XXXVI INTERNATIONAL CONFERENCE ON INTERACTION OF INTENSE ENERGY FLUXES WITH MATTER
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IIEFM 2021

Thermodynamics of non-ideal plasma in the SAHA model

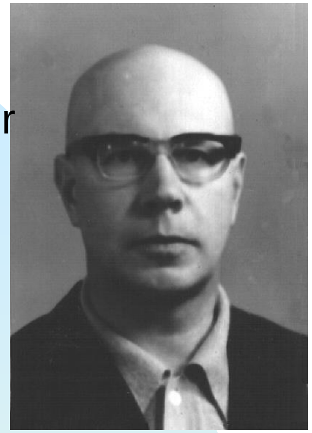
V.K.Gryaznov, I.L.Iosilevskiy, A.N.Ivanova, A.N.Starostin

Institute of Problems of Chemical Physics RAS
Joint Institute for High Temperature RAS
SRC RF Troitsk Institute for Innovation and Fusion Research

Development of a gas-phase nuclear reactor

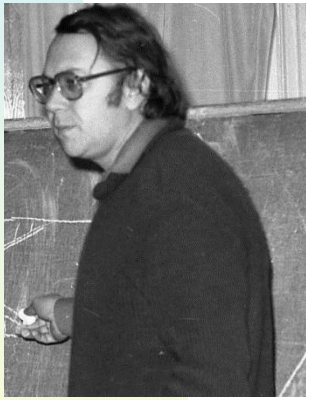
(1950-1980)

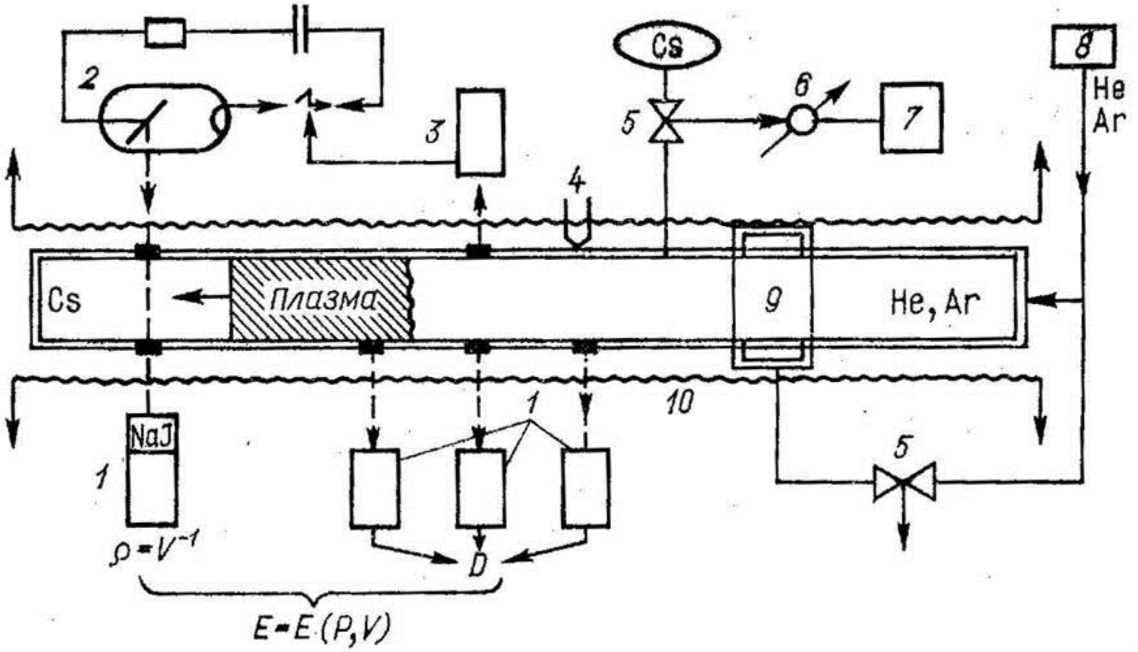
corr.-member
AS USSR



V.M.Ievlev

Heated Shock Tube



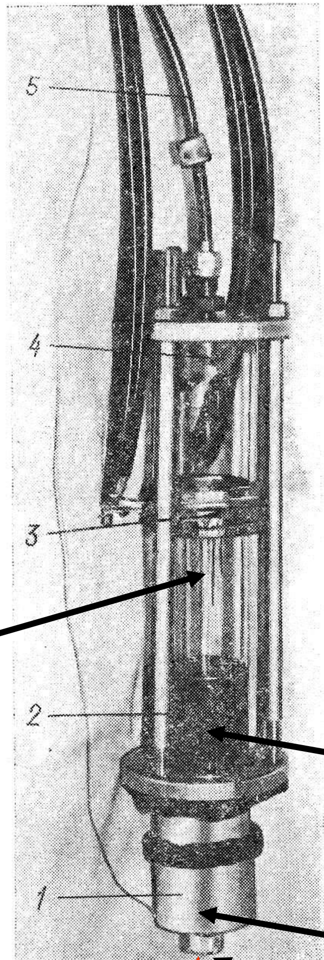


B.N.Lomakin

V.E.Fortov

Схема подогреваемой ударной трубы:
1 — ФЭУ с катодным повторителем; 2 — рентгеновская трубка; 3 — схема импульсной рентгенографии; 4 — термопары; 5 — кран; 6 — вакуумметр; 7 — вакуумные насосы; 8 — компрессор; 9 — мембраны; 10 — обмотка обогревателя

ICP(Branch) AS USSR. Explosive Shock Tube



Фотография взрывной ударной трубы:
1 — детонационная линза; *2* — заряд ВВ; *3* — кольцо-вставка с электроконтактными датчиками и окном для рентгеновских измерений; *4* — зеркало для оптических регистраций; *5* — трубка для подачи газа

Ar, Xe, Ne

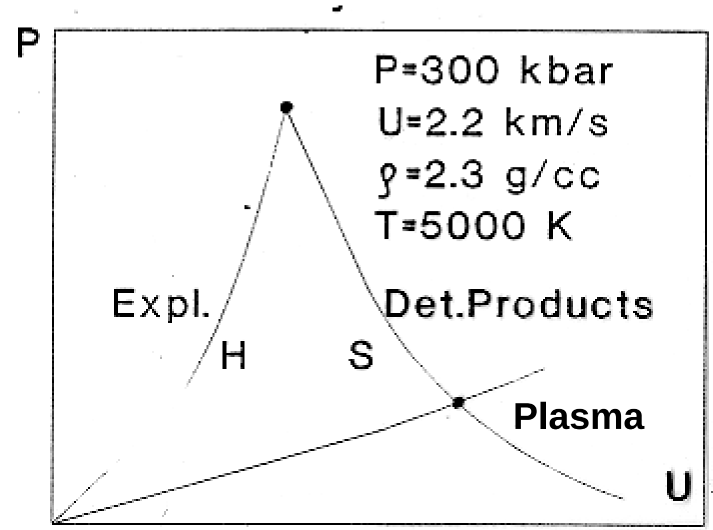
High Explosive Charge

Lens

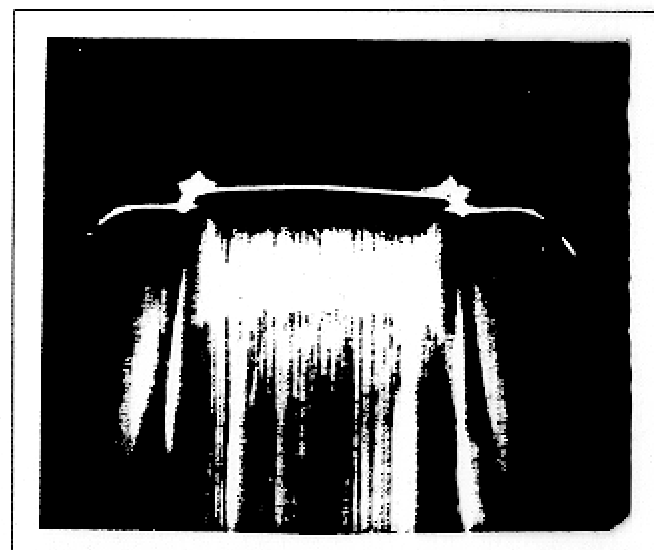
Detonator

Energy ~ 3MJ

Power ~ 100 GW



Shock Front Curvation



ПМТФ, № 3, 1973

УДК 533.951 : 533.6.011.72.001.24

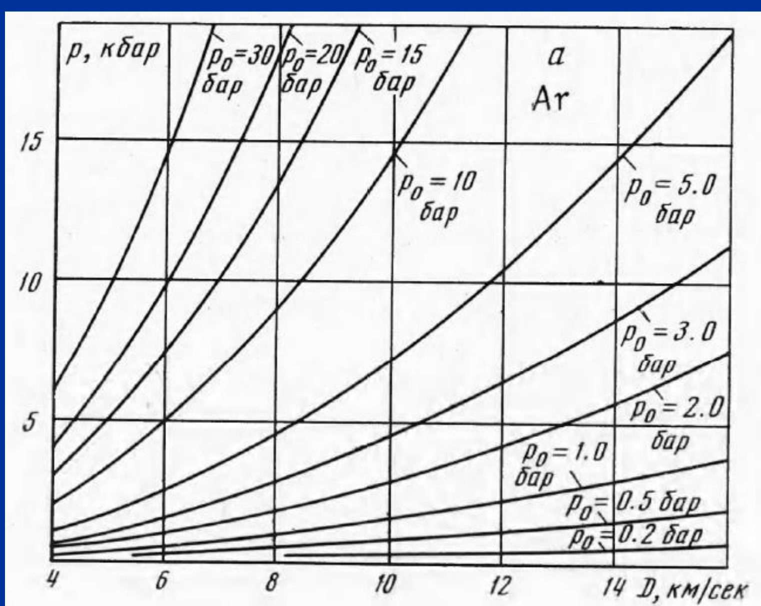
РАСЧЕТ УДАРНЫХ АДИАБАТ АРГОНА И КСЕНОНА

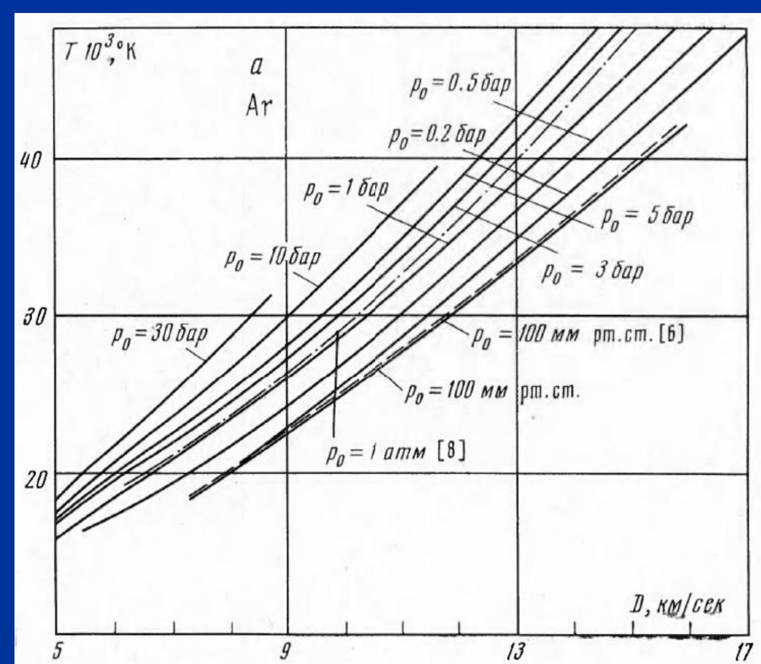
В. К. Грязнов, И. Л. Иосилевский, В. Е. Фортов
(Москва)

$$D = V_0 \left(\frac{P - P_0}{V_0 - V} \right)^{1/2}$$

$$u = [(P - P_0)(V_0 - V)]^{1/2}$$

$$H - H_0 = {}^1/_2 (P - P_0)(V_0 + V)$$





Quasi-chemical representation for describing the thermodynamics of high-temperature highly compressed media

High temperature highly compressed media:

mixture of ***L*** components

electrons, atoms, molecules, ions

(atomic and molecular)

Given:

volume ***V***, temperature ***T***

and the number of nuclei K of chemical elements

$$F \equiv F_i^{(id)} + F_e^{(id)} + F_{ii,ie,ee,...}^{(int)}$$

Quasi-chemical representation

Thermodynamic equilibrium conditions

$$F(\{n_i\}, V, T) \xrightarrow[\{n_j\}]{} \min$$

$$\sum_{j=1}^{L} \nu_k^j N_j = N_k^0; \quad k = 1, 2, \ldots, K+1$$

$$\sum_{j=1}^{L} \left(\frac{\partial F}{\partial N_j} \right)_{V,T} dN_j = 0; \quad \frac{\partial F}{\partial N_j} = \mu_j$$

Equilibrium equations

Chemical picture. Applicability problem

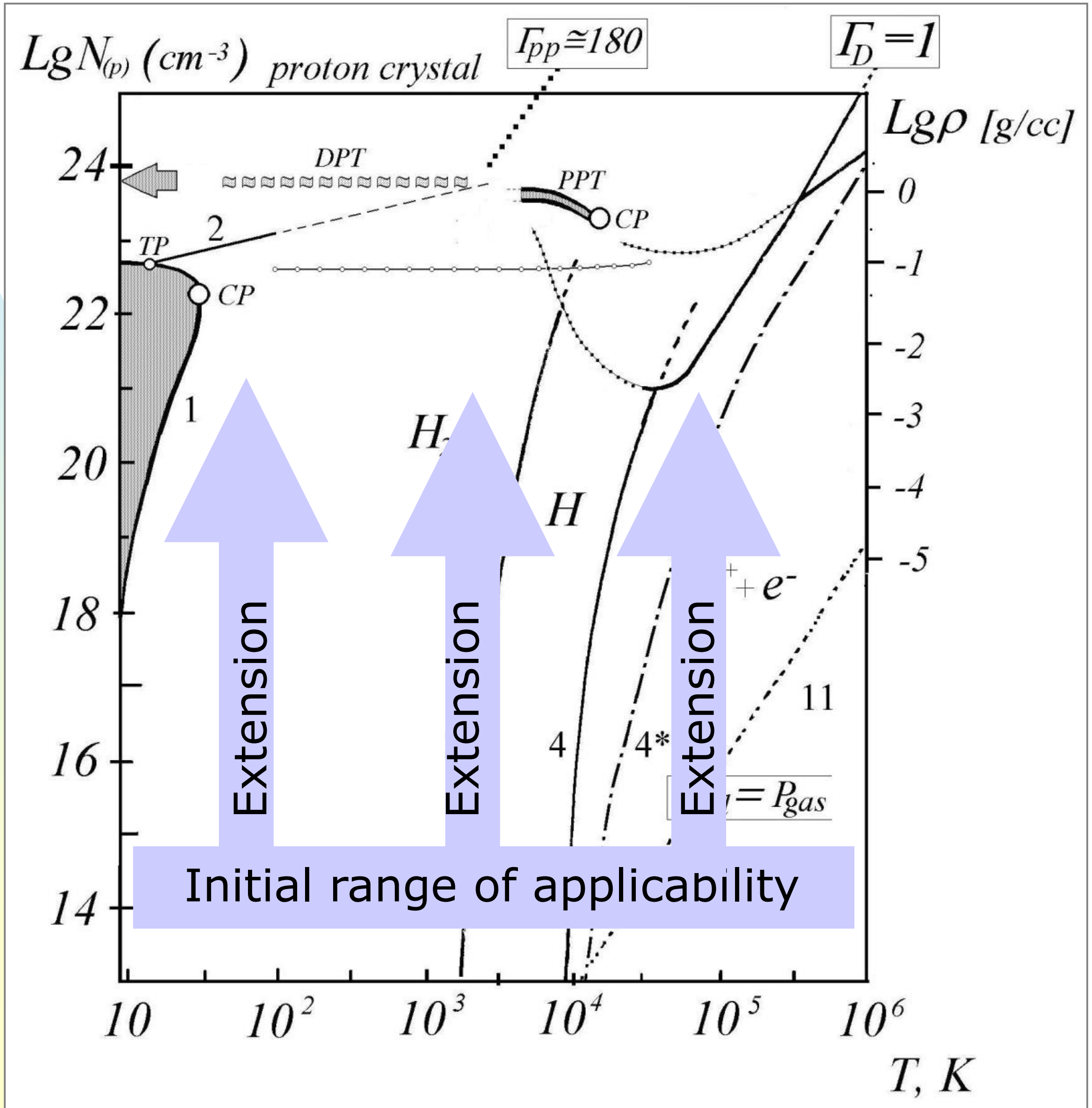
Coulomb non-ideality

Short-range repulsion

Short-range attraction

Electron degeneracy

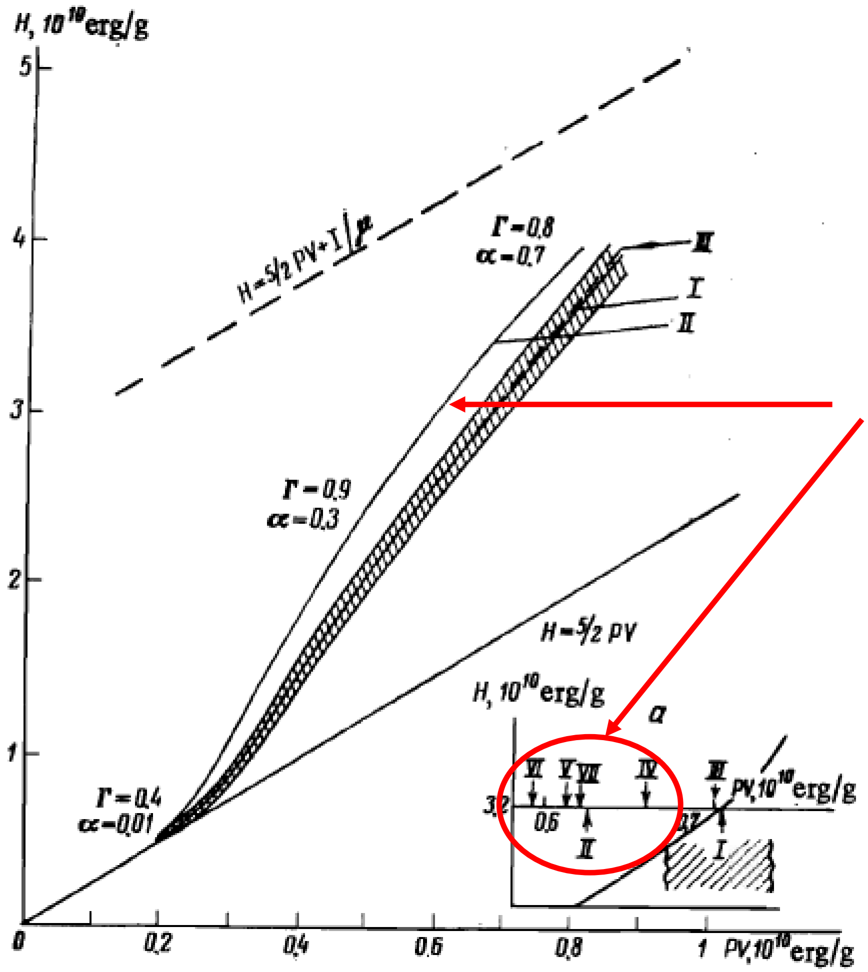
Hydrogen phase diagram



Confined Atom Model

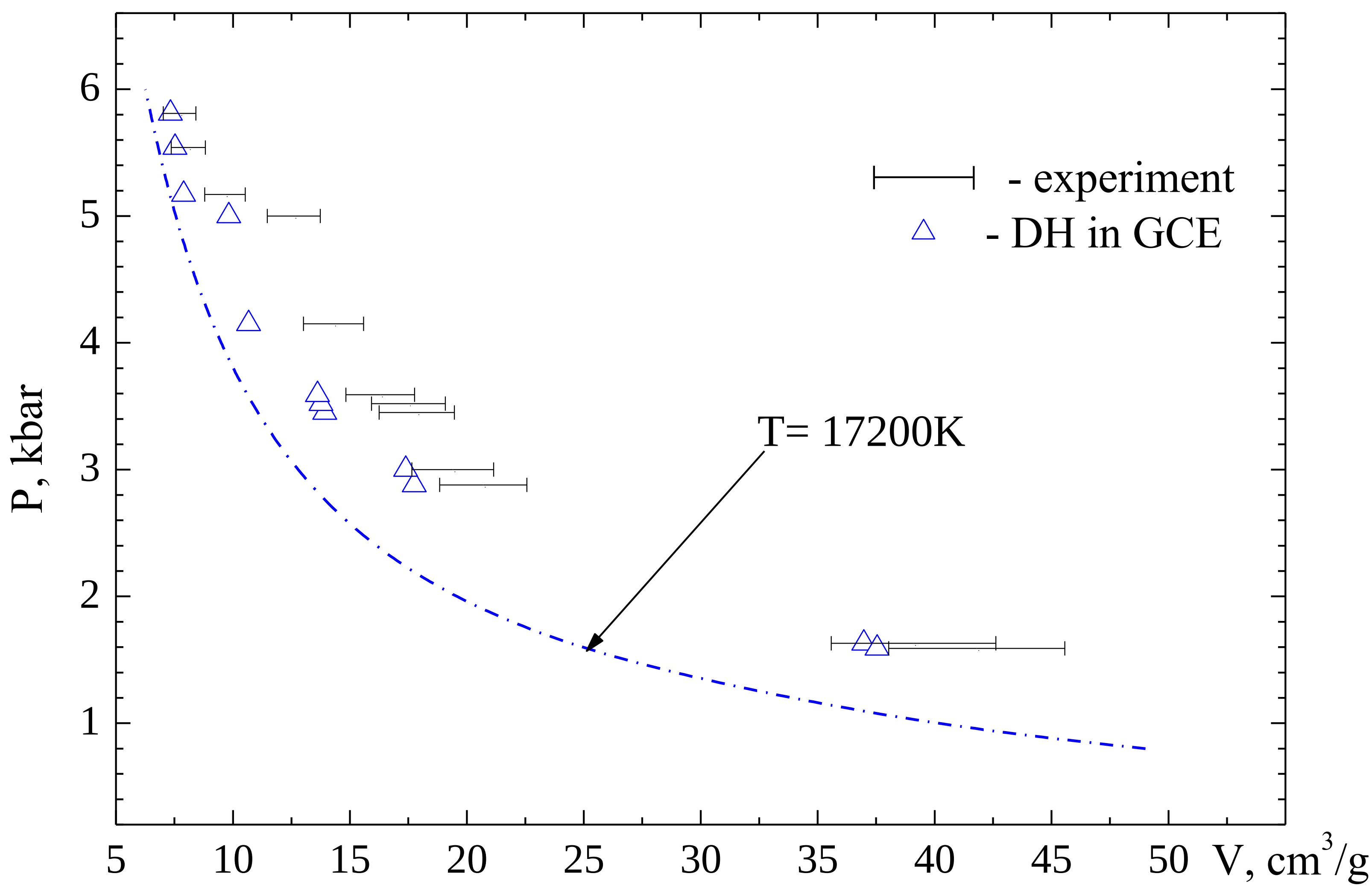
Thermodynamics of nonideal cesium plasma

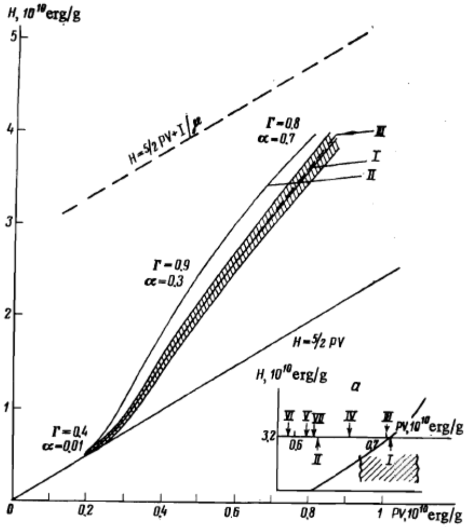
A. V. Bushman, B. N. Lomakin, V. A. Sechenov, V. E. Fortov, O. E. Shchekotov, and I. I. Sharipdzhanov

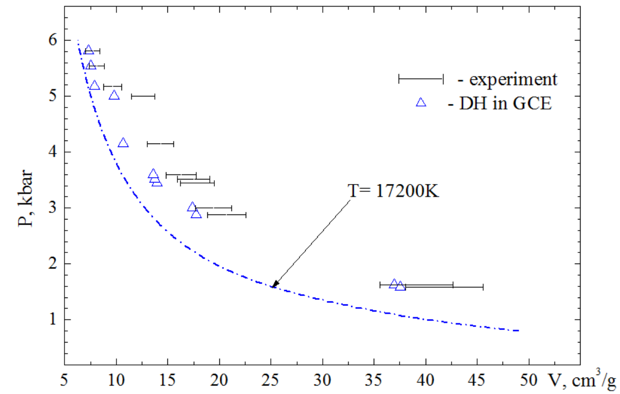


It is possible that an appreciable decrease of the energy contribution of the bound states to the enthalpy, together with the decrease of the correction for the interaction of the free charges in the equation of state, is due to the deformation and to the distortion of the energy levels at high densities. A quantitative description of this phenomenon calls for complicated self-consistent quantum-mechanical calculations [16] with introduction of special assumptions concerning the character of the interparticle interaction in the system.

Argon thermal equation of state



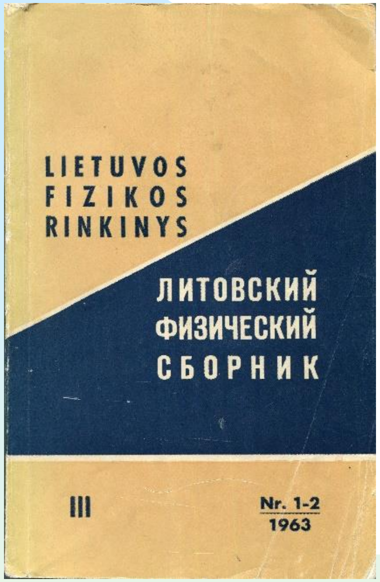




Confined atom model idea

Non-ideal plasma chemical picture

Hartree-Fock calculation of atomic structures



III LIETUVOS FIZIKOS RINKINYS 1—2
ЛИТОВСКИЙ ФИЗИЧЕСКИЙ СБОРНИК
1963

РАСЧЕТЫ ЭЛЕКТРОННЫХ ОБОЛОЧЕК НЕКОТОРЫХ АТОМОВ ПО МЕТОДУ ХАРТРИ—ФОКА

А. В. ИВАНОВА, А. Н. ИВАНОВА, А. И. ПРИХОЖЕНКО,
И. И. ПЯТЕЦКИЙ-ШАПИРО, Б. Л. ТАРНОПОЛЬСКИЙ

В связи с задачей расчета поперечных сечений фотоионизации некоторых легких атомов выполнен ряд расчетов волновых функций по методу Хартри—Фока на электронной машине. В статье излагается методика расчета волновых функций в основном и возбужденных состояниях и волновых функций непрерывного спектра.

Canadian Journal of Physics
Volume 41, Number 11
November 1963

←Previous Next→

Canadian Science Publishing

NUMERICAL SOLUTION OF THE HARTREE–FOCK EQUATIONS

Charlotte Froese

Vol. 41 • No. 11 • pp. 1895–1910

Procedures for solving the Hartree–Fock equations on an automatic computer such as the IBM 7090 are described. Particular attention is given to the question of numerical accuracy and to the problem of devising automatic procedures.

Calculation of compressed atomic structures by the Hartree-Fock method

The variational principle of quantum mechanics

$$E_{\Psi} = \left(\Psi, \hat{H}\Psi\right) = \int \Psi^{*} \hat{H} \Psi \, d\boldsymbol{x}_1 \ldots d\boldsymbol{x}_N \Rightarrow min$$

For the Hamiltonian

$$\hat{H} = -\sum_{i=1} \left[\frac{1}{2} \Delta_i + \frac{Z}{r_i} \right] + \sum_{i<j} \frac{1}{\left| \vec{r}_i - \vec{r}_j \right|}$$

under conditions

$$\int \left| \Psi \right|^2 d\boldsymbol{x}_1 \ldots d\boldsymbol{x}_N = 1; \qquad \boldsymbol{x}_i = \left(\boldsymbol{r}_i \delta_i \right)$$

Wave function in the Hartree-Fock approximation (RHF)

$$\Psi = \sum_i C_i \Phi_i$$

$$\hat{L}^2 \Psi = L(L+1)\Psi$$

$$\hat{S}^2 \Psi = S(S+1)\Psi$$

$$\Phi_i = \frac{1}{N!} \begin{vmatrix} \varphi_{i_1}(\vec{x}_1) \ldots & \varphi_{i_1}(\vec{x}_N) \\ \varphi_{i_2}(\vec{x}_1) \ldots & \varphi_{i_2}(\vec{x}_N) \\ \ldots\ldots & \ldots\ldots \\ \varphi_{i_N}(\vec{x}_1) \ldots & \varphi_{i_N}(\vec{x}_N) \end{vmatrix}$$

$$\varphi_i(\vec{x}) = R_{n_i l_i}(r) Y_{l_i}^{m_i}(\theta, \varphi) \chi_i(\delta)$$

$$R_{nl}(r) = \frac{f_{nl}(r)}{r}$$

$\{nl\} = 1s^2\ 2s^2\ 2p^6\ 3s^2\ 3s^2\ 3d^2 \ldots$

Calculation of compressed atomic structures by the Hartree-Fock method

Hartree-Fock system of integro-differential equations

$$\left[\frac{d^2}{dr^2}+V_{nl}(r)-\lambda_{nl}\right]f_{nl}(r)+x_{nl}(r)-\sum_{n'l'\neq nl}\frac{1}{q_{nl}}\lambda_{nl,n'l'}\delta_{l,l'}f_{n'l'}(r)=0$$

$$x_{nl}(r)=-\sum_{\substack{n'l'\in f+g\\ n'l'\neq nl}}\frac{2b_k(nl,n'l')}{q_{nl}}f_{n'l'}(r)\int_0^\infty U_k(r,r')f_{nl}(r')\hat{f}_{n'l'}(r')dr'$$

λ_{nl} u $\lambda_{nl,n'l'}$ are determined from the orthonormality conditions

$$\int_0^\infty f_{nl}(r)f_{n'l'}(r)dr=\delta_{nn'}$$

Solution method - iterative self-consistency procedure

at every step

$$y''+v(r)y+\int_0^{r_c} g(r,r')y(r')dr'=\lambda y$$

$$y(0)=y(r_c)=0$$

$$\int_0^{r_c} y^2(r)dr=1$$

→

$$y''+v(r)y+x(r)=\lambda y$$

$$y(0)=y(r_c)=0$$

$$y(r_1)=y_1>0$$

Boundary conditions for radial wave functions

EXISTENCE OF THERMODYNAMICS FOR REAL MATTER WITH COULOMB FORCES

J. L. Lebowitz*
Belfer Graduate School of Science, Yeshiva University, New York, New York 10033
and
Elliott H. Lieb†
Department of Mathematics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

VOLUME 22, NUMBER 13 PHYSICAL REVIEW LETTERS 31 MARCH 1969

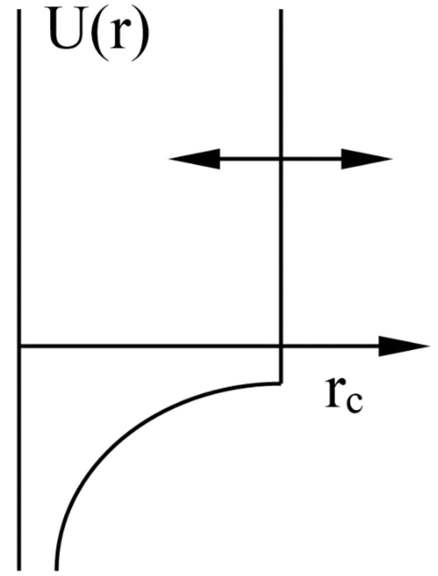
$$Z(N,\Omega) \geqslant \prod_{1}^{D} Z(N_i,\Omega_i).$$

$$\Downarrow$$

$$F_{Model}(V,T,\{N_j\}) \geq F(V,T,\{N_j\})$$

$$\Downarrow$$

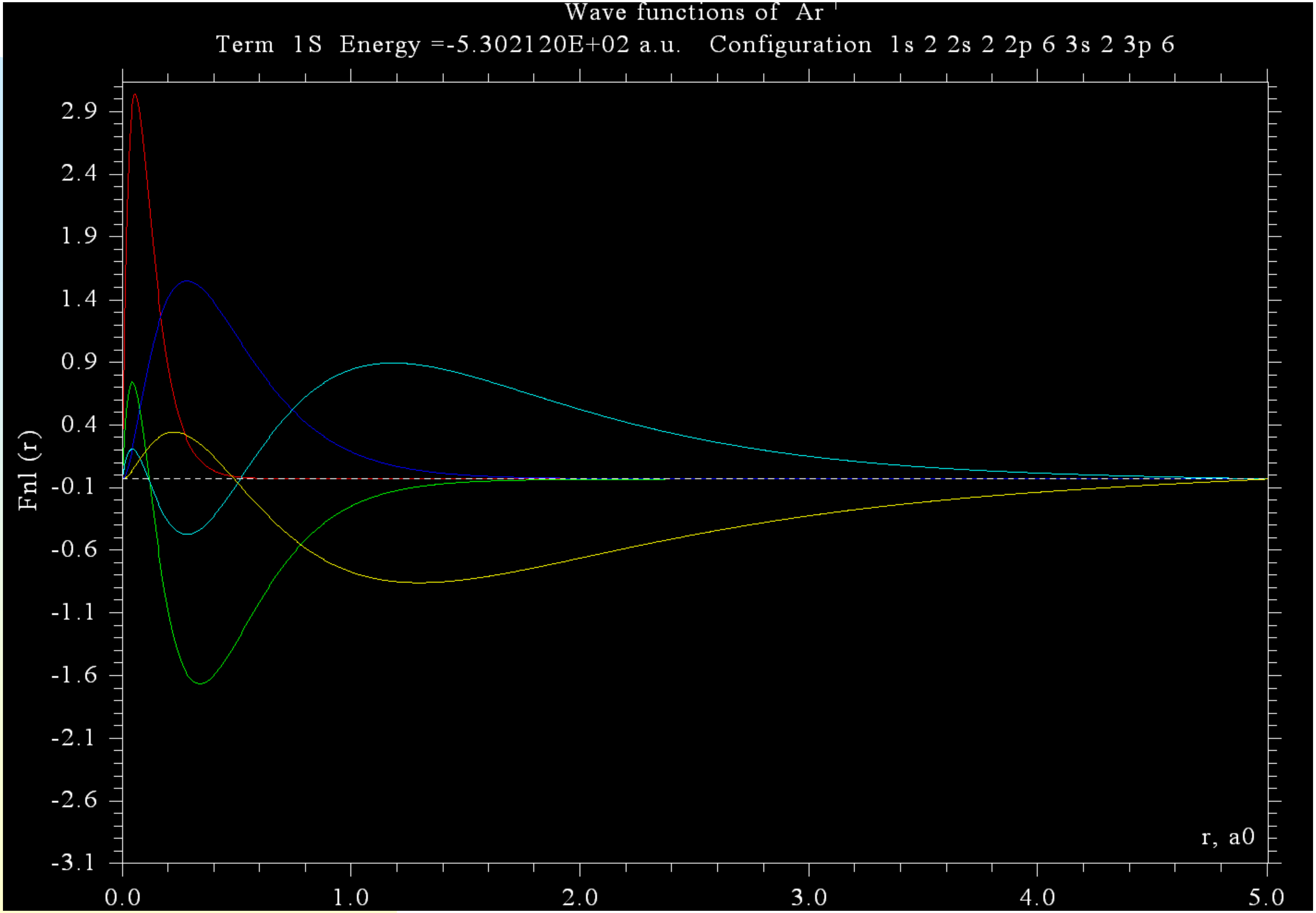
$$f_{nl}(r_c) = 0$$



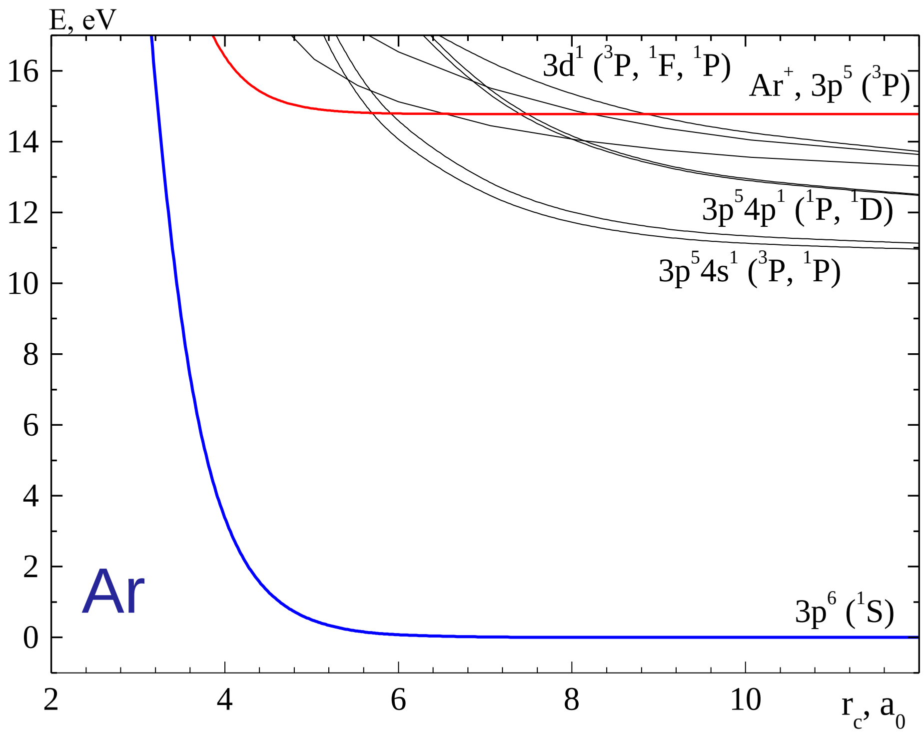
$$f_{nl}(r_c) = 0 \quad f_{nl}(0) = 0$$

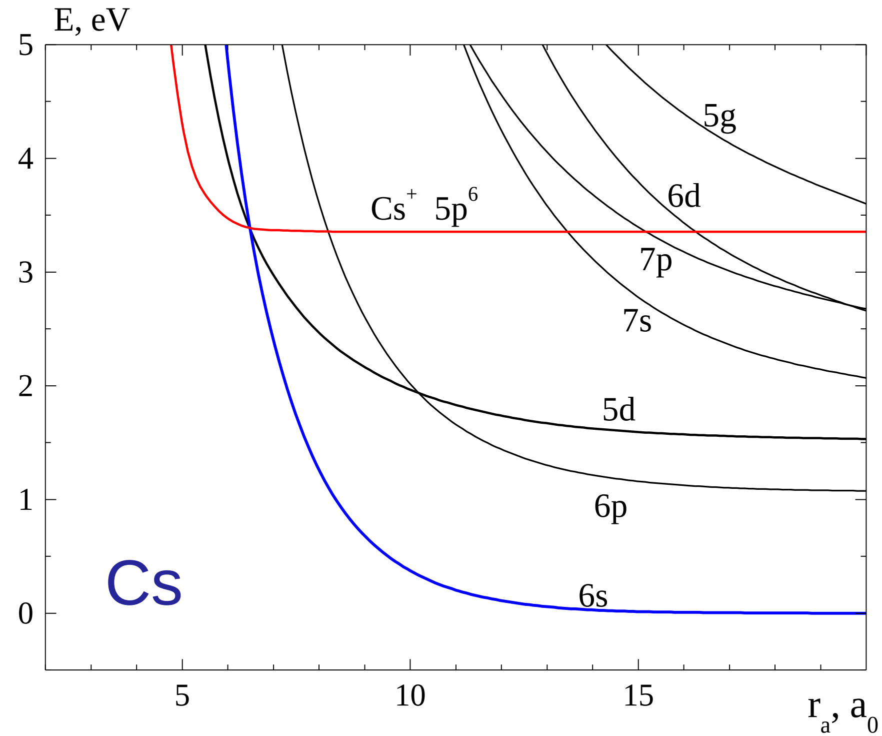
$$\int_0^{r_c} f_{nl}(r)\, f_{n'l}(r)\, dr = \delta_{nn'}$$

Boundary conditions for radial wave functions



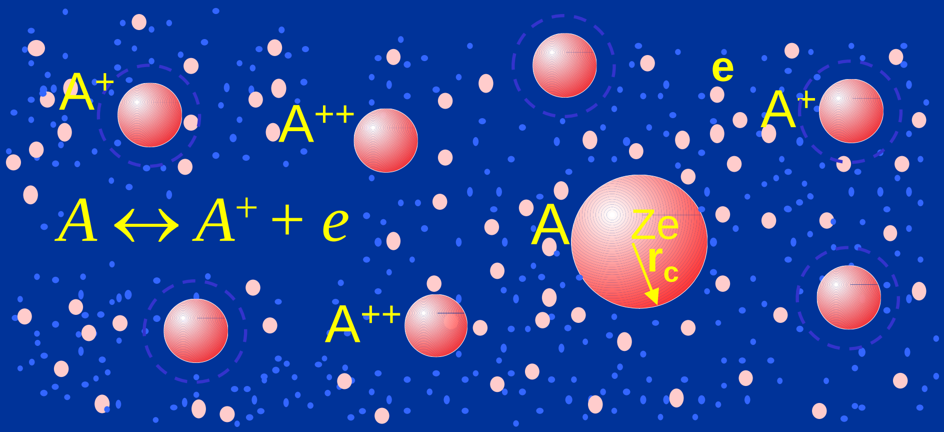
Energy levels of compressed argon and cesium atoms





Thermodynamic model

$$F(\{N_j\},V,T) = F_{id}(\{N_j\},V,T) + \\ + \Delta F_{HS}(\{N_j\},V,T) + \Delta F_{Coul}(\{N_j\},V,T)$$



Atoms, ions and electrons :

$$F_{id} = -k_B T\left[N_a \ln\frac{Q_a(r_c)}{n_a\lambda_a^3} + N_e \ln\frac{2Q_i}{n_e^2\lambda_i^3\lambda_e^3} + (N_a + 2N_e)\right]$$

Nonideality effects:

- Coulomb corrections :
  Debye approximation in GCE
  pseudopotential model, ...
- Short-range repulsion :
  atoms are hard spheres of finite radius

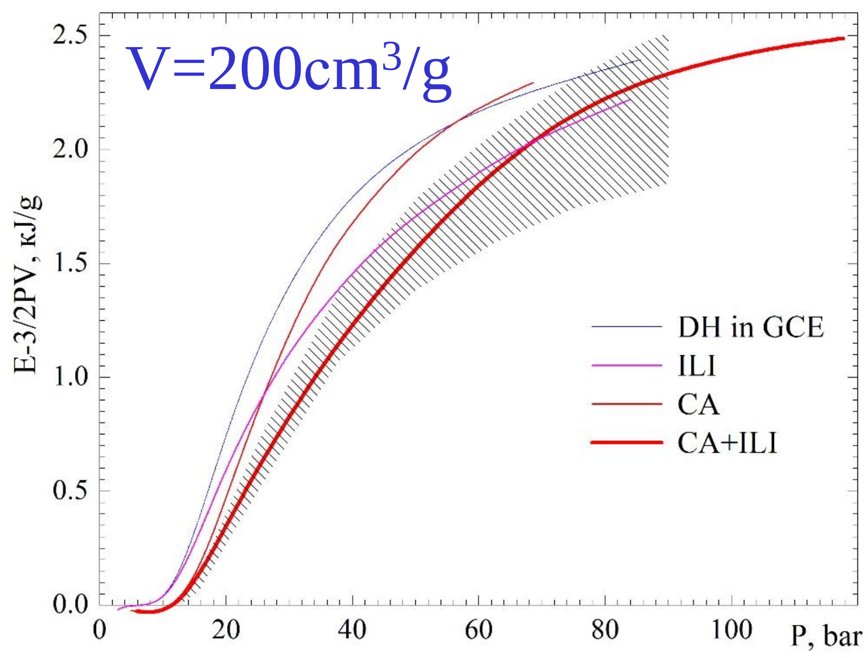
Atomic partition functions:

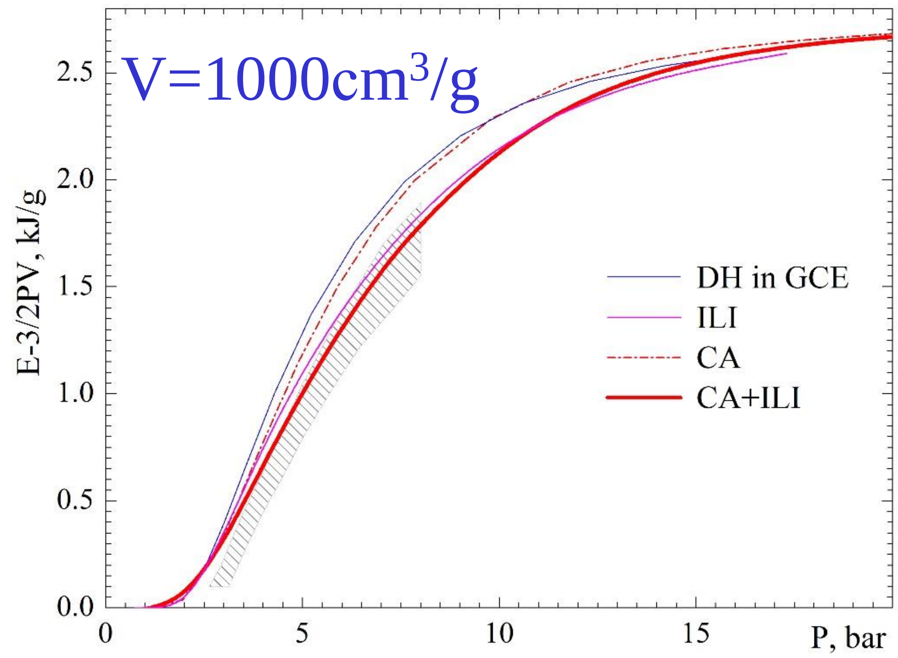
$$Q_a(r_c) = \sum_i g_i \exp\left[-\frac{\varepsilon_i^{HF}(r_c)}{k_B T}\right]$$

$$\Delta F_{HS} = N_a k_B T y \frac{4-3y}{(y-1)^2}; \quad y = n_a(4\pi r_c^3/3)$$

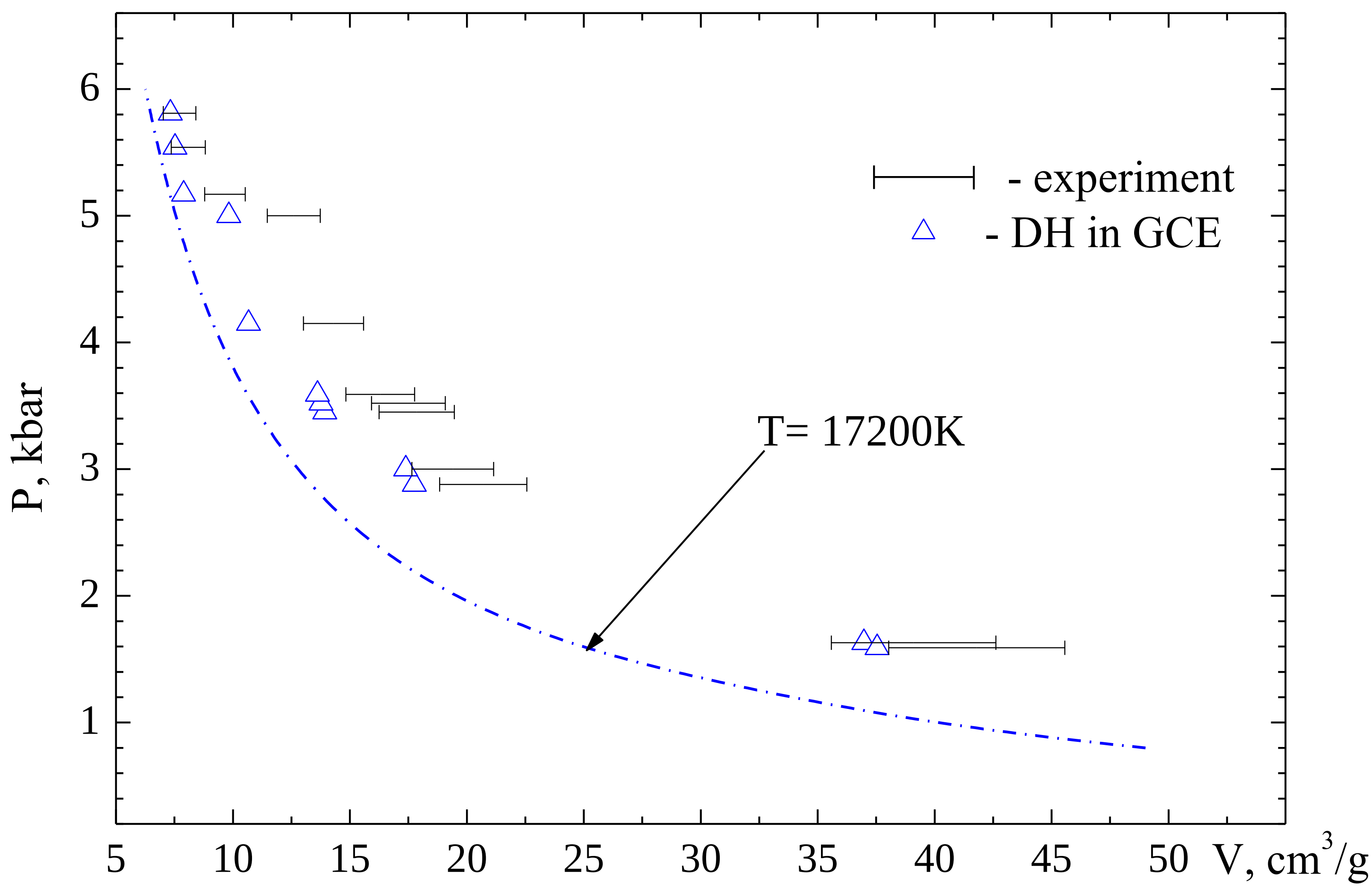
$$\frac{\partial F}{\partial r_c} = 0 \quad \Rightarrow \quad 3 r_c y f'(y) = \frac{1}{Q_a}\frac{\partial Q_a}{\partial r_c} \quad \Rightarrow \quad r_c$$

Caloric equation of state for cesium

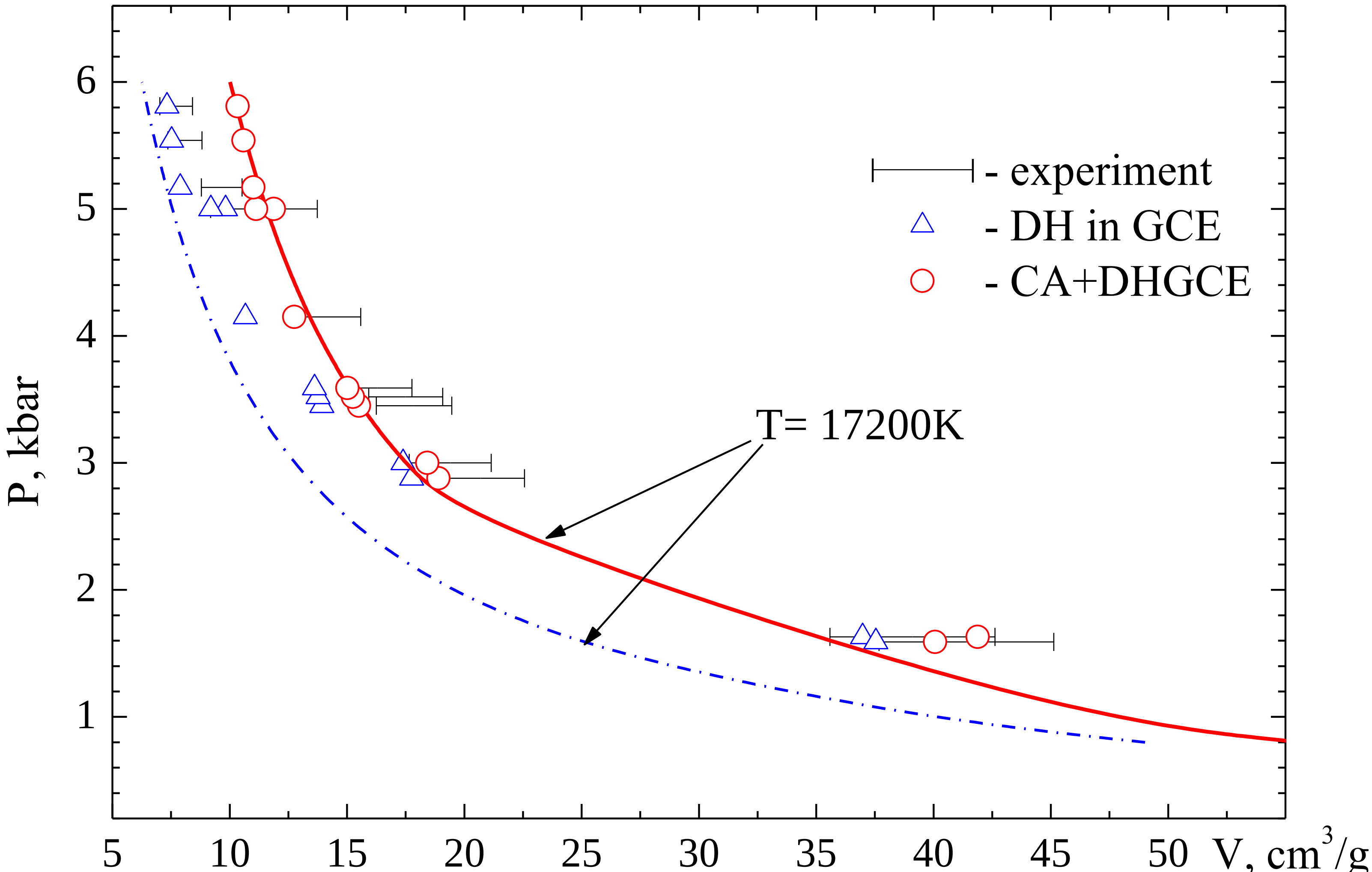




Thermal equation of state for argon



Thermal equation of state for argon



Radiation emitted by a shock-compressed high-pressure argon plasma

V. E. Bespalov, V. K. Gryaznov, and V. E. Fortov

Division of Institute of Chemical Physics, USSR Academy of Sciences

Zh. Eksp. Teor. Fiz. 76, 140–147 (January 1979)

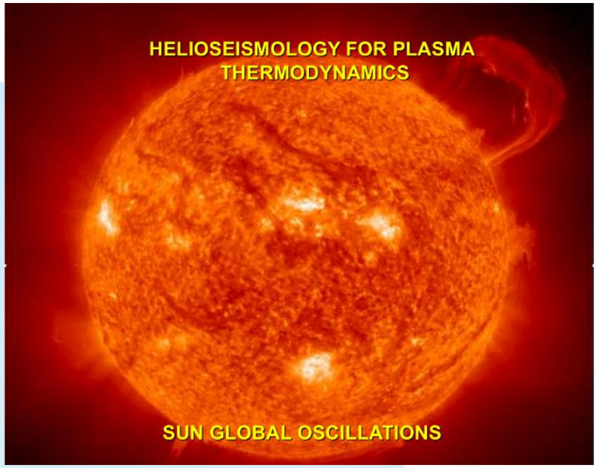
Electric conductivity of a high-temperature nonideal plasma

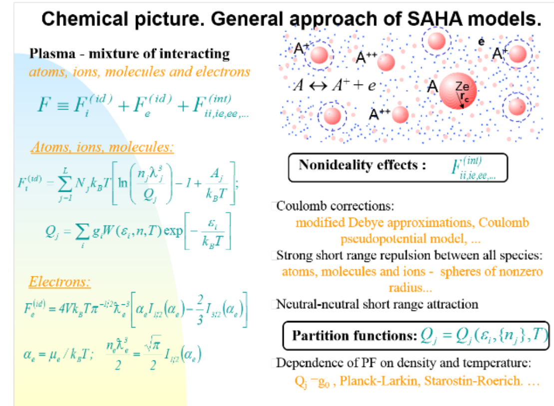
V. B. Mintsev, V. E. Fortov, and V. K. Gryaznov

Institute of Chemical Physics, USSR Academy of Sciences

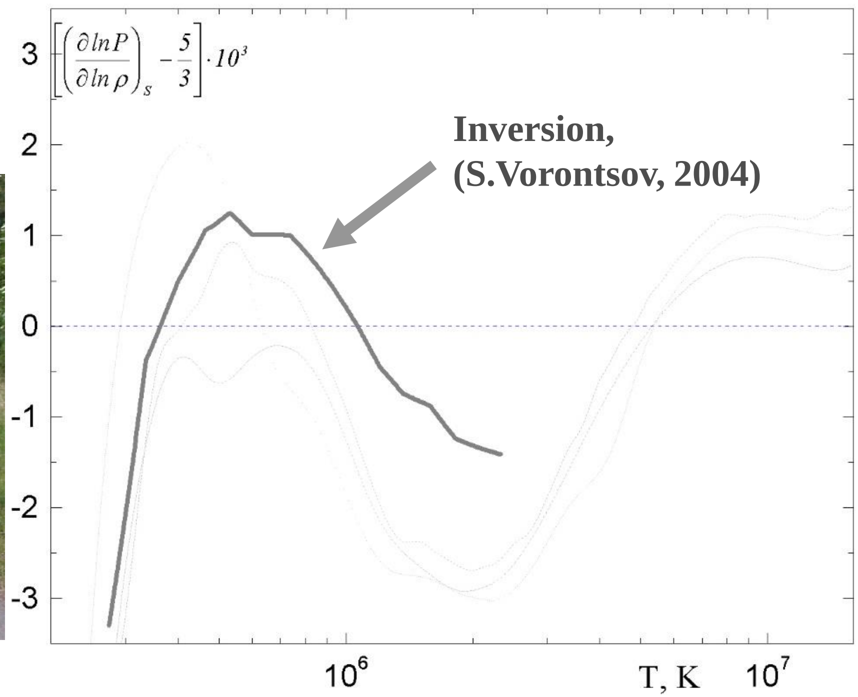
Zh. Eksp. Teor. Fiz. **79**, 116–124 (July 1980)

Weakly non-ideal plasma.
Solar plasma thermodynamics.
SAHA-S model

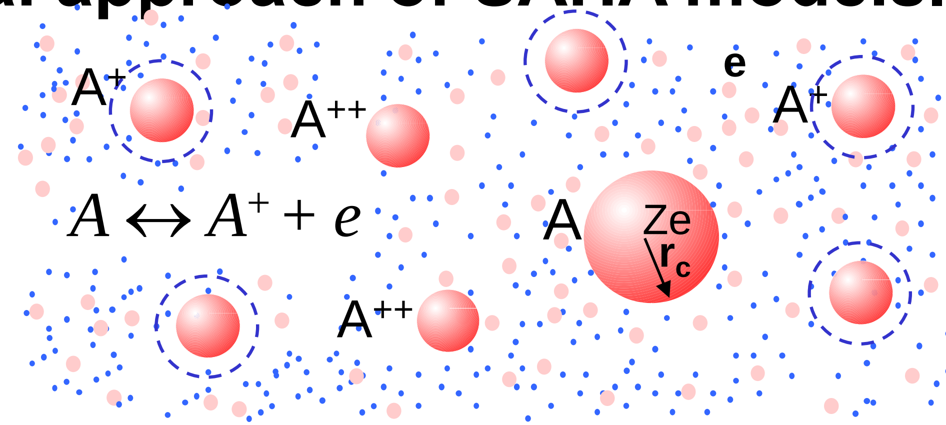

HELIOSEISMOLOGY FOR PLASMA THERMODYNAMICS
SUN GLOBAL OSCILLATIONS


Chemical picture. General approach of SAHA models.
Plasma - mixture of interacting
atoms, ions, molecules and electrons
$F \equiv F_i^{(id)} + F_e^{(id)} + F_{ii,ie,ee,...}^{(int)}$
Atoms, ions, molecules:
$F_i^{(id)} = \sum_{j=1}^{L} N_j k_B T \left[\ln\left(\frac{n_j \lambda_j^3}{Q_j}\right) - 1 + \frac{A_j}{k_B T} \right];$
$Q_j = \sum_i g_i W(\varepsilon_i, n, T) \exp\left[-\frac{\varepsilon_i}{k_B T}\right]$
Electrons:
$F_e^{(id)} = 4V k_B T \pi^{-1/2} \lambda_e^{-3} \left[\alpha_e I_{1/2}(\alpha_e) - \frac{2}{3} I_{3/2}(\alpha_e) \right]$
$\alpha_e = \mu_e / k_B T; \quad \frac{n_e \lambda_e^3}{2} = \frac{\sqrt{\pi}}{2} I_{1/2}(\alpha_e)$
A+
A++
e
$A \leftrightarrow A^+ + e$
A
Ze
r_c
Nonideality effects : $F_{ii,ie,ee,...}^{(int)}$
Coulomb corrections:
modified Debye approximations, Coulomb pseudopotential model, ...
Strong short range repulsion between all species:
atoms, molecules and ions - spheres of nonzero radius...
Neutral-neutral short range attraction
Partition functions: $Q_j = Q_j(\varepsilon_i, \{n_j\}, T)$
Dependence of PF on density and temperature:
$Q_j = g_0$, Planck-Larkin, Starostin-Roerich. …

?


$\left[\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_S - \frac{5}{3}\right] \cdot 10^3$
Inversion,
(S.Vorontsov, 2004)
3
2
1
0
-1
-2
-3
10^6
T, K
10^7

Chemical picture. General approach of SAHA models.



Plasma - mixture of interacting

atoms, ions, molecules and electrons

$$F \equiv F_i^{(id)} + F_e^{(id)} + F_{ii,ie,ee,...}^{(int)}$$

Atoms, ions, molecules:

$$F_i^{(id)} = \sum_{j=1}^{L} N_j k_B T \left[\ln\left(\frac{n_j \lambda_j^3}{Q_j} \right) - 1 + \frac{A_j}{k_B T} \right];$$

$$Q_j = \sum_i g_i W(\varepsilon_i, n, T) \exp\left[-\frac{\varepsilon_i}{k_B T} \right]$$

Electrons:

$$F_e^{(id)} = 4V k_B T \pi^{-1/2} \lambda_e^{-3} \left[\alpha_e I_{1/2}(\alpha_e) - \frac{2}{3} I_{3/2}(\alpha_e) \right]$$

$$\alpha_e = \mu_e / k_B T; \quad \frac{n_e \lambda_e^3}{2} = \frac{\sqrt{\pi}}{2} I_{1/2}(\alpha_e)$$

Nonideality effects : $F_{ii,ie,ee,...}^{(int)}$

- Coulomb corrections:
  modified Debye approximations, Coulomb pseudopotential model, ...
- Strong short range repulsion between all species:
  atoms, molecules and ions - spheres of nonzero radius...
- Neutral-neutral short range attraction

Partition functions: $Q_j = Q_j(\varepsilon_i, \{n_j\}, T)$

- Dependence of PF on density and temperature:
  $Q_j = g_0$, Planck-Larkin, Starostin-Roerich. …

SAHA-S

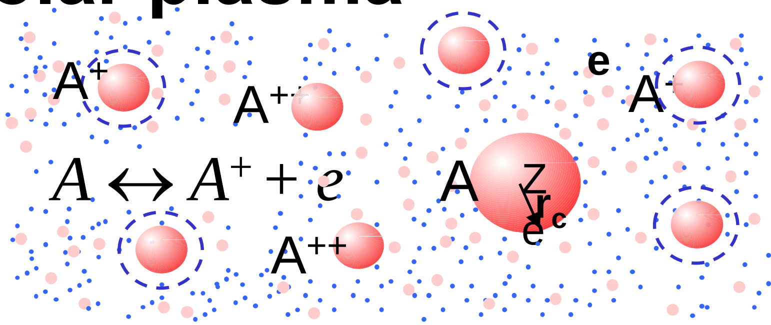
Thermodynamics of solar plasma

Equilibrium composition (SAHA-S1)

54 species (H He   C N O Ne):

{e, H, H^+, ..., He, He+, He^{+2},

C, C+, …, N, N+,…, O, O+, …, Ne, Ne+, …},



+ Si Fe (SAHA-S2) > 90 species + Mg S (SAHA-S3) > 150 species

Coulomb interaction:

Debye approximation
in Grand canonical ensemble

$$\frac{\Delta P^{cc}}{k_B T} = -\frac{\tilde{\Gamma}_D^3}{24\pi f^3};$$

$$\frac{\Delta \mu_i}{k_B T} = -\ln\left(1 + Z_i^2 \frac{\tilde{\Gamma}_D}{2}\right);$$

$$\tilde{\Gamma}_D^2 = 4\pi f^3 \sum_{i=1}^{L} \frac{Z_i^2 n_i}{1 + Z_i^2 \frac{\tilde{\Gamma}_D}{2}}$$

Partition functions:

Modification of Planck-Larkin partition function (A.Starostin, 2002-2004)

$$\Delta\Omega_e = -T\varsigma_e\varsigma_i ƛ_{ei}^3 \sum_{n=1}^{\infty} n^2 F_n(\beta) \exp\left[\frac{Ry}{n^2 T}\right]$$

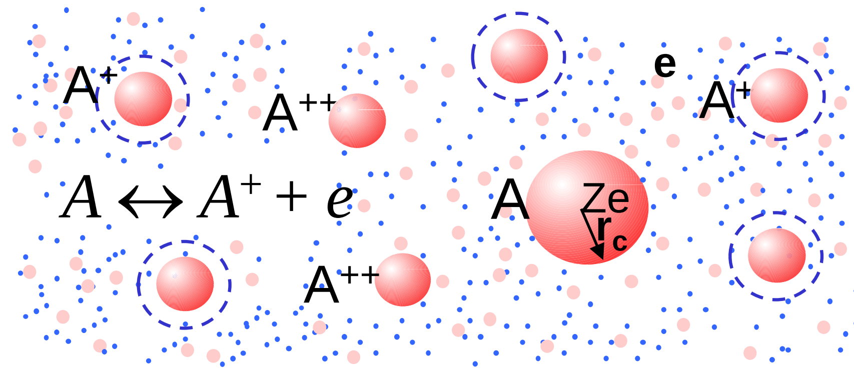
$$F_n(\beta) = 1 -$$

$$-e^{-\beta E_n}\left[4 - \frac{6}{\sqrt{\pi}}(\beta E_n)^{1/2} + \frac{4}{\sqrt{\pi}}(\beta E_n)^{3/2}\right] +$$

$$+\frac{\Gamma(1/2, \beta E_n)}{\sqrt{\pi}}\left[3 - 4\beta E_n + 4(\beta E_n)^2\right]$$

SAHA-S

Thermodynamics of solar plasma



Relativistic corrections:

$$\frac{\Delta P^{rel}}{k_B T} = 0$$

$$\frac{\Delta \mu_e^{rel}}{k_B T} = -\ln\left[1 + \frac{15 k_B T}{8 m_e c^2}\right]$$

$$\frac{\Delta E^{rel}}{k_B T} = \zeta_e \frac{15 k_B T}{8 m_e c^2}$$

Exchange corrections:

$$\frac{\Delta P^{exch}}{n_e k_B T} = -\frac{\zeta_e}{n_e}\frac{\zeta_e \bar\lambda_e^2 f}{4}$$

$$\frac{\Delta \mu_e^{exch}}{k_B T} = -\ln\left(1 + \frac{1}{2}\zeta_e \bar\lambda_e^2 f\right)$$

$$\frac{\Delta E^{exch}}{n_e k_B T} = \frac{\zeta_e}{n_e}\frac{\zeta_e \bar\lambda_e^2 f}{2} = 2\frac{\Delta P^{exch}}{n_e k_B T}$$

Diffraction corrections:

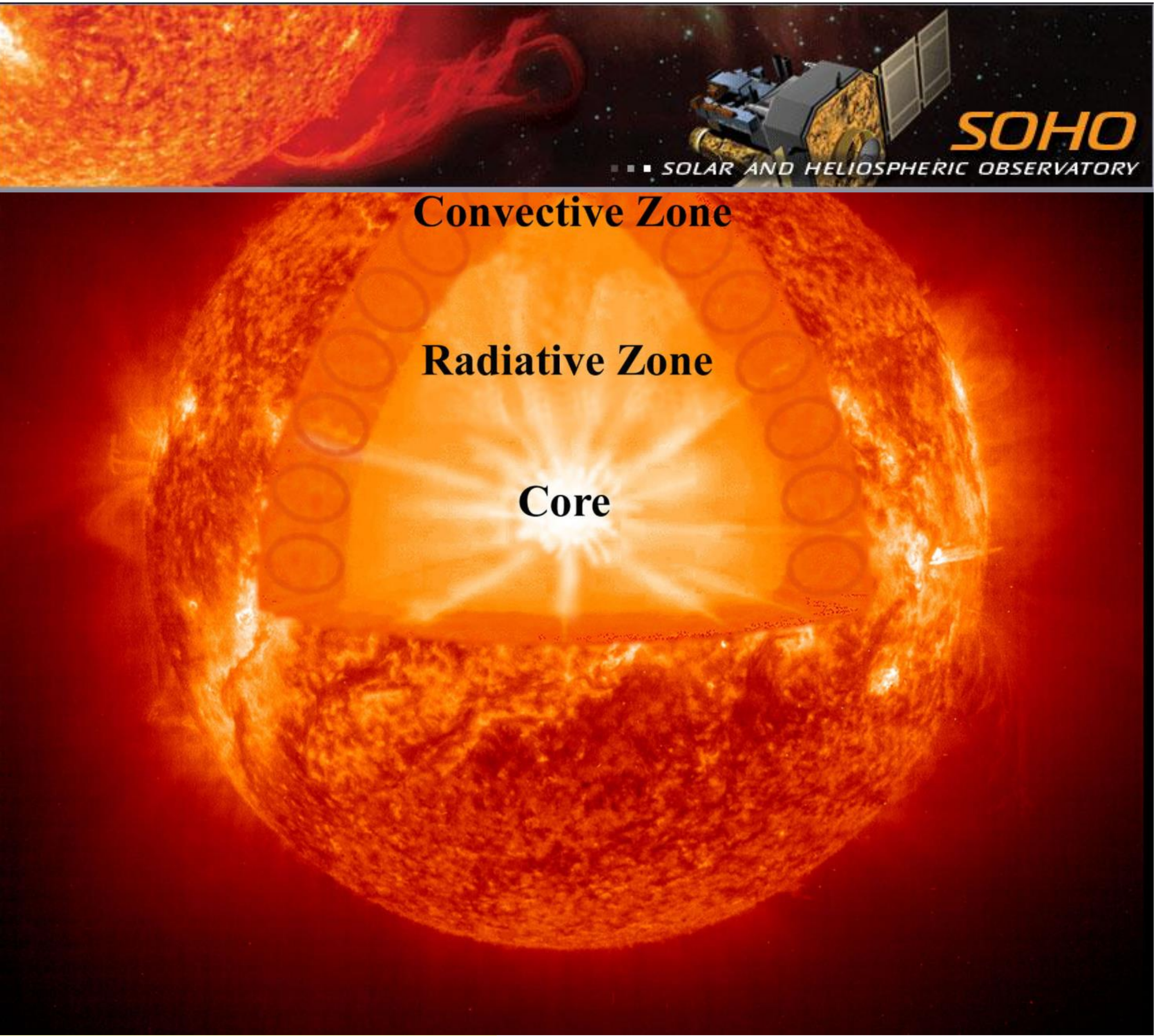
$$\frac{\Delta P^{diff}}{n_e k_B T} = \frac{\bar\lambda_e \zeta_e f^2}{4}\frac{\tilde\Gamma^2}{4 n_e f^3} + \frac{\pi \bar\lambda_e f^2 \zeta_e}{4}\frac{\zeta_e}{n_e}\left\{\frac{(1-\sqrt{2})}{\sqrt{2}} + \frac{1}{2}\sum_{i=2}^{I}\sum_{k=2}^{I} Z_i^2 Z_k^2 \frac{\zeta_i}{\zeta_e}\frac{\zeta_k}{\zeta_e}\frac{\bar\lambda_{ik}}{\bar\lambda_e}\right\}$$

$$\frac{\Delta \mu_e^{diff}}{k_B T} = \ln\left(1 - \frac{\pi \bar\lambda_e f^2 \zeta_e}{4}\left[\sqrt{2} + \sum_{i=2}^{I} Z_i^2 \frac{\zeta_i}{\zeta_e}\right]\right)$$

$$\frac{\Delta \mu_i^{diff}}{k_B T} = \ln\left(1 - \frac{\pi \bar\lambda_e f^2 \zeta_e Z_i^2}{4}\left(1 + \sum_{k=2}^{I} Z_k^2 \frac{\zeta_k}{\zeta_e}\frac{\bar\lambda_{ik}}{\bar\lambda_e}\right)\right)$$

$$\frac{\Delta E^{diff}}{n_e k_B T} = \frac{5}{2}\frac{\Delta P^{diff}}{n_e k_B T}$$

Structure of the Sun



- Core:

$$0 < \frac{r}{R_{\oplus}} < 0.3$$

- Radiative zone:

$$0.3 < \frac{r}{R_{\oplus}} < 0.7$$

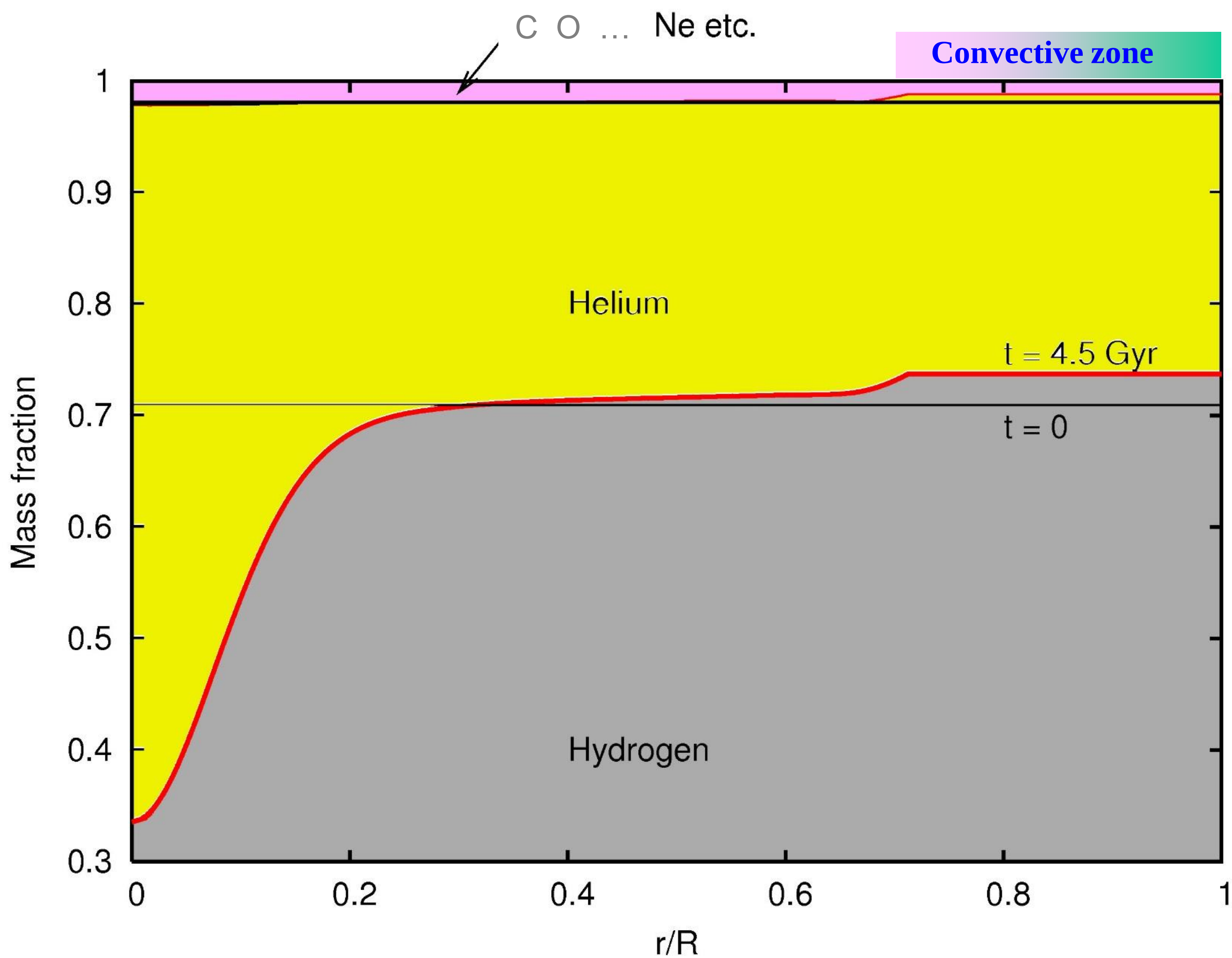
- Convective zone:

$$0.7 < \frac{r}{R_{\oplus}} < 1$$

Standard solar model

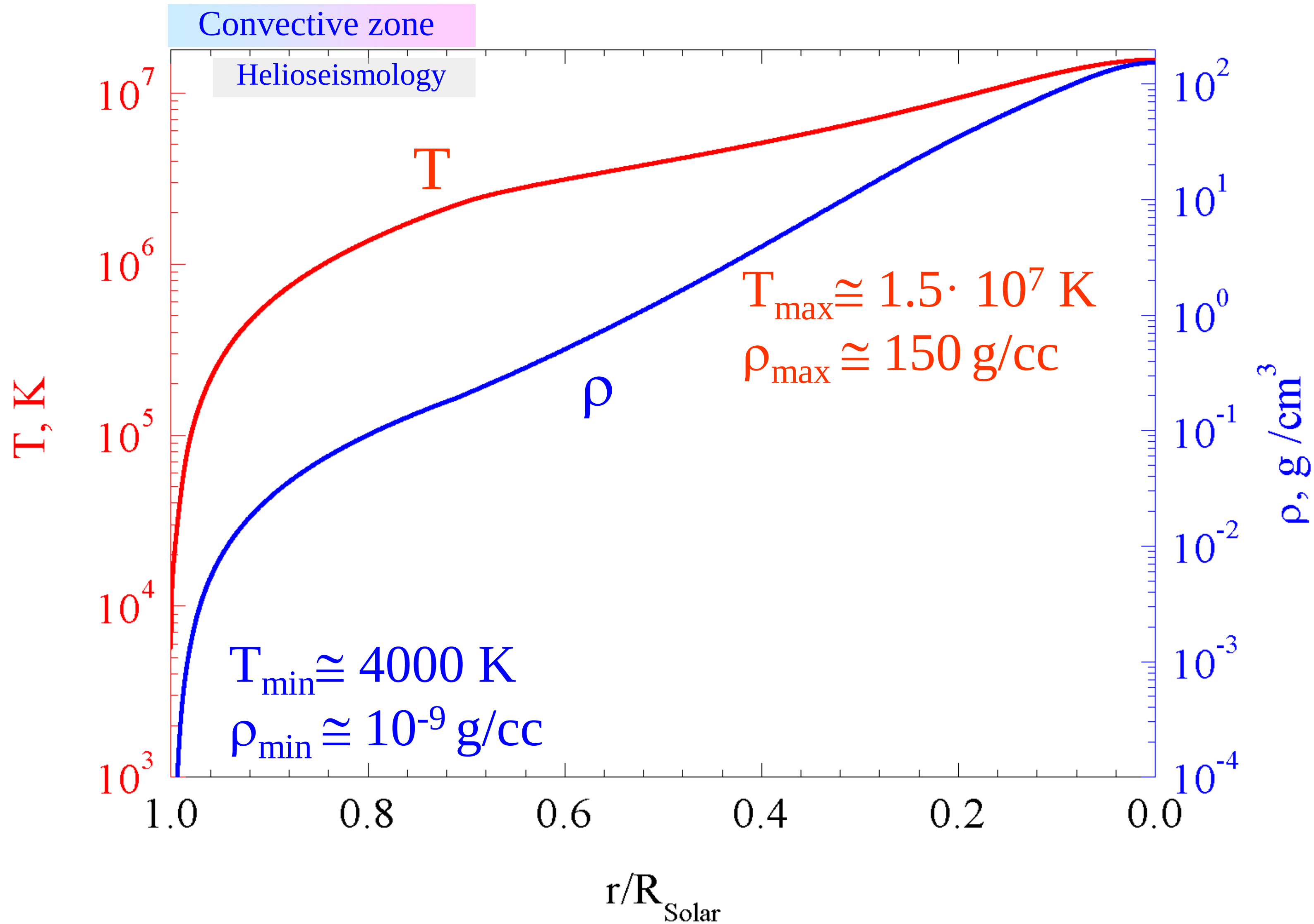
Element composition of solar plasma

H He C O …

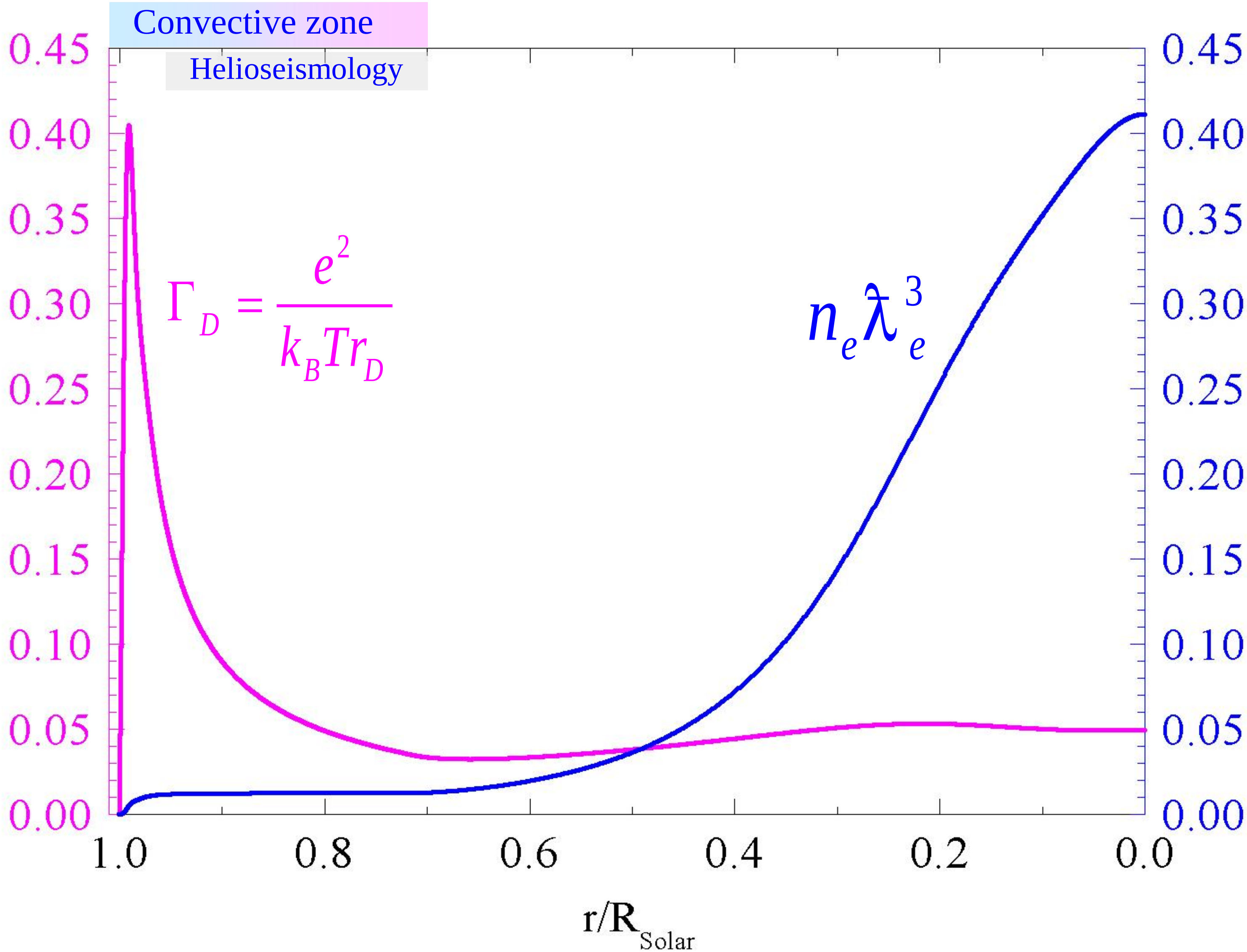


Standard solar model

Density and temperature along solar trajectory

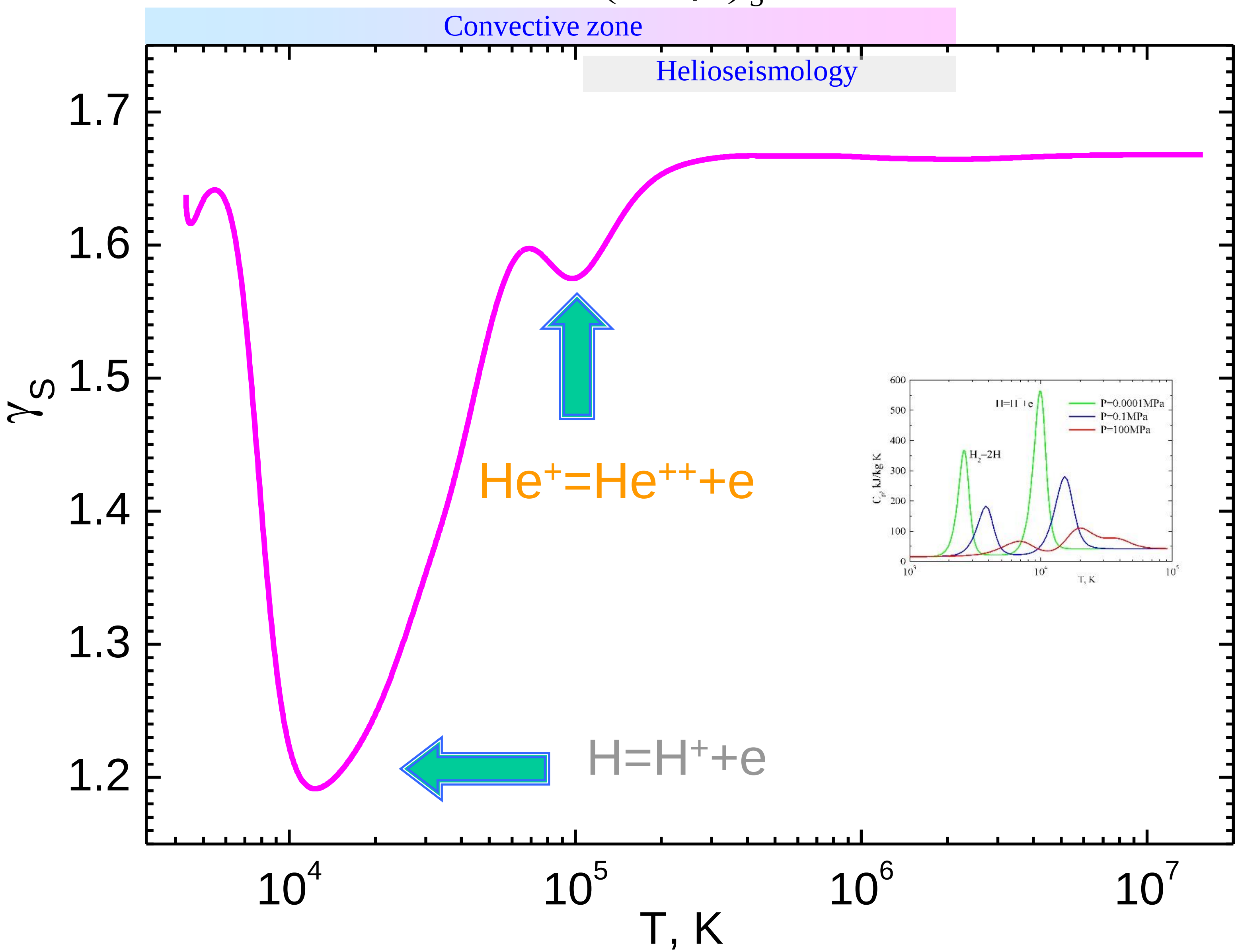


Plasma parameters along solar trajectory

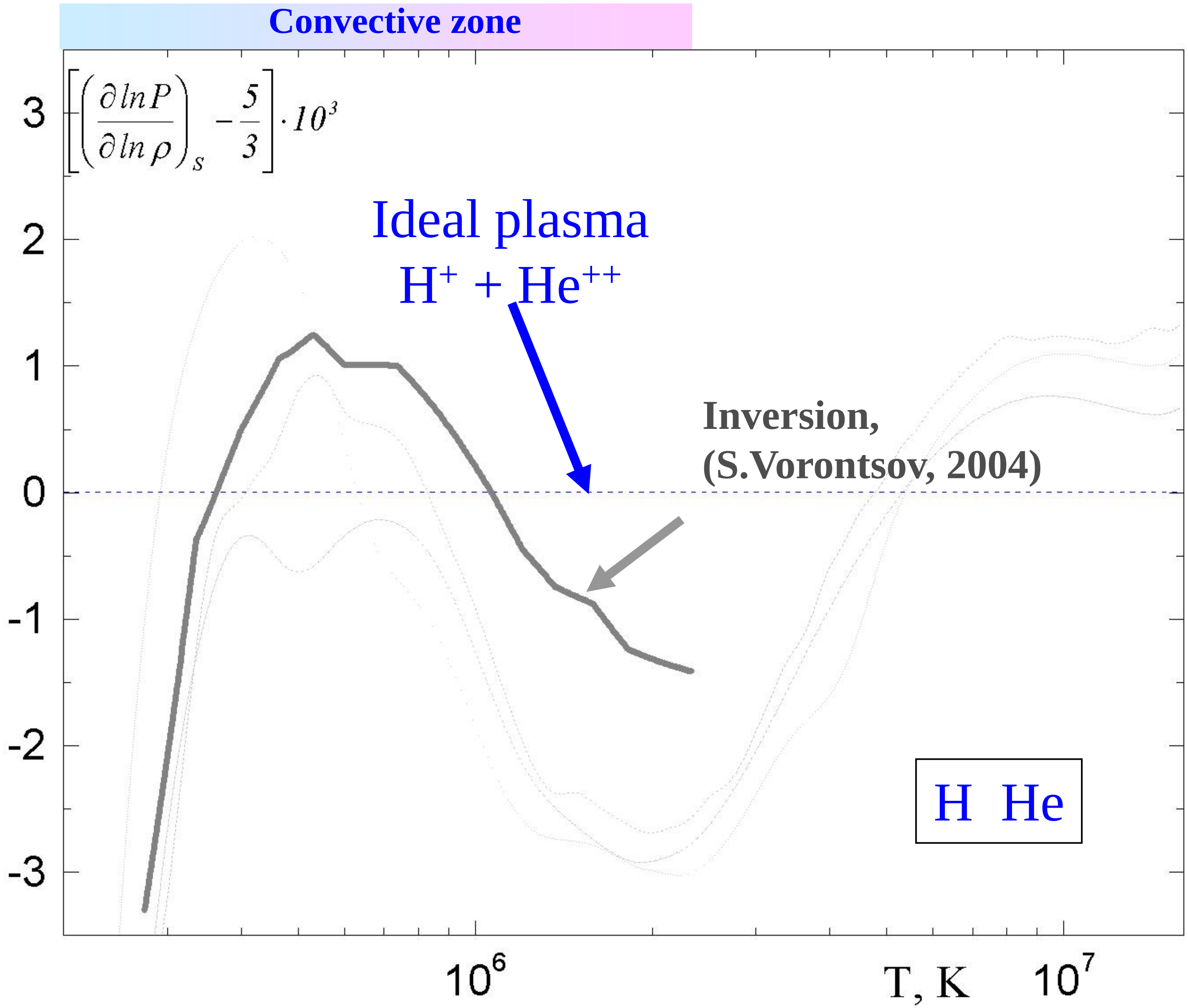


Adiabatic exponent. SAHA-S calculations

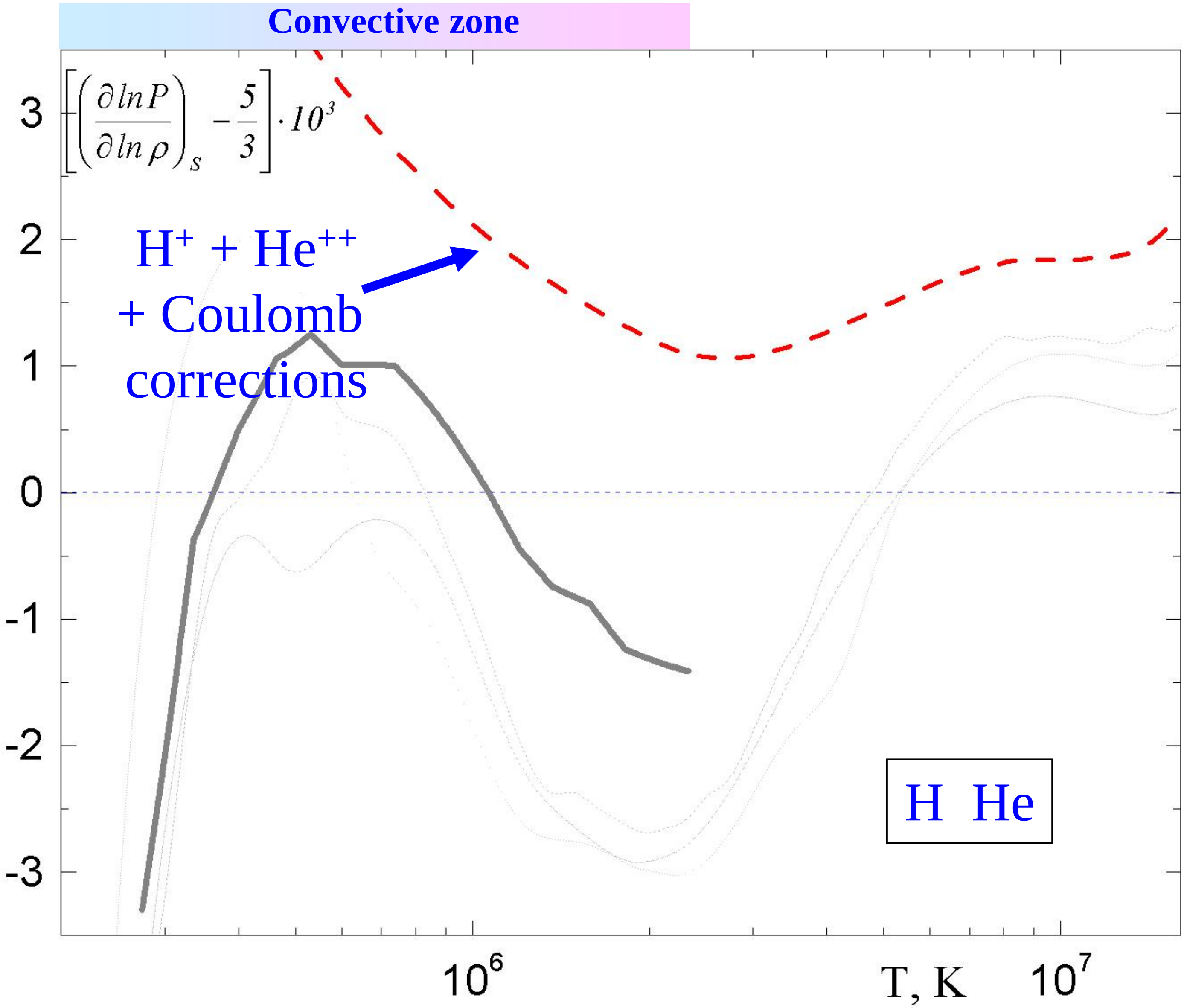
$$\gamma_S \equiv \left(\frac{\partial \ln P}{\partial \ln \rho} \right)_S$$



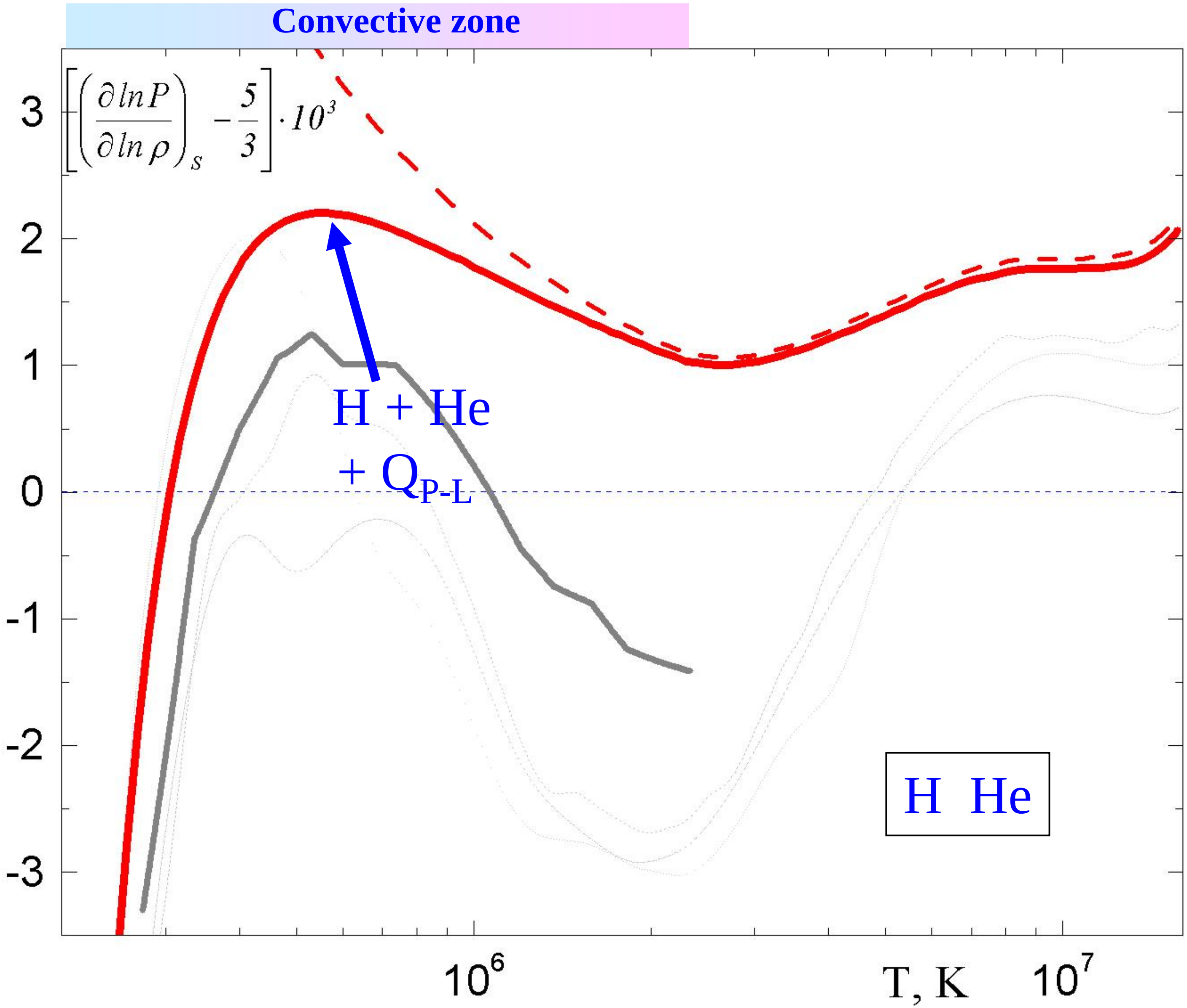
Adiabatic exponent. Models and inversion results



Adiabatic exponent.
Models and inversion results

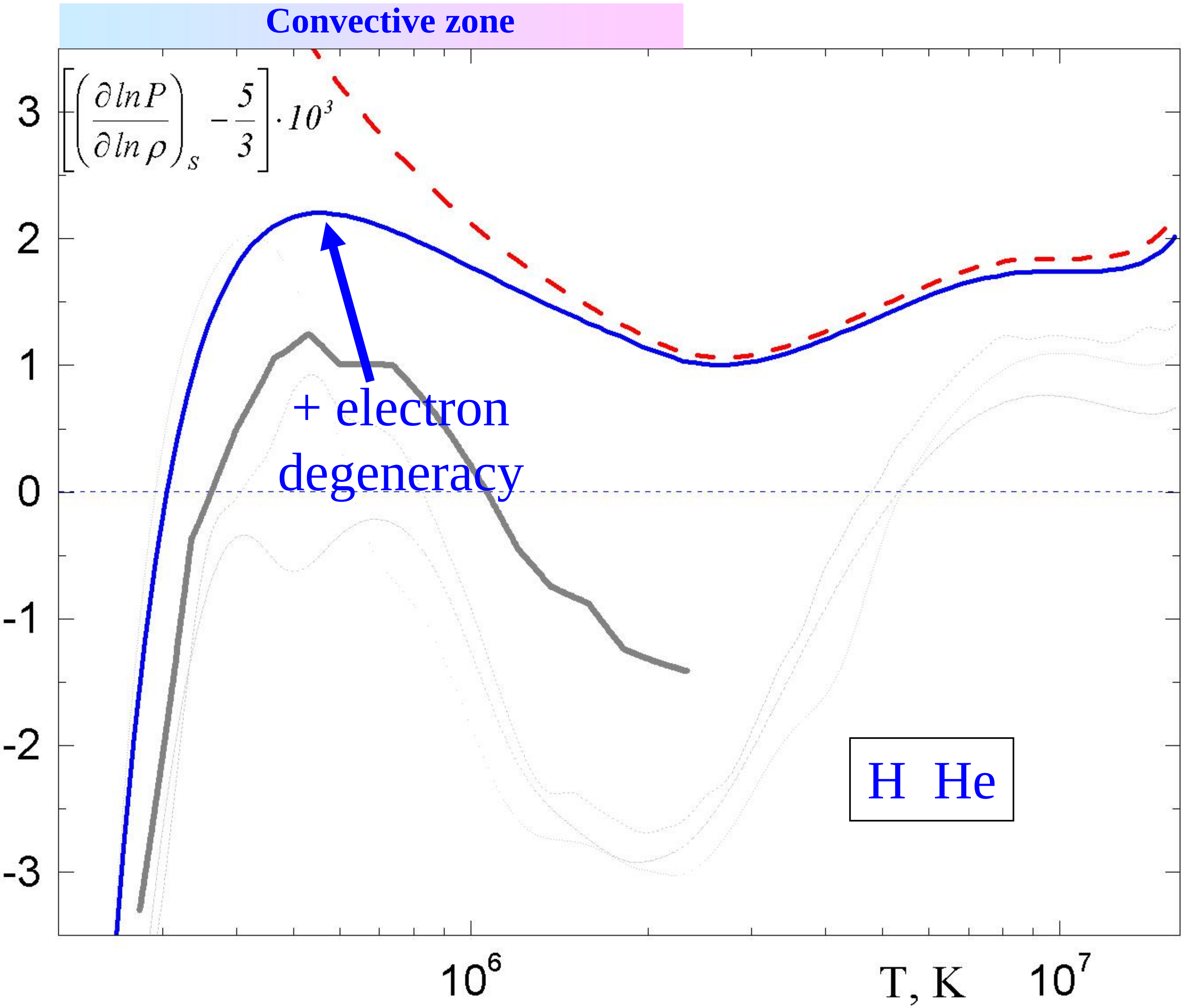


Adiabatic exponent. Models and inversion results

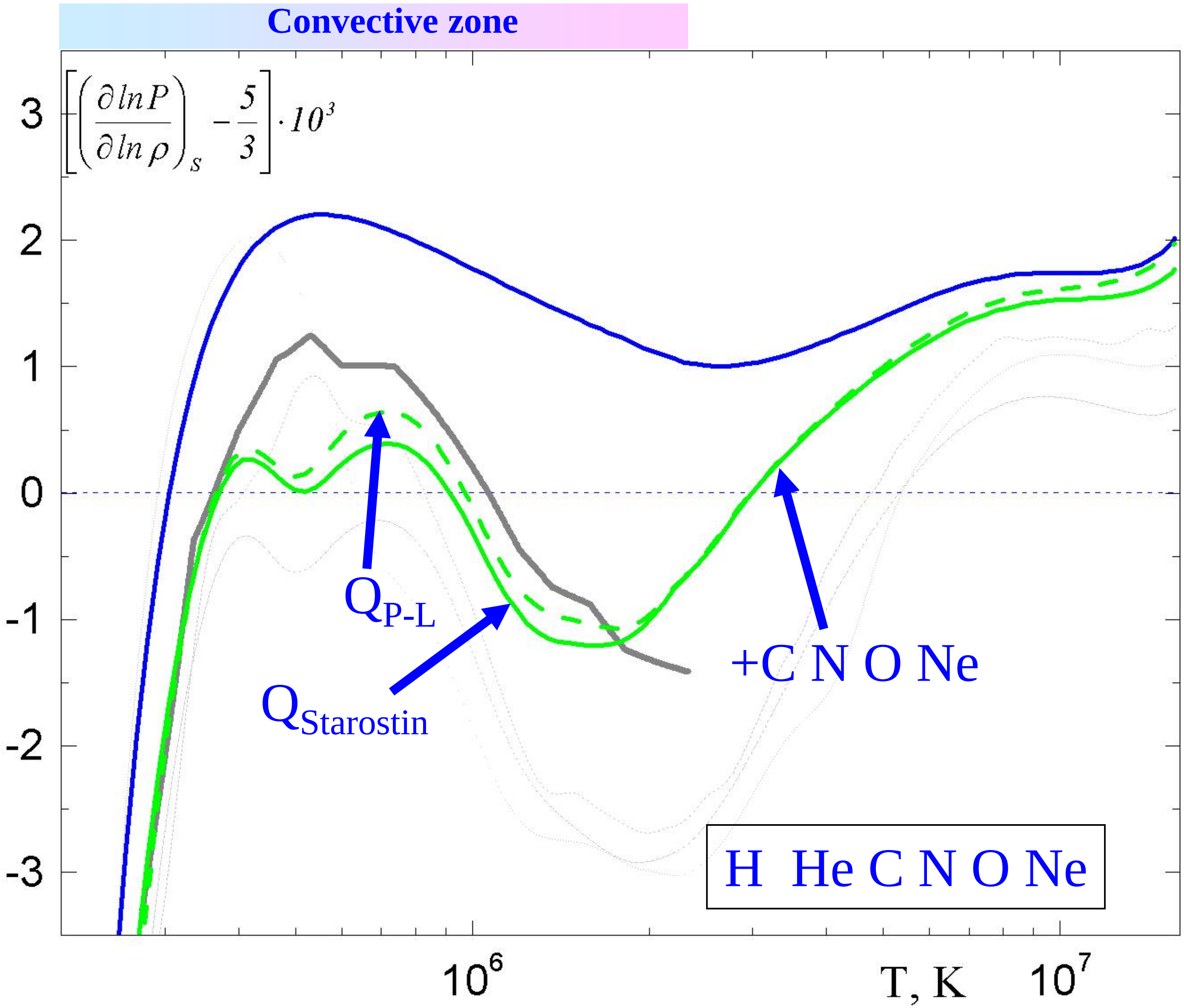


SAHA -S

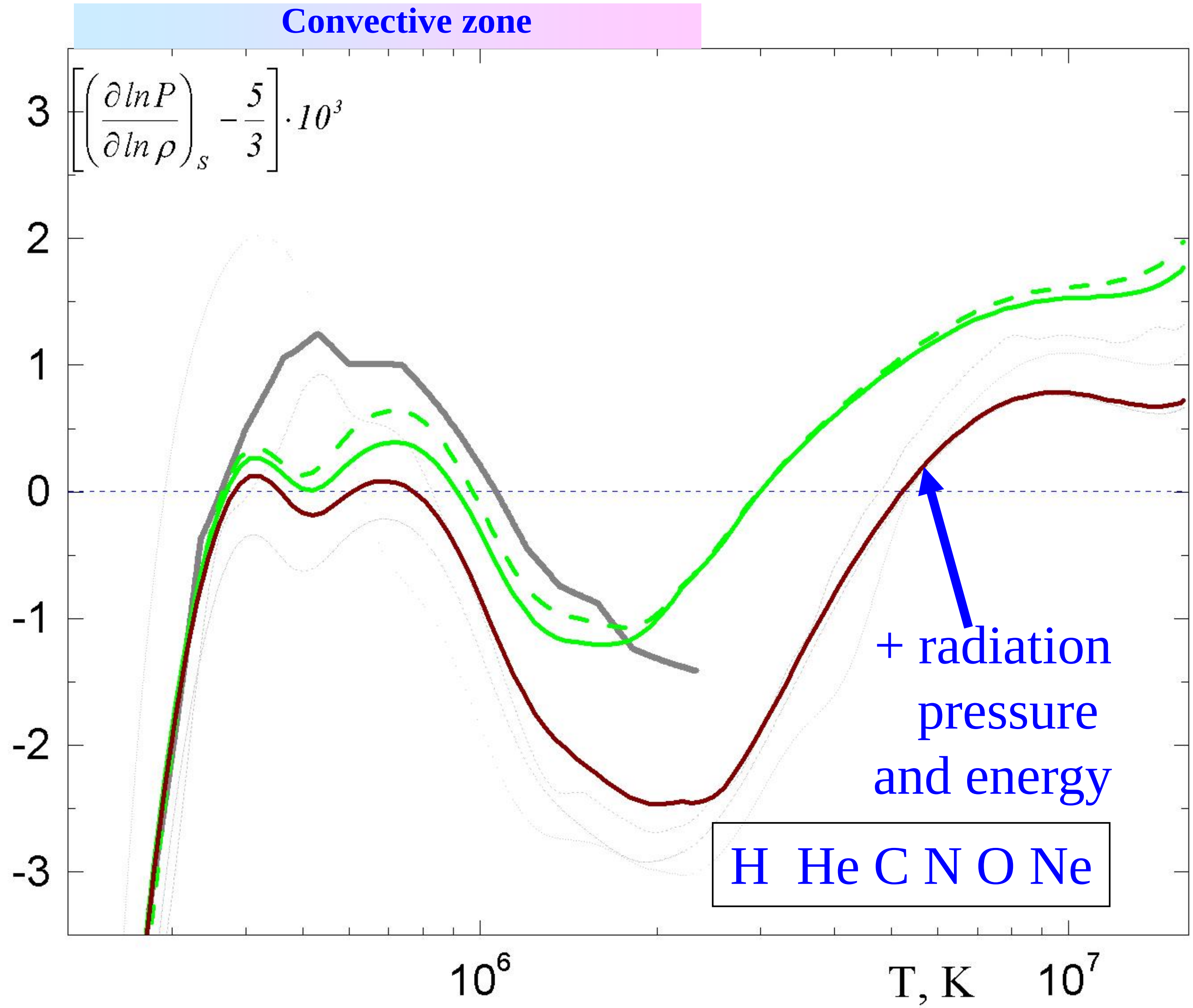
Adiabatic exponent. Models and inversion results



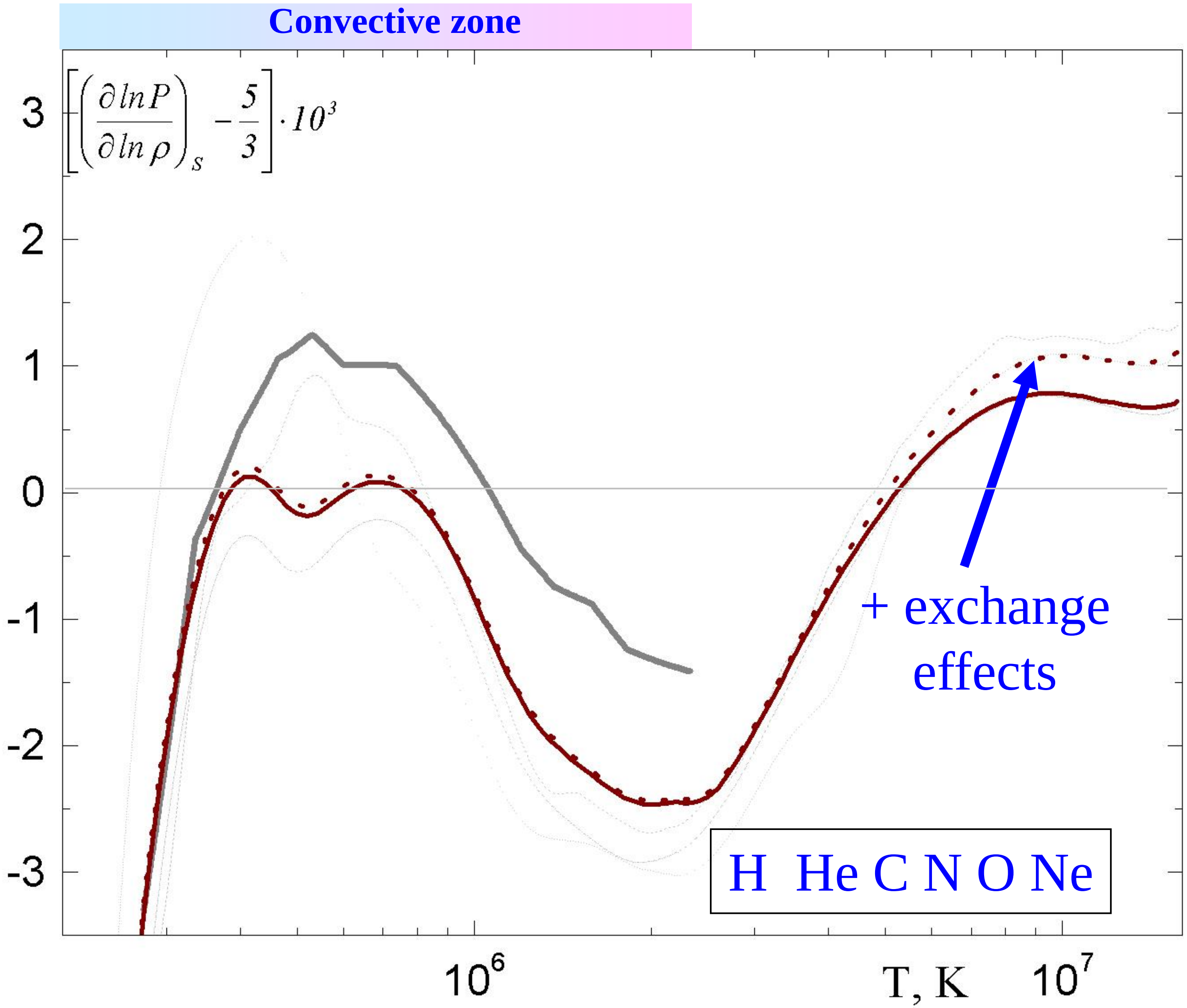
Adiabatic exponent. Models and inversion results



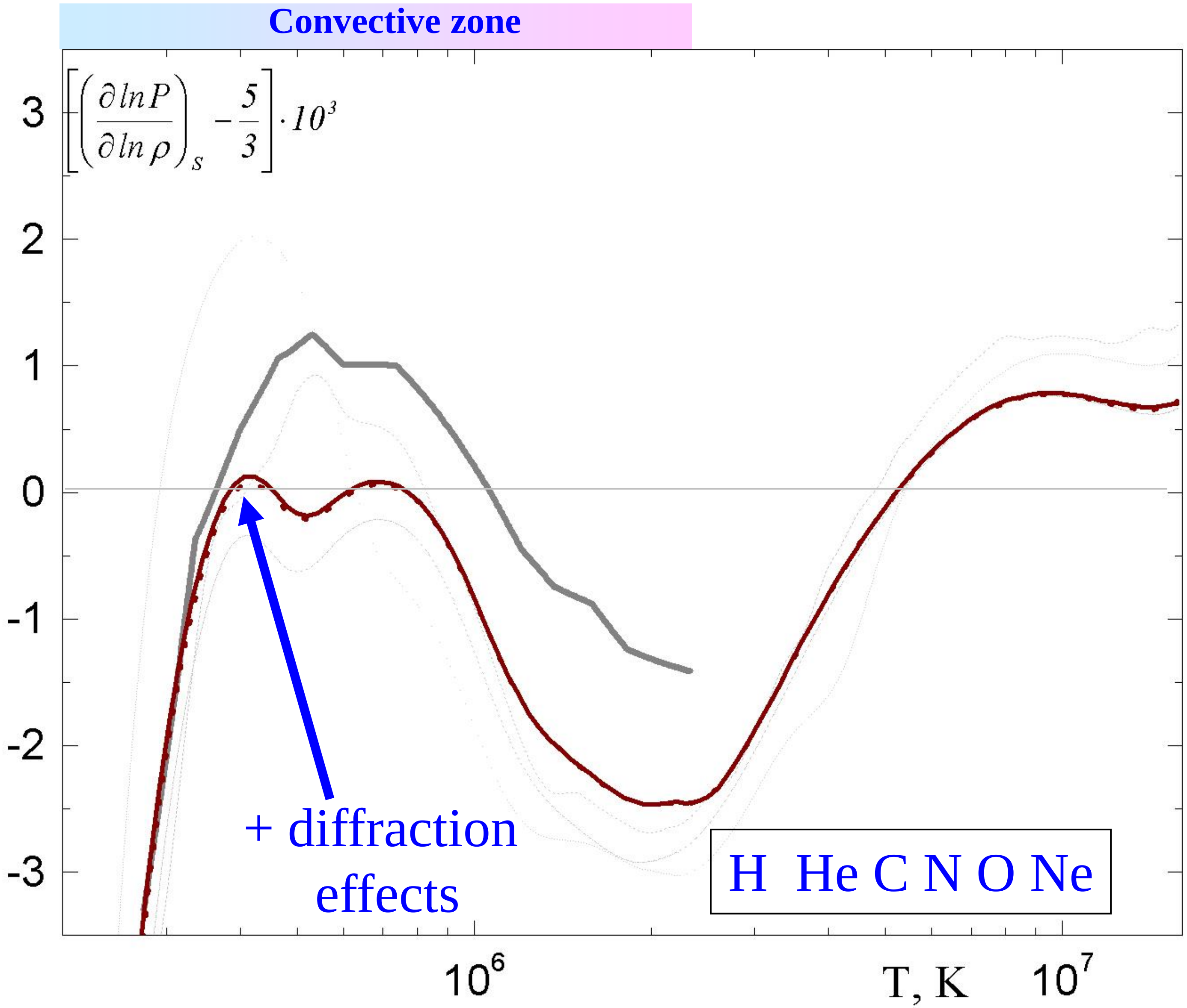
Adiabatic exponent.
Models and inversion results



Adiabatic exponent. Models and inversion results

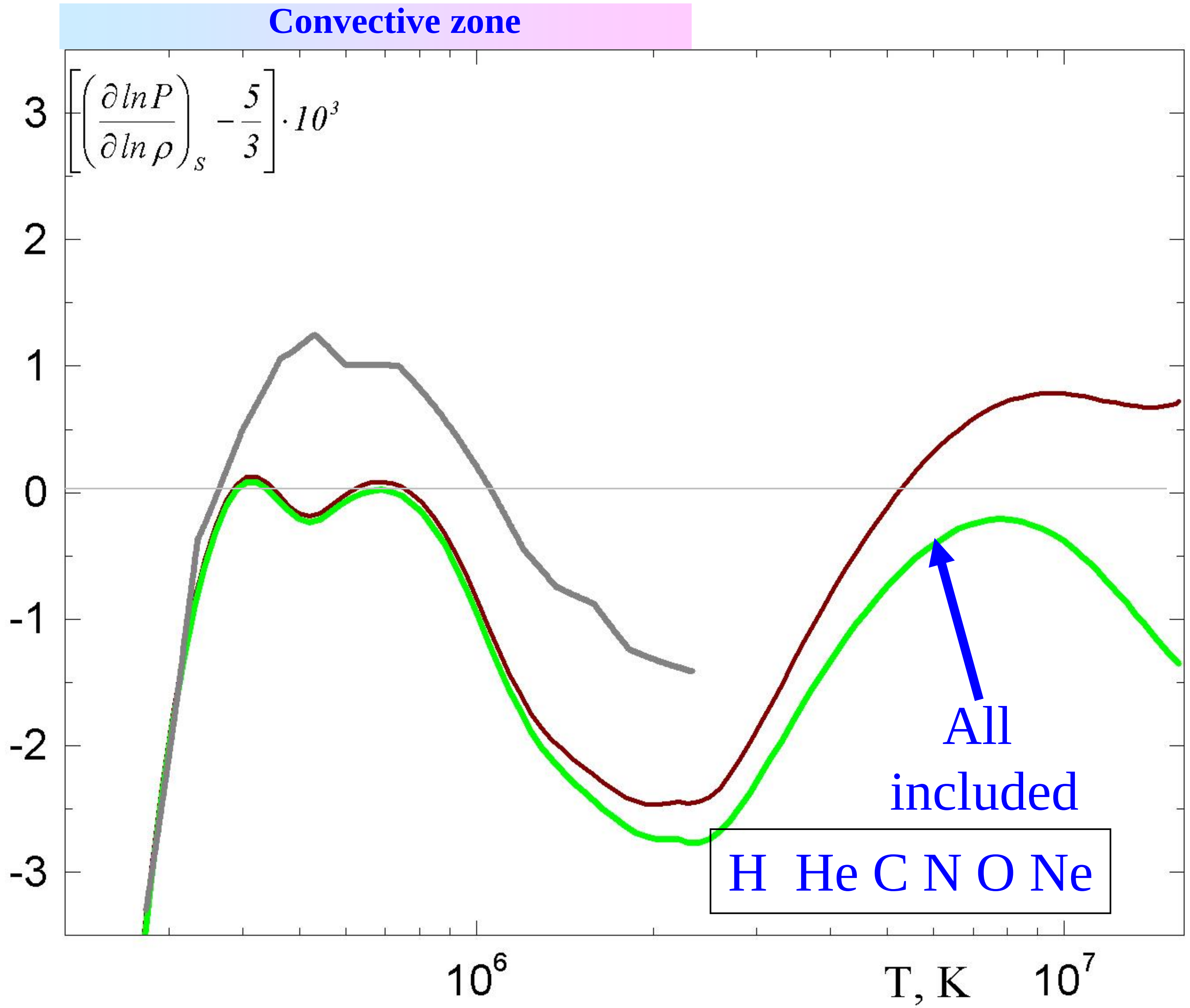


Adiabatic exponent. Models and inversion results

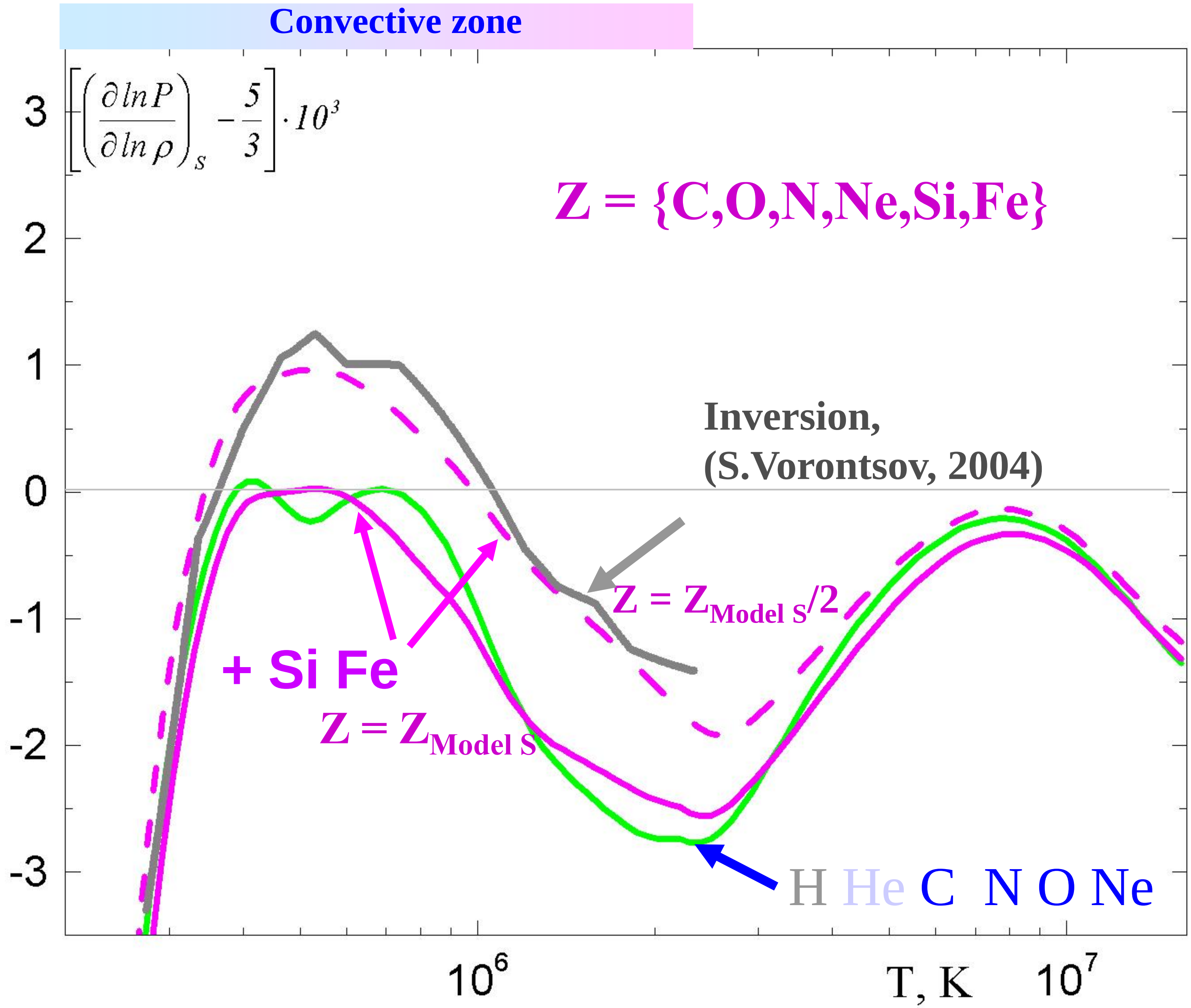


SAHA -S

Adiabatic exponent.
Models and inversion results



Adiabatic exponent.
Heavy elements contribution



Versions of SAHA-S models

SAHA-S1

Element composition — Heavy elements: H He (C N O Ne)

Heavy element abundance — 0.01 ÷ 0.02

50 species of particles

SAHA-S2

Element composition — Heavy elements: H He (C N O Ne Si Fe)

Heavy element abundance — 0.01 ÷ 0.02

95 species of particles, ground states of heavy elements

SAHA-S3 ... ⇒ SAHA-S7

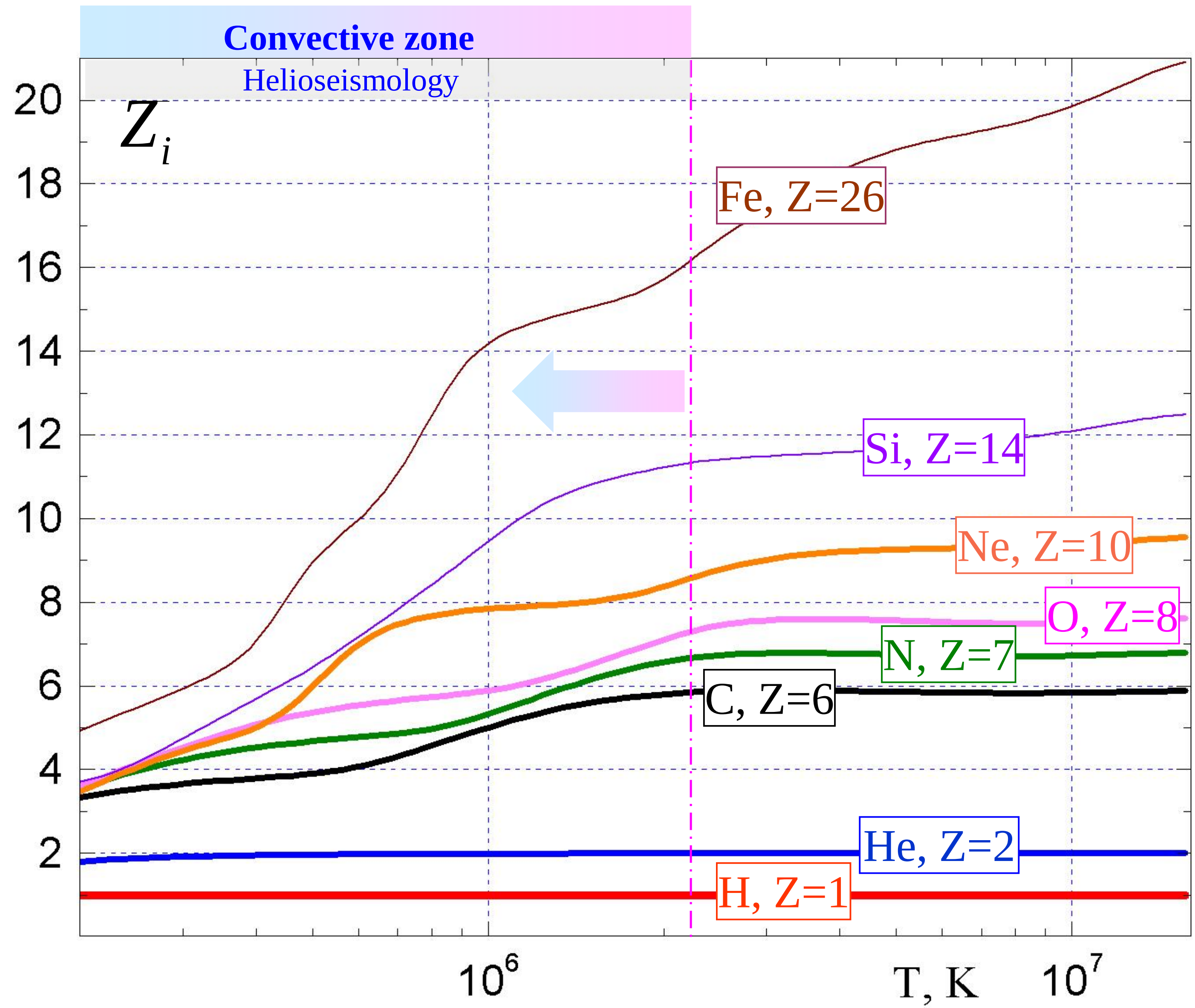
Element composition — Heavy elements: H He (C N O Ne Si Fe Mg S)

Heavy element abundance — 0.005 ÷ 0.02

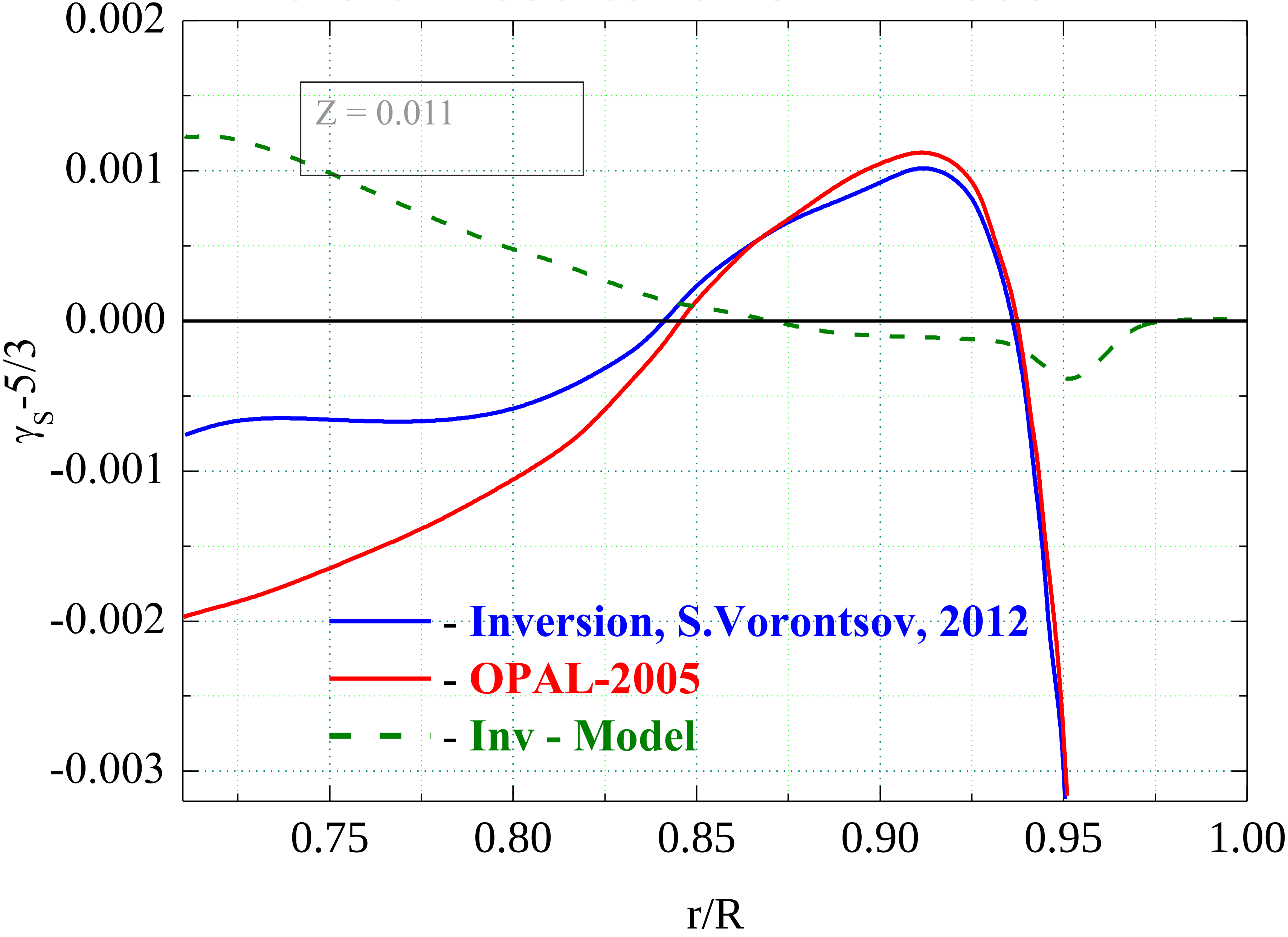
145 species of particles, detailed excitation spectrum of all particles

SAHA–S calculations

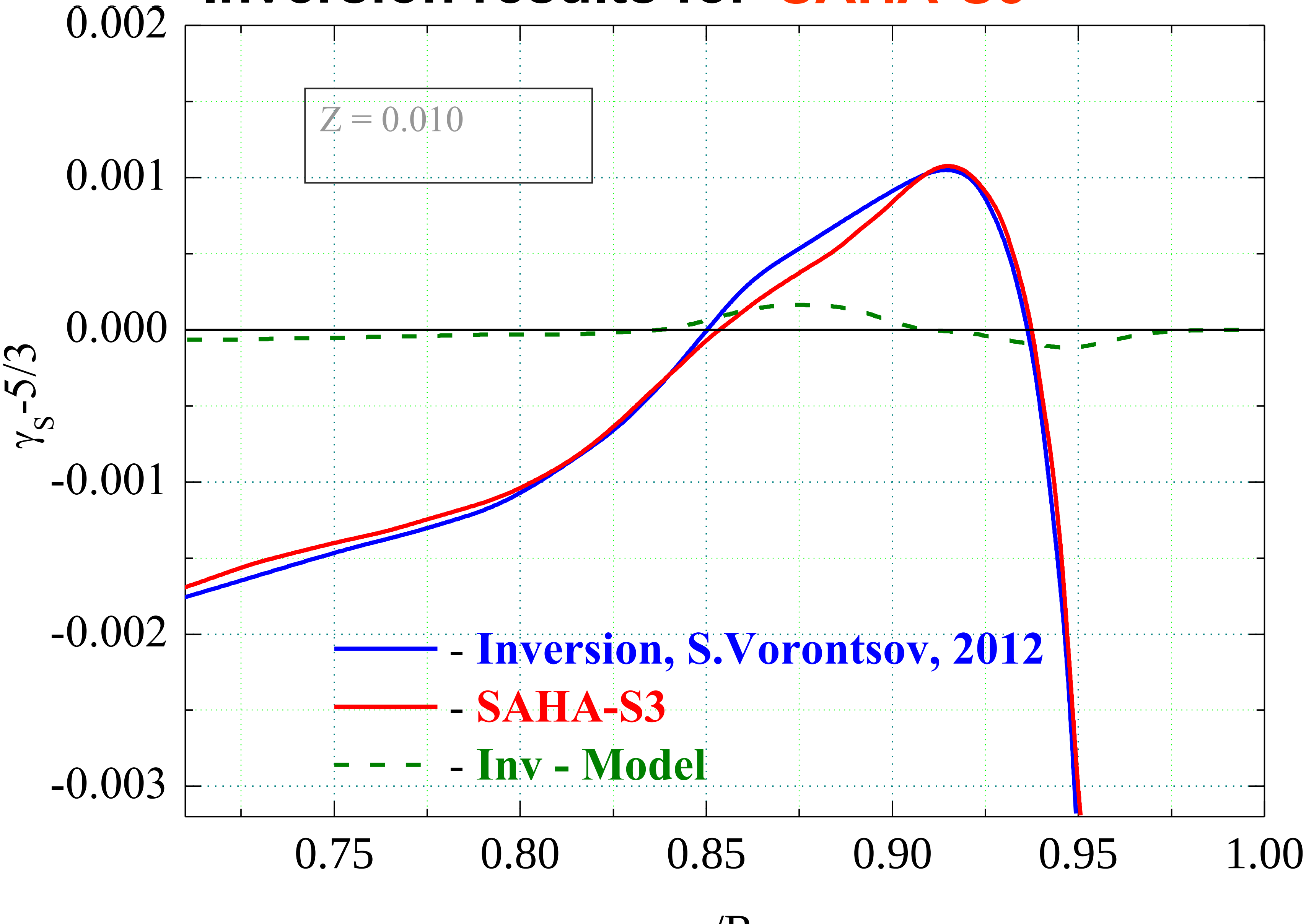
Mean charge of ions along solar trajectory



Adiabatic exponent
Inversion results for OPAL-2005



Adiabatic exponent
Inversion results for SAHA-S3



Hydrogen. Deviations to the ideal Saha pressure along isochore

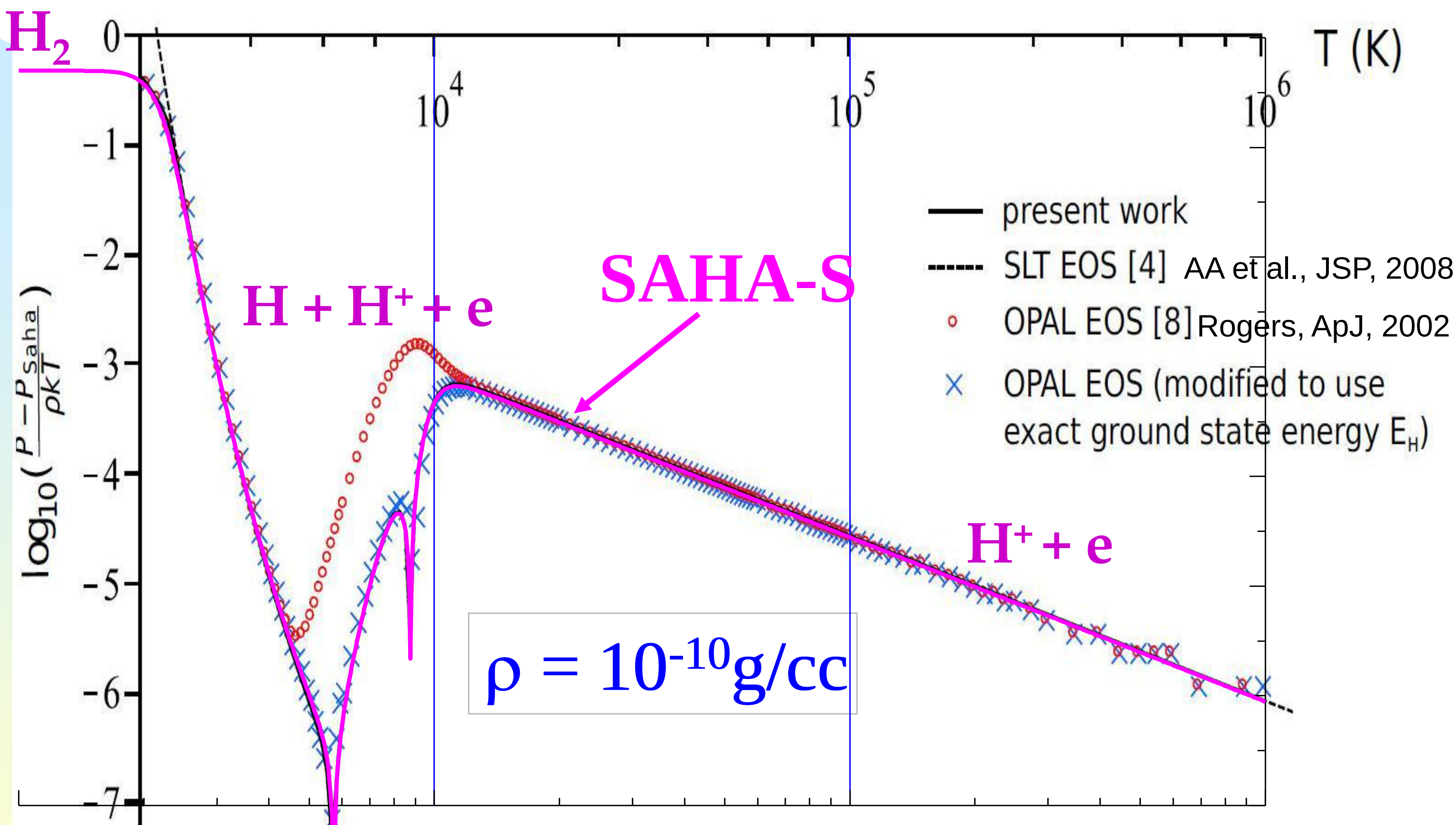


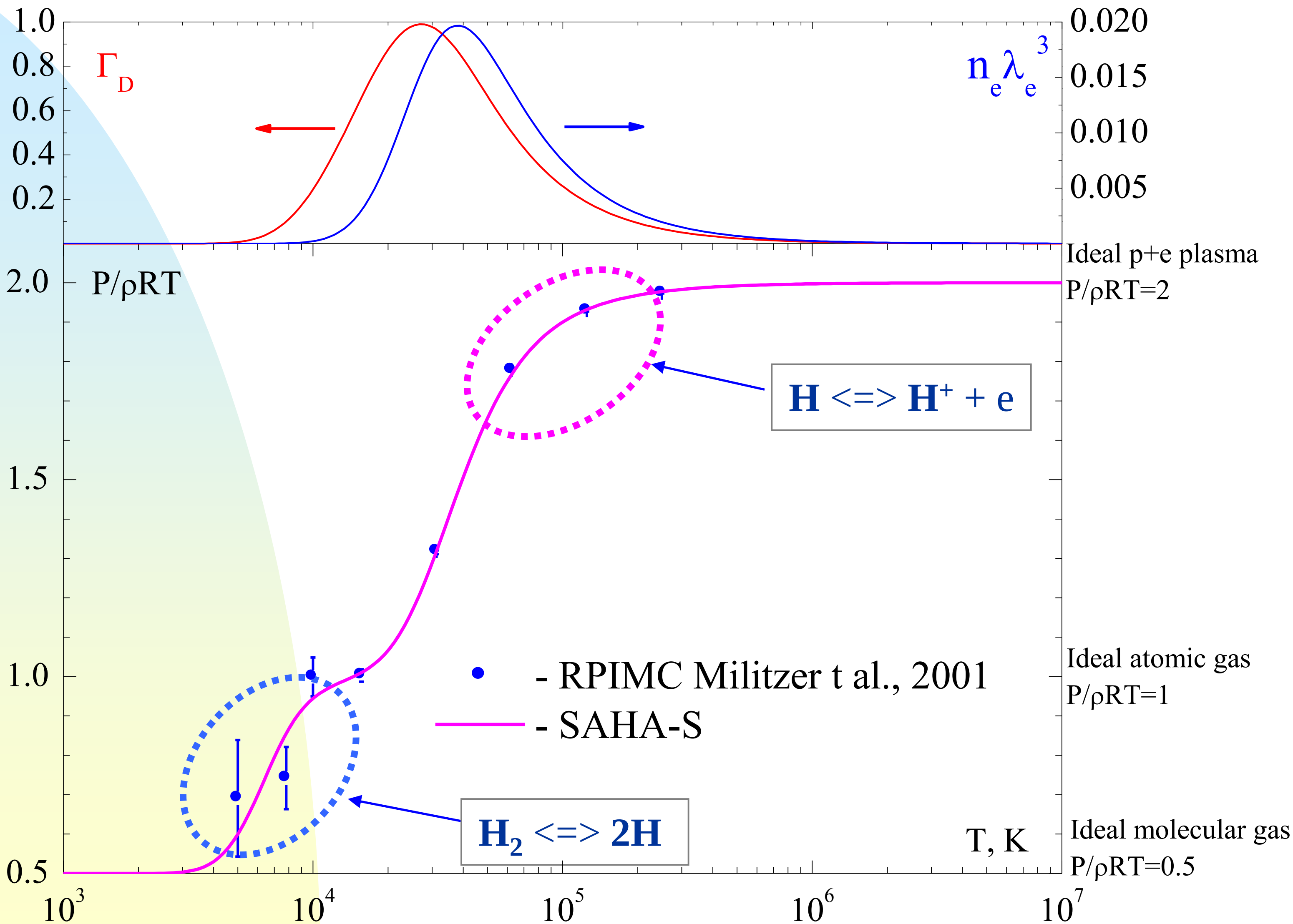
Fig. 2 Log plot of deviations to the ideal Saha pressure along isochore 10^{-10} g/cc. Our predictions (solid line) are compared to the analytical SLT expansion (dashed line) and to the tabulated OPAL equation of state (circles). The crosses correspond to the OPAL EOS modified to account for the finite mass of the proton in the binding energy of the hydrogen atom, i.e. using $E_H = -me^4/(2\hbar^2) \simeq -13.5983$ eV instead of $E_H \simeq 1$ Ry $= -m_e e^4/(2\hbar^2) \simeq -13.65057$ eV. We corrected the OPAL values only at the level of the ideal terms: $P_{\text{OPAL, corr}} = P_{\text{OPAL}} + P_{\text{Saha}}[E_H] - P_{\text{Saha}}[1\ \text{Ry}]$.

Fig. from A. Alastuey and V. Ballenegger, Contrib. Plasma Phys. 52, 2012

Thermal EOS of hydrogen along isochore

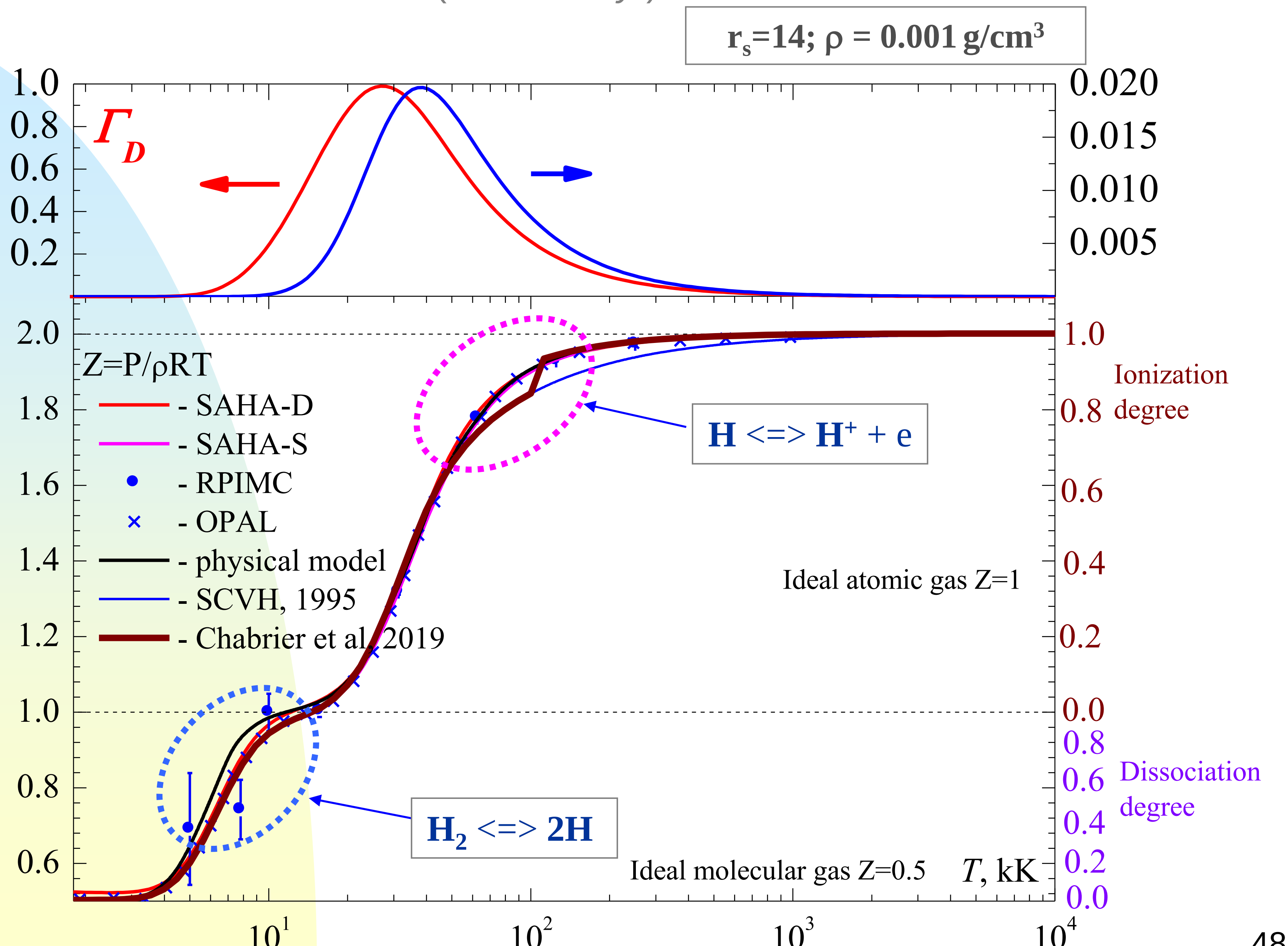
(*low density*)

r_s=14; ρ = 0.001 g/cm^3



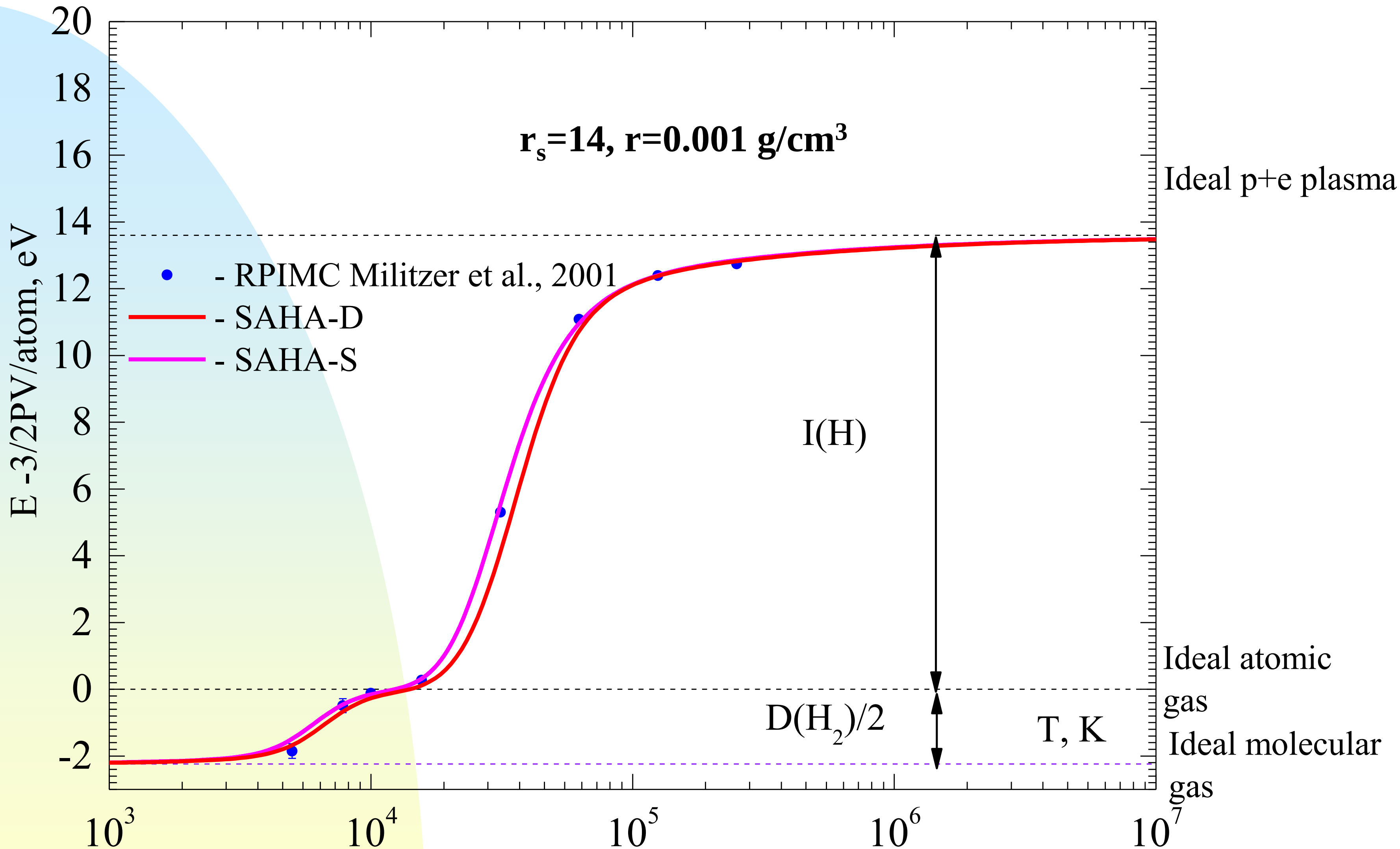
Thermal EOS of hydrogen along isochore

(*low density*)

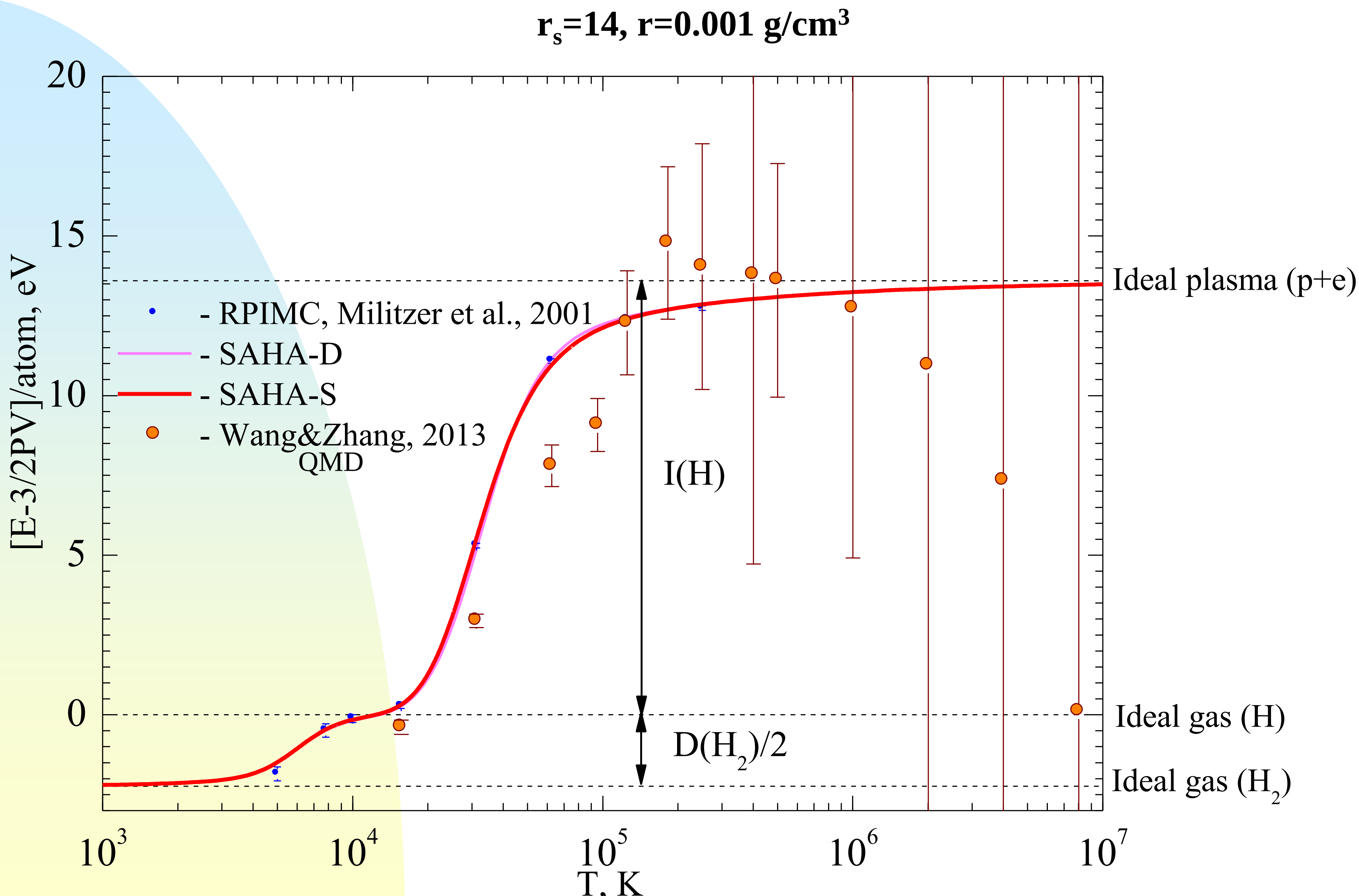


G. Chabrier, S. Mazevet, F. Soubiran, A New Equation of State for Dense Hydrogen–Helium Mixtures, The ApJ, 872:51, 2019

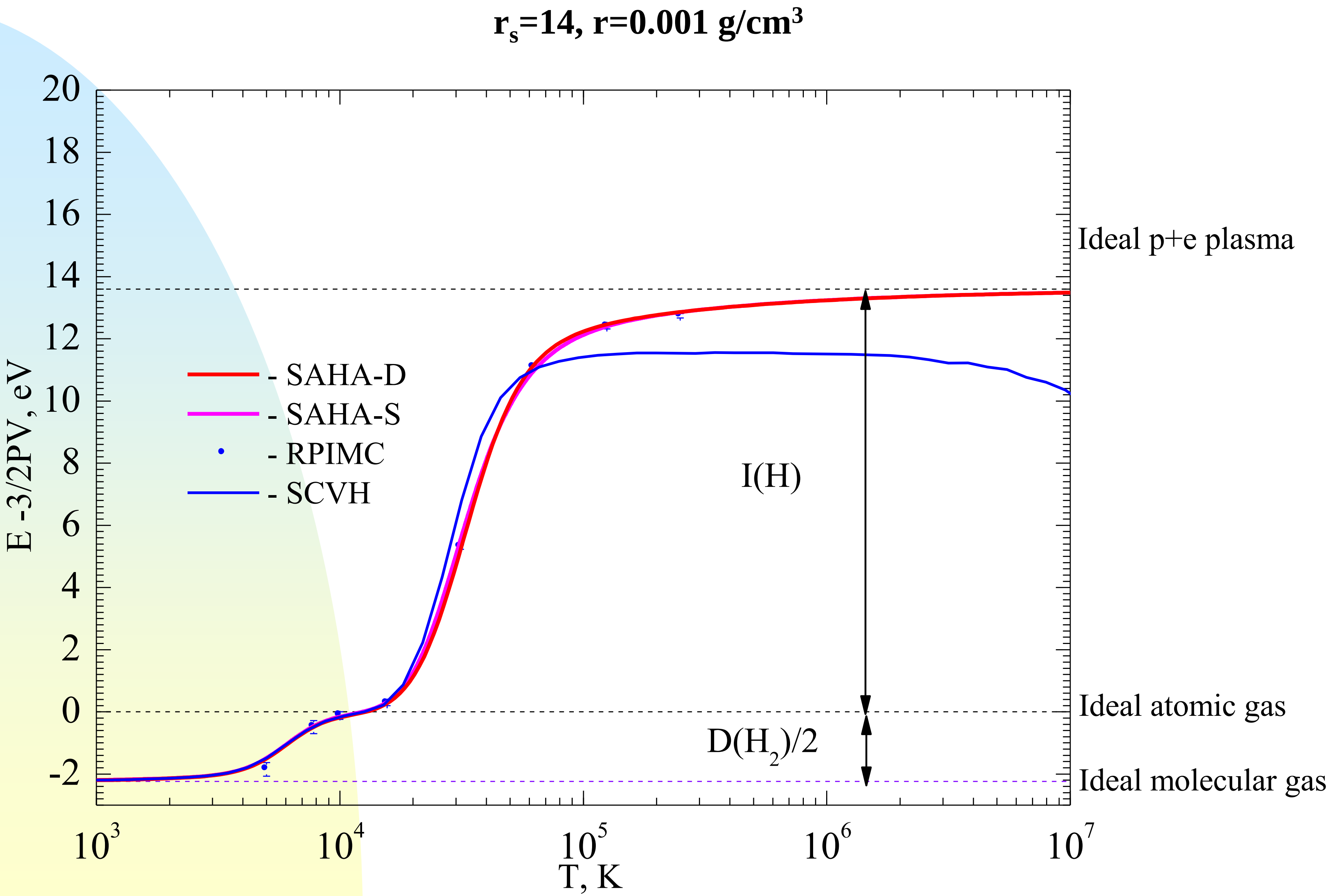
Caloric EOS of Hydrogen along isochore



Caloric EOS of Hydrogen along isochore

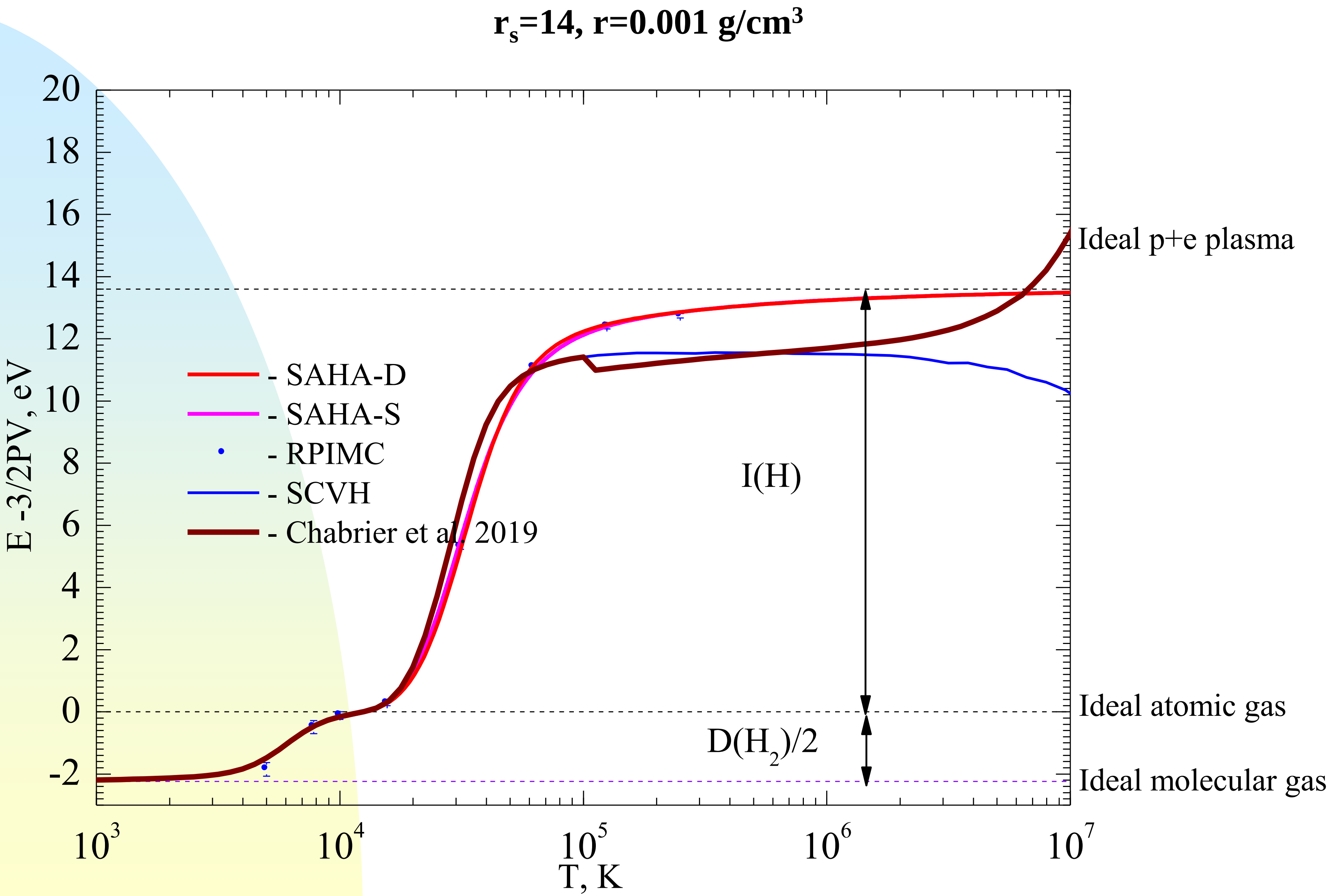


Caloric EOS of Hydrogen along isochore



D Saumon, G Chabrier, HM Van Horn, An equation of state for low-mass stars and giant planets, The ApJ Supplement Series 99, 713, 1995

Caloric EOS of Hydrogen along isochore

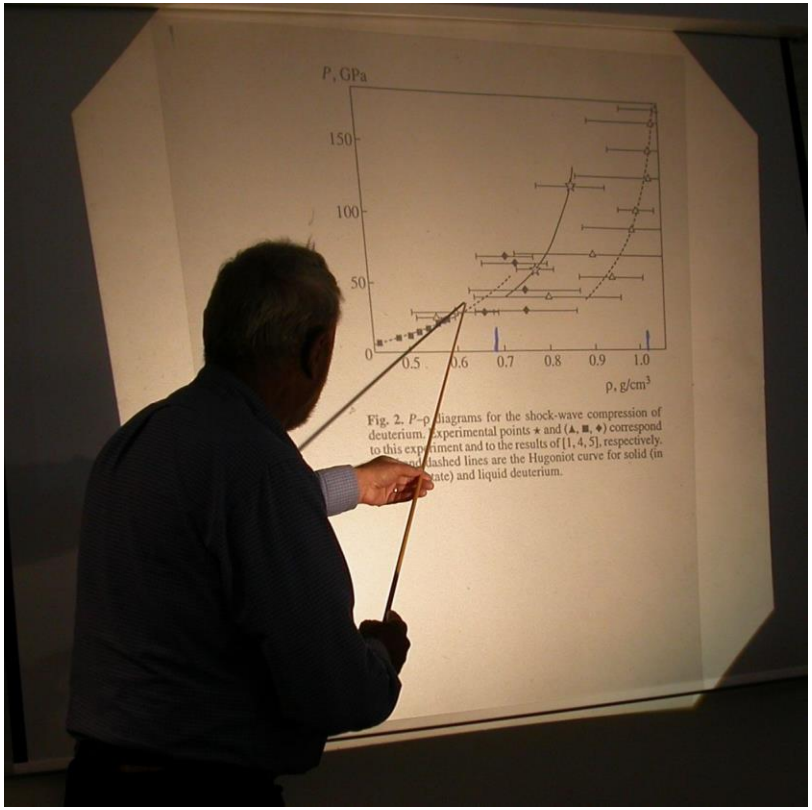


G. Chabrier, S. Mazevet, F. Soubiran, A New Equation of State for Dense Hydrogen–Helium Mixtures, The ApJ, 872:51, **2019**

Leiden 2004

Lorentz Center

Equation-of-State and Phase-Transition Issues in Models of Ordinary Astrophysical Matter
from 2 Jun 2004 through 11 Jun 2004



Thank you!