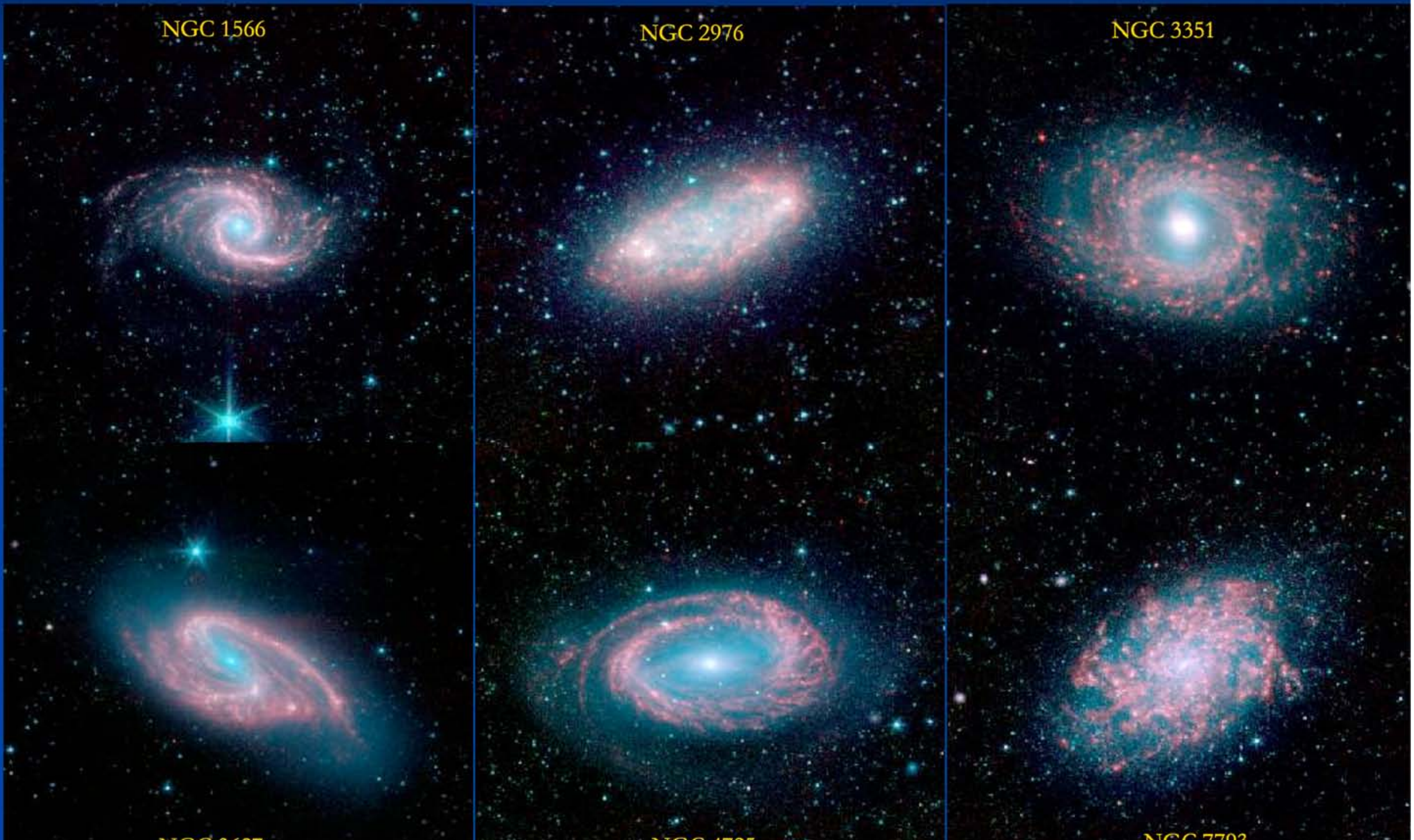
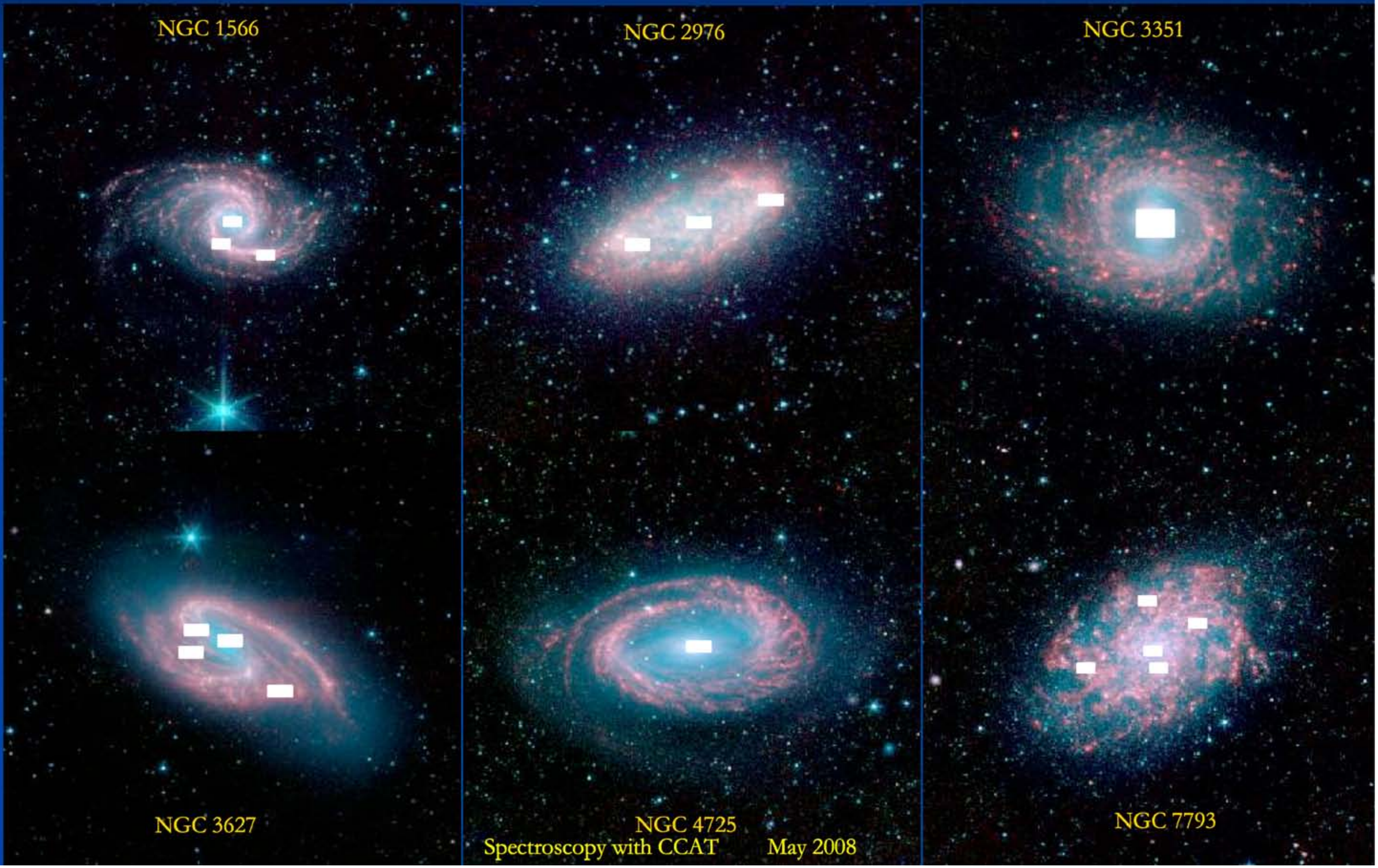
Infrared Spectroscopy in Nearby Galaxies

Daniel Dale (Wyoming) and the SINGS team



Infrared Spectroscopy in Nearby Galaxies

Daniel Dale (Wyoming) and the SINGS team



Outline

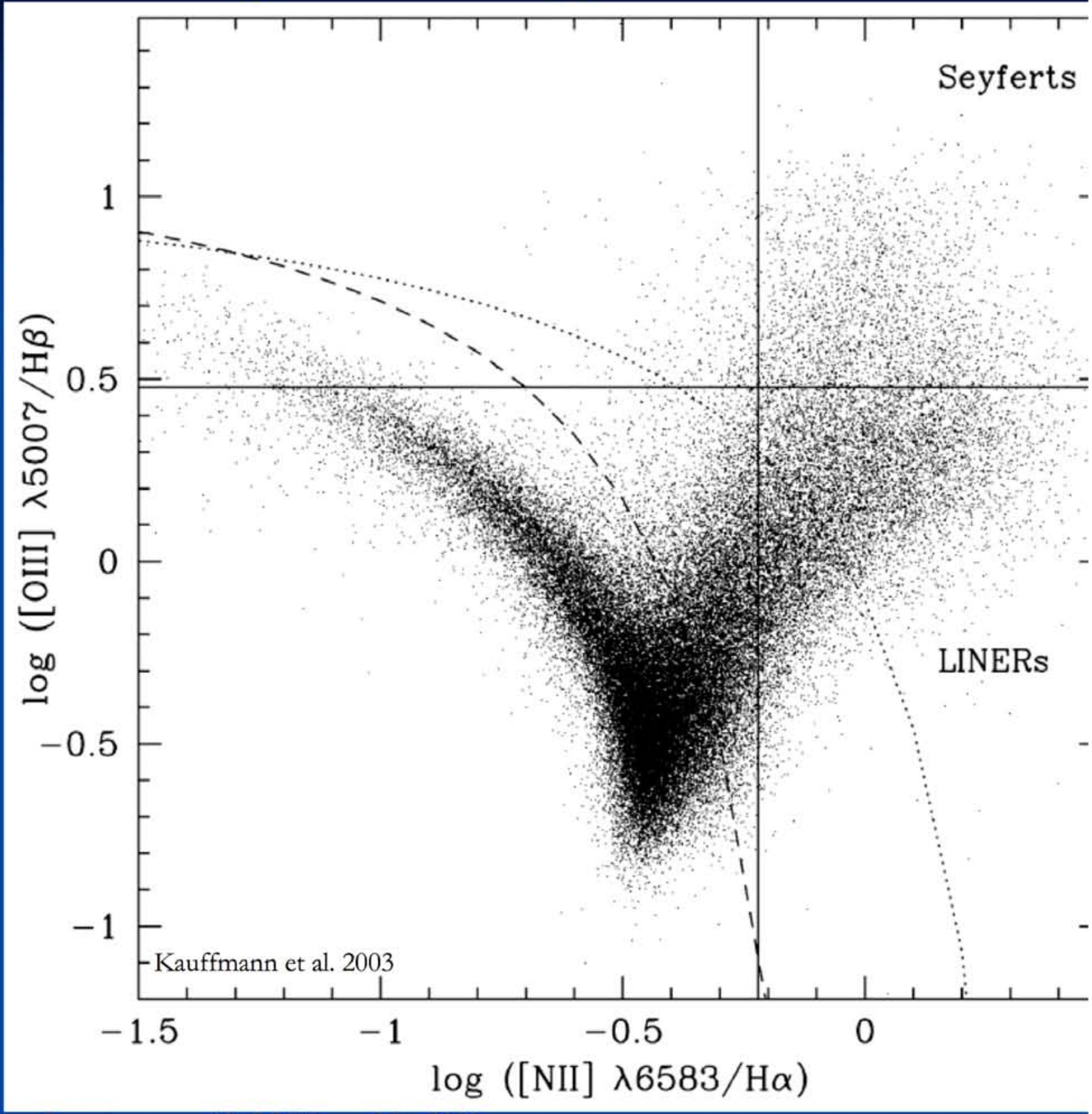
- Traditional optical diagnostics
- Characteristics of mid-infrared spectra
- *ISO* mid-infrared diagnostics
- *Spitzer* mid-infrared diagnostics from SINGS
- *ISO* far-infrared diagnostics
- Summary

Traditional Optical Diagnostics

Nuclear power sources traditionally categorized via optical line ratios

What is the effect of reddening in extremely dusty systems?

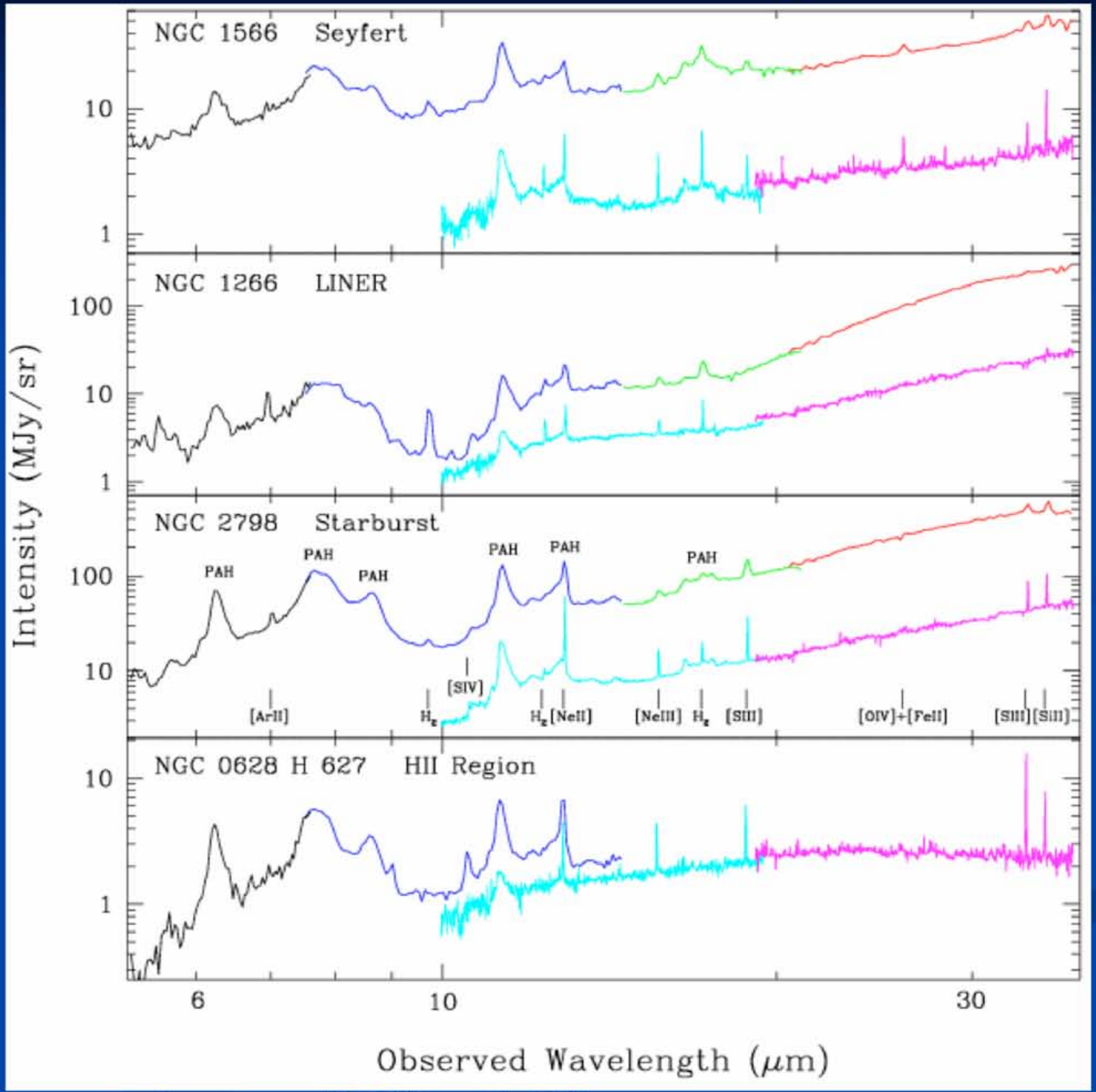
Baldwin, Phillips & Terlevich 1981
Veilleux & Osterbrock 1987
Ho, Filippenko & Sargent 1997
Kewley et al. 2001
Kauffmann et al. 2003



Representative Mid-Infrared Spectra

Many prominent nebular lines, PAH features, H_2, PDR tracers, …

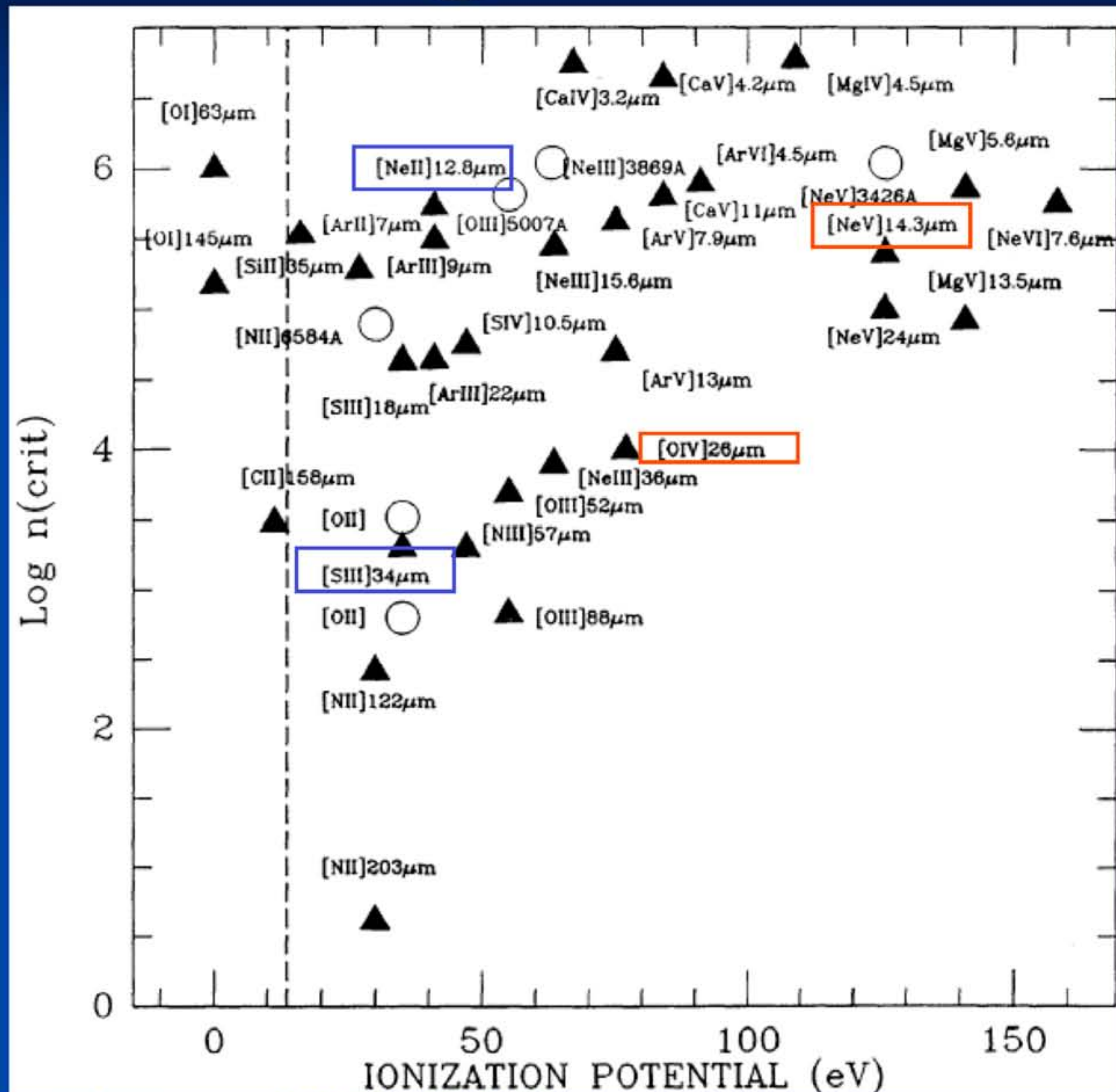
Strong variations in line-to-line and line-to-continuum with environment



Dale et al. 2006

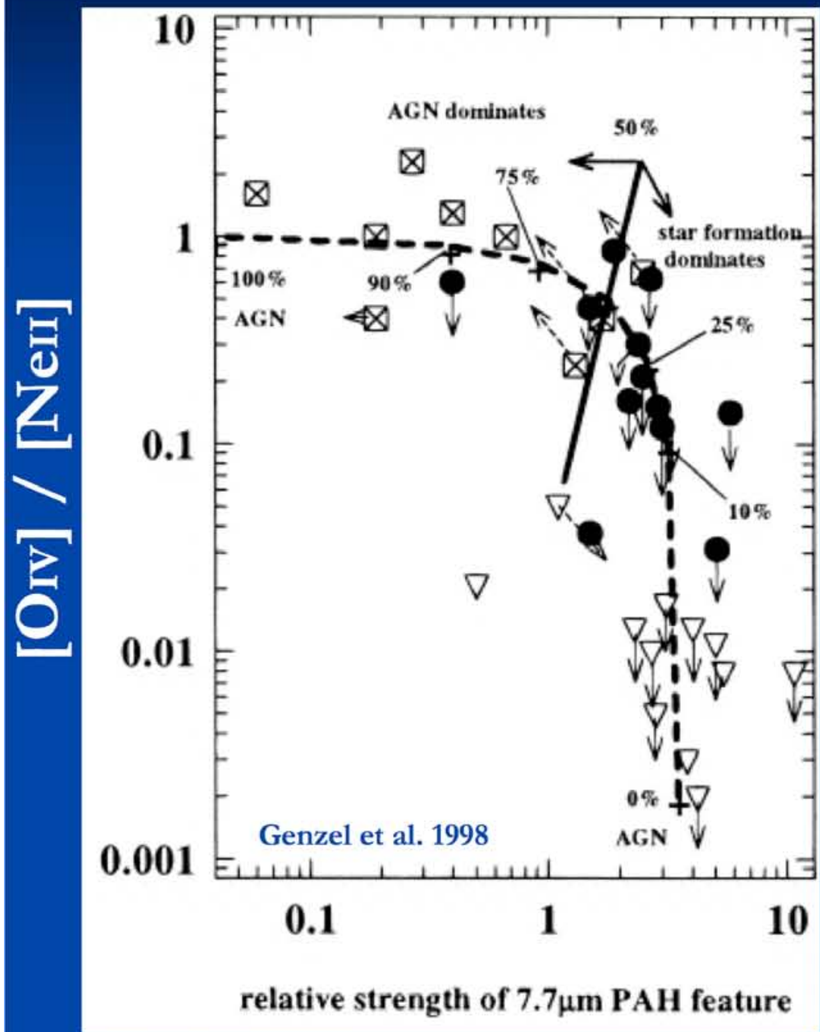
Infrared Diagnostics

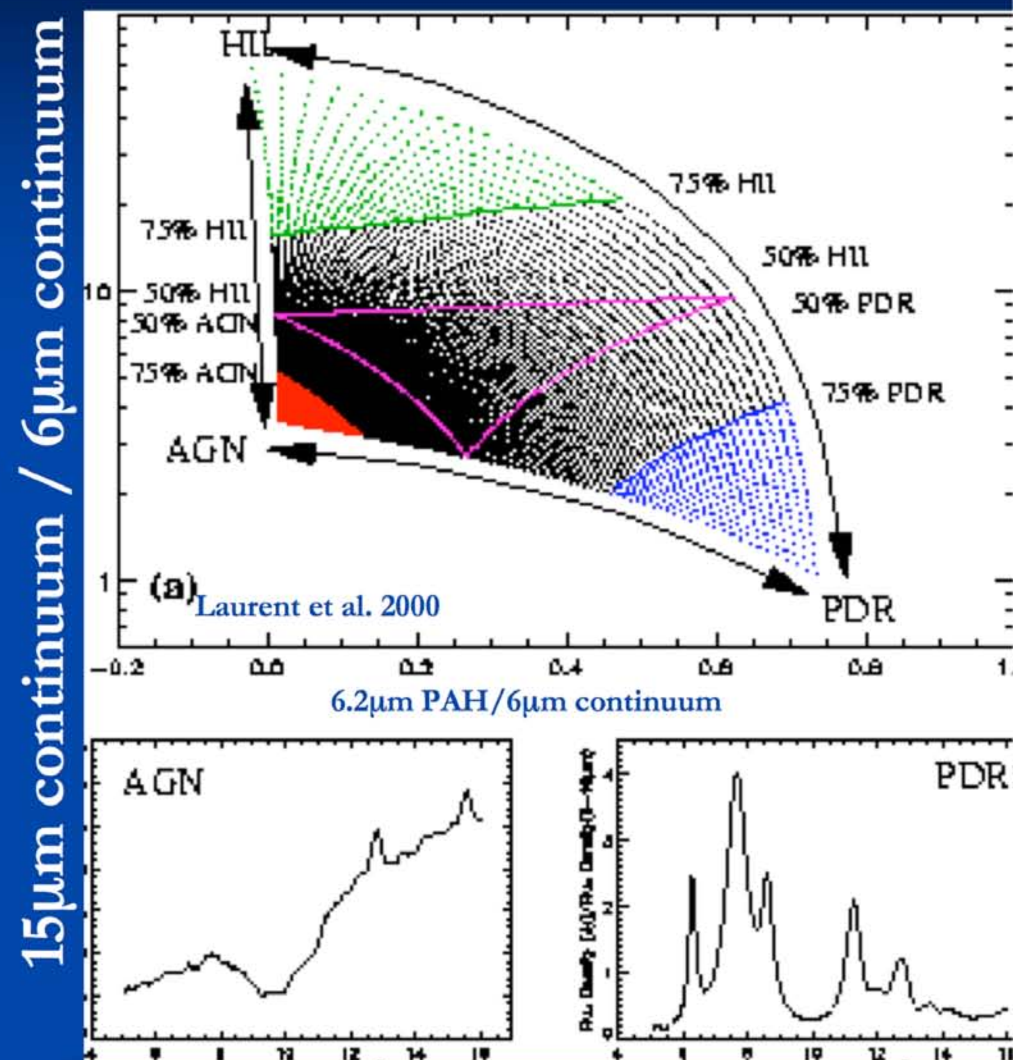
Ratios of lines with significantly different ionization potentials probe the radiation field



Spinoglio & Malkan 1992

ISO mid-infrared diagnostics





Genzel et al. 1998
Laurent et al. 2000
Sturm et al. 2002
Peeters et al. 2004

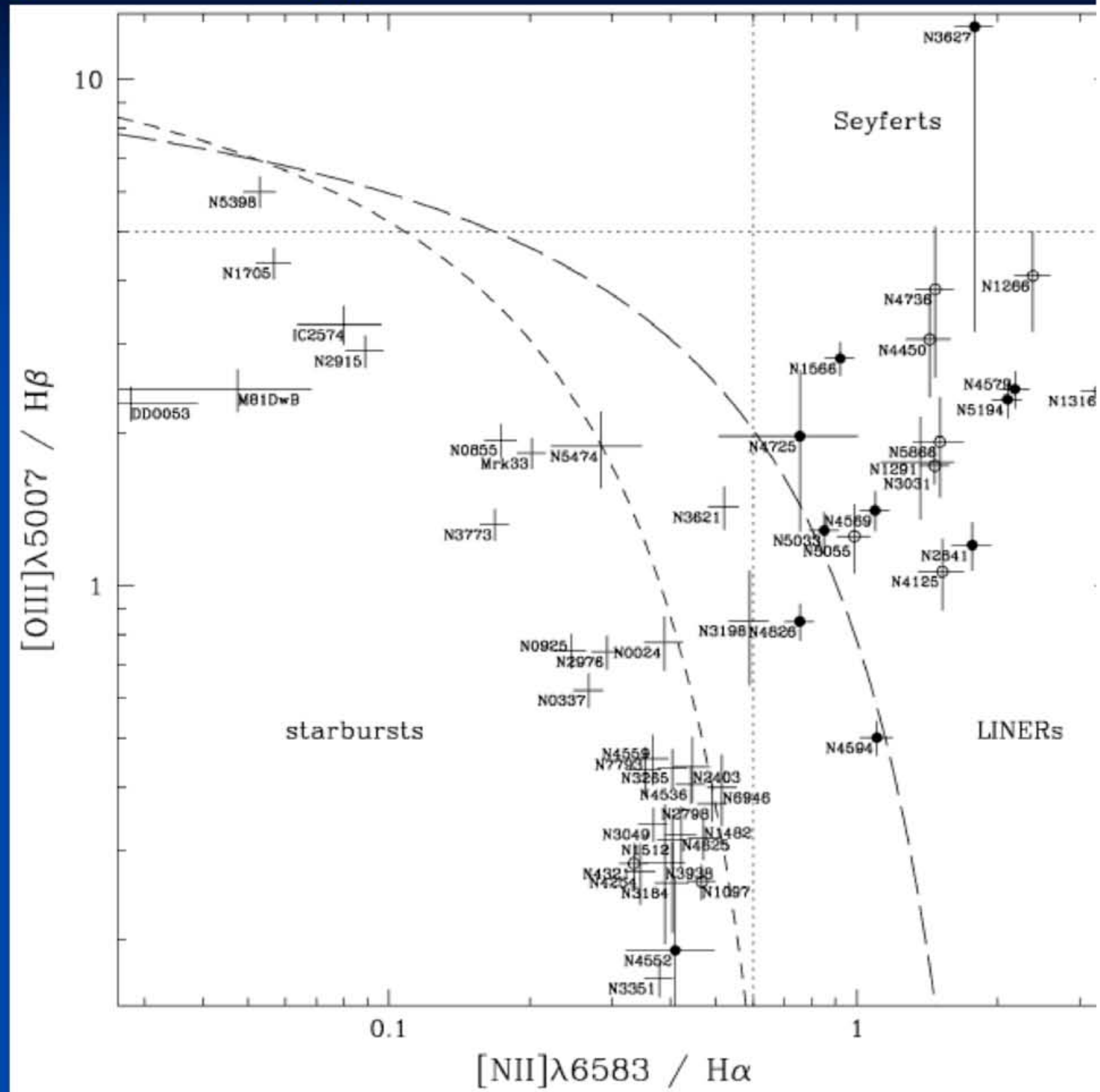
SINGS – Spitzer Infrared Nearby Galaxies Survey

- Imaging and spectroscopic survey of 75 nearby galaxies
- Spans broad range of physical and star formation properties
- Copious ancillary data: UV, BVRI, Hα, Pα, JHK, submm, CO, HI, radio continuum
- SFRs, dust, PAH formation, metals, …

Optical Diagnostics

The SINGS sample contains:

- **a variety of nuclear power sources** ($10^7 < L_{TIR} < 10^{11}$ L_o)
- **a large collection of optically- and IR-selected extra-nuclear regions**
- **Mostly systems with moderate extinctions** (A_V~1 mag)



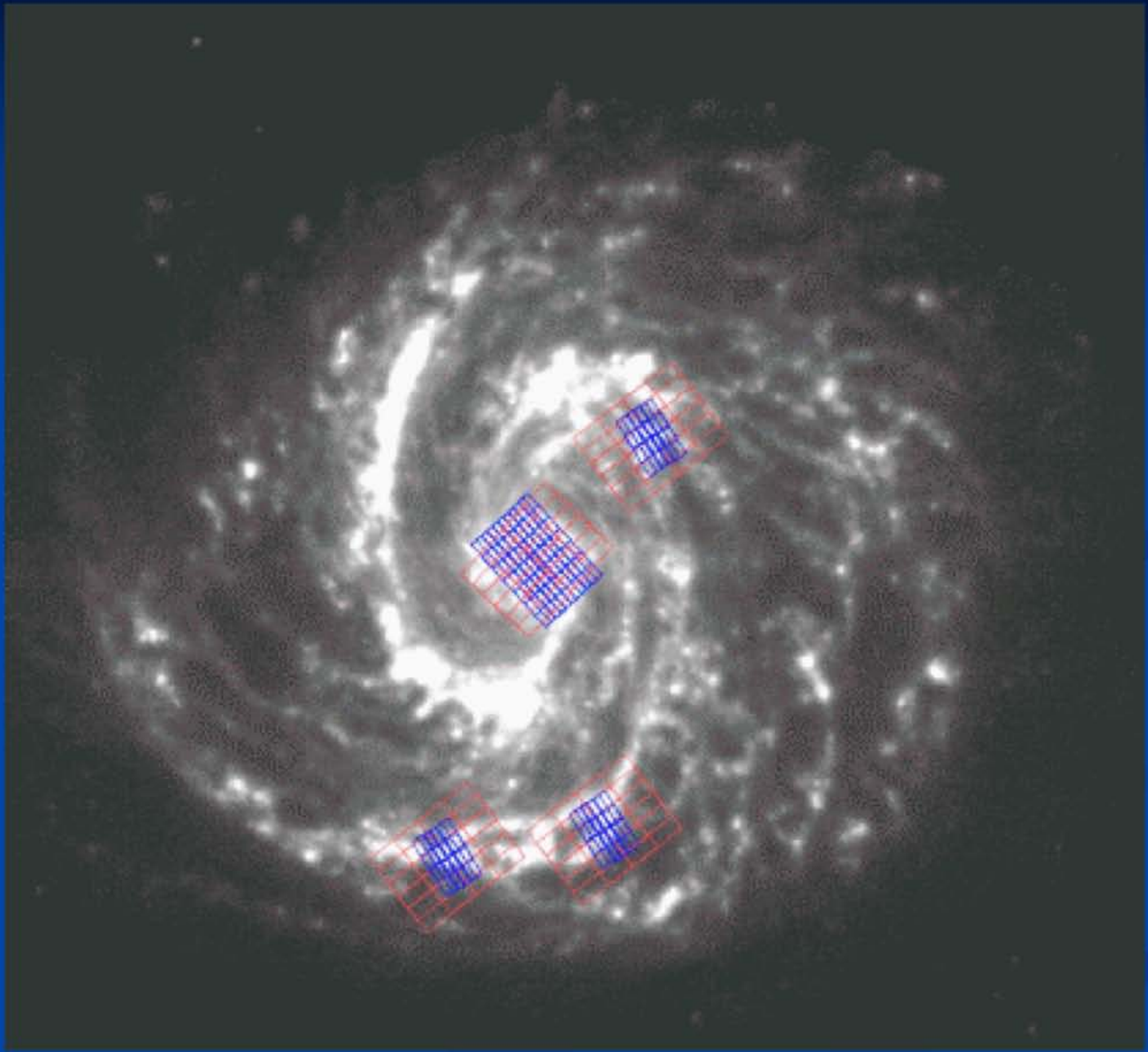
Dale et al. 2006

SINGS (High Resolution) Spectral Maps

HighRes
***R*~600**
10-37μm

67 nuclei
88 extra-nuclear

0.1-3 kpc



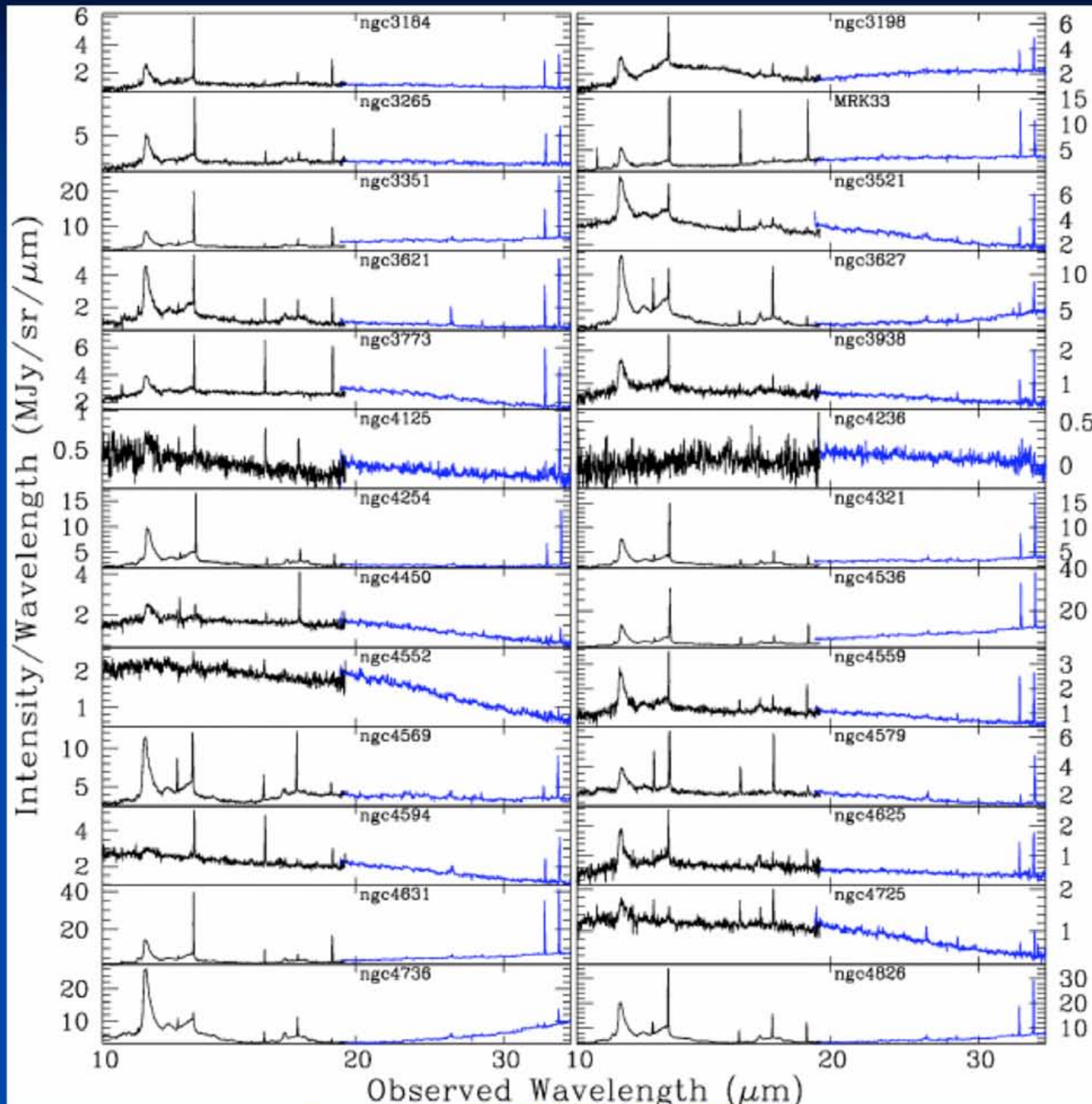
NGC 4321

Dale et al. 2008

Example SINGS High Resolution Spectra

HighRes
R~600
10-37μm

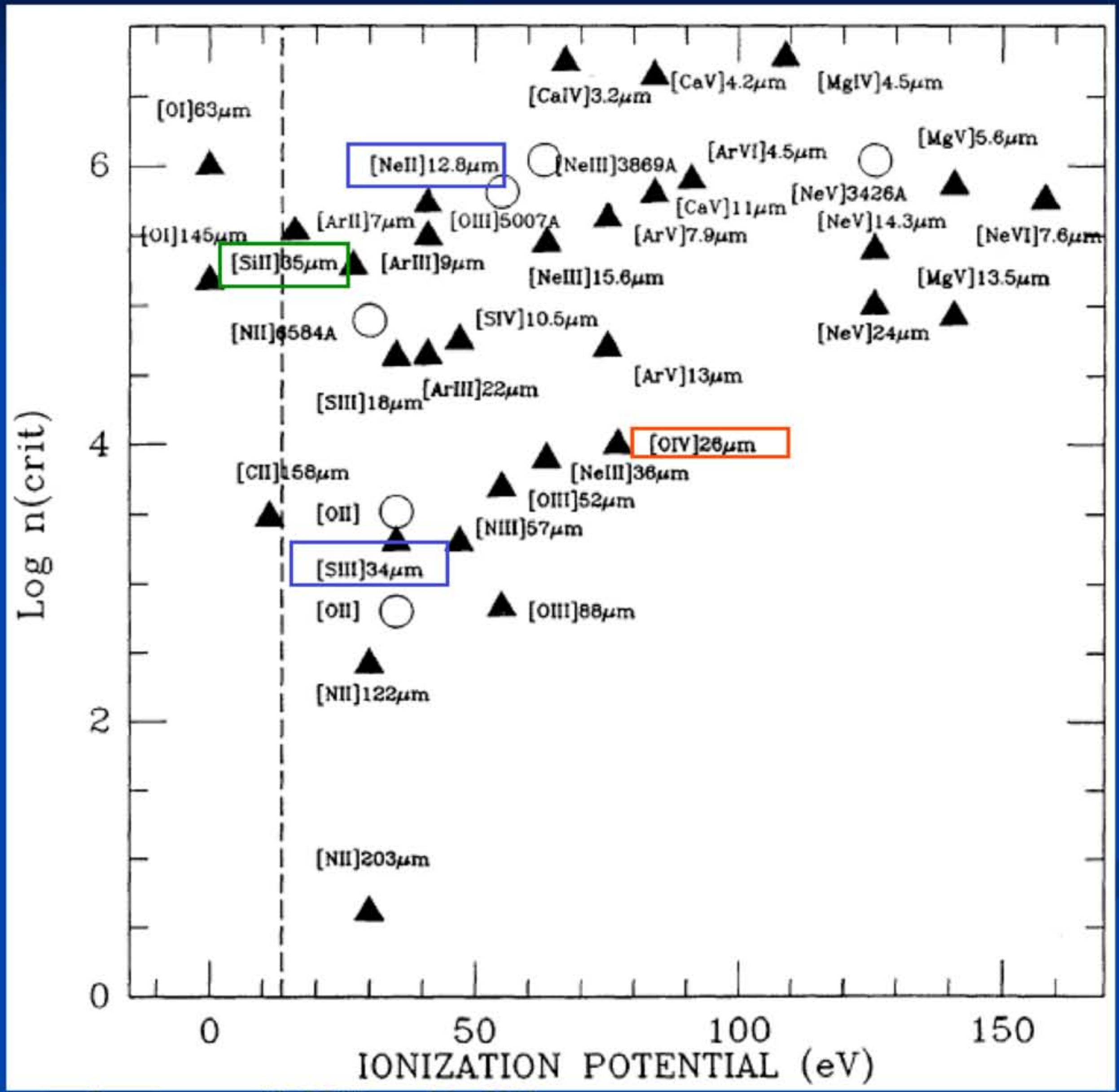
67 nuclei
88 extra-nuclear



Dale et al. 2008

Infrared Diagnostics

Ratios of lines with significantly different ionization potentials probe the radiation field



Spinoglio & Malkan 1992

Spitzer mid-infrared diagnostics

High-to-medium excitation

- **AGN: weak PAH and strong high excitation line emission**
- ***ISO* diagnostics solidified and extended to lower-luminosity nuclei and HII regions.**

Low-to-medium excitation

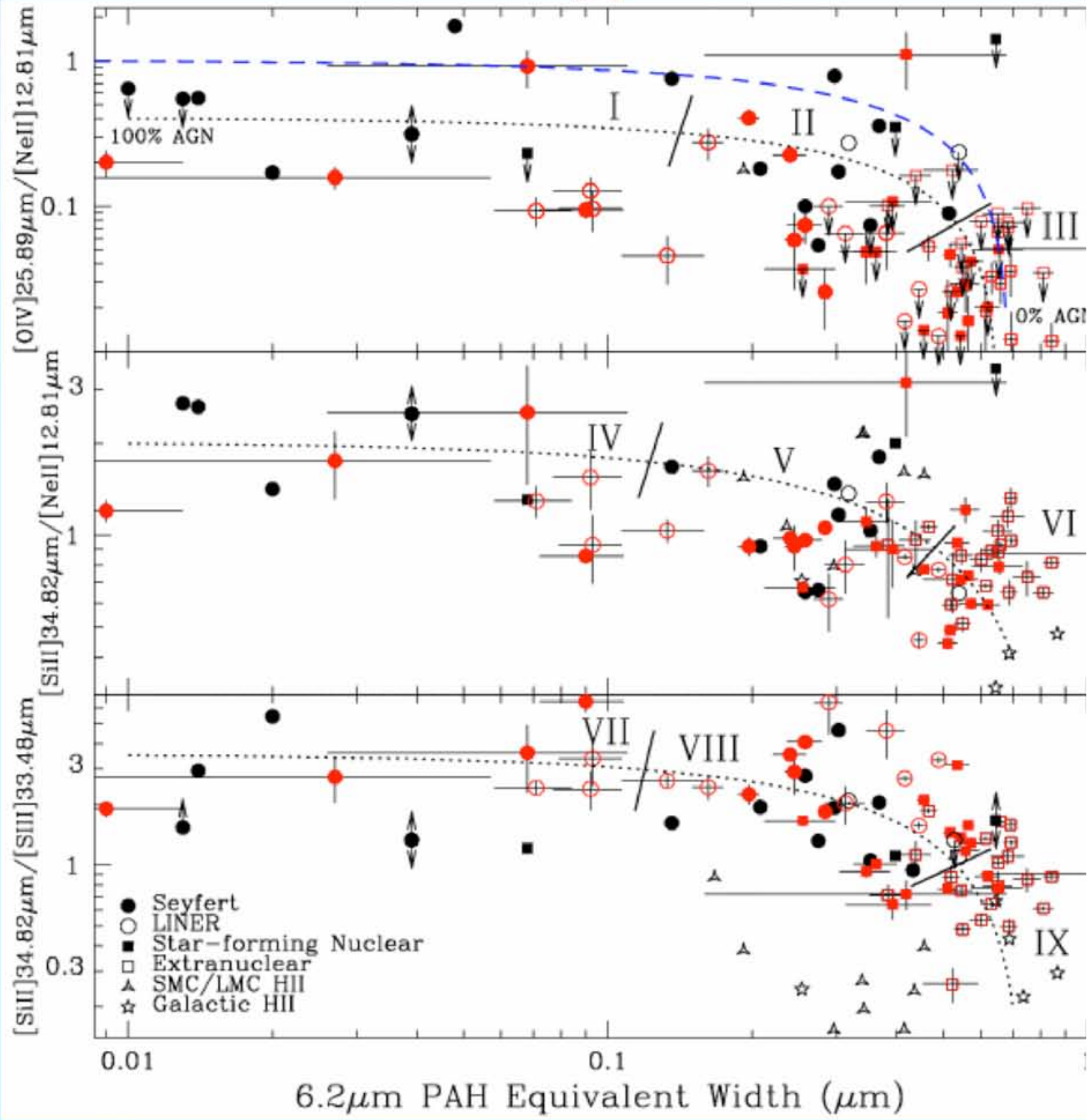
- **AGN: weak PAH and strong low excitation line emission**
- **[SiII] strong coolant in dense and/or X-ray dominated regions**

Demographics

Regions with >90% AGN

Regions with >90% SF

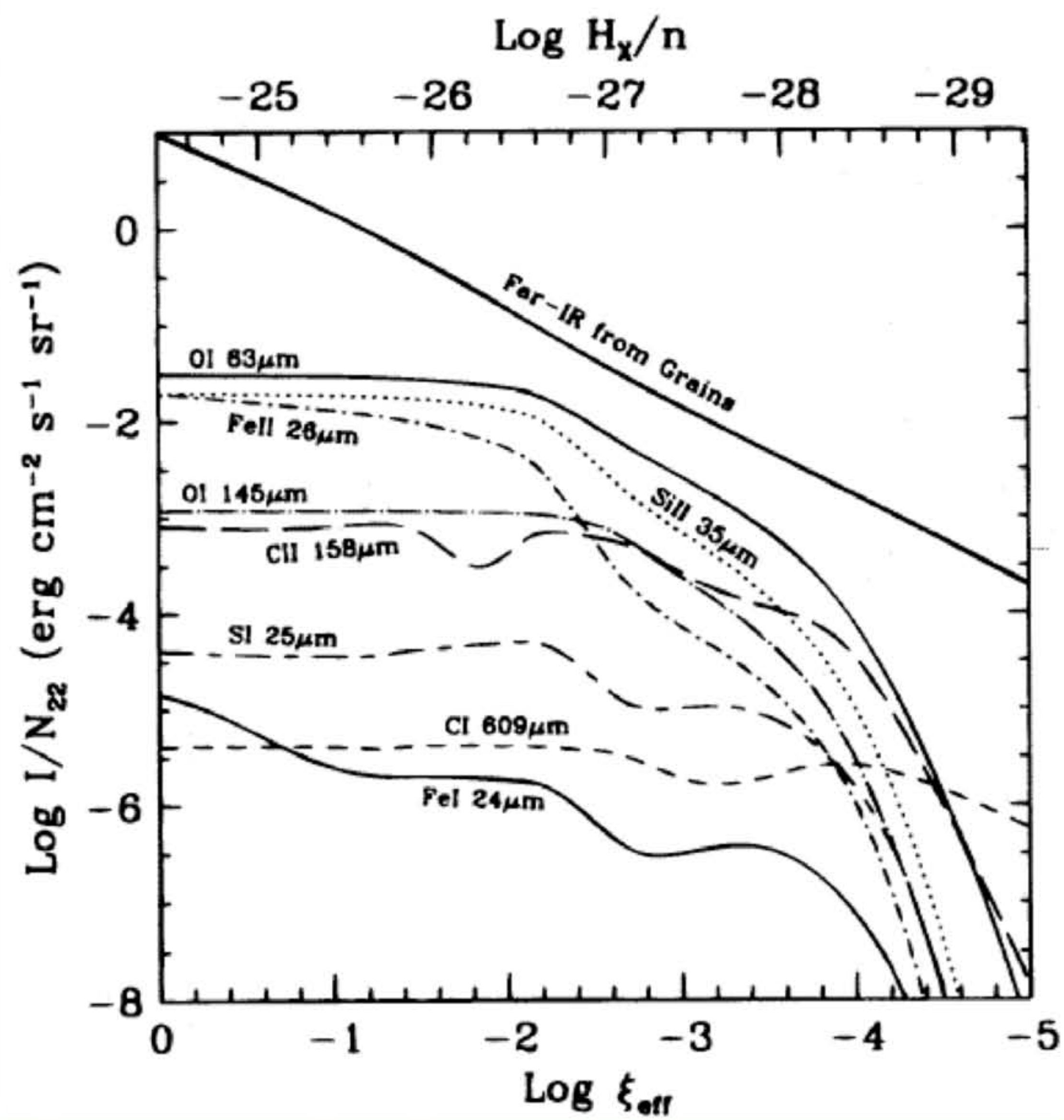
[SiII], [SIII], [NeII] bright!



Dale et al. 2006

Infrared Diagnostics

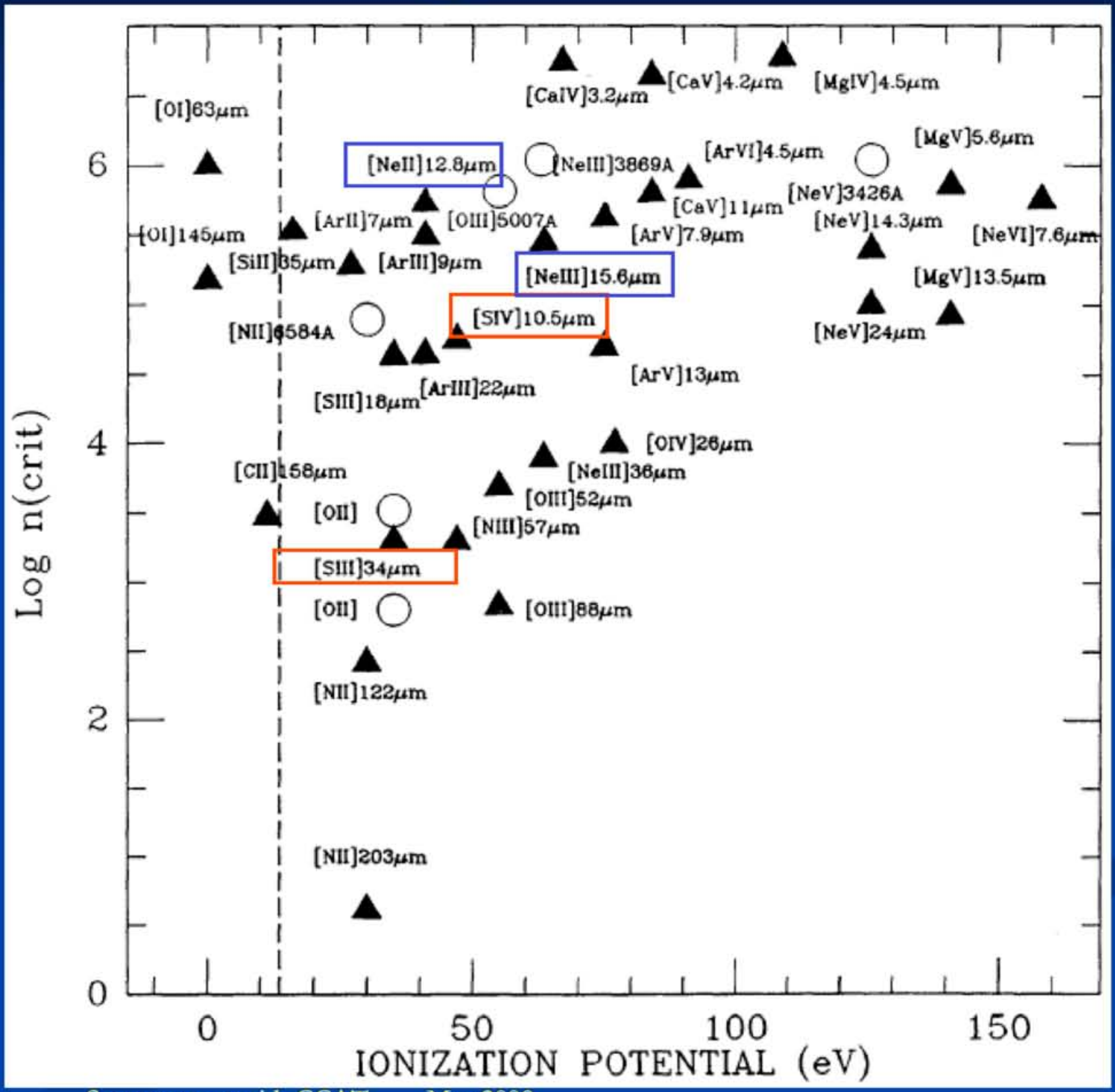
Low ionization lines such as [OI]6300Å, [OI]63μm, [SiII]35μm, and [FeII]26μm can be prominent coolants of X-ray-dominated regions



Maloney, Hollenbach, & Tielens 1996

Infrared Diagnostics

Line ratios involving two different ionization states of the same element probe the hardness of the radiation field

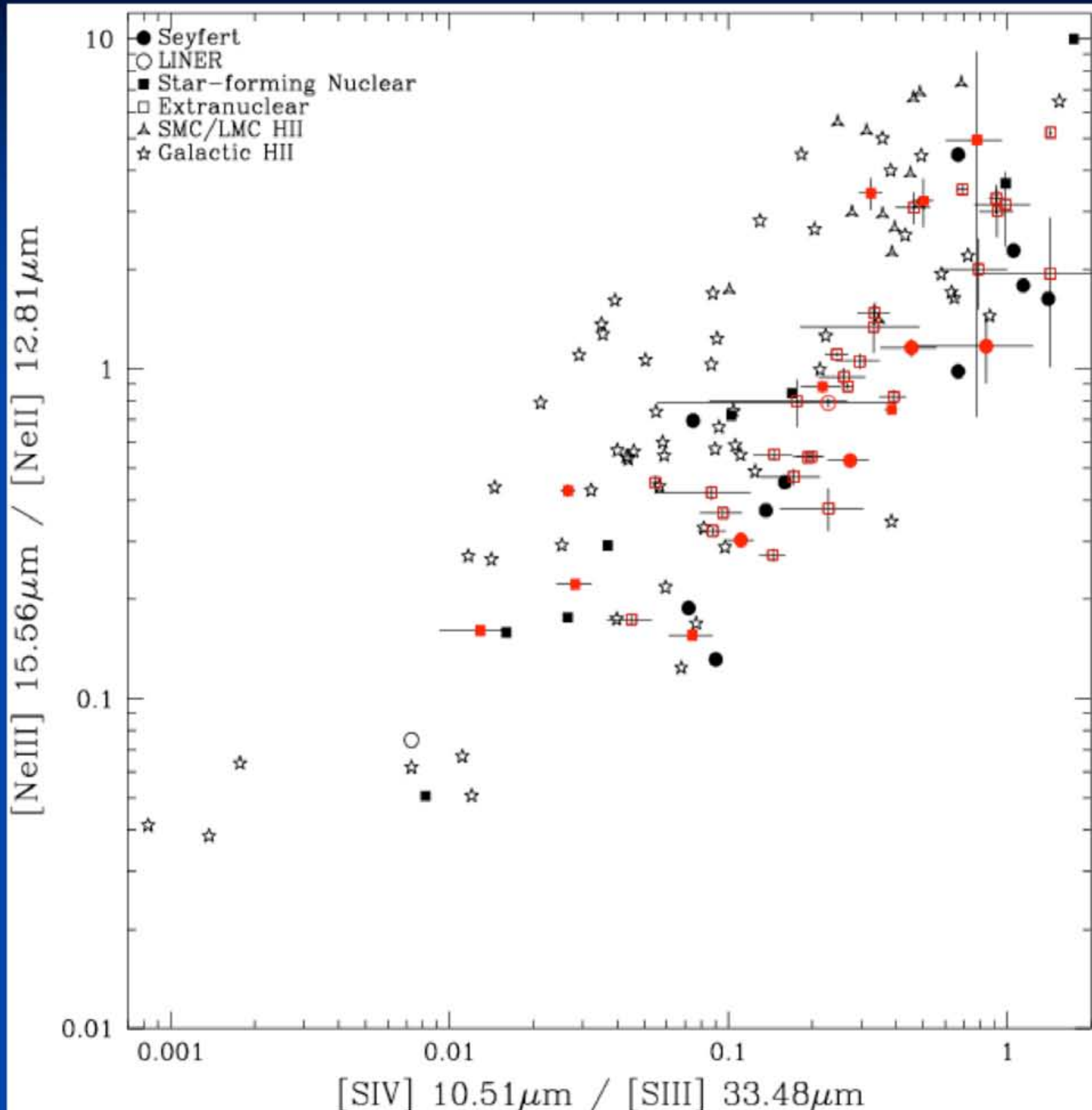


Spinoglio & Malkan 1992

[NeIII]/[NeII] vs [SIV]/[SIII]

Examples of two IR line ratios that are tracers of T_{eff} (e.g., Morisset 2004)

Fairly insensitive to environment, though low-metallicity SMC/LMC data are preferentially in the upper right corner



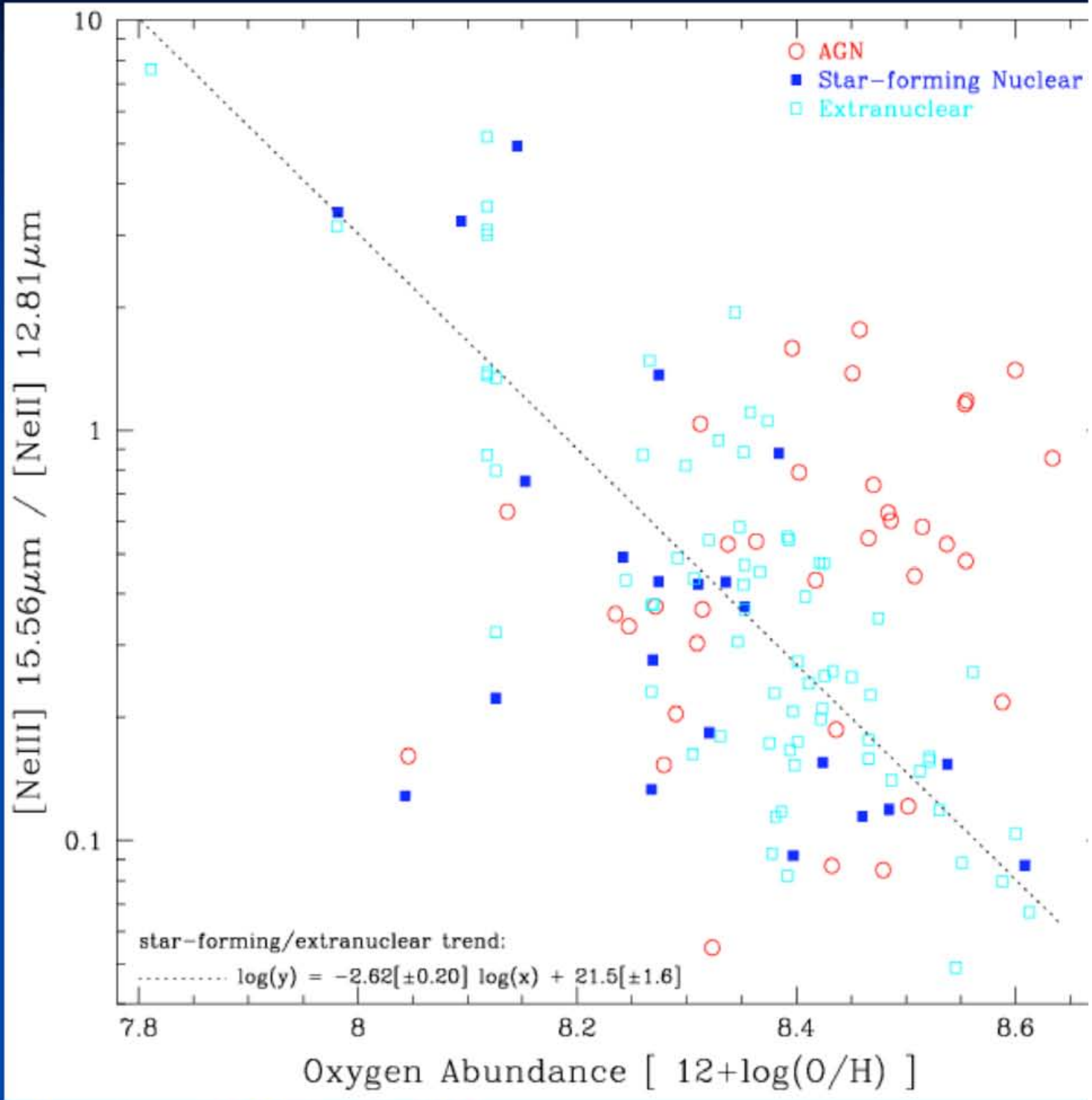
Dale et al. 2006

[NeIII]/[NeII] vs Oxygen Abundance

Star-forming regions (blue and cyan points): Low metallicity regions exhibit higher ratios

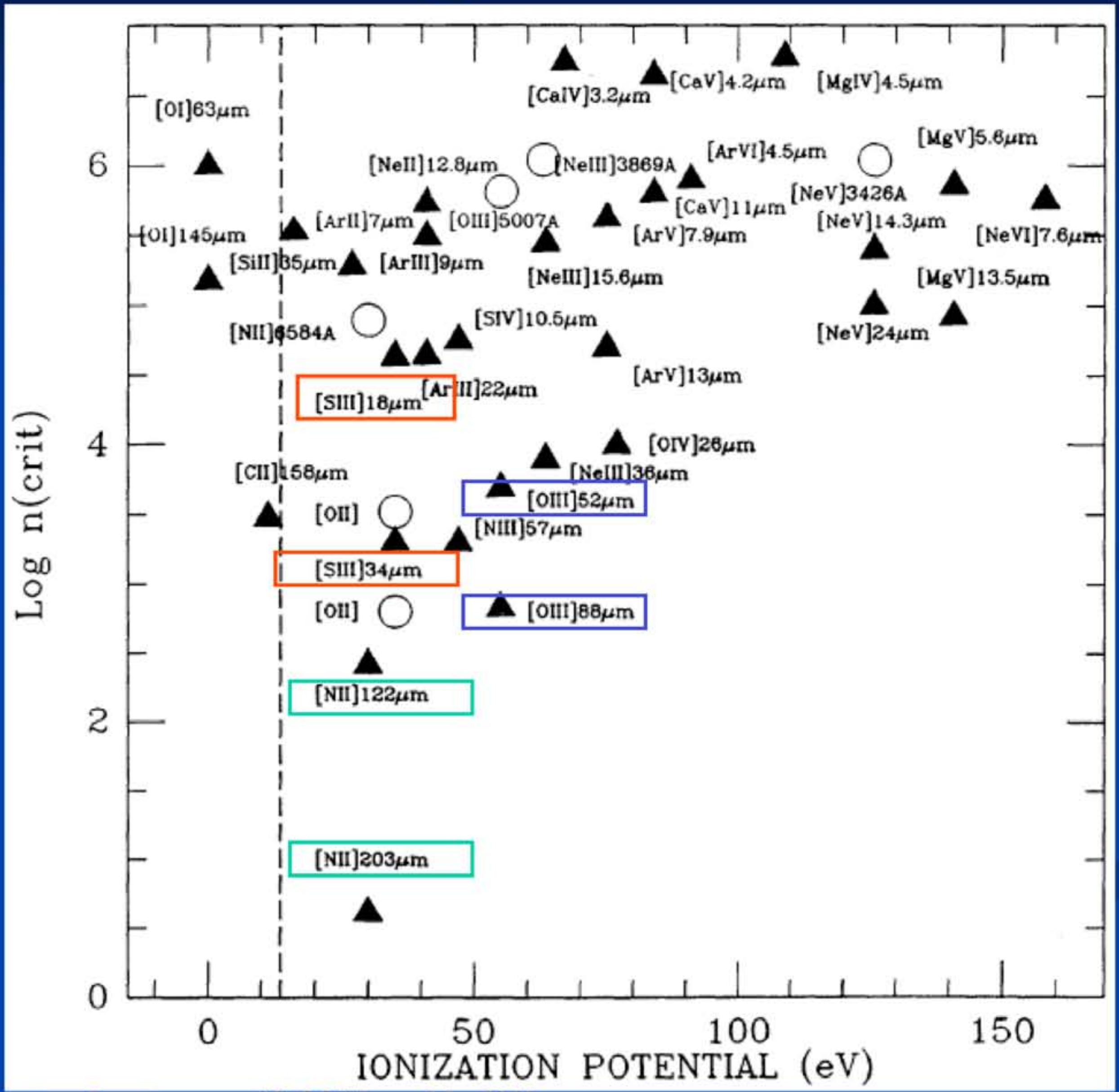
Hardness independent of metal content for AGN, and for sources with at least solar solar metallicity, AGN fields are harder

Dale et al. 2008



Infrared Diagnostics

Line ratios involving two transitions of the same species trace the interstellar electron density



Spinoglio & Malkan 1992

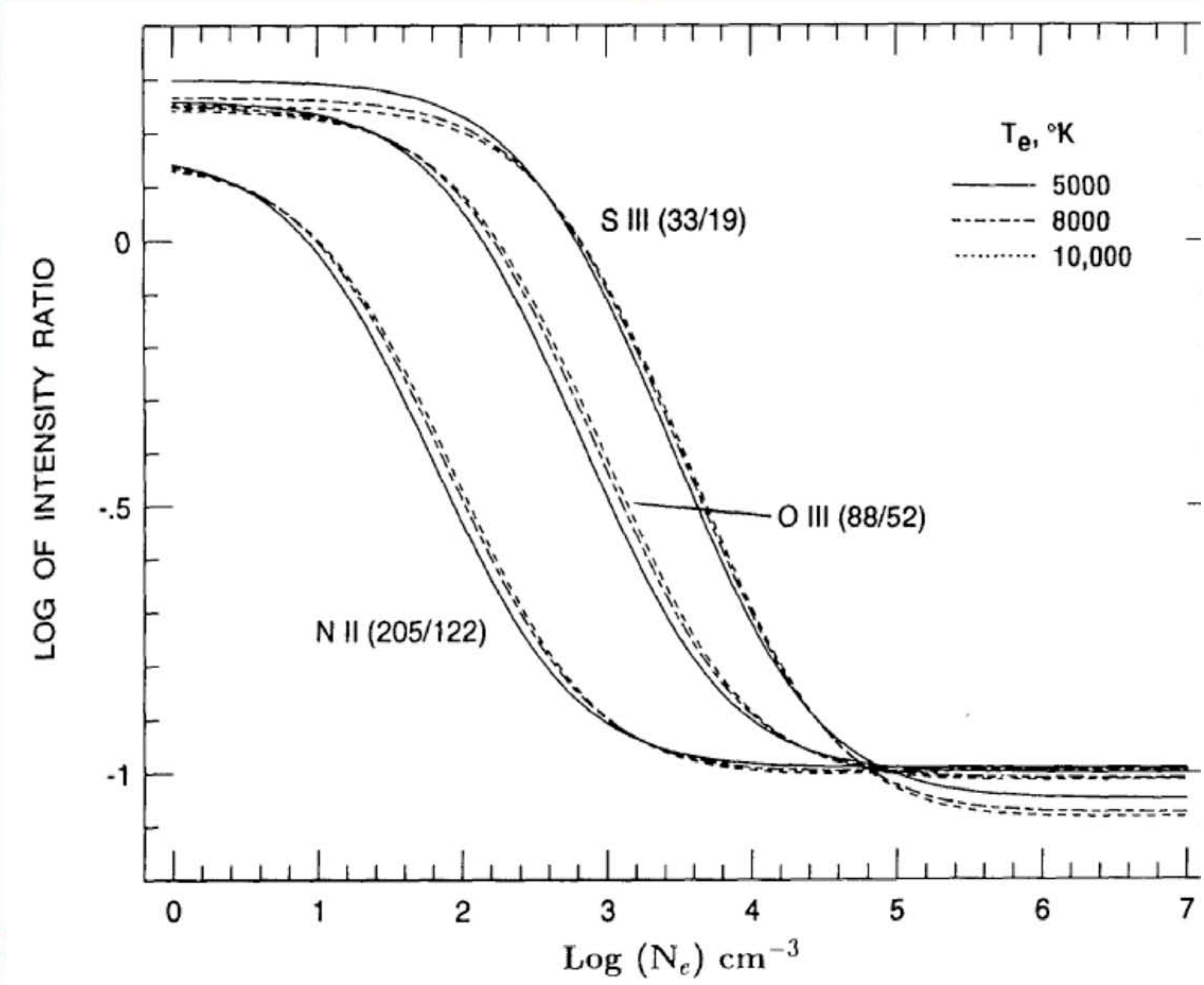
Infrared Density Diagnostics

Ratios of lines with different critical densities but the same ionization potentials probe the interstellar electron density

Fairly insensitive to temperature

High density [SIII]33/[SIII]19

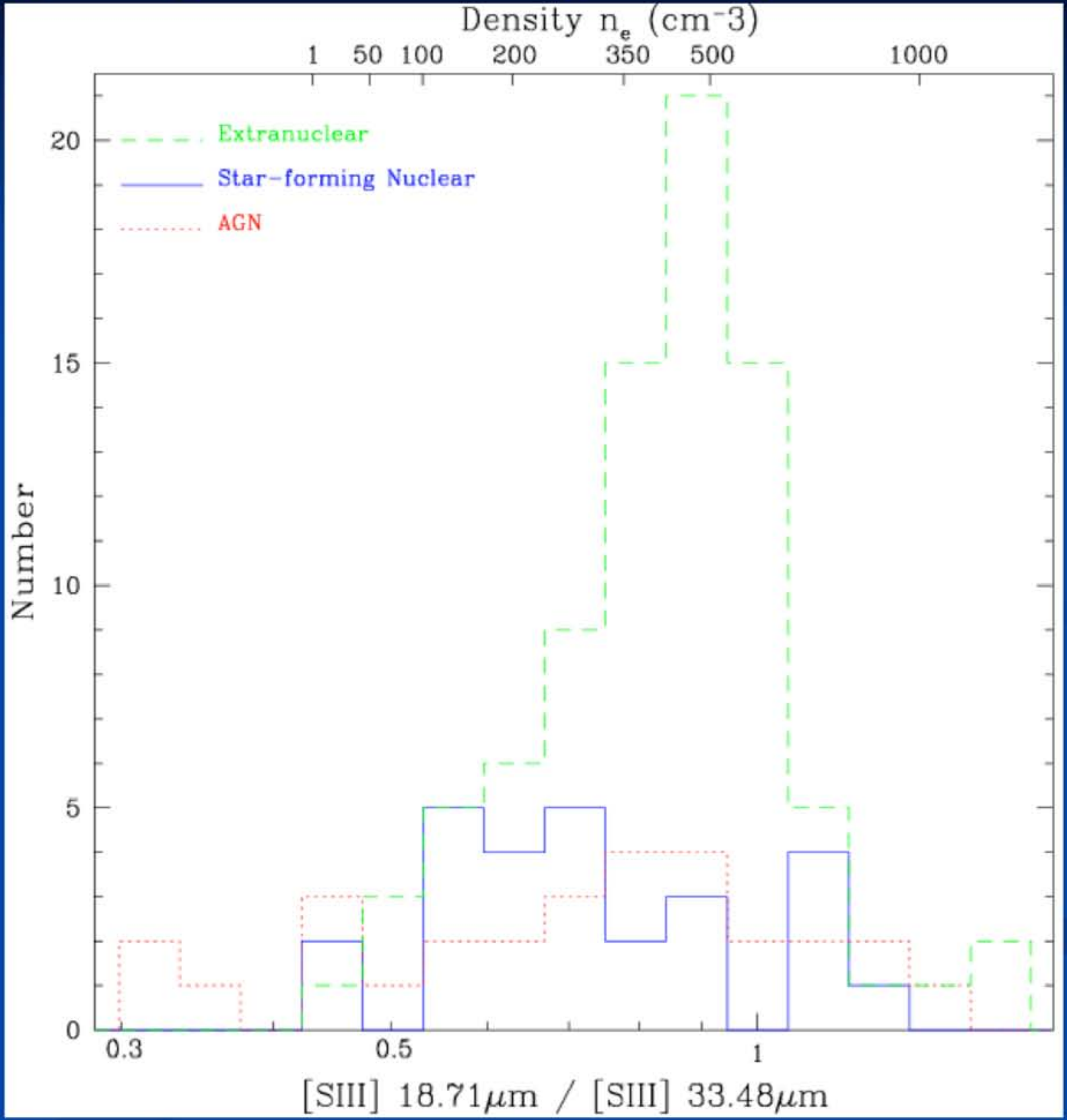
Low density [NII]205/[NII]122



Rubin et al. 1994

[SIII]18.7/[SIII]33.5 Density Diagnostic

$n_e \sim$ 300-400 cm^{-3}, roughly independent of power source, though with large dispersions



Dale et al. 2006

[FeII]/[NeII] vs [SiII]/[SIII]

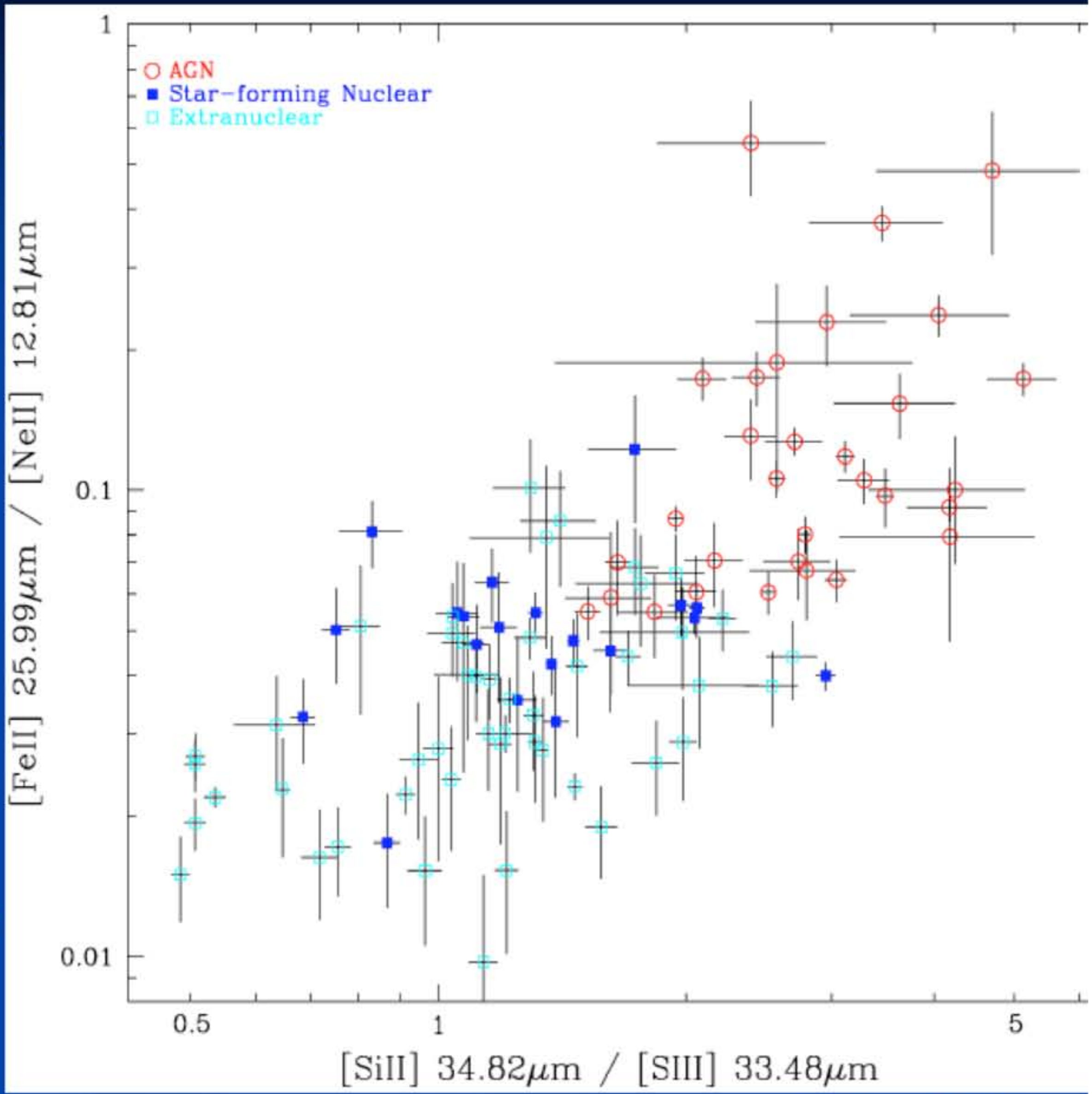
[SiII] and [FeII] coolants of X-ray dominated regions around AGN, and dense PDRs

nebular [SIII] and [NeII] Strömgren coolants

AGN/SF separation becomes less dramatic when the nebular lines used for normalization have higher ionization potentials
(SIV 35eV, NeIII 41eV, OIV 55eV, NeV 97eV)

Power source surrounded by layers of ionized gas at various levels of ionization?

Refractory elements returned to ISM via grain destruction in AGN?



Dale et al. 2008

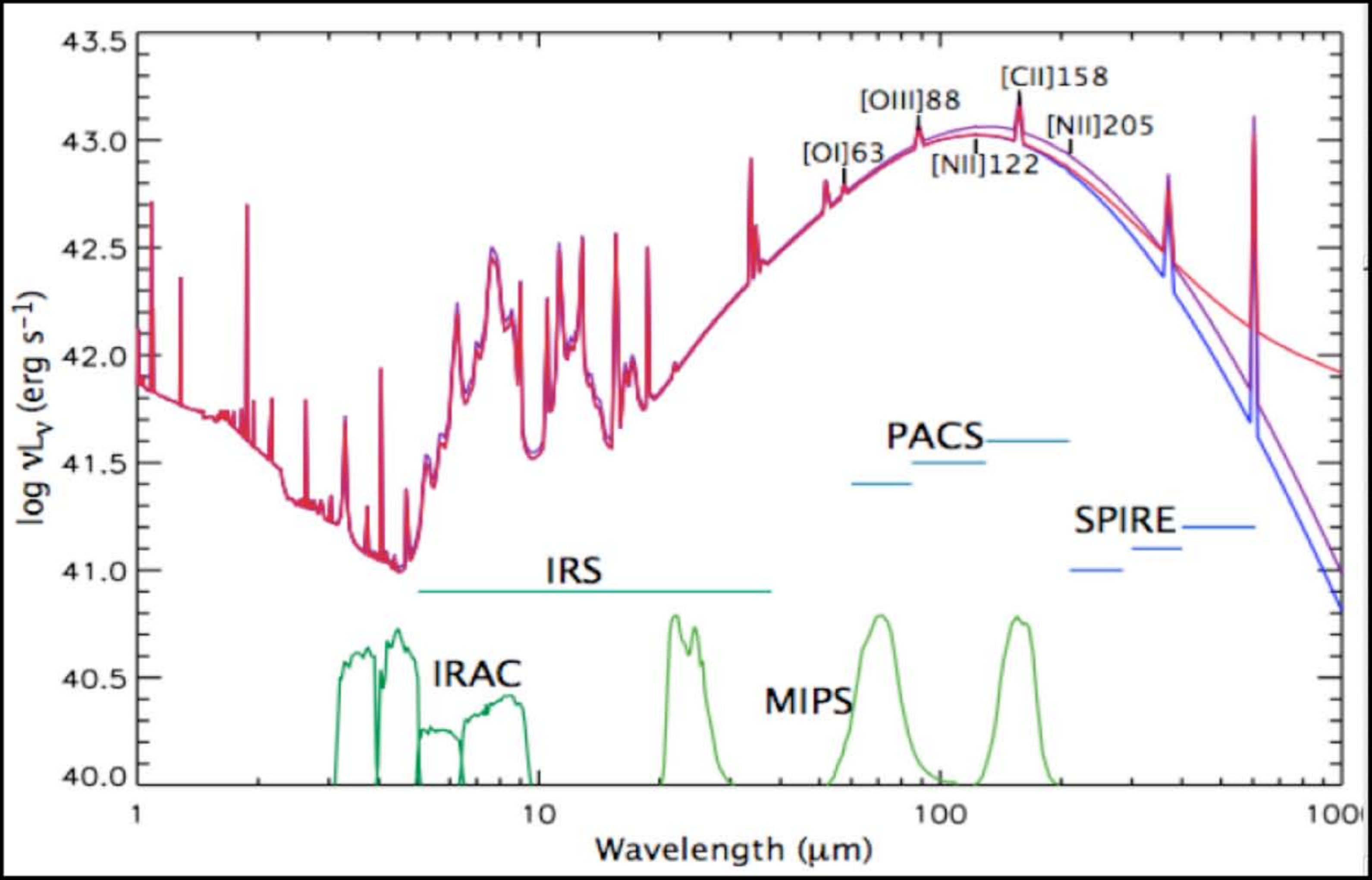
KINGFISH – Key Insights on Nearby Galaxies: A Far-Infrared Survey with Herschel

- A Herschel Space Observatory key project
- Far-IR/submm imaging and spectroscopy of 61 nearby galaxies (57 from SINGS)
- Imaging: 75, 110, 170, 250, 350, 500 microns

  physical resolution (50-300pc) matched to sizes of star-forming regions and molecular cloud complexes
- Spectra: [OI]63,[OIII]88,[NII]122,[CII]158,[NII]205

  SINGS+KINGFISH will cover all the main IR PDR cooling lines except for [CI]307, [CI]609

SINGS+KINGFISH

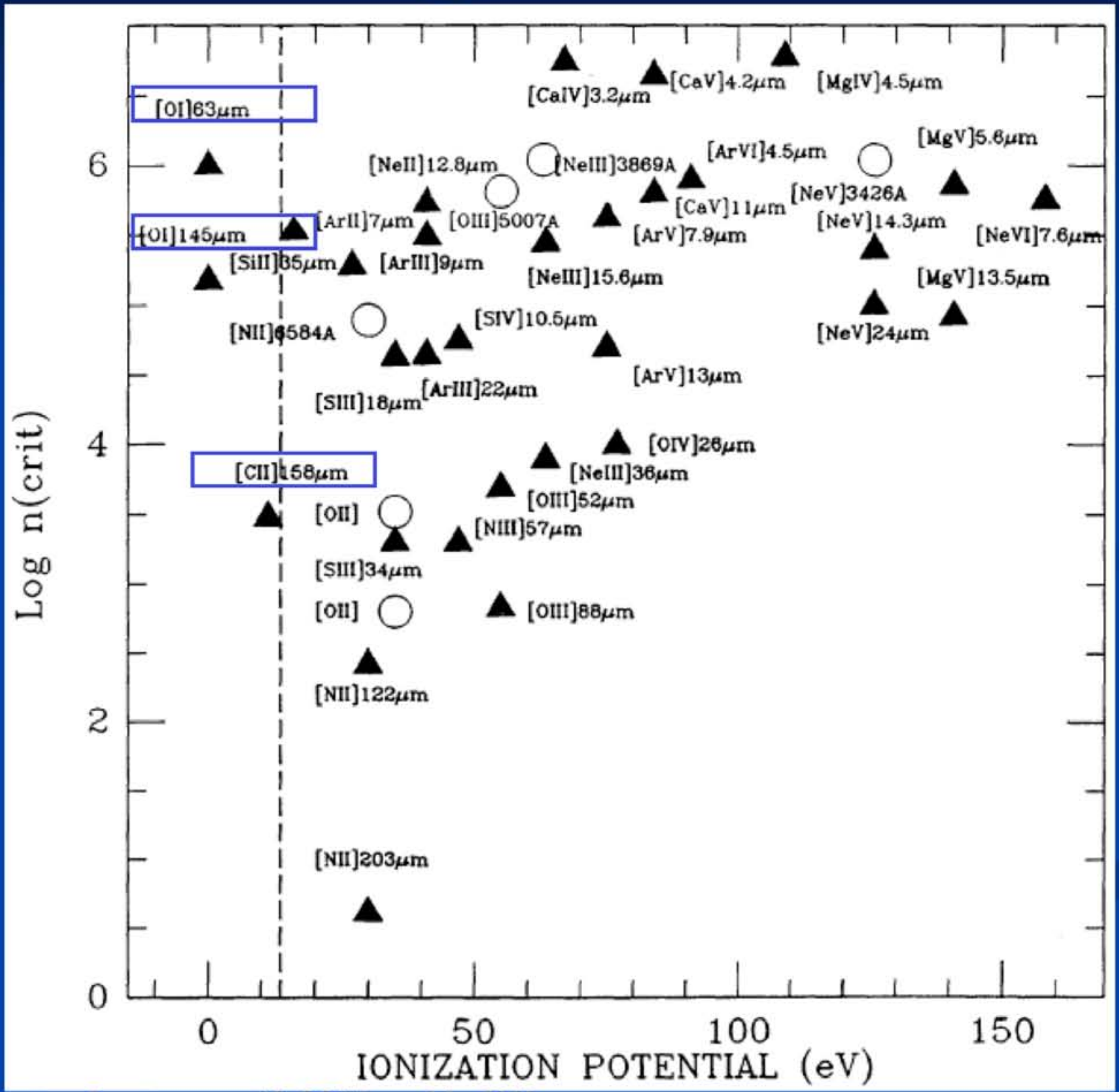


Infrared Diagnostics

Far-Infrared lines found in the neutral ISM probe PDRs

The following plots utilize ISO archival data for a parent sample of 227 galaxies
(Brauher, Dale, & Helou 2008)

Spinoglio & Malkan 1992

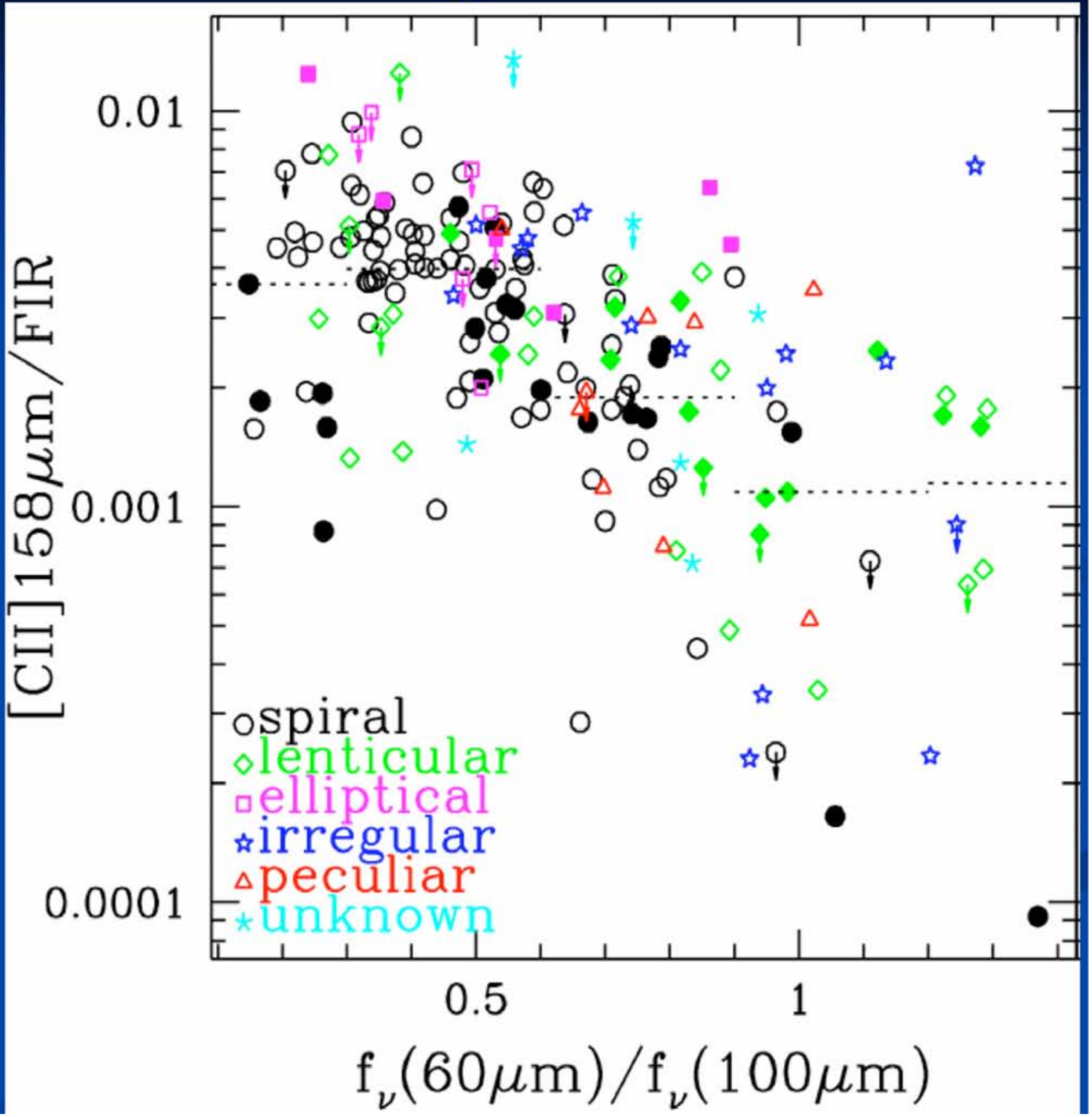


Far-Infrared Diagnostics

Brightest (IR) line

[CII]158 is the dominant coolant of the neutral ISM
$\Delta E/k \sim 91$ K

[CII]158/FIR drops with increasingly warm infrared color, consistent with increased quenching of photo-electric effect as PAHs becoming increasingly ionized.

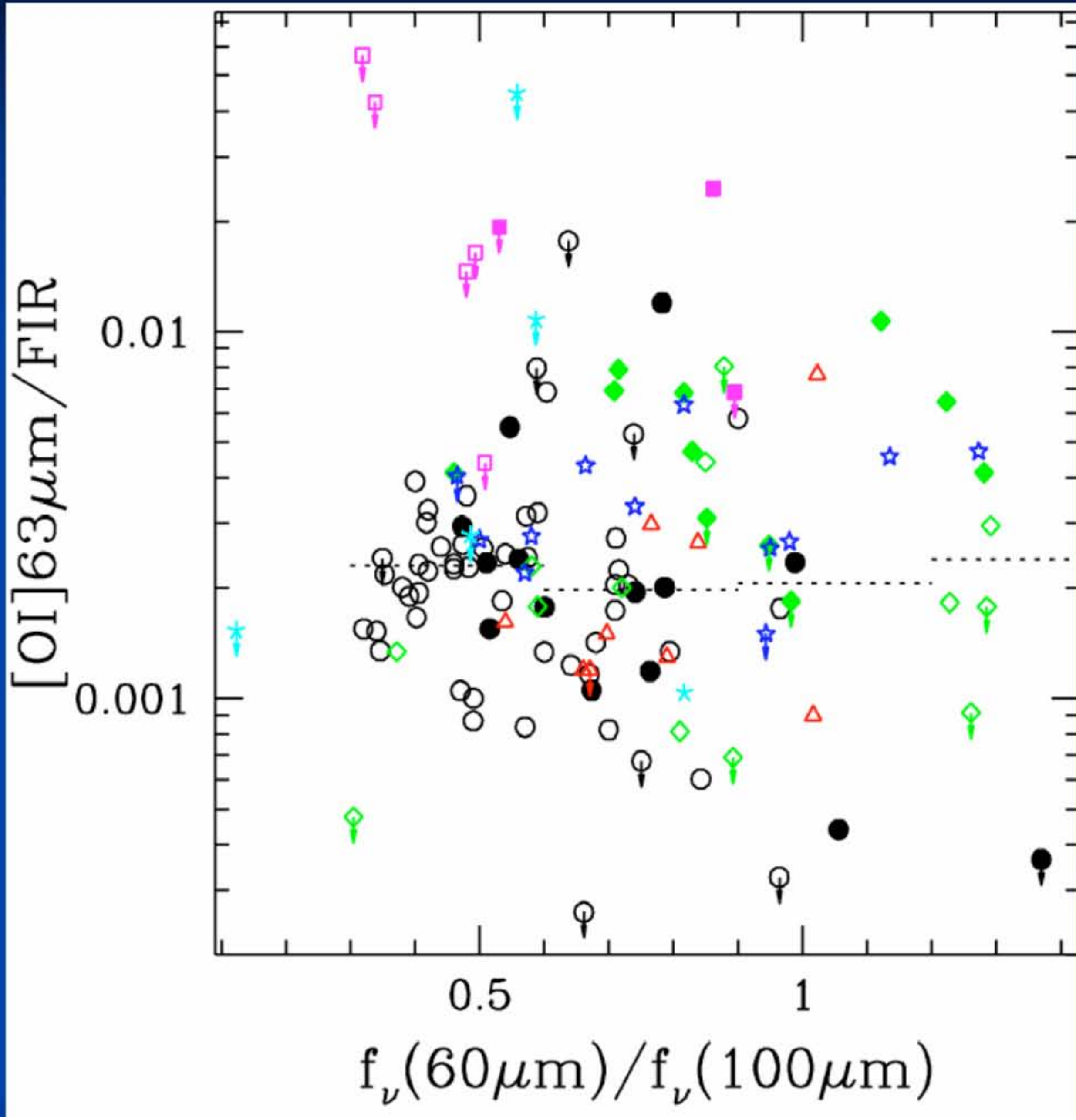


Brauher, Dale, & Helou 2008

Far-Infrared Diagnostics

[OI]63 cools the denser, warmer phases of the neutral ISM
$\Delta E/k \sim 228$ K

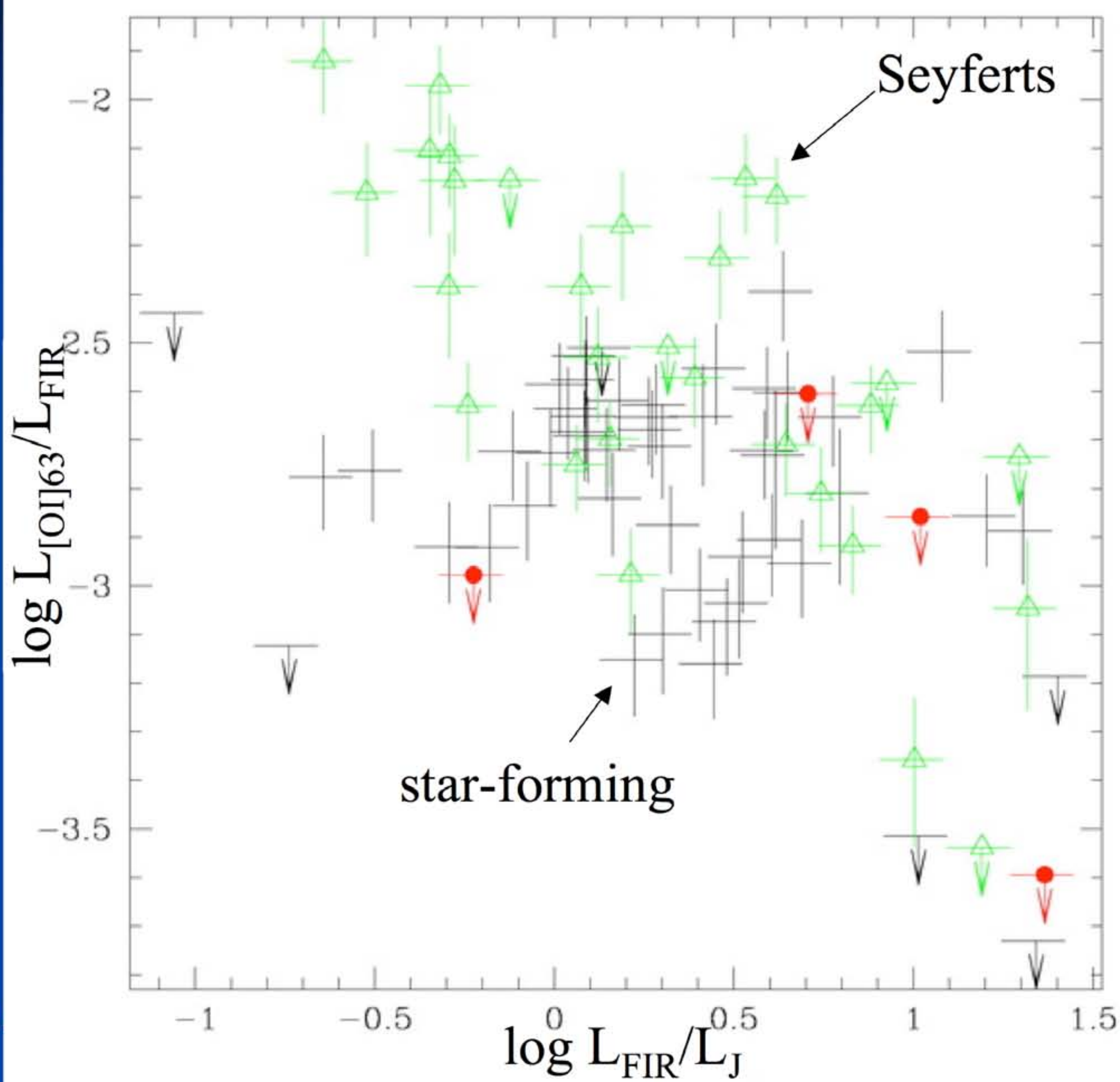
[OI]63/FIR ~constant with infrared color, suggesting that the importance of [OI]63 as an interstellar coolant does not significantly vary with environment.



Brauher, Dale, & Helou 2008

Additional Diagnostic Possibilities with SPICA

PDR lines such as [OI]63 can perhaps distinguish between star-forming and AGN galaxies

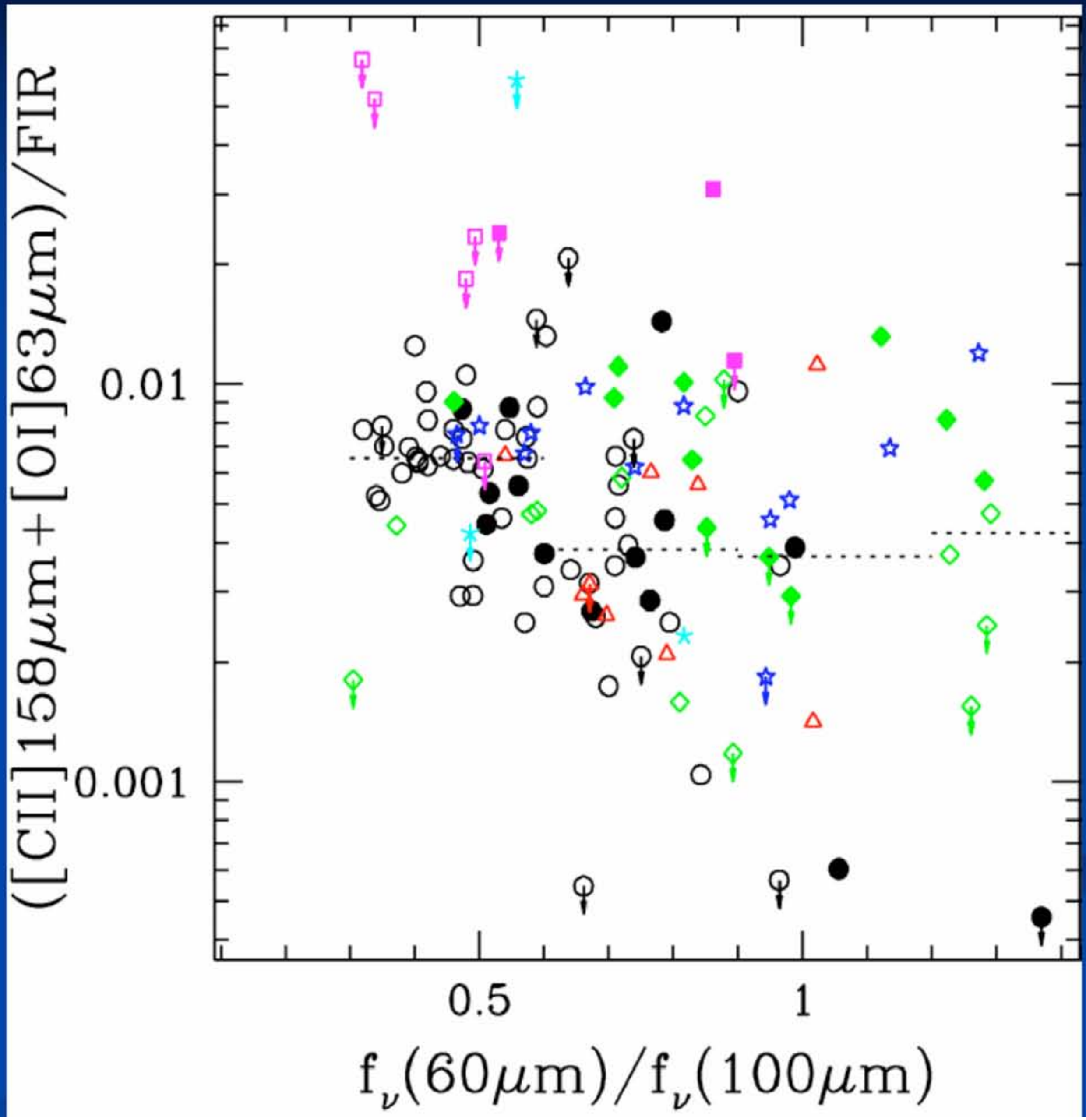


Dale et al. 2004

Far-Infrared Diagnostics

([OI]63+[CII]158)/FIR provides a more complete picture of ISM cooling Efficiency

Constrains G_o/n, the ratio of the UV radiation field intensity to gas density



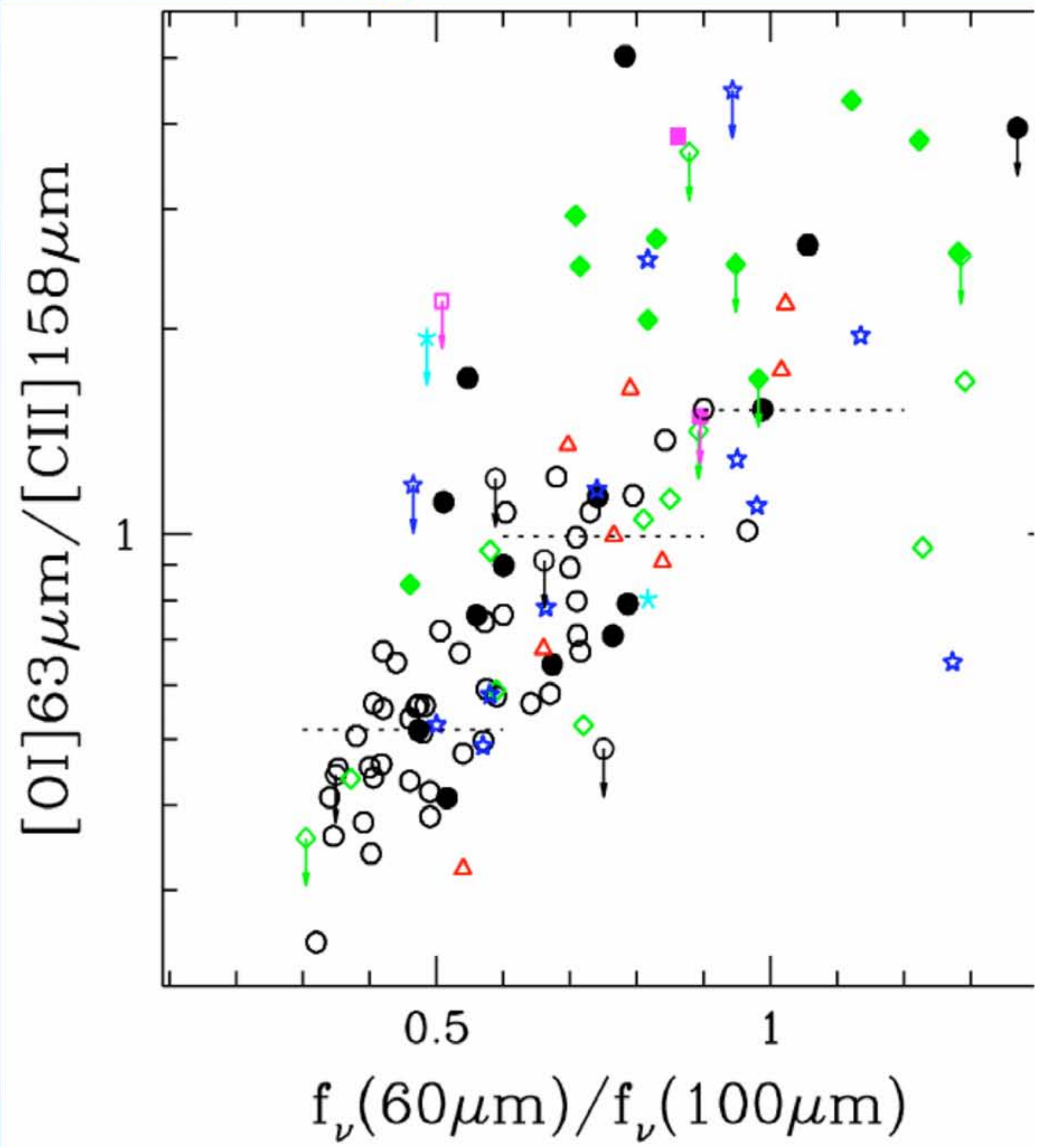
Brauher, Dale, & Helou 2008

Far-Infrared Diagnostics

[OI]63/[CII]158 tracks with dust temperature/star formation activity level, but does scatter to higher values for Seyferts
→different excitation mechanisms for AGN vs SF?

High redshift [CII]158μm surveys should be complemented by efforts directed toward [OI]63μm

Brauher, Dale, & Helou 2008

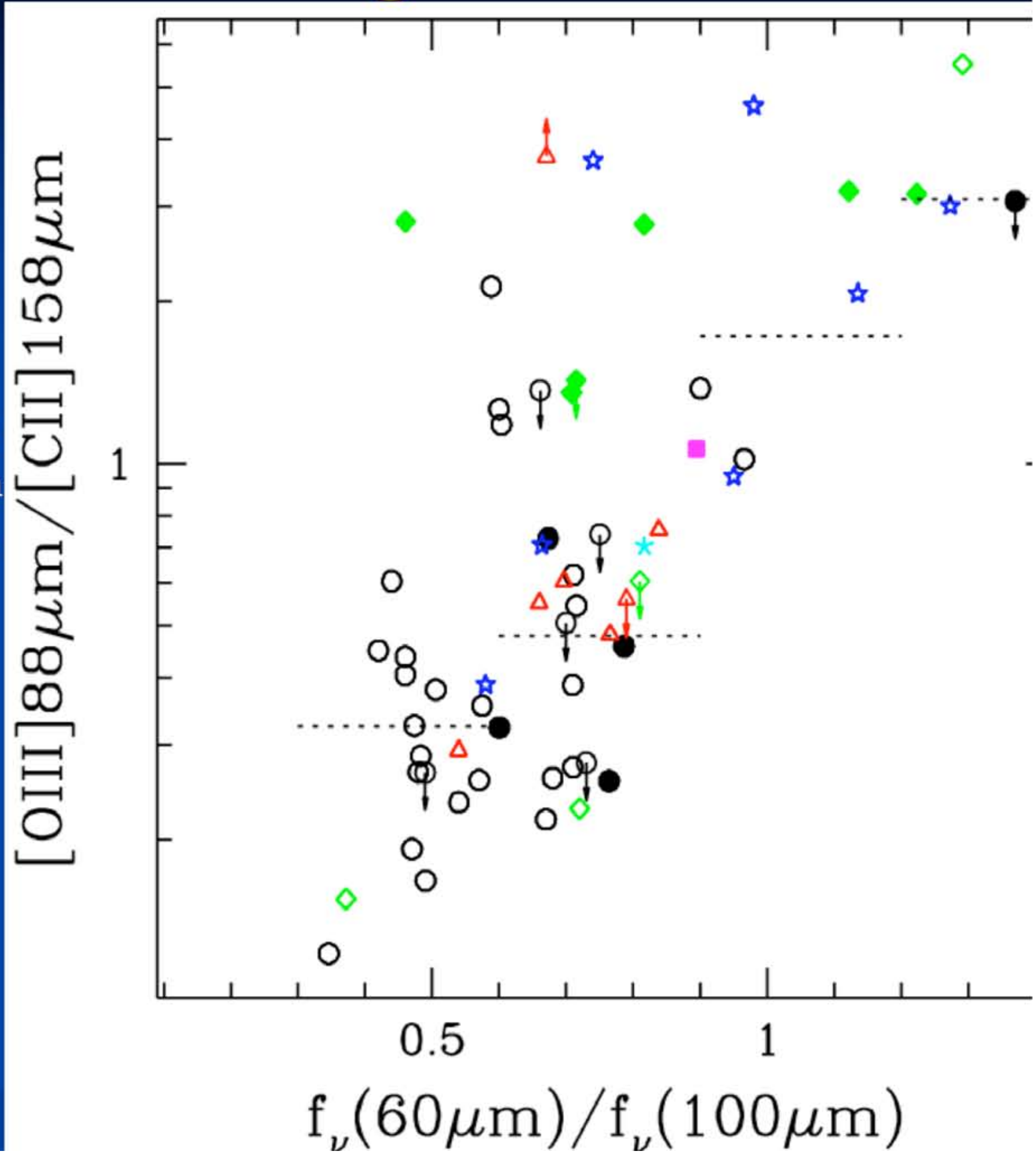


Far-Infrared Diagnostics

[OIII]88/[CII]158 tracks with infrared color

Since [NII]122/[CII]158 conversely shows no trend, the implication is that C^+ emission from HII regions originates in lower density evirons

Brauher, Dale, & Helou 2008



Summary

- SINGS offers unique mid-infrared spectral maps for diagnosing power sources and characterizing the physical properties of the ionized ISM (density, T_{eff}, …)
- New, easily observable low-to-medium ionization line ratios effectively discriminate between AGN and star formation. Interpretation is still a challenge: are [SiII]35 and [FeII]26 tracers of XDRs? Dense PDRs? Grain destruction processes?
- Far-Infrared diagnostics constrain the physics of neutral ISM cooling, the efficiency of microprocesses such as photo-ejection from PAHs, … Is [OI]63 an XDR tracer as well?