Calypso Tutorial

Hiroaki Matsui
(UC Davis)

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Goal of this tutorial

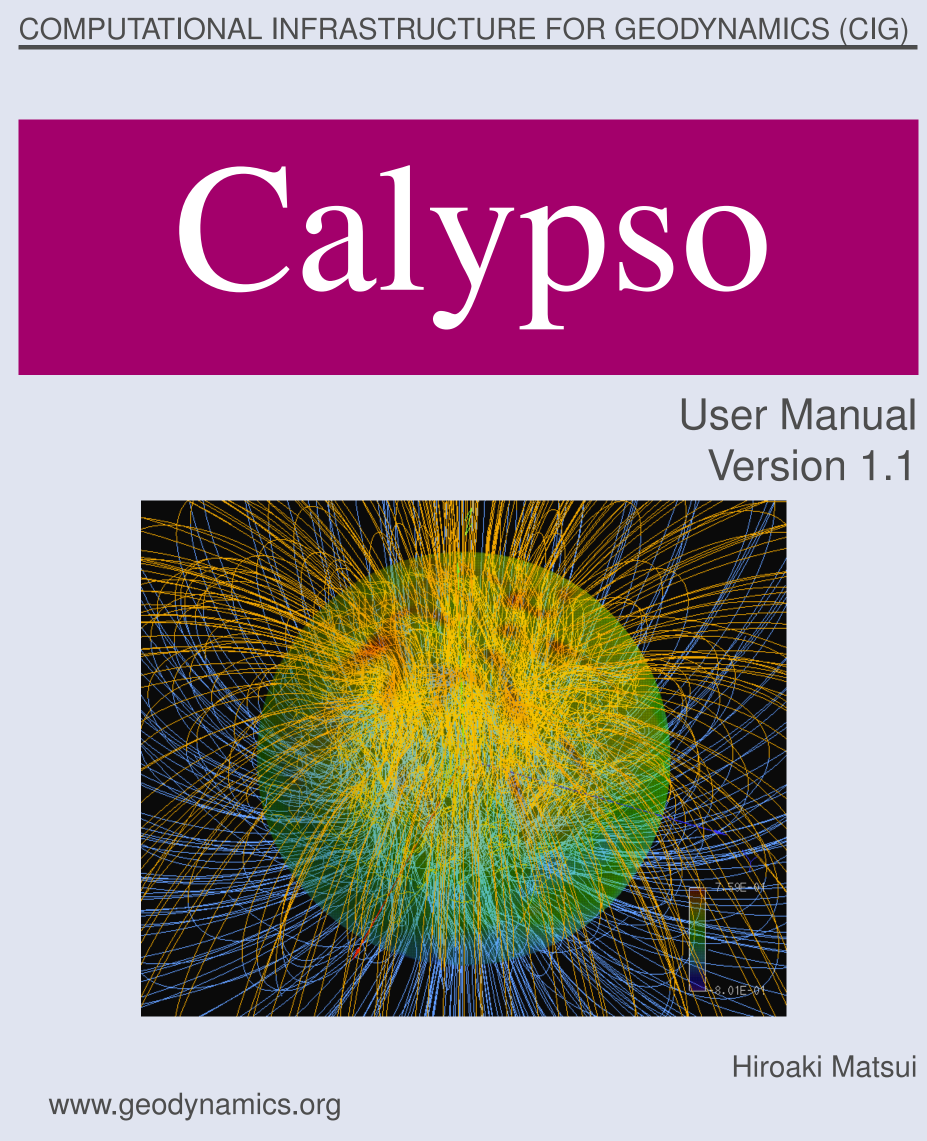
- Learn to run a geodynamo model using Calypso
- Understand parameter files for Calypso
- Run a non-magnetic convection model
- Check scaling with changing Rayleigh number

What is Calypso?

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

- Geodynamo model using spherical harmonics transform and Finite Difference method
  - MPI / OpenMP parallelization
  - Large flexibility
  - Various output

- More than 80 pages of documentation


COMPUTATIONAL INFRASTRUCTURE FOR GEODYNAMICS (CIG)

Calypso

User Manual
Version 1.1

Hiroaki Matsui

www.geodynamics.org

What can Calypso do?

- Magnetohydrodynamics (MHD) simulation in a rotating spherical shell
  - Boussinesq fluid
  - Double diffusive (temperature and composition)
  - Thermal and compositional buoyancy
  - Conductive or insulated inner core
  - Thermal and compositional heterogeneity at boundaries

  - Data output
    - Time history (Energies, Nusselt number)
    - Field data in Cartesian coordinates for visualization

Governing equations for non-magnetic rotating convection

- Momentum equation

Coriolis force

$$\left[\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\, \boldsymbol{u}\right] + 2\,(\boldsymbol{\Omega} \times \boldsymbol{u}) = -\nabla P + \nu \nabla^2 u - \alpha T \boldsymbol{g}$$

- Energy equation

$$\frac{\partial T}{\partial t} + (\boldsymbol{u} \cdot \nabla)\, T = \kappa \nabla^2 T,$$

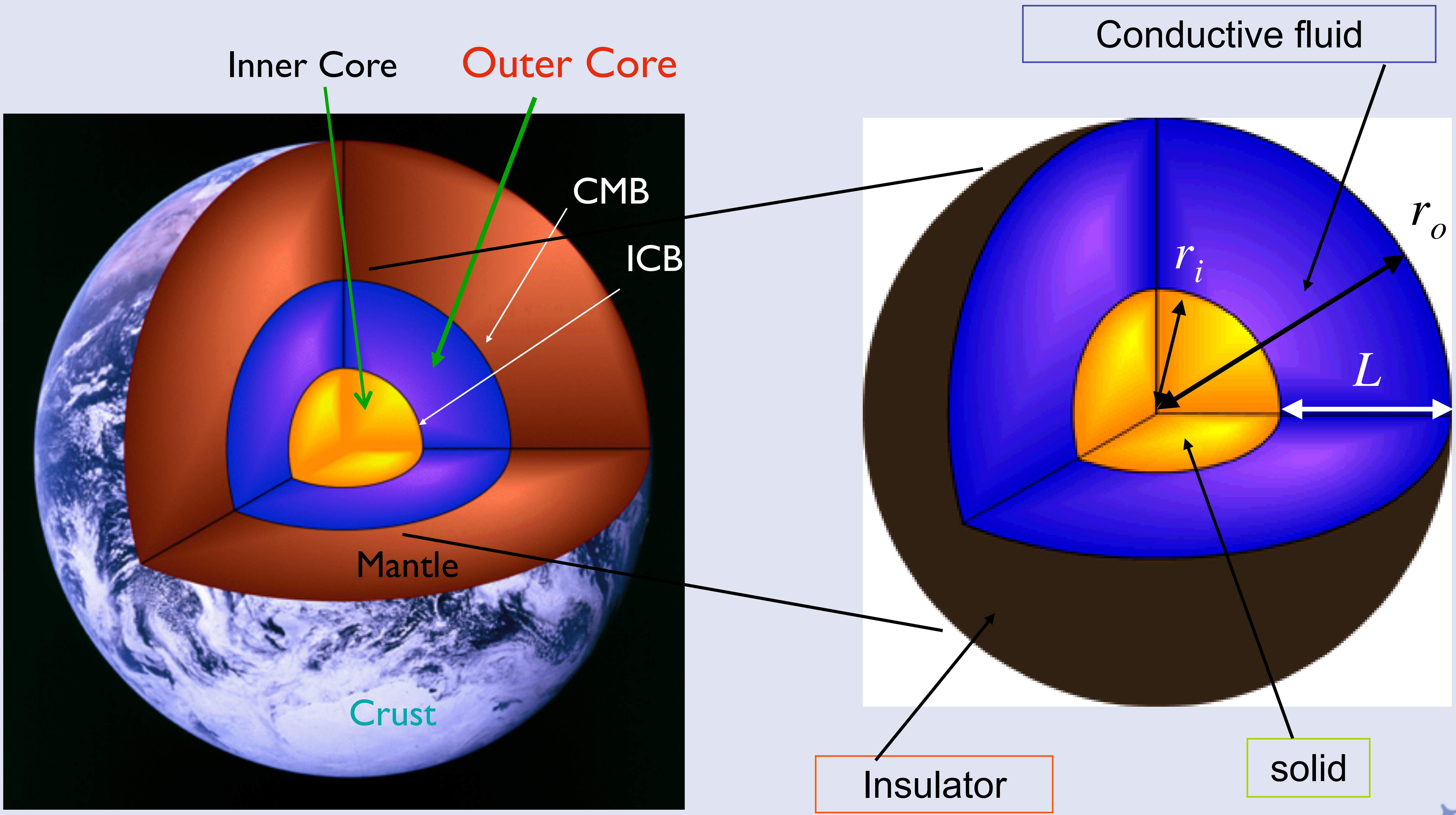
- Conservation of Mass

$$\nabla \cdot \boldsymbol{u} = 0.$$

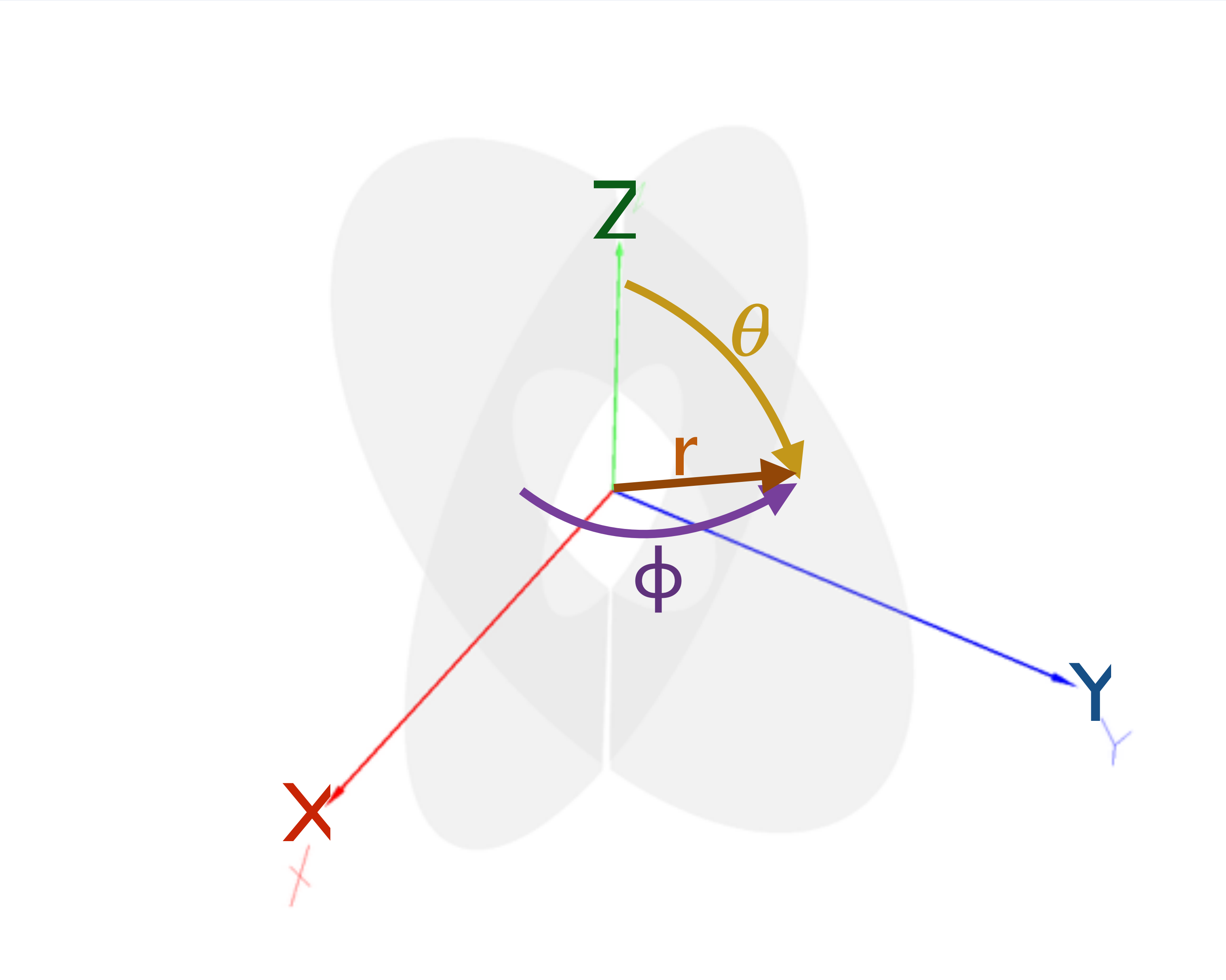
$\boldsymbol{\Omega}$: Rotation of system ν: Kinetic viscosity

α: Thermal expansion κ: Thermal diffusivity

Rotating spherical shell for geodynamo simulations



Spherical coordinate system



- r: Radial direction
- θ: Meridional direction
- ϕ: Zonal direction (Longitudinal)

- Domain is discretized to evaluate nonlinear terms

Spherical harmonics Y_l^m

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See http://mathworld.wolfram.com/SphericalHarmonic.html

$m=0$ $m=1$ $m=2$ $m=3$ $m=4$ $m=5$

$l=1$

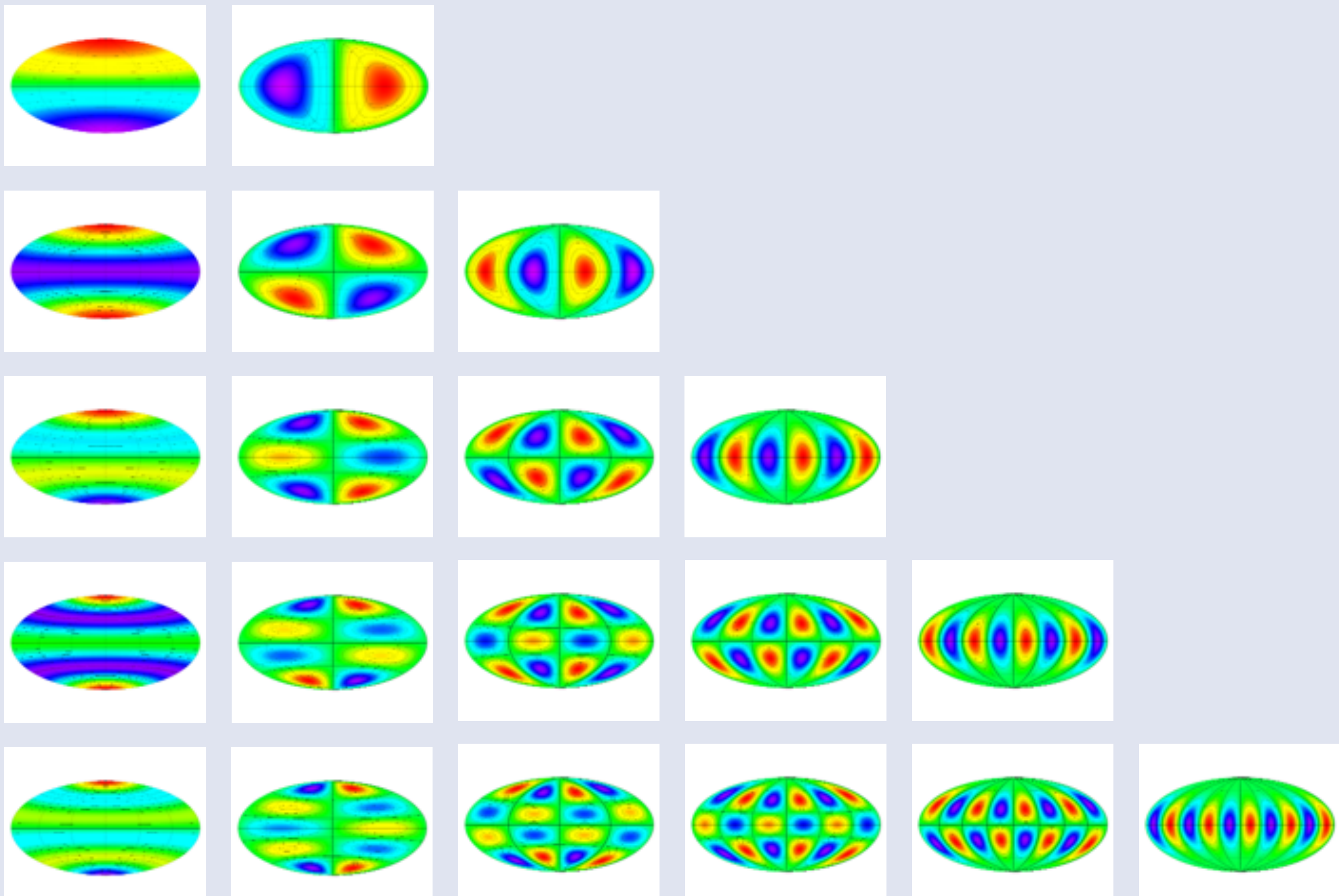
$l=2$

$l=3$

$l=4$

$l=5$

$\vdots$



Truncation degree l_{max}

Contacts for Calypso

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

- Homepage
  - http://geodynamics.org/cig/software/calypso/
- Mailing list
  - cig-geodyn@geodynamics.org
- Wiki
  - http://wiki.geodynamics.org/software:calypso:start

Procedure of simulation

1. Preprocessing: Prepare spherical harmonics index table

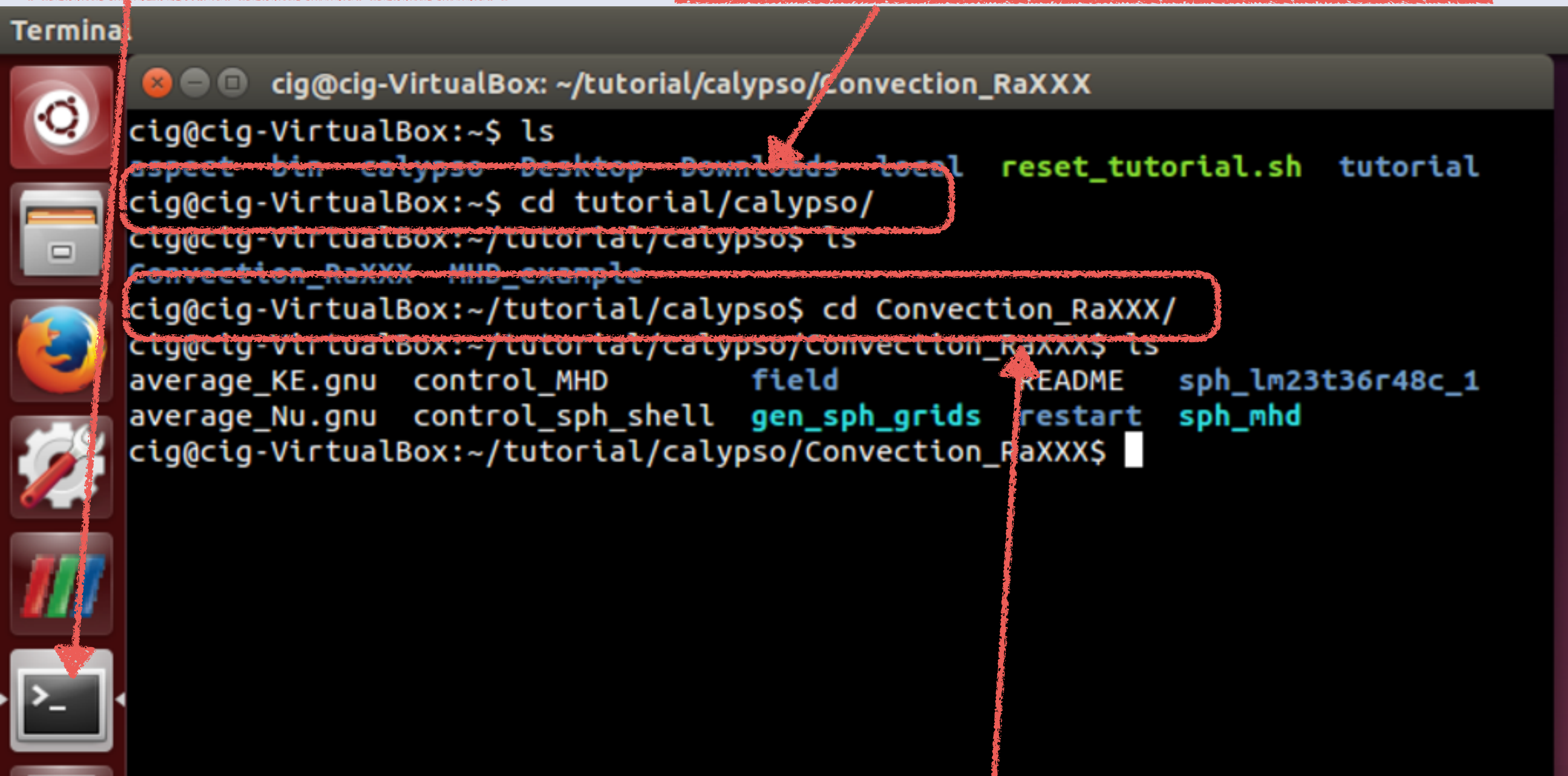
2. Run simulation

3. Postprocessing

Data for the tutorial

1. Open Terminal

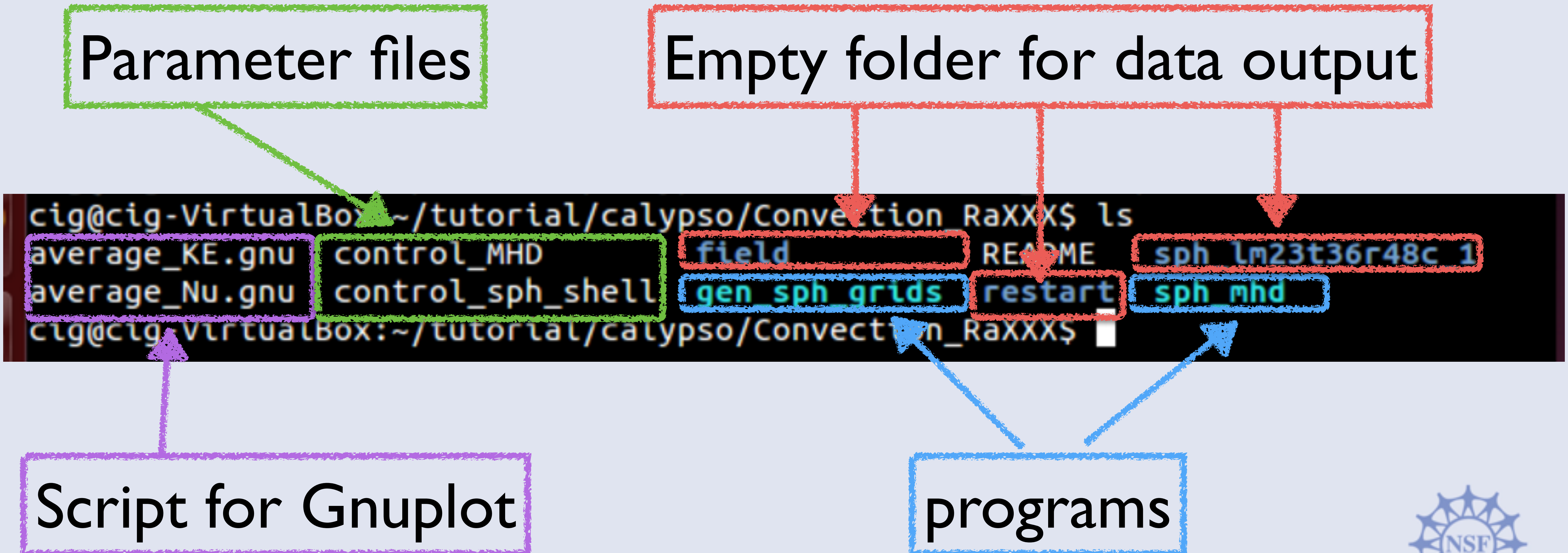
2. $ cd tutorial/calypso



3. $ cd Convection_RaXXX

Check file list

- Type `$ ls`
- Programs and input files are ready



Procedure of simulation

1. Preprocessing: Prepare spherical harmonics index table
   - Command: `$ ./gen_sph_grid`
   - Parameter file: control_sph_shell
2. Run simulation

3. Postprocessing

Start preprocessing program

1. Preprocessing: Prepare spherical harmonics index table
   – Command: `$ ./gen_sph_grids`
   – Parameter file: control_sph_shell

```
average_Nu.gnu  control_sph_shell  gen_sph_grids  restart  sph_mhd
cig@cig-VirtualBox:~/tutorial/calypso/Convection_RaXXX$ ./gen_sph_grids
 truncation degree:                       23
 number of grid for f(r,t,p):             49           36           72
 subdomain for f(r,t,p):                   1            1            1
 subdomain for f(r,t,m):                   1            1            1
 subdomain for f(r,l,m):                   1            1
 subdomain for spectr f(r,j):              1            1
 radial grid is written in radial_point.dat
 Write ascii spectr modes file: sph_lm23t36r48c_1/in.0.rlm
 Write ascii grid file: sph_lm23t36r48c_1/in.0.rtm
```

Start preparation program

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Truncation l_{max} | # of meridional | # of radial grids | # of parallelization

- Files are generated in sph_lm23t36r48c_1

  (Directory name is specified in file `control_sph_shell`)

```
 Write ascii spectr modes file: sph_lm23t36r48c_1/in.0.rj
Spherical modes and grids for domain      0 is done.
 Write ascii mesh file: sph_lm23t36r48c_1/in.0.gfm
FEM mesh for domain      0 is done.
 program is normally terminated
cig@cig-VirtualBox:~/tutorial/calypso/Convection_RaXXX$ ls
average_KE.gnu  control_sph_shell  radial_point.dat  sph_lm23t36r48c_1
average_Nu.gnu  field              README            sph_mhd
control_MHD     gen_sph_grids      restart
cig@cig-VirtualBox:~/tutorial/calypso/Convection_RaXXX$ ls sph_lm23t36r48c_1/
in.0.gfm  in.0.rj  in.0.rlm  in.0.rtm  in.0.rtp  README
cig@cig-VirtualBox:~/tutorial/calypso/Convection_RaXXX$
```

Procedure of simulation

1. Preprocessing: Prepare spherical harmonics index table

2. Run simulation
   – Command: `$ mpirun -np 1 ./sph_mhd`
   – Parameter file: control_MHD
3. Postprocessing

Dimensionless numbers

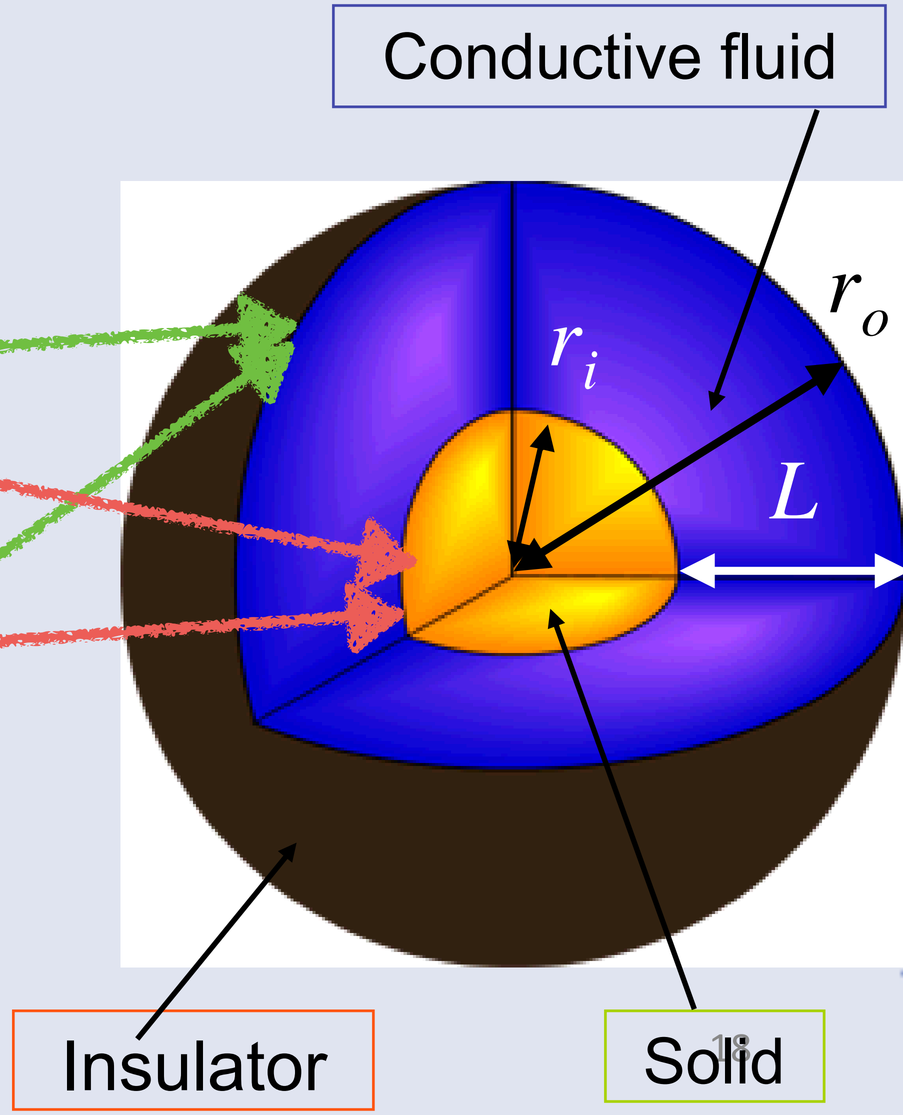
$$\text{Prandtl number: } Pr = \frac{\nu}{\kappa} = \frac{\text{Viscous diffusivity}}{\text{Thermal diffusivity}}$$

$$\text{Ekman number: } E = \frac{\nu}{\Omega L^2} = \frac{\text{Viscous diffusivity}}{\text{Coriolis force}}$$

$$\text{Rayleigh number: } Ra = \frac{\alpha g \Delta T L^3}{\nu \kappa} = \frac{\text{Buoyancy}}{\text{Diffusivity}}$$

Model for tutorial

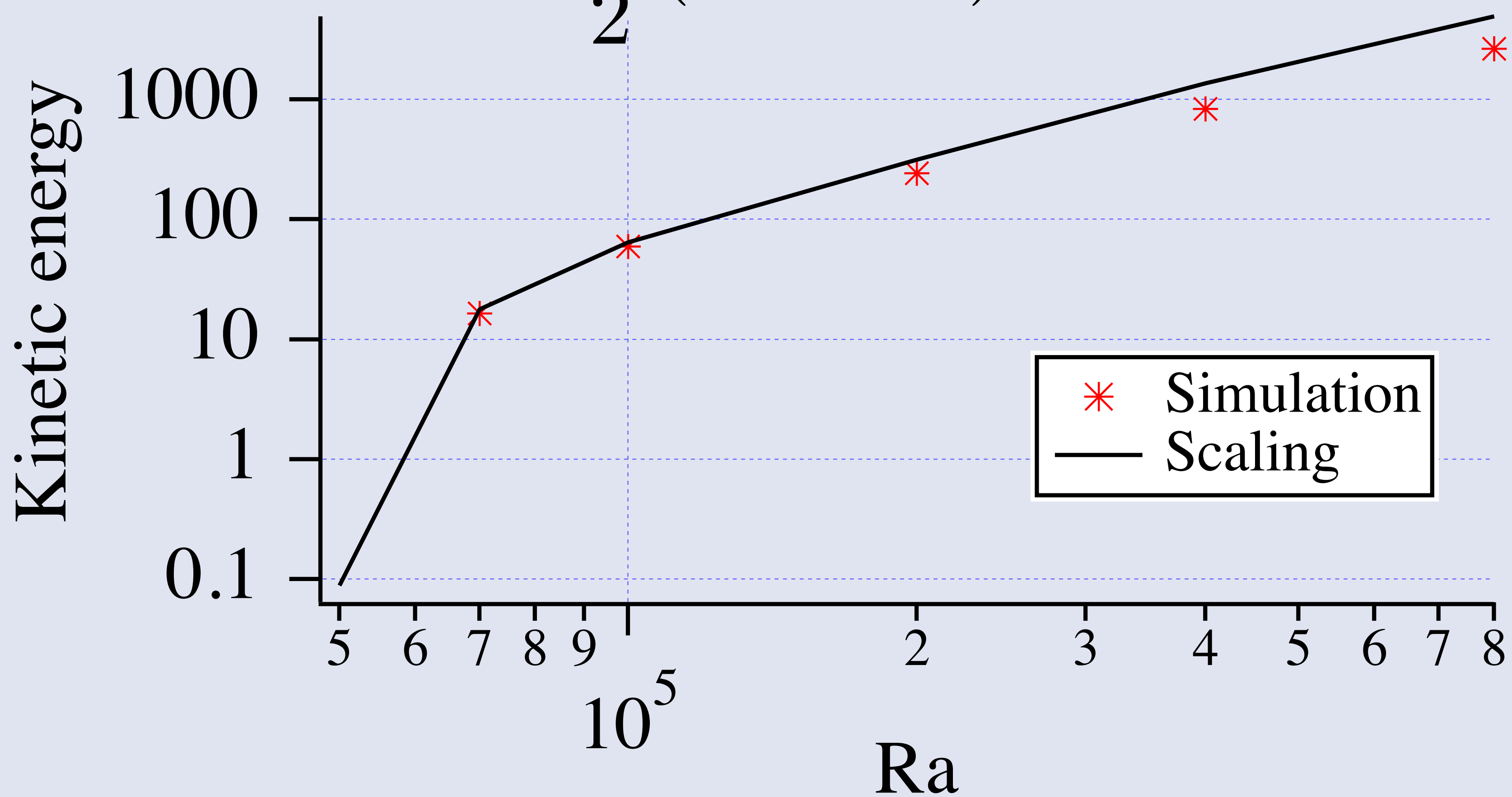
- You will perform simulation by changing Rayleigh number
  - *Ra* = 7.0e4, 1.0e5, 2.0e5, 4.0e5, 8.0e5
- The other dimensionless number is fixed
  - *Pr* = 1.0, *E* = 1.0E-3
- Non-slip boundary
  - $\boldsymbol{u} = 0$
- Isothermal condition
  - T = 1.0 at ICB
  - T = 0.0 at CMB



Expected scaling plot

- You will perform simulation by changing Rayleigh number
  - *Ra* = 7.0e4, 1.0e5, 2.0e5, 4.0e5, 8.0e5
- Obtain scaling law between kinetic energy and Nusselt number

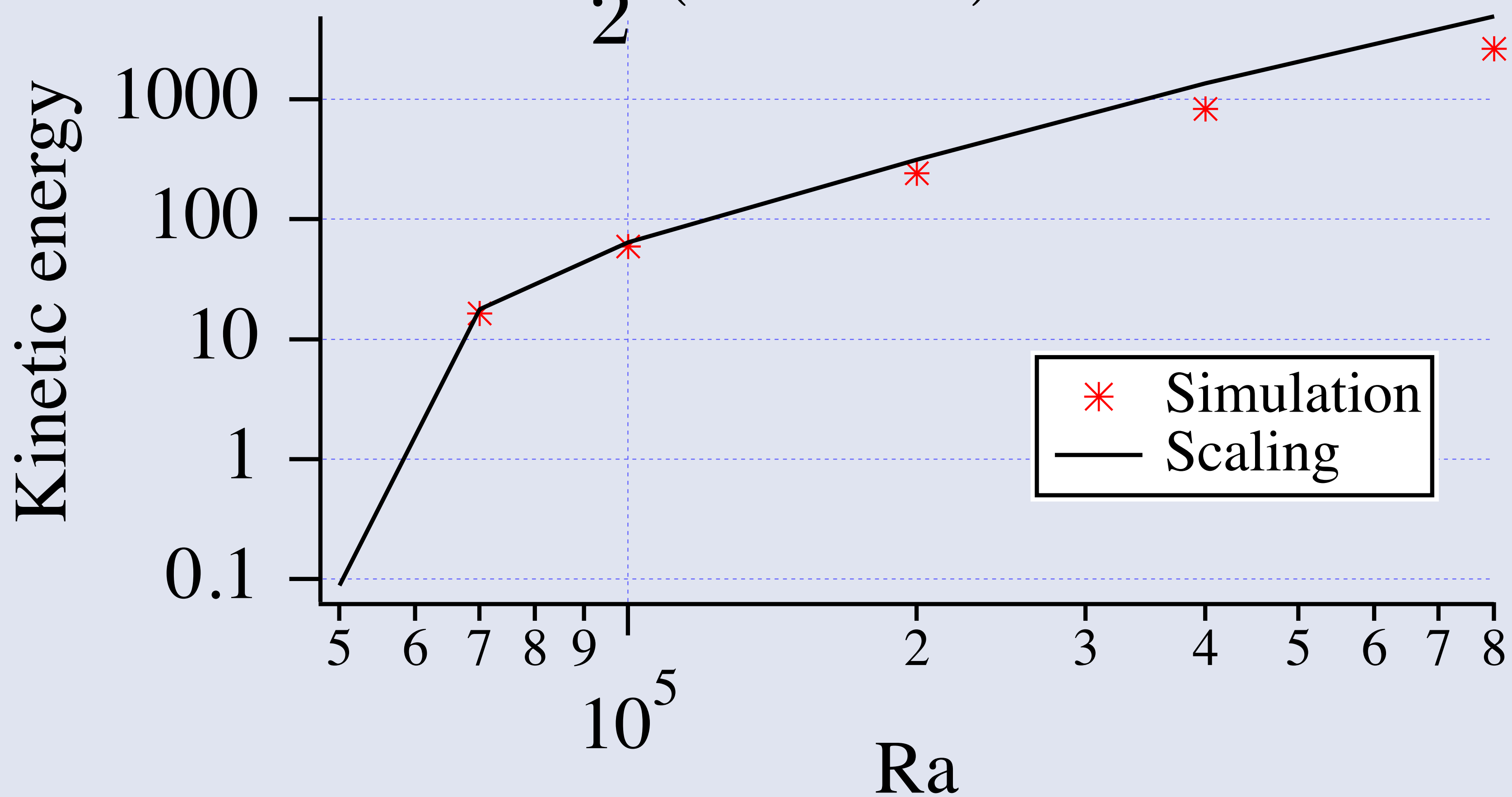
$$E_{kin} = \frac{1}{2}(Nu - 1)\,E^{2/3} Ra Pr^{-2}$$



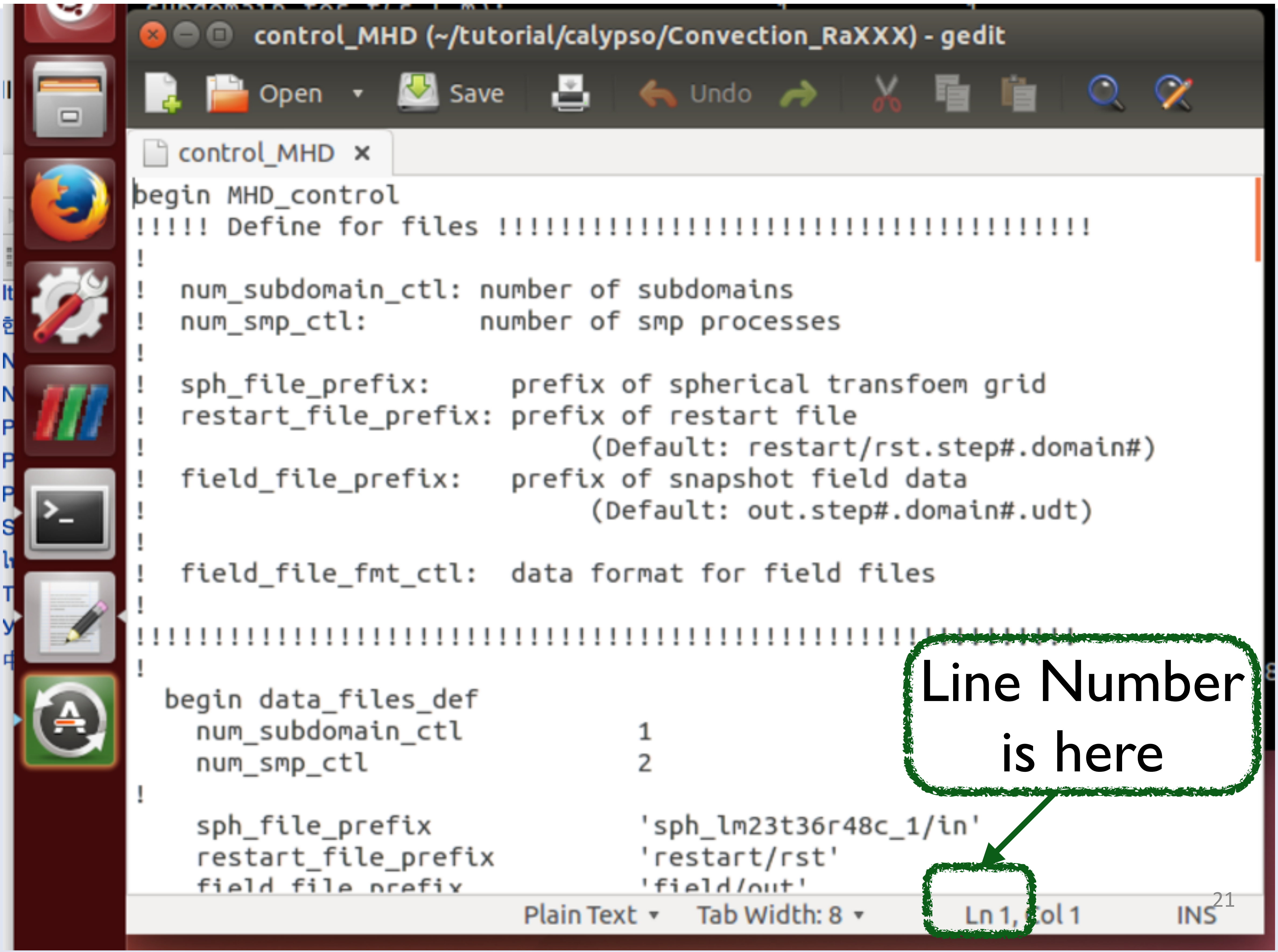
Expected scaling plot

- Details of the scaling law will be explained in Bruce's Lecture on this Friday

$$E_{kin} = \frac{1}{2}\left(Nu - 1\right) E^{2/3} Ra Pr^{-2}$$



Open Control_MHD



Parameter file format

```
  begin dimensionless_ctl
    array dimless_ctl 4
      dimless_ctl  Pr          1.0e+0
      dimless_ctl  Ra          1.0E+5
      dimless_ctl  E           1.0e-3
      dimless_ctl  r_o         1.53846154e+0
    end array dimless_ctl
  end dimensionless_ctl
```

- Parameter name
  - (defined by program)
- If many parameters are defined with the same name, number of items is defined by ‘array [name] # of item’ block.
- Parameter block is defined by ‘begin’ and ‘end’

Modification for control_MHD

- Perform simulation by changing Rayleigh number
- Ra = 7.0e4, 1.0e5, 2.0e5, 4.0e5, 8.0e5
- If Ra = 8.0e5 is chosen, one more modification is required for the shorter time stepping

```
    begin dimensionless_ctl
      array dimless_ctl 4
        dimless_ctl  Pr                 1.0e+0
        dimless_ctl  Ra                 1.0E+5
        dimless_ctl  E                  1.0e-3
        dimless_ctl  r_o                1.53846154e+0
     end array dimless_ctl
    end dimensionless_ctl
```

Change here!

Change time step length for Ra = 8.0E5 Case

```
    begin time_step_ctl
      i_step_init_ctl             0
      i_step_finish_ctl        4000
!
      i_step_check_ctl           20
      i_step_rst_ctl           2000
      i_step_field_ctl          500
!
      dt_ctl                 2.0e-4
      time_init_ctl          0.0e-8
    end time_step_ctl
```

- Change the total number of time steps to 8000
- Change length of time step to 1.0e-4

How to run MPI programs?

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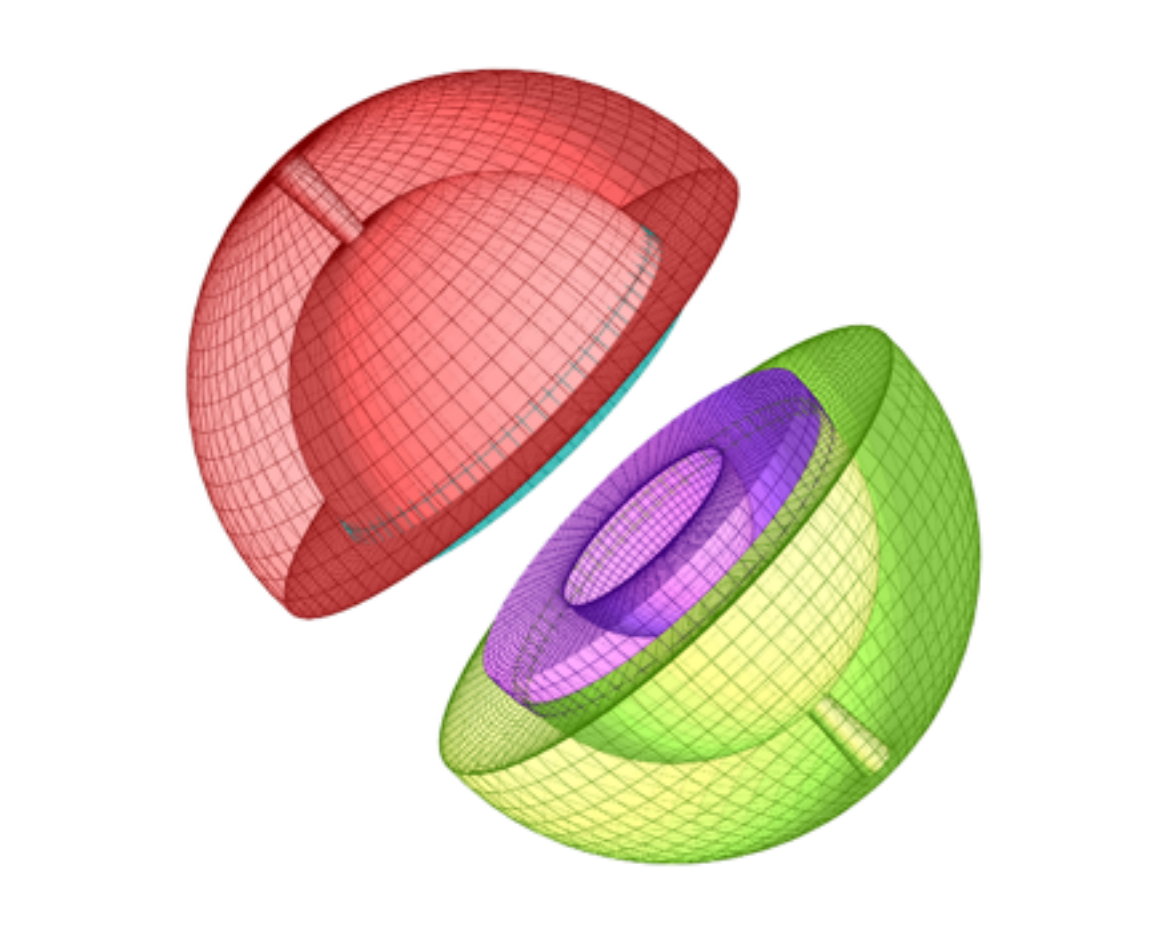
```
$ mpirun -np 4 ./sph_mhd
```

- `mpirun`: Command to invoke MPI program
- `-np 4`: Number of Processes
- `./sph_mhd`: Executable file name



Process 0

Process 1

Process 2

Process 3

Now, we use only one process

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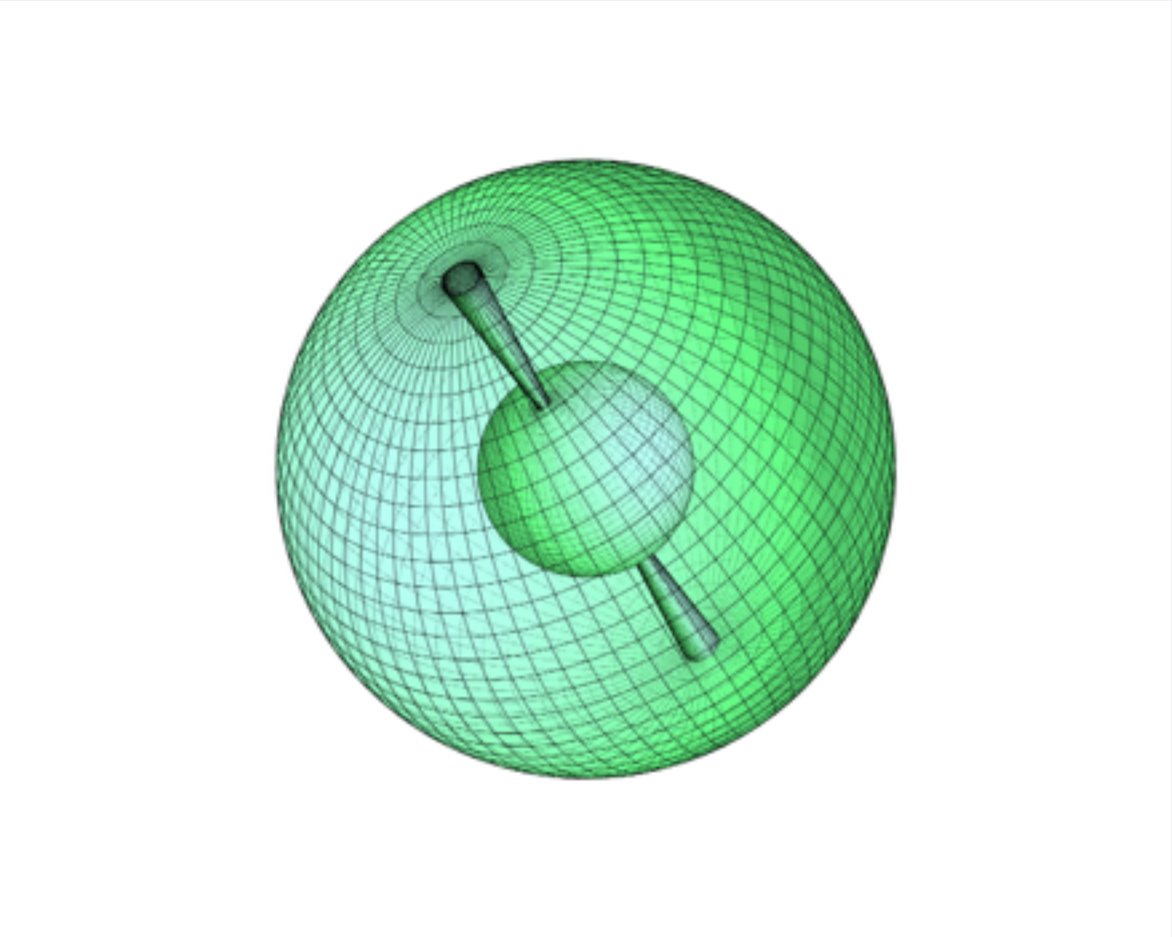
```
$ mpirun -np 1 ./sph_mhd
```

Command to invoke MPI program

Number of Processes

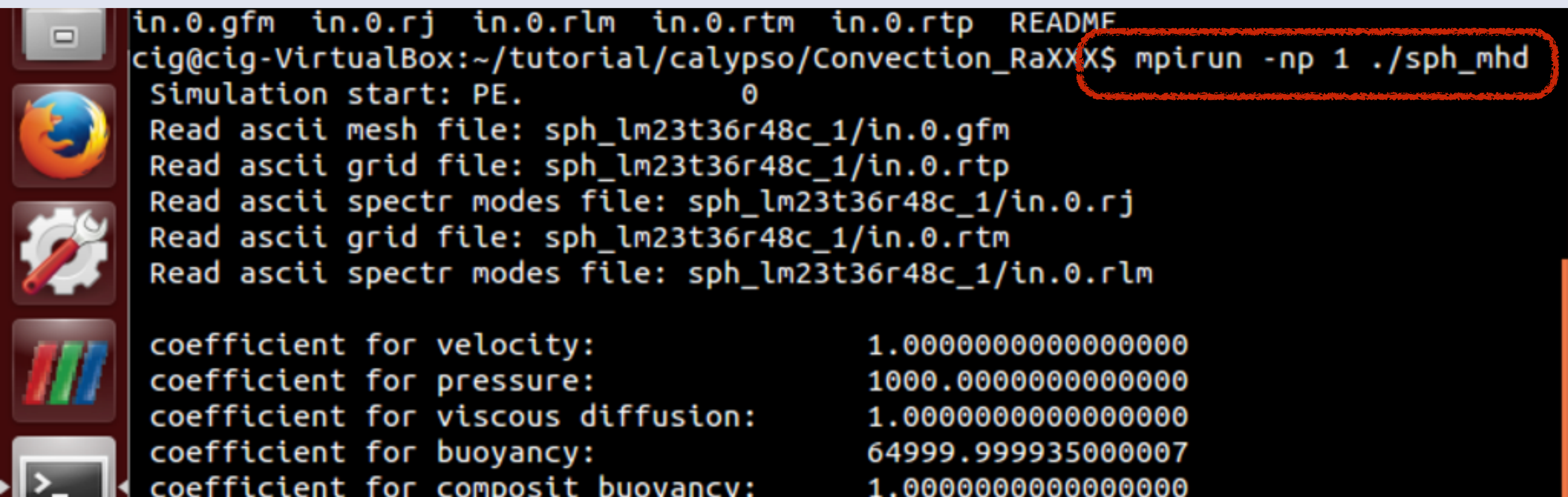
Executable file name



Process 0

Start simulation

2. Run simulation
   - Command: `$ mpirun -np 1 ./sph_mhd`
   - Parameter file: control_MHD



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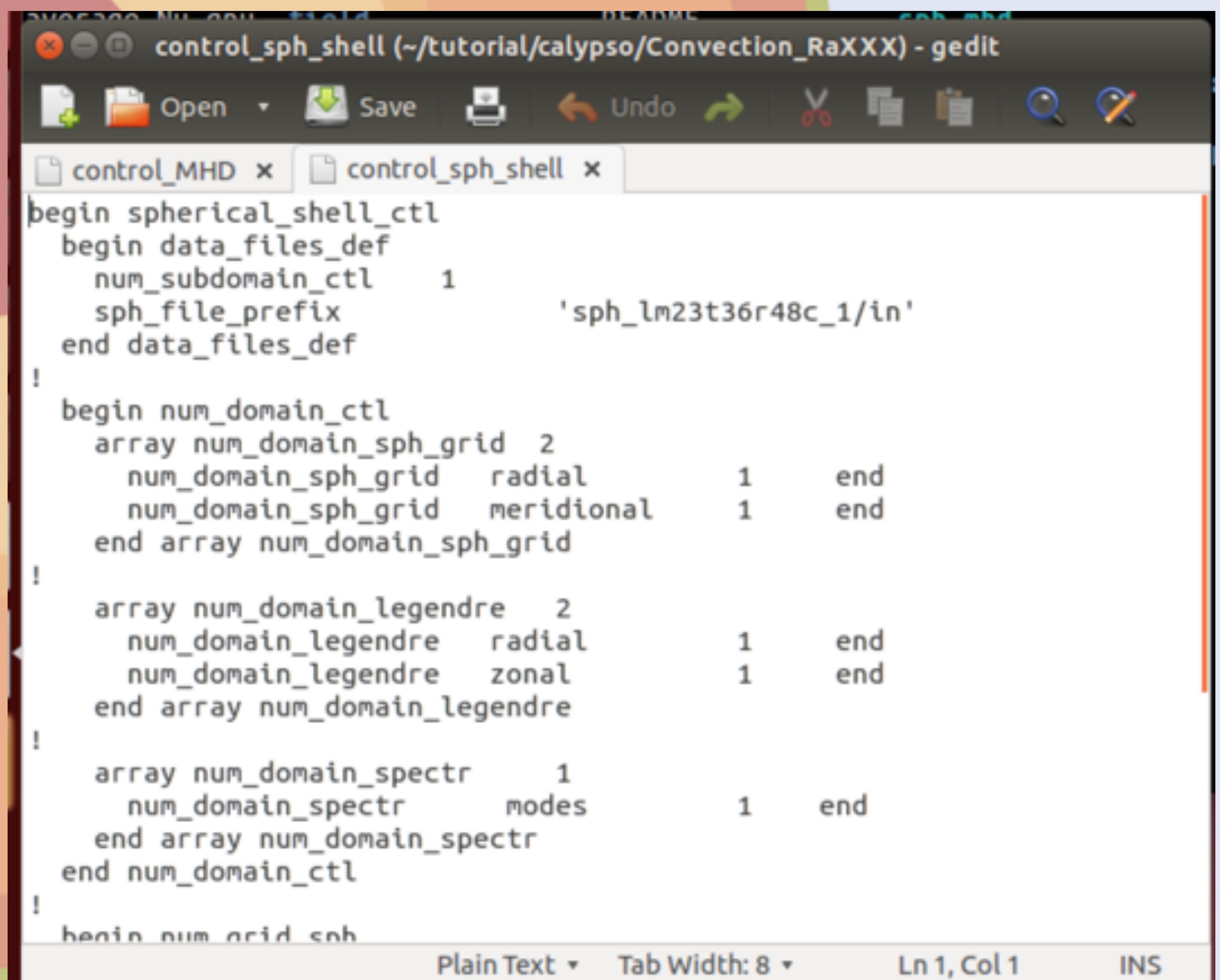
Input file for preprocessing (control_sph_shell)




```
begin spherical_shell_ctl
  begin data_files_def
    num_subdomain_ctl     1
    sph_file_prefix              'sph_lm23t36r48c_1/in'
  end data_files_def
!
  begin num_domain_ctl
    array num_domain_sph_grid  2
      num_domain_sph_grid   radial         1     end
      num_domain_sph_grid   meridional     1     end
    end array num_domain_sph_grid
!
    array num_domain_legendre   2
      num_domain_legendre   radial         1     end
      num_domain_legendre   zonal          1     end
    end array num_domain_legendre
!
    array num_domain_spectr     1
      num_domain_spectr      modes         1    end
    end array num_domain_spectr
  end num_domain_ctl
!
  begin num_grid_sph
```

Blocks for control_sph_shell

- File prefix
- Parallelization
- Spatial resolution

```
1: begin spherical_shell_ctl
2:    begin data_files_def
   …
5:    end data_files_def
6: !
7:    begin num_domain_ctl
   …
21:   end num_domain_ctl
22: !
23:   begin num_grid_sph
   …
33:   end num_grid_sph
34: end spherical_shell_ctl
```

Parallel computation with MPI

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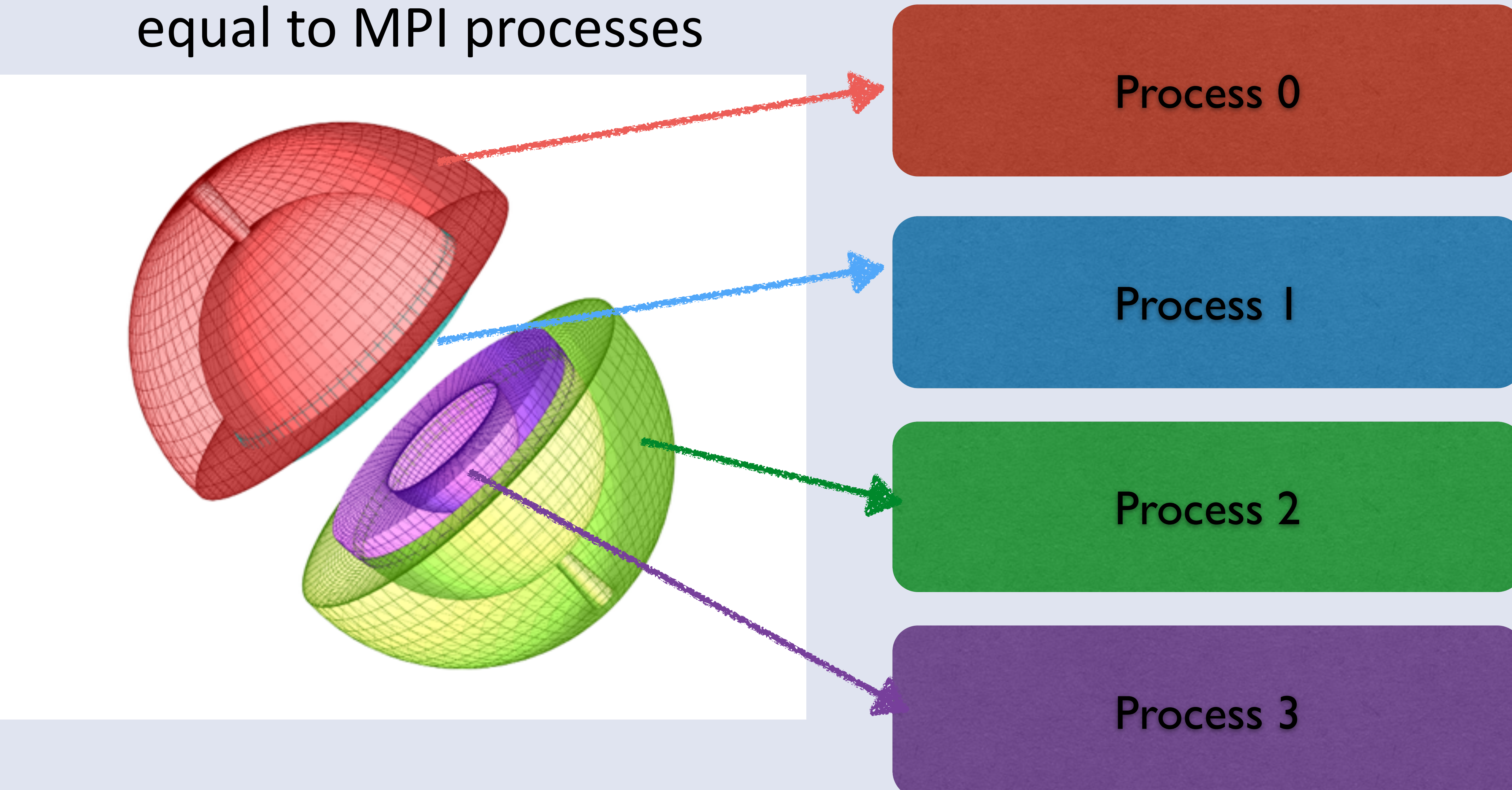
- Number of subdomain is equal to MPI processes



File names

of MPI process

```
begin data_files_def
  num_subdomain_ctl     1
  sph_file_prefix     'sph_lm31r48c_1/in'
end data_files_def
```

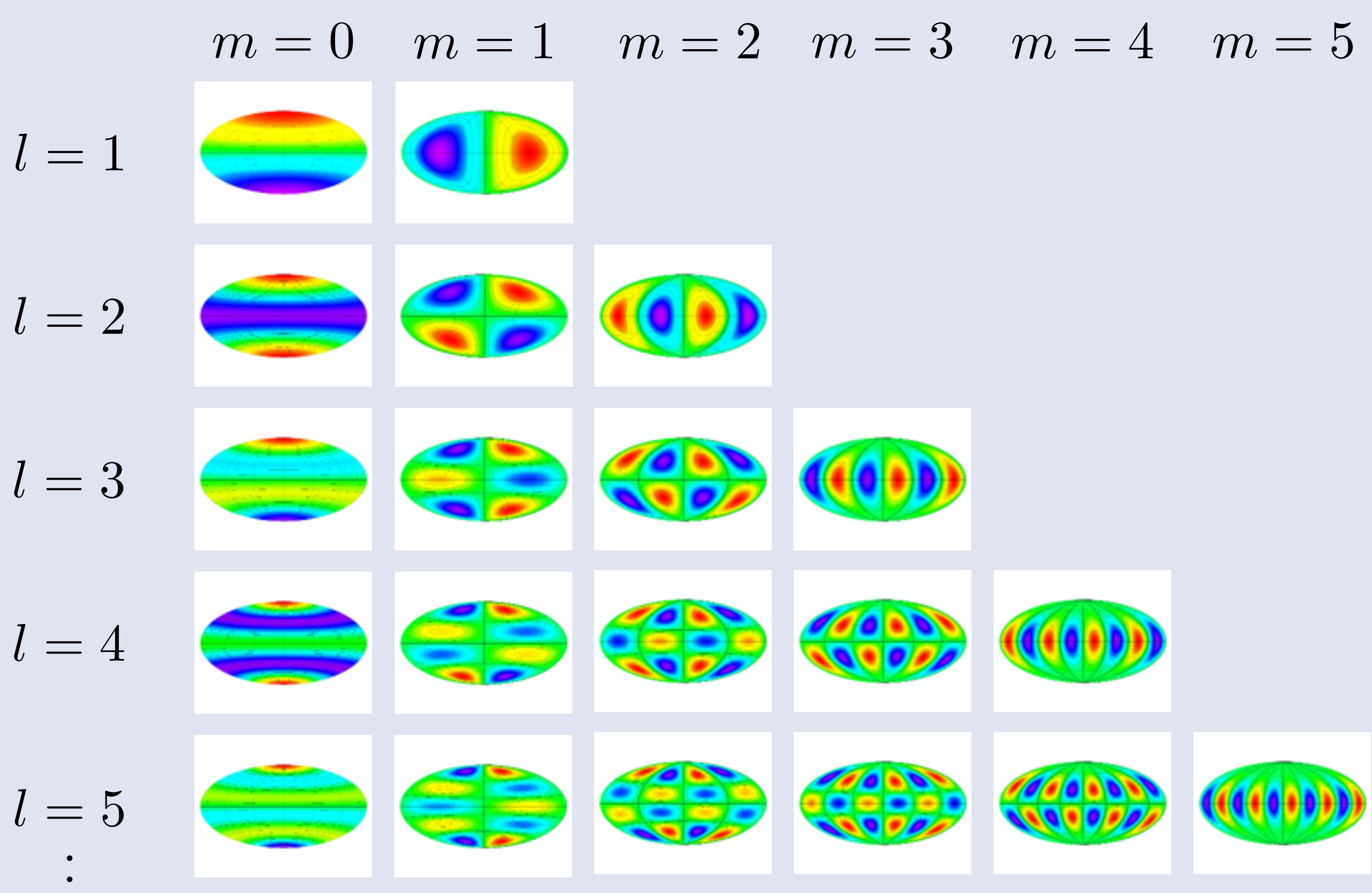
File prefix for harmonics indexing data

```
cig@cig-VirtualBox:~/tutorial/calypso/Convection_RaXXX$ ls
average_KE.gnu  control_MHD        field           README    sph_lm23t36r48c_1
average_Nu.gnu  control_sph_shell  gen_sph_grids   restart   sph_mhd
cig@cig-VirtualBox:~/tutorial/calypso/Convection_RaXXX$
```

Definition of spatial resolution -Horizontal direction-

```
truncation_level_ctl    23
!
ngrid_meridonal_ctl     36
ngrid_zonal_ctl         72
```

Truncation degree l_{max}

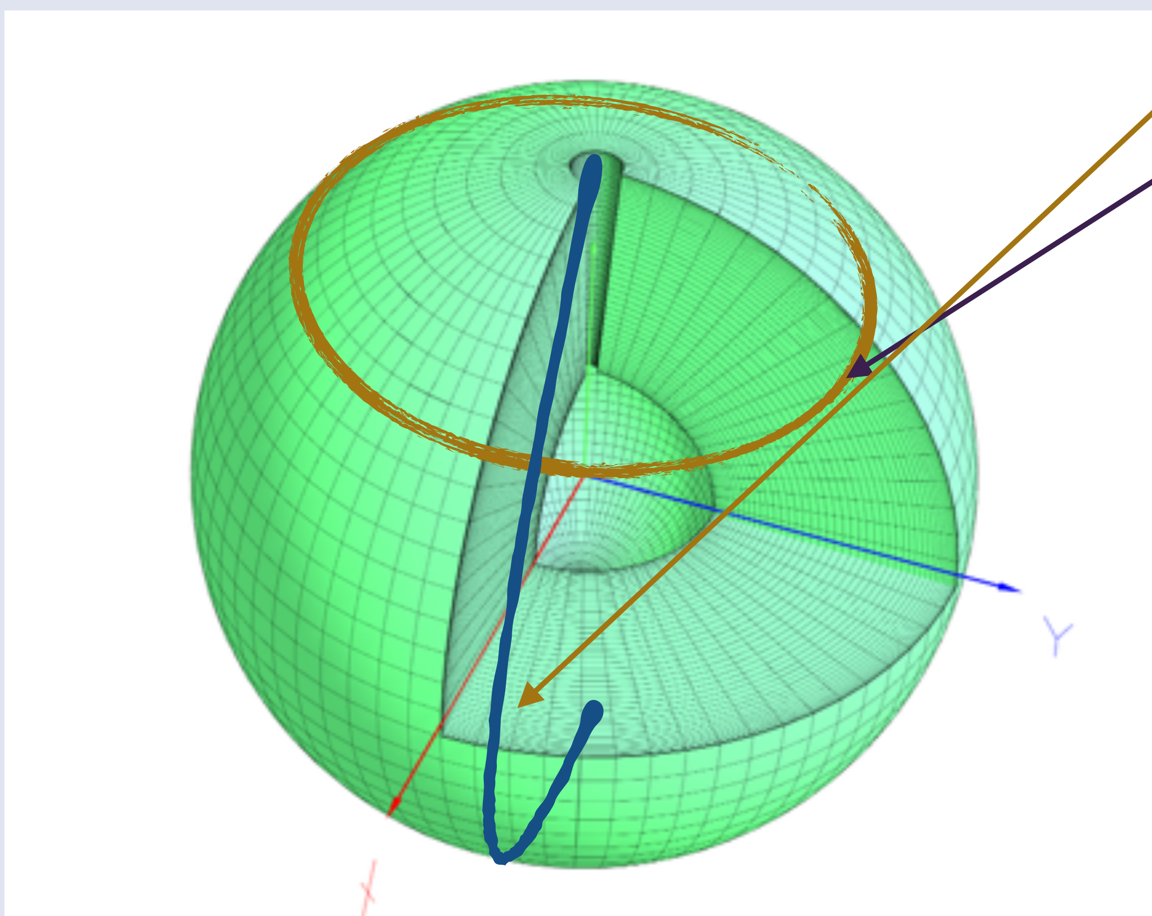


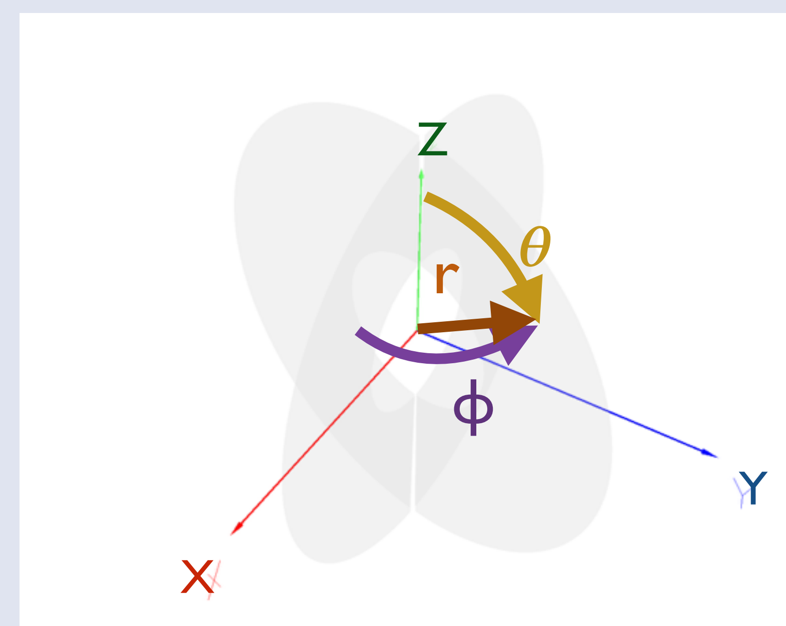
Definition of spatial resolution -Horizontal direction-


```
24:      truncation_level_ctl   23
25:!
26:      ngrid_meridonal_ctl    36
27:      ngrid_zonal_ctl        72
```

Number of meridional grid N_θ

Number of zonal grid N_ϕ

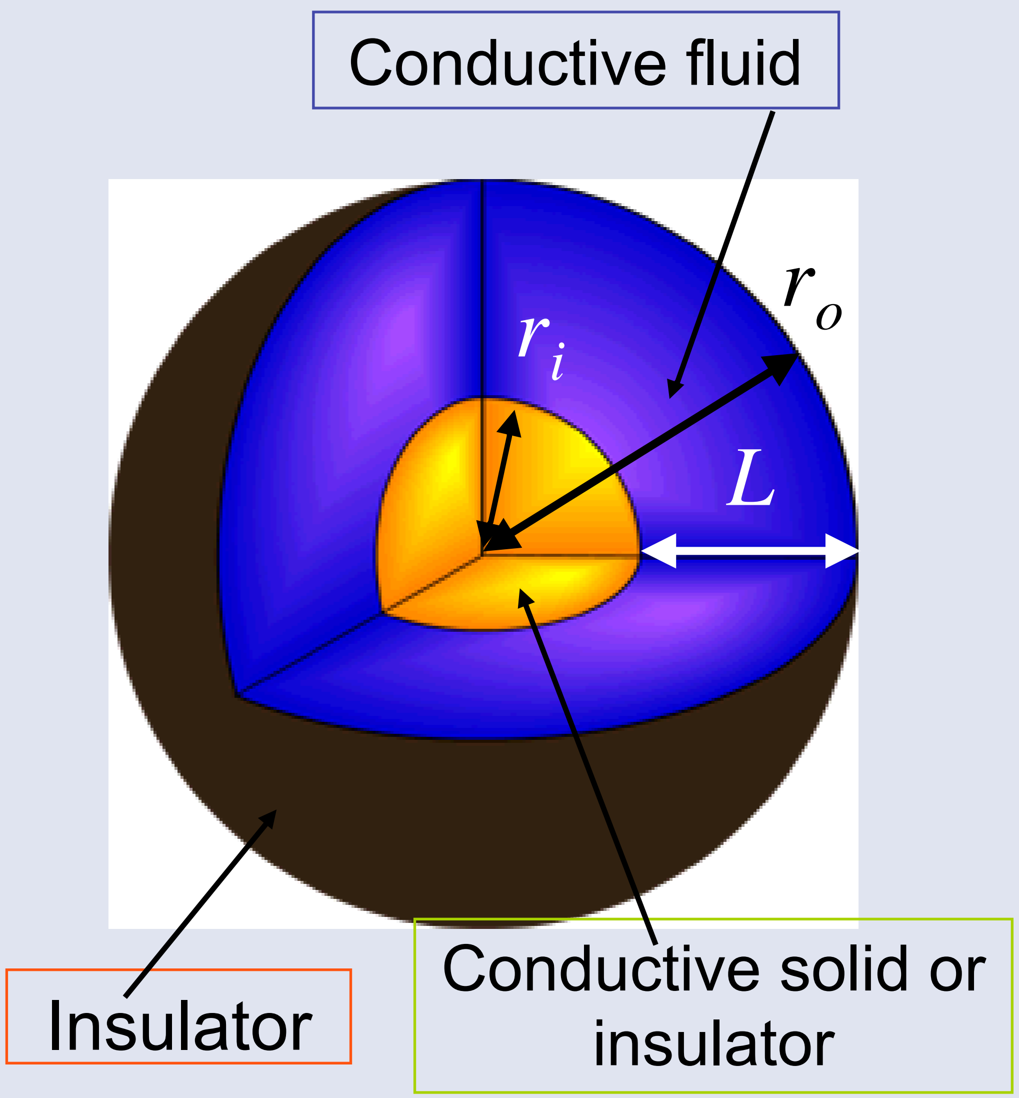


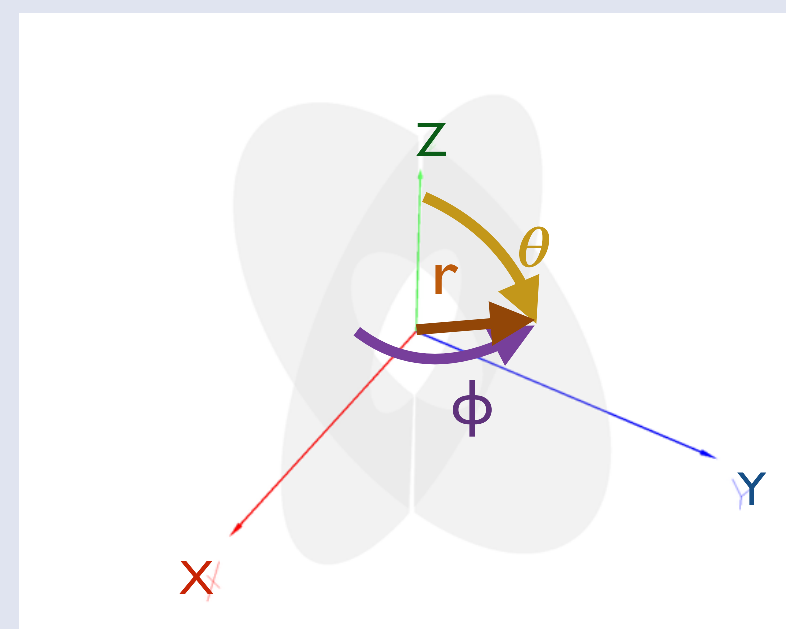


Definition of radial grid


```
30:   num_fluid_grid_ctl       48
31:   fluid_core_size_ctl     1.0
32:   ICB_to_CMB_ratio_ctl    0.35
```

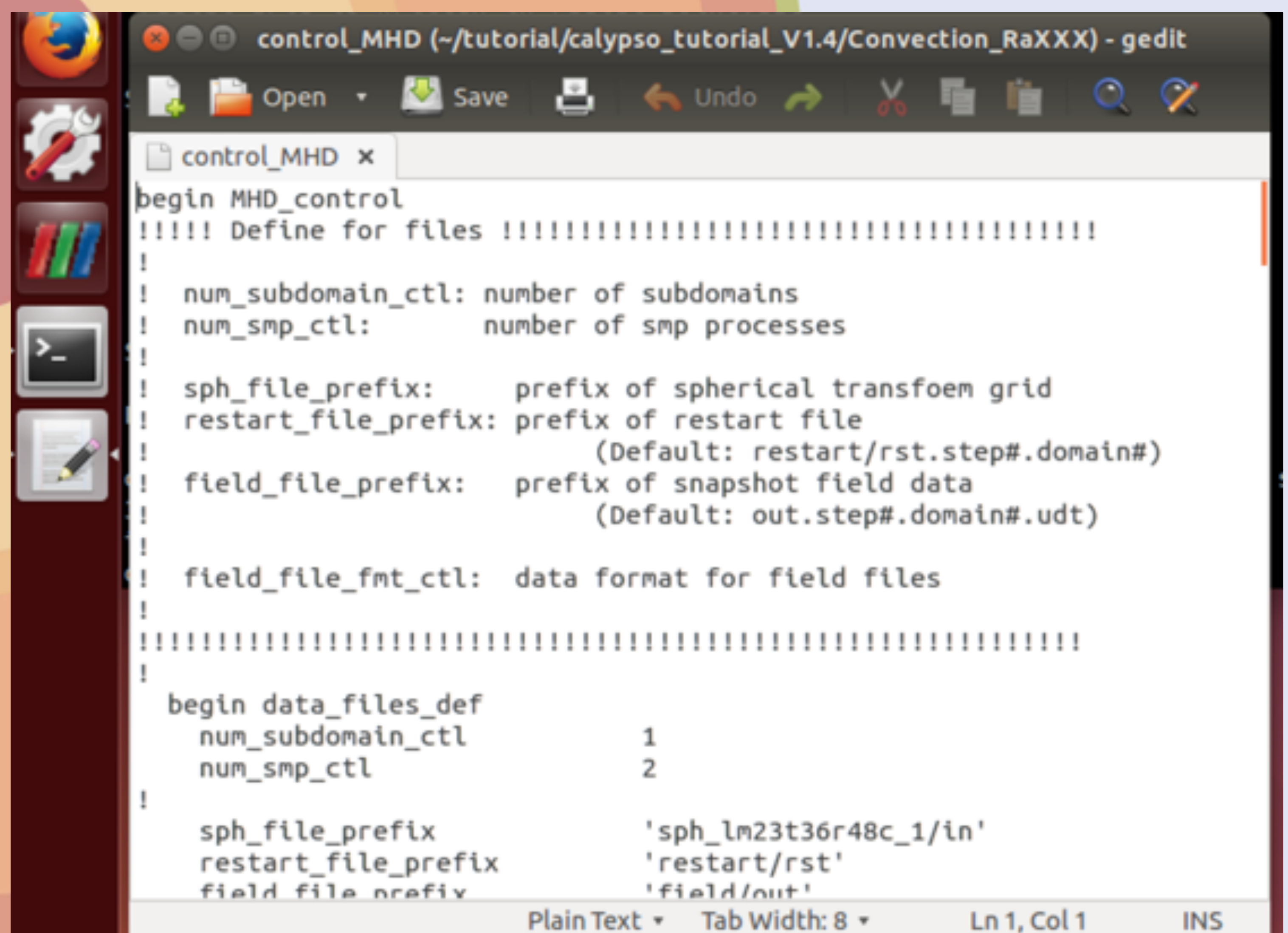
- 48 ← Number of Layers
- 1.0 ← Size of fluid shell L
- 0.35 ← Ratio of inner core to whole shell $\frac{r_i}{r_o}$





CIG COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

Parameter file for simulation (control_MHD)




```
begin MHD_control
!!!!! Define for files !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
!  num_subdomain_ctl: number of subdomains
!  num_smp_ctl:       number of smp processes
!
!  sph_file_prefix:     prefix of spherical transfoem grid
!  restart_file_prefix: prefix of restart file
!                         (Default: restart/rst.step#.domain#)
!  field_file_prefix:   prefix of snapshot field data
!                         (Default: out.step#.domain#.udt)
!
!  field_file_fmt_ctl:  data format for field files
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
 begin data_files_def
   num_subdomain_ctl          1
   num_smp_ctl                2
!
   sph_file_prefix            'sph_lm23t36r48c_1/in'
   restart_file_prefix        'restart/rst'
   field_file_prefix          'field/out'
```

data_files_def
File setting

```
  begin data_files_def
    num_subdomain_ctl     1
    num_smp_ctl           2
!
    sph_file_prefix      'sph_lm23t36r48c_1/in'
    restart_file_prefix  'restart/rst'
    field_file_prefix    'field/out'
!
    field_file_fmt_ctl     'VTK'
  end data_files_def
```

```
cig@cig-VirtualBox:~/tutorial/calypso/Convection_RaXXX$ ls
average_KE.gnu   control_MHD         field            README    sph_lm23t36r48c_1
average_Nu.gnu   control_sph_shell   gen_sph_grids    restart   sph_mhd
cig@cig-VirtualBox:~/tutorial/calypso/Convection_RaXXX$
```

Data definition
phys_values_ctl

```
begin phys_values_ctl
  array nod_value_ctl    4
    nod_value_ctl   velocity      Viz_On    Monitor_On
    nod_value_ctl   temperature   Viz_On    Monitor_On
    nod_value_ctl   pressure      Viz_Off   Monitor_On
    nod_value_ctl   vorticity     Viz_On    Monitor_On
  end array nod_value_ctl
end phys_values_ctl
```

Field name

Field data output flag

Time series output flag

Choose of time integration
time_evo_ctl

```
begin time_evolution_ctl
  array time_evo_ctl    2
    time_evo_ctl   temperature
    time_evo_ctl   velocity
 end array time_evo_ctl
end time_evolution_ctl
```

Field for time integration

label	field name	Description
velocity	Velocity	$\boldsymbol{u}$
temperature	Temperature	T
composition	Composition variation	C
magnetic_field	Magnetic field	$\boldsymbol{B}$

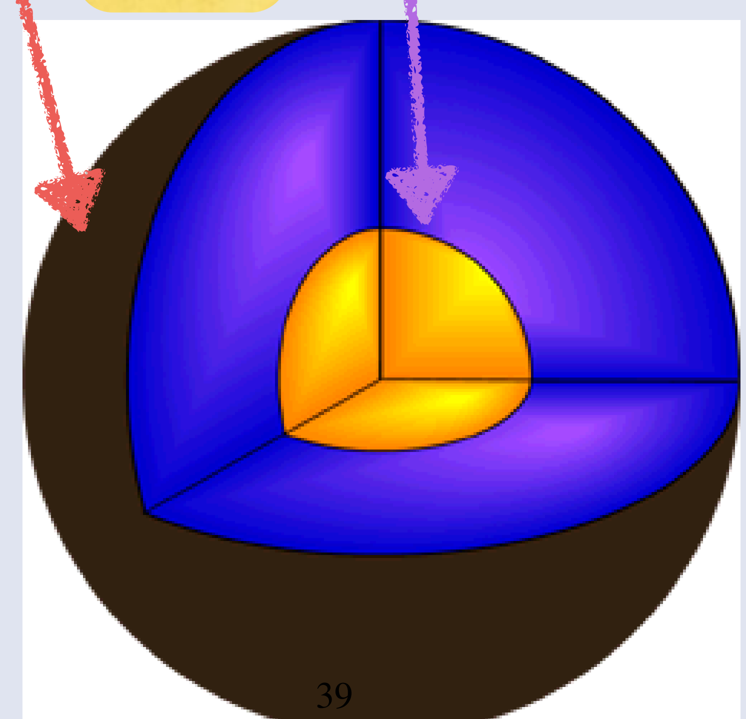
Boundary conditions
boundary_condition


```
begin boundary_condition
    array bc_temperature  2
      bc_temperature   fixed ICB  1.000
      bc_temperature   fixed CMB  0.000
    end array bc_temperature
!
    array bc_velocity    2
      bc_velocity  non_slip_sph    ICB   0.000
      bc_velocity  non_slip_sph    CMB   0.000
    end array bc_velocity
end boundary_condition
```

Boundary condition type

Place to be defined

B.C. Value



Forcing terms
forces_define

```
    begin forces_define
      array force_ctl        2
        force_ctl    gravity
        force_ctl    Coriolis
      end array force_ctl
    end forces_define
```

Available forces

Label	Field name	Equation
Coriolis	Coriolis force	$-2\Omega\hat{z} \times \boldsymbol{u}$
Lorentz	Lorentz force	$\boldsymbol{J} \times \boldsymbol{B}$
gravity	Thermal buoyancy	$-\alpha_T T \boldsymbol{g}$
Composite_gravity	Compositional buoyancy	$-\alpha_C C \boldsymbol{g}$

Governing equations for rotating convection

Coriolis force

$$
\begin{aligned}
1\left[\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\,\boldsymbol{u}\right] + 2E^{-1}(\hat{z}\times\boldsymbol{u}) &= -E^{-1}\nabla P + 1\nabla^2 u + r_o^{-1} Ra Pr T \boldsymbol{r} \\
1\left[\frac{\partial T}{\partial t} + (\boldsymbol{u}\cdot\nabla)\,T\right] &= Pr^{-1}\nabla^2 T, \\
\nabla\cdot\boldsymbol{u} &= 0.
\end{aligned}
$$

$$
Pr = \frac{\nu}{\kappa},\; E = \frac{\nu}{\Omega L^2},\; Ra = \frac{\alpha g \Delta T L^3}{\kappa\nu}
$$

Coefficients to be defined by the control file

Scaling for momentum equation momentum (Cont'd)

$$1\left[\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\,\boldsymbol{u}\right] + 2E^{-1}\left(\hat{z}\times\boldsymbol{u}\right) \quad = \quad -E^{-1}\nabla P + 1\nabla^2 u + r_o^{-1} Ra Pr T \boldsymbol{r}$$

```
array coef_4_v_diffuse_ctl                    1
  coef_4_v_diffuse_ctl  One                 1.0
end array coef_4_v_diffuse_ctl
!
array coef_4_buoyancy_ctl                     3
  coef_4_buoyancy_ctl  r_o                 -1.0
  coef_4_buoyancy_ctl  Ra                   1.0
  coef_4_buoyancy_ctl  Pr                   1.0
end array coef_4_buoyancy_ctl
```

Dimensionless numbers dimensionless_ctl

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```
    begin dimensionless_ctl
      array dimless_ctl 4
        dimless_ctl  E              1.0e-3
        dimless_ctl  Pr             1.0e+0
        dimless_ctl  Ra             1.0E+5
        dimless_ctl  r_o            1.53846154e+0
     end array dimless_ctl
    end dimensionless_ctl
```

Name of numbers

Values

- Name of parameters are arbitrary.
- Parameter names are case sensitive

Parameters for time integration
time_step_ctl

```
    begin time_step_ctl
      i_step_init_ctl            0
      i_step_finish_ctl       3000
!
      i_step_check_ctl          20
      i_step_rst_ctl          2000
      i_step_field_ctl         500
!
      dt_ctl                2.0e-4
      time_init_ctl         0.0e-8
    end time_step_ctl
```

- Time step to start
- Time step to finish
- Length of time step
- Initial time

Parameters for time integration
time_step_ctl

```
    begin time_step_ctl
      i_step_init_ctl              0
      i_step_finish_ctl         3000
!
      i_step_check_ctl            20
      i_step_rst_ctl            2000
      i_step_field_ctl           500
!
      dt_ctl                     2.0e-4
      time_init_ctl              0.0e-8
    end time_step_ctl
```

- Increment for time sequence data
- Increment for restarting data
- Increment for field data output

Time series data setting
sph_monitor_ctl

```
begin sph_monitor_ctl
   volume_average_prefix       'sph_ave_volume'
   volume_pwr_spectr_prefix    'sph_pwr_volume'
!
  nusselt_number_prefix        'Nusselt'
end sph_monitor_ctl
```

name	Parallelization	I/O
control_MHD	Serial	Input
[sph_prefix].[domain#].rj	Distributed	Input
[sph_prefix].[domain#].rlm	Distributed	Input
[sph_prefix].[domain#].rtm	Distributed	Input
[sph_prefix].[domain#].rtp	Distributed	Input
[sph_prefix].[domain#].gfm	Distributed	Input
[boundary_data_name]	Single	Input
[rst_prefix].[step#].[domain#].fst	Distributed	Input/Output
[vol_pwr_prefix].dat	Single	Output
[vol_pwr_prefix]_l.dat	Single	Output
[vol_pwr_prefix]_m.dat	Single	Output
[vol_pwr_prefix]_lm.dat	Single	Output
[vol_ave_prefix].dat	Single	Output
[layer_pwr_prefix]_l.dat	Single	Output
[layer_pwr_prefix]_m.dat	Single	Output
[layer_pwr_prefix]_lm.dat	Single	Output
[gauss_coef_prefix].dat	Single	Output
[picked_sph_prefix].dat	Single	Output
[nusselt_number_prefix].dat	Single	Output
[fld_prefix].[step#].[domain#].[extension]	-	Output

Postprocessing

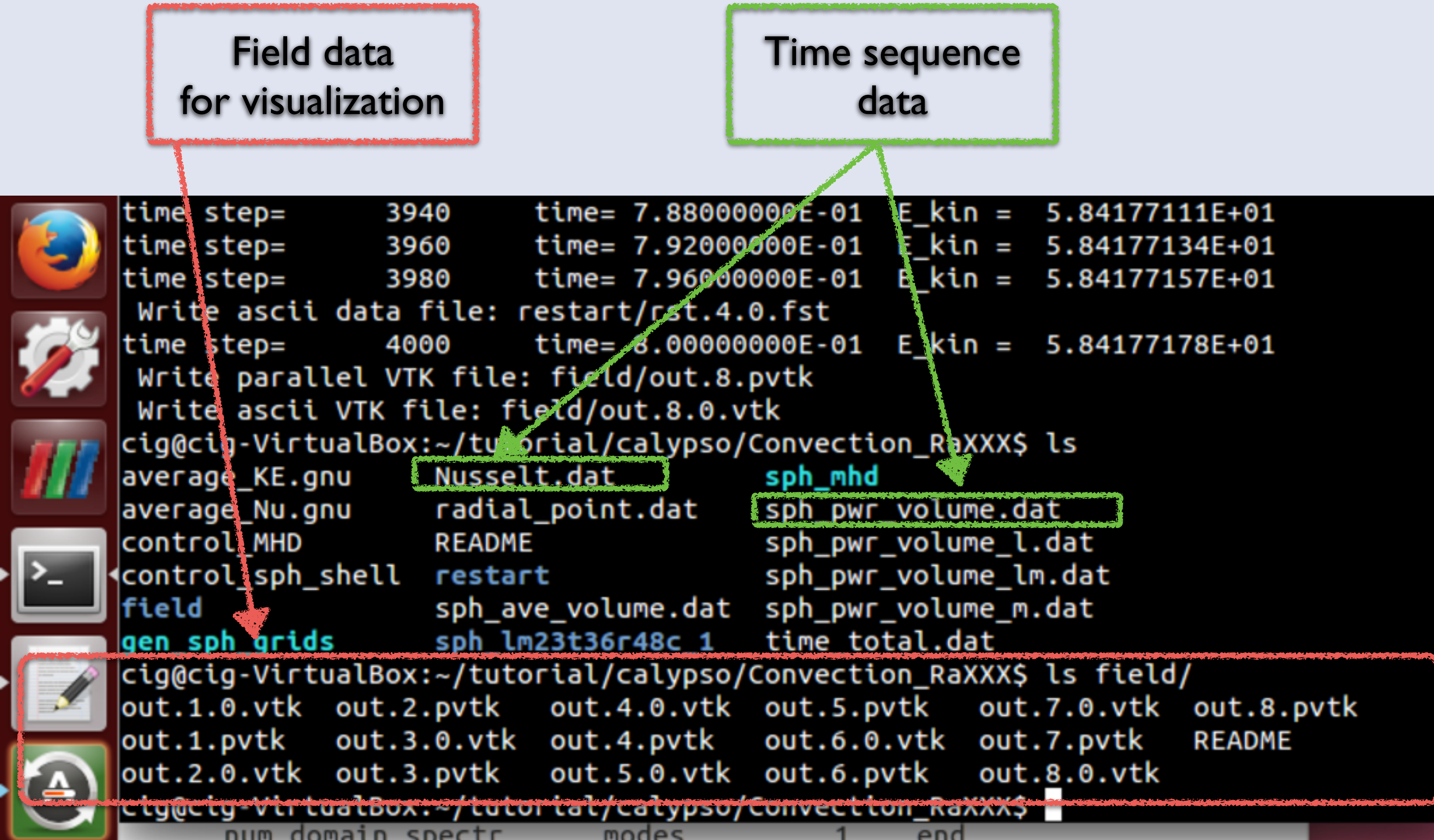
Procedure of simulation

1. Preprocessing: Prepare spherical harmonics index table

2. Run simulation

3. Postprocessing
   - Check Scaling law by Gnuplot
   - Visualization by Paraview

files after simulation



Data analysis by Gnuplot

- Mean square data consists of time series data

- Make a line plot and take a time average by Gnuplot

Which column should be used?

- *Time* is in the 2nd column
- *Nu* at ICB is in the 3rd column
- *Nu* at CMB is in the 4th column

```
out.2.0.vtk  out.3.pvtk   out.5.0.vtk  out.6.pvtk   out.8.0.vtk
cig@cig-VirtualBox:~/tutorial/calypso/Convection_RaXXX$ more Nusselt.dat
# Inner_radius, Outer_radius
   5.38461538461538E-001   1.53846153846154E+000
t_step     time      Nu_ICB     Nu_CMB
        20  4.00000000000000E-003  1.00201594246366E+000  1.00213480315182E+000
        40  7.99999999999999E-003  1.00619668098559E+000  1.00743933682635E+000
        60  1.20000000000000E-002  1.01430018065005E+000  1.01432829581630E+000
        80  1.60000000000000E-002  1.02607049869886E+000  1.02032185400044E+000
       100  2.00000000000000E-002  1.04100666627049E+000  1.02587679487352E+000
       120  2.40000000000000E-002  1.05968146246822E+000  1.03149275995523E+000
```

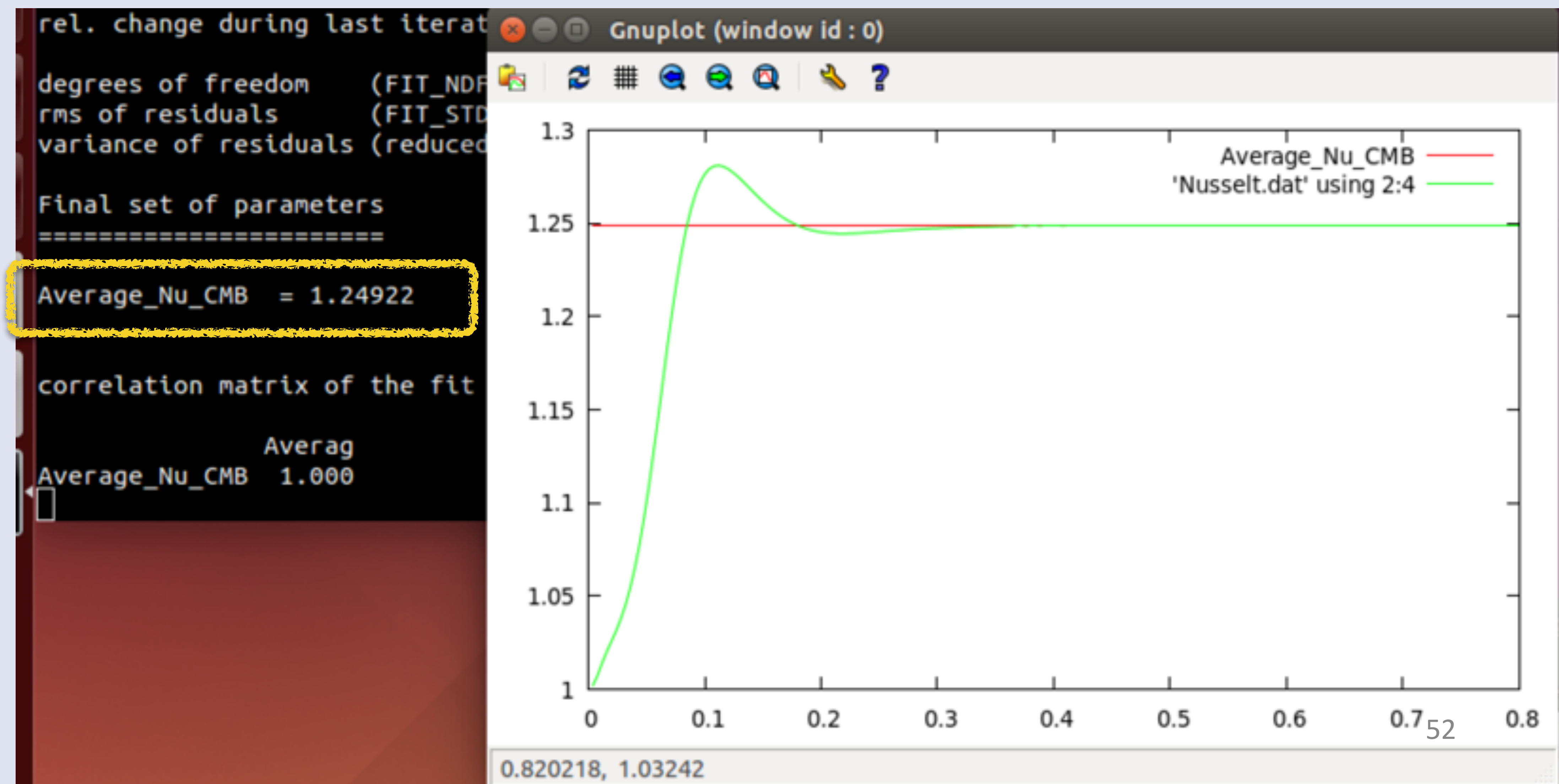
Obtain time averaged Nusselt number

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

- Run Gnuplot with "average_Nu.gnu"

```
cig@cig-VirtualBox:~/tutorial/calypso_tutorial_V1.4/Convection_RaXXX$ gnuplot av
erage_Nu.gnu
```

- Averaged Nusselt number is displayed on Terminal



Which column should be used?

CIG COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

- Time is in the 2nd column
- Kinetic energy is in the 5th column

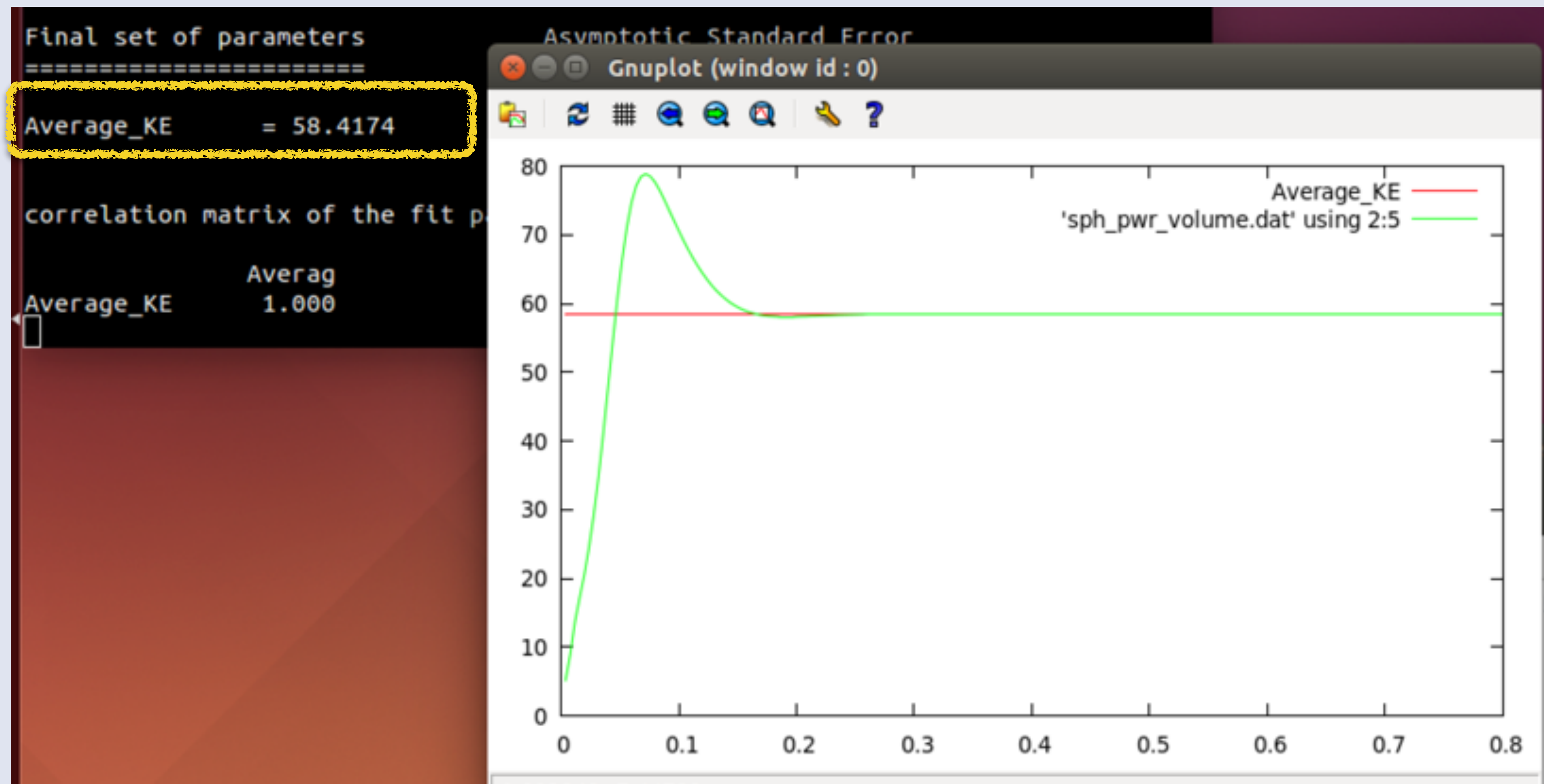
```
cig@cig-VirtualBox:~/tutorial/calypso/Convection_RaXXX$
cig@cig-VirtualBox:~/tutorial/calypso/Convection_RaXXX$ more sph_pwr_volume.dat
radial_layers, truncation
        49         23
ICB_id, CMB_id
         1         49
number of components
         3          7
    3    1    3
t_step    time    K_ene_pol    K_ene_tor    K_ene    temperature    vorticity_po
l    vorticity_tor    vorticity
        20  4.00000000000000E-003  1.79583422259195E+000  3.36798559698955E+000
 5.16381981958150E+000  8.35965158490096E-002  4.79449697263297E+002  3.22878754
242708E+002  8.02328451506006E+002
        40  7.99999999999999E-003  3.03586924148587E+000  5.87318860233336E+000
 8.90905784381922E+000  8.34712341521374E-002  9.18593101631710E+002  5.31664748
513151E+002  1.45025785014486E+003
```

Obtain time averaged kinetic energy

- Run Gnuplot with “average_KE.gnu”

```
out.2.0.vtk  out.3.pvtk   out.5.0.vtk  out.6.pvtk   out.8.0.vtk
cig@cig-VirtualBox:~/tutorial/calypso_tutorial_V1.4/Convection_RaXXX$ gnuplot av
erage_KE.gnu
```

- Averaged kinetic energy is displayed on Terminal



Results

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

$$E_{kin} = \frac{1}{2}(Nu - 1)\, E^{2/3} Pr^{-2} Ra \frac{1}{r_o} \frac{dT_{diff}}{dr}$$

Effect of geometry

Ra	*E*	*Nu*	E
7.0x10	15.9	1.10	15.6
1.0x10	58.4	1.25	58.0
2.0x10	234.2	1.57	266.2
4.0x10	820.5	2.24	1151.4
8.0x10	2651.4	3.42	4483.4

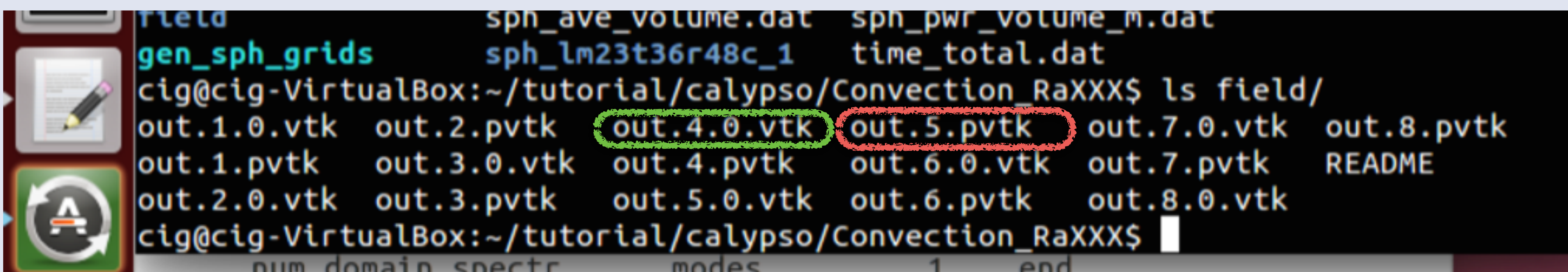
- Kinetic energy departs from the scaling with the larger *Ra.*
- Need more resolution

Look a flow pattern aligned with rotation axis

- Open Parallel VTK data by paraview

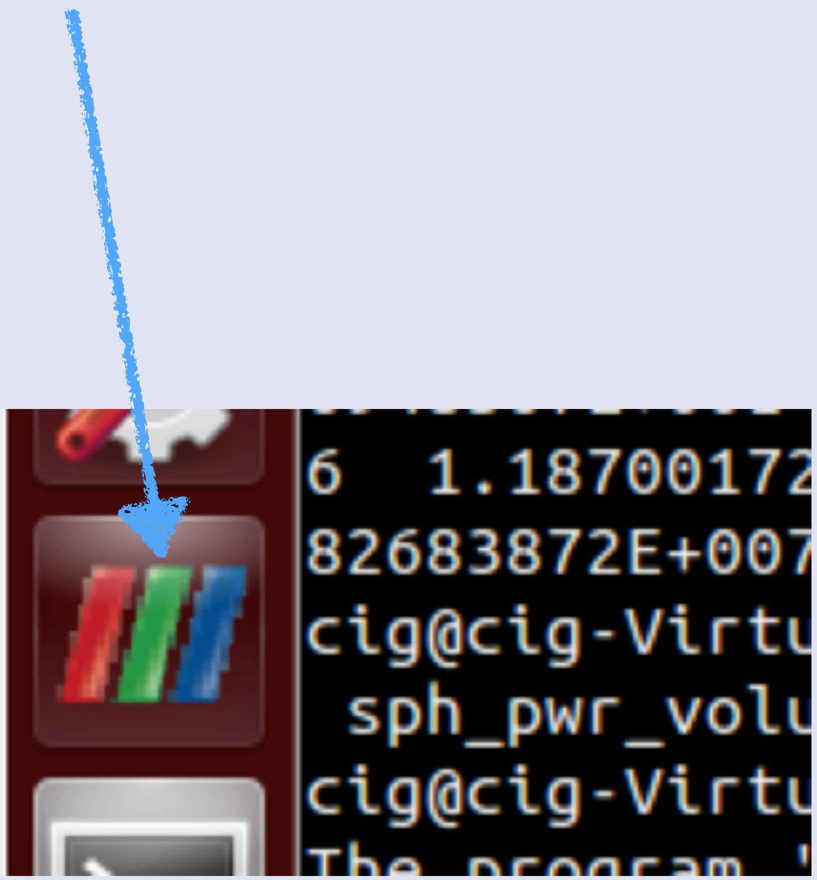
  out.[step#].pvtk
- Field data for each subdomain are in

  out.[step#].[domain#].vtk



Start ParaView

- Click ParaView Icon!!



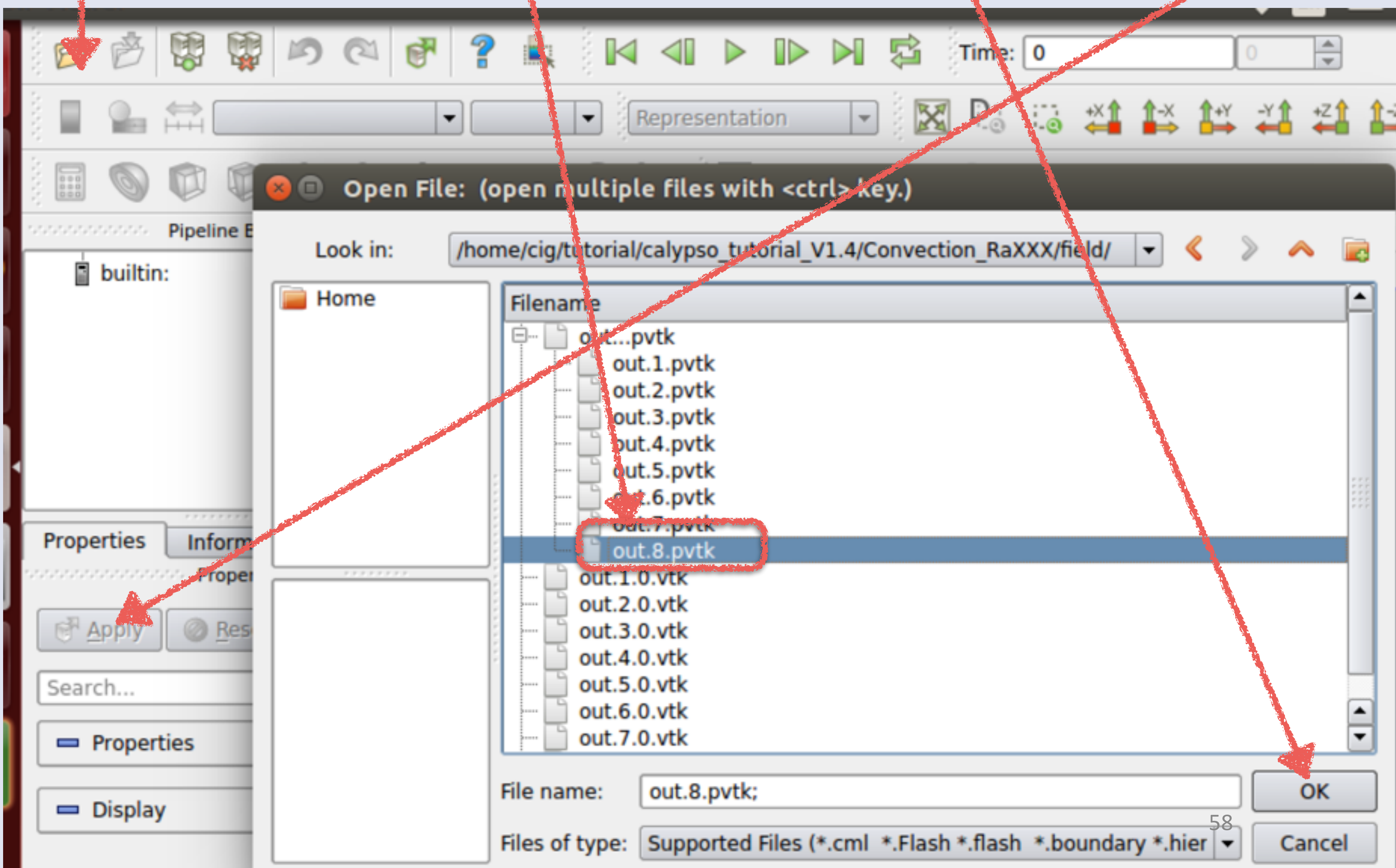
Open field data by Paraview

1. Push "open file"

2. Select a file

3. Push "OK"

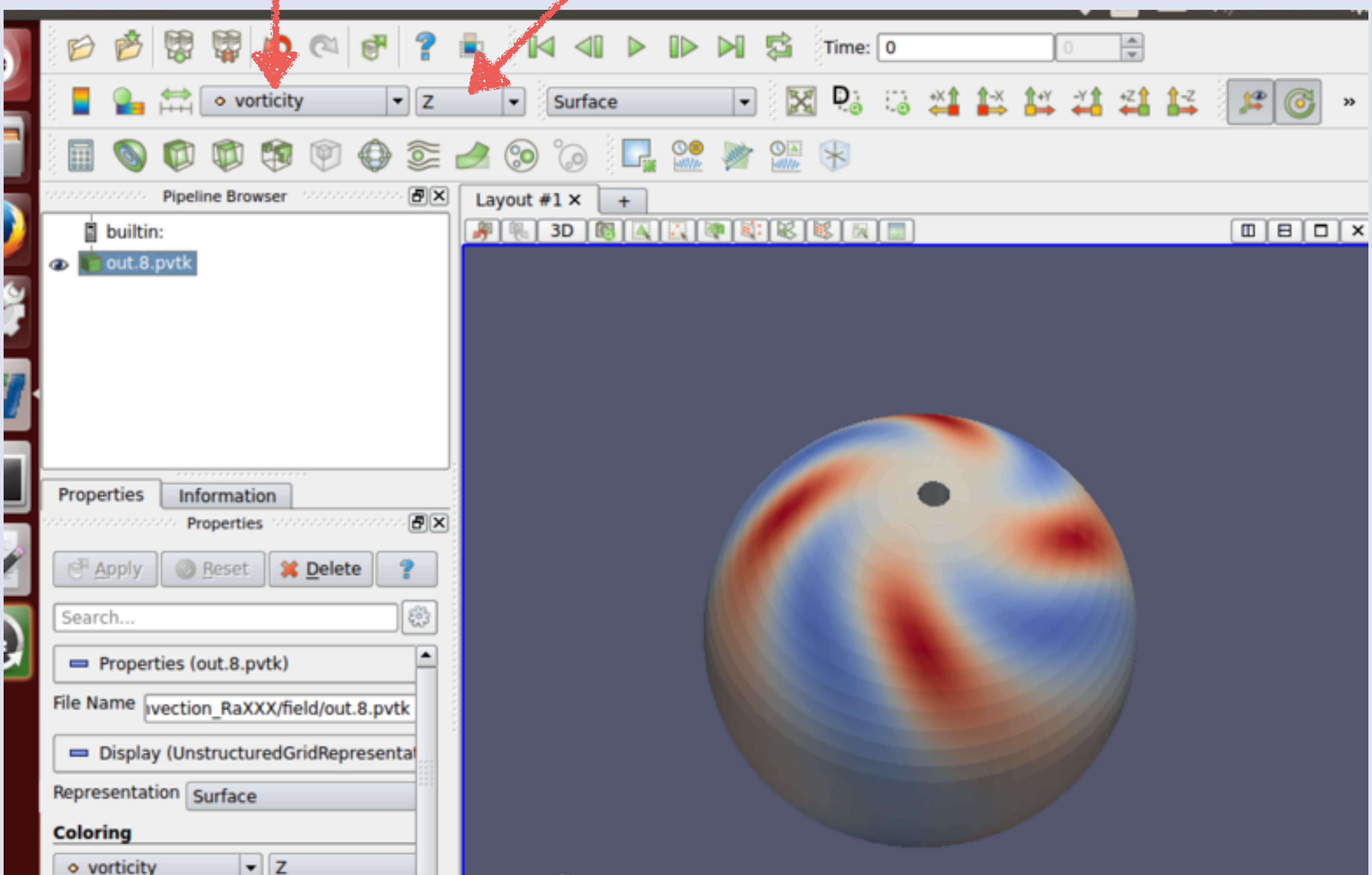
4. Push "Apply"



Choose z-component of vorticity

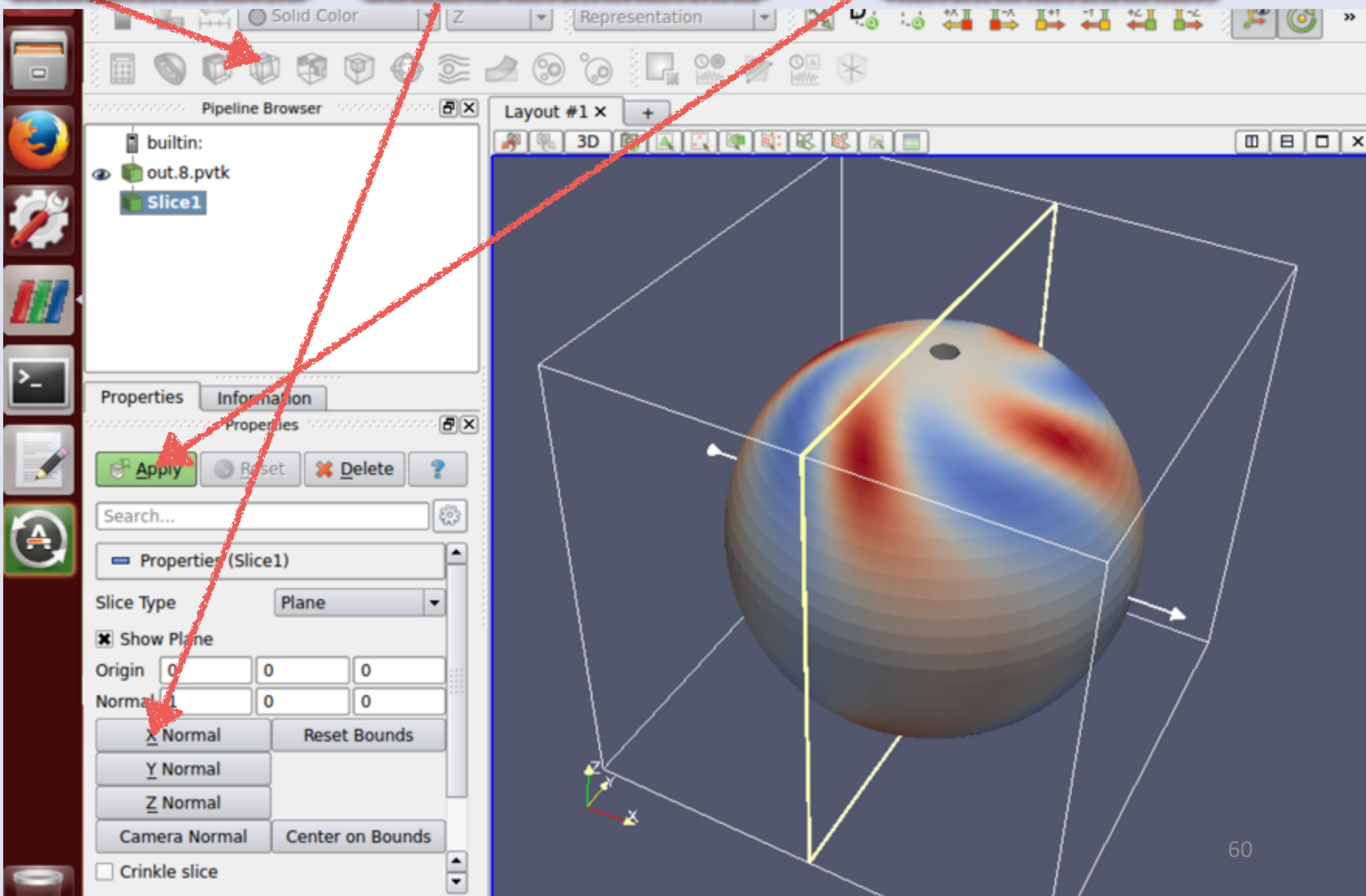
1. Select "vorticity"

2. Select "Z"



Look vorticity at a meridional section

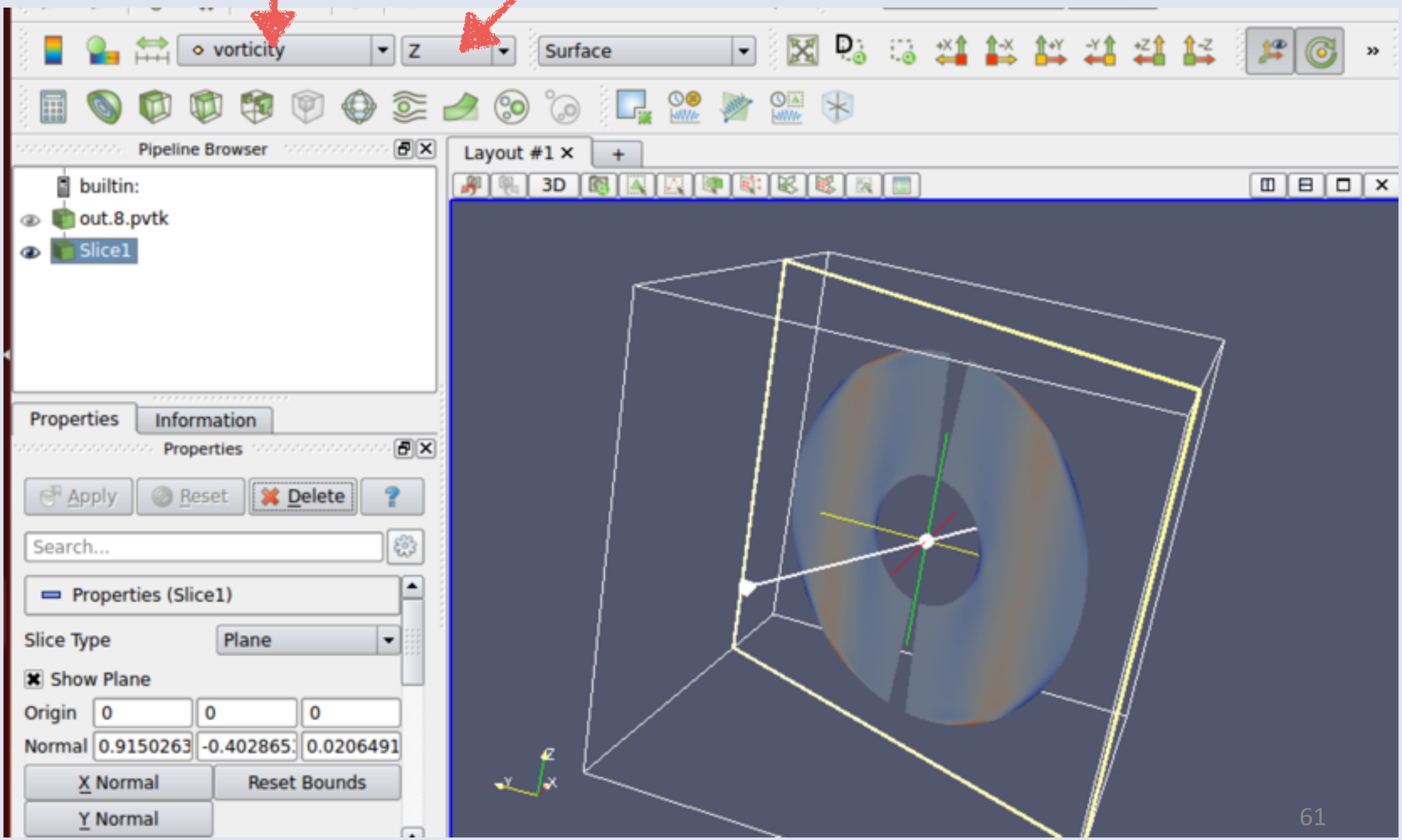
1. Push "slice"
2. Push "X Normal"
3. Push "Apply"



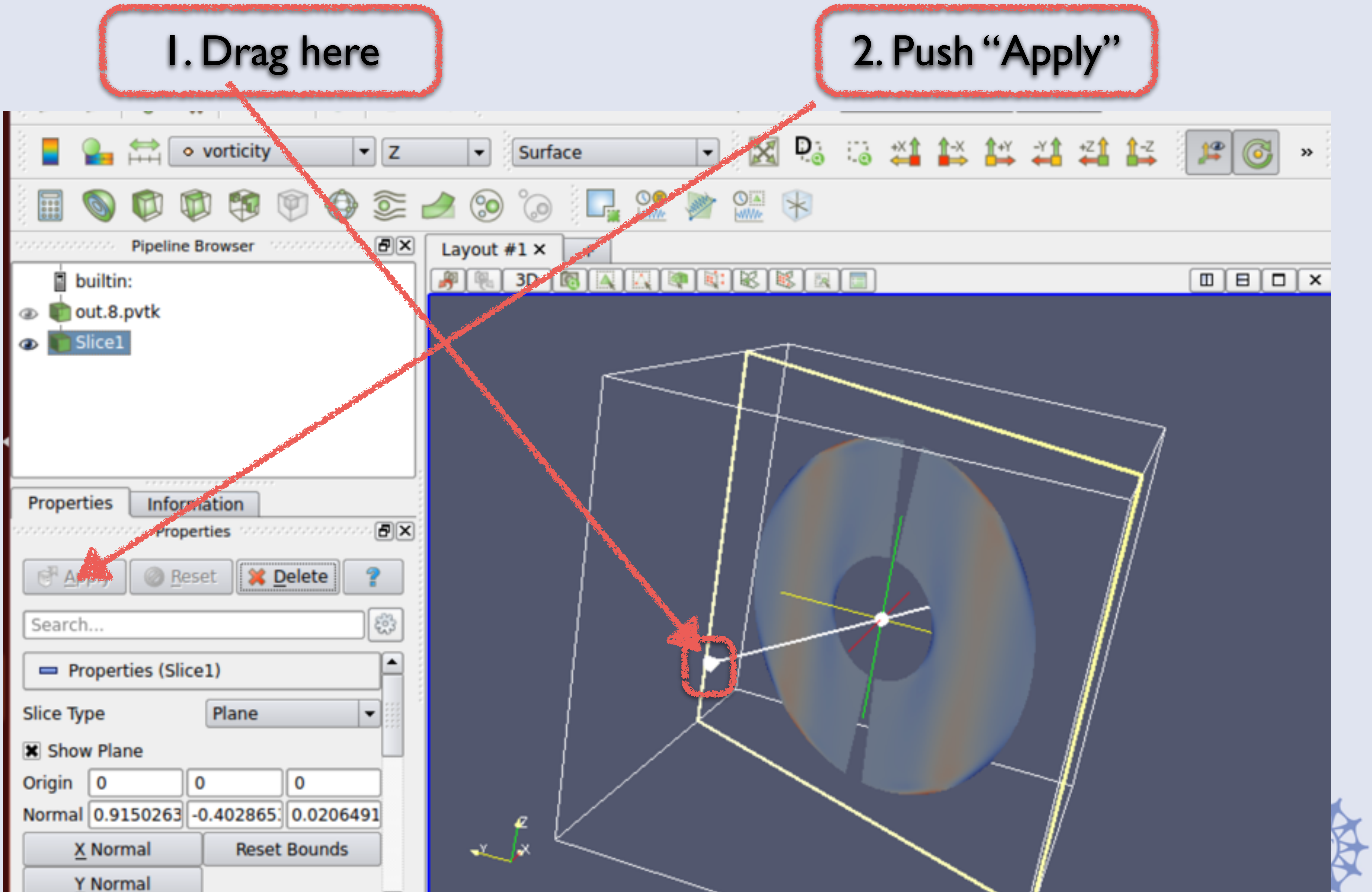
Choose vorticity-z (Again!!)

1. Select "vorticity"

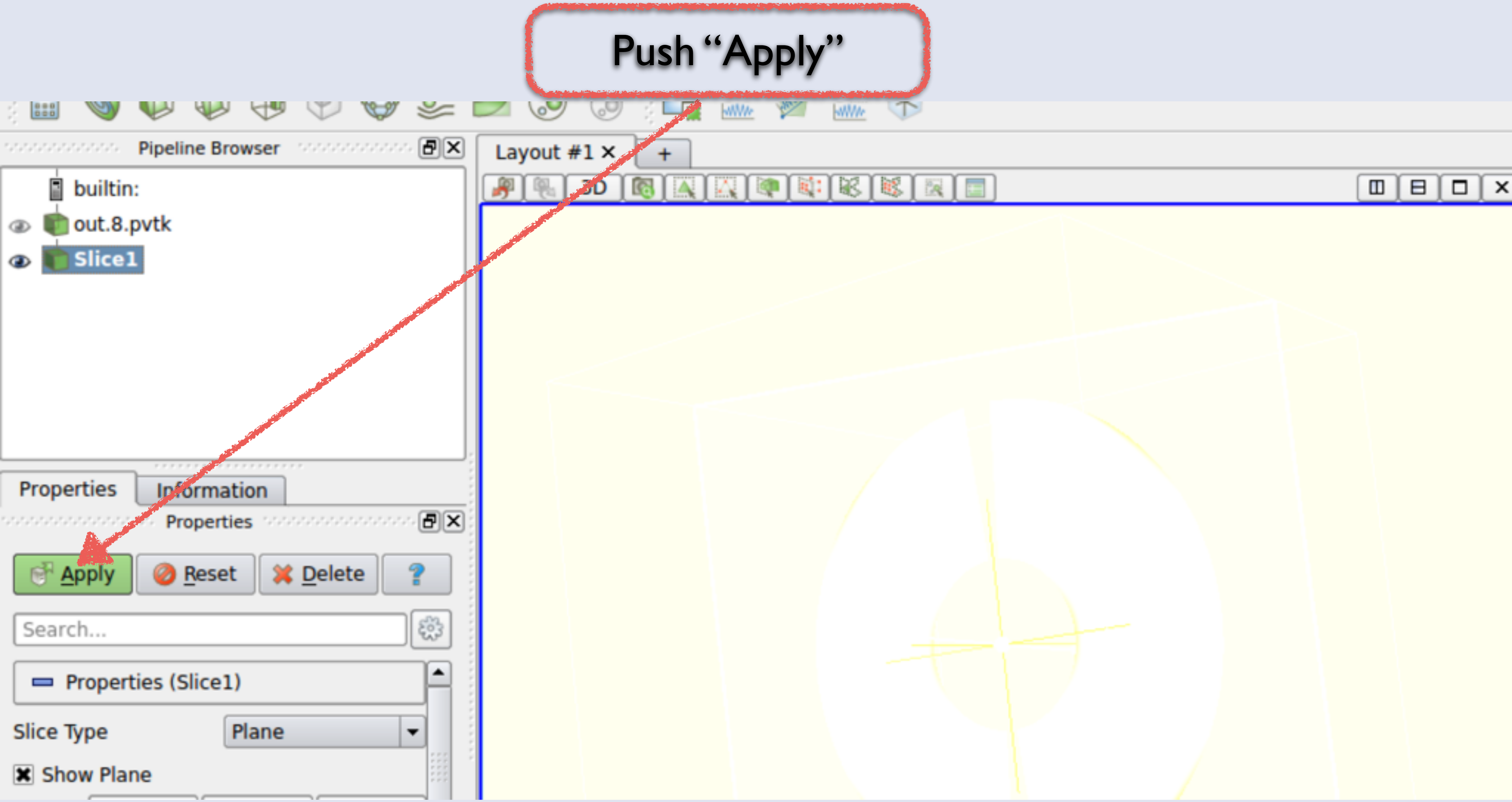
2. Select "Z"



To look a different section...



If screen becomes white...



Virtualbox's graphic emulation makes this problem.

Pick z-component of vorticity

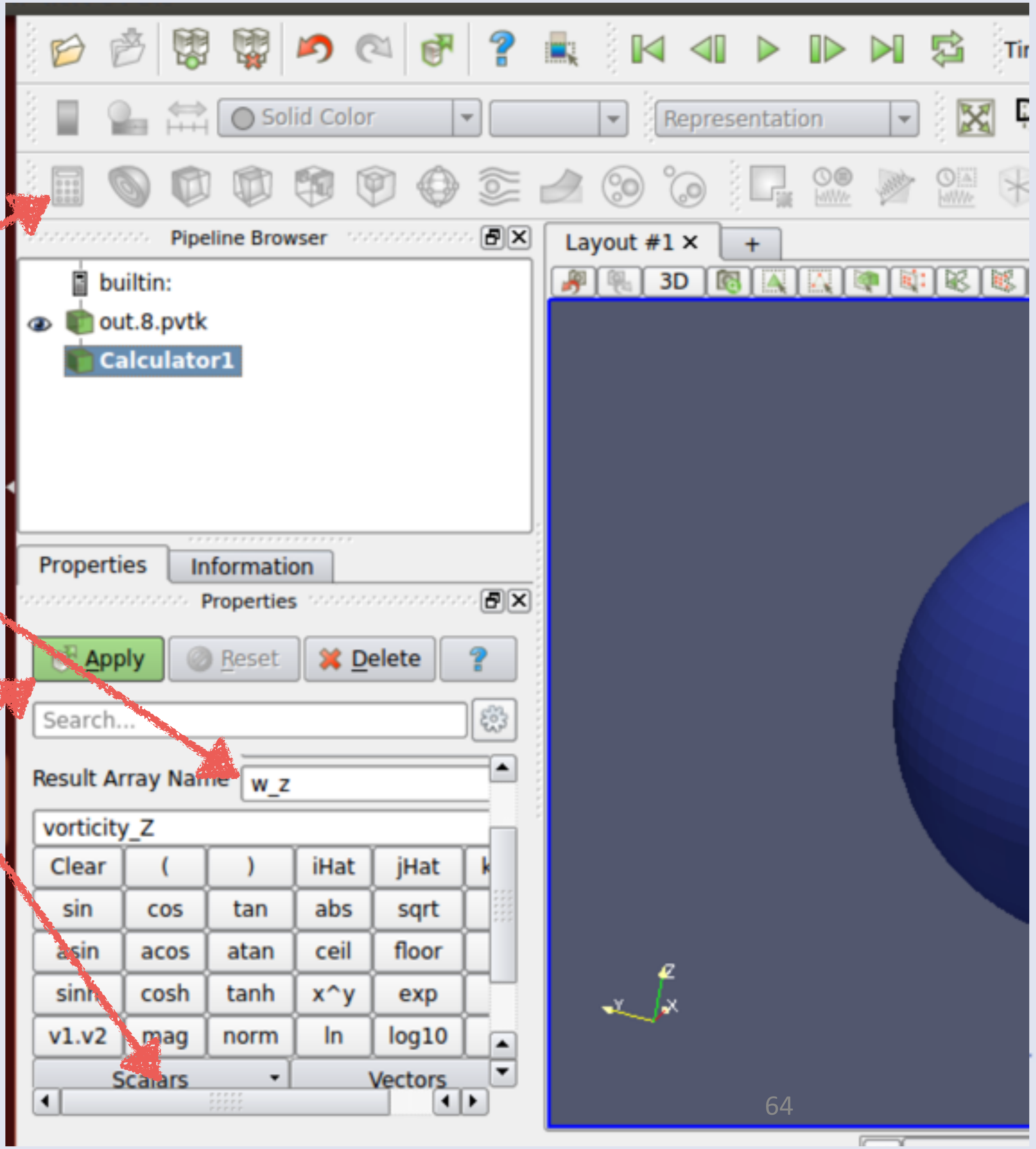
CIG COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

1. Push calculator

2. Input name "w_z"

3. Select "VORTICITY-Z"

4. Push "Apply"

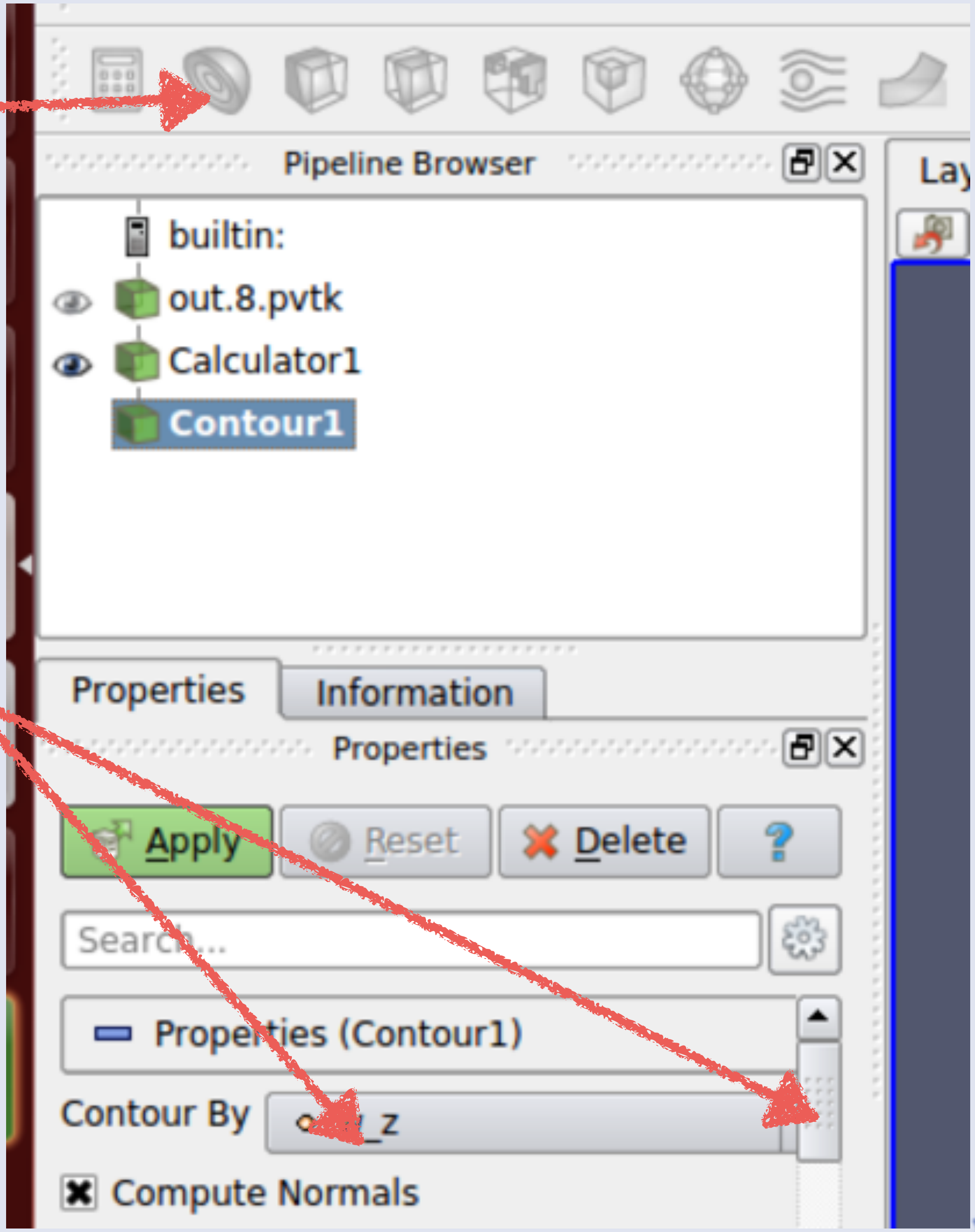


Generate Isosurfaces

1. Push contour

2. Select “w_z”

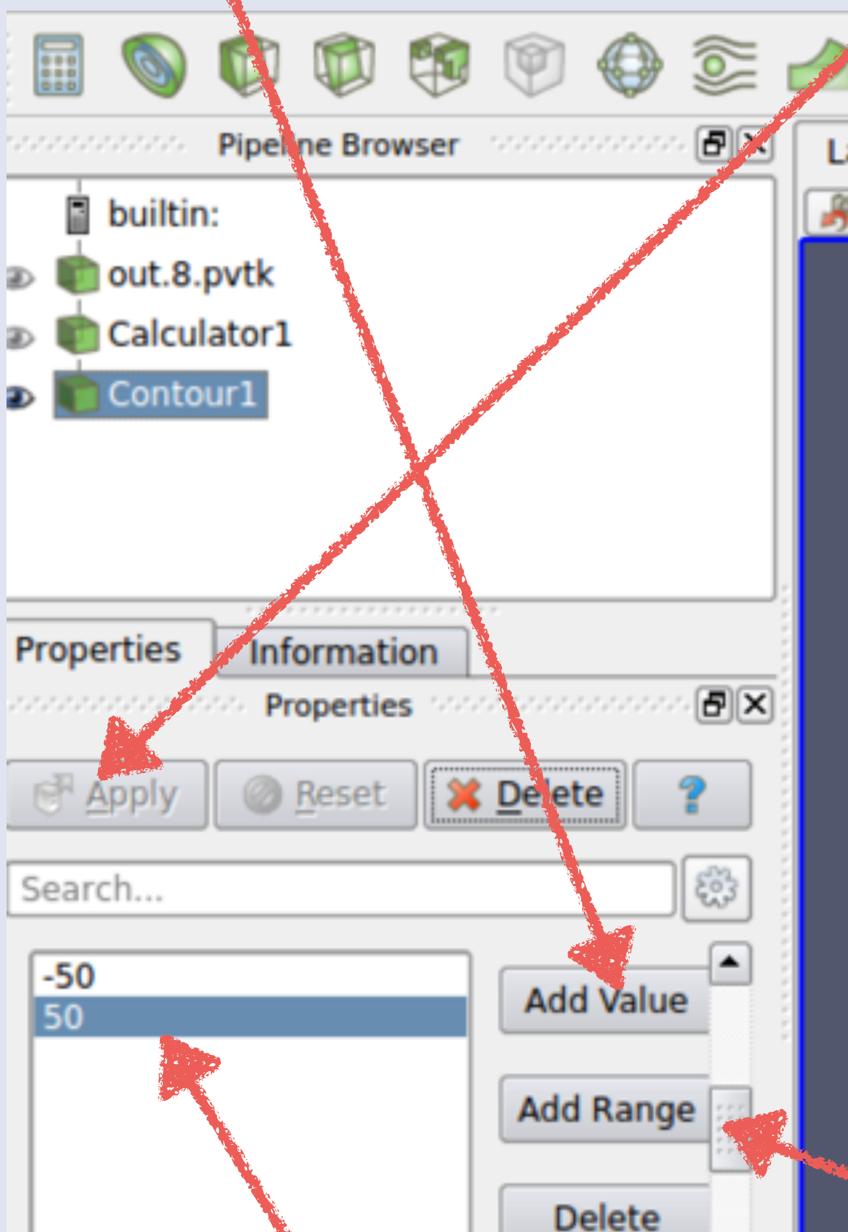
3. Go down



Set Isosurface parameteres

1. Push "Add value"

3. Push Apply



- Suggested values:
  - Ra=100… -50, 50

2. Input values for isosurface

4. Go down

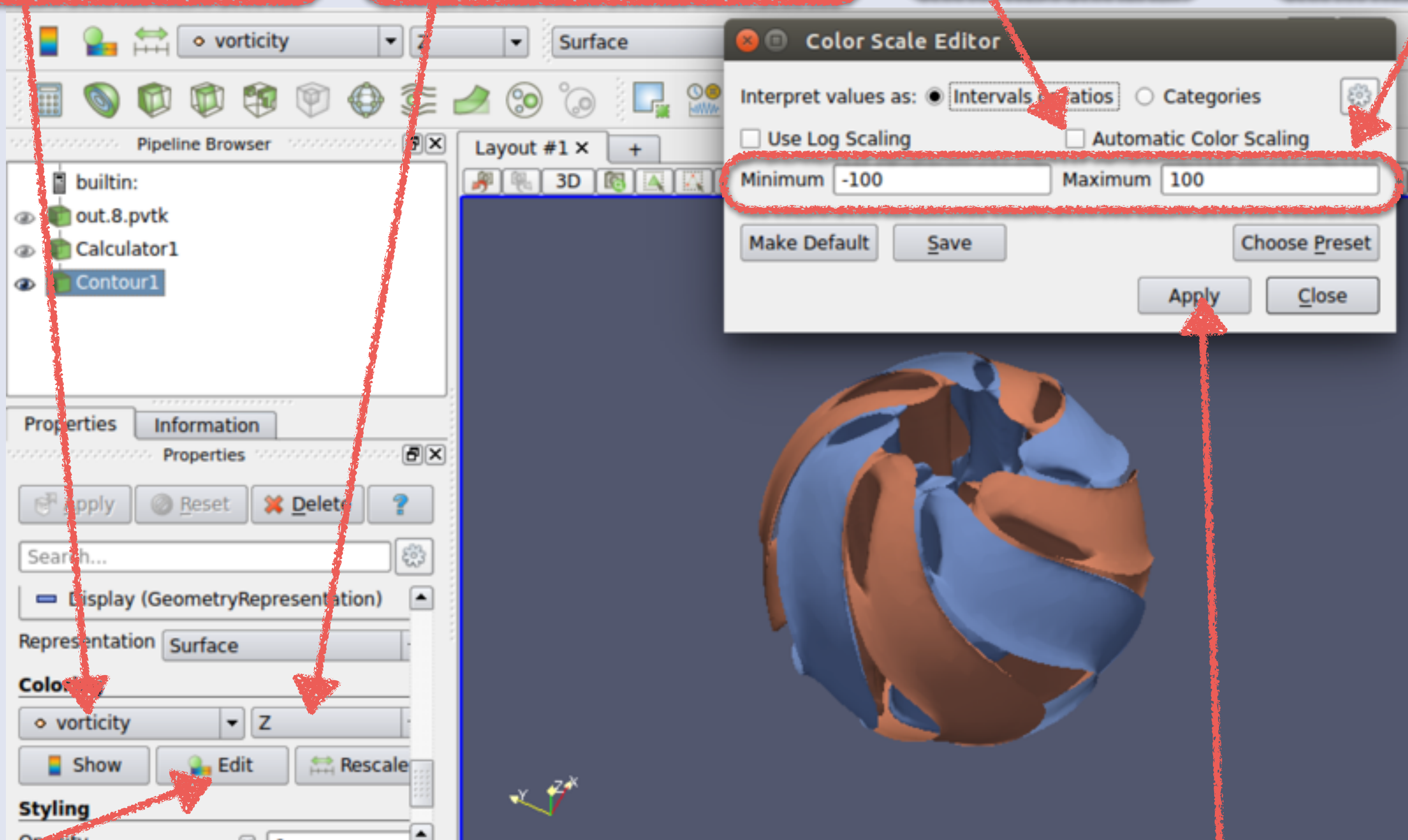
Set color for Isosurface

1. Select "vorticity"

2. Select "Z"

4. Turn Off

5. Set range



3. Push "Edit"

6. Push Apply

Delete boundary layer

1. Select "Contour1"

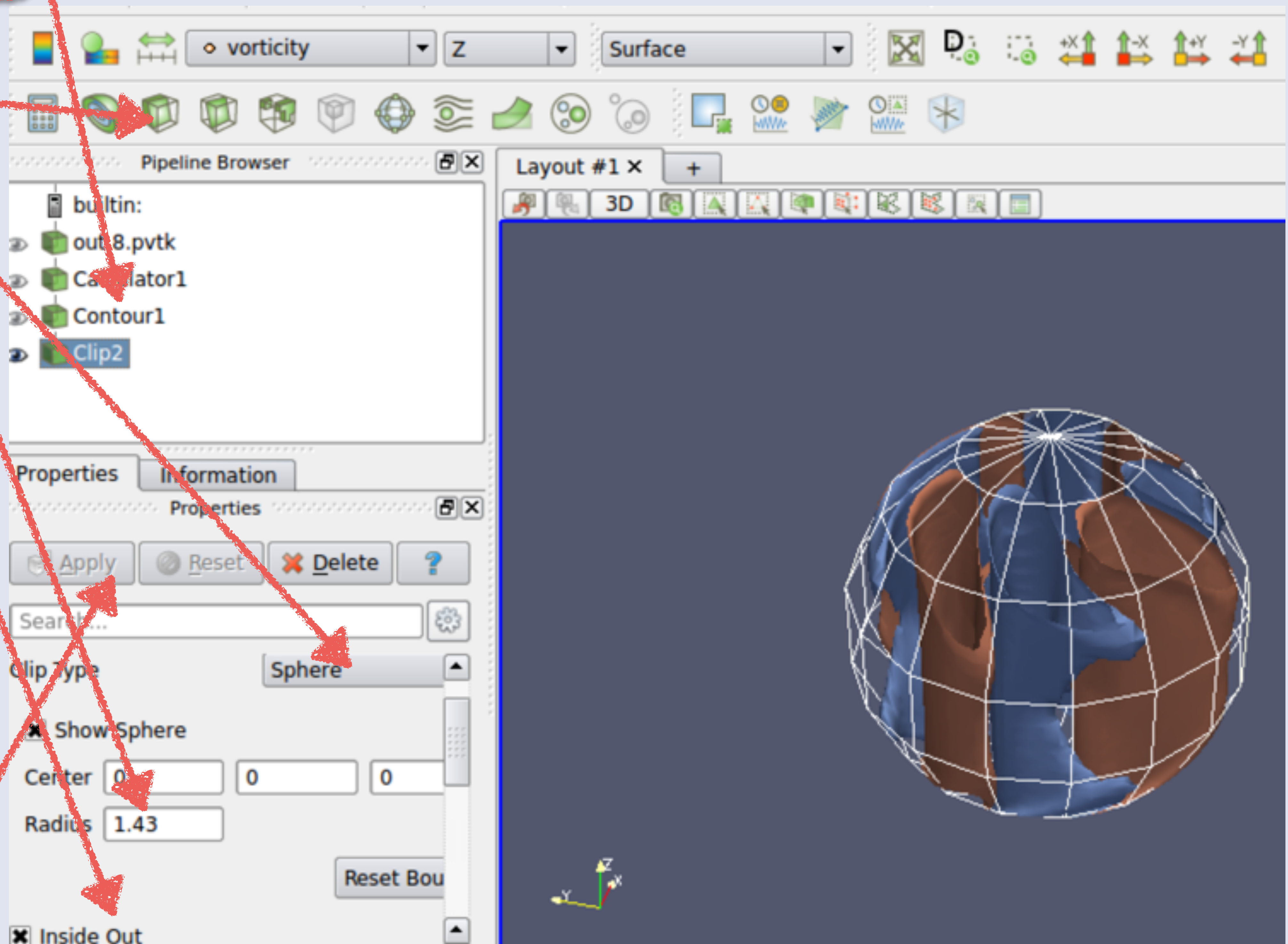
2. Push "Clip"

3. Select "Sphere"

4. Set r=1.43

5. Check "Inside Out"

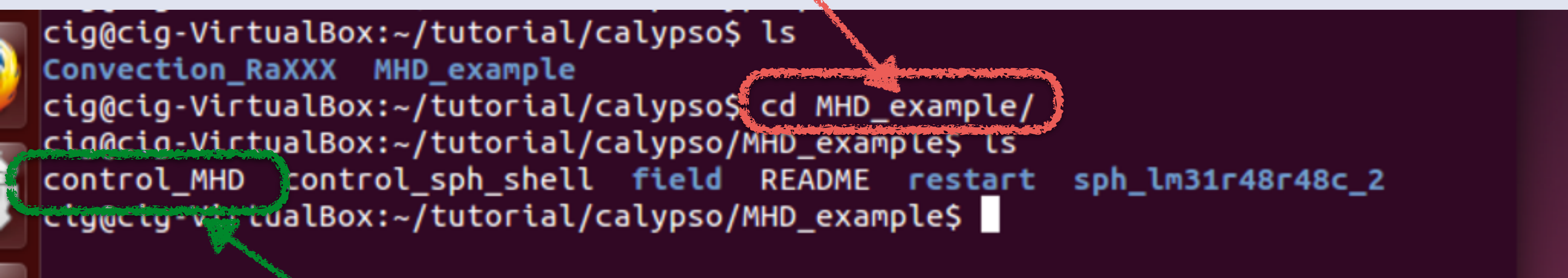
6. Push Apply



How to run MHD dynamos?

Example for MHD dynamo

Go to MHD_example folder



Example of control file

Governing Equations

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\,\boldsymbol{u} = -\frac{1}{E}\nabla P + \nabla^2 u - 2\frac{1}{E}(\hat{z} \times \boldsymbol{u}) + \frac{Ra}{E} E^{-1} T \frac{\boldsymbol{r}}{r_o} + \frac{1}{EPm}(\nabla \times \boldsymbol{B}) \times \boldsymbol{B},$$

$$\frac{\partial T}{\partial t} + (\boldsymbol{u} \cdot \nabla)\,T = \frac{1}{Pr}\nabla^2 T,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \frac{1}{Pm}\nabla^2 \boldsymbol{B} + \nabla \times (\boldsymbol{u} \times \boldsymbol{B}),$$

$$\nabla \cdot \boldsymbol{u} = \nabla \cdot \boldsymbol{B} = 0.$$

Data definition
phys_values_ctl

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

```
begin phys_values_ctl
  array nod_value_ctl   6
    nod_value_ctl  velocity                Viz_On   Monitor_On
    nod_value_ctl  temperature             Viz_On   Monitor_On
    nod_value_ctl  pressure                Viz_On   Monitor_On
    nod_value_ctl  vorticity               Viz_On   Monitor_On
    nod_value_ctl  magnetic_field          Viz_On   Monitor_On
    nod_value_ctl  current_density         Viz_On   Monitor_On
  end array nod_value_ctl
end phys_values_ctl
```

Field name

field data output flag

Monitoring data output flag

Choose of time integration time_evo_ctl

```
begin time_evolution_ctl
  array time_evo_ctl    3
    time_evo_ctl  temperature
    time_evo_ctl  velocity
    time_evo_ctl  magnetic_field
  end array time_evo_ctl
end time_evolution_ctl
```

Field for time integration

label	field name	Description
velocity	Velocity	$\boldsymbol{u}$
temperature	Temperature	T
composition	Composition variation	C
magnetic_field	Magnetic field	$\boldsymbol{B}$

Boundary conditions
boundary_condition

```
begin boundary_condition
  array bc_temperature  2
    bc_temperature  fixed  ICB  1.000
    bc_temperature  fixed  CMB  0.000
  end array bc_temperature
!
  array bc_velocity    2
    bc_velocity  non_slip_sph  ICB   0.000
    bc_velocity  non_slip_sph  CMB   0.000
  end array bc_velocity
!
 array bc_magnetic_field   2
    bc_magnetic_field  insulator  ICB  0.000
    bc_magnetic_field  insulator  CMB  0.000
  end array bc_magnetic_field
end boundary_condition
```

Place to be defined

Boundary condition type

B.C.Value

Forcing terms
forces_define

```
begin forces_define
  array force_ctl          3
    force_ctl   gravity
    force_ctl   Coriolis
    force_ctl   Lorentz
  end array force_ctl
end forces_define
```

List for forces

Label	Field name	Equation
Coriolis	Coriolis force	$-2\Omega\hat{z} \times \boldsymbol{u}$
Lorentz	Lorentz force	$\boldsymbol{J} \times \boldsymbol{B}$
gravity	Thermal buoyancy	$-\alpha_T T \boldsymbol{g}$
Composite_gravity	Compositional buoyancy	$-\alpha_C C \boldsymbol{g}$

Governing Equations

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\,\boldsymbol{u} = -\frac{1}{E}\nabla P + \nabla^2 u - 2\frac{1}{E}\left(\hat{z} \times \boldsymbol{u}\right) + \frac{Ra}{E}E^{-1}T\frac{\boldsymbol{r}}{r_o} + \frac{1}{EPm}\left(\nabla \times \boldsymbol{B}\right) \times \boldsymbol{B},$$

$$\frac{\partial T}{\partial t} + (\boldsymbol{u} \cdot \nabla)\,T = \frac{1}{Pr}\nabla^2 T,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \frac{1}{Pm}\nabla^2 \boldsymbol{B} + \nabla \times \left(\boldsymbol{u} \times \boldsymbol{B}\right),$$

$$\nabla \cdot \boldsymbol{u} = \nabla \cdot \boldsymbol{B} = 0.$$

Scaling for momentum equation momentum (Cont’d)

$$
\begin{aligned}
\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\,\boldsymbol{u} \quad &= \quad -E^{-1}\nabla P + \nabla^2 u - 2E^{-1}\left(\hat{z} \times \boldsymbol{u}\right) \\
&\quad + \frac{Ra}{Er_0} T\boldsymbol{r} + \frac{1}{PmE}\left(\nabla \times \boldsymbol{B}\right) \times \boldsymbol{B},
\end{aligned}
$$

```
  array coef_4_Coriolis_ctl                    2
    coef_4_Coriolis_ctl  Two                   1.0
    coef_4_Coriolis_ctl  E                    -1.0
  end array coef_4_Coriolis_ctl
!
  array coef_4_Lorentz_ctl                     2
    coef_4_Lorentz_ctl  Pm                    -1.0
    coef_4_Lorentz_ctl  E                     -1.0
  end array coef_4_Lorentz_ctl
end momentum
```

Scaling for magnetic induction

$$\frac{\partial B}{\partial t} = \frac{1}{Pm}\nabla^2 \boldsymbol{B} + \nabla \times (\boldsymbol{u} \times \boldsymbol{B})$$

```
begin induction
    array coef_4_magnetic_ctl    1
      coef_4_magnetic_ctl          One           1.0
    end array coef_4_magnetic_ctl
!
    array coef_4_m_diffuse_ctl  1
      coef_4_m_diffuse_ctl          Pm          -1.0
    end array coef_4_m_diffuse_ctl
  !
    array coef_4_induction_ctl  1
      coef_4_induction_ctl         One          -1.0
    end array coef_4_induction_ctl
end  induction
```

Dimensionless numbers
dimensionless_ctl


```
    begin dimensionless_ctl
      array dimless_ctl 5
        dimless_ctl  Pr                          1.0e-0
        dimless_ctl  mod_Ra                      1.0E+2
        dimless_ctl  E                           1.0e-3
        dimless_ctl  Pm                          5.0e+0
        dimless_ctl  r_o                   1.53846154e+0
      end array dimless_ctl
    end dimensionless_ctl
```

Name of parameters   Values

- Name of parameters are arbitrary.
- Same parameter names are used in coefficients_ctl

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

Enjoy!!

Delete header and insert space in the beginning of label

- % tail -n +8 sph_pwr_volume.dat | sed -e 's/t_step/ t_step/g' > sph_pwr_volume.csv

```
radial_layers, truncation
          49          31
ICB_id, CMB_id
           1          49
number of components
           8          16
    3    1    1    3    3    3    1    1
t_step    time    K_ene_pol    K_ene_tor    K_ene    temperature    pressure
vorticity_pol    vorticity_tor    vorticity    M_ene_pol    M_ene_tor    M_ene
current_density_pol    current_density_tor    current_density    Lorentz_work
buoyancy_flux
           5  2.5000000000000E-004  1.2686879936036E-001  3.8915117611731 2E-001
5.1601997605334 8E-001  8.3724037837960 9E-002  2.8788282343513 5E+000  9.8668697551929 7E+001
```

Need a space

Delete here!

```
2.7861512411597 6E+001  1.2653020996352 7E+002  2.8864491309485 1E+000  3.1783008011355 4E+000
6.0647499320840 5E+000  1.0295645698269 1E+002  3.7488189164086 9E+001  1.4044464614677 8E+002
4.6148188595464 8E+007  9.0191178595737 9E+005
          10  5.0000000000000E-004  6.0806095592401 7E-001  1.3483300511666 3E+000
1.9563910070906 4E+000  8.3715526162796 6E-002  3.0816558316753 3E+000  2.6457531091771 0E+002
1.0046981401607 8E+002  3.6504512493378 8E+002  2.8853669561108 9E+000  3.1666021369369 8E+000
6.0519690930478 7E+000  1.0302485841185 3E+002  3.7552641694836 4E+001  1.4057750010668 9E+002
1.5802727025174 3E+008  3.7486593963624 3E+006
```