Wide-field observations of PSF variations with SCAO

In this example we will show the effect of the off-axis AO correction on the shape of the PSF when observing with the SCAO mode. To make a semi-realistic observation, we will observe an open cluster created by the `ScopeSim_Templates` package. This cluster extends over the full MICADO field of view. As such it should show the full extend of the expected PSF variations over the field.

It should be noted that adding PSF field variations is a computationally expensive process. ScopeSim does it's best to reduce the level of complexity by discretising the PSF variation into different zones over the field of view. Occasionally the borders between these zones is visible

In [1]:

```
import numpy as np
import matplotlib.pyplot as plt
from matplotlib.colors import LogNorm
from astropy import units as u

import scopesim as sim
import scopesim_templates as sim_tp

%matplotlib inline
%config Completer.use_jedi = False
```

The PSF field-variation are complex and computationally expensive. Hence this functionality is not inluded in the `MICADO_Sci` package. For this use case we must use the pipeline-oriented `MICADO` package. However as we will be using the SCAO mode, we can ignore the `MAORY` module.

In [2]:

```
sim.server.database.download_package(["locations/Armazones.zip",
                                      "telescopes/ELT.zip",
                                      "instruments/MICADO.zip"])
```

Out[2]:

```
['F:\\temp\\scopesim_fdr_notebooks\\Armazones.zip',
 'F:\\temp\\scopesim_fdr_notebooks\\ELT.zip',
 'F:\\temp\\scopesim_fdr_notebooks\\MICADO.zip']
```

Set up an open cluster `Source` object

The first step is to create a `Source` object. Here we take advantage of the `cluster` function from the `ScopeSim_Templates.basic.stars` submodule. The `cluster` function draws masses from an standard Kroupa IMF until the `mass` limit has been reached. It then generates randomly draw positions from a 2D gaussian distribution with a HWHM equal to the given `core_radius`. The positions are scaled by the `distance` parameter such that the final position is in units of `arcsec` from the centre of the cluster. Spectra for all the stars are taken from the Pickles (1998) catalogue and are imported from the `Pyckles` python packages.

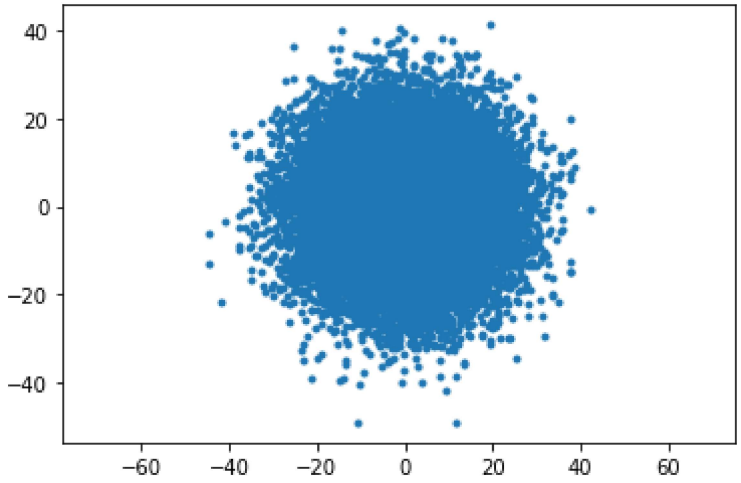
Here we choose a cluster with a mass of 10000 solar masses (~250000 stars) with a core radius of 0.5 parsec, located at a distance of 8 kpc. This essentially gives us a cluster that covers the whole MICADO filed of view in wide-field mode (4mas / pixel).

In [3]:

```
cluster = sim_tp.basic.stars.cluster(mass=10000, core_radius=0.5, distance=8000)
```

In [4]:

```
plt.plot(cluster.fields[0]["x"], cluster.fields[0]["y"], ".")
plt.axes().set_aspect('equal', 'datalim')
```



Set up the MICADO optical system for SCAO and include a field-varying PSF

The next step is the standard proceedure - set the instrument to `MICADO` and the modes to `SCAO` and `IMG_4mas`, then create an `OpticalTrain` object.

In [5]:

```
cmd = sim.UserCommands(use_instrument="MICADO", set_modes=["SCAO", "IMG_4mas"])
micado = sim.OpticalTrain(cmd)
```

By default the PSF model in the pipeline-oriented `MICADO` package is set to use a field-constant PSF cube. We need to change this to use a Field-Varying PSF model.

Note: to view all the optical effects contained within the optical model, use the `.effects` attribute in the `OpticalTrain` class.

Here we see the PSF model in the 4th last line:

In [6]:

```
micado.effects
```

Out[6]:

Table length=23

element	name	class	included
str21	str32	str31	bool
armazones	armazones_atmo_default_ter_curve	AtmosphericTERCurve	True
armazones	armazones_atmo_dispersion	AtmosphericDispersion	False
armazones	armazones_atmo_skycalc_ter_curve	SkycalcTERCurve	False
ELT	scope_surface_list	SurfaceList	True
ELT	scope_vibration	Vibration	True
ELT	eso_combined_reflection	TERCurve	False
MICADO	micado_static_surfaces	SurfaceList	True
MICADO	micado_ncpas_psf	NonCommonPathAberration	True
MICADO	filter_wheel_1	FilterWheel	True
MICADO	filter_wheel_2	FilterWheel	True
...	...	...	...
micado_detector_array	qe_curve	QuantumEfficiencyCurve	True
micado_detector_array	exposure_action	SummedExposure	True
micado_detector_array	dark_current	DarkCurrent	True
micado_detector_array	detector_linearity	LinearityCurve	True
micado_detector_array	shot_noise	ShotNoise	True
micado_detector_array	readout_noise	PoorMansHxRGReadoutNoise	True
default_ro	relay_psf	FieldConstantPSF	True
default_ro	relay_surface_list	SurfaceList	True
MICADO_IMG_LR	micado_wide_field_mirror_list	SurfaceList	True
MICADO_IMG_LR	micado_adc_3D_shift	AtmosphericDispersionCorrection	False

We can access the PSF model using the standard python dictionary notion using the name of the element. In this case it is called `relay_psf` as this refers to the internal MICADO relay optics which are connected to the SCAO system.

We do not want to use the default `relay_psf` object, so we need to tell ScopeSim not to include it

In [7]:

```
micado["relay_psf"].include = False
```

Next we want to add a `FieldVaryingPSF` object from the ScopeSim library of optical effect. Before we initialise the object though, we will need the correct PSF cube.

A small library of precomputed PSFs can be found on the ScopeSim server: https://www.univie.ac.at/simcado/InstPkgSvr/psfs/ (https://www.univie.ac.at/simcado/InstPkgSvr/psfs/)

Once we have downloaded the PSF cube of our choice (in this case the cube corresponding to ESO median atmospheric conditions) we can pass the file path to the `FieldVaryingPSF` object.

In [8]:

```
fv_psf = sim.effects.psfs.FieldVaryingPSF(filename="AnisoCADO_SCAO_FVPSF_4mas_EsoMedian_201
```

We now need to add the new PSF to the MICADO relay optics element inside the `MICADO` optical train.

In [9]:

```
micado.optics_manager["default_ro"].add_effect(fv_psf)
```

Viewing an on-axis PSF is boring. Therefore we will move the 1024x1024 detector window off centre 10 arcseconds in both x and y directions. We will also increase the exposure time to 60 seconds.

Now we are ready to obsere and readout the MICADO detector window

In [10]:

```
micado.cmds["!OBS.dit"] = 600    # [s]
micado.cmds["!DET.x"] = 2500     # [pixel] equivalent of 10 arcseconds (10 arcsec / 0.004 a
micado.cmds["!DET.y"] = 2500

micado.observe(cluster)
hdus = micado.readout()
```

```
Preparing 2 FieldOfViews
```

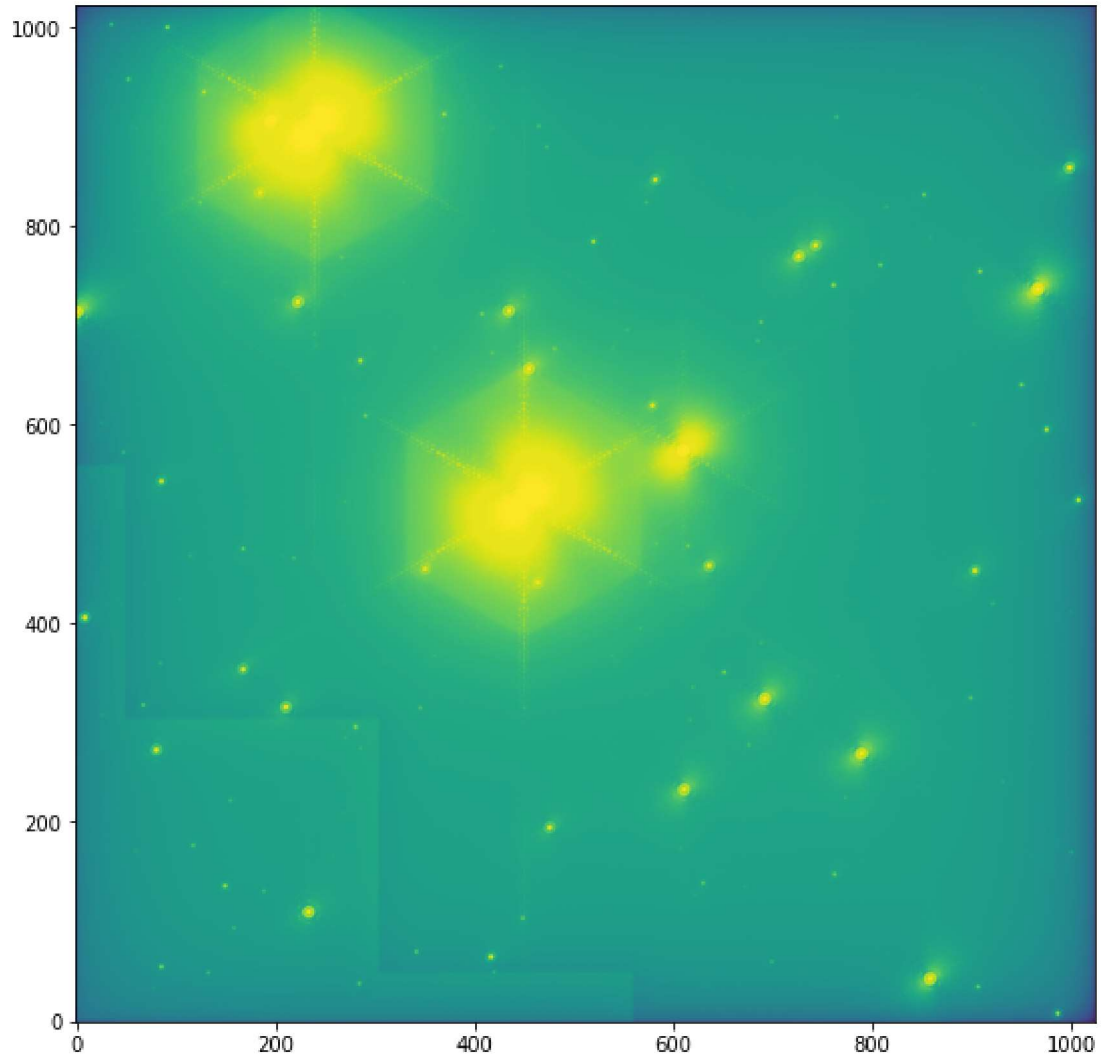
The elongation of the PSF along the radial axis is quite visible.

In [11]:

```
plt.figure(figsize=(20, 20))
plt.subplot(121)
im = hdus[0][1].data
plt.imshow(im, origin="lower", norm=LogNorm())
```

Out[11]:

```
<matplotlib.image.AxesImage at 0x2c21f68fbe0>
```



Alternatively we could re-centre the detector window, but expand the window size to 4096x4096 pixels (16x16 arcsecond) which is the equivalent of the central MICADO detector.

In [12]:

```
micado.cmds["!DET.x"] = 0
micado.cmds["!DET.y"] = 0
micado.cmds["!DET.width"] = 4096
micado.cmds["!DET.height"] = 4096

micado.observe(cluster)
hdus = micado.readout()
```

```
Preparing 2 FieldOfViews
```

It should be noted, the larger the detector size, the longer the simulation takes to run. Hence the two options.

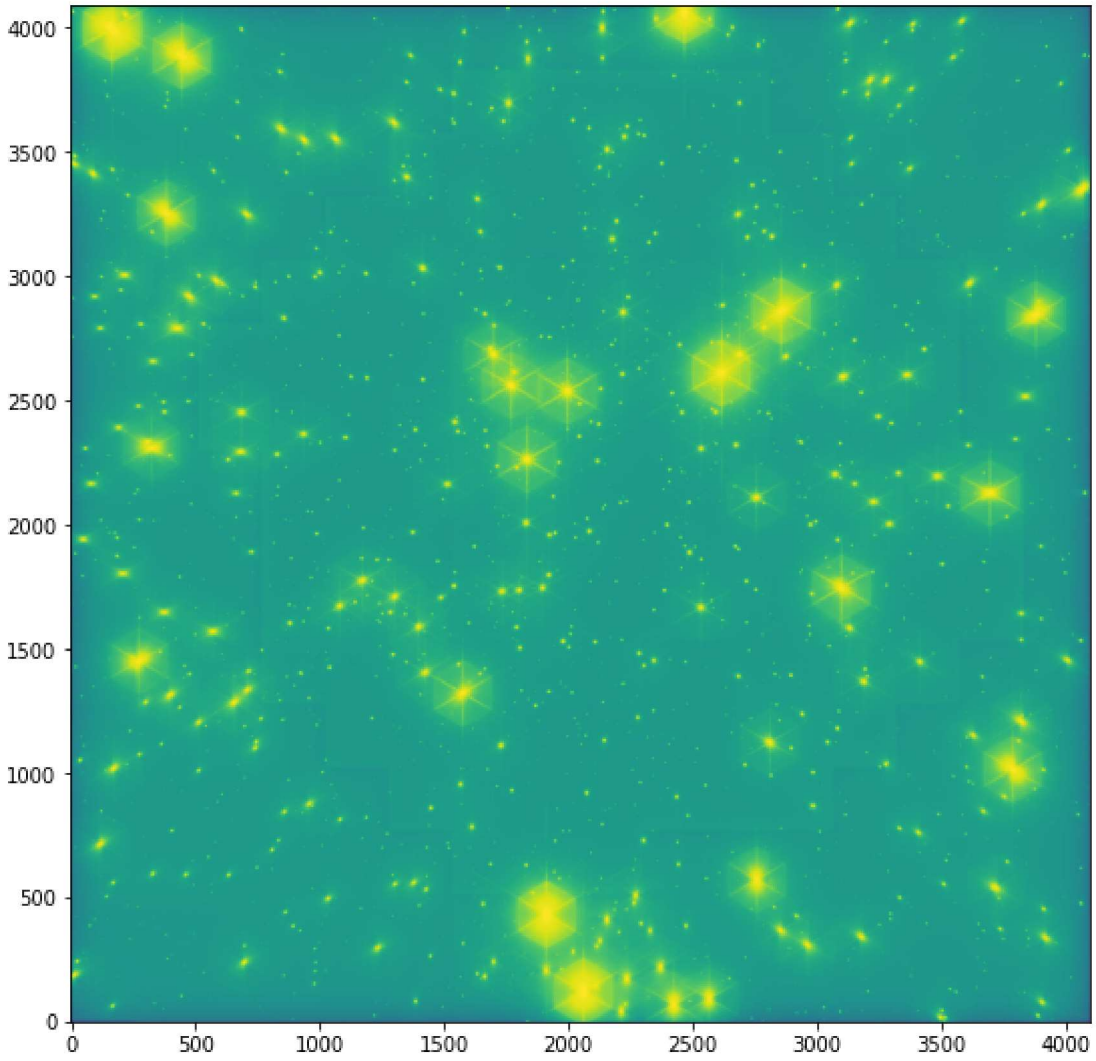
This option does however let us see the change in orientation of the PSF elongation around the on-axis position

In [13]:

```
plt.figure(figsize=(20, 20))
plt.subplot(121)
im = hdus[0][1].data
plt.imshow(im, origin="lower", norm=LogNorm())
```

Out[13]:

```
<matplotlib.image.AxesImage at 0x2c21fd10860>
```



Swap between a detector window and the full detector array

WARNING! It is ONLY recommended to run the full MICADO detector configuration is you have >8 GB of RAM

While the `MICADO_Sci` package only has a customisable detector window for simulated observations, the `MICADO` package contains a full description of the 9 detectors in the MICADO detector array.

This requires simulating a ~13000x13000 pixel field, which understandable takes a lot of computer resources and takes on the **order of 10 minutes to run.**

Ideally the user would write a script using the commands in this notebook and run that script in the background.

That said, swapping to the full detector array is a simple matter of setting the `.include` parameter to `True` and `False` for the two Detector options provided in the `MICADO` package (see `micado.effects` table above).

In [14]:

```
micado["full_detector_array"].include = True
micado["detector_window"].include = False
```

In this case, it is worth saving the final `HDUList` to disk as a multi-extension FITS file so the data are safe in case something happens to the Python session

In [15]:

```
# micado.observe(cluster)
# micado.readout(filename="micado_full_detector.fits")
```