A Far-IR View of z = 2 ULIRGs

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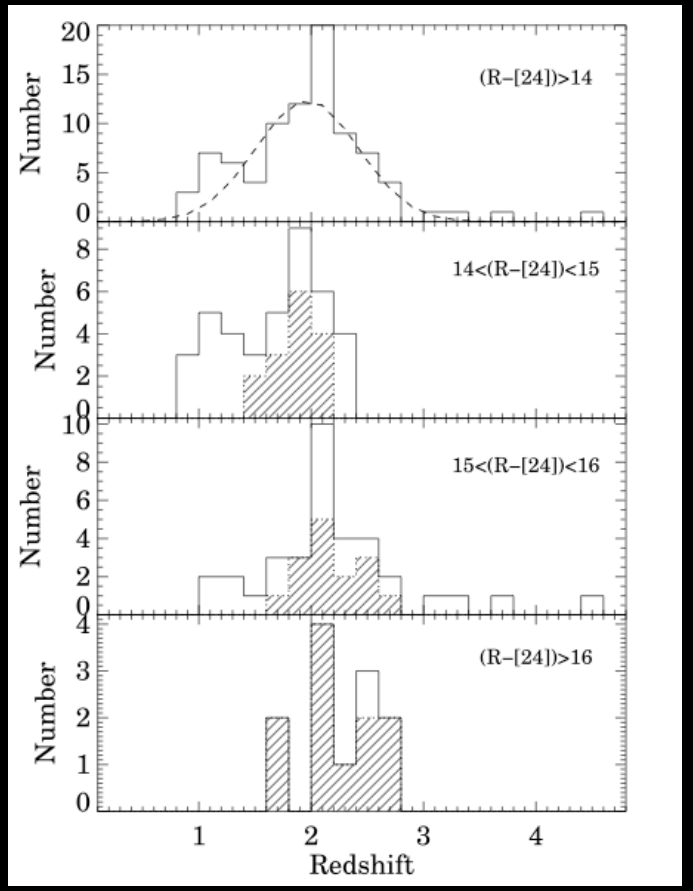
Simple Selection Criteria Picks Out z = 2 ULIRGs

Bright in the MIR, Faint in the Optical

- R - [24] > 14
- F_ν (24) / F_ν (R) > 1000
- F_ν (24) > 0.3 mJy

Called Dust Obscured Galaxies (DOGs)

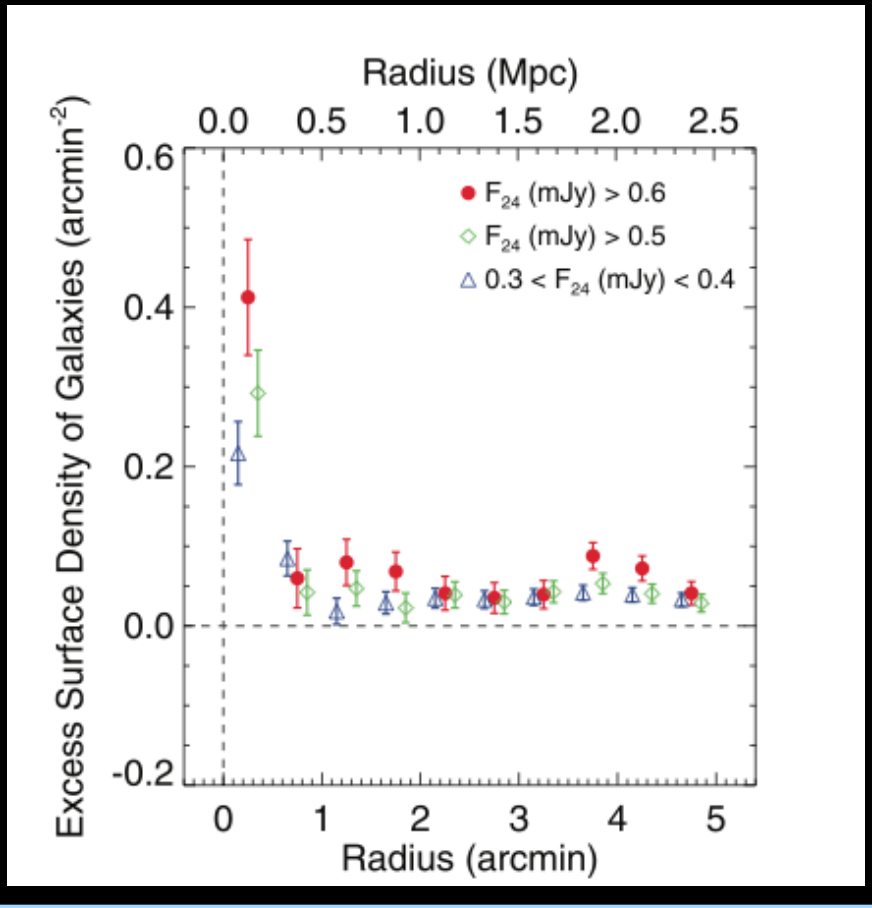


Dey et al. 2008

DOGs May be Progenitors of Today's Massive Ellipticals

only seen at a time of rapid star formation or black hole growth

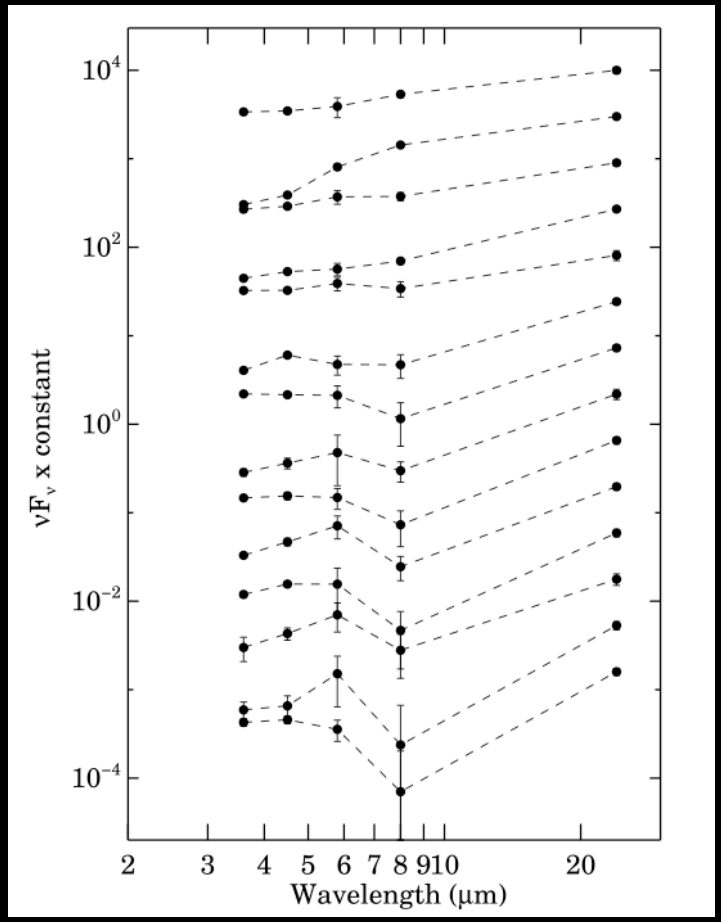
- Highly Clustered
- Live In Dense Environments
- Likely to Evolve into 3-7 L* Galaxies



Brodwin et al. 2008

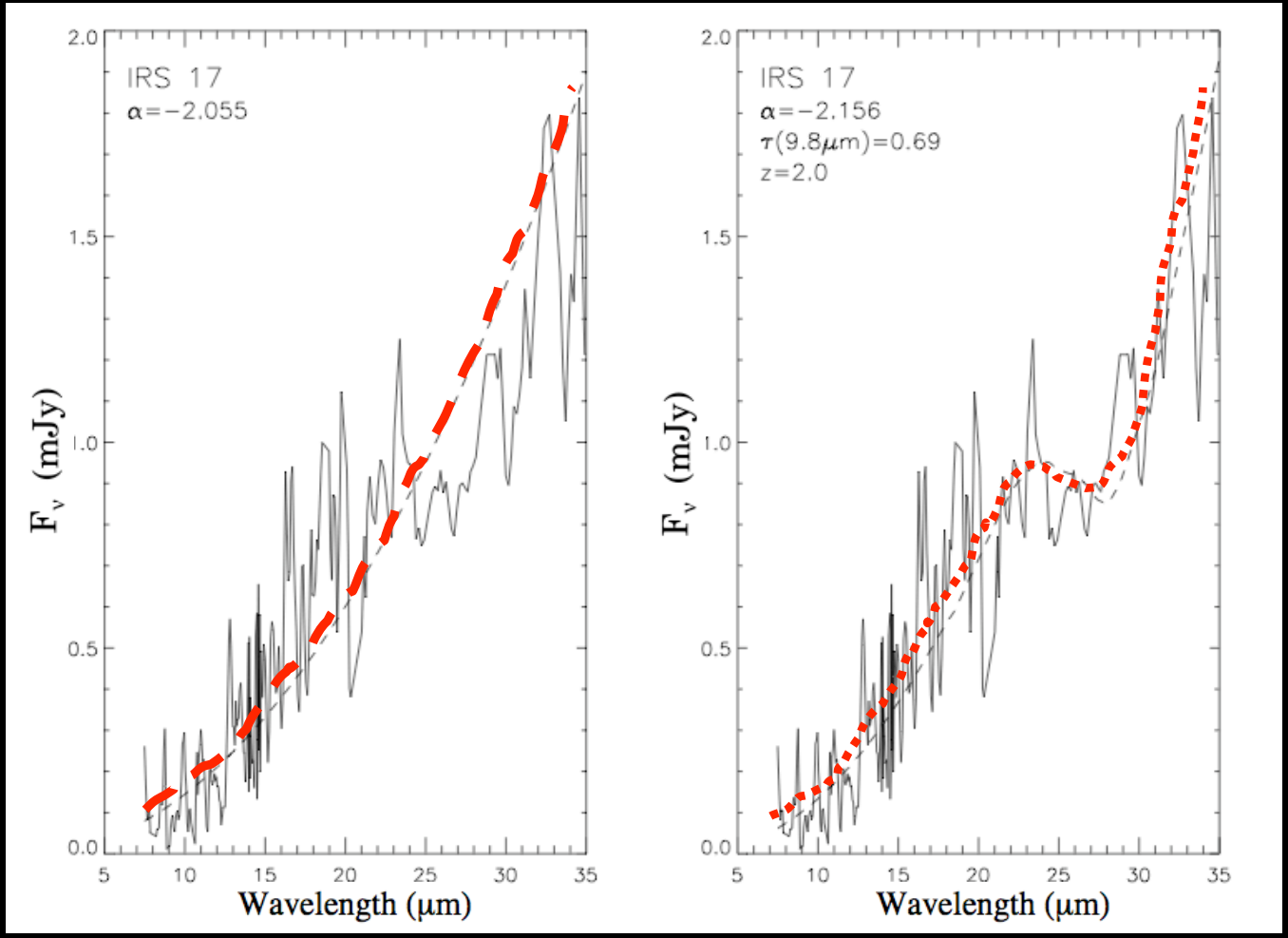
Spectral Energy Distributions Vary with 24 micron Flux

- Brighter DOGs tend to show power-law SEDs.
- Fainter DOGs tend to show a “bump” in the observed mid-IR



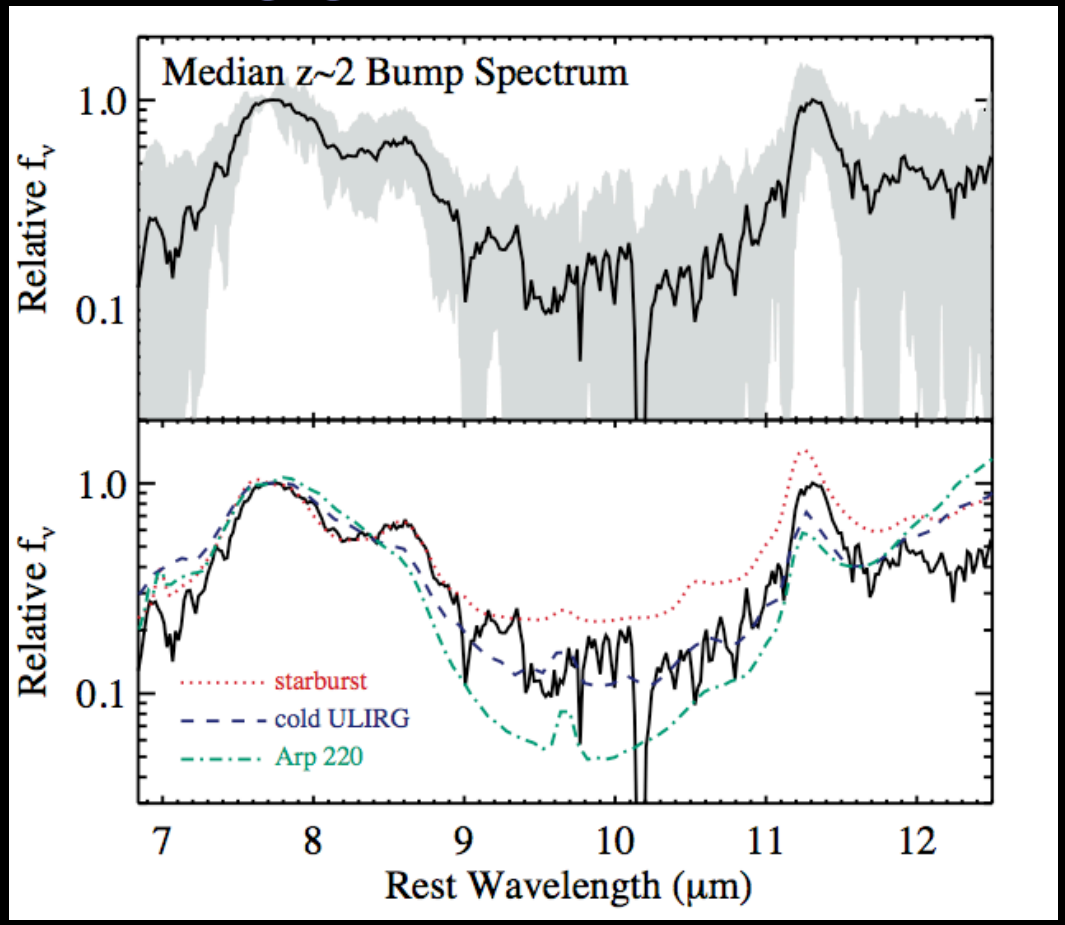
Dey et al. 2008

Spitzer Spectra of Power-Law DOGs Suggest AGN Activity



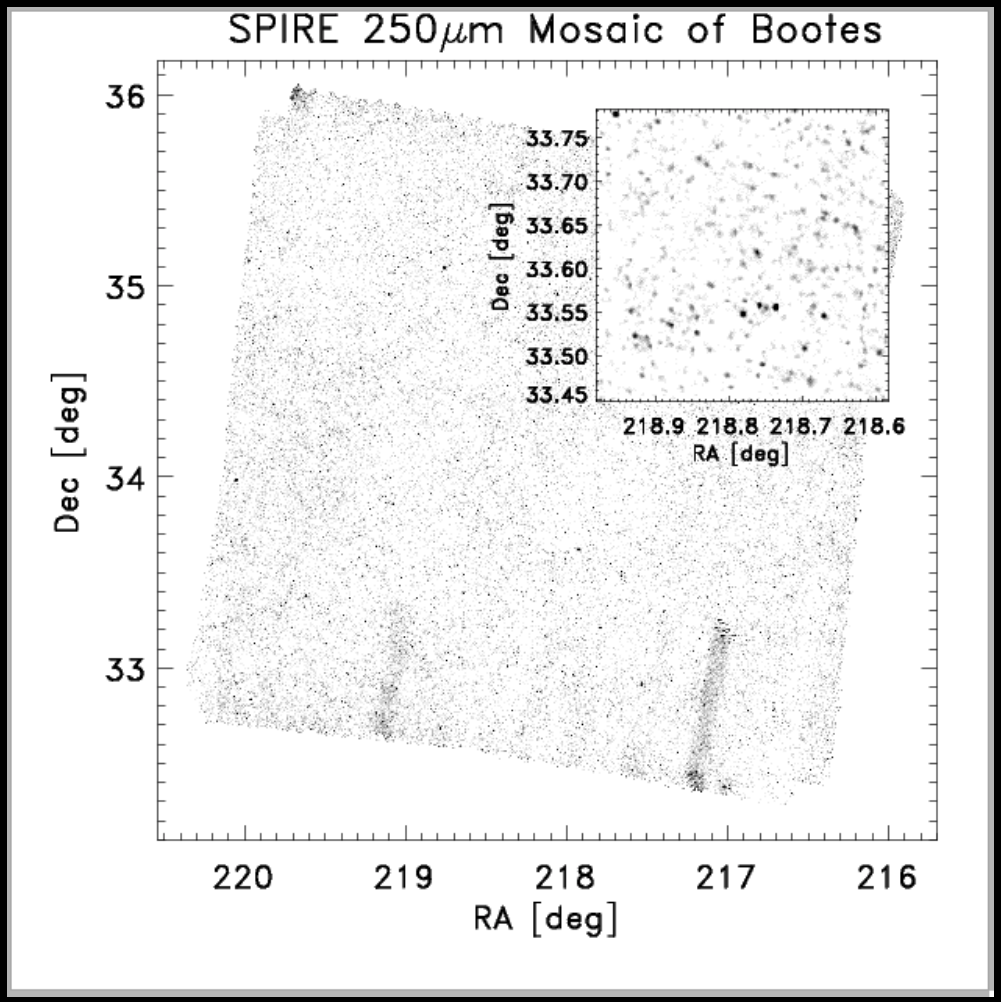
Weedman et al. 2005

Spitzer Spectra of "Bump" DOGs Suggest Star Formation

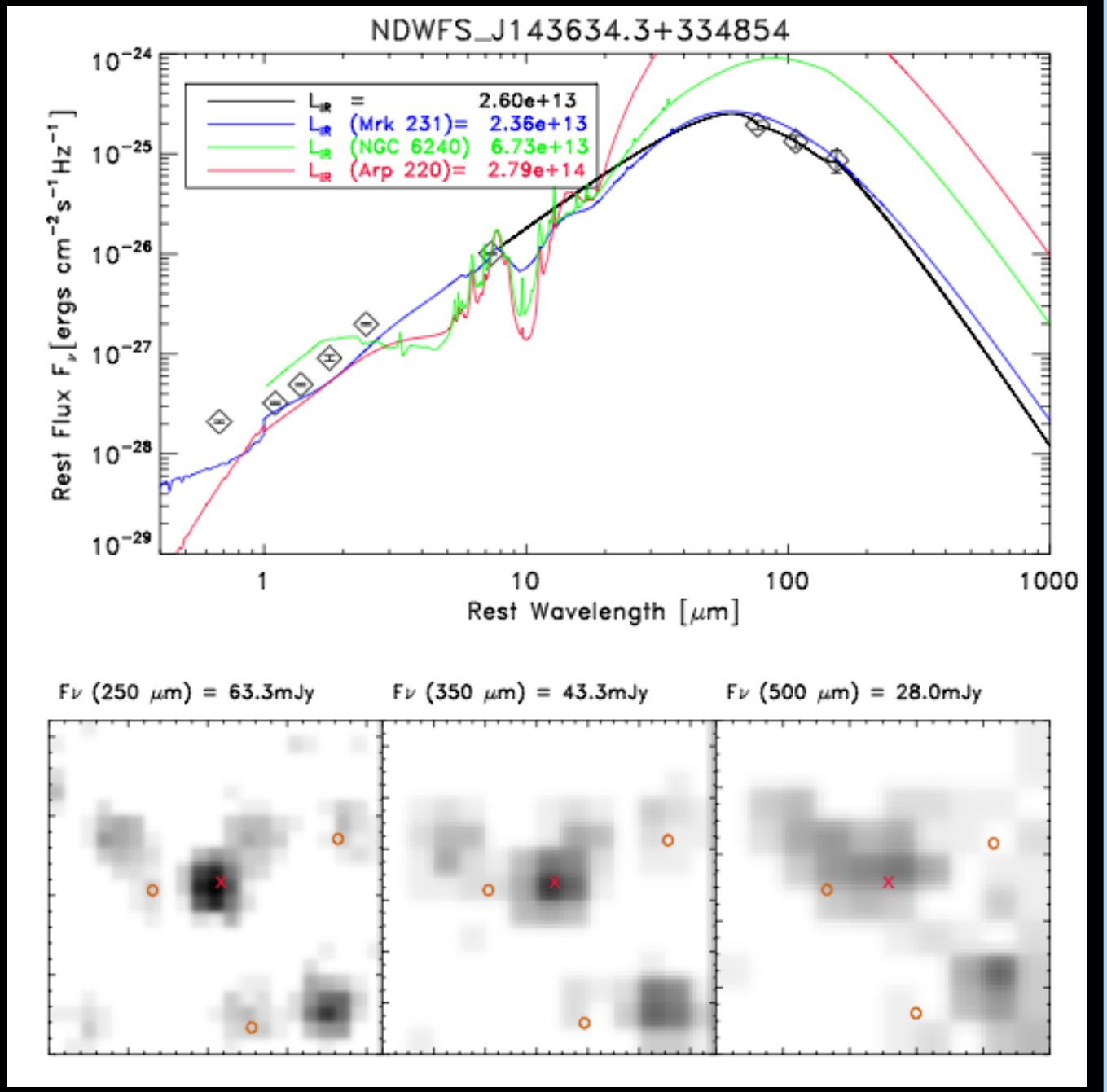


Desai et al. 2009

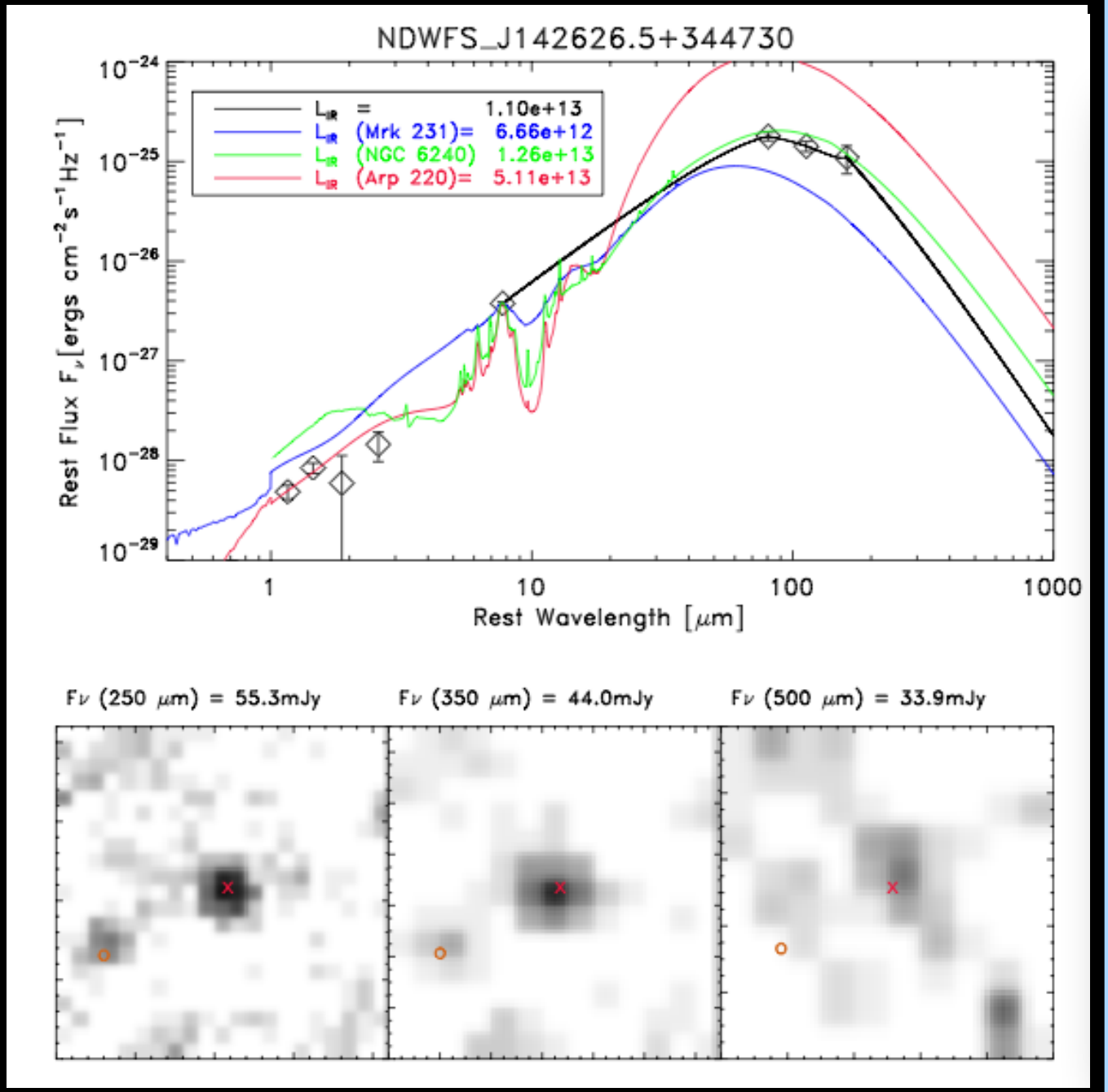
NDWFS of Bootes Observed With Herschel SPIRE as Part Of HerMES



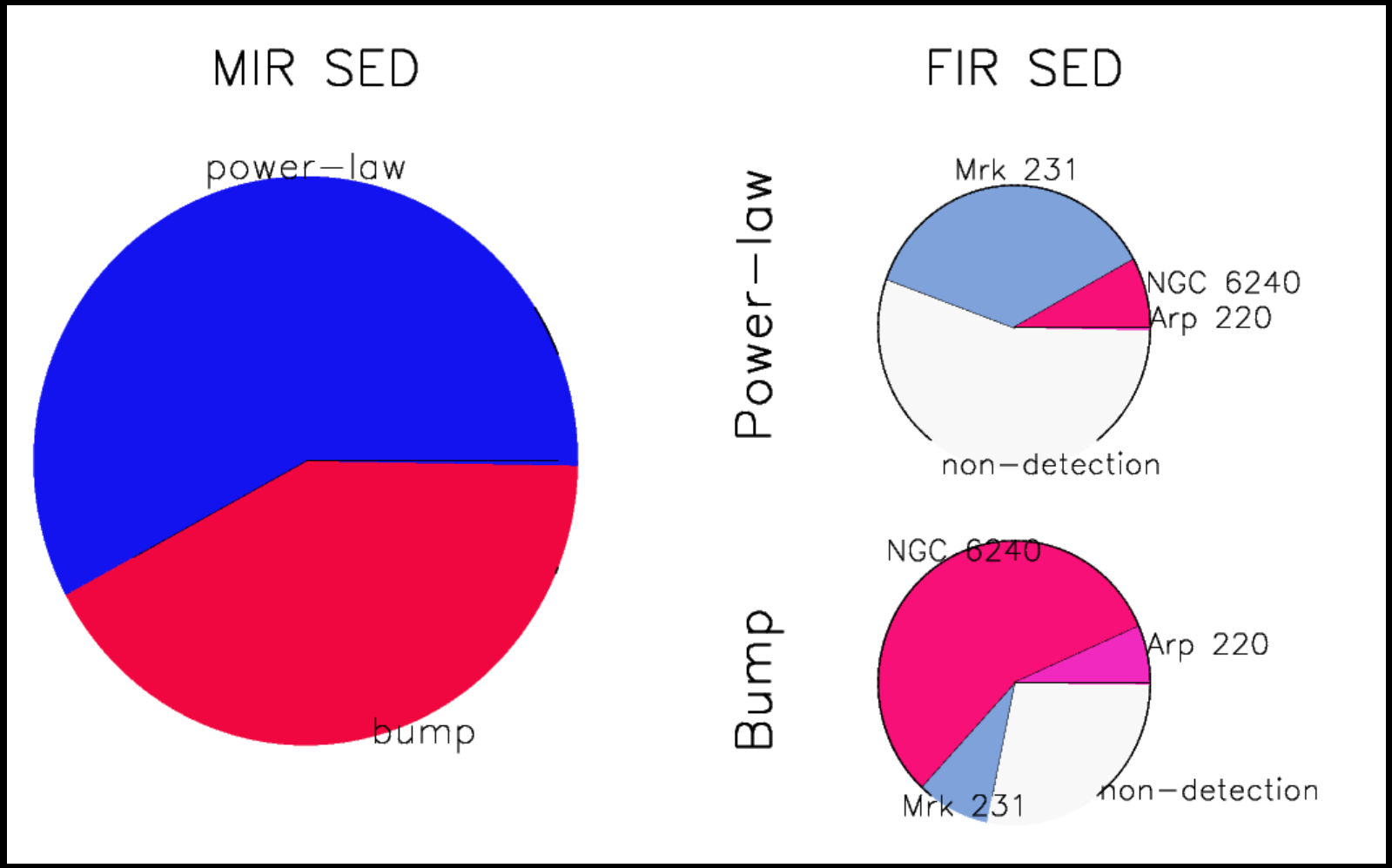
Some DOGs Have FIR SEDs Similar to Mrk 231 (AGN)



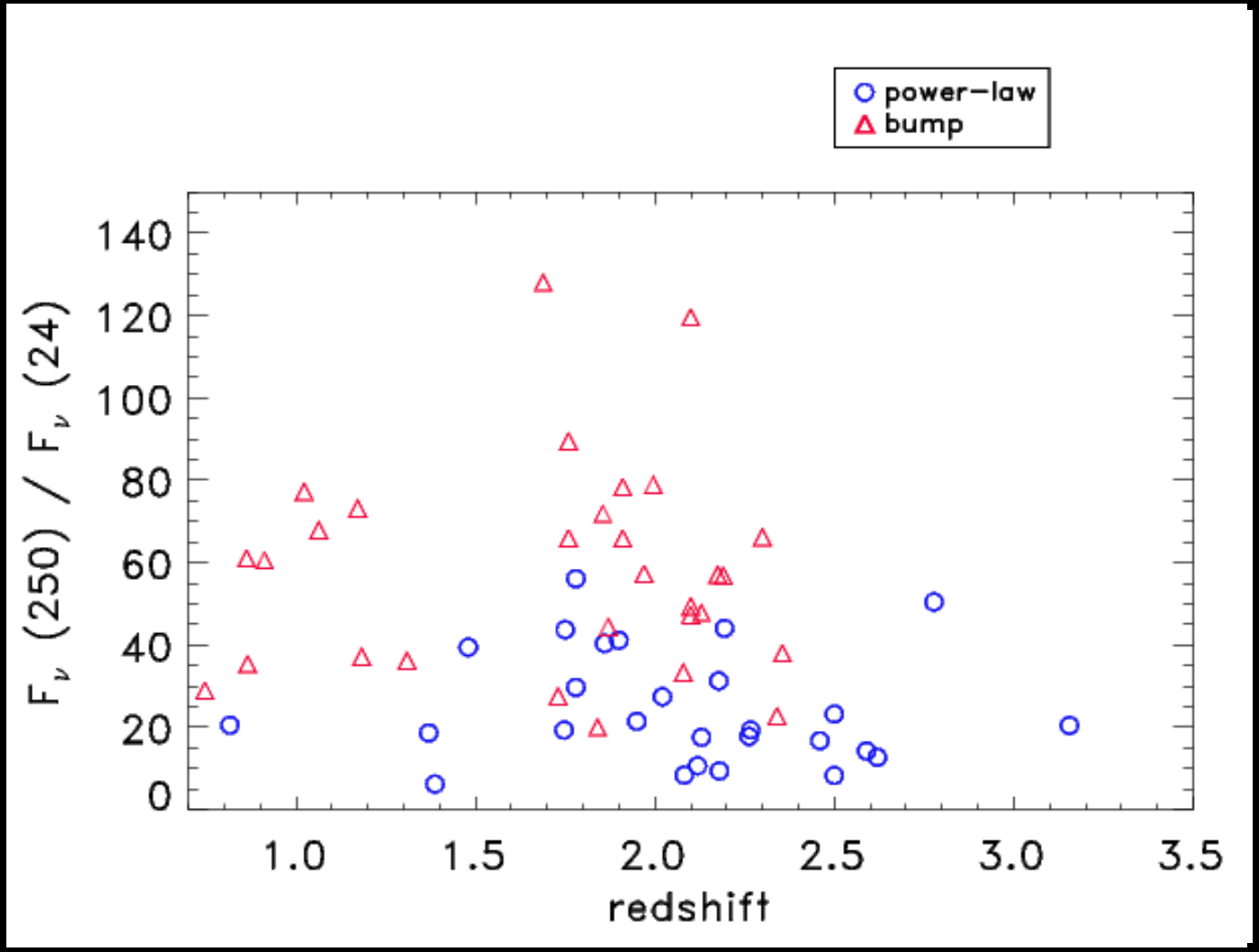
Some DOGs Have FIR SEDs Similar to NGC 6240 (Starburst)



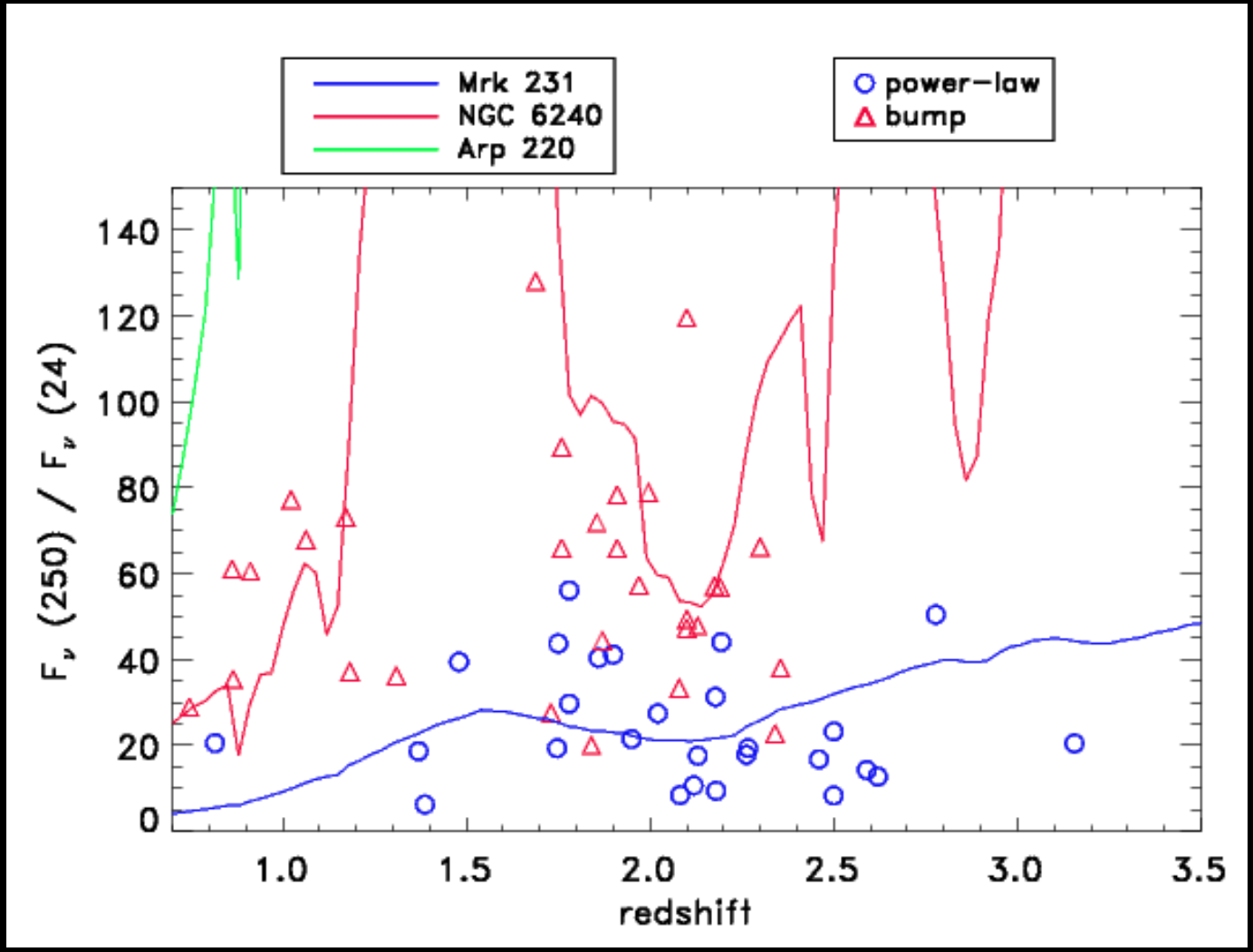
Power-Law DOGs are less likely to be detected in the FIR, and are more likely to have AGN-like SEDs



Power-Law DOGs are Missing from FIR samples because they have small 250/24 micron ratios

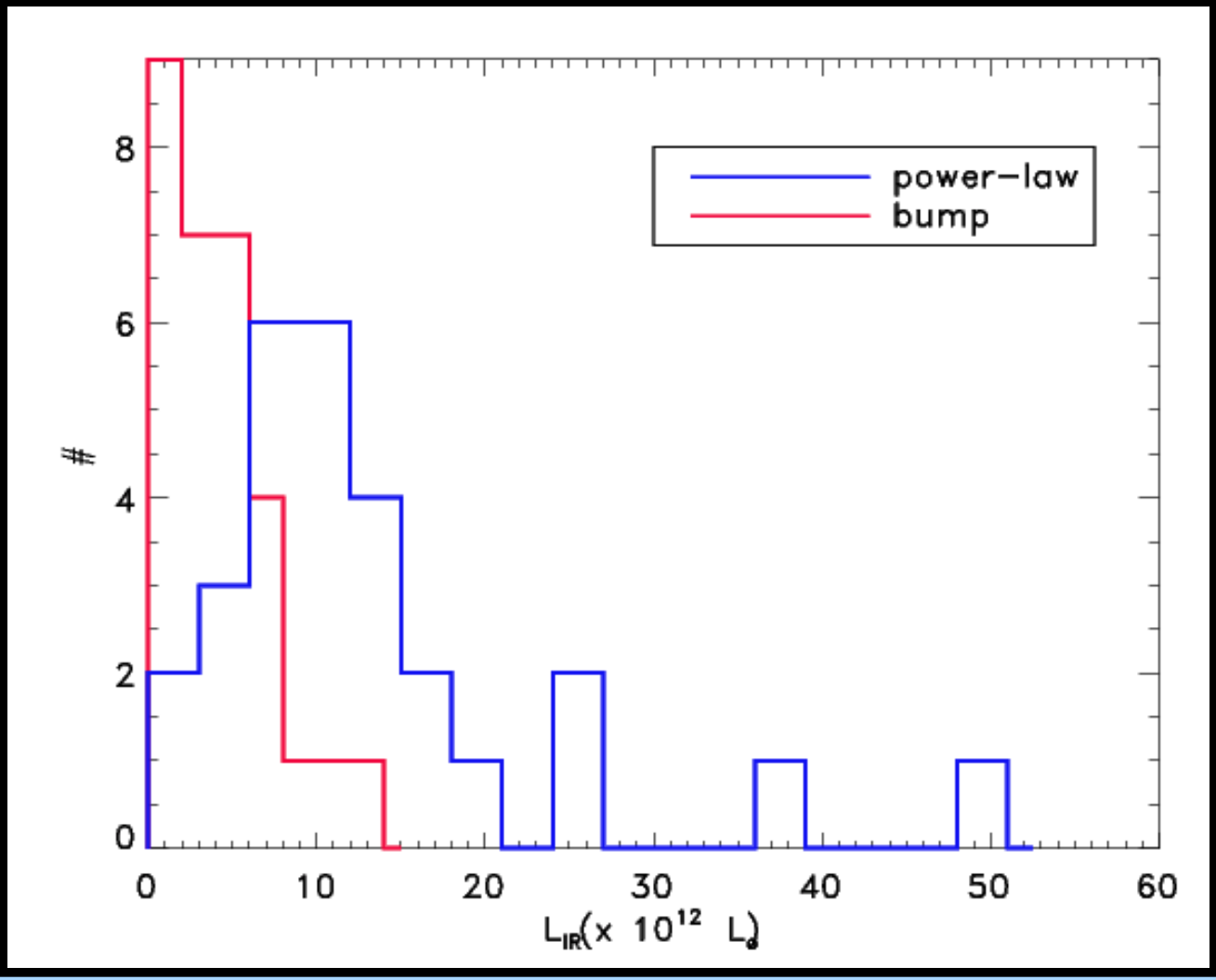


Power-Law DOGs have AGN-like 250/24 micron ratios
Bump DOGs have Starburst like ratios

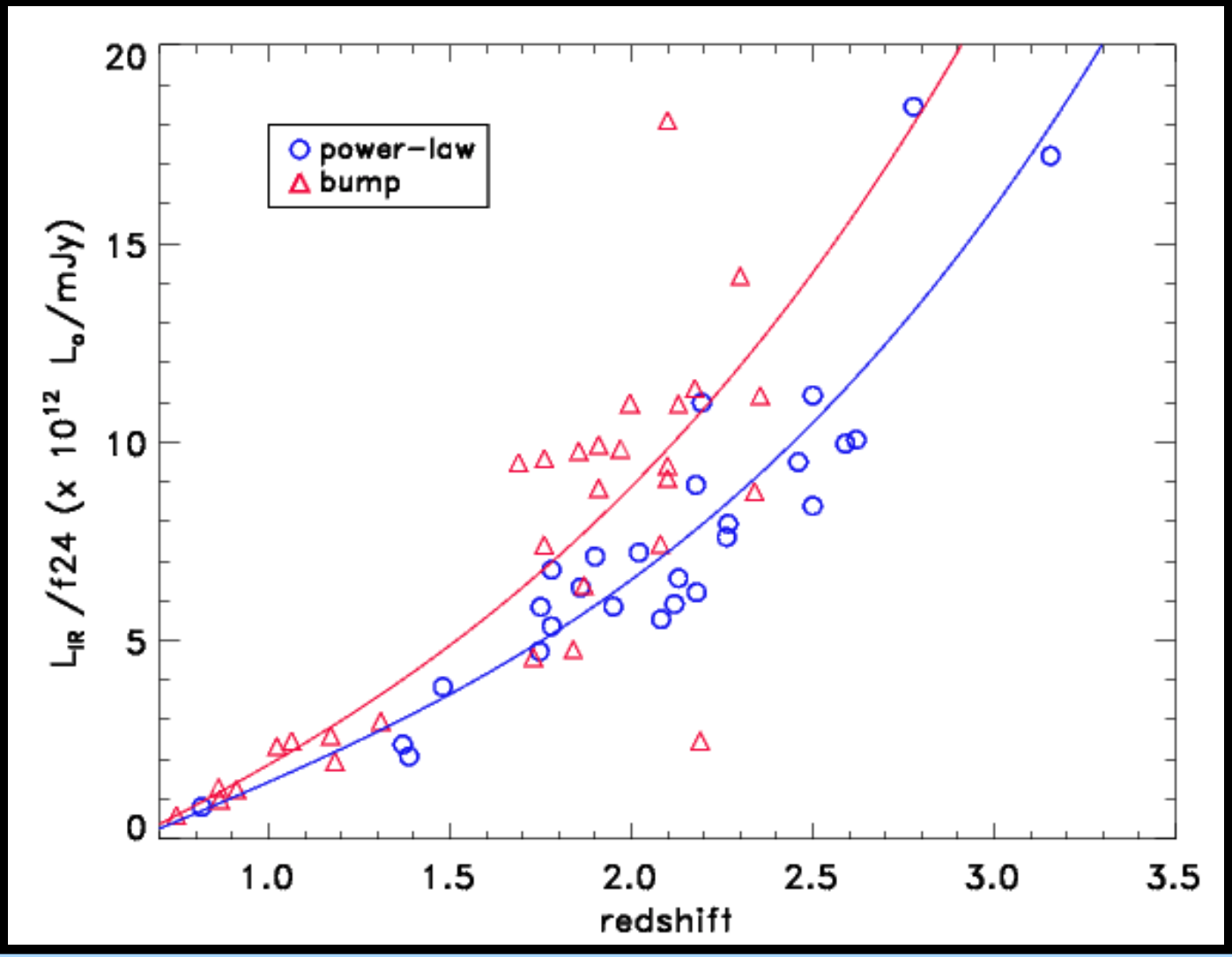


But the Power-law DOGs have higher L_{IR} than the Bump DOGs

(A 250 um selection can miss AGN powered ULIRGs)



Surprisingly 24 um flux is still a great way to predict total L_{IR}

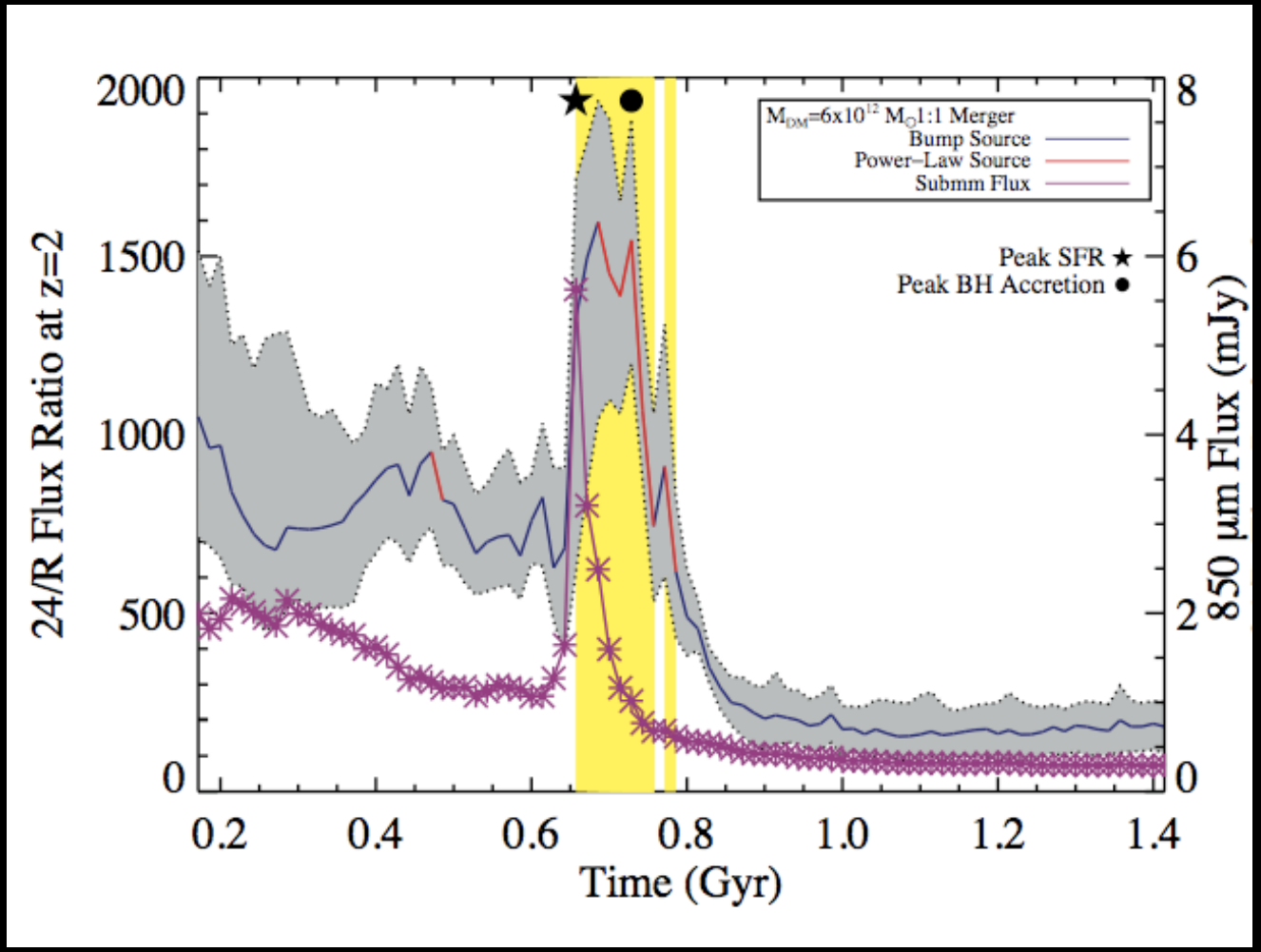


Conclusions

- We have photometered 100 DOGs at 250, 350, and 500 um with Herschel SPIRE.
- Power-law DOGs have AGN-like FIR SEDs.
- Bump DOGs have Starburst-like FIR SEDs.
- Power-law DOGs are less likely to be detected that bump DOGs, because they have smaller 250/24 micron ratios.
- However, Power-law DOGs tend to have higher total L_{IR}, because of the large flux contribution from warm dust.
- Confusion-limited SPIRE surveys will miss large fractions of z=2 AGN-like ULIRGs.

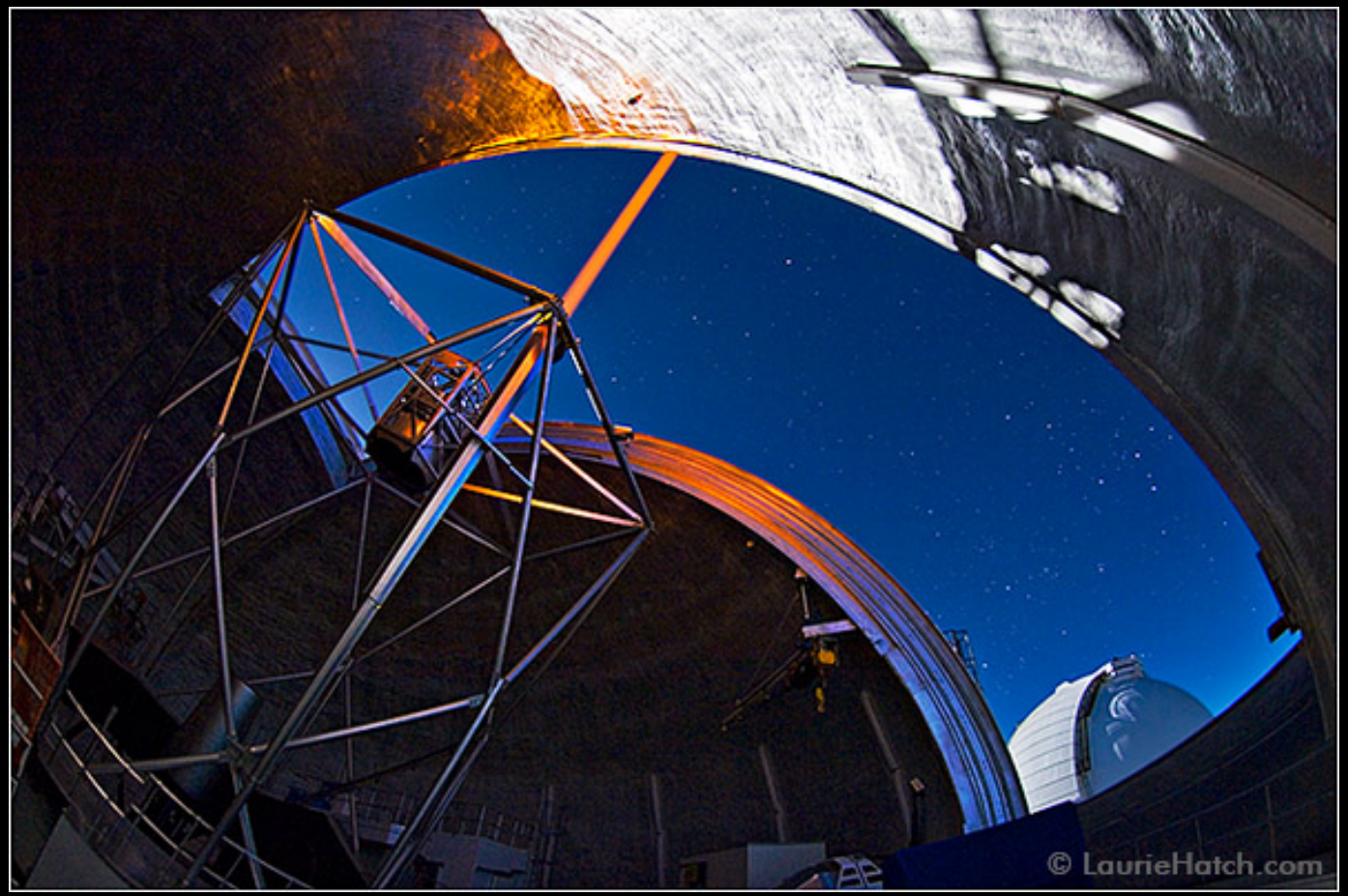
A Unified Theoretical Picture:

Mergers Induce Star Formation Followed by Black Hole Accretion

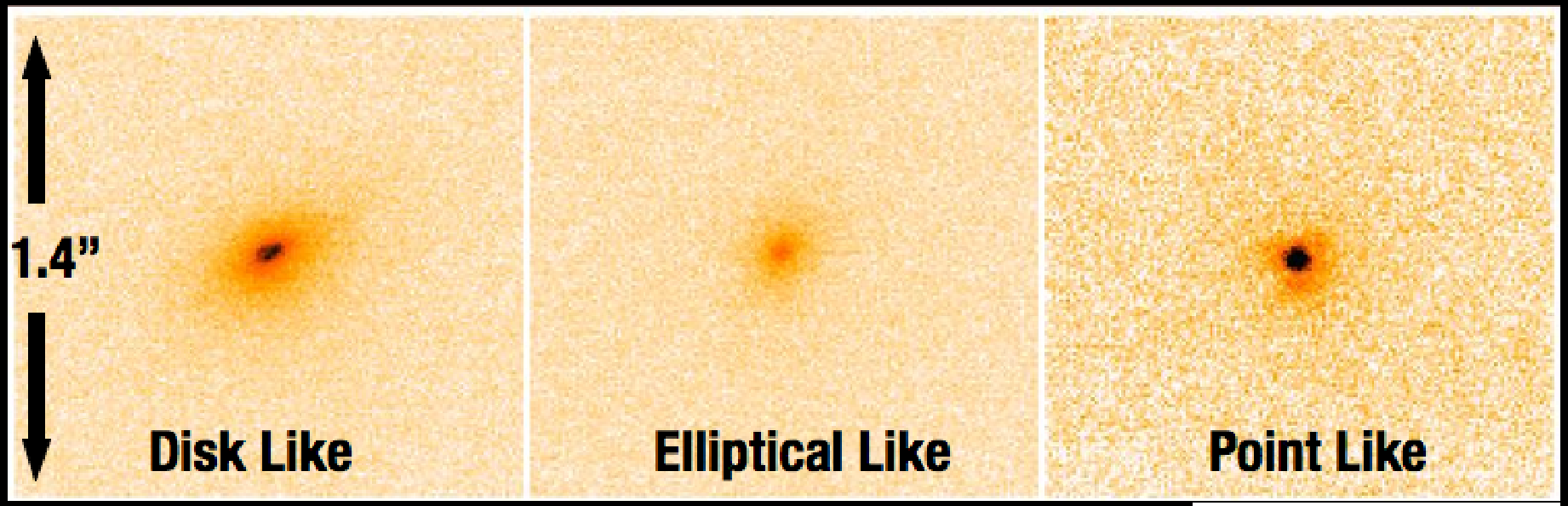


Narayanan et al. 2009

Testing the Theory with High Spatial Resolution HST & Adaptive Optics Imaging and Integral Field Spectroscopy

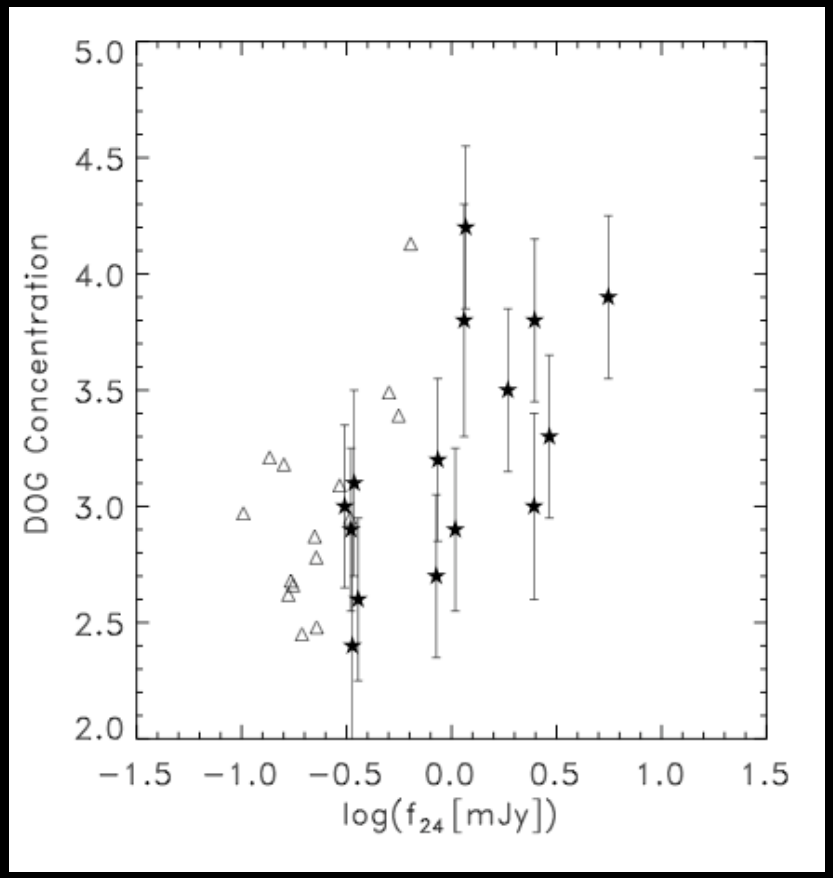


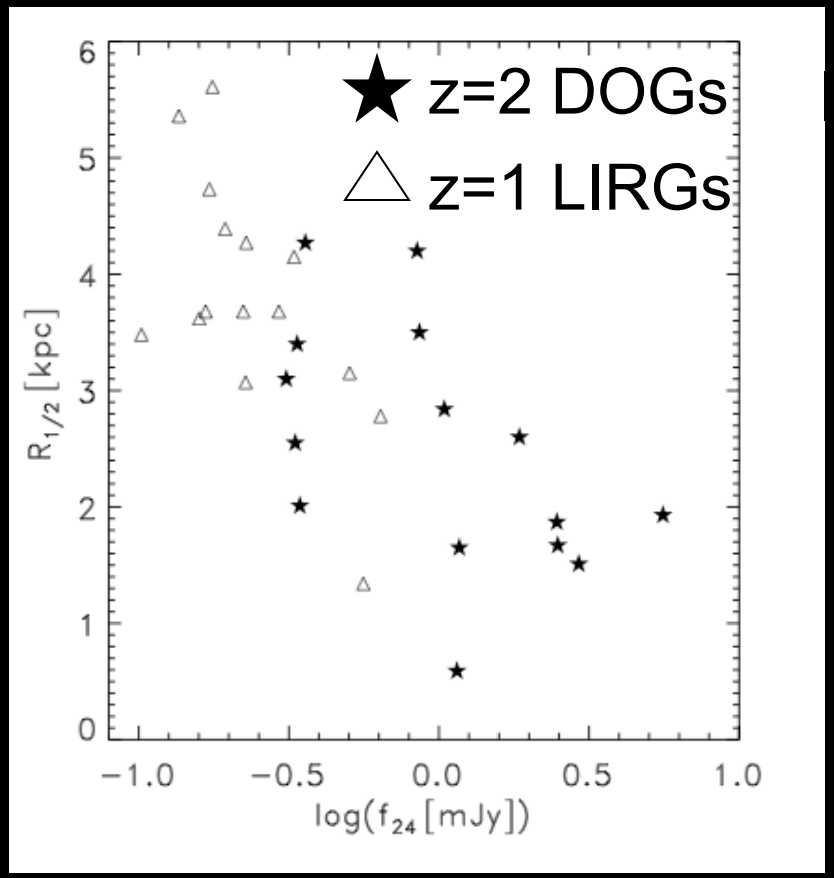
Keck AO Images Reveal a Variety of DOG Morphologies



Melbourne et al. 2008

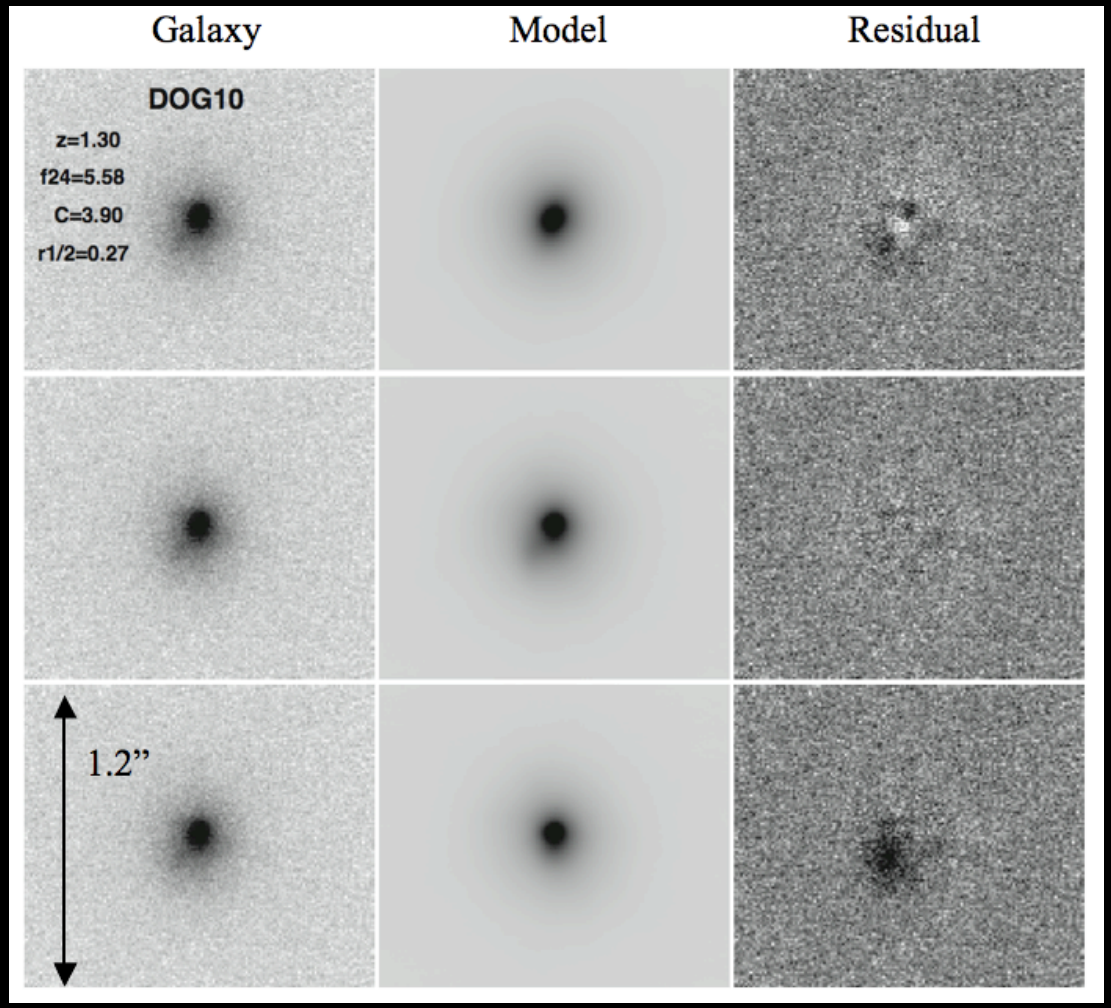
Brighter DOGs are More Compact than Fainter DOGs





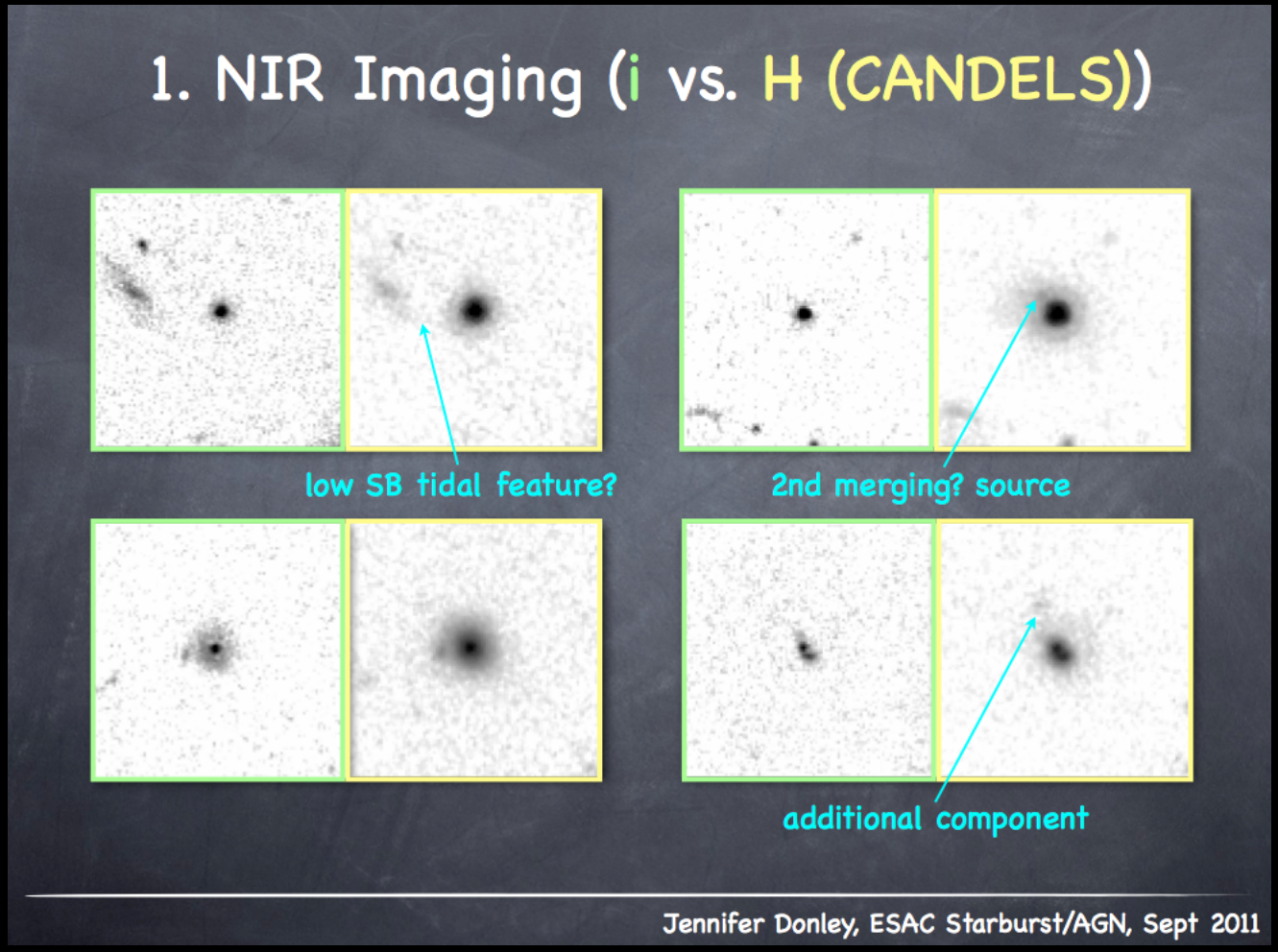
Melbourne et al. 2009

Some DOGs (10-20%) Show Evidence of a Recent Merger

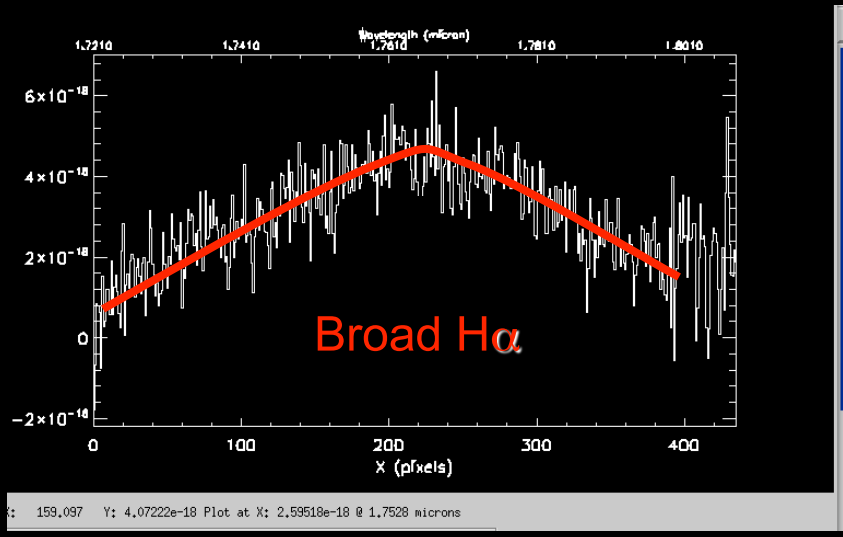


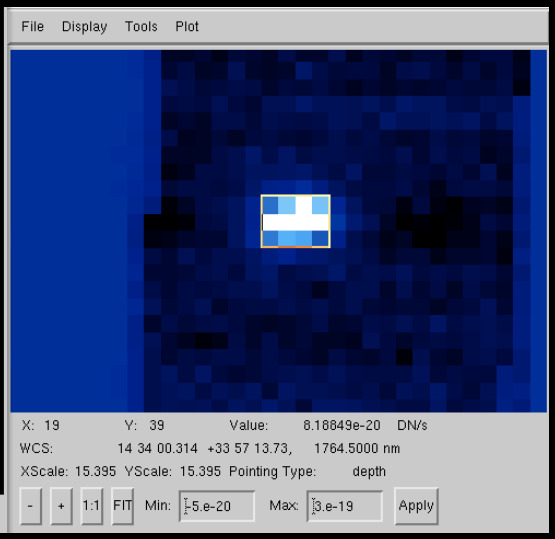
Melbourne et al. 2009

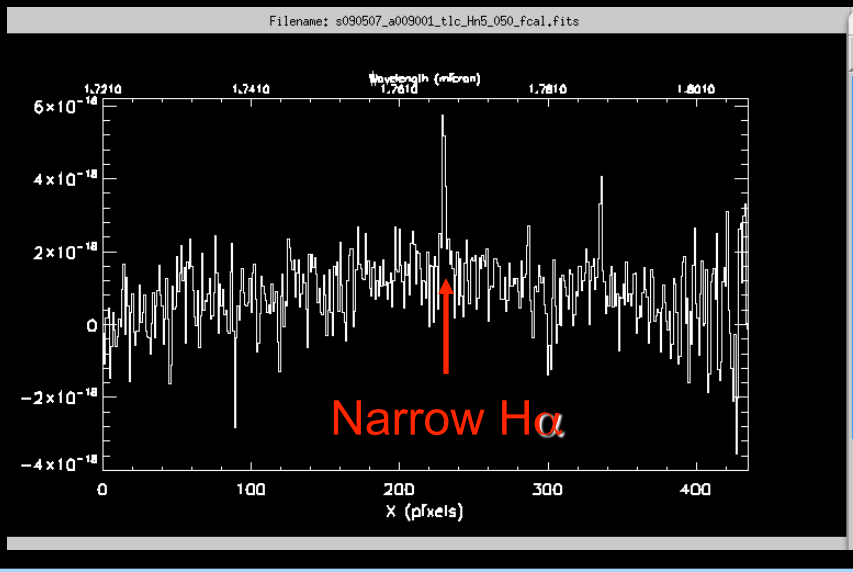
With deeper imaging Donley showed disturbed morphology in a higher fraction

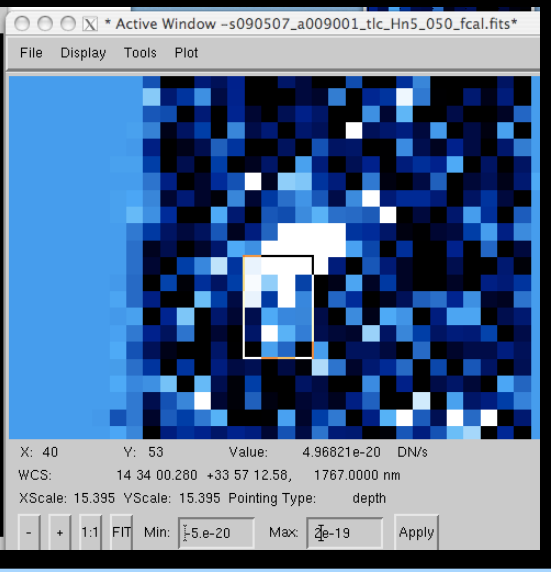


OSIRIS integral field spectroscopy of power-law DOGs separates broad and narrow-lines

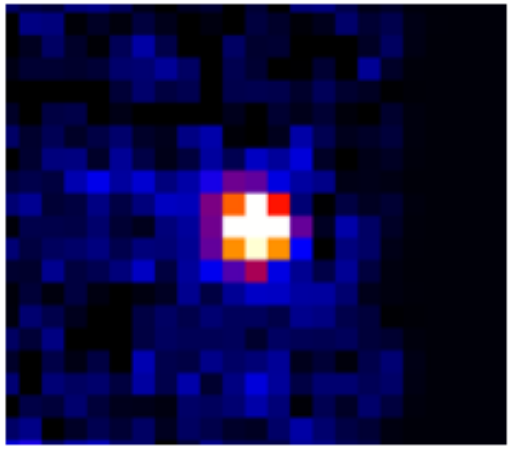


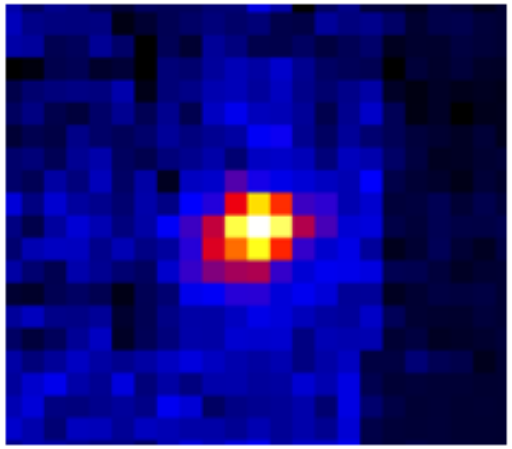


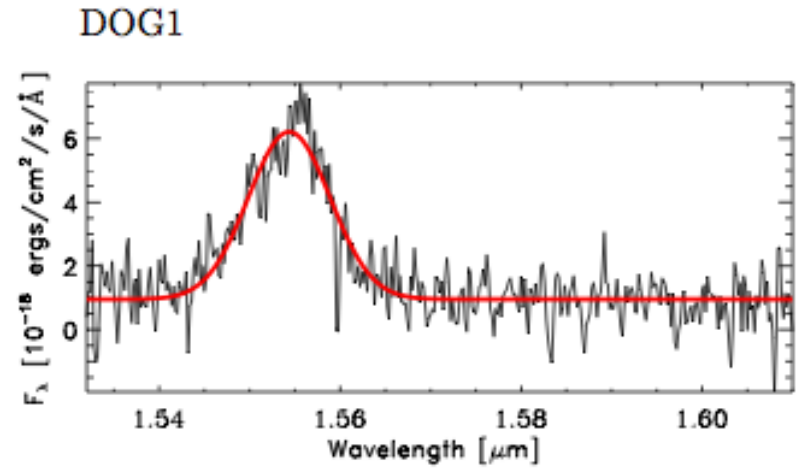


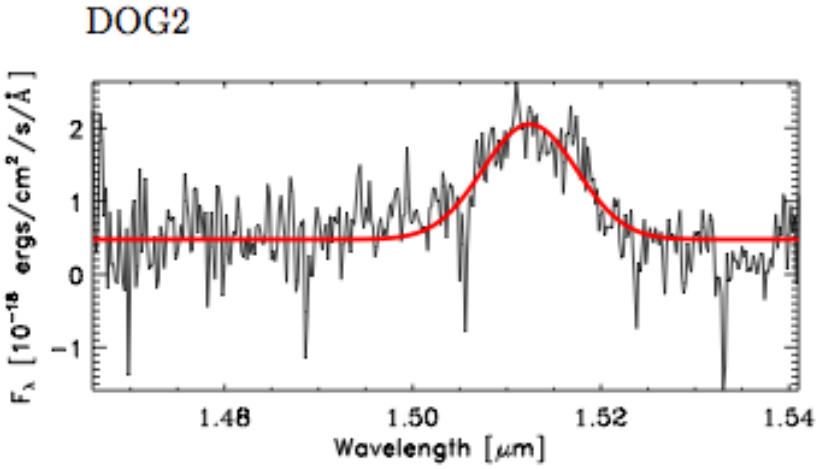


Broad Hα line widths (>2000 km/s) suggest AGN activity









Melbourne et al. 2011

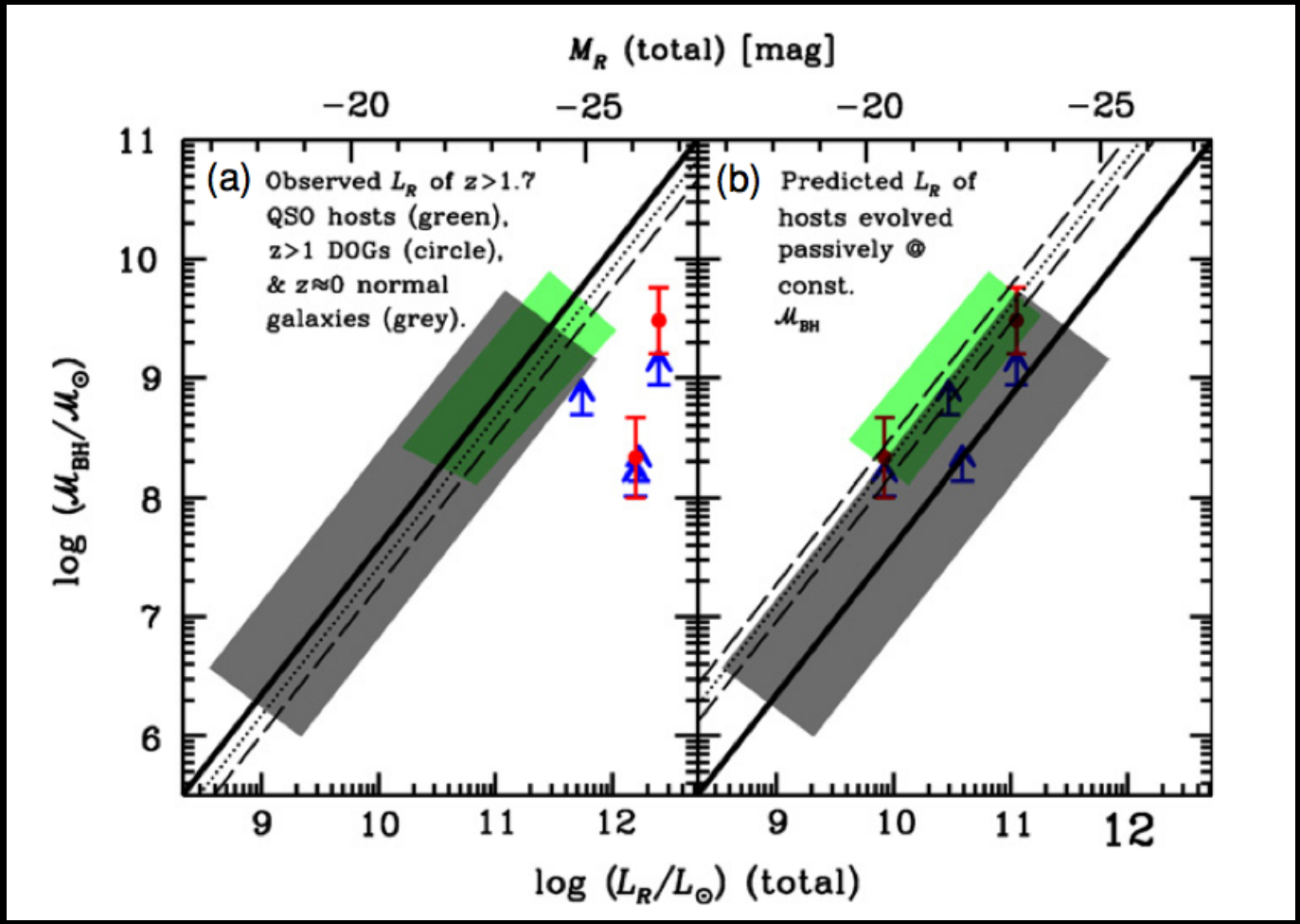
From Line-Width and Line-Flux Calculate the BH-mass

$$L5100 = 1.23 \times 10^{7} \cdot (L_{H\alpha})^{0.864}$$

$$M_{BH} = 9.7 \times 10^{6} \cdot \left(\frac{\mathrm{L5100}}{1 \times 10^{44}[\mathrm{ergs/s}]} \right)^{0.59} \cdot \left(\frac{\mathrm{line\text{-}width}}{1000[\mathrm{km/s}]} \right)^{2.06} M_{\odot}$$

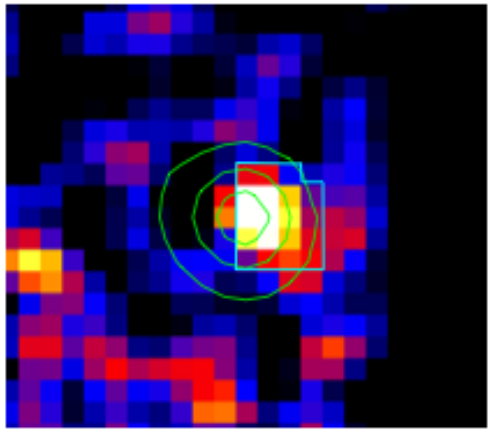
Greene & Ho 2005
Peng et al. 2006

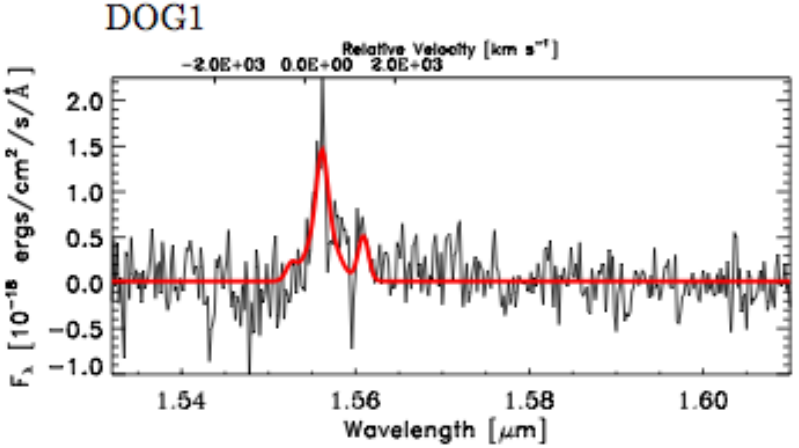
BH-masses of DOGs are small given their host galaxy luminosity

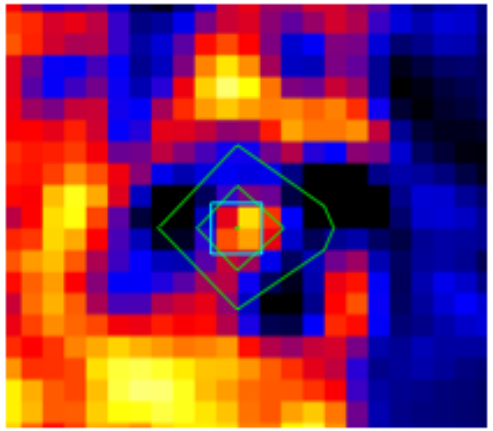


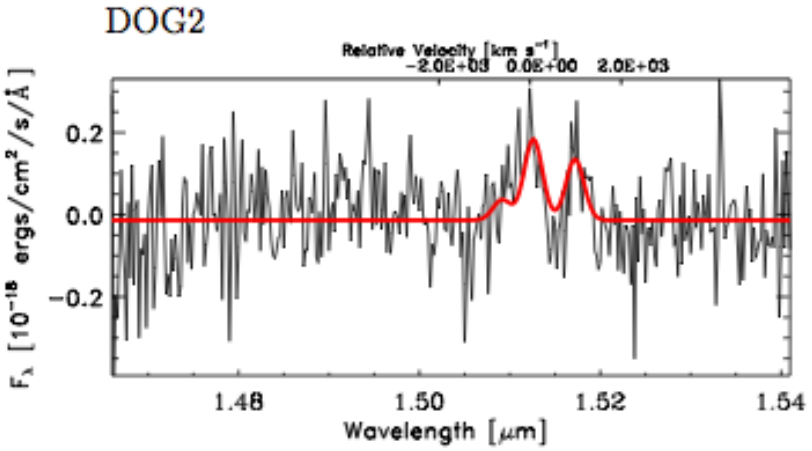
Melbourne et al. 2011

Star formation is located in several bright knots with SFR < 2 $M_\odot$ /yr



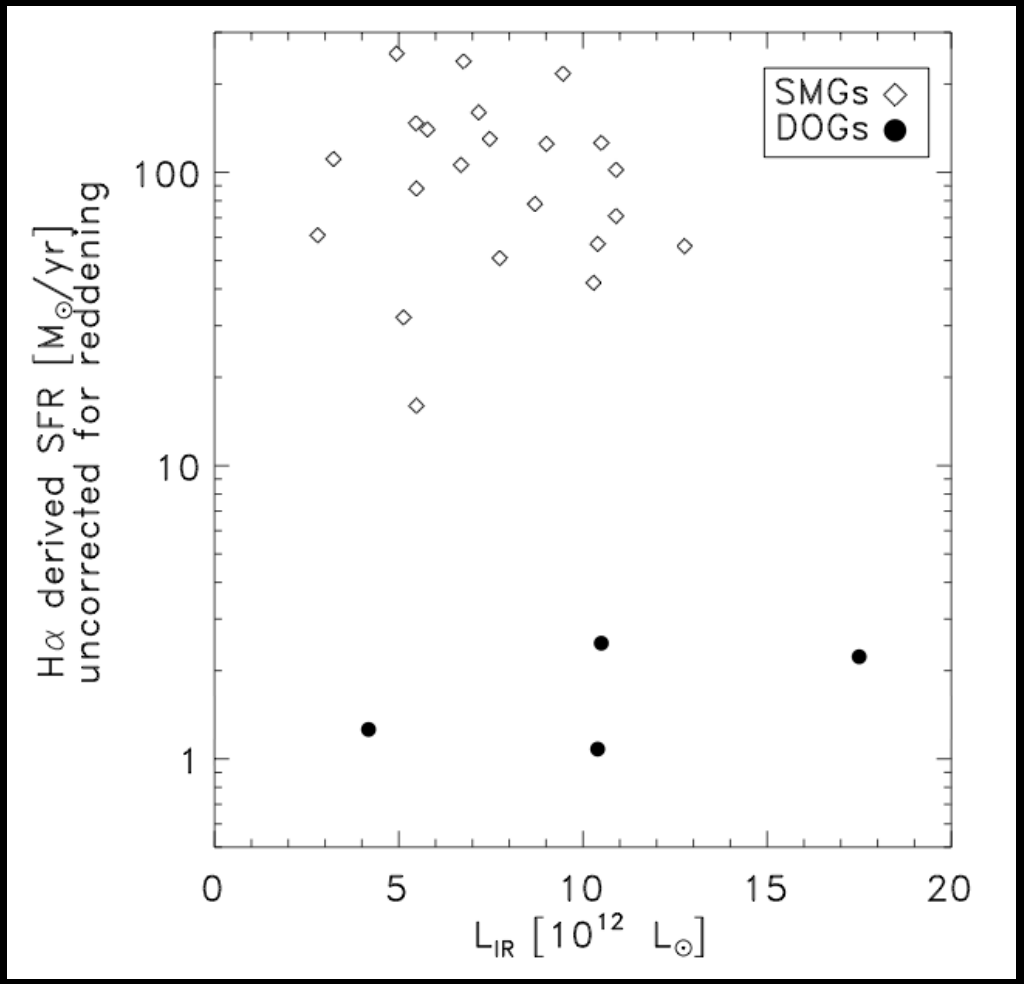






Melbourne et al. 2011

SFRs are small compared with other $z = 2$ ULIRGs such as sub-mm galaxies

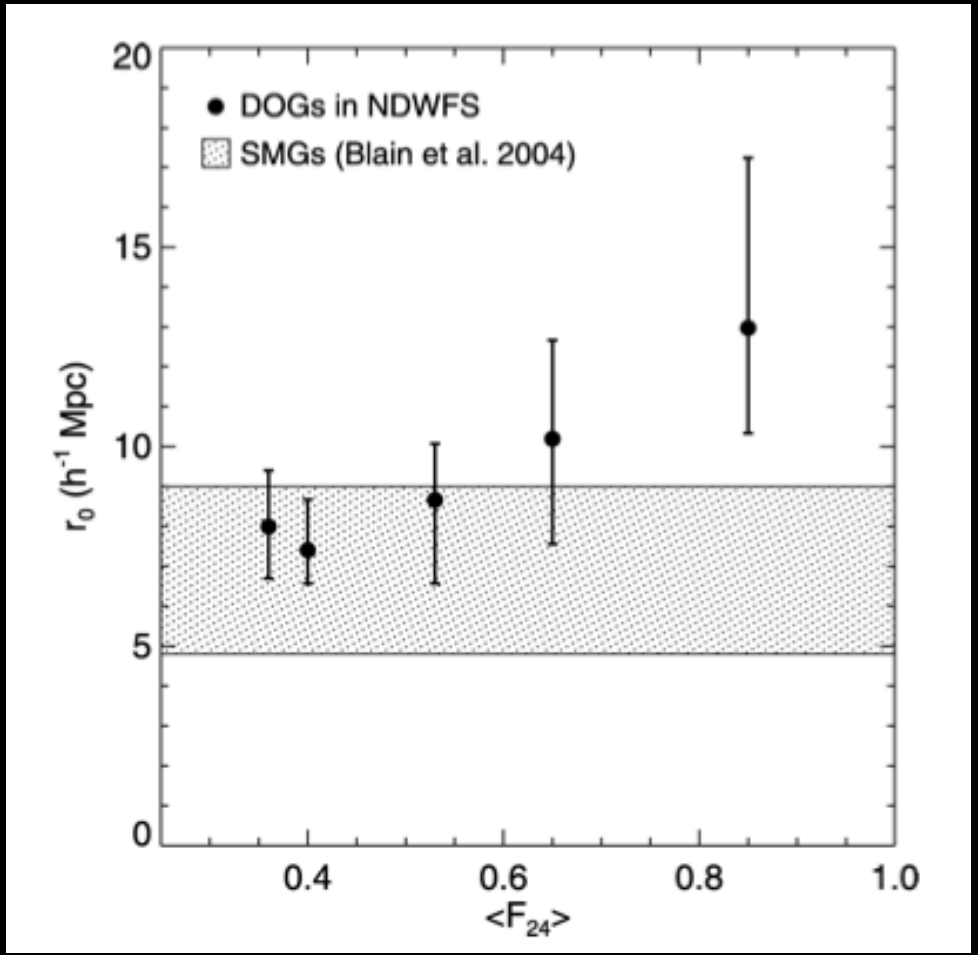


Melbourne et al. 2011

Summary

- A simple optical to mid-IR color selection identifies extreme $z = 2$ ULIRGs.
- These Dust Obscured Galaxies (DOGs) may evolve into massive ellipticals.
- DOGs are powered by a combination of SF and AGN activity possibly driven by mergers.
- Black hole masses and SFRs of the AGN dominated DOGs appear low given the dust corrected galaxy luminosity in optical and IR bands.

Also Have Similar Clustering to Sub-mm Galaxies



Brodwin et al. 2008

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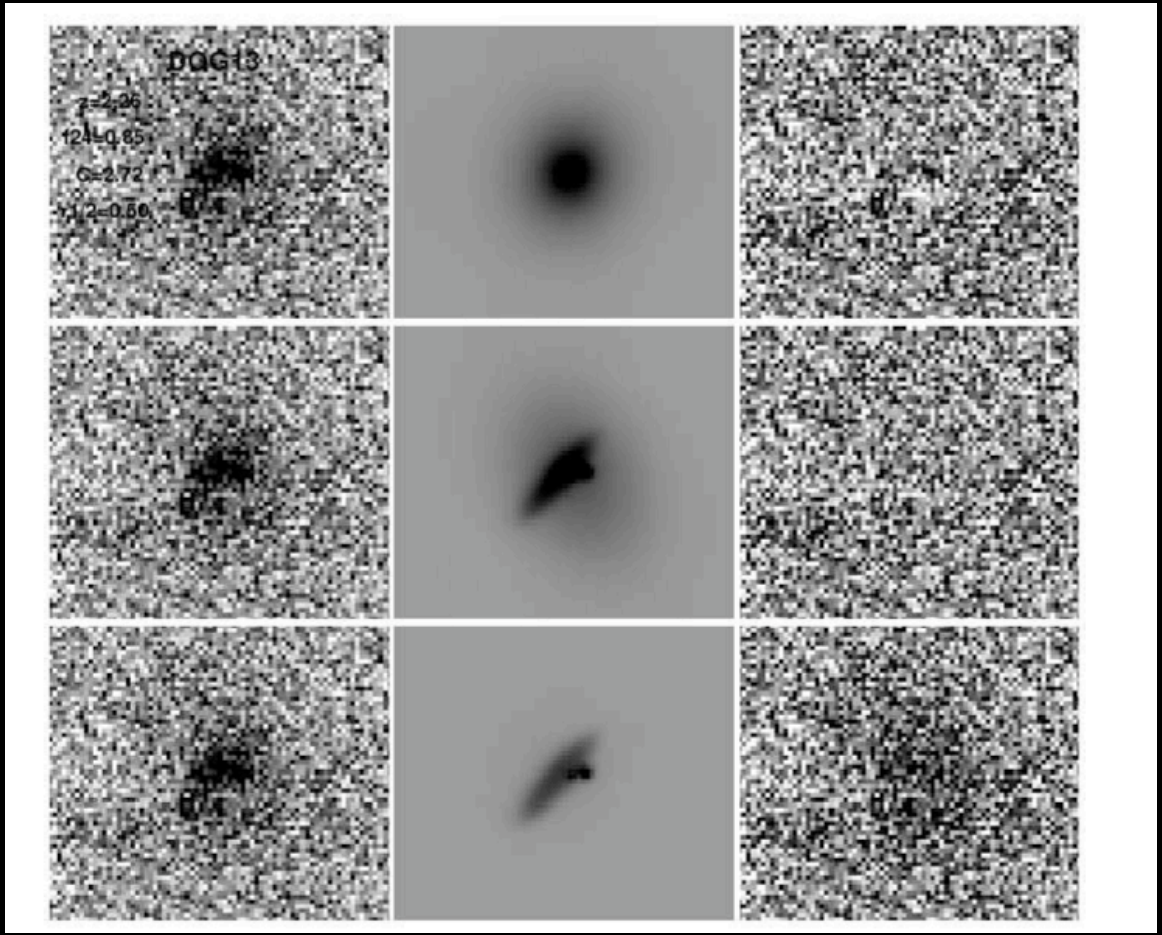

Melbourne et al. 2009