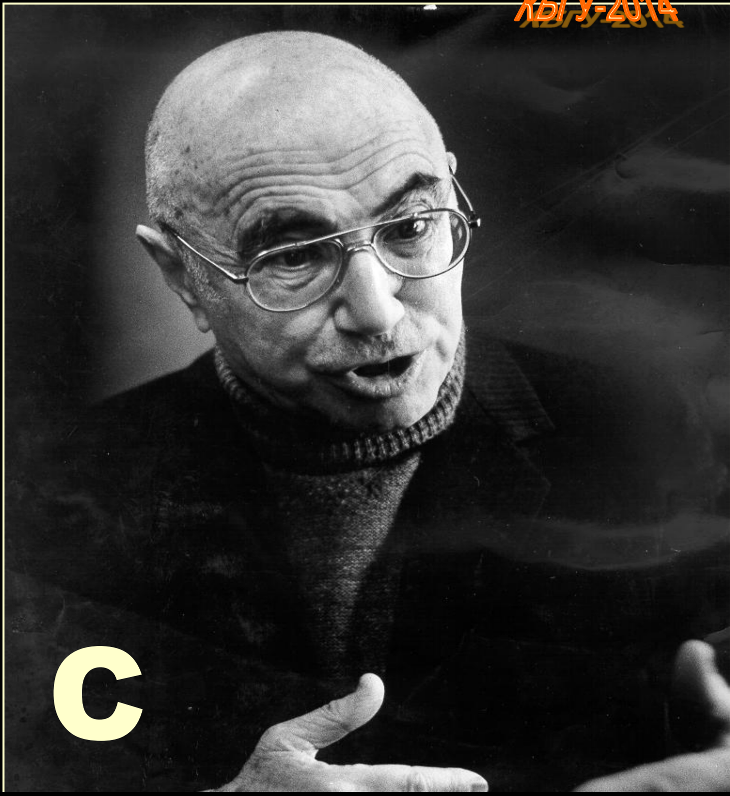
INTENSE SHOCK AND DETONATION WAVES FOR STUDY OF EXTREME STATES OF MATTER

V.Fortov,I.Lomonosov
IHED, IPCP

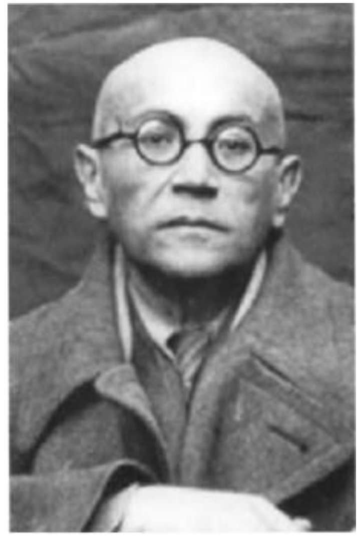
- \# Extreme states of matter
- \# Dynamical methods
- \# Drivers
- \# Hot and cold shock compressions
- \# Adiabatic rarefaction
- \# Plasma phase transitions
- \# Metalisation
- \# Dielectrisation
- \# Chemical and electro-detonations
- \# Shock wave stability
- \# Semiemphirics



Представлено на XXIX International Conference on Equations of State for Matter, devoted to the 100th anniversary of birth of academician Yakov Borisovich Zeldovich (8.03.1914–2.12.1987).
March 1-6, 2014, Elbrus, Kabardino-Balkaria, Russia

Я. Б. Зельдович: биография

Мать – Анна Петровна Зельдович, переводчица, член Союза писателей (1890-1975)



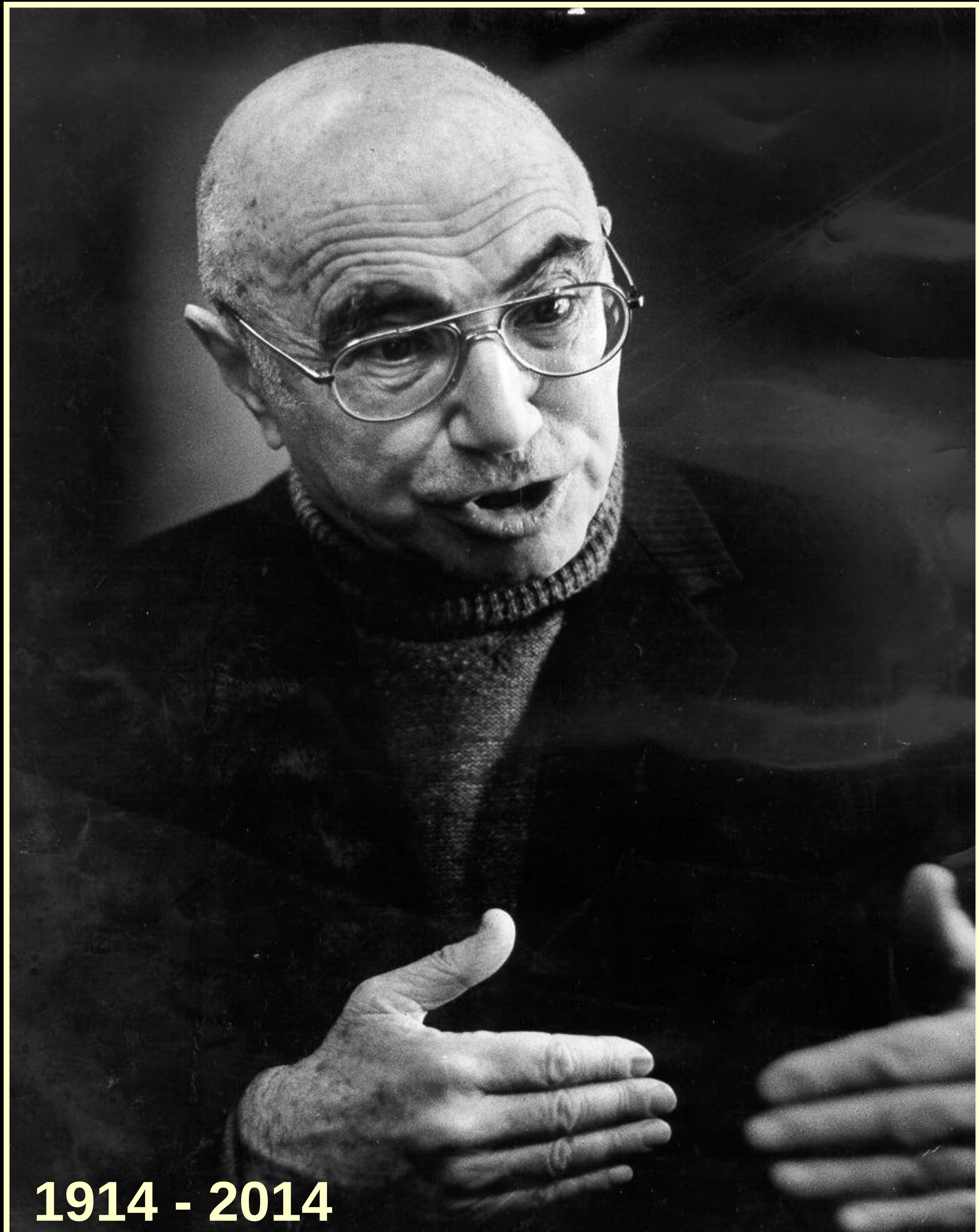
Отец – Борис Наумович Зельдович, юрист, член коллегии адвокатов (1889-1943)

С родителями

В Ленинграде, 1938 г.

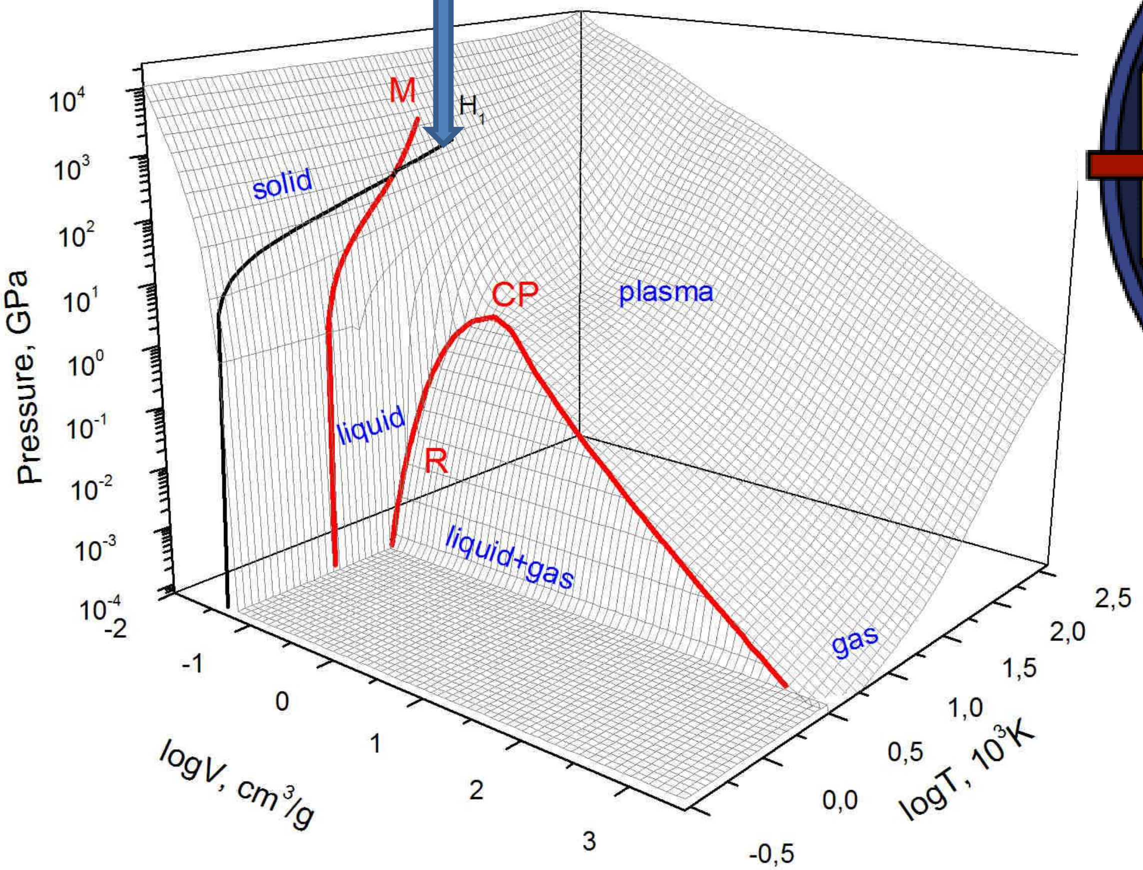
«Много лет спустя я услышал три легенды. Первая: Механобр отдал меня Химфизике в обмен на масляный насос. Вторая: академик А. Я. Иоффе написал в Механобр, что для решения практических задач я никогда не буду пригоден. Третья: Иоффе терпеть не мог вундеркиндов и потому отдал меня в Химфизику.
До сих пор не знаю, сколько истины в каждом из них.»

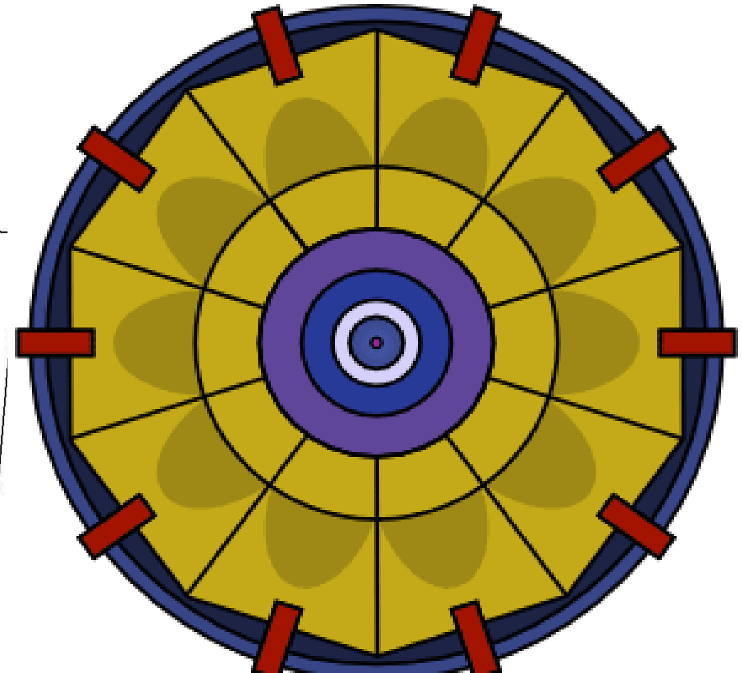
Я. Б. Зельдович. Избранные труды. Числа, ядра, Вселенная. М., 1985, 435-446.


1914 - 2014

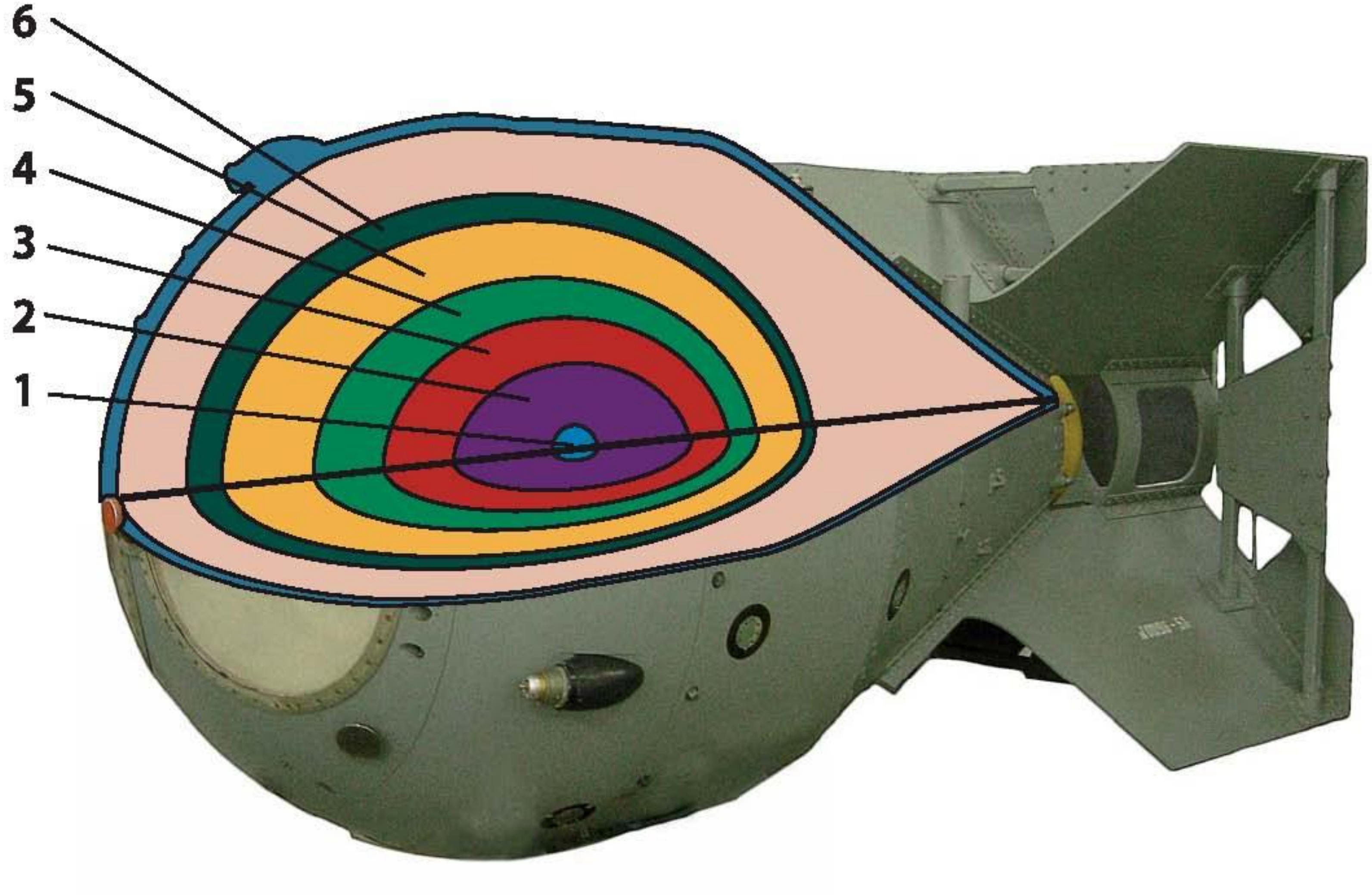
Фундаментальные идеи Я.Б. Зельдовича

УРС урана, конец 1940-х г.





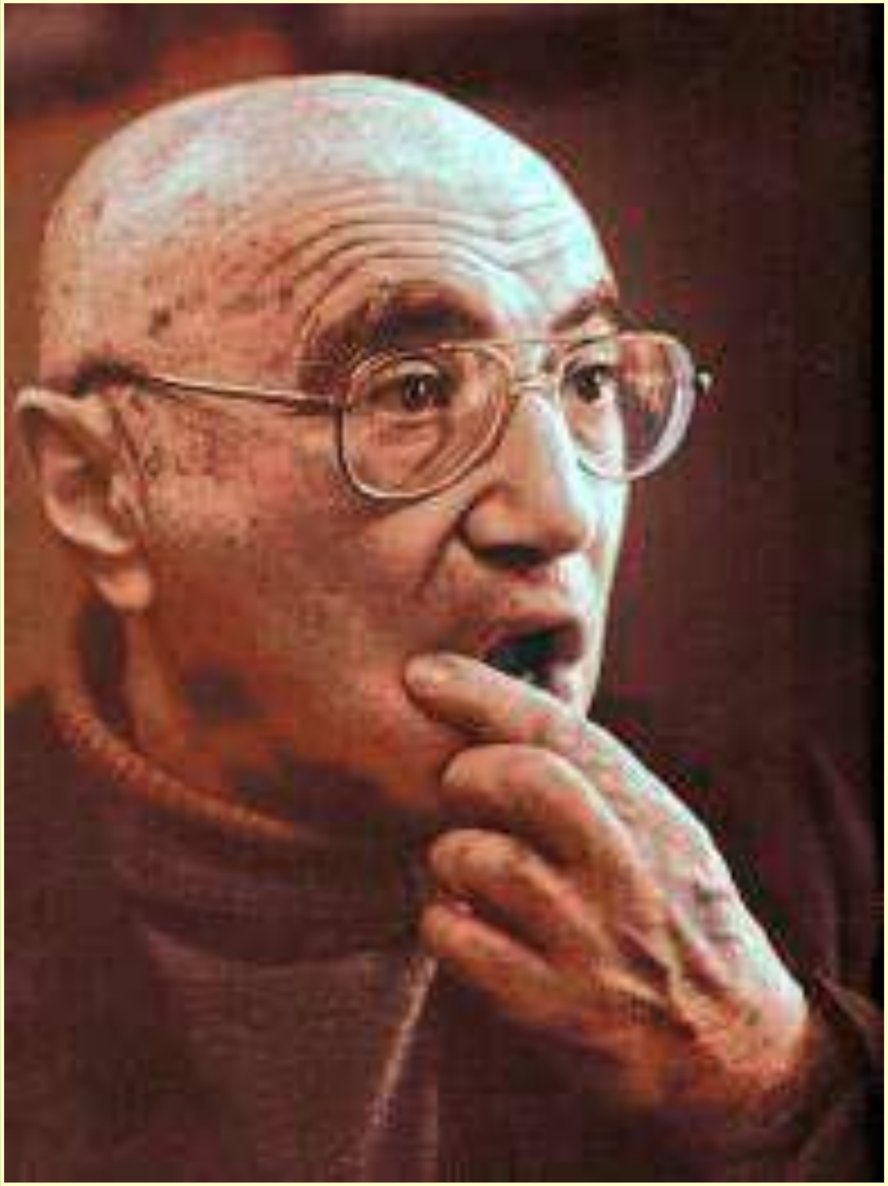
Достаточно ли знать только ударную адиабату?



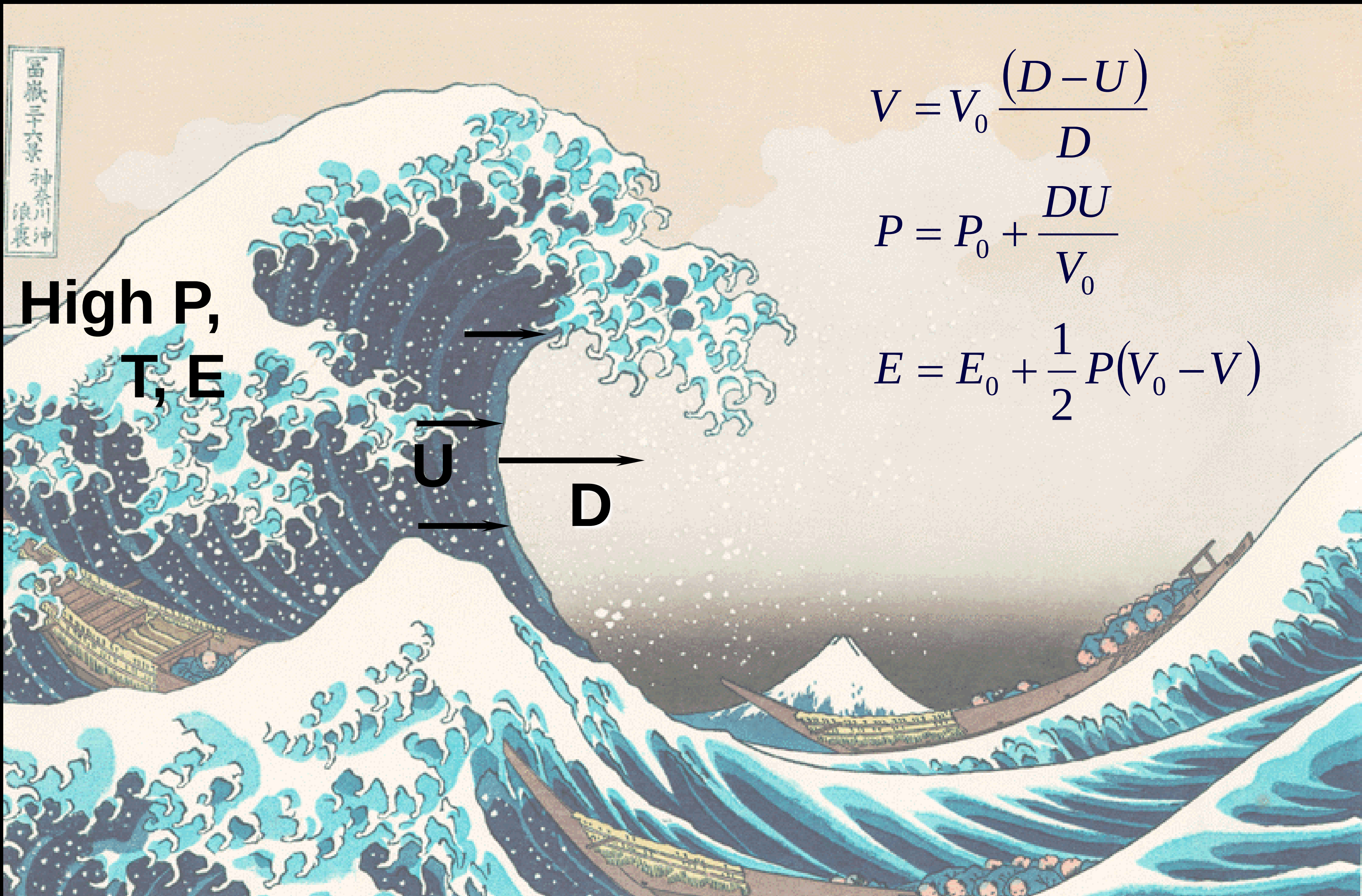
Принципиальная схема первой советской имплозионной атомной бомбы, являющейся
аналогом американской бомбы ”Fat Man”

Мы должны знать
в десять раз
больше того,что
нужно знать
непосредственно
для изделия…

Акад. Я.Б. Зельдович



SHOCK WAVE

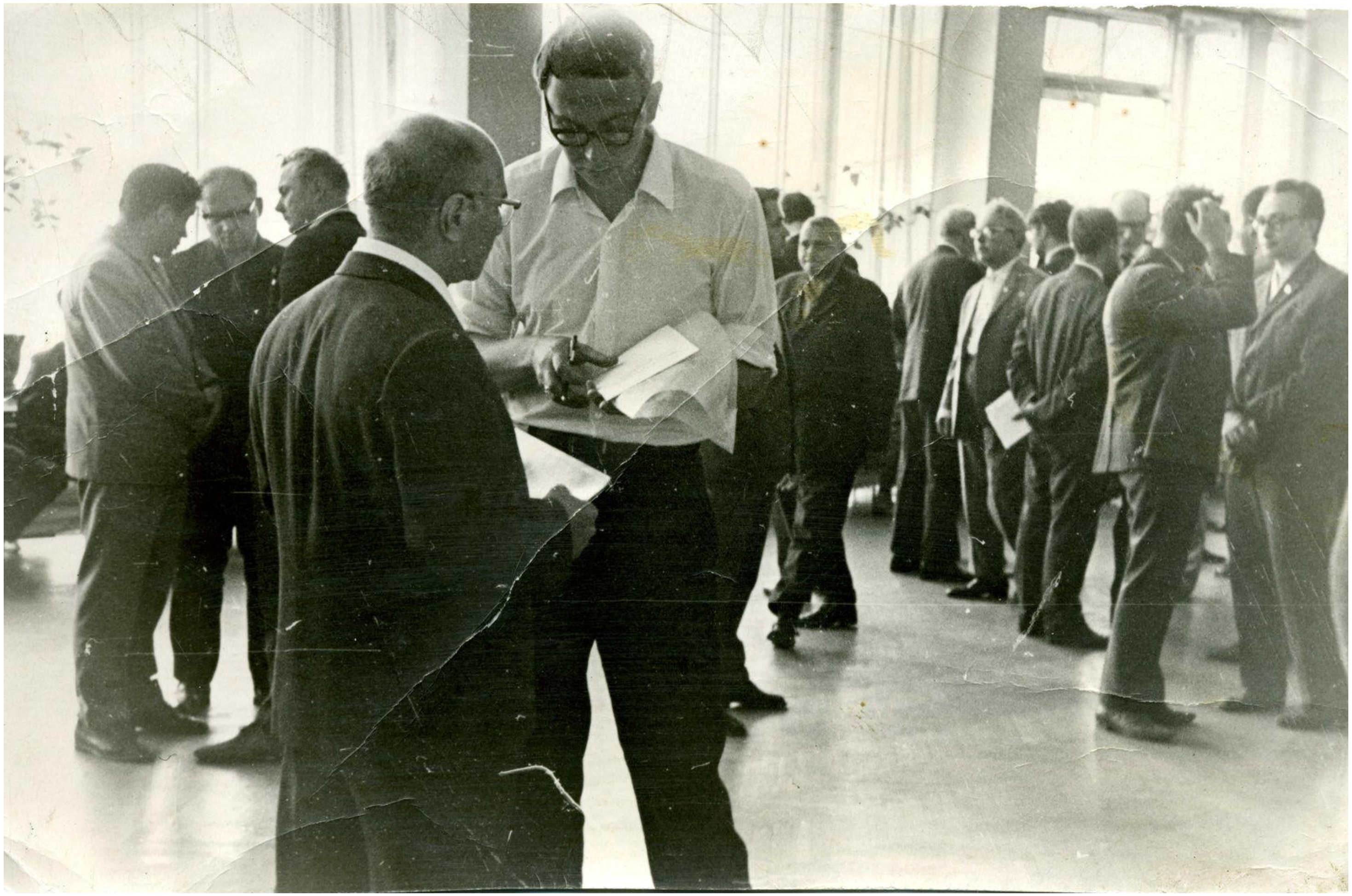


$$V = V_0 \frac{(D - U)}{D}$$

$$P = P_0 + \frac{DU}{V_0}$$

$$E = E_0 + \frac{1}{2} P(V_0 - V)$$

Задача Ферми - Зельдовича



Третий Всесоюзный симпозиум по горению и взрыву,
, 4 – 10 июля 1971 г., Ленинград

ZELDOVICH – FERMI PROBLEM

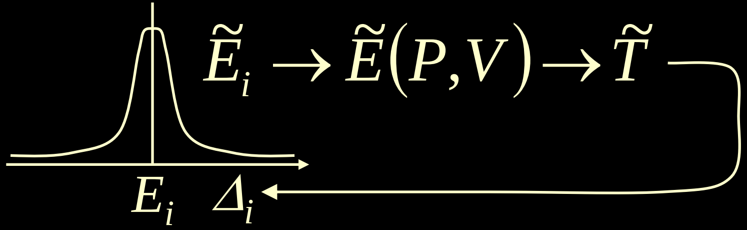
$$\begin{array}{c} D, U, E, P, V \\ \downarrow \\ E = E(P,V) \end{array}$$

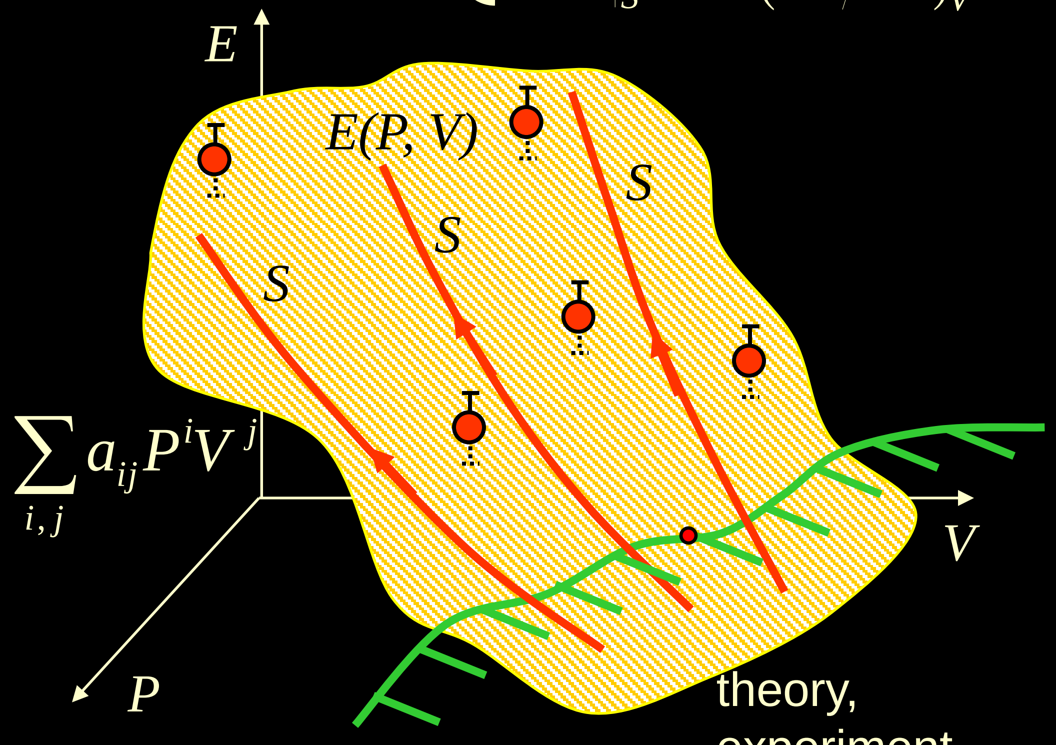
$$TdS = dE + PdV \rightarrow \left[P + \left(\frac{\partial E}{\partial V} \right)_P \right] \frac{\partial T}{\partial P} - \left(\frac{\partial E}{\partial P} \right)_V \frac{\partial T}{\partial V} = T$$

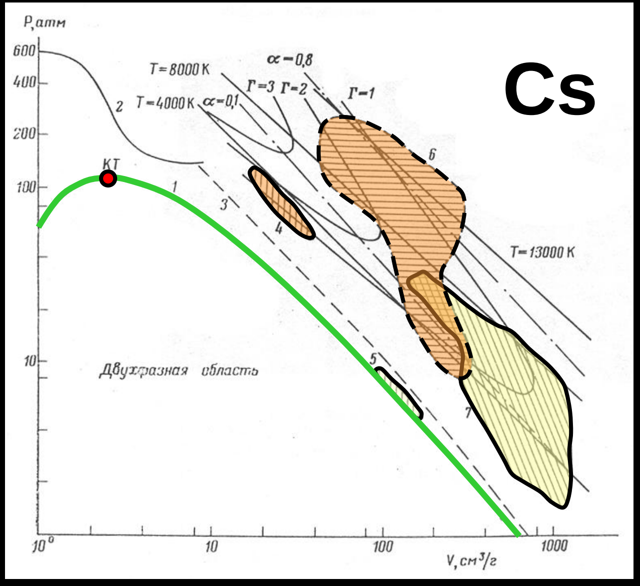
$$\begin{cases} \left. \dfrac{dP}{dV} \right|_S = -\dfrac{P + (\partial E / \partial V)_P}{(\partial E / \partial P)_V} \\ \left. \dfrac{dT}{dV} \right|_S = -\dfrac{T}{(\partial E / \partial P)_V} \end{cases}$$

Monte Carlo

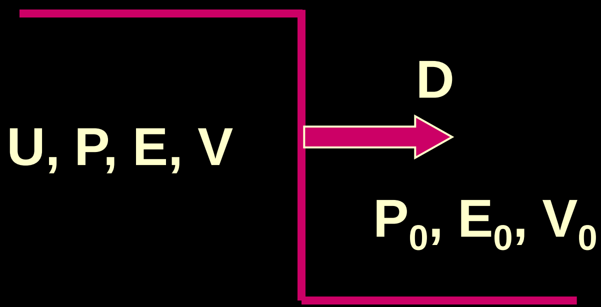
$$\tilde{E}_i \rightarrow \tilde{E}(P,V) \rightarrow \tilde{T}$$







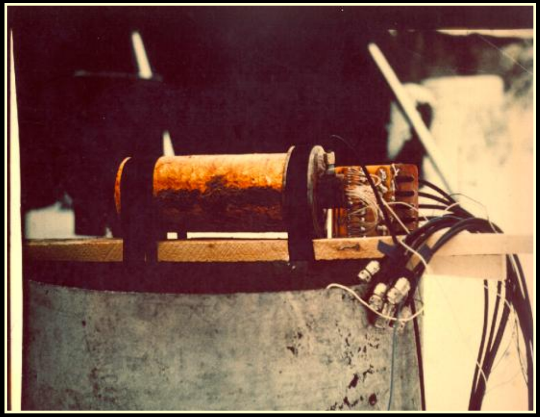
ДИНАМИЧЕСКИЕ МЕТОДЫ



shock compression

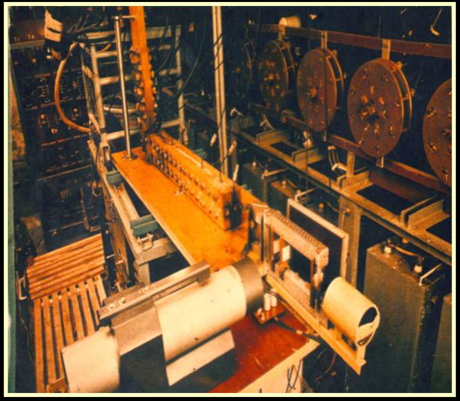
Hugoniot relations

$$V_0 / V = D/(D-U)$$
$$P = P_0 + DU / V_0$$
$$E = E_0 + 1/2(V_0 - V)(P_0 + P)$$



HE gun

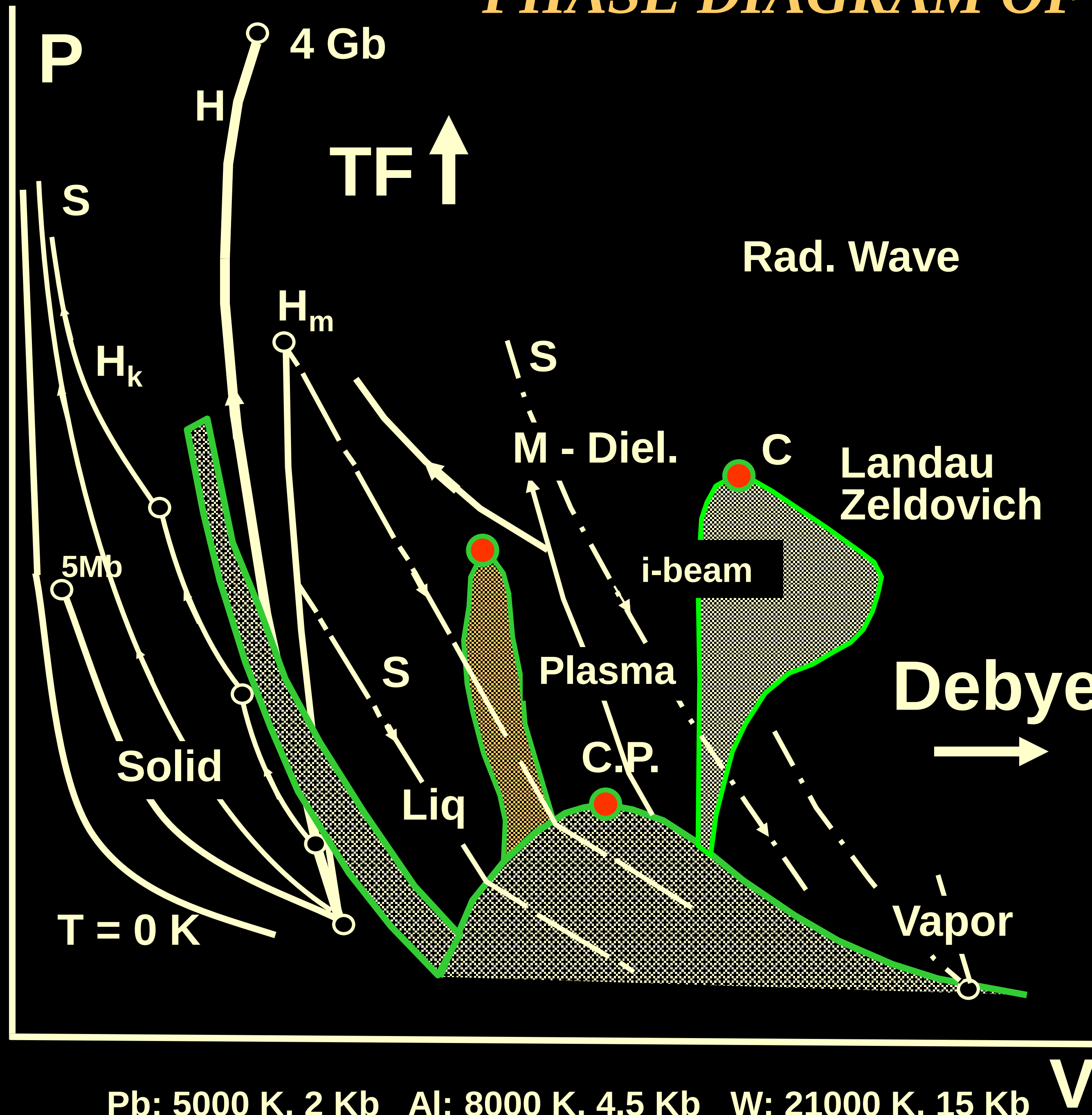
Lasers



Z-pinch

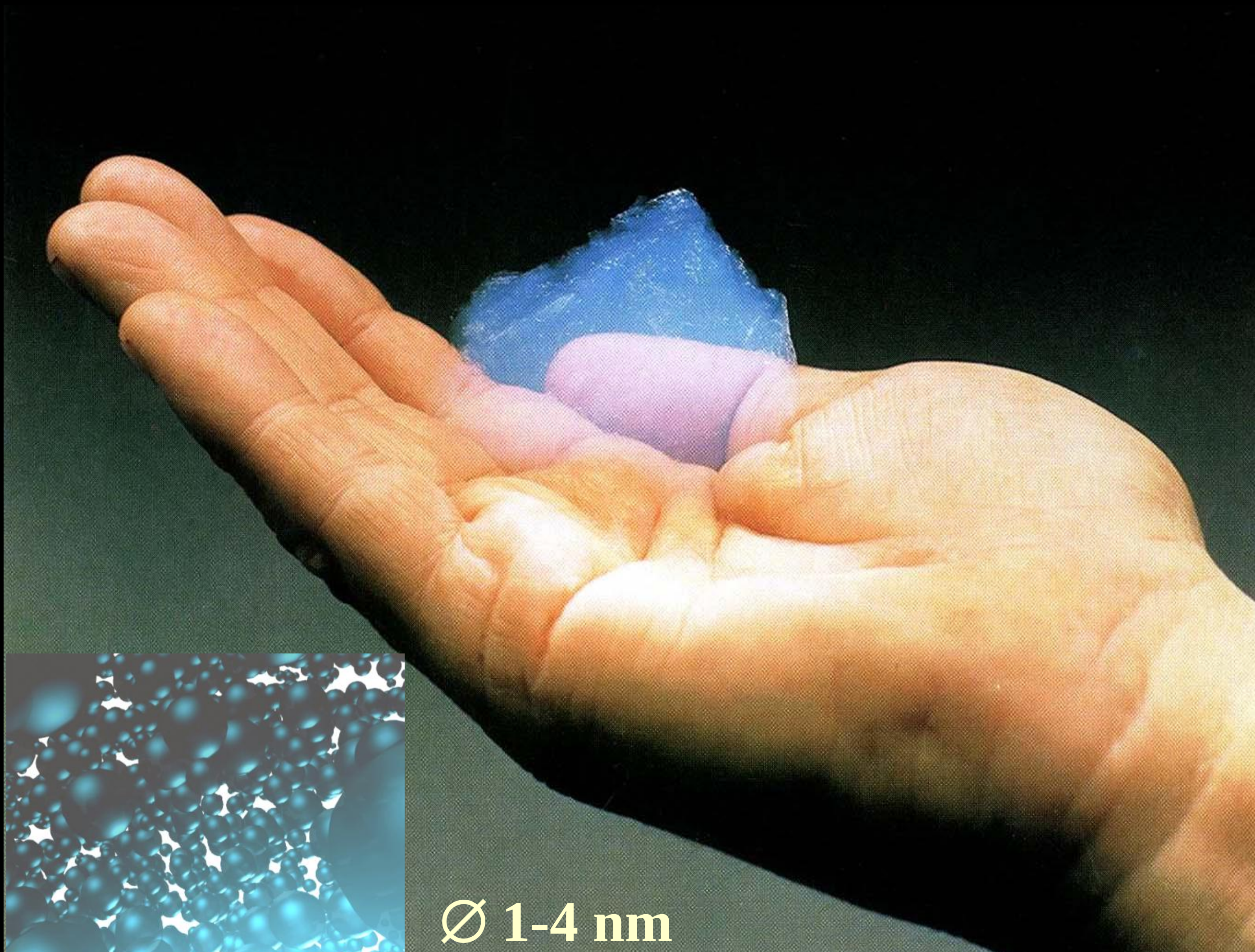
Railgun

PHASE DIAGRAM OF MATTER



Pb: 5000 K, 2 Kb   Al: 8000 K, 4.5 Kb   W: 21000 K, 15 Kb

СЖАТИЕ ПОРИСТЫХ МИШЕНЕЙ



$E = P(V_{00} - V)/2$

↓

Porous Metals

$m = \rho_0 / \rho_{00} \leq 10$

$P \leq 10$Mbar

$E \sim 10$MJ/cc

Aerogel

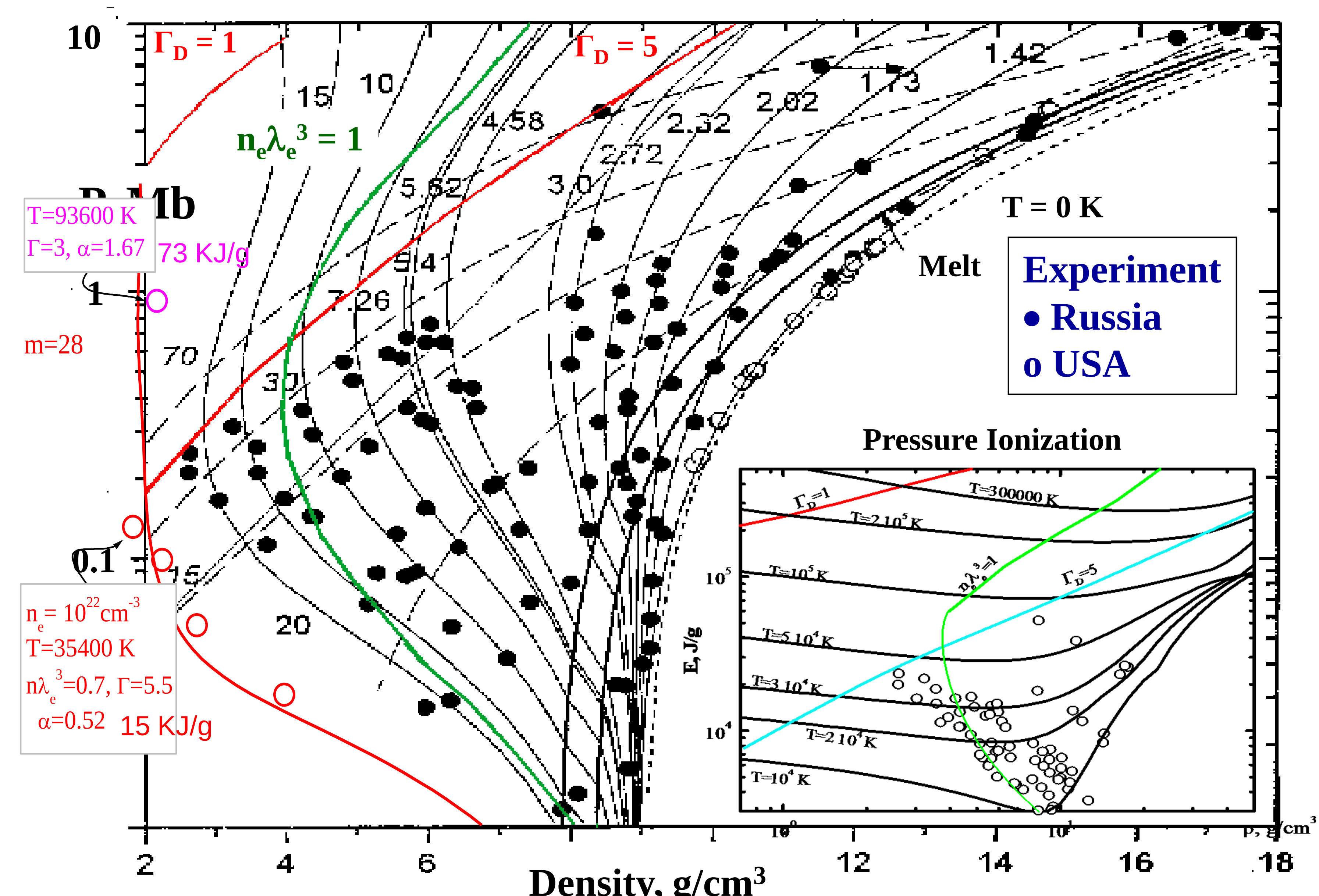
$m \sim 10^2 - 10^3$

$\rho_{00} \sim 10$mg/cc

$P \sim 0.1$Mb

Ni PLASMA THERMODYNAMICS AT MEGABARS

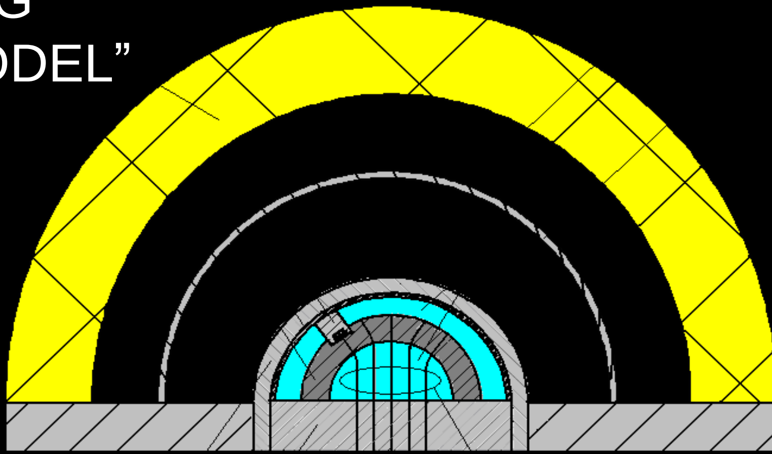
$E = P(V_{00}-V)/2$

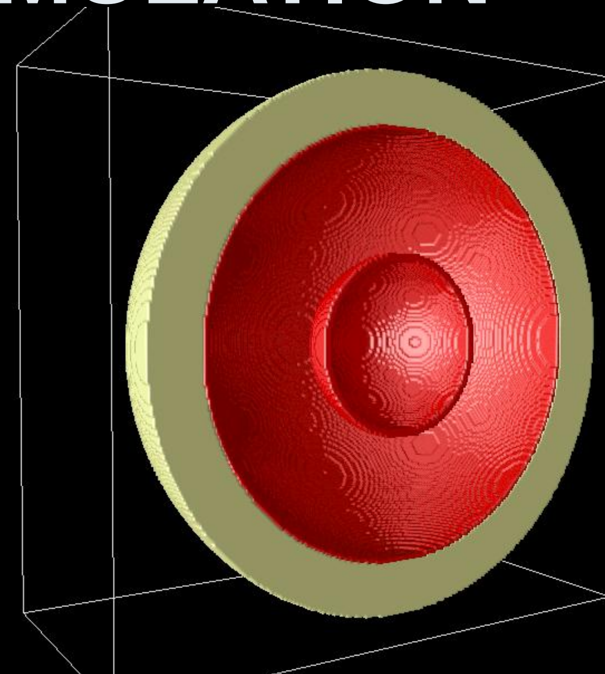


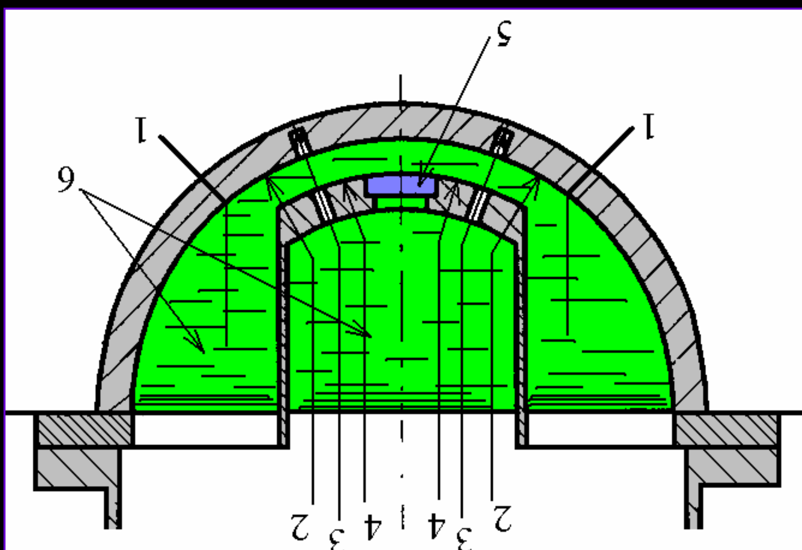
M.Zernokletov et al

SPHERICAL CUMULATION

"BIG MODEL"



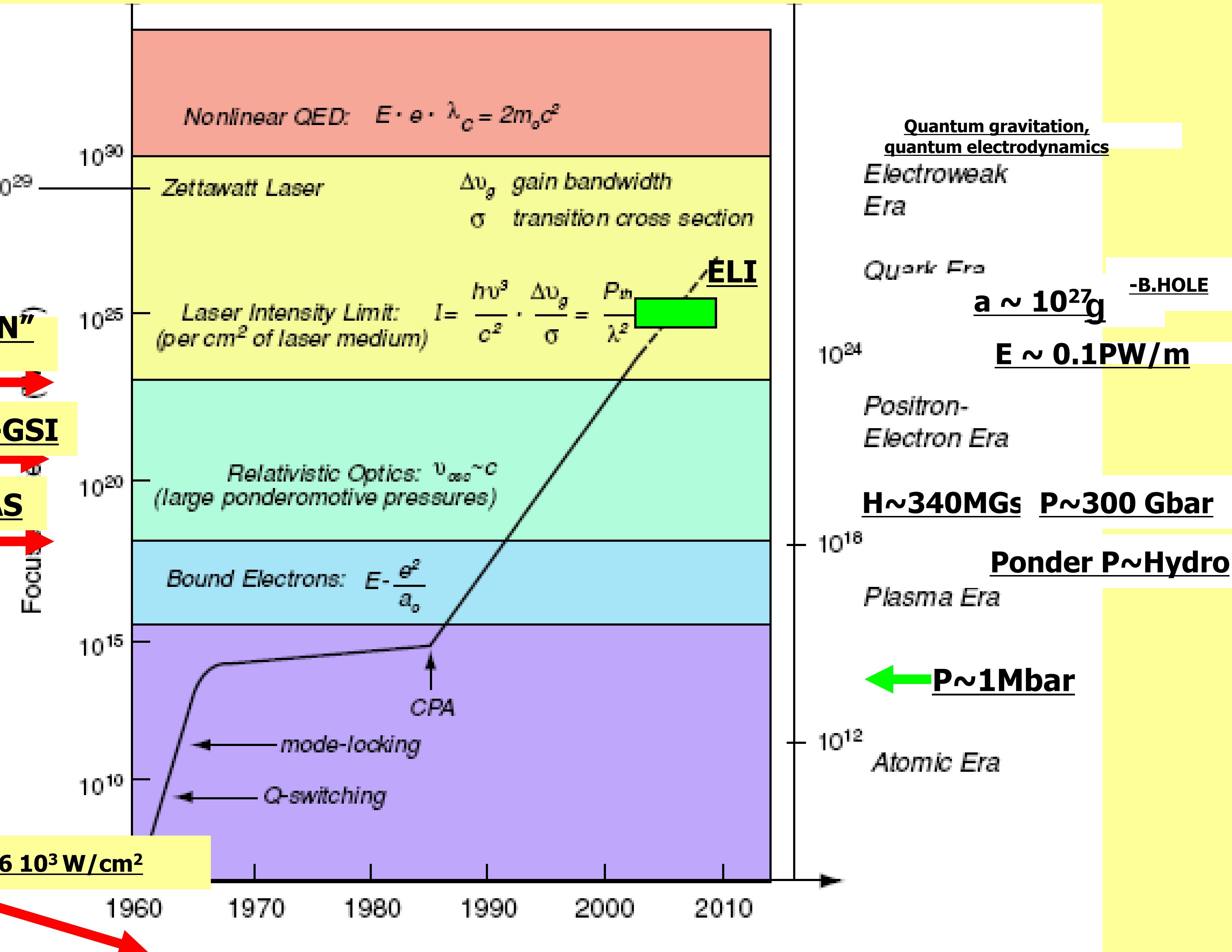




Cryogenic Target

Power ~ 5 TW, Energy ~ 500 MJ, HE weight 100 kg

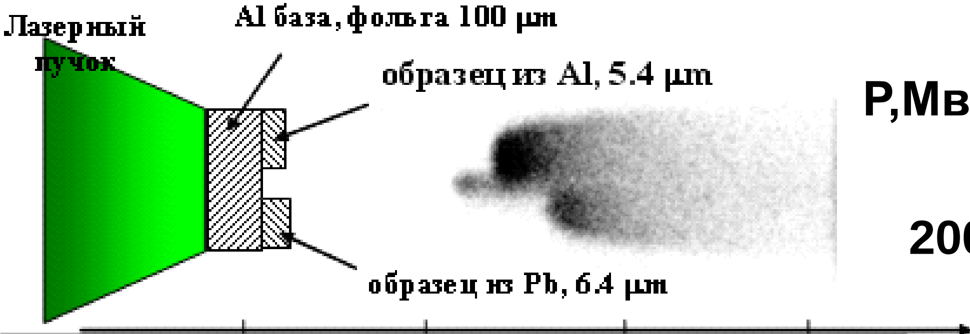
TIME DEPENDENT OF LASER INTENSITY



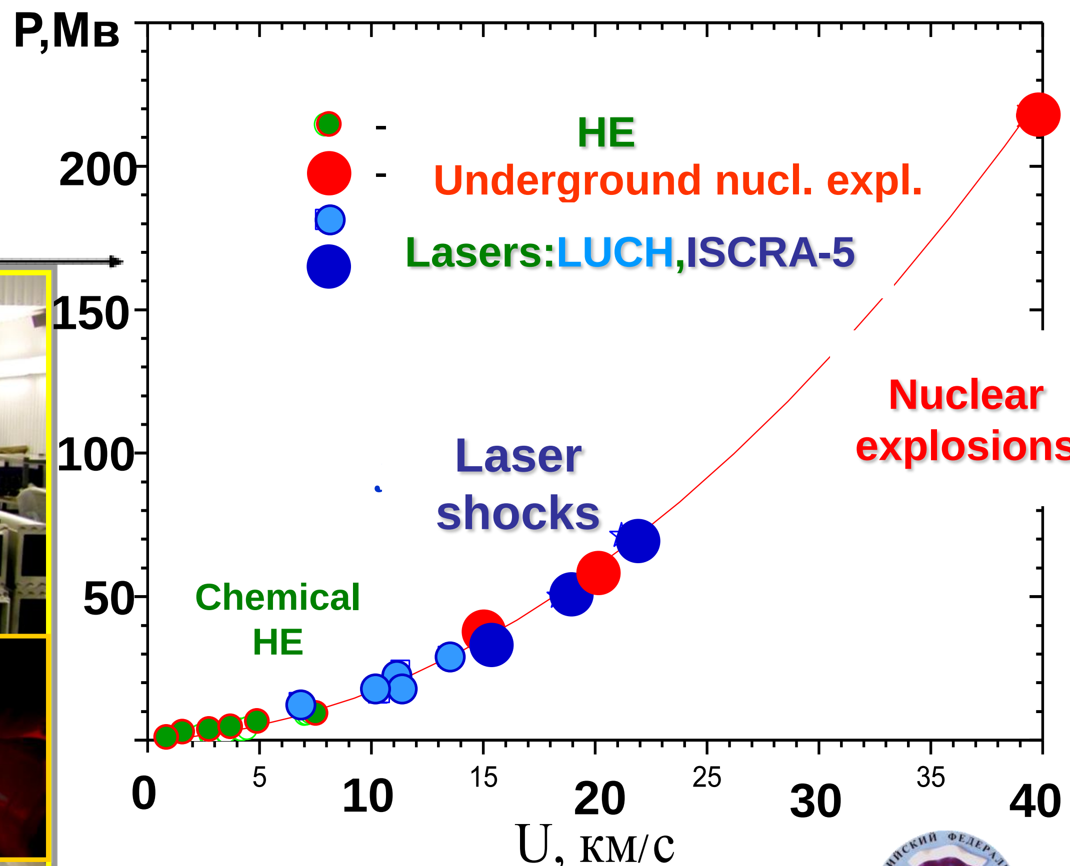
Sun-5.6 10^3 W/cm²

Laser shock compression of Pb nonideal plasma

Plasma parameters registration

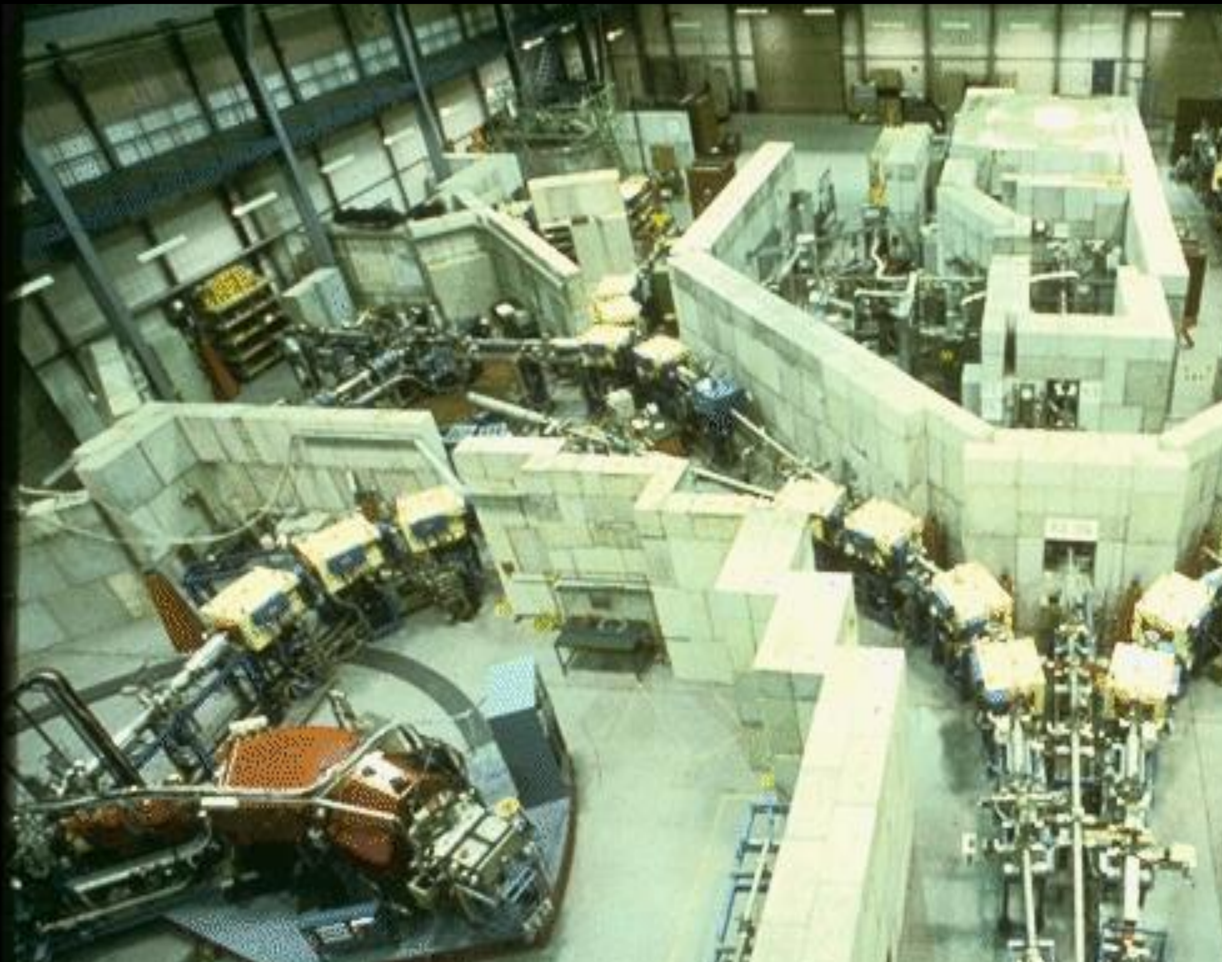


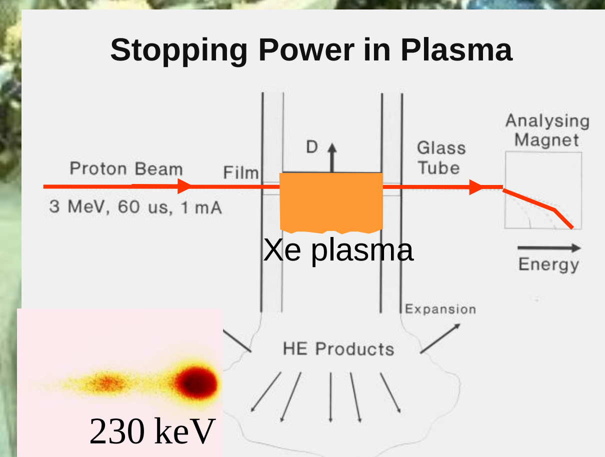
Pb nonideal plasma pressure

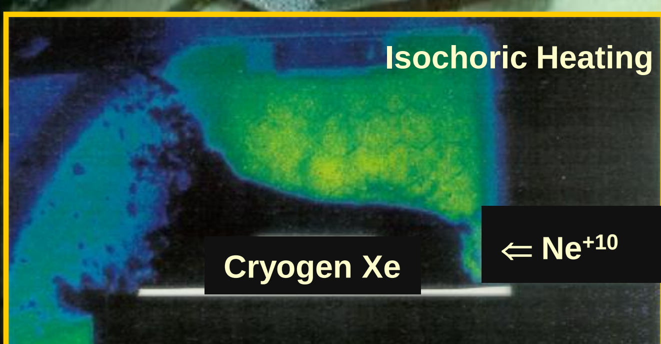


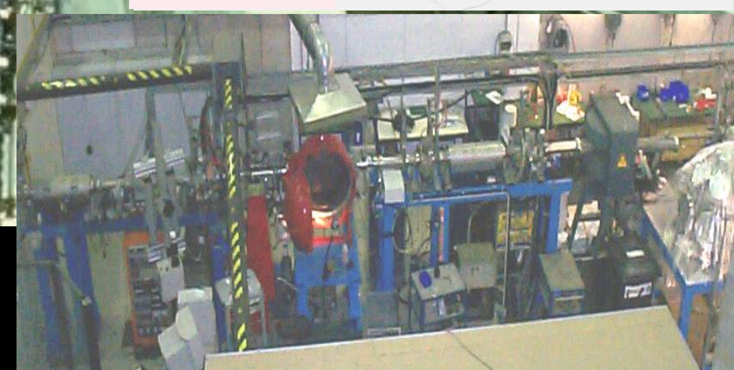
Plasma pressure -71 Mbar

Relativistic Ion Beam-Plasma Interaction at 4 GeV



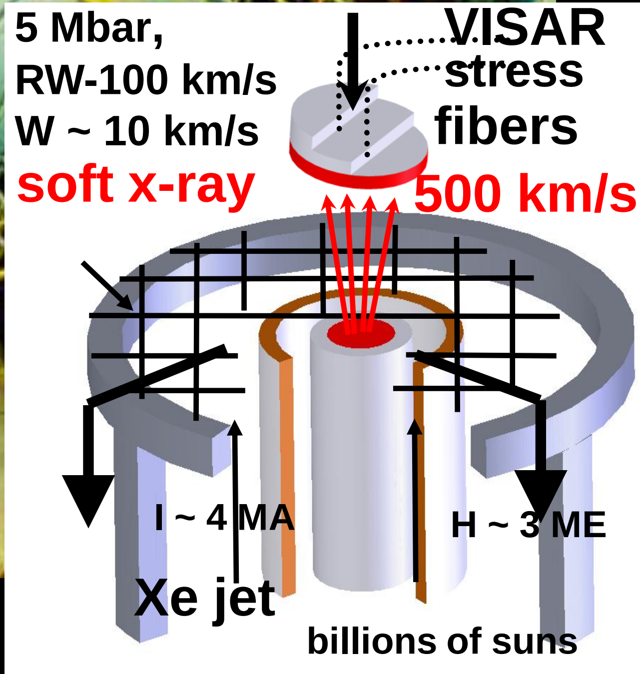






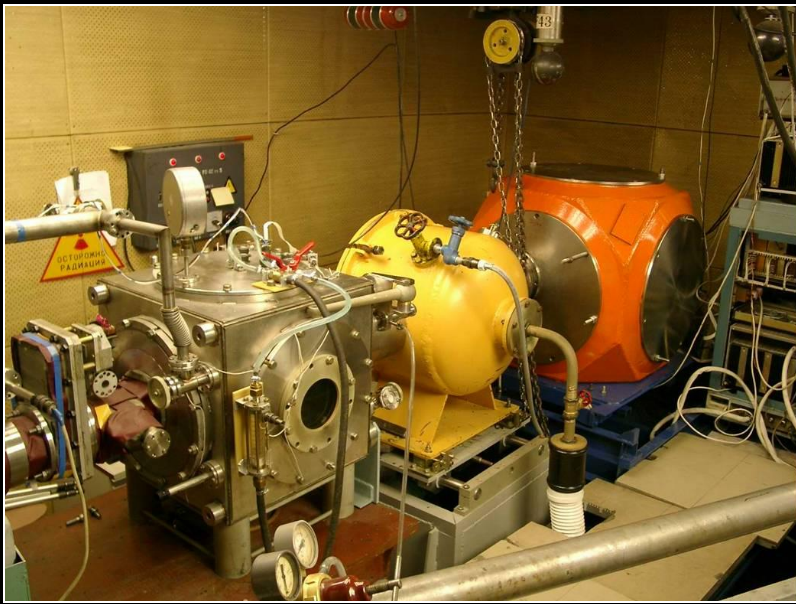
A. Hoffmann, B.Sharkov, V. Mintzev et al.

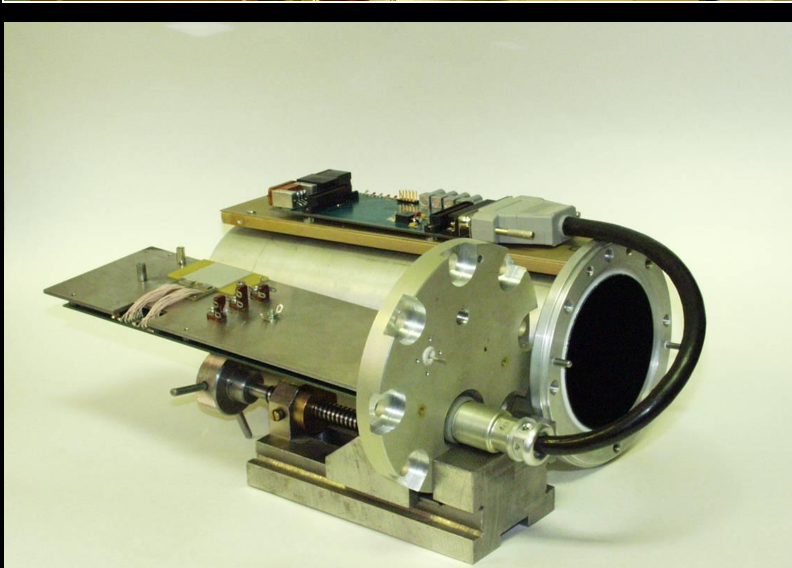
PULSED POWER FOR SHOCK WAVE



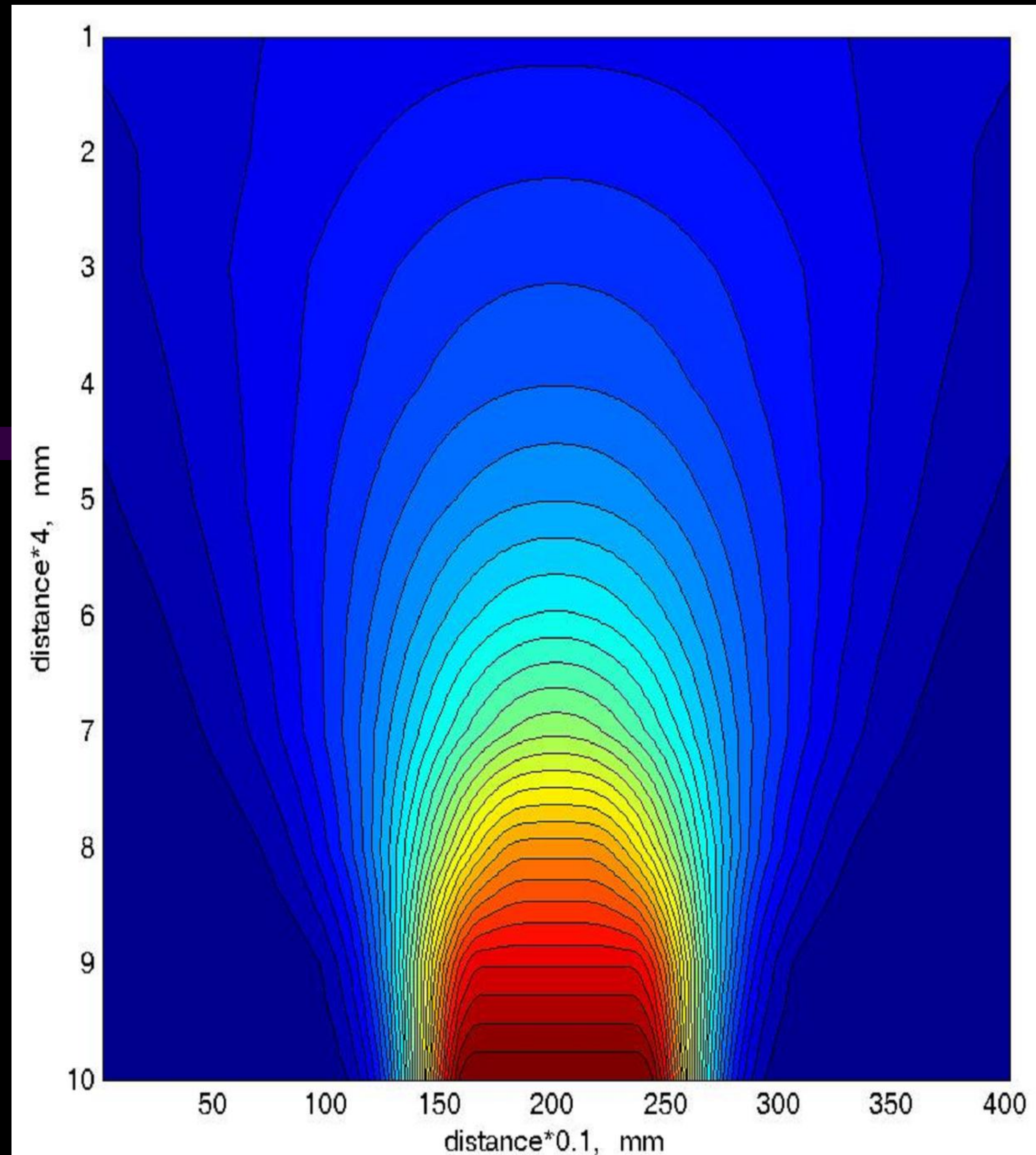
Q ~ 60 KJ, τ ~ 90 ns, W ~ 10 TW, J ~ 6 MA

SINCHROTRON RADIATION. DENSITY DISTRIBUTION OF CYLINDRICAL HE DETONATION

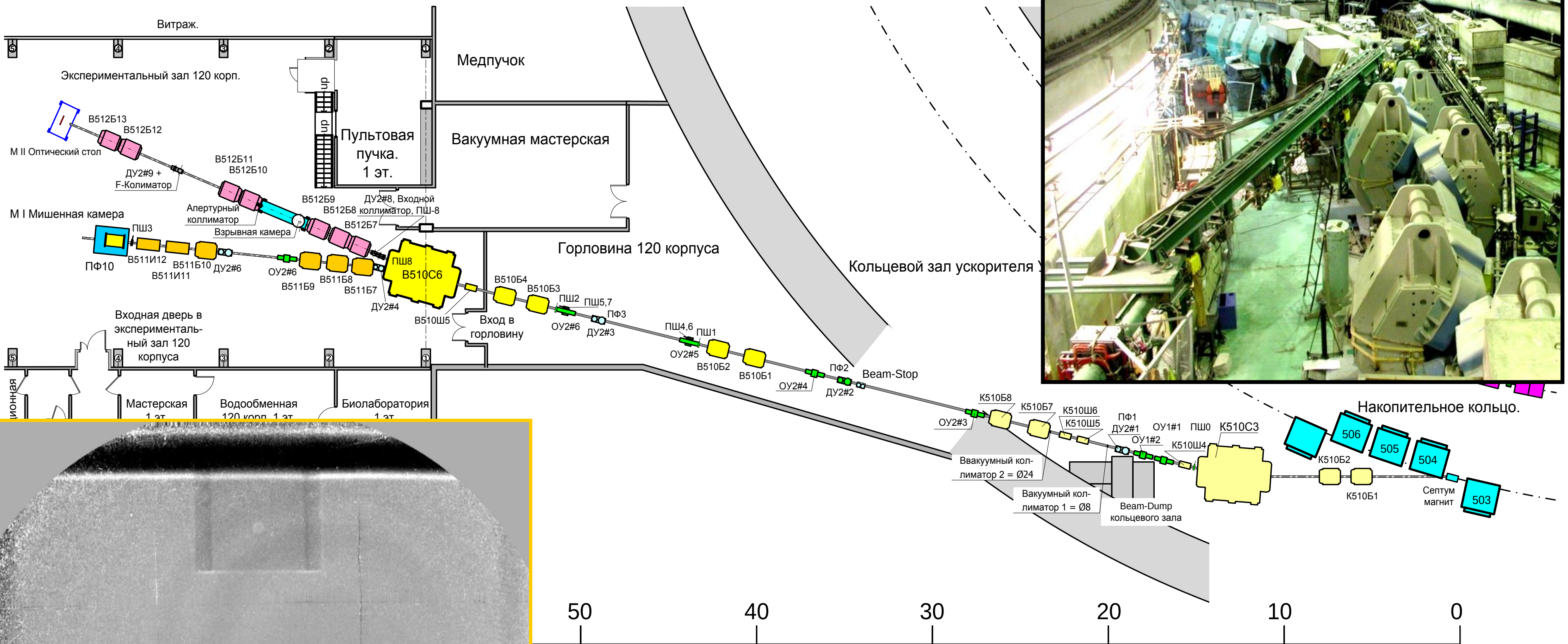


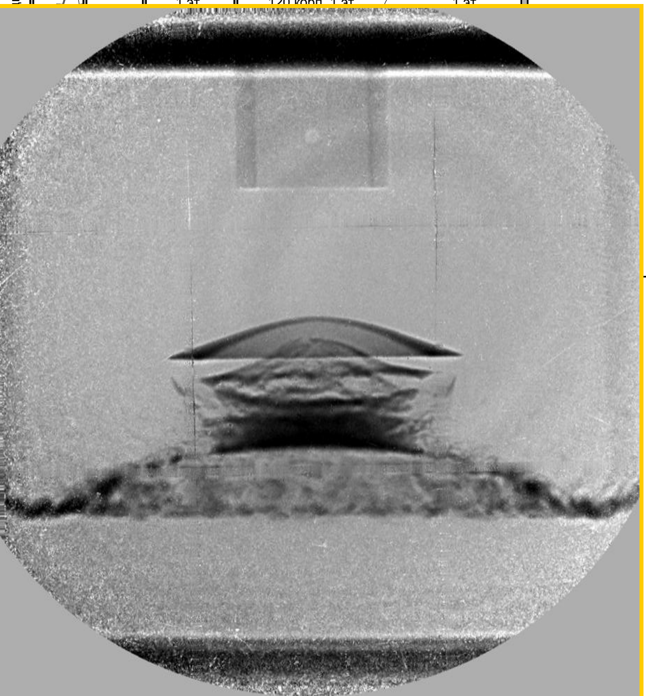


V. Titov, K. Ten



PROTON RADIOGRAPHY- ТВН-ИТЭФ

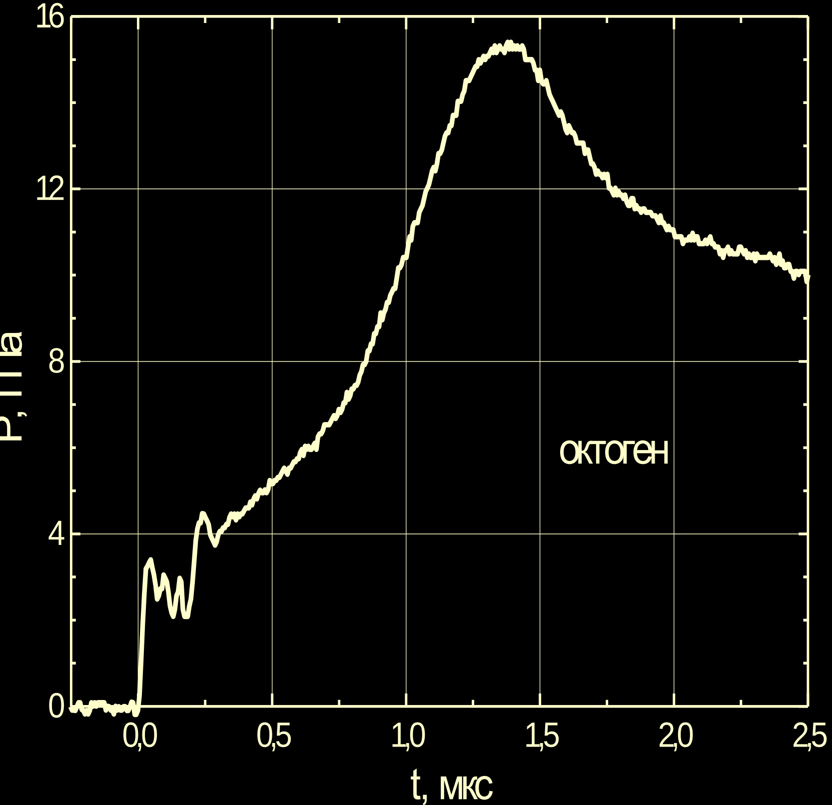




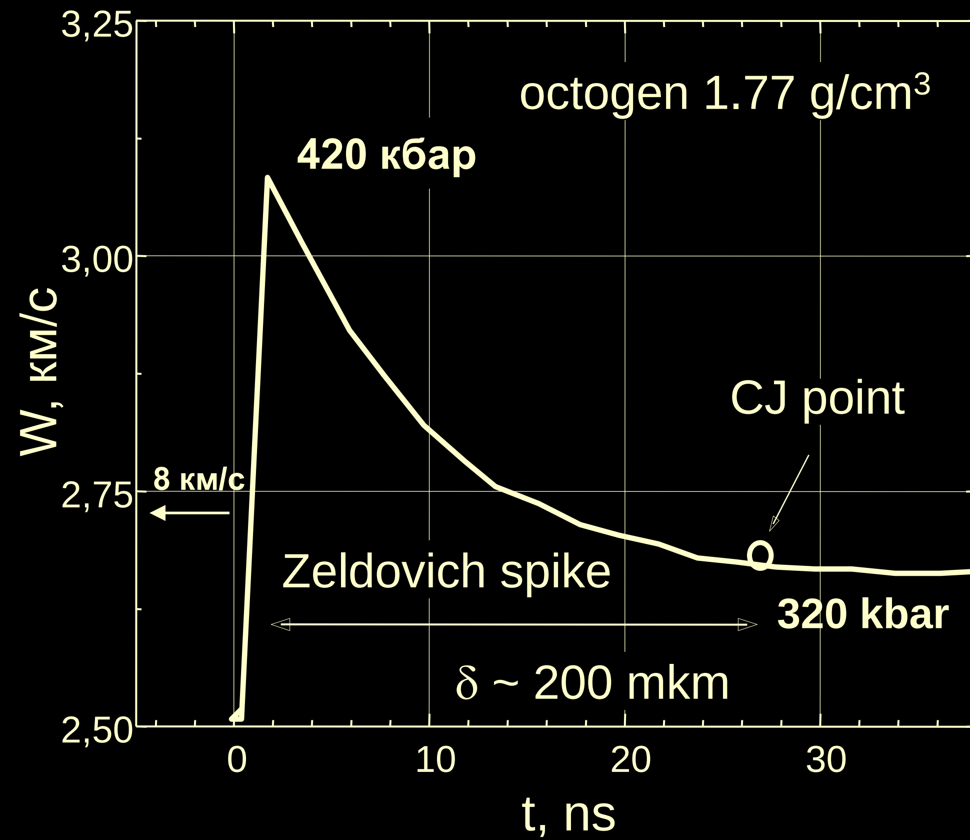
Параметры протонно-радиографической установки:

Энергия протонов	800 МэВ
Поле зрения	до 40 мм
Исследуемые объекты	до 60 г/см^2
Пространственное разрешение	текущее ~ 500 мкм, теоретическое ~ 50 мкм
Временная структура пучка	4 пакета / 1 мкс

HE CHEMICAL DECOMPOSITION KINETICS IN SHOCK AND DETONATION WAVES



q ~ 10^{10} W/см^2, h ~ 1 TW/g



G. Kanel, A. Utkin et al.

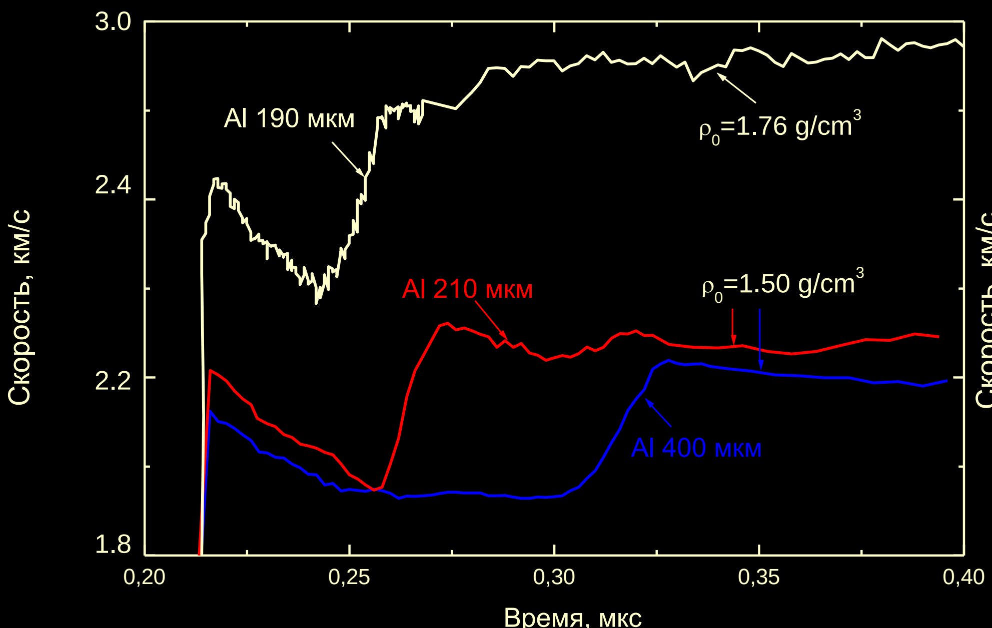
STATIONARY DETONATION WAVE WITHOUT CHEMICAL SPIKE IN TNETB

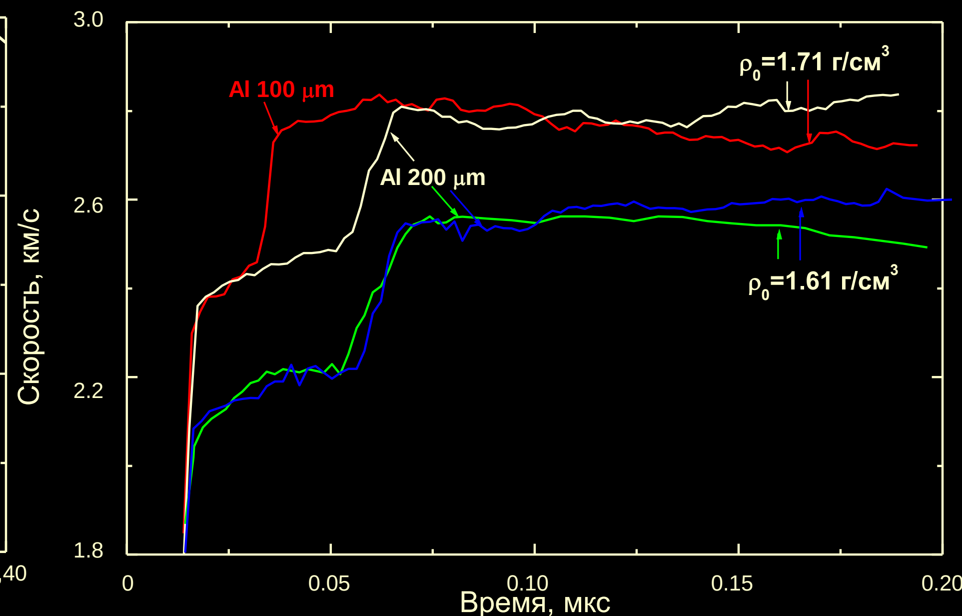
2`,2`,2`-ТРИНИТРОЭТИЛ-4,4,4-ТРИНИТРОБУТИРАТ

кислородный баланс =-4.15%, плотность монокристалла = 1.839 г/см^3

При $\rho_0 < 1.56$ г/см^3 и $\rho_0 > 1.72$ г/см^3 регистрируется химпик

В интервале плотностей 1.56 г/см^3 < ρ_0 <1.72 г/см^3 химпик отсутствует

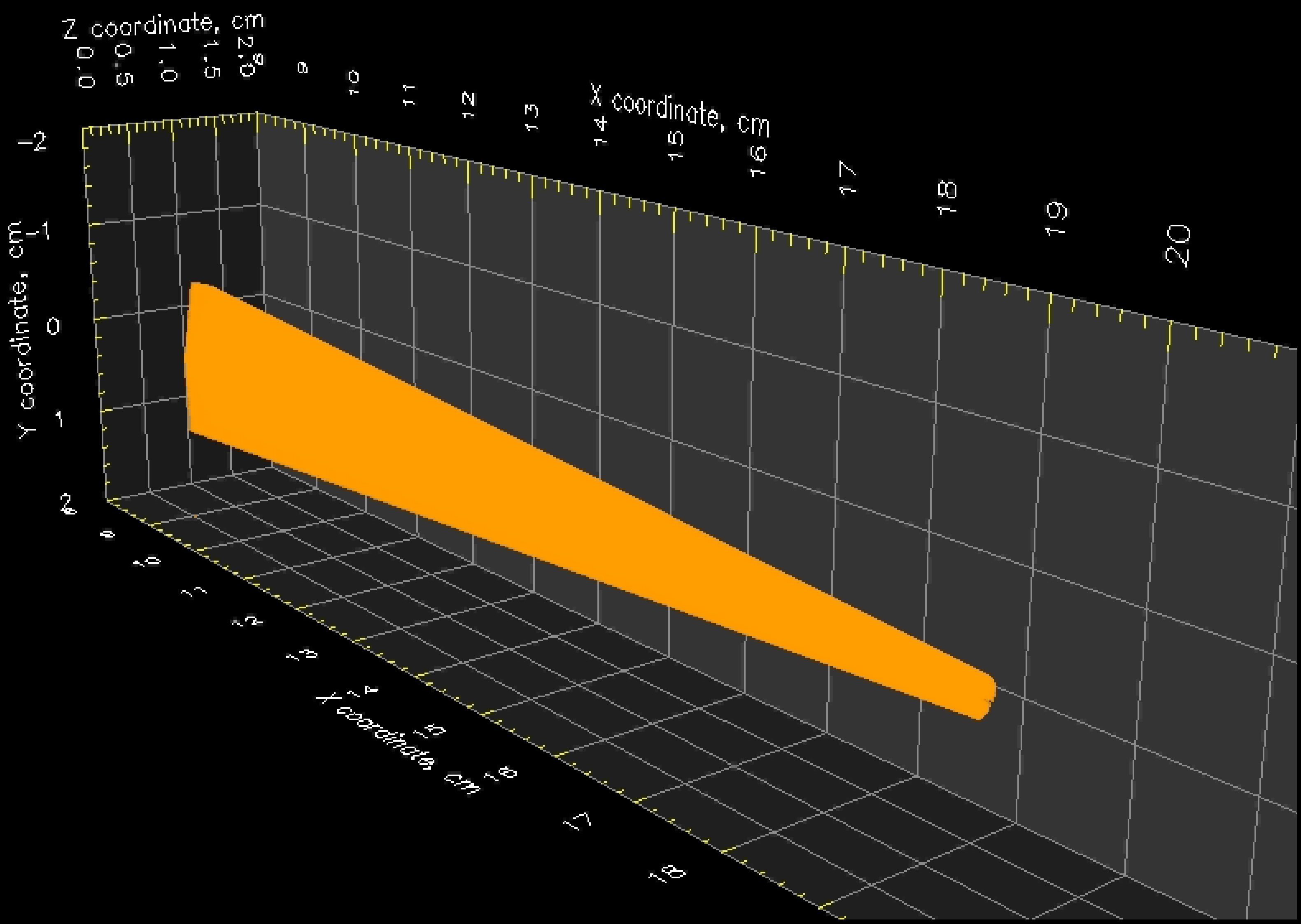




Скорость границы Al фольга – водяное окно при различной начальной плотности TNETB

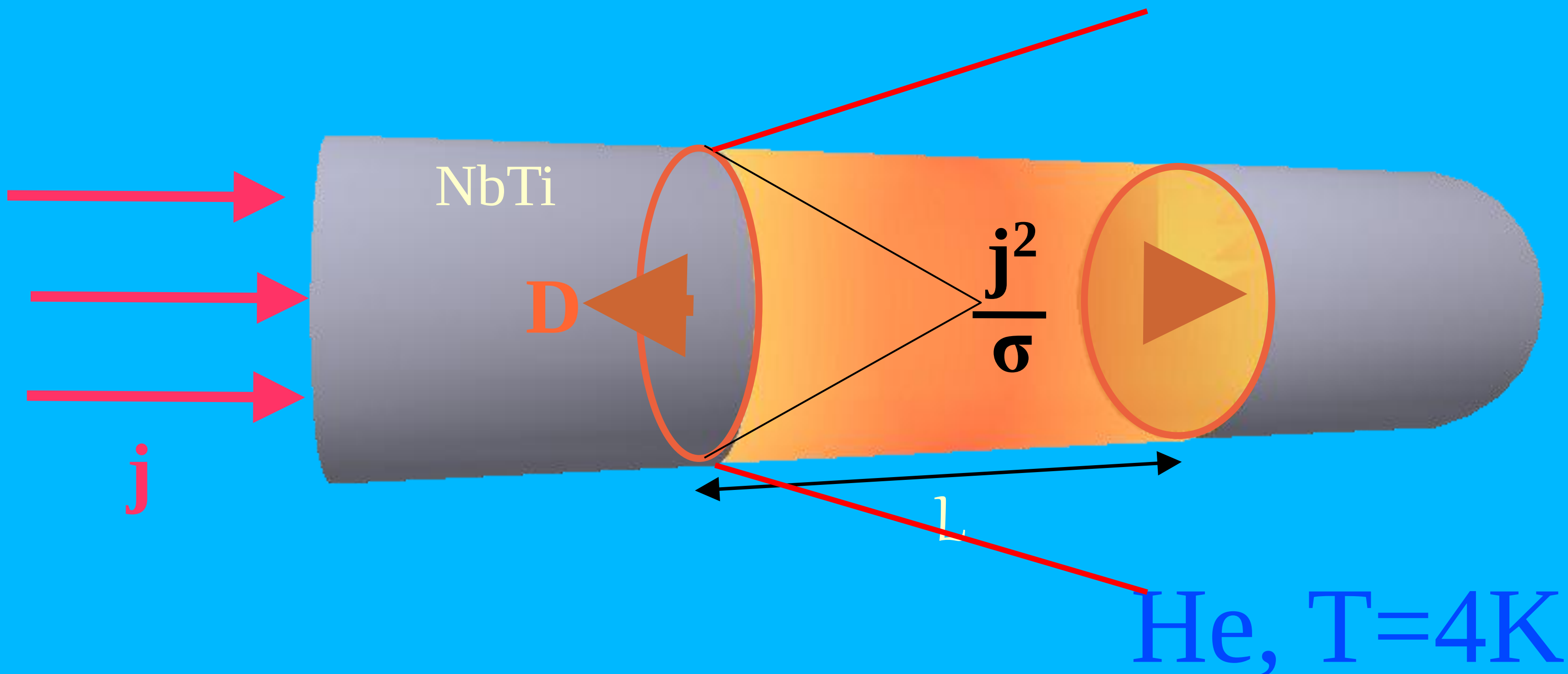
A. Utkin et al.

FAILURE DIAMETER



A. Shutov et al.

ELECTRODETONATION



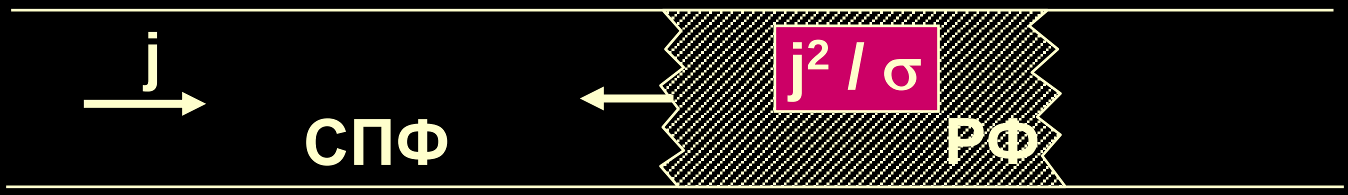
DYNAMICS **HEAT**

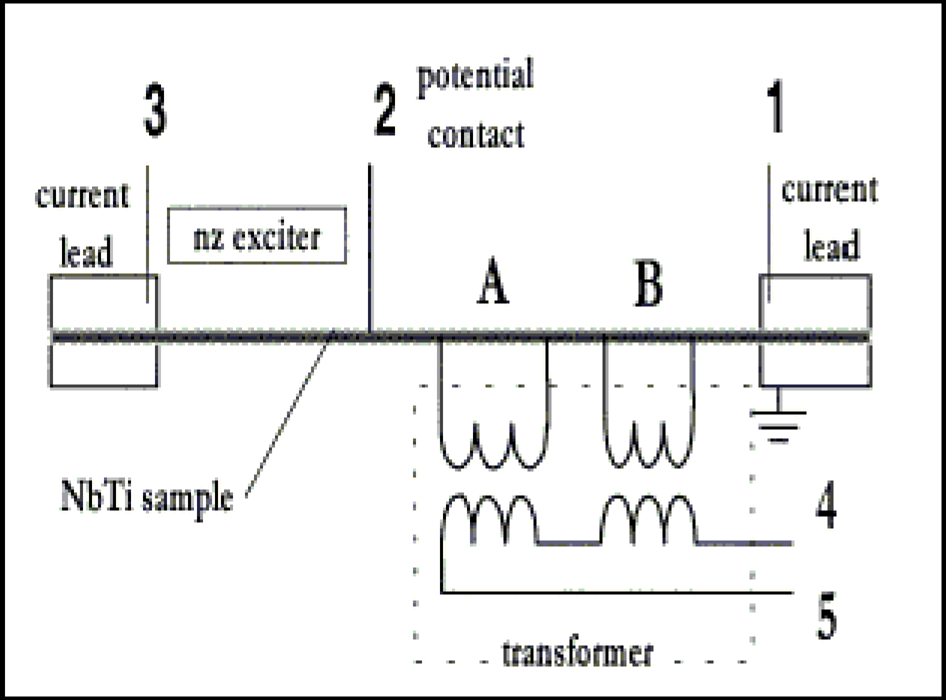
$$J^2 L / \sigma = \rho_0 D\, E\,(V, T)$$

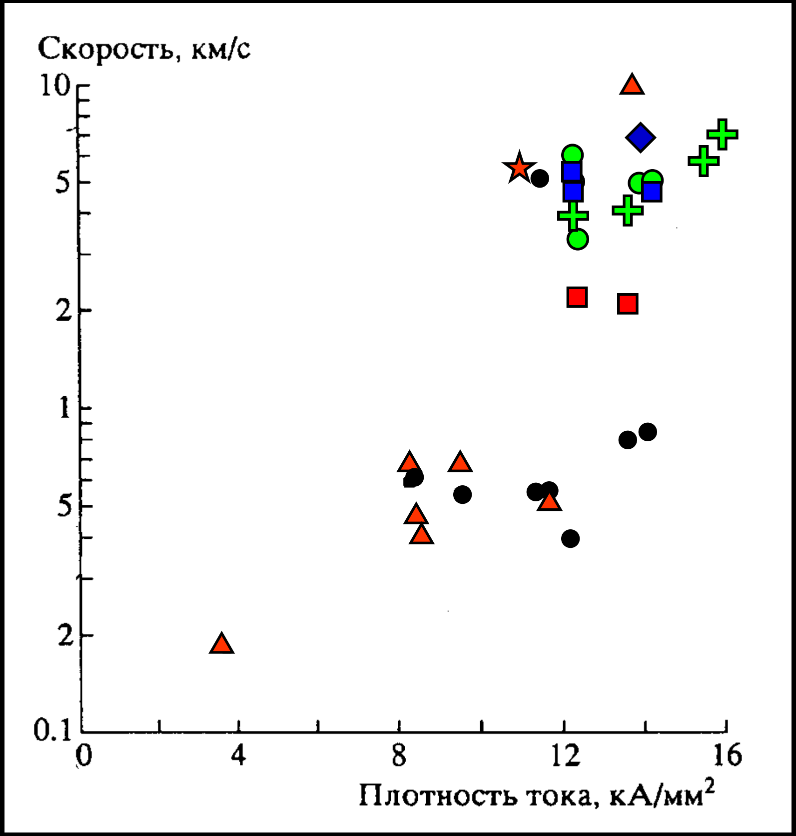
$$L \sim \frac{DR}{C_S}$$

$$L_\lambda \sim \frac{C_S C_P \rho}{\lambda} R^2$$

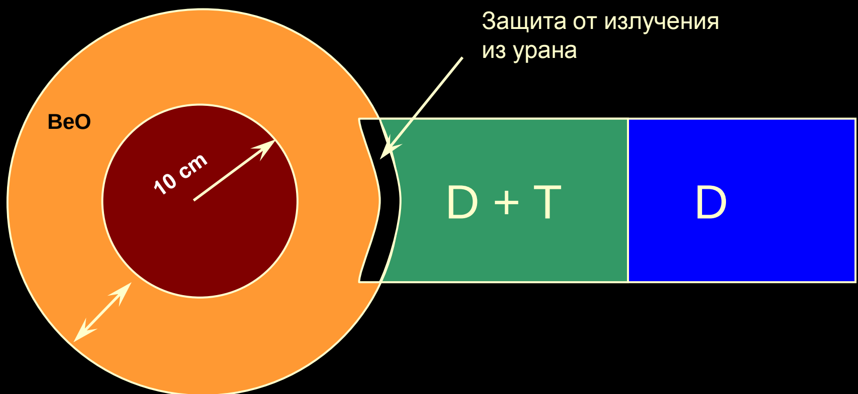
ELECTRO-DETONATION IN SUPERCONDUCTORS

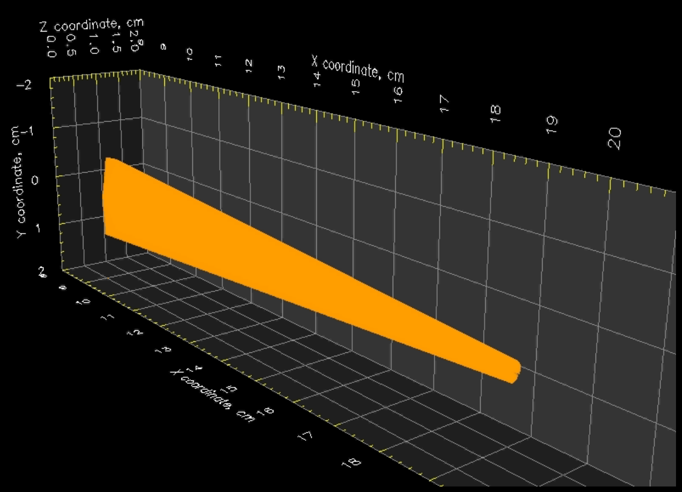






«Классический Супер»





Описание Классического Супера,
с рукописным пояснением Я. Зельдовича

Сов. секретно 7

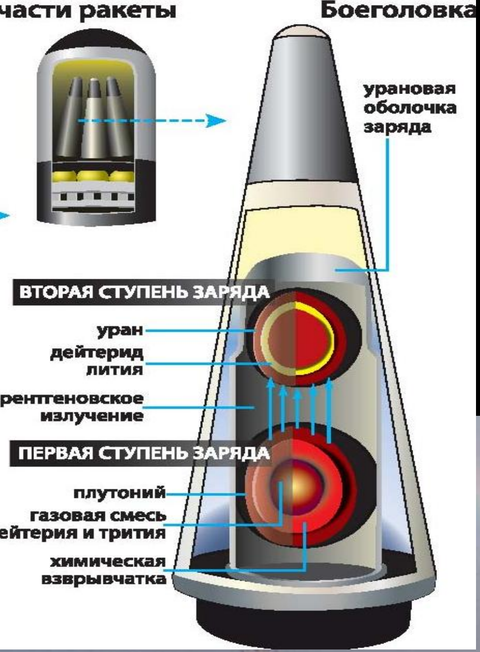
Товарищу Харитон Ю.Б.

Об использовании изделия для целей обжатия сверхизделия РДС6С.

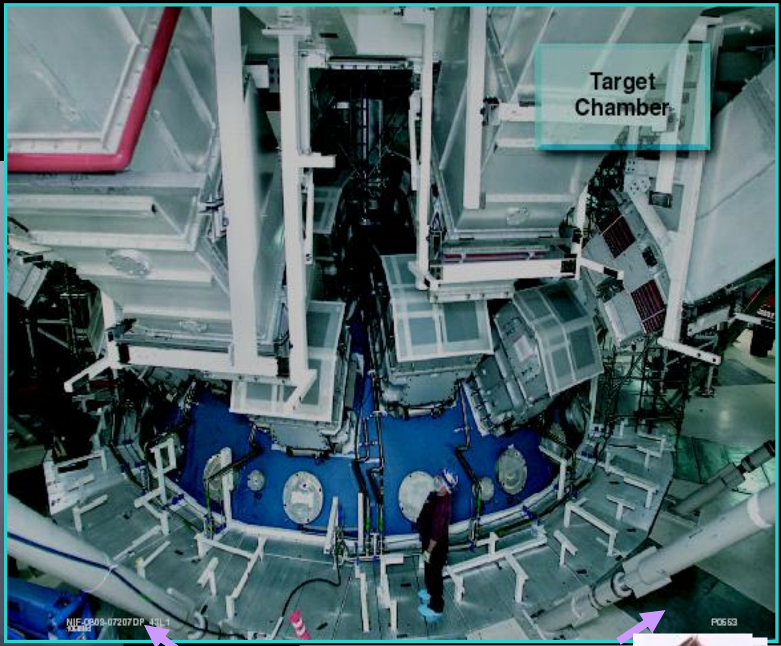
В настоящей записке сообщается предварительная схема устройства для ао сверхизделия и оценочные расчеты её действия. Идея применение ао было предложено В.А.Давиденко.

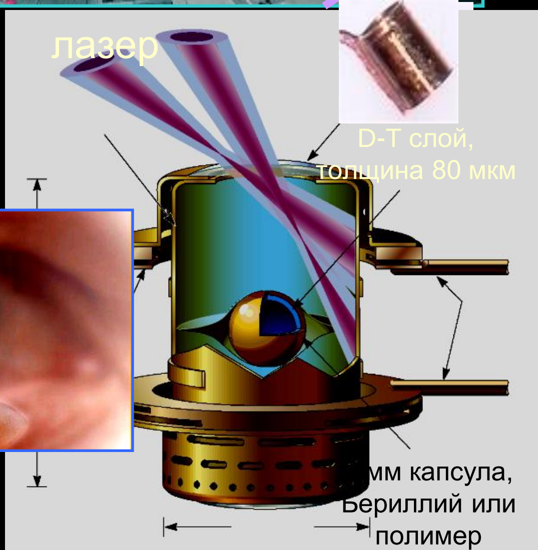
Схема.

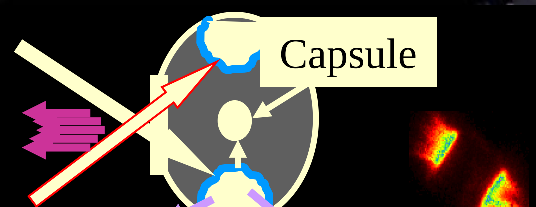
NIF, Ливерморская национальная лаборатория



192 Beams
~1.8MJ at 351nm

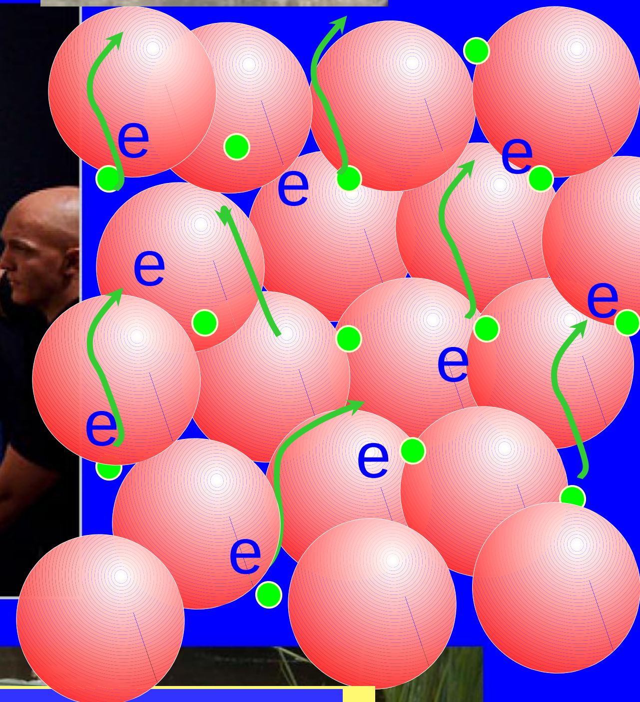




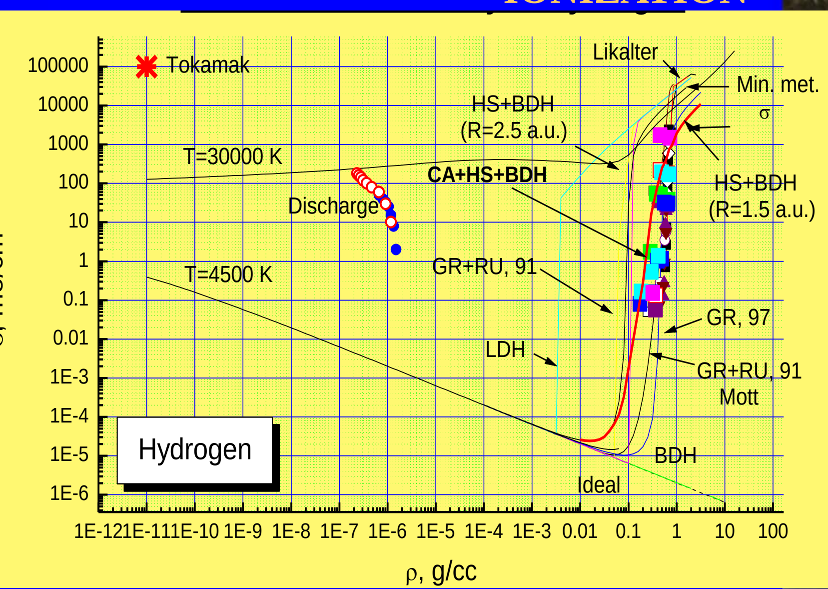


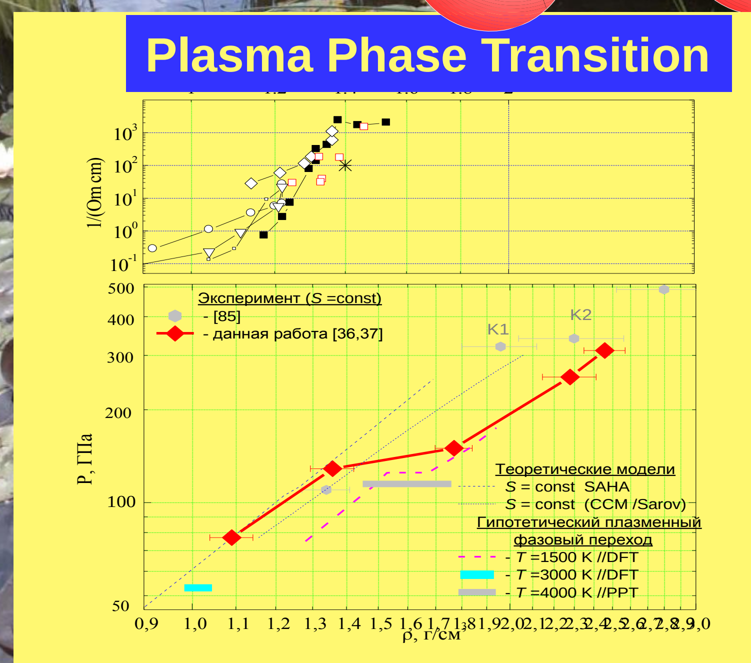
Plasma ablation of wall

PRESSURE IONIZATI



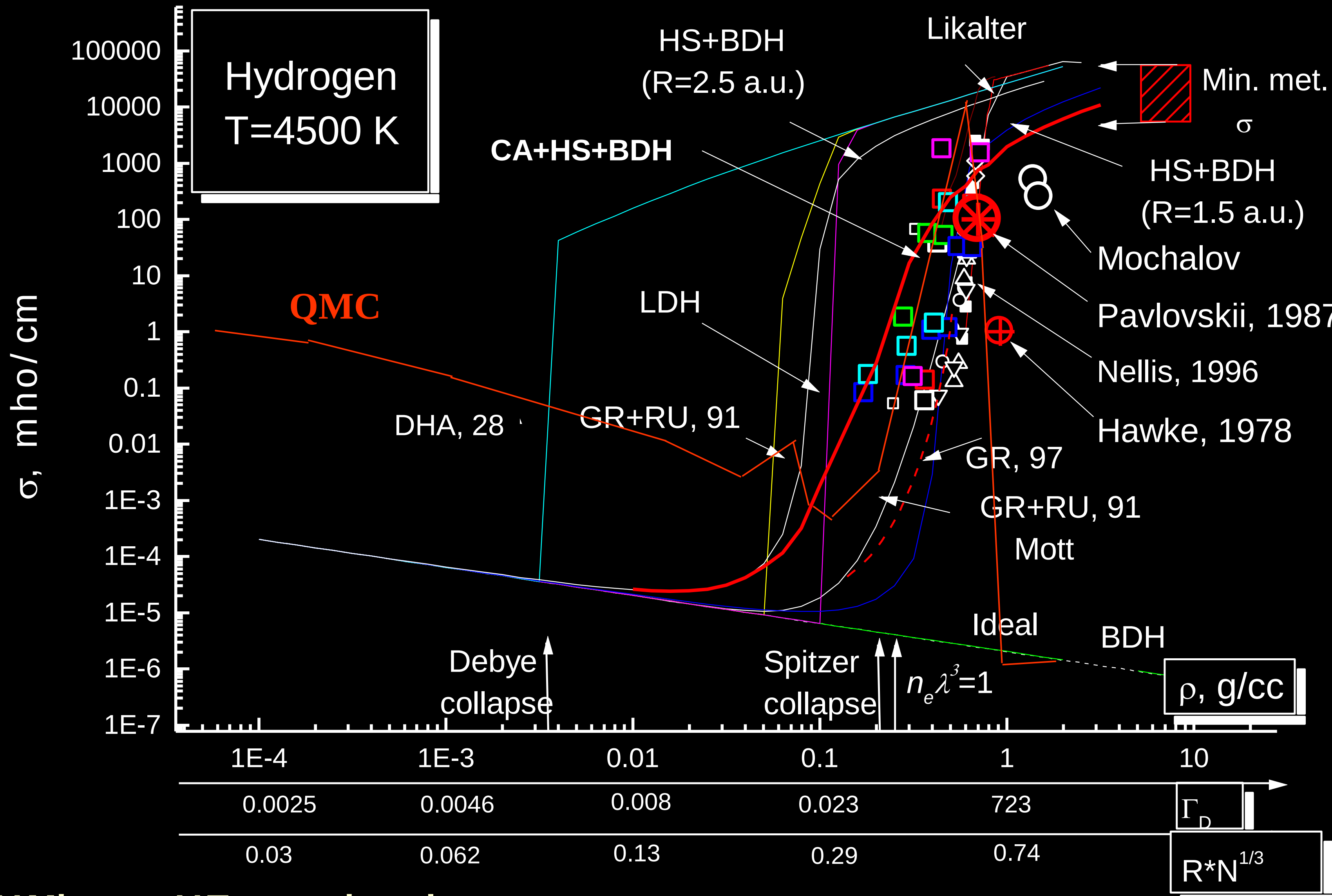
HYDROGEN PRESSURE IONIZATION





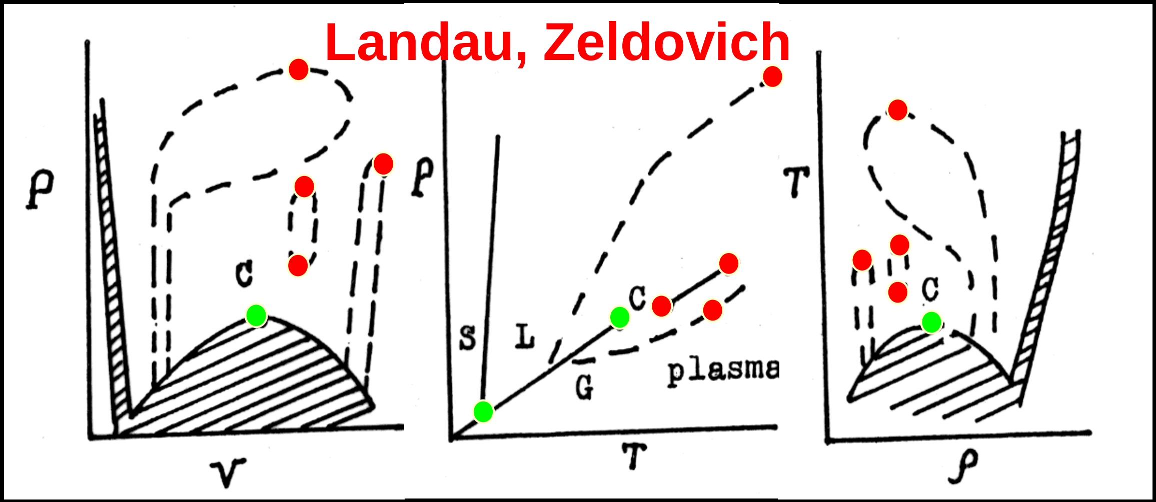
HYDROGEN PRESSURE IONIZATION

Electrical Conductivity of Hydrogen

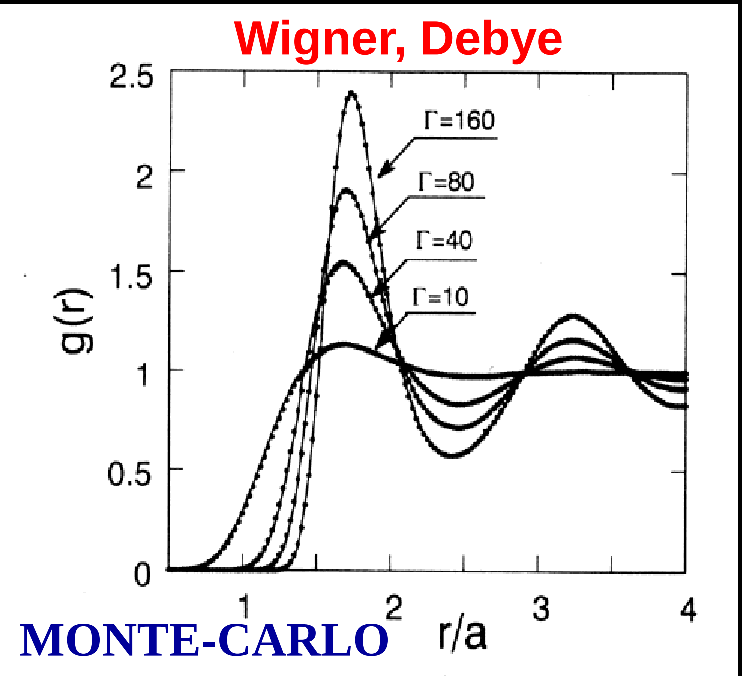


V.Mintzev ,V.Ternovoj et.al.

PHASE TRANSITIONS IN PLASMA



- dusty plasma
- collodial plasma
- ions in traps
- ions in accelerators
- 2d electrons on He
- ie - plasma - ???



FERMI: Charge Density Waves $2 \leq r_s \leq 7$

Wigner Crystal $r_s \sim 75 \quad \varepsilon_c \sim e^2 n^{1/3} \quad n \to 0$

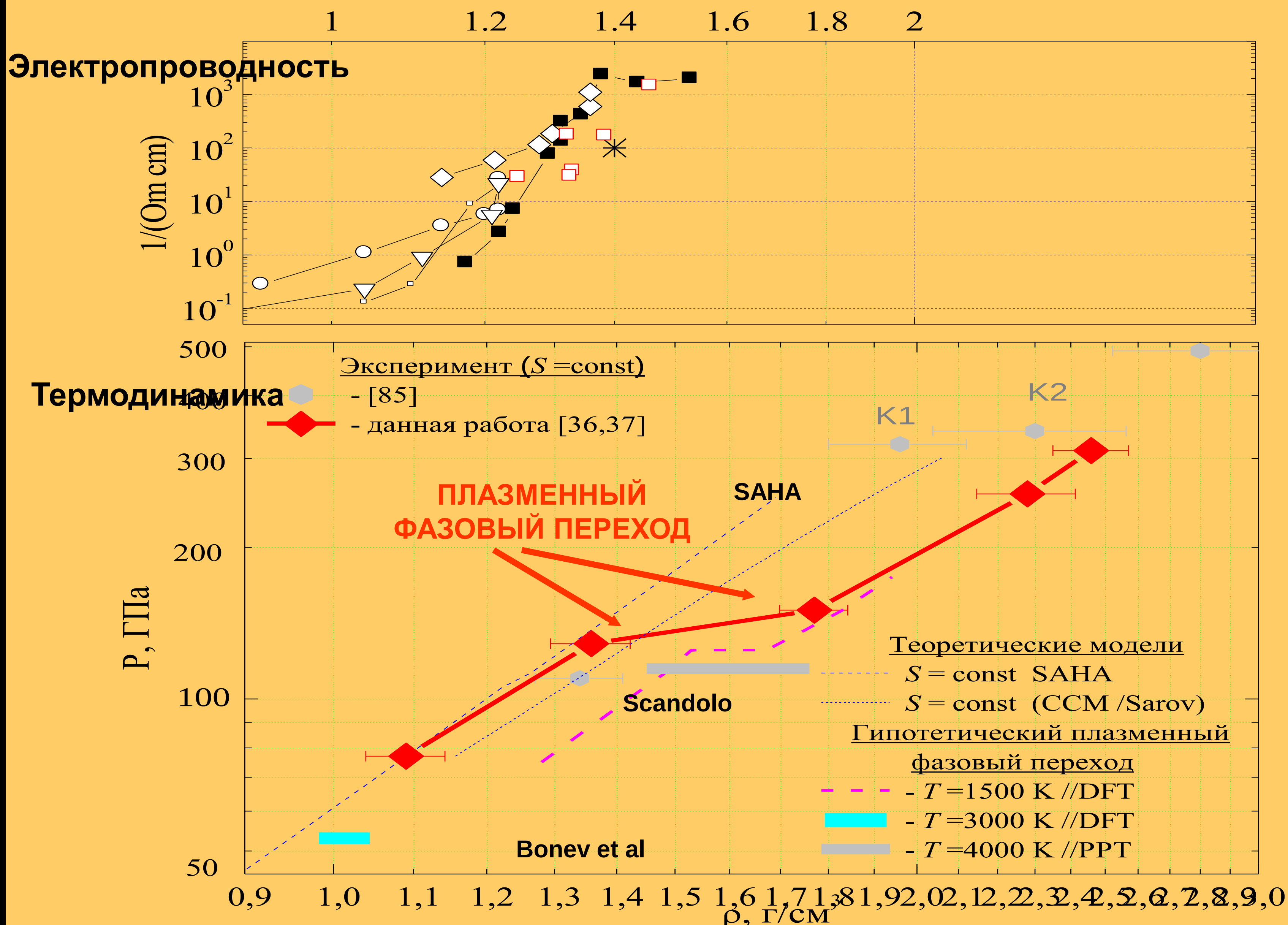
$\varepsilon_k \sim \varepsilon_f \sim n^{1/3} \quad \varepsilon_k < \varepsilon_c$

BOLTZMANN: g(r) oscillations $\Gamma \sim 2{,}5$

$\Gamma \sim 3{,}1 \quad \left(\frac{\partial P}{\partial V}\right)_T \geq 0$

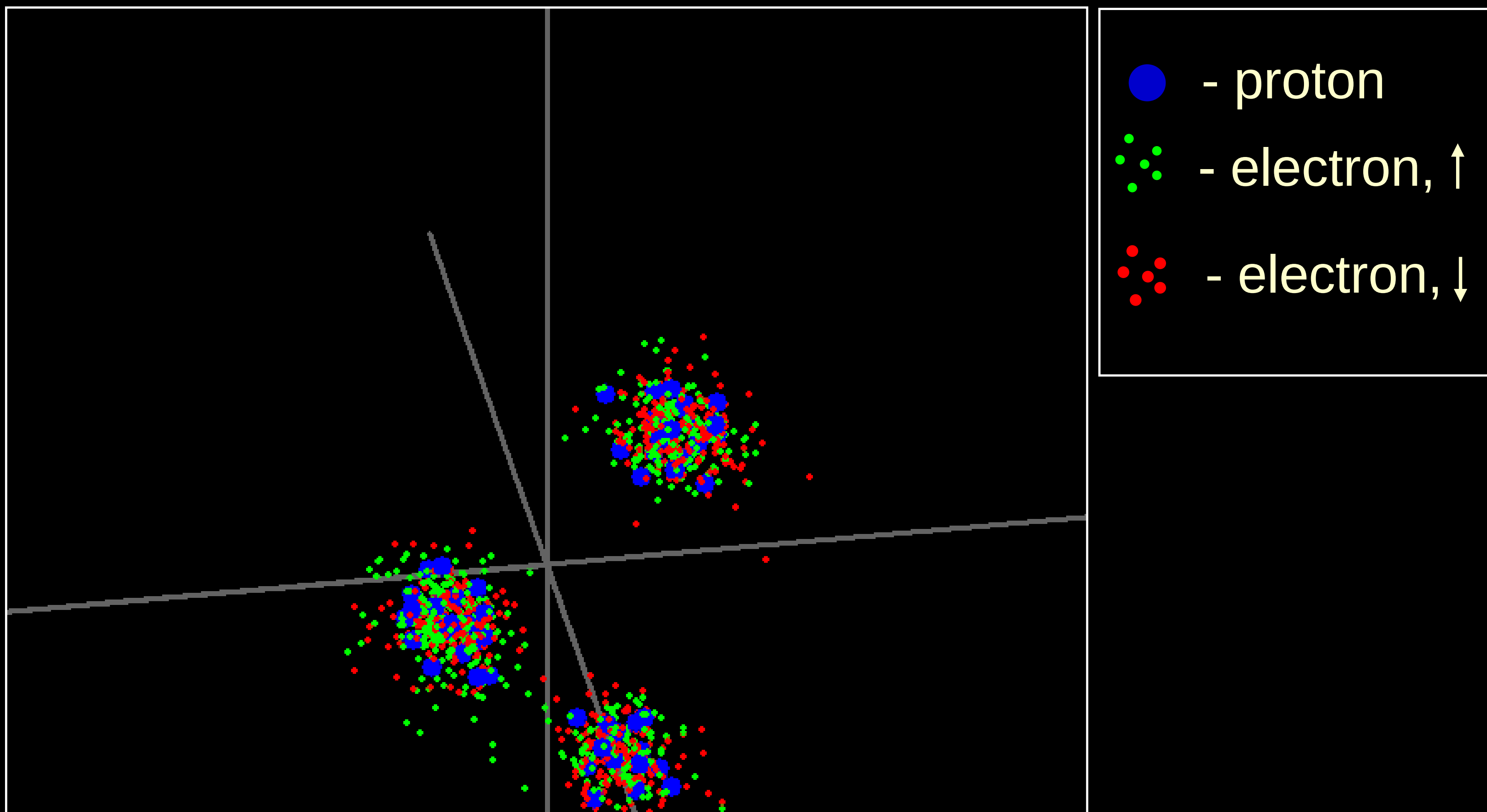
Phase Transition $\Gamma \sim 170$

Квазиизэнтропическое сжатие дейтерия



QUANTUM MONTE-CARLO SIMULATIONS

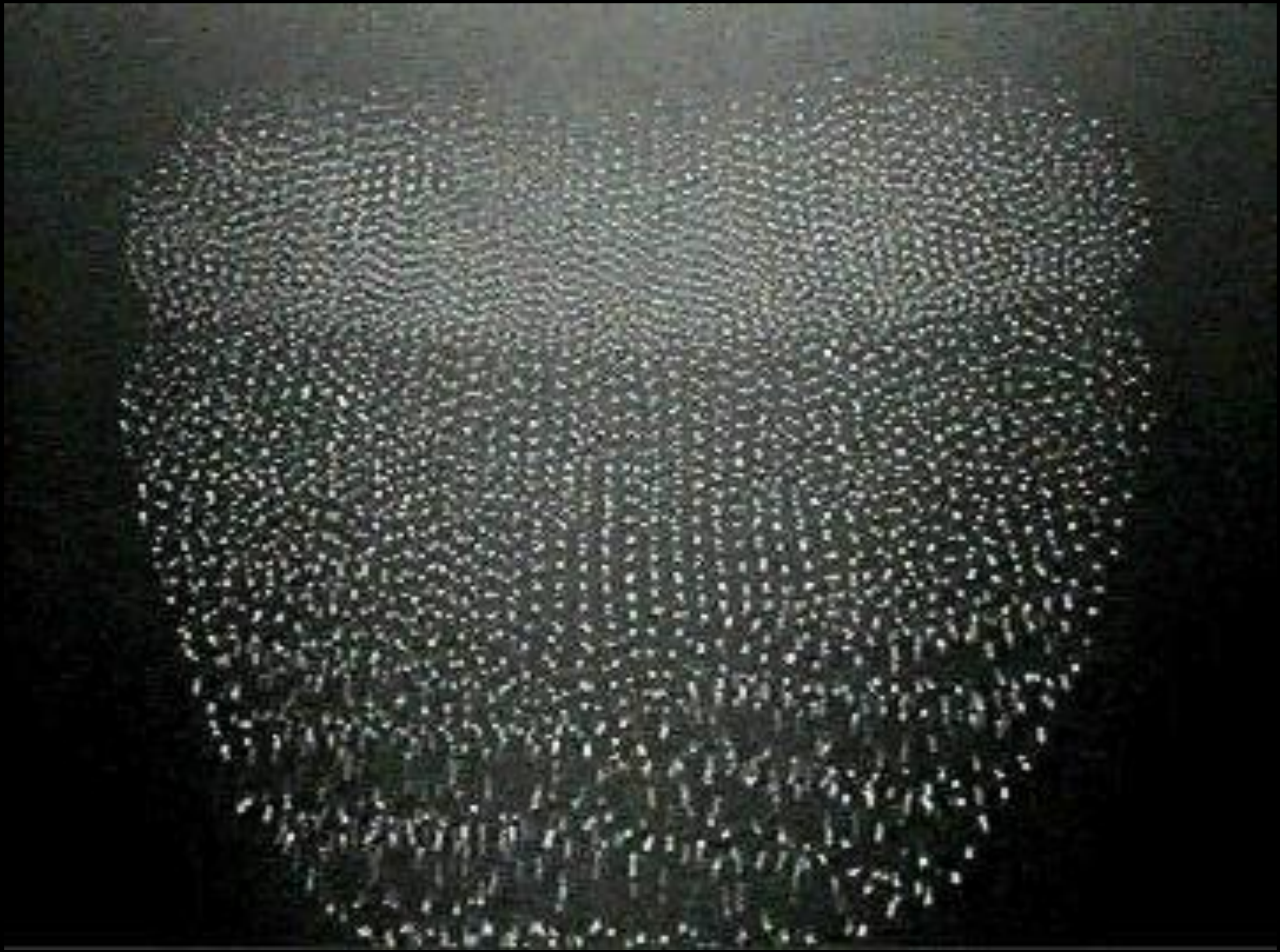
Hydrogen, phase transition



$T = 10000$ K, $n = 3 \cdot 10^{22}$ cm^{-3}, $\rho = 0.05$ g/cm^3

DUST PLASMA STRUCTURES, MOTIONS AND WAVES

CONVECT



CRYSTAL

LIQUID

WAVES

MF particles
Neon gas
∅ = 1.87 μm
P = 0.3 Torr
I = 5 mA

WHAT IS METAL?

Sir Newill Mott:

"I've thought a lot about "what is a metal" and I think one can only answer the question at T = 0 K. Thus a metal conducts and nonmetal doesn't".

Acad. Lev Landau, Ya. Zeldovich:

"A dielectric can be strictly identified from a metal only at the absolute zero temperature".

Prof. Friedrich Hensel :

"The only rigorous criterion for differentiating between a metal and a non-metal is the value of the electrical conductivity at T=0".

Practical Example:

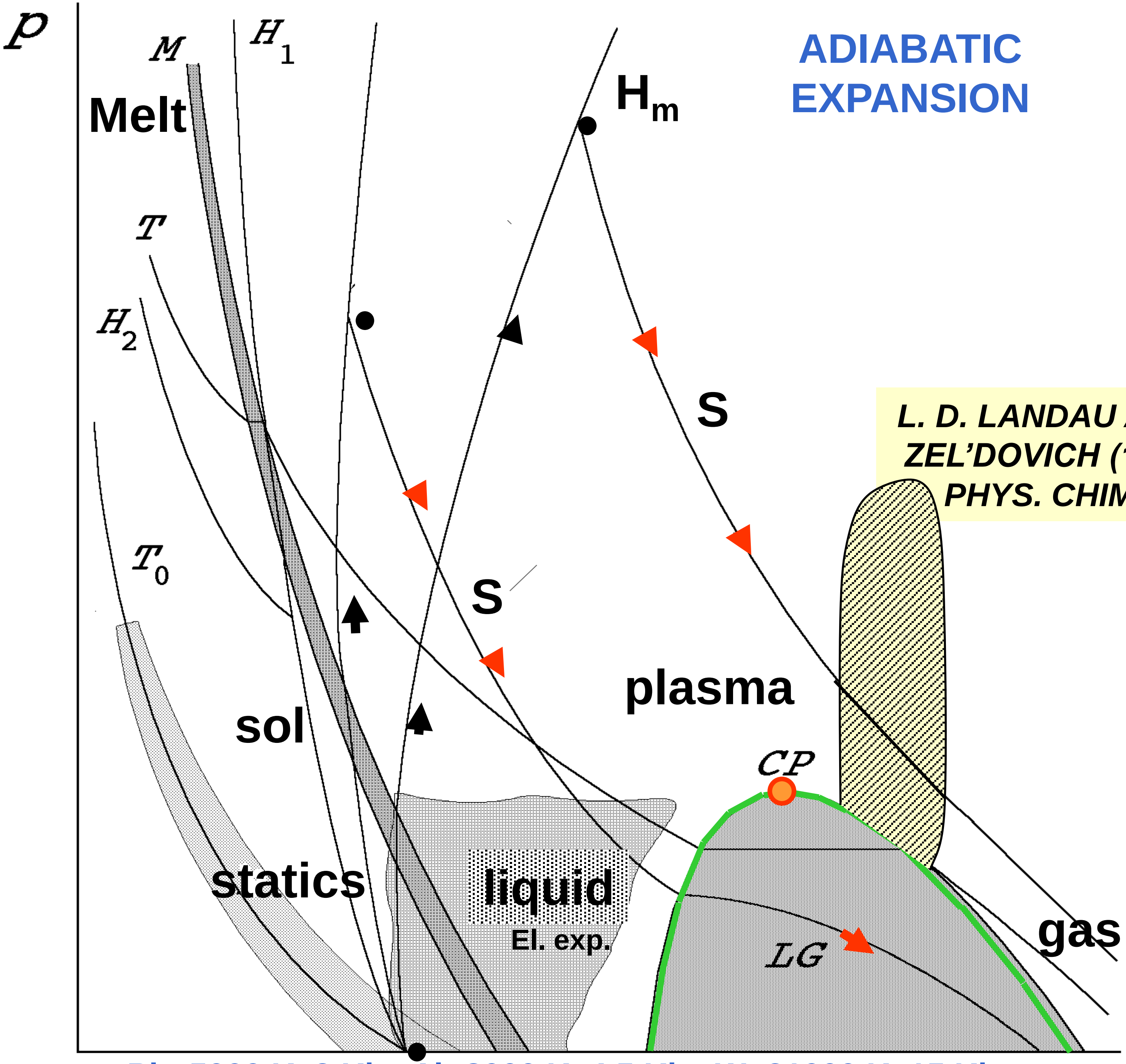
Tokomak plasma:

$n_e \sim 10^{14}$, $T \sim 10^7$ K,

$\sigma_{Tp} \sim 3{\cdot}10^5$ $(\mathrm{Ohm{\cdot}cm})^{-1}$ $\sim 6\sigma_{Pb} \sim 3\sigma_{Fe} \sim \sigma_{Al}$

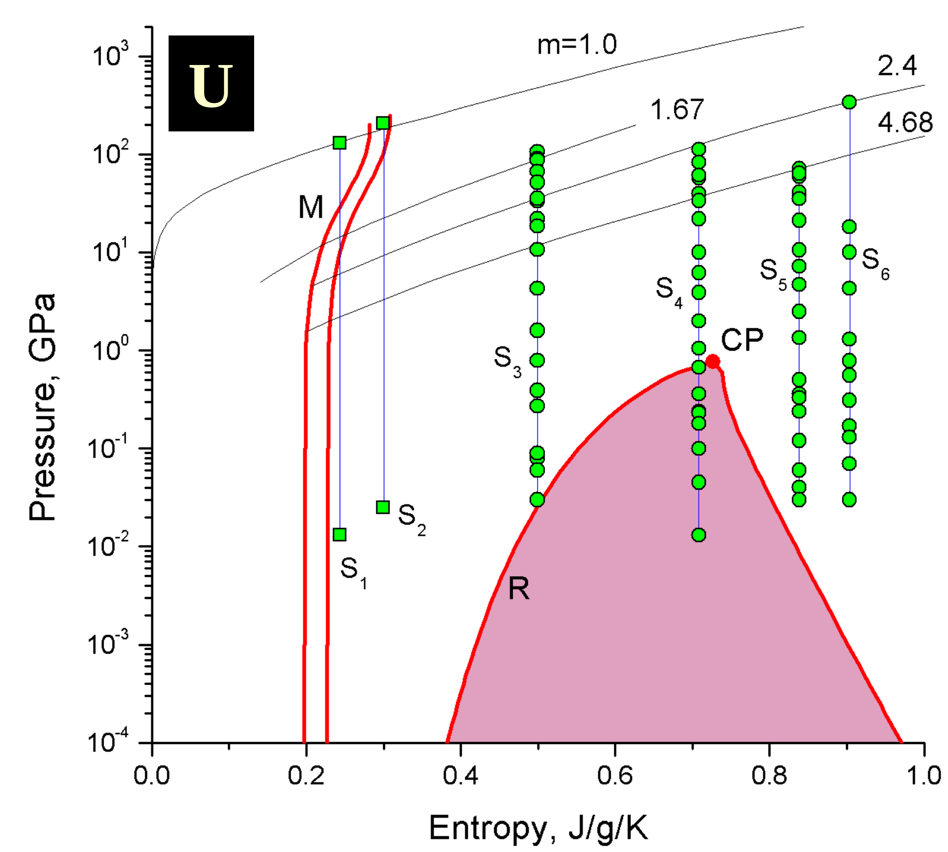
ADIABATIC EXPANSION

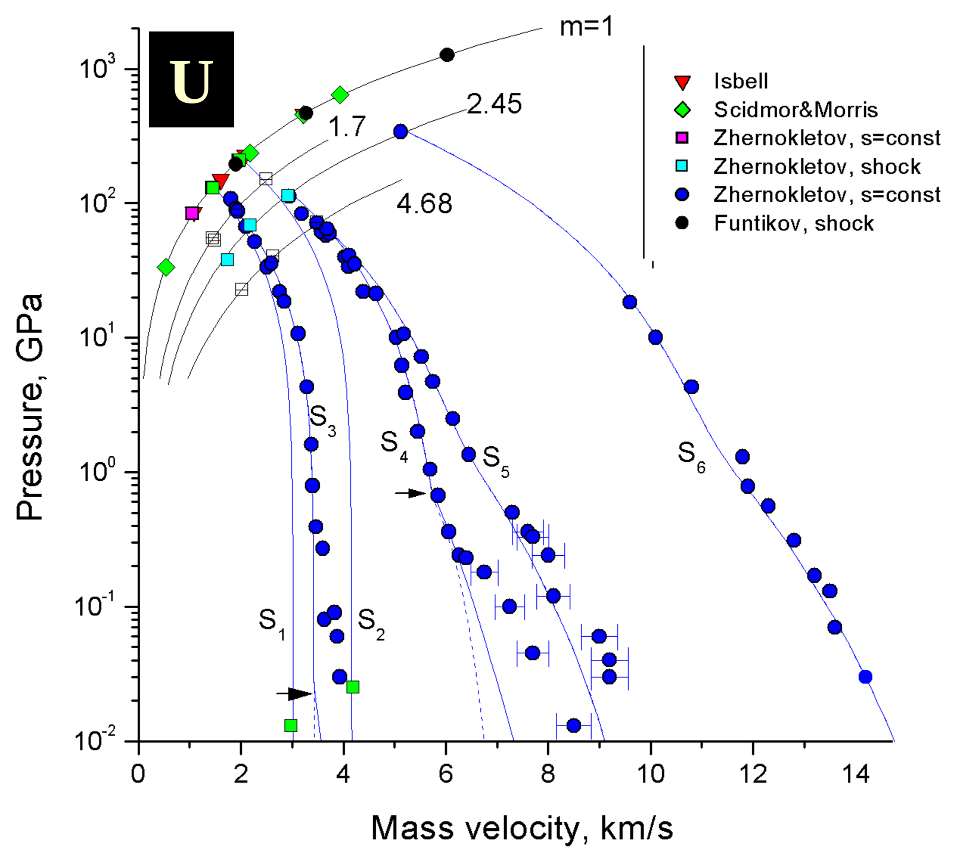
L. D. LANDAU AND Ya. B. ZEL'DOVICH (1943, ACTA PHYS. CHIM. USSR)



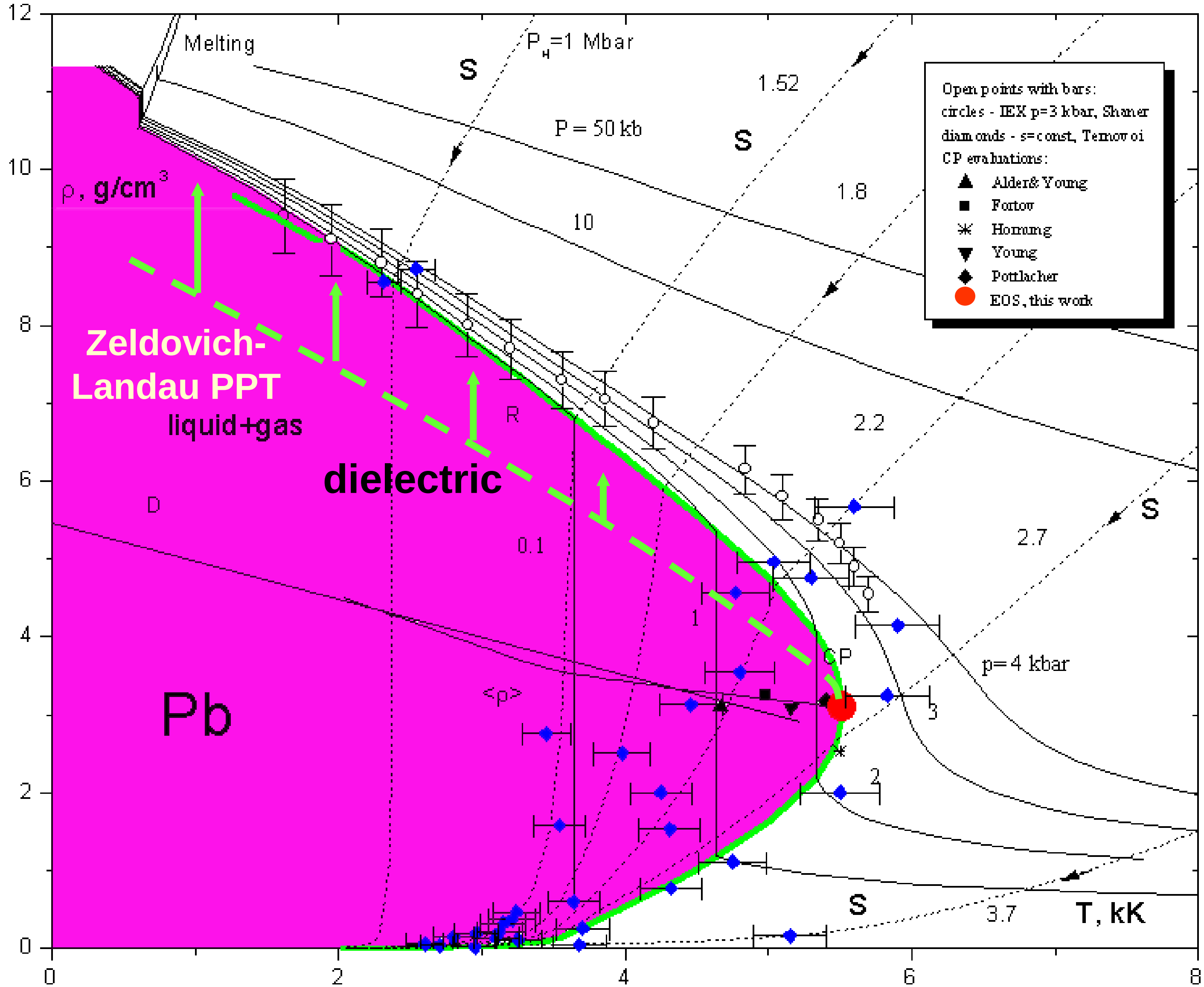
Pb: 5000 K, 2 Kb   Al: 8000 K, 4.5 Kb   W: 21000 K, 15 Kb

ADIABATIC EXPANSION

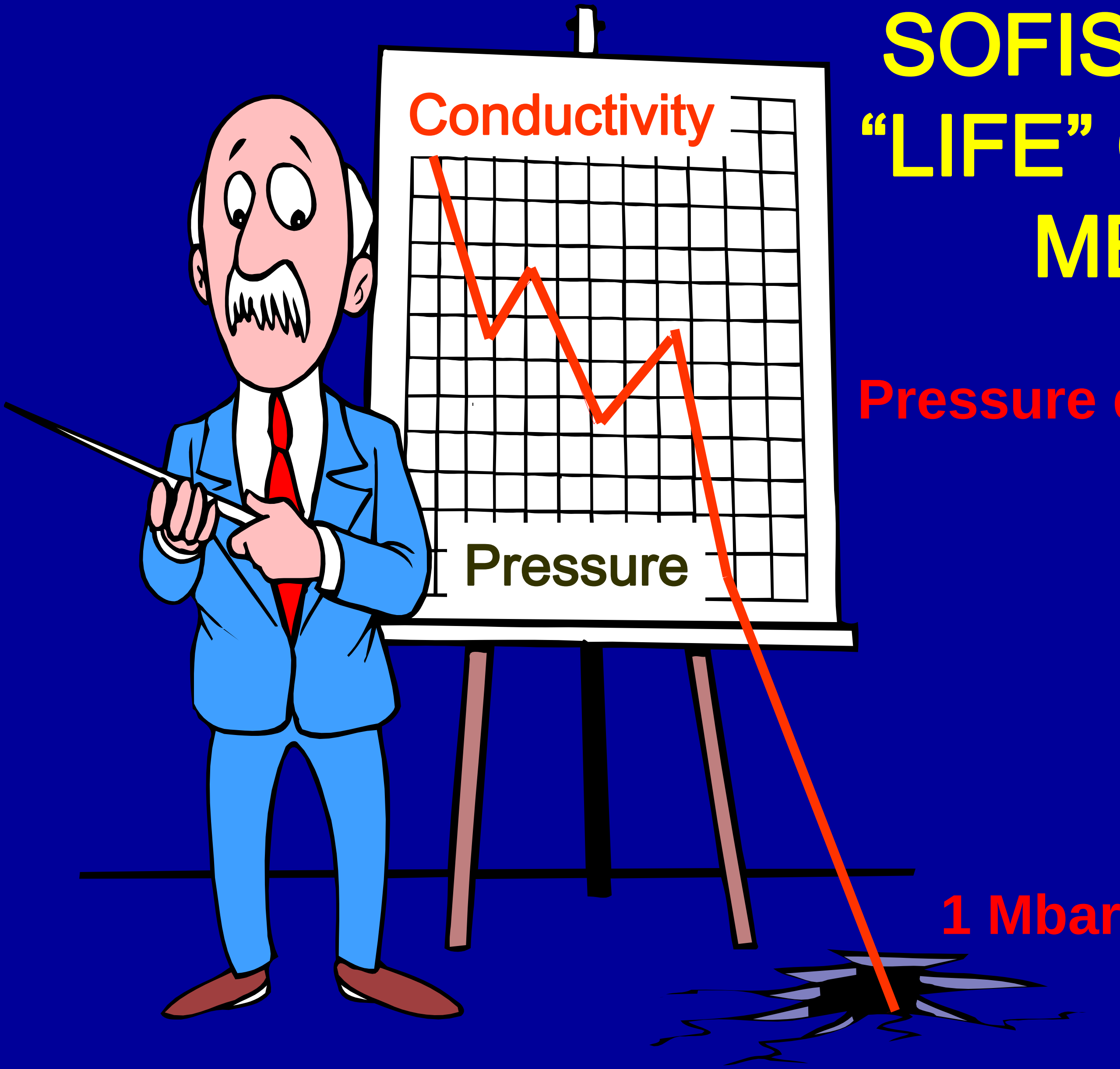




HIGH-TEMPERATURE EVAPORATION



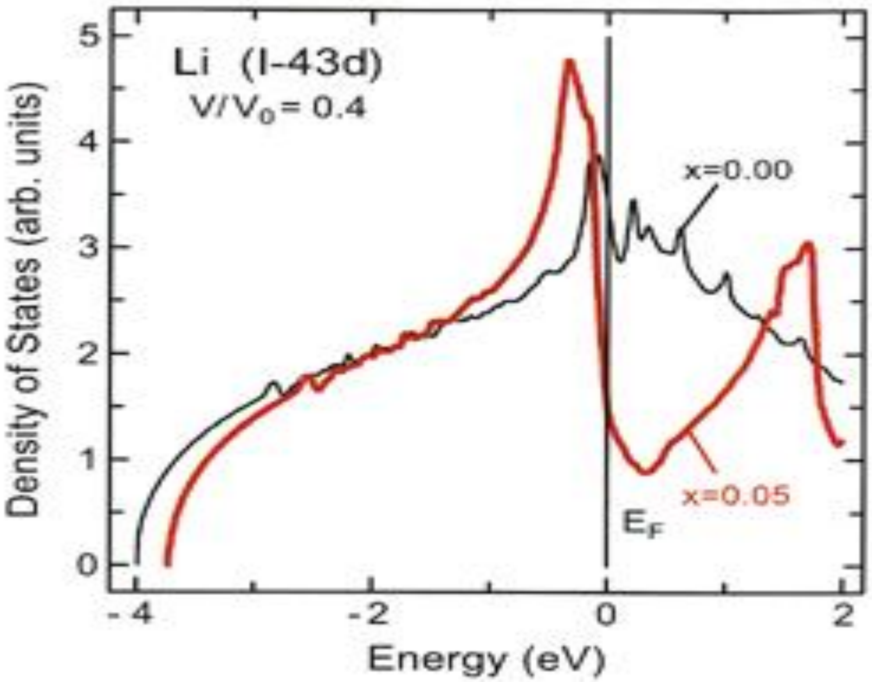
SOFISTICATED "LIFE" OF SIMPLE METALS:

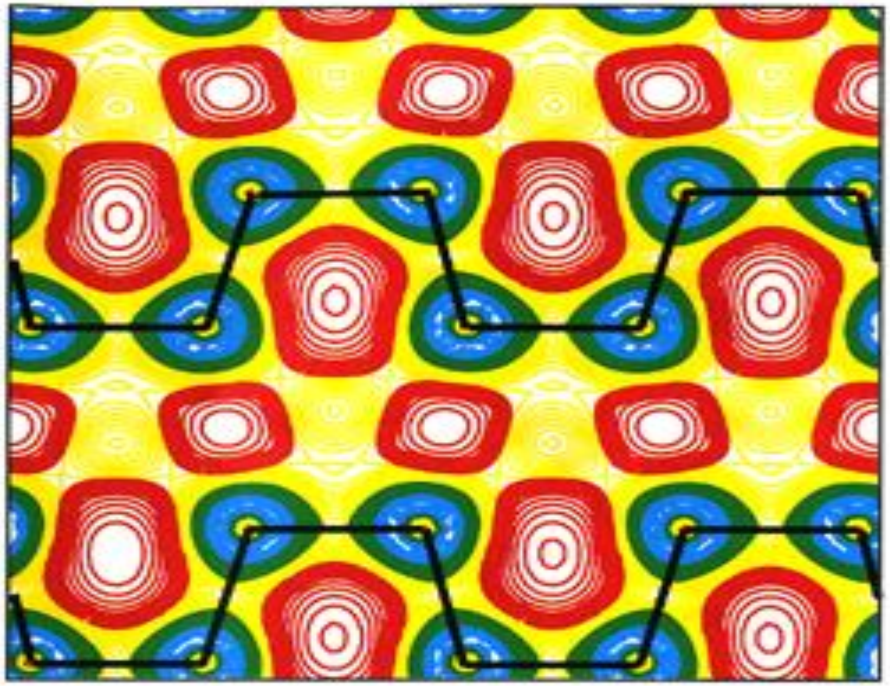


Pressure dielectrisation !!

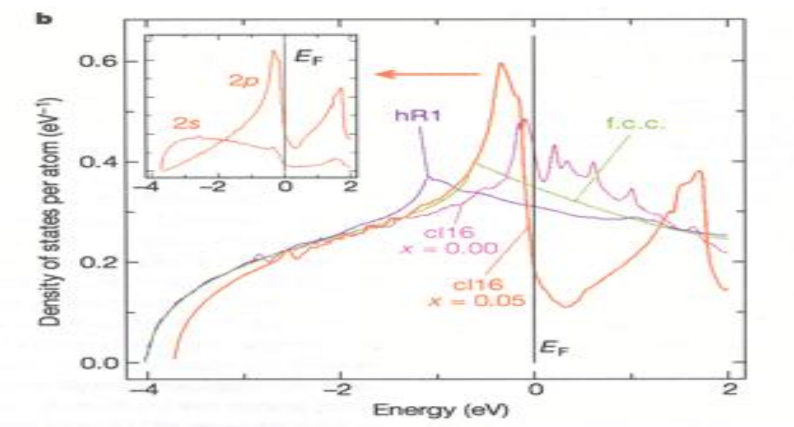
Li at V/V_0 = 0.4, P ~ 48,8GPa

VALENCE ELECTRONS DENSITY DESTRIBUTIONS

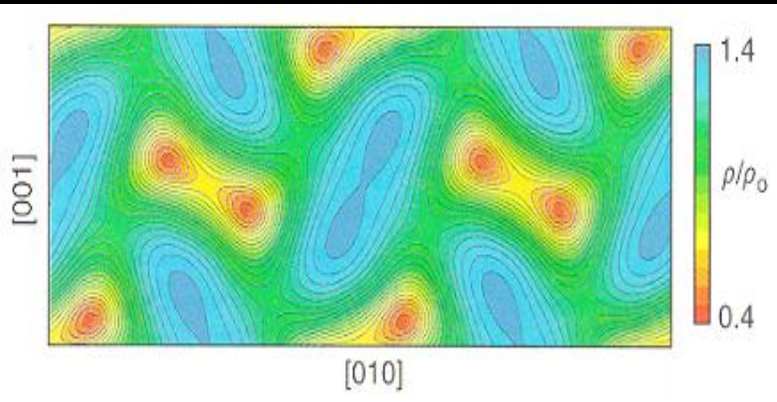




ELECTRONIC DENSITY OF STATES

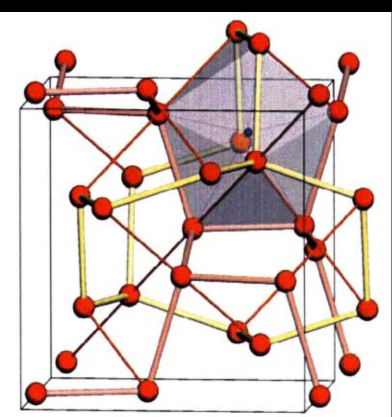


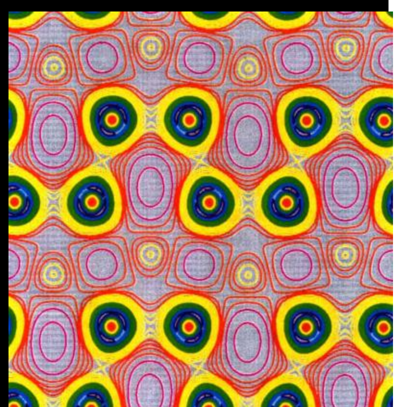
Li AT HIGH PRESSURE



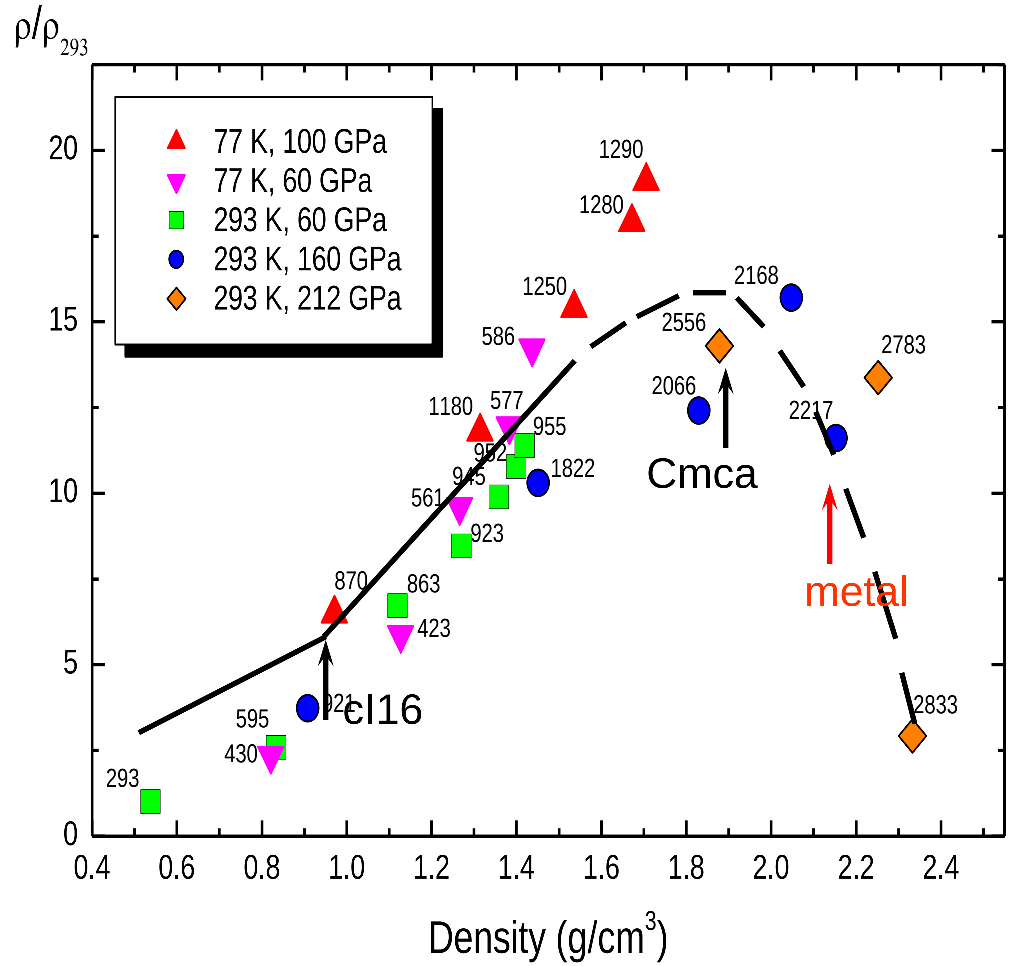
Cmca structure **J. Neaton, N. Ashcroft**

cI16 structure





Hanfland et al.,



Pastnov, Fortov et al.,

bcc → 16GPa → fcc → 41GPa → hR1 → 48GPa → cI16 → 165GPa → Cmca

Hanfland et al.,

Модель УРС $F(V,T)=F_c(V)+F_a(V,T)+F_e(V,T)$

Кристалл

$$F_c^{(s)}(V)=3V_{0c}\sum_{i=1,5}\frac{a_i}{i}\left(\sigma_c^{i/3}-1\right),\qquad \sigma_c=V_{0c}/V$$

$$\sum_{i=1,5}a_i=0\quad \sum_{i=1,5}a_i\,i/3=B_{0c}\quad \sum_{i=1,5}a_i\left(i/3\right)^2=B'_{0c}$$

σ_c=25÷500

$$\Re(x)=\sum_{n=1,N}g_n\left[1-\frac{P_c(a_i,\sigma_n)}{P_c^{TFC}(\sigma_n)}\right]^2+\lambda\sum_{i=1,5}a_i+$$

$$+\mu\left(\sum_{i=1,5}a_i\,i/3-B_{0c}\right)+\nu\left(\sum_{i=1,5}a_i\left(i/3\right)^2-B'_{0c}\right)$$

$$F_a^{(s)}(V,T)=3RT\ln\frac{\theta_c^{(s)}(V)}{T}$$

$$\theta_c^{(s)}(V)=\theta_{0s}\sigma^{2/3}*$$
$$\exp\left\{\frac{\left(\gamma_{0s}-2/3\right)\left(B_s^2+D_s^2\right)}{B_s}arctg\left[\frac{xB_s}{B_s^2+D_s\left(x+D_s\right)}\right]\right\}$$

Жидкость

$$F_c^{(l)}(V)=3V_{0c}\sum_{i=1,5}\frac{a_i}{i}\left(\sigma_c^{i/3}-1\right),\qquad \sigma_c\geq 1$$

$$F_c^{(l)}(V)=V_{0c}\left[A_c\frac{\sigma_c^m}{m}+B_c\frac{\sigma_c^n}{n}+C_c\frac{\sigma_c^l}{l}\right]+E_{sub}\qquad \sigma_c<1$$

$$F_a^{(l)}(V,T)=F_t(V,T)+F_m(V,T)$$

$$F_t^{(l)}(V,T)=c_a(V,T)T\ln\frac{\theta^{(l)}(V,T)}{T}$$

$$c_a(V,T)=\frac{3R}{2}\left[1+\frac{\sigma T_a}{(\sigma+\sigma_a)(T+T_a)}\right]\quad \theta^{(l)}(V,T)=T_{sa}\frac{\left(T_{ca}\theta_c^{(l)}+T\right)\sigma_c^{2/3}}{T_{ca}+T}$$

$$\theta_c^{(l)}(V)=\theta_0^l\exp\left\{\frac{\left(\gamma_{0l}-2/3\right)\left(B_l^2+D_l^2\right)}{B_l}arctg\left[\frac{xB_l}{B_l^2+D_l\left(x+D_l\right)}\right]\right\}$$

$$F_m(V,T)=3R\left\{\frac{2\sigma_m^2T_{m0}}{1+\sigma_m^3}\left[C_m+\frac{2A_m}{5}\left(\sigma_m^{5/3}-1\right)\right]+\left(B_m-C_m\right)T\right\}$$

Модель УРС: электроны

$$F_e(V,T) = -c_e(V,T)T \times \ln\left[1 + \frac{B_e(T)T}{2c_{ei}}\sigma^{-\gamma_e(V,T)}\right]$$

$$c_e(V,T) = \frac{3R}{2}\left[Z + \frac{\sigma_z T_z^2(1-Z)}{(\sigma+\sigma_z)(T^2+T_z^2)}\right]\exp\left[-\frac{\tau_i}{T}\right] \qquad B_e(T) = \frac{2}{T^2}\int\left(\int_0^T \beta(\tau)d\tau\right)dT$$

$$\beta(T) = \beta_i + \left(\beta_0 - \beta_i + \beta_m\frac{T}{T_b}\right)\exp\left[-\frac{T}{T_b}\right] \qquad \tau_i = T_i\exp(-\sigma_i/\sigma) \qquad c_{ei} = \frac{3RZ}{2}$$

$$\gamma_e(V,T) = \gamma_{ei} + \left(\gamma_{e0} - \gamma_{ei} + \gamma_m\frac{T}{T_g}\right)\exp\left[-\frac{T}{T_g} - \frac{(\sigma-\sigma_e)^2}{\sigma\sigma_d}\right]$$

$$T << T_{Fermi} \quad F_e(V,T) = -\frac{\beta_0 T^2}{2}\sigma^{-\gamma_0} \qquad T \to \infty \quad F_e(V,T) = \frac{3RZ}{2}\ln\left(\sigma^{2/3}const/T\right)$$

УРС Al: 3D P-V-T

Hugoniots H_1, H_p: U_s-U_p (P,V,E)

ICE: P(V,S=const)

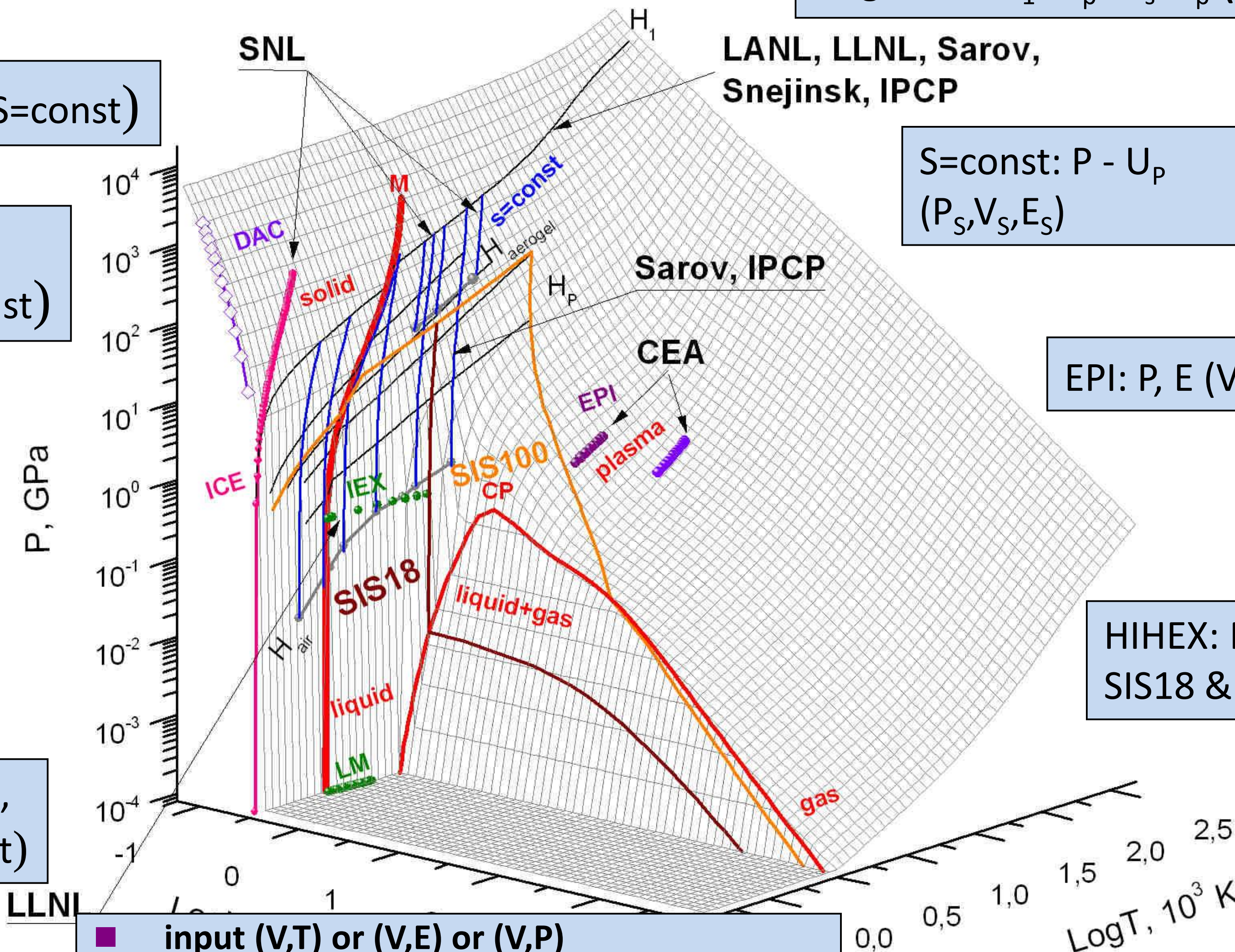
DAC: P(V,T=const)

S=const: P - U_P (P_S,V_S,E_S)

EPI: P, E (V=const)

HIHEX: P, E, T (t) SIS18 & SYS100

IEX: E,V,T,H, Cs (P=const)

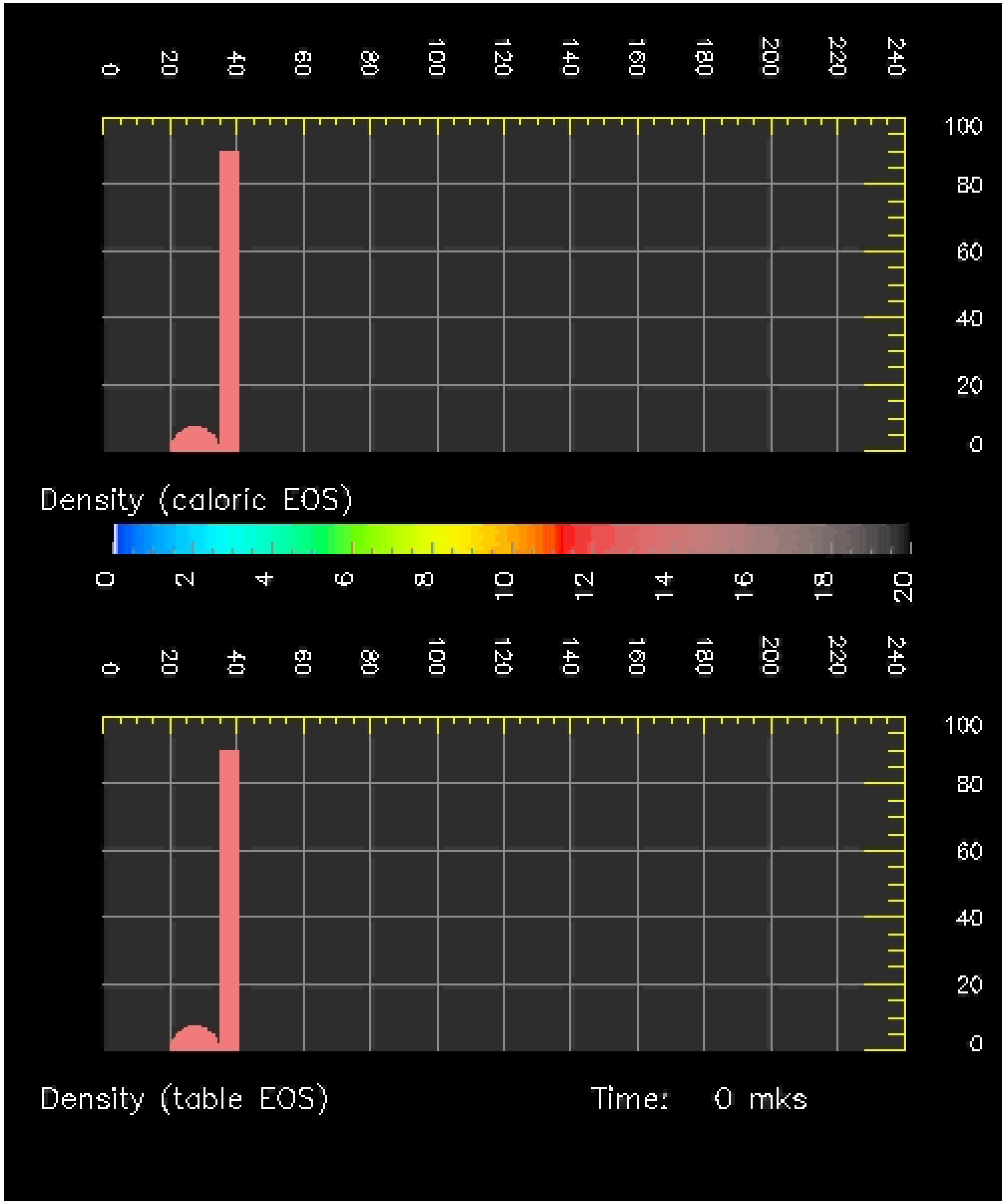


- input (V,T) or (V,E) or (V,P)
- output – all derivatives, P, Cs, …
- grid: to 256x256, linear, logarithm or arbitrary

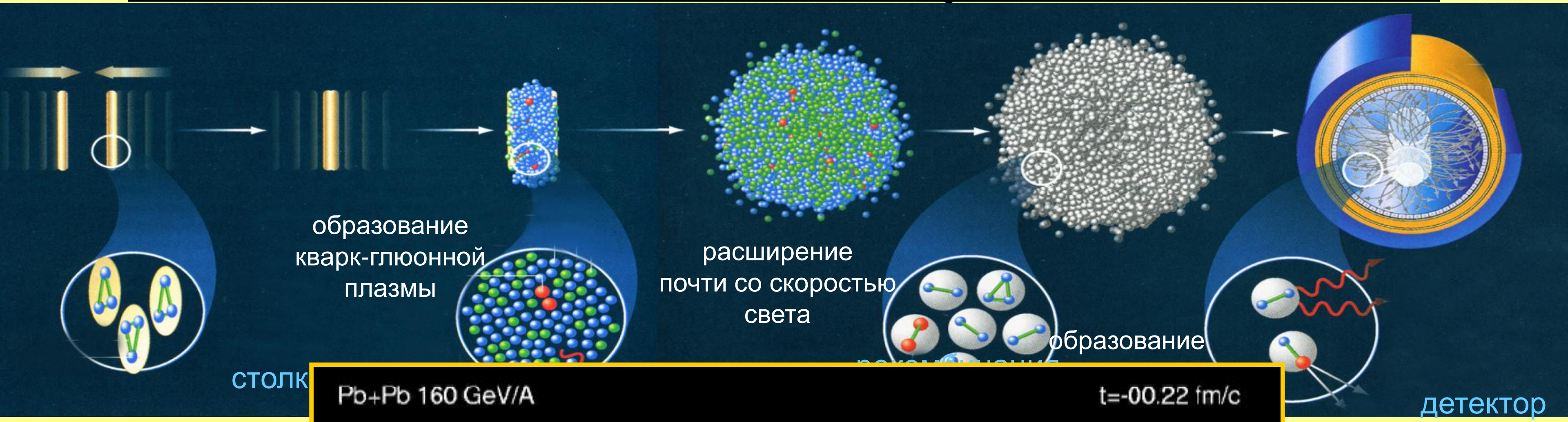
Результаты моделирования: плотность

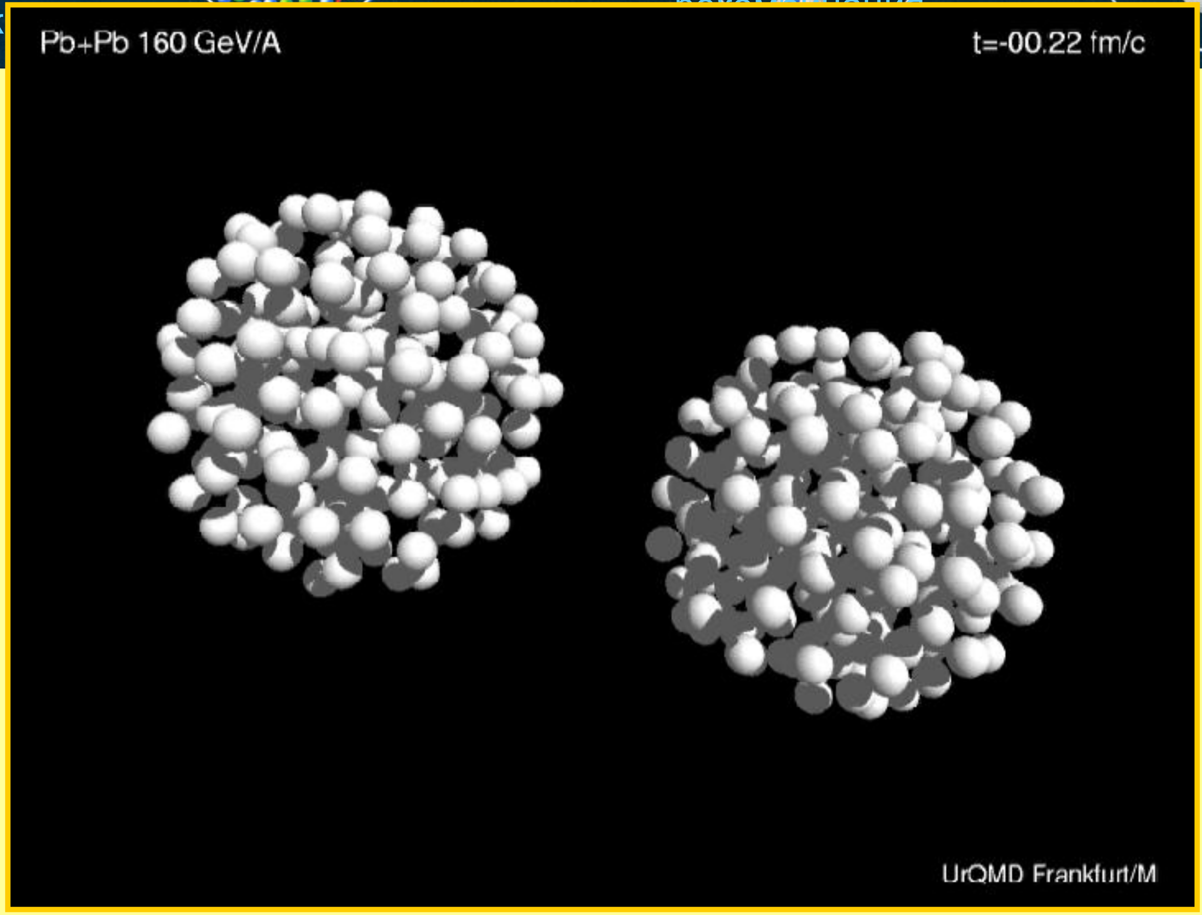
Caloric EOS

Multi-phase EOS



RELATIVISTIC NUCLEAR COLLISIONS:QUARC-GLUON PLASMA

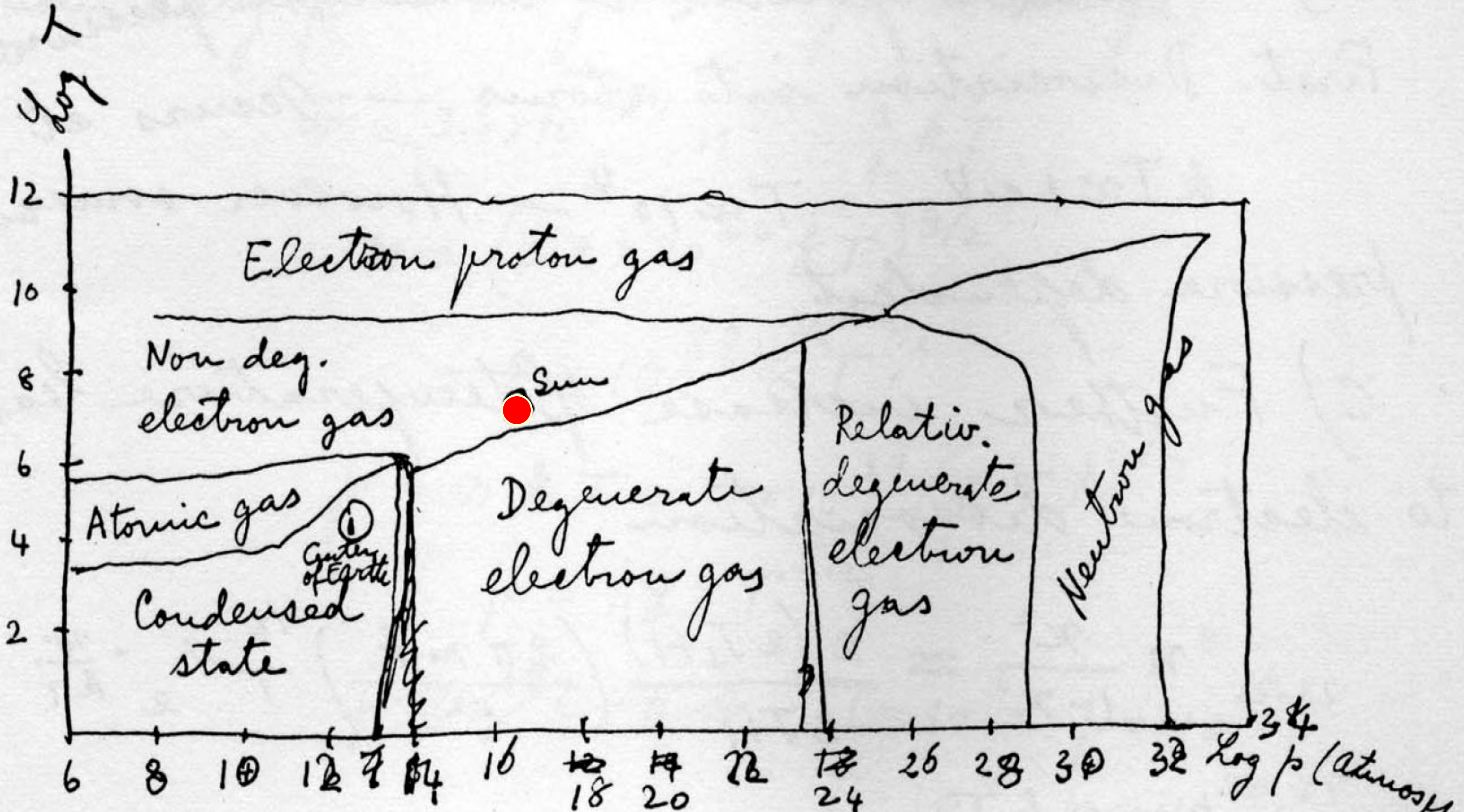




2.10^{7}-7.10^{13} K,
10^{15} g/cc,10^{30} Bar

E.Fermi:Notes on Thermodynamics and Statistics (1953)

70 — Matter in unusual conditions 70 a



Start from ordinary condensed matter with ~~dominant~~ equation of state controlled by ordinary chemical forces.

ФАЗОВАЯ ДИАГРАММА ВЕЩЕСТВА

98% of VISIBLE MATTER-under EXTREME conditions

Я. Б. Зельдович: биография

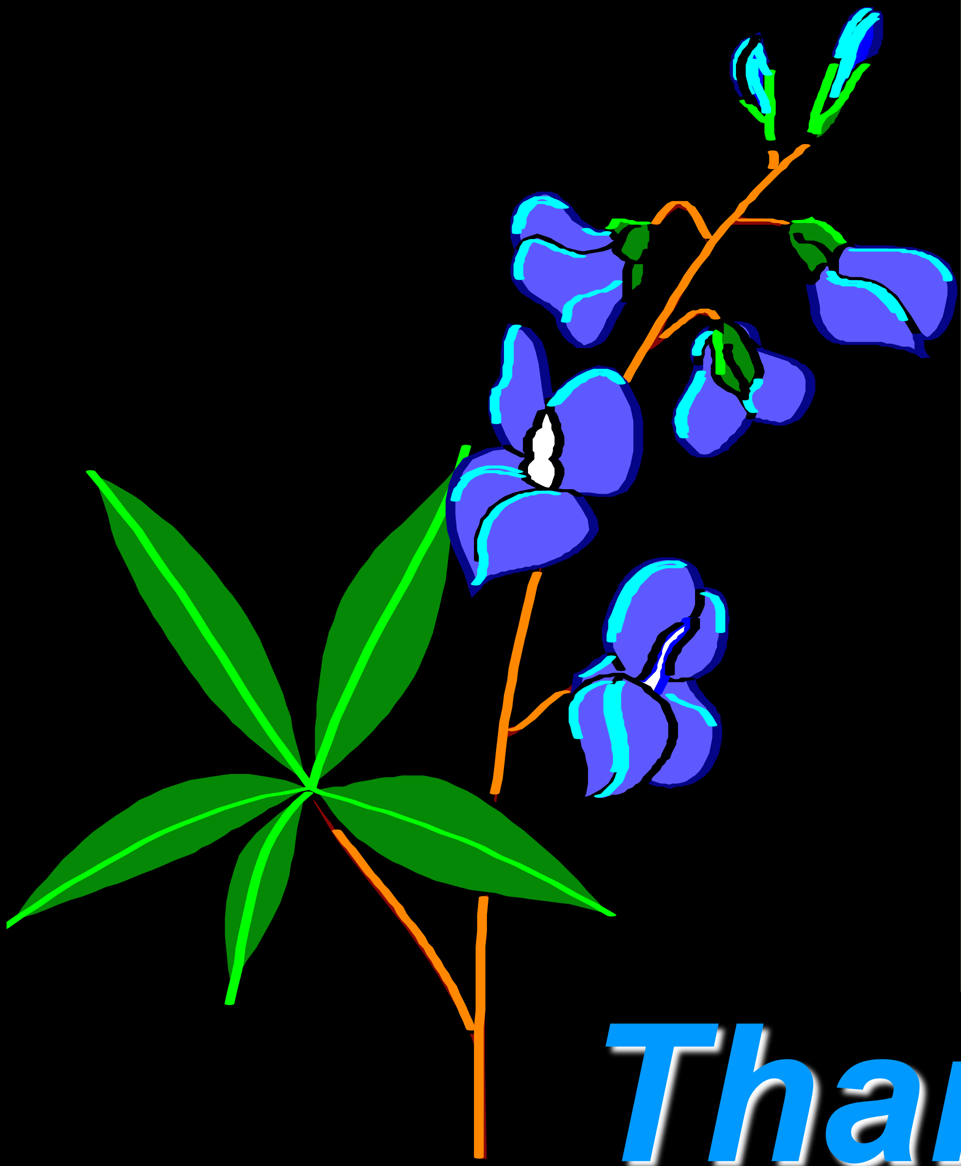
Я.Б.Зельдович, А.Д.Сахаров и Д.А.Франк-Каменецкий, Саров, 1952 г.

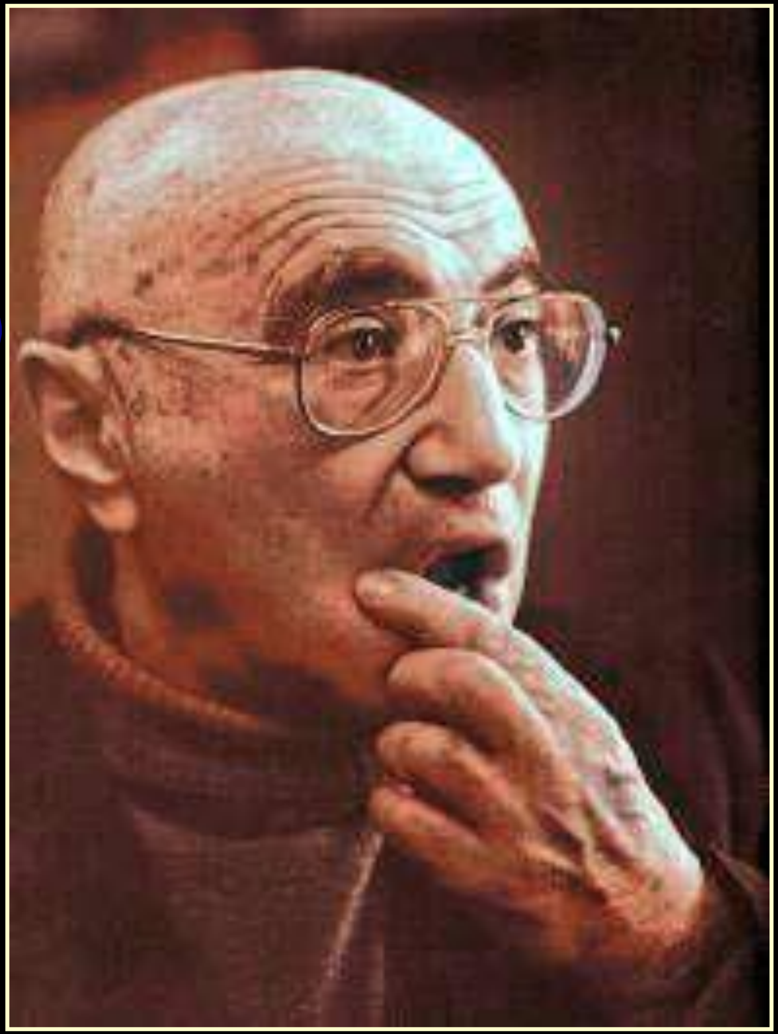
С сыном Борисом, 1954г.

1960 г.

Я.Б.Зельдович, Ю.Б.Харитон и Н.Н. Семенов на юбилее ИХФ АН ССР, Москва, 1976 г.

Я.Б.Зельдович и Ю.Б.Харитон на общем 150 летнем юбилее (80 лет ЮБ и 70 лет ЯБ), Москва, ИХФ АН СССР, 1984 г.





Thank You...