Unveiling the physical processes that regulate Galaxy Evolution through space observations

Luigi Spinoglio (IAPS-INAF, Roma)

- Dust obscured star formation and black hole accretion at z=1-3 during galaxy evolution, and their mutual feedback processes, can be studied with rest frame mid-to-far IR spectroscopy.

- At these wavelengths (10-200μm) dust extinction is at its minimum and a variety of atomic and molecular transitions, tracing most astrophysical domains, occur.

- The future IR space telescope mission, SPICA, with its 2.5m telescope cooled to T<8K, will collect mid-to-far IR spectroscopy at a sensitivity 100 times better than what Herschel did.

- Strong complementarities and synergies of SPICA with the X-ray ESA mission Athena include the study of the BH accretion (Compton thick AGN) rate history along cosmic time and the study of violent outflows from AGN.

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Special thanks to the SAFARI Consortium (PI: Peter Roefsema) and the SPICA Japanese Team (PI: Hiroshi Shibai, PS: Takashi Onaka, System Study M: Takao Nakagawa, PLM: Hideo Matsuhara, PI for SMI: Hidehiro Kaneda)

To study galaxy evolution we need to trace star formation and AGN accretion over cosmic times. So we want to know:

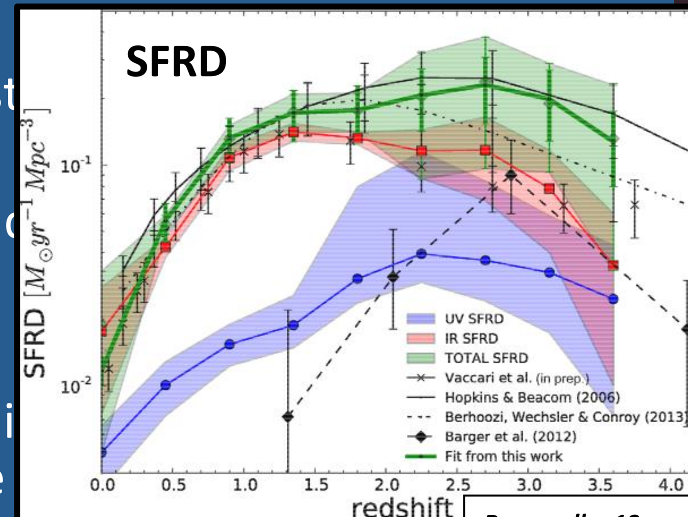
- the full cosmic history of energy generation by st
  AGNs (black hole accretion)

  (it's not just quasars, but Seyfert galaxies which c
  Luminosity Function)

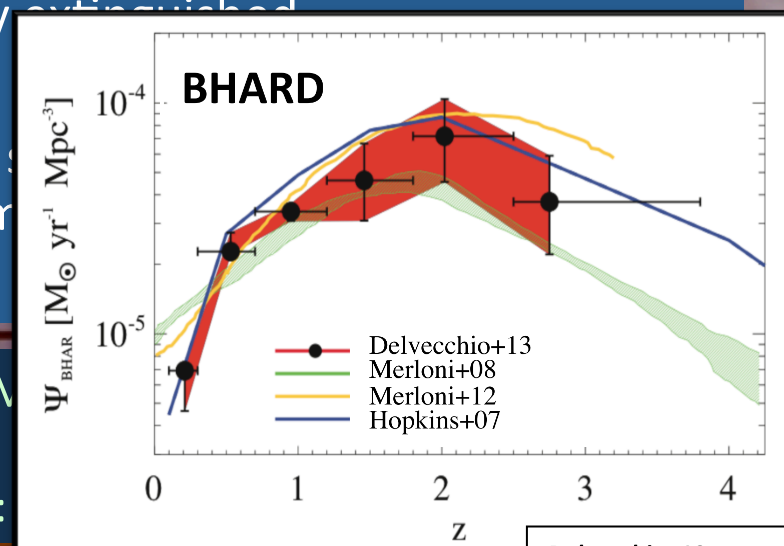
- these energy production rates correspond to bui
  hole, or galactic stars), and must--ultimately--be

- Uncover how much of this is partly or heavily

- Seek cosmic connections between a galaxy's s
  understand the how and why of these system



Burgarella+13



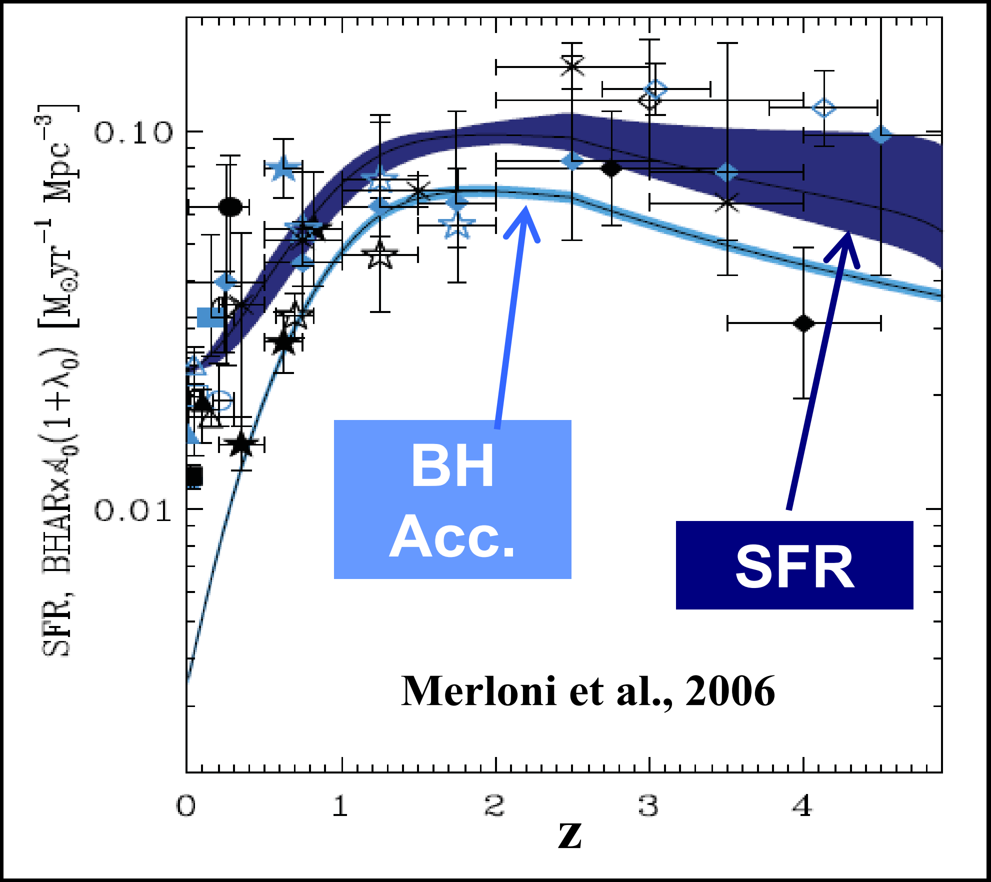
Delvecchio+13

So we propose to make spectroscopic surveys in the M

Done so far: Local Universe: Spitzer/Herschel

To do now: intermediate redshift (z=1-3) Universe:

Co-eval Growth of Black Holes and Host galaxies



- Dust-enshrouded AGN accretion phase undergone by all galaxies?
- Need to compare evolution of BH mass function with galaxy mass and luminosity functions in large samples
- Must include heavily obscured AGN
- Both peak at z = 2 – 3, when most SF was in LIRGs – current data very limited
- Key AGN signature: high-excitation fine structure lines e.g., [NeV] 14.3 μm
  [OIV] 26 μm
- Line widths indicative of BH mass

The strong correlation in the local Universe between the mass of the black hole and the stellar velocity dispersion of the galactic bulge (the “Magorrian Plot”) implies a strong physical relation between black hole accretion and star formation.

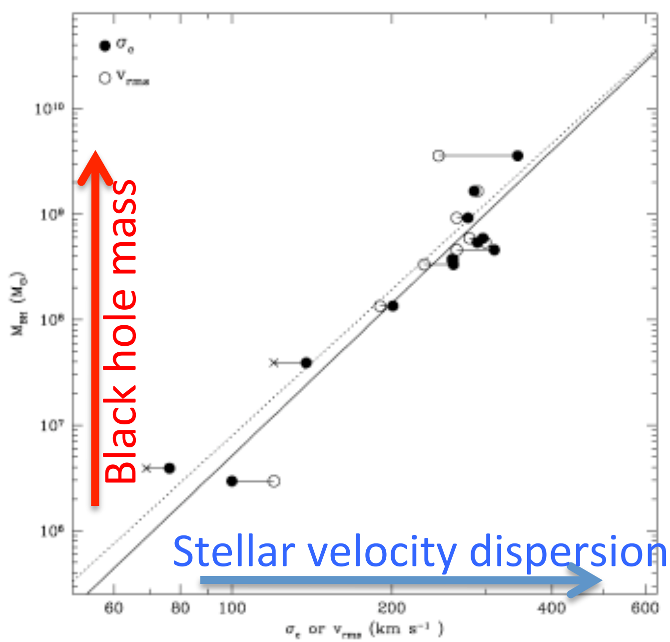
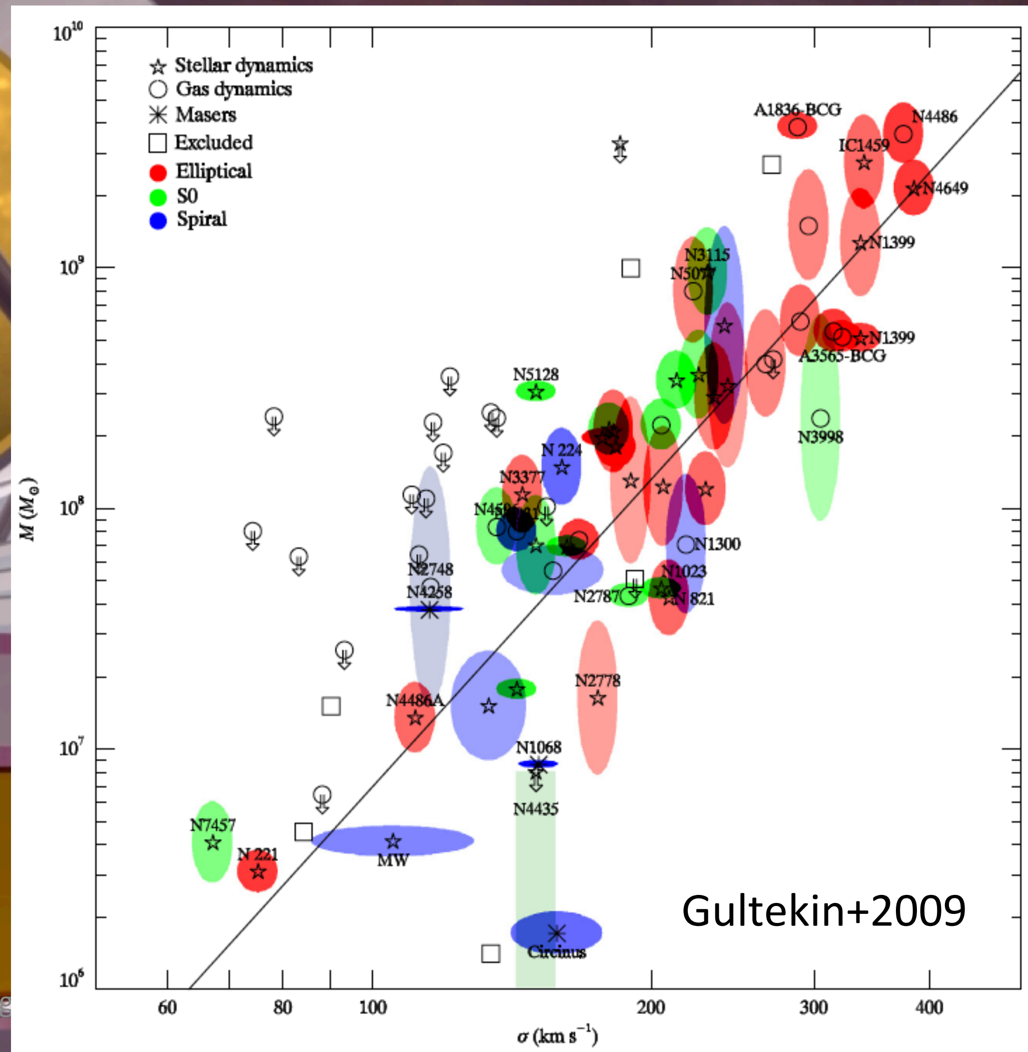


FIG. 2.—BH mass vs. the central velocity dispersion σ_c of the host elliptical galaxy or bulge (*filled circles*) or the rms velocity v_{rms} measured at one-fourth of the effective radius (*open circles*). Crosses represent lower limits in v_{rms}. The solid and dashed lines are the best linear fits using σ_c (as in Fig. 1*b*) and v_{rms}, respectively.

Ferrarese and Merrit 2000 (ApJ,539,L9) first publish a relation between the black-hole mass and the stellar velocity dispersion in the galactic bulges of galaxies: $M_{BH} = \sigma^{4.8\pm0.5}$

The formation of spheroids (bulges) is linked to the growth of the Black Holes



Comparing different wavelengths for separating AGN and SF

No single criteria distinguish AGN & SF ➔ limits and potentialities of different techniques

– UV/Optical/NIR observations ➔ galaxy morphology and spectra,
BUT they seriously suffer from dust obscuration

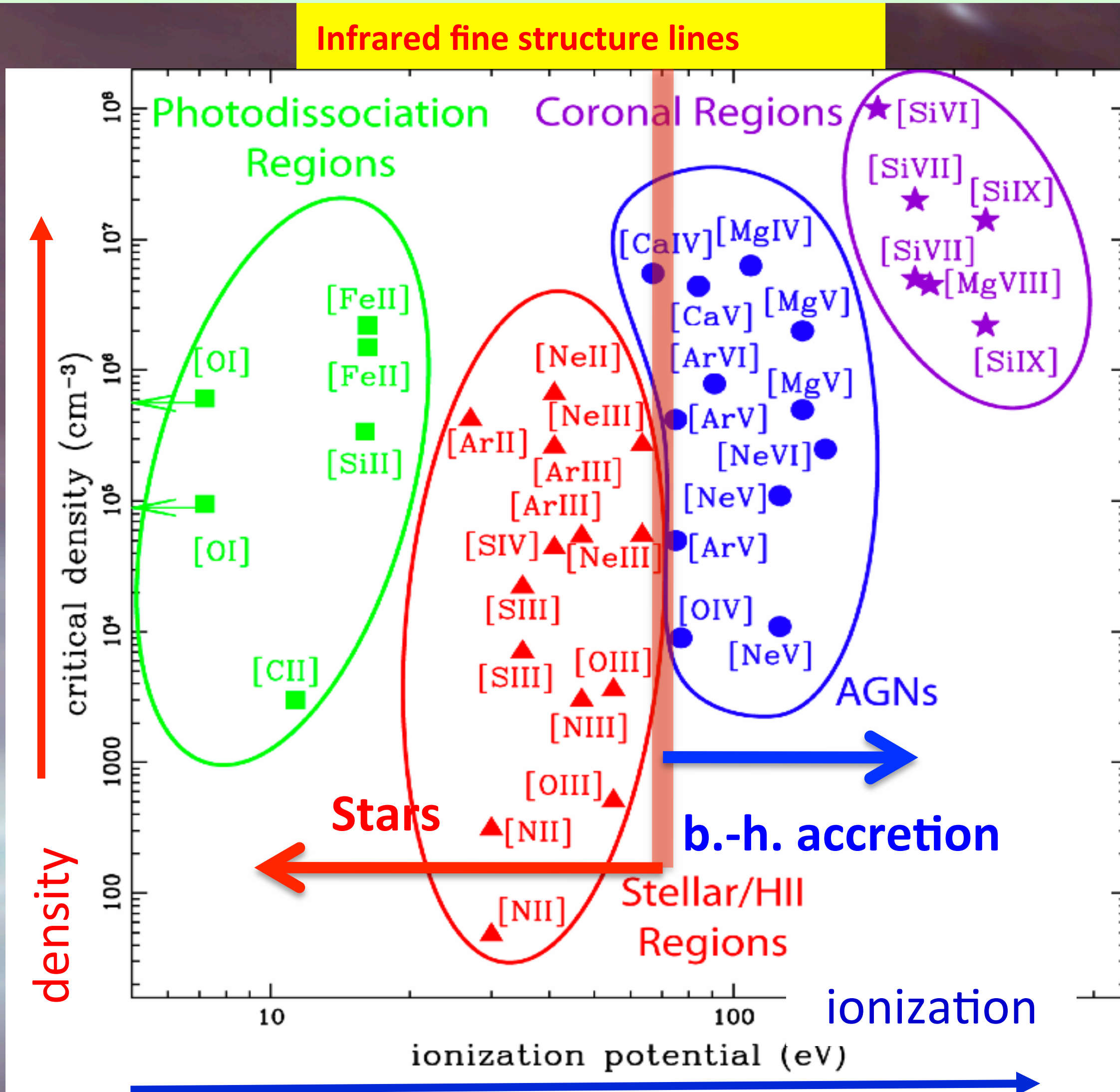
– X-ray observations ➔ good tracers of AGN,
BUT only weak X-ray emission can be detected from star formation
BUT heavily-obscured AGN (Compton-thick) completely lost.

– Radio observations (EVLA, SKA) ➔ can detect AGN and SF to large z and can see through gas and dust, ➔measure morphology and spectral SED, detect polarization and variability,
BUT not always redshifts can be measured. (at its highest frequencies SKA will measure redshifted molecular lines in the ISM of galaxies).

– mm/submm observations (e.g. ALMA, CCAT) ➔ spectra from SF (redshifted CO, CII, etc.), BUT need to find AGN tracers. One candidate is CO: SLED different from PDR (SF) and XDR (AGNs).

Rest-frame MIR/FIR imaging spectroscopy ➔ complete view of galaxy evolution and the role of BH and SF because it can (provided that large field of view and high sensitivity can be reached)
➔ trace simultaneously both SF and AGN,
➔ measure redshifts
➔ see through large amounts of dust.
➔ the most promising technique.

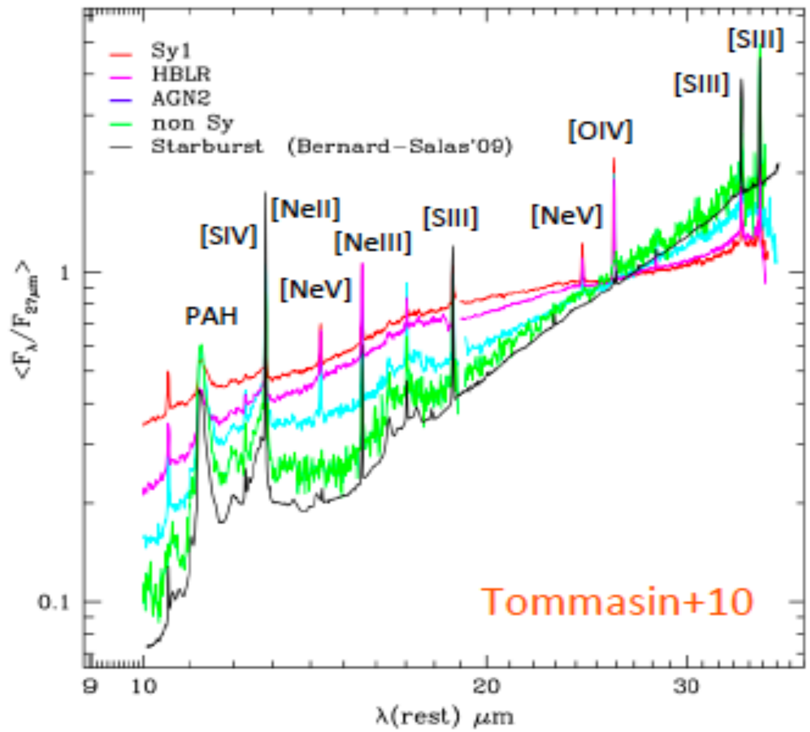
Why infrared spectroscopy is the best tool to isolate star formation and accretion?

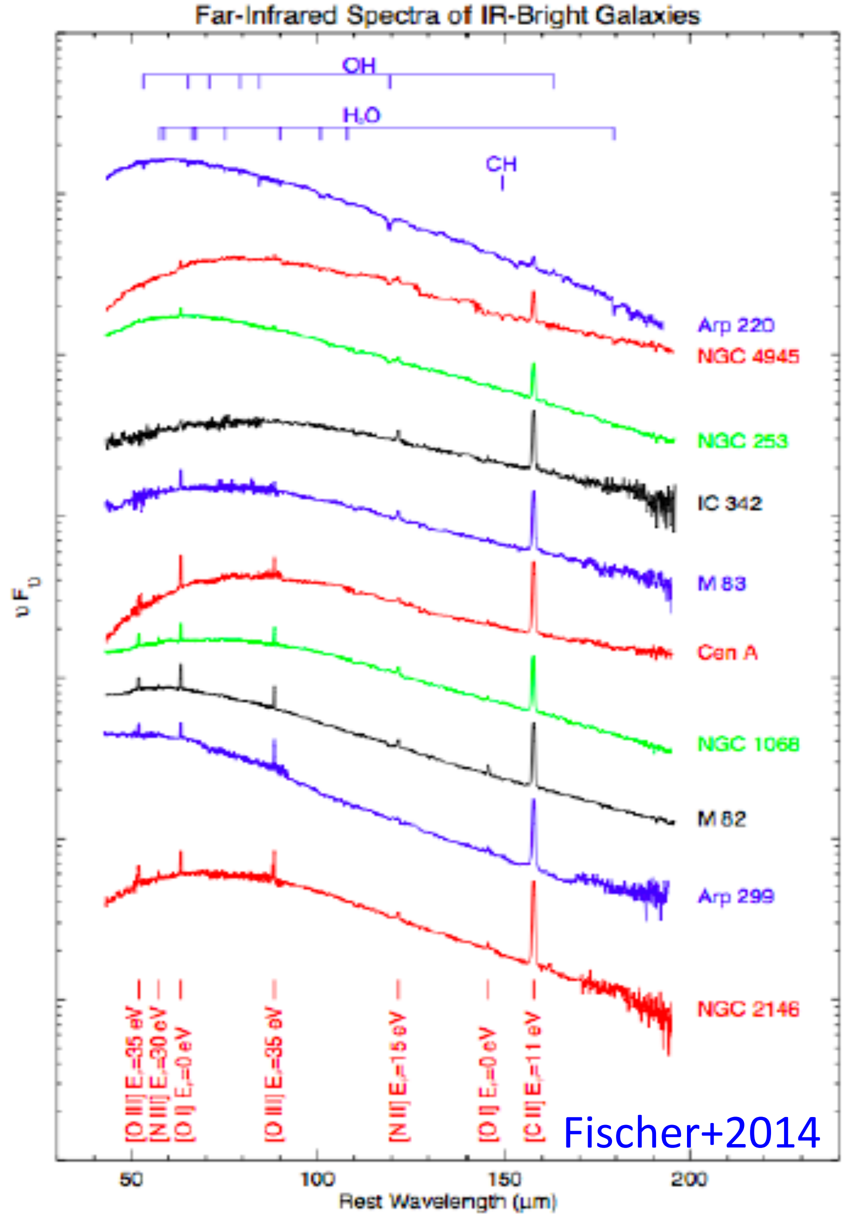


IR fine structure lines:
- separate different physical mechanisms,
- cover the ionization-density parameter space
- do not suffer heavily from extinction

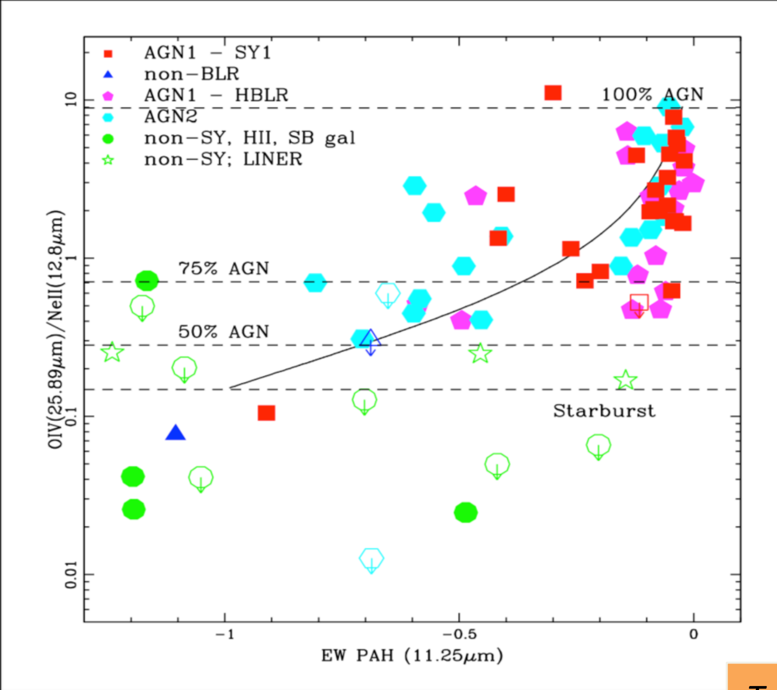
Spinoglio & Malkan (1992) predicted for the first time the line intensities of IR lines in active and starburst galaxies, before the launch of ISO.

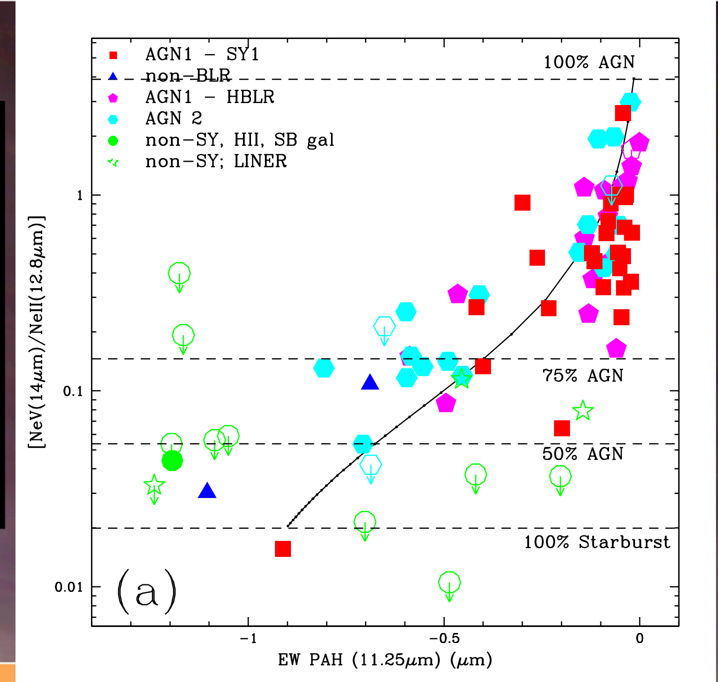
Plenty of strong mid- and far-IR features to detect high-z galaxies and measure redshifts



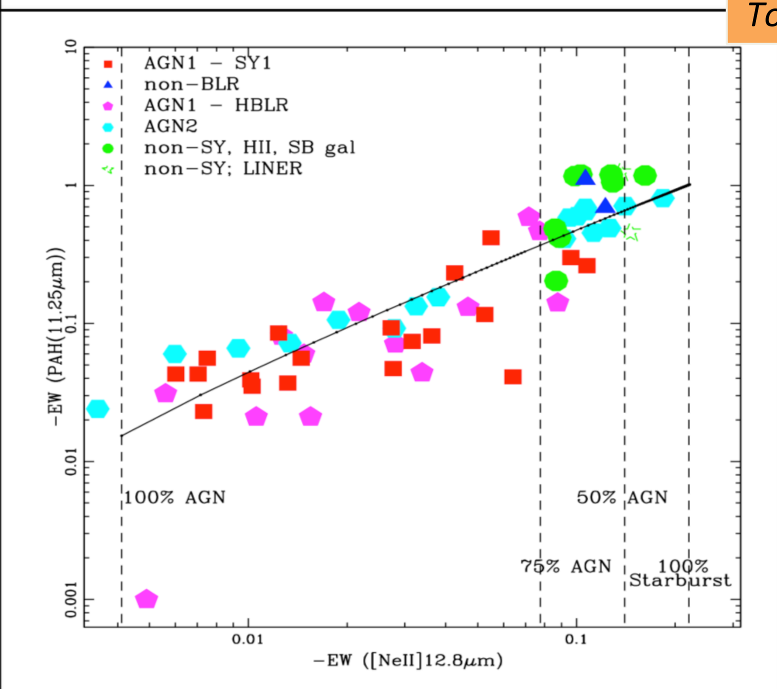


Mid-IR Diagnostics *Spitzer* Redshift ~ zero





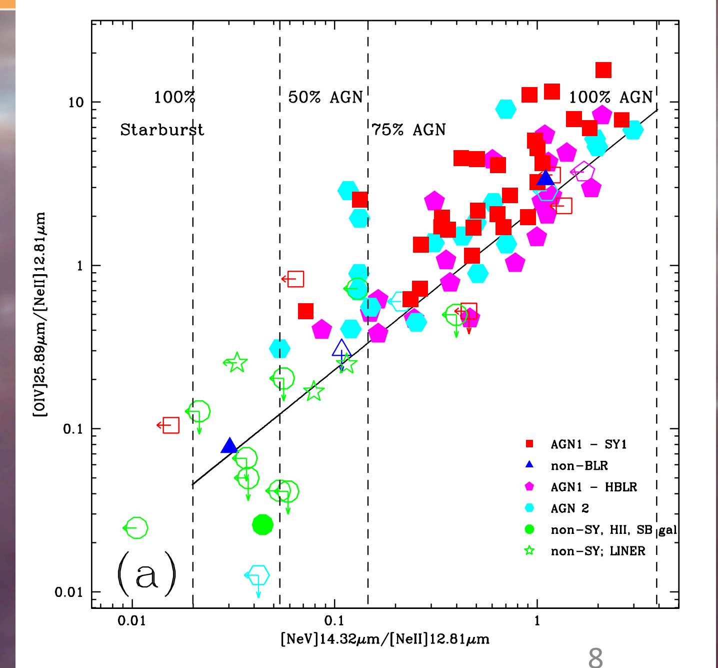
Tommasin+10, ApJ, 709, 1257



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

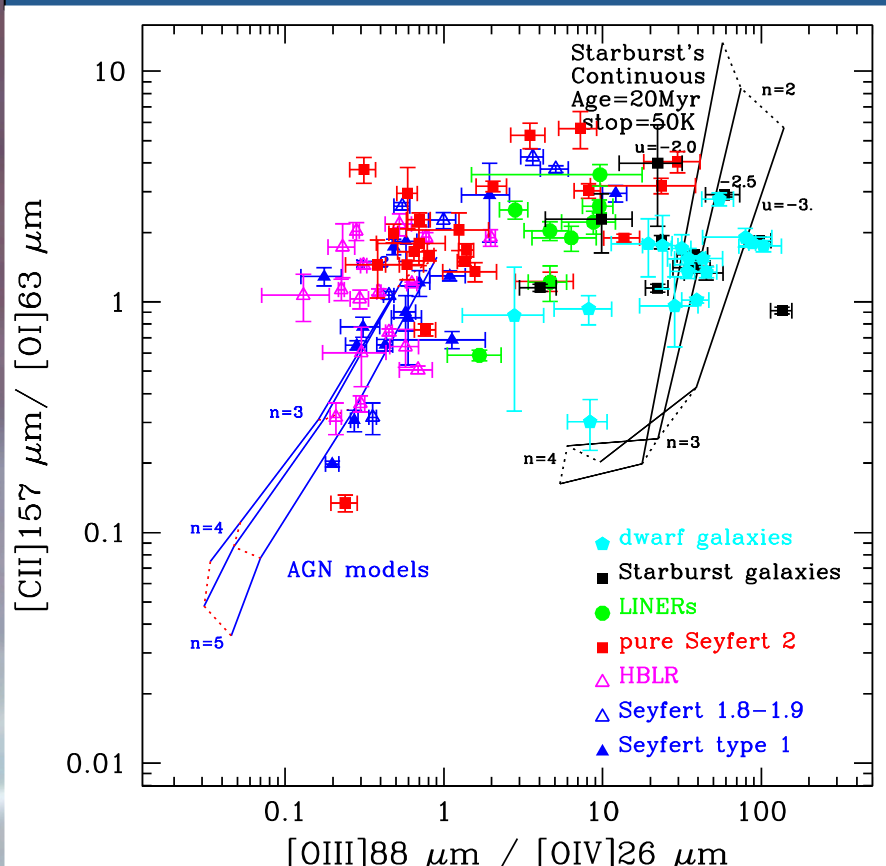
↓

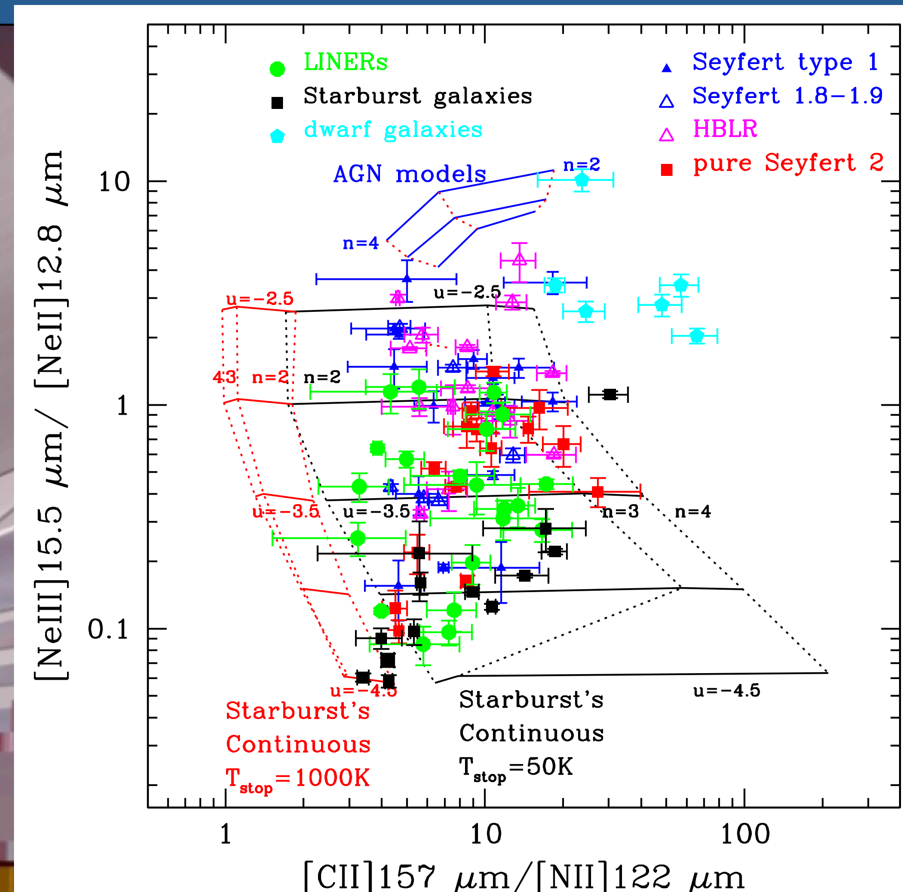
Disentangle AGN from starburst



Mid-IR + Far-IR Diagnostics: Spitzer + Herschel Redshift ~ zero

Plenty of strong mid- and far-IR features to detect high-z galaxies and measure redshifs
➔ Disentangle AGN from starburst





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

Spinoglio+15, ApJ, 799, 21; Fernández-Ontiveros, LS et al 2016, subm.)

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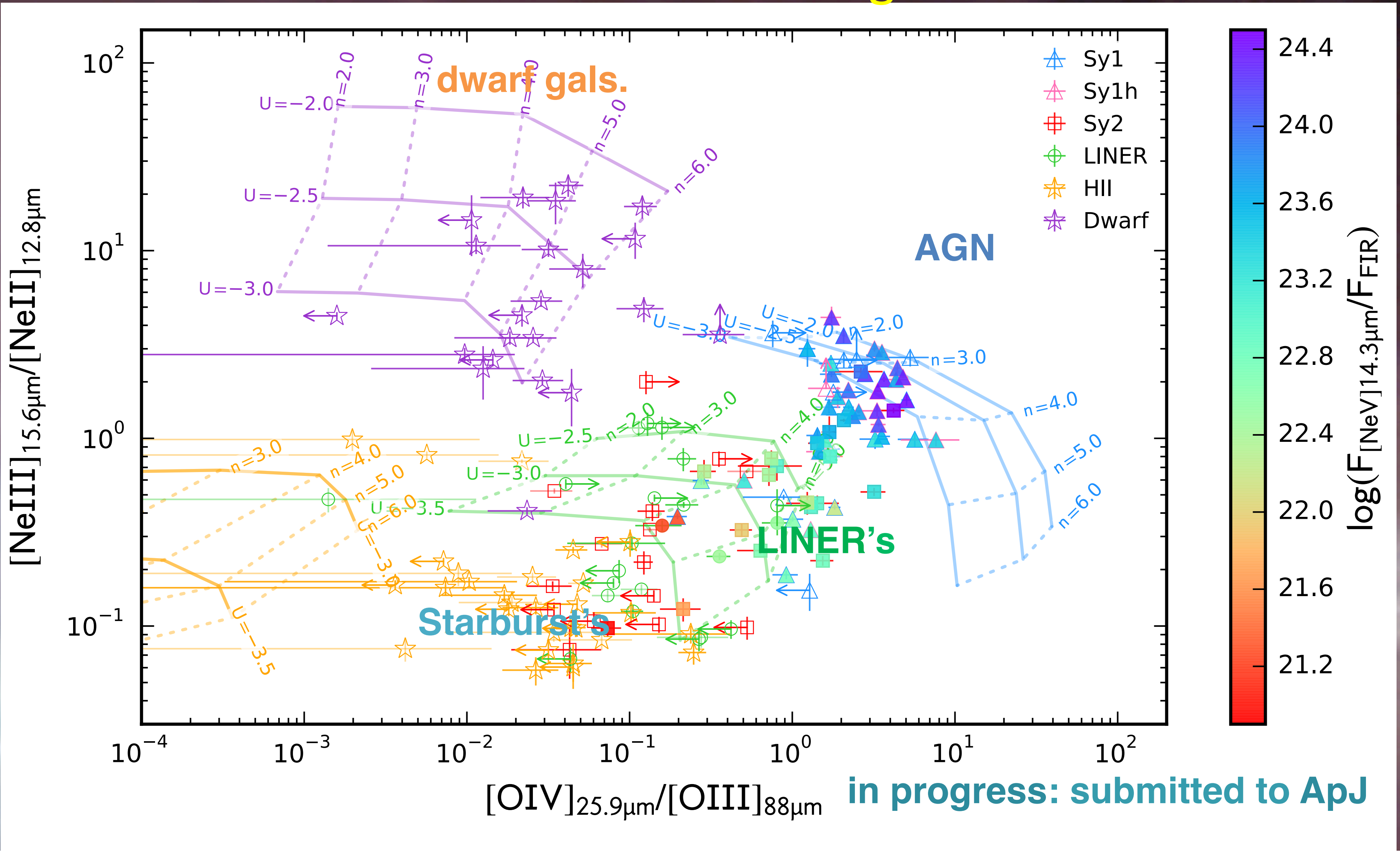
The new IR BTP diagram



in progress: submitted to ApJ

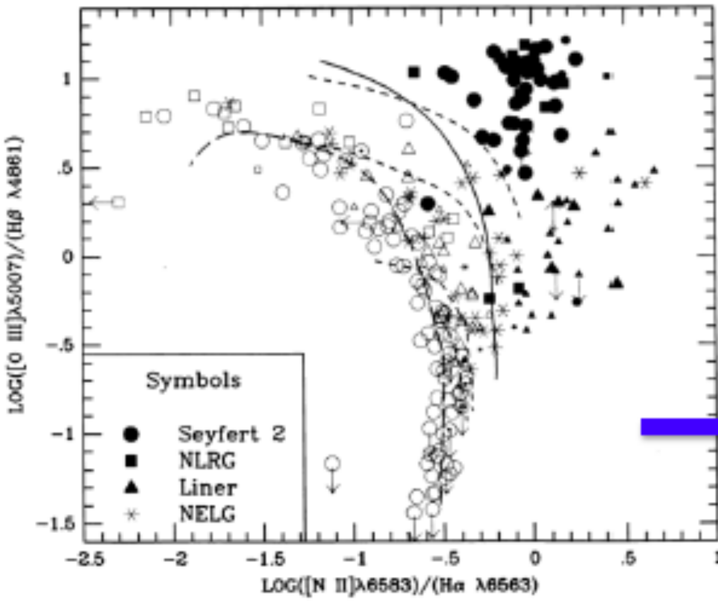
IR line ratios separate the different galaxies because of the differences in the primary ionising spectra, due to AGNs or stars or possibly to shocks in the ISM (J.A. Fernandez-Ontiveros, LS, et al subm. 2016)

What is going to happen now?

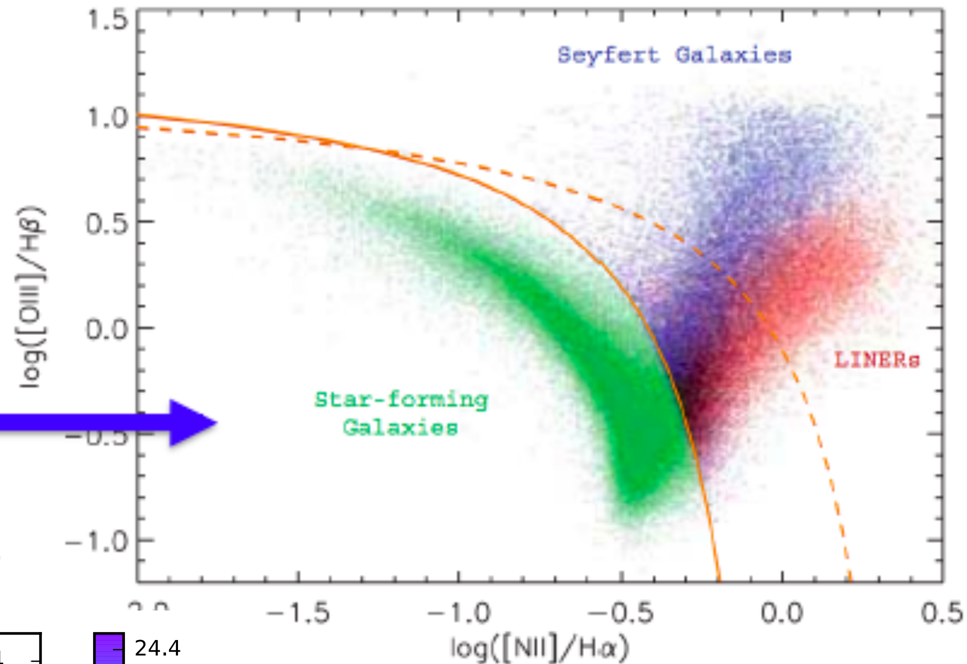
- We know the tools ($\lambda_{REST\text{-}FRAME}$~10-100μm), but we need a new space telescope to do the job.
- JWST will not cover the z=1-4 redshift region in the mid-IR tracers due to its spectral range limited to λ<28μm
- ALMA (λ>350μm) can observe only higher redshift (z>4) sources
- SPICA only with its cooled telescope will be able to cover the range (λ=10-230μm)

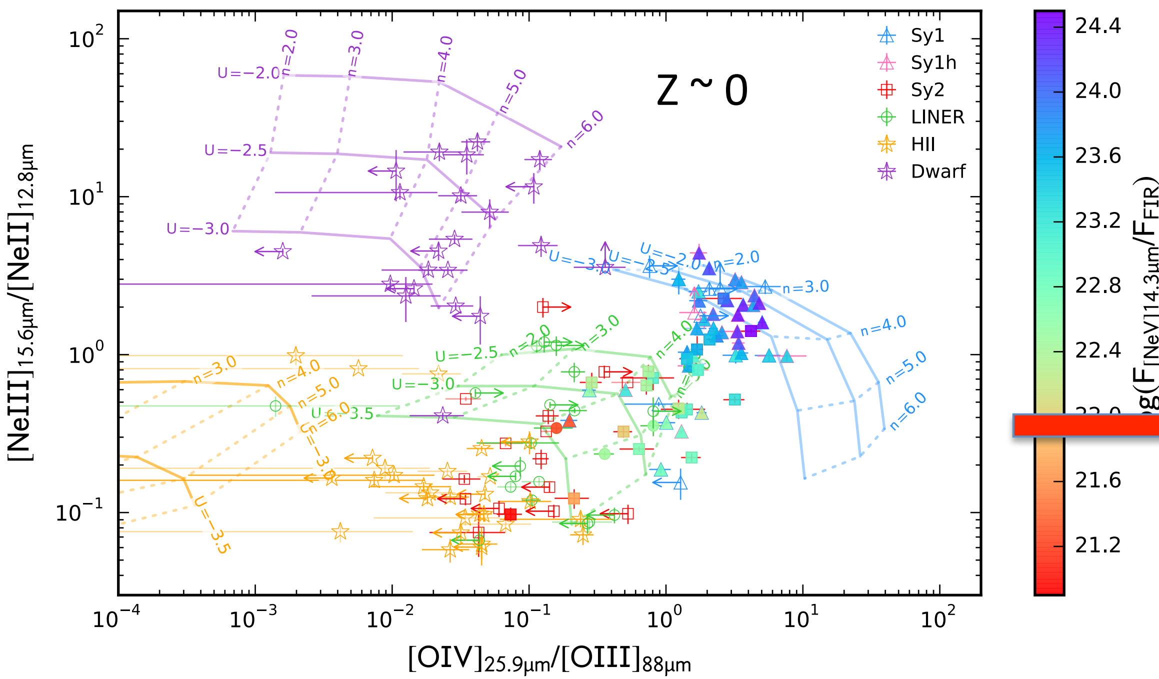
OPTICAL SPECTROSCOPY

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



Groves+ **2006** (>10⁵ galaxies)





Z ~ 1-3

SPICA ... ~ 2028

The main and crucial objectives that only SPICA will be able to reach are:

- Determine the major physical processes that regulate the star formation in galaxies through a complete characterization of their mid-/far-infrared spectral properties

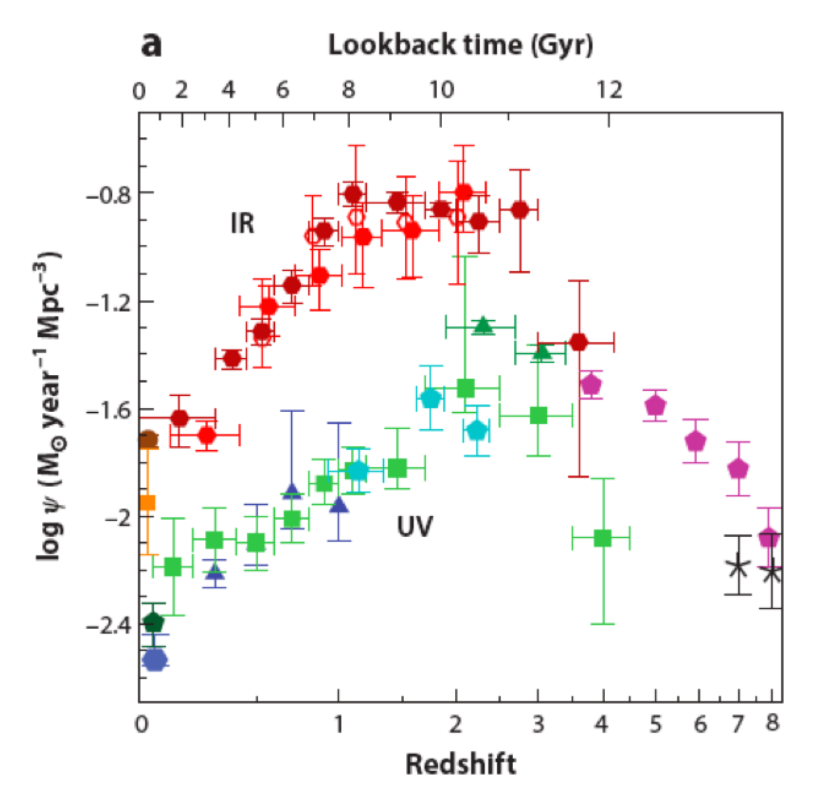
- Trace the co-evolution of star formation and black hole accretion in thousands of galaxies at z~1-3 by measuring their contribution to the total infrared emission

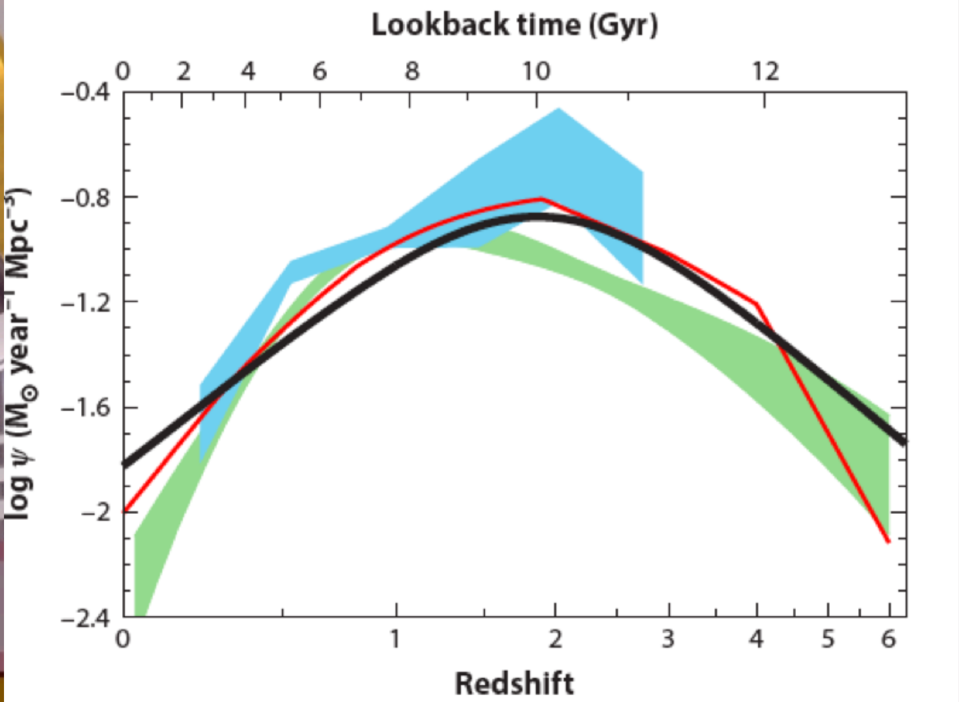
- Study the mutual feedback between star formation and black hole growth by detecting outflows and inflows of atomic and molecular gas in hundreds of galaxies

- Investigate the production of heavy elements and dust in the interstellar medium and their evolution as a function of cosmic history

1. Physical conditions of Star Formation and Black Hole Accretion

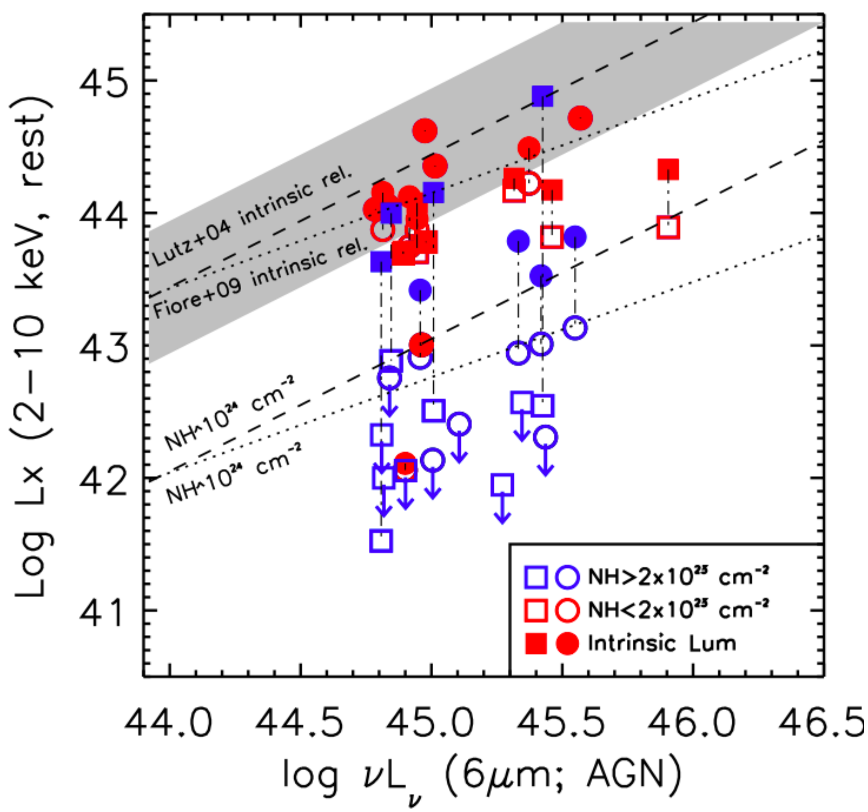
- *What processes start, regulate, and eventually stop star formation in the Universe ?*
- *What are the relative contributions of nuclear fusion (stars) and gravitational potential energy (accreting black holes) to photon production after Re-ionization ?*
- *What are the physical processes in the most obscured regions in the Universe though cosmic time?*

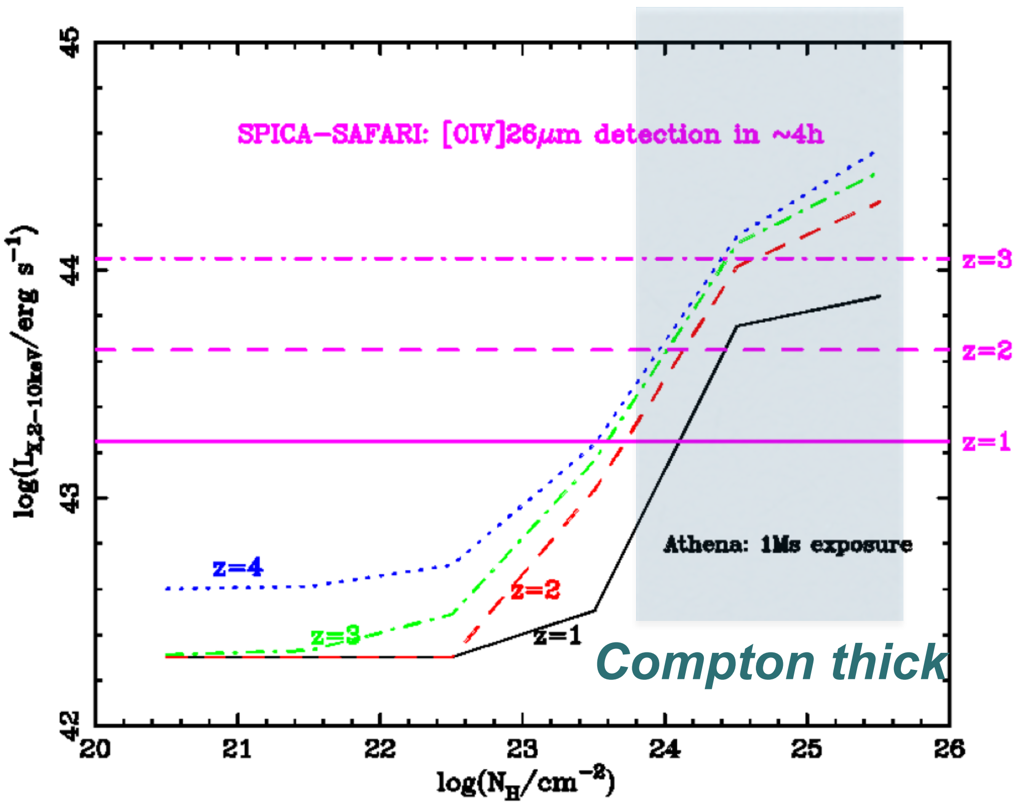




Left: SFR densities in the FUV, uncorrected for dust extinction (blue, green, magenta) in the far-IR (red). Right: Massive BH accretion history from X-ray (red line and green shading) and IR data (blue shading), scaled up by a factor of 3300, compared to SF history (black line). (Madau & Dickinson, 2014).

SPICA will be complementary to Athena to detect and characterise Compton thick AGNs: SYNERGIES WITH ATHENA



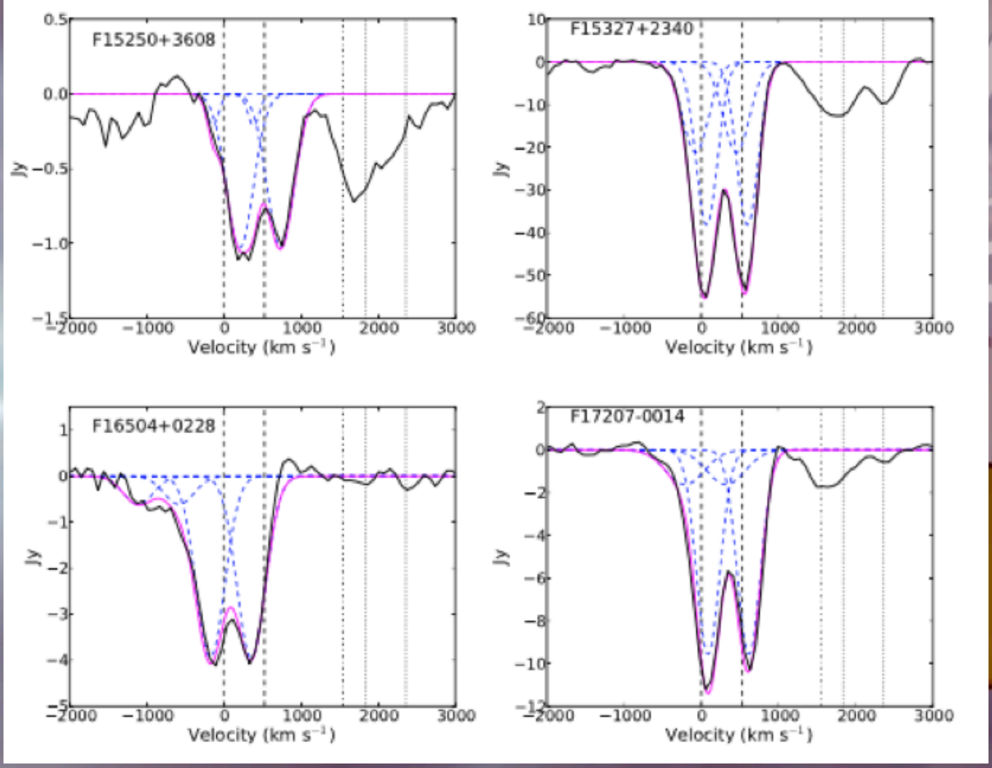


Left: Incompleteness of X-ray surveys. 2–10 keV rest-frame luminosity vs. AGN 6μm luminosity. Open symbols show the observed X-ray luminosity, while filled symbols the intrinsic luminosity. More than 25% of the AGN are undetected at X-rays while visible in the mid-IR via hot dust emission. (Del Moro et al 2015)

Right: Comparison between SPICA-SAFARI and ATHENA. Luminosity limits, at z=1,2,3, of ATHENA for a 1Ms (~280 hours) survey, and of SPICA/SAFARI for a pointed observation of ~4 hours for the [OIV]26μm AGN line. The conversion between bolometric and X-ray luminosity has been taken from Marconi et al. (2004).

2. AGN and Starburst feedback and feeding

- *Can AGN-driven molecular outflows be responsible for the decline of SF in the last 7 Gyr?*
- *Are these outflows responsible for creating the majority of red-and-dead galaxies?*
- *What physical processes – mechanical or thermal energy injection or radiation pressure on dust – drive molecular outflows?*
- *How much of the wind escapes the galaxy and seeds the IGM with metal-enriched gas?*

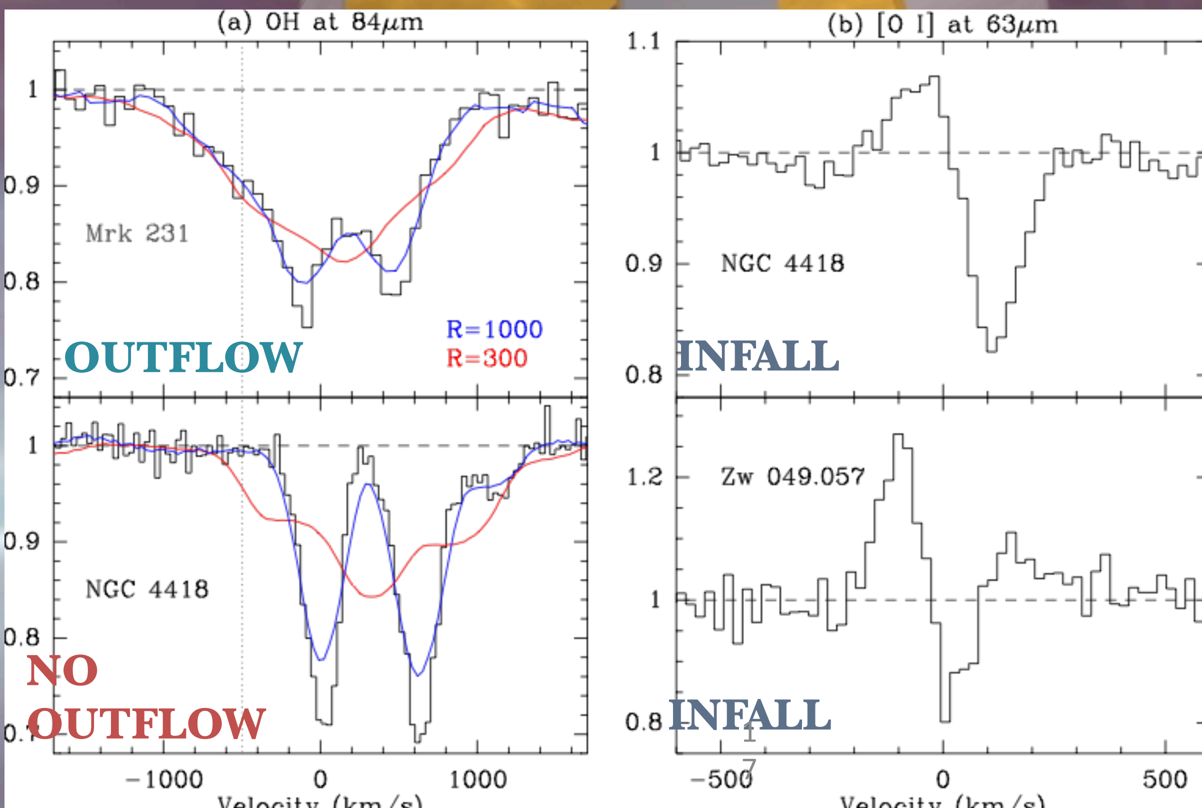


Herschel PACS profiles of the OH 119μm line in a sample of 43 nearby (z < 0.3) galaxy mergers, mostly ultraluminous infrared galaxies (ULIRGs) and QSOs. (Veilleux et al 2013, ApJ)

Measuring outflows at higher z (z~1.2-1.5) — Measuring infall

(a: *Left)* OH84μm doublet observed with *Herschel*/PACS in Mrk231, with a strong outflow, and in NGC4418, without outflow (GA2014, 2012). Herschel/PACS spectral resolution at this wavelength was R~2300. Blue and red lines show the line profiles smoothed to a resolution of R=1000 and 300, respectively. The "new" high resolution baseline of SAFARI (M.-P.I) will have R>~2000, allowing to obtain the same results in terms of spectral resolution that Herschel/PACS obtained in the local Universe, but at z~<1.5.

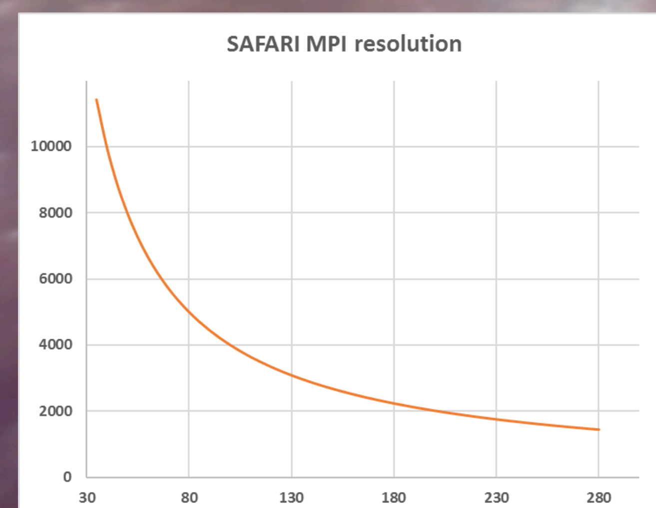
(b: *Right)* [OI]63μm inverse P-Cygni profiles observed by *Herschel*/PACS in NGC 4418 (GA12) and Zw049.051 (Falstad et al. 2015), with a resolution of R~3500 illustrating gas inflow into the circum-nuclear regions.



The new baseline configuration of the SAFARI high resolution mode, with the Martin-Pupplet interferometer reaches 5 sigma 1 hour line sensitivities of

Limiting Flux = 0.8 – 1.0 x 10^-19 W/m^2

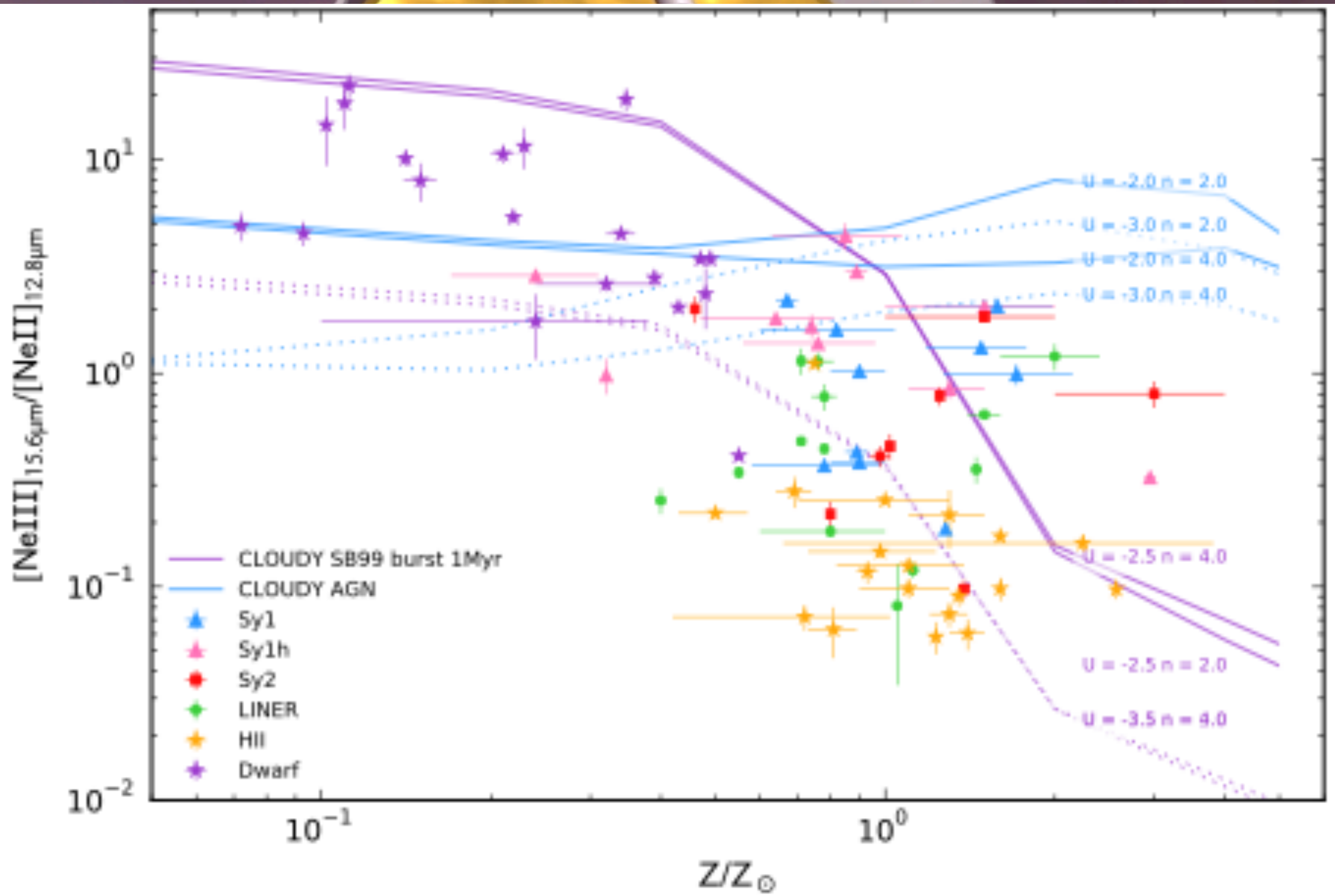
With the spectral resolution shown here



3. Metallicity evolution

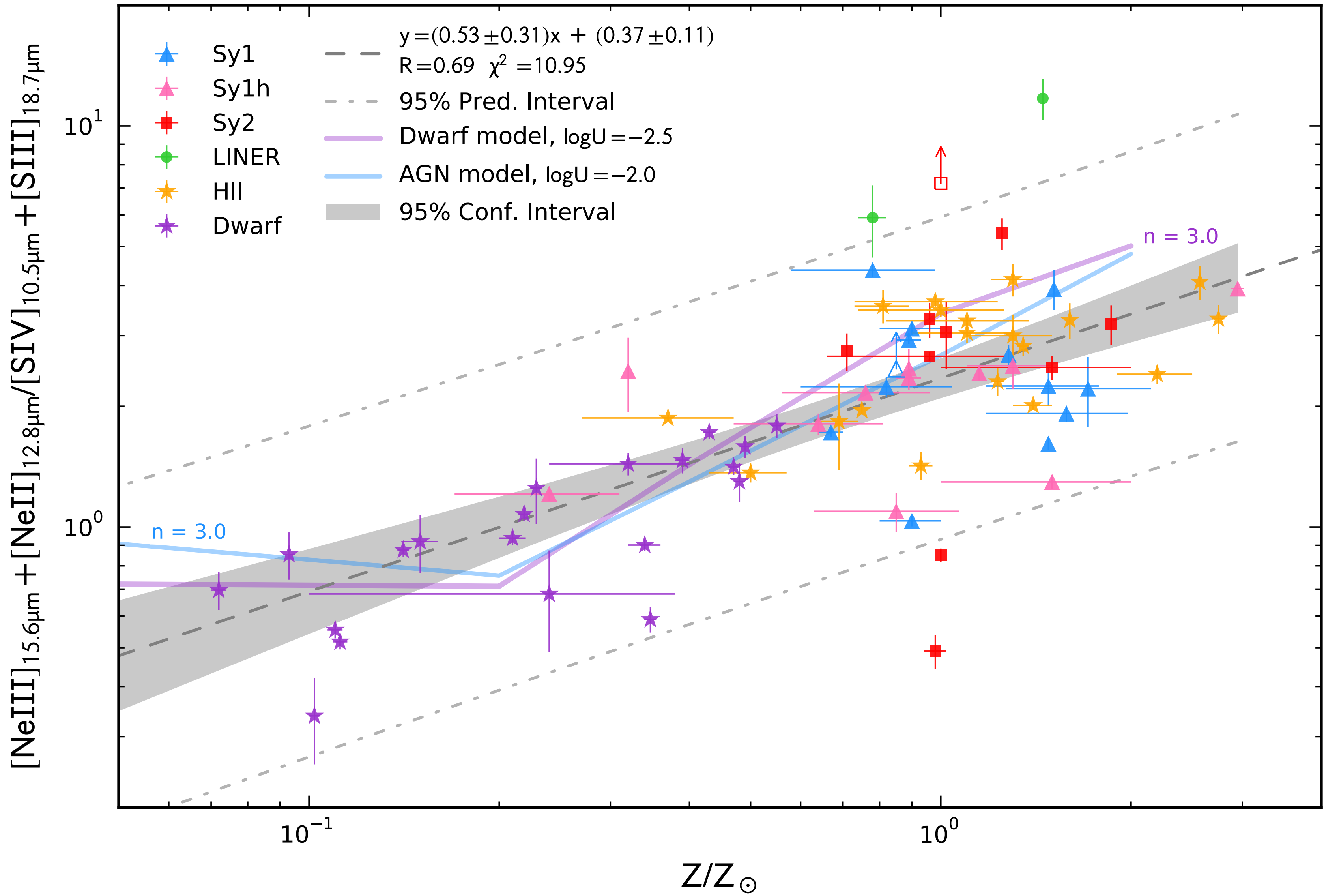
- How does the gas inside (and outside of –ATHENA) galaxies get enriched with metals over time?

- What is the origin (where and when) of the heavy elements and the fundamental metallicity relation in obscured regions of galaxies?



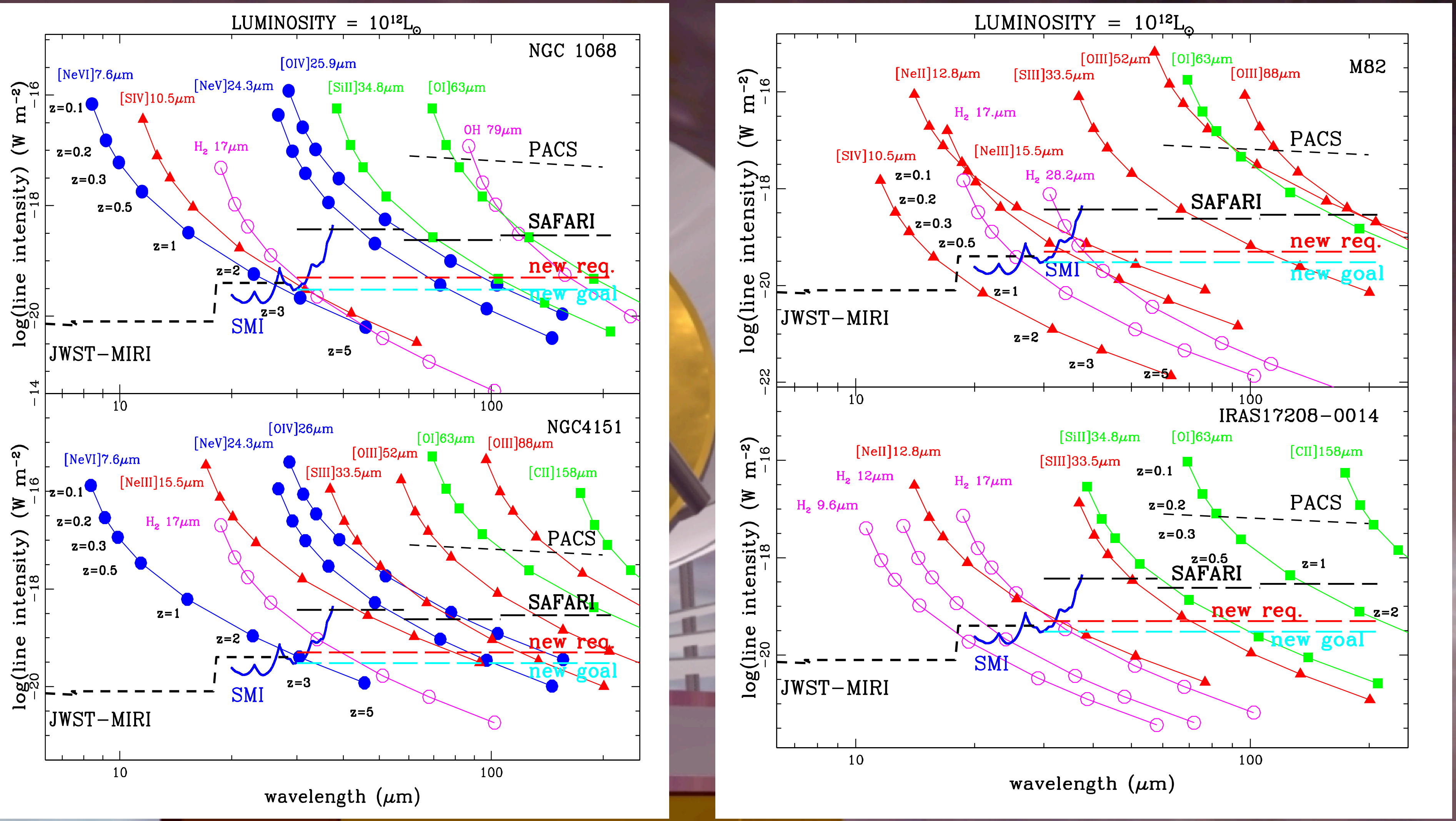
Optical metallicity vs. [NeIII]15.6 μm/[NeII]12.8 μm line ratio for objects in the samples of AGN, starburst, and dwarf galaxies. (J.A. Fernandez-Ontiveros, LS et al. 2016, subm.)

AGN - Fernandez-Ontiveros, LS , subm.



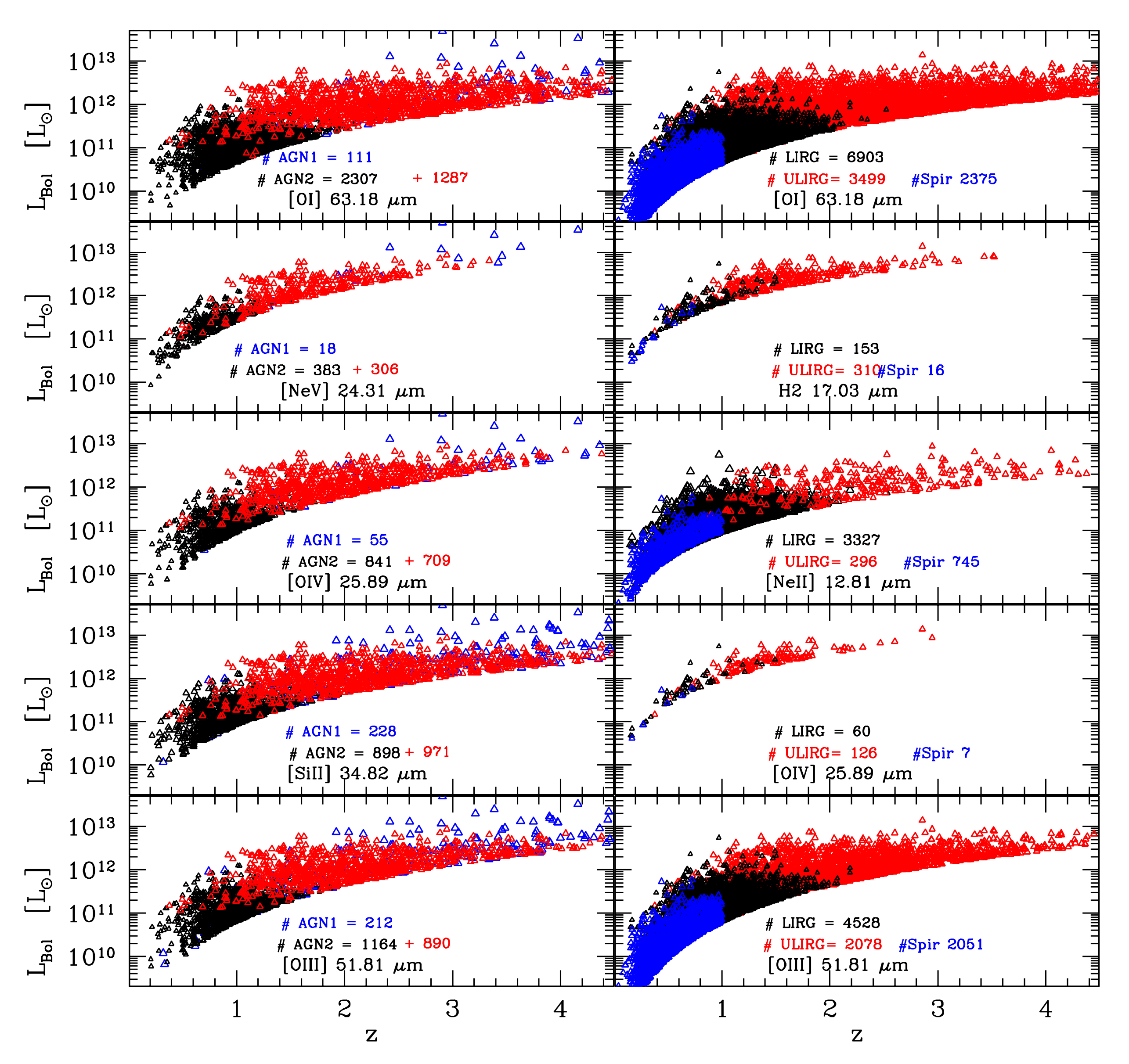
([Ne iii]15.6+[Ne ii]12.8)/([S iv]10.5+[S iii]18.7) line ratio vs optical metallicities. Note that the AGN and dwarf galaxy models shown here include the effect of Sulphur depletion (J.A. Fernandez-Ontiveros, LS, et al subm. 2016)

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



Predictions of lines observable with SAFARI, SMI and with an hypothetic spectrometer with a required and goal 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 an intrinsic luminosity of 10^12 L☉. The expected JWST-MIRI sensitivities are also shown. (Spinoglio et al. 2012, 2014). Left: AGN templates. Right: Starburst templates.

What will be needed ?

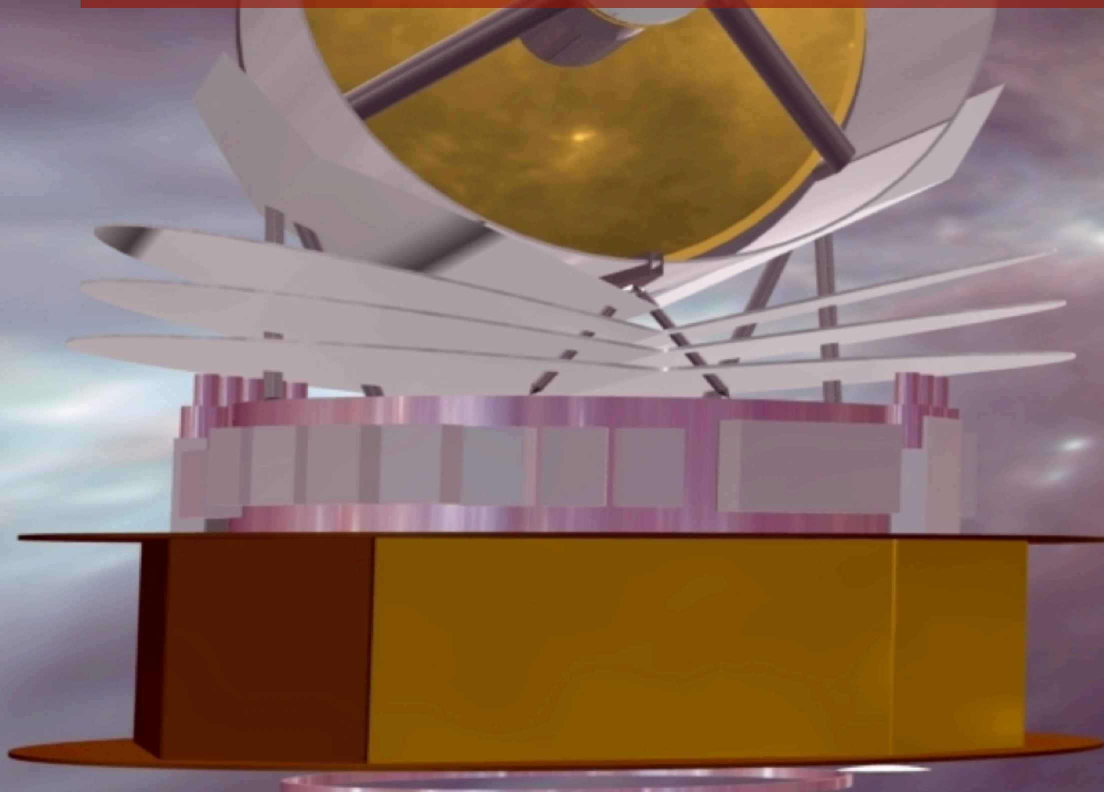


AGN (left panels) and starburst galaxies (right panels) in the bolometric luminosity-redshift plane in a field of 0.5 square deg. detectable with an instrument reaching in 1 hour line fluxes of 5x10^-20 W/m^2 (at 5σ).

Left panels: AGNs are shown color coded according to the following classes: AGN1 (blue), AGN2 in LIRG (black) and in ULIRG (red).

Right panels color coded as: "Spirals" (blue), LIRG (black), ULIRG (red).

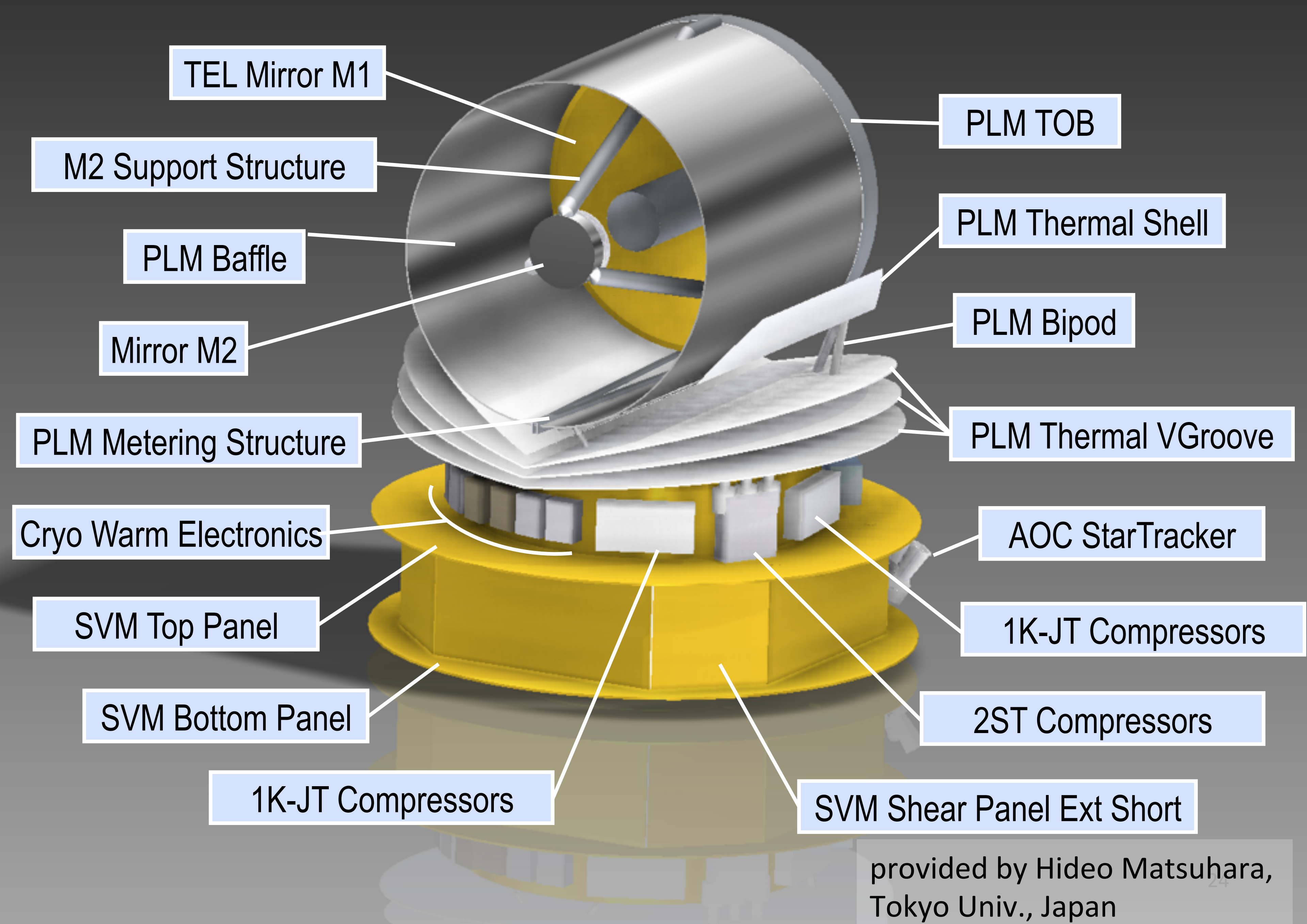
New telescope and new instruments → SPICA is completely redesigned to be able to win the M5 competition in ESA Cosmic Vision



The baseline mission concept

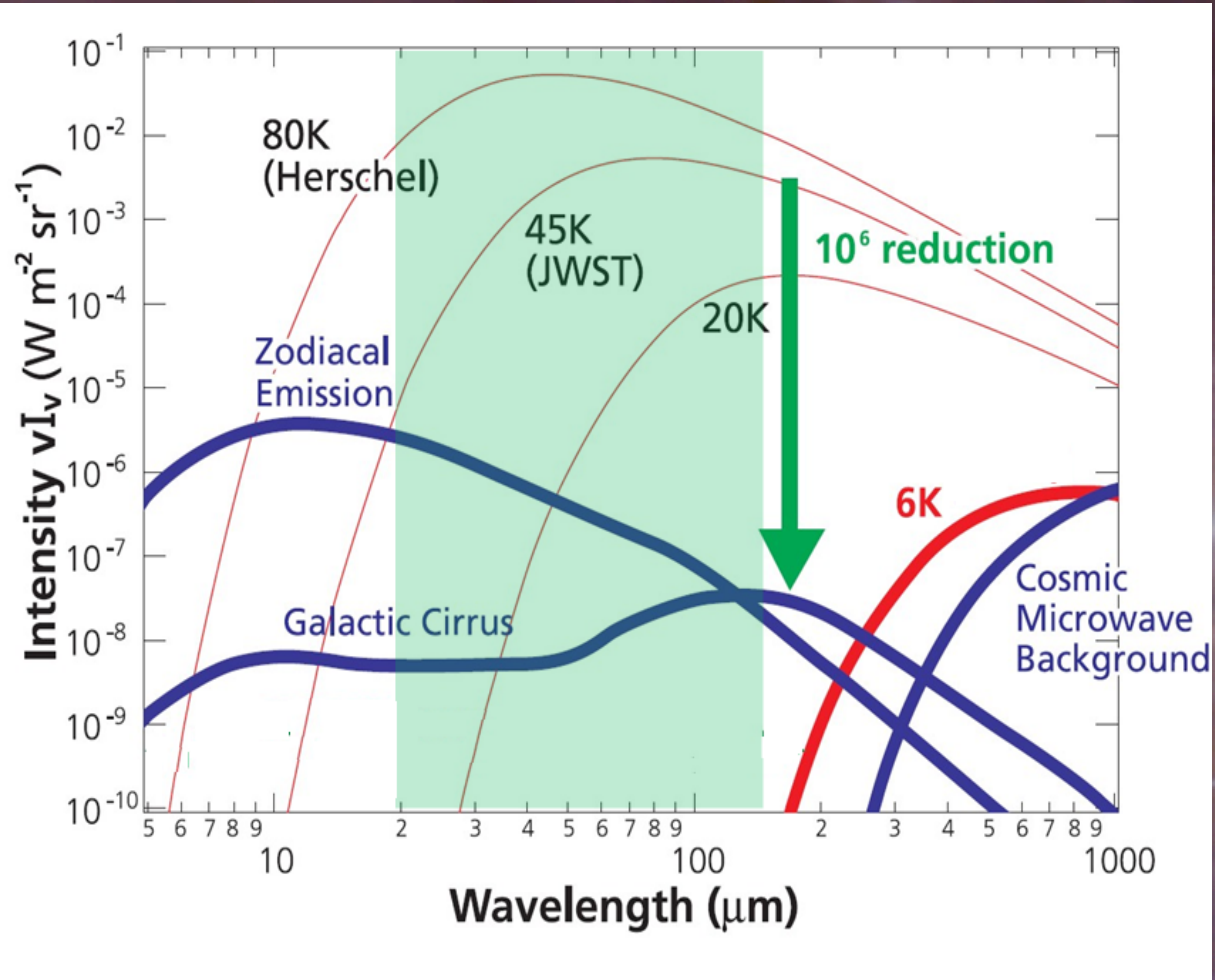
Joint ESA-JAXA mission

- ‘PLANCK configuration’
  - Size - Φ4.5 m x 5.3 m
  - Mass - 3450 kg (wet, with margin)
  - V-grooves
- 2.5 meter telescope, T< 8K
  - Warm launch
- 12 - 230 µm spectroscopy
  - MIR imaging spectroscopy – SMI
  - FIR spectroscopy – SAFARI
- ‘standard’ Herschel/Planck SVM
- Japanese H3 launcher, L2 halo orbit
- 5 year goal lifetime



provided by Hideo Matsuhara, Tokyo Univ., Japan

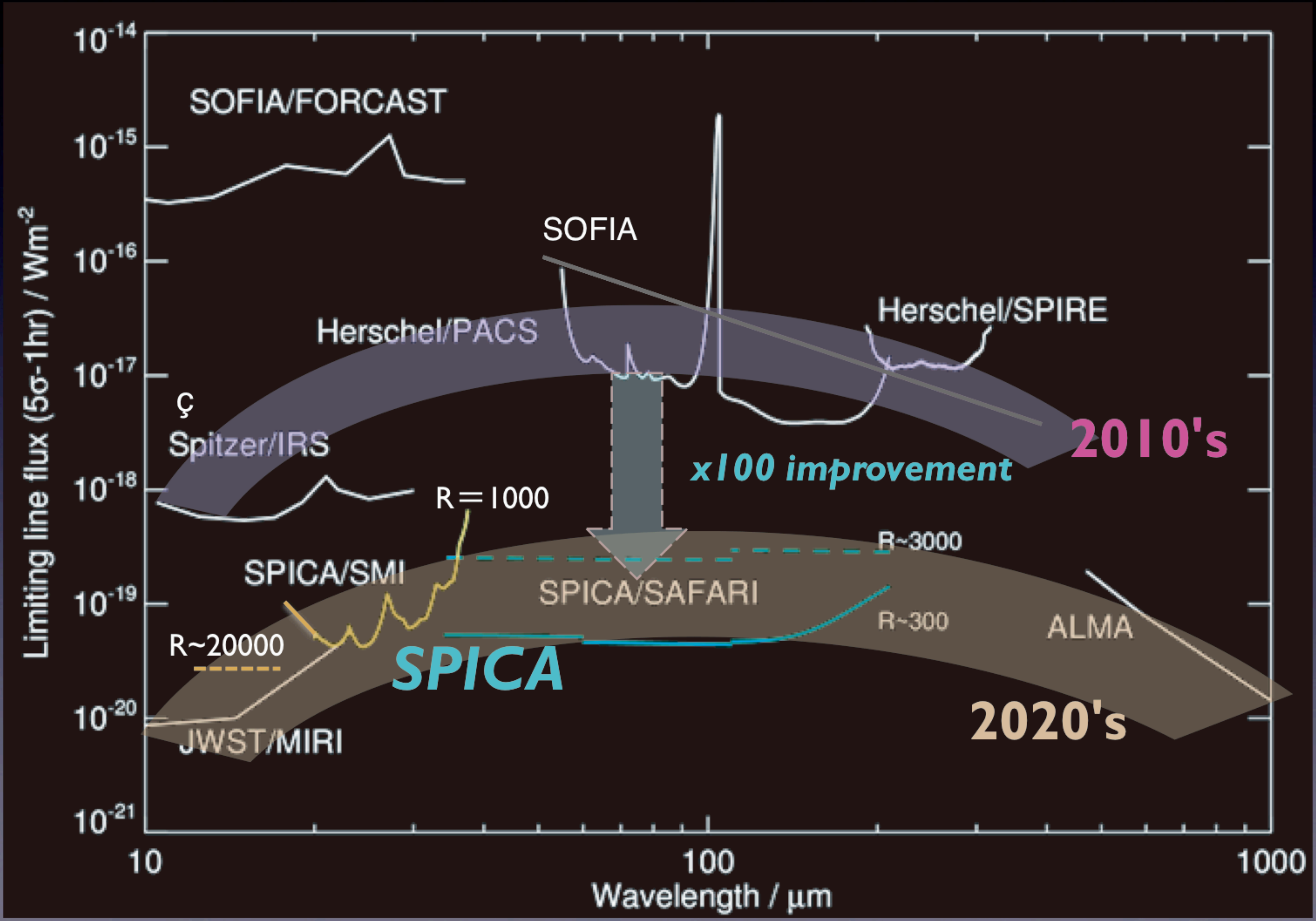
Thermal Backgrounds



Expected sensitivity:
35-210μm spectroscopy:
~5 x 10^-20 W/m^2

i.e. 100 times better than Herschel

SPICA sensitivity and other facilities



SPICA/SAFARI Fact Sheet

SAFARI Overview

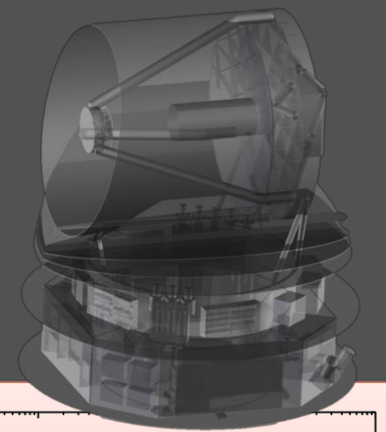
- Four band ***grating spectrometer***
- Continuous spectroscopic capability from 34-230 µm

Parameter		Waveband			
		SW	MW	LW	LLW
Band centre / µm		45	72	115	185
Wavelength range / µm		34-56	54-89	87-143	140-230
Band centre beam FWHM		4.5″	7.2″	12″	19″
Point source spectroscopy (5σ-1hr)					
R~300	**Limiting flux** / x10^{-20} Wm^{-2}	7.2	6.6	6.6	8.2
R~300	**Limiting flux density** / mJy	0.31	0.45	0.72	1.44
High R	**Limiting flux** / x10^{-20} Wm^{-2}	13	13	13	15
High R	**Limiting flux density** / mJy	18	17	17	19
Mapping spectroscopy* (5σ-1hr)					
R~300	**Limiting flux** / x10^{-20} Wm^{-2}	84	49	30	23
R~300	**Limiting flux density** / mJy	3.6	3.3	3.3	4.1
High R	**Limiting flux** / x10^{-20} Wm^{-2}	189	113	73	51
High R	**Limiting flux density** / mJy	253	151	97	67
Photometric mapping* (5σ-1hr)					
Limiting flux density / µJy		209	192	194	239
Confusion limit (5σ)		15 µJy	200 µJy	2 mJy	10 mJy

Sensitivities based on detector NEP 2×10^{-20} W/√Hz
* Mapping performance is for a reference area of 1 arcmin^2

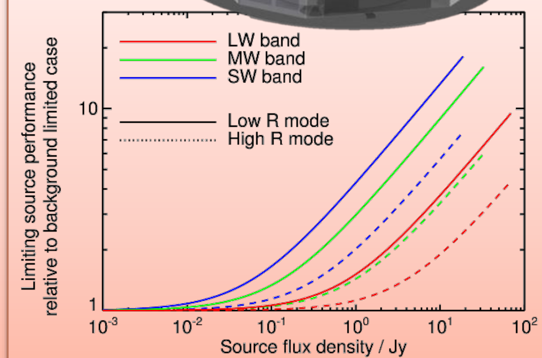
SPICA Mission

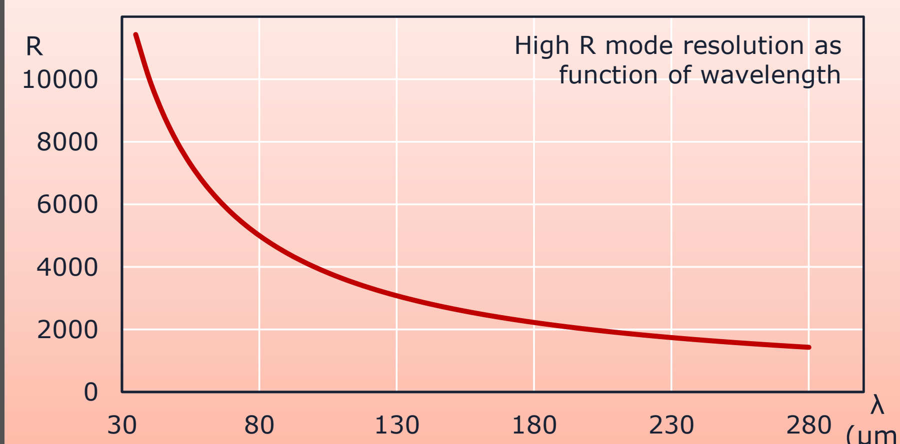
- ESA/JAXA collaboration
- Telescope effective area 4.6 m^2
- Primary mirror temperature 8K
- Goal mission lifetime – 5 years



System performance v.s. target flux density, relative to the background limited case

- The sensitivity decrease is due to the increased photon noise from the target source
- Data given up to the instrument saturation limits for each band (31, 51 and 87 Jy for the SW, MW and LW bands respectively.

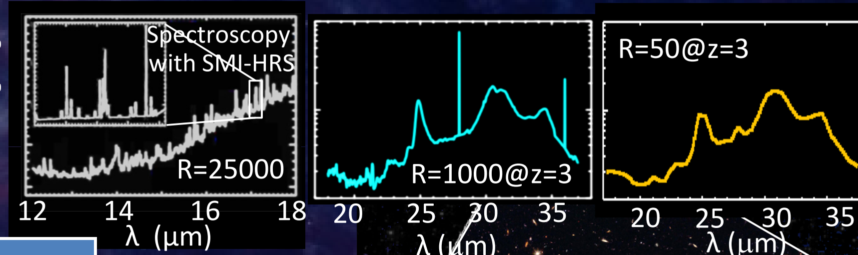


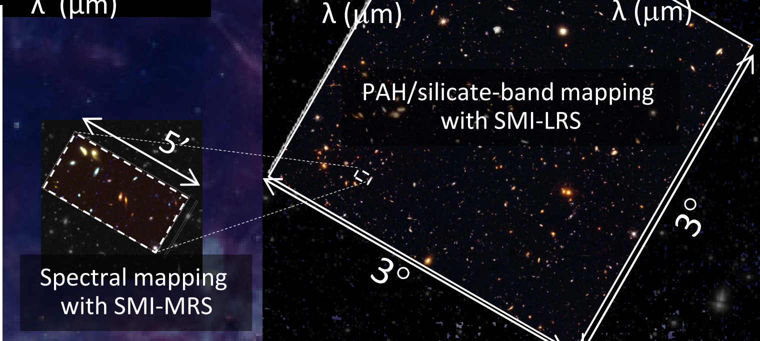


SAFARI

SPICA / SMI Fact Sheet

SPICA Mid-infrared Instrument (SMI) covers the wavelength range of 12–36 μm with three spectroscopic channels: LRS, MRS, and HRS.

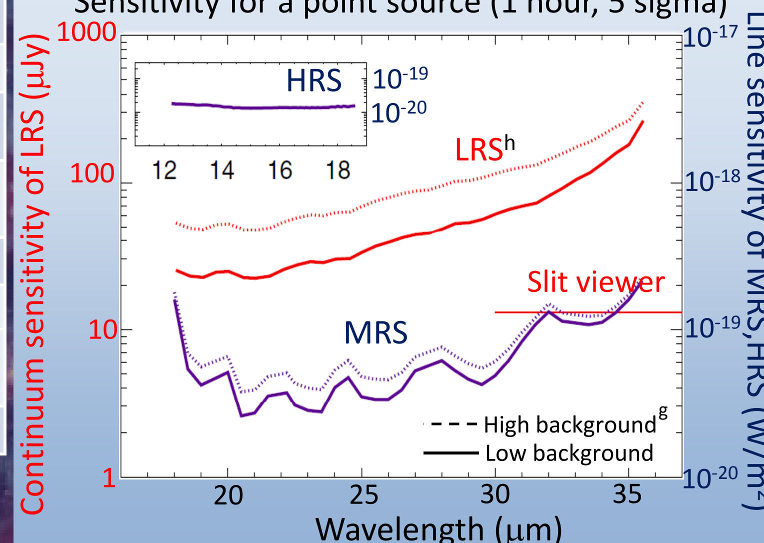




Parameter		Function: LRS – Multi slit spec.	Function: LRS – Slit viewer	Function: MRS	Function: HRS
Wavelength range		17 – 36 μm	34 μm	18 – 36 μm	12 – 18 μm [a]
Spectral resolution		50 – 120 [b] (point source) 20 – 110 (diffuse)	5	1300 – 2300 [b] (point source) 1100 – 1400 (diffuse)	28000 [c]
Field of View		600"x 3."7 x 4 slits	600" x 600"	60" x 3."7 (slit)	4"x1."7 (slit)
FWHM		2."0 (20 μm) – 3."6 (36 μm), 2."0 (12 – 20 μm)			
Pixel scale		0."7x 0."7	0."7 x 0."7	0."7	0."5
Detector		Si:Sb 1K x 1K	Si:Sb 1K x 1K	Si:Sb 1K x 1K	Si:As 1K x 1K
Point source	Cont. sensitivity (1 hr, 5 sigma)	20 – 200 μJy	13 μJy	300 – 3000 μJy	2 – 3 mJy
Point source	Line sensitivity [d] (1 hr, 5 sigma)	(8 – 20) x 10^{-20} W/m^2	-	(3 – 20) x 10^{-20} W/m^2	(1.5 – 2) x 10^{-20} W/m^2
Point source	Survey speed [e]	~16 arcmin^2/hr	~5900 arcmin^2/hr	~1.5 arcmin^2/hr	-
Diffuse	Sensitivity [f] (1 hr, 5 sigma)	Continuum		Line	
Diffuse		0.02– 0.1 MJy/sr	0.05 MJy/sr	(0.7 – 4) x 10^{-10} W/m^2/sr	(1.5 – 2) x 10^{-10} W/m^2/sr
Saturation limit		~20 Jy	~1 Jy	~1000 Jy	~20000 Jy

a: continuous coverage up to 17.3 μm + partial coverage for H_2O 17.77 and 18.66 μm
b: λ/δλ = 120 (LRS) and 1300 (MRS) at λ = 36 μm.
c: designed for λ20 μm diffraction limited PSF.
d: sensitivity for an unresolved line.
e: survey speed for the 5 sigma detection of a point source with the continuum flux of 100 μJy for LRS at λ = 30 μm (slit viewer at 34 μm) and the line flux of 3×10^{-19} W/m^2 for MRS at λ = 28 μm, both in the low background case (see the right-hand figure).

Sensitivity for a point source (1 hour, 5 sigma)



f: sensitivity for a diffuse source in a 4" x 4" (LRS & MRS) or 2" x 2" area (HRS)
g: background levels are assumed to be 80 MJy/sr (High) and 15 MJy/sr (Low) at 25 μm.
h: continuum sensitivity rescaled with R=50

SMI Factsheet v10 – 4 Jan 2016

Cosmological survey with SMI-LRS

Spitzer / IRS-LL

R = 60 – 120
slit size: 168”x11”

3.3’x3.3’

JWST / MIRI-MRS

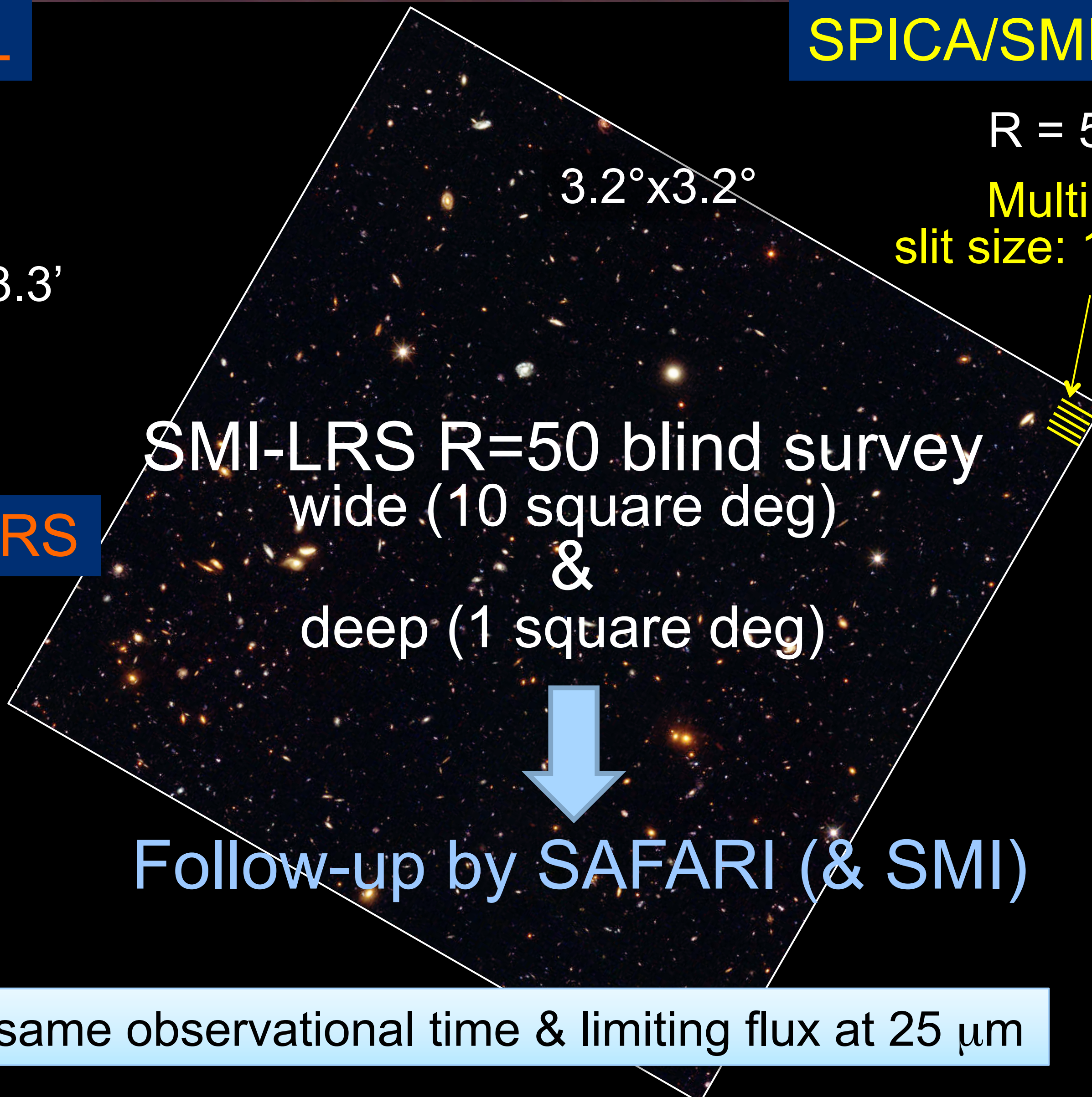
R = 2000
slit size: 7.7”x7.7”

2’x2’

SPICA/SMI-LRS

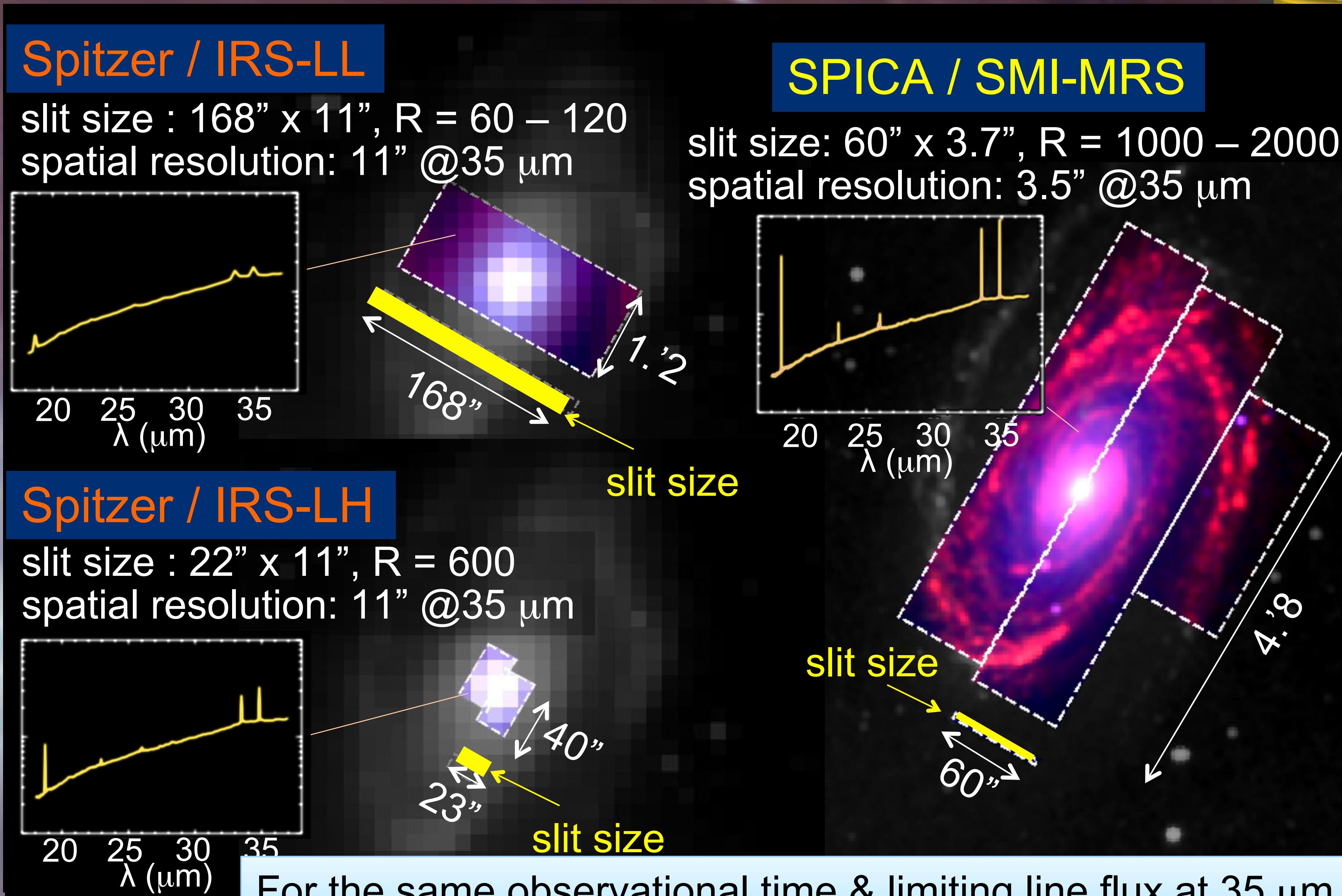
R = 50

Multi slit
slit size: 10’x3.7”



For the same observational time & limiting flux at 25 μm

Spectral mapping of galaxies with SMI-MRS



For the same observational time & limiting line flux at 35 μm

Conclusions

- After 30 years of efforts… we are close to having reliable IR measures of STAR FORMATION RATE and AGN ACCRETION POWER, through IR/FIR SPECTROSCOPIC SURVEYS, unaffected by dust, allowing us to study dust-obscured evolution of galaxies in terms of stellar fusion and gravity powers
- Accurately measuring star formation and BH accretion as a function of cosmic time is the first step towards understanding galaxy evolution over the history of the Universe
- We learned how to measure these in local galaxies through mid/far-IR spectroscopy
- FIR spectroscopic surveys with SPICA will be the way to "physically" measure galaxy evolution
- Given the expected sensitivity of the grating spectrometer onboard of SPICA ~5 x 10^-20 (5σ,1 hr.) thousands of sources will be detected in more than 4 lines through pointed observations.
- For details on counts predictions: see Spinoglio et al 2012, ApJ 745, 171; ____2014, ApJ, 791, 138.