Code Comparison Project – two-layer setup 3D simulation 256cubed (averaging window study of RANS analysis)

```
In [2]: run ransX.py
#----------------------------------------------------#
('Datafile with space-time averages: ', 'DATA/TSERIES/tseries_ccptwo_256c_cosma_180secs.npy')
('Central time (in s): ', 1017.1)
('Averaging windows (in s): ', 180.0)
('Time range (in s from-to): ', 0.0, 1999.0)
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Resolution: 256 256 256
Radial size of computational domain (in cm): 4.02e+08 1.20e+09
Radial size of convection zone (in cm):  4.11e+08 9.52e+08
Extent of convection zone (in Hp): 2.754587
Averaging time window (in s): 180.000000
RMS velocities in convection zone (in cm/s):  1.79e+07
Convective turnover timescale (in s)  6.03e+01
P_turb o P_gas 1.33e-03
Mach number Max 3.53e-02
Mach number Mean 2.74e-02
Dissipation length scale (in cm): 1.57e+09
Total nuclear luminosity (in erg/s): 4.51e+45
Rate of TKE dissipation (in erg/s): 1.06e+45
Dissipation timescale for TKE (in s): 43.709265
Reynolds number: 963
```

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In [3]: run ransX.py
#----------------------------------------------------#
('Datafile with space-time averages: ', 'DATA/TSERIES/tseries_ccptwo_256c_cosma_600secs.npy')
('Central time (in s): ', 1017.1)
('Averaging windows (in s): ', 600.0)
('Time range (in s from-to): ', 0.0, 1999.0)
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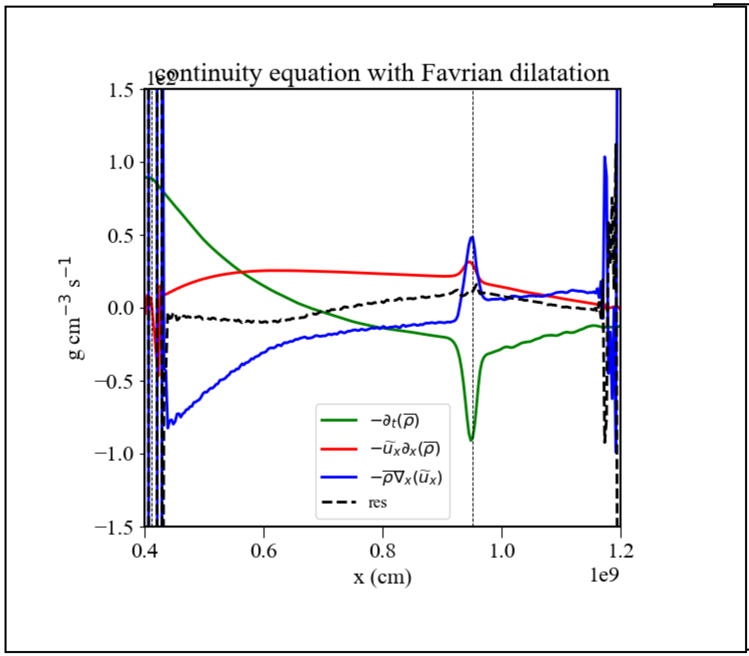
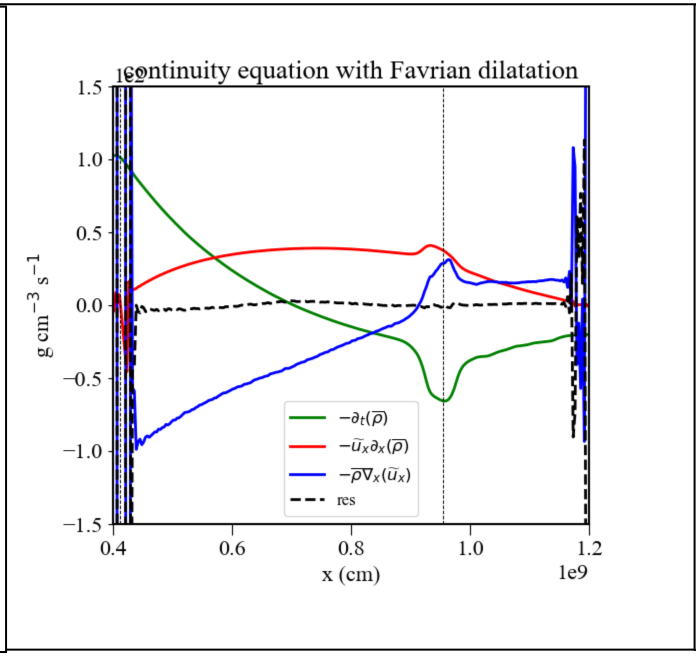
Resolution: 256 256 256
Radial size of computational domain (in cm): 4.02e+08 1.20e+09
Radial size of convection zone (in cm):  4.11e+08 9.55e+08
Extent of convection zone (in Hp): 2.770521
Averaging time window (in s): 600.000000
RMS velocities in convection zone (in cm/s):  1.74e+07
Convective turnover timescale (in s)  6.24e+01
P_turb o P_gas 1.28e-03
Mach number Max 3.37e-02
Mach number Mean 2.70e-02
Dissipation length scale (in cm): 1.46e+09
Total nuclear luminosity (in erg/s): 4.51e+45
Rate of TKE dissipation (in erg/s): 1.04e+45
Dissipation timescale for TKE (in s): 41.870512
Reynolds number: 971
```

```
In [4]: run ransX.py
#----------------------------------------------------#
('Datafile with space-time averages: ', 'DATA/TSERIES/tseries_ccptwo_256c_cosma_1500secs.npy')
('Central time (in s): ', 1017.1)
('Averaging windows (in s): ', 1500.0)
('Time range (in s from-to): ', 0.0, 1999.0)
--------------
Resolution: 256 256 256
Radial size of computational domain (in cm): 4.02e+08 1.20e+09
Radial size of convection zone (in cm):  4.11e+08 9.70e+08
Extent of convection zone (in Hp): 2.850421
Averaging time window (in s): 1500.000000
RMS velocities in convection zone (in cm/s):  1.73e+07
Convective turnover timescale (in s)  6.45e+01
P_turb o P_gas 1.32e-03
Mach number Max 3.43e-02
Mach number Mean 2.74e-02
Dissipation length scale (in cm): 1.49e+09
Total nuclear luminosity (in erg/s): 4.51e+45
Rate of TKE dissipation (in erg/s): 1.02e+45
Dissipation timescale for TKE (in s): 42.955814
Reynolds number: 1008
```

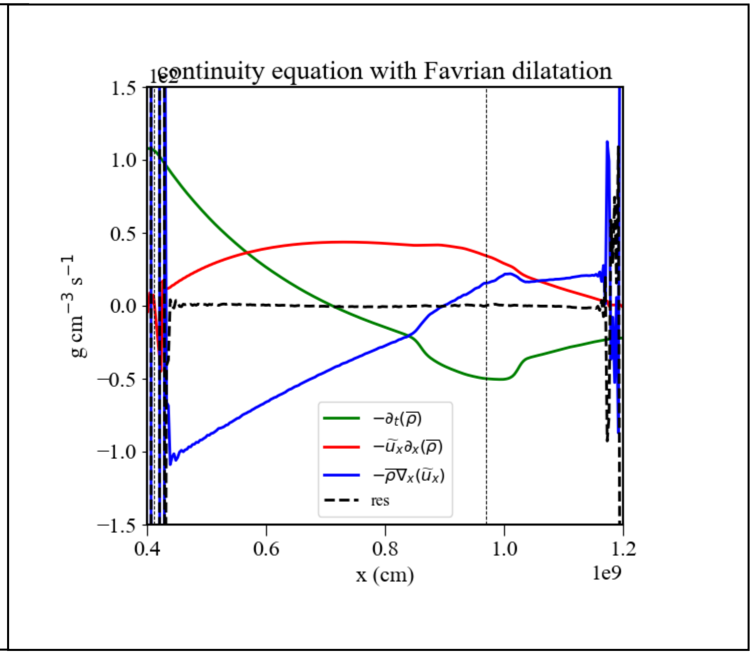
180 secs (3 TOs)

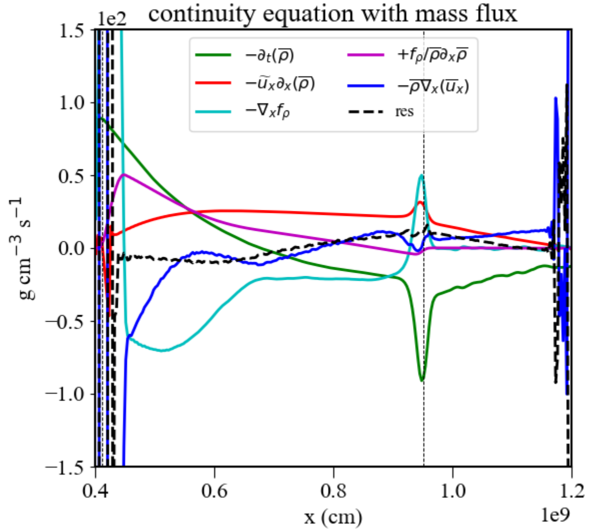


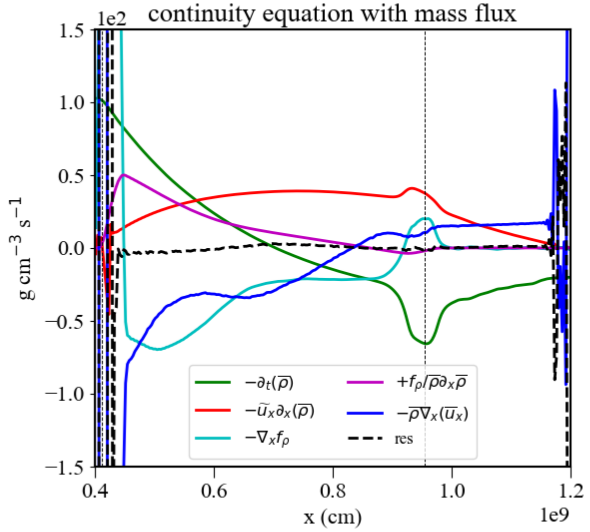
600 secs (10 TOs)

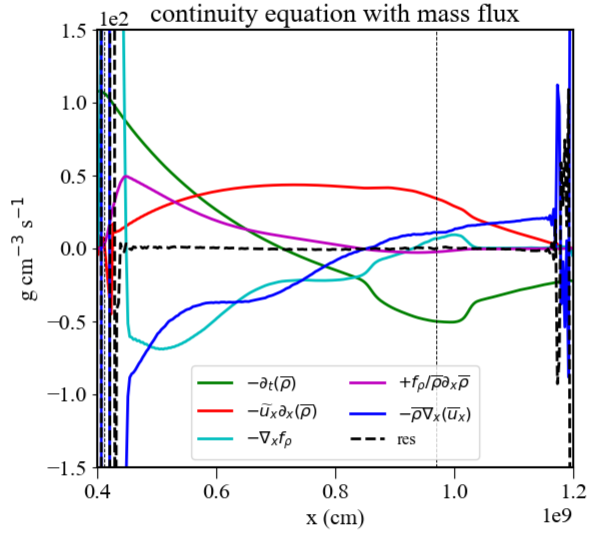


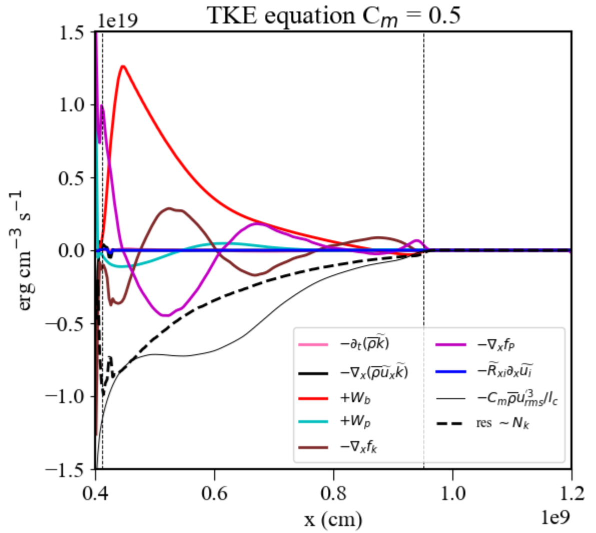
1500 secs (25 TOs)

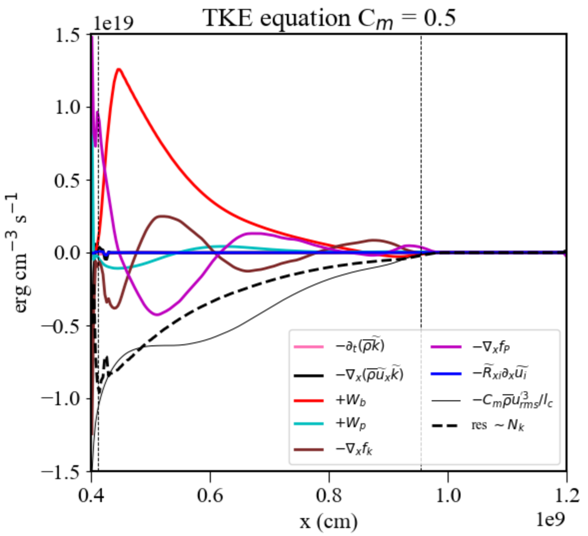


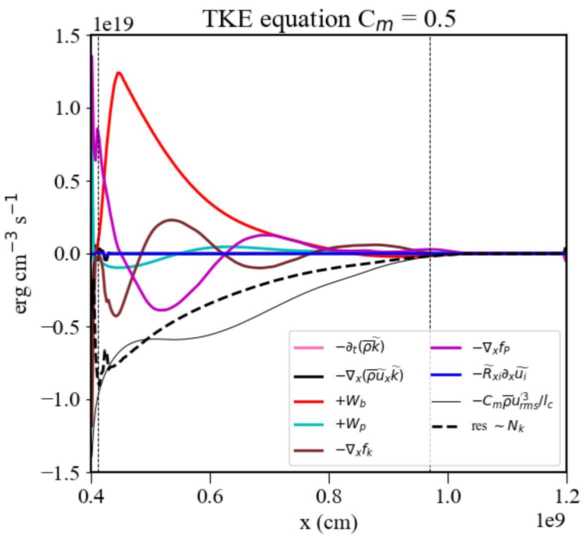

continuity equation with mass flux
1e2
g cm^{-3} s^{-1}
x (cm)
1e9
$-\partial_t(\overline{\rho})$
$-\widetilde{u}_x\partial_x(\overline{\rho})$
$-\nabla_x f_\rho$
$+f_\rho/\overline{\rho}\partial_x\overline{\rho}$
$-\overline{\rho}\nabla_x(\overline{u}_x)$
res

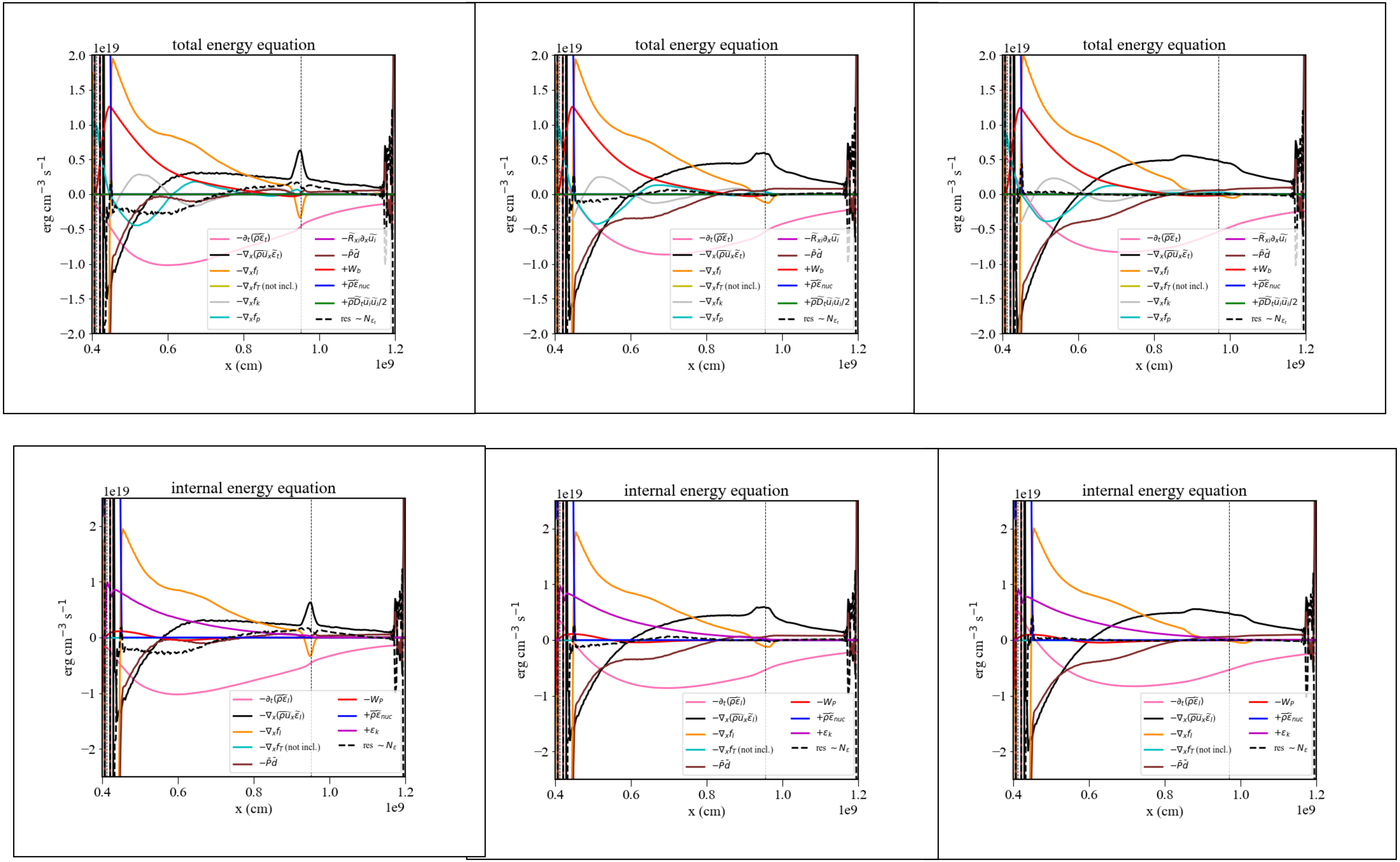

continuity equation with mass flux
1e2
g cm^{-3} s^{-1}
x (cm)
1e9
$-\partial_t(\overline{\rho})$
$-\widetilde{u}_x\partial_x(\overline{\rho})$
$-\nabla_x f_\rho$
$+f_\rho/\overline{\rho}\partial_x\overline{\rho}$
$-\overline{\rho}\nabla_x(\overline{u}_x)$
res

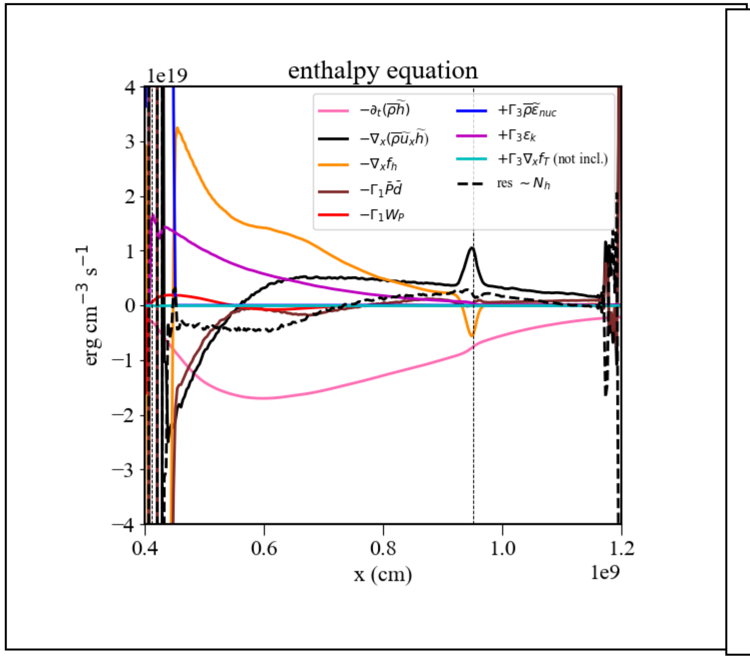
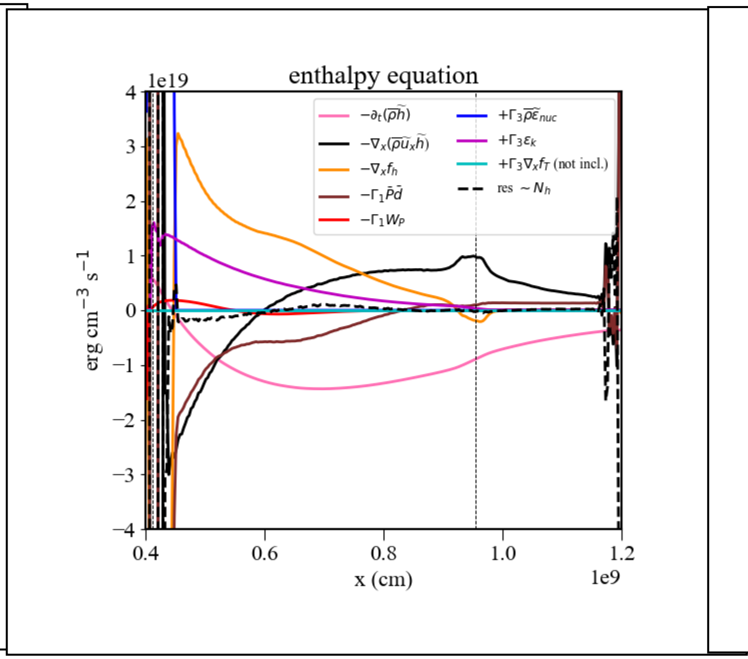
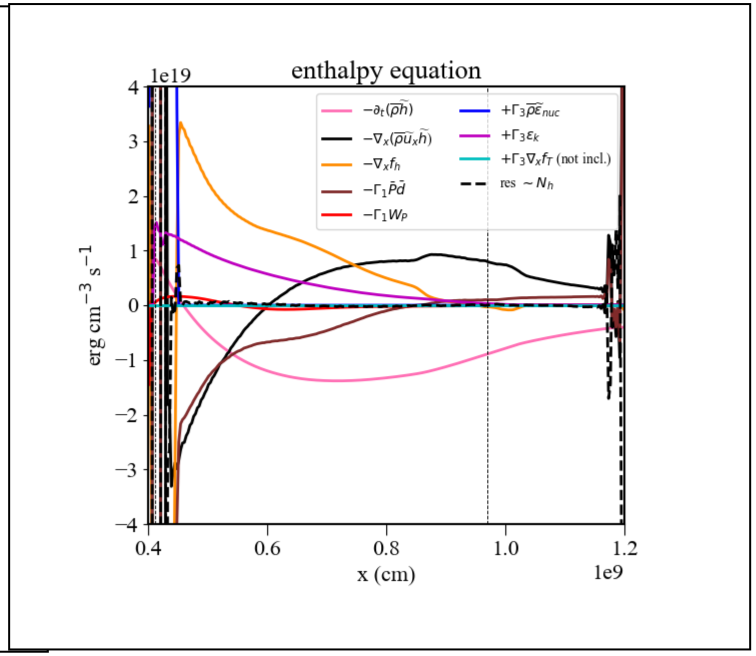
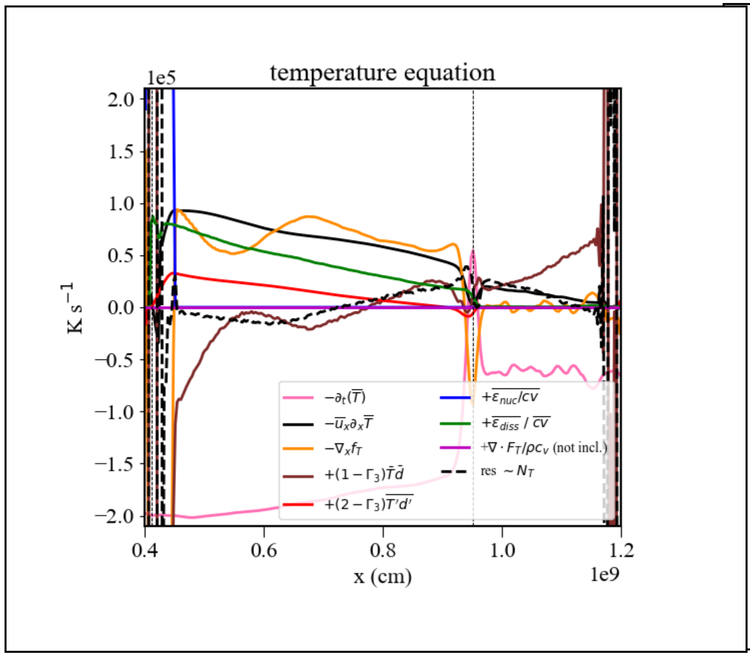
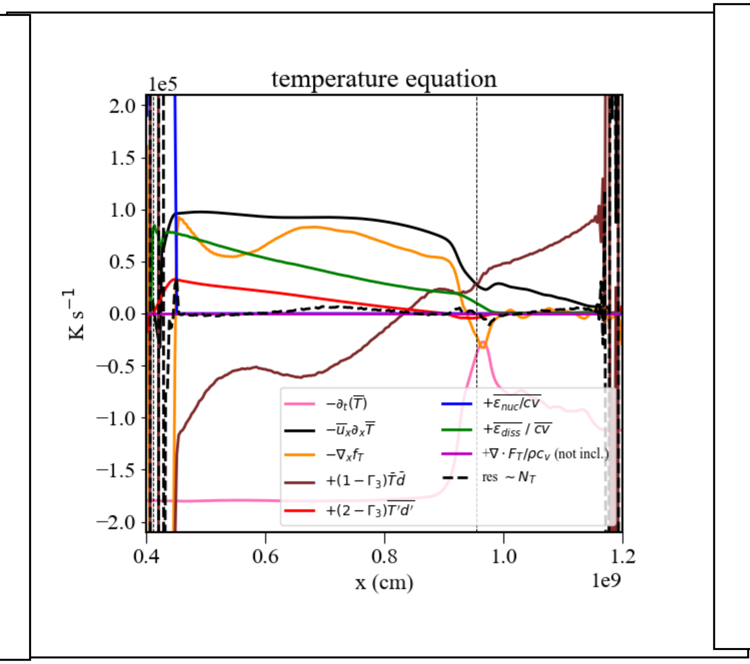
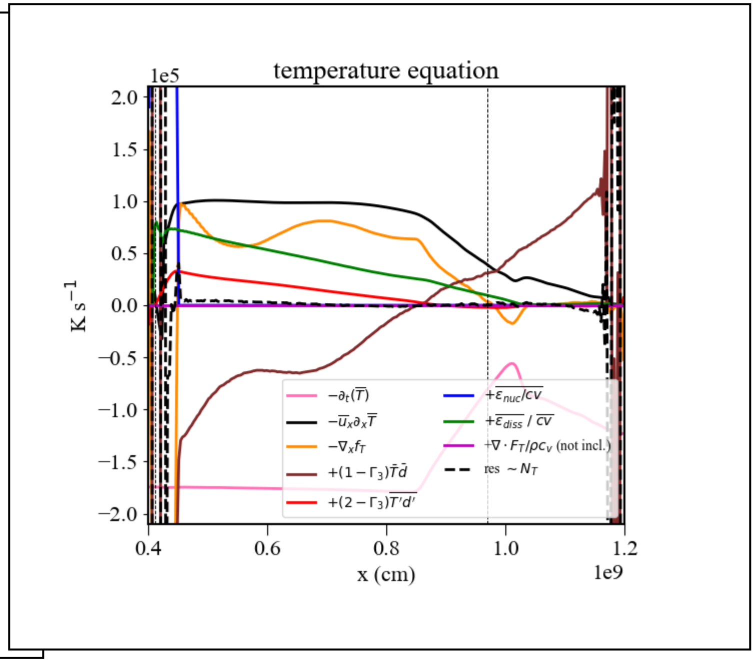

continuity equation with mass flux
1e2
g cm^{-3} s^{-1}
x (cm)
1e9
$-\partial_t(\overline{\rho})$
$-\widetilde{u}_x\partial_x(\overline{\rho})$
$-\nabla_x f_\rho$
$+f_\rho/\overline{\rho}\partial_x\overline{\rho}$
$-\overline{\rho}\nabla_x(\overline{u}_x)$
res

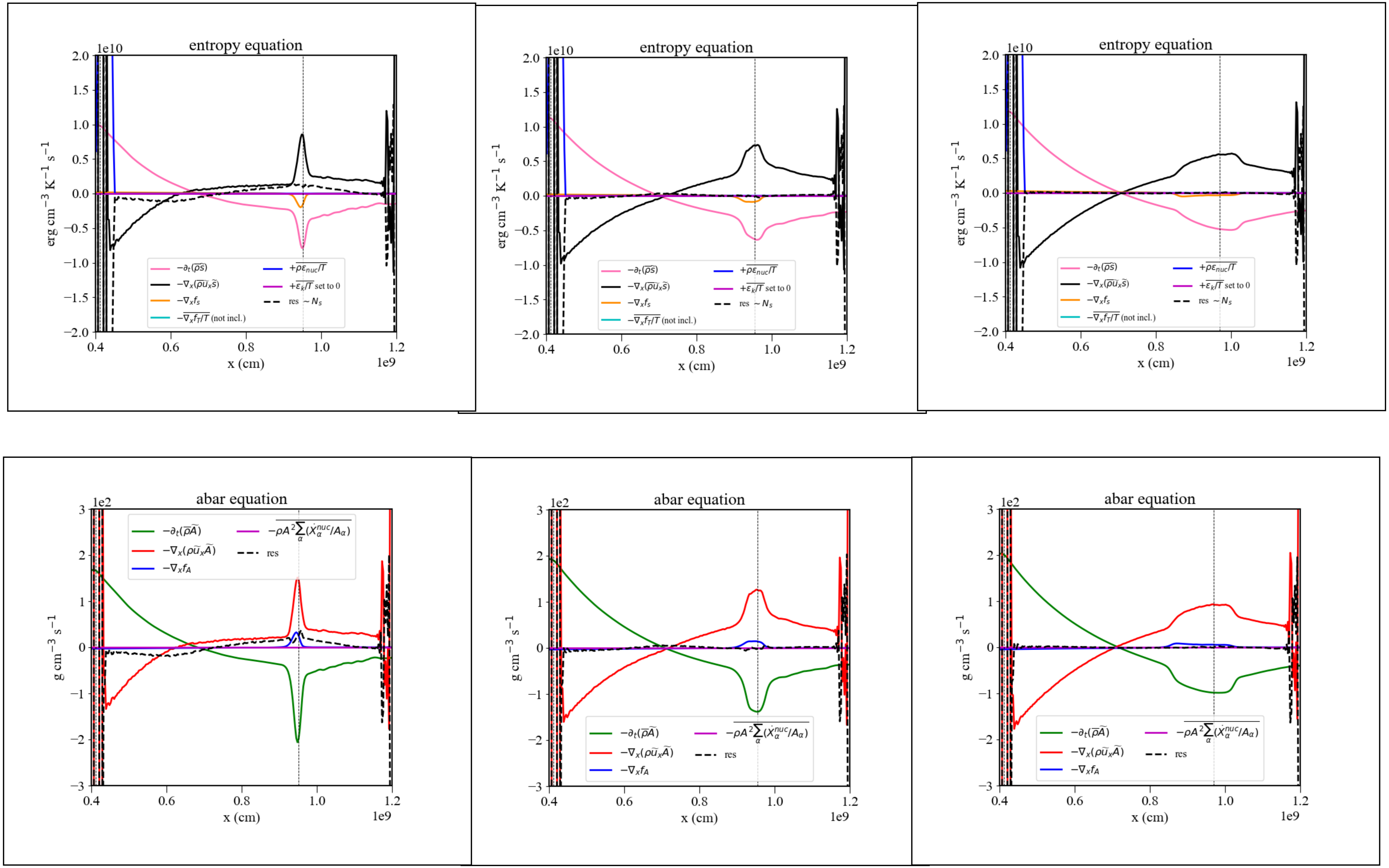

TKE equation C$_m$ = 0.5
1e19
erg cm^{-3} s^{-1}
x (cm)
1e9
$-\partial_t(\overline{\rho}\widetilde{k})$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\widetilde{k})$
$+W_b$
$+W_p$
$-\nabla_x f_k$
$-\nabla_x f_P$
$-\widetilde{R}_{xi}\partial_x\widetilde{u_i}$
$-C_m\overline{\rho}u_{rms}^{\prime 3}/l_c$
res $\sim N_k$


TKE equation C$_m$ = 0.5
1e19
erg cm^{-3} s^{-1}
x (cm)
1e9
$-\partial_t(\overline{\rho}\widetilde{k})$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\widetilde{k})$
$+W_b$
$+W_p$
$-\nabla_x f_k$
$-\nabla_x f_P$
$-\widetilde{R}_{xi}\partial_x\widetilde{u_i}$
$-C_m\overline{\rho}u_{rms}^{\prime 3}/l_c$
res $\sim N_k$

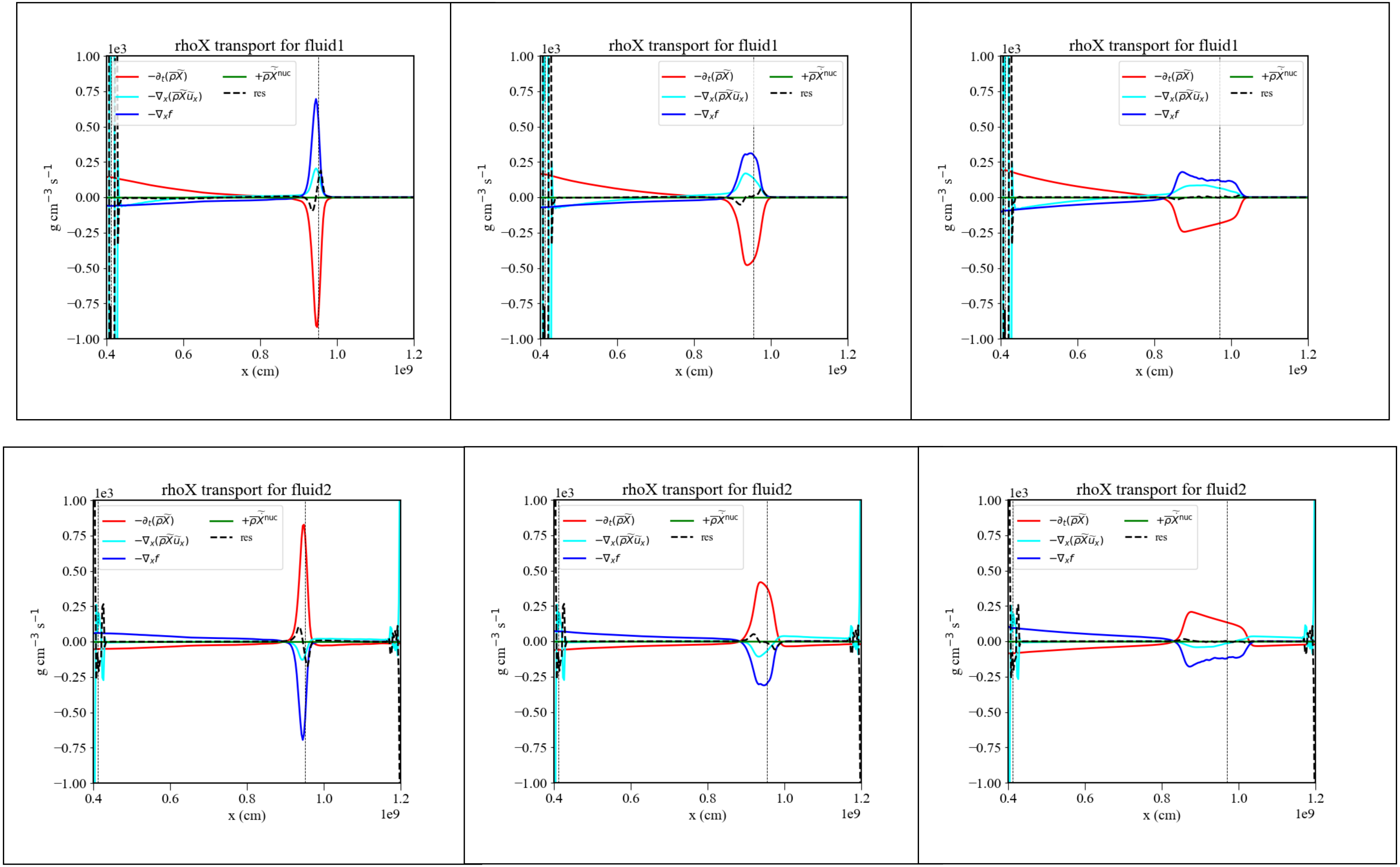

TKE equation C$_m$ = 0.5
1e19
erg cm^{-3} s^{-1}
x (cm)
1e9
$-\partial_t(\overline{\rho}\widetilde{k})$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\widetilde{k})$
$+W_b$
$+W_p$
$-\nabla_x f_k$
$-\nabla_x f_P$
$-\widetilde{R}_{xi}\partial_x\widetilde{u_i}$
$-C_m\overline{\rho}u_{rms}^{\prime 3}/l_c$
res $\sim N_k$


total energy equation
1e19
erg cm^{-3} s^{-1}
x (cm)
1e9
$-\partial_t(\overline{\rho}\widetilde{\epsilon}_t)$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\widetilde{\epsilon}_t)$
$-\nabla_x f_I$
$-\nabla_x f_T$ (not incl.)
$-\nabla_x f_k$
$-\nabla_x f_p$
$-\widetilde{R}_{xi}\partial_x\widetilde{u}_i$
$-\bar{P}\bar{d}$
$+W_b$
$+\overline{\rho}\widetilde{\epsilon}_{nuc}$
$+\overline{\rho}\widetilde{D}_t\widetilde{u}_i\widetilde{u}_i/2$
res $\sim N_{\epsilon_t}$
internal energy equation
$-\partial_t(\overline{\rho}\widetilde{\epsilon}_I)$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\widetilde{\epsilon}_I)$
$-\nabla_x f_I$
$-\nabla_x f_T$ (not incl.)
$-\bar{P}\bar{d}$
$-W_P$
$+\overline{\rho}\widetilde{\epsilon}_{nuc}$
$+\epsilon_k$
res $\sim N_\epsilon$

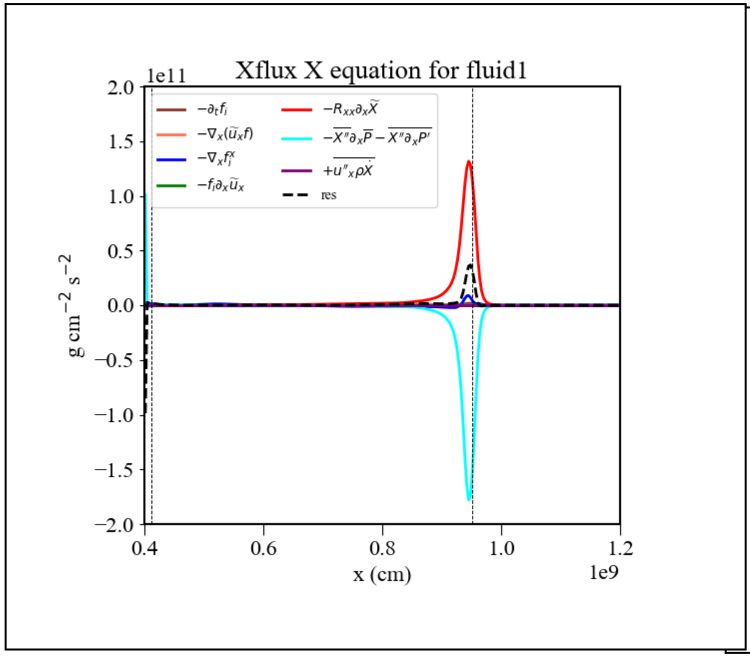

enthalpy equation
1e19
erg cm^{-3} s^{-1}
x (cm)
1e9
$-\partial_t(\overline{\rho}\widetilde{h})$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\widetilde{h})$
$-\nabla_x f_h$
$-\Gamma_1 \bar{P}\bar{d}$
$-\Gamma_1 W_P$
$+\Gamma_3 \overline{\rho}\widetilde{\epsilon}_{nuc}$
$+\Gamma_3 \varepsilon_k$
$+\Gamma_3 \nabla_x f_T$ (not incl.)
res $\sim N_h$

enthalpy equation
1e19
erg cm^{-3} s^{-1}
x (cm)
1e9
$-\partial_t(\overline{\rho}\widetilde{h})$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\widetilde{h})$
$-\nabla_x f_h$
$-\Gamma_1 \bar{P}\bar{d}$
$-\Gamma_1 W_P$
$+\Gamma_3 \overline{\rho}\widetilde{\epsilon}_{nuc}$
$+\Gamma_3 \varepsilon_k$
$+\Gamma_3 \nabla_x f_T$ (not incl.)
res $\sim N_h$

enthalpy equation
1e19
erg cm^{-3} s^{-1}
x (cm)
1e9
$-\partial_t(\overline{\rho}\widetilde{h})$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\widetilde{h})$
$-\nabla_x f_h$
$-\Gamma_1 \bar{P}\bar{d}$
$-\Gamma_1 W_P$
$+\Gamma_3 \overline{\rho}\widetilde{\epsilon}_{nuc}$
$+\Gamma_3 \varepsilon_k$
$+\Gamma_3 \nabla_x f_T$ (not incl.)
res $\sim N_h$

temperature equation
1e5
K s^{-1}
x (cm)
1e9
$-\partial_t(\overline{T})$
$-\overline{u}_x \partial_x \overline{T}$
$-\nabla_x f_T$
$+(1-\Gamma_3)\bar{T}\bar{d}$
$+(2-\Gamma_3)\overline{T'd'}$
$+\overline{\epsilon_{nuc}/cv}$
$+\overline{\epsilon_{diss}}$ / $\overline{cv}$
$+\nabla \cdot F_T/\rho c_v$ (not incl.)
res $\sim N_T$

temperature equation
1e5
K s^{-1}
x (cm)
1e9
$-\partial_t(\overline{T})$
$-\overline{u}_x \partial_x \overline{T}$
$-\nabla_x f_T$
$+(1-\Gamma_3)\bar{T}\bar{d}$
$+(2-\Gamma_3)\overline{T'd'}$
$+\overline{\epsilon_{nuc}/cv}$
$+\overline{\epsilon_{diss}}$ / $\overline{cv}$
$+\nabla \cdot F_T/\rho c_v$ (not incl.)
res $\sim N_T$

temperature equation
1e5
K s^{-1}
x (cm)
1e9
$-\partial_t(\overline{T})$
$-\overline{u}_x \partial_x \overline{T}$
$-\nabla_x f_T$
$+(1-\Gamma_3)\bar{T}\bar{d}$
$+(2-\Gamma_3)\overline{T'd'}$
$+\overline{\epsilon_{nuc}/cv}$
$+\overline{\epsilon_{diss}}$ / $\overline{cv}$
$+\nabla \cdot F_T/\rho c_v$ (not incl.)
res $\sim N_T$

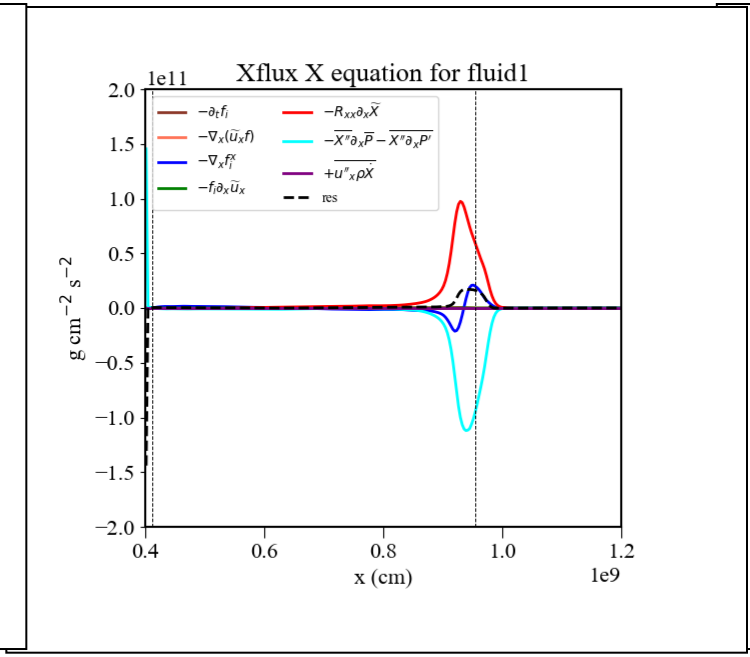


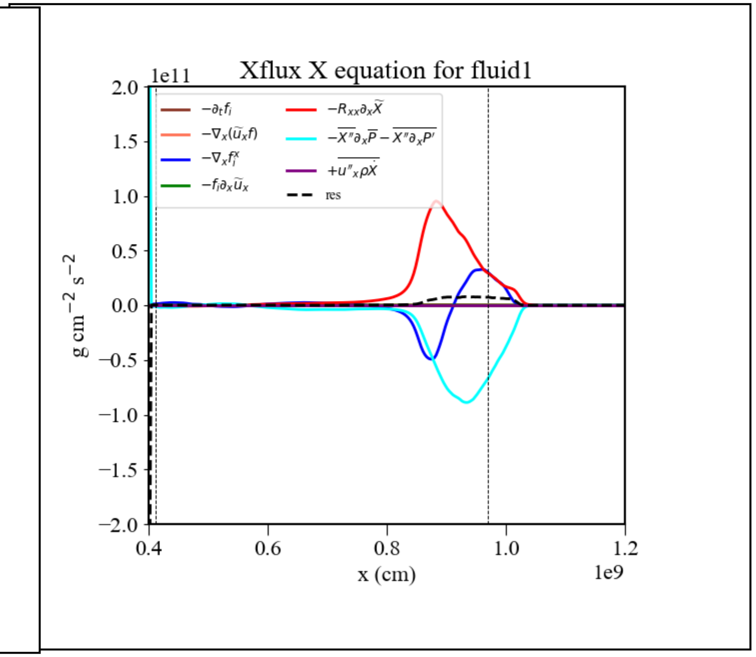
entropy equation
1e10
erg cm^{-3} K^{-1} s^{-1}
x (cm)
1e9
$-\partial_t(\overline{\rho}\widetilde{s})$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\widetilde{s})$
$-\nabla_x f_s$
$-\nabla_x \overline{f_T/T}$ (not incl.)
$+\overline{\rho\epsilon_{nuc}/T}$
$+\overline{\varepsilon_k/T}$ set to 0
res $\sim N_s$
abar equation
1e2
g cm^{-3} s^{-1}
x (cm)
1e9
$-\partial_t(\overline{\rho}\widetilde{A})$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\widetilde{A})$
$-\nabla_x f_A$
$-\overline{\rho A^2 \sum_\alpha (\dot{X}_\alpha^{nuc}/A_\alpha)}$
res

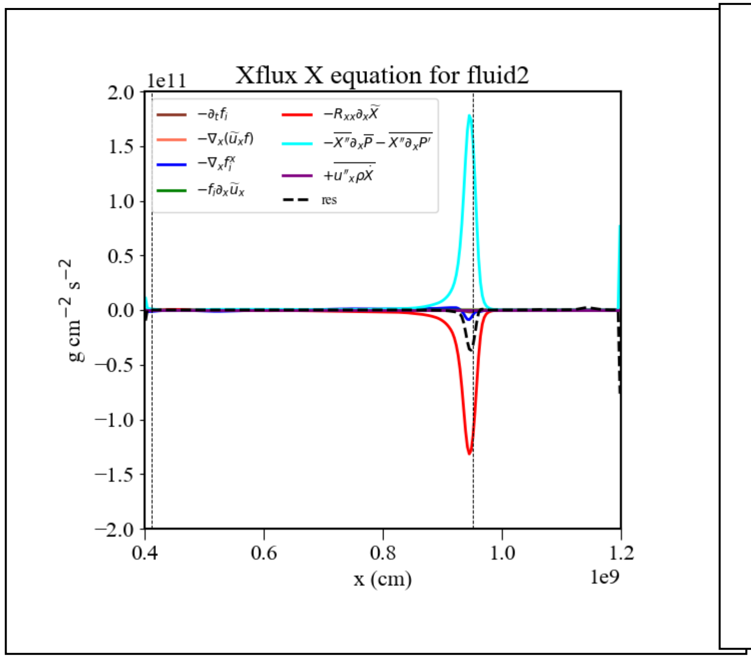


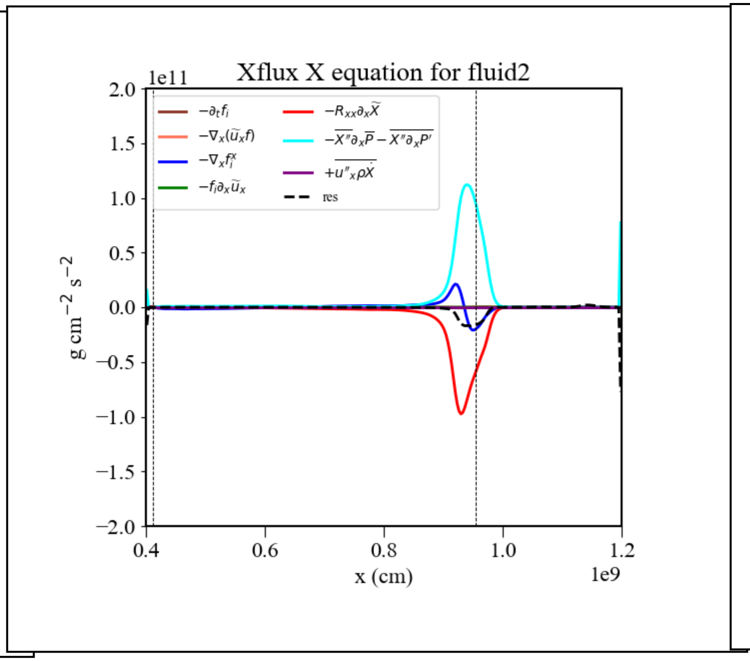
rhoX transport for fluid1
rhoX transport for fluid1
rhoX transport for fluid1
rhoX transport for fluid2
rhoX transport for fluid2
rhoX transport for fluid2
$-\partial_t(\overline{\rho}\widetilde{X})$
$-\nabla_x(\overline{\rho}\widetilde{X}\widetilde{u}_x)$
$-\nabla_x f$
$+\overline{\rho}\widetilde{\dot{X}}^{\rm nuc}$
res
g cm^{-3} s^{-1}
x (cm)
1e3
1e9

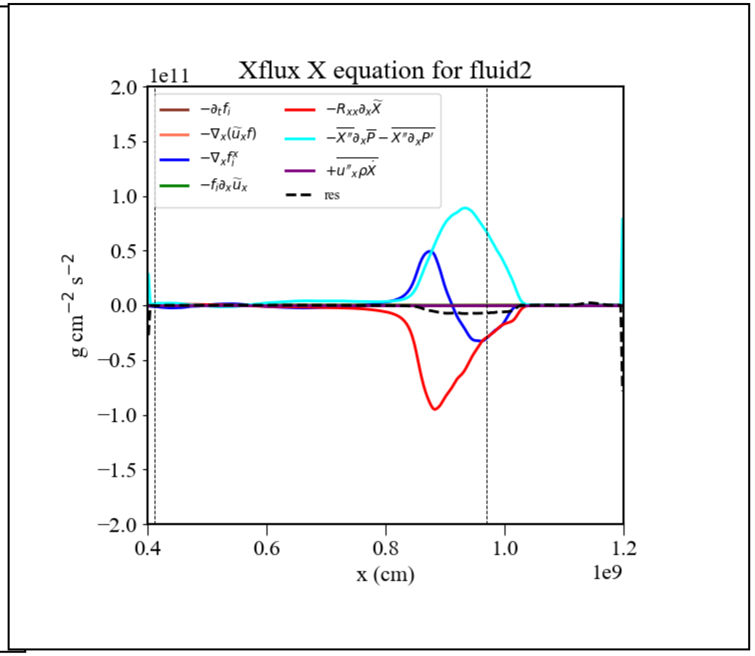

Xflux X equation for fluid1
1e11
g cm^{-2} s^{-2}
x (cm)
1e9
$-\partial_t f_i$
$-\nabla_x(\widetilde{u}_x f)$
$-\nabla_x f_i^x$
$-f_i \partial_x \widetilde{u}_x$
$-R_{xx}\partial_x \widetilde{X}$
$-\overline{X''}\partial_x \overline{P} - \overline{X''\partial_x P'}$
$+\overline{u''_x \rho \dot{X}}$
res

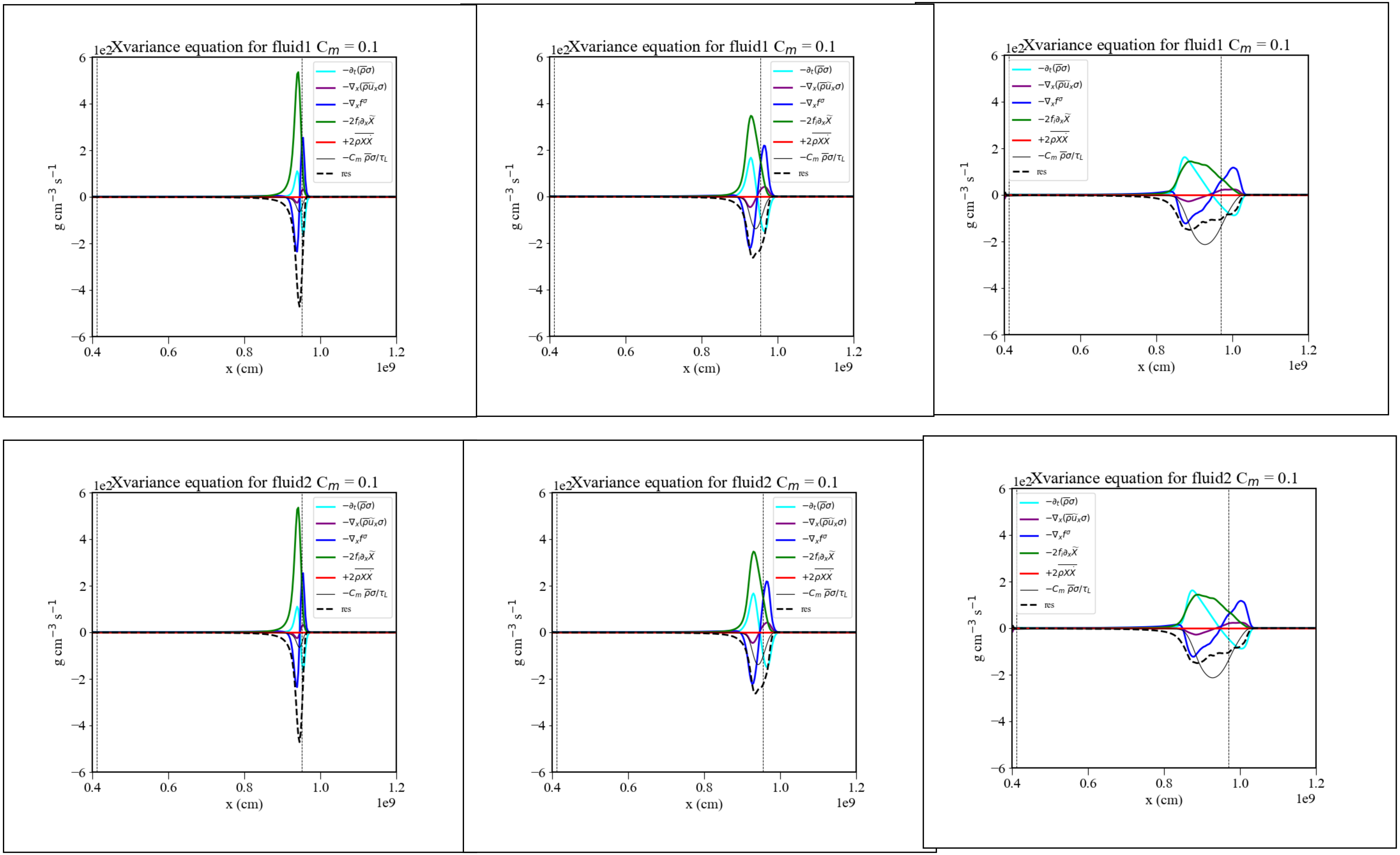

Xflux X equation for fluid1
1e11
g cm^{-2} s^{-2}
x (cm)
1e9
$-\partial_t f_i$
$-\nabla_x(\widetilde{u}_x f)$
$-\nabla_x f_i^x$
$-f_i \partial_x \widetilde{u}_x$
$-R_{xx}\partial_x \widetilde{X}$
$-\overline{X''}\partial_x \overline{P} - \overline{X''\partial_x P'}$
$+\overline{u''_x \rho \dot{X}}$
res


Xflux X equation for fluid1
1e11
g cm^{-2} s^{-2}
x (cm)
1e9
$-\partial_t f_i$
$-\nabla_x(\widetilde{u}_x f)$
$-\nabla_x f_i^x$
$-f_i \partial_x \widetilde{u}_x$
$-R_{xx}\partial_x \widetilde{X}$
$-\overline{X''}\partial_x \overline{P} - \overline{X''\partial_x P'}$
$+\overline{u''_x \rho \dot{X}}$
res


Xflux X equation for fluid2
1e11
g cm^{-2} s^{-2}
x (cm)
1e9
$-\partial_t f_i$
$-\nabla_x(\widetilde{u}_x f)$
$-\nabla_x f_i^x$
$-f_i \partial_x \widetilde{u}_x$
$-R_{xx}\partial_x \widetilde{X}$
$-\overline{X''}\partial_x \overline{P} - \overline{X''\partial_x P'}$
$+\overline{u''_x \rho \dot{X}}$
res


Xflux X equation for fluid2
1e11
g cm^{-2} s^{-2}
x (cm)
1e9
$-\partial_t f_i$
$-\nabla_x(\widetilde{u}_x f)$
$-\nabla_x f_i^x$
$-f_i \partial_x \widetilde{u}_x$
$-R_{xx}\partial_x \widetilde{X}$
$-\overline{X''}\partial_x \overline{P} - \overline{X''\partial_x P'}$
$+\overline{u''_x \rho \dot{X}}$
res


Xflux X equation for fluid2
1e11
g cm^{-2} s^{-2}
x (cm)
1e9
$-\partial_t f_i$
$-\nabla_x(\widetilde{u}_x f)$
$-\nabla_x f_i^x$
$-f_i \partial_x \widetilde{u}_x$
$-R_{xx}\partial_x \widetilde{X}$
$-\overline{X''}\partial_x \overline{P} - \overline{X''\partial_x P'}$
$+\overline{u''_x \rho \dot{X}}$
res



1e2Xvariance equation for fluid1 C$_m$ = 0.1
$-\partial_t(\overline{\rho}\sigma)$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\sigma)$
$-\nabla_x f^\sigma$
$-2f_i\partial_x\widetilde{X}$
$+2\overline{\rho XX}$
$-C_m\,\overline{\rho}\sigma/\tau_L$
res
g cm^{-3} s^{-1}
x (cm)
1e9
1e2Xvariance equation for fluid1 C$_m$ = 0.1
$-\partial_t(\overline{\rho}\sigma)$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\sigma)$
$-\nabla_x f^\sigma$
$-2f_i\partial_x\widetilde{X}$
$+2\overline{\rho XX}$
$-C_m\,\overline{\rho}\sigma/\tau_L$
res
g cm^{-3} s^{-1}
x (cm)
1e9
1e2Xvariance equation for fluid1 C$_m$ = 0.1
$-\partial_t(\overline{\rho}\sigma)$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\sigma)$
$-\nabla_x f^\sigma$
$-2f_i\partial_x\widetilde{X}$
$+2\overline{\rho XX}$
$-C_m\,\overline{\rho}\sigma/\tau_L$
res
g cm^{-3} s^{-1}
x (cm)
1e9
1e2Xvariance equation for fluid2 C$_m$ = 0.1
$-\partial_t(\overline{\rho}\sigma)$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\sigma)$
$-\nabla_x f^\sigma$
$-2f_i\partial_x\widetilde{X}$
$+2\overline{\rho XX}$
$-C_m\,\overline{\rho}\sigma/\tau_L$
res
g cm^{-3} s^{-1}
x (cm)
1e9
1e2Xvariance equation for fluid2 C$_m$ = 0.1
$-\partial_t(\overline{\rho}\sigma)$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\sigma)$
$-\nabla_x f^\sigma$
$-2f_i\partial_x\widetilde{X}$
$+2\overline{\rho XX}$
$-C_m\,\overline{\rho}\sigma/\tau_L$
res
g cm^{-3} s^{-1}
x (cm)
1e9
1e2Xvariance equation for fluid2 C$_m$ = 0.1
$-\partial_t(\overline{\rho}\sigma)$
$-\nabla_x(\overline{\rho}\widetilde{u}_x\sigma)$
$-\nabla_x f^\sigma$
$-2f_i\partial_x\widetilde{X}$
$+2\overline{\rho XX}$
$-C_m\,\overline{\rho}\sigma/\tau_L$
res
g cm^{-3} s^{-1}
x (cm)
1e9