Definition and Characterization of Local Analogs to High-z Galaxies

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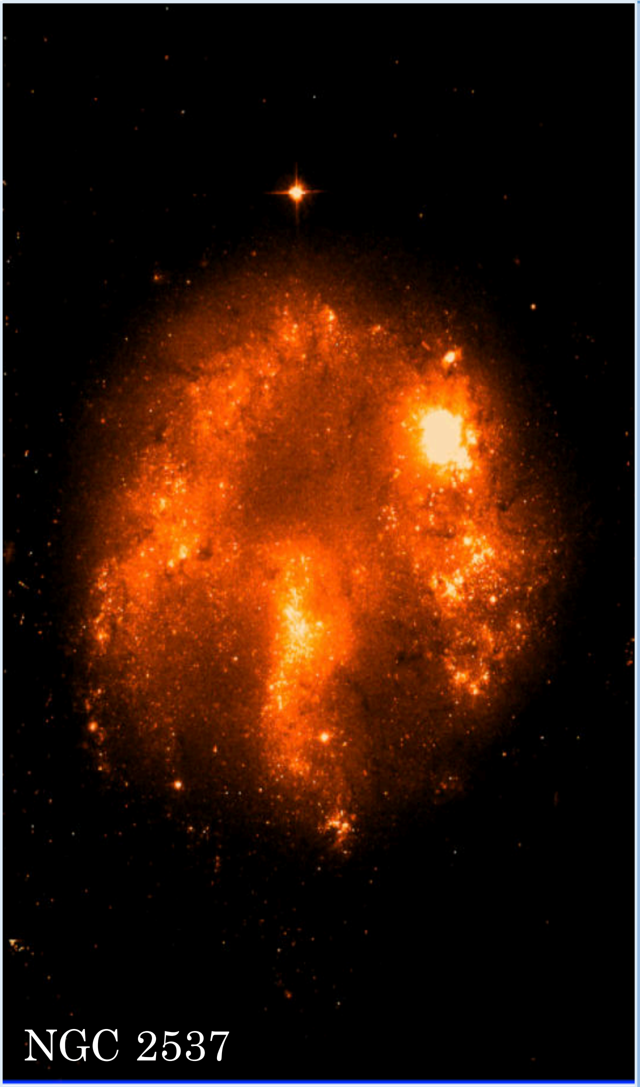
Outline



- ⭑ Introduction and Motivation.
- ⭑ Sample Selection.
- ⭑ Observations.
- ⭑ Modeling:
  - ⭑ Dust emission
  - ⭑ UV-FIR SED
- ⭑ Fine Structure lines.
- ⭑ Results.
- ⭑ Summary and Future Prospects.

Motivation

The Hubble Ultra 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 Local Analogs (low-*z*) to high-*z* galaxies.

Ultra Deep Field

Credits: VISUALIZATION: Frank Summers (STScI), Alyssa Pagan (STScI), Leah Hustak (STScI), Greg T. Bacon (STScI), Zolt G. Levay (STScI), Lisa Frattare (STScI)
SCIENCE: Anton M. Koekemoer , Bahram Mobasher HUDF Team (STScI), MUSIC: Dee Yan-Key

Motivation

The Deep Field

Local Analogs

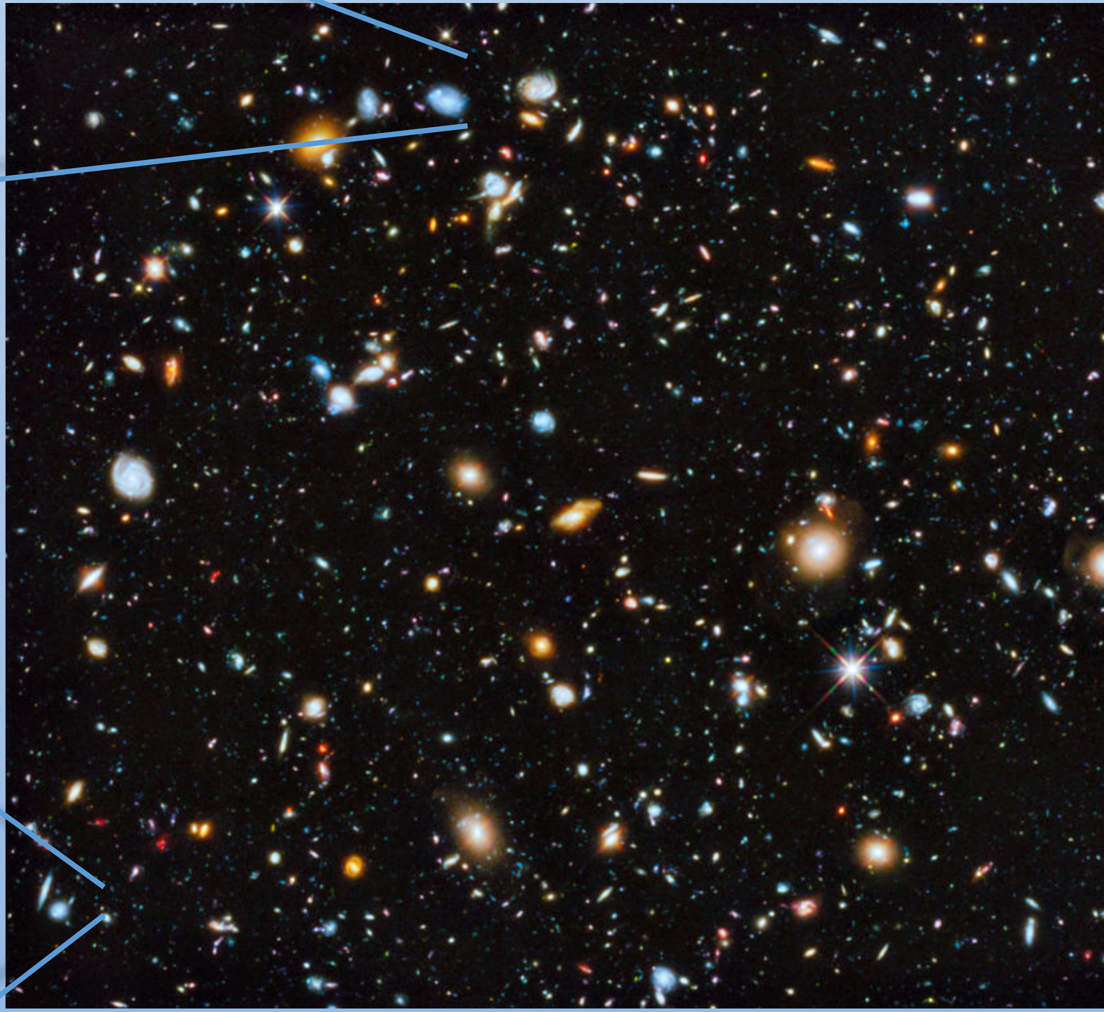
(Low Redshift):

- Irregular, Small, High Star Formation.
- Main features observable in the UV – Optical – Infrared

Early Galaxies

(High Redshift):

- Irregular, Small, High Star Formation.
- Main features (UV-optical) **redshifted** to the Infrared.

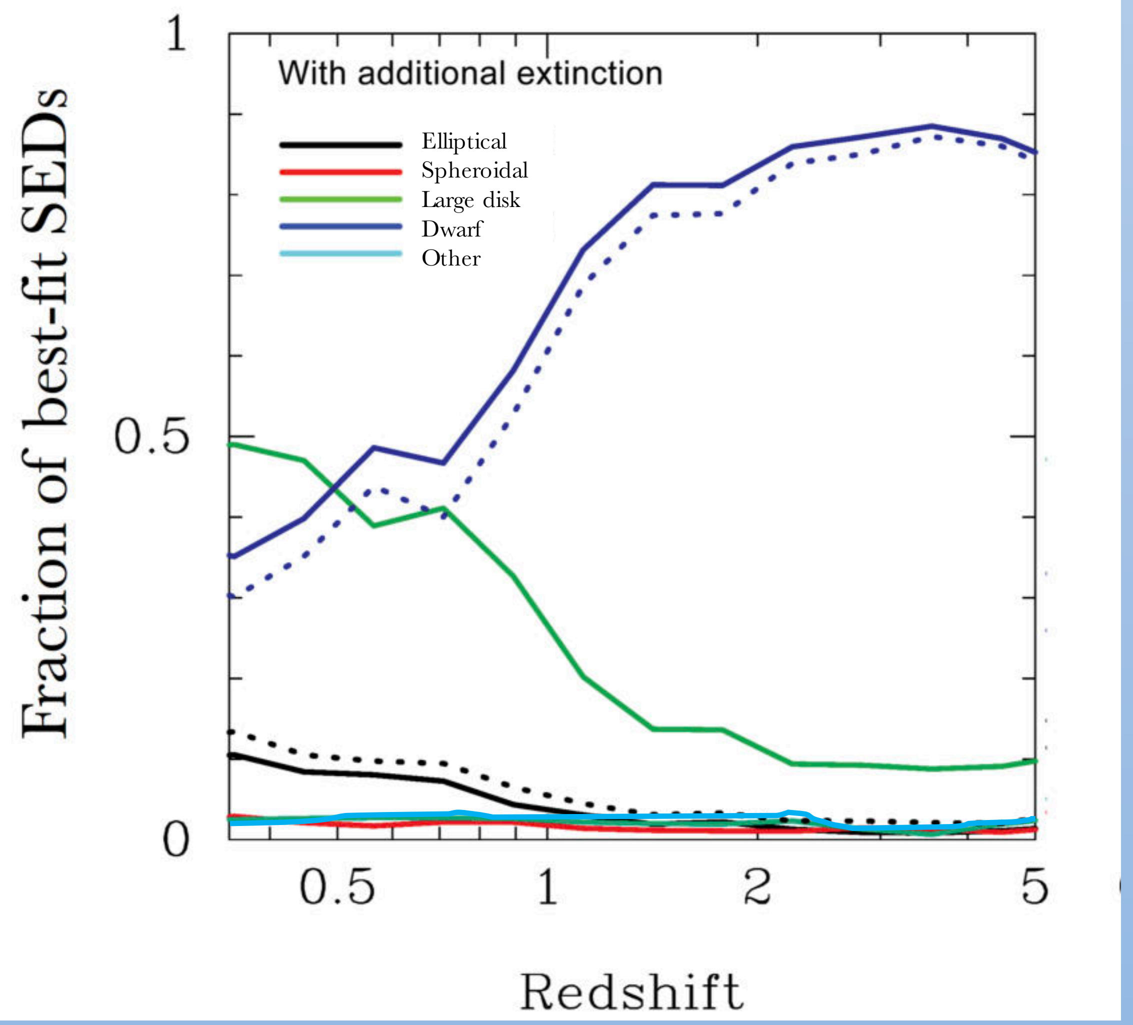


Ultraviolet Coverage of the Hubble Ultra Deep Field (UVUDF) project.
Credit: H. Teplitz and M. Rafelski (IPAC/Caltech), A. Koekemoer (STScI), R. Windhorst (Arizona State University), and Z. Levay (STScI) NASA, ESA,

Local Analogs Sample Selection

- Previous works: FUV luminosity, W(Hα), *i.e. Ostlin 2014, Hoopes 2007, Overzier 2014*.
- Novel Technique.
- 129 local galaxy templates (Brown+ 2014).
- Fitting observe SED of 159,645 high-z galaxies (z up to 5, CANDELS[1]).

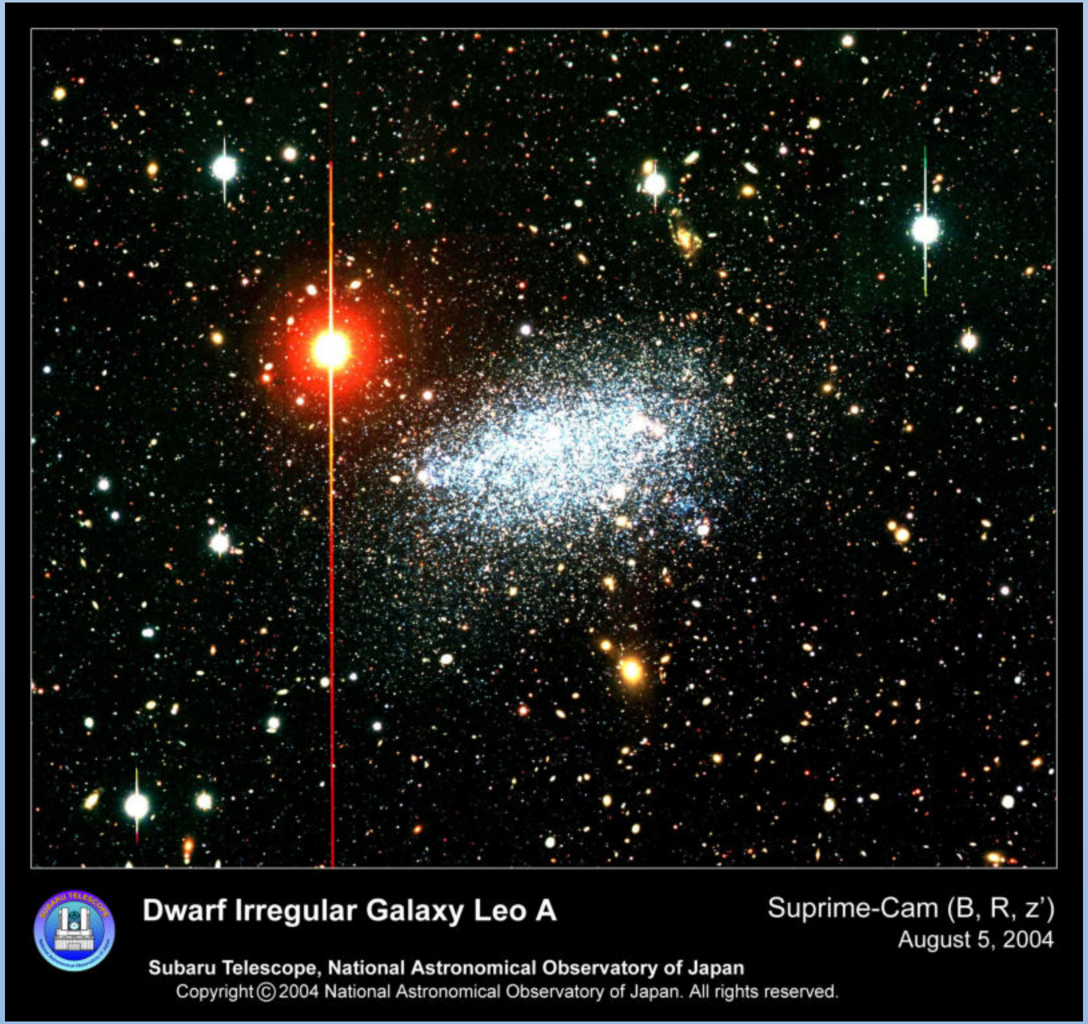
- **For galaxies at z>2 just 11 of the local template galaxies provide >90% of all the best-fit SEDs.**
- **Unique sample.**



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

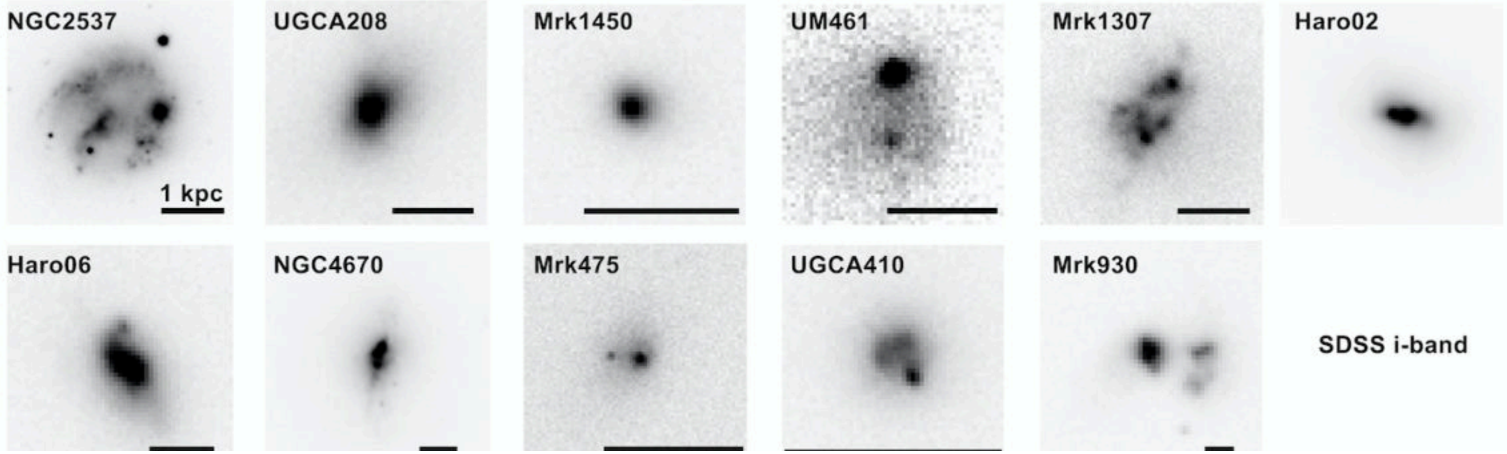
Dwarf Galaxies

- Dwarf Elliptical and Spheroidal
  - 10^7 to 10^8 M_{sun}
  - No evidence of star formation.
- Dwarf Irregulars
  - 10^9 M_{sun}
  - Clear evidence for ongoing star formation.
  - **Blue Compact Dwarf Galaxies**
    - **Young stellar population.**



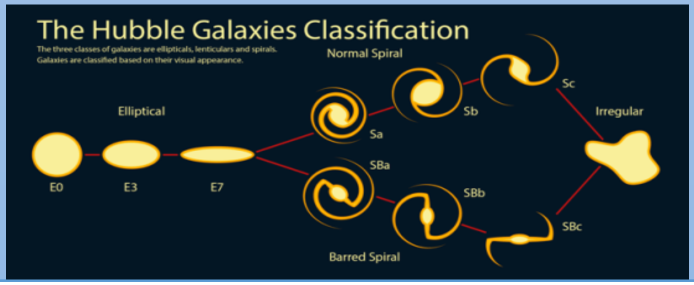
Baby Galaxies?

The Sample of Local Analogs: **Blue Compact Dwarf Galaxies** (BCDGs)



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

BCDGs do not fit in the Hubble sequence classification.



No.	Galaxy Name	RA (J2000.0)	Dec (J2000.0)	D Mpc	log $M_*^{(a)}$ $M_\odot$	log $M_{HI}^{(b)}$ $M_\odot$	$f_{gas}^{(c)}$ $M_\odot$	Metallicity$^{(d)}$ 12 + log (O/H)	Alternative Name
1	NGC 2537	08:13:14.4	+45:59:13	8.6	9.02	8.43	0.17	8.19	Arp 6; 'Bear Paw'
2	Mrk 140	10:16:28.3	+45:19:18	27.6	8.60	8.90	0.56	8.30	Mrk 140
3	Haro 02	10:32:31.9	+54:24:02	23.7	9.21	8.03	0.02	8.45	Mrk 033
4	Mrk 1450	11:38:35.6	+57:52:27	14.7	7.27	7.35	0.54	7.96	
5	UM 461	11:51:33.1	-02:22:22	20.7	7.37	8.47	0.96	7.78	
6	Mrk 1307	11:52:37.4	-02:28:09	21.0	8.07	8.73	0.81	7.96	UM 462
7	Haro 06	12:15:18.4	+05:45:39	35.1	8.58	8.83	0.69	8.18	
8	NGC 4670	12:45:17.1	+27:07:31	20.0	9.38	9.02	0.37	8.30	Arp 163
9	Mrk 475	14:39:05.5	+36:48:21	10.9	6.95	6.62	0.56	7.93	
10	UGCA 410	15:37:04.2	+55:15:48	10.5	7.26	7.58	0.57	8.10	Mrk 487
11	Mrk 930	23:31:58.6	+28:56:50	77.5	8.89	9.51	0.74	8.08	

(a) *Stellar mass* M_* This work. (b) *HI* data from Paturel et al. (2003), except for Mrk 1450 (van Driel et al. 2016). (c) *Gas fraction* is defined as $f_g = M_g/(M_g + M_*)$. (d) *Metal Abundances* UM 461 and UM 462 (Campos-Aguilar et al. 1993), Haro 02 (Davidge 1989).

Studying the physical properties of Galaxies

Interstellar Medium

Stellar Emission. + [Dust Emission. + Emission Lines (Gas).] = Energy characterization of Galaxies.

Stellar emission

The **star light** can be observed:

- Directly in the UV-Optical.
- Indirectly in the Infrared.
- Modeled as **black body radiation.**

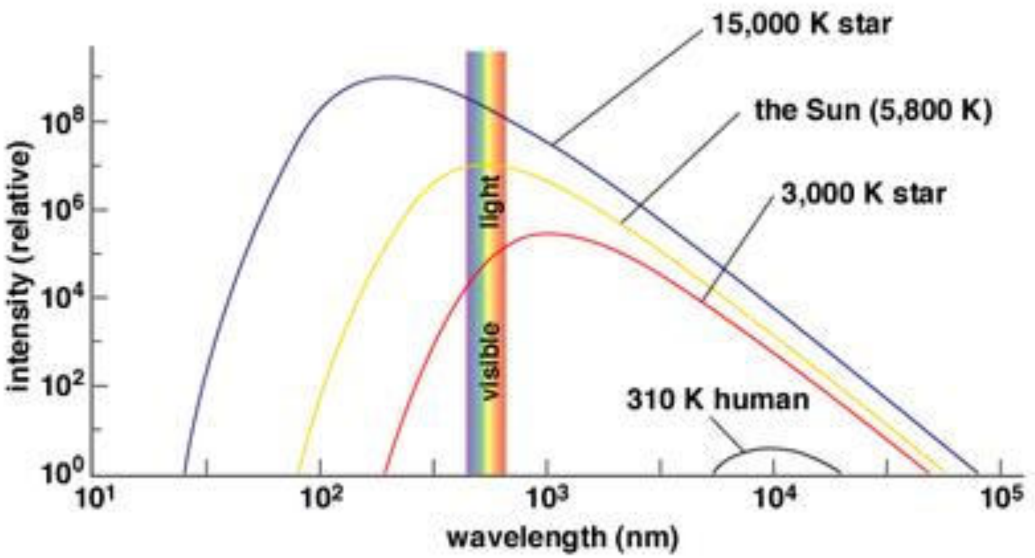


Image credits:
1. *NGC 4775 cluster Wide Field Imager (WFI) on the MPG/ESO La Silla Observatory.*
2. *BB temperatures by Adison Wesley*

Dust

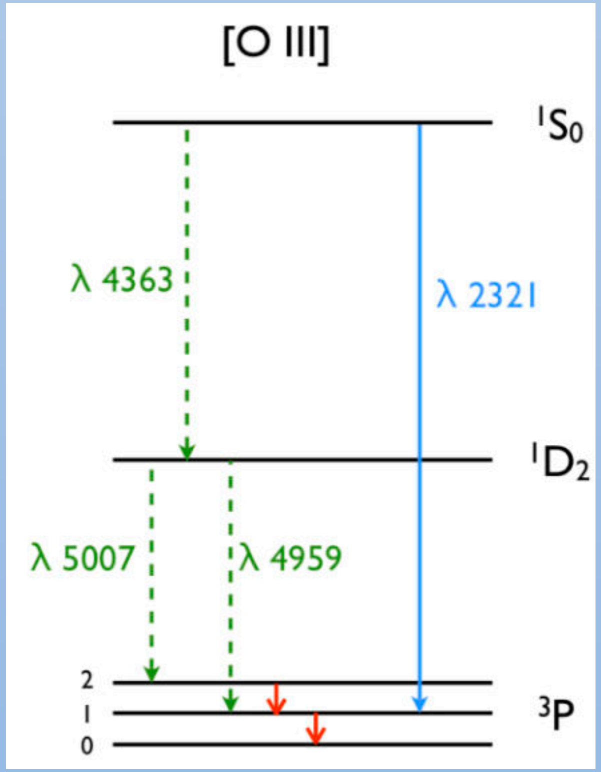
- Interstellar space appears to be empty. However, this is wrong!

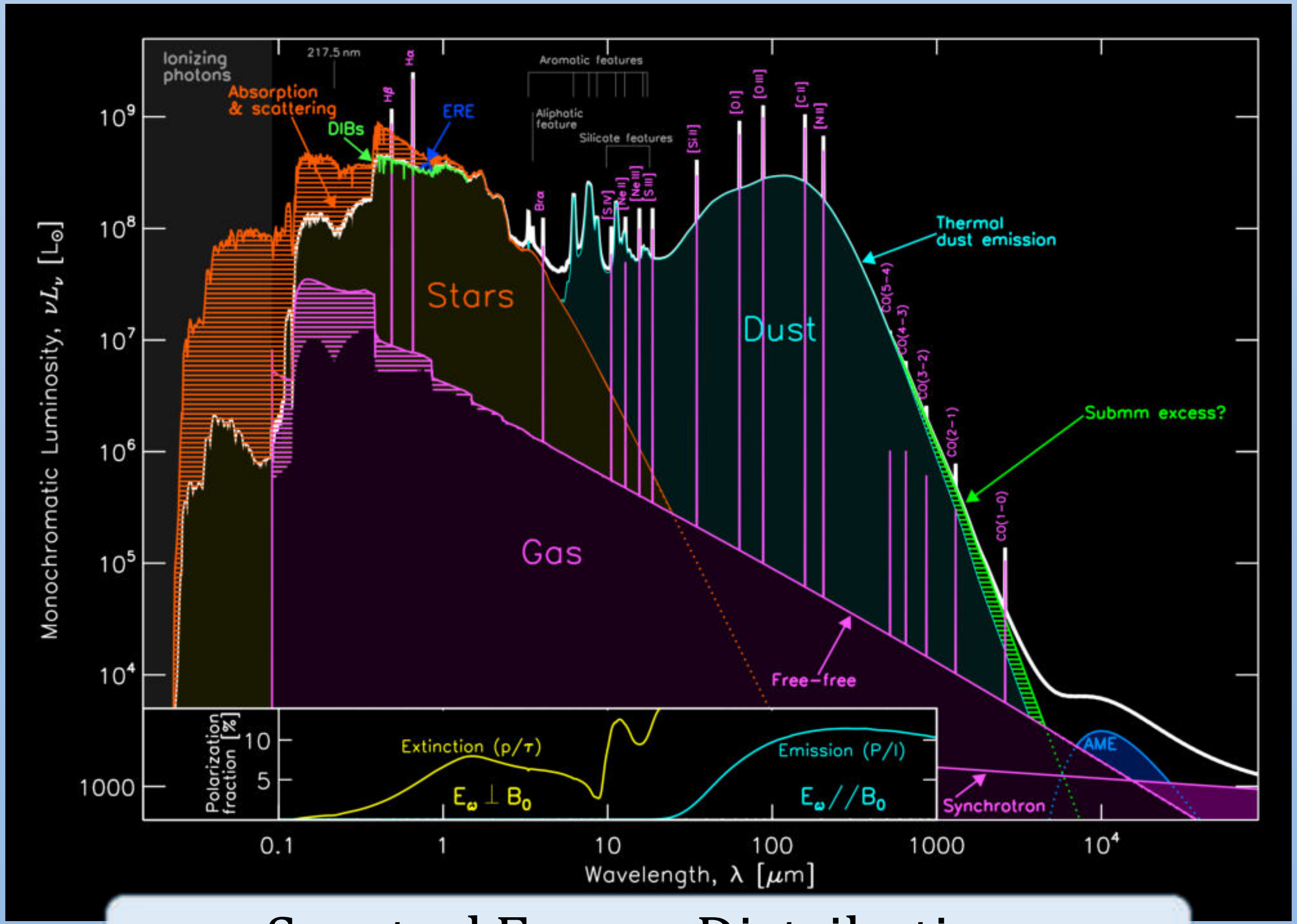
- Interstellar dust in galaxies absorbs energy from starlight; this absorbed energy is then re-radiated at infrared (IR) and far-IR (FIR) wavelengths.

Image Credits:
Left: NGC1333 - NASA/CXC/JPL-Caltech/NOAO/DSS.
Right: Horse Nebula. NASA GODDARD. GSFC_20171208_Archive_e001518

Interstellar Gas Emission Lines

Powered by Star Formation.





Spectral Energy Distribution.

Observations: 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]

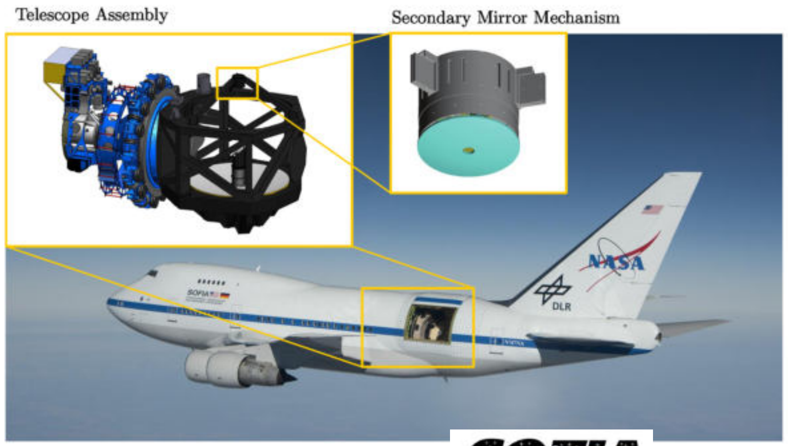
- **FIFI-LS**

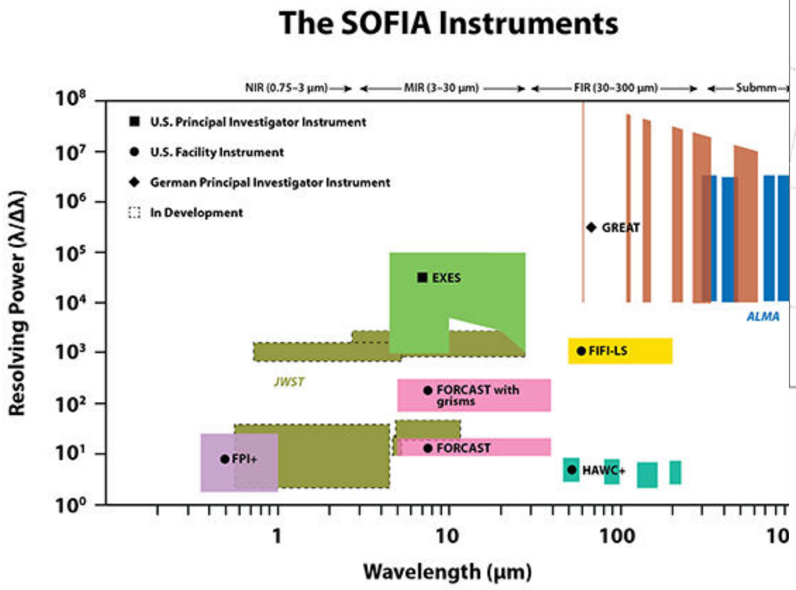
Field Imaging Far Infrared – Line Spectrometer [42 – 210 μm].

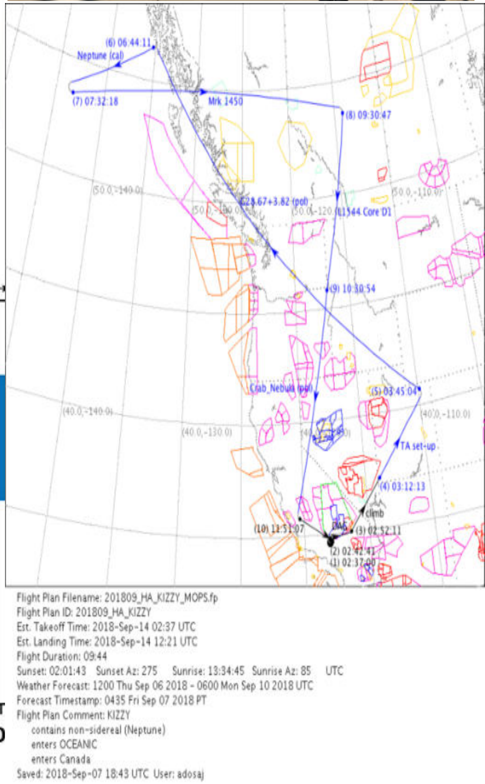
Allows us to map FIR fine structure lines.

  - [CII] 157.77 μm
  - [OIII] 88.36 μm

- Ancillary data:
  - **Spitzer**
  - **Herschel**
  - **WISE**
  - **AKARI**





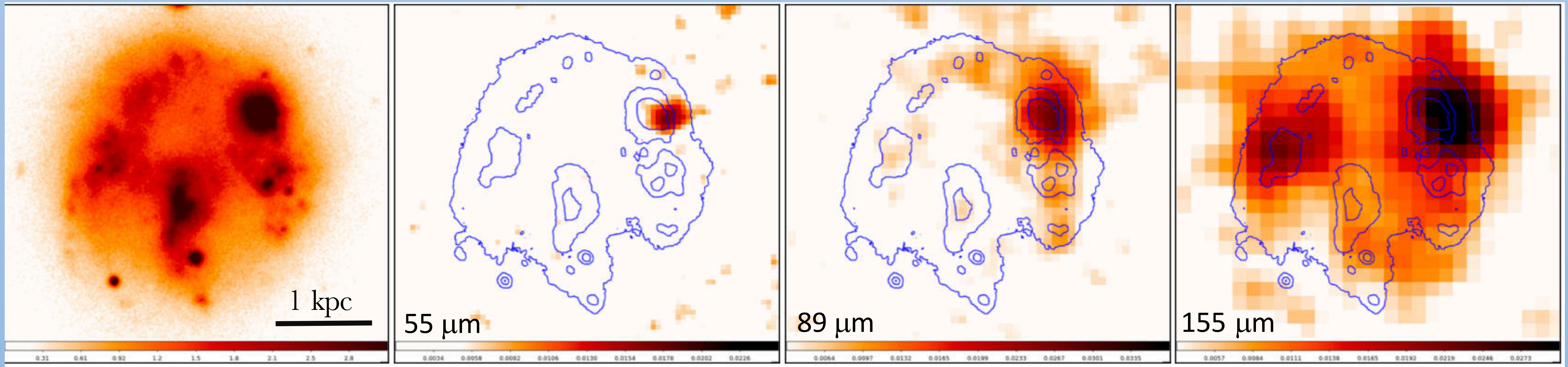


SOFIA products:

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

Galaxy: **NGC 2537**

HST Optical + 155 μm Contours



Black Body modeling

- Modified Black Body Function:

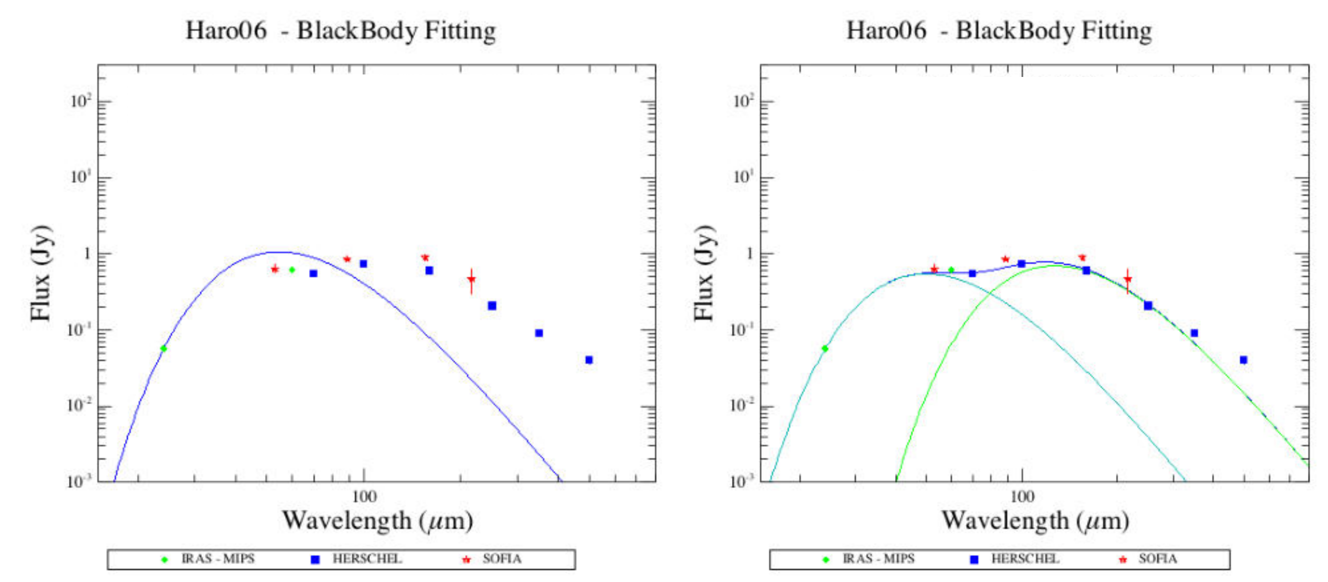
$$B_\nu(T) = \frac{2h\nu^3/c^3}{e^{h\nu/kT}-1}$$

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

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

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

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



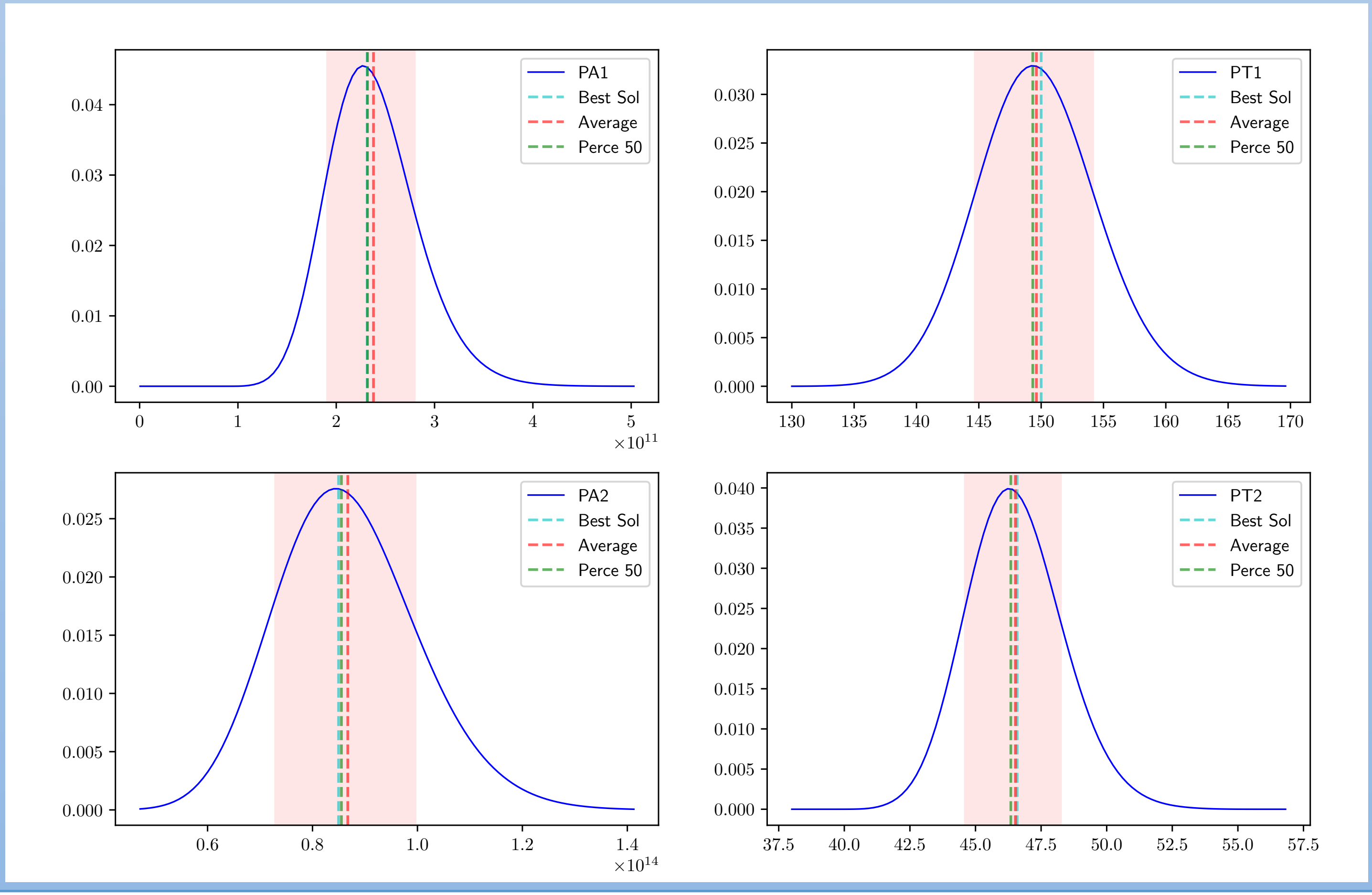
- SOFIA-HAWC+: 55, 89, 155, and 216 μm (in red).
- Herschel: 70, 100, 160, 250, 350, 500 μm (in blue).
- Spitzer- MIPS: 24 μm (in green).

Bayesian Inference of parameters

- Parameters:
  - Temperatures: T_1, T_2,
  - Norm Const: Ω_1, Ω_2.
  - β, λ_0 – Constants.
  - Grid 4D **100x100x100x100** over the parameter space.
  - **10^8** models.
- Likelihood: $p(D_i|\phi)$

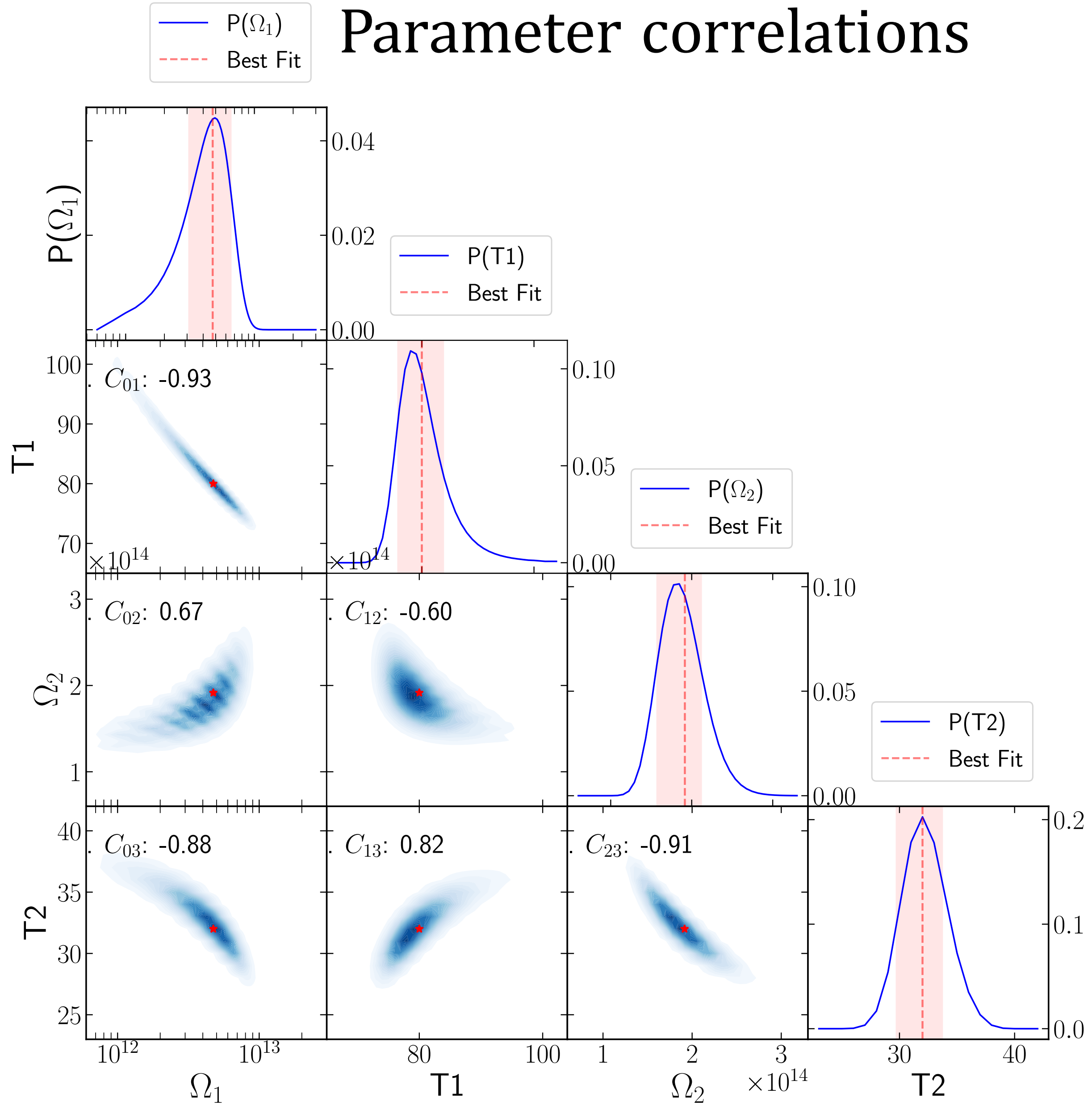
$$p \propto \exp\left(-\chi^2/2\right).$$

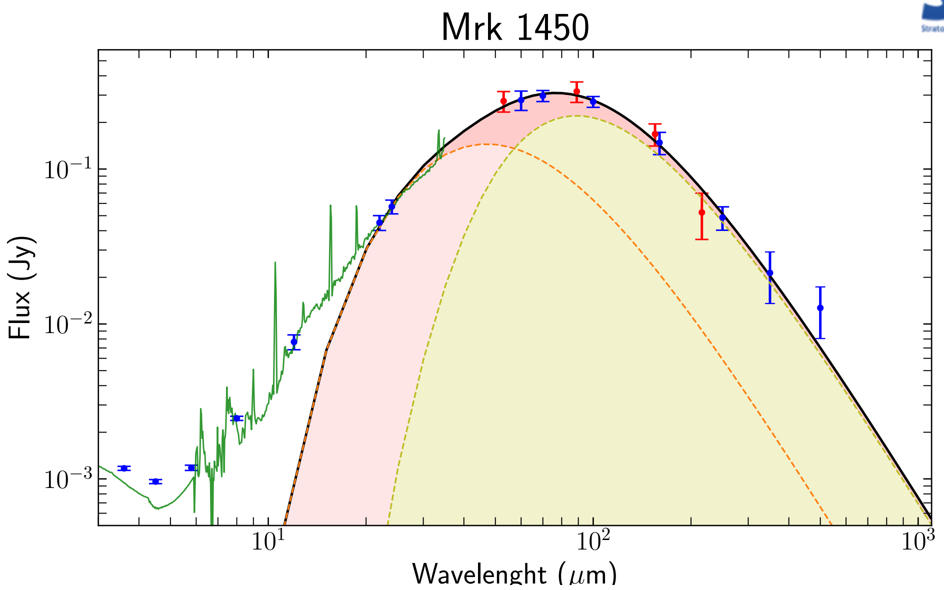
Posterior: Marginalized Probability Distributions
Mrk 1307



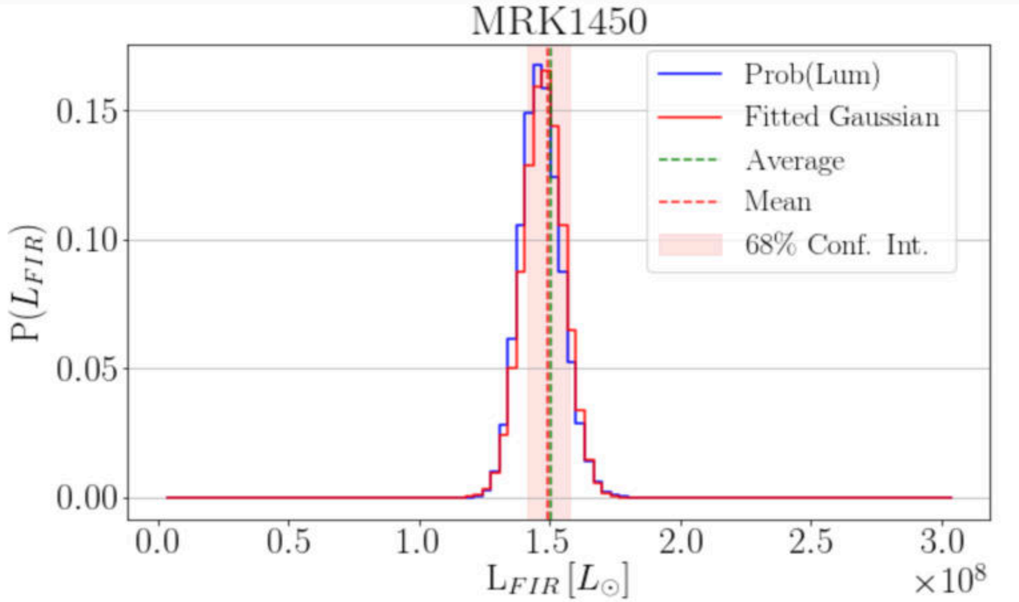
Diagnostic plots for the SED fits

Parameter correlations



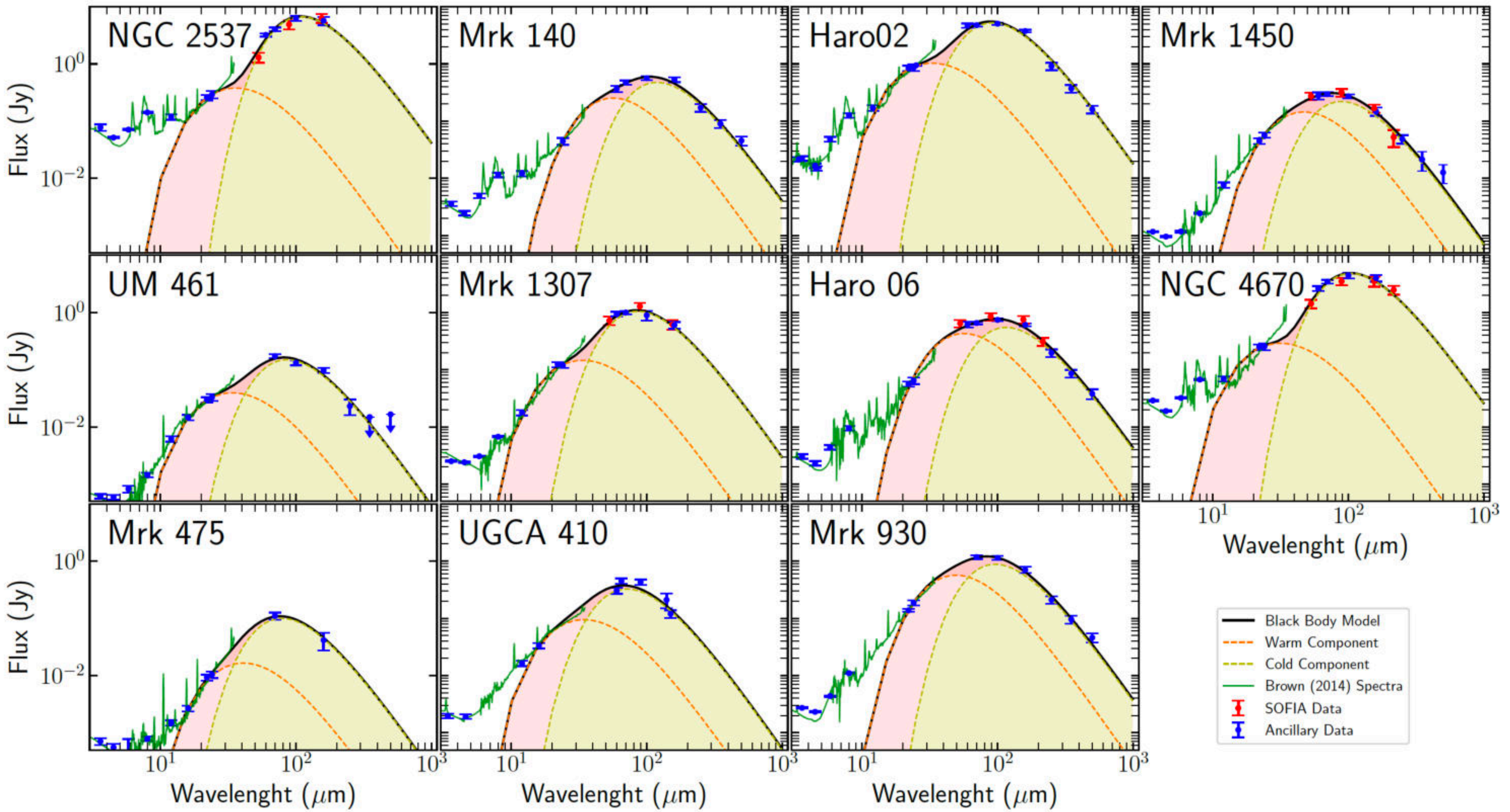


- FIR Luminosity



SOFIA
Stratospheric Observatory for Infrared Astronomy

Results | Black Body Models

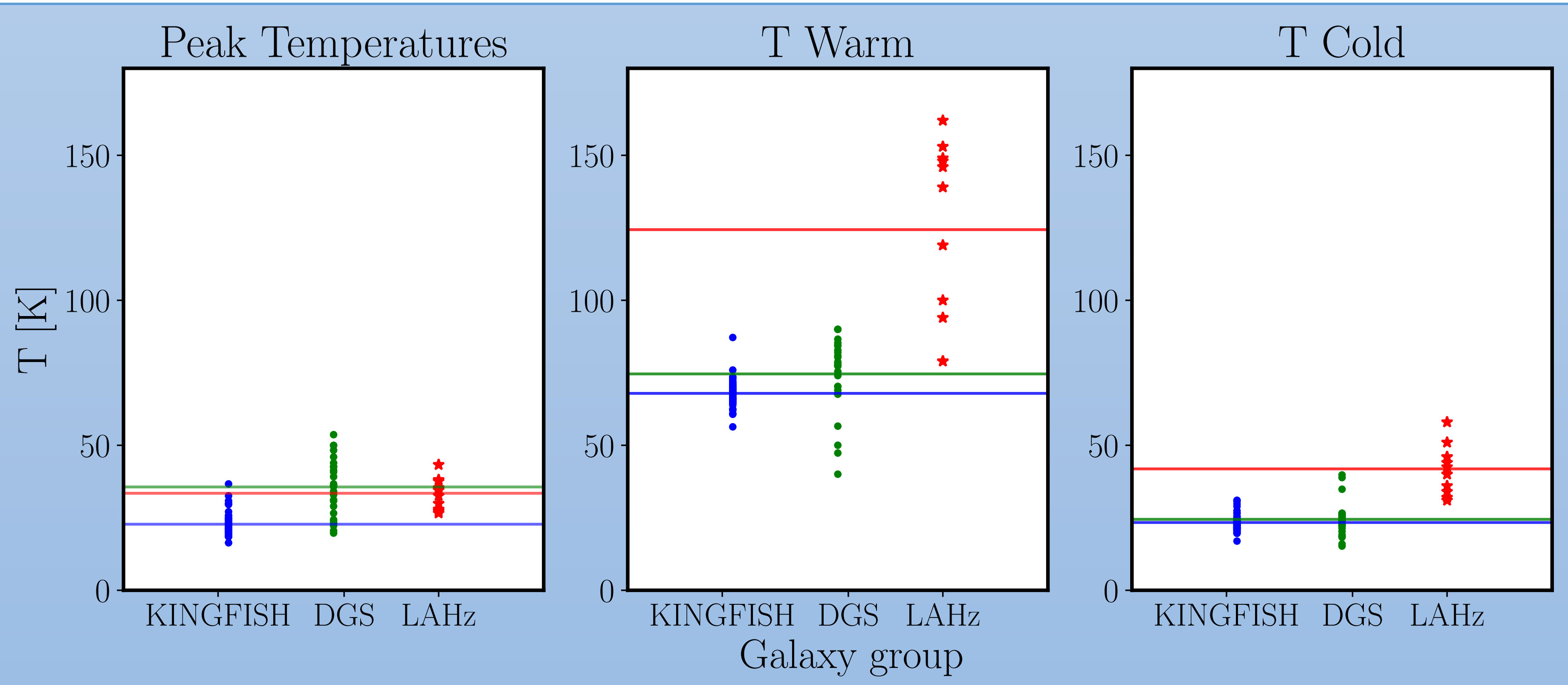


SOFIA (53-216 m) in red.

Herschel (60-500 m), Spitzer (24, 60, 100, 160 m) and other ancillary data points are in blue.

Solid green line is Brown+2014 spectra. (Not fitted).

Results | Black Body Models

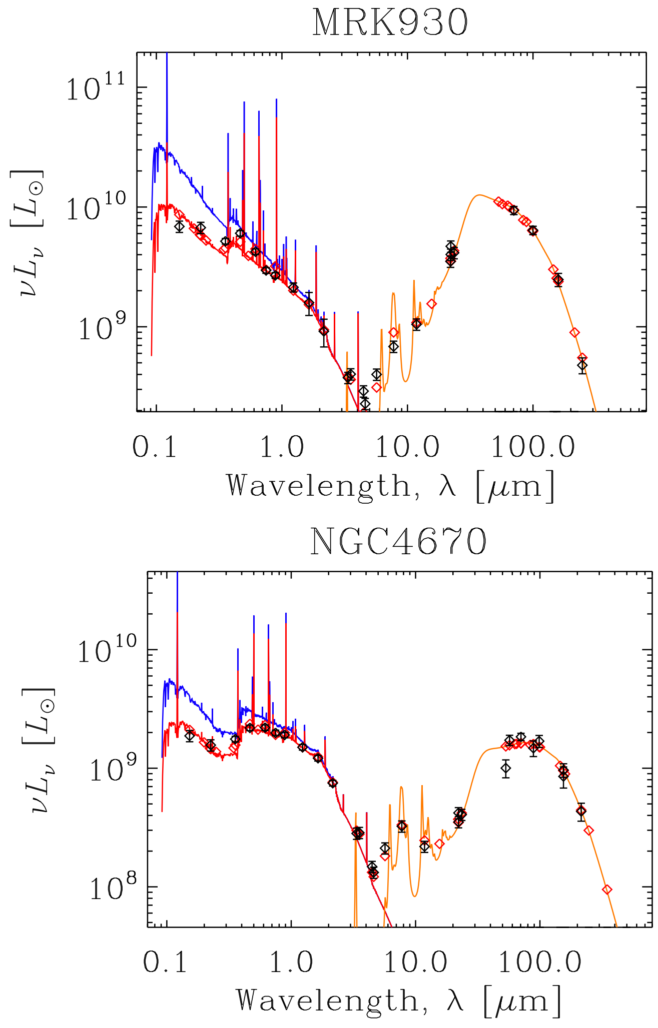


NAME	$T_{d\,Peak}$ K	$T_{d\,Warm}$ K	$T_{d\,Cold}$ $M_\odot$
Local Analogs	33.5	124.4 ± 29.8	41.9 ± 8.0

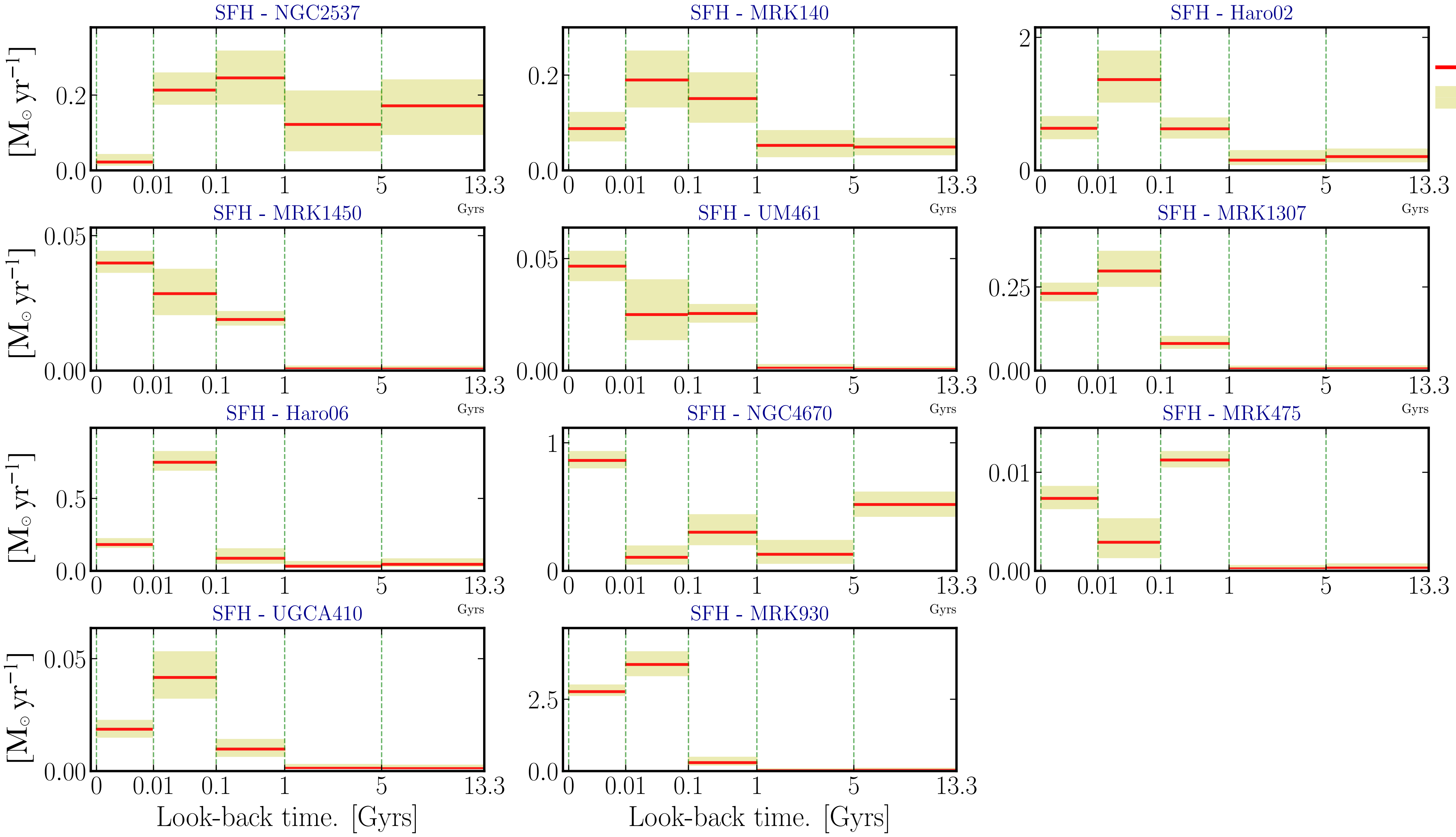
FUV– FIR: Spectral Energy Distribution (SED)

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



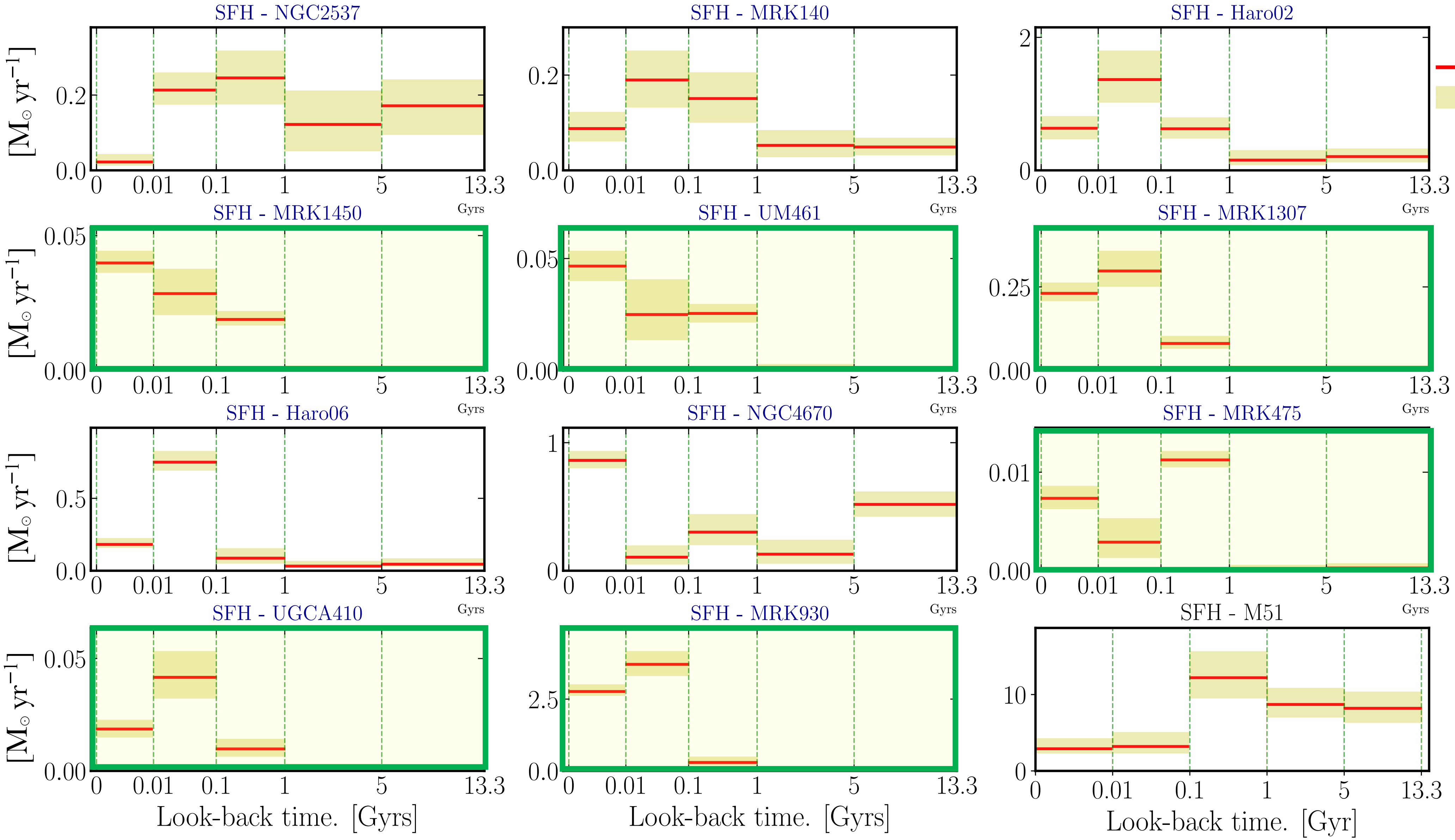
Results | Star Formation History



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

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

Results | Star Formation History



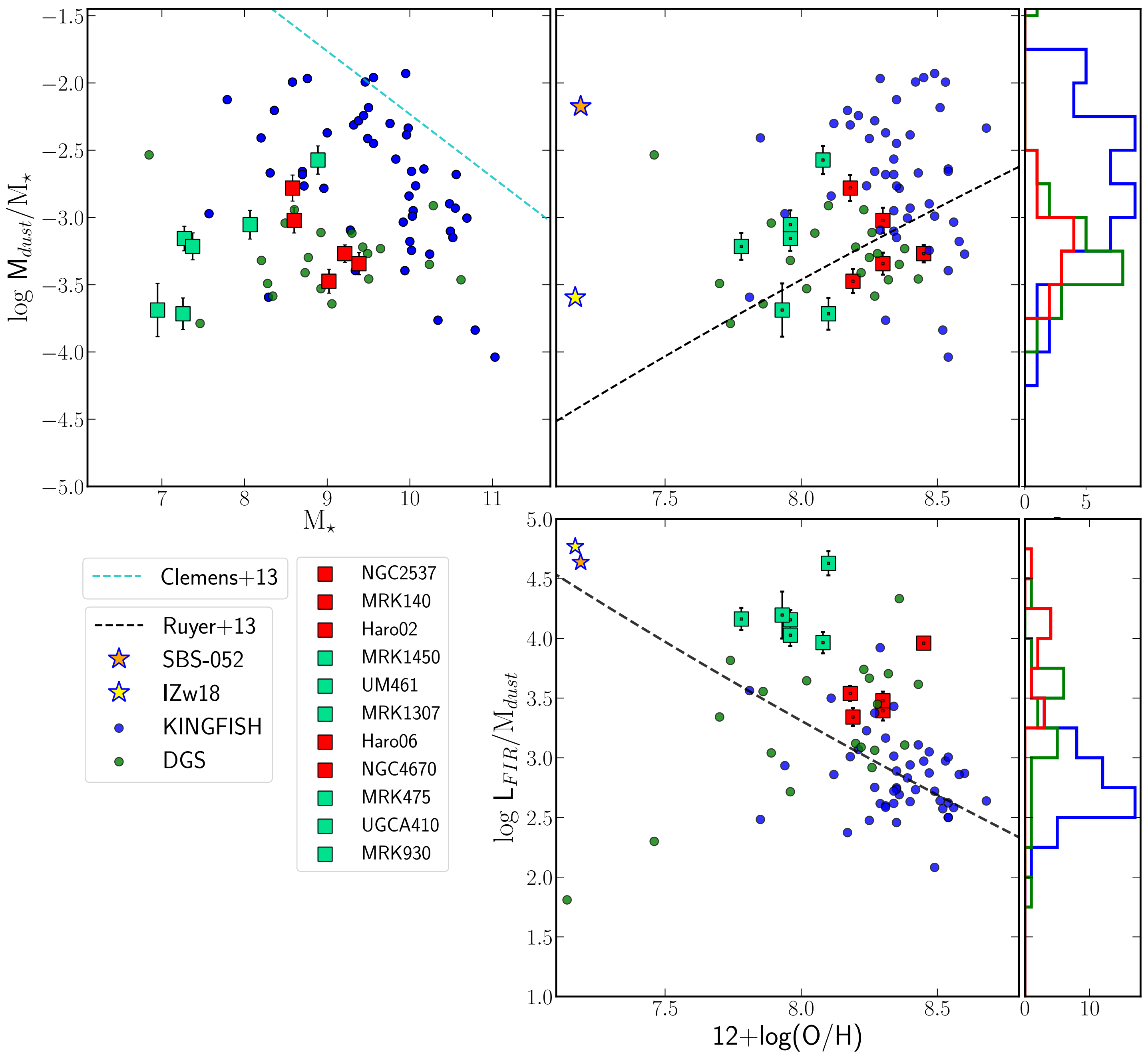
Red solid line: Median.
The 16th and 84th percentiles, enclosing the yellow areas.

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

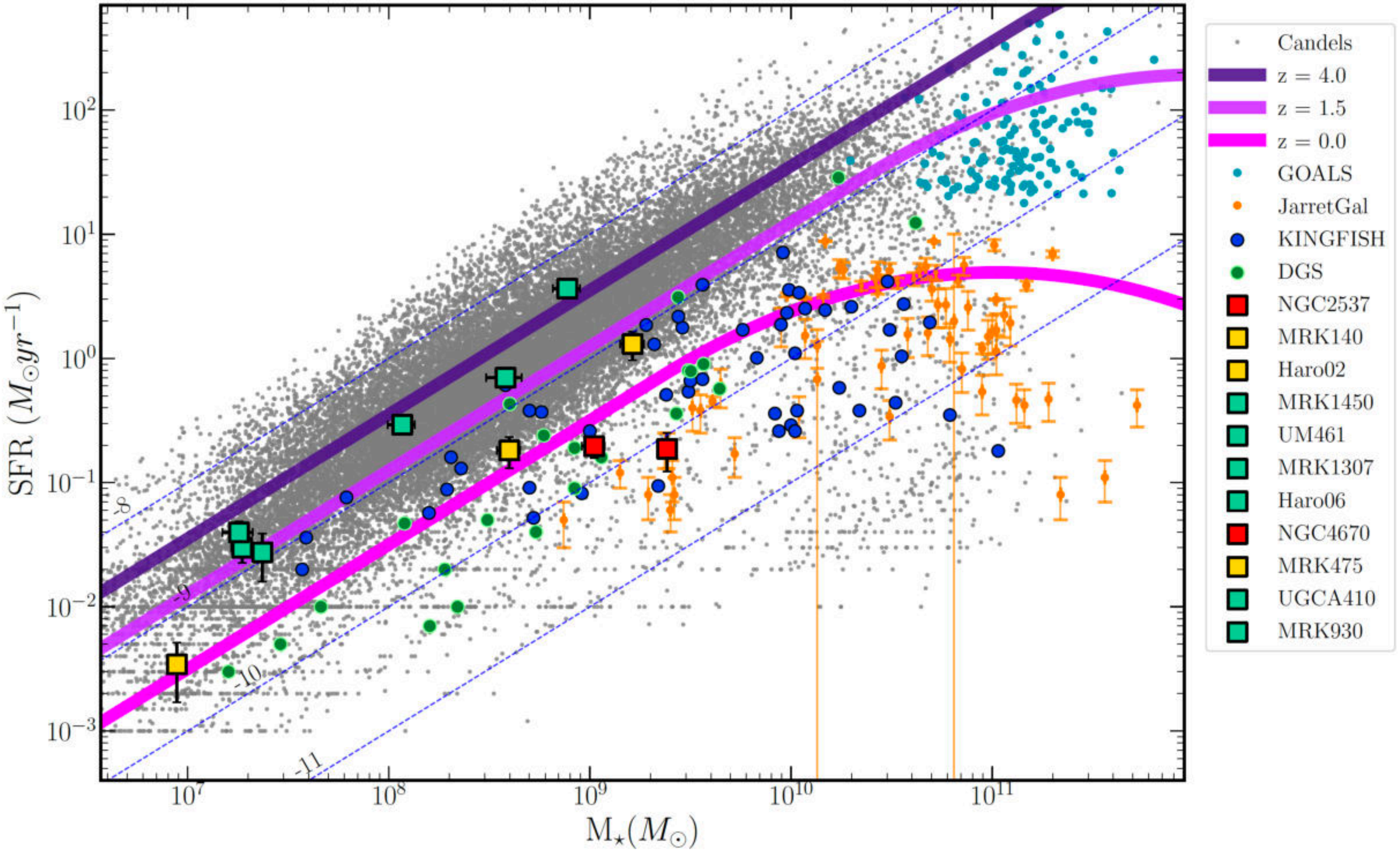
Messier 51 (The Whirlpool Galaxy)

SFH Ref: Eufrasio et al. 2017.
Image Credits: NASA, ESA, S. Beckwith (STScI) and the Hubble Heritage Team (STScI/AURA)

Dust Mass relations.



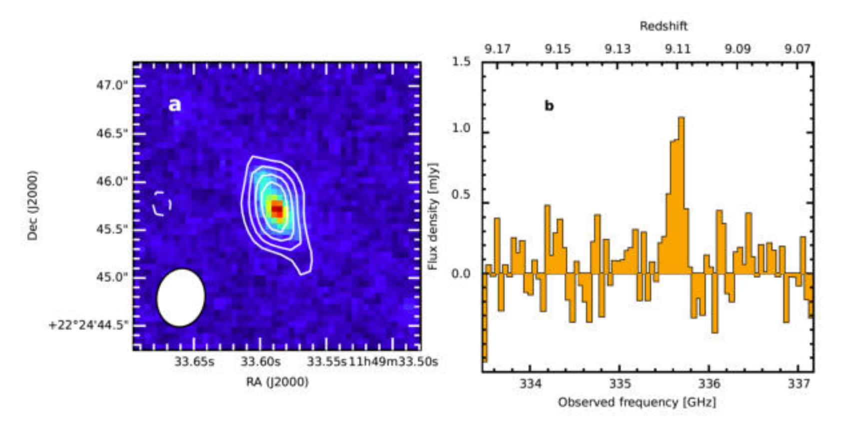
Results | Star Formation Rate vs Stellar Mass



- 9 Galaxies are
  - Starburst at z = 0.
  - Star Forming at z > 1.5 - 4
- NGC2537 and NGC4670.
- Motiño Flores et al. 2021. arxiv.org/abs/2105.03034

Fine Structure Lines Emission

	Transition Prob. A(s^{-1})	Wavelenght λ	n_{crit} cm^{-3}	Ionization Potential
[CII]	2.3 x 10^{-6}	157.74 µm	3000	11.26 eV
[OIII]	2.7 x 10^{-6}	88.356 µm	2000	35.10 eV



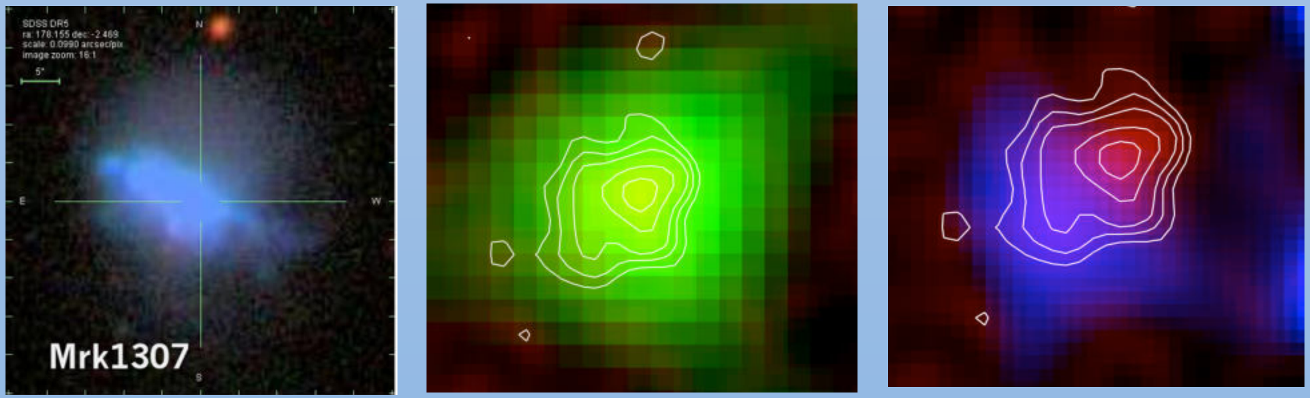
z = 9.1
earliest detected galaxy.
[OIII]88 µm
Ref: Paolo Serra 2017

Mrk1307: SOFIA HAWC+ and FIFI-LS observations showing:

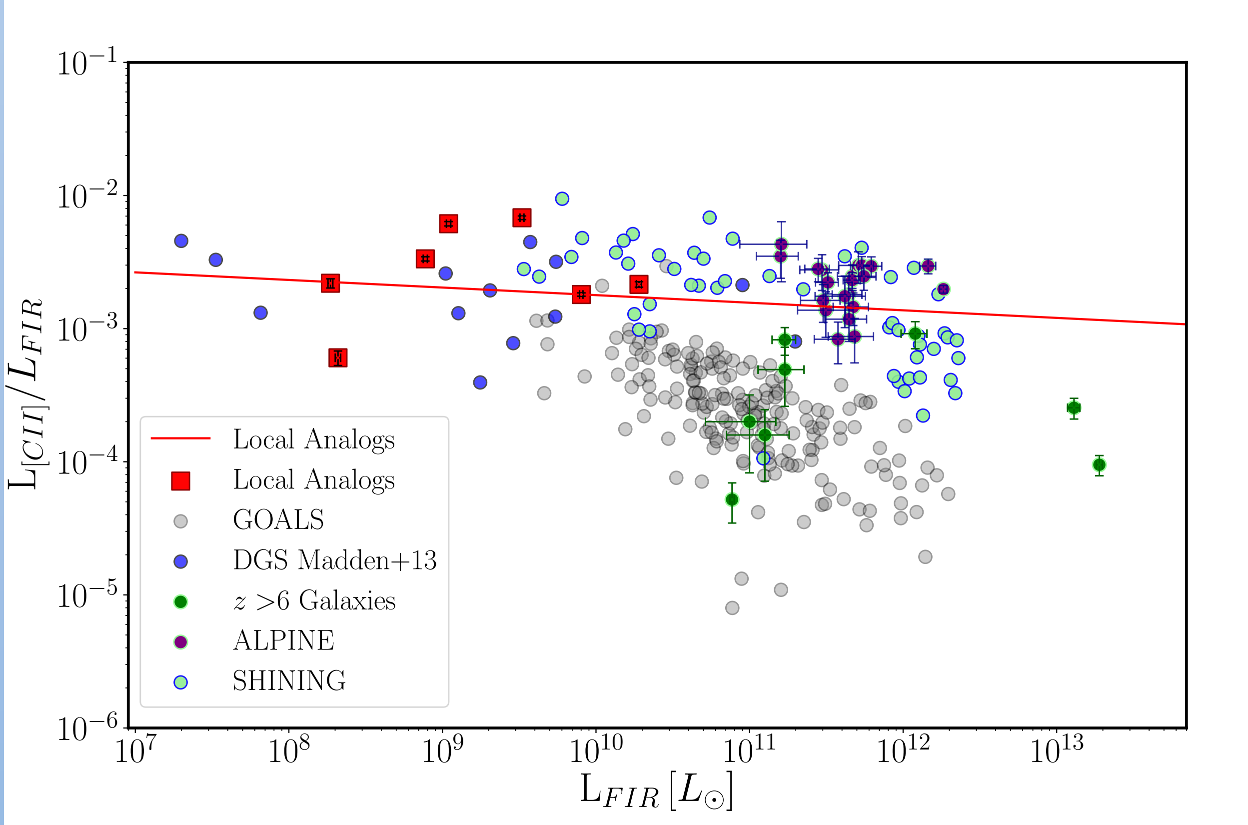
Distribution of dust continuum (red color and contours)

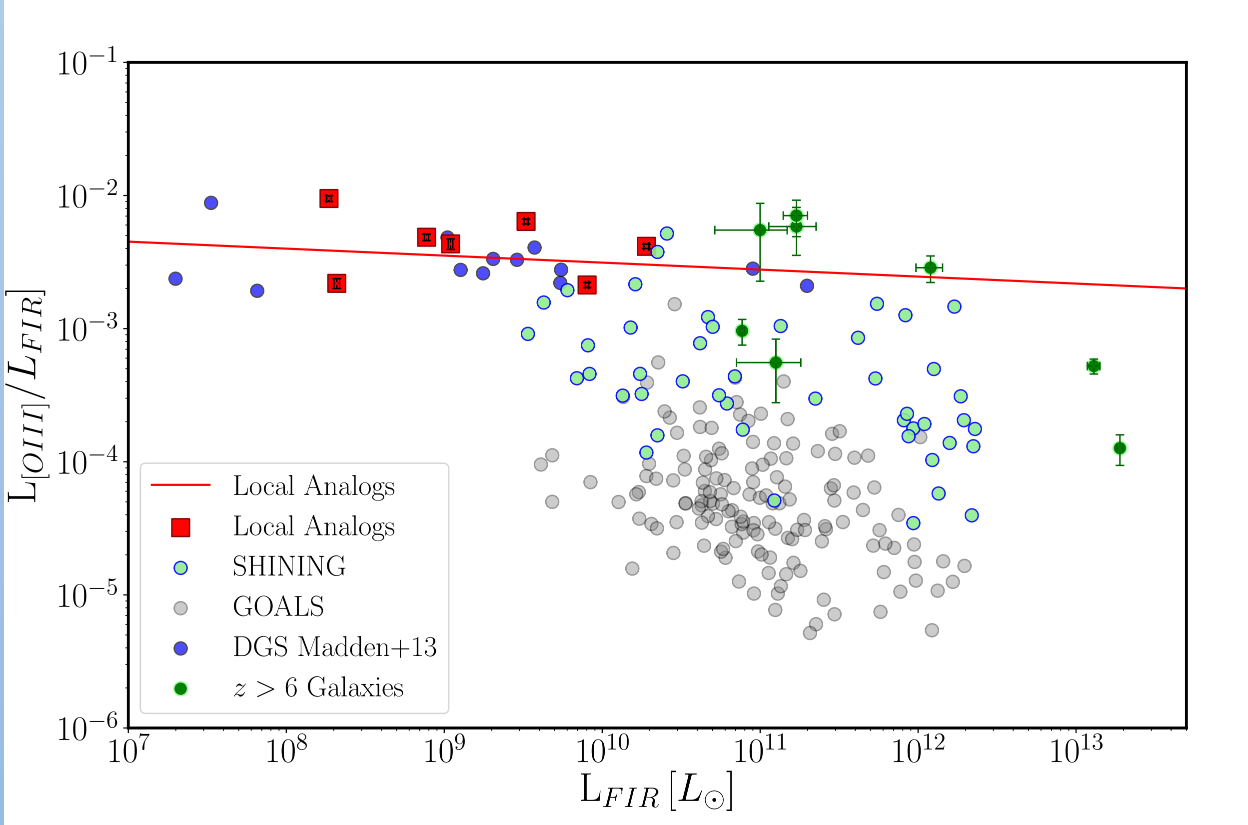
[CII] 158 µm (green)

[OIII] 88 µm (blue).



Preliminary Results:
[CII]157μm and [OIII]88μm, Relation with Star Formation.

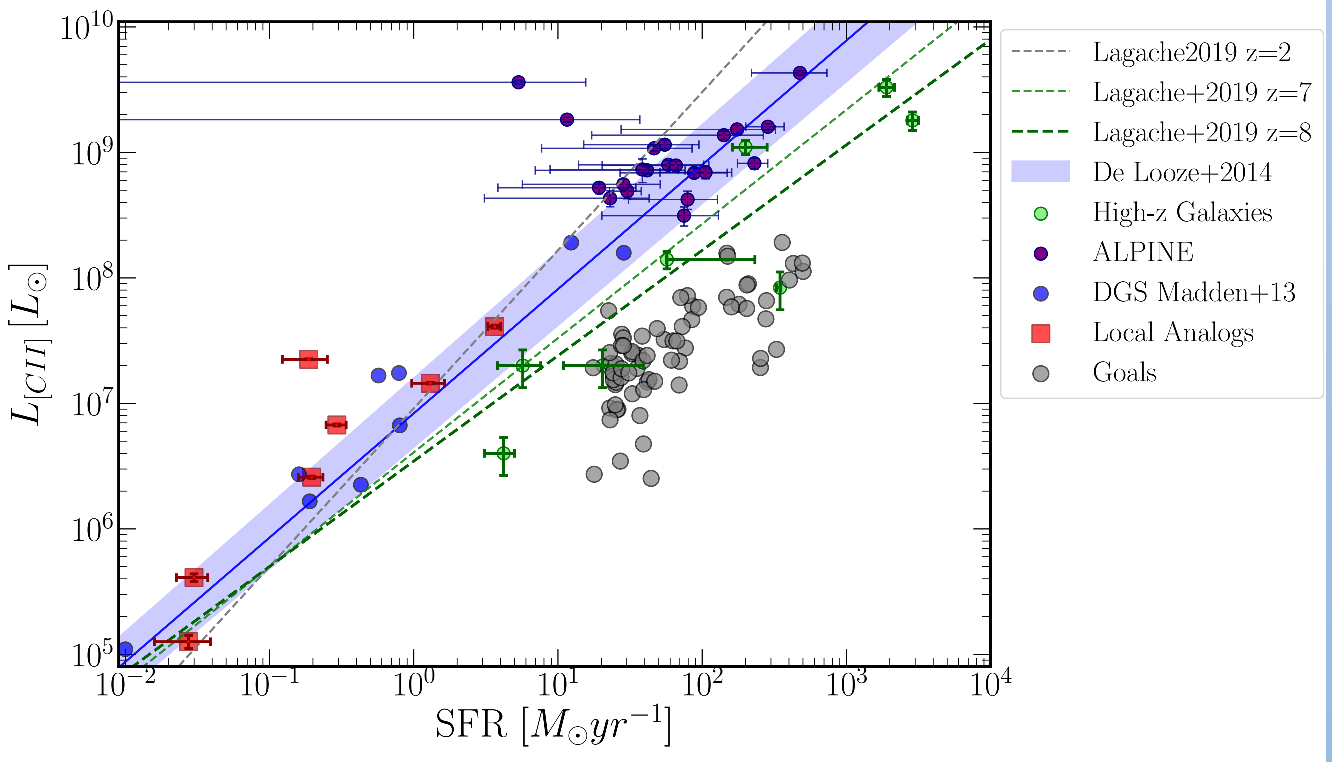


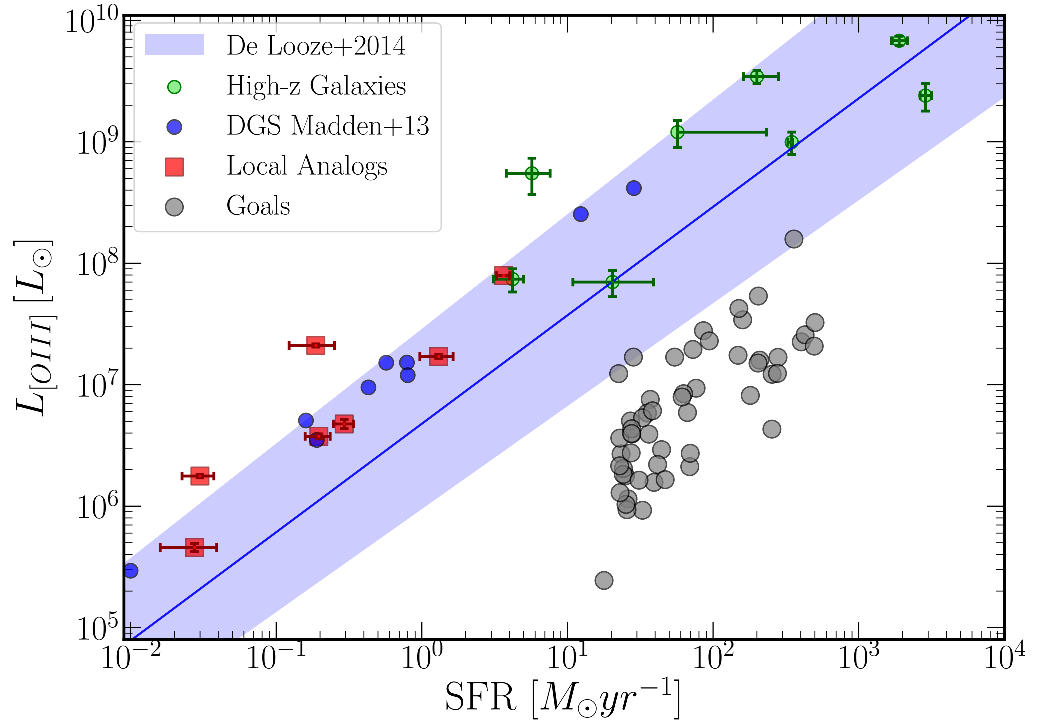


Refs: DGS from Madden et al.(2013), SHINING from Herrera-Camus et al. (2008); GOALS from Armus et al. (2009);
High-z Galaxies: ALPINE (4 < z < 6) Le Fevre (2019). z=7.2120 Inoue et al. (2016); z=7.1521, Hashimoto et al. (2019); z=7.1 from Maiolino et al. (2015), z = 8.31 from Bakx et al. (2020)
z = 8:38 and z = 9:11 from Laporte et al. (2019).

Preliminary Results:

[CII]157 µm and [OIII]88 µm





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Summary and Conclusions

- Definition of candidates based on SED, dust characteristics, Star Formation History, and Gas fraction.

- Dust: Warmer than other star-forming local galaxies. Consistent with high-z galaxies.
  - M_d/M_* consistent with gas rich galaxies.

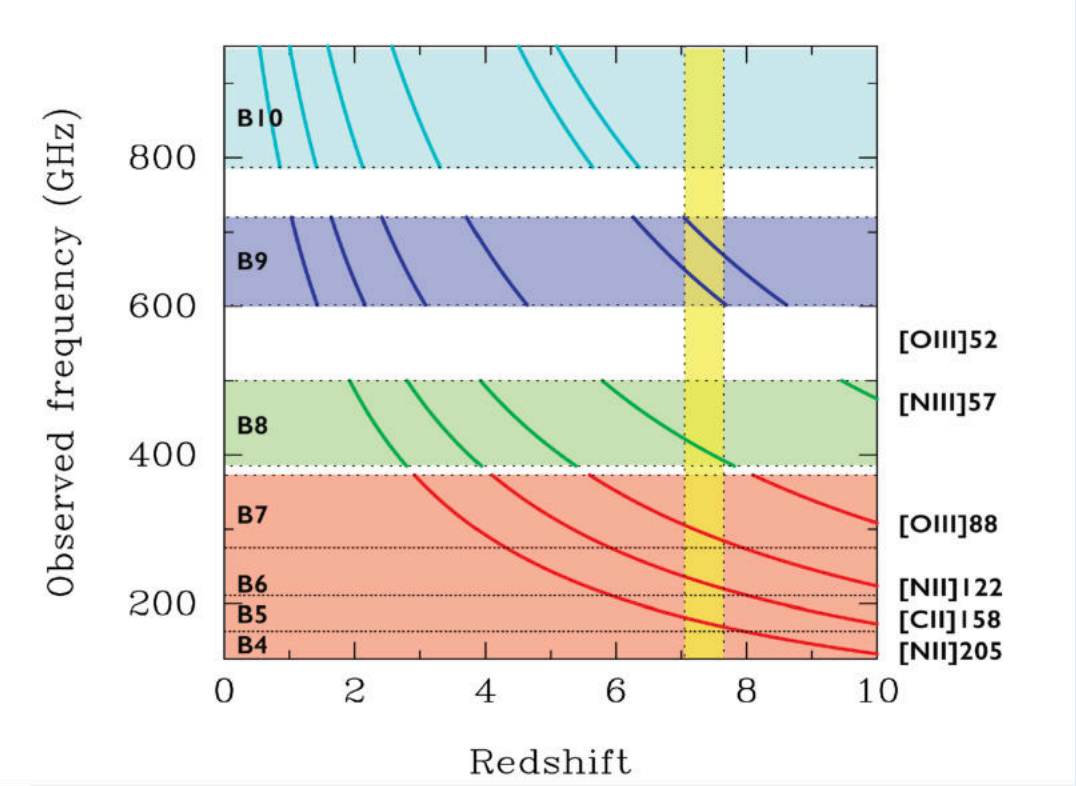
- Gas characterization: [CII]157µm and [OIII]88µm:
  - [CII] levels consistent with high Star formation Activity.
  - High gas ionization levels consistent with detections for High-z galaxies.

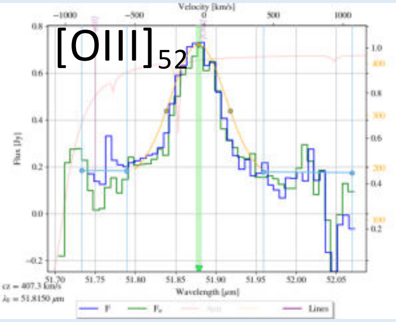
- Star formation history (SFH): 6 Galaxies are truly young systems, show SF < 1Gyr.

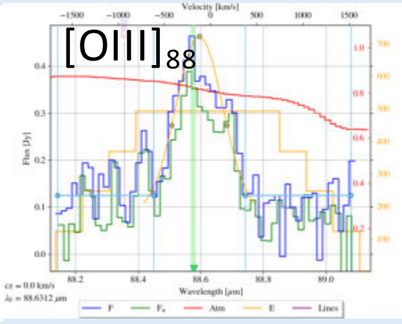
  Best Local Analogs: **Mrk 1450, UM 461, Mrk1307, Mrk 475 , UGCA 410, and Mrk 930.**

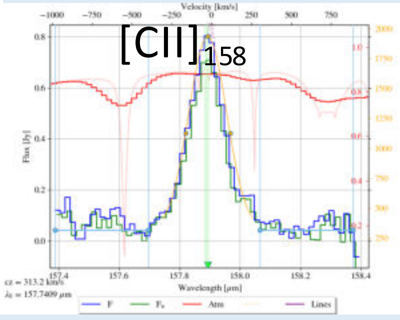
- The correlation found between the local analogs, and the high-z galaxies, highlights the relevance of more detailed studies of the physical processes in BCDGs.

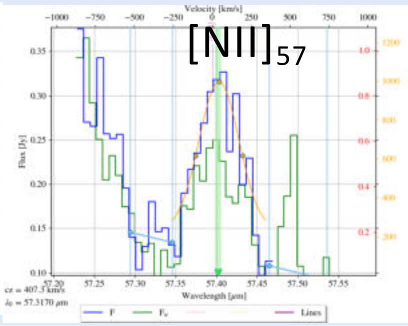
Future research Interest:











- ❑ SOFIA observations for extended sample.
- ❑ Molecular gas (CO) component and Hα. ALMA.
- ❑ Study of the gas-phase metallicity of nearby low metallicity galaxies.
- ❑ Synergy with ALMA observations of high-z galaxies.

Thanks

- Dr. T. Wiklind, and Dr. R. Eufrasio

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

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Questions?