Galaxy Evolution with far-IR/submm spectroscopy from the space

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Summary

Why infrared spectroscopy is needed ?

1. **Galaxy Evolution**

   trace the main energy production mechanisms: Star Formation & Black Hole Accretion

   Optical/UV: only ~1/10 of total light

2. **Baryon Cycle**

   Feeding/Feedback to/from AGN and Starbursts are needed to understand the Baryon Cycle

   Chemical evolution: dust and gas evolve during galaxy evolution

- **Previous space (ISO, Spitzer, Herschel) and airborne IR telescopes (SOFIA) have paved the way showing the power of IR spectra**
- **JWST (2021?) (λ< 28μm) will do only part of the job (λmax = 28 μm)**
- **SPICA, in spite of the huge preparation work that has been done (~15 years) has been cancelled by ESA from the 5th Medium Class Mission competition**
- **Millimetron and the NASA Origins Space Telescope can do this study:**
  - **Characterize galaxies "physically" through IR spectroscopy up to z~4 ($t_{LOOKBACK}$~12 Gyr)**
  - **Measure feeding and feedback of AGN and Starbursts,**
  - **Measure chemical evolution of heavy elements and dust**

The galaxy evolution goals

1. 3-D spectroscopic view of hidden star formation and black hole accretion in all environments, from voids to cluster cores over 90% of cosmic time.

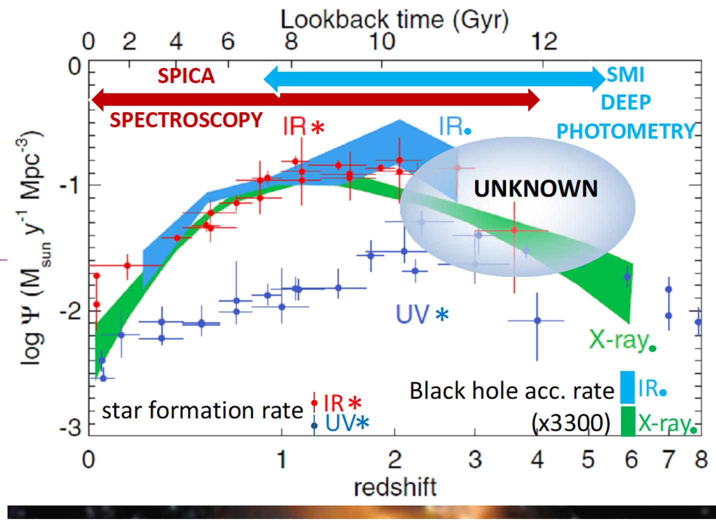
- the star formation in galaxies
- the black hole accretion in the nuclei of galaxies, including heavily obscured Compton thick nuclei.

2. measure AGN/starburst feedback and how influences galaxy evolution

➔ role of AGN in quenching star formation

➔ origin of the low stellar to dark matter halo mass ratio in massive galaxies.

➔ origin of the change in the efficiency of SF and accretion at cosmic noon

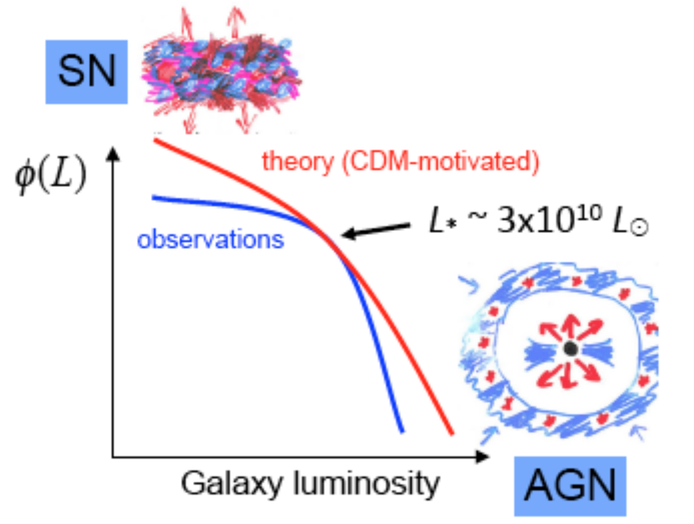


3. measure the build up of metals, molecules and at Cosmic Noon, how metals are recycled in ISM and injected into CGM.

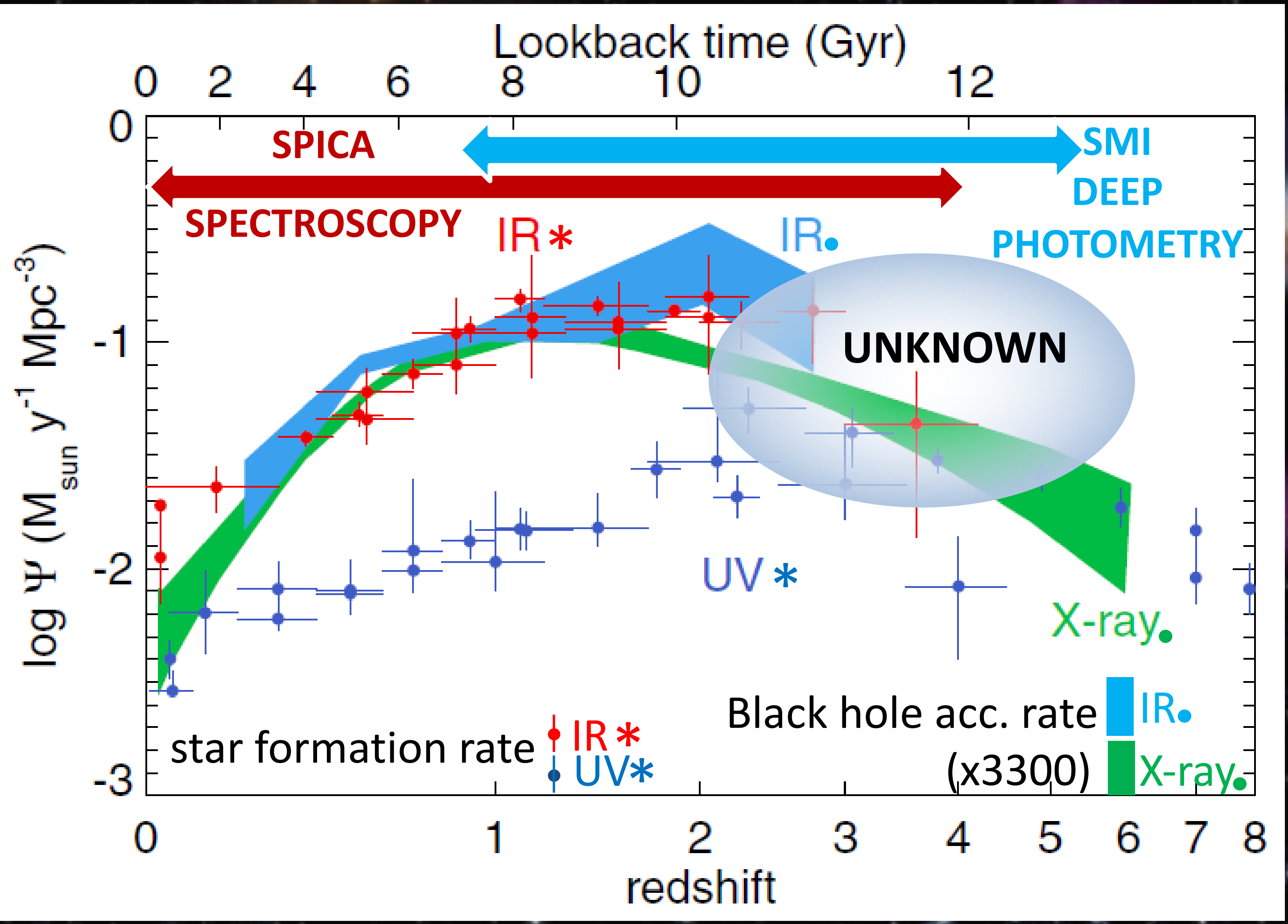
➔ measure the metallicity (and the N/O ratio) over cosmic time

➔ probe the first production of dust and metals,

➔ assess the presence of hot dust in the most distant galaxies (z≥6) and determine the physical properties of infrared bright galaxies and quasar hosts at the epoch of reionization.



Galaxy evolution is obscured by dust at redshifts of z~1-4



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 ~1/10 of 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.

White papers by LS et al. (2017, 2021, astro-ph & PASA)

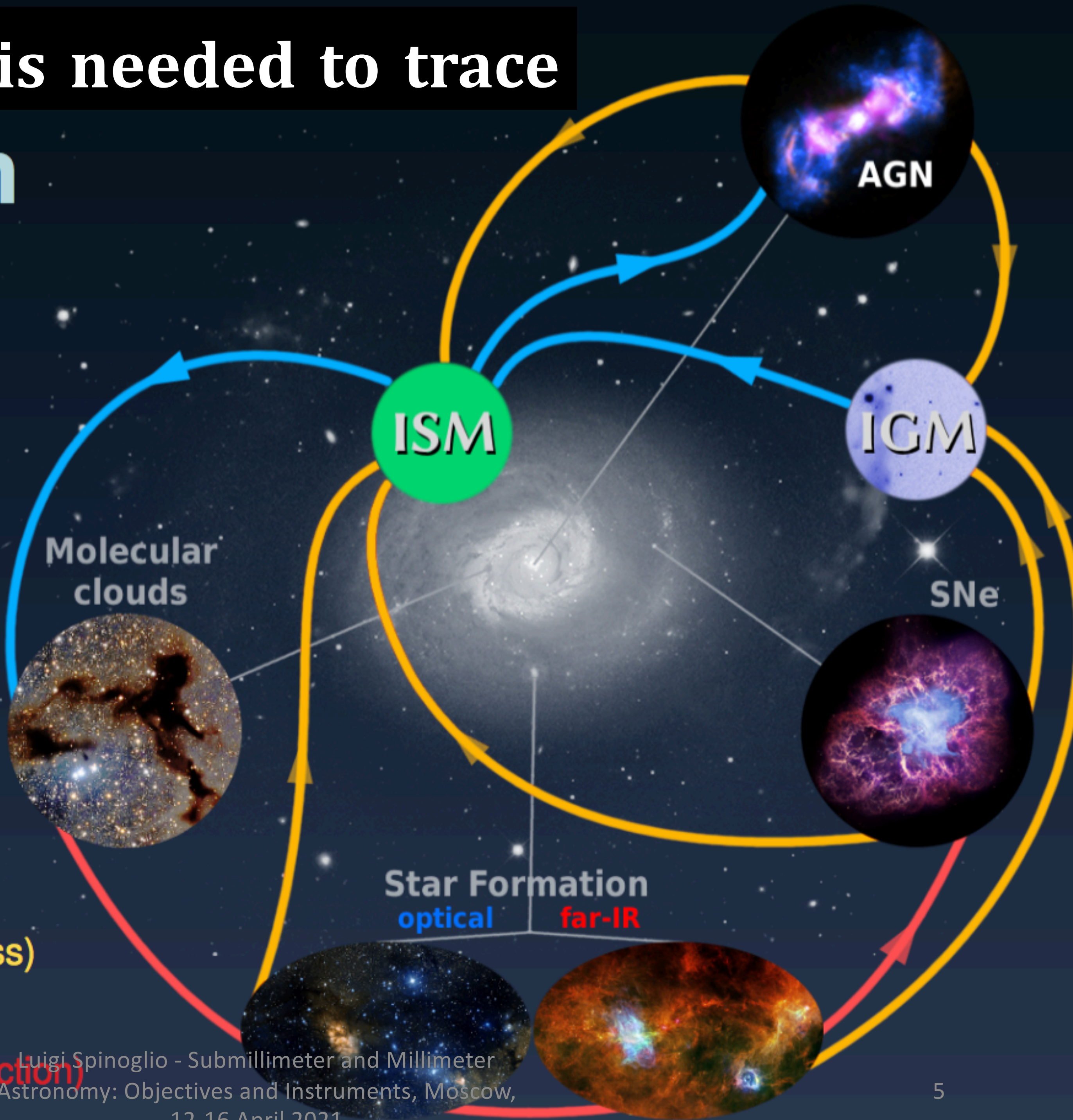
IR spectroscopy is needed to trace

The Baryon Cycle

FEEDING
(inflow, gas cooling)

FEEDBACK
(outflows, jets, stellar-mass loss)

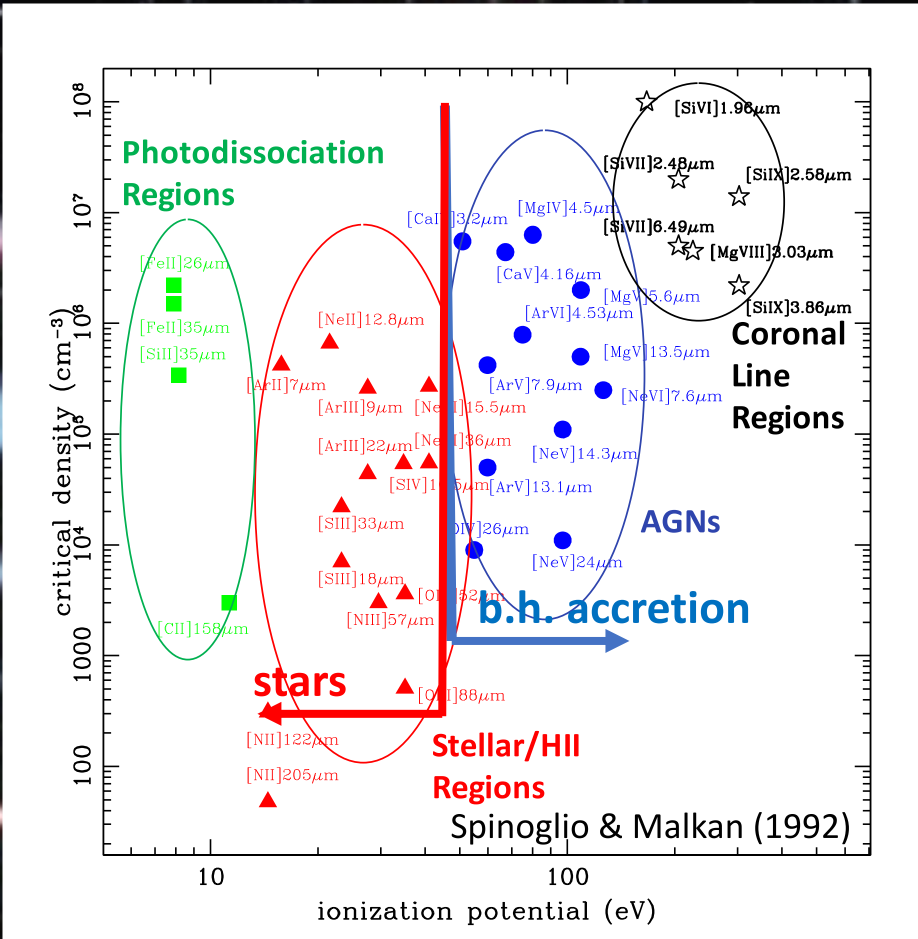
CHEMICAL EVOLUTION
(metal enrichment, dust production)

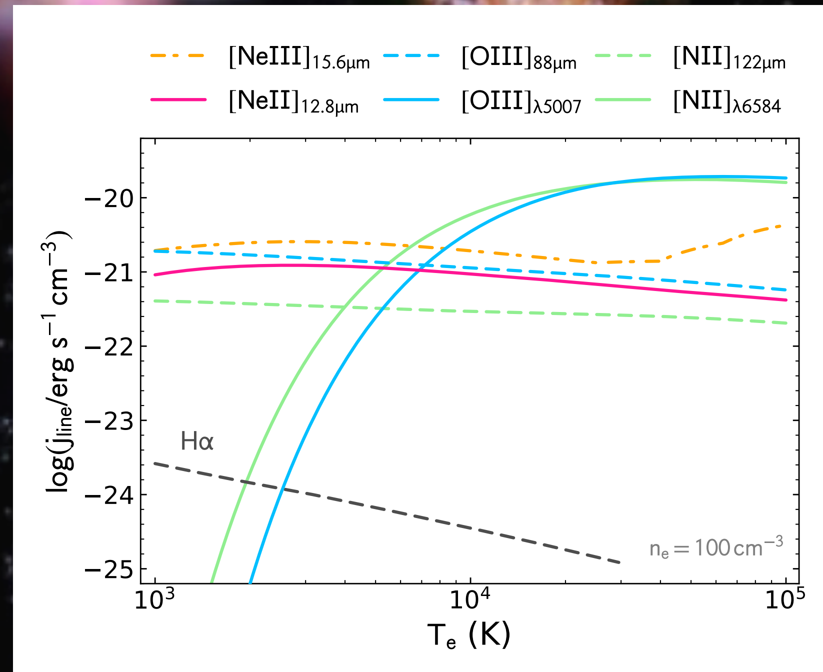


Why infrared spectroscopy ?

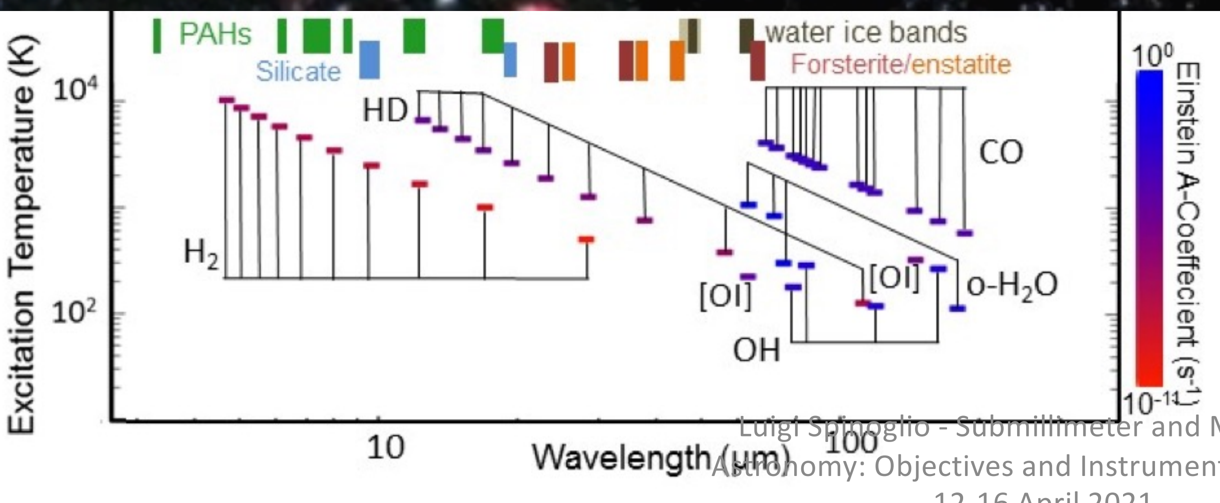
Ionic fine structure lines

- avoid most of extinction
- well cover ionization-density space
- trace star formation vs black hole accretion
- have a very weak dependence on temperature





See Fernàndez-Ontiveros+2021 (arXiv:2103.09253)

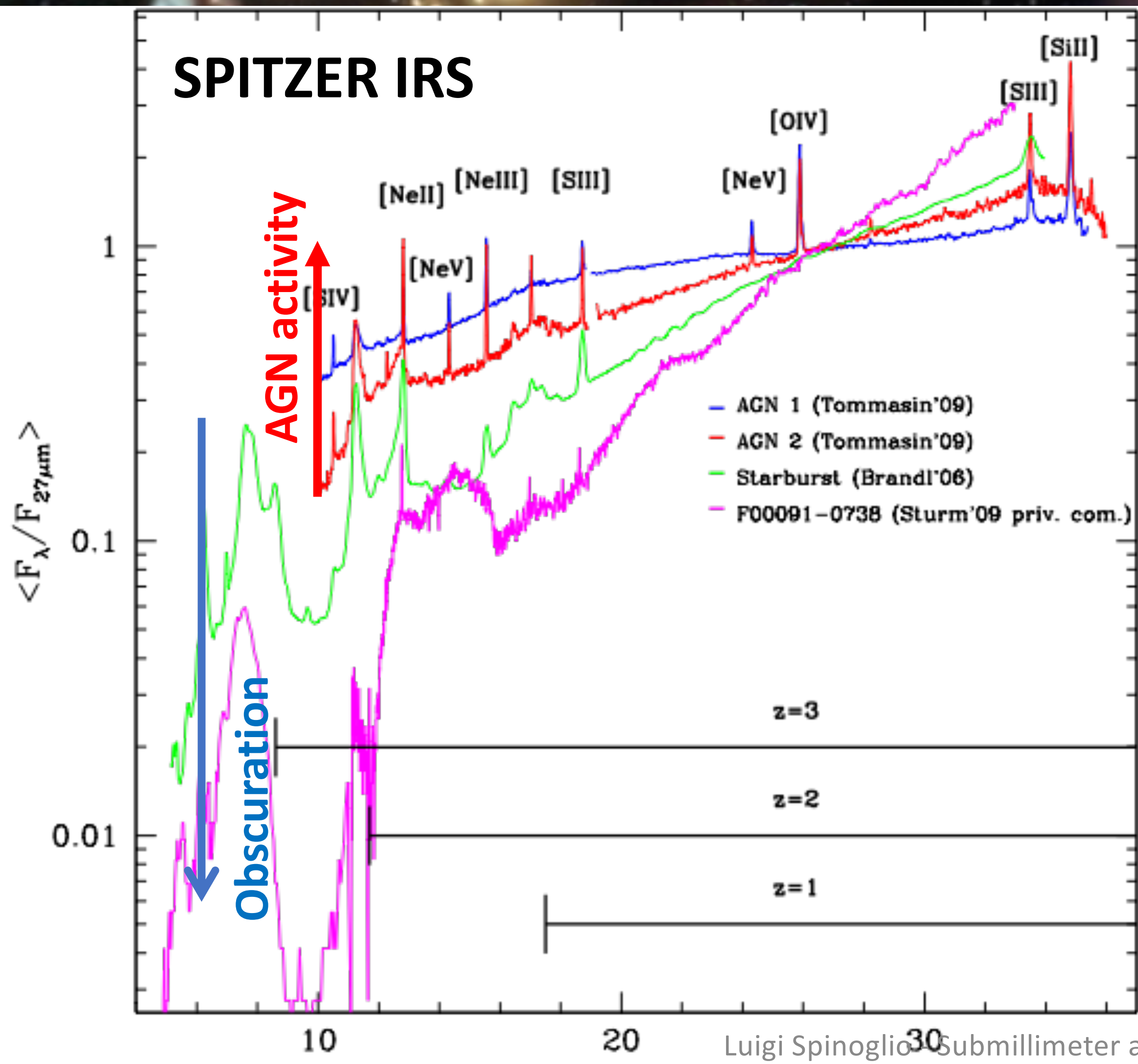


+

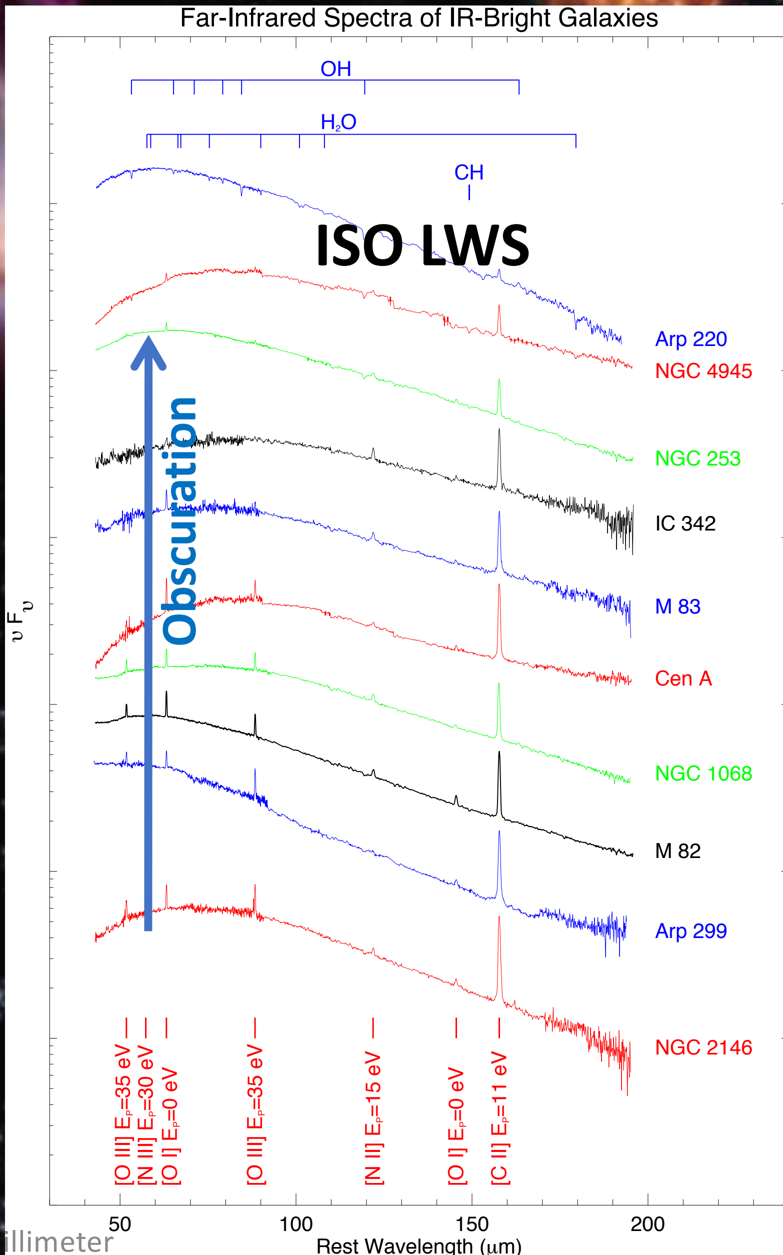
Molecular lines + PAH + Dust features

What was done by ISO & Spitzer

The richness of infrared spectra



Tommasin et al 2010; Sturm p.c.

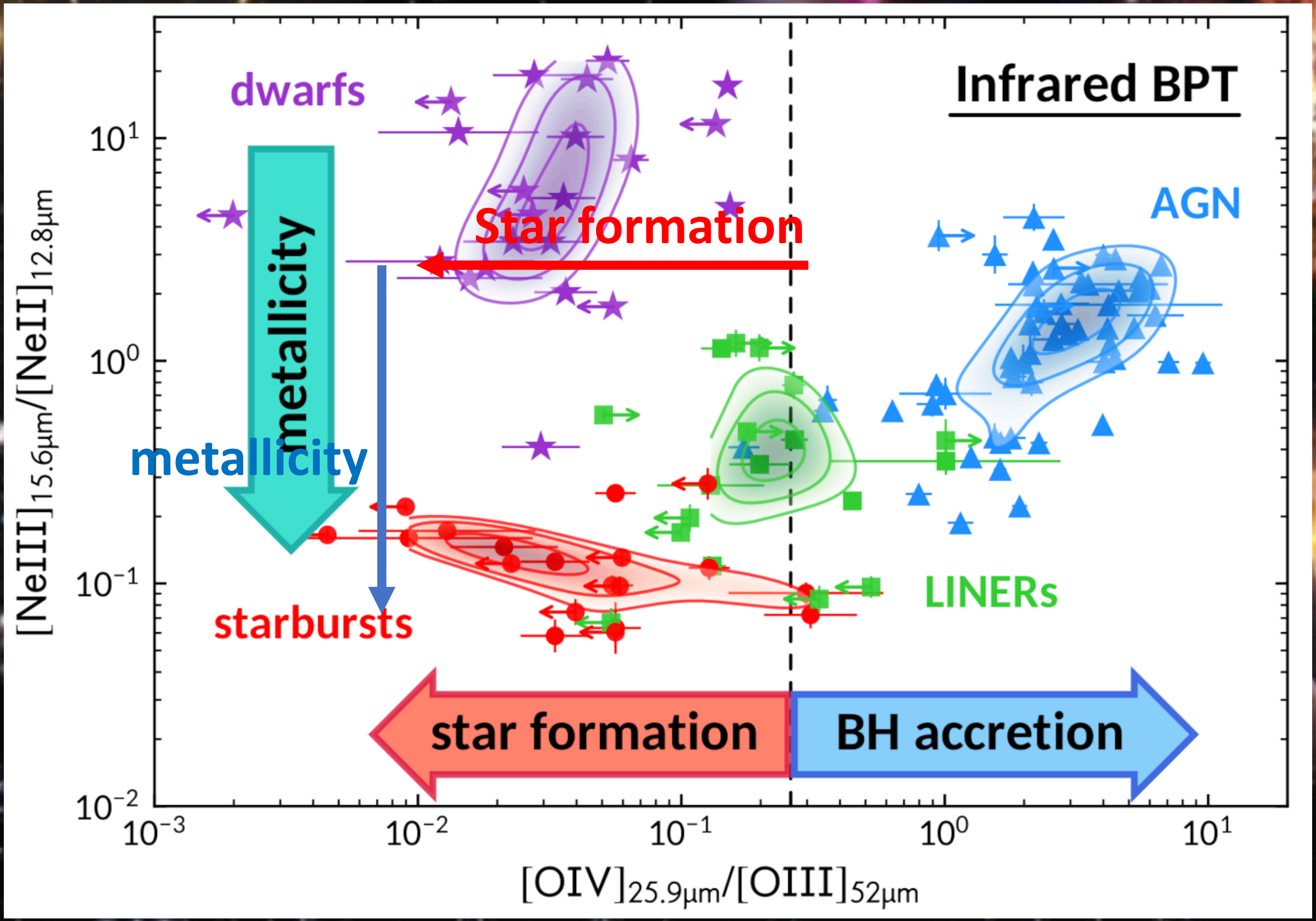


Fischer et al 2009.

Combining Herschel and Spitzer

The new “IR BPT DIAGRAM”

The new BPT diagram separates any type of AGN (Seyfert vs LINER) from any type of SF dominated galaxy (Starburst vs Dwarf galaxies).



- The new BPT diagram (Fernandez-Ontiveros, LS+2016) distinguishes any type of AGN (Seyfert and LINER) from any type of Star Formation dominated galaxy (either Starburst or Dwarf galaxies).

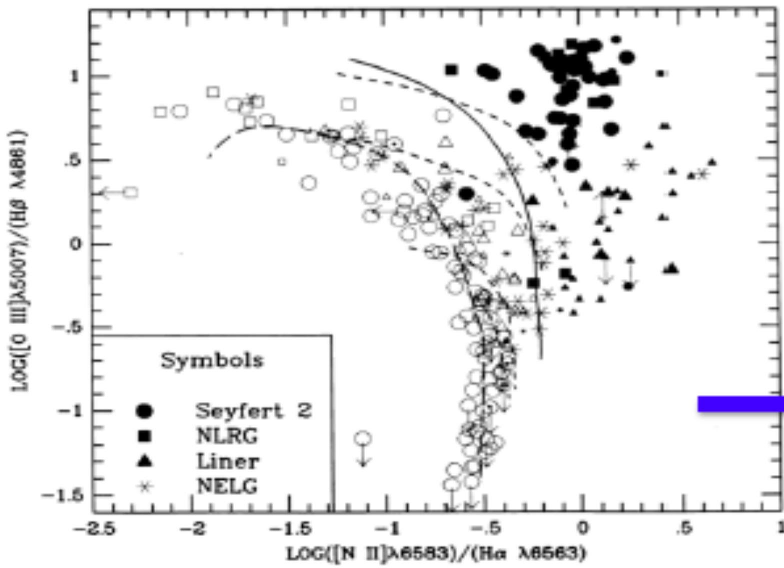
What is next?
We want to apply IR diagnostics to study galaxy evolution with at the Cosmic Noon (z~1-3) and beyond

- We know the tools ($\lambda_{REST-FRAME}$~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)
- **We need a large cooled telescope to cover the missing range (λ=40-350µm)**

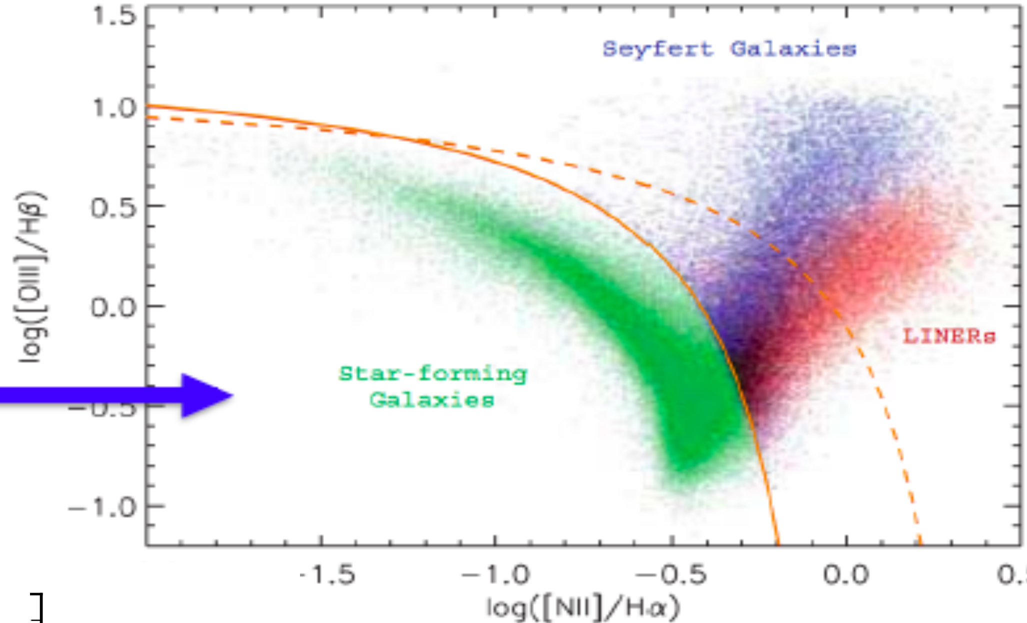
What we want to do?

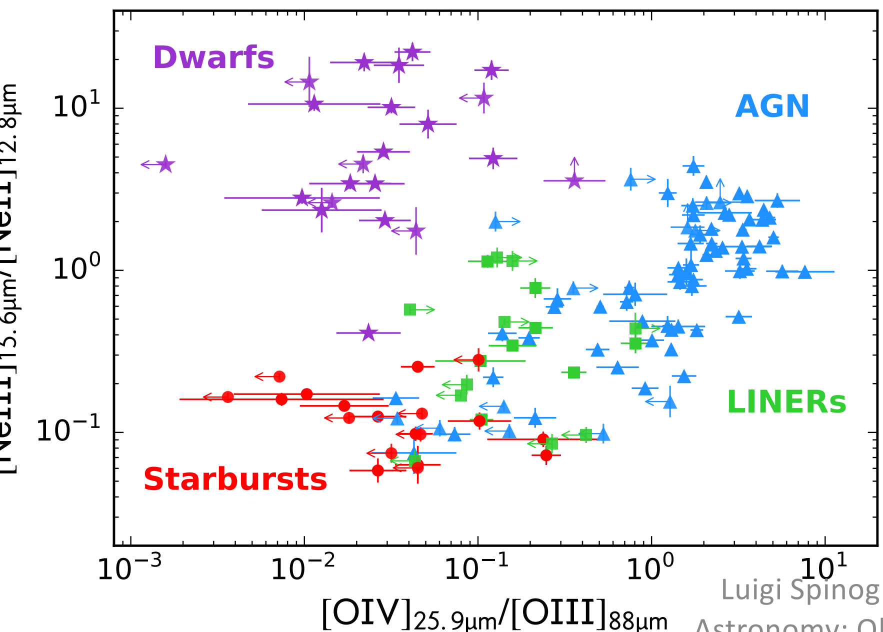
OPTICAL SPECTROSCOPY

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



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





z ~ 1-5

OST/Millimetron?

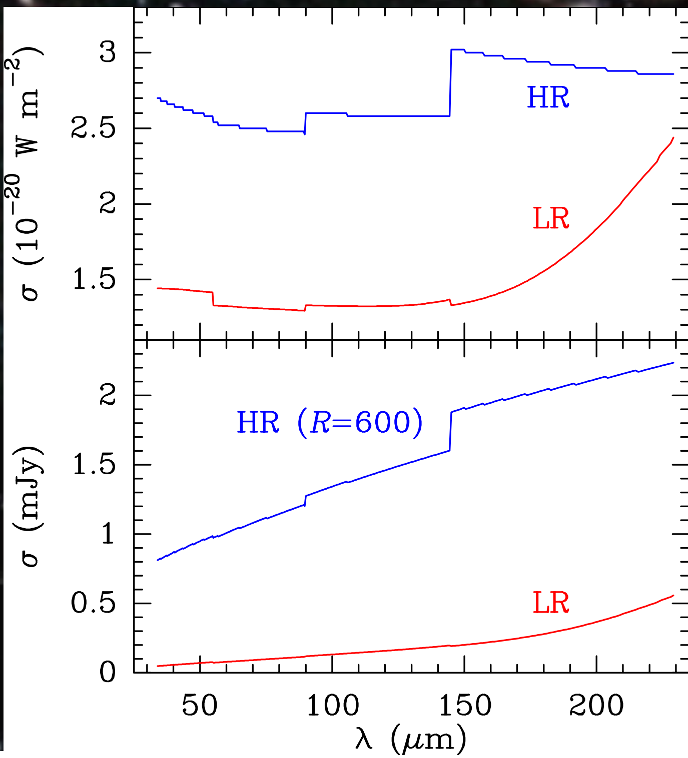
~ 2030-2035

Feedback & Feeding in the context of galaxy evolution
Does feedback stop star formation?

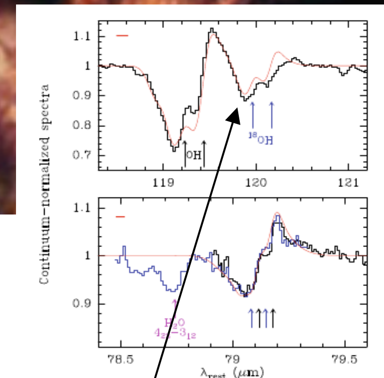
Low spectral resolution observations to measure statistics (outflow occurrence)

→ key tracers of atomic and molecular outflows/inflows in galaxies near the peak epoch of Star Formation (z < 2).

White paper by Eduardo González-Alfonso et al. (2017, PASA)

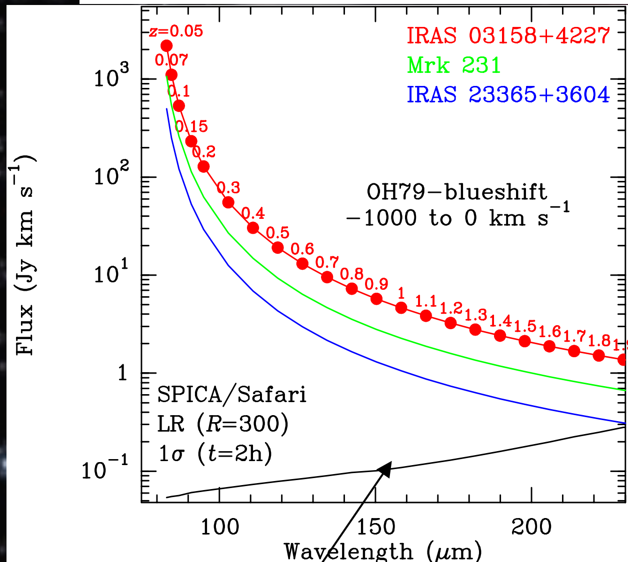


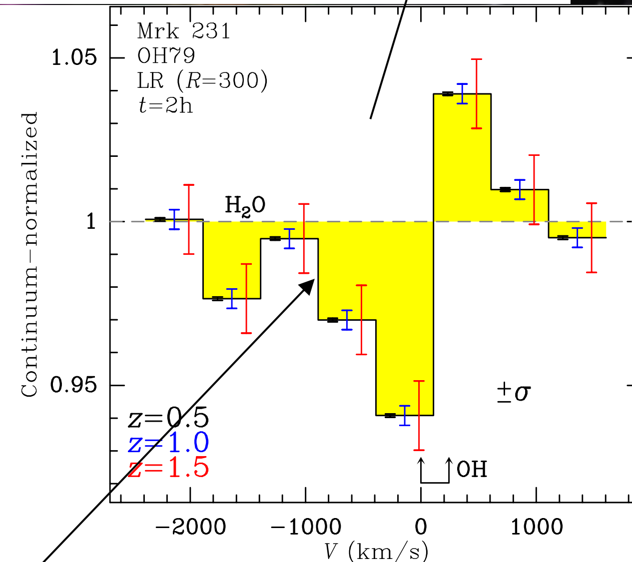
Current SAFARI Low resolution (LR) and high-resolution (HR) sensitivities



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

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





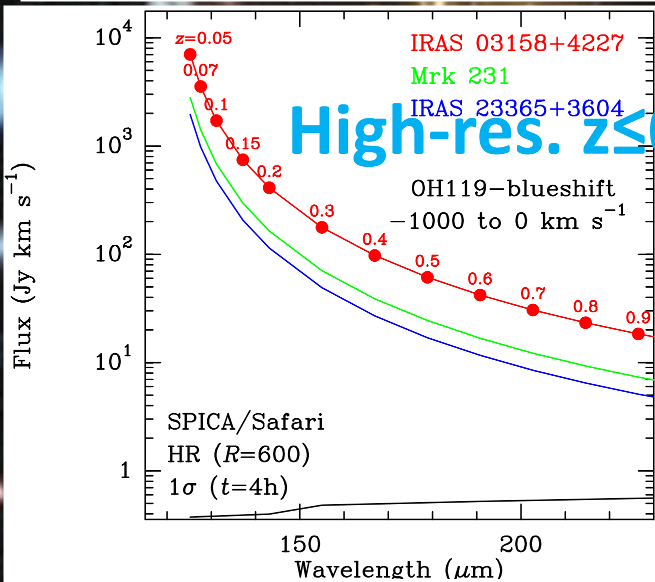
*OH79 shows P-Cygni in many local ULIRGs
*We use 3 templates: flux of blueshifted wings vs z
**Black curve*: Safari sensitivities in LR (R=300) mode
**Continuum-normalized vs velocity* is redshift-invariant
*Errorbars: +/-1σ at z=0.5, 1, 1.5 (Mrk 231, LR-2h)

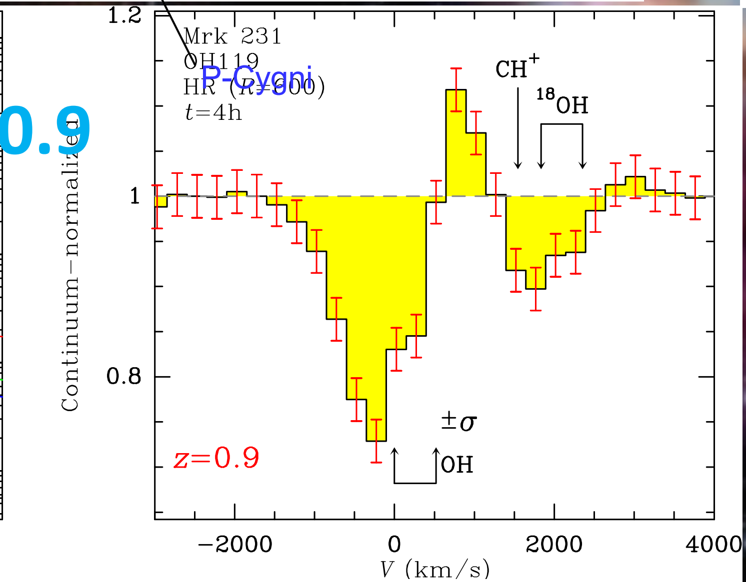
Low-res.
z≤1.9

Feedback & Feeding in the context of galaxy evolution

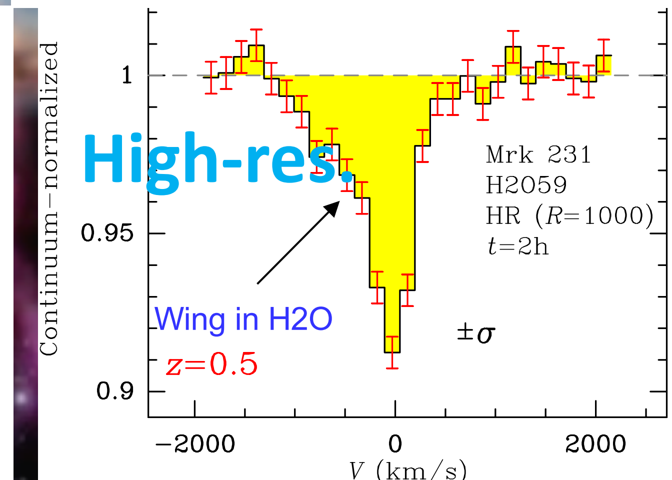
High spectral resolution observations to measure physical parameters (mass, energy, velocity...)

At high-R the OH doublet at 119 μm can be observed up to z~0.93

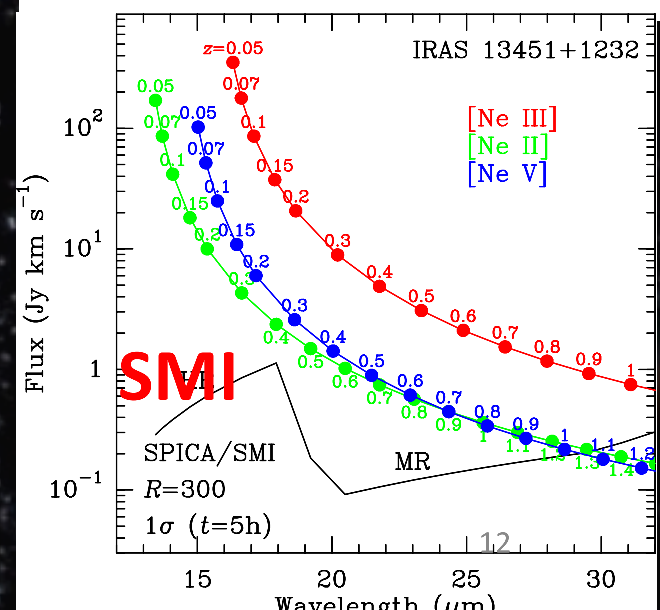




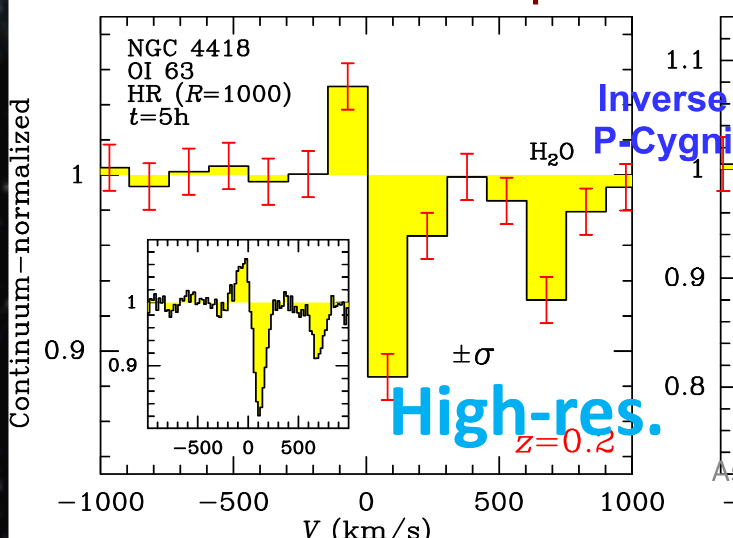
Outflows in other molecules, like H2O

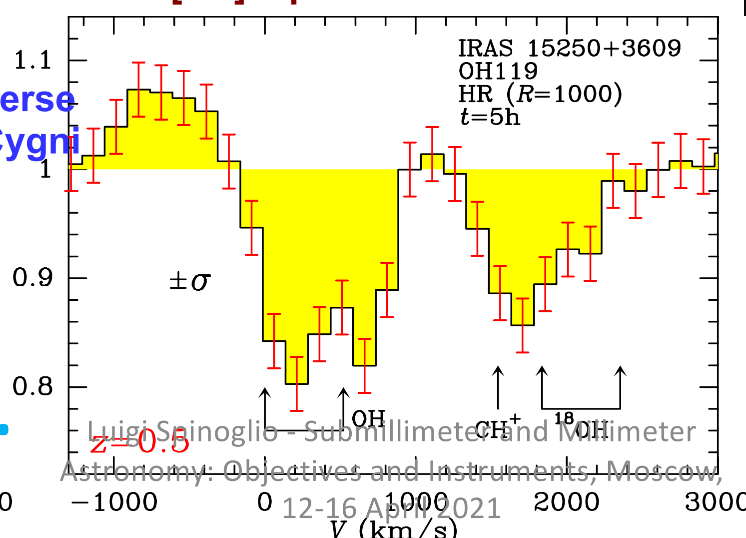


SMI will detect outflows in Ne lines



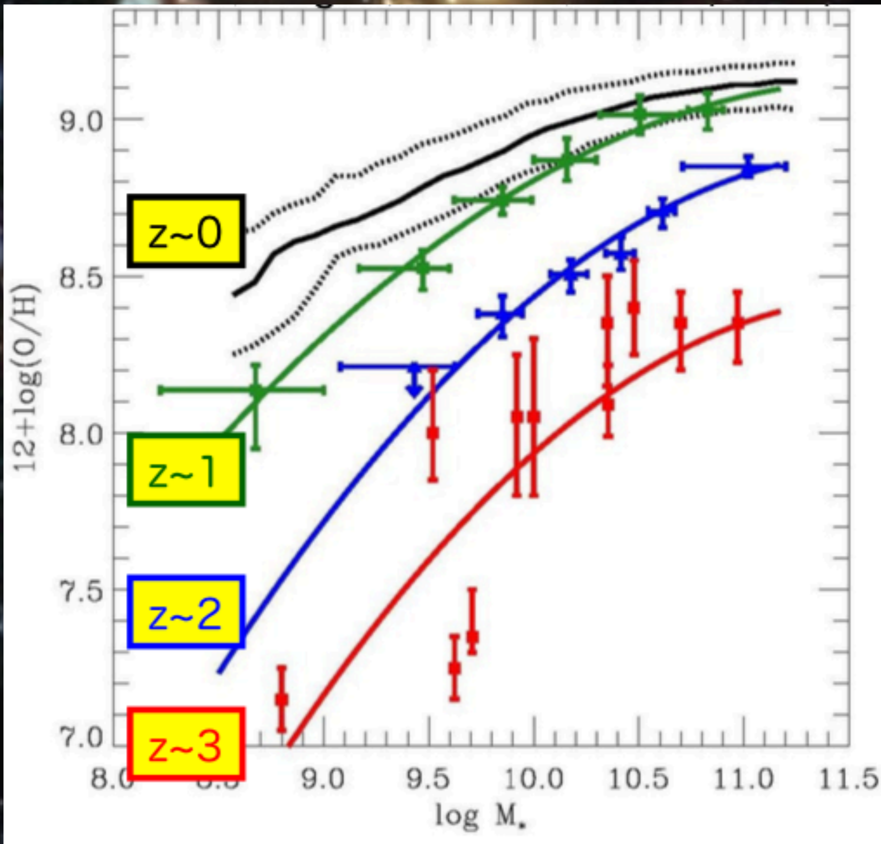
We will also explore inflows in [O I]63μm and OH





Chemical Evolution with Far-IR lines

REVISE the Mass-Metallicity relation



Maiolino, Nagao & Grazian et al. (2008)

based on optical lines, which have two strong biases:

1. Optical lines strongly depend on temperature
2. At z>1 dust obscuration prevents the observation of the embedded star formation (~90%): at high redshift (z~3) optical lines might only see the external parts of galaxies

SPICA and the Chemical Evolution of Galaxies: The Rise of Metals and Dust
white paper by Juan Antonio Fernandez-Ontiveros et al. (2017, PASA)

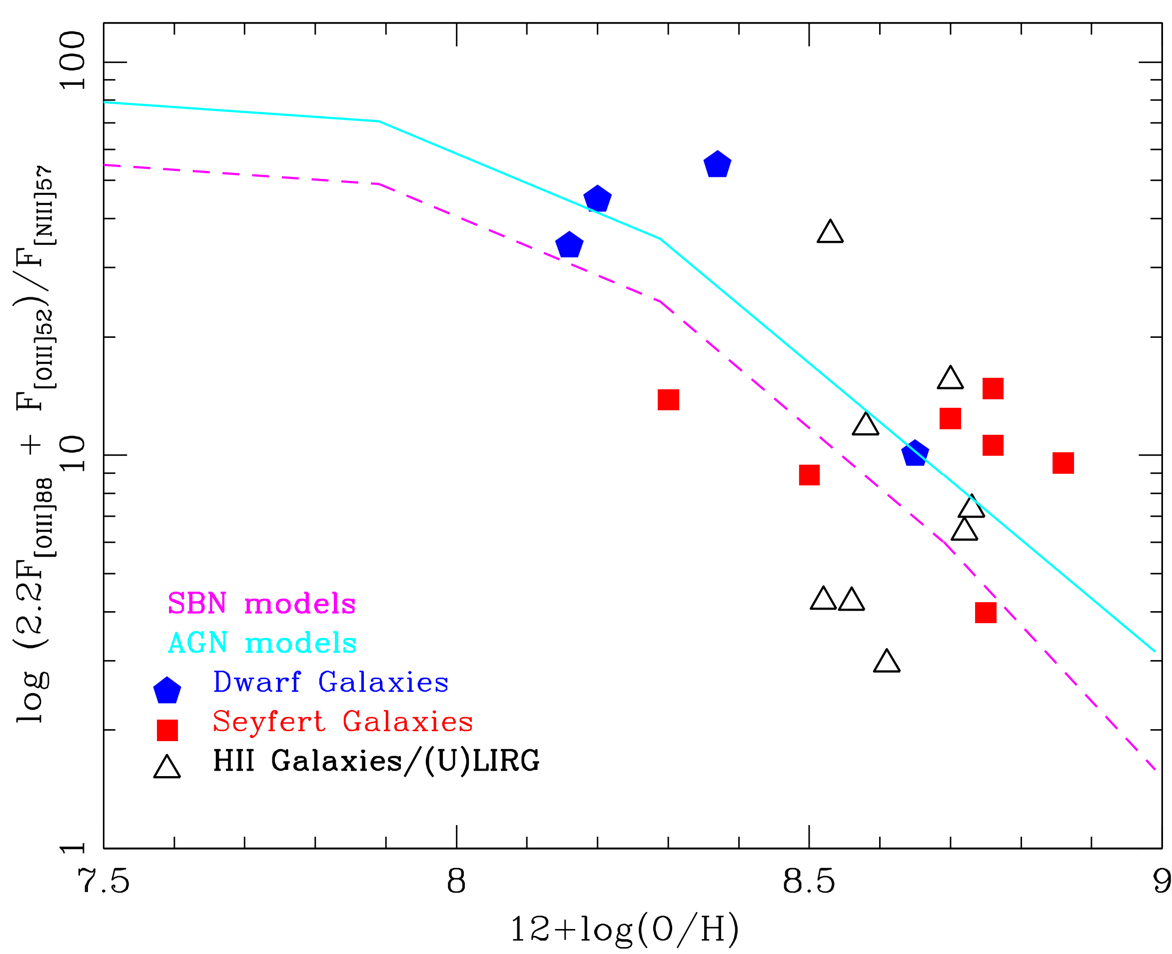
Measuring metallicities with FIR lines

Indirect method:

- Calibration is given by photoionization models (for AGN and starburst)
- Measure

2.2x[Oiii]88μm+[Oiii]52μm /[Niii]57μm

(Nagao+2011 and Pereira- Santaella et al. 2017)



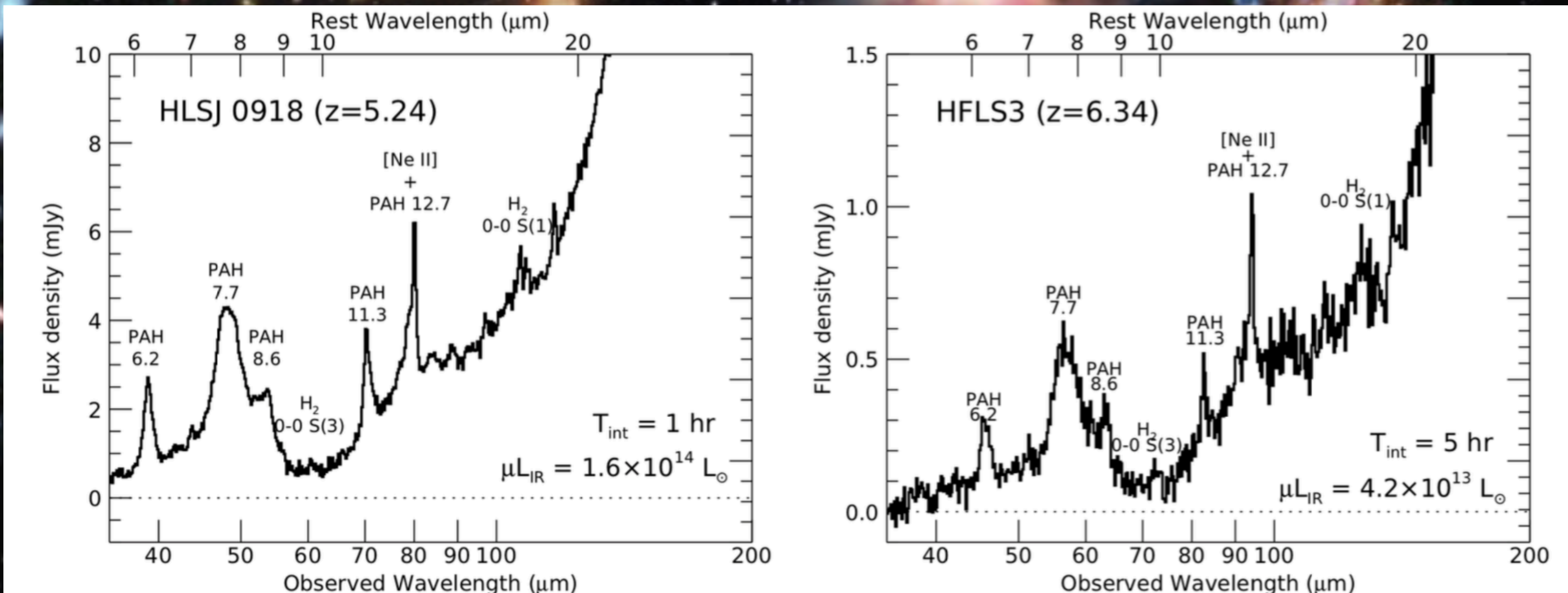
N/O ratio estimator versus optical metallicity for a small sample of local galaxies (data from Herschel & SOFIA)

We have developed a new method to derive heavy element abundances using the fine-structure lines in the mid- to far-infrared (IR) range. (Fernàndez-Ontiveros+2021 (arXiv:2103.09253, A&A, in press)

See the web page where the code is available: https://www.iaa.csic.es/~epm/HII-CHI-mistry.html

Probing the High-Redshift Universe with FIR spectroscopy

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.



Simulated SAFARI spectra of HLSJ0918 and HFLS3 produced with the L_{IR}~10^{12} $L_{\odot}$ galaxy spectral template (Rieke et al. 2009), scaled to μL_{IR}=16 and 4×10^{13} $L_{\odot}$, respectively. These are both gravitationally lensed by factors of 9 and 2, respectively.

White paper by Eiichi Egami et al. (2018, PASA)

The galaxy evolution observing strategy

The observing strategy will consider a step by step observational sequence:

1. **Deep spectrophotometric surveys in the mid-IR**, at the shortest λ (40µm?) imaging spectrometer of large fields (of order 1- 10 deg^2) to very faint limits (i.e. 3-10µJy in the continuum at 40µm and 2-5 x 10^-20 W/m^2 in the spectral lines). Complement these observations with the camera at 70µm

   ➔ **provide a 3-D view of galaxy evolution**

2. **Identification of a sample of galaxies based the above surveys**, in terms of redshift, mid-IR luminosity, classification (i.e. Starburst-dominated or AGN-dominated), ✚ Stellar Masses, Dust Masses and Bolometric Luminosities using available multifrequency data.

3. **Deep follow-up observations with grating spectrometers** (50-450µm) of the above defined sample.

➔ **complete spectral atlas of galaxies as a function of redshift, luminosity and stellar mass**

4. **Measure all physical properties:** Star Formation Rate (SFR), Black Hole Accretion Rate (BHAR), metal abundances, outflow/infall occurrence, etc.

The evolution of these physical quantities as a function of cosmic time will tell us the "physical" history of galaxy formation and evolution.

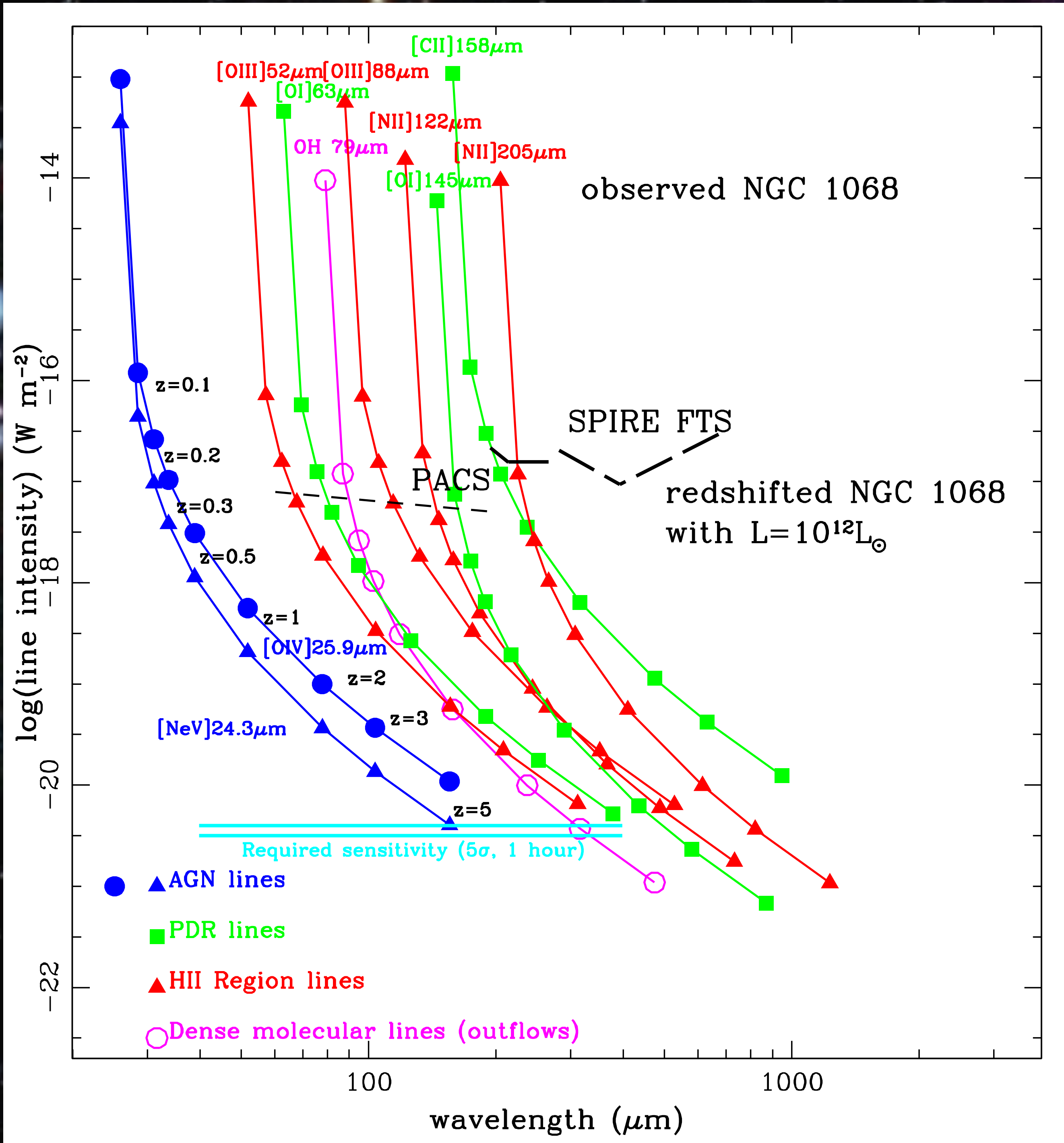
How do we understand galaxy evolution with FIR spectroscopy from the space?

- Galaxy evolution mission program outcome:

1. Mapping the role of Star Formation and Black-Hole Accretion (and their interactions) though cosmic time
2. Mapping AGN feedback through high resolution (R>1000) observations of P-Cygni profiles in AGN and Starburst galaxies at $0.5<z<4$
3. Mapping metallicity evolution through FIR lines of [OIII]52 & 88μm and [NIII]57μm at $0.5<z<4$
4. Exploring FIR spectra of $5<z<8$ galaxies and quasars to understand the origin of cosmic dust

what are the science requirements?

- we need to have a 3-D view of Galaxy Evolution in large fields with spectrophotometric imaging at e.g. 40-70μm
- we need to trace Star Formation and Black Hole Accretion
- we need sensitivities of the order of 10^(-21) W/m^2
- we will follow-up targets in the range 70-400μm with pointed grating spectroscopy



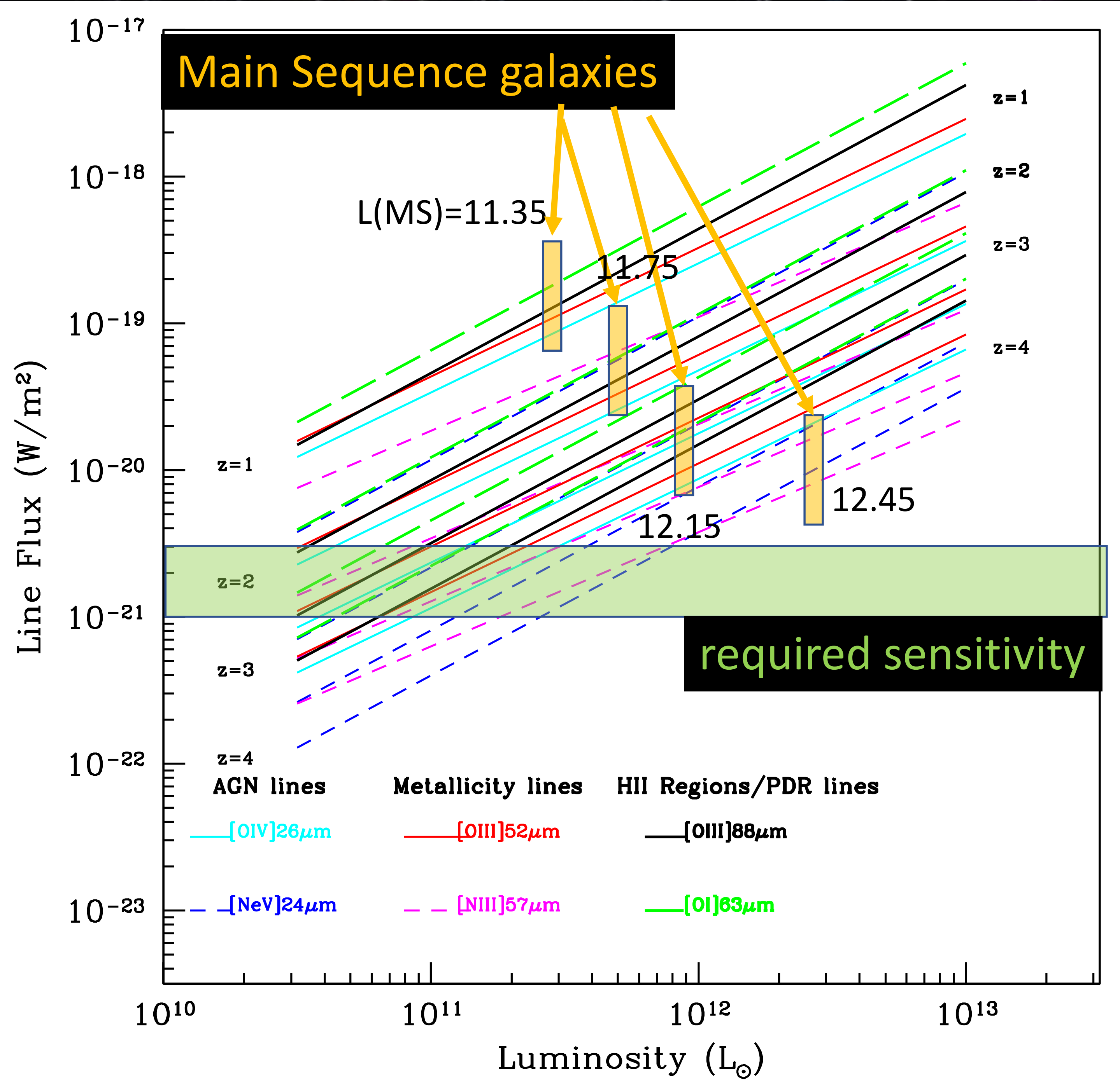
science requirements

tracing BHAR up to z~5 requires detecting the [OIV]26μm or the [NeV]24μm line

tracing the SFR up to z~5 requires detecting either one of the [OIII] and [OI] lines

We need a sensitivity of the order of 10^-21 W/m^2 (5**σ**, 1 hour)

science requirements



The predicted line flux is plotted against the total IR luminosity of a galaxy at different redshift.

For the four redshifts given (1<z<4) the luminosity of a "Main Sequence" galaxy of mass M=10^10-10^11 Mo is given.

The required line sensitivity to detect galaxies below their main Sequence at redshift z=4 is of the order of 10^(-21) W/m^2 (5**σ**, 1 hour)

Preliminary Science Payload of "Millimetron"

1) **S**pace-**VLBI** receivers (**S-VLBI**): **0.3 - 7 mm**

2) **M**mtron **H**eterodyne **I**nstrument
for the **F**ar-**I**nfrared (**MHIFI**): **60 - 600 μm**

3) **S**hort-wave **A**rray **C**amera **S**pectrometer **(SACS):**
- **Camera**: 4 bands: **70, 125, 230, 375 μm**
- **Spectrometer**: long slit grating spectrometers: **50 - 450 μm**

4) **L**ong wave-**A**rray **C**amera **S**pectrometer **(LACS):**
- **Camera**: 4 bands: **0.4, 0.7, 1.2, 2.3 mm**
- **Spectrometer**: the FTS: **0.3 - 3 mm**

- need to have a imaging (grism/grating) spectrometer at low spectral resolution (R~300-600) able to cover instantaneously large sky areas (few arcmin^2) to obtain a 3-Dimensional view of the hidden star formation and BH accretion at the Cosmic Noon

- need also to have grating/FTS spectrometer for pointed follow up observations of targets ➔ full characterization of galaxies ➔ measuring feedback at R>1000

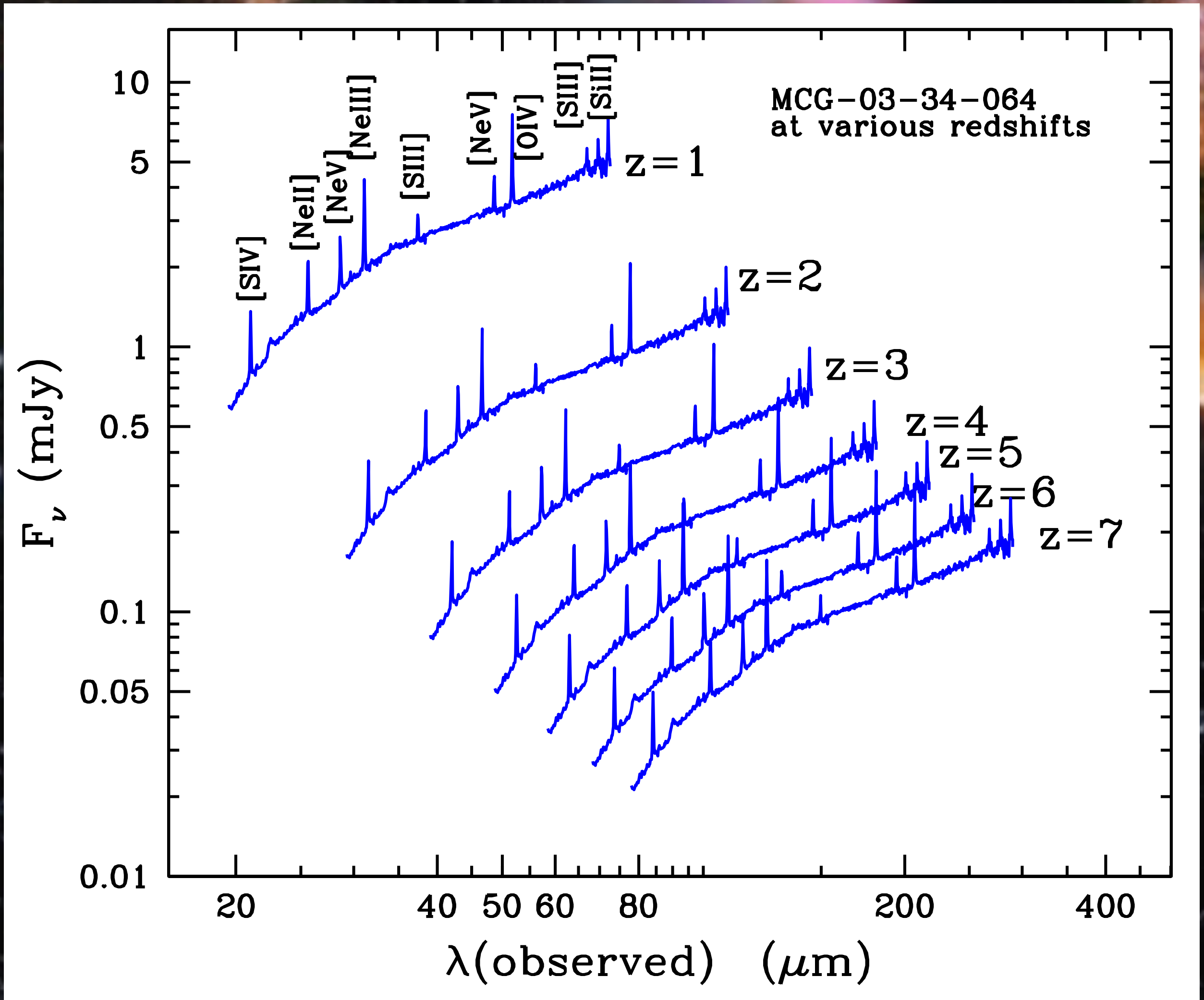
Conclusions

- We can measure the hidden star formation and AGN accretion, through FIR spectroscopy, unaffected by dust, to study the evolution of galaxies **- the first step towards understanding galaxy evolution over the history of the Universe**
- We worked 15 years on the SPICA mission, that suddendly – just few months before the final selection - has been cancelled by ESA for an unclear overcost problem: **we need another mission and not disperse the huge work done.** (Spinoglio+21 astro-ph & PASA)
- A large FIR space telescope will "physically" measure galaxy evolution through spectra:

1. SF and SMBH growth, AGN feedback, molecular and atomic outflows, and gas inflow out to z~2 (with resolution R~2000-10000) and to z~4 in low resolution (R~300)
2. **Detect dust during re-ionization and chart the production of heavy elements and organic molecules in the ISM of galaxies as a function of cosmic time.**
3. Collect rest-frame mid-IR spectra up to z~10 for luminous galaxies ($L_{IR}>2\times10^{13}L_\odot$).

- **Millimetron, if equipped with powerful imaging multiplexing spectrometers (R=300-600) (able to reach 10^{-21} W/m^2) + higher R (1,000+) pointed spectrometers, can do the job.**

Backup Slides



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.