

# The Role of SOFIA in Extragalactic Science

*A Roadmap exercise*

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# Points I want to make in this presentation

- [CII] is the workhorse of SOFIA for local universe galaxies
  - [CII] is one of the brightest coolants of the neutral ISM of galaxies
  - [CII] => SFR in local and high-z galaxies
  - [CII] => tracer of CO-dark gas (especially in low Z galaxies where CO is faint or not detected)
  - SOFIA FIFI-LS has already mapped galaxies completely in [CII]
- [CII] mapping is a starting point: need to tackle the complex multiphase ISM
  - Structure of the ISM ? Ionized phase: Low n & high n ? Molecular/PDR ?
  - Low metallicity ISM is a particular niche : [OIII] is brighter than [CII]. SOFIA can do the 52  $\mu$  [OIII] line that Herschel/PACS could not do.
  - SOFIA can do some OI 63, OIII 88 & 52 in galaxies, but needs improved spectral resolution (especially in the blue channel of FIFI-LS)
- *Big Science Goal*: What is the structure of the ISM and how does it evolve in terms of porosity, phases, metal enrichment, star-formation, feedback?
- The local universe is the laboratory to help interpret high-z observations and develop diagnostic tools – SOFIA's role!

## Conclusion:

How can SOFIA grow the exgal community ?

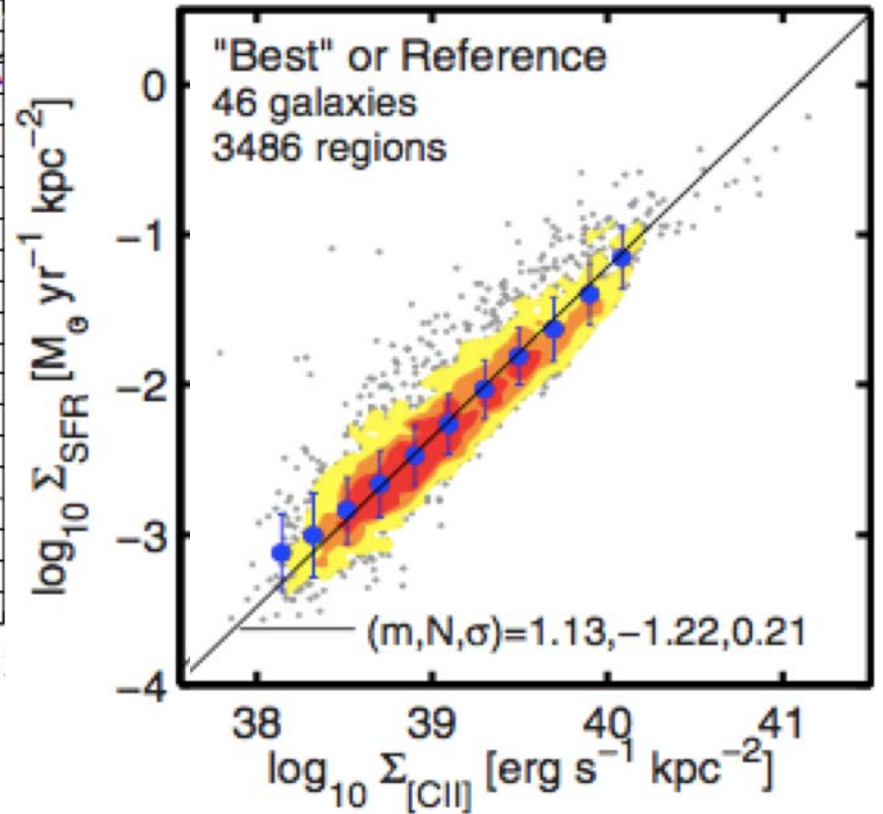
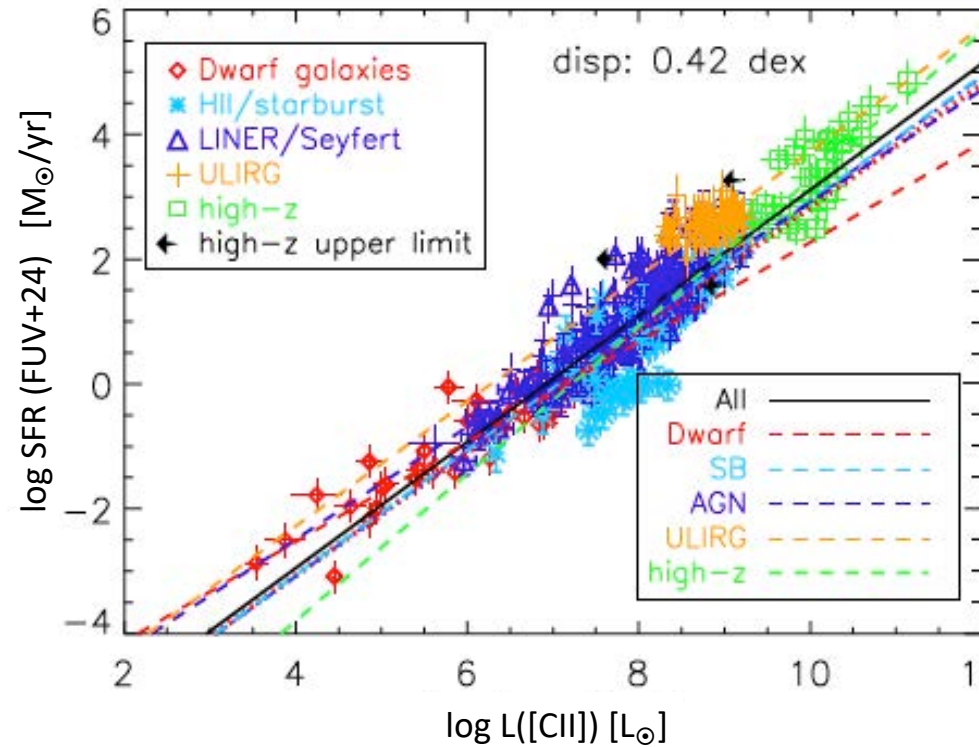
- FIFI-LS is a mapping machine for galaxies, but needs improved *spectral resolution* by factor of 2 (at least the blue channel is very low R ) & needs more spaxels (to map faster)
- Map other ISM phases with SOFIA. SOFIA should expand to shorter wavelengths – bright nebular lines covering wide range of critical densities & ionisation energies. Ideally ~ *to fill the gap where EXES ends and FIFI-LS+ (with higher FoV & spectral resolution) begins.*
- HIRMES would be a perfect solution: higher R in MIR/FIR, faster mapping, wavelength coverage and improved sensitivity
- SOFIA's *BIGGEST* extragalactic niche: Magellanic Clouds => *more NZ flights*
- *upGREAT* => *an [OIII] channel* (88 or 52  $\mu$ m) ?
- SOFIA : the only MIR-FIR we have to prepare for *SPICA & Origins*

# Tracing star formation with [CII] – Local galaxies

Herrera-Camus + 2015

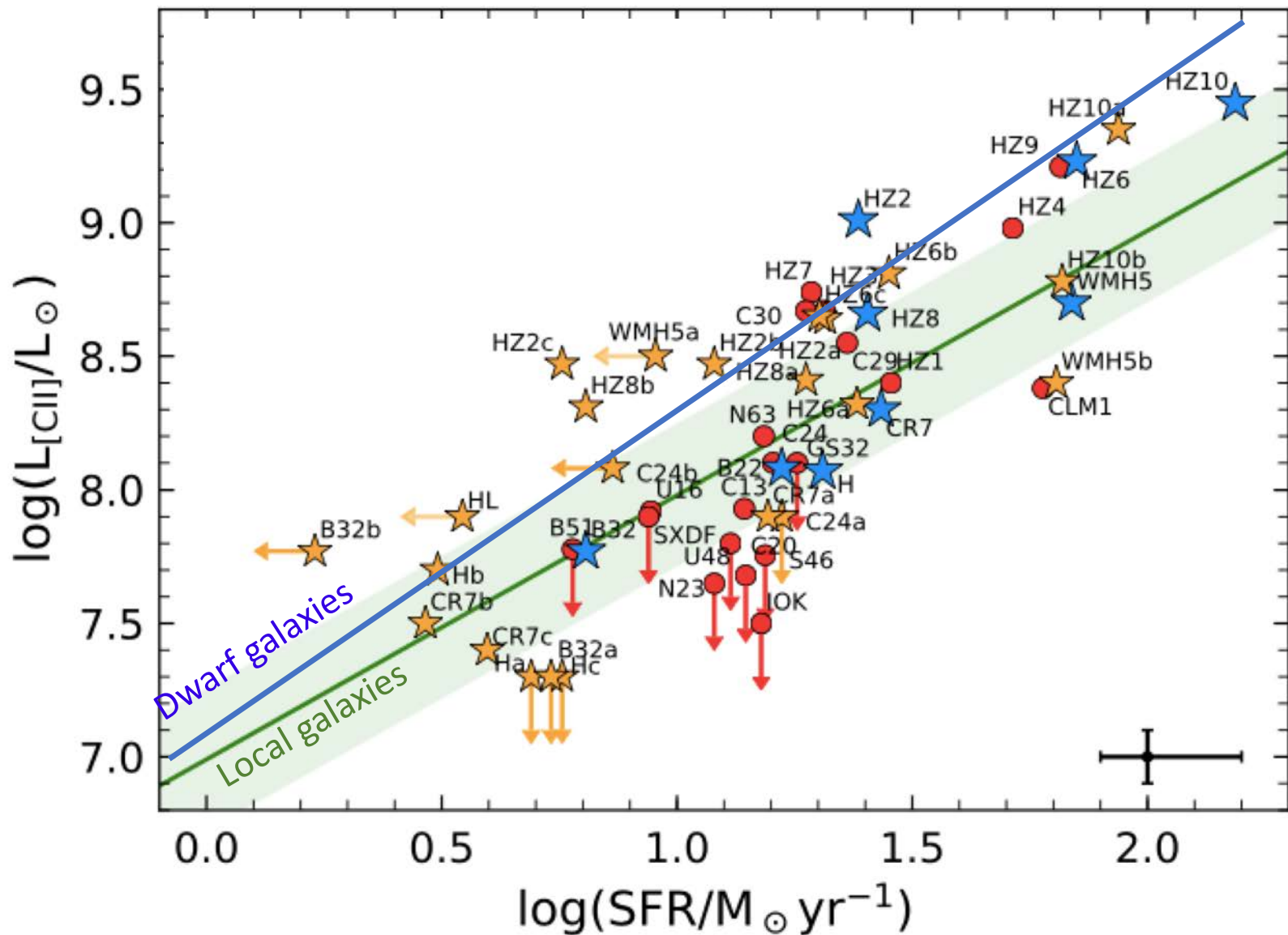
KINGFISH galaxies

de Looze +. 2014





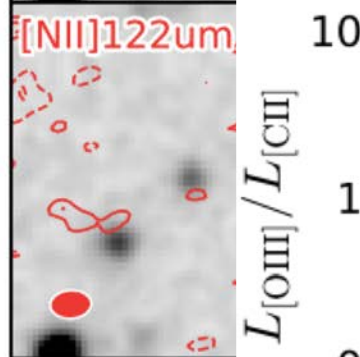
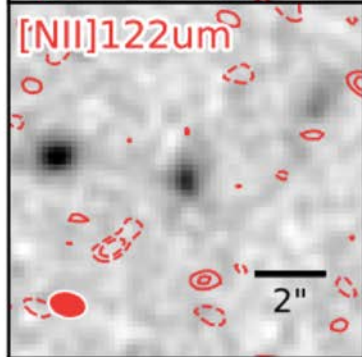
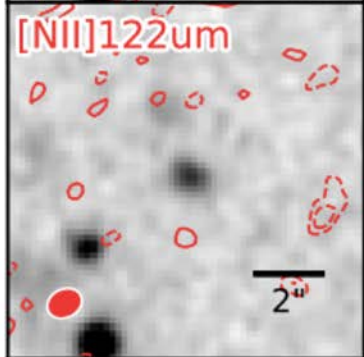
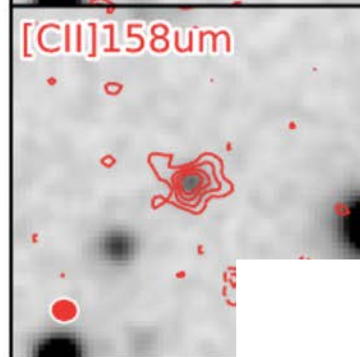
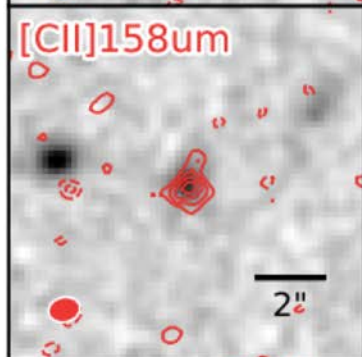
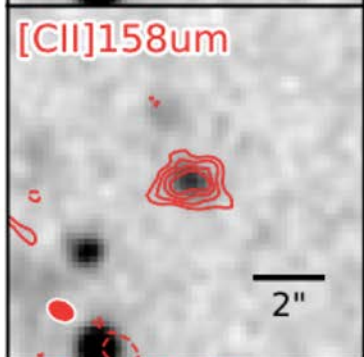
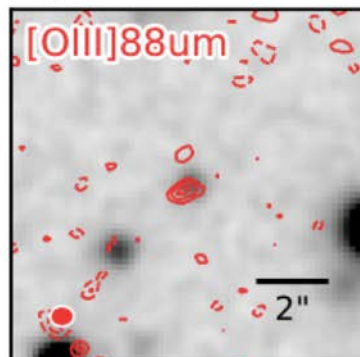
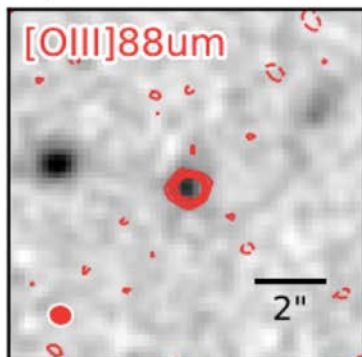
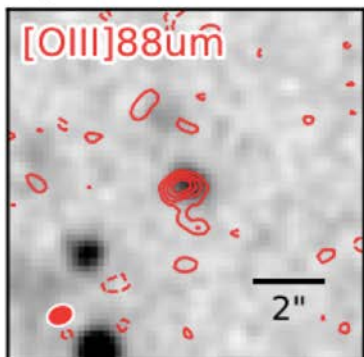
# Tracing star formation with [CII] – high redshift



J1211-0118

J0235-0532

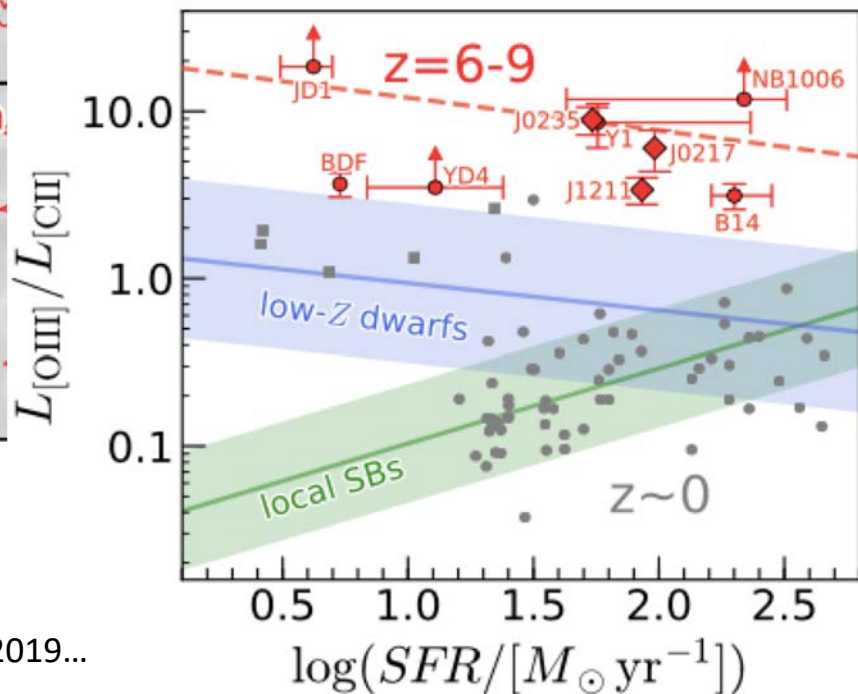
J0217-0208



[CII], [OIII], [NII] @ z>6

High [OIII]/[CII]  
Z=6-9 galaxies

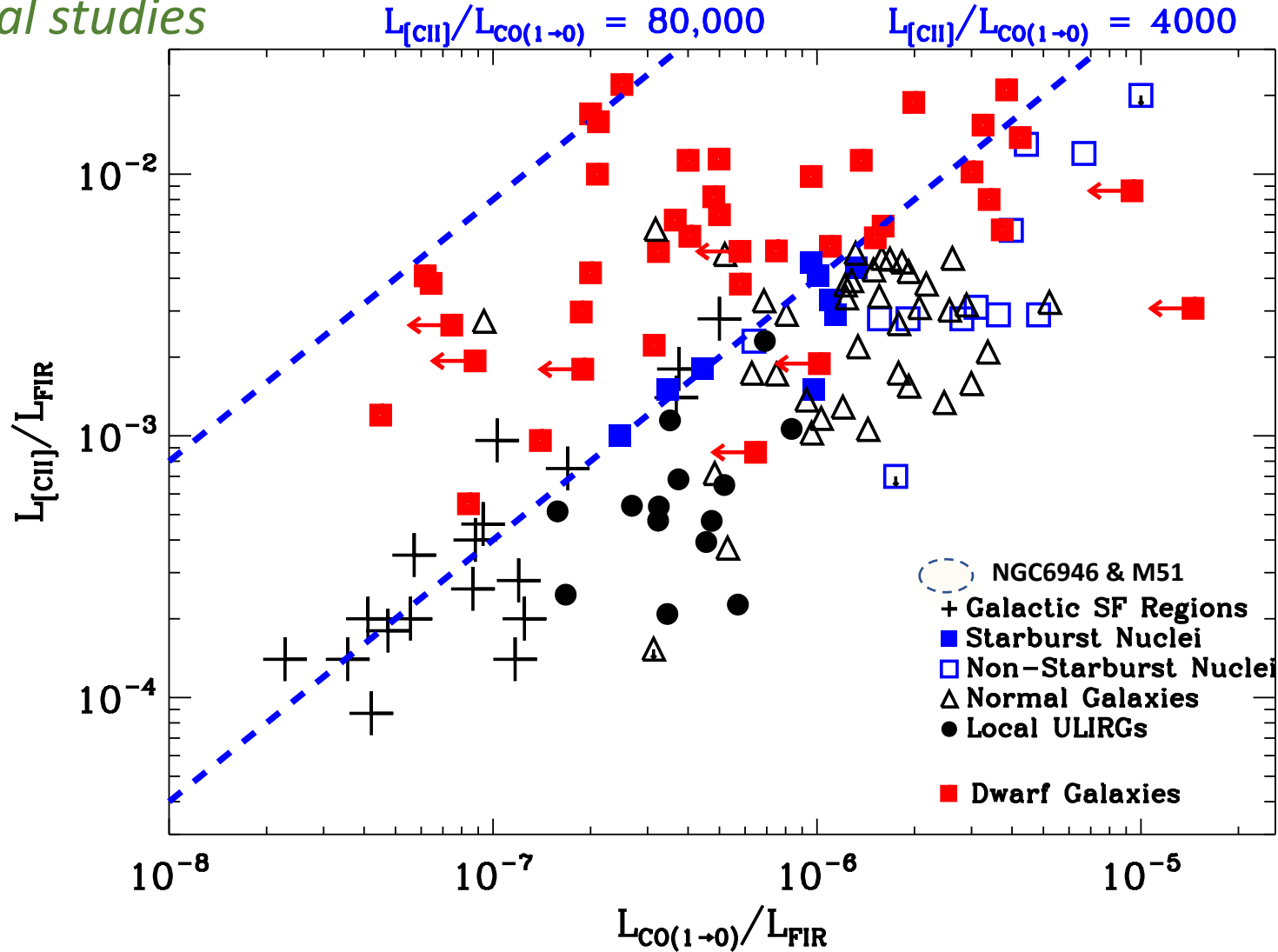
Harikane + 2020



also: Inoue+2014, 2016, Hashimoto+2018; Tamura+2019; Laporte+2019...

# [CII] and CO in Galaxies: metal-rich vs. metal-poor

*Global studies*



*Madden + 2000, 2020*

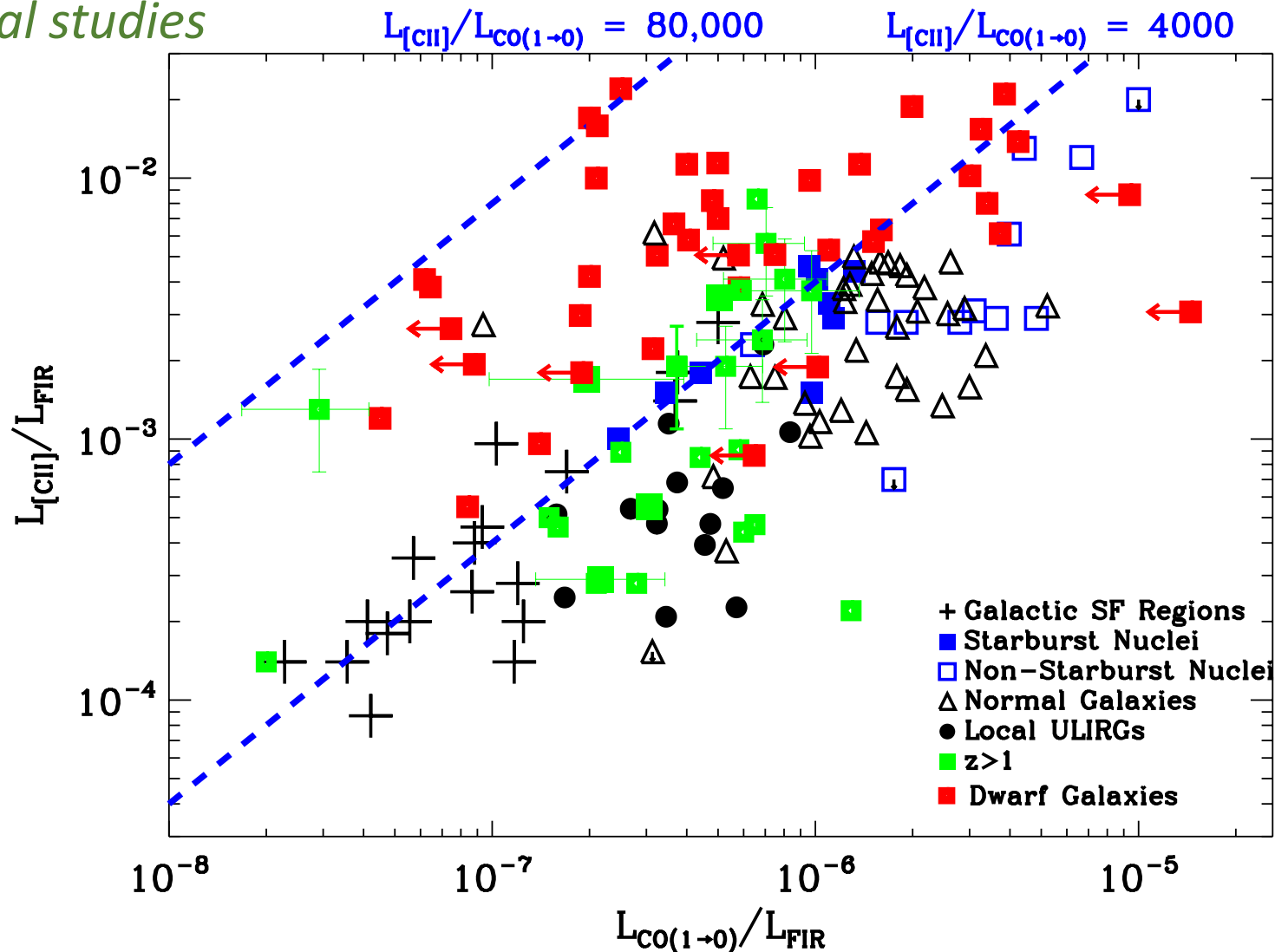
*Stacey + 1991, 2010, Hailey-Dunsheath et al.*

*2010,....*



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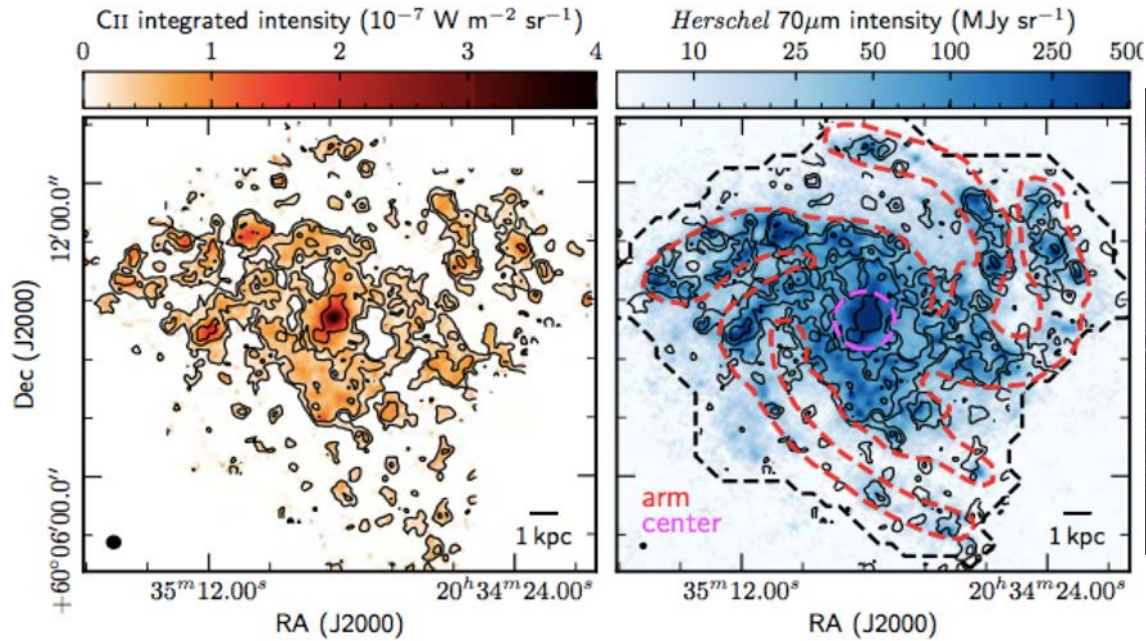
*Madden + 2000, 2020*

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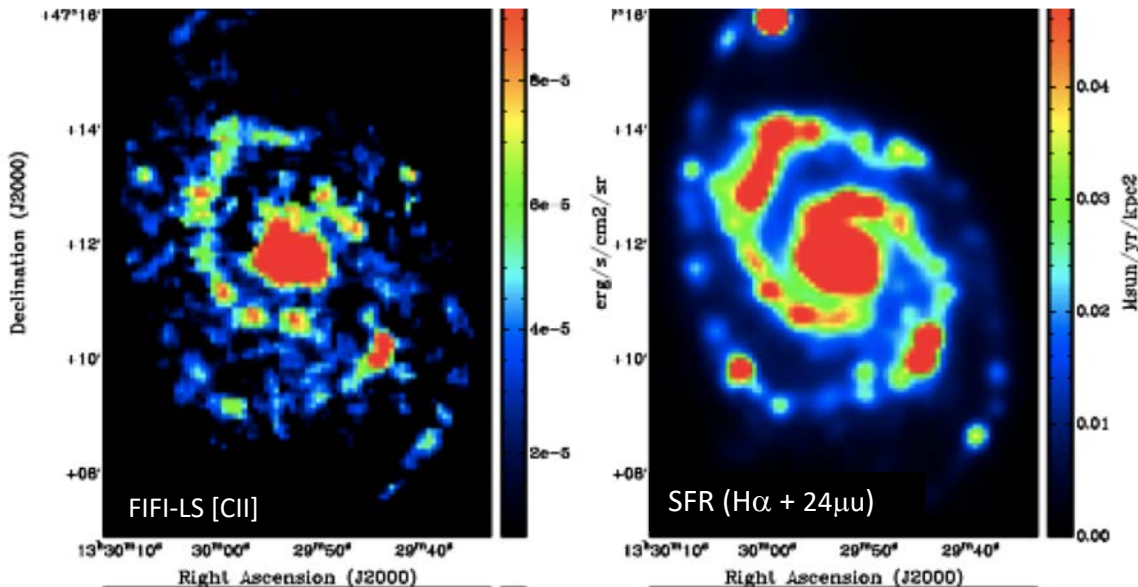
*2010, Gullberg + 2015, Aravena + 2016;*

*Maiolino + 2005, Wang + 2013, Benford...*

# Full-Disk CII Mapping of NGC6946 & M51 with SOFIA



Bigiel+ 2020



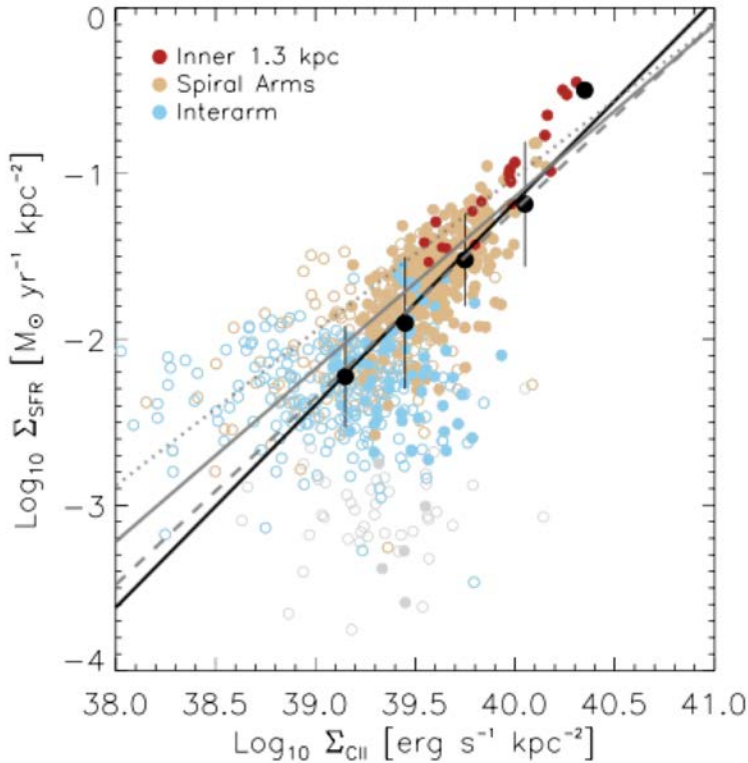
Optical+X-ray

Pineda+ 2018

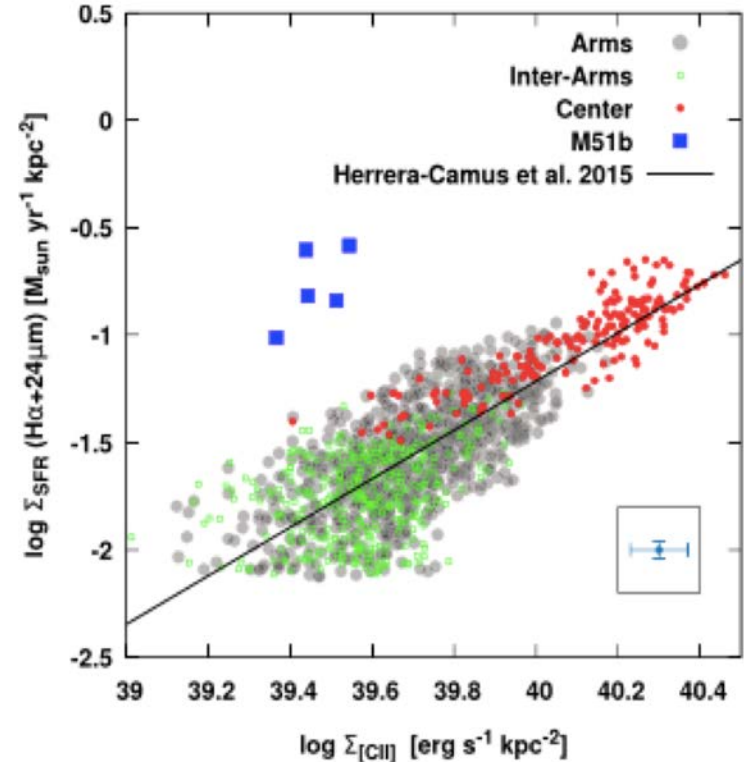
# Full-Disk CII Mapping of NGC6946 & M51 with SOFIA

## Spatially resolved $L_{[CII]} - SFR$

NGC6946: Bigiel+ 2020



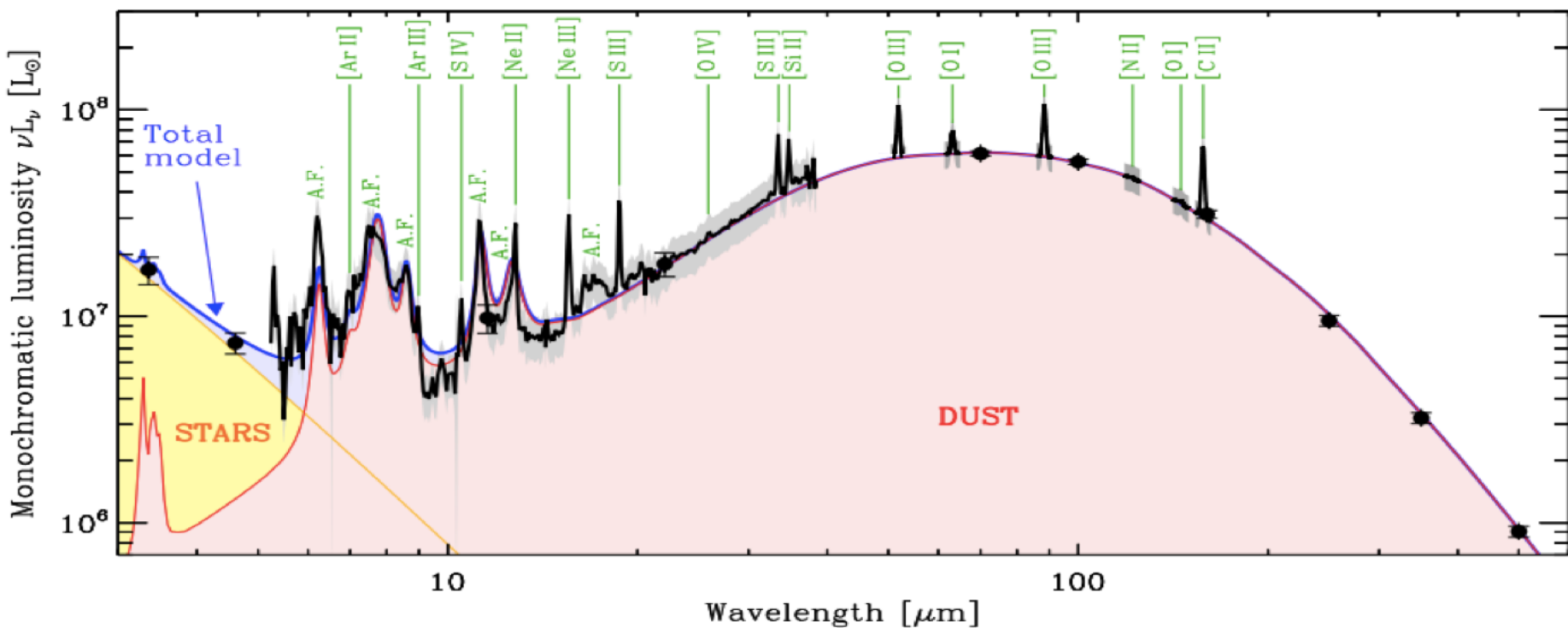
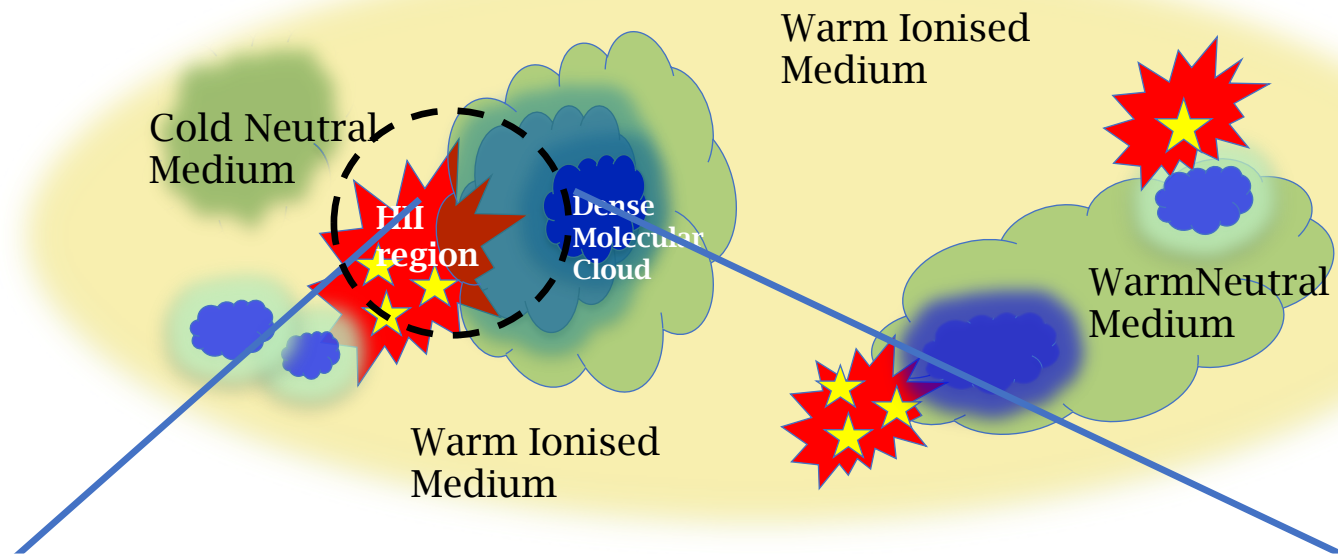
M51: Pineda + 2018



Separate galactic components: what contributes to the [CII] emission on global scales?  
integrated flux  $\sim$ 75% arm, 15% center, 10% interarm

Some other galaxies with SOFIA FIR spectroscopy:  
FIFI-LS full maps of M82 (Fischer; Latzko) & NGC253 (Beck), IC10 (Polles).....  
upGREAT pointings in M51 (Pineda); M101 (Tarantino), NGC4214 (Fahrion + 2014)

# The Complexity of the Multi-Phase ISM

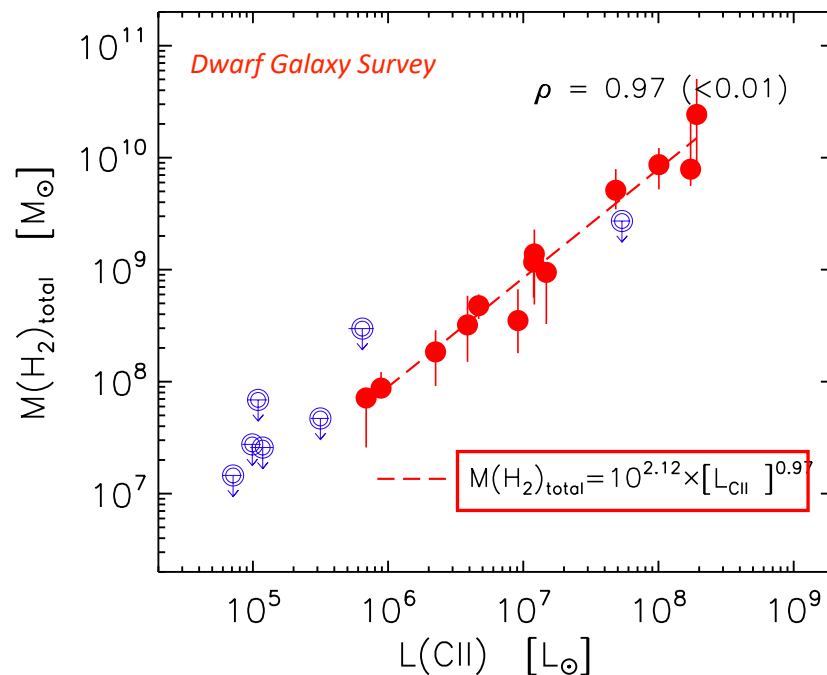
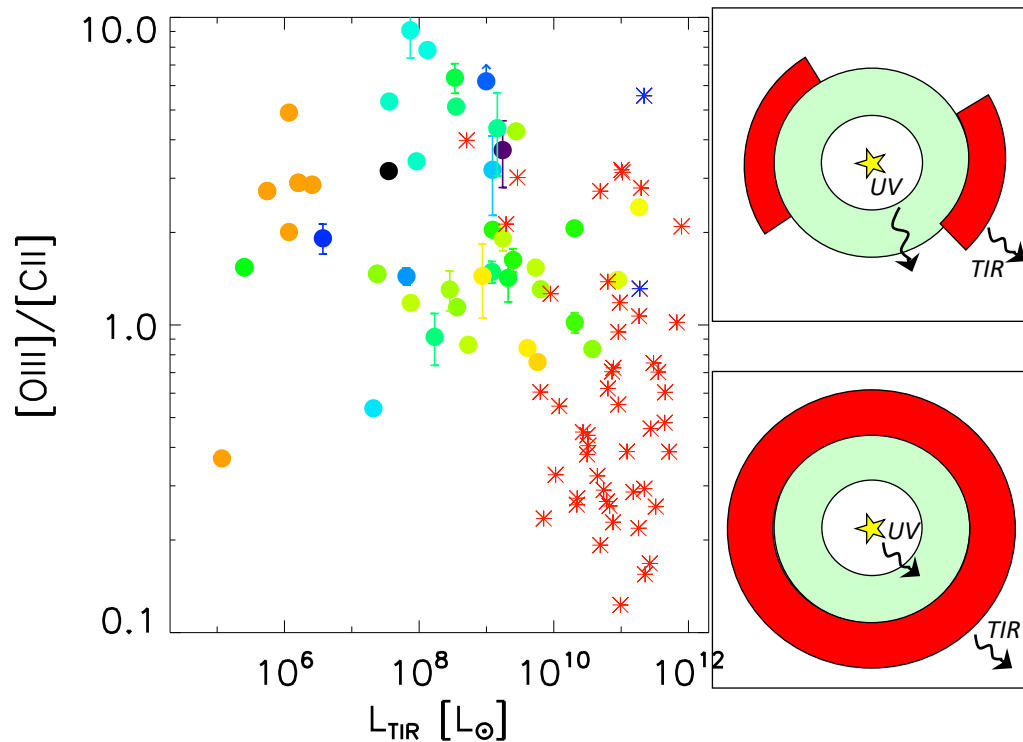


# Modeling of the ISM – from many MIR-FIR lines to physical conditions

Global scales of galaxies

Multiphase models:  
e.g. Cormier+15, 19;

(global)  $[CII] \Rightarrow$  total  $H_2$  Mass



Madden + 2020

ISM structure at low  $Z$ : VERY porous, clumpy. Small covering factor of PDRs. High filling factor of diffuse gas where UV photons escape from HII regions.

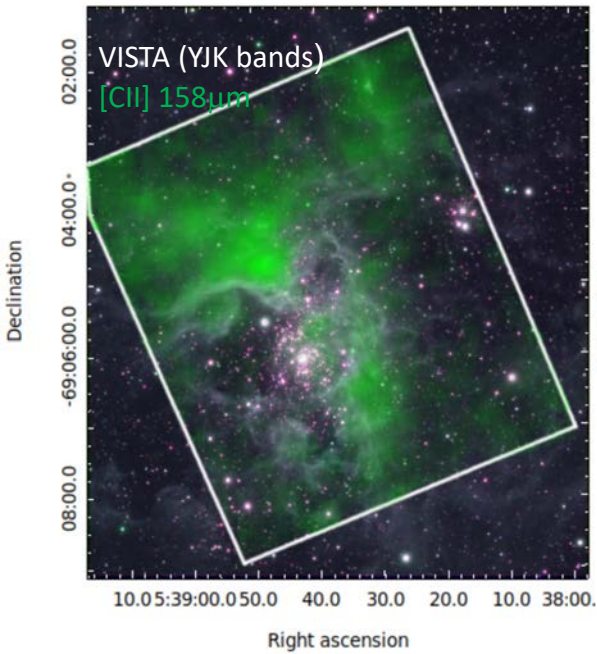
# Resolve ISM phases in Local Group galaxies

## *Low metallicity star-forming galaxies*

### LMC 30 Dor

$Z = 1/2 Z_{\odot}$

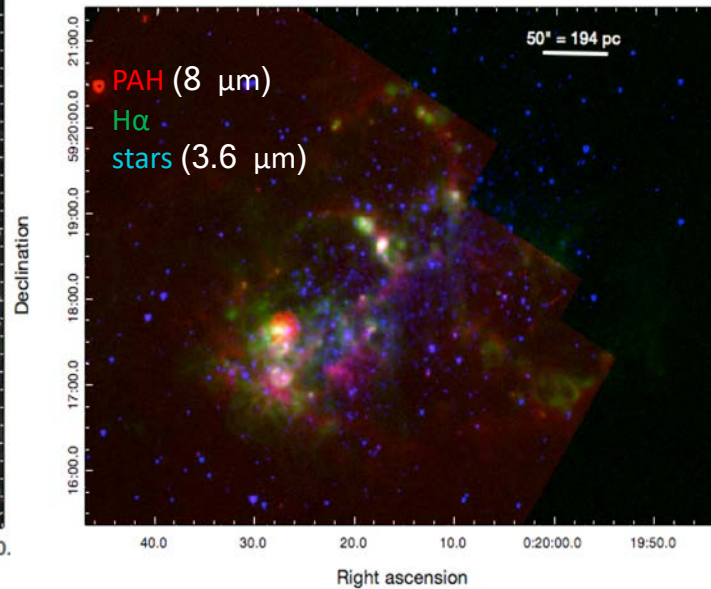
D = 50 kpc



### IC10

$Z = 1/3 Z_{\odot}$

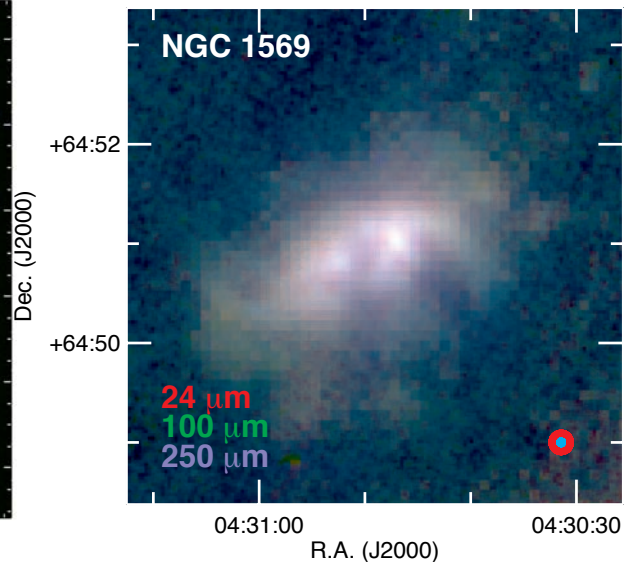
D = 700 kpc



### NGC1569

$Z = 1/4 Z_{\odot}$

D = 3.36 Mpc

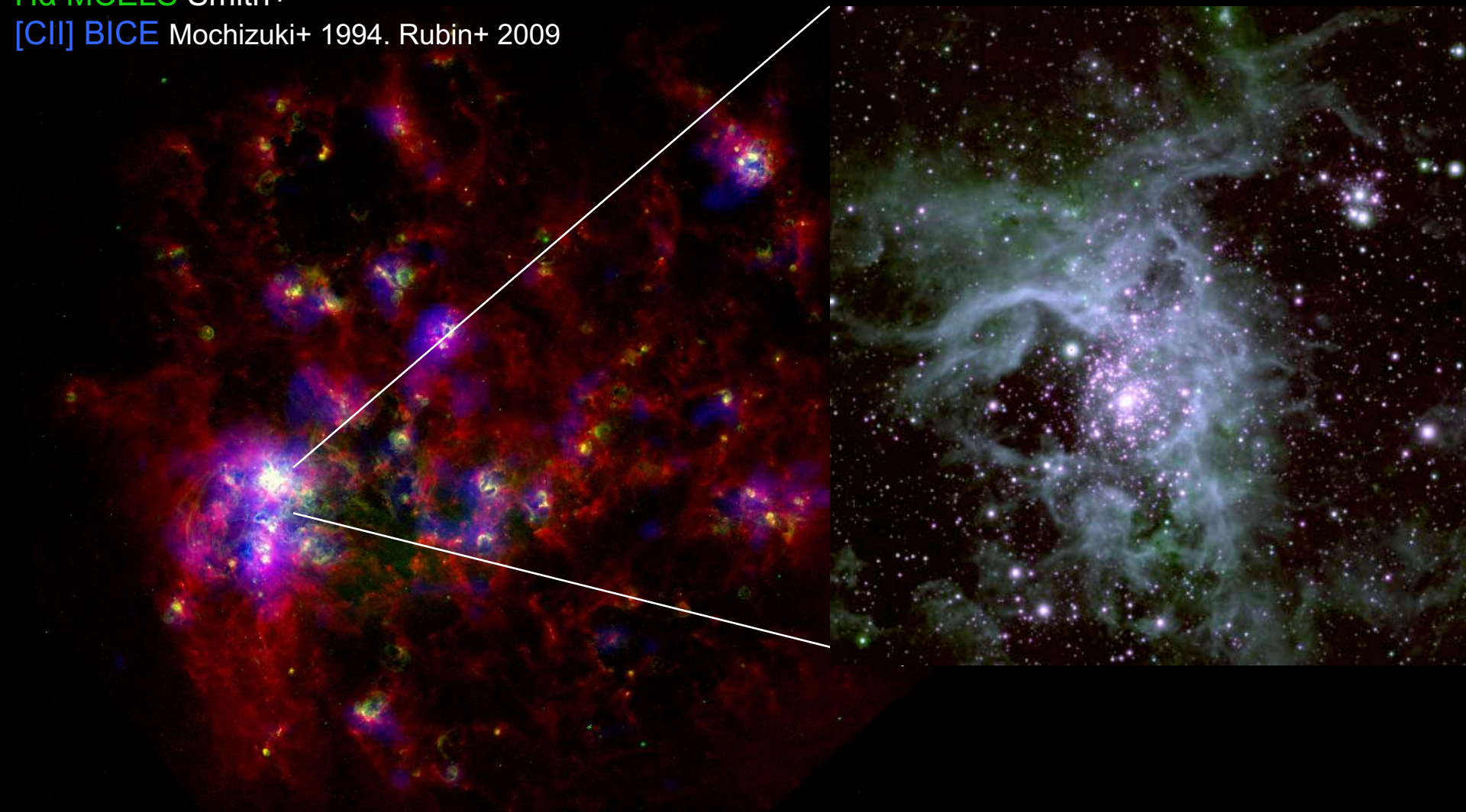


# Resolve ISM phases in Local Group galaxies: LMC

160 $\mu$ m HERITAGE Meixner+ 2010

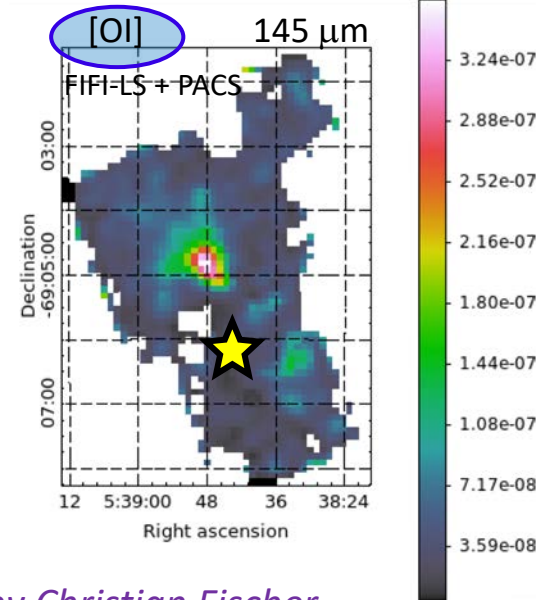
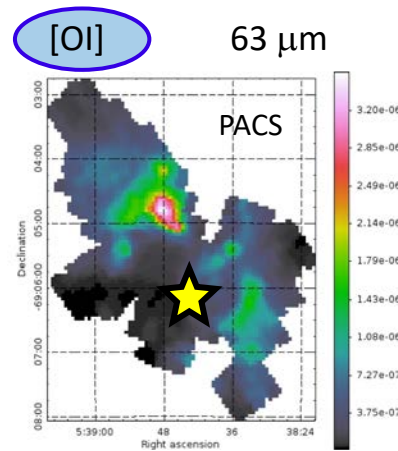
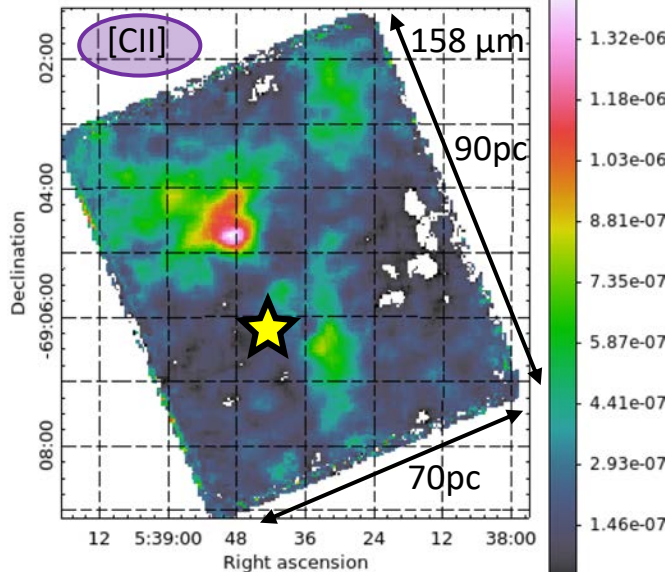
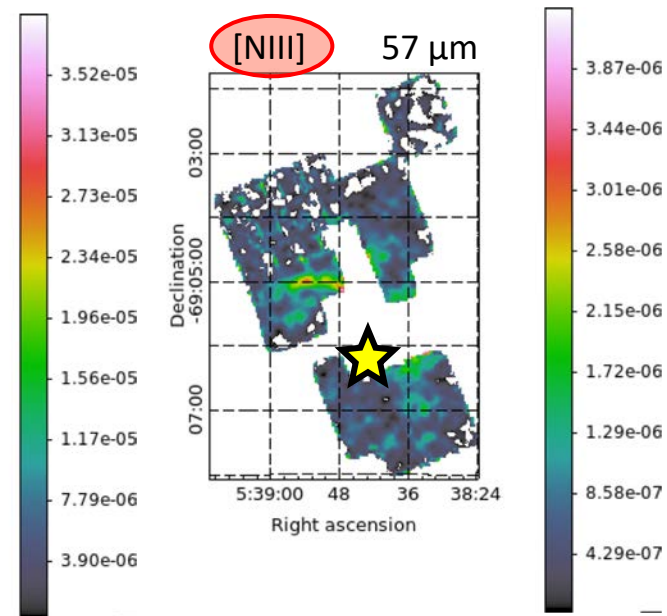
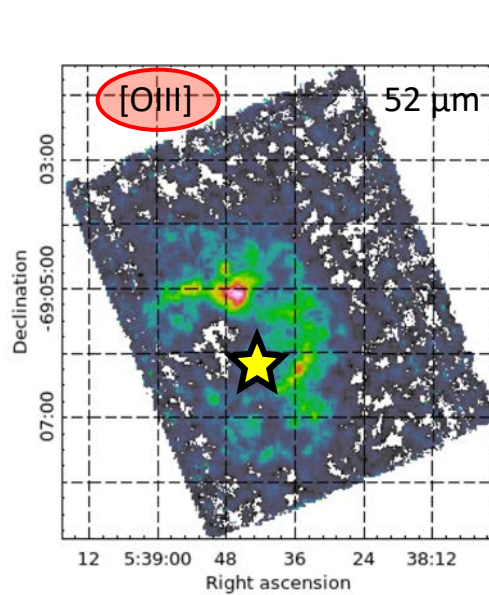
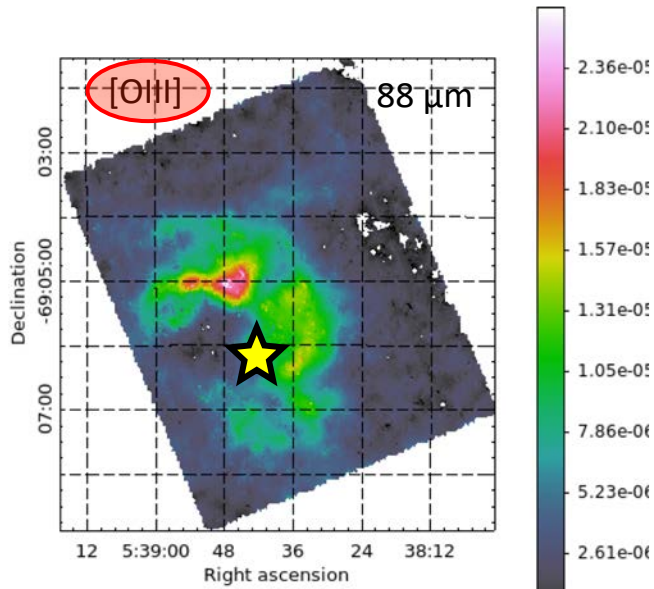
H $\alpha$  MCELS Smith+

[CII] BICE Mochizuki+ 1994. Rubin+ 2009



Zoom into 30 Doradus PDR

# Resolve ISM phases in Local Group galaxies: LMC



6' x 5' SOFIA/FIFI-LS: 80pc x 70pc tracing ionized + neutral gas

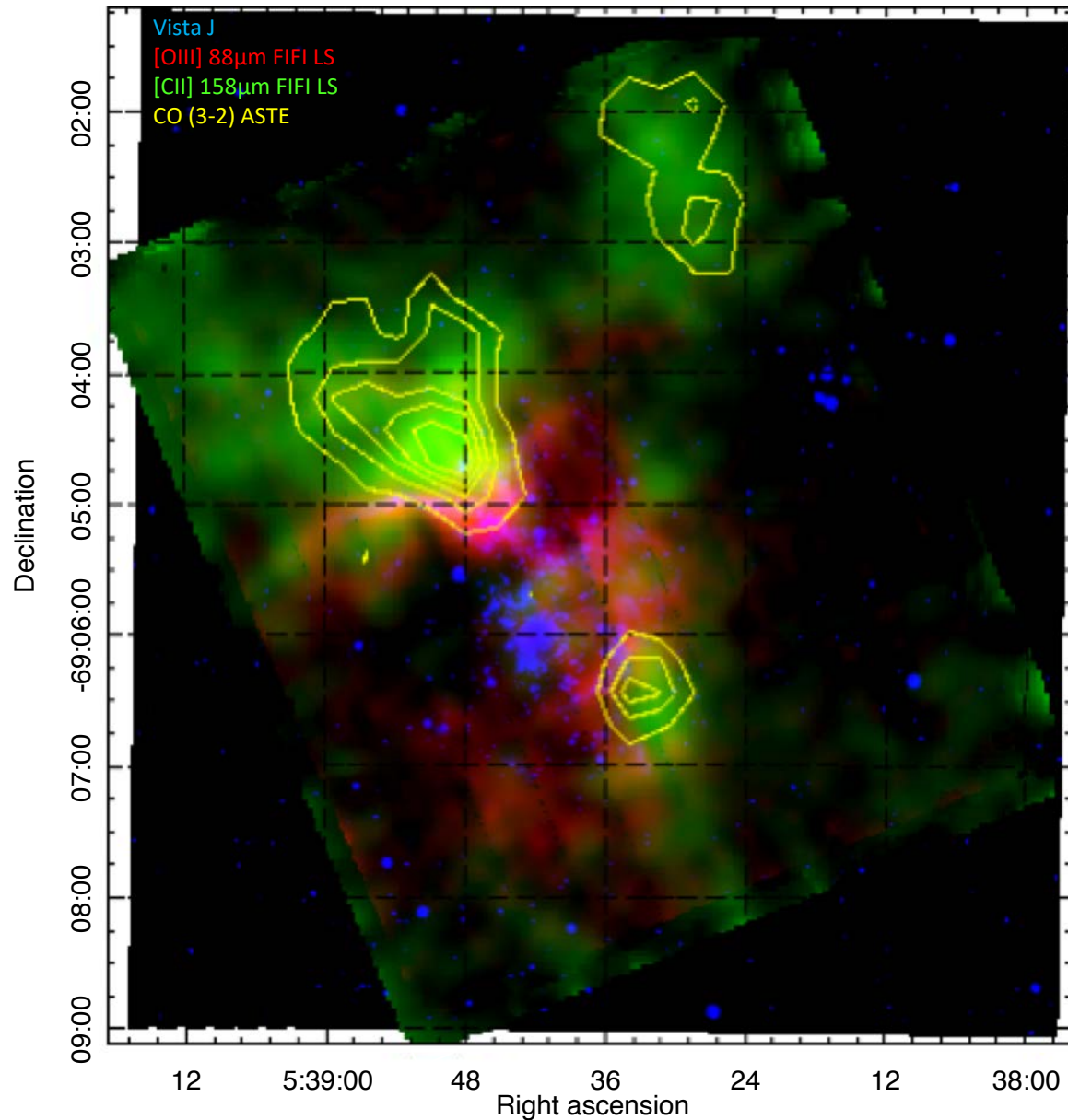
Chevance + 2020

maps by Christian Fischer

PDR modelling => little CO-bright H<sub>2</sub> but 75% CO-dark gas



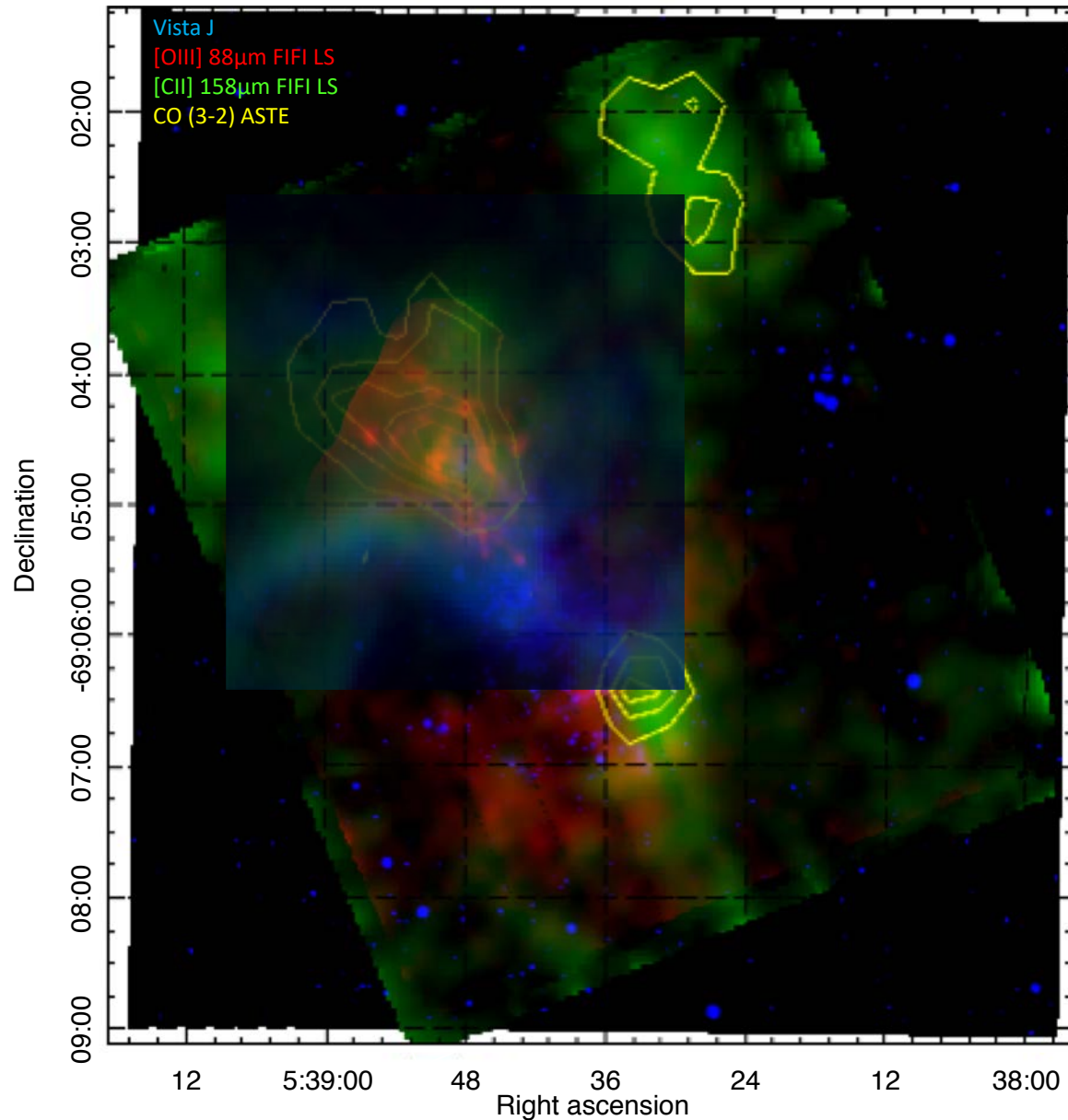
# Resolve ISM phases in Local Group galaxies: LMC



*Indebetouw + 2013: ALMA CO(2-1) resolves subpc clumps/filaments.*

***Chevance+2020: PDR modelling => little CO-bright H<sub>2</sub> but 75% CO-dark gas***

# Resolve ISM phases in Local Group galaxies: LMC



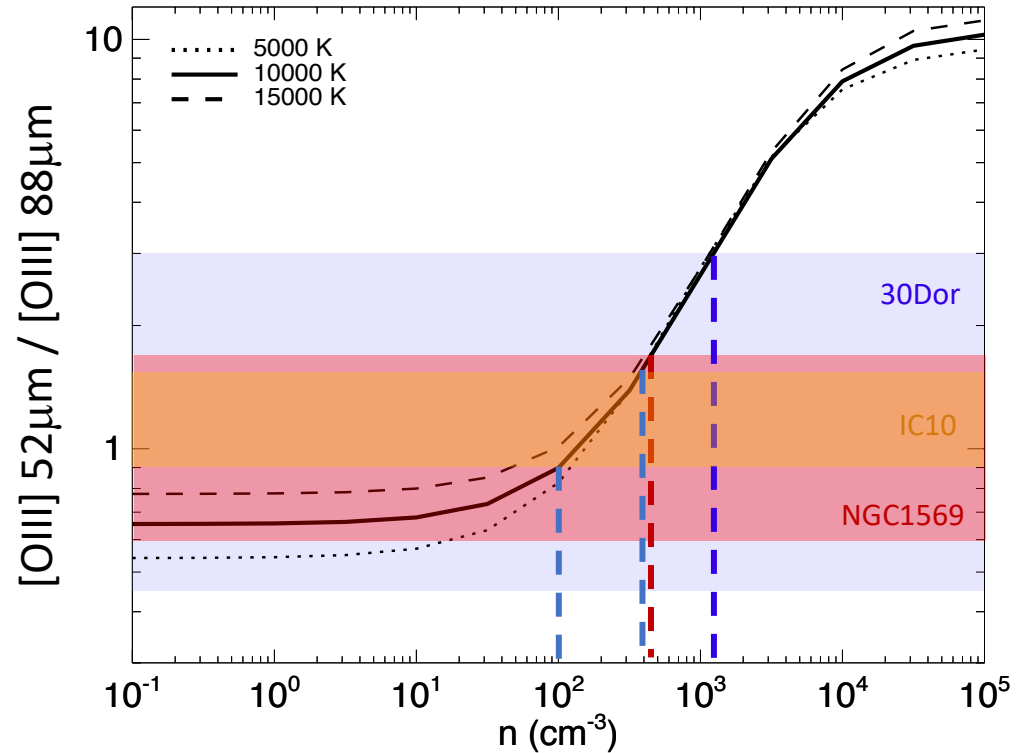
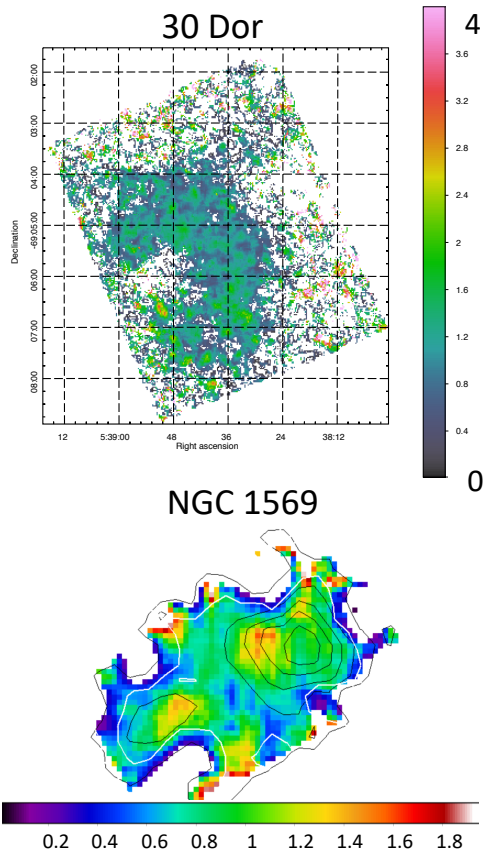
*ALMA + SOFIA =>  
excellent science  
synergy!*

*Indebetouw + 2013: ALMA CO(2-1) resolves subpc clumps/filaments.*

***Chevance+2020: PDR modelling => little CO-bright H<sub>2</sub> but 75% CO-dark gas***

## *Electron density in the ionised gas*

[OIII] 52 $\mu$ m / [OIII] 88 $\mu$ m



- 30Dor: electron density in the ionised gas < 1000 cm<sup>-3</sup>
- IC10: density ranges between 100 and 400 cm<sup>-3</sup>
- NGC1569: electron density < 500 cm<sup>-3</sup>

# Summary

- SOFIA/FIFI-LS is a mapping machine for complete wide-field maps of [CII] in nearby galaxies.
- NGC6946 and M51 case studies shows significant and systematic variation of key line ratios CII/SFR, CII/CO across the disk. Should have maps in more galaxies – statistical studies. Link the local conditions to the global.
- Nearby Low metallicity galaxies show different ISM structure than disk SF galaxies: [OIII] is the brightest FIR line, not [CII]. [OIII] can be exploited by SOFIA in low metallicity galaxies
- Low metallicity star-forming galaxies: little CO detected, but vigorous SF:
  - \*\*most of the H<sub>2</sub> is not traced by CO.
  - [CII] tracing total H<sub>2</sub> gas mass in low Z galaxies – other environments?
- Local Group Galaxies, especially the Magellanic Clouds, are SOFIA's extragalactic strong points: diverse environments, including low metallicity laboratories and close enough to be well resolved.
- Bridging cloud-scale conditions to the larger scale environment:
  - LMC & SMC - SOFIA and ALMA synergy
- SOFIA needs to map galaxies in more diagnostic lines

## Conclusion: How can SOFIA grow the exgal community ?

- FIFI-LS is a mapping machine for galaxies, but needs improved *spectral resolution* by factor of 2 (at least the blue channel is very low R ) & *larger FoV* (*mismatch of blue vs red FoV*)
  - SOFIA should expand to shorter wavelengths – bright nebular lines covering wide range of critical densities & ionisation energies. Ideally ~ *to fill the gap where EXES ends and FIFI-LS (with higher spectral resolution and FoV) begins.*
  - *upGREAT* => *an [OIII] channel* (88 or 52  $\mu$ m) ?
  - HIRMES would be a perfect solution: higher R in MIR/FIR, faster mapping, wavelength coverage and improved sensitivity
    - faster mapping of many more galaxies: PHANGS, SAMI, CALIFA...statistically significant properties within galaxies
    - To map full galaxies also in OI, OIII, NII
    - The versatility of HIRMES would definitely bring the exgal community on board
  - SOFIA's BIG niche: Magellanic Clouds => *more NZ flights !!!*
  - SOFIA : the only MIR-FIR we have to prepare for *SPICA & Origins*
- SOFIA to exploit the nearby universe to calibrate distant, high-z universe*