What we have learned from Spitzer

JWST@ROE
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- Obscured star formation rates out to z = 2 and down to 10 $M_{\odot}$/yr
- Finding complete samples of AGNs down to faint limits
- Are ULIRGs nurseries for quasars?
- Looking for true type-2 Seyfert galaxies

Accurate SFRs can be determined from 24μm (and MIRI 21μm) photometry up to z ~ 2

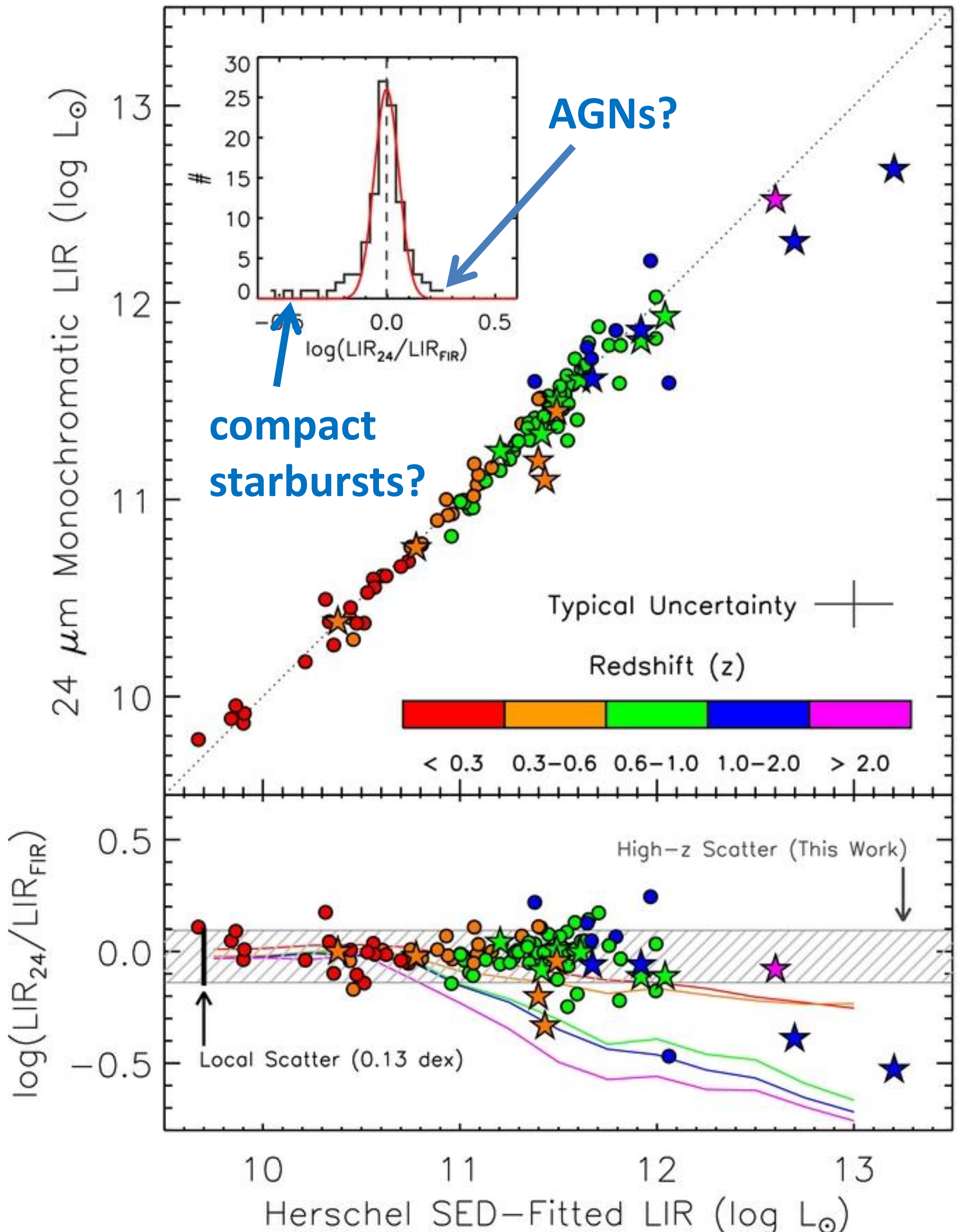
Except:

- **Residual compact SF galaxies (mostly z < 1) will be underestimated**

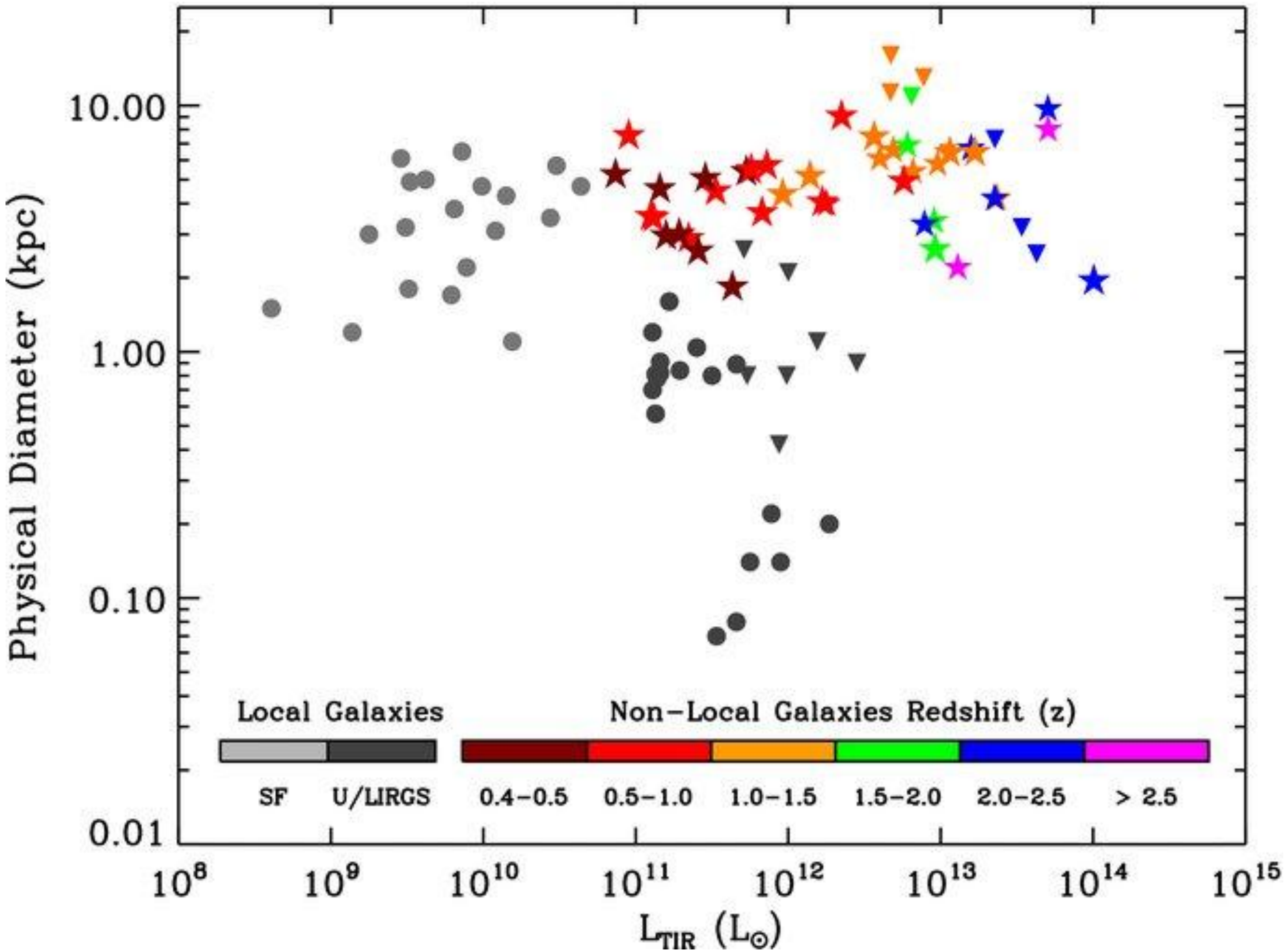
- **What are metallicity effects?**

- **AGNs will be overestimated**

Will discuss these issues later – first will explore why this works

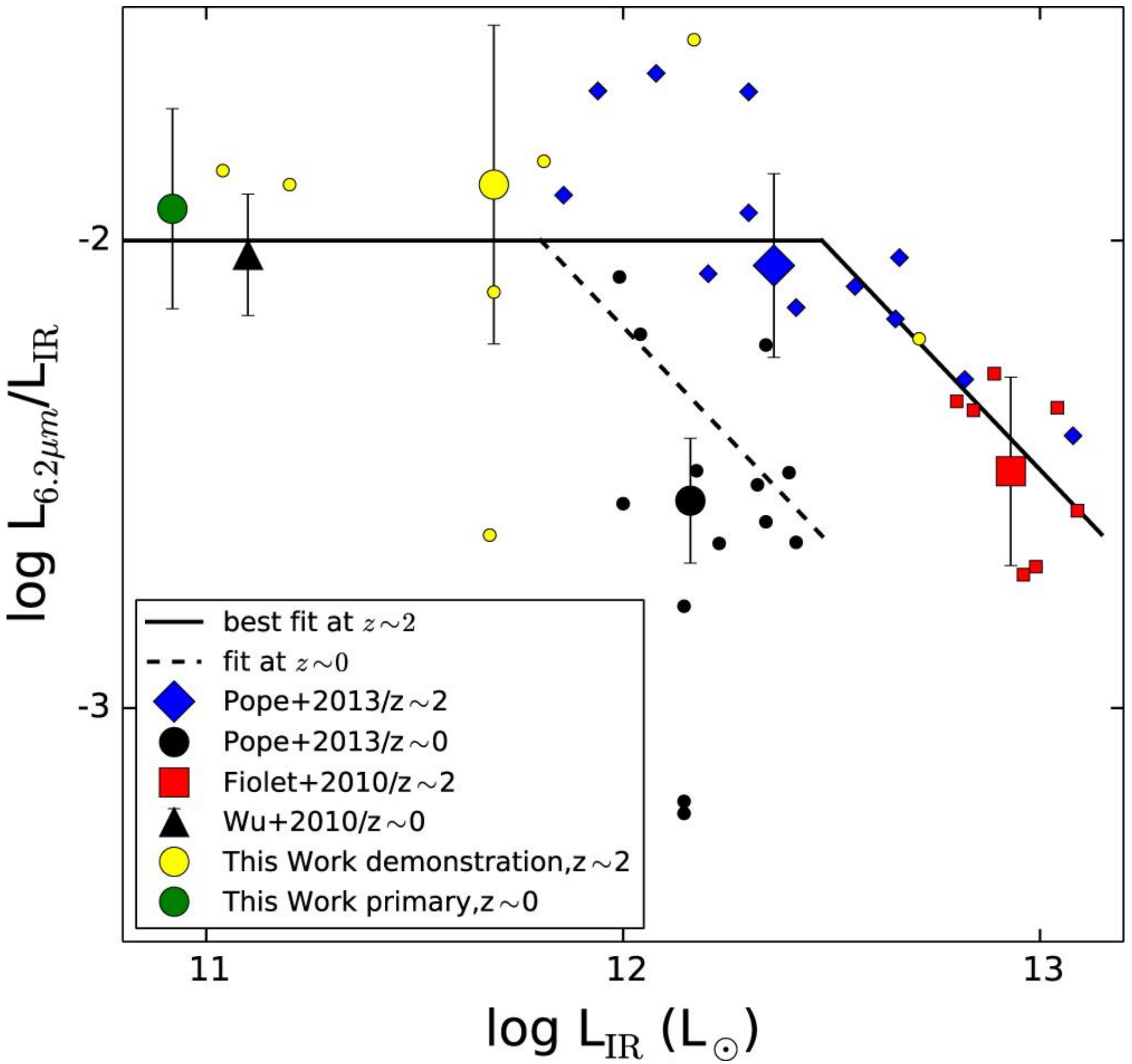


IR galaxies are ~ 4 – 6 kpc in diameter by z > 1



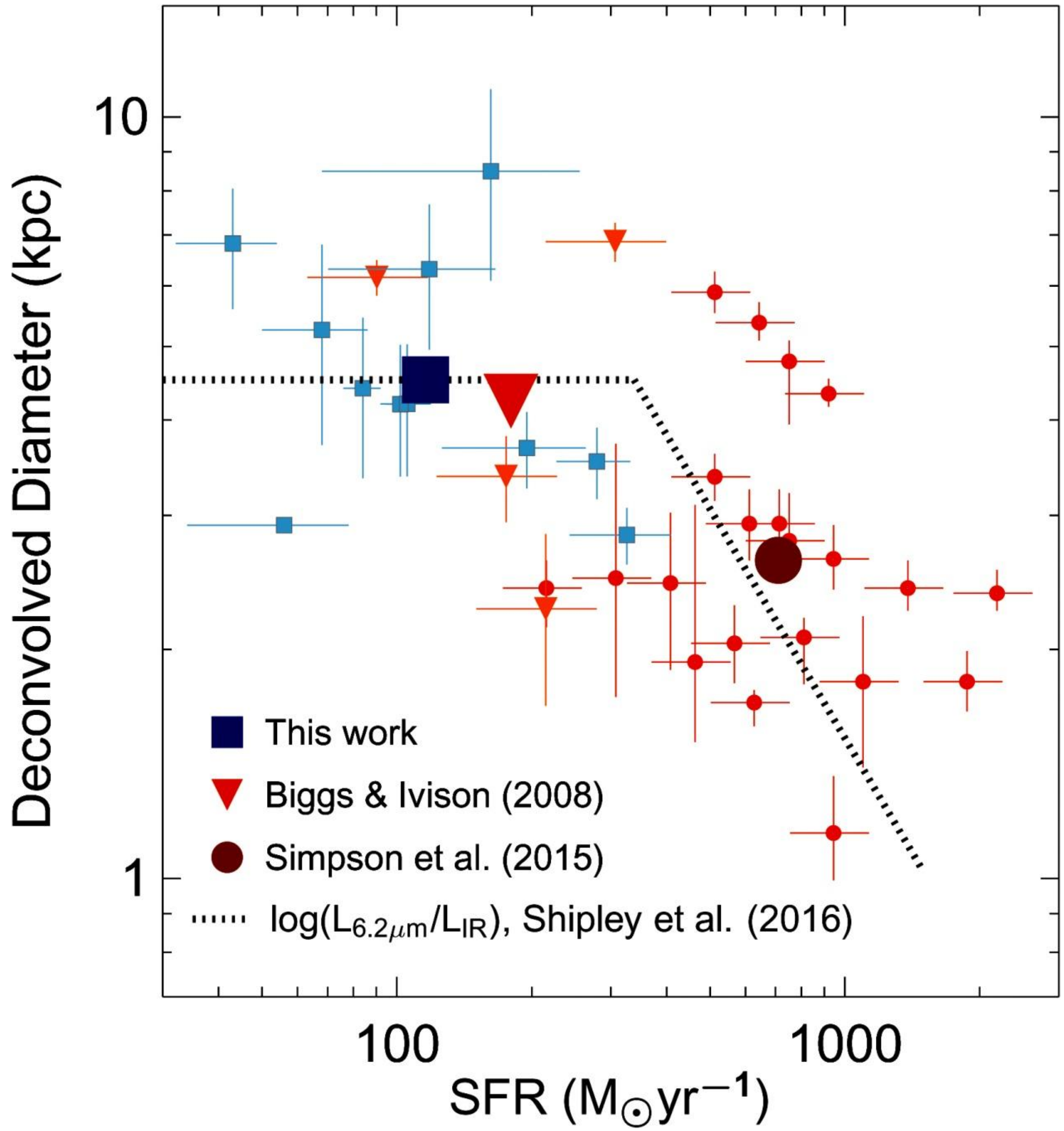
From Rujopakarn et al. 2011, ApJ, 726, 93

Consequently the suppression of the aromatic bands characteristic of local ULIRGs is shifted to higher luminosities



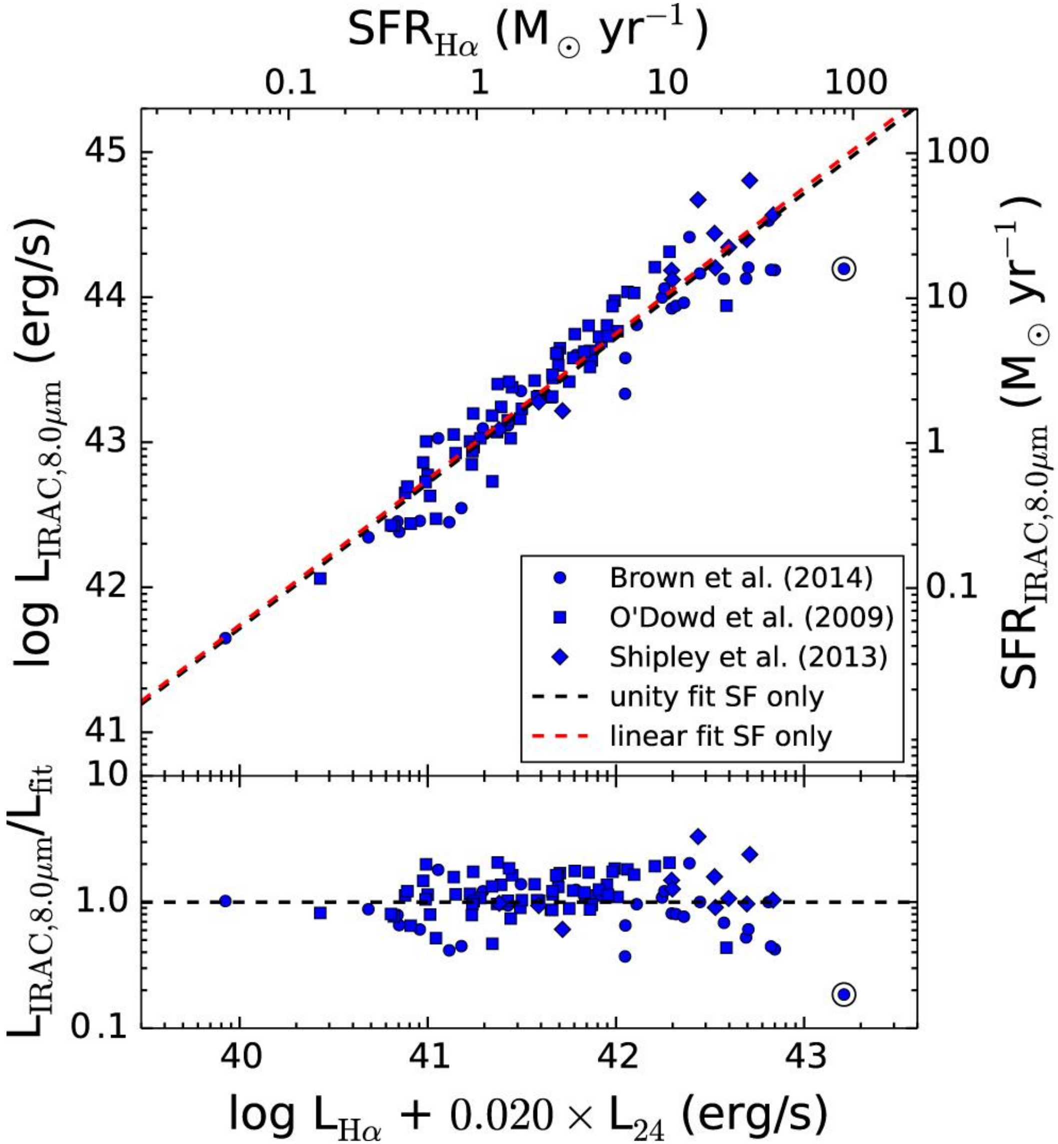
From Shipley et al. 2016, ApJ, 818, 60

This picture is confirmed by JVLA/ALMA observations.



From Simpson et al. 2015, ApJ, 799, 81 and Rujopakarn et al. 2016, in prep.

Until this suppression sets in, aromatic bands and ~ 8 μm photometry can provide accurate SFRs



From Shipley et al. 2016

Except:

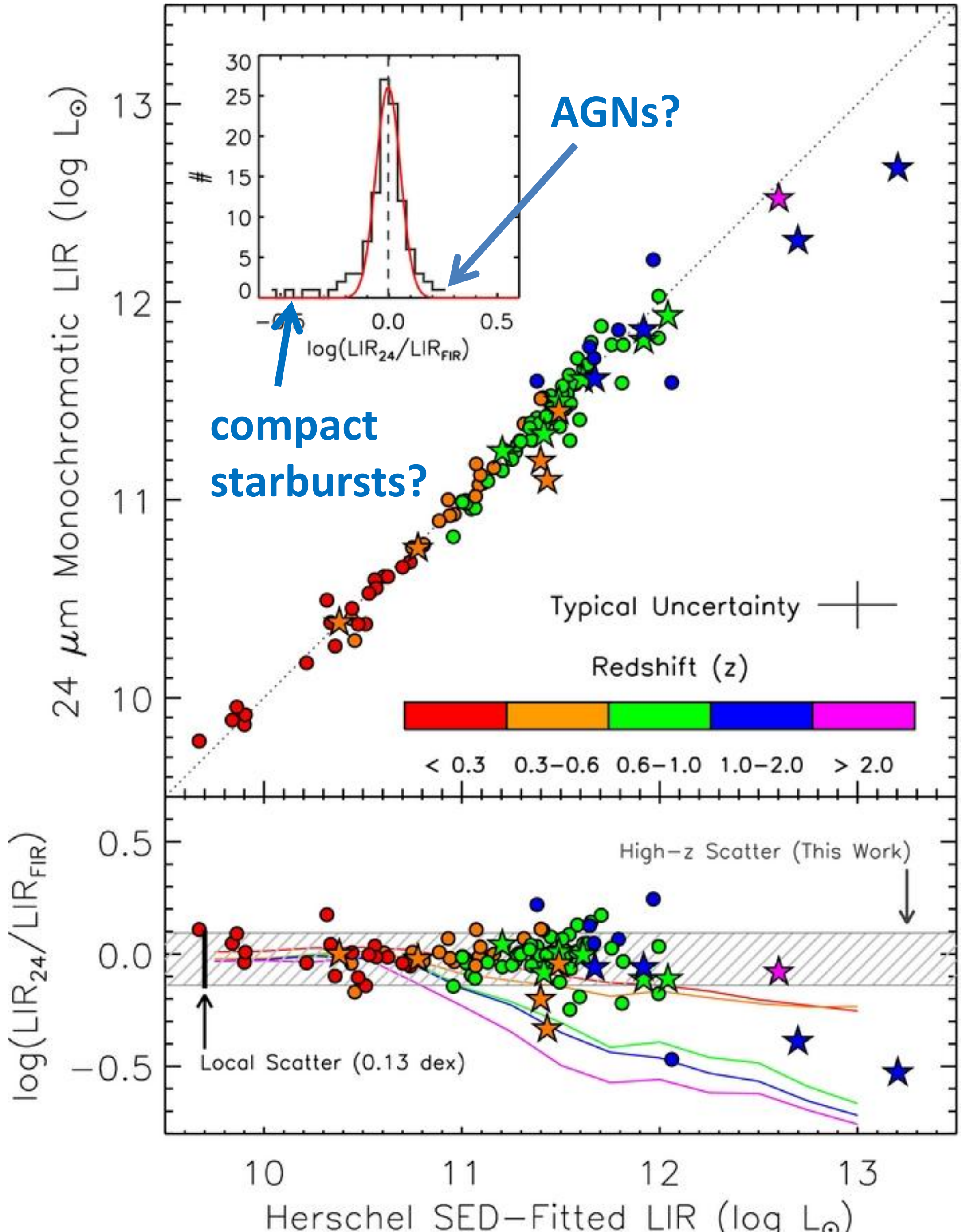
- **Residual compact SF galaxies (mostly z < 1) will be underestimated**
- **What are metallicity effects?**
- **AGNs will be overestimated**

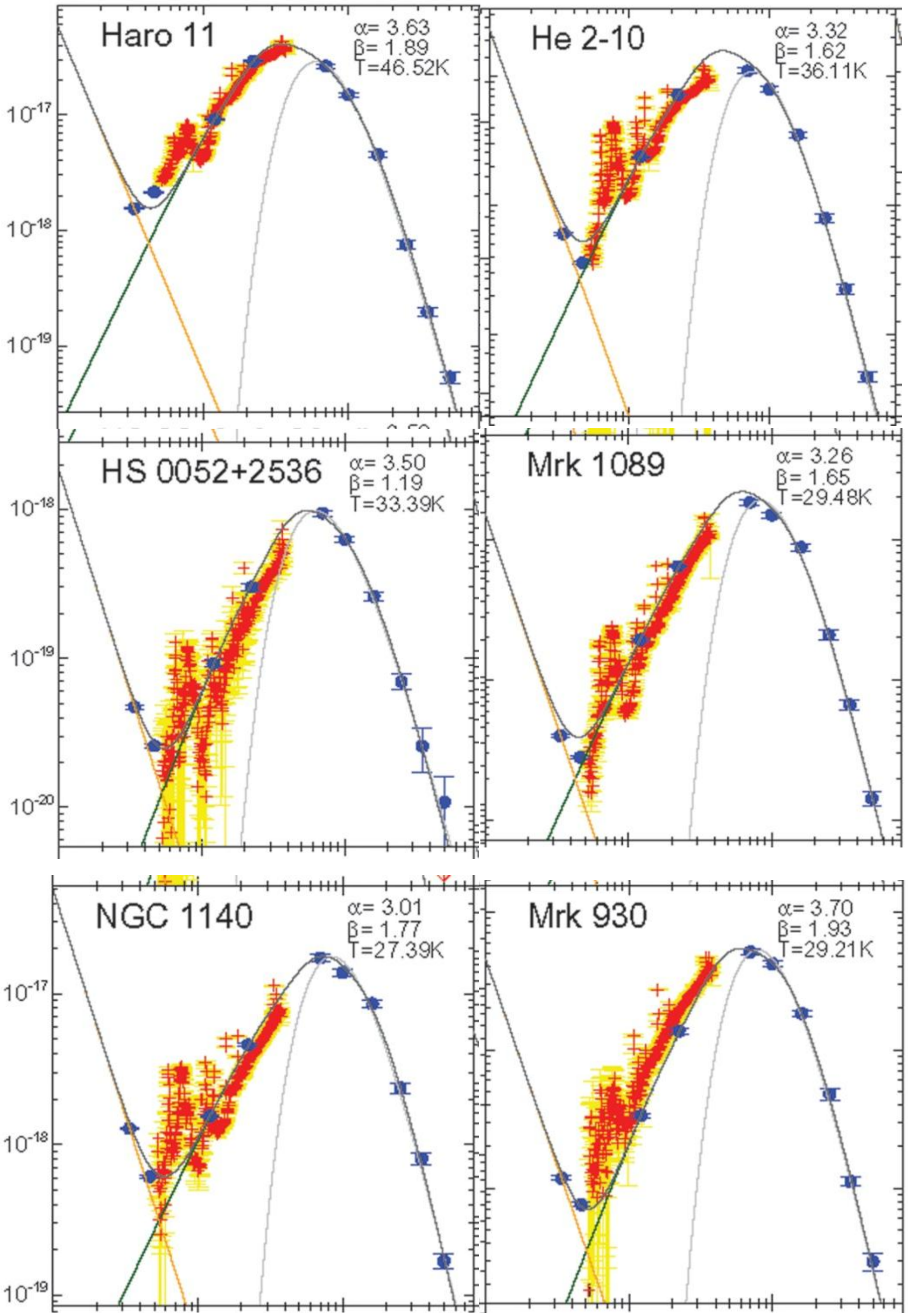
Need shorter MIRI bands to deal with these issues

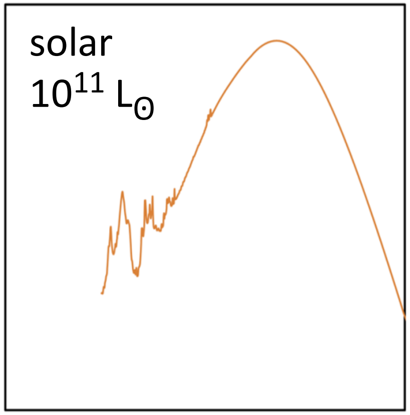
Compact galaxies:

- **for 0 < z < 0.6, ratio of f(21)/f(12.8) is > 1.5 times larger for log(LIR) = 12.25 template than for log(LIR) = 11.25 one**
- **Extend to z = 1 with relatively shallow 25.5 μm measurement, use f(25.5)/f(15)**

Therefore, a simple strategy identifies most compact galaxies







Ratios of SFR deduced from 8 μm + UV to that from full far IR + UV for 12 + log(O/H) = 8.2

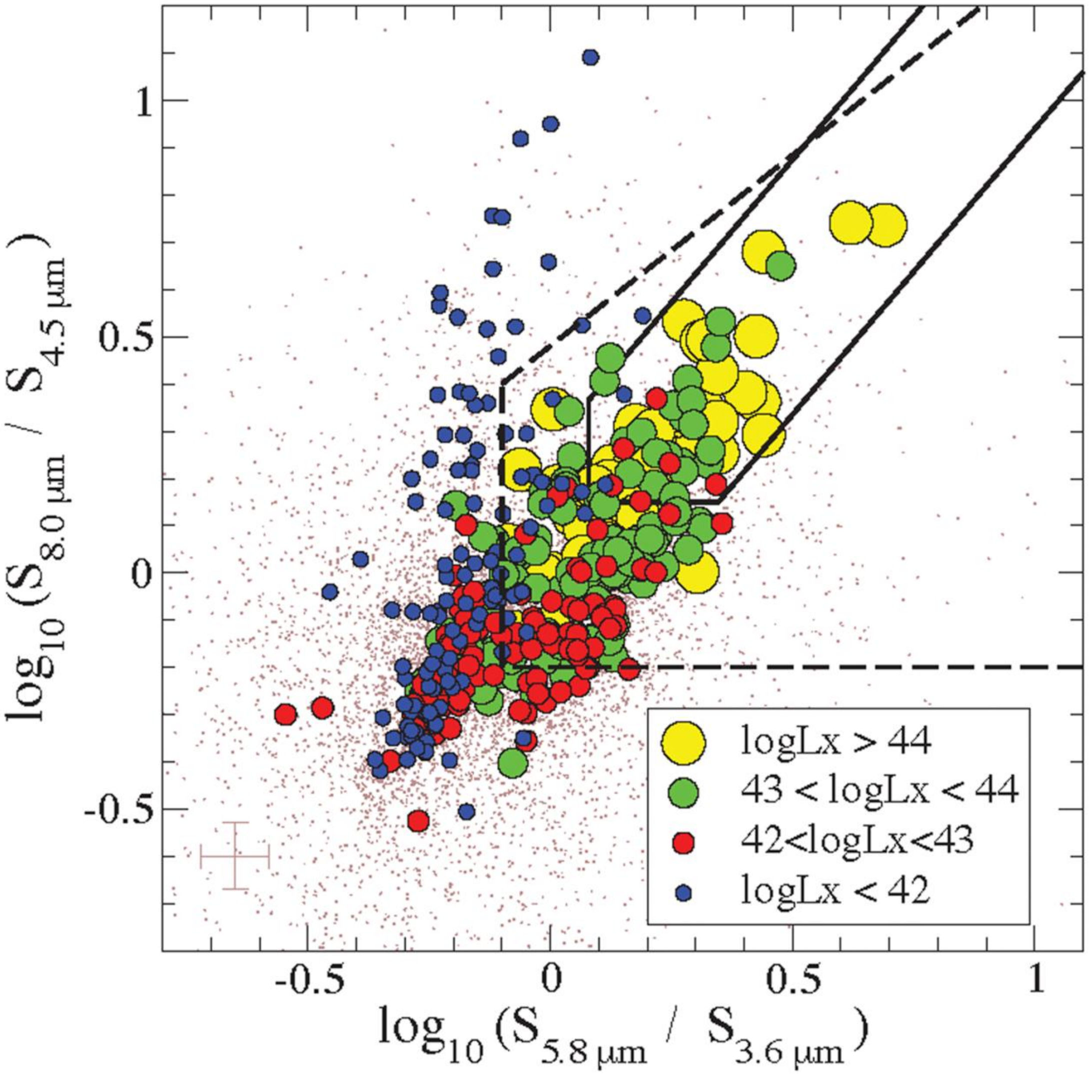
Haro 11	0.81
Haro 3	0.47
HS 0052	0.51
Mrk 1089	0.46
Mrk 930	0.59
NGC 1140	0.57
UM 448	0.42

Calibration will remain valid over relevant range of metallicity.

Spectral changes are subtle for 12 + Log(O/H) > 8.

Haro 11 has exceptionally high star formation density.

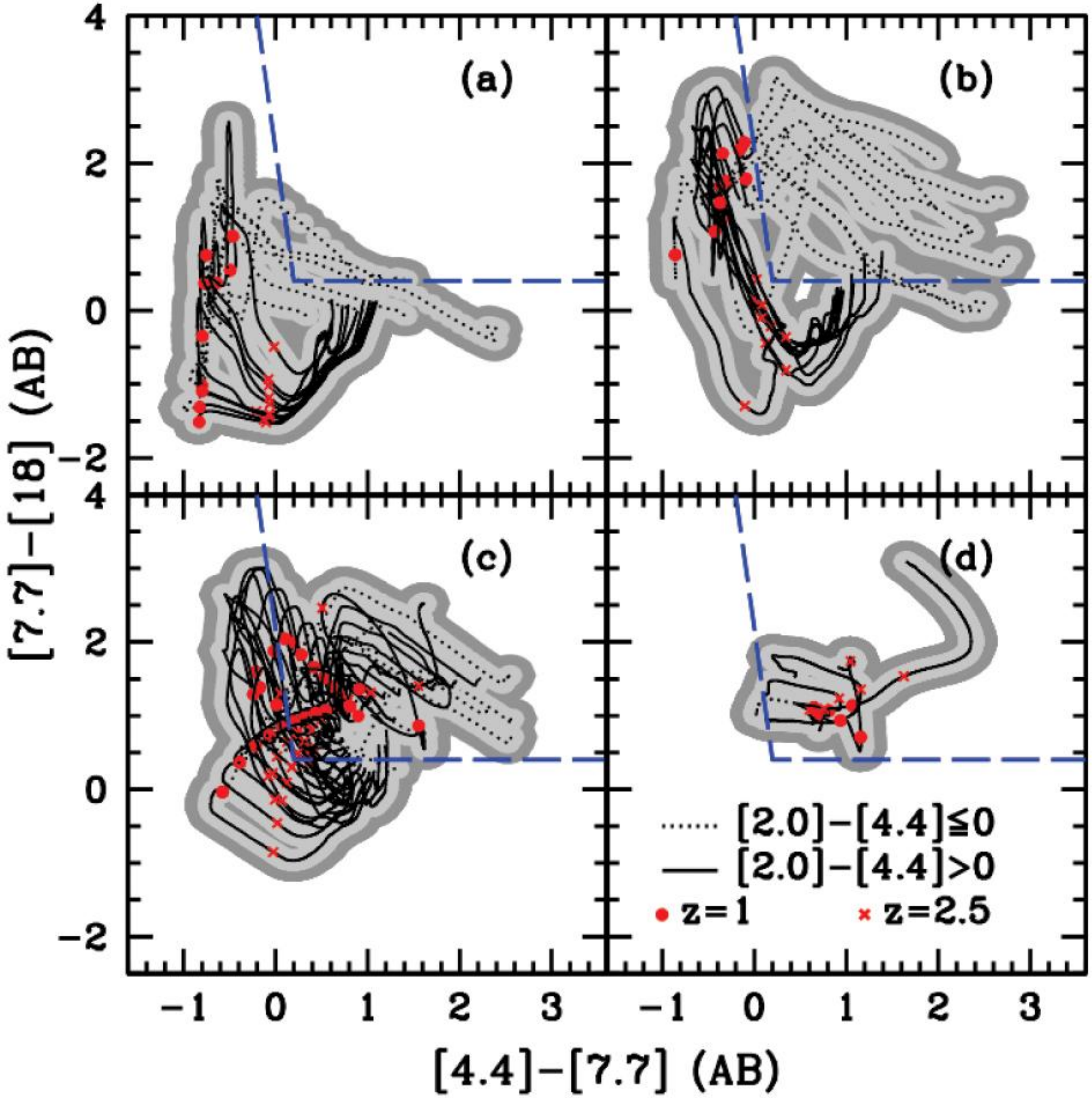
AGNs bright enough in the infrared to affect the SFR estimates can in principle be determined from color-color plots similar to those developed for IRAC (and WISE) photometry.



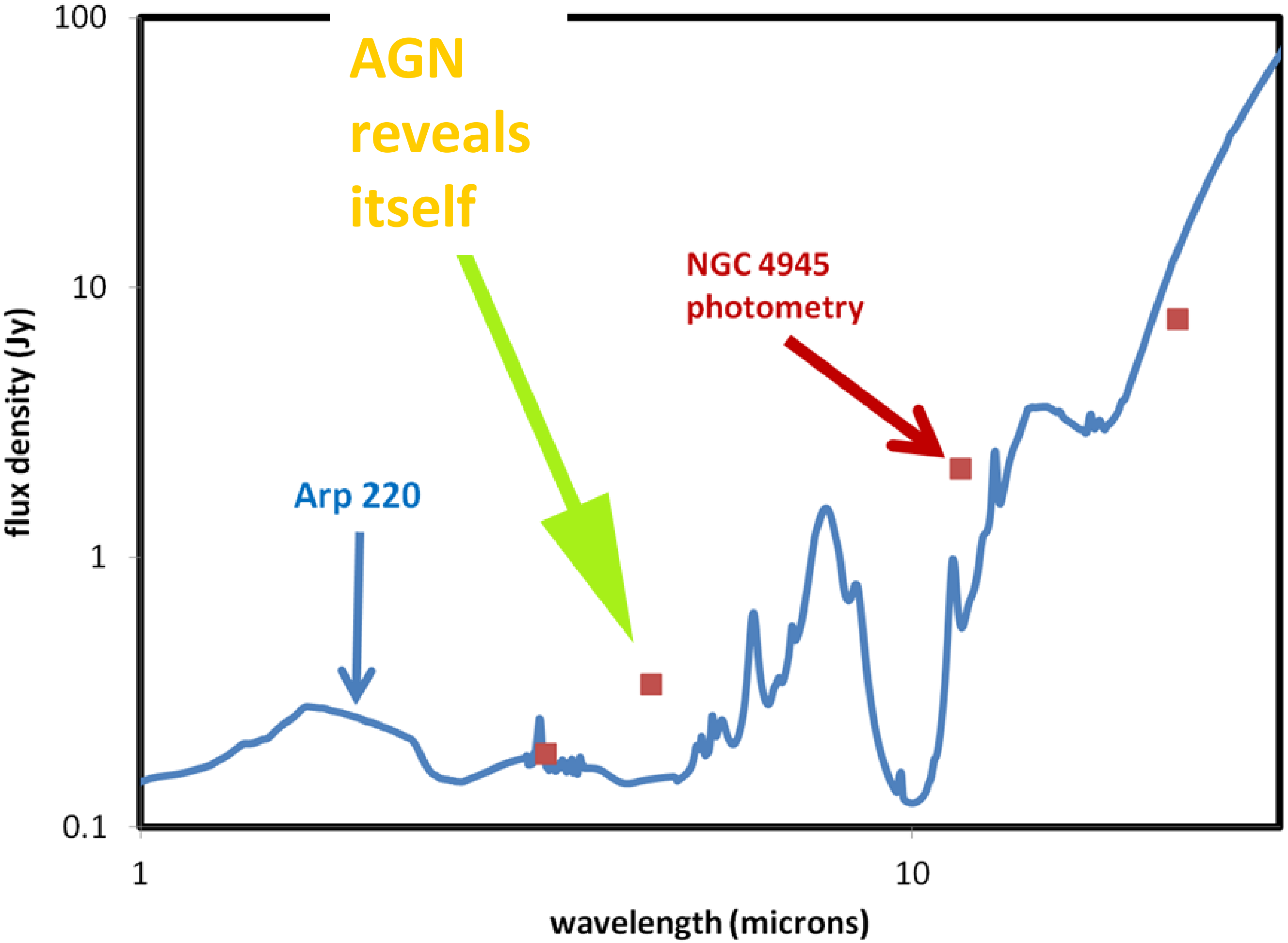
IRAC color-color diagram showing the location of X-ray AGN with different X-ray luminosities in the Chandra Deep Field South 4Ms catalogue (circles), with respect to other IRAC galaxies not detected in X-ray, or detected but not classified as AGN (background dots).
The dashed and solid lines delimit the color regions proposed for AGN selection by Lacy et al. and Donley et al., respectively. From K. Caputi 2014, arXiv 1405.7940v1

Messias et al. 2014, A&A, 562A, 144 have proposed such diagrams for use with NIRCam and MIRI.

These methods focus on identifying power law continua.

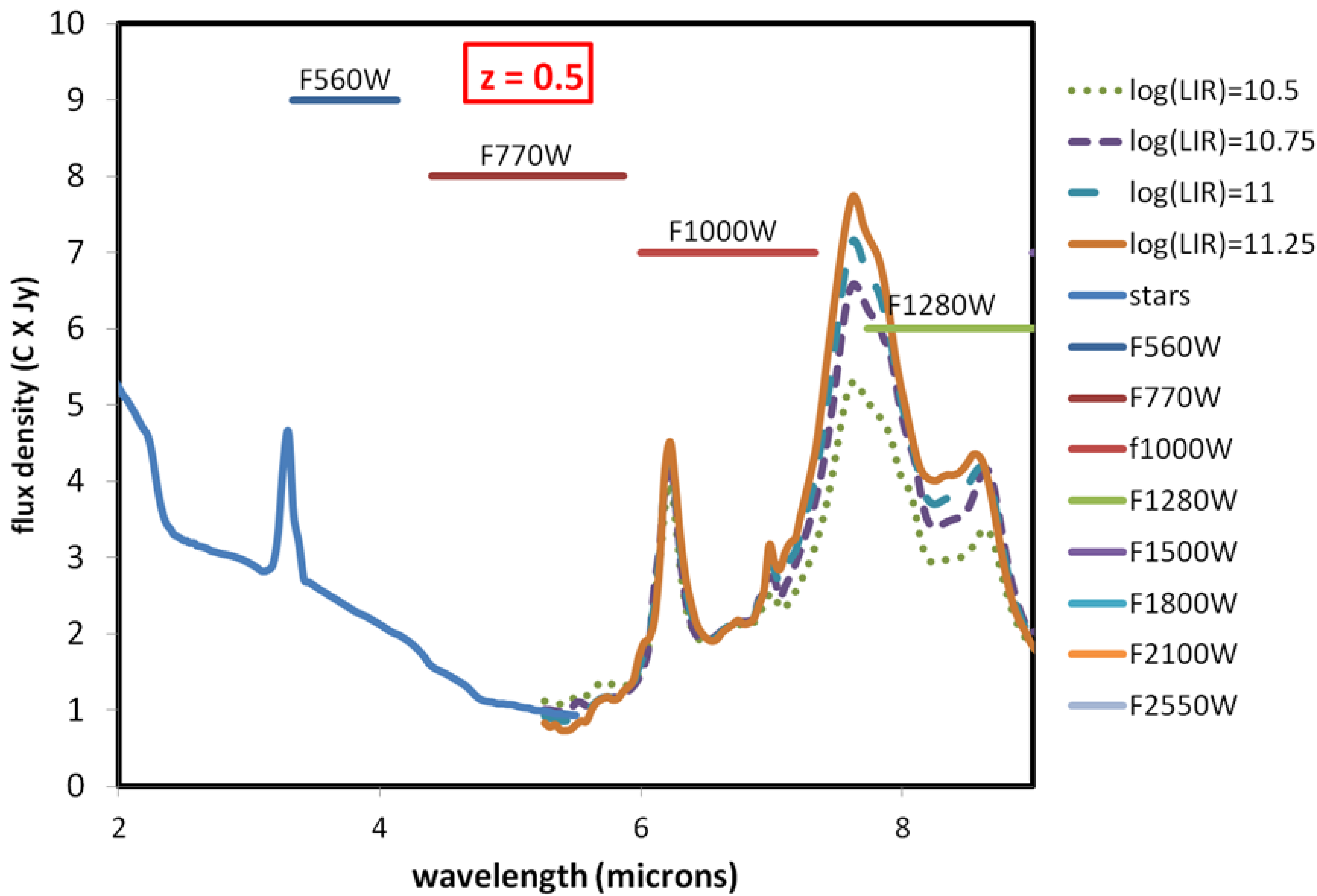


A better strategy for AGNs

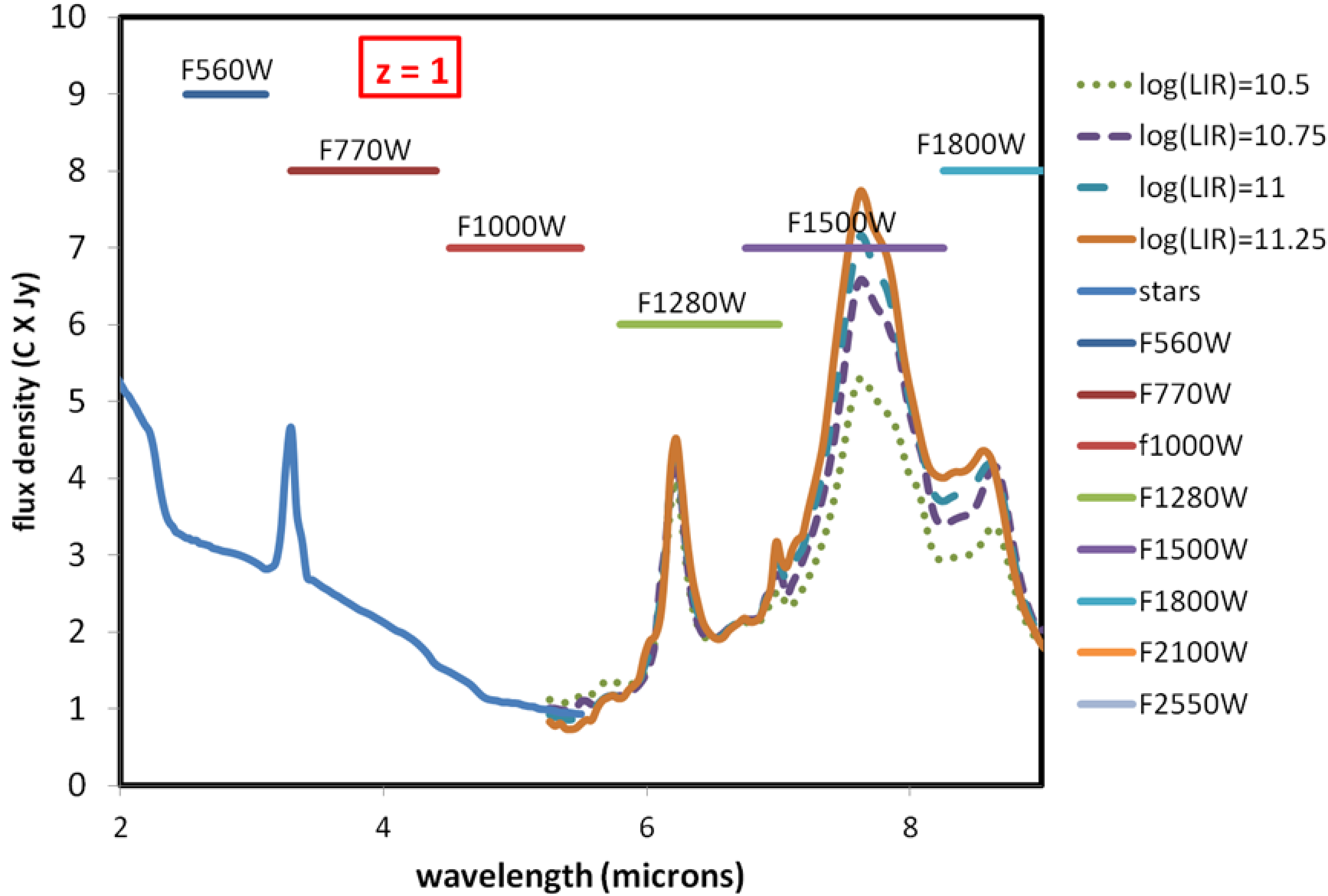


With the additional photometric bands available with MIRI, it may be more powerful to utilize the spectral minimum in star forming galaxies between 3.5 and 5.5 μm.

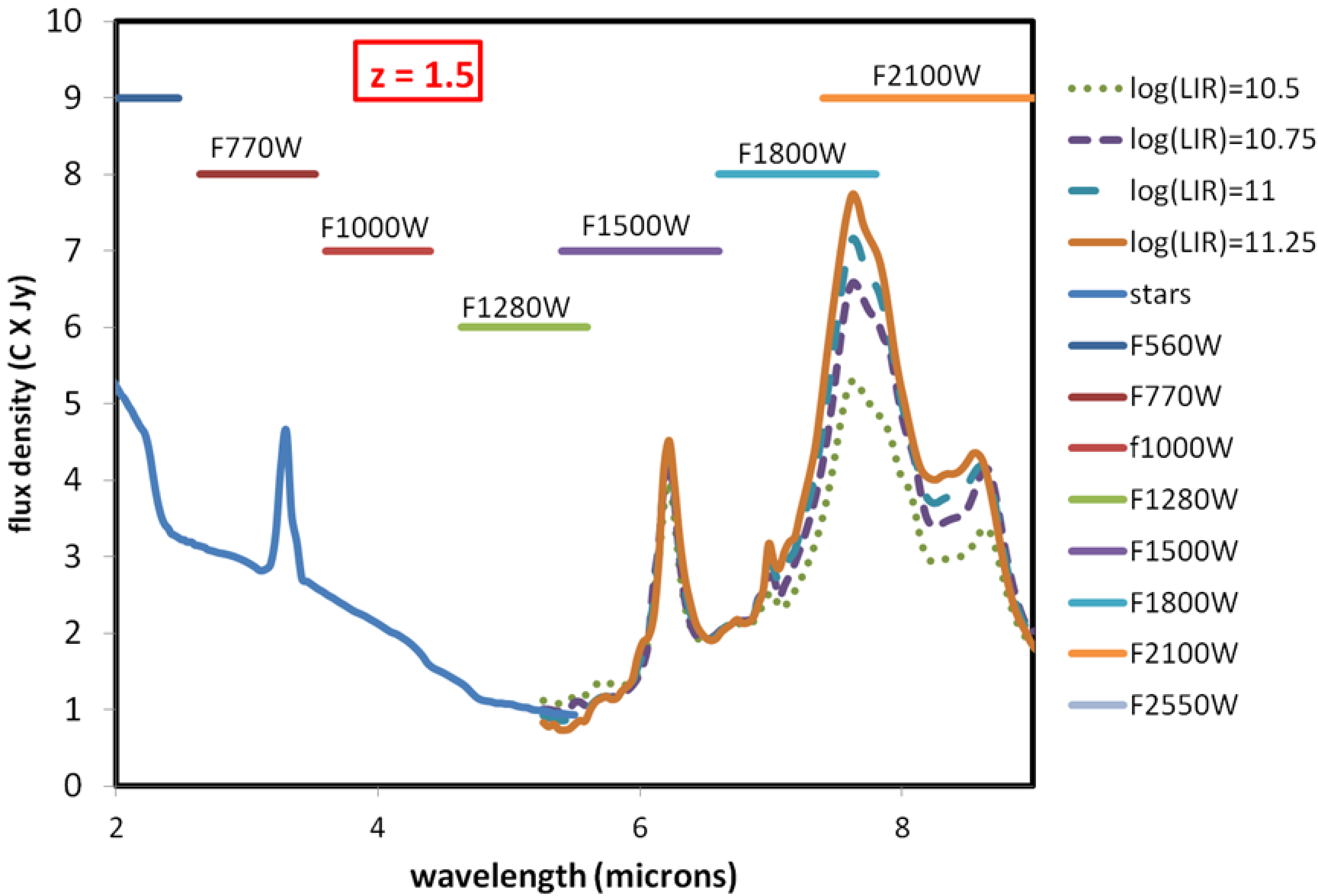
- It is hard for an AGN to hide if one can observe this rest wavelength
- As an example, here is photometry of NGC 4945 (a highly obscured local AGN with 2 – 10 keV reduced by X 35), normalized to the spectrum of Arp 220
- **We will get more complete identifications of AGNs with many MIRI bands that let us isolate the 3.5 – 5.5 μm (rest) spectral region**



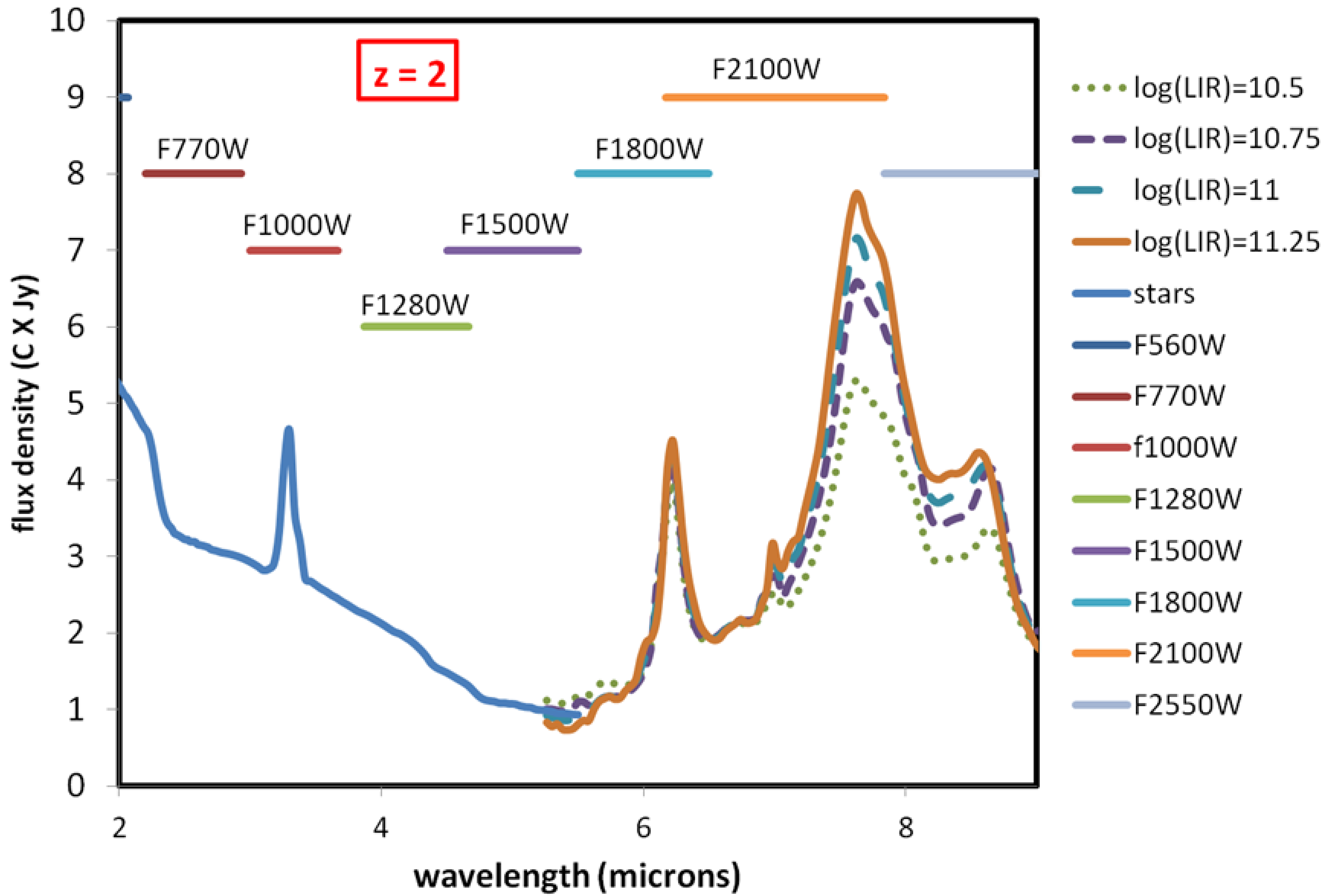
z = 0.5
F560W
F770W
F1000W
F1280W
flux density (C X Jy)
wavelength (microns)
0
1
2
3
4
5
6
7
8
9
10
2
4
6
8
log(LIR)=10.5
log(LIR)=10.75
log(LIR)=11
log(LIR)=11.25
stars
F560W
F770W
f1000W
F1280W
F1500W
F1800W
F2100W
F2550W



z = 1
F560W
F770W
F1000W
F1280W
F1500W
F1800W
flux density (C X Jy)
wavelength (microns)
0
1
2
3
4
5
6
7
8
9
10
2
4
6
8
log(LIR)=10.5
log(LIR)=10.75
log(LIR)=11
log(LIR)=11.25
stars
F560W
F770W
f1000W
F1280W
F1500W
F1800W
F2100W
F2550W



z = 1.5
F770W
F1000W
F1280W
F1500W
F1800W
F2100W
flux density (C X Jy)
wavelength (microns)
10
9
8
7
6
5
4
3
2
1
0
2
4
6
8
log(LIR)=10.5
log(LIR)=10.75
log(LIR)=11
log(LIR)=11.25
stars
F560W
F770W
f1000W
F1280W
F1500W
F1800W
F2100W
F2550W



z = 2
F770W
F1000W
F1280W
F1500W
F1800W
F2100W
10
9
8
7
6
5
4
3
2
1
0
2
4
6
8
flux density (C X Jy)
wavelength (microns)
log(LIR)=10.5
log(LIR)=10.75
log(LIR)=11
log(LIR)=11.25
stars
F560W
F770W
f1000W
F1280W
F1500W
F1800W
F2100W
F2550W

Complete Measurement of Embedded Star Formation to z = 2

- There is a viable strategy to measure obscured SFRs to z ~ 2, based on MIRI 21 μm imaging.

- 3 hours integration will reach SFRs of 10 $M_{\odot}$/yr, 10-σ

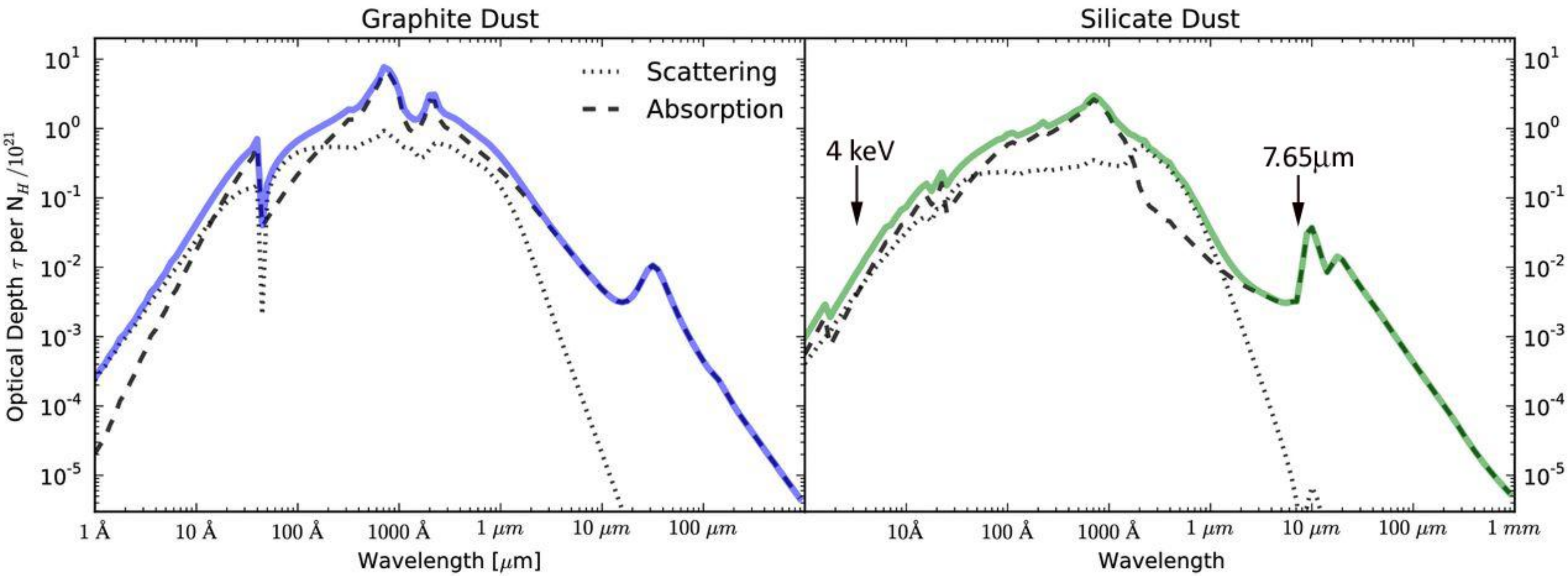
- A critical part of the strategy is appropriately deep imaging in the shorter wavelength MIRI bands

- Time needed for other bands depends on final strategy, but is less than that necessary at 21 μm

- These measurements will provide very complete identification of AGNs

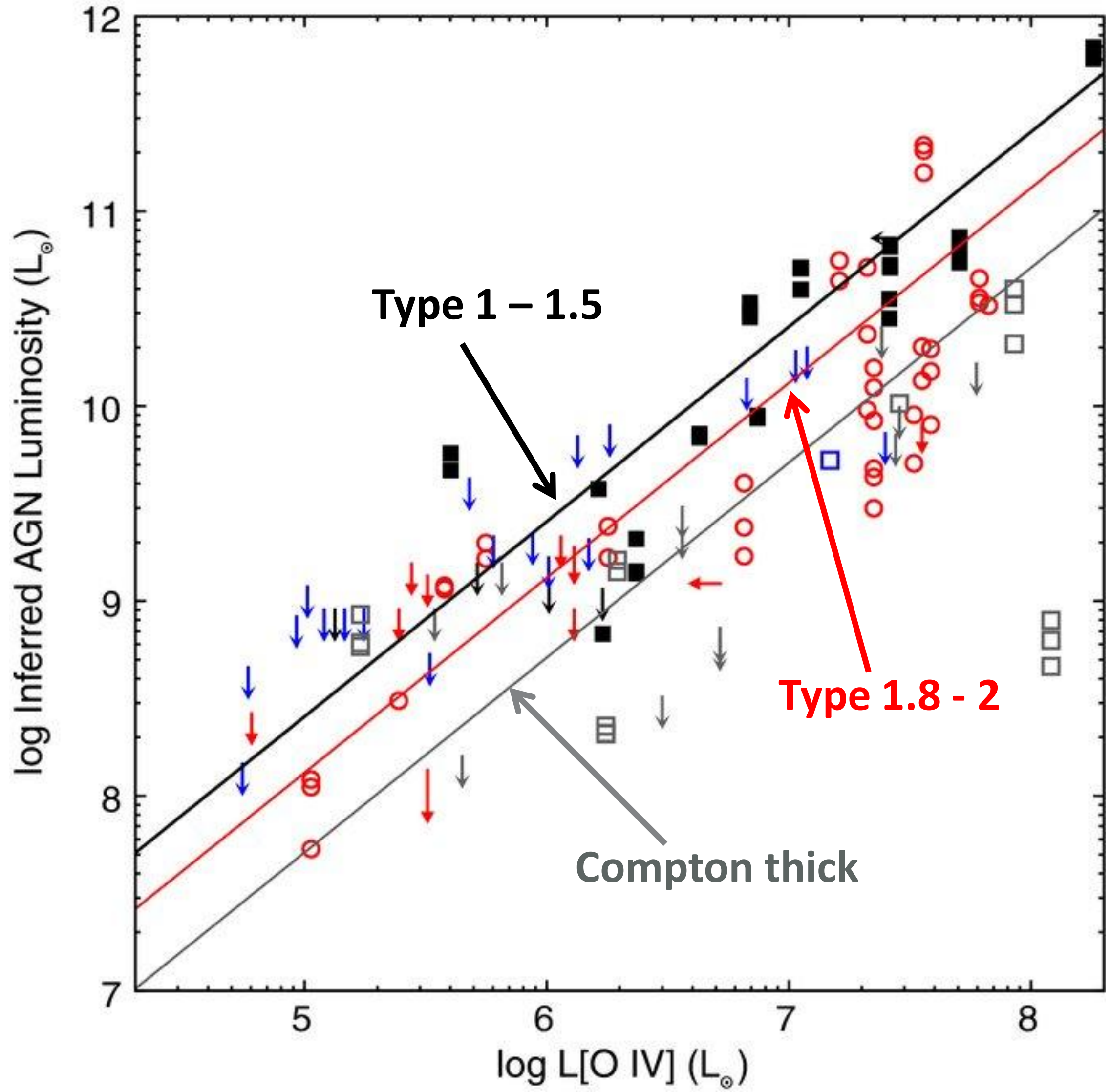
- They will also let us compare the fraction of compact LIRGs and ULIRGs with the more extended ones, as a function of redshift

Mid-IR spectroscopy is competitive with hard X-rays (HX) for AGN studies



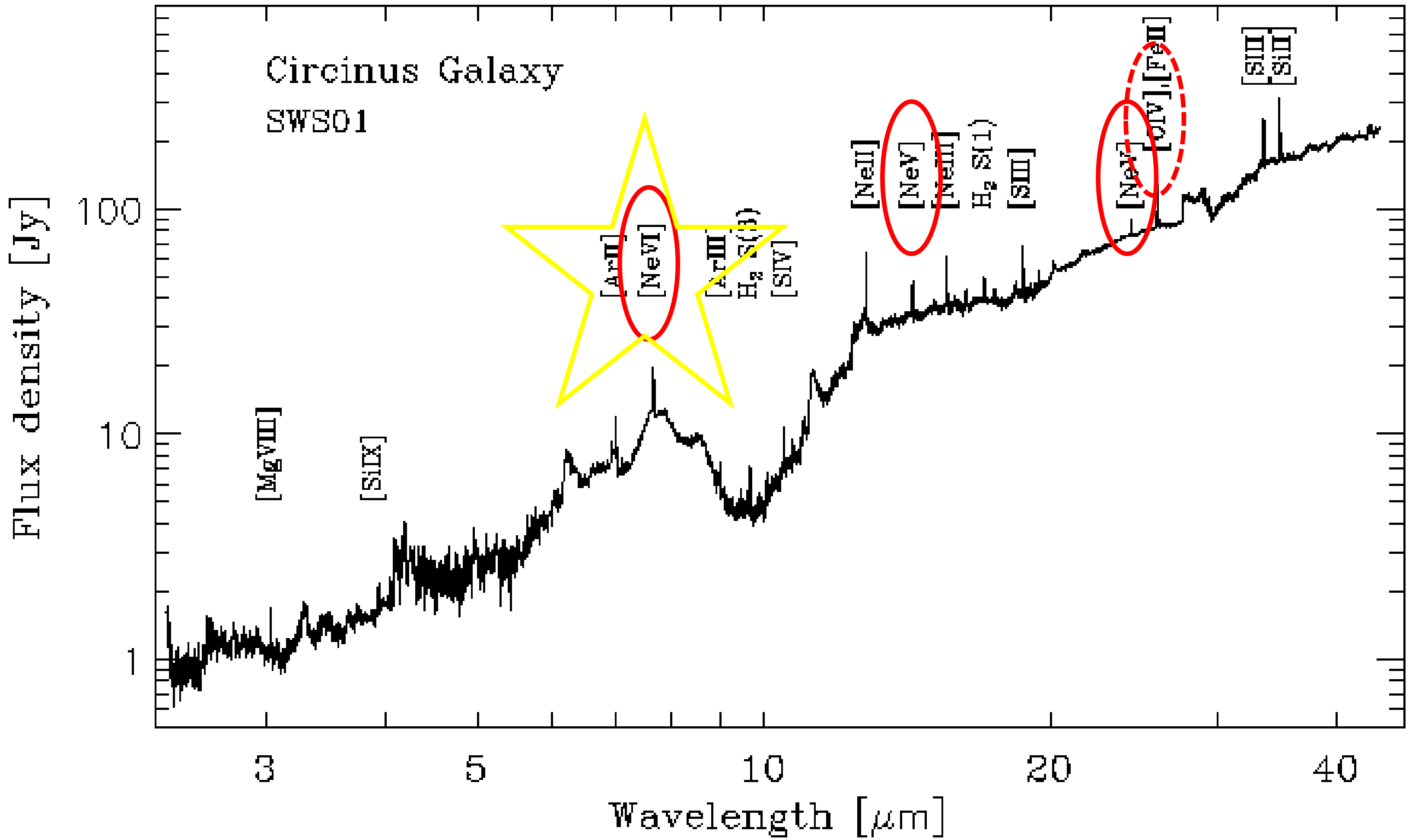
Optical depth at [Ne VI] (7.65 μm) and [O IV] (25.89 μm) is no more than that at about 8 keV. From Corrales et al. 2016, MNRAS, 458, 1345

Comparison of AGN luminosity estimated from hard X-rays with that from [O IV] 25.89 μm. The trend lines show an increasing ratio of L([O IV])/L(X) with increasing absorption.

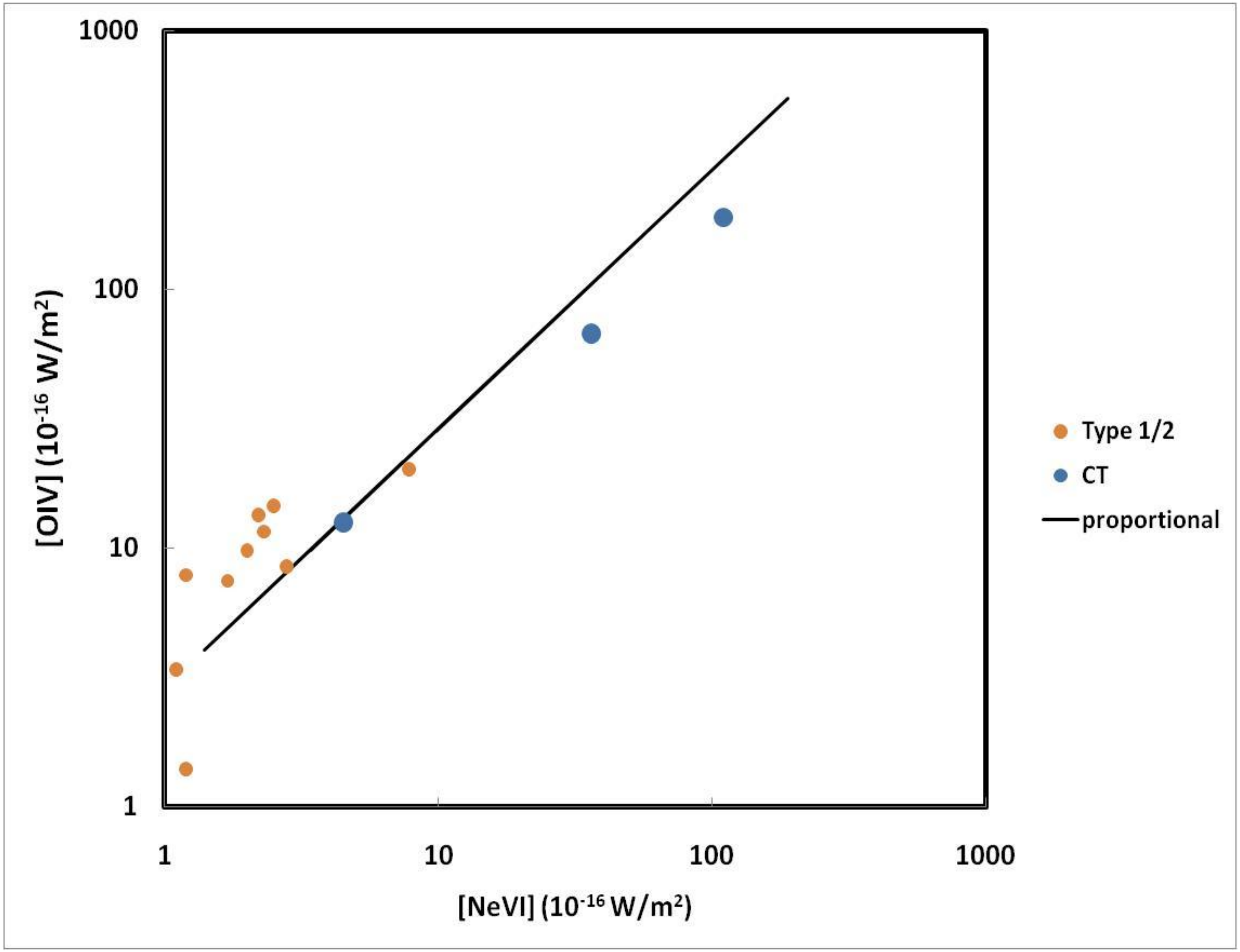


Compton-thin Seyfert 1.8–2 AGNs are plotted as red open circles and arrows; Seyfert 1.8–2 of unknown column are plotted as blue arrows or squares; and Compton-thick AGNs are plotted as light gray open squares and arrows. From Rigby et al. 2009, ApJ, 700, 1878

There are a number of mid-IR fine structure lines indicative of active galactic nuclei



- [Ne VI] 7.65 μm has ionization potential of 158 eV , much too high for stars
- Also critical density of ~ 10^6 cm^{-3} and very low interstellar extinction
- Ratio to hydrogen recombination lines virtually independent of ionization parameter
- Not readily confused with high mass X-ray binaries

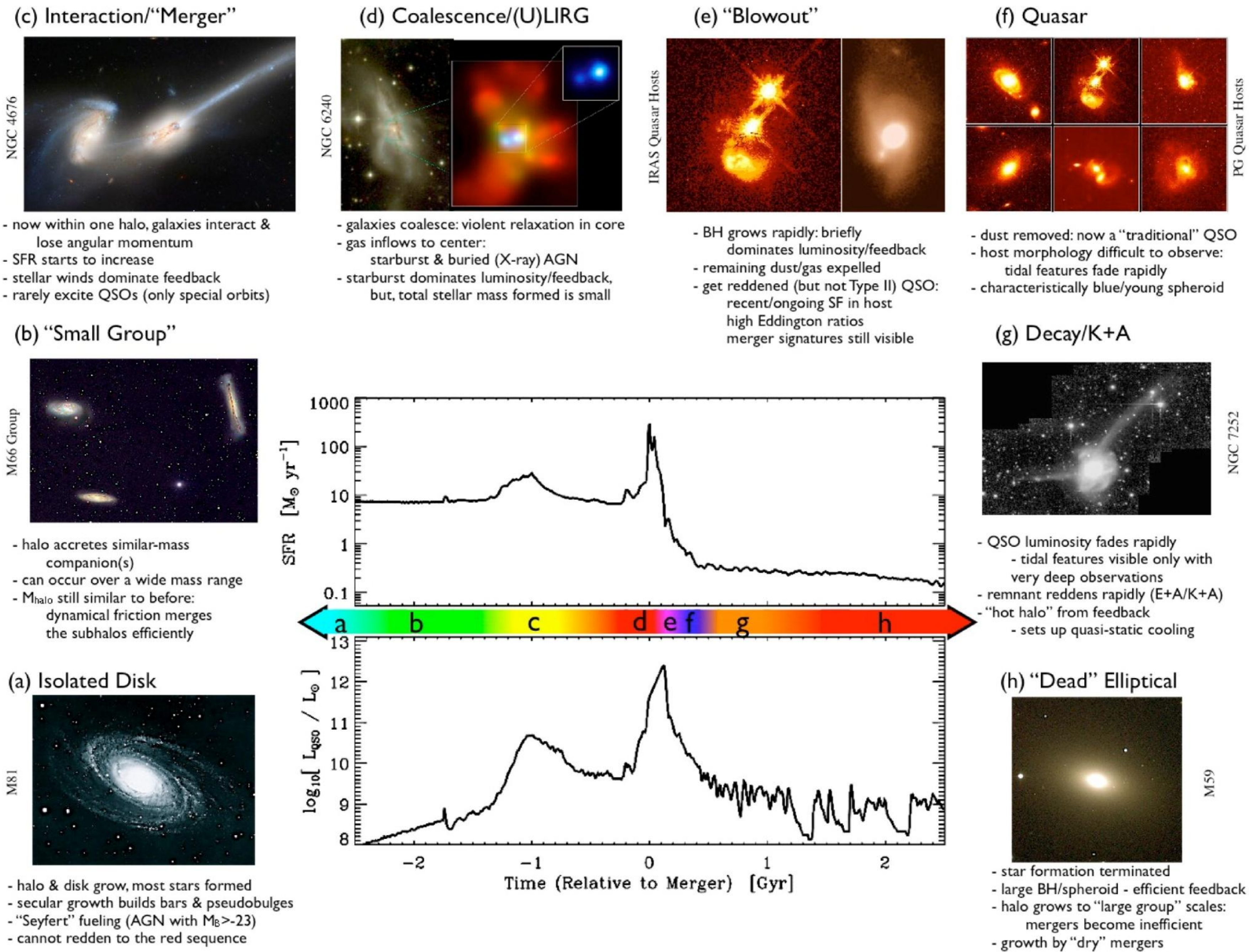


[O IV] and [Ne VI] track each other closely in identifying AGN. Mostly from Sturm et al. 2002, A&A, 393, 821

Applications of MIRI Spectroscopy to AGN

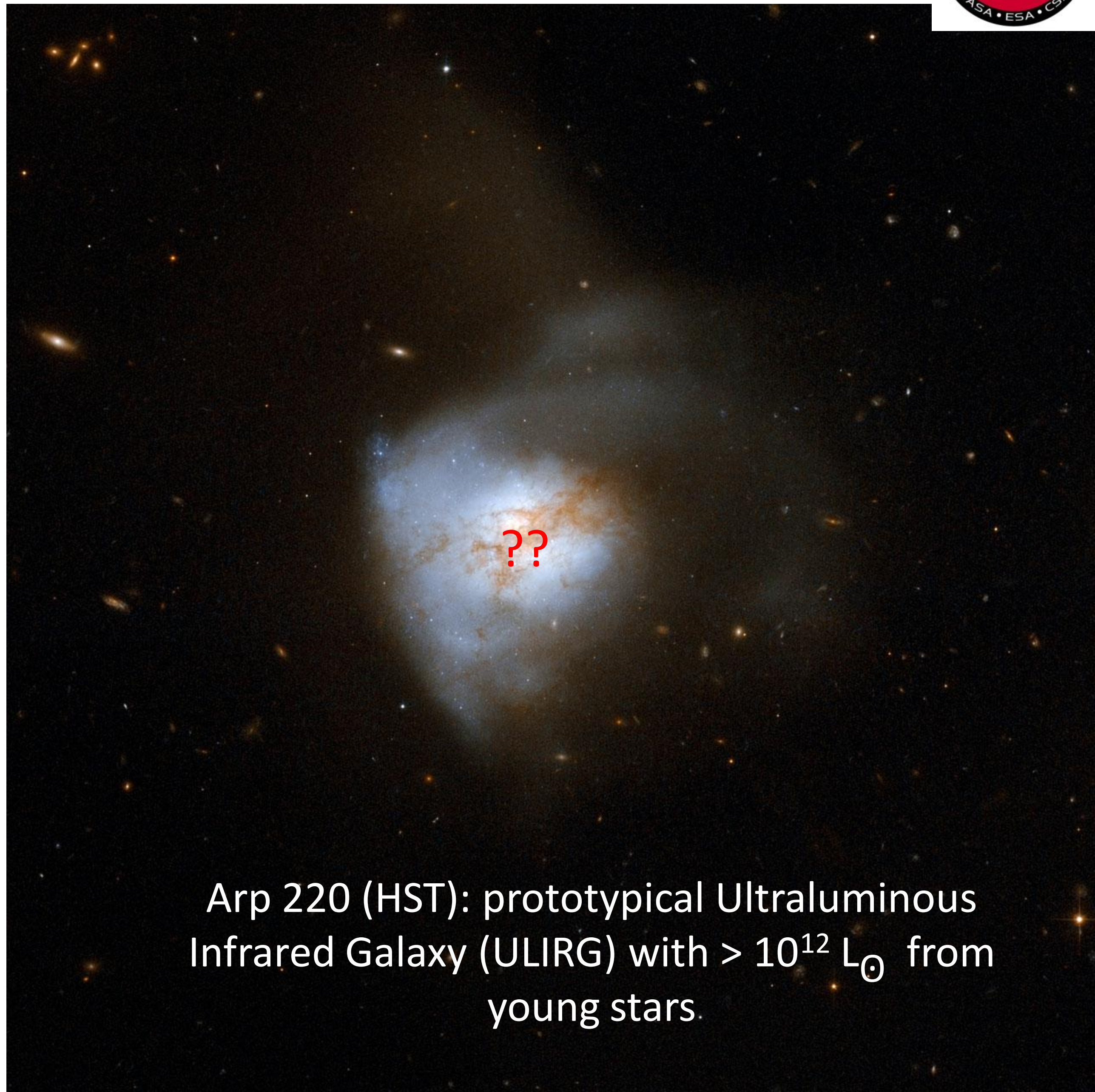
- **Testing whether ULIRGs are the nurseries for AGN**
- **Identifying true Type-2 AGN**

The famous Hopkins ULIRG/QSO evolutionary scenario



But are ULIRGs really the nurseries for active galactic nuclei???

- 1 hour with JWST could detect an AGN with a luminosity of $\sim 10^7\ L_\odot$
- This is $< 10^{-5}$ the luminosity in young stars
- [NeVI] is less affected by extinction than are hard X-rays
- [NeVI] should not be excited by ultraluminous X-ray sources (ULXs) or high-mass X-ray binaries (HMXBs)



Arp 220 (HST): prototypical Ultraluminous Infrared Galaxy (ULIRG) with $> 10^{12}\ L_\odot$ from young stars

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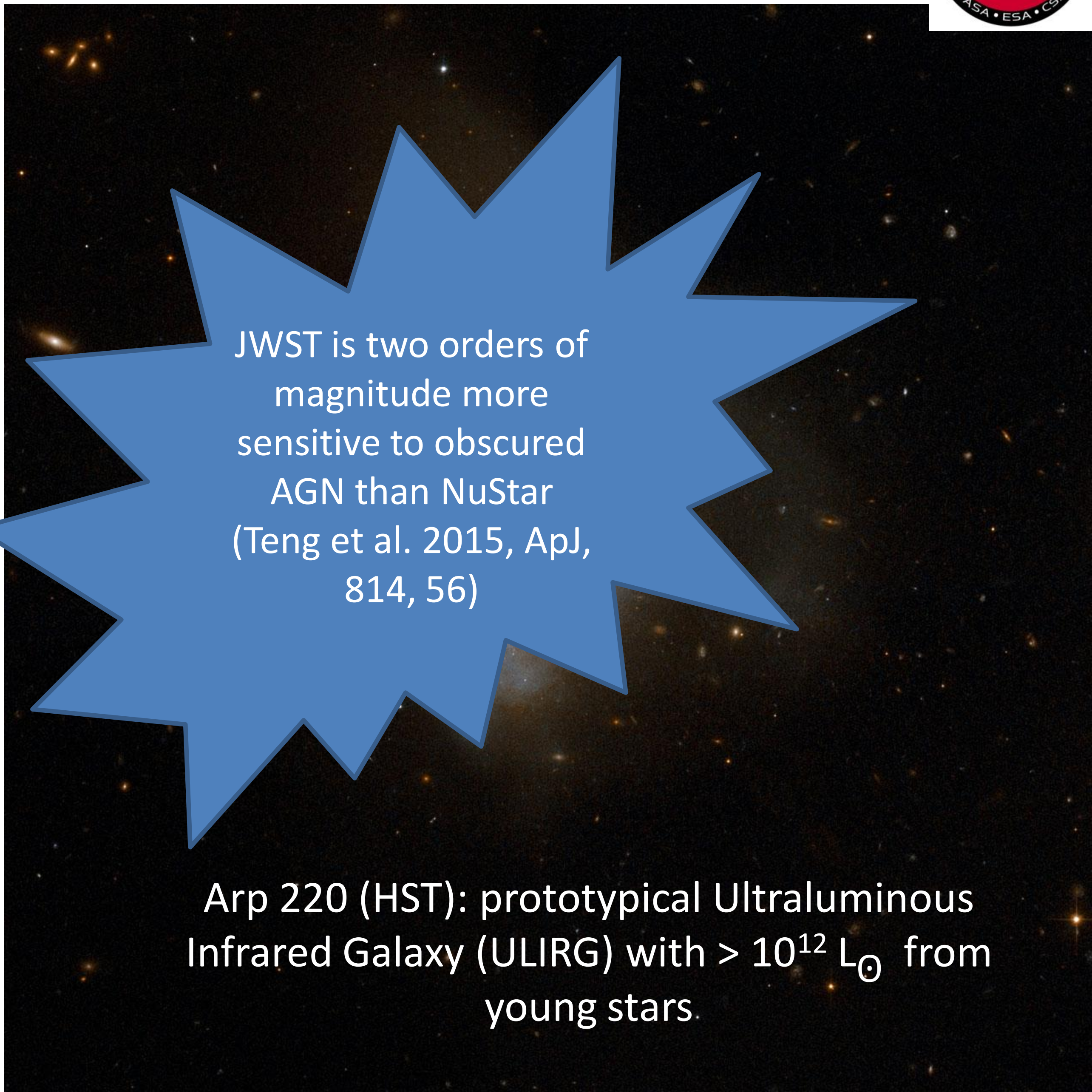
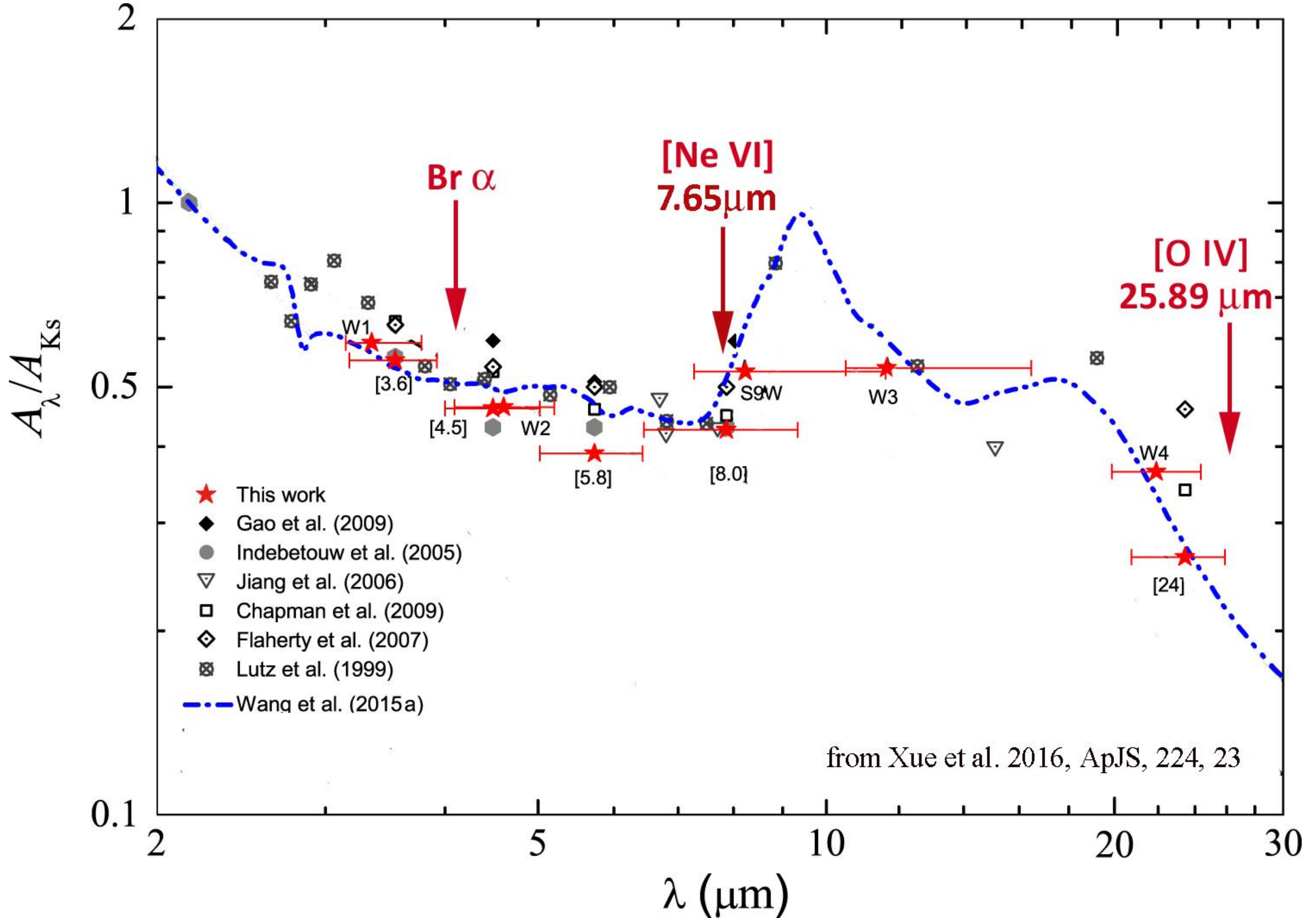


Arp 220 (HST): prototypical Ultraluminous Infrared Galaxy (ULIRG) with > $10^{12} L_\odot$ from young stars

[Ne VI] 7.65 μm and Br α 4.05 μm fall within a broad minimum in interstellar extinction, facilitating a number of possible investigations

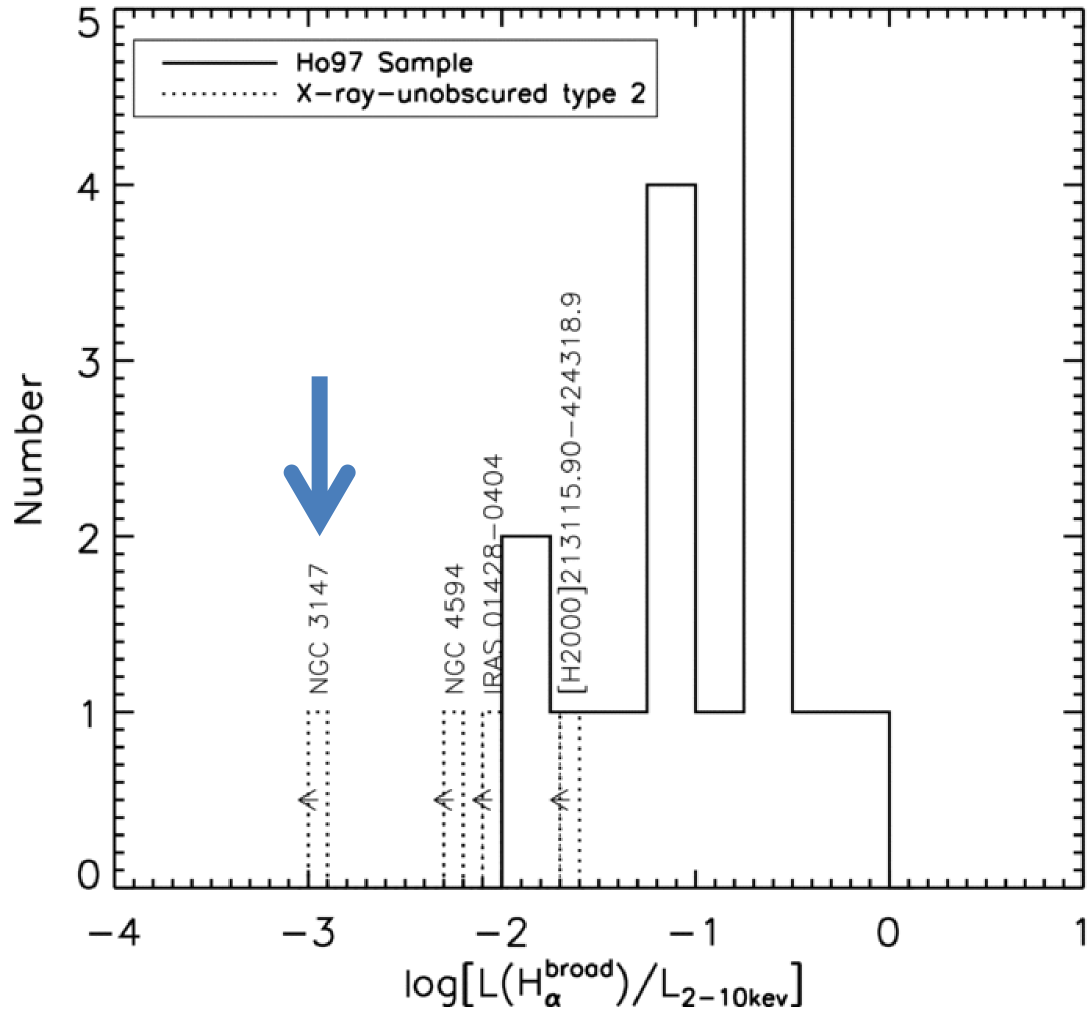


An application: True Type 2 AGN

True type-2 AGN, i.e., with no BLR can be a critical test of central engine models, i.e. the disk-wind scenario for the BLR (Elitzur & Netzer 2016, MNRAS, 459, 585

There are a few reasonably convincing examples: Shi et al. 2010; Miniutti et al. 2013

It is very difficult to be sure, given variability of central engine, changes in its obscuration, and possible extinction to the optical lines usually used to search for broad components.



From Shi et al. 2010, ApJ,714, 115

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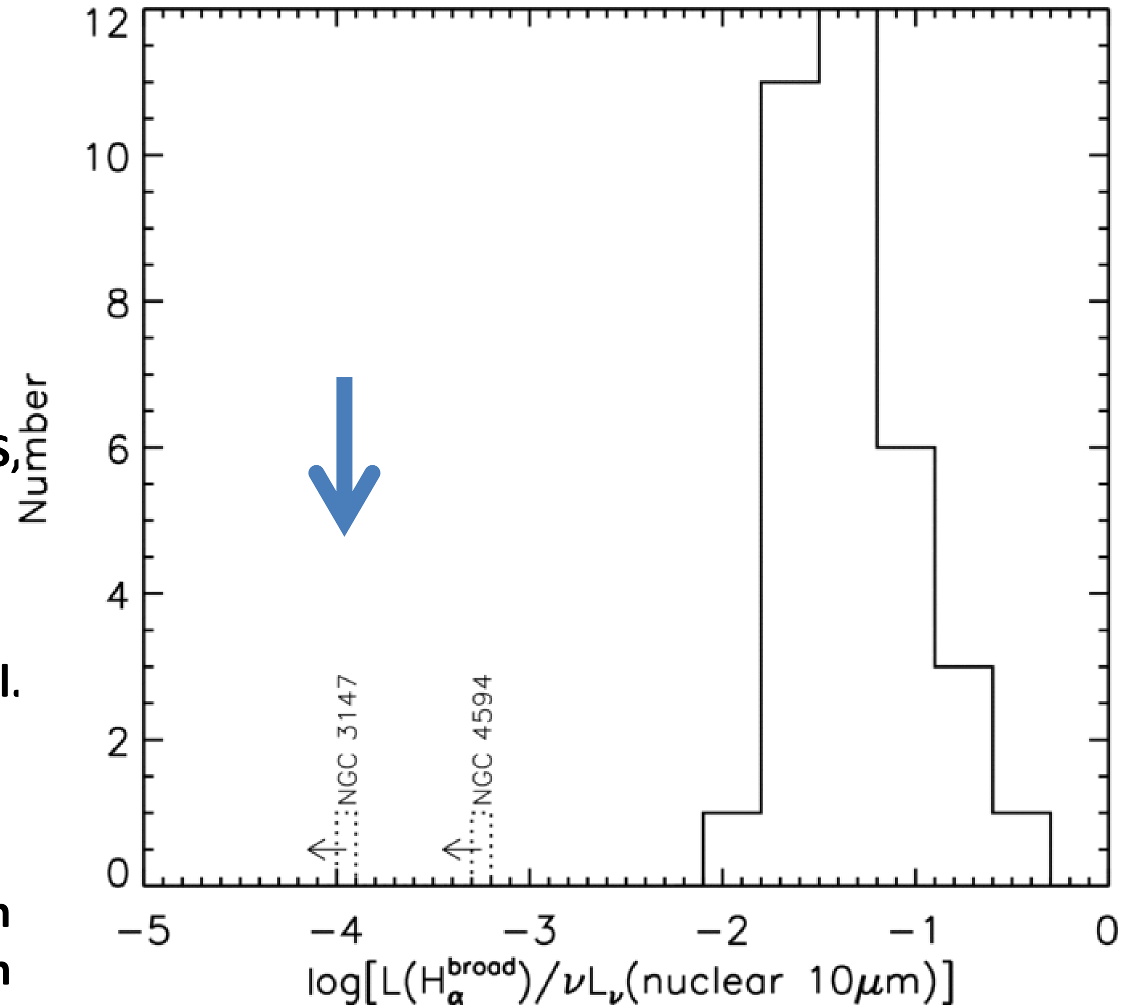

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JWST and True Type 2 AGN

- The [Ne VI] 7.65 μm line can be used to measure the instantaneous luminosity of the central engine

- Can get a simultaneous measurement of the hydrogen line profiles

- If use Pa α or even better Br α the obscuration will be minimized

- JWST therefore allows unambiguous comparison of intrinsic AGN properties
    - Provides a definitive determination if the AGN is true type 2

Summary

- [Ne VI] 7.65 μm line is foundation for many AGN investigations
  - Ionization potential of 158 eV , much too high for stars
  - Critical density of ~ 10^6 cm^{-3} and very low interstellar extinction
  - Ratio to hydrogen recombination lines virtually independent of ionization parameter
  - Not readily confused with high mass X-ray binaries
- Samples
  - Probing ULIRGs for very faint embedded AGN
  - Simultaneous AGN lumnosity and emission lines – true type 2 AGN (?)

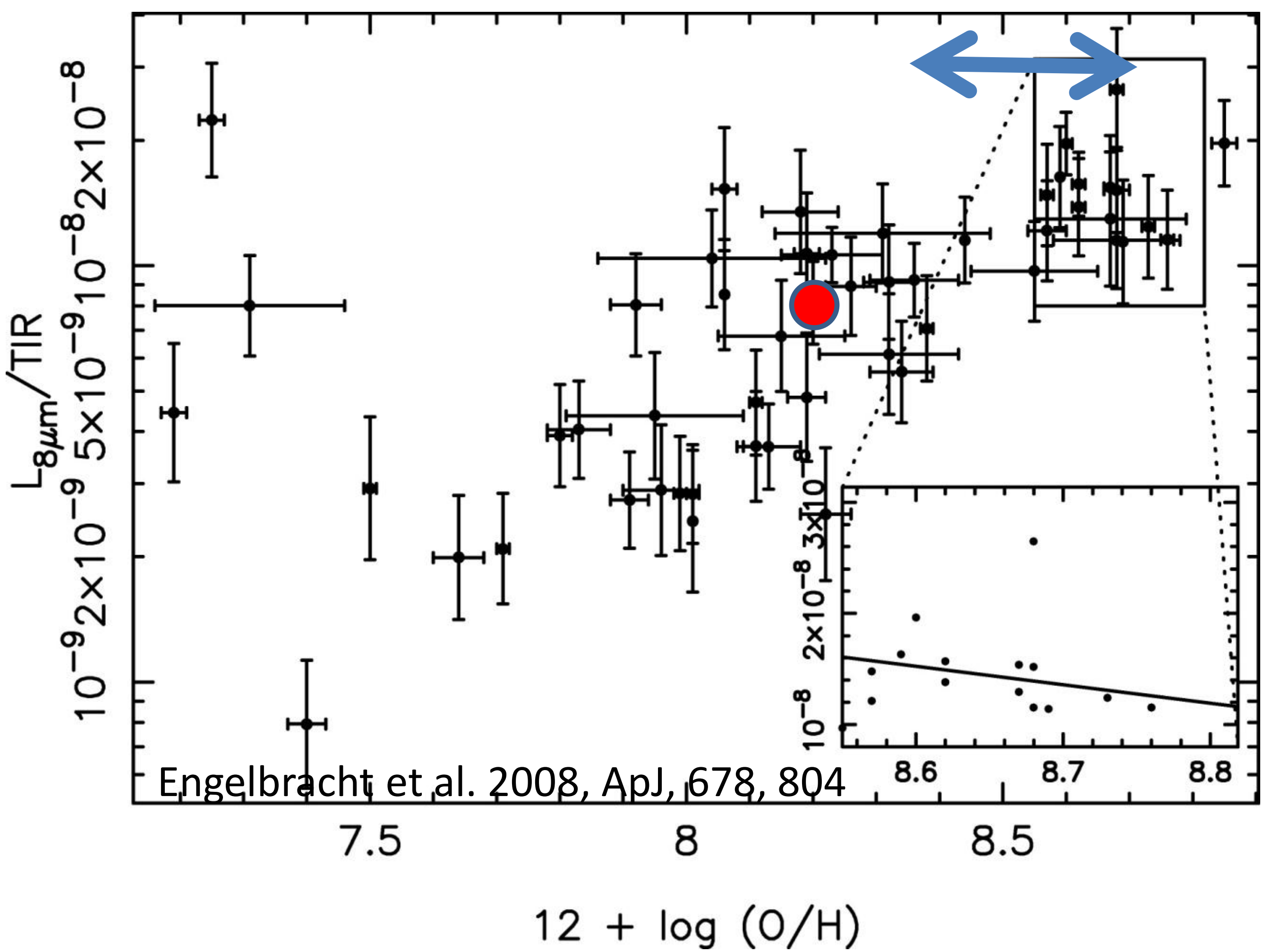
Overall: Spitzer Foundations for JWST Studies

- Determining embedded star formation rates out to $z \sim 2$
  - Depends on 21 μm plus shorter integrations in other MIRI bands to identify problematic galaxies
- Identifying AGN by documenting spectral minimum near 5 μm
- Use of [Ne VI] line to identify AGN, measure intrinsic lumnosity
- Pa α and Br α show hydrogen line structure with minimal extinction

backup

The calibration should remain valid over the expected range of metallicity.

The arrow extends from solar metallicity to that expected for a main sequence galaxy at z = 2 forming stars at 10 $M_\odot$ yr^{-1} (e.g., Erb et al. 2006, ApJ, 644, 813; Zahid et al. 2013, ApJL, 771, 19



Relatively low mass/high z will need multiband photometry to test aromatic strengths.