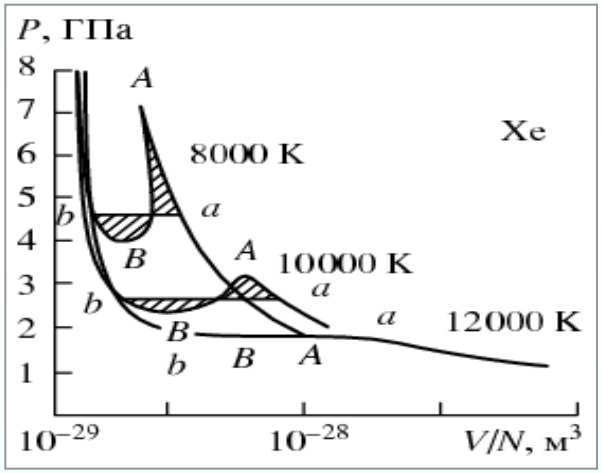
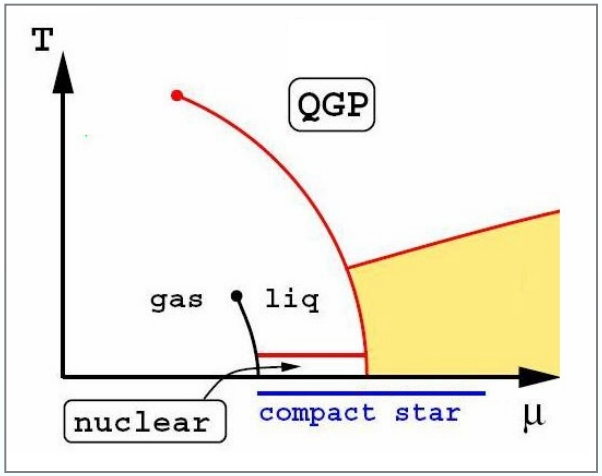
Brainstorming on Compact objects, their equation of state, related explosive events, and their nucleosynthesis
Sept. 29-Oct. 01 2016, Workshop, Basel, Switzerland

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

The main point

Proposal:

Additional subdivision *(classification)* **of all 1st-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 it in much more general context

arXiv:1403.8053 arXiv:1504.058050

The key feature

Enthalpic vs entropic PT

PT under isothermal compression

GLPT $\Leftrightarrow \Delta H < 0$

Enthalpic PT

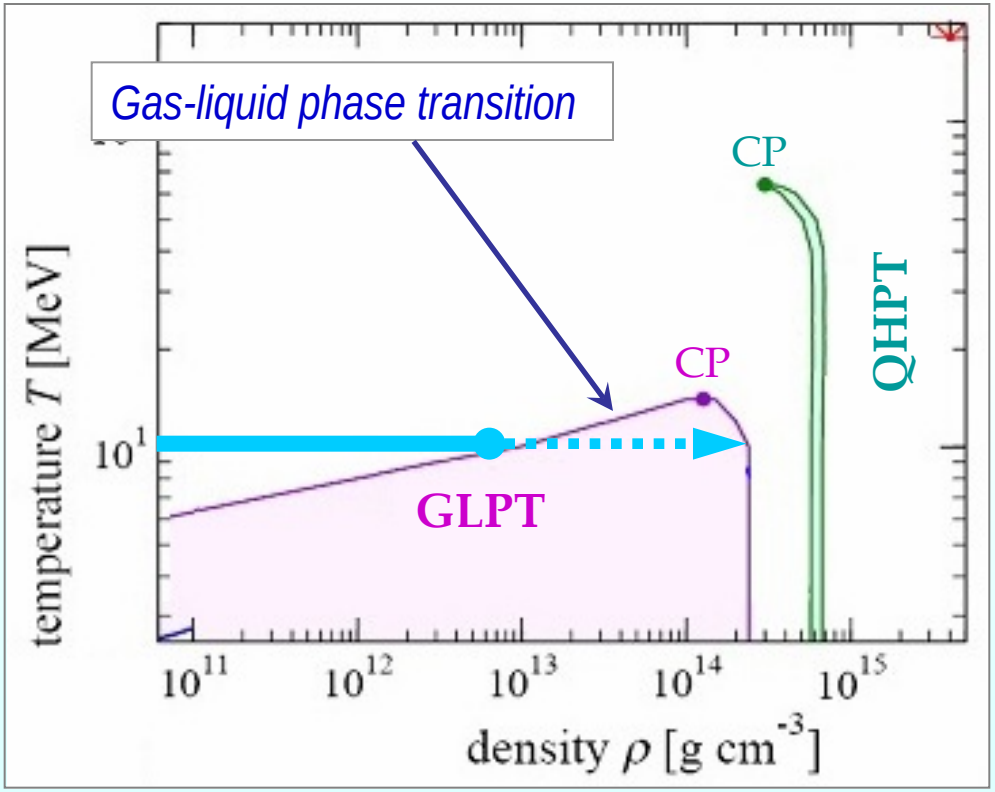


Figure after David Blaschke

The key feature

Enthalpic vs entropic PT

PT under isothermal compression

GLPT $\Leftrightarrow$ $\Delta H < 0$

QHPT $\Leftrightarrow$ $-T\Delta S < 0$

Enthalpic PT

Entropic PT

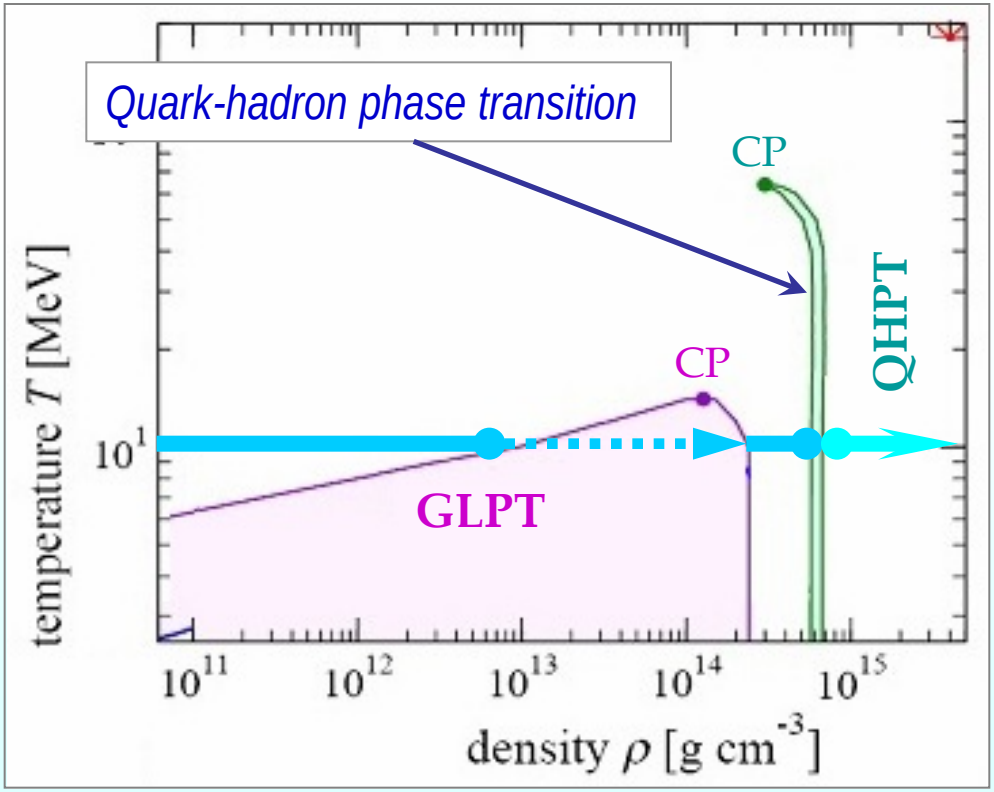


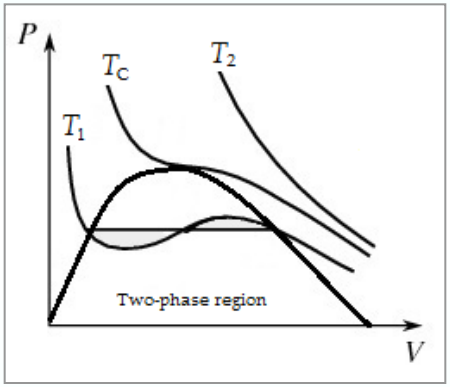
Figure after David Blaschke

Definition

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

$$G = H - TS$$

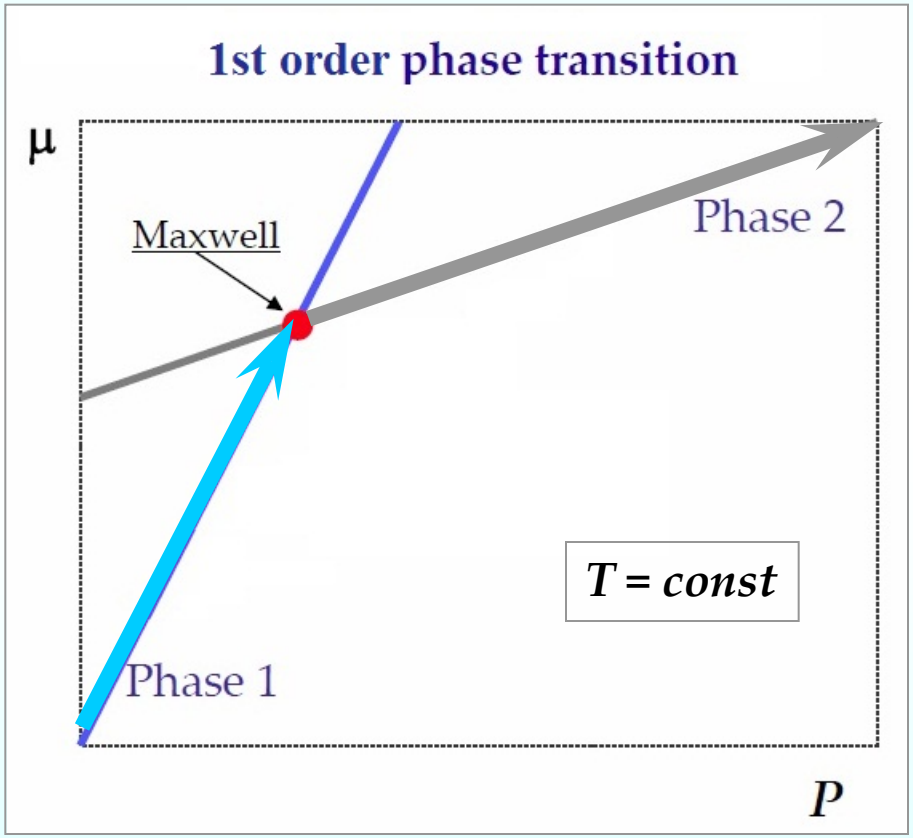
VdW-like PT



Maxwell “Equal squares”

Enthalpic PT

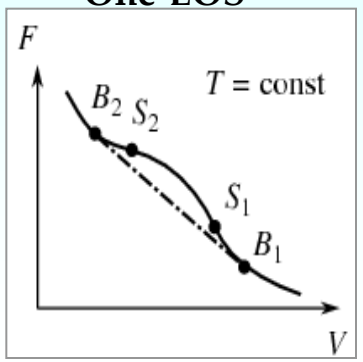
$\Delta H = T\Delta S \; < 0$



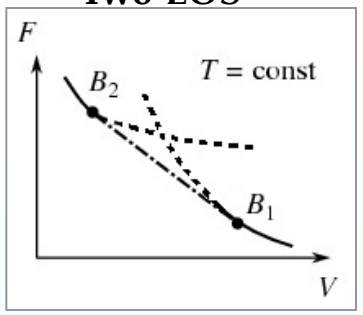
Iso-*T* compression

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

One-EOS



Two-EOS



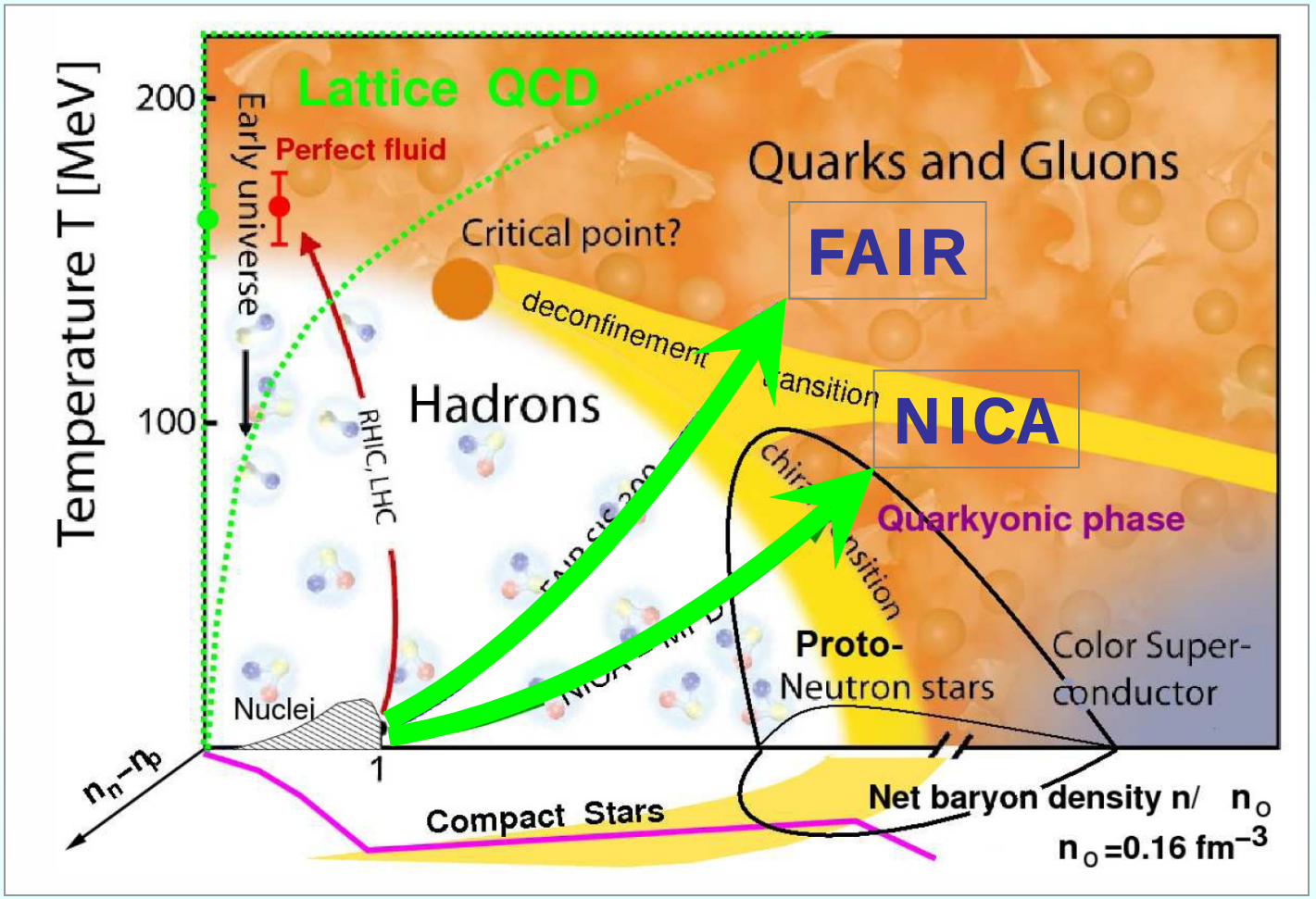
“Double tangent”

Entropic PT

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

Motivation

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

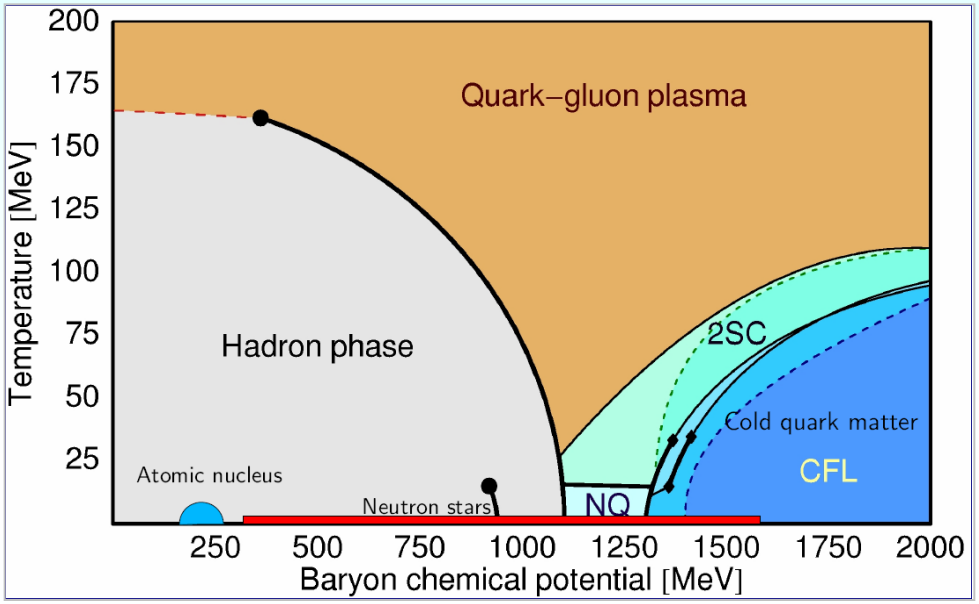


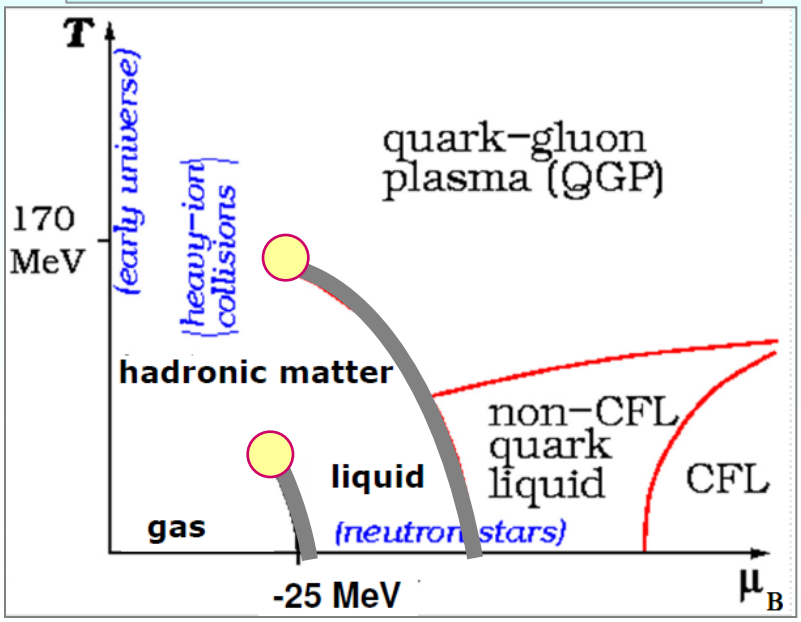
NICA White Book

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

Phase diagram of matter in ultra-high energy and density

(*schematic*)

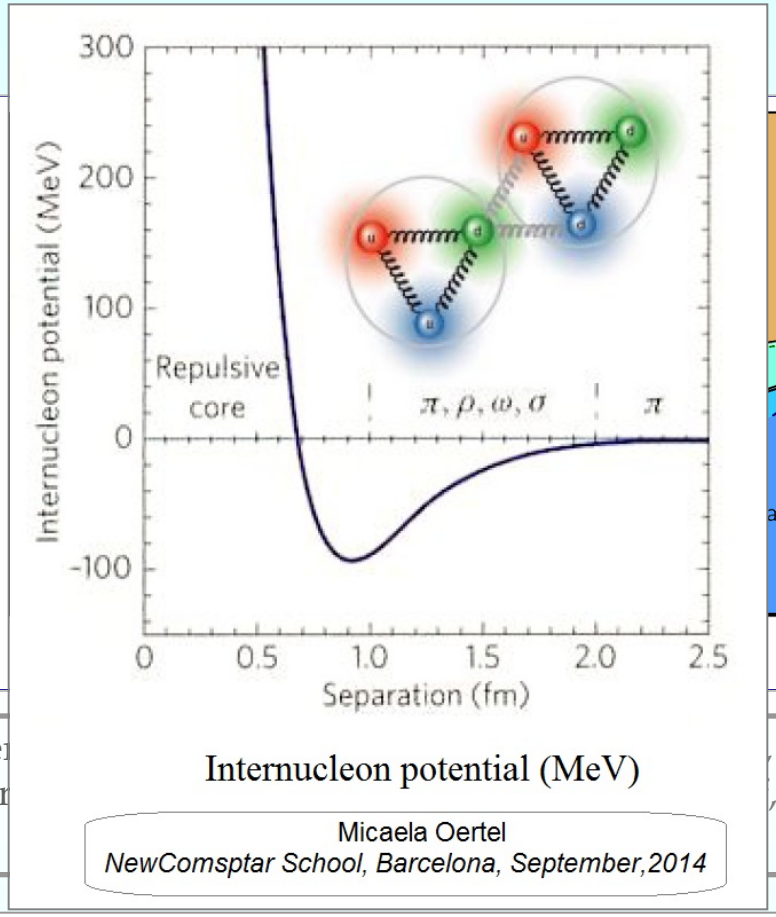




After Fridolin Weber, WEHS Seminar, Bad Honnef, 2006
After David Blaschke, WEHS Seminar, Bad Honnef, 2007
……..

Source: WIKIPEDIA

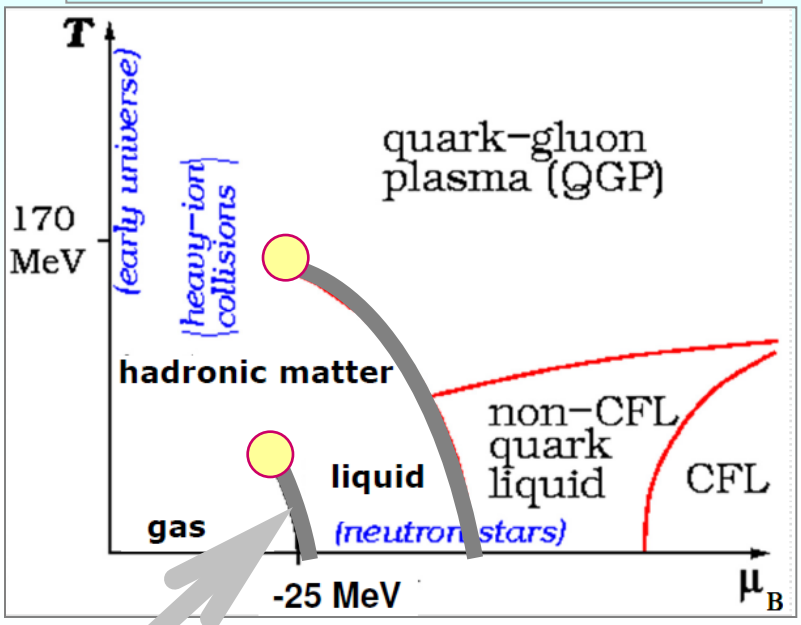
Phase diagram of matter in ultra-high energy and density



Internucleon potential (MeV)

Micaela Oertel
NewComsptar School, Barcelona, September,2014

(*schematic*)

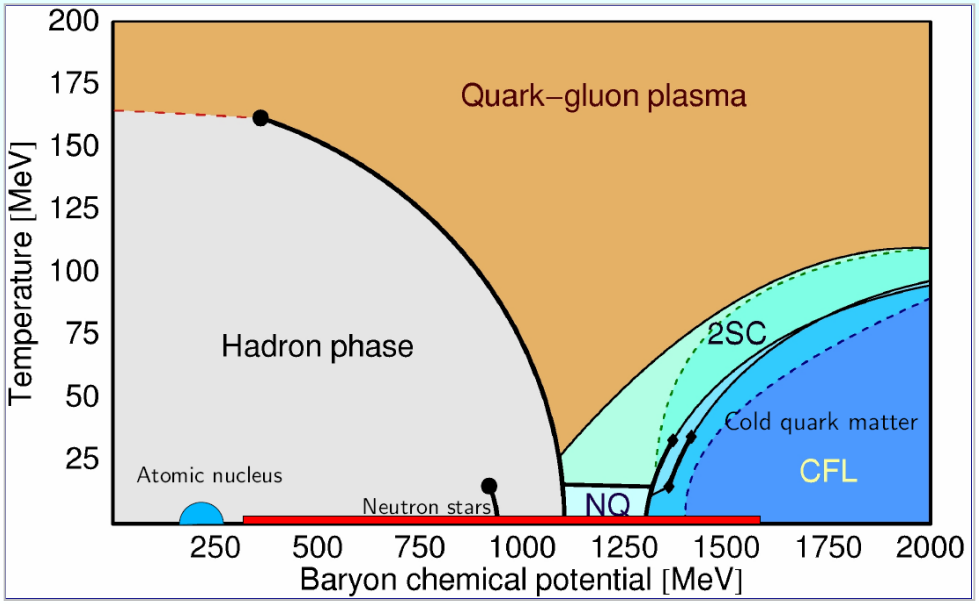


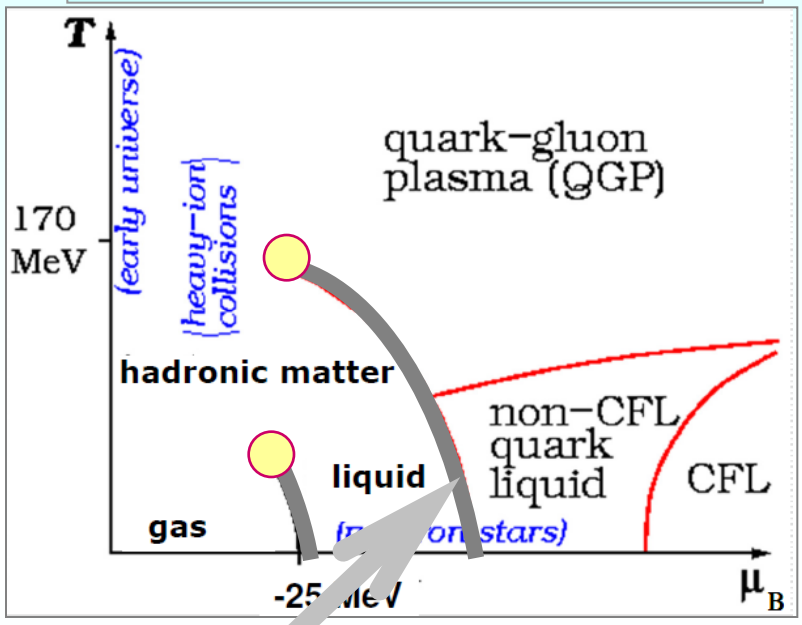
Source: WIKIPEDIA

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

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
……..

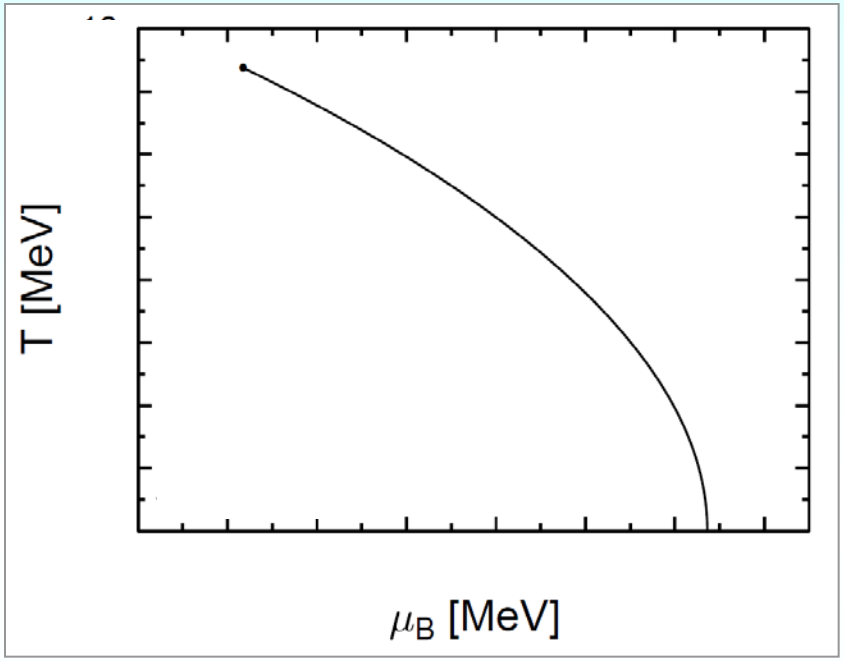
Source: WIKIPEDIA

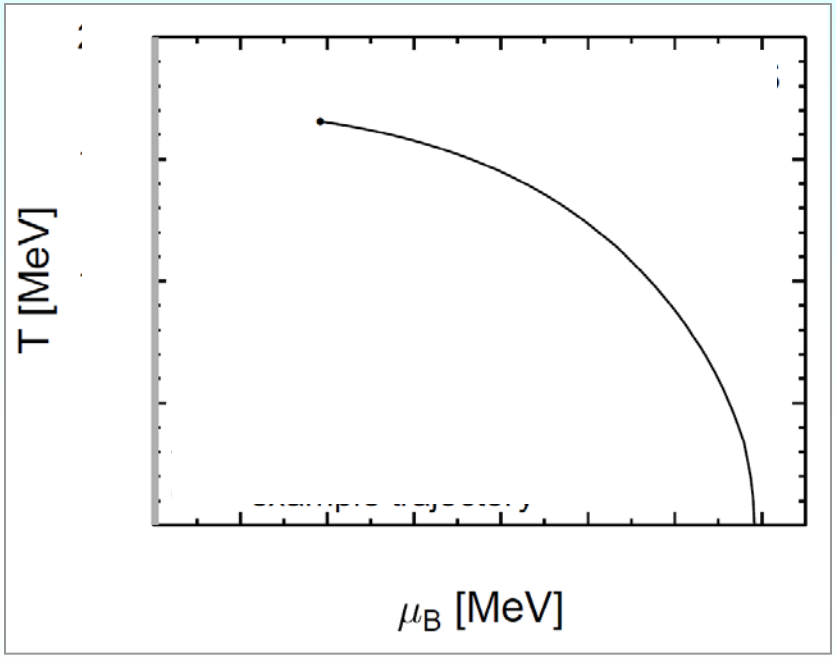
"Gas-liquid" phase transition in Coulombless system {***p,n,N(A,Z)***}
/ GLPT /

Quark-Hadron phase transition
/ QHPT /

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

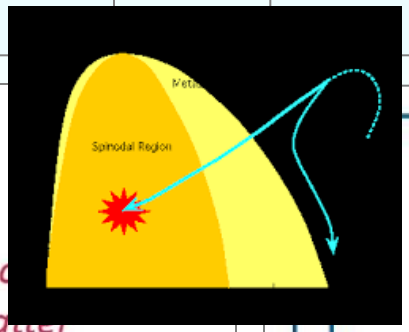
NB!

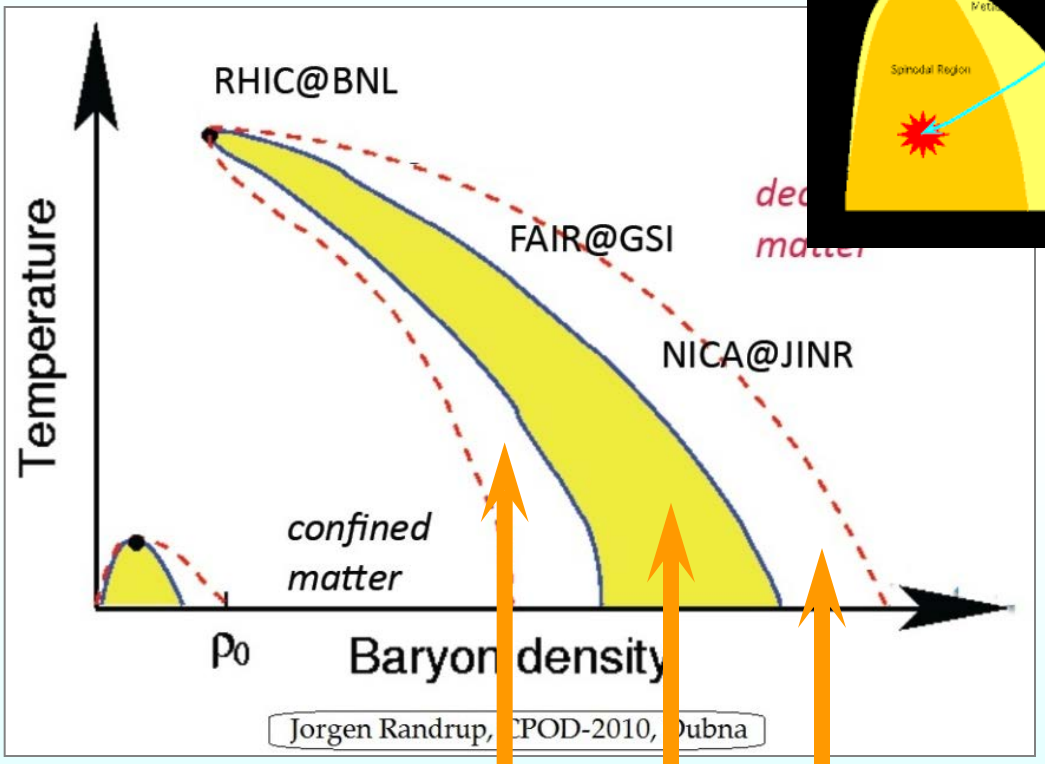
One could not distinguish GLPT vs. **QHPT** in T- μ plane

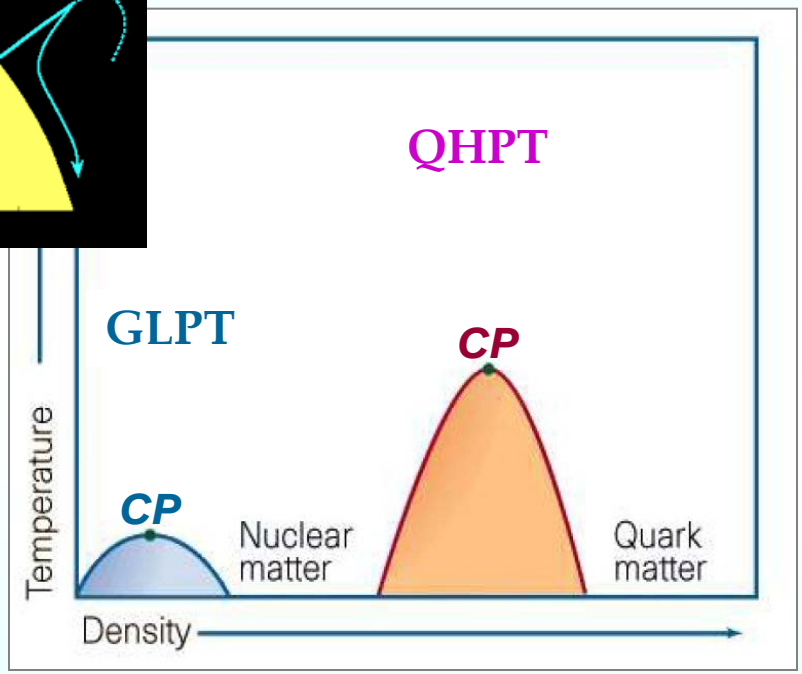
Gas-liquid *and* Quark-hadron phase transitions are often considered as similar

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

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







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

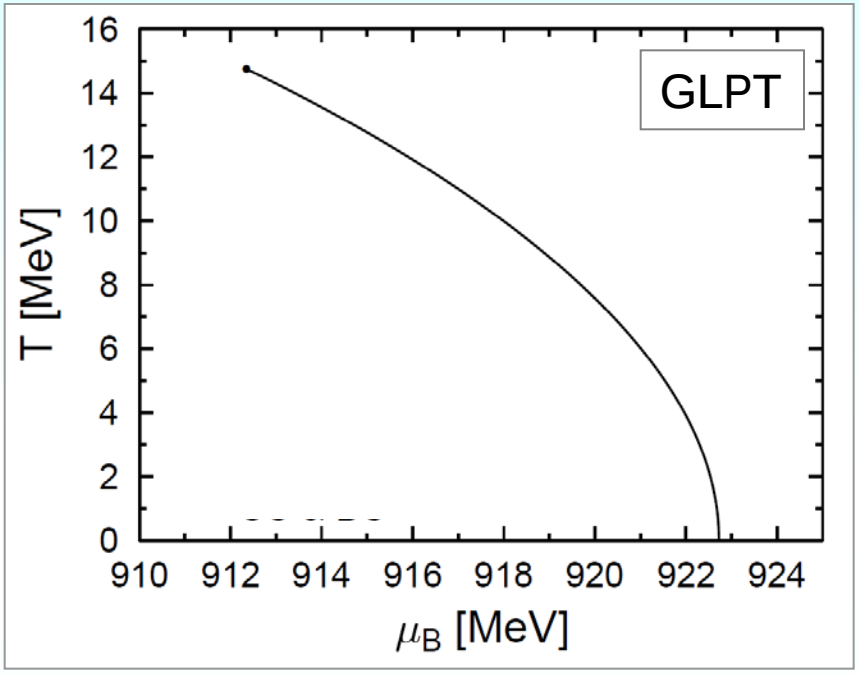
Metastable

Spinodal region

Metastable

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

(symmetric case)

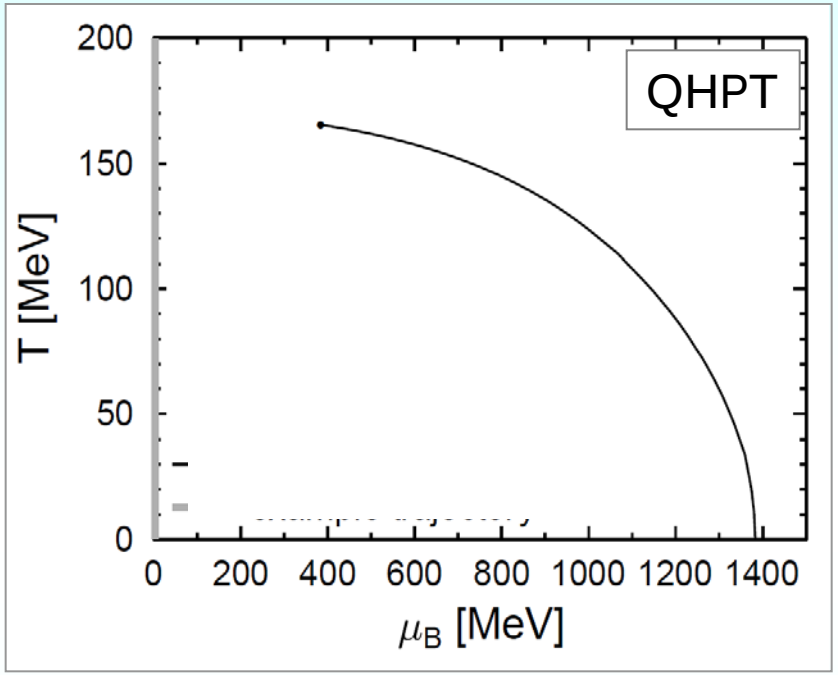


FSUGold (*Matthias Hempel* (*))

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)

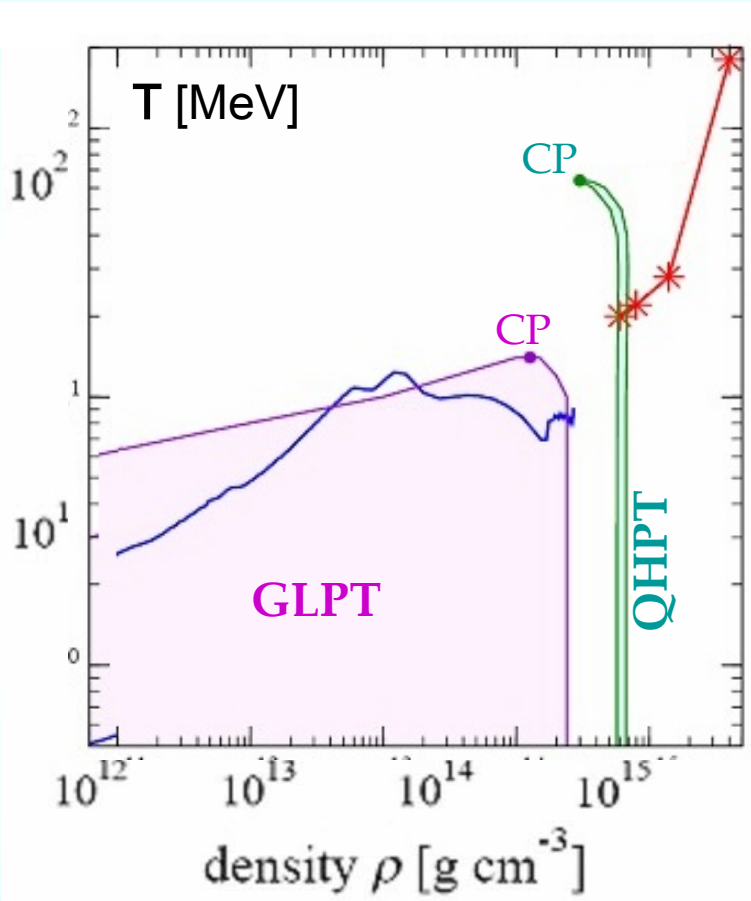
arXiv:1302.2835

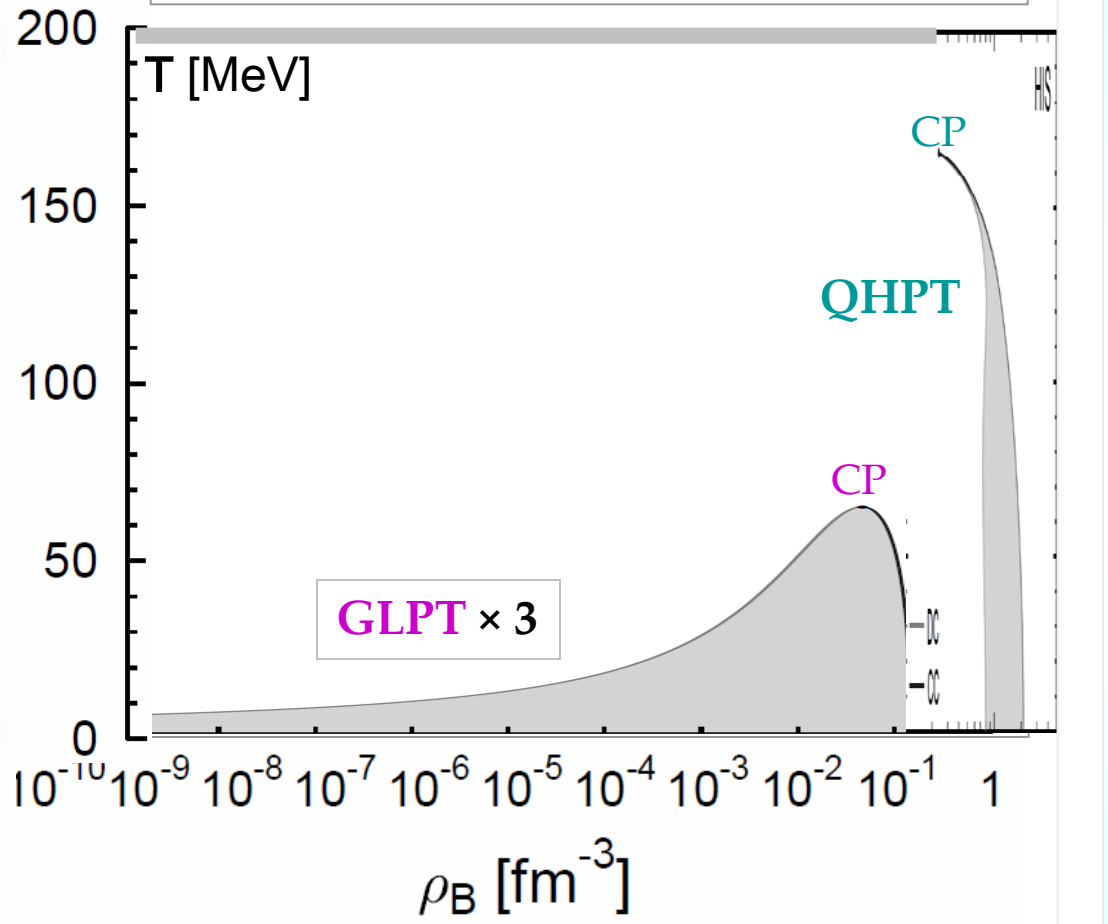
No!

Enthalpic PT ≠ **Entropic PT**

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

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

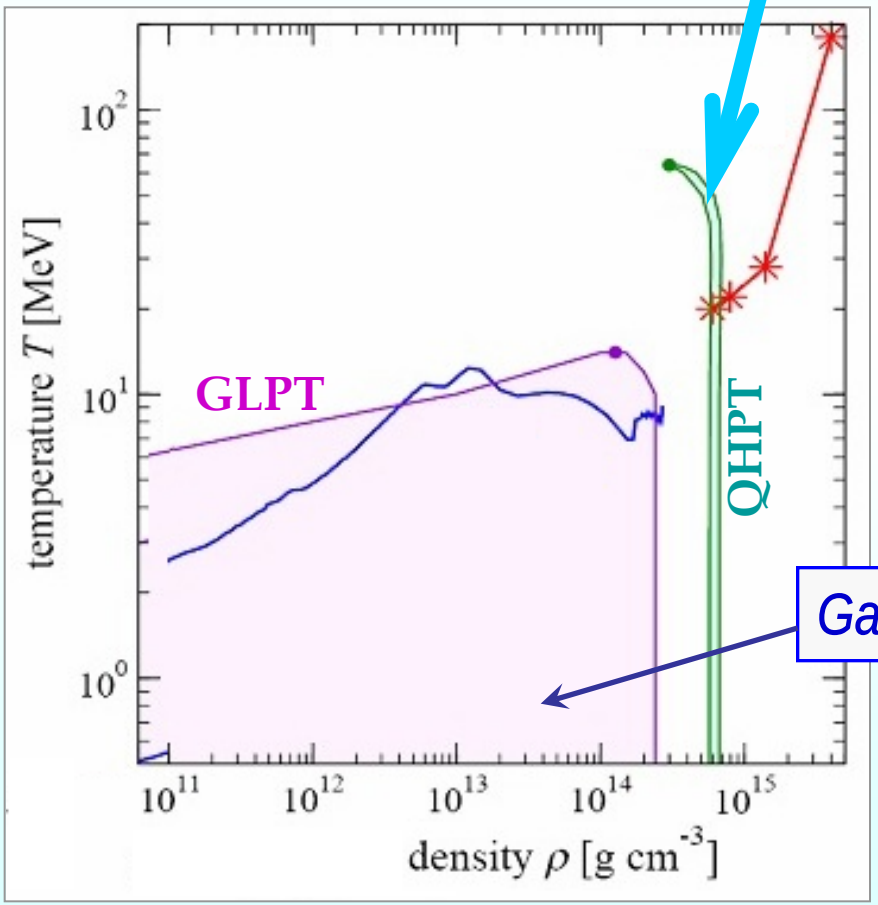
FSUGold (*Matthias Hempel*)	SU(3) model (*Veronica Dexheimer*)
GLPT	**QHPT**

arXiv:1302.2835

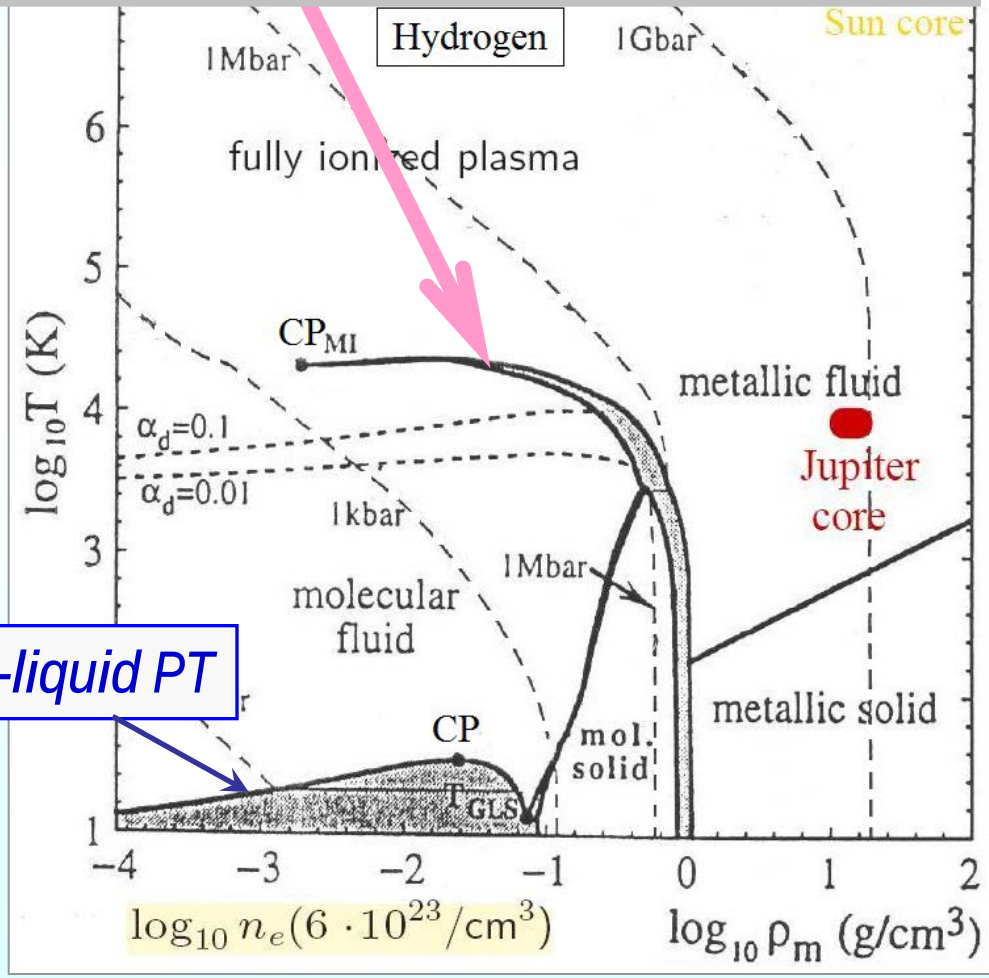
Ionization-driven (*entropic*) phase transition *in* hydrogen

Deconfinement-driven (*entropic*) phase transition *in* QCD

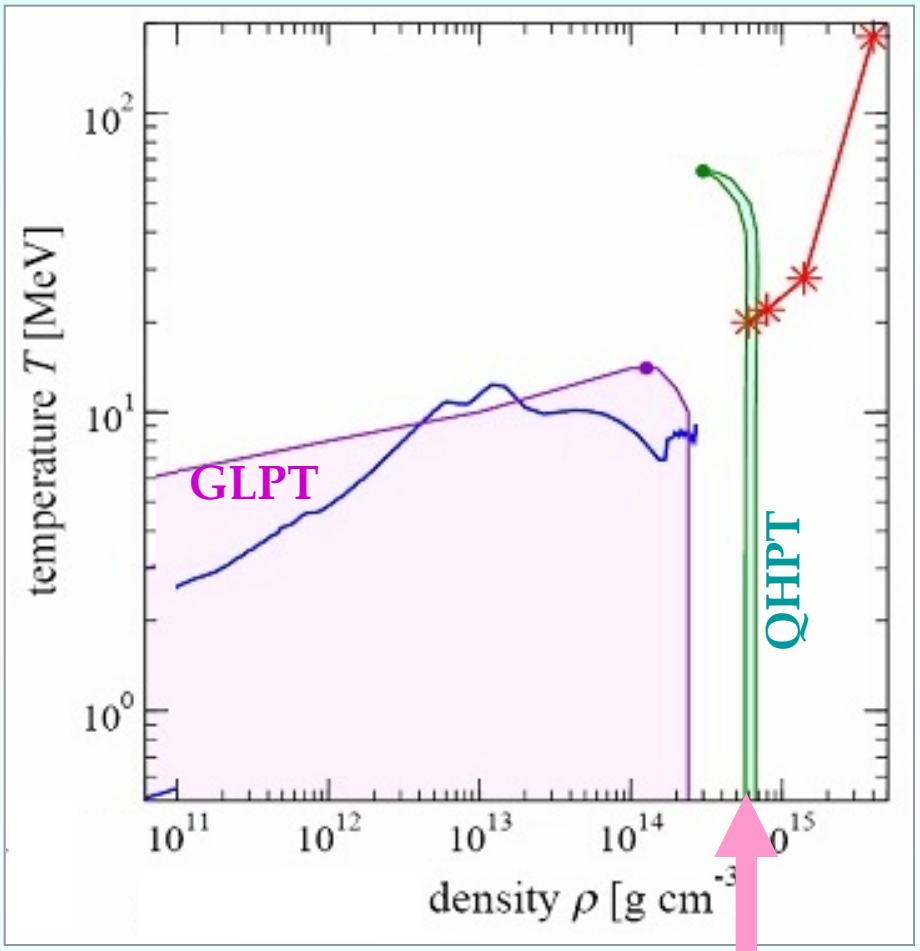
General: **Delocalization-driven** PT-s *in* matter *of* **extreme state**

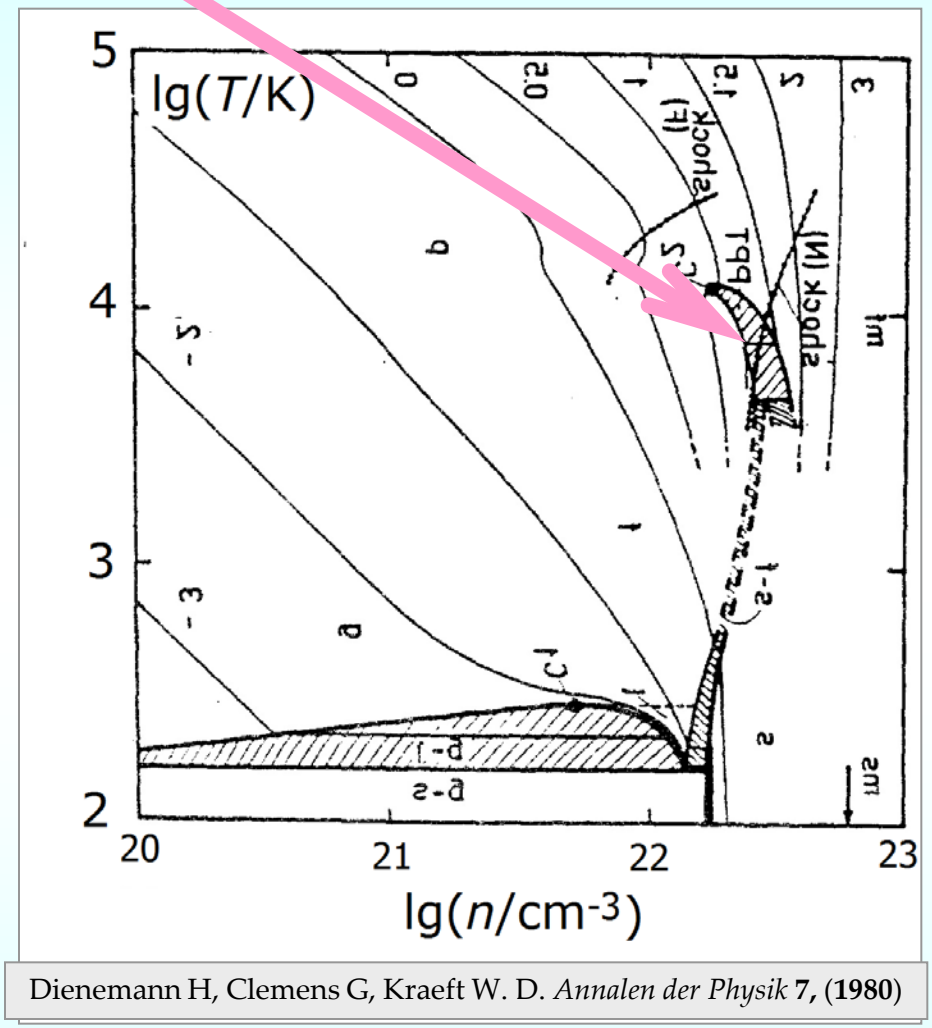


Gas-liquid PT



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





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

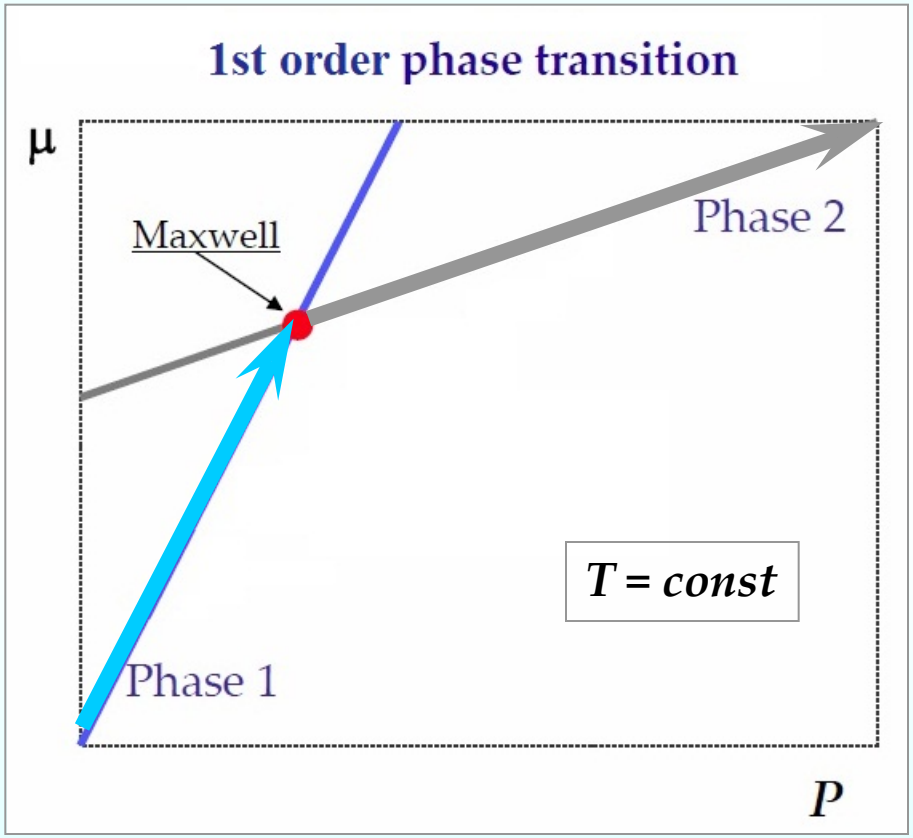
Gas-liquid *and* **deconfinement-driven** PT *in* dense nuclear matter

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

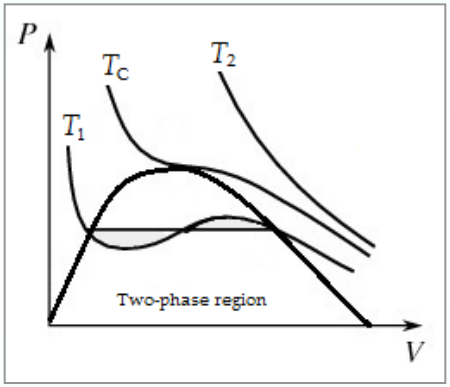
Definition

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

$$G = H - TS$$

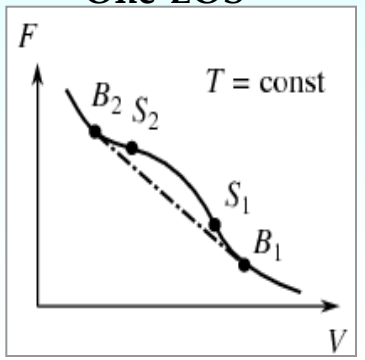


VdW-like PT

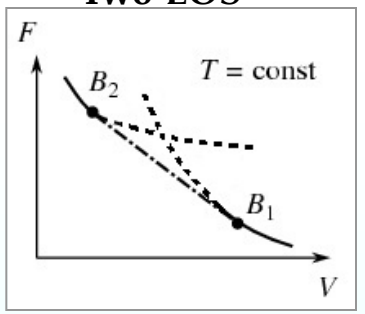


Maxwell "Equal squares"

One-EOS



Two-EOS



"Double tangent"

Enthalpic PT

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

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

Iso-*T* compression

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

Entropic PT

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

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

Enthalpic *vs* Entropic PTs

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

GLPT – *gas-liquid phase transition*

PPT – *plasma phase transition*

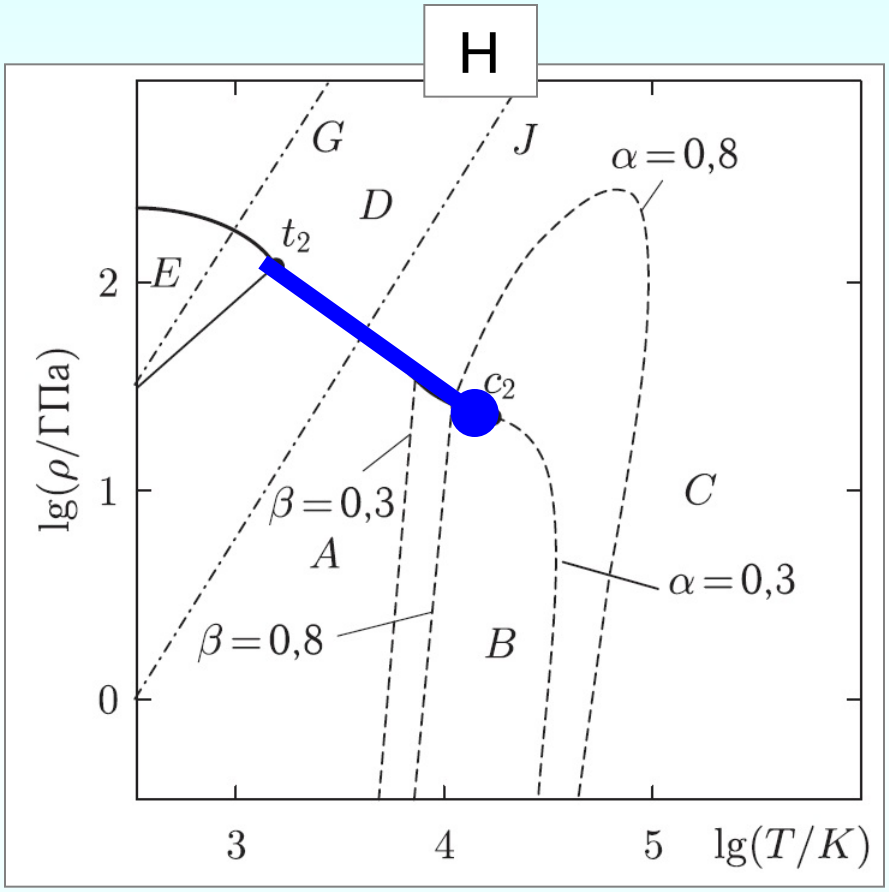
Enthalpic PT

$$\left(d\boldsymbol{P}/d\boldsymbol{T}\right)_{\text{binodal}} > \mathbf{0}$$

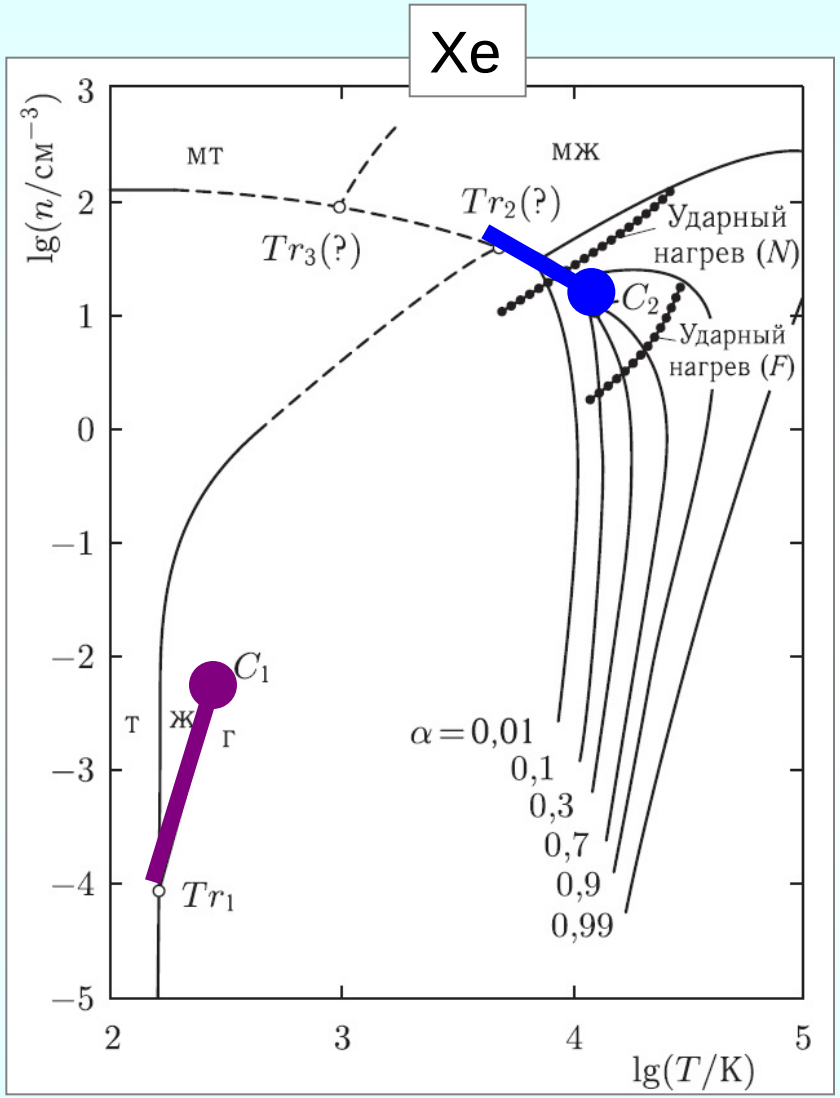
Entropic PT

$$\left(d\boldsymbol{P}/d\boldsymbol{T}\right)_{\text{binodal}} < \mathbf{0}$$

P-T diagram *of* plasma phase transition



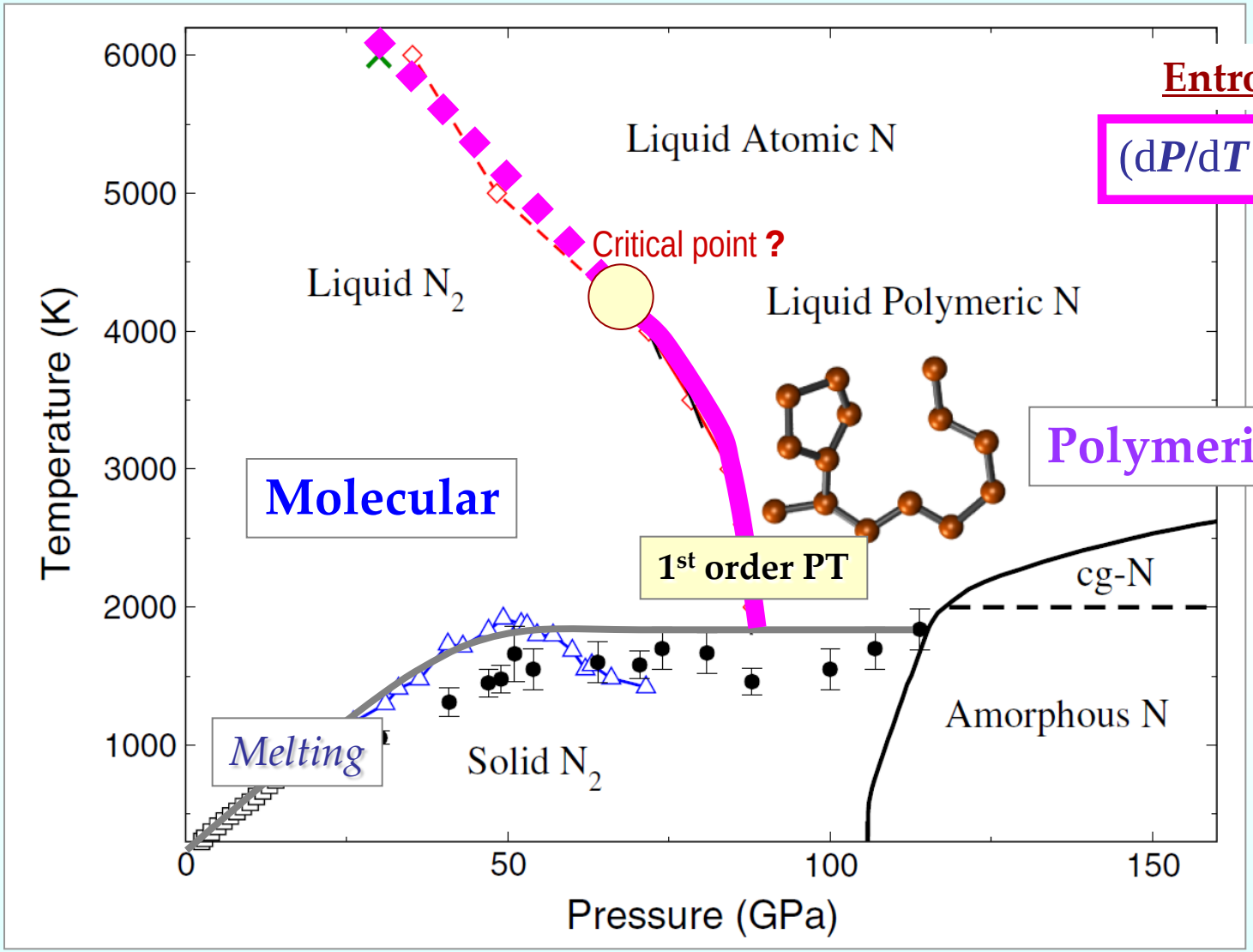
Ebeling W., Reichert W.
Phys. Lett. A, **80** (1985)



Ebeling W., Foerster A., Reichert W.

Gas-liquid phase transition

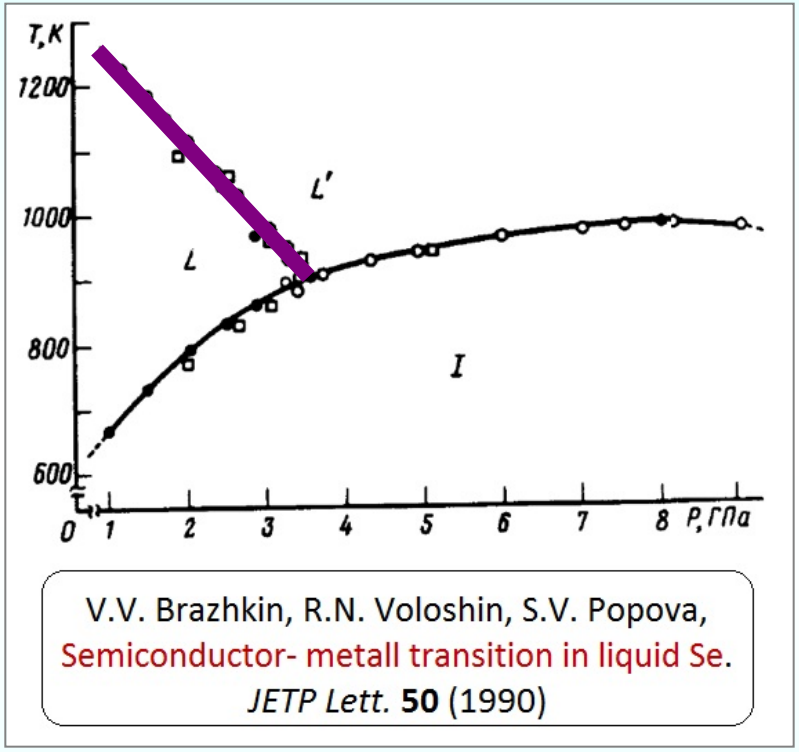
Entropy-driven fluid-fluid phase transitions (N_2)



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

Entropy-driven fluid-fluid phase transitions

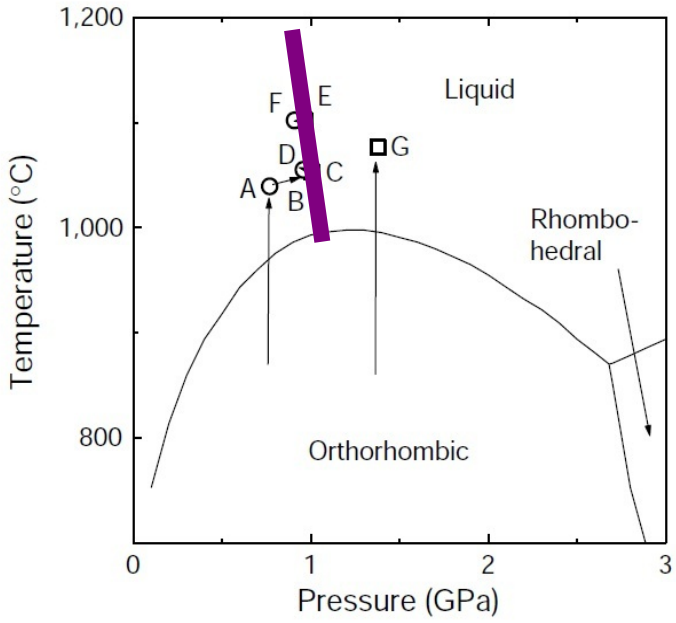
Selenium



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

Experiment

Phosphor



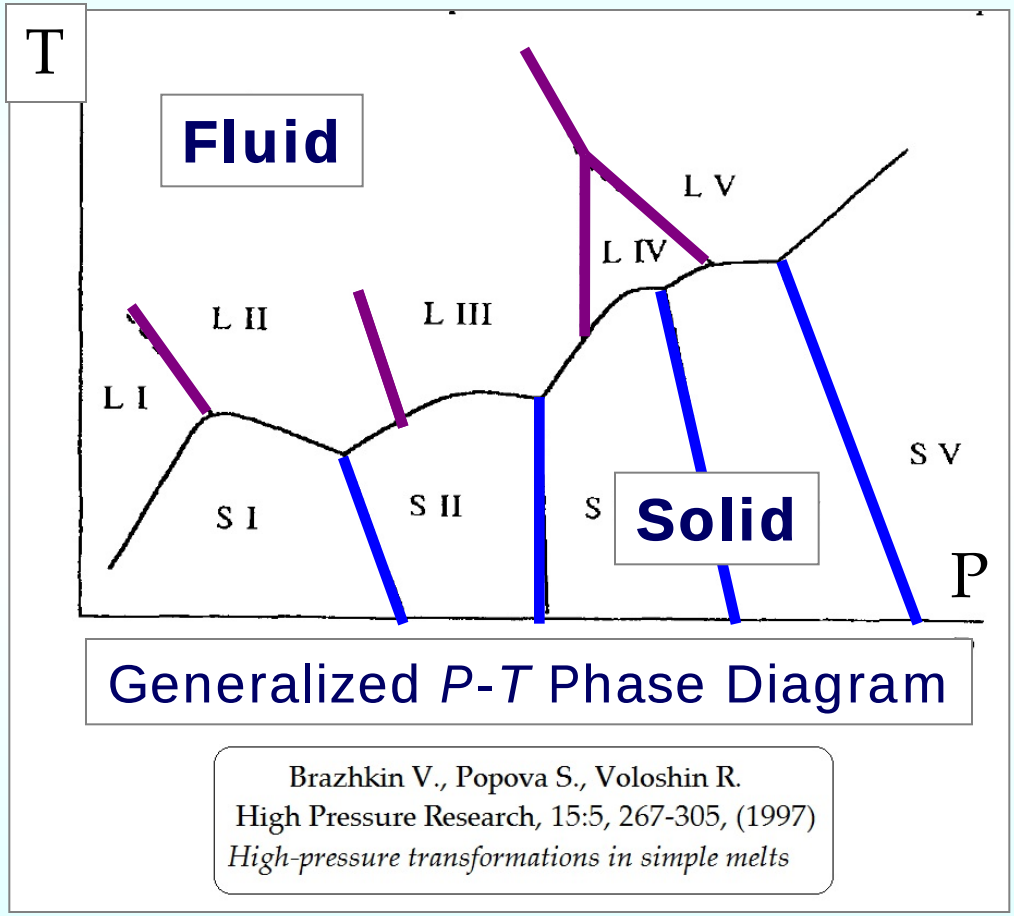
Katayama Y., Mizutani T. *et al.* (*Nature* **403**, 170 (2000)

Experiment

Entalpic and Entropic Phase Transitions ?

Generalized *P-T* Phase Diagram

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 and fluid-fluid PTs are *Entropic* !

Enthalpic *vs* Entropic PTs

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

GLPT – *gas-liquid phase transition*

Enthalpic PT

$$\left(d\boldsymbol{P}/d\boldsymbol{T}\right)_{\text{binodal}} > \mathbf{0}$$

QHPT – *quark-hadron phase transition*

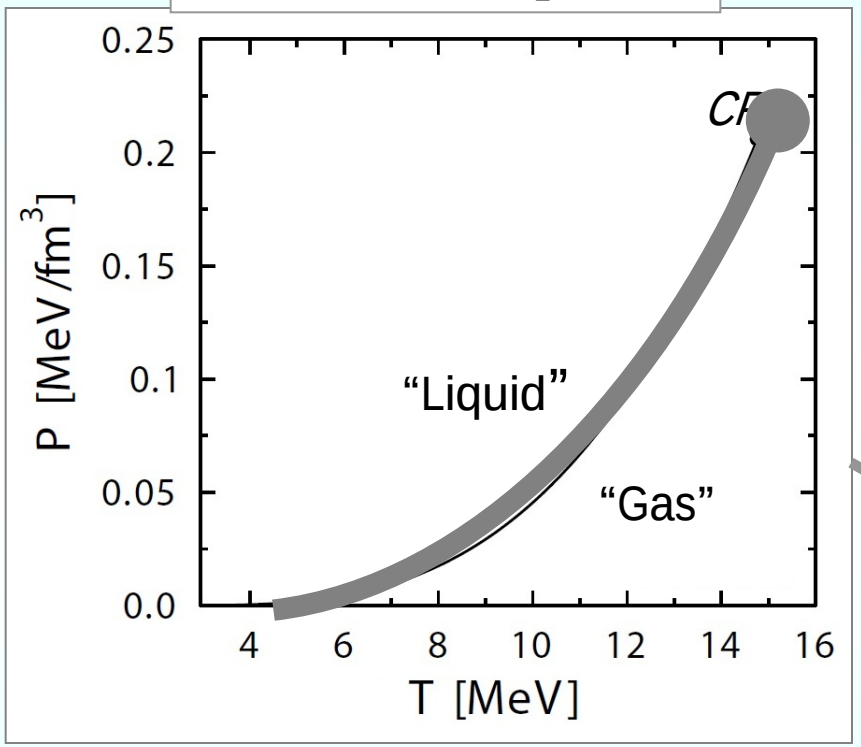
Entropic PT

$$\left(d\boldsymbol{P}/d\boldsymbol{T}\right)_{\text{binodal}} < \mathbf{0}$$

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

One-EOS approach (*critical point*)

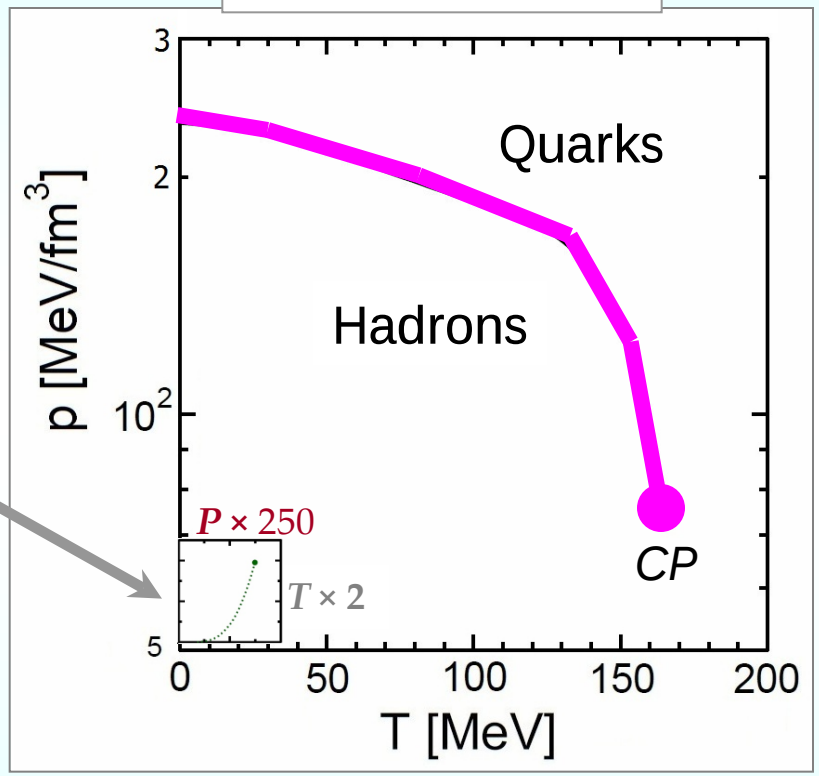
Nuclear Gas-Liquid PT



Standard VdW-like behavior

(*enthalpic PT*)

Quark-Hadron PT



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

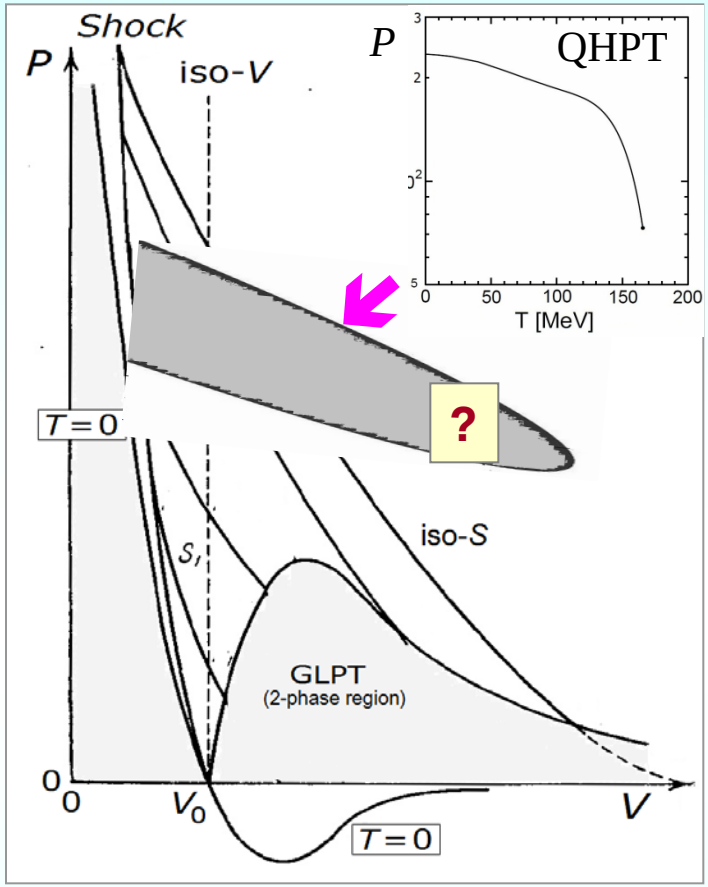
(*entropic PT*)

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

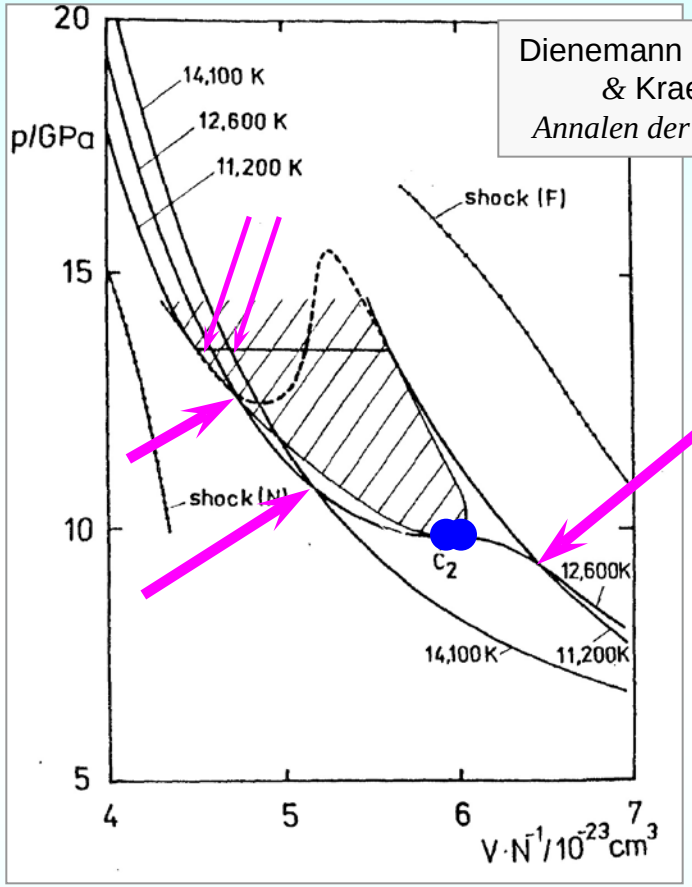
Enthalpic *vs.* Entropic phase transitions

P-V **phase diagram !**

Ionization-driven (entropic) 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**

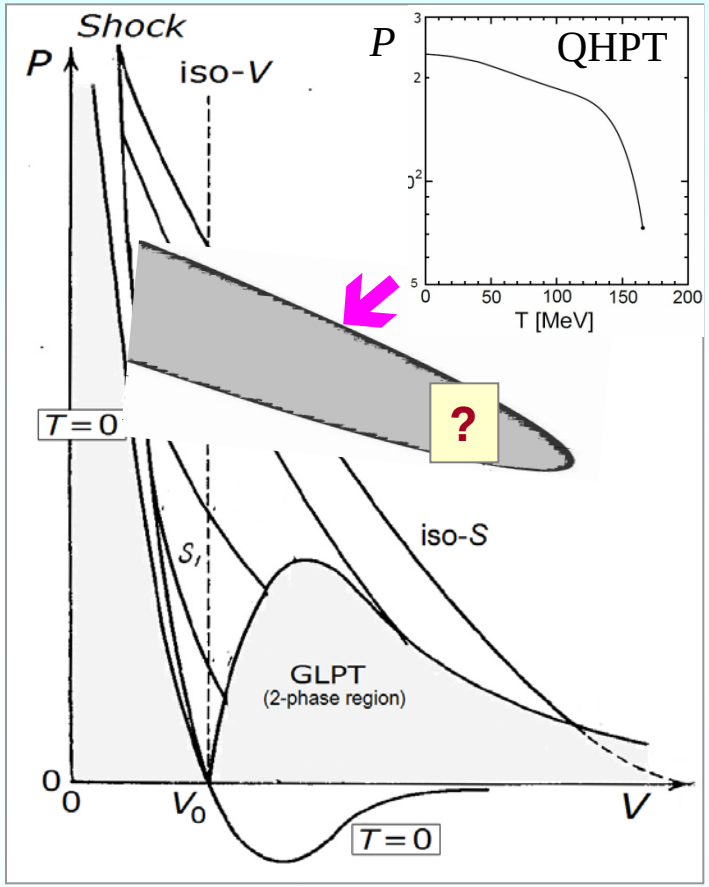
NB ! **Abnormal order** and **crossing** of **isotherms !**

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

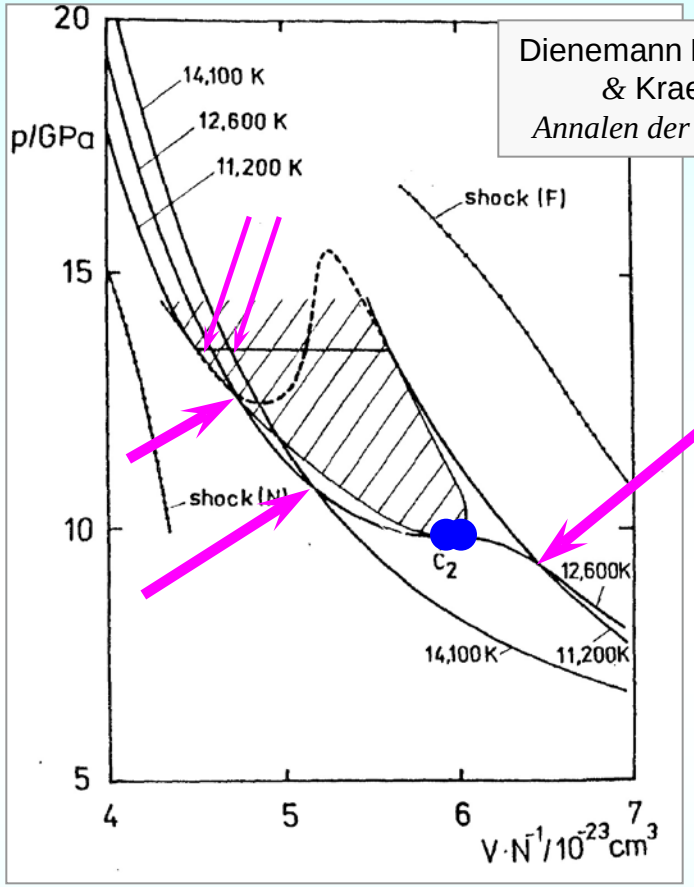
In the **vicinity** of **entropic PT** one meets **abnormal thermodynamics !**

(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)

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 !**

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

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

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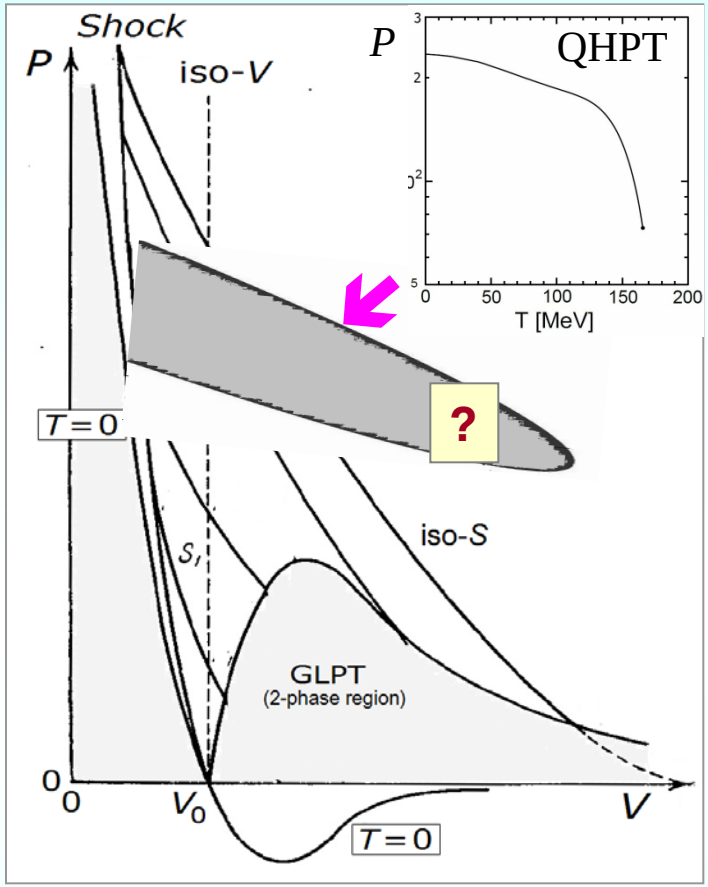

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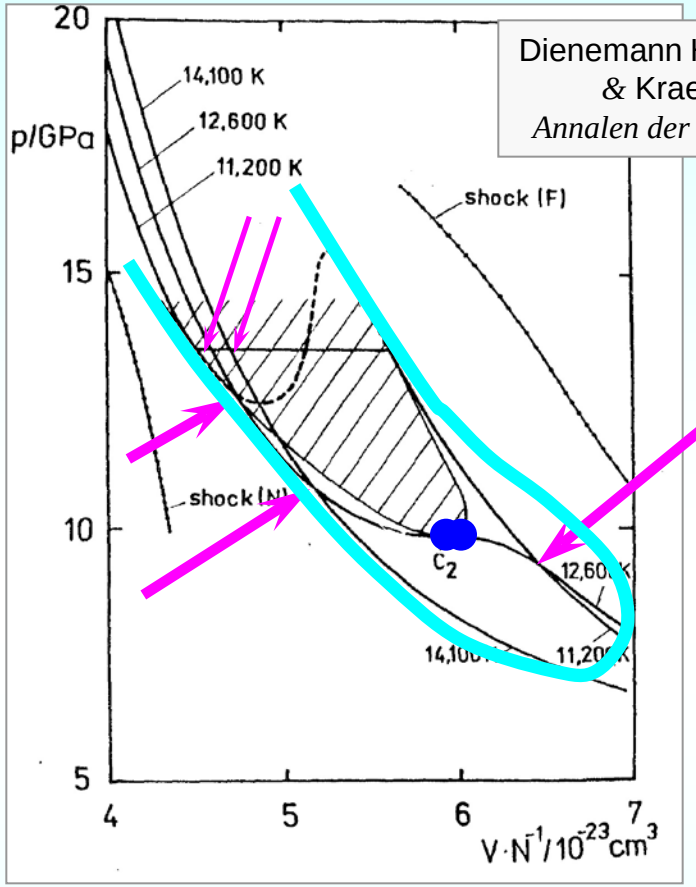

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In the **vicinity** of **entropic PT** one meets **abnormal thermodynamics !**

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

Abnormal Thermodynamics Region - *ATR*

Normally positive second cross derivatives became *negative simultaneously !*

Normal > 0 | **Abnormal** < 0

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

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

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

$\mathrm{Gr} \equiv V(\partial P/\partial U)_V < 0$ – Negative Gruneizen parameter !

$(\partial T/\partial P)_S < 0$ – temperature fall under isentropic compression !

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 !**

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

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

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

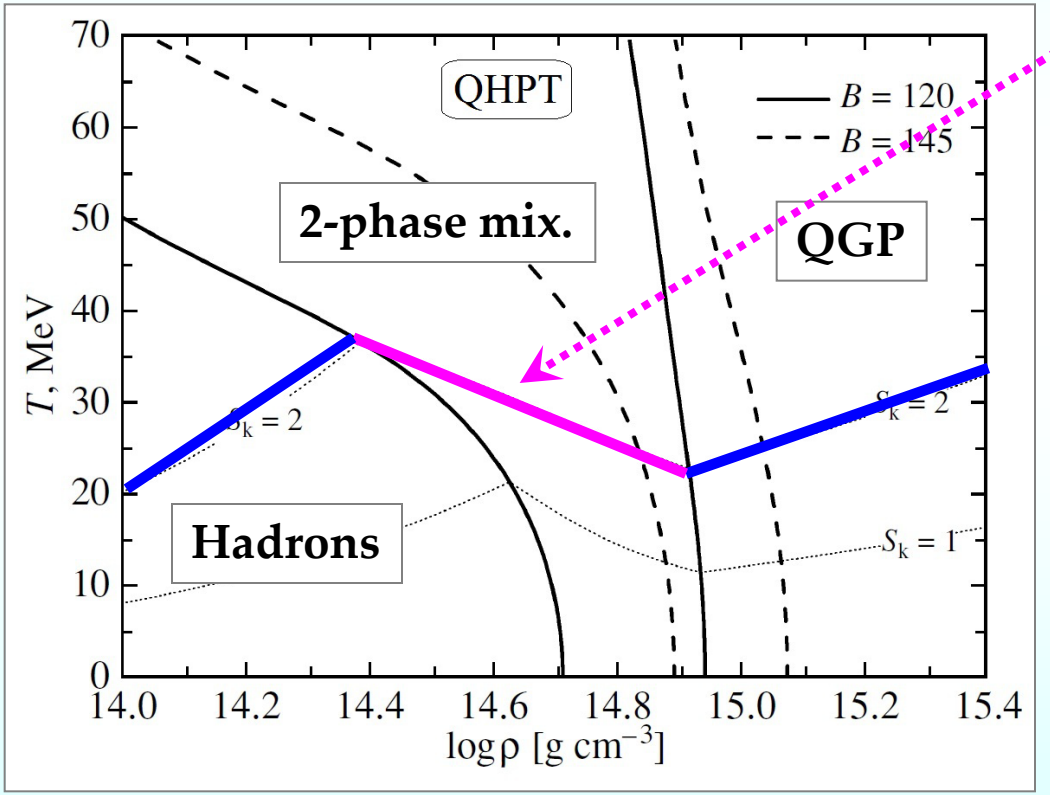
$(\partial S/\partial V)_T < 0$ → **Abnormal decreasing (*increasing*) entropy *under* isothermal expansion *(compression)* !**

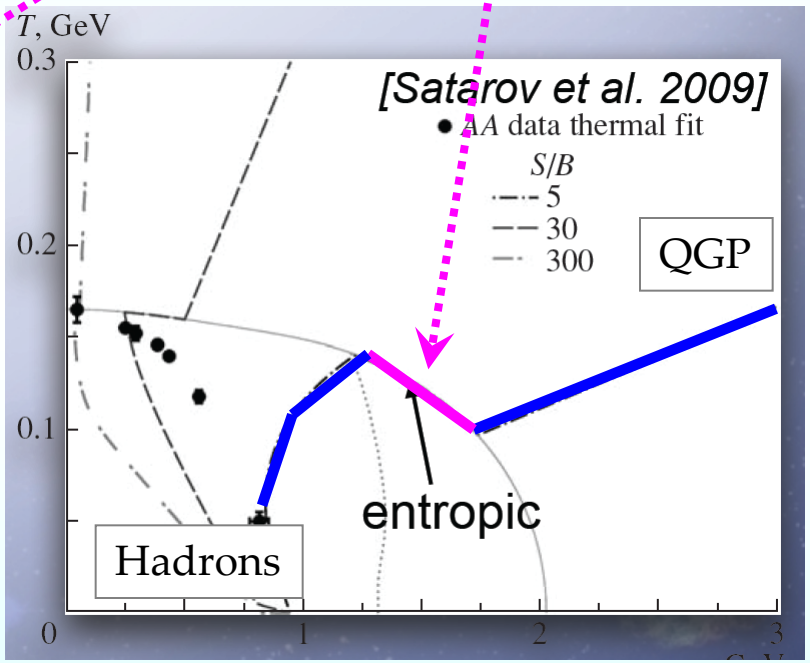
Negative Gruneizen parameter - - $Gr \equiv V(\partial P/\partial U)_V < 0$

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

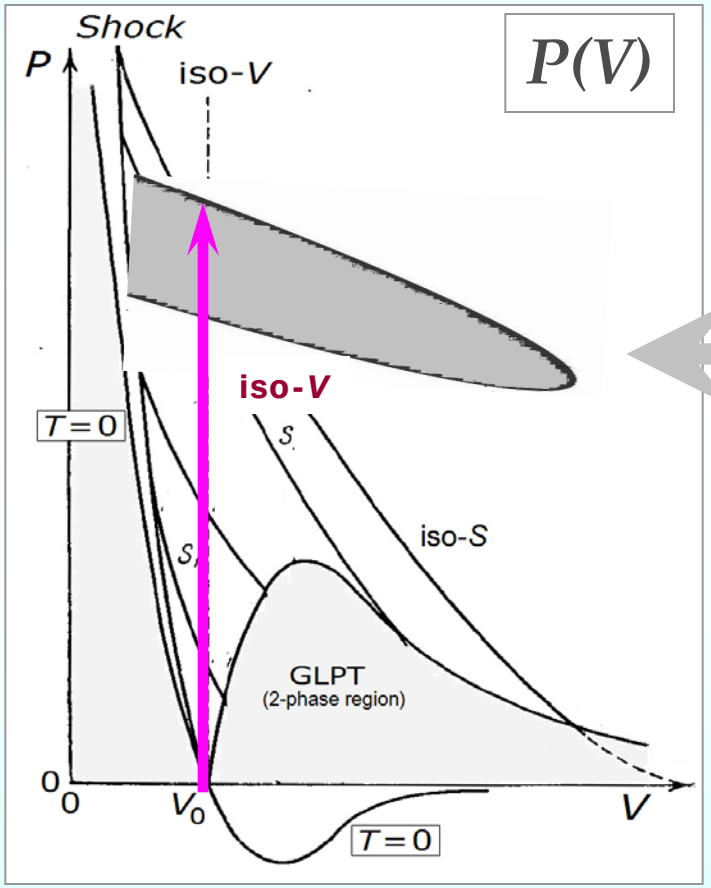




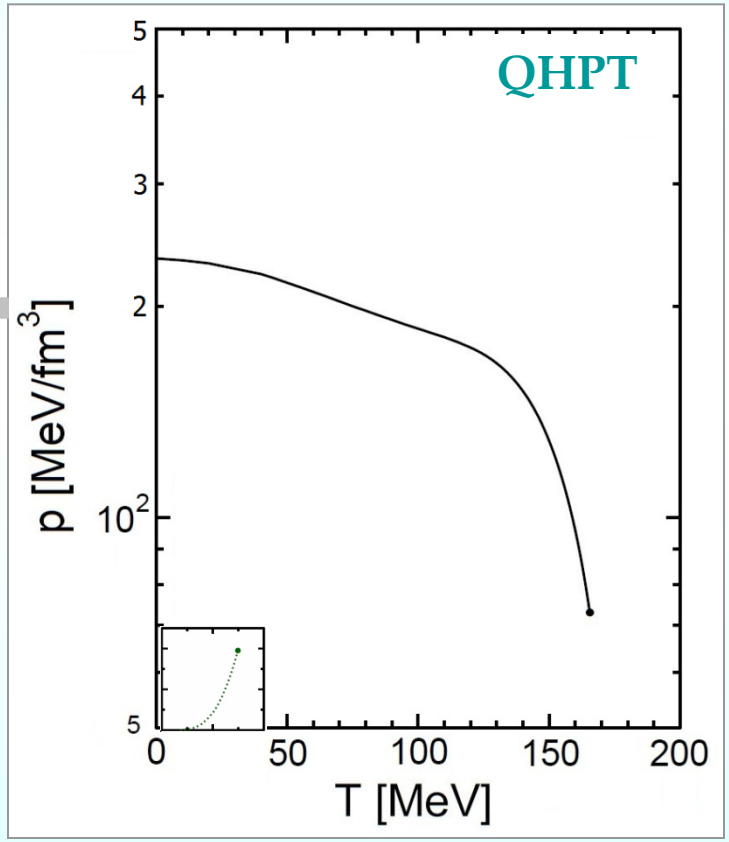
Matthias Hempel
Istanbul, 25.04.2016

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

Multi-layered structure *of* thermodynamic surfaces *T(p,V), U(p,V), S(p,V)…* *for* entropic phase transitions



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



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

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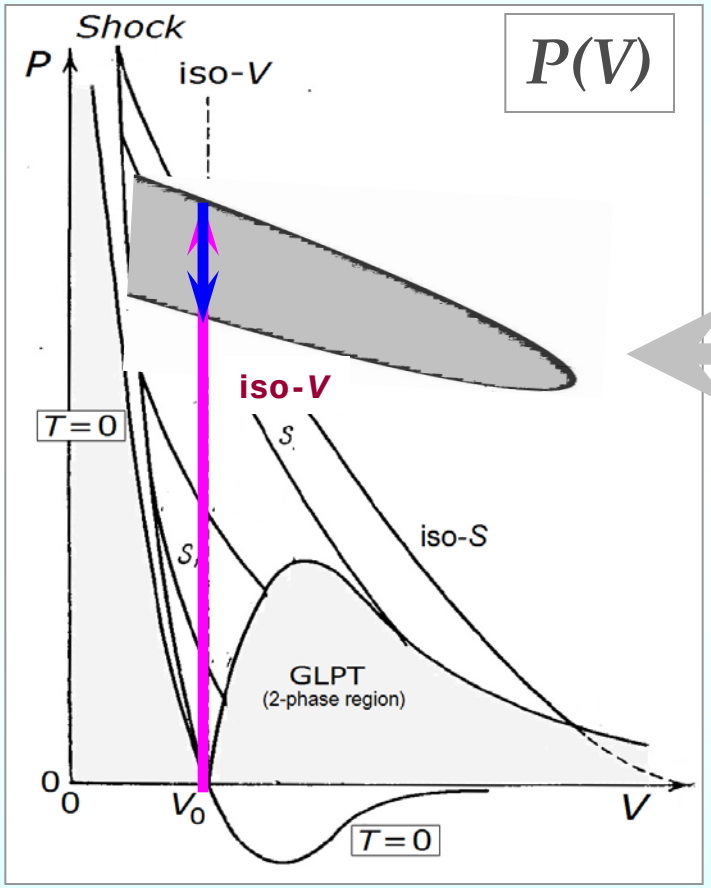

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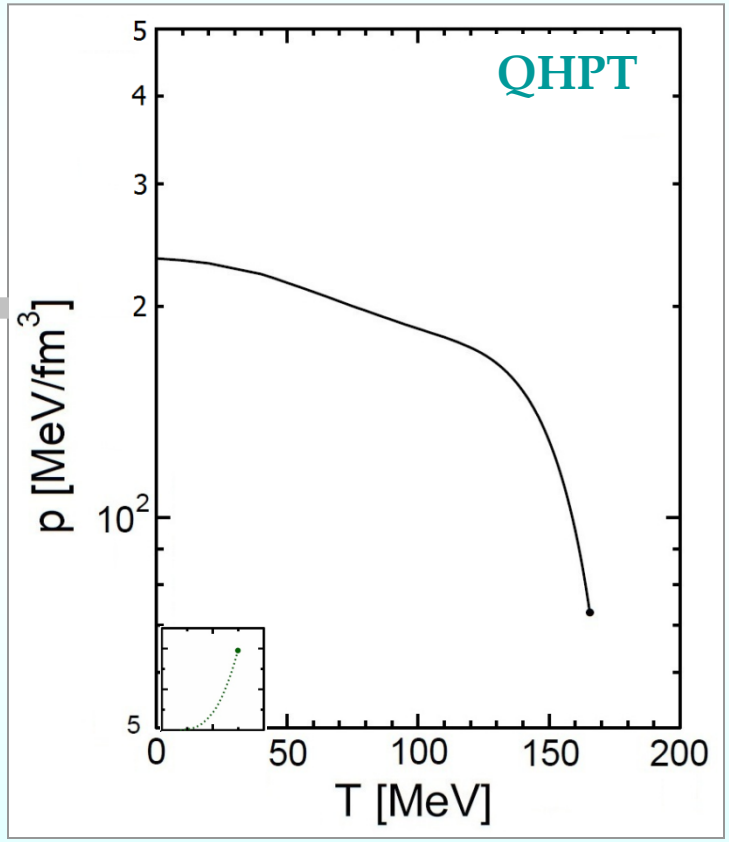

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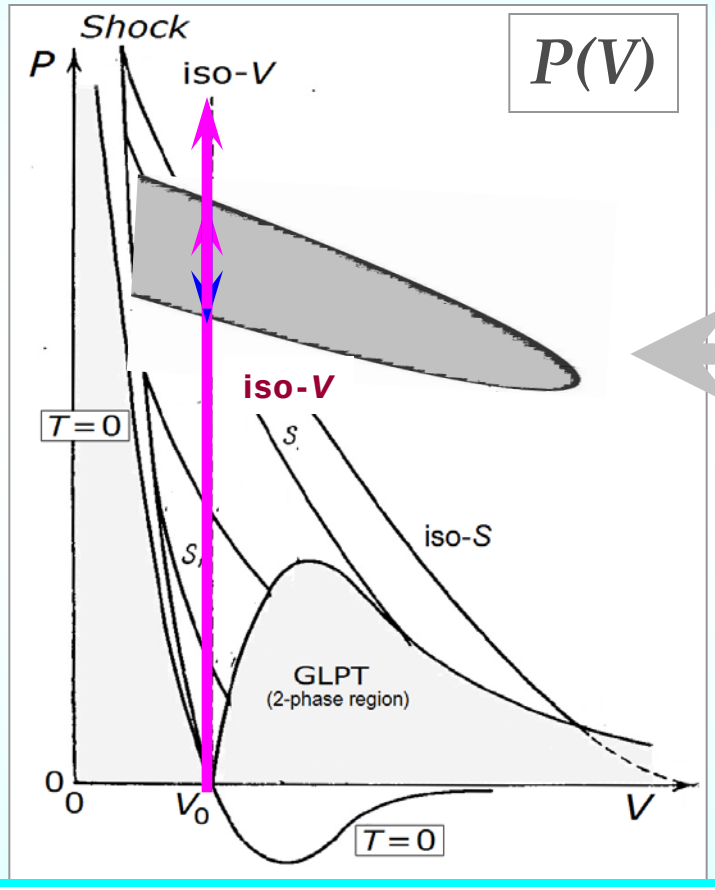
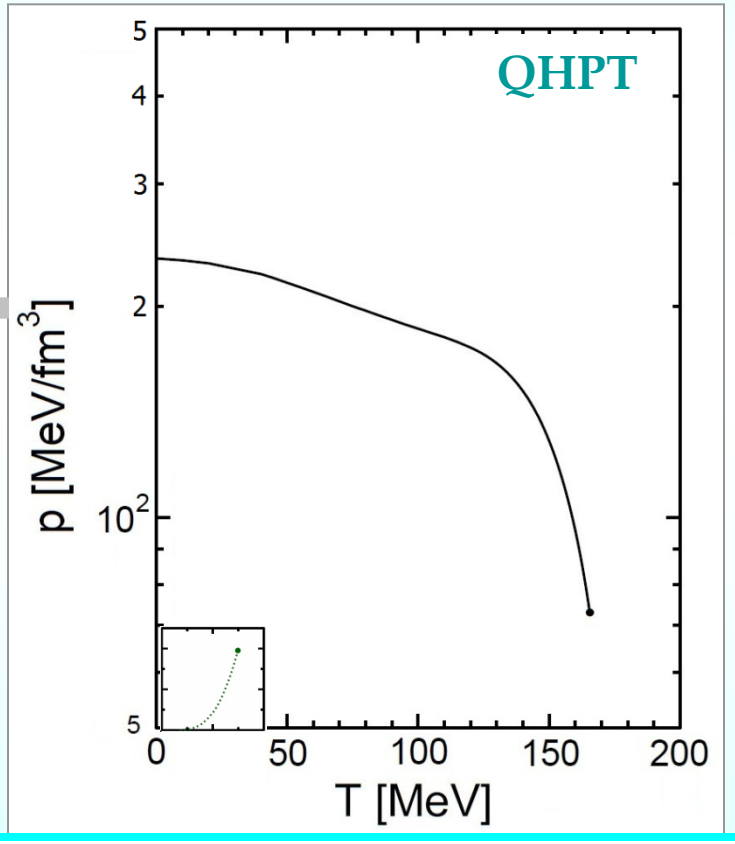
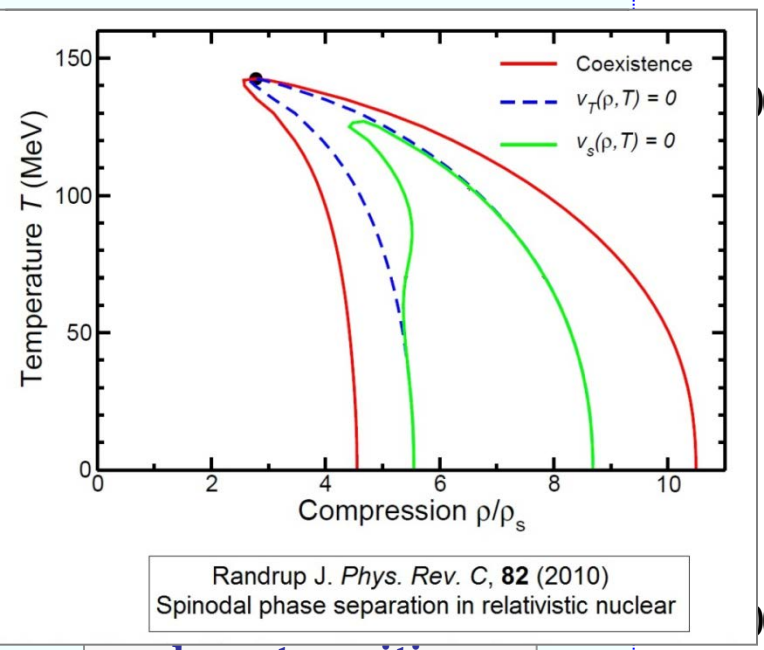




One comes *under*.., then *through*.., then *over* two-phase region during isochoric heating <===> $(\partial P/\partial T)_V < 0$

Hypothetical dissociation-driven (*entropic*) PT

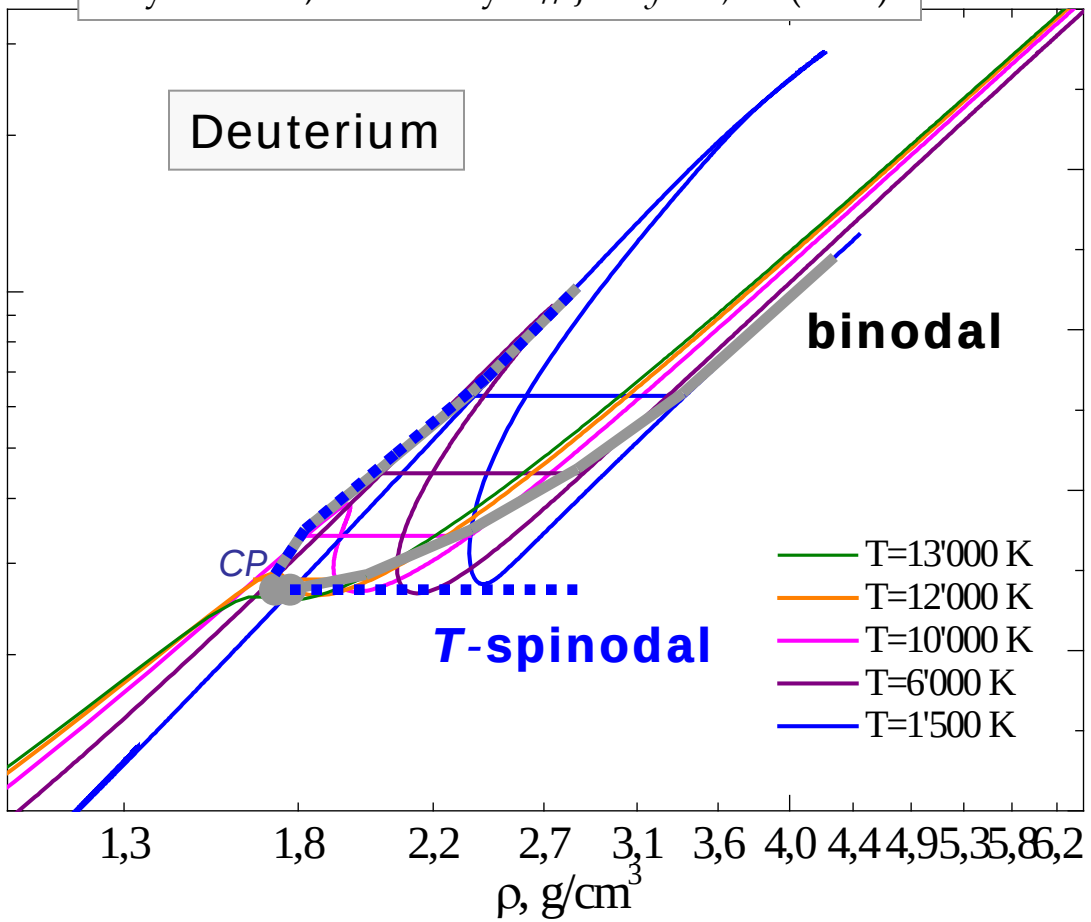
CP
Binodal
T-spinodal
S-spinodal



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**

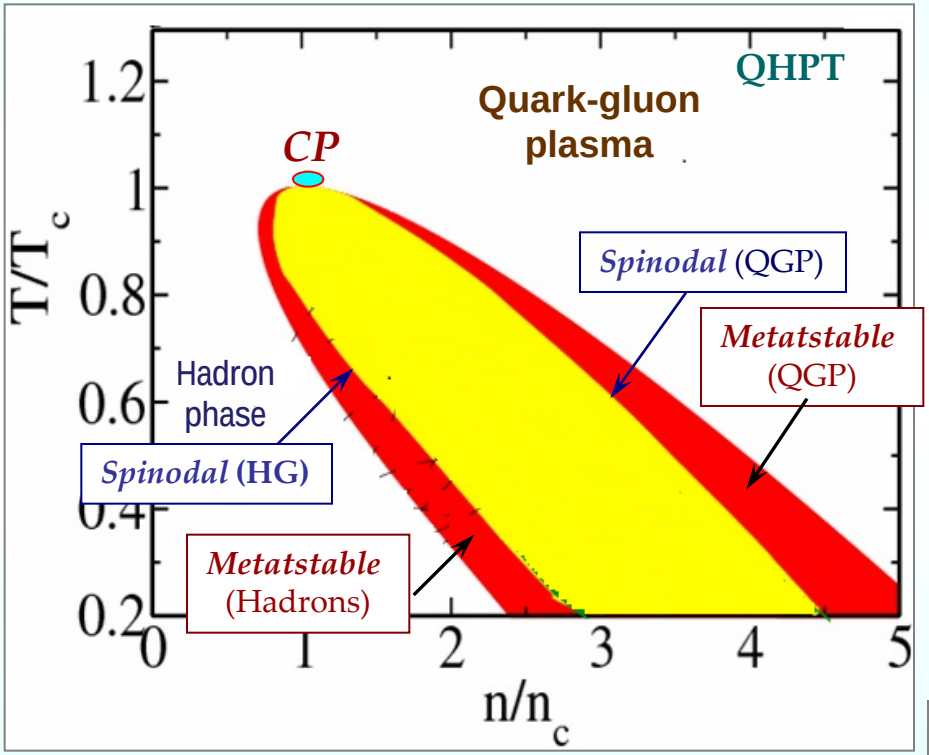
Iso-*S* spinodal $\{(\partial P/\partial V)_S = 0\}$ is located **outside** of **iso-*T* spinodal !**

Abnomal topology *of* binodals *and* spinodals

in the region of entropic phase transition

(T - ρ diagram)

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



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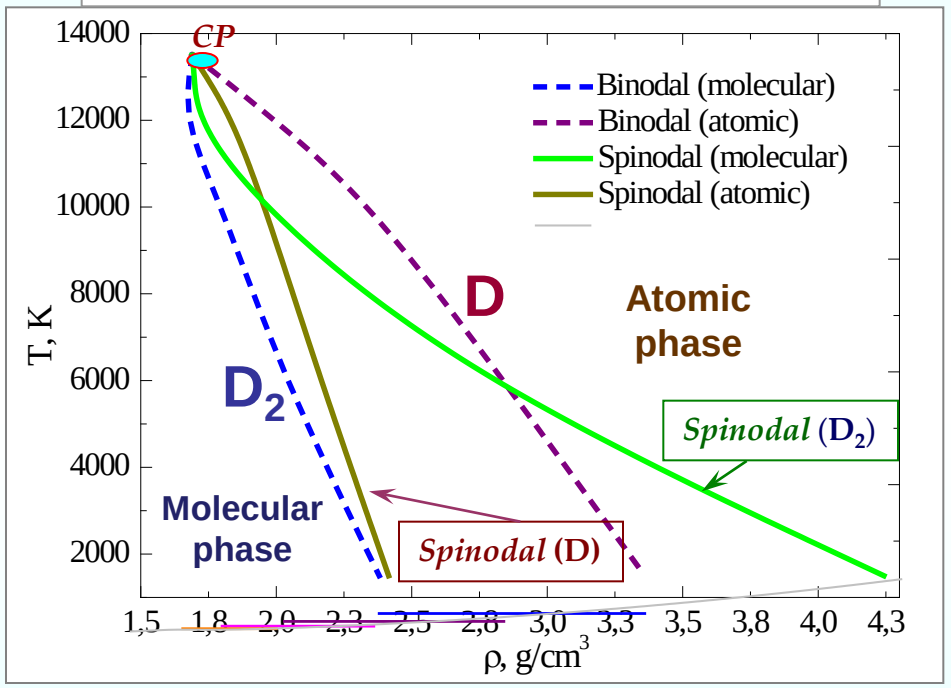

"**Night bat**" structure of metastable "**wings**"

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.

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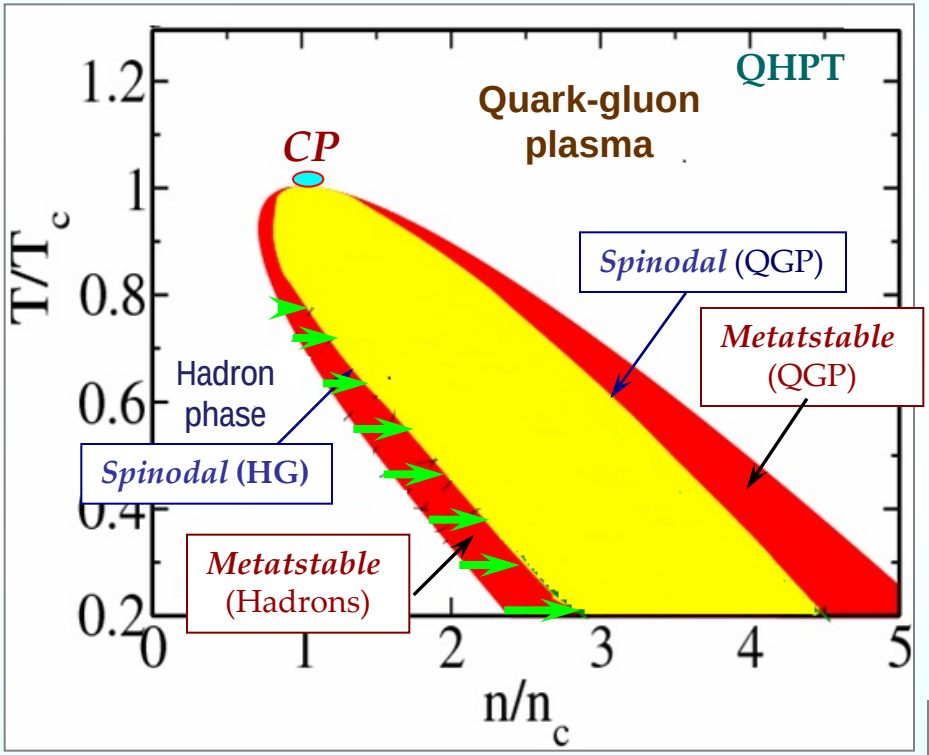

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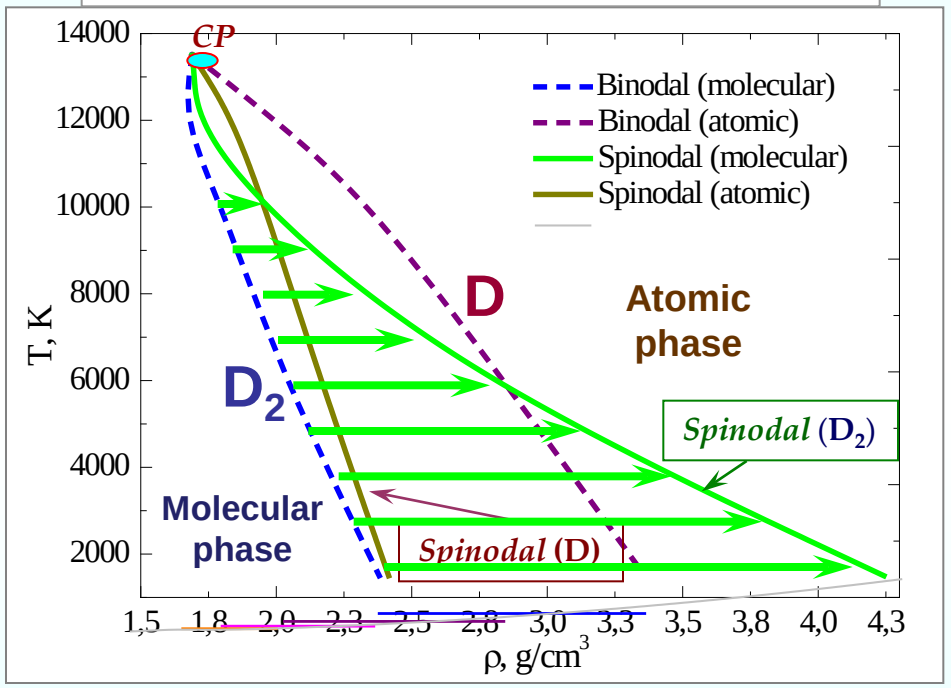

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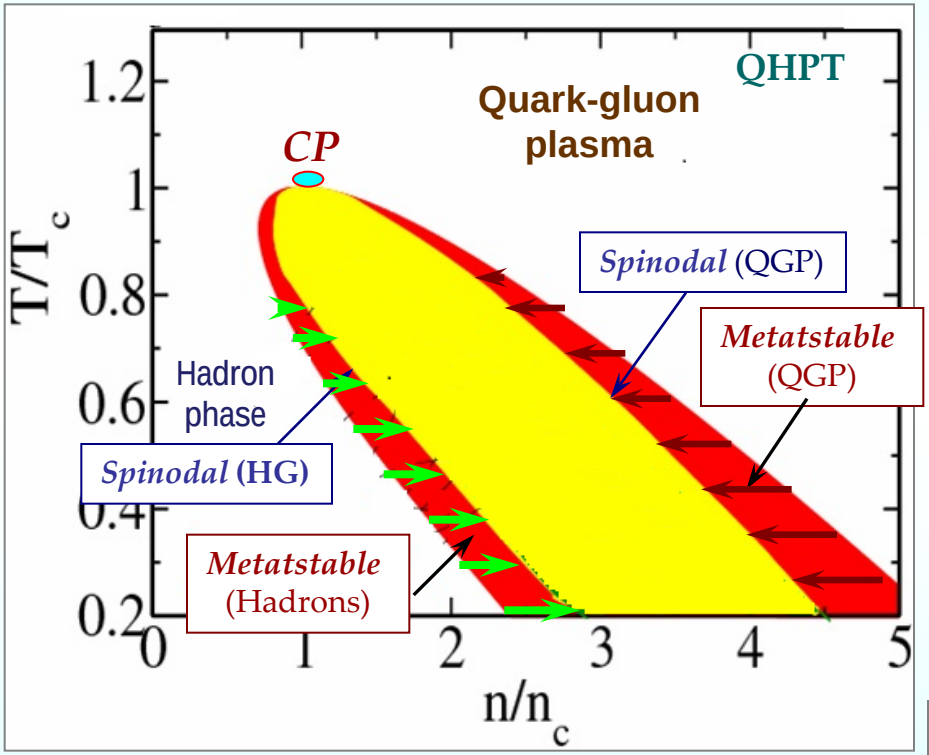

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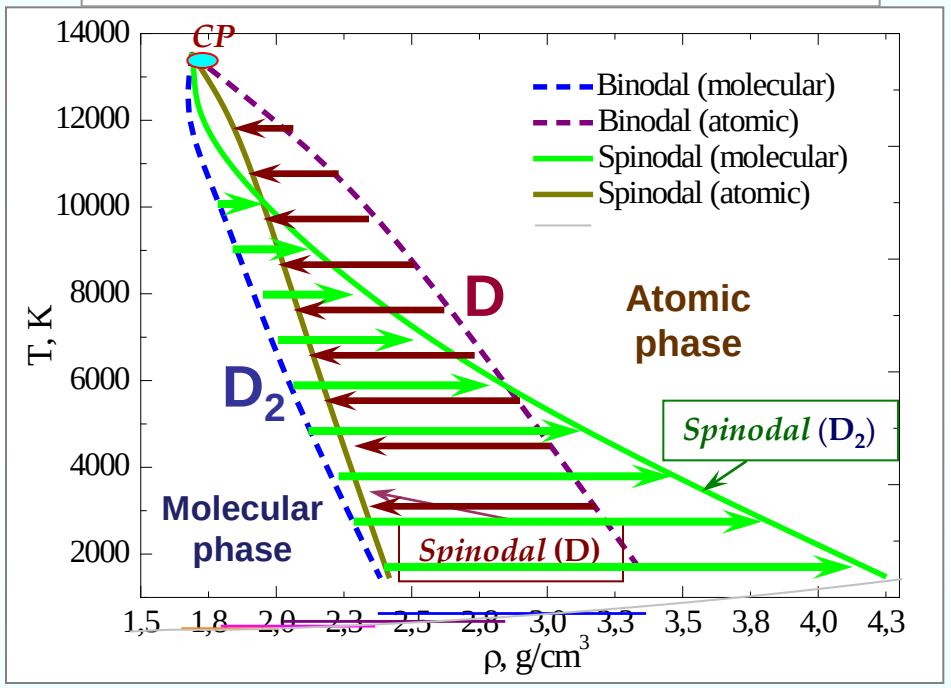
Gryaznov V., Iosilevskiy I. // *J. Phys.* ***A***, **42** (2009)



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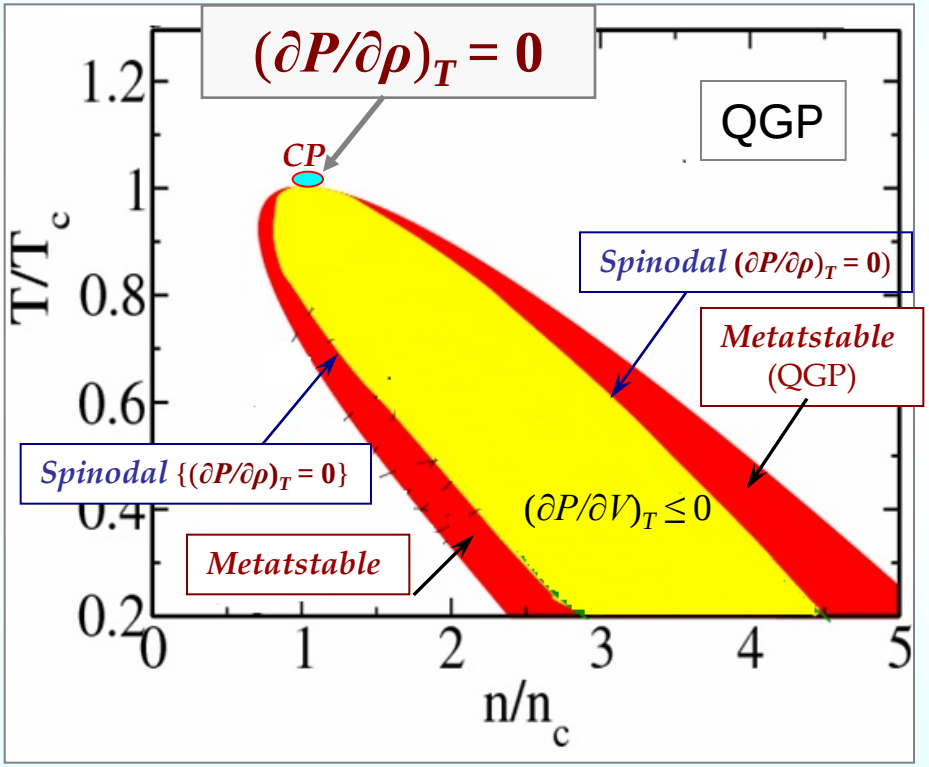
Abnomal features *of* entropic phase transition

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

($T-\rho$ diagram)

QHPT

After Vladimir Skokov, *Int. Conf.* “Prerow-2009”



QHPT

HA-D

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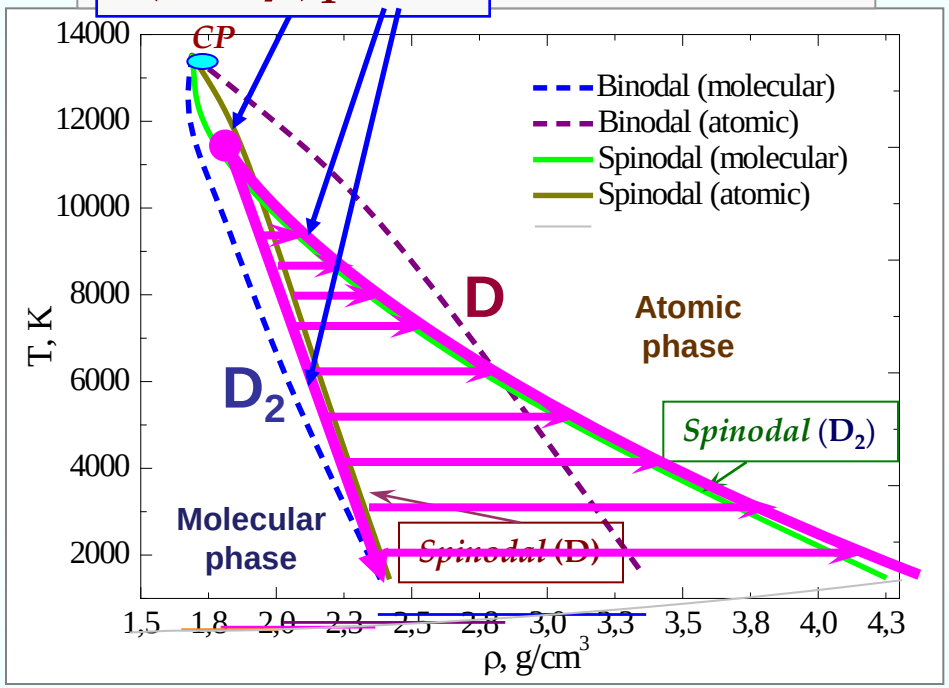


NB !

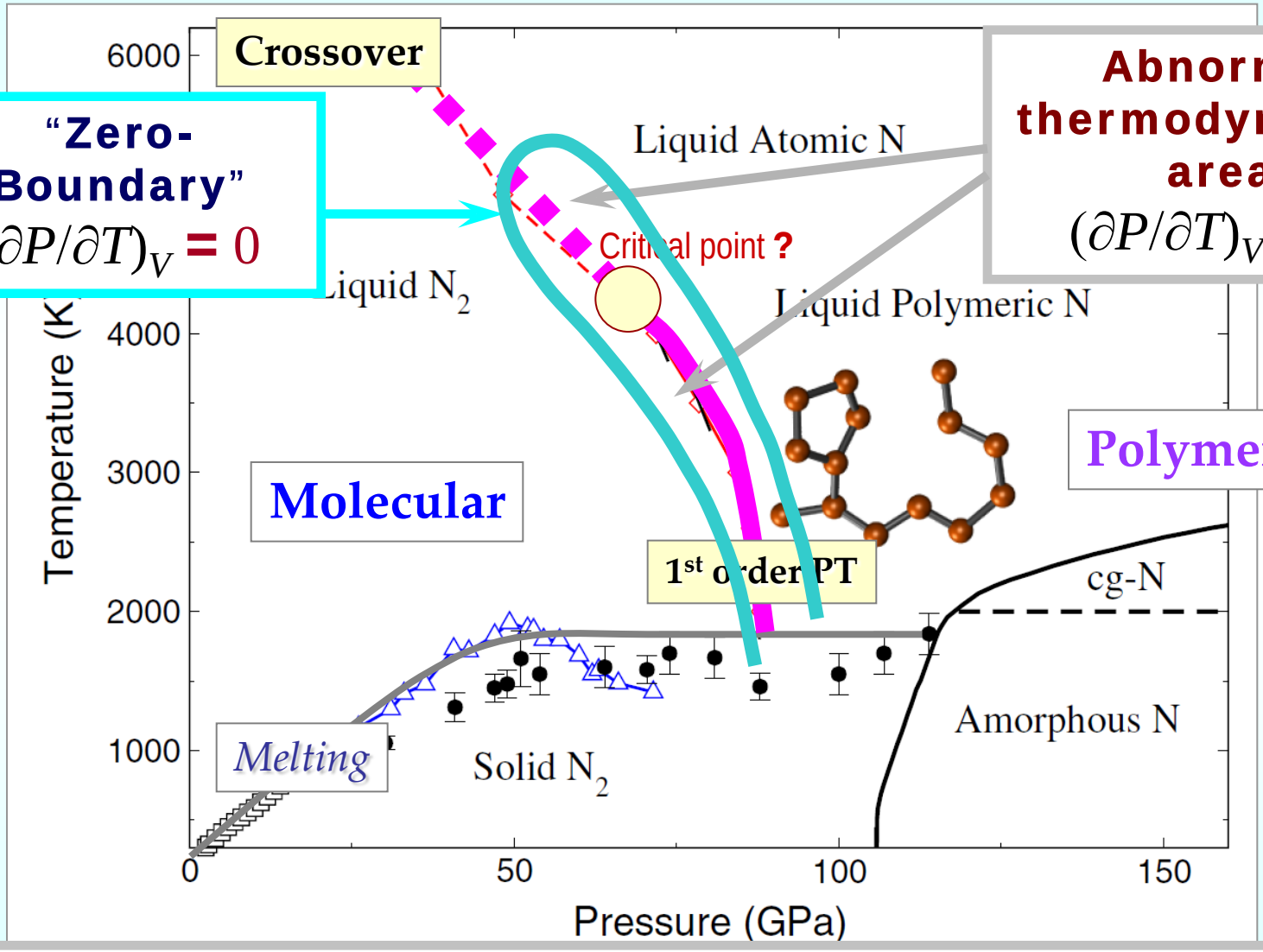
New (additional) region of metastable state $\Leftrightarrow$ $(\partial P/\partial\rho)_T \ge 0$

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

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

Entropy-driven fluid-fluid phase transitions (N_2)

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



"Zero-Boundary" $(\partial P/\partial T)_V = 0$

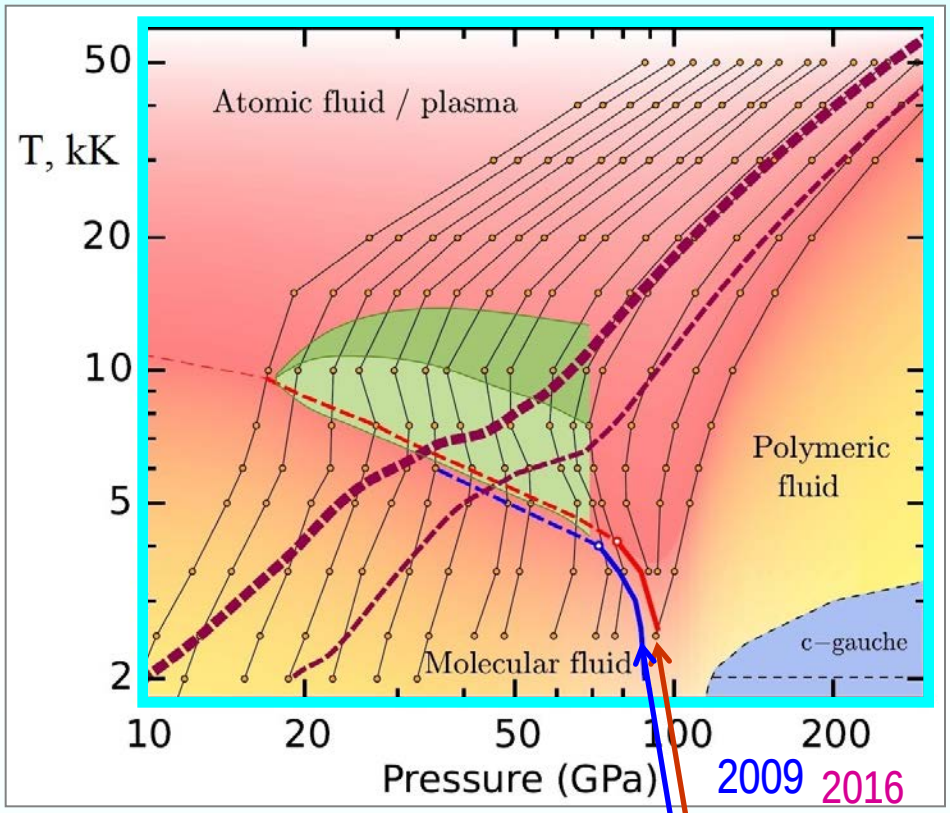
Abnormal thermodynamics area $(\partial P/\partial T)_V < 0$

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

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

Phase Diagram of Warm Dense Nitrogen

(abnormal thermo- and hydrodynamics)



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

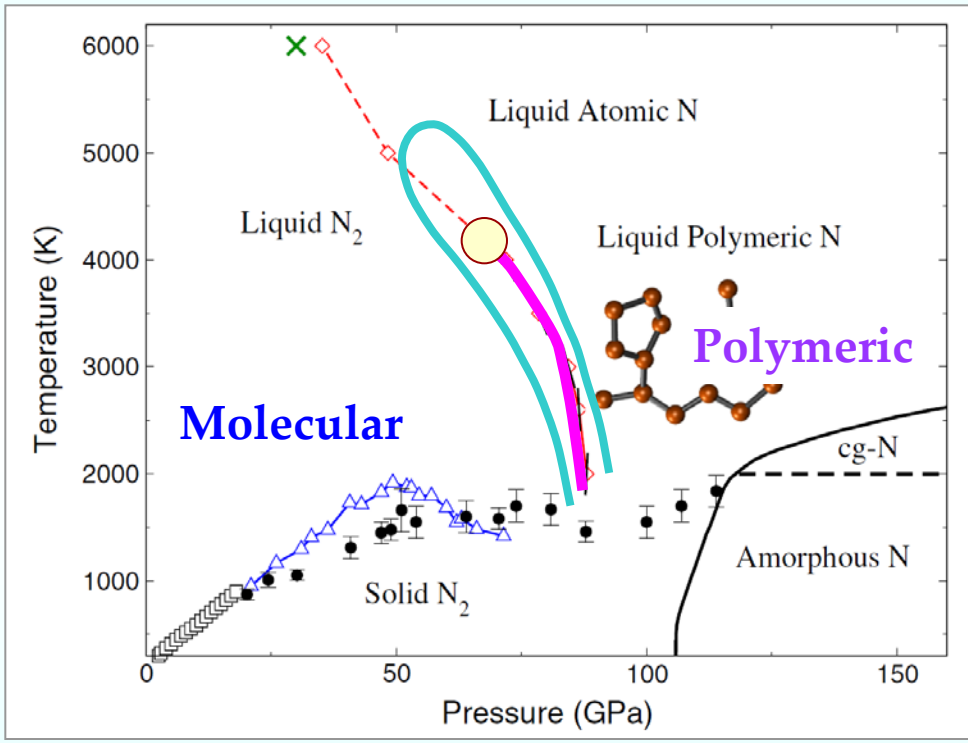
(2009) $T_c \approx 400$ K, $P_c = 70$ GPa

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)



Driver K.P. & Militzer B., *Phys. Rev. B*, 93 (2016)

Principles Equation of State of Warm Dense Nitrogen

I.I. / arXiv:1504.0585

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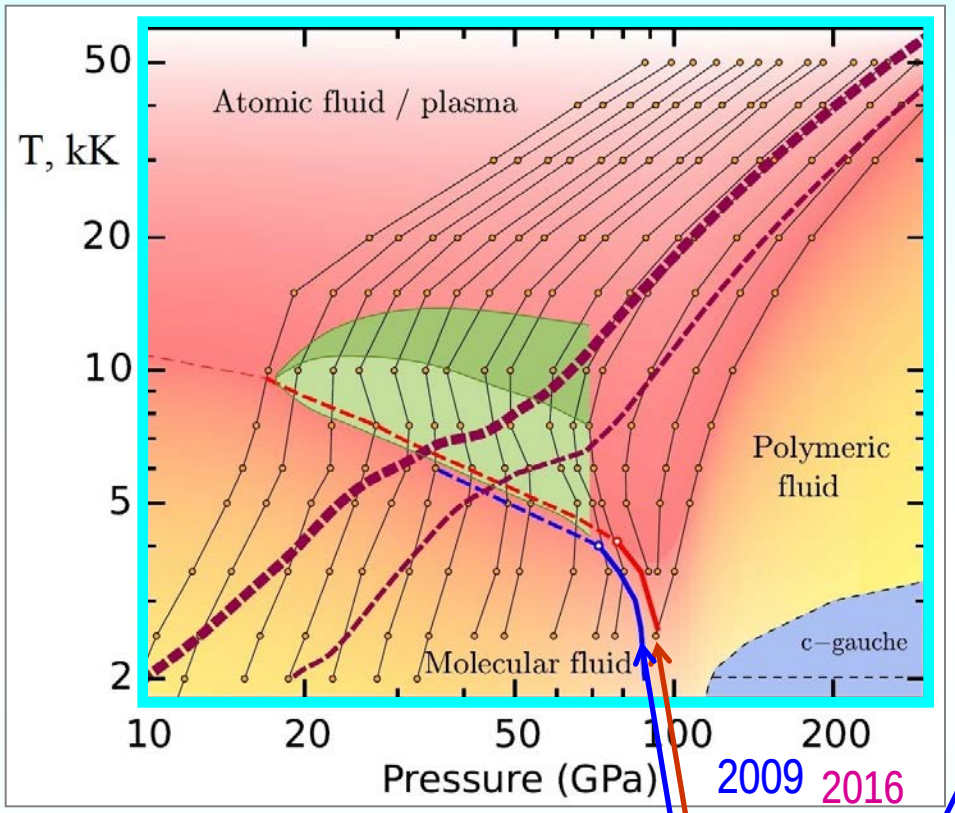
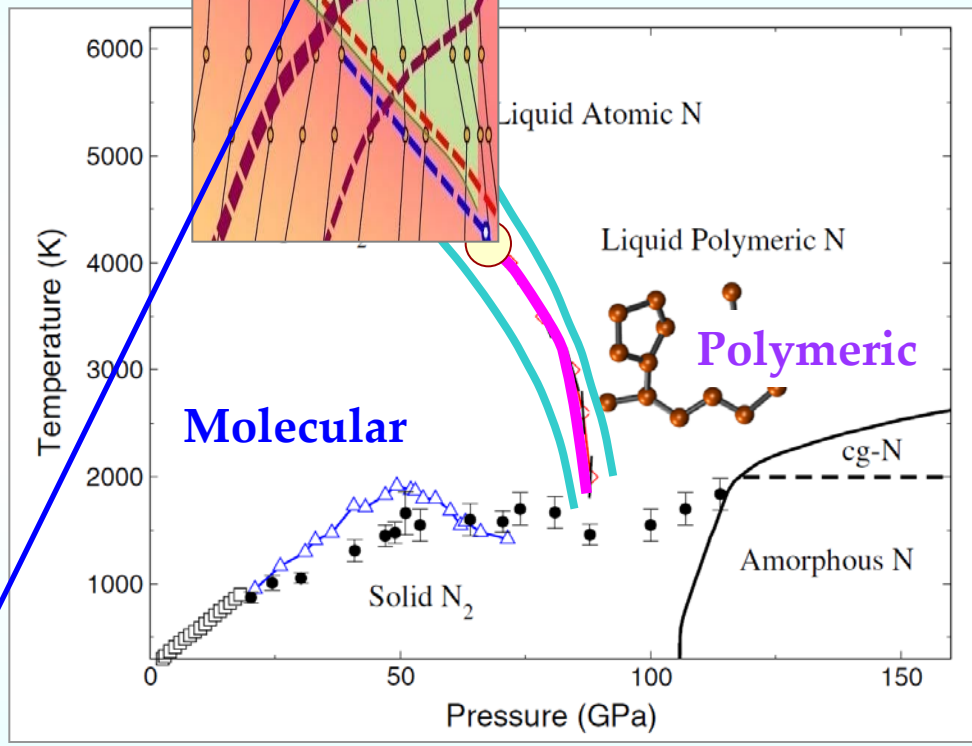
(abnormal thermo- and hyd s)





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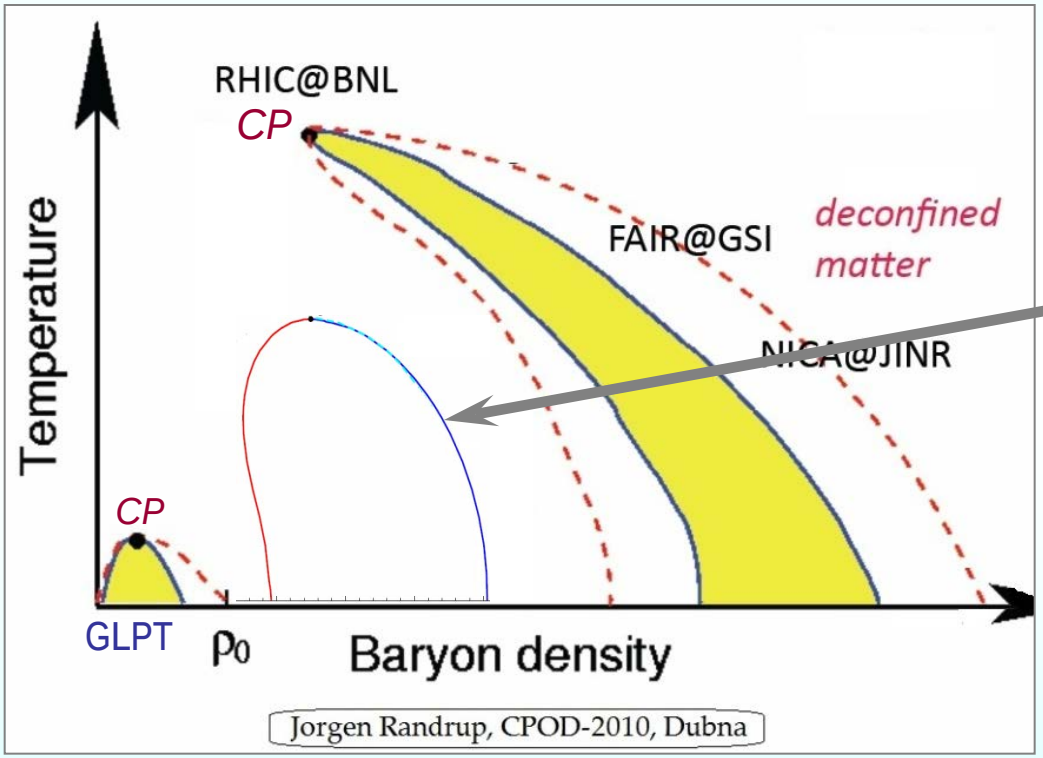
I.I. / arXiv:1504.0585

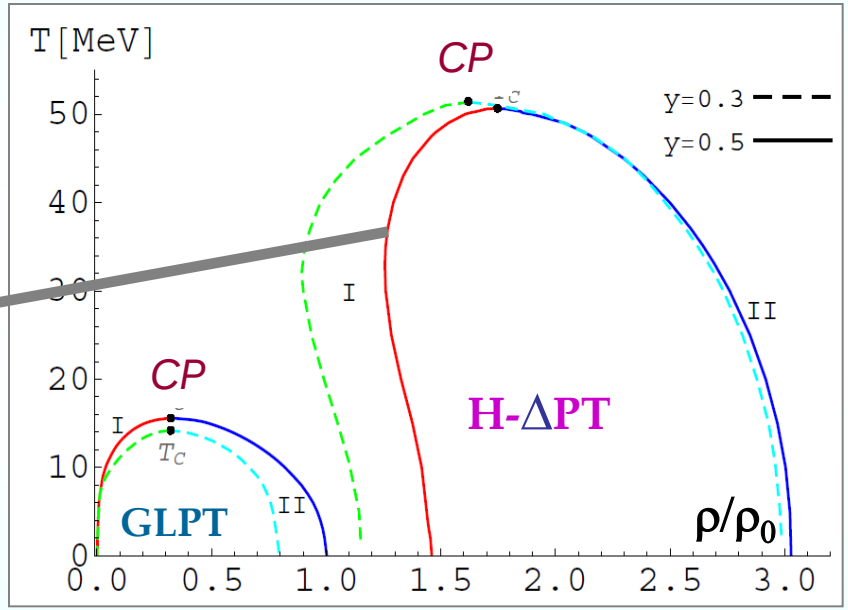
Gas–liquid, Hadron–Δ-meson *and* Quark–hadron phase transitions are often considered as similar

Prerow 2009

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



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

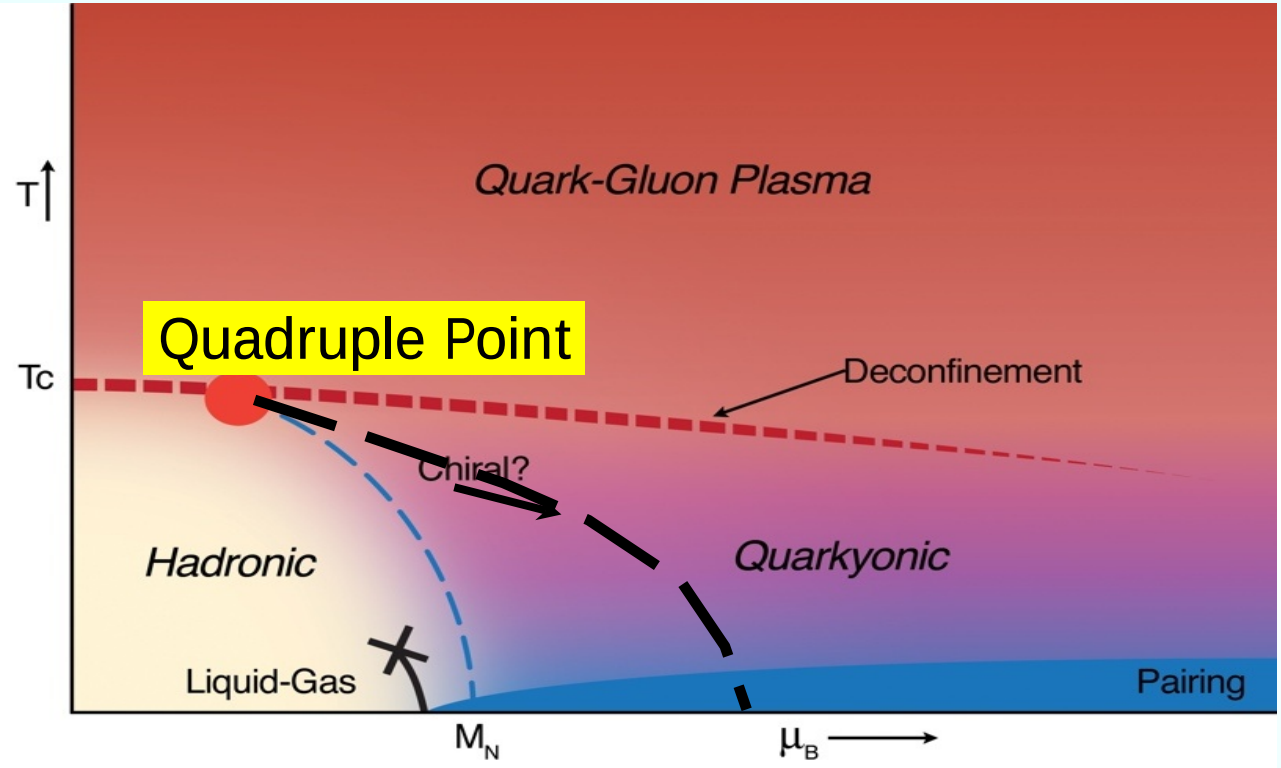


Lavagno A., Drago A., Pagliara G., Pigato D.
J. of Phys. **527** (2014)
Thermodynamic instability *in nuclear matter and in* ***compact stars***

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

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:
- 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** {$U(p,V)$, $T(p,V)$, $S(p,V)$ … }

Thank you!

Support: RAS Scientific Program "Physics of Extreme States of Matter"
Russian Scientific Fund (Grant No: 14-50-00124)

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

Welcome to Elbrus-2017

(01-06 March 2017)

"Equation of State for Matter"

http://www.ihed.ras.ru/Elbrus17