The Slit-Less Spectroscopic Survey of Galaxies (SPICY) with AKARI/IRC – perspective to SPICA

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Y. Ohyama, T. Wada, H. Matsuhara, et al. 2018 A&A 618, A101 (2018)

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- AKARI NEP extragalactic survey
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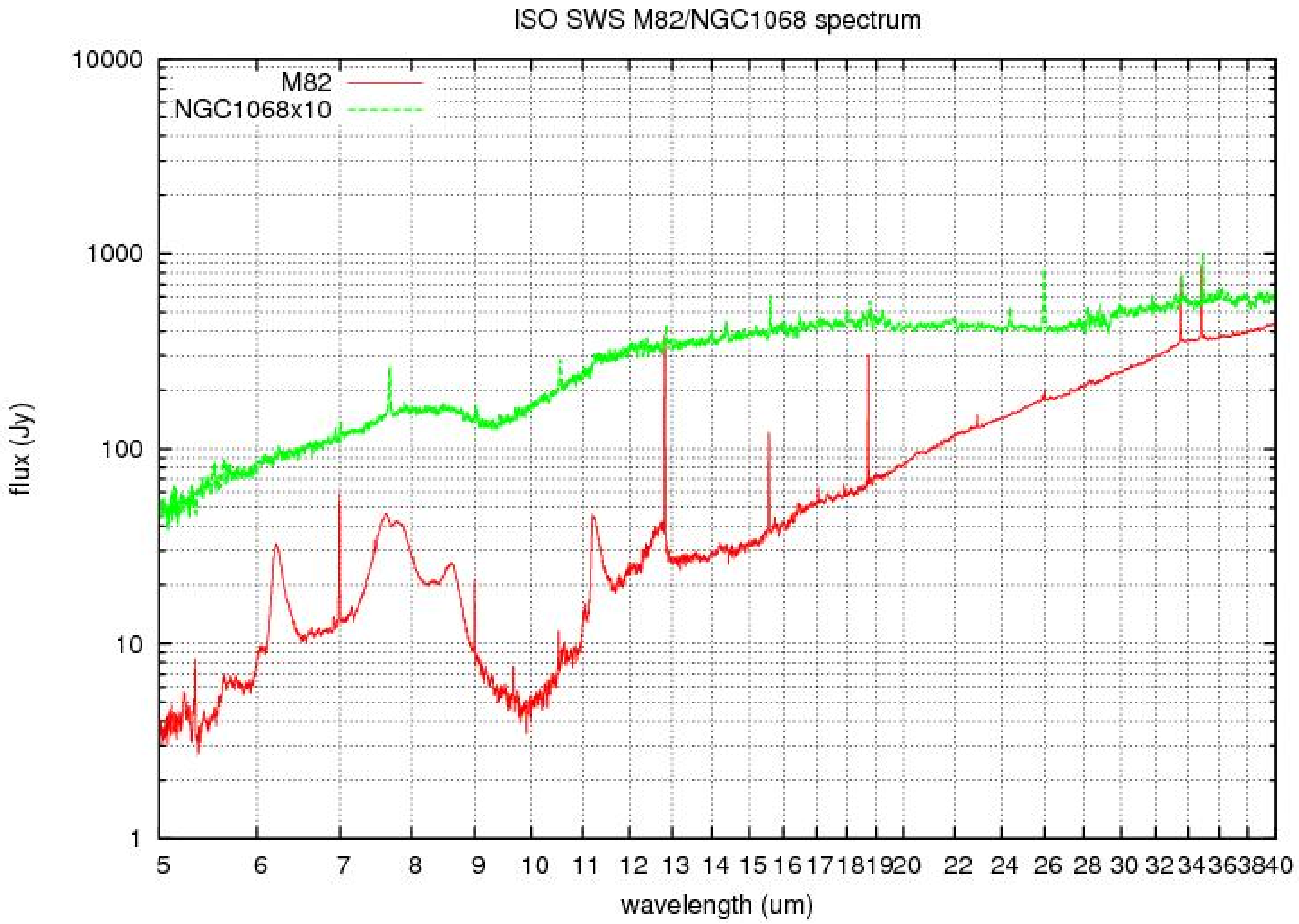
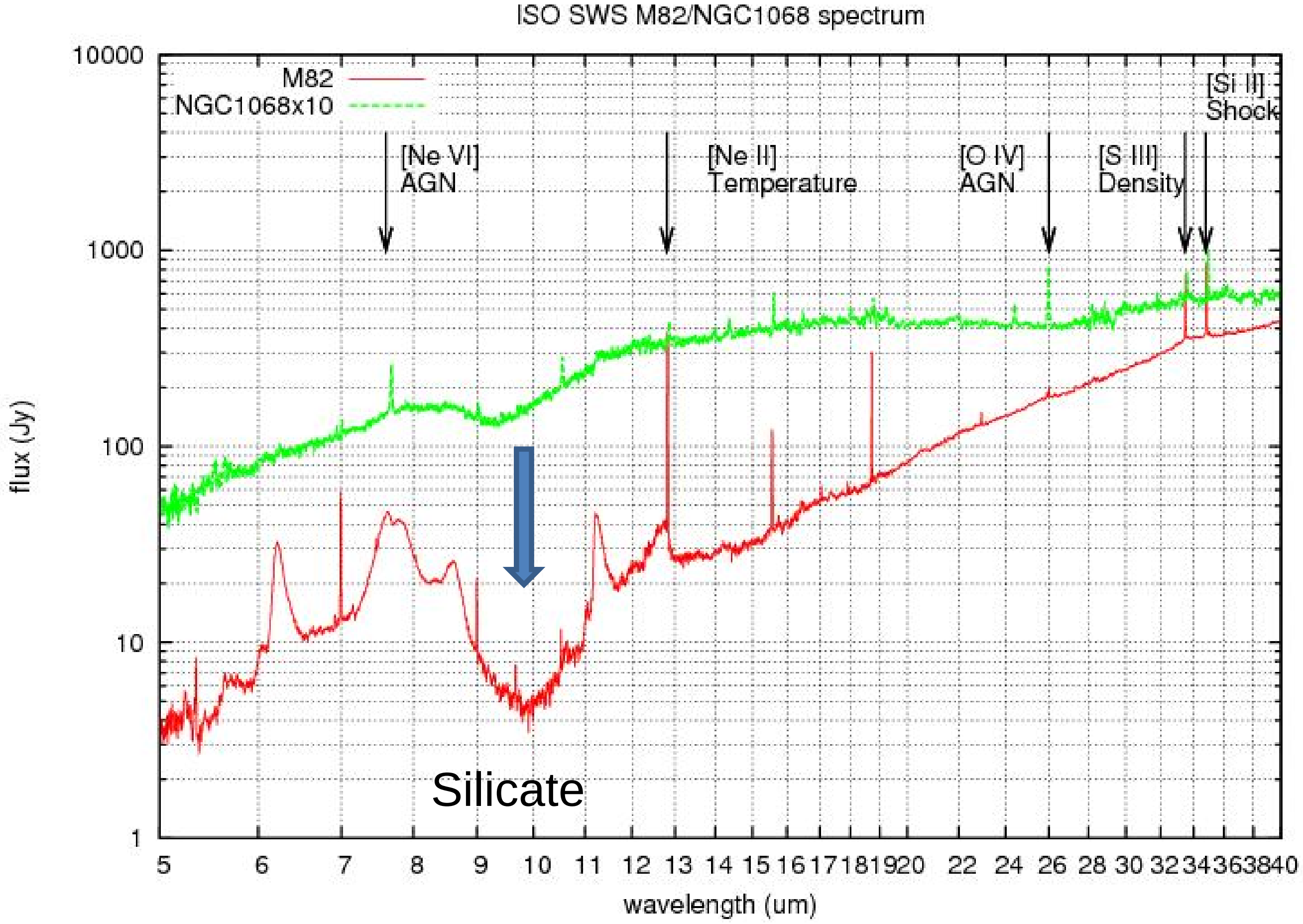
- Toward SPICA

Mid-infrared spectra of galaxies



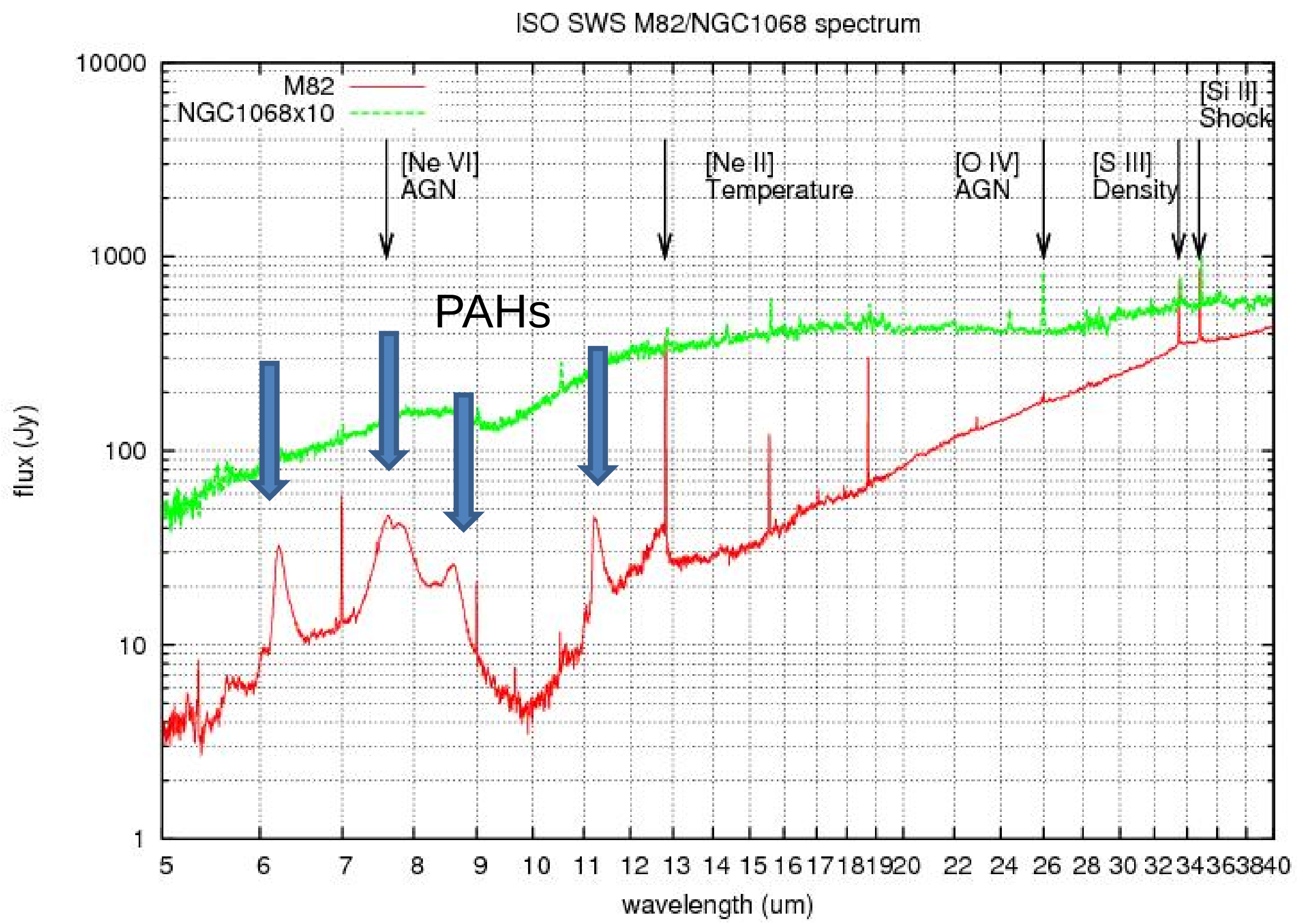
(Sloan et al. 2003)

Mid-infrared spectra of galaxies



(Sloan et al. 2003)

Mid-infrared spectra of galaxies



(Sloan et al. 2003)

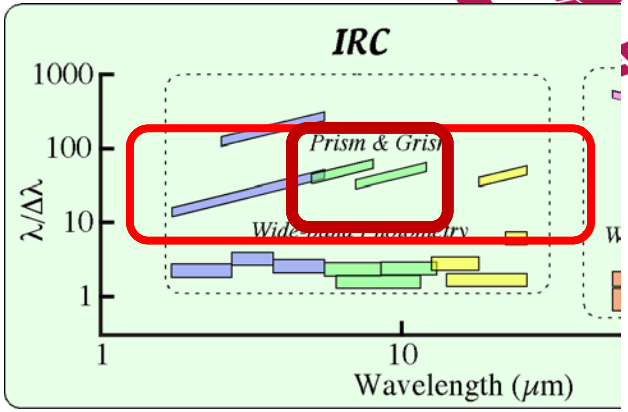
Why PAH?

- “spectroscopic” redshift
- Star-formation/AGN indicator
- **More luminous** than the other diagnostic lines
  - High-z or low-L
- **Broad** feature matches **low-R spectroscopy**
  - Wide FoV can be obtained with same # of detector pixels
  - Higher survey speed
- Follow-up spectroscopy is necessary for accurate measurement of physical conditions, but a lot of information can be obtained by PAH.

What AKARI brings us?

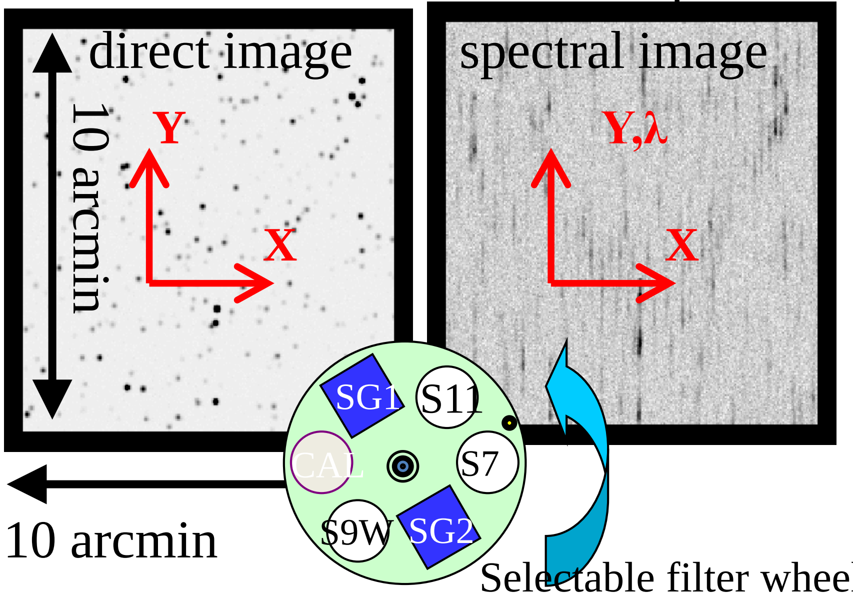
- AKARI NEP DEEP/WIDE survey
  - 2-24um, 9 contiguous bands, no "IRAC/MIPS gap"
  - DEEP 0.4 sq deg. 120uJy at 15um (Wada et al. 2008)
  - WIDE 6 sq deg. 150uJy at 15um (Lee et al. 2009)
- Slit-less spectroscoPIC survey of galaxY (SPICY)
  - 2.5-24um (15-18um is lost)
  - Spectral resolution of R=30-50
  - 10 of 10'x10' fields in NEP DEEP/WIDE area
  - 100 minutes per field, 17 hours in total.
  - Flux limited complete sample, S(9um) > 0.3mJy

InfraRed Camera (IRC) as a spectrograph



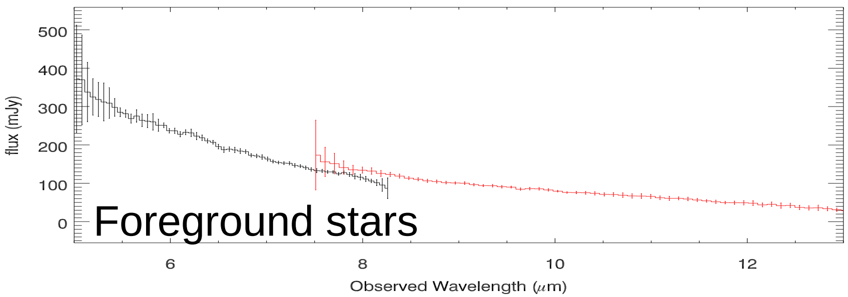
- ✓ For NIR-MIR imaging & *spectroscopy*
  - Comprising of three channels (NIR/MIR-S/MIR-L)
  - With selectable filters/*grisms* or *prism*
- ✓ Uniqueness/Advantage over the *Spitzer*:
  - Larger FOV/*Slit-less* spectroscopy
  - Wide and continuous spectral coverage over entire NIR-MIR (2~25μm)

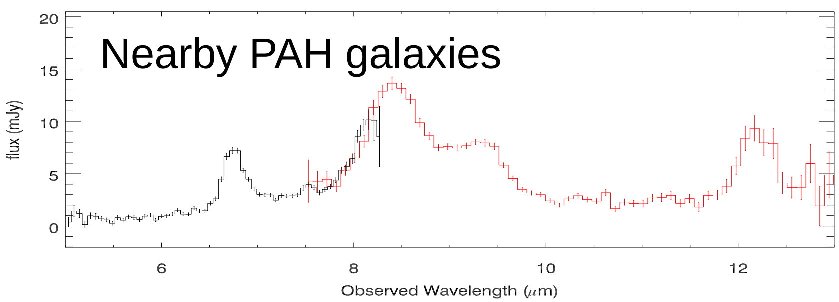
The ``Slit-less'' Concept

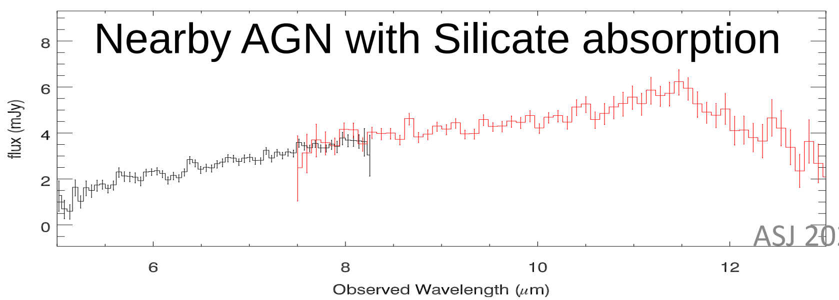


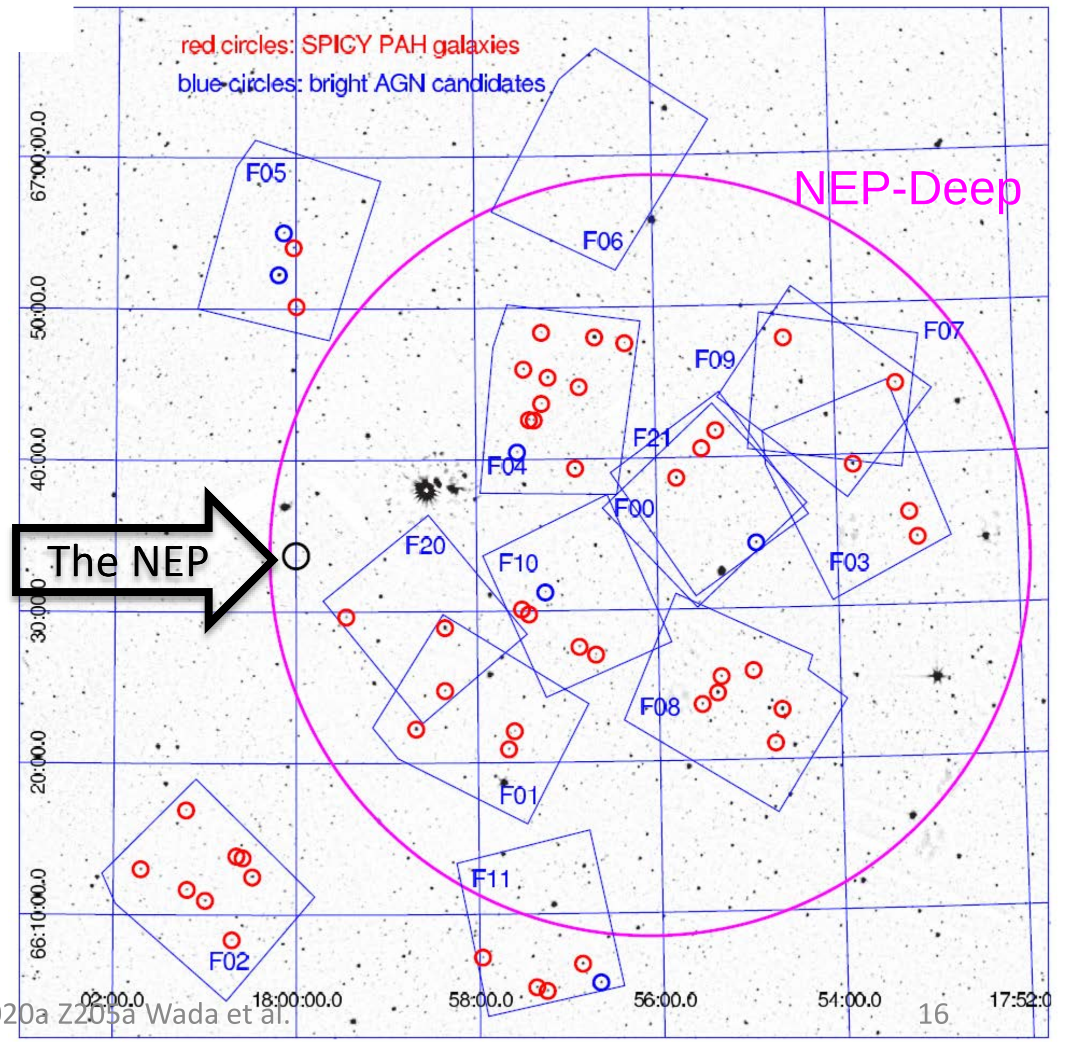
The SPICY dataset

Blind MIR spectroscopic survey
5 – 13 μm spectra of all object > 0.3mJy
at 9um (Ohyama et al. 2018)









Ohyama et al. 2018

- In total N=171 galaxies
- ***SPICY* PAH galaxies: *N*=48**
- PAH-*undetected* galaxies: *N*=112
- *Photometric* AGN candidates: *N*=11

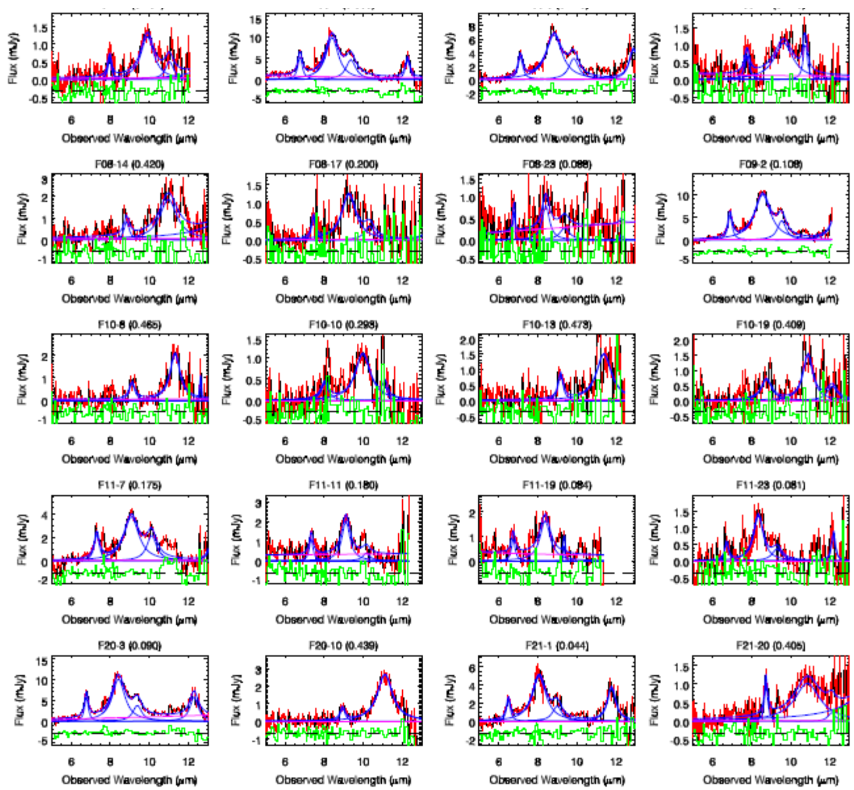


Fig. B.1. continued.

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Astronomy & Astrophysics

AKARI mid-infrared slitless spectroscopic survey of star-forming galaxies at $z \lesssim 0.5$

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ABSTRACT

Context. Deep mid-infrared (MIR) surveys have revealed numerous strongly star-forming galaxies at redshift $z \lesssim 2$. Their MIR fluxes are produced by a combination of continuum and polycyclic aromatic hydrocarbon (PAH) emission features. The PAH features can dominate the total MIR flux, but are difficult to measure without spectroscopy.
Aims. We aim to study star-forming galaxies by using a blind spectroscopic survey at MIR wavelengths to understand evolution of their star formation rate (SFR) and specific SFR (SFR per stellar mass) up to $z \simeq 0.5$, by paying particular attention to their PAH properties.
Methods. We conducted a low-resolution ($R \simeq 50$) slitless spectroscopic survey at 5–13 μm of 9 μm flux-selected sources (>0.3 mJy) around the north ecliptic pole with the infrared camera (IRC) onboard AKARI. After removing 11 AGN candidates by using the IRC photometry, we identify 48 PAH galaxies with PAH 6.2, 7.7, and 8.6 μm features at $z < 0.5$. The rest-frame optical–MIR spectral energy distributions (SEDs) based on CFHT and IRC imaging covering 0.37–18 μm were produced, and analysed in conjunction with the PAH spectroscopy. We defined the PAH enhancement by using the luminosity ratio of the 7.7 μm PAH feature over the 3.5 μm stellar component of the SEDs.
Results. The rest-frame SEDs of all PAH galaxies have a universal shape with stellar and 7.7 μm bumps, except that the PAH enhancement significantly varies as a function of the PAH luminosities. We identify a PAH-enhanced population at $z \gtrsim 0.35$, whose SEDs and luminosities are typical of luminous infrared galaxies. They show particularly larger PAH enhancement at high luminosity, implying that they are vigorous star-forming galaxies with elevated specific SFR. Our composite starburst model that combines a very young and optically very thick starburst with a very old population can successfully reproduce most of their SED characteristics, although we cannot confirm this optically think component from our spectral analysis.

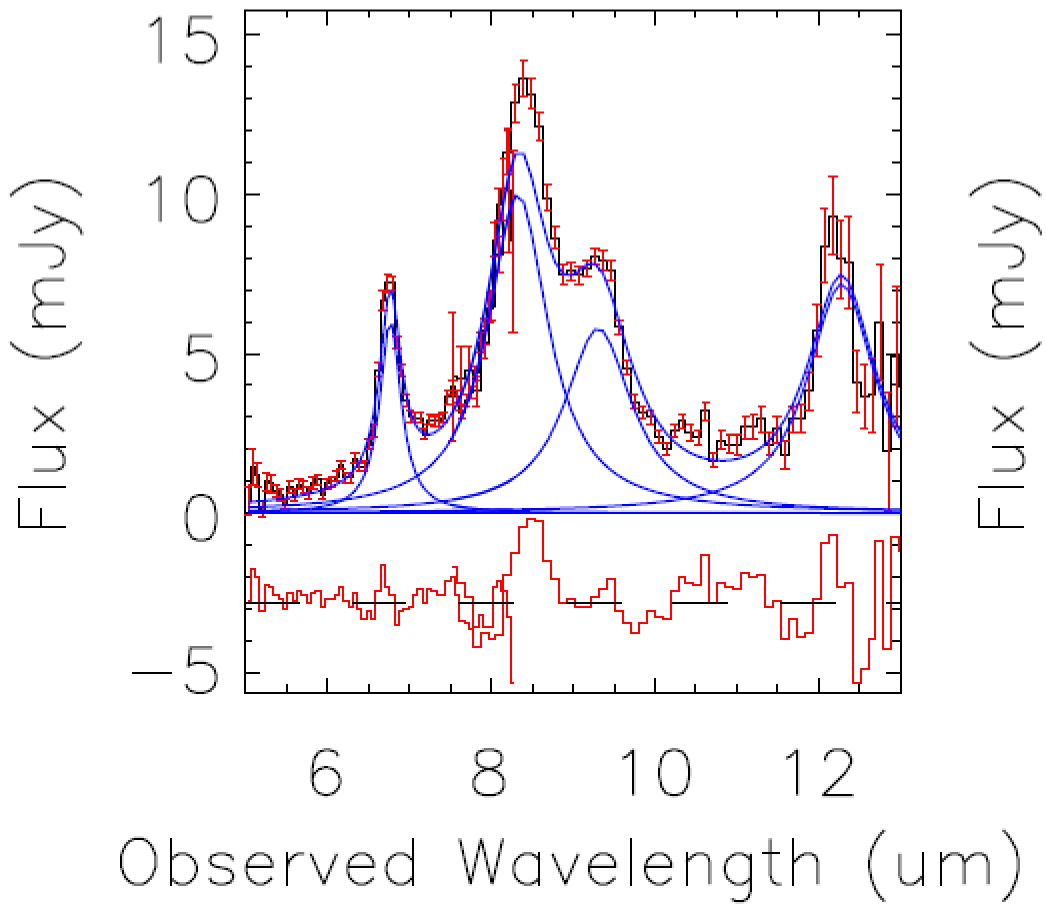
Key words. galaxies: starburst – infrared: galaxies – galaxies: active – galaxies: evolution

1. Introduction

Mid-infrared (MIR) extragalactic studies have been providing new insights about galaxies in the distant universe, for three main reasons: first, about half of the total energy throughout cosmic history is emitted between the MIR and far-infrared (FIR) wavelengths (e.g. Elbaz et al. 2002; Le Floc'h et al. 2005; Dole et al. 2006; Caputi et al. 2007; Goto et al. 2011a). Second, the effect of dust extinction is much less prominent at MIR wavelengths when compared to optical (OPT) and near-infrared (NIR) wavelengths, and is a good spectral region for measuring activity from star formation as well as active galaxy nuclei (AGNs), even in the presence of copious amounts of dust. Third, under limited technology at the time of AKARI (Murakami et al. 2007) and before, in particular about the large cryogenic space telescope for sharper diffraction-limited resolution and the sensitive detector system, the MIR spectral region has been more sensitive to flux from distant astronomical sources than the FIR one. The importance of deep MIR extragalactic surveys was first recognised by the discovery of strong evolution from 15 μm source counts by using ISOCAM (Cesarsky et al. 1996) onboard the Infrared Space Observatory (ISO; Kessler et al. 1996). The rapidly evolving population was found as an excess of 15 μm sources at a flux of 0.1–0.5 mJy (e.g. Elbaz et al. 1999; Serjeant et al. 2000; see also Lagache et al. 2004; Wada et al. 2008; Pearson et al. 2010). Later, extensive studies at MIR and other wavelengths helped to define the global spectral energy distribution (SED) shapes across the OPT–NIR–MIR–FIR for various types of luminous galaxies (such as AGNs, starburst galaxies, luminous infrared galaxies (LIRGs), and ultra-luminous infrared galaxies (ULIRGs); e.g. (Spinoglio et al. 1995; Pearson 2001; Lagache et al. 2004; Rowan-Robinson et al. 2004; Le Floc'h et al. 2005). Such studies clearly indicate that most of these galaxies, excluding AGNs, show prominent emission features in their MIR spectra, which are believed to originate in polycyclic aromatic hydrocarbons (PAHs; e.g. Lutz et al. 1998; Xu et al. 1998). The luminosity of the PAH features, as well as that of the underlying hot dust continuum, has been used as a measure of star formation rate (SFR), using conversions from MIR luminosity to the FIR one, where the bulk of the energy from star-forming regions is emitted (e.g. Genzel et al. 1998; Rigopoulou et al. 1999; Farrah et al. 2007; Shipley et al. 2016).

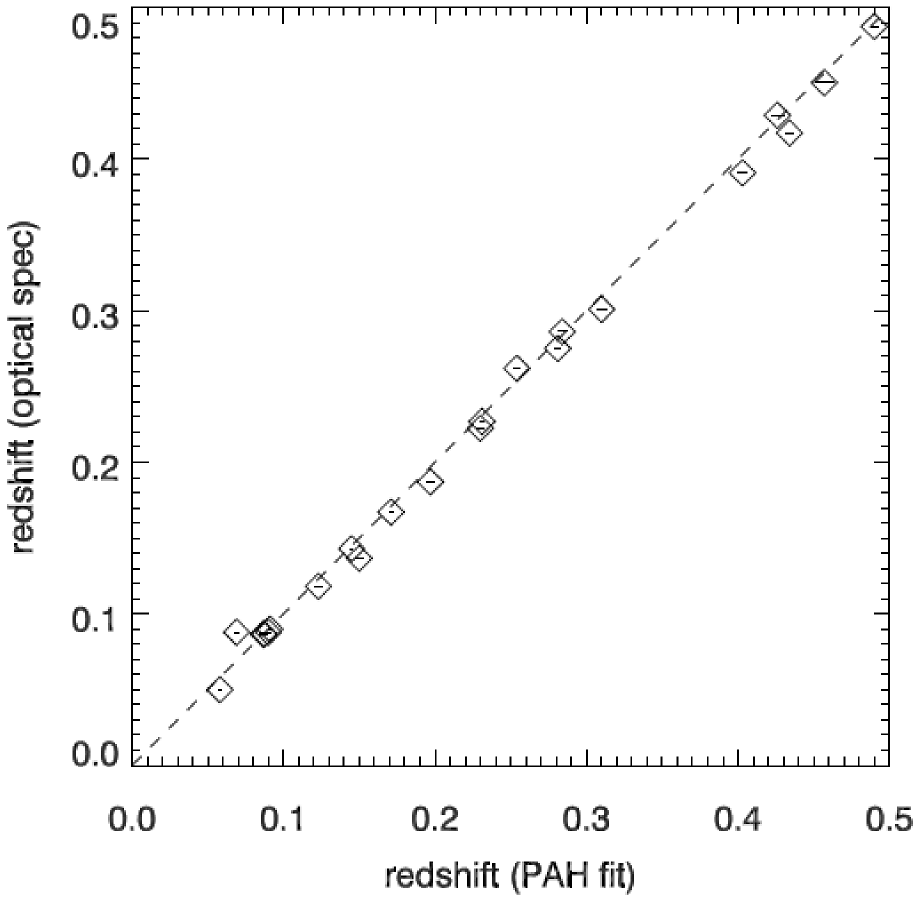
The unprecedented sensitivity of *Spitzer* at MIR wavelengths has greatly improved our understanding of cosmic galaxy evolution, with help of various diagnostics of galaxies for their activities up to $z \sim 2$–4 provided by both MIPS imager (Rieke et al. 2004) at 24 μm and IRS spectrometer (Houck et al. 2004; e.g. Sajina et al. 2007; Yan et al. 2007; Pope et al. 2008; Wu et al. 2010; see also Spoon et al. 2007). Cosmic star formation history,

Identification of PAH



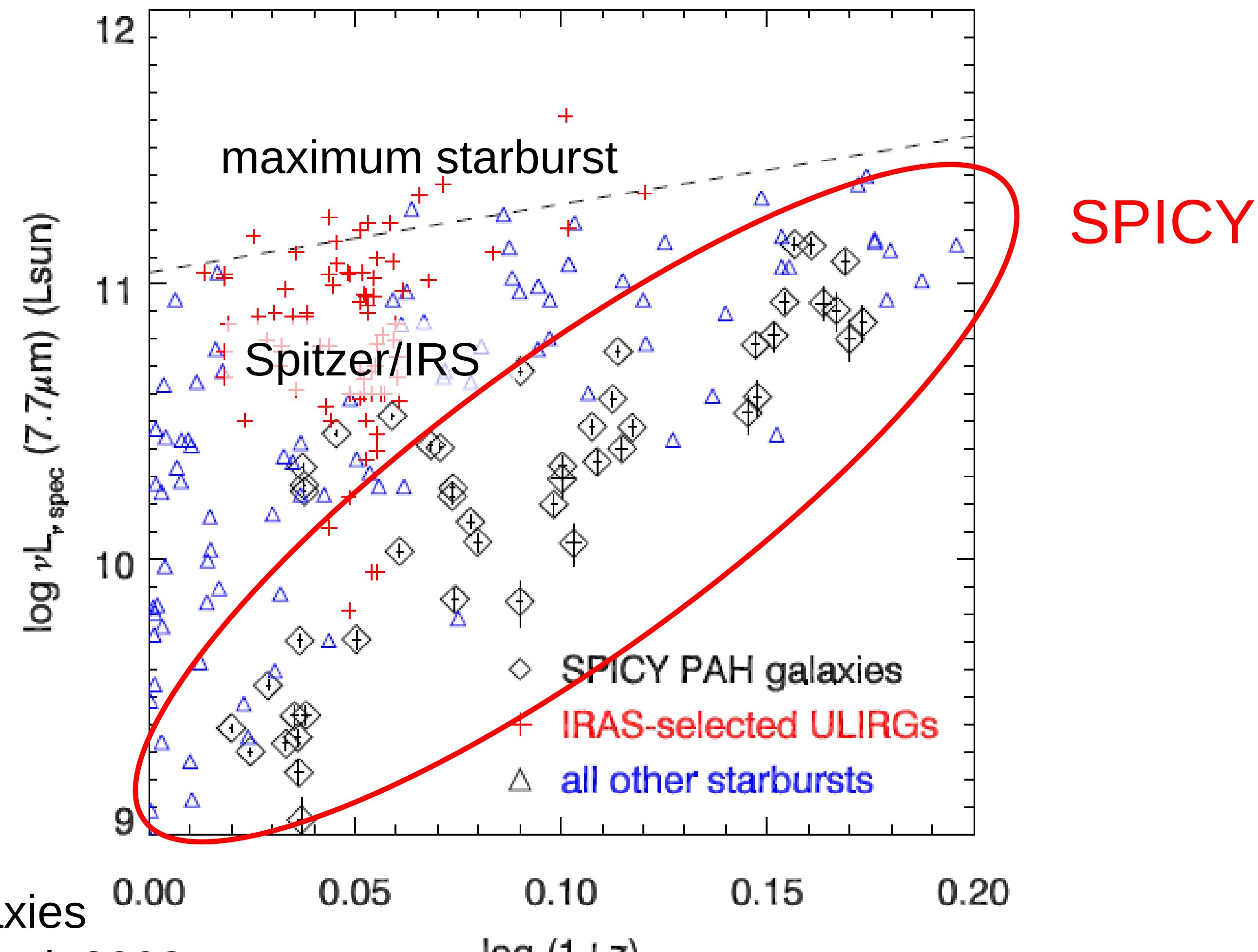
- Fit by 6.2, 7.7, 8.6, and 11.3um PAH feature and baseline
- Free-parameters are
  - Redshift
  - Each PAH peak and sigma (Gaussian)
- 48 galaxies are successfully identified as SPICY PAH galaxies.

Accuracy in Redshift determination



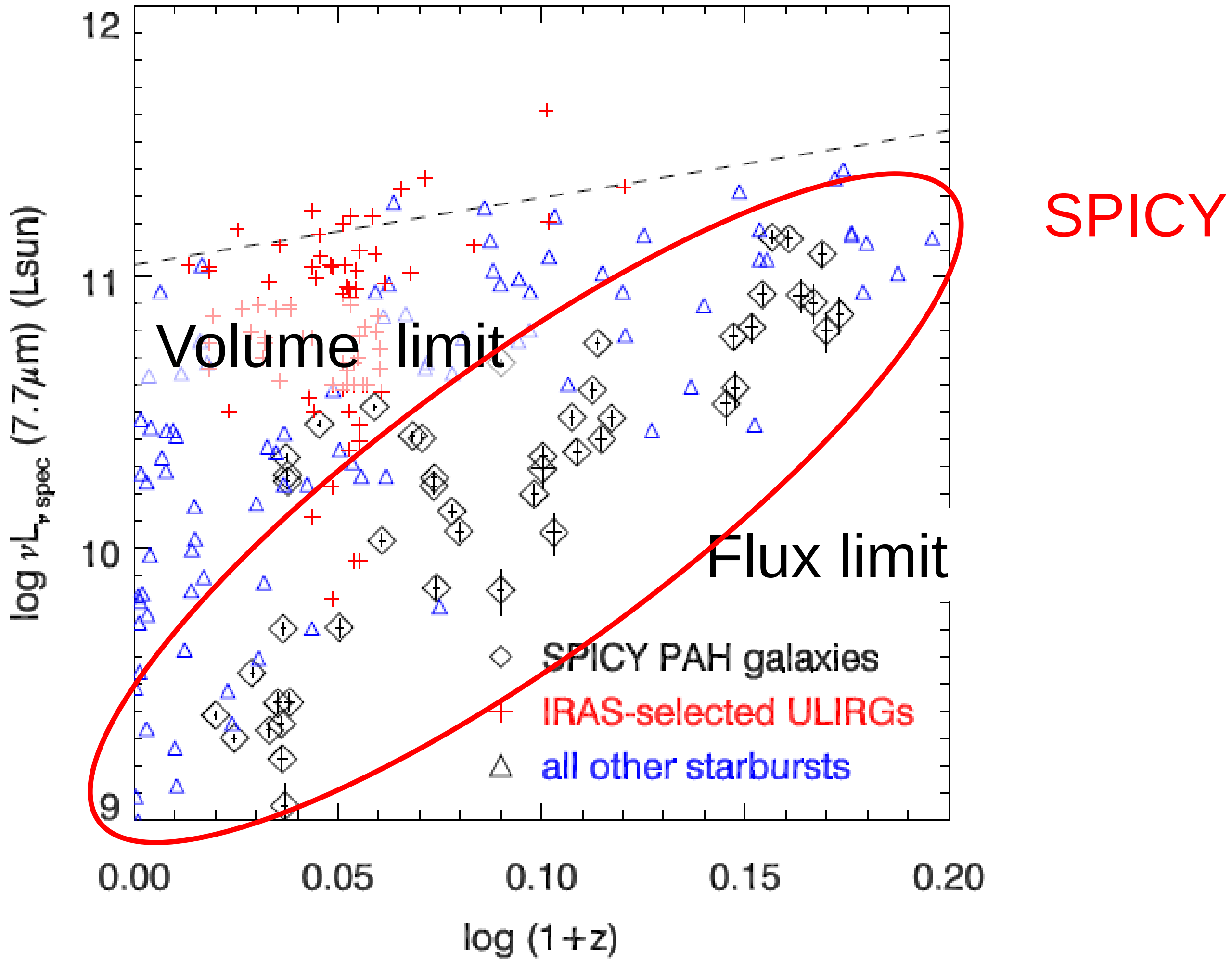
- Red redshift obtained by PAH fitting is consistent with that by optical spectroscopy. (Shim et al. 2013)
- Simple fitting with low-resolution spectroscopy of PAH gives us a good redshift measurement.

property of SPICY PAH gals



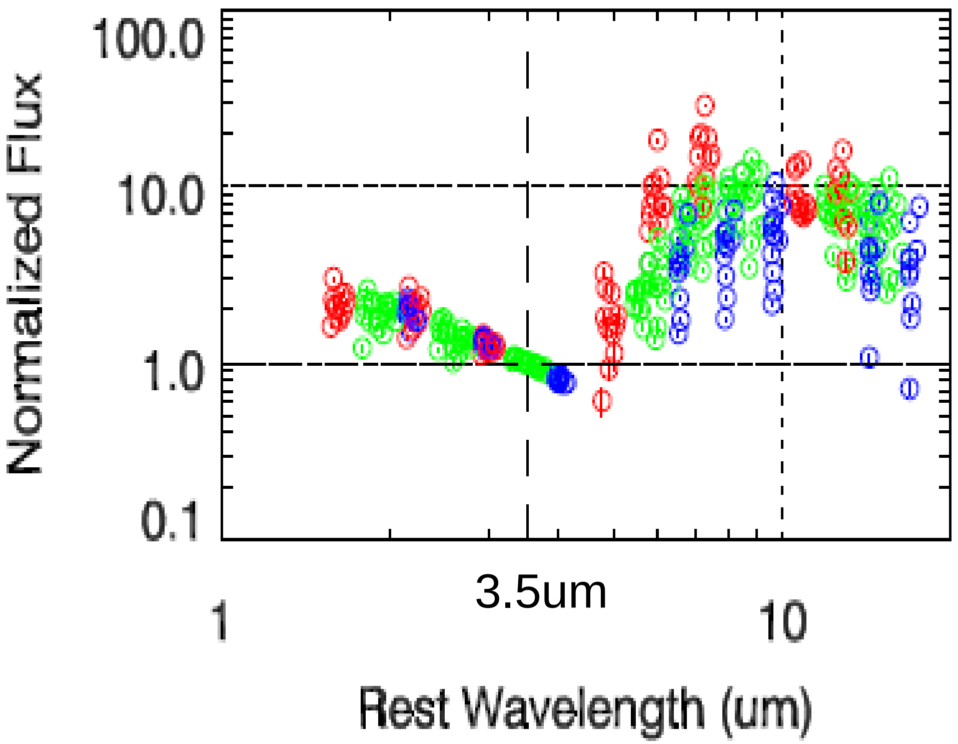
Spitzer/IRS galaxies
Weedman & Houck 2008

property of SPICY PAH gals

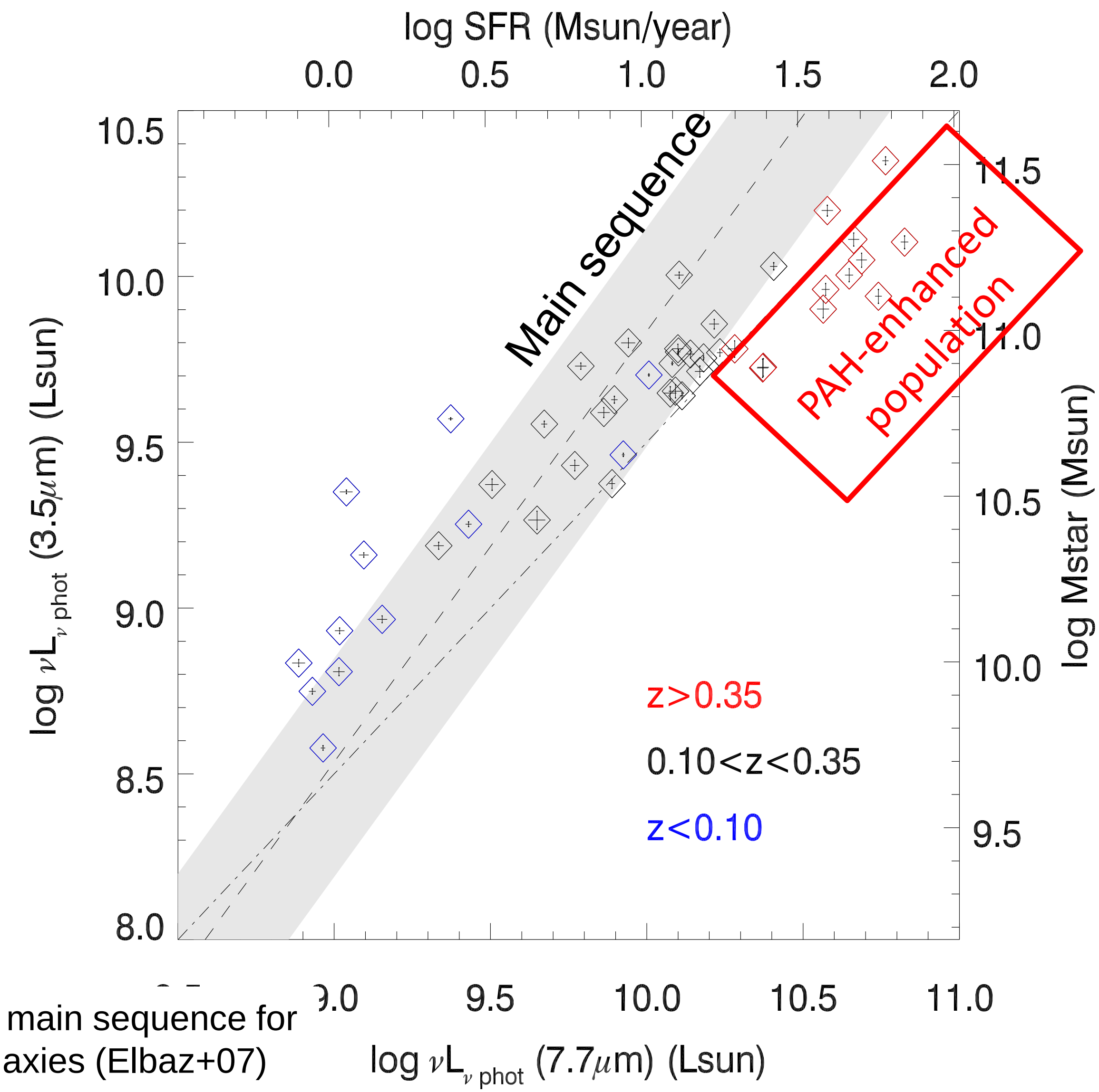


Stellar continuum by NEP/WIDE NIR phtometory

SEDs of 48 SPICY PAH galaxies
(rest-frame)



PAH enhanced population

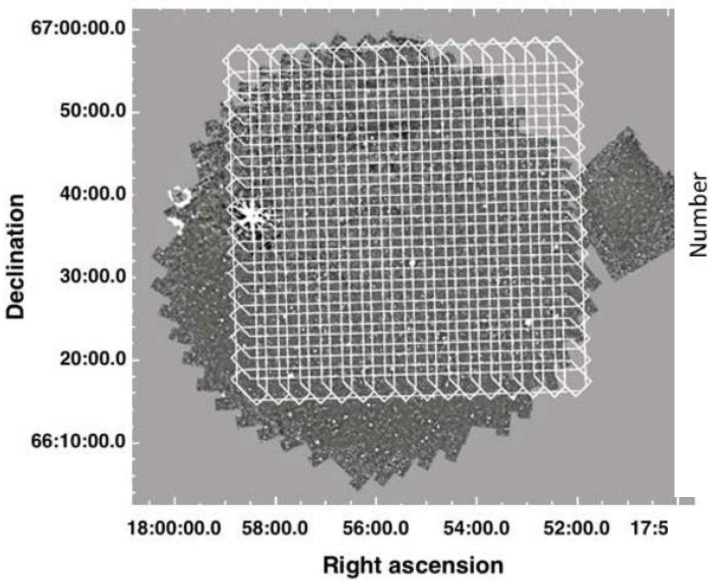


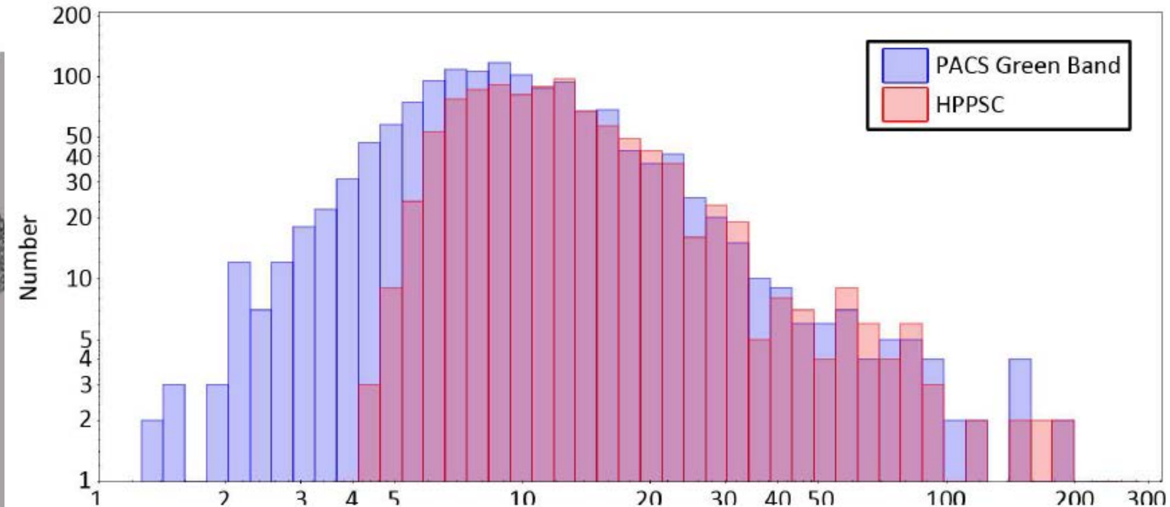
- Gray shaded area: main sequence for *z*~0 blue SDSS galaxies (Elbaz+07)

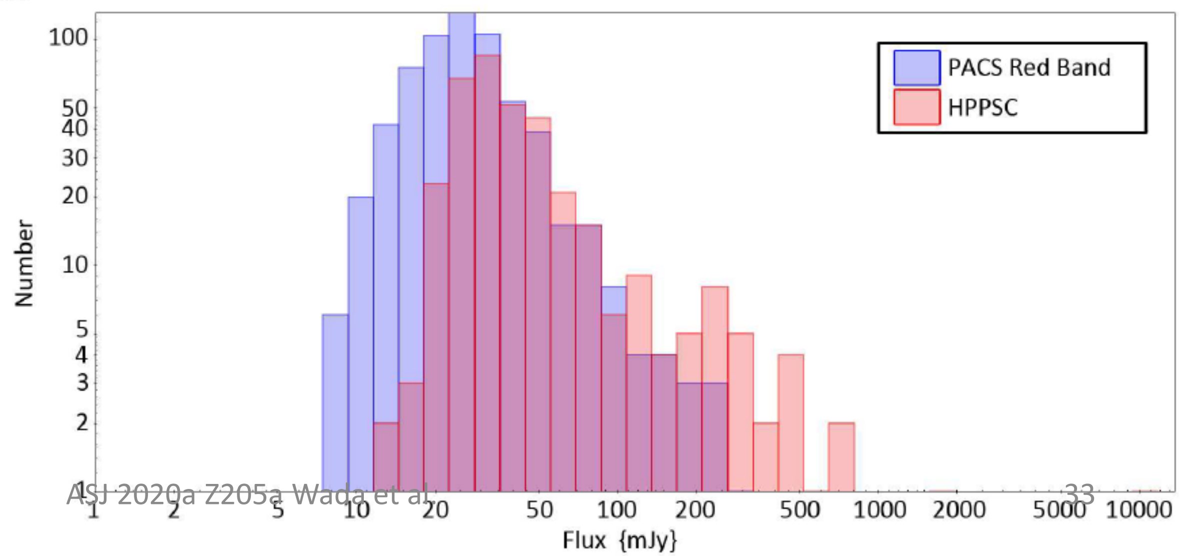
FIR-PAH relation

The Herschel-PACS North Ecliptic Pole Survey

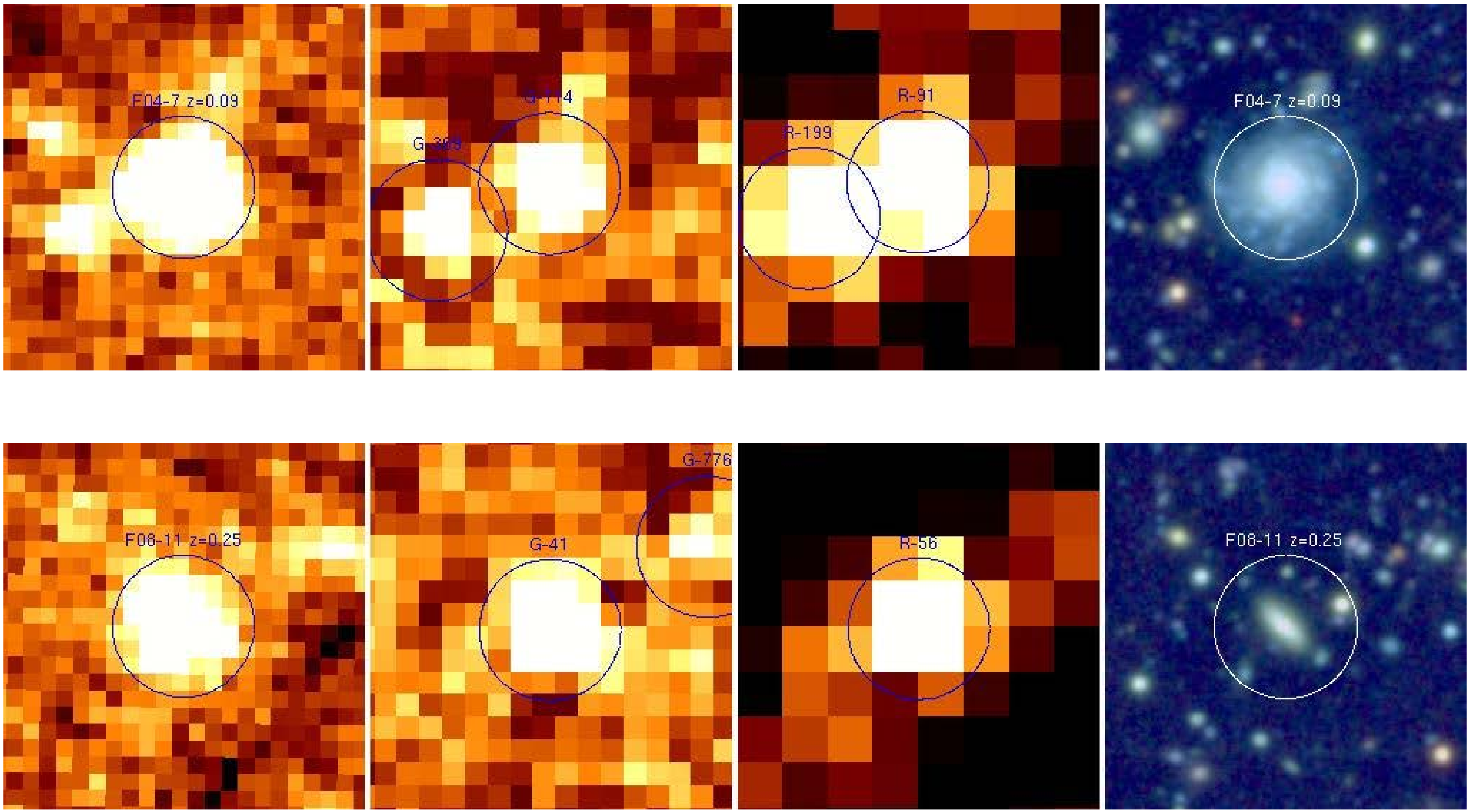
Pearson et al. 2019



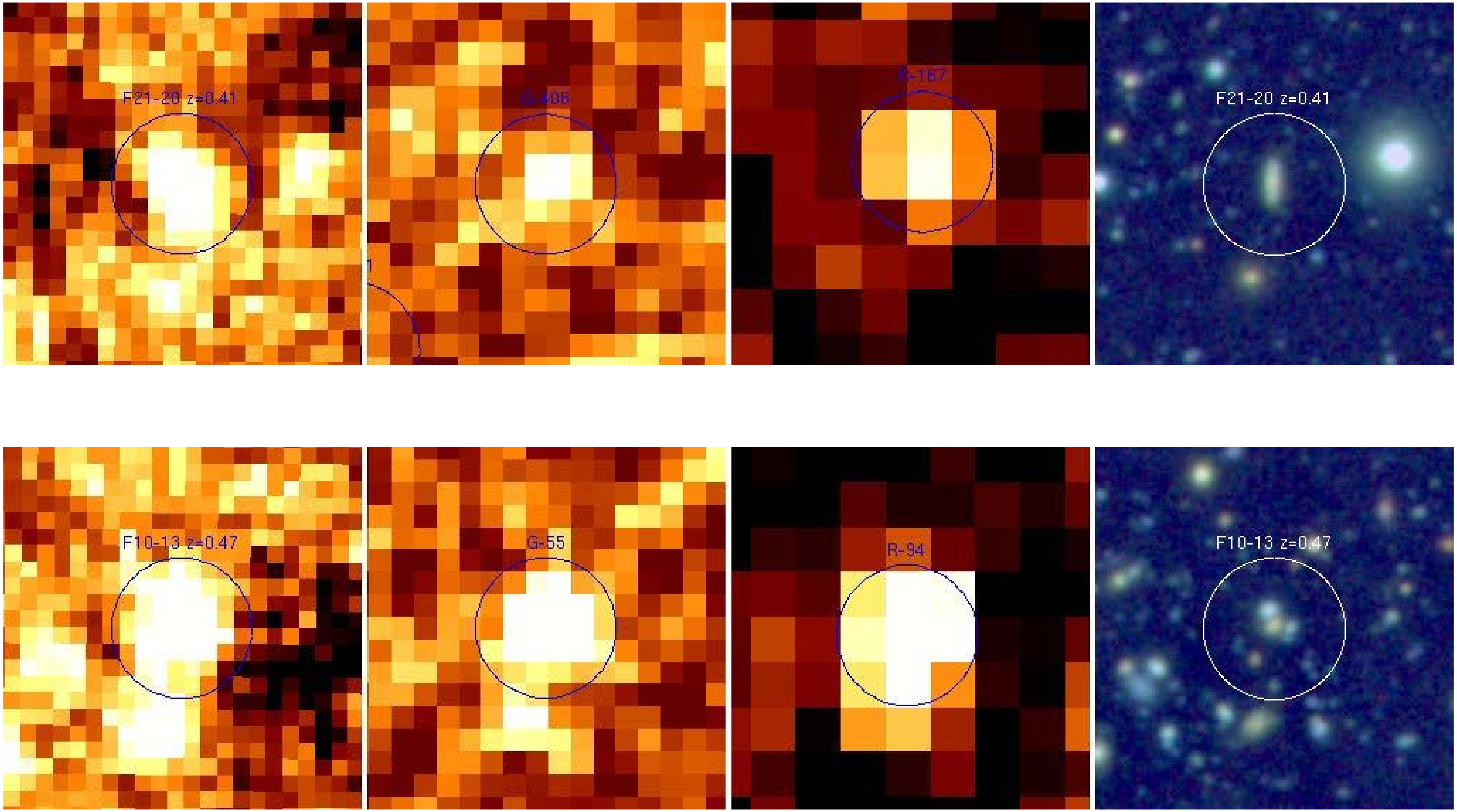




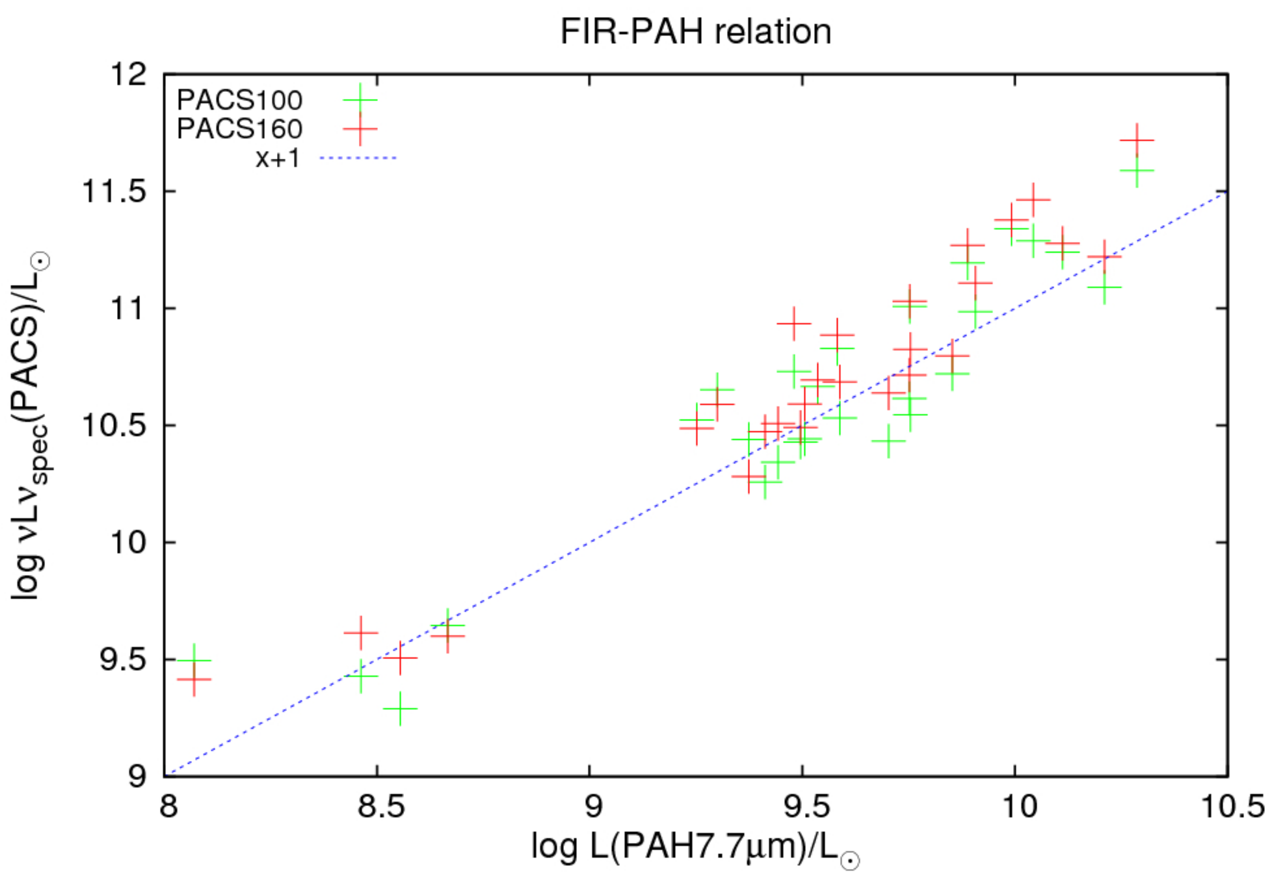
9um, 100um, 160um, OPT images of SPICY PAH galaxies



9um, 100um, 160um, OPT images of SPICY PAH galaxies

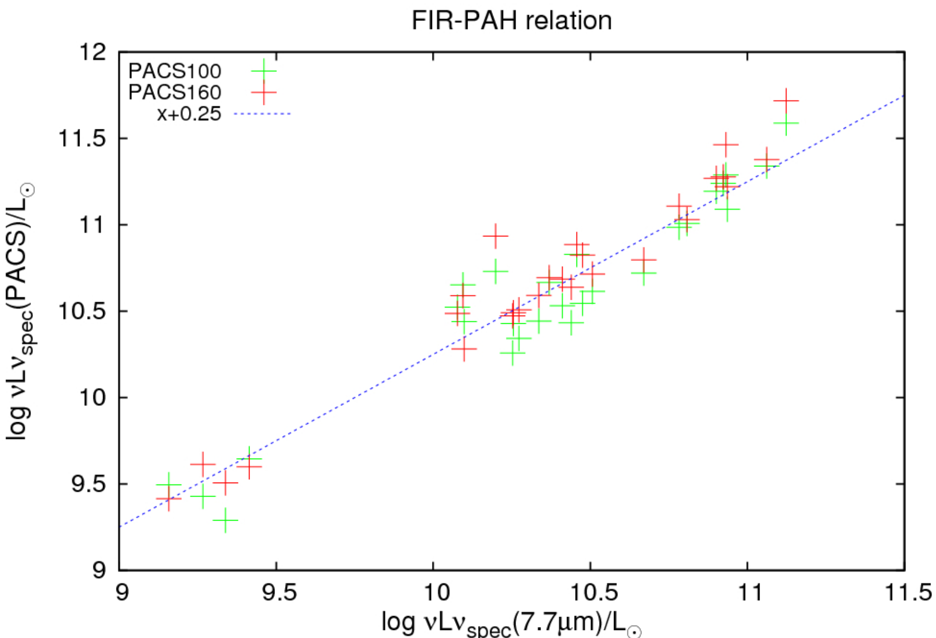


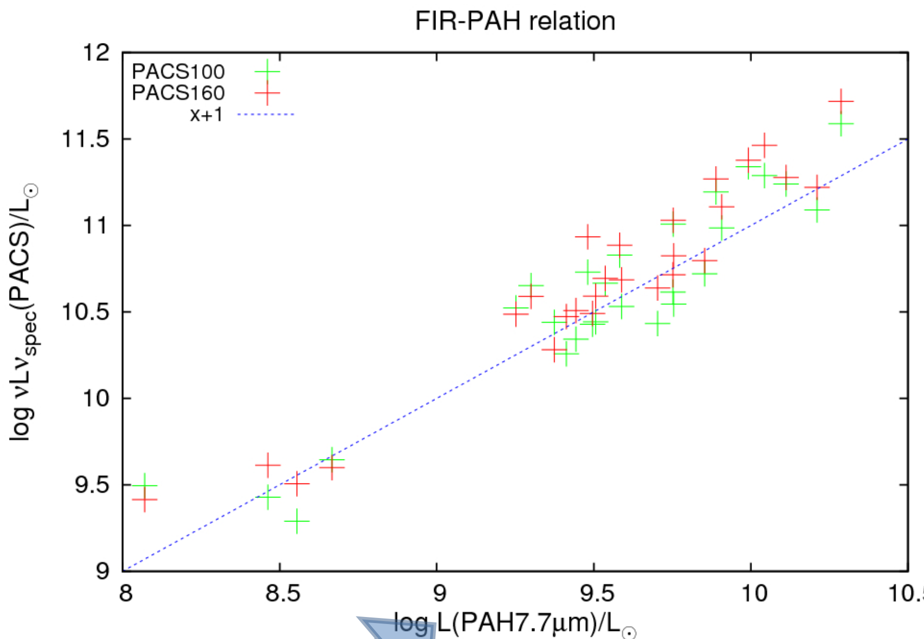
FIR-PAH relation

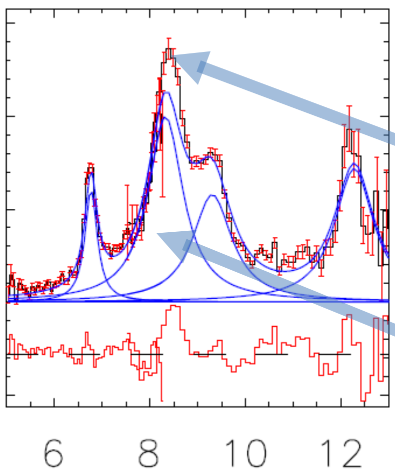


Log $\nu L\nu$ (PACS)/Lsun = 1 + log LPAH7.7μm/Lsun

FIR-PAH relation



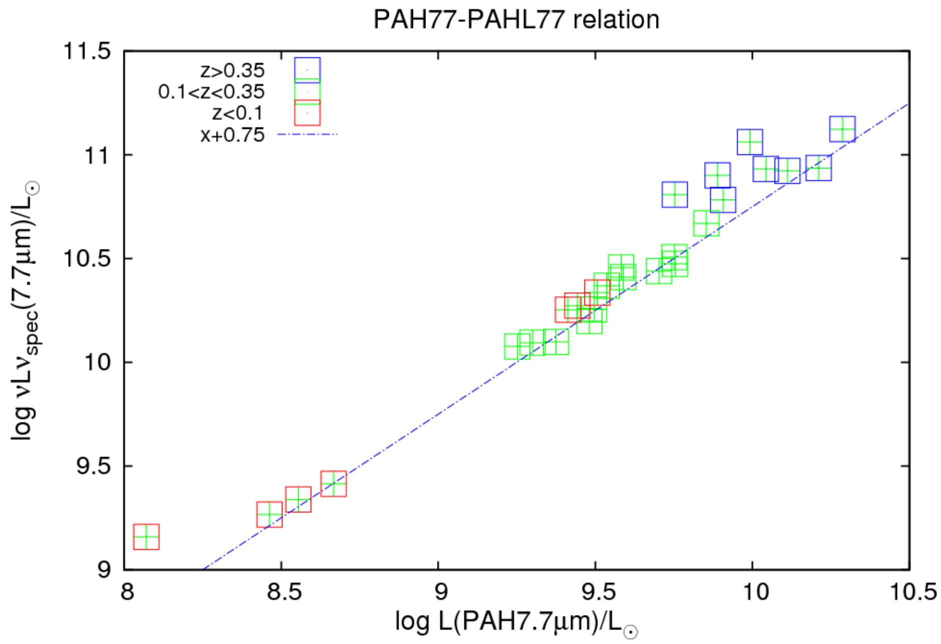




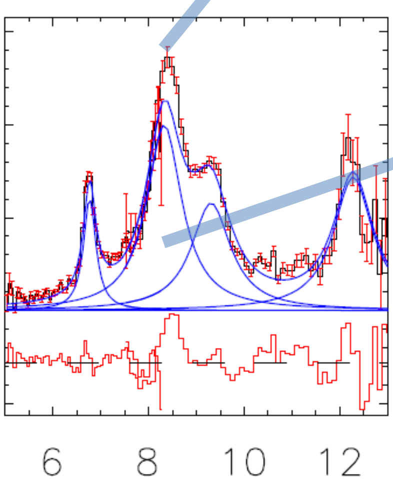
$\upsilon L \upsilon$7.7μm: monochromatic luminosity at 7.7μm or "peak luminosity of the PAH7.7 μm; (Weedman & Houck 2008)" Including underlying continuum gives better correlation.

L(PAH 7.7μm):
Luminosity of PAH 7.7μm

Peak Luminosity of PAH 7.7μm



Log $\upsilon L\upsilon$7.7μm/Lsun = 0.75 + log LPAH7.7μm/Lsun



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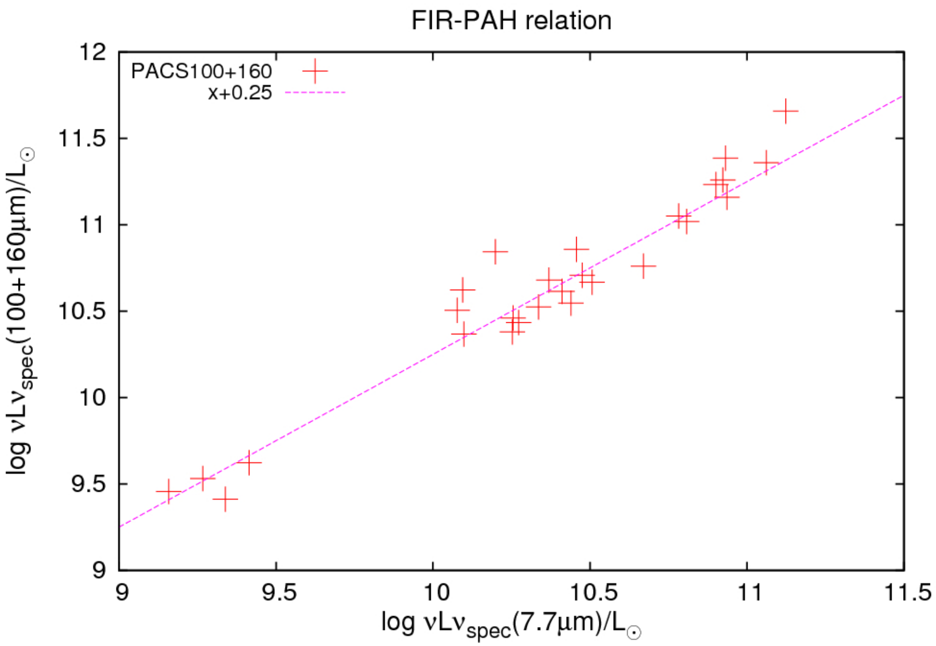
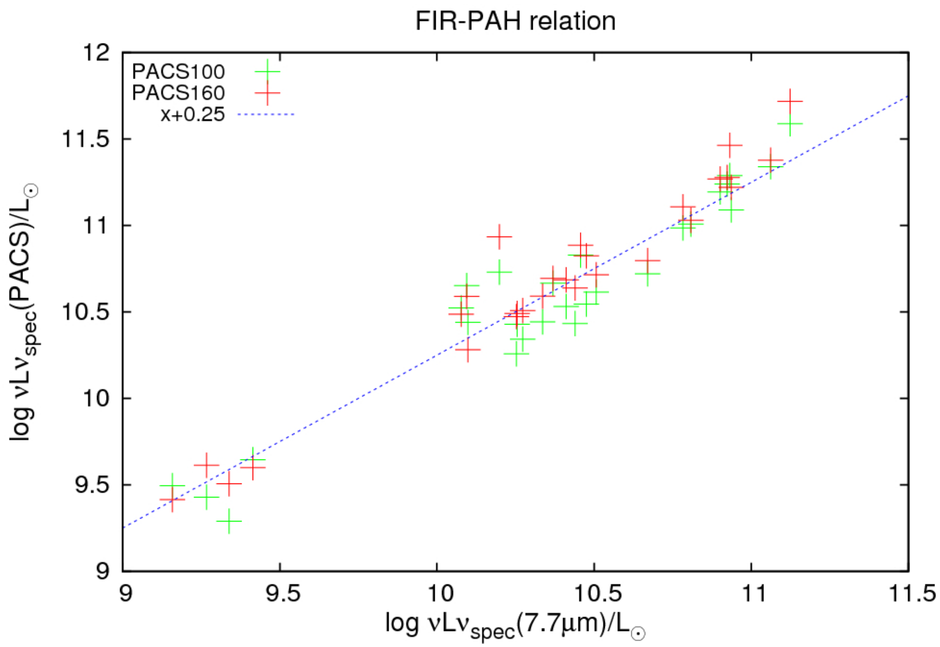
Including underlying continuum gives better correlation.

L(PAH 7.7μm):
Luminosity of PAH 7.7μm

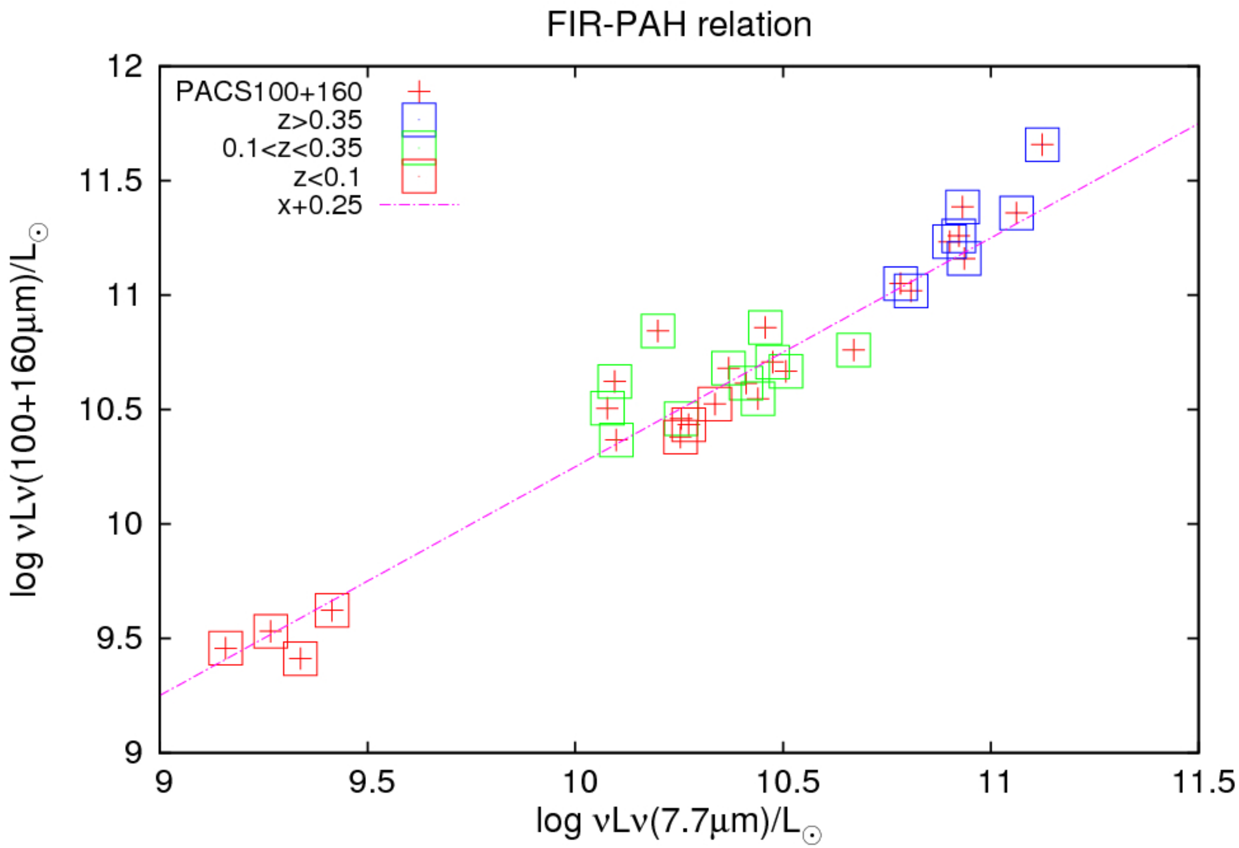
FIR-PAH relation





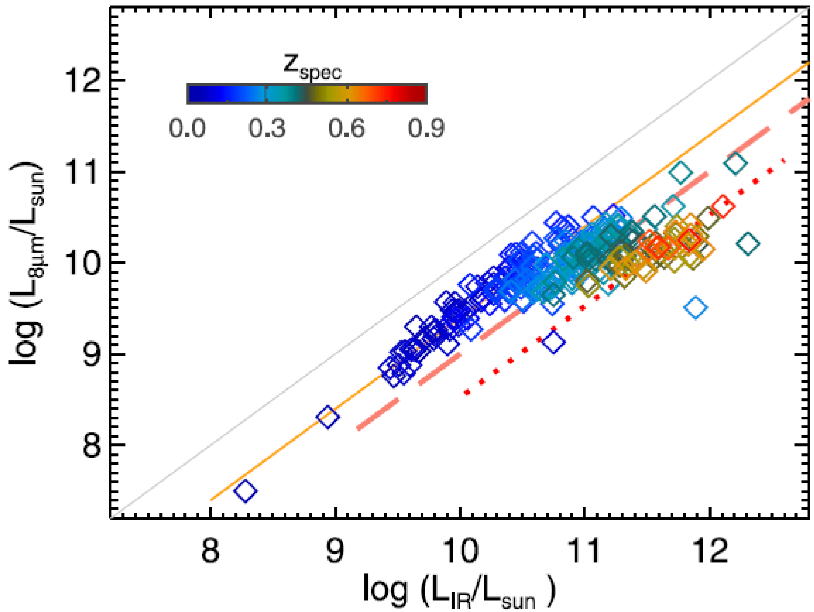
$\upsilon L\upsilon$(100+160μm): mean luminosity of PACS 100 and PACS 160
= ($\upsilon L\upsilon$PACS(100μm)+:$\upsilon L\upsilon$PACS(160μm))/2

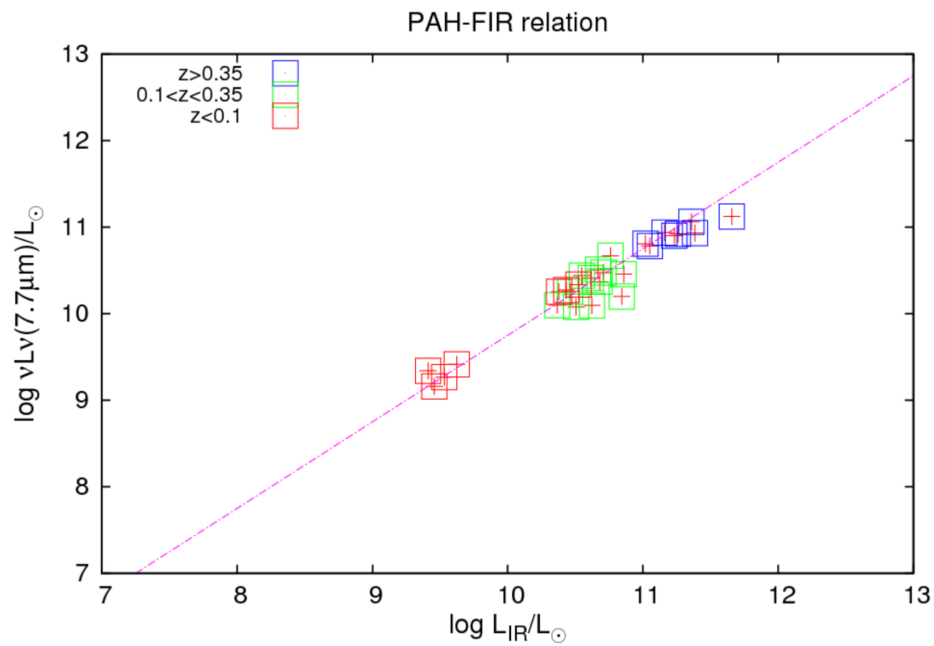
FIR-PAH relation



Log $\nu L\nu$(100+160μm)/Lsun = 0.25 + Log $\nu L\nu$7.7μm/Lsun

FIR-PAH relation photometric and spectroscopic





Kim et al. 2019, PASJ 71, 11.
Photometric L8um

This work
Spectroscopic PAH luminosity

SPICY summary

- The world first MIR unbiased spectroscopic survey has been conducted (>0.3mJy at 9um).
- 48 PAH galaxies are detected z=0.1~0.5 with LIR=$10^{9.5-11.5}$ Lsun
- Good correlation between spectroscopic redshift of OPT and PAH; PAH is a good redshift indicator.
- We found PAH-enhanced galaxies at high-z(z>0.35) or high-L PAH, which has higher PAH/stellar mass ratio rather than the main sequence galaxies.
- Good correlation between PAH and FIR luminosity: PAH is cost-effective indicator of star-formation.

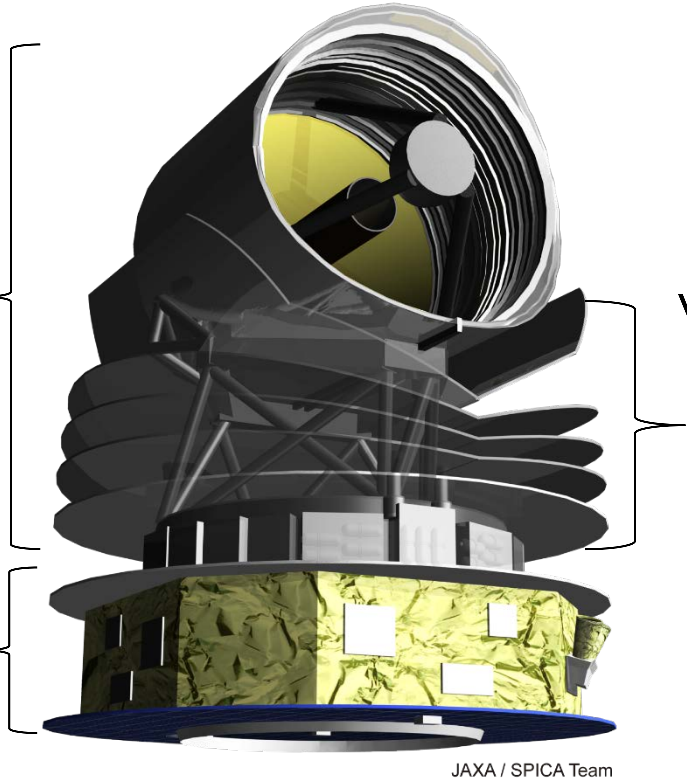
SPICA (Space Infrared Telescope for Cosmology and Astrophysics)

- Large aperture大口径:2.5m
- Cooled 冷却 telescope: 8K
- Spectroscopy in MIR-FIR (12-230μm)

- Cooled by Radiation and cooler
- No more LHe and vacuum chamber

- JAXA H3 Rocket
- L2 mission (1.5 million km)
- Early 2030’s
- ESA/JAXA mission

- JAXA Strategic Large Class: Phase-A
- ESA CV M5 Phase-A
- ESA CV M5 final selection (2021)



- Dimension：Φ4500 mm x 5285 mm
- Mass：2614 kg (dry, nominal),
  - 3450 kg (wet, with margin)

Toward SPICA

- D=68cm => 2.5m diffraction limited image
  - Sharp beam with larger collecting area
    - Low luminosity galaxies
    - High-z
    - Less source confusion
- Longer and wider spectral coverage
  - 2-24um (AKARI/IRC)=> 17-36um (SMI/LR)
  - Trace the PAH(11.3-6.2) at z=0.5-4, where the cosmic star-formation rate peaks!
  - 12-230um contiguous spectrum, MIR-FIR spectrum since ISO.

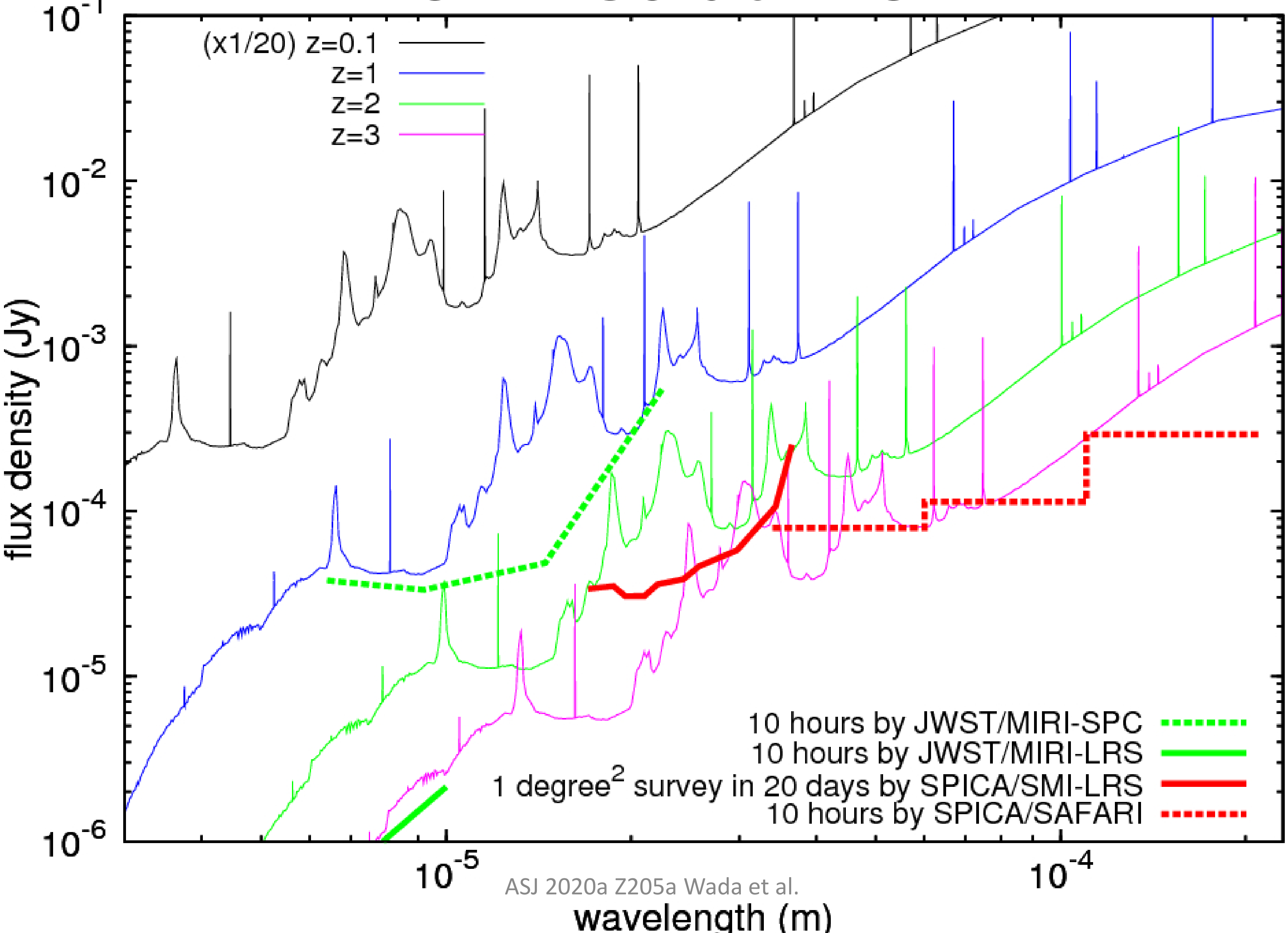
SPICA/SMI/LR+CAM

- 17-36um R=100 spectrometer with 34um camera
- Wide field of view (10’x3.7”x4 slit spec. and 10’x12’ img.)
- 30uJy level sensitivity with 1 hour 5 sigma
- z=3 ULIRGs can be detected in blind survey!

SPICA/SMI/MR+SAFARI

- 17-230um R=300-1000 spectrometer
- A few 10^{-20}W/m^2 level line sensitivity with 1 hour 5 sigma
- z=3 ULIRGs can be followed up by dust extinction free IR diagnostic lines!

uJy level sensitivity probes ULIRGs at z=3



Blind survey and follow-up

Unbiased spectroscopic survey SMI/LR

(17–37 μm, R=50–100) + (34 μm R=5)

◆ 10 deg^2 blind survey (600 hrs)

Better statistics

(51,000 PAH galaxies 3,700 AGNs 13,000 MS stars)

◆ 1 deg^2 blind survey (500 hrs)

Fainter objects

(sub-L* galaxies, faint debris disks)

Follow-up observations

(18–230 μm, R=300–1000)

SMI/MR･SAFARI

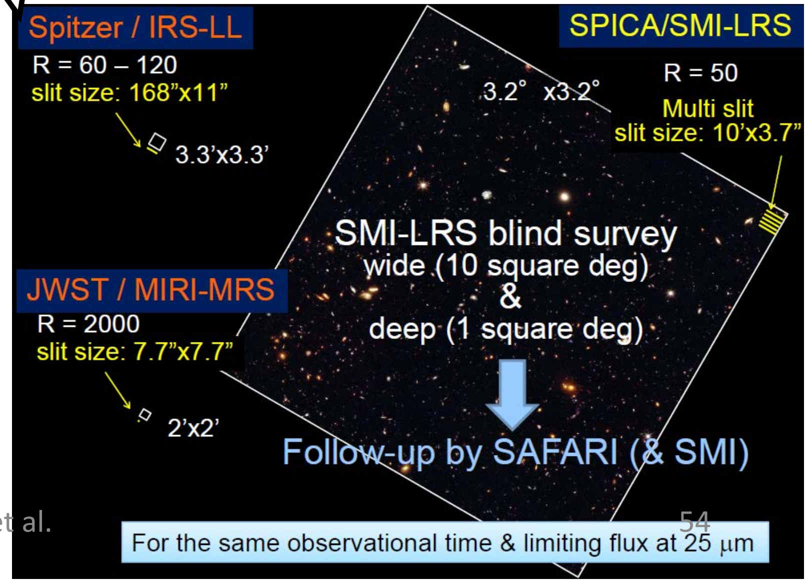
- ◆ Pointed spectroscopy
- ◆ Spectral mapping of nearby galaxies
- ◆ Spectral mapping of Galactic objects

Targets observed by

AKARI, Subaru, Spitzer, Herschel, ALMA, JWST, Euclid, SKA, TMT, ATHENA, TESS,

P

- ◆ high-z galaxies, AGN outflow, nearby dwarf galaxies,,,
- ◆ proto-planetary disks, debris disks, exo-planets,,,



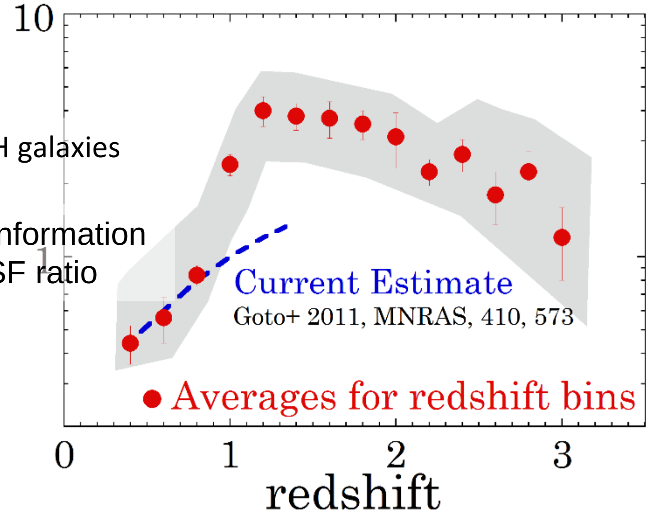
皮算用

SF/AGN Diagnostics by PAH and silicate

All the 51,000 PAH galaxies
3,700 AGNs
with basic information
z, L, AGN/SF ratio

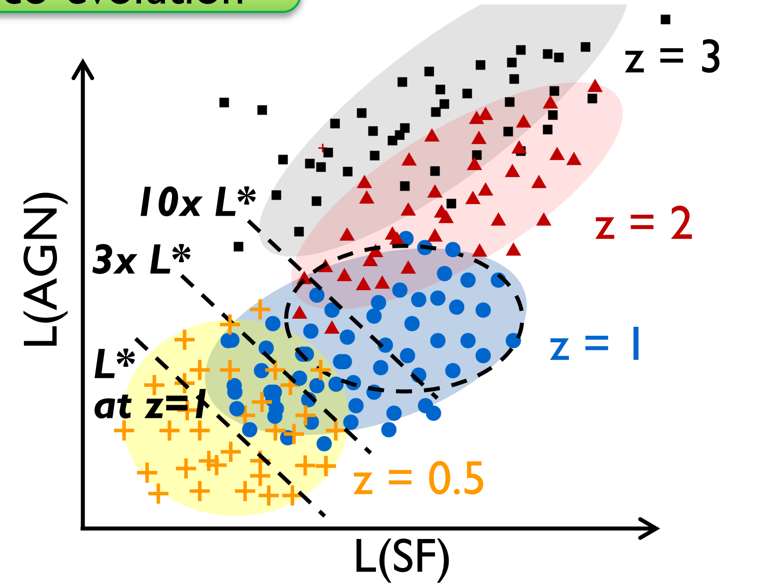
Uniformly sampled
> 1,000 galaxies

AGN contribution

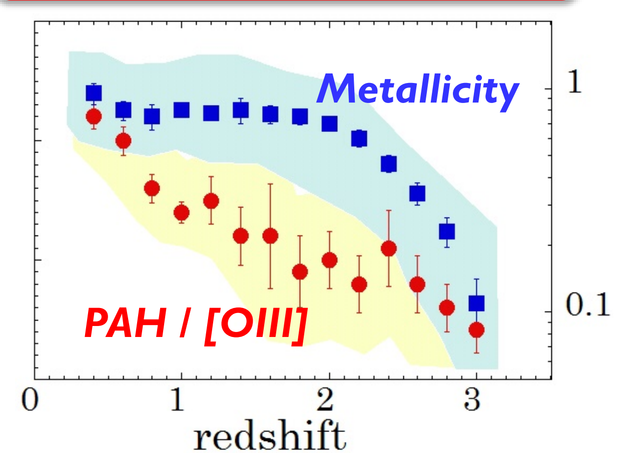


AGN/starburst co-evolution

For **SF/AGN mixture**



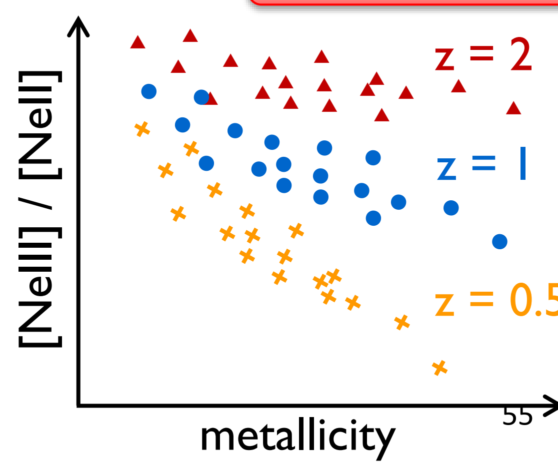
Dust formation & growth
Relation to metal enrichment



For pure SF galaxies,

- [NIII]57/[OIII]52
  → metallicity
- PAH/[OIII]
  → (dust/gas)/(metallicity)
- [NeIII]/[NeII]
  → radiation temperature

Top-heavy IMF ?



summary

- The world first MIR unbiased spectroscopic survey has been conducted (>0.3mJy at 9um).
- 48 PAH galaxies are detected z=0.1~0.5 with LIR=$10^{9.5-11.5}$ Lsun
- Good correlation between spectroscopic redshift of OPT and PAH; PAH is a good redshift indicator.
- We found PAH-enhanced galaxies at high-z(z>0.35) or high-L PAH, which has higher PAH/stellar mass ratio rather than the main sequence galaxies.
- Good correlation between PAH and Herschel PACS FIR luminosity: PAH is cost-effective indicator of star-formation.
- SPICA will probe these galaxies redshift at z=0.5-4, the most active era of galaxy evolution.