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Using YT for analysis and visualization of volumetric data

ALEX RAZOUMOV
alex.razoumov@westgrid.ca



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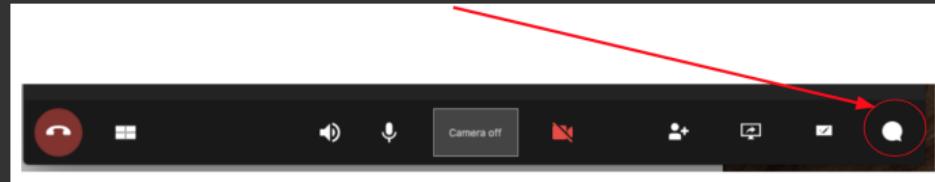
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To ask questions

- Websteam: email info@westgrid.ca
- Vidyo: use the GROUP CHAT to ask questions



- Please mute your mic unless you have a question
- Feel free to ask questions via audio at any time

HTTP://YT-PROJECT.ORG

- Python package for analyzing and visualizing volumetric, multi-resolution data
 - ▶ really a library for non-interactive use, does not offer 3D interactivity found in such tools as ParaView and VisIt
 - ▶ **discretization: structured, unstructured, variable-resolution (curvilinear), particle data**
 - ▶ very easy to learn, wonderful documentation at <https://yt-project.org/doc>
 - ▶ great for batch off-screen rendering (including HPC clusters)
 - ▶ parallelized with `mpi4py`
- Initially written for analysing *Enzo* output data, adapted to understand other data formats from astrophysics and beyond
 - ▶ documentation strongly focused on astrophysical data (do not let this deter you)
 - ▶ areas: astrophysics, seismology, nuclear engineering, molecular dynamics, oceanography
- This presentation is really targeted at non-astrophysicists
 - ▶ astro folks are already aware of YT and either use it, or have a good reason not to
 - ▶ researchers from many other fields deal with 3D volumetric data, could benefit from YT

Historical context

- Astrophysicists have been running multi-dimensional simulations for the last 40+ years, needed a tool to visualize data
- In the early 2000s no access to good, open-source, multi-platform, scalable multi-dimensional scientific visualization tools
 - ▶ many researchers developed visualization and data analysis workflows in IDL and MATLAB (both commercial with lots of limitations)
 - ▶ ParaView and VisIt were only starting, not yet known and/or regarded as too general-purpose or too large by many
- Many wrote tools (IFrIT, FTTE, ...) for their own use, some were open-sourced
- One of these tools was YT, initially written by Matthew Turk around ~2007
 - ▶ Python-based ⇒ high-level abstractions for data manipulation!
 - ▶ intuitive interface
 - ▶ soon invited other researchers to use and develop it
 - ▶ currently 128 listed contributors

Data formats

ART	ARTIO	Athena	Athena++	AMReX
Pluto	Enzo	Enzo-P	Exodus II	FITS
FLASH	Gadget	GAMER	Generic AMR	Generic array
Semi-structured (hexahedral) grid	Unstructured grid	Generic particle	Gizmo	Halo catalog
openPMD	PyNE	RAMSES	SPH Particle	Tipsy

Installing YT and add-ons (data, tutorial Jupyter Notebooks)

install YT itself

```
$ conda install -c conda-forge yt
or 'pip install yt'
or 'git clone https://github.com/yt-project/yt && cd yt && python setup.py develop'
```

```
$ cd /tmp/yt-data
$ url=http://yt-project.org/data
$ wget $url/enzo_tiny_cosmology.tar.gz    # 32^3 base + 5 additional AMR levels
$ wget $url/Enzo_64.tar.gz                 # 64^3 base + 4 additional AMR levels
$ wget $url/IsolatedGalaxy.tar.gz          # 32^3 base + 8 additional AMR levels
$ wget $url/MOOSE_Sample_data.tar.gz      # unstructured mesh (from a finite-element code)
$ wget $url/ArepoBullet.tar.gz
$ wget $url/geos.tar.gz
$ wget $url/DICEGalaxyDisk_nonCosmological.tar.gz
unpack them
```

```
$ git clone https://github.com/yt-project/yt
$ cd yt/doc/source/quickstart
$ yt notebook
```

Loading and examining data

```
>>> import yt
>>> ds = yt.load('/tmp/yt-data/IsolatedGalaxy/galaxy0030/galaxy0030')
yt : [INFO ] 2018-11-17 17:36:02,879 Parameters: current_time      = 0.0060000200028298
yt : [INFO ] 2018-11-17 17:36:02,879 Parameters: domain_dimensions     = [32 32 32]
yt : [INFO ] 2018-11-17 17:36:02,879 Parameters: domain_left_edge      = [0. 0. 0.]
yt : [INFO ] 2018-11-17 17:36:02,879 Parameters: domain_right_edge     = [1. 1. 1.]
yt : [INFO ] 2018-11-17 17:36:02,880 Parameters: cosmological_simulation = 0.0

>>> ds.print_stats()      # actually read the mesh, print stats
Parsing Hierarchy : 100% 173/173 [00:00<00:00, 9581.22it/s]
yt : [INFO ] 2018-11-17 17:36:02,908 Gathering a field list (this may take a moment.)
level # grids      # cells      # cells^3
-----
0          1          32768        32
1          8          34304        33
2          8          181888       57
3          8          646968       87
4         15          947856       99
5         51          874128       96      Smallest Cell:
6         18          786328       93      Width: 1.221e-04 Mpc
7         28          446776       77      Width: 1.221e+02 pc
8         36          209400       60      Width: 2.518e+07 AU
                                         Width: 3.767e+20 cm
-----
173        4160416

t = 6.00002000e-03 = 1.39768066e+16 s = 4.42898275e+08 years
```

Loading and examining data: dataset fields

```
>>> ds.field_list      # list all 55 dataset fields (grouped into categories)
[('all','creation_time'), ('all','dynamical_time'), ('all','metallicity_fraction'),
('all','particle_index'), ('all','particle_mass'), ('all','particle_position_x'),
('all','particle_position_y'), ('all','particle_position_z'), ('all','particle_type'),
('all','particle_velocity_x'), ('all','particle_velocity_y'), ('all','particle_velocity_z'),
('enzo','Average_creation_time'), ('enzo','Bx'), ('enzo','By'), ('enzo','Bz'),
('enzo','Cooling_Time'), ('enzo','Dark_Matter_Density'), ('enzo','Density'),
('enzo','Electron_Density'), ('enzo', 'Forming_Stellar_Mass_Density'),
('enzo','Galaxy1Colour'), ('enzo','Galaxy2Colour'), ('enzo', 'HII_Density'),
('enzo','HI_Density'), ('enzo','HeIII_Density'), ('enzo','HeII_Density'),
('enzo','HeI_Density'), ('enzo','MBHColour'), ('enzo','Metal_Density'),
('enzo','PhiField'), ('enzo','Phi_pField'), ('enzo','SFR_Density'),
('enzo','Star_Particle_Density'), ('enzo','Temperature'), ('enzo','TotalEnergy'),
('enzo','gammaHI'), ('enzo','kphHI'), ('enzo','kphHeI'), ('enzo','kphHeII'),
('enzo','x-velocity'), ('enzo','y-velocity'), ('enzo','z-velocity'), ('io','creation_time'),
('io','dynamical_time'), ('io','metallicity_fraction'), ('io','particle_index'),
('io','particle_mass'), ('io','particle_position_x'), ('io','particle_position_y'),
('io','particle_position_z'), ('io','particle_type'), ('io','particle_velocity_x'),
('io','particle_velocity_y'), ('io','particle_velocity_z')]

>>> len(ds.derived_field_list)      # list all 405 dataset + derived fields

>>> print(ds.field_info["gas", "vorticity_x"].get_source())    # see derived field definition
```

Loading and examining data: domain parameters

```
>>> ds.domain_width      # box size in code units
YTArray([1., 1., 1.]) code_length

>>> ds.domain_center      # in code units
YTArray([0.5, 0.5, 0.5]) code_length

>>> ds.domain_left_edge    # in code units
YTArray([0., 0., 0.]) code_length

>>> ds.domain_right_edge   # in code units
YTArray([1., 1., 1.]) code_length

>>> ds.domain_dimensions    # base grid size
array([32, 32, 32])

>>> ds.parameters      # list all 402 simulation parameters (outputs a Python dictionary)
>>> ds.parameters['StarMakerMinimumMass']
8000

>>> print(ds.domain_width.in_units("kpc"))
[1000.10448889 1000.10448889 1000.10448889] kpc

>>> print(ds.domain_width.in_units("au"))
[2.06286359e+11 2.06286359e+11 2.06286359e+11] au
```

Loading and examining data: subgrids in the AMR hierarchy

```
>>> print(ds.index.num_grids, ds.index.max_level)
173 8

>>> ds.index.grid_levels
array([[0], [1],
       ...,
      [8], [8]], dtype=int32)

>>> ds.index.grid_dimensions
array([[32, 32, 32], [16, 18, 16],
       ...,
      [8, 16, 20], [8, 12, 12]], dtype=int32)

>>> ds.index.grid_left_edge
YTArray([[0., 0., 0.], [0.25, 0.21875, 0.25],
       ...,
      [0.49902344, 0.49560547, 0.49755859],
      [0.49804688, 0.49609375, 0.49853516]]),
code_length

>>> ds.index.grid_right_edge
YTArray([[1., 1., 1.], [0.5, 0.5, 0.5],
       ...,
      [0.5 , 0.49755859, 0.5 ],
      [0.49902344, 0.49755859, 0.5 ]]),
code_length

>>> ds.index.grid_particle_count
array([[0], [13],
       ...,
      [736], [369]], dtype=int32)

>>> g = ds.index.grids[0]
>>> g.ActiveDimensions
array([32, 32, 32], dtype=int32)

>>> g.LeftEdge, g.RightEdge
(YTArray([0., 0., 0.]) code_length,
 YTArray([1., 1., 1.]) code_length)

>>> g.Level
0

>>> g.Children
[EnzoGrid_0002, EnzoGrid_0003, EnzoGrid_0004,
 EnzoGrid_0005, EnzoGrid_0006, EnzoGrid_0007,
 EnzoGrid_0008, EnzoGrid_0009]

# all grids at level=8
>>> gs = ds.index.select_grids(ds.index.max_level)

>>> g2 = gs[0] # select the first of these
>>> print(g2,g2.Parent)
EnzoGrid_0028 EnzoGrid_0023

>>> g2["density"][:, :, 0] # subsetting print density
YTArray([[1.0136369e-25, 3.4564638e-25, 6.4192590e-25, ...,
          5.9669651e-25, 5.1001470e-25, 4.2170473e-25],
          ...,
          [9.0090510e-26, 6.8866435e-26, 6.3422531e-26, ...,
          9.1754346e-27, 9.5285530e-27, 1.0011084e-26]],
          dtype=float32) g/cm**3
```

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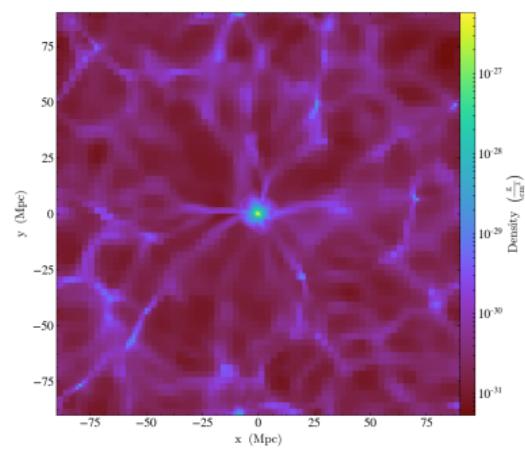
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Slice plots



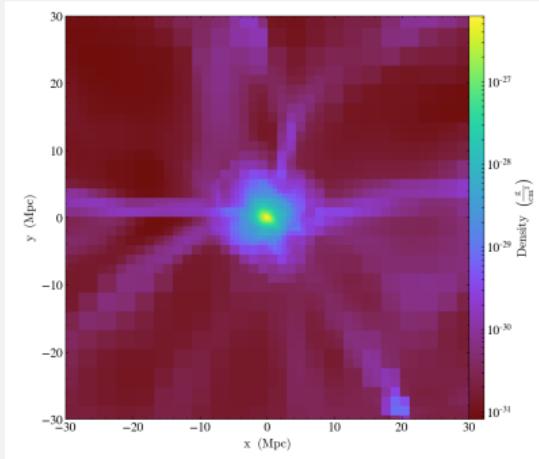
```
import yt

ds = yt.load('/tmp/yt-data/Enzo_64/DD0043/data0043')
print('Redshift =', ds.current_redshift)

slc = yt.SlicePlot(ds, normal='z', fields='density',
                    center='max')
slc.save('slice1.png')

# help(yt.SlicePlot)
# center='c'                      # center of the volume
# center=[0.1,0.3,0.5]              # specific coordinates
# center='max'                     # highest density point
# center=('min','temperature')     # lowest temp. point
# center=('max','dark_matter_density')
```

Slice plots: zoom and window size

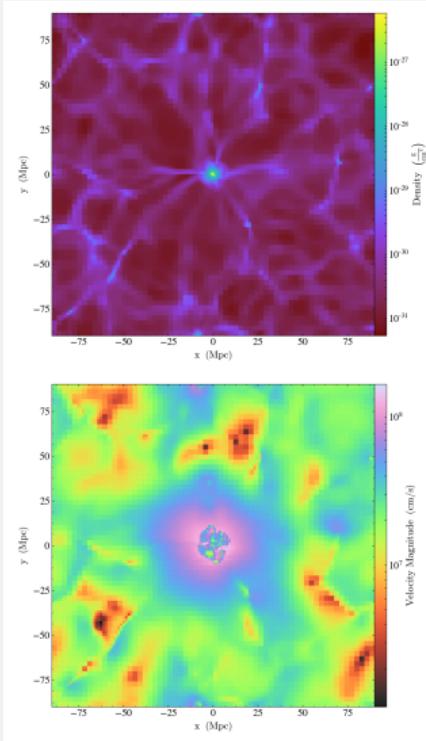


```
slc.zoom(5)
slc.save('slice2.png')

# from yt.units import kpc, Mpc
# slc.set_width(10*Mpc)          # set box size
# slc.save('slice2a.png')

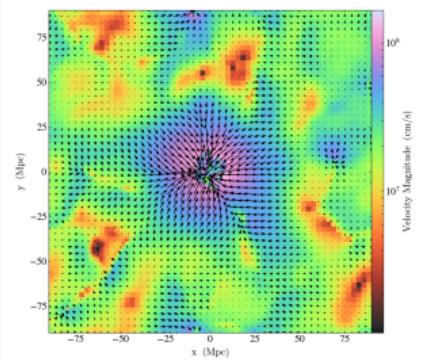
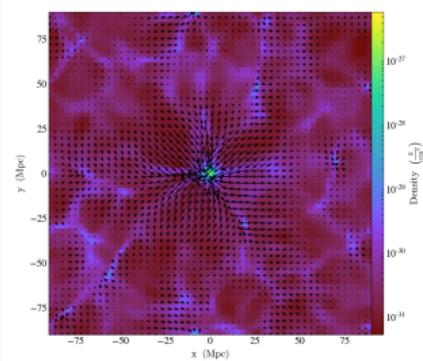
# yt.SlicePlot(ds, normal='z', fields='density', center='max',
#             width=20*Mpc).save('slice2b.png')
```

Slice plots: multiple fields and non-default colourmaps



```
slc = yt.SlicePlot(ds, normal='z',
                   fields=['density', 'velocity_magnitude'],
                   center='max')
slc.set_cmap('velocity_magnitude', 'kamae')
slc.save()      # save two images
```

Slice plots: velocity annotations



```
slc.annotate_velocity() # add velocity arrows  
slc.save()
```

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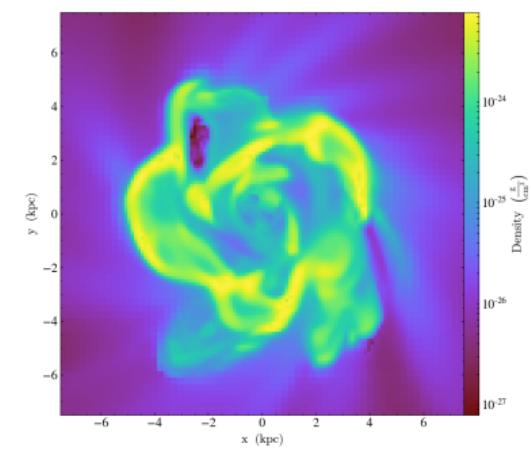
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Slice plots: width as argument



```
ds = yt.load("/tmp/yt-data/IsolatedGalaxy/galaxy0030/galaxy0030")
yt.SlicePlot(ds, 'z', 'density', center='c',
            width=15*kpc).save('slice5.png')    # disk-on
```

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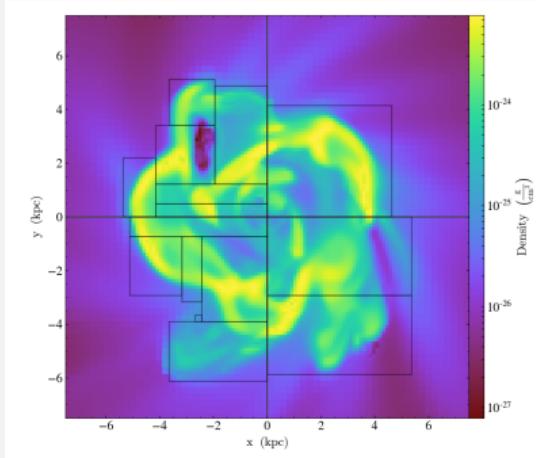
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Slice plots: grid annotations



```
yt.SlicePlot(ds, 'z', 'density', center='c',
            width=15*kpc).annotate_grids().save('slice5a.png')
```

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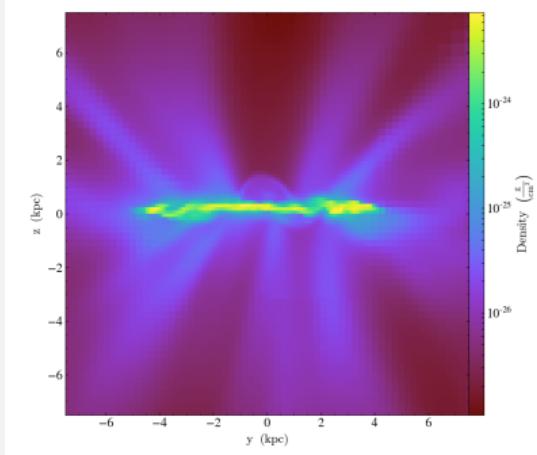
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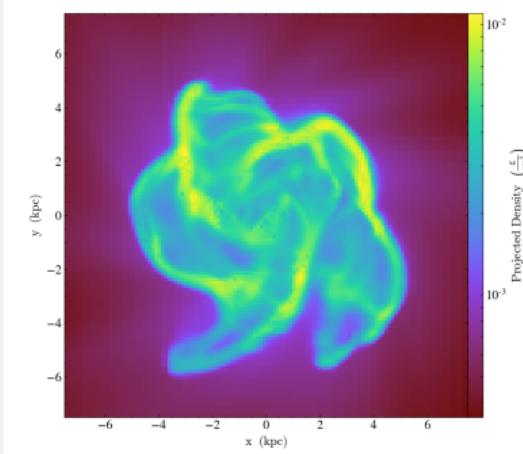
Slice plots: edge-on



```
yt.SlicePlot(ds, 'x', 'density', center='c',  
            width=15*kpc).save('slice6.png')      # edge-on
```

Projection: integrate without a weight field

- Density \Rightarrow column density



```
import yt
from yt.units import kpc
ds = yt.load('/tmp/yt-data/IsolatedGalaxy/galaxy0030/galaxy0030')

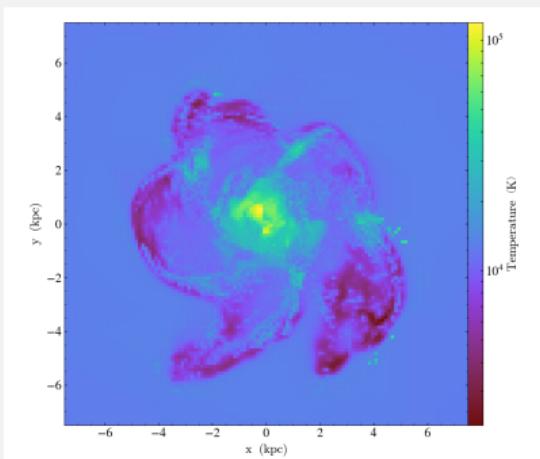
yt.ProjectionPlot(ds, axis='z', fields='density',
                  method='integrate',
                  width=15*kpc).save('projection1.png')

# help(yt.ProjectionPlot)
```

Projection: integrate along the line of sight with a weight field

- Temperature \Rightarrow mass-weighted temperature

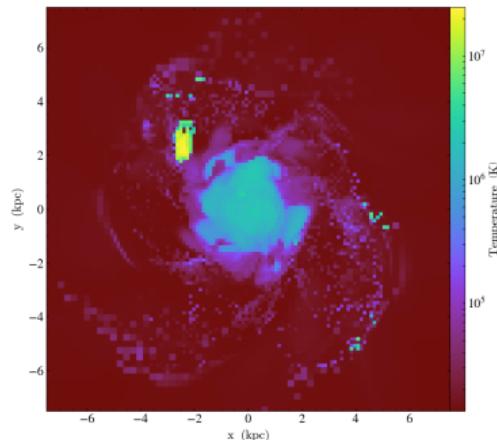
$$\langle T \rangle = \frac{\int_{\text{LOS}} \rho T dl}{\int_{\text{LOS}} \rho dl}$$



```
yt.ProjectionPlot(ds, axis='z', fields='temperature',
                  method='integrate', width=15*kpc,
                  weight_field='density').save('projection2.png')
```

Projection: pick out the maximum value along the line of sight

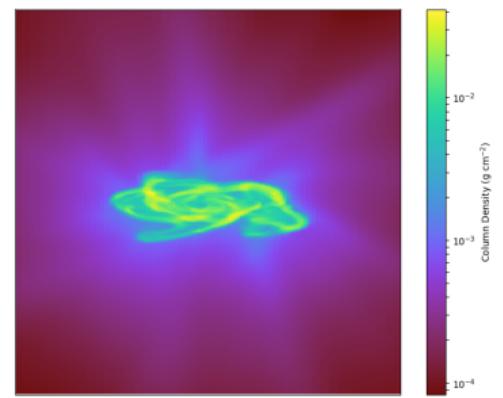
- Obviously, not a physical quantity, but still very useful for identifying unusual regions



```
yt.ProjectionPlot(ds, axis='z', fields='temperature',
                  method='mip',
                  width=15*kpc).save('projection3.png')
```

Projection: off-axis

- Integrates through the volume at an arbitrary angle
- Can do a variety of methods with/without a weight
- Returns an image plane instead of a plot



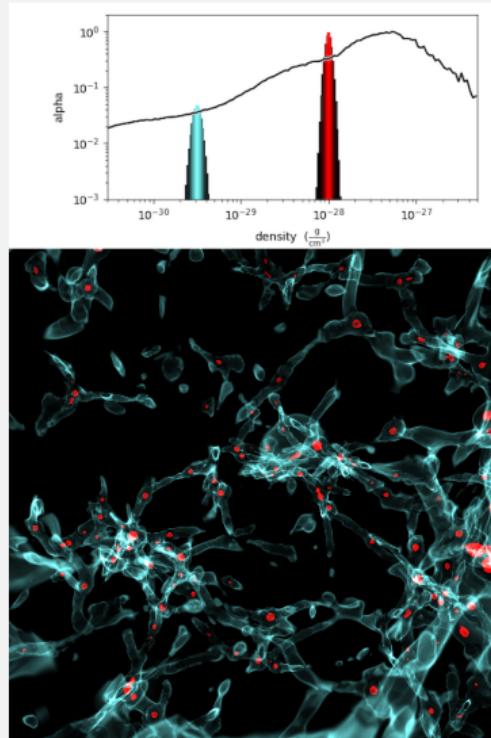
```
image = yt.off_axis_projection(data_source=ds,
                               center=[0.5,0.5,0.5], normal_vector=[0,1,0.3],
                               width=[0.02,0.02,0.02], resolution=600,
                               item='density', method="integrate")
image.shape
yt.write_projection(image, "projection4.png",
                     colorbar_label="Column Density (g cm$^{-2}$)")

# no colourbar, does not automatically pick the log scale
# from numpy import log10
# yt.write_image(log10(image), 'projection4.png')
```

Volume rendering

- https://yt-project.org/doc/visualizing/volume_rendering.html
- This is what you see on magazine covers
- Computationally much more demanding
- Currently software ray-tracing
- OpenGL versions “under development”

Volume rendering: manual Gaussians



```
import yt
from numpy import log10
ds = yt.load('/tmp/yt-data/Enzo_64/DD0043/data0043')

# set up a scene for volume rendering
sc = yt.create_scene(ds, lens_type='perspective')

# the first (and the only) source in the scene to be rendered
source = sc[0]
source.set_field('density') # set the source's field to render
source.set_log(True)      # use log (and not linear) space

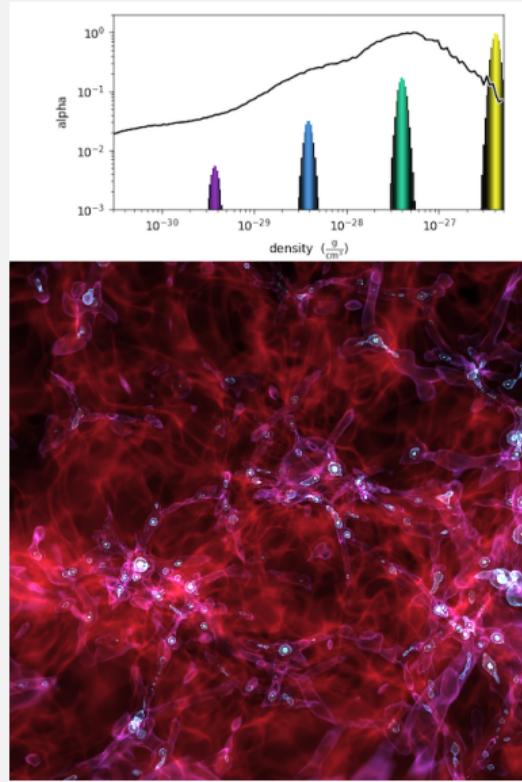
# start building the transfer function
bounds = (3e-31, 5e-27)
tf = yt.ColorTransferFunction(x_bounds=log10(bounds))
# help(yt.ColorTransferFunction)

# add a red spike [r,g,b,alpha] and then a cyan spike
tf.add_gaussian(location=-28, width=0.003, height=[1,0,0,1])
tf.add_gaussian(location=-29.5, width=0.005, height=[0.5,1,1,0.05])
print(tf)

# apply our transfer function to the source
source.tfh.tf = tf      # t(fh stands for TransferFunctionHelper
source.tfh.bounds = bounds
source.tfh.plot('transferFunction.png', profile_field='density')

# save the image, flooring especially bright pixels
sc.save('volume.png', sigma_clip=4)
```

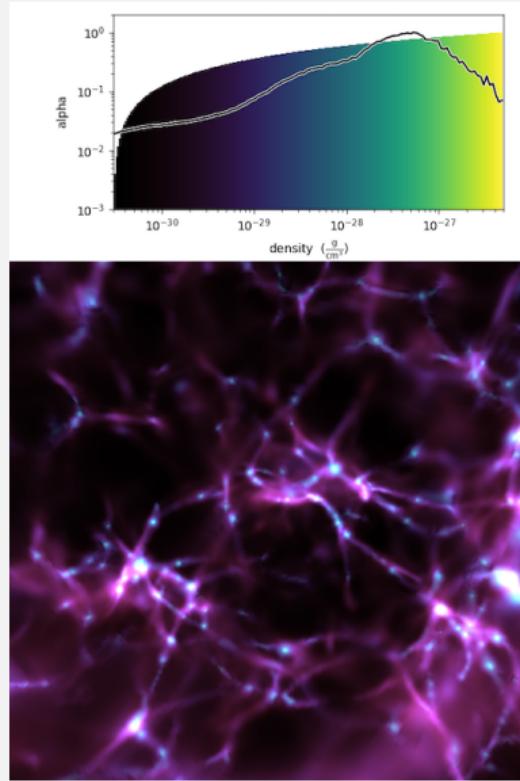
Volume rendering: automatic Gaussians



```
% 18,20c18,19
< # add a red spike [r,g,b,alpha] and then a cyan spike
< tf.add_gaussian(location=-28, width=0.003, height=[1,0,0,1])
< tf.add_gaussian(location=-29.5,width=0.005,height=[0.5,1,1,0.05])
---
> # add multiple evenly-spaced "automatic" Gaussians
> tf.add_layers(N=5, colormap='arbre')

>>> print(tf)
<Color Transfer Function Object>:
x_bounds:[-31, -26] nbins:256 features:
    ('gaussian', 'location(x):-30', 'width(x):0.0039',
     'height(y):(0.45, 0.077, 0.1, 0.001)')
    ('gaussian', 'location(x):-29', 'width(x):0.0039',
     'height(y):(0.55, 0.22, 0.72, 0.0056)')
    ('gaussian', 'location(x):-28', 'width(x):0.0039',
     'height(y):(0.3, 0.58, 0.86, 0.032)')
    ('gaussian', 'location(x):-27', 'width(x):0.0039',
     'height(y):(0.18, 0.84, 0.63, 0.18)')
    ('gaussian', 'location(x):-26', 'width(x):0.0039',
     'height(y):(0.95, 0.94, 0.19, 1)')
```

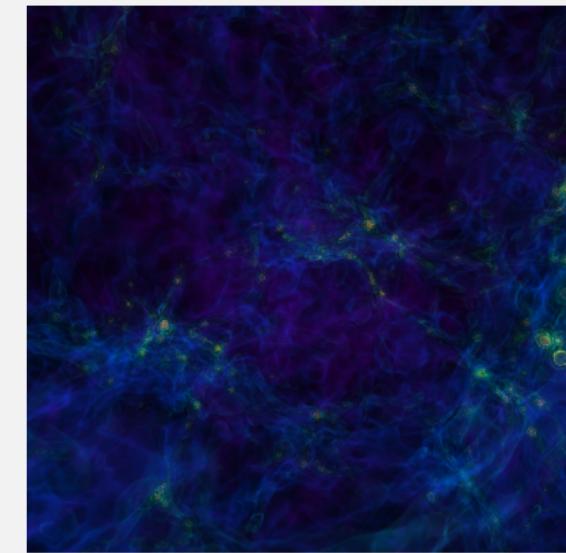
Volume rendering: linear colourmap



```
% 18,19c18,23
< # add multiple evenly-spaced "automatic" Gaussians
< tf.add_layers(N=5, colormap='arbre')
---
> # user-defined function to scale the alpha channel
> def linramp(vals, minval, maxval):
>     return (vals - vals.min())/(vals.max() - vals.min())
> # define a colourmap over a range of densities
> tf.map_to_colormap(mi=log10(3e-31), ma=log10(5e-27),
>                     colormap='arbre', scale_func=linramp)

>>> print(tf)
<Color Transfer Function Object>
x_bounds:[-31, -26] nbins:256 features:
    ('map_to_colormap', 'start(x):-31', 'stop(x):-26',
     'value(y): 1')
```

Volume rendering: fully automatic



```
import yt
ds = yt.load('/tmp/yt-data/Enzo_64/DD0043/data0043')
sc = yt.create_scene(ds, lens_type='perspective')
sc.save('volume4.png')
```

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Moving the scene camera

https://yt-project.org/doc/cookbook/complex_plots.html#cookbook-camera-movement

```
sc = yt.create_scene(ds, ...)  
cam = sc.camera  
  
cam.iter_zoom(final, nzoom)      # return an object that produces 'nzoom'  
                                  # snapshots until the current view has been  
                                  # zoomed in to 'final' factor  
  
cam.iter_move(center, nmove)     # return an object that produces 'nmove'  
                                  # snapshots until the current view has been  
                                  # moved to a final 'center'  
  
cam.iter_rotate(angle, nspin)    # return an object that produces 'nspin'  
                                  # snapshots until the current view has been  
                                  # rotated by 'angle' radians around the  
                                  # vertical axis or the optional 'rot_vector'  
  
sc.save('frame0000.png')         # save an image at the starting orientation  
for i in cam.iter_rotate(pi, 30):    # rotate by 180 degrees over 30 frames  
    sc.save('frame%04d.png' % (i+1))  # save frame{0001..0030}.png
```

Parallel YT via mpi4py

Currently, YT can do the following in parallel:

- slice plots
- projection plots
- off-axis slices
- covering grids (examining grid data in a fixed-resolution array)
- creating and processing derived quantities
- 1D / 2D / 3D profiles and histograms
- halo analysis (halo analysis)
- volume rendering
- isocontours and flux calculations

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Installing YT on Cedar and Graham in your directory

```
% # initial setup for CPU rendering
$ cedar
$ module load python
$ virtualenv astro      # install Python tools in your $HOME/astro
$ source ~/astro/bin/activate
$ pip install cython
$ pip install numpy
$ pip install yt
$ pip install mpi4py

# usual use
$ source ~/astro/bin/activate      # load the environment
$ python
...
$ deactivate
```

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Rotating a cosmological volume with grids annotations

More on parallel YT at https://yt-project.org/doc/analyzing/parallel_computation.html

On a cluster, save this as grids.py:

```
import yt
from numpy import pi
yt.enable_parallelism()      # turn on MPI parallelism via mpi4py
ds = yt.load("Enzo_64/DD0043/data0043")
sc = yt.create_scene(ds, ('gas', 'density'))
cam = sc.camera
cam.resolution = (1024, 1024)    # resolution of each frame
sc.annotate_domain(ds, color=[1, 1, 1, 0.005])    # draw the domain boundary [r,g,b,alpha]
sc.annotate_grids(ds, alpha=0.005)    # draw the grid boundaries
sc.save('frame0000.png', sigma_clip=4)
nspin = 900
for i in cam.iter_rotate(pi, nspin):    # rotate by 180 degrees over nspin frames
    sc.save('frame%04d.png' % (i+1), sigma_clip=4)
```

and this as yt-mpi.sh:

```
#!/bin/bash
#SBATCH --time=3:00:00    # walltime in d-hh:mm or hh:mm:ss format
#SBATCH --ntasks=4        # number of MPI processes
#SBATCH --mem-per-cpu=3800
#SBATCH --account=...
source $HOME/astro/bin/activate
srun python grids.py
```

Rotating a cosmological volume with grids annotations (cont.)

- Submit the job

```
% sbatch yt-mpi.sh
```

- In one wallclock hour
 - ▶ serial: 88 frames
 - ▶ parallel on 4 cores: 243 frames
- Make a Quicktime-compatible MP4 right on the cluster

```
% ffmpeg -r 30 -i frame%04d.png -c:v libx264 -pix_fmt yuv420p -vf \  
    "scale=trunc(iw/2)*2:trunc(ih/2)*2" grids.mp4
```

- Download it to your laptop

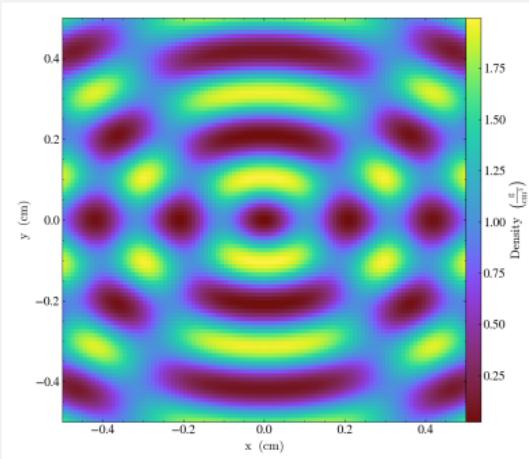
```
% rsync -av --progress cedar.computeCanada.ca:/path/to/grids.mp4 .
```

- Final video
 - ▶ online (rather compressed) <https://vimeo.com/301503962>
 - ▶ on presenter's laptop grids.mp4

Generic array data

- This is Python \Rightarrow can start with any array in any form
- Let's read from a NetCDF file storing the **3D sine envelope wave function** defined inside a unit cube ($x_i \in [0, 1]$) at 100^3 resolution

$$f(x_1, x_2, x_3) = \sum_{i=1}^2 \left[\frac{\sin^2 \left(\sqrt{\xi_{i+1}^2 + \xi_i^2} \right) - 0.5}{[0.001(\xi_{i+1}^2 + \xi_i^2) + 1]^2} + 0.5 \right], \text{ where } \xi_i \equiv 30(x_i - 0.5)$$

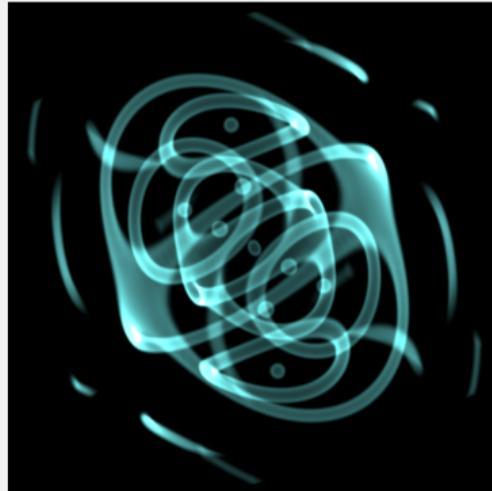
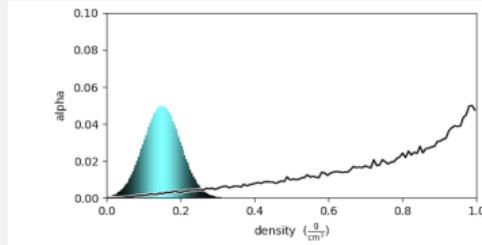


```
import yt
import numpy as np
from netCDF4 import Dataset
all = Dataset('sineEnvelope.nc', 'r')
rho = all.variables['density'][::,::,:]
data = dict(density = rho)
bbox = np.array([[0,1],[0,1],[0,1]])

# create a yt-native dataset
ds = yt.load_uniform_grid(data=data, domain_dimensions=rho.shape,
                           length_unit=1., bbox=bbox)

slc = yt.SlicePlot(ds, 'z', 'density', center='c')
slc.set_log('density', False)      # use linear colormap
slc.save('slice7.png')
```

Generic array data (cont.)



```
sc = yt.create_scene(ds, 'density')
source = sc[0]    # the object in the scene to be rendered
source.set_field('density')    # set the field
source.set_log(False)    # use linear colourmap

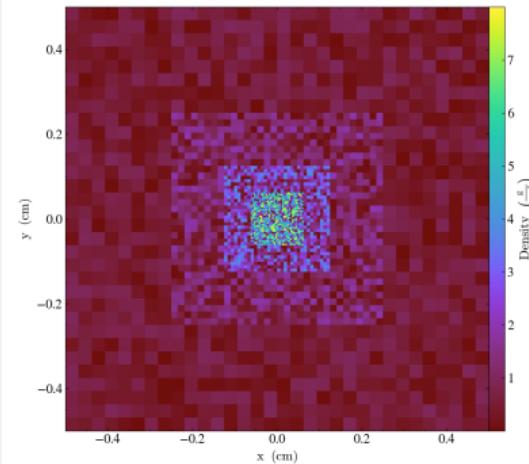
# build the transfer function with a cyan spike
bounds = (0,1)
tf = yt.ColorTransferFunction(x_bounds=bounds)
tf.add_gaussian(location=0.15, width=0.005,
                height=[0.5,1,1,0.05])    # [r,g,b,alpha]

# apply our transfer function to the source
source.tfh.tf = tf    # tfh stands for TransferFunctionHelper
source.tfh.bounds = bounds
source.tfh.plot('transferFunction.png', profile_field='density')

sc.camera.resolution = (1024,1024)
sc.camera.position=[1,1,1.5]
sc.save('volume5.png', sigma_clip=3) # remove esp. bright pixels
```

Generic multi-resolution data: set up and plot the grids

- In this toy example let's ignore parent-children relationships between grids
 - ▶ YT will attempt to set them, but not necessarily correctly in this case
 - ▶ for real AMR patches we (or the dataset reader function) should specify these relationships explicitly



```
import yt
import numpy as np

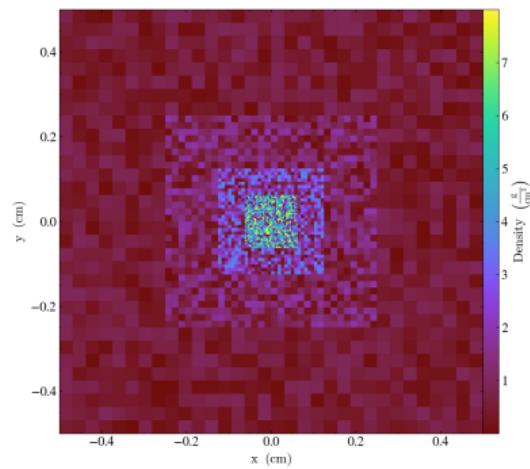
dims = [32,32,32]
gridData = [
    dict(left_edge=[0.]*3,      right_edge=[1.]*3,
         level=0, dimensions=dims),
    dict(left_edge=[0.25]*3,    right_edge=[0.75]*3,
         level=1, dimensions=dims),
    dict(left_edge=[0.375]*3,   right_edge=[0.625]*3,
         level=2, dimensions=dims),
    dict(left_edge=[0.4375]*3,  right_edge=[0.5625]*3,
         level=3, dimensions=dims)]

for g in gridData:
    top = 2*g['level']
    g['density'] = np.random.random(g['dimensions']) * top

ds = yt.load_amr_grids(gridData, domain_dimensions=dims)

slc = yt.SlicePlot(ds, 'z', 'density', center='c')
slc.set_log('density', False)      # use linear colormap
slc.save('slice8.png')
```

Generic multi-resolution data: examine the grids



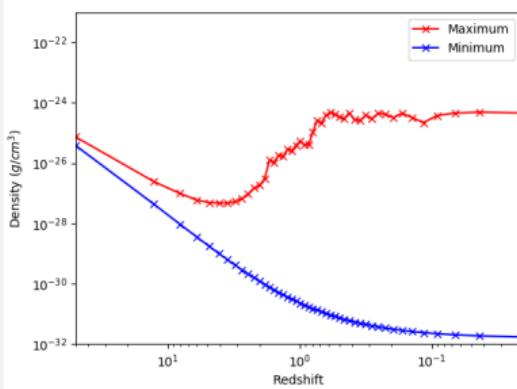
```
>>> print(ds.index.num_grids, ds.index.max_level)
4 3

>>> ds.index.grid_levels
array([[0], [1], [2], [3]], dtype=int32)
>>> ds.index.grid_dimensions
array([[32, 32, 32], [32, 32, 32],
       [32, 32, 32], [32, 32, 32]], dtype=int32)
>>> ds.index.grid_left_edge
YTArray([[0., 0., 0.], [0.25, 0.25, 0.25],
         [0.375, 0.375, 0.375], [0.4375, 0.4375, 0.4375]]) code_length
>>> ds.index.grid_right_edge
YTArray([[1., 1., 1.], [0.75, 0.75, 0.75],
         [0.625, 0.625, 0.625], [0.5625, 0.5625, 0.5625]]) code_length

>>> ds.index.grids[0]['density'][0,0,0]
0.49203435485203484 g/cm**3
>>> ds.unit_system['length']
cm
>>> ds.unit_system['density']
g/cm**3

>>> point = ds.point([0.1,0.5,0.5])      # in dataset units
>>> point
YTPoint (AMRGridData): , p=[0.1 0.5 0.5] cm
>>> point['density']      # print density at specific (x,y,z)
YTArray([0.70887875]) g/cm**3
```

Time-series analysis



```
import yt

# load a time sequence DD00{00..46}
ts = yt.load('/tmp/yt-data/enzo_tiny_cosmology/DD????/DD????')

print(len(ts))    # print the number of steps (should be 47)

# scan all time outputs
rho_ex, redshift = [], []
for ds in ts:
    print(ds)    # print basic dataset info
    dd = ds.all_data()    # region = entire simulation domain
    rho_ex.append(dd.quantities.extrema('density'))
    redshift.append(ds.current_redshift)

import numpy as np
rho_ex = np.array(rho_ex)

# plot min/max density vs. redshift
from matplotlib import pylab
pylab.loglog(redshift, rho_ex[:,1], '-xr', label='Maximum')
pylab.loglog(redshift, rho_ex[:,0], '-xb', label='Minimum')
pylab.xlabel('Redshift')
pylab.ylabel('Density ($g/cm^3$)')
pylab.legend()
pylab.xlim(50, 0)
pylab.ylim(1e-32, 1e-21)
pylab.show()
```

Not covered today

- Working with non-astrophysical variable-resolution (curvilinear) and unstructured grids
- Working with particle data
- Bash command-line YT
- 1D / 2D / 3D profiles and histograms
- Data objects – think of them as filters used to define subsets, derivative datasets, collections
 - ▶ surfaces (isocontours), streamlines, ...
 - ▶ flux calculations
 - ▶ subsetting domains and plotting subsets with fixed-resolution buffer
- Intel's EMBREE software ray tracing in YT
- GPU rendering in YT

Intro
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Slices
ooooooo

Projections
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Volumes
oooooooooooo

Generic
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Summary
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Questions?