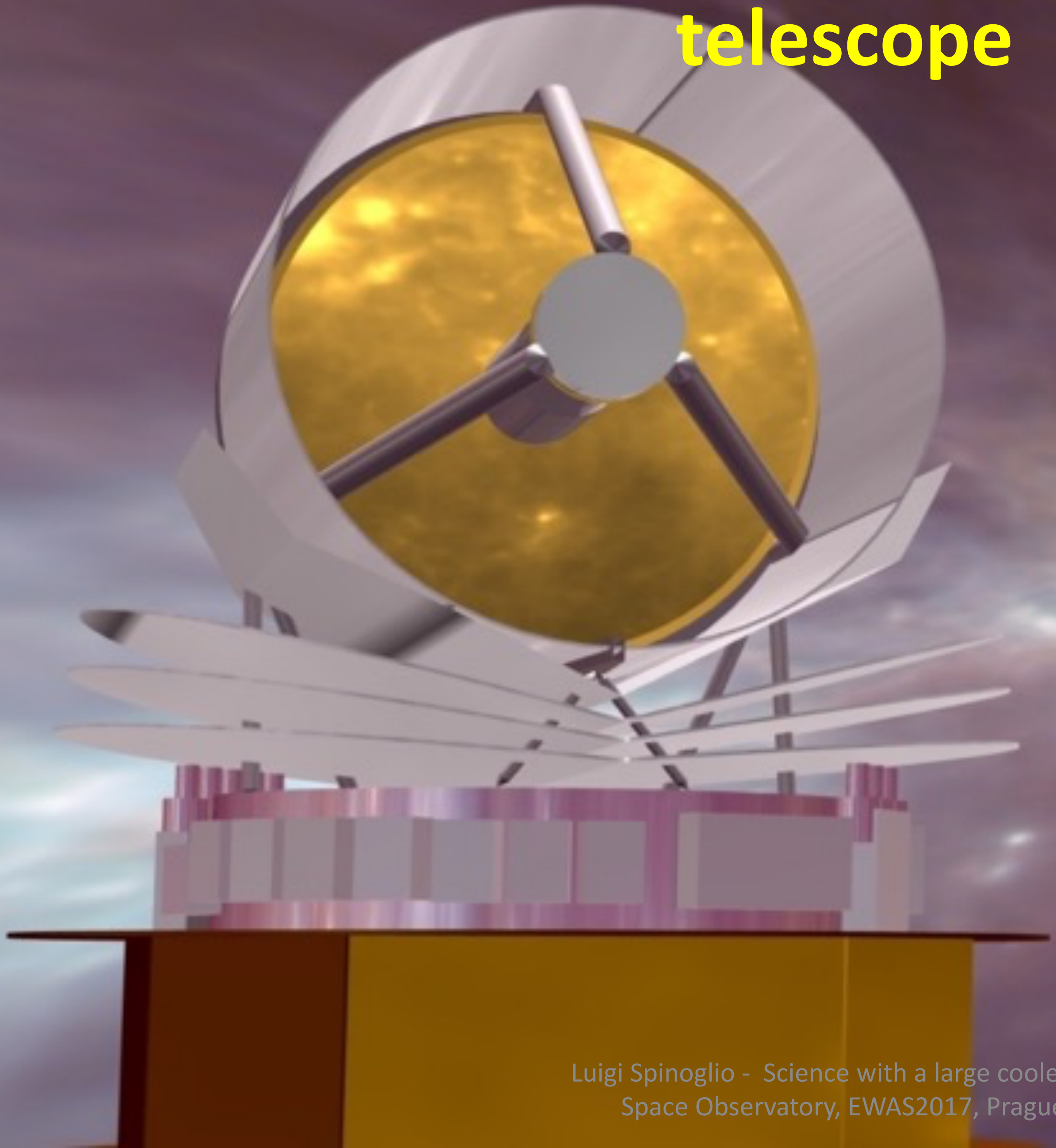
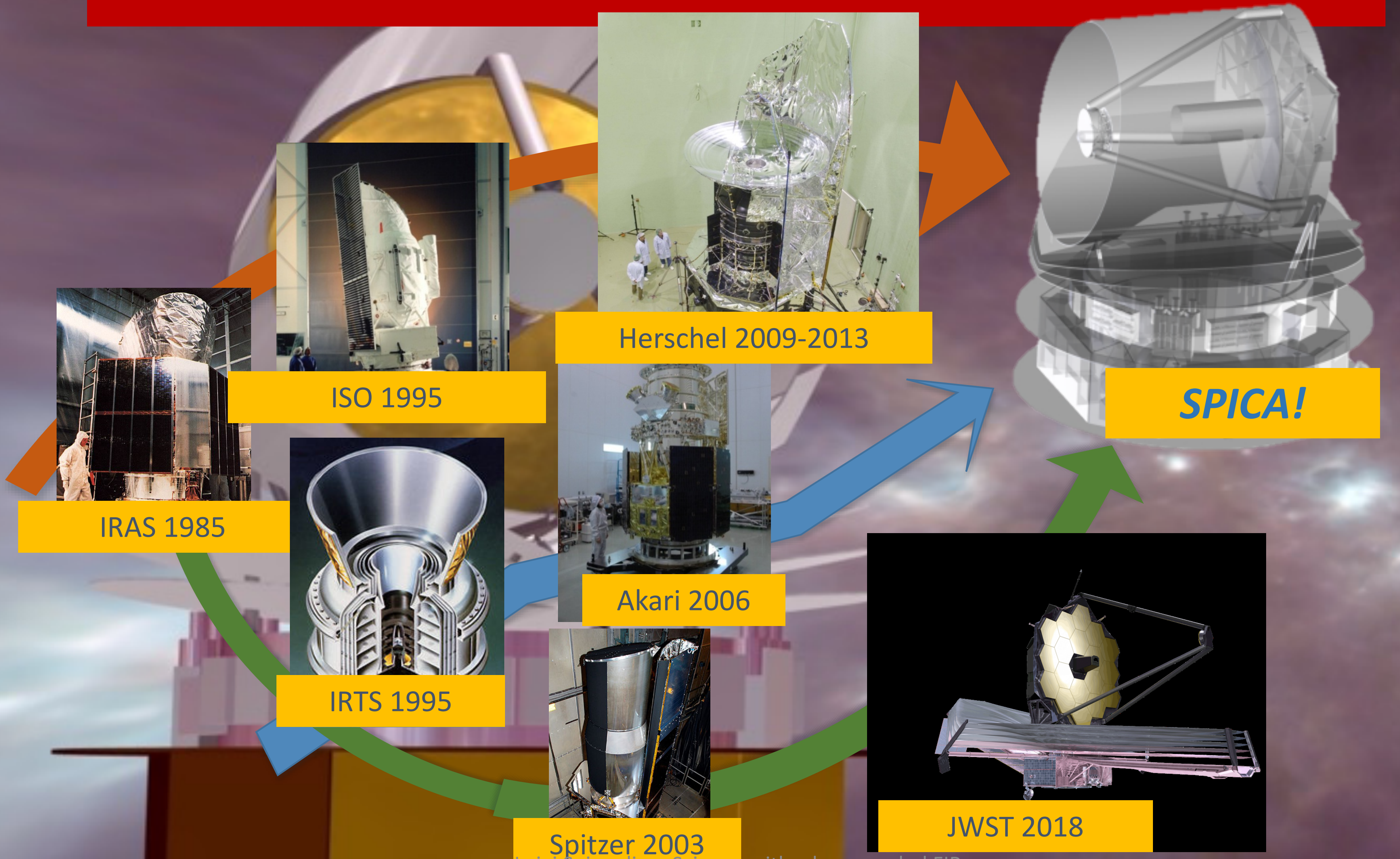
Galaxy Evolution studies with the future SPICA telescope



Luigi Spinoglio – IAPS, INAF, Roma, Italy

On behalf of the SPICA Galaxy Evolution WG and the SPICA consortium

Infrared Space Observatories



IRAS 1985

ISO 1995

IRTS 1995

Herschel 2009-2013

Akari 2006

Spitzer 2003

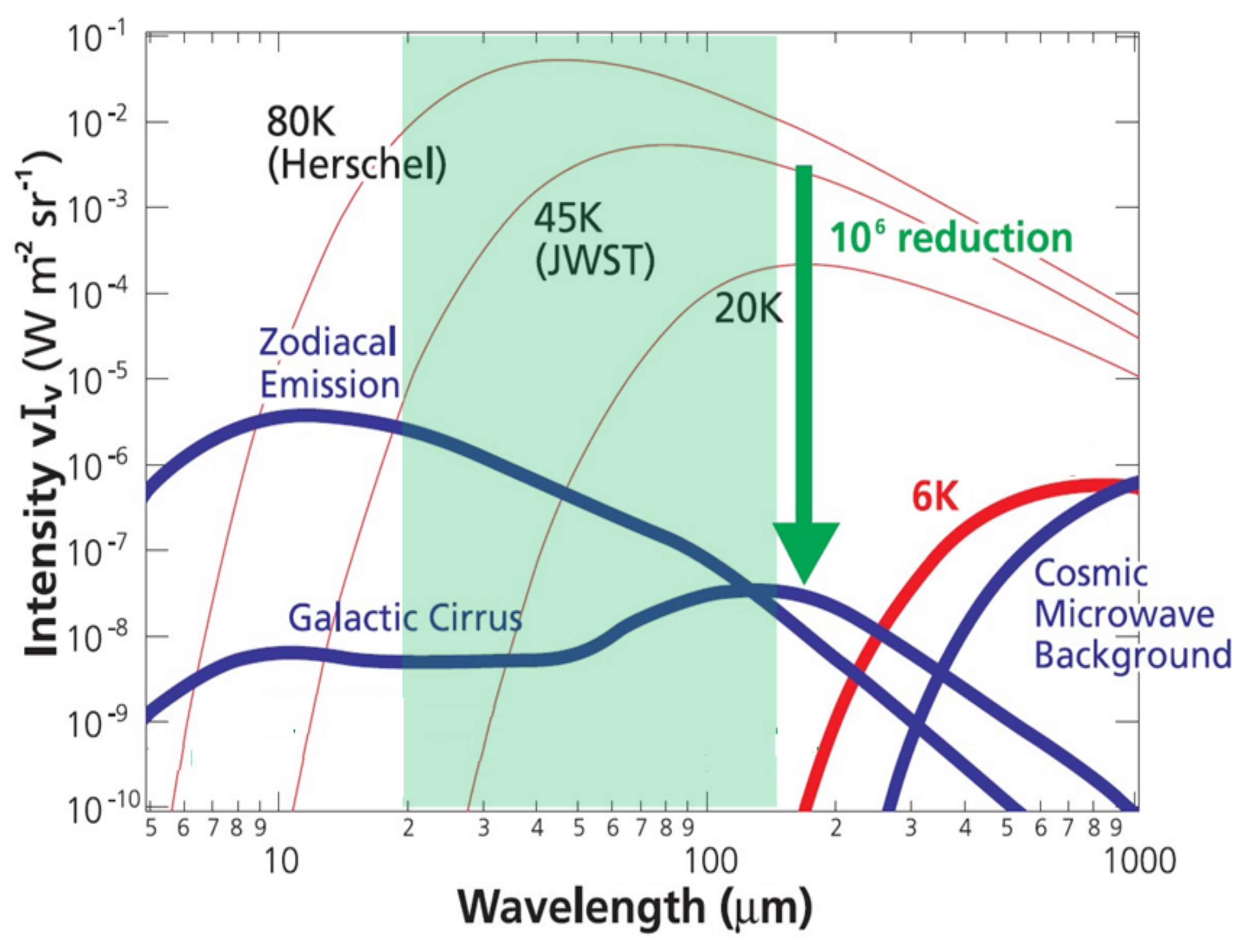
JWST 2018

SPICA!

The SPICA baseline mission concept

- Joint ESA-JAXA mission
- ‘PLANCK configuration’ from the ESA CDF study of the Next Generation-Cryogenic cooled IR Telescope (NG-CryoIRTel)
  - Size - Φ4.5 m x 5.3 m
  - Mass - 3450 kg (wet, with margin)
  - V-grooves
- 2.5 meter telescope, < 8K
  - Warm launch
- 12 - 230 μm spectroscopy
  - MIR imaging spectroscopy – SMI
  - FIR spectroscopy – SAFARI
- FIR imaging polarimetry - BiBoP
- ‘standard’ Herschel/Planck SVM
- Japanese H3 launcher, L2 halo orbit
- 5 year goal lifetime

Thermal Backgrounds



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

i.e. 100 times better than Herschel

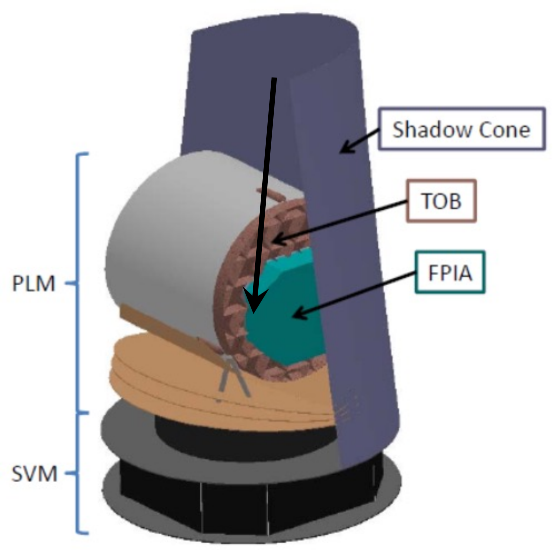
The SPICA focal plane assembly

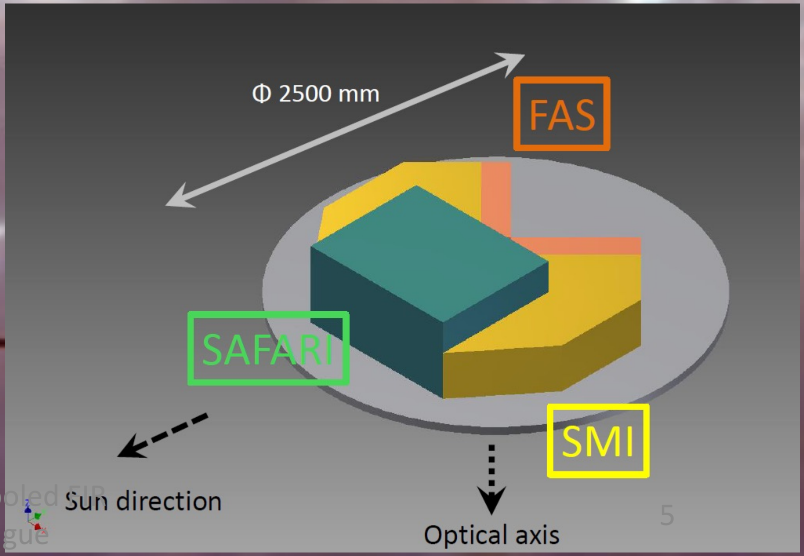
- Focus on spectroscopic capability
  - SAFARI 35–230 μm – R~300/3000
  - SMI 17–35 μm – R~100/1500
  - SMI 12–18 μm – R ~ 28000

- Imaging capability
  - SMI 17–35 μm camera
  - 100-350μm imaging polarimeter

- Final FPIA iterations ongoing

- Options for consideration
  - Extending SAFARI to 300/350 μm





Who provides what

🇪🇺 Telescope (ESA)

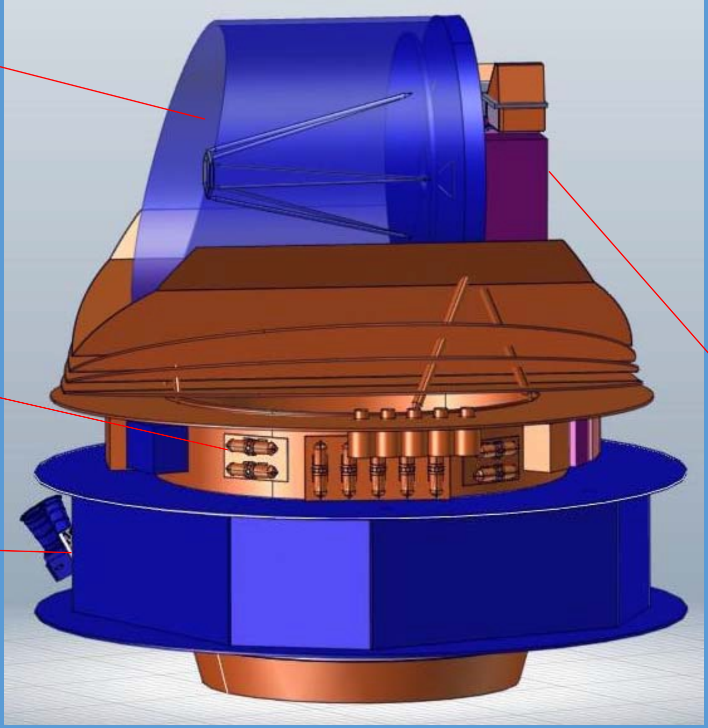
🇯🇵 Payload Module

🇯🇵 Cryocooler

🇪🇺 Bus Module

🇯🇵 Launcher

SPICA Data Center
🇯🇵 🇪🇺



🇪🇺 Focal Plane Attitude Sensor

Focal Plane Instrument Assembly

FIR Spectrometer (SAFARI)
🇪🇺 🇳🇱
Europe lead by NL
+ Canada & US

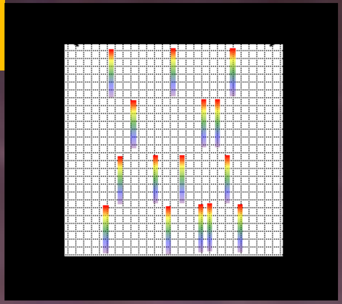
MIR Instrument (SMI)
🇯🇵

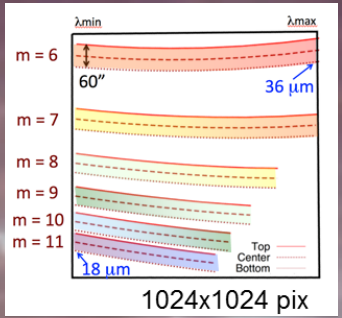
Complexity in responsibilities and interfaces
→ challenging AIV program

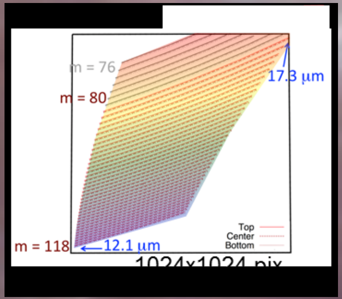
SMI - SPICA Mid-infrared Instrument

- **LRS** – large area low resolution surveyer
  - 17 – 36 μm, R = 50 – 120
  - 4 slits (10’ long) with prism
  - Detector: Si:Sb
  - Camera mode with slit viewer
- **MRS** – medium resolution mapper
  - 18 – 36 μm, R = 1200 – 2300,
  - 1 slit (1’ long) with grating
  - Detector: Si:Sb w/ beam-steering mirror
- **HRS** – molecular physics/kinematics
  - 12 – 18 μm, R = 28,000
  - 1 slit (4” long) with immersion grating
  - Detector: Si:As

- SMI Consortium
  - Nagoya Univ., Univ. of Tokyo, Osaka Univ.
  Tohoku Univ., Kyoto Univ., & ISAS/JAXA



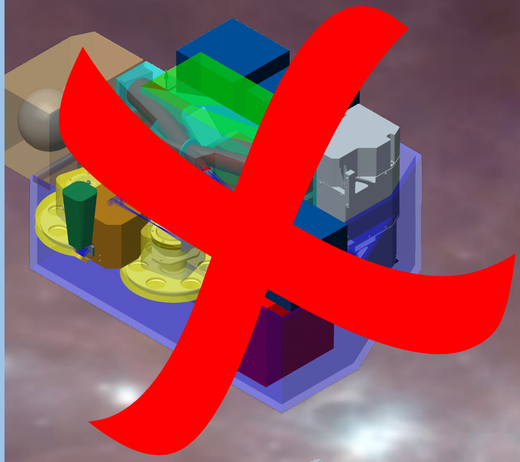


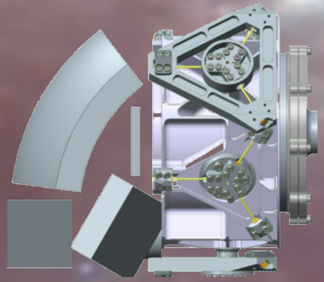


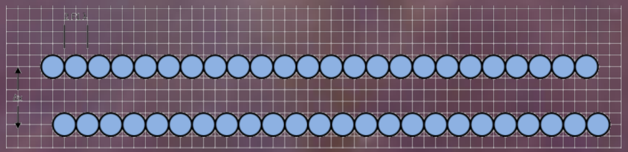
The SAFARI grating spectrometer

A new concept – dictated by science!

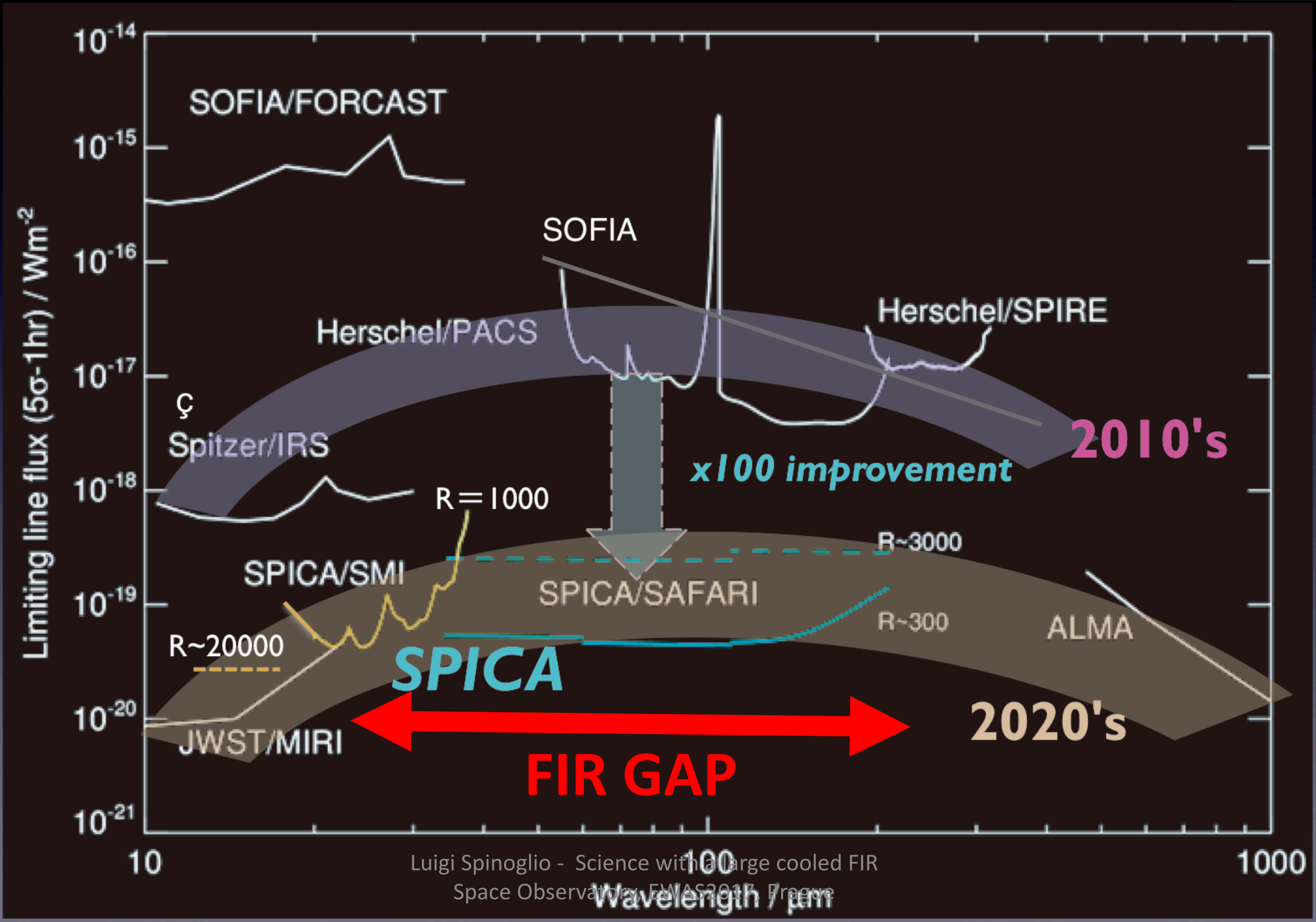
- Grating based spectrometer
  - Basic R~300 mode
    → 1hr/5σ ~**4-6×10^{-20} W/m^2** (6m^2)
  - 3 pixels simultaneous on-sky
  - 4 bands covering ***35-230 µm***
  - Martin Puplett Interferometer to provide R~3000 mode
    - Better resolution: ***R~11000*** @ 34 µm to R~1800 @ 230 µm







SPICA sensitivity and other facilities



SPICA/SAFARI Fact Sheet

SAFARI Overview

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

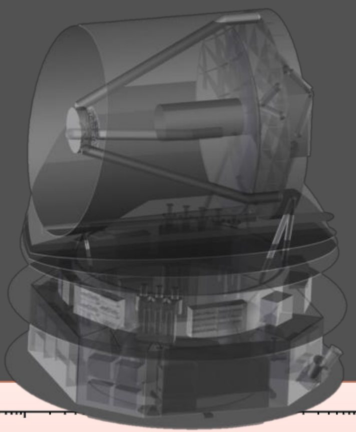
Parameter	Waveband			
	SW	MW	LW	LLW
Band centre / μm	45	72	115	185
Wavelength range / μm	34-56	54-89	87-143	140-230
Band centre beam FWHM	4.5″	7.2″	12″	19″
Point source spectroscopy (5σ-1hr)				
R~300 **Limiting flux** / x10⁻²⁰ Wm⁻²	7.2	6.6	6.6	8.2
R~300 **Limiting flux density** / mJy	0.31	0.45	0.72	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 arcmin²

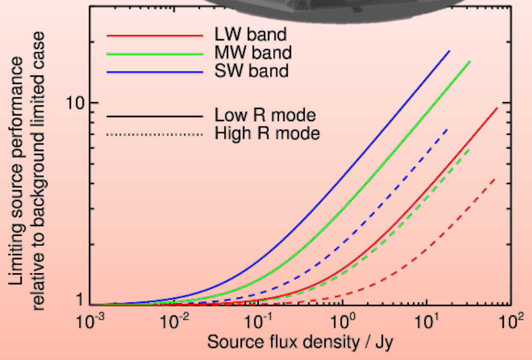
SPICA Mission

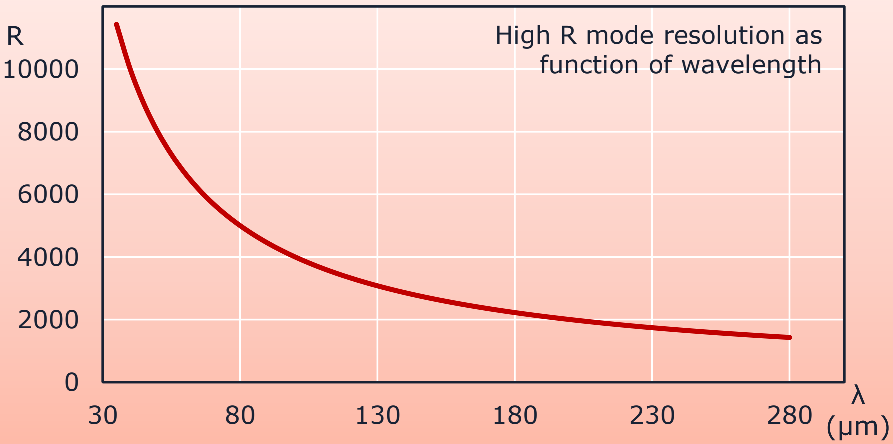
- ESA/JAXA collaboration
- Telescope effective area 4.6 m²
- Primary mirror temperature 8K
- Goal mission lifetime – 5 years



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

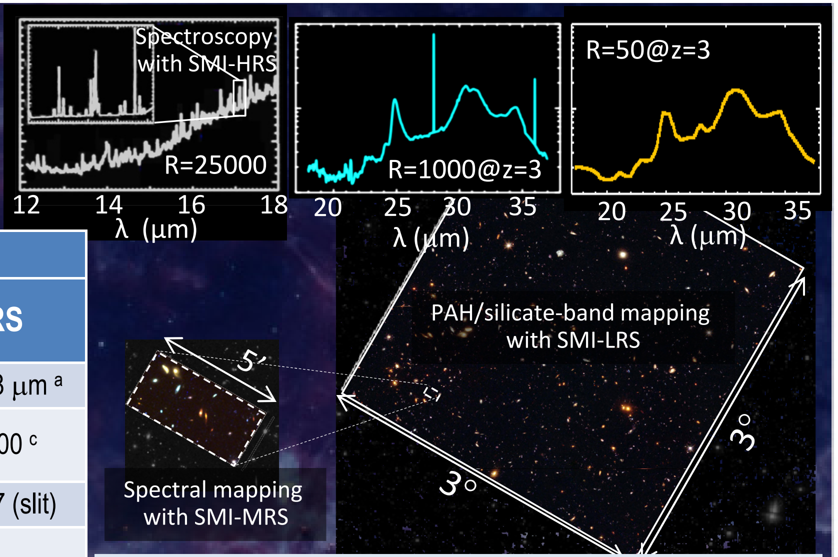
- The sensitivity decrease is due to the increased photon noise from the target source
- Data given up to the instrument saturation limits for each band (31, 51 and 87 Jy for the SW, MW and LW bands respectively.





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		MRS	HRS
		Multi slit spec.	Slit viewer		
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
	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
	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	
		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

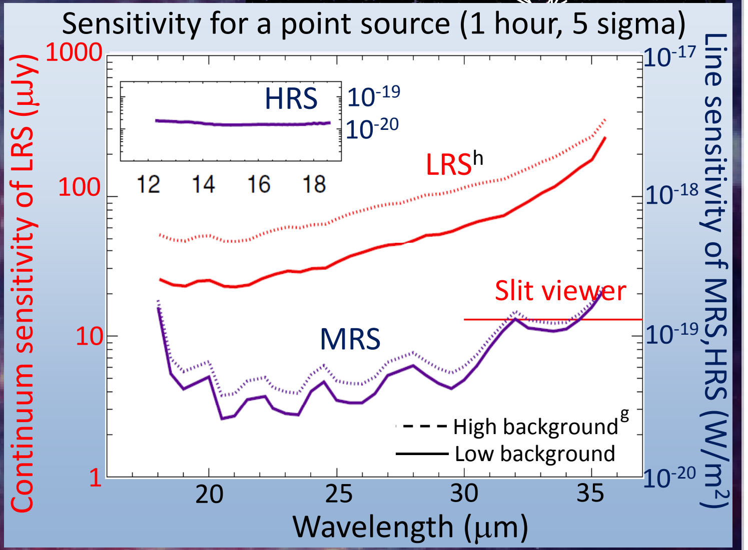
b: λ/δλ = 120 (LRS) and 1300 (MRS) at λ = 36 μm.

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)

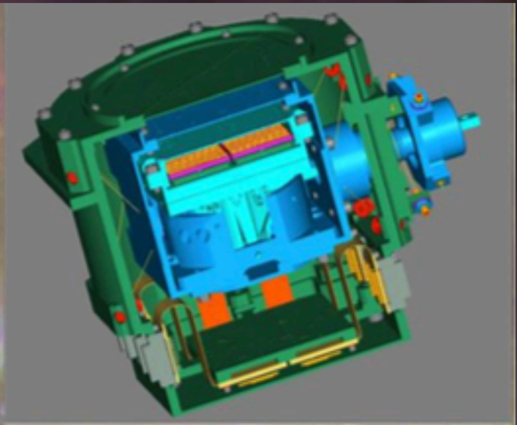
g: background levels are assumed to be 80 MJy/sr (High) and 15 MJy/sr (Low) at 25 μm.

h: continuum sensitivity rescaled with R=50

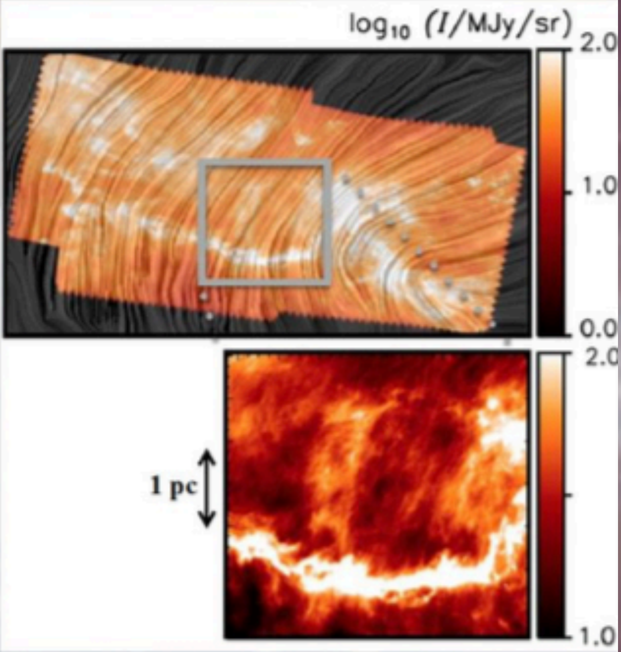
SMI Factsheet v10 – 4 Jan 2016

SPICA - SAFARI/POL Fact Sheet

A polarimetric camera with
3 simultaneous bands 100, 200 & 350 µm
on the same FOV : 2,6’ x 2,6’ @ 0,6 f#λ sampling



	100µm	200µm	350µm
Band edges	75—125µm	150—250µm	280—420µm
# of pixels	32 x 32 (x 2)	16 x 16 (x 2)	8 x 8 (x 2)
Pixel size	5" x 5"	10" x 10"	20" x 20"
Band centre beam FWHM	9"	18"	32"
PS sensitivity 5σ/1h/FOV (unpolarised)	21µJy	42µJy	85µJy
PS sensitivity in Stokes (Q,U) 5σ/1h/FOV (polarised)	30µJy	60µJy	120µJy
PS sensitivity 5σ/10h/1deg^2 (unpolarised)	0.16 mJy	0.32 mJy	0.65 mJy
PS sensitivity in Stokes (Q,U) 5σ/10h/1deg^2 (polarised)	0.23 mJy	0.46 mJy	0.92 mJy
Surface brightness sensitivity 5σ/10h/1deg^2 (unpolarised)	0.09 MJy/sr	0.045 MJy/sr	0.025 MJy/sr
Sensitivity to map Stokes parameters (Q,U) at 5% level 5σ/10h/1deg^2	2.5 MJy/sr	1.25 MJy/sr	0.7 MJy/sr



The filamentary structure of Star forming regions: Combined images from Herschel SPIRE @ 250 µm and Planck polarisation @ 850µm

What are the hot science topics for SPICA?

- Galaxy evolution studies: **this talk**
    1. Mapping BHAR and SFR through spectroscopy at 0<z<4
    2. Feedback & Feeding in the context of galaxy evolution
    3. Chemical Evolution of Galaxies: The Rise of Metals and Dust
    4. Towards the epoch of Re-Ionization: early black holes and starbursts
    5. Glimpse at the first stars and first galaxies
- Tracing the gas, dust and ice evolution in planetary systems with SPICA **Marc Audard talk tomorrow**
- Probing the role of magnetic fields in the formation and evolution of interstellar filaments with FIR polarimetric imaging from space **Philippe André talk**

Galaxy evolution studies with SPICA

The evolution of galaxies is fueled by two major energy production processes:

- Star Formation
- Supermassive Black Hole Accretion.

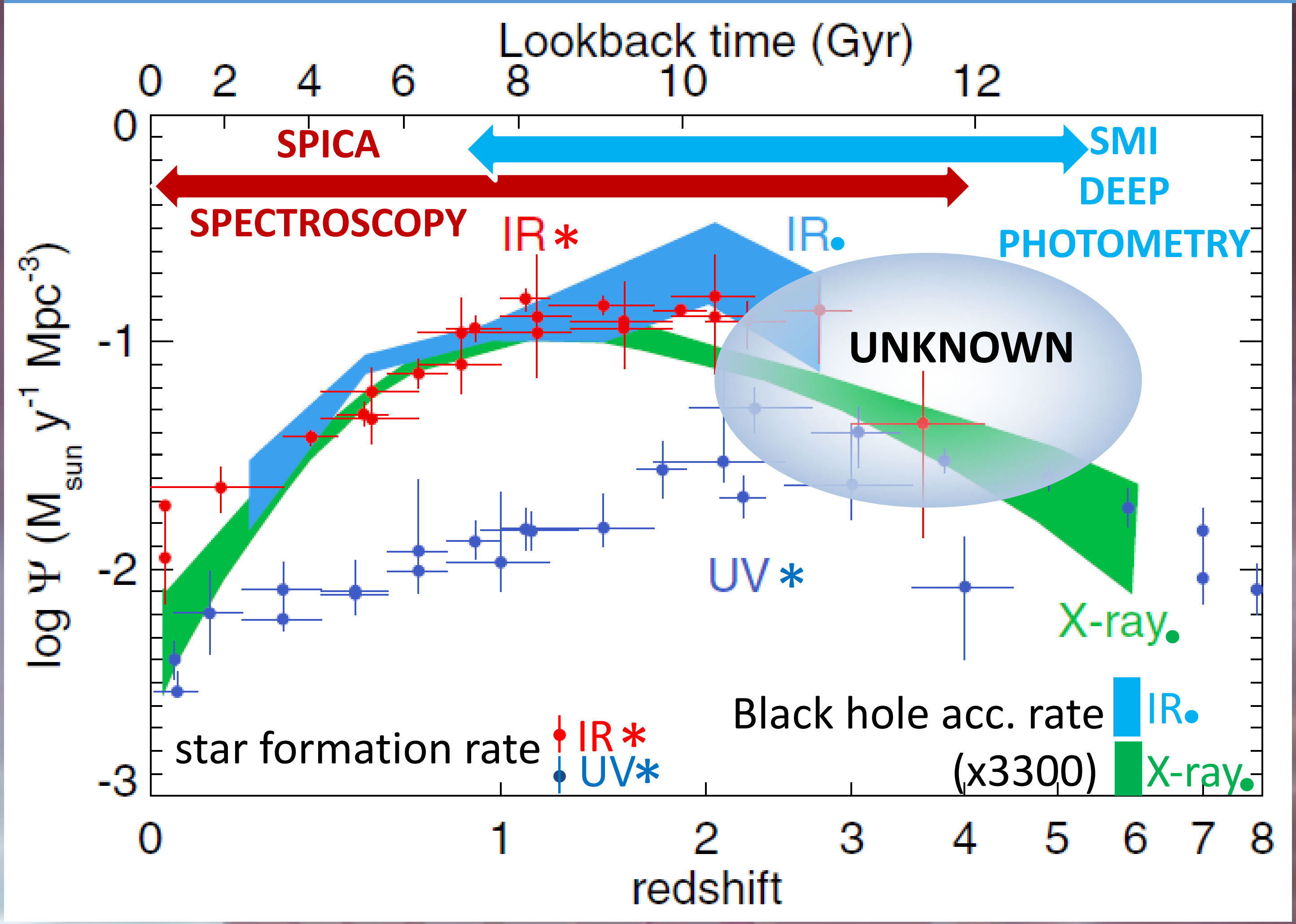
Both are profoundly dust obscured at the peak of their density functions (z=1-4) ➔ to establish their role, as well as their mutual feedback/feeding processes, rest frame mid-to-far IR spectroscopy is needed.

At these frequencies 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, fully redesigned with its 2.5m telescope cooled down to T<8K, will be able to perform deep IR spectroscopic surveys.

These surveys will allow for the first time “physically linked” measurements of the Star Formation Rate and the Black Hole Accretion Rate Histories of the Universe through dust unaffected line observations.

Galaxy evolution is obscured by dust at redshifts of z~1-3

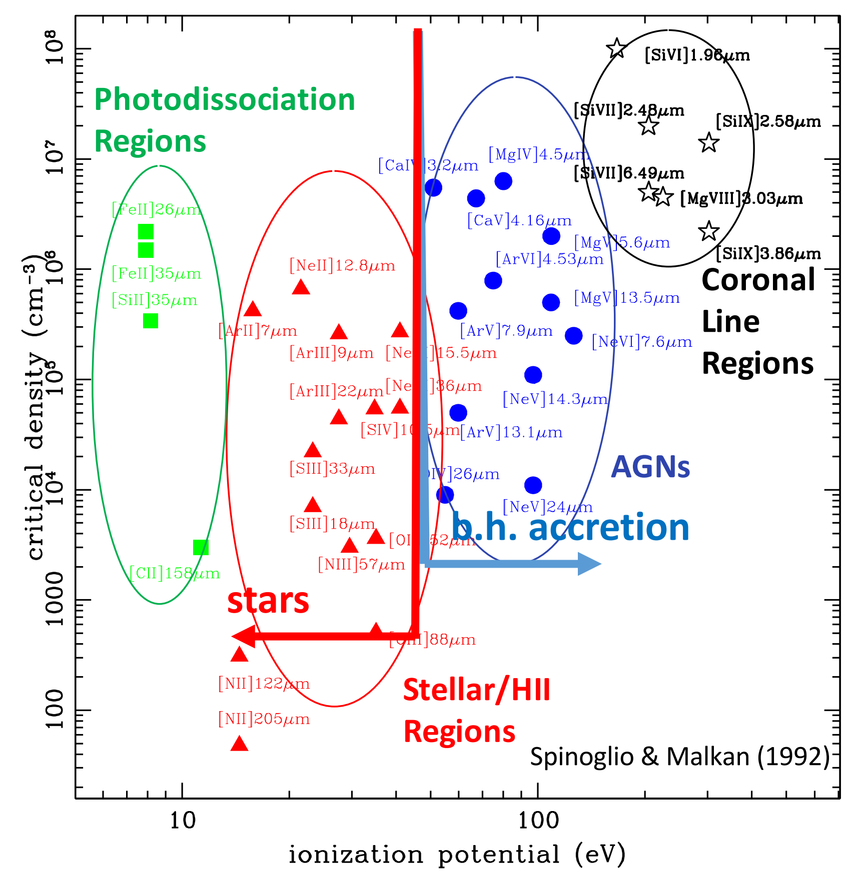


Spitzer + Herschel photometric surveys
➔ bolometric luminosities of galaxies
➔ estimates of the SFR and BHAR density functions.

However,
AGN/SF separation is not based on observed physical quantities but is model-dependent (used local SED templates, with large uncertainty and degeneracy).

- UV/opt. spectroscopy (from e.g. SLOAN) track only marginally (~10%) the total integrated light.
- BHAR X-ray estimates are affected by the large uncertainties of the adopted bolometric corrections.
- SFR density at z>2-3 very uncertain, since it is from UV surveys, highly affected by dust extinction.

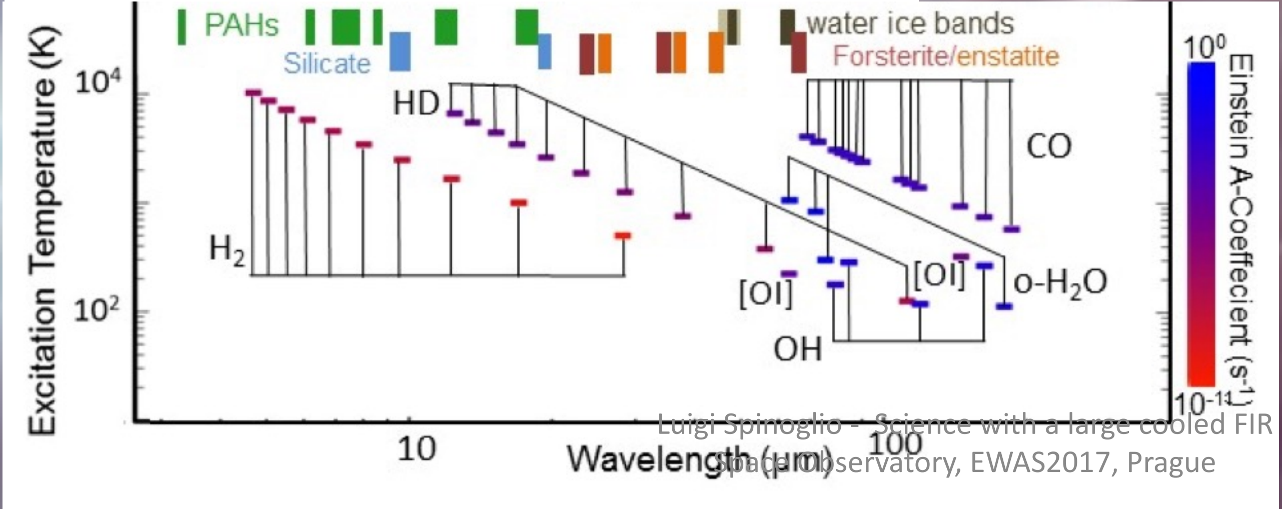
Why infrared spectroscopy ?



Spinoglio & Malkan (1992)

- **Avoid most of extinction**
- **Well cover ionization-density space**
- **Trace star formation vs black hole accretion**

Ionic fine structure lines



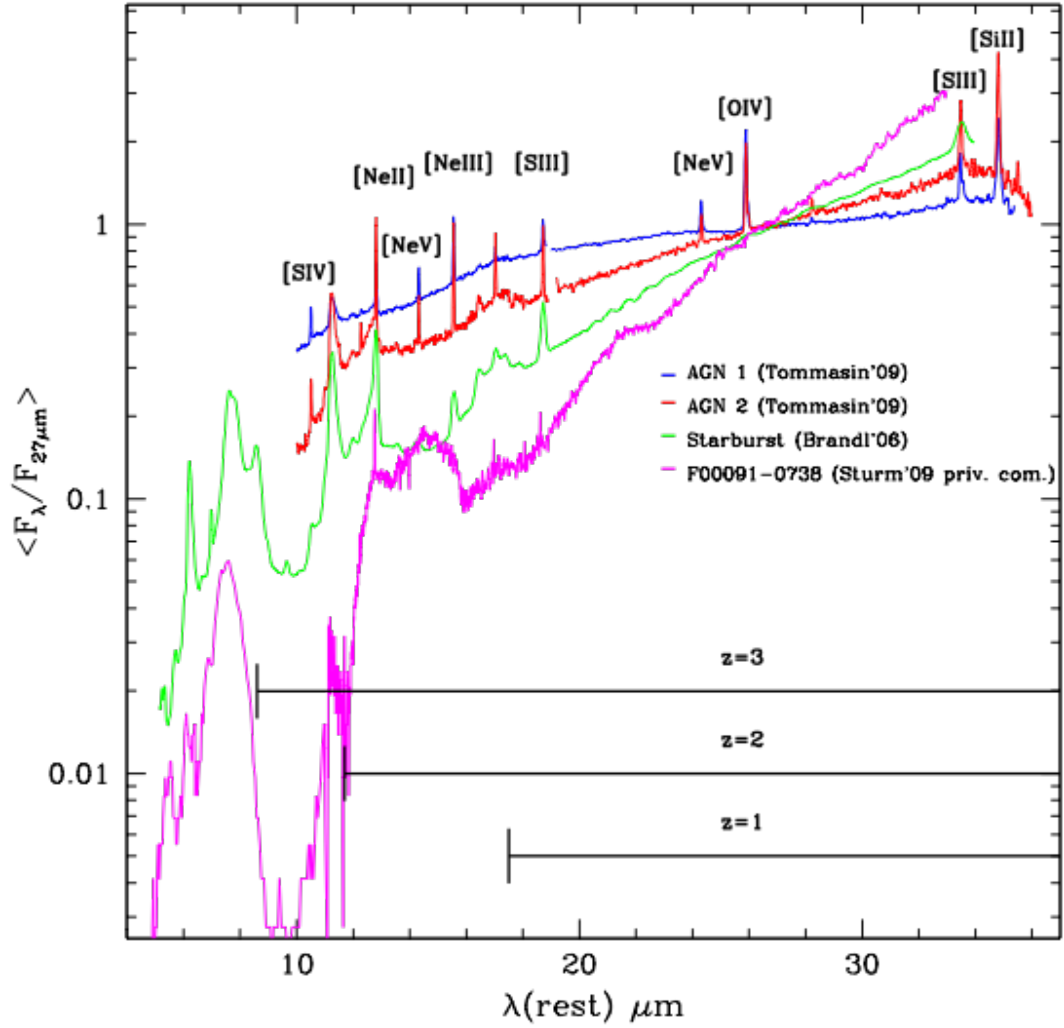
+

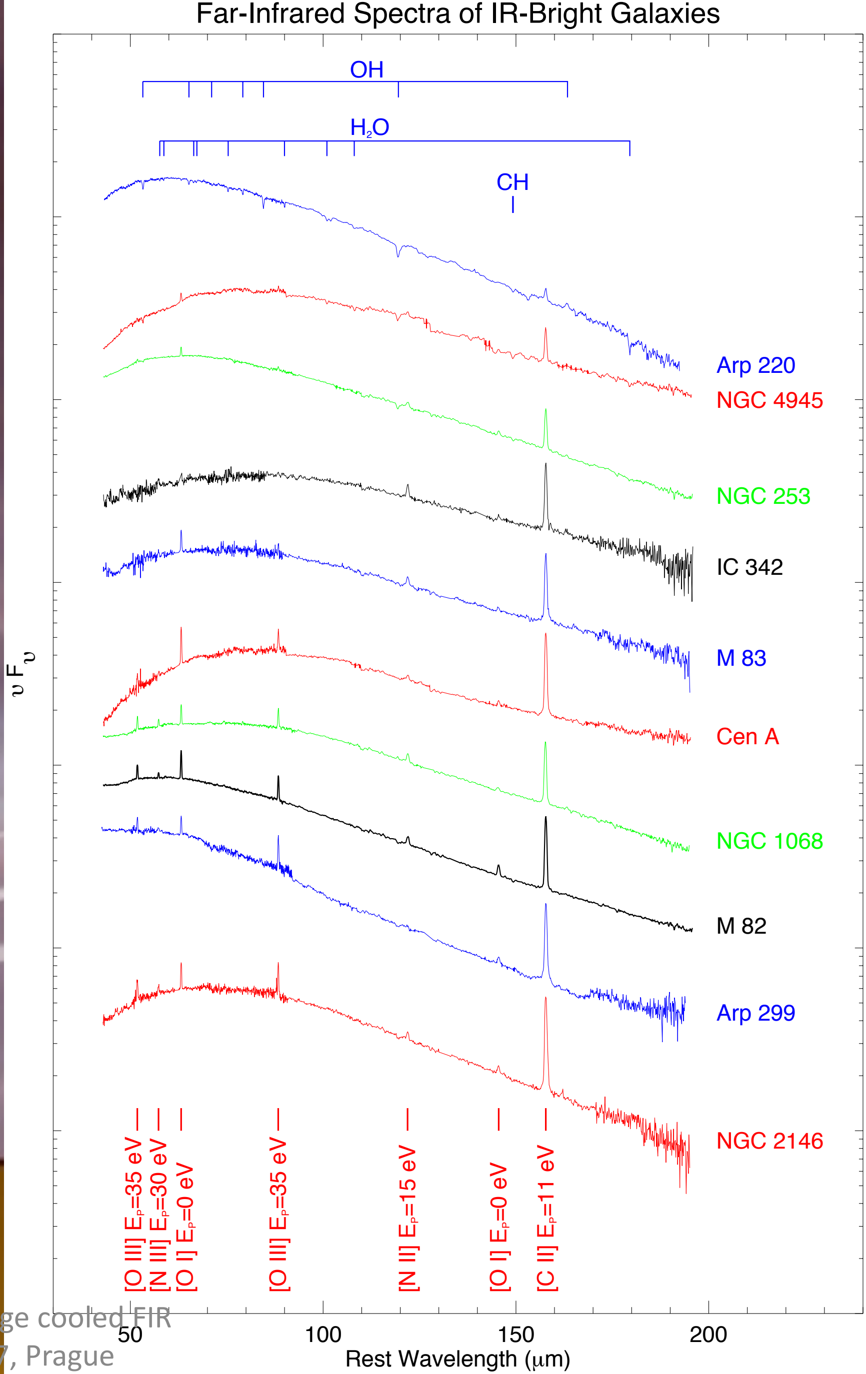
Molecular lines +

PAH +

Dust features

The richness of infrared spectra





Tommasin et al 2010; Sturm p.c.; Fischer et al 2009.

The main astrophysical questions SPICA will address :

- **What are the roles of star formation, accretion onto and feedback from central black holes and supernovae in shaping galaxy evolution over cosmic time?**

- **What are the relative contributions of nuclear fusion (stars) and gravitational potential energy (accreting black holes) to photon production after Re-ionization**

- **How are metals and dust produced and destroyed in galaxies? How does the matter cycle within galaxies and between galactic disks, halos and intergalactic medium ?**

- **How did primordial gas clouds collapse into the first galaxies and black holes?**

SPICA will uniquely perform observations that will:

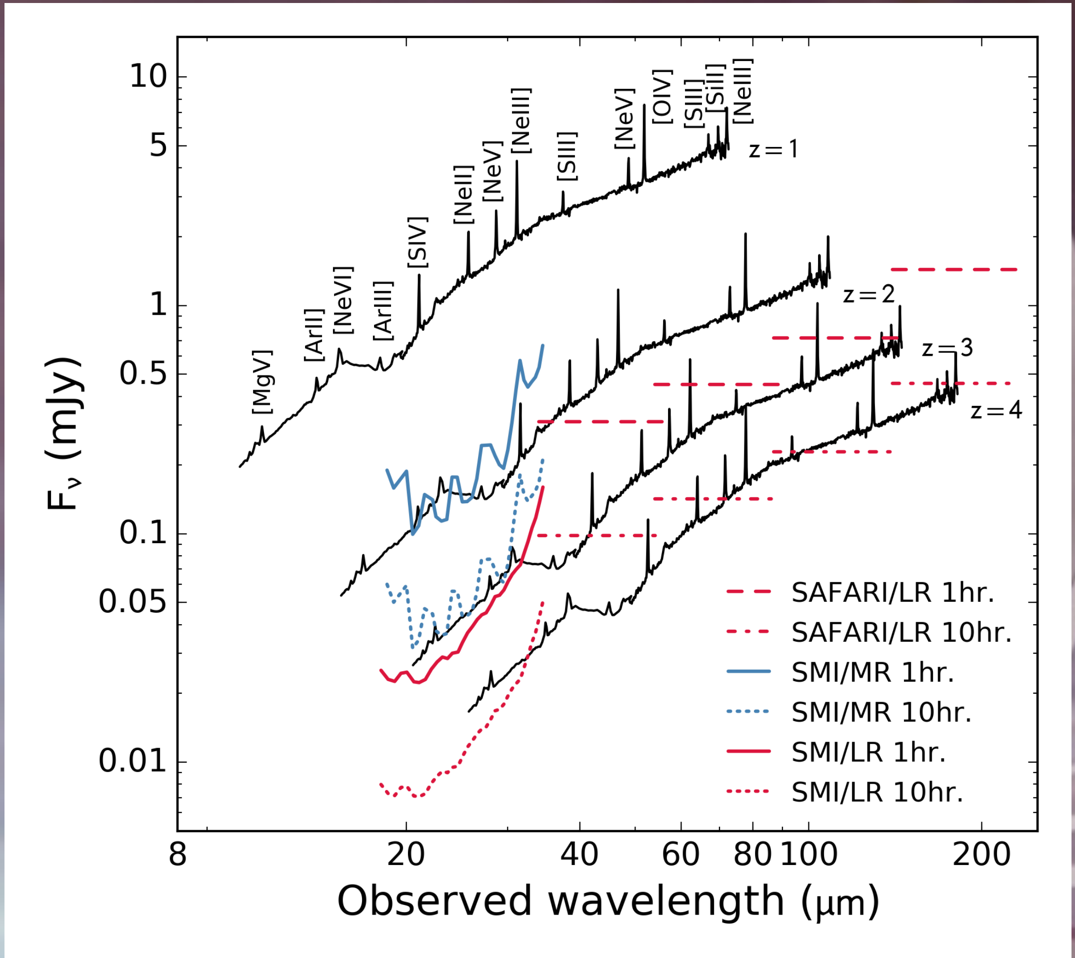
- **Study the physical conditions (ionization, density, metallicity, extinction) in the interstellar medium in dust obscured galaxies before and after the SFRD peak at z~2.**

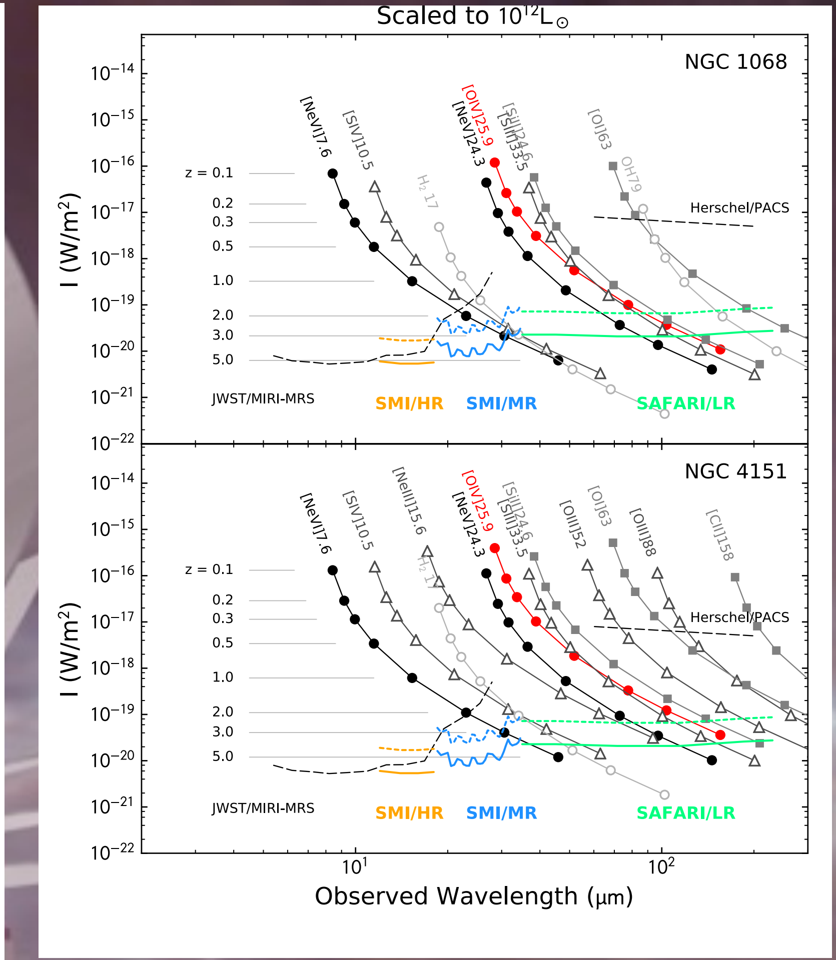
- **Trace star formation and SMBH accretion in large samples of L* galaxies to z ~3-4**

- **Study the interactions between SF and SMBH growth, including AGN feedback, molecular and atomic outflows, and gas inflow out to z~1 (with "high" resolution spectroscopy R~2000-10000) and to z~2 in low resolution (R~300)**

- **Detect dust during the epoch of re-ionization and chart the production of heavy elements and organic molecules in the interstellar medium of galaxies as a function of cosmic time.**

Line detectability with the SPICA spectrometers SAFARI & SMI

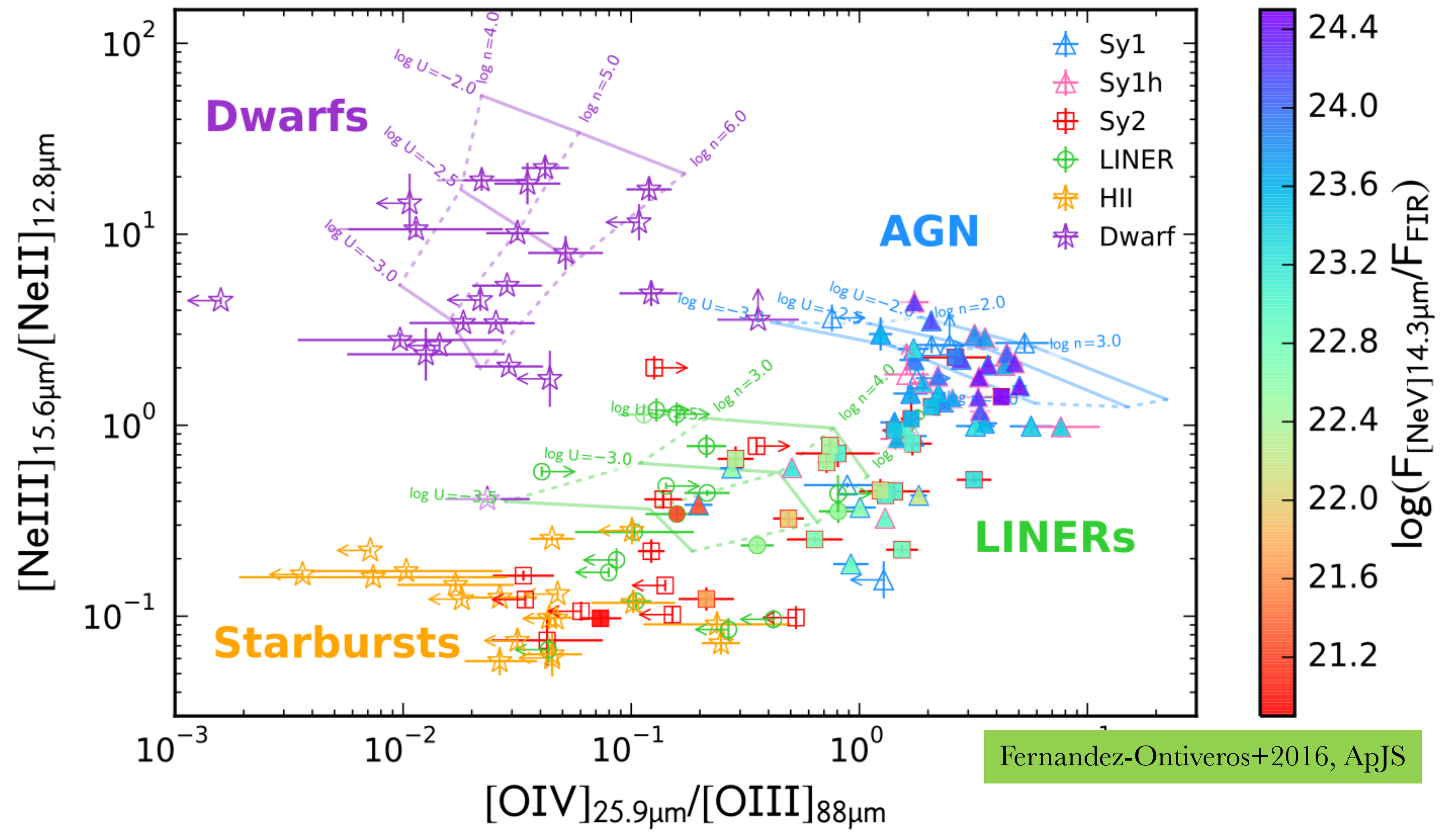




The IR spectrum of MCG-3-34-64, a nearby active galaxy, rescaled to a luminosity of L=10^{12} $L_\odot$ at redshifts z from 1 to 4. At z=3, the "main sequence luminosity" L=10^{12} $L_\odot$, implying that we will map the "bulk" of the galaxy population up to this redshift. The SAFARI and SMI sensitivities (in medium and low resolution) are shown.*

The new “IR BPT DIAGRAM”

SPICA will study both obscured starbursts and AGN across cosmic history, from a time when the Universe was only 1-2 billion years old.

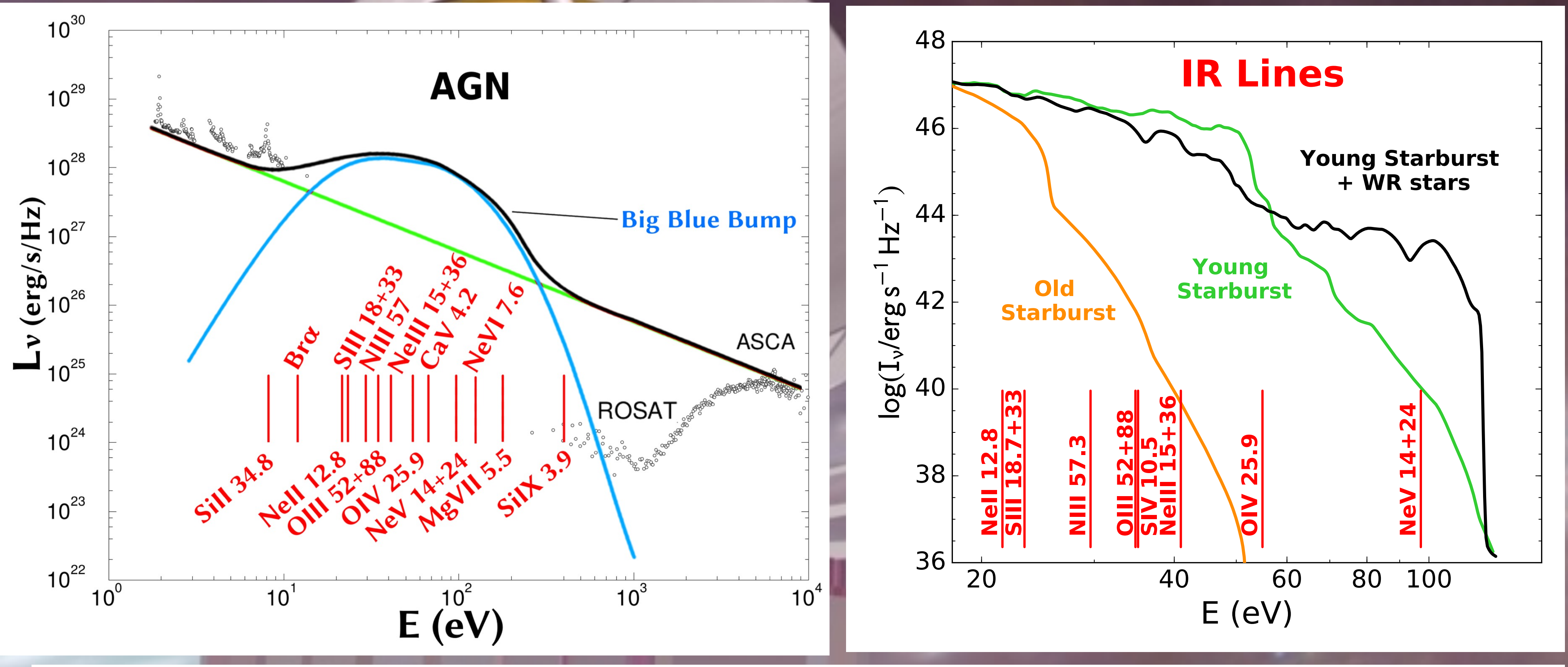


Fernandez-Ontiveros+2016, ApJS

- The new BPT diagram distinguishes any type of AGN (Seyfert and LINER) from any type of Star Formation dominated galaxy (either Starburst or Dwarf galaxies).

Mapping the primary ionizing spectra of AGN and starburst galaxies

The IR fine structure lines are formed at ionization energies that can map the primary ionizing spectrum, where it is not observable because of absorption from our Galaxy.

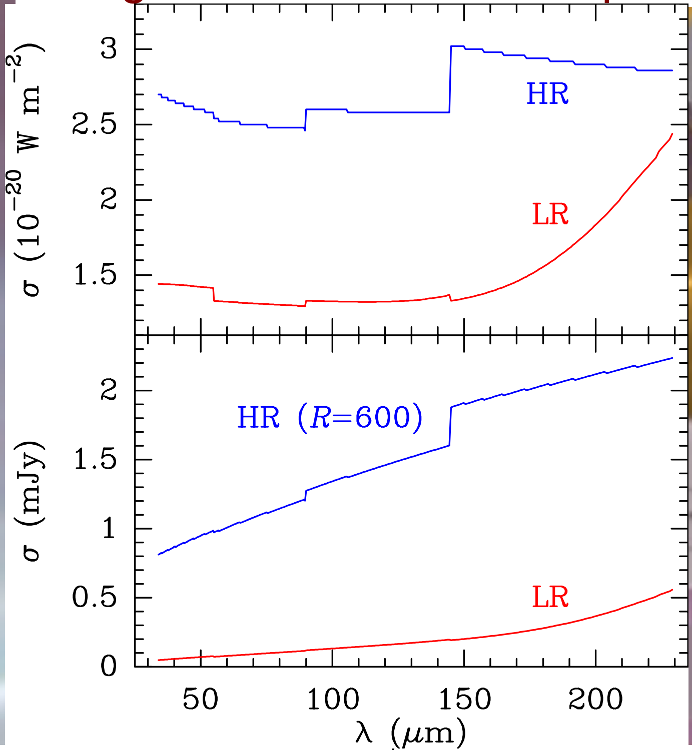


Left: Overlay of the NGC4151 primary spectrum (black points) with a sketched "blue bump" and a power law (adapted from Alexander et al 1999). Right: A typical young and old starburst spectrum (models from Leitherer et al 1999). In both cases the key IR diagnostic lines are indicated. SPICA is a powerful probe of of the invisible primary ionizing spectra of both AGN and starbursts.

Feedback & Feeding in the context of galaxy evolution

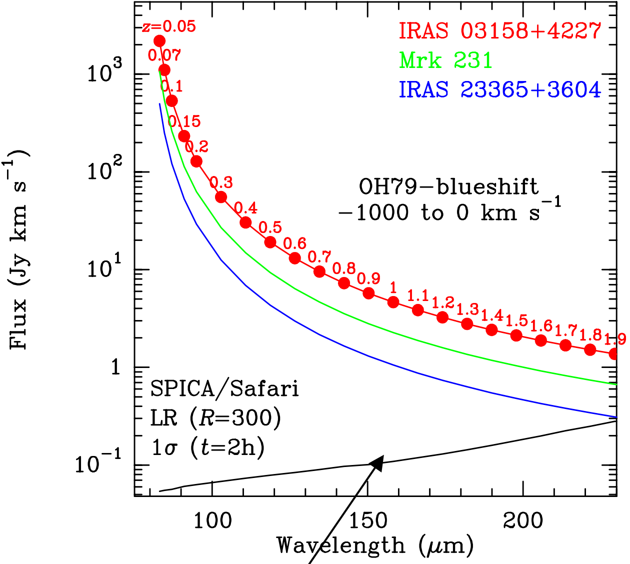
white paper by Eduardo González-Alfonso et al. (2017, in prep.)
& poster 6.22 at this conference

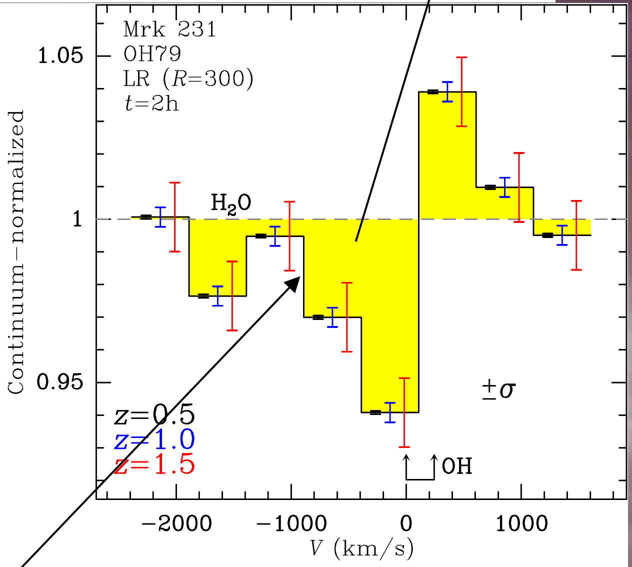
Goals: Predictions for line fluxes (P-Cygni, wings) as a function of redshift and detectability with *SPICA*:
Can we detect massive molecular outflows at high z, using local ULIRGs as templates?



Current SAFARI Low resolution (LR) and high-resolution (HR) sensitivities

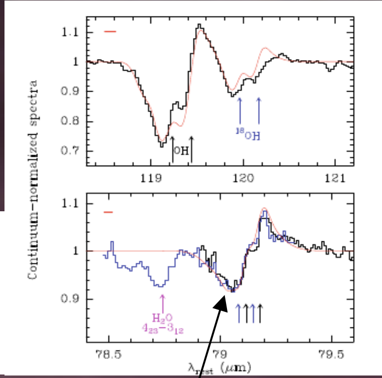
The OH doublet at 79 μm can probe outflows up to z~1.4-1.9





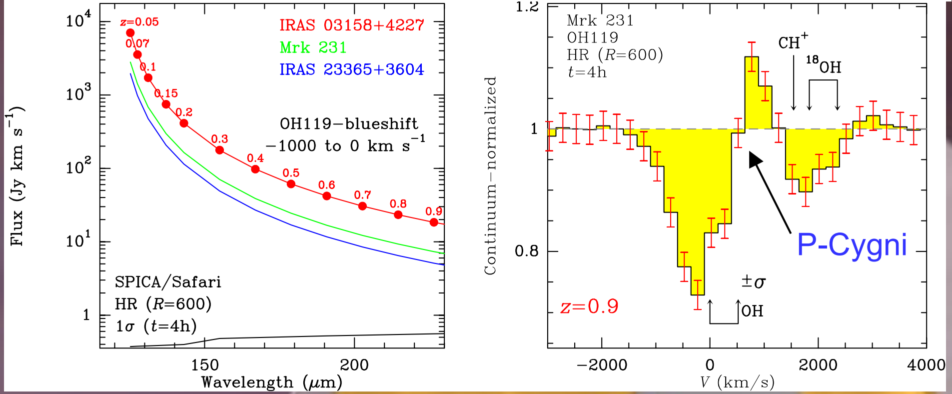
- *OH79 shows P-Cygni in many local ULIRGs
- *We use 3 templates: flux of blueshifted wings vs z
- **Black curve*: Safari sensitivities in LR (R=300) mode
- **Continuum-normalized vs velocity* is redshift-invariant
- *Errorbars: +/-1σ at z=0.5, 1, 1.5 (Mrk 231, LR-2h)

(P-Cygni OH profiles in Mrk 231; Fischer+2010)



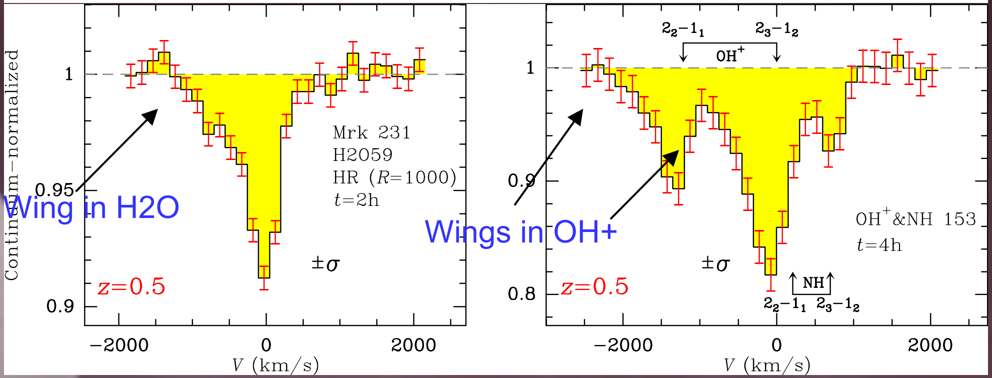
SPICA will measure the key tracers of atomic and molecular outflows and inflow in galaxies to the peak epoch of star formation

The OH doublet at 119 μm can be observed up to z~0.93: high-quality spectra with HR mode



P-Cygni

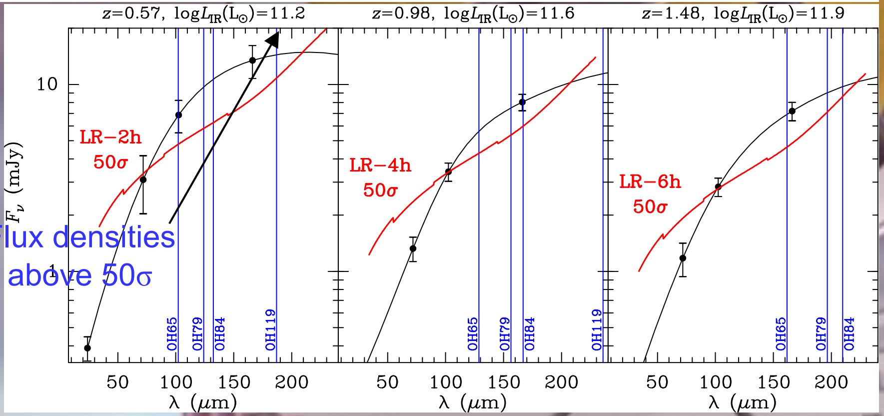
Outflows in other molecules, like H2O and OH+, can also be detected



Wing in H2O

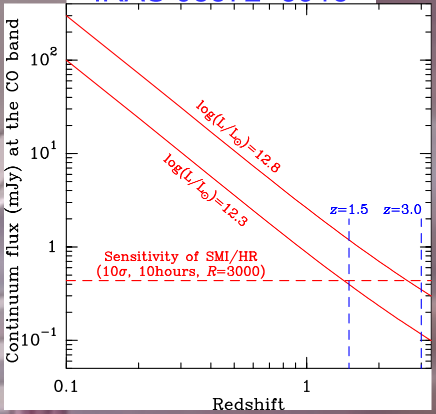
Wings in OH+

The incidence of outflows in high-M* main-sequence Galaxies would be explored (in OH, LR mode)

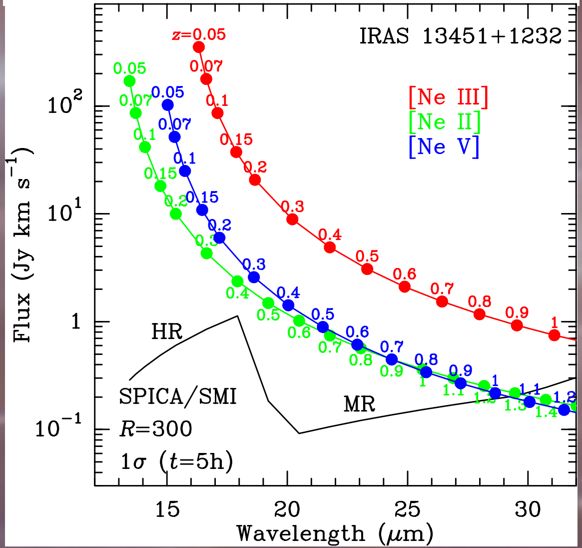


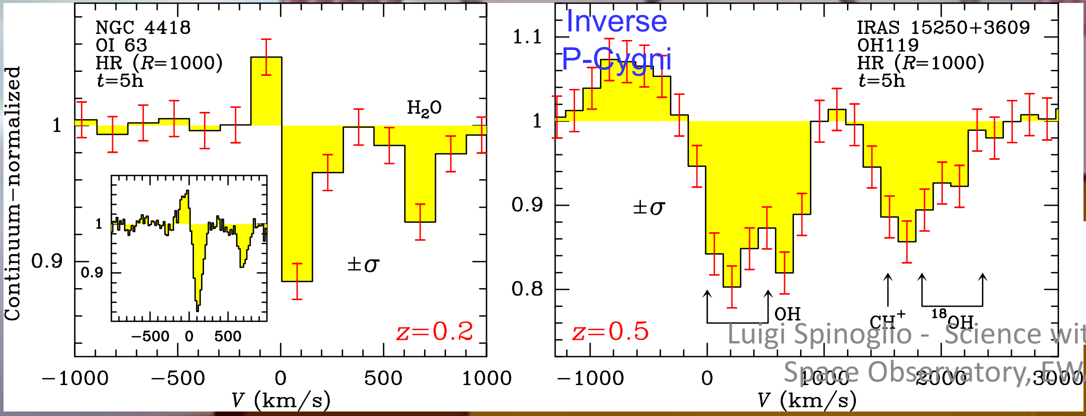
Flux densities above 50σ

CO band IRAS 08572+3915



In the mid-IR, outflows in molecular bands and in Ne ions would also be detected



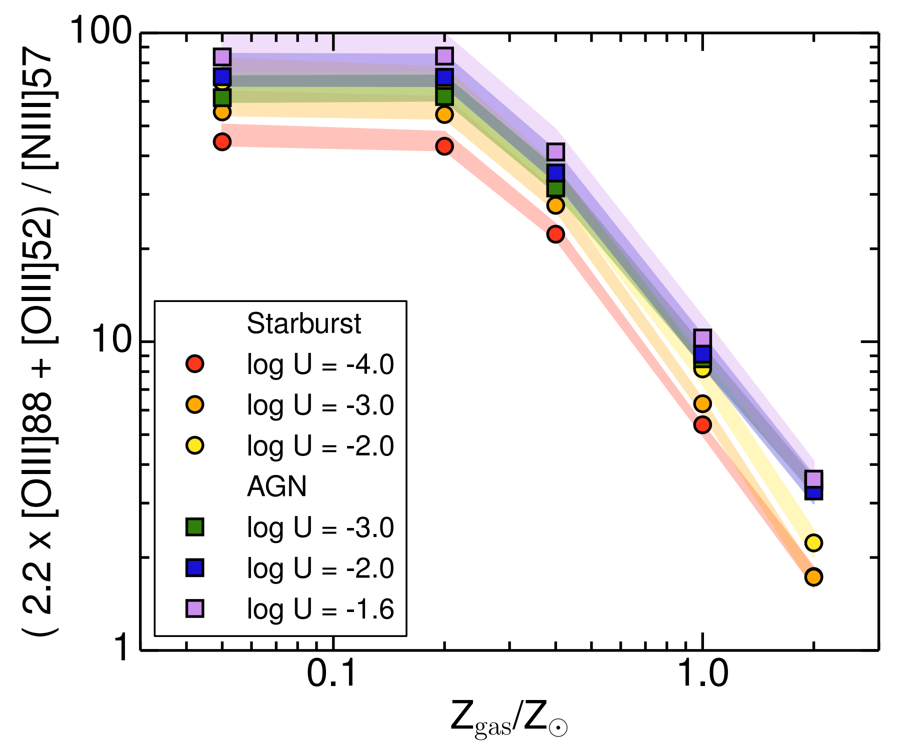


Inverse P-Cygni

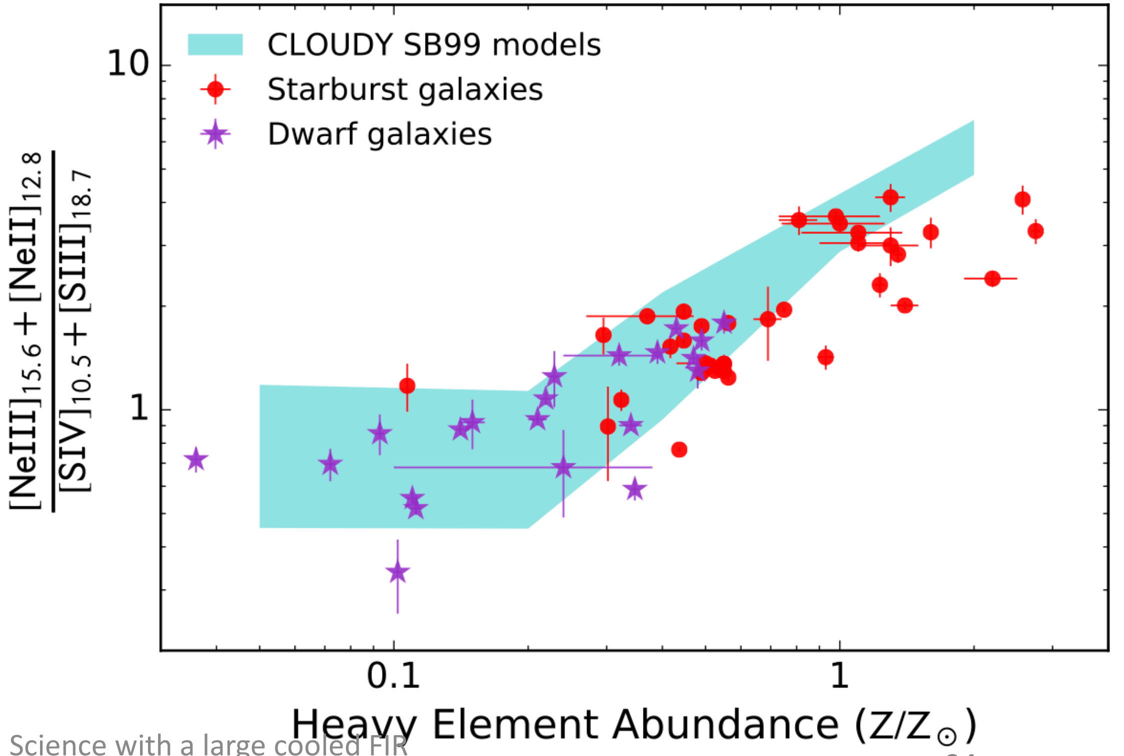
We will also explore inflows in [O I]63um and OH

SPICA and the Chemical Evolution of Galaxies: The Rise of Metals and Dust

white paper by Juan Antonio Fernandez-Ontiveros et al. (2017, in prep.)



Models for (2.2x[Oiii]88µm+[Oiii]52µm)/[N iii]57µm as a function of the gas-phase metallicity (Nagao+2011). For each metallicity bin, starburst models at given ionisation are indicated by a circle, AGN models with a square. Figure from Pereira-Santaella et al. (2017).

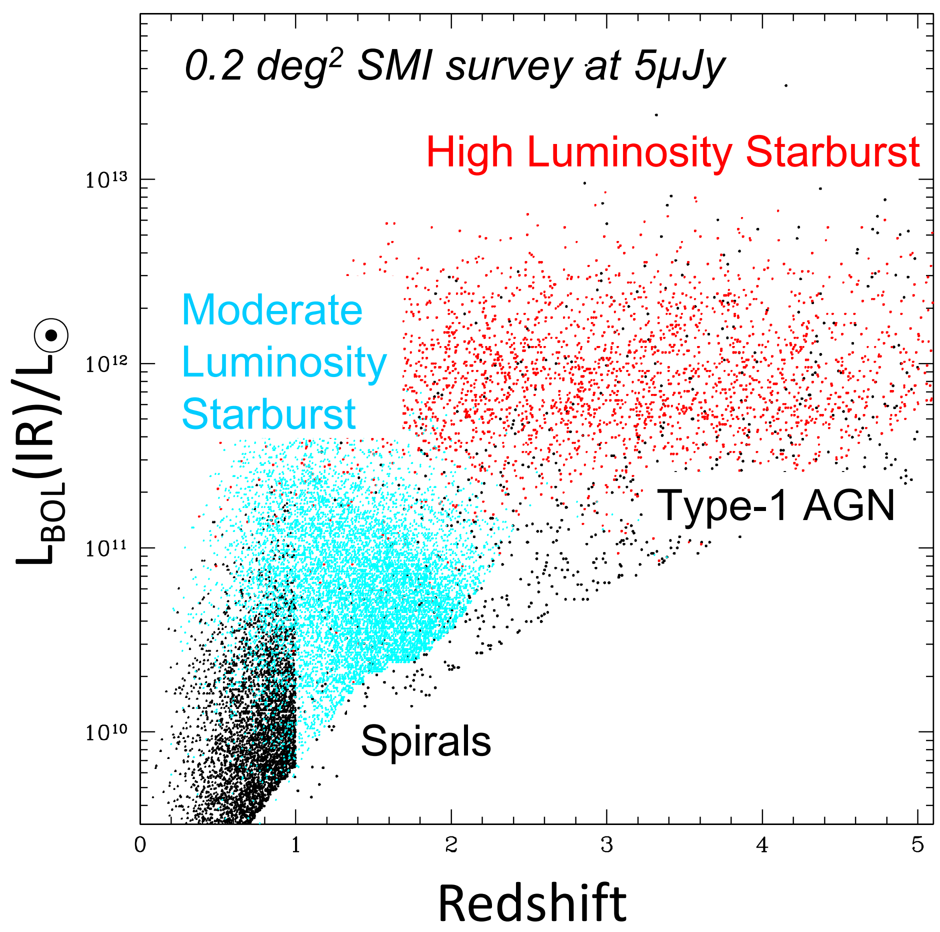


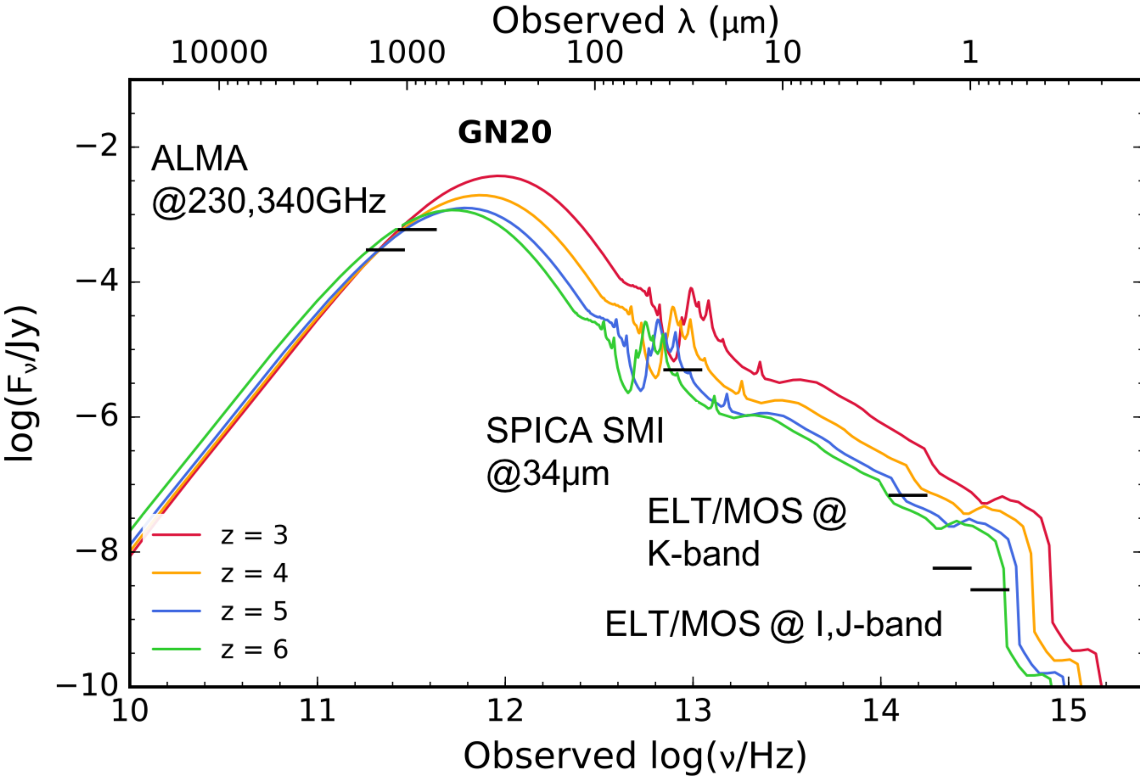
([Neii]12.8µm+[Ne iii]15.6µm)/([S iii]18.7µm+ [S iv] 10.5µm) line ratio from Spitzer /IRS observations of starburst galaxies in the Local Universe vs. indirect gas-phase metallicity determined from strong optical lines (Moustakas et al. 2010; Pilyugin et al. 2014). Cloudy models including sulphur depletion above Z > 1/5 Zo are in agreement with the observations (adapted from Fernandez-Ontiveros et al. 2016).

Towards the epoch of Re-Ionization: early black holes and starbursts

White paper by Carlotta Gruppioni et al. (2017, in prep.)

SPICA SMI deep surveys will detect AGN and starburst galaxies up to z~5-6, which will be characterized by the ELTs and ALMA





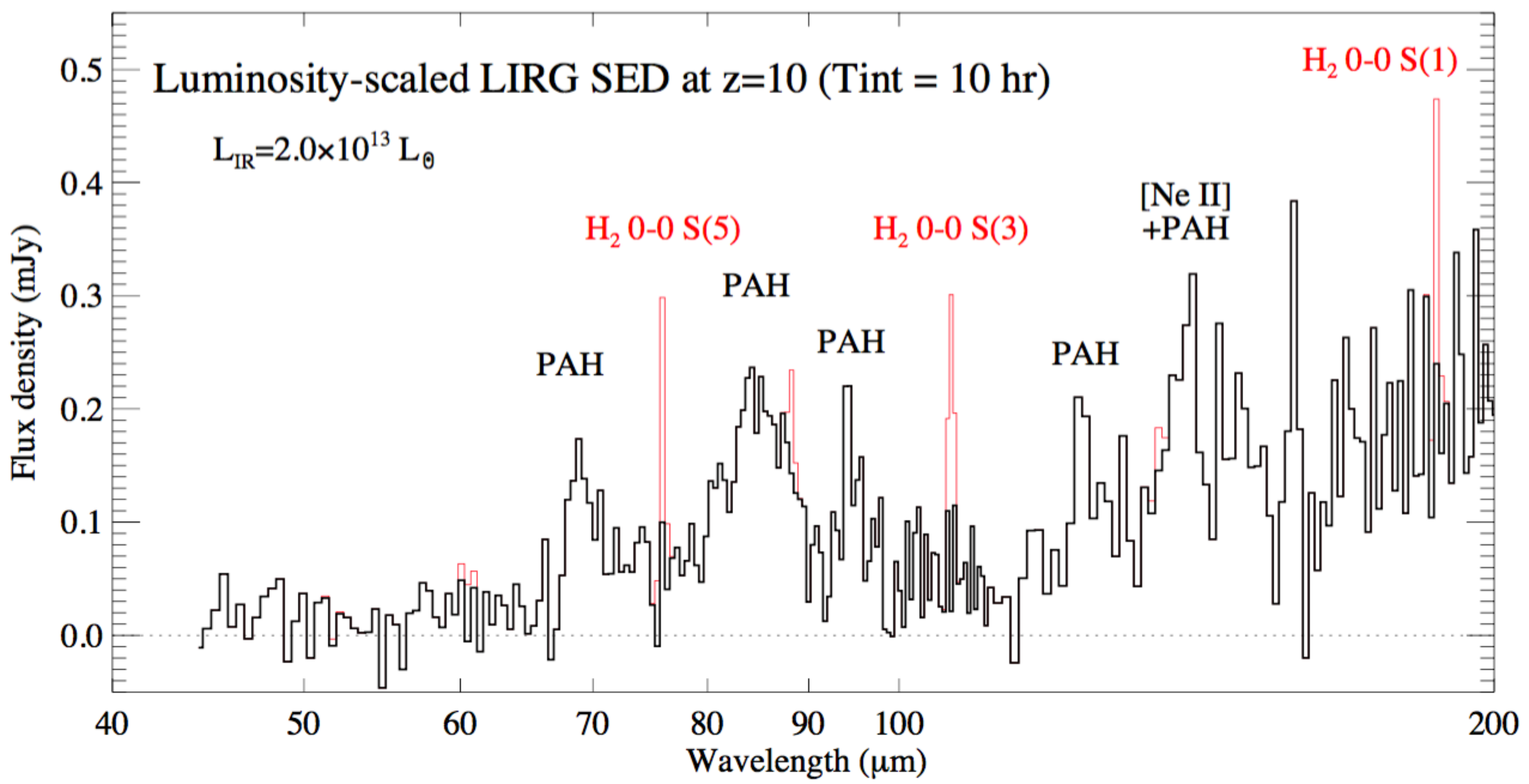
Left: L-z plane coverage of a 0.2 deg^2 SMI survey at the confusion limit (5μJy, 10 hours/frame).

Right: The SED fit to the z=4.3 starburst galaxy GN20 (Efstathiou & Siebenmorgen 2009) rescaled to L=10^{12} L$_\odot$ for z=3-6. The detection limits of ALMA (10 minutes), ELT/MOS and ELT/ MICADO (3 hours) are shown. SPICA will map large areas to the confusion limit one hundred times faster than JWST, finding large numbers of dust-enshrouded AGN and starbursts at z > 5.

The first stars and galaxies

White paper by Eiichi Egami et al. (2017, in prep.)

SPICA can detect the cooling gas in the first galaxies or in collapsing clouds through H_2 boosted by shocks.



Simulated SAFARI spectrum produced with the $L_{IR}=10^{11.75}\ L_\odot$ galaxy spectral template (Rieke et al. 2009) at z=10, scaled to $L_{IR}=2\times10^{13}\ L_\odot$. The red lines show simulated shock-excited (i.e., thermalized) H_2 emission lines produced by $3\times10^{10}M_\odot$ of T=200 K gas and $3\times10^{8}M_\odot$ of T=1000 K gas. The predicted fluxes of the S(1), S(3) and S(5) lines are 3.5, 5.2 and 7.3×10^{-20} W m^{-2}, respectively (and thus detectable with SAFARI at 5σ in 5.5, 1.6 and 0.8 hours)

SAFARI will collect rest-frame mid-IR spectra up to *z*~10 for sufficiently luminous galaxies ($L_{IR}>2\times10^{13}\ L_\odot$).

These galaxies, mostly gravitationally lensed, are being discovered at *z*>5, (e.g. Combes et al. 2012; Riechers et al. 2013).

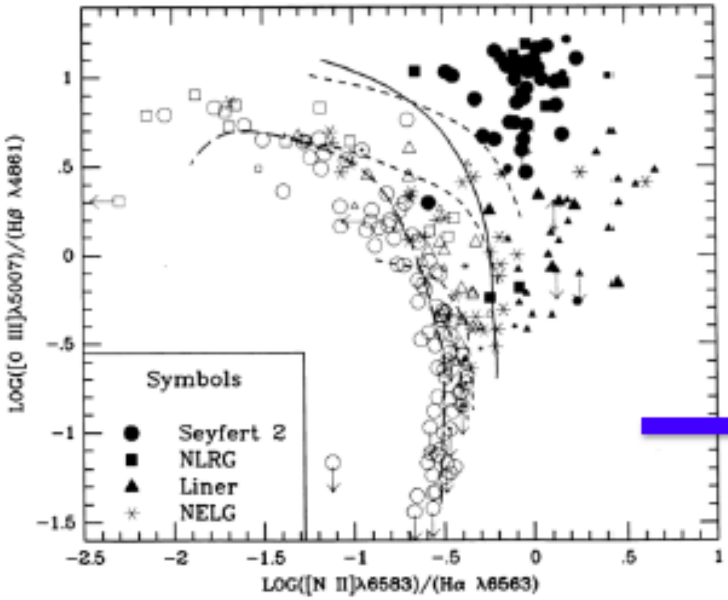
SPICA will offer the first opportunity to study the rest-frame mid-IR spectra of galaxies at *z*>4-5 and up to *z*~10 in significant numbers.

What is next?
We want to apply IR diagnostics to study galaxy evolution with SPICA

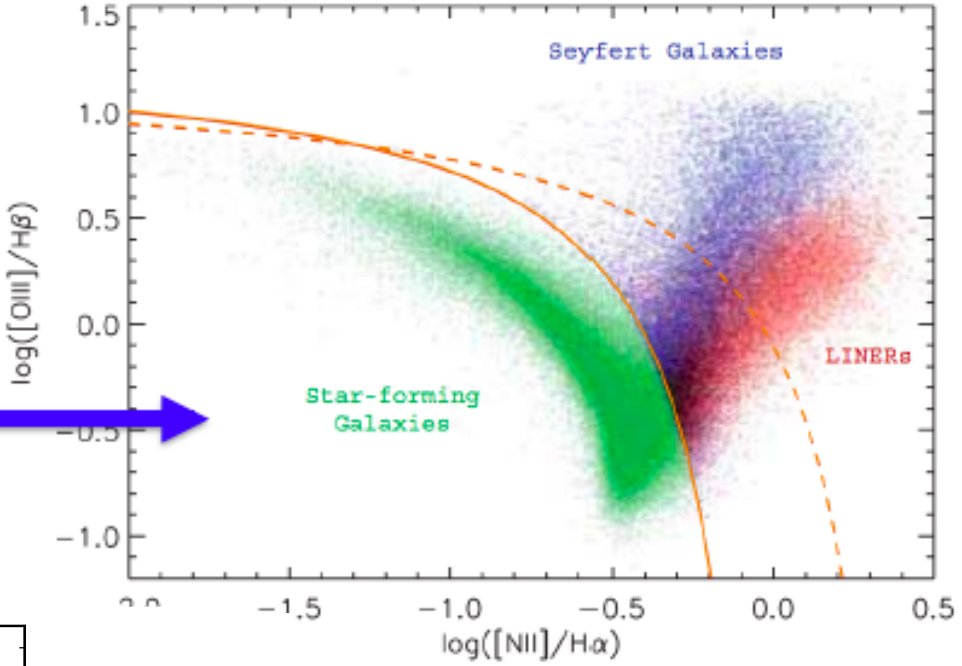
- We know the tools ($\lambda_{\text{REST-FRAME}}$~10-100μm), but we need a new space telescope to do the job.
- JWST will not cover the z=1-4 redshift region in the mid-IR tracers due to its spectral range limited to λ<28μm
- ALMA (λ>350μm) can observe only higher redshift (z>4) sources in IR fine-structure lines (at λ_{REST}>70μm, e.g. [OIII]88μm)
- **SPICA only with its cooled telescope will be able to cover the missing range (λ=10-230μm)**

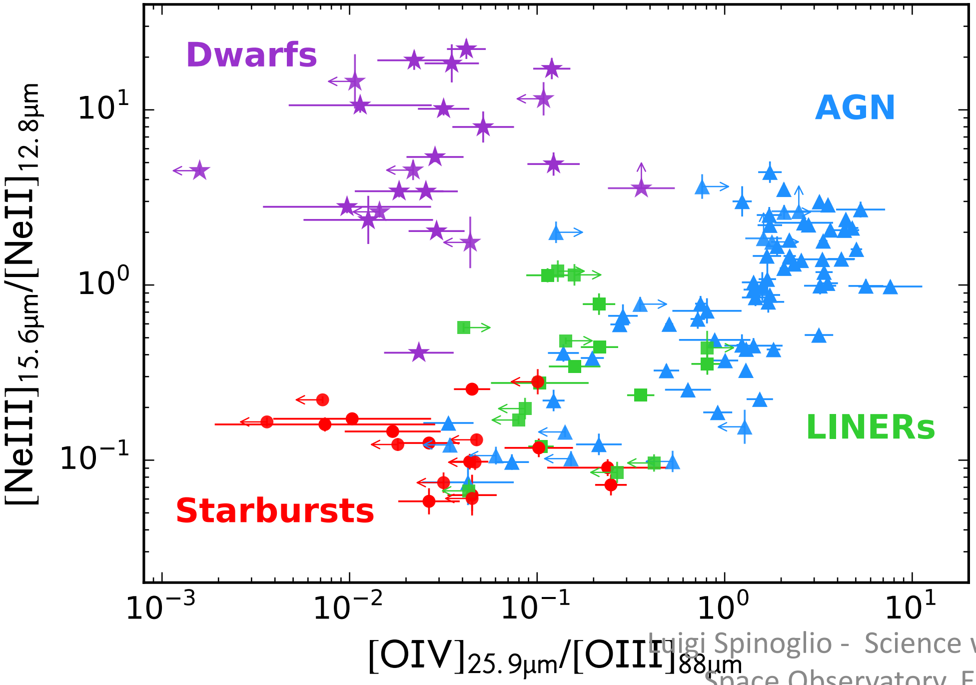
OPTICAL SPECTROSCOPY

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



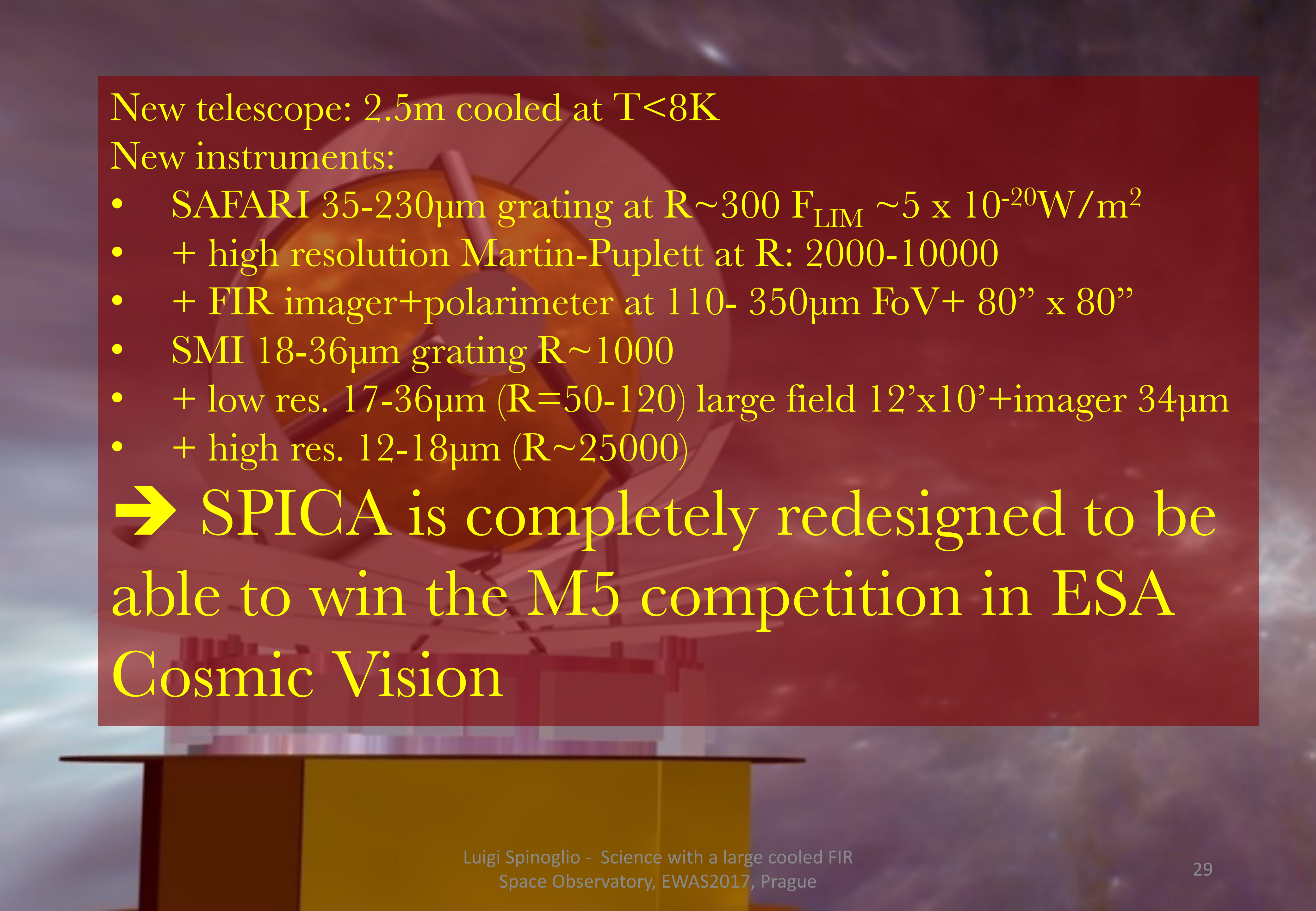
Groves+ **2006** (>10^5 galaxies)





Z ~ 1-3

SPICA … ~ 2028



New telescope: 2.5m cooled at T<8K

New instruments:

- SAFARI 35-230μm grating at R~300 F_{LIM} ~5 x $10^{-20}W/m^2$
- + high resolution Martin-Puplett at R: 2000-10000
- + FIR imager+polarimeter at 110- 350μm FoV+ 80" x 80"
- SMI 18-36μm grating R~1000
- + low res. 17-36μm (R=50-120) large field 12'x10'+imager 34μm
- + high res. 12-18μm (R~25000)

➔ SPICA is completely redesigned to be able to win the M5 competition in ESA Cosmic Vision

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, completely unaffected by dust, allowing us to study the evolution of galaxies in terms of stellar fusion and gravity powers
- Accurately measuring the fusion-power and gravity-power 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
- SPICA will allow us to study the interactions between SF and SMBH growth, including AGN feedback, molecular and atomic outflows, and gas inflow out to z~1 (with “high” resolution spectroscopy R~2000-10000) and to z~2 in low resolution (R~300)
- Detect dust during the epoch of re-ionization and chart the production of heavy elements and organic molecules in the interstellar medium of galaxies as a function of cosmic time.
- SPICA can detect the cooling gas in the first galaxies or in collapsing clouds through H2 boosted by shocks.
- 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.