# The dynamic ISM: the fuel and exhaust of galaxies

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*for the SPICA nearby galaxies working group:*

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SRON Netherlands Institute for Space Research

Netherlands Organisation for Scientific Research

# The ISM of galaxies: Current key questions

What mechanisms promote and inhibit star formation?

How to disentangle them in different galactic environments?

so far: mid/far IR lines limited to bright (regions in) galaxies

SPICA: full suite of lines

How do galaxies acquire dust; how do dust properties evolve?

so far: broadband IR limited to normal galaxies

SPICA: probe low-Z / dwarf galaxies

What is the nature of the 'dark gas' in galaxies?

so far: use CO and dust as tracers of cold $H_2$

SPICA: use HD, $C^+$ and full line suite

Many more SPICA science cases possible;

***your input needed for discussion!***

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# SPICA general strategy

Environmental dependence of

star formation rate

main gas reservoir

dust composition / mass

Spectral maps of nearby galaxies in mid & far infrared ranges

- characterize physical and chemical conditions
- in nuclei, disks, arms, halo ...
- ... even interarm & intergalactic gas

Cover broad range in *L, Z,* SFR, type

- volume-limited to ~100 Mpc (single field, $N \sim 10^4$)
- well-resolved to ~10 Mpc (multi field, $N \sim 100$)
- First complete set of dwarf galaxies (Euclid will find $\sim 10^5$)

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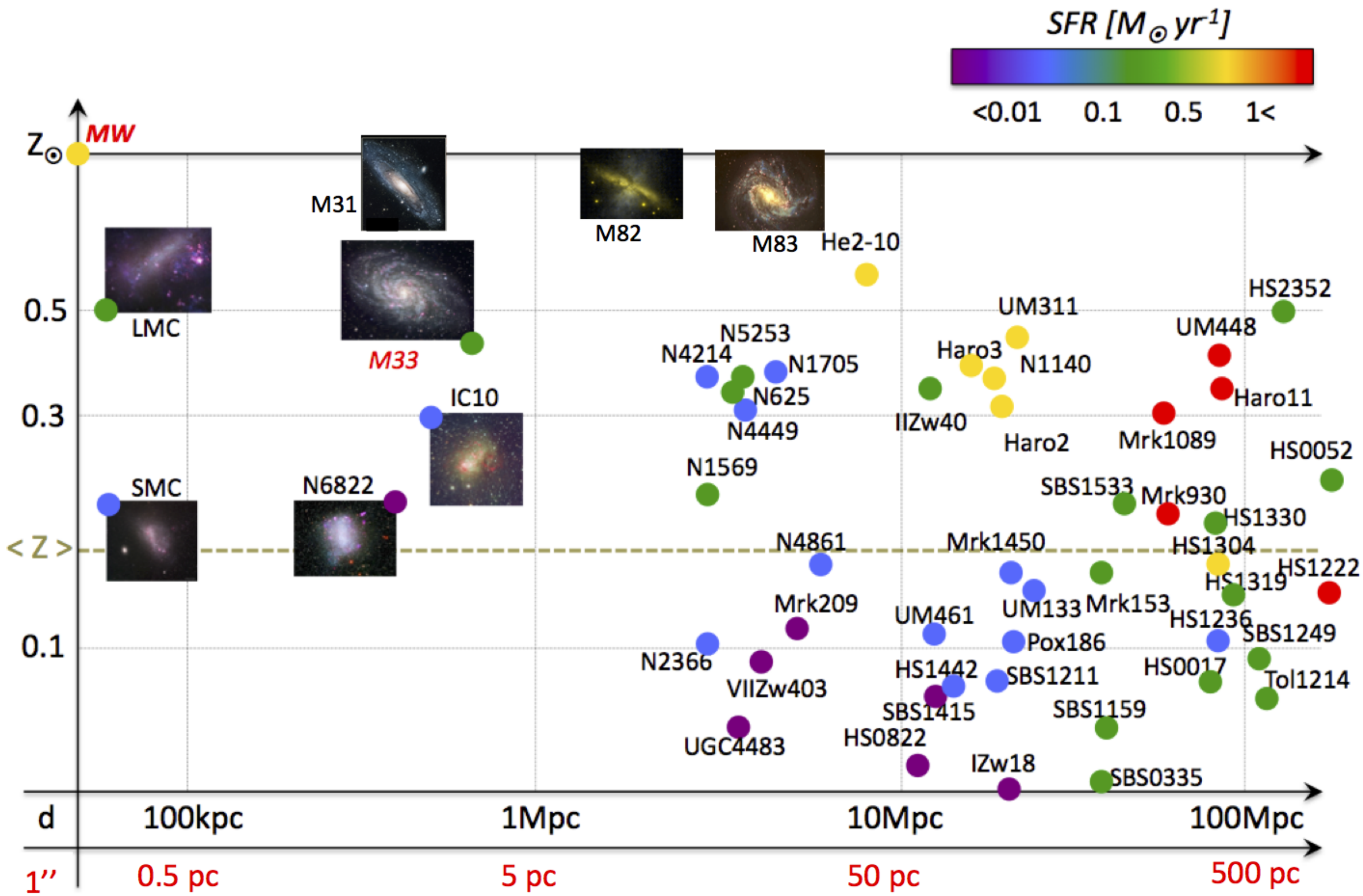
# SPICA laboratory: the Local Universe

## Survey parameter space of local universe

Wide range of type, spatial resolution , Metallicity, star formation, etc…



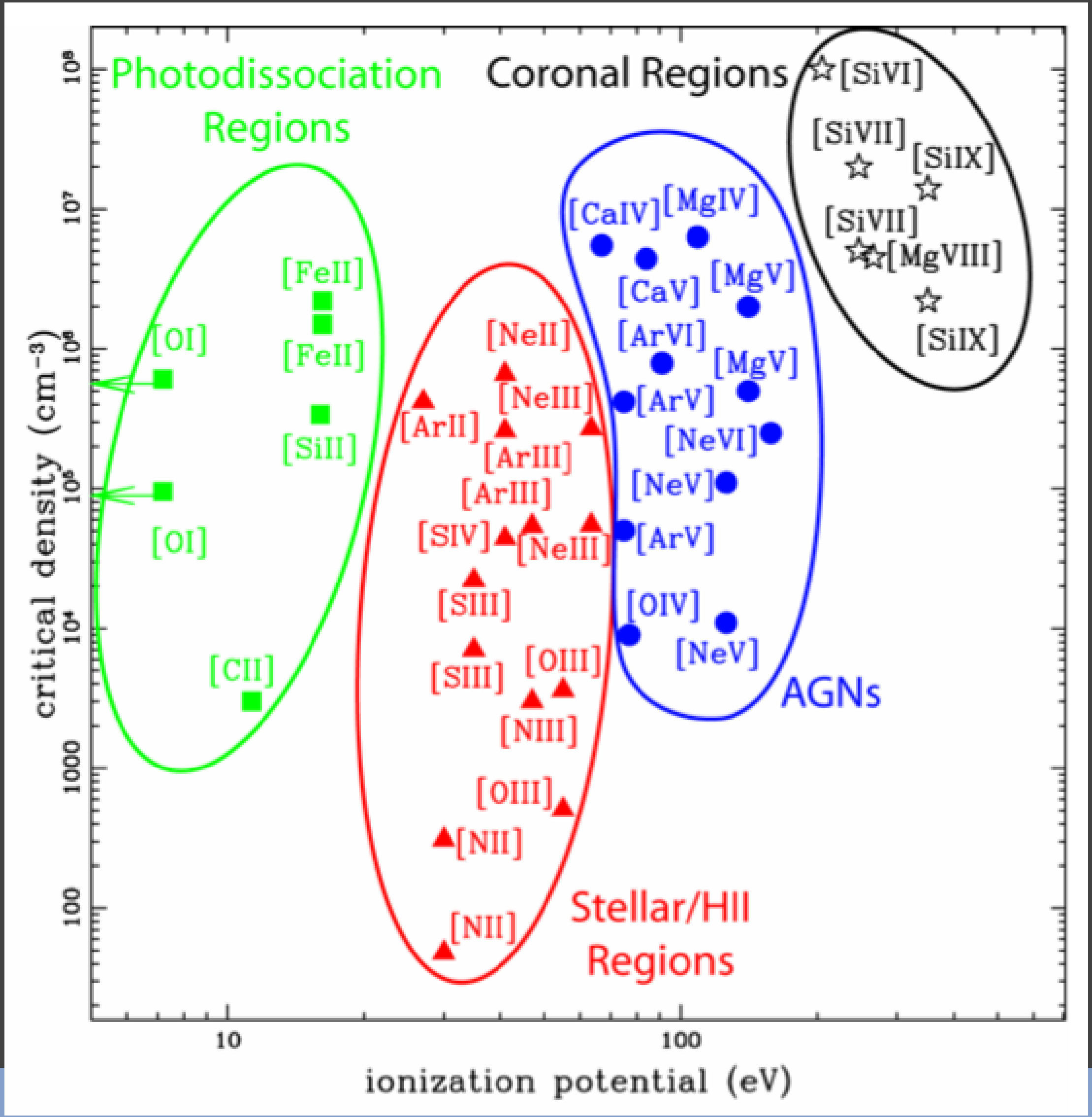

Diane Cormier

# SPICA toolbox: Mid- and far-infrared lines

As good as optical lines, but without the extinction

- probe ionized, neutral, molecular, and solid phases

*Spinoglio et al 1992*

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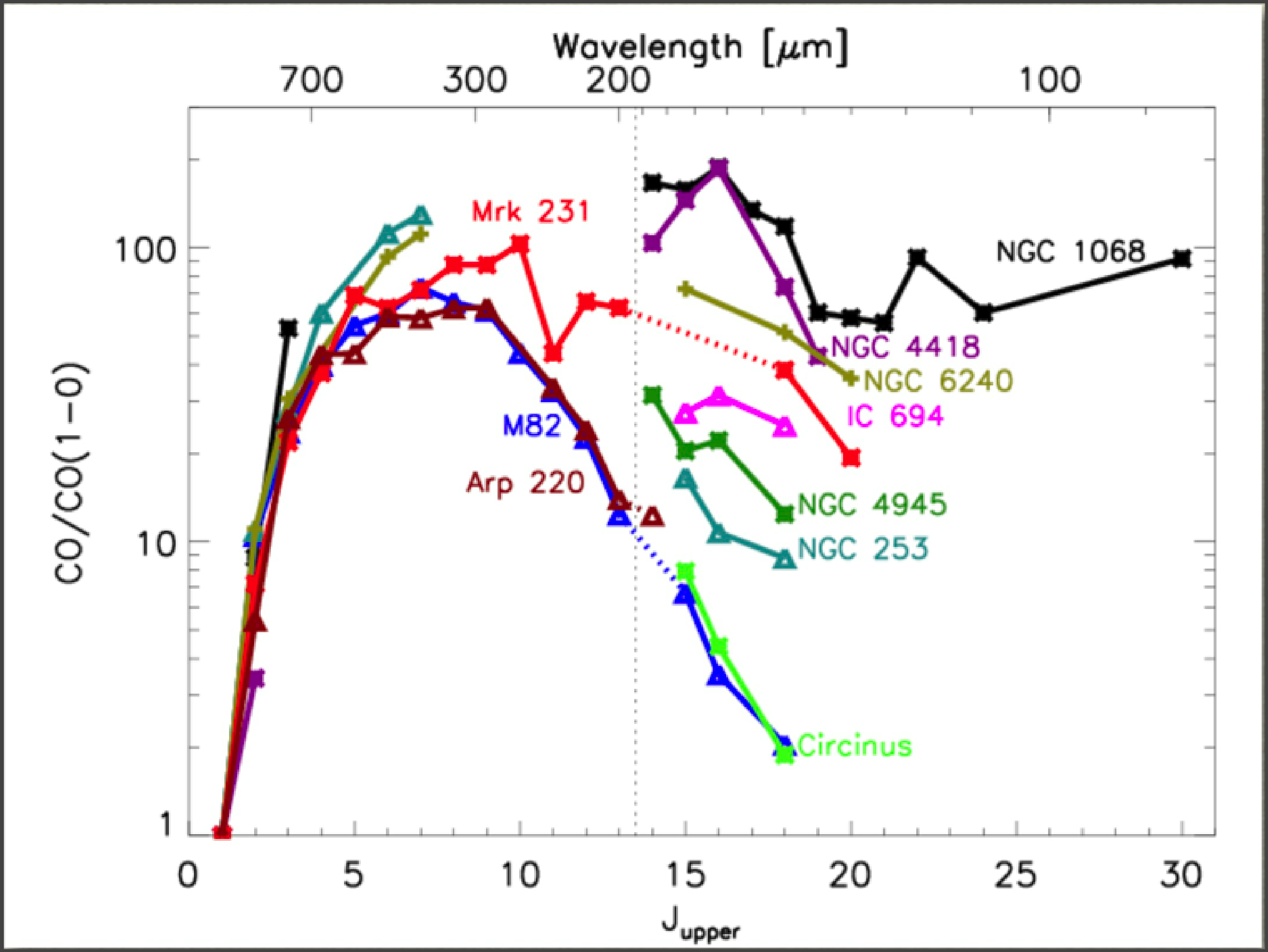
# Molecular lines: warm dense gas

SPICA probes right part of CO ladder

- Shock models: Flower & Pineau des Forêts 2010
- PDR / XDR models: Meijerink et al 2005, 2007

*Mashian et al 2015*

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# Key lines & features in the far-IR

| Species | Wavelength (μm) | Diagnostic of |
|---|---|---|
| [C II] | 158 | star formation rate |
| [O I] | 63, 145 | UV irradiation, shocks |
| [O III] | 88, 52 | shocks; ionization source |
| [N II] | 122, 205 | low-density ionized gas |
| [N III] | 57 | hardness radiation field |
| HD | 112, 56 | cold molecular gas |
| OH | 119, 84, 163, 53 | galactic winds |
| high-*J* CO | various | energetic irradiation |
| $H_2O$ | various | shocks |
| crystalline silicate | 69 | dust mineralogy |
| $H_2O$ ice | 62, 44 | dust processing |

*Herschel: low S/N, scratch surface*

*SPICA: high S/N, take full advantage*

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# Key lines & features in the mid-IR

| Species | Wavelength (µm) | Diagnostic of |
|---|---|---|
| [Si II] | 35 | UV irradiation, shocks |
| [S III], [Fe II] | 18, 33; 25 | shocks |
| $H_2$ | 17, 28 | warm molecular gas |
| [O IV], [Ne V] | 14, 24 | active nucleus |
| [Ne II], [Ne III] | 12.8, 15.6 | gas temperature |
| HCN, HNC | 14-15 | dense molecular gas |
| $CO_2$, $C_2H_2$, $H_2O$ | 14-15 | warm molecular gas |
| MgS / graphite | 30 | dust |
| SiC | 11.3 | dust |
| amorphous silicate | 9.7, 18 | dust |

*Note importance of 9-18 µm range!*

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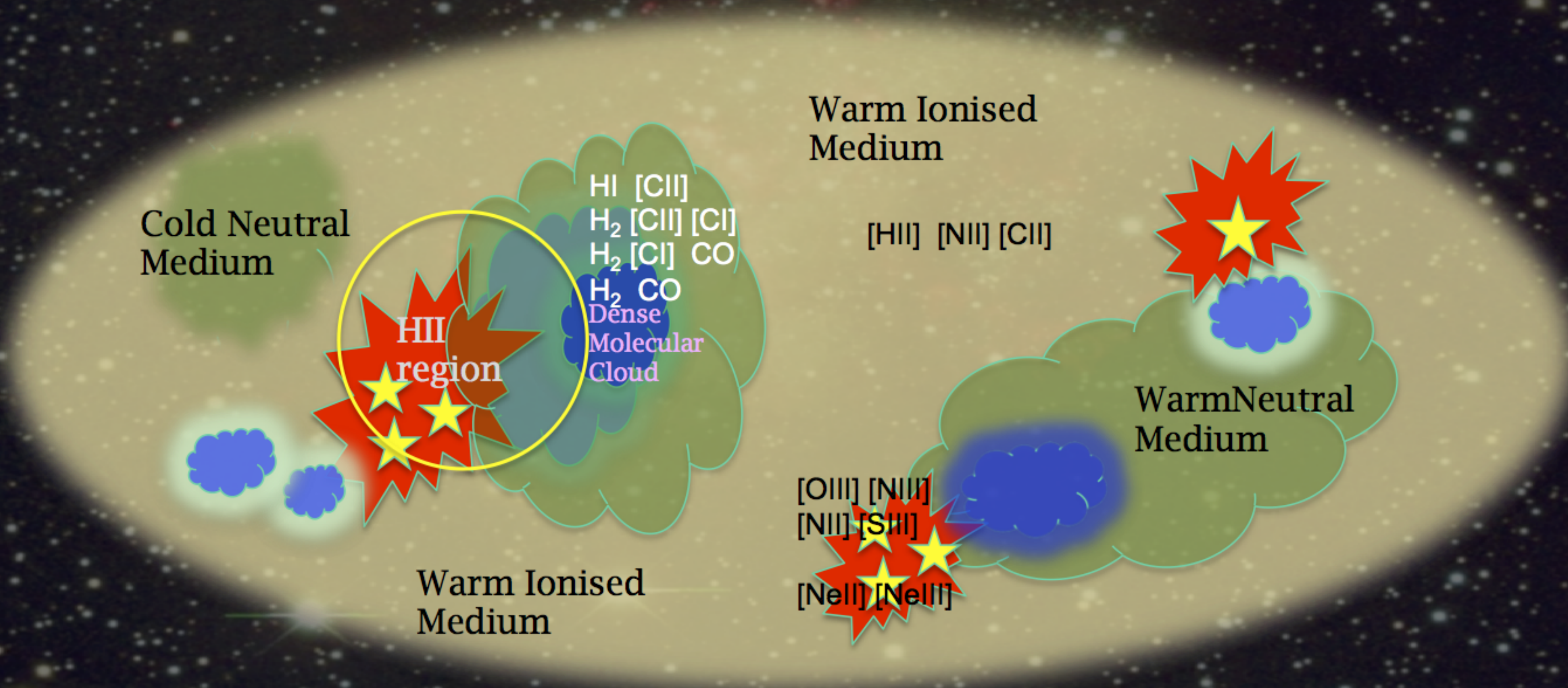
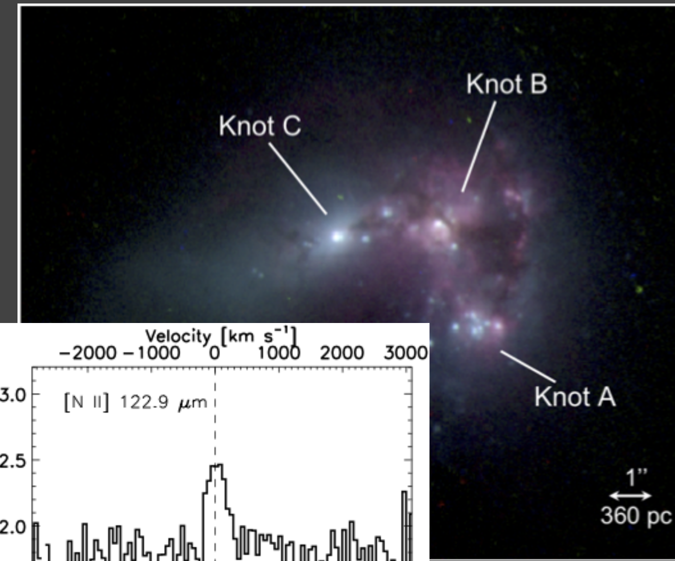
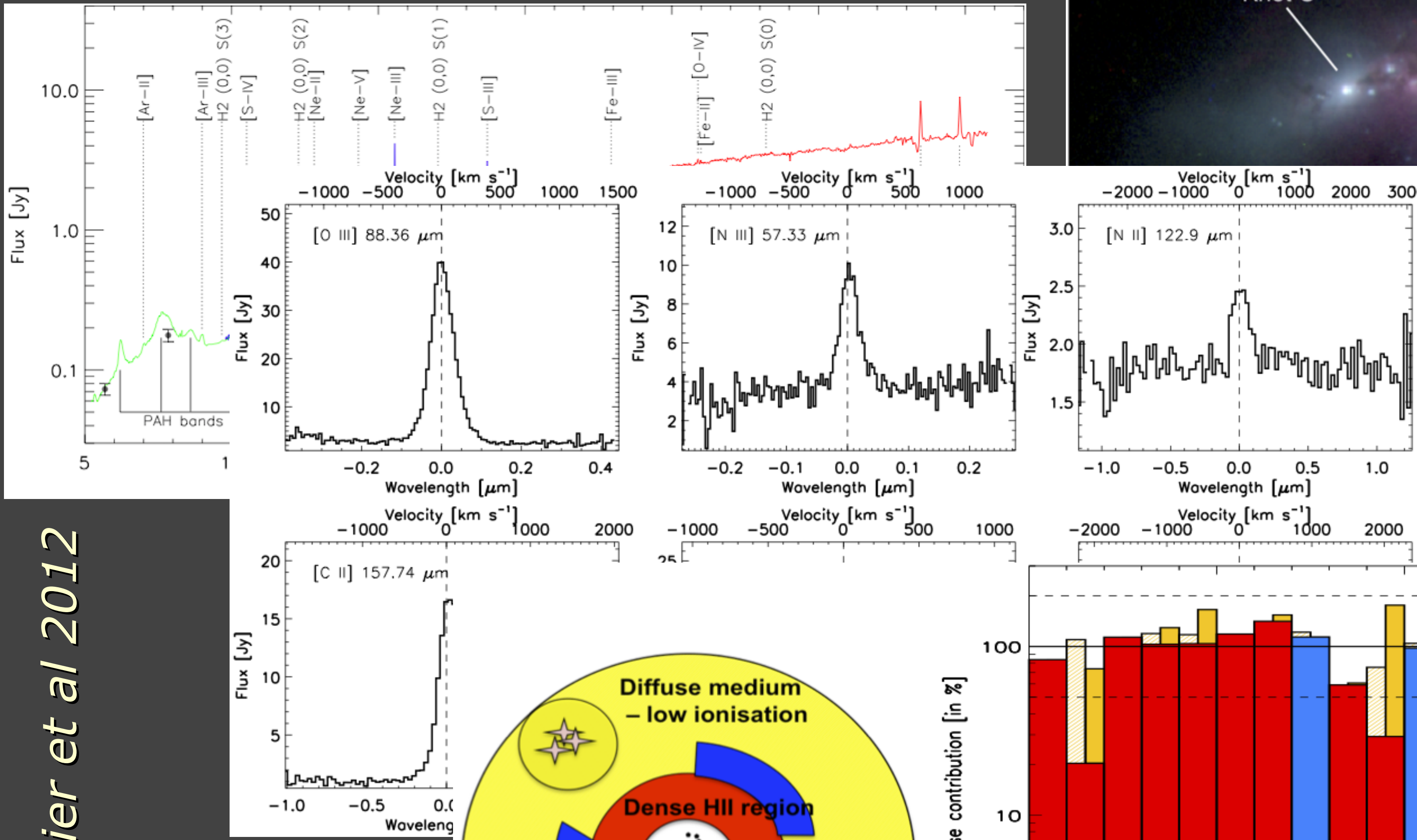
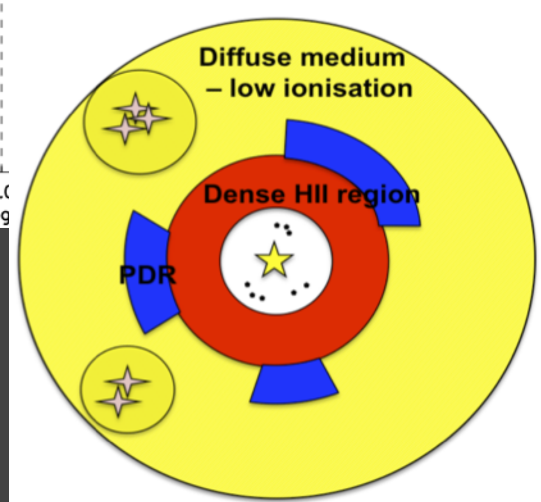
# The Complex Multiphase ISM of Galaxies

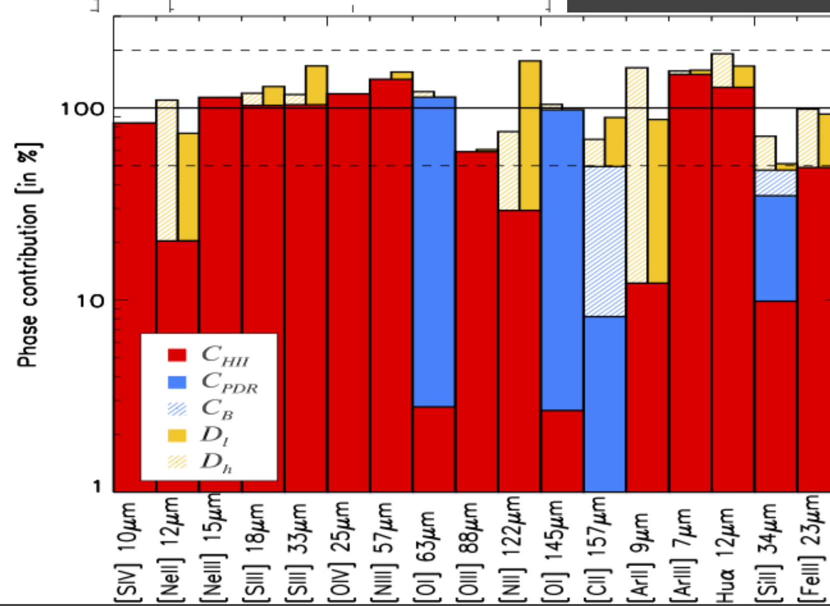


# Example: dwarf galaxy Haro-11



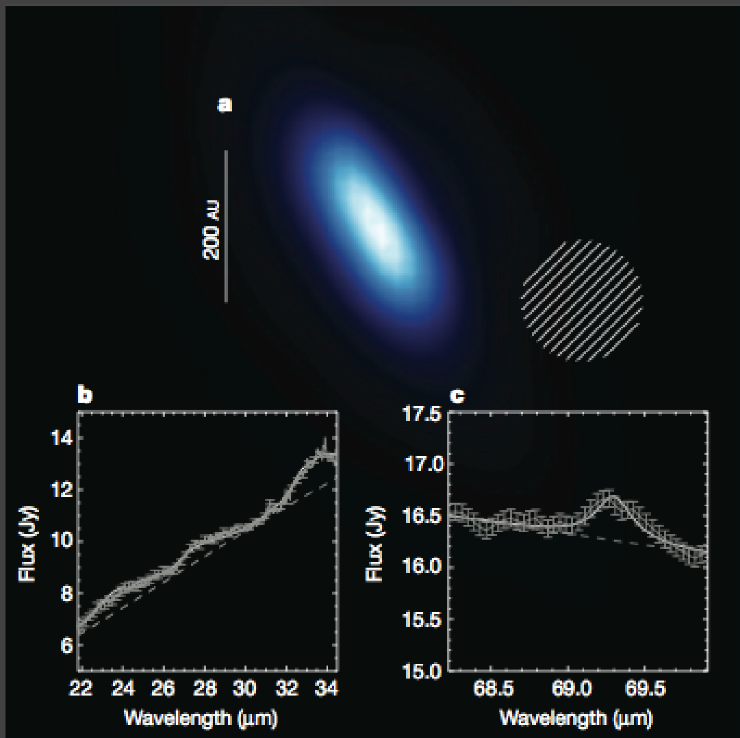



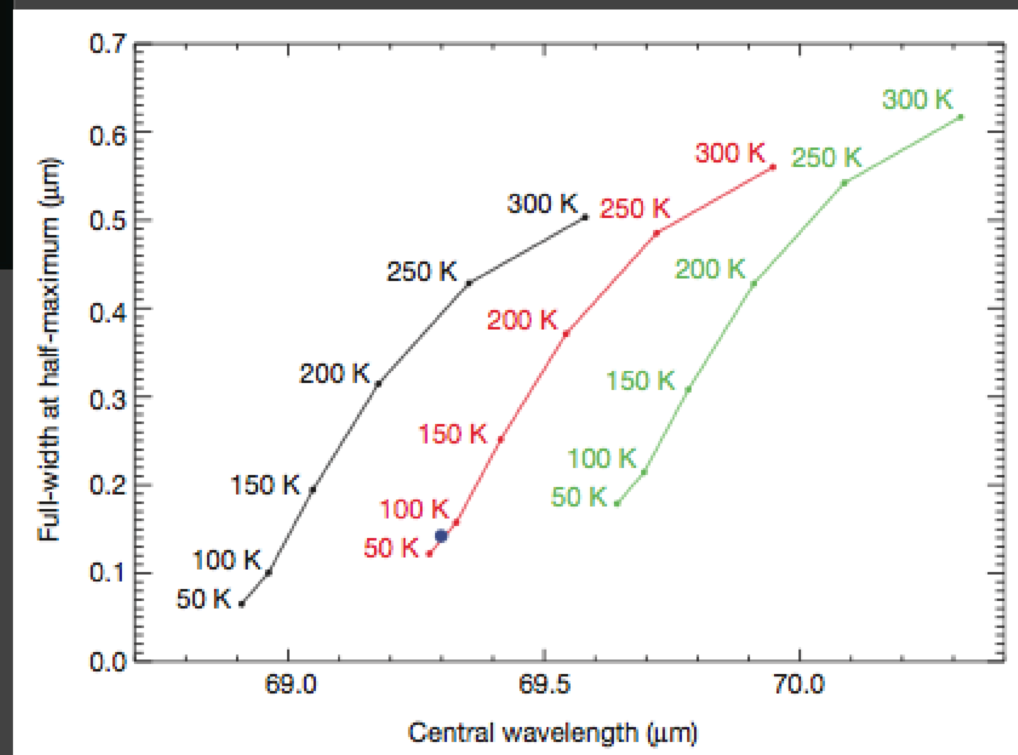




*Cormier et al 2012*

# Dust example: Forsterite in β Pic debris disk




Constrain *T* & Fe content
far-IR features best




*De Vries et al 2012*

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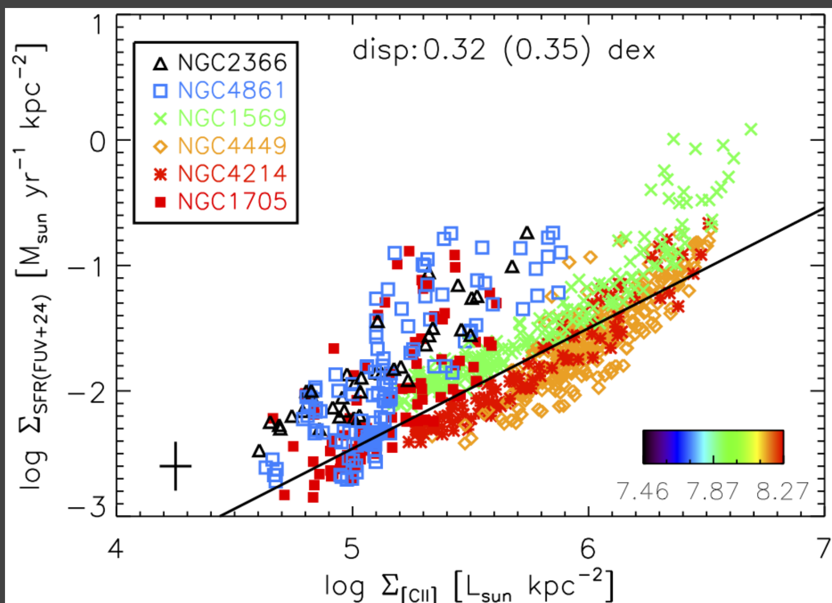
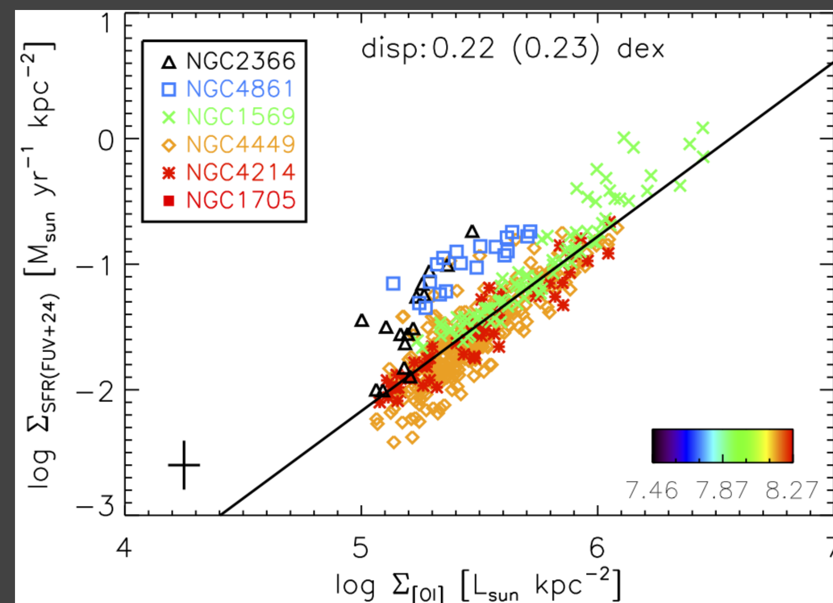
# Goal 1: Star formation vs environment

SFR varies widely among and within galaxies ... why?

- retrieve ISM properties with PDR / Cloudy models
- couple with maps of SFR (JWST), HI (SKA), stars (Euclid), cold dust (Herschel)
- cannot fully resolve: link properties statistically
- provide robust SFR estimators for high-*z* studies




*[CII] and [OI] as SFR tracers: De Looze et al 2014*

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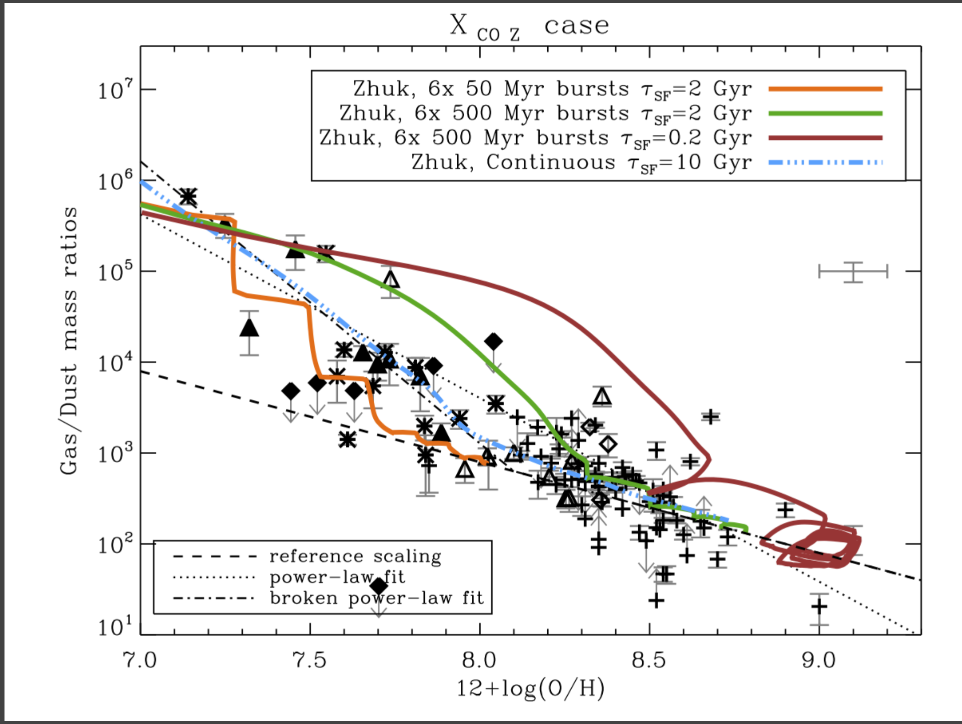
# Goal 2: The dust evolution of galaxies

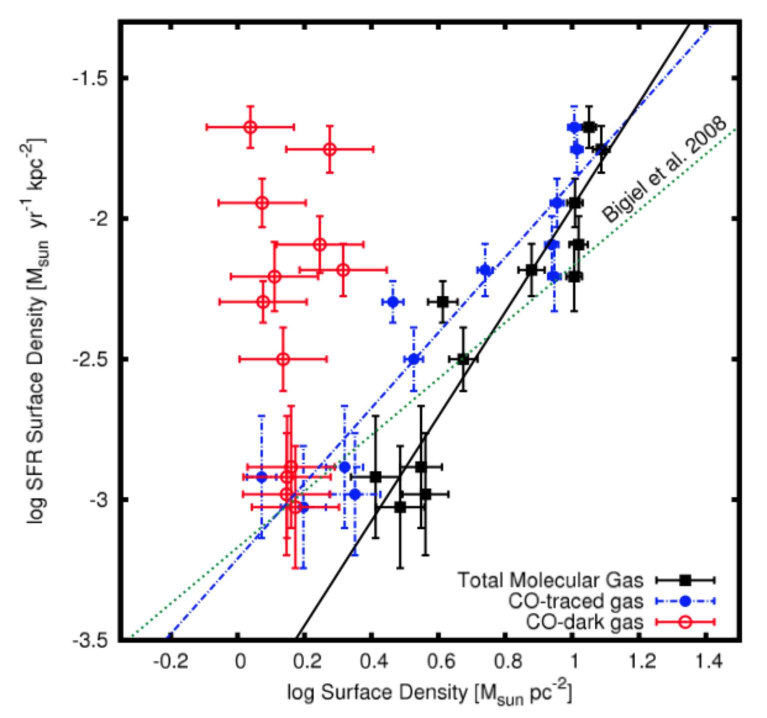
- Dust masses of lowest-*Z* galaxies unknown
- Herschel: suggests break in g/d ratio vs Z
- SPICA: adds dust masses at low Z
- Goal: understand how galaxies are enriched in dust



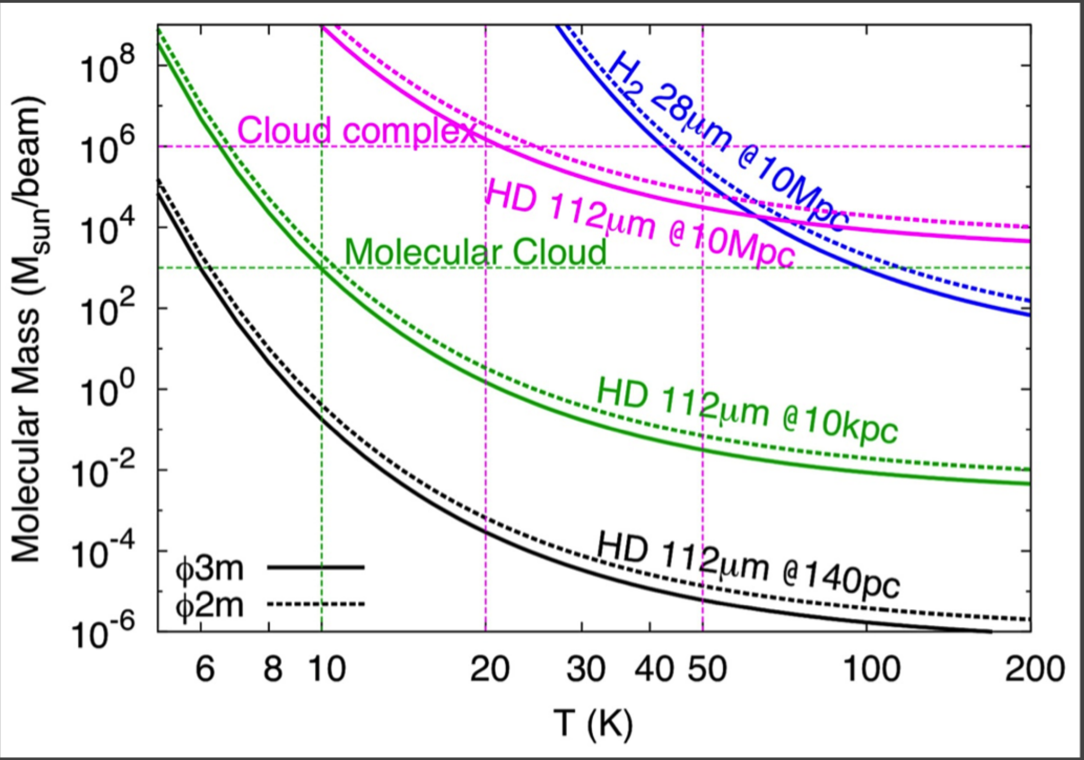

*Remy-Ruyer et al 2014*

# Goal 3: Probing CO-dark $H_2$ with HD and $C^+$

- Direct tracer of $H_2$ without $X_{CO}$-factor uncertainty
  - needs grating sensitivity
  - main uncertainty: gas temperature (CO with ALMA)




*Pineda et al 2014*




*Hidehiro Kaneda*

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# Many other 'use cases'

Feeding and feedback of galactic nuclei (Eduardo González-Alfonso)

- Far-IR OH, $H_2O$ lines: outflow tracers (Sturm et al)
- Fine structure lines to trace feeding of nucleus

Crystalline silicates (Ciska Kemper)

- probes of star formation activity and cosmic-ray flux
- key features in 25-70 μm range

Supernova dust (Mikako Matsuura)

- what is role of SNe in dust production?
- monitor SED of newly exploded SNe to trace *T,M* evolution

AGB/starburst coevolution (Dave Clements)

- how much bolometric power from obscured AGN
- SPICA is only probe of key mid-IR range

Local group galaxies (Jonathan Braine)

- detailed connection between dust/gas properties and star formation
- e.g. LMC/SMC provides ~pc resolution in range of *Z*

Elliptical galaxies (Hidehiro Kaneda)

- end points of galaxy evolution, but too faint for Herschel
- how do star formation and gas/dust reservoirs differ from spiral galaxies?

# Summary science case

A big step beyond Herschel

- from 2-3 lines to multi-phase ISM
- from nuclei to full galaxies
- from special cases to statistical samples

Large impact on other studies

- SPICA's high-$z$ program
- local star formation

Science legacy

- will know how galaxies make stars and metals
- locally and at peak of cosmic SFR

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