How did galaxies and MBHs Form and Evolve? The IR View

Why go to the trouble of faint galaxy spectroscopy in the Far-IR?

1. 1. Go fainter and deeper than previously possible, new detections,
2. better SNR, blah blah blah

3. 2. Observe our best diagnostics at higher redshifts

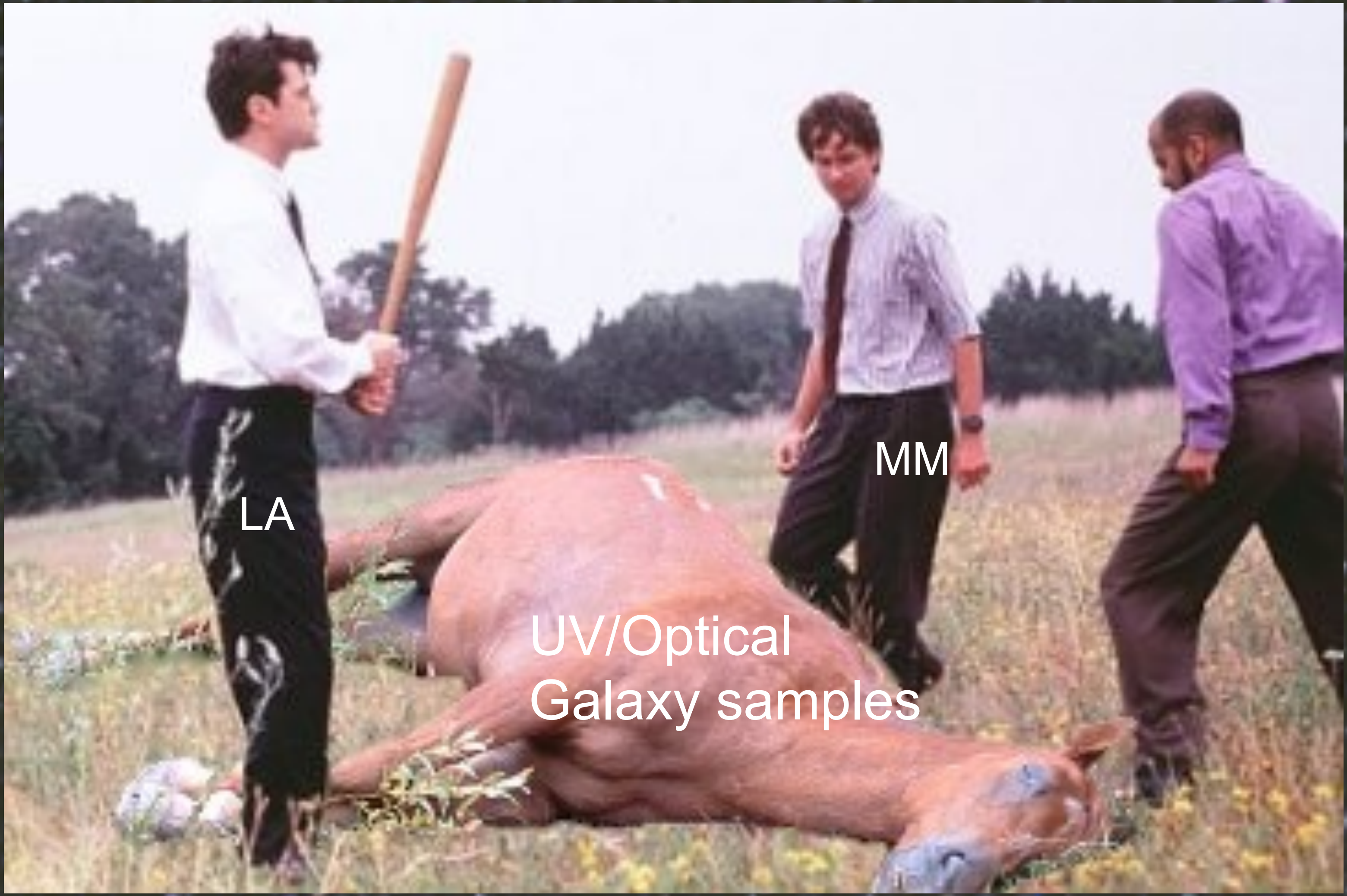
4. 3. Uncover energy generation in galaxies that is heavily dust extincted

5. 4. Obtain better ionized gas diagnostics than UV/optical emission lines, to learn about power generation, dynamics, mergers/interactions, element enrichment

1. 5. Study galaxy components that are hardly visible at other wavelengths
   - A. Dust grains
   - B. Molecules (shocking example: Phil Appleton, tomorrow)

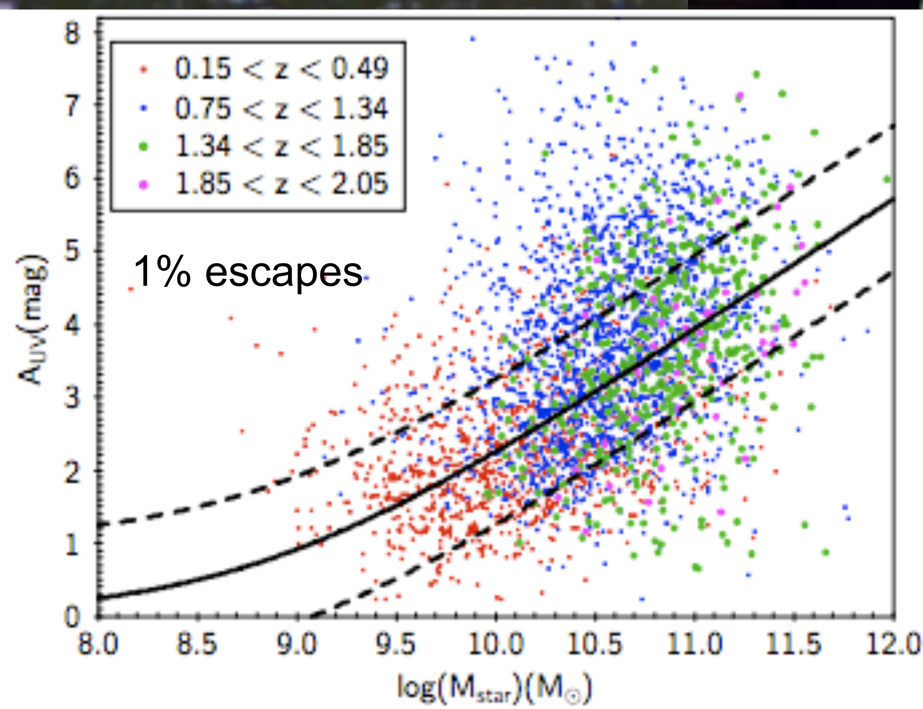
To see the key processes that grow stars (disks, bulges) and MBHs, eg. inflows/feeding, outflows/winds/feedback

I'm reluctant to beat a dead horse. But…

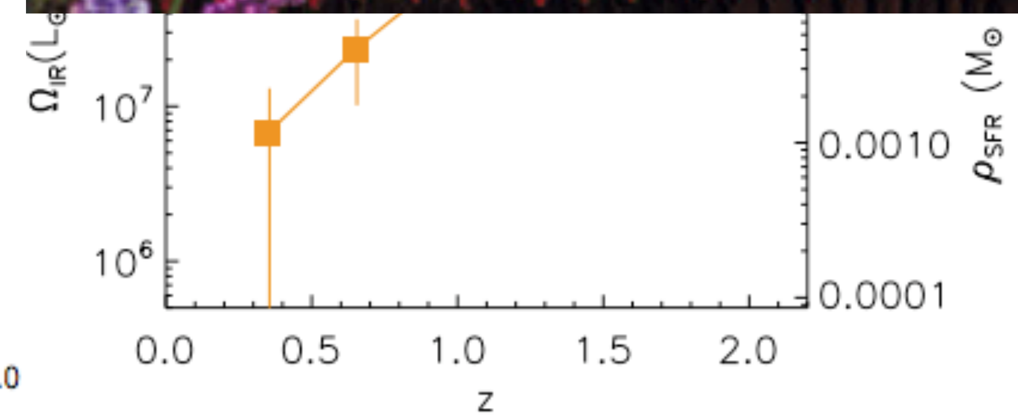


This one still seems to be breathing!

We infer larg
Optical data miss 'most
Most En
(Av>3mag starl
NB: some previously shown figures
but since those conclusions relied n
UV selection, we really have no idea



Buat et al. 2015)

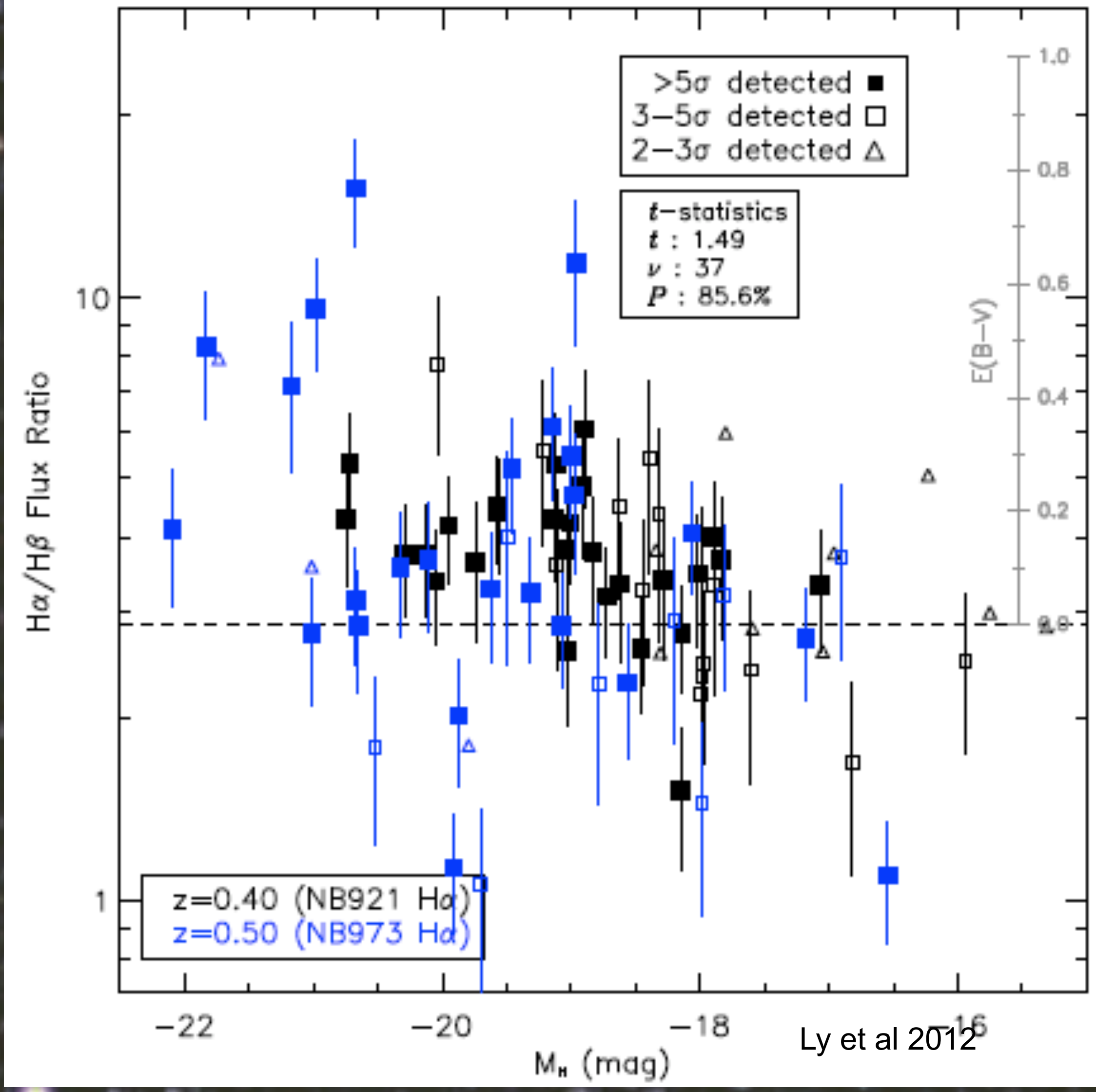


•Goto et al 2015

Balmer Decrements in SDF: "Gold Standard"… for Av<2

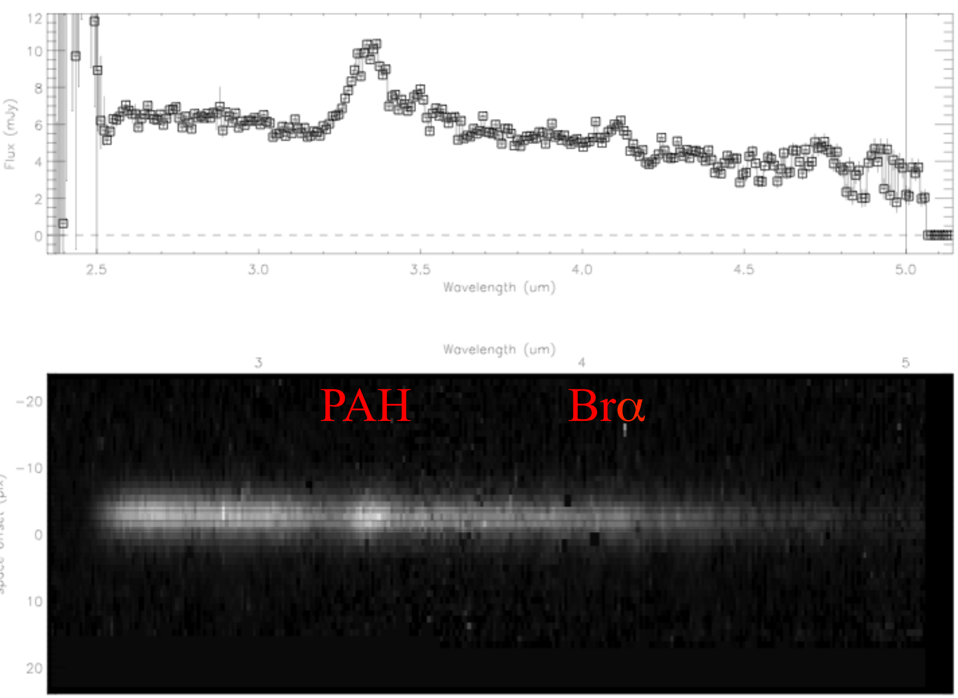
- Gas reddening increases alarmingly
with stellar mass

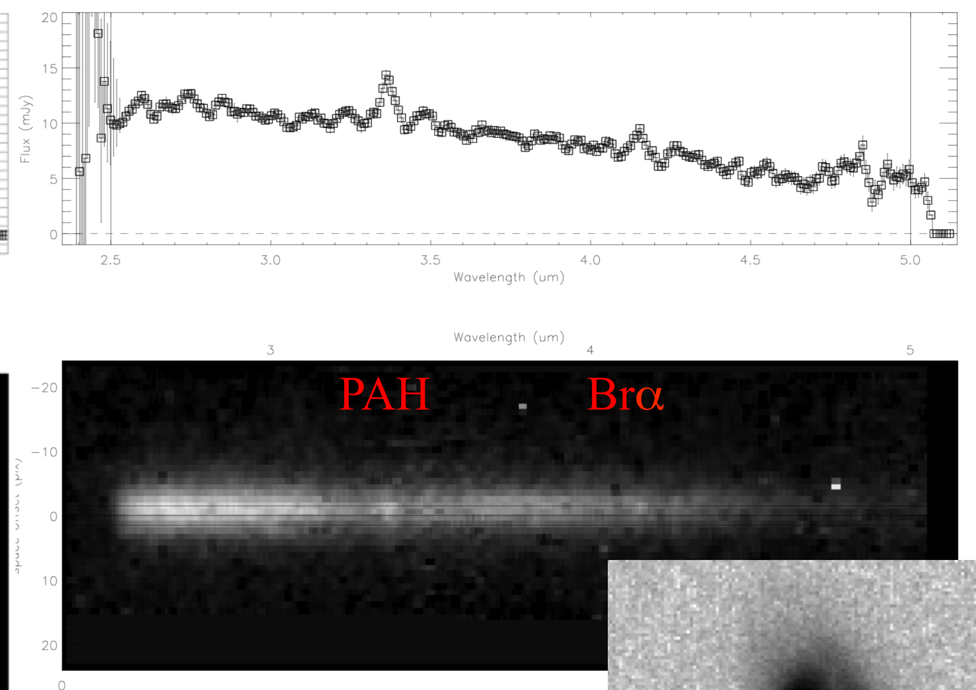
Sorry, but even near-IR observations will suffer from (uncertain) large extinction

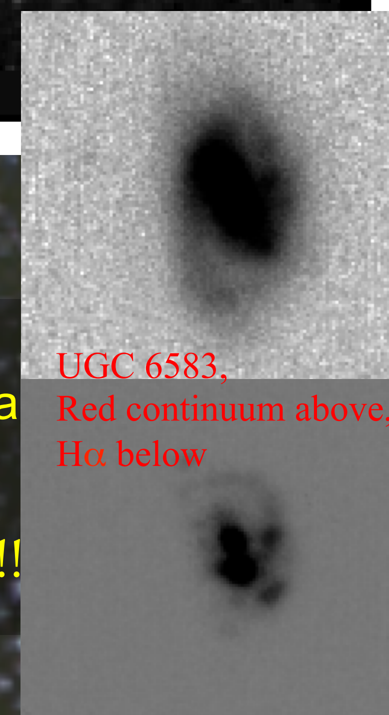


Ly et al 2012

In starburst galaxies, is the standard 1 magnitude of extinction correction for Hα enough?





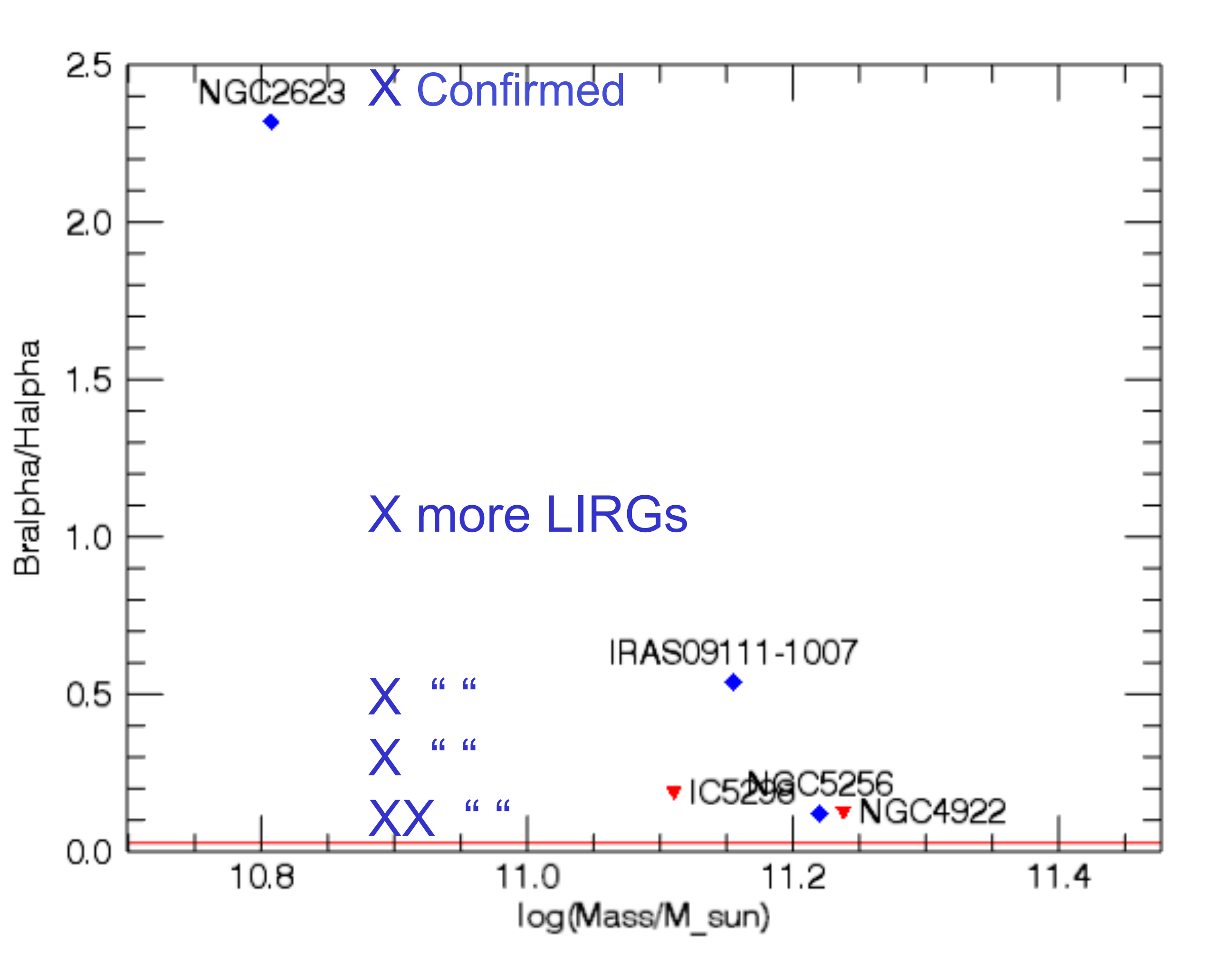


- Akari/IRC Warm Mission: 2.5--5um low-resolution Grism
- Slitless Spectroscopy of Starbursts (MM with Matsuhara, Sakai, Ohya

Brα is a few--ten times 'too strong' for Hα!

We need to replace the "Gold Standard" with a Platinum Standard!!

Akari Grism Spectrosopy of Br-α in LIRGs



Whether you measure Hα with wide slits, or NB imaging,
In more than half of these galaxies it is far too weak to be explained
By Case B recombination and the usual 1 mag of extinction

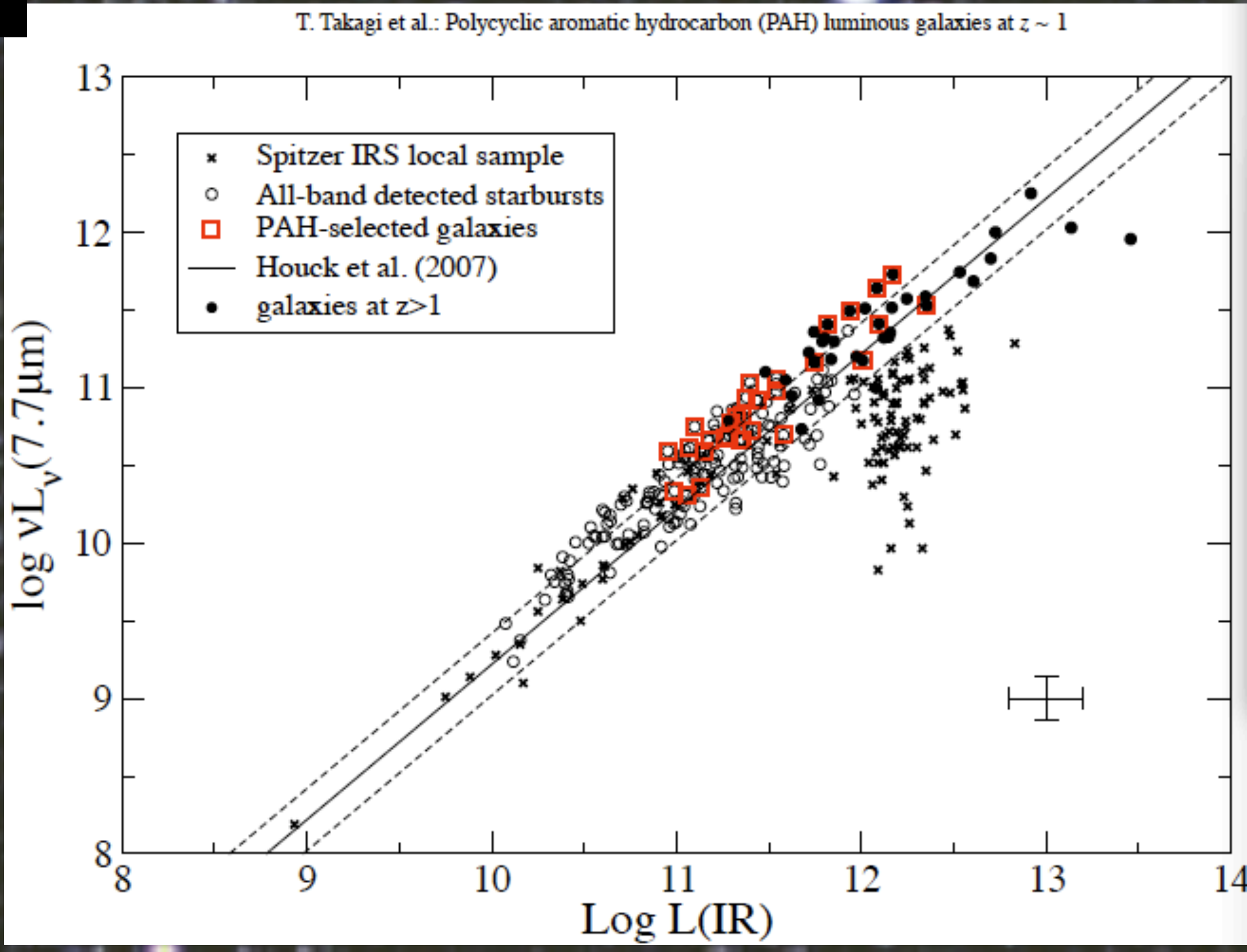
Besides simply ‘getting around’ all this dust,
it’s important to study grain EMISSION:
7.7um PAH feature is the strongest, most informative spectral signature,
Mostly powered by young stars

- PAHs can dominate an entire broad mid-IR band
- AKARI/IRC/NEP (with 9 IR filters 3--24um) measured them at z>1:

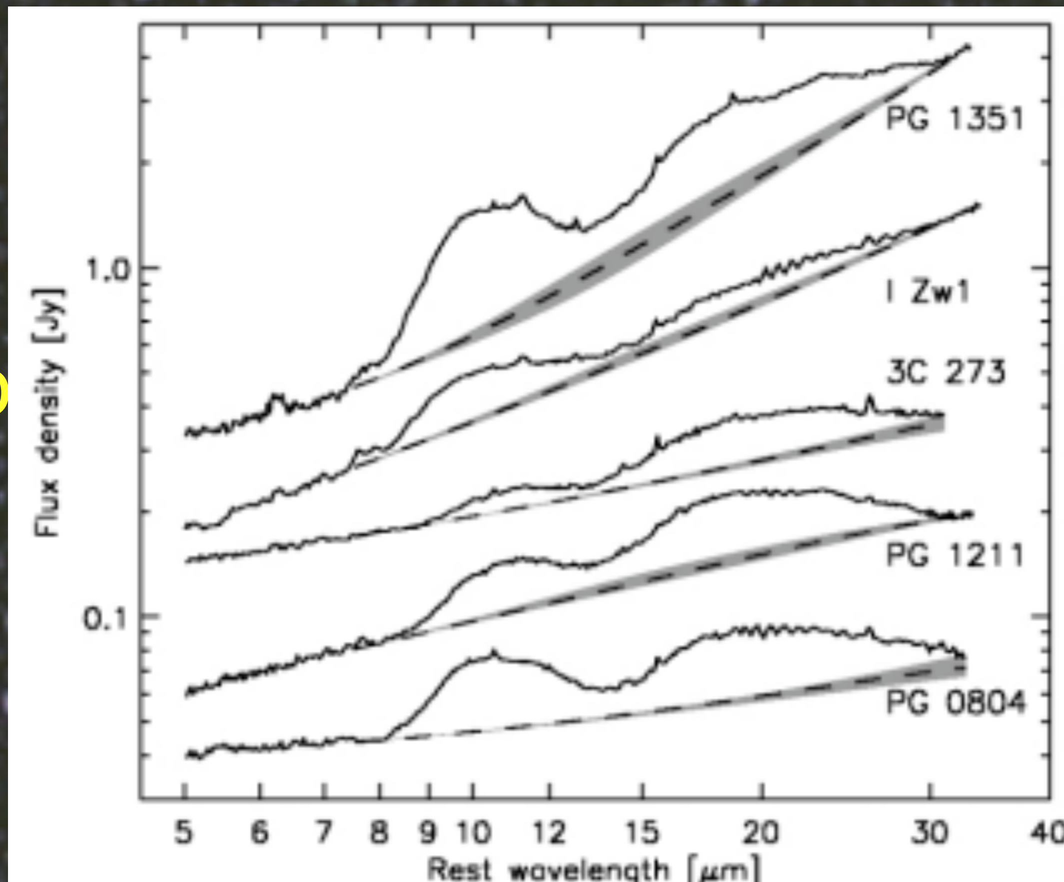
- In local galaxies, the PAHs become weaker in ULIRGs and in Seyfert nuclei

But at higher redshifts, It’s a different story!

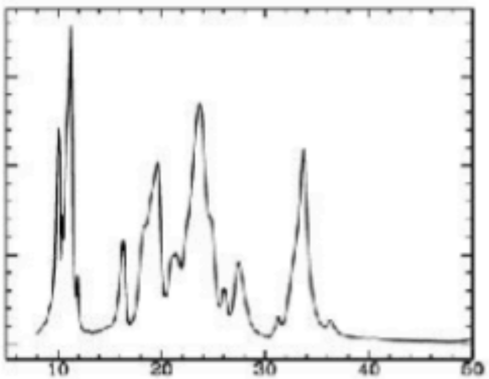
The ‘ULIRGs’ instead Are like 10x scaled-up ‘Normal’ Spirals (global starbursts?). There are even some “Super-PAH” galaxies

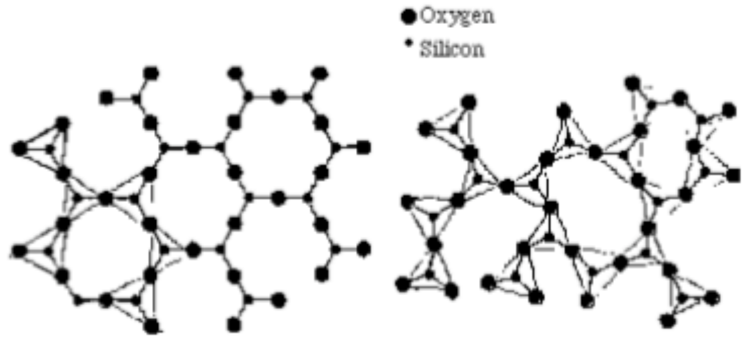


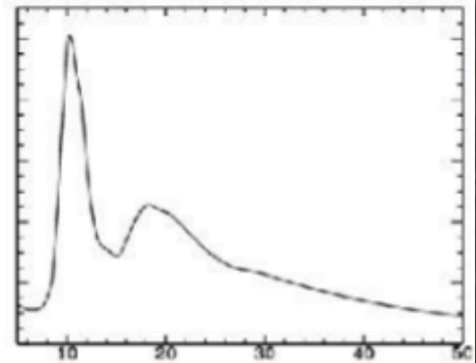
IRS sp … n in all



Crystallinity of silicates







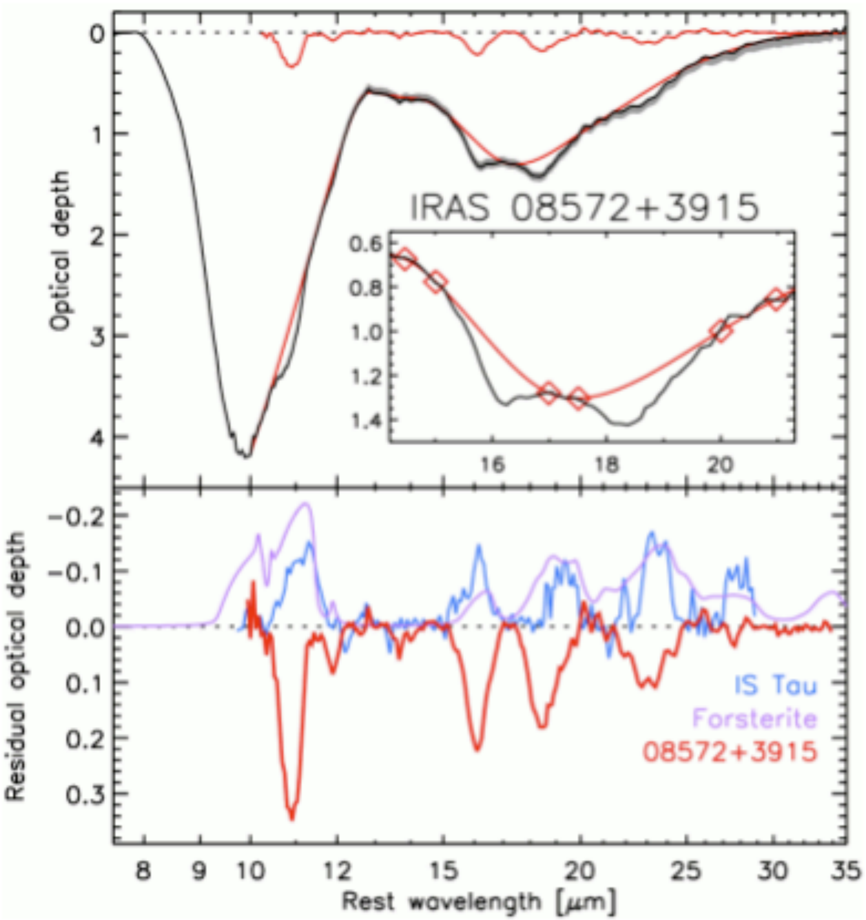
The glass temperature T_{glass} ~1000 K for silicates
(T_{evap} ~1500 K)

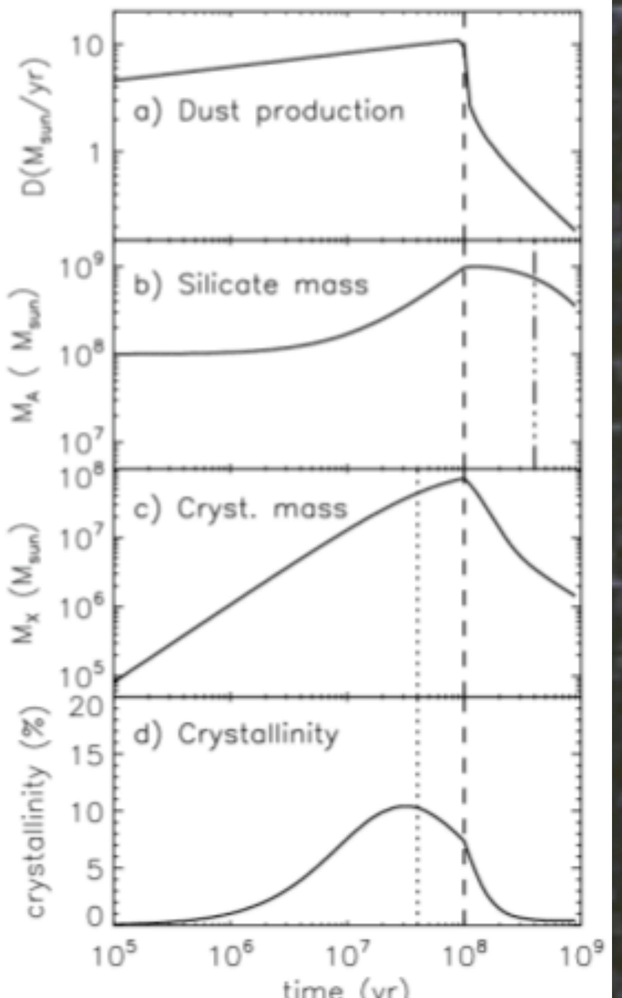
$T_{cond} > T_{glass}$: atoms in mineral are mobile, crystallization may occur

$T_{cond} < T_{glass}$: immediate freeze out → amorphous silicate

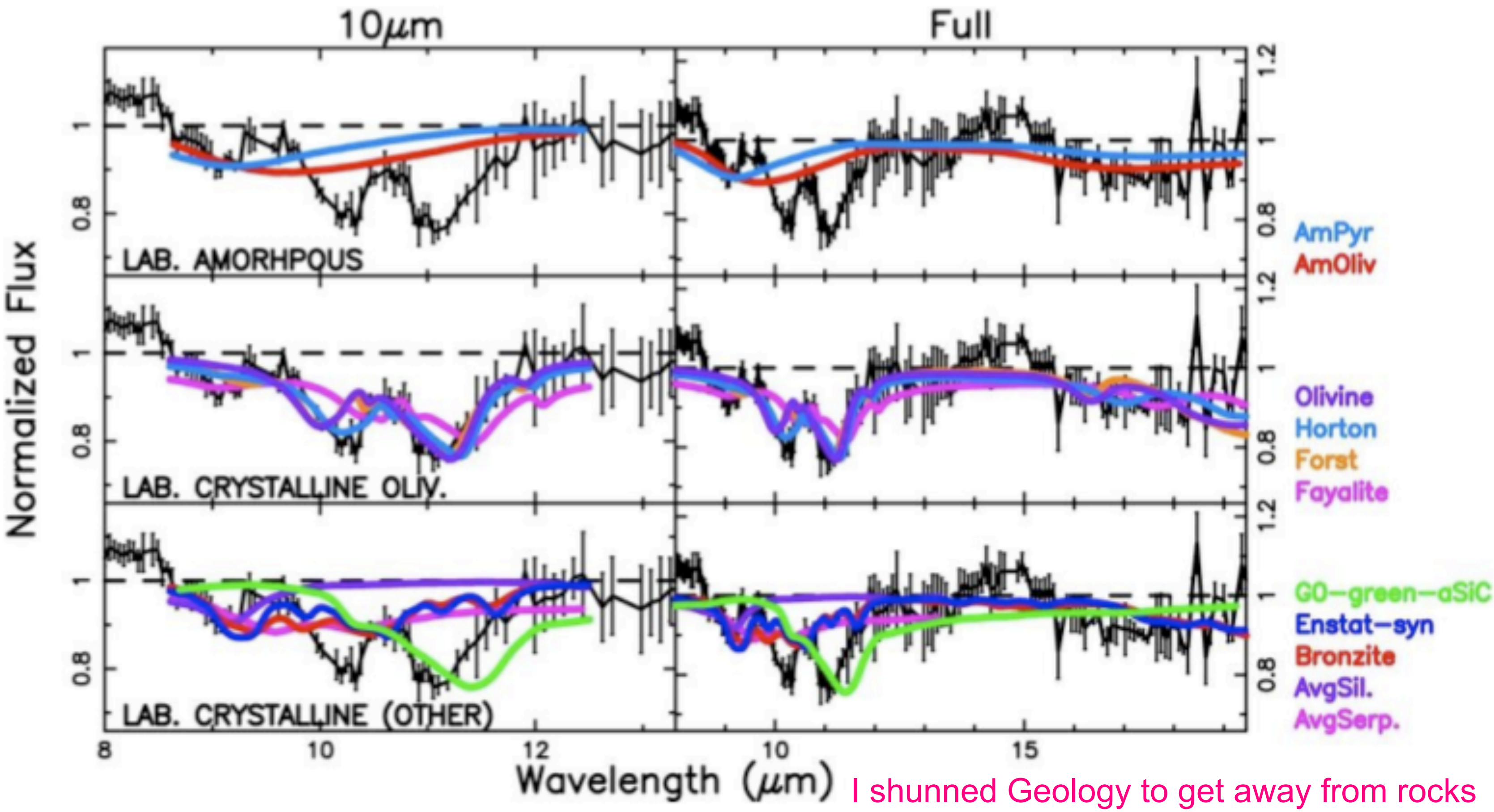
Slides from Ciska Kemper

~12/77 starburst galaxies have silicate crystallinities of 6-13%





Quasar foreground absorber (Damped Lyα system) has a crystallinity of 95%



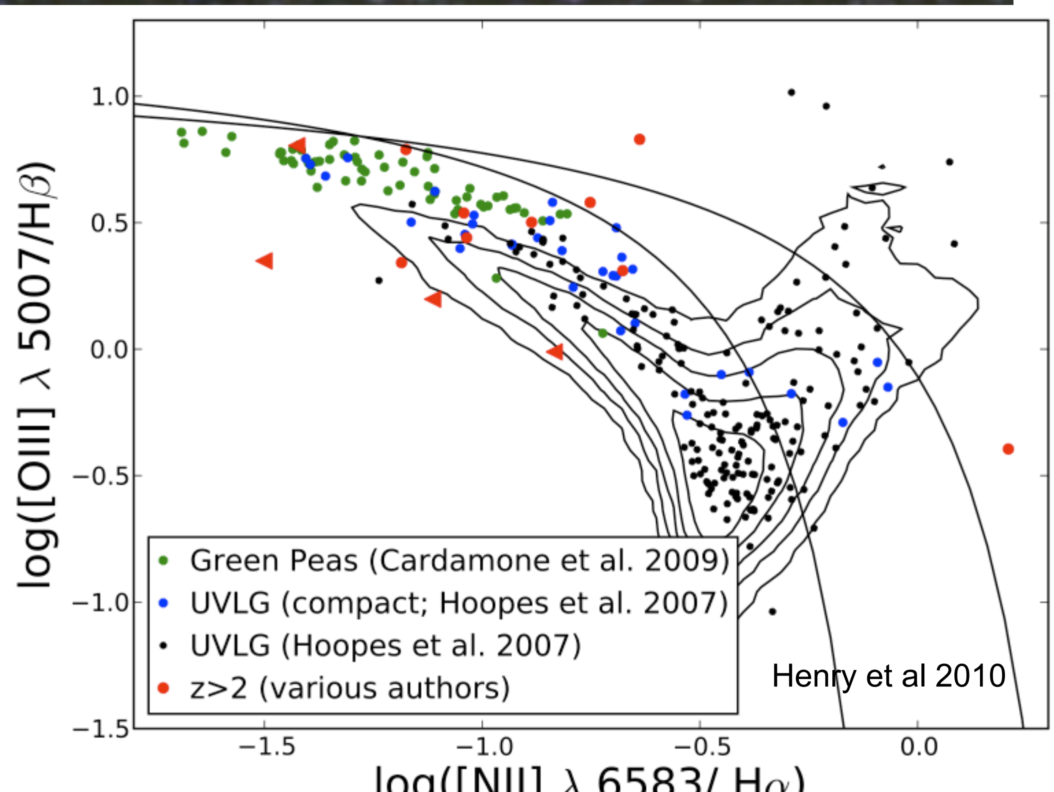
I shunned Geology to get away from rocks

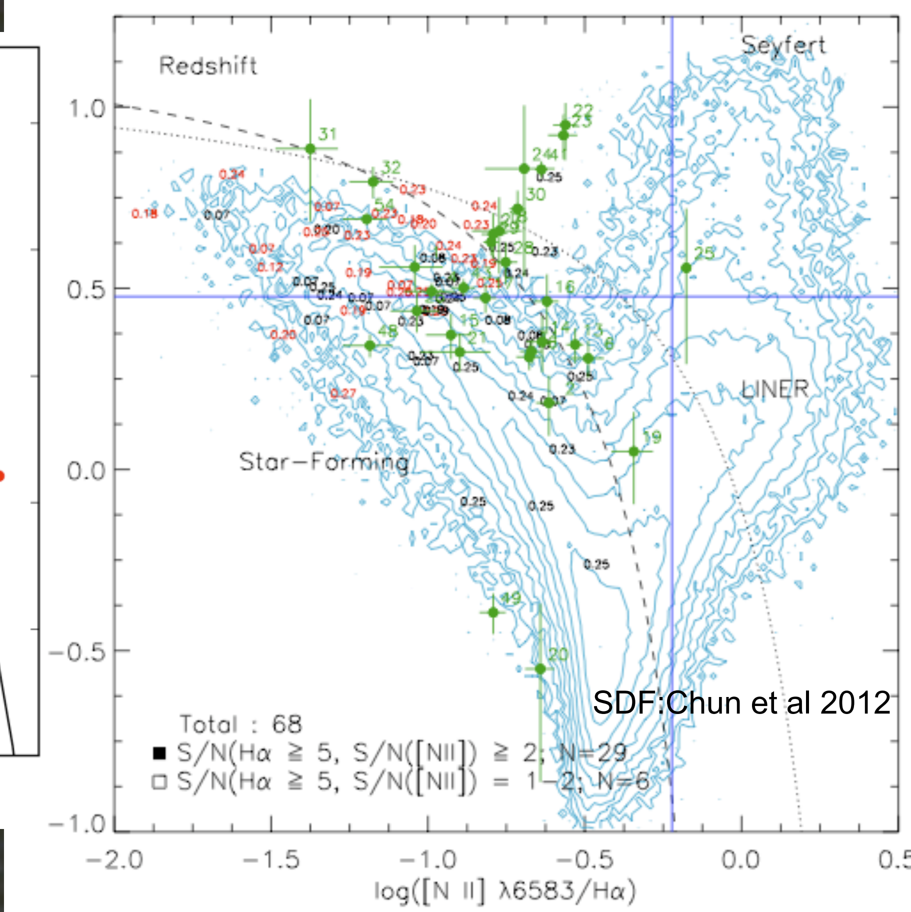
Help! Our rest-frame *gas diagnostics* are broken!
The [OIII] Problem at z>0

Starburst Galaxies are Different from local ones:
Extremely High-Ionization gas ([OIII]/Hβ > 3)

It messes up our key line ratio diagnostics, such as the *BPT* diagram:

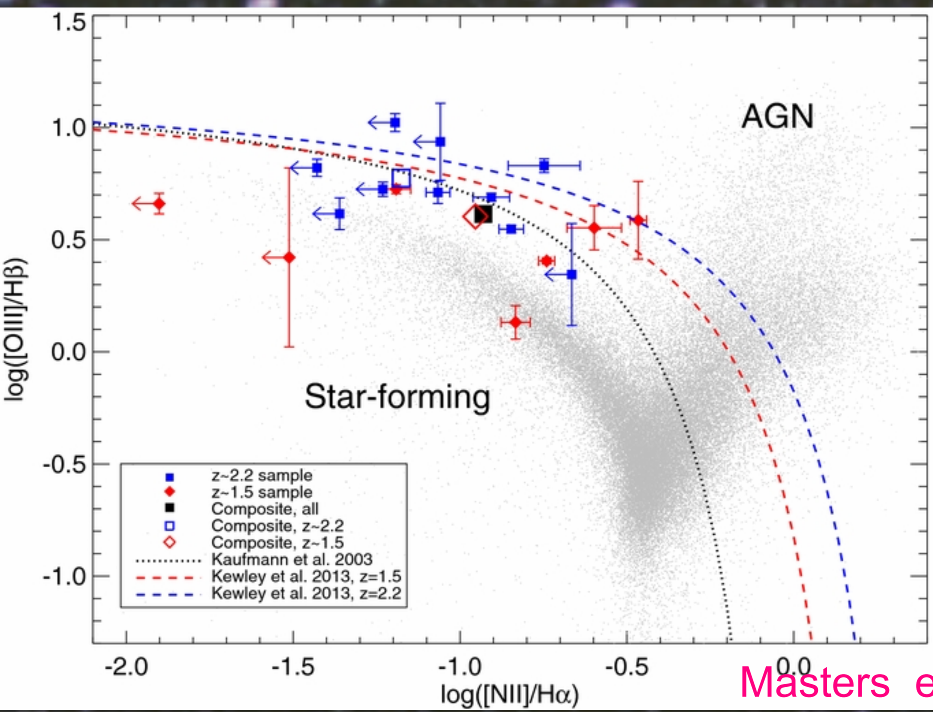
- Purely (?) Star-forming galaxies are shifted (wrt Sloan local contours) towards the "Composite" (AGN+HII) region, due to their excessive ionization

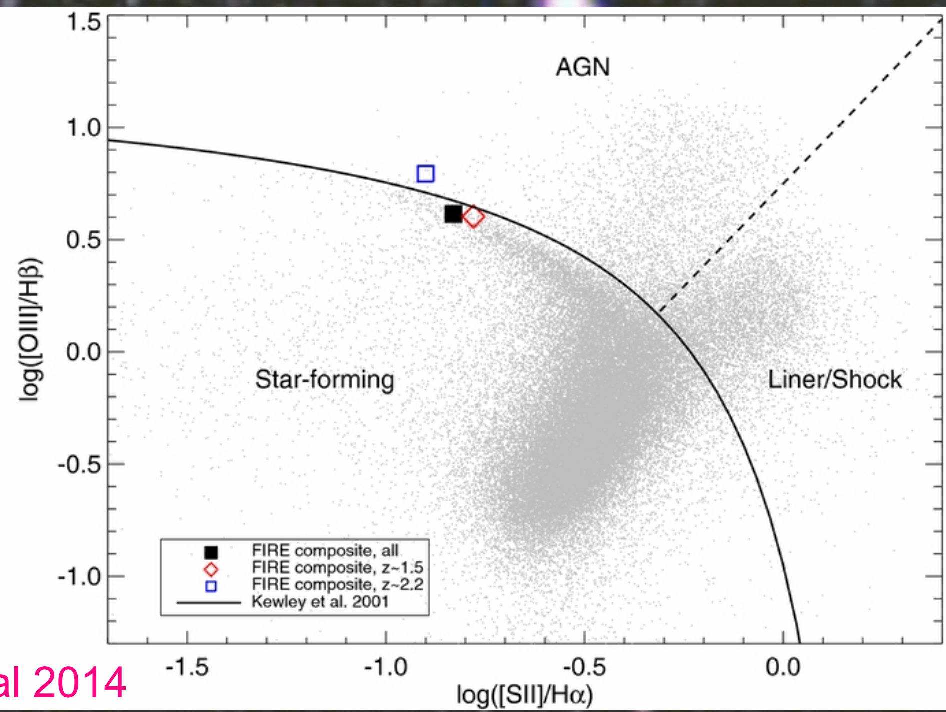




Proposed Solutions(?) to the [OIII] Problem:

1. Lower Metallicity (No: problem is at fixed [O/H])
2. Higher Ionization Parameter (No: would suppress [NII])
3. Higher Density (No: contradicts [SII] ratios)
4. AGN Component (No supporting evidence for AGN, shocks)
5. Harder Ionizing Spectrum (No: other lines 'normal')
6. "Enhanced" N/O ratio? Could it be the [NII]/Ha is 'too high'?



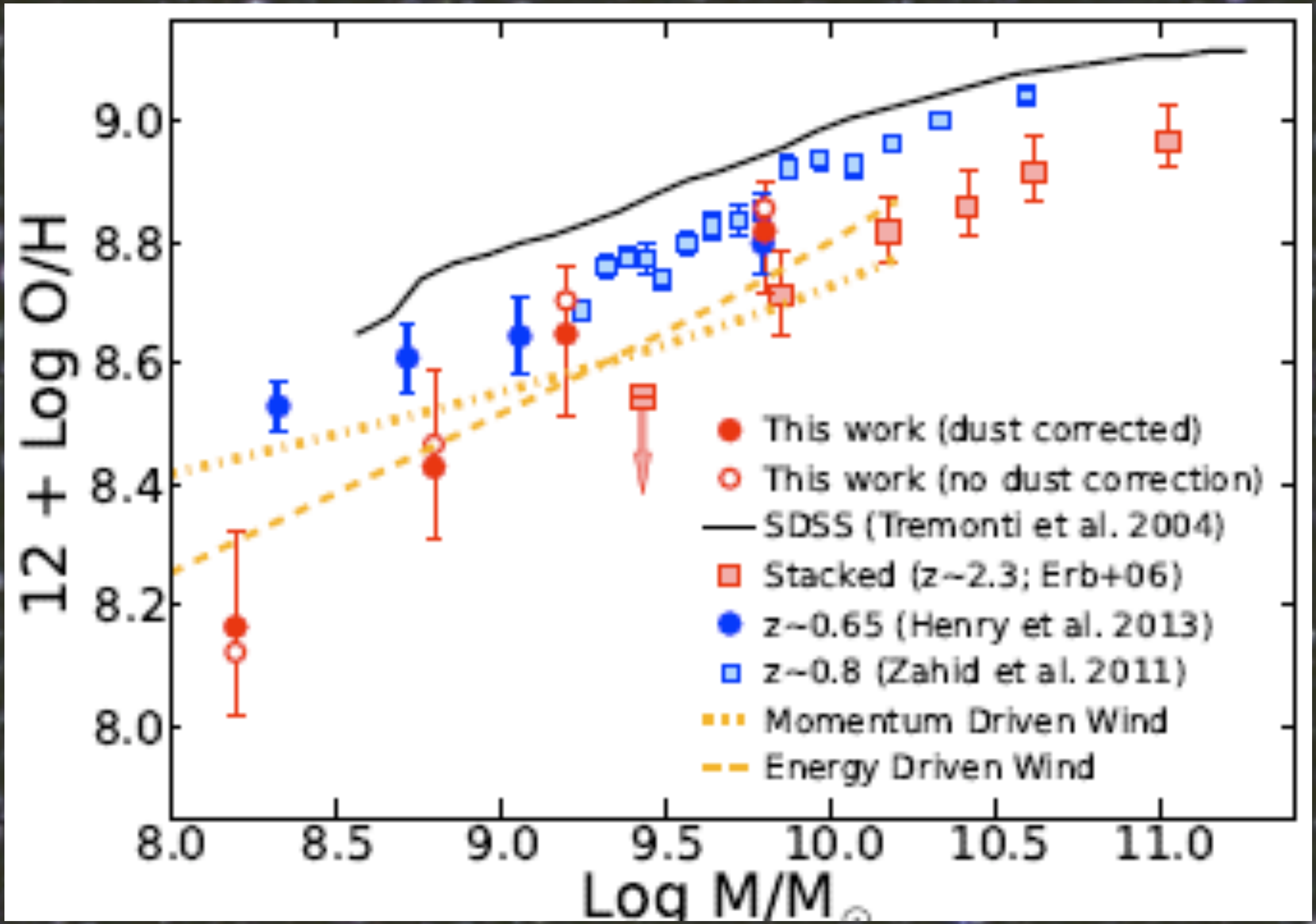


Masters et al 2014

Our Rest Frame Optical (“strong line”) Metallicity Measures
…Are also broken

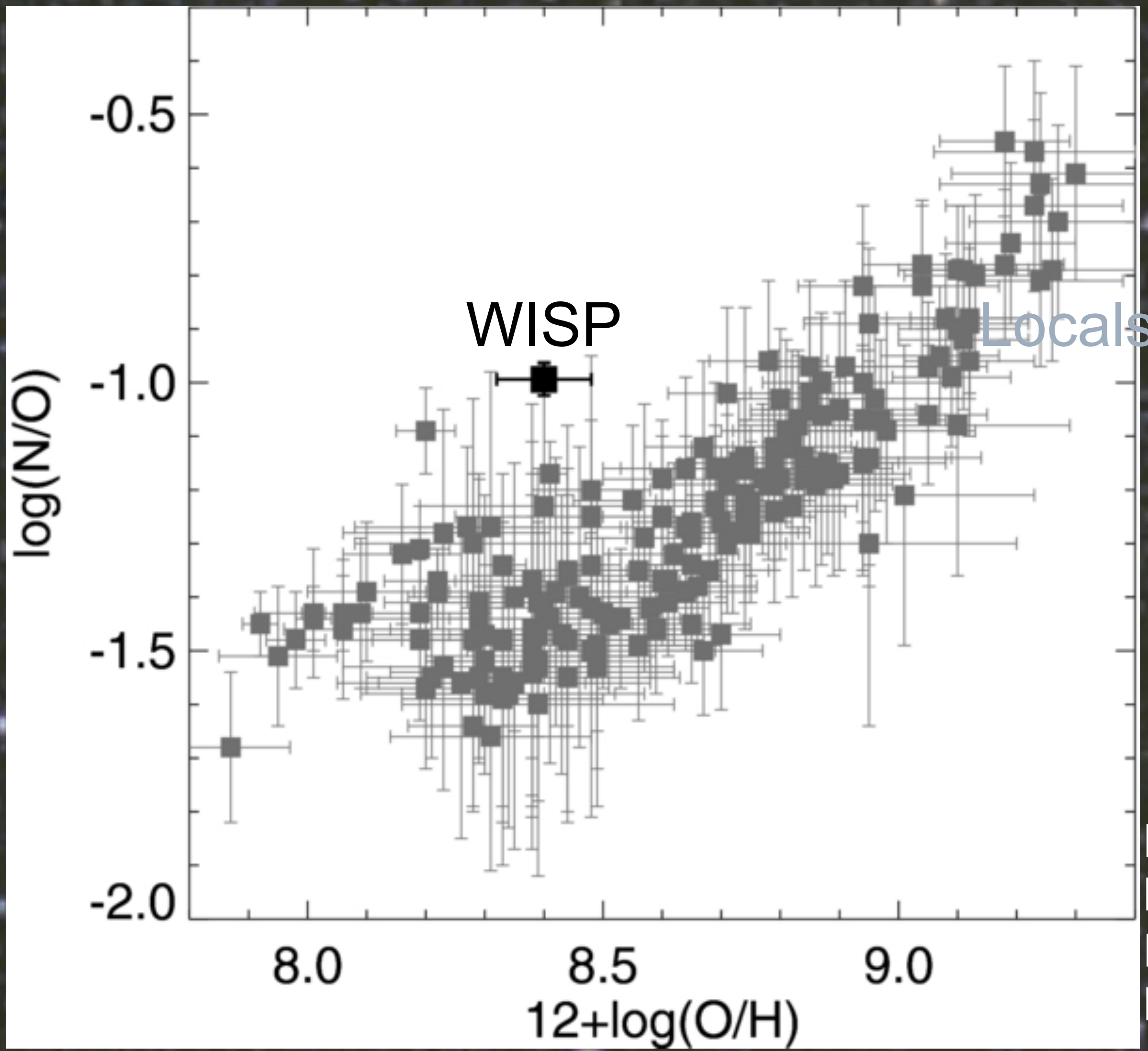
WISP Emission Line ratios *Indicate* very low metal abundances

But we cant trust Mass/ Metallicity relations



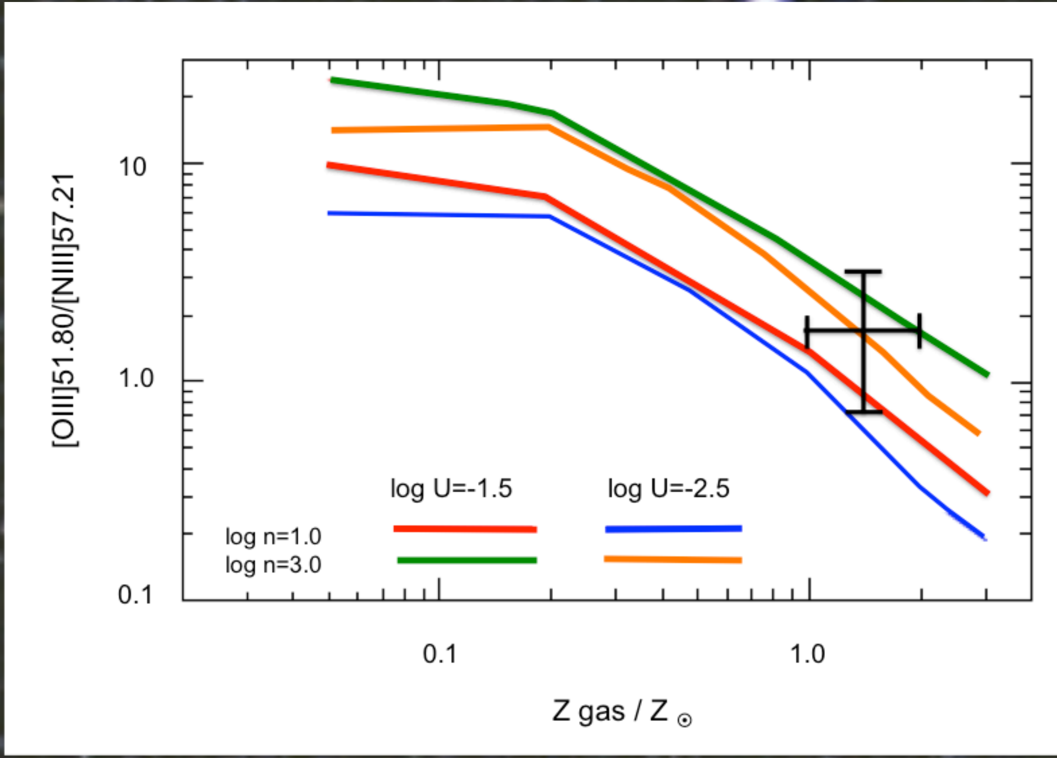
Henry, et al 2013

Build-up of ‘secondary’ nucleosynthesis product Nitrogen, relative to ‘primary’ Oxygen may have been more rapid at earlier cosmic times



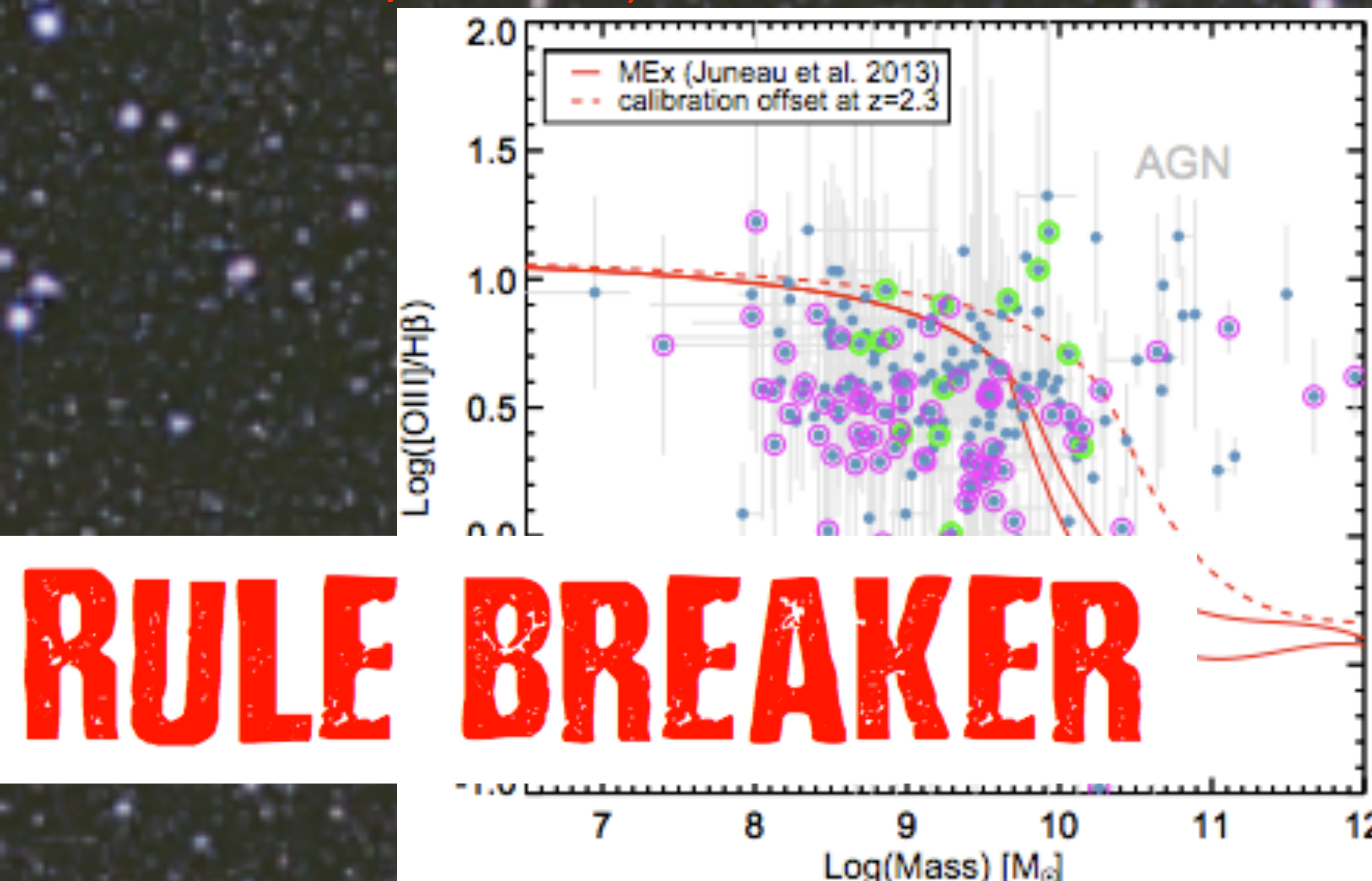
Don’t trust either axis,
Based on strong optical
Emission lines
Masters et al 2014

To the Rescue!
MIR-FIR spectroscopy of fine structure lines
to measure galaxies metallicities throughout the redshift range z=0-3



- determine metallicity through modelling: a number of mid and far infrared lines can be used for this purpose. Nagao et al (2011) showed how metallicities can be determined without hydrogen line detections.
- [OIII]52μm, [NII]57μm and [OIII]88μm are quite strong and unaffected by dust so these will be used to measure metallicities.

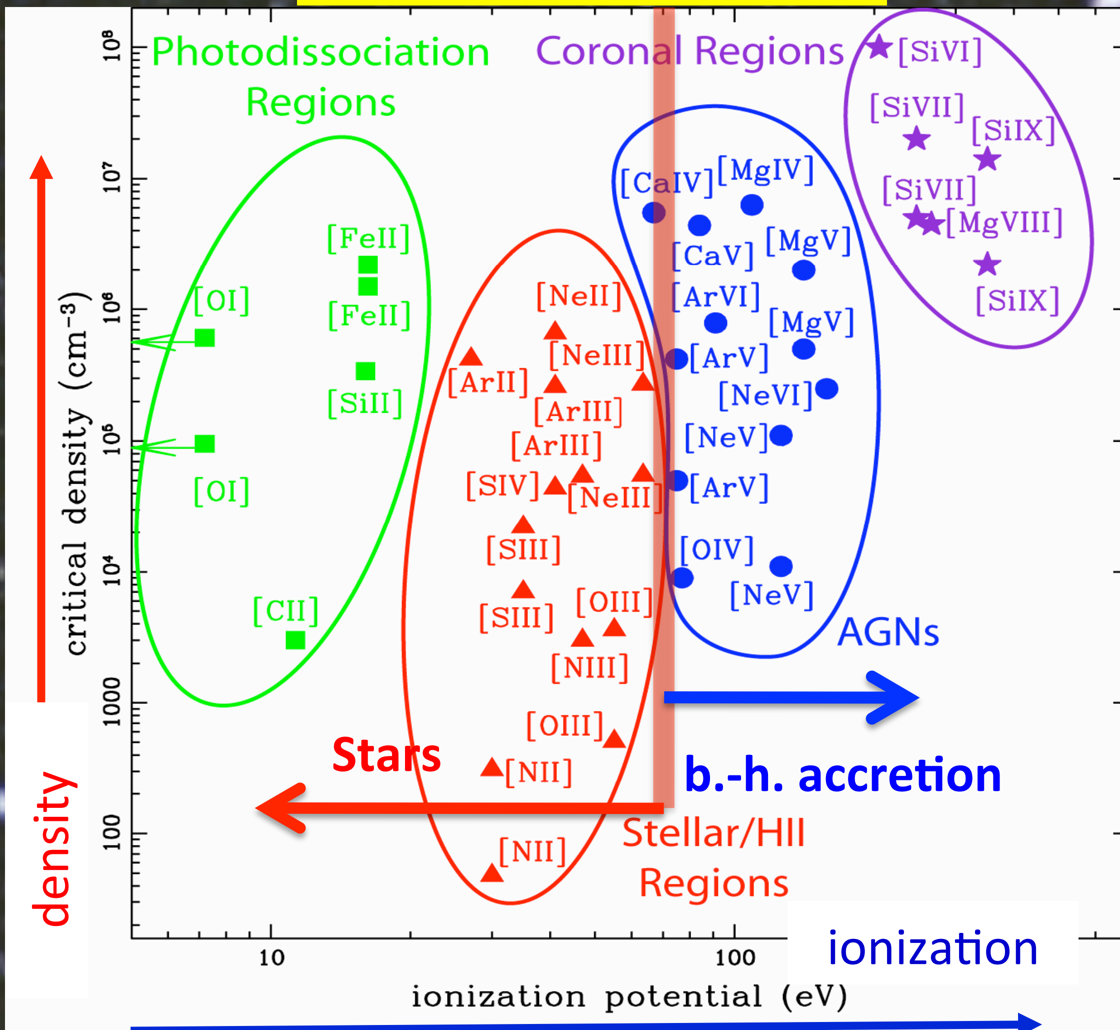
The local MEx diagram is similarly in trouble at higher redshifts.
(Its power to discriminate AGN from starbursts drops at z>1)



Juneau, Atek et al 2014, and others…

Why is infrared spectroscopy the best tool to isolate star formation and accretion?

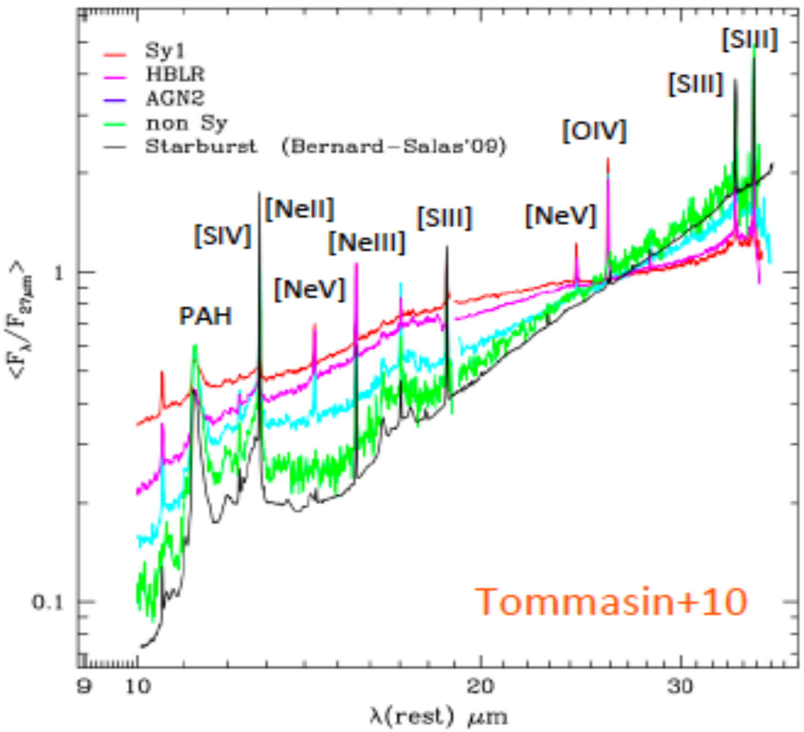
Infrared fine structure lines



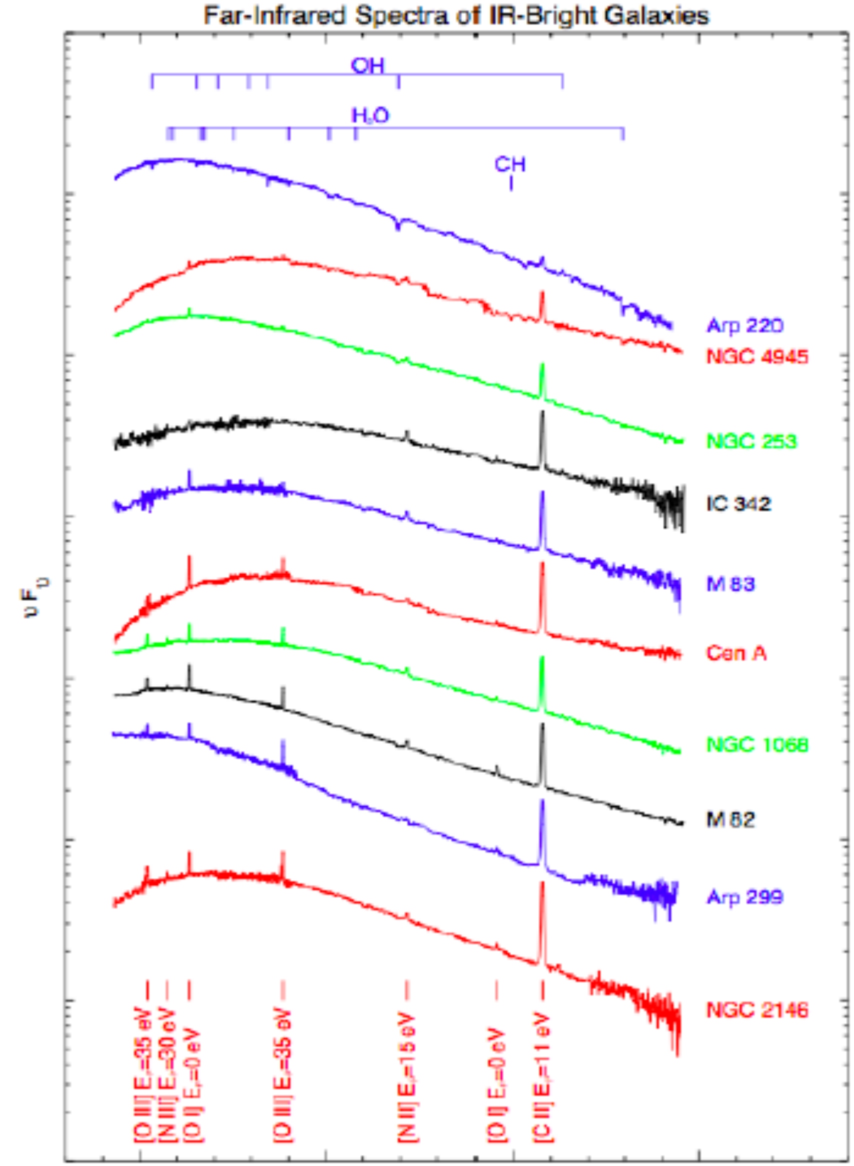
IR fine structure lines:
- separate different physical mechanisms,
- fully cover the ionization-density parameter space
- do not suffer from extinction

Spinoglio & Malkan '92 predicted line intensities of IR lines in active and starburst galaxies, before ISO launch.

Plenty of strong mid- and far-IR features to detect high-z galaxies and measure redshifts

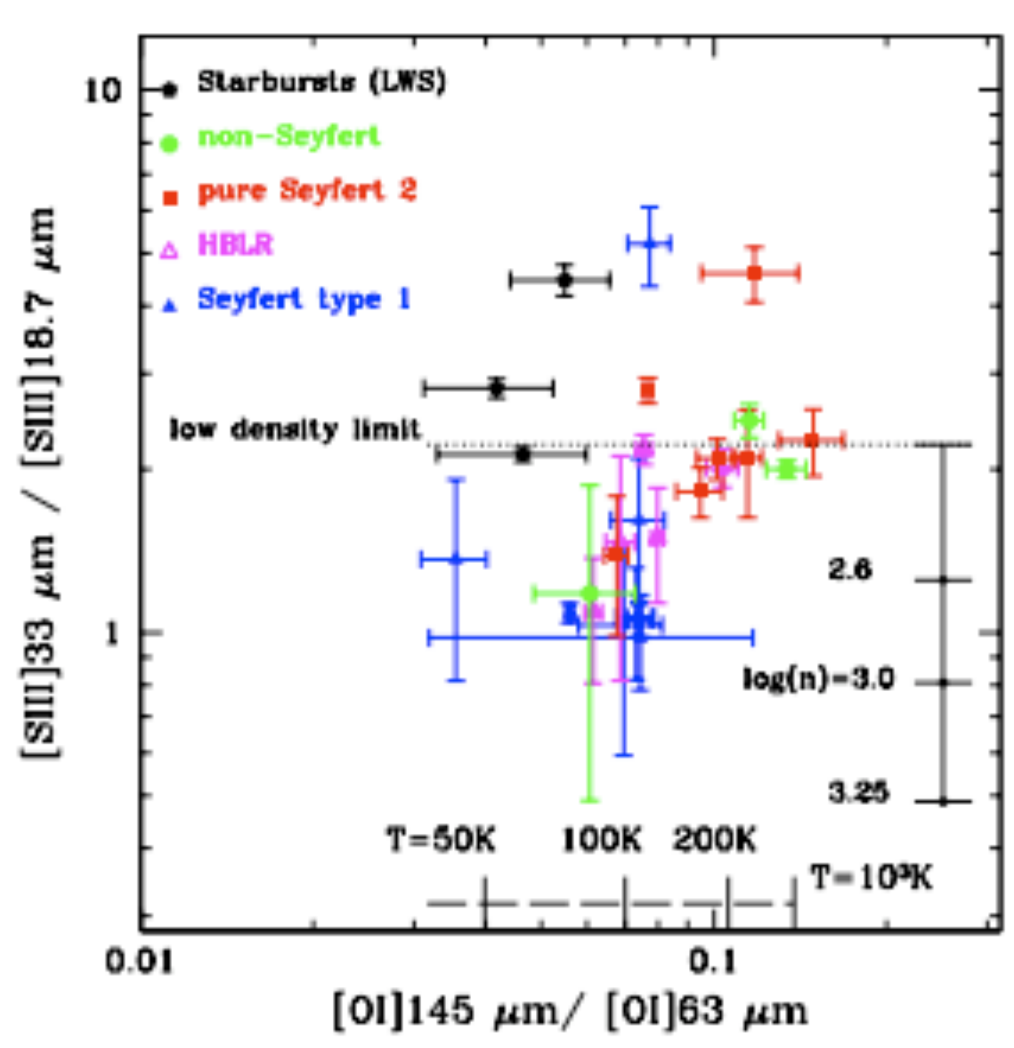


High z--IRS



Intermediate z--ISO/LWS

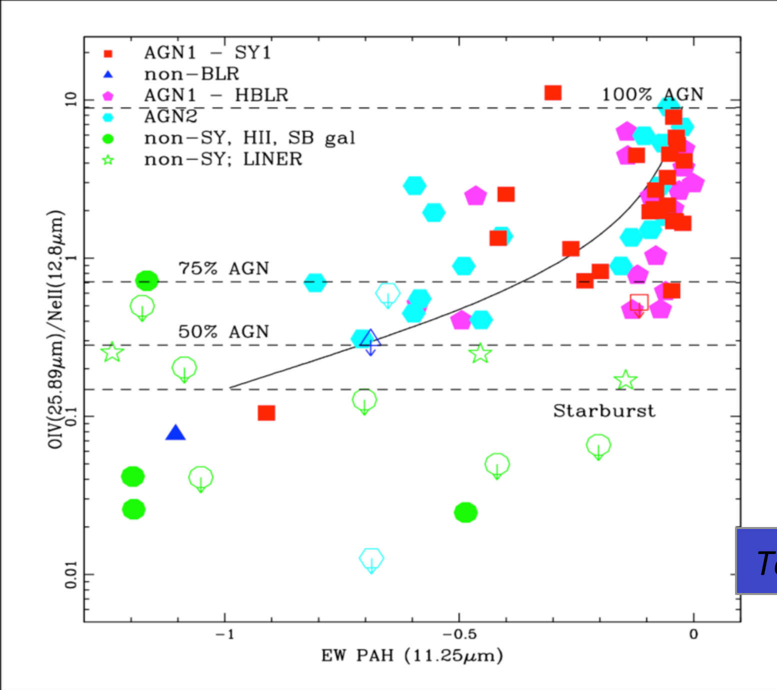
Gas Diagnostics
(Many line ratios give density, temperature over the full range of astrophysical conditions)

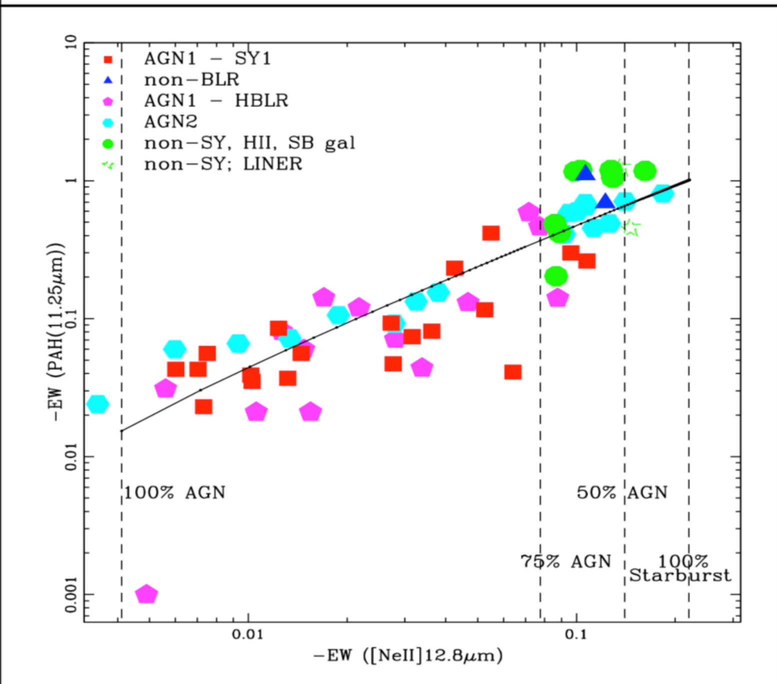


Herschel/PACS Spinoglio et al 2015

Mid-IR Line Diagnostics Spitzer/IRS

Tommasin+10, ApJ, 709, 1257

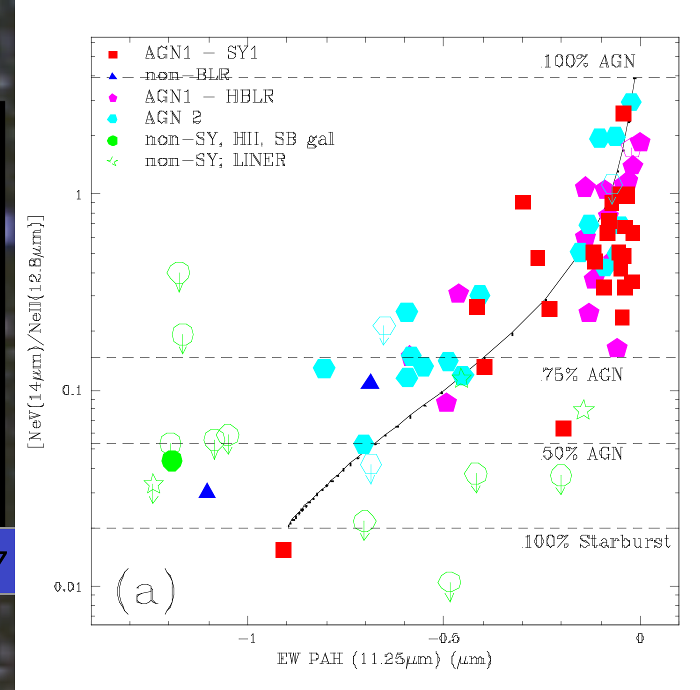


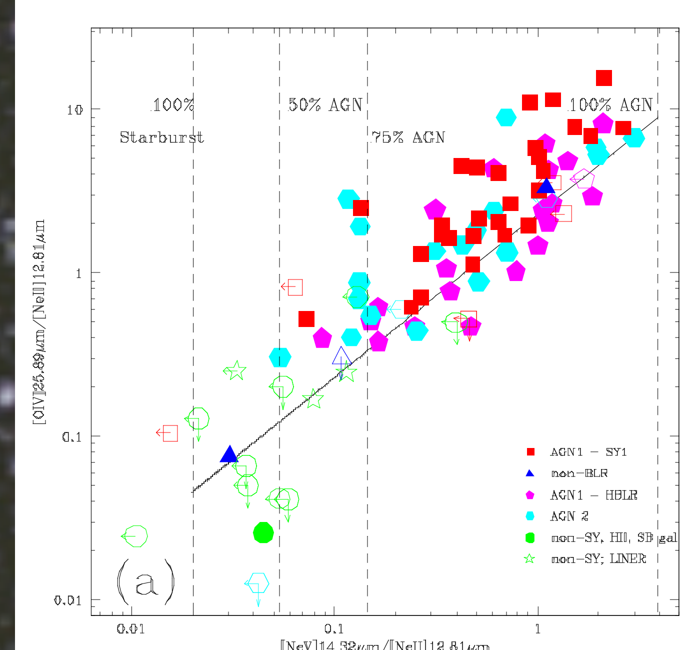


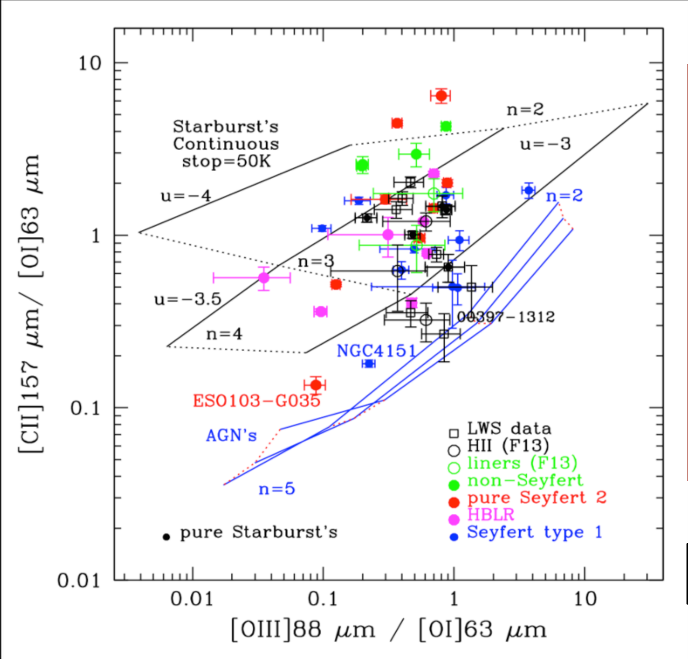
Strong mid--IR features to detect high-z galaxies and measure redshifs

↓

IRS 7" spatial resolution was inadequate even for these local galaxies, but spectra Quantitatively disentangle AGN from starburst

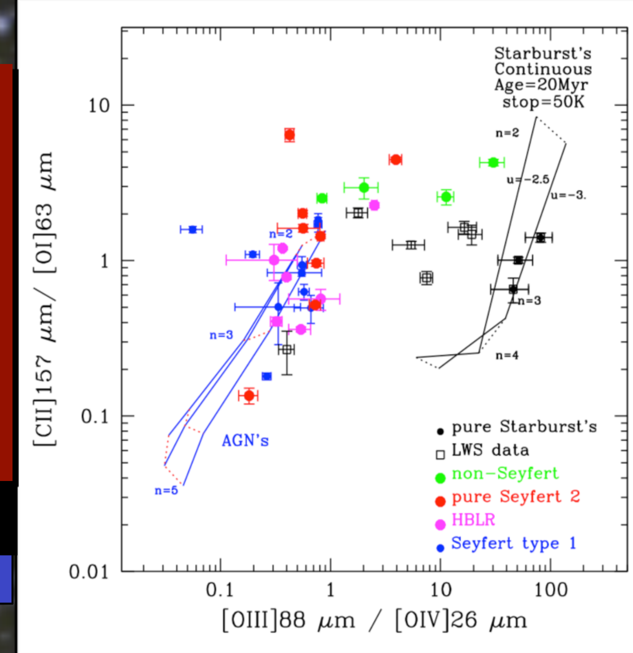


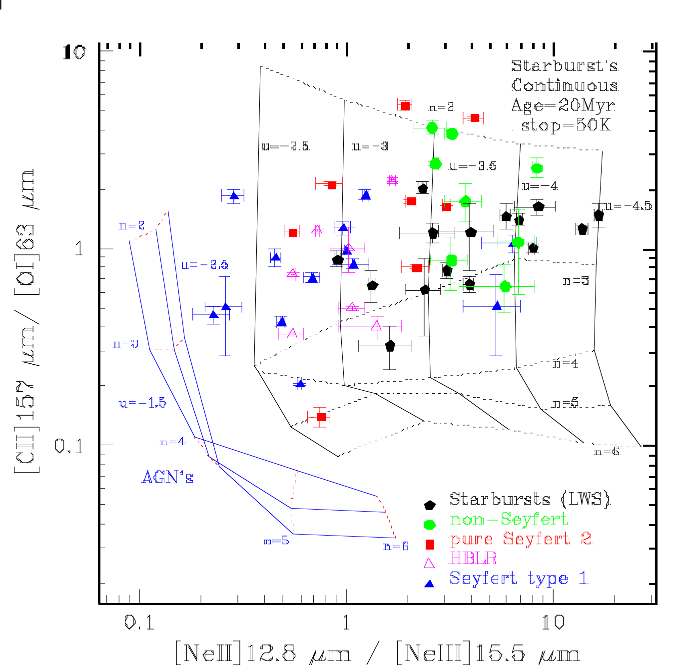




Mid-IR + Far-IR Diagnostics: Spitzer + Herschel

Spinoglio+15, ApJ, 799, 21





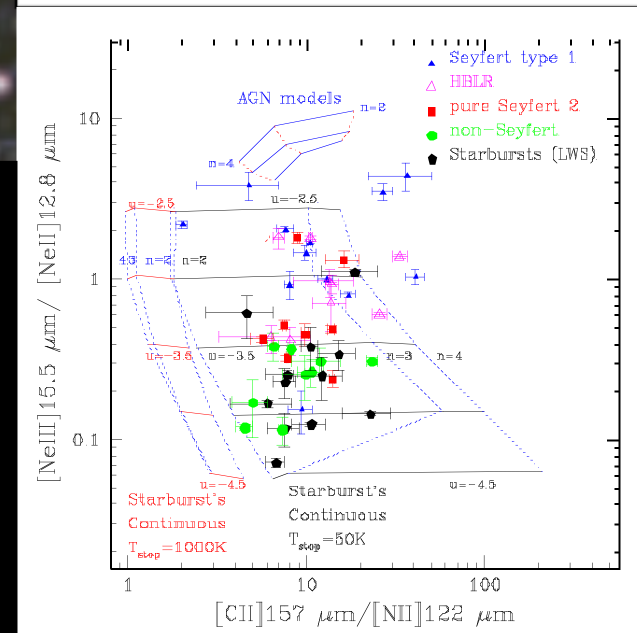
far-IR lines (from [NII] and [CII] can measure the contribution of PDR (Photo-Dissociation Regions)

↓

Disentangle AGN and HII regions from PDR

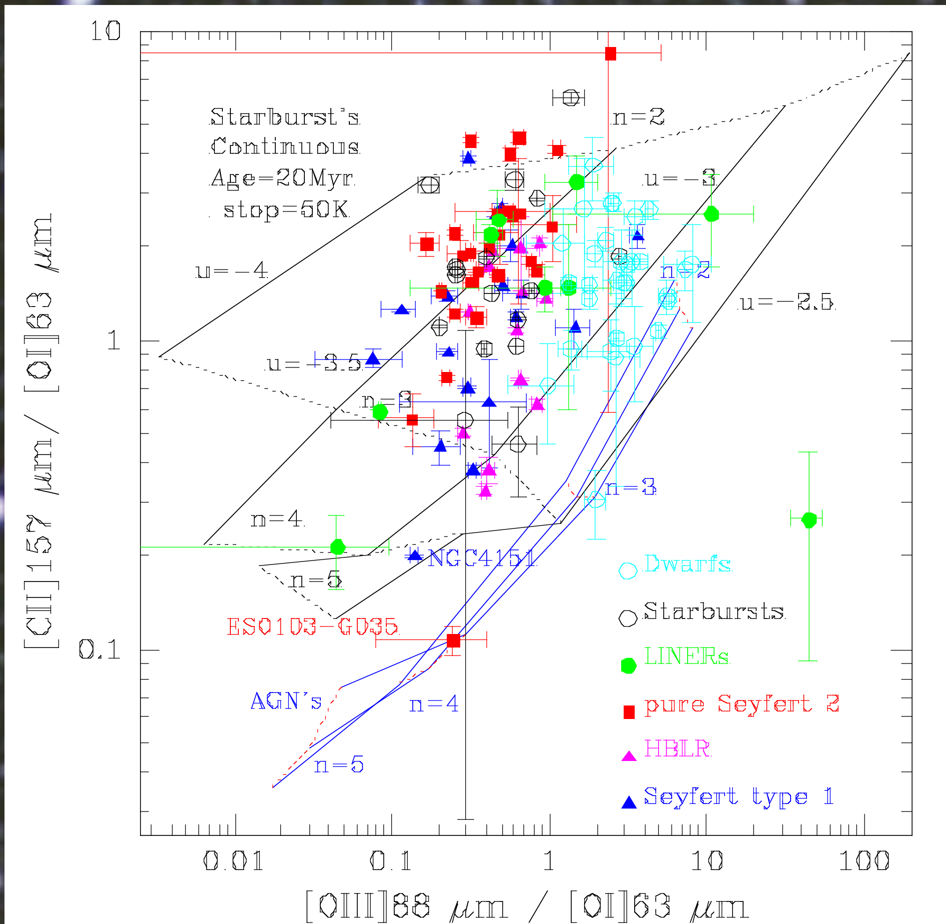
We'll have a good local z=0 baseline

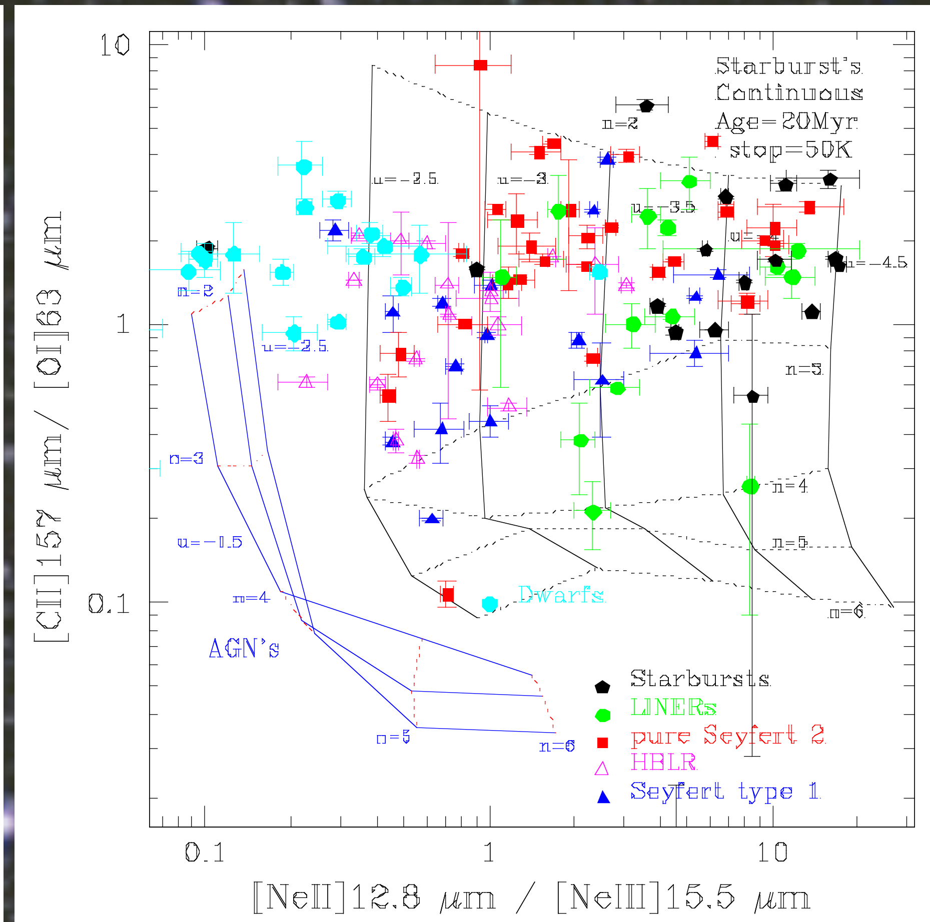
(At high z, galaxies are going to be very hard to map in IR)



22

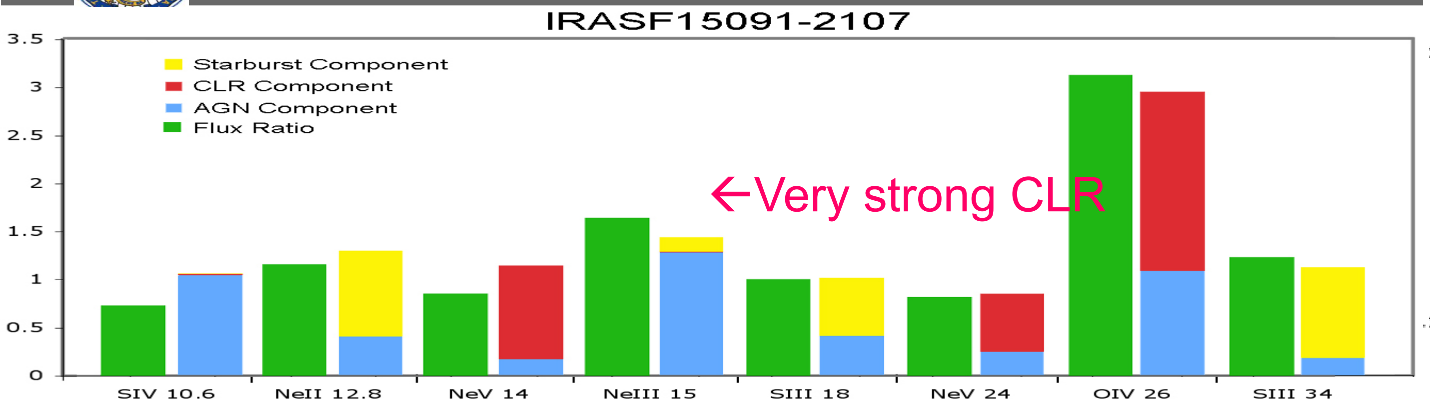
Extending the work to all AGNs measured in the Local Universe with Herschel-PACS spectroscopy (about 170 AGNs) (Juan Antonio Fernández-Ontiveros, LS et al 2015)

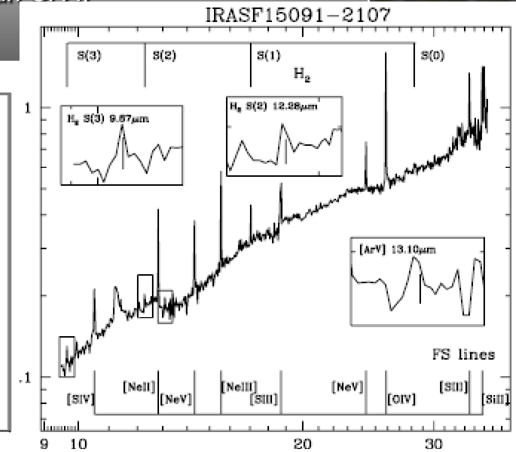


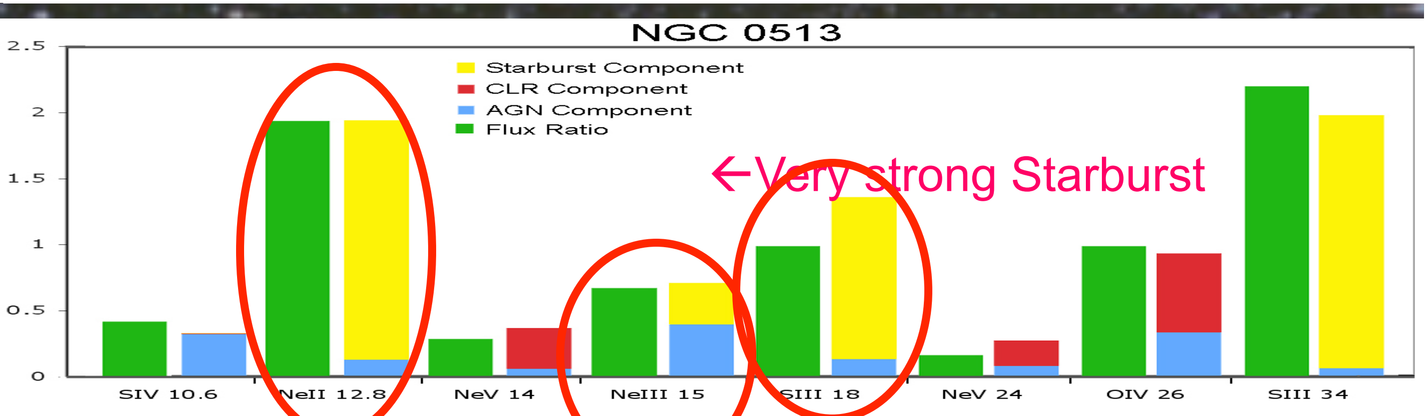


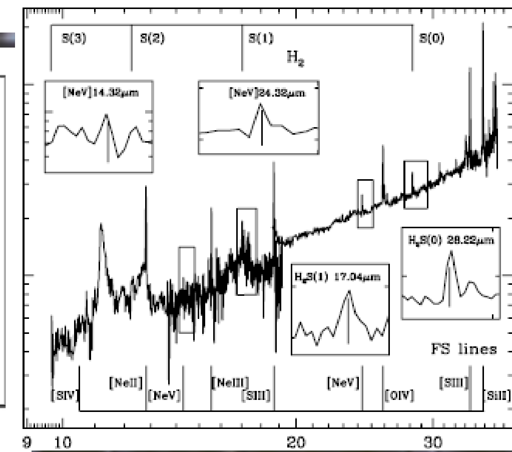
Mid-infrared Line Diagnostics Of Seyfert Galaxies From The 12 μM Sample

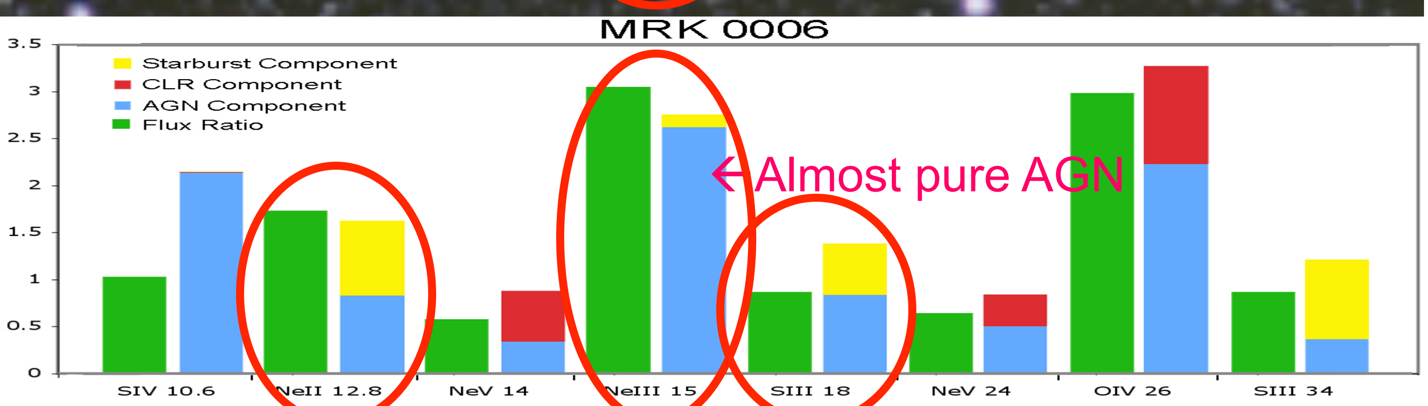
K. Hainline (UCLA), M. Malkan (UCLA), L. Spinoglio (INAF, Italy), H. Smith (Harvard-Smithsonian CFA)

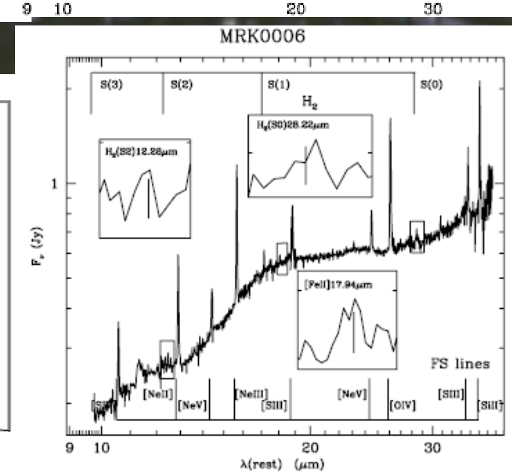








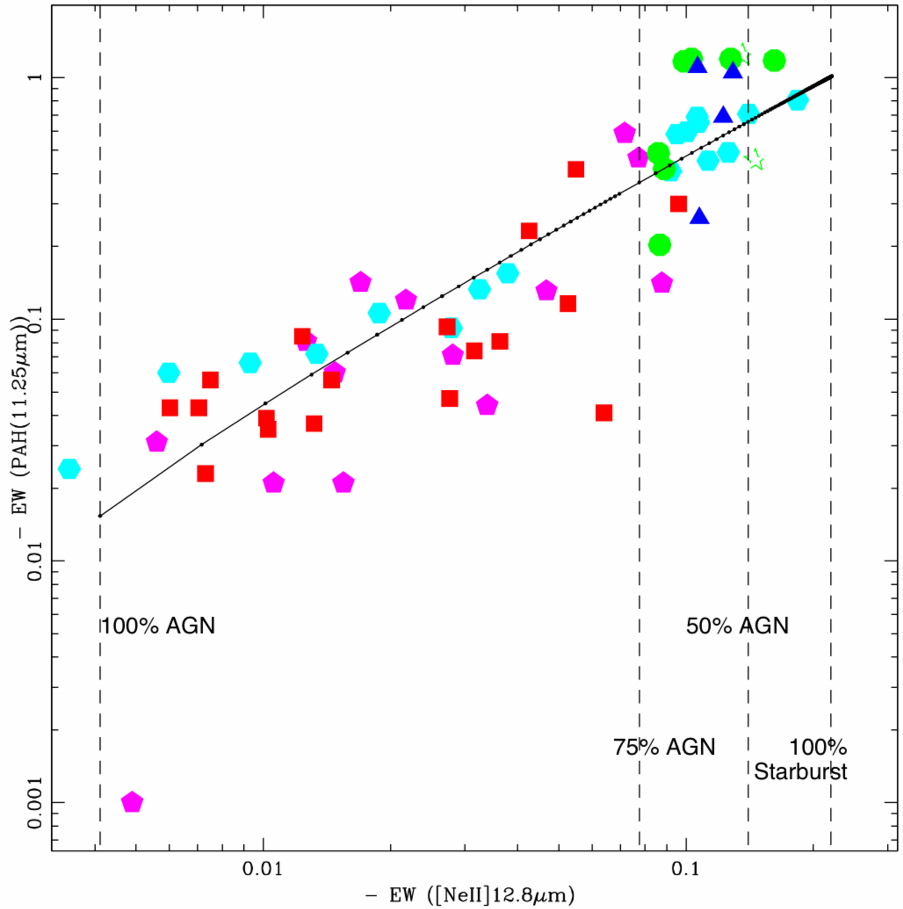


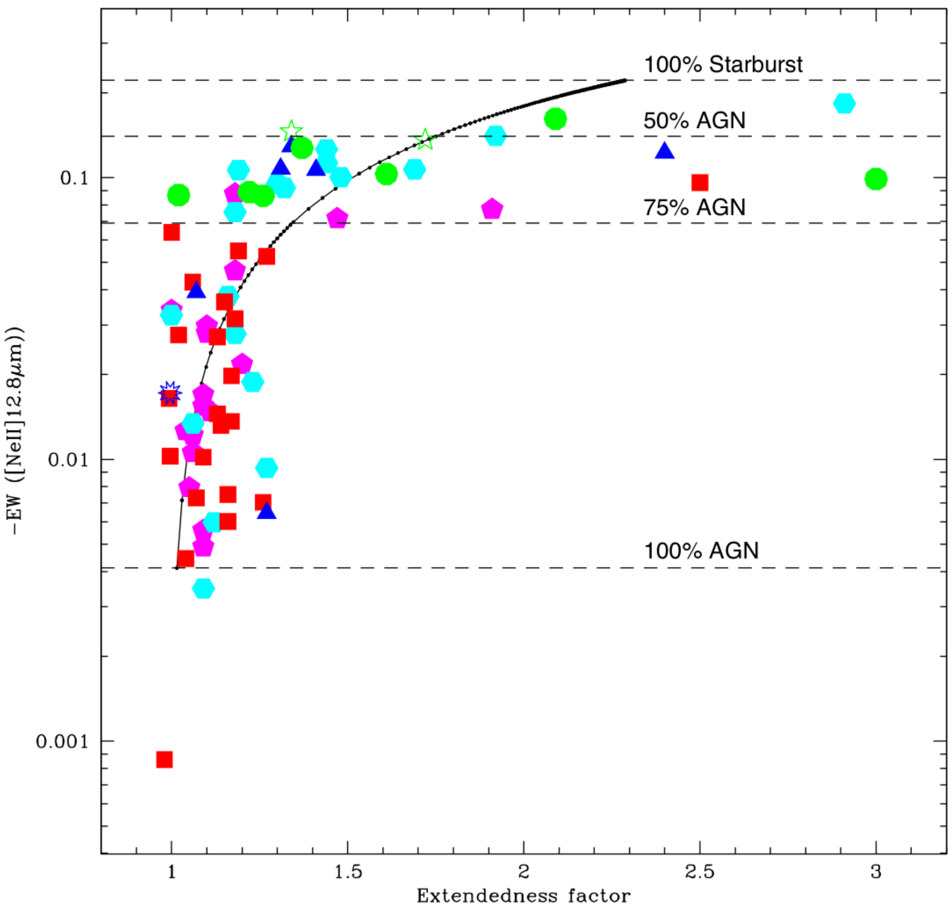


Equivalent width=ratio of non-AGN emission to underlying AGN Mid-IR continuum

- Thus E.W. of non-AGN emission such as [NeII] and PAHs is inversely proportional to AGN fraction of mid-IR light.
- And the more AGN light, the more compact the mid-IR continuum:

  “Extendedness” = Ratio of 19um continuum in big slit/small slit



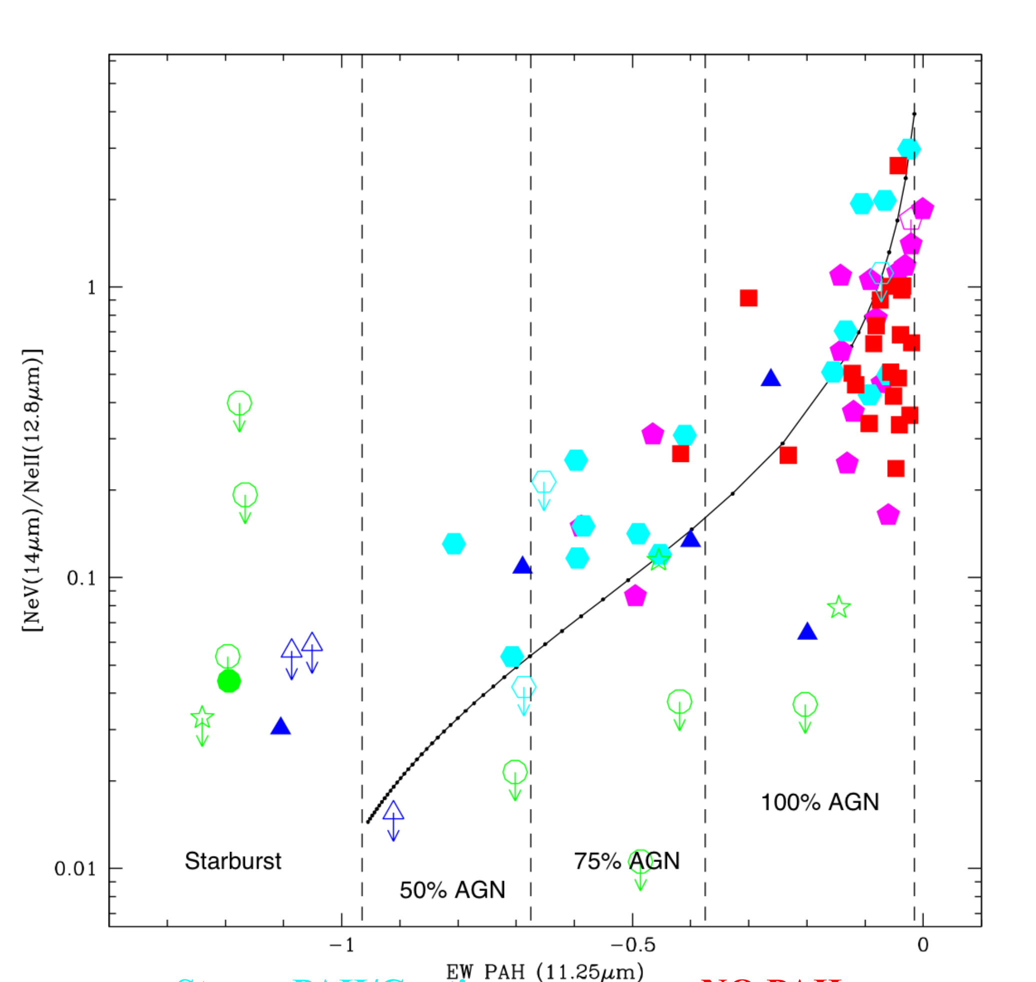


AGN/Starburst Mixing Diagrams comparing Lines and Continua

Seyfert 1's (red) and Seyfert 2's with Polarized Broad Lines (magenta) have mid-IR emission dominated by AGN, in contrast to starbursts and LINERs (green). *Seyfert 2's without Polarized Broad Lines (cyan) are a mixed bag. Some probably have their central AGN shut down currently* (ie this century).

These ionization-sensitive []-line ratios give the same quantitative estimates as the IR dust continuum:

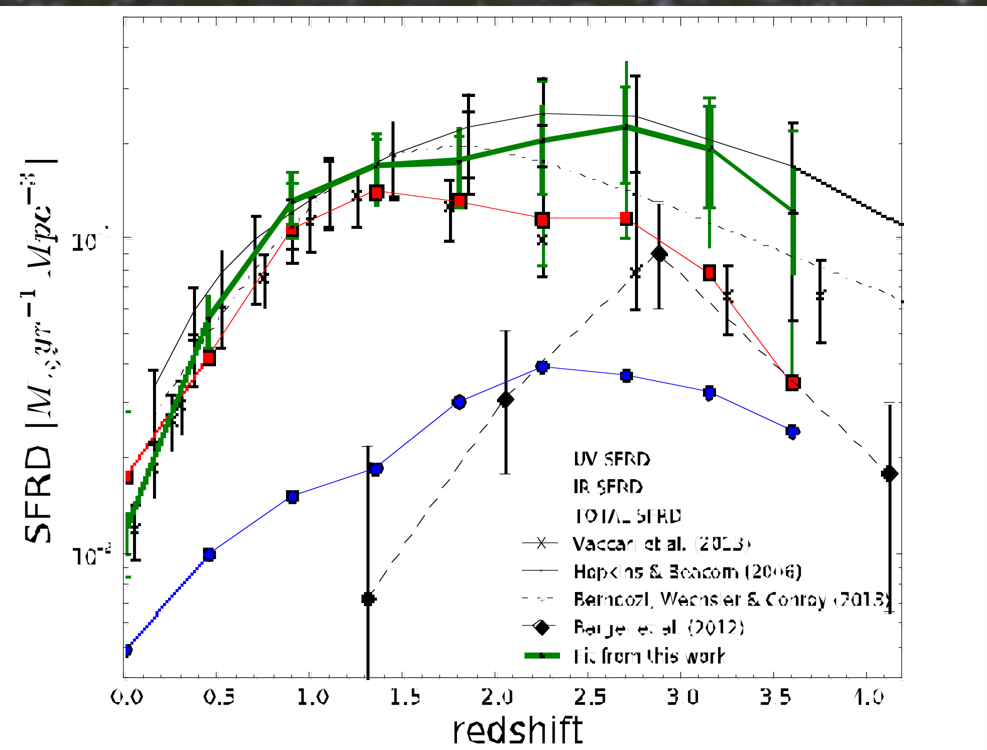
A stronger AGN *line* contribution is closely tied to stronger (nonstellar) 2--25um *continuum* from hot dust near the nucleus, with NO PAH's.

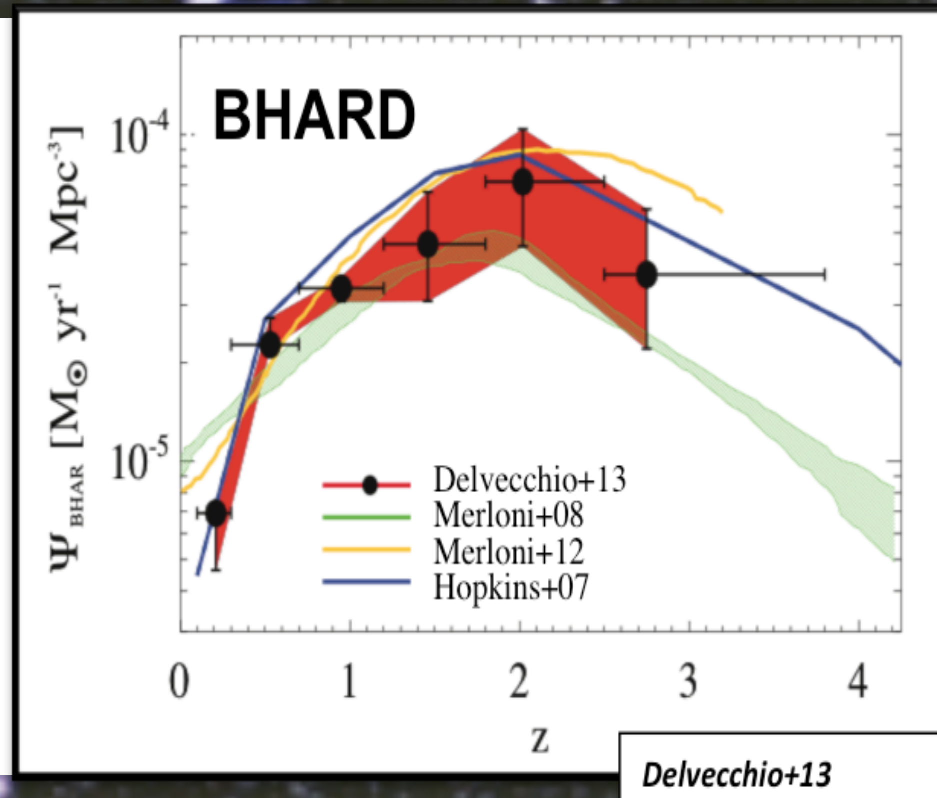


Strong PAH/Continuum **NO PAHs**

[At her IPAC talk I first asked my future wife for her phone number. As a good scientist, …]

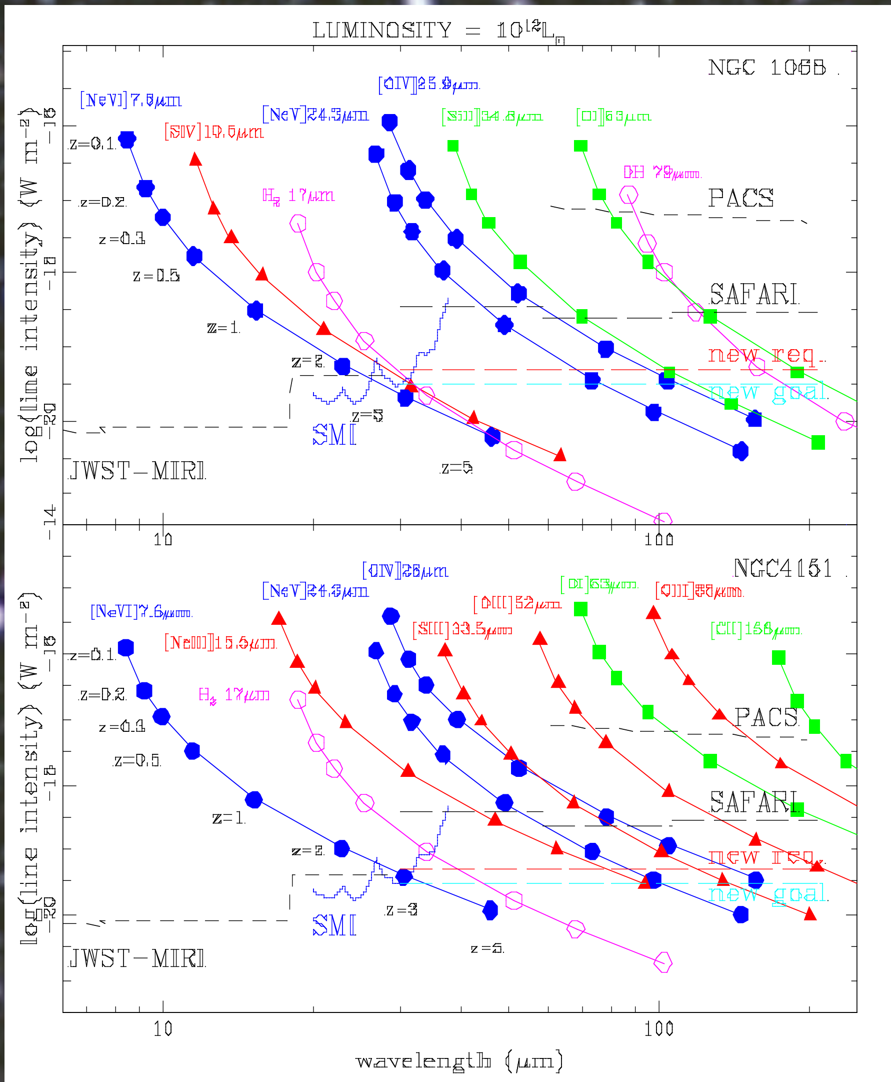
What we want to measure with MIR/FIR spectroscopy the Star formation peak and the MBH Accretion peak at *z=1-6*

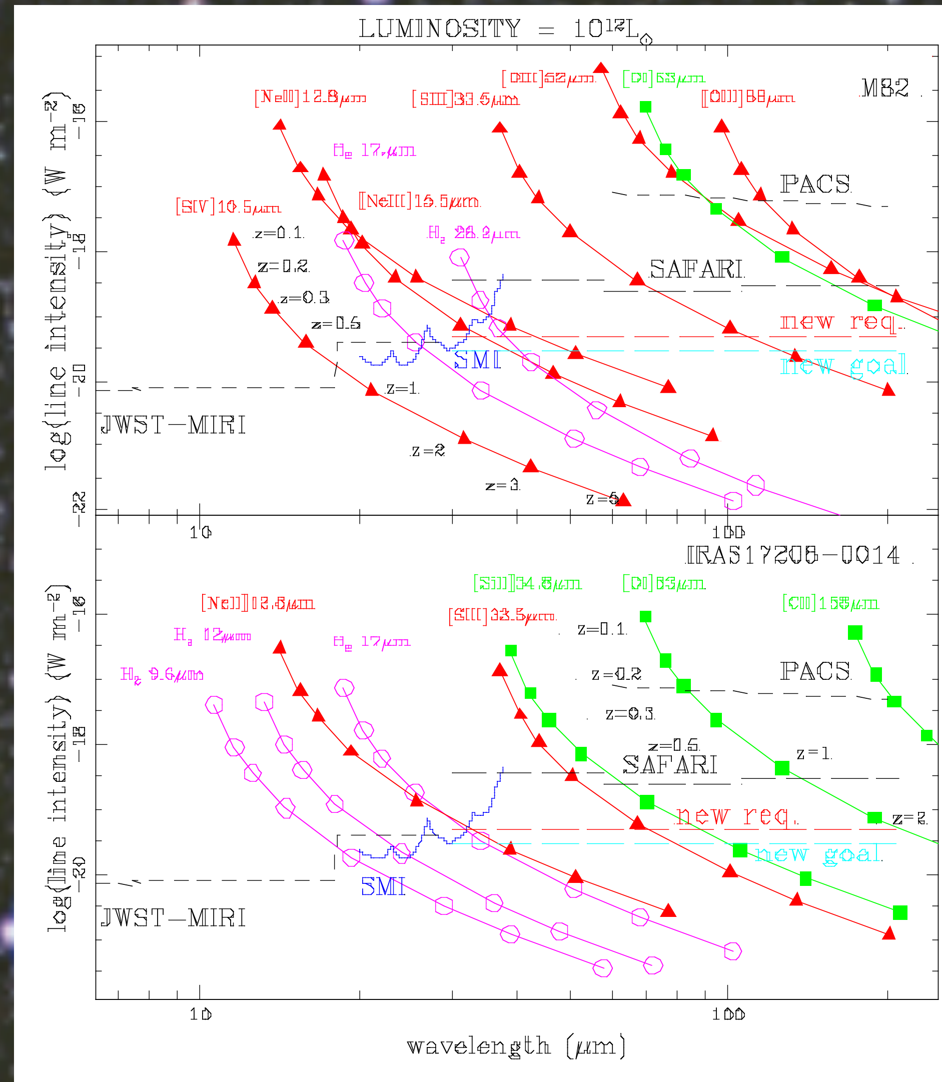




Evolution of the Star Formation Rate Density (SFRD) and of the Black Hole Accretion Rate Density (BHAR) as a function of redshif (Burgarella et al. 2013; Delvecchio et al 2014)

Four local templates: at what redshift can SPICA detect their lines ?

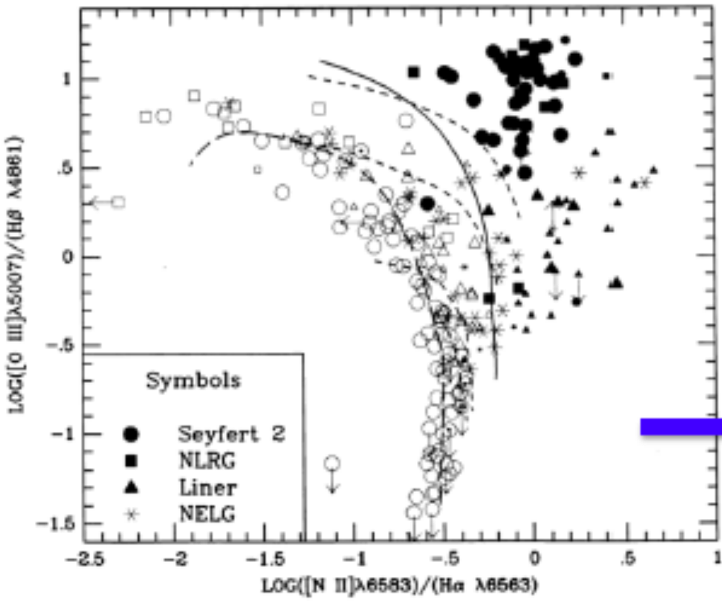




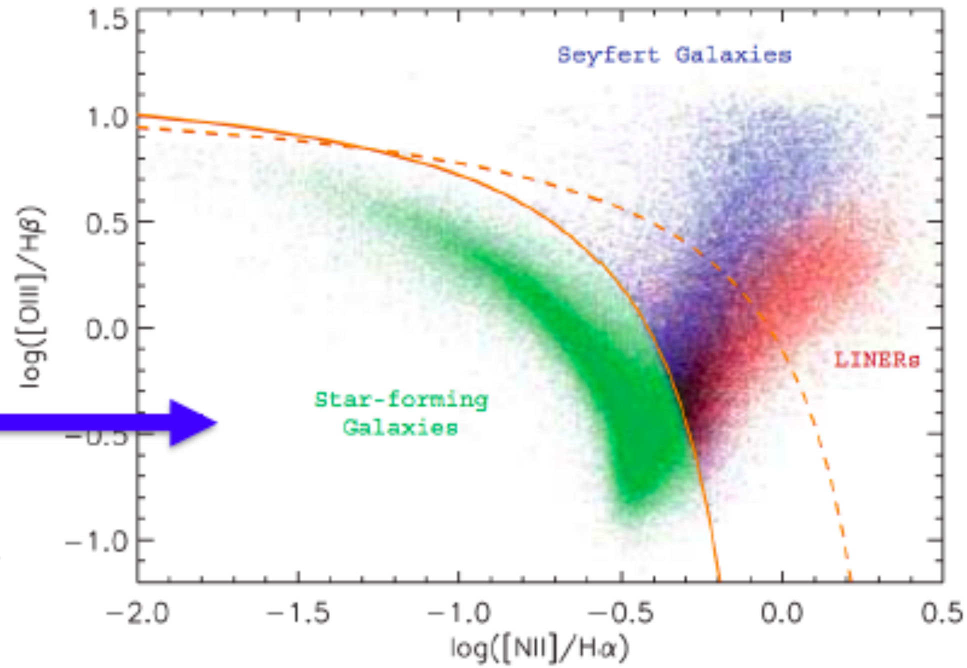
Predictions of lines observable with SAFARI, SMI and with a hypothetic spectrometer with a required line sensitivity of 5x10^{-20} W/m^2 and of 3x10^{-20} W/m^2 (1 hr. 5σ), respectively, based on local templates, scaled to a luminosity of 10^{12} L$_\odot$. Expected JWST-MIRI sensitivities are also shown. (Spinoglio et al. 2012, 2014-- also Onaka-san's talk). Left: AGN templates. Right: Starburst templates.

OPTICAL SPECTROSCOPY

Veilleux & Osterbrock **1987** (~100 galaxies)

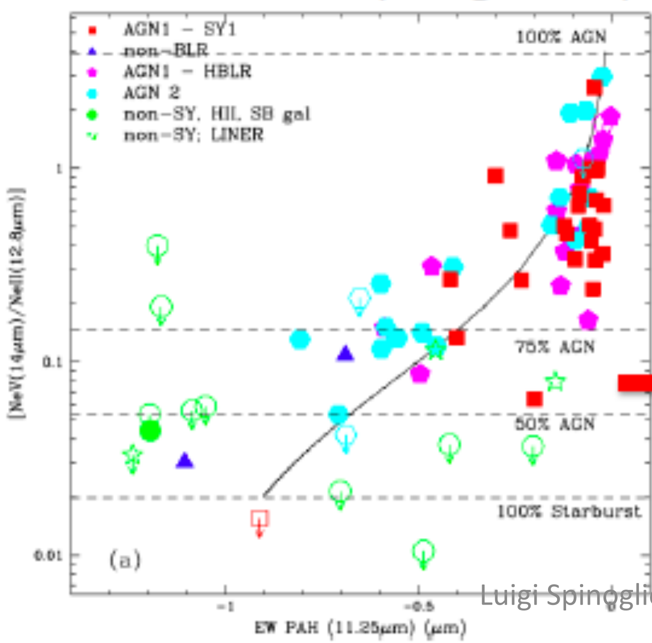


Groves+ **2006** (>10^5 galaxies)



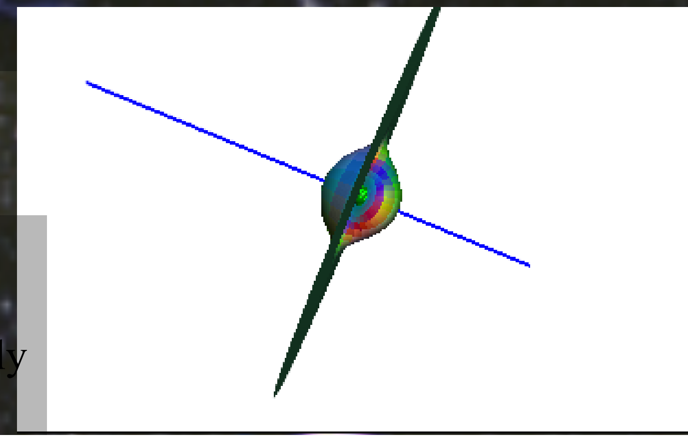
MIR-FIR SPECTROSCOPY

Tommasin+ **2010** (~60 galaxies)



SPICA ...

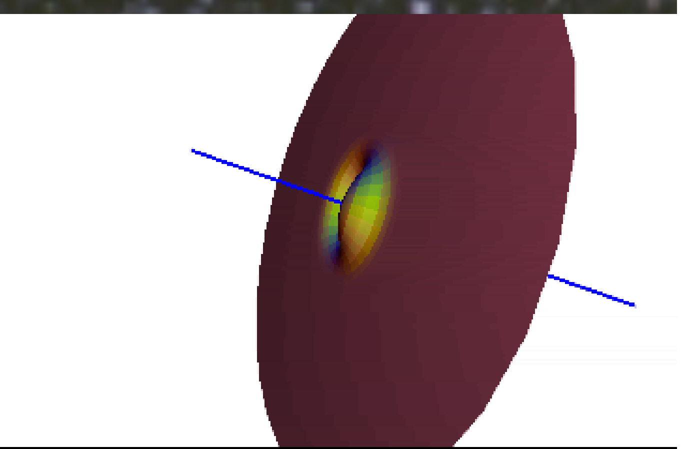
Dust must intercept much of the sky as seen from the AGN central engine. But there are several possibilities for the location of this obscuration besides a “torus”

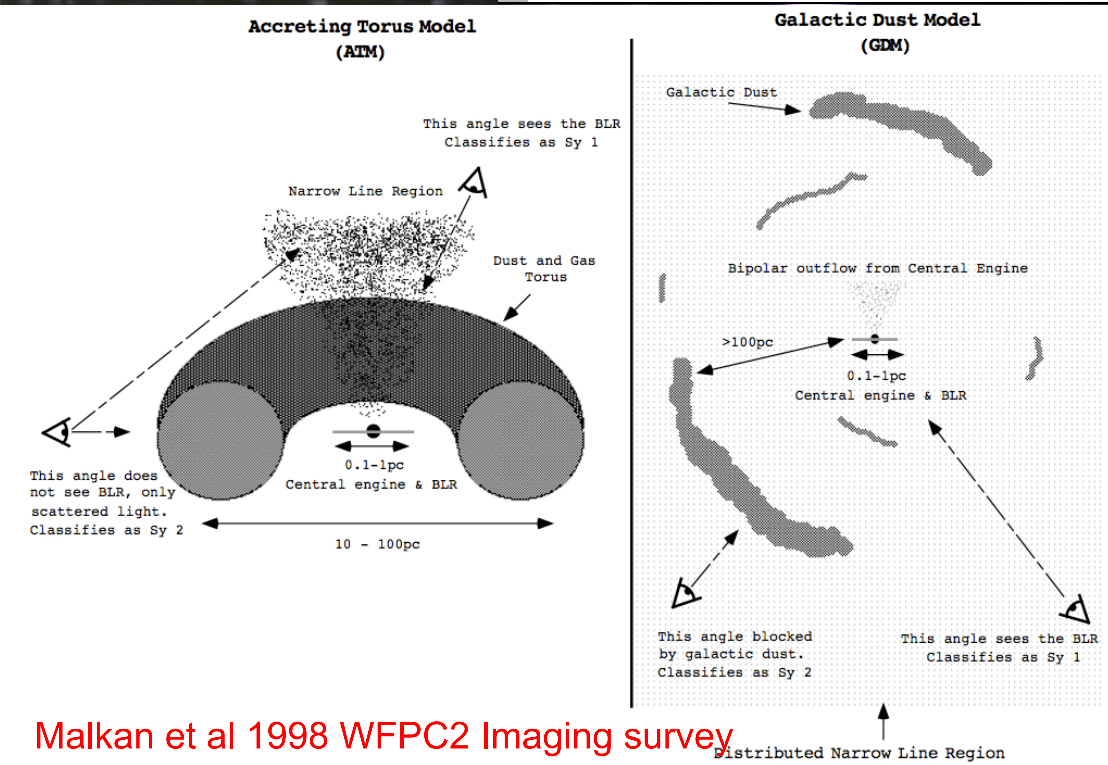


If the difference between all Seyfert 1’s and all Seyfert 2’s is entirely obscuration, we still do not know where it occurs!
We need to think ‘outside the donut’, to consider warped disks and/or radiatively driven dust walls

To constrain the geometry, we must figure out the true ratio of space densities of Sy 1s/ Sy 2s:
It’s not what you think.

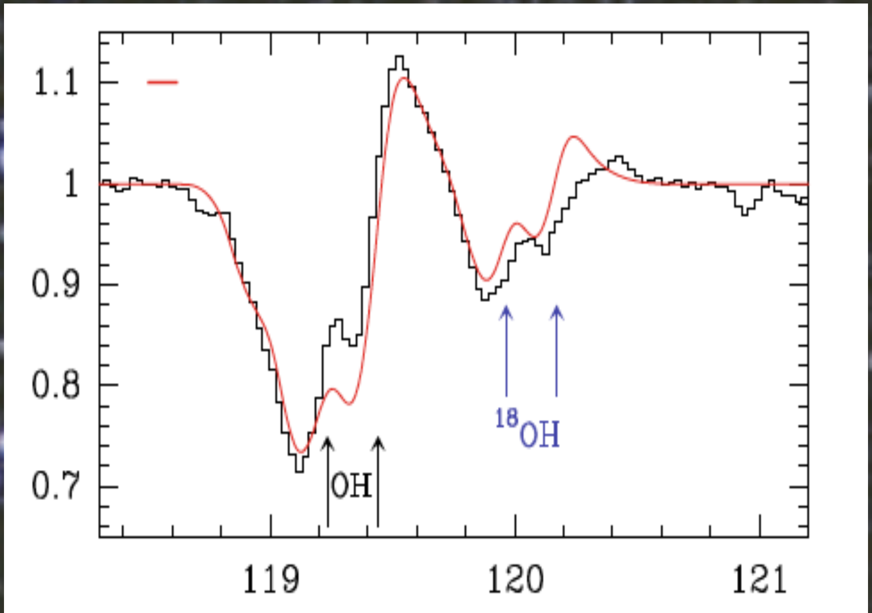
From Andy Lawrence’s Warped imagination:
(next step is do this properly With Wolfgang’s SHAPE)

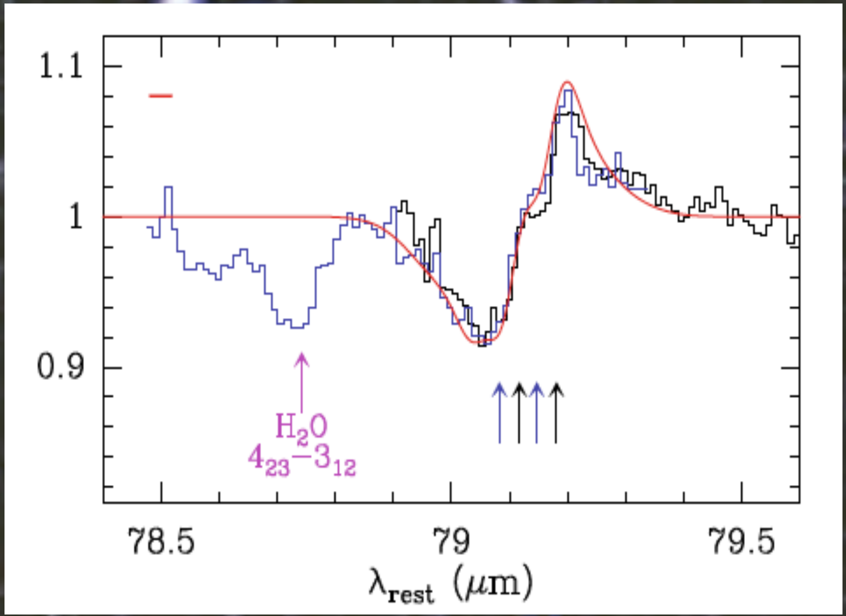




- Malkan et al 1998 WFPC2 Imaging survey

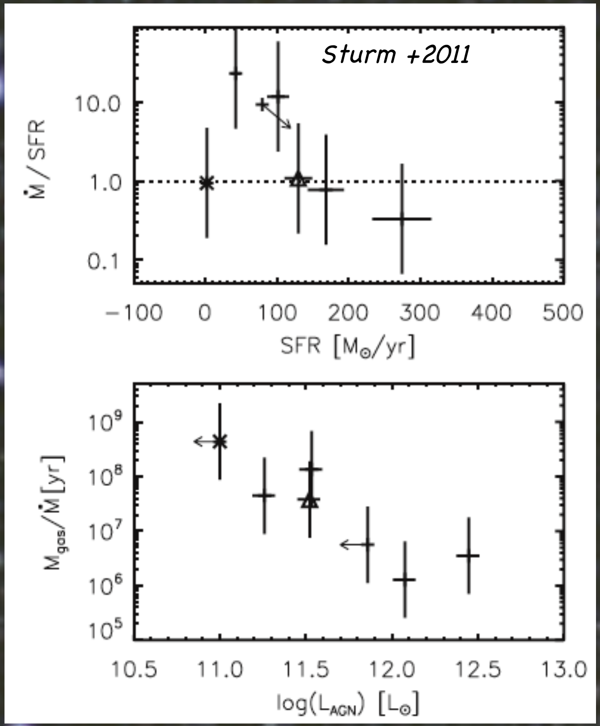
We want to measure AGN feed-back/SF quenching/boosting through FIR spectroscopy of OH, H_2O in the redshift range z=0-3





P-Cygni profiles of the OH 119 µm and ^{18}OH 120 µm partially resolved doublets (*left*) and the OH 79 µm unresolved doublet in Mrk 231 compared with modeled profiles (solid red curves (see Fischer et al 2010, A&A 518, L41). Absorption in the H_2O 4_{23}–3_{12} transition with a possible blue-shifted wing is also shown. The zero velocity rest-frame wavelengths are marked with black (OH), blue (^{18}OH), and magenta (H_2O) arrows and the instrumental *FWHM* is indicated in each panel with horizontal red bars.

ULIRG Molecular Outflows and X-ray chemistry



- Herschel/PACS: Blue-shifted OH FIR absorption in Mrk 231 and other ULIRGs *(Fischer +2010, Sturm +2011)*

- High velocity (≈1000 km/s) outflows correlated with AGN power (IRS data).

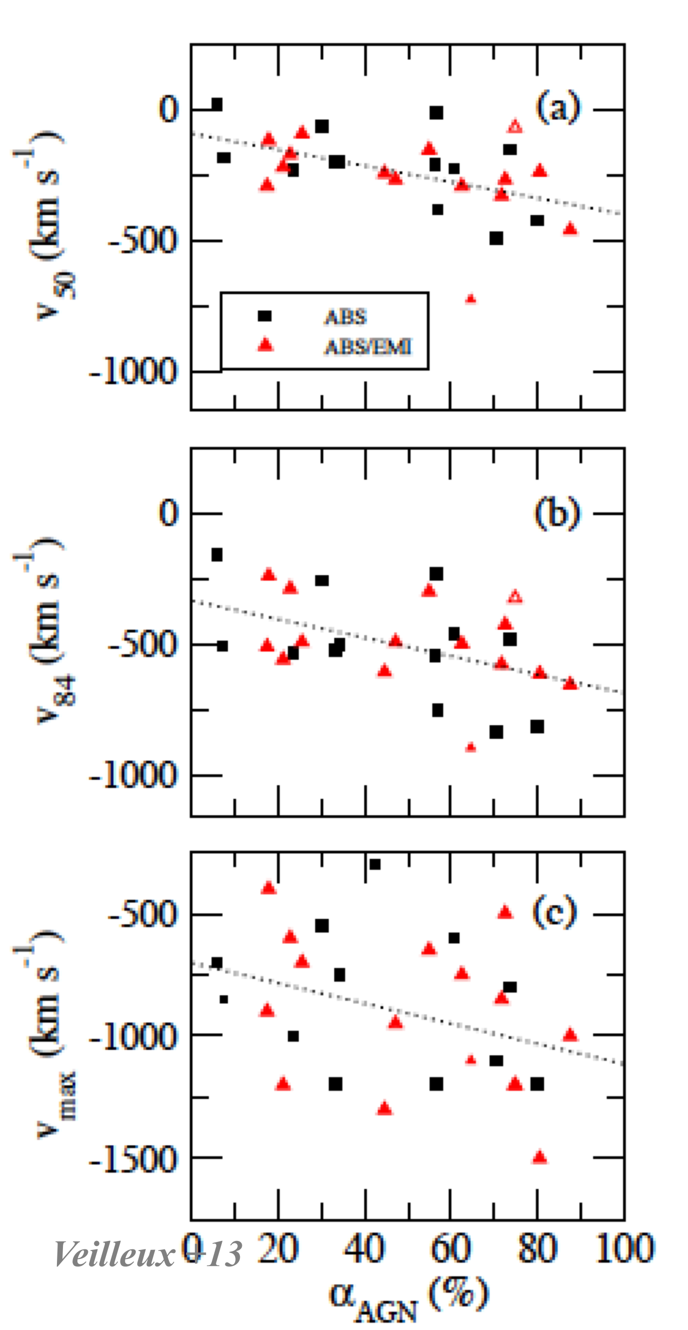
- High mass outflow rates: (500-1000 $M_\odot$ yr^{-1}) imply very short gas depletion timescales (< 10^7 yrs). Much smaller than the merger timescales. Breakout phase ?

Molecular Outflows

- Blueshifted OH absorption (outflows) seen in 70% (26) of LIRGs with OH. Redshifted absorption is rare (11%)

  >> molecular outflows are common at z=0 but numbers are still very small

- Terminal velocities up to ≈1000 km/s
- Outflows seen in SB and AGN, but LIRGs with more dominant and luminous AGN have faster outflows
- correlation of OH EQW and silicate depth locates outflows inside most of the obscuring dust *(Spoon +13)*



Veilleux +13

Molecular Outflows with CALISTO

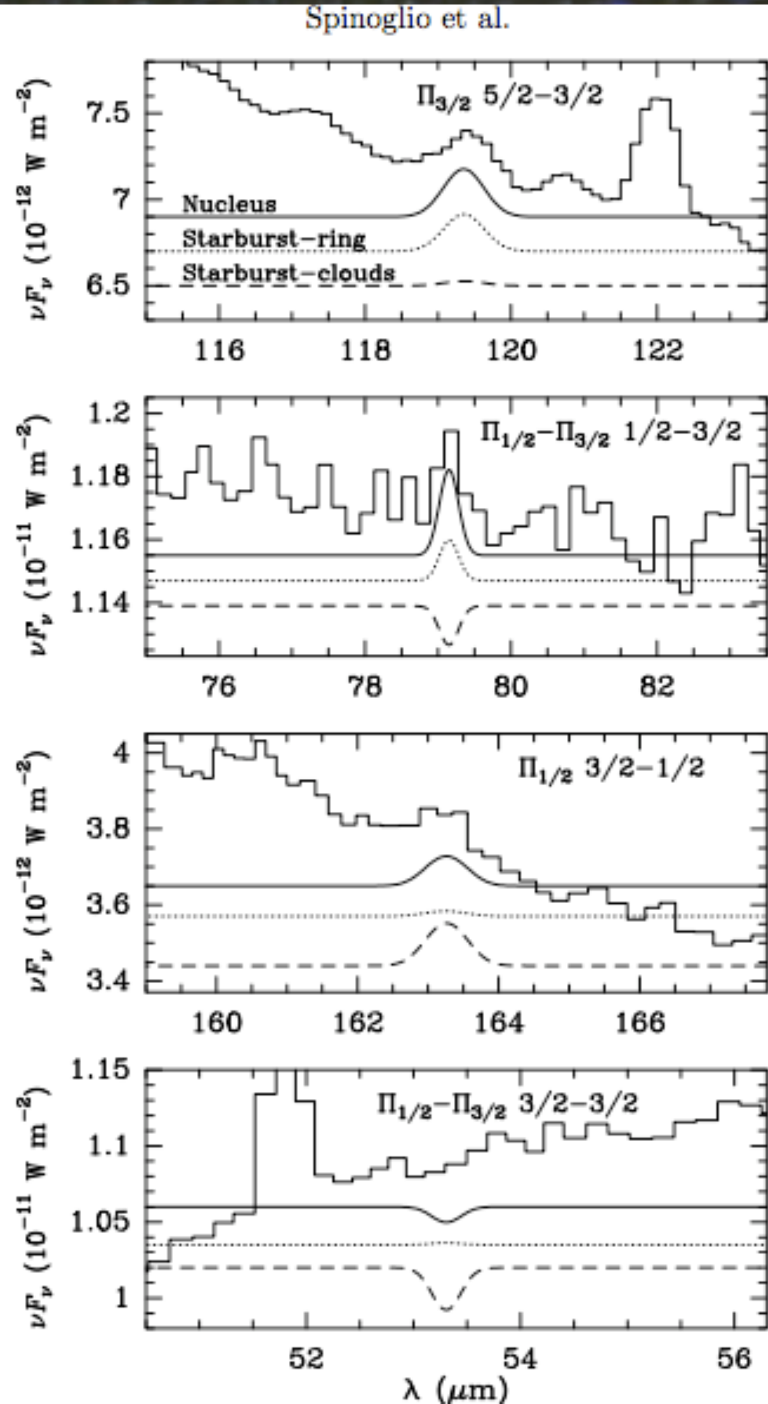
- Scaling from local ULIRGs with strong outflows, expect OH 79, 119 μm lines to have fluxes of about 2×10^{-20} W m^{-2} at z=1, 4×10^{-21} W m^{-2} at z=2.

- CALISTO should be able to detect these lines in about 10 mins at z=1, and under an hour at z=2*. Starbursts above the MS would be even faster.

- Would enable a large spectroscopic survey of LIRGs and ULIRGs (hundreds) for molecular outflows, all of which will have quantitative measures of the SB/AGN fractions and luminosities – tie AGN power to mass outflow rate and velocity in the molecular gas.

- *LA, priv. comm.

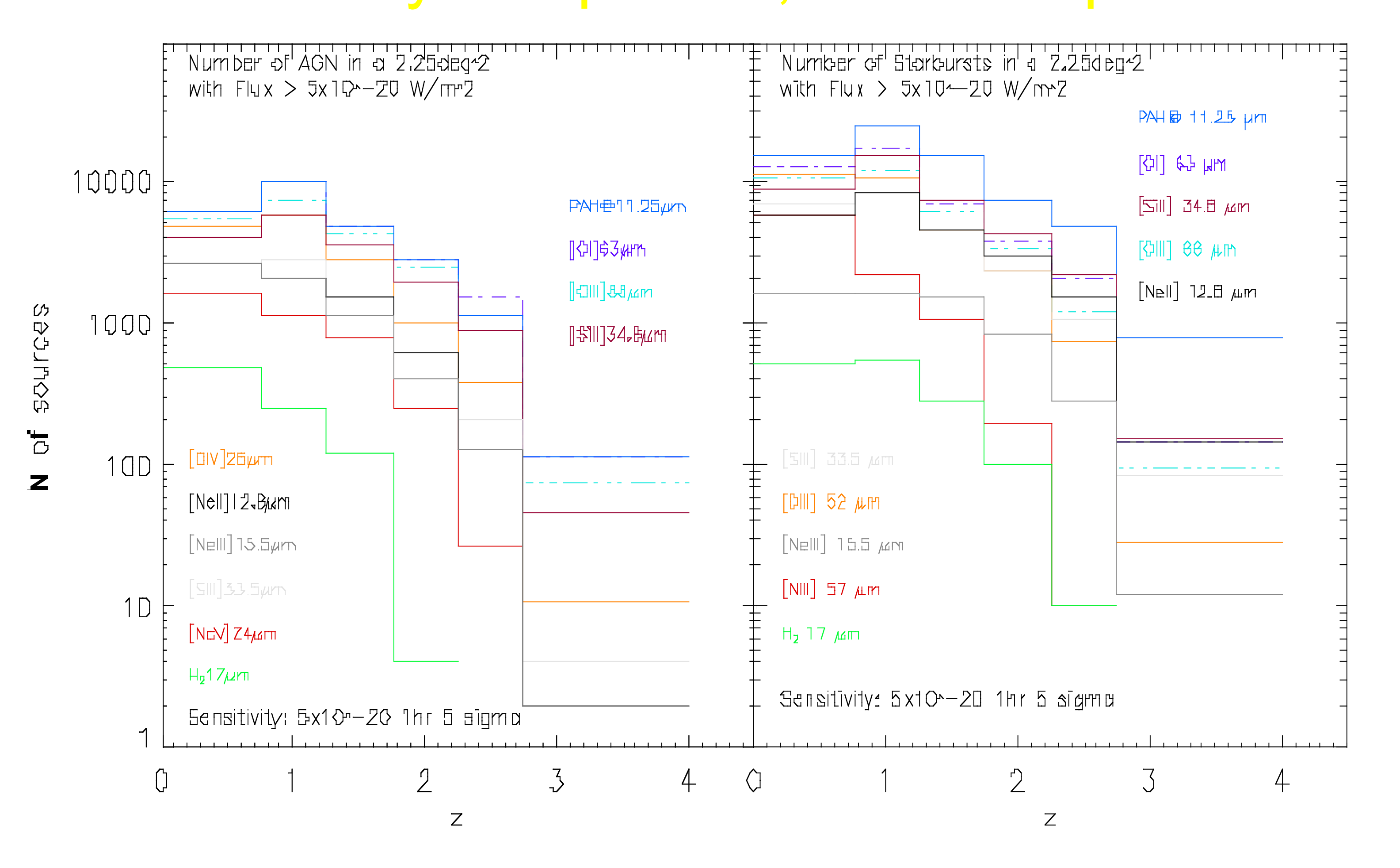
OH Lines in *Emission* only in the archetypical Seyfert 2 galaxy, NGC 1068!



Line id.λ	Flux ($10^{-19} W cm^{-2}$) Observed	Modeled	Notes
34μm	< .5	-0.5	(absorption)
48μm	···	0.12	
53μm	< 1.2	-0.4	(absorption)
65μm	< 1.2	0.2	
79μm	0.80	1.10	
84μm	< 1.2	0.5	
96μm	···	0.3	
98μm	< 1.2	0.4	
115μm	···	.004	
119μm	1.20	1.31	
163μm	0.74	0.60	

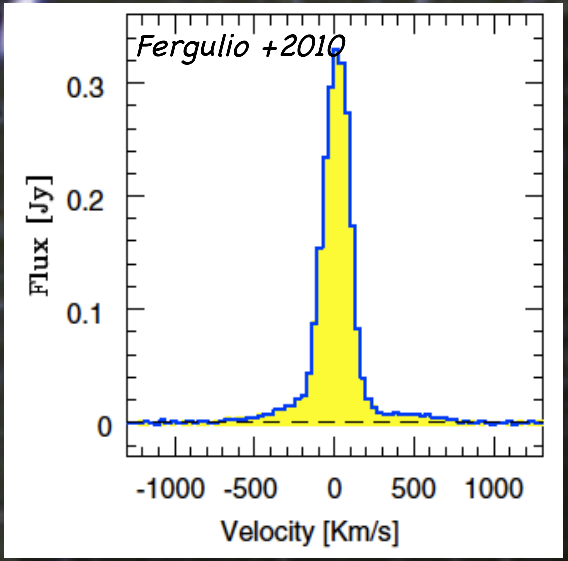
- Spinoglio, Malkan,et al 2003

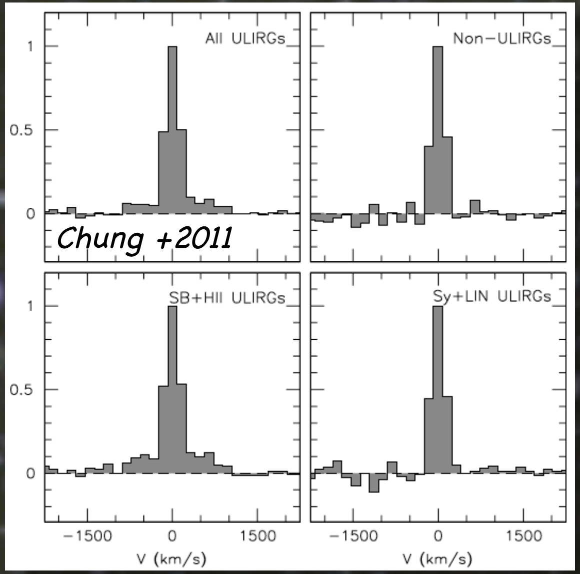
At this depth, huge samples of distant galaxies available in any Deep Field, with little pre-selection



Number of AGN (left) and starburst galaxies (right) as a function of redshift in a field of 2.25 square degrees with line fluxes above the threshold of 5x10^-20 W/m^2 (at 5σ). (NB: This is a 'heroic' Large Project for SPICA, ~thousand hours)

Molecular Outflows



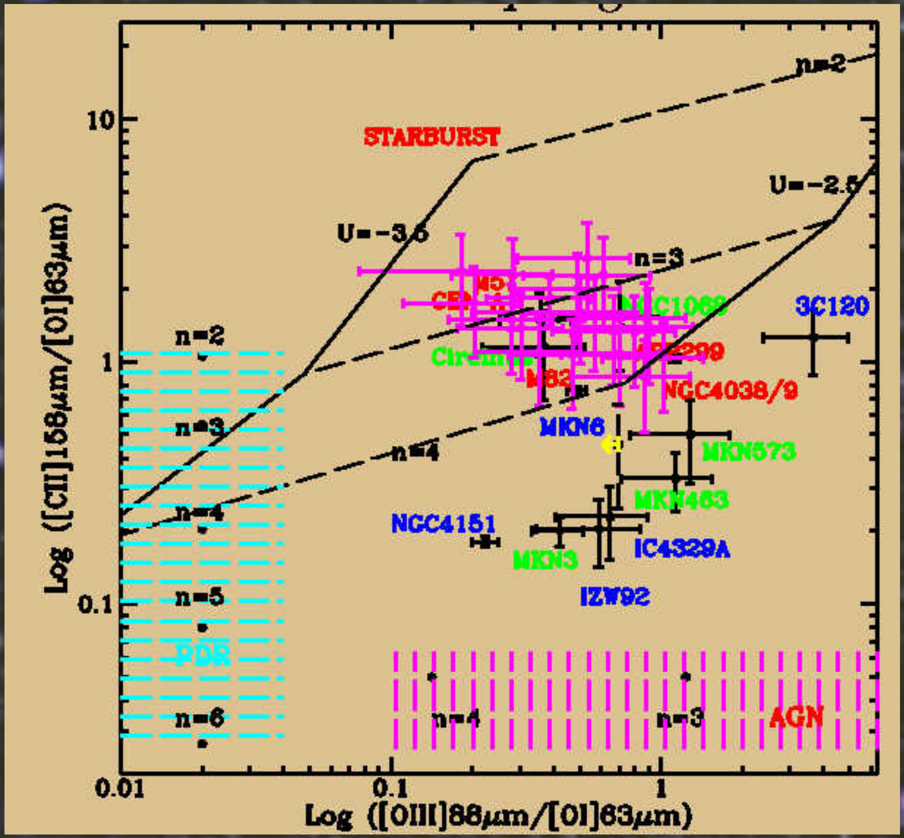


- Faint, broad wings on CO (1-0) emission in Mrk 231 and other ULIRGs *(Feruglio +2010; Chung +2011).* FWZI = 750-2000 km/s.

- Mdot highly uncertain (200 – 2000 $M_{\odot}$/yr), so SB may/may not have enough power. Broad wings only seen in stacked SB ULIRGs (Chung et al.).

- Broad HCN, HCO^+: dense (n > 1E4 cm^{-3}), resolved (1 kpc) fast (750 km/s) outflow in Mrk 231 *(Aalto + 2010).*

- P-cygni profiles in HCO^+, CO (3-2) in Arp 220 at 100 km/s level *(Sakamoto +2009).*

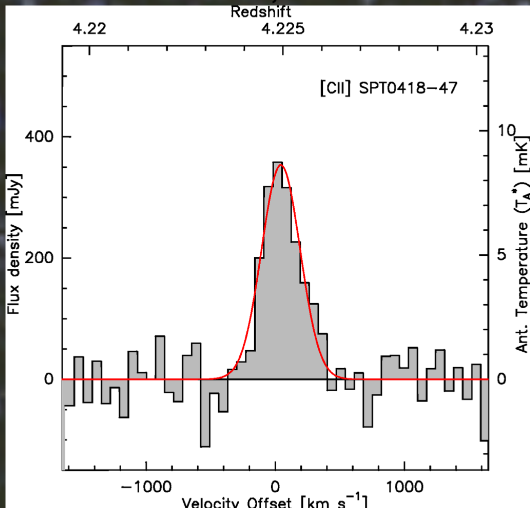


Conclusion:

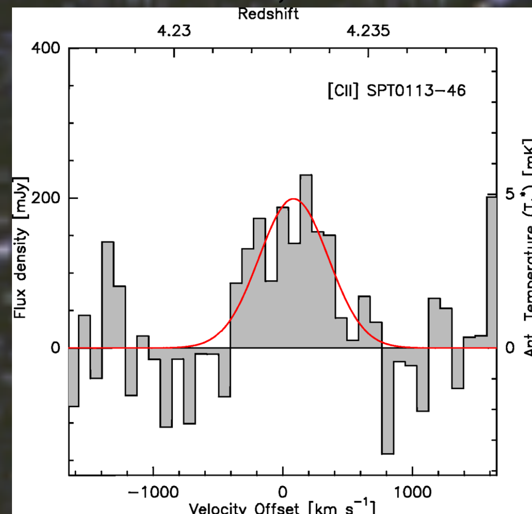
•ISO/LWS Spinoglio & Malkan proposed Strong far-IR []line diagnostics:
quiescent galaxies are PDR-dominated,
starbursts produce more O++, while Seyfert has O I from denser gas
ALMA Band 10 will allow this for galaxies out to the highest redshifts!

[CII]158um at $z > 4$ detected with APEX/FLASH in ~few hours: Opens a new window on ionized gas in most distant galaxies

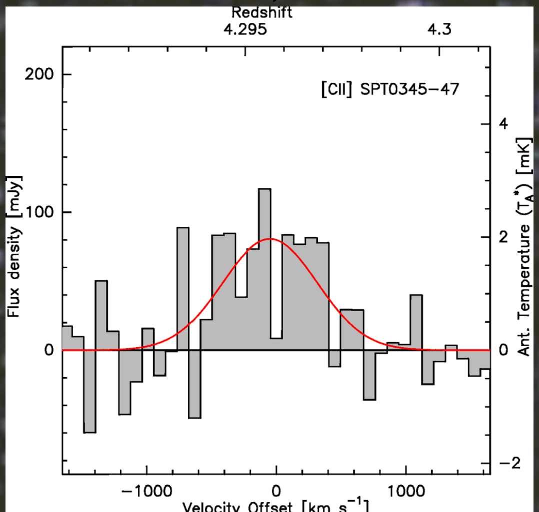
$z = 4.23$; t = 1.5h



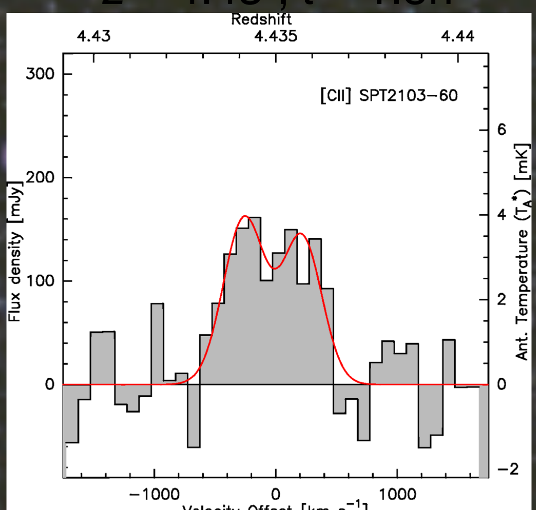
$z = 4.23$; t = 2.3h



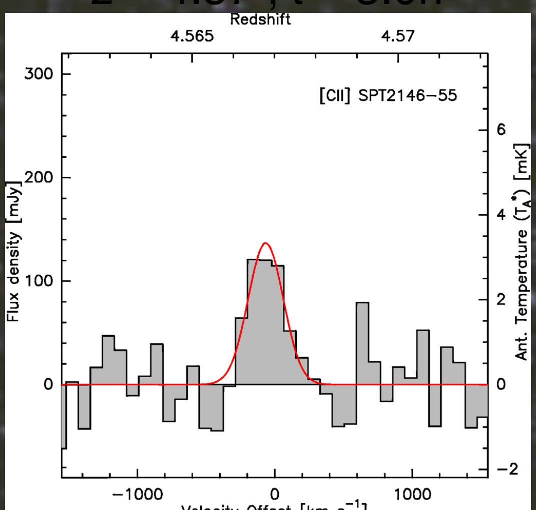
$z = 4.30$; t = 2.3h



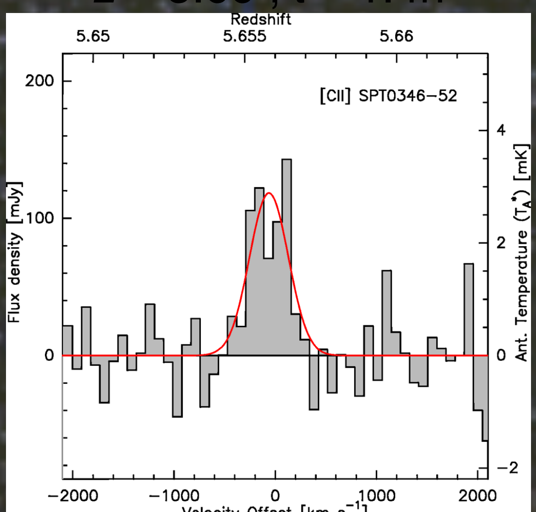
$z = 4.43$; t = 1.5h

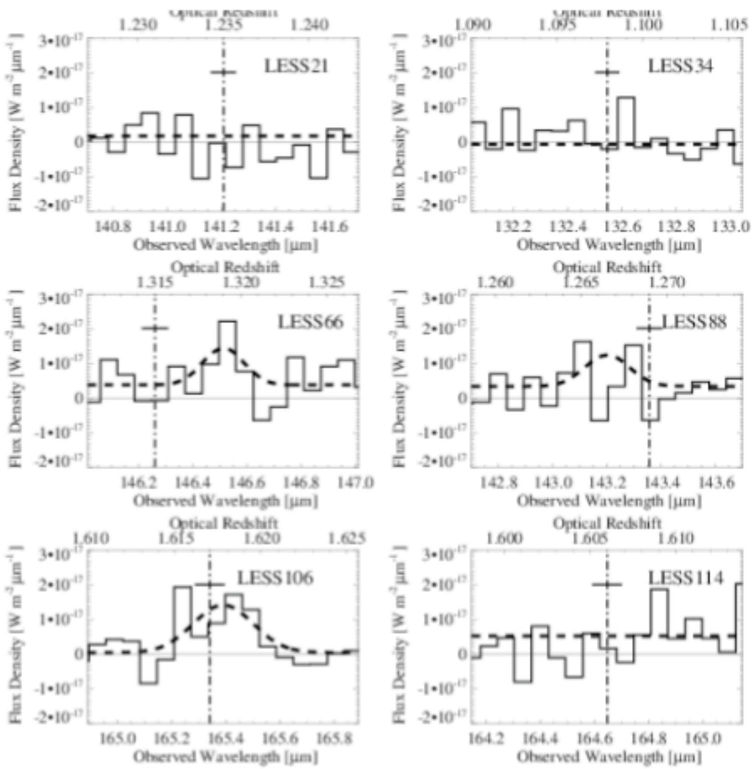


$z = 4.57$; t = 3.0h



$z = 5.66$; t = 1.4h





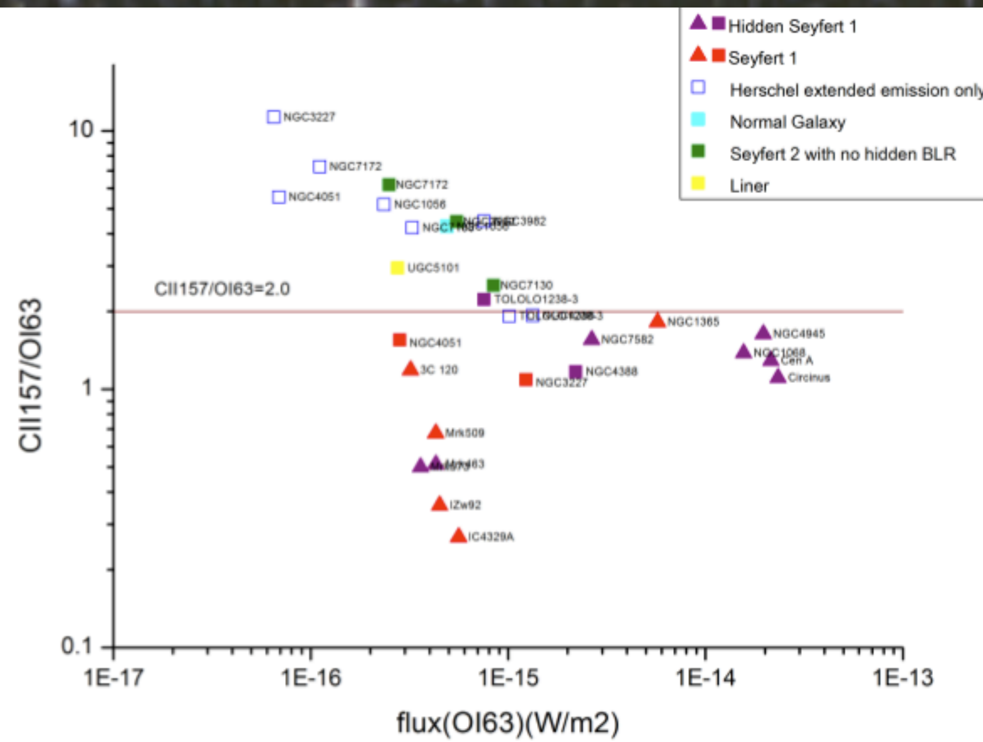
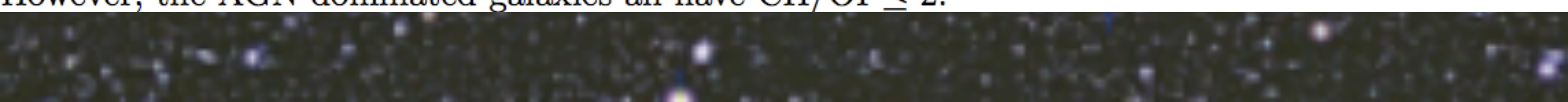
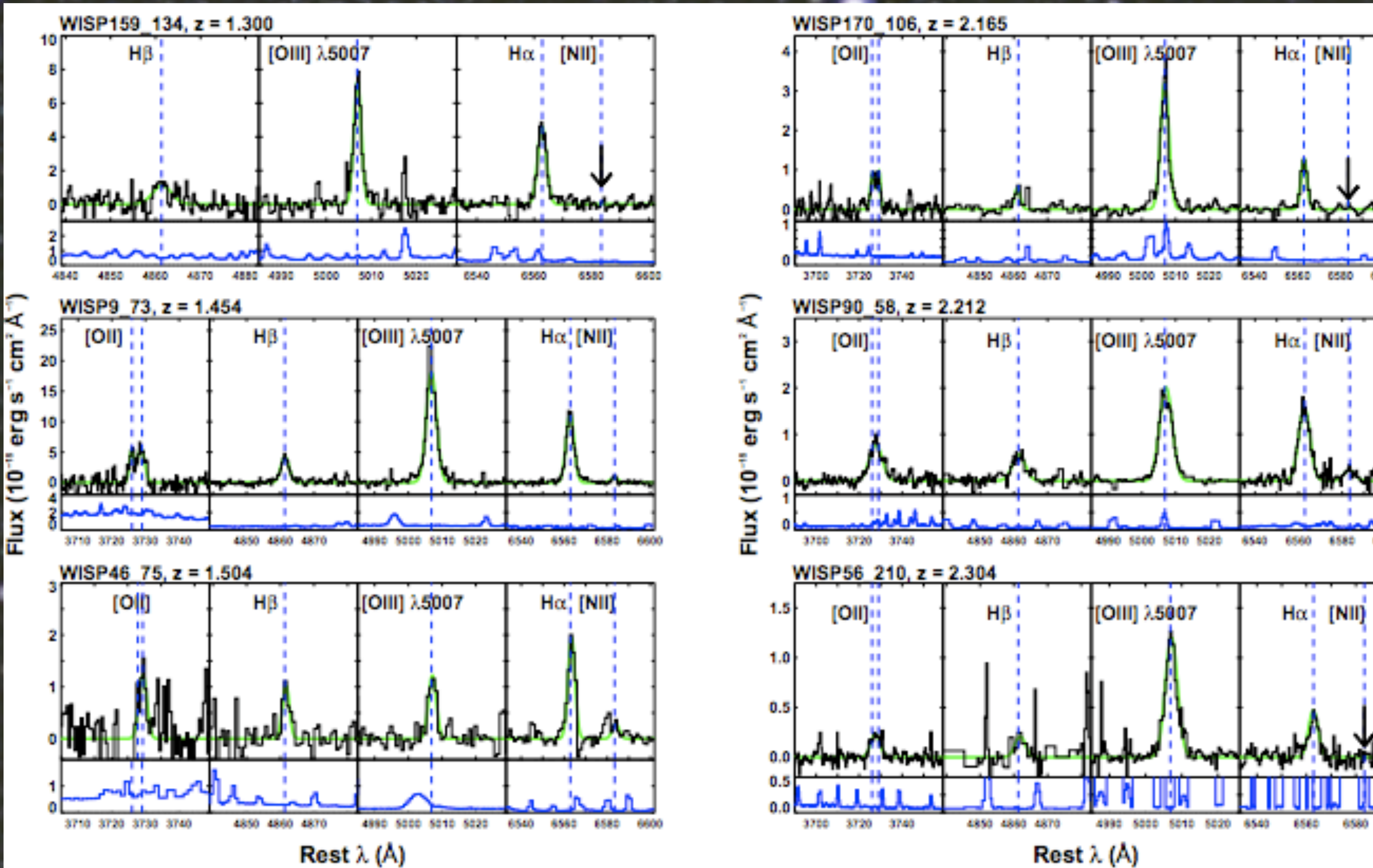


Figure 1 (right): [OI] 63μm spectra of 6 ALESS sources observed with *Herschel*/PACS (from Coppin et al. 2012). *Figure 2 (left):* [CII] 158μm/[OI] 63μm for nearby galaxies. Note the large spread. However, the AGN-dominated galaxies all have CII/OI ≤ 2.



FIRE Resolves all the lines

Masters et al 2014 (not thesis)



<Sigma> ~ 70 km/sec

Masters, et al. 2013