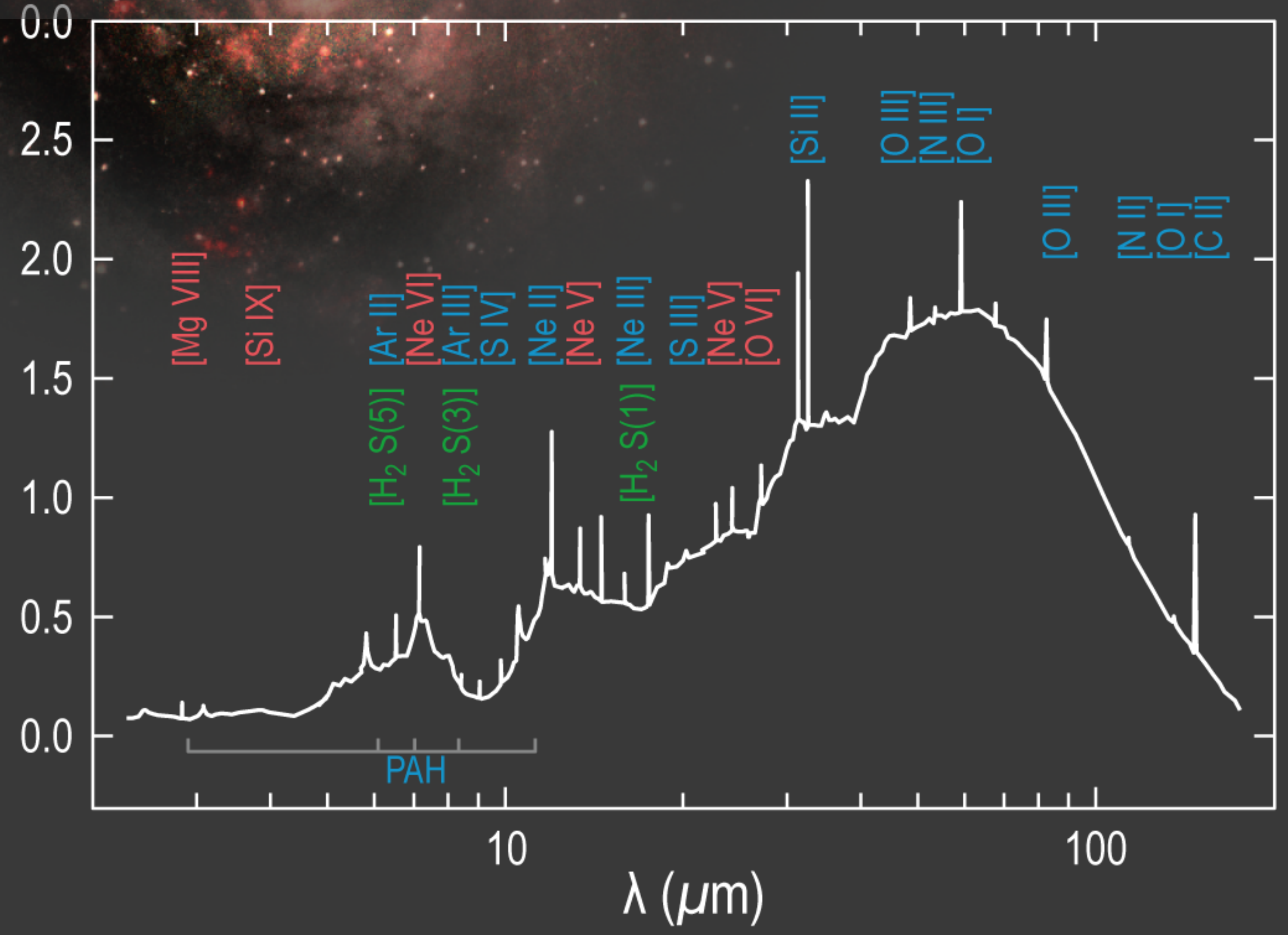
# The landscape of extragalactic infrared astronomy over the next decade





Alexandra Pope (UMass Amherst)


*AAS 237 – IRSIG Splinter Session*

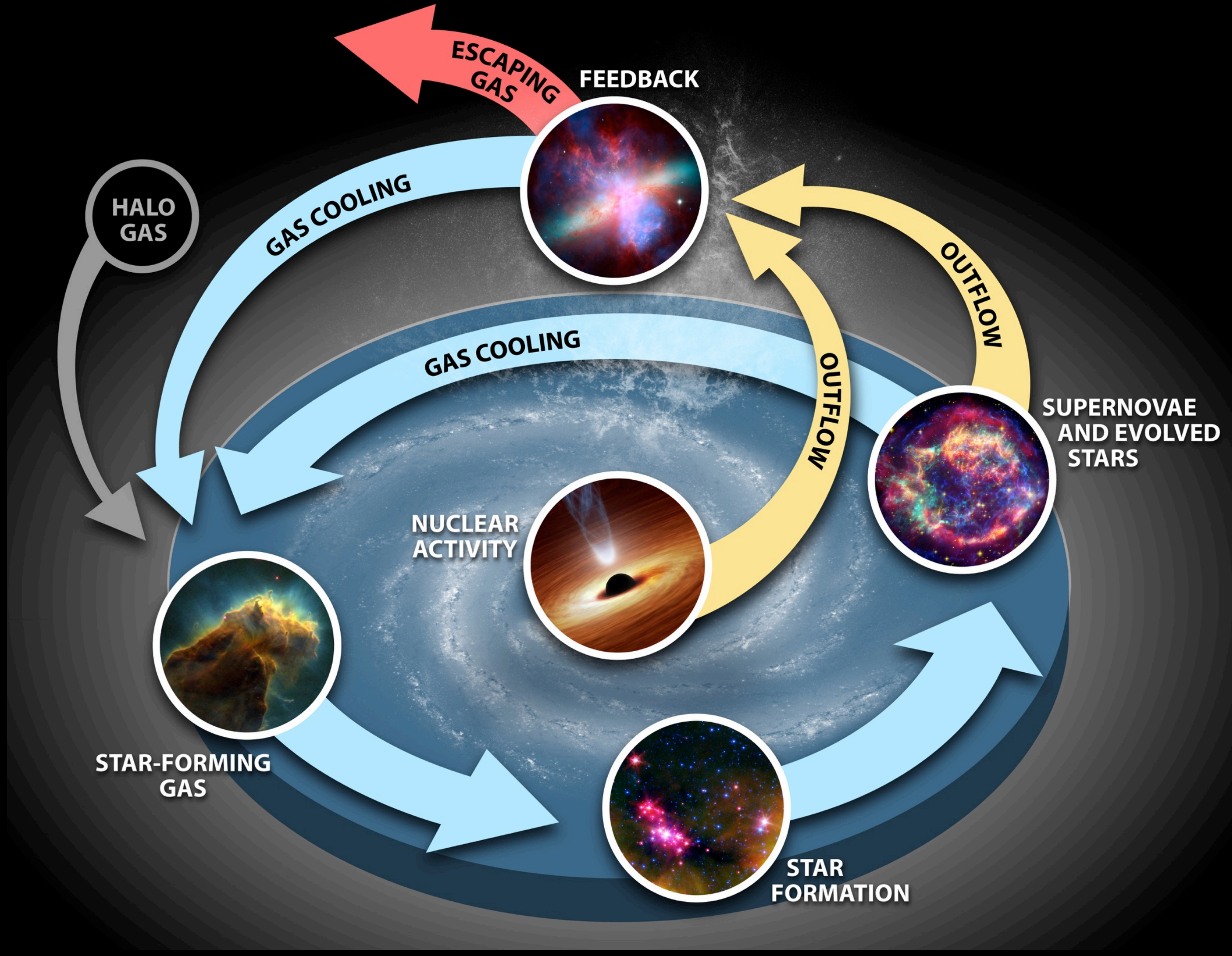
January 12, 2021

# Three outstanding questions

1. How did the first stars and black holes form?

2. How are metals formed and distributed in galaxies?

3. How do galaxies and supermassive black holes coevolve?




*Origins Space Telescope* mission concept study report, 2019

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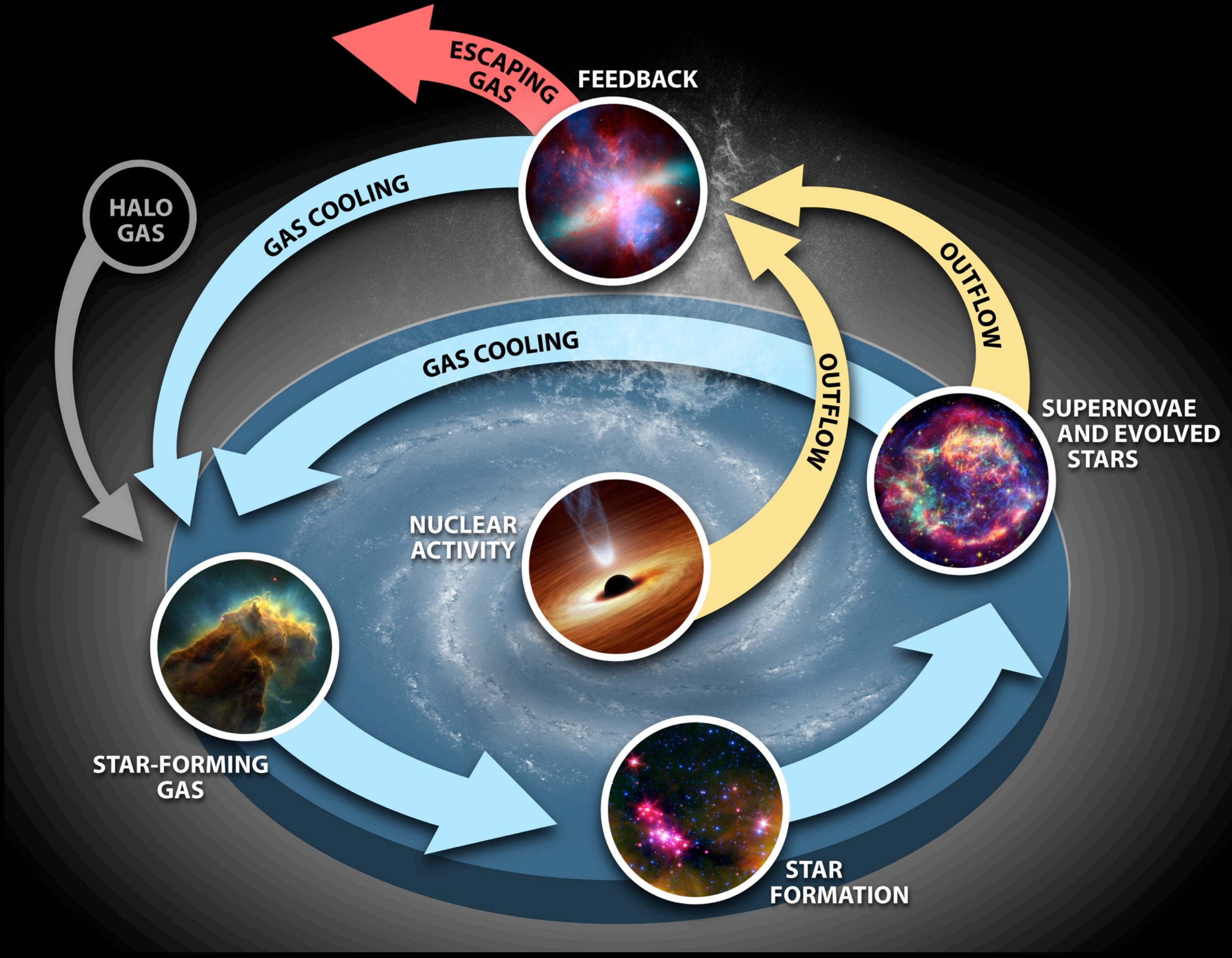
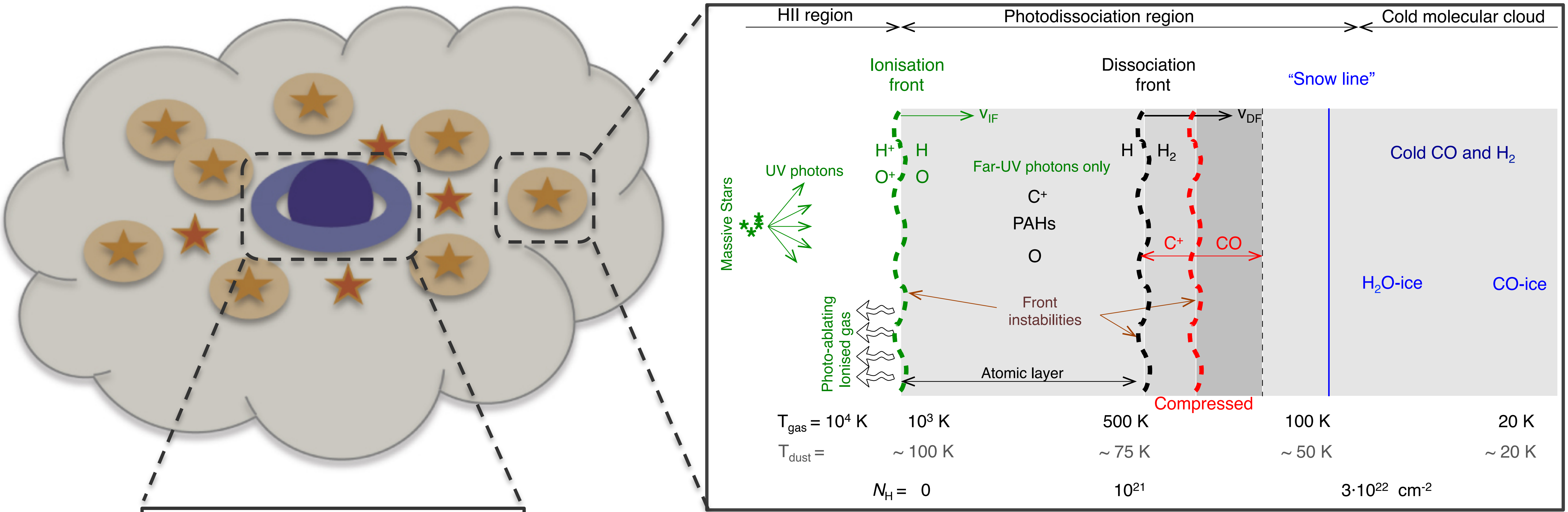


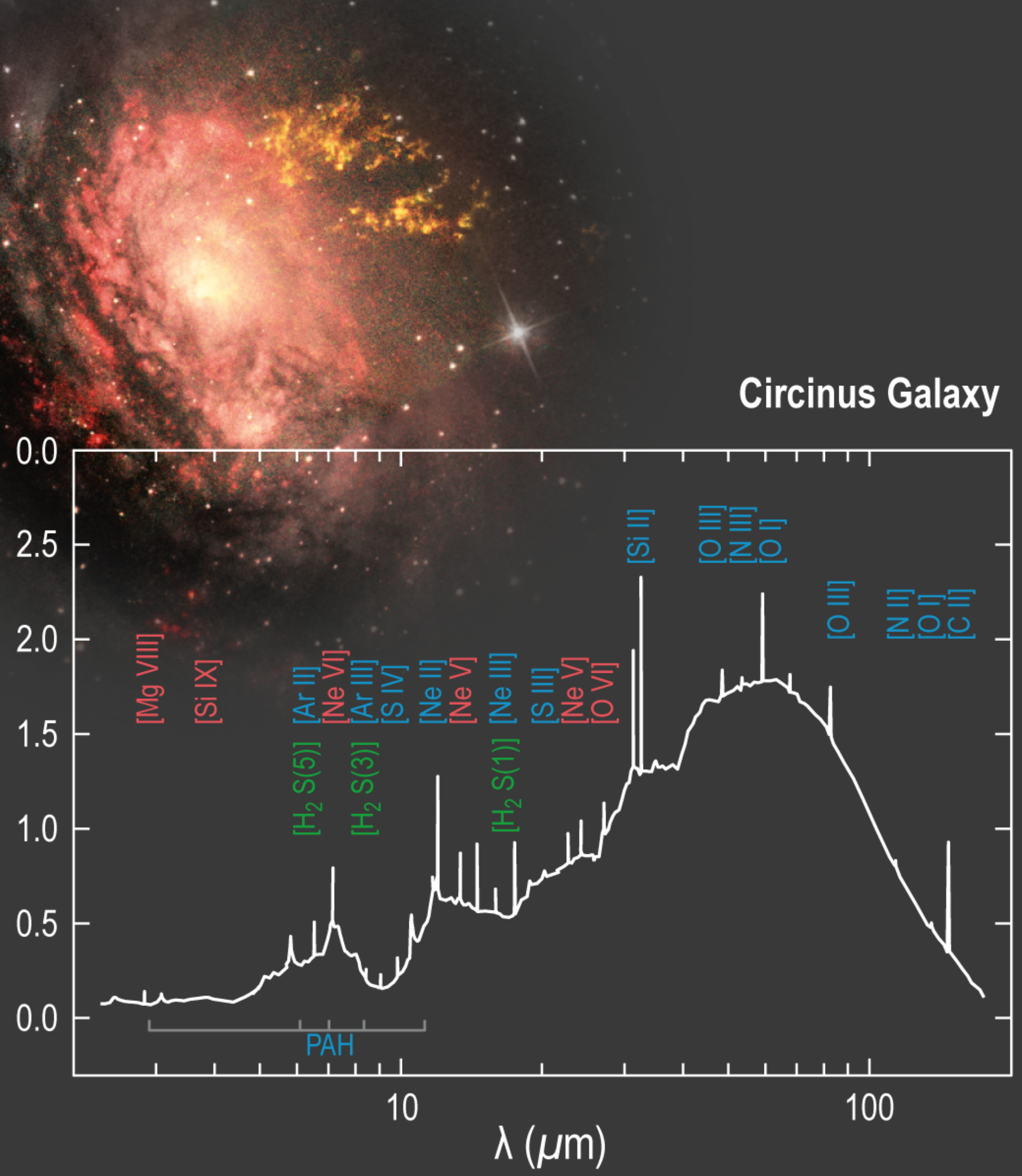

**What role should IR astronomy play in answering these questions?**

# The interstellar medium:
# Gateway to understanding galaxy evolution




[NeV], [OIV], hot dust

Figures adapted from Roebuck et al. 2016 and Goicoechea et al. 2016

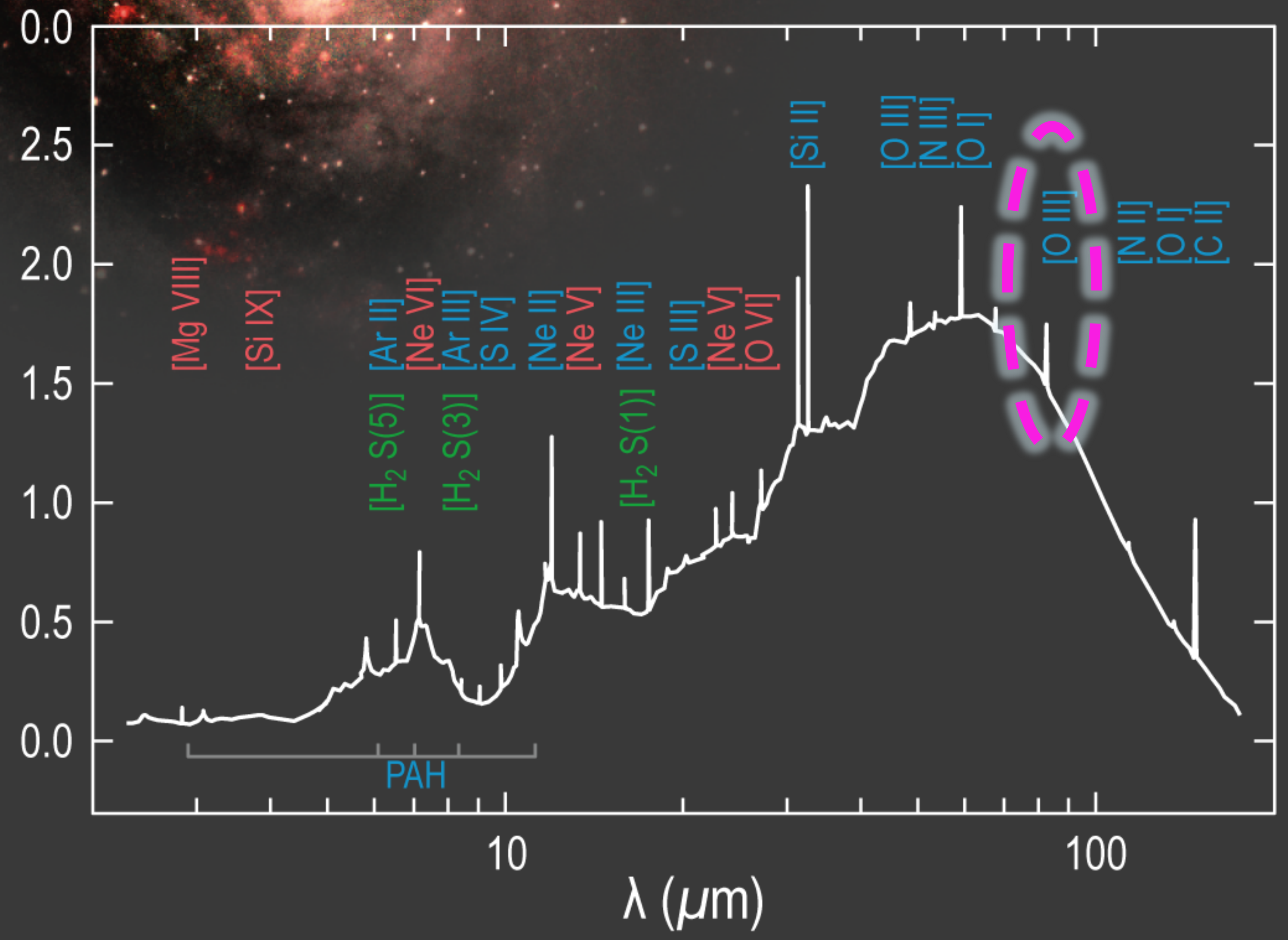


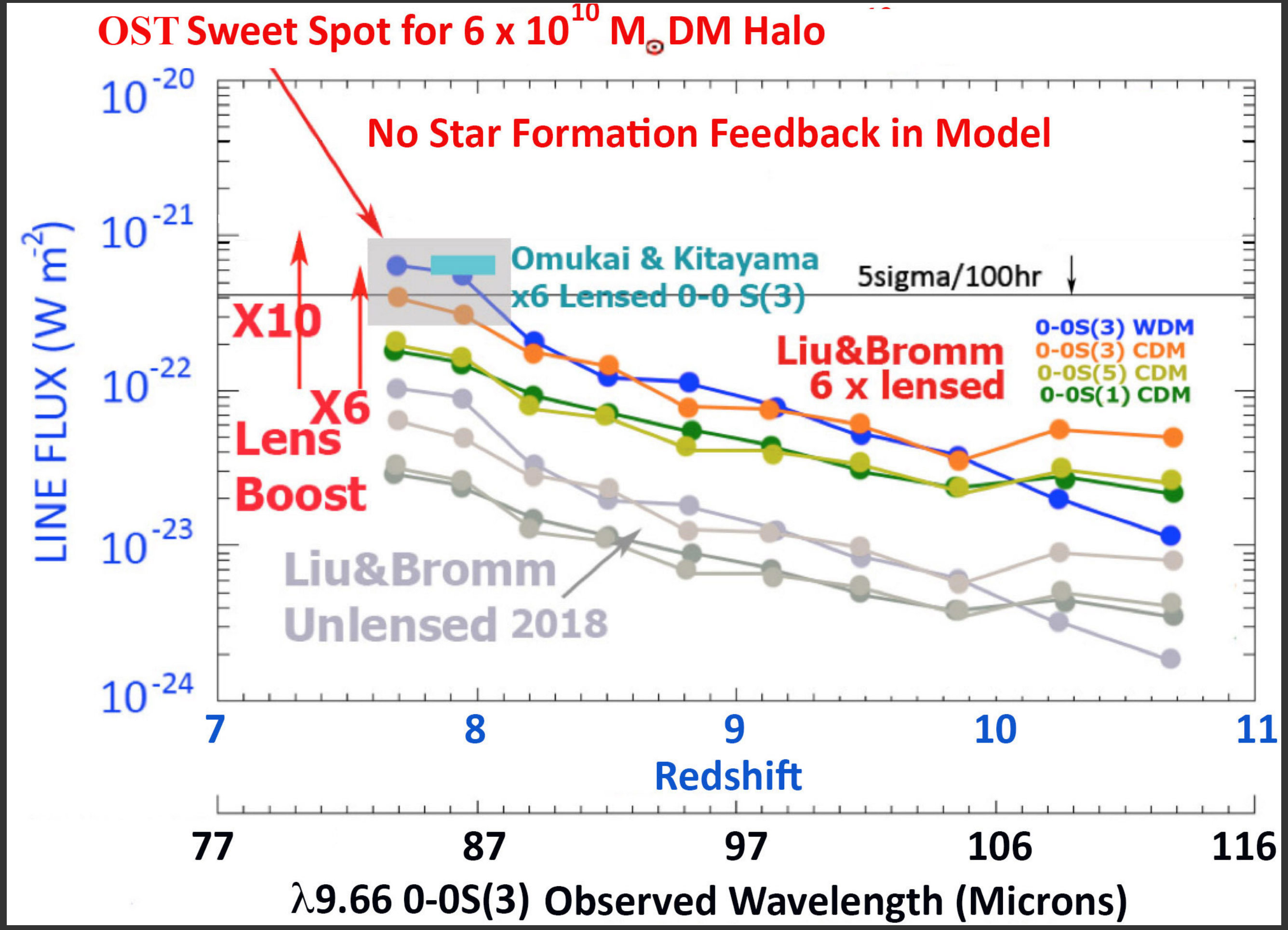

| Table 1.1-1 Key infrared diagnostic features | | | |
|---|---|---|---|
| **Species** | **Wavelength** | **Φ[eV]** | **Diagnostic Utility** |
| **Ionized Atomic Gas** | | | |
| Ne V | 14.3, 24.3 | 97.1 | AGN strength/accretion rate |
| O IV | 25.9 | 54.9 | AGN strength/accretion rate (hot stars) |
| S IV | 10.5 | 34.8 | SB strength/SFR/HII region density, |
| Ne II | 12.3 | 21.6 | ionization |
| Ne III | 15.6, 36.0 | 41.0 | " |
| S III | 18.7, 33.5 | 23.3 | " |
| Ar III | 21.83 | 27.6 | " |
| O III | 51.8, 88.4 | 35.1 | " |
| N III | 57.3 | 29.6 | " |
| N II | 122, 205 | 14.5 | " |
| | | | " |
| **Neutral Atomic Gas** | | | |
| Si II | 34.8 | 8.2 | |
| O I | 63.1, 145 | | Density and temperature probes of photo- |
| C II | 158 | 11.3 | dissociated neutral gas at the interface |
| C I | 370 | | between HII regions and molecular clouds |
| **Molecular Gas** | | | |
| $H_2$ | 9.66 12.3, 17.0, 28.2 | | Warm (100-500 K) molecular gas/feedback |
| HD | 37, 56, 112 | | D/H ratio/gas mass |
| OH | 34.6, 53.3, 79.1, 119 | | Column density of cold, dense gas, |
| OH | 98.7, 163 | | abundance/feedback |
| $H_2O$ | 73.5, 90, 101, 107, 180 | | " |
| CO | ~2600/J | | High-J, warm/dense molecular gas/feedback |
| **Dust** | | | |
| Silicate | **9.7, 18** | | Optical depth. Hot dust emission in QSOs |
| PAH | **6.7, 7.7, 8.5, 11.3, 17** | | PDR tracer. Star formation rate. Grain properties |

*Origins Space Telescope* mission concept study report, 2019

# 1. How did the first stars and black holes form?

ALMA detected [OIII] at z=9.1!
(Hashimoto+2018)

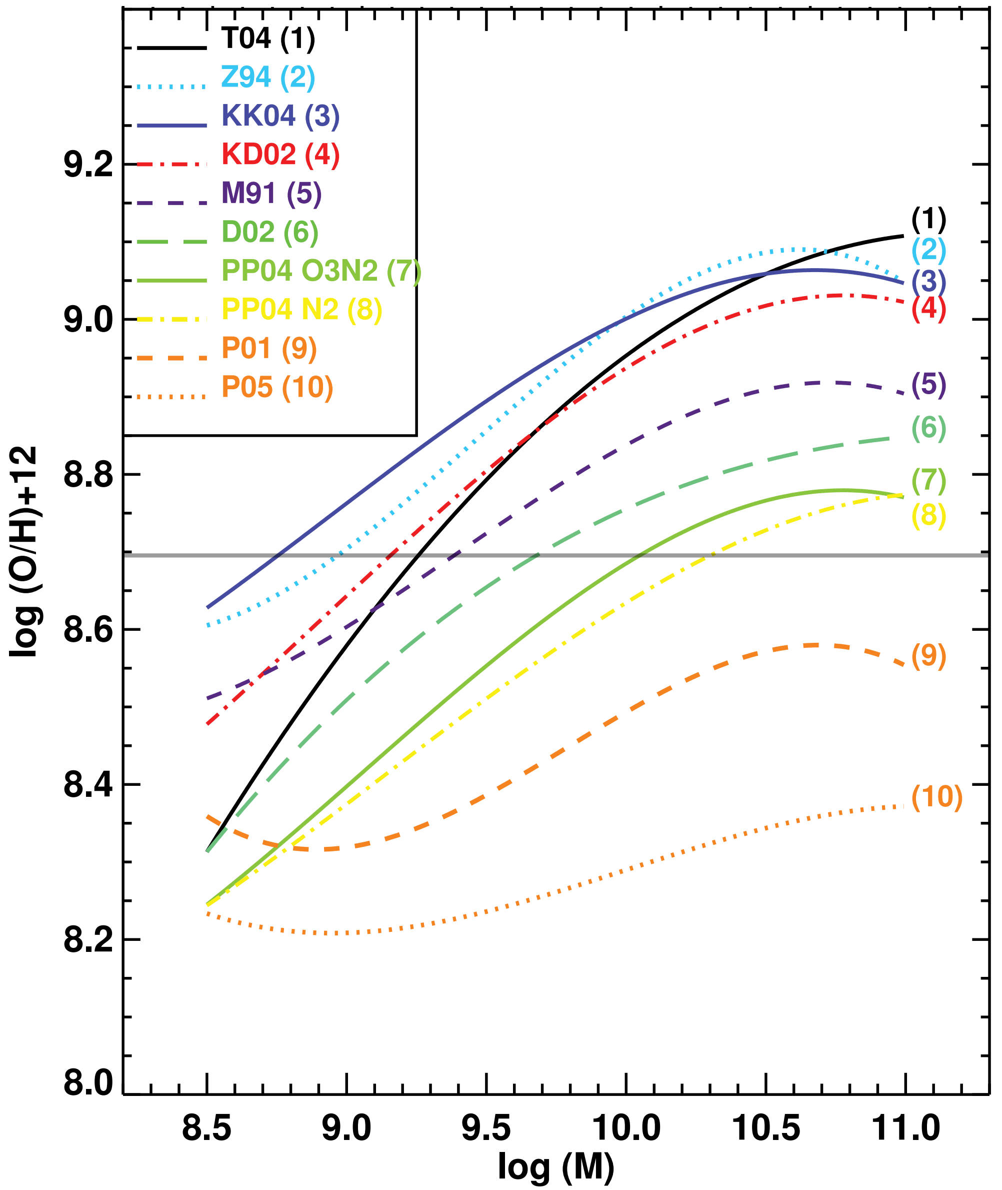



*"H2 emission/absorption may be the only way to directly probe the gas cooling and feeding the most massive metal-free dark matter halos and to assess the molecular reservoirs inside dust- and metal-free star forming regions at the earliest epochs."*

Appleton et al. 2019, Astro2020 whitepaper

# 2. How are metals formed and distributed in galaxies?

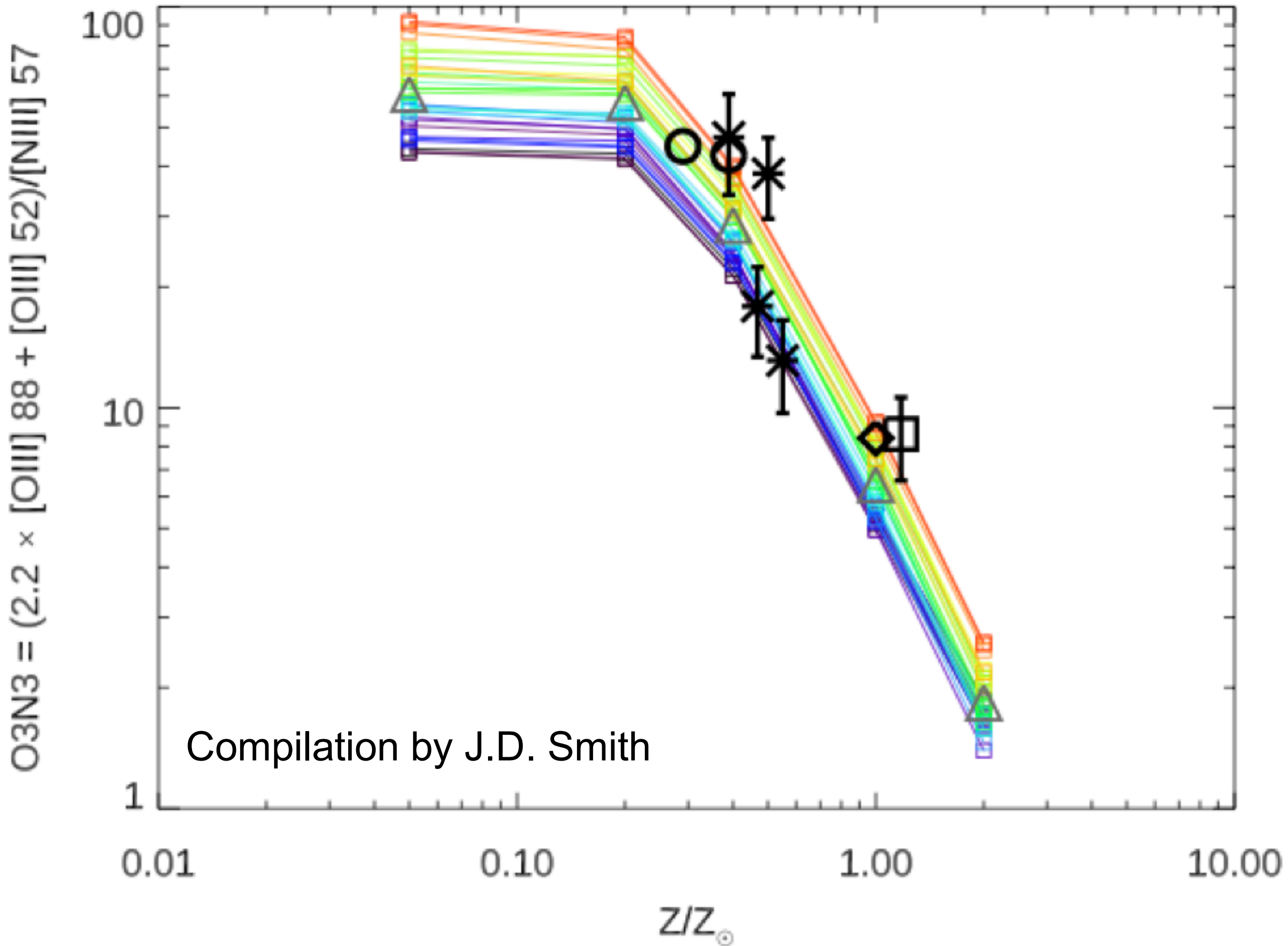



Kewley & Ellison 2008

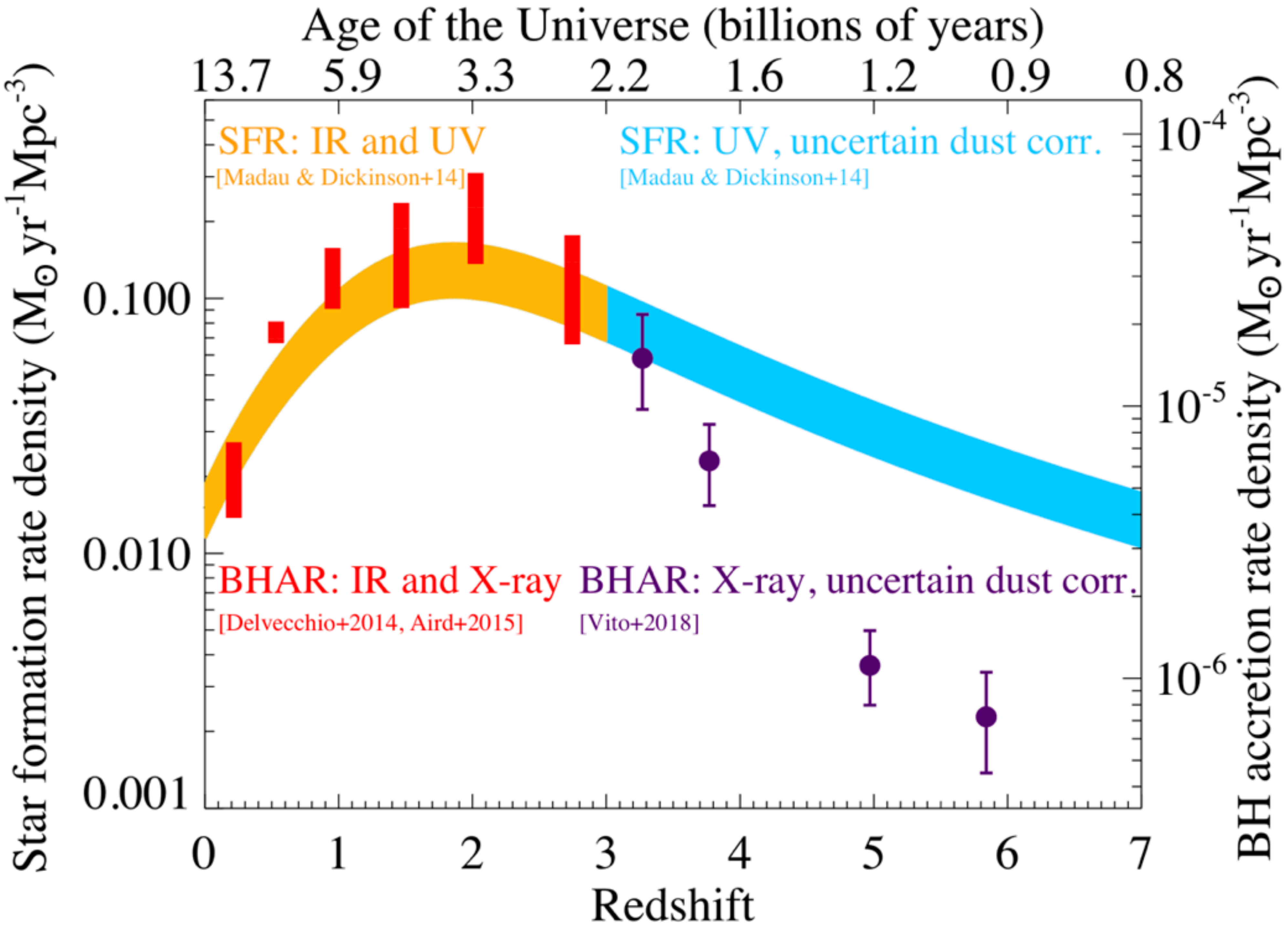
| Method Name | Observations | Features | z | Facilities |
|---|---|---|---|---|
| ***Strong UV*** | UV Strong (C,N,O), H/HeRec | Ionbal | 2–7 | Ground 8–30m, JWST |
| ***Direct Optical*** | Opt Strong+Weak (O,N), HRec | TempIns, Ionbal, ModInd | 0–3 | Ground 8–30m, JWST |
| ***Strong Optical*** | Opt Strong (O,N), HRec | Ionbal | 0–8 | Ground 4–30m, JWST |
| ***Direct FIR*** | FIR Strong (O), HRec/FF | TempIns, DustIns, ModInd | 0–8 | *FIRSurv*/ALMA, JWST/ngVLA |
| ***Modeled IR*** | IR Strong (O+N,Ne+S) | TempIns, DustIns | 0–6 | JWST, *FIRSurv* |
| ***Dust-Metals*** | IR Dust (PAH) | DustIns | 0–6 | JWST, *FIRSurv* |

**Strong**=Strong Collisional Lines, **Weak**=Weak/Auroral Collisional Lines, **HRec**=Hydrogen Recombination Lines, **HeRec**=Helium Recomb. Lines, **FF**=Free-Free Continuum Emission, **Ionbal**=Directly measures Ionization Balance, **ModInd**=Independent of Photo-ionization Models, **TempIns**=Insensitive to Unknown Temperature Variations, **DustIns**=Insensitive to Moderate Dust Extinction, **FIRSurv**=A Space Far-Infrared Spectroscopic Survey Facility, **PAH**=Polycyclic Aromatic Hydrocarbon Bands and Band Ratios

Smith et al. 2019 Astro2020 whitepaper



# 3. How do galaxies and supermassive black holes coevolve?

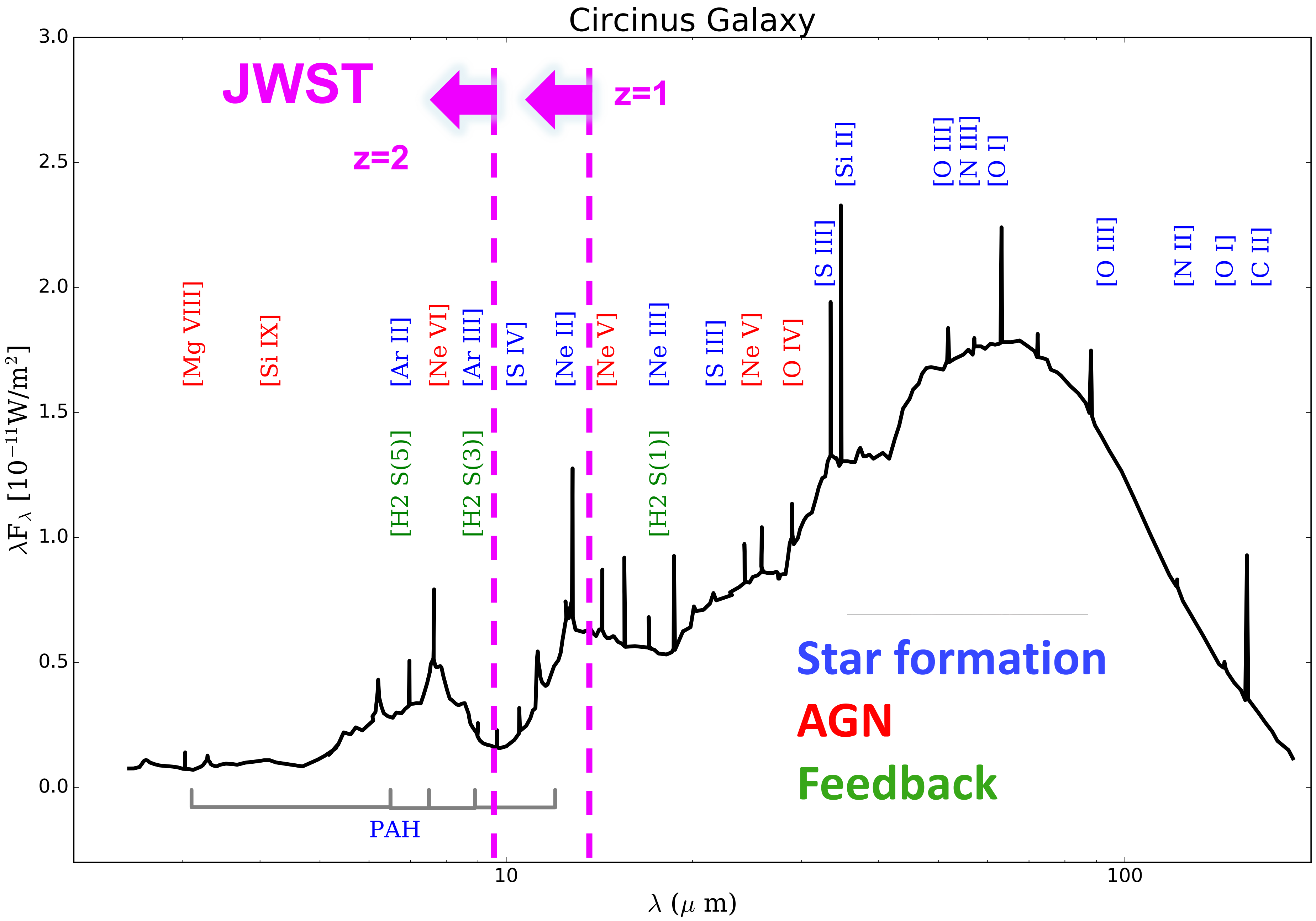


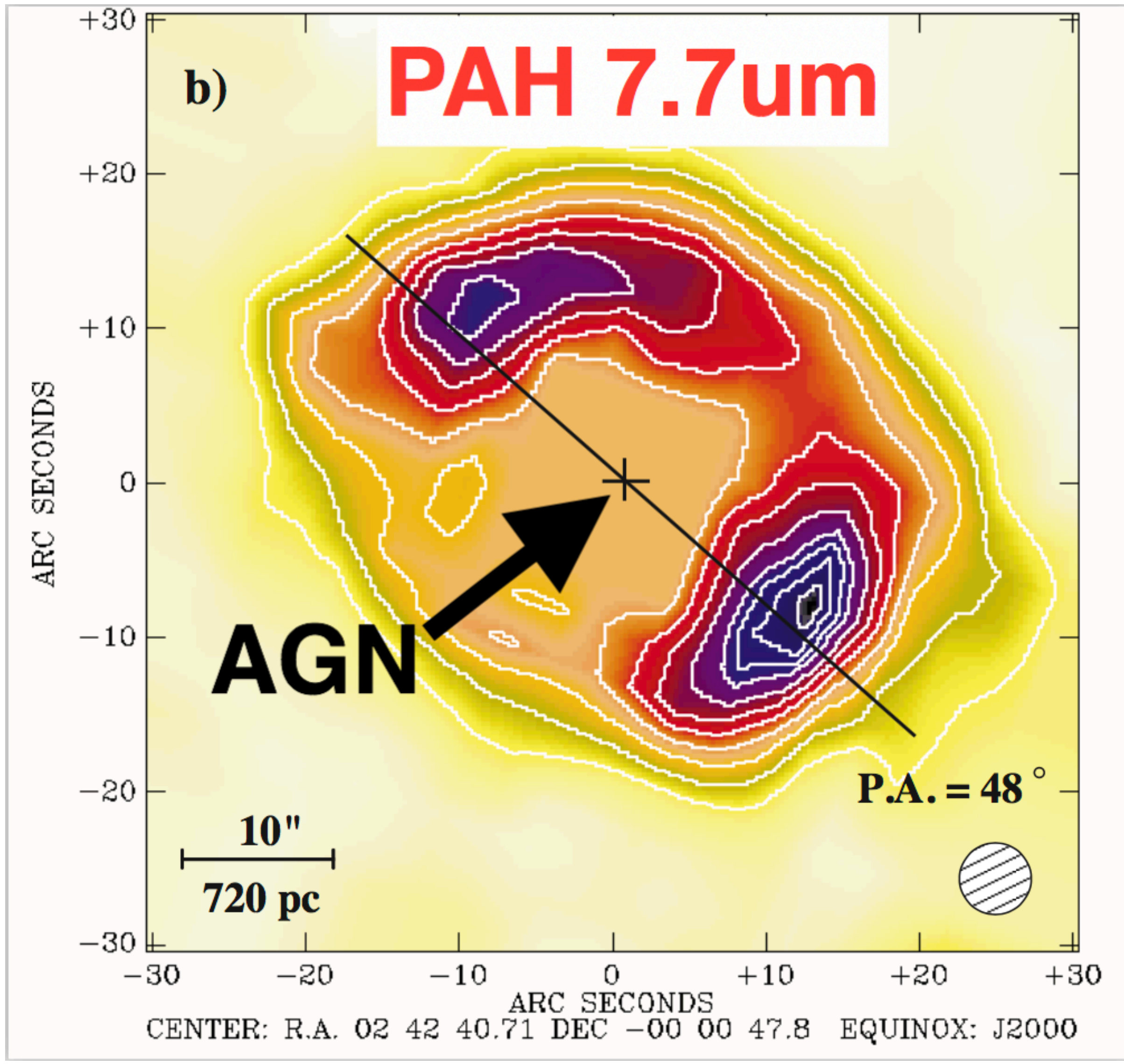

Need to make simultaneous measurements of the SFR and the BHAR in the same galaxies.

**Only the infrared can do this!**

Pope et al. 2019 Astro2020 whitepaper

# *JWST* will extend these powerful MIR diagnostics to z~1-2 and begin to spatially resolve




NGC 1068, Le Floc'h et al. 2001

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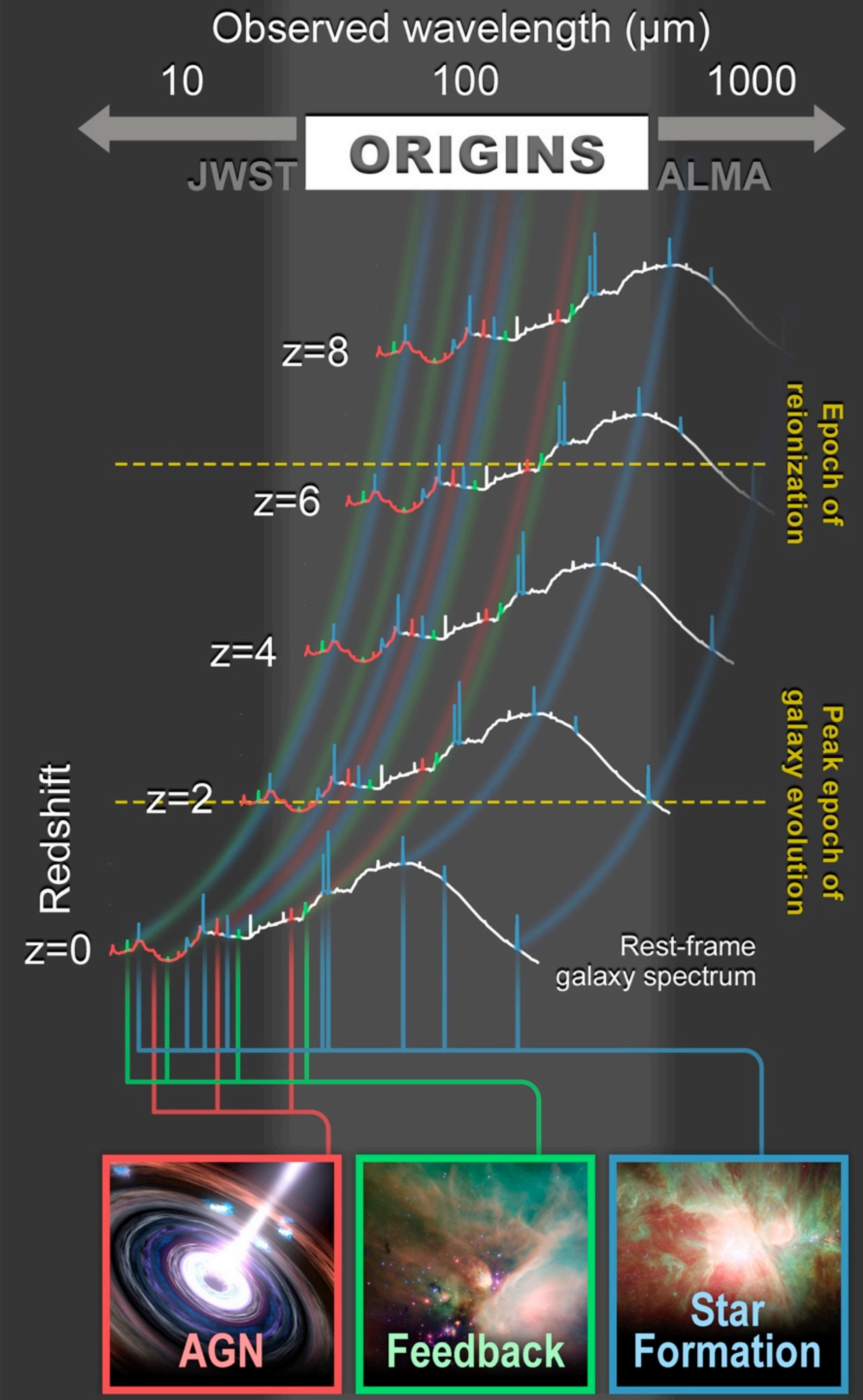


Order-of-magnitude gap in wavelength coverage between *JWST* and ALMA hiding the rich array of spectral lines.

Small probe missions such as GEP can make important progress on these outstanding science questions.

*Origins Space Telescope* has the sensitivity to follow these diagnostics over all cosmic time.