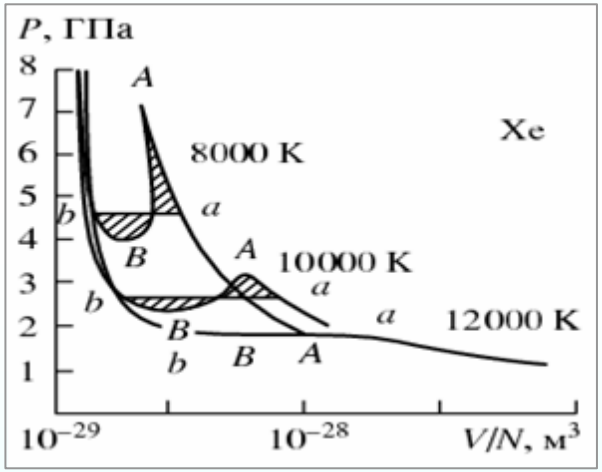
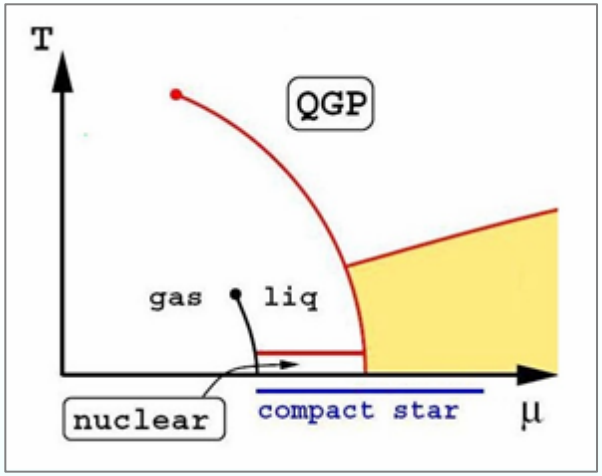
Strangeness in Quark Matter
6-11 July 2015, Dubna, Russia

Entropic *and* Enthalpic Phase Transitions

in high energy density matter





Igor Iosilevskiy

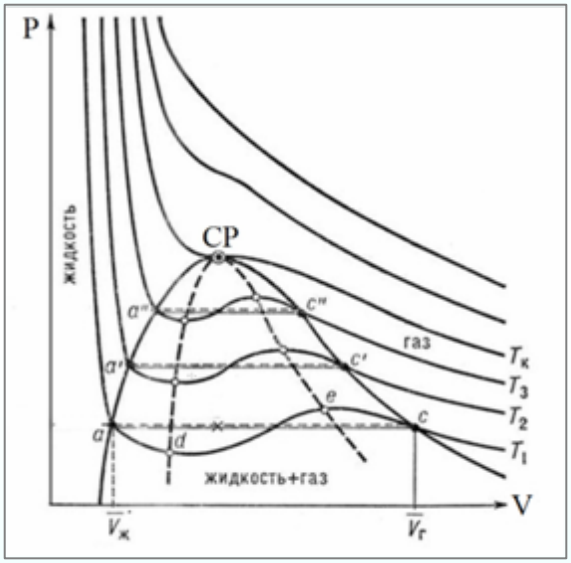
Joint Institute for High Temperature (Russian Academy of Science)
Moscow Institute of Physics and Technology (Federal Research University)

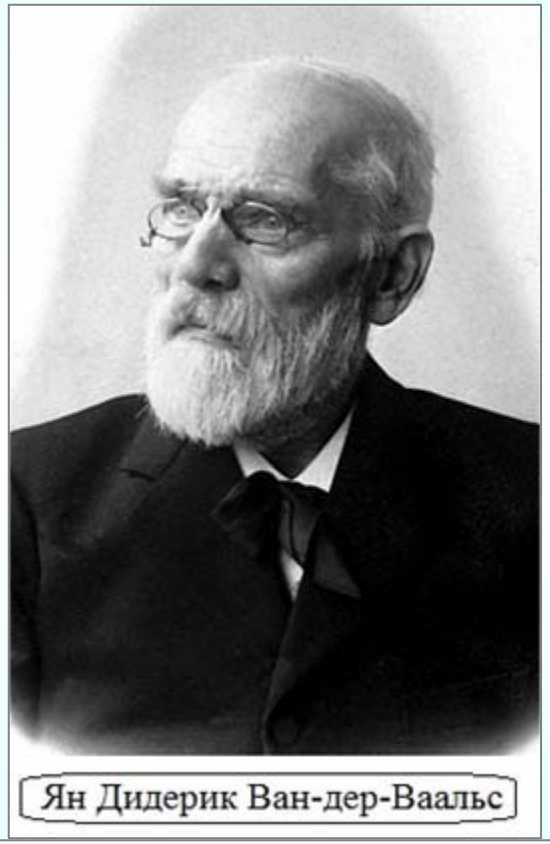
arXiv:1403.8053

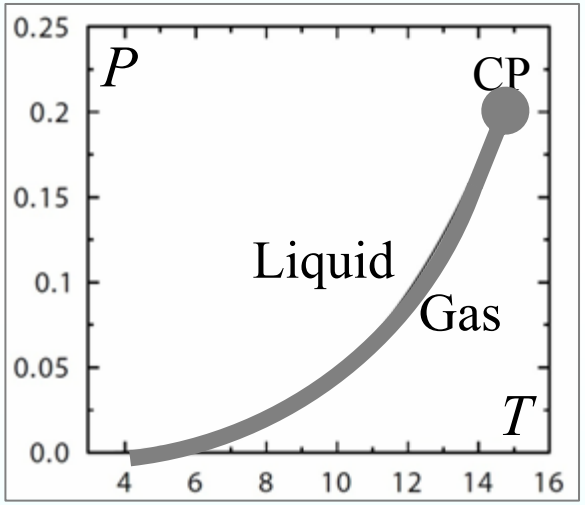
arXiv:1504.058050

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

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




Ян Дидерик Ван-дер-Ваальс



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

142 years

Debye – Hückel non-ideality correction

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

Peter Debye

Erich Hückel

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

NB!

$$\Gamma_D = 4$$

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

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

(1923)

92 years

Phase transitions *of* 1^{st} *and* 2^{nd} order

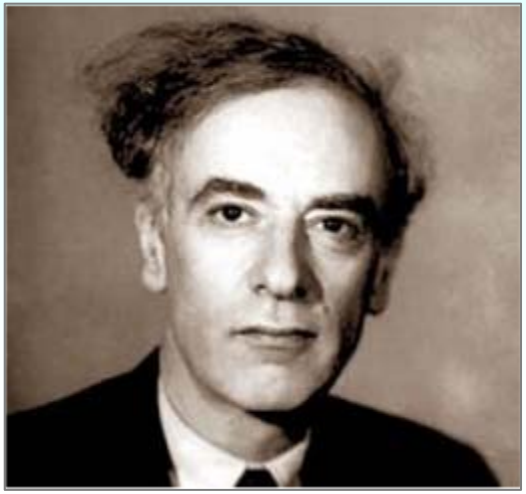
Пауль Эренфест
(1880 - 1933)

82 years

1^{st}- and 2^{nd}-order phase transitions
(1933)

Hypothesis *on* 1st order phase transition
"dielectric-conductor" *in* metals

(1943)

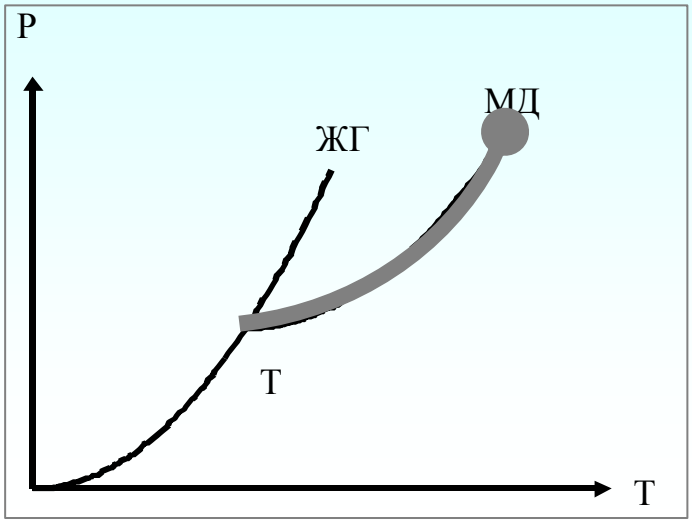


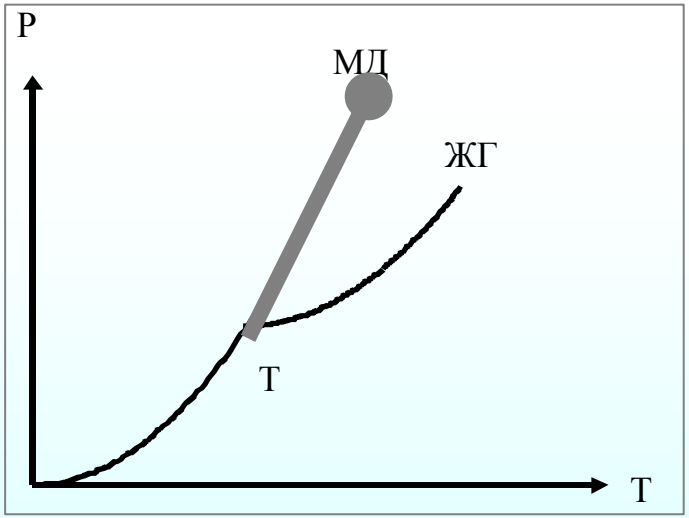
Lev Landau

Yakob Zel'dovich

(1914 - 1987)

72 years





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

“Plasma” phase transitions theory

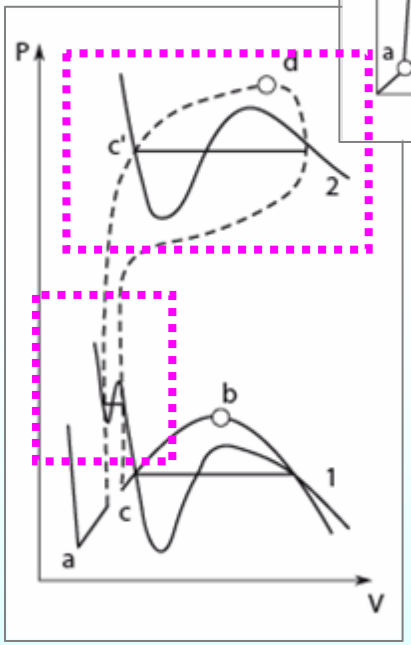
(Coulomb attraction + quantum repulsion)

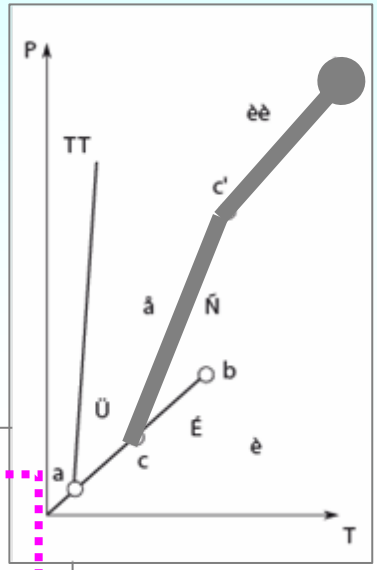
(1968-1970)

Andrew Starostin

45 yaers

Henry Norman





Norman H., Starostin A. *High Temperature*, **6**, 410 (1968)
Plasma phase transitions

When one meets unexplored phase transition:
- what should he classify ?

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

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

Enthalpic *or* **entropic ?**

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

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** –

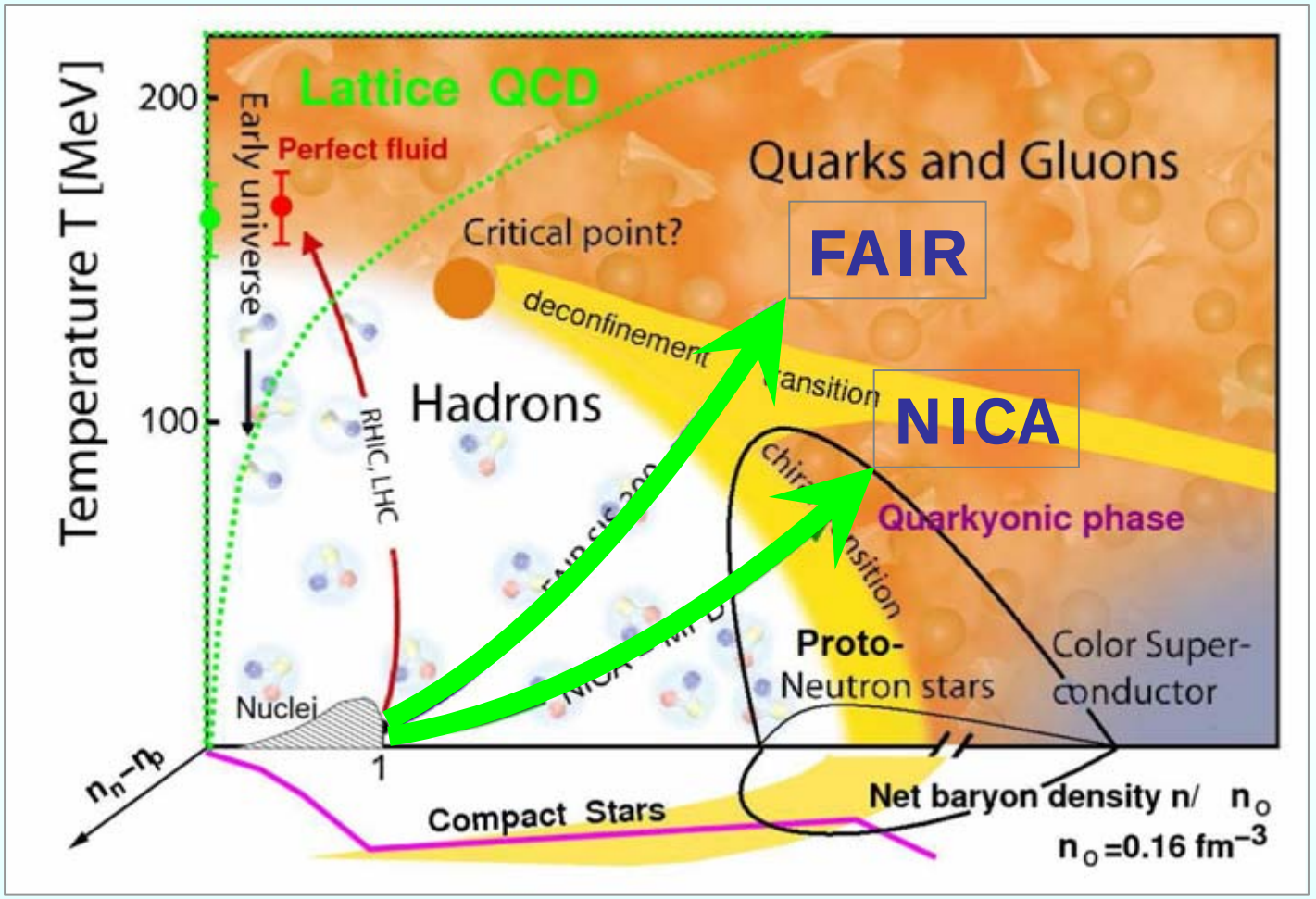
– **Macro-** *or* **Mesoscopic ?**

Phase transitions *in* high energy density nuclear matter

Enthalpic *or* **Entropic**

?

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

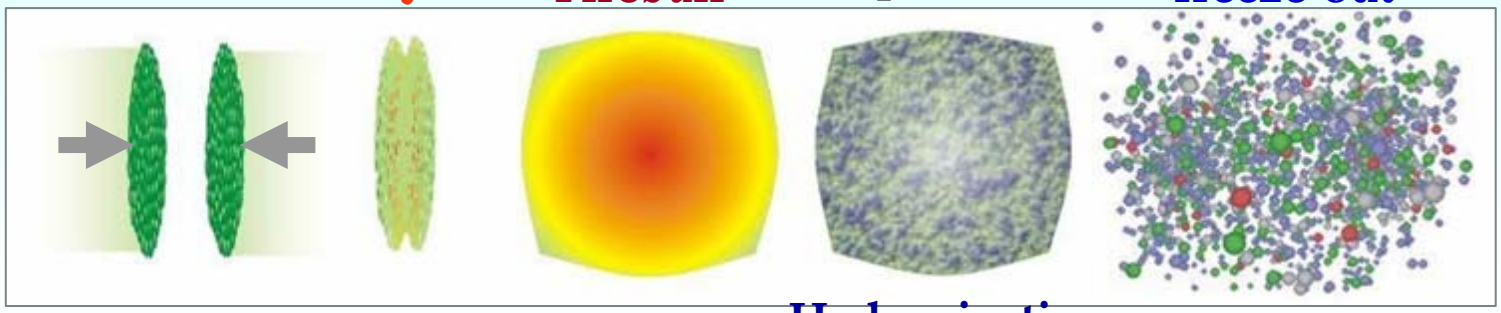


NICA White Book

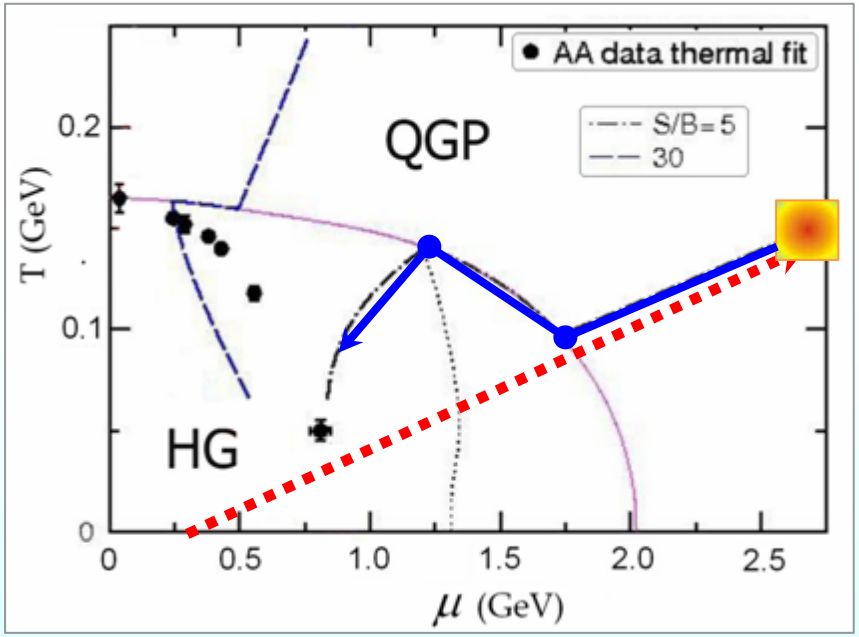
After David Blaschke, *NICA Workshop, Dubna,* 2009

Impact *and* fireball hydrodynamics *in* RHIC

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

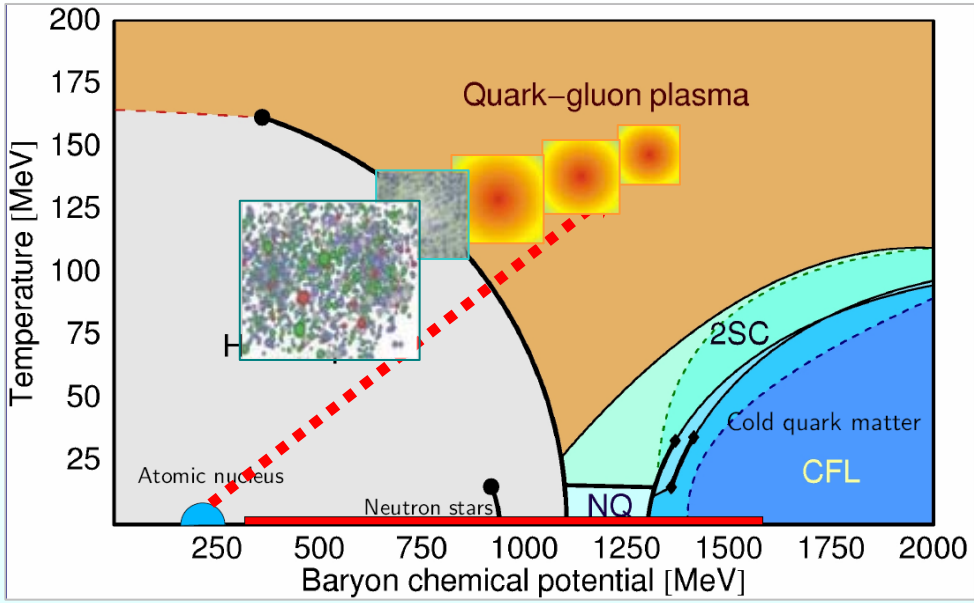


Hadronization



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

Shock adiabat of Renkine-Hugoniot-Taub

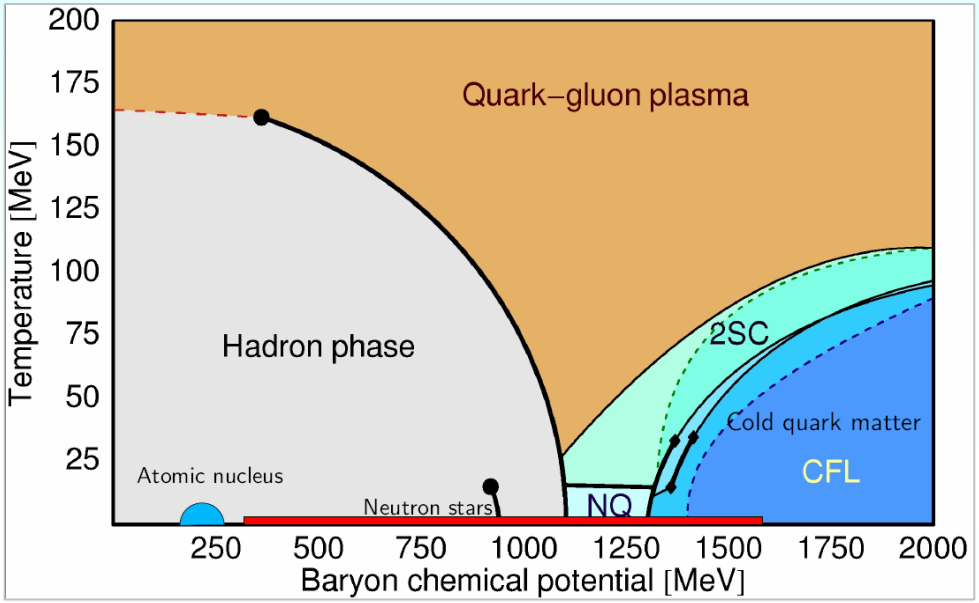


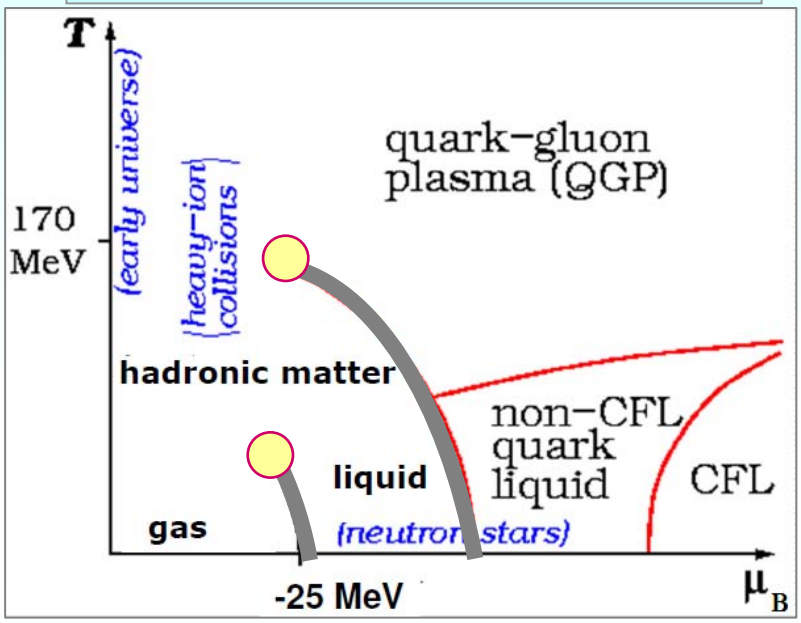
Widely accepted phase diagram of matter

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

Phase transitions in matter of ultra-high energy and density

(*schematic*)

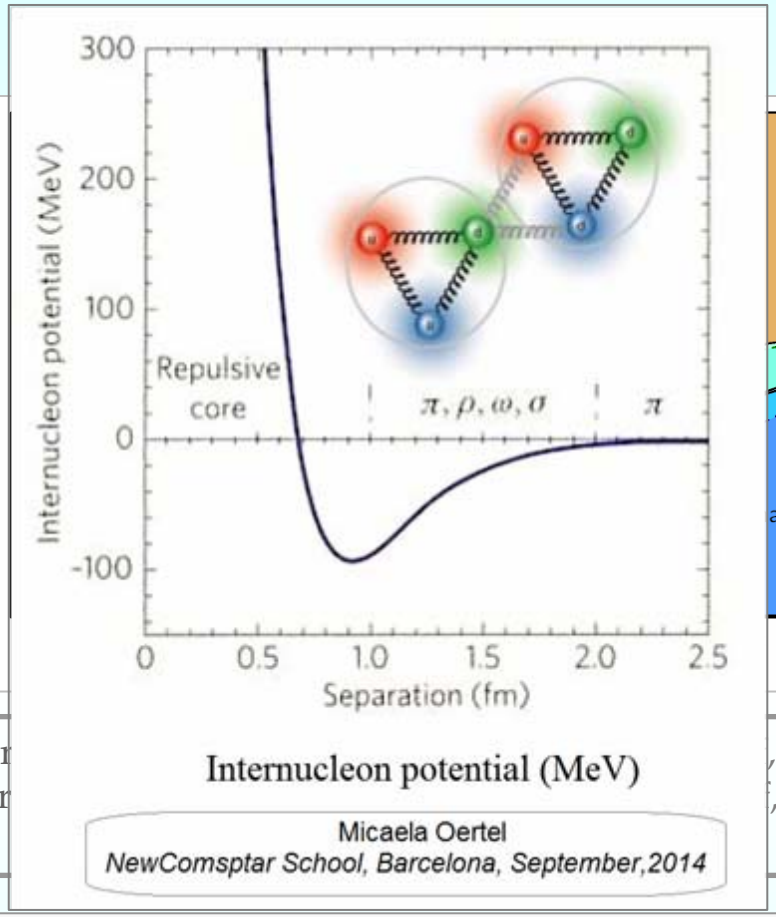




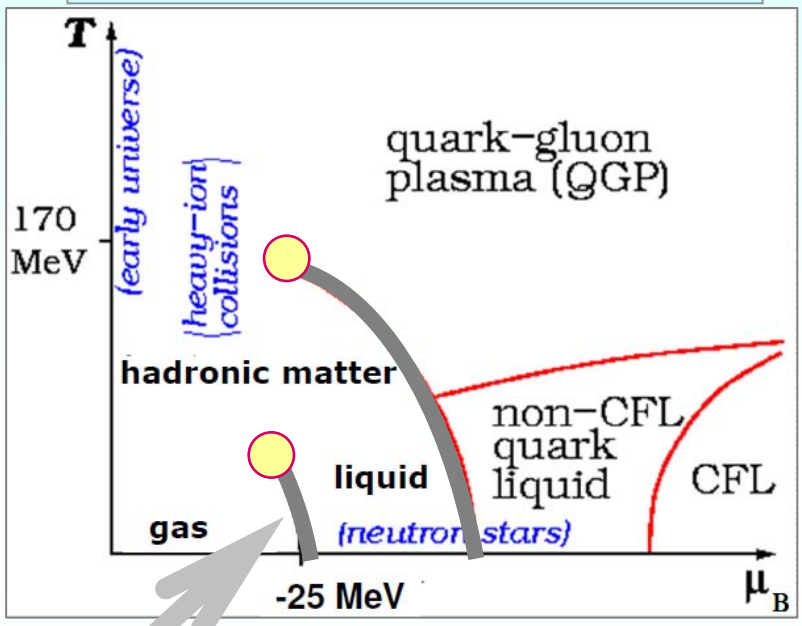
After Fridolin Weber, WEHS Seminar, Bad Honnef, 2006
After David Blaschke, WEHS Seminar, Bad Honnef, 2007
……..

Source: WIKIPEDIA

Phase transitions in matter of ultra-high energy and density



(*schematic*)

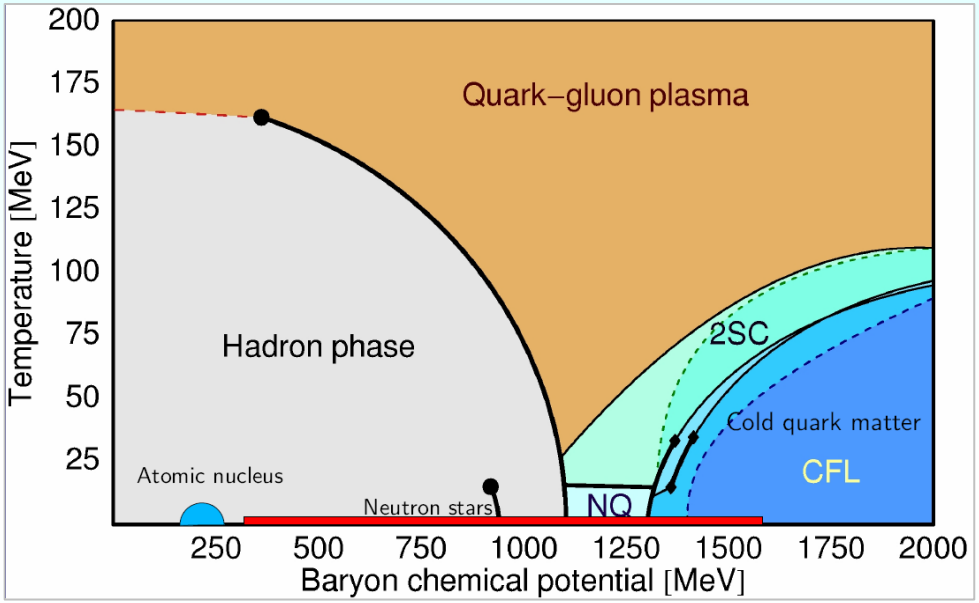


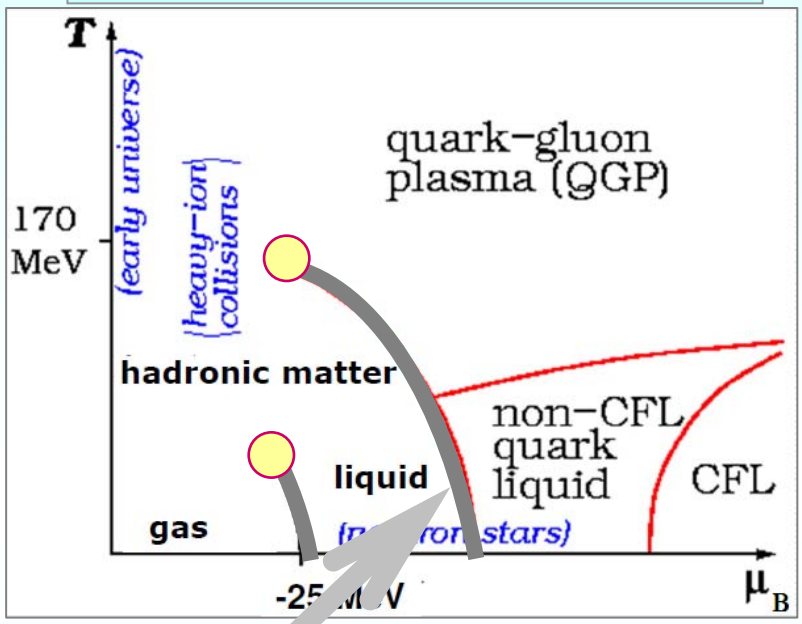
Source: WIKIPEDIA

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

Phase transitions in matter of ultra-high energy and density

(*schematic*)





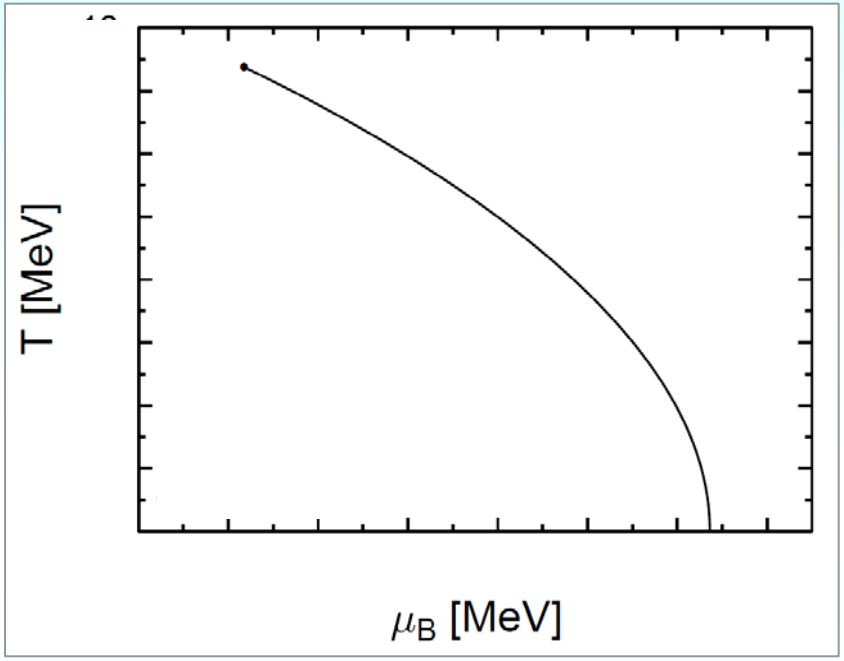
After Fridolin Weber, WEHS Seminar, Bad Honnef, 2006
After David Blaschke, WEHS Seminar, Bad Honnef, 2007
……..

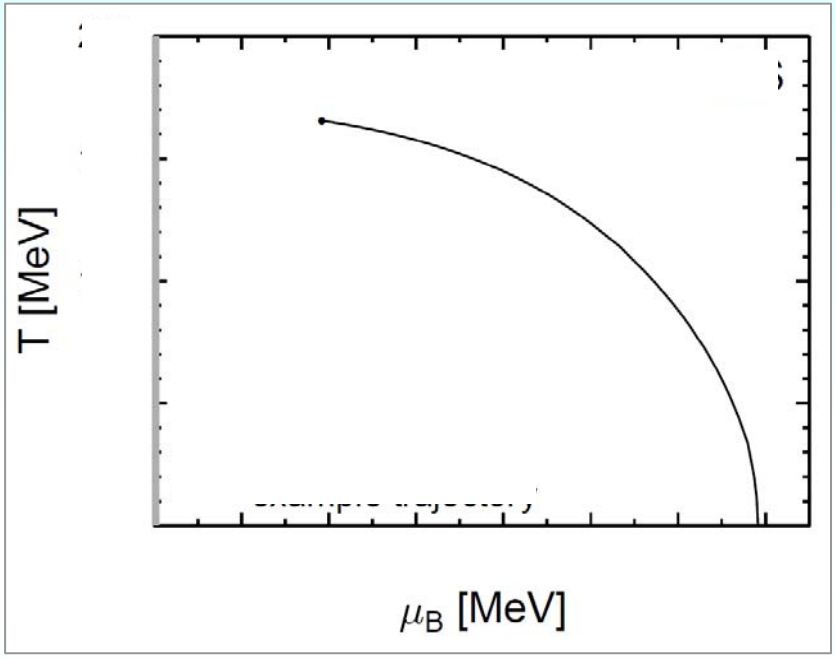
Source: WIKIPEDIA

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

T-μ phase diagram *of* 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)

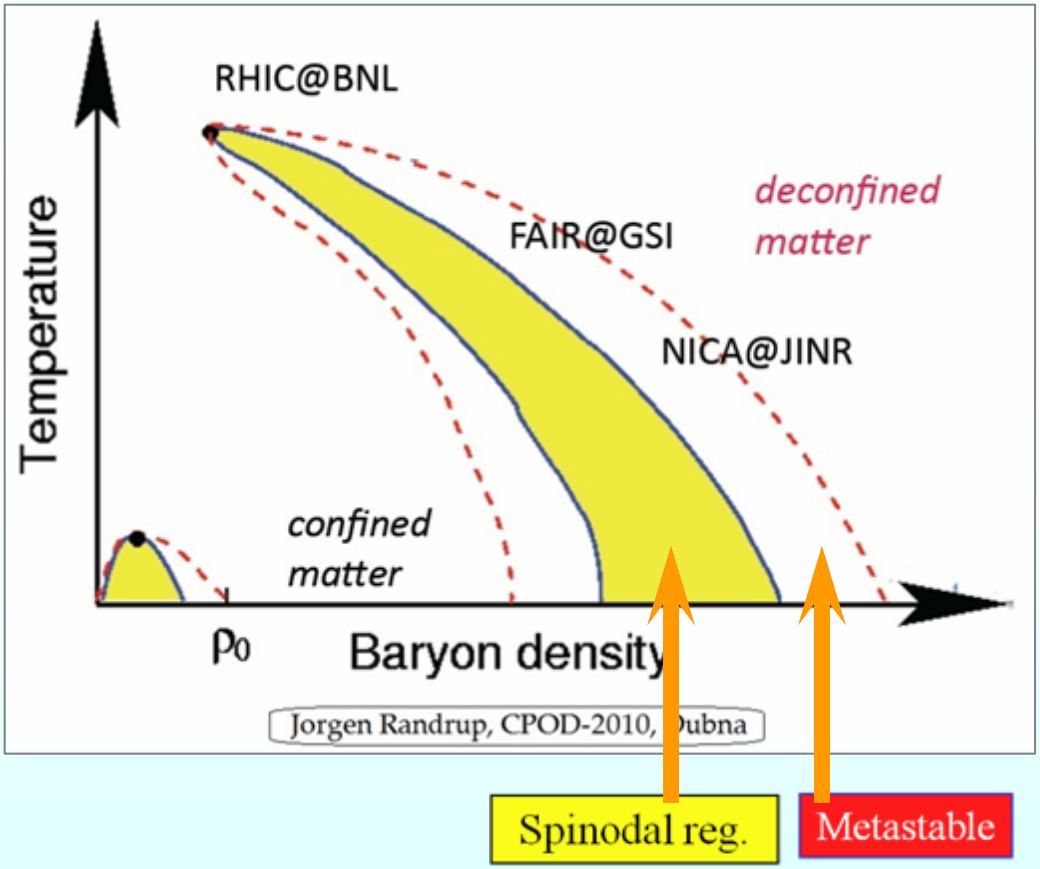
arXiv:1302.2835

NB !

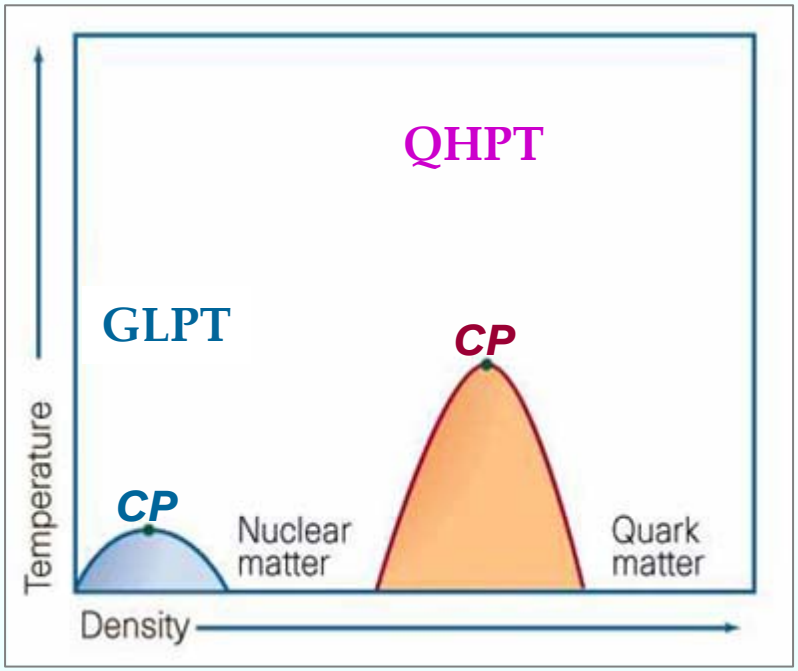
Gas-liquid *and* **quark-hadron phase transitions** *are often* **considered as similar** *to each other within* **simple scaling / GLPT ~ ~ QHPT/**

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

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

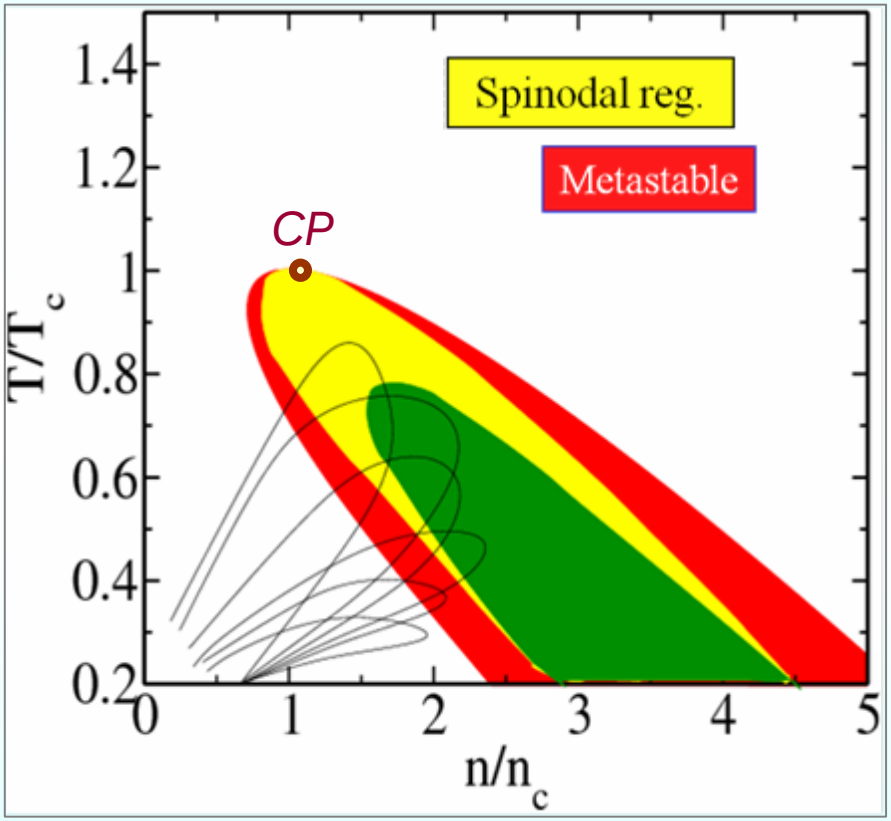


"*Critical Point and Onset of Deconfinement*"
Napa, USA, 2013



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

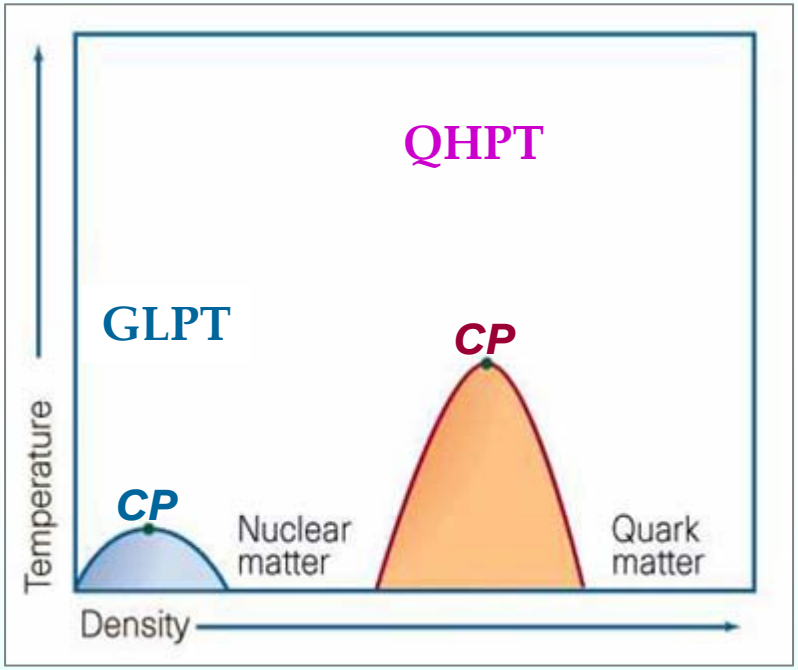
Gas-liquid *and* quark-hadron phase transitions are often considered as similar



Vladimir Skokov (GSI, Darmstadt)

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

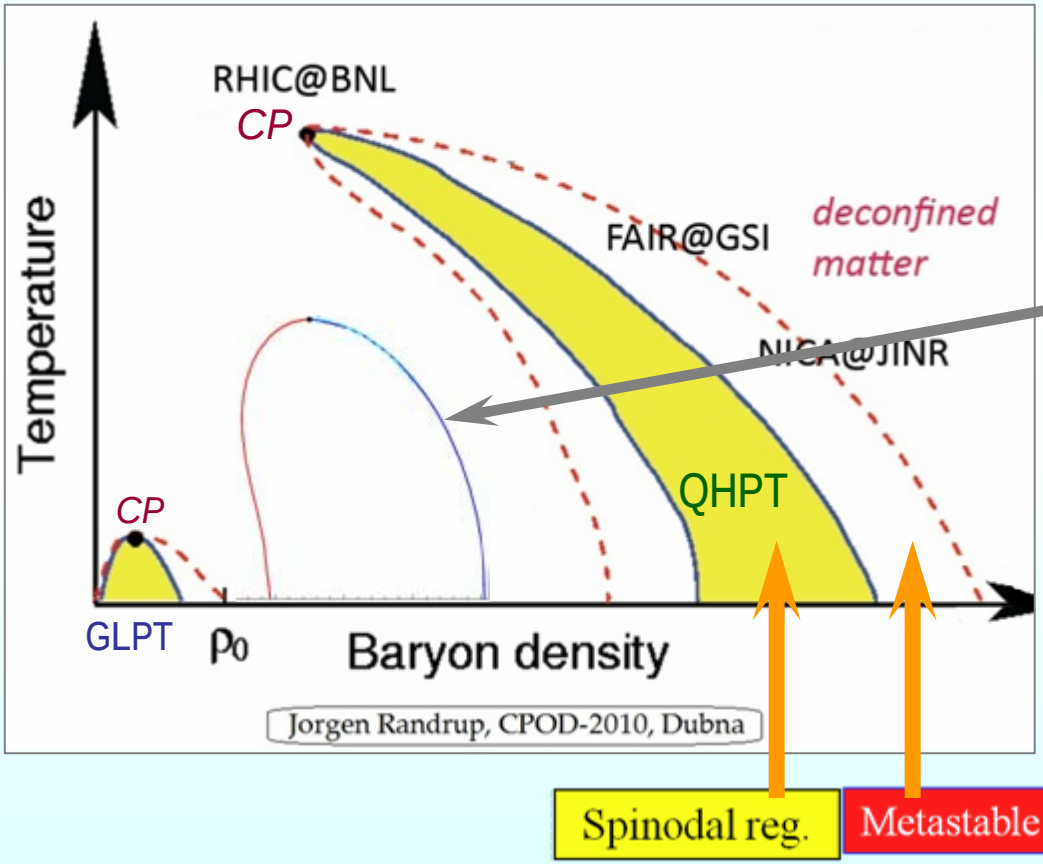
"*Critical Point and Onset of Deconfinement*" Int. Conference, Napa, USA, 2013



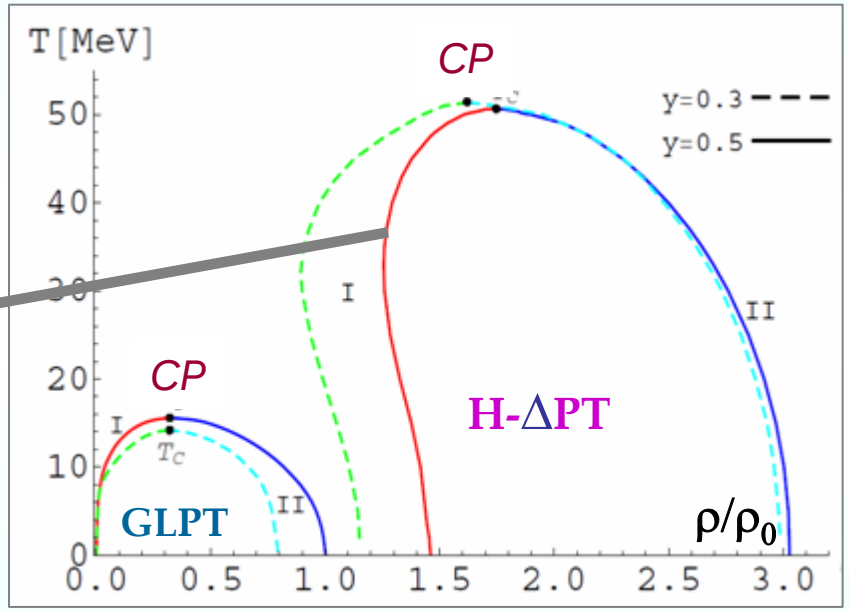
J. Steinheimer & J. Randrup, *CPOD*-2013

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

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



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

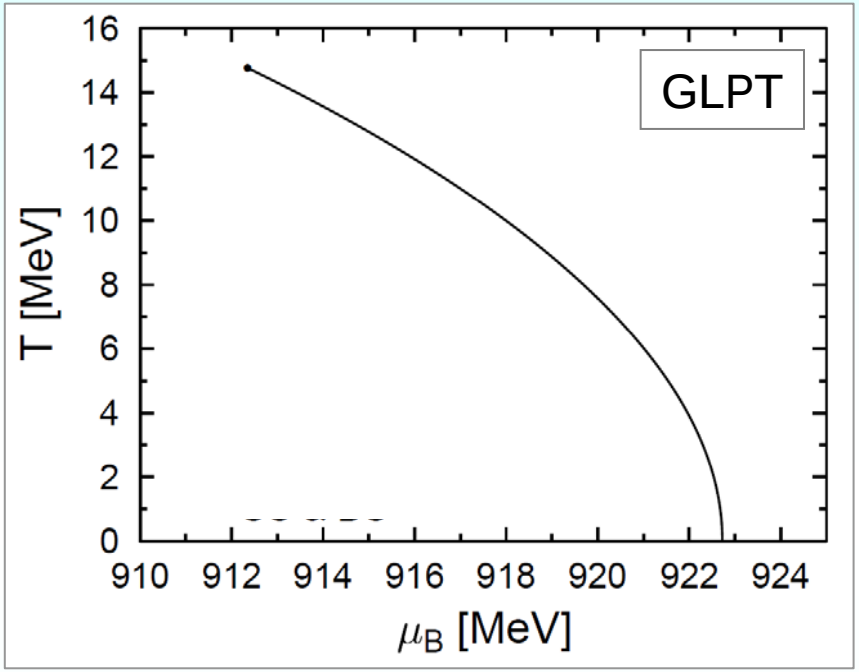


Lavagno A., Pigato D.
Phys. Rev. C., **86**, (2012)
Thermodynamic instability in warm and dense nuclear matter

All three phase transitions: - are they isomorphic ?

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

(symmetric case)

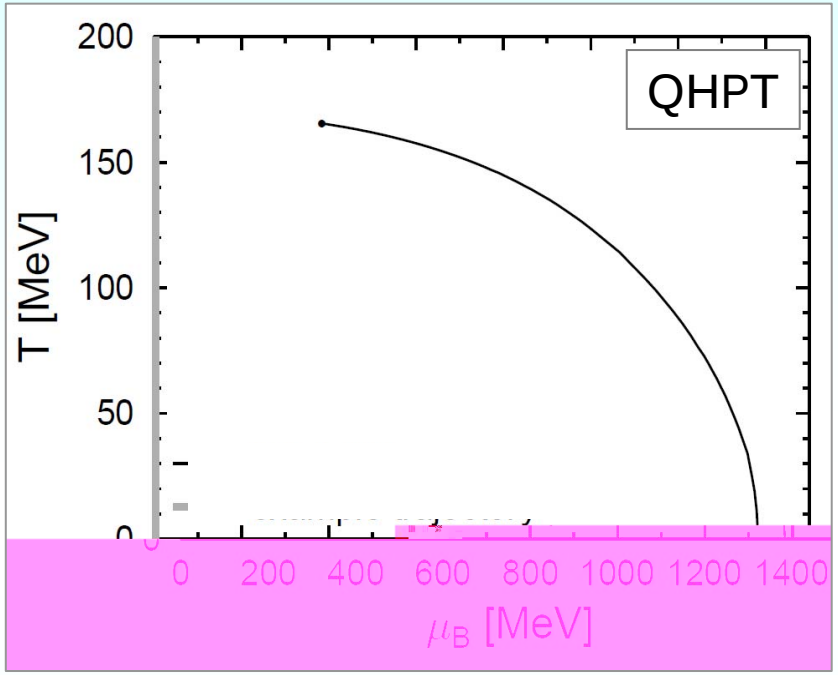


FSUGold (*Matthias Hempel* (*))

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)

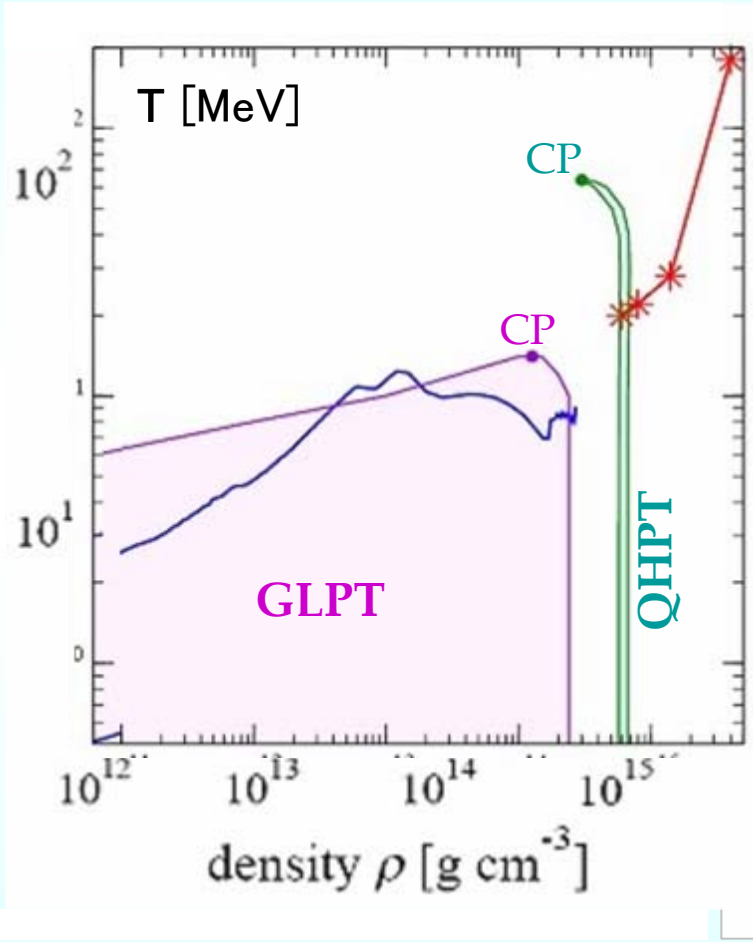
arXiv:1302.2835

No!

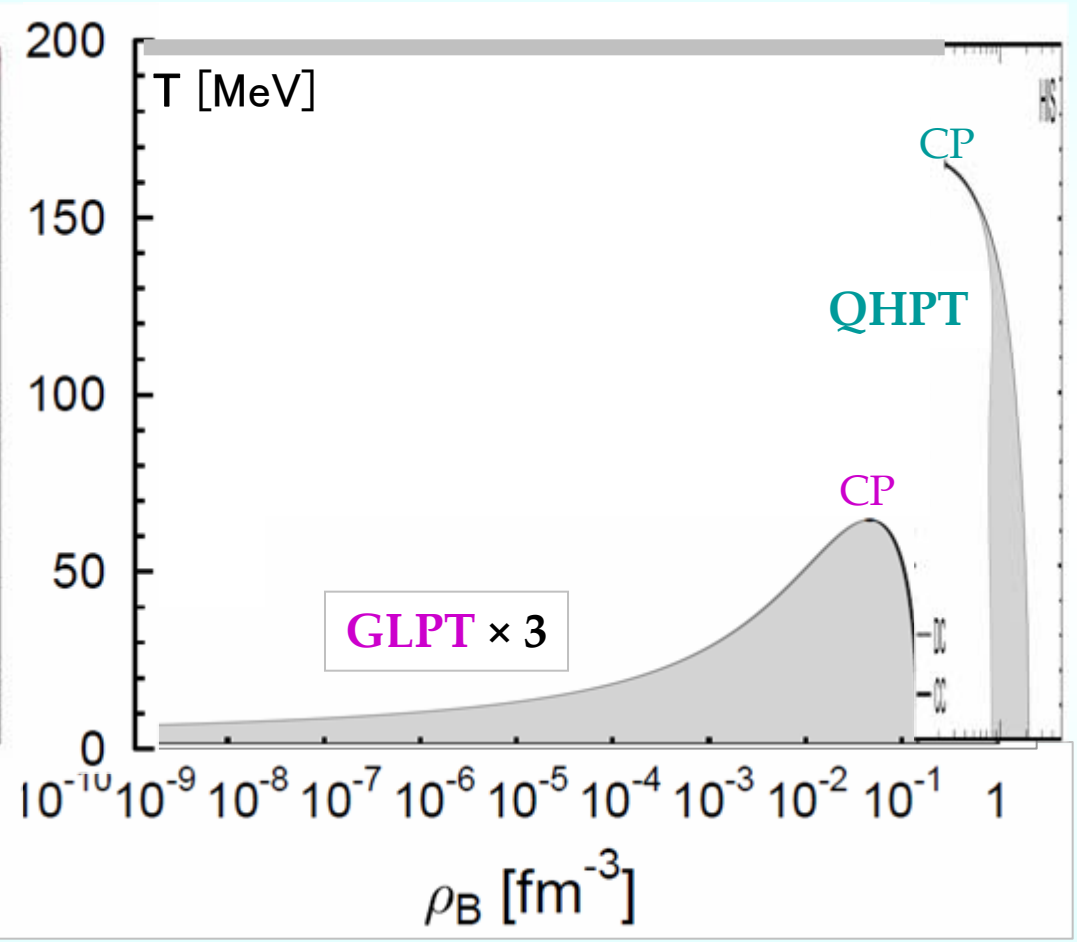
Enthalpic PT ≠ **Entropic PT**

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

(the same structure in old and new calculations)



after David Blaschke,
"Extreme Matter", Elbrus-2010



FSUGold (*Matthias Hempel*)
GLPT

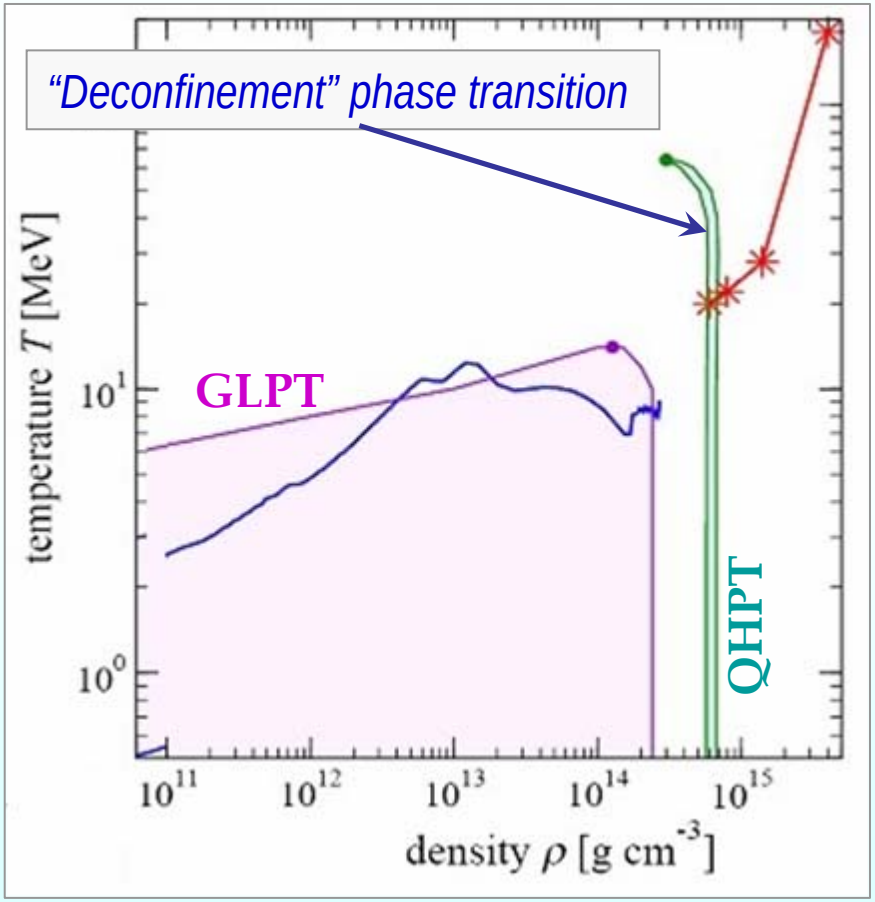
SU(3) model (*Veronica Dexheimer*)
QHPT

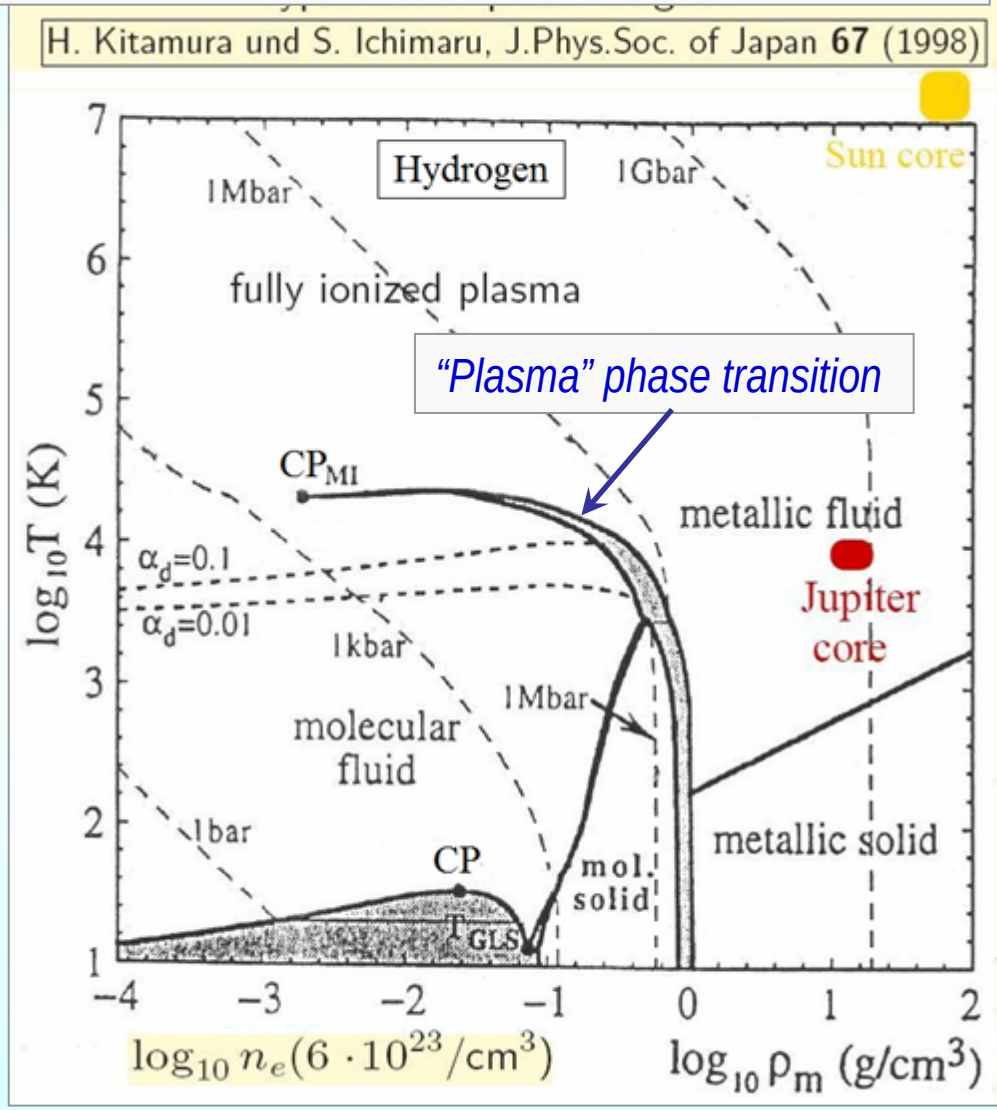
arXiv:1302.2835

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

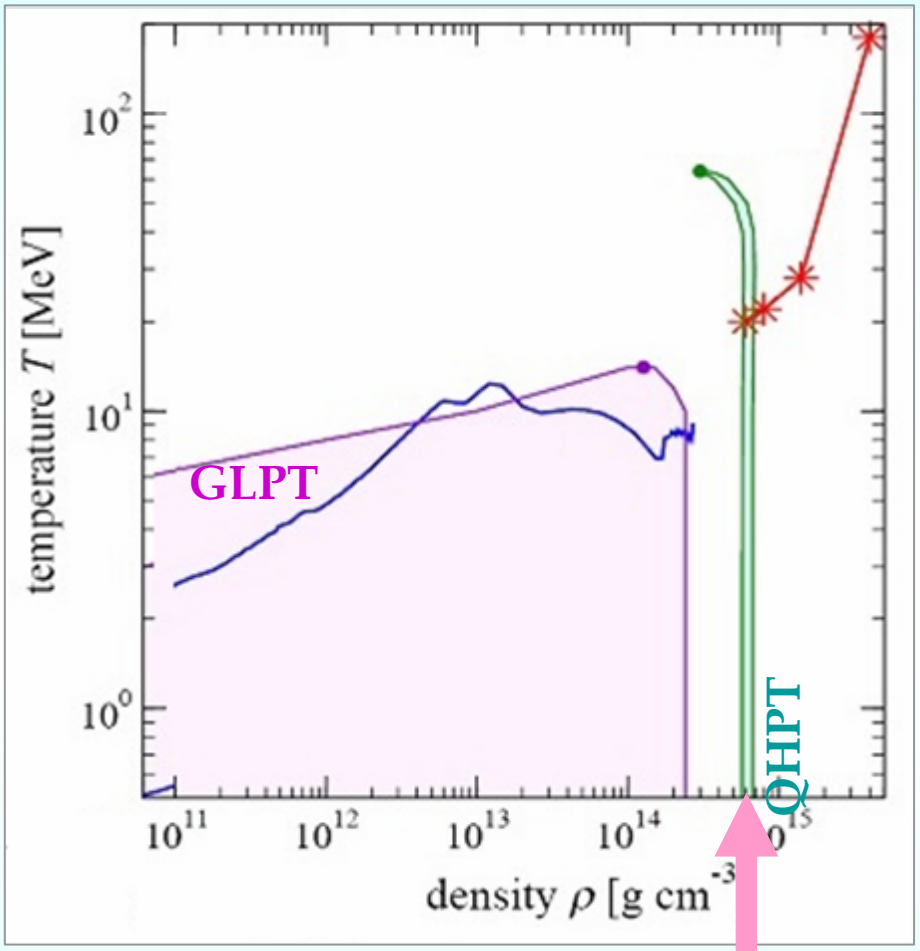
Enthalpic *and* **entropic** phase transitions *in* **electromagnetic plasma**

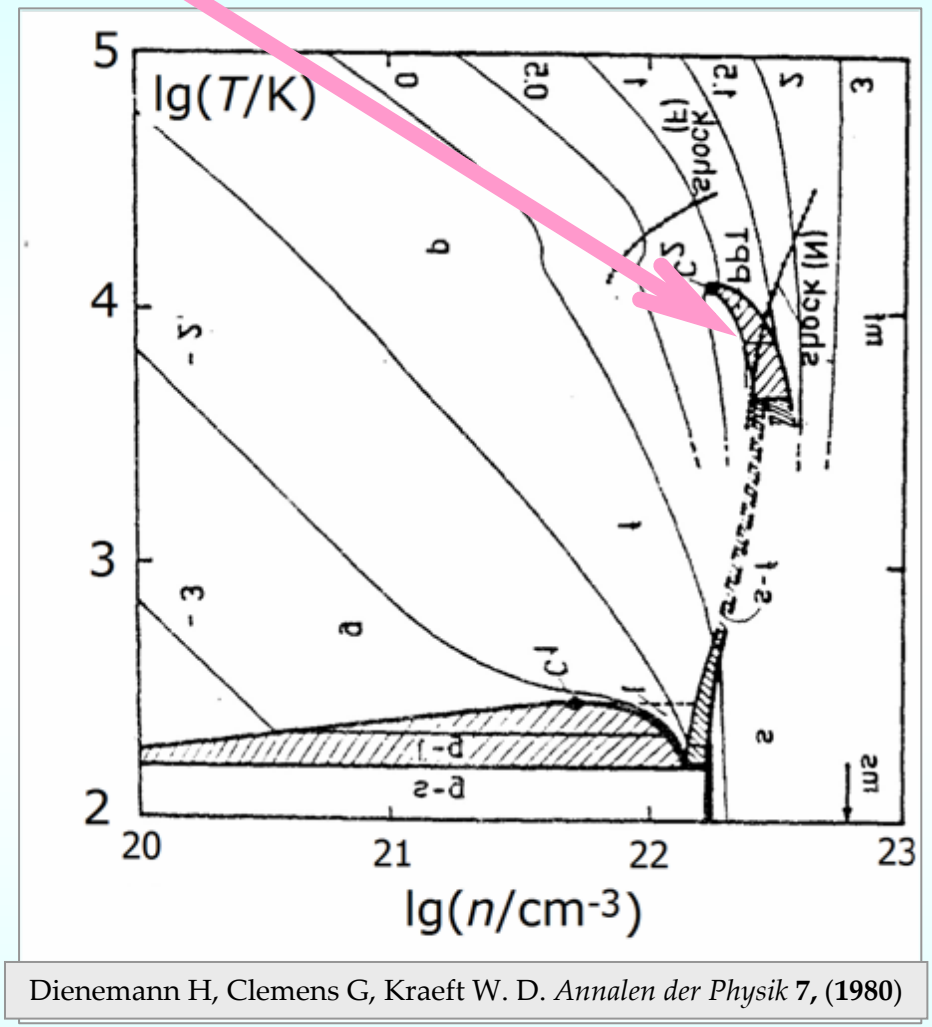
Hydrogen phase diagram with hypothetical “plasma” phase transition





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**

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

PT under isothermal compression

GLPT ⇔ $\Delta H < 0$ ⇔ GLPT

QHPT ⇔ $-T\Delta S < 0$ ⇔ PPT

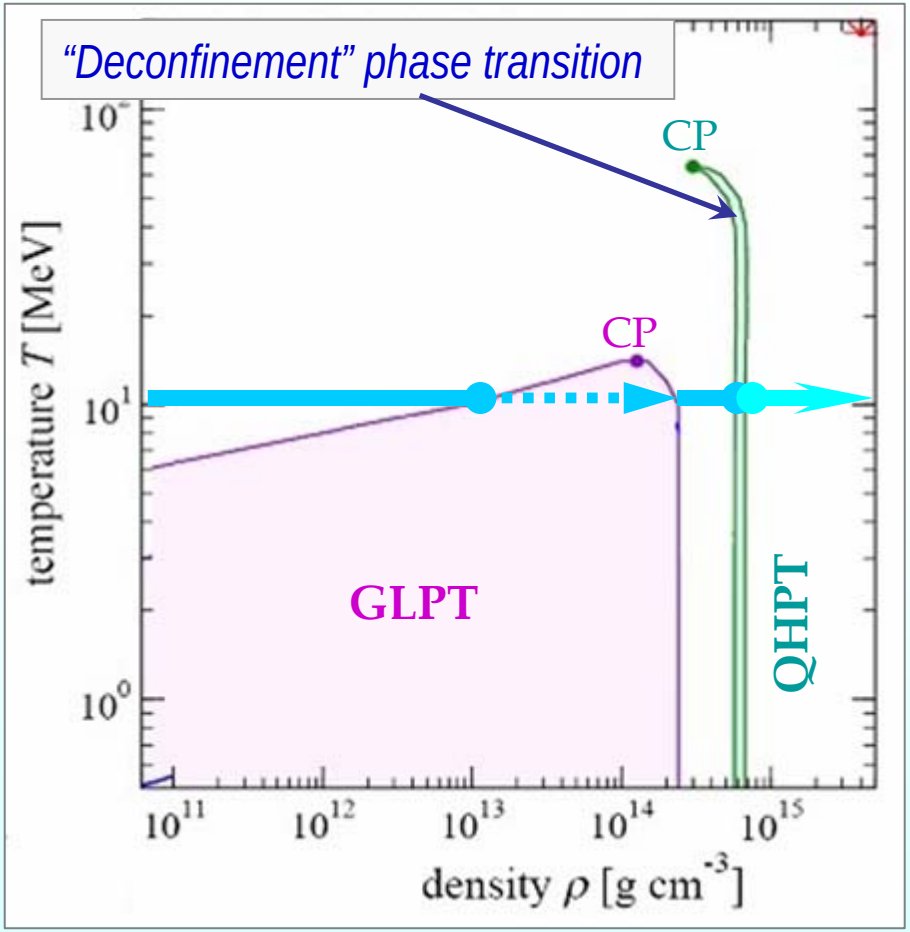
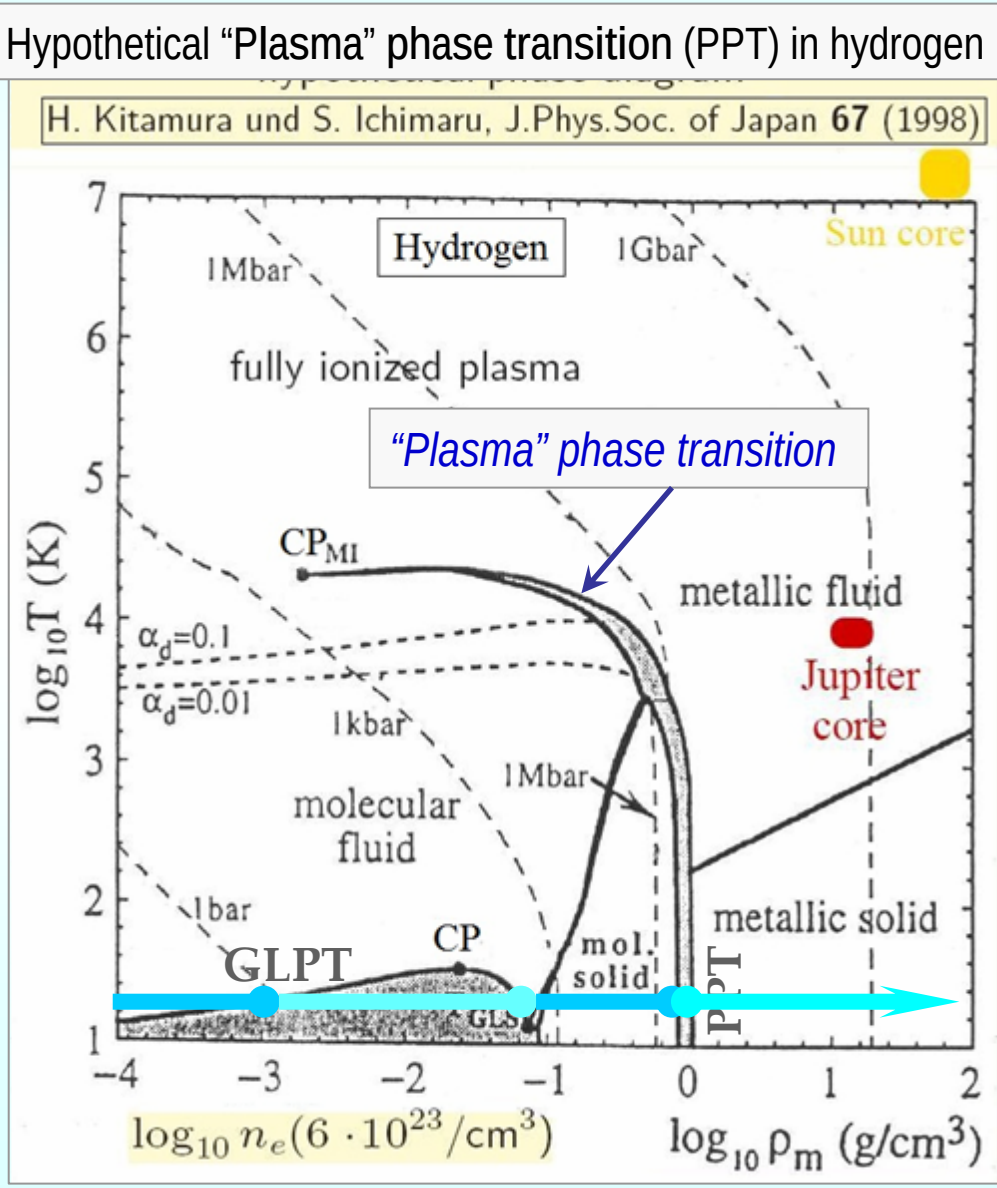


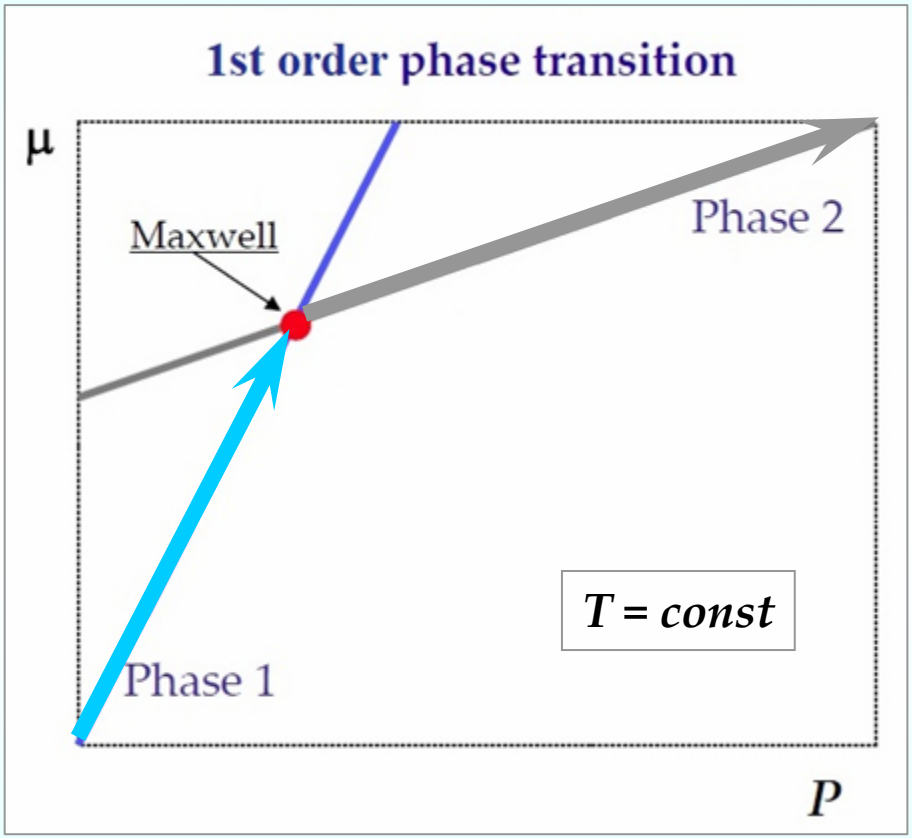
Figure after David Blaschke

Hypothetical "Plasma" phase transition (PPT) in hydrogen



Phase transitions: **Enthalpic** *vs.* **Entropic ?**

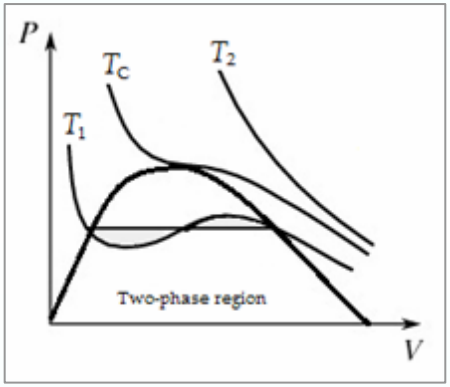
$$G = H - TS$$



Iso-*T* compression

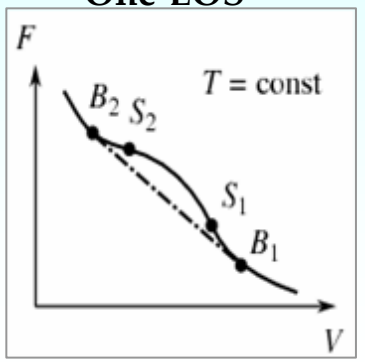
$$\Delta G = 0 \quad \Leftrightarrow \quad \Delta H = T\Delta S$$

VdW-like PT

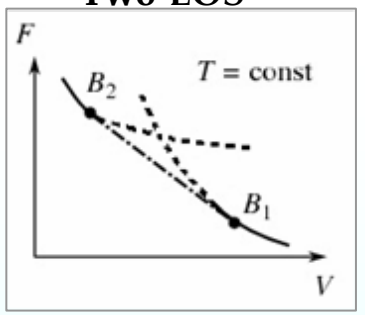


Maxwell "Equal squares"

One-EOS



Two-EOS



"Double tangent"

Enthalpic PT

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

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

Entropic PT

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

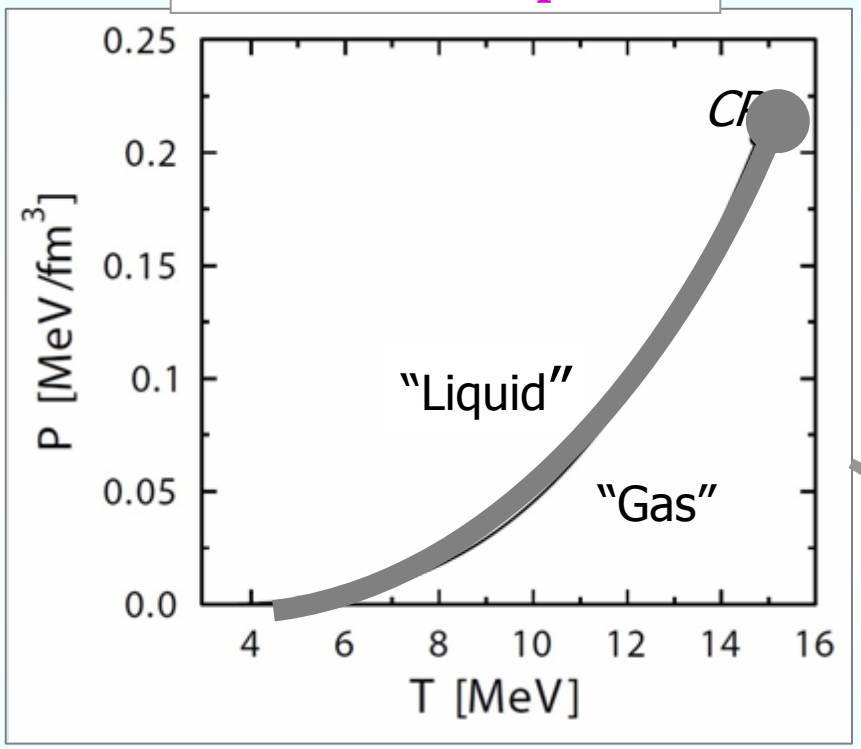
$$(dP/dT)_{binodal} < 0$$

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

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

One-EOS approach (*with critical point*)

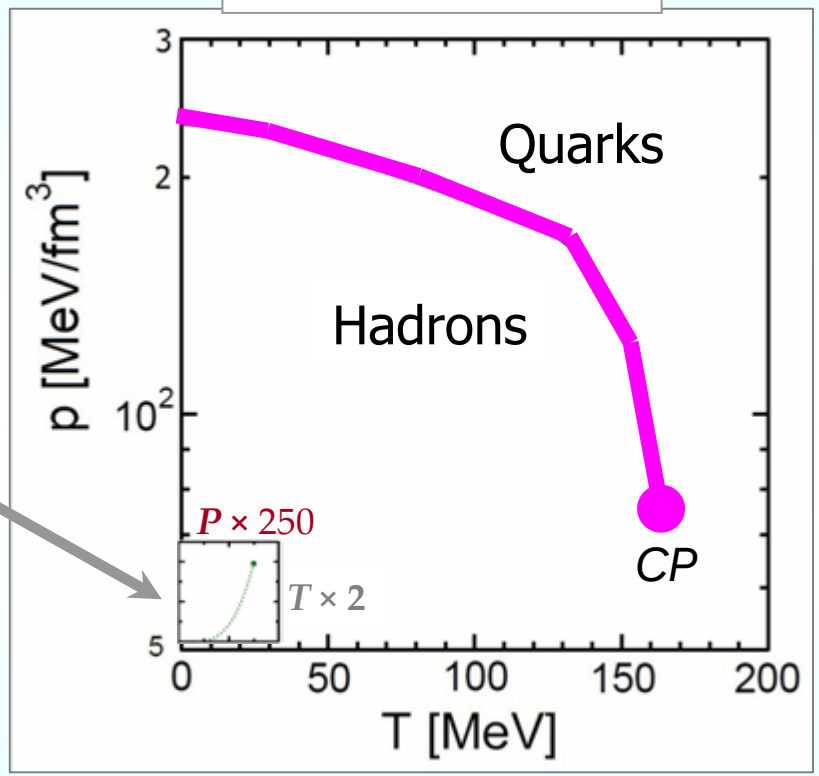
Nuclear Gas-Liquid PT



Standard VdW-like behavior

(*enthalpic PT*)

Quark-Hadron PT



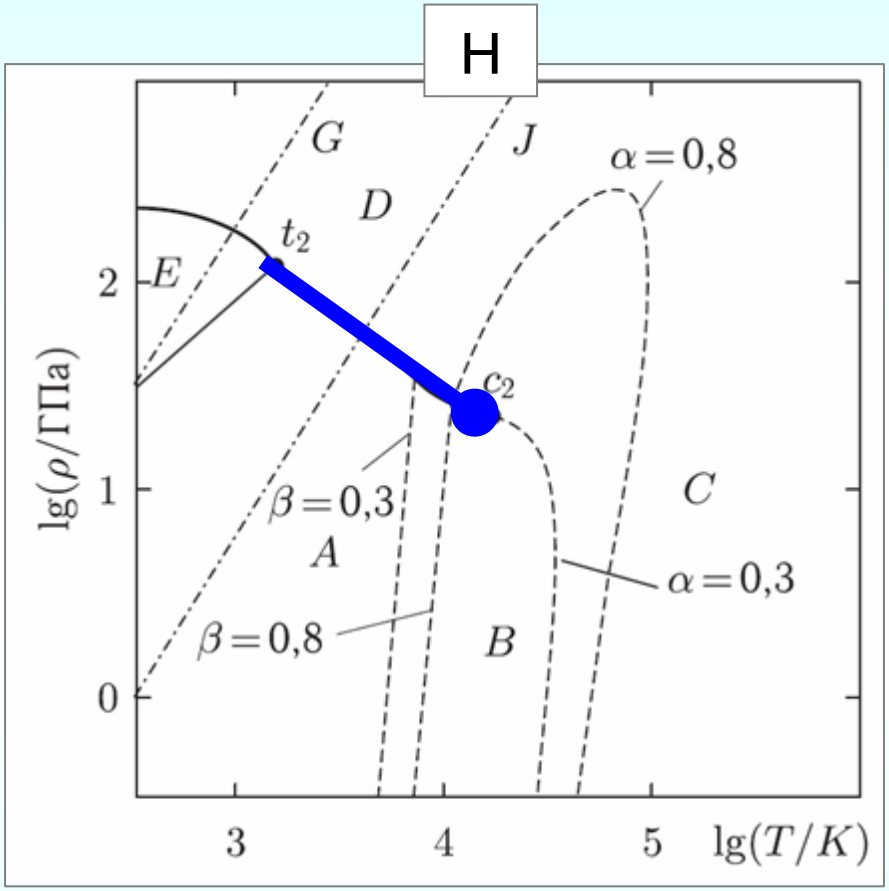
Non-standard behavior: $(dP/dT)_{\text{binodal}} < 0$

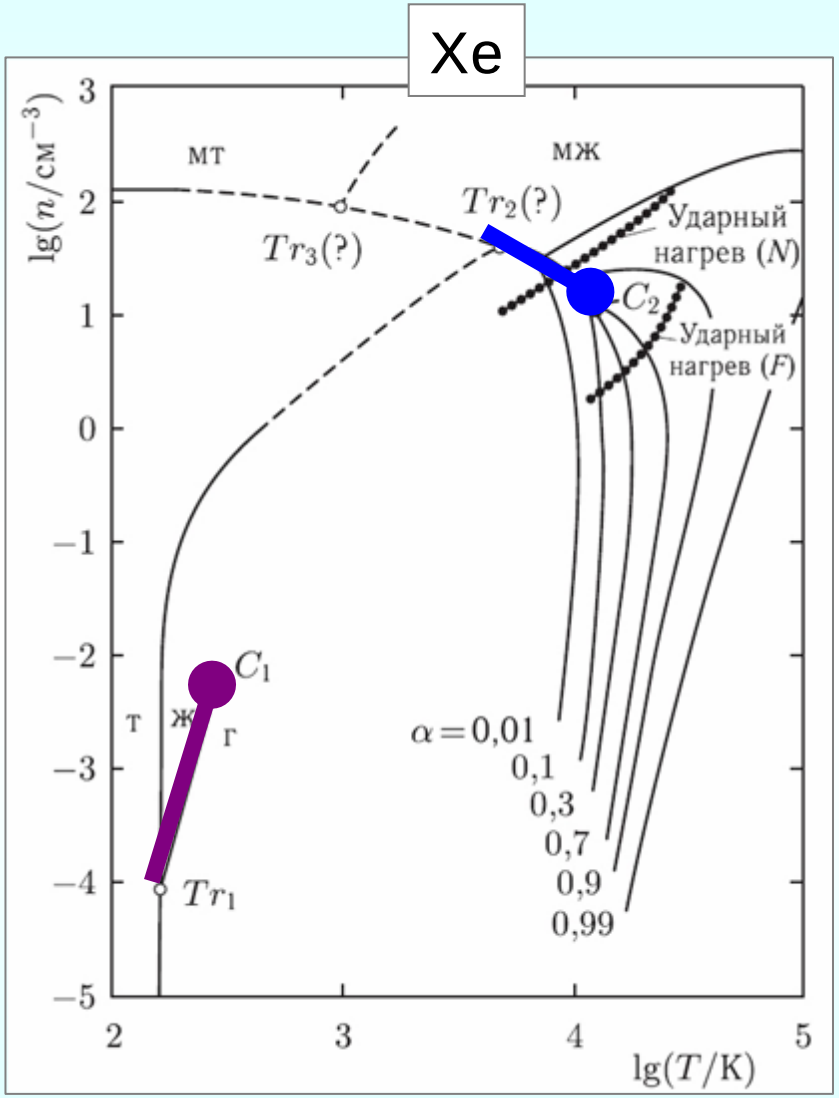
(*entropic PT*)

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

P-T diagram *of* plasma phase transitions

P-T diagram *of* plasma phase transition





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

- enthalpic *(gas-liquid)* PT
- entropic *(plasma)* PT

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

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

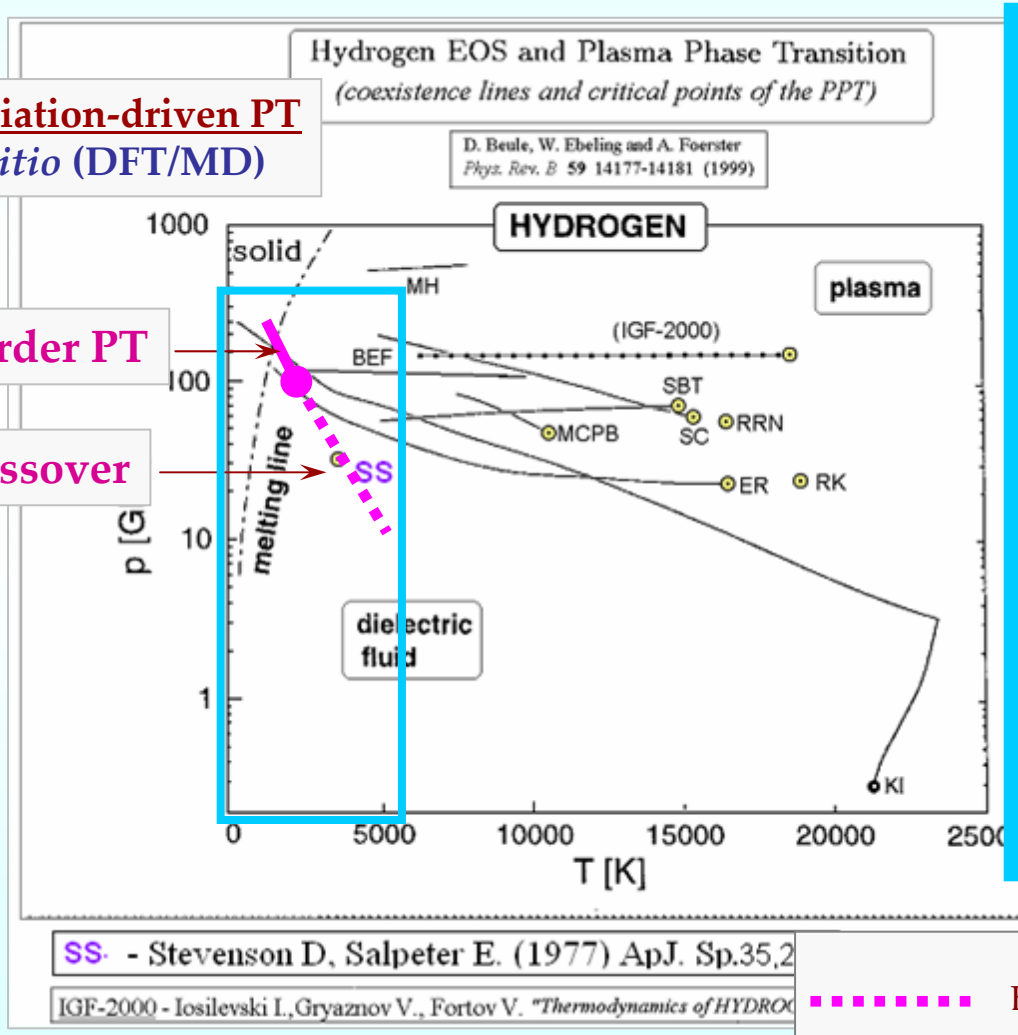
(*mostly entropic*)

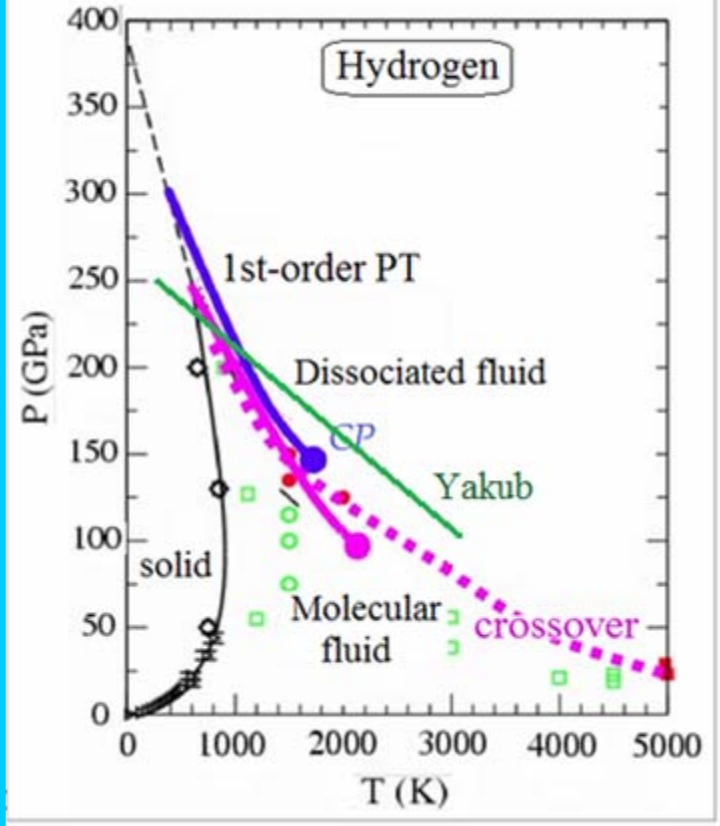
Non-standard behavior: $(dP/dT)_{binodal} < 0$ *or* $(dP/dT)_{binodal} \approx 0$

Dissociation-driven PT
ab initio (DFT/MD)

1st-order PT

Crossover

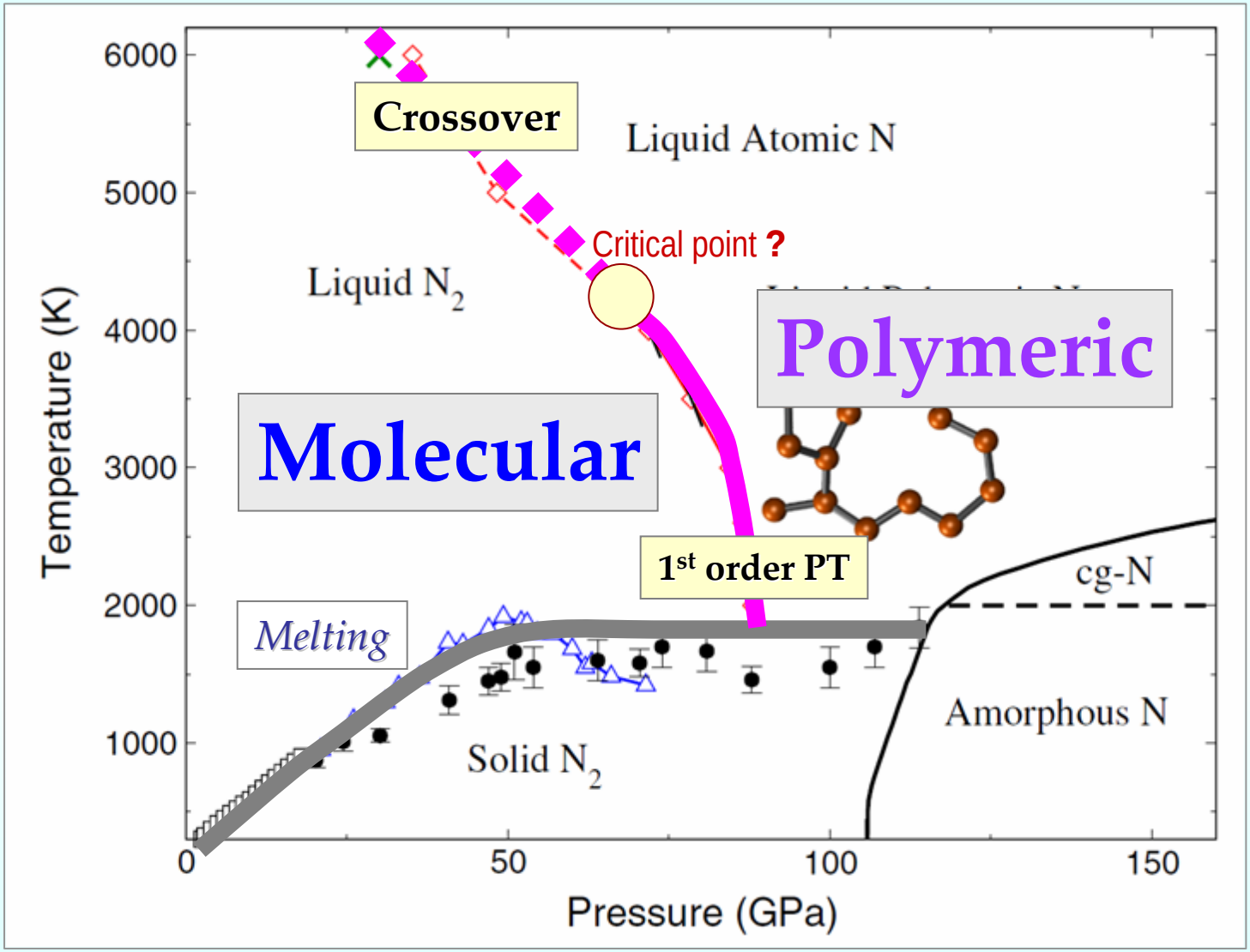




Dissociation-driven PT (*ab initio*)

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)

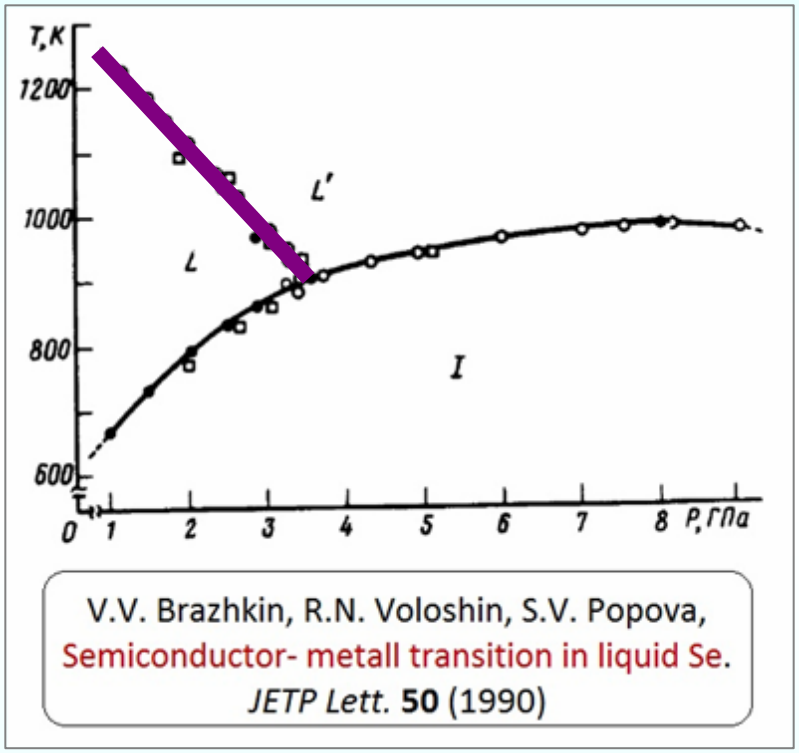
Entropy-driven fluid-fluid phase transitions (N_2)



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

Entropy-driven fluid-fluid phase transitions

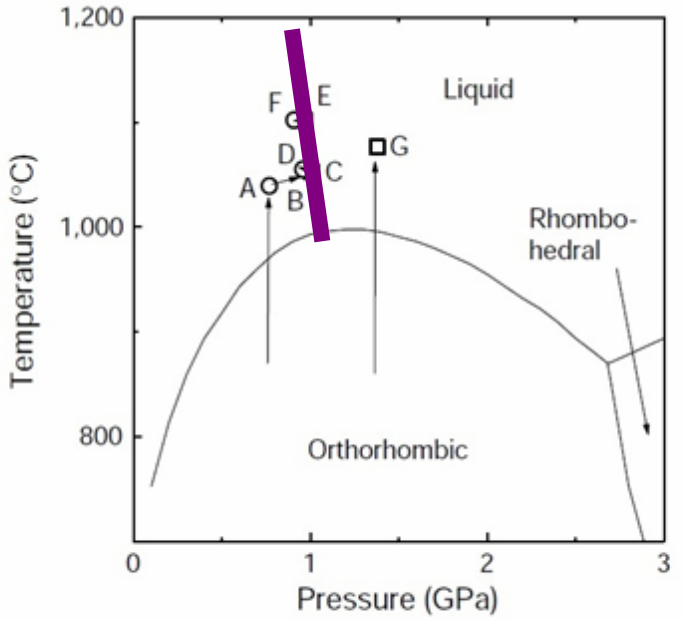
Selenium



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

Experiment

Phosphor

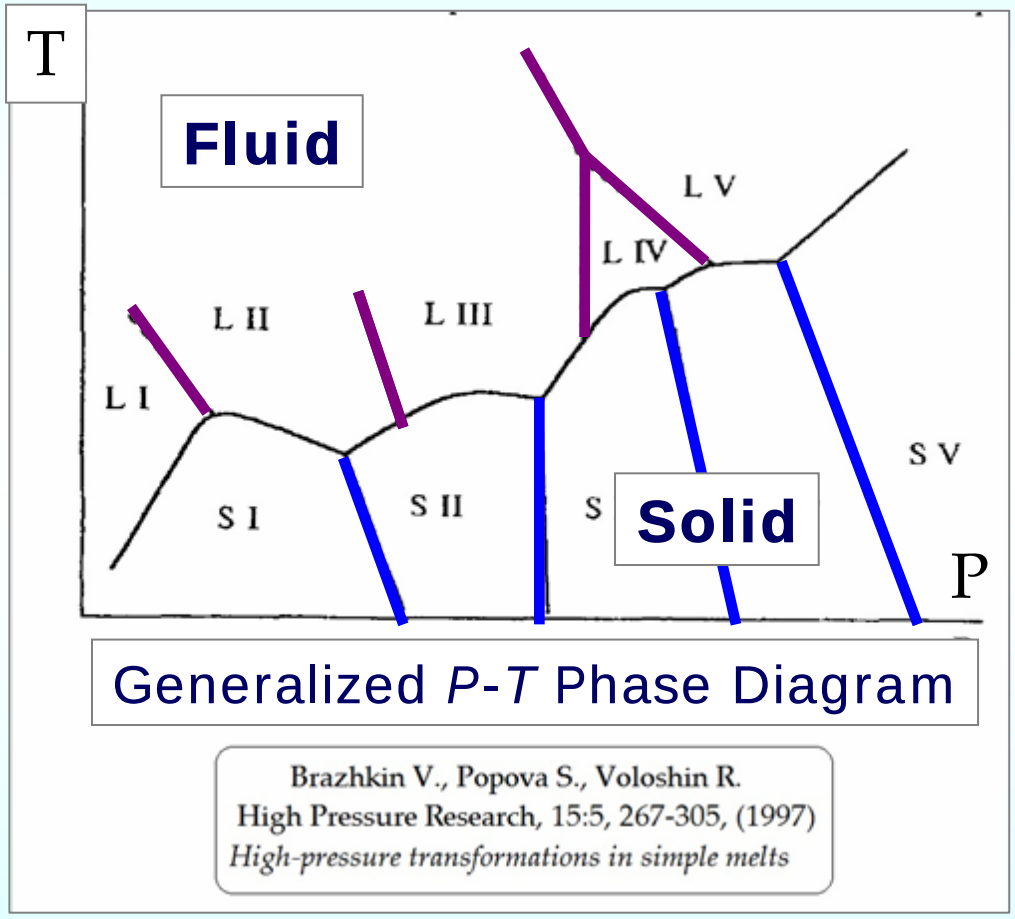


Katayama Y., Mizutani T. *et al.* (*Nature* **403**, 170 (2000)

Experiment

Enthalpic *vs* Entropic Phase Transitions ?

V. Brazhkin (1997)



Generalized *P-T* Phase Diagram

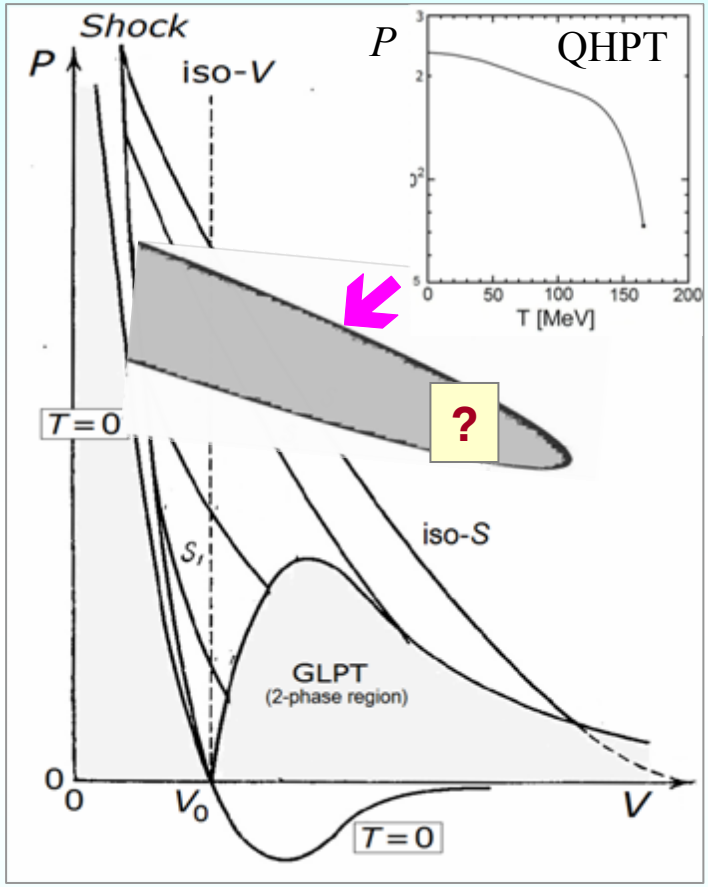
Brazhkin V., Popova S., Voloshin R.
High Pressure Research, 15:5, 267-305, (1997)
High-pressure transformations in simple melts

NB !

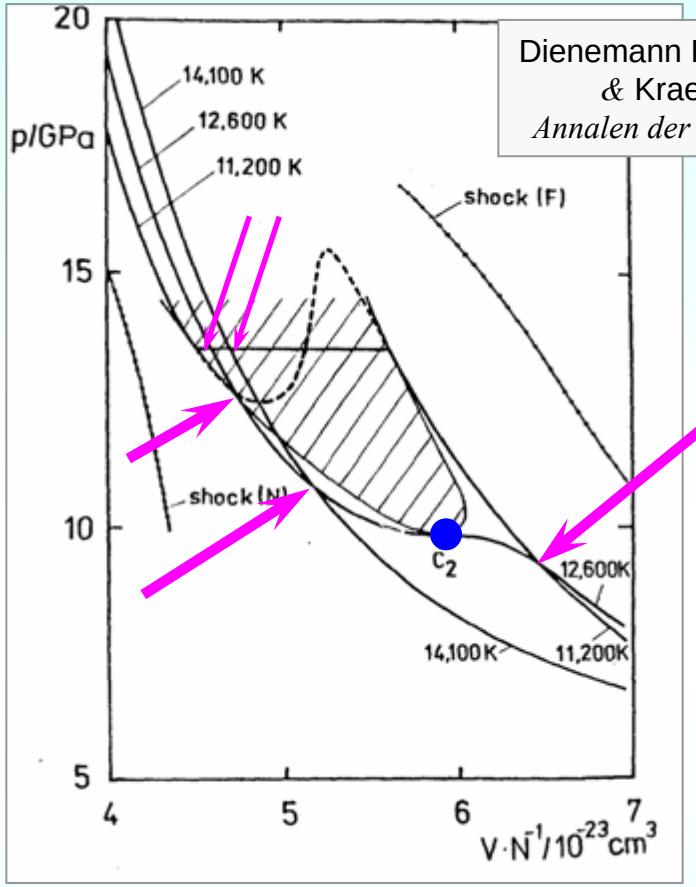
All polymorphic and all fluid-fluid PTs are *Entropic* !

P-V **phase diagram**

Ionization-driven ("plasma") phase transition



P(V)



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

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

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

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

$$(\partial P/\partial T)_V < 0 \rightarrow V(\partial P/\partial U)_V < 0 \Leftrightarrow (\partial P/\partial S)_V < 0 \Leftrightarrow (\partial V/\partial T)_P < 0$$

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

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

Abnormal Thermodynamics Region - *ATR*

Normally positive cross derivatives became *negative simultaneously !*

Normal > 0 **Abnormal** < 0

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

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

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

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

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

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

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

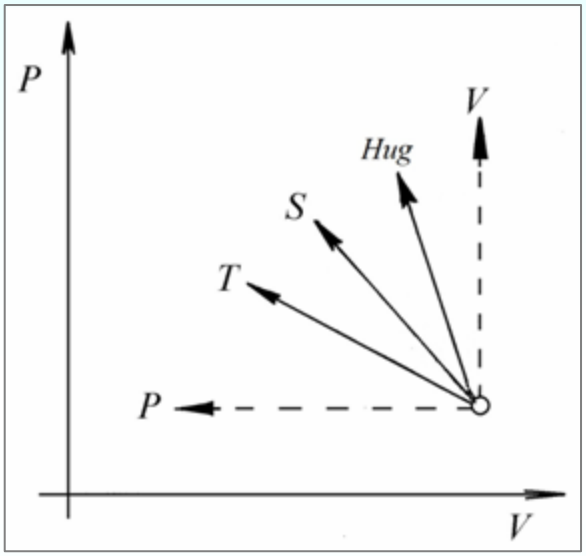
$(\partial P/\partial T)_V < 0$	→	**Abnormal order + crossing *of* isotherms !**
$(\partial P/\partial S)_V < 0$	→	**Abnormal order + crossing *of* isentropes !**
= = « » = =	→	**Isentropes *go* less steeper *than* isotherms !**
= = « » = =	→	**Shock adiabats *go* less steeper *than* isentropes !**
$V(\partial P/\partial U)_V < 0$	→	**Abnormal order + crossing *of* Hugoniots *(shock adiabats)* !**

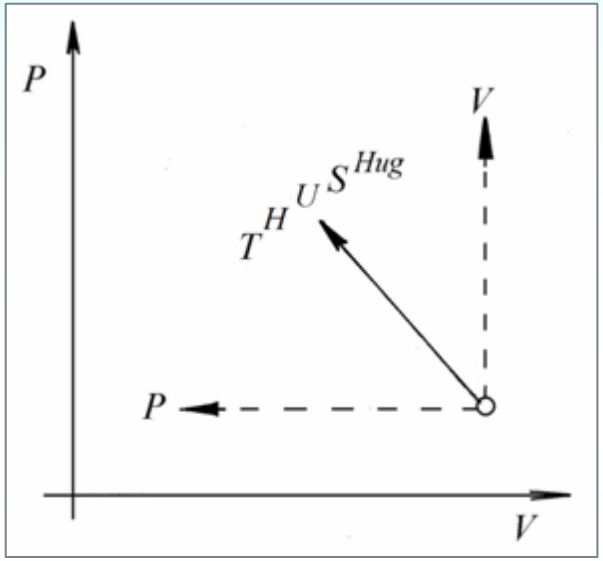
See e.g. A.Medvedev & R.Trunin, *Uspekhi (UFN)* **182** (2012) and V.Brazhkin's critique (="=)

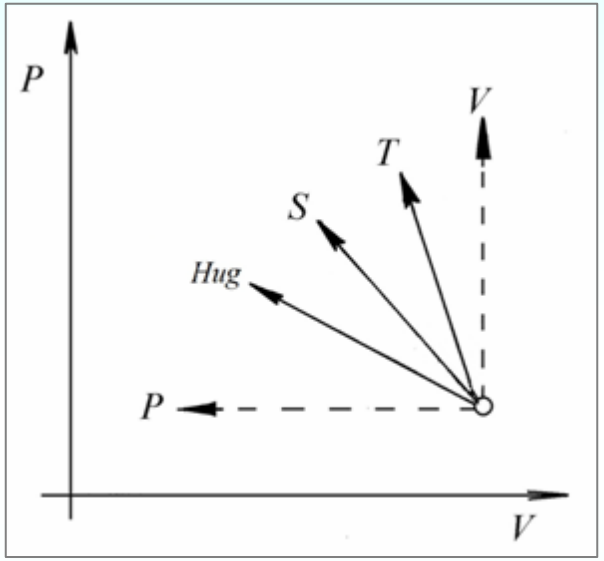
$(\partial T/\partial P)_S < 0$	→	**Abnormal decreasing** (*increasing*) **temperature** *under* **isentropic compression** (*expansion*) !
$(\partial S/\partial V)_T < 0$	→	**Abnormal decreasing** (*increasing*) **entropy** *under* **isothermal expansion** (*compression*) !

ATR – abnomal thermodynamics region

ZB – Zero-boundary (ATR boundary)







Normal

$(\partial P/\partial T)_V > 0$

$(\partial P/\partial U)_V > 0$

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

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

Zero-line

$(\partial P/\partial T)_V = 0$

$(\partial P/\partial U)_V = 0$

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

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

Ubnormal

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

$(\partial P/\partial U)_V < 0$

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

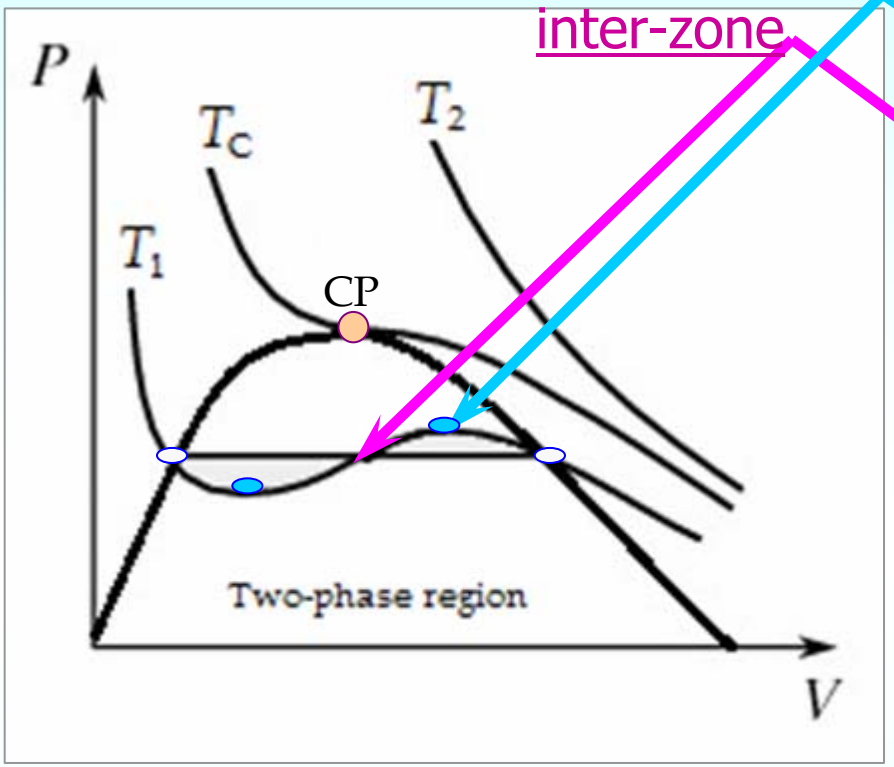
$(\partial T/\partial P)_S < 0$

Enthalpic (GLPT) *vs* Entropic (PPT)

(continued)

spinodal points

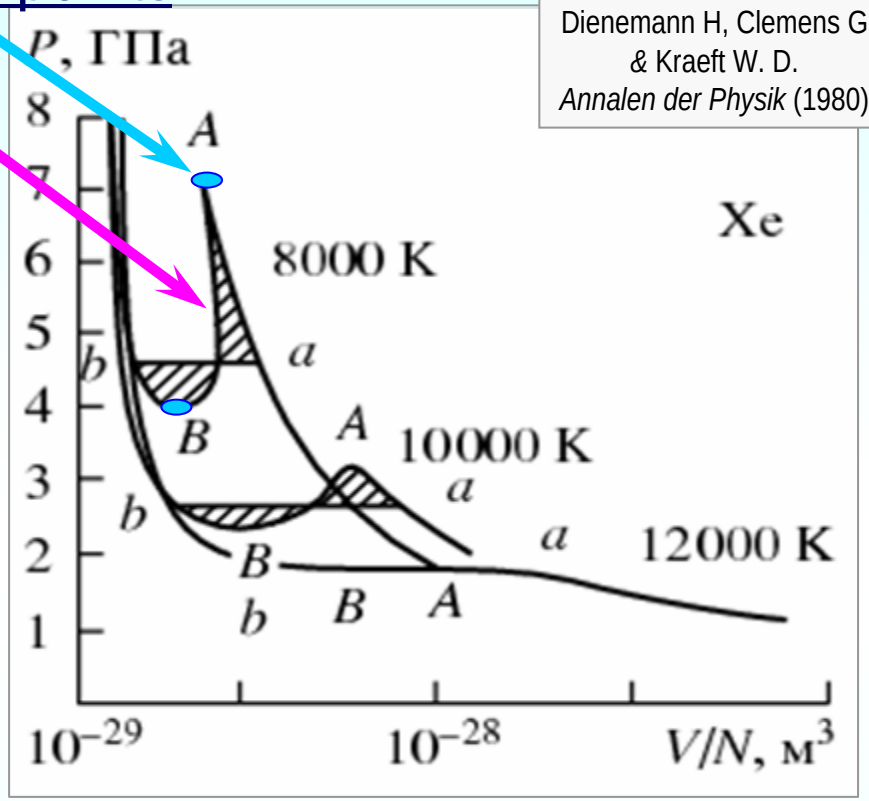
inter-zone



VdW-like phase transition

(*enthalpic PT*)

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



Ionization-driven phase transition in xenon

(*entropic PT*)

NB !

$T \ll T_c$

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

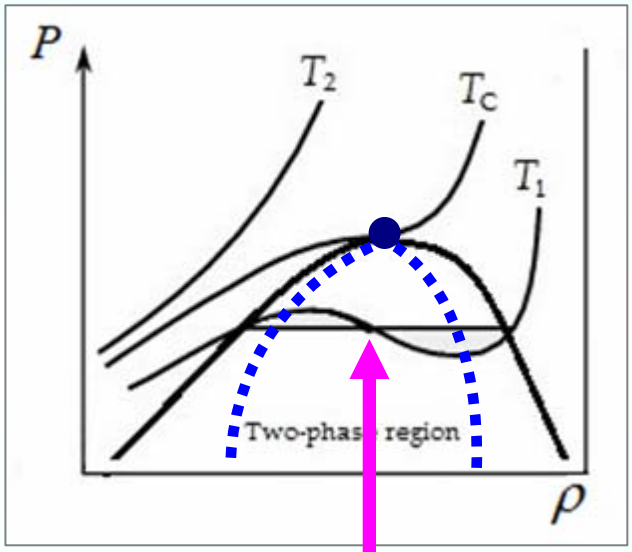
Third branch with $(\partial P/\partial V)_T < 0$ appears on **isotherms** in **spinodal** region **!**

Hypothetical dissociation-driven PT

(*entropic PT*)

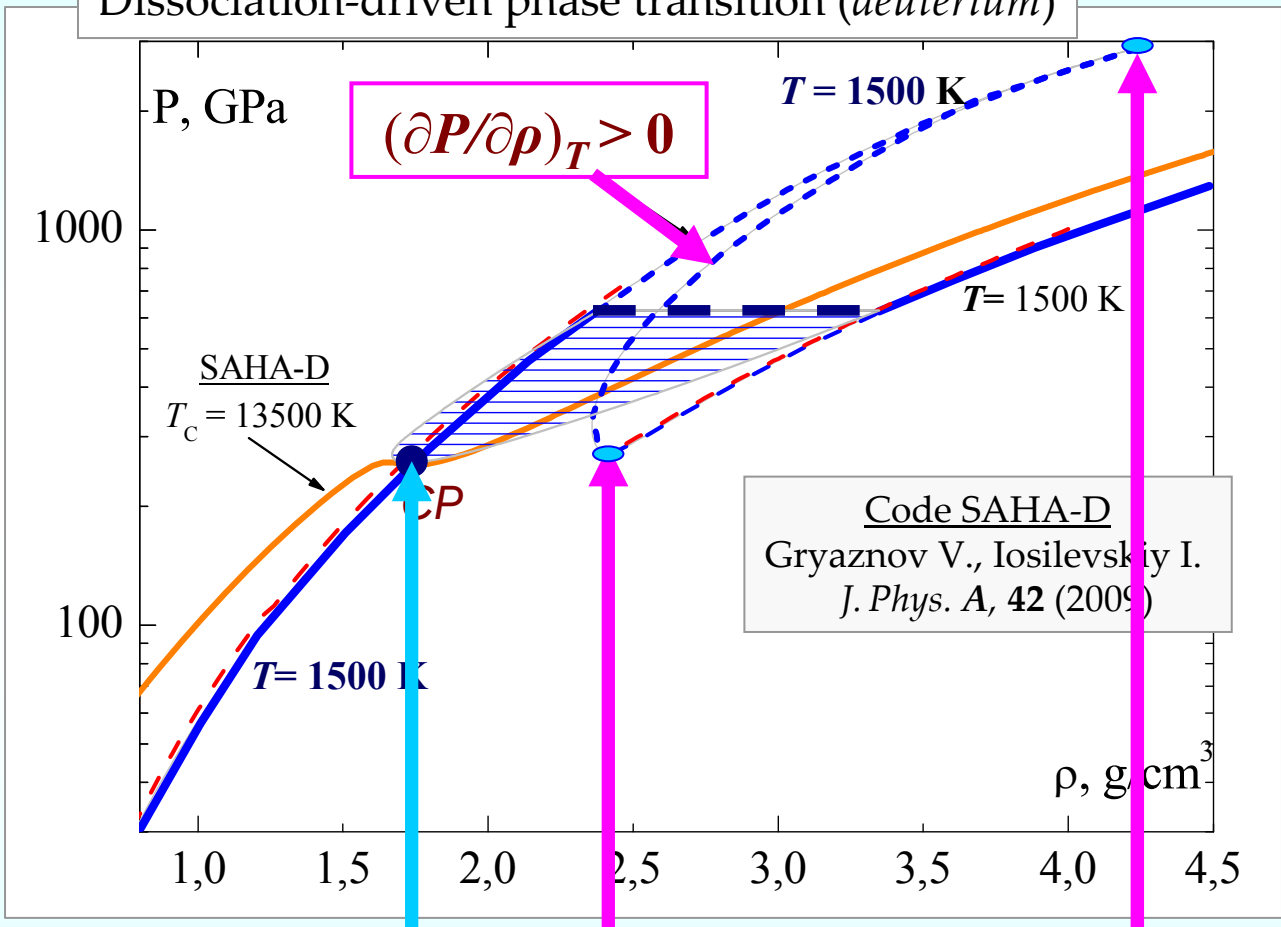
(*enthalpic PT*)

VdW-like phase transition



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

Dissociation-driven phase transition (*deuterium*)



NB !

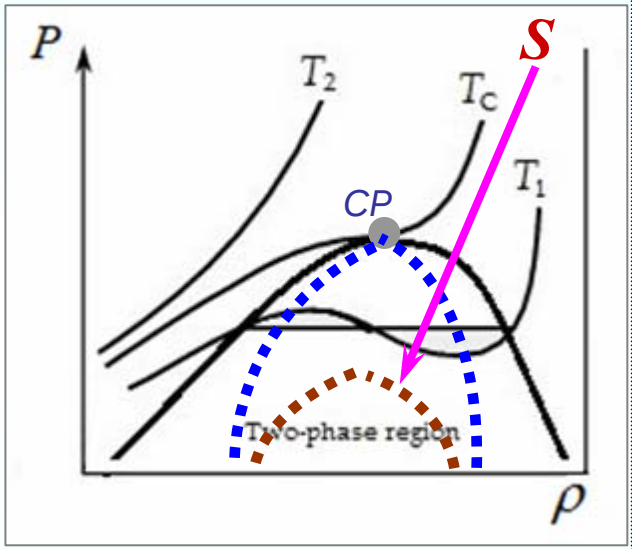
Not one, but **three isotherms intersect critical point** in *P-V* plane**!**

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

Hypothetical dissociation-driven (*entropic*) PT

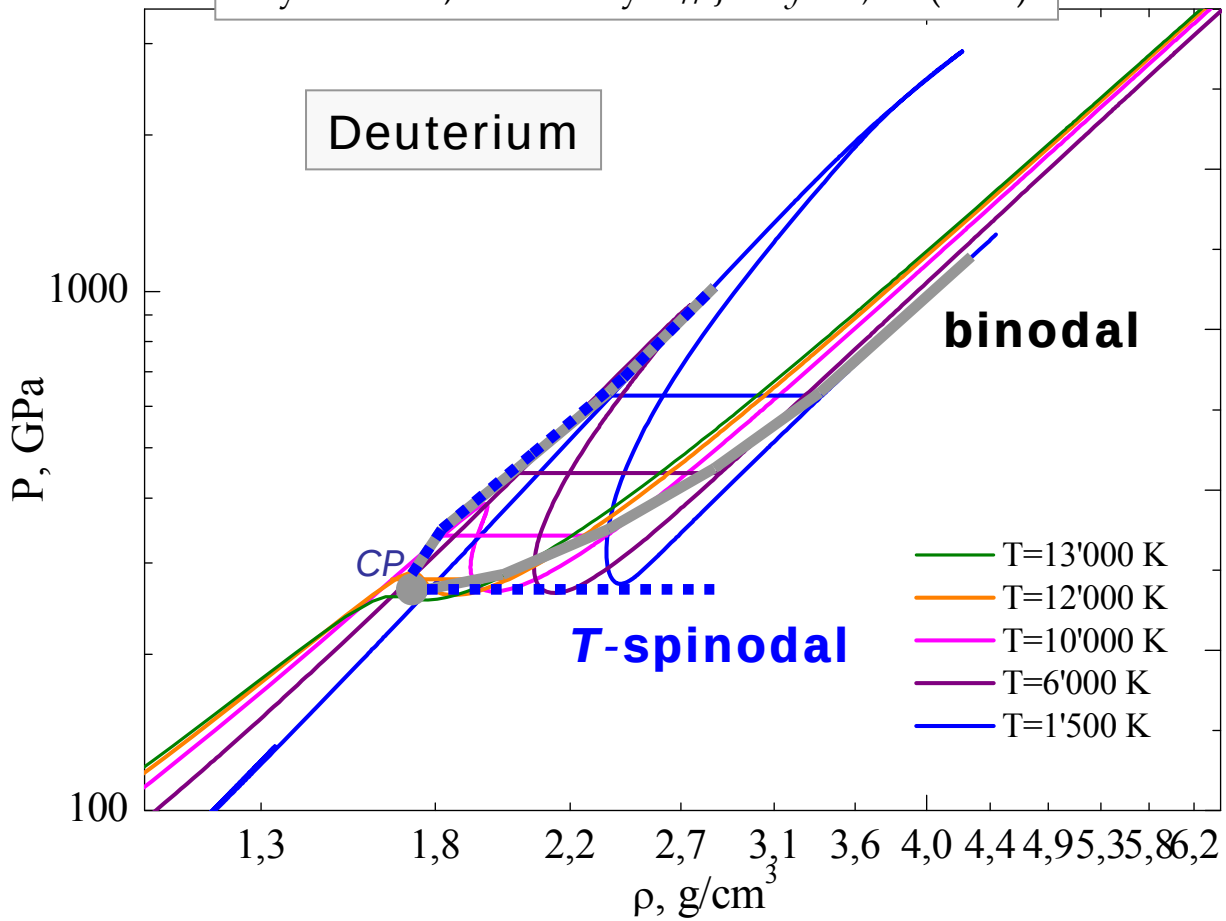
Zeldovich Ya., *Zh. Eksp. Teor. Fiz.* **32**, (1957)

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



VdW-like (*enthalpic*) phase transition

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



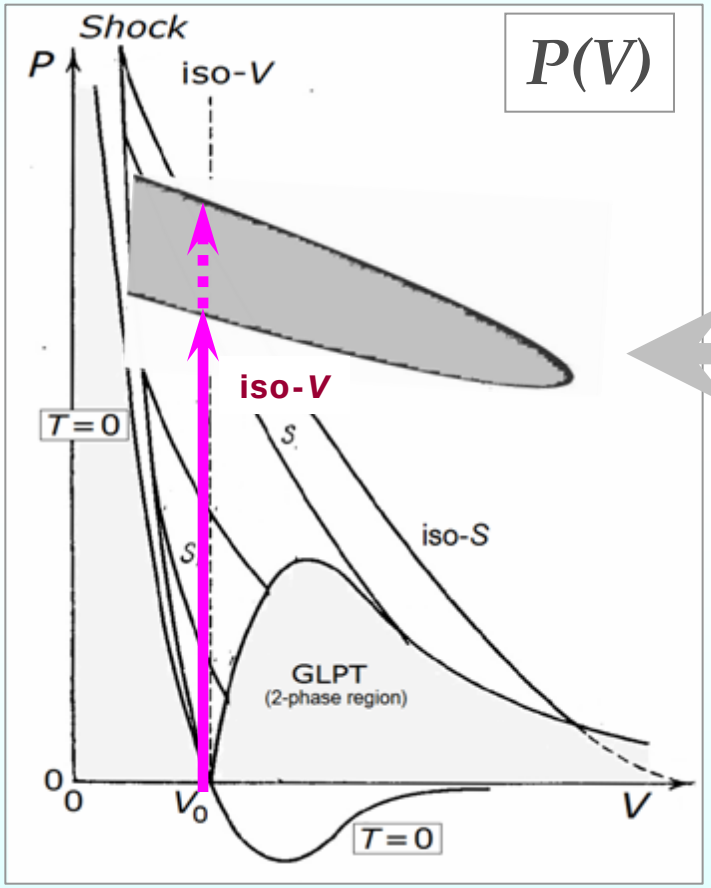
NB ! **Iso-*T* spinodal** $\{(\partial P/\partial V)_T = 0\}$ is located **outside** of **binodal**

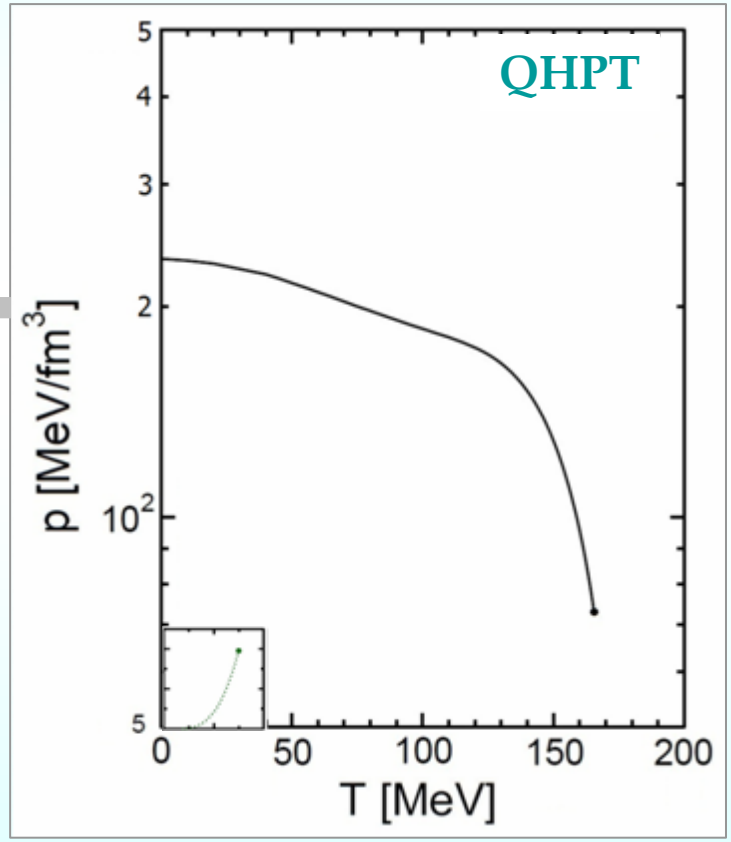
Iso-*S* spinodal $\{(\partial P/\partial V)_S = 0\}$ is located **outside** of **iso-*T* spinodal !**

Multy-layered structure *of* thermodynamic surfaces *for* entropic phase transition *over* *p-V* plane

T(p,V), U(p,V), S(p,V)…

Path under two-phase region via lower layer





Gas-liquid phase transition
(*Van-der-Waals-like*)

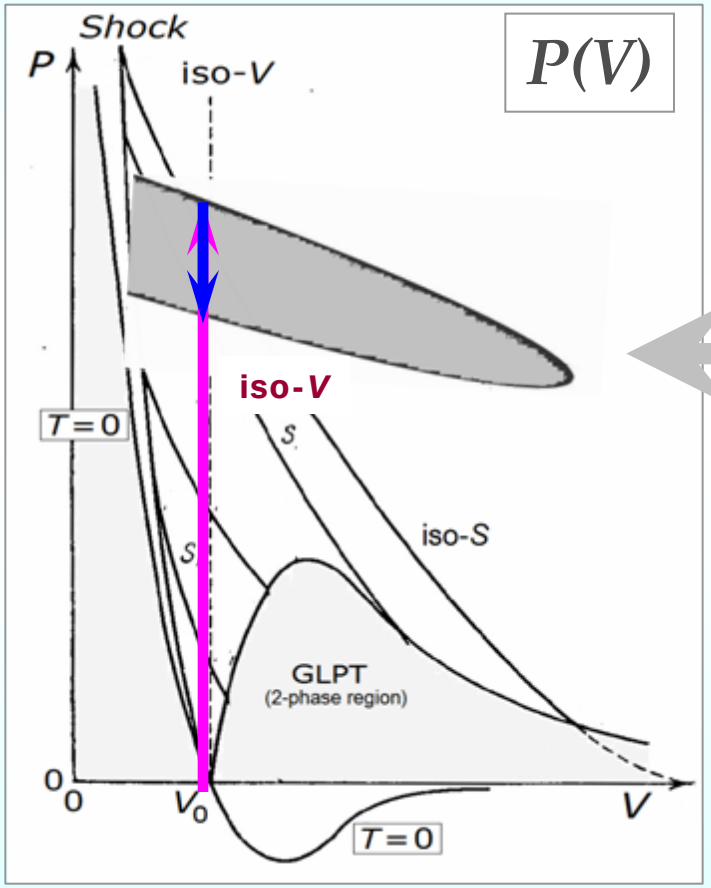
Entropic (*deconfinement-driven*) **phase transition**
SU(3) model (*Veronica Dexheimer & Stefen Schramm*)

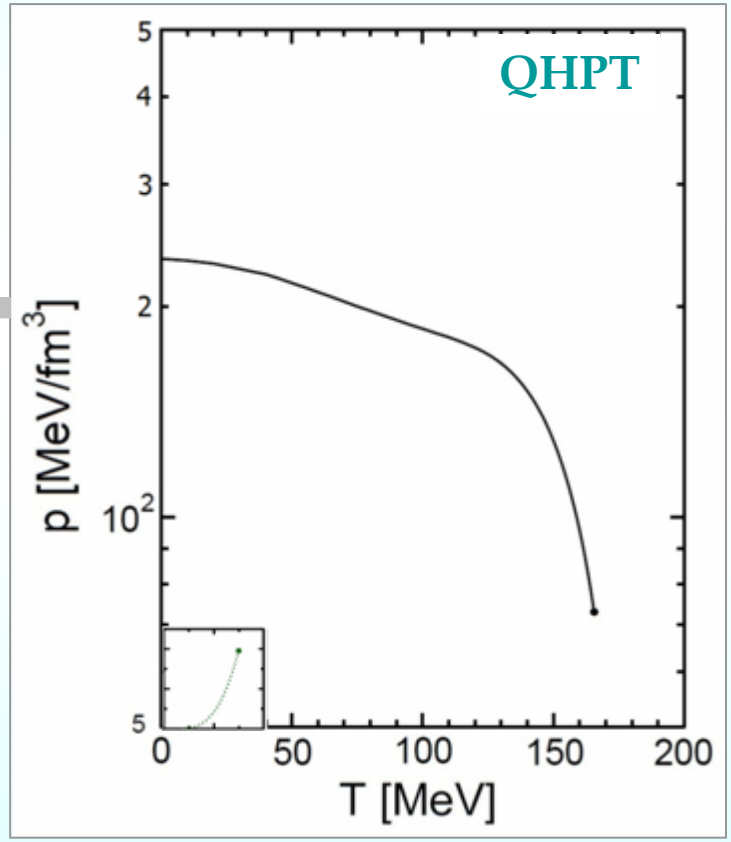
Crossing of two-phase region via isochoric heating

Multy-layered structure *of* thermodynamic surfaces *for* entropic phase transition *over* *p-V* plane

T(p,V), U(p,V), S(p,V)…

Path through two-phase region via middle layer





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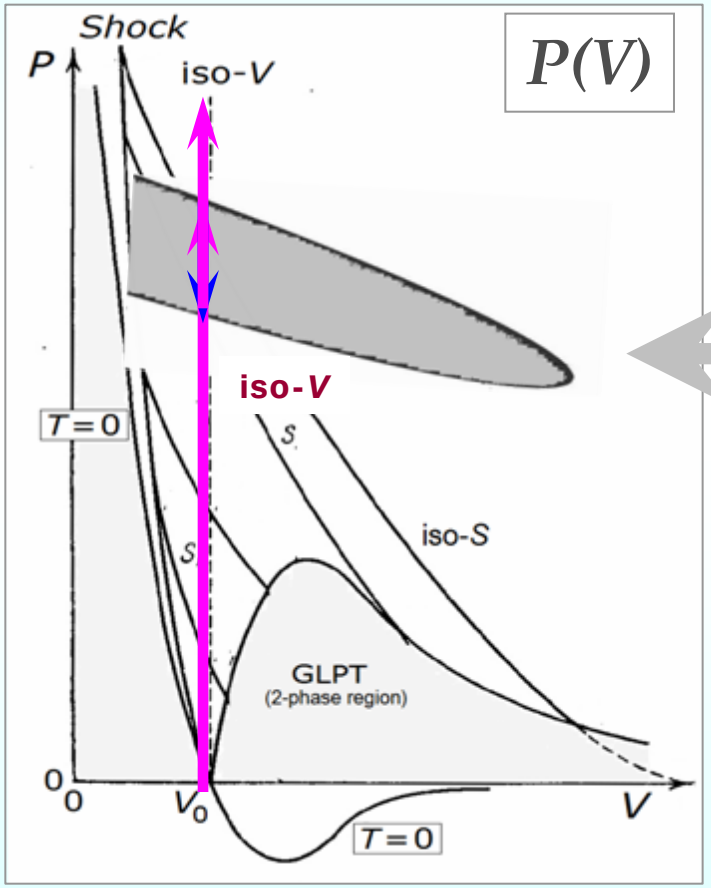
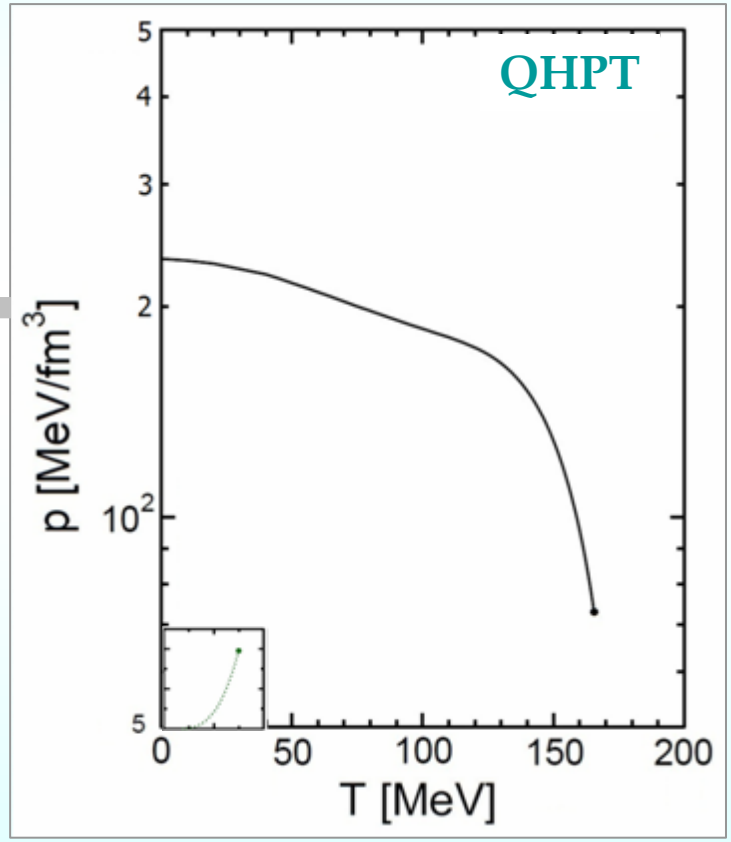
T(p,V), U(p,V), S(p,V)…

Path over two-phase region via upper layer





Gas-liquid phase transition
(*Van-der-Waals-like*)

Entropic (*deconfinement-driven*) **phase transition**
SU(3) model (*Veronica Dexheimer & Stefen Schramm)*

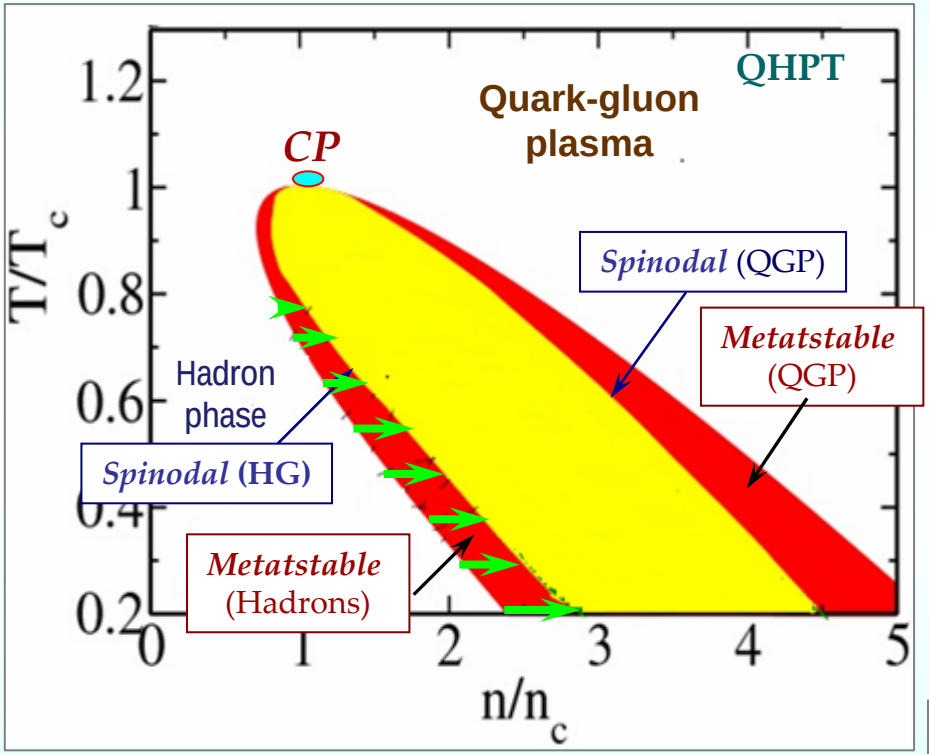
Crossing of two-phase region via isochoric heating

Abnomal topology *of* binodals *and* spinodals

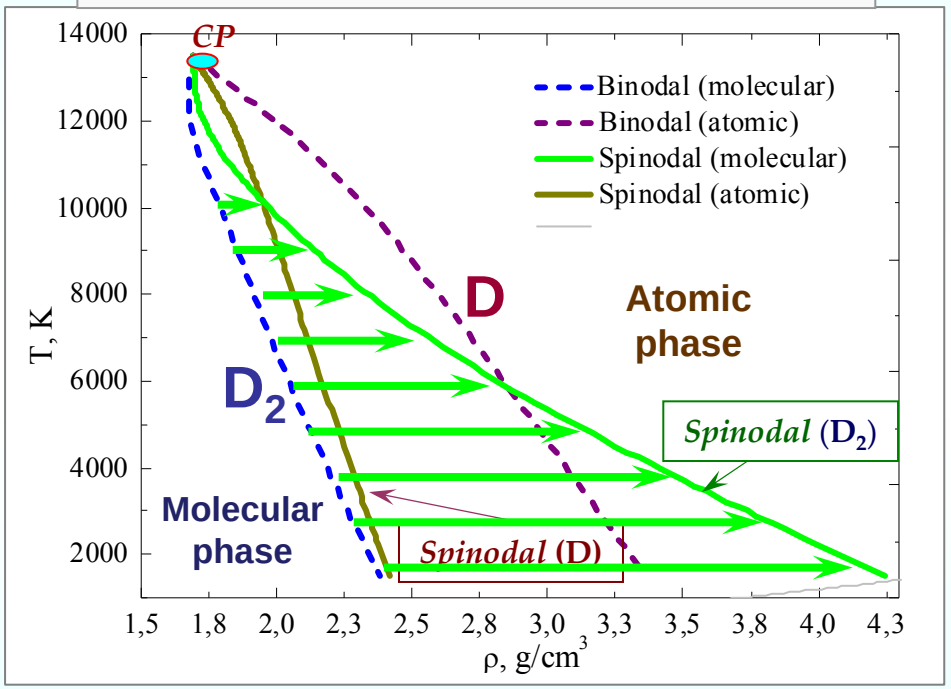
in the region of entropic phase transition

(T - ρ diagram)

Vladimir Skokov, *Int. Conference* "Prerow-2009"



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



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

NB !

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

Iosilevskiy I. // in "*Physics of Extreme States of Matter*", Eds. V. Fortov et al. (Chernogolovka: IPCP RAS), Russia, (2013) 136.

Abnomal topology *of* binodals *and* spinodals

in the region of entropic phase transition

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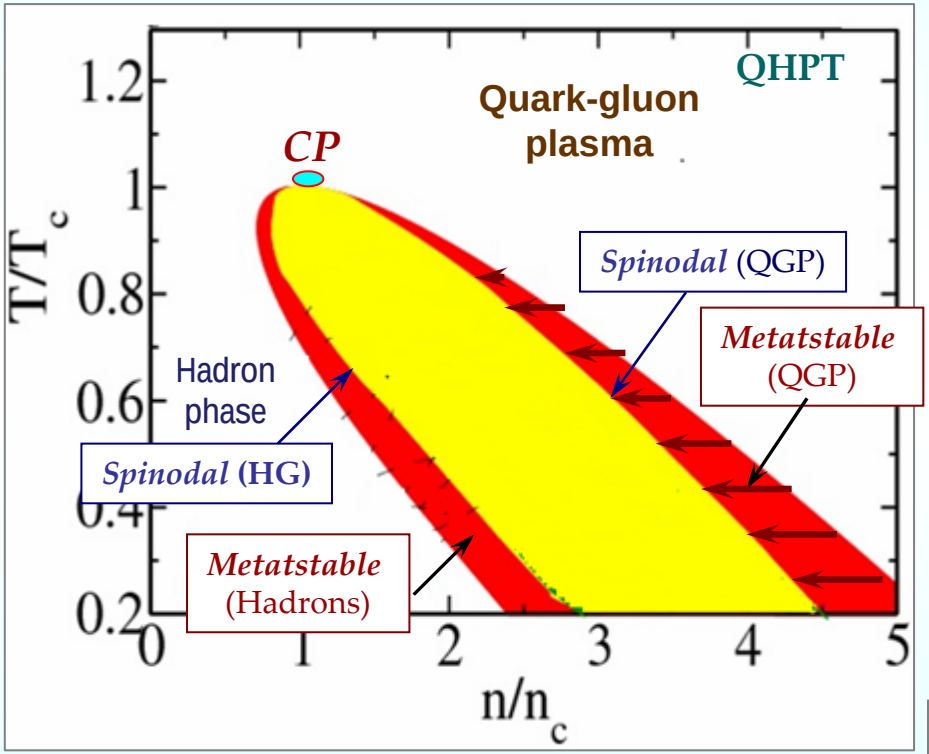
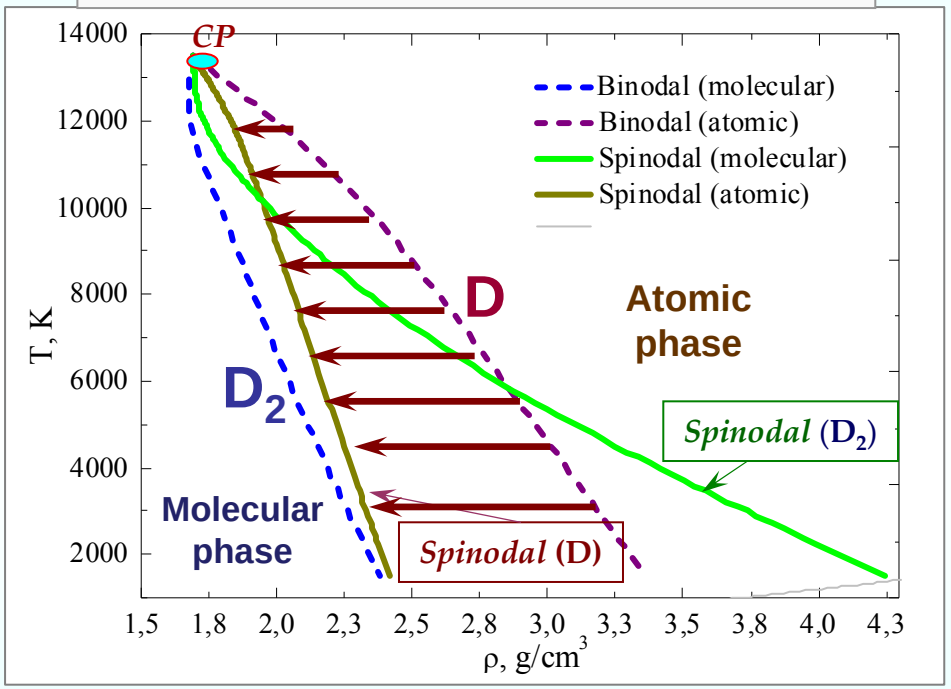


Code SAHA-D
Gryaznov V., Iosilevskiy I. // *J. Phys. A*, **42** (2009)



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Iosilevskiy I. // in "*Physics of Extreme States of Matter*", Eds. V. Fortov et al. (Chernogolovka: IPCP RAS), Russia, (2013) 136.

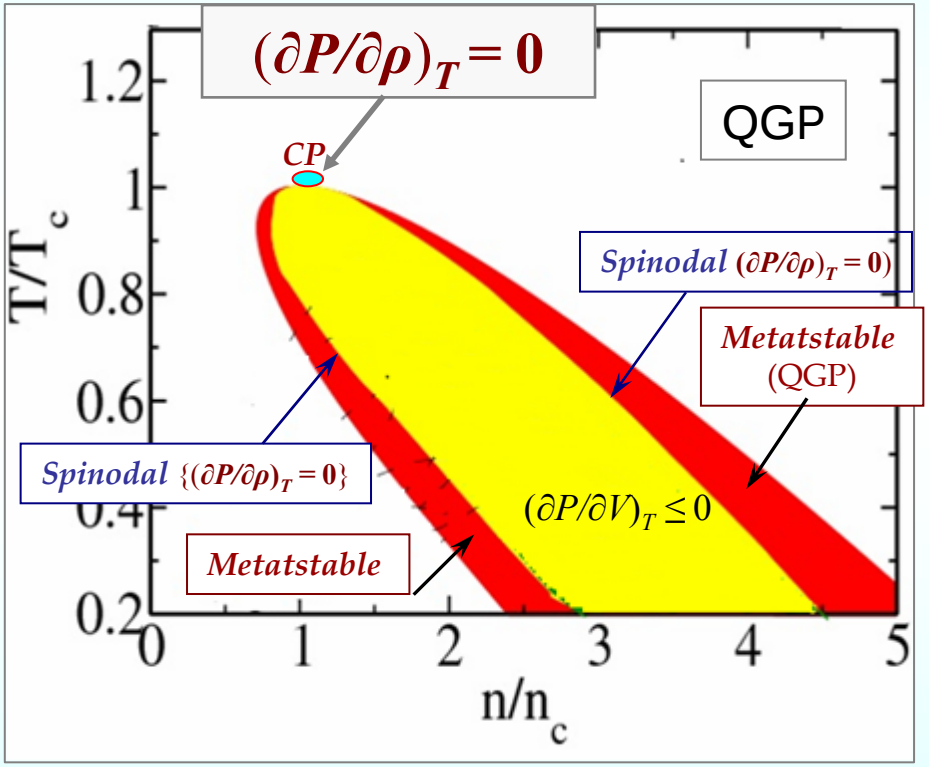
Abnomal features *of* entropic phase transition

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

(T - ρ diagram)

QHPT

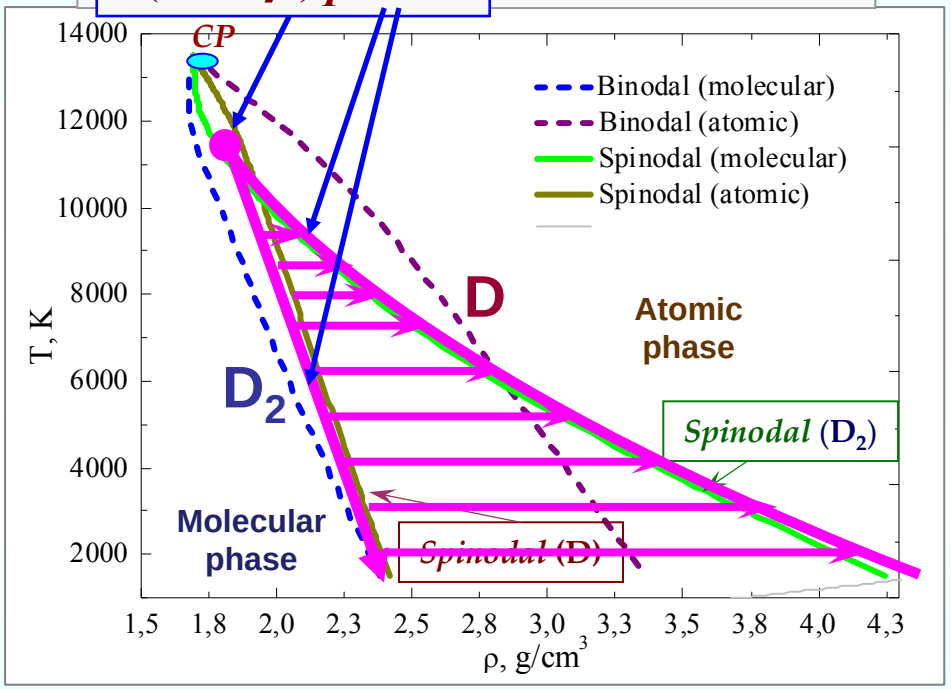
After Vladimir Skokov, *Int. Conf.* "Prerow-2009"



QHPT

HA-D

I. // J. Phys. A, **42** (2009)



NB !

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

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

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

Features of entropic phase transitions

(*ionization- and dissociation-driven*)

Entropic PT obeys to anomalous thermodynamics !

- *negative Gruneizen parameter* $(\partial P/\partial U)_V < 0$
- *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.*

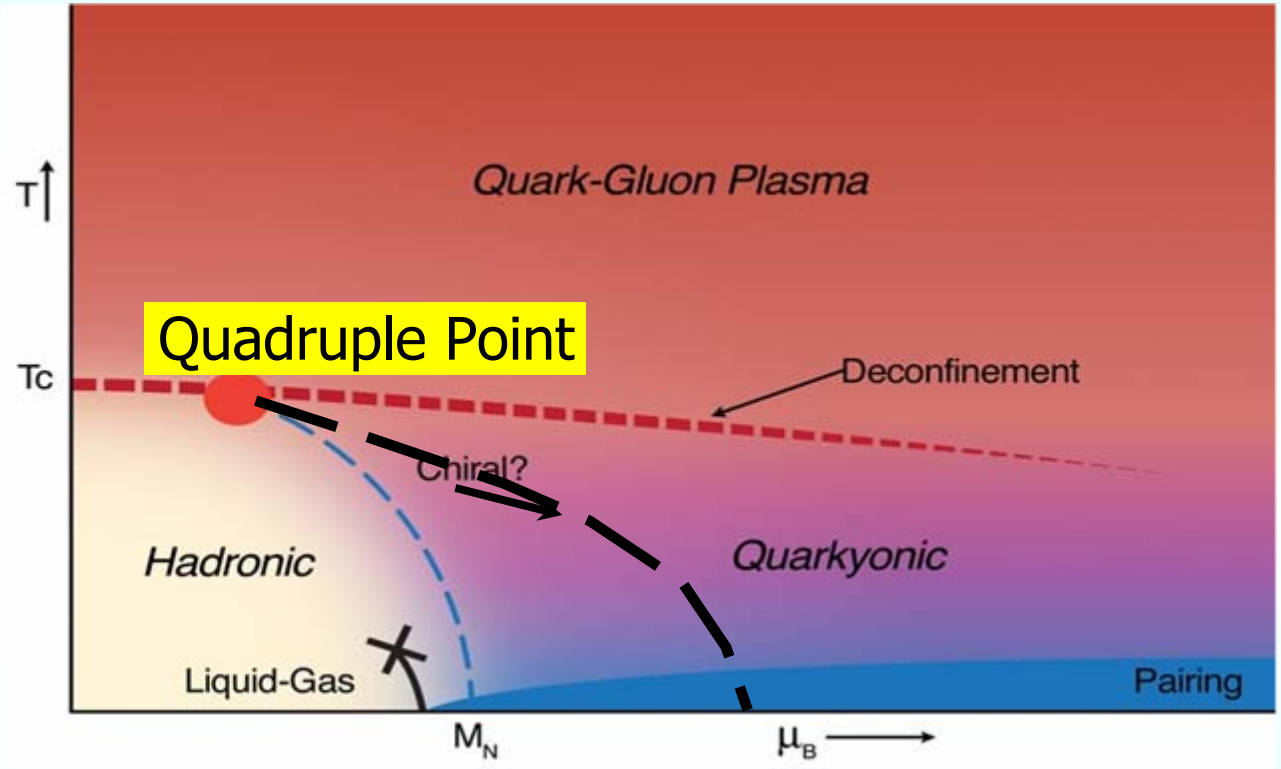
- *abnomal order of isotherms (!)*
- *abnomal order of isentropes (!)*
- *abnomal order of iso-H and iso-U (!)*
- *abnomal order of shock adiabats (Hugoniots !)*
- *. . . . . etc. etc.*

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

I. Iosilevskiy, *Entropic Phase Transitions,* in "Physics of Extreme States of Matter" Eds. V. Fortov et al. *J. Phys: Conf. Ser.* (IOP Pub.) 2015

Outlook

Inventory of new hypothetical phase transitions

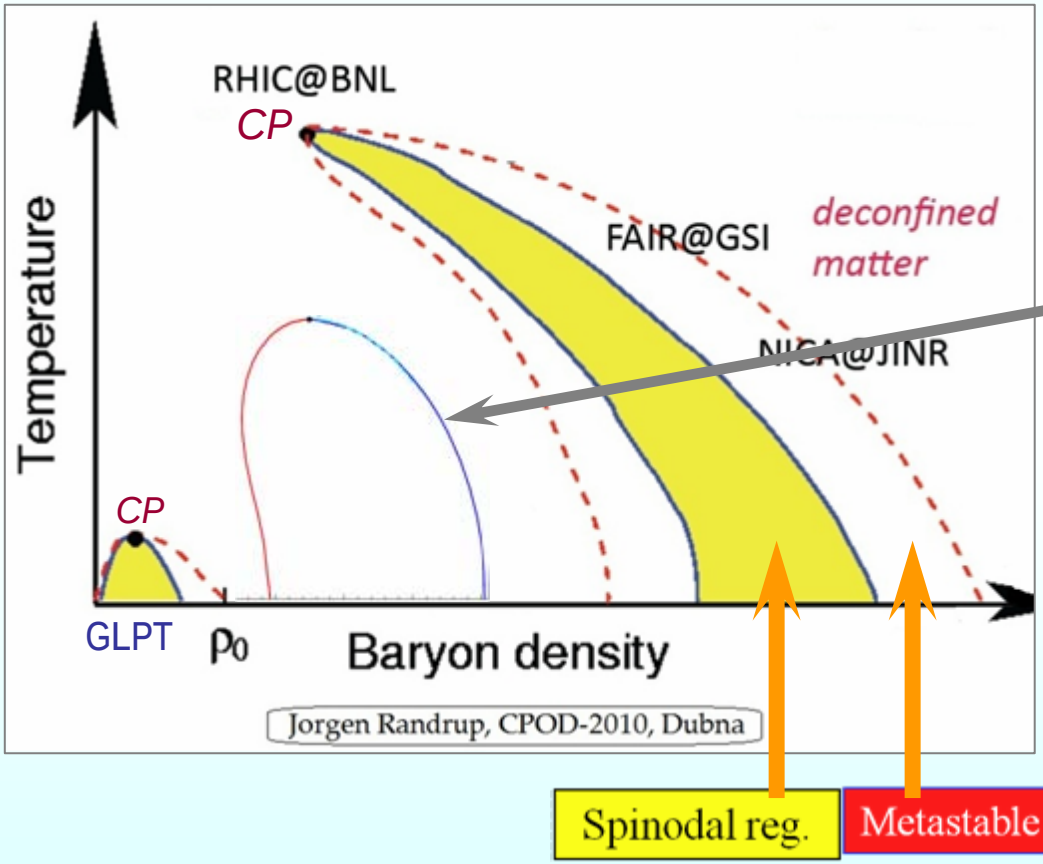


R.Pisarski & L.McLerran, EMMI-Wroclaw /2009/, QCD-Bad Honnef /2010/

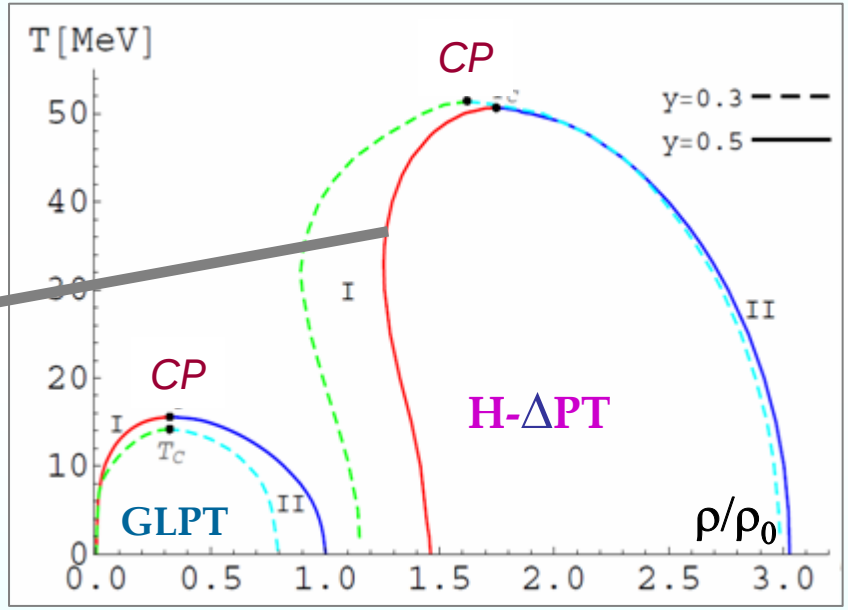
What type of all these hypothetical phase transitions:
- are they enthalpic or entropic PTs ?

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

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



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



Lavagno A. and Pigato D.
Phys. Rev. C., **86**, (2012)
Thermodynamic instability in warm and dense nuclear matter

Spinodal reg. | Metastable

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

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**.

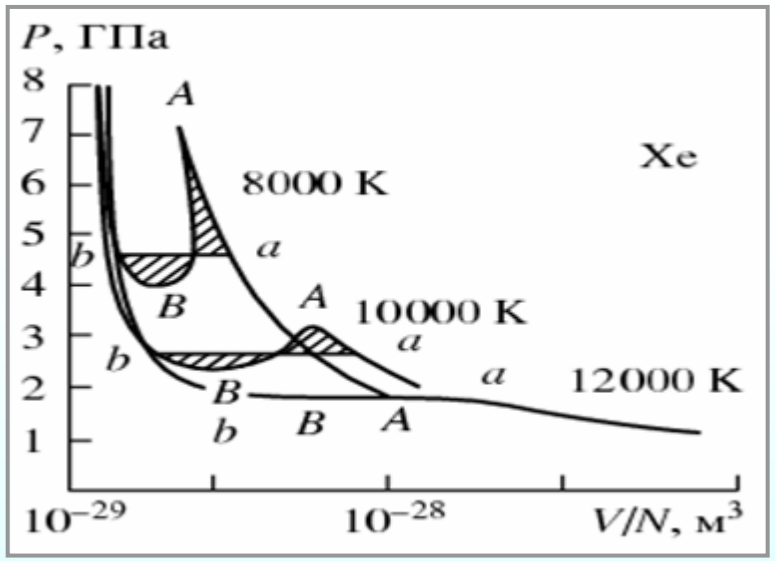
- **In spite of** many order **difference** in density and energy of **deconfinement-driven PT** and **ionization-driven PT** (dissociation-driven, polimerization-driven...) the both have many **common features** because both are **entropic PT**s.

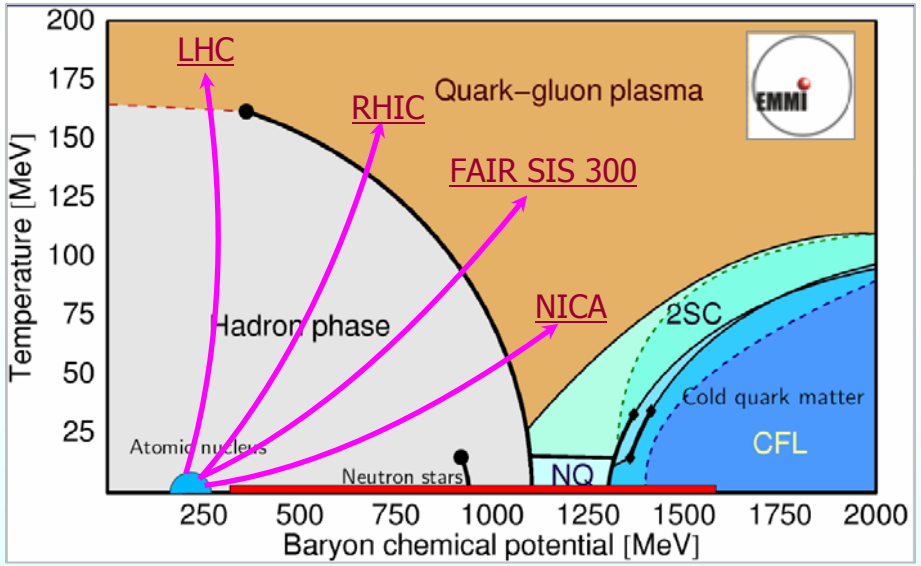
- **Properties** of **entropic PT**s **differ significantly** from those of **enthalpic PT**s.

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

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

Thank you!





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