1 SPH w/ nuclear reaction

Suppose we know acceleration, time derviative of energy, coefficient viscosity, and the next timestep at the initial time. We integrate each particle as follows:

1. Calculate the position, and predict the velocity and energy:

$$\boldsymbol{r}_i = \boldsymbol{r}_i^{(0)} + \boldsymbol{v}_i^{(0)}\Delta t + \frac{1}{2}\boldsymbol{a}_i^{(0)}\Delta t^2 \tag{1}$$

$$\boldsymbol{v}_i^{(1/2)} = \boldsymbol{v}_i^{(0)} + \frac{1}{2}\boldsymbol{a}^{(0)}\Delta t \tag{2}$$

$$u_i^{(1/2)} = u_i^{(0)} + \frac{1}{2}\dot{u}^{(0)}\Delta t \tag{3}$$

$$\tilde{\boldsymbol{v}}_i = \boldsymbol{v}_i^{(0)} + \boldsymbol{a}_i^{(0)}\Delta t \tag{4}$$

$$\tilde{\boldsymbol{u}}_i = \boldsymbol{u}_i^{(0)} + \dot{\boldsymbol{u}}_i^{(0)}\Delta t \tag{5}$$

$$\tilde{\alpha}_i = \alpha_i^{(0)} + \dot{\alpha}_i^{(0)}\Delta t. \tag{6}$$

2. Calculate the density, kernel-support length and grad-h term of each particle by an iterative method:

   (a) Estimate the density by the following expression:

   $$\rho_i = \sum_j m_j W_i \tag{7}$$

   $$\Omega_i = 1 + \frac{1}{D}\frac{H_i}{\rho_i}\sum_j m_j \frac{\partial W_i}{\partial H_i} \tag{8}$$

   where $W_i = W(r_{ij}, H_i)$, $r_{ij} = |\boldsymbol{r}_{ij}|$, and $\boldsymbol{r}_{ij} = \boldsymbol{r}_i - \boldsymbol{r}_j$. The kernel function is expressed as

   $$W(r, H) = H^{-D} w(r/H), \tag{9}$$

   $$\frac{\partial W(r, H)}{\partial H} = -H^{-(D+1)}\left[D w(q) + q\frac{\partial w}{\partial q}\right]. \tag{10}$$

   The formula of $w(q)$ and $\partial w/\partial q$ are described in Appendix A.

   (b) calculate the kernel length as follow:

   $$H_i = (H/h) \times \eta \left(\frac{m_i}{\rho_i}\right)^{1/D}, \tag{11}$$

   where h is the kernel length. The values of η and H/h are described in Appendix A.

   (c) Return to step (2a) unless this is the 3rd time.

(d) Calculate divergence and rotation of $\boldsymbol{v}$:

$$\nabla \cdot \tilde{\boldsymbol{v}}_i = -\frac{1}{\Omega_i \rho_i} \sum \tilde{\boldsymbol{v}}_{ij} \cdot \left[m_j \frac{\partial W_i}{\partial r_{ij}} \frac{\boldsymbol{r}_{ij}}{r_{ij}} \right], \tag{12}$$

$$\nabla \times \tilde{\boldsymbol{v}}_i = \frac{1}{\Omega_i \rho_i} \sum \tilde{\boldsymbol{v}}_{ij} \times \left[m_j \frac{\partial W_i}{\partial r_{ij}} \frac{\boldsymbol{r}_{ij}}{r_{ij}} \right]. \tag{13}$$

The derivative of the kernel function is as follows:

$$\frac{\partial W(r, H)}{\partial r} = H^{-(D+1)} \frac{\partial w(r/H)}{\partial (r/H)}. \tag{14}$$

3. Calculate the pressure ($\tilde{P}_i$) and sound speed ($\tilde{c}_{\mathrm{s},i}$) as follows:

$$P_i = (\gamma - 1)\rho_i \tilde{u}_i \tag{15}$$

$$c_{\mathrm{s},i} = \left(\gamma \frac{P_i}{\rho_i} \right)^{1/2}, \tag{16}$$

or Helmholtz EOS, in which case the temperature ($\tilde{T}_i$) is also obtained.

4. Calculate energy generation ($\epsilon_{\mathrm{nuc},i}$) through nuclear reaction. When the reaction is exothermic, the density (ρ_i) and temperature ($\tilde{T}_i$) are fixed. On the other hand, when the reaction is endothermic, only the density (ρ_i) is fixed.

5. Calculate the Balsara switch:

$$f_i = \frac{|\nabla \cdot \tilde{\boldsymbol{v}}_i|}{|\nabla \cdot \tilde{\boldsymbol{v}}_i| + |\nabla \times \tilde{\boldsymbol{v}}_i| + 0.0001 \tilde{c}_{\mathrm{s},i}/h_i}. \tag{17}$$

6. Calculate the acceleration and the time derivative of the energy:

$$\boldsymbol{a}_i = -\sum \left(\frac{\tilde{P}_i}{\Omega_i \rho_i^2} + \frac{\tilde{P}_j}{\Omega_j \rho_j^2} + f_{ij}\Pi_{ij} \right) \left[\frac{m_j}{2} \left(\frac{\partial W_i}{\partial r_{ij}} + \frac{\partial W_j}{\partial r_{ij}} \right) \frac{\boldsymbol{r}_{ij}}{r_{ij}} \right], \tag{18}$$

$$\dot{u}_i = \sum \left(\frac{\tilde{P}_i}{\Omega_i \rho_i^2} + \frac{f_{ij}\Pi_{ij}}{2} \right) \left[\frac{m_j}{2} \left(\frac{\partial W_i}{\partial r_{ij}} + \frac{\partial W_j}{\partial r_{ij}} \right) \frac{\boldsymbol{r}_{ij}}{r_{ij}} \right] \cdot \tilde{\boldsymbol{v}}_{ij}, \tag{19}$$

where $f_{ij} = (f_i + f_j)/2$, and Π_{ij} is an artificial viscosity. The artificial viscosity is expressed as follows:

$$\Pi_{ij} = -\frac{\tilde{\alpha}_i}{2} \frac{v_{ij}^{\mathrm{sig}} w_{ij}}{\rho_{ij}} \tag{20}$$

$$v_{ij}^{\mathrm{sig}} = c_{\mathrm{s},i} + c_{\mathrm{s},j} - 3w_{ij} \tag{21}$$

$$w_{ij} = \begin{cases} \dfrac{\boldsymbol{r}_{ij} \cdot \tilde{\boldsymbol{v}}_{ij}}{|\boldsymbol{r}_{ij}|} & (\boldsymbol{r}_{ij} \cdot \tilde{\boldsymbol{v}}_{ij} < 0) \\ 0 & (\boldsymbol{r}_{ij} \cdot \tilde{\boldsymbol{v}}_{ij} \geq 0) \end{cases} \tag{22}$$

where $\rho_{ij} = (\rho_i + \rho_j)/2$.

7. Calculate $\dot{\alpha}$:

$$\dot{\alpha}_i = -\frac{\tilde{\alpha}_i - \alpha_{\min}}{h_i/(0.25\tilde{c}_{s,i})} + S_i \tag{23}$$
$$S_i = \max\left[-(\nabla \cdot \tilde{\boldsymbol{v}}_i)(\alpha_{\max} - \tilde{\alpha}_i), 0\right] \tag{24}$$

8. Correct the velocity and energy:

$$\boldsymbol{v}_i = \boldsymbol{v}_i^{(1/2)} + \frac{1}{2}\boldsymbol{a}_i \Delta t \tag{25}$$
$$u_i = u_i^{(1/2)} + \frac{1}{2}\dot{u}_i \Delta t + \epsilon_{\mathrm{nuc},i} \tag{26}$$
$$\alpha_i = \alpha_i^{(1/2)} + \frac{1}{2}\dot{\alpha}_i \Delta t. \tag{27}$$

9. Calculate the next timestep:

$$\Delta t_{\mathrm{next}} = C \min_i \left[\frac{2H_i}{\max_j\left(v_{ij}^{\mathrm{sig}}\right)}, \Delta t \left|\frac{u_i^{(0)}}{u_i - u_i^{(0)}}\right|\right]. \tag{28}$$

10. Return to step 1.

2 Helmholtz EOS

Coorporate Timmes's EOS. The compositions are 100 % carbon, 50 % carbon and 50 % oxygen, and will be 100 % helium.

A Kernels

A.1 Cubic spline kernel

We describe the cubic spline kernel:

$$w(r/H) = 2^D \sigma \times \begin{cases} \left(1 - 6q^2 + 6q^3\right) & (0 \le q < 1/2) \\ \left[2(1-q)^3\right] & (1/2 \le q < 1) \\ 0 & (q \ge 1) \end{cases} \tag{29}$$

$$\frac{\partial w(q)}{\partial q} = (-6)2^D \sigma \times \begin{cases} 1/3 & (0 \le q < 1/3) \\ \left(2q - 3q^2\right) & (1/3 \le q < 1/2) \\ (1-q)^2 & (1/2 \le q < 1) \\ 0 & (q \ge 1) \end{cases}, \tag{30}$$

$$\tag{31}$$

where $\sigma = 2/3$ (1D), $10/7\pi$ (2D), and $1/\pi$ (3D).

For this kernel, $\eta = 1.2$, and $H/h = 2$.

A.2 Wendland C^2 kernel

We describe Wendland C^2 kernel: In the case of $D = 1$,

$$w(q) = C_{\mathrm{W}}(1-q)_+^3(1+3q) \tag{32}$$

$$\frac{\partial w(q)}{\partial q} = 3C_{\mathrm{W}}\left[(1-q)_+^3 - (1-q)_+^2(1+3q)\right], \tag{33}$$

and in the case of $D = 2, 3$,

$$w(q) = C_{\mathrm{W}}(1-q)_+^4(1+4q) \tag{34}$$

$$\frac{\partial w(q)}{\partial q} = 4C_{\mathrm{W}}\left[(1-q)_+^4 - (1-q)_+^3(1+4q)\right], \tag{35}$$

where $C_{\mathrm{W}} = 5/4$ $(D = 1)$, $7/\pi$ $(D = 2)$, and $21/(2\pi)$ $(D = 3)$. For this kernel, $\eta = 1.6$, and $H/h = 1.620185(D = 1)$, $1.897367(D = 2)$, and $1.93492(D = 3)$.

A.3 Wendland C^4 kernel

We describe Wendland C^4 kernel: In the case of $D = 1$,

$$w(q) = C_{\mathrm{W}}(1-q)_+^5(1+5q+8q^2) \tag{36}$$

$$\frac{\partial w(q)}{\partial q} = C_{\mathrm{W}}(1-q)_+^4\left[-5(1+5q+8q^2) + (1-q)_+(5+16q)\right] \tag{37}$$

and in the case of $D = 2, 3$,

$$w(q) = C_{\mathrm{W}}(1-q)_+^6\left[1+6q+(35/3)q^2\right] \tag{38}$$

$$\frac{\partial w(q)}{\partial q} = C_{\mathrm{W}}(1-q)_+^5\left\{-6\left[1+6q+(35/3)q^2\right] + (1-q)_+\left[6+(70/3)q\right]\right\} \tag{39}$$

where $C_{\mathrm{W}} = 3/2$ $(D = 1)$, $9/\pi$ $(D = 2)$, and $495/(32\pi)$ $(D = 3)$. For this kernel, $\eta = 1.6$, and $H/h = 1.936492(D = 1)$, $2.171239(D = 2)$, and $2.207940(D = 3)$.

B SPH tests

1. 1D shock tube (CUBICSPLINE, USE_AT1D)
2. 3D shock tube (CUBICSPLINE)
3. Strong shock (CUBICSPLINE, USE_AT1D)
4. Point like explosion (CUBICSPLINE)
5. Evrard test (CUBICSPLINE, USE_AT3D, GRAVITY)

C EOS tests

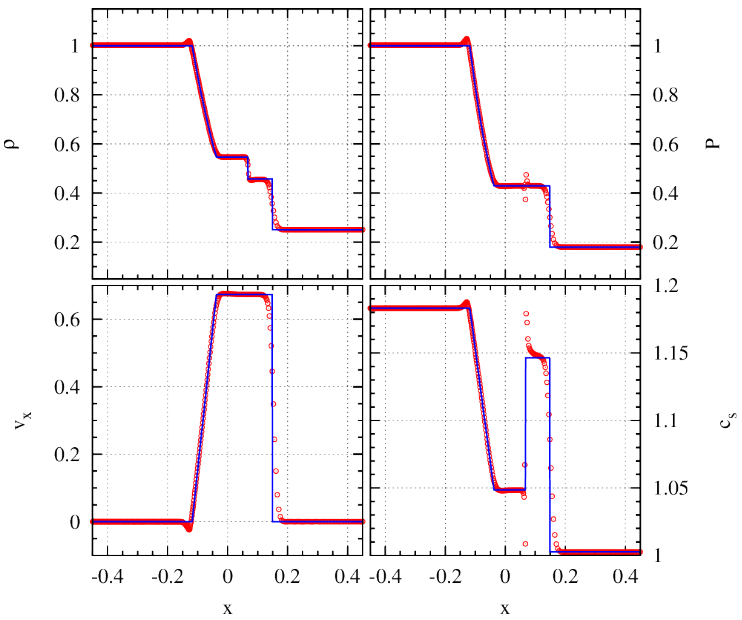

Figure 1: 1D shock tube (cubic spline, $\gamma = 1.4$, $\alpha = 1.0$).

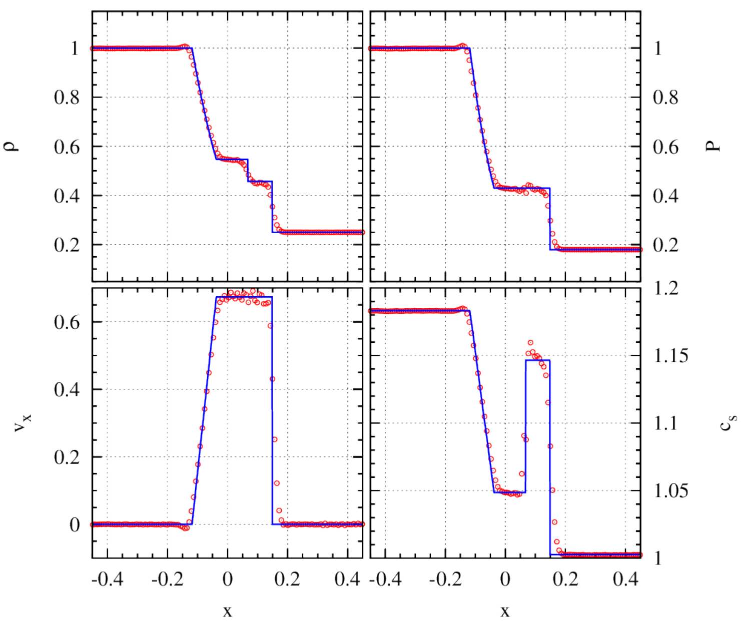

Figure 2: 3D shock tube (cubic spline, $\gamma = 1.4$, $\alpha = 1.0$).

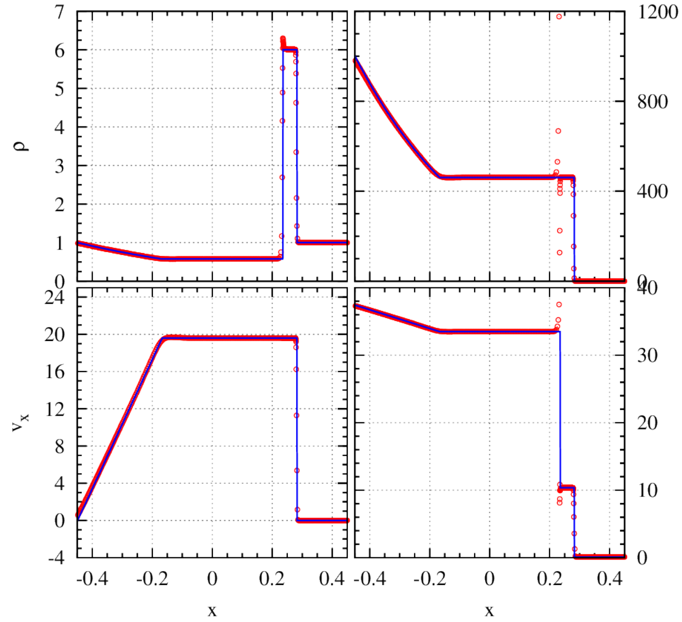

Figure 3: Strong shock (cubic spline, $\gamma = 1.4$, $\alpha = 1.0$).

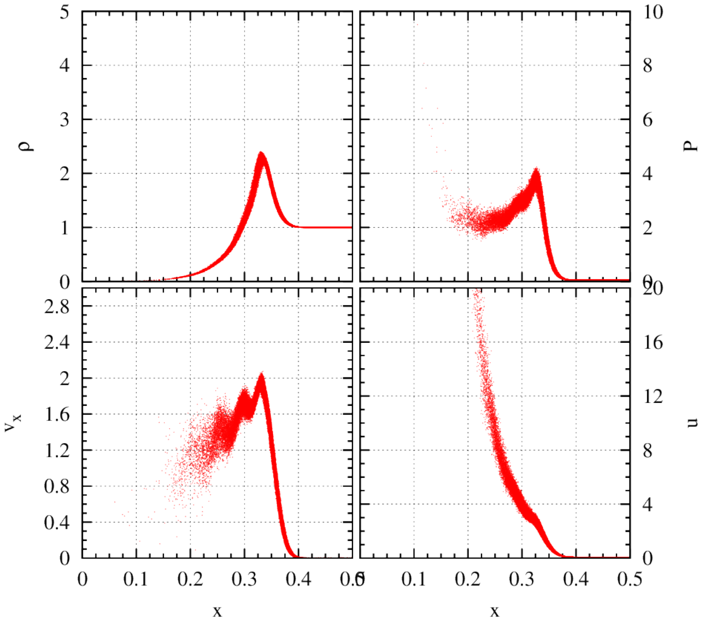

Figure 4: Point like explosion (cubic spline, $\gamma = 5/3$, $\alpha = 3.0$).

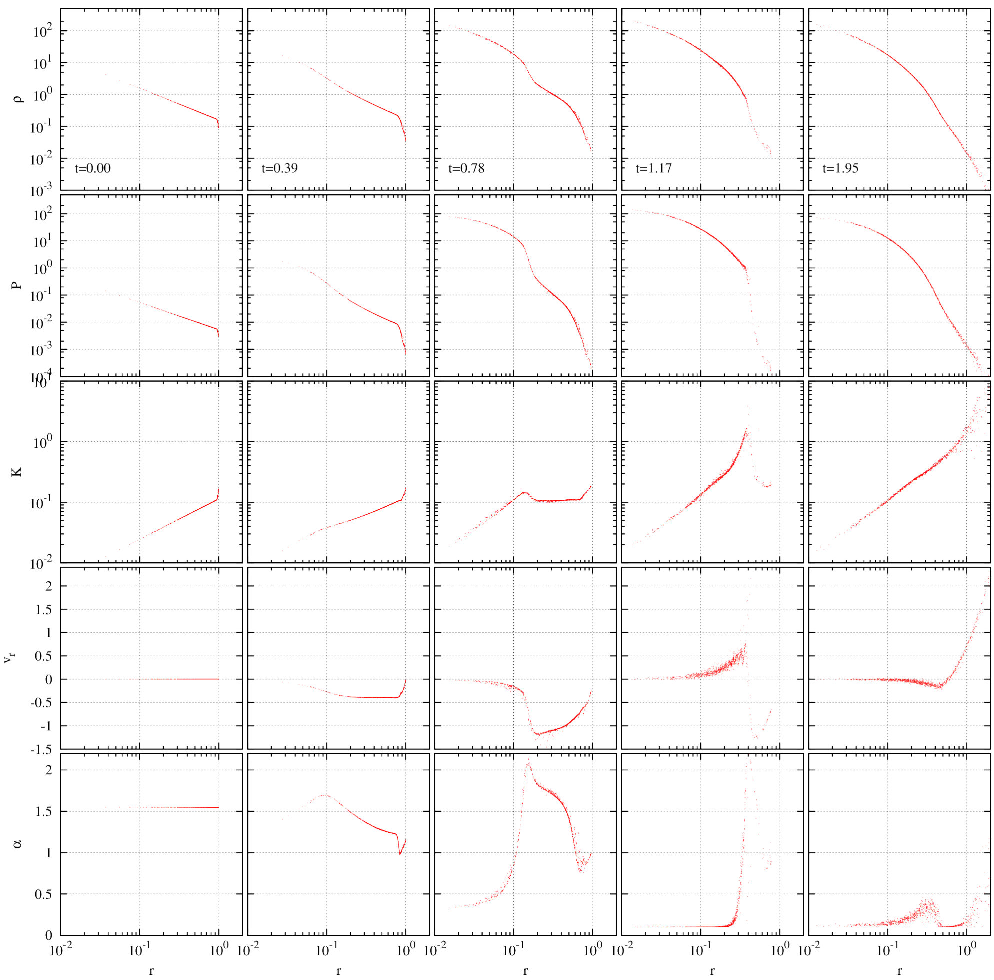

Figure 5: Evrard test (cubic spline, $\gamma = 5/3$, $\alpha_{\min} = 0.1$, $\alpha_{\max} = 3.0$).

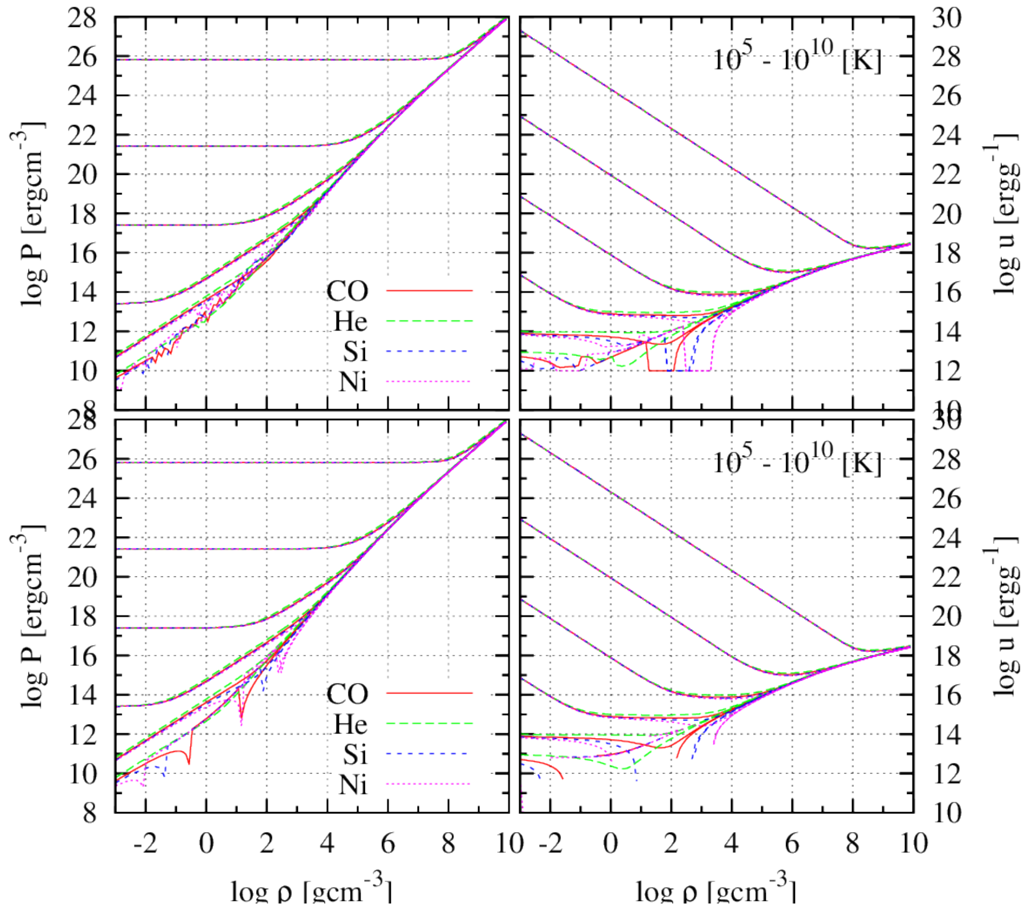

Figure 6: Helmholtz EOS w/ lookup table (top) and w/o (bottom).

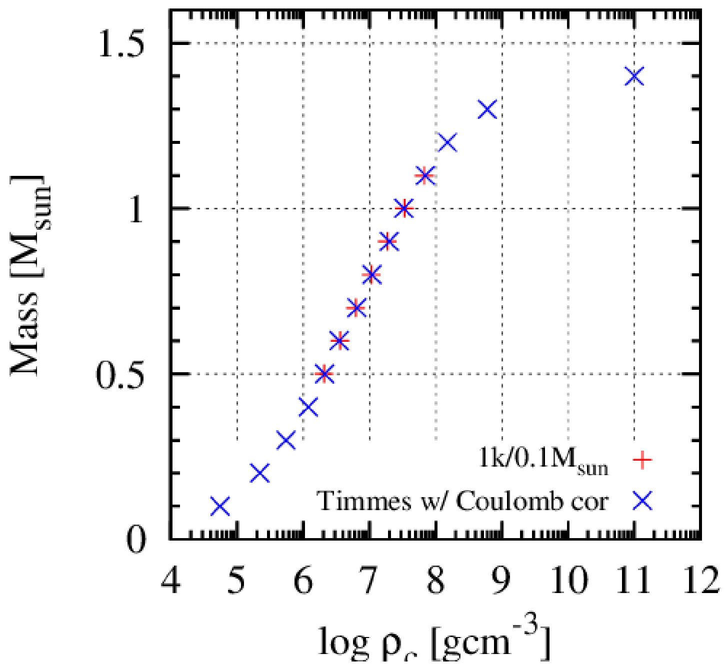

Figure 7: Single COWD equilibrium ($1k/0.1M_{\odot}$) w/ new damping. The new damping mode is the addtion of a sort of cooling during 100 s, such that $u_{\mathrm{new},i} = (u_{\mathrm{old},i} - u_{\min}(\rho_i))\exp(-0.1\Delta t) + u_{\min}(\rho_i)$.

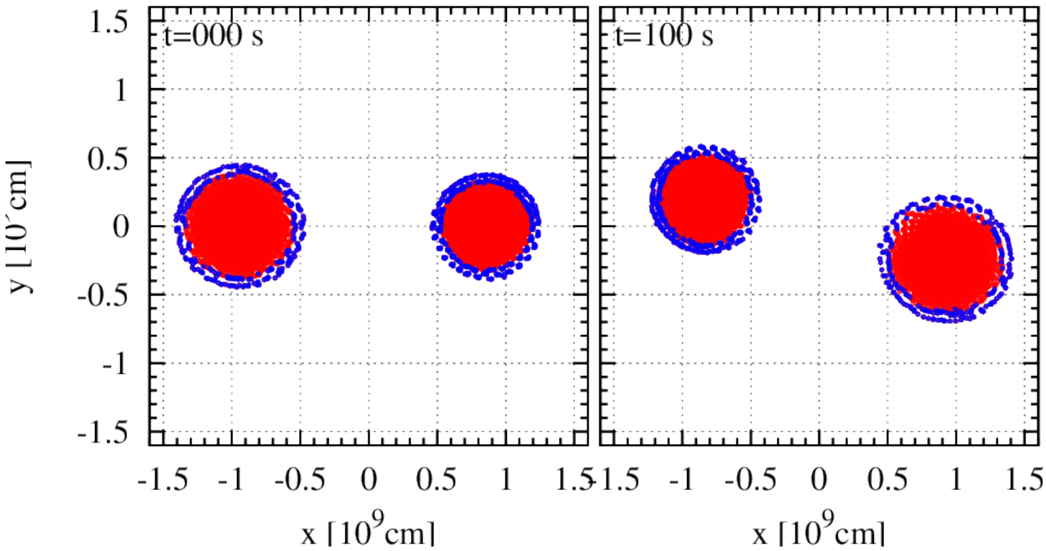

Figure 8: Density and temperature of $1.1M_{\odot}$ and $1.0M_{\odot}$ COWDs ($1k/0.1M_{\odot}$) from 1.8×10^9cm. Blue points indicate helium particles ($f_{\rm He} = 0.1$).

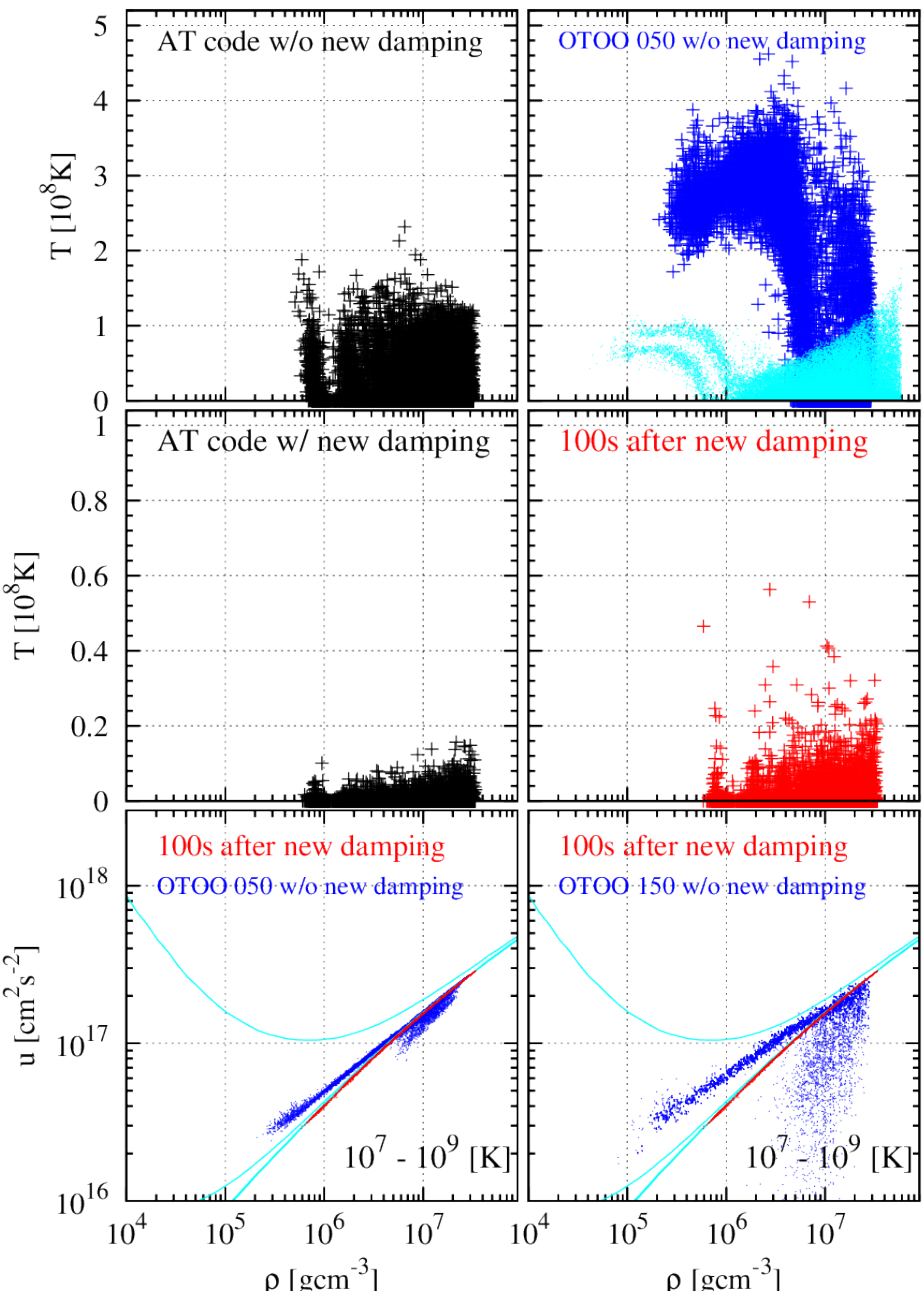

Figure 9: $1M_{\odot}$ COWD ($1k/0.1M_{\odot}$).

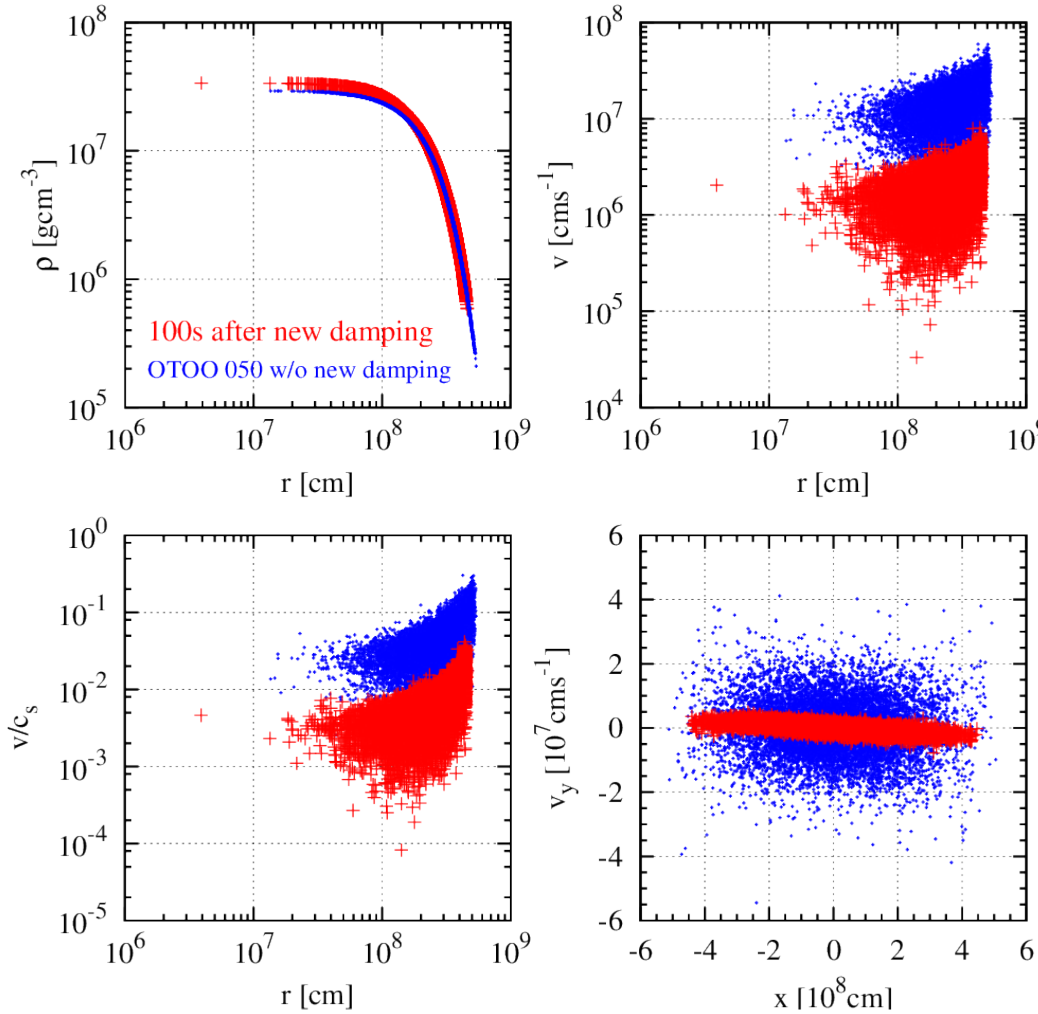

Figure 10: $1M_{\odot}$ COWD ($1k/0.1M_{\odot}$).

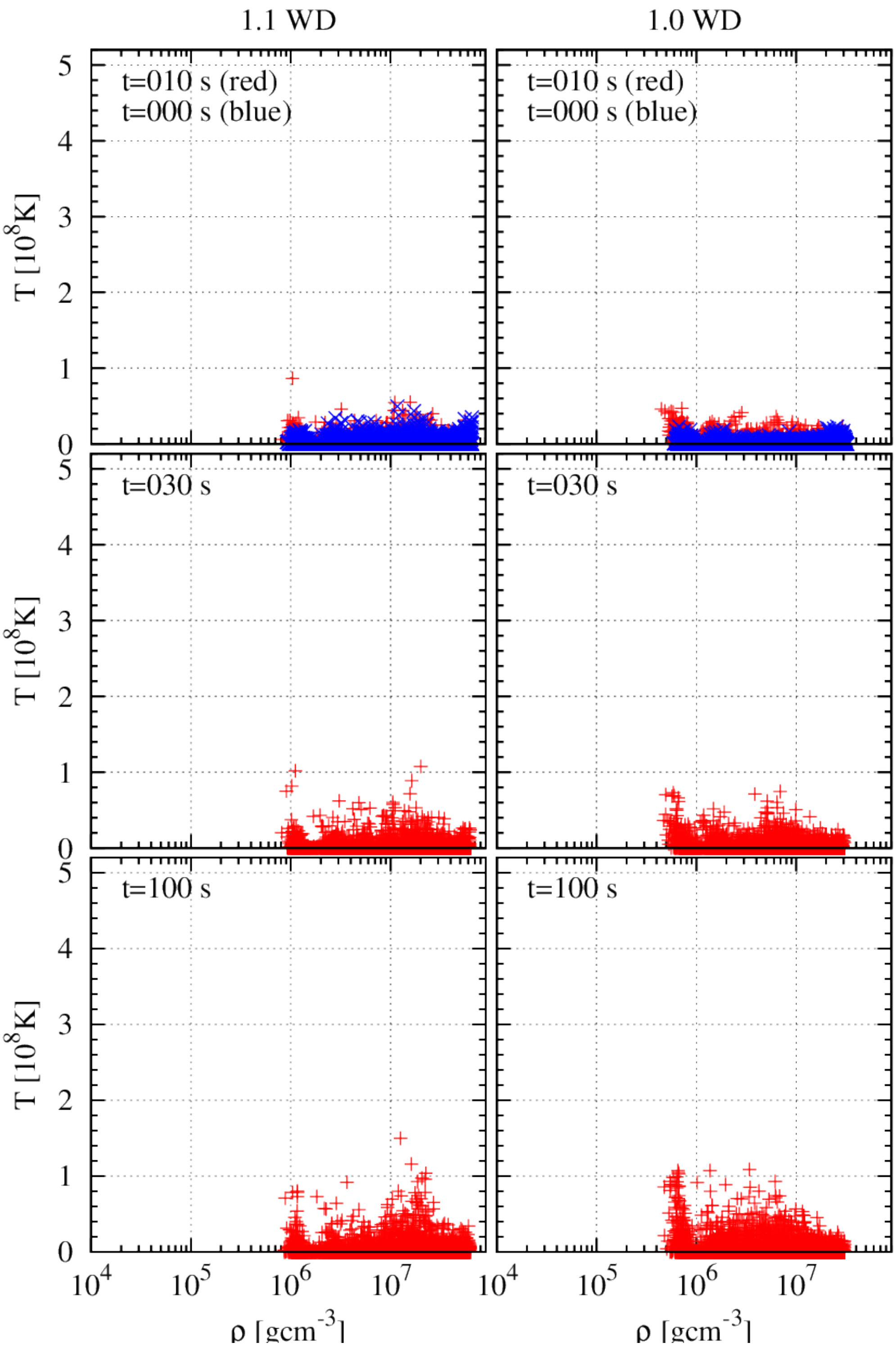

Figure 11: Density and temperature of $1.1M_{\odot}$ and $1.0M_{\odot}$ COWDs ($1k/0.1M_{\odot}$) from 1.8×10^{9}cm.

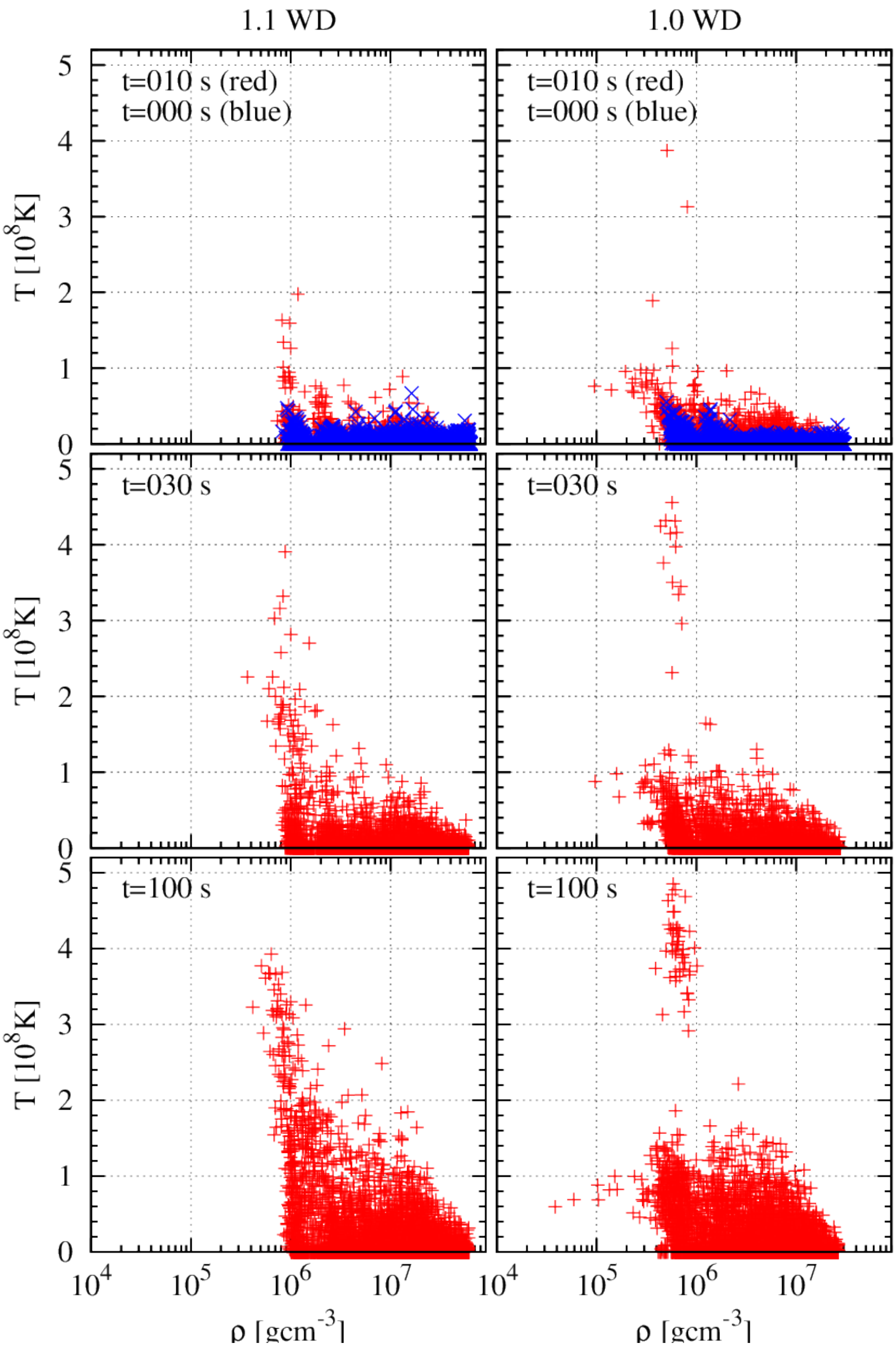

Figure 12: Density and temperature of $1.1M_{\odot}$ and $1.0M_{\odot}$ COWDs ($1k/0.1M_{\odot}$) from 1.5×10^9cm.