JETSCAPE Hydrodynamics Session

Goals

- Understand how to run JETSCAPE with a few default Fluid dynamics modules and set/change their relevant parameters, such as transport coefficients
- With a realistic hydrodynamic module, students will be able to output hydrodynamic evolution profile and analyze the evolution of temperature and the development of flow velocity with various settings
- Simulate event-by-event bulk dynamics for Au+Au @ 200 GeV and Pb+Pb @ 5020 GeV with a realistic hydrodynamics code, such as MUSIC.

Physics Background

The JETSCAPE framework employs the Trento model to generate event-by-event initial energy density profile. The energy density profile is then passed to the hydrodynamics module (MUSIC), which will evolve the collision system from a hot QGP phase to the hadron gas phase. Optionally, pre-equilibrium dynamics modeled by free-streaming can be included between the Trento and hydrodynamics. In the dilute hadronic phase, fluid cells will convert to individual hadrons. This process is denoted as the particlization. The JETSCAPE framework uses iSS to perform particlization. The produced hadrons can be fed to a hadronic transport model (SMASH), which accounts for scattering processes among hadrons and decays of excited resonance states.

Setup a docker container

If you plan to do exercises on a remote computer with `ssh`, please use the following command to log in to your remote machine,

```
ssh -L 8888:127.0.0.1:8888 user@server
```

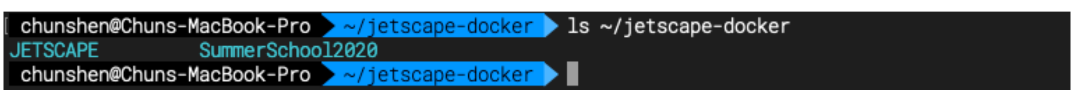
The port information is essential to properly setup jupyter notebook.

Before we begin our session, please make sure all the code packages are already in the correct place on your computer. You should have a `jetscape-docker` folder under your home directory. Try to list the folder inside `jetscape-docker` with the following command,

```
ls ~/jetscape-docker
```

You need to make sure the following folders are present,

- JETSCAPE
- SummerSchool2020



In this session, we need to launch a docker container that supports the jupyter notebook. Please use the following command:

macOS: `docker run -it -p 8888:8888 -v ~/jetscape-docker:/home/jetscape-user --name myJSHydroSession jetscape/base:v1.4`

Linux:
`docker run -it -p 8888:8888 -v ~/jetscape-docker:/home/jetscape-user --name myJSHydroSession --user $(id -u):$(id -g) jetscape/base:v1.`

- `--rm` This option will delete the current docker container at the exit. (If you want to delete the container, you can add this option.)
- `-p 8888:8888` This option creates a port for your web browser outside the docker container to load a jupyter notebook. All the python packages are in the docker container.

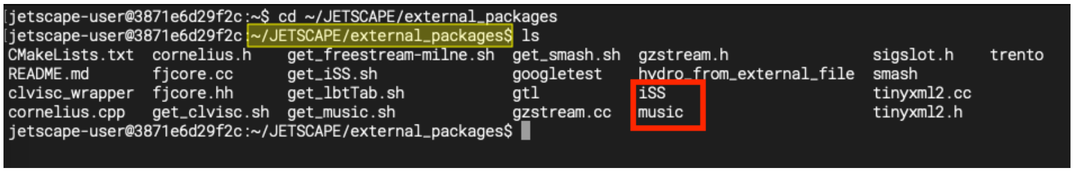
Under Linux, if you encounter an error about `permission denied`, you can use `sudo` in front of the docker run command.

Build JETSCAPE with MUSIC and iSS

We will do all of our exercises in the **`JETSCAPE/build`** directory. Please make sure all the external code packages (MUSIC and iSS) have been downloaded. You can check this by the following commands,

```
cd ~/JETSCAPE/external_packages
ls
```

Please check the folder `music` and `iSS` are present.



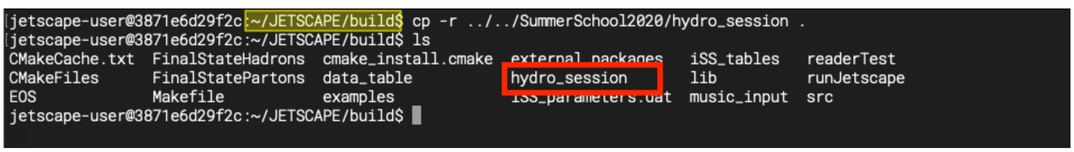
If not, please run the following commands,

```
./get_music.sh
./get_iSS.sh
```

When you enter the docker container, type the following commands to setup the working directory,

```
cd ~/JETSCAPE
mkdir -p build
cd build
cmake .. -DUSE_MUSIC=ON -DUSE_ISS=ON
make -j4
cp -r ../../SummerSchool2020/hydro_session .
```

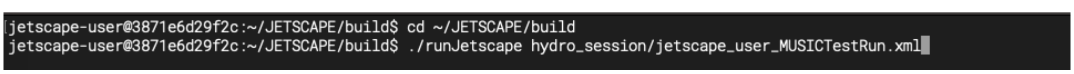
The last command copies the hand-on materials of this session to the working folder.

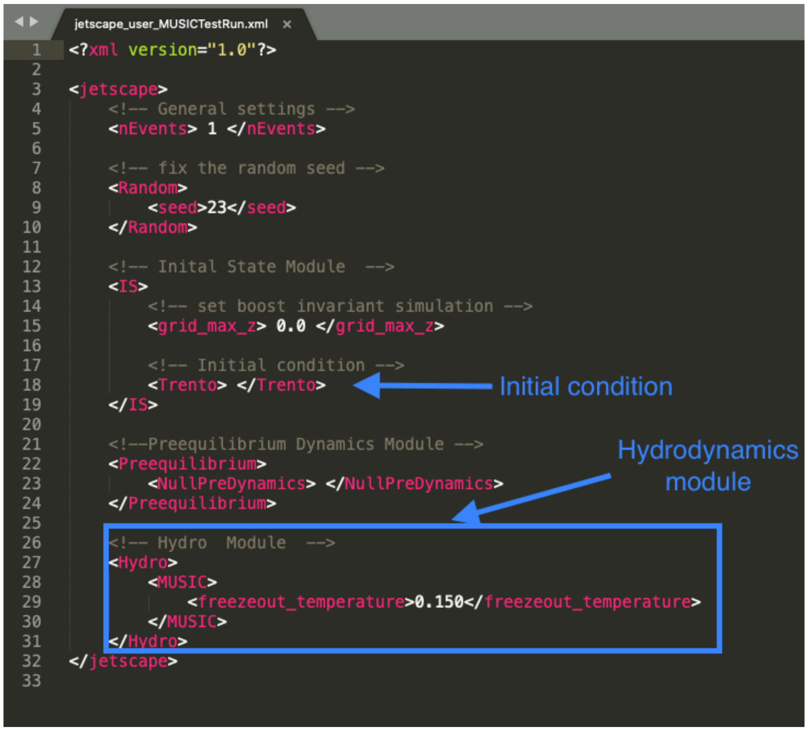


1. A Test Run for JETSCAPE with MUSIC

To perform a test run for JETSCAPE with MUSIC in our working directory (**`~/JETSCAPE/build`**),

```
cd ~/JETSCAPE/build
./runJetscape hydro_session/jetscape_user_MUSICTestRun.xml
```





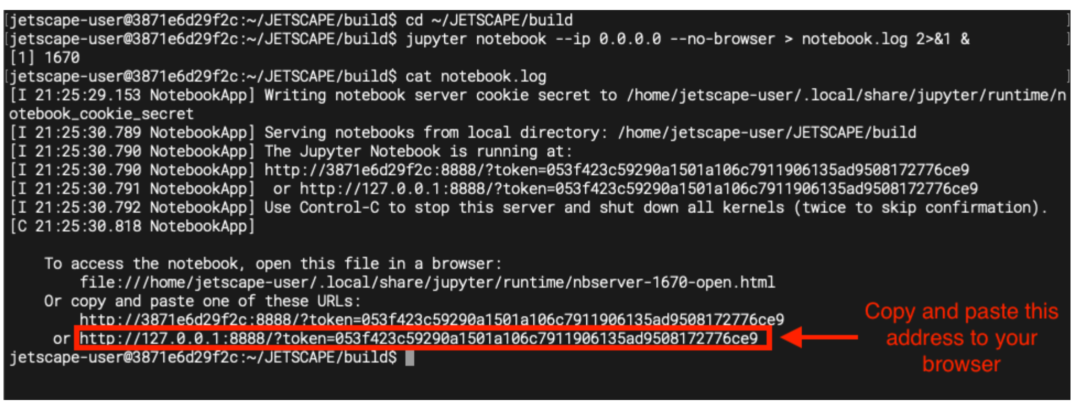

```xml
<?xml version="1.0"?>

<jetscape>
    <!-- General settings -->
    <nEvents> 1 </nEvents>

    <!-- fix the random seed -->
    <Random>
        <seed>23</seed>
    </Random>

    <!-- Inital State Module  -->
    <IS>
        <!-- set boost invariant simulation -->
        <grid_max_z> 0.0 </grid_max_z>

        <!-- Initial condition -->
        <Trento> </Trento>
    </IS>

    <!--Preequilibrium Dynamics Module -->
    <Preequilibrium>
        <NullPreDynamics> </NullPreDynamics>
    </Preequilibrium>

    <!-- Hydro  Module  -->
    <Hydro>
        <MUSIC>
            <freezeout_temperature>0.150</freezeout_temperature>
        </MUSIC>
    </Hydro>
</jetscape>
```

Visualization with Jupyter Notebook

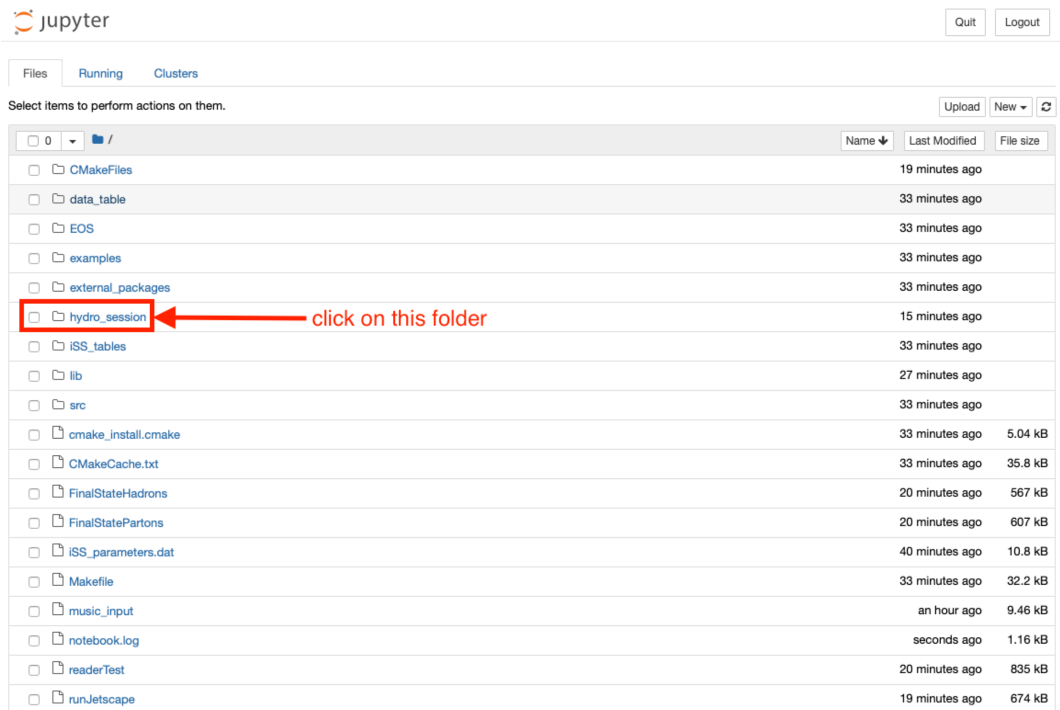
Launch jupyter notebook inside the docker contain with the following command in our working directory (`~/JETSCAPE/build`),

```
cd ~/JETSCAPE/build
jupyter notebook --ip 0.0.0.0 --no-browser > notebook.log 2>&1 &
cat notebook.log
```

Once the jupyter notebook is running in the background, the user can click on the link by holding the `ctrl` key. The link is displayed at the second to the last line and begins with `http://127.0.0.1:8888/?token=...` After the click, your web browser should be launched in the current directory. If your terminal does not recognize html addresses, you can open your browser and enter the following address, `http://127.0.0.1:8888/?token=...`

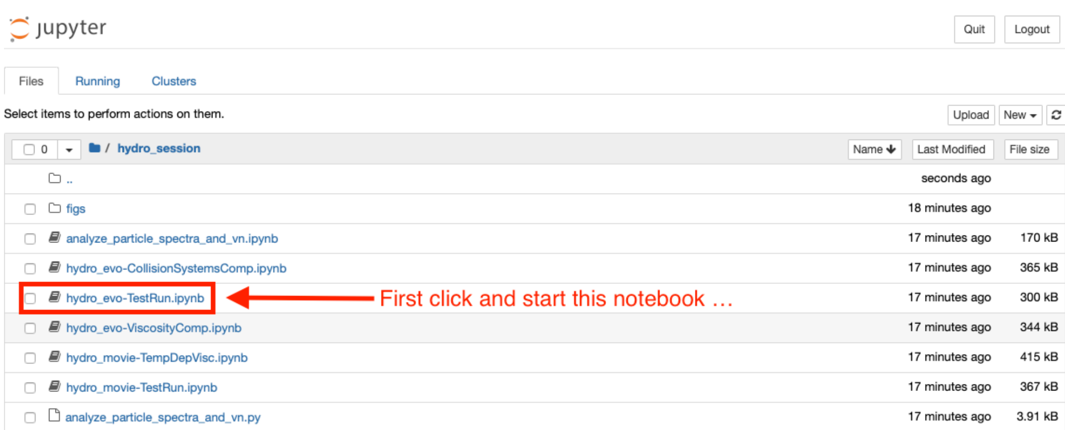



```
jetscape-user@3871e6d29f2c:~/JETSCAPE/build$ cd ~/JETSCAPE/build
jetscape-user@3871e6d29f2c:~/JETSCAPE/build$ jupyter notebook --ip 0.0.0.0 --no-browser > notebook.log 2>&1 &
[1] 1670
jetscape-user@3871e6d29f2c:~/JETSCAPE/build$ cat notebook.log
[I 21:25:29.153 NotebookApp] Writing notebook server cookie secret to /home/jetscape-user/.local/share/jupyter/runtime/n
otebook_cookie_secret
[I 21:25:30.789 NotebookApp] Serving notebooks from local directory: /home/jetscape-user/JETSCAPE/build
[I 21:25:30.790 NotebookApp] The Jupyter Notebook is running at:
[I 21:25:30.790 NotebookApp] http://3871e6d29f2c:8888/?token=053f423c59290a1501a106c7911906135ad9508172776ce9
[I 21:25:30.791 NotebookApp]  or http://127.0.0.1:8888/?token=053f423c59290a1501a106c7911906135ad9508172776ce9
[I 21:25:30.792 NotebookApp] Use Control-C to stop this server and shut down all kernels (twice to skip confirmation).
[C 21:25:30.818 NotebookApp]

    To access the notebook, open this file in a browser:
        file:///home/jetscape-user/.local/share/jupyter/runtime/nbserver-1670-open.html
    Or copy and paste one of these URLs:
        http://3871e6d29f2c:8888/?token=053f423c59290a1501a106c7911906135ad9508172776ce9
     or http://127.0.0.1:8888/?token=053f423c59290a1501a106c7911906135ad9508172776ce9
jetscape-user@3871e6d29f2c:~/JETSCAPE/build$
```



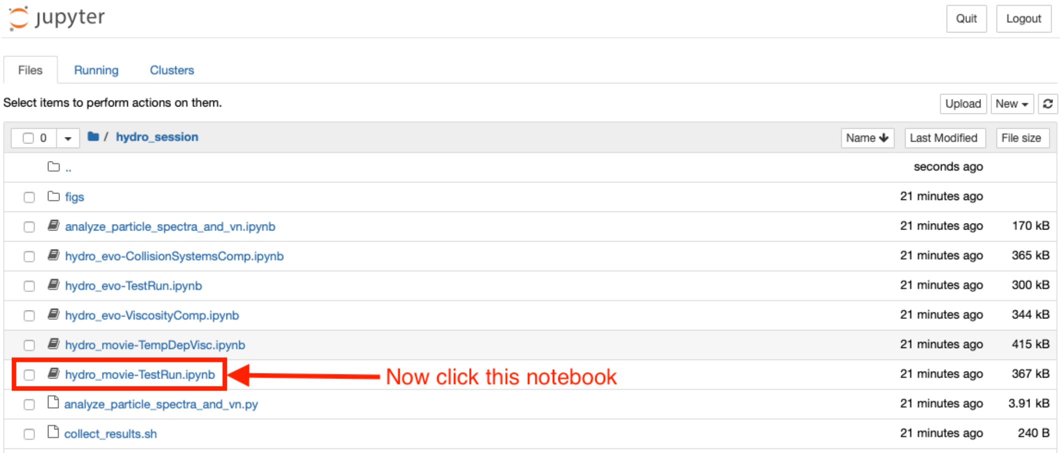
1. Plot averaged temperature and flow velocity evolution

In your browser, we first go into the `hydro_session` folder *(in your browser)*. We can open the notebook `hydro_evo_TestRun.ipynb` by click on it inside the browser. Once the notebook is opened, the user can execute every cell in this notebook one-by-one. Press **`shift+enter`** to execute the cell block in the notebook.



2. Animation of averaged temperature and flow velocity evolution

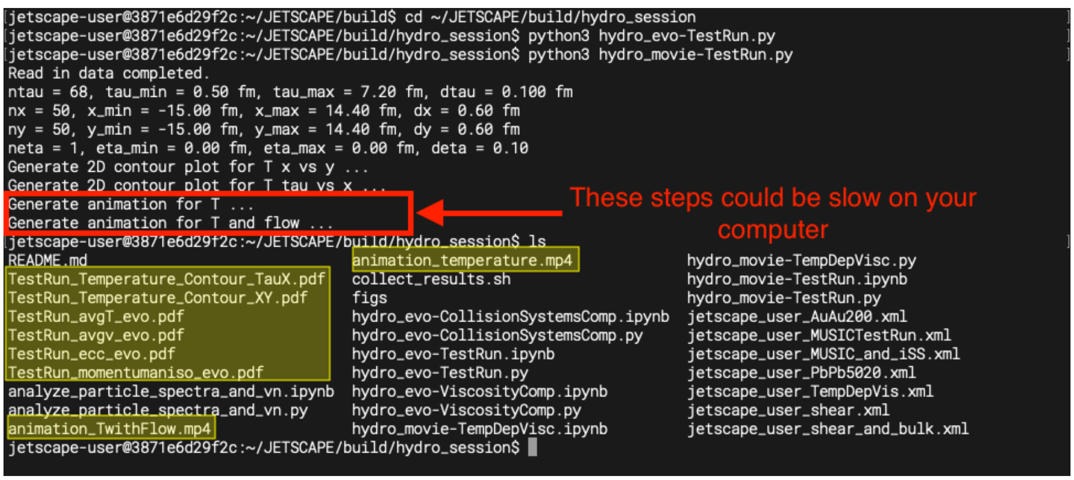
Similar to the previous exercise, this time we will open the second notebook under `hydro_session` folder, `hydro_movie_TestRun.ipynb`. After it is opened inside your browser, you can execute the code cells one by one to generate 2D color contour plots as well as animation for the temperature and fluid velocity evolution.

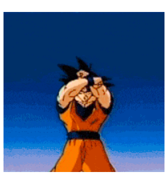


No Jupyter Notebook?

If you can not use jupyter notebook, there are python scripts in the `hydro_session` folder to generate the same plots and animation. Users can run these scripts as follows,

```
cd ~/JETSCAPE/build/hydro_session
python3 hydro_evo-TestRun.py
python3 hydro_movie-TestRun.py
```





2. Change the collision systems

The users can specify the types of collision systems in JETSCAPE xml file,

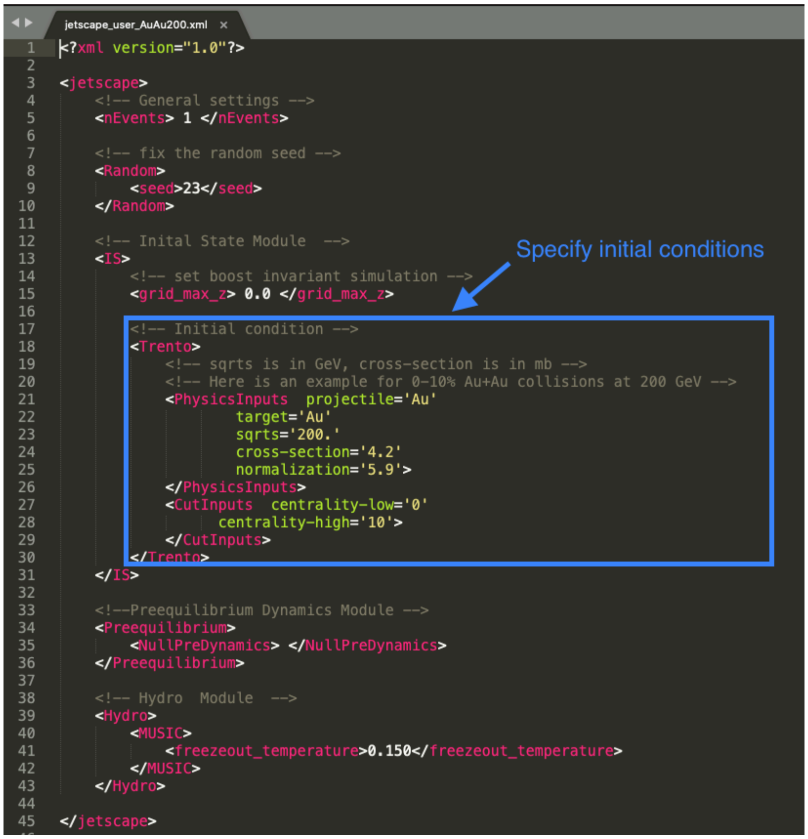
- Collision Energy
- Colliding Nuclei
- Centrality

In the user configuration file `hydro_session/jetscape_user_AuAu200.xml`, one can modify model parameters for the initial state module to simulate his/her desired collision system. In between **`<Trento>`** and **`<\Trento>`**, we can specify the type of colliding nucleus, collision energy, and centrality.

[Run 1] Simulate a 0-10% Au+Au collision at 200 GeV in our working directory (**`~/JETSCAPE/build`**),

```
cd ~/JETSCAPE/build
./runJetscape hydro_session/jetscape_user_AuAu200.xml
./hydro_session/collect_results.sh Run_AuAu200_C0-10
```

The last command collects all the results into a new folder, `Run_AuAu200_C0-10`.



```
jetscape_user_AuAu200.xml
<?xml version="1.0"?>

<jetscape>
    <!-- General settings -->
    <nEvents> 1 </nEvents>

    <!-- fix the random seed -->
    <Random>
        <seed>23</seed>
    </Random>

    <!-- Inital State Module  -->
    <IS>
        <!-- set boost invariant simulation -->
        <grid_max_z> 0.0 </grid_max_z>

        <!-- Initial condition -->
        <Trento>
            <!-- sqrts is in GeV, cross-section is in mb -->
            <!-- Here is an example for 0-10% Au+Au collisions at 200 GeV -->
            <PhysicsInputs  projectile='Au'
                    target='Au'
                    sqrts='200.'
                    cross-section='4.2'
                    normalization='5.9'>
            </PhysicsInputs>
            <CutInputs  centrality-low='0'
                  centrality-high='10'>
            </CutInputs>
        </Trento>
    </IS>

    <!--Preequilibrium Dynamics Module -->
    <Preequilibrium>
        <NullPreDynamics> </NullPreDynamics>
    </Preequilibrium>

    <!-- Hydro  Module  -->
    <Hydro>
        <MUSIC>
            <freezeout_temperature>0.150</freezeout_temperature>
        </MUSIC>
    </Hydro>

</jetscape>
```


Here the nucleon-nucleon cross section is specified in the unit (fm^2) (1[fm^2]= 10[mb])

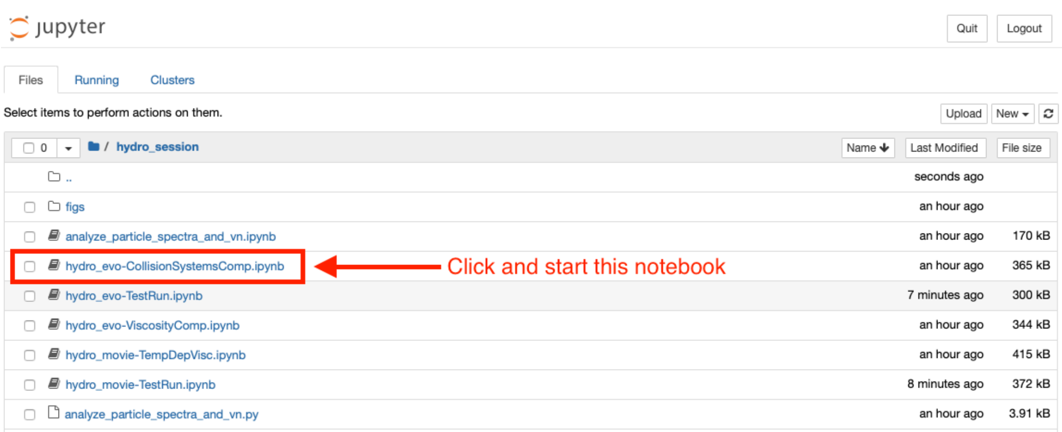
[Run 2] Simulate a 20-30% Pb+Pb collisions at 5.02 TeV in our working directory (**`~/JETSCAPE/build`**),

```
./runJetscape hydro_session/jetscape_user_PbPb5020.xml
./hydro_session/collect_results.sh Run_PbPb5020_C20-30
```

```xml
<?xml version="1.0"?>

<jetscape>
    <!-- General settings -->
    <nEvents> 1 </nEvents>

    <!-- fix the random seed -->
    <Random>
        <seed>23</seed>
    </Random>

    <!-- Inital State Module  -->
    <IS>
        <!-- set boost invariant simulation -->
        <grid_max_z> 0.0 </grid_max_z>

        <!-- Initial condition -->
        <Trento>
            <!-- sqrts is in GeV, cross-section is in mb -->
            <!-- Here is an example for 20-30% Pb+Pb collisions at 5.02 TeV -->
            <PhysicsInputs  projectile='Pb'
                    target='Pb'
                    sqrts='5020.'
                    cross-section='6.7'
                    normalization='18.4'>
            </PhysicsInputs>
            <CutInputs  centrality-low='20'
                    centrality-high='30'>
            </CutInputs>
        </Trento>
    </IS>

    <!--Preequilibrium Dynamics Module -->
    <Preequilibrium>
        <NullPreDynamics> </NullPreDynamics>
    </Preequilibrium>

    <!-- Hydro  Module  -->
    <Hydro>
        <MUSIC>
            <freezeout_temperature>0.150</freezeout_temperature>
        </MUSIC>
    </Hydro>

</jetscape>
```

Specify initial conditions

Now we can compare the evolution temperature and flow velocity between these two systems. You can visualize the comparison using the jupyter notebook, `hydro_evo-CollisionSystemsComp.ipynb`. Launch this notebook in your browser and run the code cells one-by-one to see the comparisons (same procedure as in the previous exercise). Alternatively, you can directly run `hydro_evo-CollisionSystemsComp.py` to generate the same plots.



The results plots can be found in the `hydro_session` folder,

```
jetscape-user@3871e6d29f2c:~/JETSCAPE/build/hydro_session$ python3 hydro_evo-CollisionSystemsComp.py
jetscape-user@3871e6d29f2c:~/JETSCAPE/build/hydro_session$ ls
README.md                                    analyze_particle_spectra_and_vn.py    hydro_movie-TempDepVisc.py
RunCollisionSystemComp_avgv_evo.pdf          animation_TwithFlow.mp4               hydro_movie-TestRun.ipynb
RunCollisionSystemComp_ecc2_evo.pdf          animation_temperature.mp4             hydro_movie-TestRun.py
RunCollisionSystemComp_momentumaniso_evo.pdf collect_results.sh                    jetscape_user_AuAu200.xml
RunCollisionSystemsComp_avgT_evo.pdf         figs                                  jetscape_user_MUSICTestRun.xml
TestRun_Temperature_Contour_TauX.pdf         hydro_evo-CollisionSystemsComp.ipynb  jetscape_user_MUSIC_and_iSS.xml
TestRun_Temperature_Contour_XY.pdf           hydro_evo-CollisionSystemsComp.py     jetscape_user_PbPb5020.xml
TestRun_avgT_evo.pdf                         hydro_evo-TestRun.ipynb               jetscape_user_TempDepVis.xml
TestRun_avgv_evo.pdf                         hydro_evo-TestRun.py                  jetscape_user_shear.xml
TestRun_ecc_evo.pdf                          hydro_evo-ViscosityComp.ipynb         jetscape_user_shear_and_bulk.xml
TestRun_momentumaniso_evo.pdf                hydro_evo-ViscosityComp.py
analyze_particle_spectra_and_vn.ipynb        hydro_movie-TempDepVisc.ipynb
jetscape-user@3871e6d29f2c:~/JETSCAPE/build/hydro_session$
```

 3. Study the effects of viscosity in hydrodynamic evolution

- Specific shear viscosity eta / s
- Specific bulk viscosity $zeta / s$

Using a realistic hydrodynamic module inside the JETSCAPE, the users have freedom to change a few physical parameters for the hydrodynamic simulations. The most interesting ones are the specific shear and bulk viscosity. All the relevant parameters are under the block `<hydro>` **`<MUSIC>`**.

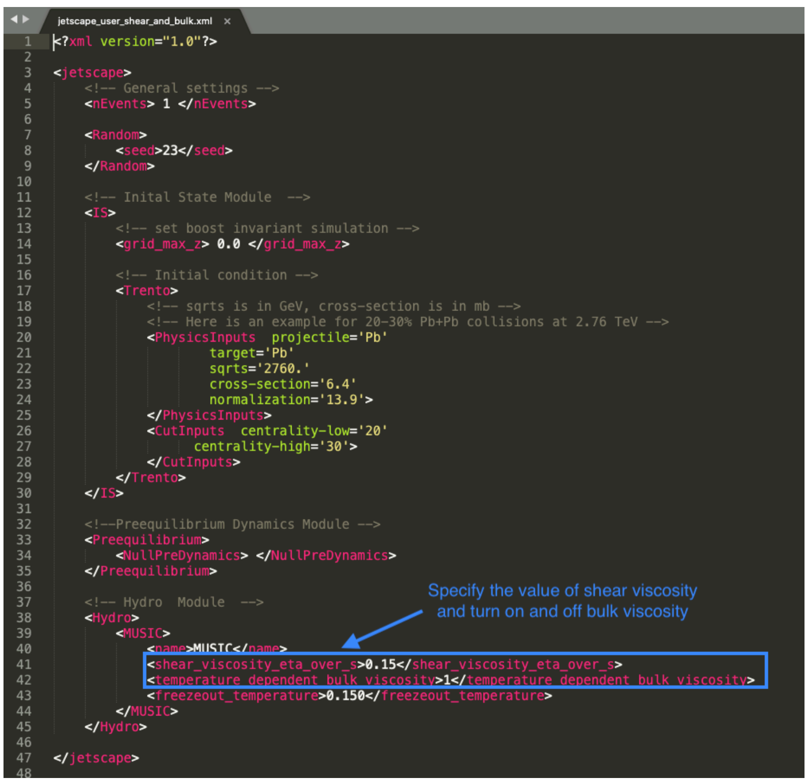
The user can set a constant specific shear viscosity by changing the value for the parameter **`<shear_viscosity_eta_over_s>`**. A physical η/s needs to be a positive value. We recommend the users to try any real value between **0** and **0.3** in the exercises.

Moreover, the users can include a non-zero bulk viscosity in the hydrodynamic simulations. Because the QCD bulk viscosity is related to the breaking of conformal symmetry, we expect the specific bulk viscosity to depend on temperature, $(zeta / s)(T)$.

Users can set the parameter `<temperature_dependent_bulk_viscosity>` to **1**, in the xml file to include a temperature dependent $(zeta / s)(T)$. Setting `<temperature_dependent_bulk_viscosity>` to **0** will set $zeta / s = 0$.

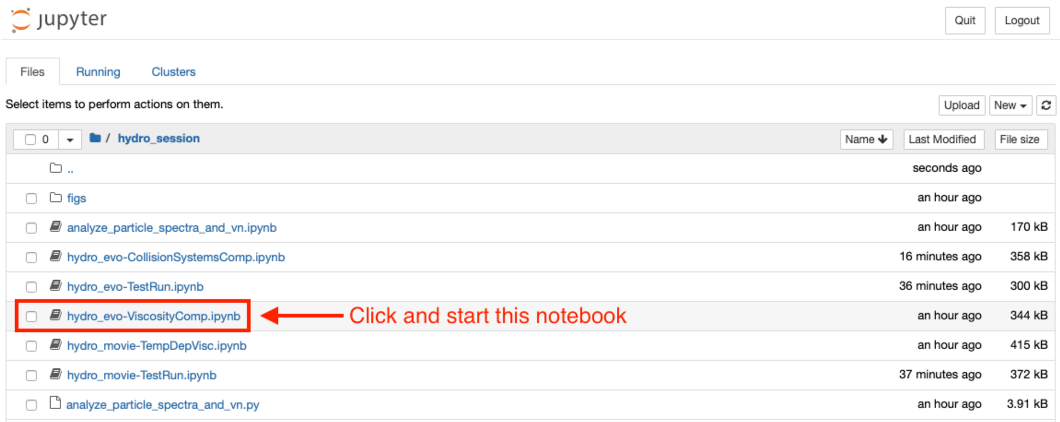
Users can run the JETSCAPE with two example config files,

```
cd ~/JETSCAPE/build
./runJetscape hydro_session/jetscape_user_shear.xml
./hydro_session/collect_results.sh Run_shear_only
./runJetscape hydro_session/jetscape_user_shear_and_bulk.xml
./hydro_session/collect_results.sh Run_shear_and_bulk
```

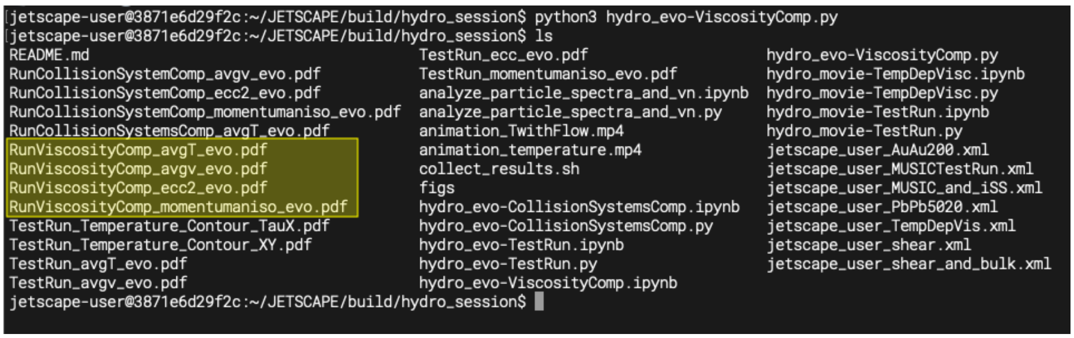



```
<?xml version="1.0"?>

<jetscape>
    <!-- General settings -->
    <nEvents> 1 </nEvents>

    <Random>
        <seed>23</seed>
    </Random>

    <!-- Inital State Module  -->
    <IS>
        <!-- set boost invariant simulation -->
        <grid_max_z> 0.0 </grid_max_z>

        <!-- Initial condition -->
        <Trento>
            <!-- sqrts is in GeV, cross-section is in mb -->
            <!-- Here is an example for 20-30% Pb+Pb collisions at 2.76 TeV -->
            <PhysicsInputs  projectile='Pb'
                    target='Pb'
                    sqrts='2760.'
                    cross-section='6.4'
                    normalization='13.9'>
            </PhysicsInputs>
            <CutInputs  centrality-low='20'
                   centrality-high='30'>
            </CutInputs>
        </Trento>
    </IS>

    <!--Preequilibrium Dynamics Module -->
    <Preequilibrium>
        <NullPreDynamics> </NullPreDynamics>
    </Preequilibrium>

    <!-- Hydro  Module  -->
    <Hydro>
        <MUSIC>
            <name>MUSIC</name>
            <shear_viscosity_eta_over_s>0.15</shear_viscosity_eta_over_s>
            <temperature_dependent_bulk_viscosity>1</temperature_dependent_bulk_viscosity>
            <freezeout_temperature>0.150</freezeout_temperature>
        </MUSIC>
    </Hydro>

</jetscape>
```

Comparison plots can be made using the jupyter notebook `hydro_evo-ViscosityComp.ipynb` or `hydro_evo-ViscosityComp.py`.



The resulting plots can be found under the `hydro_session` folder.



4. Temperature dependent $(\eta/s)(T)$ and $(\zeta/s)(T)$

One can further try a temperature-dependent $(\eta/s)(T)$ by setting the variable `<T_dependent_Shear_to_S_ratio>` to **3**. Once this parameter is set to 3, the previous parameter `<shear_viscosity_eta_over_s>` will be ineffective. The users need to further specify the following four parameters,

```
1. <eta_over_s_T_kink_in_GeV>
2. <eta_over_s_low_T_slope_in_GeV>
3. <eta_over_s_high_T_slope_in_GeV>
4. <eta_over_s_at_kink>`
```

to characterize the temperature dependence of $(eta\,/\,s)(T)$.

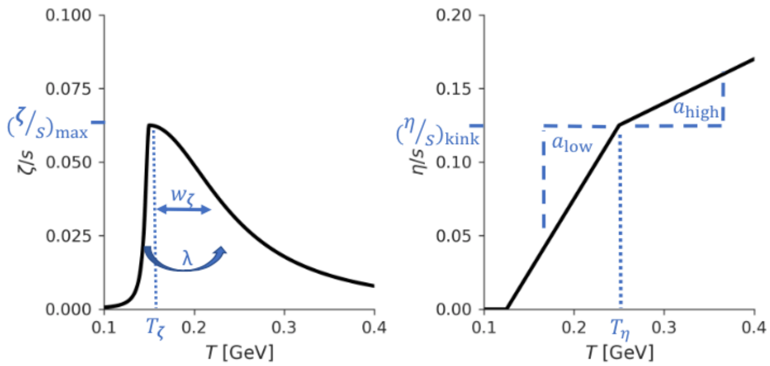
$$\frac{\eta}{s}|_{\rm lin}(T) = a_{\rm low}(T - T_\eta)\Theta(T_\eta - T) + (\eta/s)_{\rm kink} \\ \qquad + \; a_{\rm high}(T - T_\eta)\Theta(T - T_\eta).$$

Siimilar to the case for $(\eta/s)(T)$, the uses can set the parameter `<temperature_dependent_bulk_viscosity>` to **3** in the xml file to include a temperature dependent $(\zeta/s)(T)$. With `<temperature_dependent_bulk_viscosity>` set to 3, the users needs to further provide four additional parameters to characterize the shape of $(zeta\,/\,s)(T)$. They are as follows,

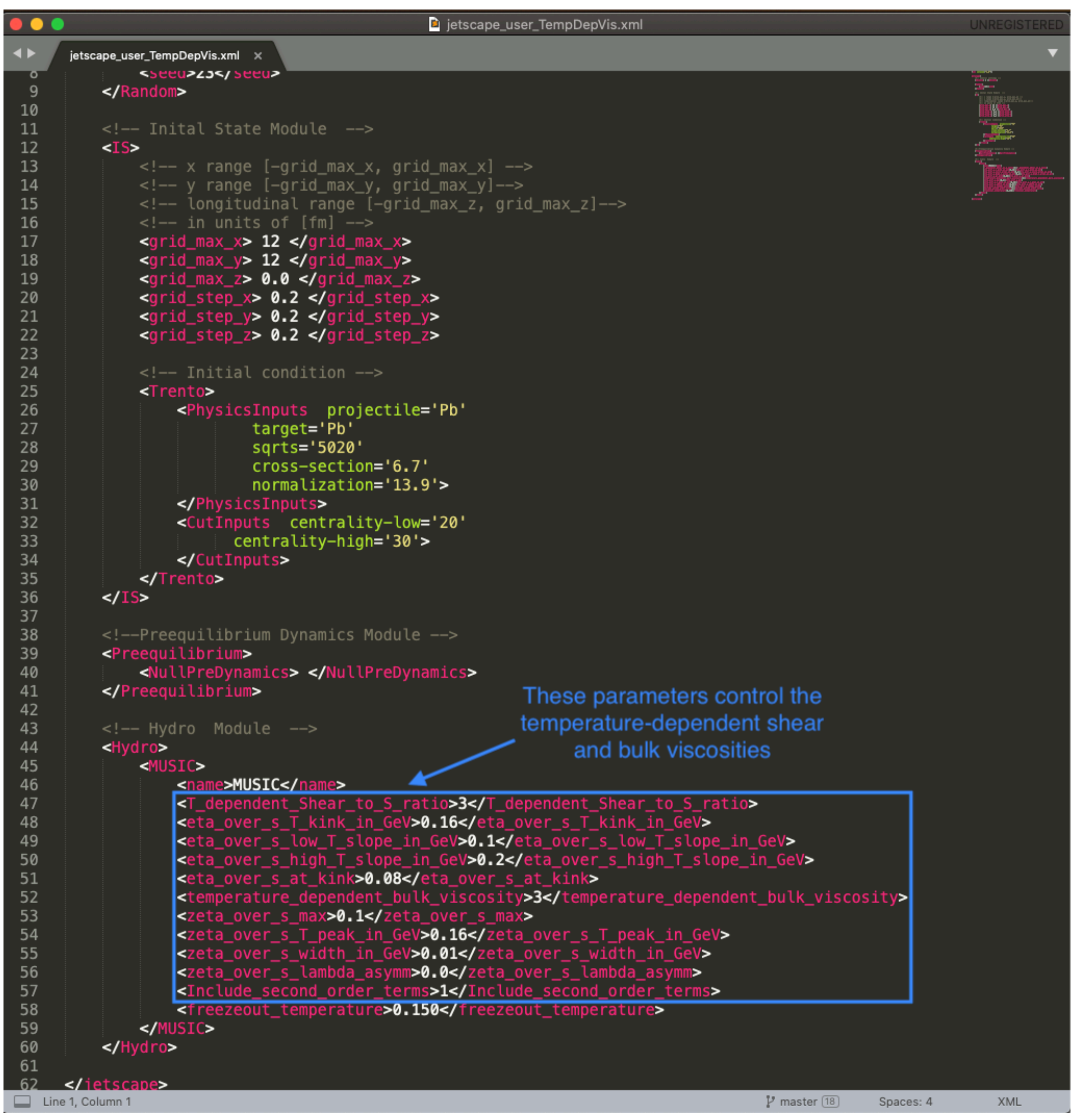
```
1. <zeta_over_s_max>
2. <zeta_over_s_T_peak_in_GeV>
3. <zeta_over_s_width_in_GeV>
4. <zeta_over_s_lambda_asymm>
```

The parameterization is

$$
\frac{\zeta}{s}(T) = \frac{(\zeta/s)_{\max}\Lambda^2}{\Lambda^2 + (T - T_{\zeta,c})^2},
$$
$$
\Lambda = w_\zeta \left[1 + \lambda \,\mathrm{sign}\left(T - T_{\zeta,c}\right)\right].
$$



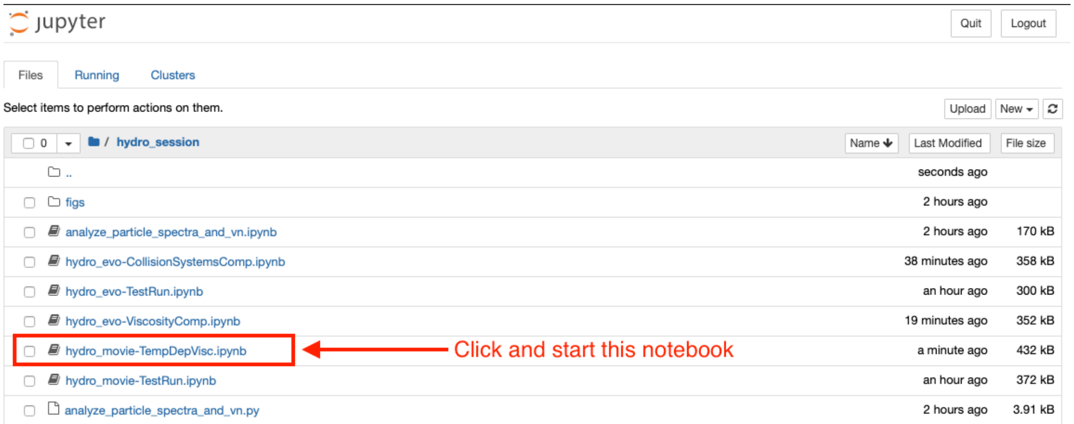
Users can play with settings in `hydro_session/jetscape_user_TempDepVis.xml`.

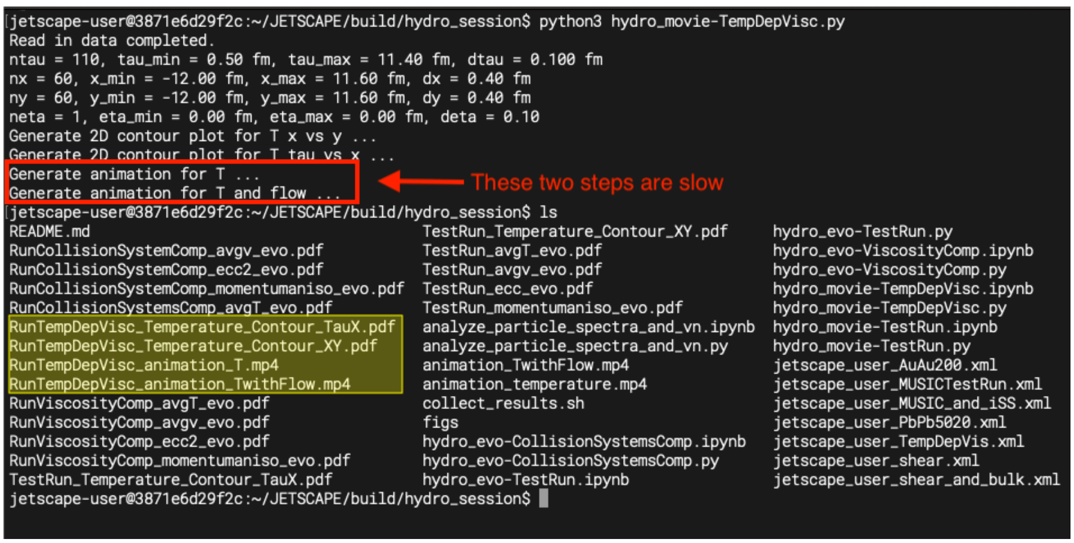



```xml
        <seed>23</seed>
    </Random>

    <!-- Inital State Module  -->
    <IS>
        <!-- x range [-grid_max_x, grid_max_x] -->
        <!-- y range [-grid_max_y, grid_max_y]-->
        <!-- longitudinal range [-grid_max_z, grid_max_z]-->
        <!-- in units of [fm] -->
        <grid_max_x> 12 </grid_max_x>
        <grid_max_y> 12 </grid_max_y>
        <grid_max_z> 0.0 </grid_max_z>
        <grid_step_x> 0.2 </grid_step_x>
        <grid_step_y> 0.2 </grid_step_y>
        <grid_step_z> 0.2 </grid_step_z>

        <!-- Initial condition -->
        <Trento>
            <PhysicsInputs  projectile='Pb'
                    target='Pb'
                    sqrts='5020'
                    cross-section='6.7'
                    normalization='13.9'>
            </PhysicsInputs>
            <CutInputs  centrality-low='20'
                  centrality-high='30'>
            </CutInputs>
        </Trento>
    </IS>

    <!--Preequilibrium Dynamics Module -->
    <Preequilibrium>
        <NullPreDynamics> </NullPreDynamics>
    </Preequilibrium>

    <!-- Hydro  Module  -->
    <Hydro>
        <MUSIC>
            <name>MUSIC</name>
            <T_dependent_Shear_to_S_ratio>3</T_dependent_Shear_to_S_ratio>
            <eta_over_s_T_kink_in_GeV>0.16</eta_over_s_T_kink_in_GeV>
            <eta_over_s_low_T_slope_in_GeV>0.1</eta_over_s_low_T_slope_in_GeV>
            <eta_over_s_high_T_slope_in_GeV>0.2</eta_over_s_high_T_slope_in_GeV>
            <eta_over_s_at_kink>0.08</eta_over_s_at_kink>
            <temperature_dependent_bulk_viscosity>3</temperature_dependent_bulk_viscosity>
            <zeta_over_s_max>0.1</zeta_over_s_max>
            <zeta_over_s_T_peak_in_GeV>0.16</zeta_over_s_T_peak_in_GeV>
            <zeta_over_s_width_in_GeV>0.01</zeta_over_s_width_in_GeV>
            <zeta_over_s_lambda_asymm>0.0</zeta_over_s_lambda_asymm>
            <Include_second_order_terms>1</Include_second_order_terms>
            <freezeout_temperature>0.150</freezeout_temperature>
        </MUSIC>
    </Hydro>

</jetscape>
```

```
cd ~/JETSCAPE/build
./runJetscape hydro_session/jetscape_user_TempDepVis.xml
./hydro_session/collect_results.sh Run_TempDepVisc
```

The associated ploting scripts are `hydro_movie-TempDepVisc.ipynb` and `hydro_movie-TempDepVisc.py` .





Side notes

In addition to specific shear and bulk viscosity, the users have freedom to change the starting time of hydrodynamics, `<Initial_time_tau_0>` (0.2-1.0 fm) , whether to include second order transport coefficients, `<Include_second_order_terms>` (0 or 1), and particlization temperature, `<freezeout_temperature>` (0.13 to 0.16 GeV)

Initial state module, between `<IS>` and `</IS>` , also define the 3D grid that we would like to simulate hydrodynamic evolution. If one set `grid_max_z` to 0, the JETSCAPE framework will perform a (2+1) hydrodynamic simulations assuming longitudinal boost-invariant.

Cheet sheet for normalization factors in `Trento` ,

Collision sytem	Collision energy (GeV)	norm factor	cross section (mb)
Au+Au	200	5.7	42
Pb+Pb	2760	13.9	62
Pb+Pb	5020	18.4	67

Available nucleus type in `Trento` : p, d, Cu, Xe, Au, Pb, U

Finally, the user can specify a random seed for the entire simulation. This is specified inside the block `<Random>` in the xml file. If the `<seed>` parameter is set to 0. Then the random seed will be determined by the system time. If `<seed>` is set to any positive number, the JETSCAPE will perform simulations with the given positive number is the random seed for all its modules. A fix seed simulation will be handy when we study the effect of viscosity during the hydrodynamic evolution.

After each run, please create a result folder with the viscosity information and move the following three files into the result folder,

- `eccentricities_evo_eta_-0.5_0.5.dat`

This file records the evolution of spacial eccentricity of the fireball. Format: `# tau(fm) ecc_n(cos) ecc_n(sin) (n=1-6)`

- `momentum_anisotropy_eta_-0.5_0.5.dat`

This file has the evolution information about the momentum anisotropy, average velocity, and average temperature. Format: `# tau(fm) epsilon_p(ideal) epsilon_p(shear) epsilon_p(full) ecc_2 ecc_3 R_Pi gamma T[GeV]`

- `evolution_for_movie_xyeta_MUSIC.dat`

This file contains the evolution history of fluid cells above T = 130 MeV. Every fluid cell includes the following information: `itau ix iy ieta volume[fm^4] e[GeV/fm^3] rho_B[1/fm^3] T[GeV] mu_B[GeV] u^x u^y \tau*u^\eta T^{\tau t}[GeV/fm^3] J^\tau[1/fm^3]`

[Bonus] 5. Produce hadrons from hydrodynamics

In JETSCAPE, a third-party particle sampler iSpectraSampler (iSS) is employed to convert fluid cells to particles. The iSS produces Monte-Carlo particles from the hydrodynamic hyper-surface. The spatial and momentum distributions of particles follow the Cooper-Frye Formula.

The sampled hadrons are output in the `test_out.dat`. One can run another code script `FinalStateHadrons` to extract the final state hadron list from the `test_out.dat` file. The users need to type in the following command at the build folder,

```
cd ~/JETSCAPE/build
./runJetscape hydro_session/jetscape_user_MUSIC_and_iSS.xml
./FinalStateHadrons test_out.dat hadron_list.dat
```

```xml
<?xml version="1.0"?>

<jetscape>
    <!-- General settings -->
    <nEvents> 10 </nEvents>
    <setReuseHydro> true </setReuseHydro>
    <nReuseHydro> 10 </nReuseHydro>
    <JetScapeWriterAscii> on </JetScapeWriterAscii>

    <Random>
        <seed>0</seed>
    </Random>

    <!-- Inital State Module  -->
    <IS>
        <!-- set boost invariant simulation -->
        <grid_max_z> 0.0 </grid_max_z>

        <!-- Initial condition -->
        <Trento>
            <PhysicsInputs  projectile='Pb'
                    target='Pb'
                    sqrts='5020'
                    cross-section='6.7'
                    normalization='18.4'>
            </PhysicsInputs>
            <CutInputs  centrality-low='20'
                centrality-high='30'>
            </CutInputs>
        </Trento>
    </IS>

    <!--Preequilibrium Dynamics Module -->
    <Preequilibrium>
        <NullPreDynamics> </NullPreDynamics>
    </Preequilibrium>

    <!-- Hydro  Module  -->
    <Hydro>
        <MUSIC>
            <name>MUSIC</name>
            <shear_viscosity_eta_over_s>0.15</shear_viscosity_eta_over_s>
            <freezeout_temperature>0.150</freezeout_temperature>
        </MUSIC>
    </Hydro>

    <!-- Particlization Module  -->
    <SoftParticlization>
        <iSS> </iSS>
    </SoftParticlization>
</jetscape>
```

Oversample 10 particlization events on one hydrodynamic hyper-surface

Add a Cooper-Frye Particlization module

```
jetscape-user@3871e6d29f2c:~/JETSCAPE/build$ ./FinalStateHadrons test_out.dat hadron_list.dat
[Info] 147MB  Open Input File = test_out.dat
[Info] 147MB  File opened
[Info] 147MB  Current Event = 0
Number of hadrons is: 6256
[Info] 150MB  Current Event = 1
Number of hadrons is: 6280
[Info] 151MB  Current Event = 2
Number of hadrons is: 6611
[Info] 151MB  Current Event = 3
Number of hadrons is: 6460
[Info] 151MB  Current Event = 4
Number of hadrons is: 6448
[Info] 151MB  Current Event = 5
Number of hadrons is: 6548
[Info] 151MB  Current Event = 6
Number of hadrons is: 6585
[Info] 151MB  Current Event = 7
Number of hadrons is: 6509
[Info] 151MB  Current Event = 8
Number of hadrons is: 6417
[Info] 151MB  Current Event = 9
Number of hadrons is: 6631
jetscape-user@3871e6d29f2c:~/JETSCAPE/build$
```

With the produced `hadron_list.dat` file, the users can apply their own analysis script to compute particle spectra, mean p_T, and anisotropic flow coefficients v_n. Example analysis codes are `analyze_particle_spectra_and_vn.ipynb` and `analyze_particle_spectra_and_vn.py`.

```
[jetscape-user@3871e6d29f2c:~/JETSCAPE/build/hydro_session$ python3 analyze_particle_spectra_and_vn.py
Read in total 10 events.
analyze_particle_spectra_and_vn.py:94: RuntimeWarning: invalid value encountered in true_divide
  v2diff_real.bin_y_ = v2diff_real.bin_y_/pTSpectra.bin_y_
analyze_particle_spectra_and_vn.py:95: RuntimeWarning: invalid value encountered in true_divide
  v2diff_imag.bin_y_ = v2diff_imag.bin_y_/pTSpectra.bin_y_
[jetscape-user@3871e6d29f2c:~/JETSCAPE/build/hydro_session$ ls
README.md                                    TestRun_avgT_evo.pdf                   hydro_evo-ViscosityComp.py
RunCollisionSystemComp_avgv_evo.pdf          TestRun_avgv_evo.pdf                   hydro_movie-TempDepVisc.ipynb
RunCollisionSystemComp_ecc2_evo.pdf          TestRun_ecc_evo.pdf                    hydro_movie-TempDepVisc.py
RunCollisionSystemComp_momentumaniso_evo.pdf TestRun_momentumaniso_evo.pdf          hydro_movie-TestRun.ipynb
RunCollisionSystemsComp_avgT_evo.pdf         analyze_particle_spectra_and_vn.ipynb  hydro_movie-TestRun.py
RunTempDepVisc_Temperature_Contour_TauX.pdf  analyze_particle_spectra_and_vn.py     jetscape_user_AuAu200.xml
RunTempDepVisc_Temperature_Contour_XY.pdf    animation_TwithFlow.mp4                jetscape_user_MUSICTestRun.xml
RunTempDepVisc_animation_T.mp4               animation_temperature.mp4              jetscape_user_MUSIC_and_iSS.xml
RunTempDepVisc_animation_TwithFlow.mp4       collect_results.sh                     jetscape_user_PbPb5020.xml
RunViscosityComp_avgT_evo.pdf                figs                                   jetscape_user_TempDepVis.xml
RunViscosityComp_avgv_evo.pdf                hydro_evo-CollisionSystemsComp.ipynb   jetscape_user_shear.xml
RunViscosityComp_ecc2_evo.pdf                hydro_evo-CollisionSystemsComp.py      jetscape_user_shear_and_bulk.xml
RunViscosityComp_momentumaniso_evo.pdf       hydro_evo-TestRun.ipynb                pTSpectra.pdf
TestRun_Temperature_Contour_TauX.pdf         hydro_evo-TestRun.py                   v2_pTdiff.pdf
TestRun_Temperature_Contour_XY.pdf           hydro_evo-ViscosityComp.ipynb
jetscape-user@3871e6d29f2c:~/JETSCAPE/build/hydro_session$
```

HOMEWORK

1. Study the viscous effects on hydrodynamic evolution

Simulate a Pb+Pb collision in 20-30% centrality at 5.02 TeV. In order to compare simulations with different viscosity, we need to fix the random seed. You can choose your favorite number for the seed. (42?)

- Compare the development of flow anisotropy as a function of proper time with two different shear viscosities
- Compare the development of averaged radial with and without the specific bulk viscosity
- Compare the averaged temperature evolution with two choices of the specific bulk viscosity $(zeta / s)(T)$

2. Produce animation for the temperature and flow velocity profiles in the transverse plane

- Pick your favorite collision system (colliding nuclei, collision energy, and centrality) and generate a hydrodynamic evolution file.

You can try different color maps or even define your own to make the animation vivid.

Please send your best animation to chunshen@wayne.edu. We will select the most impressive ones and post them on the school website.

3. [Bonus] Compute particle spectra and flow anisotropic flow Qn vectors from the event-by-event simulations for one heavy-ion collision system.

To accumulate statistic, you can set `<nEvents>` to 50 and `<nReuseHydro>` to 50 in the xml file to avoid running 50 hydrodynamic simulations. With the generated `test_out.dat` file, apply `FinalStateHadron` and analysis the output to get p_T-spectra for charged hadrons and their flow anisotropy coefficients.