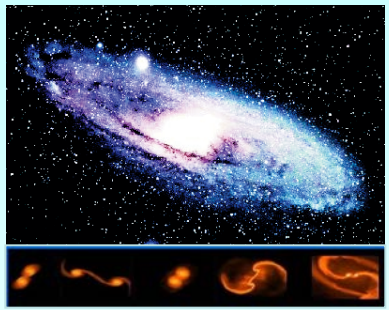
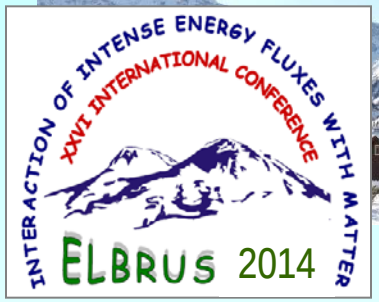




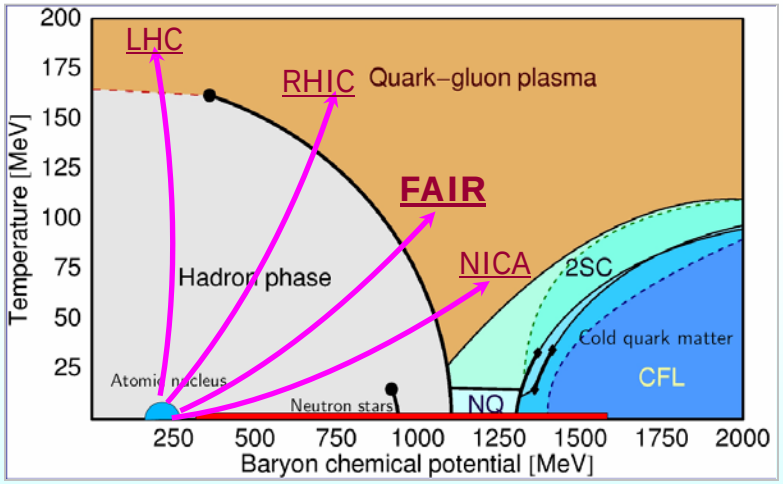



# Binodal Layer

## *in* Isentropically Expanding Hot Dense Matter

(“


Cooperation:
D.Borovikov,
A.Konyukhov,
A.Likhachev,
P.Levashov,
H.Valiev,
A.Kraiko


NICA


JIHT RAS

Igor Iosilevskiy

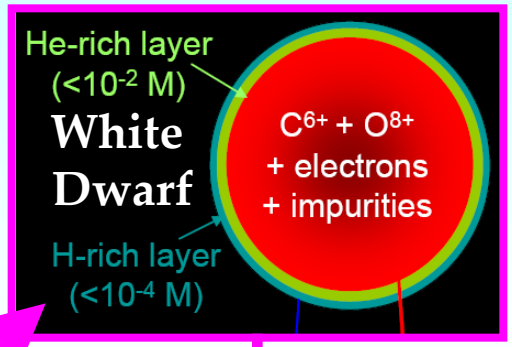
*Joint Institute for High Temperature (Russian Academy of Science)*
*Moscow Institute of Physics and Technology (State University)*



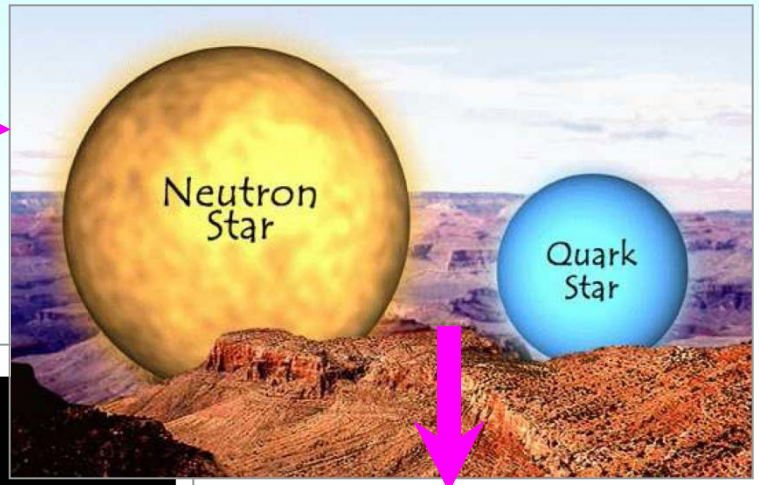
arXiv:1401.5481

# Compact stars

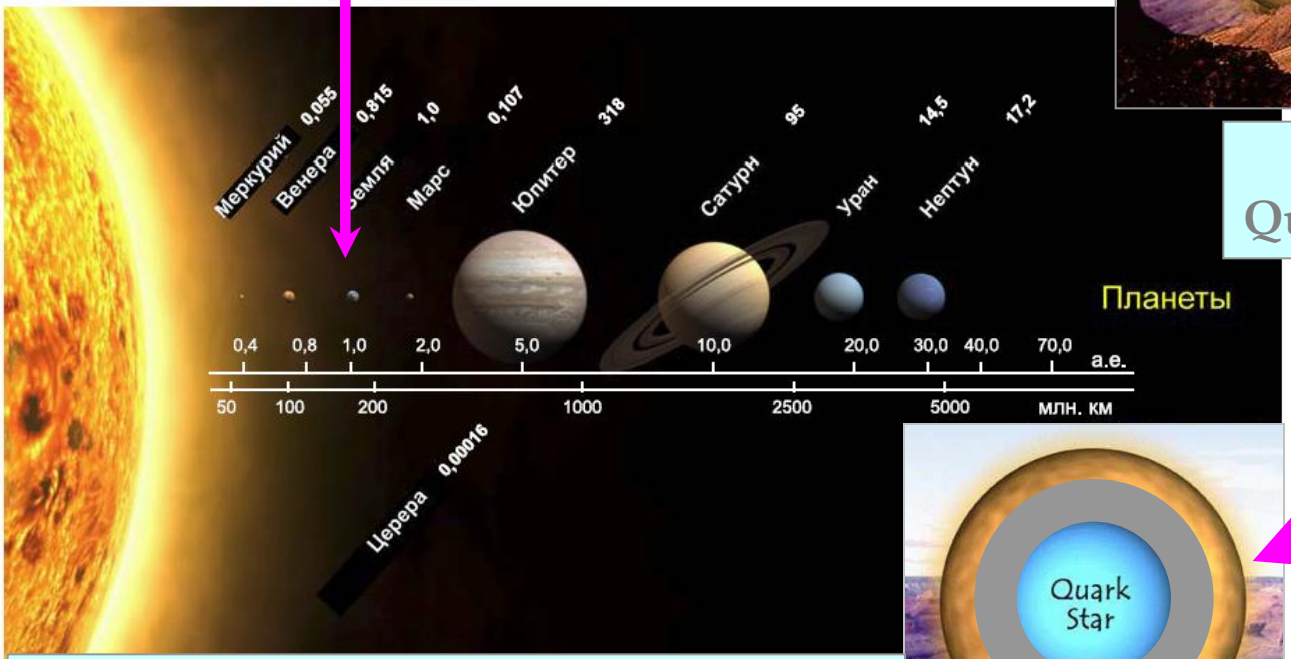
*White dwarfs, Neutron stars, "Strange" (quark) stars, Hybrid stars*




## Neutron *and* "Strange" Stars



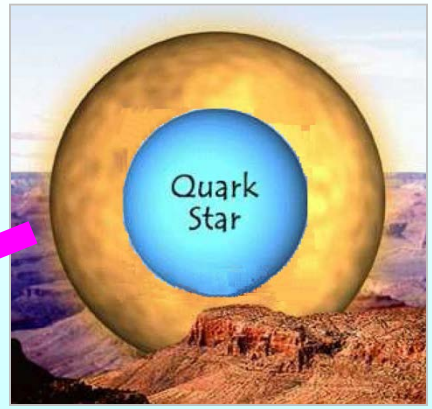

**Hybrid Stars**
Quark core + Hadron crust





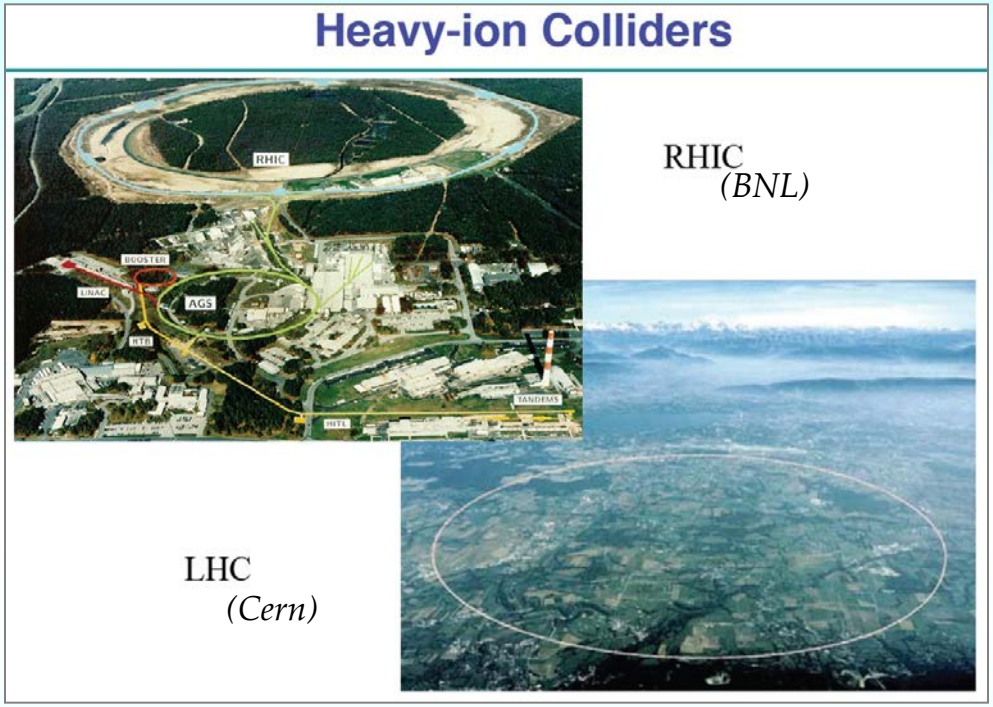


**Hybrid Stars - II**
Quark core + Hadron crust + **Mixed phase**

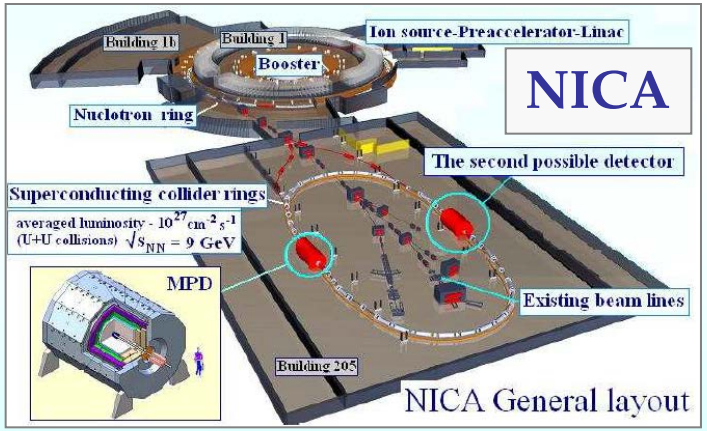



$|\leftarrow R \sim 10\ \text{km} \rightarrow|$

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







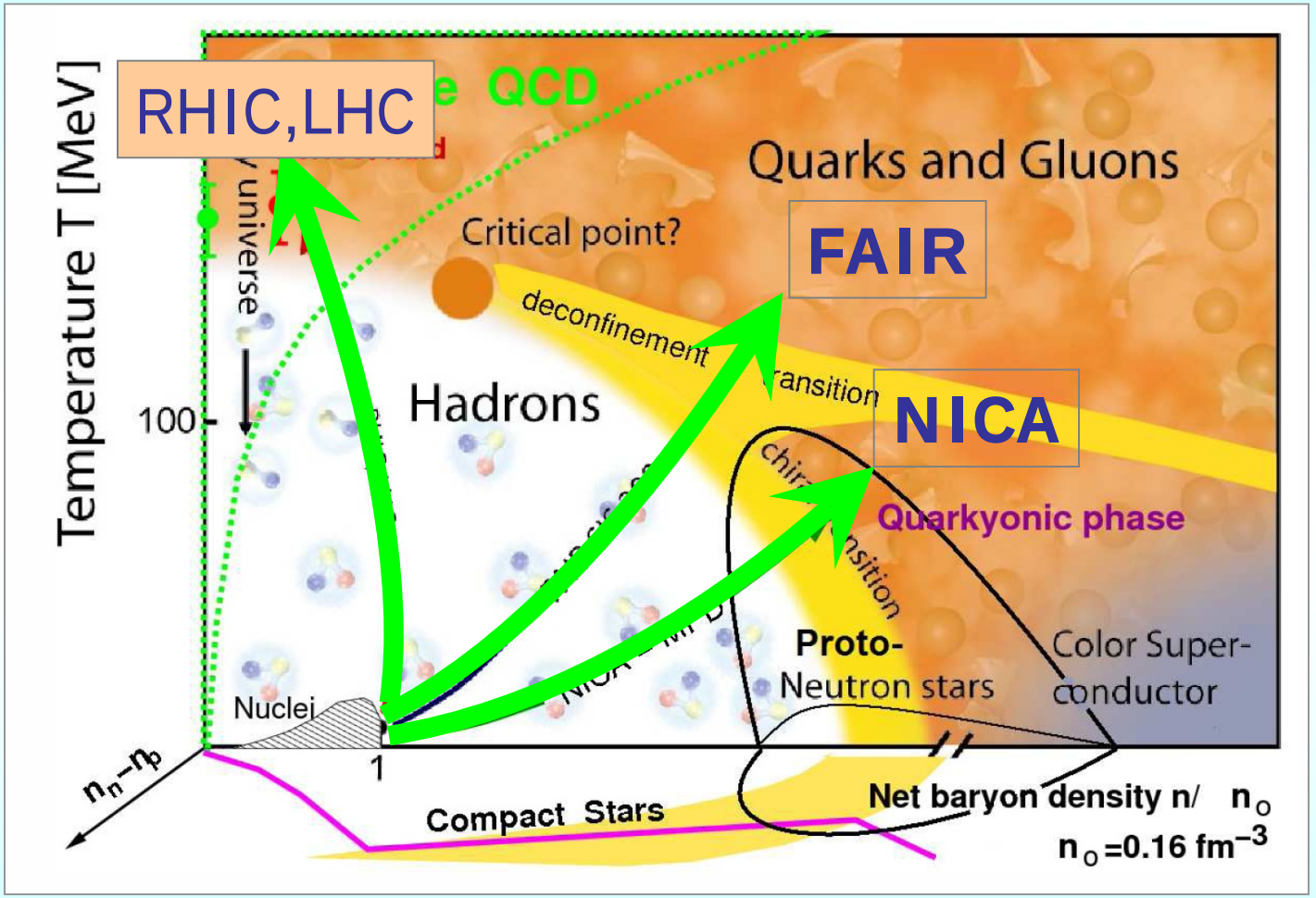


**FAIR**

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

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

# Quark-hadron phase transition

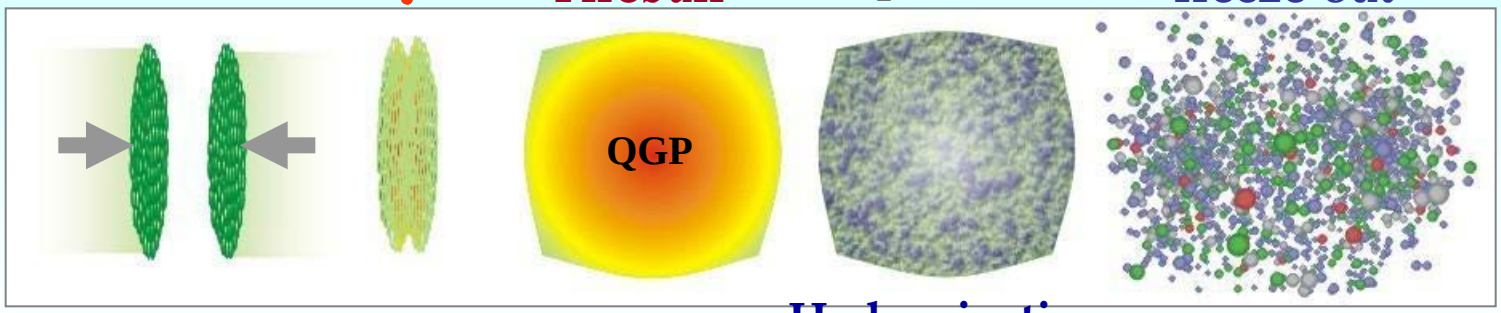


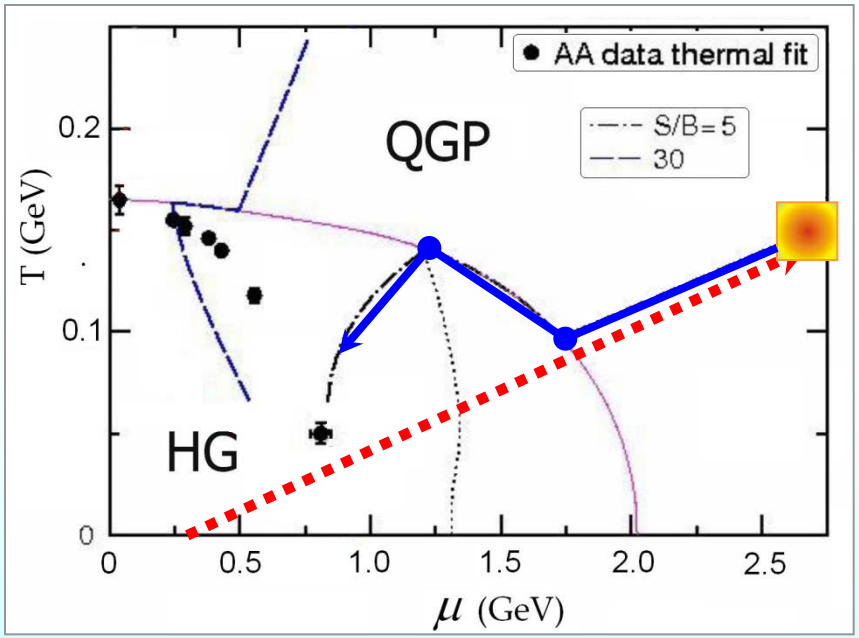

[NICA White Book]

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

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

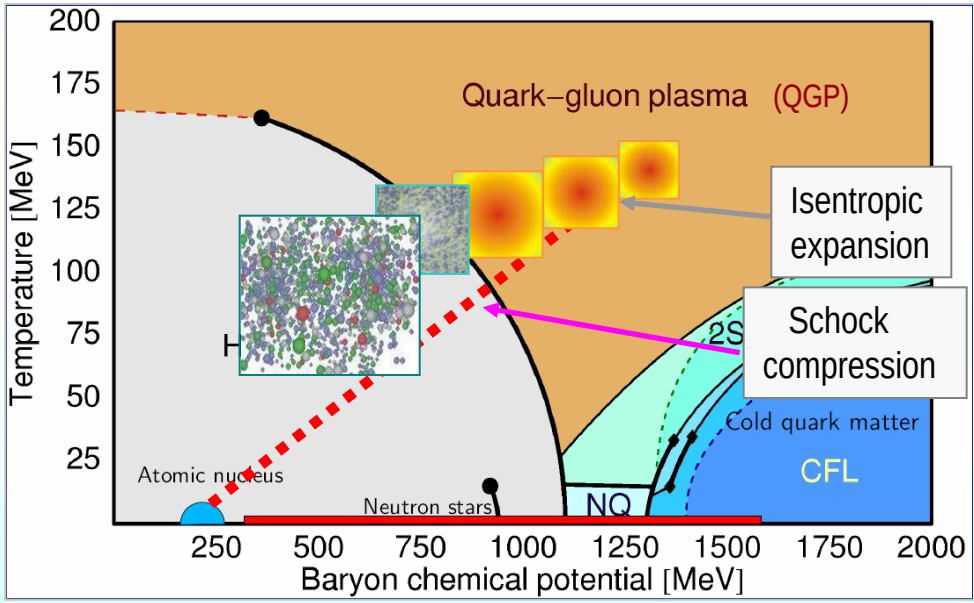
# Impact *and* fireball hydrodynamics *in* RHIC



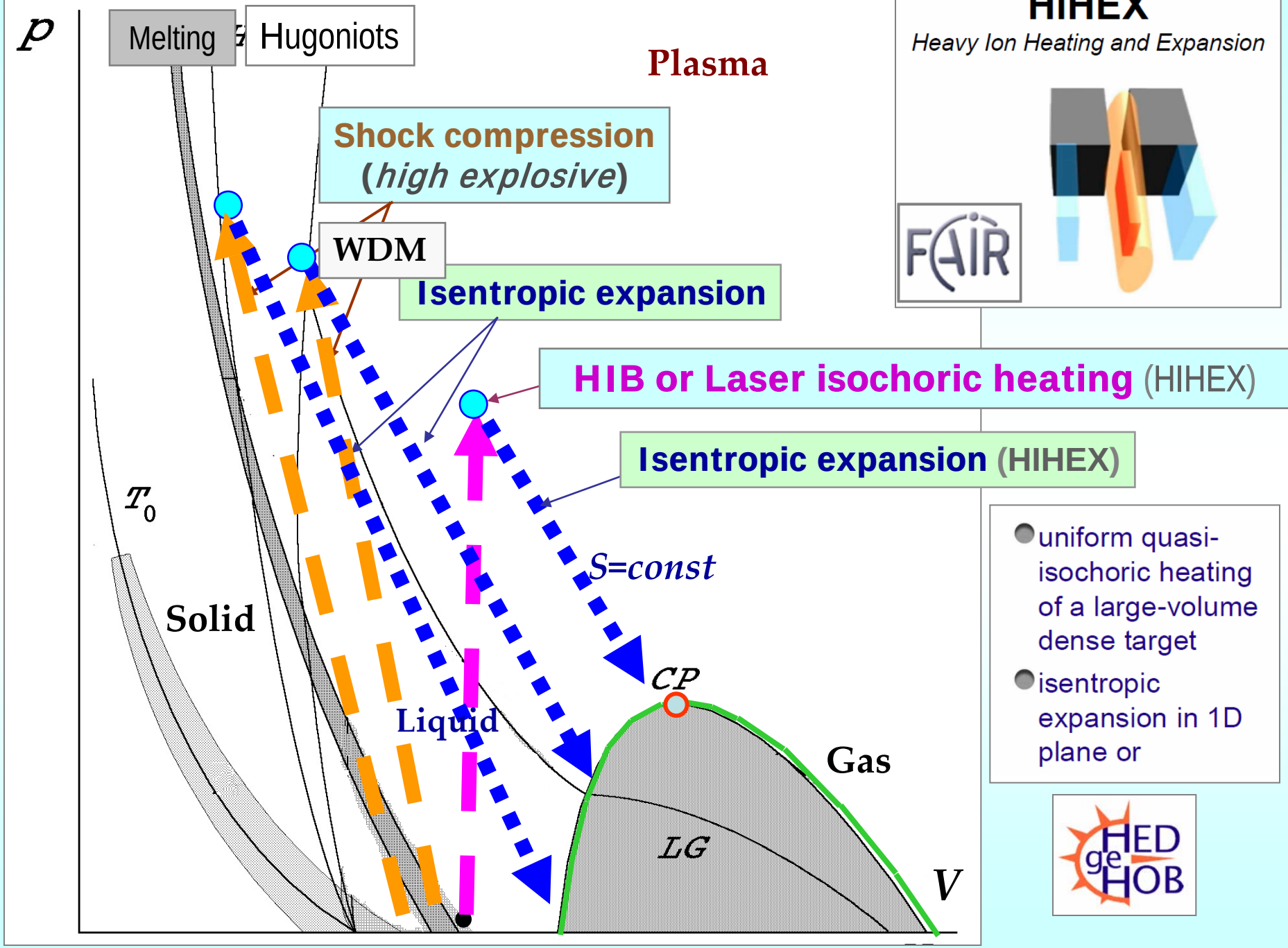

Background phase diagram:
L. Satarov, M. Dmitriev, I. Mishustin //arXiv: 0901.1430

## Hadronization




Widely accepted phase diagram of matter under extreme conditions

Iosilevskiy I.L. in "*Physics of Extreme States of Matter*", Eds. V. Fortov *et al.* // IPCP RAS, Russia, 99 (**2011**) // arXiv:1401.5481

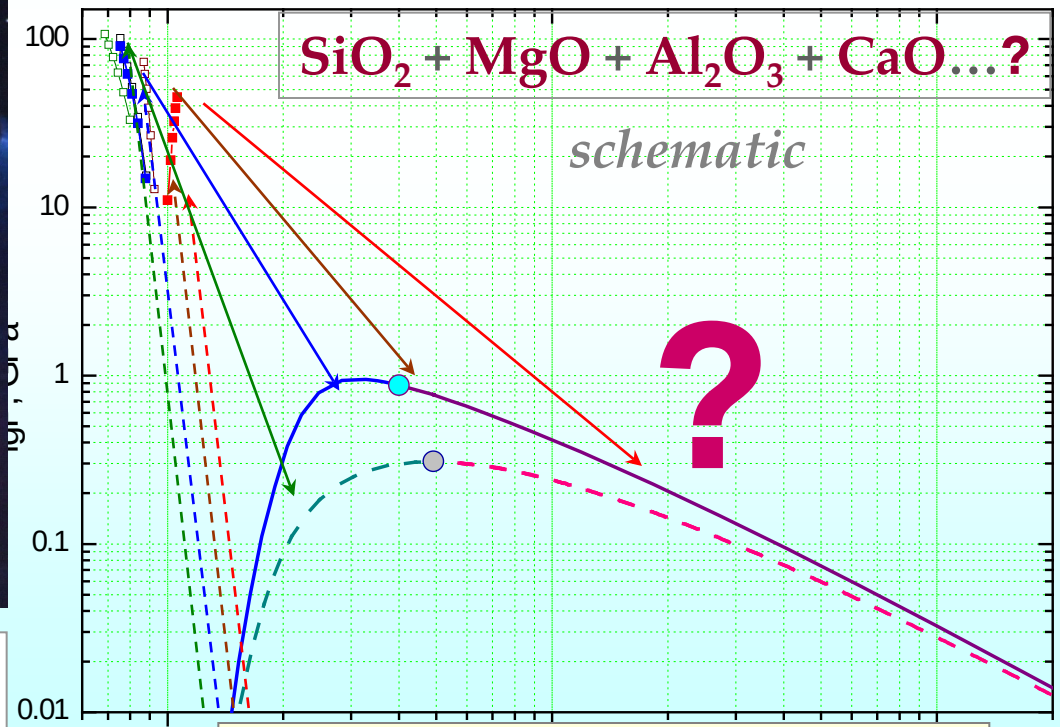

HIHEX
Heavy Ion Heating and Expansion
FAIR
p
Melting
Hugoniots
Plasma
Shock compression
(high explosive)
WDM
Isentropic expansion
HIB or Laser isochoric heating (HIHEX)
Isentropic expansion (HIHEX)
T0
Solid
S=const
CP
Liquid
Gas
LG
V
uniform quasi-isochoric heating of a large-volume dense target
isentropic expansion in 1D plane or
HED geHOB


**Hypothetical catastrophic collision ("Megaimpact") ~ 4,5 · GY :**
***Theia*** ⇔ ***Earth*** ($T_{shock}$ ~ 1-2 eV, $v$ ~ 5-10 km/s, $P_{shock}$ ~ 1-2 Mb)

**Phase transition in the mixture ($SiO_2$, $MgO$, $Al_2O_3$, $CaO$…) must be *non-congruent* !**

**1st Stage – strong shock compression**

**2nd Stage – quasi-isentropic expansion**

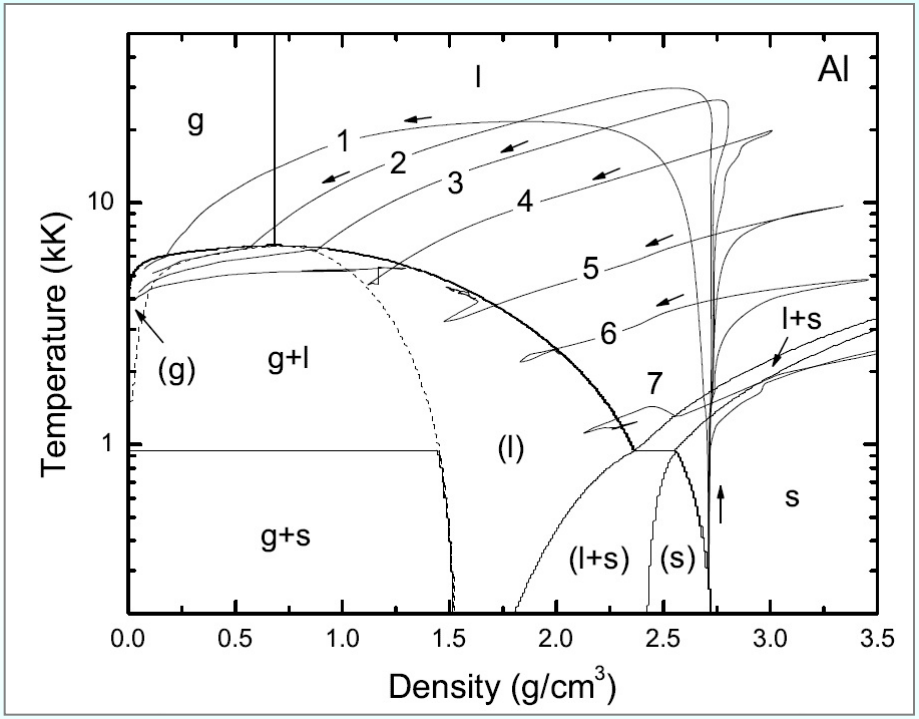



Iosilevskiy I., Gryaznov V., Solov'ev A.,
*High Temp.-High Pressure*, **43** (2014)
*Phase diagram of silica* ($SiO_2$) //arXiv:1312.7592

I. Iosilevskiy / *Elbrus + Hirschegg (2010 - 2015)*

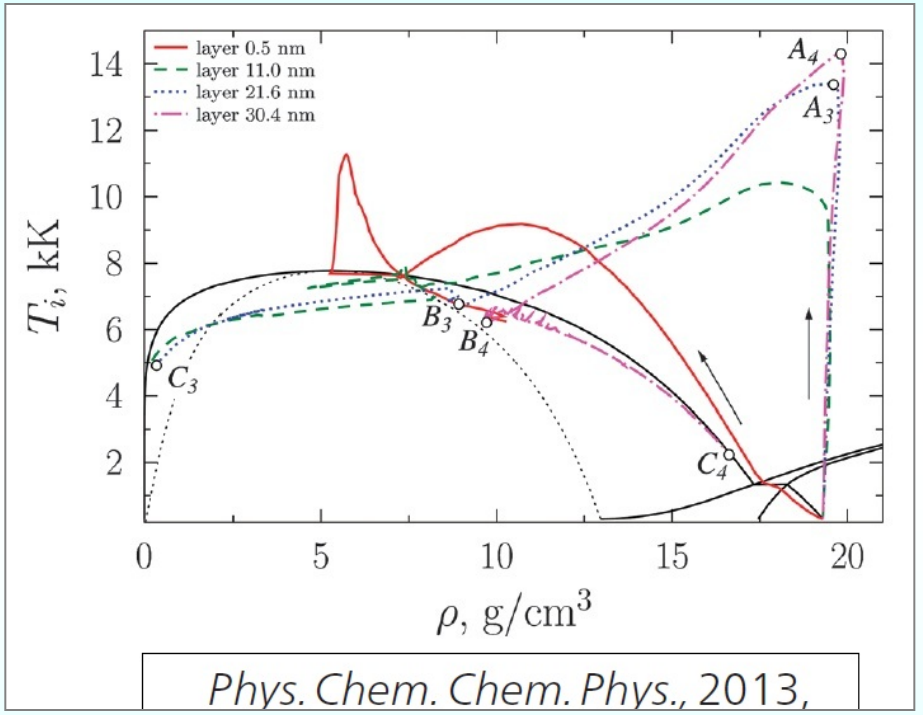
# Thermo- and hydrodynamics of expanding material under intense laser heating of condensed material

**Al**




Povarnitsyn M., Itina T., Khishchenko K., Levashov P.
*Phys. Rev. B* **75** (2007)

**Au**

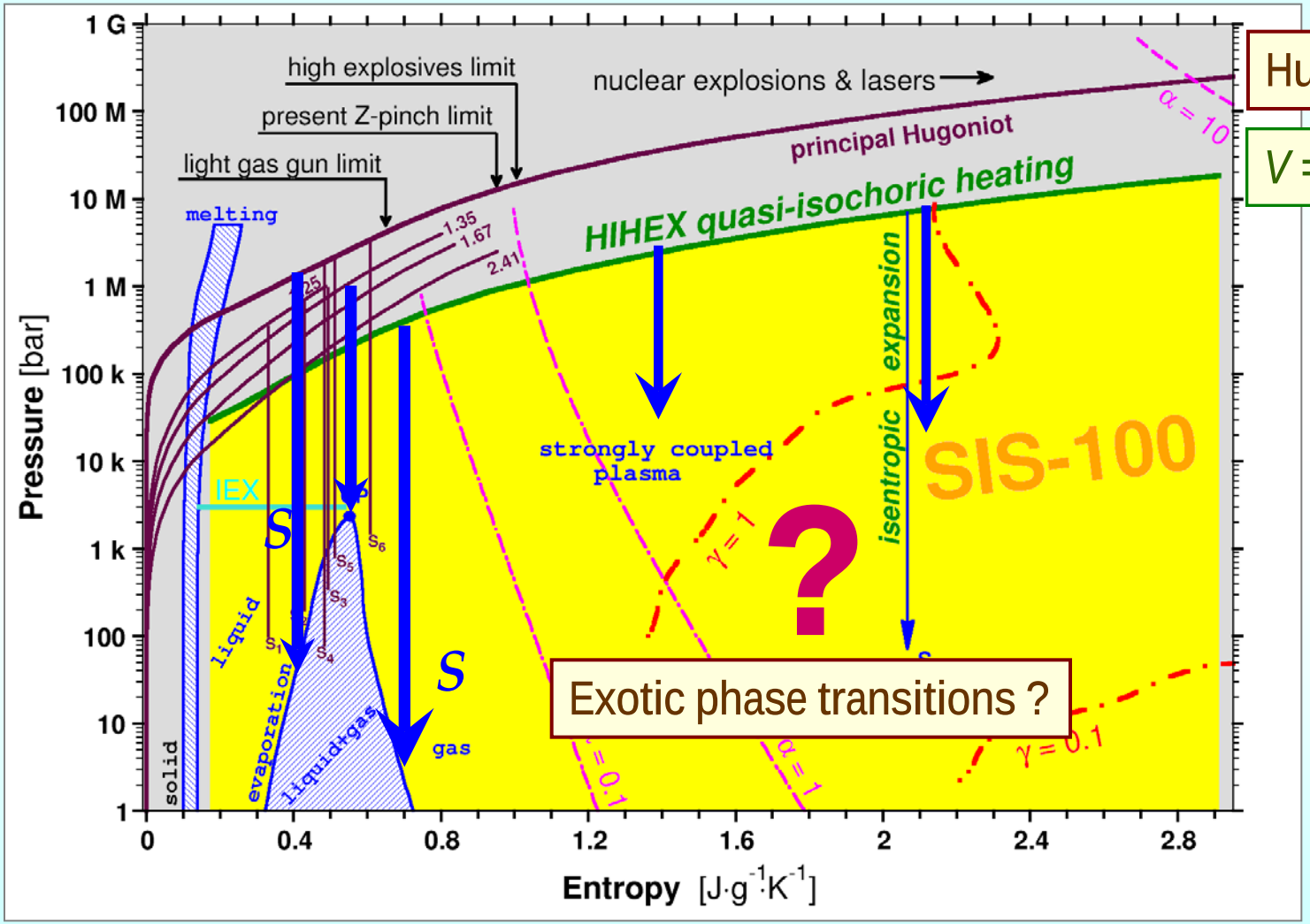



Povarnitsyn M., Khishchenko K., Levashov P.
*Phys. Chem. Chem. Phys.* **15** (2013)

## Thermodynamic paths for expansion of different layers of irradiated metallic surface

# “Terra Incognita” - regions of the phase diagram accessible in HEDgeHOB experiments at **FAIR**

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




Hugoniot

*V* = const

Courtesy of Igor Lomonosov (IPCP RAS)

**What is happened when thermodynamic path of isentropically expanding matter enters two-phase region of unexplored phase transition**

**?**

**What is happened when thermodynamic path of isentropically expanding matter enters two-phase region of unexplored phase transition ?**

**"Plateau"**

**in isentropically expanding matter profile**

(*in planar geometry*)

**is well-known**

*(e.g. Zel'dovich & Raizer, 1966)*

# Yakov Zeldovich *and* Yurii Rizer

## *Physics of Shock Waves and High-Temperature Hydrodynamics*

## (1966)

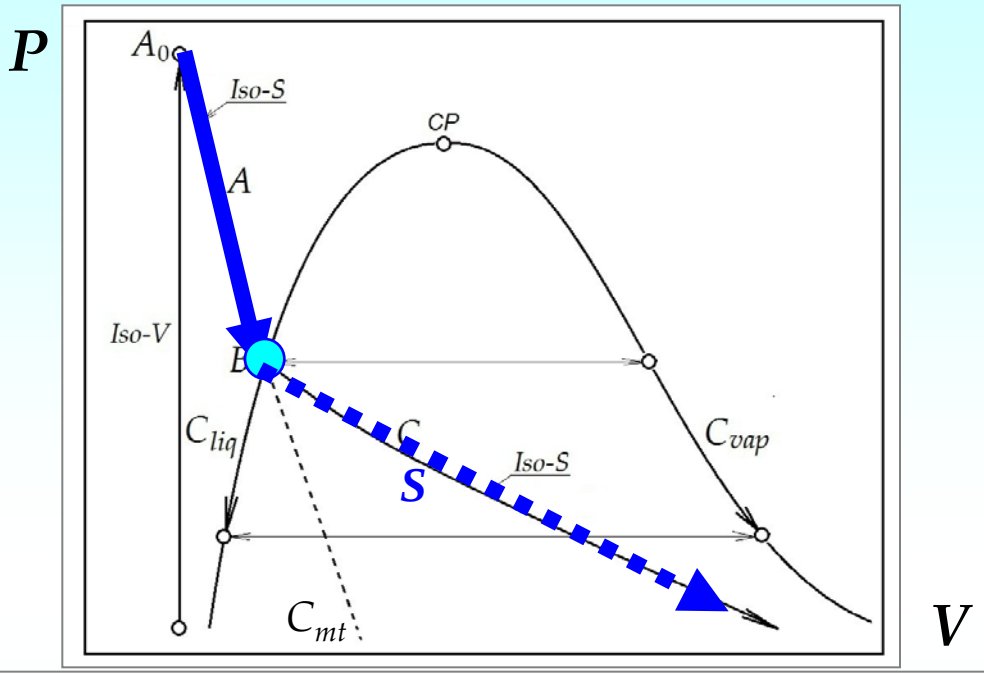
Yakov Zel'dovich


( FIZMATLIT, Moscow, 2008 )

Yurii Raizer

Ya. Zel'dovich, *JETP* **16** (**1946**) *On possibility for rarefaction shock appearsnce*

# Hydrodynamics *of* isentropic expansion *in* two-phase region




**(1) Isentrope crosses boundary of two-phase region (*binodal*)**

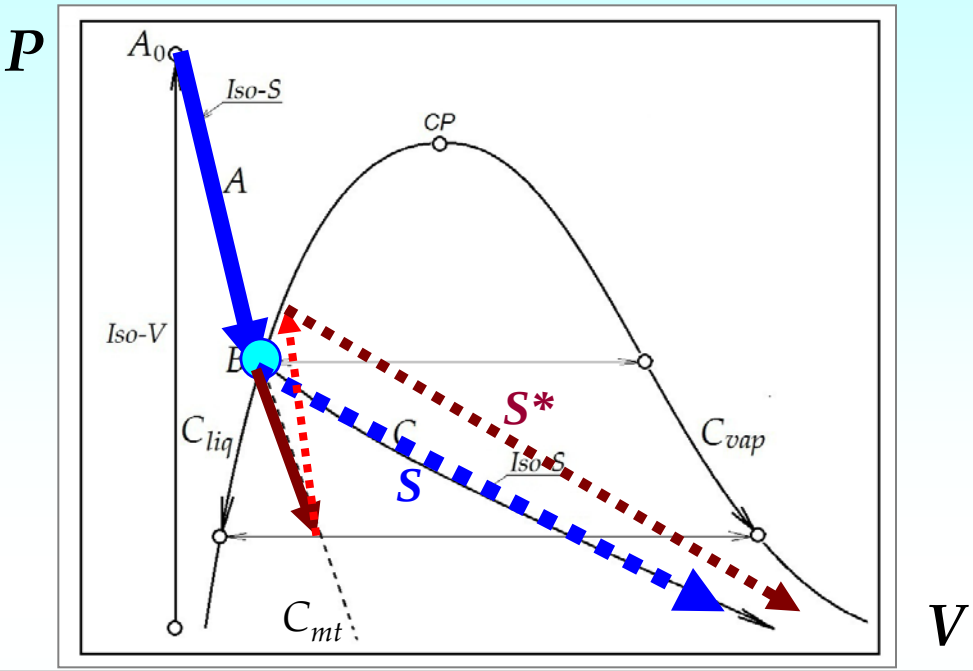
**(2) Isentropic expansion in two-phase region moves along *equilibrium* branch**
- ***Instant transition to equilibrium two-phase mixture*** *(boiling, condensation etc)*
- ***The two-phase mixture is highly dispersed !*** *(unique "mixed" phase)*

**(1) + (2) justify: *(i) + (ii)***

***(i)*** **– Description in frames of LTE** (Local Thermodynamic Equilibrium)

***(ii)*** **– Description in frames of LHD** (Local Hydrodynamic Description **-** "*One-fluid approx.*")

# Hydrodynamics *of* adiabatic expansion *in* two-phase region




**(1) Isentrope crosses boundary of two-phase region (*binodal*)**

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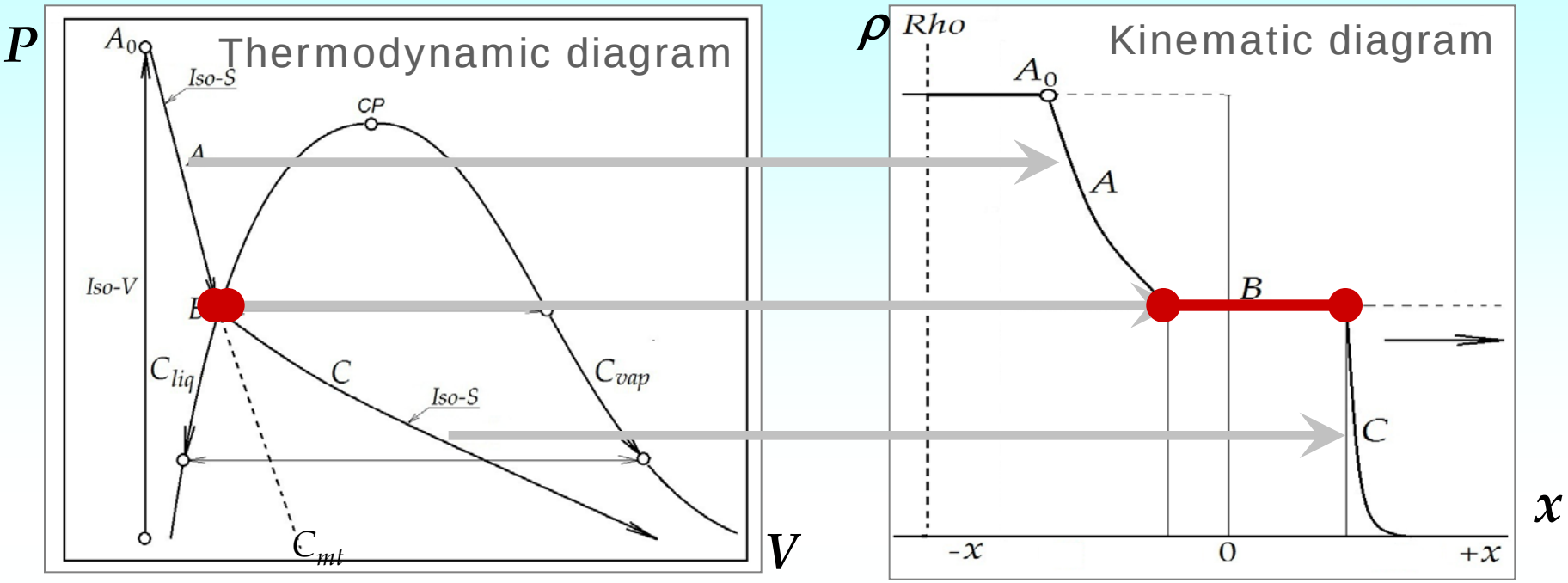
**(1) + (2) justify: *(i) + (ii)***

***(i)*** **– Description in frames of LTE** (Local Thermodynamic Equilibrium)

***(ii)*** **– Description in frames of LHD** (Local Hydrodynamic Description - "*One-fluid approx.*")

**(3)** ***Iso-S enters metastable area in 2-phase region ⇔ Instant boiling in shock ⇔ Pressure jump ⇔ Equilibrium two-phase mixture ⇔ Hydrodynamics*** ***(iso-S* > S )***

# “Boiling Layer” *in isentropic rarefaction wave*




Hydrodynamics of isentropic decay of **semi-infinite** plane sample is **self-similar** (1-D)

One **POINT** at liquid-gas BINODAL spread into **UNIFORM**, **EXTENDED** and thermodynamically **EQUILIBRIUM REGION** (”***Boiling Layer***”)

**Finite portion** of extended material (~ 1), involved into isentropic expansion, is “**stuck**” (“**freezes**”) within the **boiling layer** (*for a long time enough*)

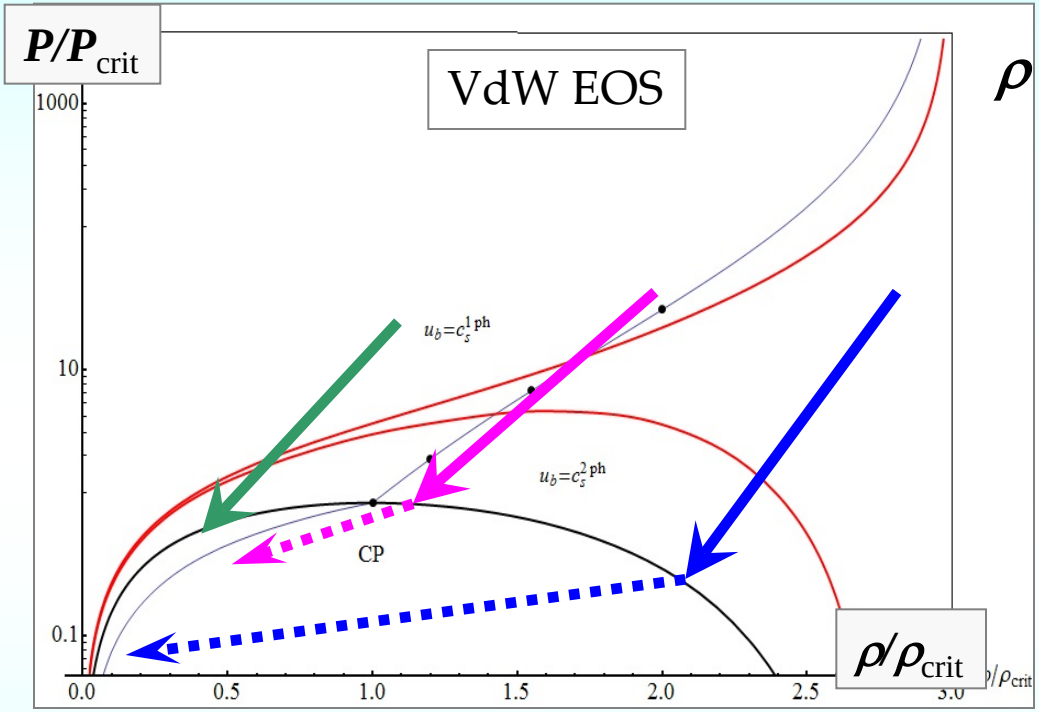
It is valid for **ANY BOUNDARY** of **ANY PHASE TRANSITION** (***Phase Freezeout*** **!**)

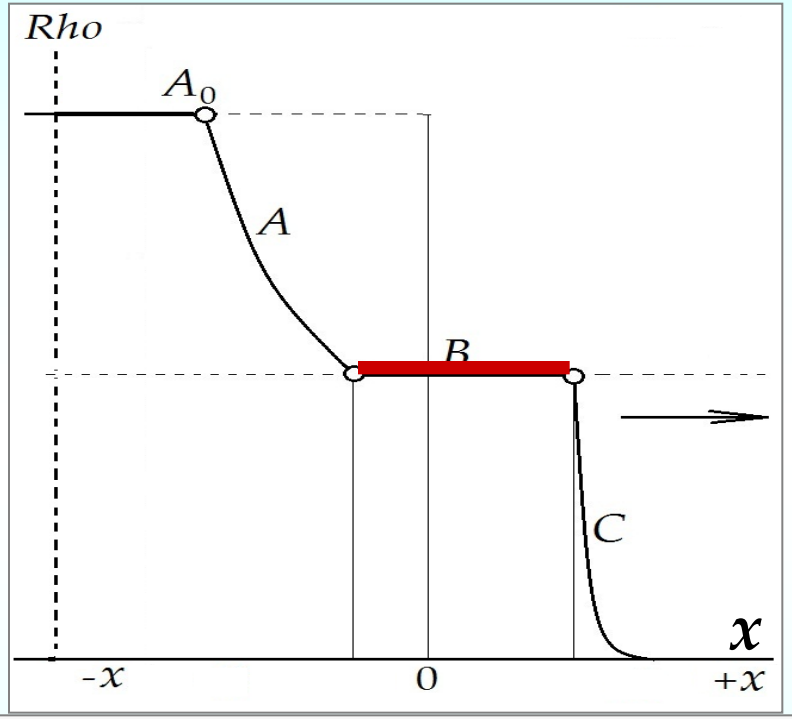

I. Iosilevskiy, *Phase freezeout in isentropically expanding matter* // in “*Physics of Extreme States of Matter*”, // Eds. V. Fortov et al. // Moscow, Russia, PP 99 // *Proc. Int. Conf. “Elbrus-2012”*/ arXiv:1401.5481

# Thermodynamics of Binodal Layer

(*three variants*)

"Liquid" layer, "Vapor" layer, "Critical" layer




**Break in *P-V* isentrope** (sound speed discontinuity) is valid for **any variants** of iso-*S* entering gas-liquid **binodal**:

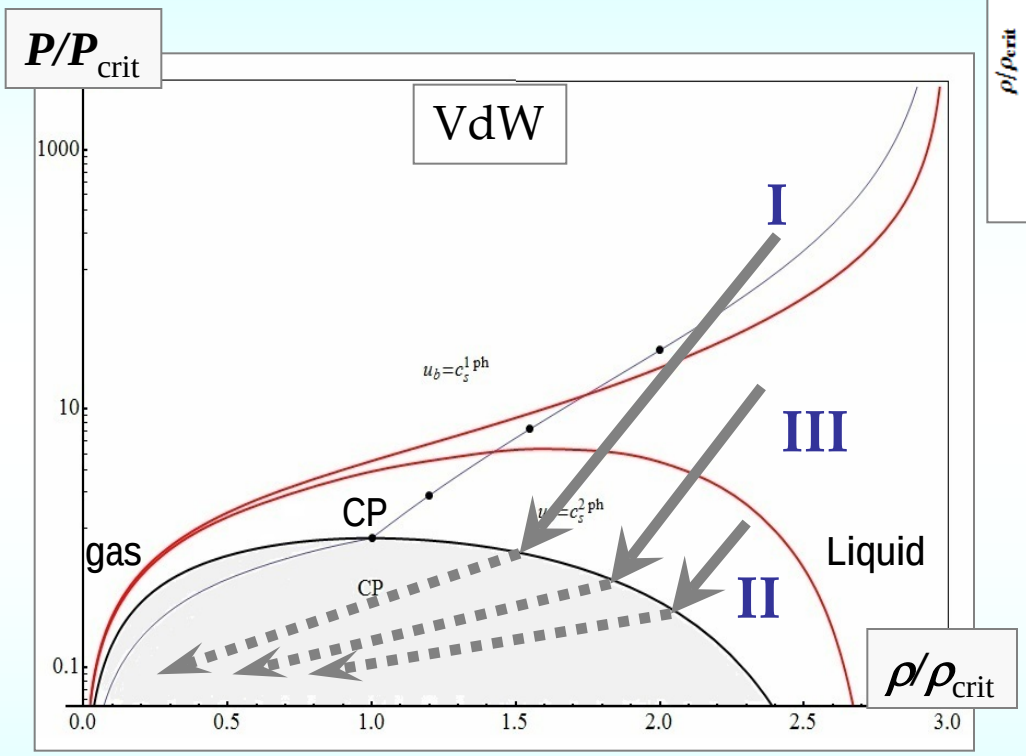
- ***boiling*** *liquid boundary*
- *vapor* ***saturation*** *boundary*
- *vicinity of* ***critical*** ***point***

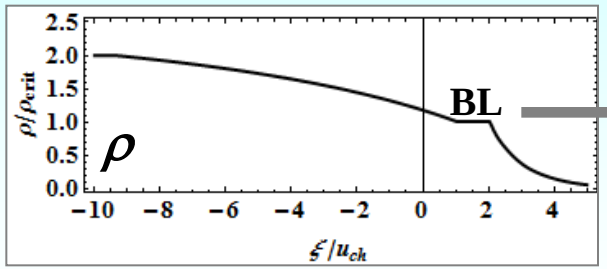

Borovikov D. & Iosilevskiy I. *in "Physics of Extreme States of Matter", Eds. V. Fortov et al. IPCP RAS Pub., Chernogolovka, Russia* (2012) // arXiv:1209.0398 /1306.2765 // *"HEDM Physics"* (Hirschegg – 2011)

# Hydrodynamics of Binodal Layer

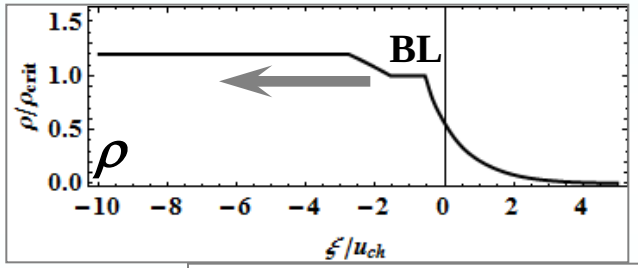
(*three variants*)

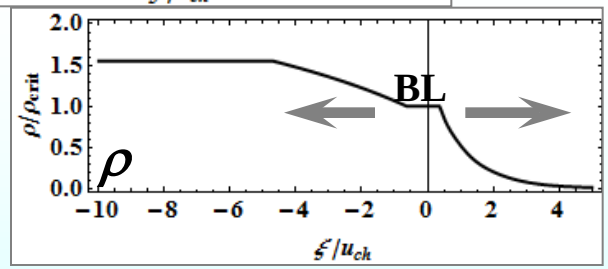
Dependence on the choice of initial state: ( iso-$S$ *and* $P_0$)




**BL**- boiling layer




**I** – **Boiling layer moves outside** of high-pressure region

**II** – **Boiling layer moves inside** of high-pressure region

**III** – **Boiling layer moves in both sides** of high-pressure region

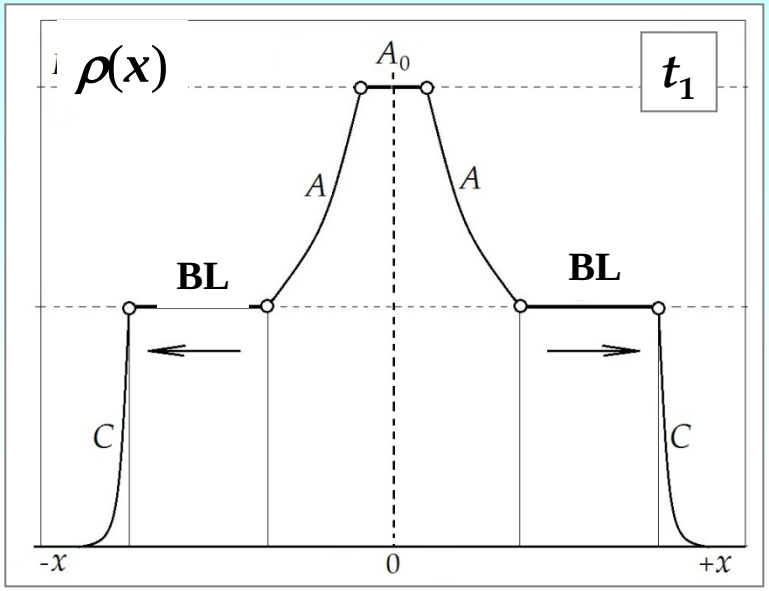

Borovikov D. & I.L.I. *in "Physics of Extreme States of Matter", Eds. V. Fortov et al. IPCP RAS Pub., Chernogolovka, Russia* (2012) //arXiv:1209.0398 / arXiv:1306.2765 // "*HEDM Physics*" (Hirschegg – 2012)

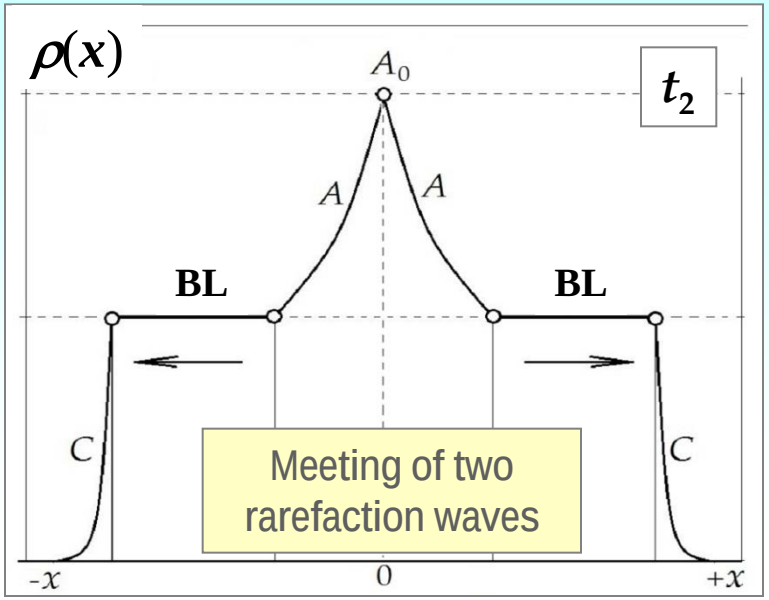
# Binodal layers in isentropically expanding slab system

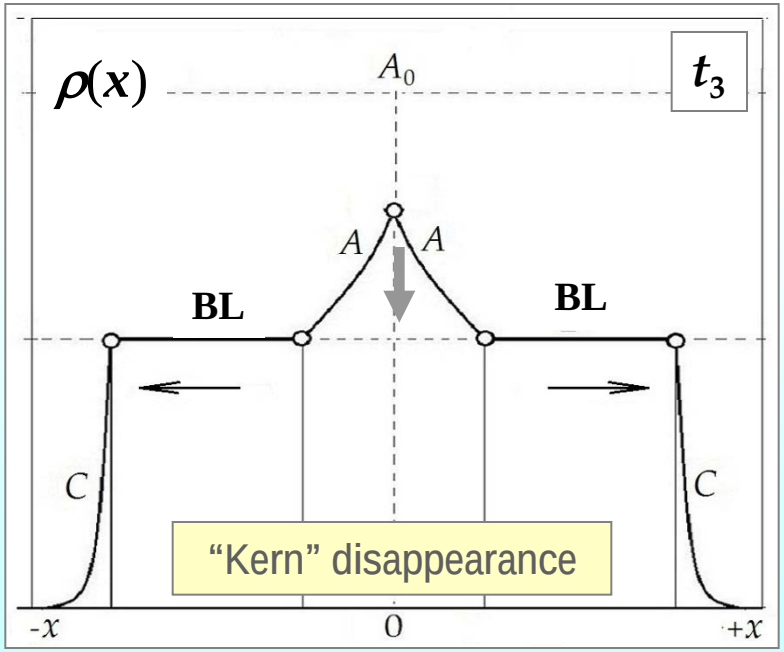
## *Dynamics of slab target under Heavy Ion Beam (HIB) irradiation*

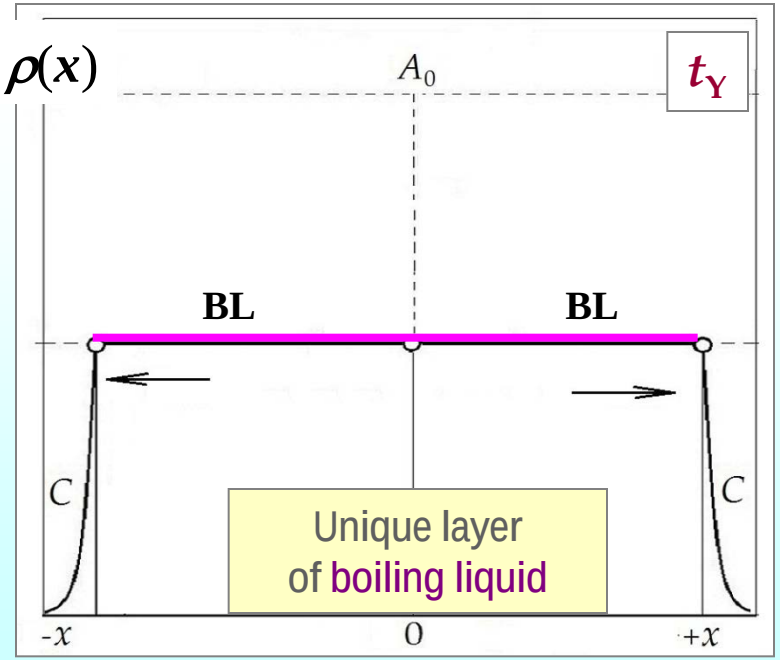
I. Iosilevskiy, *Phase freezeout in isentropically expanding matter* // in "*Physics of Extreme States of Matter*", // Eds. V. Fortov et al. // Moscow, Russia, PP 99 // *Proc. Int. Conf. "Elbrus-2012"*/ arXiv:1401.5481

# Hydrodynamics *of* isentropic expansion *for* slab target



**Shock-Wave Data-base**

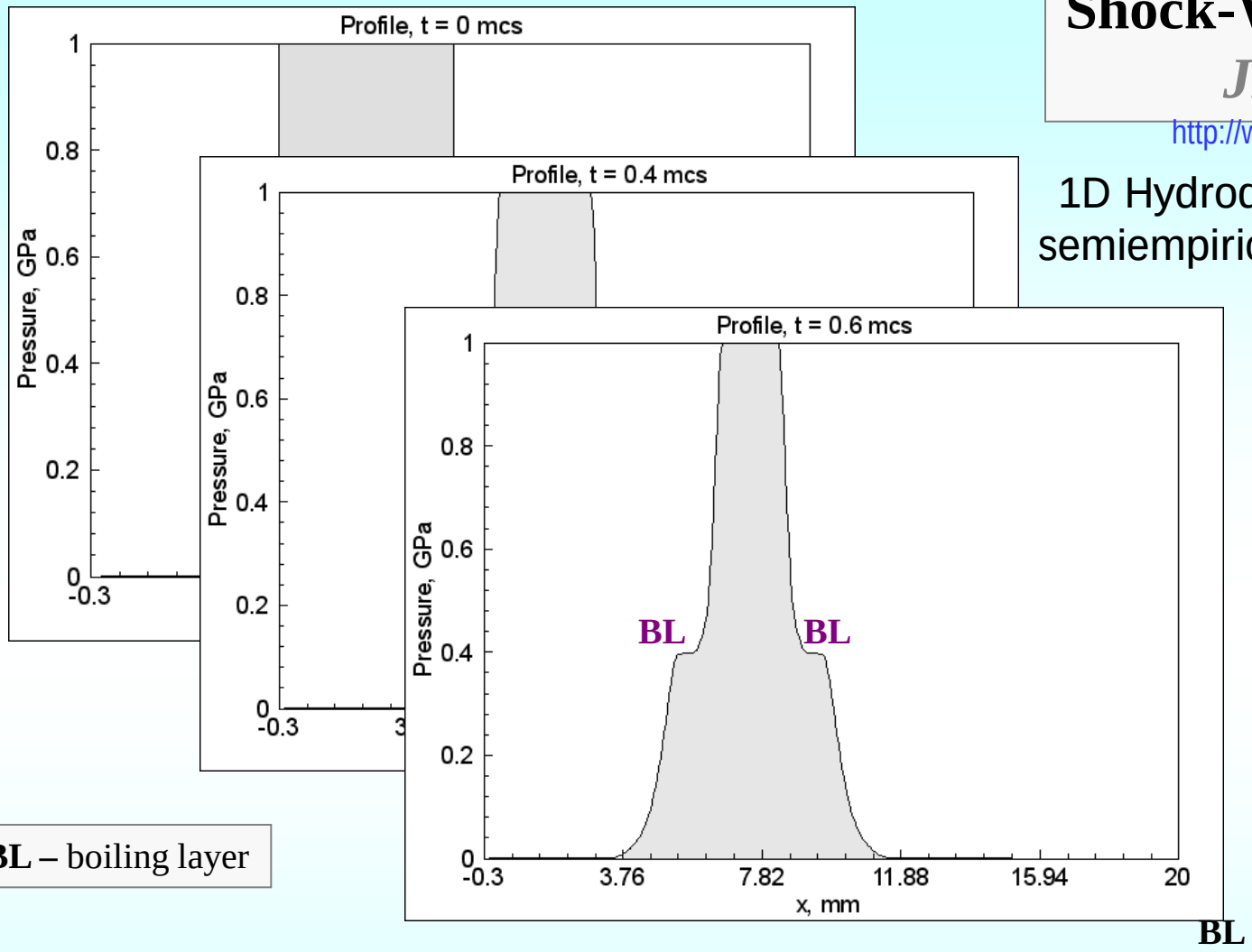
***JIHT RAS***

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

1D Hydrodynamics + realistic semiempirical “wide-range” EOS

**Al**

**Pressure profile**




**BL** – boiling layer

# Appearance of “shoulders” in pressure profile (BL)


Borovikov D. & I.L.I. *in “Physics of Extreme States of Matter”, Eds. V. Fortov et al. IPCP RAS Pub., Chernogolovka, Russia* (2012) //arXiv:1209.0398 / arXiv:1306.2765 // *“HEDM Physics”* (Hirschegg – 2012)

# Shock-Wave Data-base

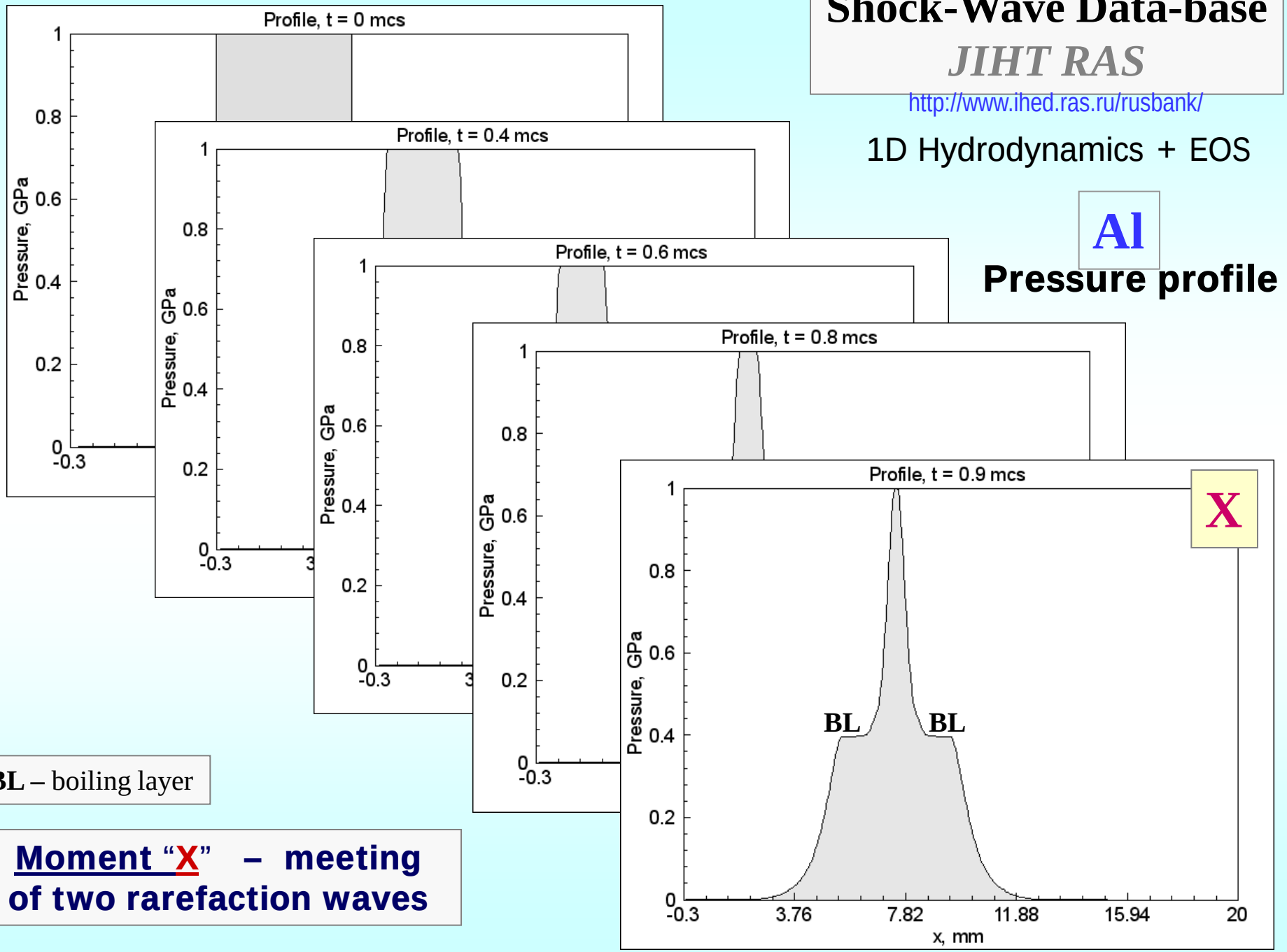
*JIHT RAS*

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

1D Hydrodynamics + EOS

**Al**

**Pressure profile**




**BL** – boiling layer

**Moment "X" – meeting of two rarefaction waves**

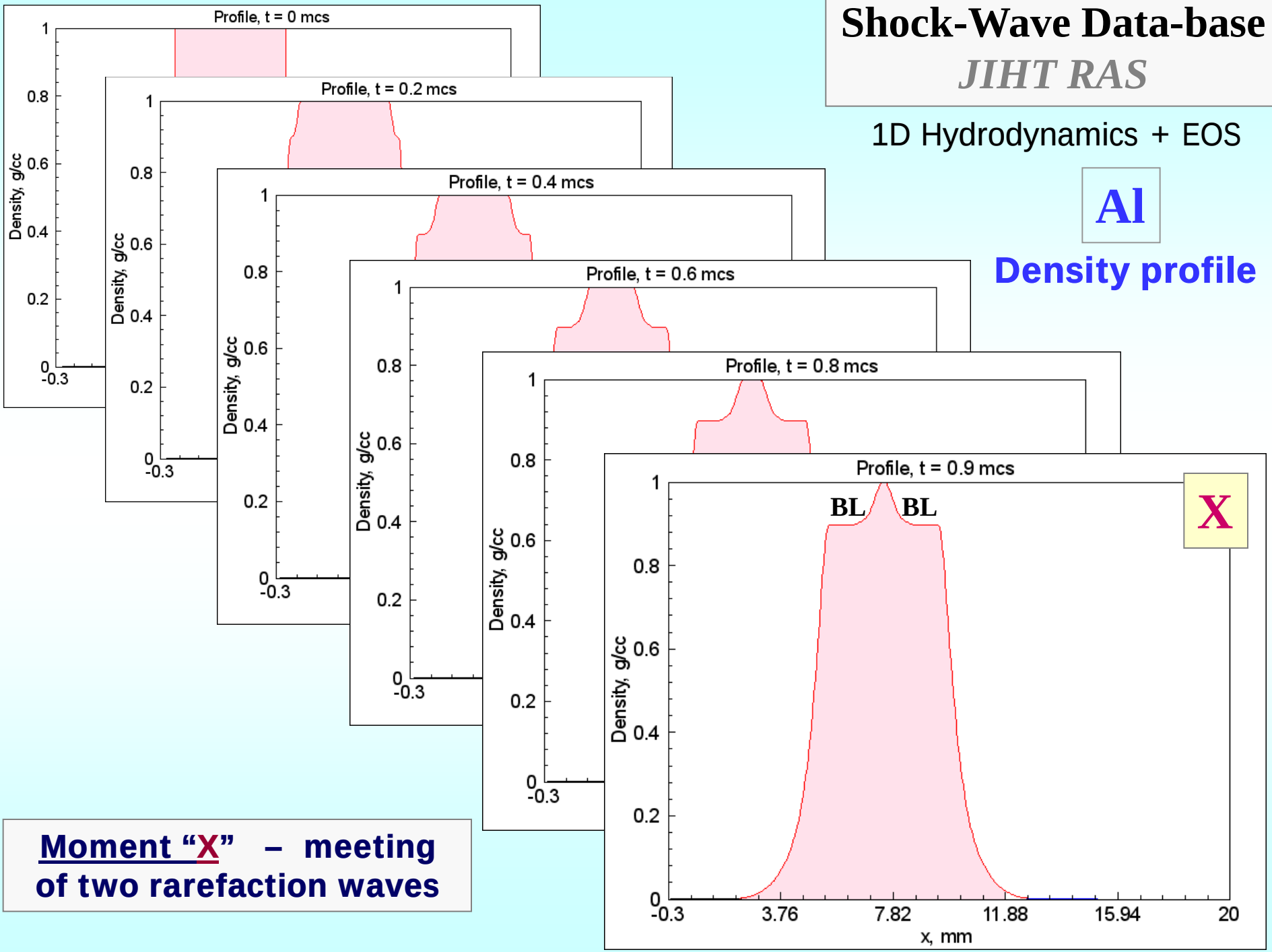
# Shock-Wave Data-base

*JIHT RAS*

1D Hydrodynamics + EOS

**Al**

**Density profile**



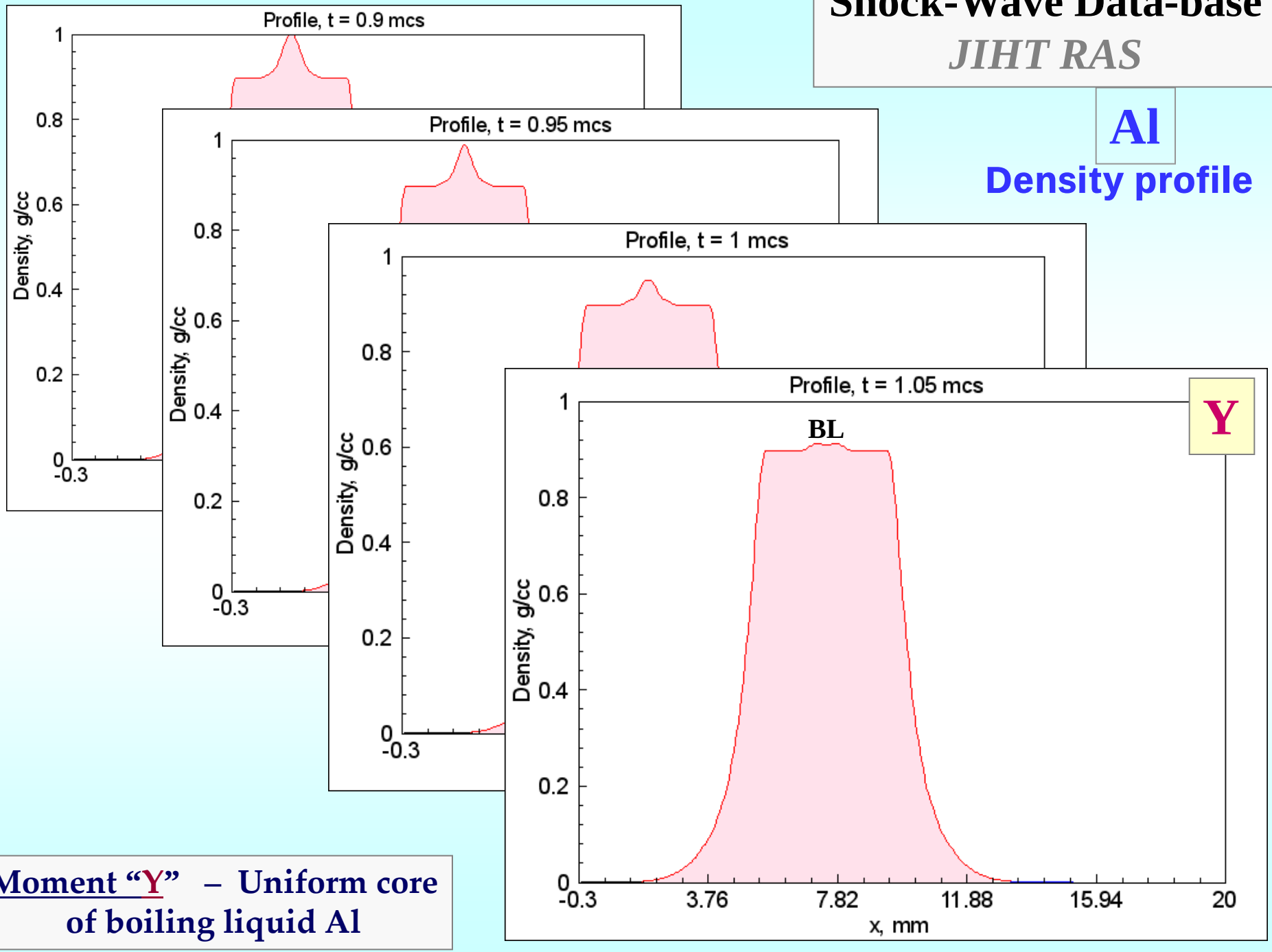

**Moment "X" – meeting of two rarefaction waves**

# Shock-Wave Data-base

*JIHT RAS*

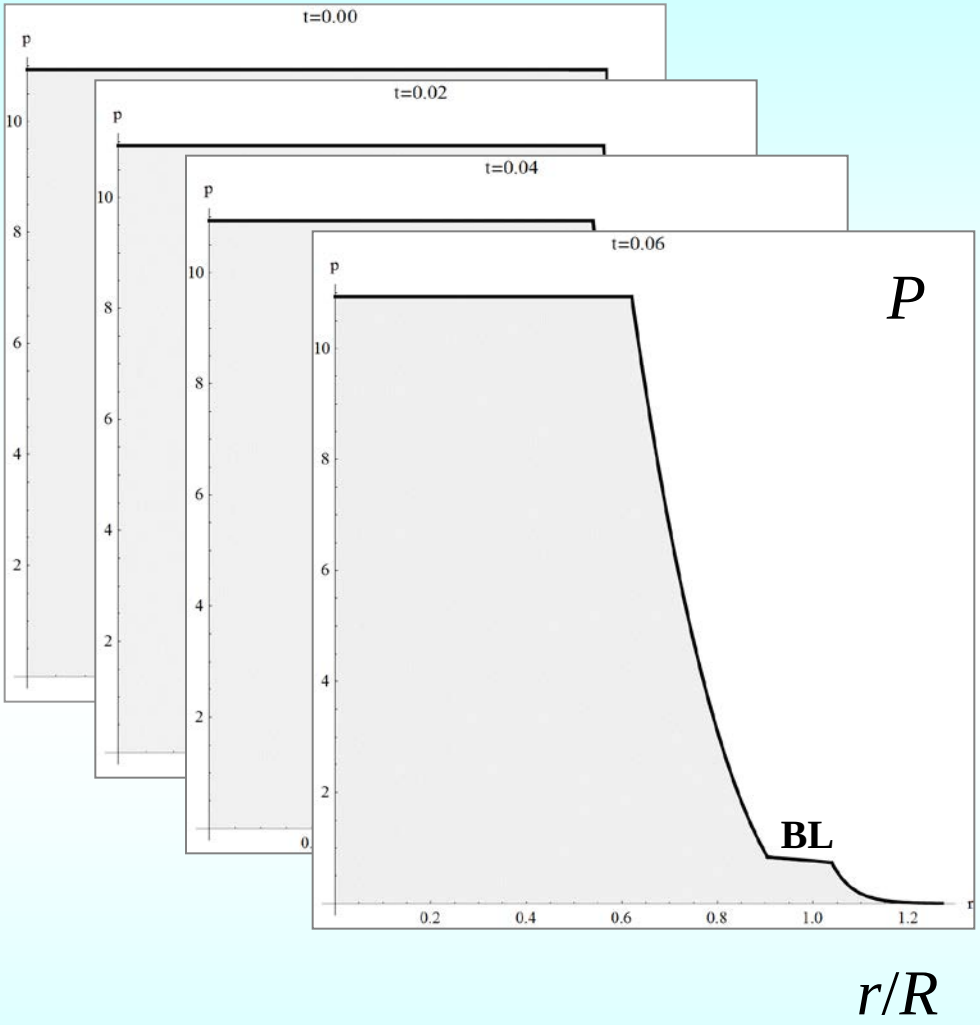
**Al**

**Density profile**




**Moment "Y" – Uniform core of boiling liquid Al**

# Binodal layer in isentropically expanding "ball"




**Pressure profiles**

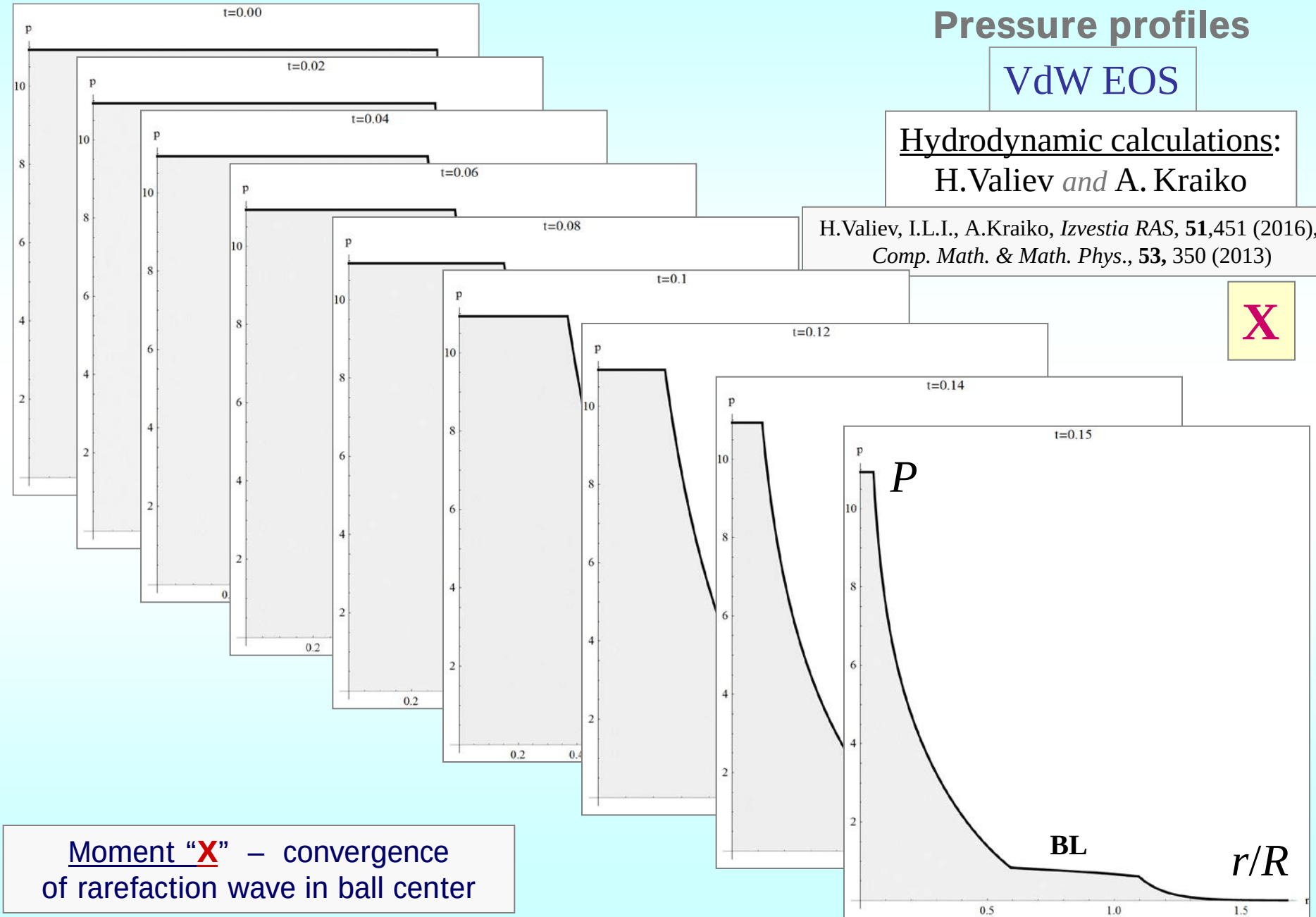
VdW EOS

Hydrodynamic calculations:
H.Valiev *and* A. Kraiko

H.Valiev, I.L.I., A.Kraiko, *Izvestia RAS*, **51**,451 (2016),
*Comp. Math. & Math. Phys.*, **53,** 350 (2013)

Moment "**X**" – convergence
of rarefaction wave in ball center

# Binodal layer in isentropically expanding "ball"




Moment "**X**" – convergence of rarefaction wave in ball center

# Fireball hydrodynamics in RHIC

## **Chemical** *and* **kinetic freeze-out**
## (*after crossing QHPT by isentropic path*)

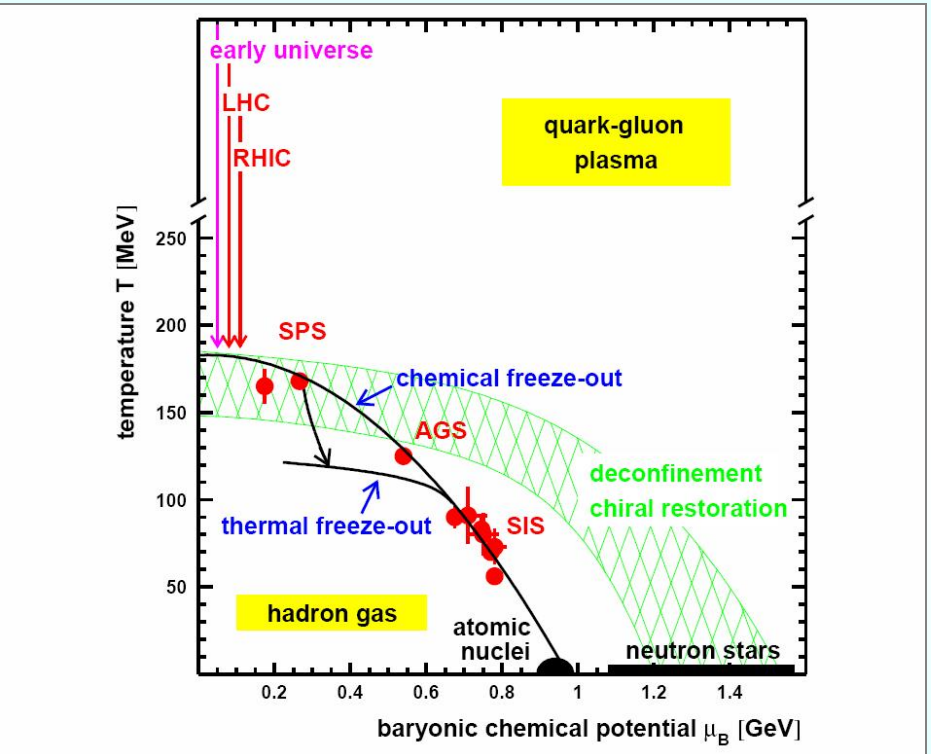



Figure 2. Phase diagram of hadronic and partonic matter. The hadrochemical freeze-out points are determined from thermal model analyses of heavy ion collision data a SIS, AGS and SPS energy. The hatched region indicates the current expectation for th phase boundary based on lattice QCD calculations at $\mu_b$=0. The a thermal freeze-out for the SPS corresponds to isentropic expansion

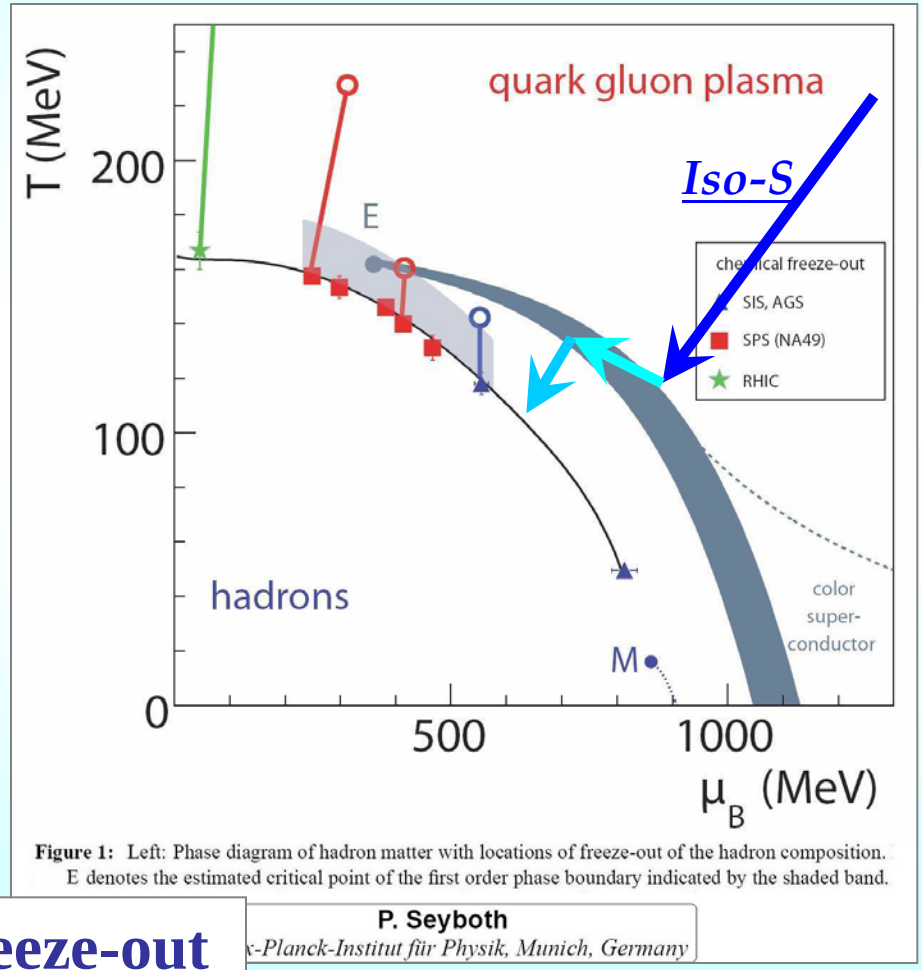


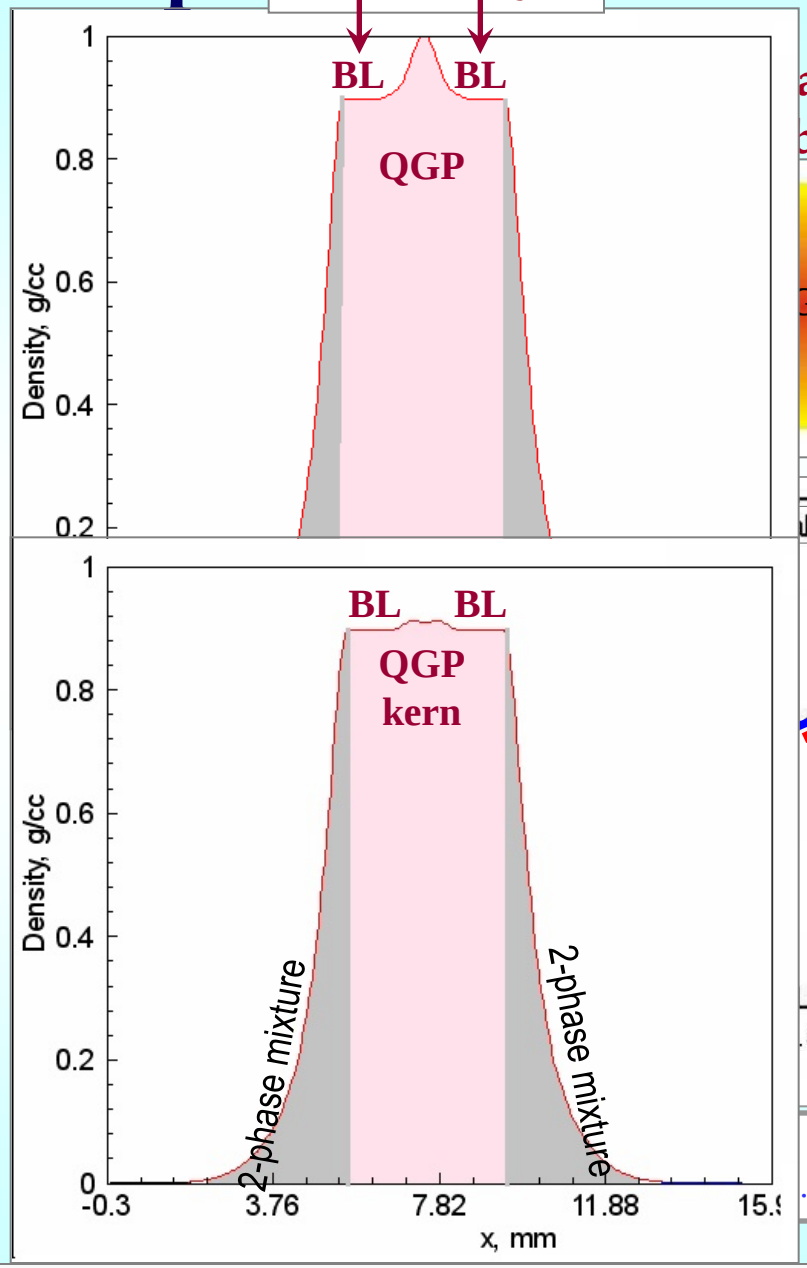

**Figure 1:** Left: Phase diagram of hadron matter with locations of freeze-out of the hadron composition. E denotes the estimated critical point of the first order phase boundary indicated by the shaded band.

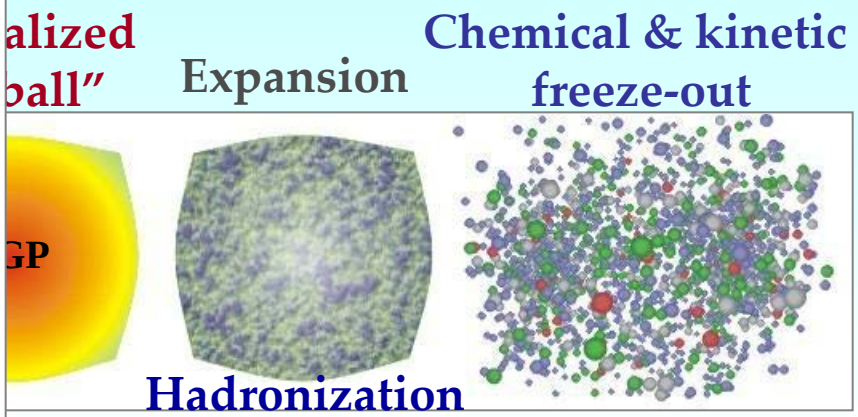

P. Seyboth
x-Planck-Institut für Physik, Munich, Germany

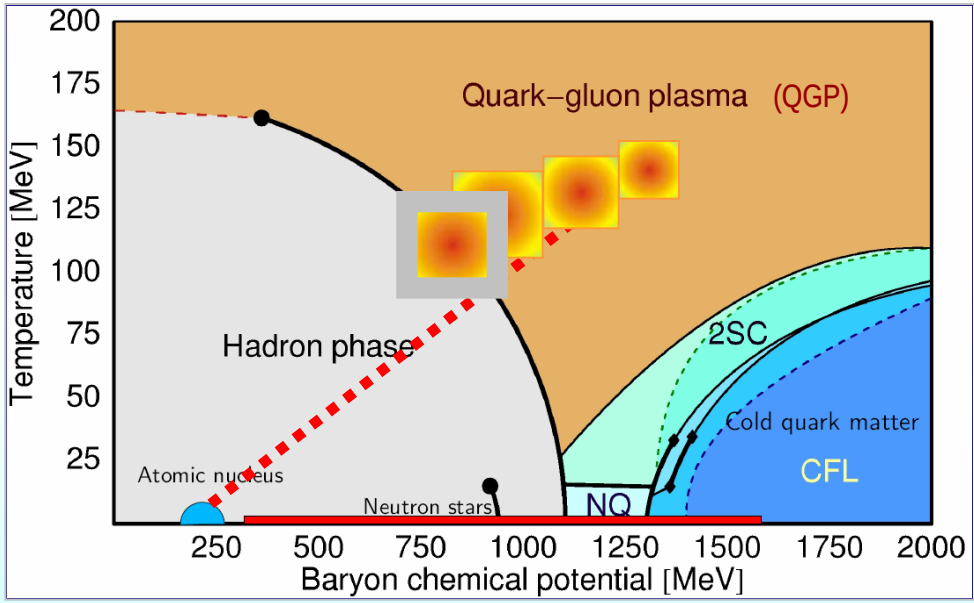

## Phase freeze-out

## ( *before isentropic path enters 2-phase region of QHPT* )

# Impa…fireball hydrodynamics *in* RHIC

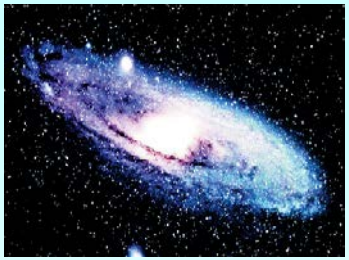



Widely accepted phase diagram of matter under extreme conditions

Iosilevskiy I.L. / in "*Physics of Extreme States of Matter*", Eds. V. Fortov *et al.* // IPCP RAS, Russia, 99 (**2011**) // arXiv:1401.5481



Compact Stars in the QCD Phase Diagram

Prerow, Germany, Sept. 2014

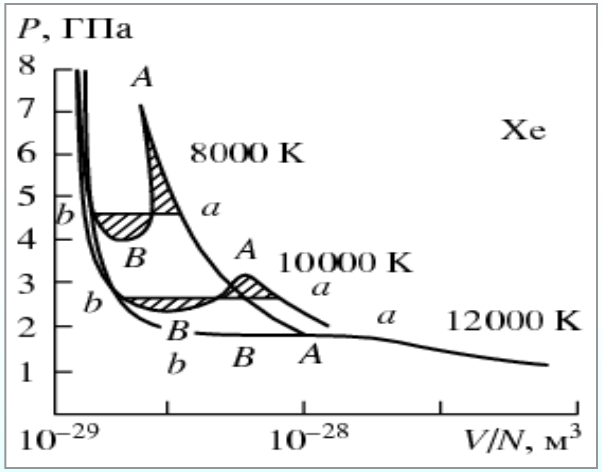

*Helmholtz International Summer School*

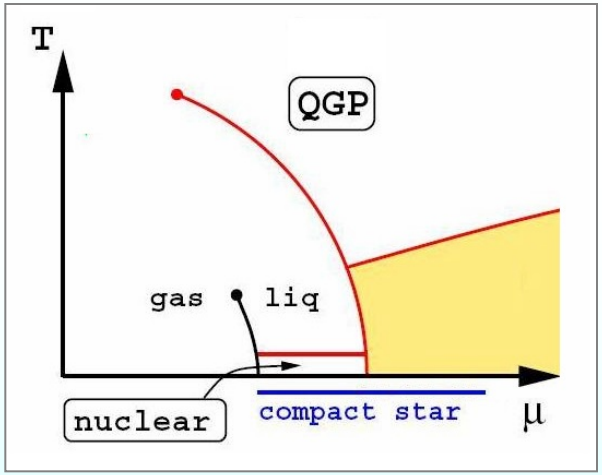
***Nuclear Theory in Astrophysics***

*Dubna, Russia, July* ***2017***

# Enthalpic *and* Entropic Phase Transitions

## *in* high energy density nuclear matter




**Igor Iosilevskiy**

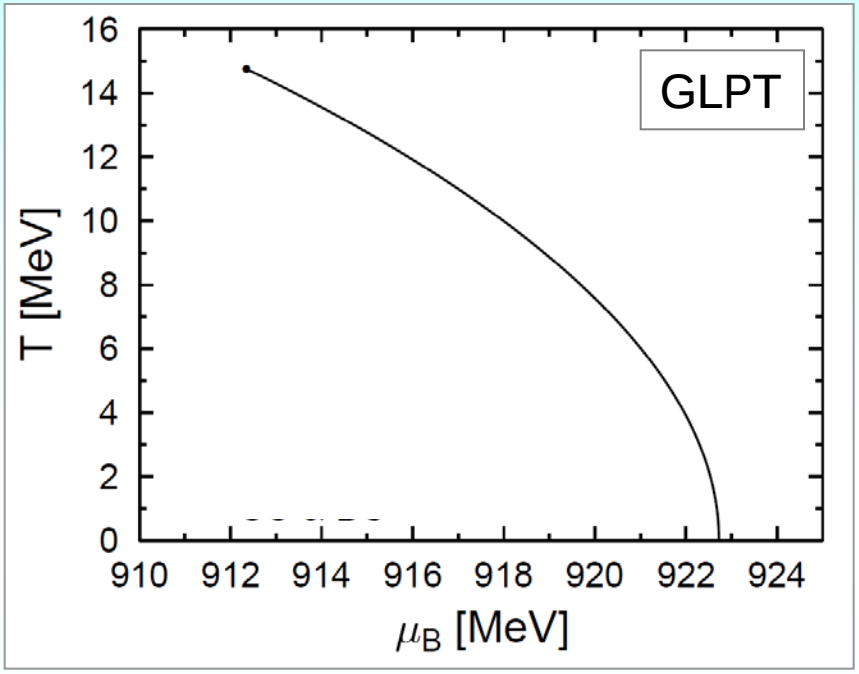
*Joint Institute for High Temperature (Russian Academy of Science)*

*Moscow Institute of Physics and Technology (State University)*

arXiv:1504.05850

# GLPT *and* QHPT look *like* equivalent *in* $T$-$\mu$ phase diagram

*(symmetric case)*

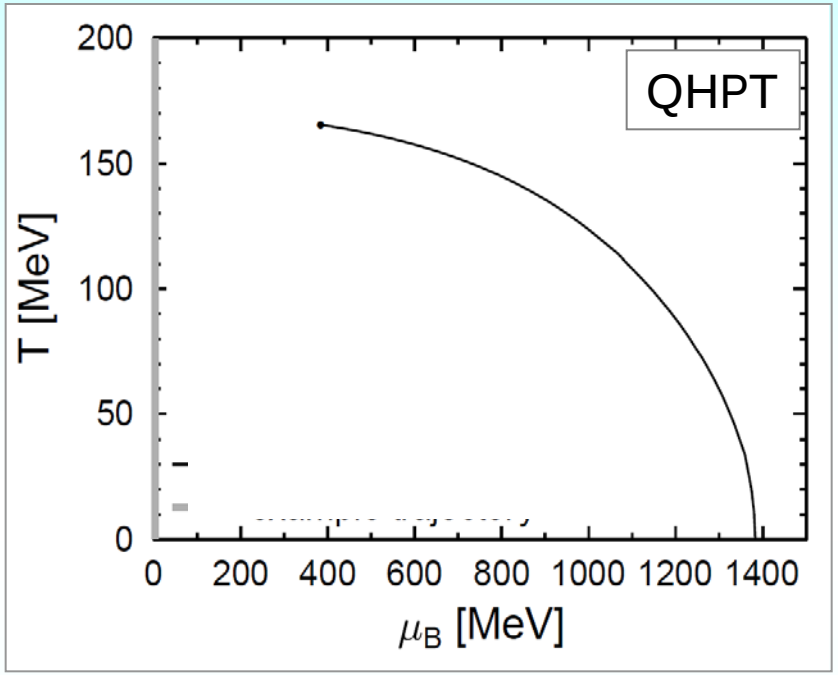



FSUGold (*Matthias Hempel* (*))

**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**

# Anomalous Thermodynamics of Entropic PT-s

**Normally positive cross derivatives became *negative simultaneously !***

**Normal** $> 0$ | **Abnormal** $< 0$

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

$$\Updownarrow \qquad \Updownarrow \qquad \Updownarrow$$

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

$$\Updownarrow \qquad \Updownarrow \qquad \Updownarrow$$

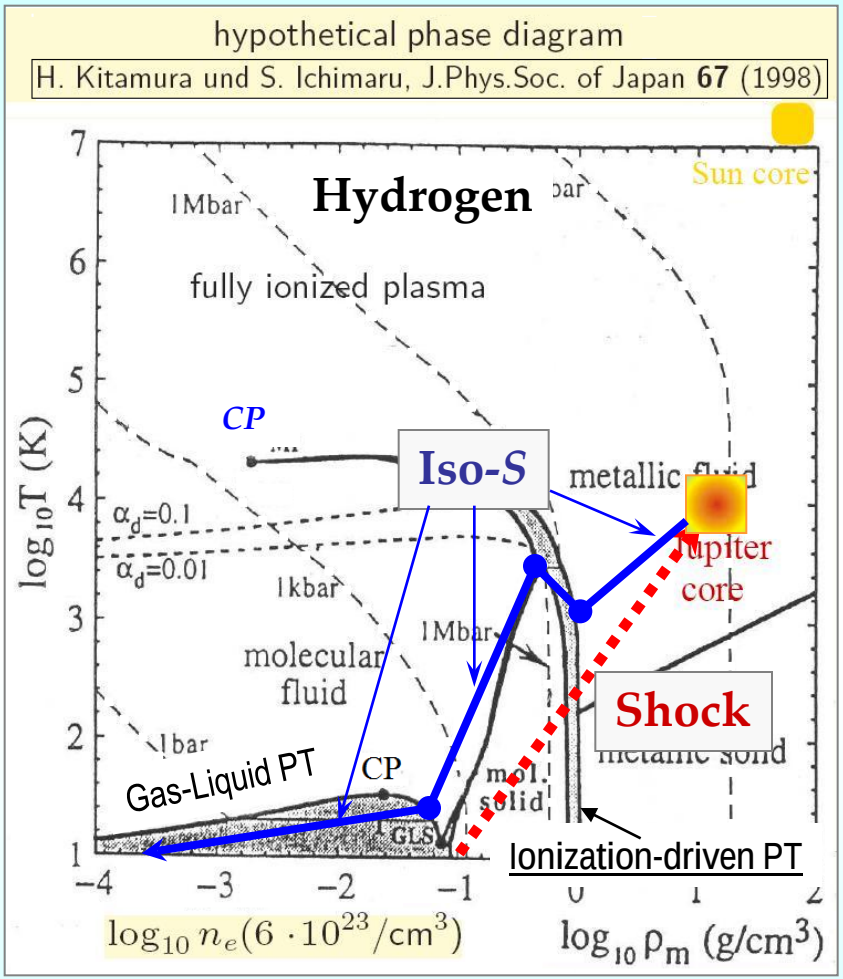
$$(\partial S/\partial V)_T \Leftrightarrow (-\partial S/\partial P)_T \Leftrightarrow (\partial T/\partial P)_S \Leftrightarrow (-\partial T/\partial V)_S$$

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

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

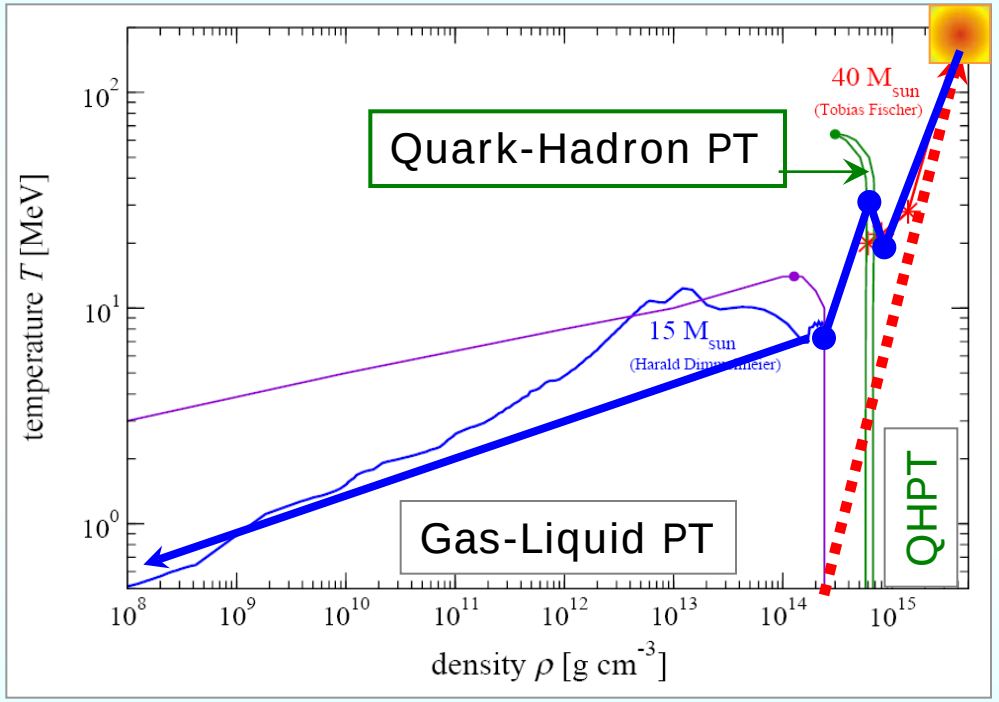
**All these cross derivatives are equal to *ZERO simultaneously !***

# Isentropic path enter *and* leave entropic QHPT



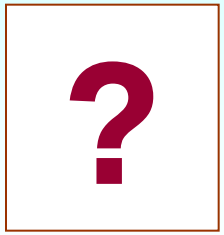

Gas-liquid (*enthalpic*) and Ionization-driven (*entropic*) phase transitions in Warm Dense Hydrogen (WDM).

Phase Diagram of High Energy Density Nuclear Matter




Phase diagram after **David Blaschke**, *Int. Conf. "Extreme State of Matter"*, ***Elbrus-2010***

**Isentropic path enter *and* never leave enthalpic GLPT**




**What is happen when isentropic expansion path enter and leave two-phase region of unexplored entropic phase transition**

( *main hydrodynamic features ?*)

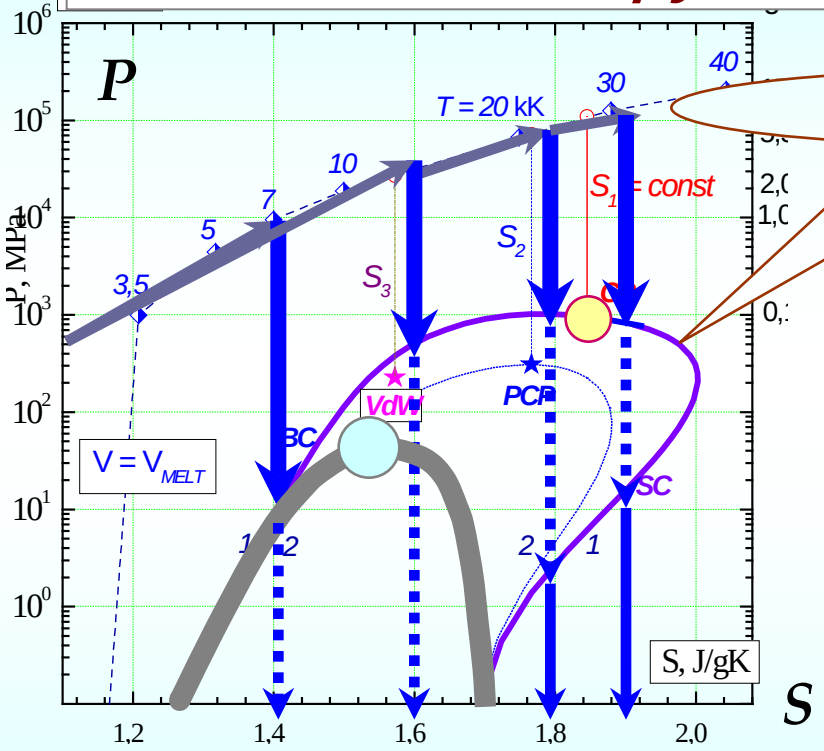
# Features of adiabatic expansion via two-phase region of non-congruent phase transition in U+O system

*$UO_2$ isochoric heating under heavy ion beam irradiation*

HIHEX

Heavy Ion Heating *and* EXpansion

## Pressure-Entropy diagram




Non-congruent PT

- Standard 2-phase boundary of forced-congruent PT
- Standard critical point
- Critical point of non-congruent phase transition

"**Retrograde regime**" – typical scenario of transition through the two-phase region of **non-congruent** phase transformation

See e.g. Iosilevskiy I. "*Phase Freezeout*" (2012) // arXiv:1401.5481

# Yakov Zel'dovich *and* Yurii Rizer

## *Physics of Shock Waves and High-Temperature Hydrodynamics*

(1966)

Yakov Zel'dovich


(ФИЗМАТЛИТ, Москва, 2008)

Yurii Raizer

Zel'dovich Ya. *JETP* **16** (**1946**) *On possibility of rarefaction shock wave*

***Научные открытия России***

Государственный реестр открытий СССР

**Научное открытие**

## "Явление образования ударных волн разрежения".

**Формула открытия:** “
Установлено неизвестное ранее явление образования ударных волн разрежения в однофазных средах, заключающееся в том, что в условиях сильного межмолекулярного взаимодействия, приводящего к уменьшению скорости звука с ростом давления, **область разрежения распространяется** в виде **ударной волны**".

**Авторы:**
А.Г. Иванов, С.А. Новиков, А.А. Борисов, Я.Б. **Зельдович**, С.С. Кутателадзе, В.Е. Накоряков

***Заявка:*** *№ ОТ-10012 от 30.01.79 / ОТ-10353 от 31.10.80.*

**Дата регистрации:** 28 августа **1986** г. !

Зельдович Я.Б. *Физика ударных волн и введение в газодинамику,* АН СССР, (**1946**)

# Appearance *of* plateau *and* rarefaction shock *in* hydrodynamic calculations *of* equilibrium adiabatic expansion *in* two-phase region *is well known*

**Zel'dovich & Raizer**

*Physics of Shock Waves and High-Temperature Hydrodynamics* - (1966)

*Adiabatic expansion*

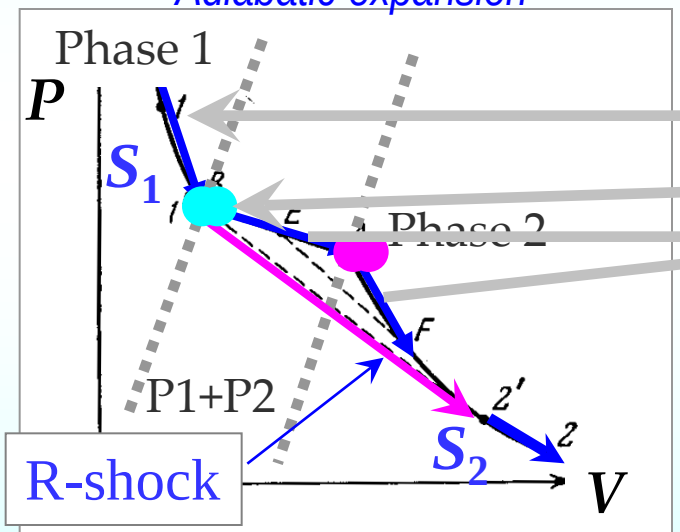
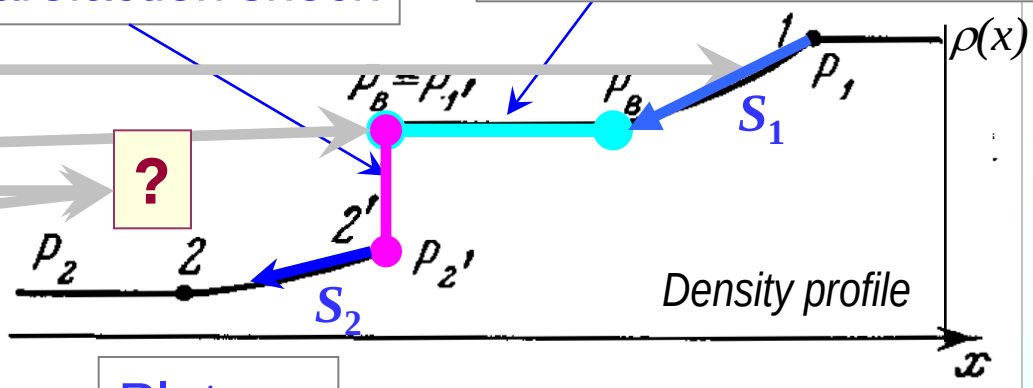



Рис. 11.51. К вопросу об эволюции области разрежения: состояния на

Rarefaction shock

"Plateau" (*binodal layer*)

?




Plateau

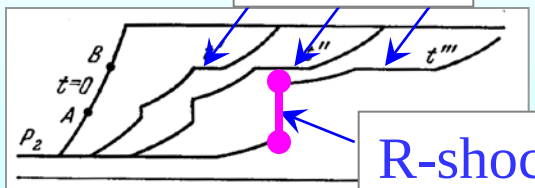



Рис. 11.54. Эволюция профиля давления в волне разрежения; образование ударной волны разрежения $t = 0, t', t'', t'''$ — последовательные моменты времени.

Рис. 11.55. Характер окончательного распределения давления в волне разрежения. Распределение растягивает- с течением времени, не меняя своей формы.

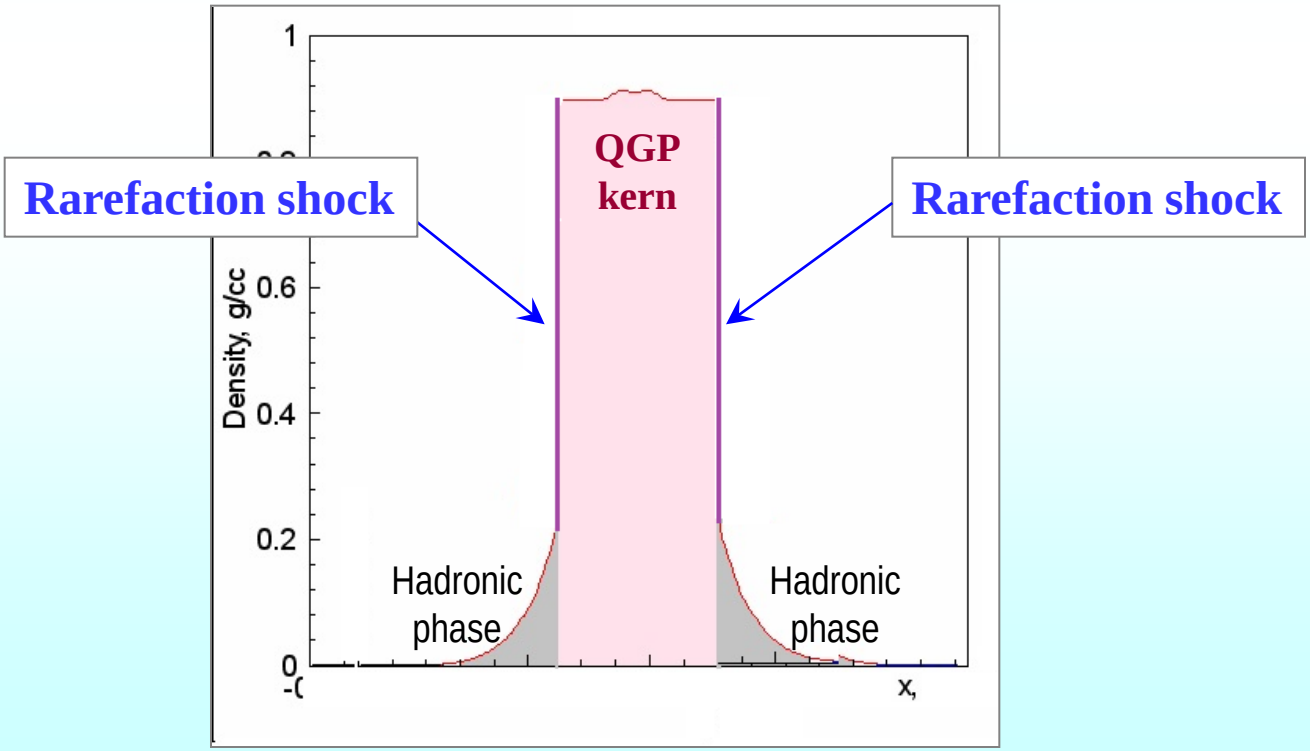
**NB !** $S_2 > S_1$

**NB !**

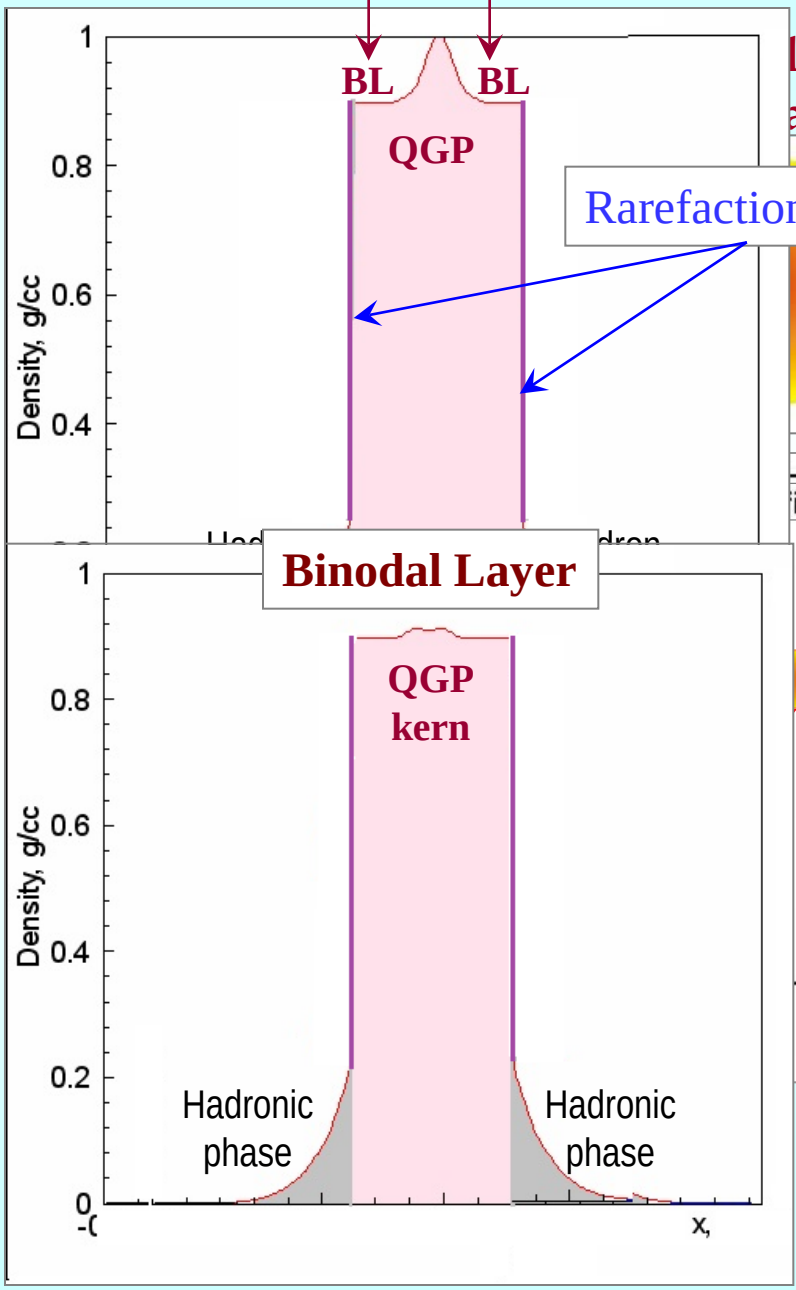
**There is no any realization for two-phase state of QHPT, when QGP-fireball expands isentropically**

**= = « i.e. » = =**

**QGP kern ⇔ QGP binodal layers ⇔ Rarefaction shock ⇔ Hadronic phase**



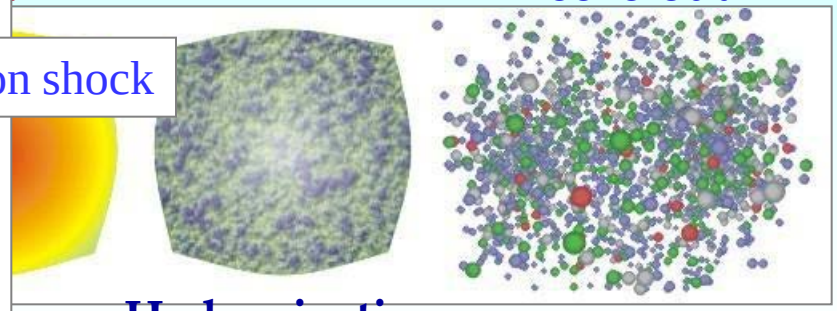
# Impac[illegible]ball hydrodynamics *in* RHIC



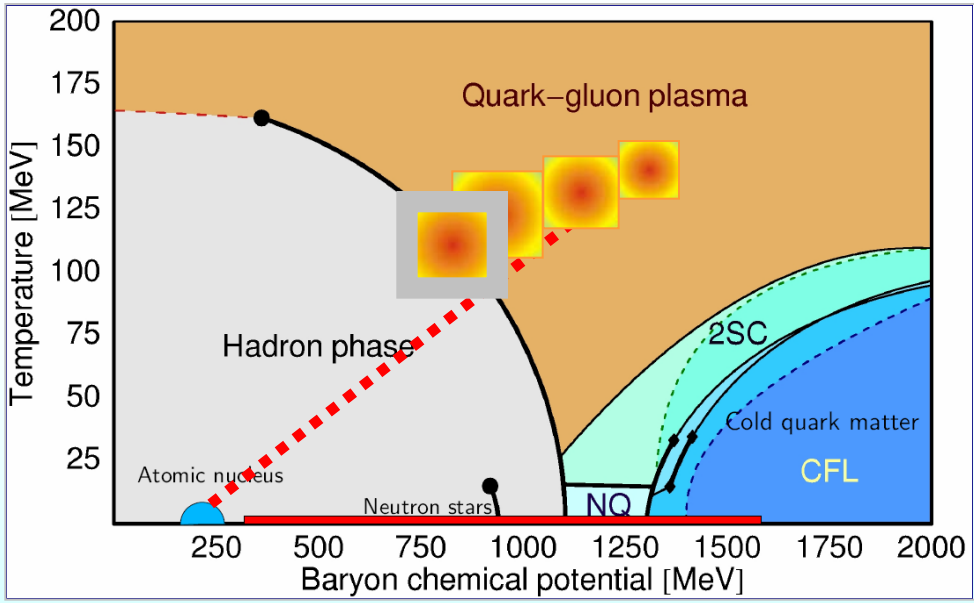

lized
all

Expansion

Chemical & kinetic
freeze-out



Hadronization



# Anomalous Thermodynamics Region – *ATR*

**Normally positive cross derivatives became *negative simultaneously !***

arXiv:1504.05850

**Normal** $> 0$ | **Abnormal** $< 0$

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

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

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

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

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

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

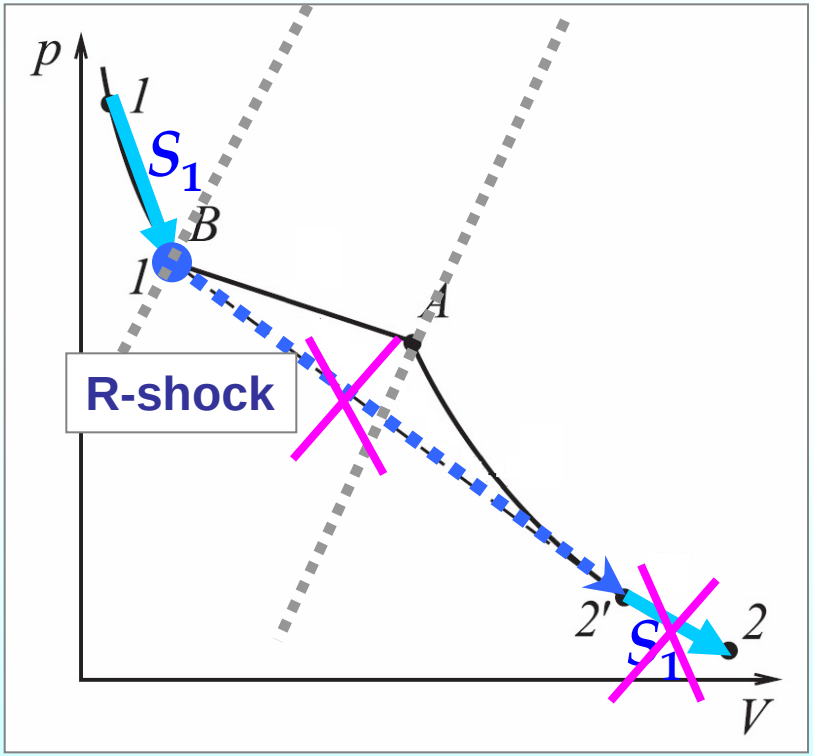
$(\partial T/\partial P)_S < 0$ → **Abnormal decreasing (*increasing*) temperature *under* isentropic compression (*expansion*) !**

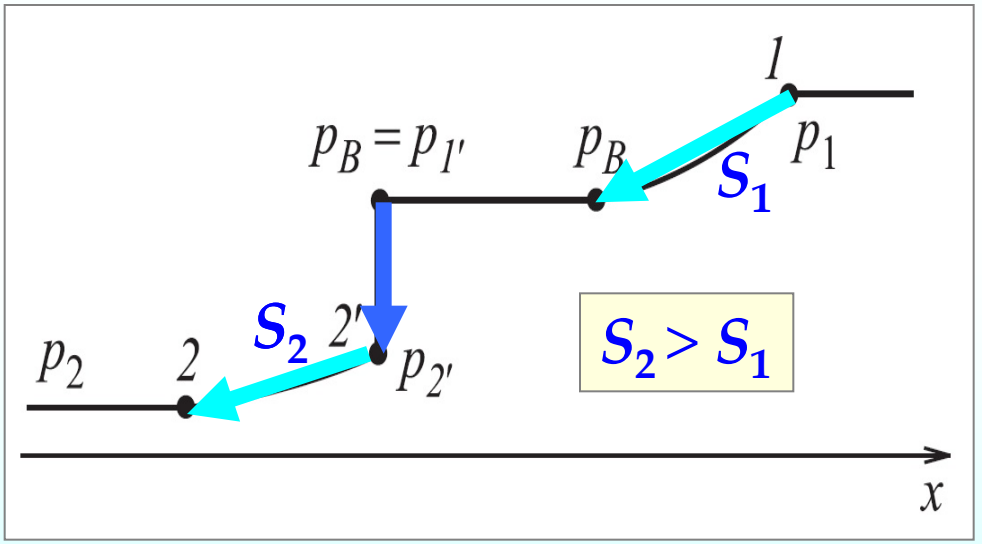
# Combined Rarefaction Wave

**Combined rarefaction wave is adiabatic but not isentropic !**

**Rarefaction shock is non-reversible process. It leads to entropy increase**

$$( S_2 > S_1 )$$



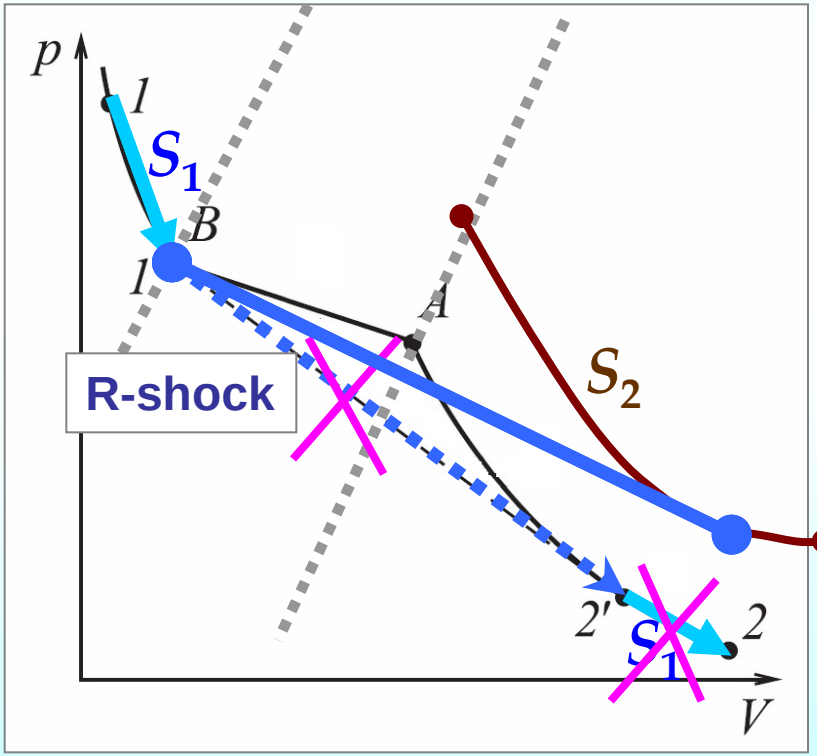



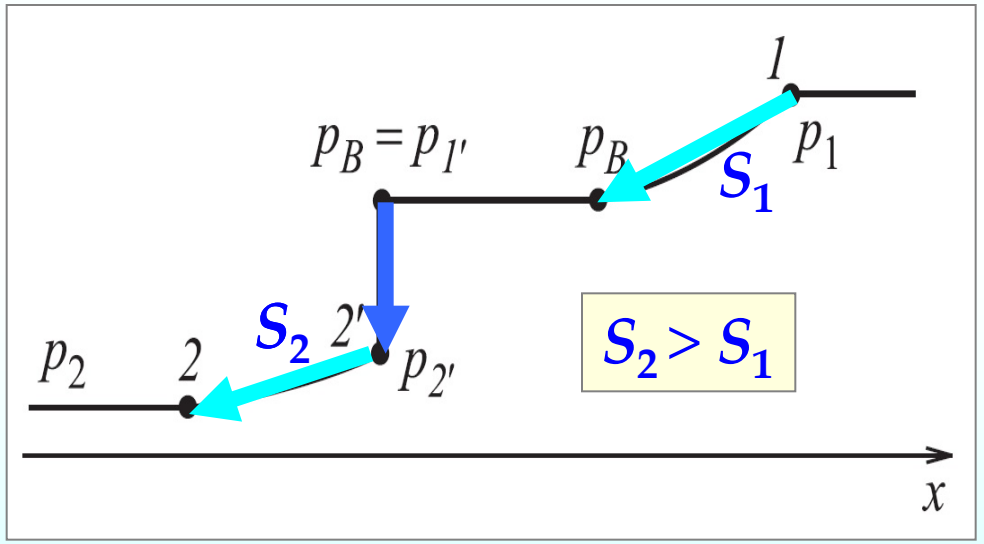

**NB!**

***But where isentope $S_2$ is located ?***

# Combined rarefaction wave is adiabatic but not isentropic !

**Rarefaction shock is non-reversible process. It leads to entropy increase** $(S_2 > S_1)$



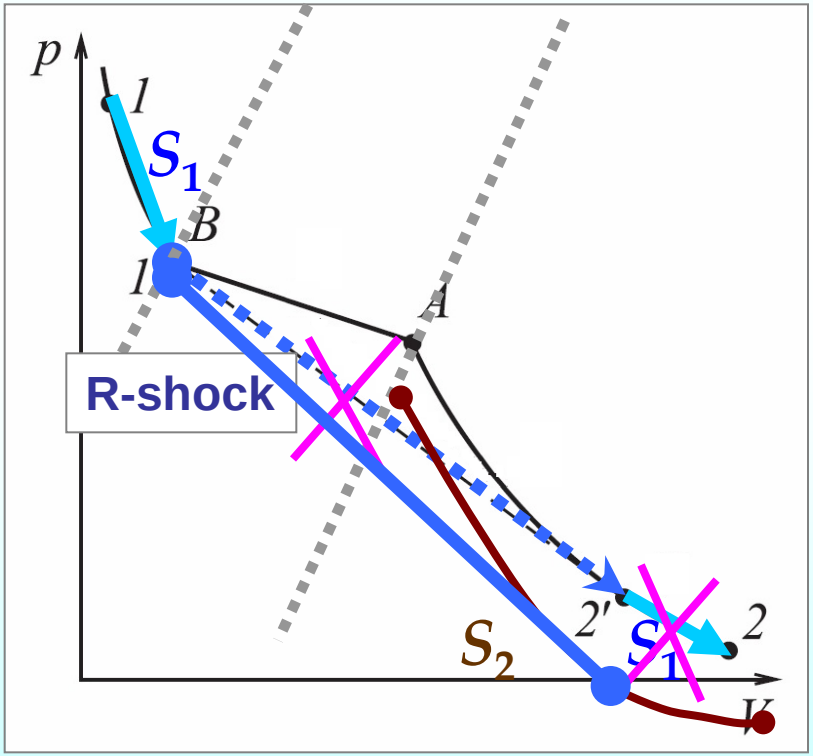

NB!
***But where isentope $S_2$ is located ?***

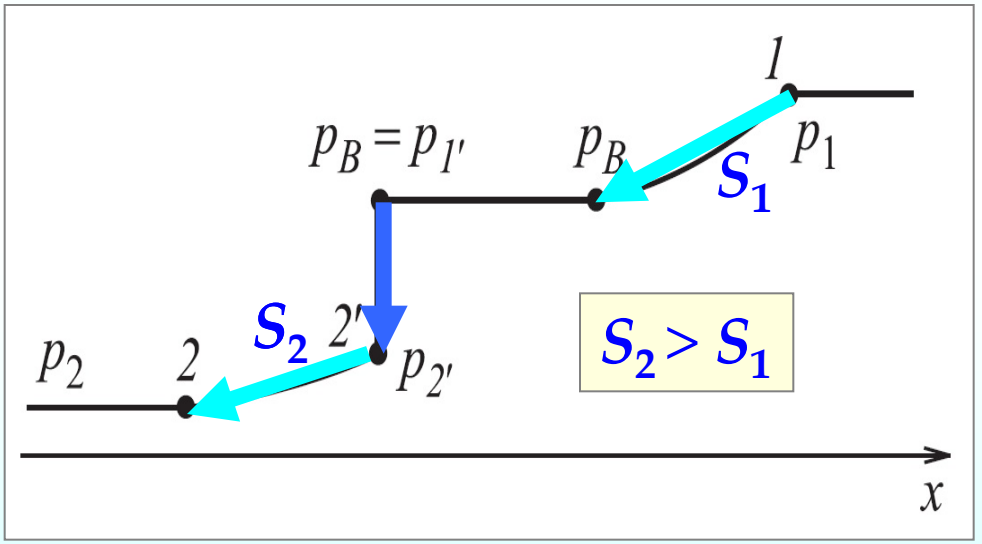
*Normal thermodynamics:* $(\partial P/\partial S)_V > 0$
$S_2$ is located **above** $S_1$ ⇔ $P(S_2) > P(S_1)$

arXiv:1504.05850

# Combined rarefaction wave is adiabatic but not isentropic !

**Rarefaction shock is non-reversible process. It leads to entropy increase** $(S_2 > S_1)$



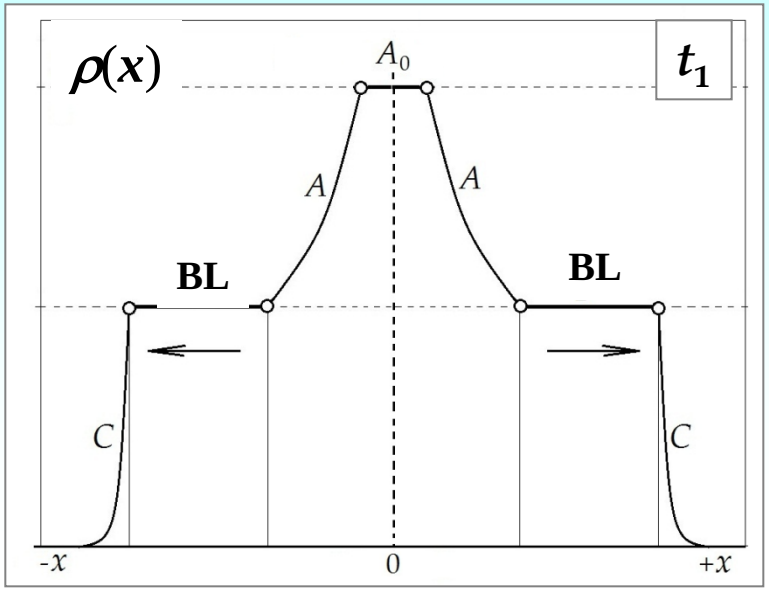

**NB!**
***But where isentope $S_2$ is located ?***

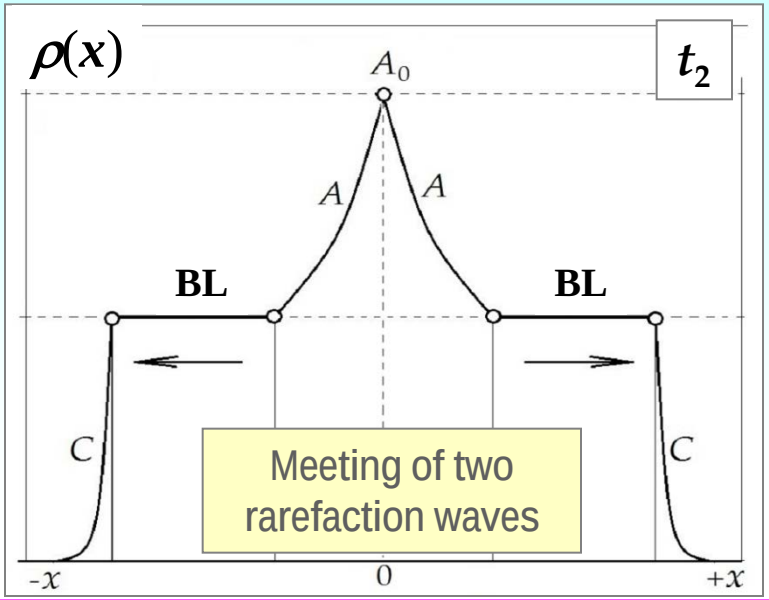
*Abnormal thermodynamics:=* $(\partial P/\partial SS)_V < 0$
$S_2$ is **below** $S_1$ **!** ⇔ $: P(S_2) < P(S_1)$

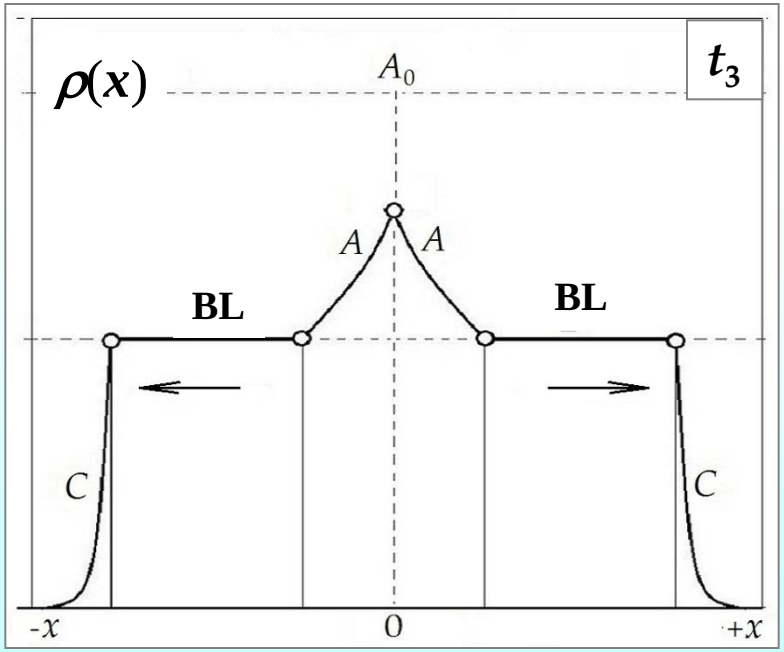
arXiv:1504.05850

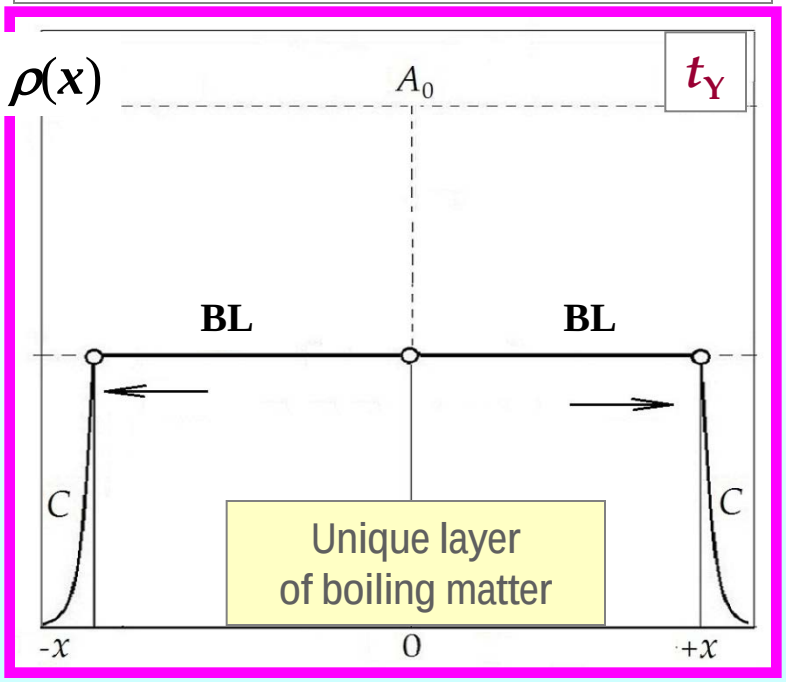
# Scattering of two binodal layers
*and* central "hole"
*within* isentropic decay *of* slab target

# Hydrodynamics *of* isentropic expansion *for* slab target



# Binodal layer in isentropic decay of slab

Y

(*Van der Waals equation of state* )

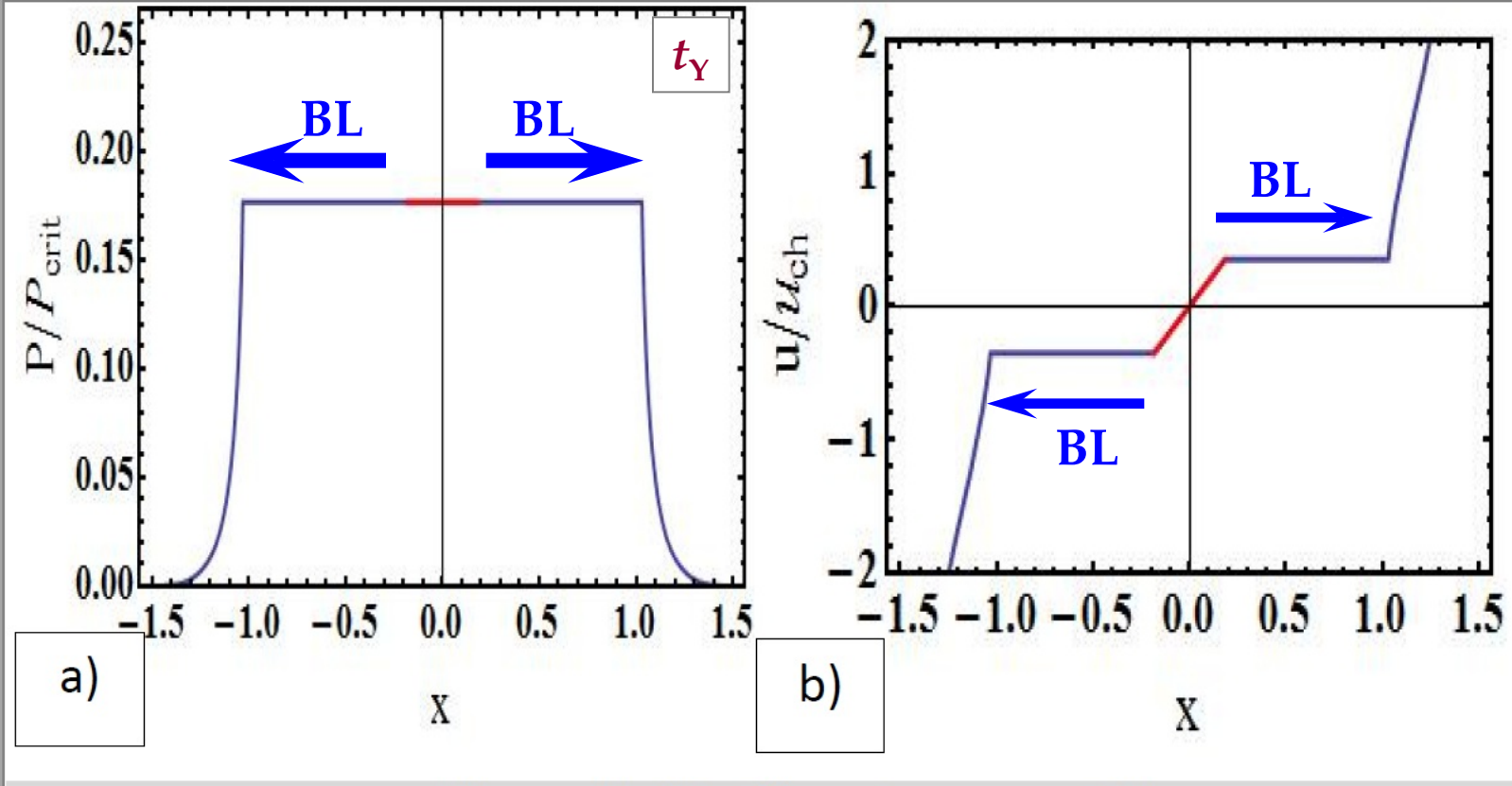
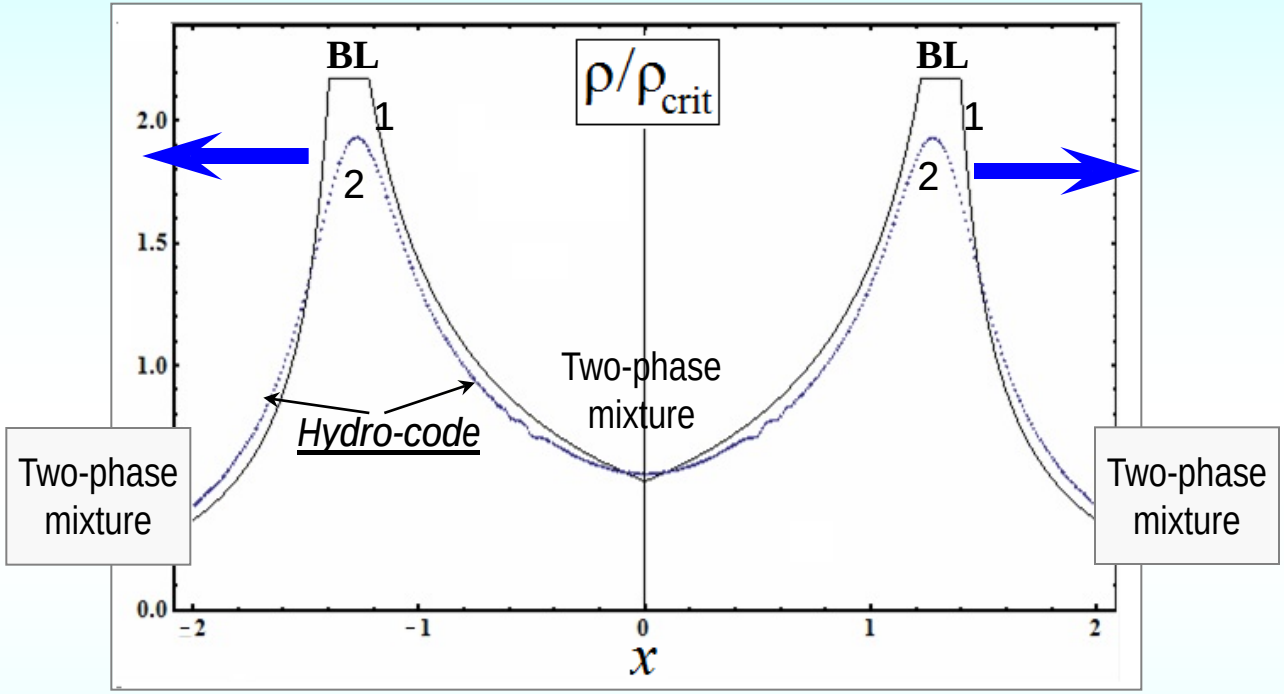



**Figure 5: Profiles at moment Y:**
**(a)pressure,** *(b)* **velocity**
*Blue line–SS part of solution, red line-nSS*


Borovikov D.S., Iosilevskiy I.L. *Binodal layer in isentropically expanding slab target with Van der Waals equation of state* "Physics of Extreme States of Matter", Eds. V. Fortov *et al*. // IPCP RAS Pub., Chernogolovka, Russia, p.140-144 (2013)

# Recession of two binodal layers *during* isentropic decay *of* WDM-slab




**Density profile**

*1* – Exact solution (Rieman integrals)
*2* – 1D_Hydro-code (*Borovikov*)

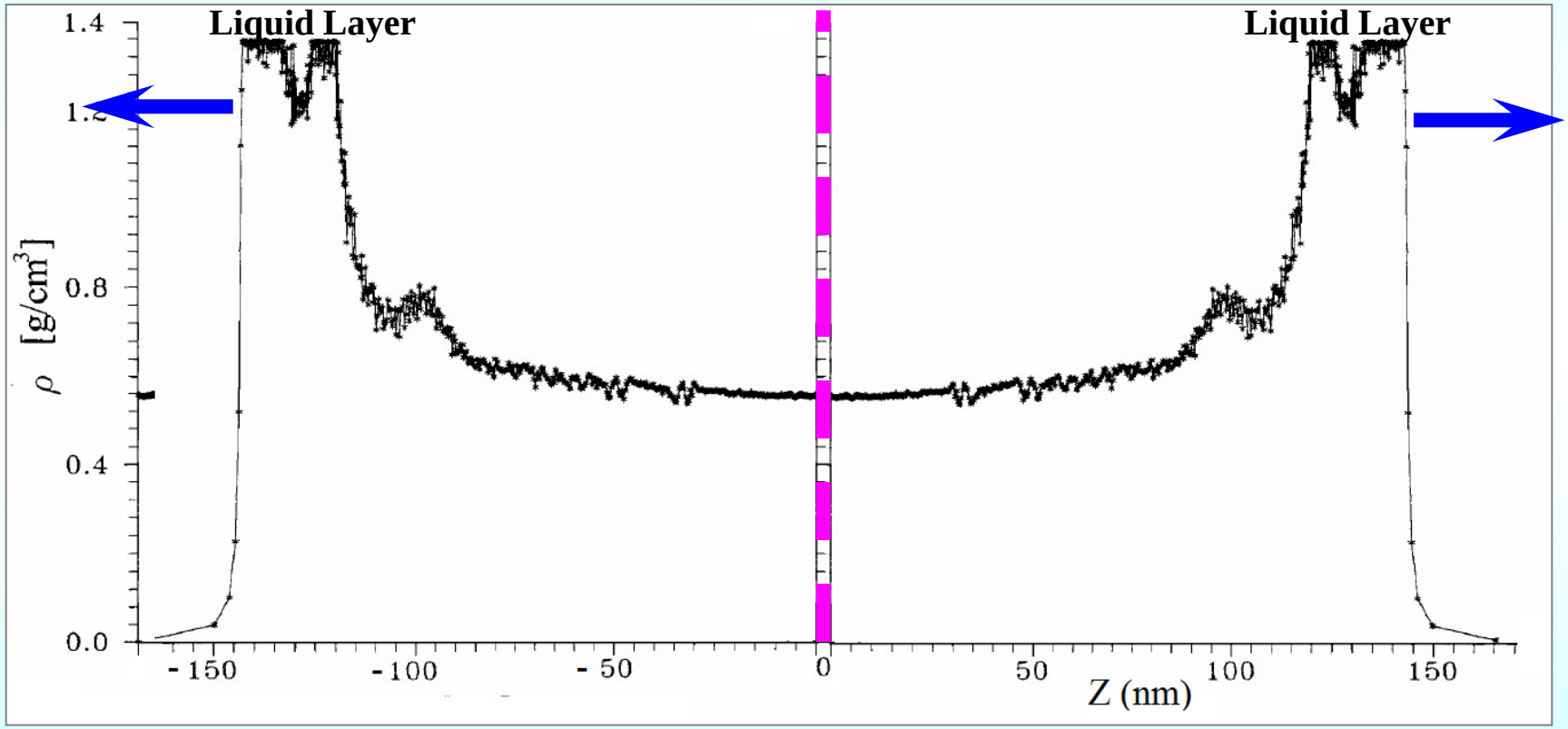
(*Van-der-Waals equation of state* )

Z

Borovikov D.S., Iosilevskiy I.L. *Binodal layer in isentropically expanding matter with Van-der-Waals equation of state* Elbrus conference "Equation of State" (2013)

# Two scattering "plateau" *and* central "hole" *in* isentropic decay *of* slab target (DNS)

Anisimov S.I., Inogamov N.A., Oparin A.M., Rethfeld B., Yabe T., Ogawa M., Fortov V.E.
*Appl. Phys.* **A 69**, 617 (1999)




**1999**

Density profile. Direct Numerical Simulations (DNS)

( $T_0$ = 6000 K // $\rho_0$= 2.7 g/cc // $\rho_{plateau} \approx ½\ \rho_0$ // 2h = 80 nm // $t$ = 50 ps )

# Explosive wire experiments

*and*

# Direct numerical simulation

**CAVITATION AND FORMATION OF FOAM-LIKE STRUCTURES INSIDE EXPLODING WIRES**

Vasily. V. Zhakhovsky*, Sergei A. Pikuz†, Svetlana I. Tkachenko**, Pavel V. Sasorov‡, Tatiana A. Shelkovenko†, Patrick F. Knapp†, Charles C. Saylor† and David A. Hammer†

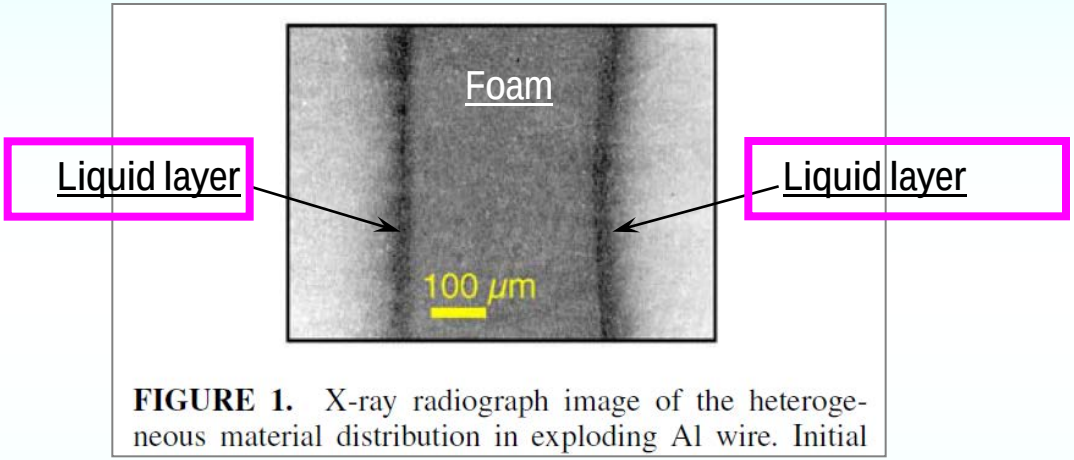
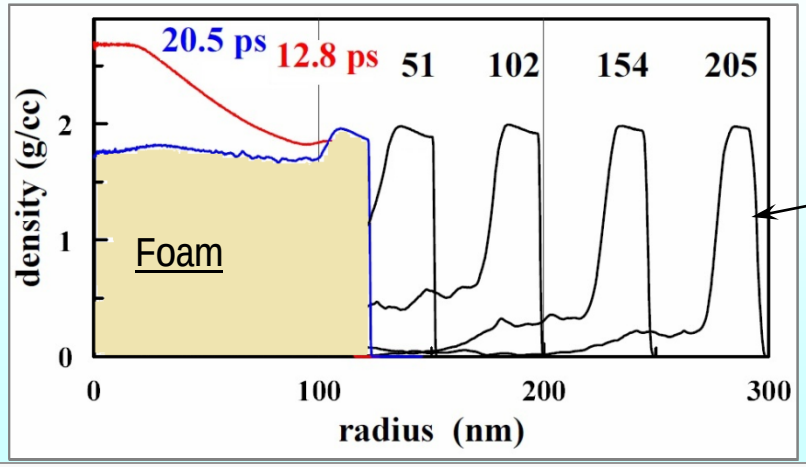



**FIGURE 1.** X-ray radiograph image of the heterogeneous material distribution in exploding Al wire. Initial




Radial profiles of density $\rho(r, t)$ obtained by MD simulation

Molecular simulation of cylinder expansion

V. Zhakhovskiy *et al.* (**2011**)

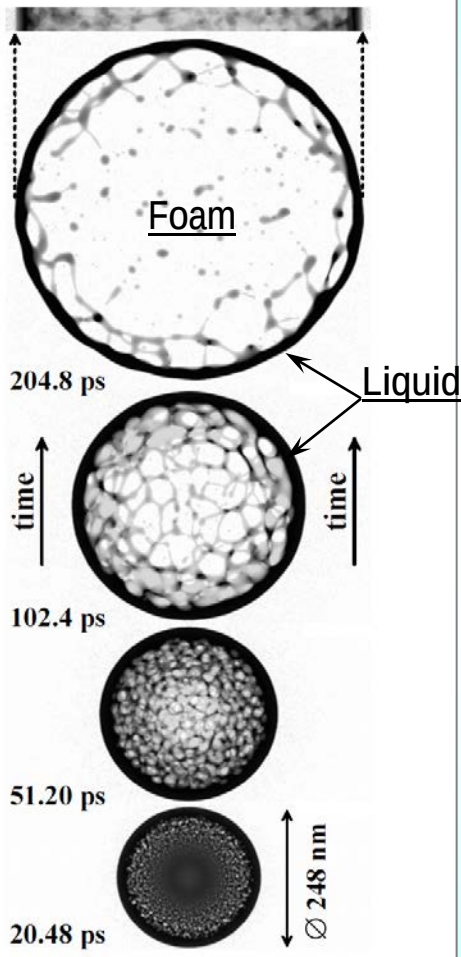



**FIGURE 2.** Snapshots of density map $\rho(x, y)$ averaged over cylinder length $l_z = 40.2$ nm. The simulation parameters of exploding Al wire are listed in caption to Fig. 3.

*Shock Compression of Condensed Matter - 2011*

AIP Conf. Proc. 1426, 1207-1210 (2012)

# Explosive wire experiments

*and*

# Direct numerical simulation

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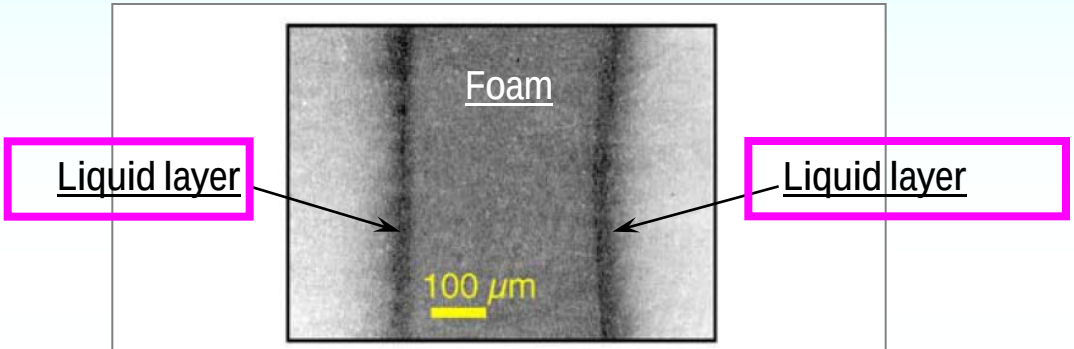
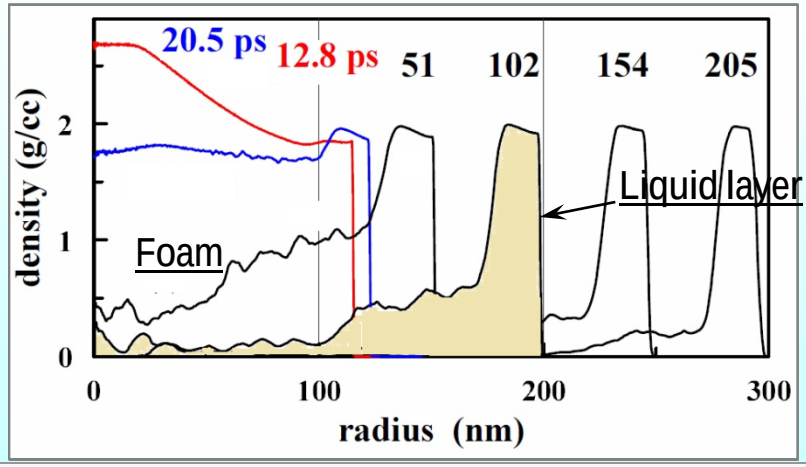



**FIGURE 1.** X-ray radiograph image of the heterogeneous material distribution in exploding Al wire. Initial




Radial profiles of density $\rho(r, t)$ obtained by MD simulation

Molecular simulation of cylinder expansion

V. Zhakhovskiy *et al.* (**2011**)

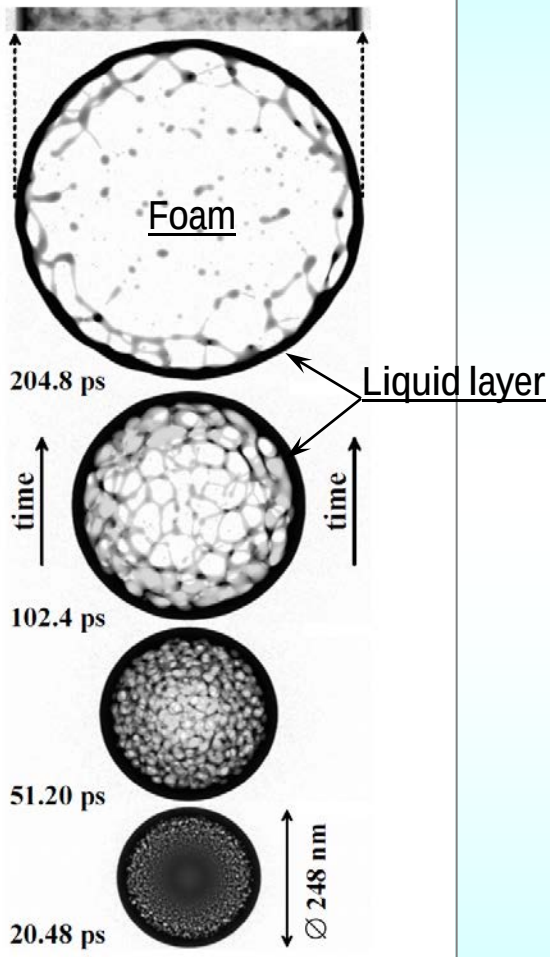



**FIGURE 2.** Snapshots of density map $\rho(x, y)$ averaged over cylinder length $l_z = 40.2$ nm. The simulation parameters of exploding Al wire are listed in caption to Fig. 3.

*Shock Compression of Condensed Matter - 2011*

AIP Conf. Proc. 1426, 1207-1210 (2012)

# Explosive wire experiments

*and*

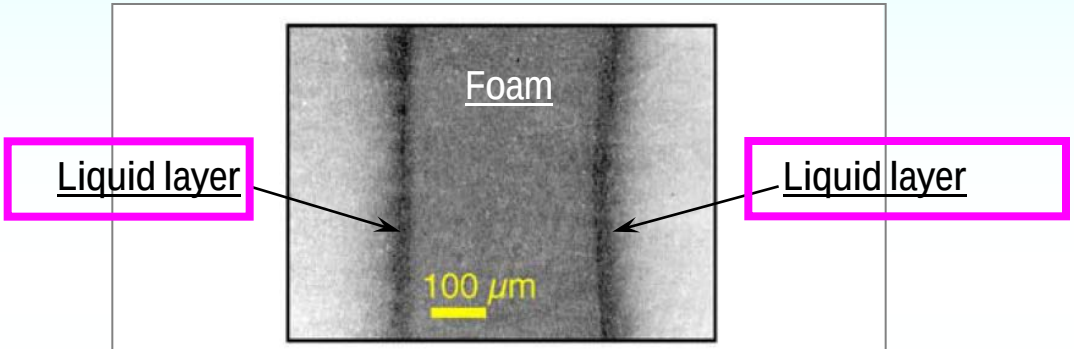
# Direct numerical simulation

Molecular simulation of cylinder expansion

V. Zhakhovskiy *et al.* (**2011**)

**CAVITATION AND FORMATION OF FOAM-LIKE STRUCTURES INSIDE EXPLODING WIRES**

Vasily. V. Zhakhovsky*, Sergei A. Pikuz†, Svetlana I. Tkachenko**, Pavel V. Sasorov‡, Tatiana A. Shelkovenko†, Patrick F. Knapp†, Charles C. Saylor† and David A. Hammer†

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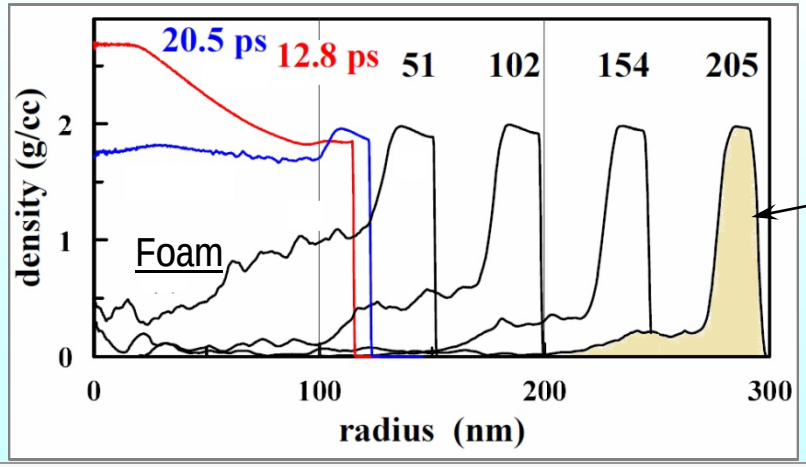


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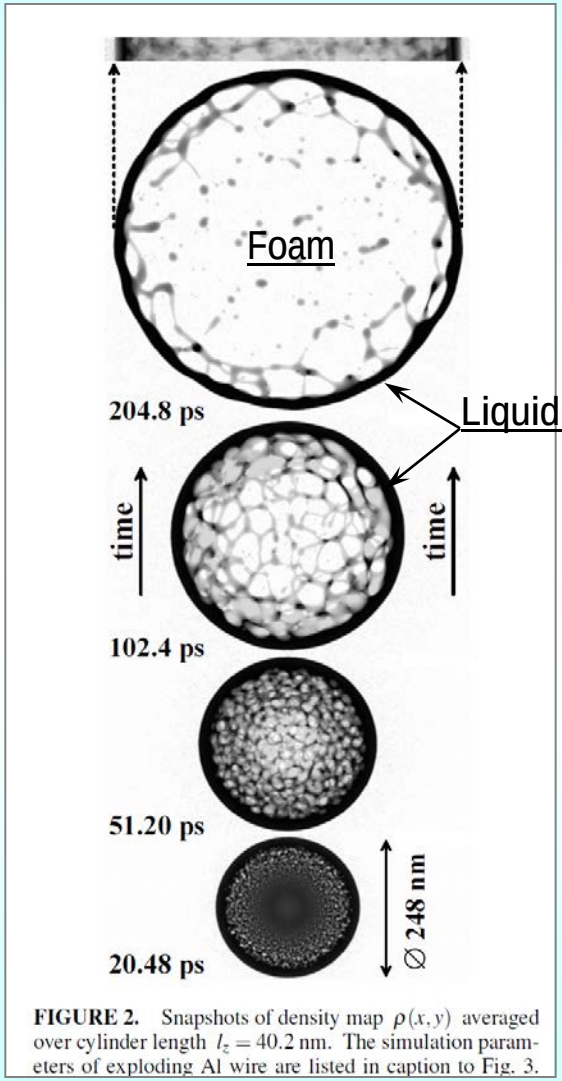


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*Shock Compression of Condensed Matter - 2011*

AIP Conf. Proc. 1426, 1207-1210 (2012)

# QHPT two-phase region does not manifest itself in QGP-fireball adiabatic expansion products !

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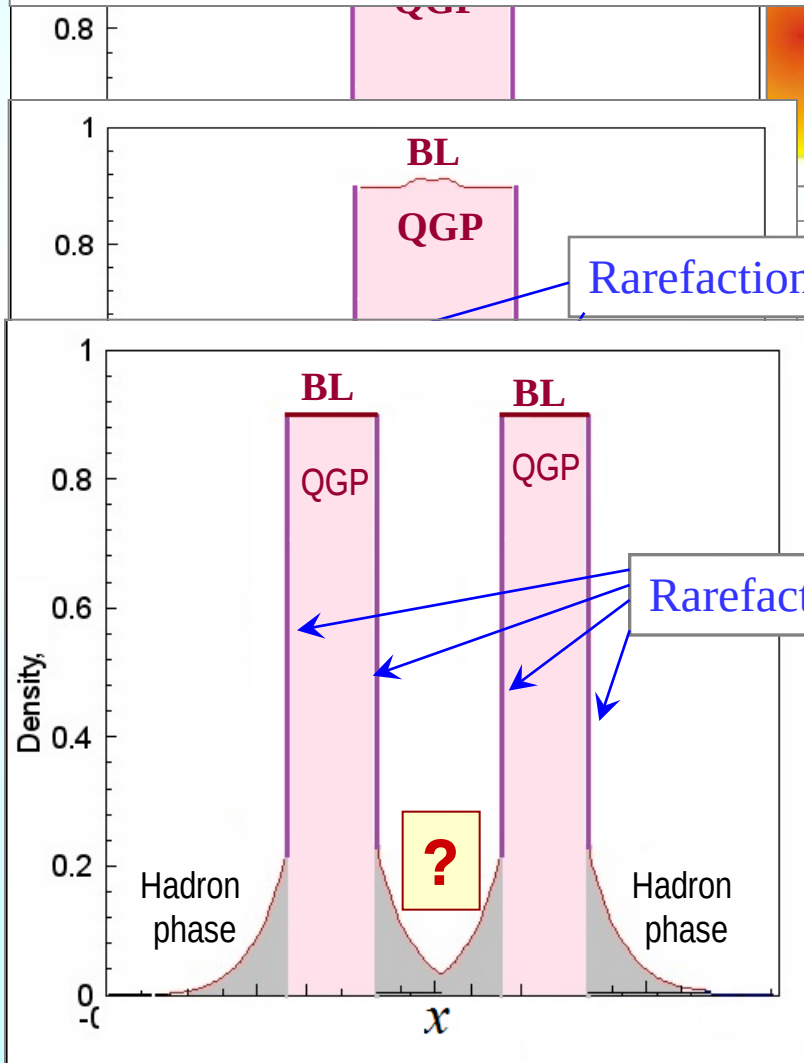
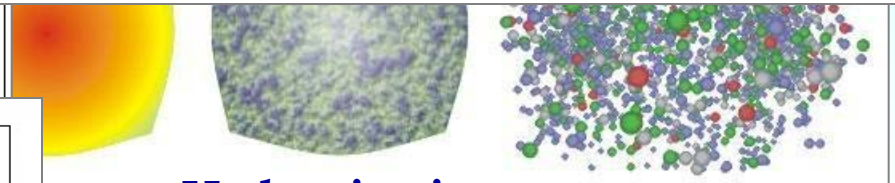
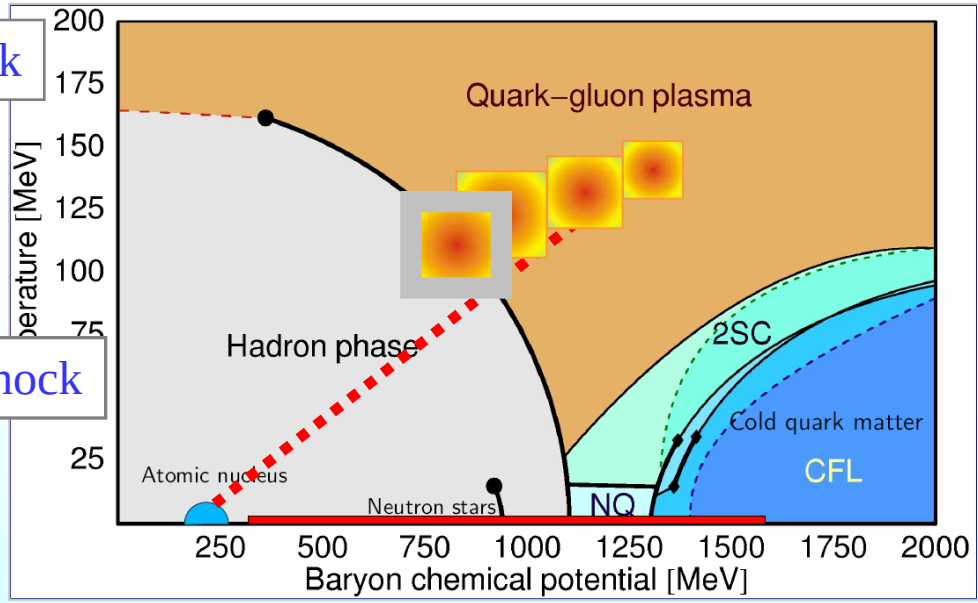
***QGP binodal layers ⇔ Rarefaction shocks ⇔ Hadronic phase***



QGP

Hadronization



# “**Binodal Layer**” in adiabatic expansion of QGP “fireslab”

Relativistic hydrodynamics + standard EOS for quark and hadron phases

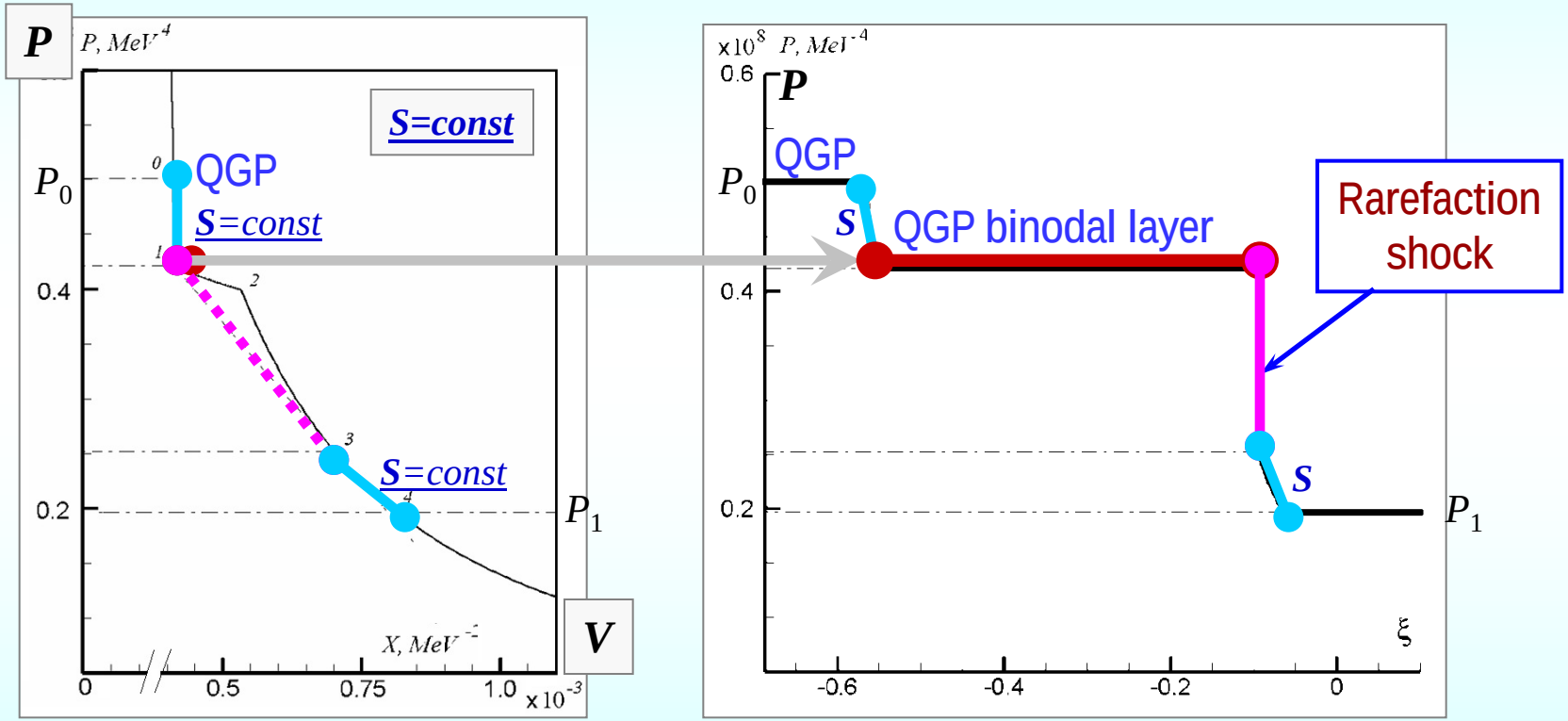



*Figure from*: A. Konyukhov, A. Likhachev / *J. Phys.* **774** (2016)

*See also*: - Konyukhov A.V., Iosilevskiy I,L,. Levashov P.R.. Likhachev A.P. Workshop RAS "*Non-ideal Plasma Physics*" (NPP-2016) Moscow, Russia, 2016

# **Binodal layer** *and* **rarefaction shock** *during* **isentropic decay** *of* **QGP elliptic body** *in frames of* **relativistic hydrodynamics**

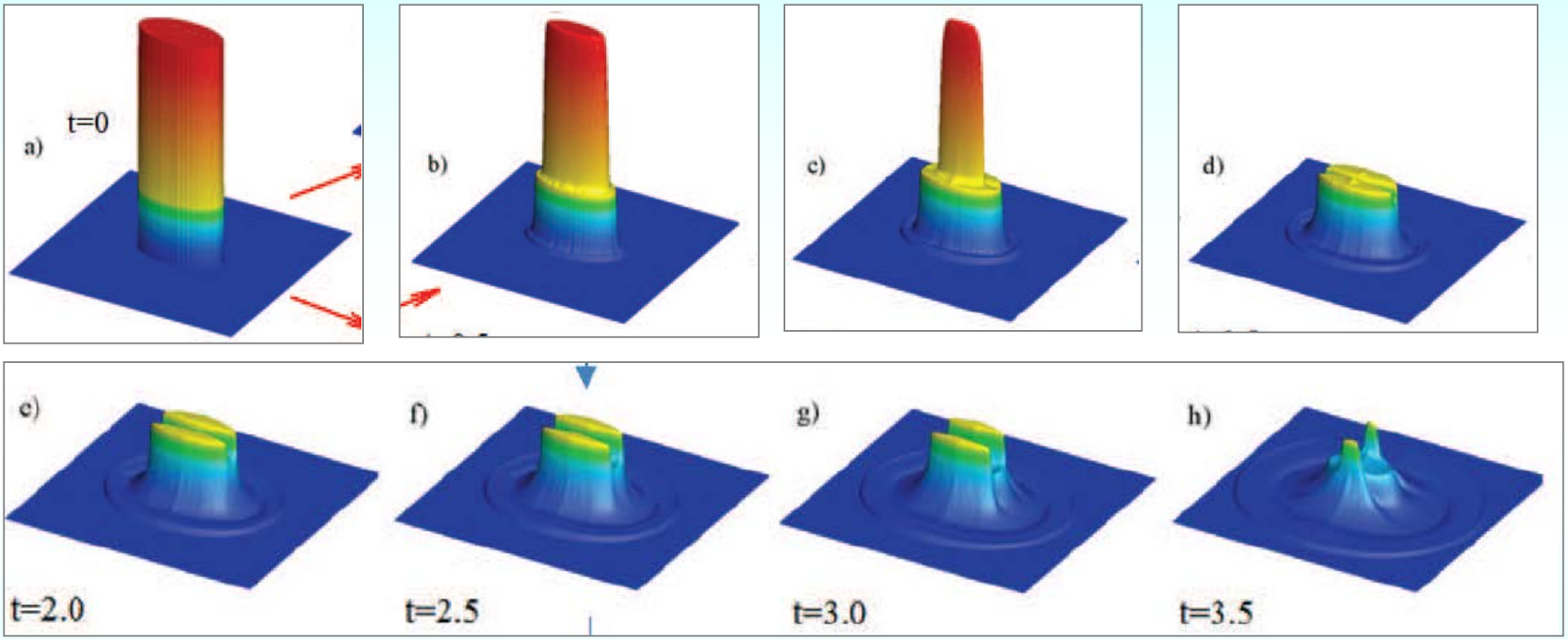



*Figure from*: A. Konyukhov, A. Likhachev / *J. Phys.* **774** (2016)

*See also*: - **Konyukhov A.V., Iosilevskiy I,L,. Levashov P.R.. Likhachev A.P.**
XXXII Int. Conference "Equation of State for Matter" Elbrus, Russia, March, 2017
***J. Phys. Conf. Ser.* 2017** (*to be published*)

# Thank you!

*Support*: **Russian Fund of Basic Research, N: 16-02-01179**

*(Lawrence Alma-Tadema)*


# *Welcome to Elbrus-2018*

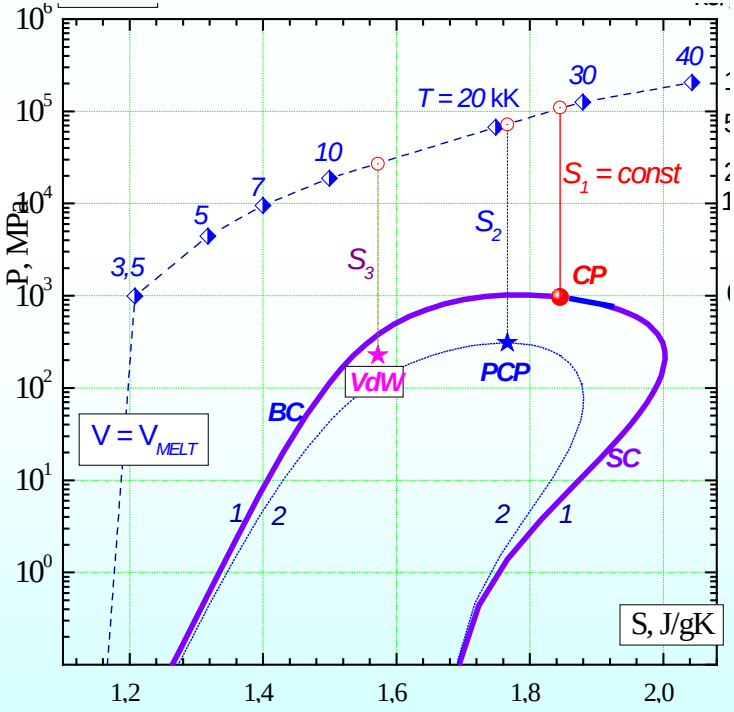
**(01-06 March)**

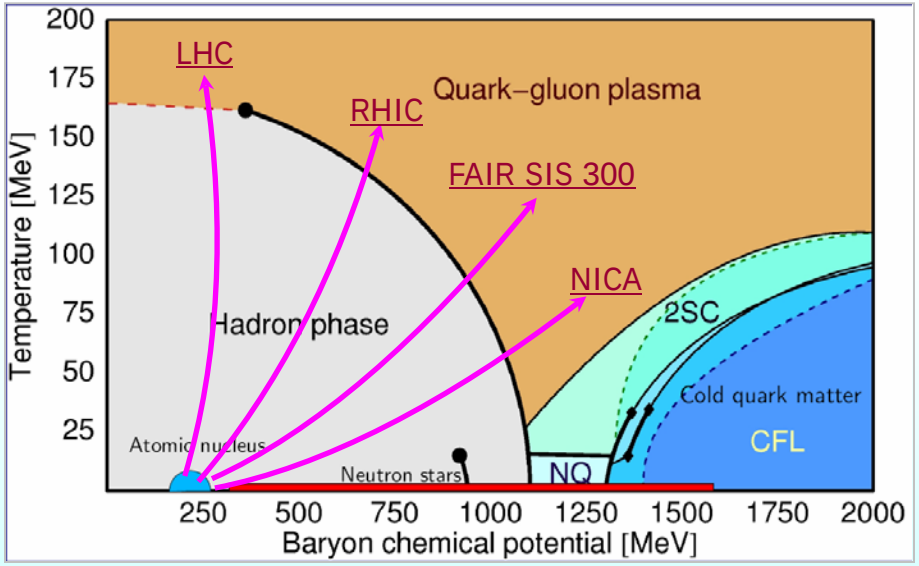
## *"Equation of State for Matter"*

**http://www.ihed.ras.ru/Elbrus18**


**Phase freezeout** *in* **adiabatically expanding matter** *in* **cosmic matter** *and in* **laboratory**

# Thank you!

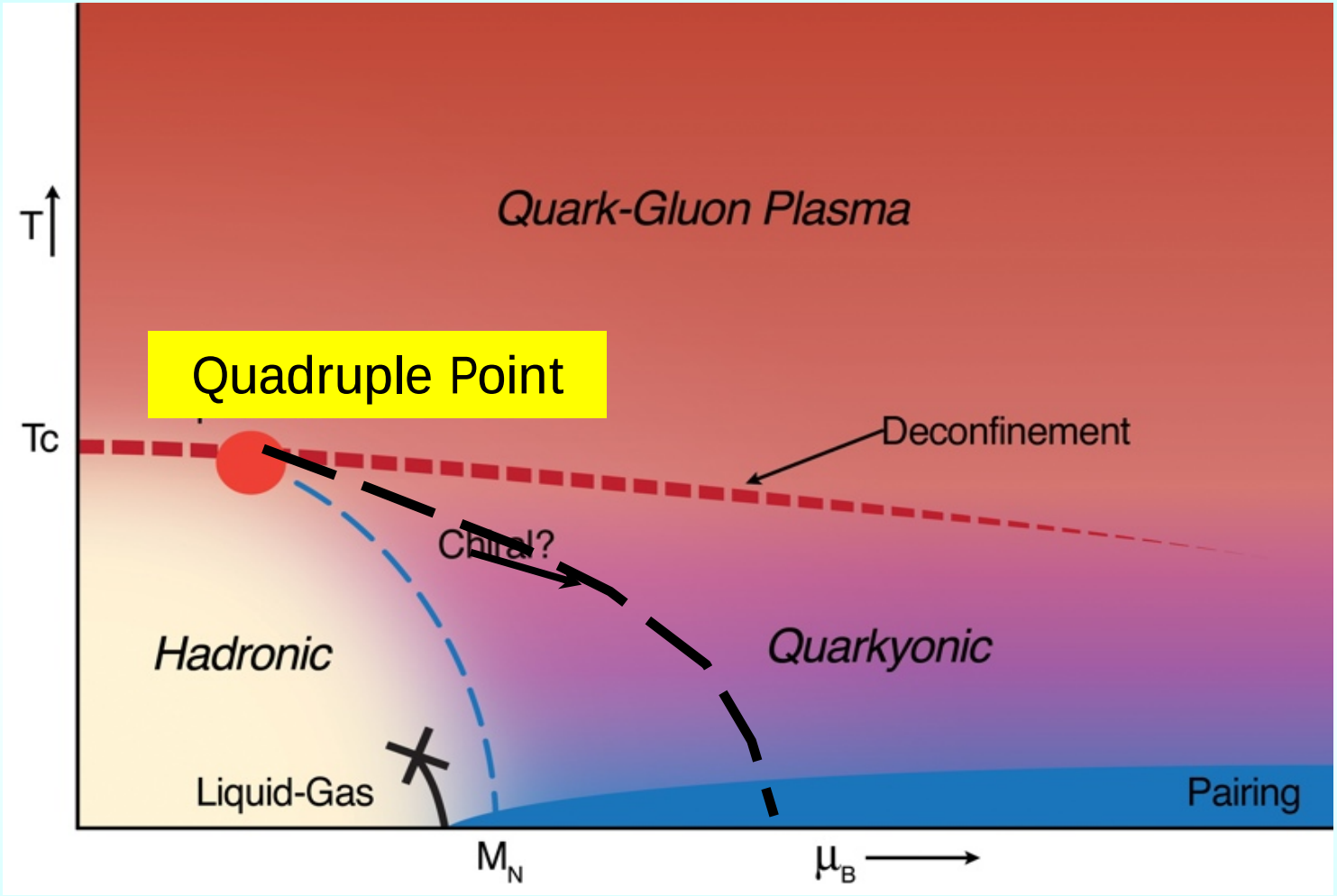



**Support**:
**RAS Scientific Programs**: "Physics of Extreme States of Matter"
**Russian Fund of Basic Research / N: 16-02-01179**

# Hypothetical phase transitions in ultra-dense matter:

are they CONGRUENT or NON-CONGRUENT ?




Hypothetical phase diagram with Triple or Quadruple Point

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

# Hypothetical phase transitions in ultra-dense matter:

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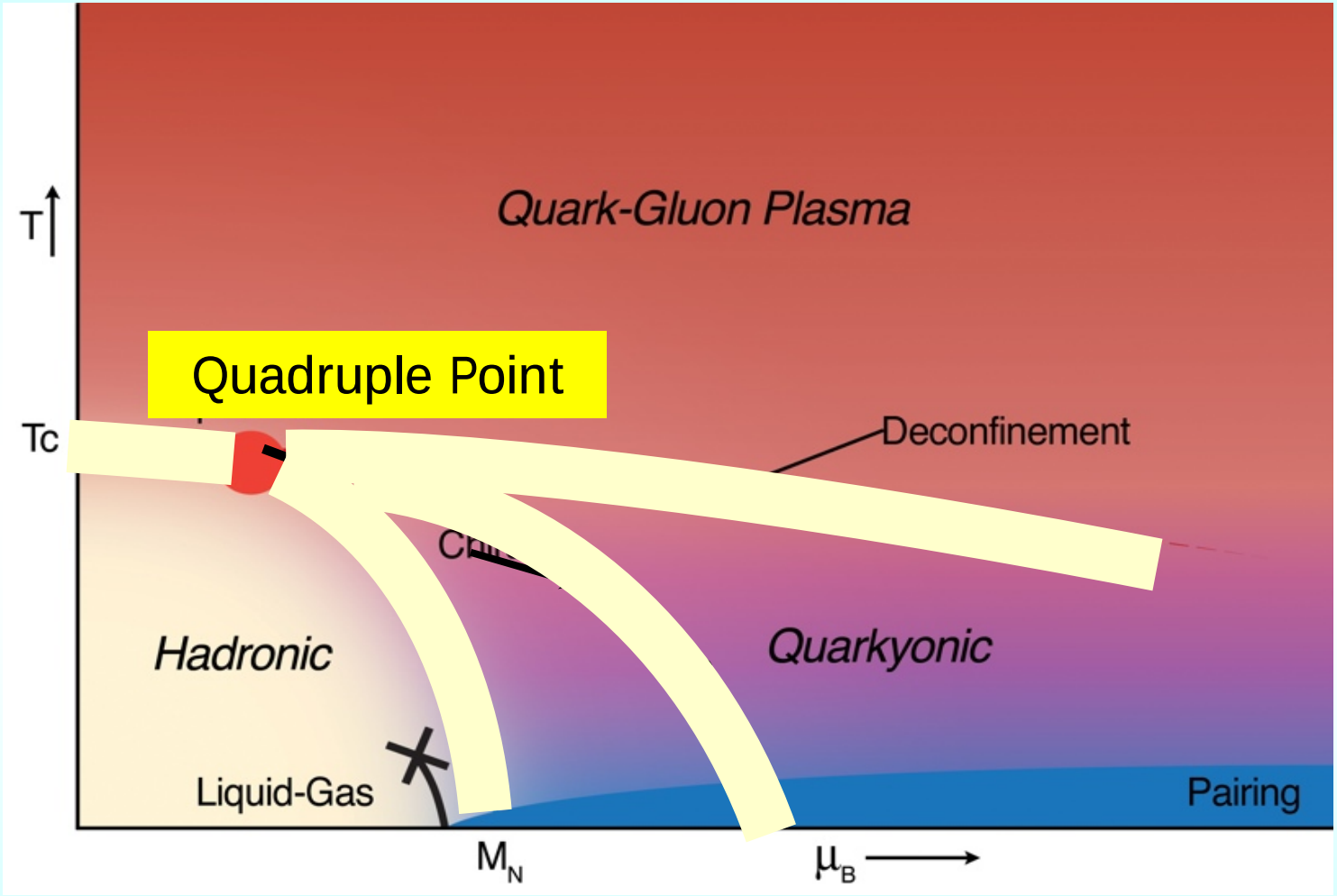


Hypothetical phase diagram with Triple or Quadruple Point

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