Definition and Characterization of Local Analogs to High-z Galaxies

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Motivation

The Deep Field

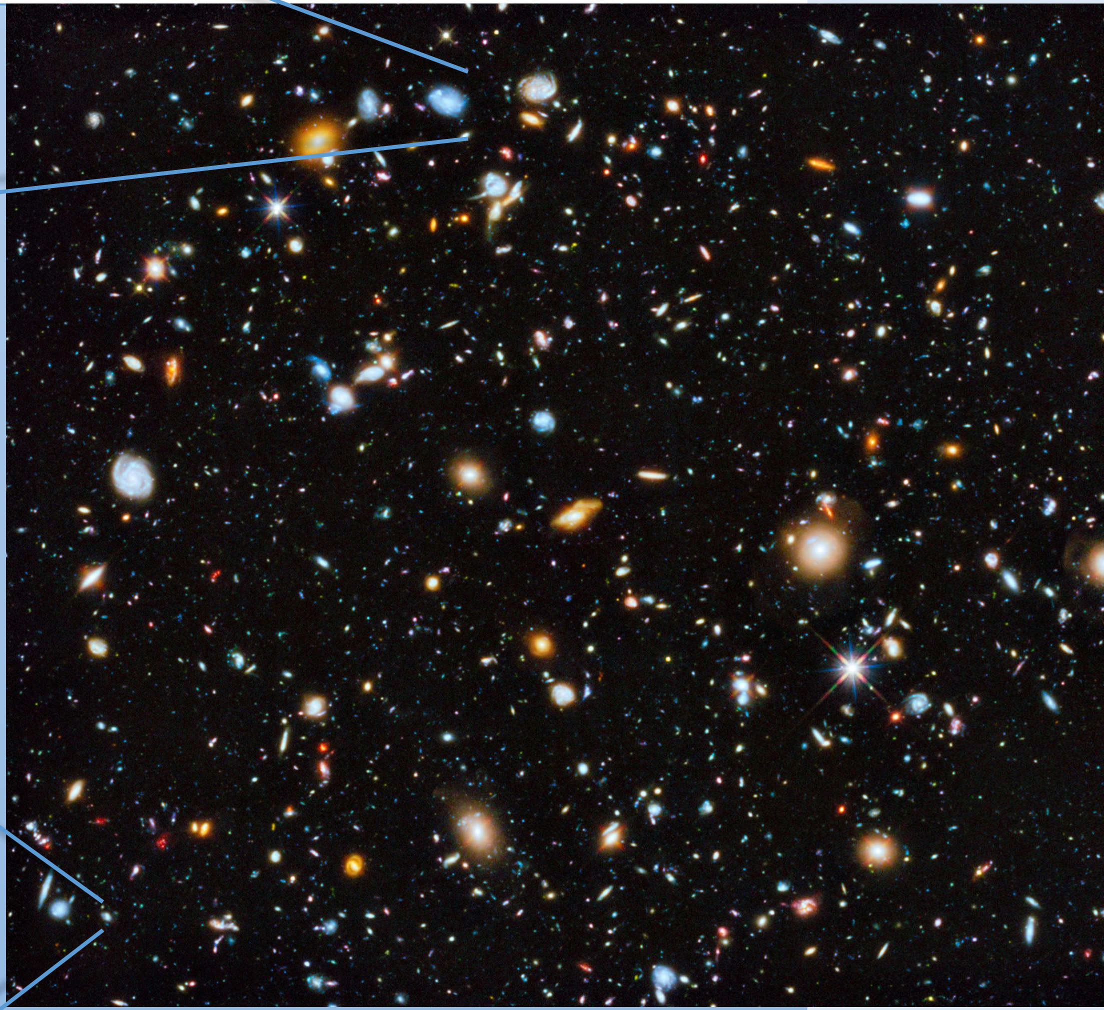
High Redshift (*z*) Universe:

- Distant and Young Galaxies.
- Small (~1 kpc).
- Small angular size.
- Blue intrinsic colors.
- Irregular morphologies.

Study the physical processes in these galaxies in detail is extremely difficult.

- **One possible solution to these difficulties is to identify low-*z* analogs to high-*z* galaxies.**

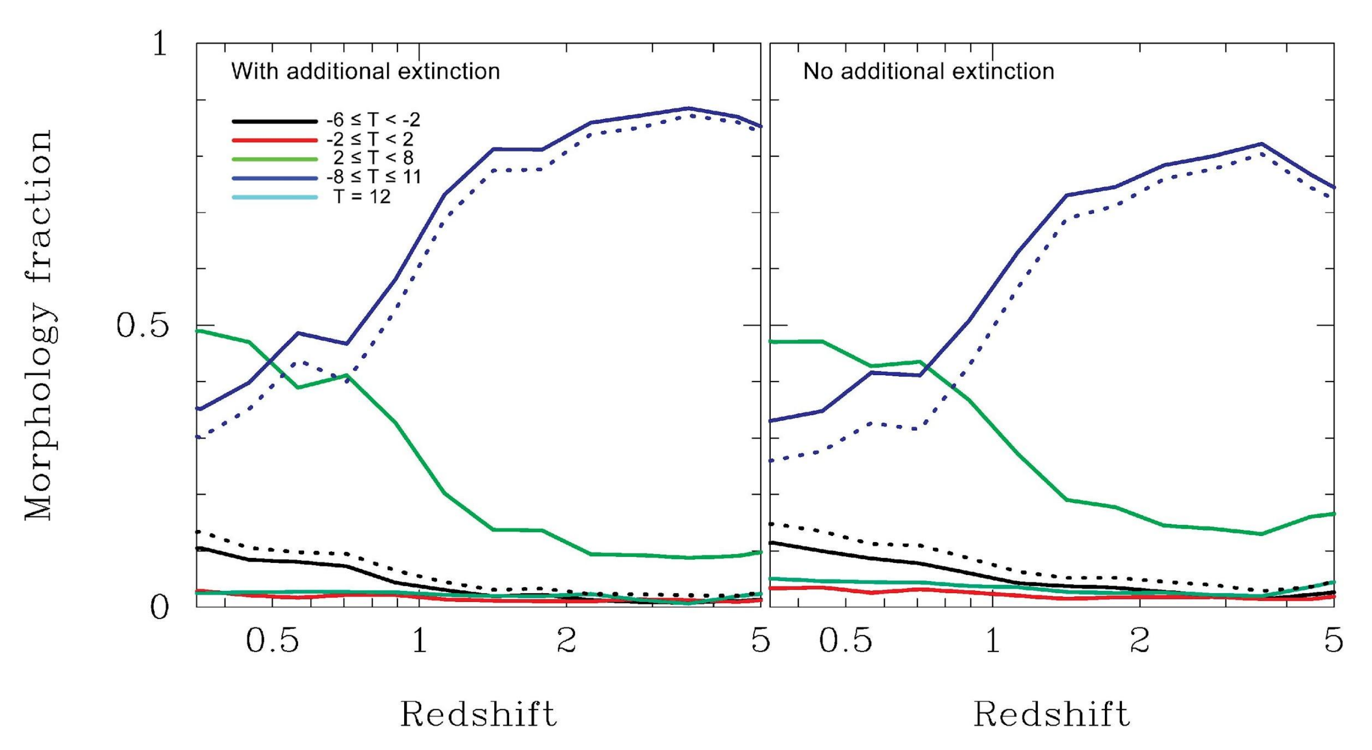
Local Analogs (Low Redshift):	Early Galaxies (High Redshift):
• Irregular, Small, High Star Formation. • Main features observable in the UV – Optical – Infrared	• Irregular, Small, High Star Formation. • Main features (UV-optical) **redshifted** to the Infrared.



Ultraviolet Coverage of the Hubble Ultra Deep Field (UVUDF) project.
Credit: E. Soto, D. De Mello (CUA), H. Teplitz and M. Rafelski (IPAC/Caltech), A. Koekemoer (STScI), R. Windhorst (Arizona State University), and Z. Levay (STScI) NASA, ESA,

Sample selection

- Previous works: FUV luminosity, W(Hα), *i.e. Ostlin 2014, Hoopes 2007, Overzier 2014*.
- Novel Technique.
- Based on the success rate of 129 local galaxy templates (from **Brown et al. 2014**) in fitting observe SED of 159,645 high-z galaxies (**CANDELS**[1]).
- High-z Galaxies with z > 2.



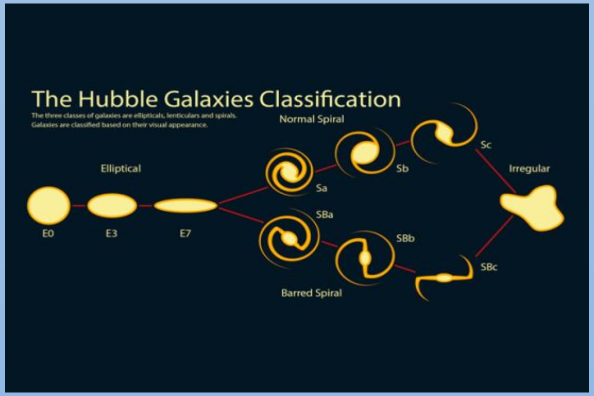
- **For galaxies at z>2 just 11 of the local template galaxies provide >90% of all the best-fit SEDs.**
- **Unique sample.**

Refs: [1]Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS). For survey details, see Grogin et al. (2011) and Koekemoer et al. (2011).

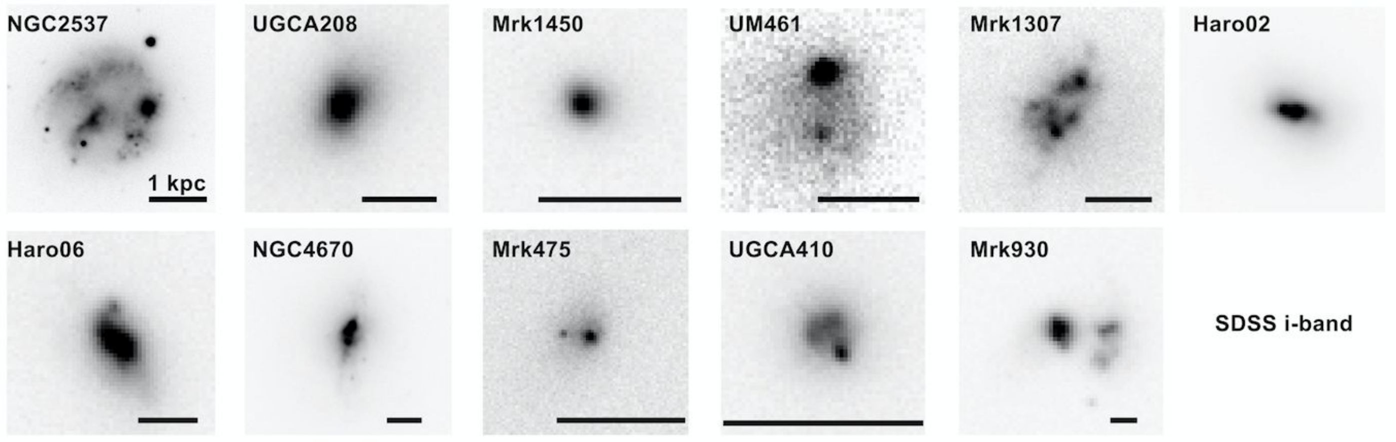
Blue Compact Dwarf Galaxies (BCDGs)

- Local galaxies.
- Compact galaxies.
- Small (optical diameter ~1 kpc)
- Low **metallicities** (1/3 to 1/41 Z_{sun})
- Blue optical colors (actively star forming).
- ---> **Are this young system**?

BCDGs do not fit in the Hubble sequence classification.



- The Sample of Local Analogs



Name	RA	Dec	D	log M_*	log M_{HI} $^{(a)}$	$f_{gas}^{(b)}$	Metallicity	Alternative
	J2000.0		Mpc	$M_\odot$	$M_\odot$	$M_\odot$	$12 + \log(O/H)$	Name
NGC 2537	08:13:14.4	+45:59:13	8.6	9.107	8.428	0.17	8.19	Arp 6; 'Bear Paw'
Mrk 140	10:16:28.3	+45:19:18	27.6	8.271	8.897	0.56	8.30	Mrk140
Haro 02	10:32:31.9	+54:24:02	23.7	9.790			8.45	Mrk 033
Mrk 1450	11:38:35.6	+57:52:27	14.7	7.272	7.351	0.54	7.96	
UM 461	11:51:33.1	-02:22:22	20.7	7.045	8.467	0.96	7.78	
Mrk 1307	11:52:37.4	-02:28:09	21.0	8.107	8.727	0.81	7.96	UM462
Haro 06	12:15:18.4	+05:45:39	35.1	8.473	8.830	0.69	8.18	
NGC 4670	12:45:17.1	+27:07:31	20.0	9.246	9.017	0.37	8.30	Arp163
Mrk 475	14:39:05.5	+36:48:21	10.9	8.100	6.624	0.56	7.93	
Mrk 487	15:37:04.2	+55:15:48	10.5	7.455	7.585	0.57	8.10	
Mrk 930	23:31:58.6	+28:56:50	77.5	9.053	9.506	0.74	8.08	

The SOFIA telescope
Stratospheric Observatory for Infrared Astronomy.

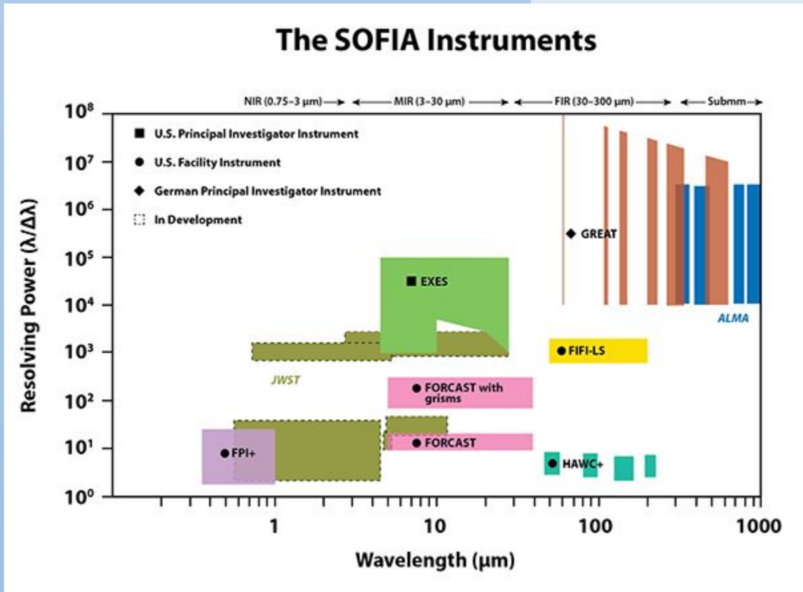
•**106 inches** (**2.7-meter**) reflecting telescope, is a 17 ton telescope!

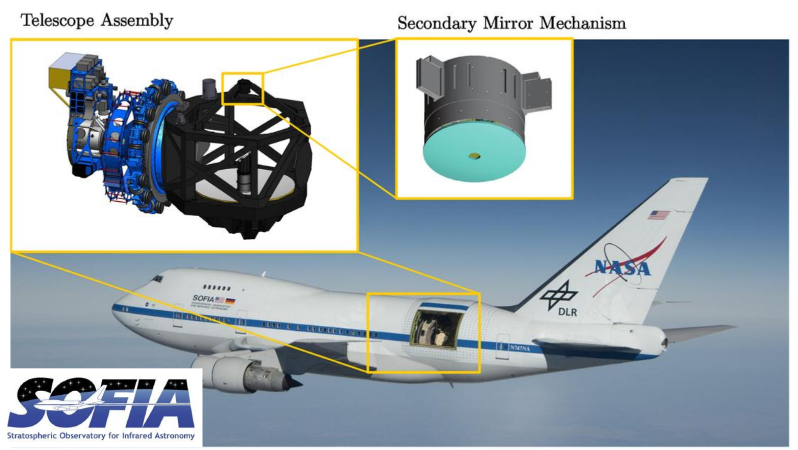
- **HAWC+**

High-resolution Airborne Wideband Camera. [50 – 240 μm]

- **HAWC+ Documentation:** https://www.sofia.usra.edu/sites/default/files/Instruments/HAWC_PLUS/Documents/hawc_data_handbook.pdf

- We also use **ancillary data** from:
  - **Spitzer**
  - **Herschel**
  - **WISE**
  - **AKARI**





Mrk 1450

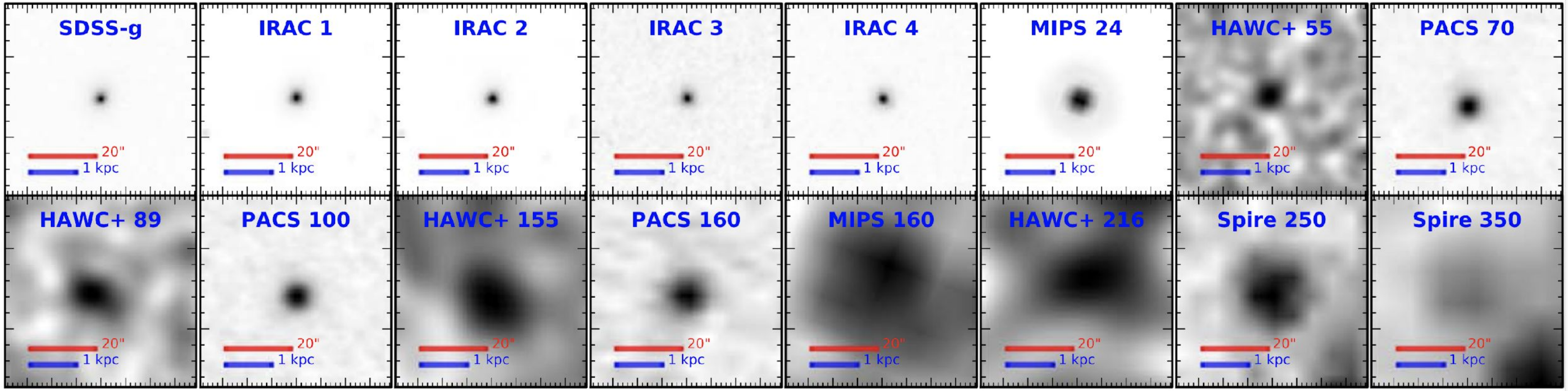


Figure 4. Optical to FIR images of Mrk 1450. The red bar corresponds to 20″, and the blue bar indicates 1 kpc.

Photometry:

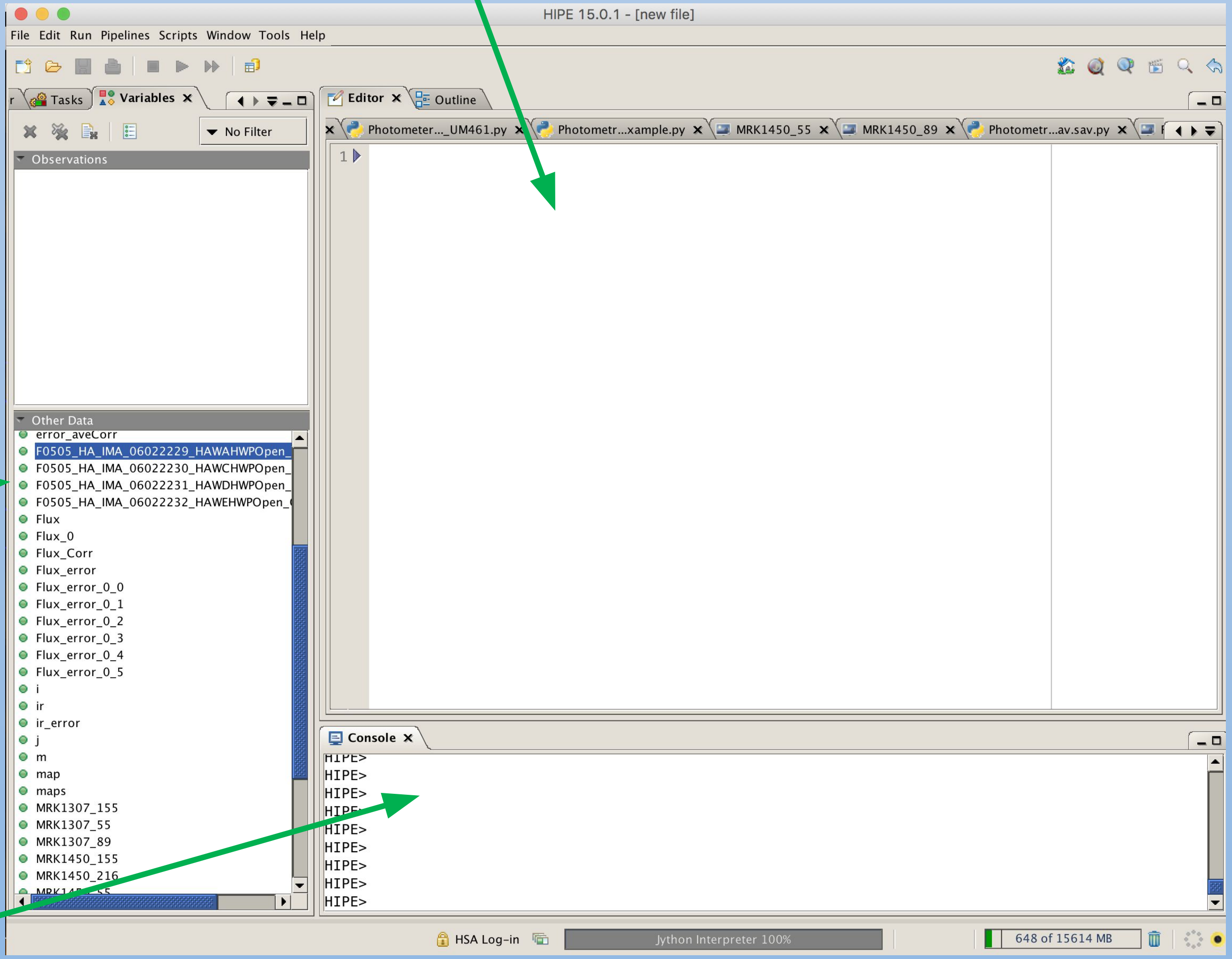
- Herschel Interactive Processing Enviroment (HIPE):

https://www.cosmos.esa.int/web/herschel/hipe-download

- Jython

https://www.jython.org/

- Predefined Task:
    - Annular Sky Aperture Photometry



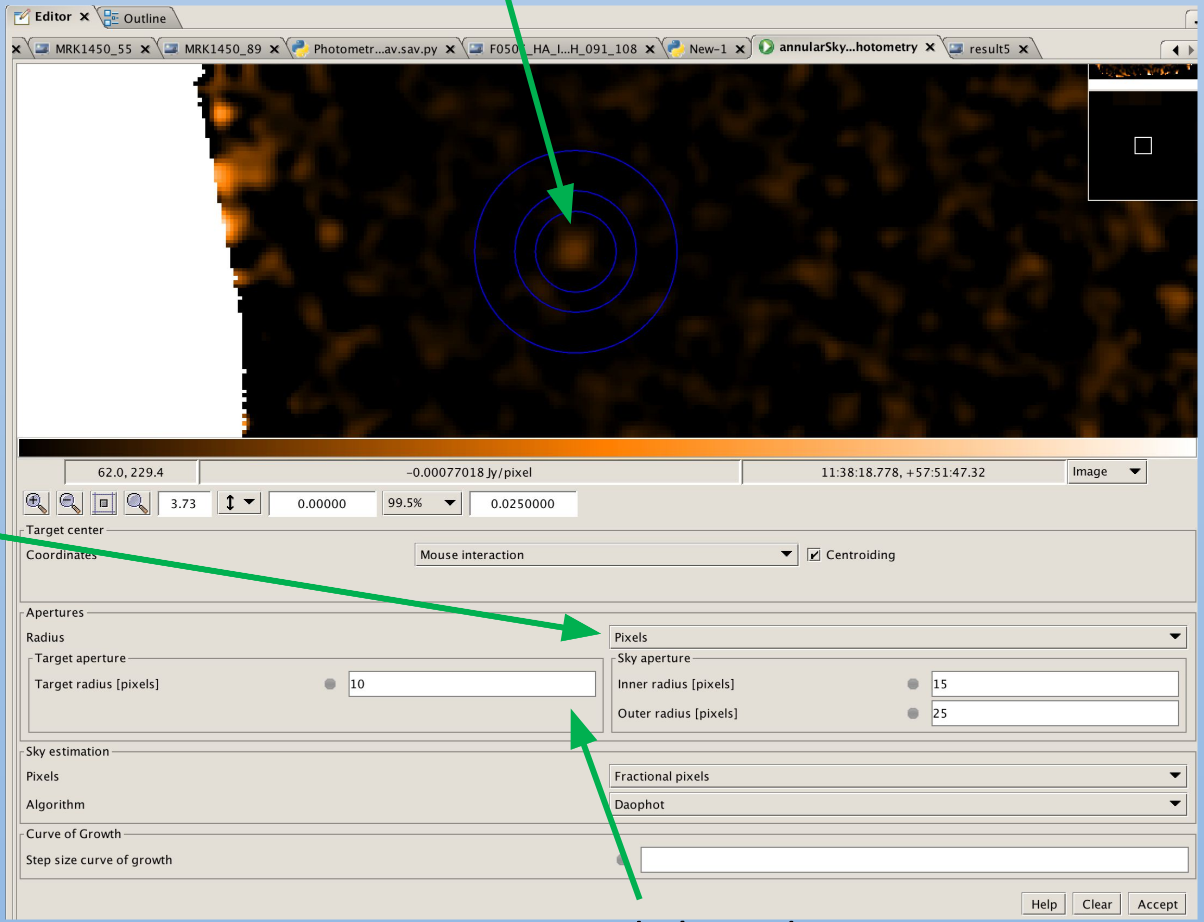
Photometry:

Galaxy!

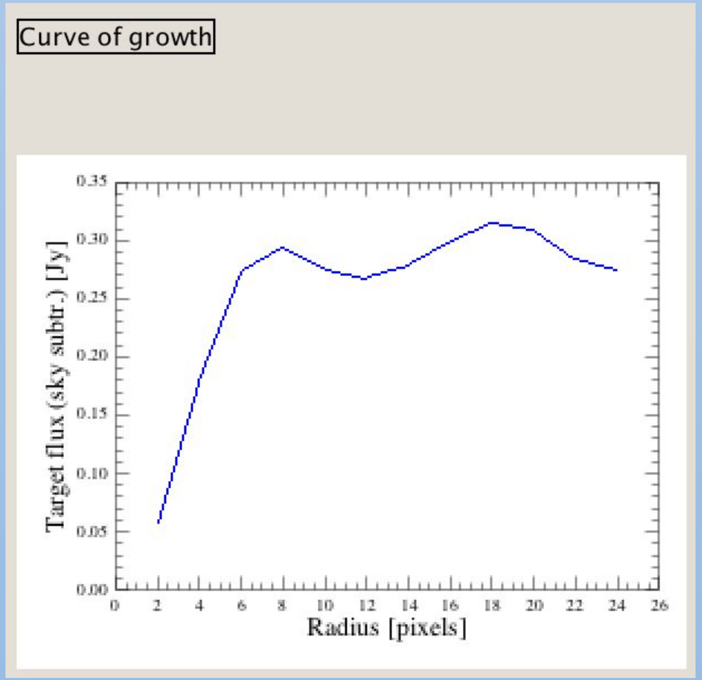
Annular Sky Aperture Photometry:

- Image Units: Jy/Pixel

Aperures (pixels or arcsec)



Source and Sky radius



HIPE> Result = annularSkyAperturePhotometry(image=MRK1450_55, centerX=94.98058210987237, centerY=103.56310730363946, radiusPixels=10.0, innerPixels=15.0, outerPixels=25.0, fractional=1, centroid=True)

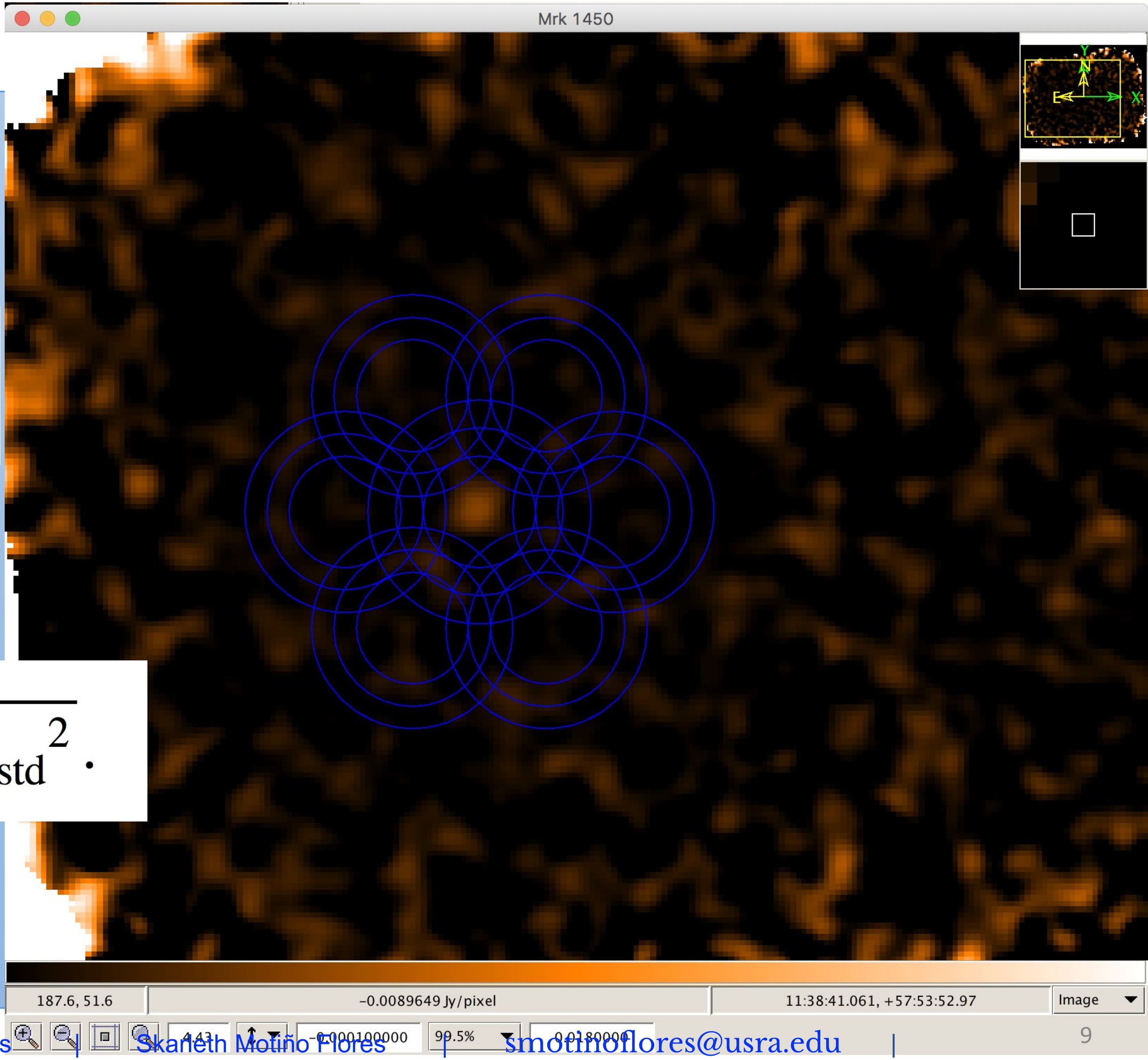
Source Flux:

$$F_{\text{source}} = (f_{\text{tot}}) - \text{Bg}_{\text{ave}}.$$

Uncertainties:

$$F_{\text{unc}} = \sqrt{(F^{*}_{\text{source}} \text{Abs}_{\text{cal}})^2 + \text{Bg}_{\text{std}}{}^2}.$$

Abs_{cal} = 10%- 15%



• Example of Script to perform photometry

```
#  'Mrk 1307'   SOFIA     'HAWC+ Bands A, C, D'
# 155 um        F0483_HA_IMA_06022239_HAWDHWPOpen_CRH_091_093.fits
#  89 um        F0483_HA_IMA_06022239_HAWDHWPOpen_CRH_067_074.fits
#  55 um        F0483_HA_IMA_06022239_HAWDHWPOpen_CRH_077_088.fits

from math import *
from java.lang.Math import PI

wl = ['55','89','155']

maps = [  F0483_HA_IMA_06022237_HAWAHWPOpen_CRH_077_088 , \
F0483_HA_IMA_06022238_HAWCHWPOpen_CRH_067_074, F0483_HA_IMA_06022239_HAWDHWPOpen_CRH_091_093]


###################### SETTING UNITS TO Jy/pixel  #######################

for i in range(3):
        map = maps[i]
        map.setUnit(herschel.share.unit.Unit.parse("Jy/pixel"))

# Save maps with units to file
        simpleFitsWriter(product=map, file='/Users/admin/HIPEScripts/SOFIA/MRK1307_Jy_pixel_wl_'+wl[i]+'um.fits')


##################### READING MAPS FROM FILE ######################################
MRK1307_55  = fitsReader(file = '/Users/admin/HIPEScripts/fits_images/SOFIA/MRK1307_Jy_pixel_wl_'+wl[0]+'um.fits')
MRK1307_89  = fitsReader(file = '/Users/admin/HIPEScripts/fits_images/SOFIA/MRK1307_Jy_pixel_wl_'+wl[1]+'um.fits')
MRK1307_155 = fitsReader(file = '/Users/admin/HIPEScripts/fits_images/SOFIA/MRK1307_Jy_pixel_wl_'+wl[2]+'um.fits')
maps = [ MRK1307_55 , MRK1307_89, MRK1307_155]

# Or read the files:
#for i in range(3):
#       maps[i] = fitsReader(file = '/Users/admin/HIPEScripts/SOFIA/MRK1307_Jy_pixel_wl_'+wl[i]+'um.fits')
#maps[i] = 'MRK1307_Jy_pixel_wl_'+wl[i]+'um.fits'


##################### Annular Photometry ########################################

### Mrk1307  Source positions in units of pixels not Astronomical Coordinates
# To obtain: On the map, Right click on the source and select Get coordinates

coordY = [108.43, 109.44, 98.0]
coordX = [173.47, 179.60, 156.0]
```

```
####
N = 3                                                           # Number of Data images. (Bands A, C, E).
Flux          =  N*[0.0]
error_ave     =  N*[0.0]
nabg          =  6                                              # Number of apertures to measure the background.
Flux_error    =  N*[[0.0, 0.0, 0.0, 0.0, 0.0, 0.0]]             # Array for for errors
ir            =  [15,  15,  15]                                 # Aperture radius in pixels
ir_error      =  [15, 15, 15]                                   # Aperture radius in pixels for the errors
Flux_Corr     =  N*[[0.0, 0.0, 0.0]]
error_aveCorr =  N*[0.0]
RADIO         =  [30, 30, 30]

for i in range(N):
        Flux[i] = annularSkyAperturePhotometry(image=maps[i], radiusPixels=ir[i], fractional=1, centerX=coordX[i],
                centerY=coordY[i], innerPixels=ir[i]+10, outerPixels=ir[i]+20)
        a    = 0.0
        b    = 0.0
        ir_error[i]      = sqrt(0.5)*ir[i]
        for j in range(nabg):
                radio = RADIO[i]
                angle = j*2*PI/(nabg)
                x = coordX[i]+radio*cos(angle)
                y = coordY[i]+radio*sin(angle)
                Flux_error[i][j] = annularSkyAperturePhotometry(image=maps[i], radiusPixels=ir_error[i], fractional=1,
                        centerX=x, centerY=y, innerPixels=ir_error[i]+8, outerPixels=ir_error[i]+12, centroid=False)
                a = a + Flux_error[i][j]["Results table"]["Total flux"].data[2]
                b = b + Flux_error[i][j]["Results table"]["Total flux"].data[2]
                print ' i=',i,' j=',j, ' FluxErr[i][j]= ',Flux_error[i][j]["Results table"]["Total flux"].data[2]
        average = b /nabg
        sigma   = 0
        for j in range(nabg):
                sigma   = sigma + (average - Flux_error[i][j]["Results table"]["Total flux"].data[2])**2
        std = (sigma)/(nabg-1)
        Flux_Corr[i] = Flux[i]["Results table"]["Total flux"].data[2]-(average)
        error_ave[i] = a/nabg
        error_aveCorr[i] = std
        print '   i= ',i,'     Flux      = ',Flux[i]["Results table"]["Total flux"].data[2],'   Error Average  = ',error_ave[i]
        print (' Backgroung Average: ',average,'     STD: ',std)
        print '   i= ',i,'     Flux_Corr = ',Flux_Corr[i],'+- Sigma_Corr:',error_aveCorr[i]
        print '\n'
        m = i
        Flux_0 = Flux[m]
        disp = Display(maps[m])
        disp.addAnnularSkyPhotometryProduct(Flux_0, java.awt.Color(200,120,0))
        for j in range(nabg):
                Flux_error_0_0 = Flux_error[m][j]
                disp.addAnnularSkyPhotometryProduct(Flux_error_0_0, java.awt.Color(50,055,055))
print 'done'
```

Black Body modeling

- Modified Black Body Function:

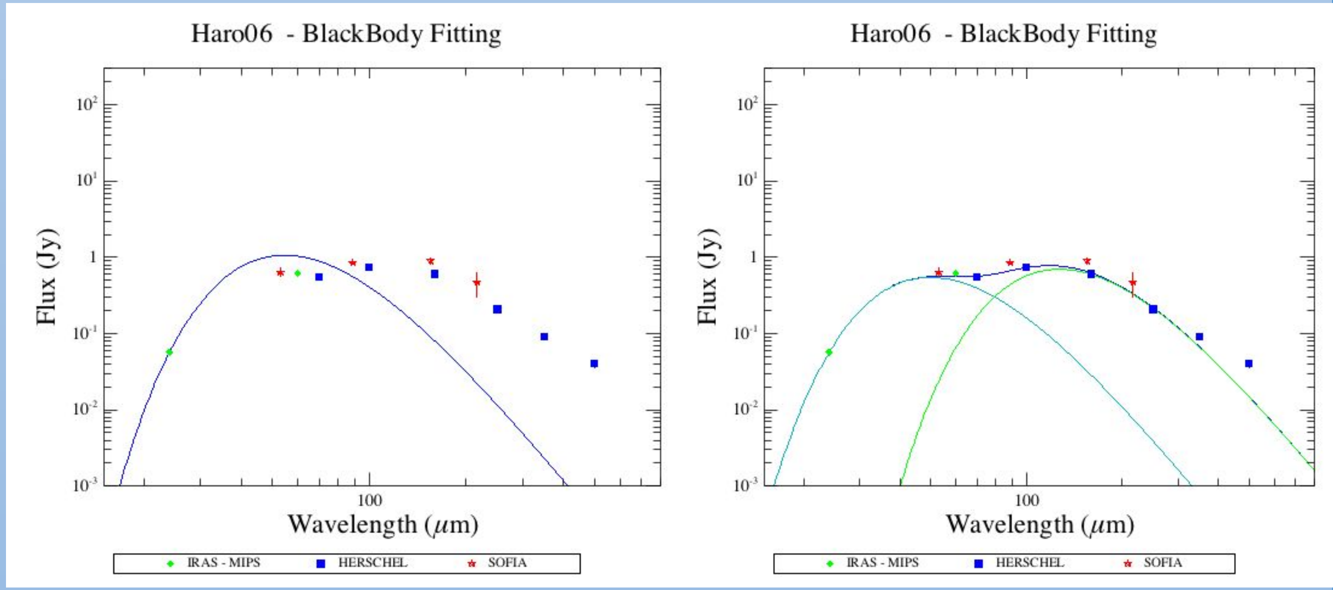
$$B_\nu(T) = \frac{2h\nu^3/c^3}{e^{h\nu/kT} - 1}$$

$$F_\nu \propto (1 - \exp(-\tau)) B_\nu(T)$$

$$B_{mod}(T) = \Omega\, B_\nu(T) \left(1 - \exp\left[-\left(\frac{\lambda_0}{\lambda}\right)^\beta\right]\right)$$

B(ν,T): the Plank function. Parameters:

- **T**: Dust temperature [k].
- **Ω**: Normalization constant.
- **β**: Dust Emissivity Coefficient.



- SOFIA-HAWC+: 55, 89, 155, and 216 μm (in red).
- Herschel: 70, 100, 160, 250, 350, 500 μm (in blue).
- Spitzer- MIPS: 24 μm (in green).

Bayesian Inference of parameters

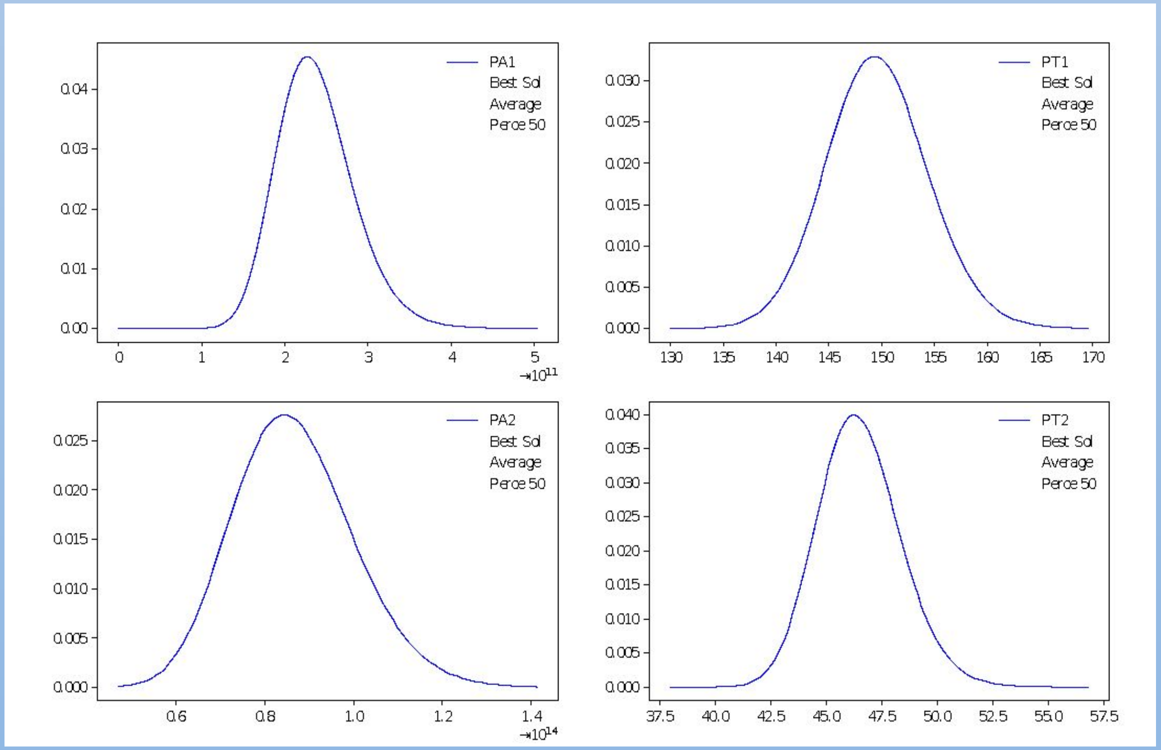
- Parameters:
  - T1, T2, A1, A2.
  - Beta, Lambda_0 - Const
  - Grid 4D **100x100x100x100** over the parameter space.
  - $\mathbf{10^8}$ models.
- Likelihood:

$$P(\theta|priors) = \exp\left(-\chi^2/2.0\right)$$

Posterior:

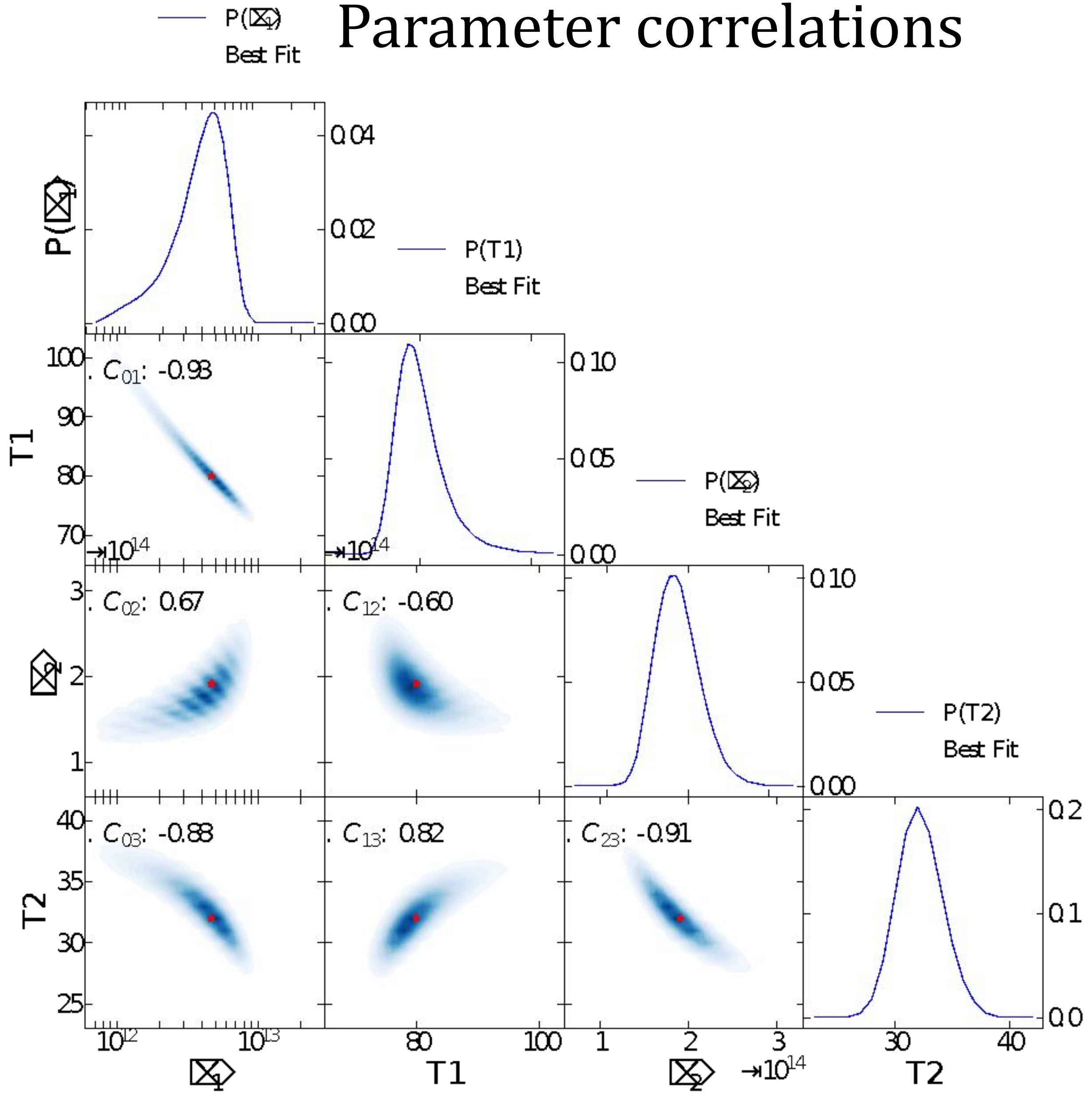
Marginalized Probability Distributions

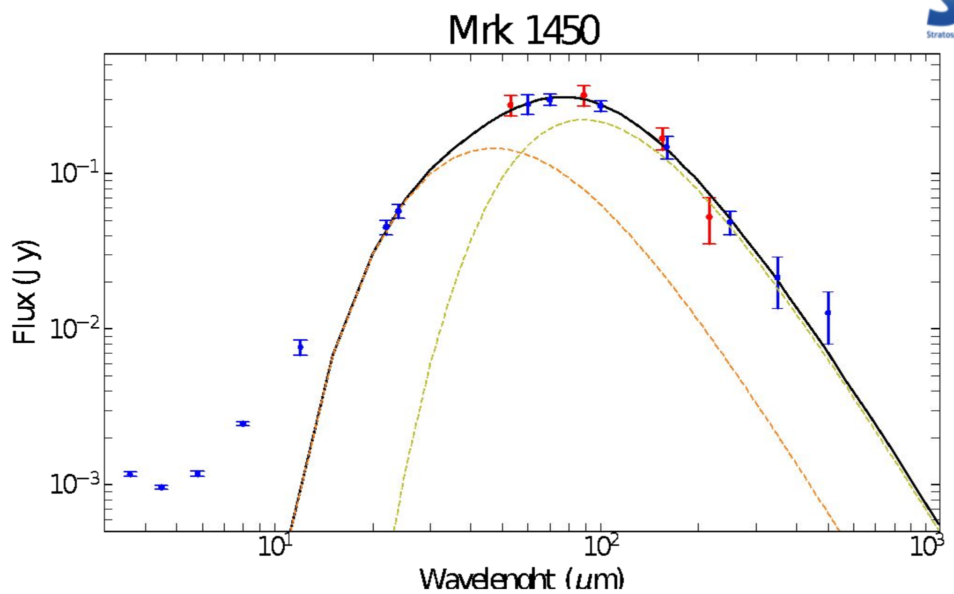
Mrk 1307



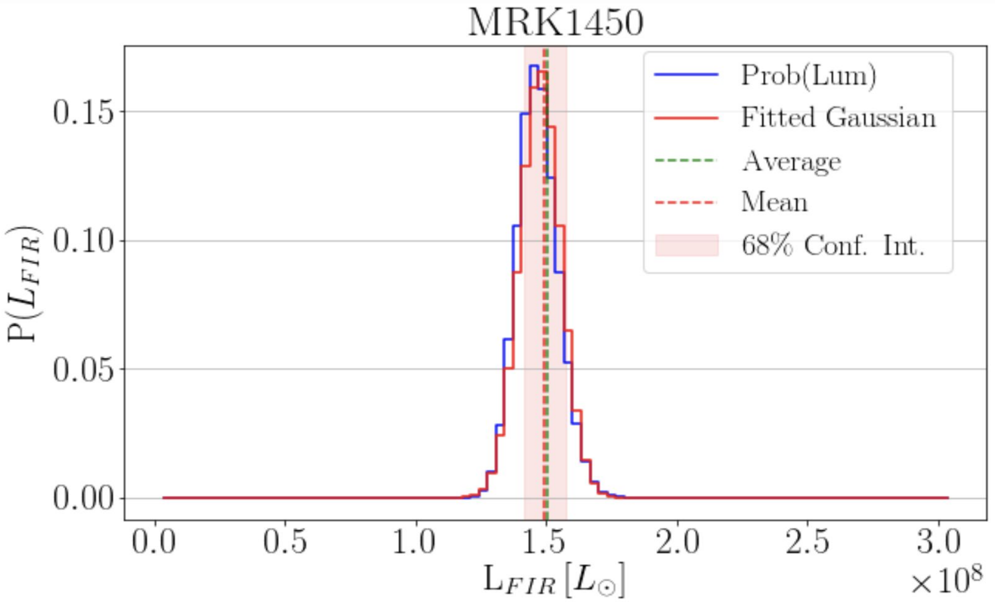
Diagnostic plots for the SED fits

Parameter correlations

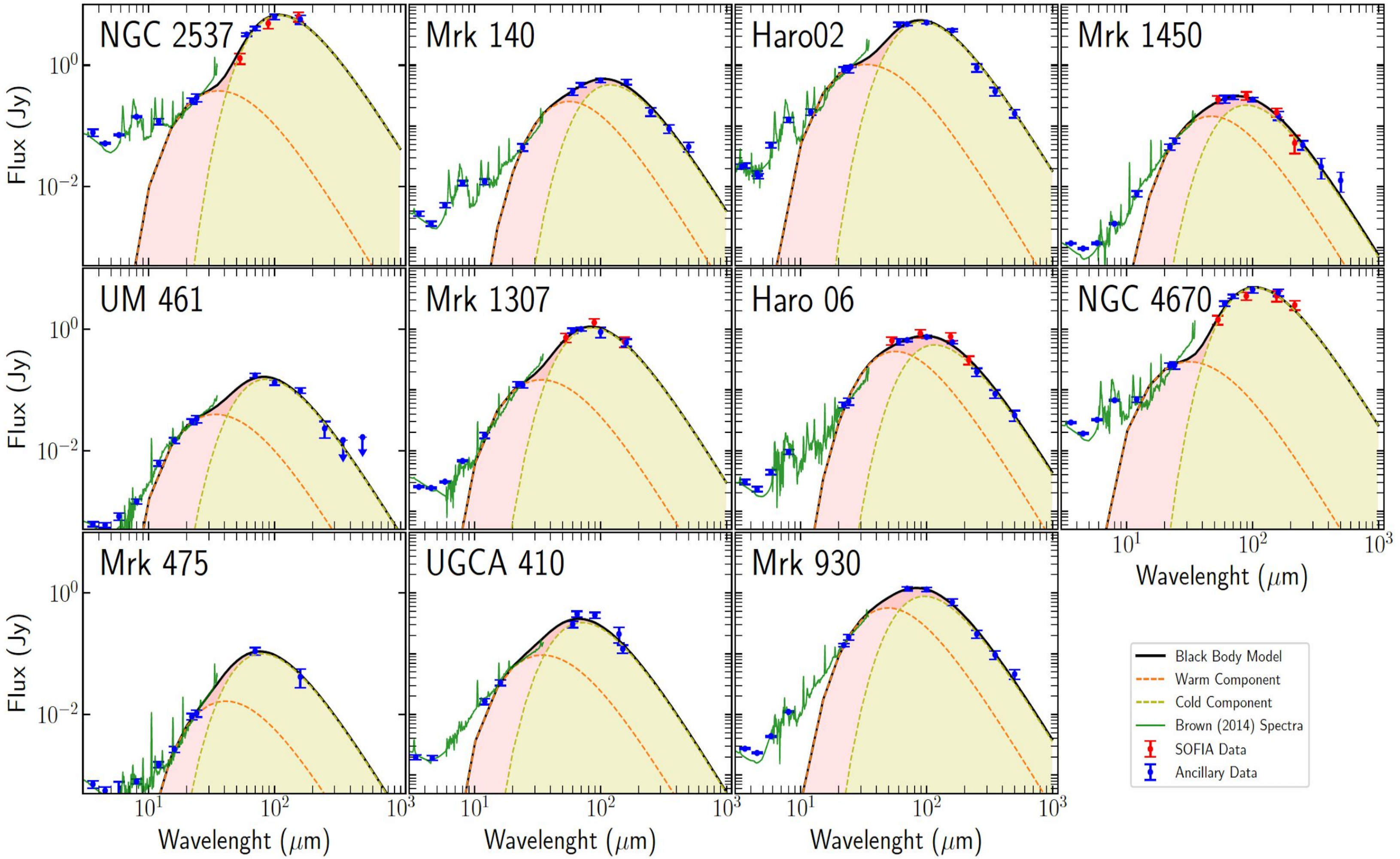


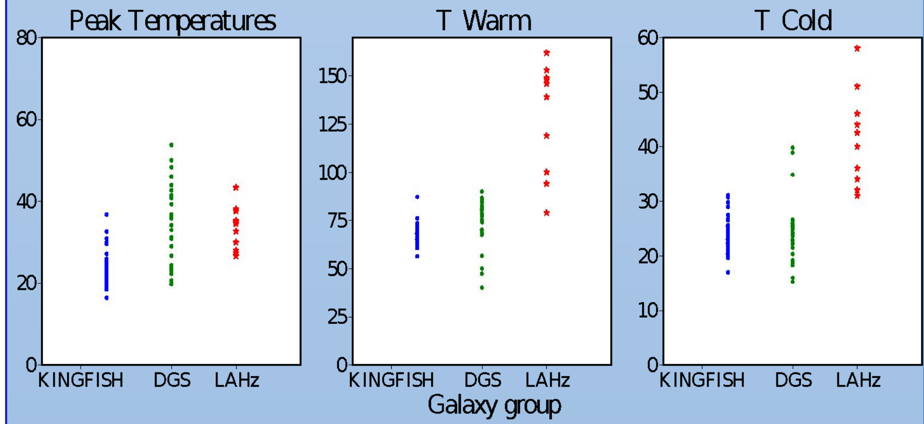


- FIR Luminosity



Results | Black Body Models
2 components





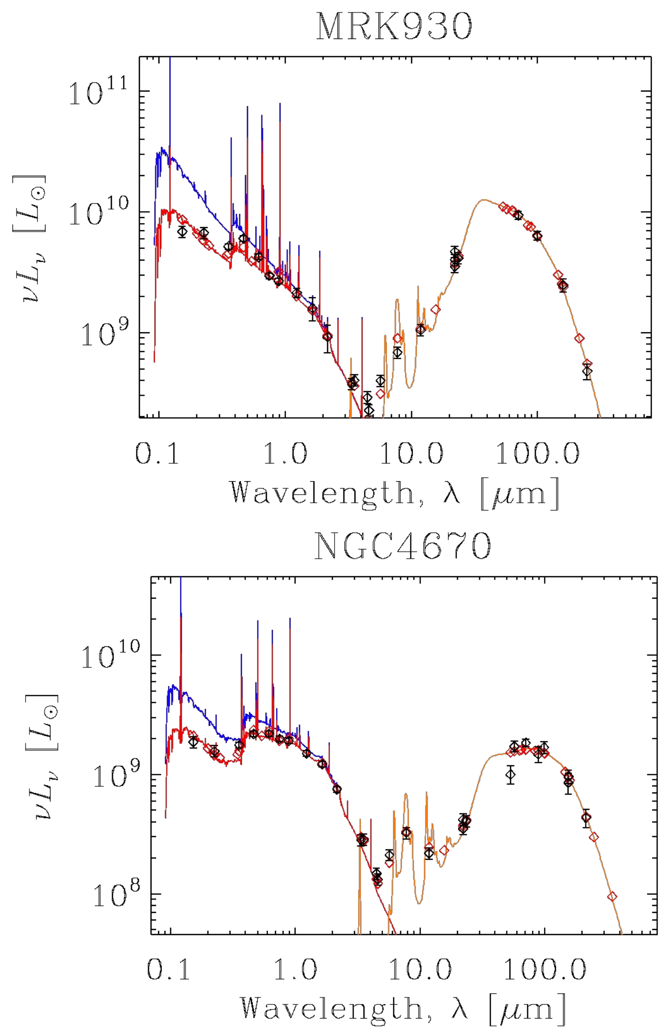
Galaxy Group	$T_{d,peak}$ K	$T_{d,Warm}$ K	$T_{d,Cold}$ K
Local Analogs to High-z	33.5 ±4.9	124.4 ±29.8	41.9 ±8.0
KINGFISH	22.7 ±4.0	67.9 ±4.72	23.4 ±3.8
Dwarf Galaxy Survey	35.6 ±9.6	74.6 ±12.8	24.5 ±5.6

FUV– FIR: Spectral Energy Distribution (SED)

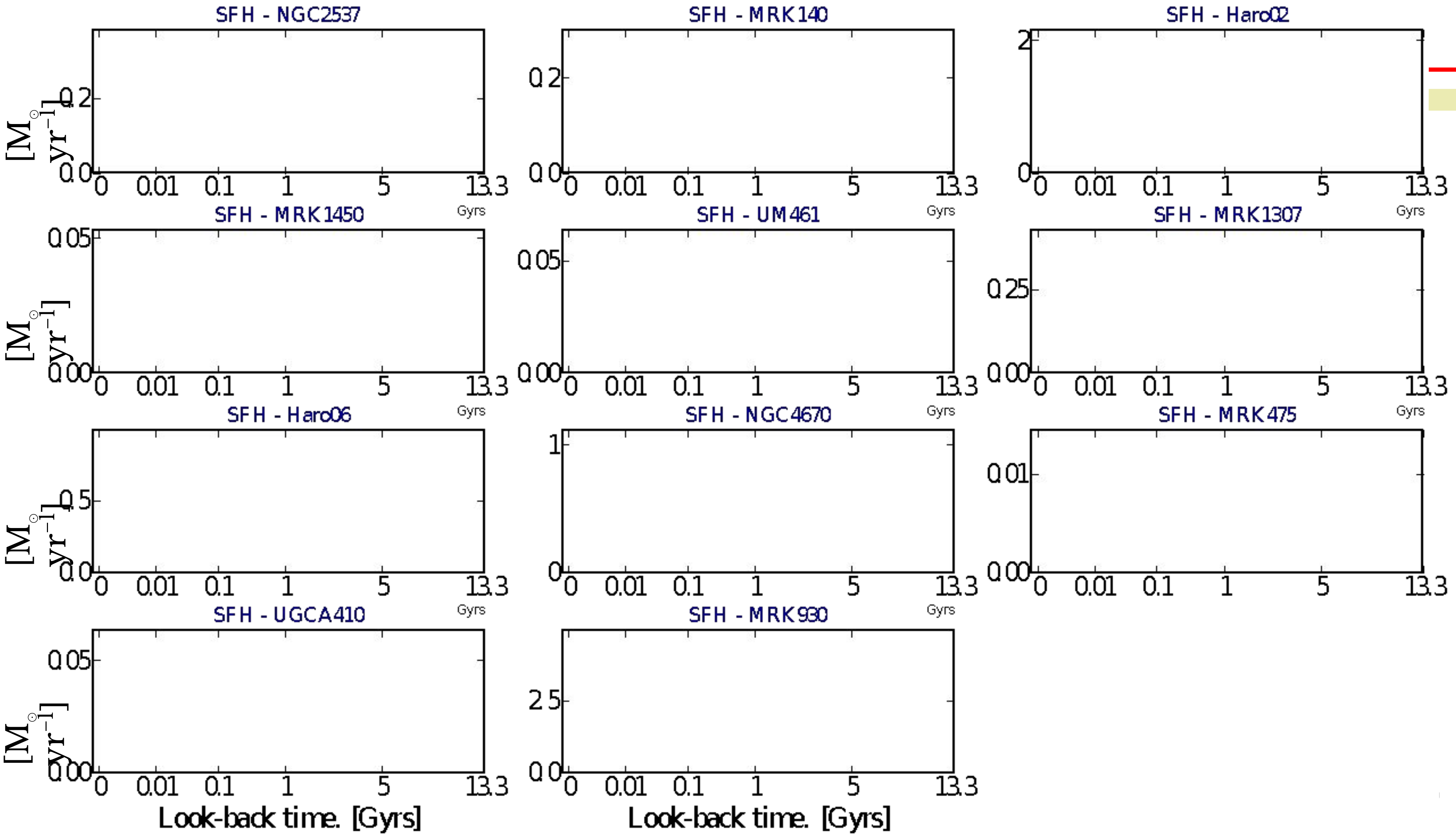
Using Lightning Package (*Eufrasio+17*):

- Fit 45 photometric bands from FUV – FIR.
- Adaptive MCMC procedure.

- Stellar emission:
  - **Star Formation Rate** (SFR).
  - **Star Formation History:** 5 look back time bins: 10, 100, 1k, 10k, 50k, 13.3k [Myr]
- IMF: Kroupa
- Dust attenuation
  - Modified Calzetti
- Dust emission
  - Draine & Li, (2007)
- For more information about LIGHTNING Package: github.com/rafaeleufrasio/lightning



Results | Star Formation History



Red solid line: Median.
The 16th and 84th percentiles, enclosing the yellow areas.

steps lookback times:
0, 10Myr, 100Myr, 1Gyr, 5Gyr, 13.3 Gyr.

Article:

- Skarleth M. Motiño Flores *et al.* 2021 *ApJ* 921, 130

https://iopscience.iop.org/article/10.3847/1538-4357/ac18cc

LIGHTNING Reference:

- Eufrasio R. et al. 2017 ApJ 851, 10.

https://iopscience.iop.org/article/10.3847/1538-4357/aa9569

Thanks

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- SOFIA Team, *FIFI-LS and HAWC+ scientific team.*

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Questions?

SOFIA products:

- Observations with SOFIA-HAWC+ (55, 89, and 155 micrometers)

Galaxy**: NGC 2537**
HST Optical + 155 μm Contours