UNIV. OF CRETE

IAASARS

# Infrared Diagnostics: Probing the physics of nuclear power in galaxies

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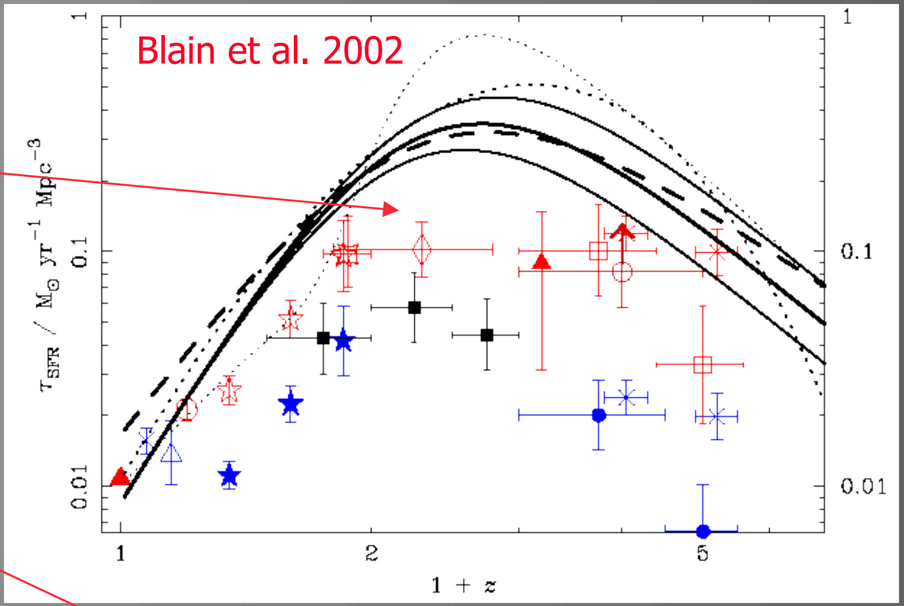
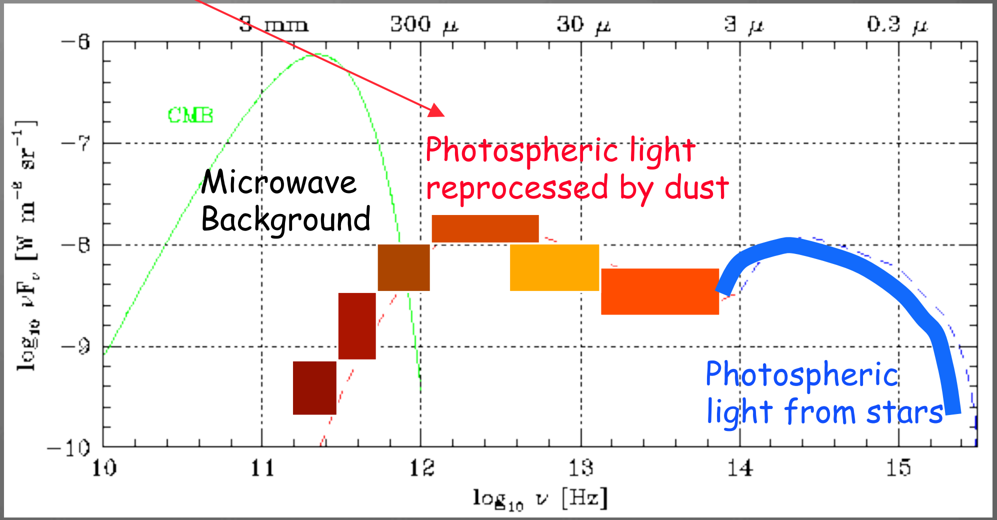
**SIRTF:** Seeking hidden secrets in the evolution of our universe ...
People: IRS team + Univ. of Crete postdocs: T. Diaz-Santos, L. Ciesla, M. Vika

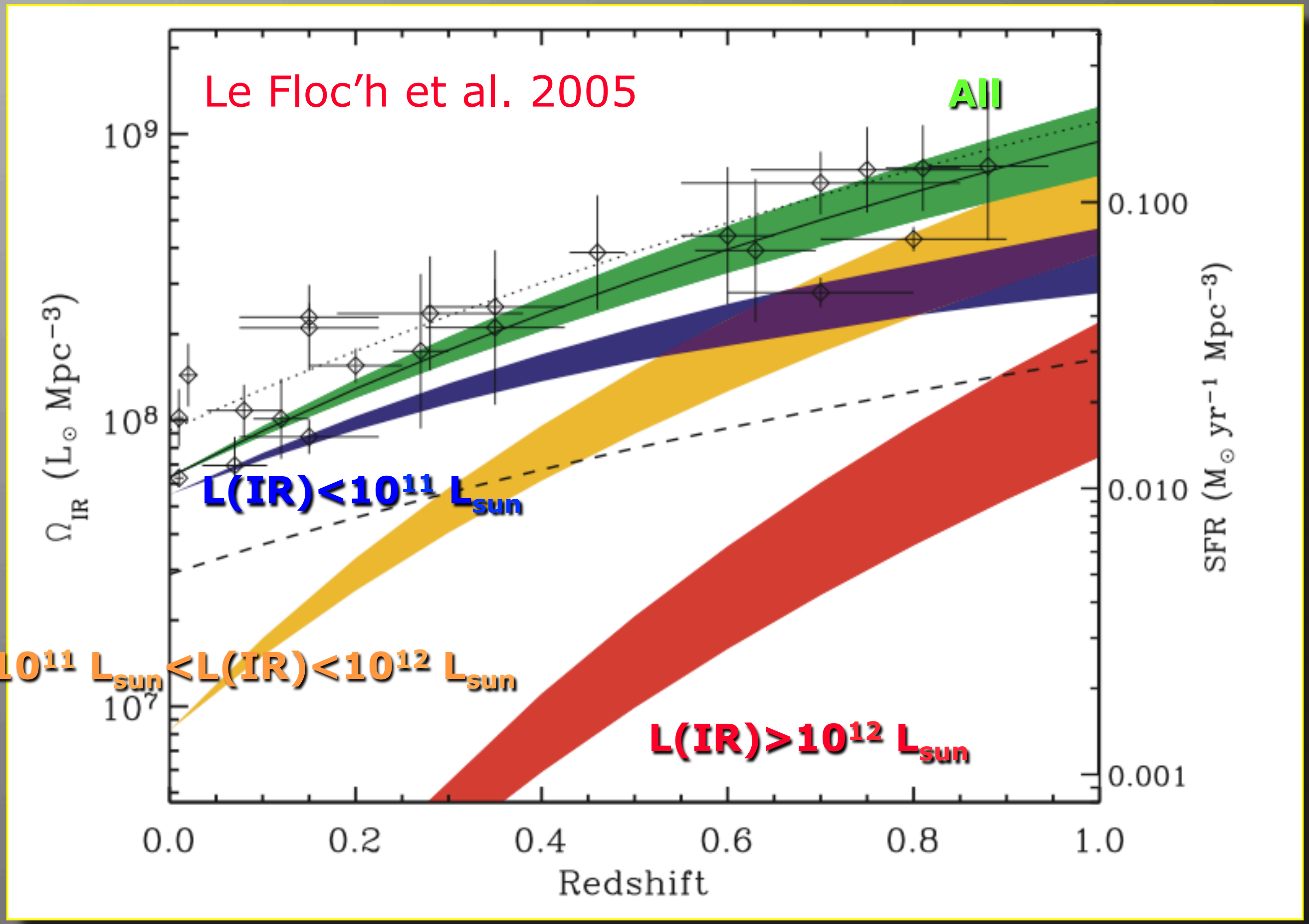
# History of Star-Formation Rate (SFR) in the Universe

- Optical surveys indicate that the mean SFR in the Universe was much greater at z > 1 (e.g. Madau et al. 1996)
- COBE revealed a cosmic far-IR background with energy > the integrated UV/optical light ⇒ dust extinction is important in the early Universe!
- IR/sub-mm surveys indicate even greater rates of star formation than seen in optical.
- To accurately determine the "SFR" requires both optical and far-IR/sub-mm surveys.
- Note that dust extinction is an important handicap in the optical. Only 1 in $10^{12}$ optical photons from the center of our Galaxy reach us. In distant dusty systems this can be substantially worse.



# MIPS: LIRGs dominate the IR/SFR at z~1



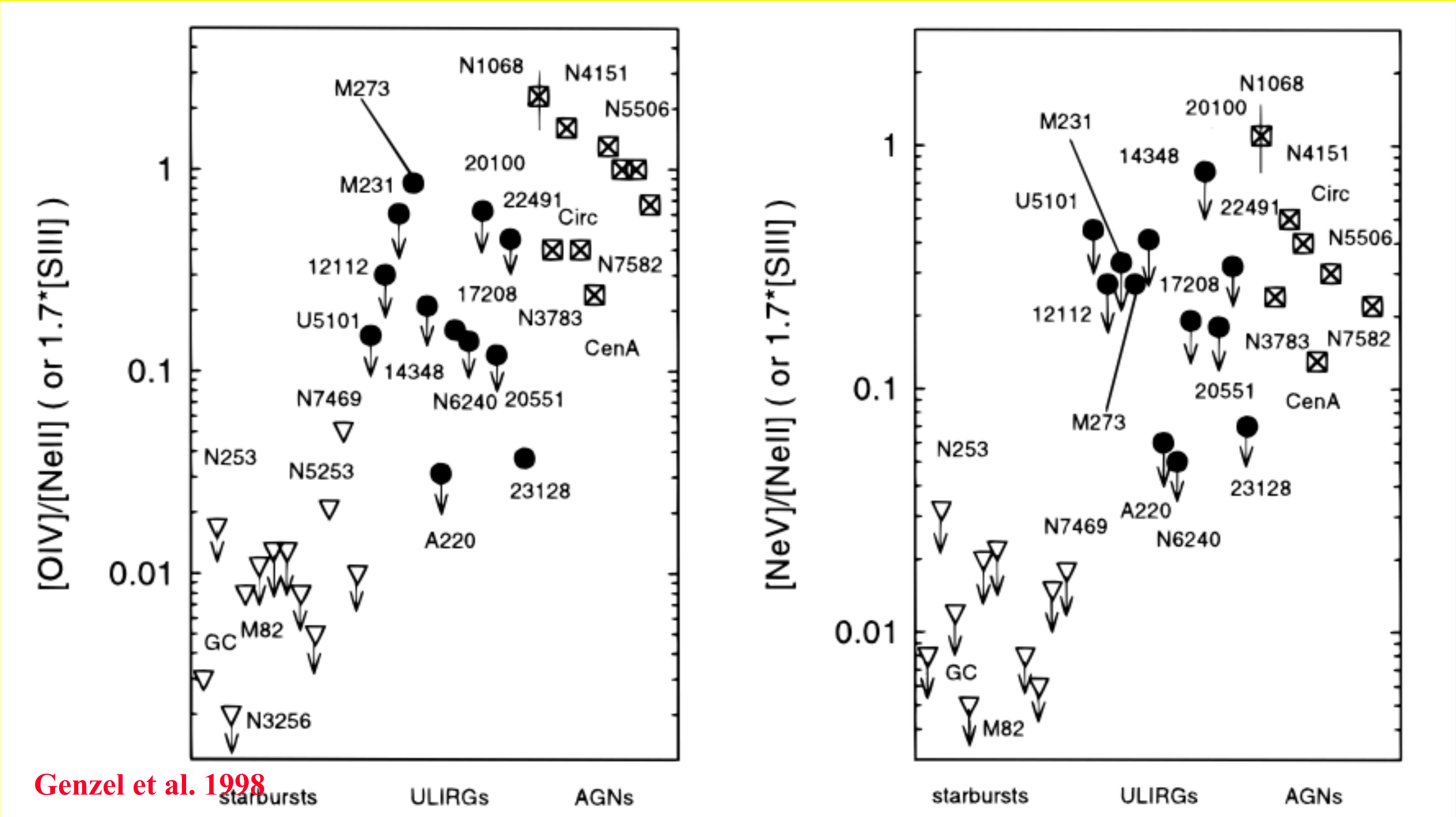

Luminous Infrared Galaxies dominate the star formation rate and energy density per co-moving volume at z >~1

# Science Motivation

- We wish to:
  - Identify the presence of an AGN (at low and high-z)
  - Estimate its contribution to the bolometric galaxy emission
  - Identify & study local analogues (ie LIRGs) as prototypes of high-z systems where observations are challenging and SED coverage scarce.
- Methods:
  - Empirical (use of templates and/or line ratios: IR due to smaller extinction)
  - Fitting part of or the full SED with various degrees of sophistication.
- A number of the observational properties of galaxies detected in the sub-mm at z~2 (Universe 3.3 Gyrs old) with $L_{IR}>10^{12}\,L_{\odot}$ such as:
  - *cold infrared colors*
  - *energy production dominated by star formation* ( > 100 $M_{\odot}$/yr)
  - *mid-IR spectral features (ie PAH strength*

  … resemble those of local LIRGs rather than Ultra-LIRGs.
- Kinematical evidence from ionized (Hα) and molecular (CO) gas are often consistent the presence of extended (~5kpc) star forming disks
- There is a "broad" connection between mid- & far-IR emission and star formation rate (with some caveats…)

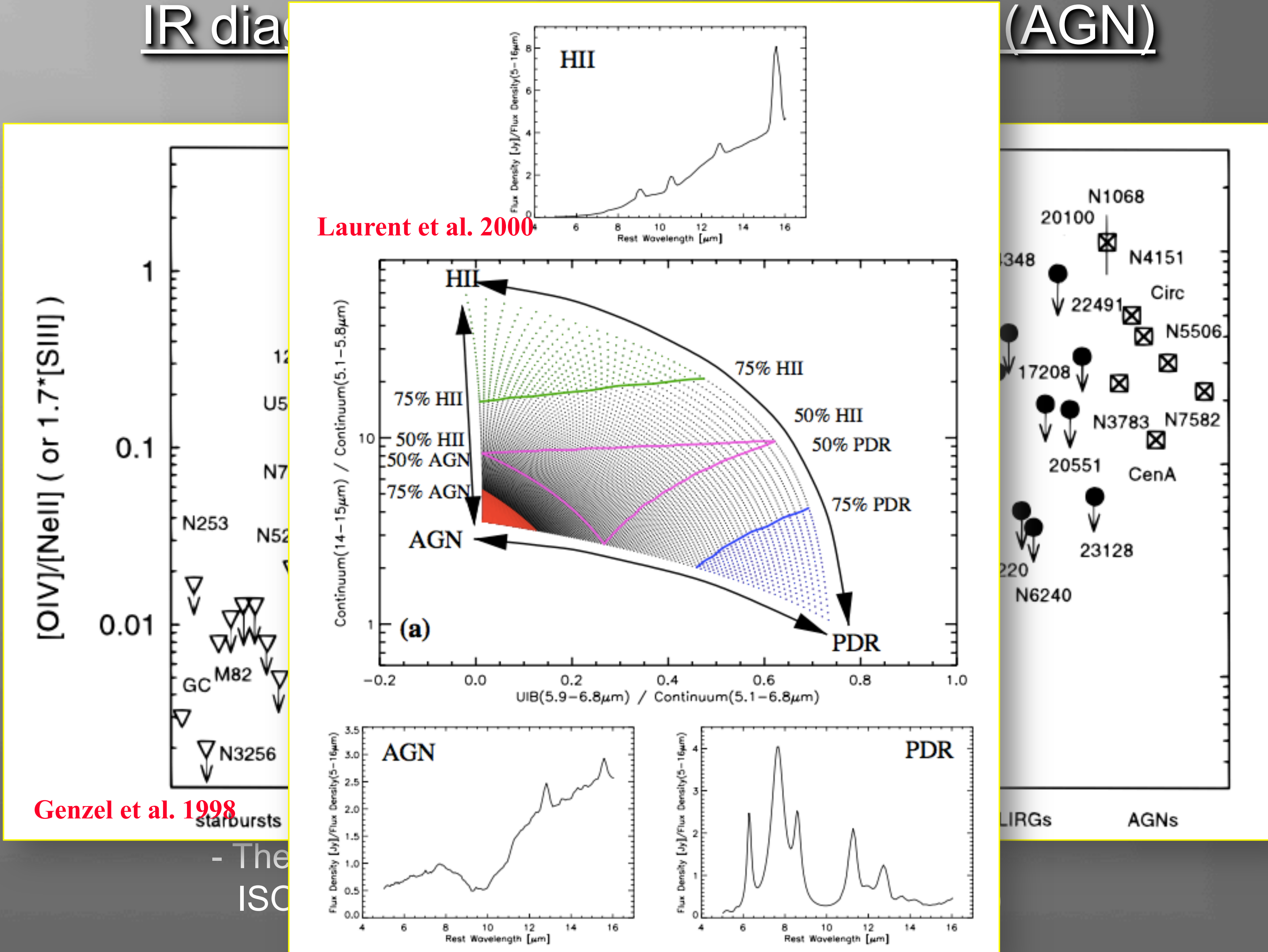
# IR diagnostics of an Active Nucleus (AGN)




Genzel et al. 1998

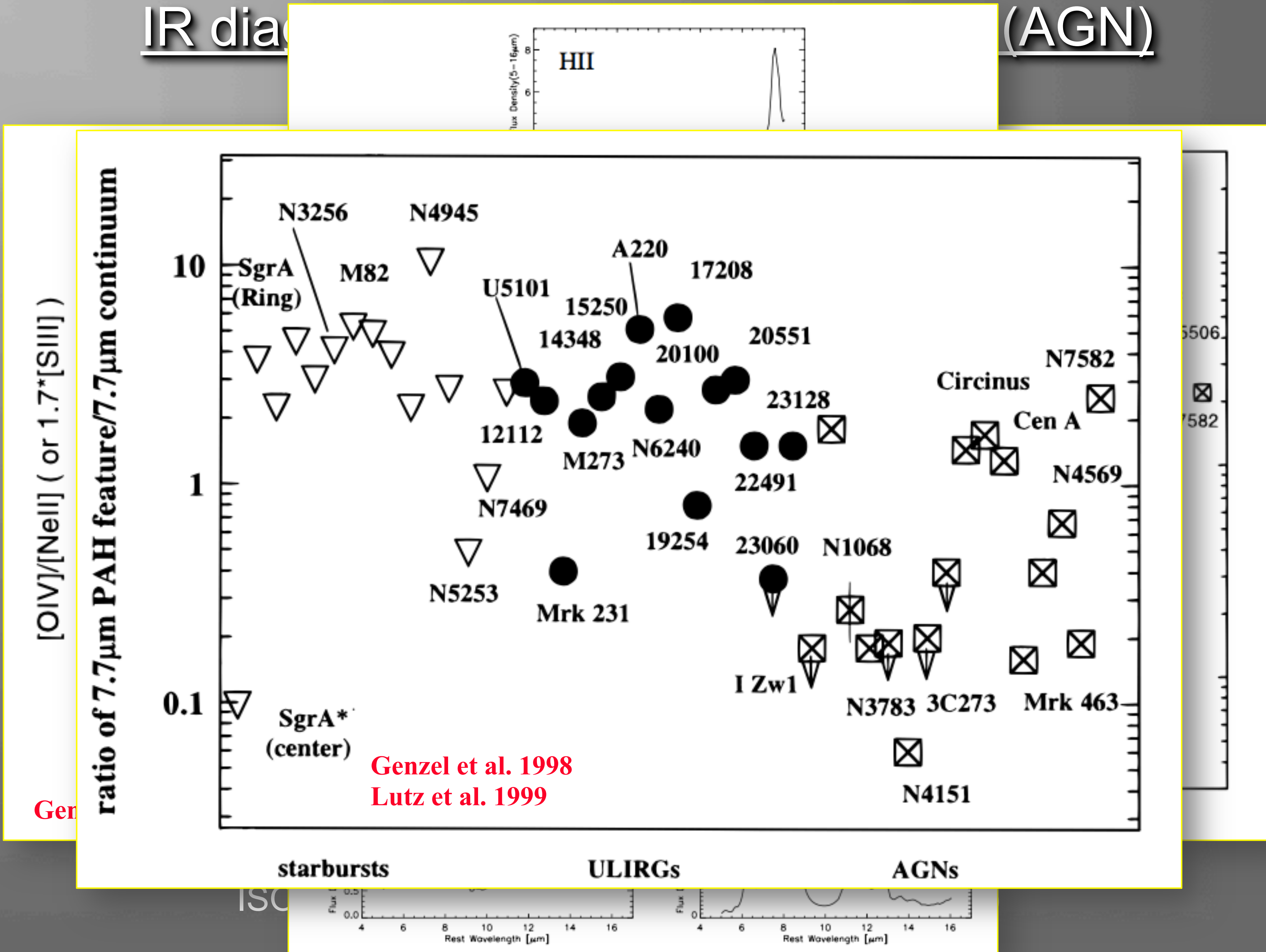
- The mid-IR continuum was not well defined with ISO PHOT-S (~11.8μm) & ISOCAM/CVF (~16μm)

# IR diag... (AGN)



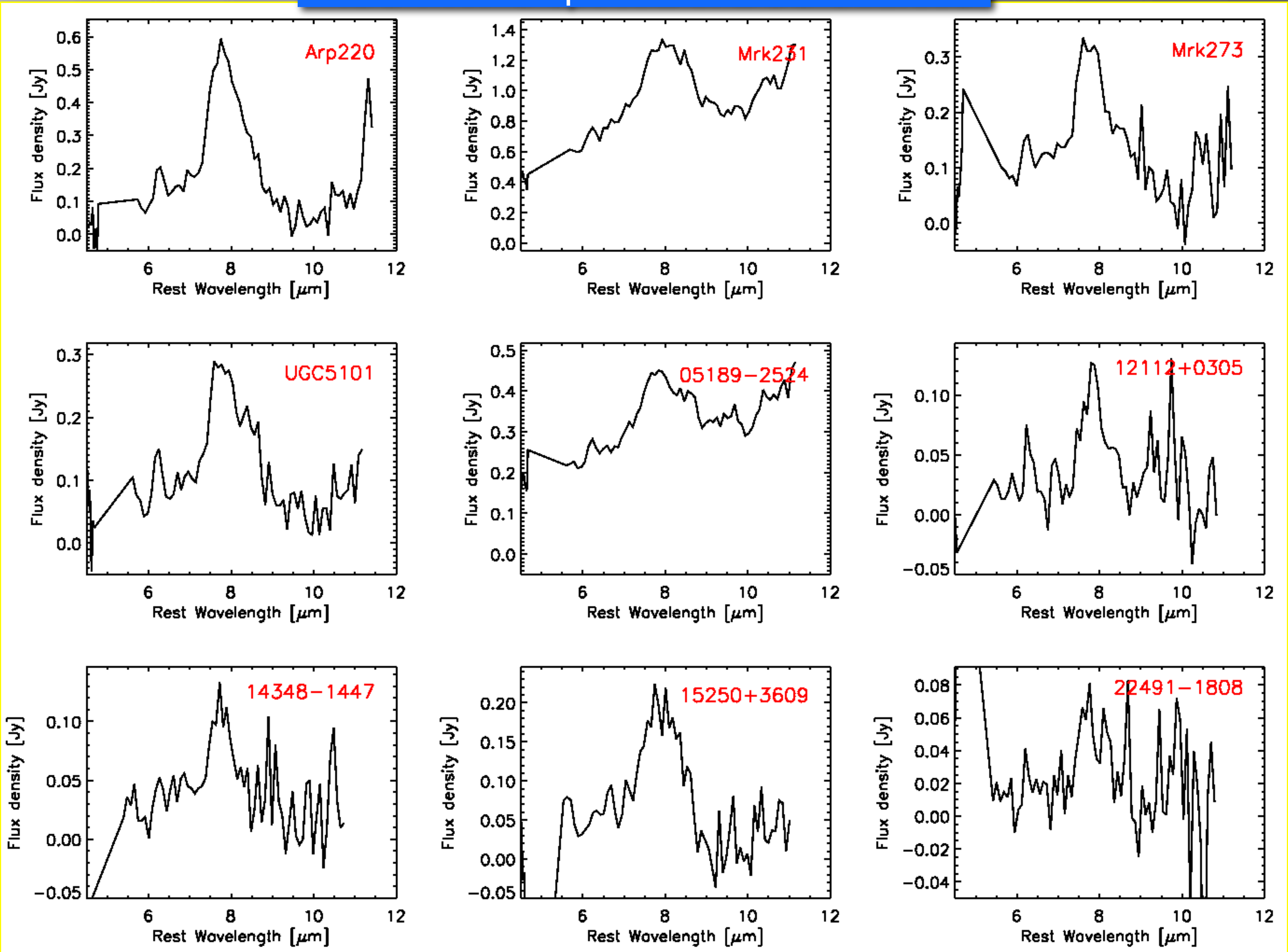

- The ...
ISO...

# IR diag… (AGN)

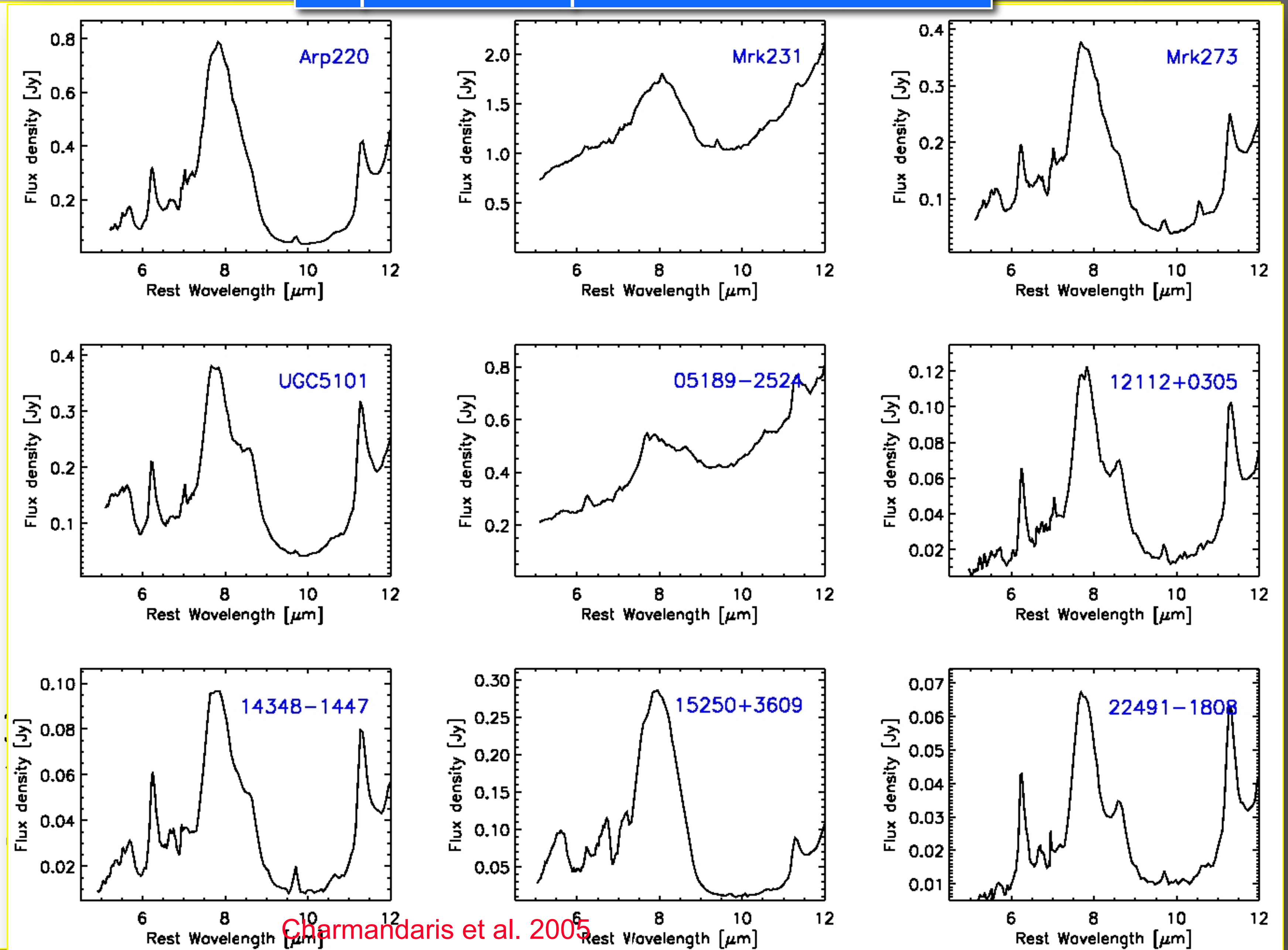


HII
ratio of 7.7µm PAH feature/7.7µm continuum
[OIV]/[NeII] ( or 1.7*[SIII] )
10
1
0.1
N3256
N4945
SgrA
(Ring)
M82
U5101
A220
17208
15250
14348
20100
20551
23128
12112
M273
N6240
22491
Circinus
N7582
Cen A
N4569
N7469
19254
23060
N1068
N5253
Mrk 231
I Zw1
N3783
3C273
Mrk 463
N4151
SgrA*
(center)
Genzel et al. 1998
Lutz et al. 1999
starbursts
ULIRGs
AGNs
Rest Wavelength [µm]
Rest Wavelength [µm]

# ISO PHT-S spectra of BGS Sources



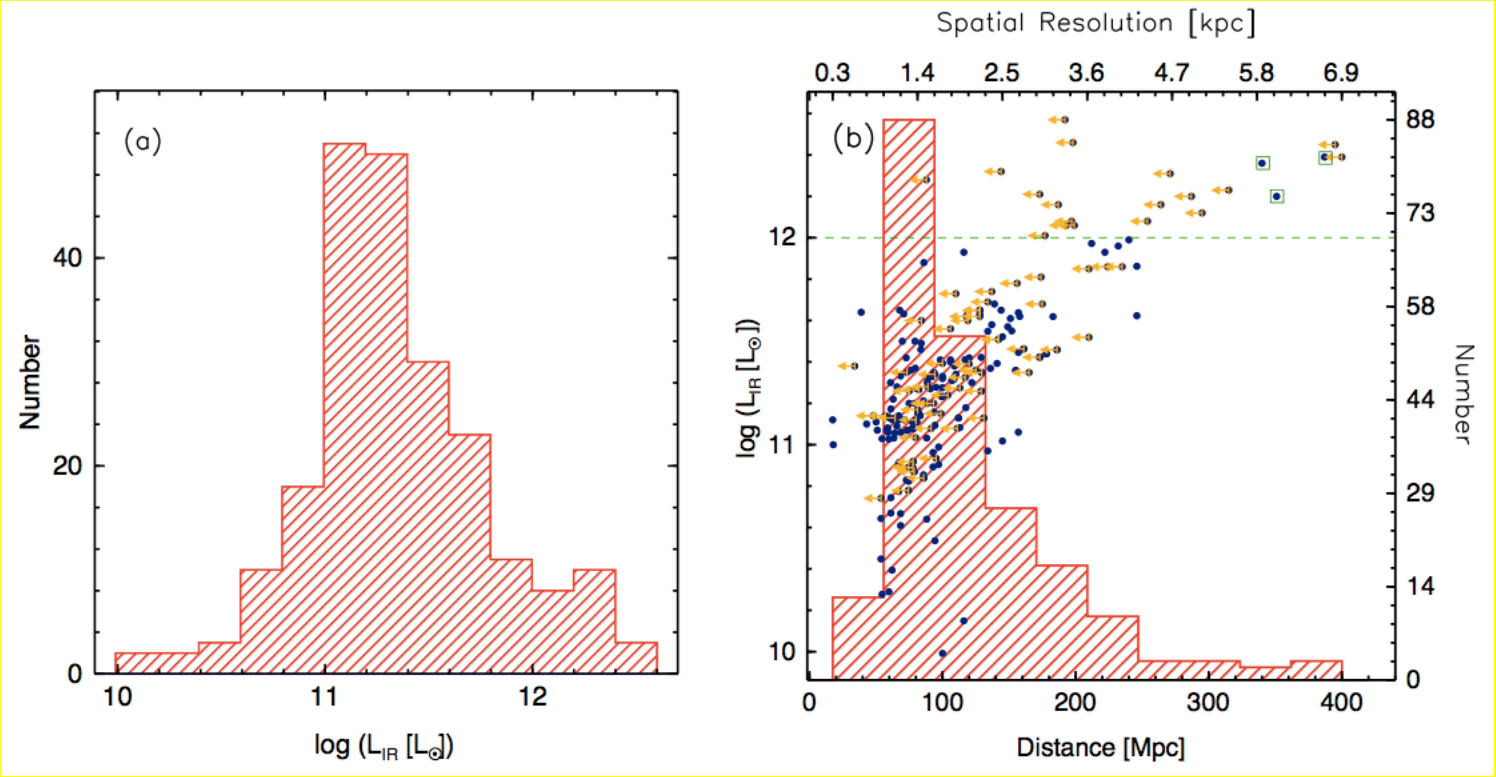
# Spitzer/IRS Spectra of BGS Sources



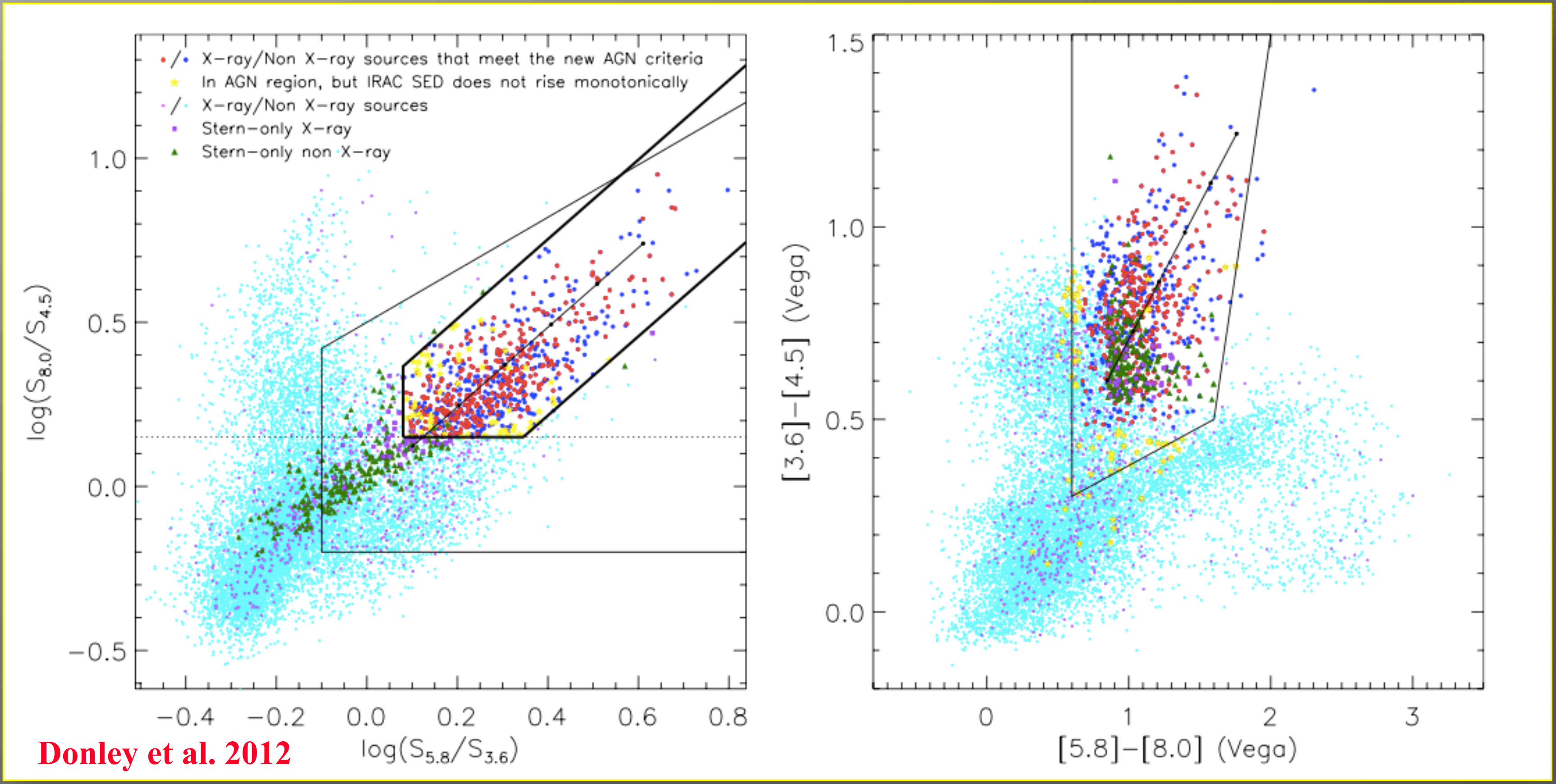

Charmandaris et al. 2005

# Testing diagnostics on obscured sources: the GOALS sample

- The sample is based on the Great Observatory Allsky LIRG Survey (GOALS; Armus et al. 2009) of 202 systems (181 of which are LIRGs)
- It covers the entire merger sequence: From isolated galaxies to merger remnants (Haan et al. 2011, Psychoyios et al. 2016, Larson et al. 2017 )
- All systems are observed with all four Spitzer/IRS modules (~5-37μm)
- Additional Spitzer & Herschel, as well as HST, GALEX, J-VLA, CO (ALMA)



# Empirical AGN Diagnostics with Spitzer



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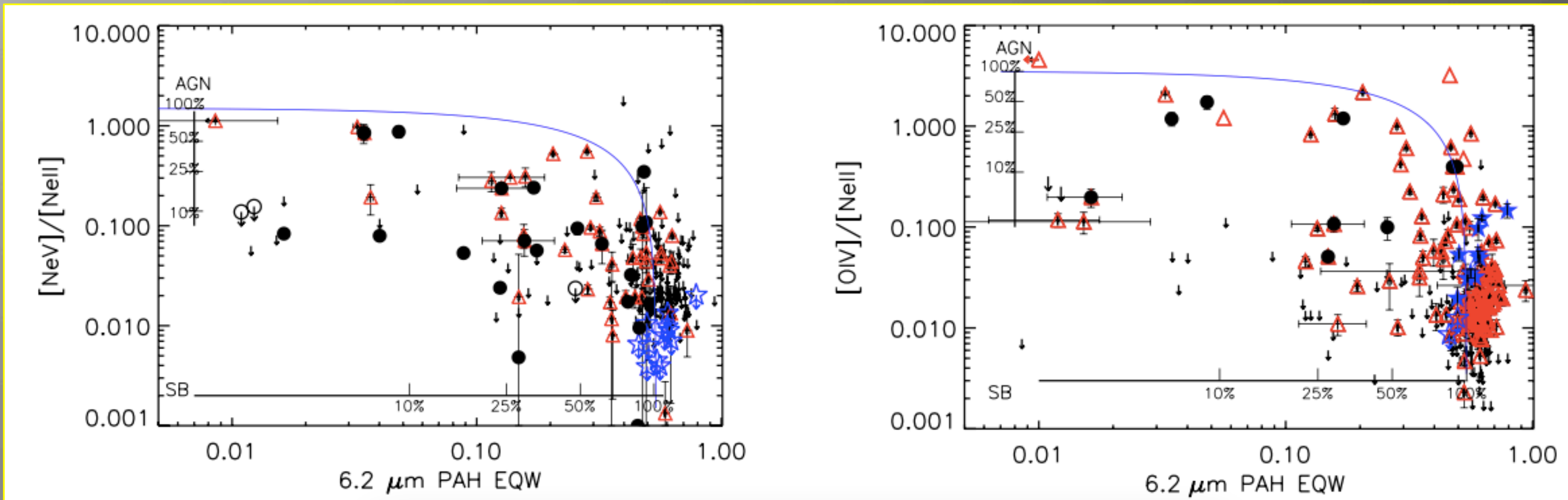


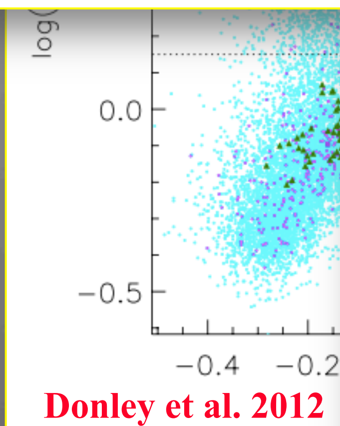


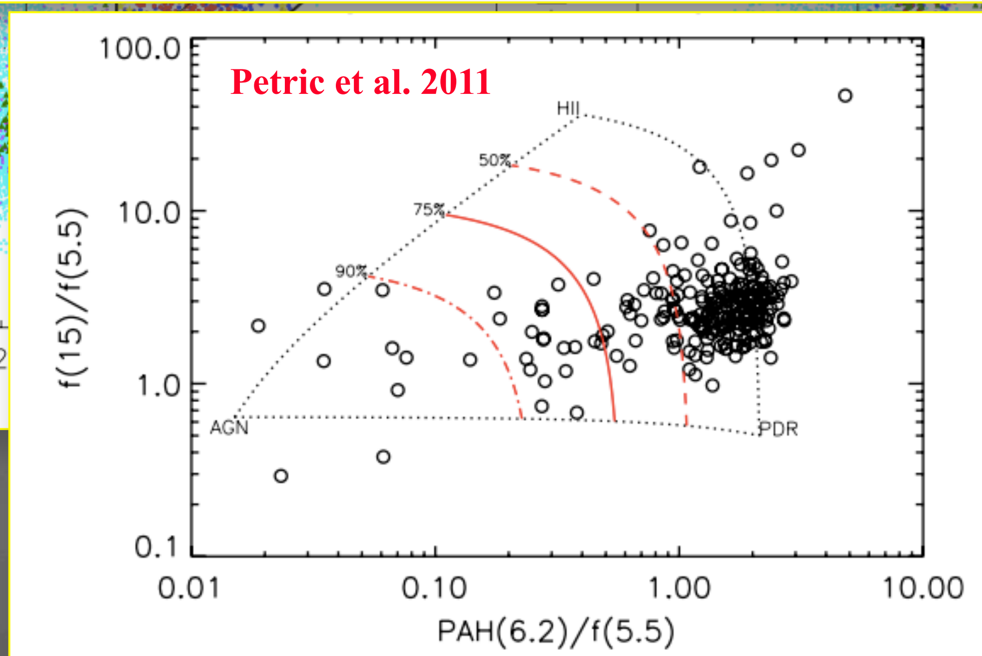

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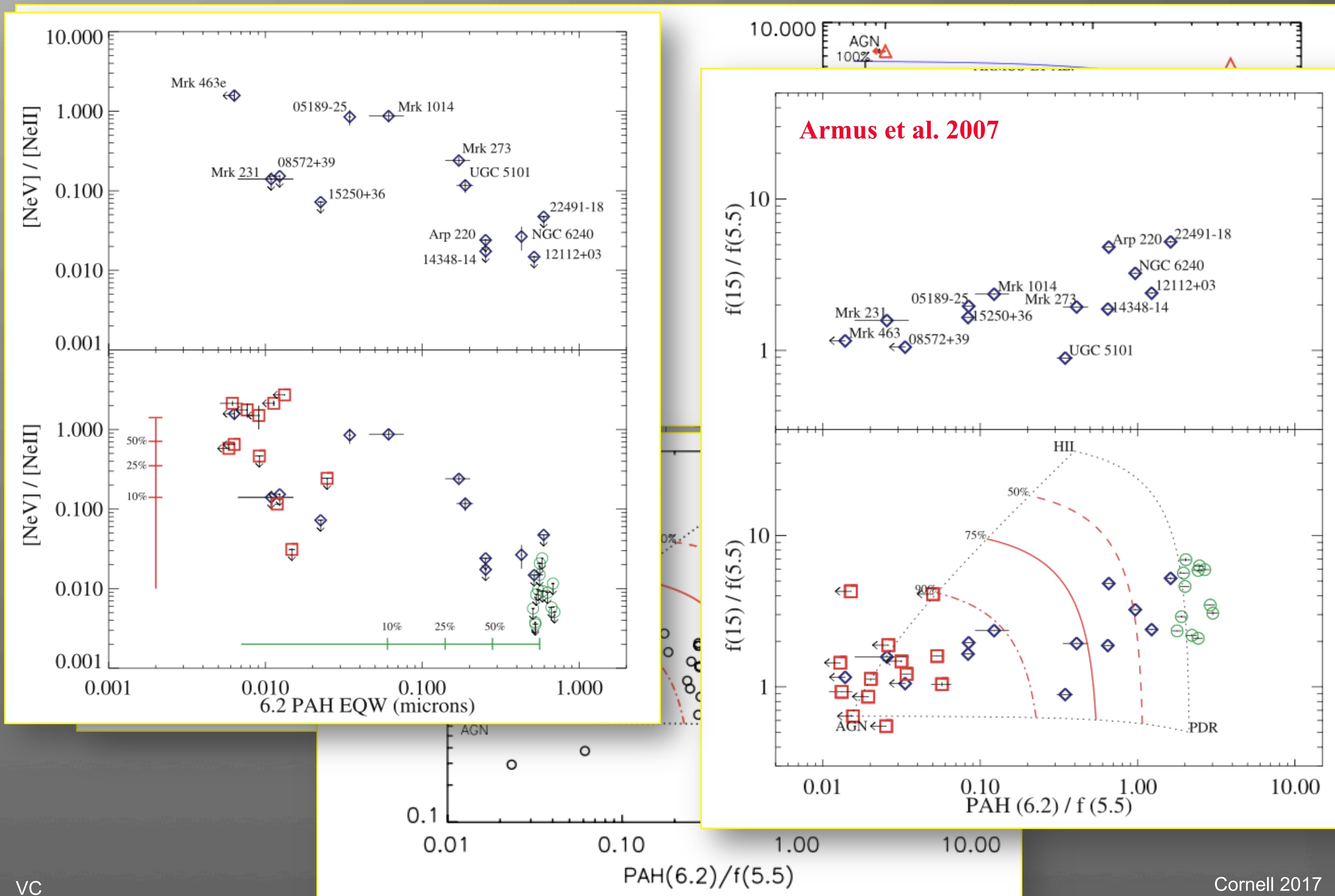
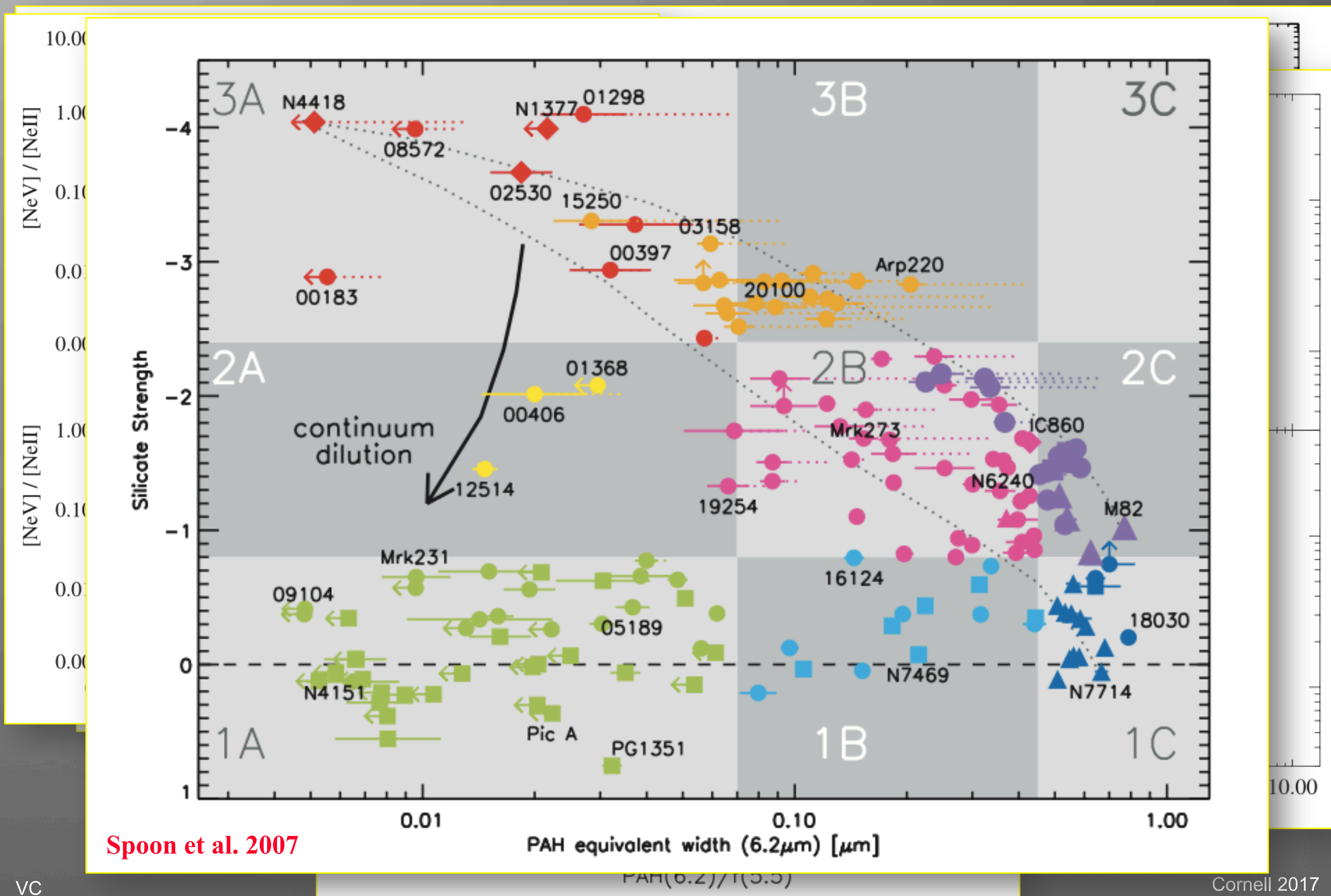
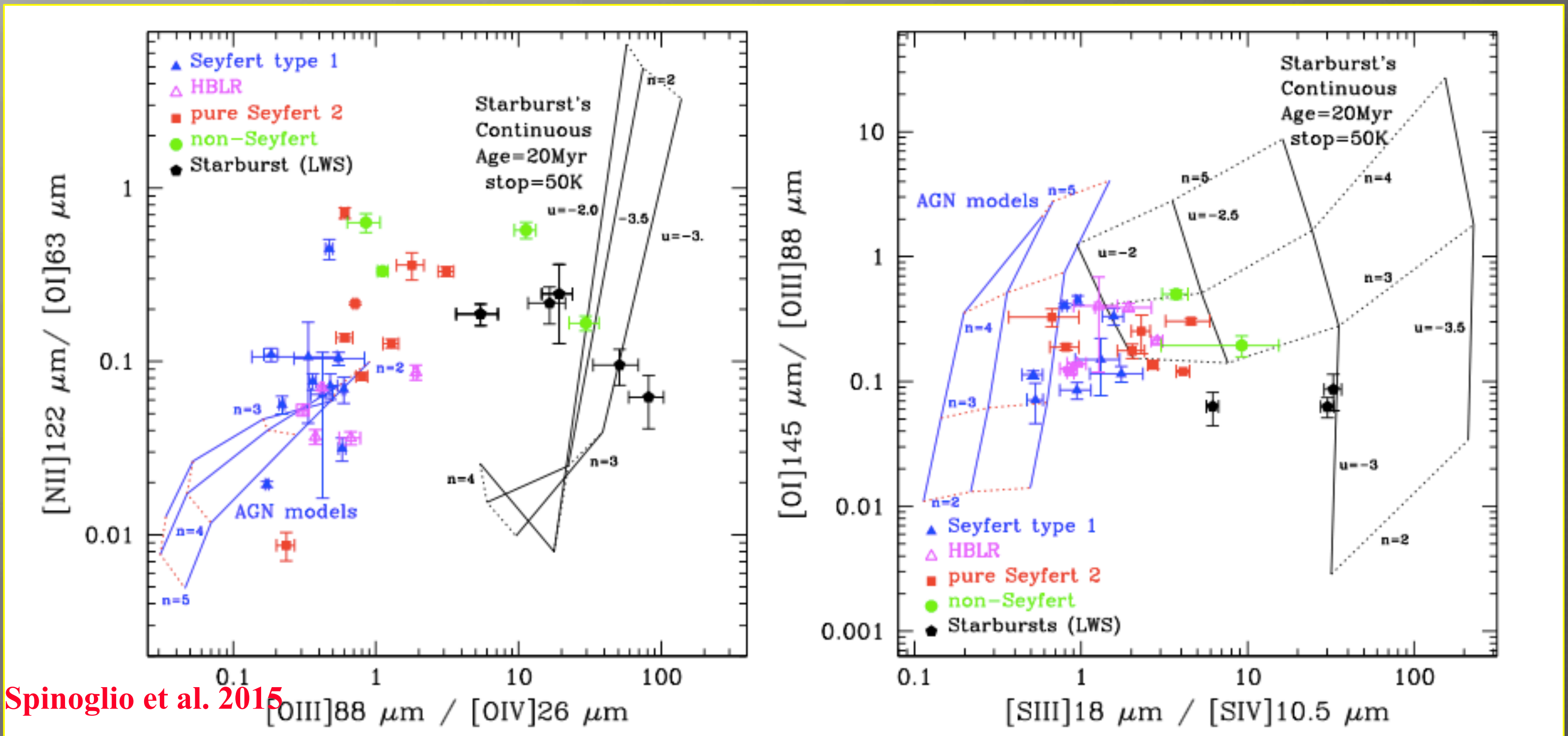


# Empirical AGN Diagnostics with Spitzer

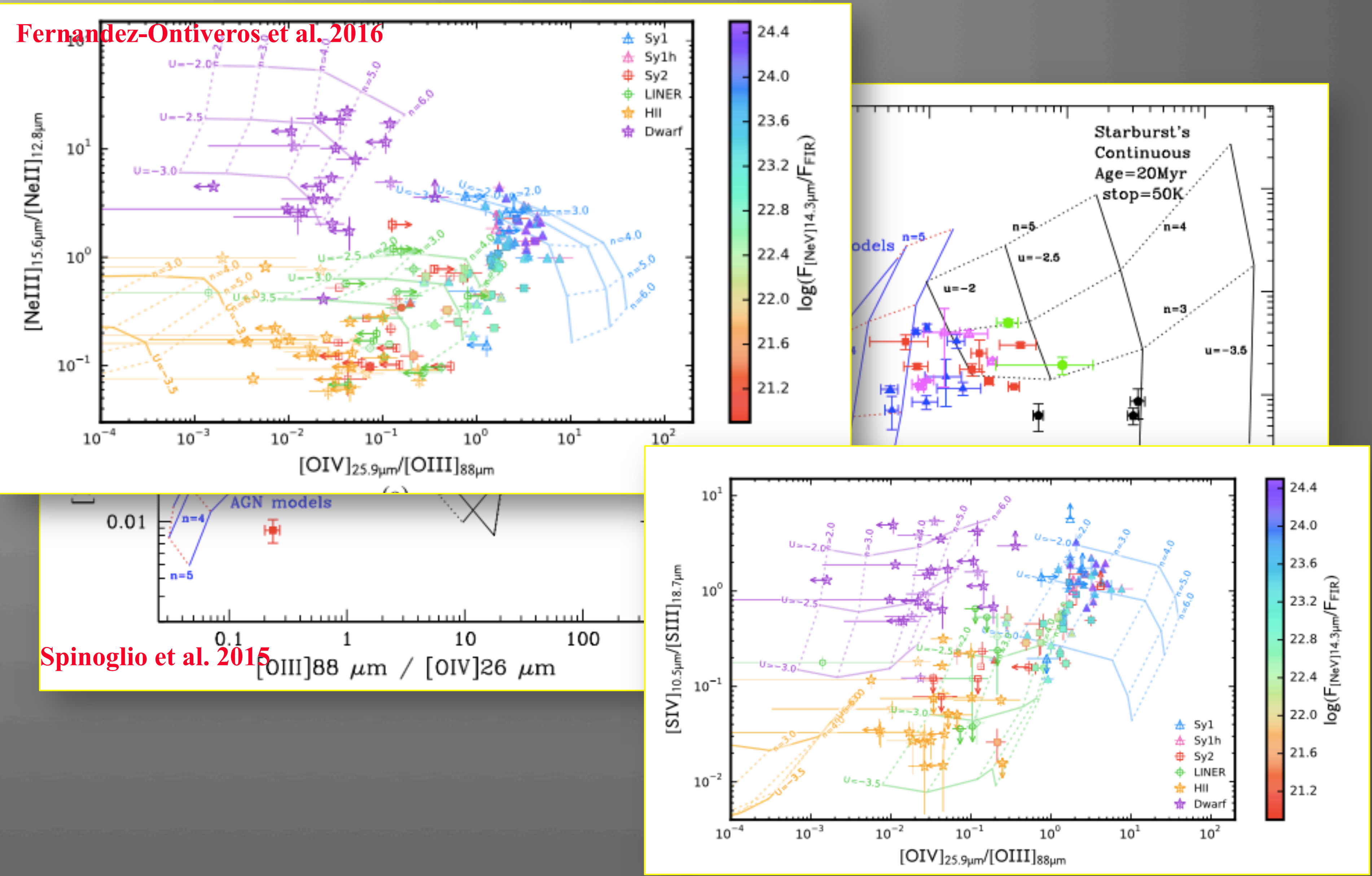


# AGN Line diagnostics with Herschel



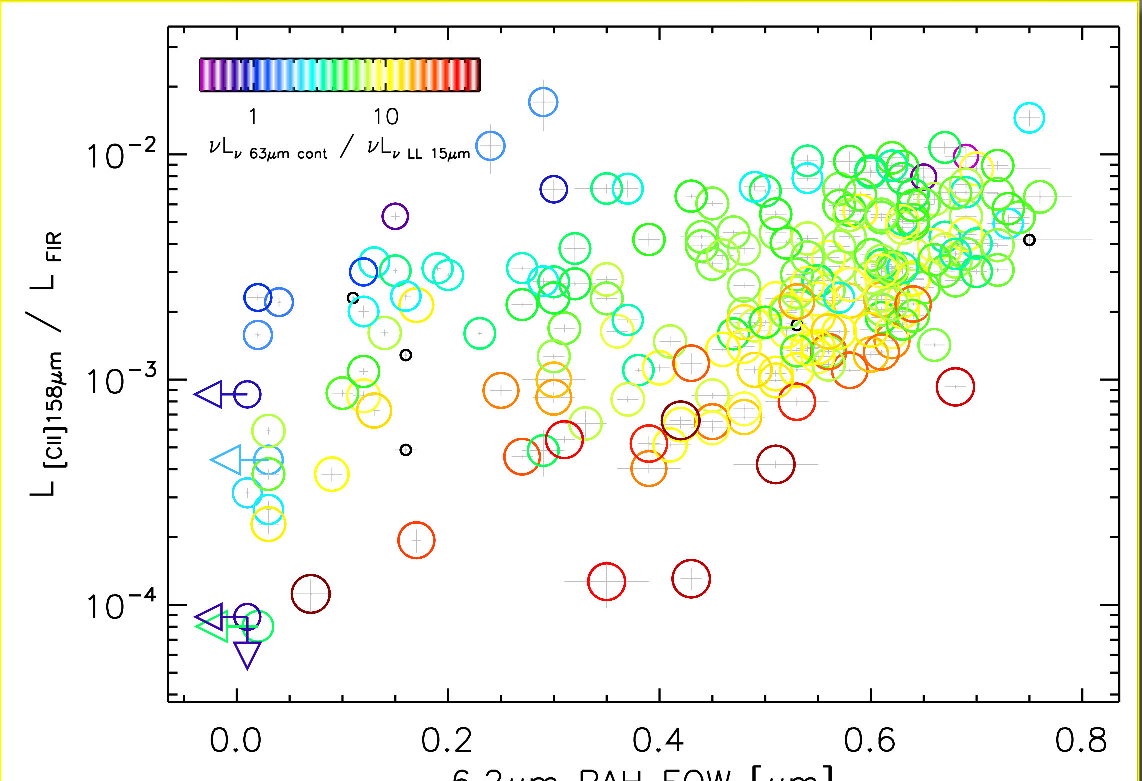

Spinoglio et al. 2015

# AGN Line diagnostics with Herschel




VC

# Herschel: The role of AGN in Far-IR

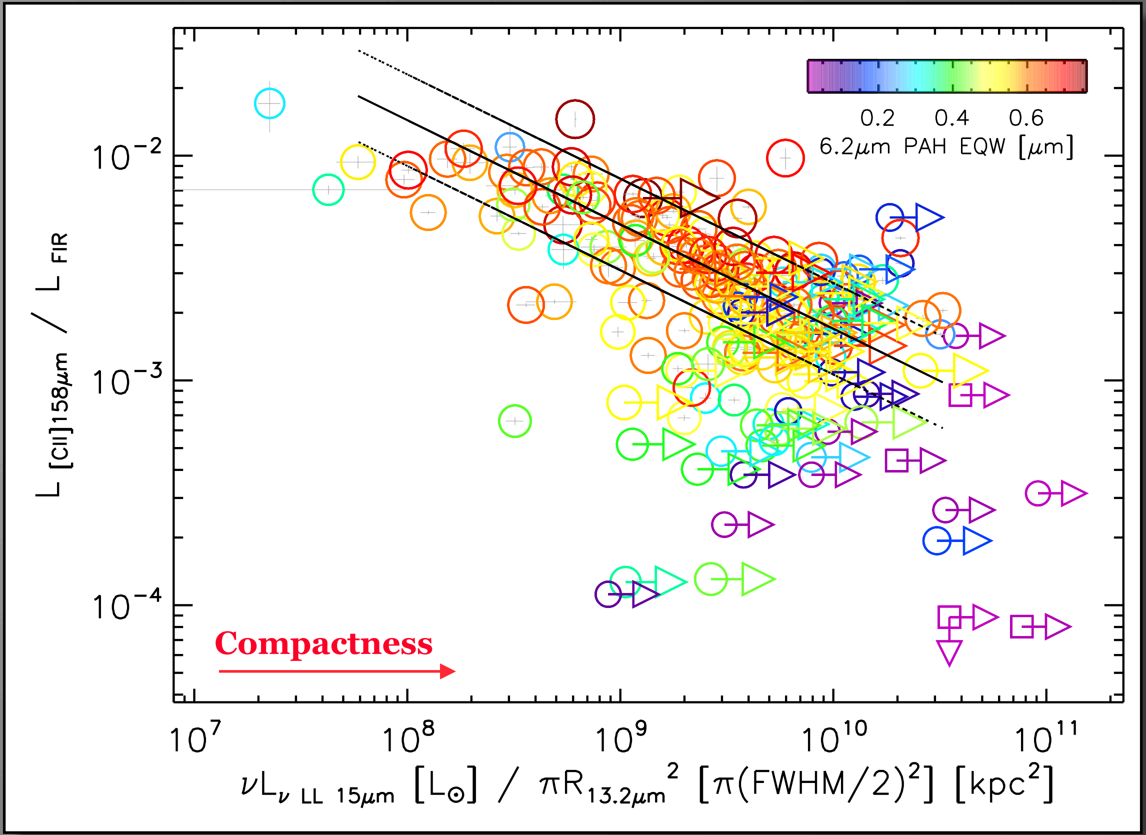



Diaz-Santos et al. 2013

- The 6.2μm PAH equivalent width is commonly used to identify AGNs in the mid-IR
- At low PAH EQWs, sources span the full range of [CII]/$L_{FIR}$ ratios (see also Sargsyan+12)
- 55% of mid-IR AGN have [CII]/$L_{FIR}$ > $10^{-3}$ ! (70% if two mid-IR diagnostics are required) -> These AGN do not contribute significantly to the far-IR emission
- Only when 6.2μm PAH EQW <~ 0.05μm the AGN can contribute ~50% to far-IR

# Compact Sources

- The compactness (concentration of light) of the mid-IR emitting region (independently of its origin) is correlated with the [CII]/$L_{FIR}$ ratio
- Even when only galaxies with 6.2μm PAH > 0.5μm are considered, there is a decline of an order of magnitude, from $10^{-2}$ to $10^{-3}$

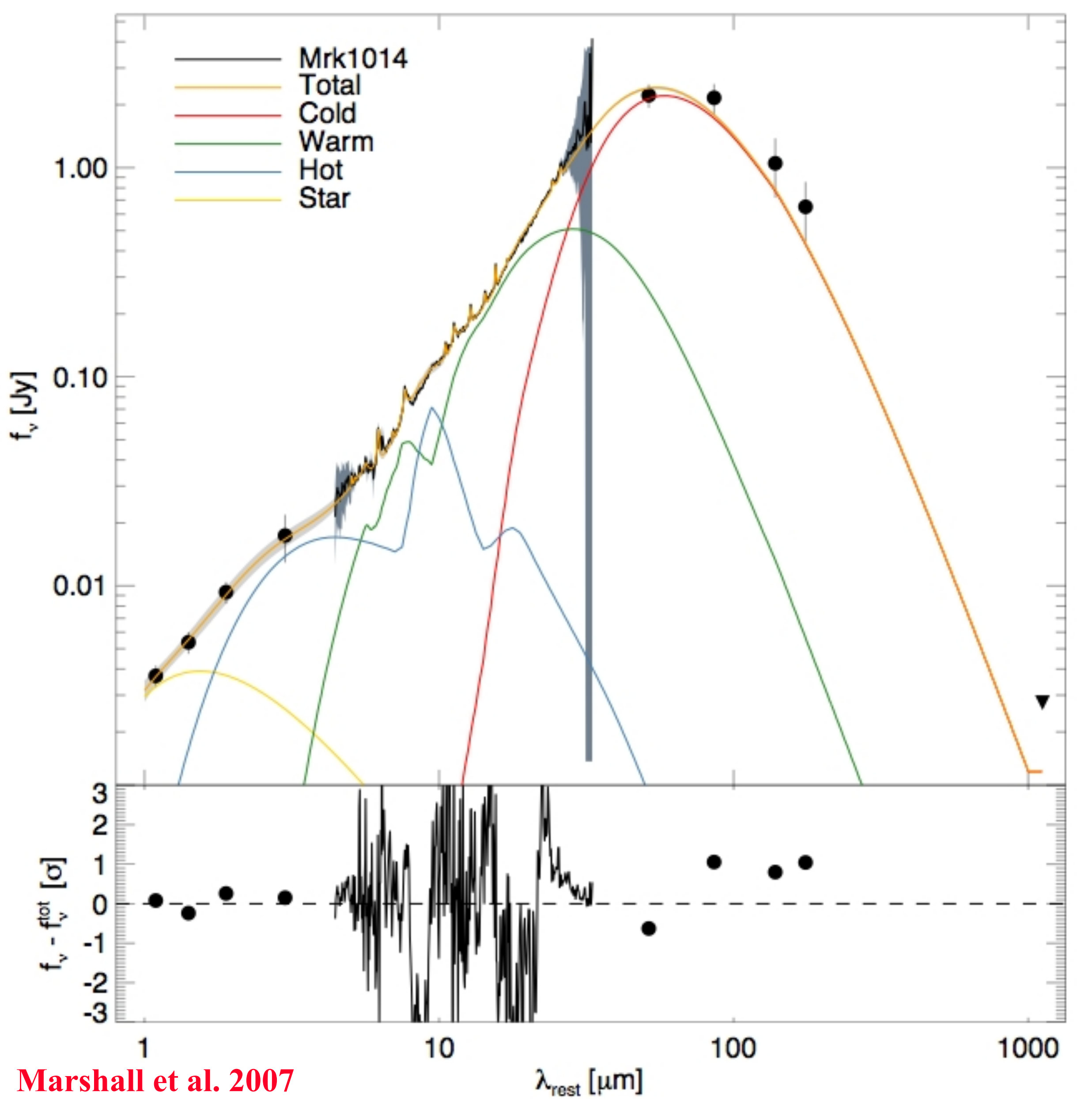



- Even in pure star-forming galaxies we see a [CII] deficit wrt to the $\Sigma_{MIR}$
- The decrease in [CII]/$L_{FIR}$ among most LIRGs is not caused by AGN activity but instead is a fundamental property of the starburst itself
- [CII] is not a good SFR tracer in most LIRGs since it does not account for the increase in warm dust emission from the compact starburst

# Infrared Continuum & Features Fitting

- Another approach to quantitatively access the contribution of the various components in the observed IR emission from a source is to fit the IR spectrum using theoretical models.
- Full radiative transfer modeling of the source (ie. Siebenmorgen & Grugel 1992,1993; Nenkova & Elitzur 2001,2002; Dopita et al. 2005) is challenging since in addition to dust it requires major assumptions on the geometry of the source. Typically applicable to detailed studies of individual sources.
- Recent methods involving stellar population synthesis models with additional dust templates for energy balance (CIGALE, MAGPHYS etc)
- Another fitting approach relying on the Spitzer/IRS 5-38μm spectra, using constrains from near-/far-IR observations has been developed (Marshall et al. 2007)…

# The case of Mrk1014: a U-LIRG




Marshall et al. 2007

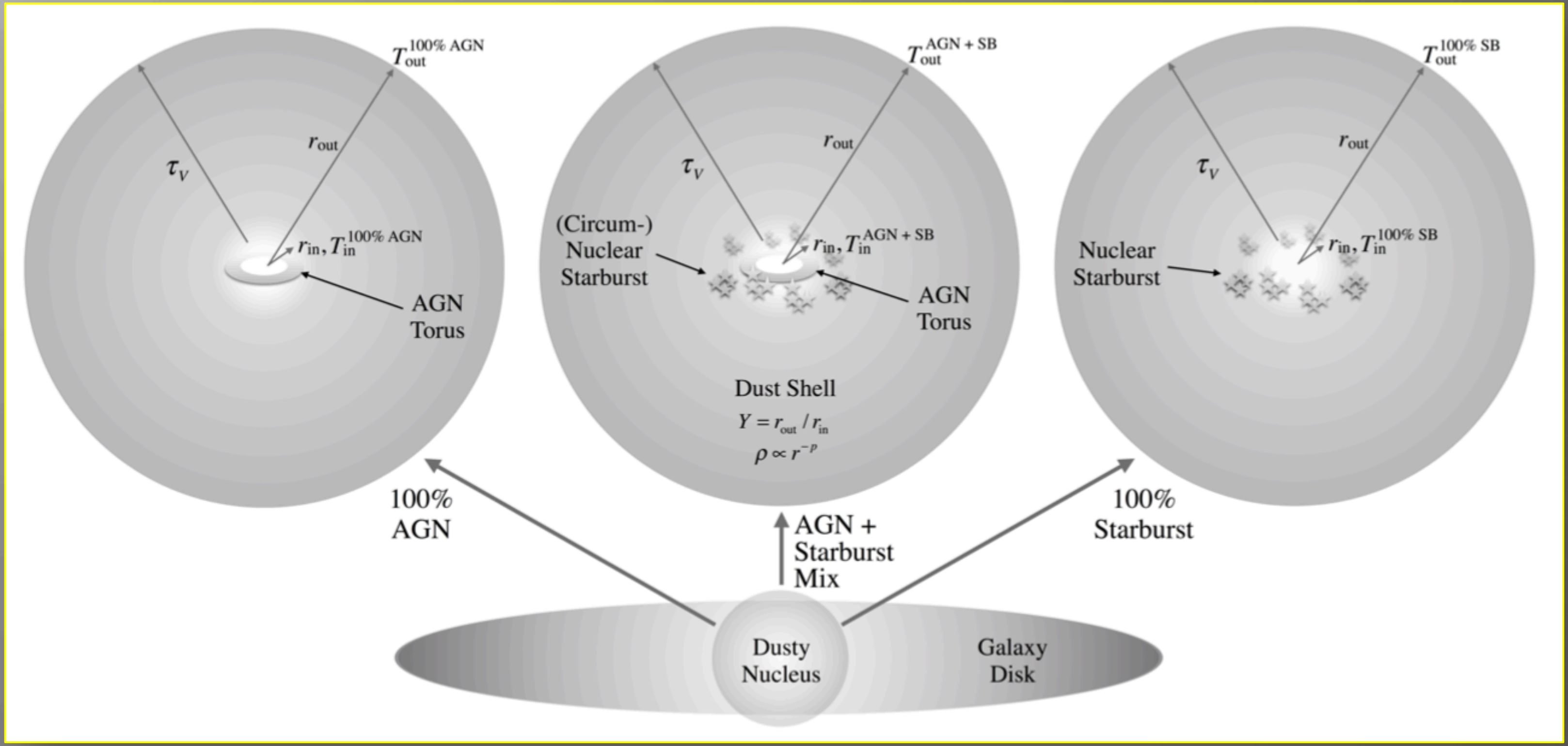
$T_*$~3300 K
$T_{cold}$~38 K
$T_{warm}$~121 K
$T_{hot}$~454 K

$\tau_{warm}$~1.7
$\tau_{ice}$~0.3

$L_{dust}$~4.2x$10^{12}$ $L_\odot$
$L_{cold}/L_{dust}$~0.57
$L_{warm}/L_{dust}$~0.32
$L_{hot}/L_{dust}$~0.1

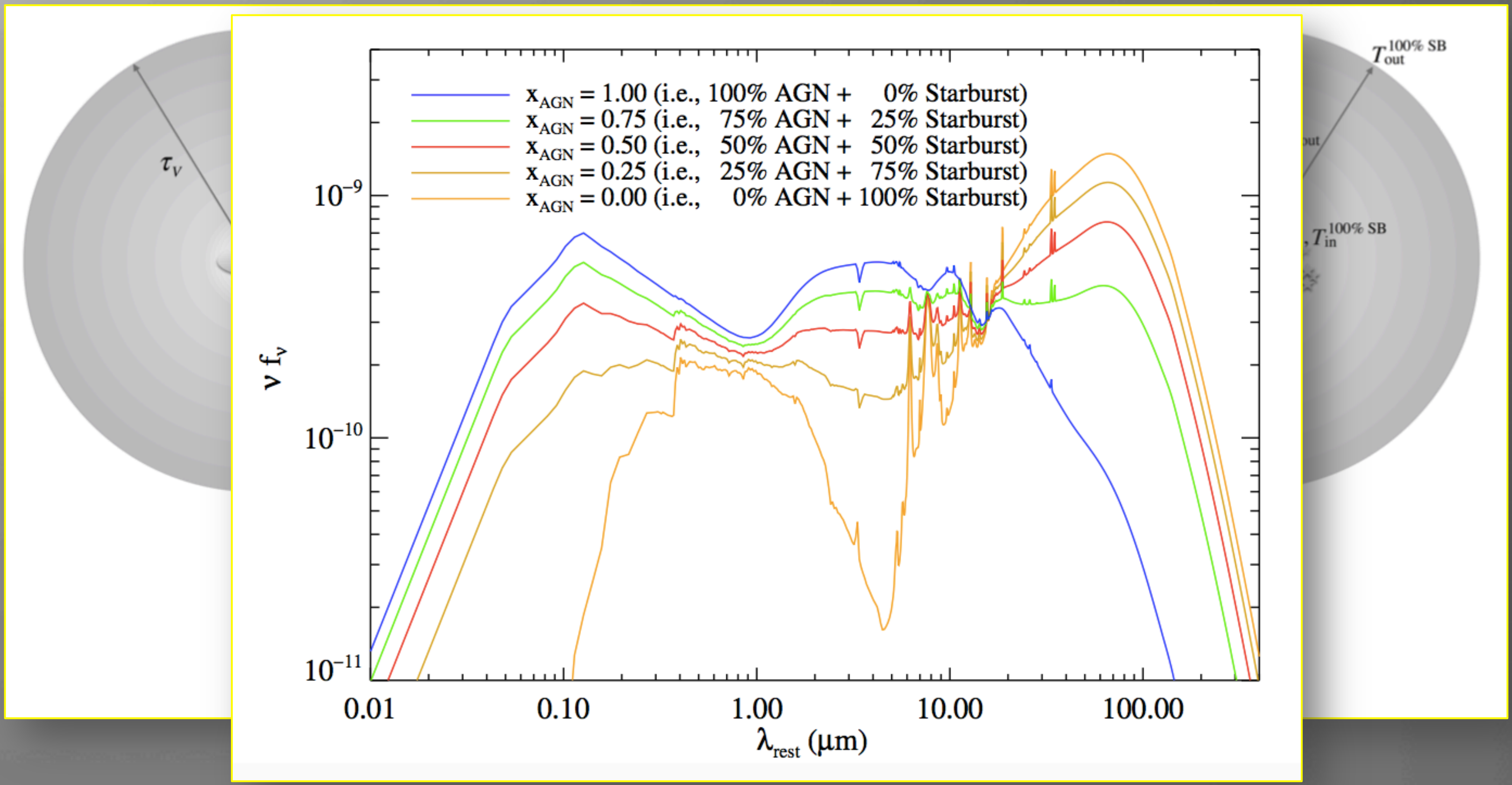
$M_{cold}$~1.5x$10^8$ $M_\odot$
$M_{warm}$~ 2.6x$10^5$ $M_\odot$
$M_{hot}$~ 83 $M_\odot$

# A new detailed model for obscured sources




In view of JWST, Marshall et al. 2017 propose a combination of templates (NGC7714 & PG0804) as input plus modeling using DUSTY to accurately reproduce the SEDs, in particular in the 1-20μm range, of deeply obscured sources (ie ULIRGs)

# A new detailed model for obscured sources

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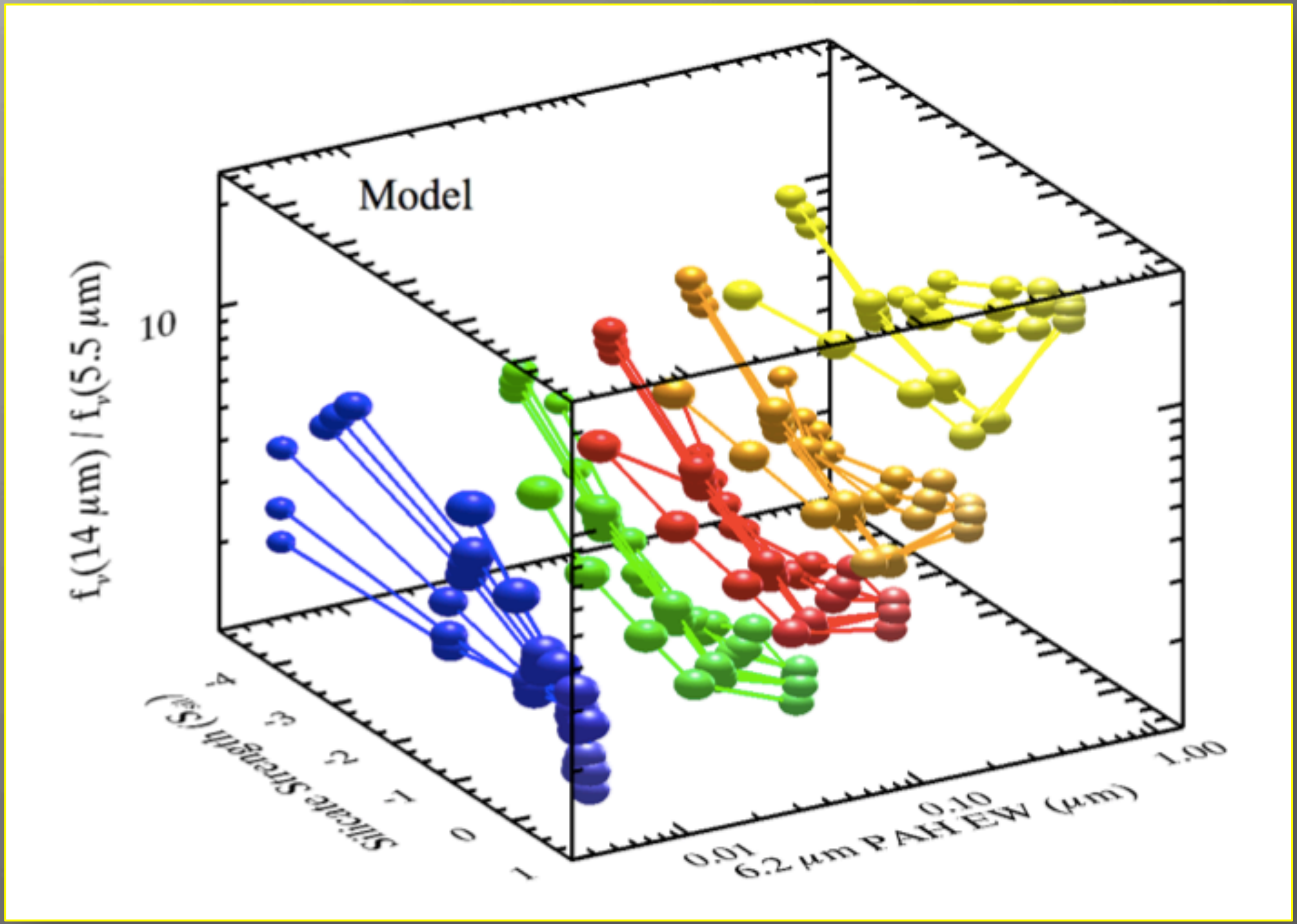
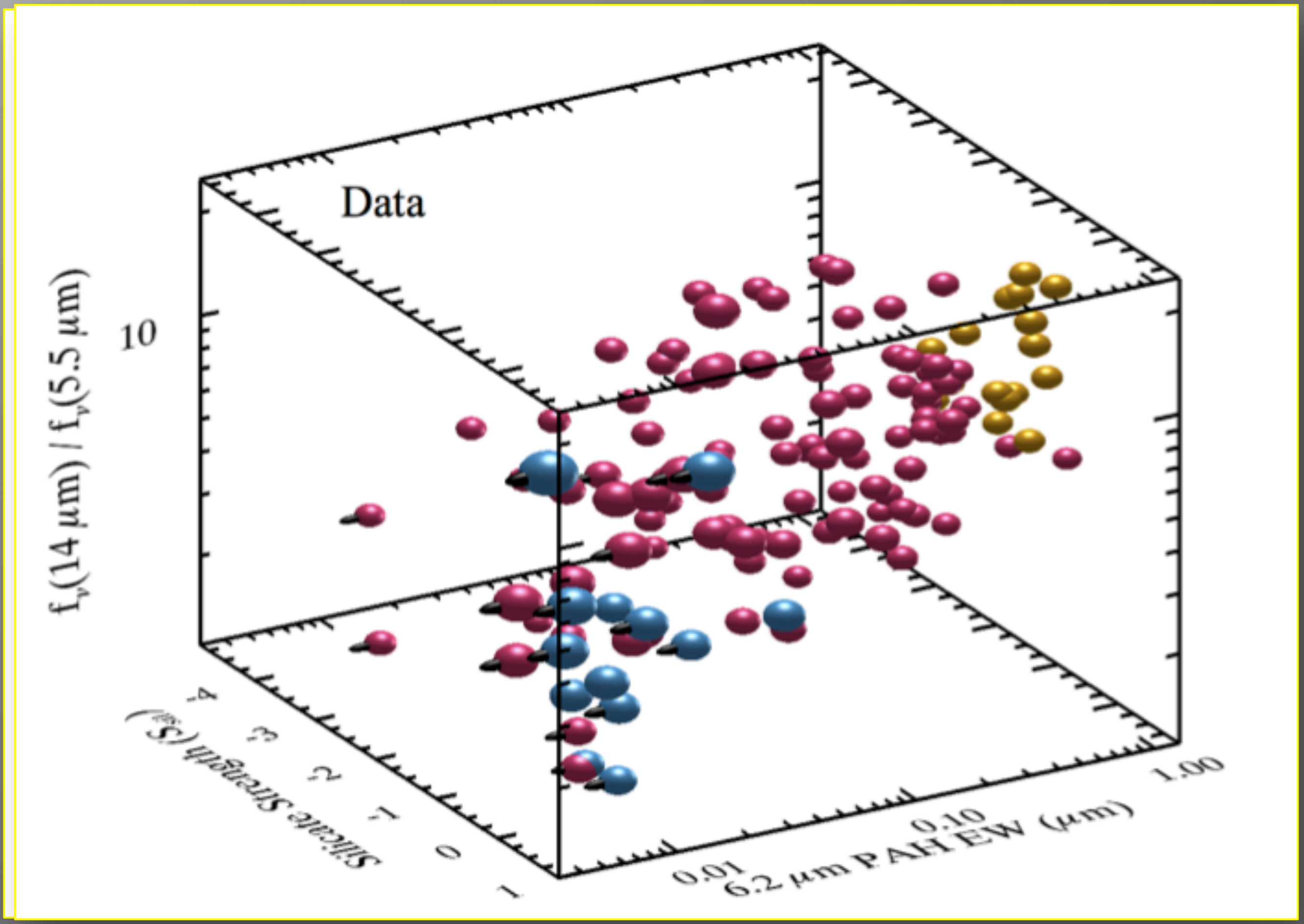
# A new detailed model for obscured sources (2)



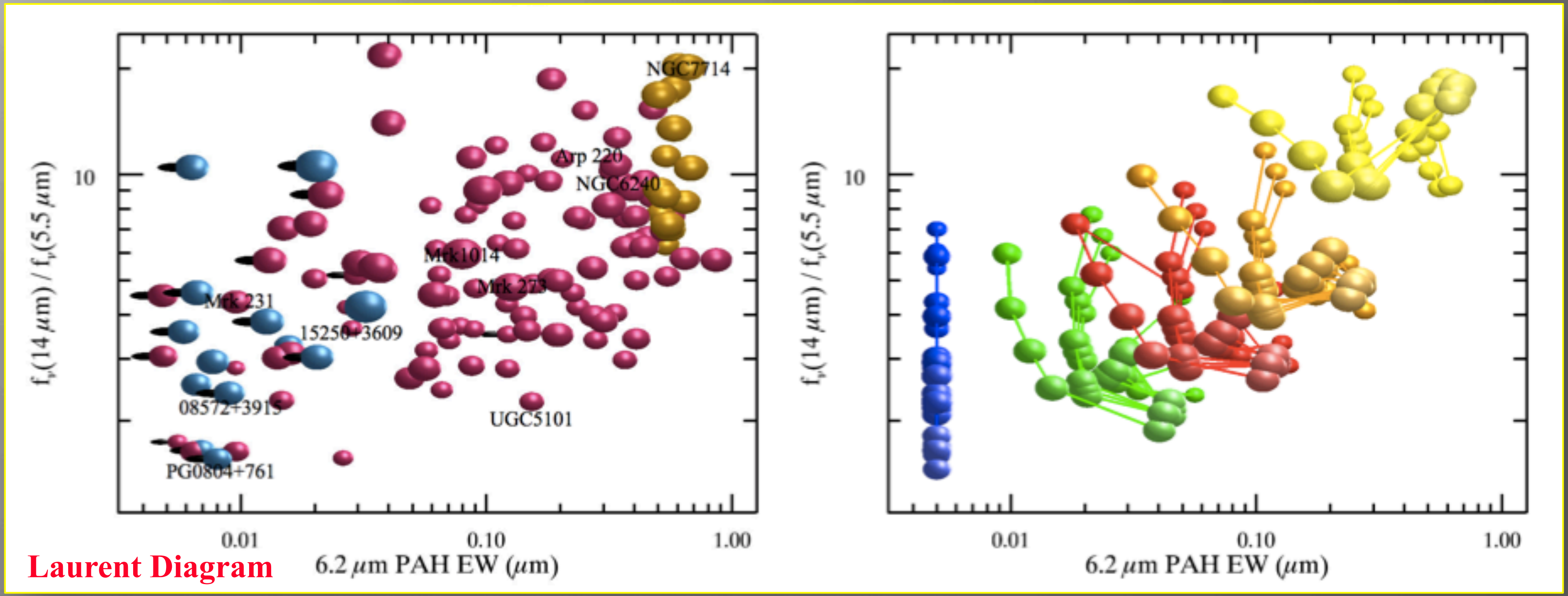

AGN %: Blue 100, Green 75, Red 50, Orange 25, yellow 0

# A new detailed model for obscured sources (2)



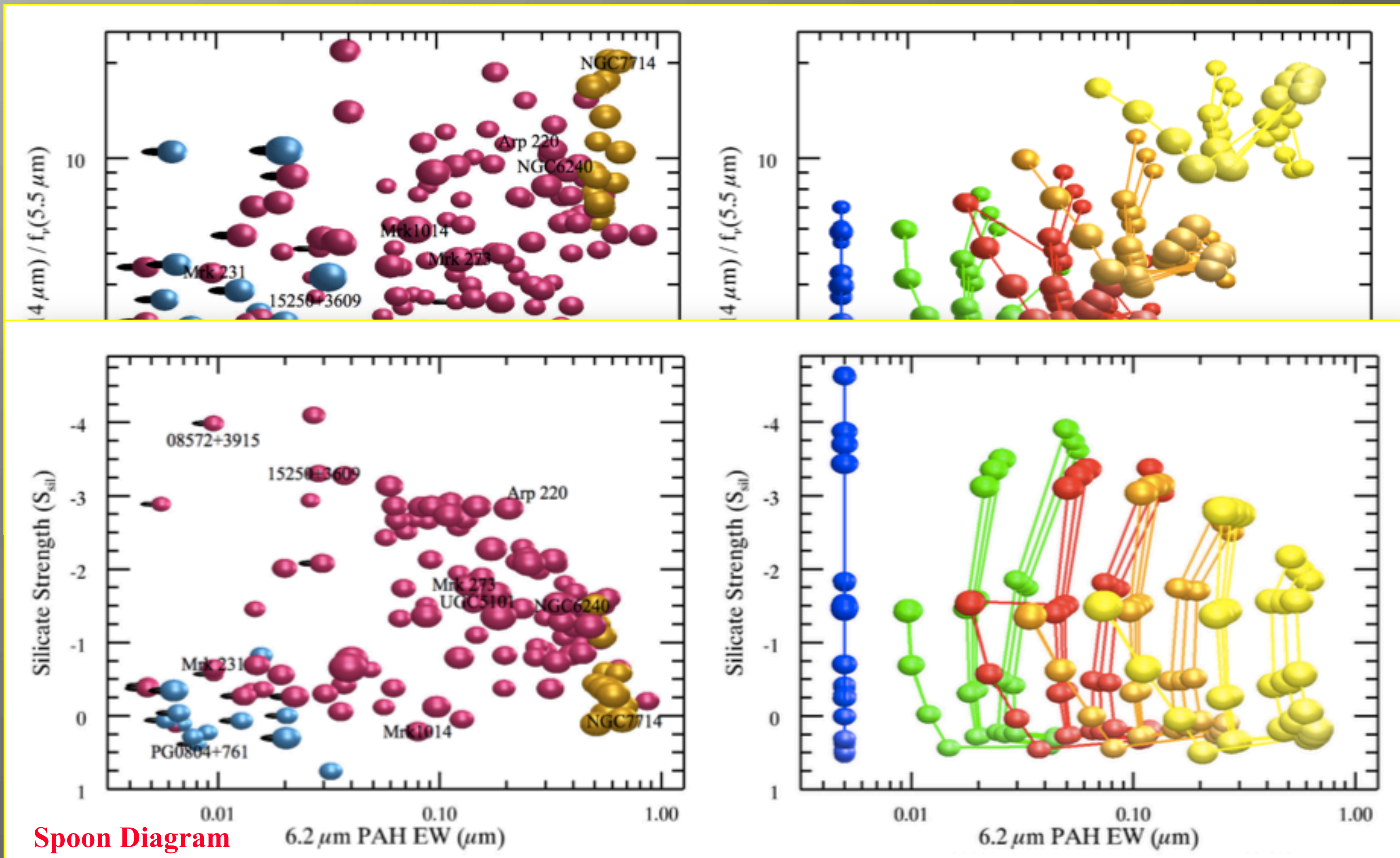

AGN %: Blue 100, Green 75, Red 50, Orange 25, yellow 0

# A new detailed model for obscured sources (3)




AGN %: Blue 100, Green 75, Red 50, Orange 25, yellow 0

# A new detailed model for obscured sources (3)

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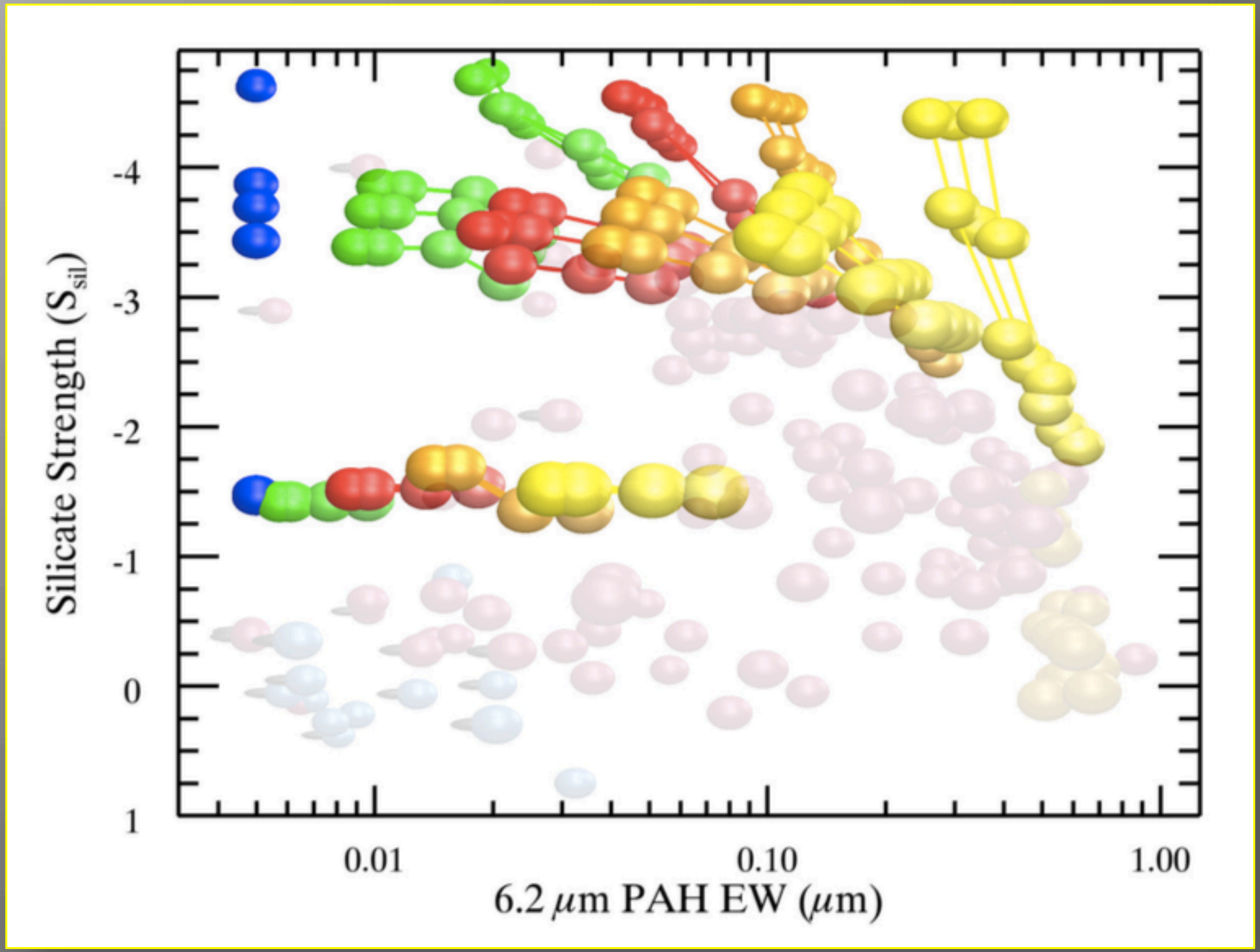
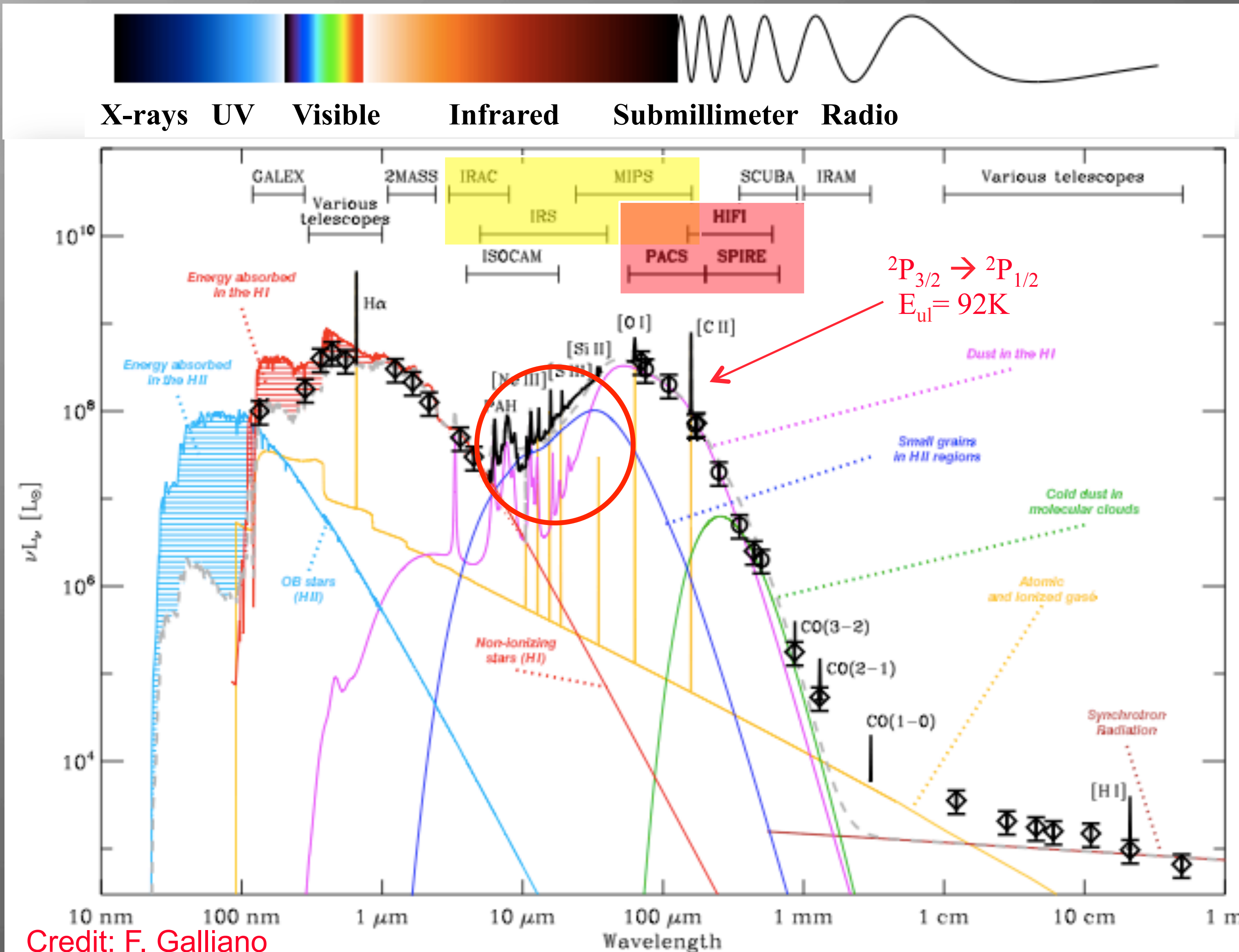
# A new detailed model for obscured sources (3)




The effect of adding unobscured PAH emission to our most deeply buried and fully covered models. From left to right and/or top to bottom, unobscured PAH emission is added at 0%, 0.1%, 0.5% and 1% of the nuclear starburst.

AGN %: Blue 100, Green 75, Red 50, Orange 25, yellow 0

# Spectral Energy Distribution (SED) of a Galaxy

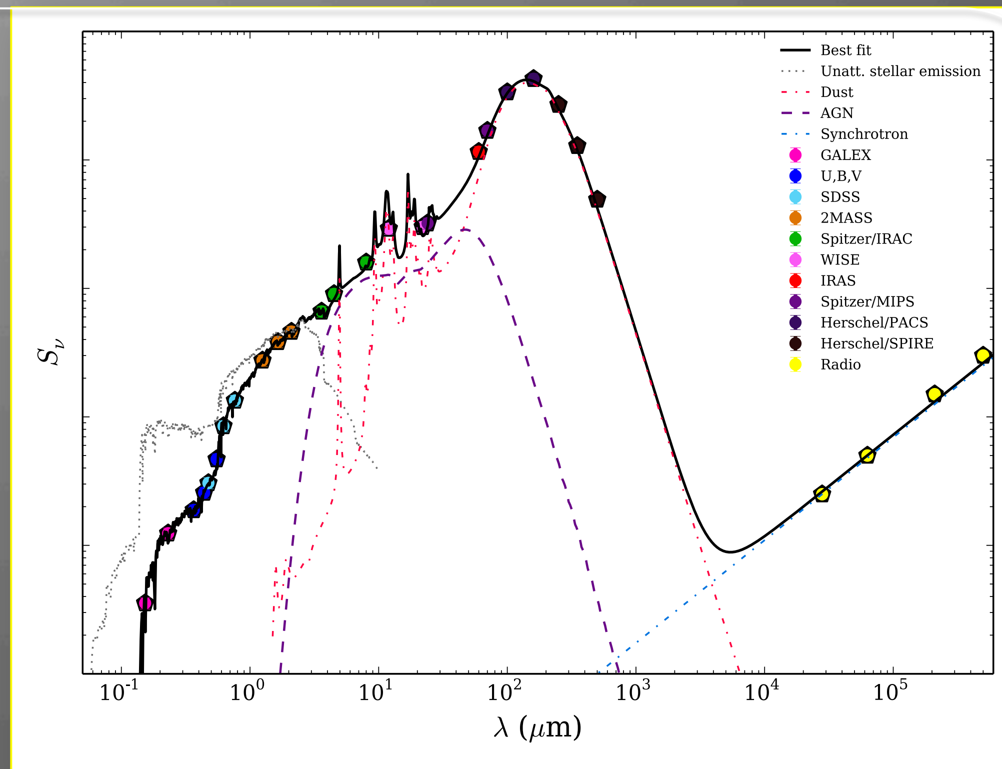


# CIGALE: Code Investigating Galaxy Emission


**http://cigale.lam.fr/**

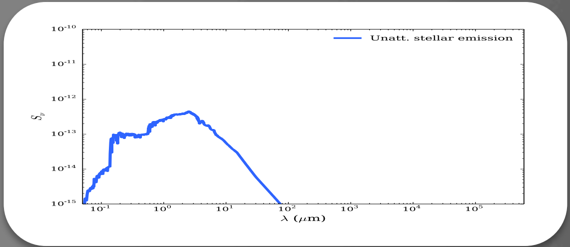
SED modeling
and
SED fitting code
based on ENERGY BALANCE

Parameter analysis through
Baysian approach on priors and
PDF analysis



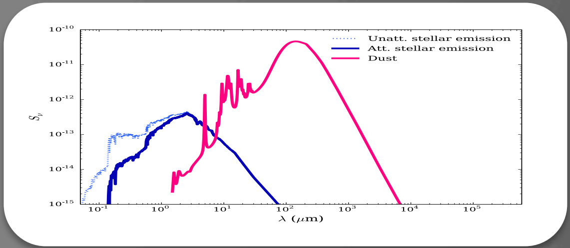
**SFH:**
Analytical (exp-dec, delayed, etc…)
Complex (SAM, etc…)

**Stellar Populations:**
Bruzual&Charlot 03
Maraston+05

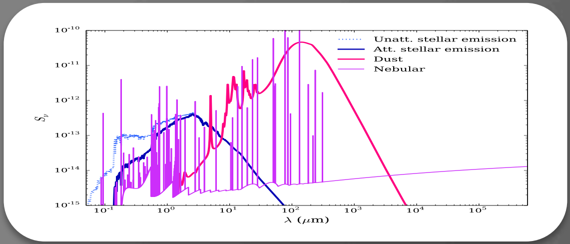



**Attenuation:**
Calzetti law, power law

**Dust emission:**
Dale+14,
Draine&Li 07 + updates
Casey+12

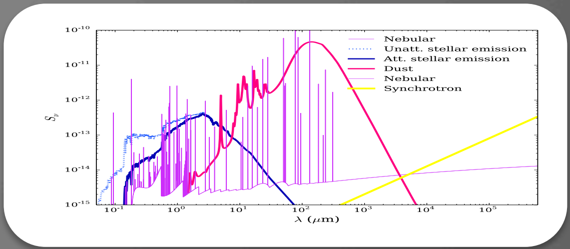



**Nebular emission:**
Inoué models

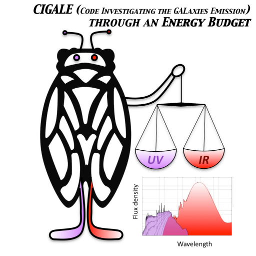



**Analysis:**
$\chi^2$ computation + probability distribution function analysis

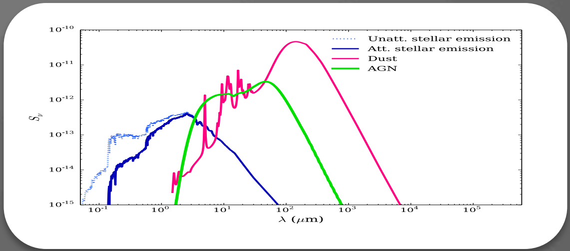
**Synchrotron from SF:**
FIR-radio correlation




Boquien +, 2016
Burgarella+, 2016
Ciesla+15 (AGN)




**AGN:**
Fritz+06



# Physical Motivation

What about AGN host galaxies?

- Broad Band UV to submm photometry widely is available
- It has been used to derive properties of large galaxy samples
- Many (most/all?) galaxies host a SMBH which is accreting

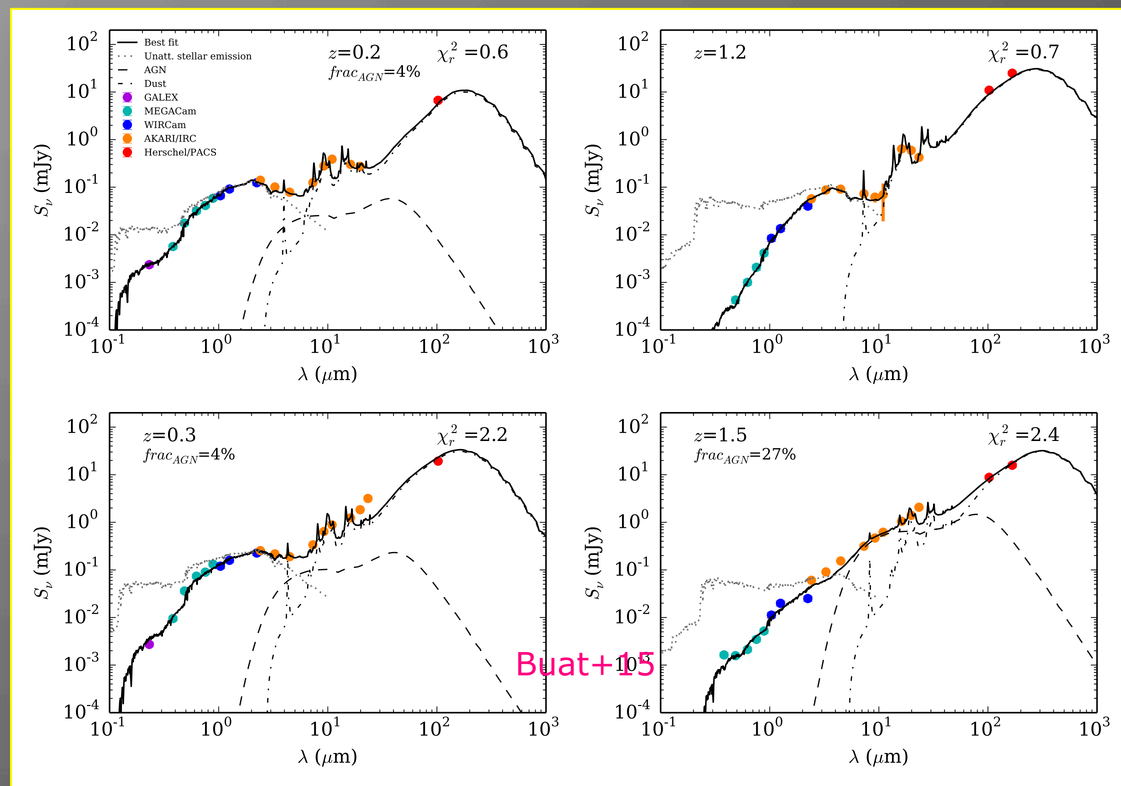
**In normal SF galaxies:**

- No systematic offset on $M_*$
- SFR well recovered as long as one IR data available

Wuyts+09, Mitchell+14, Buat+14

How well can we retrieve M* and SFRs in AGN host galaxies?

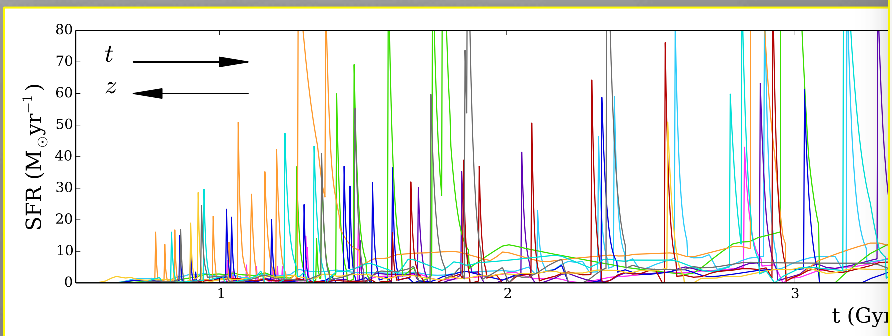
How does the AGN emission affect the SED fitting?

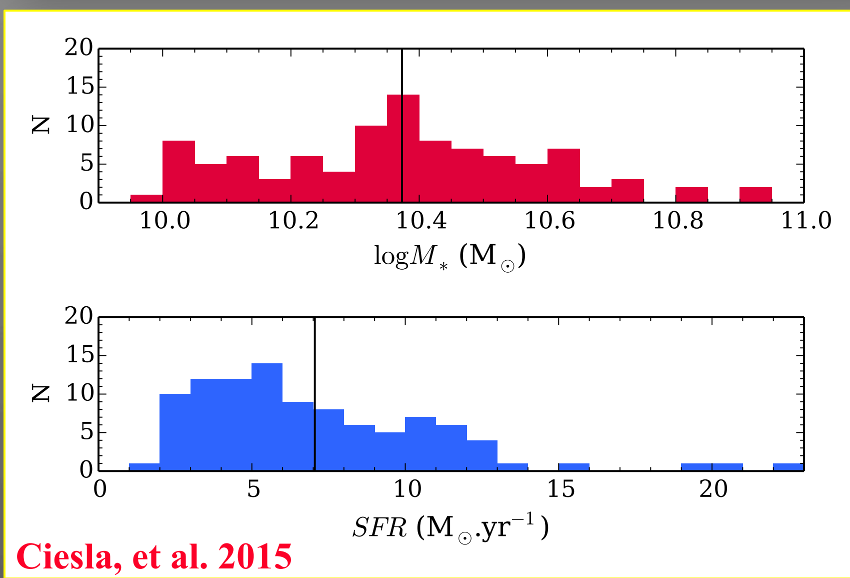



Buat+15

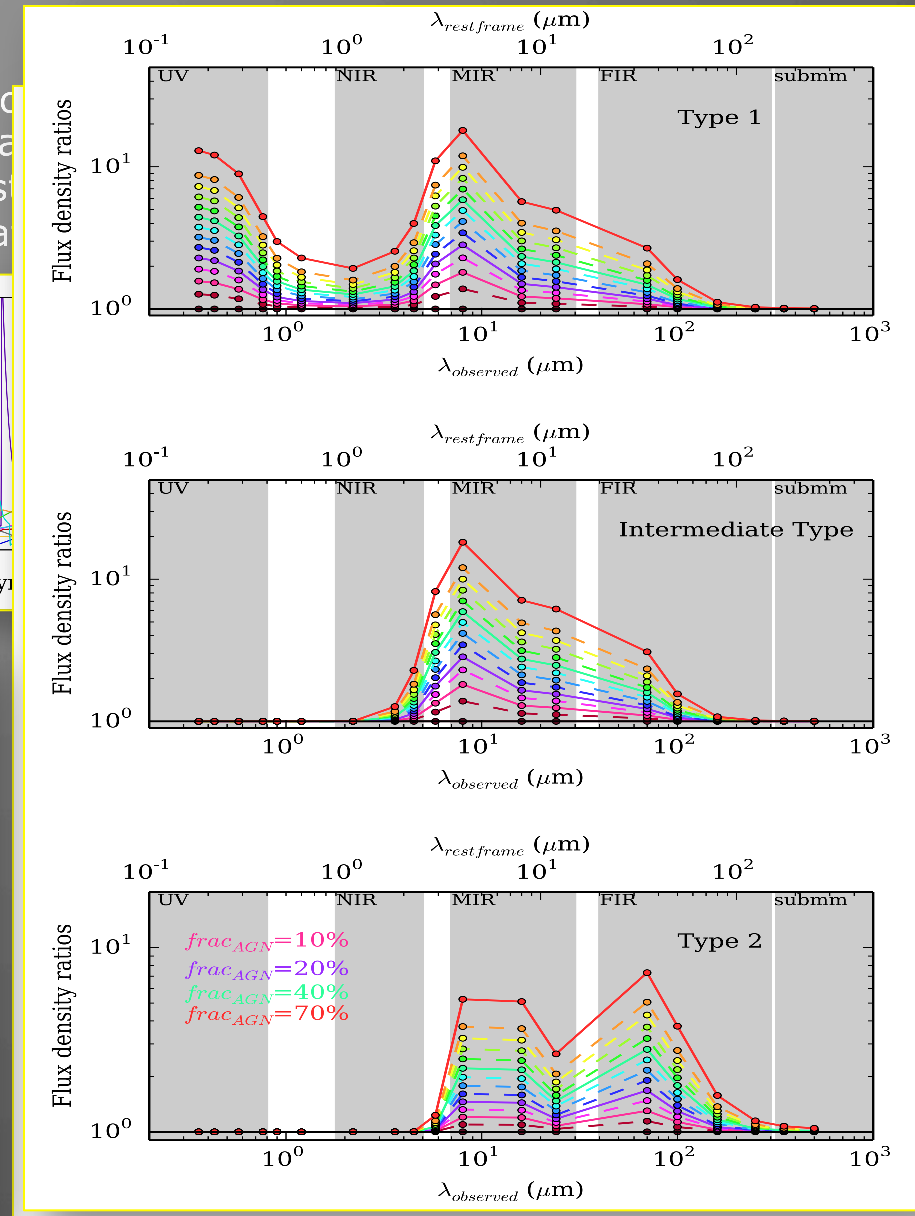
# Methodology: Semi Analytic Models + AGN

- Create mock galaxies using semi analytic
- Use their star formation history to simula
- Add the AGN contribution with variable st
- Fit the final SED with CIGALE and evalua



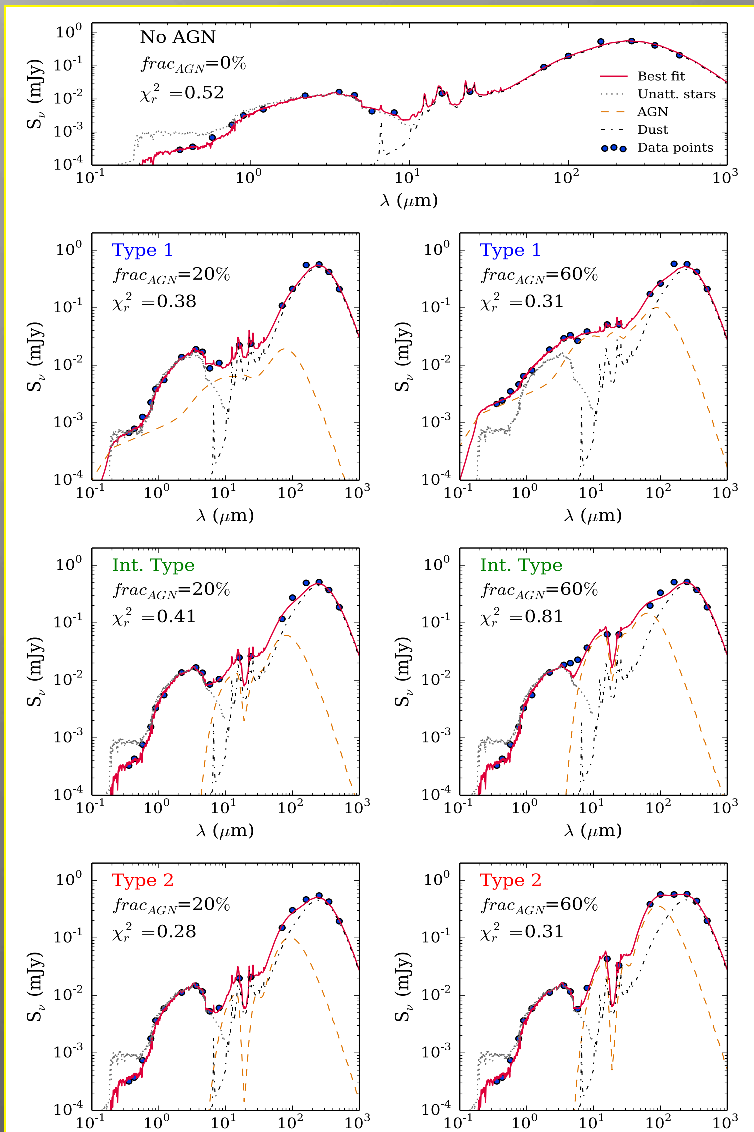




Ciesla, et al. 2015

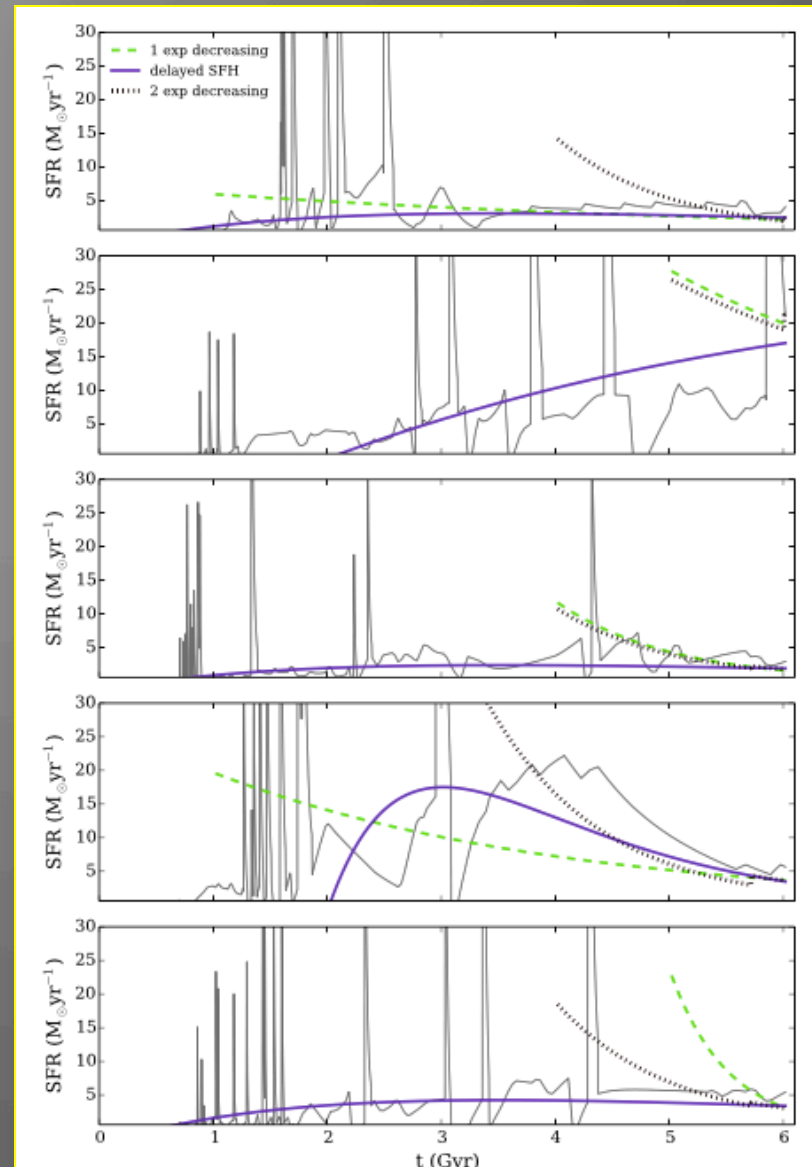



VC

# Methodology: Fit the SED with CIGALE




**Ciesla, et al. 2015**

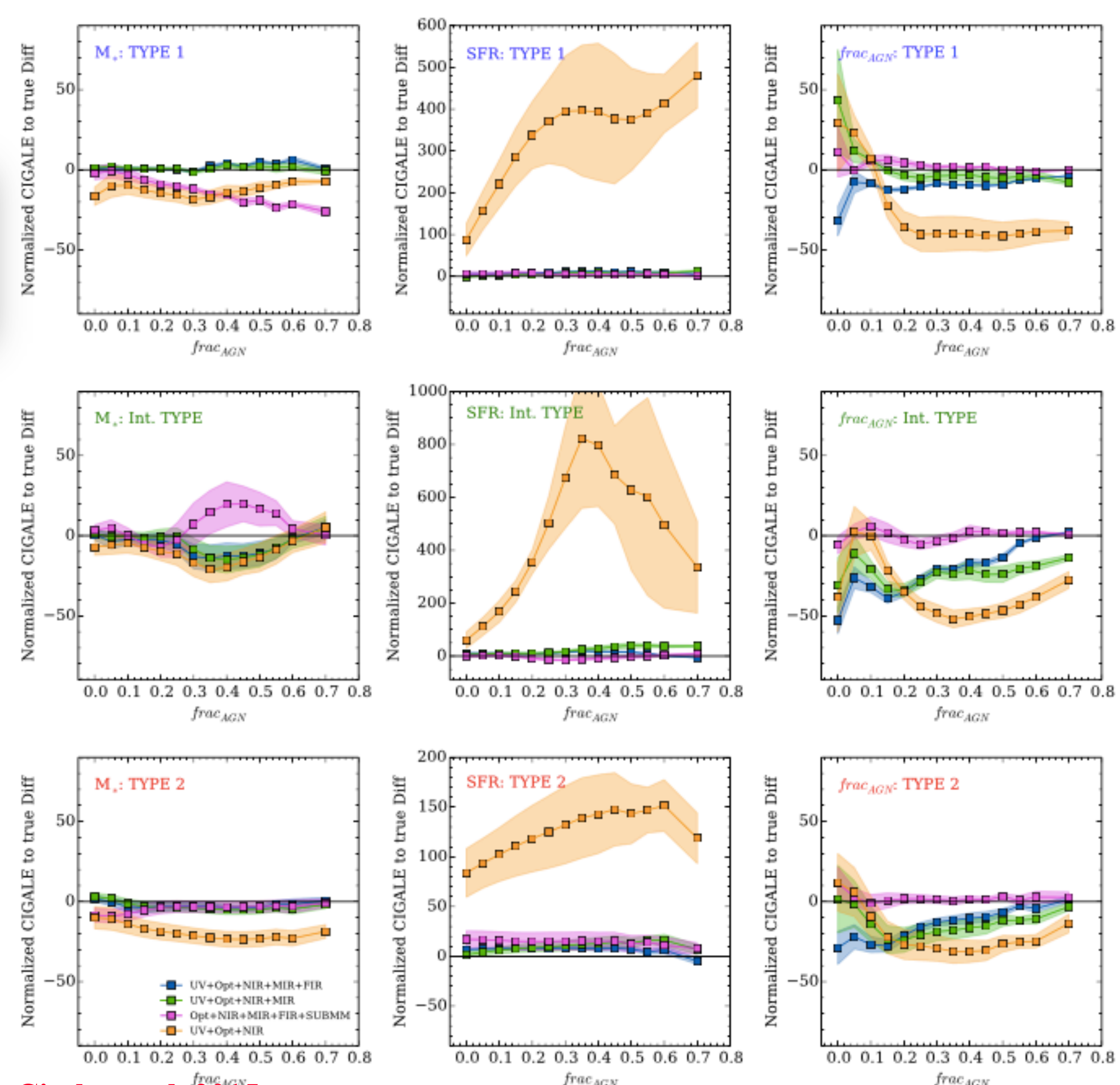


# Impact of photometric coverage

- IR is critical for all types

- UV+Opt+NIR+MIR+FIR
- UV+Opt+NIR+MIR
- Opt+NIR+MIR+FIR+SUBMM
- UV+Opt+NIR

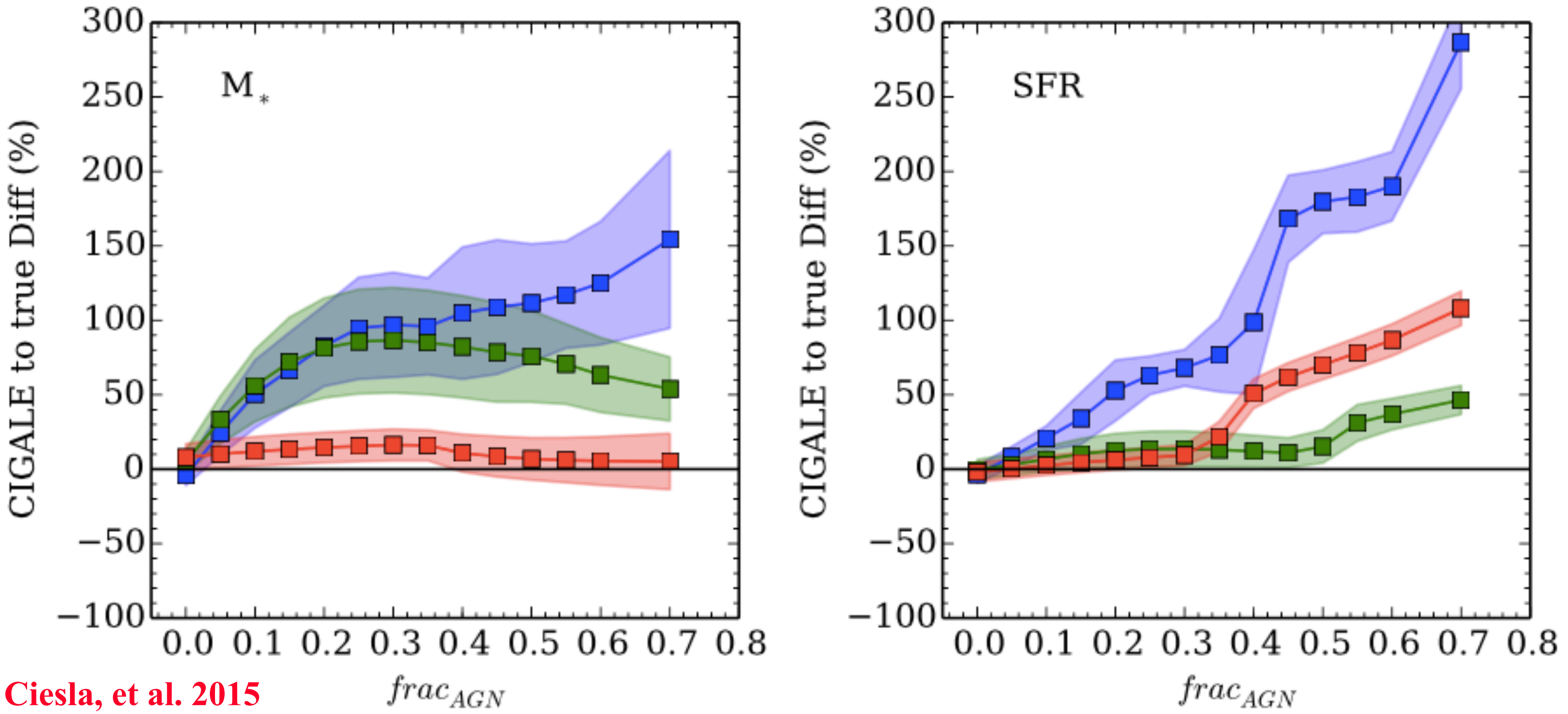
- no UV
- data up to 125 μm RF
- data up to 35 μm RF
- data up to 4 μm RF




Ciesla, et al. 2015

VC

# What if no AGN was included in the fit?




Ciesla, et al. 2015

Type 1

Intermediate Type

Type 2

# SED results

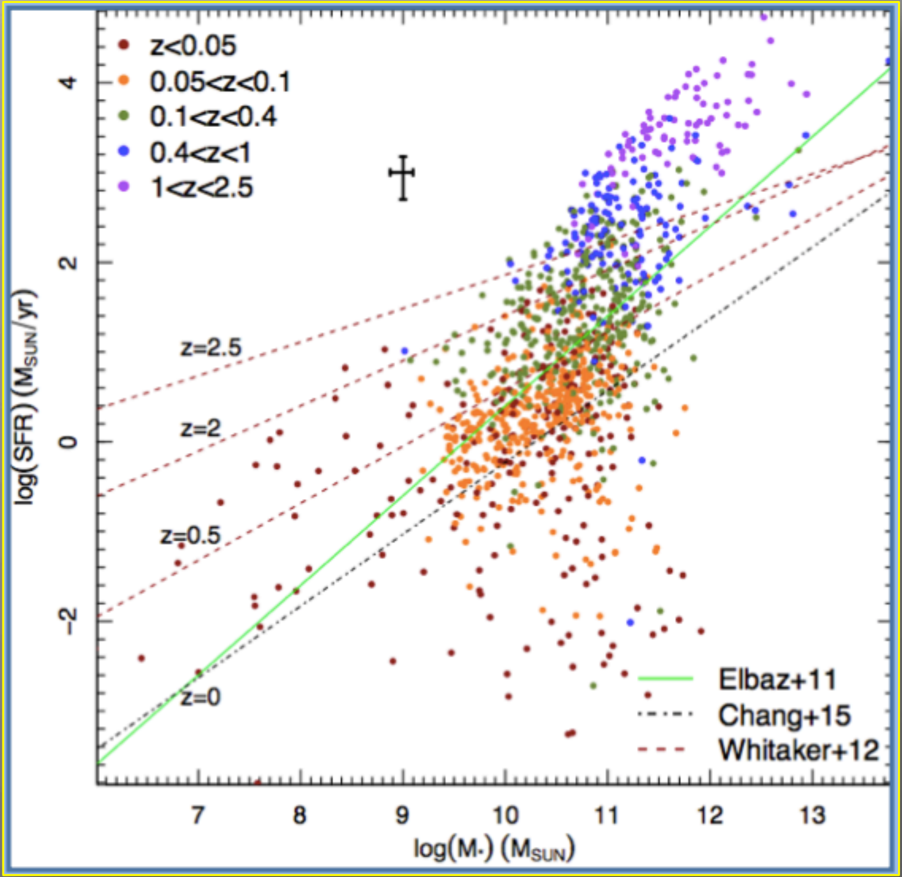
Note that:

- When AGN is present the M* is recovered up to the 40% level depending on the AGN fraction. The larger the fraction the worse the estimate
- SFR is better than 40% as long as far-IR and sub-mm data are available
- Rest frame UV is critical to constrain both M* and SFR in Type 1 objects.
- AGN can not be estimated reliably bellow a 15% AGN fraction.

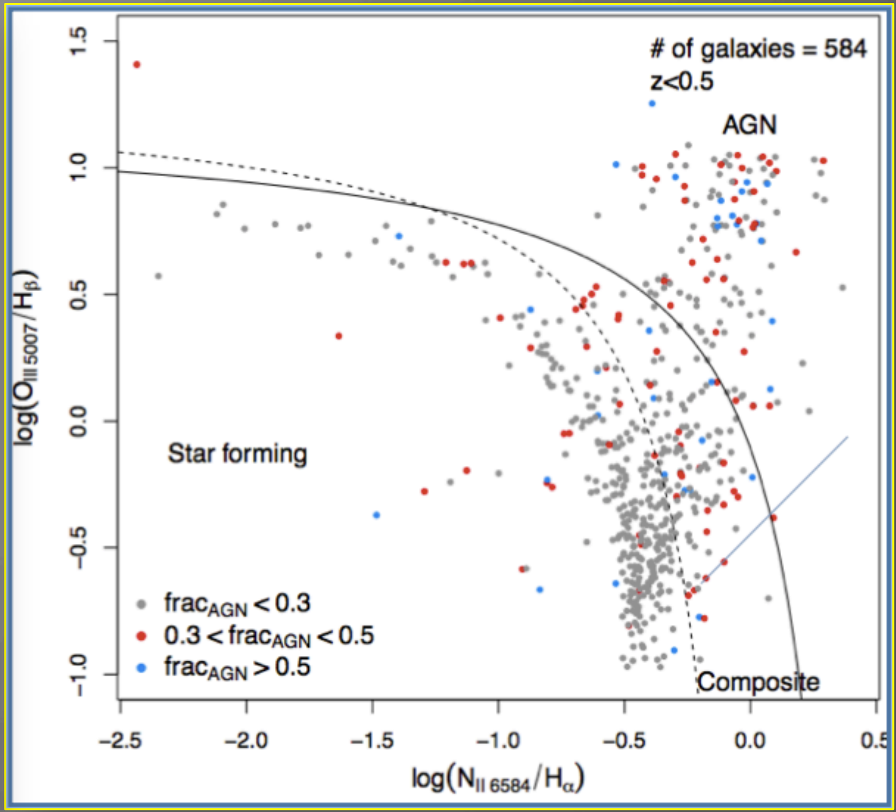
An Application:

- Compile a catalogue of all Spitzer/IRS extragalactic observations for which 5-38μm spectra exist (CASSIS) as well as UV to 22μm photometry (14 bands)
- Use optical/near-IR images (mostly SDSS/2MASS) to estimate global morphology and colors. (Vika et al. 2017)

# SED results

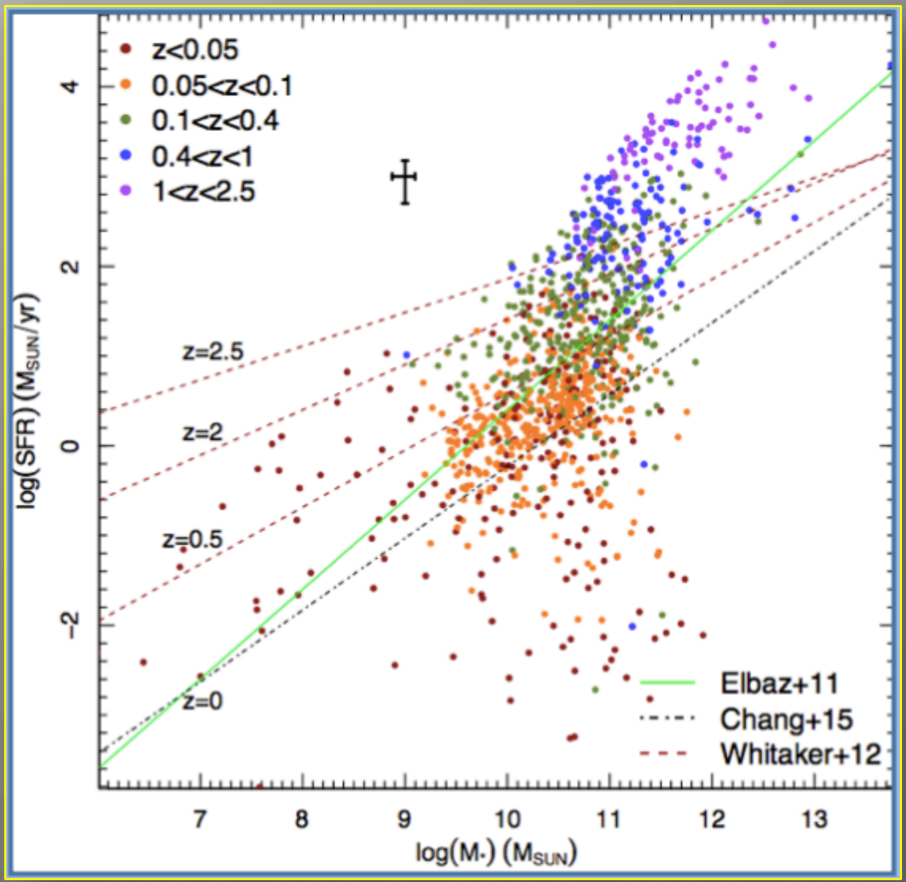


z<0.05
0.05<z<0.1
0.1<z<0.4
0.4<z<1
1<z<2.5
z=2.5
z=2
z=0.5
z=0
Elbaz+11
Chang+15
Whitaker+12
log(SFR) (MSUN/yr)
log(M*) (MSUN)

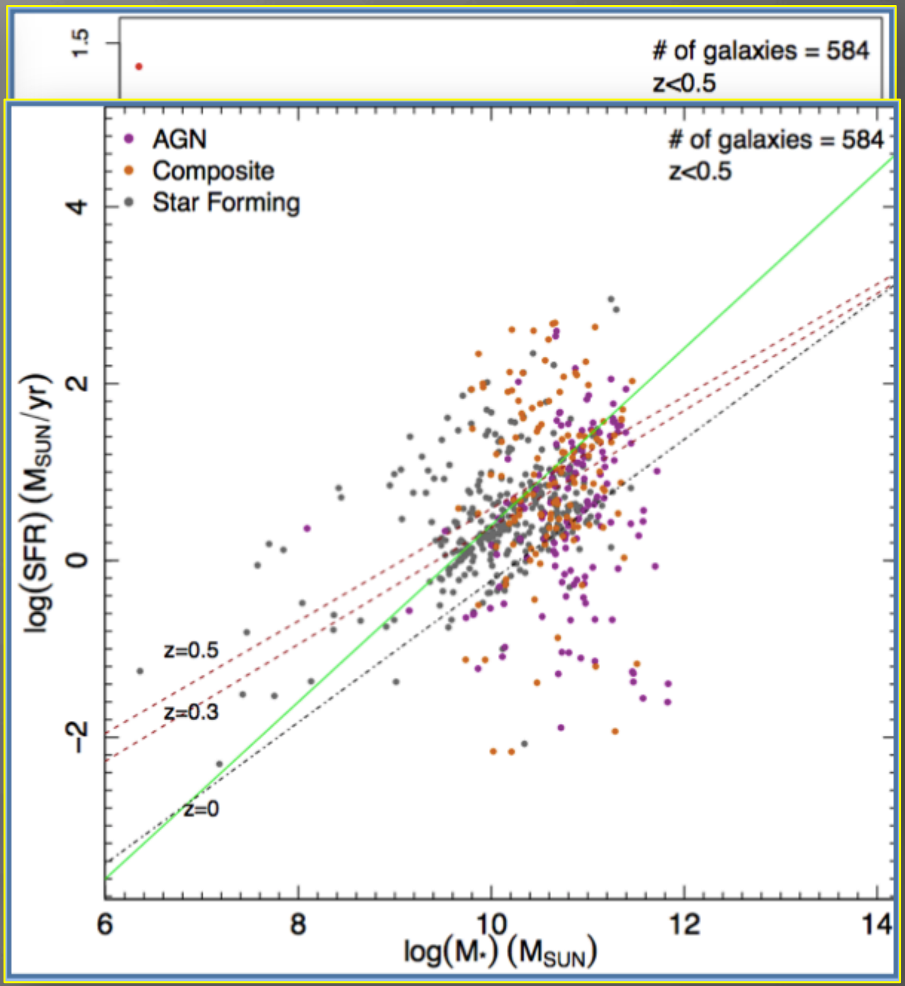



# of galaxies = 584
z<0.5
AGN
Star forming
Composite
fracAGN < 0.3
0.3 < fracAGN < 0.5
fracAGN > 0.5
log(OIII 5007/Hβ)
log(NII 6584/Hα)

# SED results

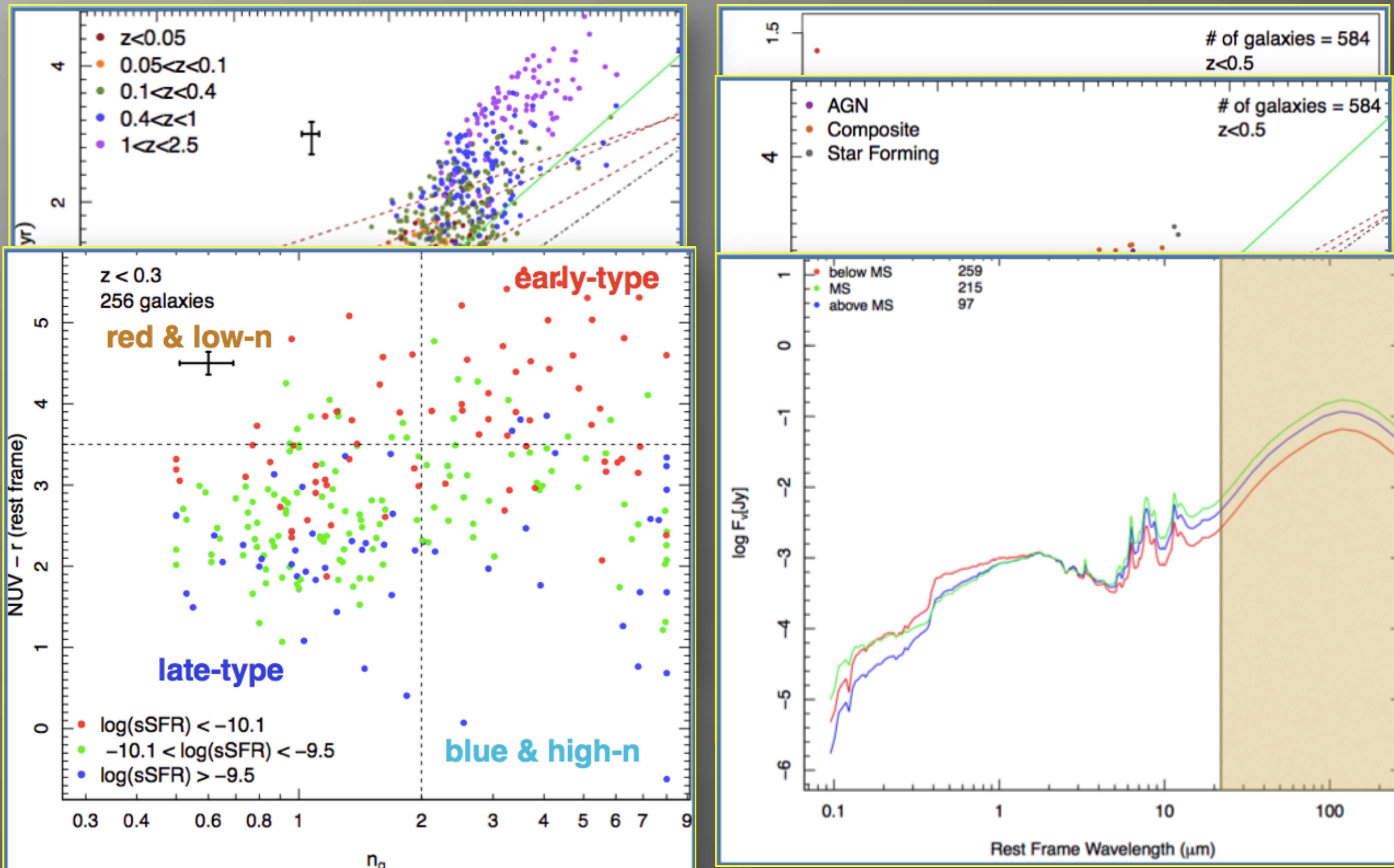


z<0.05
0.05<z<0.1
0.1<z<0.4
0.4<z<1
1<z<2.5
z=2.5
z=2
z=0.5
z=0
Elbaz+11
Chang+15
Whitaker+12
log(SFR) ($M_{SUN}$/yr)
log($M_*$) ($M_{SUN}$)

# of galaxies = 584
z<0.5
AGN
Composite
Star Forming
# of galaxies = 584
z<0.5
z=0.5
z=0.3
z=0
log(SFR) ($M_{SUN}$/yr)
log($M_*$) ($M_{SUN}$)

# SED results


z<0.05
0.05<z<0.1
0.1<z<0.4
0.4<z<1
1<z<2.5
# of galaxies = 584
z<0.5
AGN
Composite
Star Forming
# of galaxies = 584
z<0.5
z < 0.3
256 galaxies
early-type
red & low-n
late-type
blue & high-n
log(sSFR) < −10.1
−10.1 < log(sSFR) < −9.5
log(sSFR) > −9.5
NUV − r (rest frame)
n_g
below MS 259
MS 215
above MS 97
log F_ν[Jy]
Rest Frame Wavelength (μm)

# My ticket to Cornell & Ithaca ...

Date: Mon, 07 Sep 1998 09:35:03 -0400
From: Jim Houck <jrh13@cornell.edu>
Subject: Re: SIRTF Research Associate Position...
To: Vassilis Charmandaris <vassilis.charmandaris@obspm.fr>

Hi Vassilis:

Thank your for your note. Yes, please do apply for the position here. I'll need the names and addresses of three people who can write letters of recommendation. If any of them are in Europe please contact them directly, since that will save time. I read your web site, so I already know a little about you.

When would you be available? Another vexing problem concerns the US visa hassel. Do you currently hold a visa and if so what type is it? We can work around all this red tape, but I am sure you know the frustration!

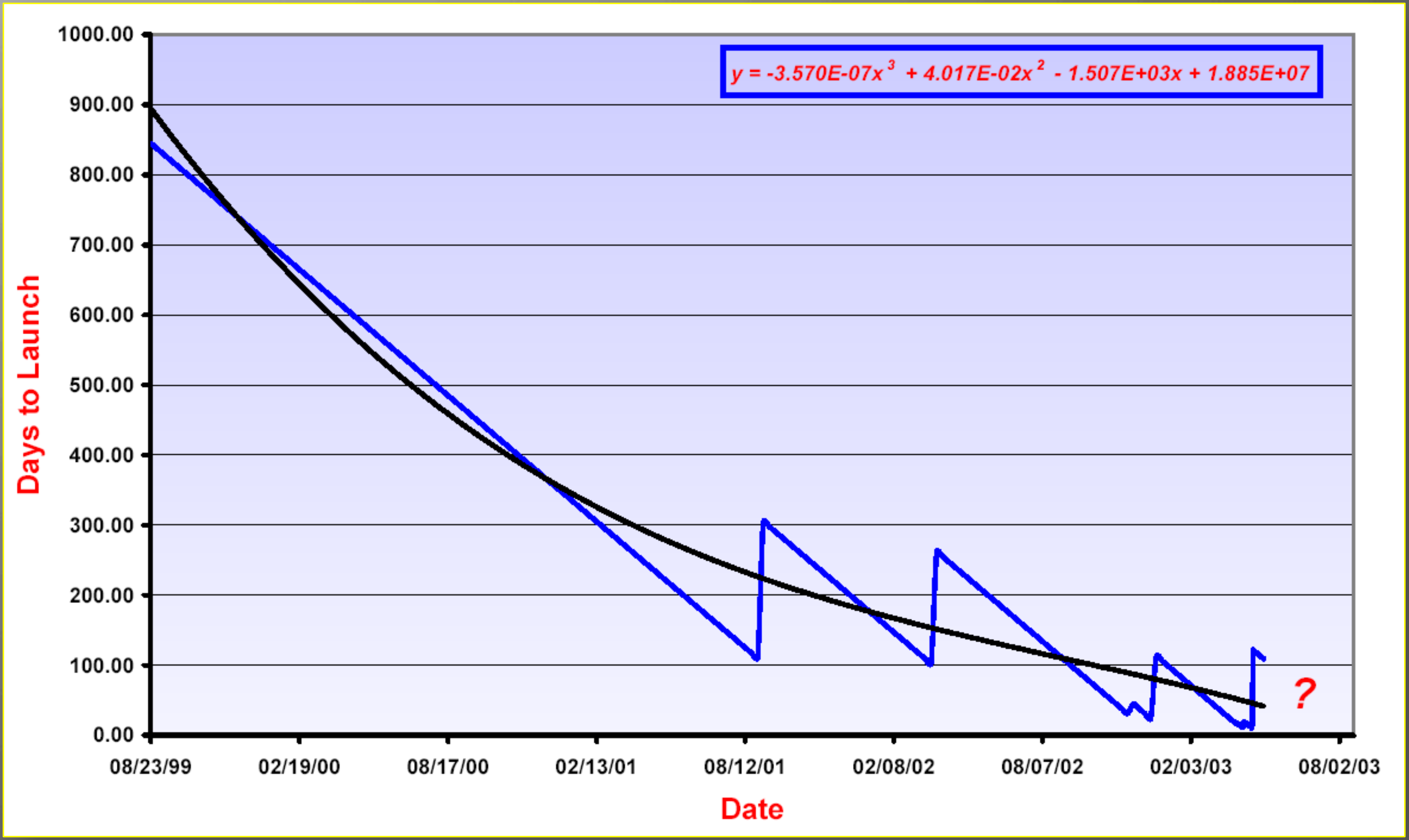
Thanks again for your interest. I hope to hear from you soon.

Sincerely

Jim

# Bernhard: SIRTF is approaching launch, really!

[Paris Oct. 1998]



# Warm Ithaca summer: preparing for IOC

# Cool Pasadena winter: post IOC celebrations



VC

# Ithaca 2007

# Ithaca 2017: “As a shadow such is life”