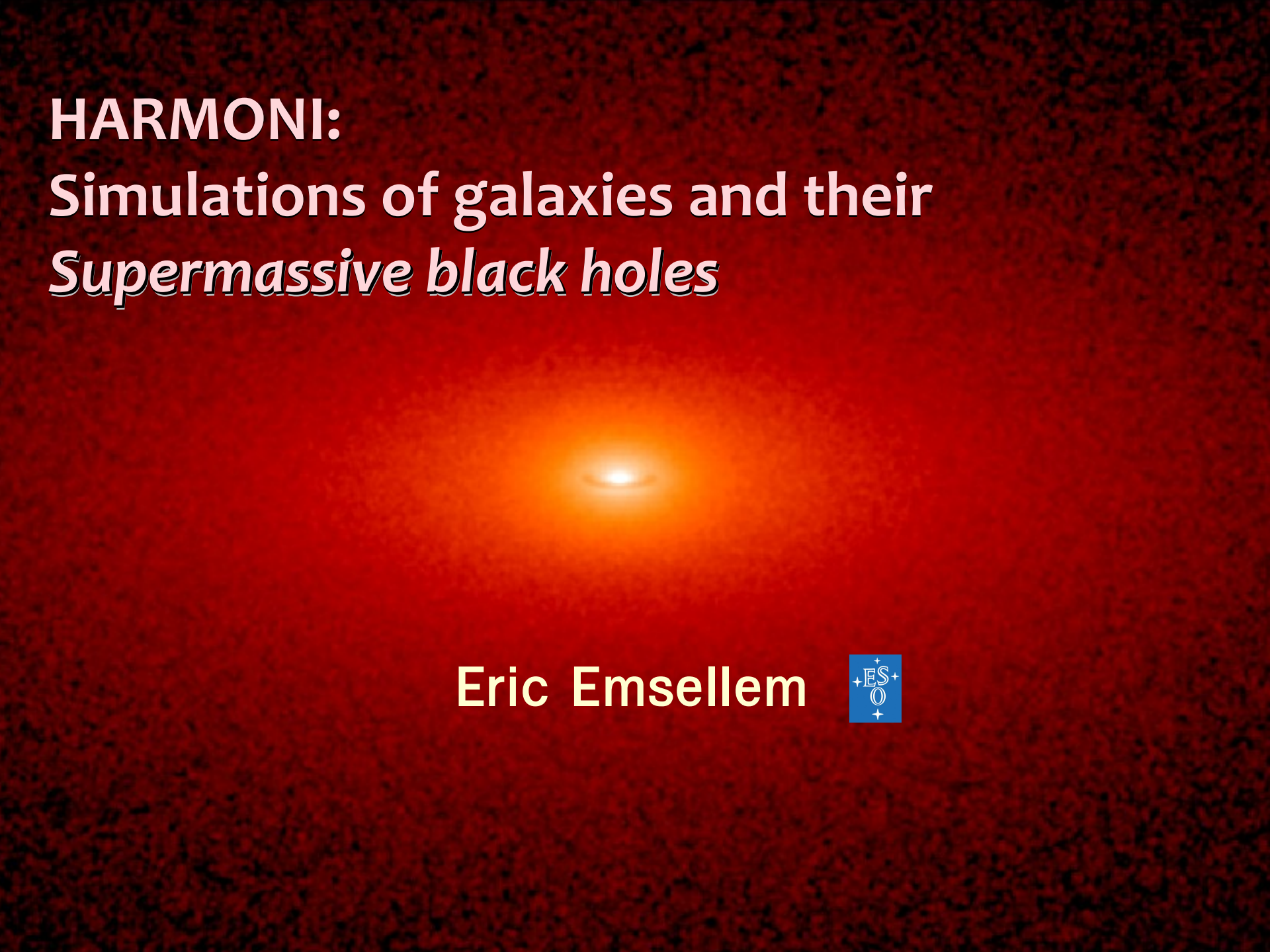
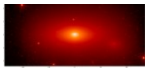
HARMONI:
Simulations of galaxies and their *Supermassive black holes*

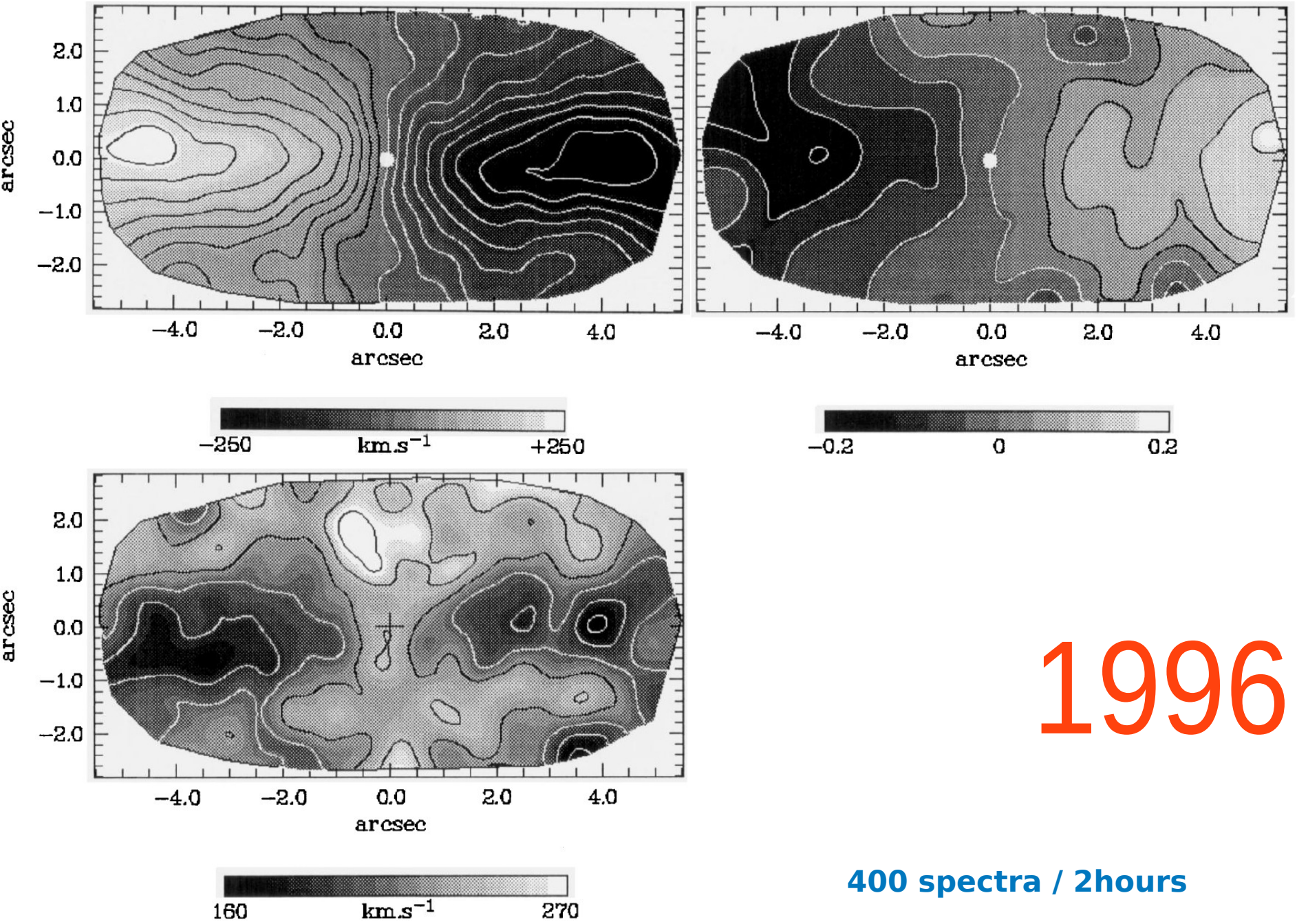


Eric Emsellem

Aside 1



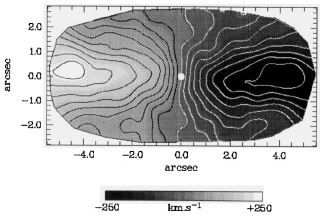
Emsellem, Bacon, Monnet, Poulain 1996

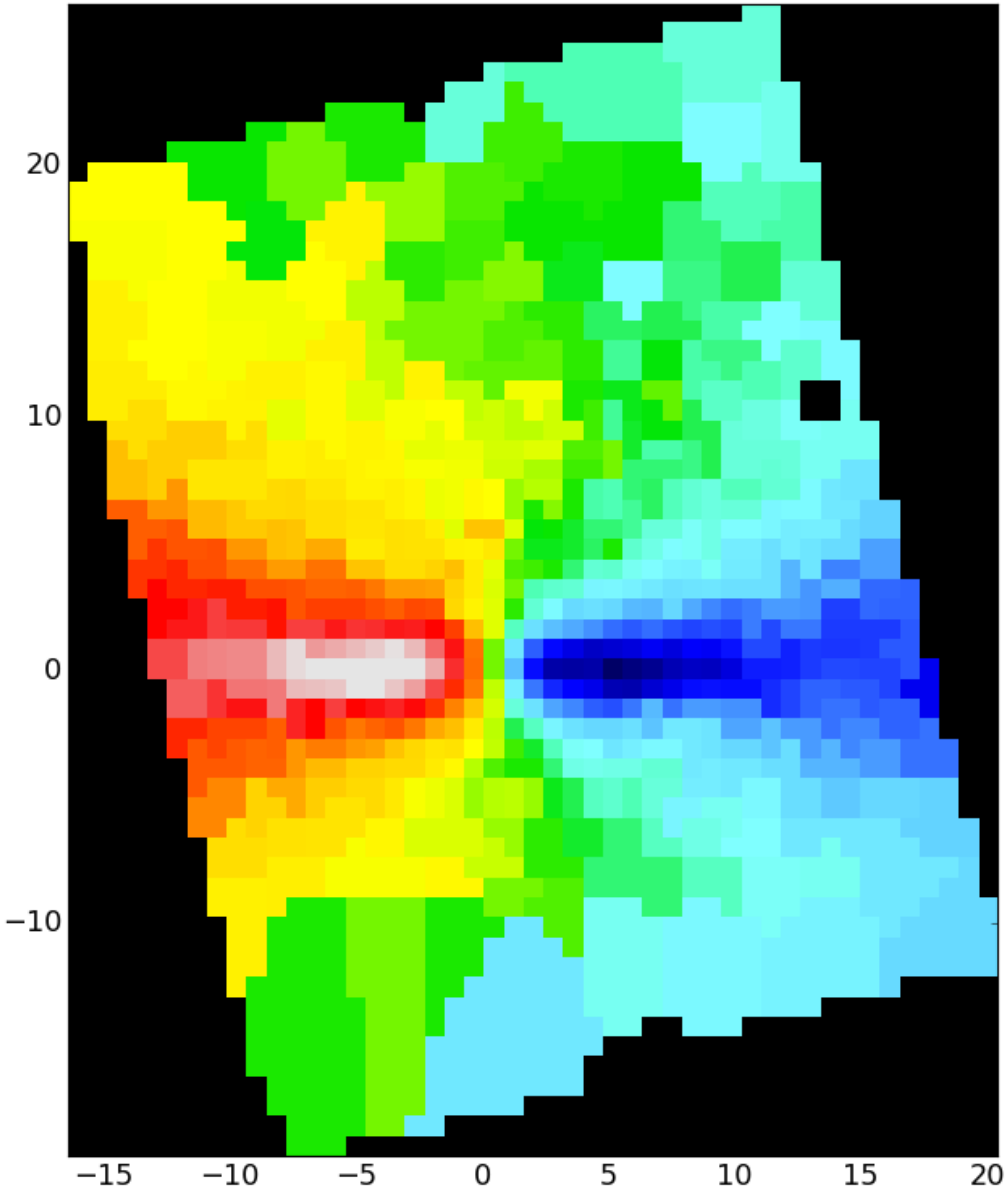


1996

400 spectra / 2hours

Emsellem et al. – never published





SAURON

2003

1500 spectra / 30'

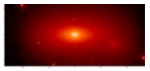
Emsellem et al. (in prep)

2015

muse
multi unit spectroscopic explorer

1.4 10^6 spectra < 4h total

Aside 2



HARMONI – what is it that we wish to achieve?

- **Testing the capacity of HARMONI to study BH**
  - Mass versus Stellar environment versus Distance
- **However…**
  - **Should we really care ?**
    - Measuring a few more BH ? Science of 2015 in 2024 ?
    - Even at low mass … after 2020 ?

    ⇒ Good benchmark to test such mode (stellar dynamics/models)

    ⇒ Dive in galactic nuclei
- **Goals for this meeting ?**
  - ✔ **Gather around a very exciting instrument / project**
  - ✔ **Are there specific issues we wish to address ?**
  - ✔ **Should we get ready / get new specific tools ?**
    - ✔ Simulator (thanks to Simon)
    - Real orbits around black holes outside the Milky Way ?

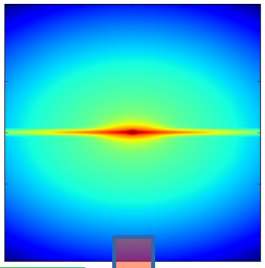
  Again

  ⇒ **what is it that we want to achieve today** / this week / next year

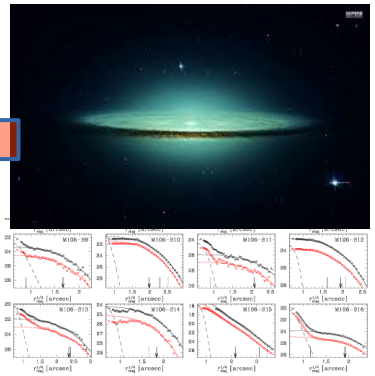
  & **how do we help making HARMONI the success** it should become ?

From models to 3D data

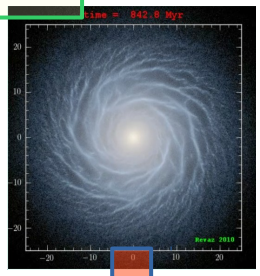
- In principle
  - easy enough
- In practice
  - very hard to do it right



Hydro / Nbody module

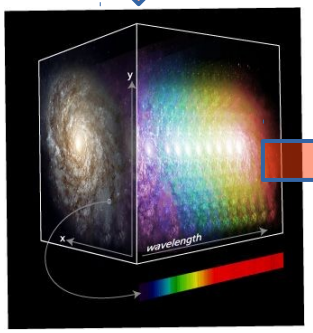


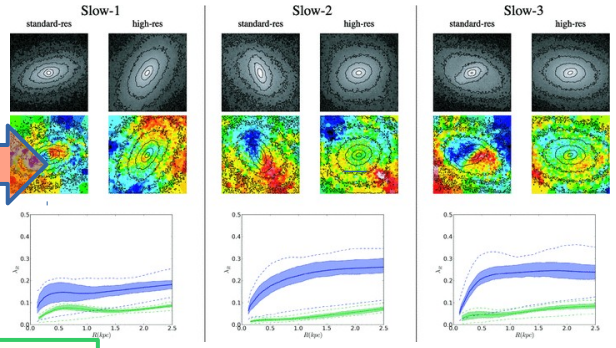
Initial Conditions module



Comparison

Mock Cube module

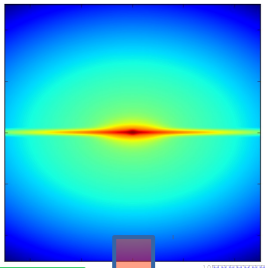




Analysis module

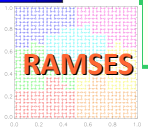
From models to 3D data

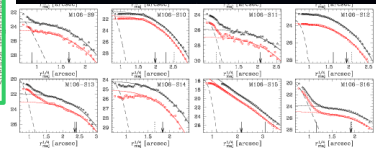
- In principle
  - easy enough
- In practice
  - very hard to do it right
- A few obstacles
  - Representative systems with
    - Proper resolution
    - Proper complexity
  - Stellar libraries

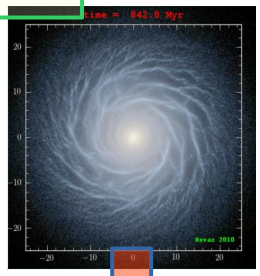


Initial Conditions module

Hydro / Nbody module



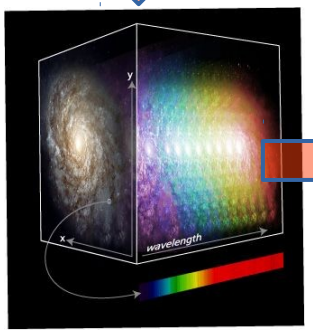


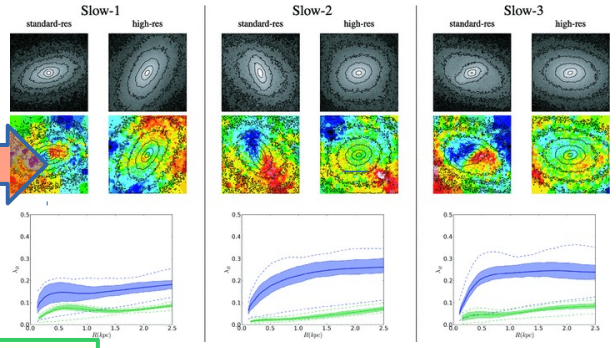


Comparison

Mock Cube module

SSPs+Gas





Instrument Simulator

Analysis module

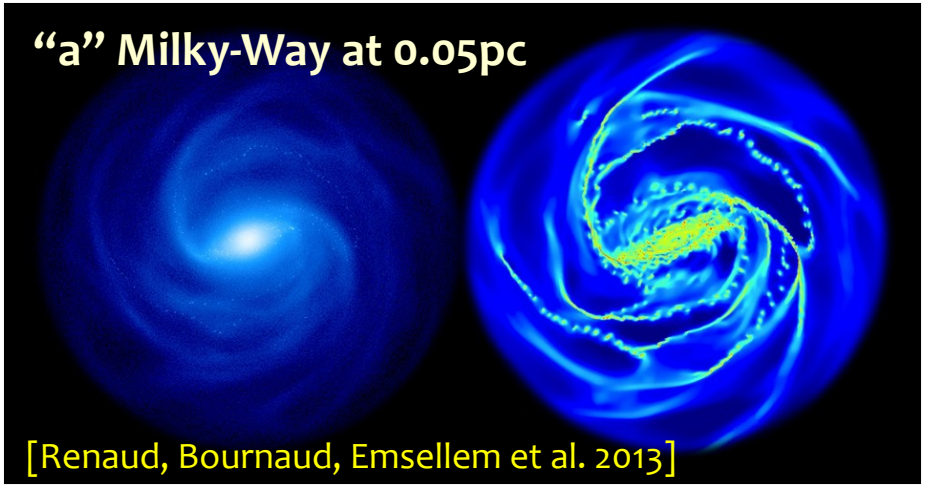
e.g. pPXF

Approach

- **Producing Harmoni-like data cubes**
  - « Realistic » galaxies with complex morphologies
  - Stellar population gradients
  - Mass distribution including (if relevant) a dark halo or central BH
  - Complex dynamics (including decoupled components)

- **How**
  - Input models (1D, 2D or 3D) or images
  - MGE and its python implementation → N-body realisations
  - Stellar libraries (SSPs)
  - Arbitrary input dynamics (via the anisotropy parameters)

- **Applied to e.g.,**
  - MUSE data cubes simulations
    - ✔ late-type and early-type galaxies
  - Individual cases
    - ✔ e.g., Milky-Way, NGC 1277
  - MaNGA simulations of spirals
    - ✔ stars + gas



[Renaud, Bournaud, Emsellem et al. 2013]

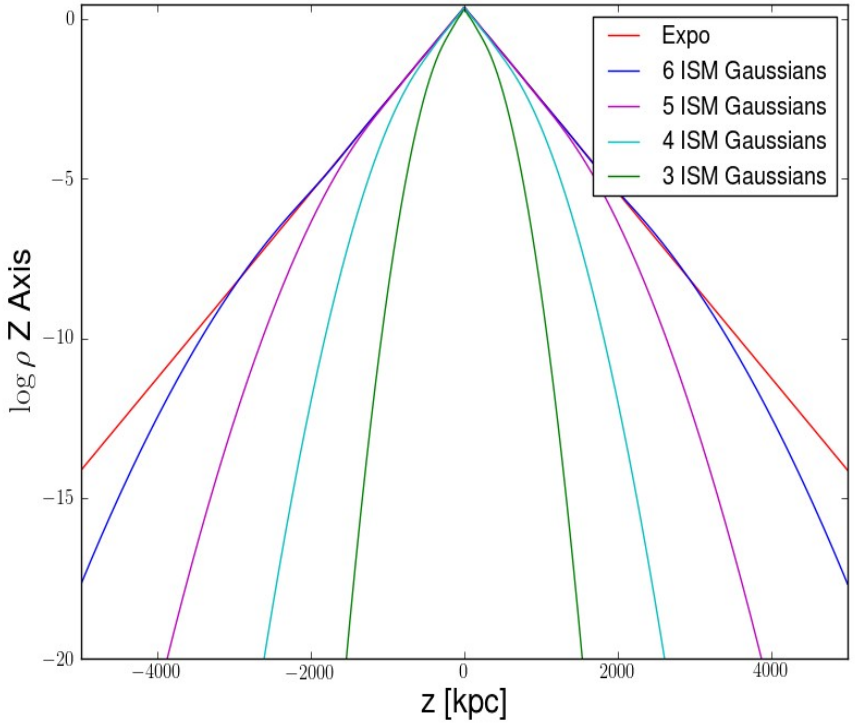
MGE ?

- **Stands for "Multi-Gaussian Expansion"**
  - 1D: see papers by Bendinelli in the 90's
  - 2D-3D: paper by Monnet et al., and Emsellem et al. (1992, 1994)
  - Implementations: C/python (Emsellem), idl/python (Cappellari)

⇒

- **Principle**
  - *Expand as a sum of **Gaussians***

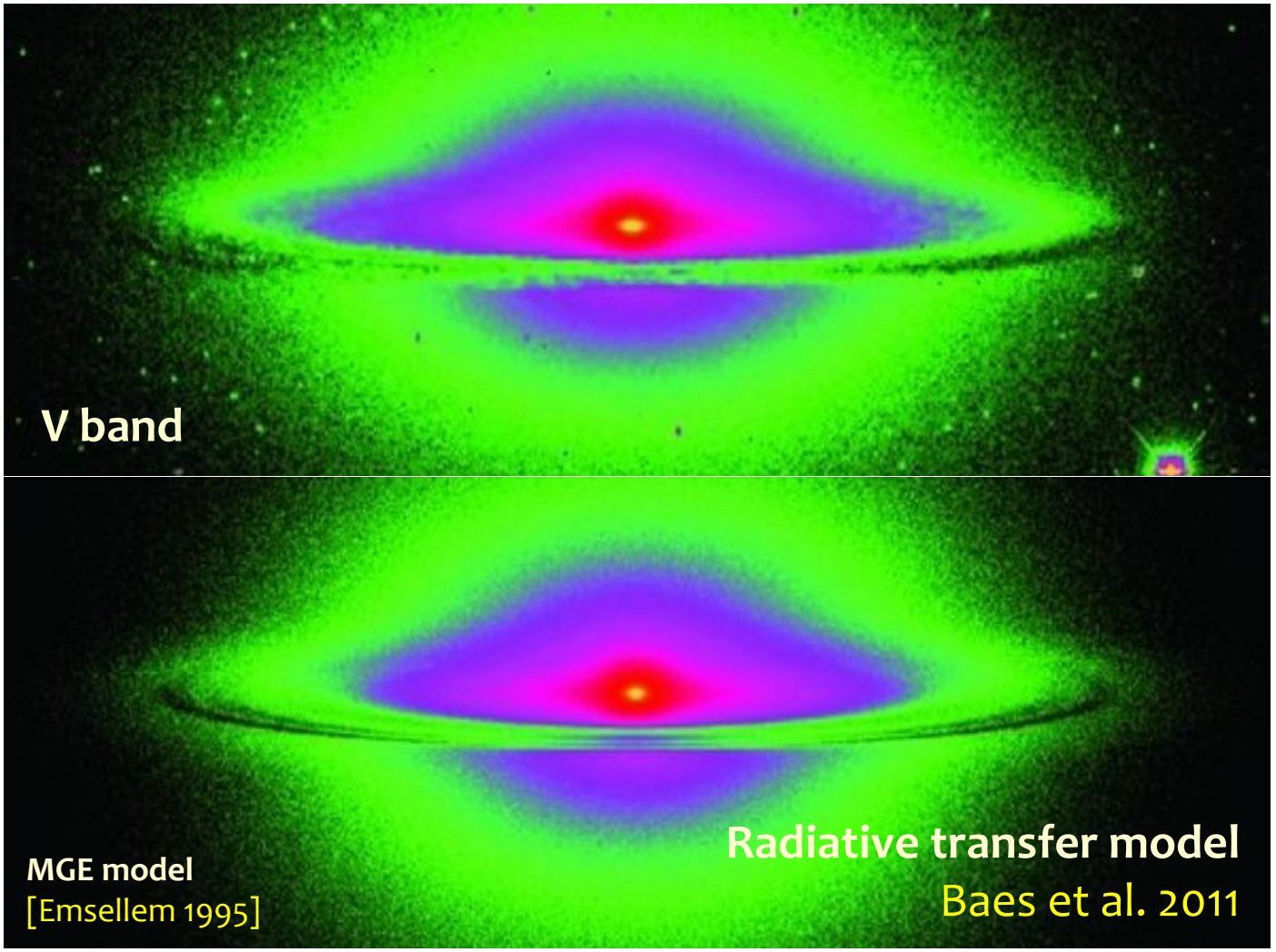
$$f_{\{1D/2D/3D\}}(X) = \Sigma\,\text{Gaussians} = \Sigma\, I \exp(-X^2 / 2\sigma^2)$$



Modelling the photometry

pyMGE (Emsellem et al. 1994, Emsellem 1995, Emsellem 2013, Emsellem & Renaud in prep.)

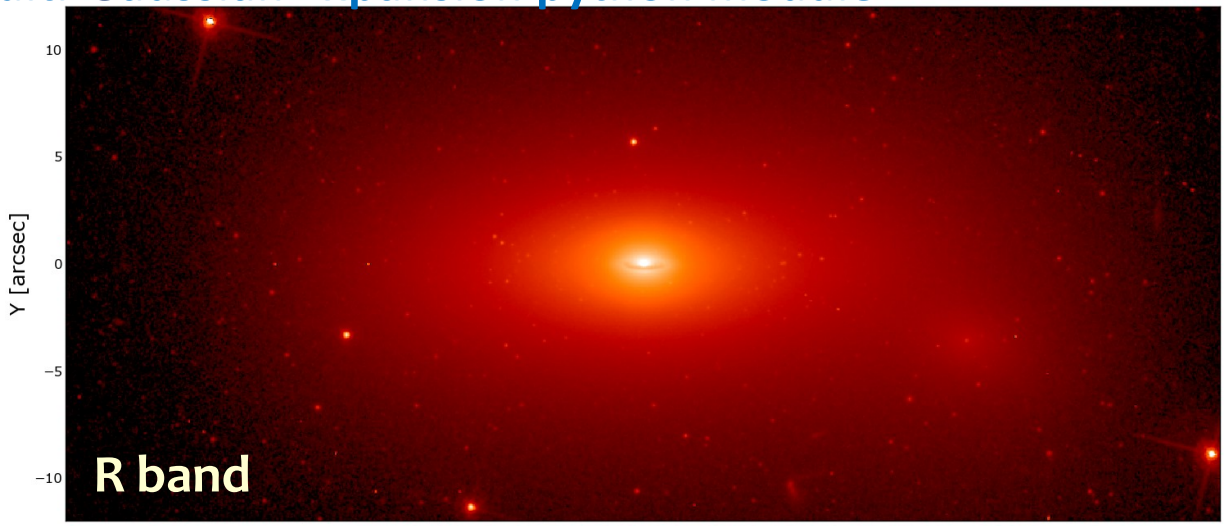
- Input images or arbitrary pre-defined functions (1D, 2D, 3D)
- Multi-Gaussian Expansion python module

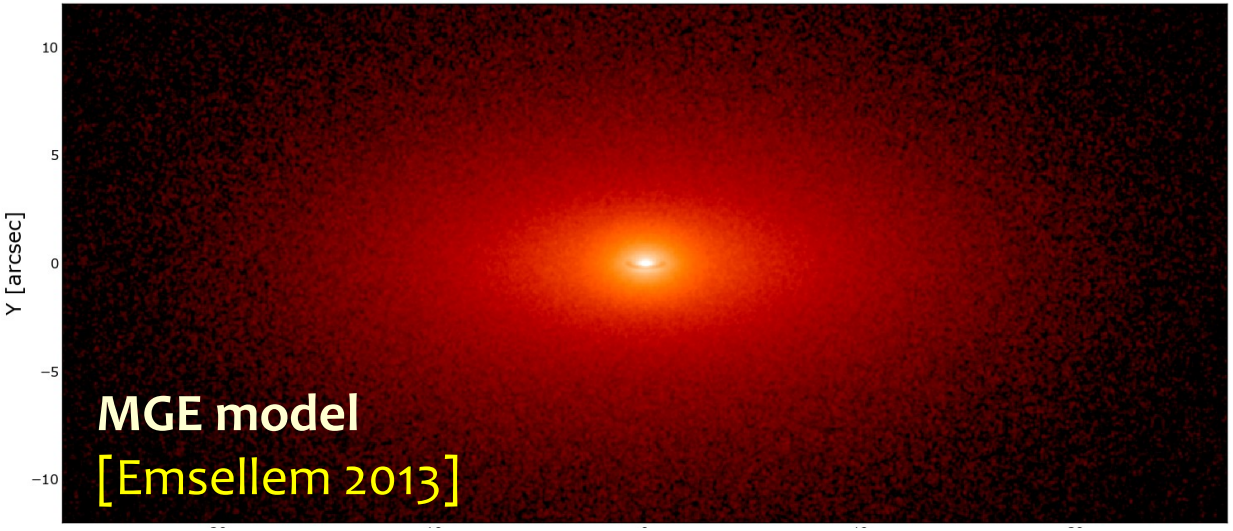


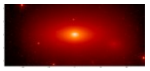
Modelling the photometry

pyMGE (Emsellem et al. 1994, Emsellem 1995, Emsellem 2013, Emsellem & Renaud in prep.)

- Input images or arbitrary pre-defined functions (1D, 2D, 3D)
- Multi-Gaussian Expansion python module

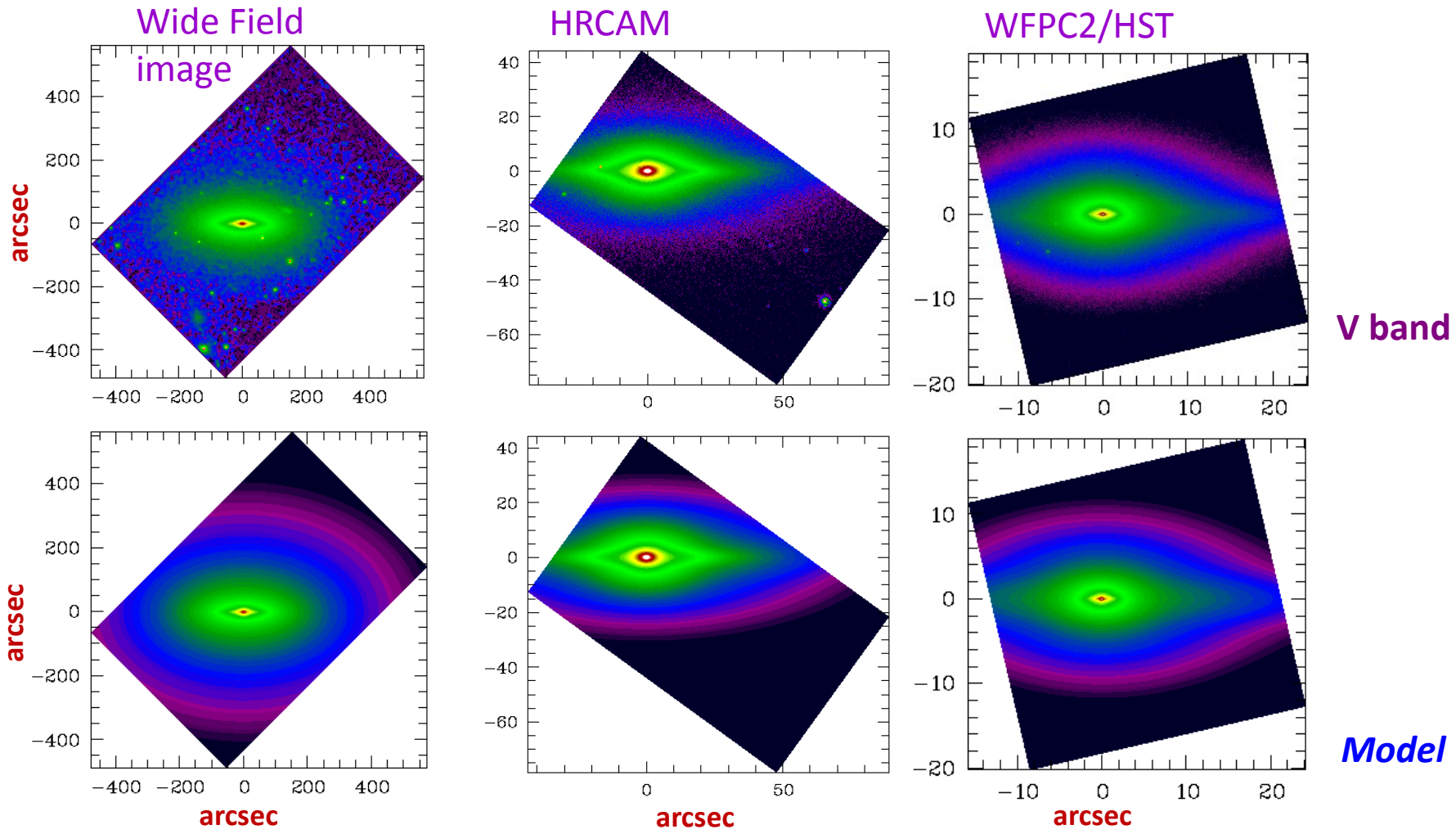






HARMONI Test case

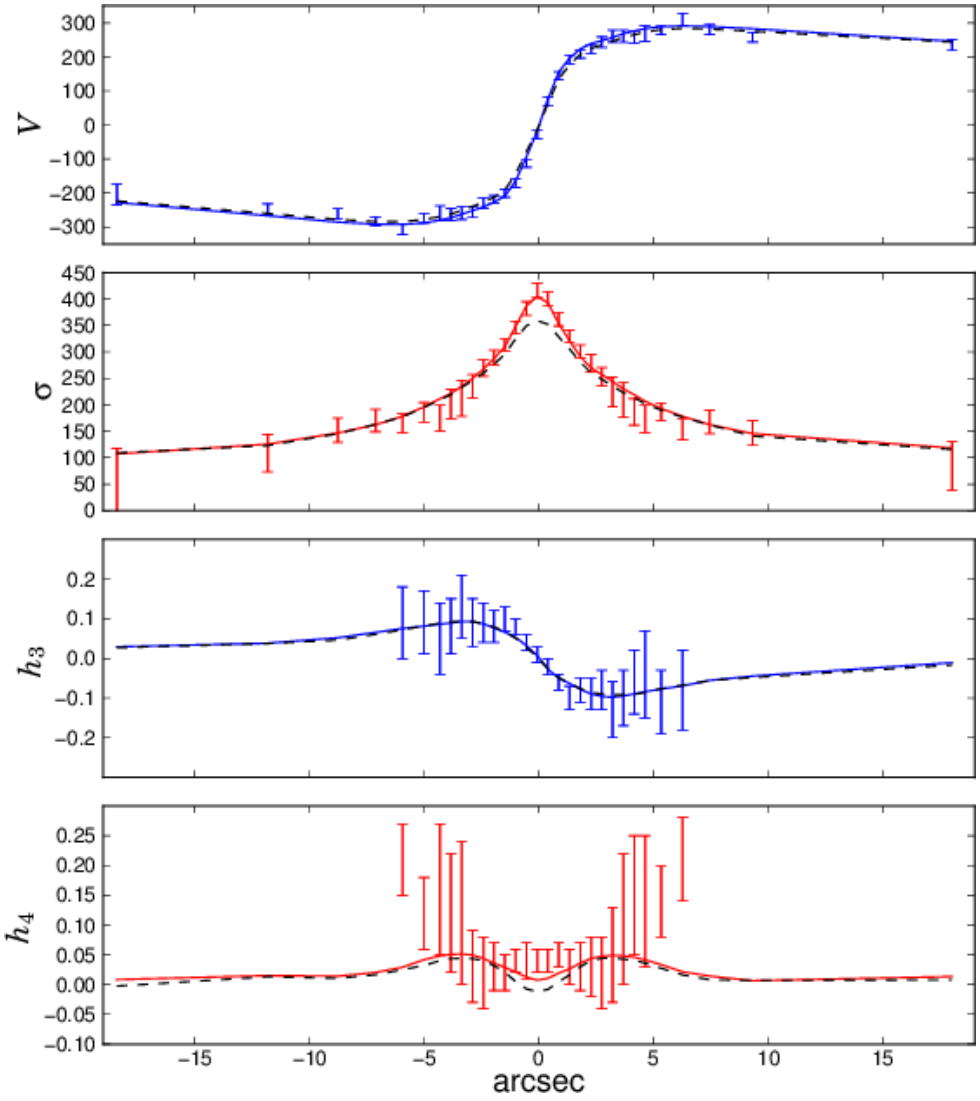
NGC 3115 at the Distance of Coma



Model from Emsellem, et al. 1999

Mock Cubes

- **Input Dynamics**
  - MGE model
  - SMBH of 5 10^8 $M_\odot$
  - Solving Jeans Eqs with generalised anisotropy
- **N-body realisations**
  - Particle-based model
  - Varying particle masses
  - Possible time evolution (bars)



Example for NGC 1277 of higher order moments

Tutorial (1/3)

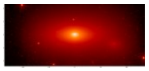
In [3]:
```
import pymge
from pymge import mge

n3115 = mge.MGE("NGC3115_model_BH5e8_Ipython.mge")
```

In [4]:
```
## Maximum radius in Parsec
maxR = 50000.
n3115.realise_Nbody(mcut=maxR, TruncationMethod="Ellipsoid", GasDisk=False)
```

In [5]:
```
## Convert into a Gadget file so we don't have to recompute things several times for this particular setup
from pymge import convert_snapshot
convert_snapshot.mge_to_gadget(n3115, filename="NGC3115_Gadget_Ipython.dat")
```

In [37]:
```
## Import the histogram functionalities
from pymge.pyhist import comp_losvd
## Number of points in the Velocity direction
nv = 101
maxV = 1000.0 ## in km/s, maximum velocity for the LOSVDs
## Number of point in the X and Y direction (the total number will be nXY * nXY)
## You can also specify a tupple for different numbers in X and Y
nXY = 101
## Compute the LOSVDs
los =  comp_losvd(n3115.x, n3115.z, n3115.Vz, weights=n3115.BodMass, \
                  limXY=[-maxR, maxR, -maxR,maxR], nXY=nXY, limV=[-maxV,maxV], nV=nv)
```

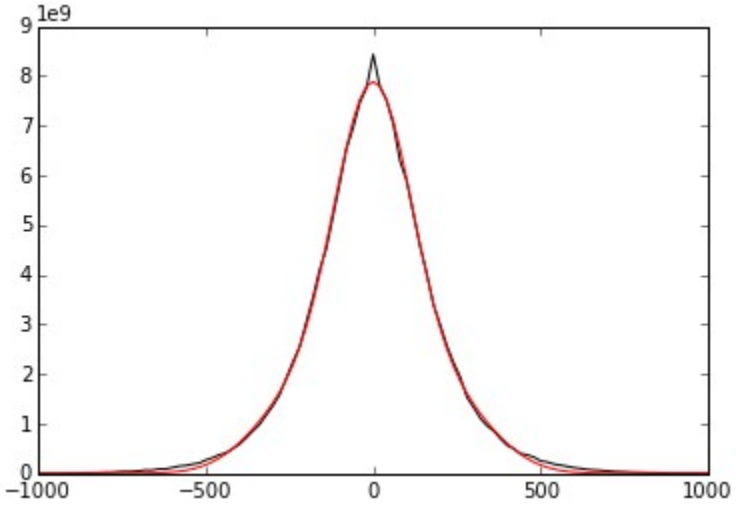
In [38]:
```
## PLotting some LOSVD. Here the sum of all computed LOSVDs
%matplotlib inline
rlos = np.linspace(-maxV, maxV, nv)
sumLOSVD = los.sum(axis=(0,1))
clf()
plot(rlos, sumLOSVD)
xlabel("V")
ylabel("LOSVD")
```



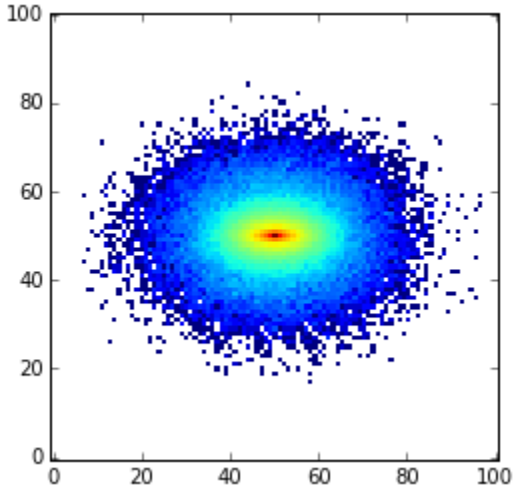
Tutorial (2/3)

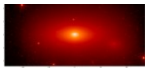
In [39]:
```
from pymge.fitting import fitGaussHermite
bestR, result, GHbest = fitGaussHermite.fitGH_mpfit(rlos, sumLOSVD, degGH=4)
```

In [40]:
```
print bestR
plot(rlos, sumLOSVD, 'k-')
plot(rlos, GHbest, 'r-')
```



In [44]:
```
imshow(np.log10(los.sum(axis=2)))
```





Mock Cubes

Input Dynamics

- MGE model
- SMBH of 5 10^8 $M_\odot$
- Solving Jeans Eqs with generalised anisotropy

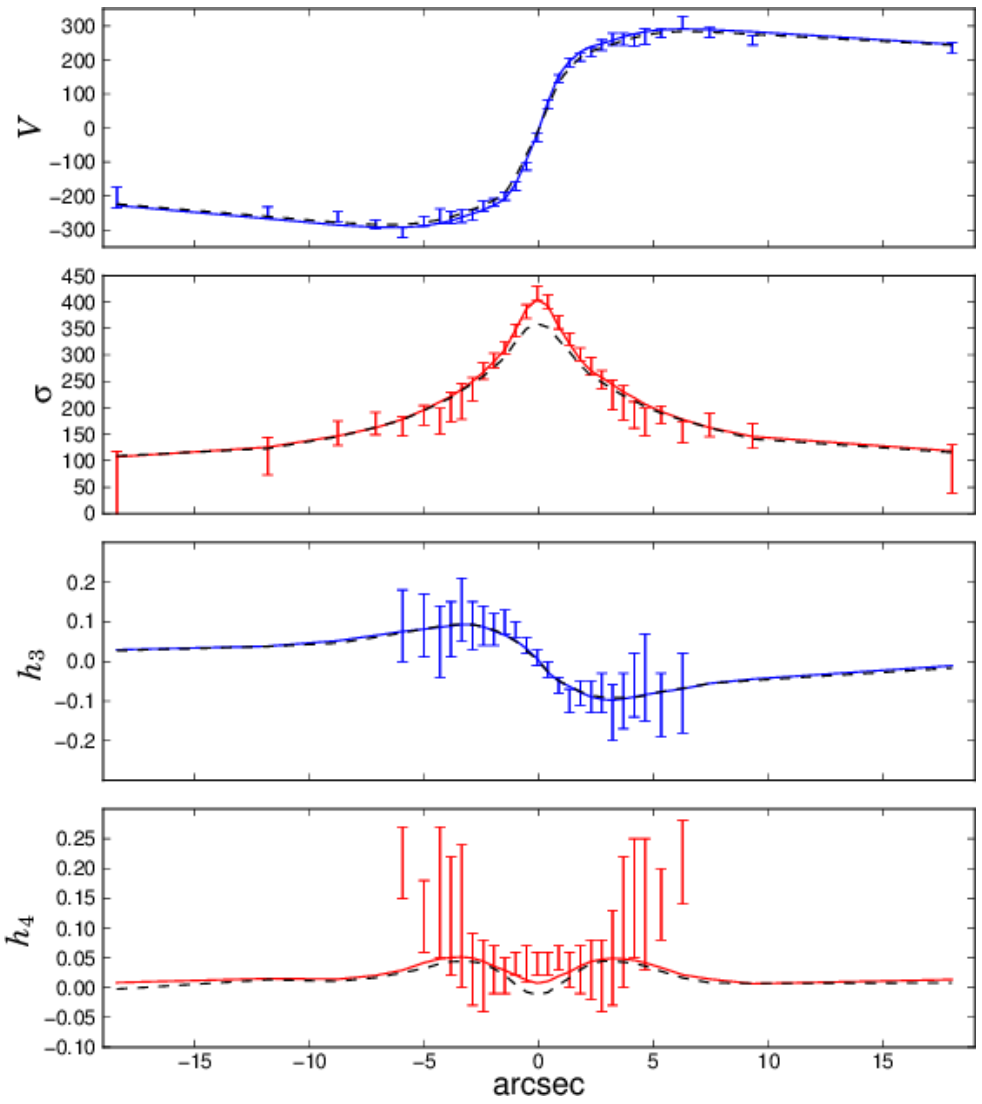
N-body realisations

- Particle-based model
- Varying particle masses
- Possible time evolution (bars)

Spectral information

- Using SSPs (MIUSCAT)
- Input population parameters
- Full spectral output on a grid

  ⇒ HARMONI Simulator



Example for NGC 1277 of higher order moments

Tutorial (3/3)

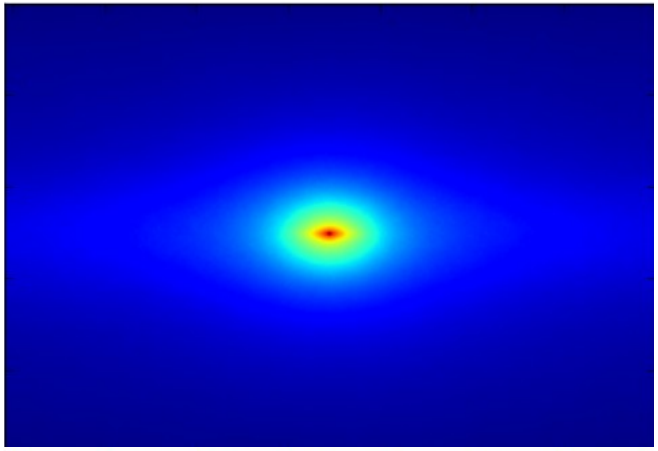
- **Spectral information**
  - ★ Using SSPs (MIUSCAT)
  - ★ Input population parameters
  - ★ Full spectral output on a grid

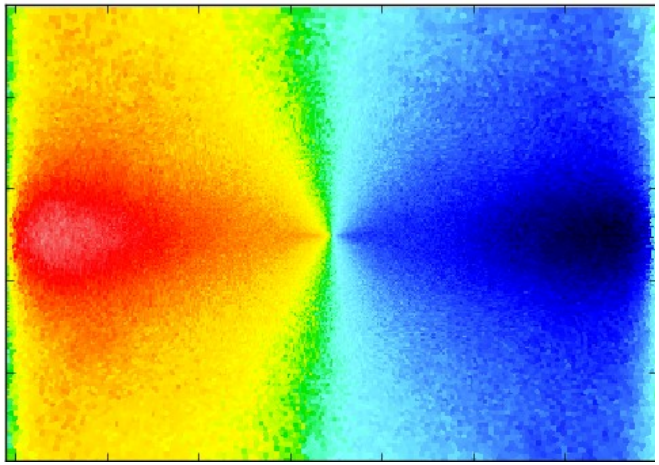
```
## Importing the build_Mock routine
from build_Mock import SSP_Spec
print "Initialise the Spectral library"
Modspec = SSP_Spec("MIUSCAT")
```

```
print "Starting the Creation of the Cube"
Modspec.create_cube_SSP_vel(x,y,V,Age,MH, weights,limits, nXY=nXY, limV=limV, Pot=None, removezeros=1, use_maxrange=0, UnitsXY="ARCSEC")
dirCubes = "Cubes_HARMONI/"
print "Saving the Cube into a 2D TAB + IMA"
Modspec.save_SSP_2DCube(nameout="Model001_HARMONI", dirout=dirCubes)
print "Saving the Cube into a 3D Cube"
Modspec.save_SSP_3DCube(nameout="Model001_HARMONI", dirout=dirCubes)
```

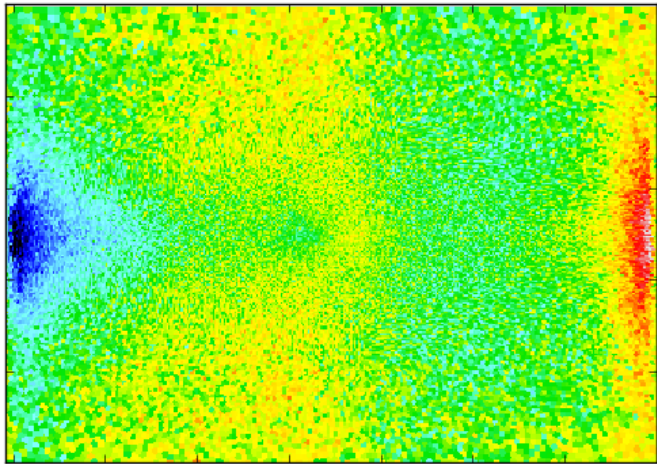
⇒ **HARMONI Simulator**
[Simon Zieleniewski]

HARMONI Maps

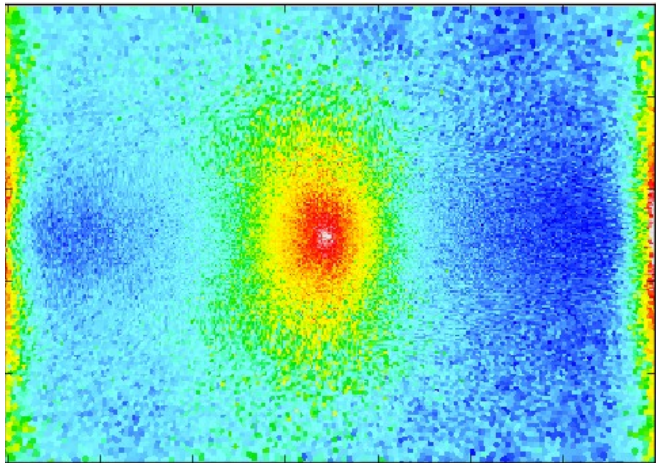




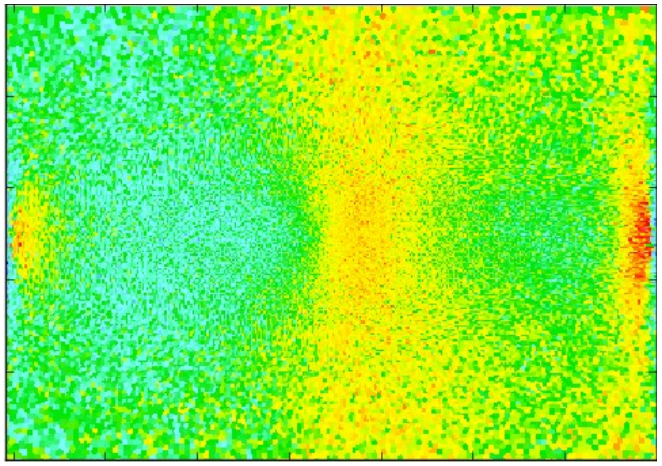
V



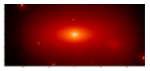
h_3



σ



h_4



- **Next steps**
  - ➔ Convolve / Compare
  - ➔ Check systematics / pixel fitting
  - ➔ Do dynamical modelling and compare output params
  - ➔ + … More models

- **MGE modelling via**

  - *Flexible tool to model galaxies*
  - *General mass distribution and spectral information*

- **For HARMONI…**
  - MUSE datacube done in ~4h (requires some RAM)
  - Input to be tuned : MGE, Metallicity/age, evolution

- **Tests**
  - ***Use different libraries and set up***

- **Need for**
  - ***Relevant Input parameters***
  - ***A good SSP library for* HARMONI…**