超高感度赤外線衛星SPICAによる宇宙進化史の解明

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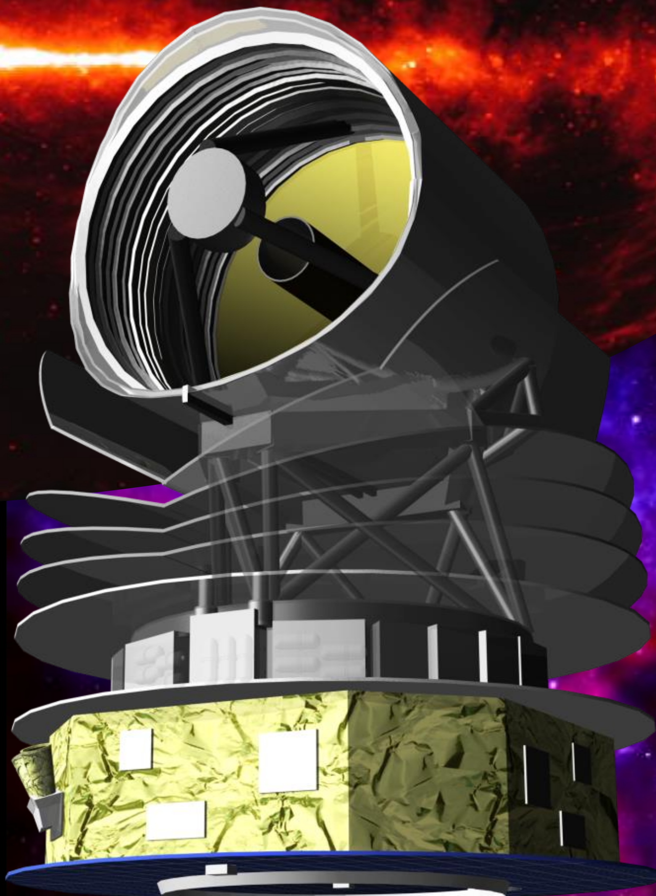
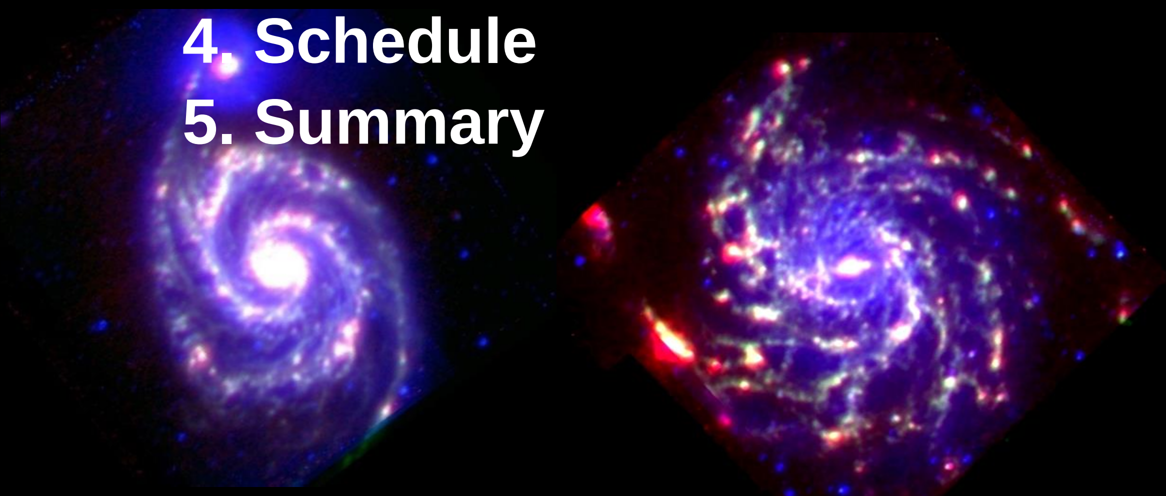
他SPICAチームメンバー

Outline:

1. Current status of SPICA
2. SPICA primary science goals
3. Science observation plans
4. Schedule
5. Summary





1. Current status of SPICA

SPICA, proposed as an ESA-JAXA collaboration mission

Specifications

- **Telescope**: 2.5 m, < 8 K with mechanical coolers
- **Wavelength range**: 10 – 350 μm
- **Orbit**: Sun – Earth L2 Halo
- **Launcher**: JAXA H3 rocket
- **Launch year:** 2029 ~ 2031 (to be discussed with ESA)
- **Lifetime**: 5-years goal（cryogen-free architecture）

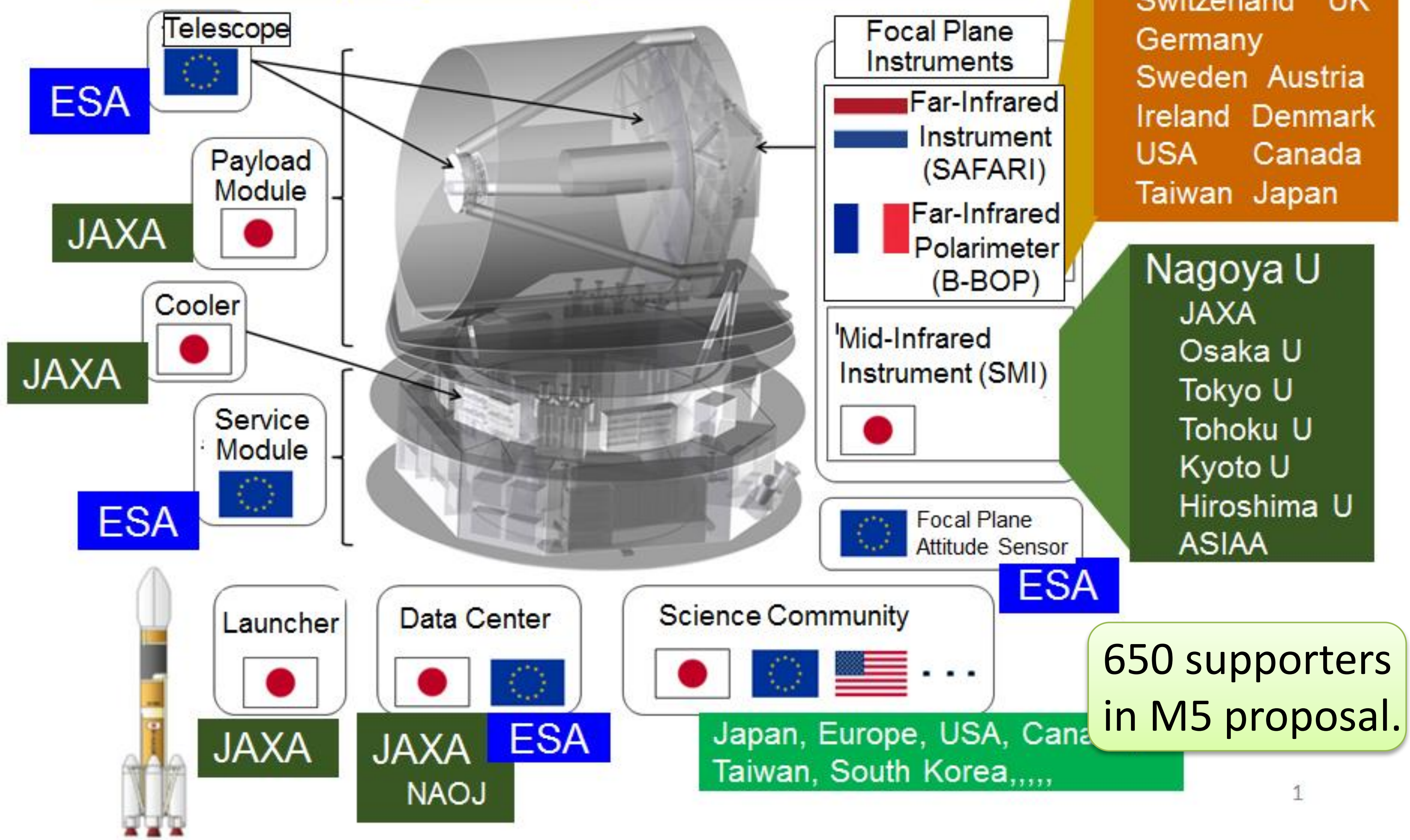
JAXA: passed MDR as a strategic L-class mission candidate (#3 slot), and started Phase-A activity (2016 ~)

ESA: selected as one of the three CV M-class mission candidates, and started Phase-A activity (May 2018 ~)

New SPICA: Technically more feasible, financially more affordable

International workshare plan

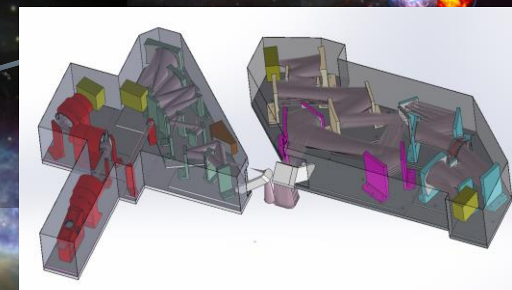
JAXA & ESA as major partners for each other.



SPICA focal-plane instruments

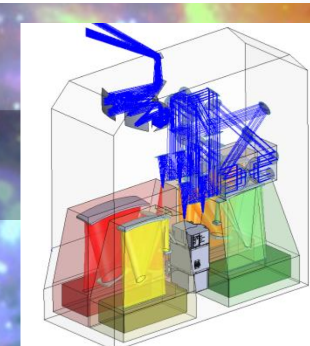
Mid-infrared instrument

- **SMI**: 17–36 μm, *R*~100 spectrometer & 10’x12’ camera
  18–36 μm, *R*~1200–2300 spectrometer
  10–18 μm, spectroscopy at *R*~30000

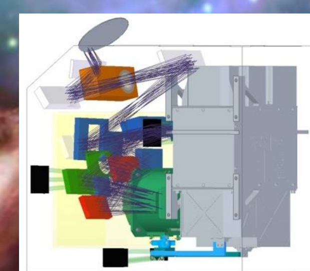


Far-infrared instruments

- **SAFARI**: 34–230 μm spectroscopy at R~300 & 11000

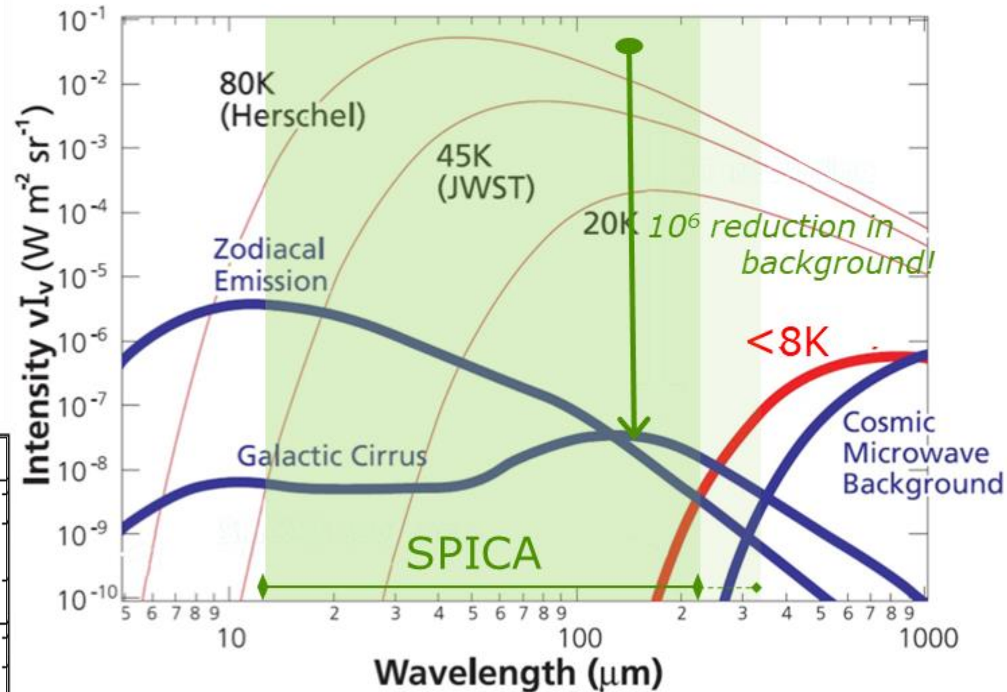


- **B-BOP**: 70, 200, 350 μm imaging polarimetry

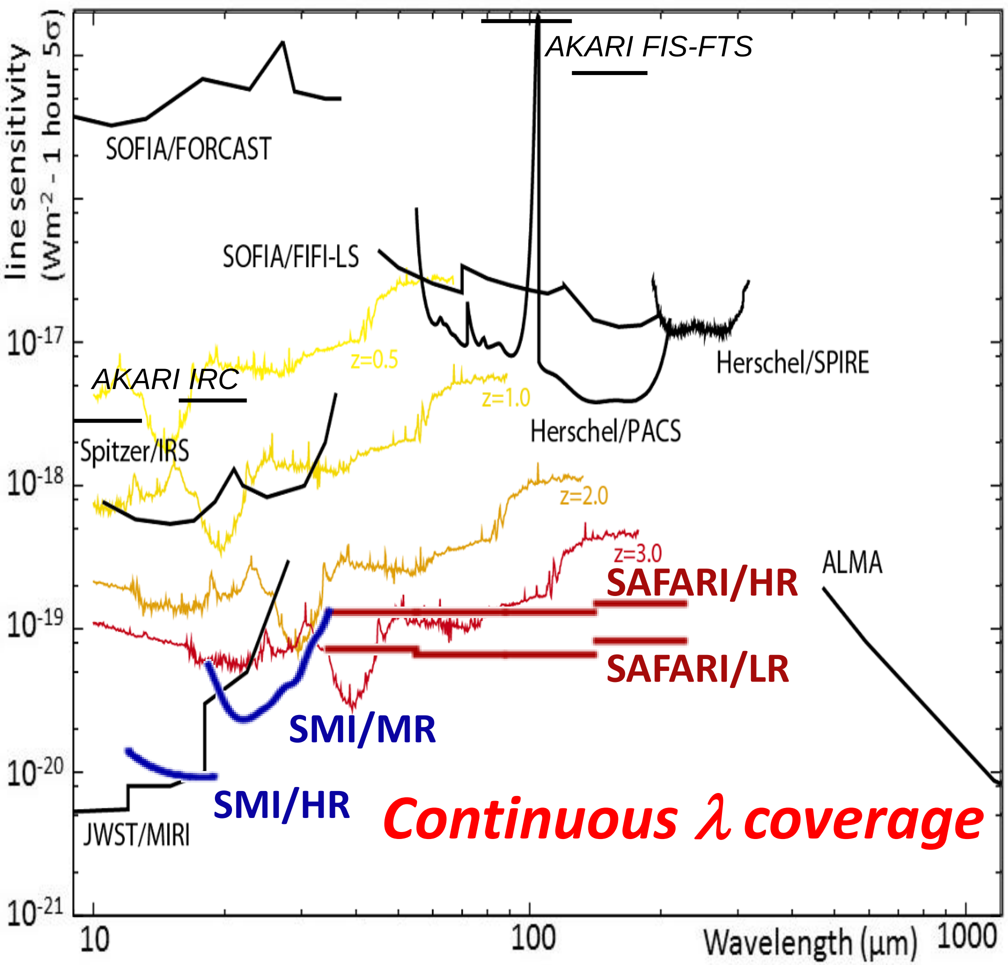


SPICA

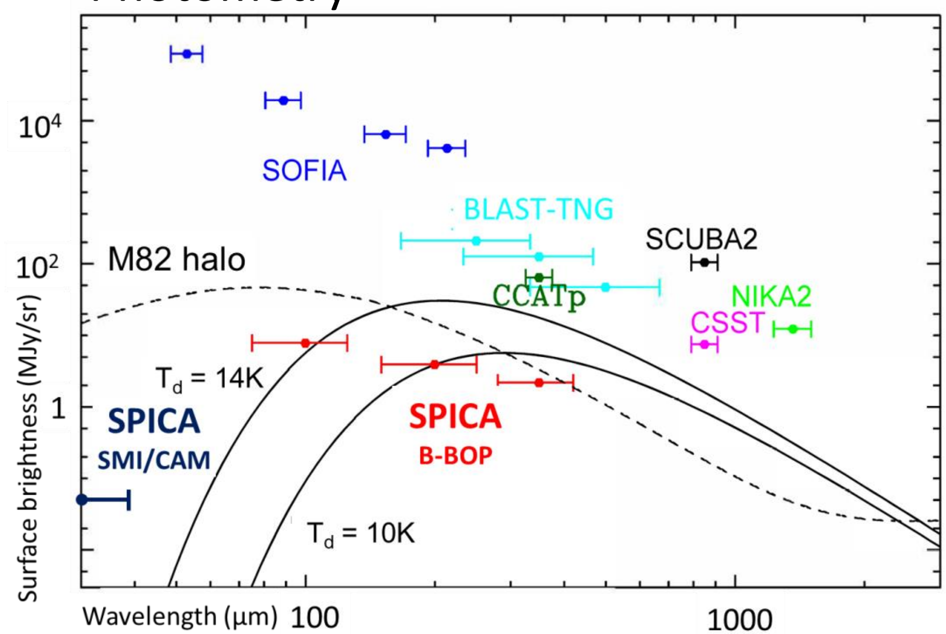
A big cooled mirror in space to unveil the cold obscured Universe



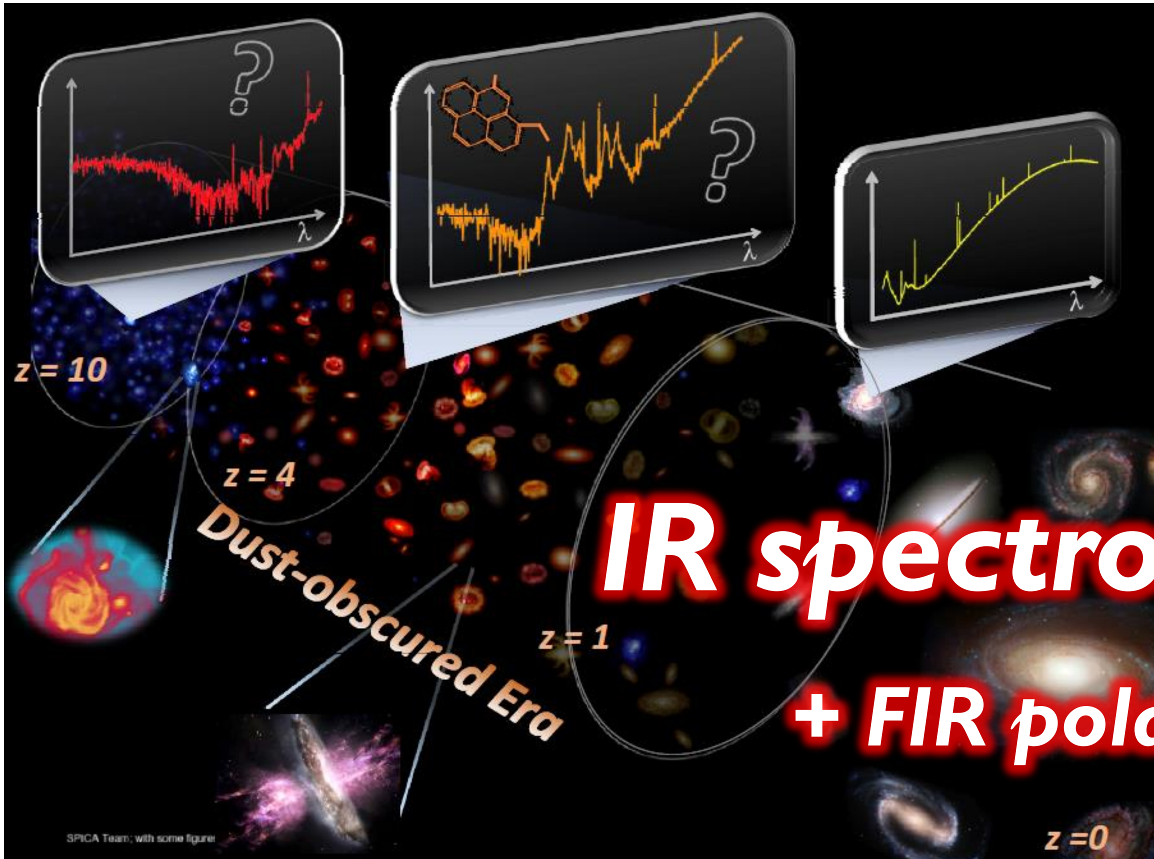
Spectroscopy

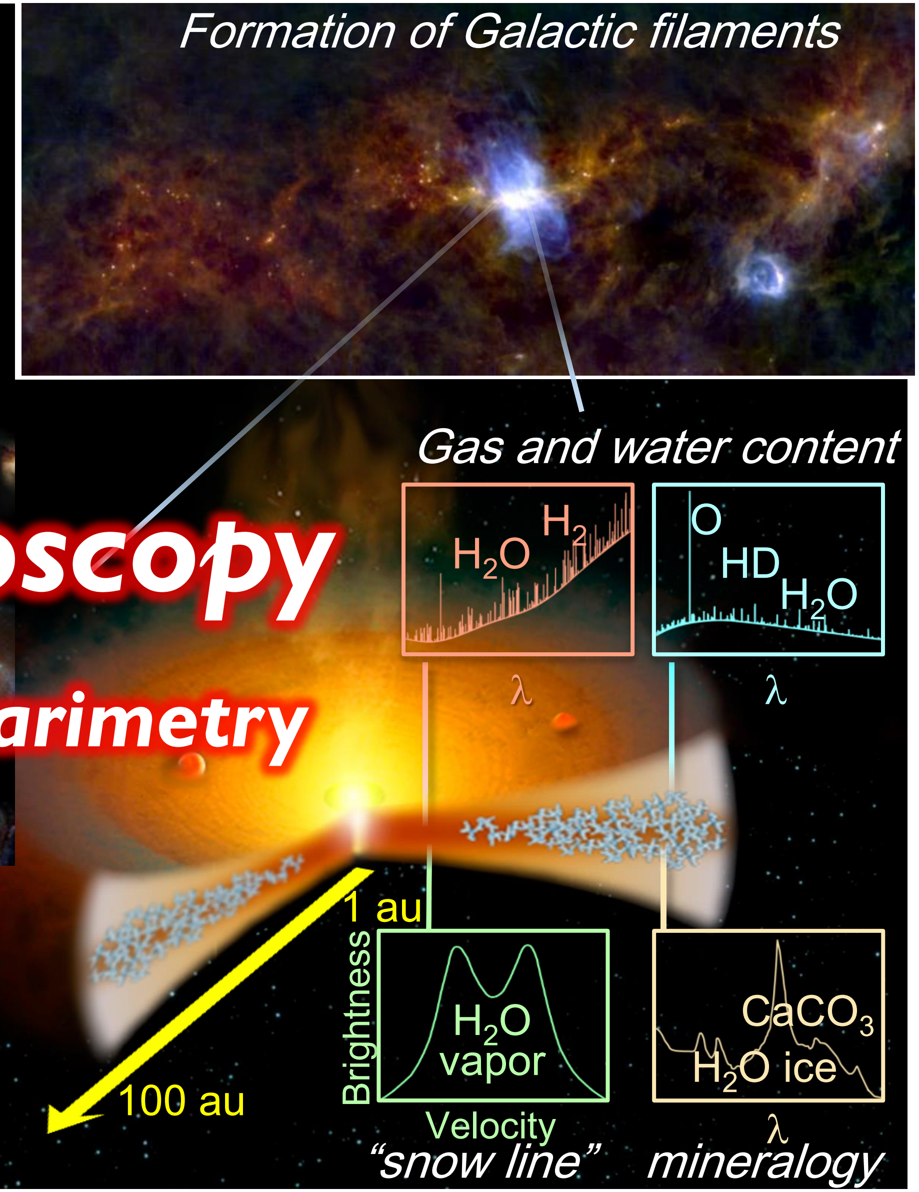


Photometry



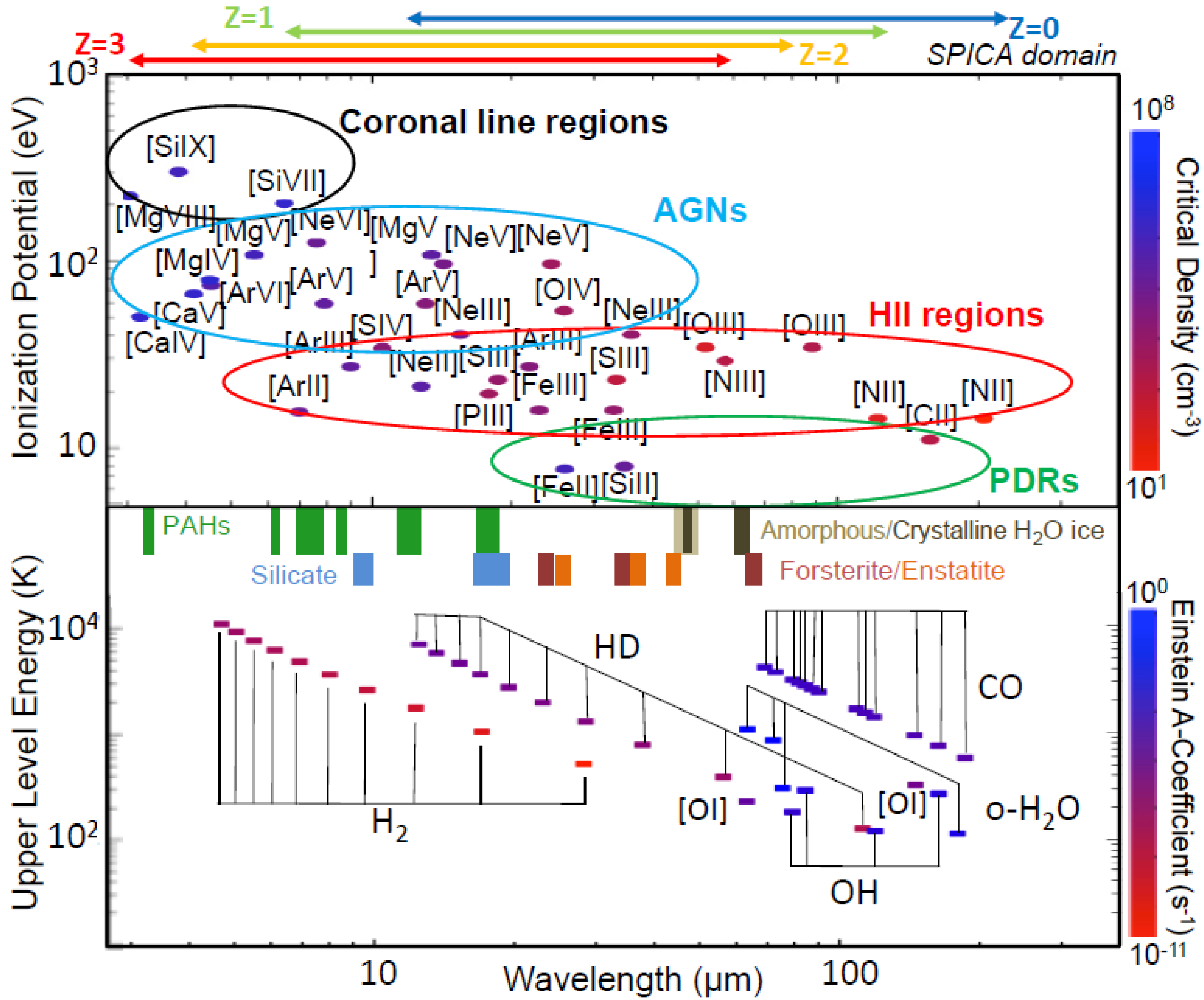
2. SPICA primary science goals





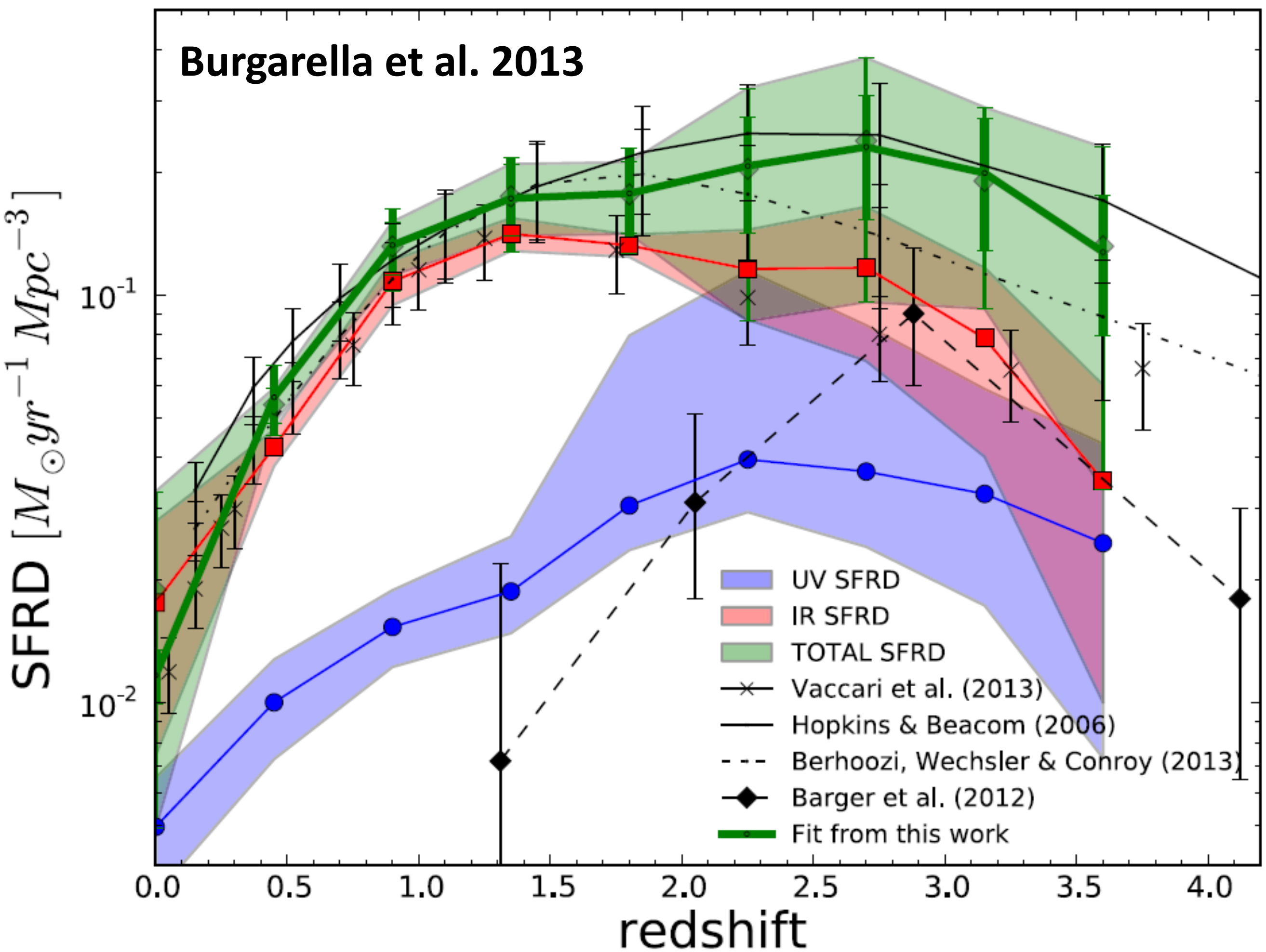
With unprecedented high IR sensitivity, SPICA would unveil the dusty era in the Universe (evolution of galaxies), and find a route to habitable planets (formation of planetary systems).

IR spectral diagnostics with SPICA

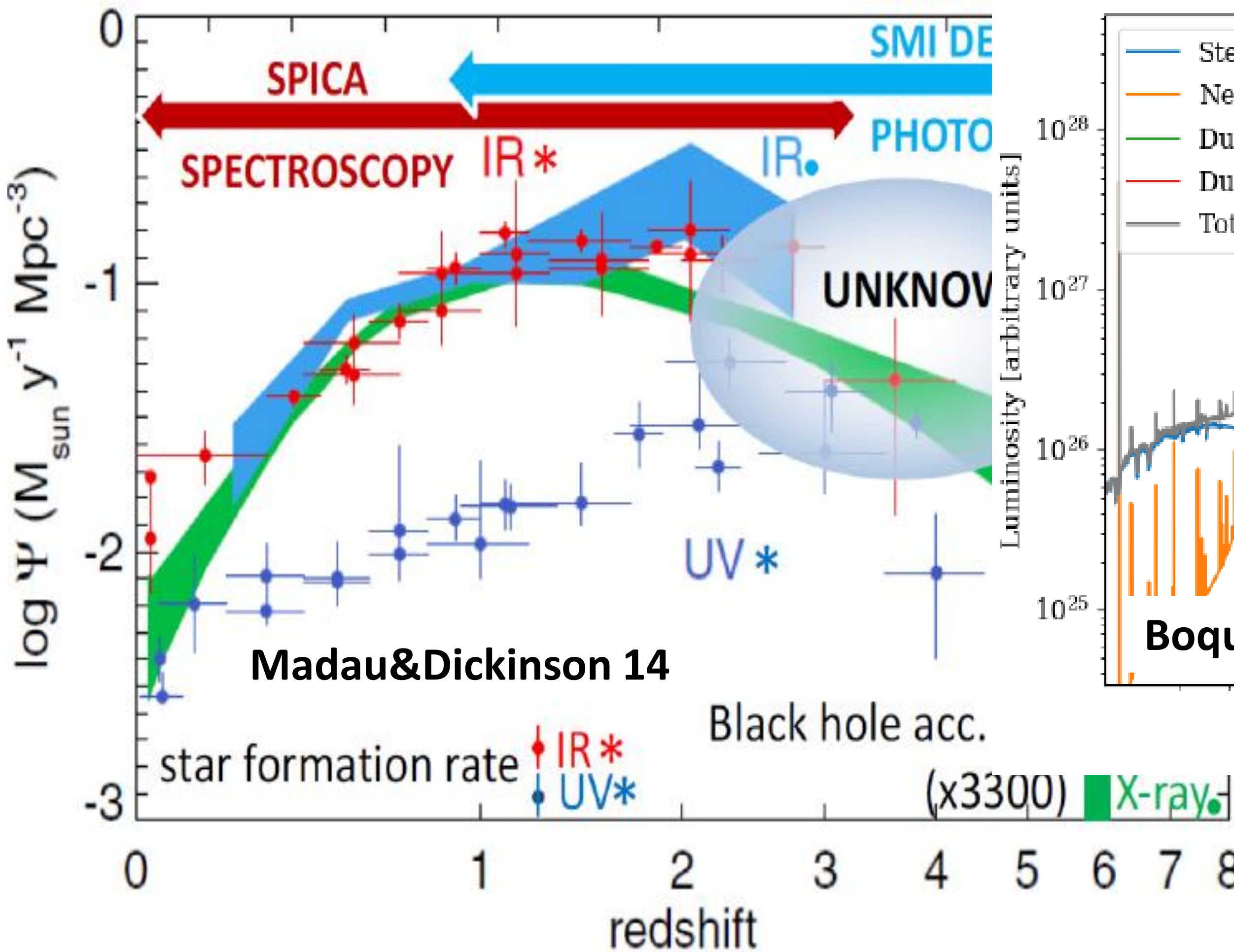


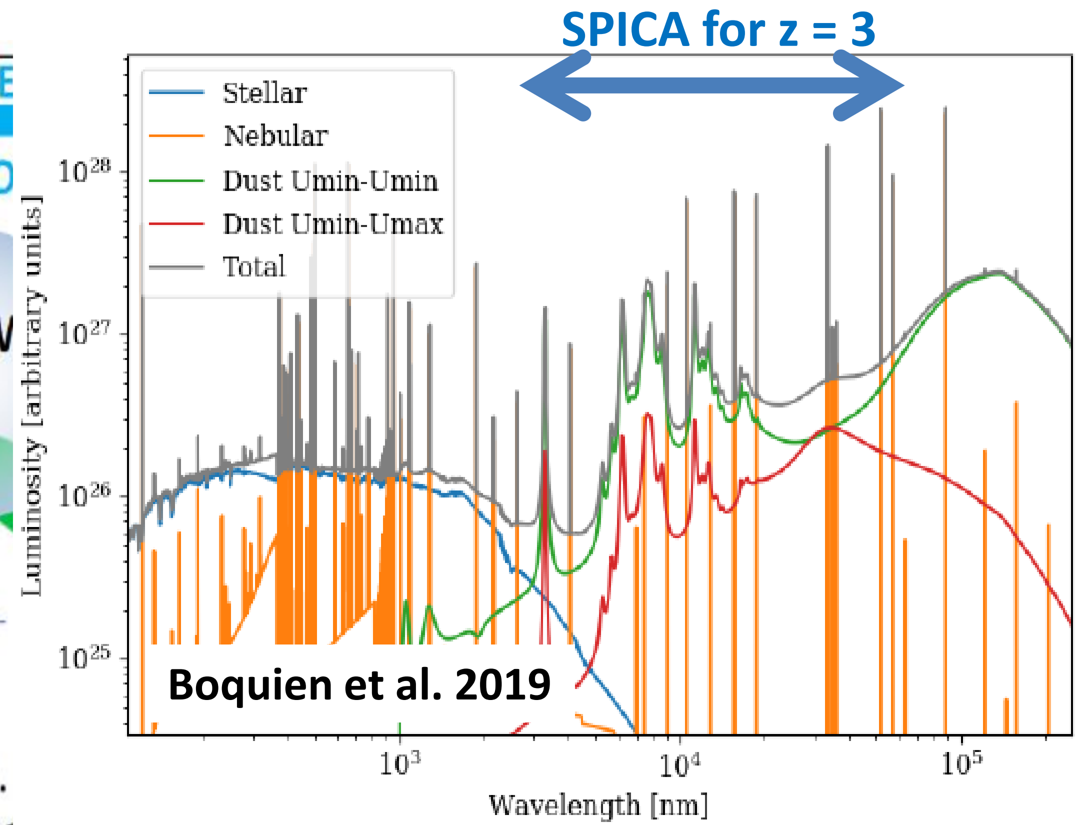
Upper: I.P. for key IR fine-structure lines (adapted from Spinoglio & Malkan, 1992).
Lower: excitation temperature of molecular transition, spectral features from PAHs, H_2O ice, silicates.

(1) Physical understanding of galaxy & SMBH evolutions



(1) Physical understanding of galaxy & SMBH evolutions





Star formation: PAH features
SMBH: continuum + silicate

The physics governing galaxy & SMBH evolutions with IR spectral diagnostics

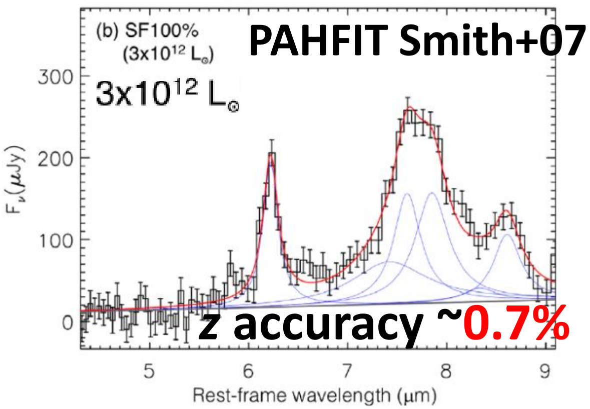
- **Dust bands → SMI large spectral surveys, overall picture**
- **Gas lines → SAFARI high-sensitivity spectroscopy, accurate**

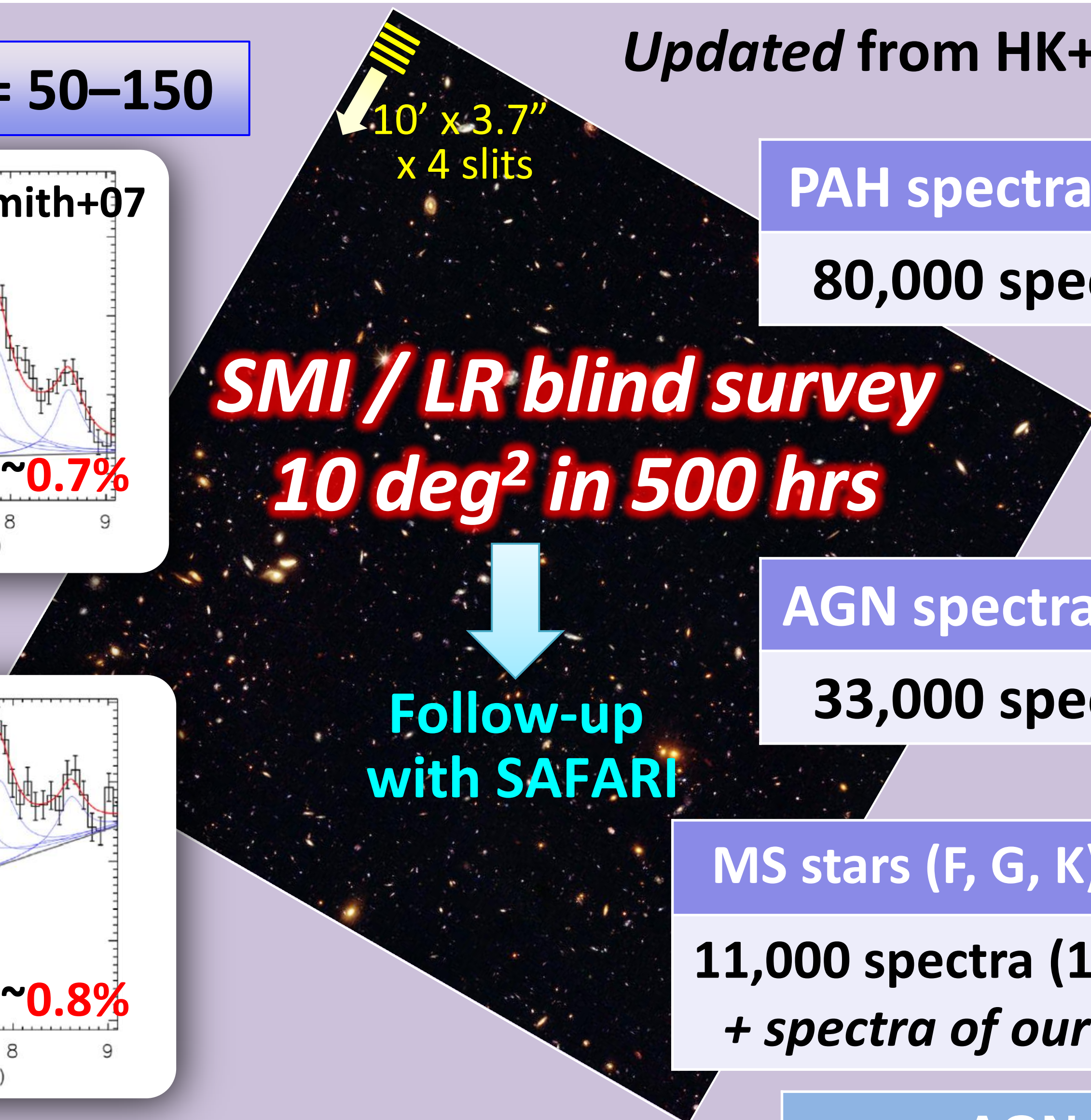
} **coordinated**

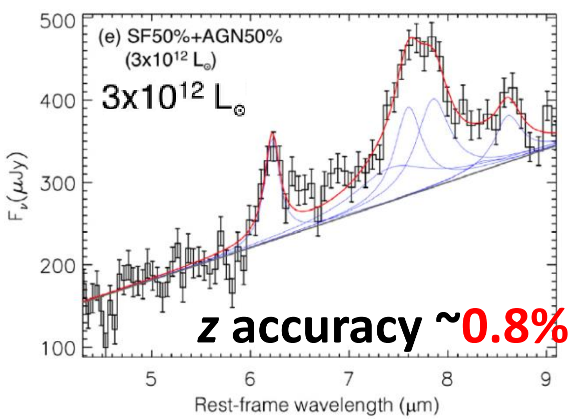
Unbiased large spectroscopic surveys by SMI/LR-CAM

LR: 17–36 μm, R = 50–150

Updated from HK+17 white paper







PAH spectra at z >1 (z=2-4)
80,000 spectra (24,000)

AGN spectra at z >1 (z=2-4)
33,000 spectra (14,000)

MS stars (F, G, K) (debris disks)
11,000 spectra (1800–2600 disks) *+ spectra of our Zodiacal cloud*

AGNs at z > 1
240,000 at 34 μm with CAM

CAM (30-36 μm) is operated simultaneously.

Expected results of SMI/LR survey (10 deg^2 in 500 hrs)

Based on the result of HK+17 white paper, updated with the latest SMI specifications

PAH galaxy spectra

Direct detection # + Stacking detection #

$\log(L_{IR}/L_\odot)$	Redshift 0.5 – 1	1 – 1.5	1.5 – 2.0	2.0 – 2.5	2.5–3.0	3.0 – 4.0	> 4.0
13.00 –	1	19	91	246	462	230	157 + 63
12.50 – 13.00	73	648	1592	2495	3083 + 7	1281 + 99	337 + 139
12.25 – 12.50	321	1825	3009	3511 + 58	2796 + 492	467 + 289	94
12.00 – 12.25	1138	4446	5519 + 85	4115 + 791	2070 + 1192	69 + 319	35
11.75 – 12.00	2969	8185 + 23	6508 + 1021	2598 + 1859	1197	125	11
11.50 – 11.75	6063	10425 + 552	4314 + 2525	1542	335	33	3
11.00 – 11.50	22907 + 1650	9522 + 4348	330 + 3173	503	92	7	0
10.50 – 11.00	16251 + 8213	1504	206	21	0	0	0
– 10.50	387 + 4245	97	3	0	0	0	0
Total	50111 + 14108	35070 + 6524	21364 + 7013	12965 + 4774	8412 + 3315	2048 + 871	494 + 344

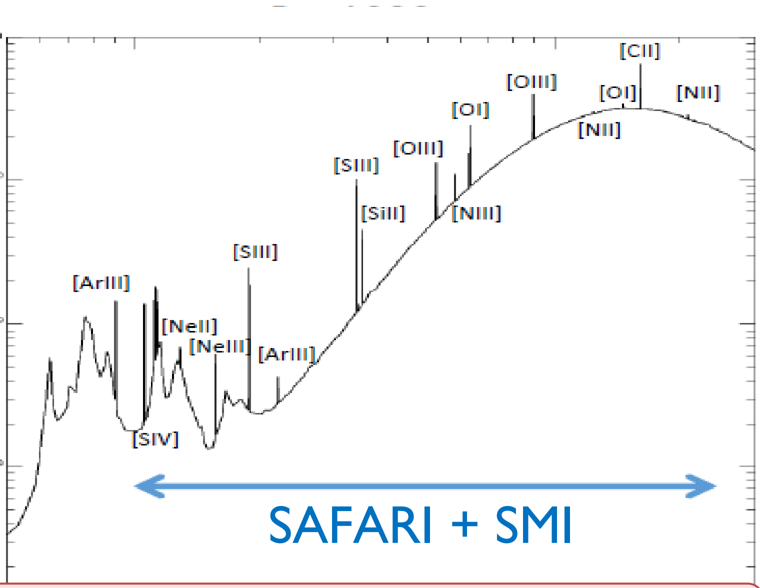
AGN spectra

$\log(L_{IR}/L_\odot)$	Redshift 0 – 1	1 – 1.5	1.5 – 2.0	2.0 – 2.5	2.5 – 3.0	3.0 – 4.0	> 4.0
13.00 –	2	15	60	157	310	185	394 + 15
12.50 – 13.00	37	276	710	1240	1808	1008 + 42	643 + 295
12.25 – 12.50	130	701	1264	1727	1798 + 118	565 + 187	29 + 220
12.00 – 12.25	434	1661	2317	1936 + 231	1073 + 441	104 + 301	120
11.75 – 12.00	1114	3035	2451 + 283	742 + 540	54 + 516	175	50
11.50 – 11.75	2293	3935 + 184	706 + 691	21 + 426	211	70	14
11.00 – 11.50	9014 + 320	2255 + 1603	61 + 586	198	89	24	1
10.50 – 11.00	7775 + 1723	8 + 394	53	10	0	0	0
– 10.50	5409 + 2216	24	0	0	0	0	0
Total	26208 + 4259	11887 + 2206	7568 + 1613	5824 + 1405	5042 + 1376	1862 + 799	1066 + 715

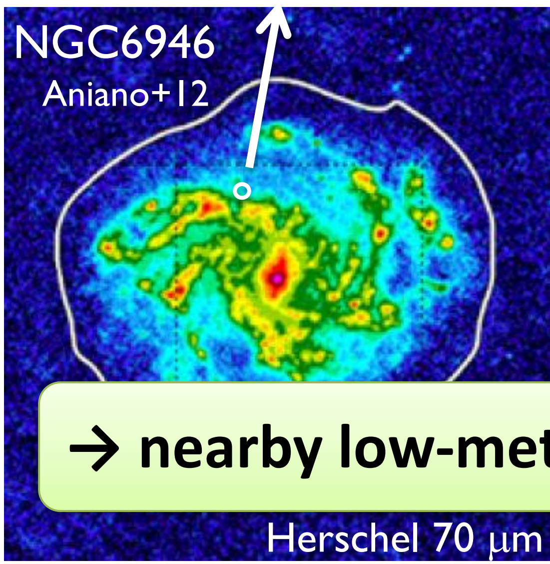
- Stacking spectra of fainter galaxies with known redshifts. Detection with S/N > 7 (red)

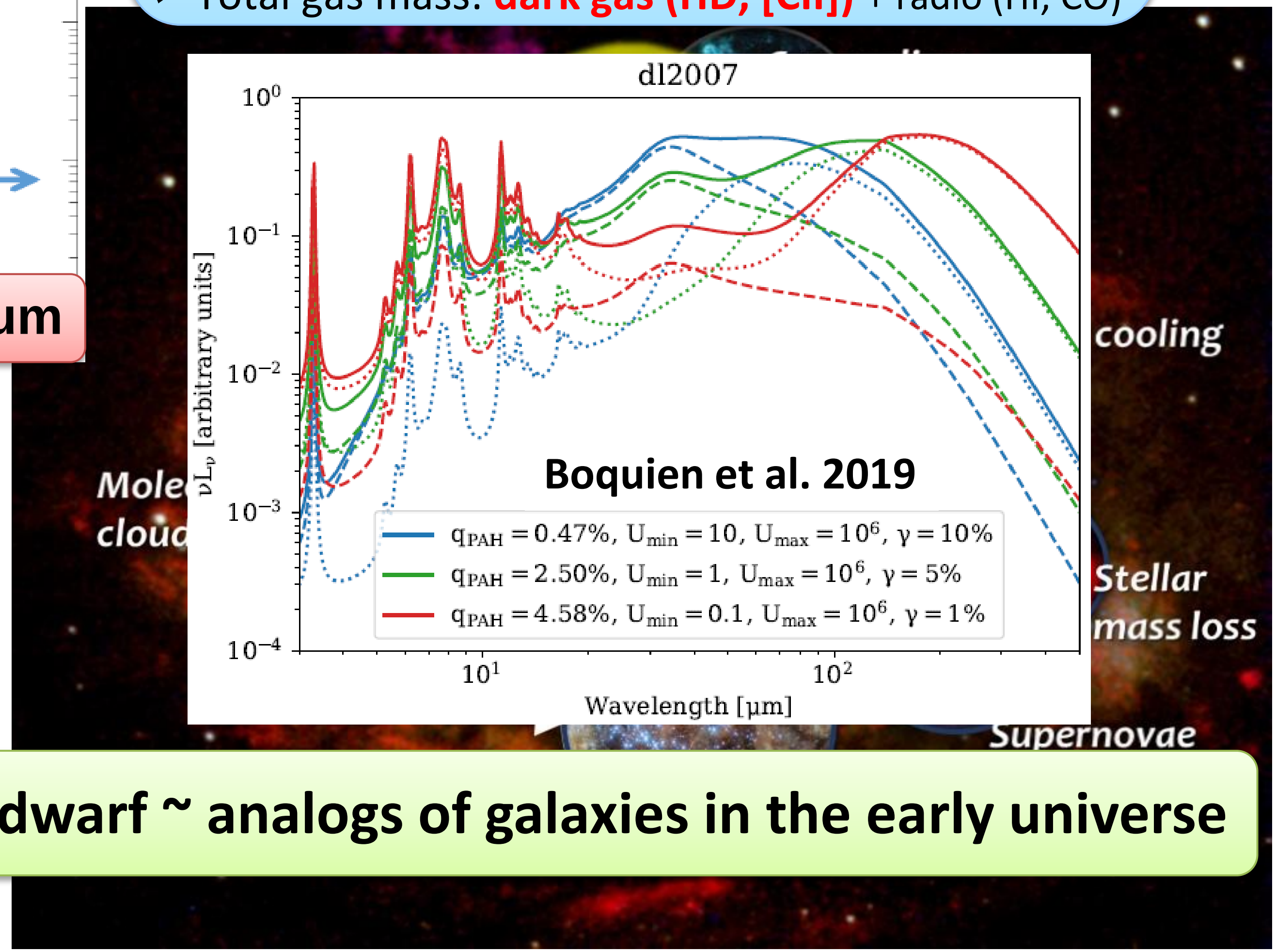
Revealing the relationship between star-formation activity, metal-dust enrichment and nuclear activity

- ✓ Star-formation rate : [OI]+[CII], [OIII], MIR-FIR
- ✓ Black hole accretion rate : [NeV], [OIV]
- ✓ Metallicity : [NIII]/[OIII], [NeII]/Huα
- ✓ Gas density, *T*, radiation, shock : lines
- ✓ Dust mass, *T*, composition : continuum, bands
- ✓ Total gas mass: **dark gas (HD, [CII])** + radio (HI, CO)



MIR-FIR continuous spectrum

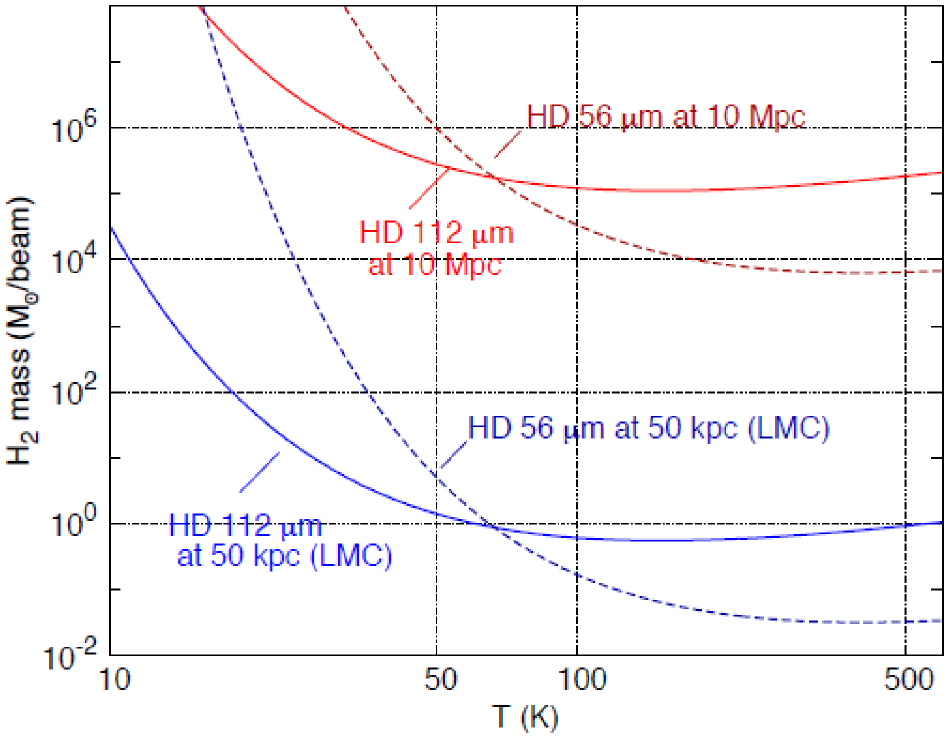




→ nearby low-metallicity dwarf ~ analogs of galaxies in the early universe

ISM reservoirs: CO-dark gas, diffuse gas with HD lines and [CII]

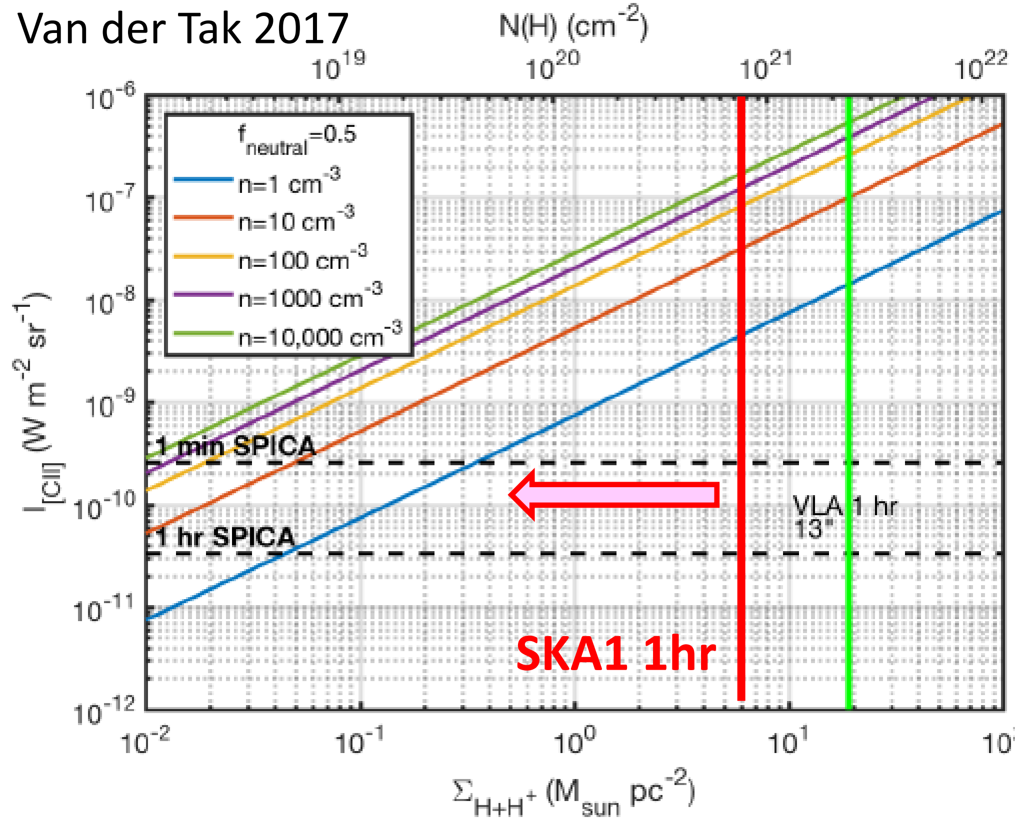
HD 112 and 56 μm lines



With the sensitivity of **5x10^{-20} W m^{-2}**, GMCs of 10^6-10^7 M_{Sun} with T = 20-30 K are detectable out to 10 Mpc distance. In dwarf galaxies, gas temperatures are expected to be higher.

diffuse [CII] line

Van der Tak 2017



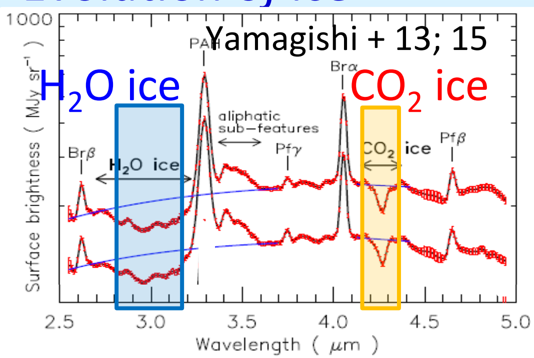
SPICA is extremely sensitive to diffuse warm gas. **10 min for 1'x1'** would reach N_H ~ 10^{18} cm^{-2}. Also uniquely suited to probe extraplanar material.

Tracing cosmological evolution of PAH and dust in galaxies

SPICA's spectroscopy of high-z objects provides the opportunity to detect PAHs and ices from the most distant galaxies ever observed.

Egami et al. 2018 white paper

Abundance ratio of H_2O to CO_2 ice → *Evolution of ice*

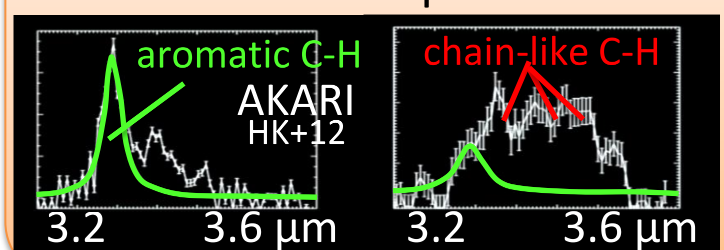


$$CO + OH \rightarrow CO_2 + H$$

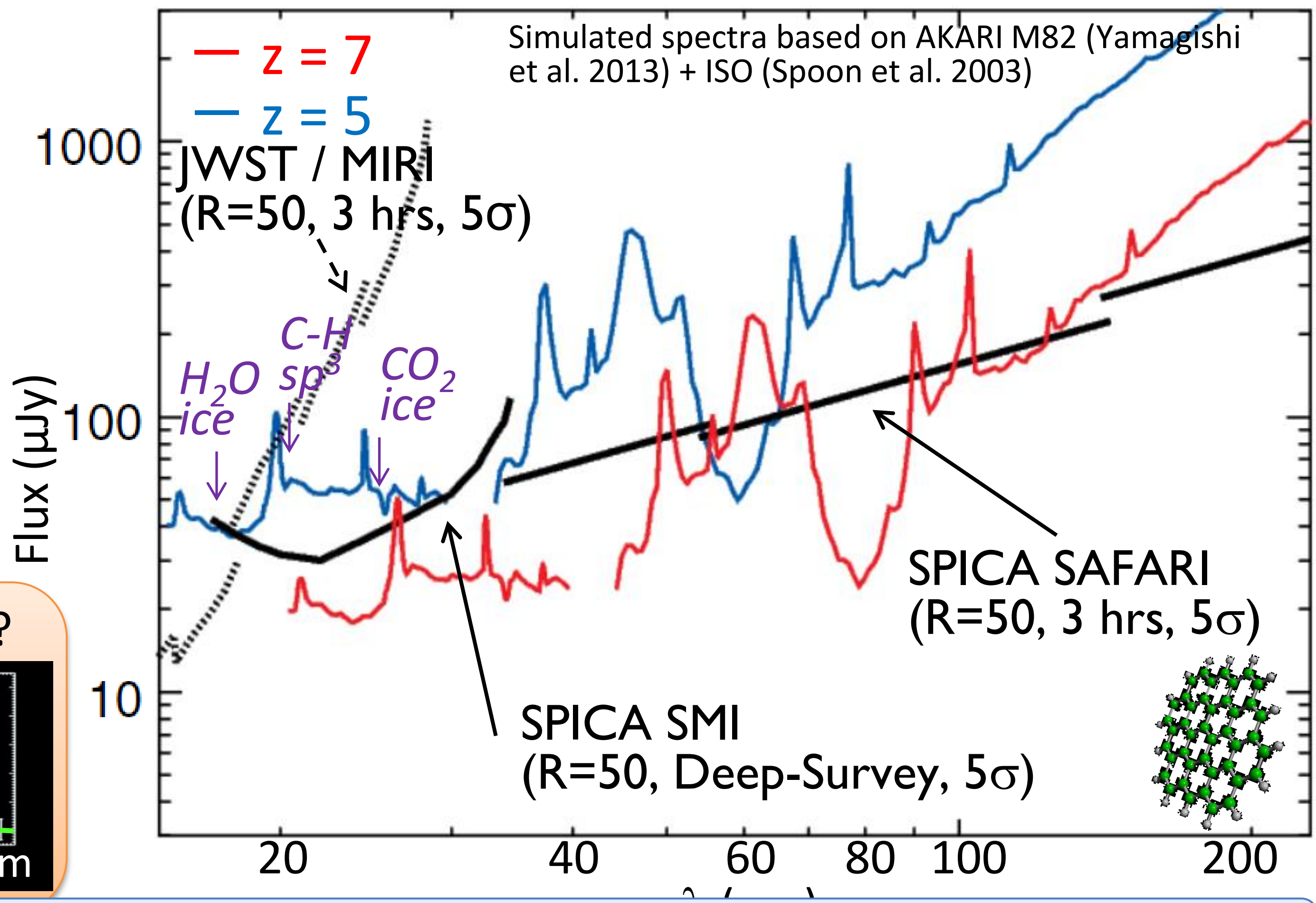
with cosmic-ray-induced UV photons.

Watanabe & Kouchi 2002

Aromatic-rich? Aliphatic-rich?



High-z star-forming galaxies ($2x10^{13}$ $L_\odot$)

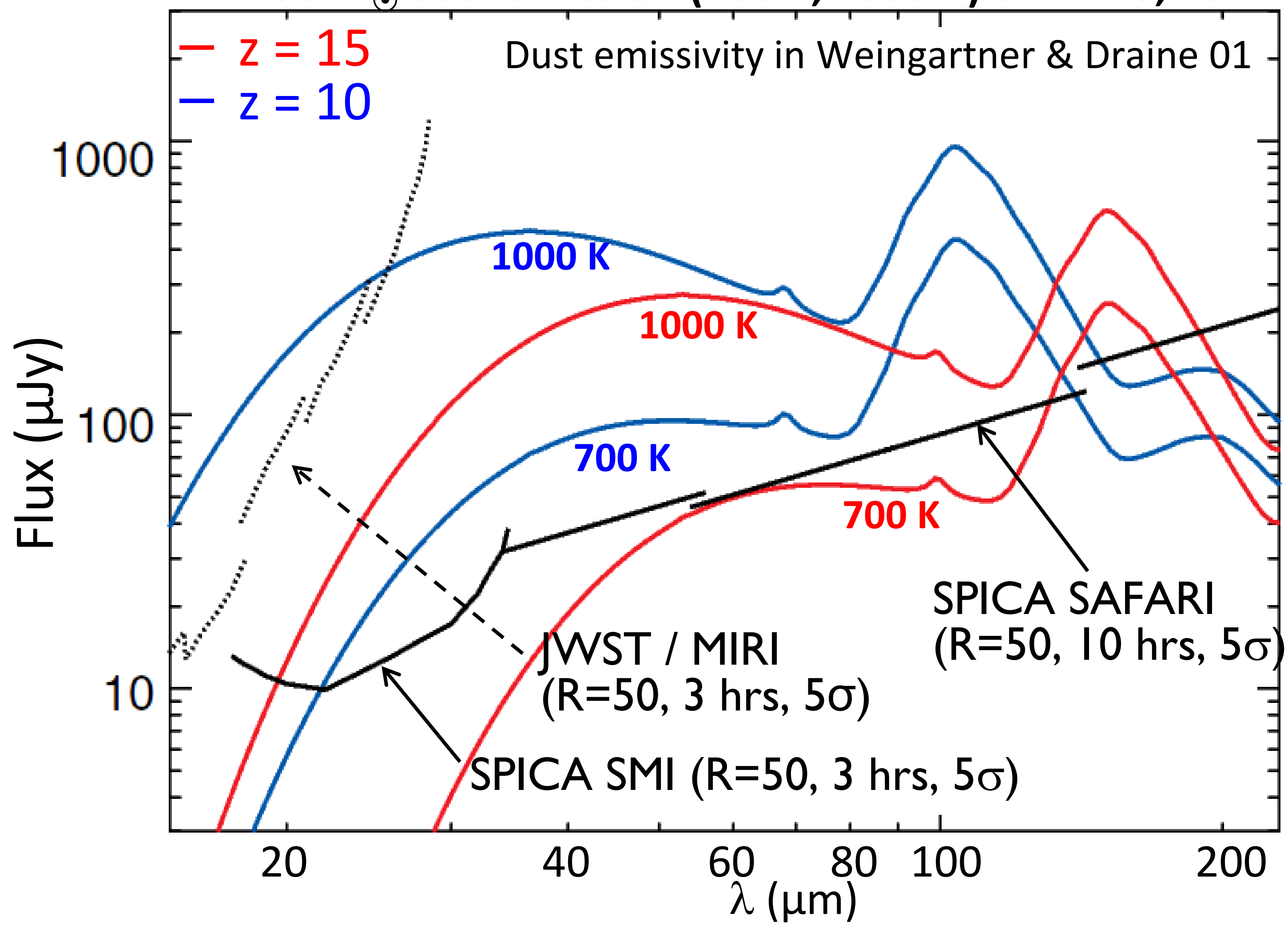


Dust studies: AKARI, Spitzer (low z) ➡ JWST (intermediate z) ➡ SPICA (high z)

Search for dust in very high-z BHs (synergy with SKA)

A very small amount (~10 $M_\odot$) of circum-nuclear dust at z = 15 is detectable.

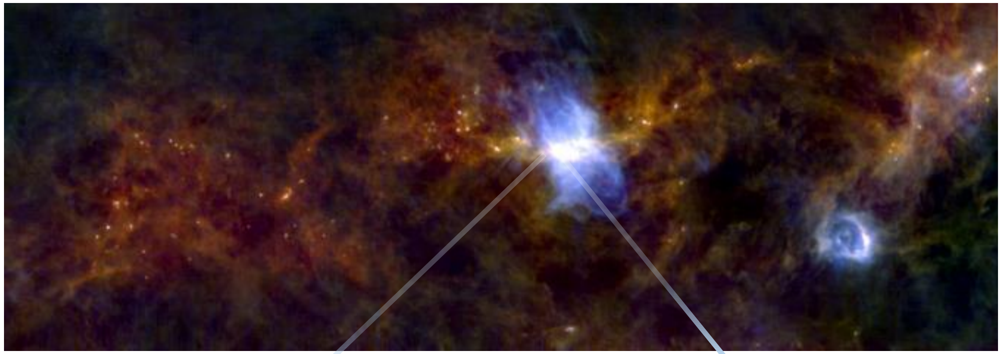
50 $M_\odot$ dust emission (700 K, 1000 K) at z = 10, 15



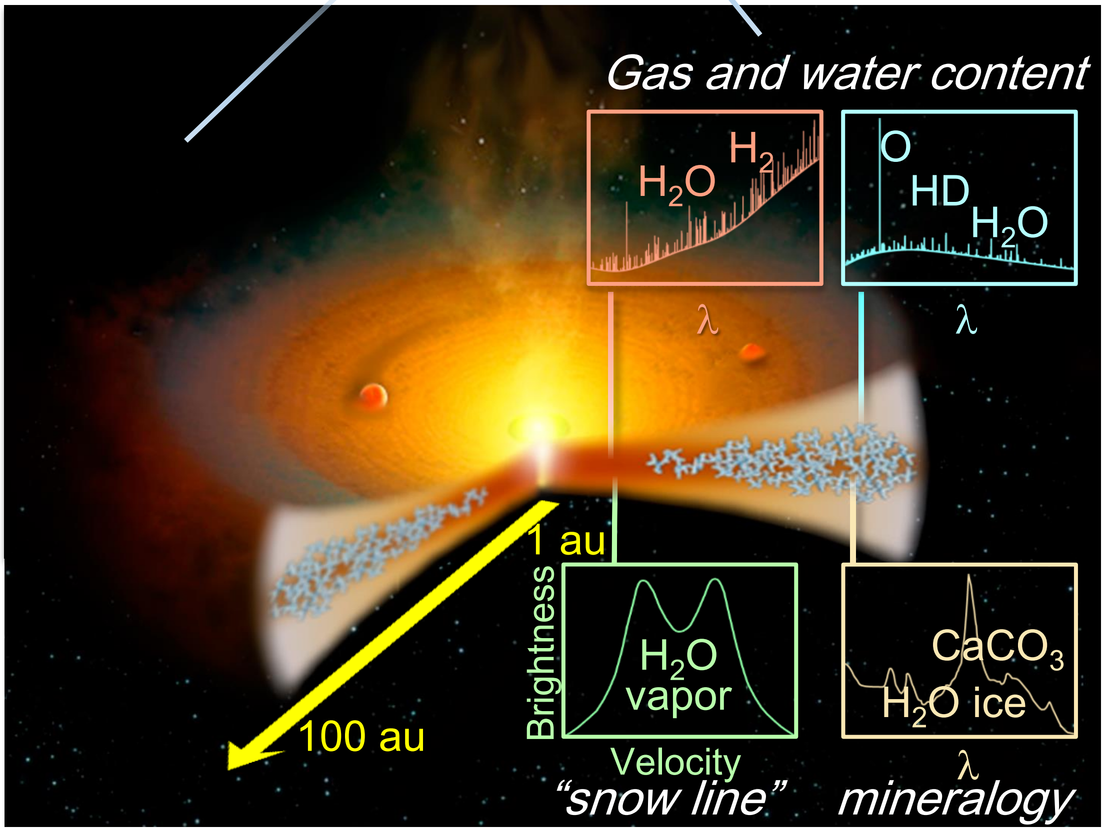
- SMI/LR obs. of very high-z BH → (at least) upper limit → origin of the BH?
  characterization of the dust with SAFARI ⟶ properties of Pop III stars

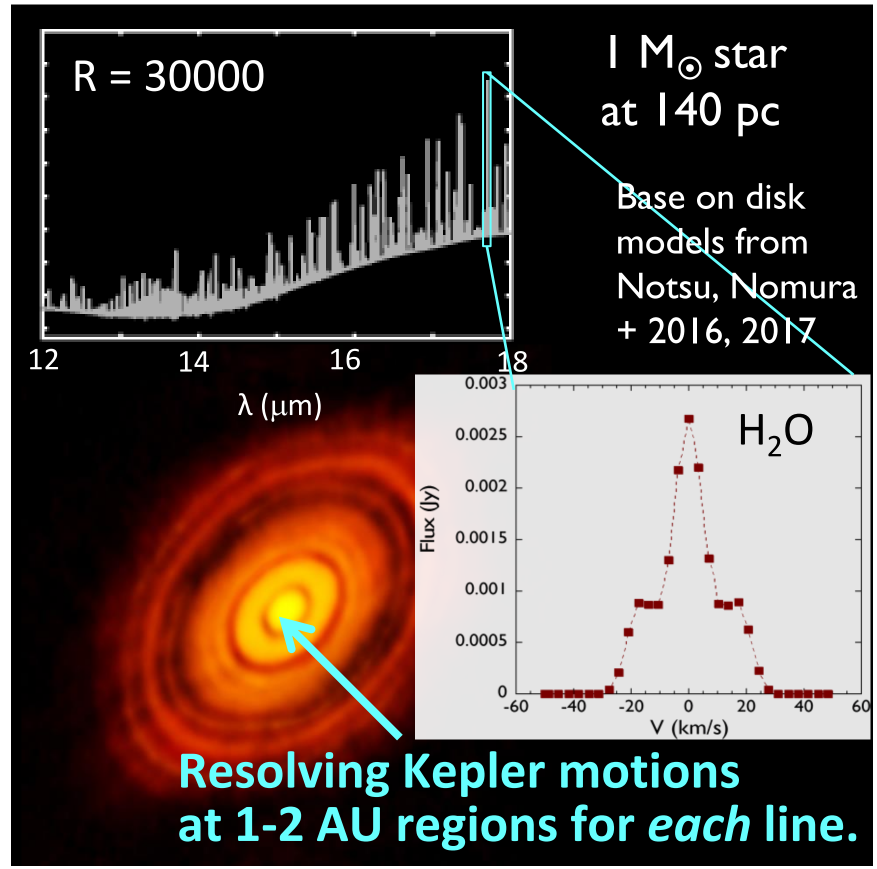
(2) Understanding the fundamentals of star & planetary formation

- **Formation of Galactic filaments : Polarimetry (B-BOP), shock-tracing (SMI)**



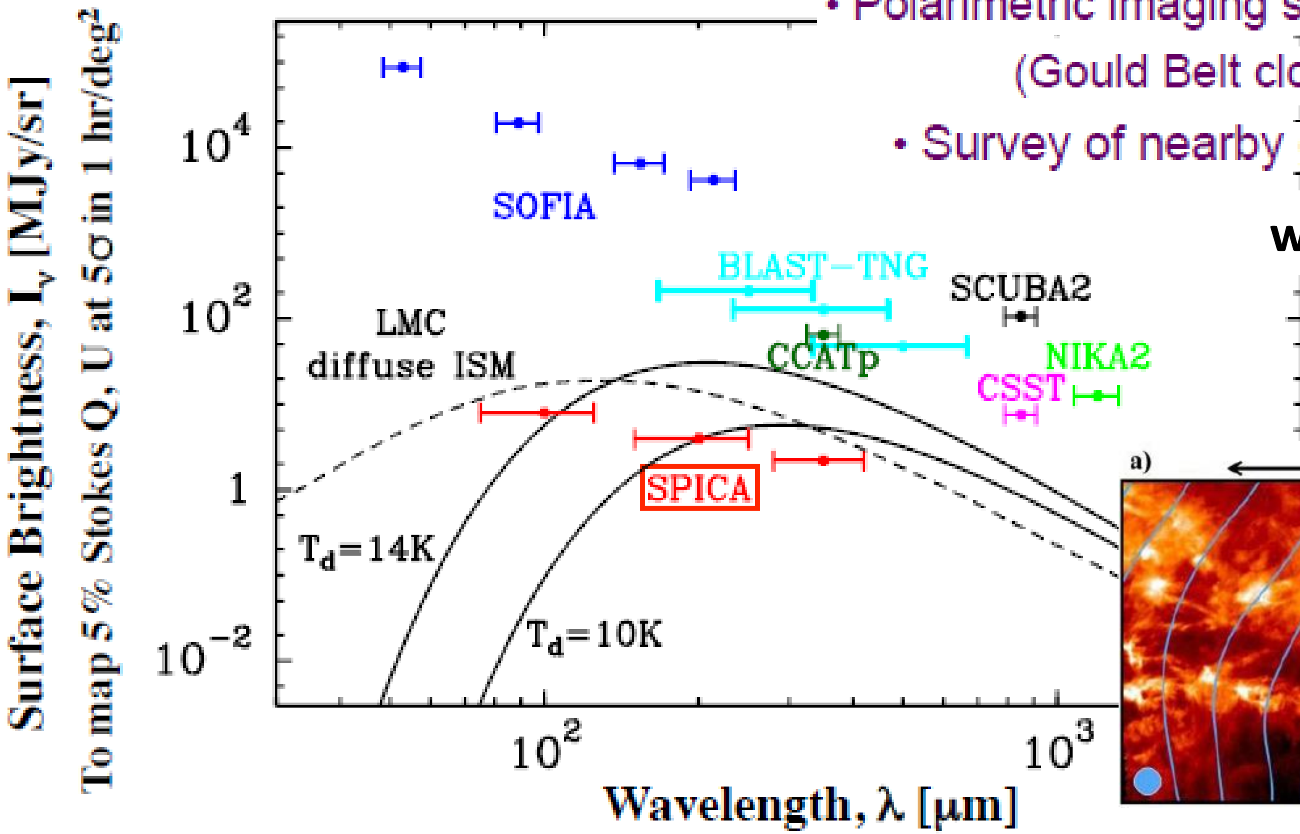
- **Molecular gas measurement : HD, H_2**
- **Gas dispersal、"3-D real snow line" : velocity-resolved H_2, H_2O (multiple)**
- **Planetesimal material : mineralogy**





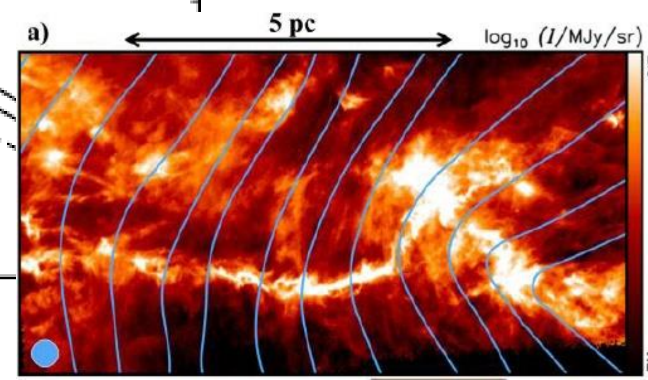
SPICA: A future revolution in FIR polarimetric imaging

- Thanks to a cooled telescope, SPICA-POL = B-BOP will be 2-3 orders of magnitude more sensitive (4-6 orders of magnitude faster) than other far-IR/submm imaging polarimeters



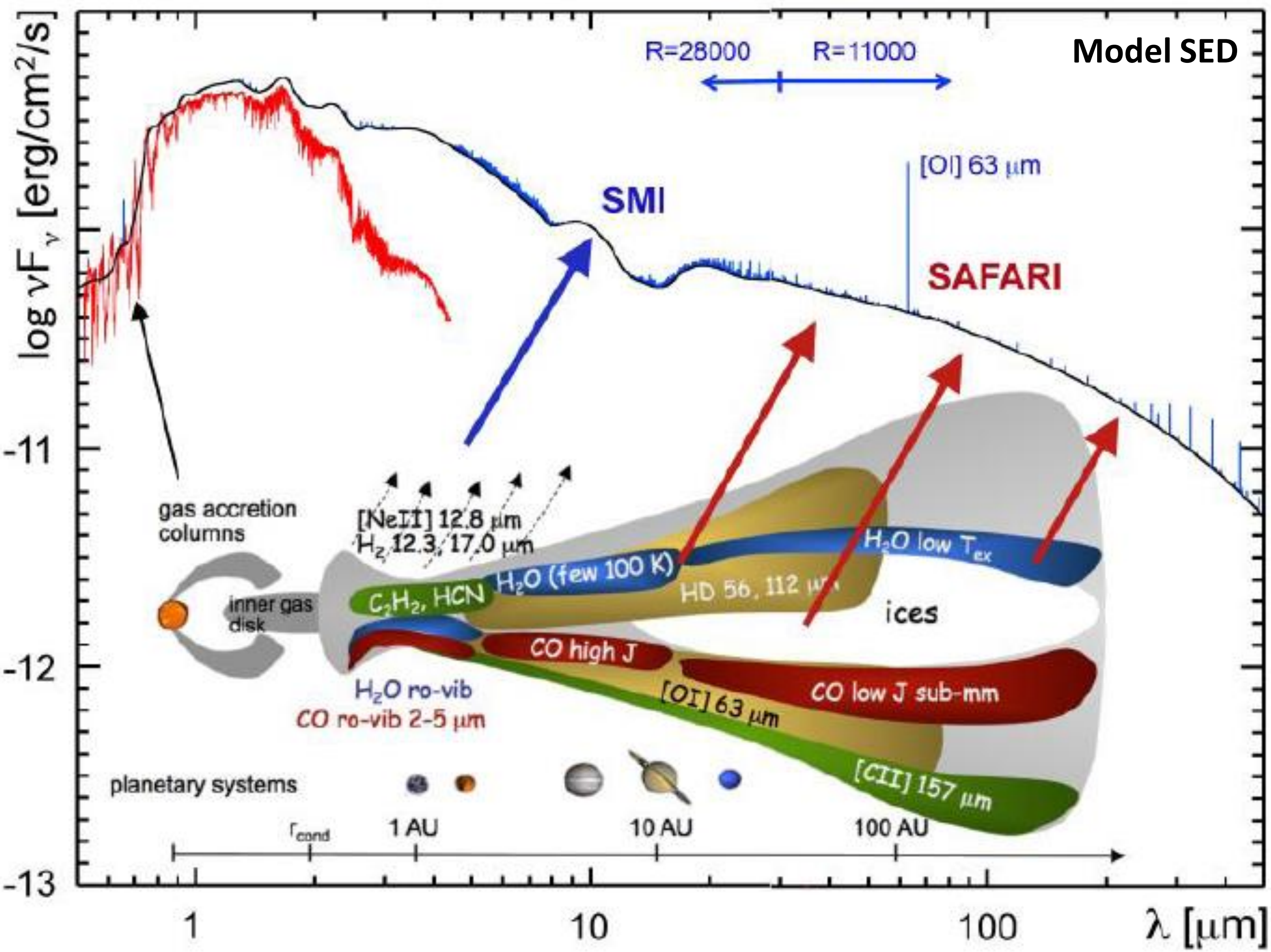
- Polarimetric imaging survey of ~ 500 deg^2 (Gould Belt clouds) in $\lesssim$ 2 months
- Survey of nearby galaxies in ~ 200 hr

w/ SMI/CAM34 μm



- B-BOP will deliver wide-field 70–350 μm images of polarized emission (Stokes Q, U) with a resolution, S/N ratio, and intensity/spatial dynamic ranges comparable to *Herschel* images in total intensity (I).

IR spectroscopy: gas, dust, ice evolution in planetary systems



Velocity-resolved studies of gases in PPDs with SMI/HR

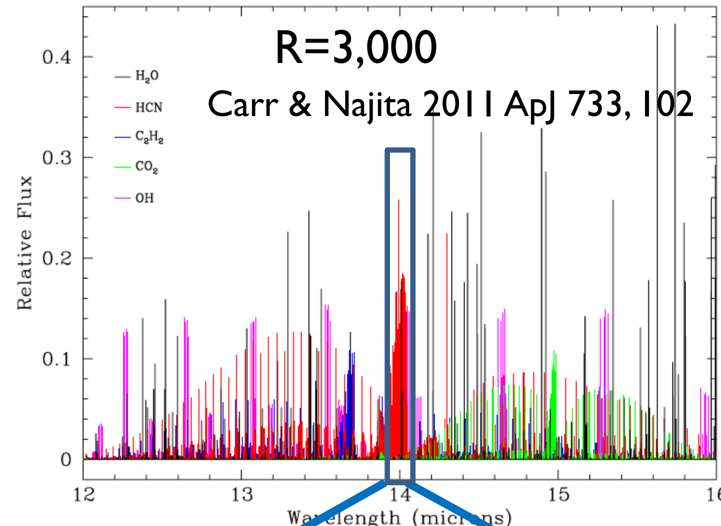
- Spectral range of 10–18 μm contains not only H_2 and atomic lines but also numerous emission bands of major C-bearing molecules, HCN, C_2H_2, and CO_2, as well as lines of H_2O and OH.

Velocity-resolved H_2, H_2O, OH, HCN, CO_2, C_2H_2 lines

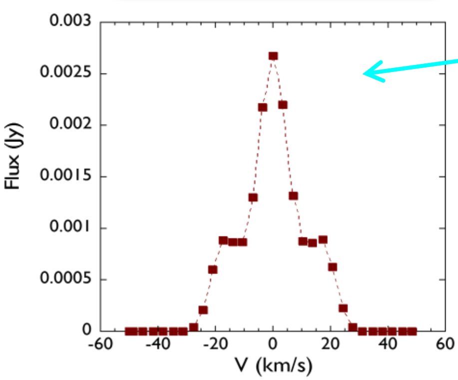
→ gas dispersal processes

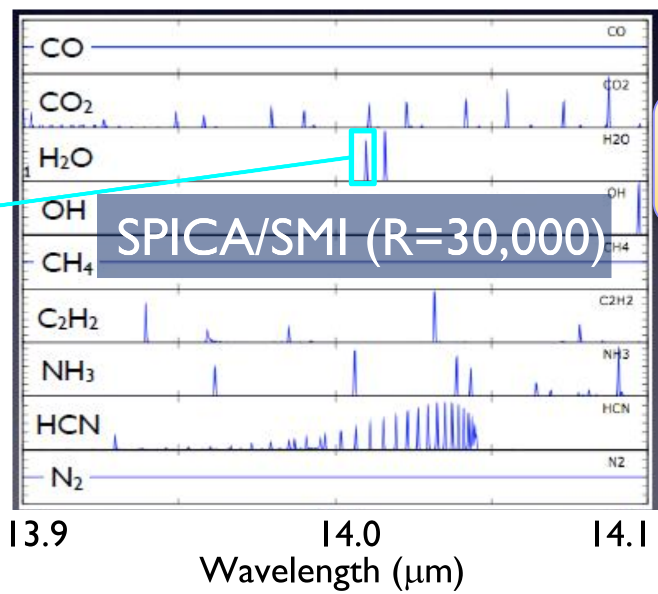
→ 3-D "real" snow line

→ C/O ratio distribution at <~1–2 AU in disks

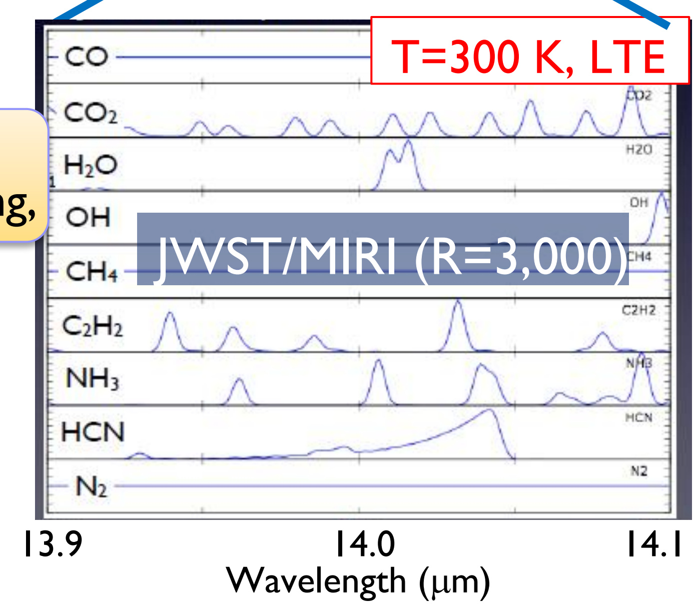


resolving molecular bands



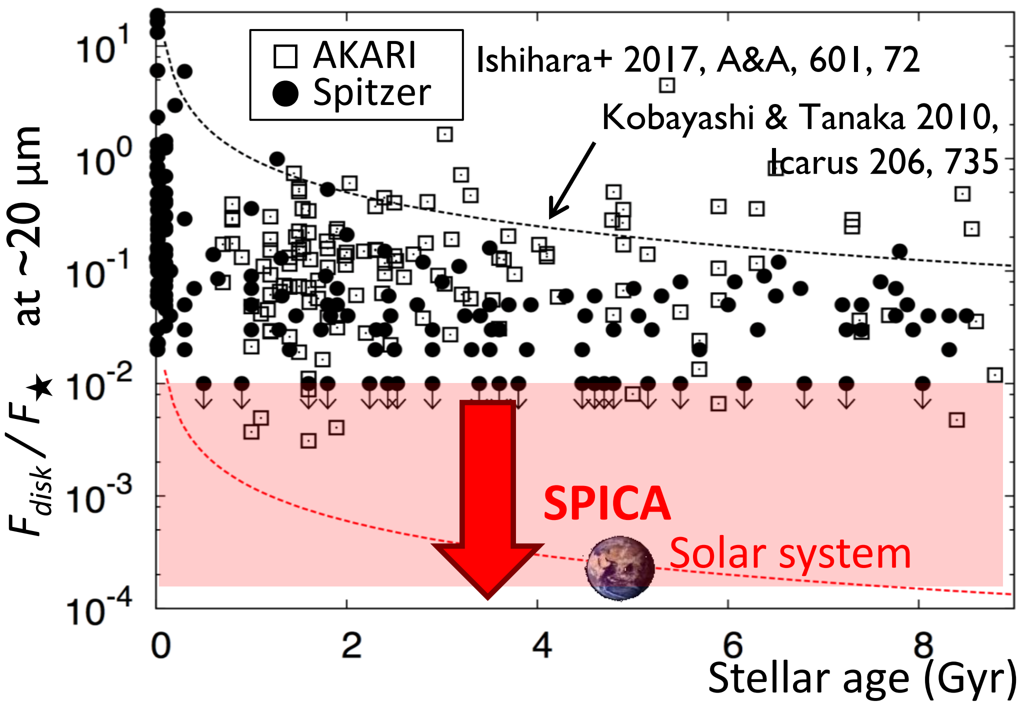


Not only de-blending,

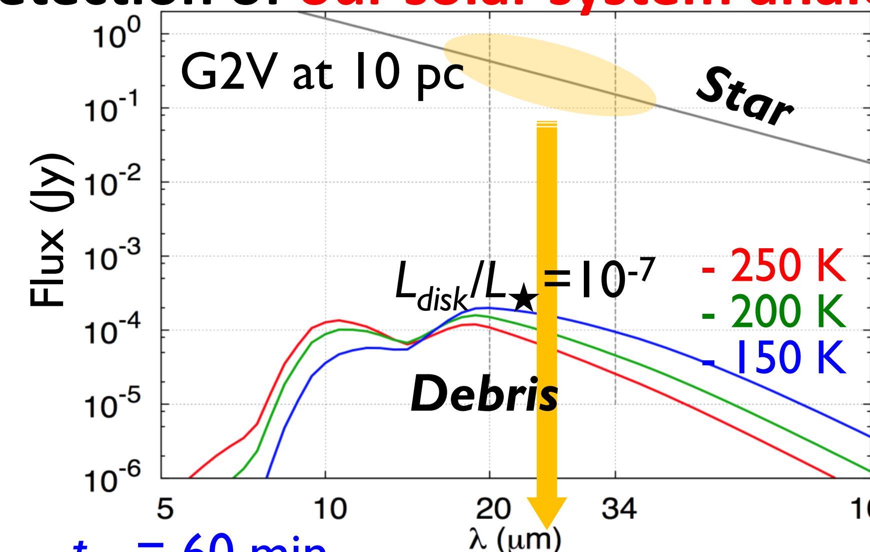


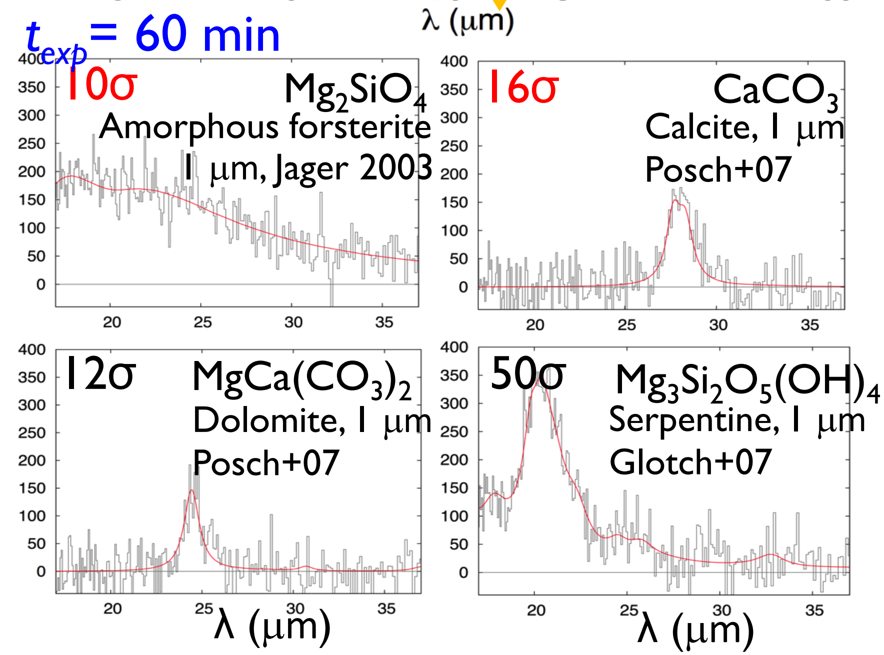
Mineralogy in disks & its relation to our solar system

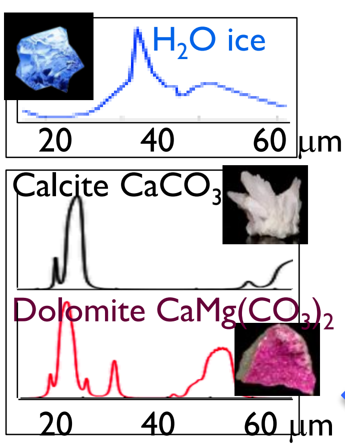
Cosmology survey (2000-3000 debris disks; HK+17) + mini surveys

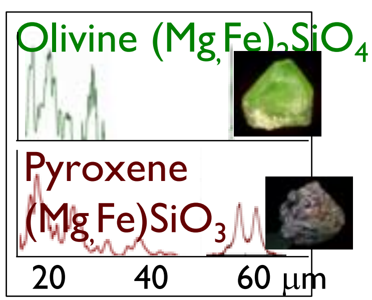


Detection of our solar system analogs









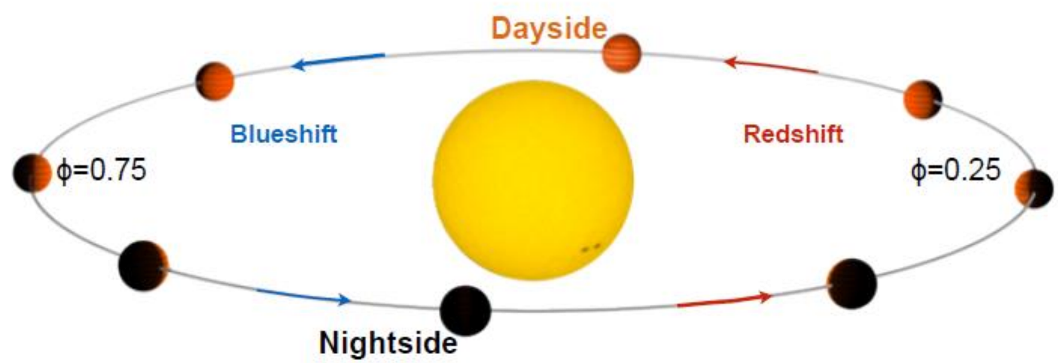
High-T minerals

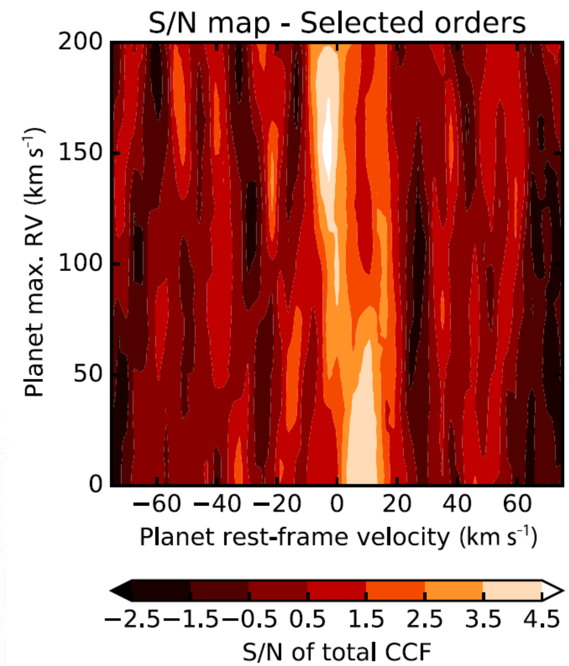
Low-T minerals formed by aqueous mineral alteration.

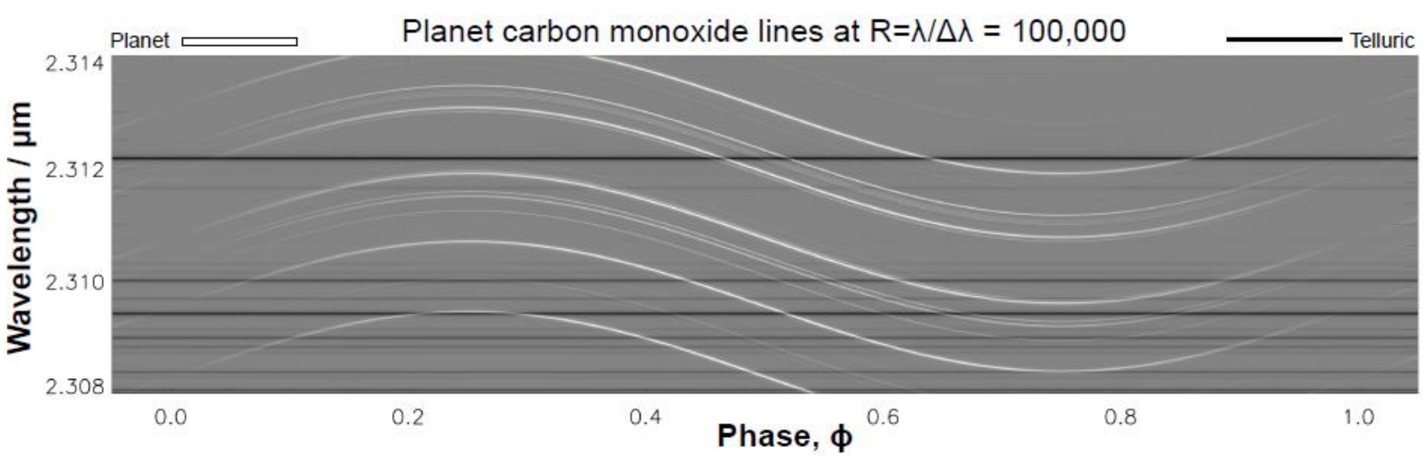
Exoplanetary atmospheres at high spectral resolution

From A. Sozzetti et al.'s talk at SPICA2019 Crete

* At R > 20,000, molecular bands are resolved in a dense forest of individual lines
* Strong Doppler effects due to orbital motion of the planet (up to >150 km/s).
- Moving planet lines are distinguished from stationary stellar lines.
- Molecules are detected by cross-correlation with libraries of synthetic spectra





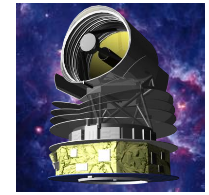


HD189733b (Brogi, Giacobbe, Guilluy et al. 2018)
HD102195b (Guilluy, Sozzetti, Brogi et al. 2019)

→ SMI/HR (R 30000) observations

Origins of organic matter and water (up to z = 10)

Solar System science with SPICA



Evolution of material leading to the formation of habitable worlds

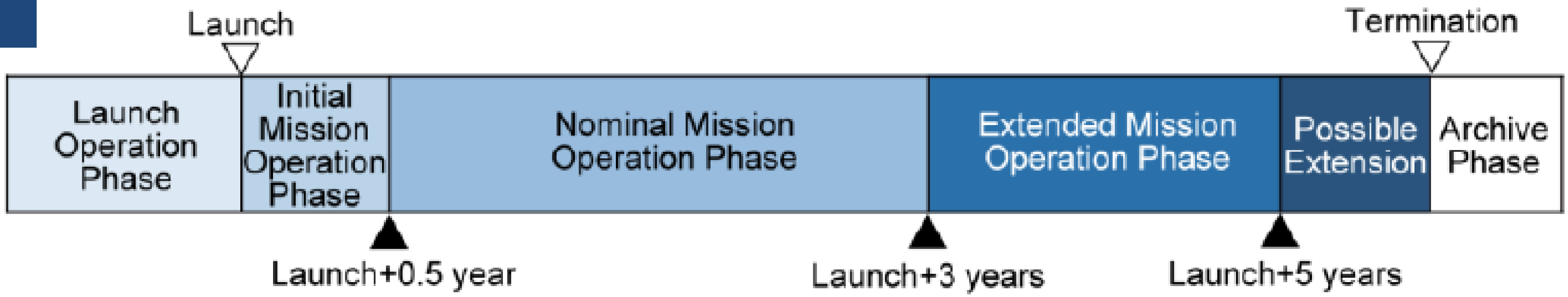
- **Characterization of the early solar system – comets**
  Spectroscopy of comas, High-*R* 10-18 μm (gas tail) and low-*R* 17-230 μm (dust trail).
  D/H ratio of comas to quantify the original water characteristics.

- **Characterization of interplanetary dust particles**
  Low-*R* spectroscopy of dust bands in the Zodiacal emission toward various directions.

- **The outer solar system: planetary atmospheres**
  High-*R* 10-18 μm spectroscopy, 10 times the resolution of VOYAGER/IRIS, CASSINI/CIRS and MEX/PFS to study the molecular composition of planetary atmospheres.

- **The outer solar system: trans-Neptunian objects**
  100s of TNOs (D < 100 km) to measure sizes, albedos, infer their internal composition.

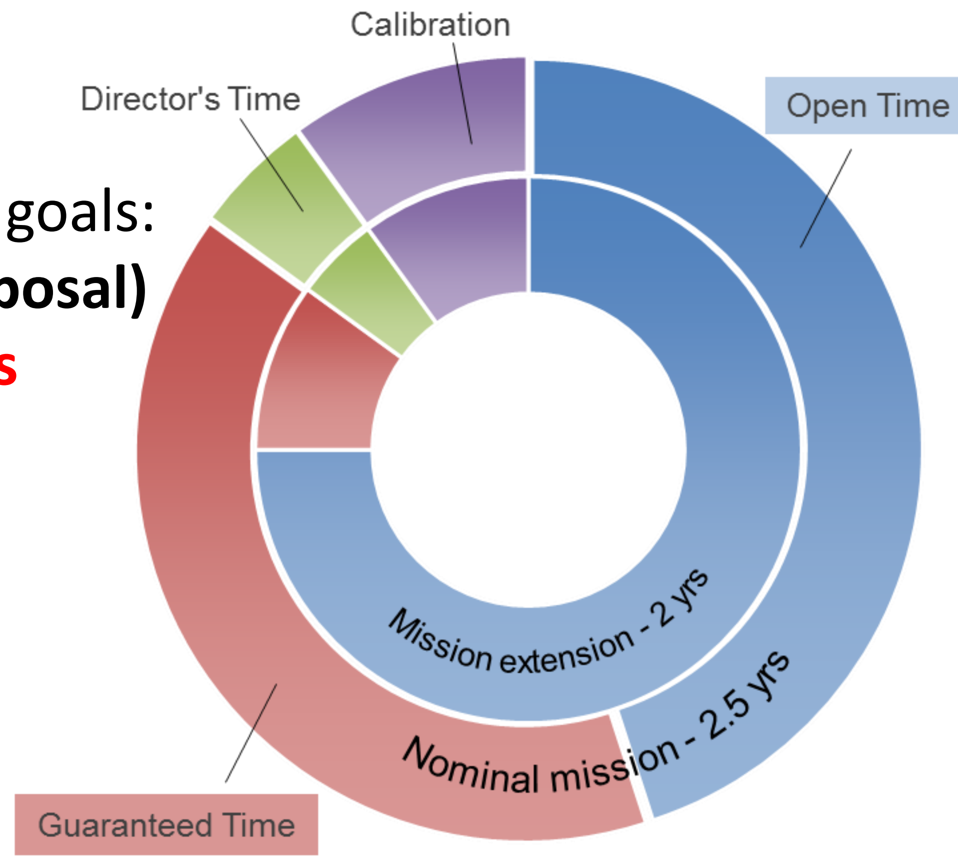
3. Science observation plans



Observing time required
to achieve the SPICA's primary science goals:

- **Reference mission scenario (M5 proposal)**
  total ~ 11000 hrs
  (14.8 months ~ 1.2 years)
- **Time for SMI ~ 3300 hrs.**
  (4.5 months)

Carried out by Key Programs
consisting of GT (> 70%) plus OT.



- **lifetime : 5-year goal → mostly as *Space Observatory*, *Open Time***

Reference mission scenario (breakdown of 11000 hours)

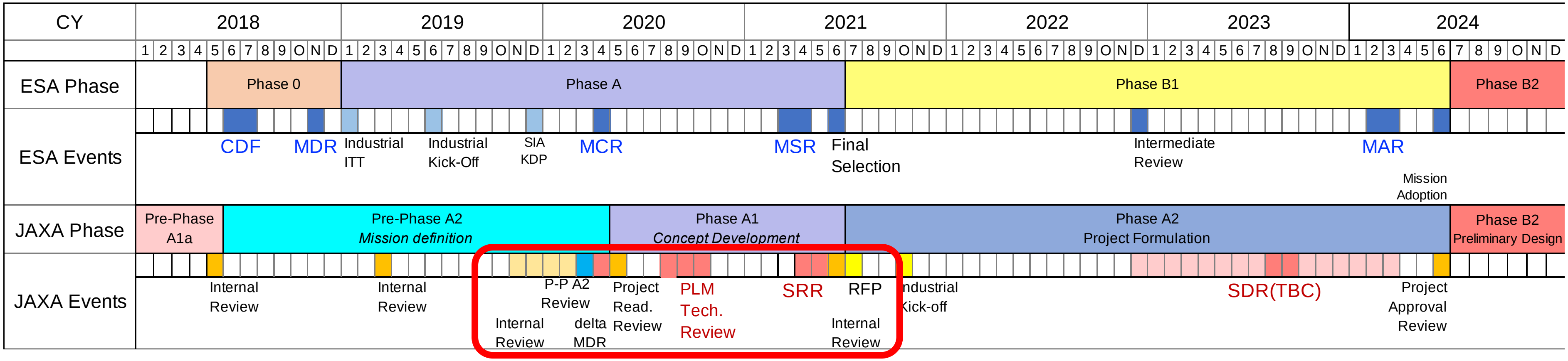
- 100,000 galaxy spectra with SMI surveys: 600 hrs
- 1300 galaxies at z = 0.5 – 10 with SAFARI: 4300 hrs
- 100 deg^2 photometry survey with SMI/CAM (& B-BOP): 200 hrs
- 500 nearby galaxies with SMI & SAFARI: 1700hrs
- 500 deg^2 polarimetry imaging of Galactic ISM with B-BOP: 500 hrs
- 2,700 PPDs with SMI, SAFARI: 2800 hrs
- 2,000 debris disks with SMI, SAFARI: 1100 hrs

On-going international science activity

- **ESA Science Study Team (Europe 6, Japan 5)**
- **Science WGs (led by Europe, + Japan, U.S.,,,)**
  - Under ESA Science Study Team, responsible for writing ESA Yellow Book.
  - **(1) Galaxy evolution, (2) Nearby galaxies, (3) ISM/Star formation, (4) Proto-planetary disks/Debris disks, (5) Solar system/exoplanets**

4. Schedule

As of May 2019



- **2019/12: ESA-JAXA Key Decision Point：telescope configuration fixed**
- 2020/1-3: ISAS Pre-Phase A2 Completion Review, Delta MDR
- **2020/04: ESA Mission Consolidation Review (MCR): mission concept fixed**
- 2020/04-(TBD): JAXA Project Preparation Review
- **2021/03-04: ESA Mission Selection Review (MSR): ESA M5 final selection**
- 2021/04-(TBD): JAXA System Requirement Review
- 2023: JAXA System Definition Review
- 2024:02-03: ESA Mission Adoption Review: ESA project approval
- 2024/06: JAXA Project Starting Review

Mission Selection Review confirms "readiness for transition into Phase B1".
Adequacy of the mission requirements,
Demonstration of "an architecture" to meet the requirements

Summary

- SPICA: mid-/far-IR astronomy mission covering 10–350 μm.
  SMI (mid-IR LR, MR, HR spectroscopy, imaging)
  SAFARI (far-IR LR, HR spectroscopy), B-BOP (polarimetry)

- SPICA would unveil the dusty era in the Universe, and find a route to habitable planets.

- Now in Phase A activity. ESA CV final selection is mid-2021.
  Launch: ~2030, mission lifetime: 5 years

- 5 Science WGs for ESA Yellow Book.

SPICA JAXA HP: http://www.ir.isas.jaxa.jp/SPICA/SPICA_HP/index-en.html
SMI HP: http://www.ir.isas.jaxa.jp/SPICA/SPICA_HP/SMI/index.html