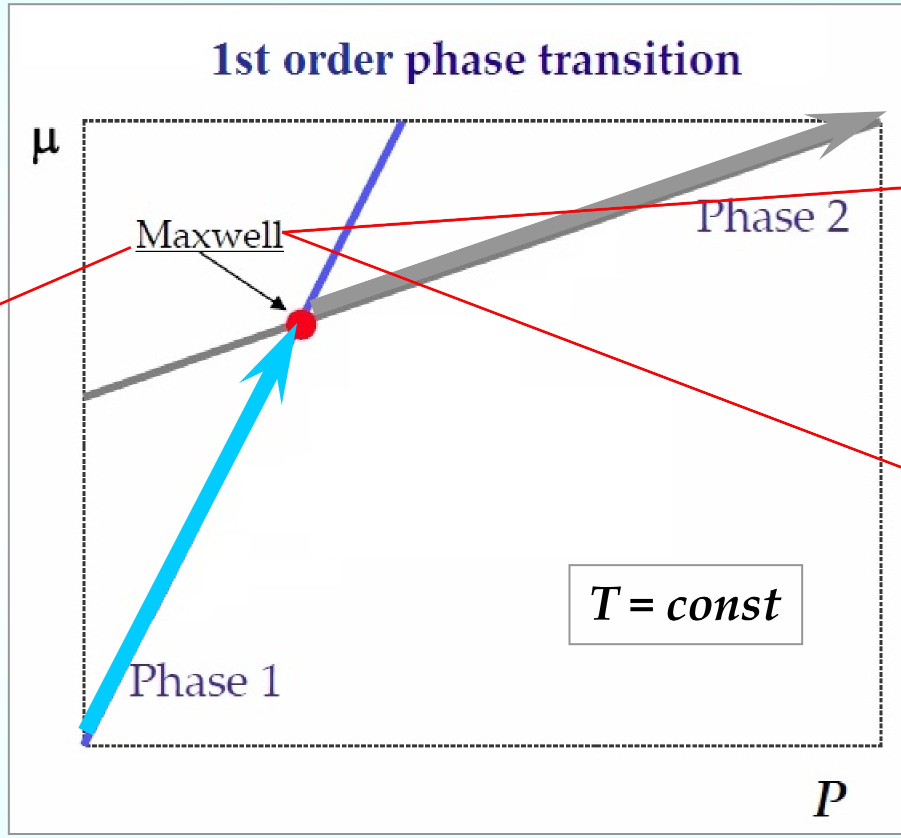
(definition)

$$G = H - TS$$

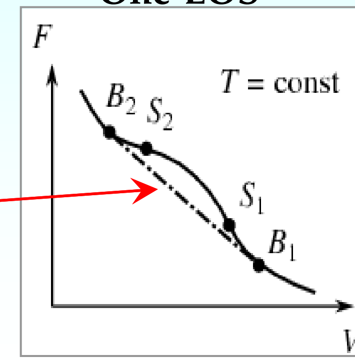
VdW-like PT



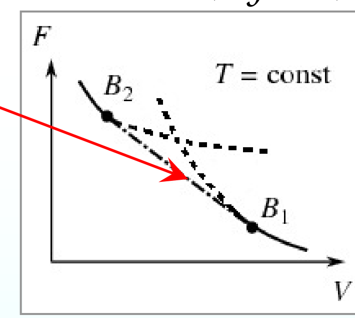
Maxwell "Equal squares"



One-EOS



Two-EOS (*Hybrid*)



"Double tangent"

Enthalpic PT

$$\Delta H = T\Delta S < 0$$

$$(dP/dT)_{binodal} > 0$$

Exothermal PT

Phase equilibrium

$$G_1 = G_2 \Leftrightarrow \Delta H = T\Delta S$$

Entropic PT

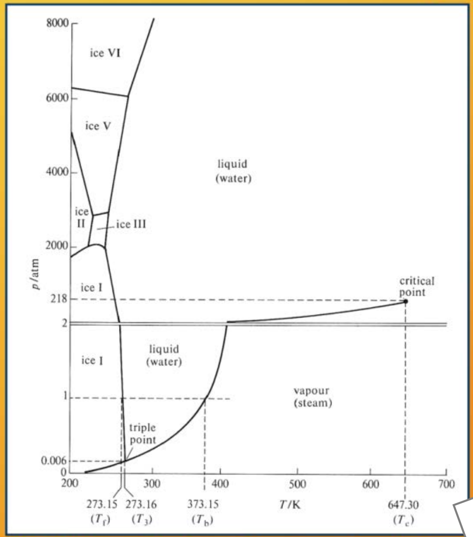
$$\Delta H = T\Delta S > 0$$

$$(dP/dT)_{binodal} < 0$$

Endothermal PT

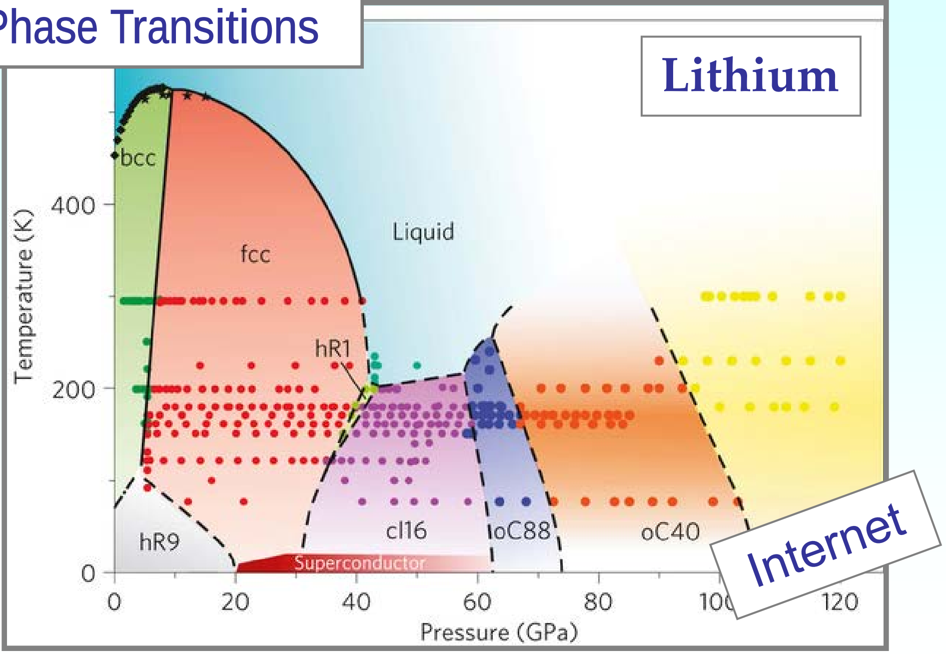
Entropic Crystal-Crystal and Crystal-Fluid Phase Transitions

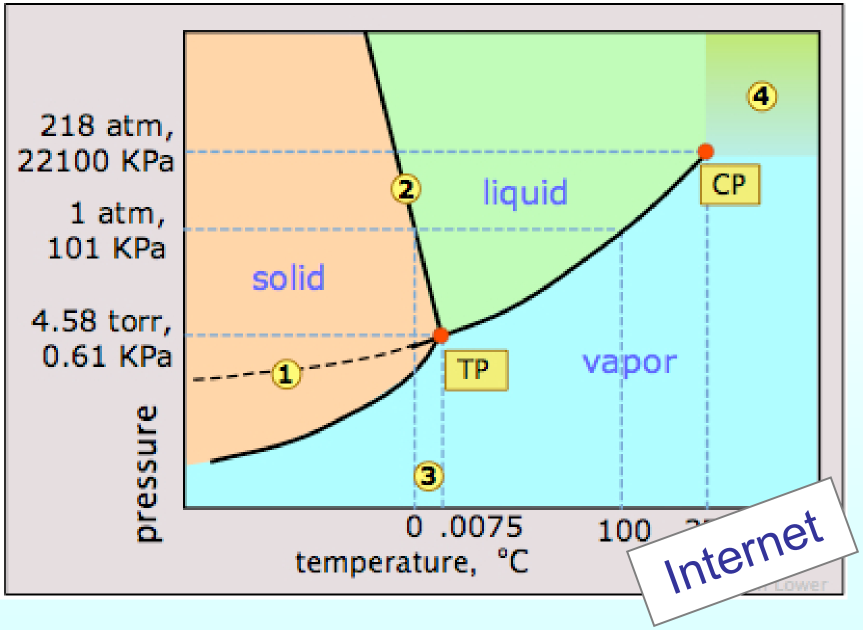
Water's Phase Diagram

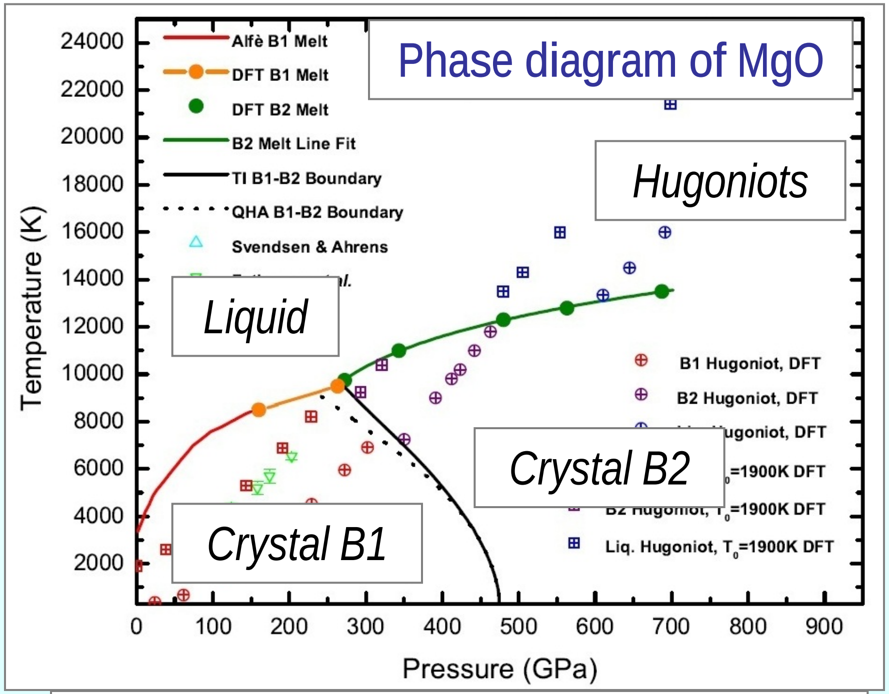


Source: P.W. Atkins, *Physical Chemistry*, 2 ed., 1978

Internet







Root S. *et al* (Sandia) / arXiv: 1502.0009

The main subject of our interest

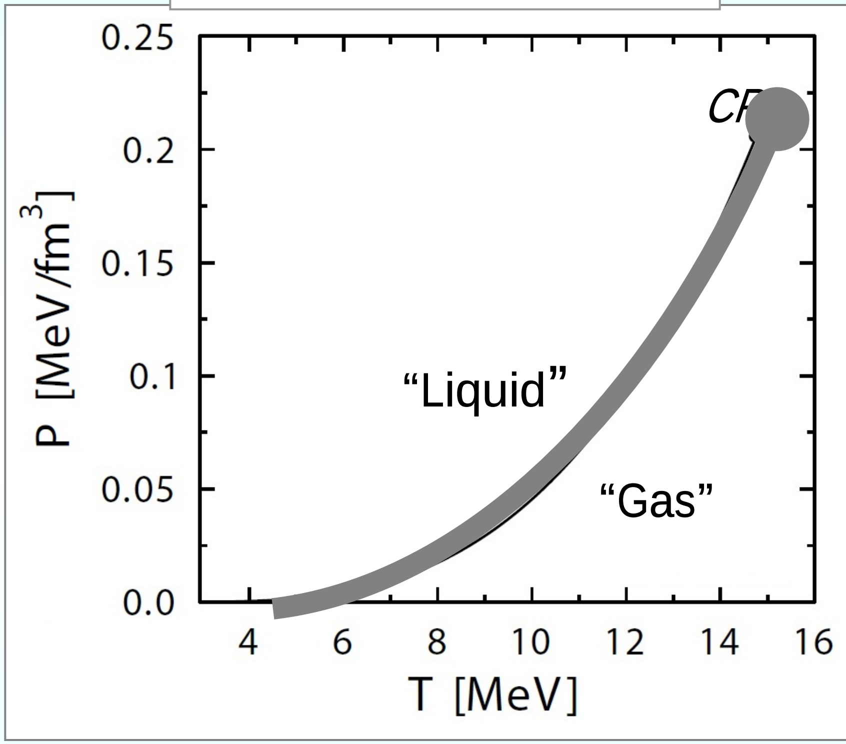
Isostructural 1^{st}-order entropic fluid-fluid phase transitions

P-T phase diagram *of* GLPT *and* QHPT

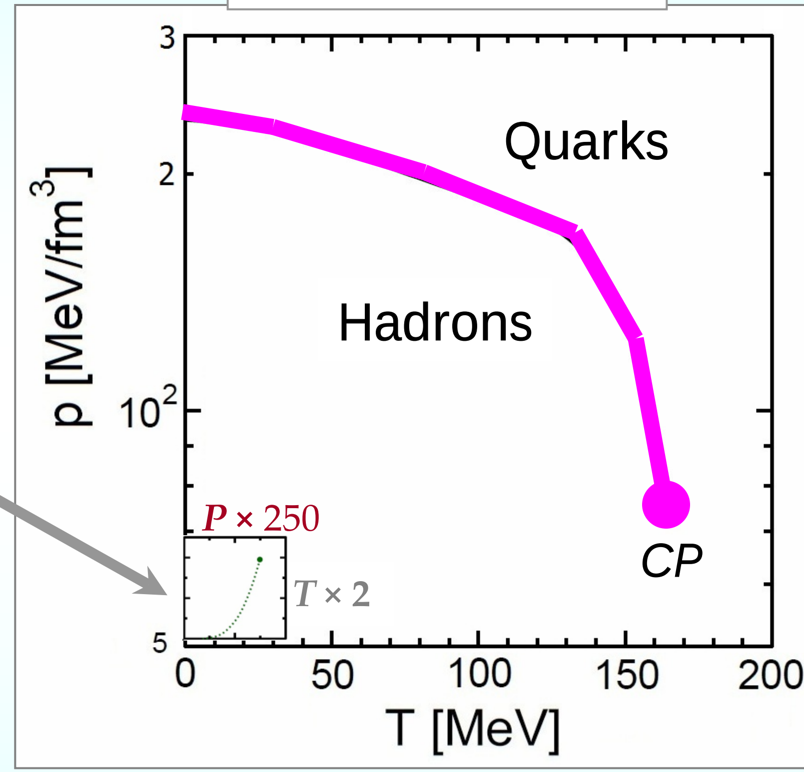
P - T phase diagram *of* symmetric Coulomb-less GLPT *and* QHPT

One-EOS approach (*critical point*)

Nuclear Gas-Liquid PT



Quark-Hadron PT



Standard VdW-like behavior

(*enthalpic PT*)

Non-standard behavior: $(dP/dT)_{binodal} < 0$

(*entropic PT*)

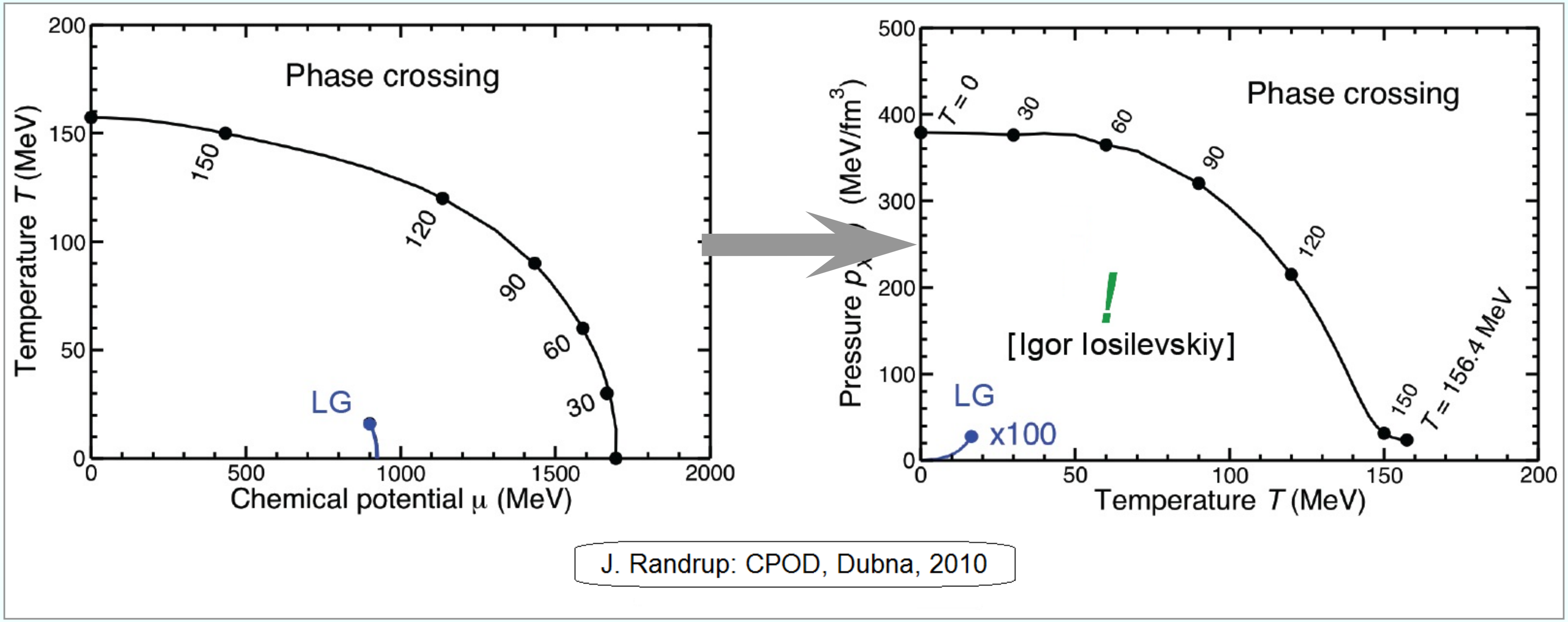
Non-congruence of the nuclear liquid-gas and the deconfinement phase transitions

M.Hempel, V.Dexheimer, S.Schramm *and* I.Iosilevskiy // *PRC*, **88** (2013)

P-T phase diagram *of* symmetric GLPT *and* QHPT

Jørgen Randrup, LBNL

GLPT *vs.* **QHPT**



GLPT		QHPT
Standard VdW-like behavior: $(dP/dT)_{binodal} > 0$	⇔	Non-standard behavior: $(dP/dT)_{binodal} < 0$

Critical Point and Onset of Deconfinement (CPOD)
23 - 29 August 2010 at Joint Institute for Nuclear Research

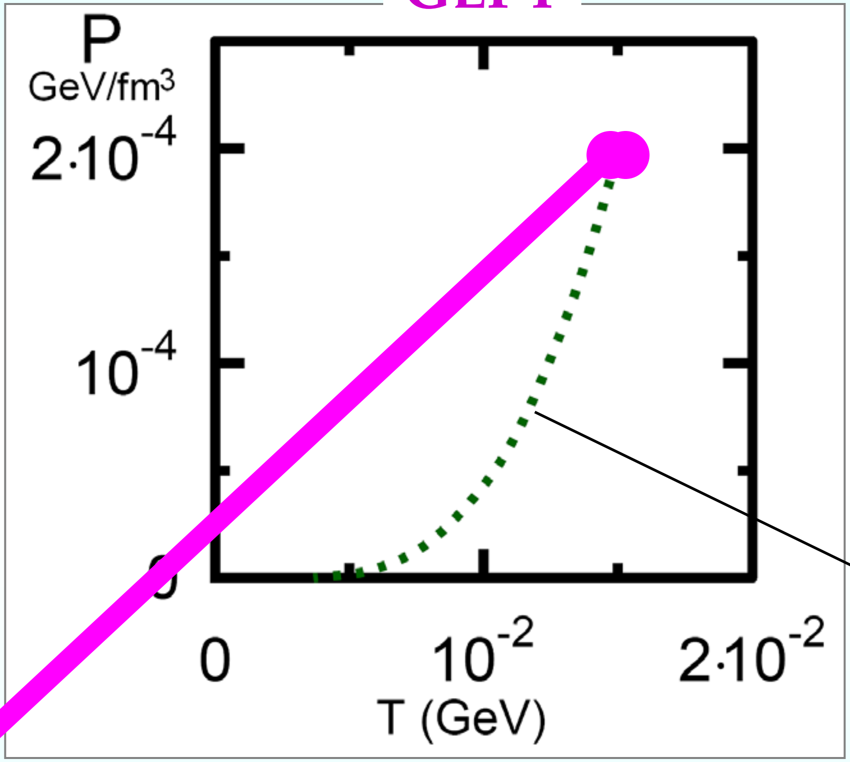
(*Dubna-2010*)

P-T phase diagram *of* symmetric GLPT *and* QHPT

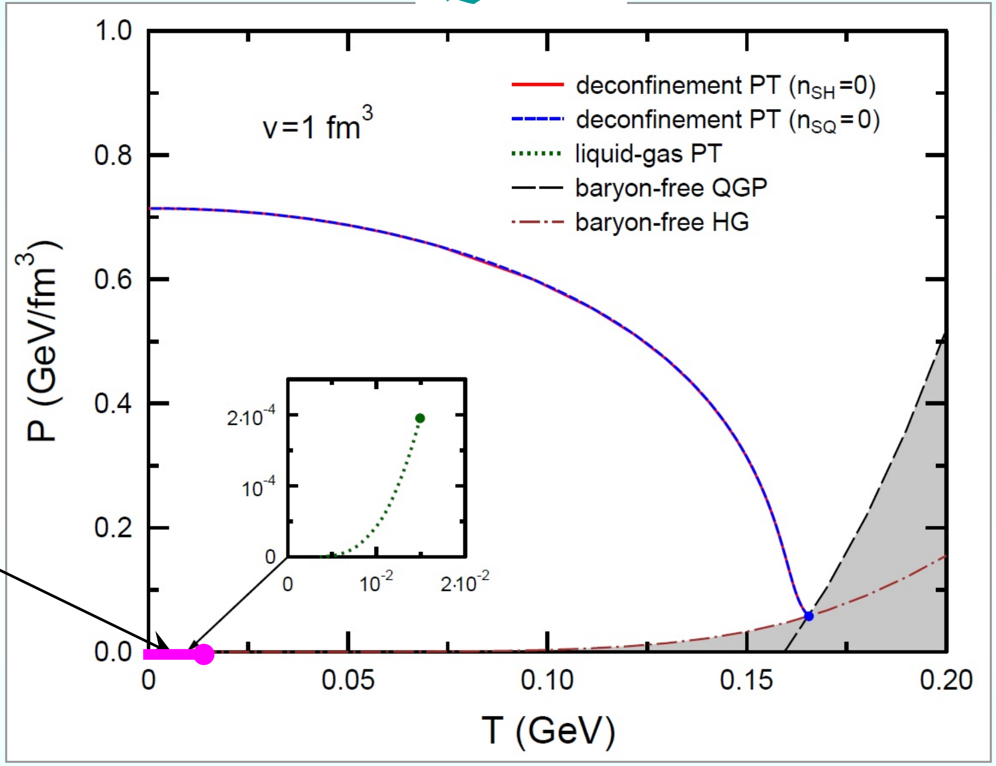
One-EOS approach (*critical point*)

Two-EOS approach (*no critical point*)

GLPT



QHPT



Standard VdW-like behavior

Non-standard behavior: $(dP/dT)_{\text{binodal}} < 0$

Figures after: Satarov L., Dmitriev M., Mishustin I. *Phys. At. Nucl.* (2009)

Phase transitions *in* high energy density matter

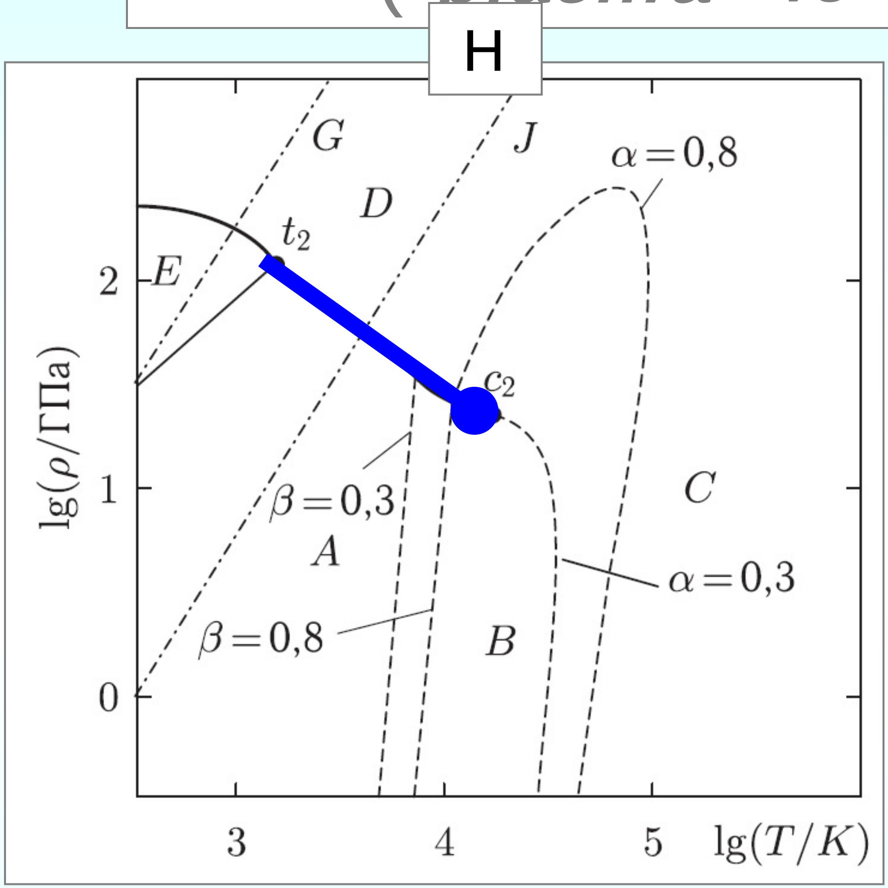
Enthalpic *vs* **Entropic**

?

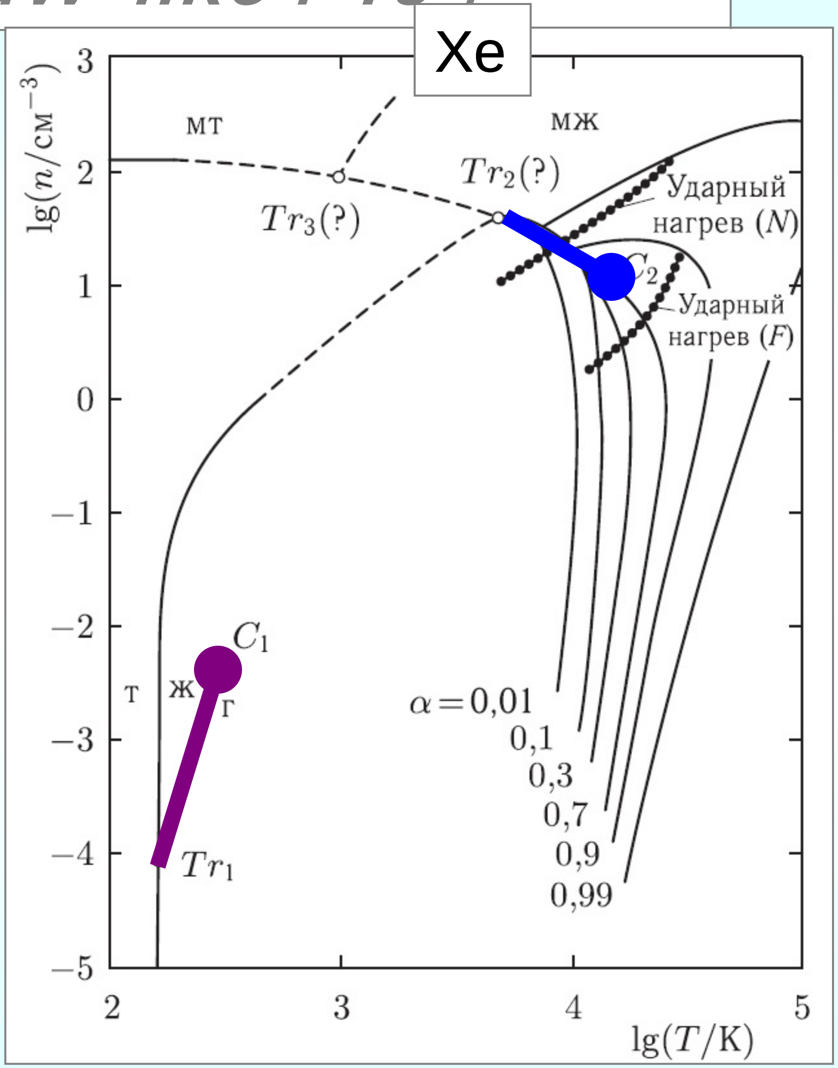
(*"Plasma" PT* vs *VdW-like PT*)

Entropic *vs* Enthalpic phase transitions

(“*plasma*” *vs VdW-like PTs*)



Ebeling W., Reichert W.
Phys. Lett. A, **80** (1985)



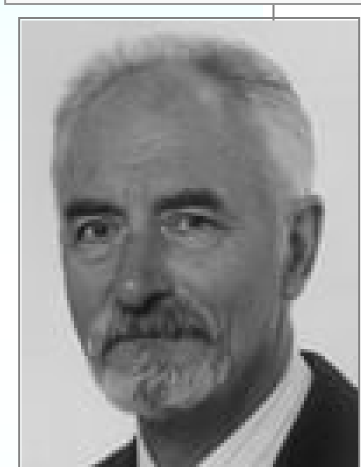
Ebeling W., Foerster A., Reichert W.
Physica A, **150** (1988)

Plasma PT (*entropic*) ($dP/dT < 0$)
Gas-liquid PT (*enthalpic*) ($dP/dT > 0$)

Fifty years of predictions for plasma phase transitions

(non-ideality models via "chemical picture" (1968 – 2017)

(*) Beulle, Ebeling *et al.* (1999)

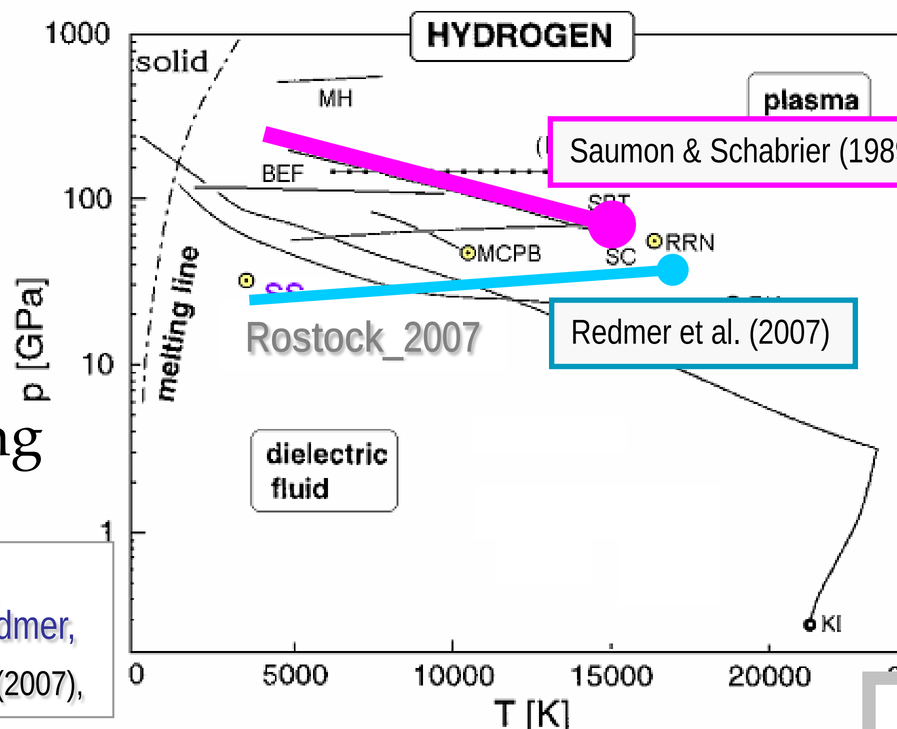


Werner Ebeling

Hydrogen EOS and Plasma Phase Transition

(coexistence lines and critical points of the PPT)

D. Beule, W. Ebeling and A. Foerster *Phys. Rev. B* **59** 14177-14181 (1999)

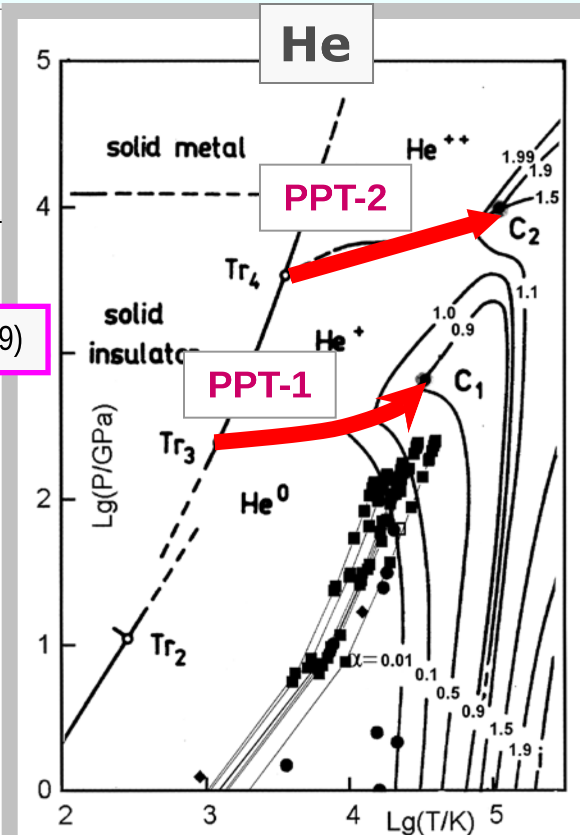


Rostock - 2007

Holst, Nettelmann, Redmer,

Contrib. Plasma Phys. 47 (2007),

SS - Stevenson D, Salpeter E. (1977) ApJ. Sp.35,221



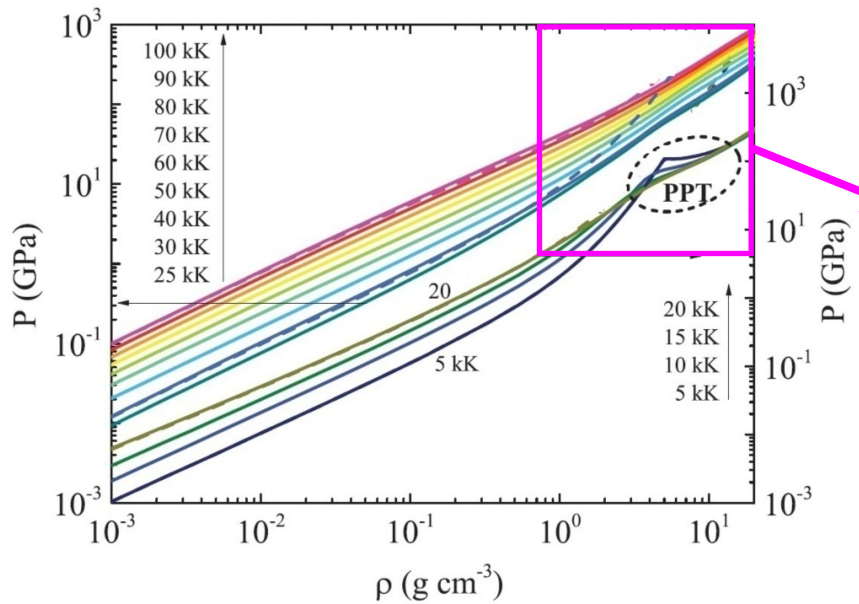
Two separate **plasma phase transitions**

(under 1st and 2nd ionization in He)

Ebeling, Foerster *et al.* (1991)

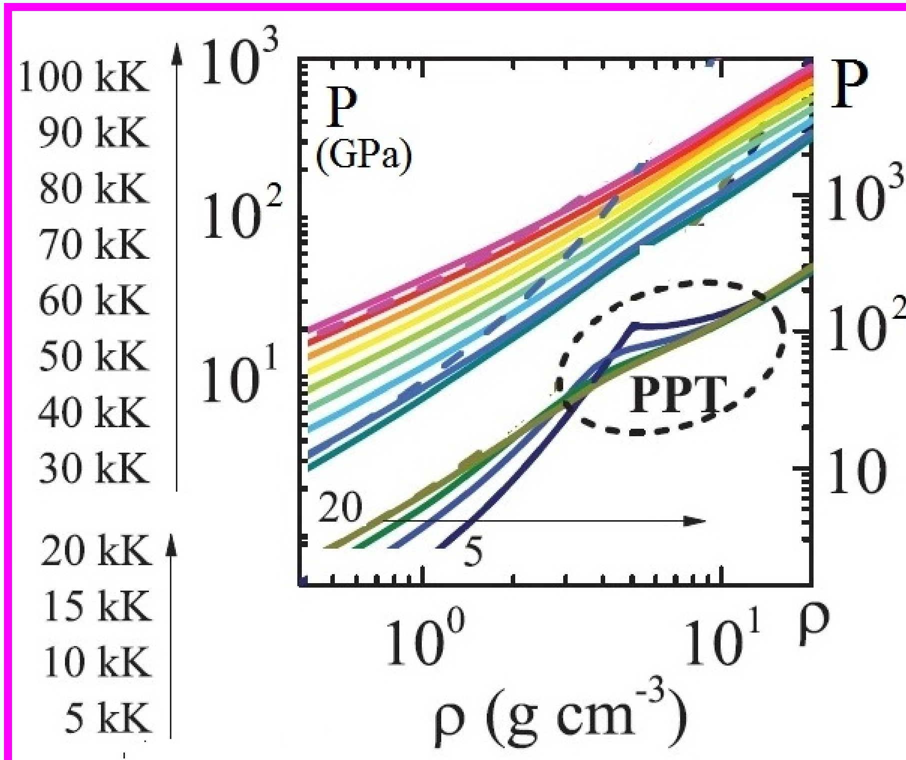
Ionization-driven *(entropic)* phase transition in Ar

(Very recent example: Plasma model in chemical picture)



Quan W.L., Chen Q.F., Fu Z.J., Sun X.,Zheng W.J., Gu Y.J.
Phys. Rev. E **91**, 023106 (2015);

Isotherms of pressure for argon plasma



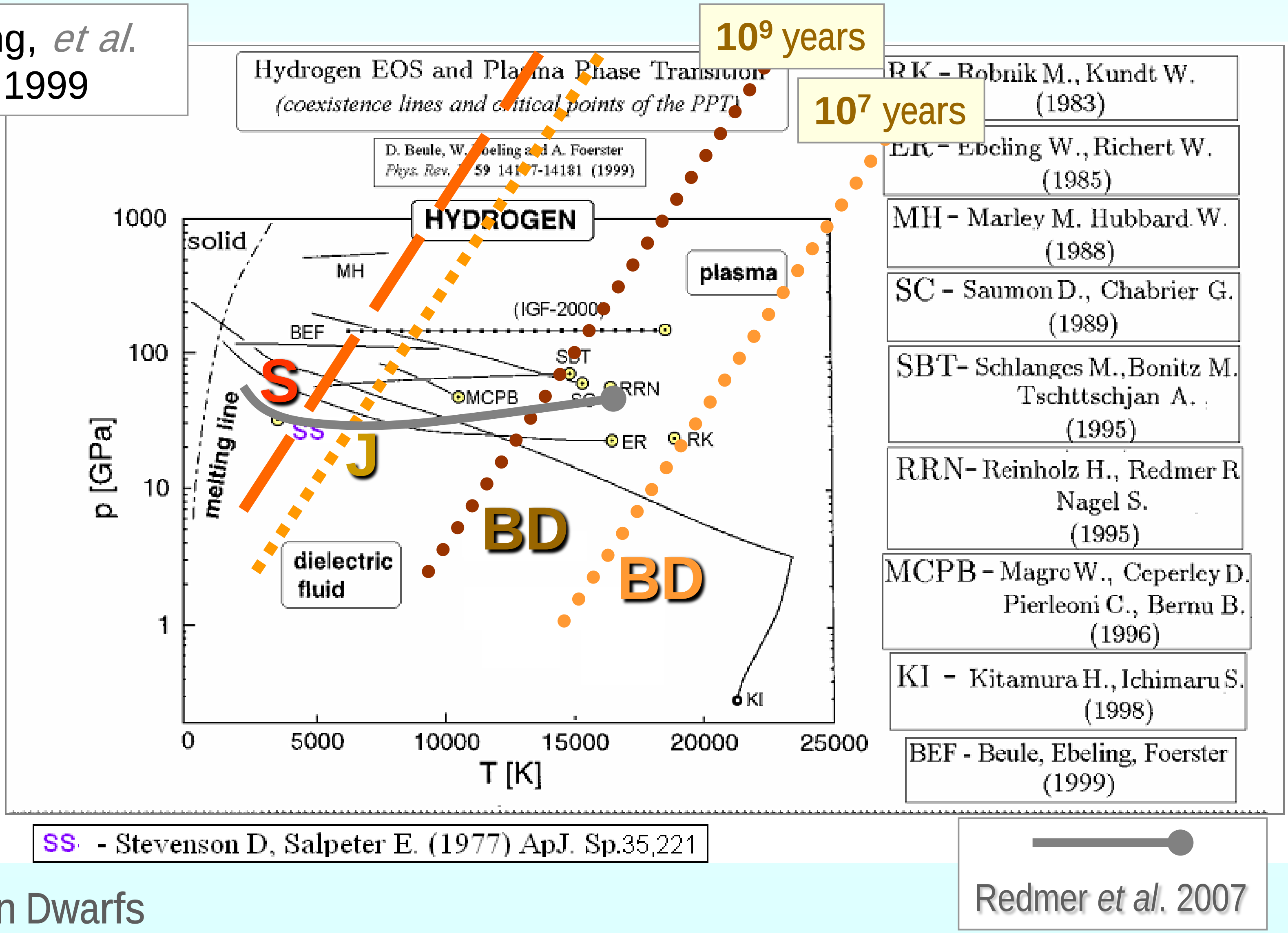
NB !

Abnormal order of isotherms

Hypothetical "plasma phase transition" in hydrogen

Relevant to the problem of formation for Giant and Extrasolar Planets and Substellar objects

W. Ebeling, *et al.*
PRB, 1999

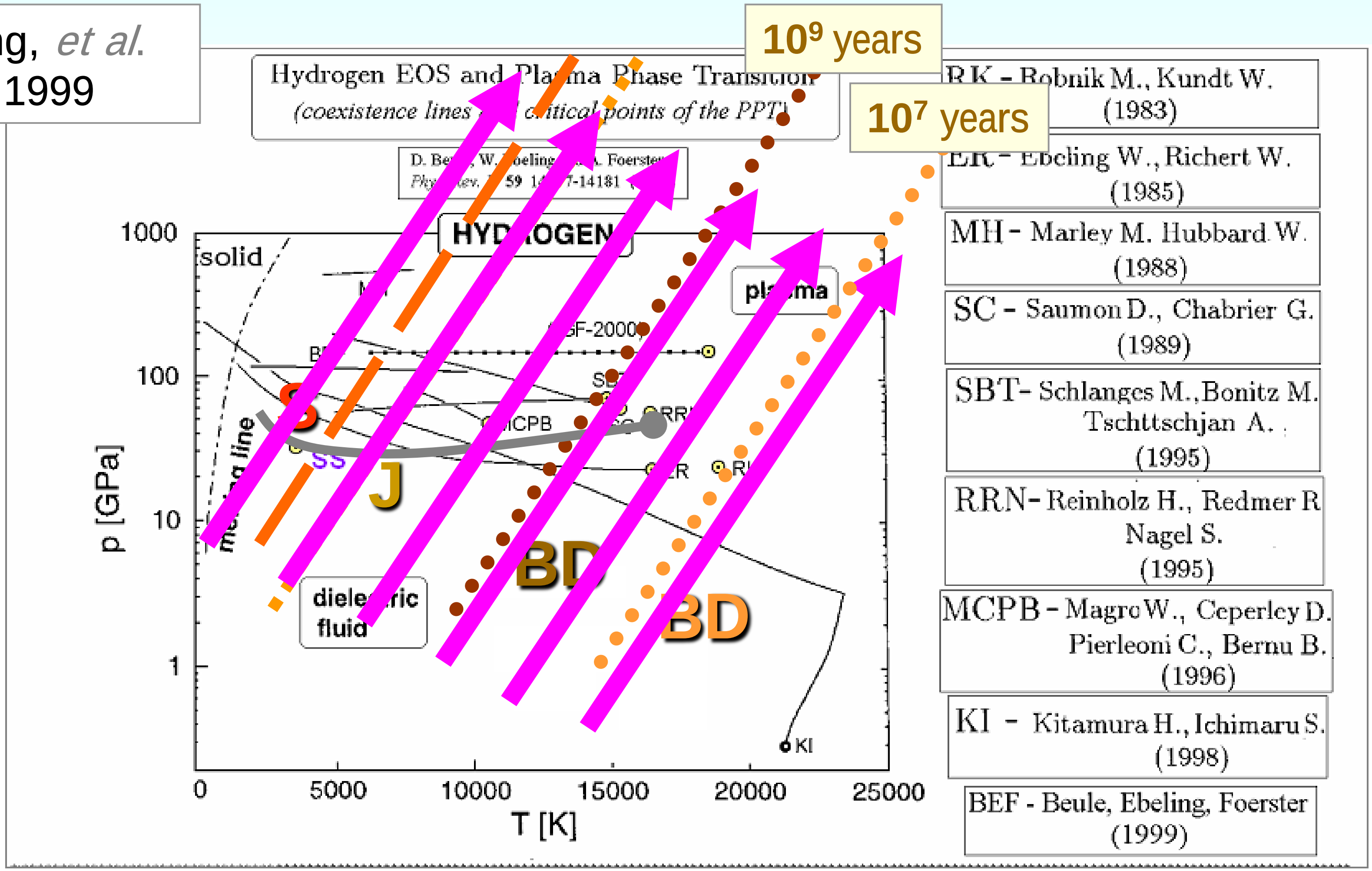


S – Saturn
J – Jupiter
BD – Brown Dwarfs

Hypothetical "plasma phase transition" in hydrogen

Relevant to the problem of formation for Giant and Extrasolar Planets and Substellar objects

W. Ebeling, *et al.* *PRB*, 1999



S – Saturn
J – Jupiter
BD – Brown Dwarfs

SS - Ste

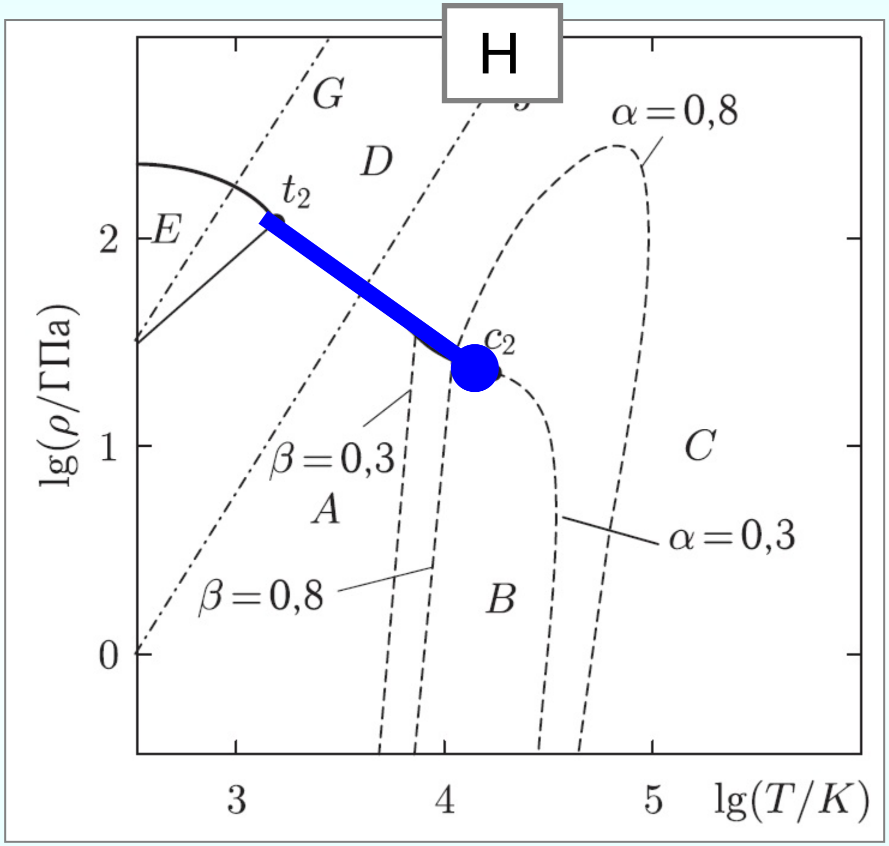
Extrasolar planets (~ 4000 !)

Redmer *et al.* 2007

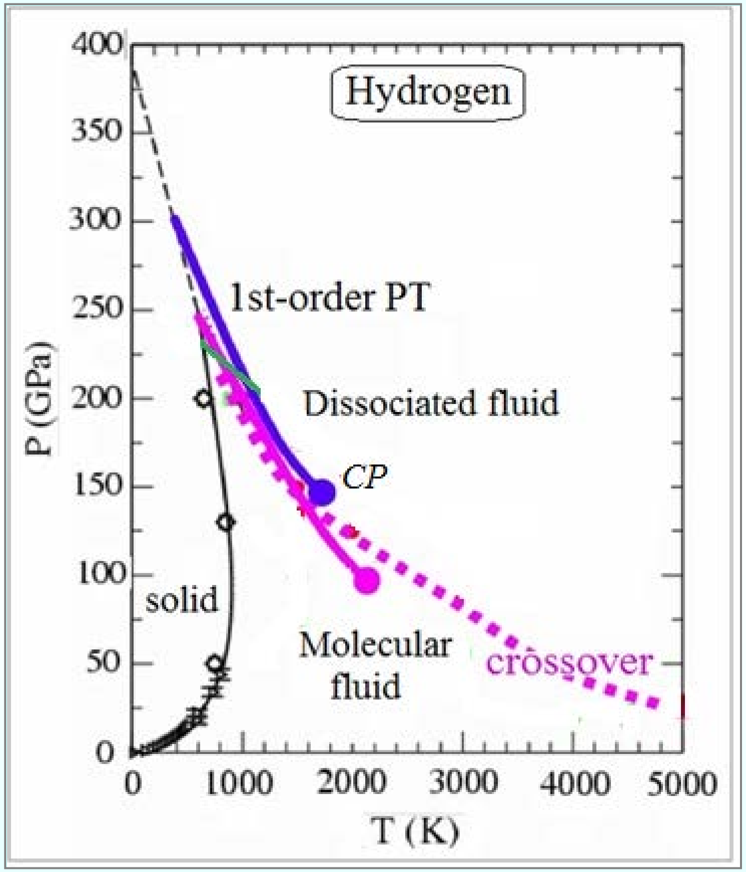
Ionization- *and* Dissociation-driven phase transitions *in* H_2

$(dP/dT)_{binodal} < 0$

(*Chemical model*)



(*ab initio* - DFT/MD)

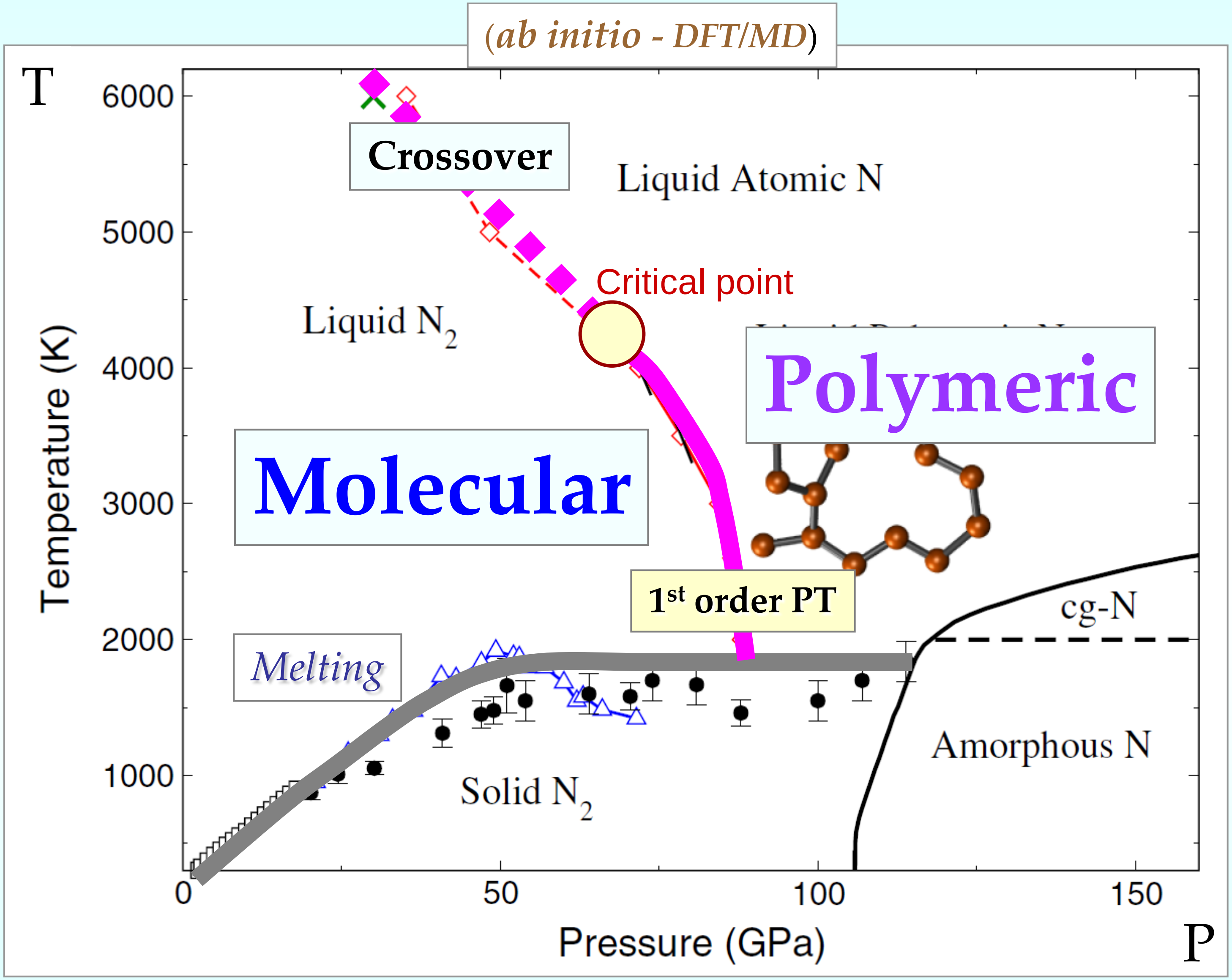


Dissociation-driven PT (evidently entropic)

Plasma PT (*entropic*) (d*P*/d*T* < 0)
Gas-liquid PT (*enthalpic*) (d*P*/d*T* > 0)

DFT/MD:
Bonev S., Militzer B. *et al.*, ***PRB*** 69 (**2004**)
Morales M. *et al.* ***PNAS*** 107, (**2010**)
Lorenzen W., Holst B., Redmer R. ***PRB*** (**2010**)

Entropic fluid-fluid phase transition in N_2



B. Boates, S. Bonev, *Phys. Rev. Lett.*, **102** (2009) // *ab initio – DFT/MD*

Ionization- *and* Dissociation-driven phase transitions *in* H_2

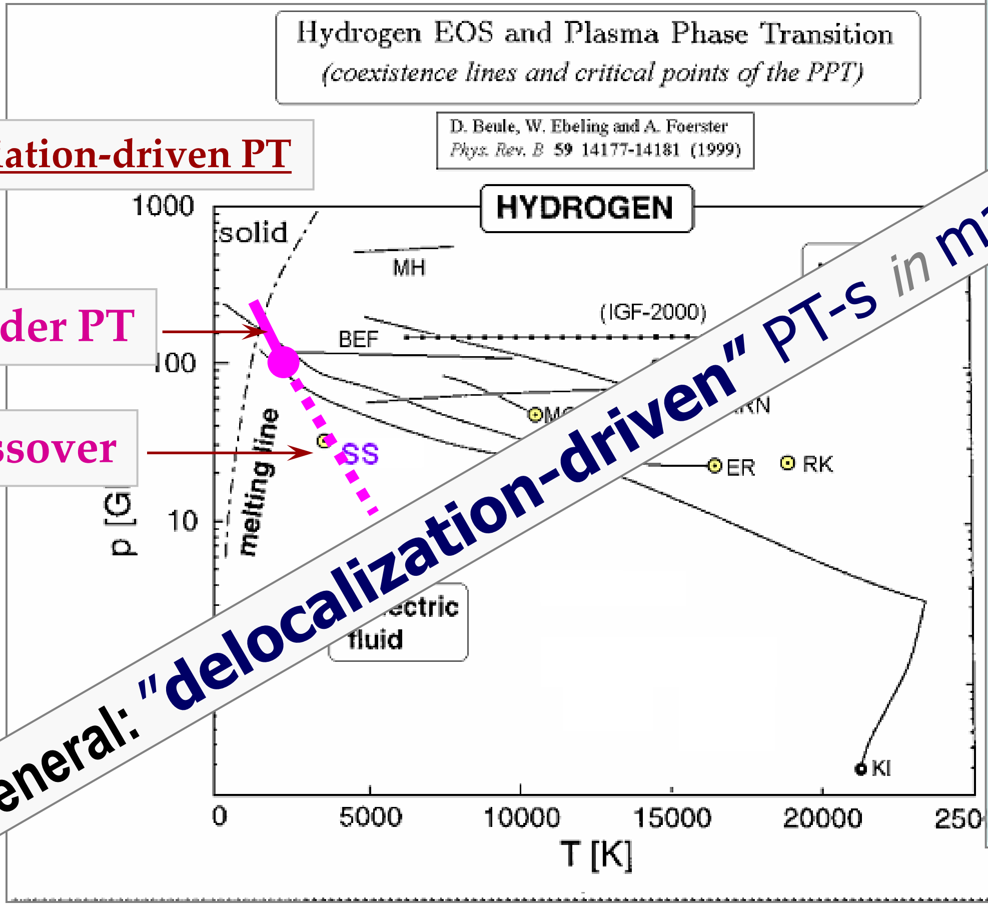
(*mostly entropic*)

Non-standard behavior: $(dP/dT)_{binodal} < 0$ *or* $(dP/dT)_{binodal}$ ...

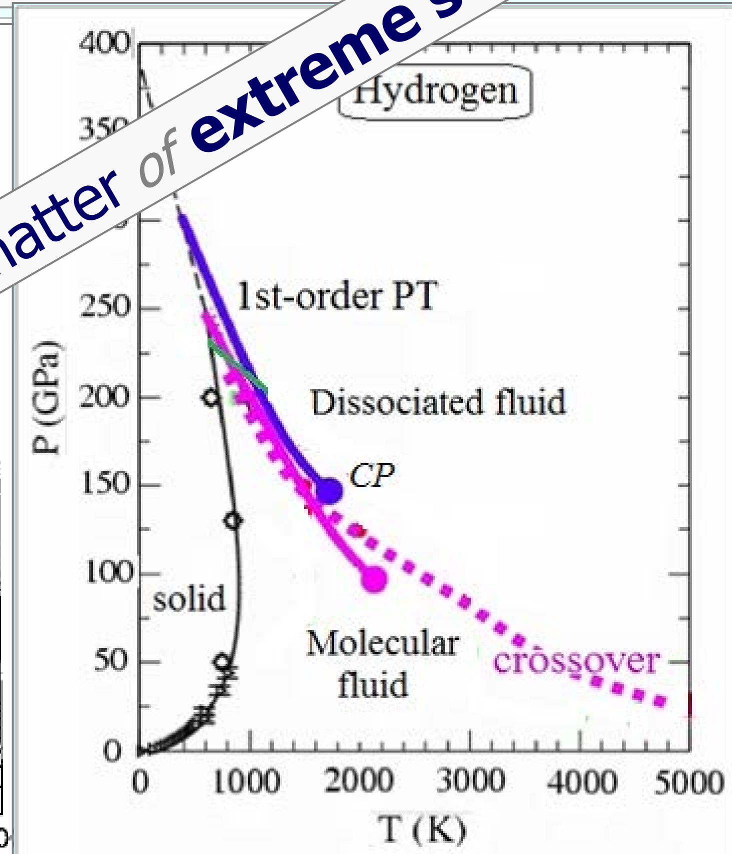
Dissociation-driven PT

1st-order PT

Crossover



General: "delocalization-driven" PT-s *in* matter *of* extreme state



Dissociation-driven PT (*ab initio*)

SS - Stevenson D, Salpeter E. (1977) ApJ. Sp.35,221

IGF-2000 - Iosilevski I., Gryaznov V., Fortov V. "Thermodynamics of HYDROGEN and Deuterium via ...

DFT/MD:

Bonev S., Militzer B. *et al.*, *PRB* 69 (2004)

Morales M. *et al.* *PNAS* 107, (2010)

Lorenzen W. *et al.* *PRB* (2010)

Phase transitions *in* high energy density matter

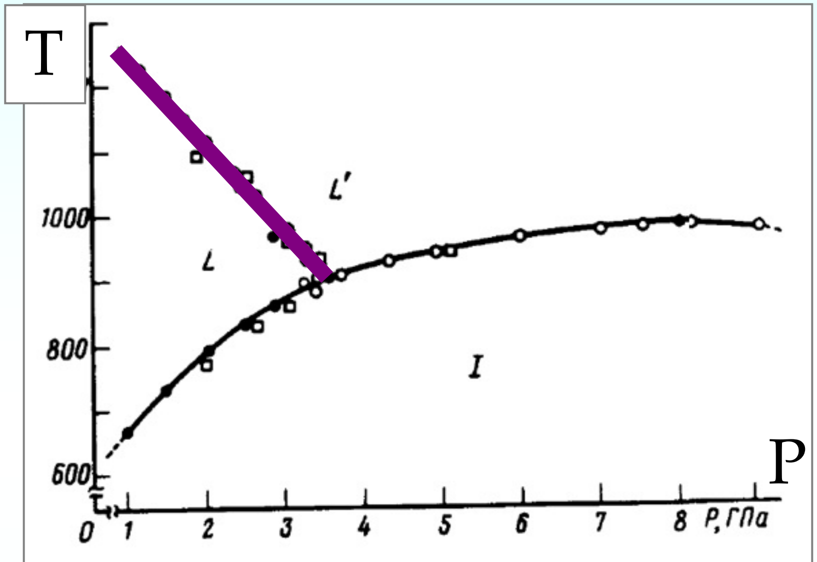
Experiment

Enthalpic *vs* Entropic

?

Entropy-driven fluid-fluid phase transitions

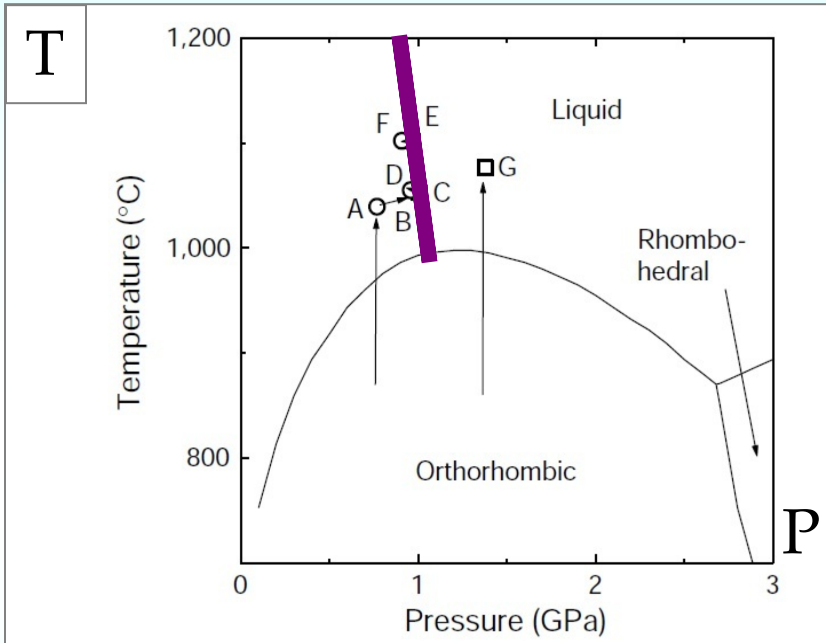
Selenium



V.V. Brazhkin, R.N. Voloshin, S.V. Popova,
Semiconductor- metall transition in liquid Se.
JETP Lett. **50** (1990)

Experiment

Phosphor

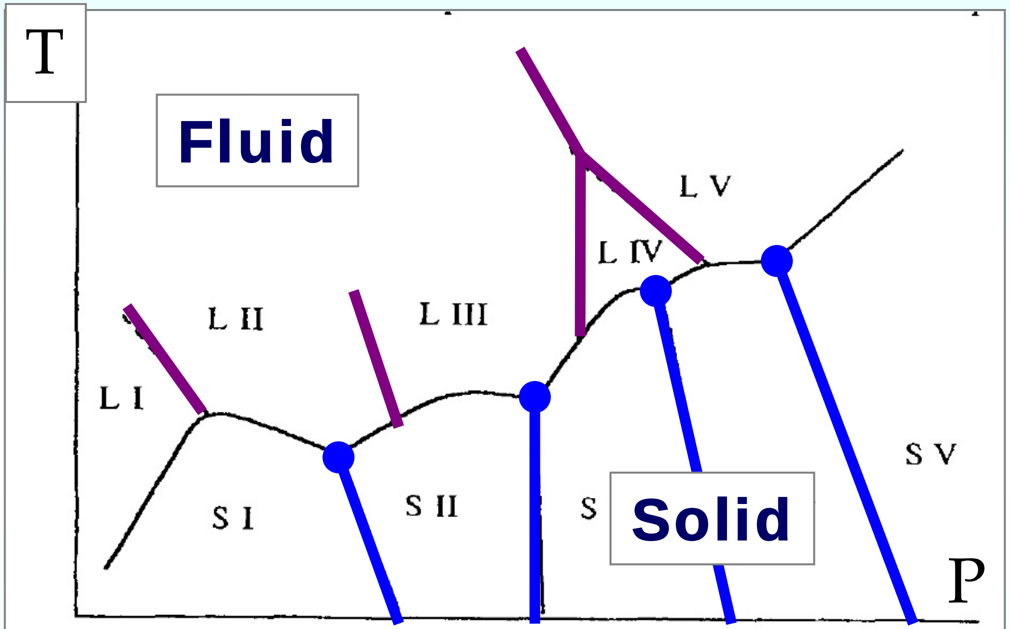


Katayama Y., Mizutani T. *et al.* (*Nature* **403**, 170 (2000))

Experiment

Enthalpic *and* Entropic phase transitions ?

V. Brazhkin (1997)

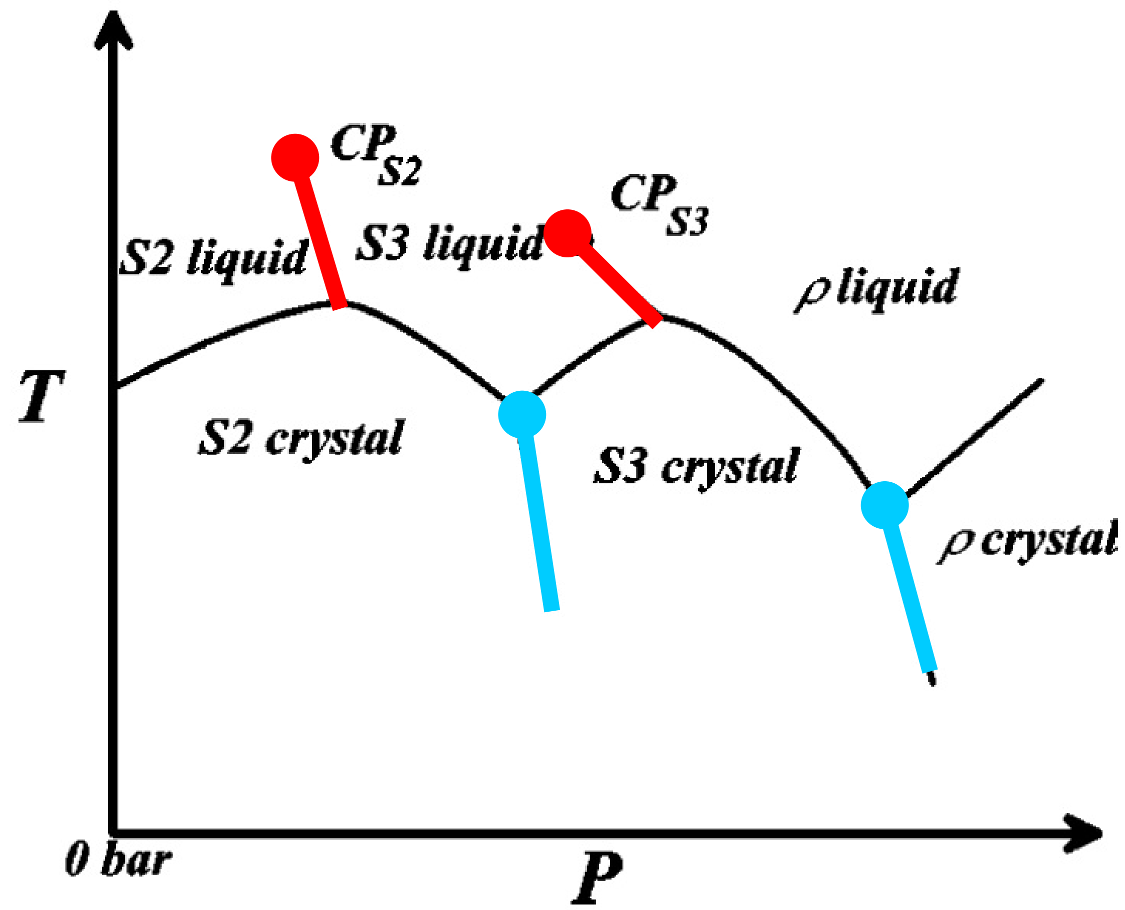


Generalized *P-T* Phase Diagram

Brazhkin V., Popova S., Voloshin R.
High Pressure Research, 15:5, 267-305, (1997)
High-pressure transformations in simple melts

All polymorphic PTs and fluid-fluid PTs are *Entropic* !

Enthalpic *and* Entropic Phase Transitions ?

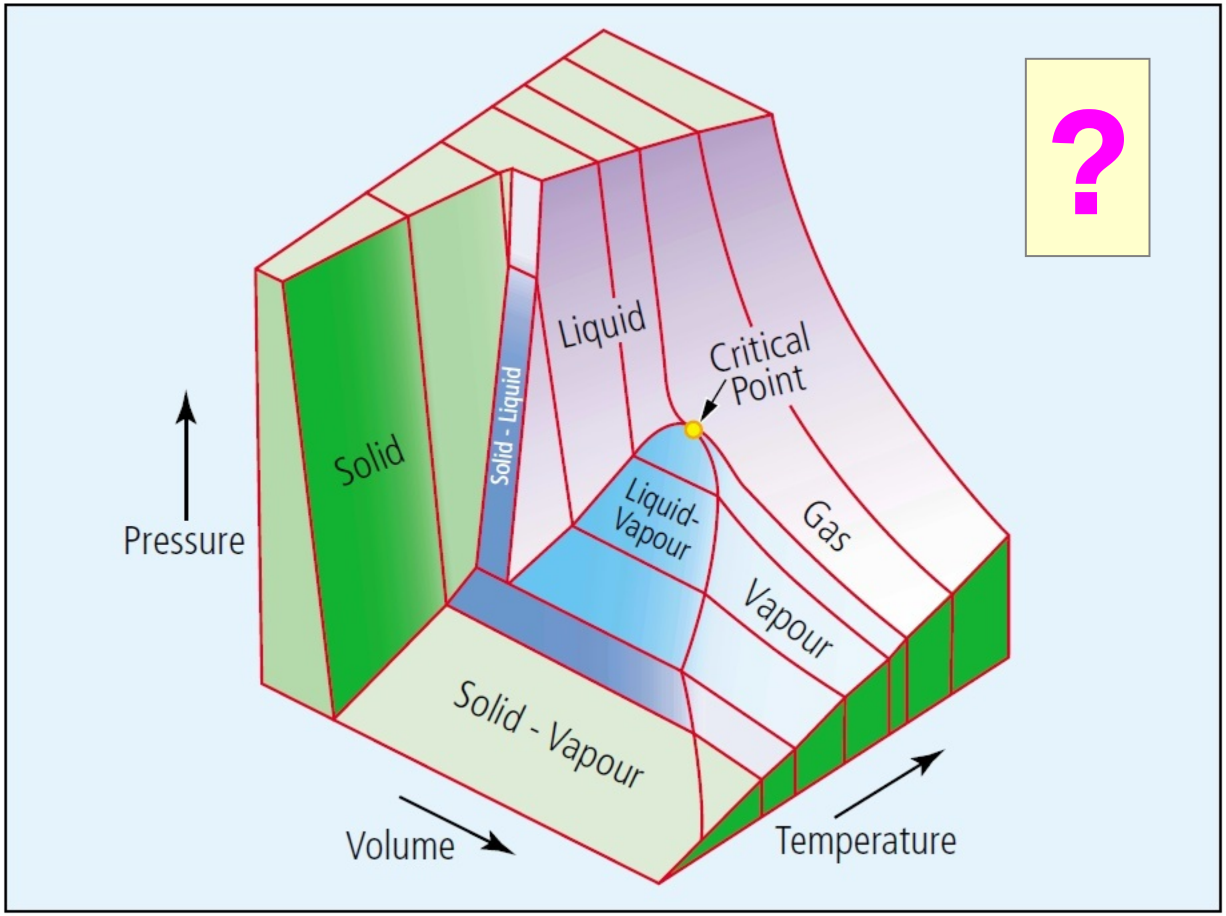


Hajime Tanaka // Phys. Rev. E, **62** (2000)
General view of a liquid-liquid phase transition

Entropic phase transitions are not exception, but they are general rule instead !

Where are entropic PTs located at standard phase diagrams ?

Wikipedia



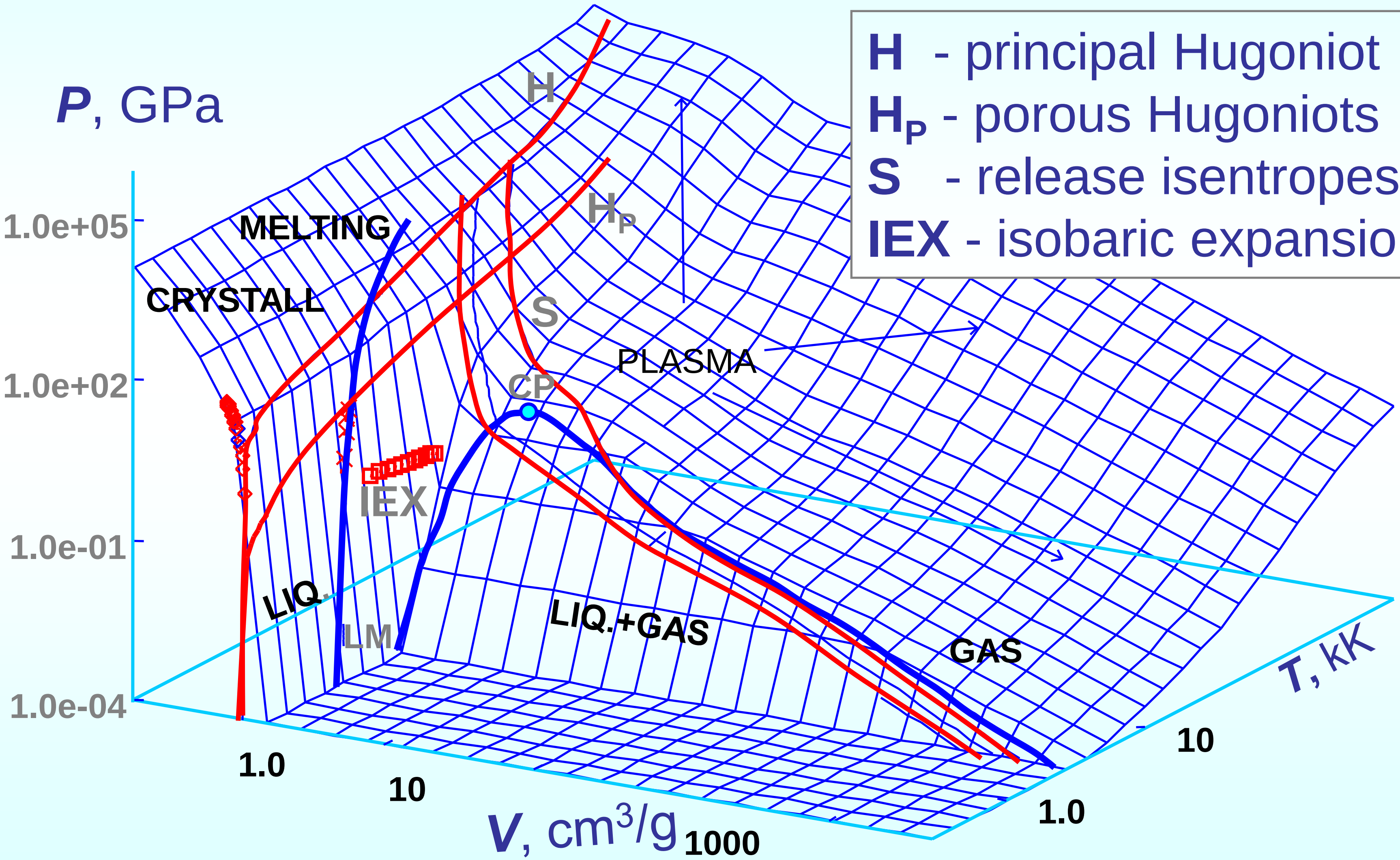
Discovery • The Science & Technology Journal

Figure 1: The three-dimensional pressure-temperature phase diagram for a simple material. The P(V,T) surface shown describes all possible states attainable for the material in question.

Dynamic Experiments

(general phase diagram)

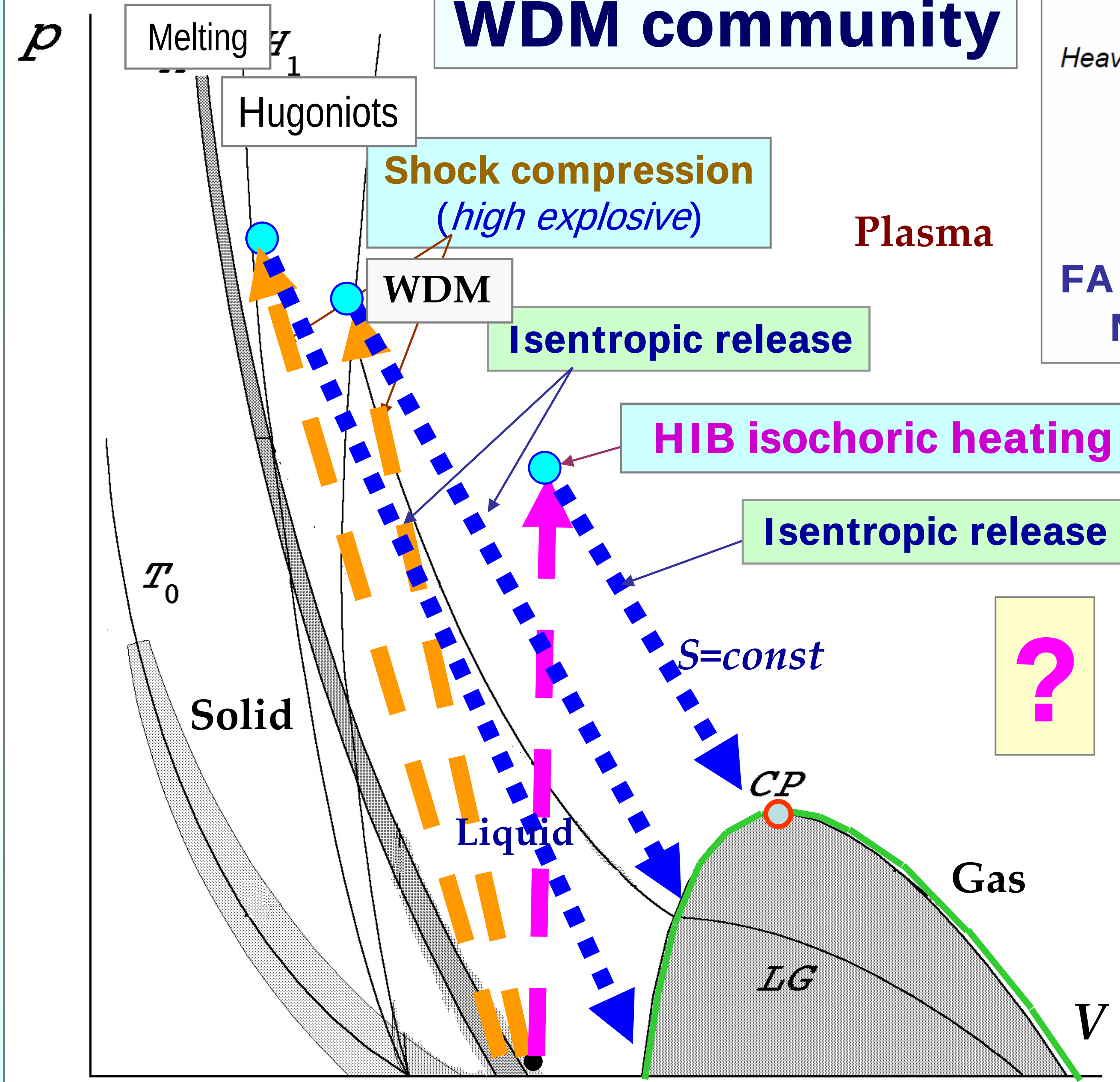
?



H - principal Hugoniot
H_P - porous Hugoniots
S - release isentropes
IEX - isobaric expansion

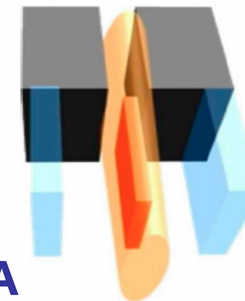
Wide-range EOS - A. Bushman, I. Lomonosov, V. Fortov

WDM community



HIHEX

Heavy Ion Heating and Expansion

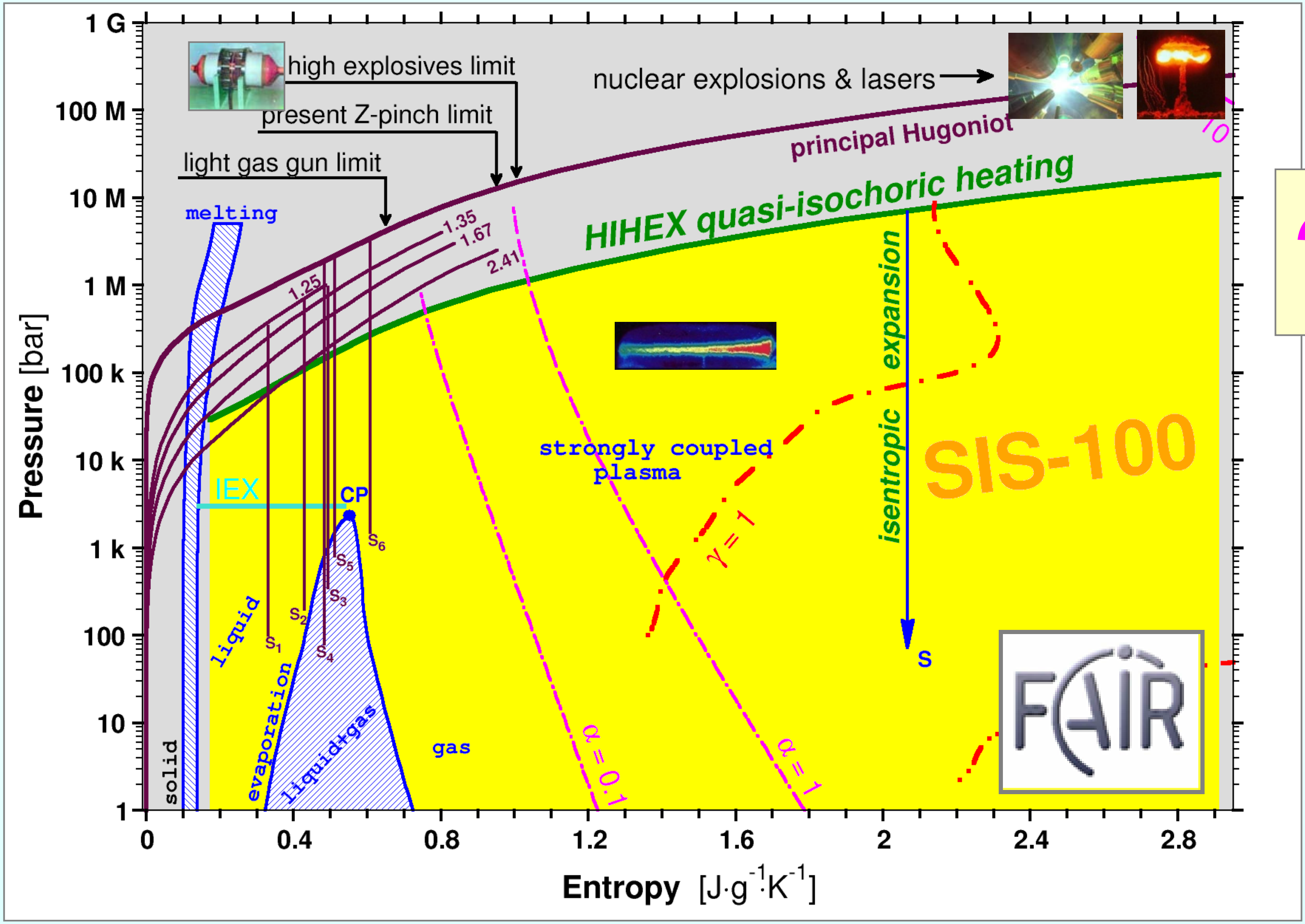


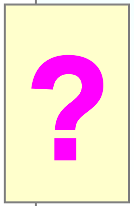
FAIR
NICA

- uniform quasi-isochoric heating of a large-volume dense target
- isentropic expansion in 1D plane or in 2D

"*Terra Incognita*" regions of the phase diagram accessible in experiments at **FAIR**

D.D,H. Hoffmann, V.E. Fortov et al. *Phys. Plasmas* **9** (2002)





Pressure – Entropy diagram (*I. Lomonosov*)

Anomalous Properties of Entropic Phase transitions

What's a matter in falling P-T **diagram**
for **entropic phase transitions . . .?**

Why should we be worried about it ?

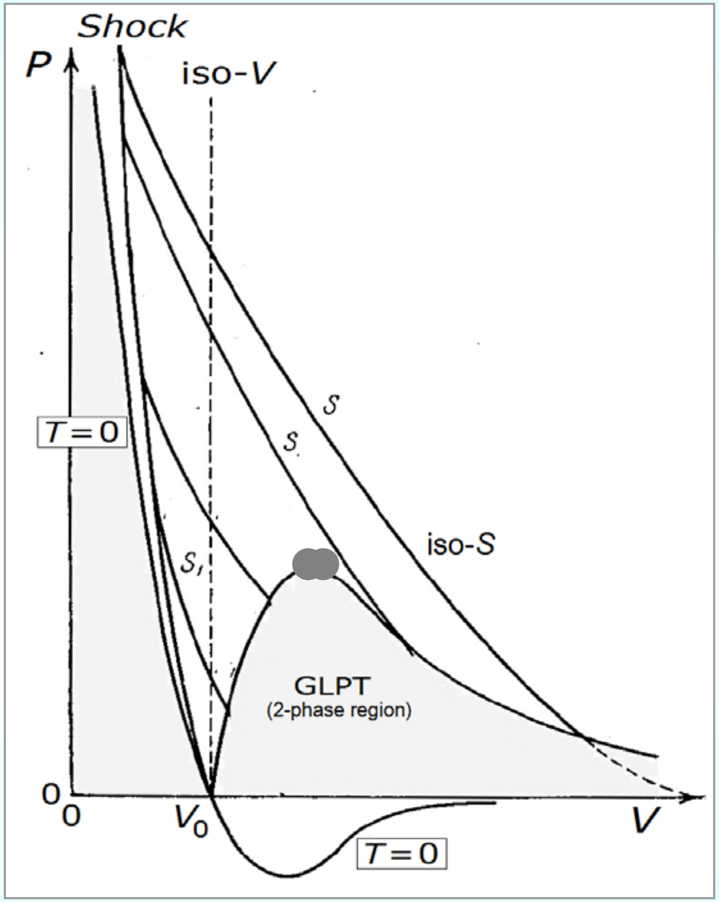
?

Enthalpic *vs.* Entropic phase transitions

in ***P-V*** **phase diagram**

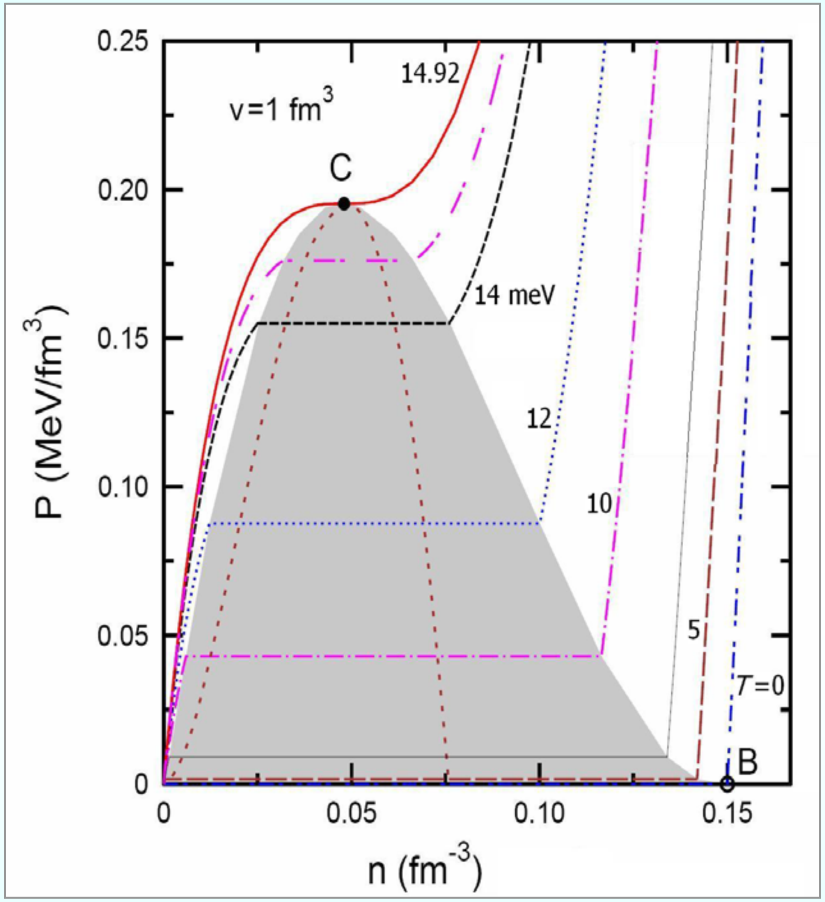
P-ρ phase diagram *of* symmetric Coulomb-less GLPT

Standard VdW-like PT



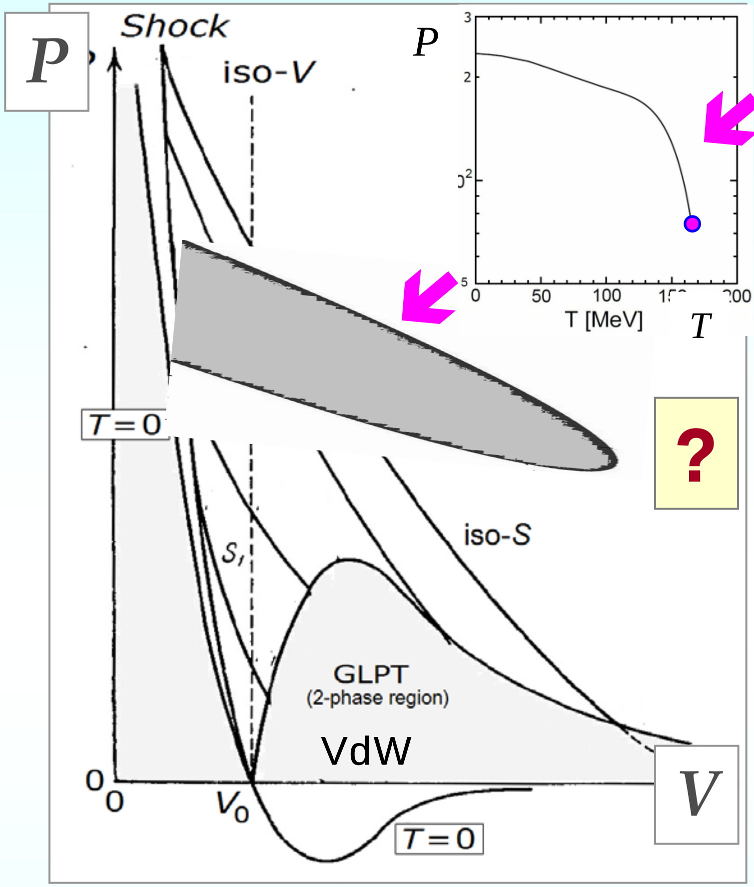
Zeldovich *and* Raizer
Moscow (1966)

"Gas-Liquid" PT in symmetric nuclear matter

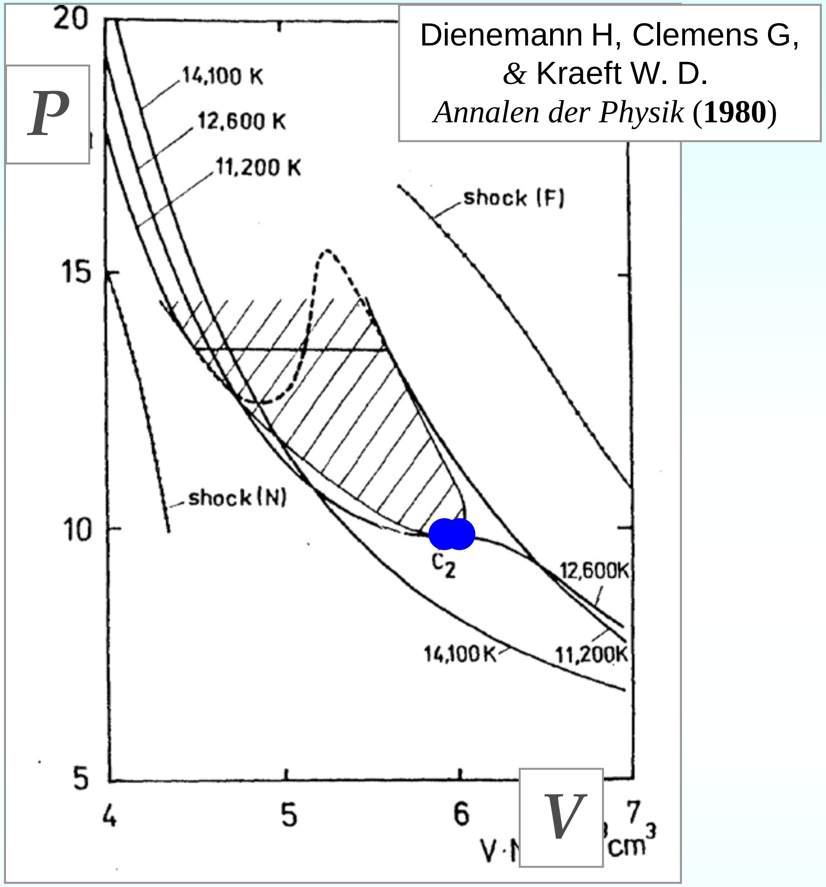


Satarov L., Dmitriev M., Mishustin I.
Phys. At. Nucl. (2009)

Ionization-driven (“plasma”) phase transition



Enthalpic (gas-liquid) **phase transition**



Entropic (*ionization-driven*) **phase transition in Xe**

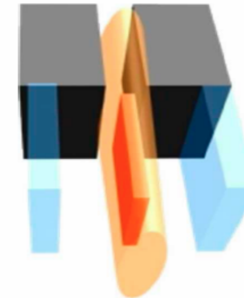
NB !

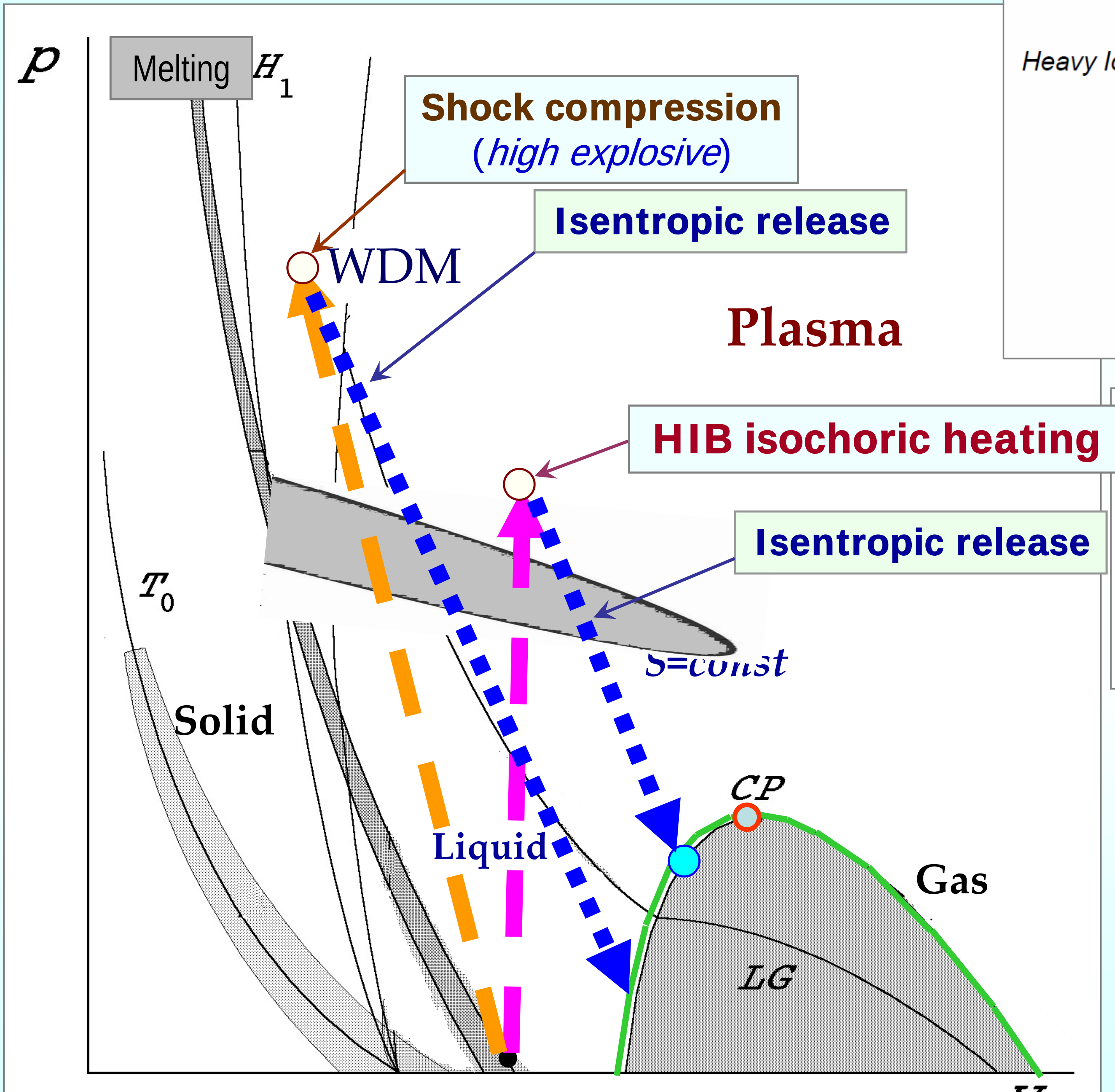
Entropic phase transition has **lower** (on pressure) **critical point !**

(e.g.: Iosilevskiy I. & Starostin A., *Encyclopedia on Low-T Plasmas,* V.I, Ch. III-1, **2000**, P.327-339) // V.III-1 (*suppl)* **2004**, P. 349)

HIHEX

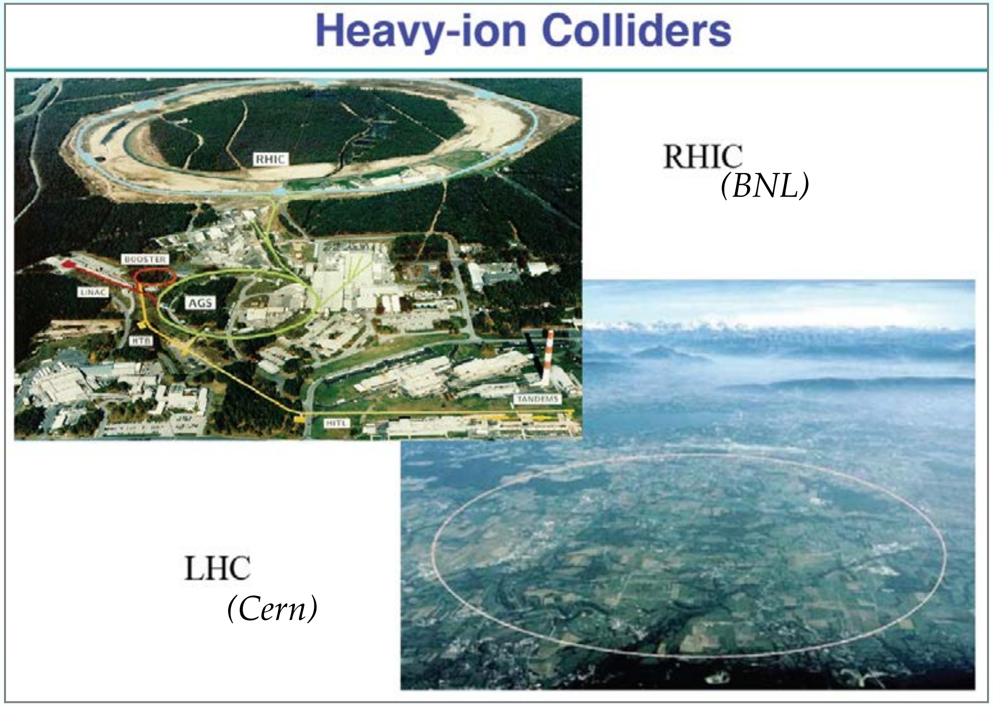
Heavy Ion Heating and Expansion

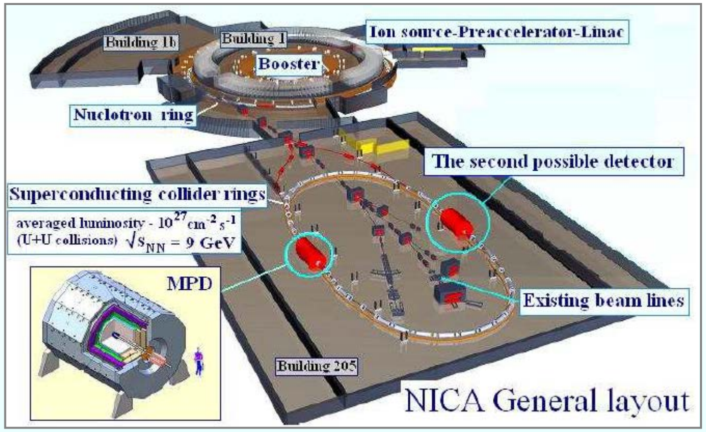




- uniform quasi-isochoric heating of a large-volume dense target
- isentropic expansion in 1D plane or

Heavy-ion beams for exploring of phase transitions *(in progress)*





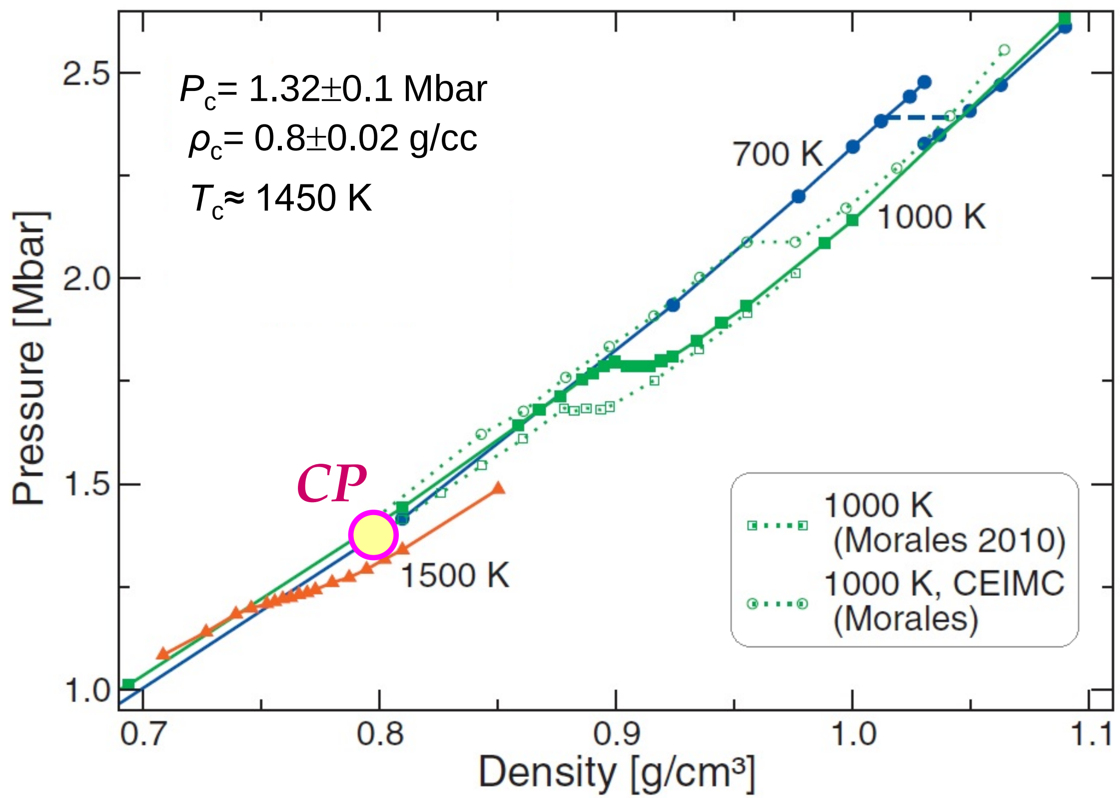
Nuclotron-Based Ion Collider fAcility (NICA)
JINR, Dubna, Russia

FAIR

(after A.A.Golubev / Hirschegg-2017)

Dissociation-driven (*entropic*) phase transitions

Hydrogen



PHYSICAL REVIEW B **82**, 195107 (2010)
W.Lorenzen, B.Holst, R.Redmer

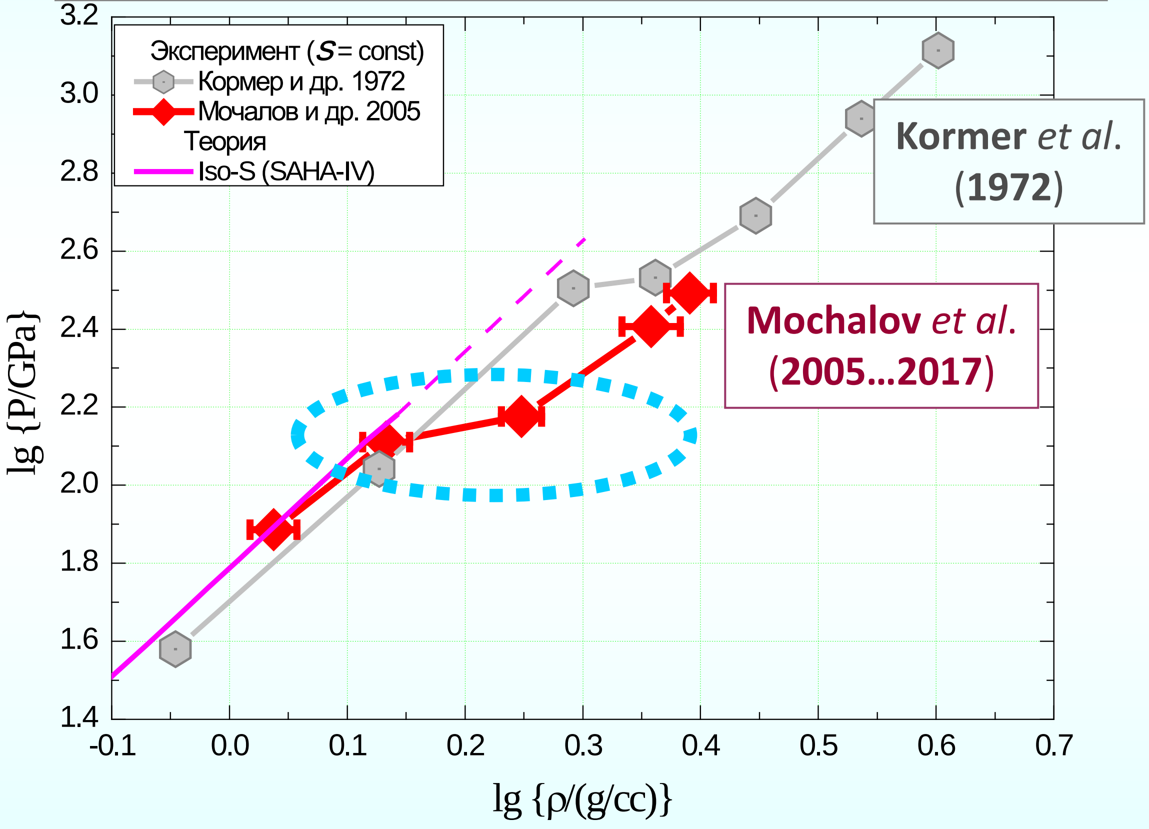
FIG. 2. Thermal EOS of dense hydrogen. A first-order phase transition is observed for temperatures below 1500 K

Anomalous order + crossing *of* isentropes !

Quasi-isentropic compression of deuterium up to the pressure 500 GPa

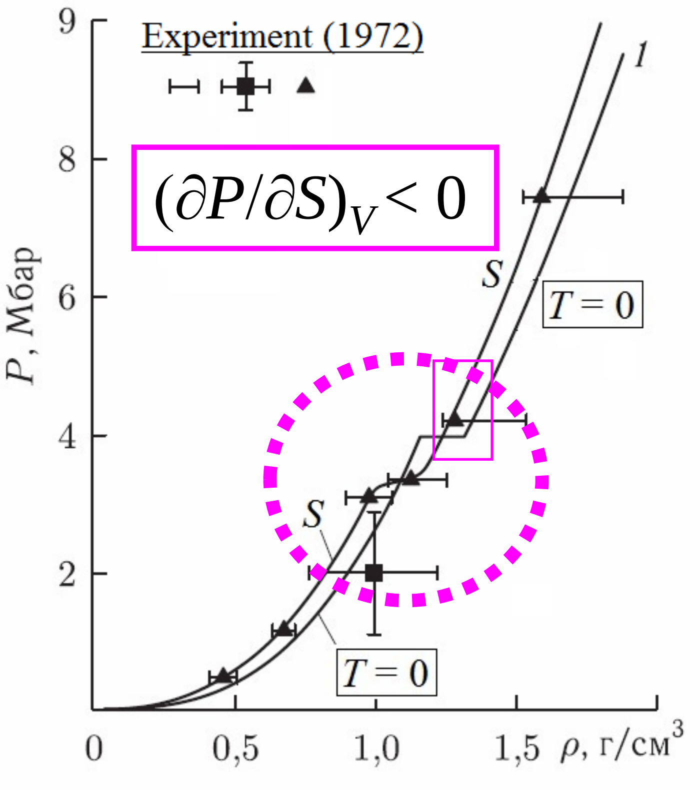
Experiments in VNIIEF (Sarov)

Density jump at quasi-isentropic compression



Fortov V., Mochalov M. *et al*. *Phys. Rev. Lett*. 99, **2007**

Mochalov M., Il'kaev R., Fortov V. *et al*. *JhETP* 124, **2017**

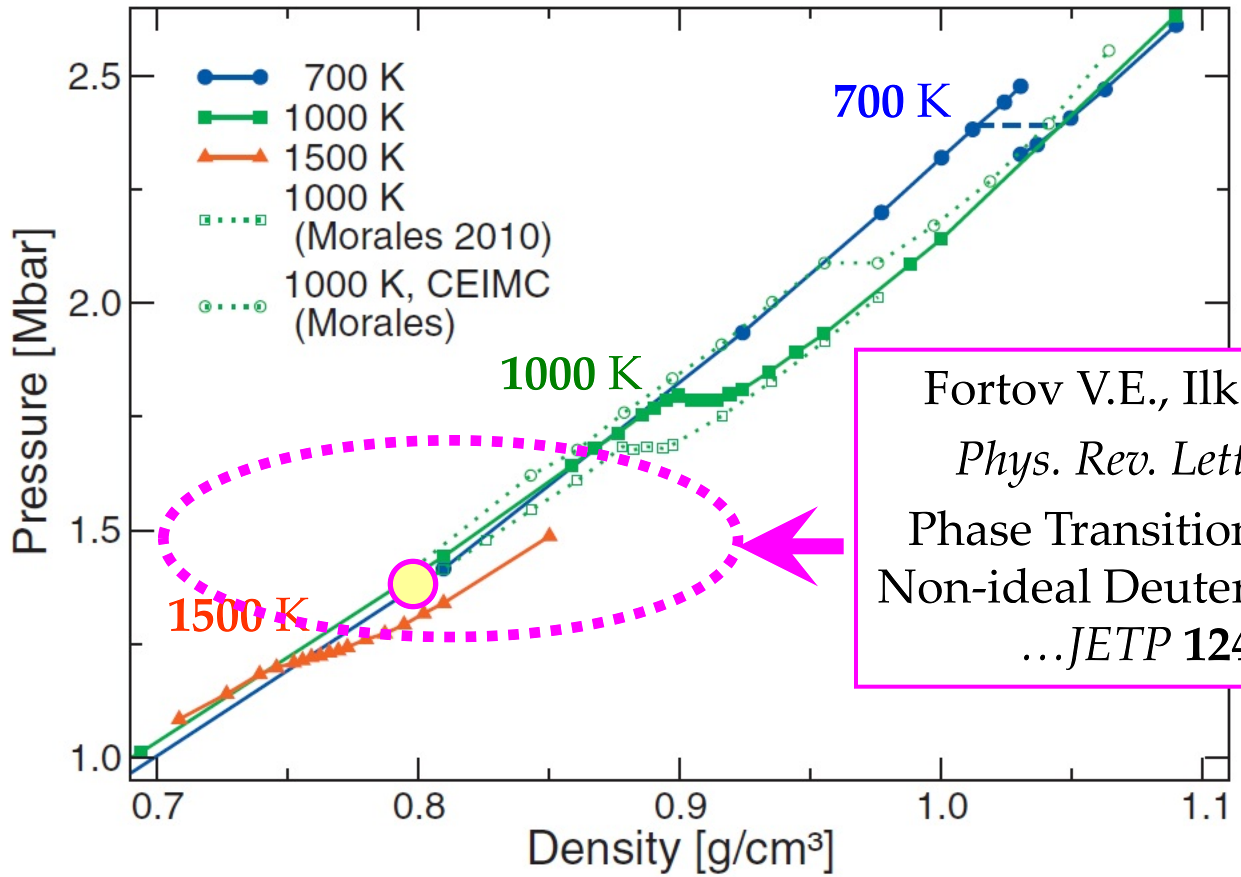


Фортов В.Е. *Уравнения Состояния*
М.: Физматлит, 2013

Нулевые изотермы (*1*) и изэнтропы (*S*) (*2*) молекулярного и металлического водорода [50]

Semiempirical EOS (VNIIEF)
Kopyshev & Khrustalev

Entropic fluid-fluid phase transition in H_2



P_c= 1.32±0.1 Mbar
ρ_c= 0.8±0.02 g/cc
T_c≈ 1450 K

Fortov V.E., Ilkaev R.I., *et al*
Phys. Rev. Lett. **99**, (2007)
Phase Transition in Strongly Non-ideal Deuterium Plasma…
…*JETP* **124**, (2017)

PHYSICAL REVIEW B **82**, 195107 (2010)
W.Lorenzen, B.Holst, R.Redmer

FIG. 2. (Color) Thermal EOS of dense hydrogen. A first-order phase transition is observed for temperatures below 1500 K and a Maxwell construction is performed (dashed line).

“…Так из смешенья стихий бесконечные сонмы созданий странных и многоразличных на вид происходят…”

Lucretius (De rerum natura)

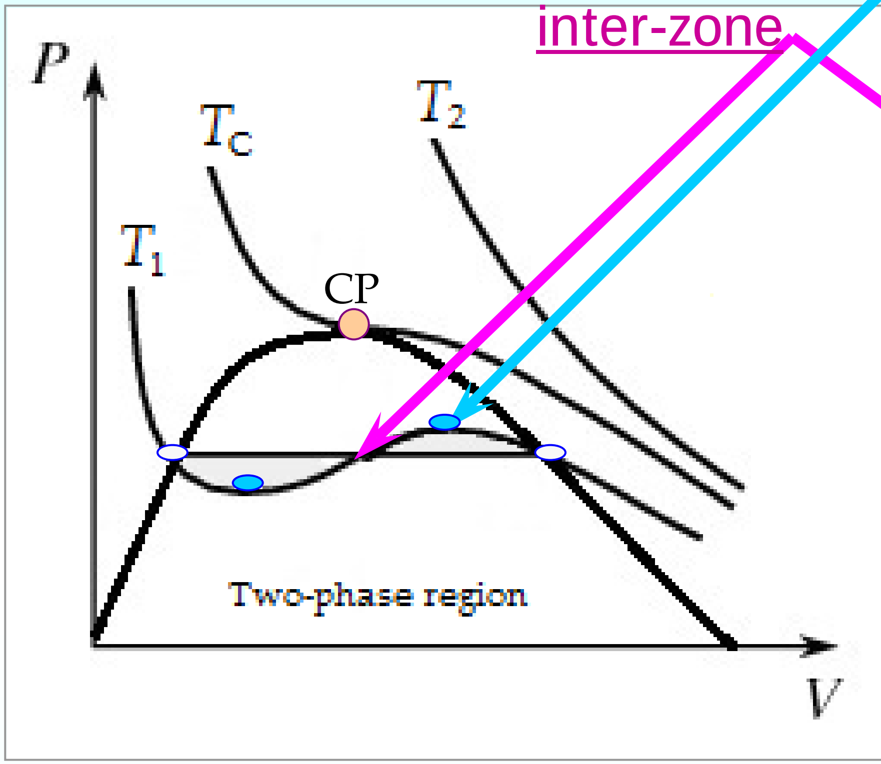
Anomalous structure *of* stable, unstable *and* metastable domains *in* entropic phase transitions

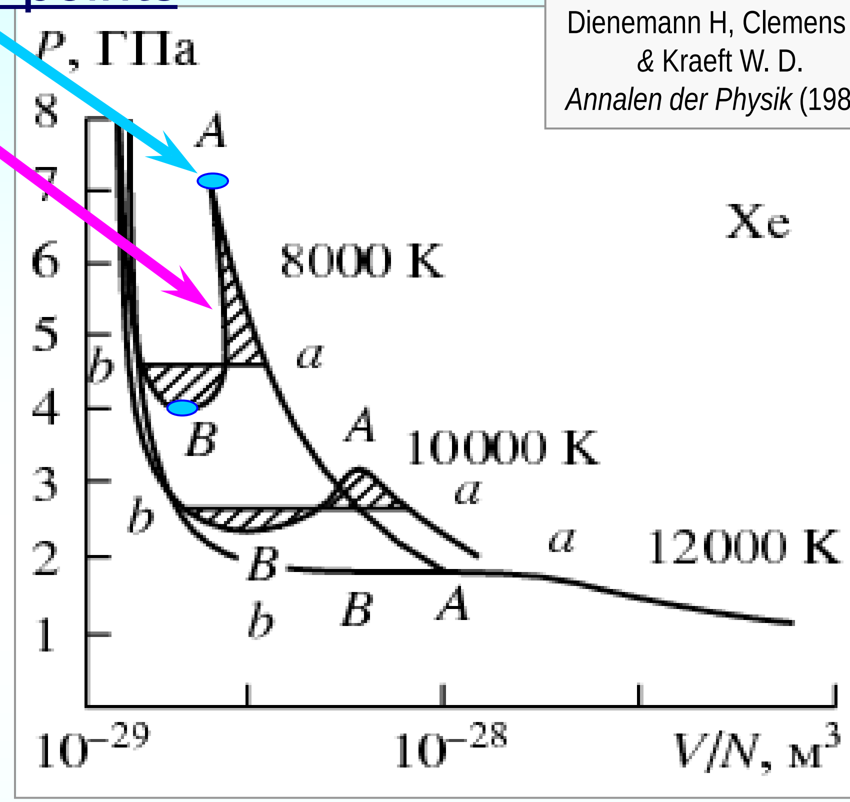
Enthalpic (GLPT) *vs* **Entropic** (PPT)

(continued)

spinodal points

inter-zone





Dienemann H, Clemens G, & Kraeft W. D. *Annalen der Physik* (1980)

VdW-like phase transition

Ionization-driven phase transition

(*enthalpic PT*)

$T \ll T_c$

(*entropic PT*)

NB !

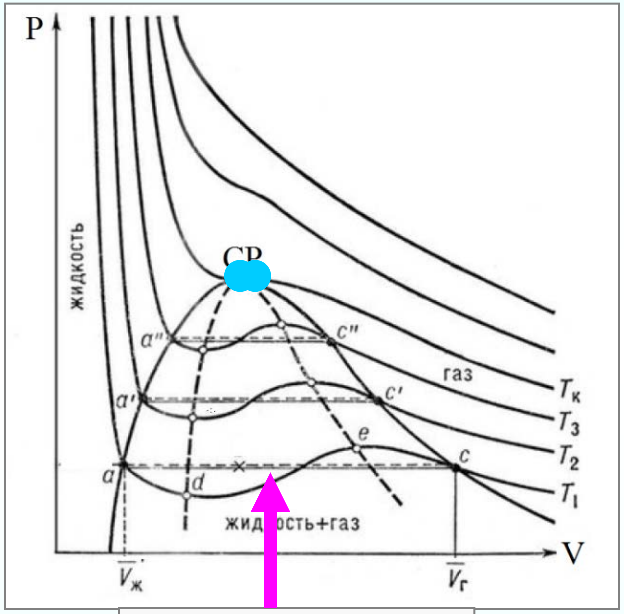
Abnomal form of **isotherms** in **spinodal** region of **entropic PT !**
{**beak-shaped spinodal point** (*in contrast to VdW-PT*)}

Third branch with $(\partial P/\partial V)_T < 0$ appears on **isotherms** in **spinodal** region **!**

Hypothetical dissociation-driven PT

(*enthalpic PT*)

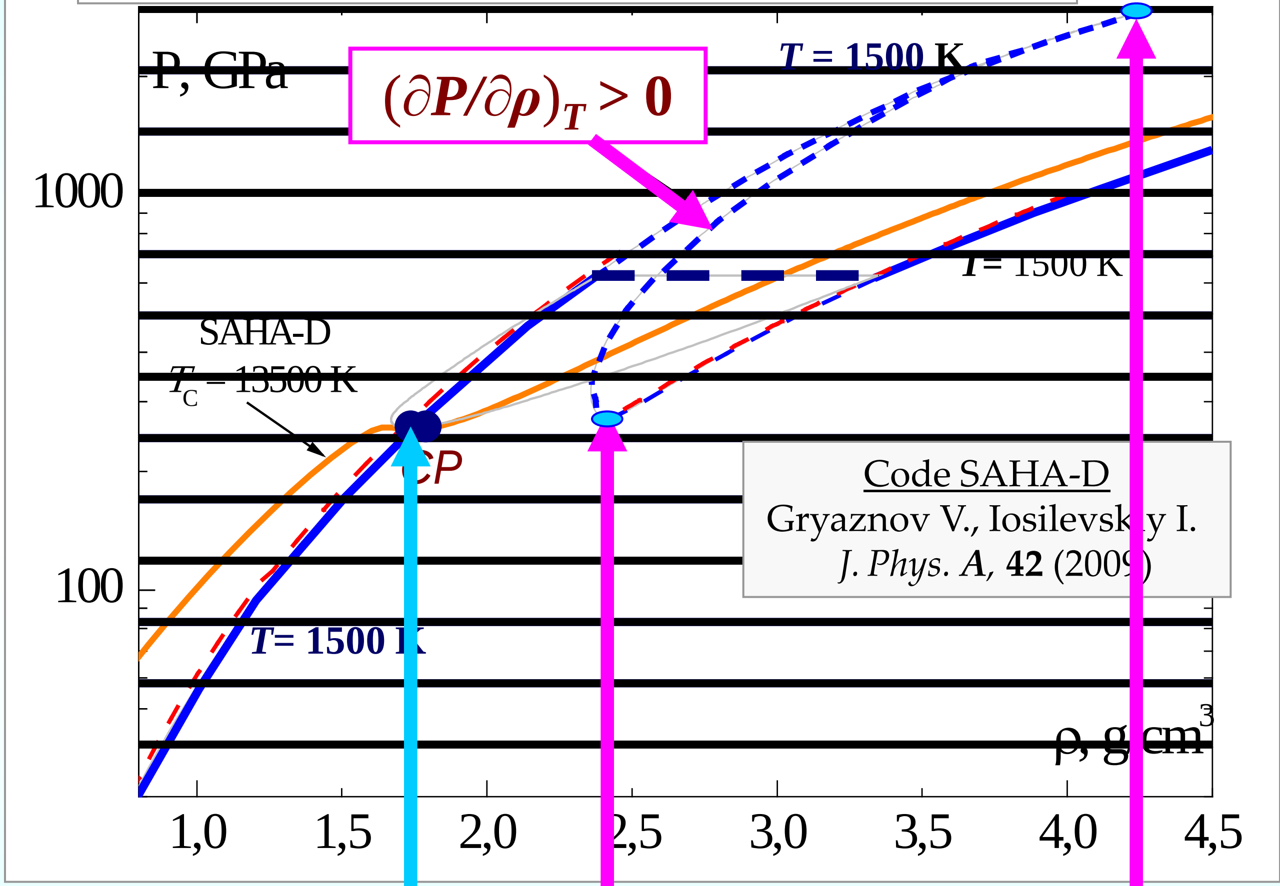
VdW-like phase transition



$(\partial P/\partial \rho)_T < 0$

(*entropic PT*)

Dissociation-driven phase transition (*deuterium*)



Code SAHA-D
Gryaznov V., Iosilevskiy I.
J. Phys. A, **42** (2009)

NB !

Not one, but **three isotherms intersect critical point** in *P-V* plane**!**

Spinodal point of **rare phase** may be of **higher density** than **spinodal** point of **dense phase !**

Hot dense matter in “chemical” representation

Code SAHA-D
Gryaznov V., Iosilevskiy I. *J. Phys.* ***A***, **42** (2009) *Thermodynamics of hot dense hydrogen*

Example – *Non-ideal hydrogen plasma*

⇔ ≈ Nuclear statistical equilibrium

Model of composition: – H_2, H, H+, H_2+, H_3+, H-, e- ...

Effective Interaction Potentials – *Modified Coulomb, Short-range repulsion and attraction (≈ ”excluded volume effect”)*

Electron degeneracy (in ideal-gas contribution and in screening length – – Modified Debye screening)

Non-ideality corrections: – *Modified pseudopotential approach for Coulomb correction // Soft spheres app. for short-range repulsion // Simplified “Bound” correction for S-R attraction*

Helmholtz Free Energy minimization – *Complicated numerical algorithm*

↓ Equilibrium composition

↓ Transport prop.

↓ Opacity

↓ Thermodynamics (EoS)

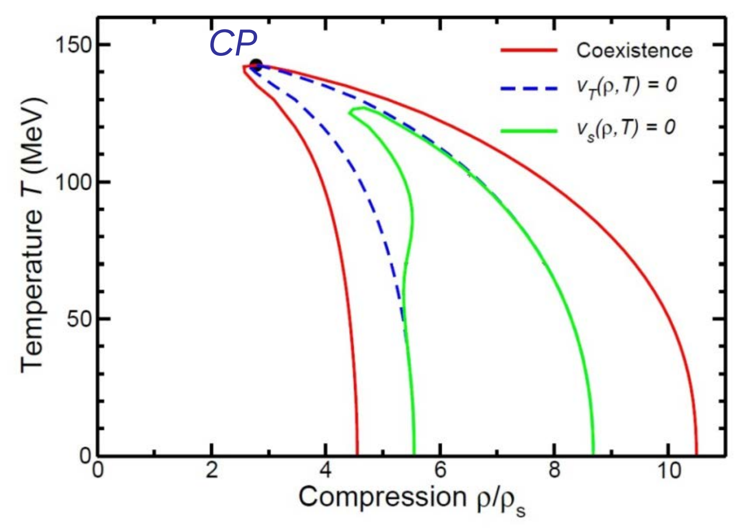
↓ Hydrodynamics of matter under extreme impact

Chemical representation /EOS-code SAHA/
Gryaznov V., Iosilevskiy I. Fortov V. *Encyclopedia of Low-Temperature Plasmas* / Moscow, Fizmztlit (2004)

Hypothetical dissociation-driven (*entropic*) PT

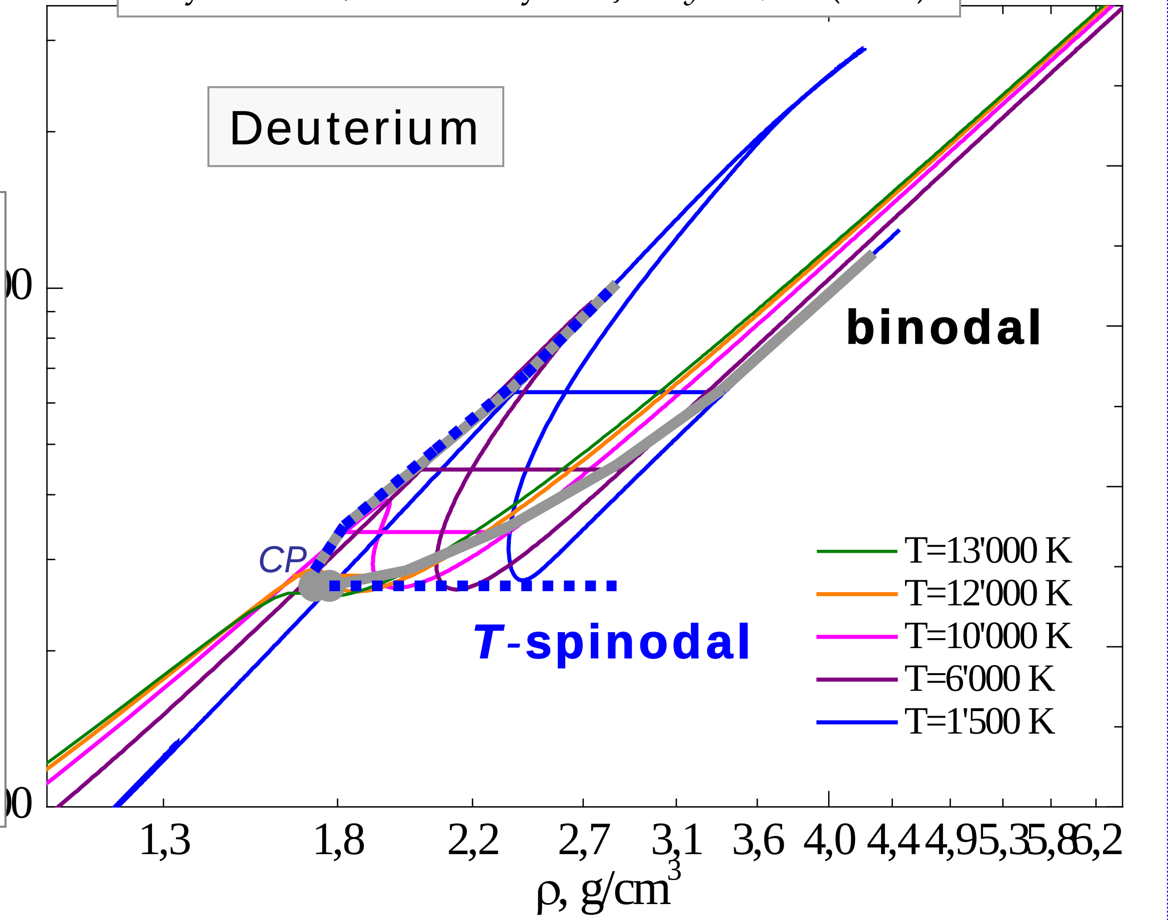
Randrup J., *Phys. Rev. C.* **82**, (2010)

CP
Binodal
***T*-spinodal**
***S*-spinodal**



Randrup J. *Phys. Rev. C*, **82** (2010)
Spinodal phase separation in relativistic nuclear
phase transition

Code SAHA-D
Gryaznov V., Iosilevskiy I. // *J. Phys. A*, **42** (2009)



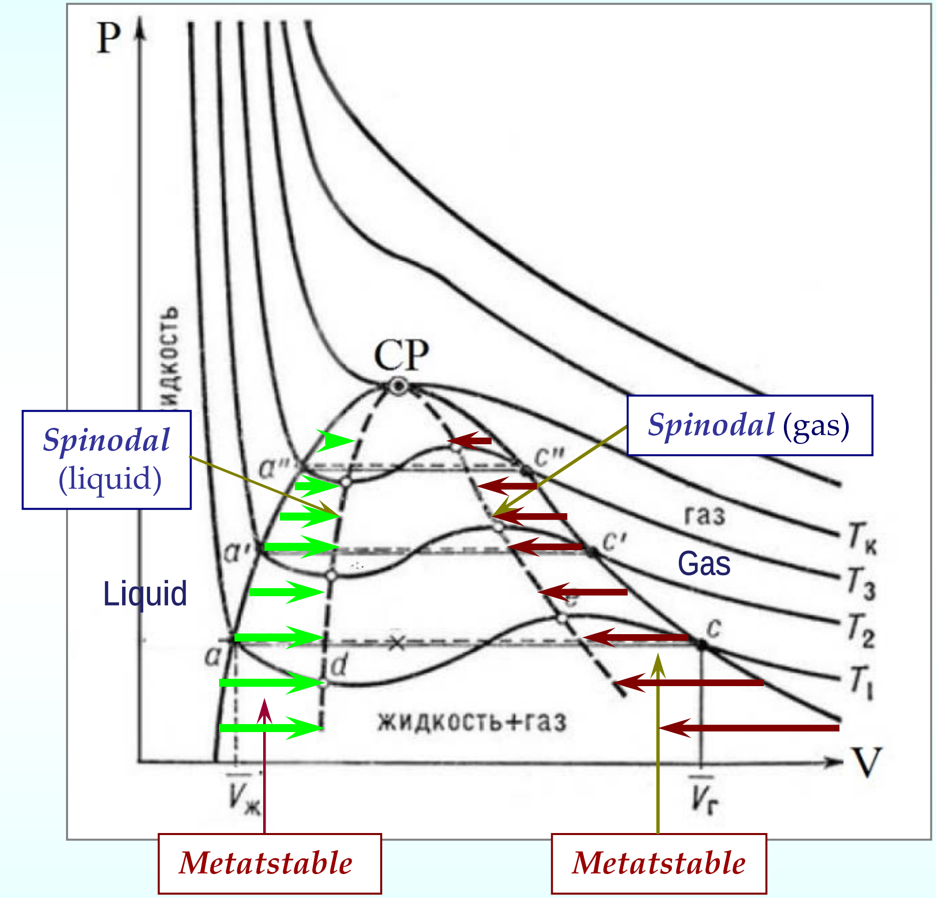
NB !

Iso-*T* spinodal $\{(\partial P/\partial V)_T = 0\}$ is located **outside** of **binodal**

Iso-*S* spinodal $\{(\partial P/\partial V)_S = 0\}$ is located **outside** of **iso-*T* spinodal !**

Anomalous topology *of* **binodals** *and* **spinodals** *in the two-phase region of* **entropic phase transition** (T - ρ diagram)

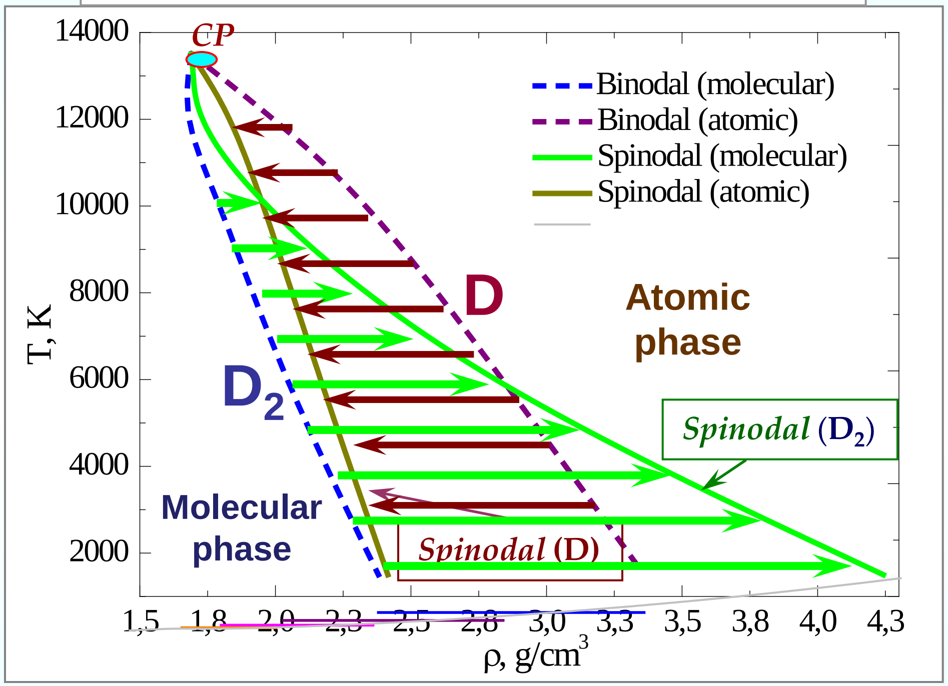
VdW (*enthalpic*) Phase Transition



Dissociation-driven (*entropic*) Phase Transition in hydrogen

Code SAHA-D

Gryaznov V., Iosilevskiy I., *J. Phys.* ***A***, **42** (2009)



"**Night bat**" structure of metastable "**wings**"

NB !

Abnomalous features *of* **entropic phase transition** *are due to* **multi-layered structure** *of* **thermodynamic surfaces !**

Iosilevskiy I. // in "*Physics of Extreme States of Matter*", Ed. V. Fortov (Chernogolovka: IPCP RAS), Russia, (**2013**)

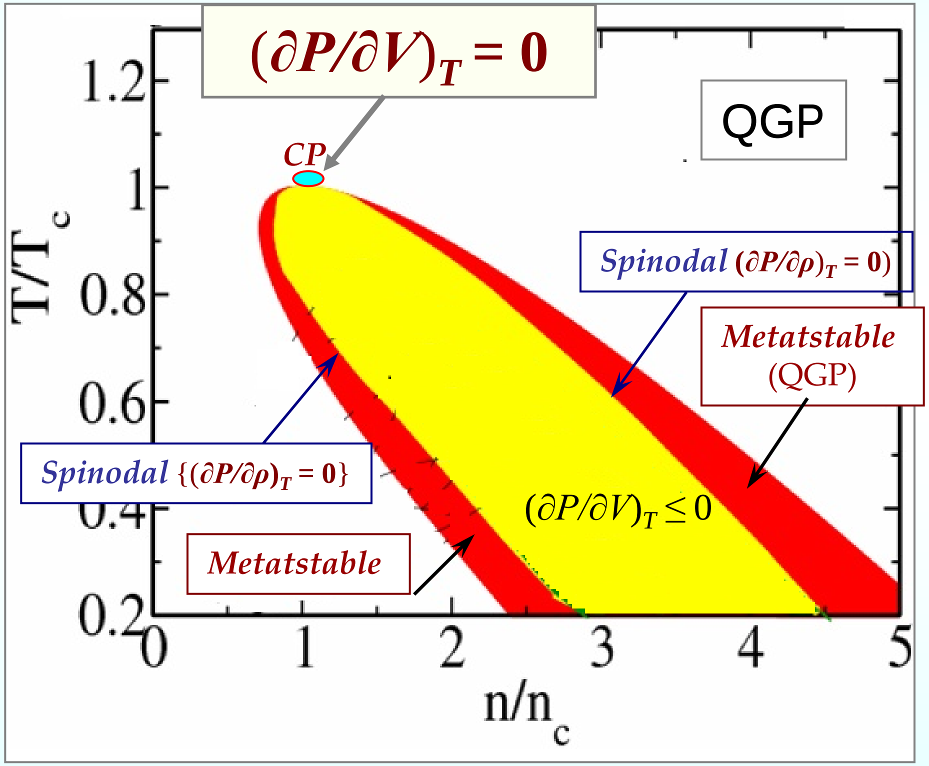
Anomalous features *of* entropic phase transition

(*due to* **multi-layered structure** *of* **thermodynamic surfaces !**)

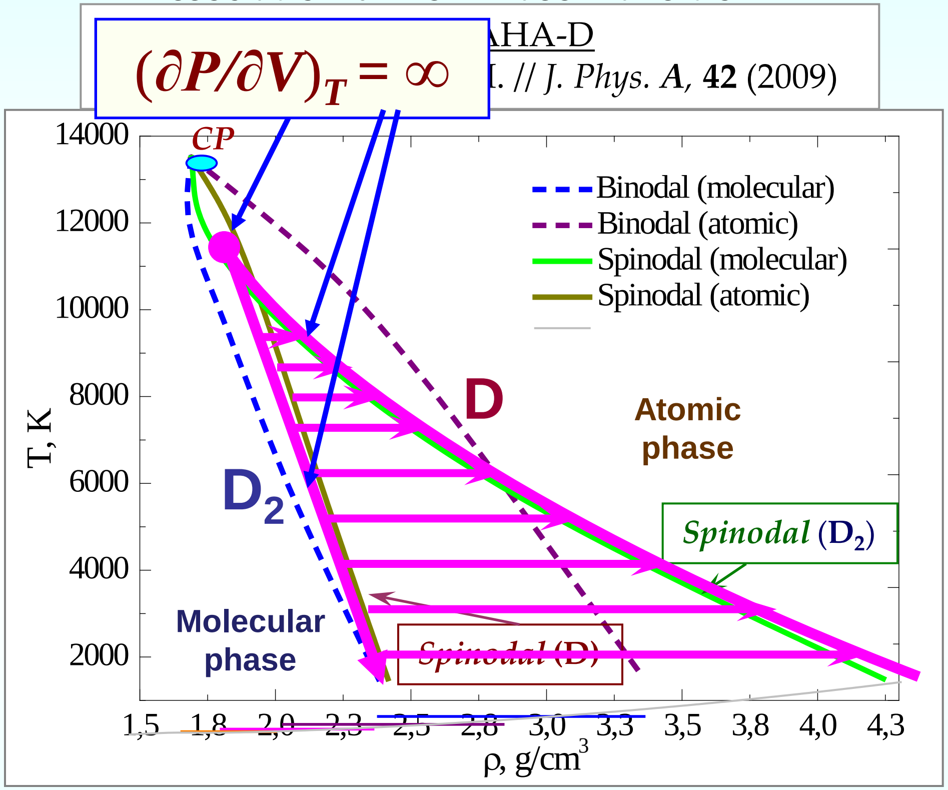
(T - ρ diagram)

Quark-Hadron Phase Transition

After Vladimir Skokov, *Int. Conf.* "Prerow-2009"



Dissociation-driven Phase Transition



{ Iosilevskiy I. // (*in preparation*) }

NB !

New (additional) region of metastable state ⇔ $(\partial P/\partial V)_T < 0$

New (additional) spinodal lines ⇔ $(\partial P/\partial V)_T = \infty$ **!**

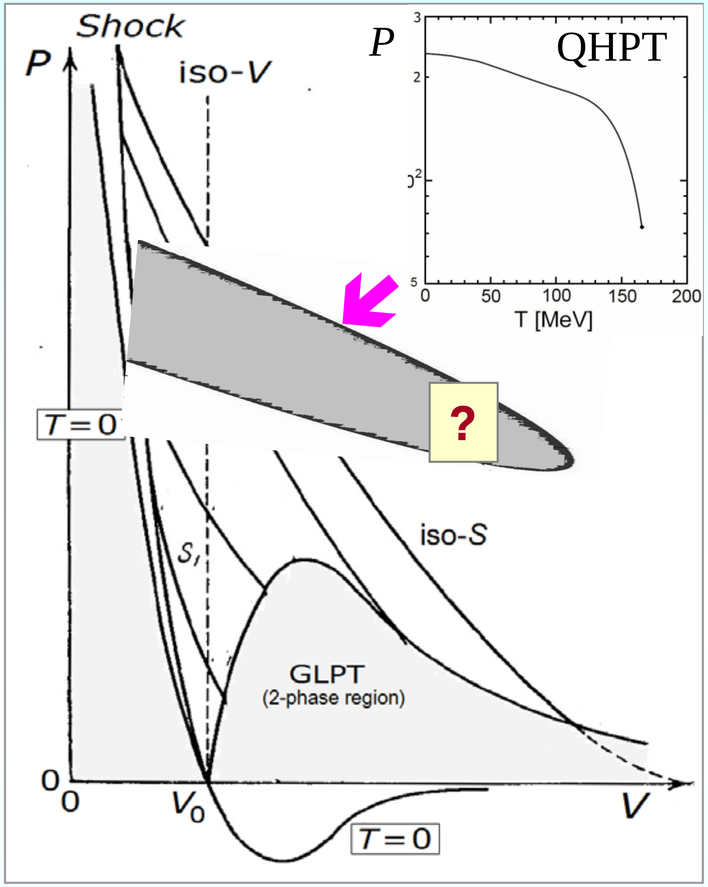
New (additional) singular point *(no-named still)* ⇔ $(\partial P/\partial V)_T = \infty$ **!**

Entropic Phase Transitions

and

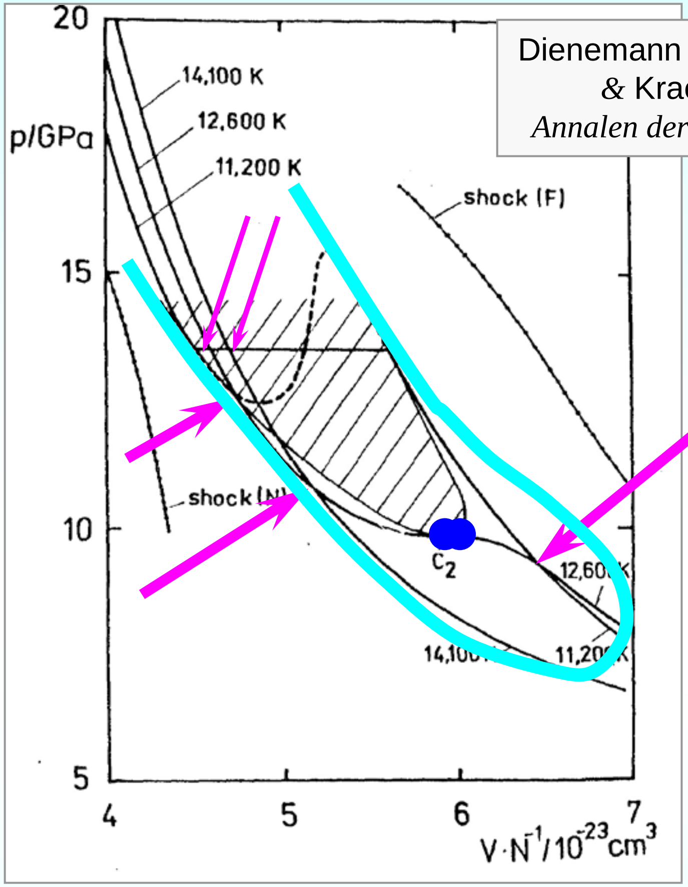
Anomalous Thermodynamics Region

Ionization-driven ("plasma") phase transition



Enthalpic (gas-liquid) phase transition

P(V)



Dienemann H, Clemens G, & Kraeft W. D.
Annalen der Physik (**1980**)

Entropic (*ionization-driven*) phase transition in Xe

NB ! **Abnormal order** and **crossing** of **isotherms !**

$(\partial P/\partial T)_V < 0$ → $V(\partial P/\partial U)_V < 0 \Leftrightarrow (\partial V/\partial T)_P < 0 \Leftrightarrow (\partial T/\partial P)_S < 0$

In the **vicinity** of **entropic PT** one meets **abnormal thermodynamics !**

New **boundary** exists with **zero cross derivatives** – "**Zero-Boundary**" (ZB)**!**

Anomalous Thermodynamics Region - *ATR*

Normally positive cross derivatives became *negative simultaneously !*

Normal > 0 **Abnormal** < 0

$(\partial P/\partial T)_V$	⇔	$(\partial P/\partial S)_V$	⇔	$(\partial P/\partial U)_V$
⇕		⇕		⇕
$(\partial V/\partial T)_P$	⇔	$(\partial V/\partial S)_P$	⇔	$(\partial V/\partial H)_P$
⇕		⇕		⇕

$(\partial S/\partial V)_T$ ⇔ $(-\partial S/\partial P)_T$ ⇔ $(\partial T/\partial P)_S$ ⇔ $(-\partial T/\partial V)_S$

$(\partial P/\partial U)_V$ - thermodynamic Gruneizen parameter, $Gr \equiv V(\partial P/\partial U)_V$

$(\partial V/\partial T)_P$ – thermal expansion coefficient, $\alpha_T \equiv V^{-1}(\partial V/\partial T)_P$

All these cross derivatives are equal to *ZERO simultaneously !*

Features of entropic phase transitions
(*ionization- and dissociation-driven*)

Entropic PT obeys to anomalous thermodynamics !

- *negative Gruneizen parameter* $V(\partial P/\partial U)_V < 0$
- *negative thermal pressure coefficient* $(\partial P/\partial T)_V < 0$
- *negative entropic pressure coefficient* $(\partial P/\partial S)_V < 0$
- *negative thermal expansion coefficient* $(\partial V/\partial T)_P < 0$
- *. . . . . etc. etc.*

- *anomalous order of isotherms (!)*
- *anomalous order of isentropes (!)*
- *anomalous order of shock adiabats (!)*
- *. . . . . etc. etc.*

- *anomalous form of isotherms in two-phase region*
- *anomalous interconnection of spinodals and binodals*
- *. . . . . etc. etc.*

I. Iosilevskiy (*in preparation*)

Anomalous thermodynamics *in the* neighborhood *of* entropic phase transition -- *(AT-region)*

$(\partial P/\partial T)_V < 0$ → **Abnormal order + crossing** *of* **isotherms !**

$(\partial P/\partial S)_V < 0$ → **Abnormal order + crossing** *of* **isentropes !**

= = « » = = → **Shock adiabats** *go* **less steeper** *than* **isentropes !**

$V(\partial P/\partial U)_V < 0$ → **Abnormal order + crossing** *of* **Hugoniots** ***(shock adiabats)* !**

See e.g. A.Medvedev & R.Trunin, *Uspekhi (UFN)* **182** (2012) and V.Brazhkin's critique (="=)

$(\partial T/\partial P)_S < 0$ → **Abnormal decreasing** (*increasing*) **temperature** *under* **isentropic compression** (*expansion*) **!**

→ **Abnormal conditions** *of* **convection instability !**

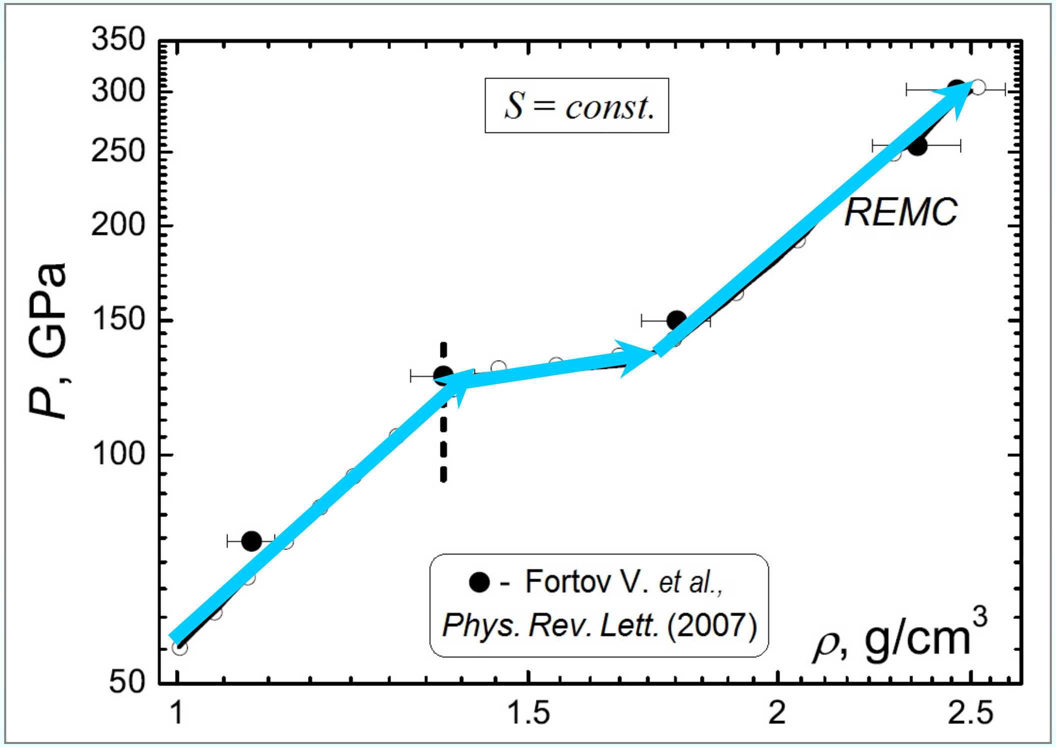
See e.g.

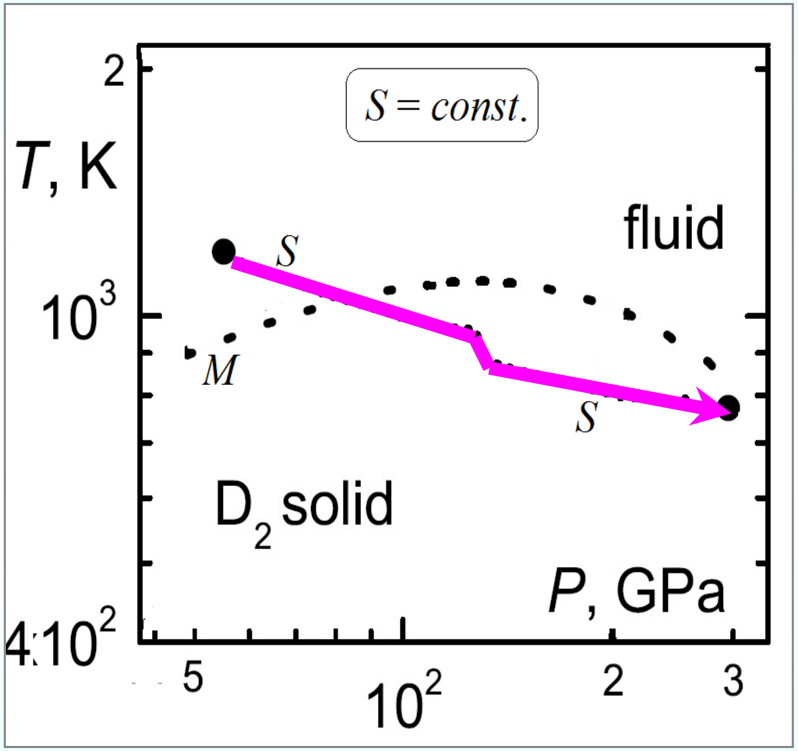
Hempel M., Heinimann O., Yudin A., Iosilevskiy I., Liebendoerfer M., Thielemann F-K.
Physical Review D, 94 (2016)
A Hot Third Family of Compact Stars and the Possibility of Core-Collapse Supernova Explosions

Reactive Ensemble Monte-Carlo - REMC

(isentropic compression)

Deuterium (2009)





J. Phys. A.: Math & Theor., **42**, (2009)
Filinov V., Levashov P., Bonitz M., Botsan A., Fortov V.
Monte-Carlo *calculations of thermodynamic properties of* ***deuterium*** *under high pressures%*

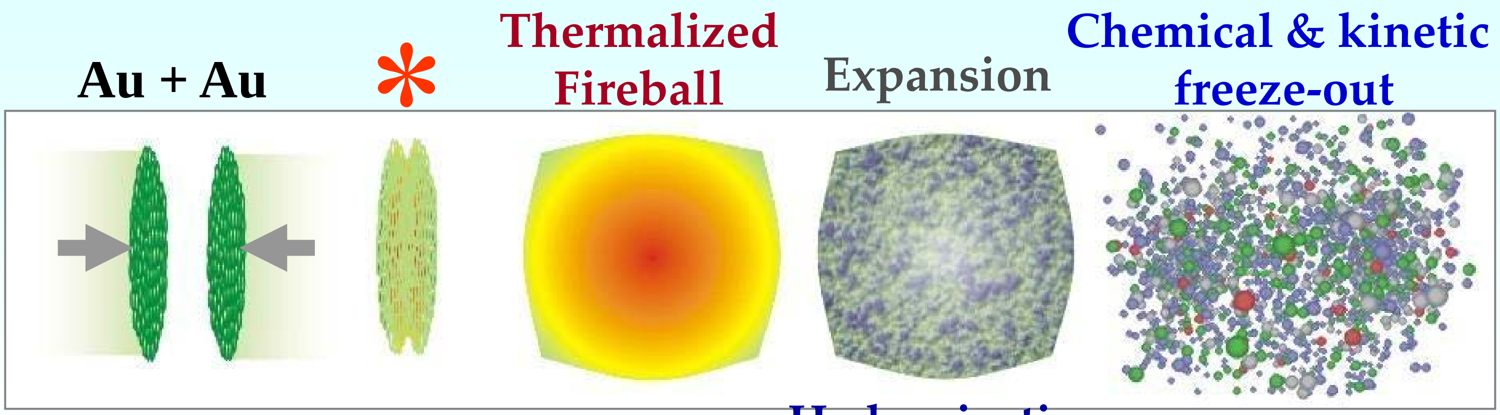
NB ! $(\partial T/\partial P)_S < 0$

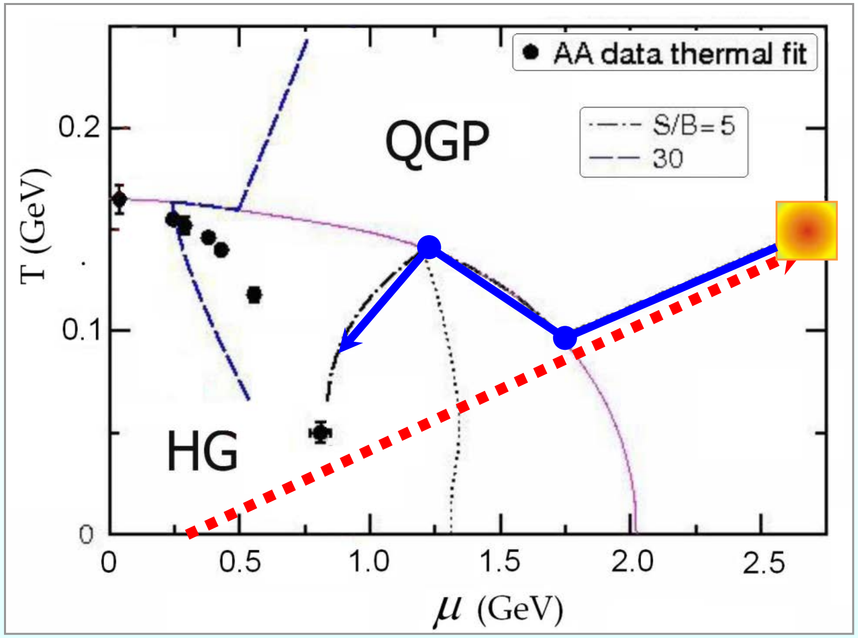
Температура *S-сжимаемого дейтерия* ***падает****, а не растет !*

NB!

What are consequences of anomalous properties of entropic phase transitions for hydrodynamic stability of adiabatic processes: *shock compression and isentropic expansion* ?

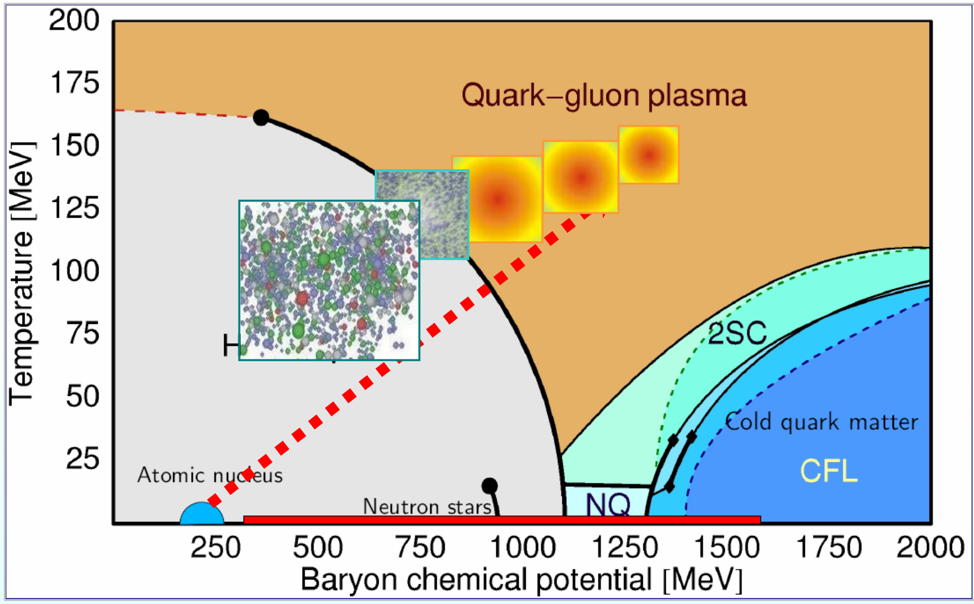
Impact *and* fireball hydrodynamics *in* RHIC





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

Shock adiabat of Renkine-Hugoniot-Taub



Widely accepted phase diagram of matter

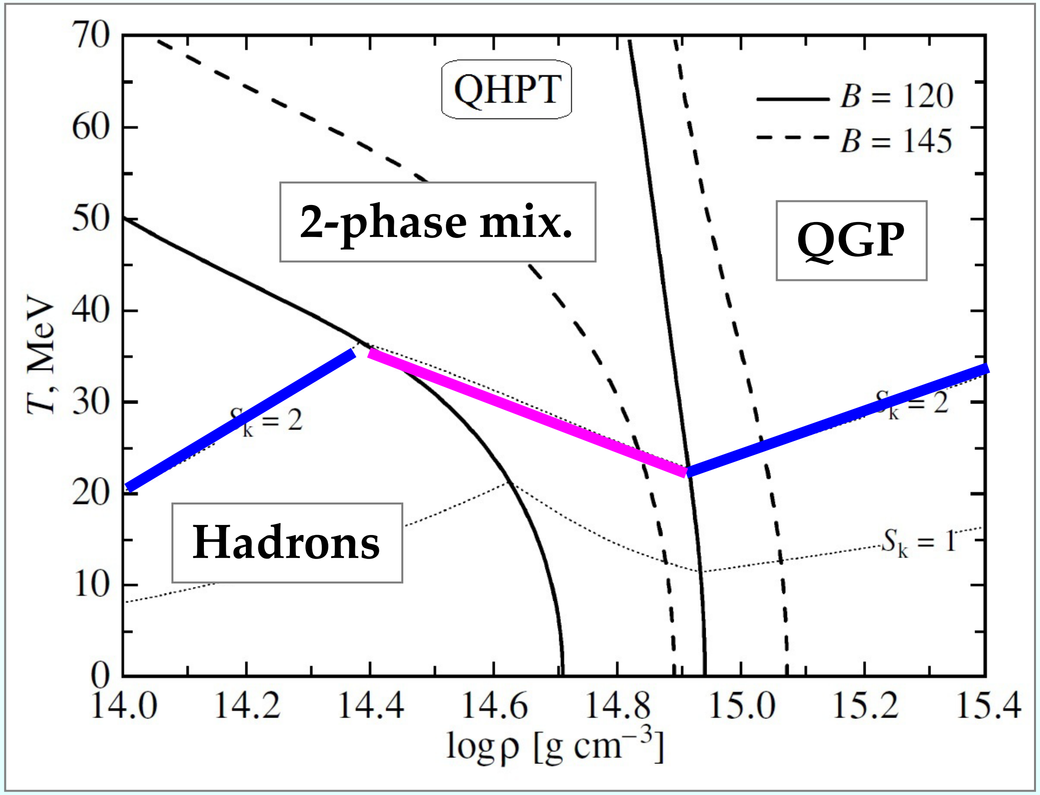
Landau L. & Lifshitz E., *Hydrodynamics*, (Moscow, 1986)

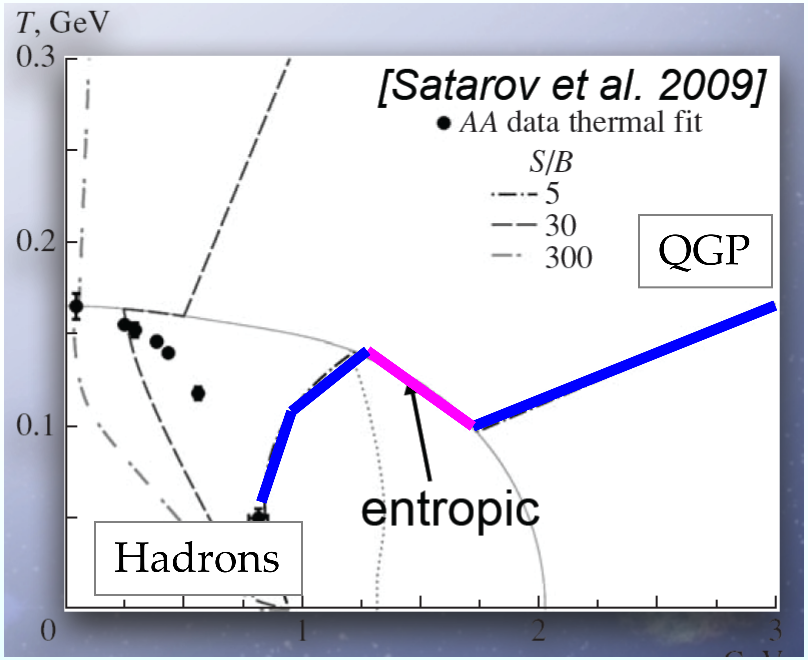
Negative Gruneizen parameter - - $Gr \equiv V(\partial P/\partial U)_V < 0$

Temperature fall under isentropic compression - - $(\partial T/\partial P)_S < 0$

Consequences of the *entropic* QCD PT: Inverted convection in proto-hybrid stars

Yudin A., Hempel M., Nadyozhin D. Razinkova T.L., *MNRAS*, 45,(2016) *Convection in hybrid stars*





Matthias Hempel
Istanbul, 25.04.2016

Hempel M., Heinimann O., Yudin A., Iosilevskiy I., Liebendoerfer M. and Thielemann F-K. *Third families of proto-compact stars, and the possibility of core-collapse supernova explosions* arXiv:1511.06551

Entropic phase transitions *are* **always accompanied** *by* **multilayered structure** *of* **thermodynamic surfaces**

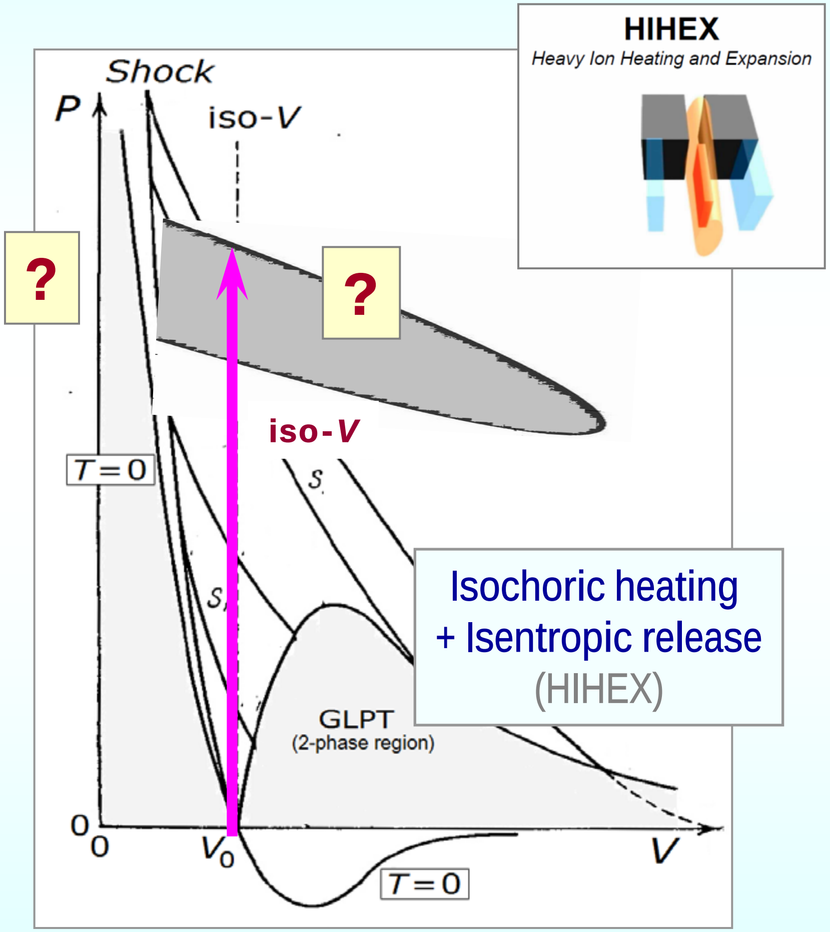
Multilayered structure *of* **thermodynamic surfaces**

T(p,V), U(p,V), S(p,V)…

in **entropic phase transition**

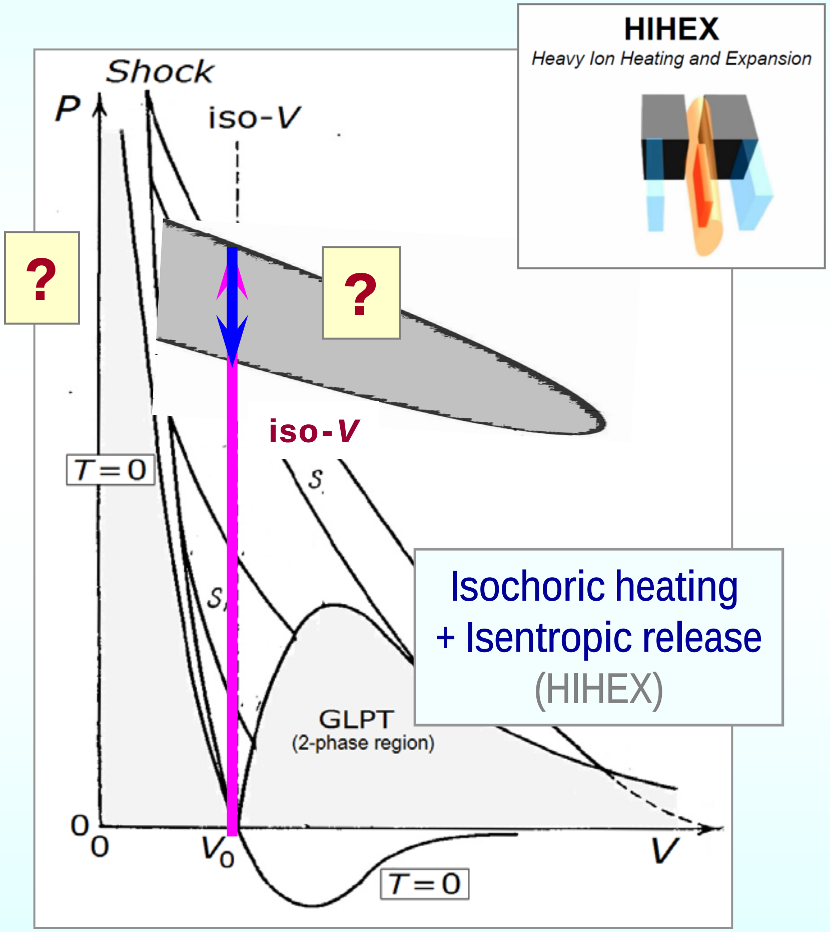
Multilayered structure *of* thermodynamic surfaces *for* entropic phase transitions

T(p,V), U(p,V), S(p,V)…



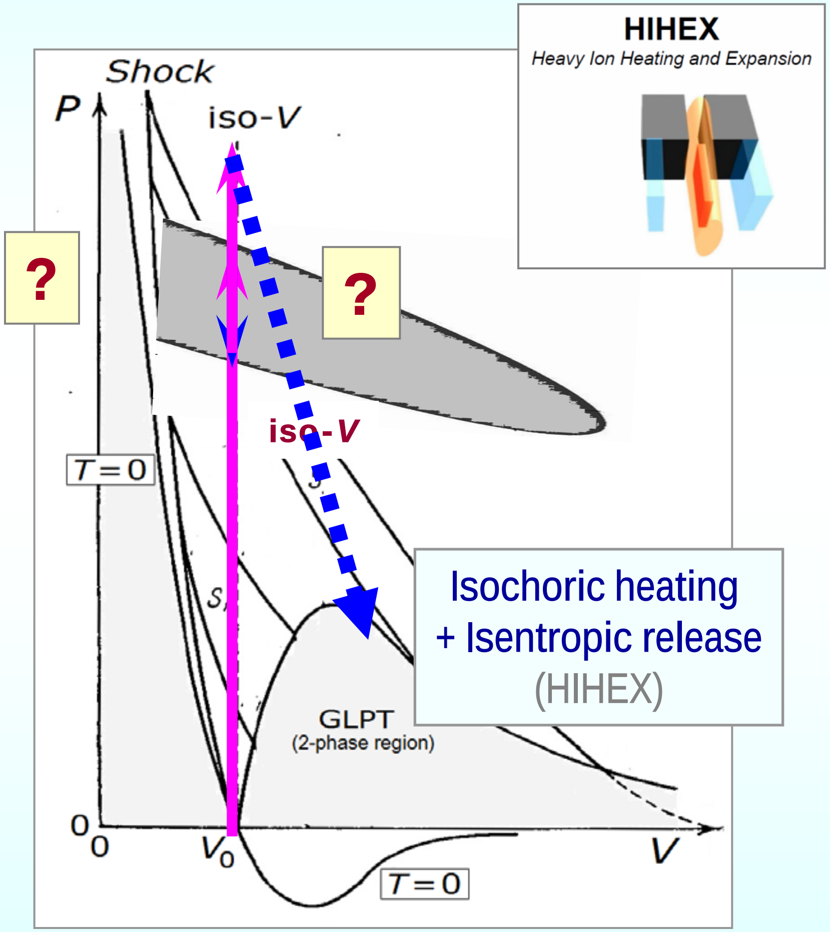
Entropic phase transition and enthalpic (*VdW-like*) **one**

Multilayered structure *of* thermodynamic surfaces *for* entropic phase transitions $T(p,V)$, $U(p,V)$, $S(p,V)$…



Entropic phase transition and enthalpic (*VdW-like*) **one**

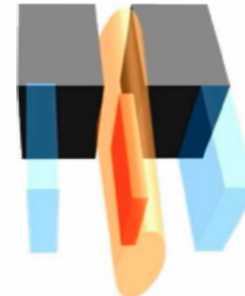
Multilayered structure *of* thermodynamic surfaces *for* entropic phase transitions $T(p,V)$, $U(p,V)$, $S(p,V)$…

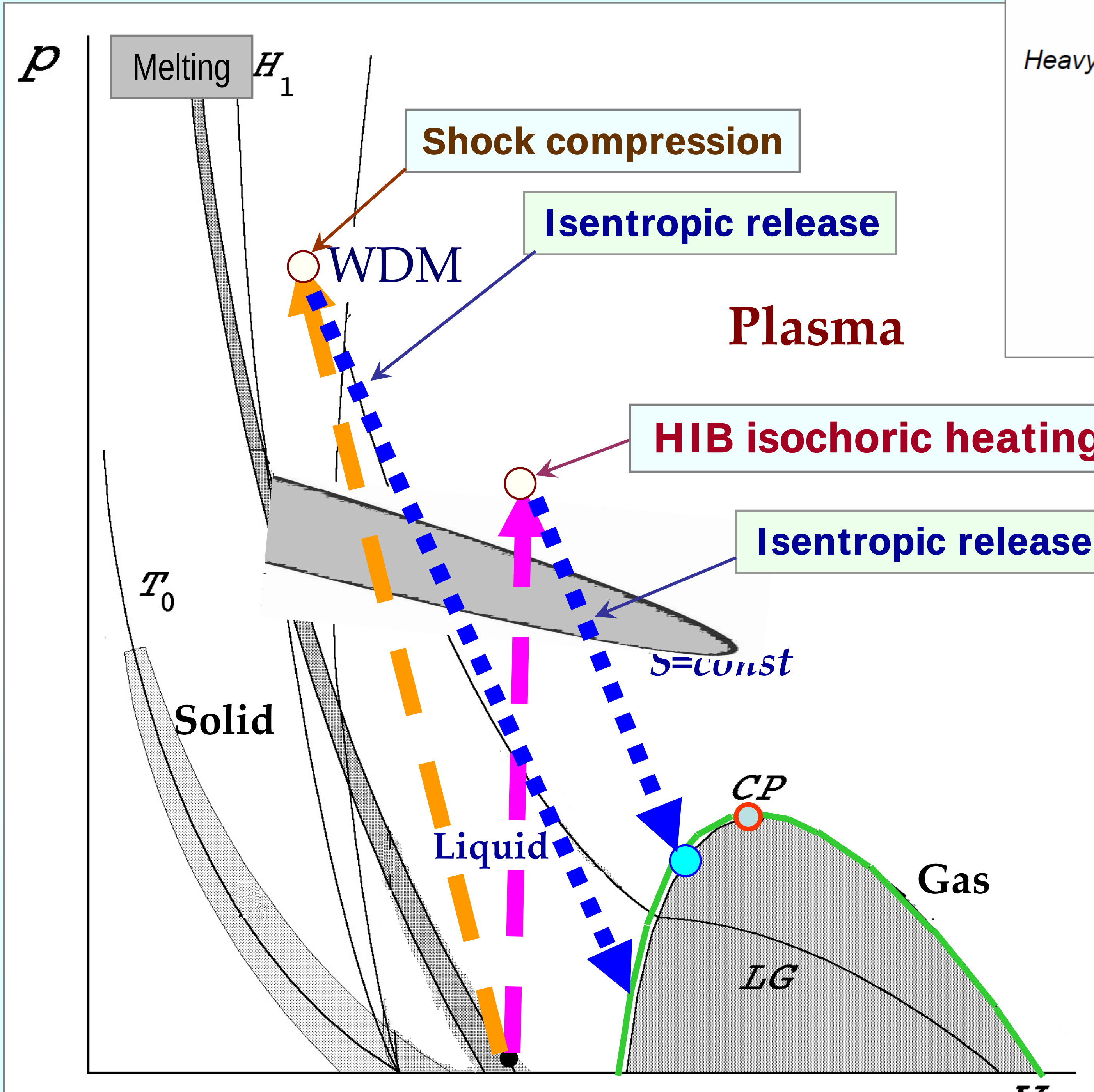


Entropic phase transition and enthalpic (*VdW-like*) one

HIHEX

Heavy Ion Heating and Expansion





- uniform quasi-isochoric heating of a large-volume dense target
- isentropic expansion in 1D plane or

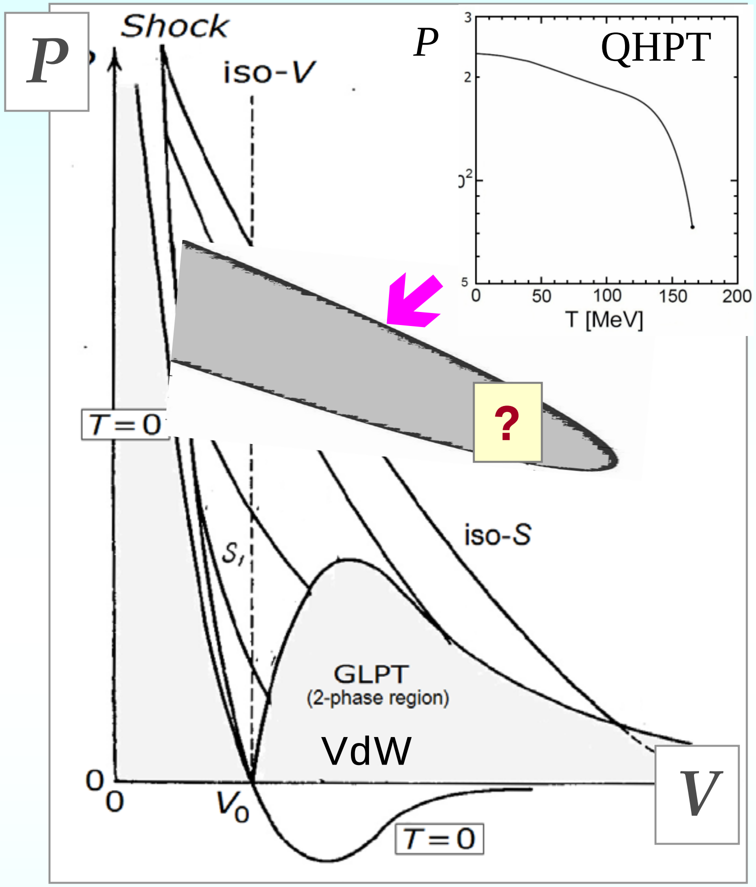
Problem of anomalous thermodynamics for entropic phase transitions

Basic points

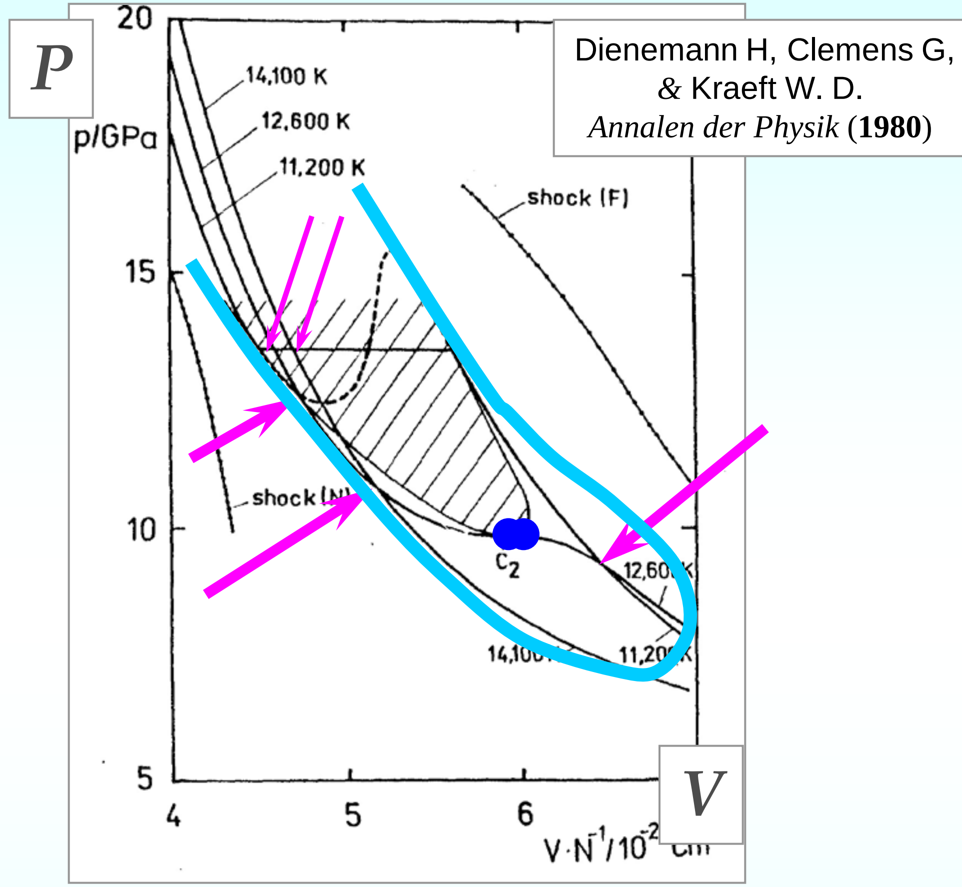
All **entropic phase transitions** are accompanied by **thermodynamic anomalies** in **two-phase** region

Most of **entropic fluid-fluid phase transitions** are accompanied by **thermodynamic anomalies** in area **nearby** the **critical point**

Ionization-driven ("plasma") phase transition



Enthalpic (gas-liquid) **phase transition**



Entropic (*ionization-driven*) **phase transition in Xe**

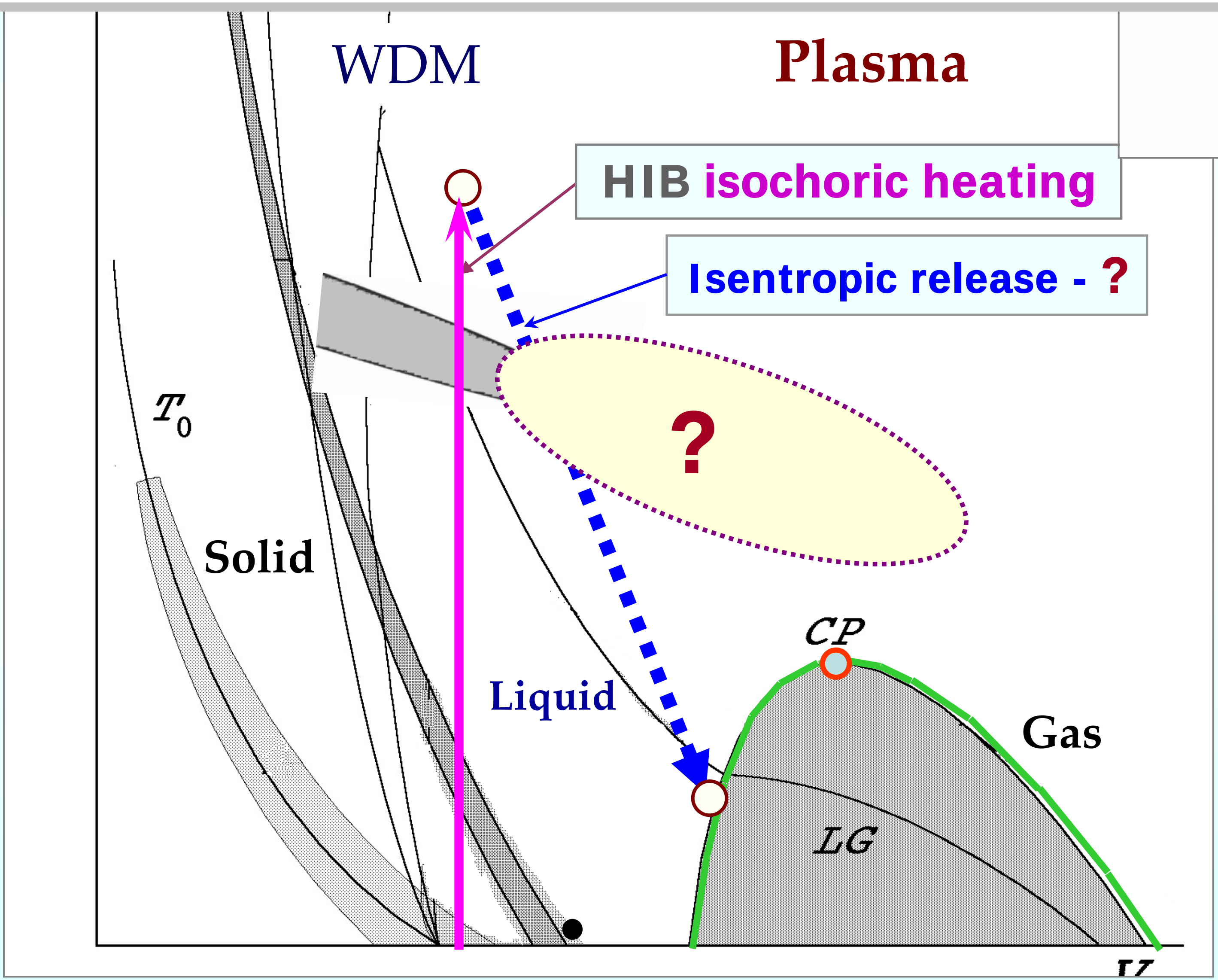
NB ! **Abnormal order** and **crossing** of **isotherms !**

$(\partial P/\partial T)_V < 0$ → $(\partial V/\partial T)_P < 0 \Leftrightarrow V(\partial P/\partial U)_V < 0 \Leftrightarrow (\partial T/\partial P)_S < 0$

In the **vicinity** of **entropic PT** one meets **abnormal thermodynamics !**

New **boundary** exists with **zero cross derivatives** – "**Zero-Boundary**" (ZB)**!**

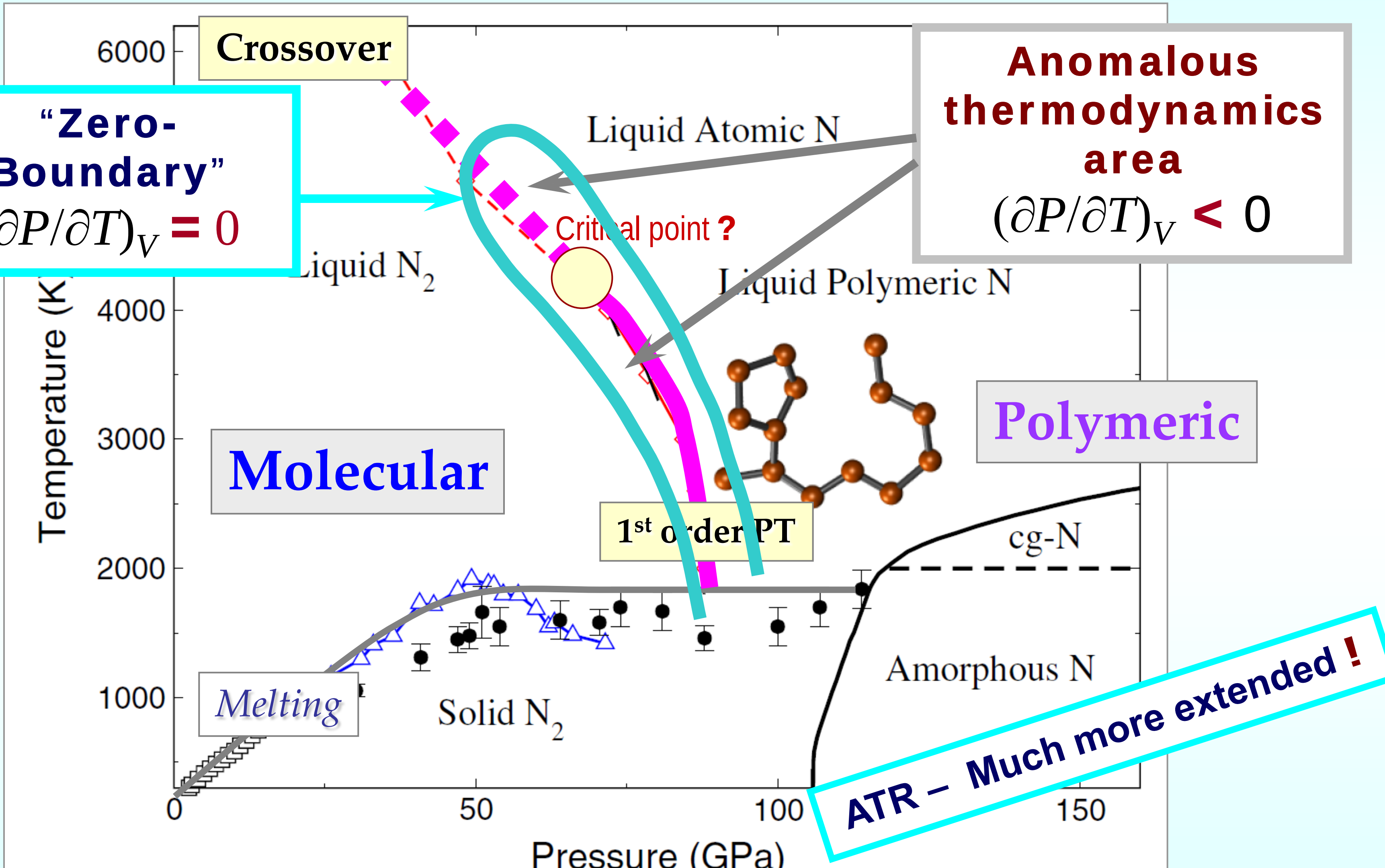
Entropic fluid-fluid phase transitions are accompanied by thermodynamic anomalies in area nearby the critical point



- uniform quasi-isochoric heating of a large-volume dense target
- isentropic expansion in 1D plane or

Entropy-driven fluid-fluid phase transitions (N_2)

Boates B., Bonev S. *Phys. Rev. Lett.* **102** (2009)/ Quantum Molecular Dynamics

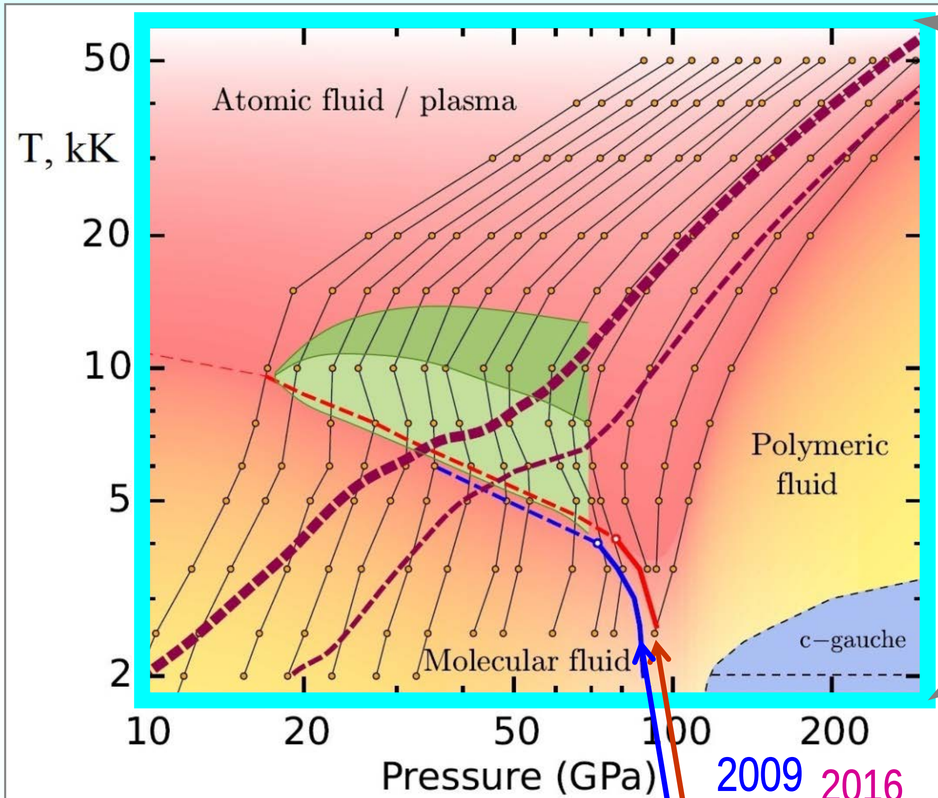


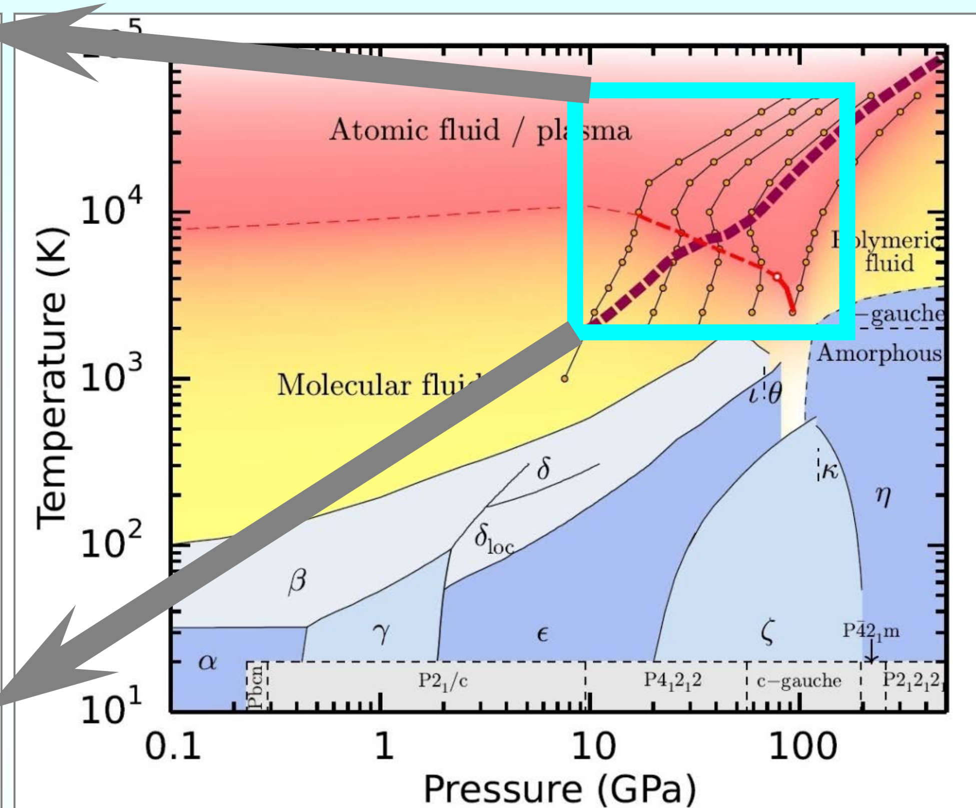
In the **vicinity** of **entropic PT** one meets **anomalous thermodynamics !**

New **boundary** exists with **zero cross derivatives** – "**Zero-Boundary**" (ZB)**!**

Phase Diagram of Warm Dense Nitrogen

(*ab initio approach*) Driver & Militzer, *Phys.Rev.B* **93** (**2016**)





Driver K.P., Militzer B.
First-Principles Equation of State Calculations of Warm Dense Nitrogen
arXiv:1601.05787

1st order *fluid-fluid* phase transition

$T_c = 4100$ K, $P_c = 78$ GPa

Liquid Hugoniot (ρ_0 = 0.808 g/cc)

Solid Hugoniot (ρ_0 = 1.035 g/cc)

Non-standard sign of $(\partial P/\partial T)_V < 0$!

Iosilevskiy / *Hirschegg-2013*

"Anomalous Thermodynamics"

$Gr \equiv (\partial P/\partial U)_P < 0$

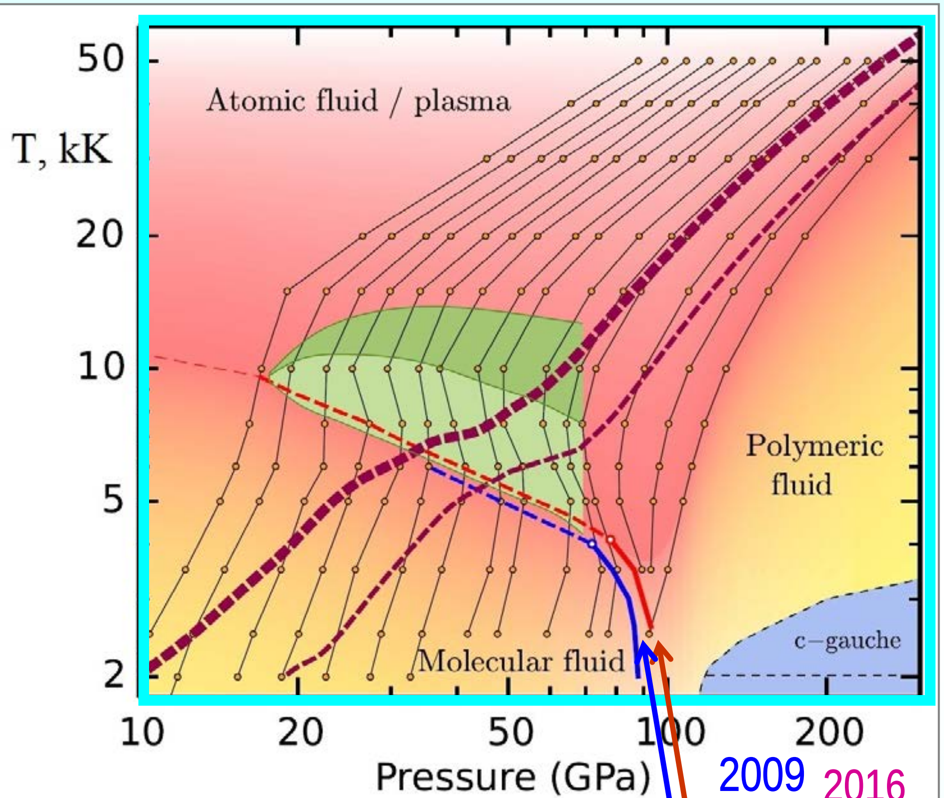
$(\partial V/\partial T)_P < 0$

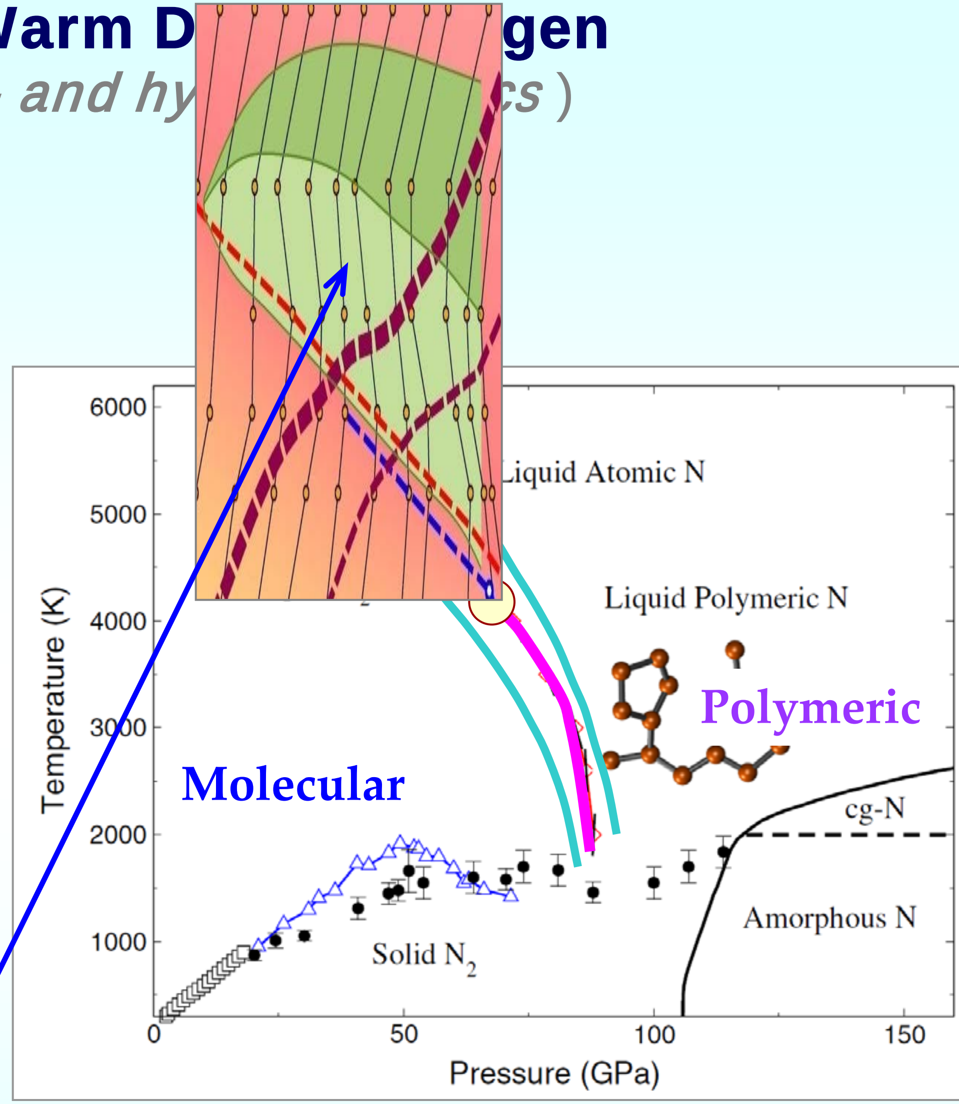
$(\partial T/\partial P)_S < 0$

arXiv:1504.0585

Phase Diagram of Warm D gen

(*anomalous thermo- and hy cs*)





(2016) 1st order *fluid-fluid* PT

(2009) $T_c \approx 400$ K, $P_c = 70$ GPa

Anomalous thermodynamics area

$(\partial P/\partial T)_V < 0$ & $(\partial T/\partial P)_S < 0$

Liquid Hugoniot (ρ_0 = 0.808 g/cc)

Solid Hugoniot (ρ_0 = 1.035 g/cc)

arXiv:1504.0585

Anomalous Thermodynamics Region – *ATR*

Normally positive cross derivatives became *negative simultaneously !*

Normal > 0

Abnormal < 0

$(\partial P/\partial T)_V \Leftrightarrow (\partial P/\partial S)_V \Leftrightarrow (\partial P/\partial U)_V$

$\Updownarrow$

$(\partial V/\partial T)_P \Leftrightarrow (\partial V/\partial S)_P \Leftrightarrow (\partial V/\partial H)_P$

$\Updownarrow$

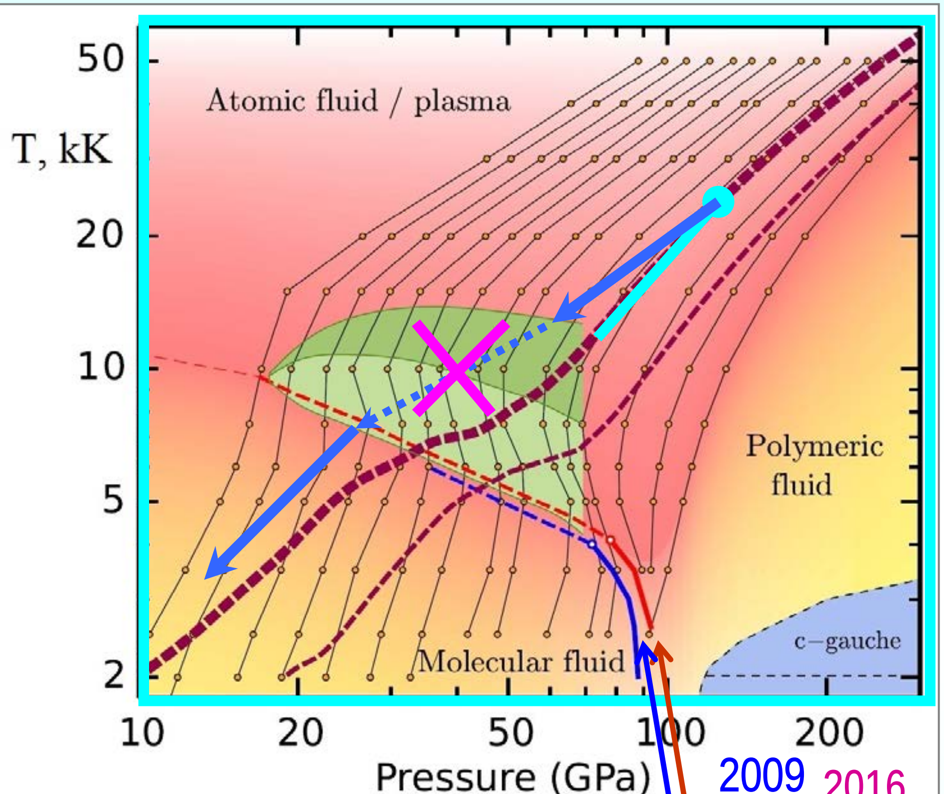
$(\partial S/\partial V)_T \Leftrightarrow (-\partial S/\partial P)_T \Leftrightarrow (\partial T/\partial P)_S \Leftrightarrow (-\partial T/\partial V)_S$

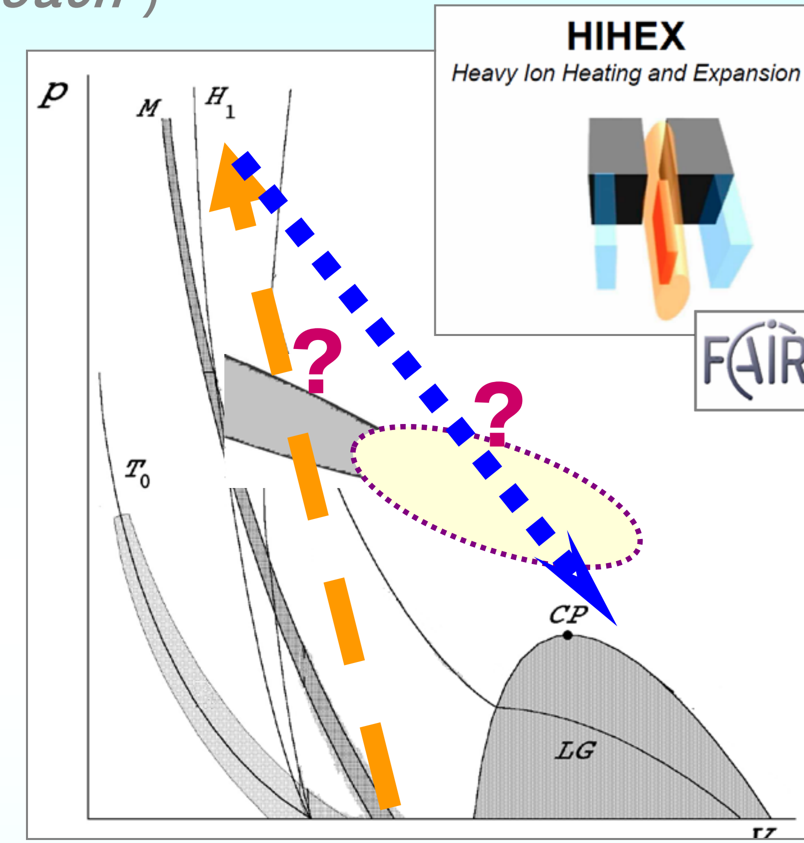
$(\partial P/\partial U)_V$ - thermodynamic Gruneizen parameter, $\mathrm{Gr} \equiv V(\partial P/\partial U)_V$

$(\partial V/\partial T)_P$ – thermal expansion parameter, $\alpha_T \equiv V^{-1}(\partial V/\partial T)_P$

Anomalies in Isentropic Expansion of Warm Dense Nitrogen

(*ab initio approach*)





Shock compression +
+ isentropic expansion

1st order *fluid-fluid* phase transition
$T_c = 4100$ K, $P_c = 78$ GPa

Liquid Hugoniot (ρ_0 = 0.808 g/cc)
Solid Hugoniot (ρ_0 = 1.035 g/cc)

Non-standard sign of $(\partial P/\partial T)_V < 0$ **!**

Iosilevskiy / *Hirschegg-2013*
"Anomalous Thermodynamics"

$(\partial T/\partial P)_S < 0$

arXiv:1504.0585

NB !

Nontrivial hydrodynamics of coming through the zone of anomalous thermodynamics of entropic phase transition

Нетривиальная гидродинамика прохождения сквозь зоны аномальной термодинамики энтропийного фазового перехода

Outlook-I

Inventory of hypothetical terrestrial phase transitions in real and "numerical" experiments and in modeling constructions:

Path Integral + MC , Density Functional Theory + MD, Wave-Packets +MD,…

Hydrodynamic features for adiabatic flow in matter with anomalous thermodynamics $(Gr < 0, \ldots)$

Topology of phase boundaries in meeting point of entropic phase transitions *(triple point, quadruple point etc.)*

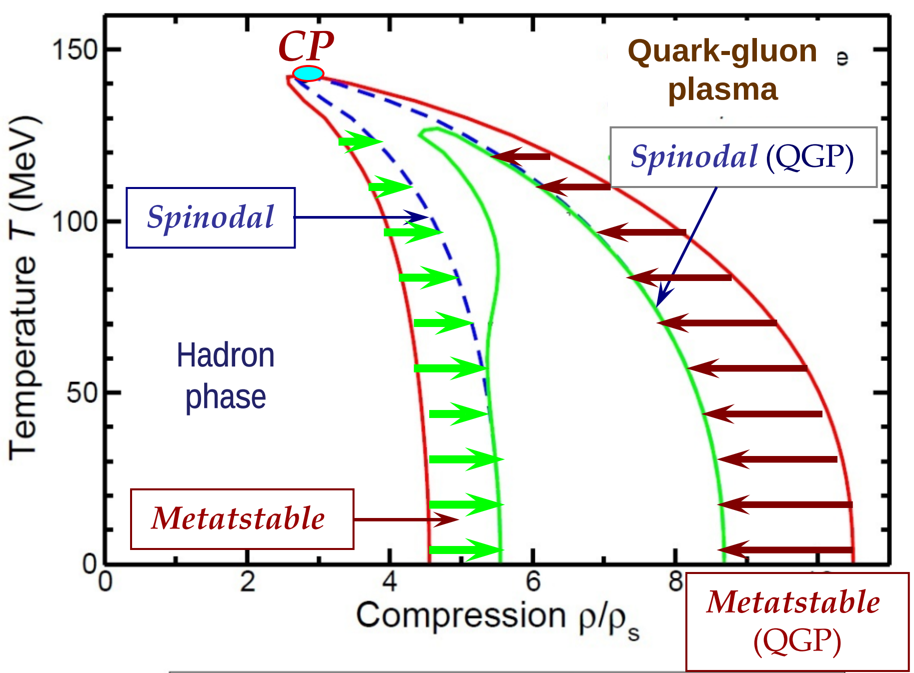
Entropic phase transitions at the "cold curve" (*isotherm* $T = 0$)

Non-congruentness and entropic phase transitions ?

Anomalous topology *of* binodals *and* spinodals *in the two-phase region of* entropic phase transition (T - ρ diagram)

Model of Quark-Hadron Phase Transition

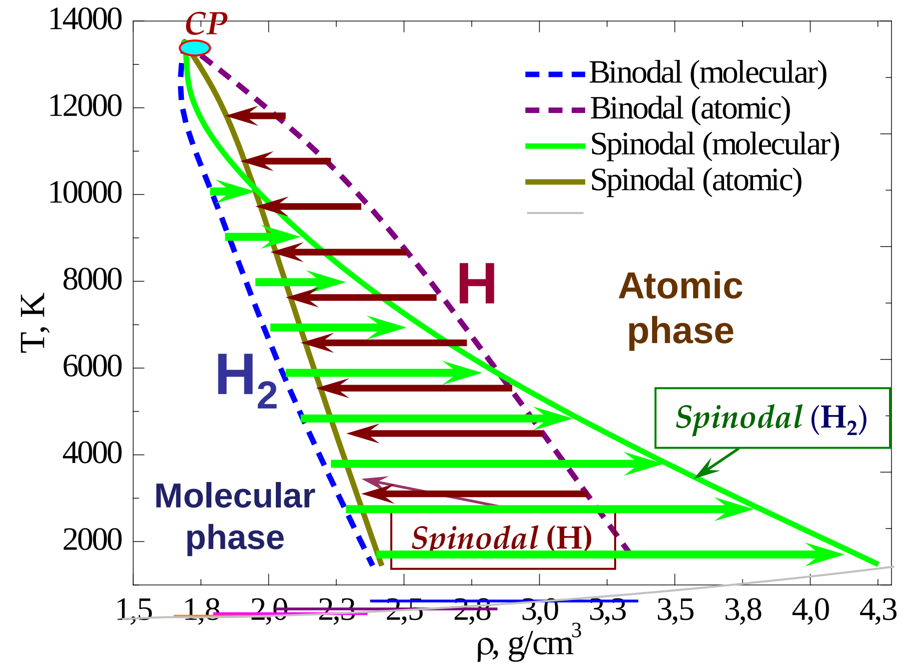
Jorgen Randrup, *Int. Conf.* CPOD-2010 (Dubna)



VdW-like structure of **metastable zones**

Dissociation-driven phase transition in hydrogen

Code SAHA-D
Gryaznov V., Iosilevskiy I. // *J. Phys. A*, **42** (2009)



"**Night bat**" structure of metastable "**wings**"

NB !

Two competing variants of structure of stable and metastable regions in quark-hadron phase transition

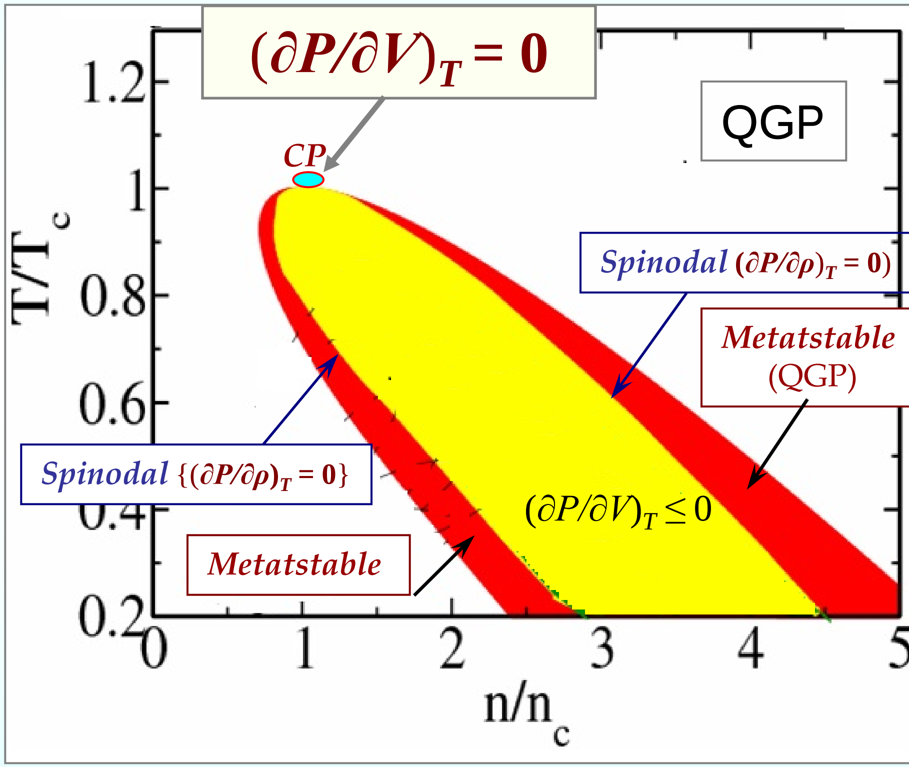
Anomalous features *of* entropic phase transition

(*due to* **multi-layered structure** *of* **thermodynamic surfaces !**)

(T - ρ diagram)

Quark-Hadron Phase Transition

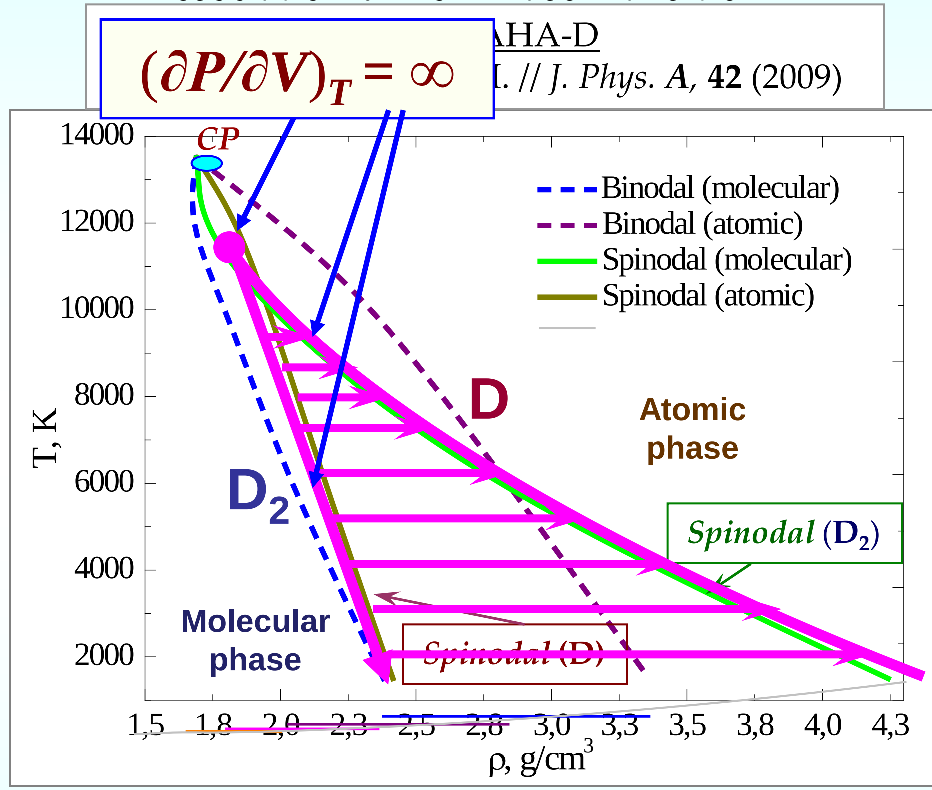
After Vladimir Skokov, *Int. Conf.* "Prerow-2009"



Dissociation-driven Phase Transition

…HA-D

…I. // *J. Phys. A*, **42** (2009)



NB !

New (additional) region of metastable state ⇔ $(\partial P/\partial V)_T \leq 0$

New (additional) singular point *(no-named still)* ⇔ $(\partial P/\partial V)_T = \infty$ **!**

{ Iosilevskiy I. // (*in preparation*) }

Enthalpic and entropic phase transitions: And what ?

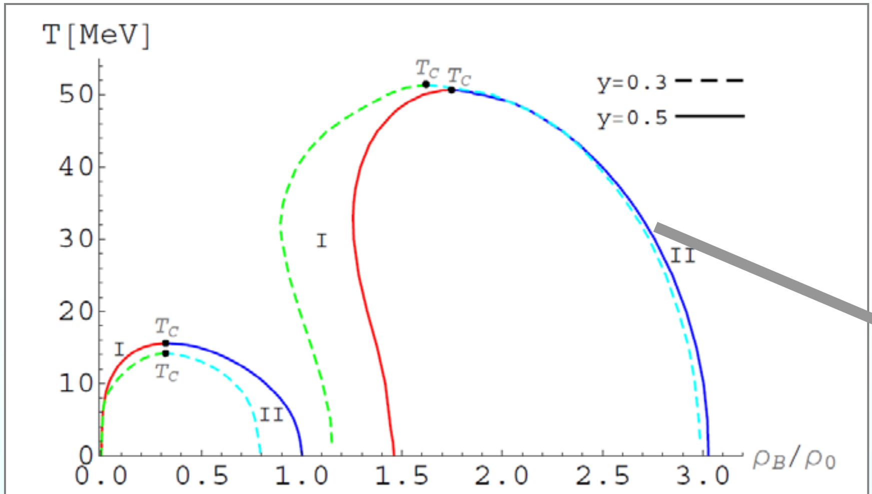
Outlook-II

Inventory of new phase transitions in simplified models

Example

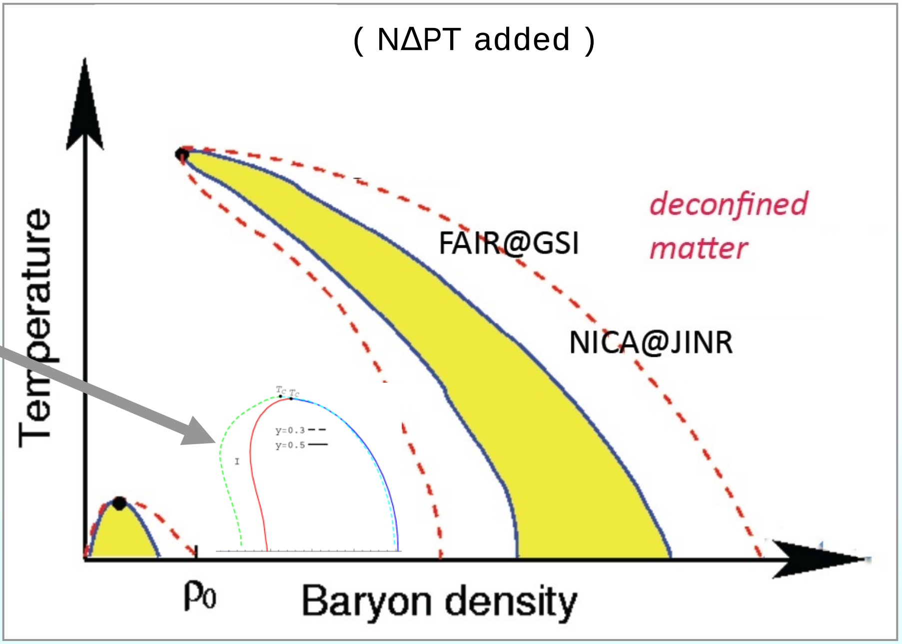
Liquid-gas and hypothetical nucleon ⇔ Δ-matter phase transitions

Lavagno & Pigato // arXiv:1210.0400 (2012)



Phase diagram of the liquid-gas and the nucleon-Δ matter phase transition for $y = 0.3$ (dashed curves) and $y = 0.5$ (continuous curves).

Jorgen Randrup, *Int. Conf.* "CPOD-2010 /Dubna, Russia

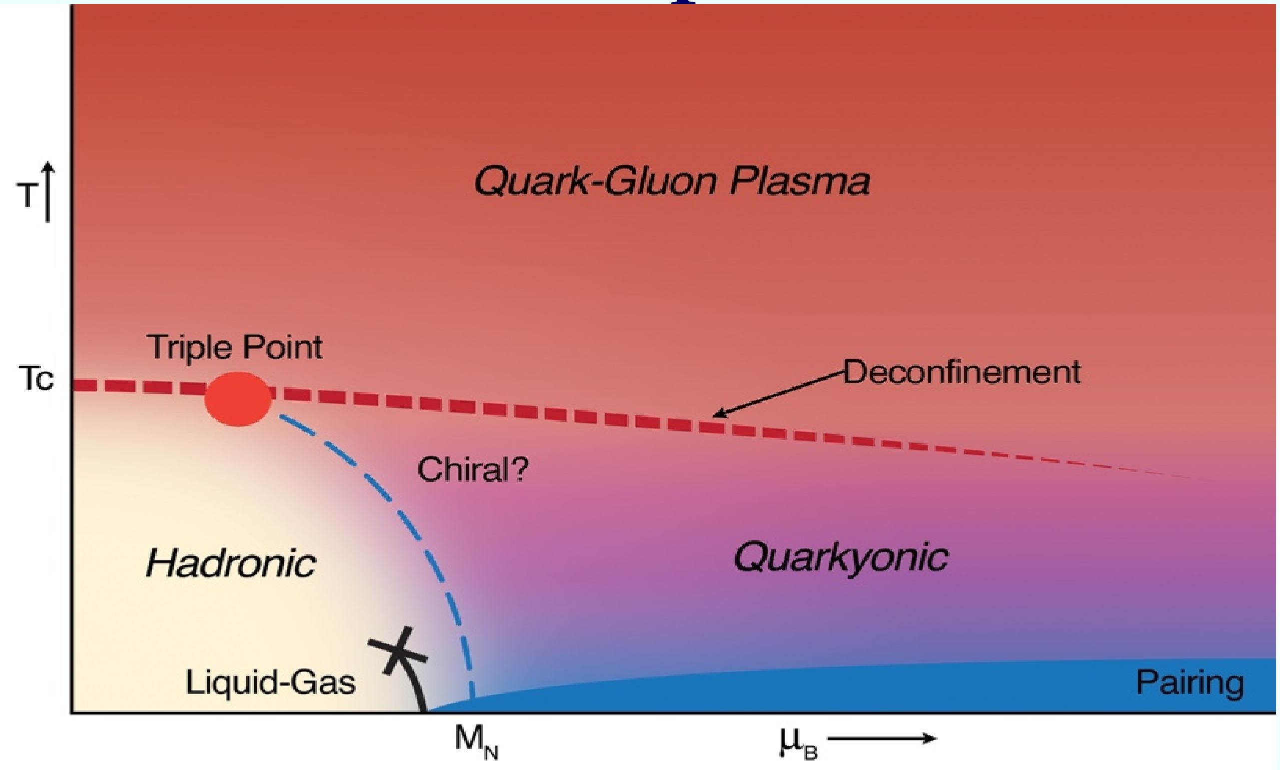


What is the type of this new phase transition: - enthalpic *or* entropic ?

Outlook-III

Inventory of new hypothetical phase transitions

Example-II



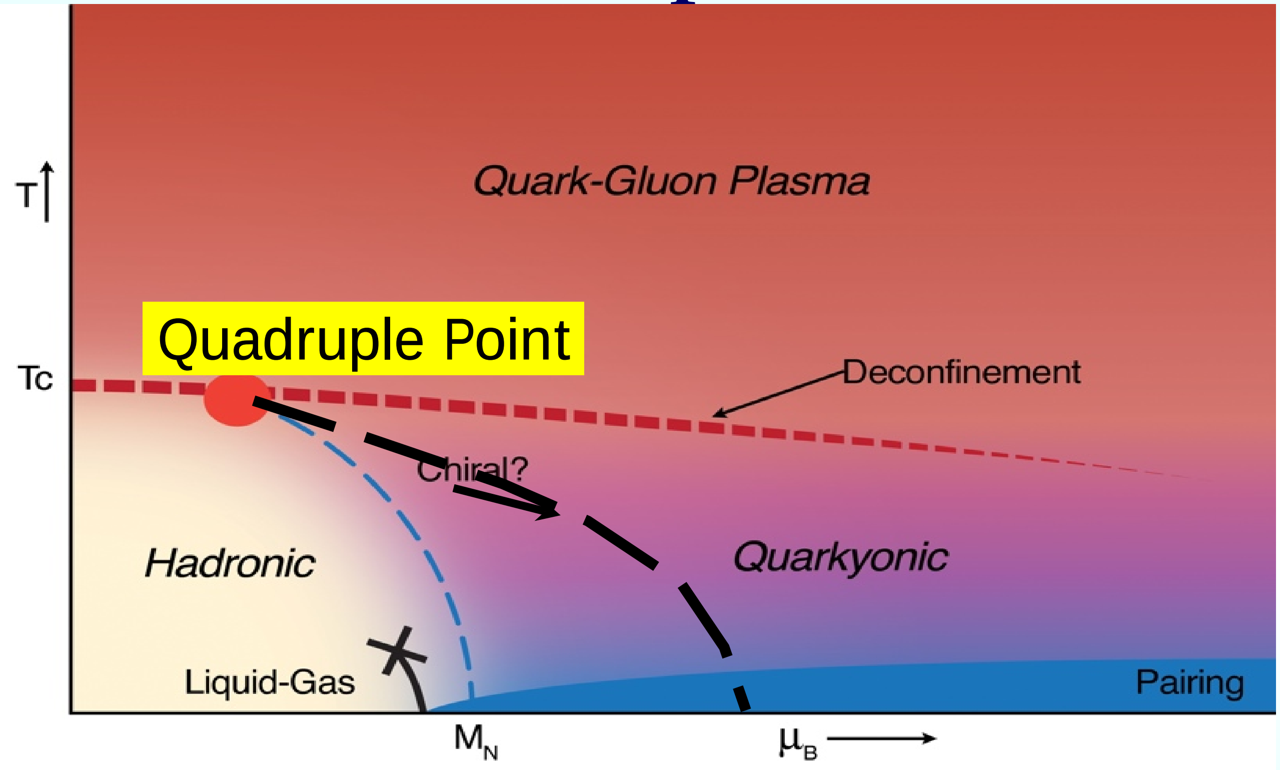
R.Pisarski & L.McLerran, EMMI (Wroclaw) /2009/, QCD (Bad Honnef) /2010/

What is the type of all these hypothetical phase transitions:
- Are they enthalpic or entropic?

Outlook-III

Inventory of new hypothetical phase transitions

Example-II

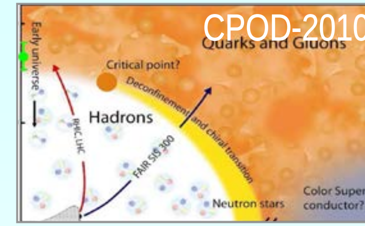


R.Pisarski & L.McLerran, EMMI-Wroclaw /2009/, QCD-Bad Honnef /2010/

What is the type of all these hypothetical phase transitions:
- Are they enthalpic or entropic?

Helmholtz International Summer School // Dubna, Russia, July ***2017***

Nuclear Theory and Astrophysical Applications



Conclusions *and* perspectives

- **Visible equivalence** of **gas-liquid-like** and **quark-hadron phase transitions**
- in high energy density nuclear matter **is illusive**.

- Both phase transitions belong to **fundamentally different classes**:
- **Gas-Liquid PT** is **enthalpic**, while **Quark-Hadron PT** is **entropic**.

- **In spite of** many order **difference** in density and energy of **deconfinement-driven PT** and **ionization-driven PT** (dissociation-driven, polimerization-driven *etc*.) they have many **common features** because both are **entropic** PTs.

- **Properties** of **entropic PTs differ significantly** from those of **enthalpic PTs**.

- **Entropic phase transitions** are always accompanied with existence of region with **anomalous thermodynamic properties** $\{(\partial P/\partial T)_V < 0,\ V(\partial P/\partial U)_V < 0\ \ (\partial P/\partial S)_V < 0,\ \ (\partial V/\partial T)_P < 0 \ldots\}$

- **Anomalous** features of **entropic phase transition** are due to **multi-layered structure** *of* **thermodynamic surfaces** $\{U(p,V),\ T(p,V),\ S(p,V)\}$

What should we classify when we meet unexplored phase transition -?

1st *or* **2nd order ?**

Isostructural *or* **non-isostructural ?**

Congruent *or* **non-congruent ?**

Enthalpic *or* **entropic ?**

Do we use **Coulomb-less approximation** *or* we take into account all consequences *of* **long-range nature** *of* **Coulomb** interaction **?**

Scenario *of* **phase transformation** *in* **two-phase region** –

– **Macro-** *or* **Mesoscopic ?**

Неконгруэнтное испарение в U-O системе

(*Совместное фазовое, ионизационное и химическое равновесие согласно условиям Гиббса – Гугенхейма*)

Диаграмма давление - плотность

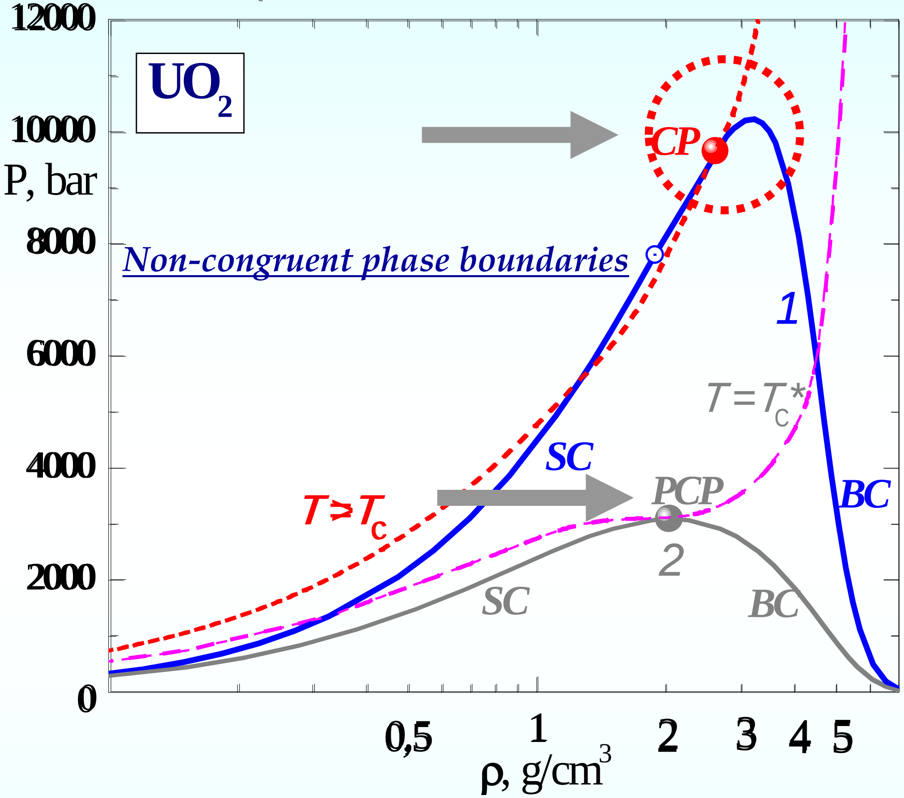
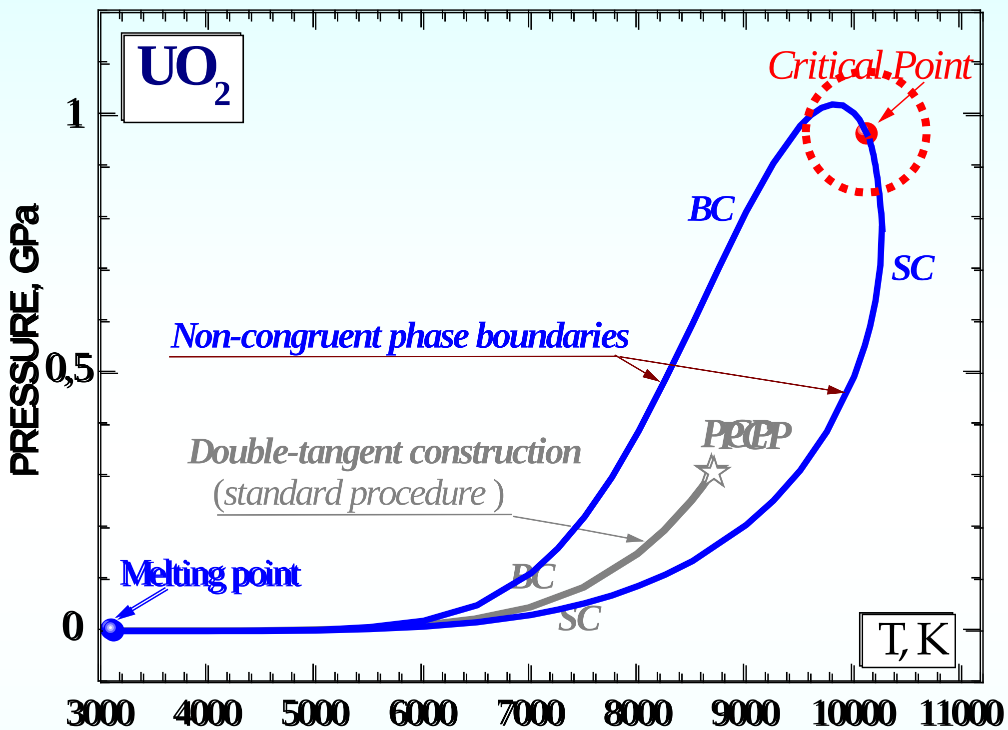


Диаграмма давление - температура



1 – Неконгруэнтное (полное) равновесие

2 – Принудительно-конгруэнтное равновесие

BC – Граница кипения жидкости

SC – Граница насыщения пара

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

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)

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

Equilibrium reactions

$ab \Leftrightarrow a + b$

(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 are not equal (*Guggenheim, 1929*)

Galvani potential

Electro-chemical potentials are equal

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

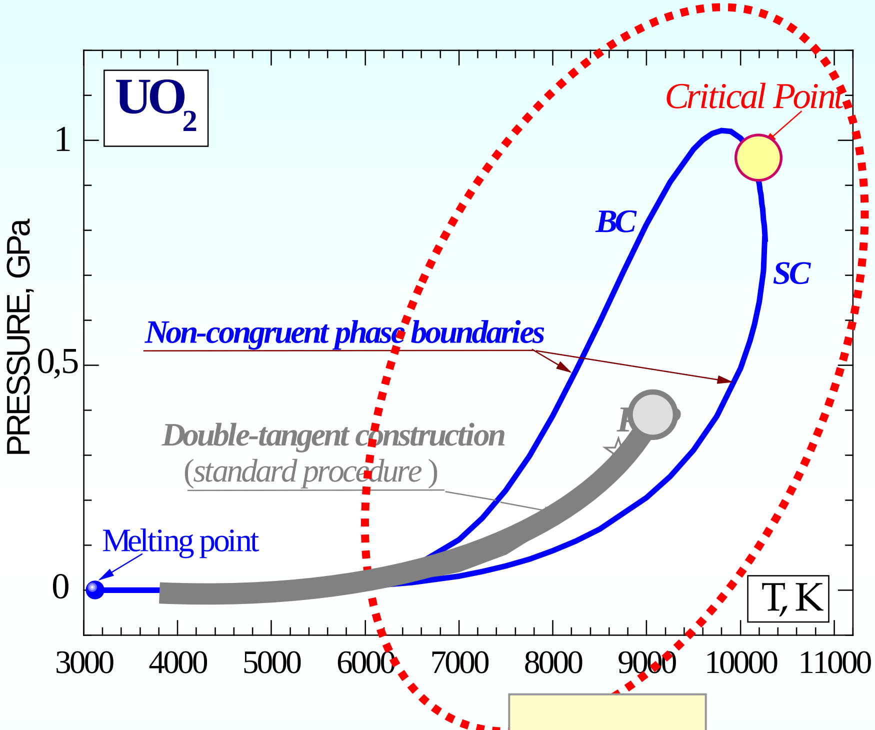
Potential drop at mean-phase interface in equilibrium Coulomb system

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

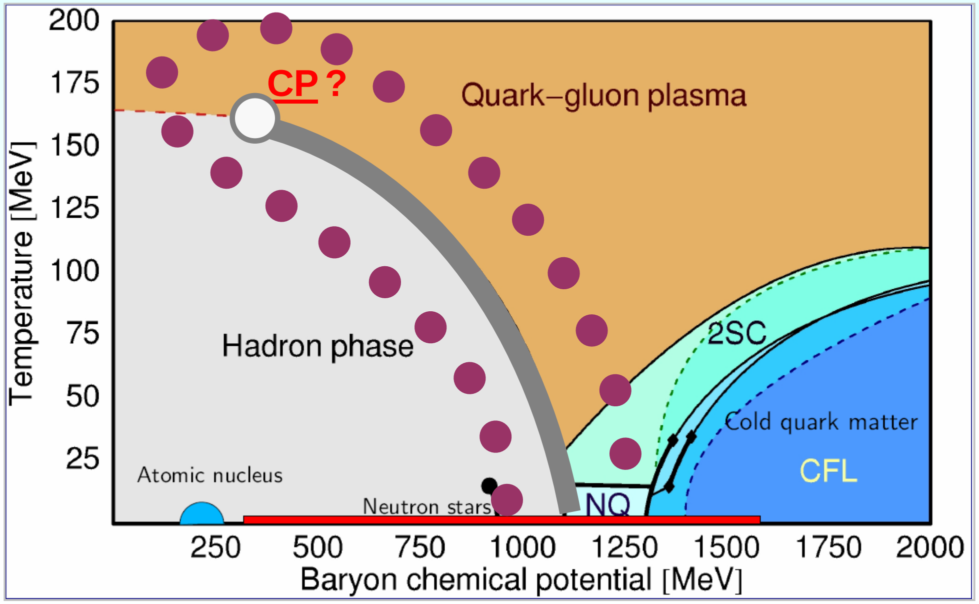
see for example : Iosilevskiy I., *Encyclopedia on Low-T Plasmas.* III-1 (Suppl) **2004**

Hypothetical phase transitions in ultra-dense matter:

are they CONGRUENT or NON-CONGRUENT ?



Phase diagram of quark-hadron matter



?

- Forced-congruent phase transition

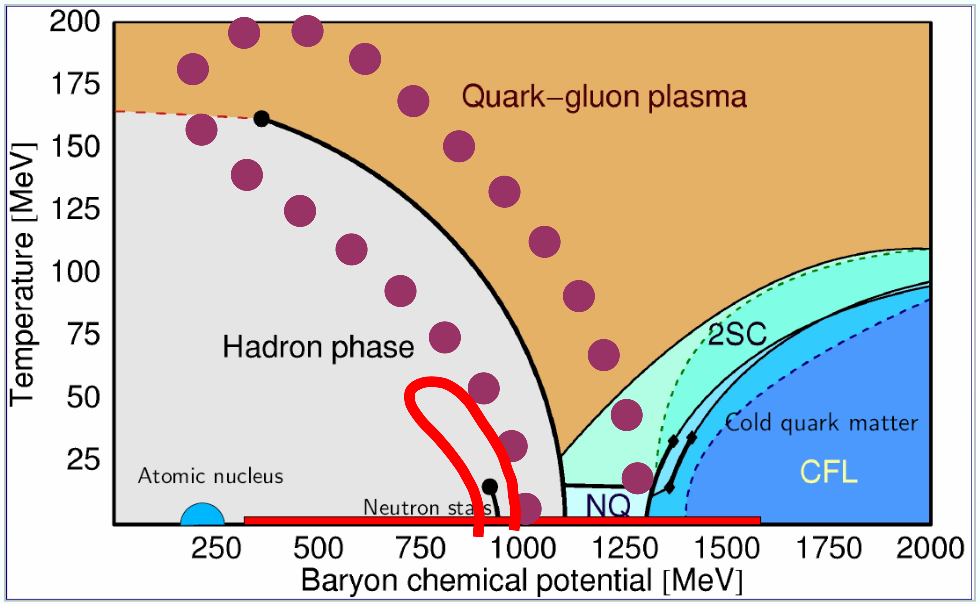
- Non-congruent phase transition

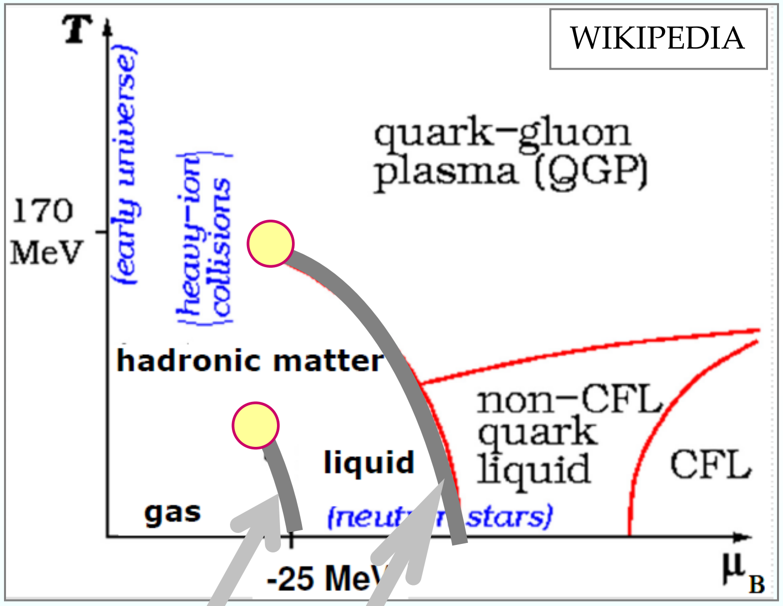
Iosilevskiy I. / Int. Conf. "***Physics of Neutron Stars***", St.-Pb. Russia, 2008
Int. Congress "***Plasma Physics***", Fukuoka, Japan, 2008
Int. Conf. "***Critical Point*** *and* ***Onset of Deconfinement***", JINR, Dubna, Russia, (2009)
Acta Phys. Polonica B (Proc. Suppl.) **3,** 589 (2010)

Non-congruence in exotic situations

(*discussion*)

Non-congruent phase transitions
in compact stars *and* supernova explosions





"Gas-liquid" phase transition in dense nuclear matter

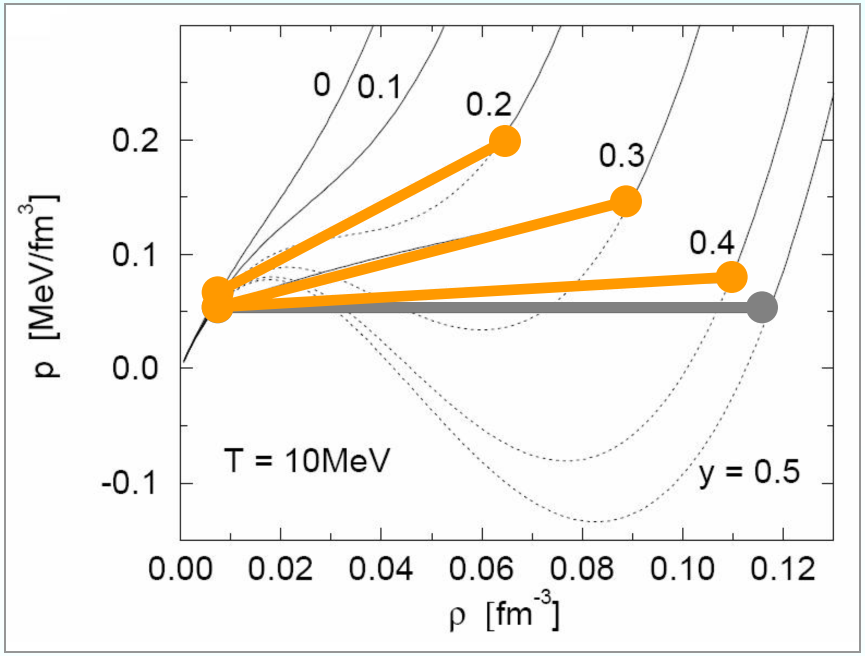
$\{p, n, N(A,Z)\}$

Quark-hadron phase transition /QHPT/

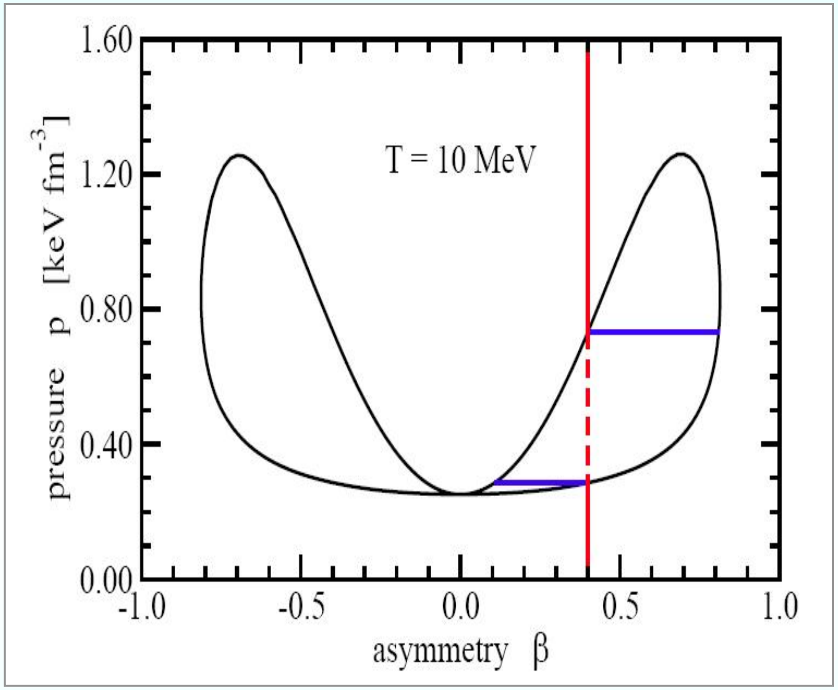
Iosilevskiy I. // EMMI Workshop - Max Born Symposium, Wroclaw, 2009 // arXiv:1005.4192

Typical features of non-congruency for "gas-liquid" phase transition in asymmetric nuclear matter of "low density" are well known

(see e.g. Muller & Serot /1995/)



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



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

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

Phase transition in ***symmetric*** *p-n-N(A,Z) system* is ***congruent*** (azeotropic) **!**

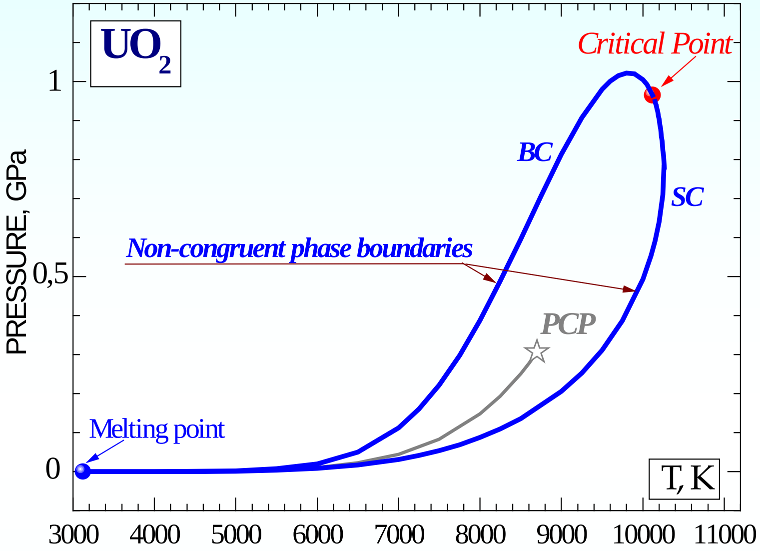
ILI, S. Typel M. Hempel *et al.* ***Non-congruence of "gas-liquid" phase transition in asymmetric nuclear matter*** (*in progress*)

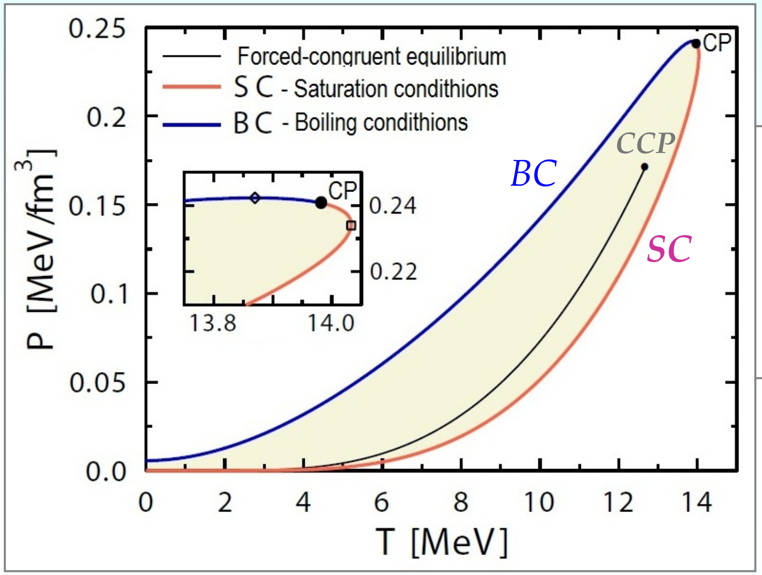
(*) EOS – Typel S., Roepke G., Klahn T., Blaschke D. and Wolter H., *Phys. Rev. C*, **81**, 015803 (2010)

Non-congruent GLPT in asymmetric nuclear matter

(*banana-like pressure - temperature diagram*)

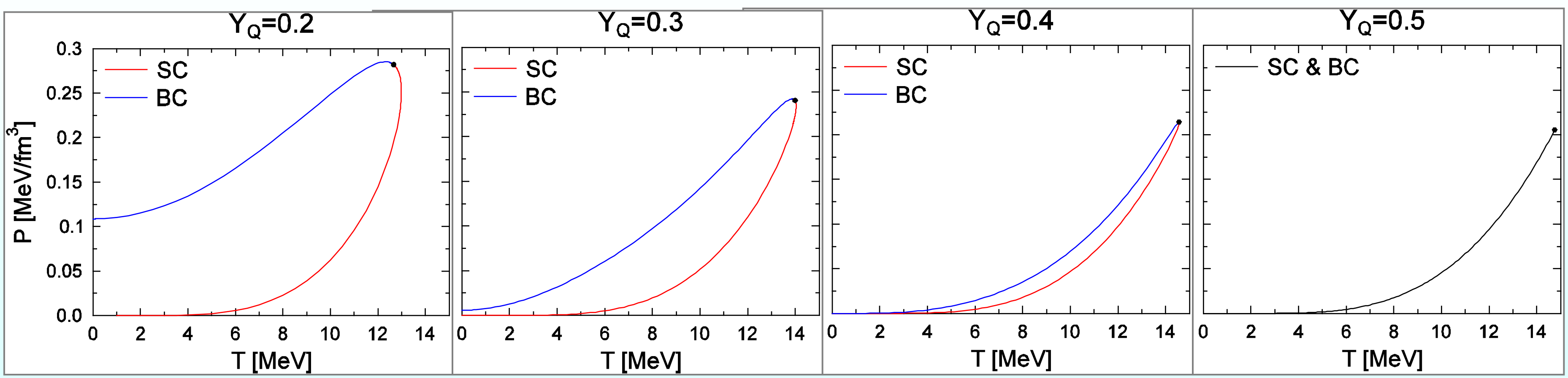
Hempel M., Dexheimer V., Schramm S. and Iosilevskiy I., *Phys. Rev. C* **88** (2013)





Y = 0.3

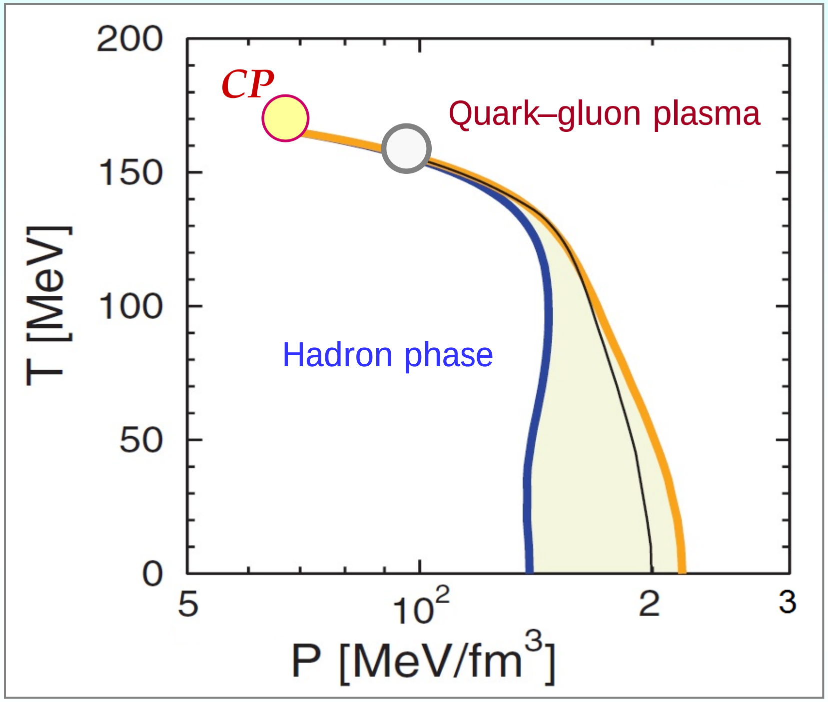
$Y \equiv$ proton fraction in $\{p,n,N(A,Z)\}$ system



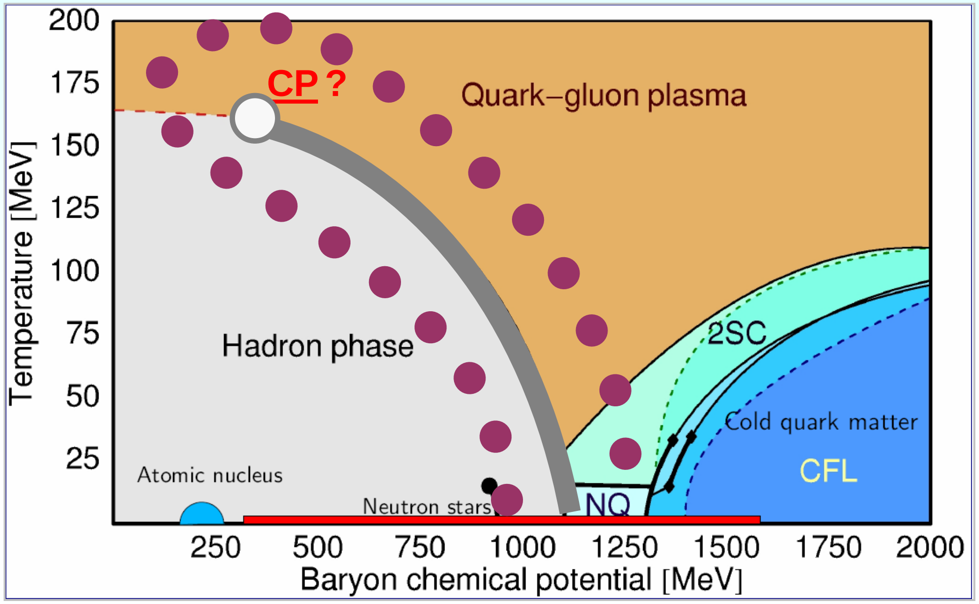
M. Hempel (supplement to: *Phys. Rev. C*, **88** (2013)) / arXiv:1302.2835

Y = **0.5** – azeotropic comp.

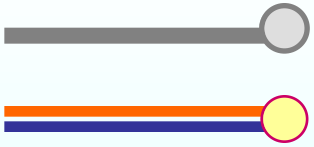
Hypothetical phase transitions in ultra-dense matter:
are they CONGRUENT or NON-CONGRUENT ?



Phase diagram of quark-hadron matter



Yes



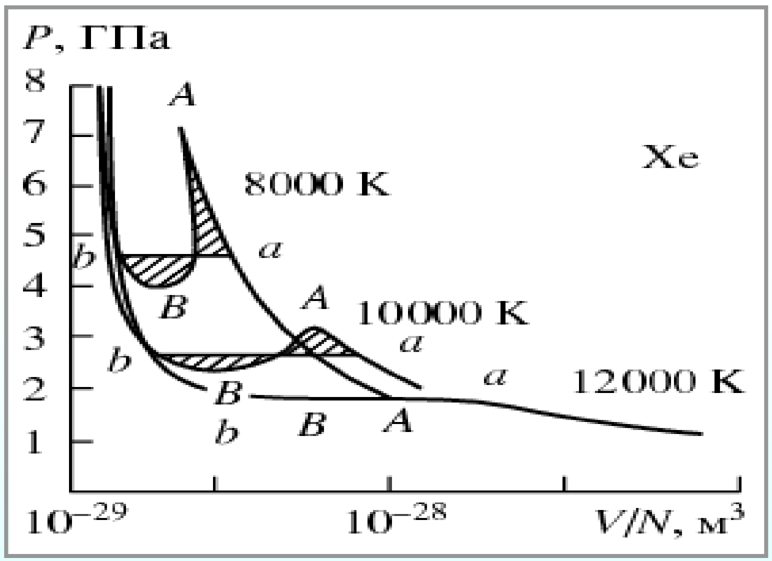
- Forced-congruent phase transition
- Non-congruent phase transition

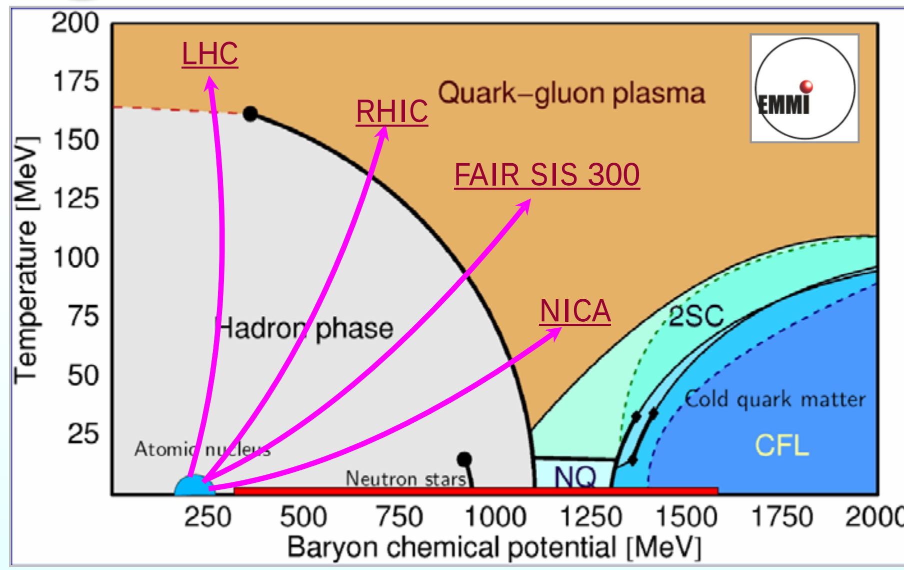
Iosilevskiy I. / Int. Conf. "***Physics of Neutron Stars***", St.-Pb. Russia, 2008 // Int. Conf. "***Critical Point** and **Onset of Deconfinement***", JINR, Dubna, Russia, 2010 //*Acta Physica Polonica B (Proc. Suppl.)* **3,** 589 (2010)

Hempel M., Dexheimer V., Schramm S. and Iosilevskiy I. // *Non-congruence of the nuclear liquid-gas and the deconfinement phase transitions* // *Phys. Rev. C* **88**, 014906 (2013) // arXiv:1302.2835

Features *of* **entropic phase transitions** *in* **cosmic matter** *and in the* **laboratory**

Thank you!





Support: RFBR 16-02-01179,
RAS Scientific Program "Physics of Extreme States of Matter"
Extreme Matter Institute – EMMI

Acknowledgements to **Victor Gryaznov** for calculations of **dissociation phase transition** in **hydrogen**

EQUATIONS OF STATE FOR MATTER

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