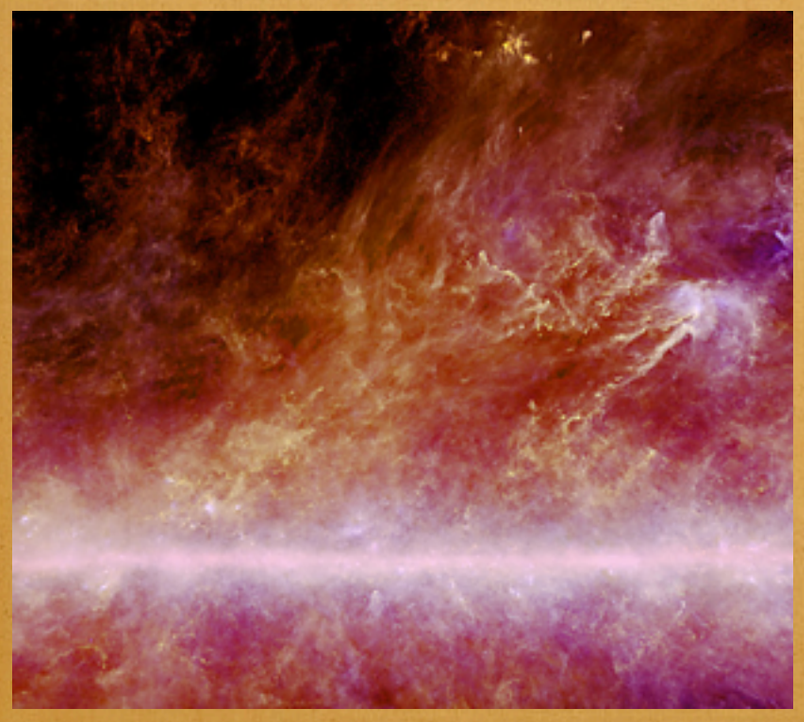
The Cooling of Gas in Nearby Galaxies

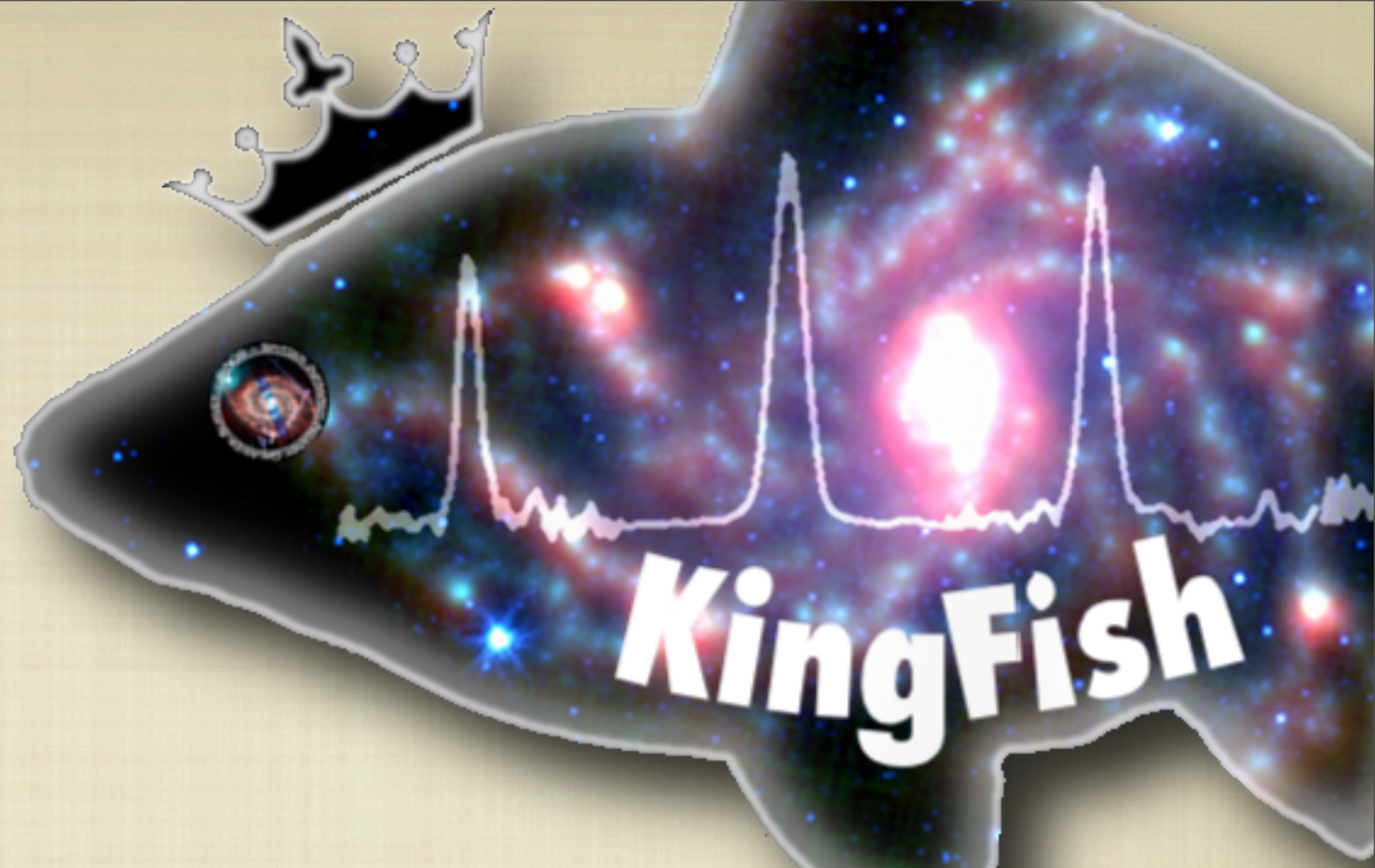
JD Smith



Studying galaxies with "names"

The Third Earl of Rosse, 1845

- Massively multi-wavelength nearby galaxy surveys (~70 galaxies <30Mpc), built around the 2001 Spitzer imaging + Spectroscopy Legacy Program **SINGS.**
- **KingFish** Herschel survey: 70–550μm, Pacs/Spire Imaging + Pacs spectroscopy, 540 hours



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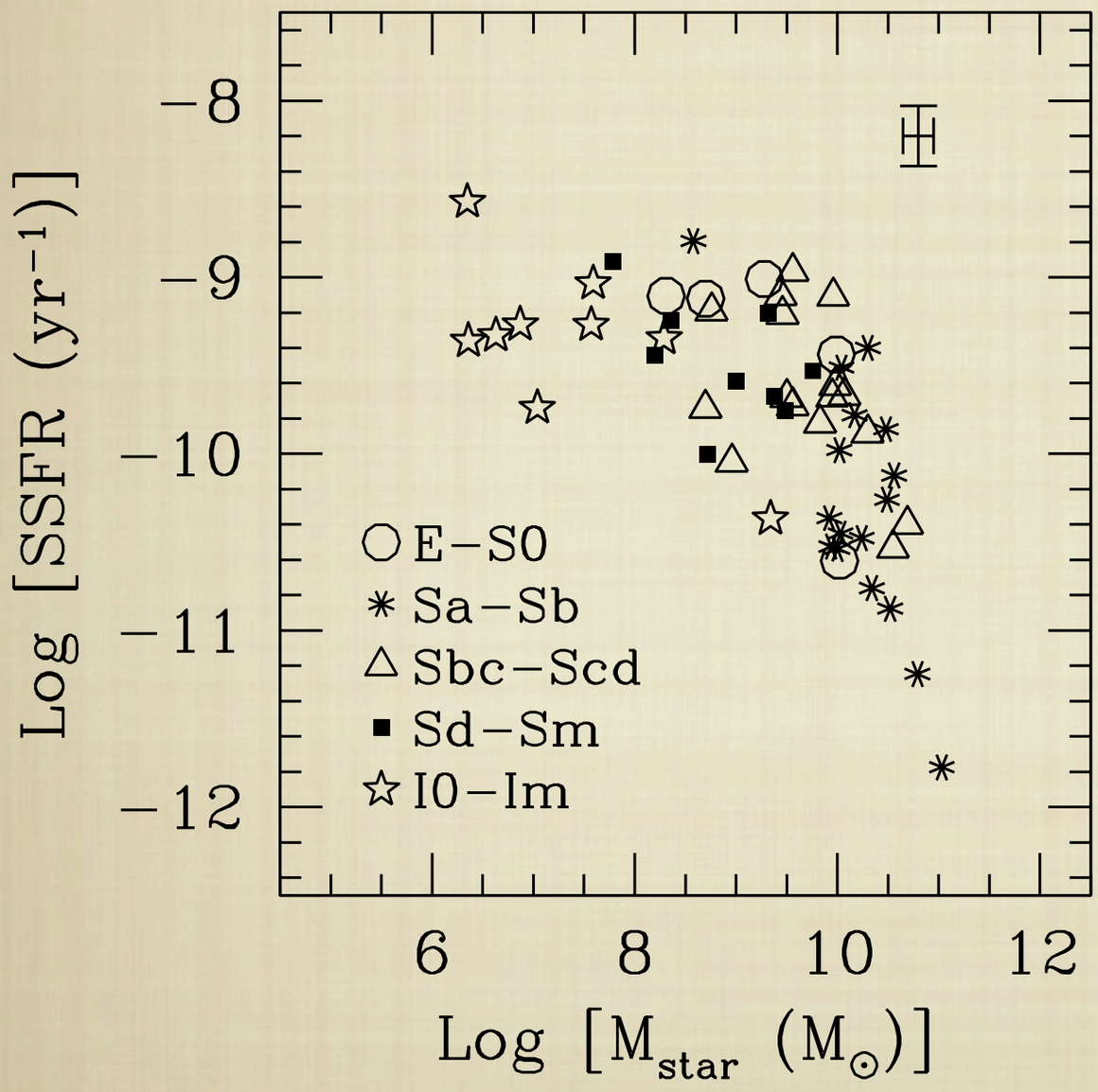
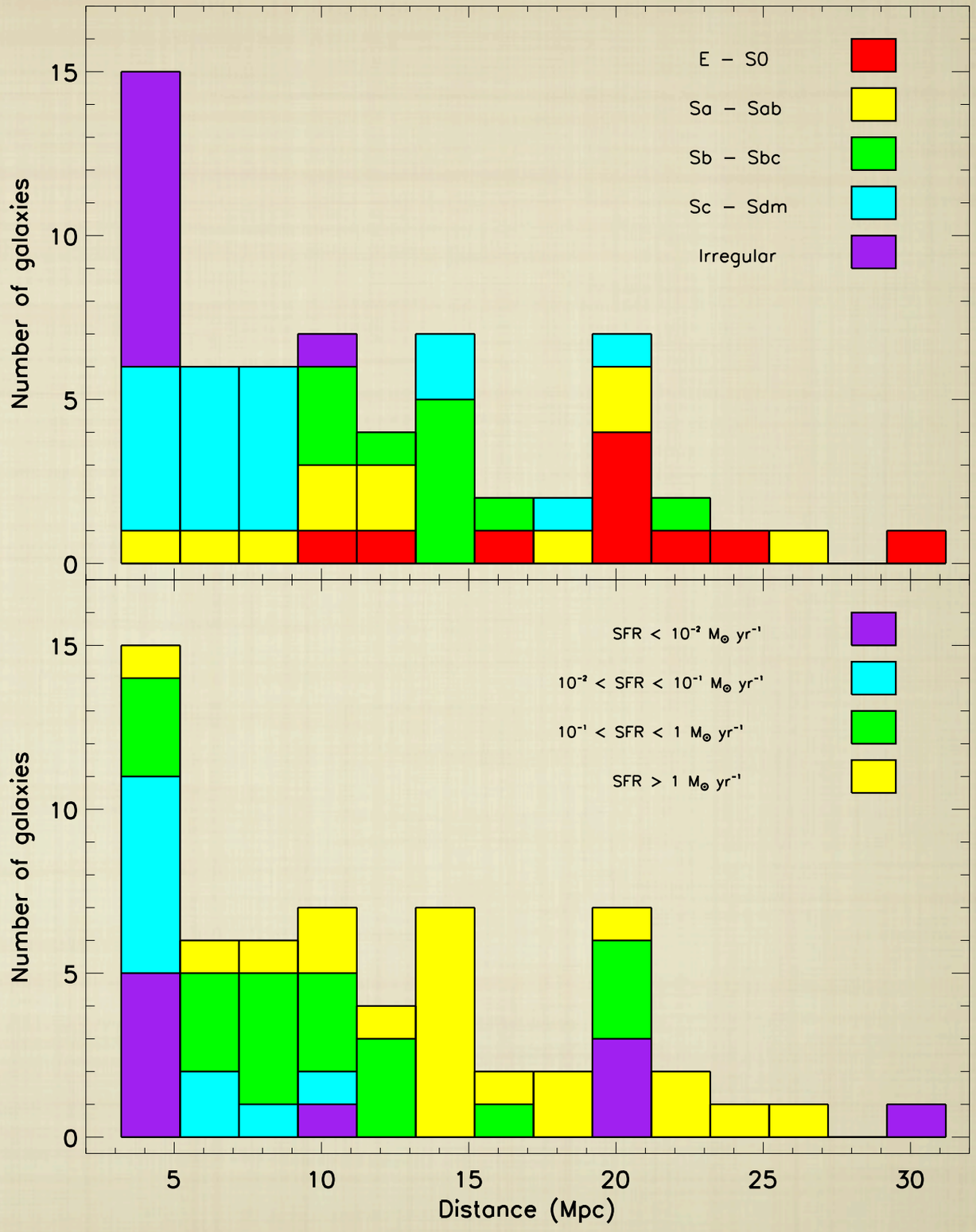
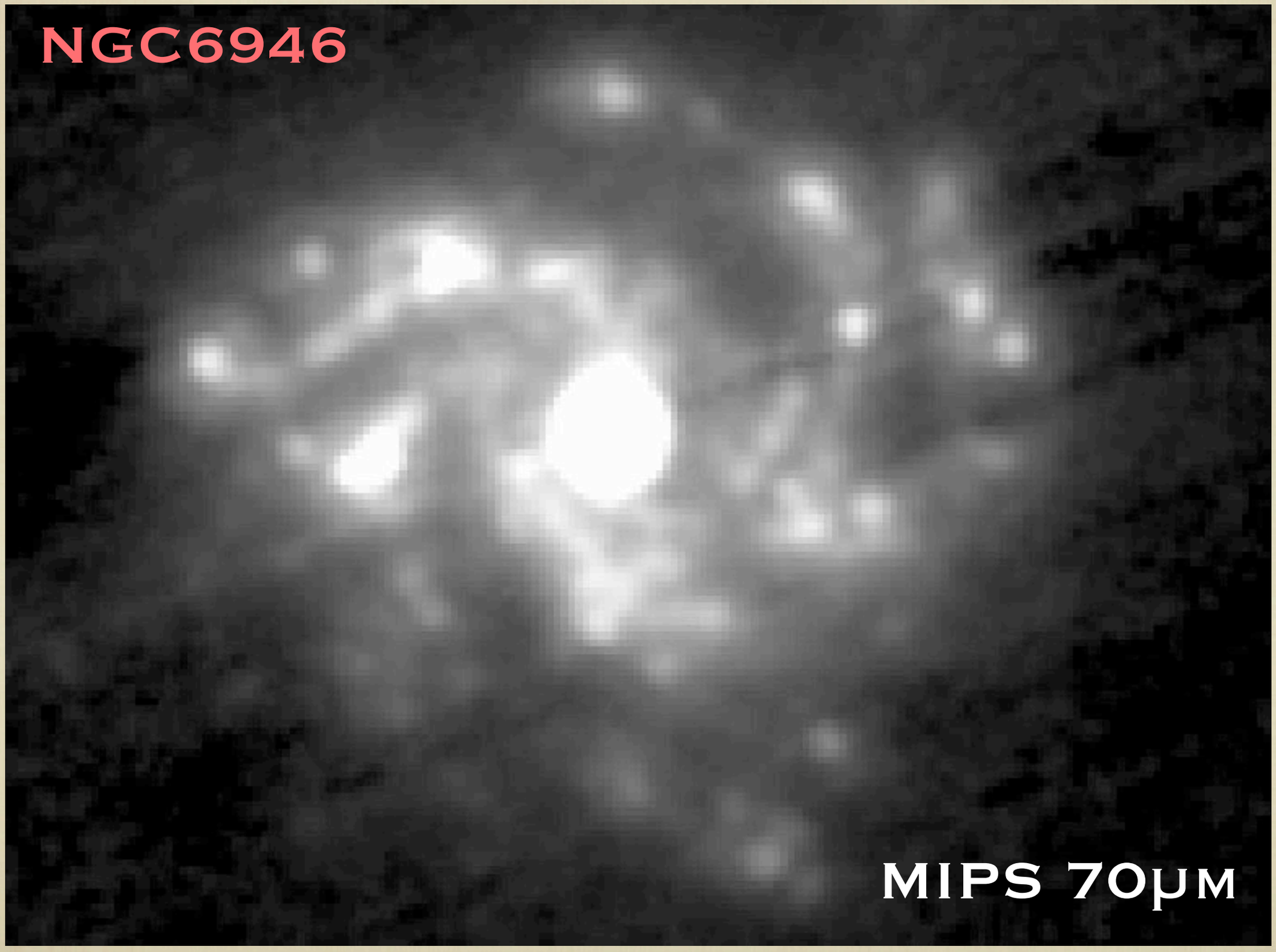
KingFish Sample

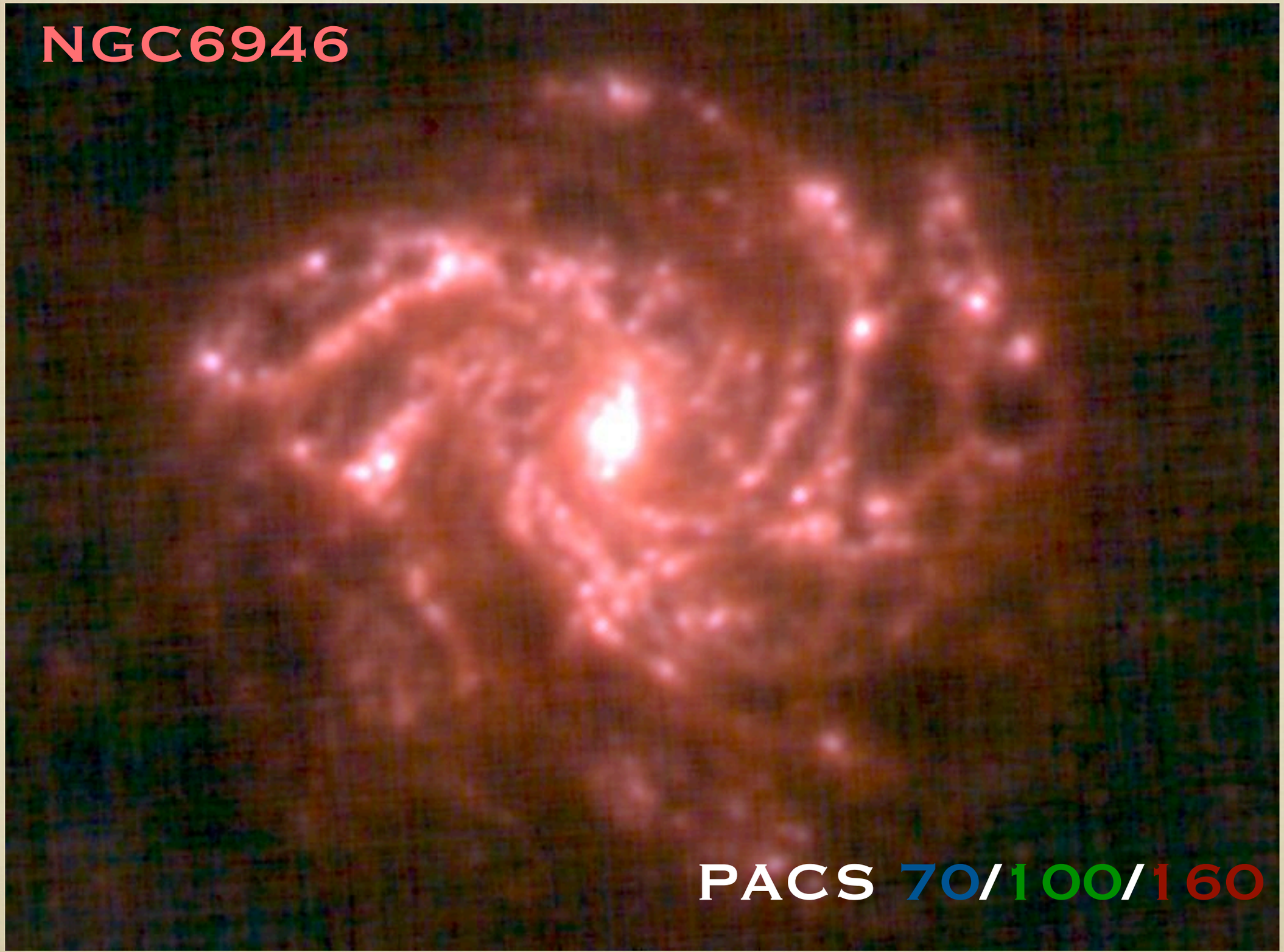




KingFish on Dust

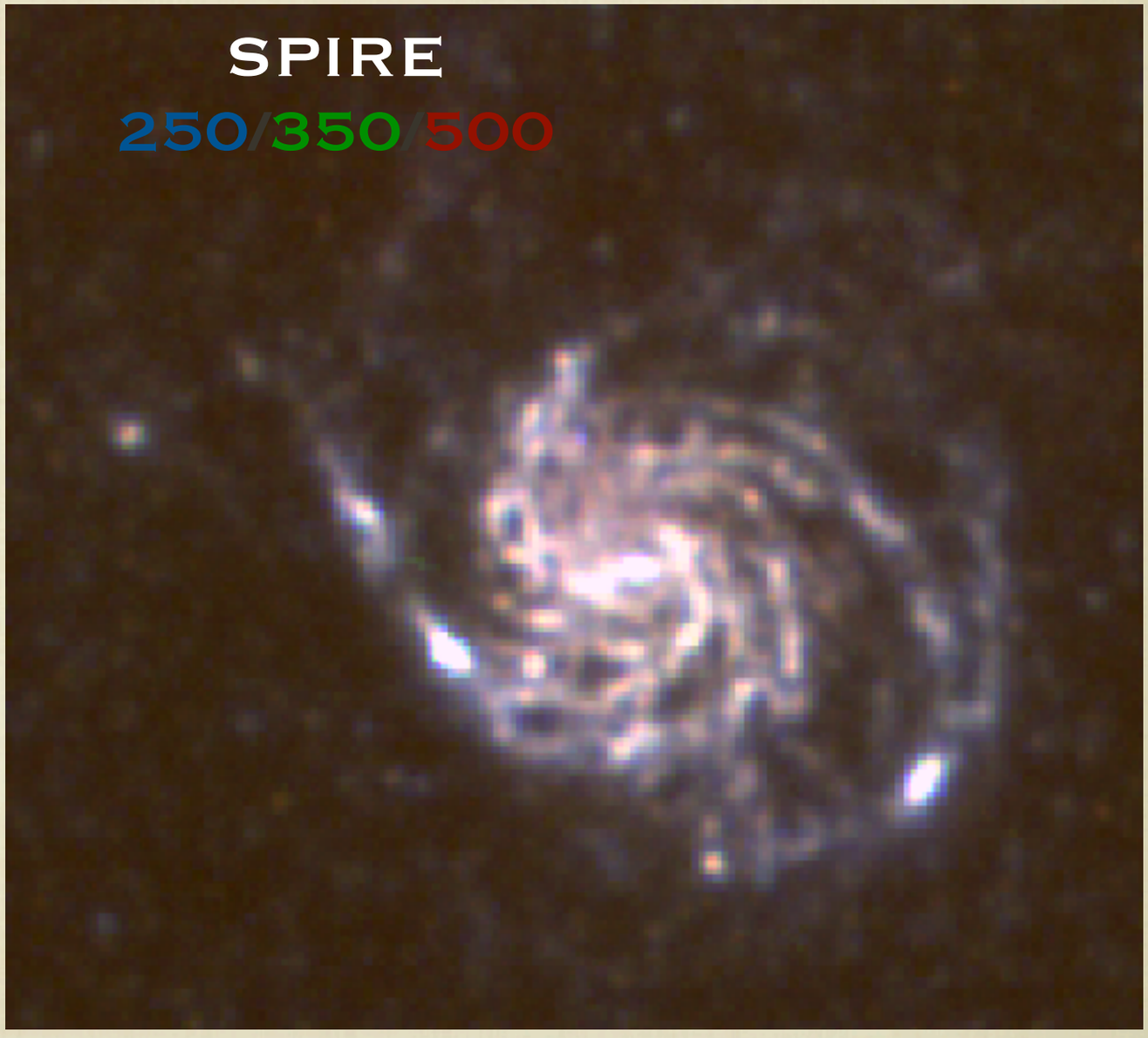


KingFish on Dust



M101

D=7.1Mpc



The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork

The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 μm, and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 μm.

The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.

More information can be found at:
http://sings.stsci.edu/

Unbarred Spirals

Weak Bulge

Strong Bulge

Ellipticals

Irregulars

Strong Bulge

Weak Bulge

Intermediate Spirals

Barred Spirals

Poster and composite images created from SINGS observations by Karl D. Gordon (Oct 2007)
Blue=IRAC 3.6μm (stars)
Green=IRAC 8μm
(aromatic features from dust grains/molecules)
Red=MIPS 24μm (warm dust)

SINGS Team

Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou

Kingfish (Key Insights on Nearby Galaxies: a Far-Infrared Survey with Herschel)

http://www.ast.cam.ac.uk/research/kingfish

NGC 2841 NGC 3938 NGC 628 NGC 7793 NGC 3190 NGC 4826 NGC 2976 NGC 4254 NGC 3621 NGC 5055 NGC 5474 NGC 3265 NGC 4594 NGC 4736 NGC 733 NGC 4321 NGC 584 NGC 3184 NGC 855 NGC 1482 NGC 4579 NGC 3521 NGC 3773 NGC 4725 NGC 1404 NGC 5866 NGC 1377 NGC 4559 NGC 6946 NGC 1316 NGC 5713 NGC 4569 IC 342 NGC 1266 NGC 3627 NGC 5457 NGC 4536 NGC 925 NGC 2798 NGC 1291 NGC 2146 NGC 3077 NGC 3049 NGC 1097 NGC 5398 NGC 337 NGC 4236 NGC 1512 NGC 4631 NGC 3351 NGC 3198

Elliptical *S0* *Sa* *Sb* *Sc* *Sd*

SBa *SBb* *SBc* *SBd*

DDO 154 NGC 2915 DDO 165 NGC 5408 DDO 53 IC 2574 Holmberg I Holmberg II M81 Dw B NGC 4625

Irregular

MIPS 24 μm / PACS 100 μm / SPIRE 250 μm

HTTP://HERSCHEL.CF.AC.UK/KINGFISH

Kingfish (Key Insights on Nearby Galaxies: a Far-Infrared Survey with Herschel)

Elliptical — S0 — Sa — Sb — Sc — Sd

SBa — SBb — SBc — SBd

Irregular

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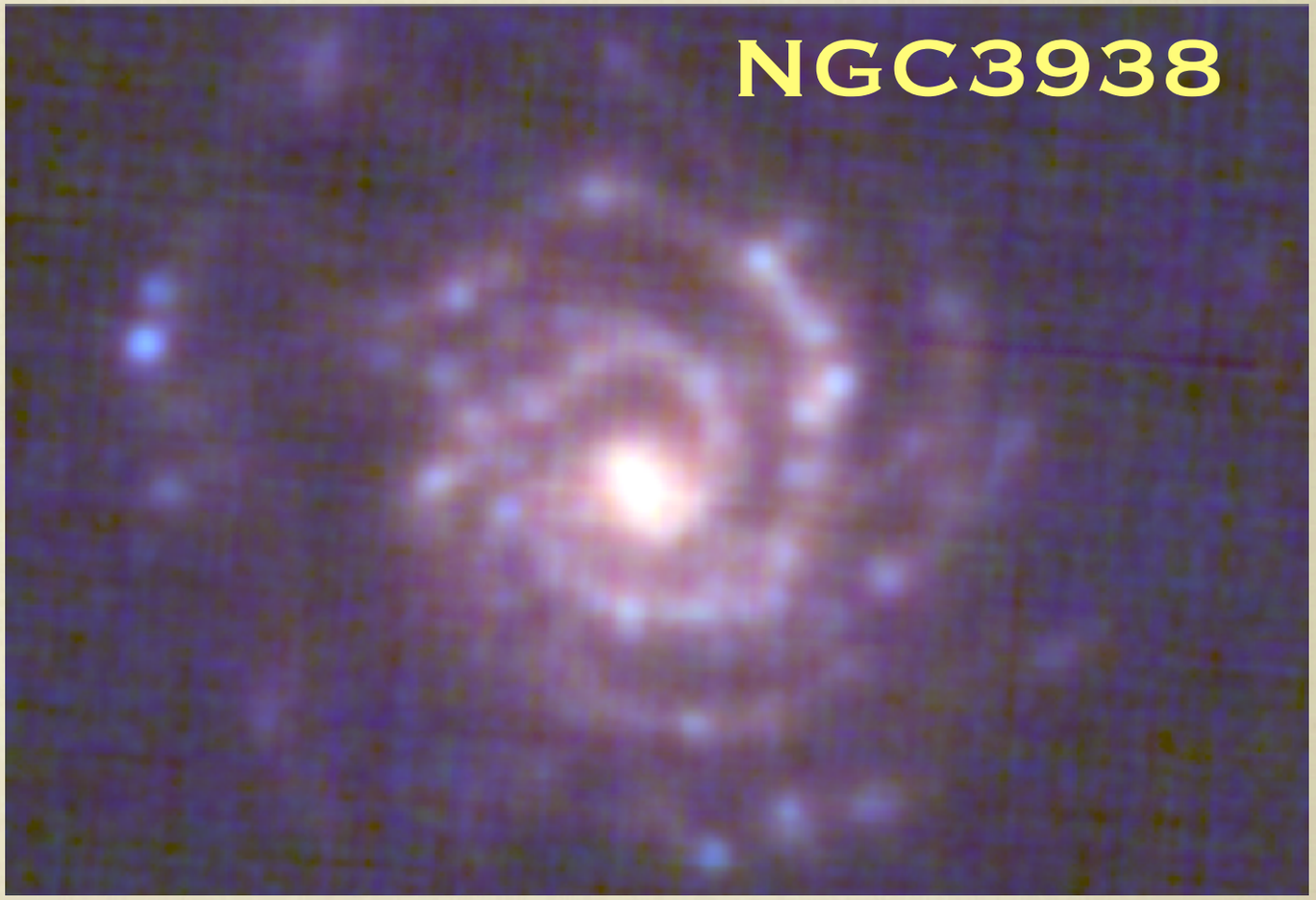
HTTP://HERSCHEL.CF.AC.UK/KINGFISH

KingFish Spectra

- 54 nuclear maps (inner ~3 kpc)
- 48 extranuclear positions in 19 galaxies.
- Radial strips, matched to SINGS IRS maps in 31 galaxies.



PACS 70/100/160

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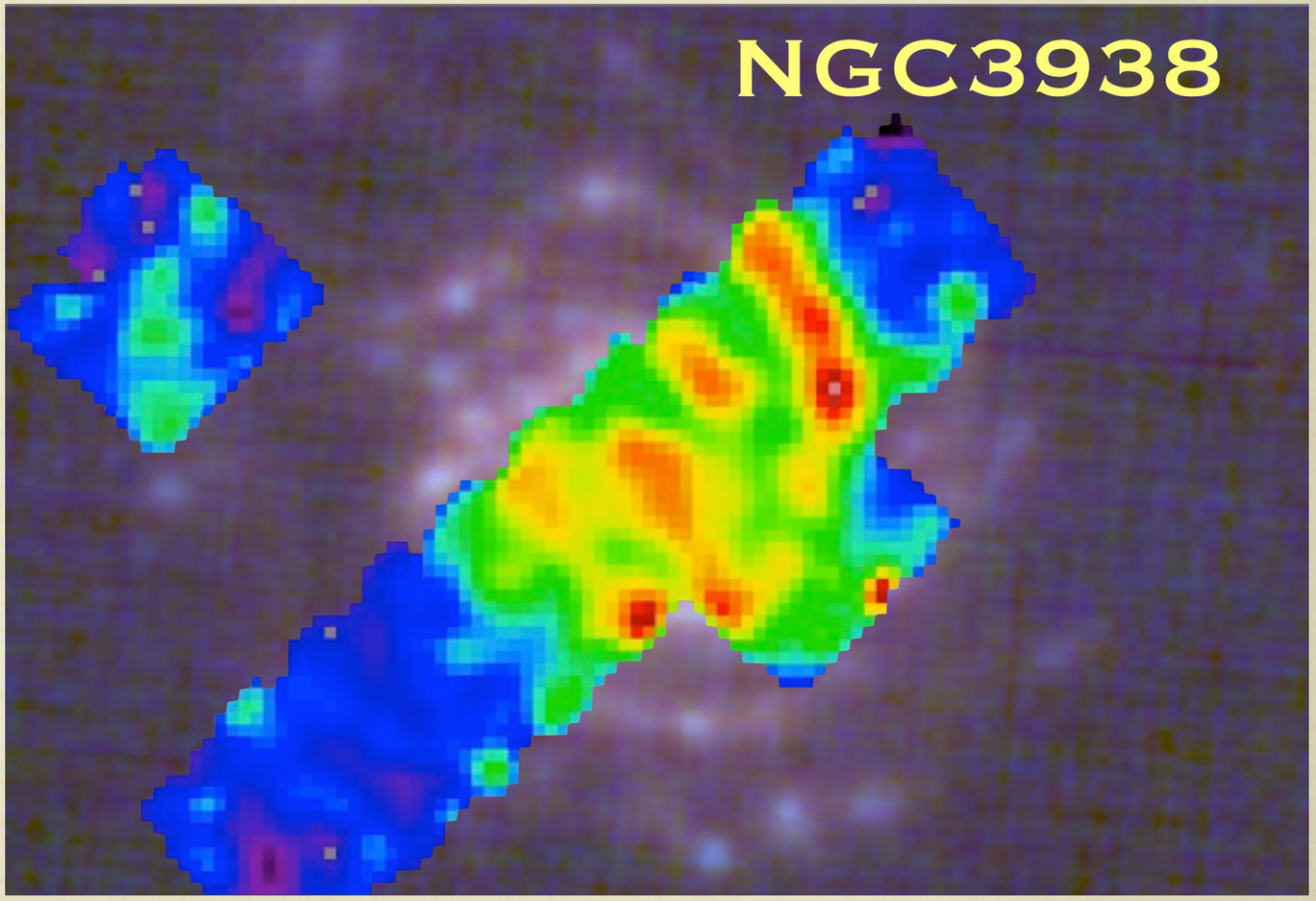
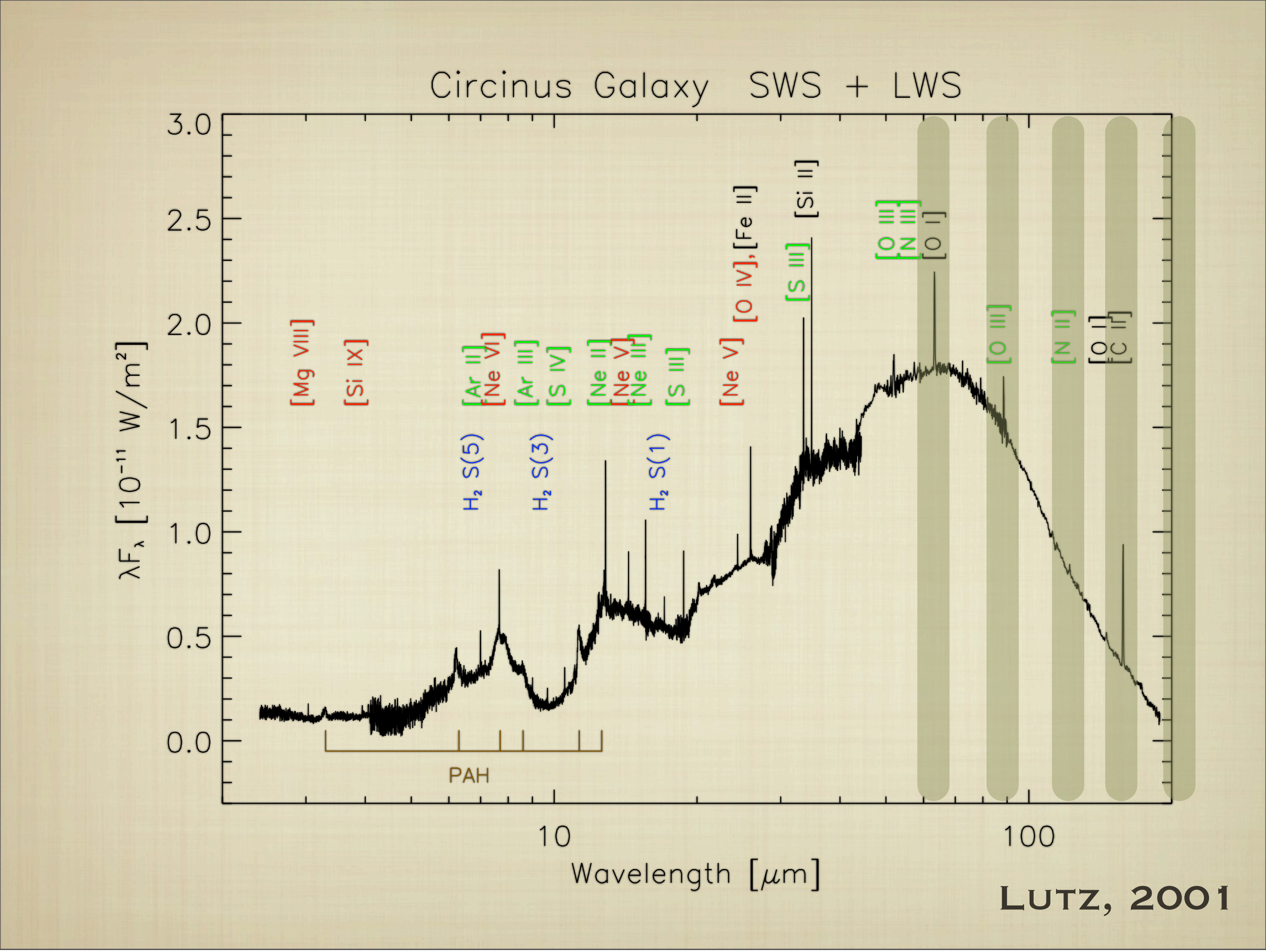
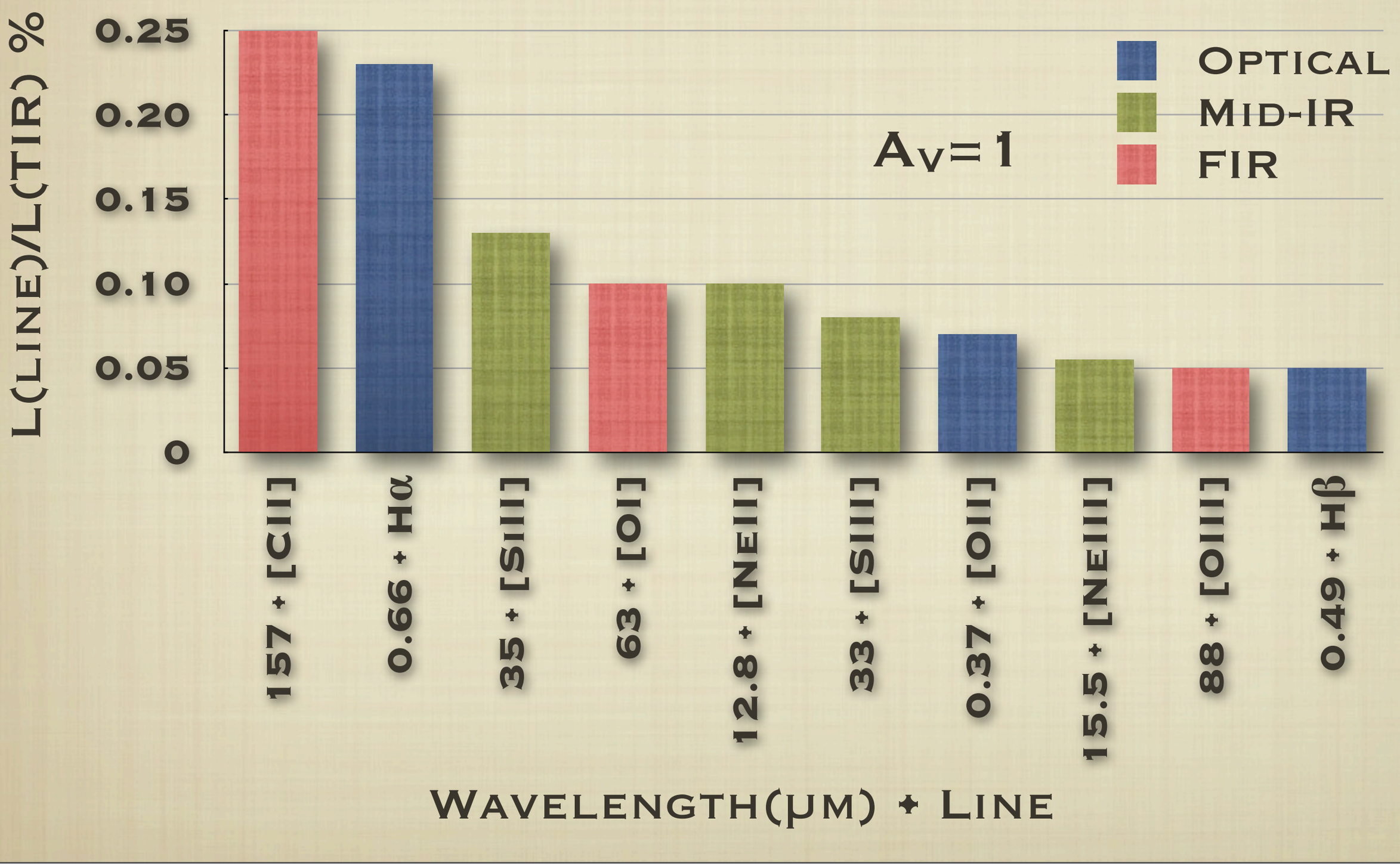


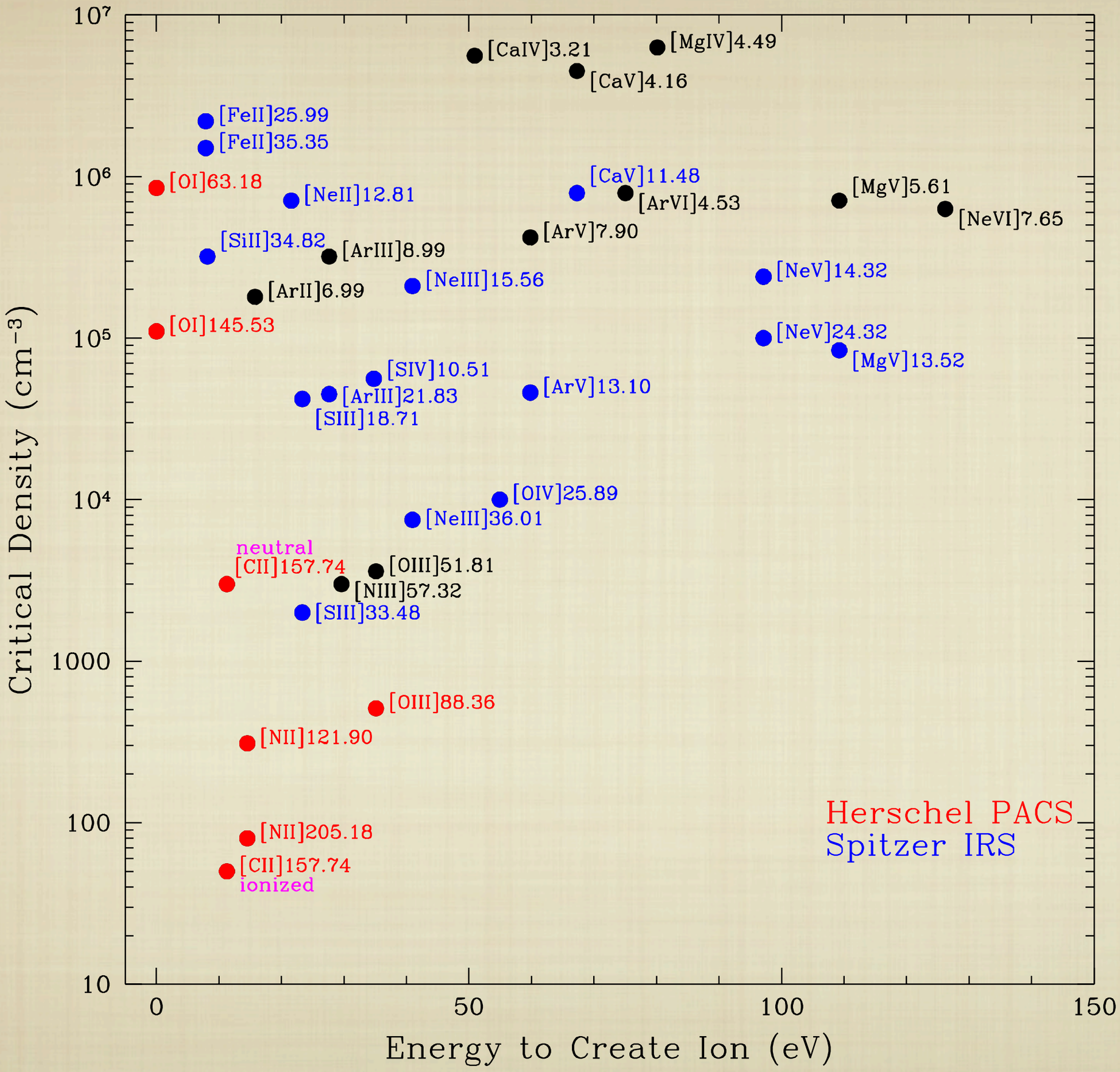
PACS 70/100/160

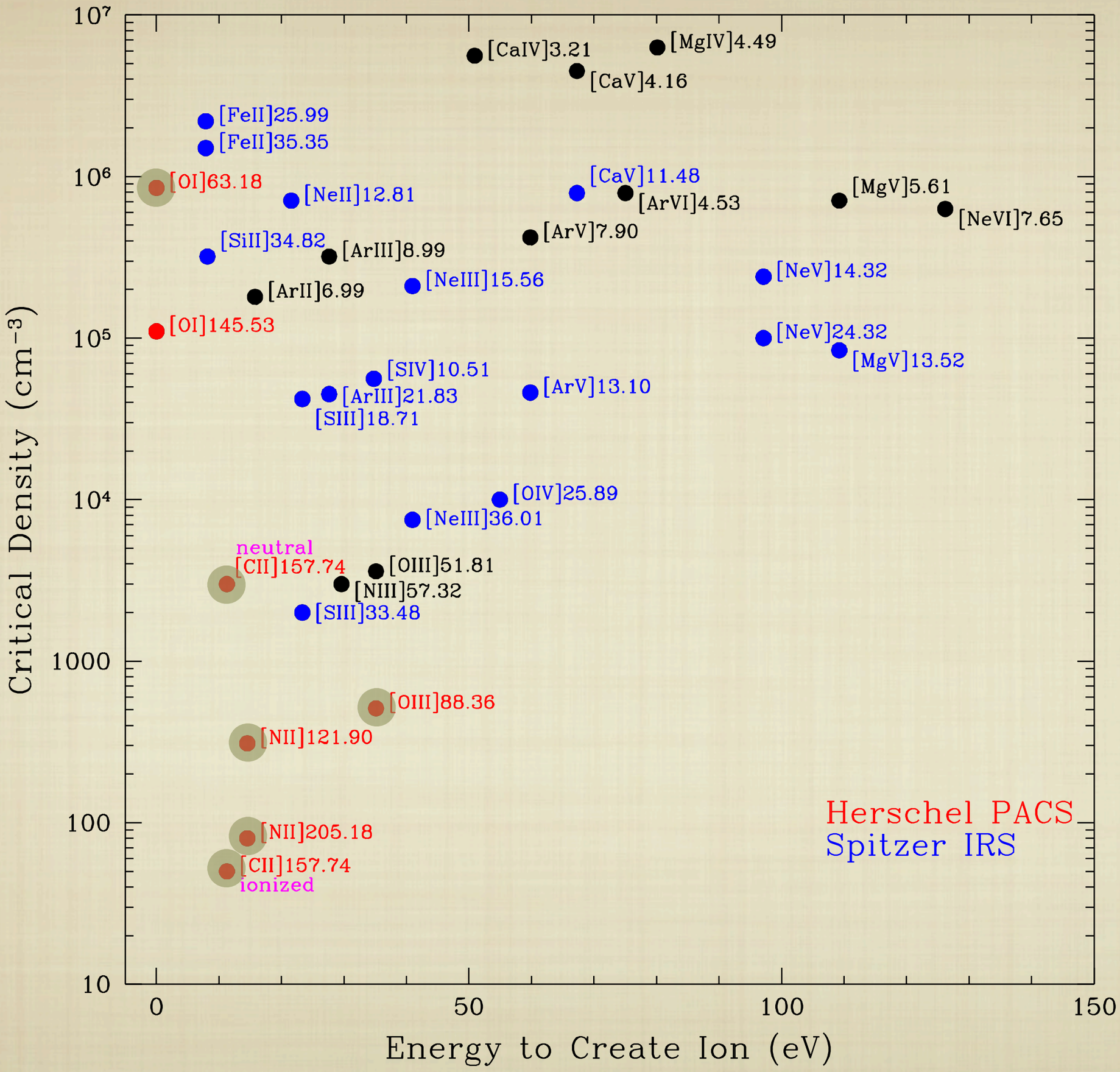
PACS [CII]


Circinus Galaxy SWS + LWS
λF_λ [10^-11 W/m^2]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
[Mg VIII]
[Si IX]
[Ar II]
[Ne VI]
[Ar III]
[S IV]
[Ne II]
[Ne V]
[Ne III]
[S III]
[Ne V]
[O IV],[Fe II]
[S III]
[Si II]
[O III]
[N III]
[O I]
[O III]
[N II]
[O I]
[C II]
H2 S(5)
H2 S(3)
H2 S(1)
H2
H2
H2
PAH
10
100
Wavelength [μm]
Lutz, 2001

The Top 10 Most Luminous (Observed) Emission Lines Of Star-Forming Galaxies




Critical Density (cm^{-3})
10^7
10^6
10^5
10^4
1000
100
10
0
50
100
150
Energy to Create Ion (eV)
[CaIV]3.21
[MgIV]4.49
[CaV]4.16
[FeII]25.99
[FeII]35.35
[OI]63.18
[NeII]12.81
[CaV]11.48
[ArVI]4.53
[MgV]5.61
[NeVI]7.65
[ArV]7.90
[SiII]34.82
[ArIII]8.99
[NeIII]15.56
[NeV]14.32
[ArII]6.99
[OI]145.53
[NeV]24.32
[MgV]13.52
[SIV]10.51
[ArIII]21.83
[ArV]13.10
[SIII]18.71
[OIV]25.89
[NeIII]36.01
neutral
[CII]157.74
[OIII]51.81
[NIII]57.32
[SIII]33.48
[OIII]88.36
[NII]121.90
[NII]205.18
[CII]157.74
ionized
Herschel PACS
Spitzer IRS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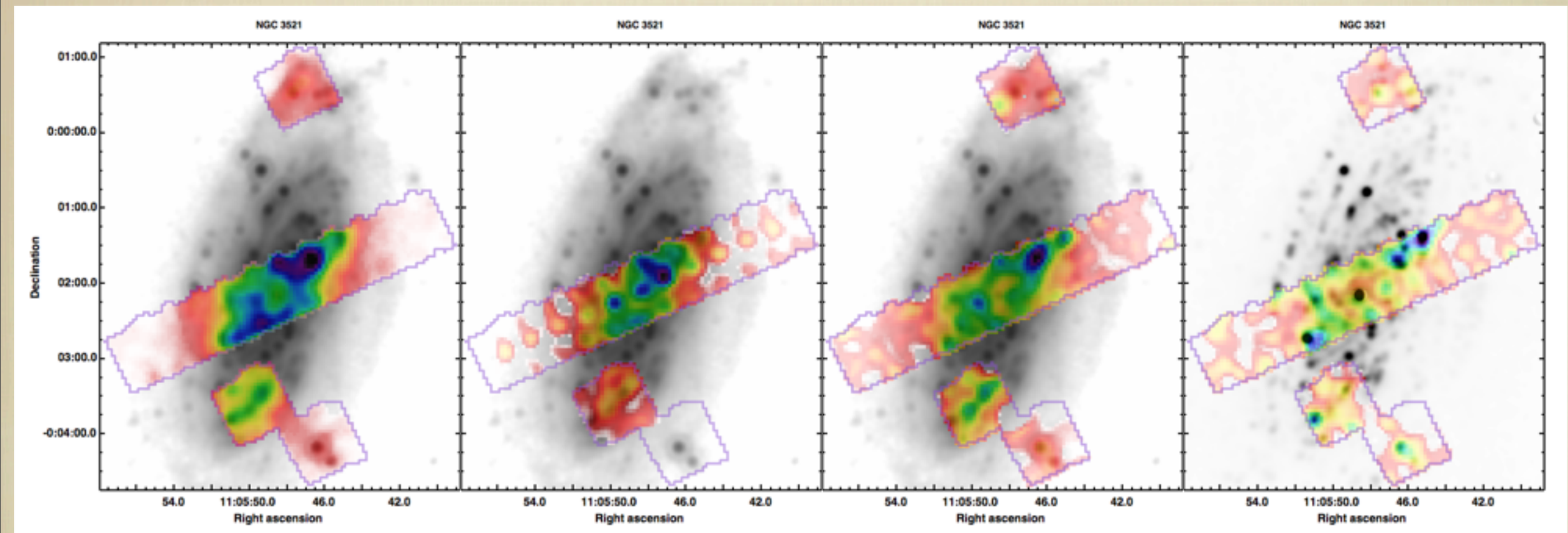
ionized
Herschel PACS
Spitzer IRS

KingFish Gas science

- **Heating/Cooling**
- Diffuse Ionized Gas
- Physical conditions of the ISM
- Kinematics
- Cooling lines as SFR tracers (Alberto's talk)
- **The heavy element abundance scale**

KingFish Gas science

[C II] [N II] [O I] [O III]



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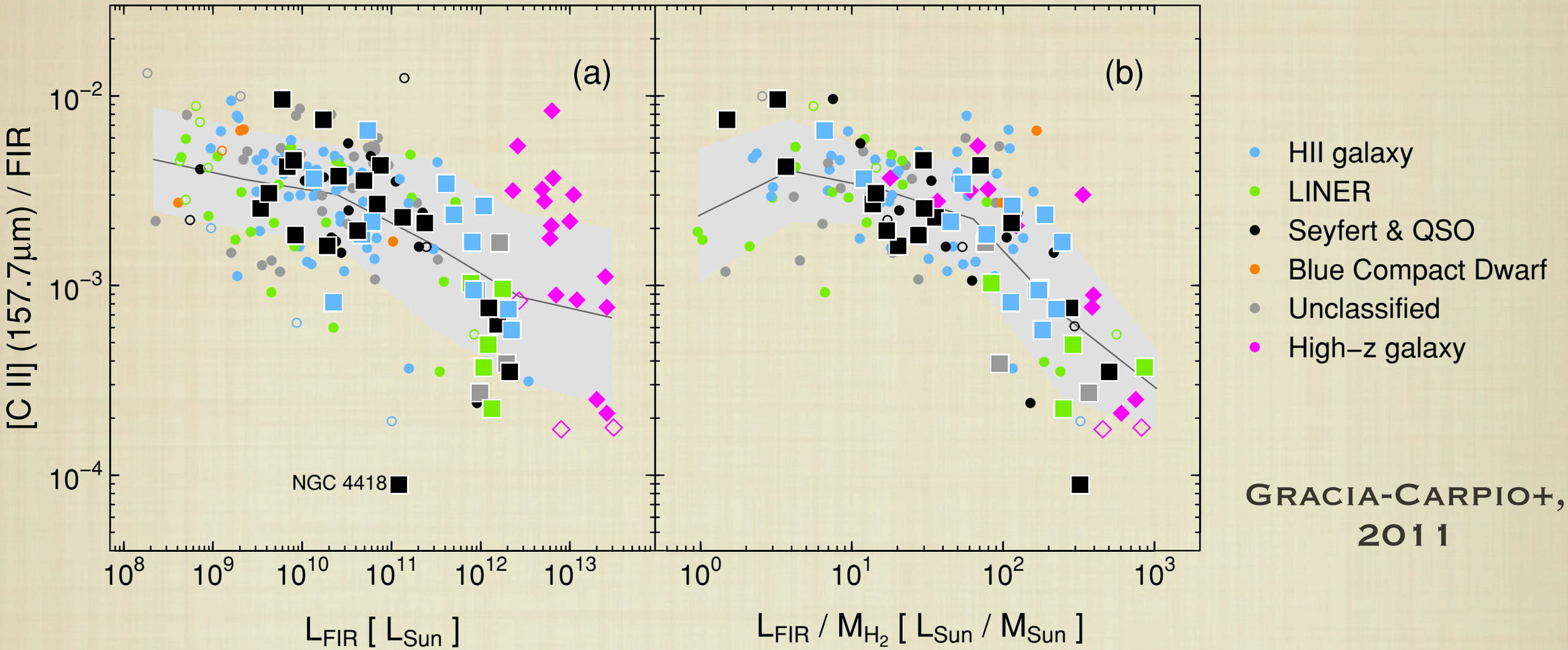
Heating
v
Cooling

The "Cooling Problem"



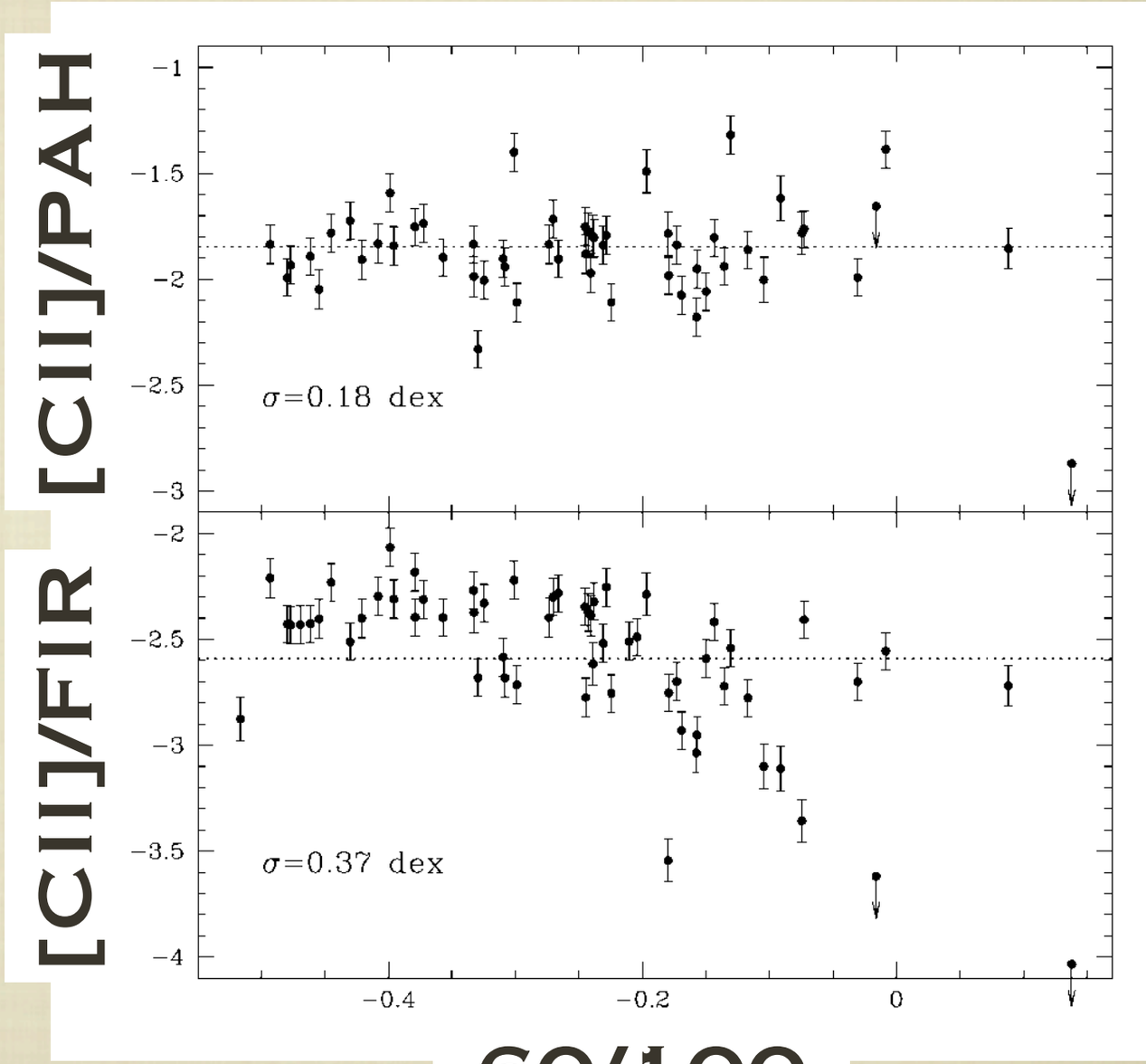
Gracia-Carpio+, 2011

- Line deficits reveal drastic drop in Cooling power in luminous galaxies.... where star formation efficiency is highest.

Grains Heating the Gas

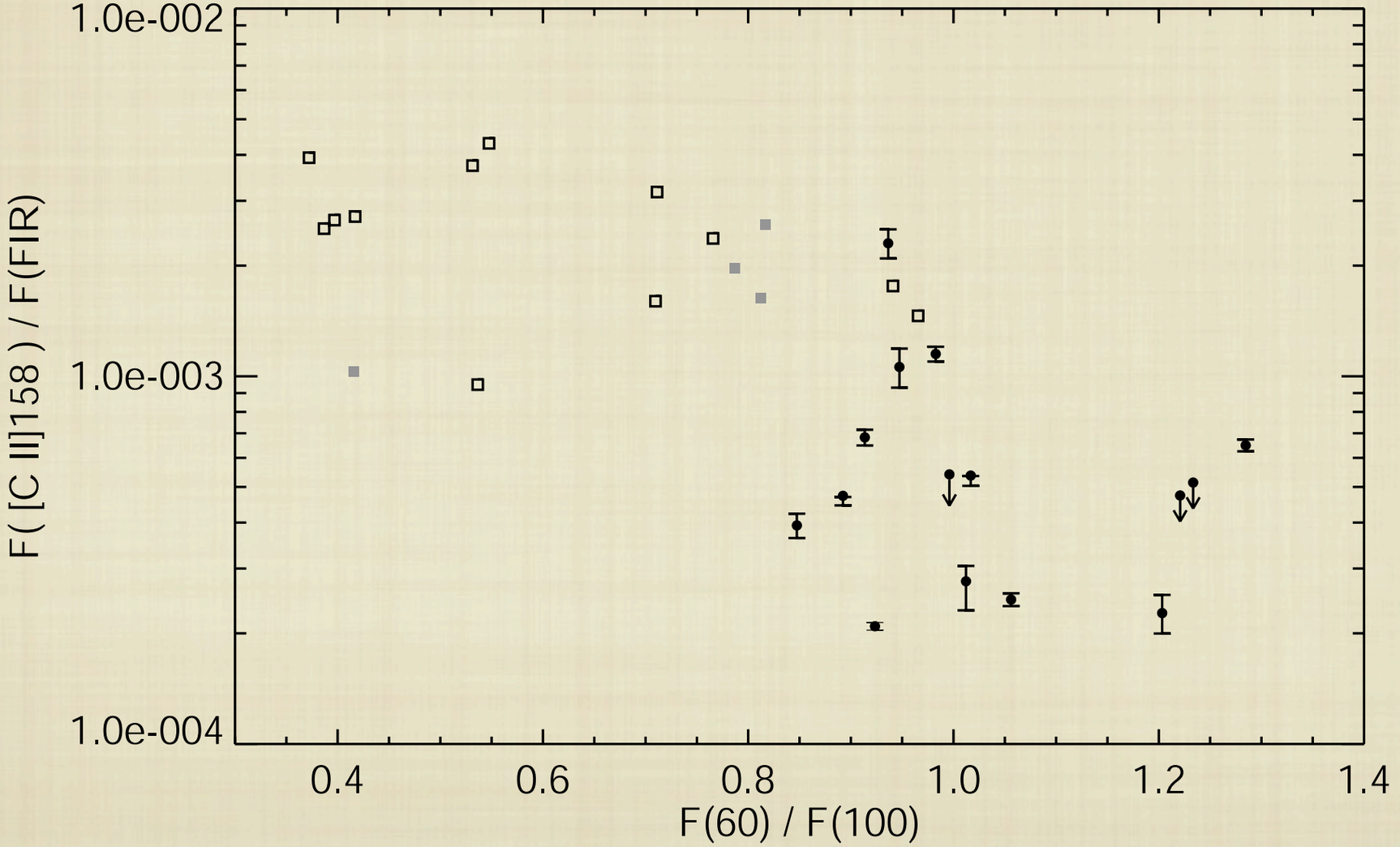
- An early look: ISO Key Project on Normal Galaxies

- Small dust grains: Primary source of photo-electrons heating UV illuminated neutral gas.



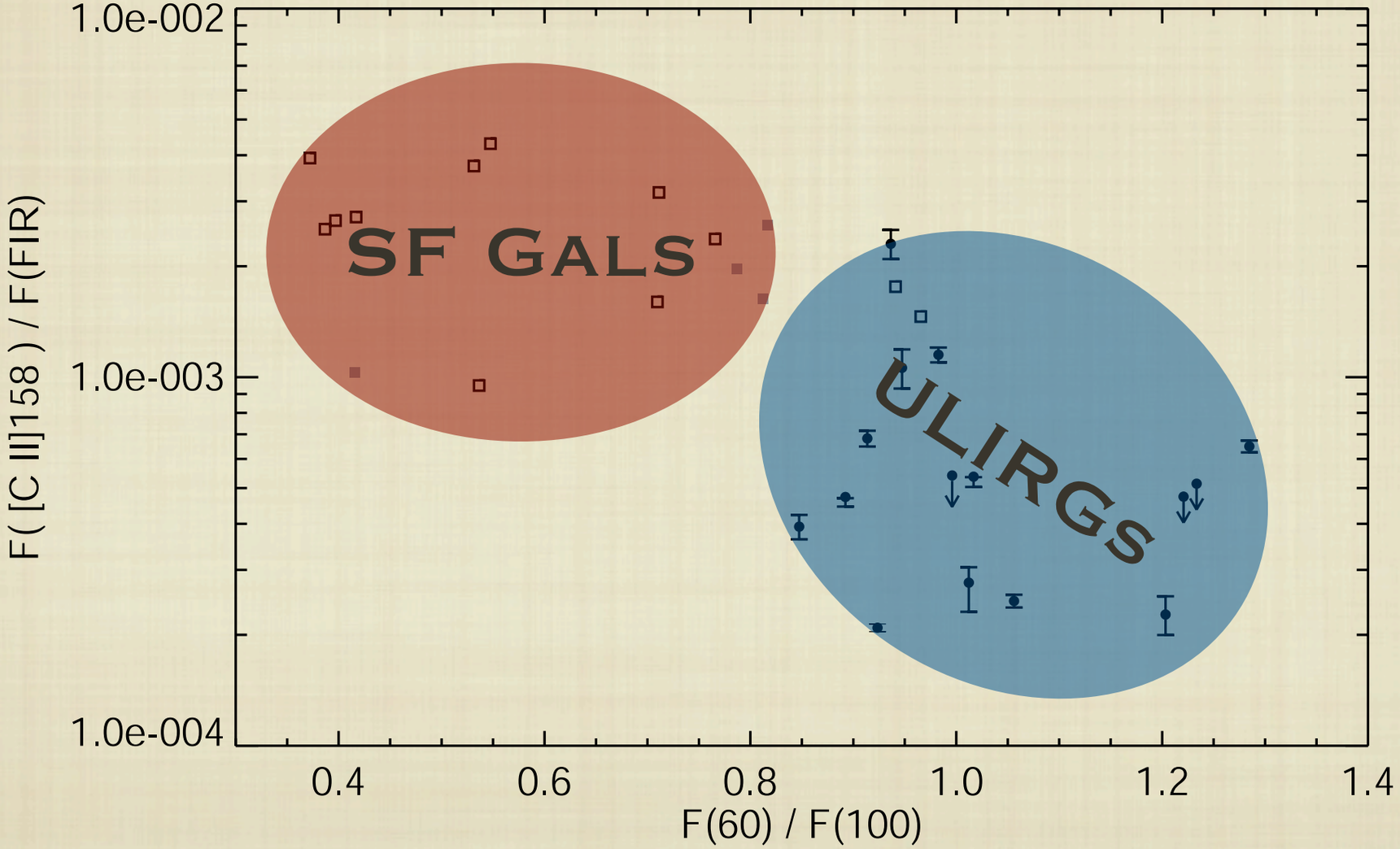
Helou et al., 2001

A ULIRG Phenomenon?

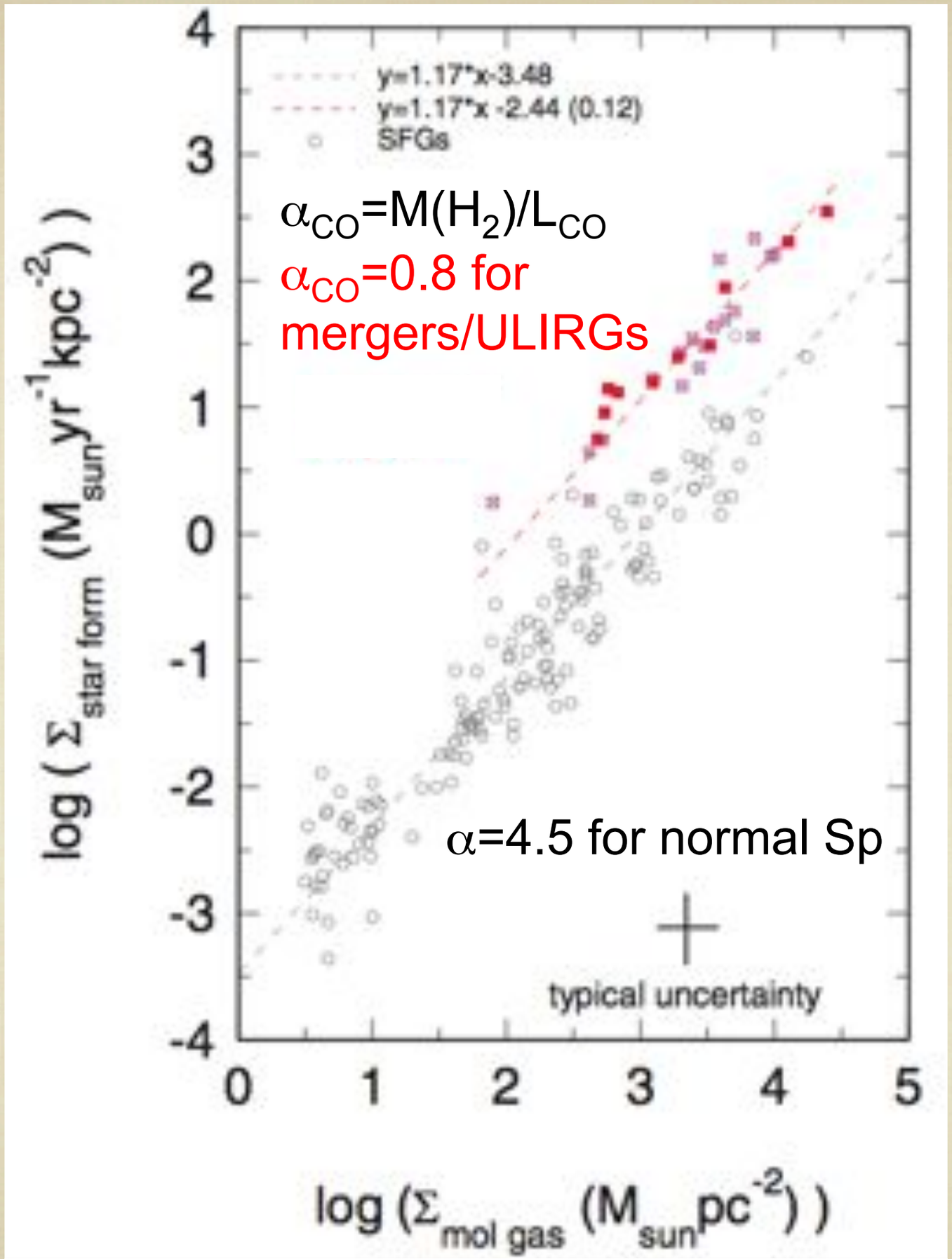


Luhman+ '03

A ULIRG Phenomenon?



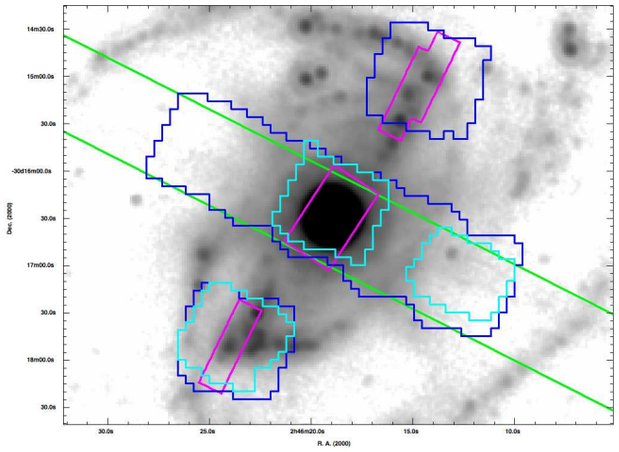
Luhman+ '03

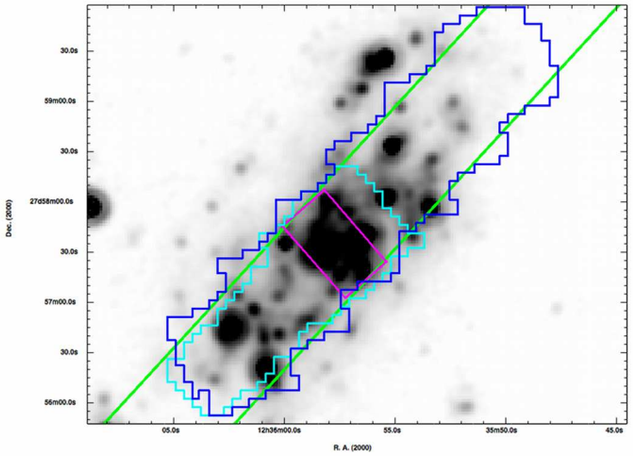

y=1.17*x-3.48
y=1.17*x -2.44 (0.12)
SFGs
$\alpha_{CO}=M(H_2)/L_{CO}$
α_{CO}=0.8 for mergers/ULIRGs
α=4.5 for normal Sp
typical uncertainty
log ($\Sigma_{star\ form}$ ($M_{sun}yr^{-1}kpc^{-2}$))
log ($\Sigma_{mol\ gas}$ ($M_{sun}pc^{-2}$))
4
3
2
1
0
-1
-2
-3
-4
0
1
2
3
4
5

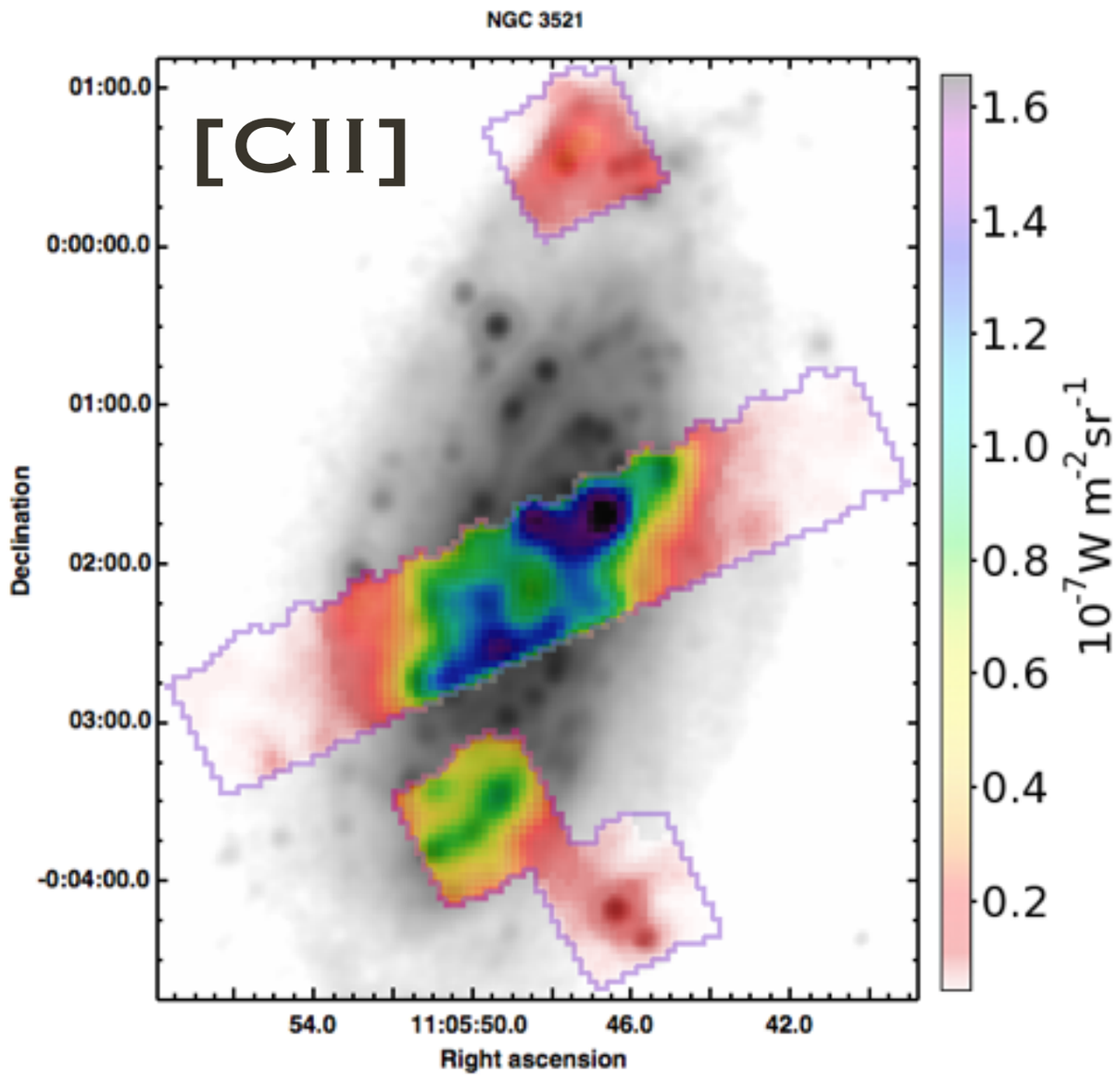
GENZEL+ 2010

Herschel Spectroscopy

- First time: access to **All** players in the heating/cooling of gas within galaxies on <kpc scales.







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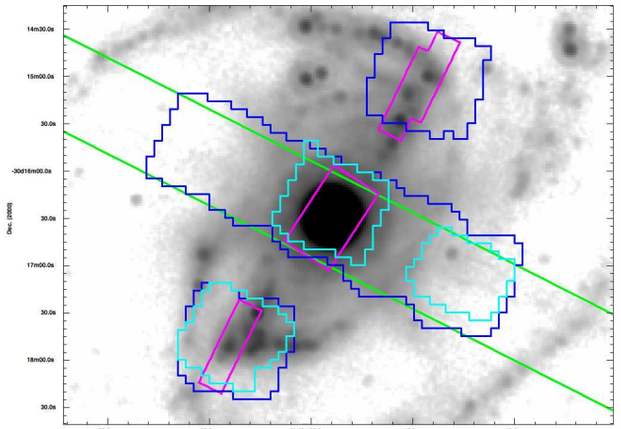
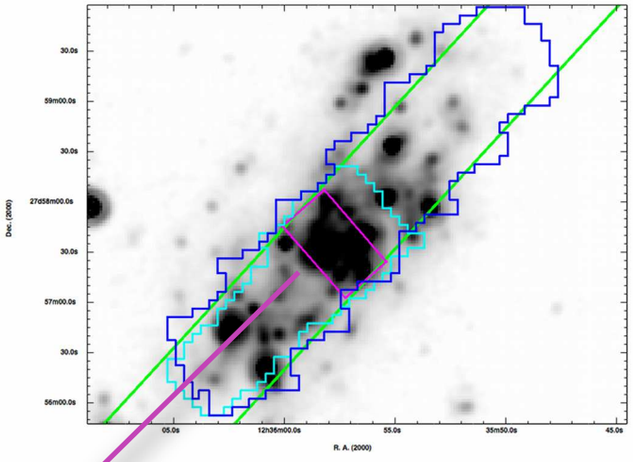
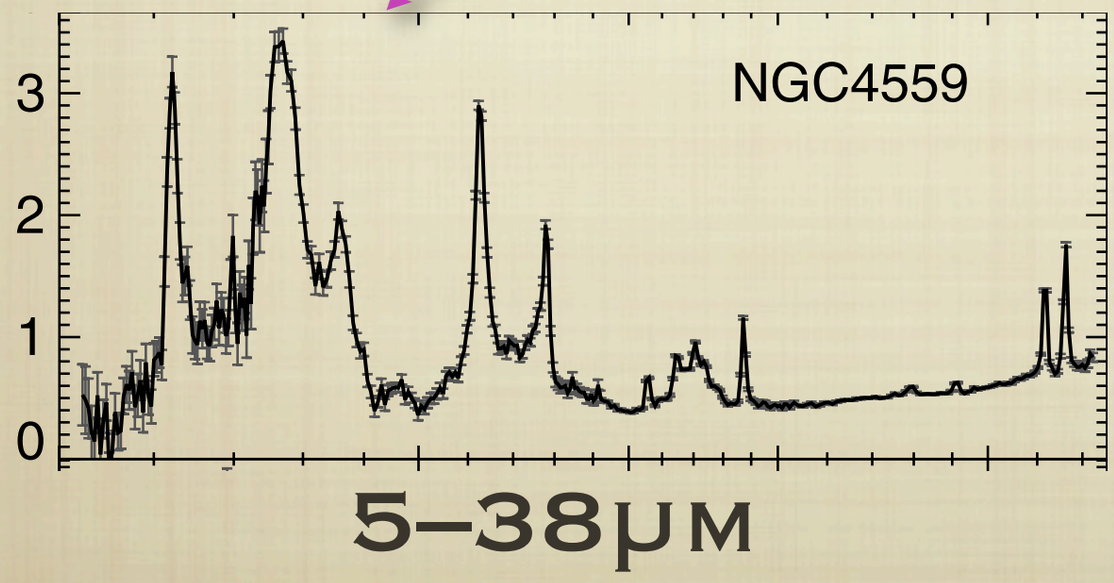
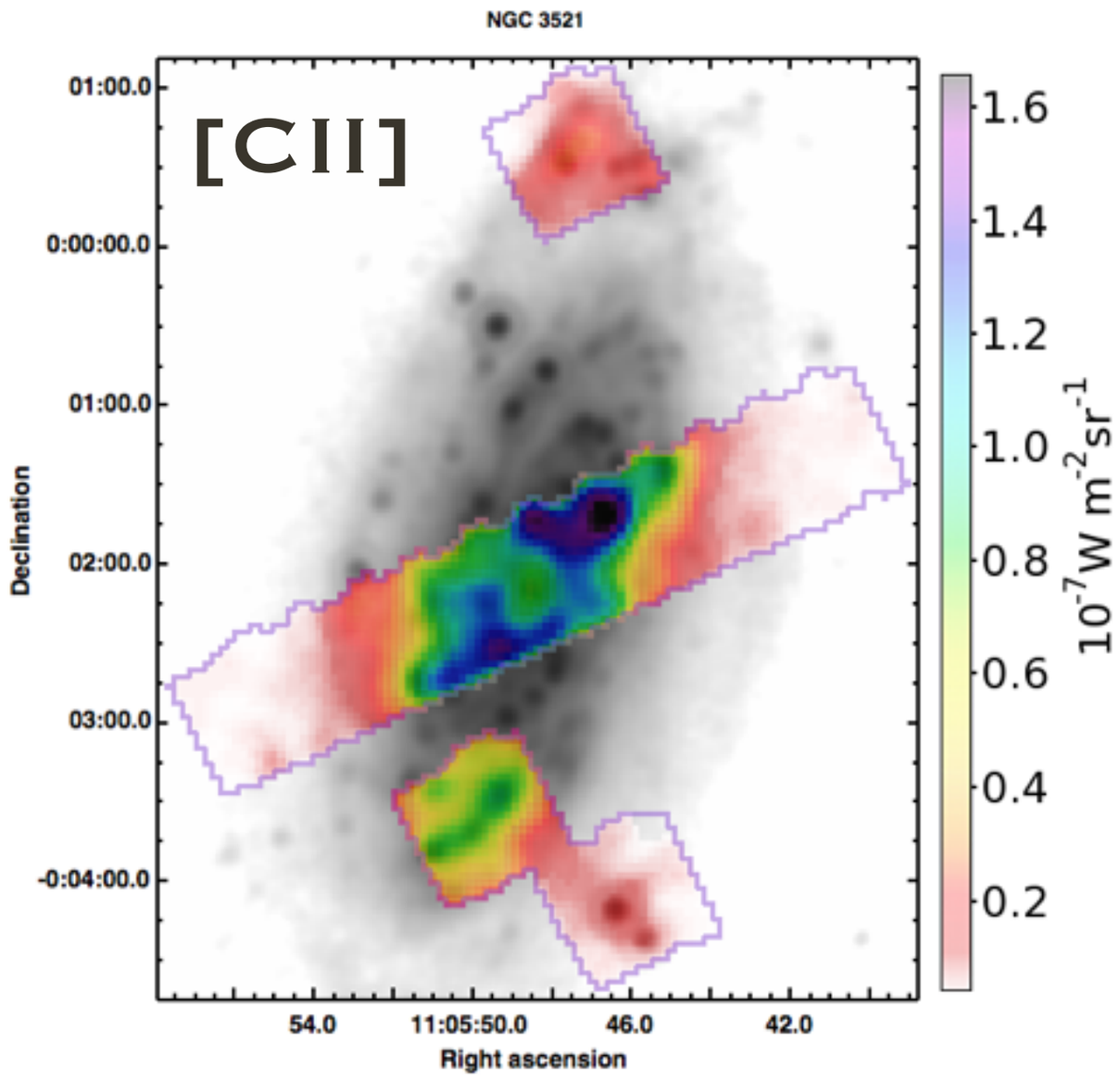


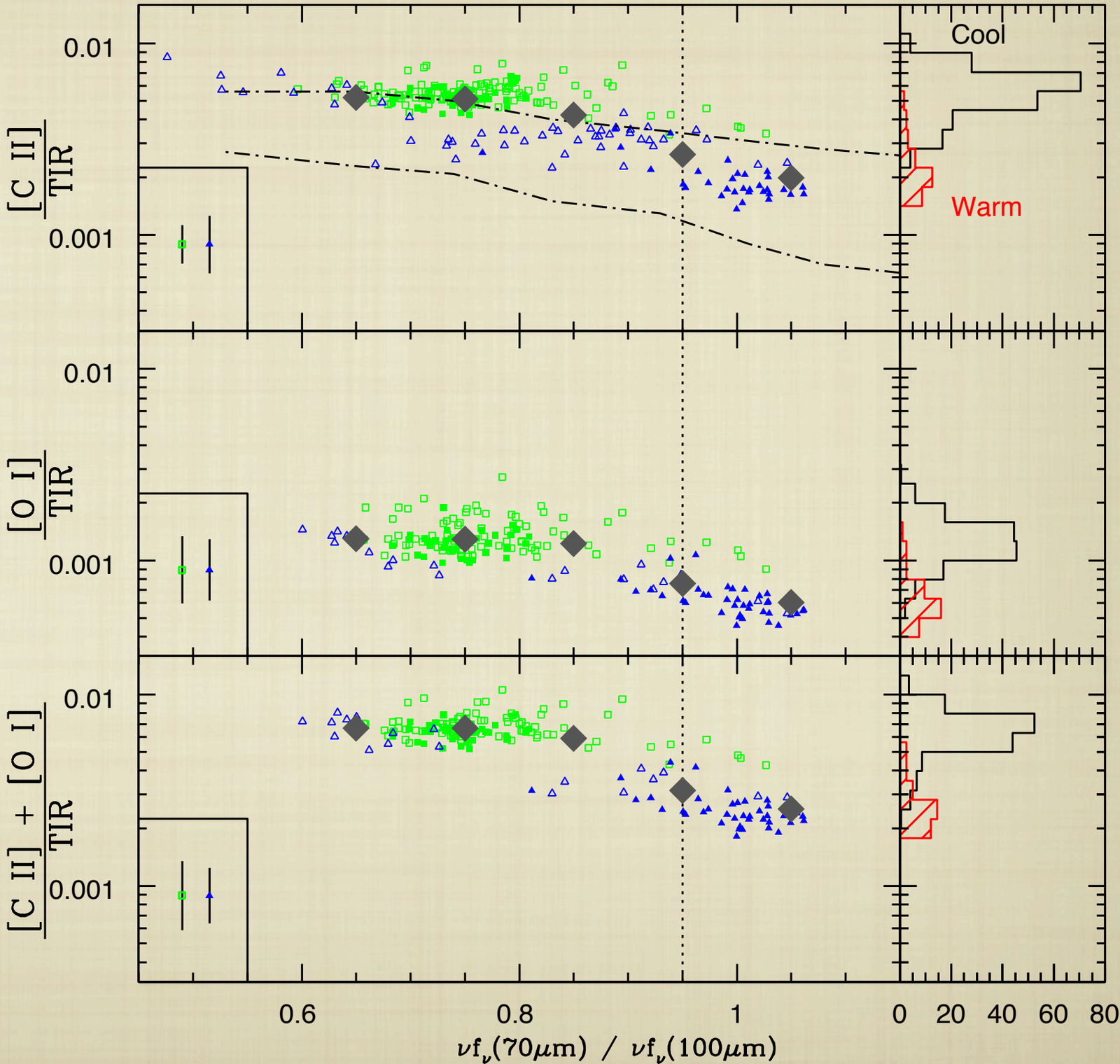






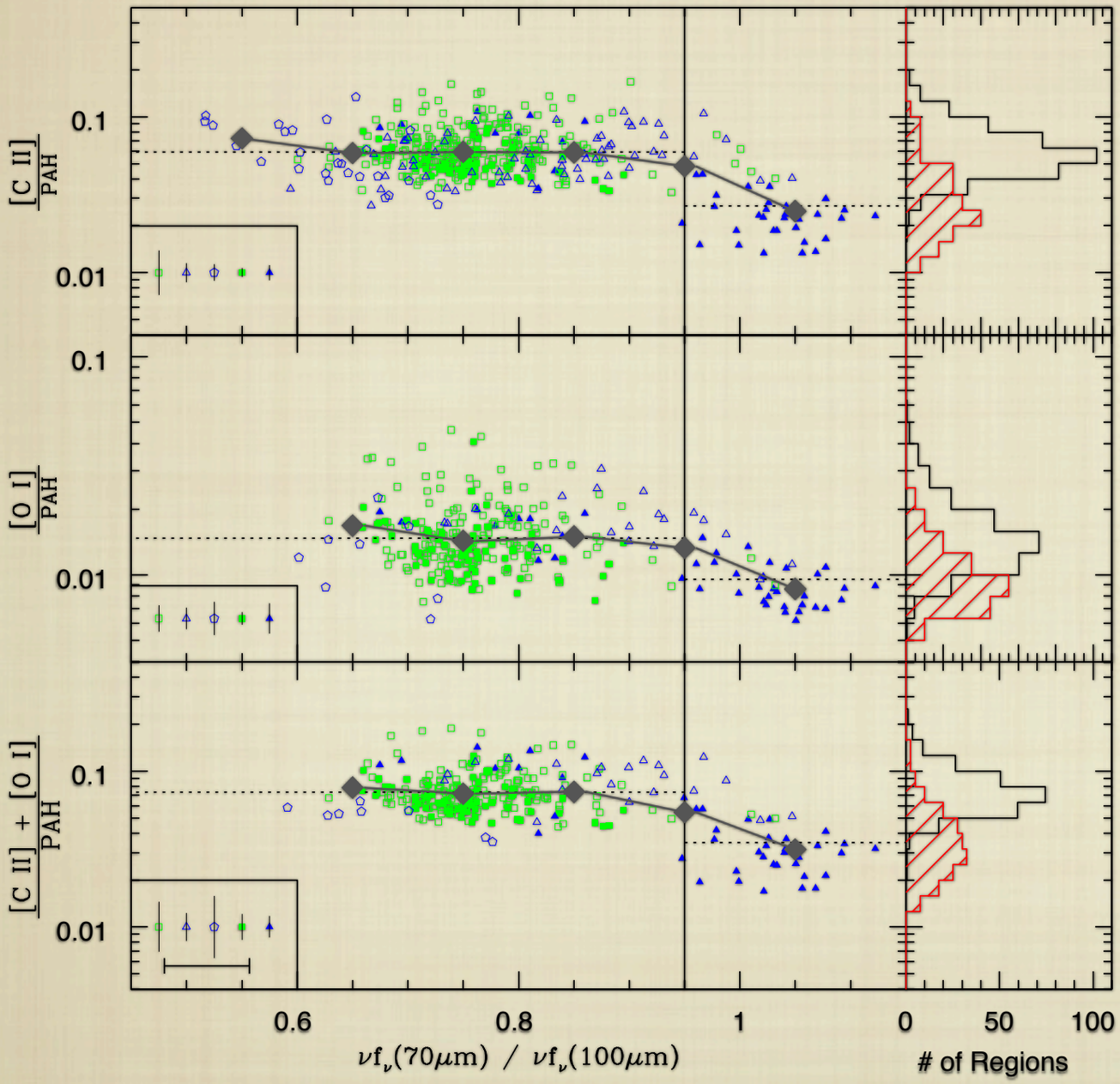
Thermal Balance

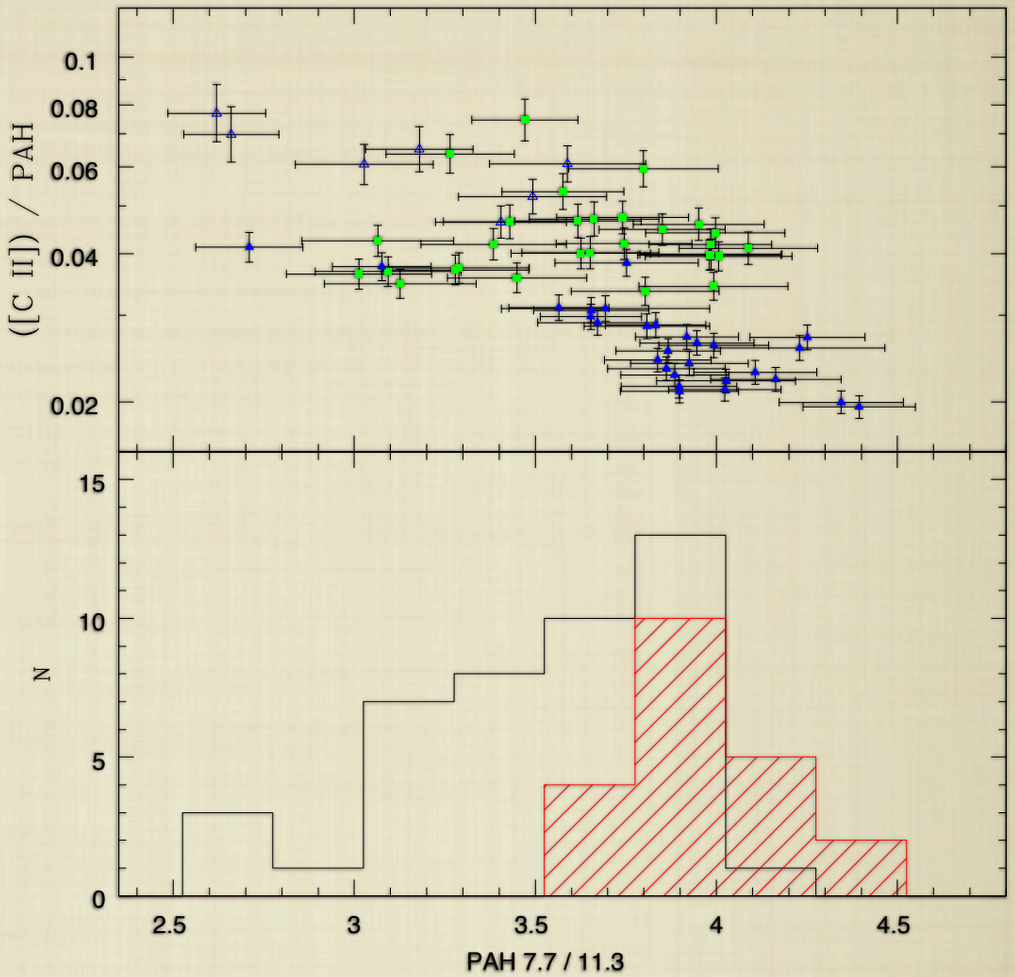
- Two pilot galaxies: NGC4559 + NGC1097



Croxall+, 2012

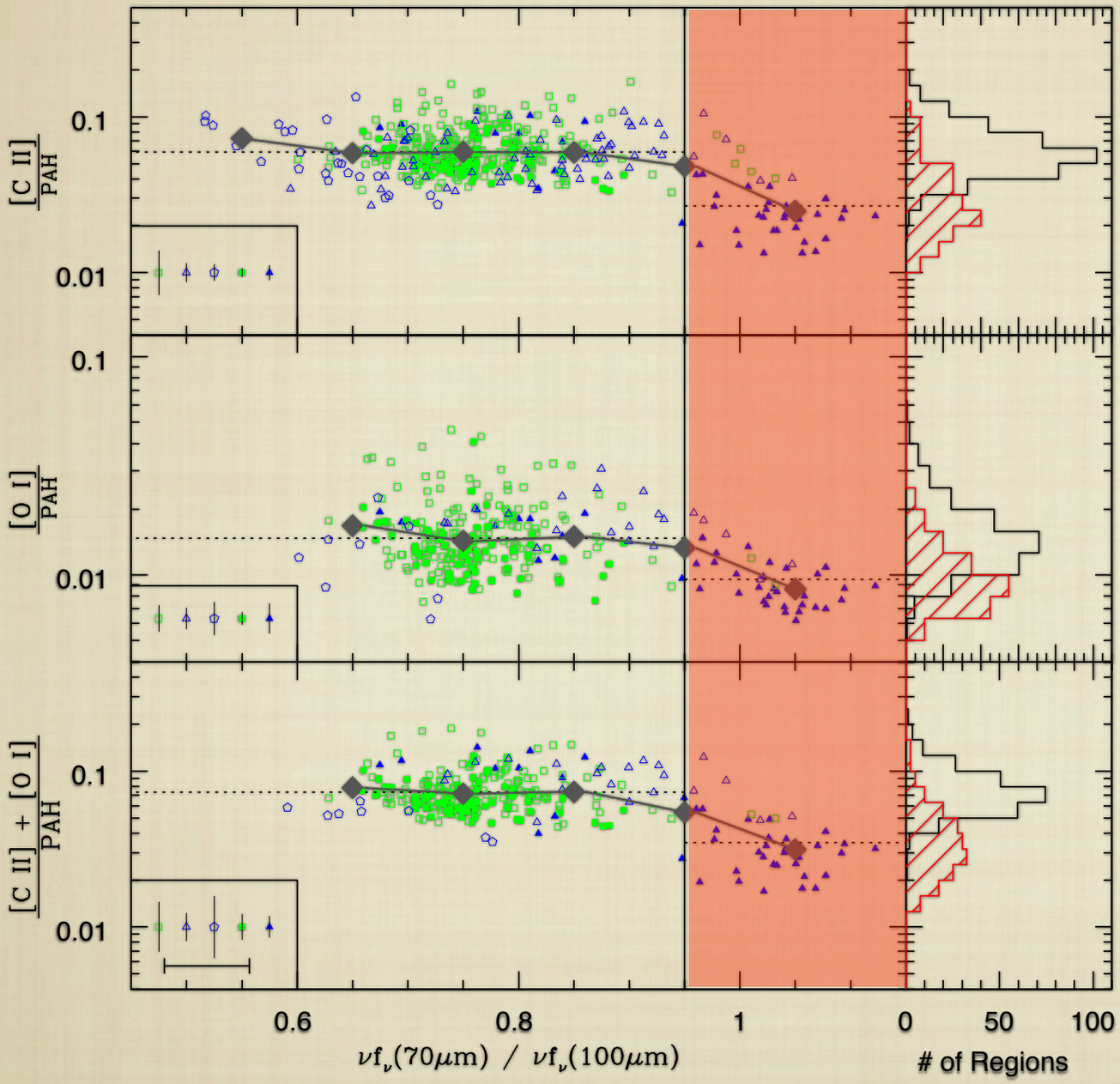
Breaking Point



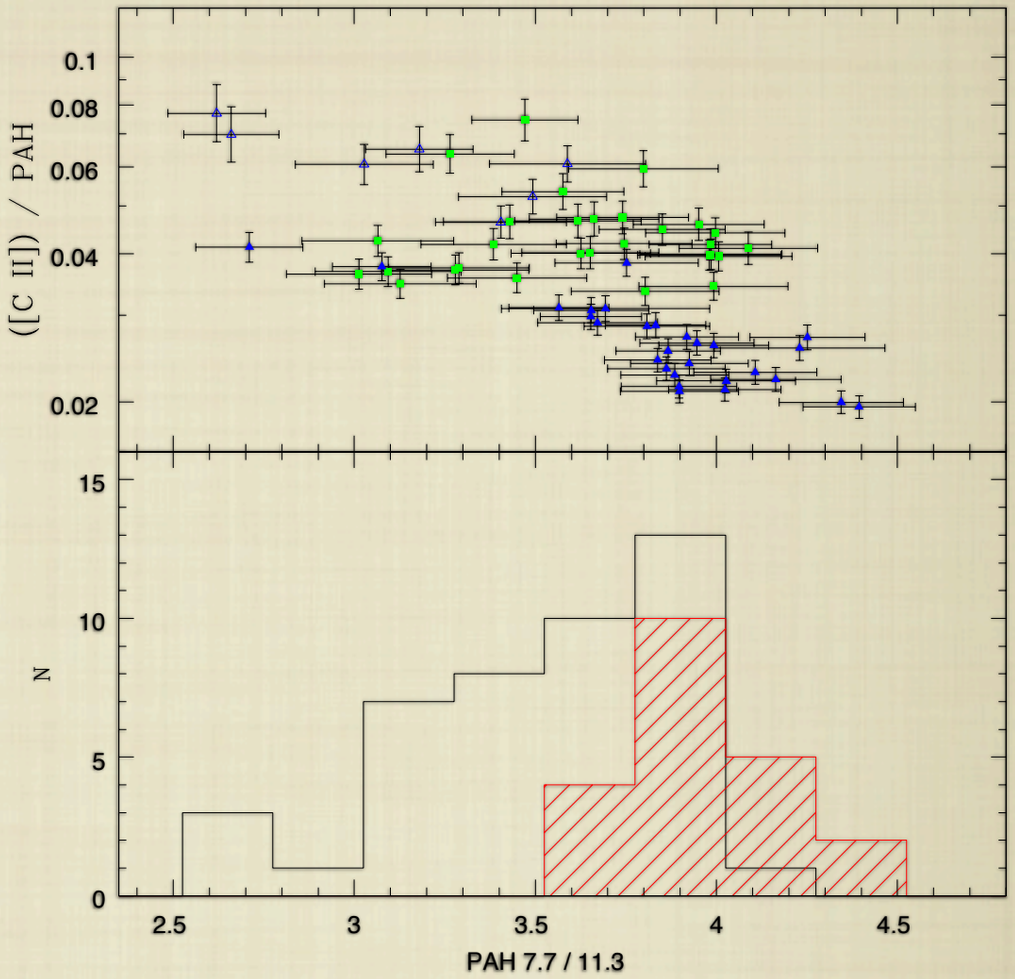


Croxall+, 2012

Breaking Point



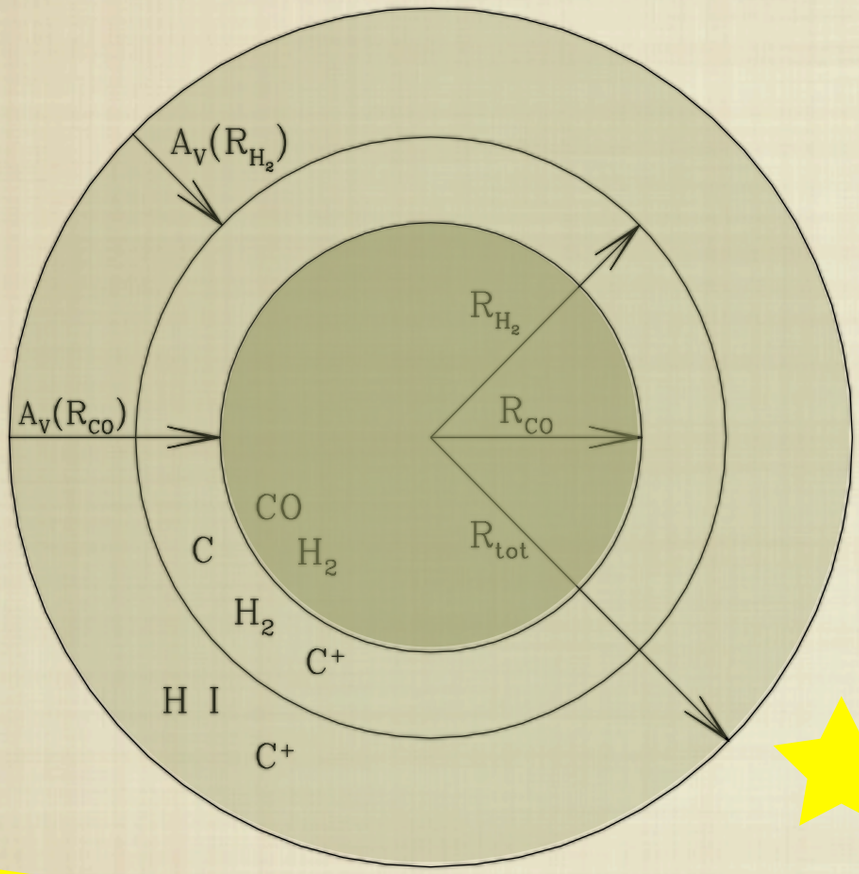
Croxall+, 2012

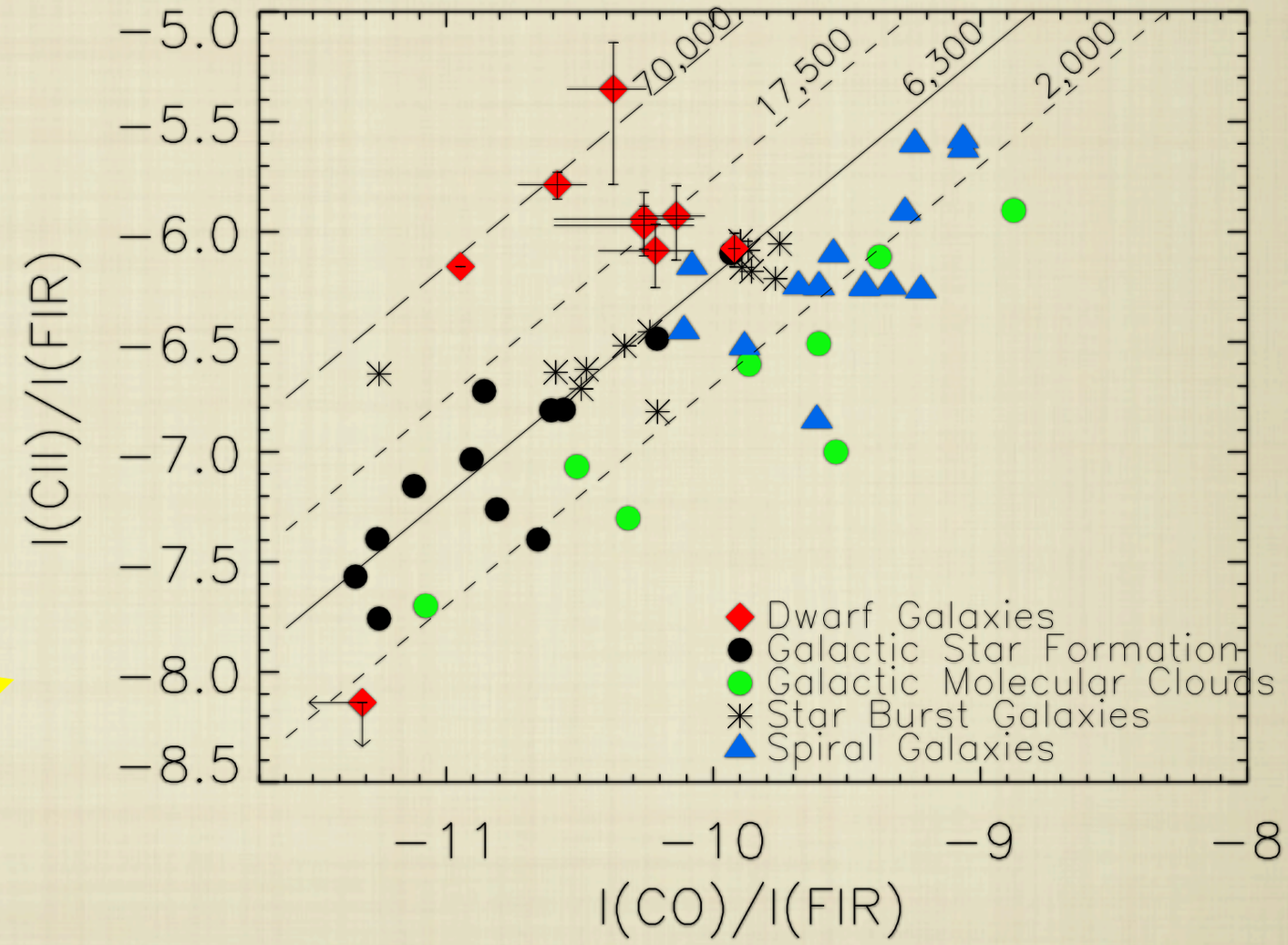


PAH Ionization

Dust Grains: less effective at heating gas when ionized!

Photons, or Metals?

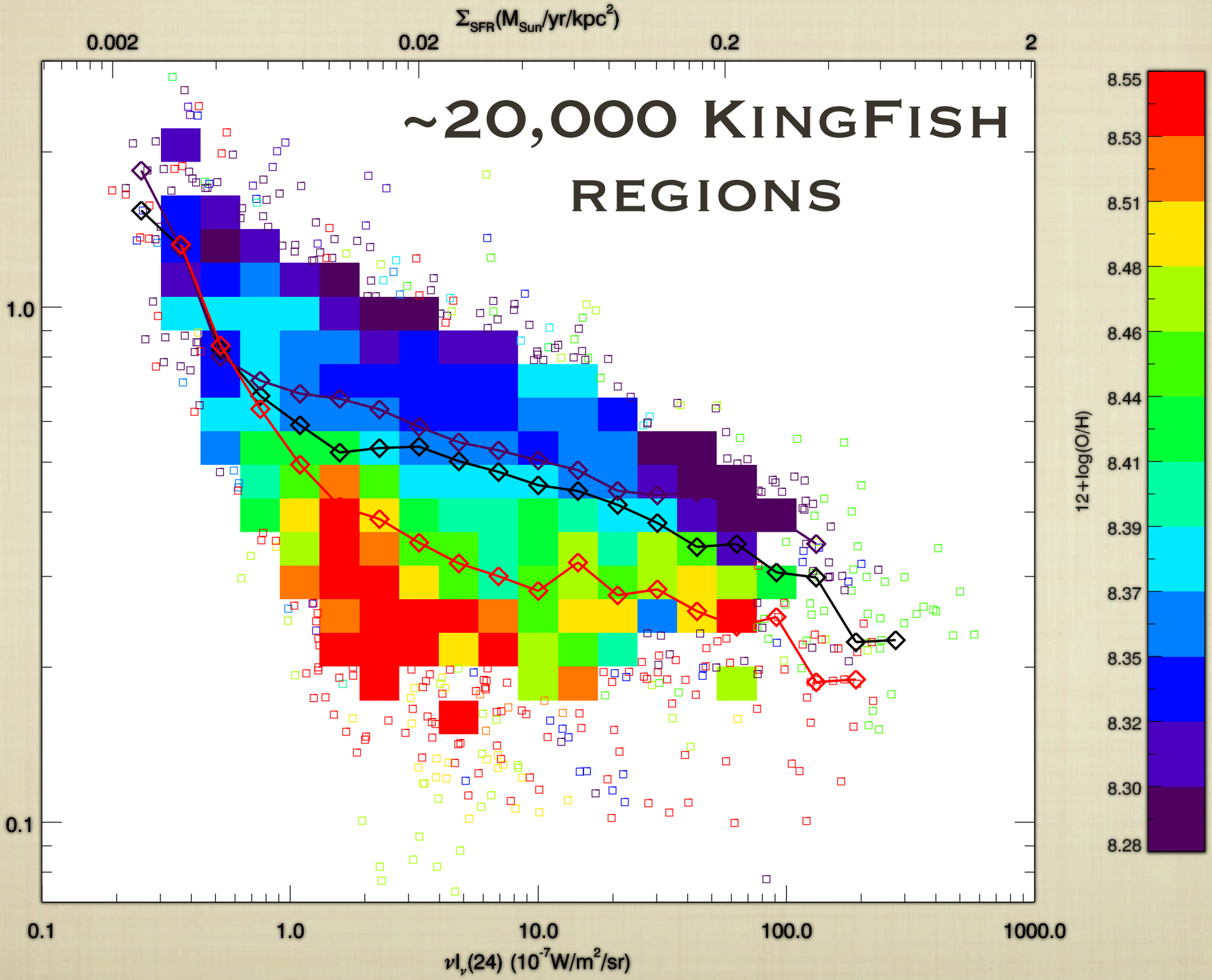




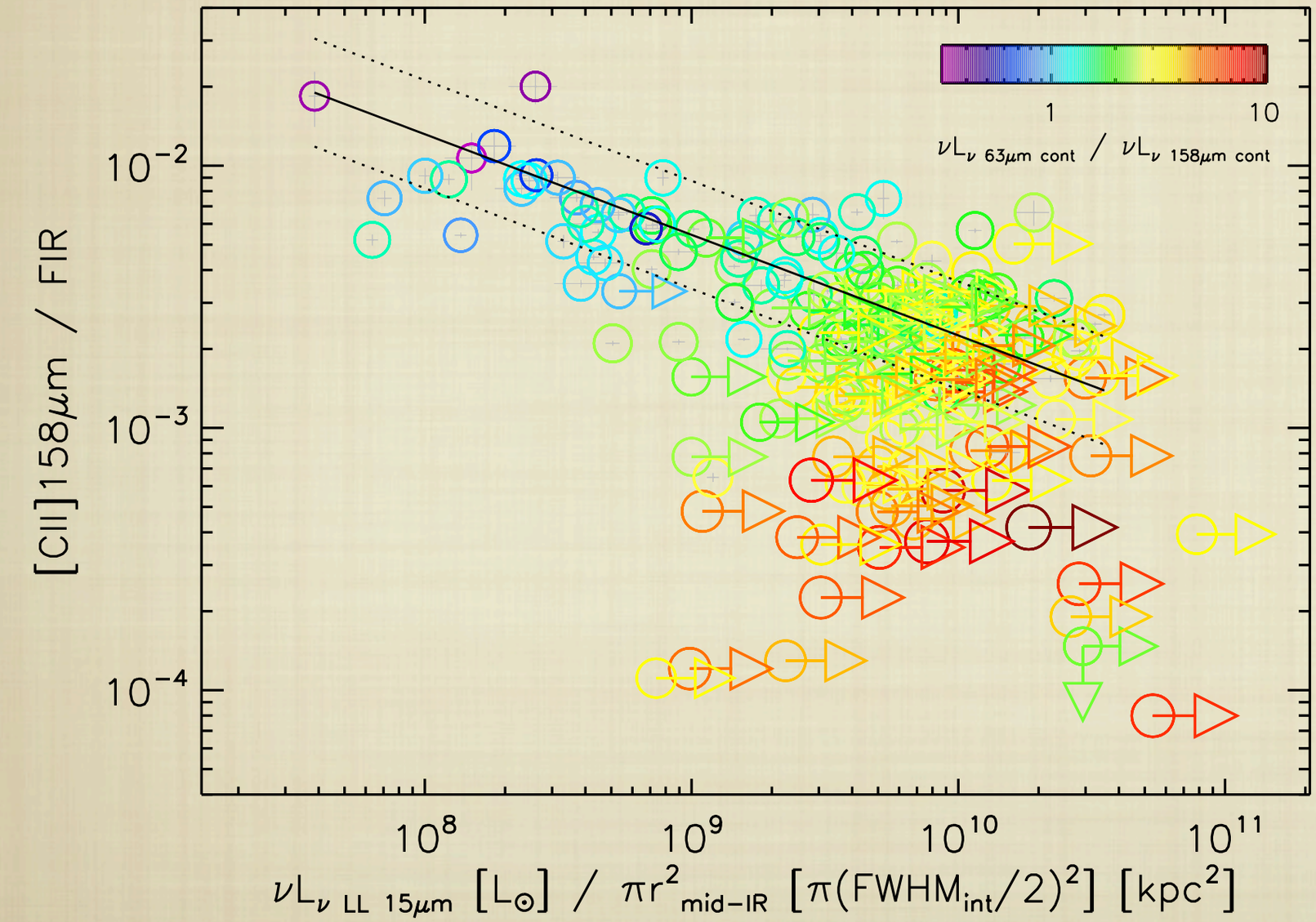
Wolfire+ 2010

Madden+ 2000

Heating v. Cooling



Deficit At higher luminosity

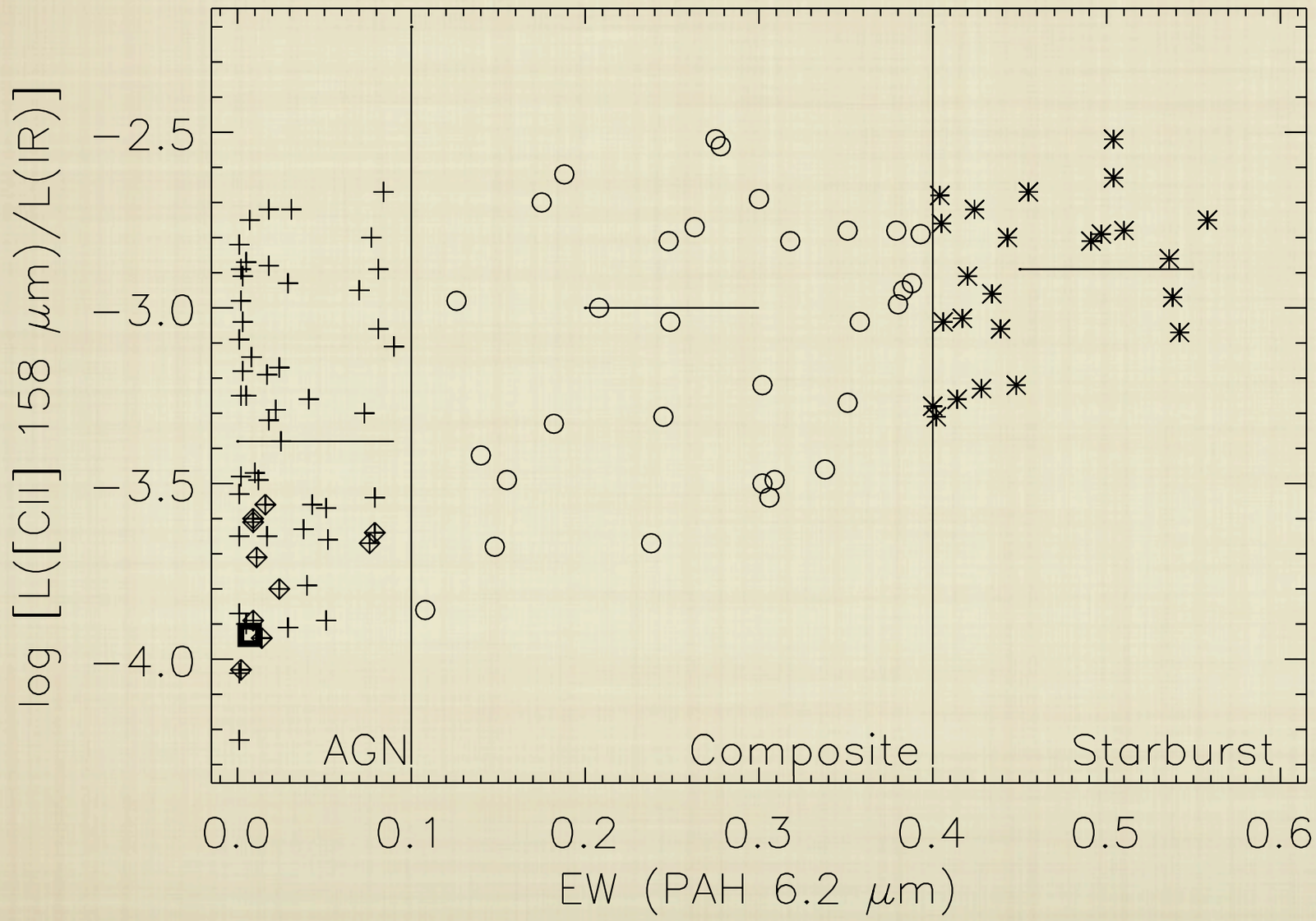


GOALS

Díaz-Santos+ 2013

Luminosity Surface Density

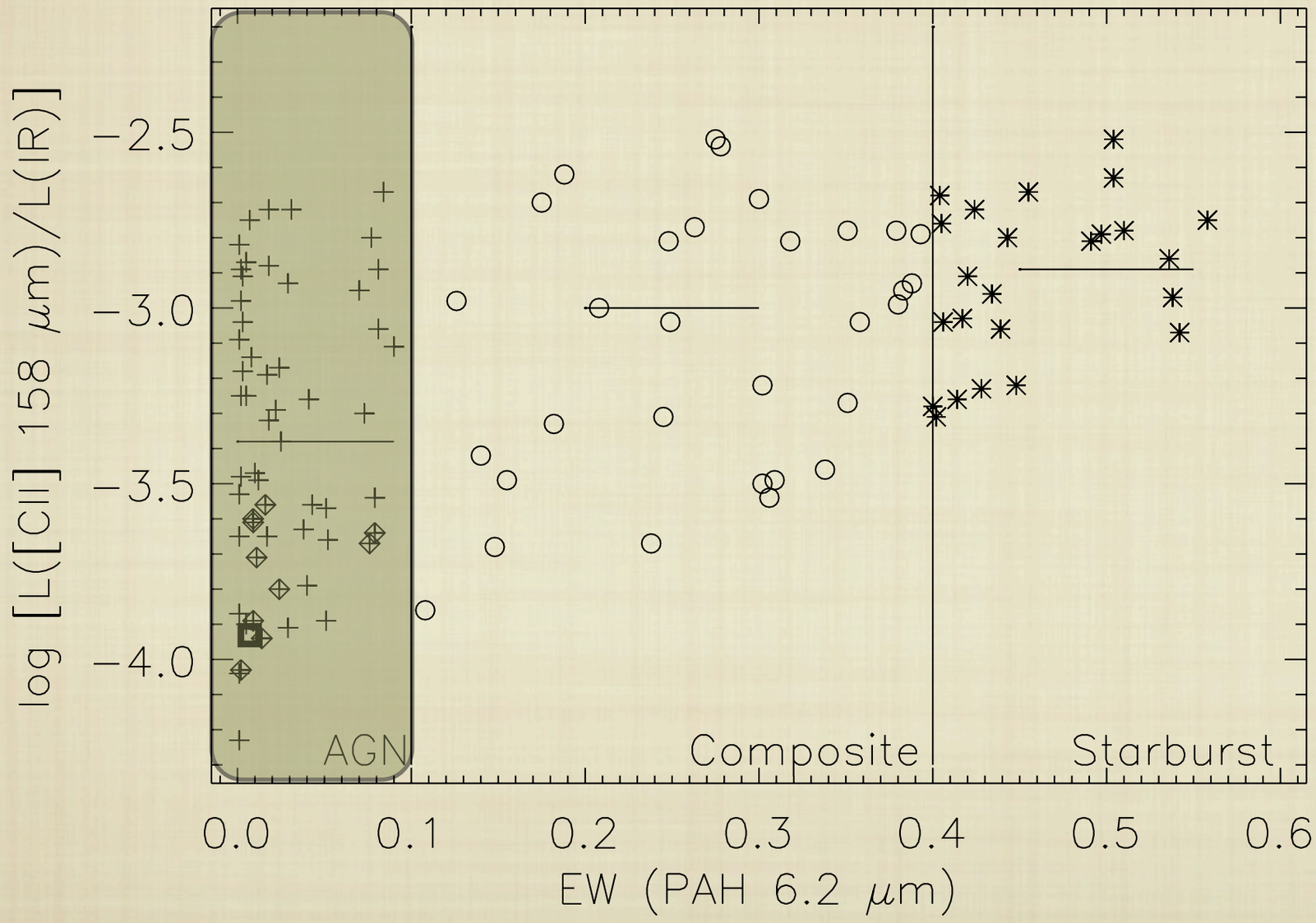
AGN Impact



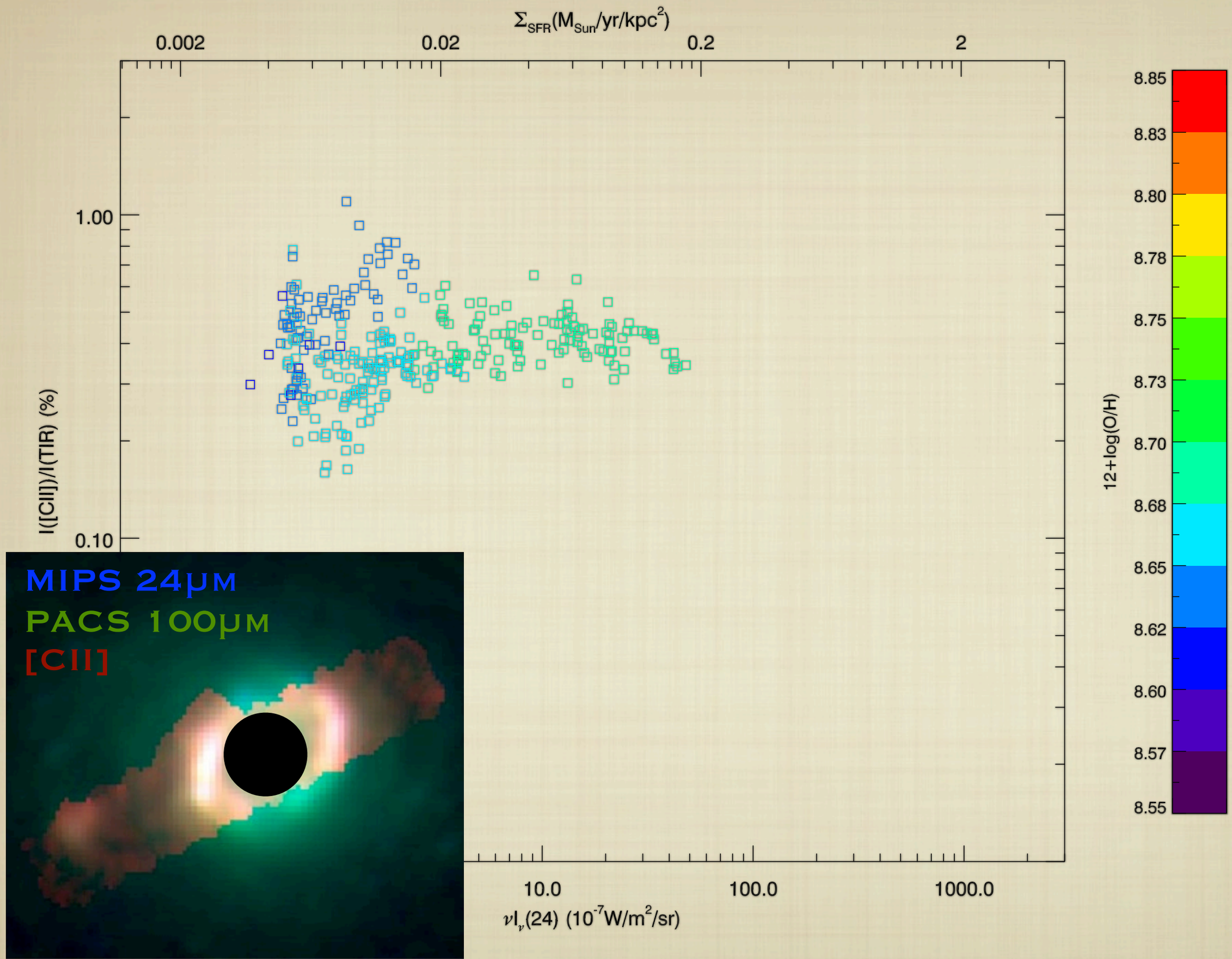
Sargsyan+ 2012

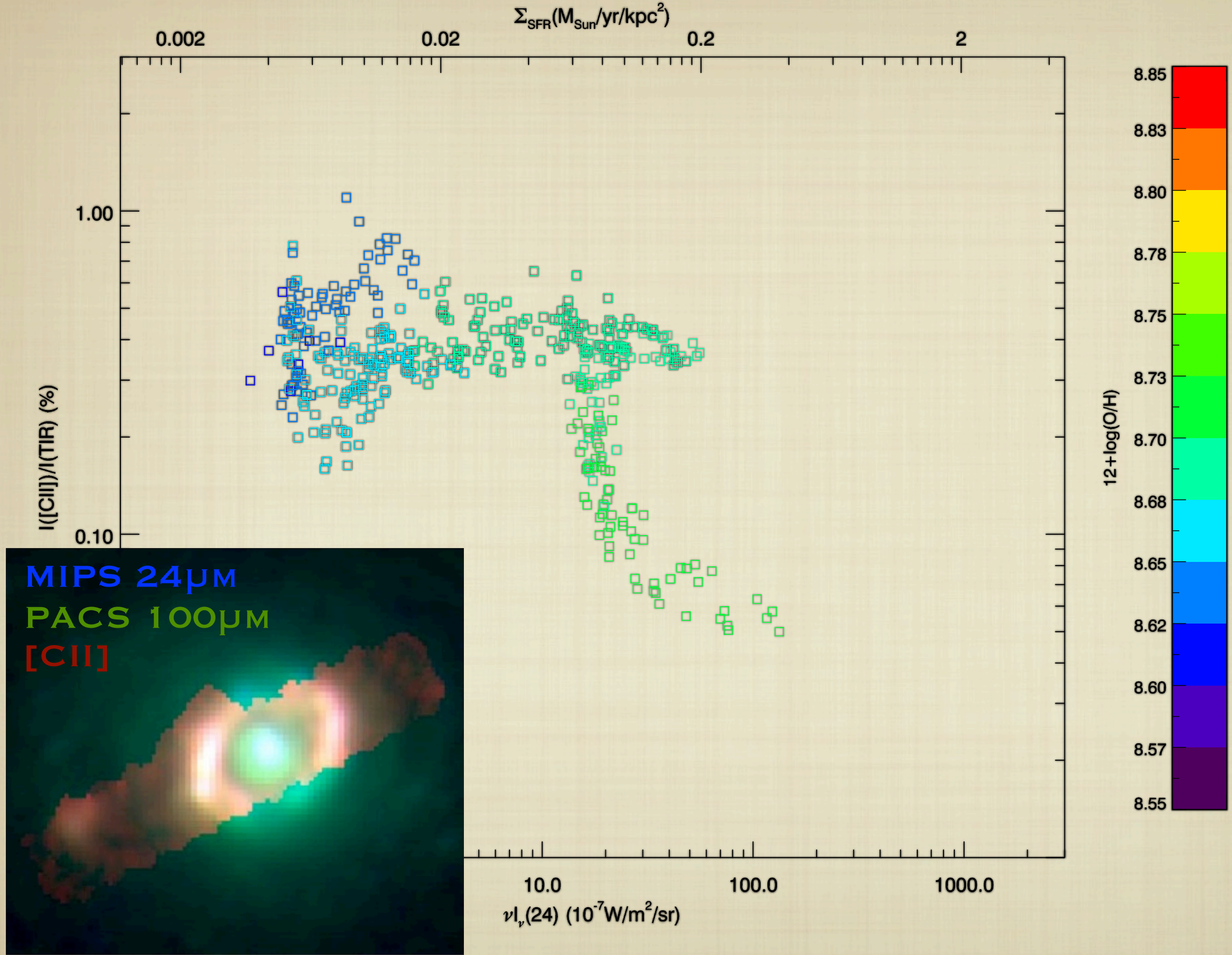
AGN Impact

Deficit: An L(AGN)/L(Total) affair?

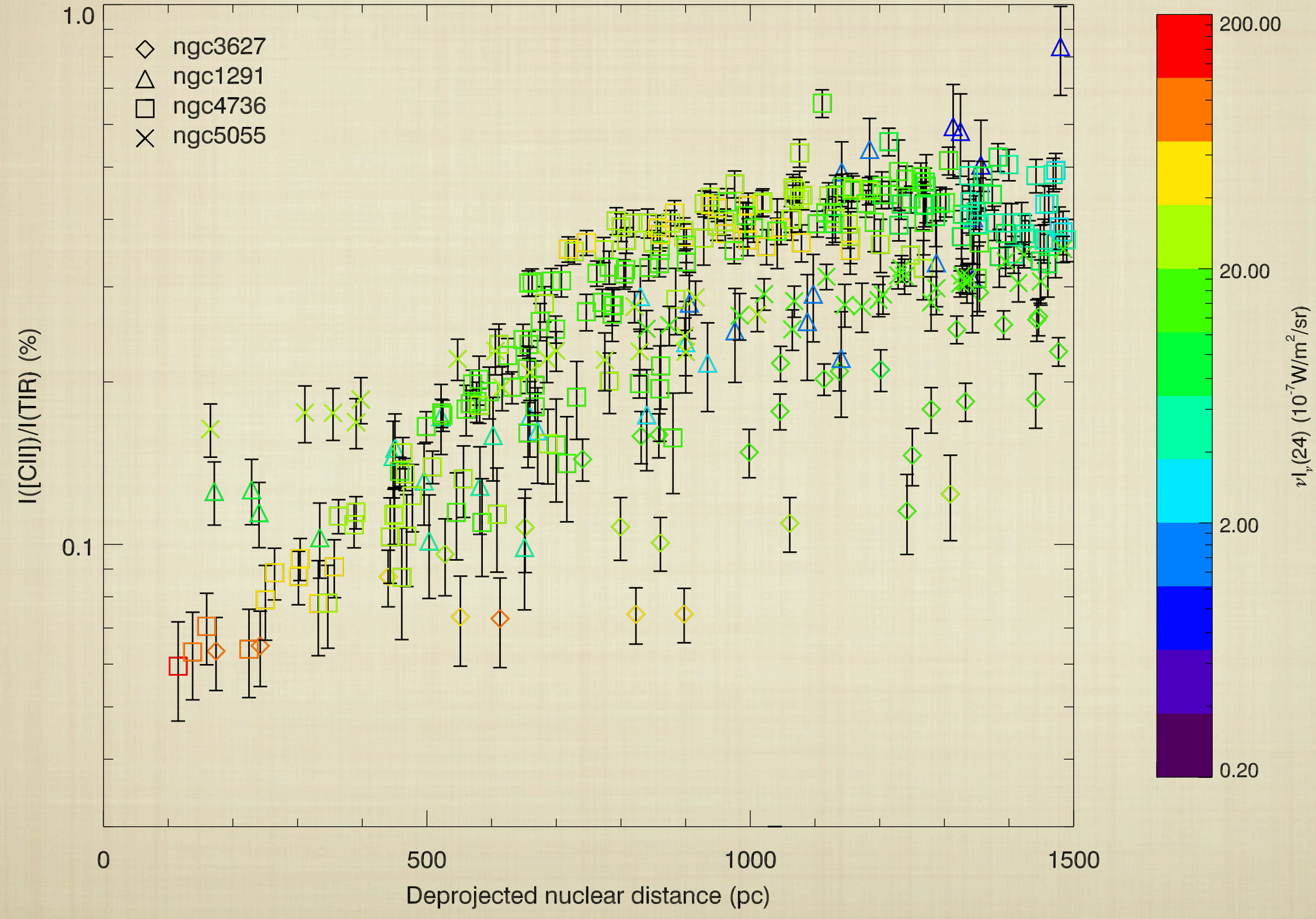


Sargsyan+ 2012

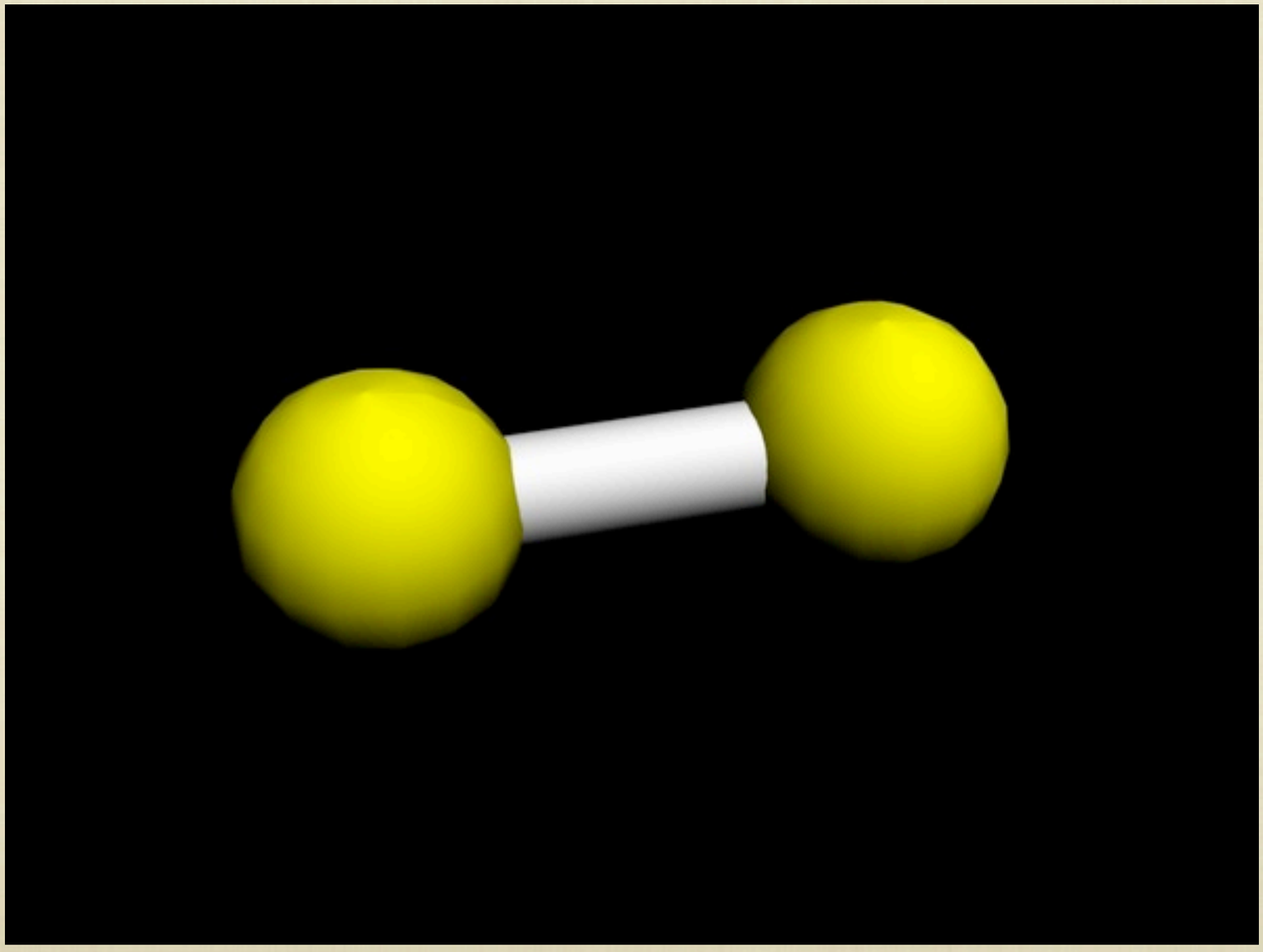

$\Sigma_{SFR}(M_{Sun}/yr/kpc^2)$
0.002
0.02
0.2
2
1.00
0.10
I([CII])/I(TIR) (%)
MIPS 24μm
PACS 100μm
[CII]
10.0
100.0
1000.0
$\nu I_\nu(24)$ (10^{-7}W/m^2/sr)
12+log(O/H)
8.85
8.83
8.80
8.78
8.75
8.73
8.70
8.68
8.65
8.62
8.60
8.57
8.55


$\Sigma_{SFR}(M_{Sun}/yr/kpc^2)$
0.002
0.02
0.2
2
1.00
0.10
I([CII])/I(TIR) (%)
MIPS 24μm
PACS 100μm
[CII]
10.0
100.0
1000.0
$\nu I_\nu(24)$ (10^{-7}W/m^2/sr)
12+log(O/H)
8.85
8.83
8.80
8.78
8.75
8.73
8.70
8.68
8.65
8.62
8.60
8.57
8.55

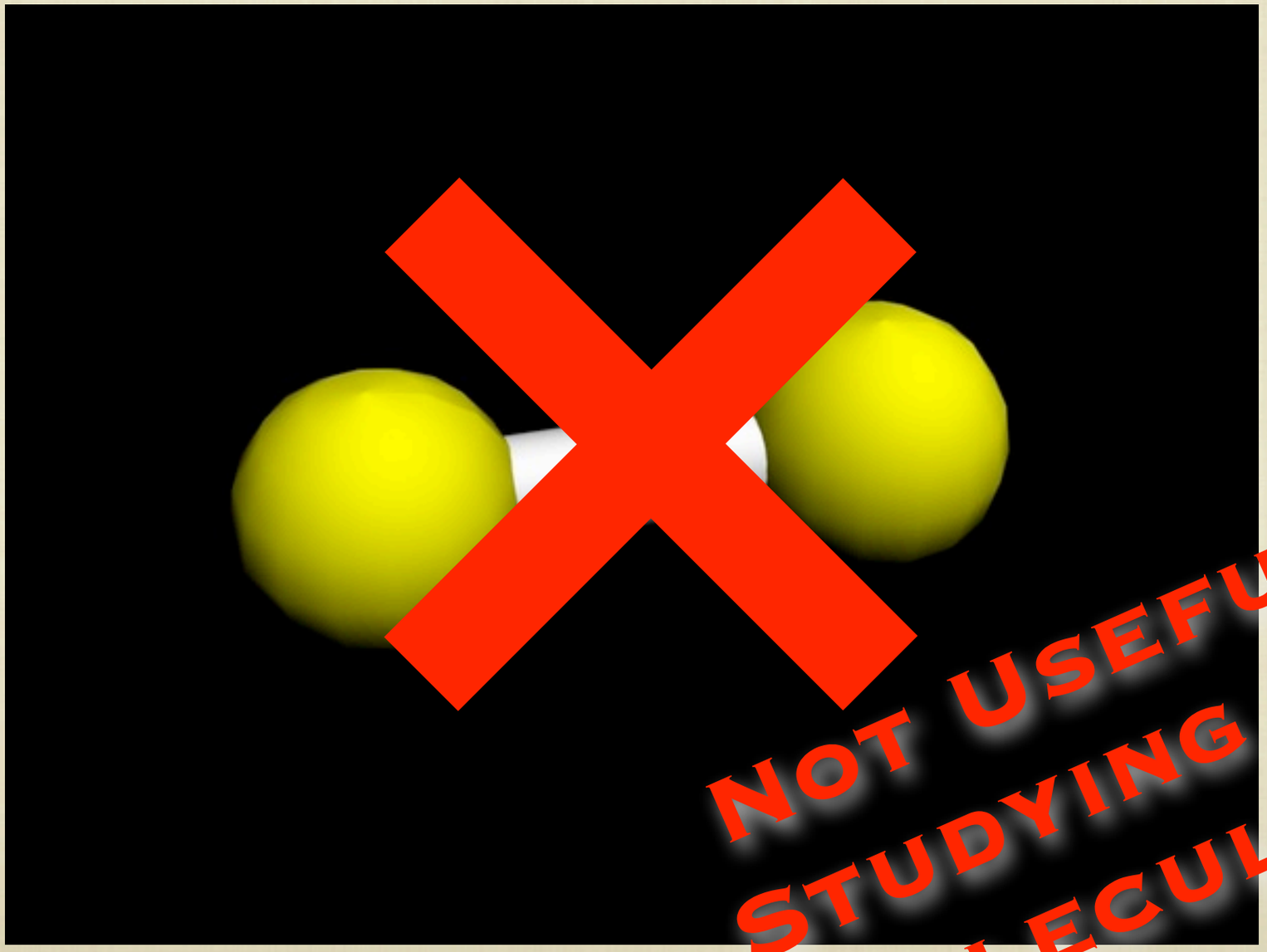
AGN IMPACT


1.0
0.1
ngc3627
ngc1291
ngc4736
ngc5055
I([CII])/I(TIR) (%)
0
500
1000
1500
Deprojected nuclear distance (pc)
200.00
20.00
2.00
0.20
νI_ν(24) (10^-7 W/m^2/sr)

In defense of the H_2 molecule



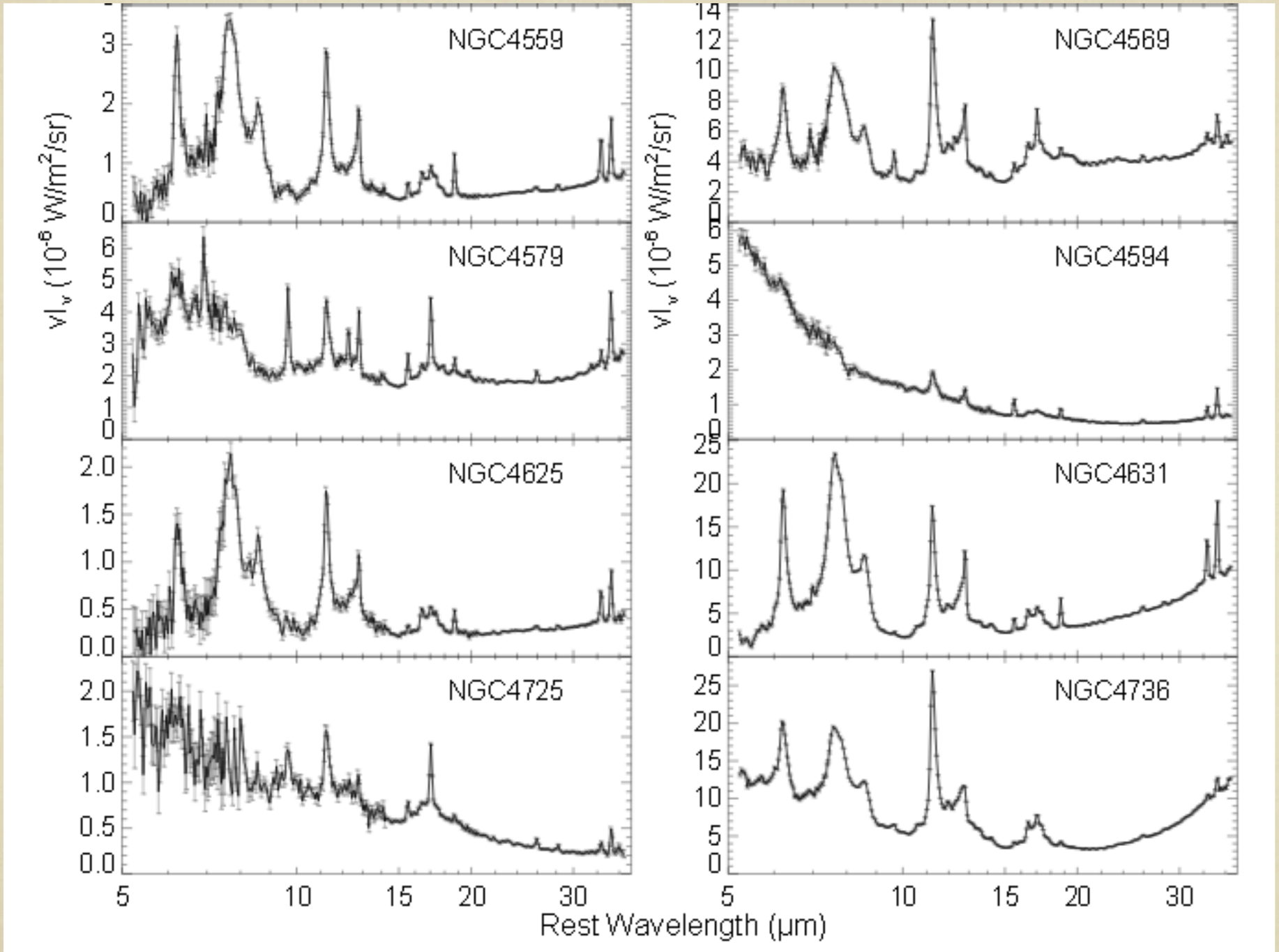
In defense of the H_2 molecule



In defense of the H_2 molecule

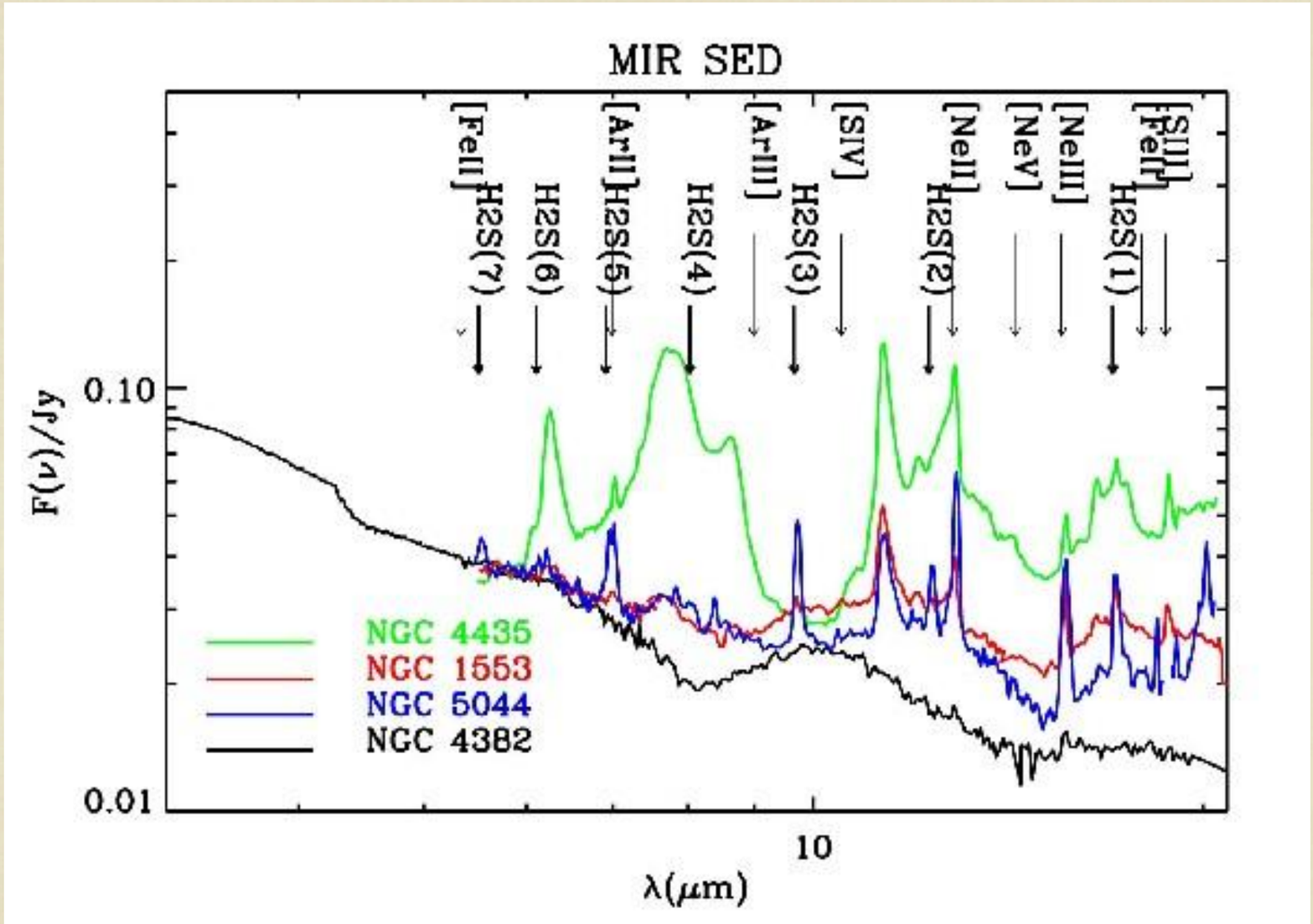
Not useful for studying "bulk" molecular gas

AND YET...



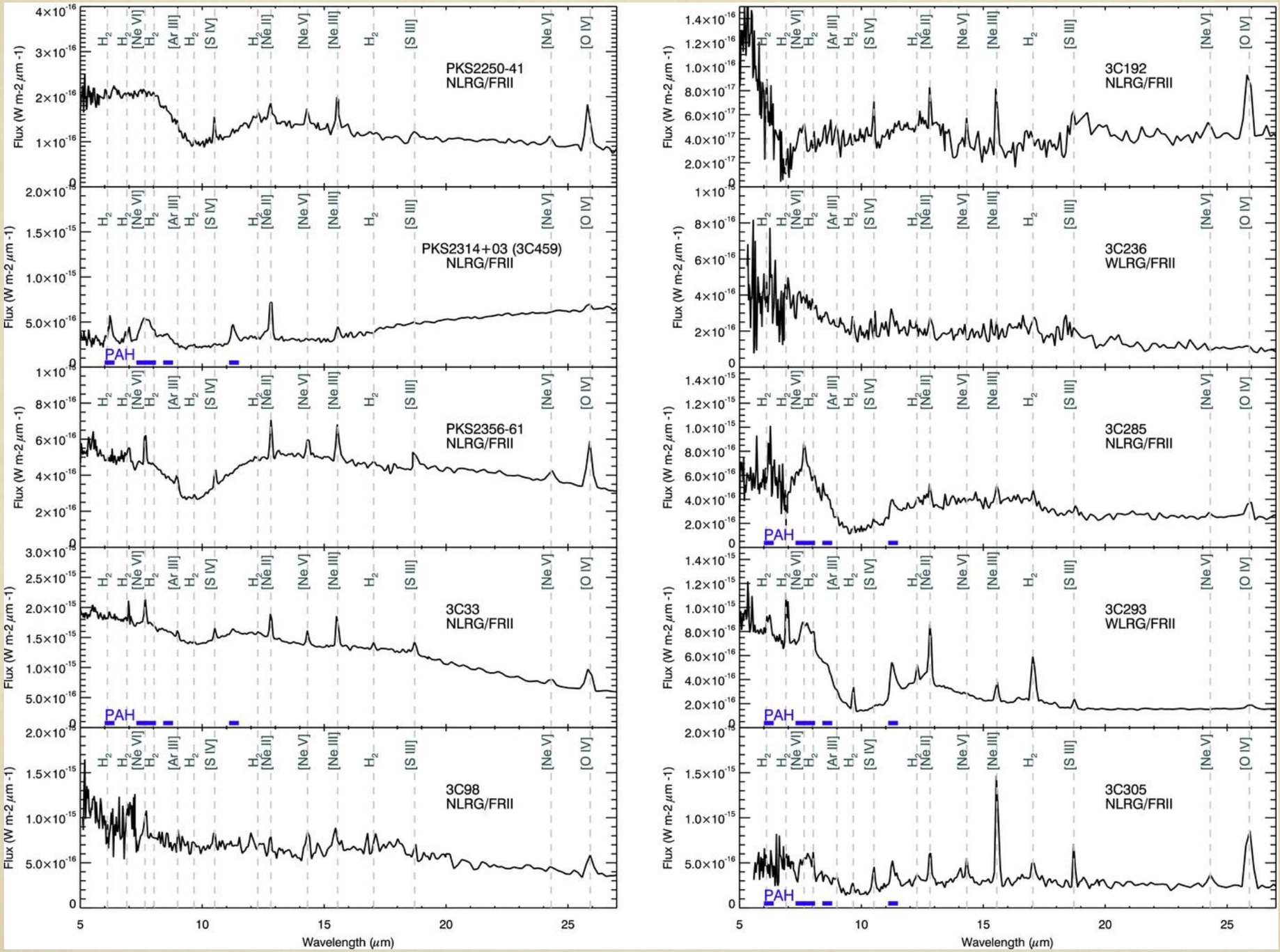
Normal Galaxies

AND YET...



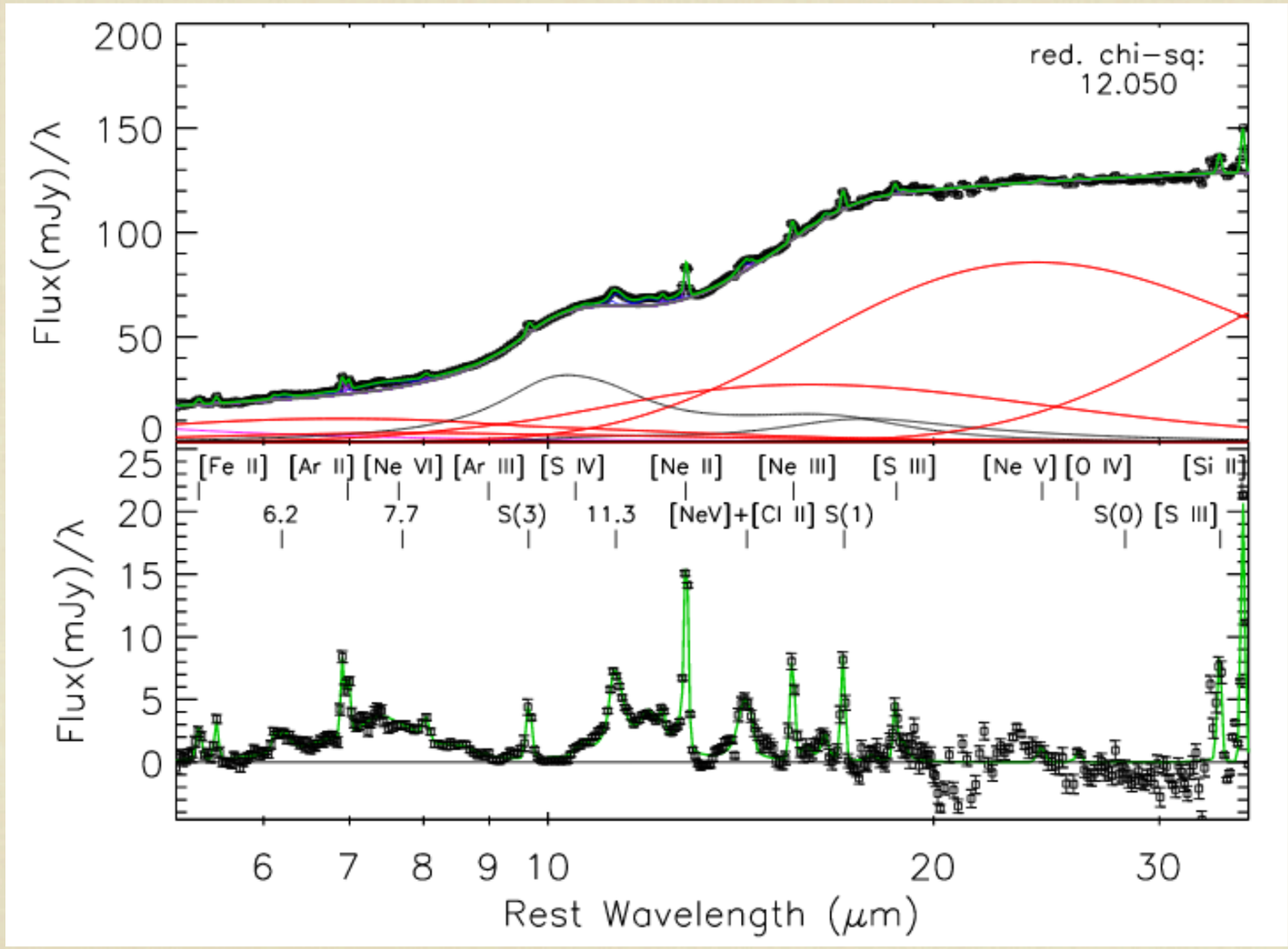
Early Type Galaxies

AND YET...



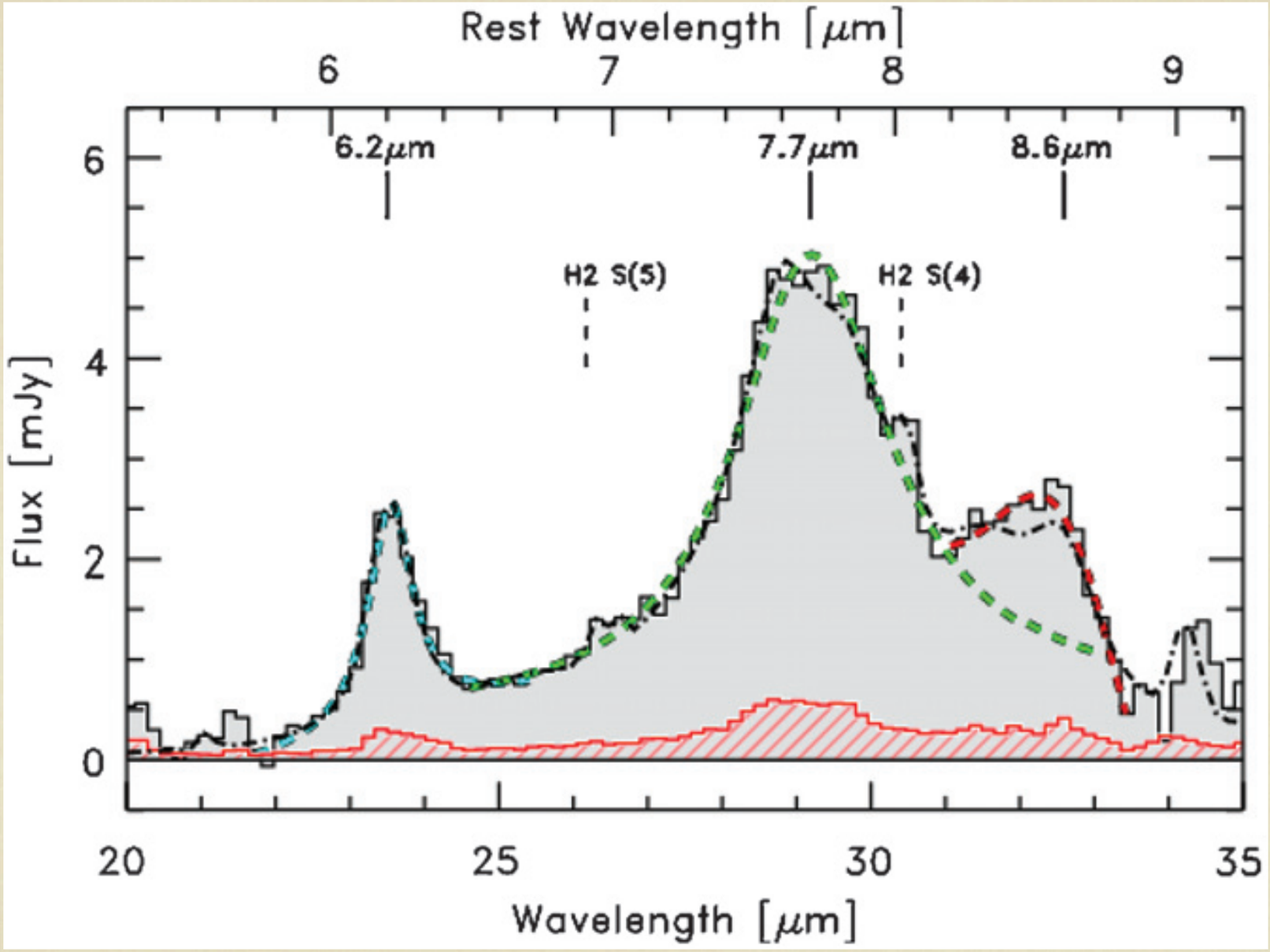
Radio Loud AGN

AND YET...



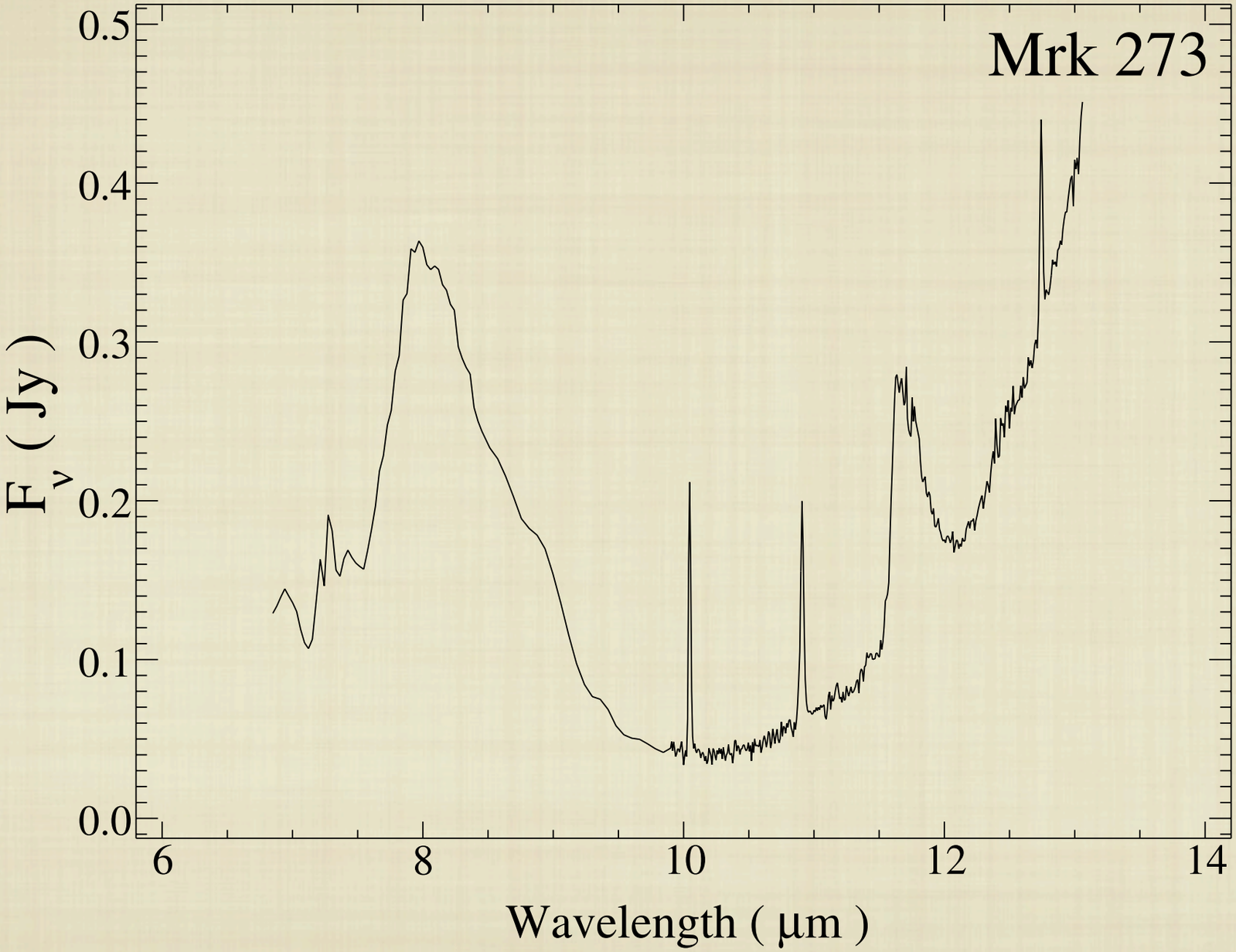
Cooling Flow Radio Galaxies

AND YET...



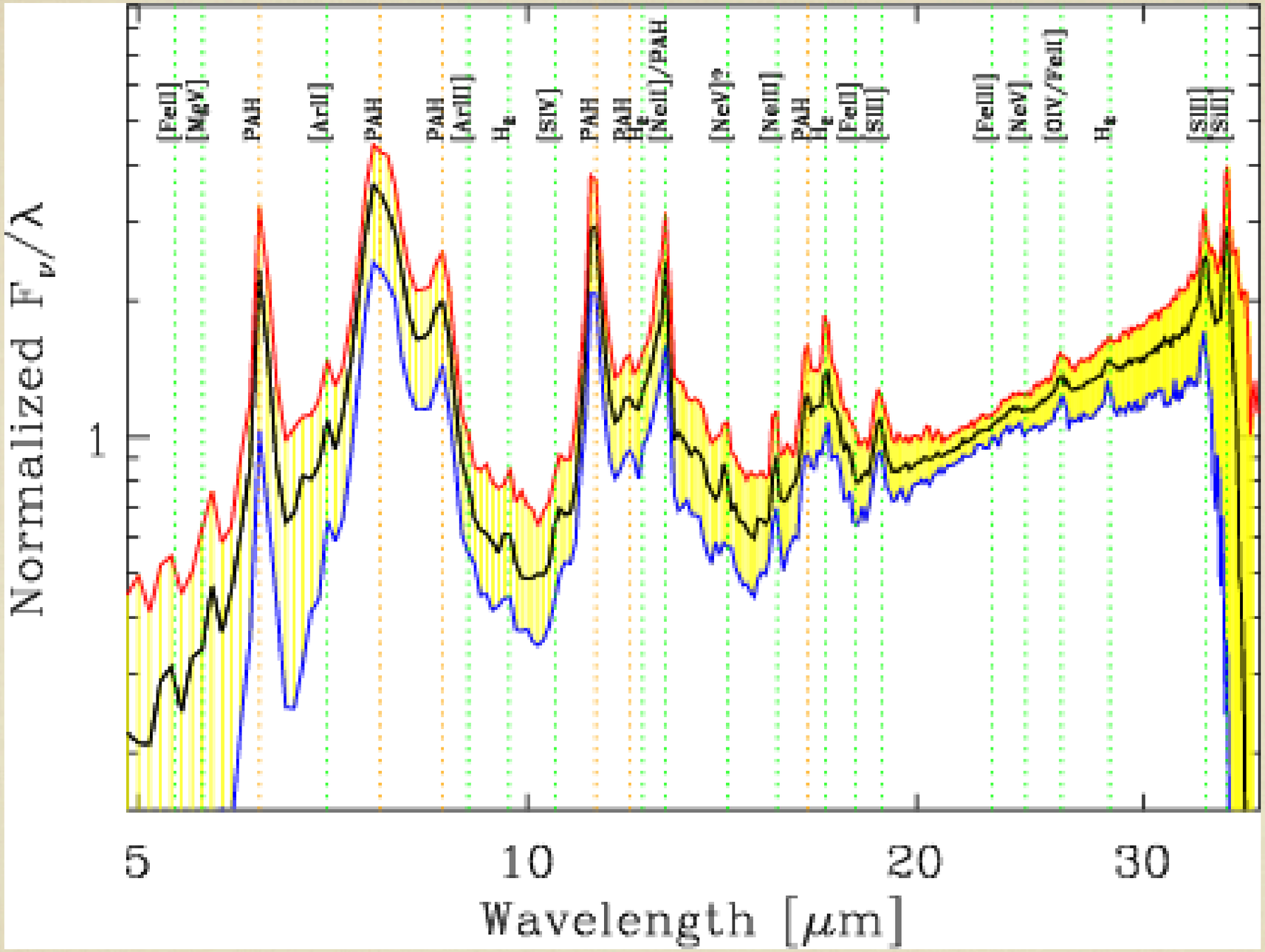
Lensed Galaxies at z~3

AND YET...



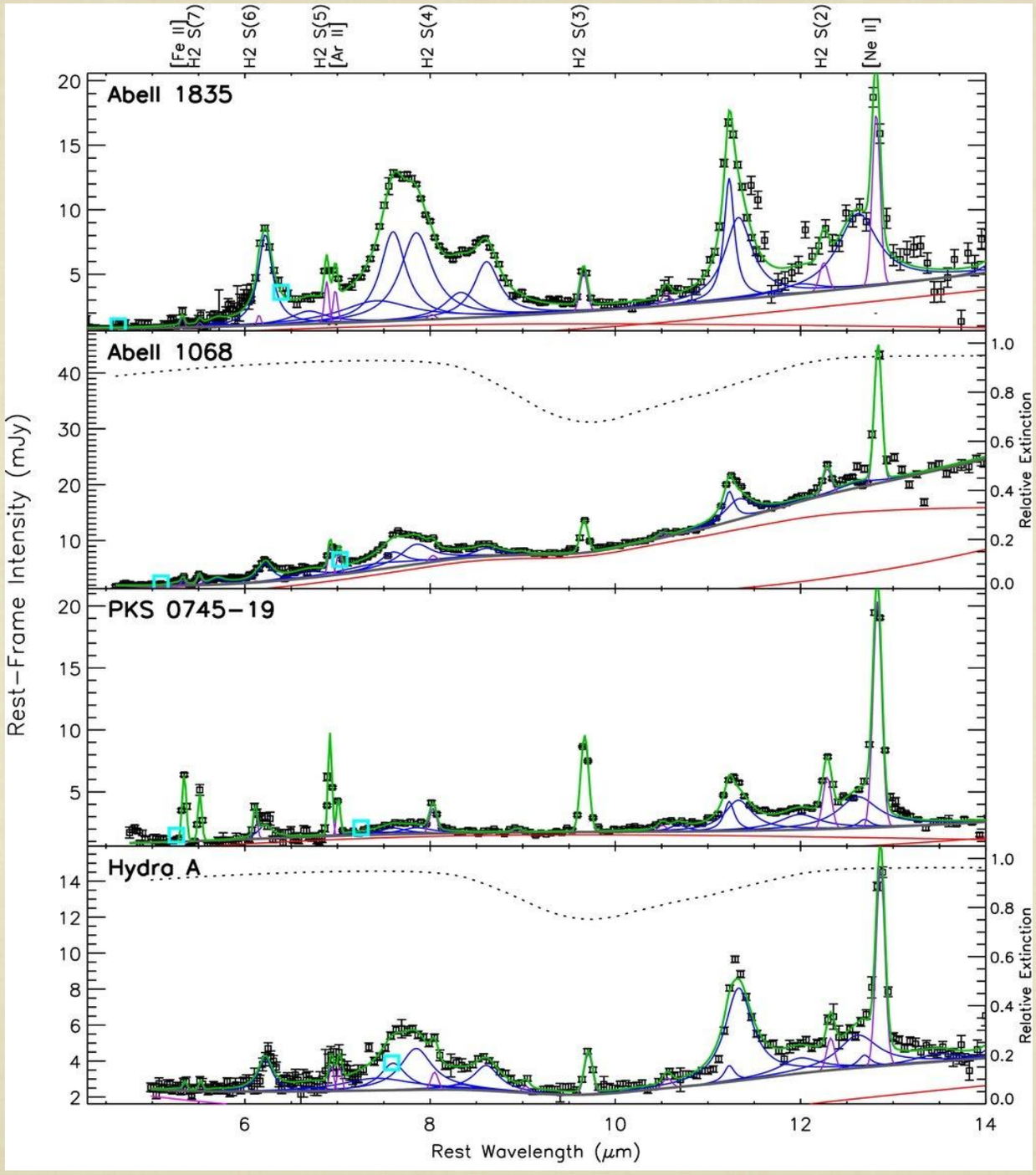
ULIRGs

AND YET...



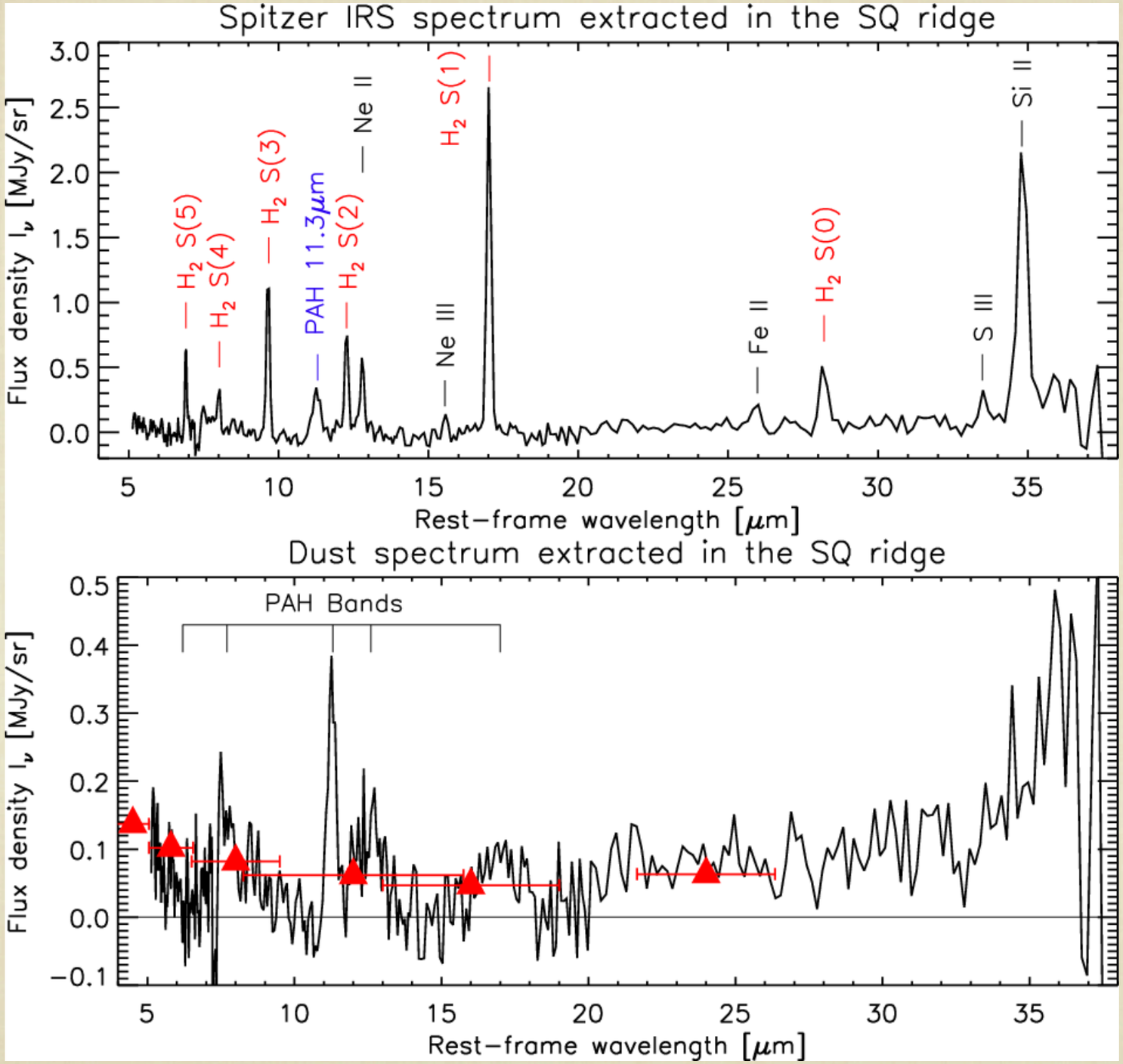
UV-selected z~0.5 galaxies

AND YET...



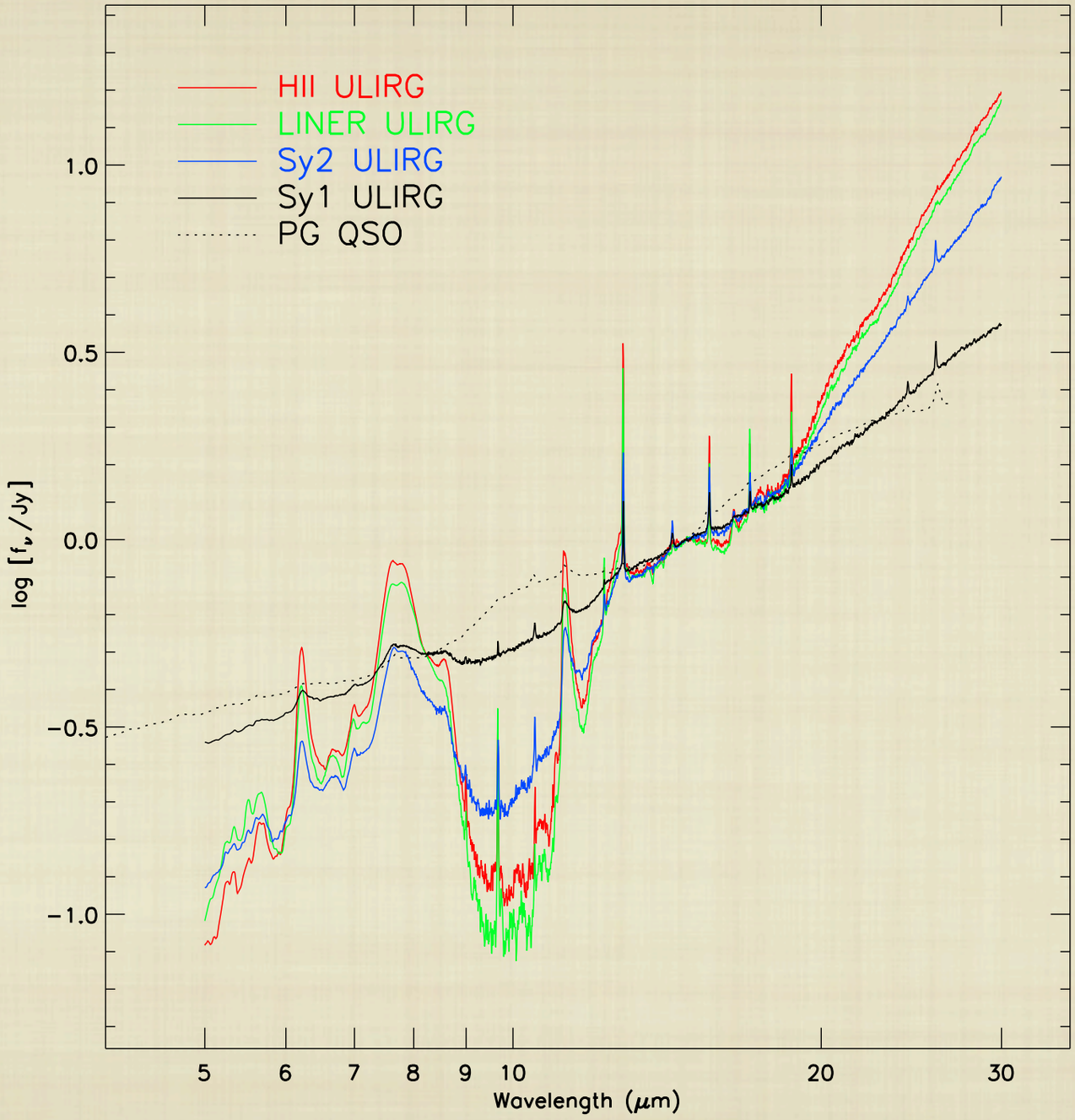
Cool core Galaxy Clusters

AND YET...



Shocked InterGalactic Ridges

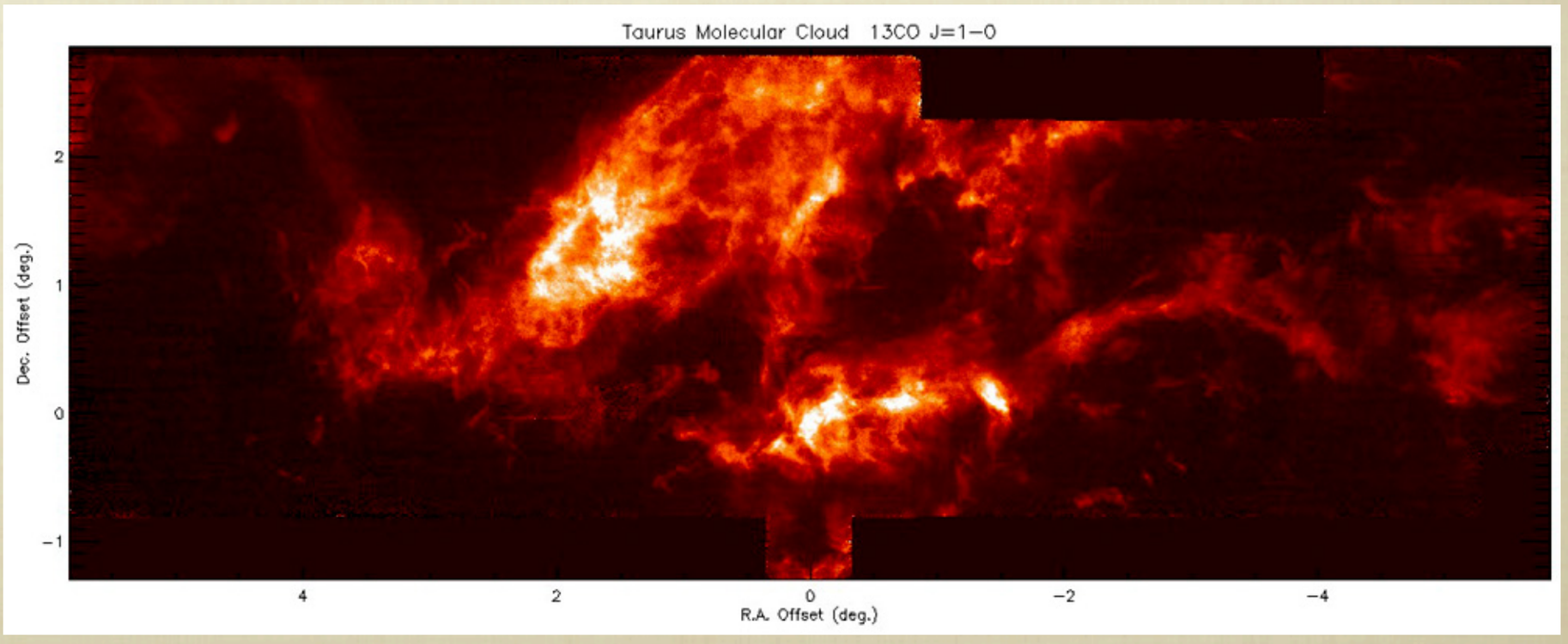
AND YET...



ULIRGs and Quasars

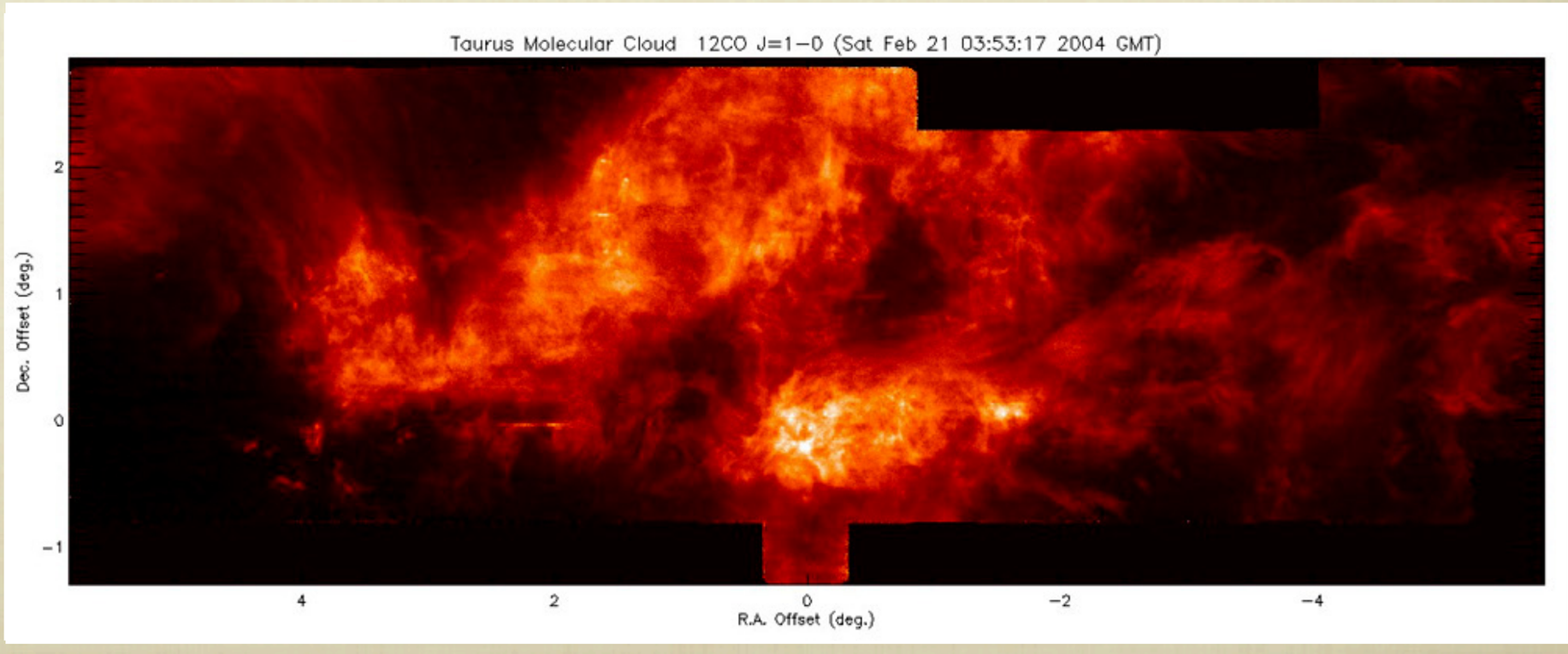
$$CO \Rightarrow H_2$$

Taurus Molecular Cloud



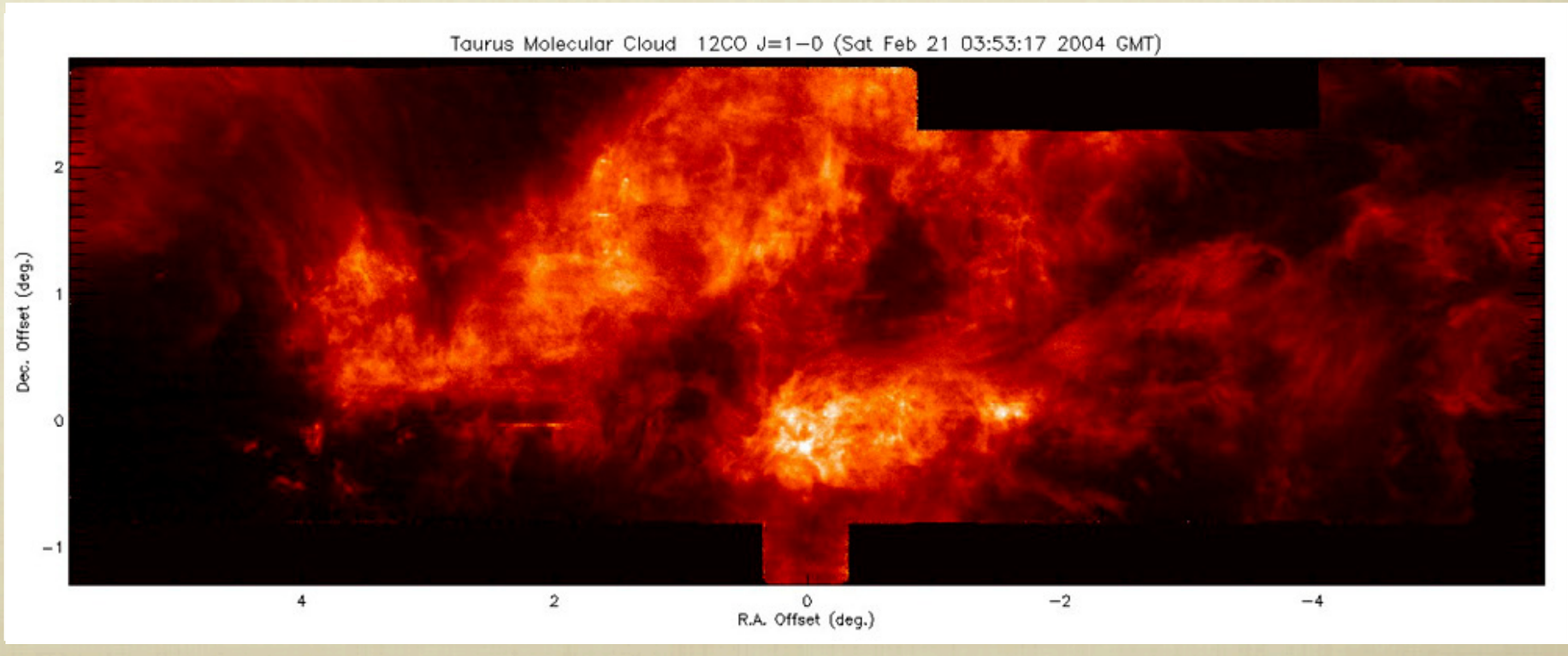
$CO \Rightarrow H_2$

Taurus Molecular Cloud

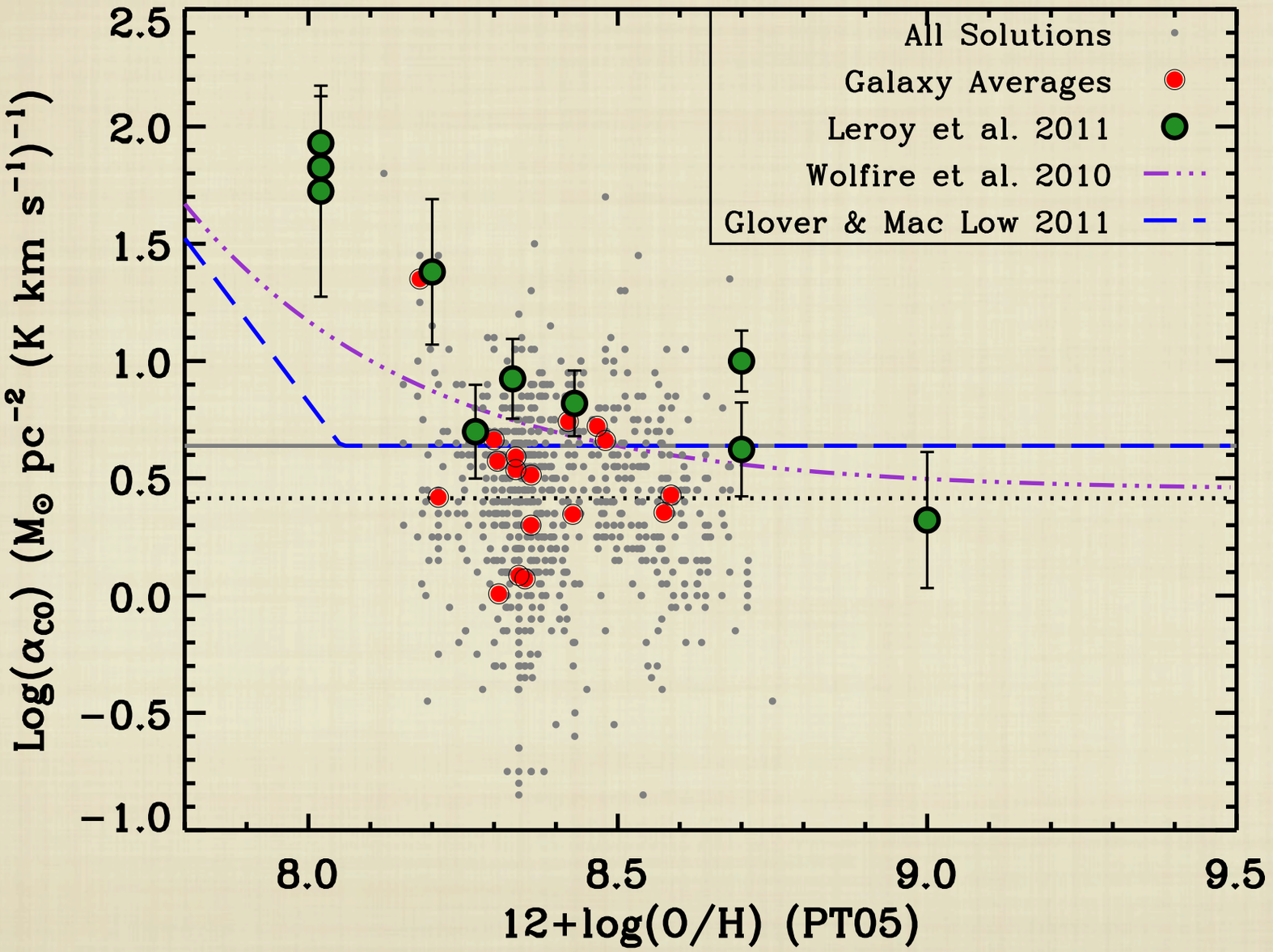


$$CO \Rightarrow H_2$$

Taurus Molecular Cloud

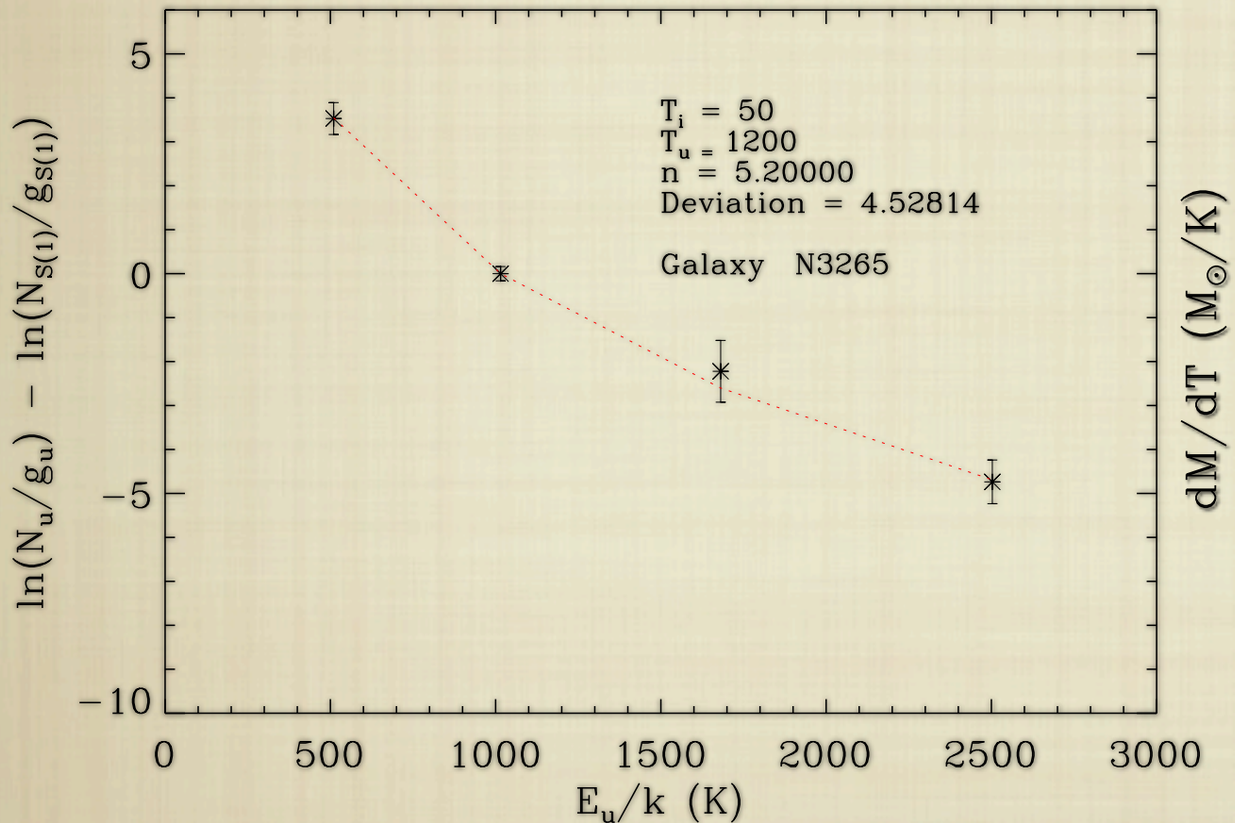


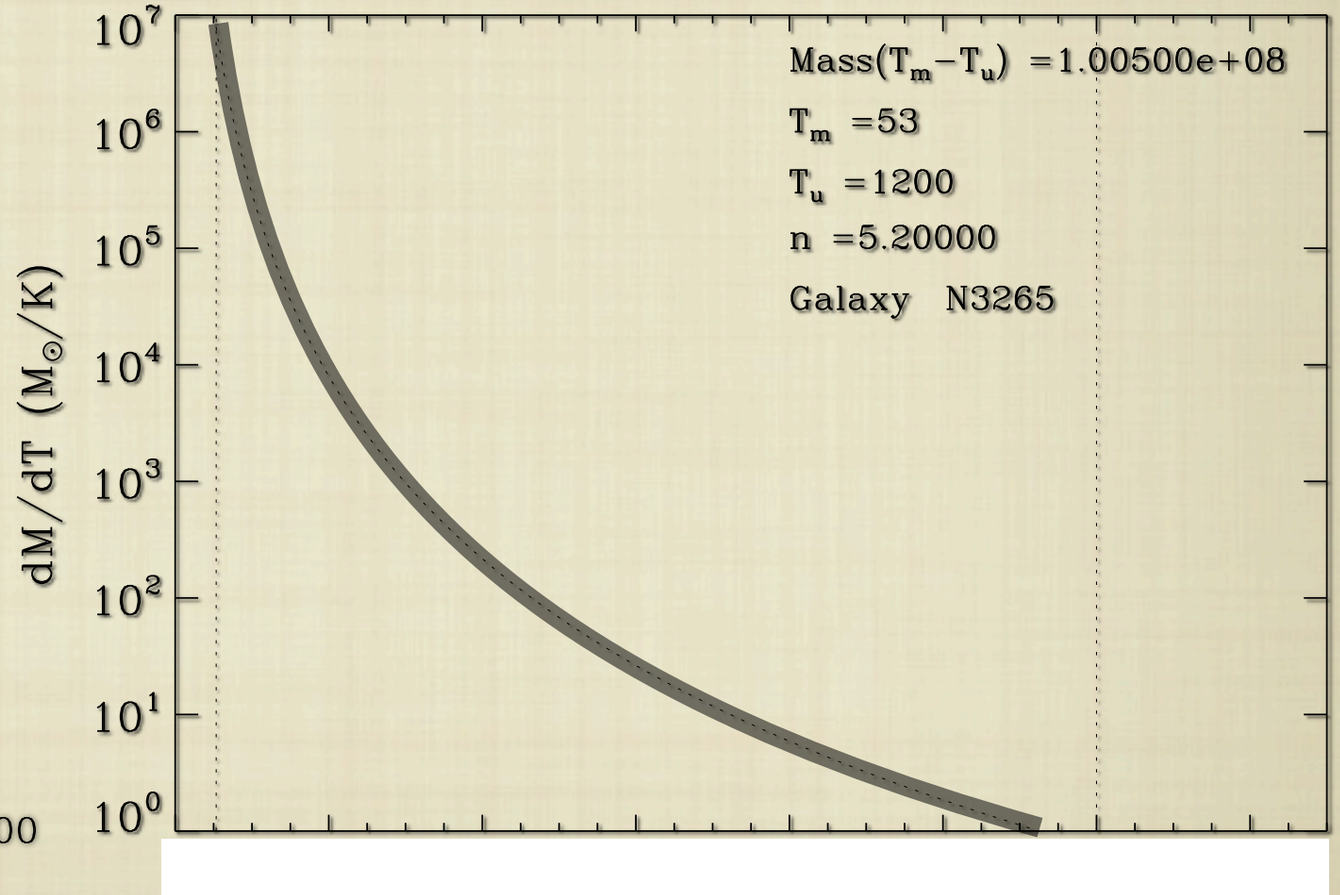
Bad Dog



Sandstrom+ accepted

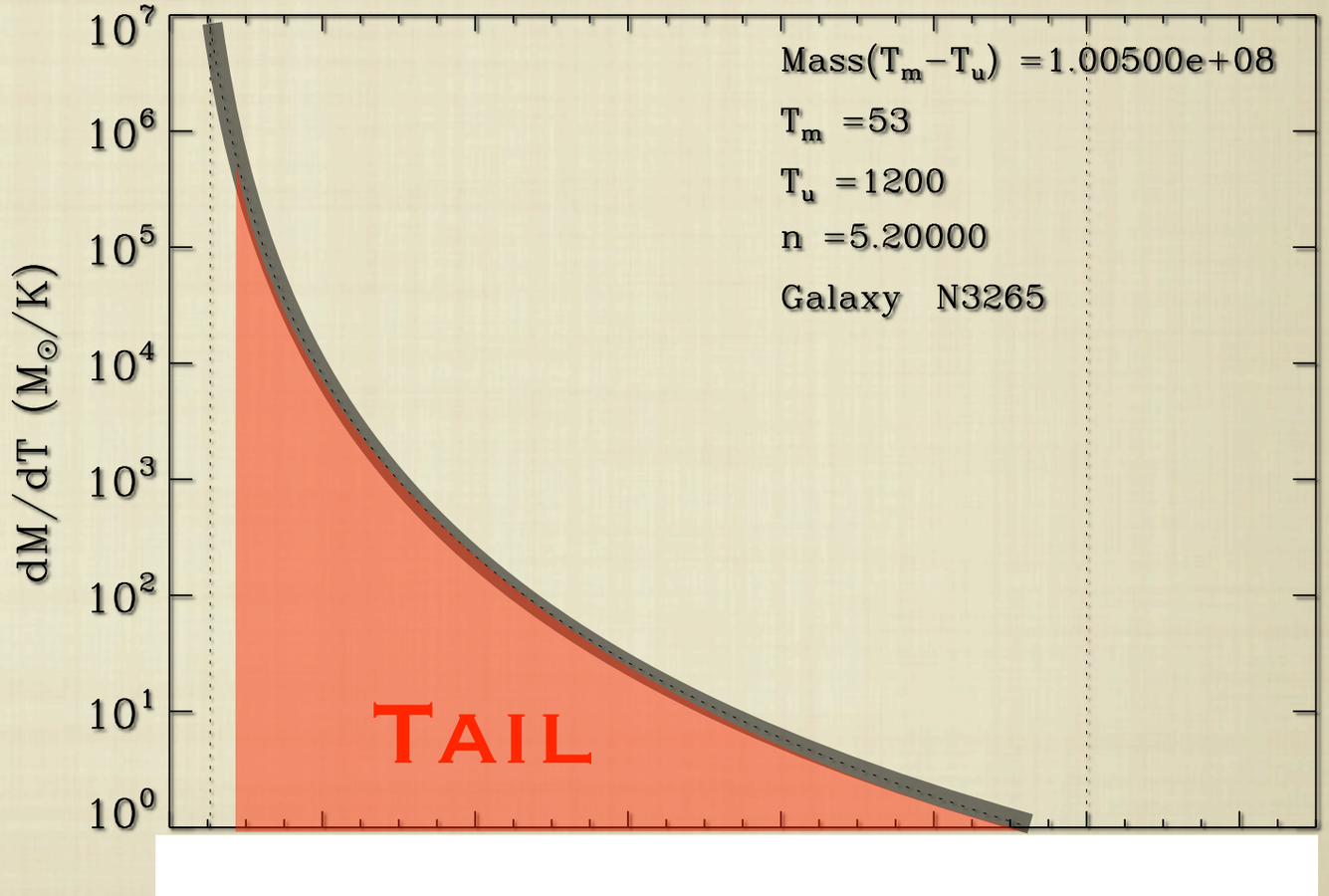
A Tail of a Dog





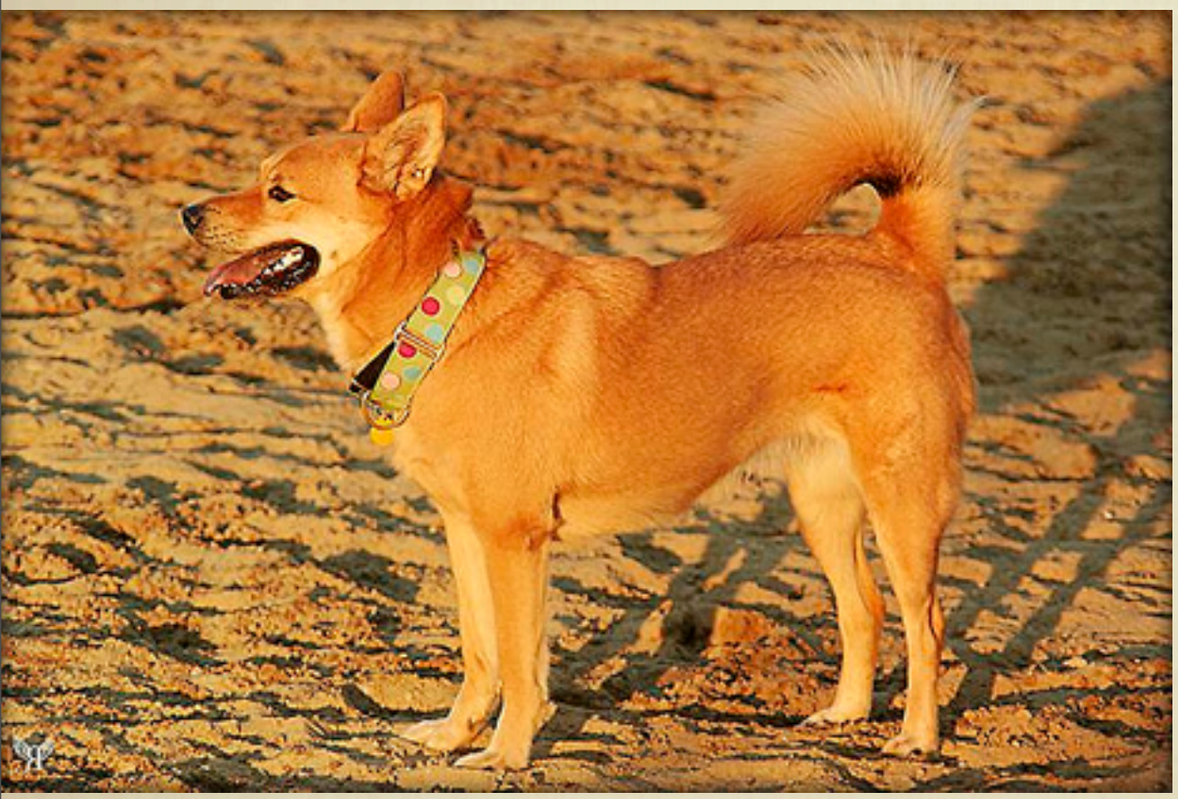
Togi & Smith, in prep

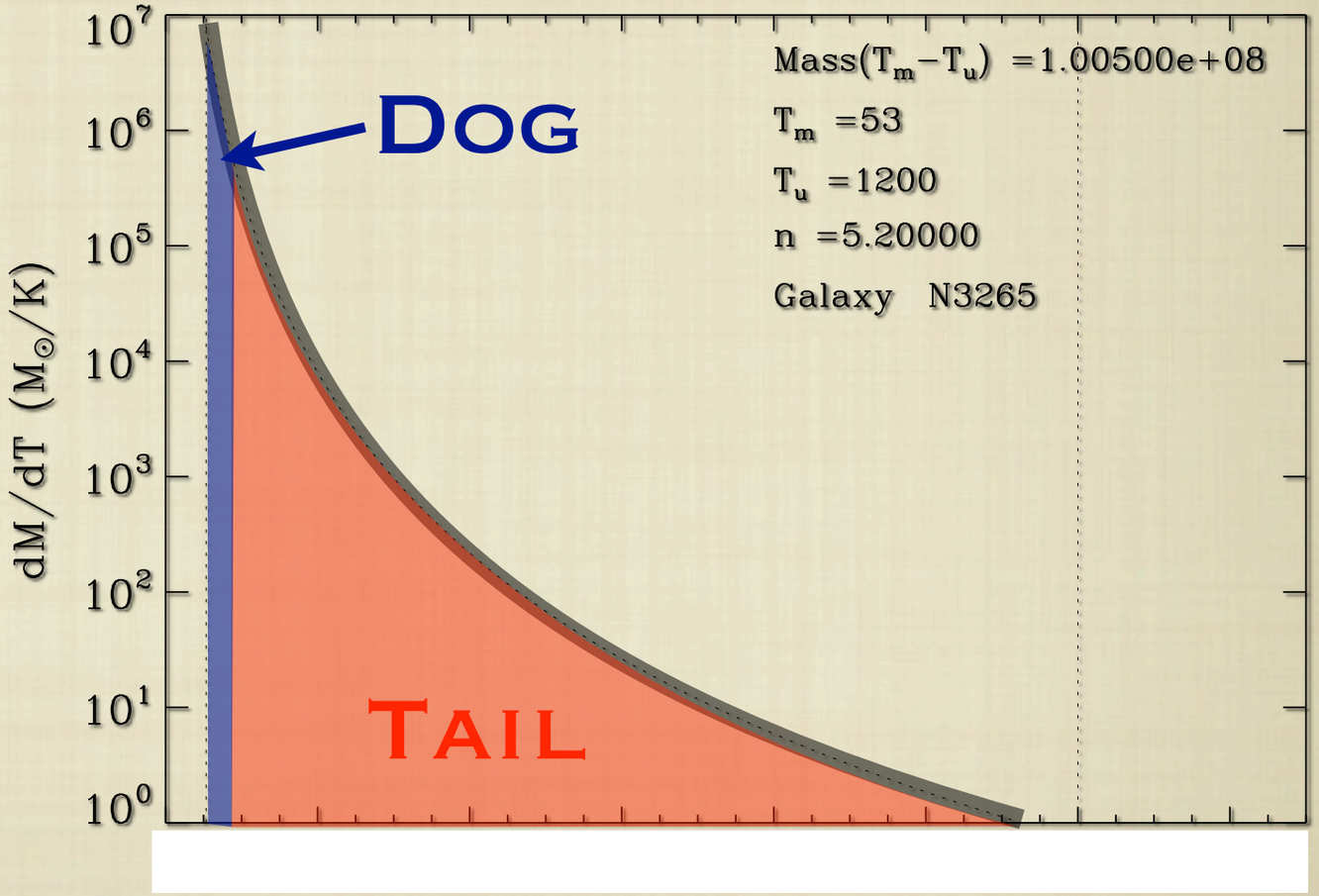
A Tail of a Dog



TOGI & SMITH, IN PREP

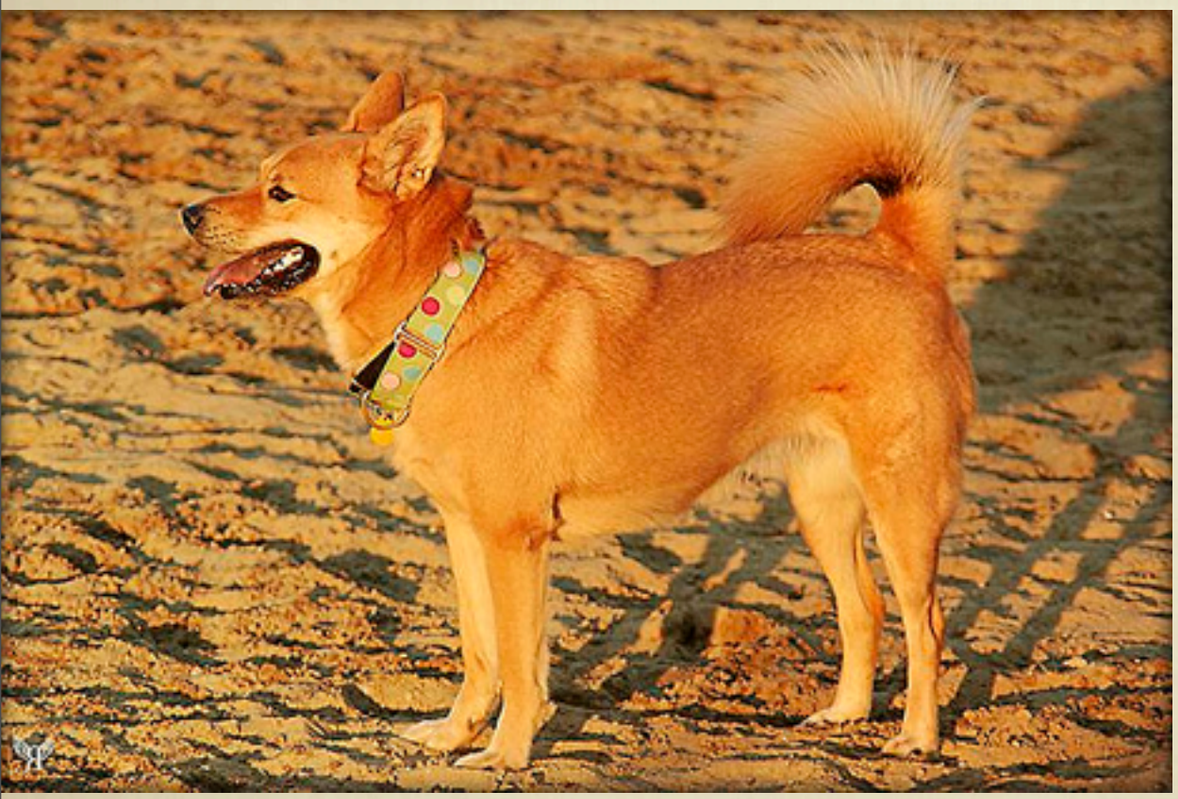
A Tail of a Dog

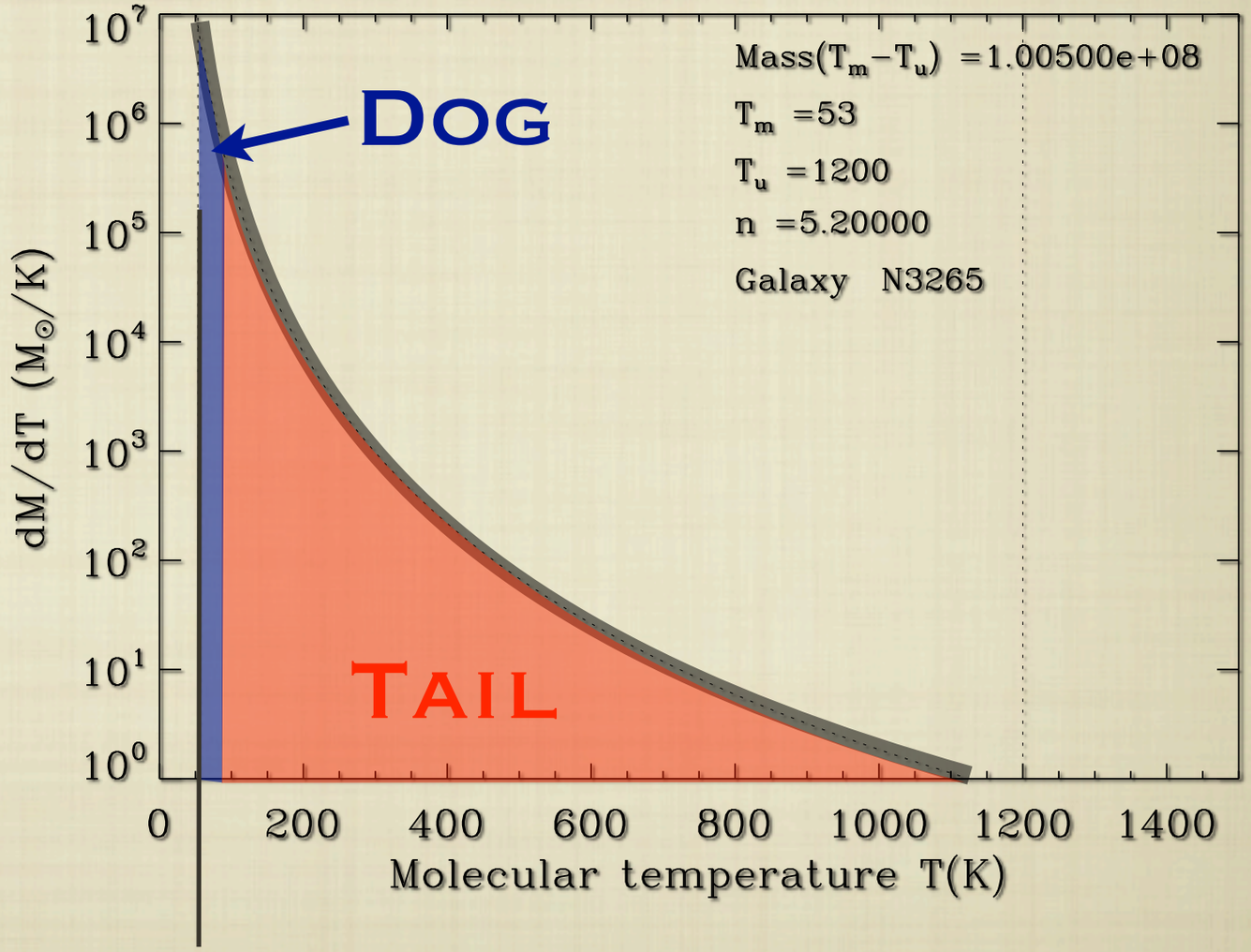




Togi & Smith, in prep

A Tail of a Dog

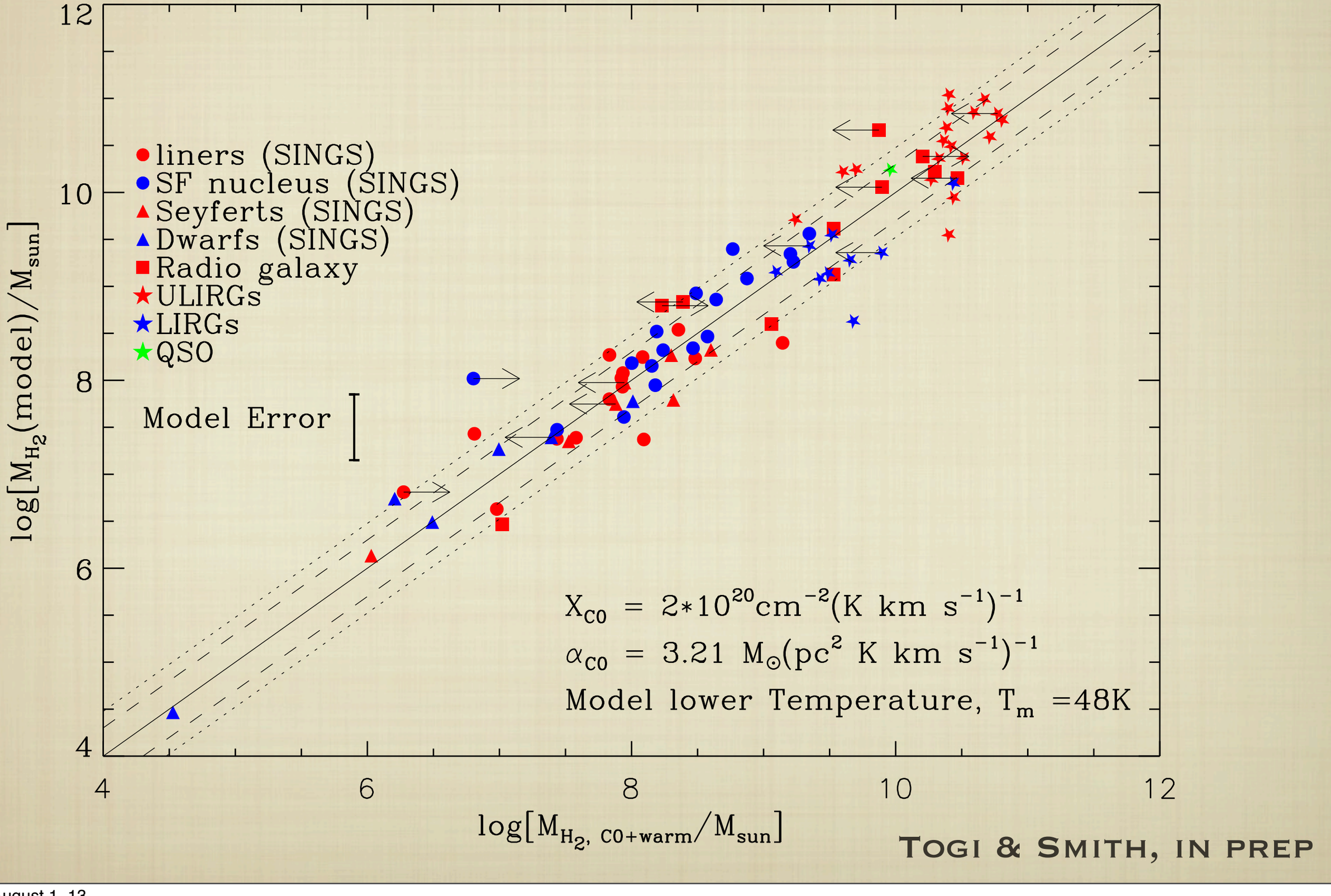




48K

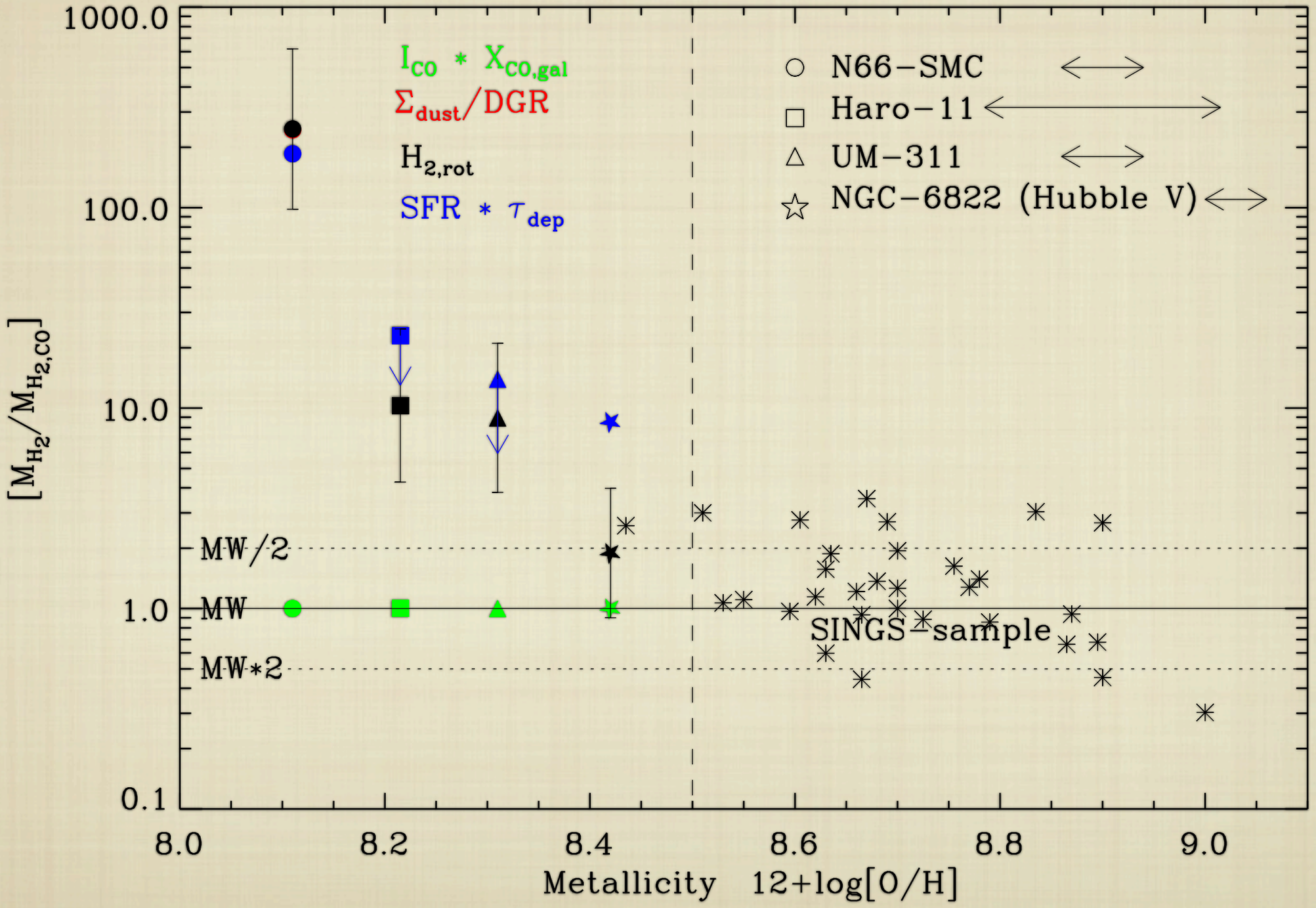
Togi & Smith, in prep

Tail: Meet Dog



Togi & Smith, in prep

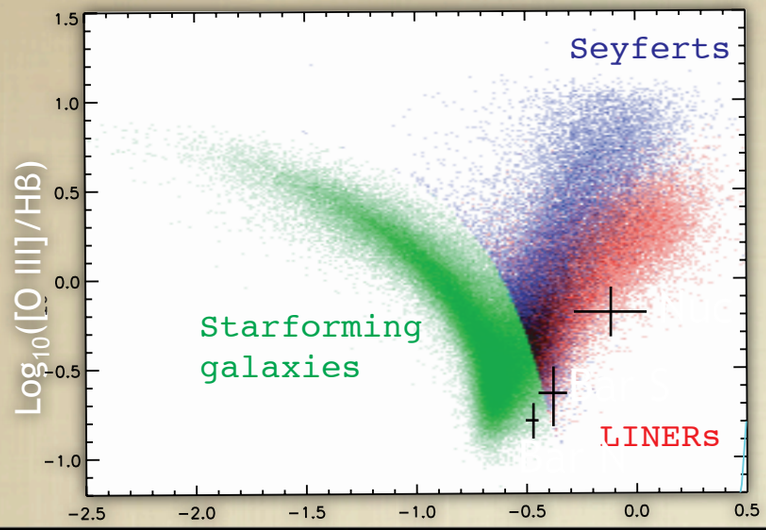
Going where no CO dares to go

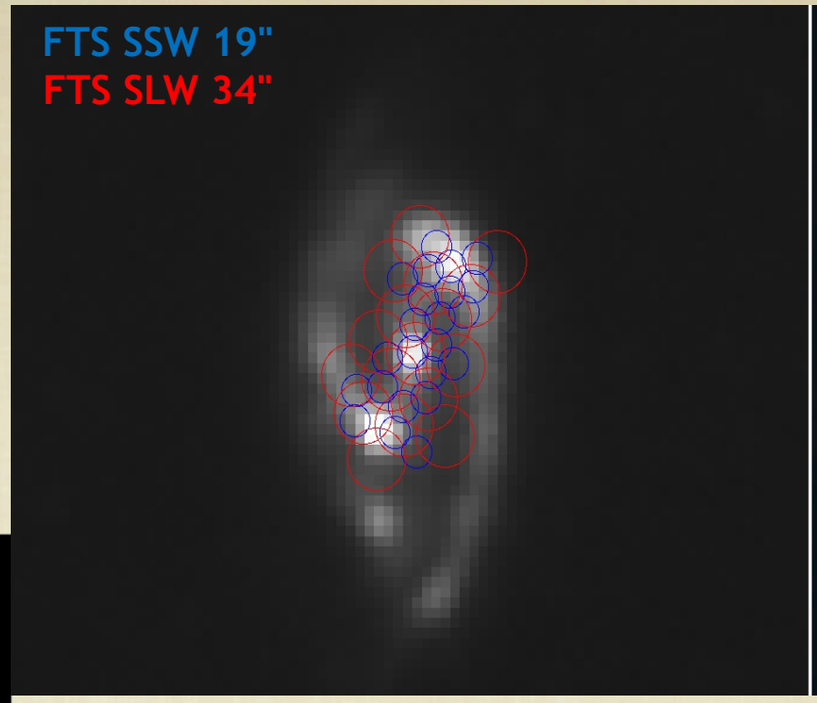



100
10
1
0.1
νI_ν (10^{-13} W m^{-2})
GALEX/optical
JHK Near-Infrared
ISOCAM Mid-Infrared
IRAS Infrared
Spitzer IRAC/MIPS
Herschel PACS/SPIRE
CUBA submm
Optical long-slit
Spitzer IRS
NGC 6946
CO(1→0),CO(2→1),CO(3→2)
1
10
100
1000
Wavelength (μm)

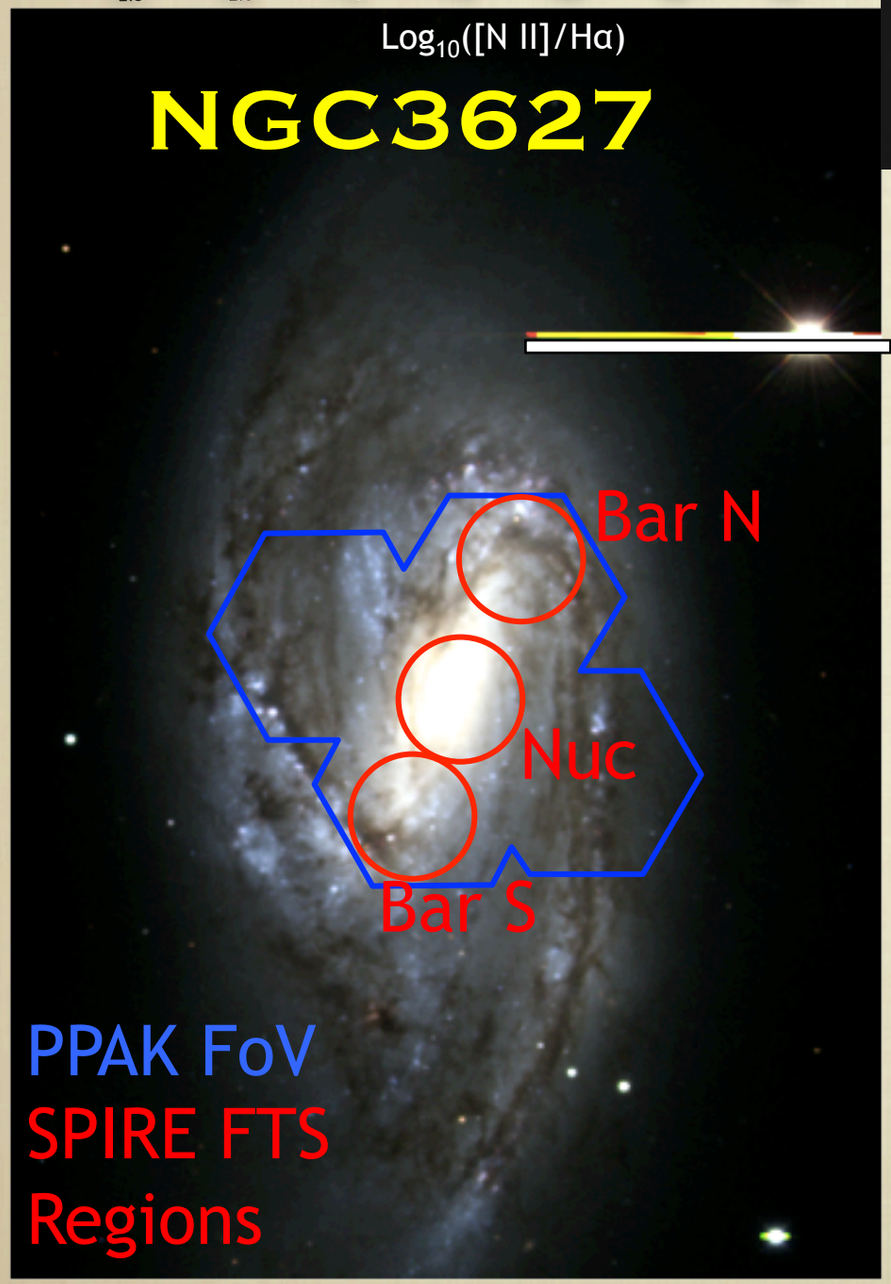
Beyond the Peak

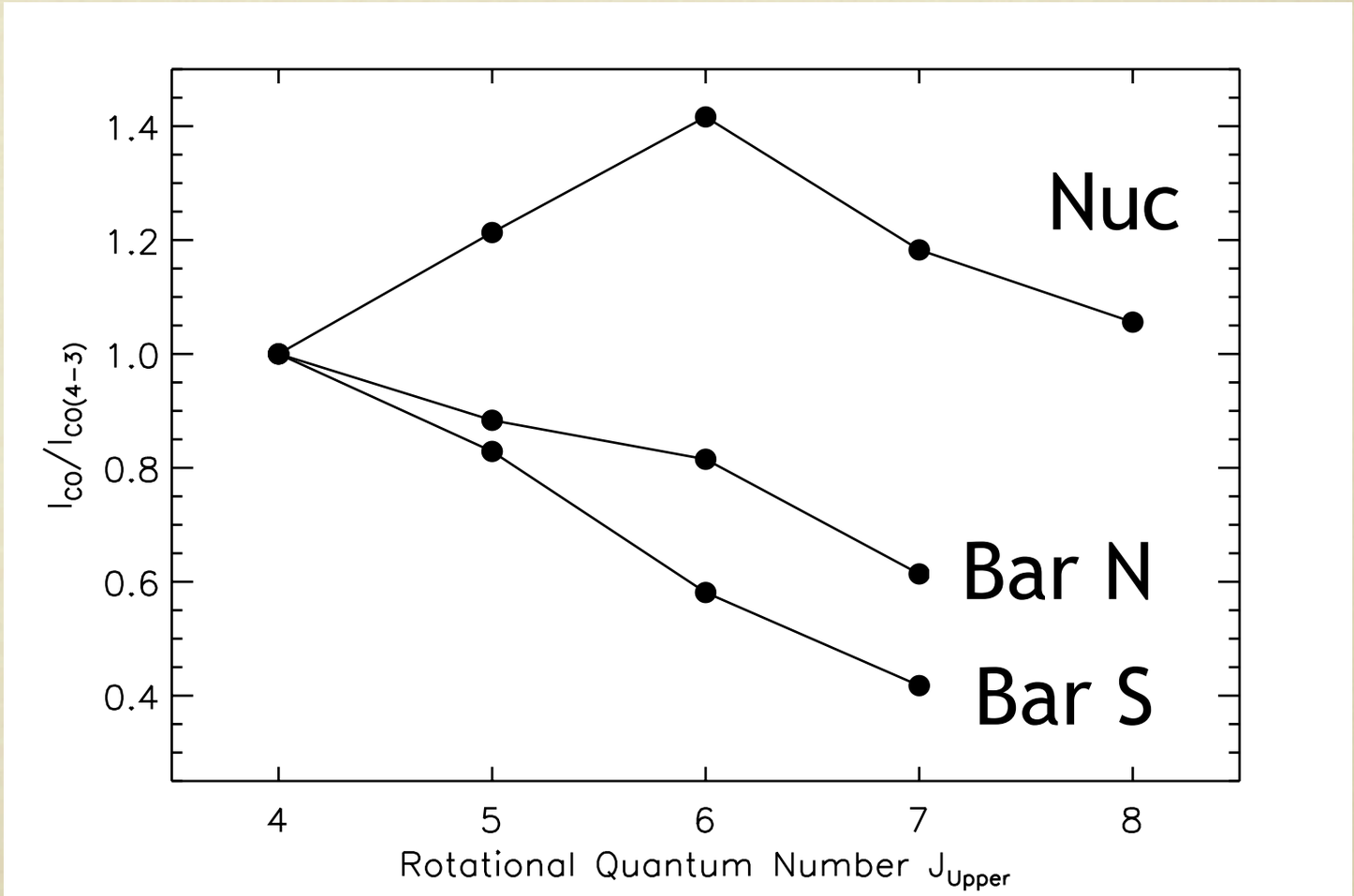
Resolved Far-Infrared Spectral Mapping of Nearby Galaxies with SPIRE/FTS


Seyferts
Starforming
galaxies
LINERs
Log10([O III]/Hβ)
Log10([N II]/Hα)

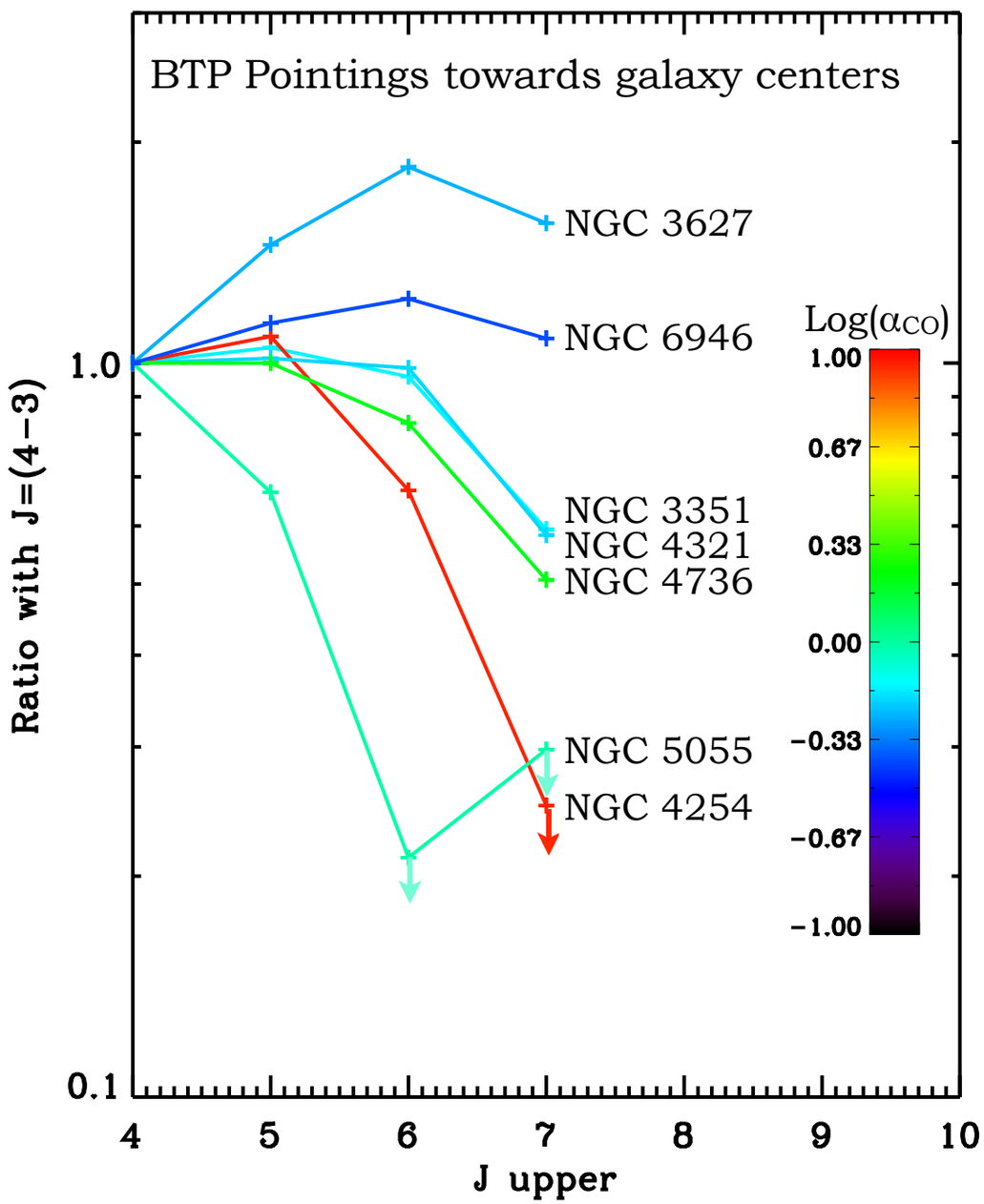

FTS SSW 19"
FTS SLW 34"


#2
#1
#3


NGC3627
Bar N
Nuc
Bar S
PPAK FoV
SPIRE FTS
Regions

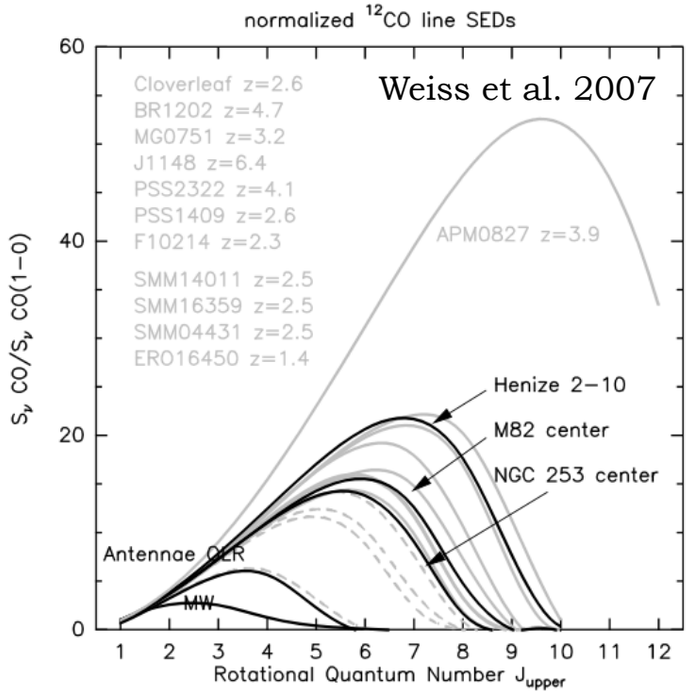

Nuc
Bar N
Bar S
Rotational Quantum Number JUpper
ICO/ICO(4-3)

α_{CO} vs. CO excitation



Evidence for enhanced CO excitation in centers with low α_{CO} from BTP.

Many galaxy centers peak at J~6, similar to M82.



courtesy K. Sandstrom

$12+\log(O/H)=8.1$

$0.2\ Z_{\odot}$

$$12+\log(OH)=8.1$$

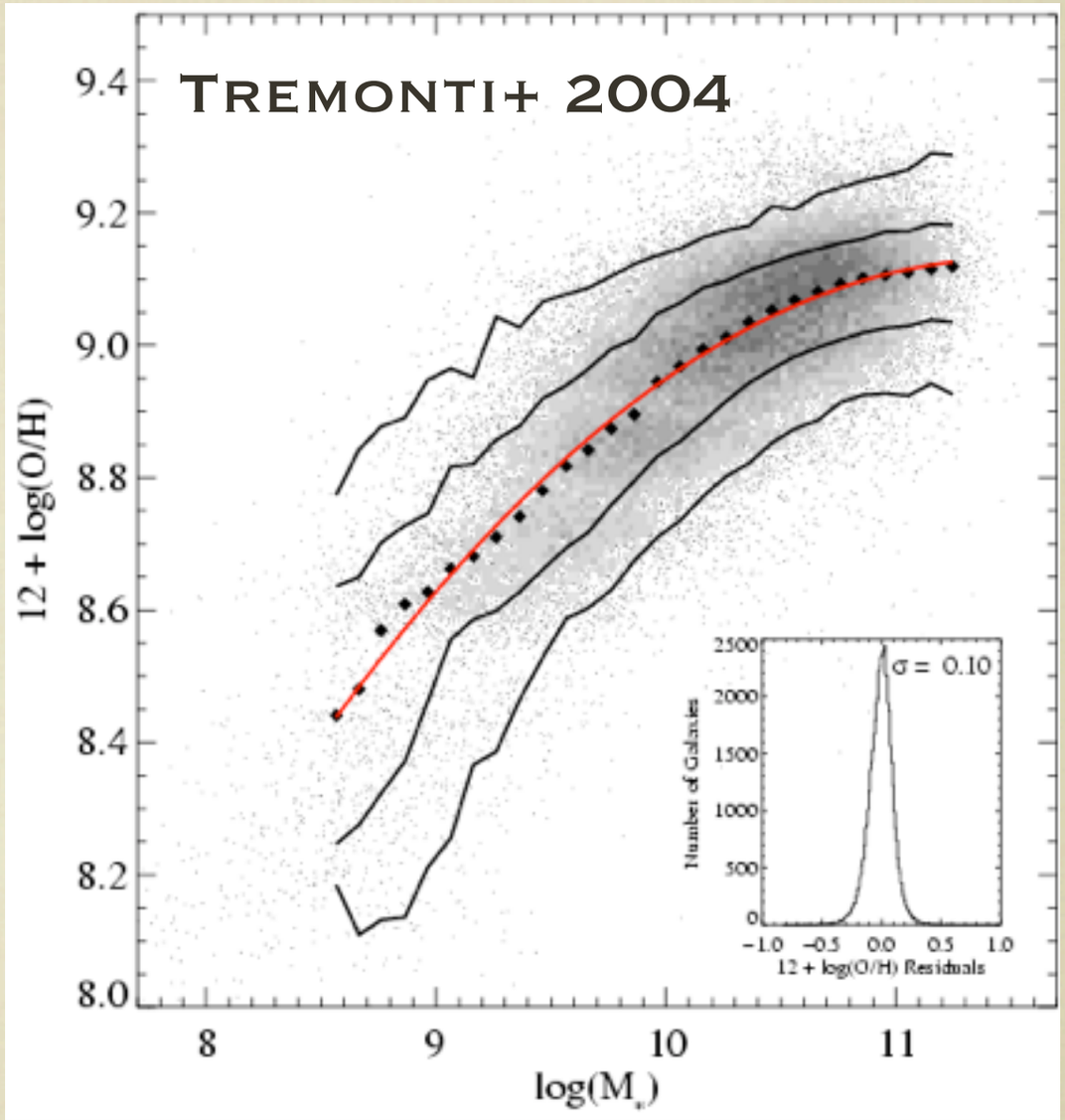
Oxygen Abundance Scale

Is the universe Super-solar, or sub-solar?

- Oxygen most common element for metal abundance determinations: convenient bright optical transitions.

- Calibrating:
  1) to models of HII regions,
  2) to "direct" temperature-sensitive measurements

- **disagree by factors of 4!**



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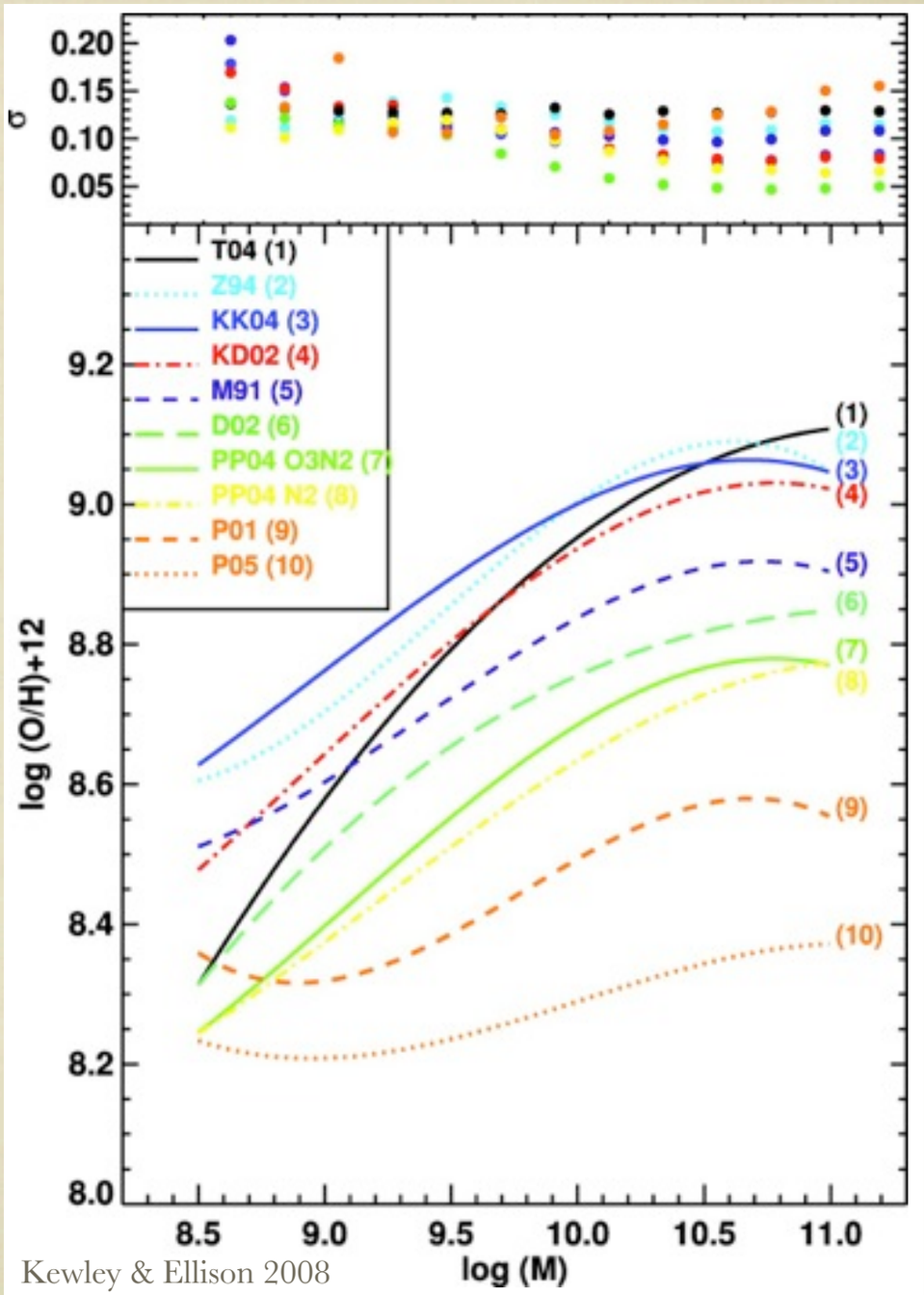

Kewley & Ellison 2008

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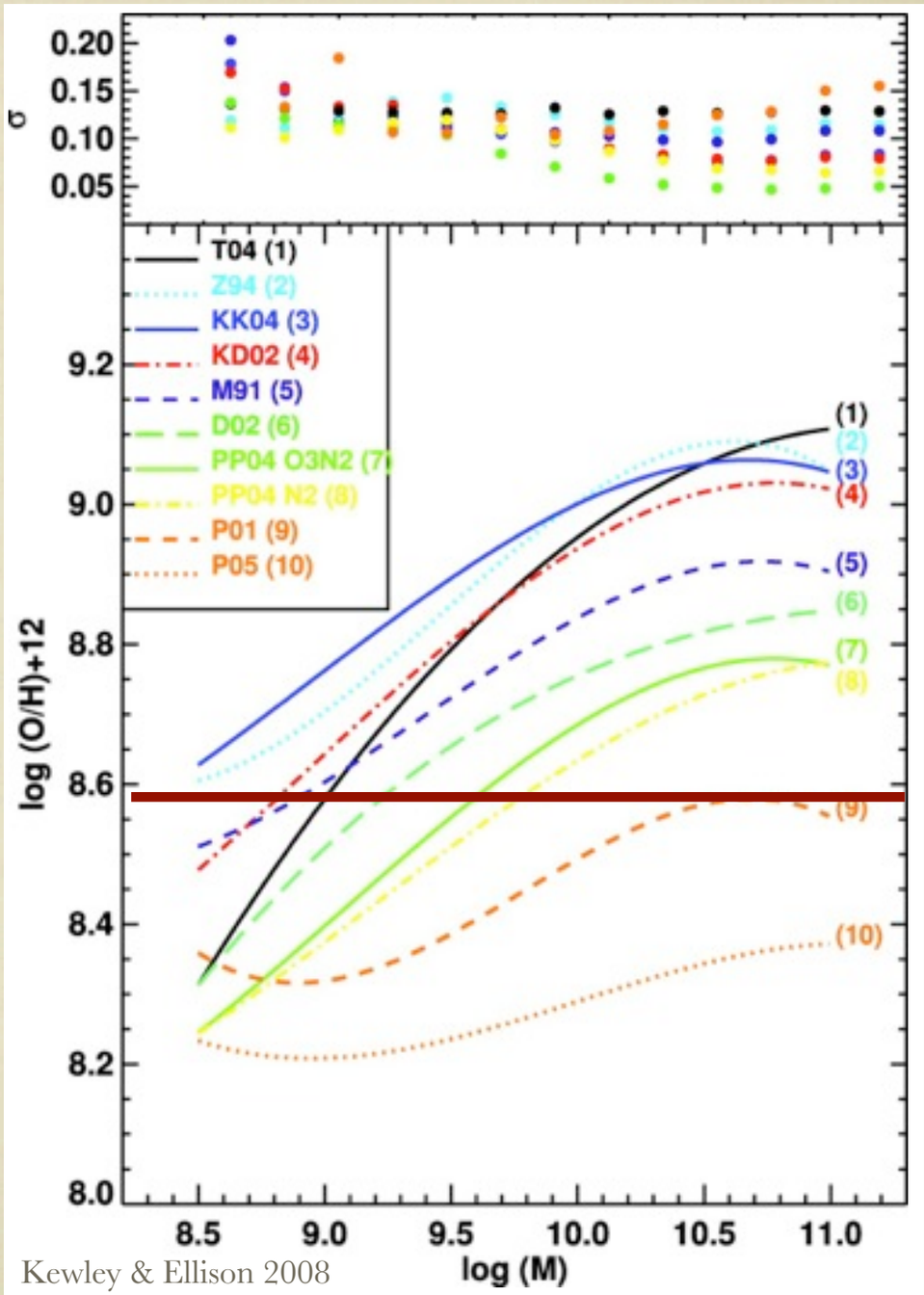
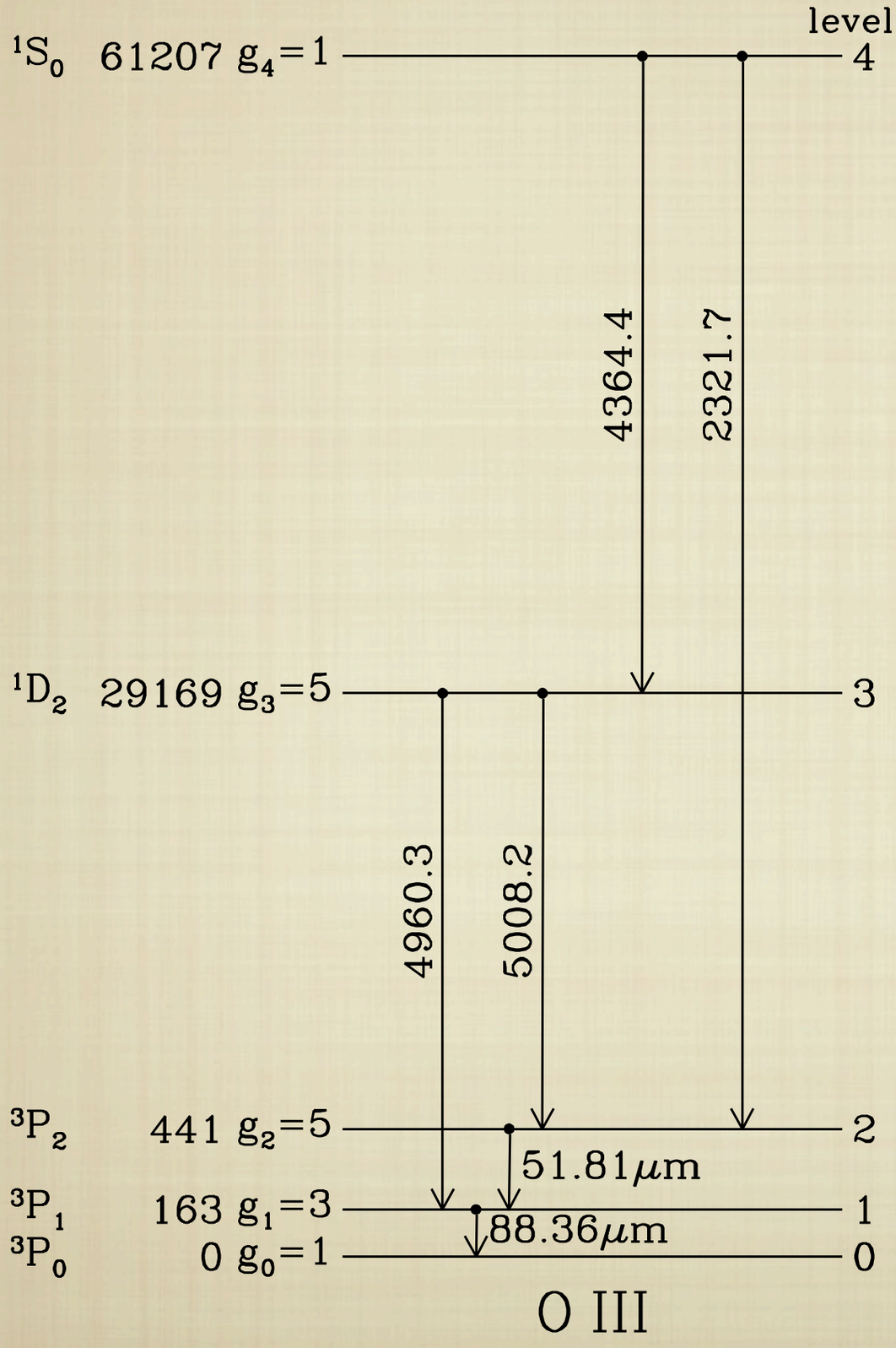
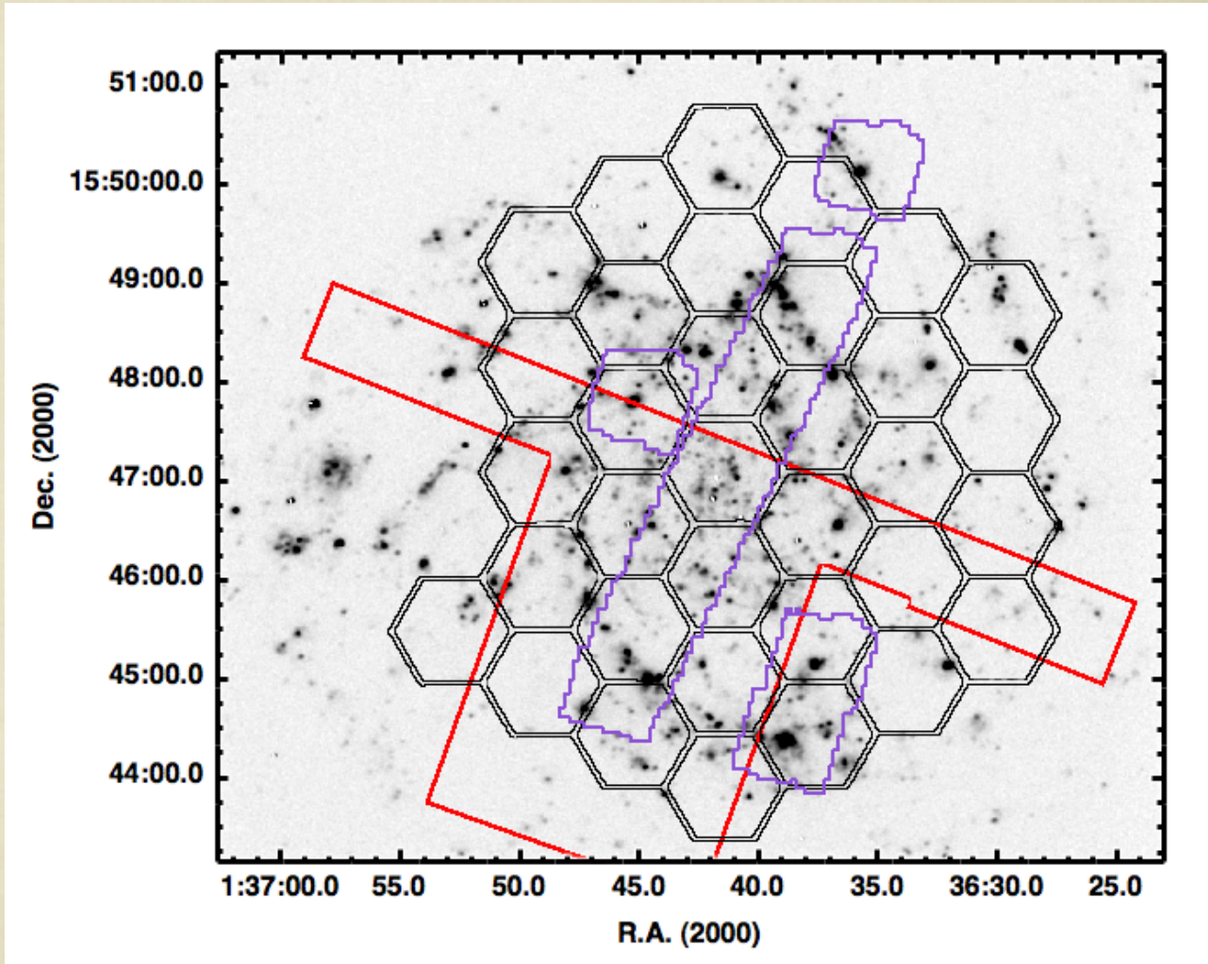


Kewley & Ellison 2008

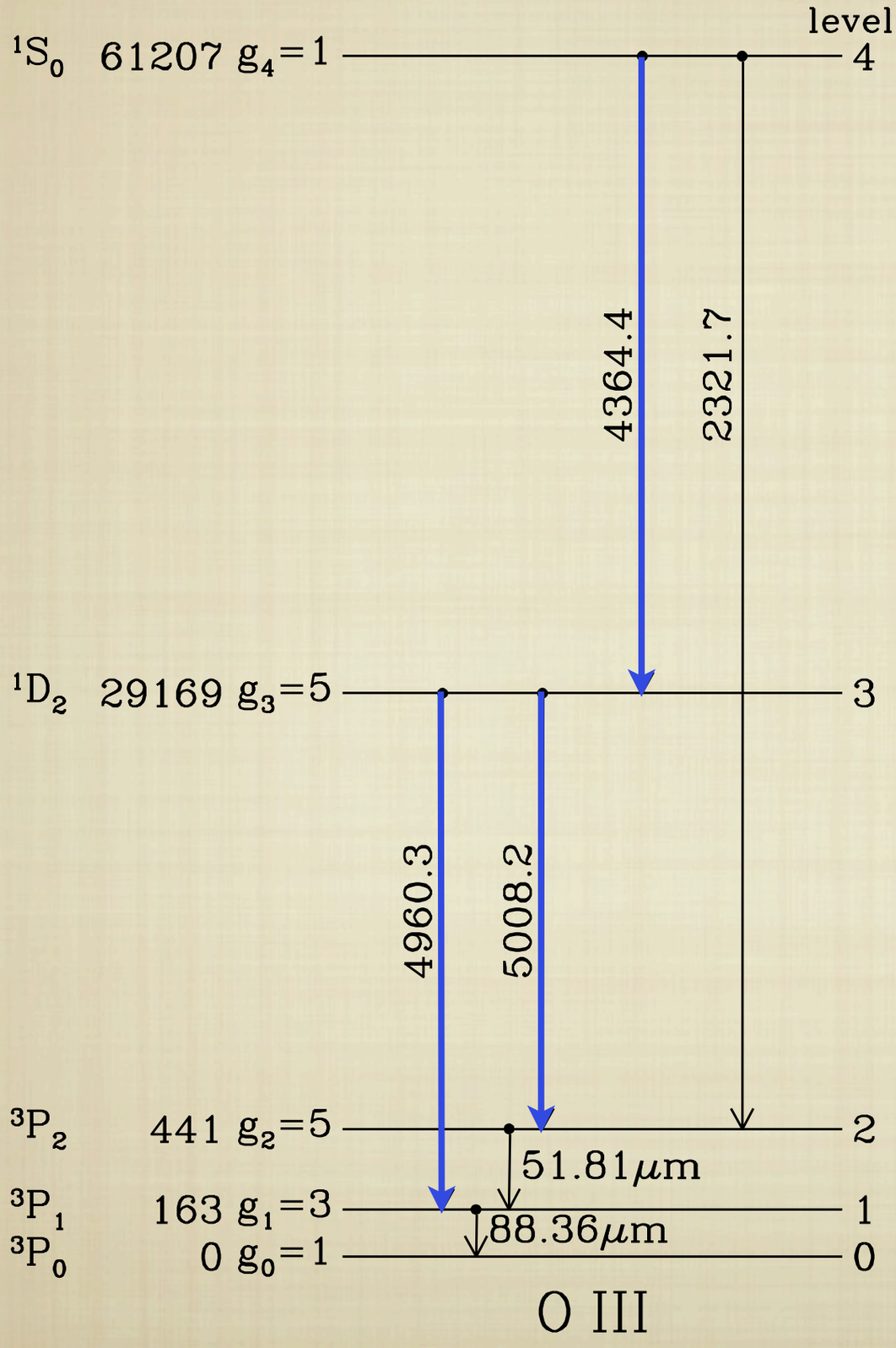
FIR TO THE RESCUE

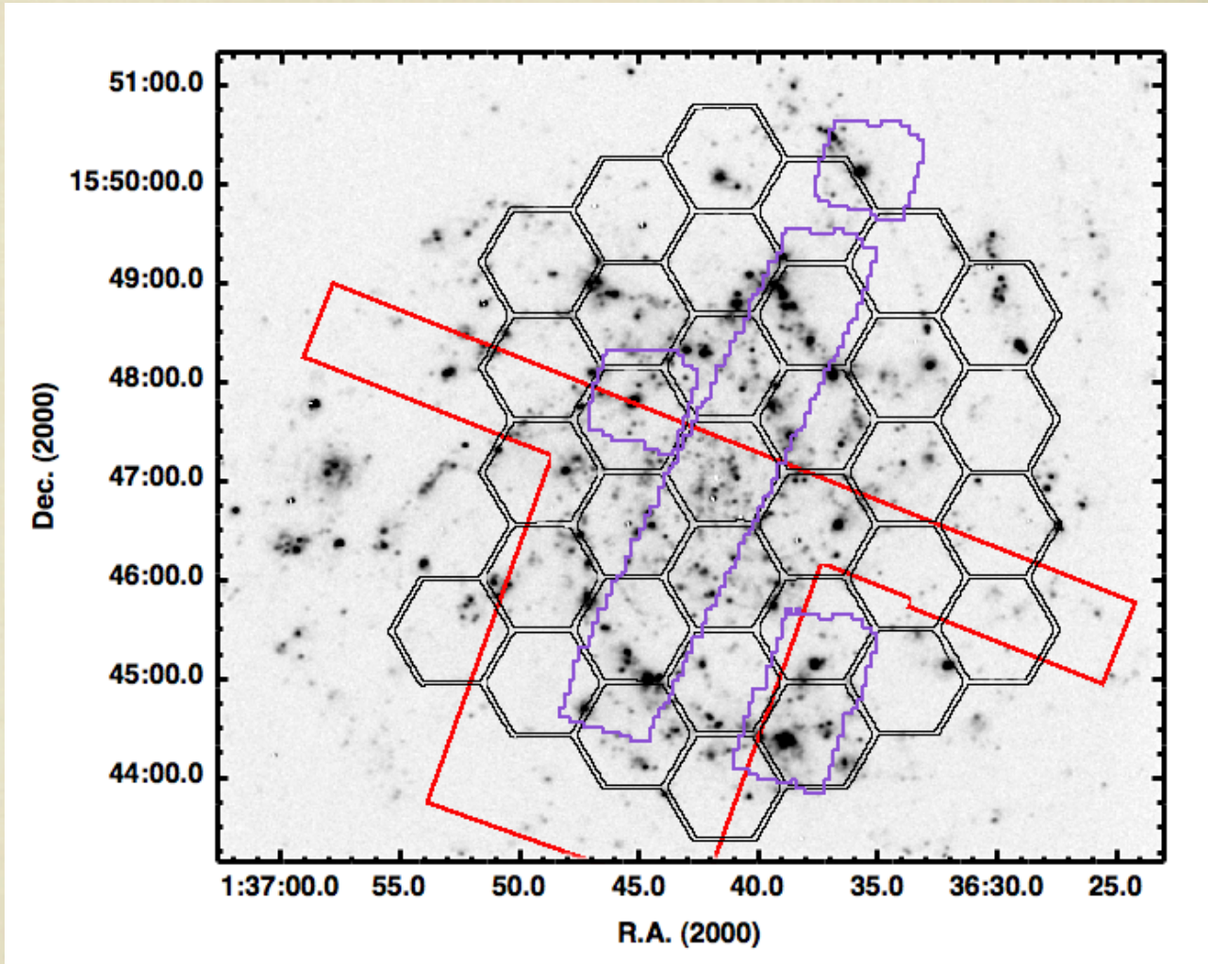


O III

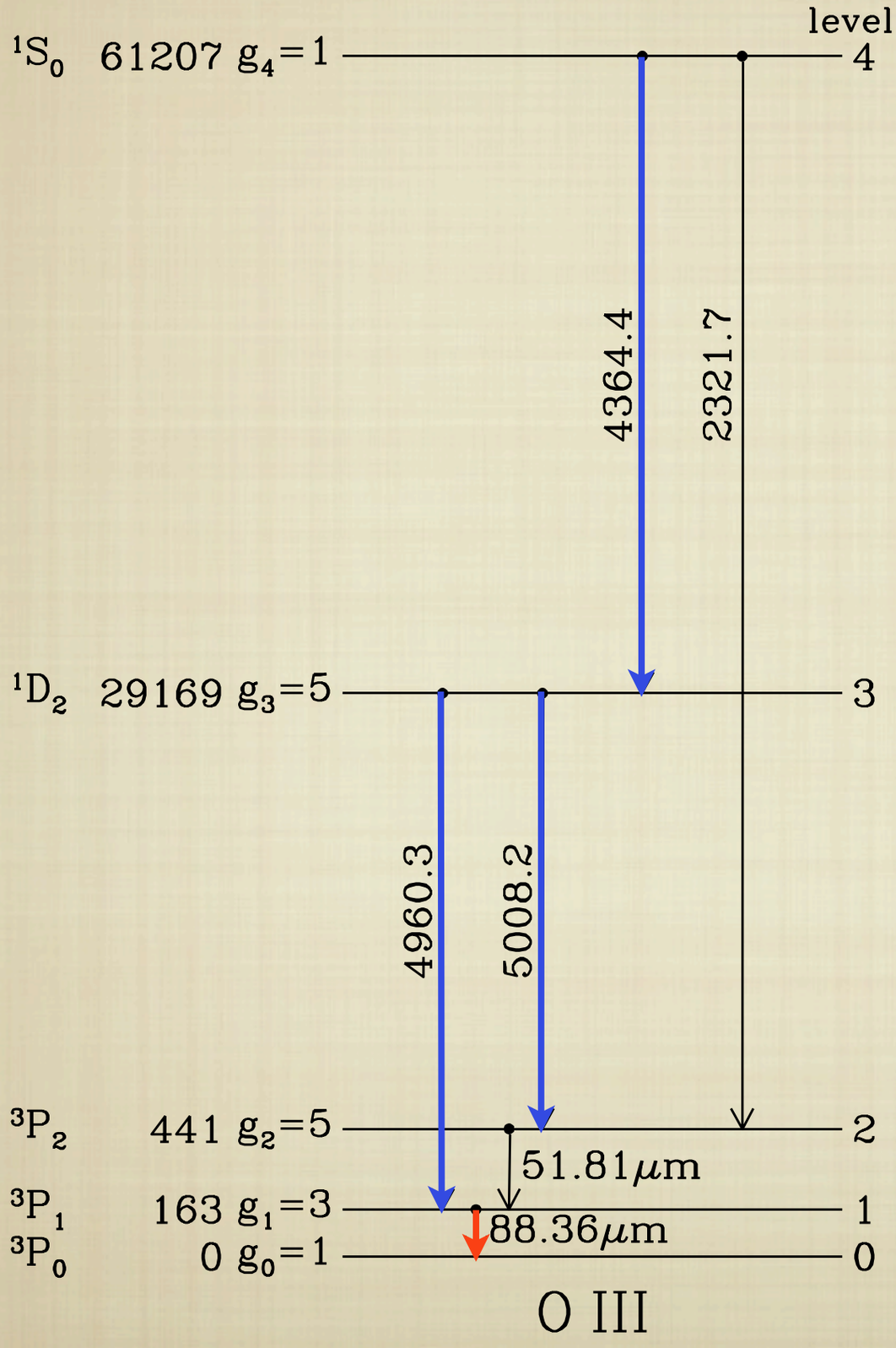


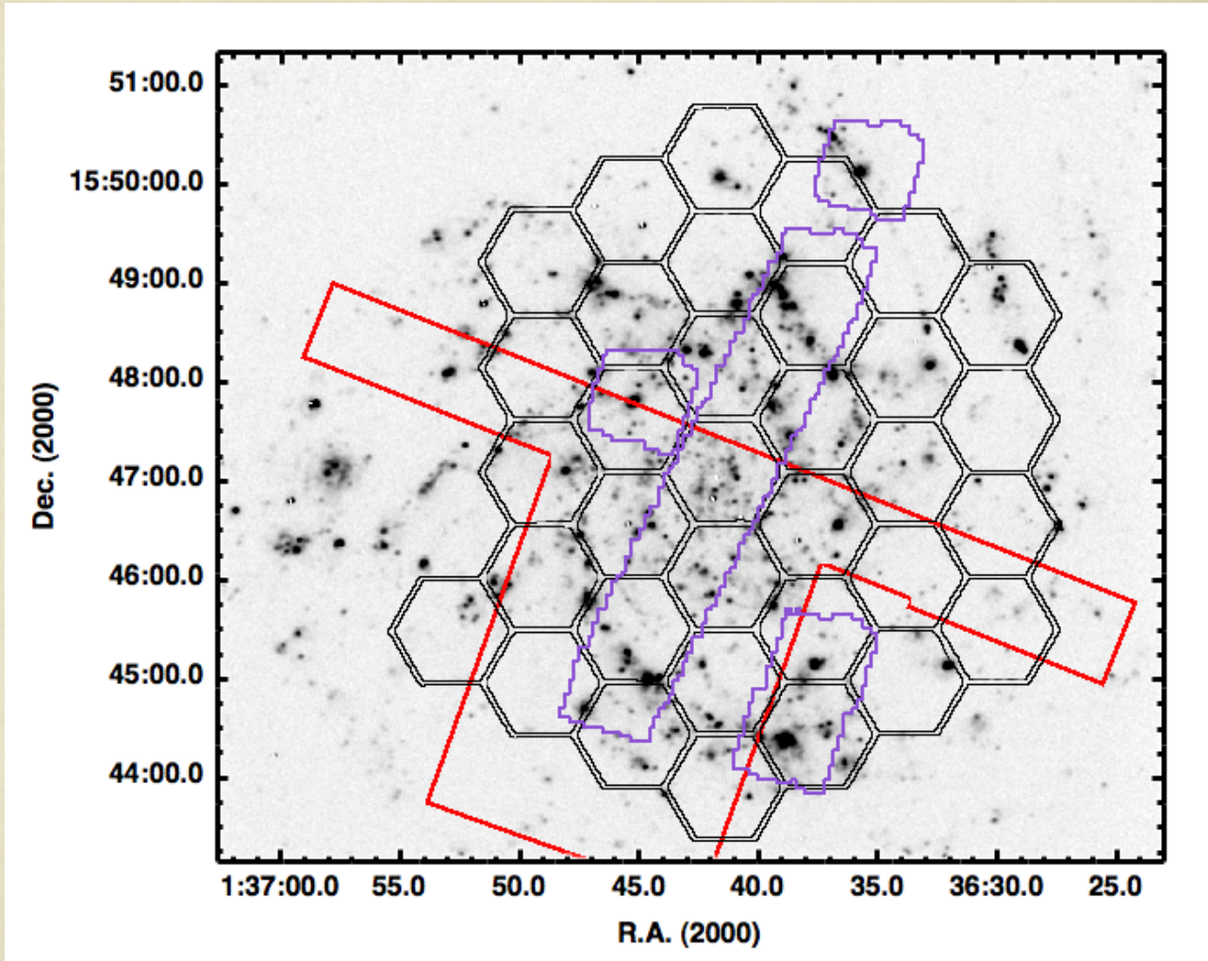
FIR TO THE RESCUE



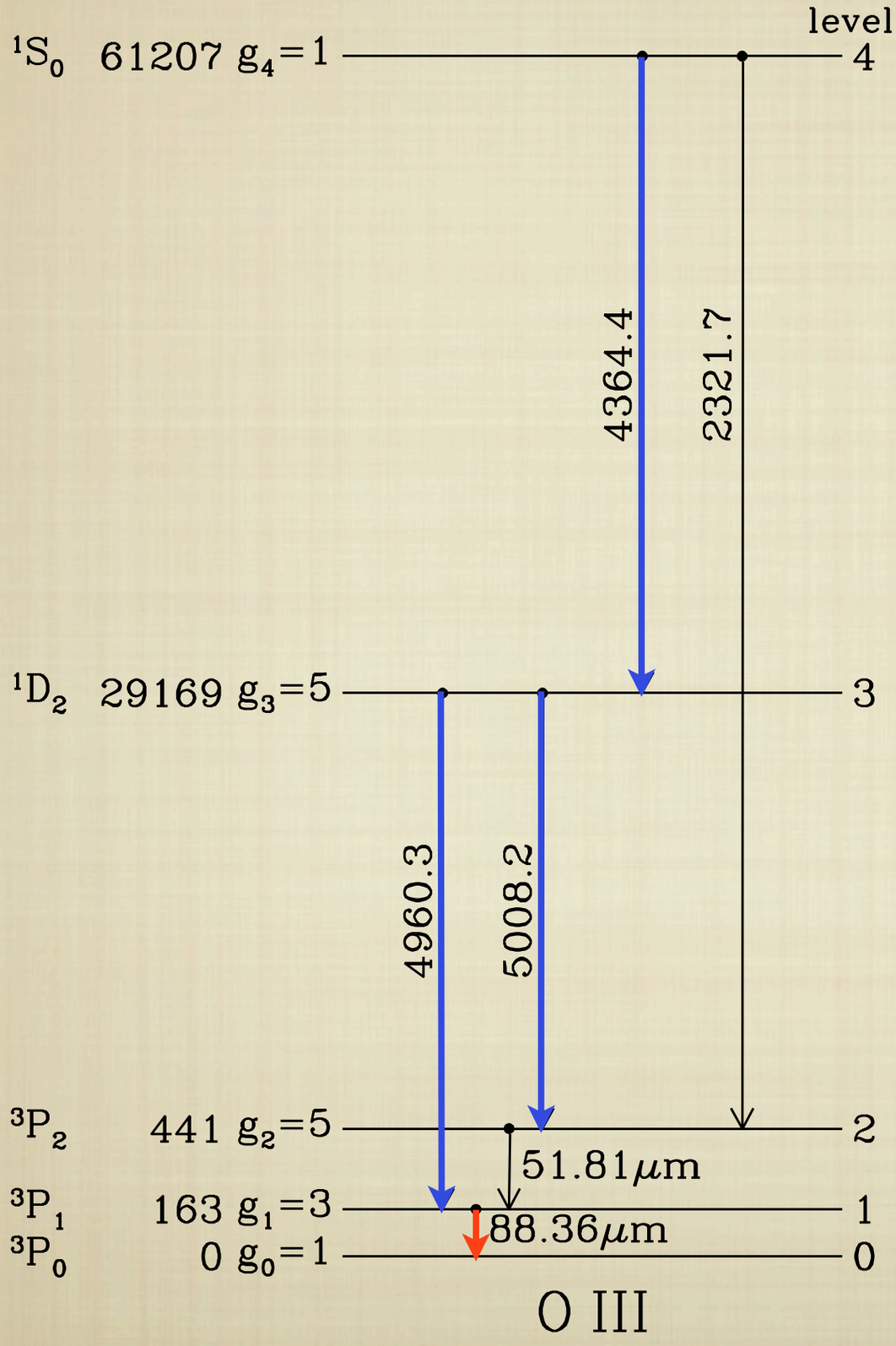


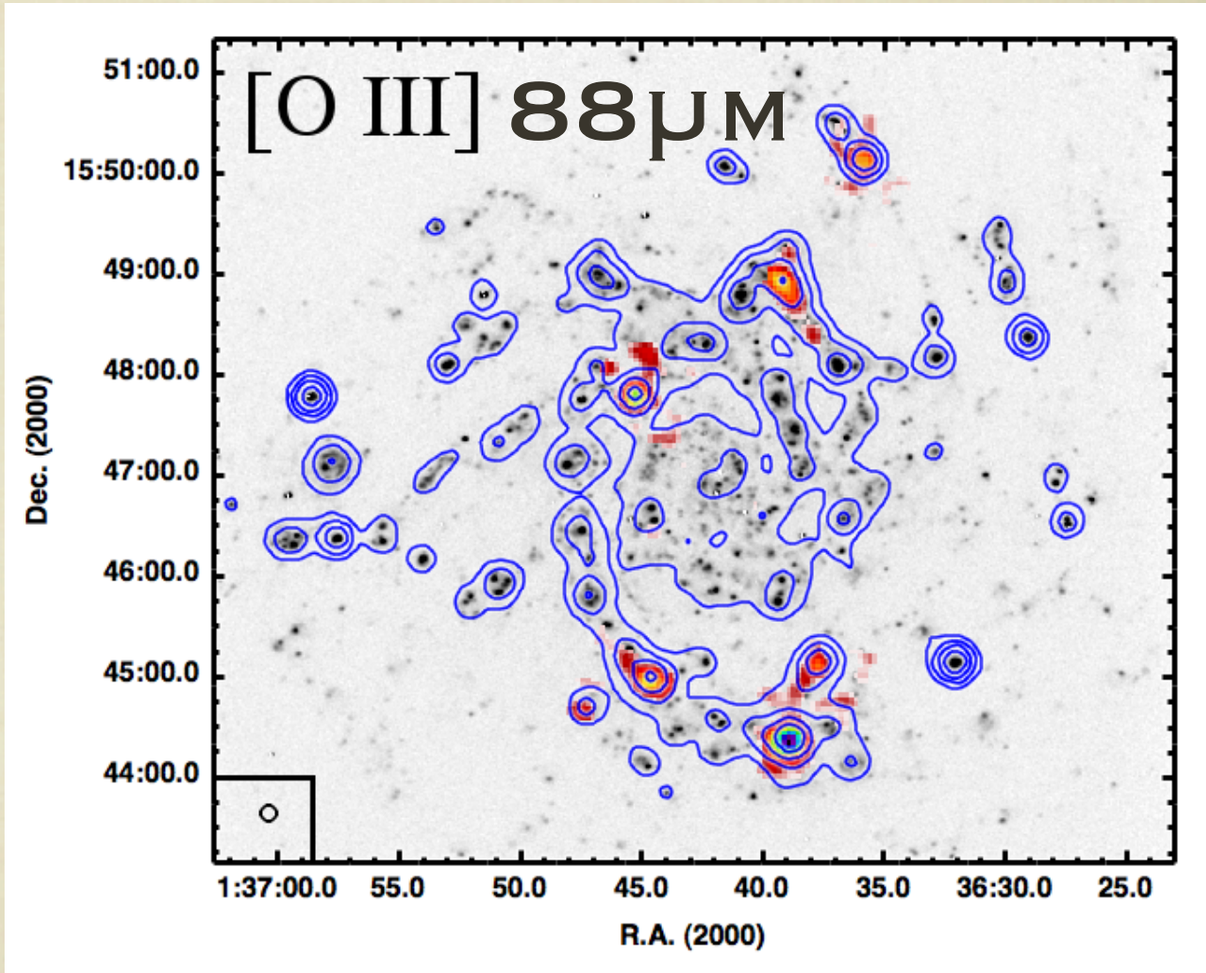
FIR TO THE RESCUE



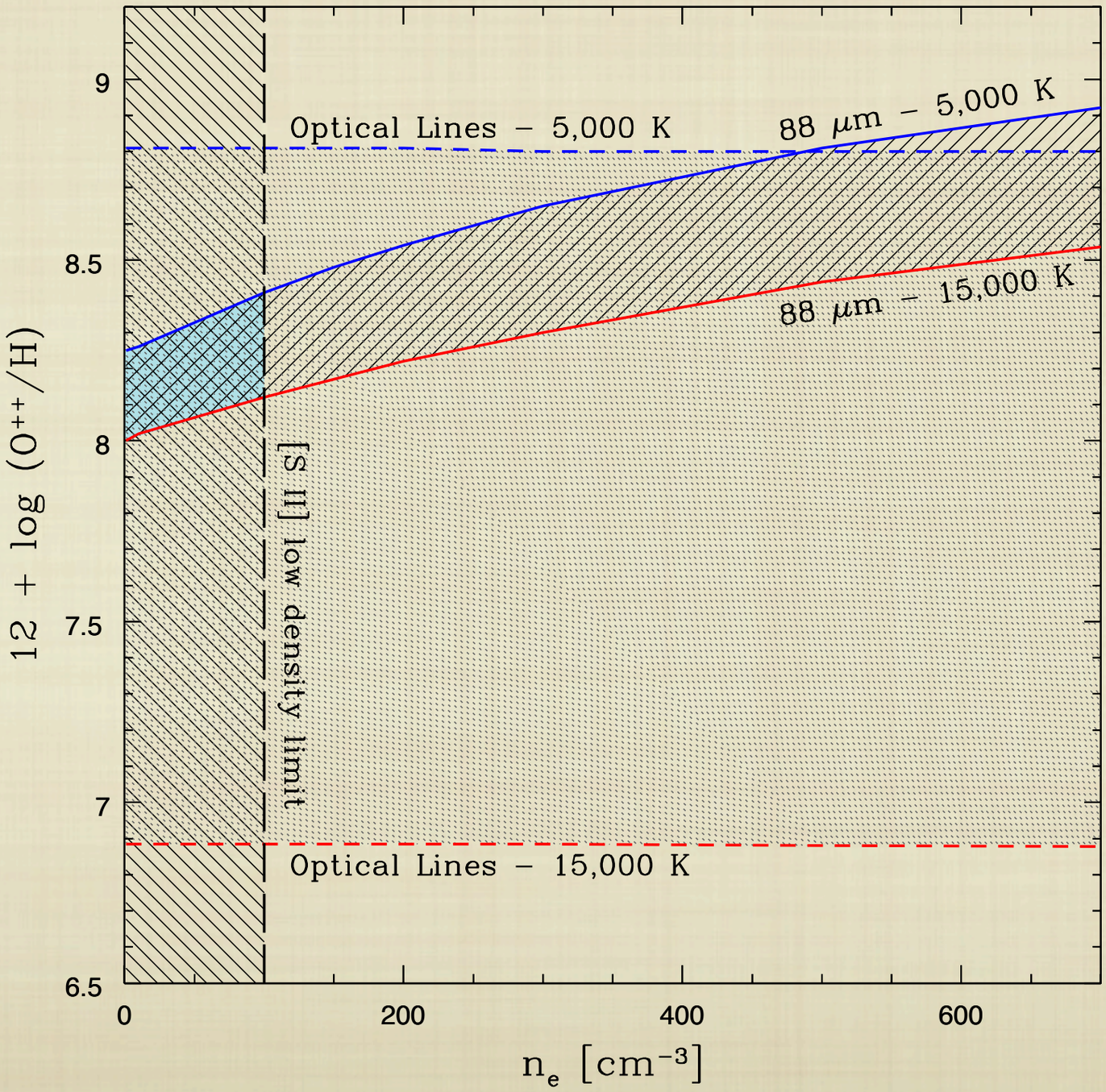


FIR TO THE RESCUE



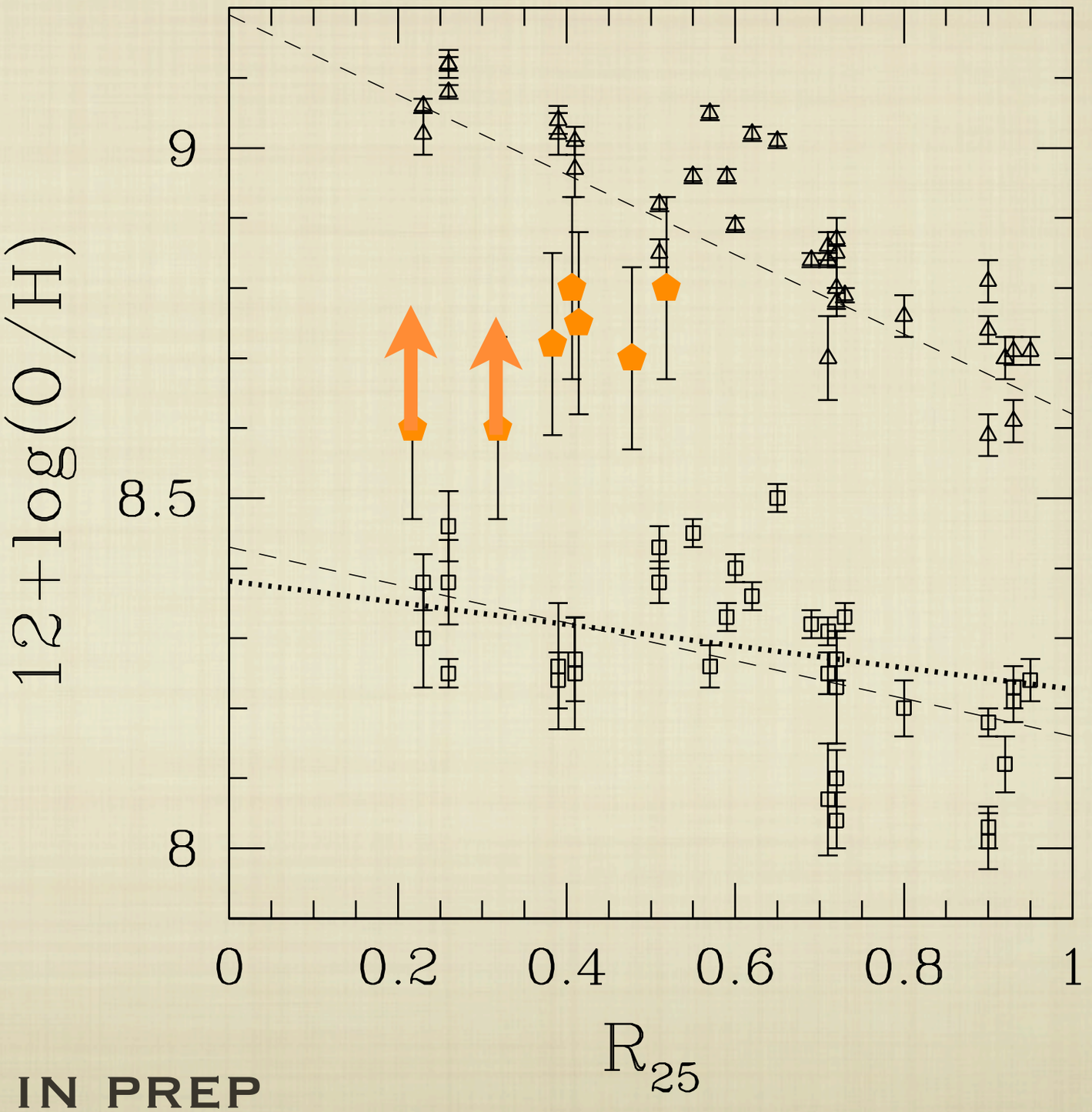


Temperature Matters



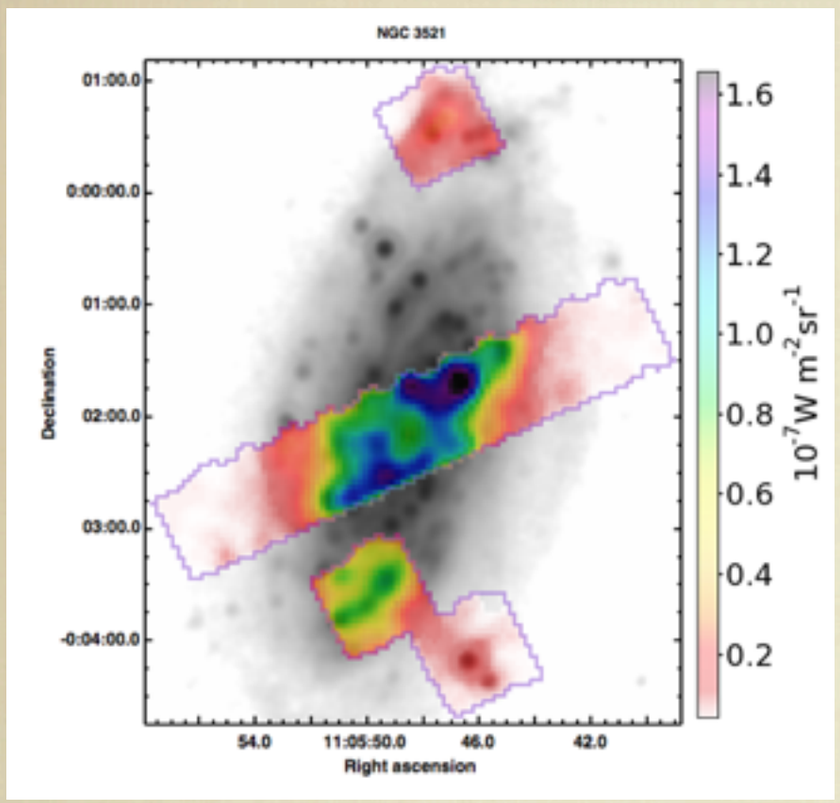
Splitting the Difference

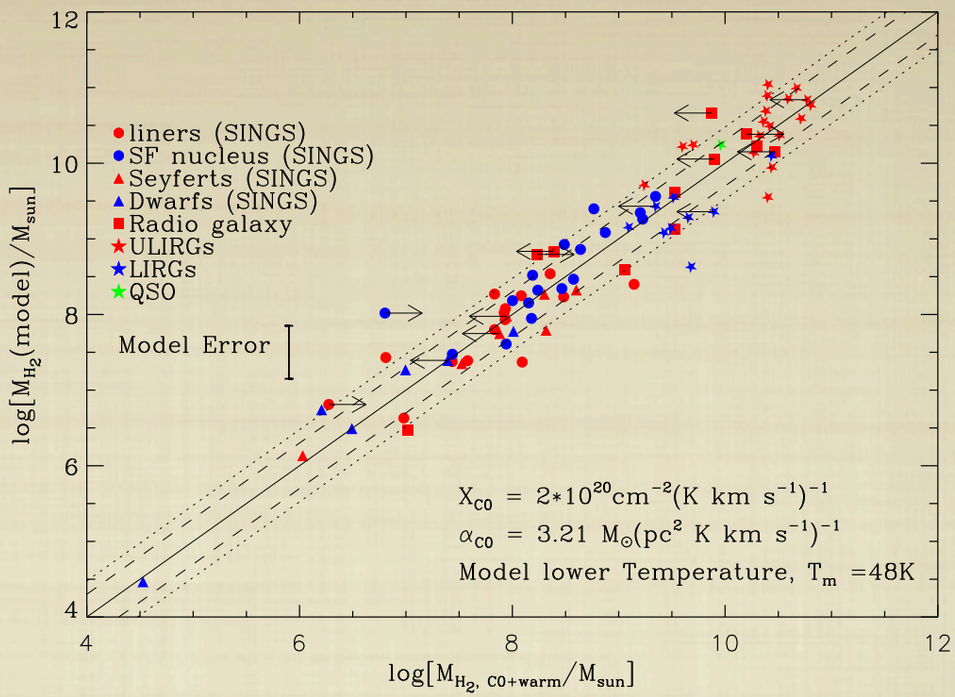
NGC628

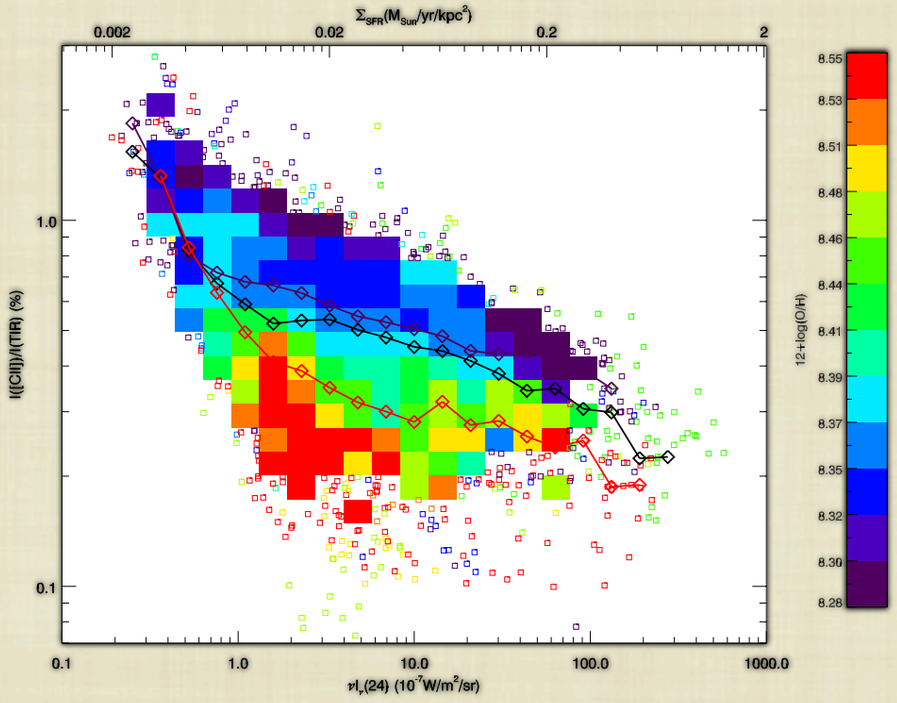


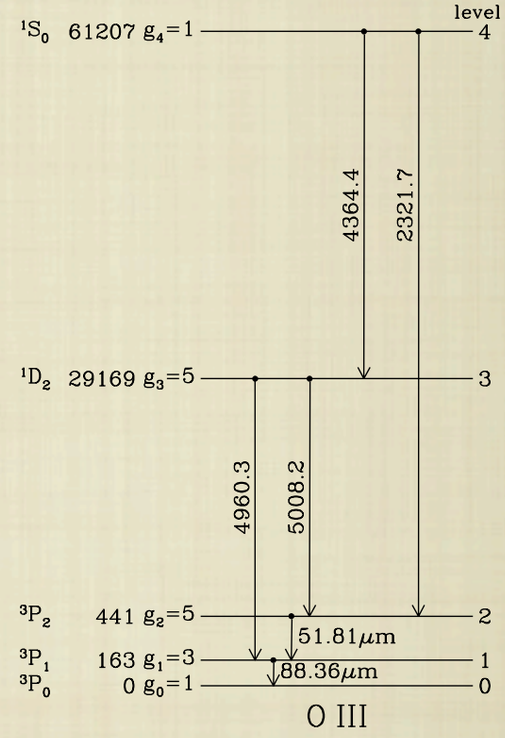
Croxall+, in prep

Take Away









KingFish Data Release:

√All imaging

Spectral Maps/Cubes: Fall, 2013

http://herschel.esac.esa.int/UserReducedData.shtml