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DataCubes in Astrophysics

Lesson 2

Model datacubes from radiative transfer

ACTIVE GALACTIC NUCLEI

An historical overview

- It all started with the discovery of a new kind of objects with very intense emission lines;
- identification of these objects as galaxies;
- identification of the center of these objects as the “emitter”;
- realization that the emitting region must be “small” (images of the center of these galaxies were point-like/unresolved);
- mass-radius constraints led to the hypothesis of very high energy densities!

ACTIVE GALACTIC NUCLEI

The breakthrough

- The 3C and 3CR catalogues included powerful radio-sources (survey limit of 9 Jy);
- many were nearby radio galaxies;
- other where unknown, unidentified sources;
- using a lunar eclipse, in 1963 M. Schmidt pinpointed the position of a powerful radio source;
- it turned out to have broad intense emission lines;
- the estimated redshift was z=0.158;
- the derived luminosity was ~100 higher than a “normal” galaxy.

ACTIVE GALACTIC NUCLEI

Radio Galaxies

Fanaroff Riley classes

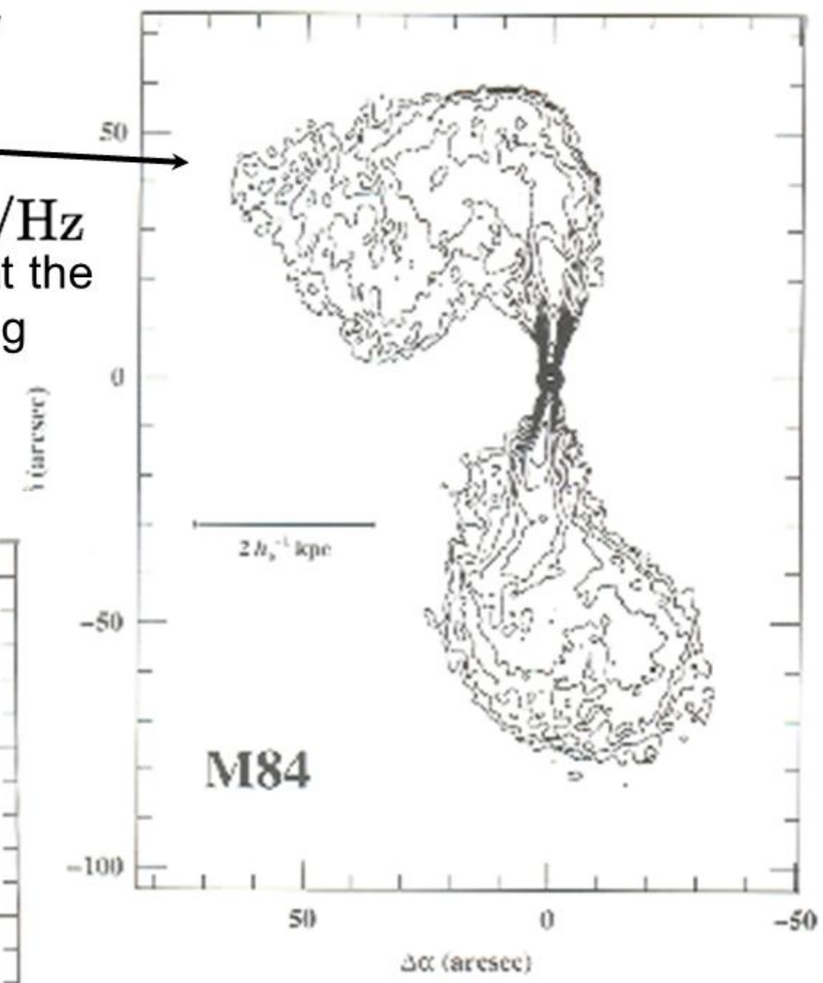
Fanaroff Riley 1974

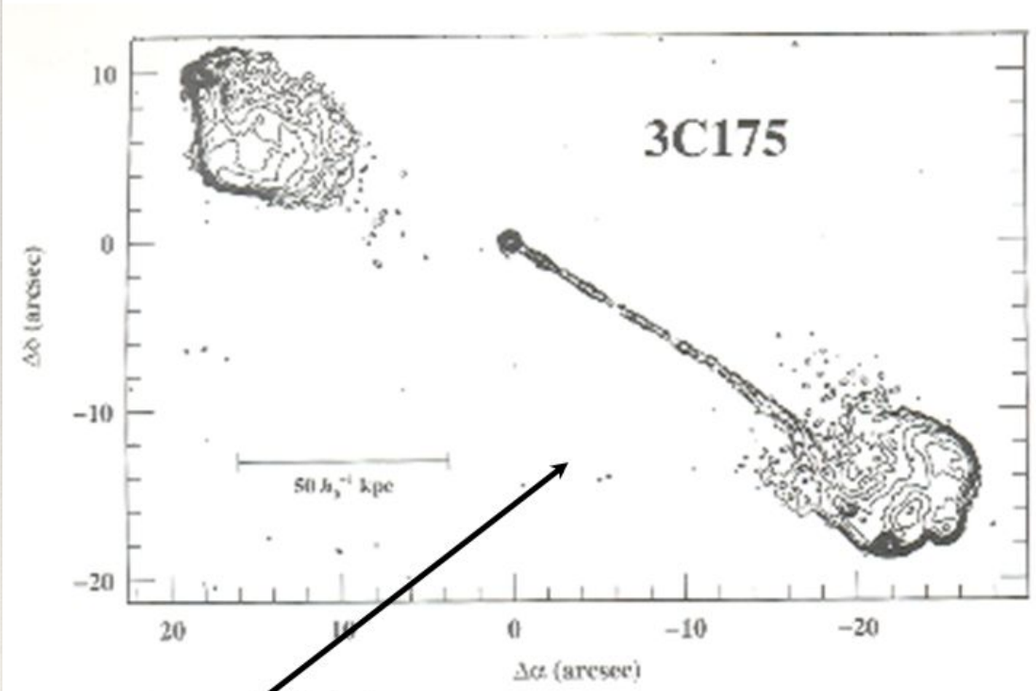
FR I

low power

$L_\nu(1.4\mathrm{GHz}) \lesssim 10^{32}$ erg/s/Hz

extended component brighter at the center, and gradually decreasing towards borders





FR II

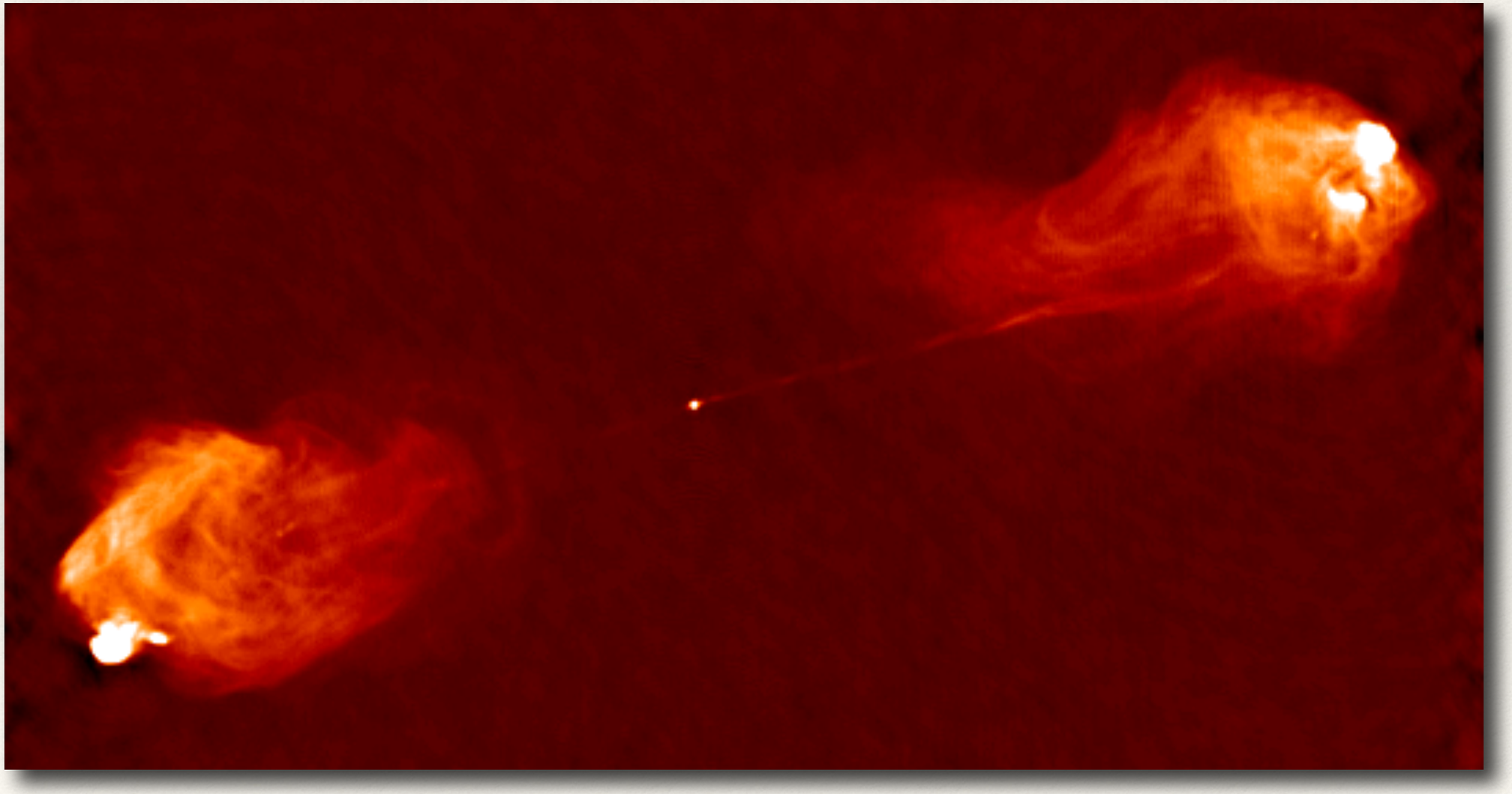
high power

extended component brighter at border

quasars are FR II sources

CYGNUS -A

@ 4.8 GHz



ACTIVE GALACTIC NUCLEI

We find different kind of objects under the AGN classification:

- Seyfert Galaxies;
- Radio Galaxies;
- QSO: Quasi-Stellar Objects;
- Quasar;
- OVV: Optically Violently Variables;
- BL Lac.

- Blazars

ACTIVE GALACTIC NUCLEI

OBSERVATIONAL FACTS:

- Very high luminosity (up to 10^4 times than a "normal" galaxy);
- this production happens in a volume less than 1 pc^3;
- the energy emission covers a wide range of frequencies;
- mechanical energy is released as well;
- extremely intense emission lines, in some cases very broad;
- great variety in the radio emission;
- can be very strongly variable.

ACTIVE GALACTIC NUCLEI

OBSERVATIONAL FACTS:

- The range of observed physical phenomena is quite broad;
- not all of the AGN display ALL of these characteristics;
- this indicates a high degree of complexity in the mechanism(s) of energy production.

Classification might be extremely difficult!

ACTIVE GALACTIC NUCLEI

They all have in common:

- Strong non-thermal emission;
- coming from the galactic nucleus;
- produced in a very small scale region;
- highly ionising;
- often variable in short time-scales.

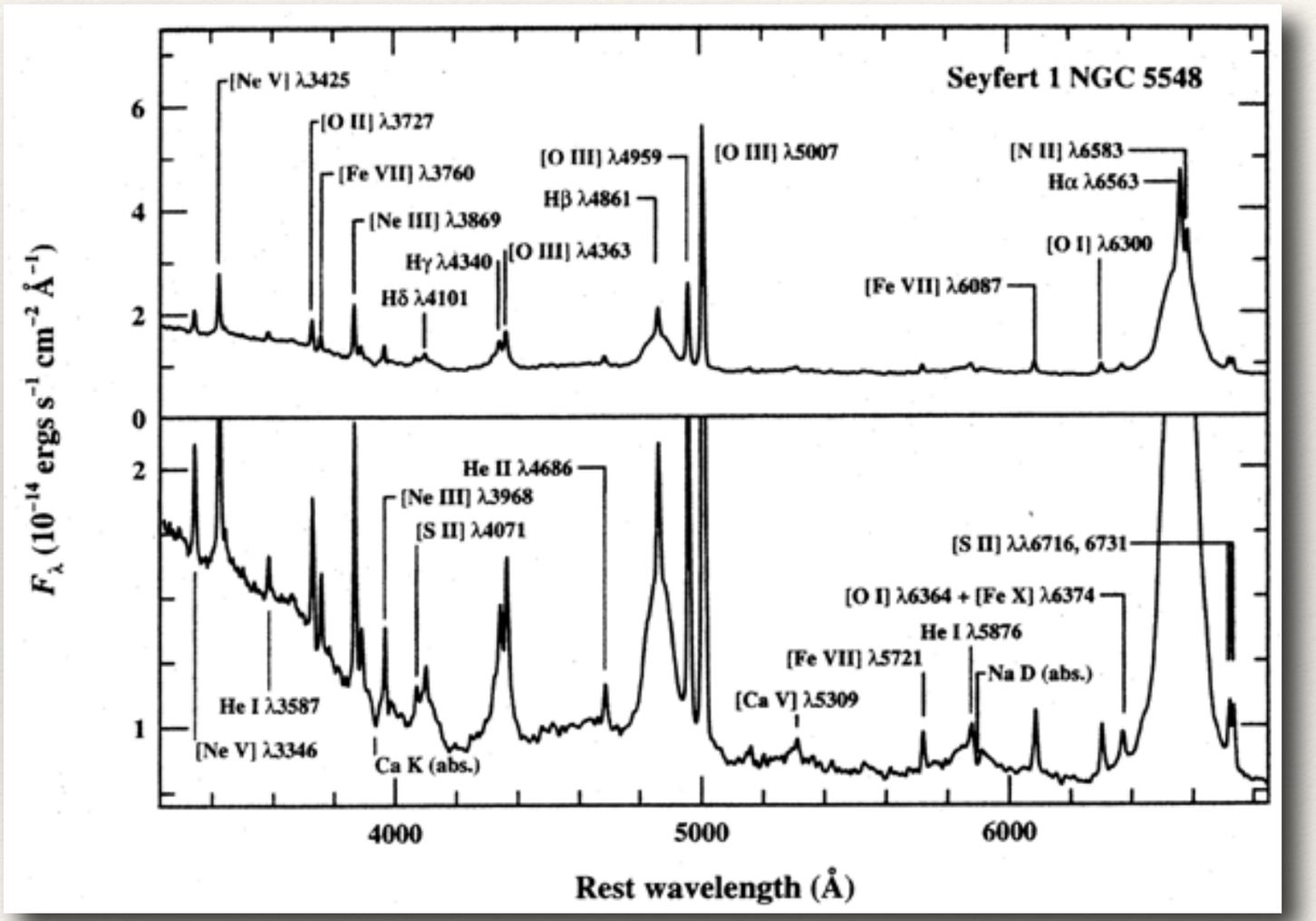
AGN: Observed features

- Bolometric luminosity between 10^{42} and 10^{48} erg s^{-1};
- this is from 0.01 to 10^4 more than a **typical** galaxy;
- typical luminosity variation are of about 10% within few years (and the period is wavelength-dependent);
- relatively "flat" (in υF_υ units) SED, ad odds with "normal" (star —powered) galaxies).

Seyfert Galaxies

- Low-luminosity AGNs;
- first to be studied in depth;
- first found in very nearby galaxies;
- identified in spiral galaxies with bright cores;
- characterized by very intense lines from highly ionized gas.

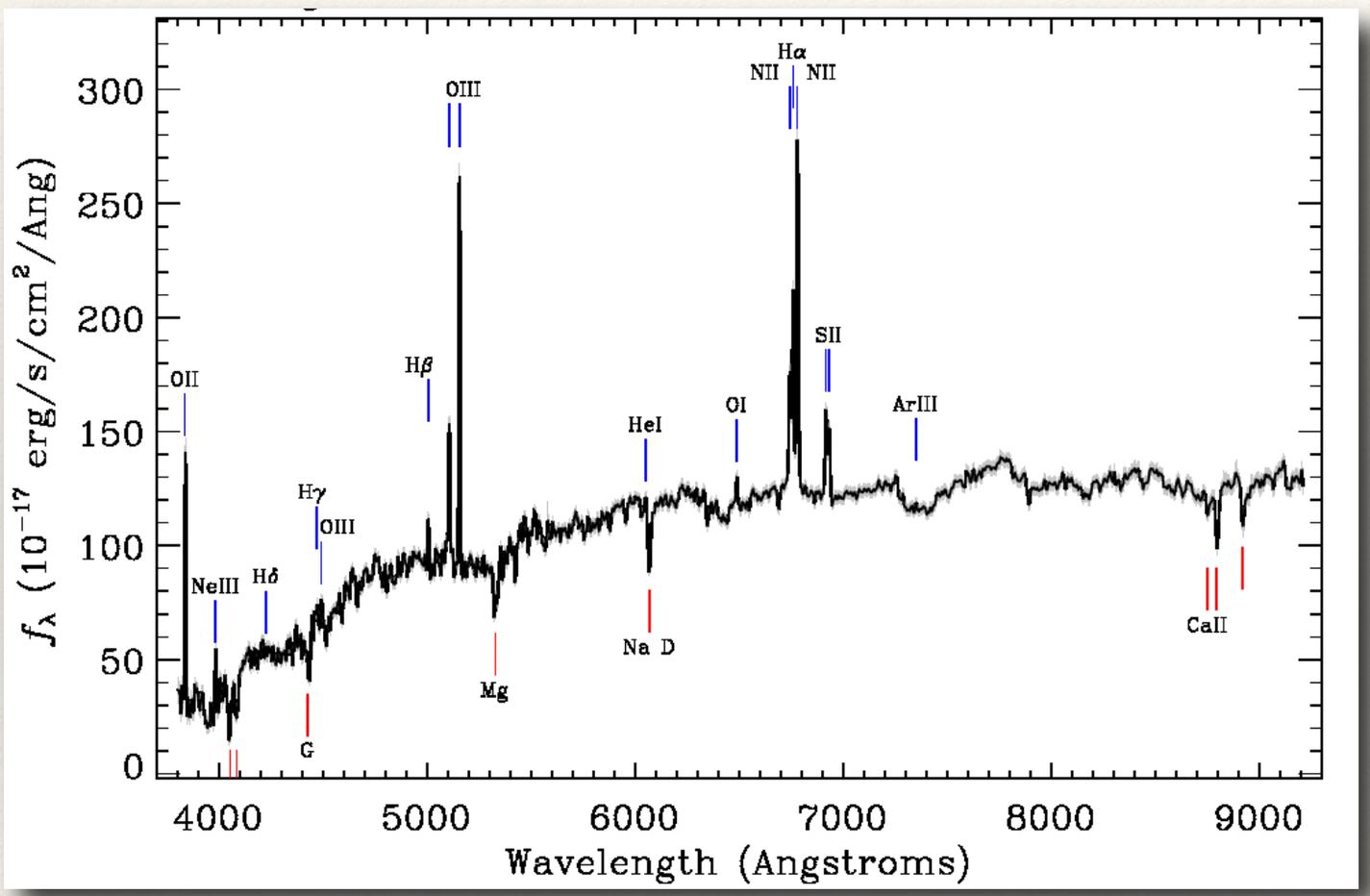
Seyfert Type 1



- broad emission lines;
- narrow emission lines as well;
- lines from highly ionized elements;
- extremely blue continuum;

They are the low-luminosity counterparts of the QSOs

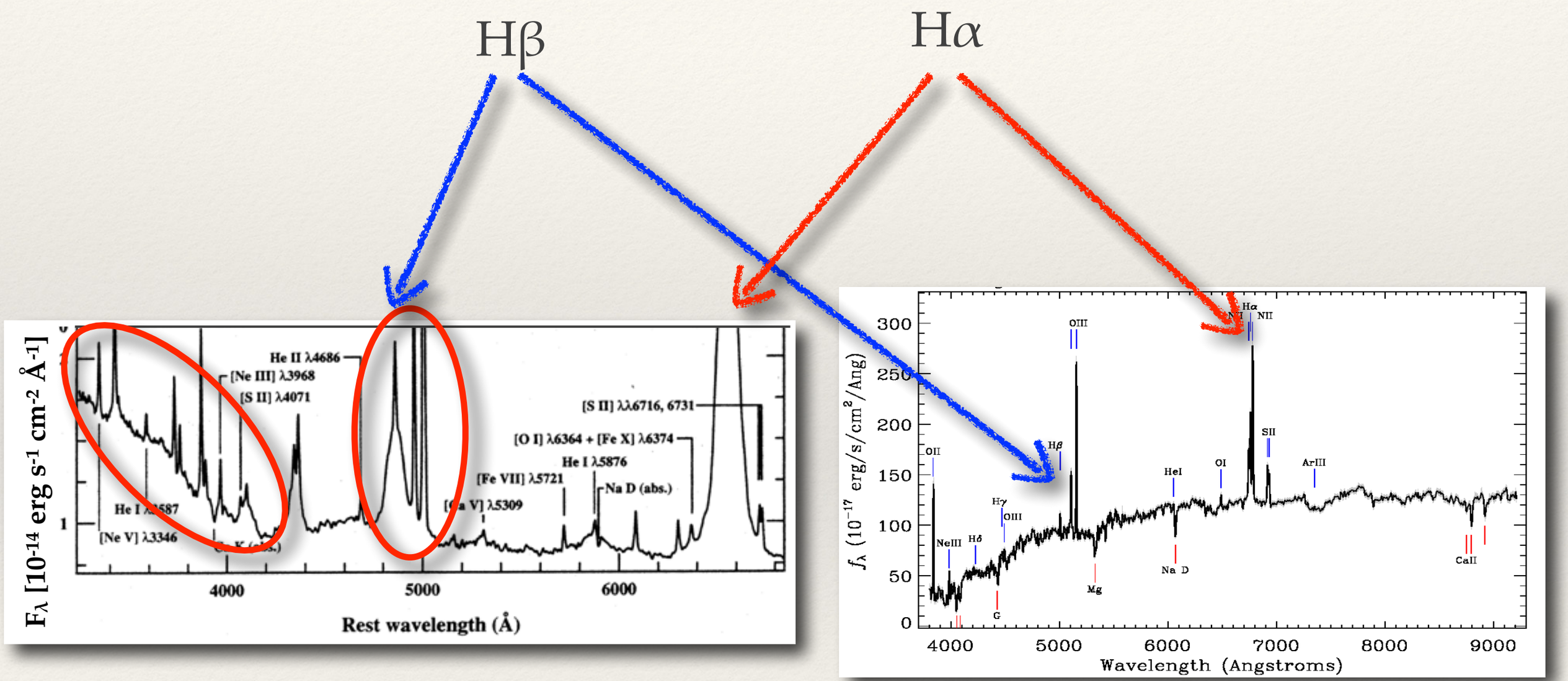
Seyfert Type 2



- no broad lines;
- lines from highly ionized elements;
- fairly "normal" continuum (i.e. stellar dominated);

It took a while for type-2 QSO to be discovered

Type 1 vs Type 2



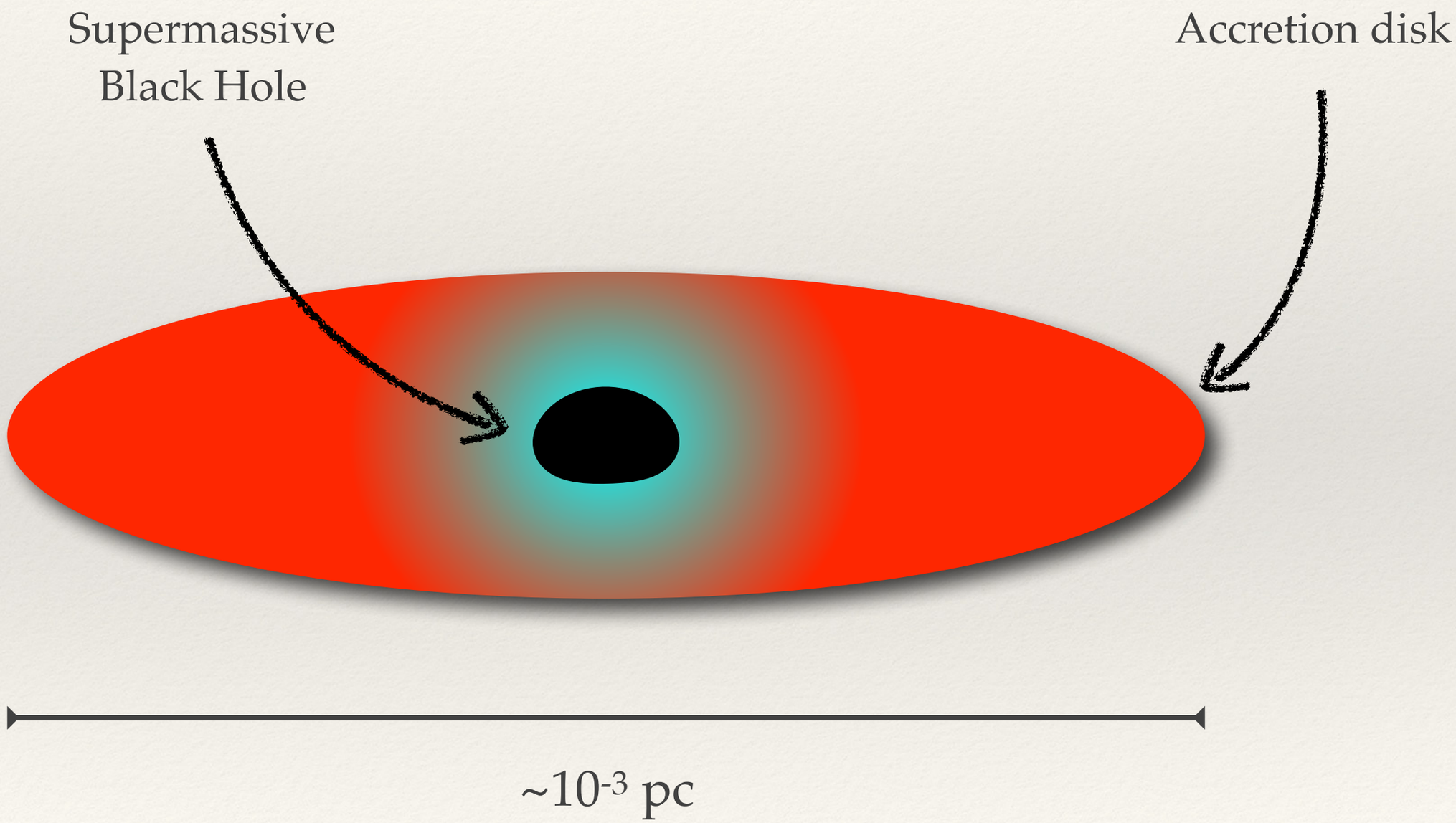
Plus: [OI], [OII], [OIII], [NII], [SII], [NeIV], …

The AGN "Unified Model"

- Both similarities and differences were spotted in this class of objects;
- focussing on the characteristics of optical spectra, and on the MIR emission, a unification scheme was proposed:

These objects represent the same kind of physical phenomena, with optically thick medium obscuring the powerful central source: <u>different class are simply explained as different viewing angles</u>.

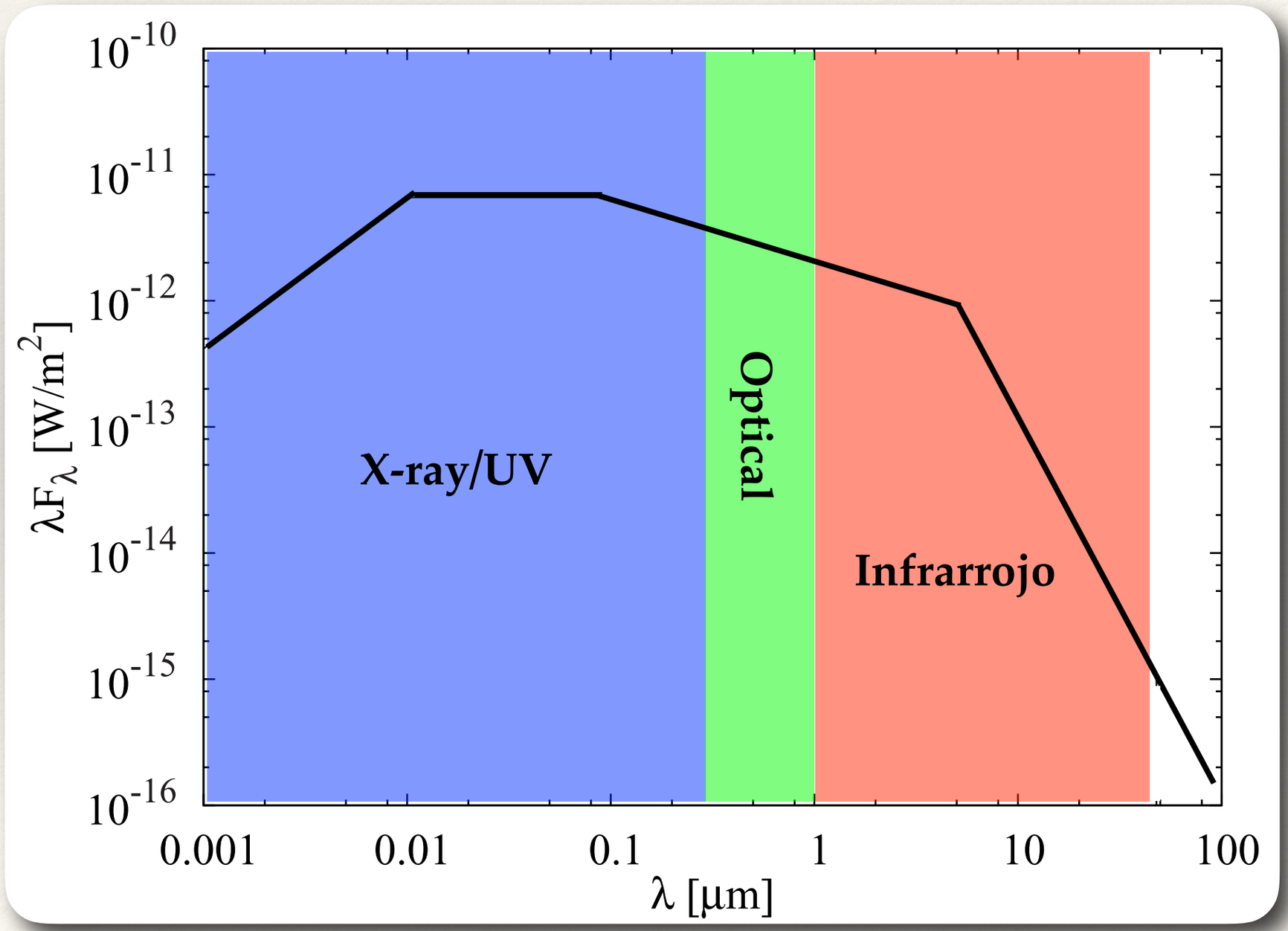
The AGN "Unified Model"



The AGN “Unified Model”

The AGN "Unified Model"

The accretion disk SED

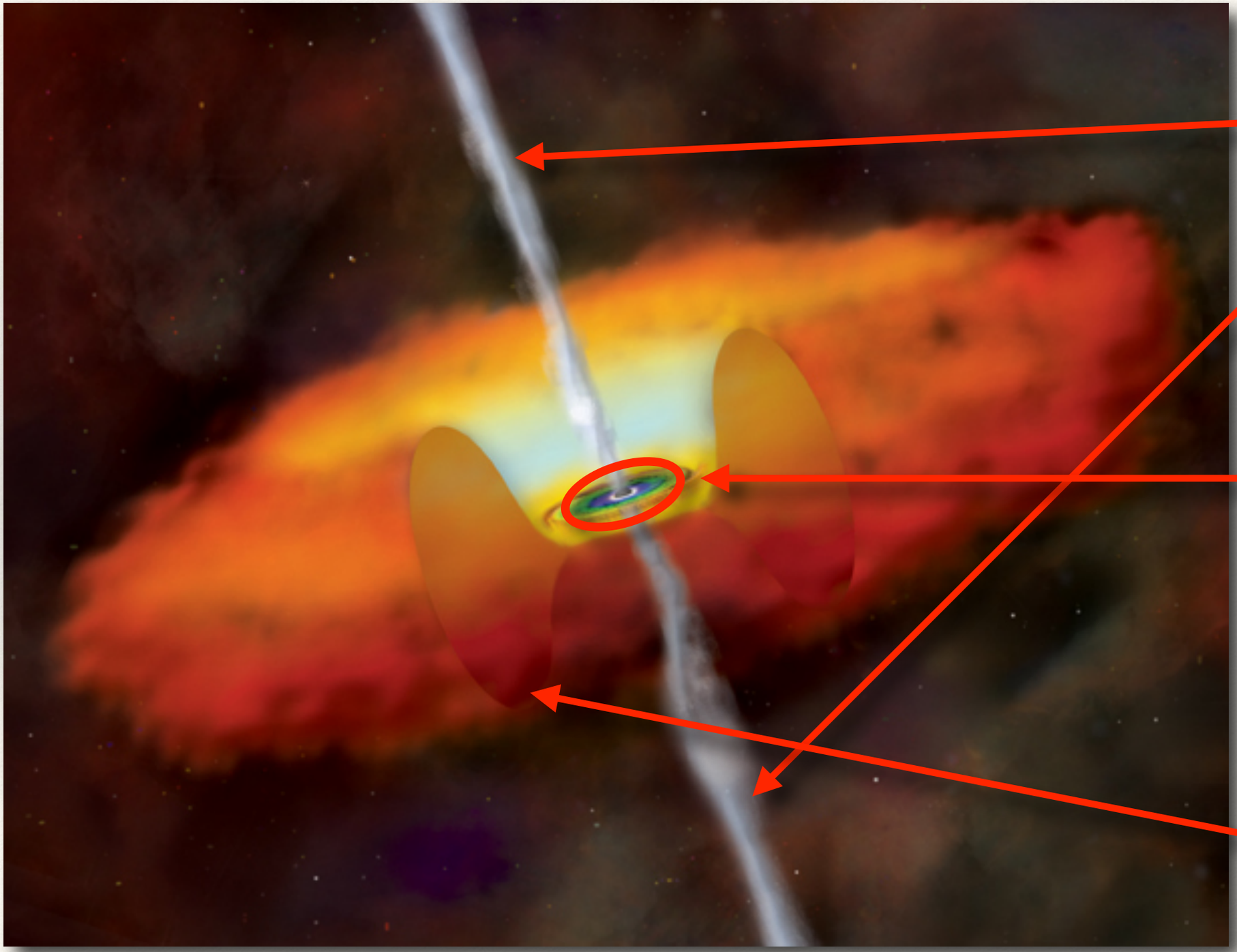


Stalevski et al. 2012

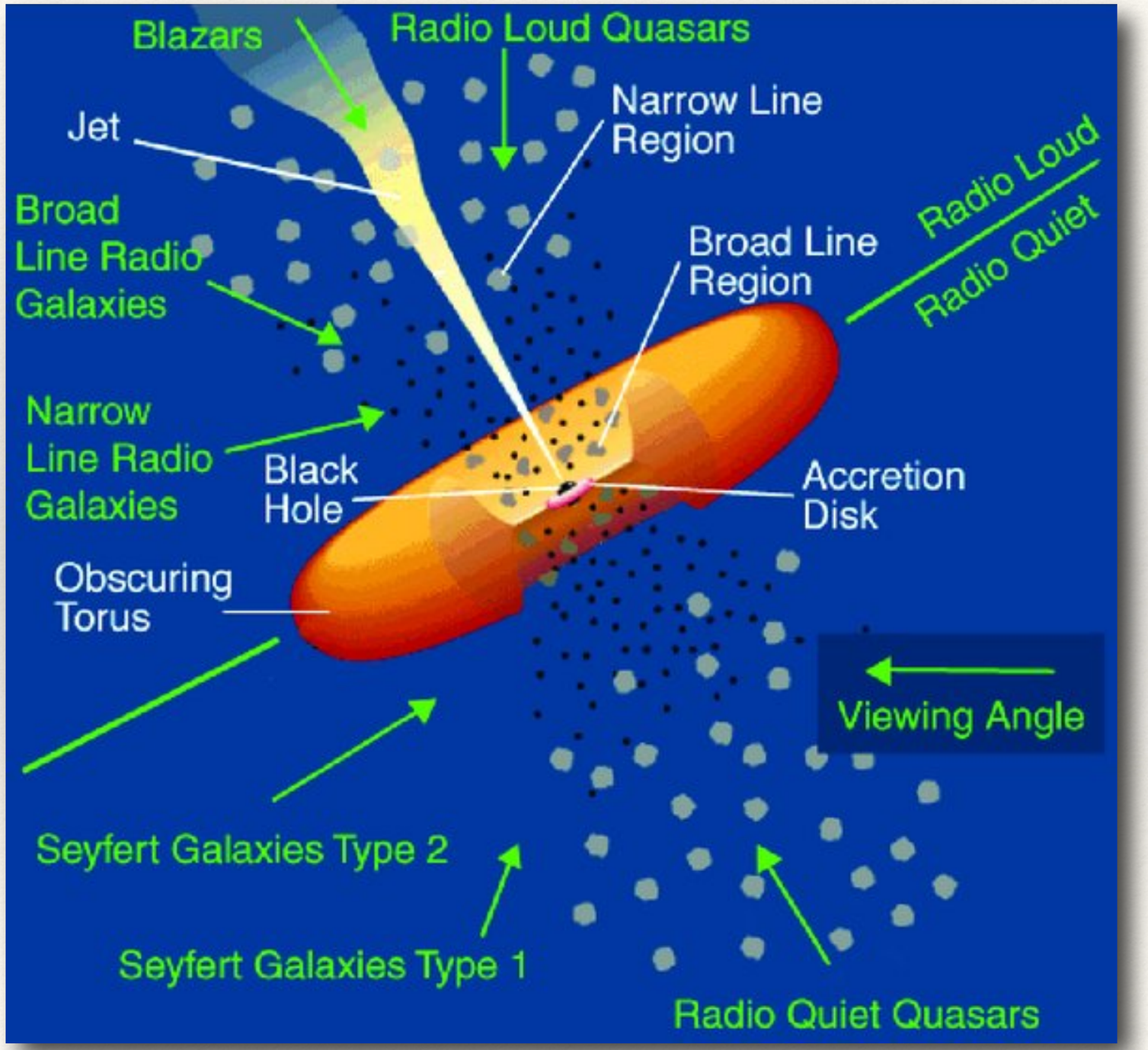
The Dusty Torus

- A further rising of the luminosity is observed towards the NIR/MIR;
- this is believed to be thermal (i.e. black body-like) emission from very hot dust;
- this emission comes from the more external regions of the accretion disk ($d \propto L^{1/2}$);
- the characteristics of this region are significantly different from those of the disk.

The Dusty Torus



The Unified Model



The Dusty Torus: consequences

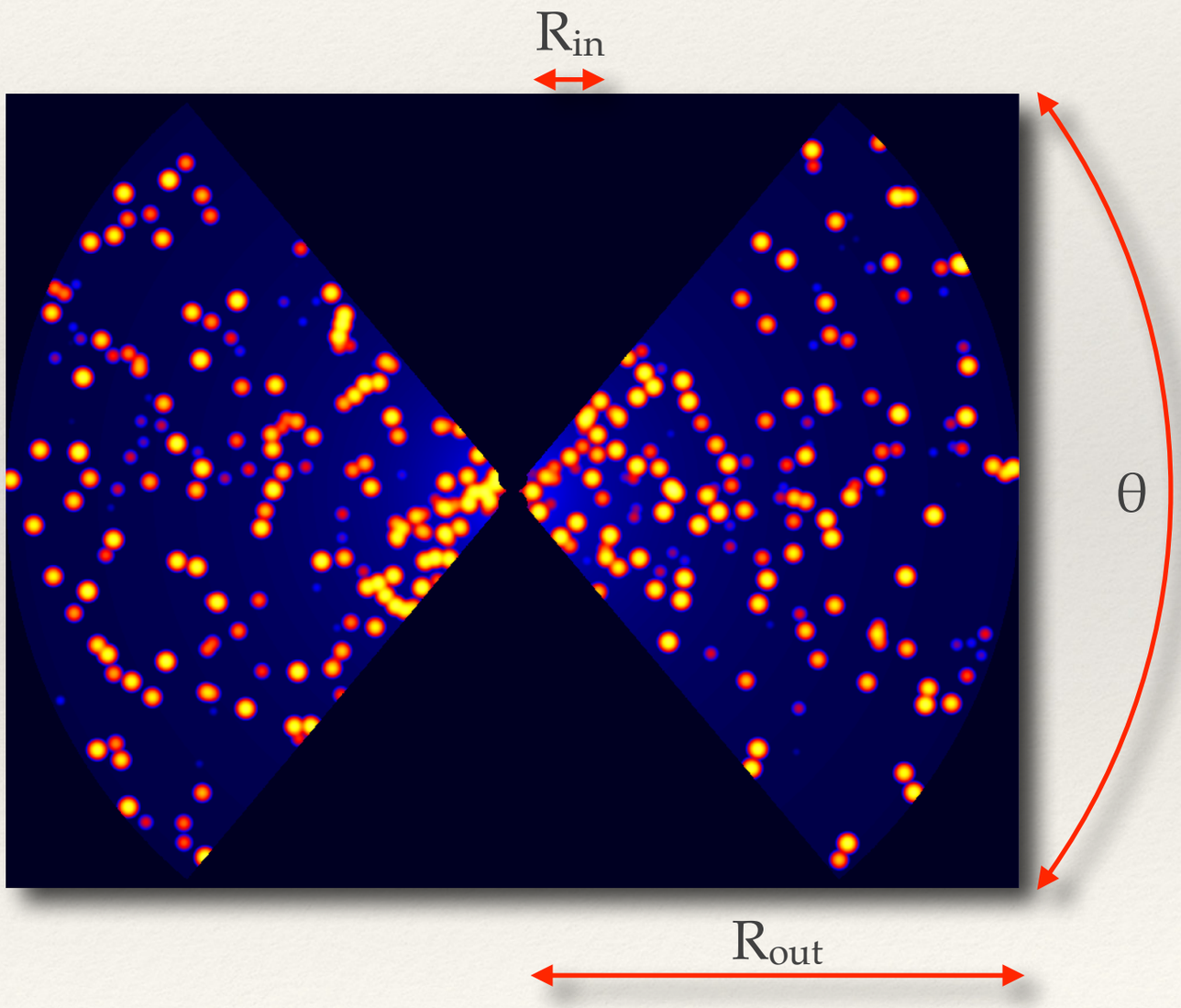
- Explains the NIR-MIR emission;
- naturally arises from a “wind scenario”;
- explains differences between the type-1 and type 2;
- explains polarimetry observations;
- probably depends on the disk luminosity (disappearing at $L<10^{42}$ erg/s and receding torus evidences).

The Dusty Torus

Characteristics

Geometrically defined by:

- inner radius;
- outer radius (questionable);
- torus opening angle;
- filling factor.



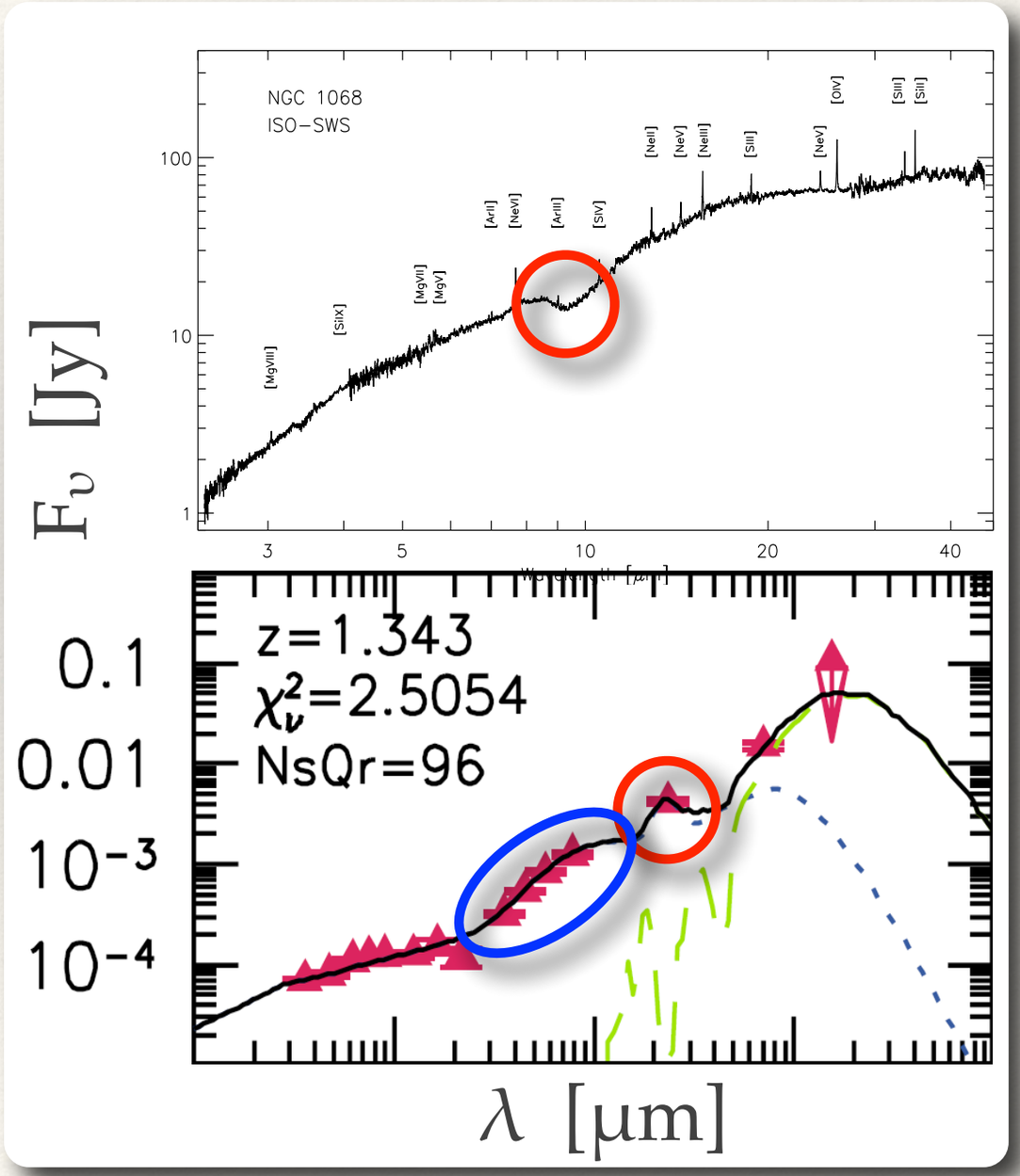
Schematic Representation

The Dusty Torus

Characteristics

Dust

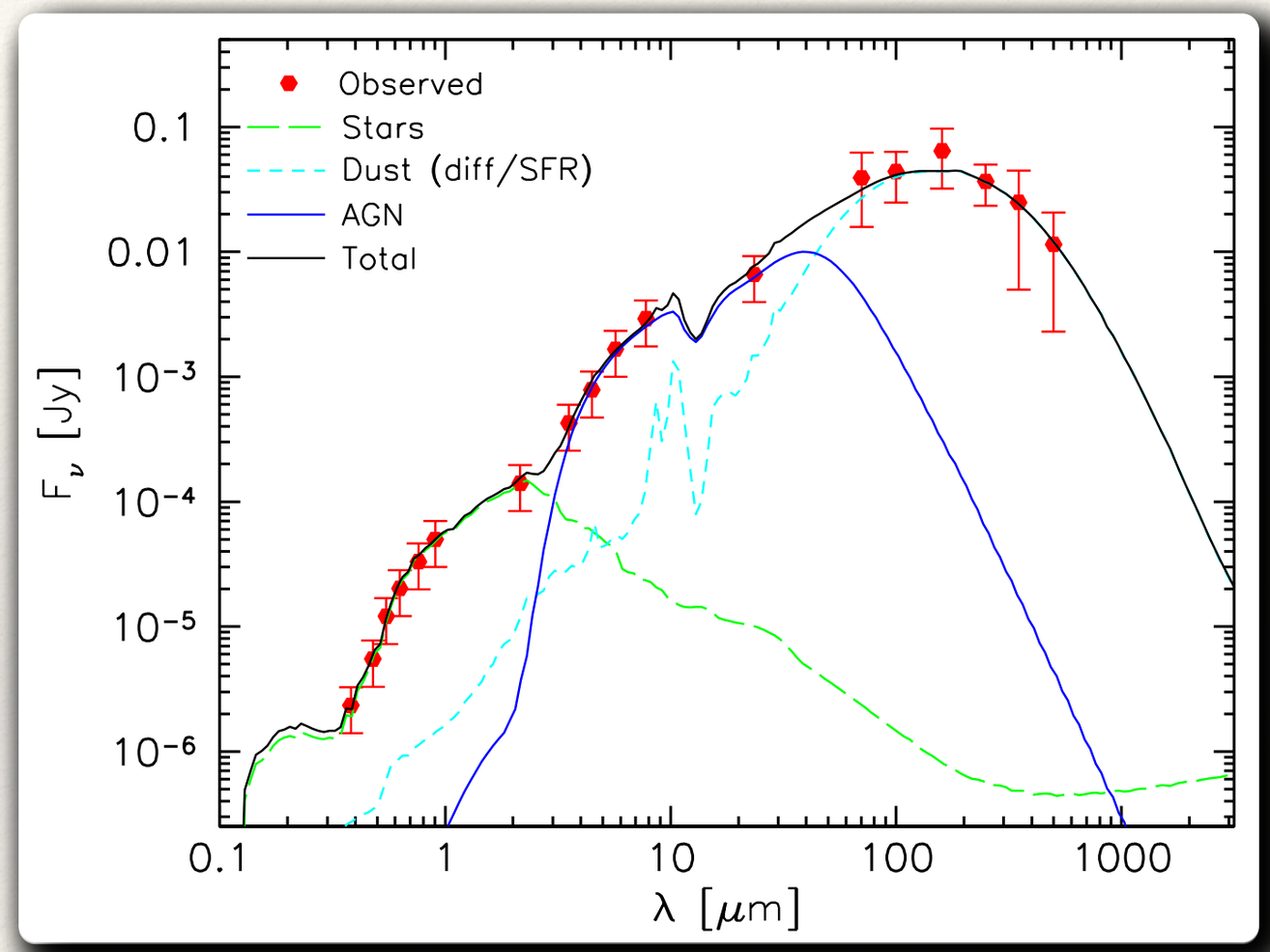
- Silicate / Graphite;
- hot temperatures (up to 1500 K) ;
- very high optical depths;
- dust masses from few tens to several thousands of $M_\odot$;
- inhomogeneous distribution.



On SED Fitting

"Composite" objects:

- Stars (optical)
- Dust (NIR to submm)
  - Warm/cold dust (stellar RF)
  - Hot dust (accretion disk-AGN)



Mandatory to explain the properties of many galaxies!

Understanding galaxies' properties

- What processes drive galaxy evolution?
- why do galaxies have the properties that we observe today?
- how and why did these properties evolve from what they were in the younger Universe?
- what are the relations connecting different components (stars, gas, dust, AGN, …) in a galaxy?

We use numerical models of the electromagnetic emission to try and answer these questions

RADIATIVE TRANSFER

- Describes the interaction between radiation and matter;
- couples extinction (in the UV-optical) to emission (infrared) through <u>energy balance</u>;
- can be used to simulate “real”, physical situations.

It is possible to reconstruct the appearance of a galaxy as we would observed it at any wavelength

RADIATIVE TRANSFER

- It is a 6D problem: 3 (space) + 2 (directions) + 1 (wavelength). 100 points in each dimension yields 10^{12} points!!
- it is non linear;
- it is non-local with respect to each of the 6 dimensions:
  1. space: photons propagates in the spatial domain;
  2. direction: scattering couples intensity in all directions;
  3. wavelength: absorption/re-emission change the wavelengths.

Solving the RT problem

Extinction Term

Source Term

$$\frac{\mathrm{d}I}{\mathrm{d}s}(\mathbf{x},\mathbf{n},\lambda) = -\kappa_{\mathrm{ext}}(\mathbf{x},\lambda)\rho(\mathbf{x})I(\mathbf{x},\mathbf{n},\lambda) + j_*(\mathbf{x},\mathbf{n},\lambda) + \kappa_{\mathrm{sca}}(\mathbf{x},\lambda)\int_{4\pi}\mathbf{\Phi}(\mathbf{n},\mathbf{x}',\mathbf{x},\lambda)I(\mathbf{x},\mathbf{n}',\lambda)\mathbf{d}\Omega'$$

Scattering Term

+ dust emission
+ dust self-absorption
+ transiently-heated grains

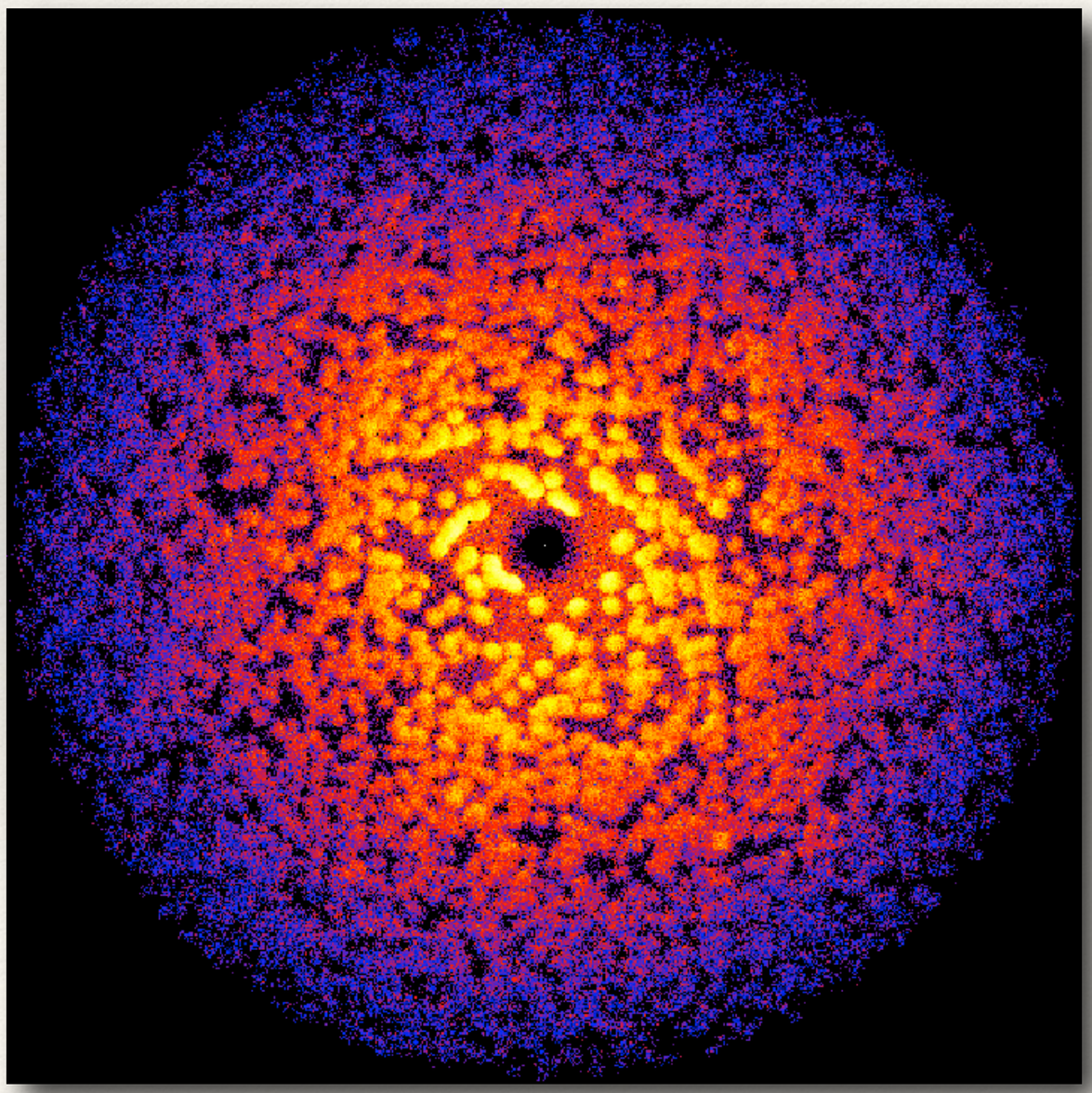
Solving the RT problem

- Probabilistic simulation method (RT equation is <u>NOT</u> solved);
- a large number of photon packages are followed individually through the dusty medium;
- the trajectory of each photon package is determined by random numbers;
- the radiation field is reconstructed by classifying photon packages by position, propagation direction, wavelength.

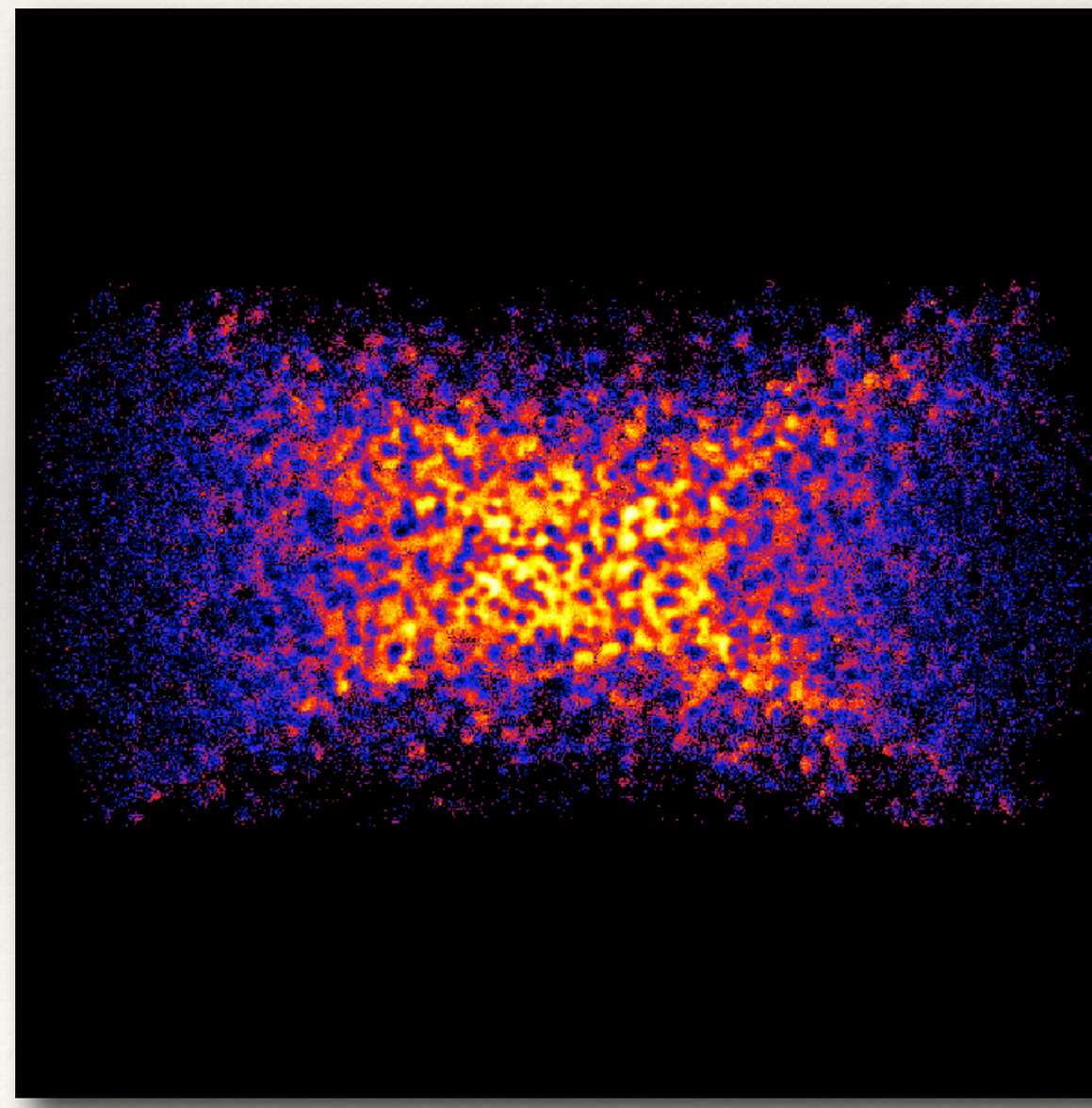
Dusty Torus Models

SKIRT MODELING

Type-1 view



Type-2 view



TASK 1

TORUS IR EMISSION MODEL

1. Use images calculated from RT models of the dusty torus emission (of a Type-1);
2. reconstruct, from the images:
    a. the total Spectral Energy Distribution;
    b. the SED of different parts of the torus.

TASK 1

- Take a type-1 torus model datacube from SKIRT;
- write a python routine to read in the model;
- calculate:
  1. the total SED (and compare to the one provided);
  2. the pure dust SED (and compare to the one provided);
  3. the AGN SED (and compare to the one provided);
  4. the dust SED of various rings.

On the models' name convention

Exponent of the angular density low

Outer-to-inner torus radius

Optical depth @ 9.7 μm

Viewing angle

`t5_p1_q1_oa30_R10_Mcl0.97_i0`

Exponent of the radial density low

Torus opening angle

Mass fraction of dust in clouds

The content of the files

t5_p1_q1_oa30_R10_Mcl0.97_i0 +

_ds_tempxy.fits

_ds_tempxz.fits

_ds_tempyz.fits

_i0_total.fits

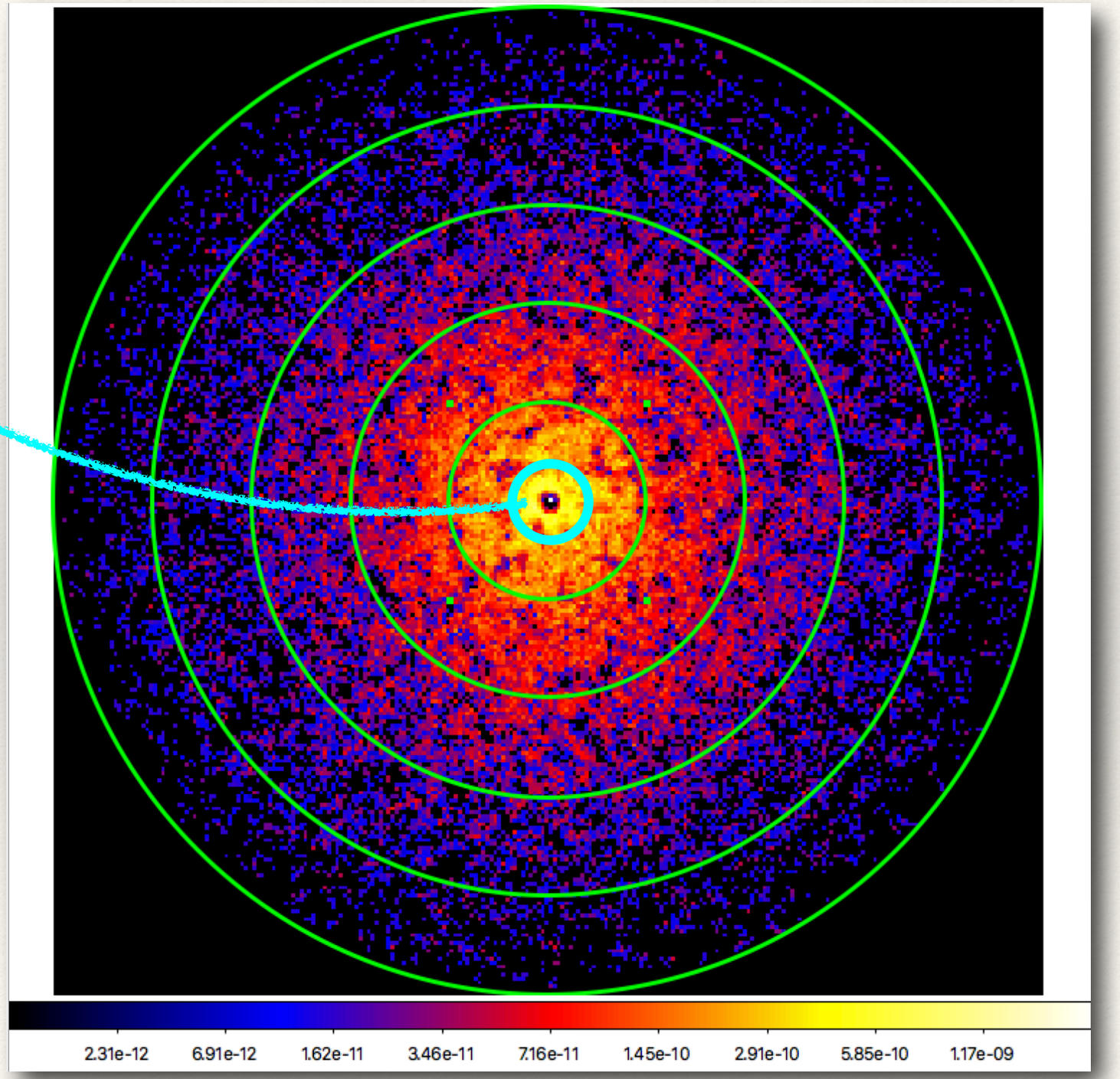
_i0_sed.dat

Let's get started!

- Open the "`total`" fits file within DS9;
- choose an appropriate scale (*log* or *sqrt* should do) and color;
- also, go to a wavelength plane with high enough emission;
- using *regions*, and adopting a circular region, enclose the full circle of emission;
- define other concentric regions at different radii;
- define a region for the innermost, dust free, region (disk);
- save all the regions in *image coordinates*.

Regions Definition

Accretion
disk emission



Open a datacube and extract infos

```
#!/usr/bin/env python
# -*- coding: utf8 -*-
import numpy as np
import astropy.io.fits as fits
import pyregion
import pyregion._region_filter as filter
```

Use to run python directly from the terminal

Need modules

```
modelname = “filename and path here”
hdulist = fits.open(modelname)
header = (hdulist[0].header)
cube = (hdulist[0].data[:,:,:])
nx = header["NAXIS1"]
ny = header["NAXIS2"]
nl = header["NAXIS3"]
```

Loads the fits structure onto a variable

Saves the header only

Saves the data only

This is the way we extract header information

The structure of the fits file can be seen with: `hdulist.info()`

Calculating the SED (total+regions)

```
source =  pyregion.open("regions.reg")
nreg = len(source)
size = (ny, nx)
tot_sed = np.zeros((nl,nreg))
for k in range(nreg):
    print "Region ",k
    source =  pyregion.open("regions.reg")
    del source[0:k]
    del source[k+1:nreg]
    mask = source.get_mask(shape=size)
    sflx = 0.0
    for m in range(nl):
        for i in range(nx):
            for n in range(ny):
                if mask[n,i] == True:
                    tot_sed[m,k] = tot_sed[m,k] + cube[m,n,i]
```

Writing the data out

Here […] calculate the SED in rings, NOT in the regions (and subtract the primary emission!!)

```
fmt = "%12.4e  %12.4e  %12.4e  %12.4e  %12.4e \n"
ff = open("sed.dat",'w')
ff.write("reg1  reg2  reg3  reg4 tot \n")
for v in zip(sed1, sed2, sed3, sed4, sedt):
    ff.write(fmt%v)
ff.close()
```

Reading text files in python

```
import astropy.io.ascii as ascii

sedfile = “_sed.dat model file here”
tdata = ascii.read(sedfile)
lamb = tdata['col1']
tflx = tdata['col2']
agn = tdata['col3']
```

Note: when comparing fluxes from the “`_sed.dat`” file, and the ones calculated from the image, check the units!!!

Units of the data

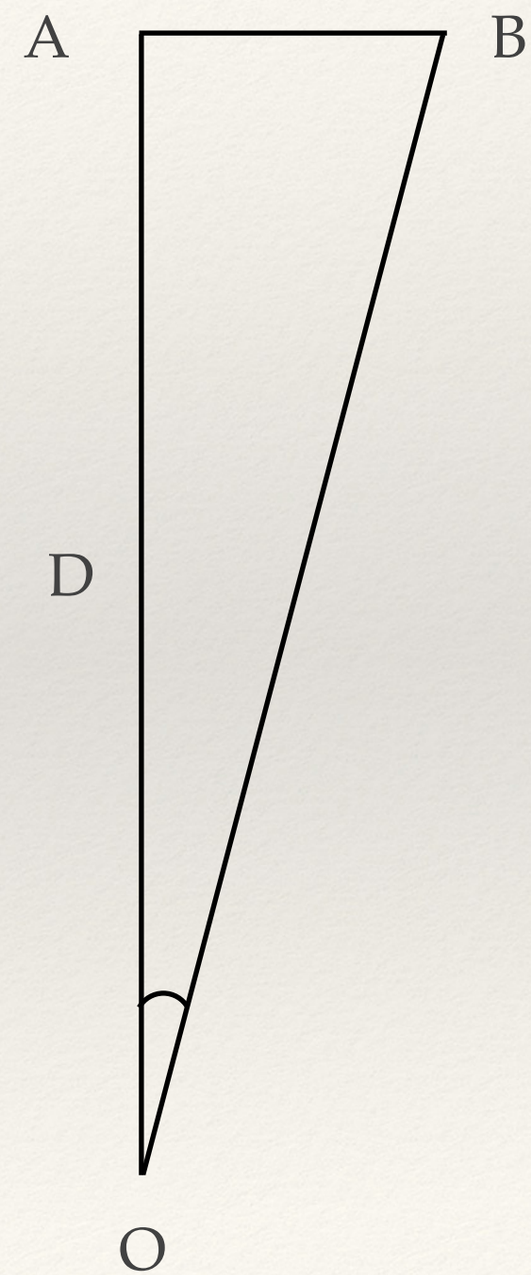
t5_p0_q0_oa30_R10_Mcl0.97_i0_total.fits

```
SIMPLE  =                    T / file does conform to FITS standard
BITPIX  =                  -32 / number of bits per data pixel
NAXIS   =                    3 / number of data axes
NAXIS1  =                  600 / length of data axis 1
NAXIS2  =                  600 / length of data axis 2
NAXIS3  =                  119 / length of data axis 3
EXTEND  =                    T / FITS dataset may contain extensions
COMMENT   FITS (Flexible Image Transport System) format is defined in 'Astronomy
COMMENT   and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H
BSCALE  =                   1.
BZERO   =                   0.
DATE    = '2018-08-07T11:06:00' / Date and time of creation (UTC)
ORIGIN  = 'SKIRT simulation'    / Astronomical Observatory, Ghent University
BUNIT   = 'W/m2/arcsec2'        / Physical unit of the array values
CRPIX1  =                 300.5 / X-axis coordinate system reference pixel
CRVAL1  =                    0. / Coordinate system value at X-axis reference pix
CDELT1  =   0.0166666666666667 / Coordinate increment along X-axis
CTYPE1  = 'pc      '            / Physical units of the X-axis increment
CRPIX2  =                 300.5 / Y-axis coordinate system reference pixel
CRVAL2  =                    0. / Coordinate system value at Y-axis reference pix
CDELT2  =   0.0166666666666667 / Coordinate increment along Y-axis
CTYPE2  = 'pc      '            / Physical units of the Y-axis increment
END
```

```
# column 1: lambda (micron)
# column 2: total flux; lambda*F_lambda (W/m2)
# column 3: direct stellar flux; lambda*F_lambda (W/m2)
# column 4: scattered stellar flux; lambda*F_lambda (W/m2)
# column 5: total dust emission flux; lambda*F_lambda (W/m2)
# column 6: dust emission scattered flux; lambda*F_lambda (W/m2)
# column 7: transparent flux; lambda*F_lambda (W/m2)
```

How do we convert?

- W m^{-2} $arcsec^{-2}$ → W m^{-2};
- what is the pixelsize in units of arcsec?
- note that the models have been calculated for a distance D of 10 Mpc.



Plotting SEDs

```
yma = max(tflx)*1.2
ymi = yma*0.001
xma = max(lamb)*1.01
xmi = min(lamb)*0.97
plt.figure(figsize=(15,10))
plt.loglog(lamb,tflx,linestyle='-',color='black')
plt.loglog(lamb,tot,linestyle='--',color='black',linewidth=4)
plt.loglog(lamb,reg1,linestyle='-',color='green')
plt.xlabel(r'$\lambda$    [$\mu$m]',fontsize=20)
plt.ylabel(r'$\lambda$F$_\lambda$   [W m$^{-2}$]',fontsize=20)
plt.tick_params(labelsize=20)
plt.xlim(xmi,xma)
plt.ylim(ymi,yma)
fig = plt.gcf()
plt.show()
```

```
import matplotlib.pyplot as plt
from matplotlib import rc, rcParams
rc('text', usetex=True)
```

Final comparison

- Take the "`####_sed.dat`" file, and compare:
    1. the total SED;
    2. the dust SED;
- compare the SEDs of the regions at the various radii/distances;
- let's compare various different models (different parameters):
- Everyone make their plots, showing the SED and the parameters;
- Discussion.

Summary

- Historical overview on Active Galactic Nuclei;
- physical and geometrical properties;
- the AGN Unified Scheme;
- the dusty torus;
- galaxy properties derivation through SED fitting;
- radiative transfer;
- working on torus emission models.