Probing the large-scale multiphase ISM of 30 Doradus in the LMC with SOFIA/FIFI LS

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Outline

1. Context and motivation

2. 30 Doradus, an extreme environment *(Chevance et al. 2016)*
   a. *Herschel/PACS* observations
   b. Physical conditions and structure of the ISM
   c. Constraining the "CO-dark" gas

3. The new *SOFIA/FIFI LS* observations (preliminary results)

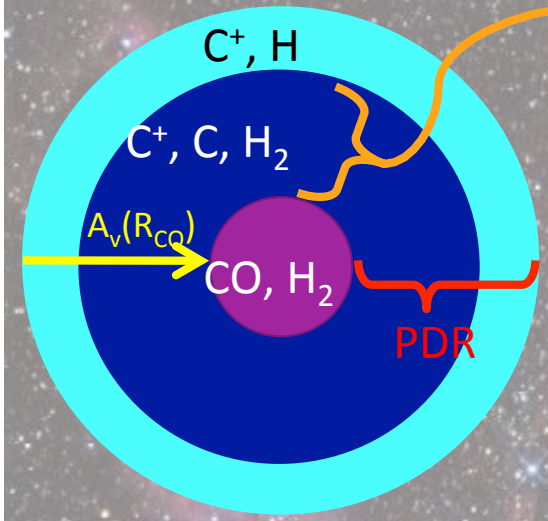
4. Summary

Context: dwarf galaxies characteristics

- Dwarf galaxies are the most numerous galaxies in the local universe
- In the local universe, Z as low as 2% $Z_{\odot}$ and wide range of star formation activities
- Hosting Super Star Clusters
- Dwarf galaxies have low metallicity -> chemically young, as primordial galaxies.

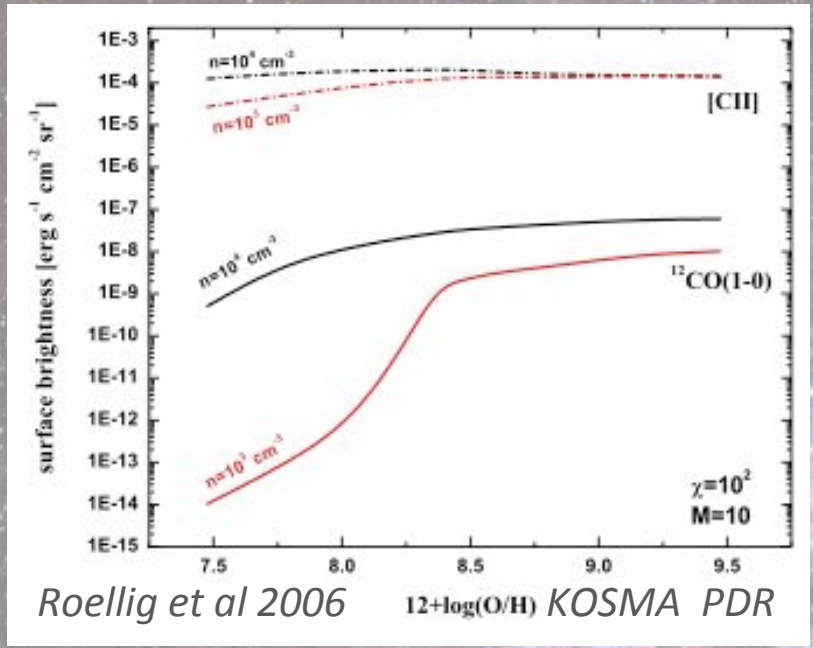
➢ Local Universe dwarf galaxies are convenient labs to study the chemical evolution of galactic dust and gas properties

Structure of the ISM at low Z

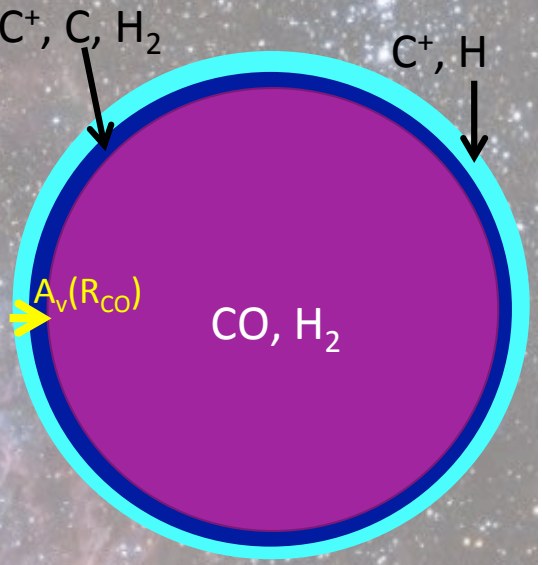


Low metallicity

Molecular gas without CO
("CO-dark" gas)



Roellig et al 2006

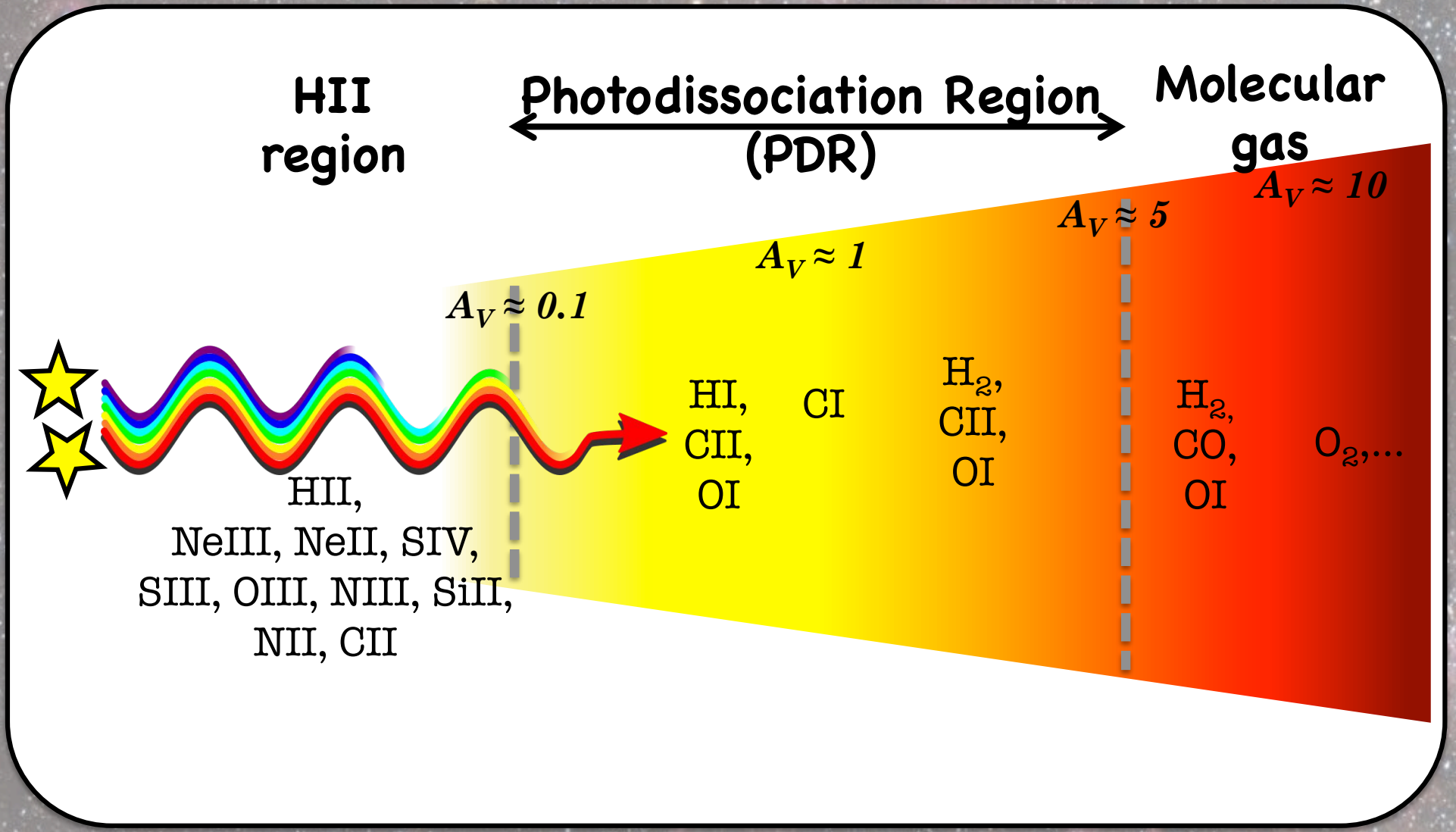


Solar metallicity

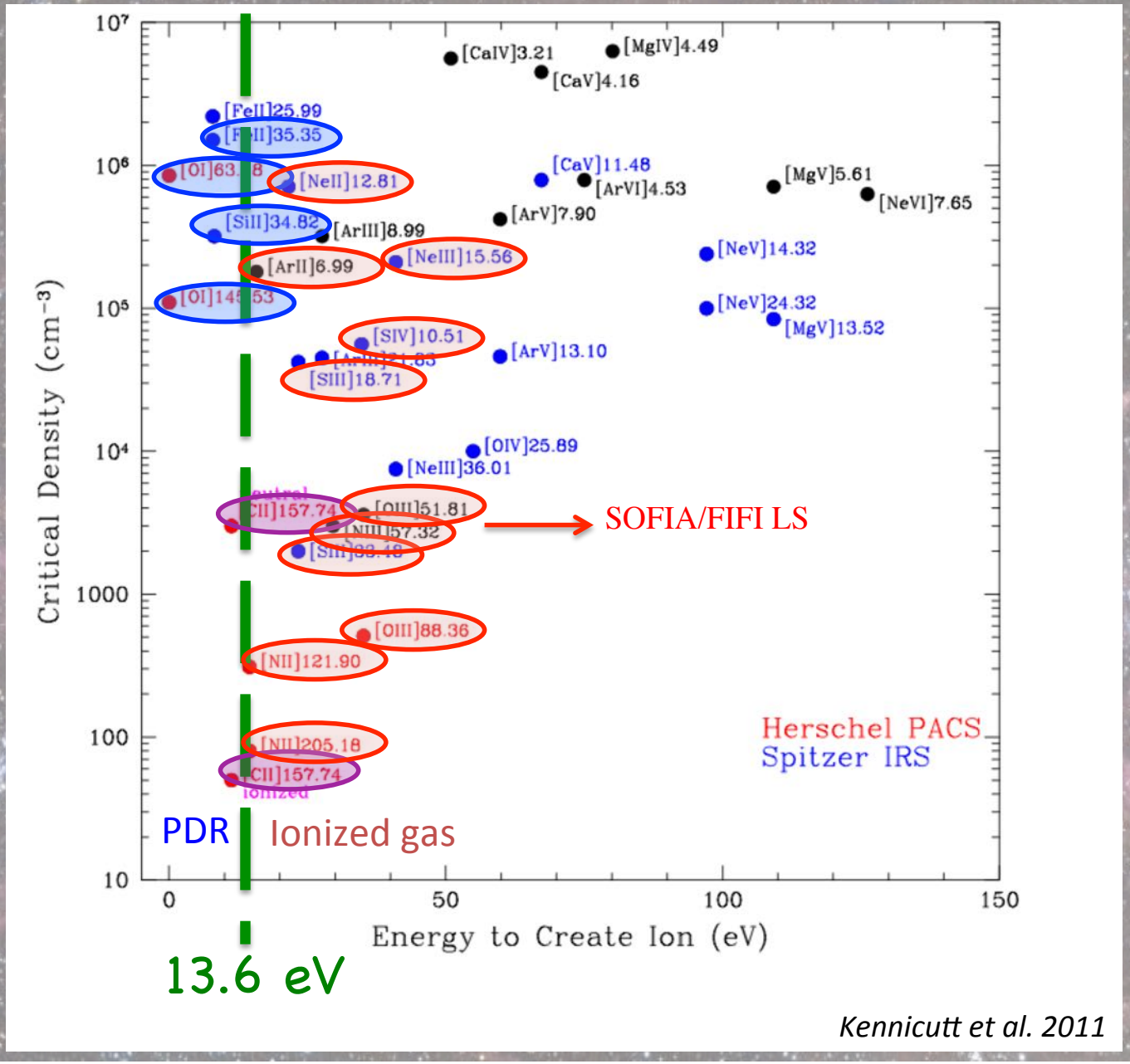
$A_V(C+/C) \sim 1$
$A_V(C/CO) \sim 5$

In some dwarf galaxies at low metallicity, we measure an important star formation rate but we hardly detect CO.
-> What are the relative distributions of H_2 and CO there ?
-> What are the relations between metallicity, ISM phases and structure, SF activity…?
-> How does star formation interact with the surrounding low metallicity PDR/ molecular gas ?

Modeling the ISM of galaxies

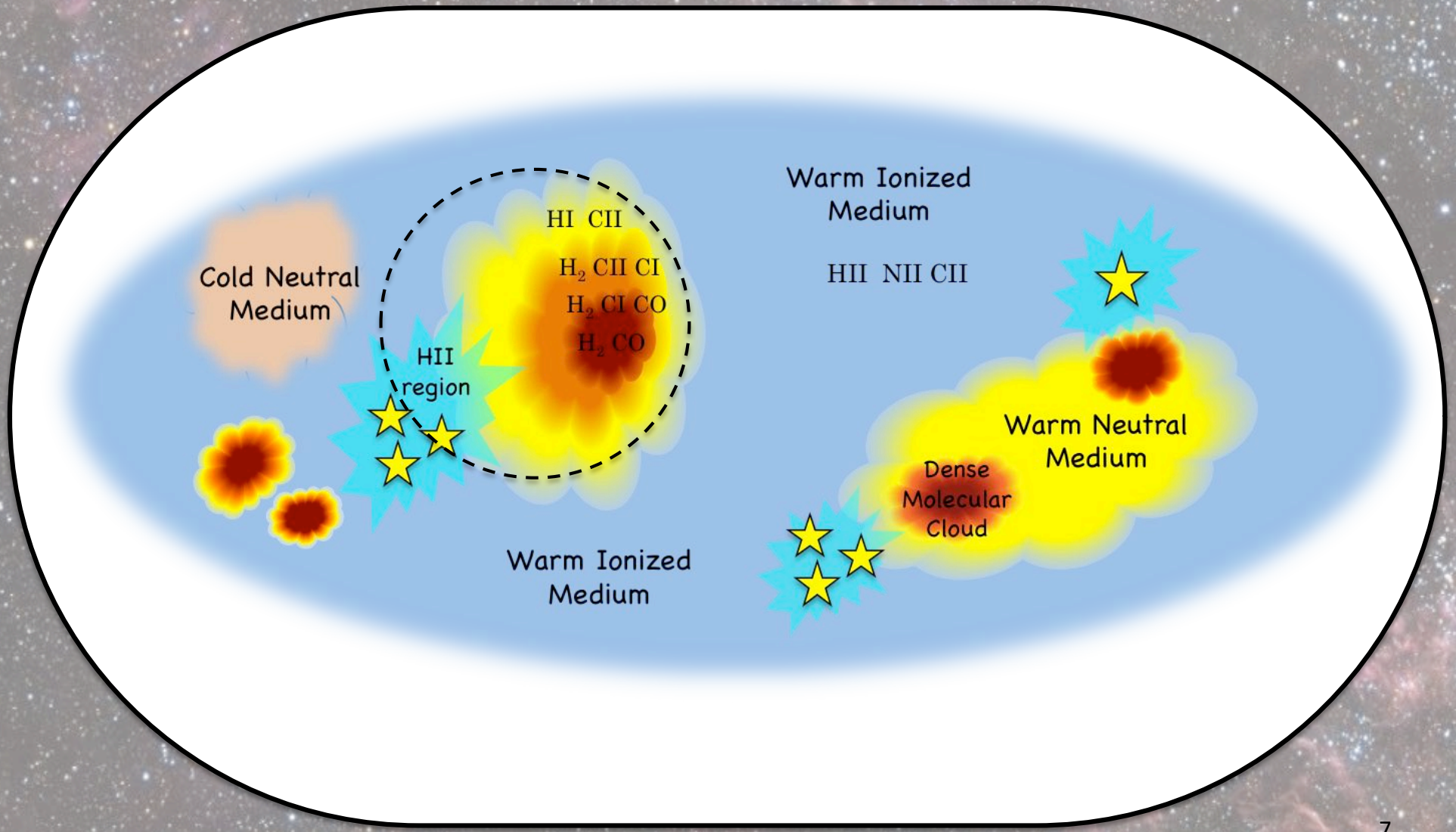


Diagnostic of various phases in the ISM

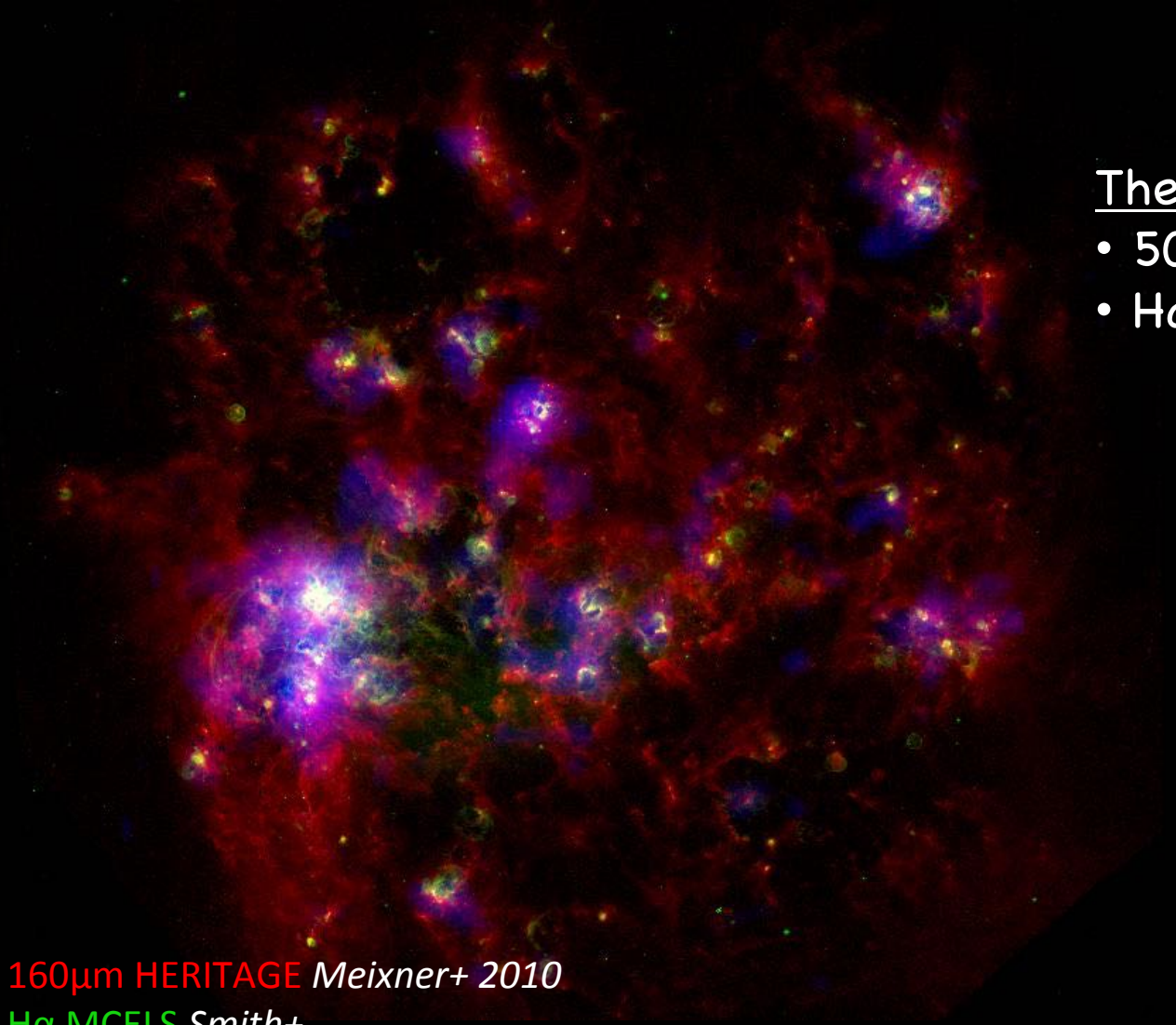


Kennicutt et al. 2011

The complex multiphase ISM of galaxies



Zooming into 30 Doradus in the LMC

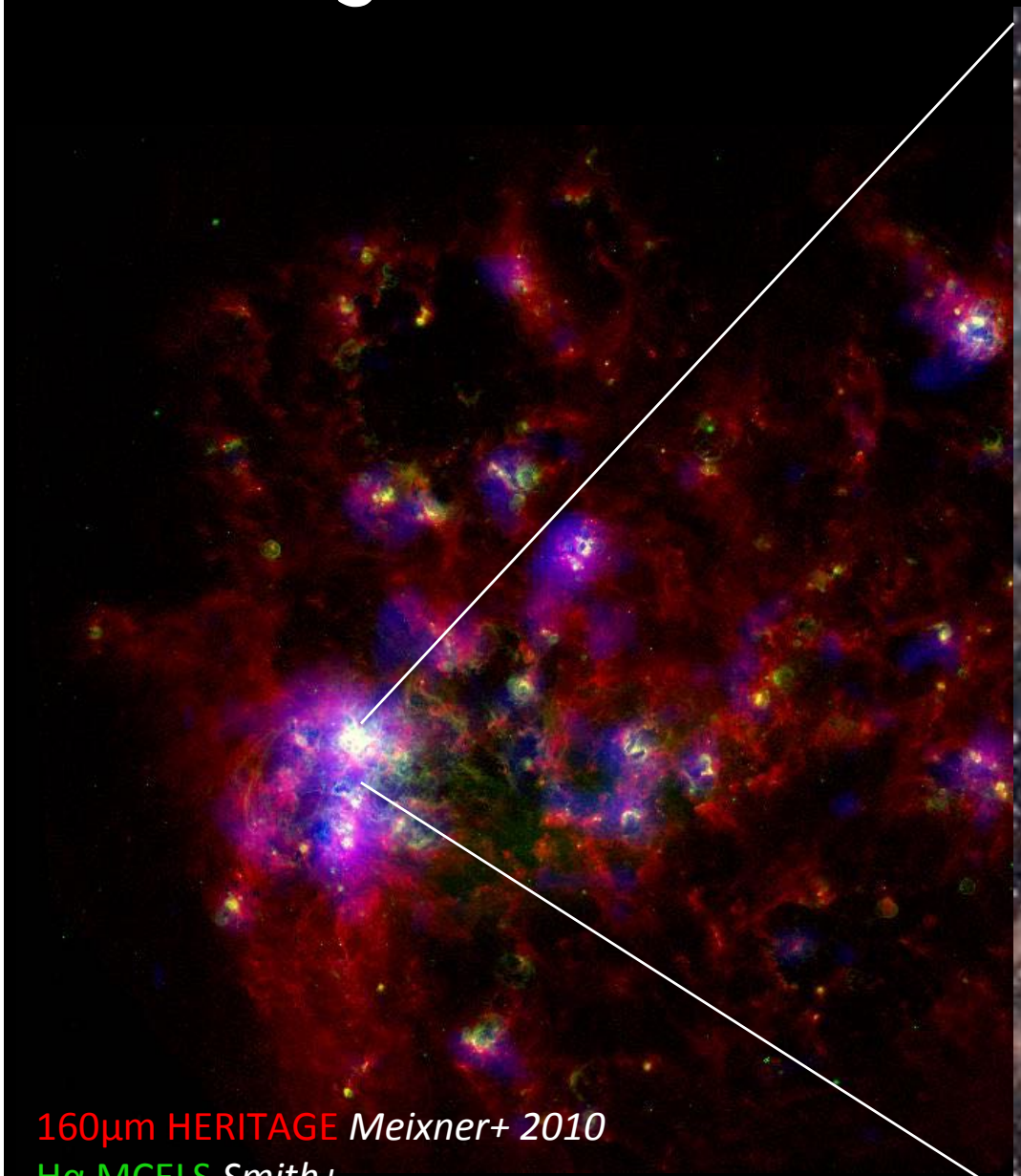


160µm HERITAGE *Meixner+ 2010*
Hα MCELS *Smith+*
[CII] BICE *Mochizuki+ 1994. Rubin+ 2009*

The Large Magellanic Cloud :

- 50 kpc
- Half solar metallicity

Zooming into 30 Doradus in the LMC



160µm HERITAGE *Meixner+ 2010*
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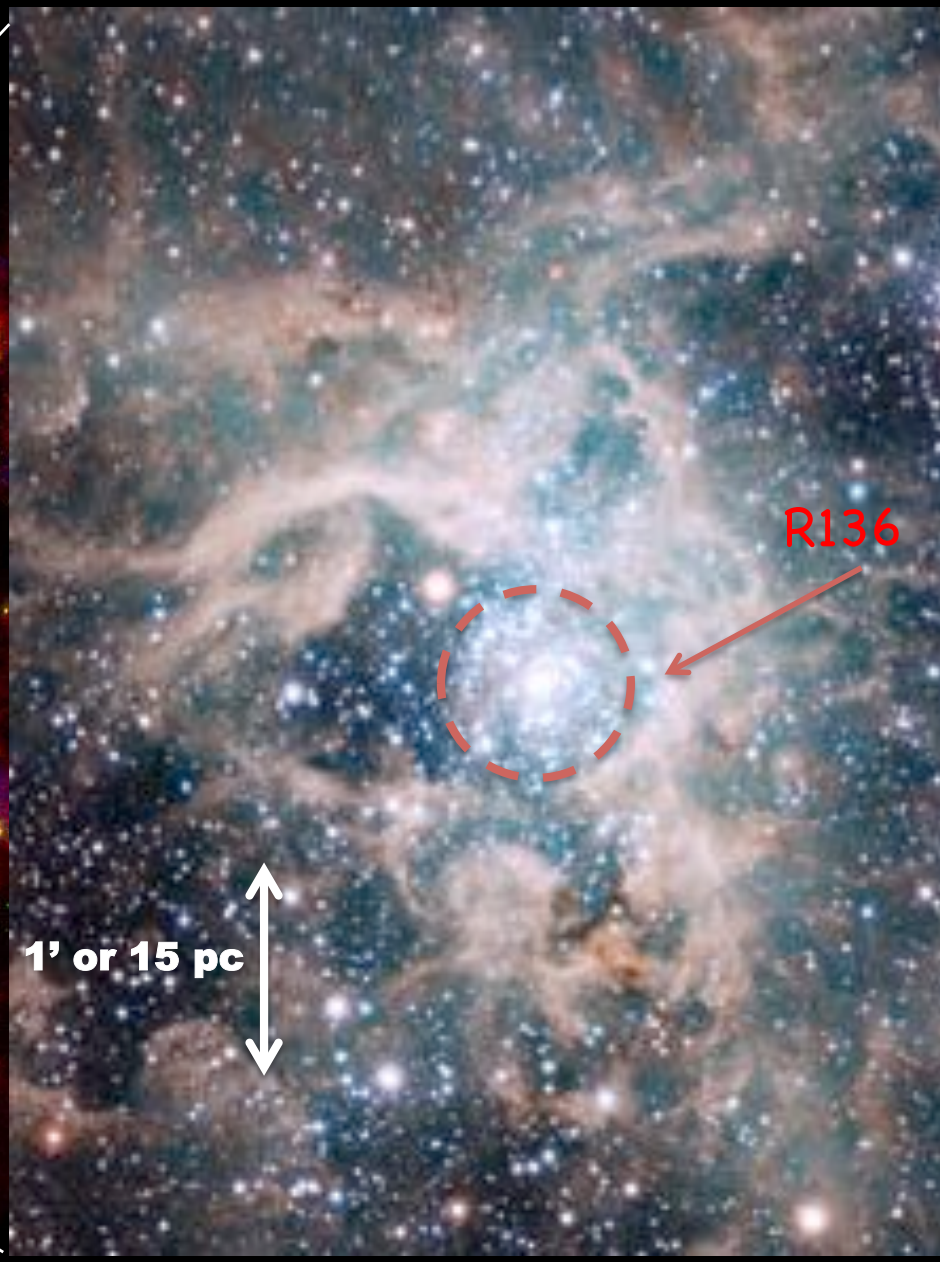
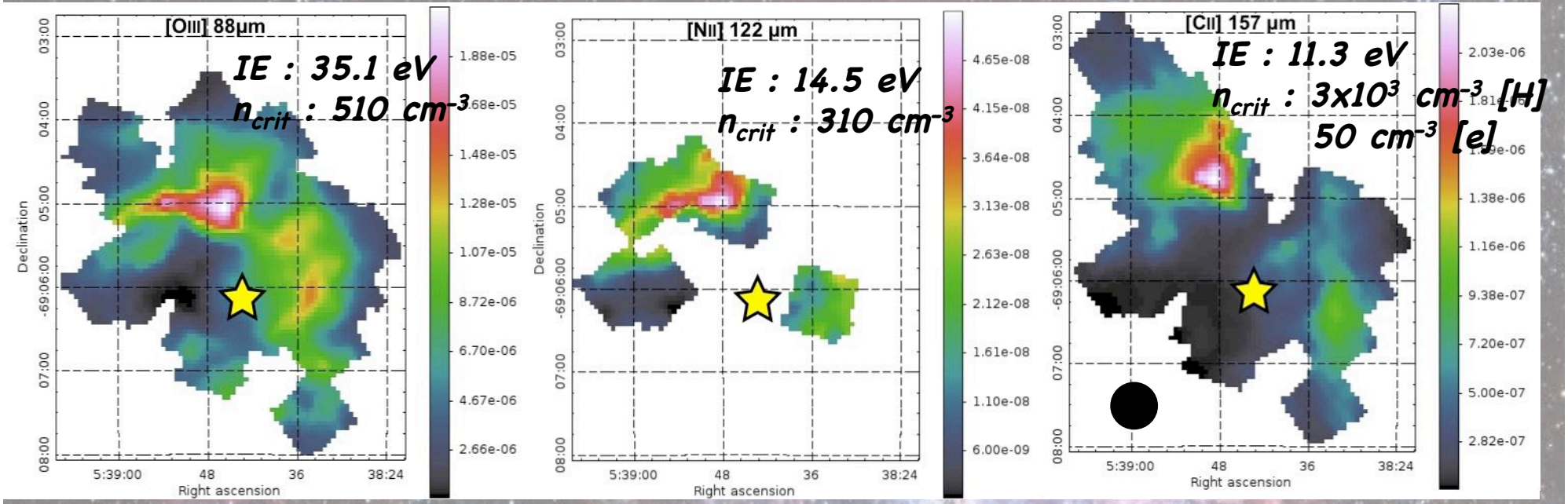
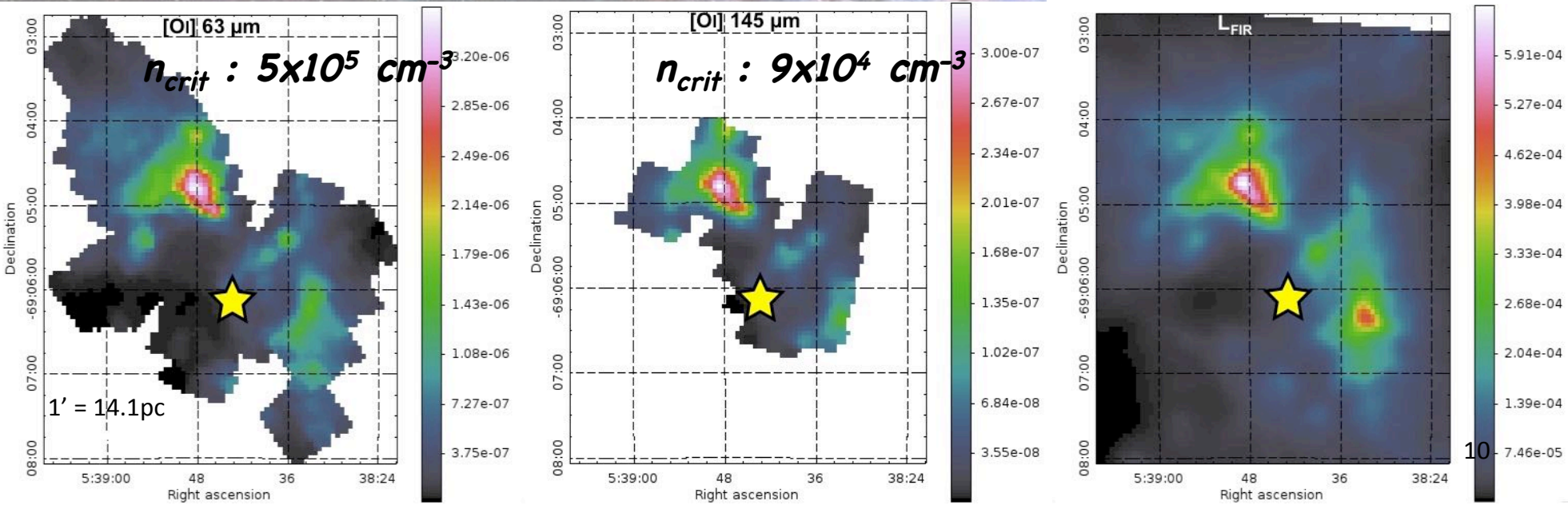


Image : Vista (Cioni et al. 2011)

Herschel PACS data ~ 12" resolution (3pc)

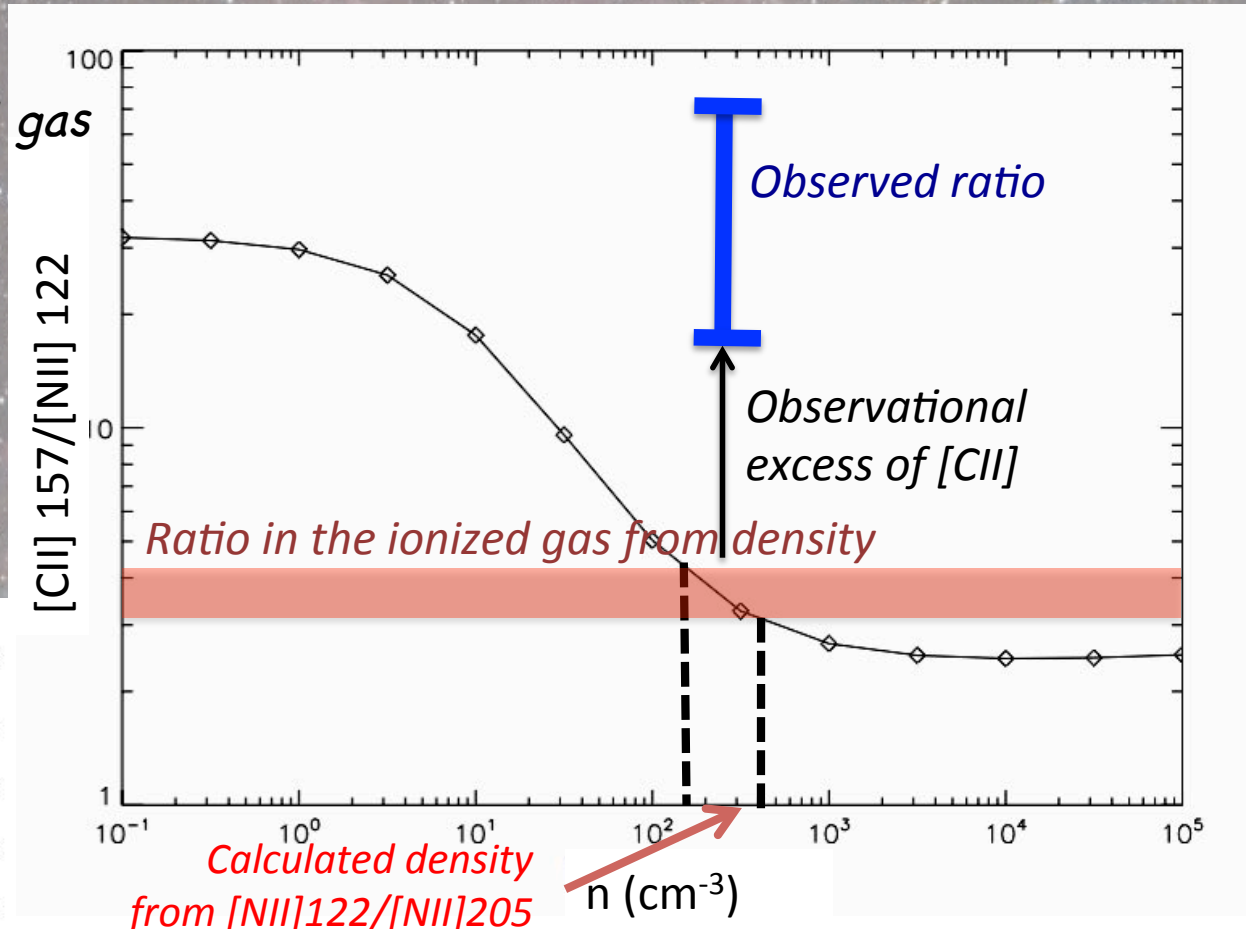




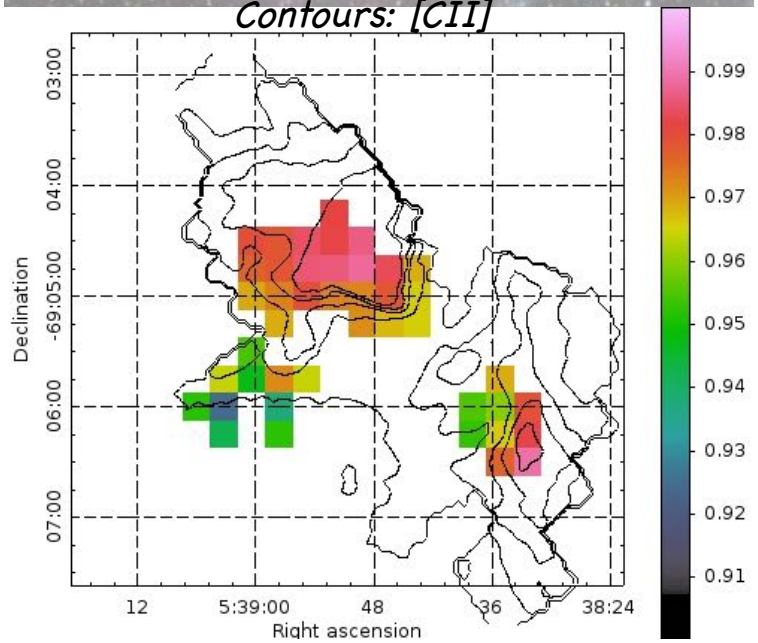
Fraction of [CII] in PDRs

How much [CII] can we expect in the ionized gas ?

Theoretical ratio in the ionized gas



Fraction of [CII] in the PDRs
Contours: [CII]



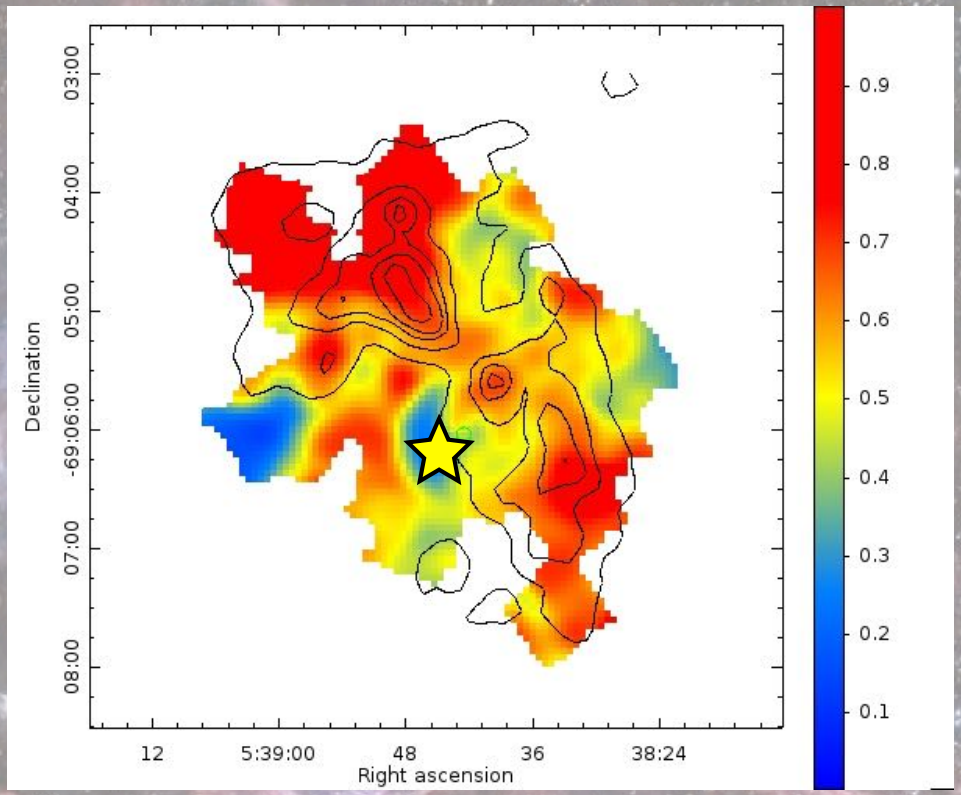
Between 92 and 99 % of [CII] in PDRs

Fraction of L_{FIR} in PDRs

Bilinear decomposition:

$$FIR_{total} = \underbrace{\alpha\ PAH}_{FIR_{PDR}} + \underbrace{\beta\ [OIII]}_{FIR_{ionised\ gas}}$$

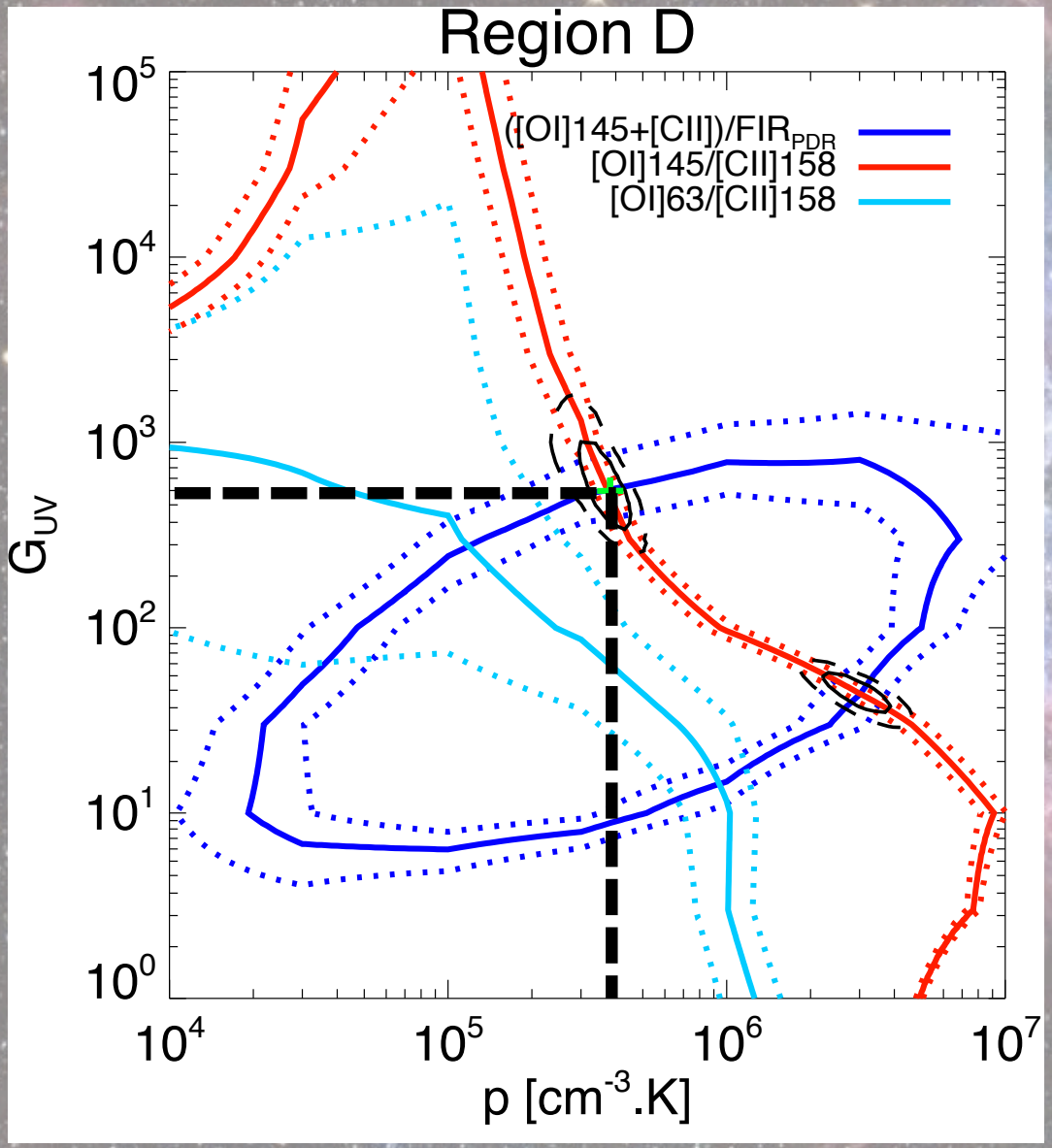
FIR_{PDR} / FIR_{total}
Contours: FIR_{total}



Between 30% and 90% of the L_{FIR} come from the PDRs

PDR modeling : Isobaric model

The Meudon PDR code (Le Petit+ 2006)
(adapted by Benjamin Godard)

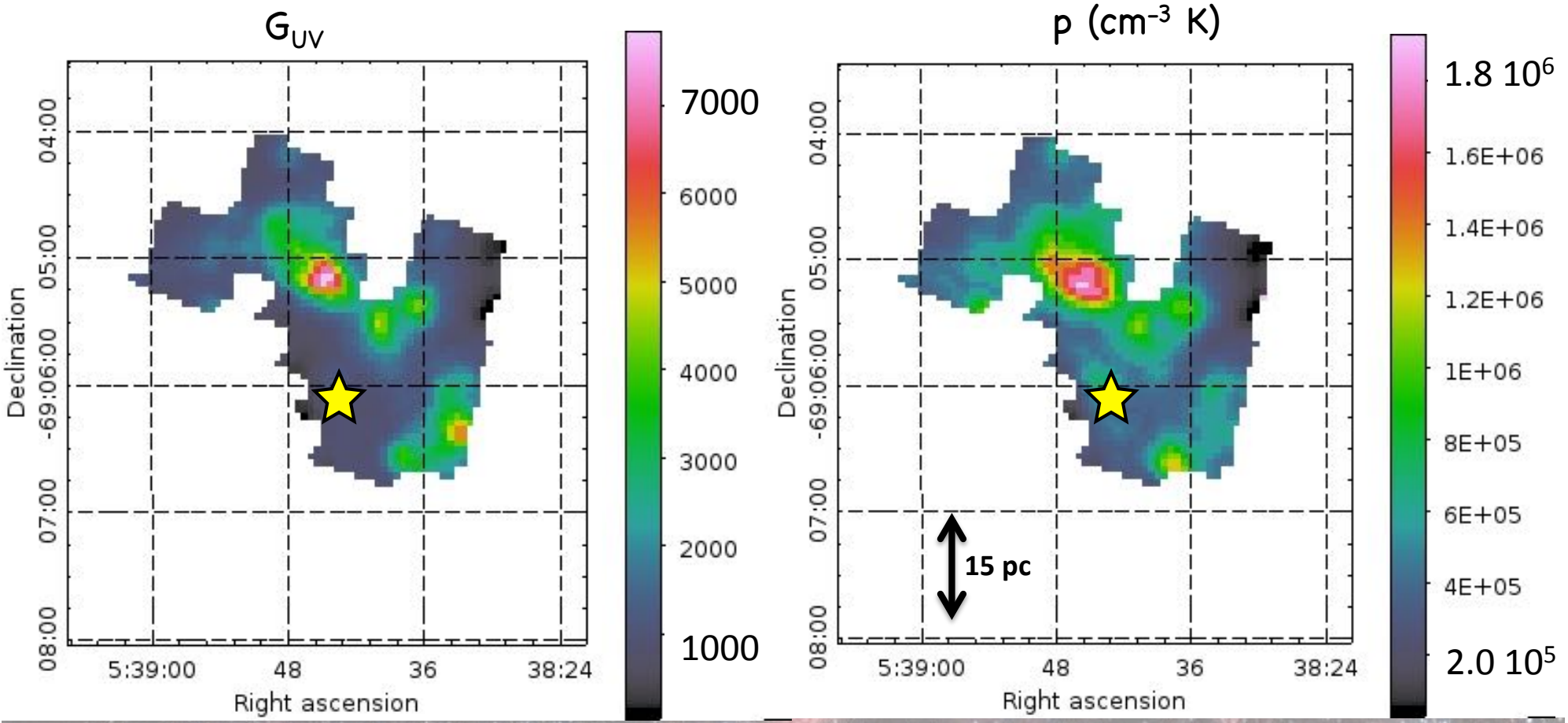


Model characteristics:
- Parallel slab geometry
- Gas phase abundances measured in 30Dor *(Pellegrini+2011)*
- Constant pressure

Key parameters:
- G_{UV}: intensity of the *incident* radiation field (in units of the Mathis field : 6.8e-14 erg/cm^3)
- p: pressure of the cloud (in cm^{-3} K)
- $A_{v,total}$: visual extinction

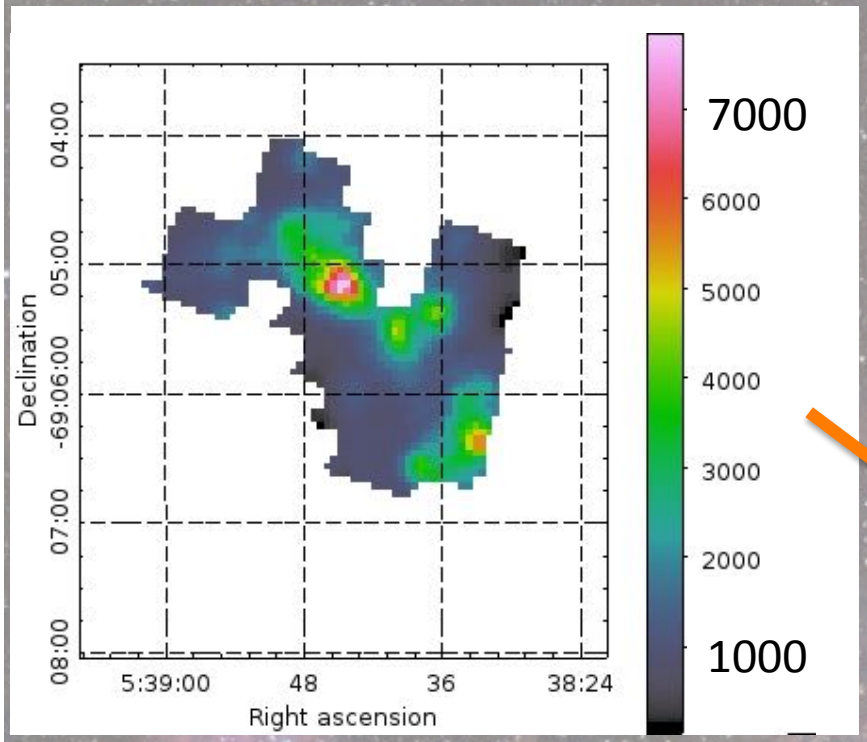
➢ *Maps* of p and G_{UV} from the observations

Results for G_{UV} and p



Chevance et al. 2016a

Physical distance between stars and clouds : a 3D view of 30Dor

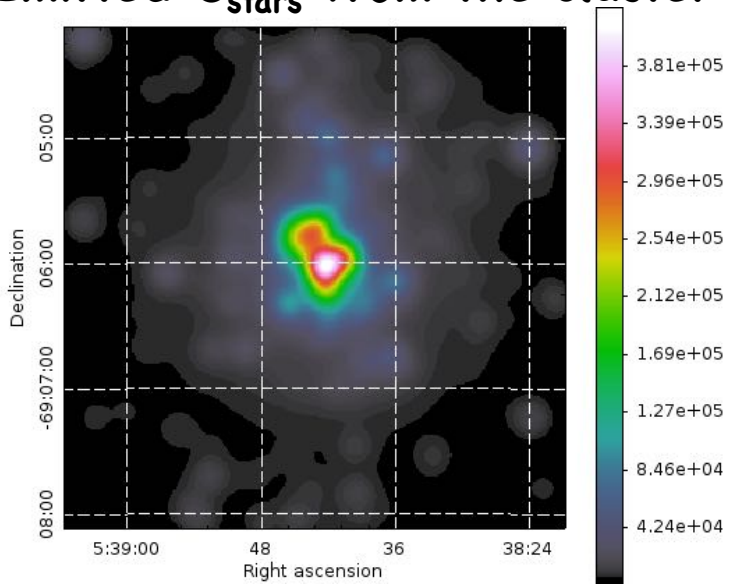


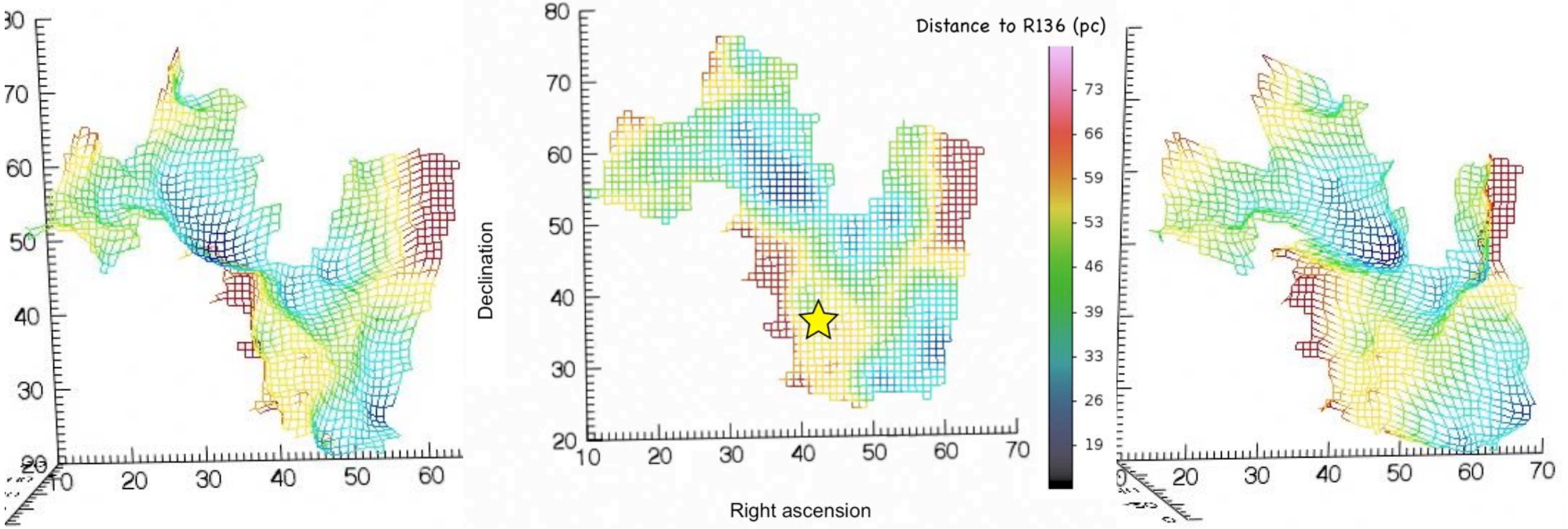
Physical distance to R136

$$G_{stars} = G_{UV} \times \frac{L^2}{d^2}$$

Projected distance

Emitted G_{stars} from the cluster



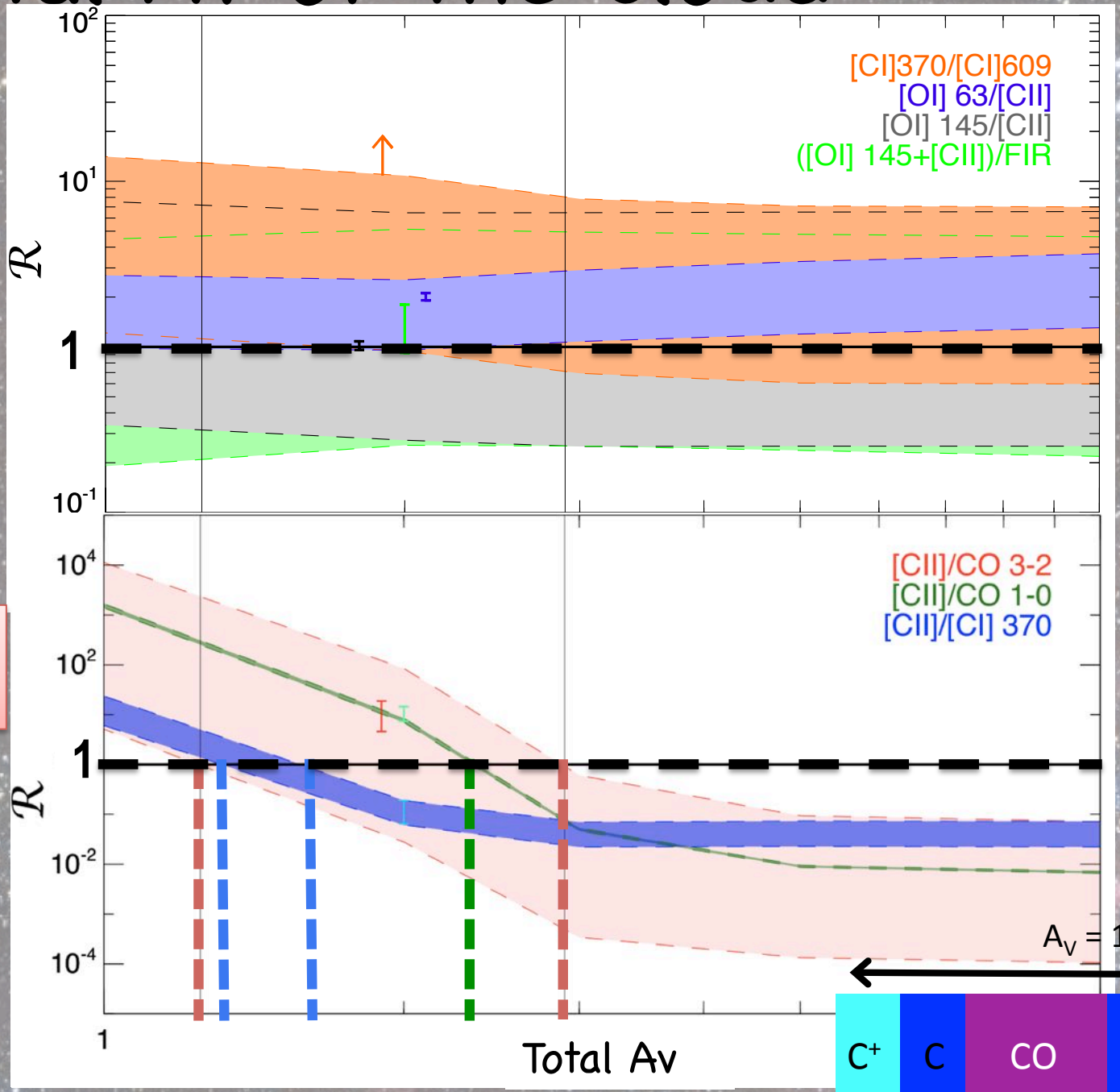


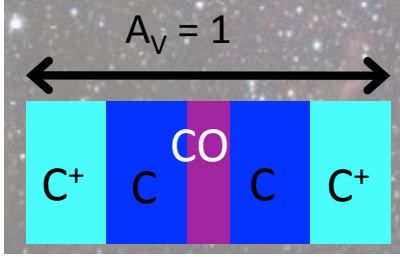
Chevance et al. 2016a

Total Av of the cloud

Predicted line ratios / Observed line ratios

If C⁺ and CO/C⁰ are associated

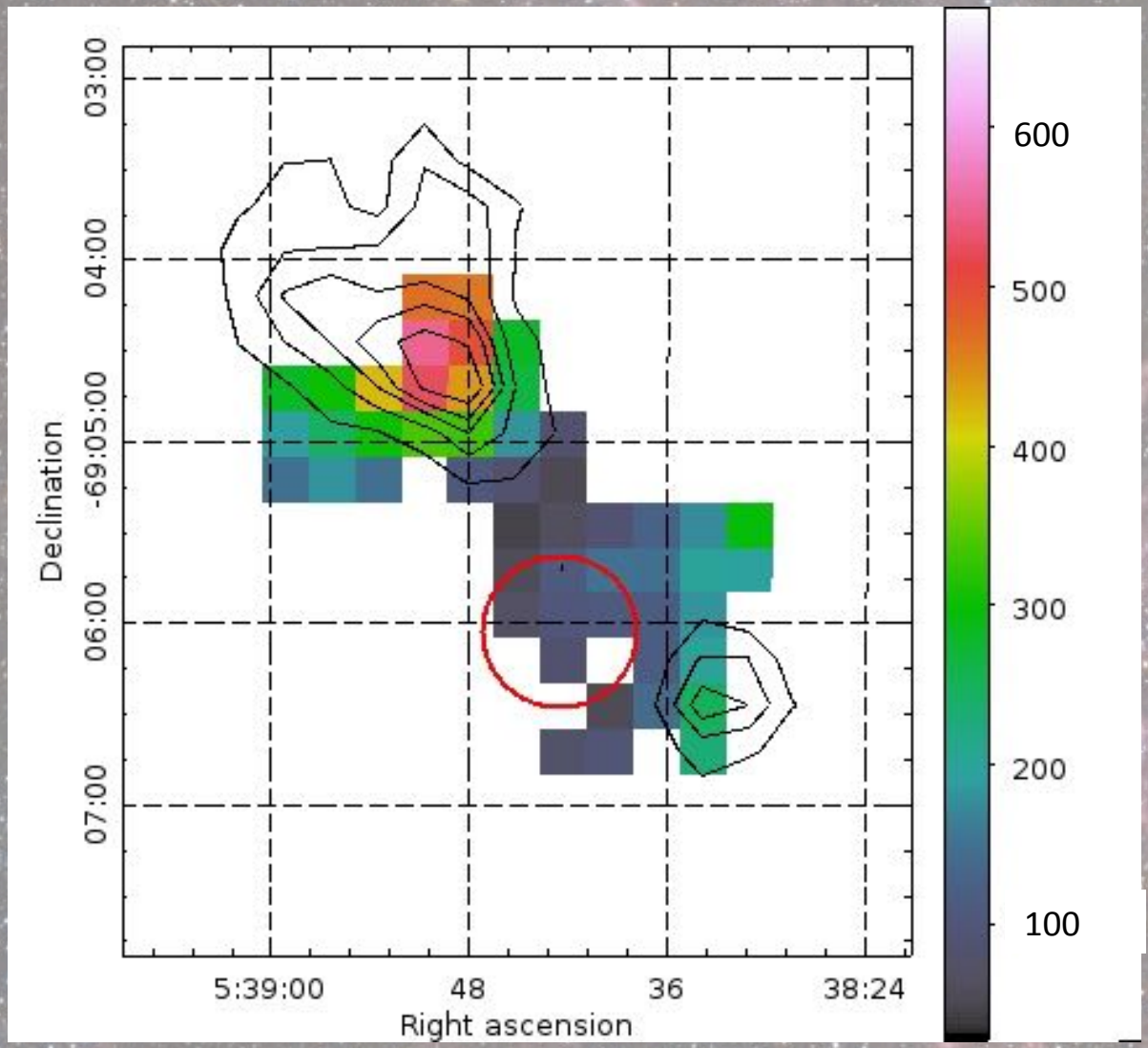




Spatial distribution of H_2

Predicted H_2 mass ($M_\odot$ / pc^2)

Contours: CO(3-2) (Minamidani+ 2011)

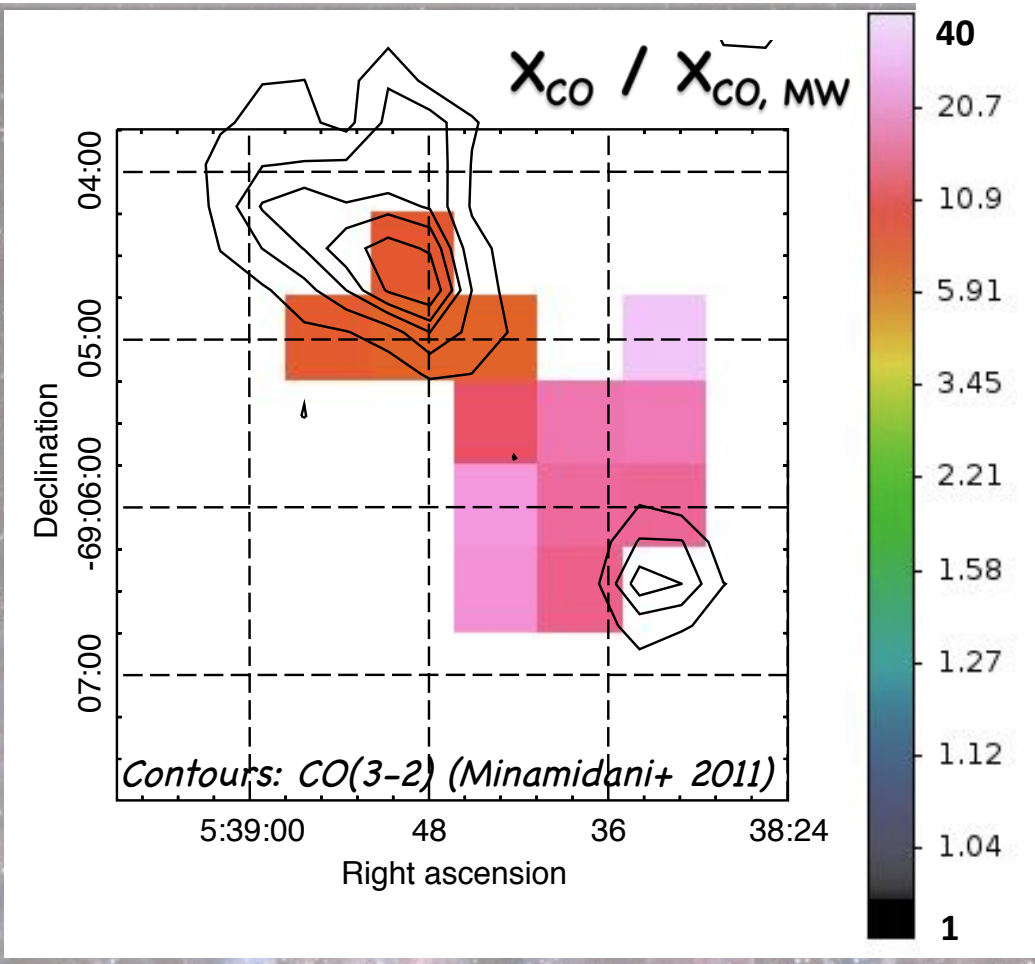


Chevance et al. 2016b in prep

X_{CO} factor in 30Dor

$$X_{CO} = \frac{N(H_2)}{I_{CO(1-0)}}$$

CO (J=1-0) from Wong et al. 2011

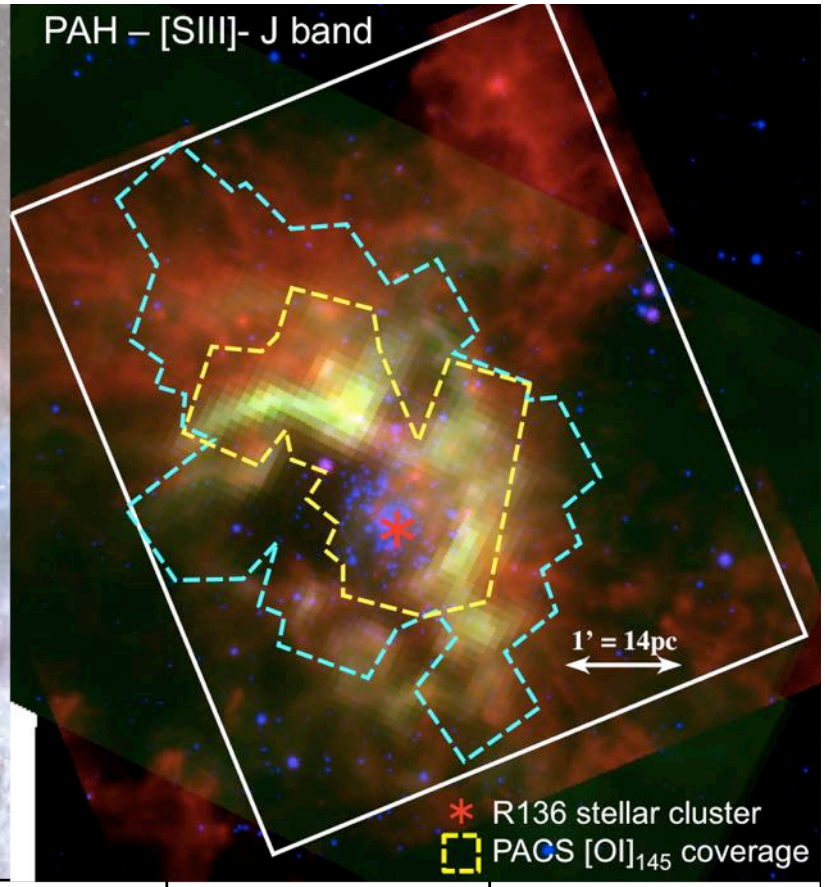


References	X_{CO} ($cm^{-2}.K^{-1}.km^{-1}.s$)	Object	Physical scale
Bolatto et al. 2013 (review)	$2x10^{20}$	*LMC, Milky Way*	
Israel 1997 (dust modeling)	$8.4x10^{21}$	*30Dor*	235 pc
Schruba et al. 2012 (constant SFE)	$4.6x10^{21}$	*LMC*	integrated
Roman-Duval et al. 2014 (dust modeling)	$< 6x10^{20}$	*LMC*	15 pc
Chevance et al. 2016b in prep	$1 - 4x10^{21}$	*30Dor*	10 pc

FIFI LS cycle 4 observations
June 28th-29th-30th and July 7th 2016

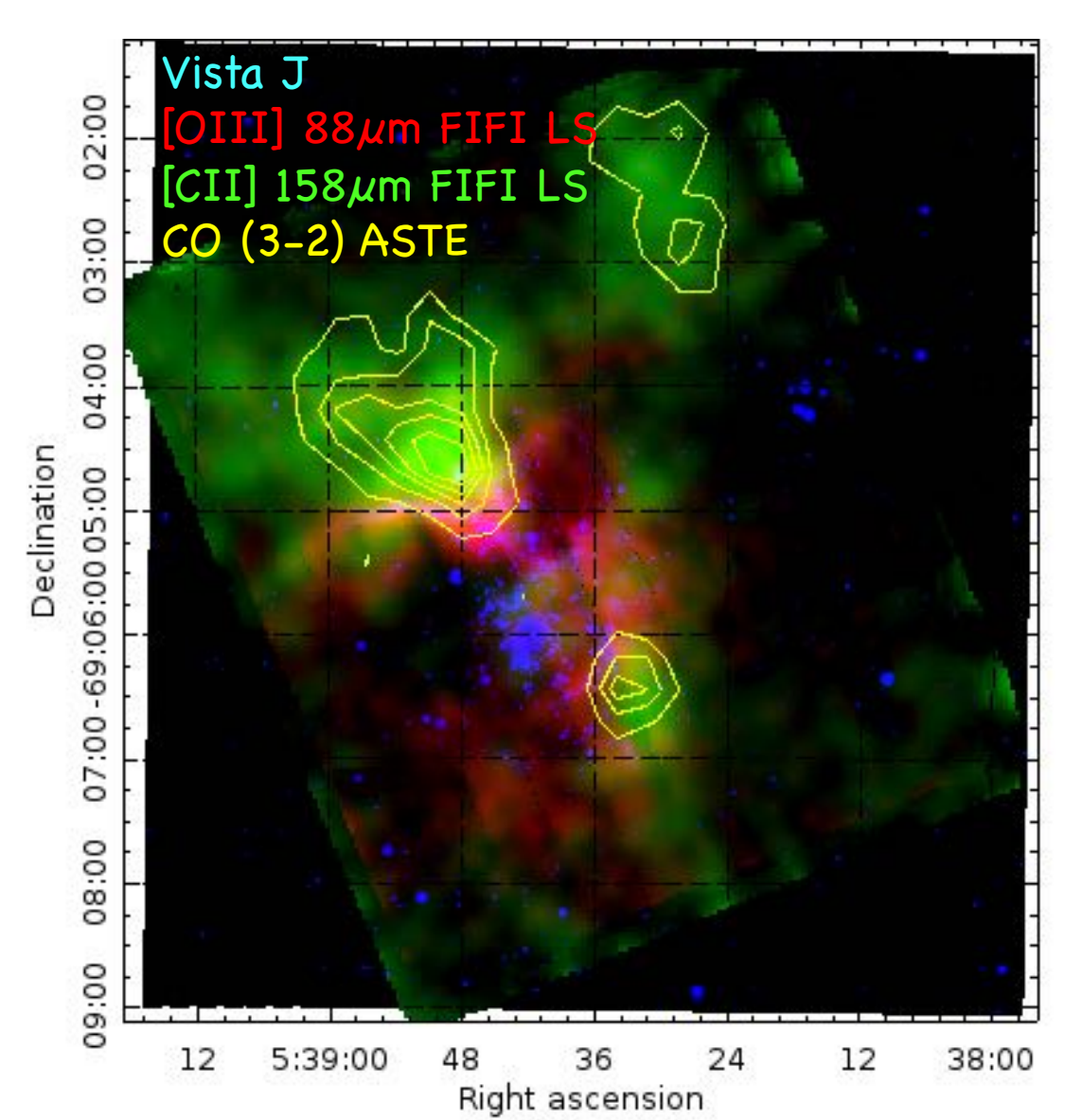
FIFI LS observations June 28th-29th-30th and July 7th 2016

Observing mode: mapping, asymmetric chopping mode



	Line	Ionization potential (eV)	Critical density (cm^{-3})	Observation time	Resolution (")
Ionized gas	[OIII] 52μm	35.1	3500	≈ 1h	6
	[OIII] 88μm	35.1	510	≈ 1h	7.3
	[NIII] 57μm	29.6	3000	≈ 1.5h	6
	[CII] 158μm	11.3	2.8e3 [H], 50 [e]	≈ 1h	13.1
Neutral gas	[OI] 63μm	0	4.7e5	≈ 2.5h	6
	[OI] 145μm	0	9.5e4	≈ 5h	12.1

FIFI LS observations: data reduction



Observations

Chop subtracted
Nods combined
Wavelength calibration
Spatial calibration
Telluric correction
Flux calibration

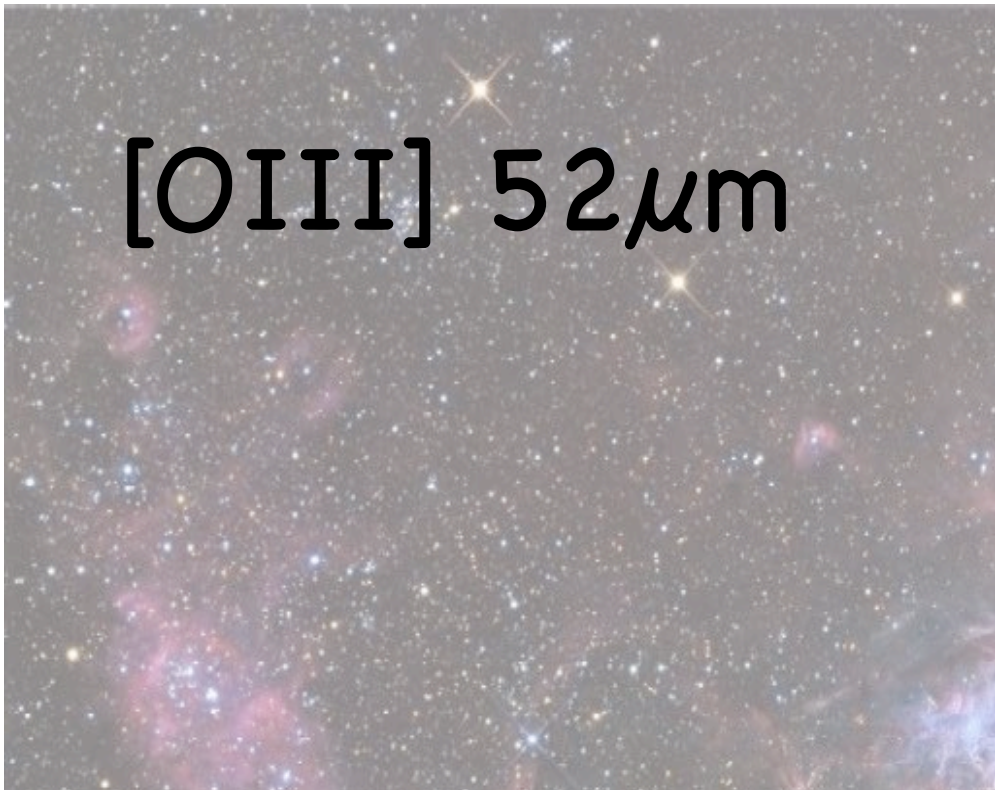
↓

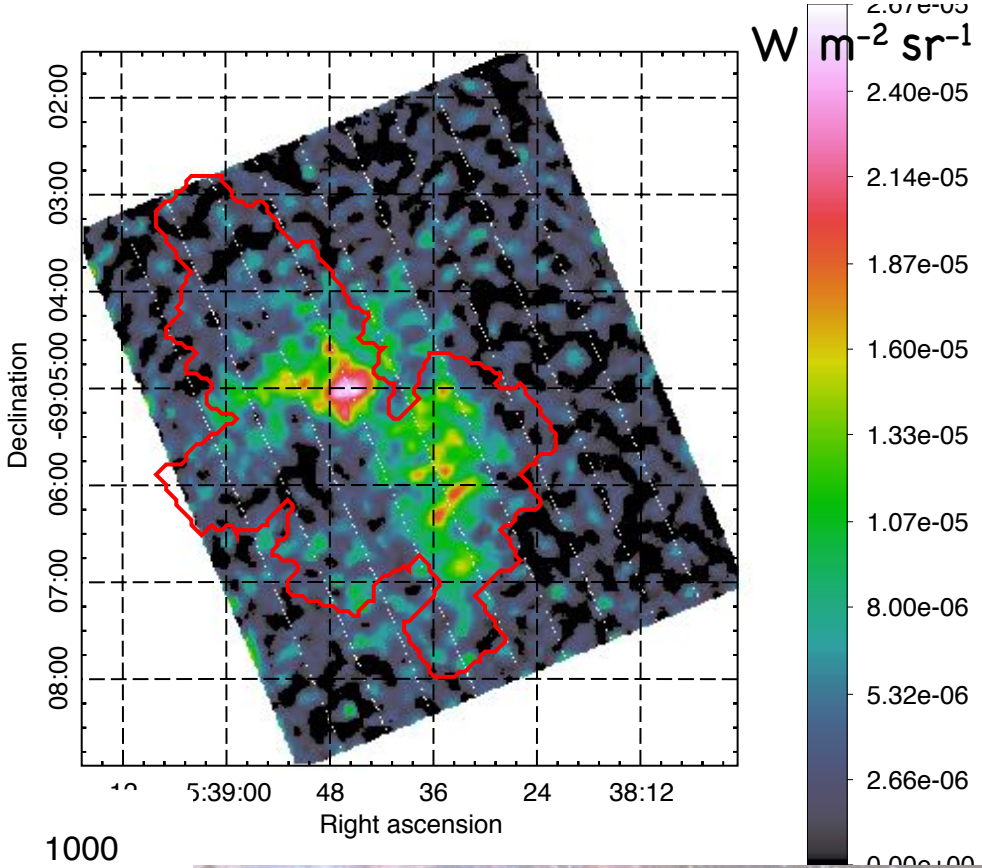
Spectral cubes

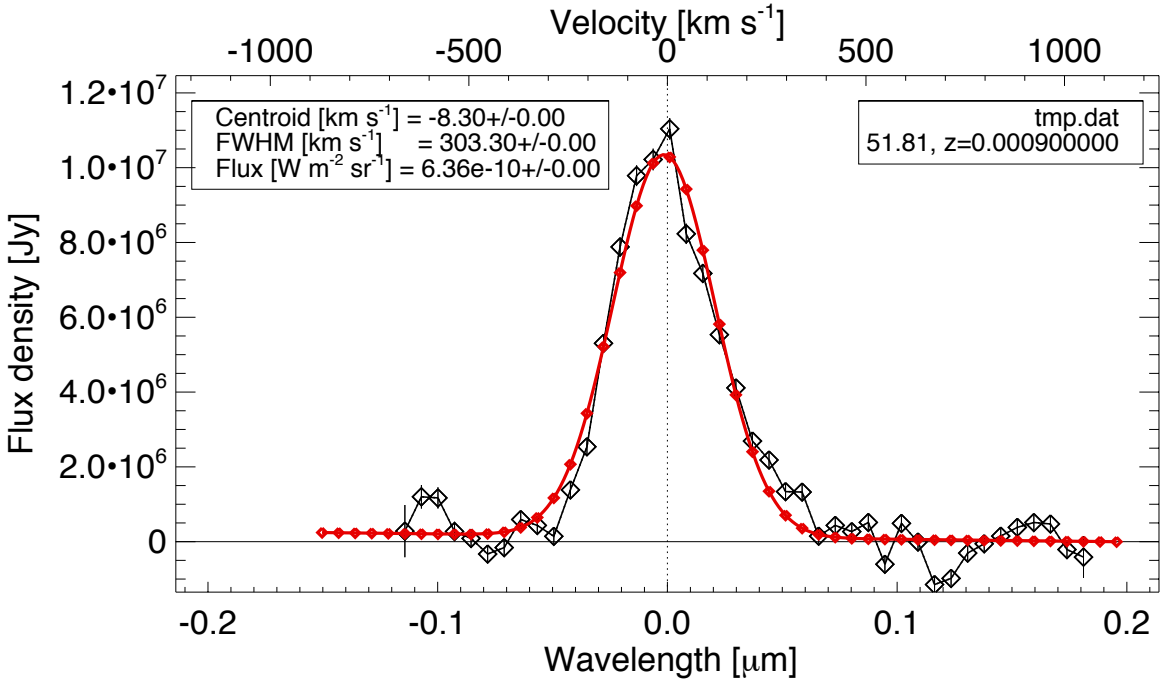
Fit baseline with a polynomial of order 1
Fit line with a Gaussian (FWHM = spectral resolution)
MC error estimation (on going)

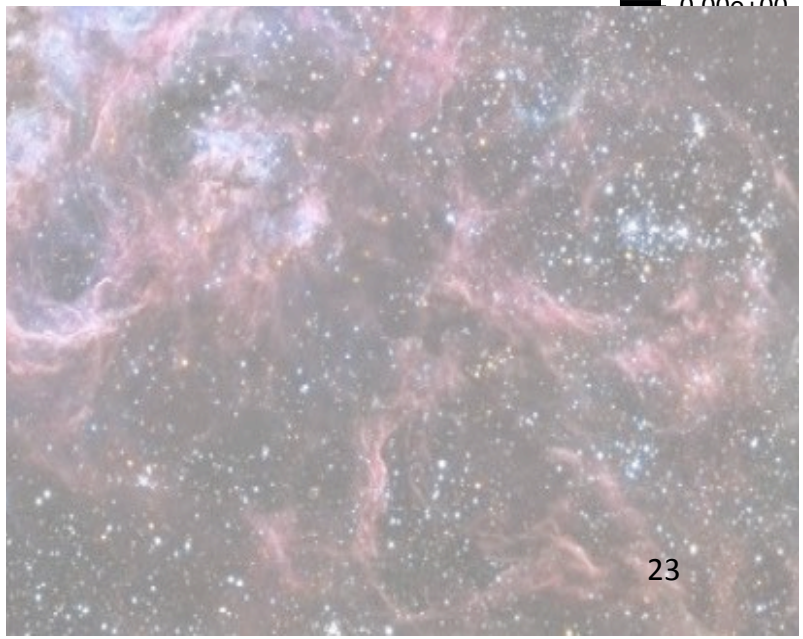
↓

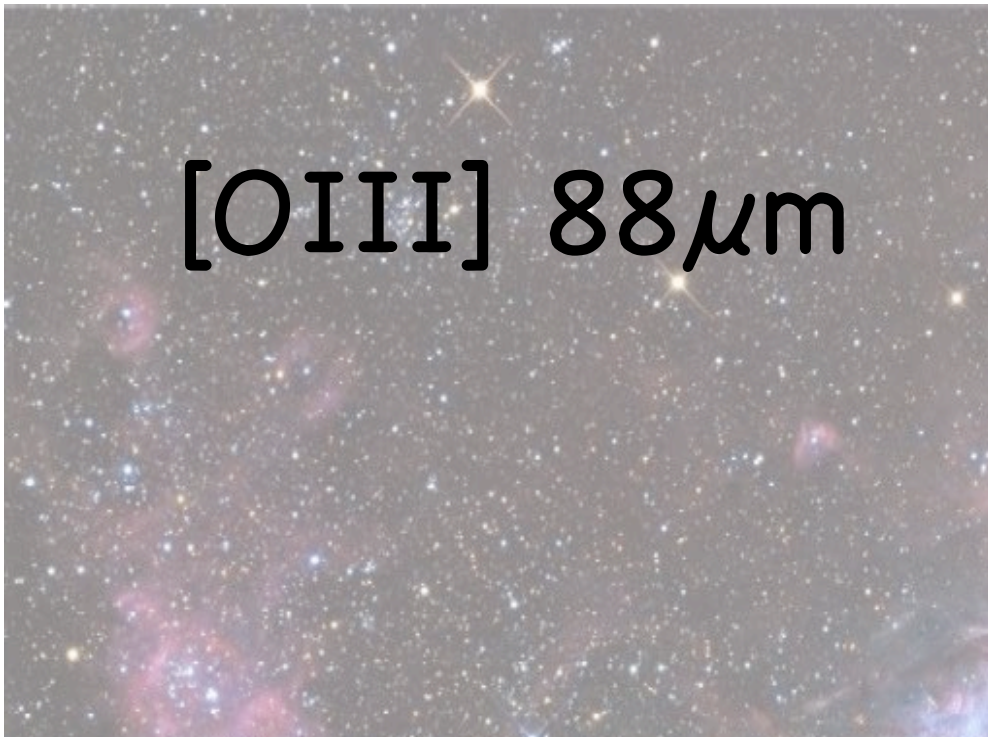
Line intensities + Velocities

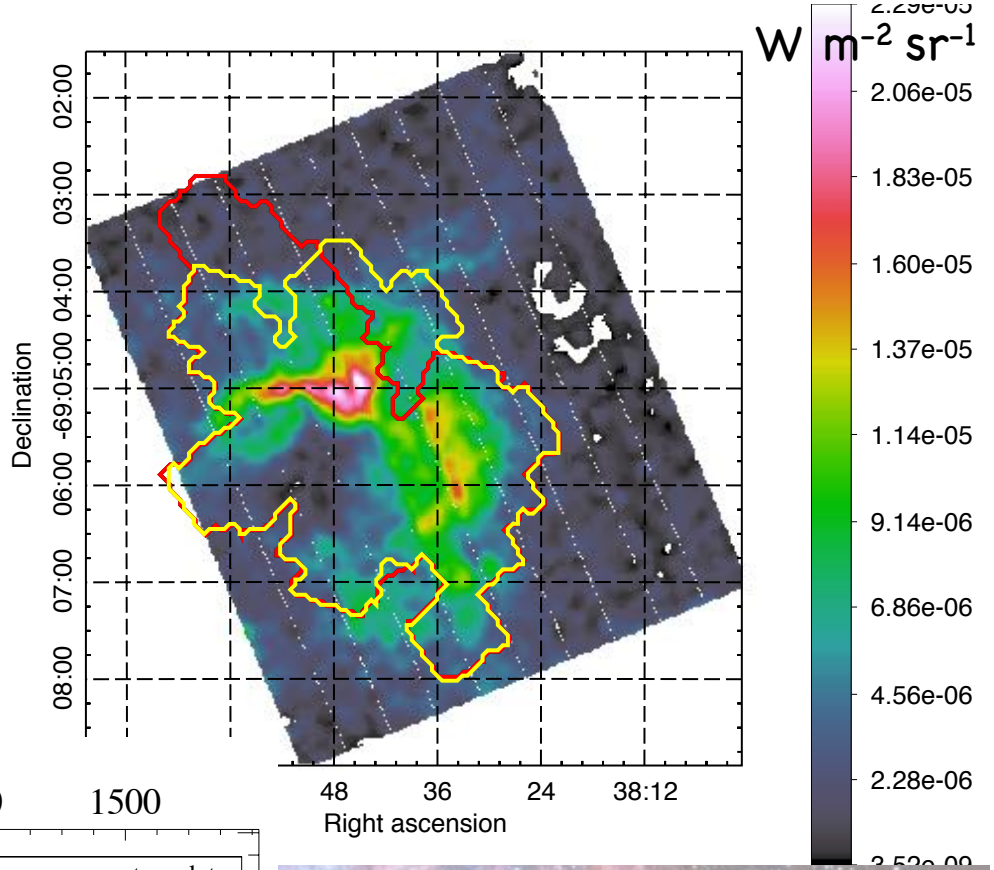

[OIII] 52μm

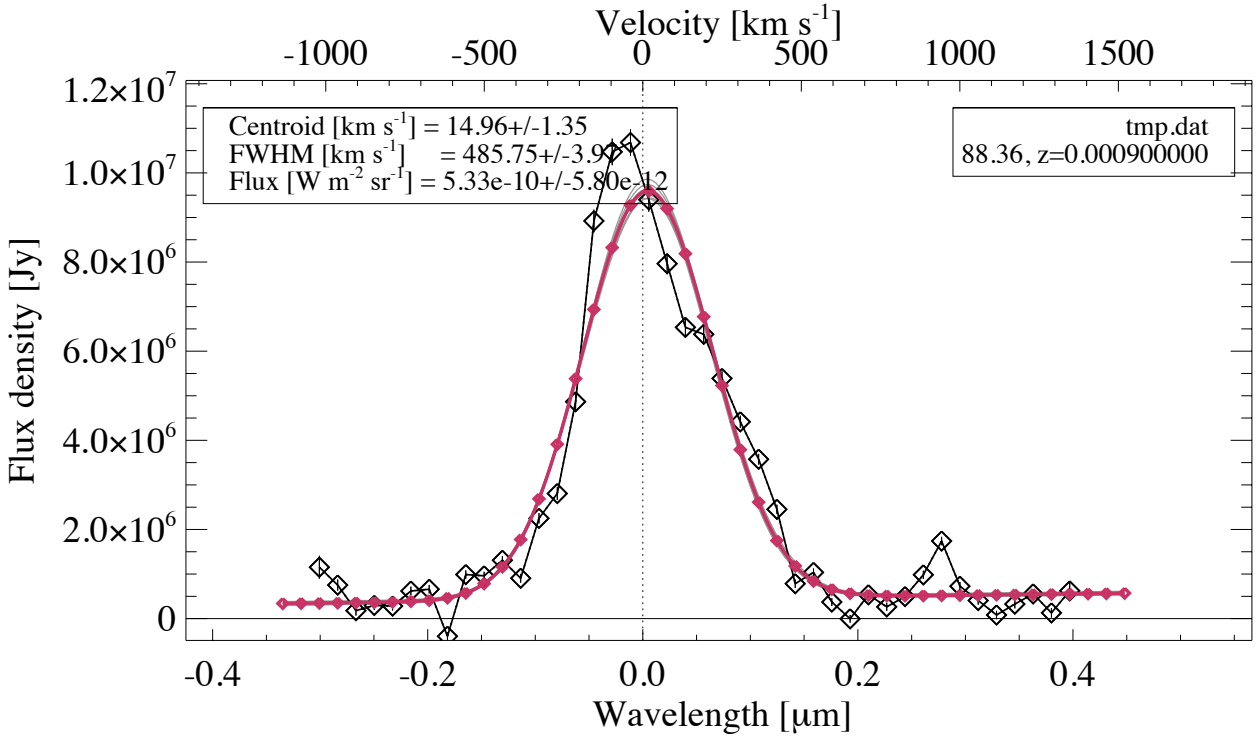

W m-2 sr-1
2.40e-05
2.14e-05
1.87e-05
1.60e-05
1.33e-05
1.07e-05
8.00e-06
5.32e-06
2.66e-06
Declination
02:00
03:00
04:00
-69:05:00
06:00
07:00
08:00
5:39:00
48
36
24
38:12
Right ascension

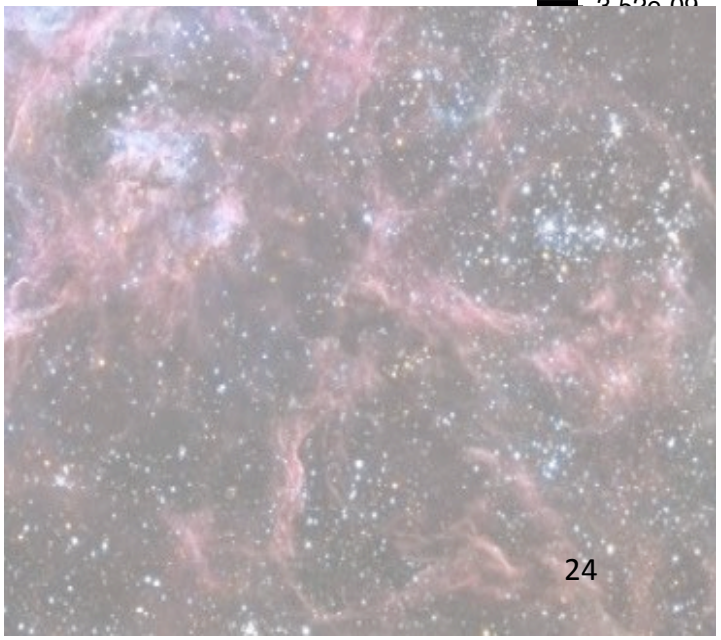

Velocity [km s-1]
-1000
-500
0
500
1000
Centroid [km s-1] = -8.30+/-0.00
FWHM [km s-1] = 303.30+/-0.00
Flux [W m-2 sr-1] = 6.36e-10+/-0.00
tmp.dat
51.81, z=0.000900000
Flux density [Jy]
1.2•10^7
1.0•10^7
8.0•10^6
6.0•10^6
4.0•10^6
2.0•10^6
0
-0.2
-0.1
0.0
0.1
0.2
Wavelength [μm]




[OIII] 88μm


W m-2 sr-1
2.06e-05
1.83e-05
1.60e-05
1.37e-05
1.14e-05
9.14e-06
6.86e-06
4.56e-06
2.28e-06
Declination
02:00
03:00
04:00
-69:05:00
06:00
07:00
08:00
48
36
24
38:12
Right ascension

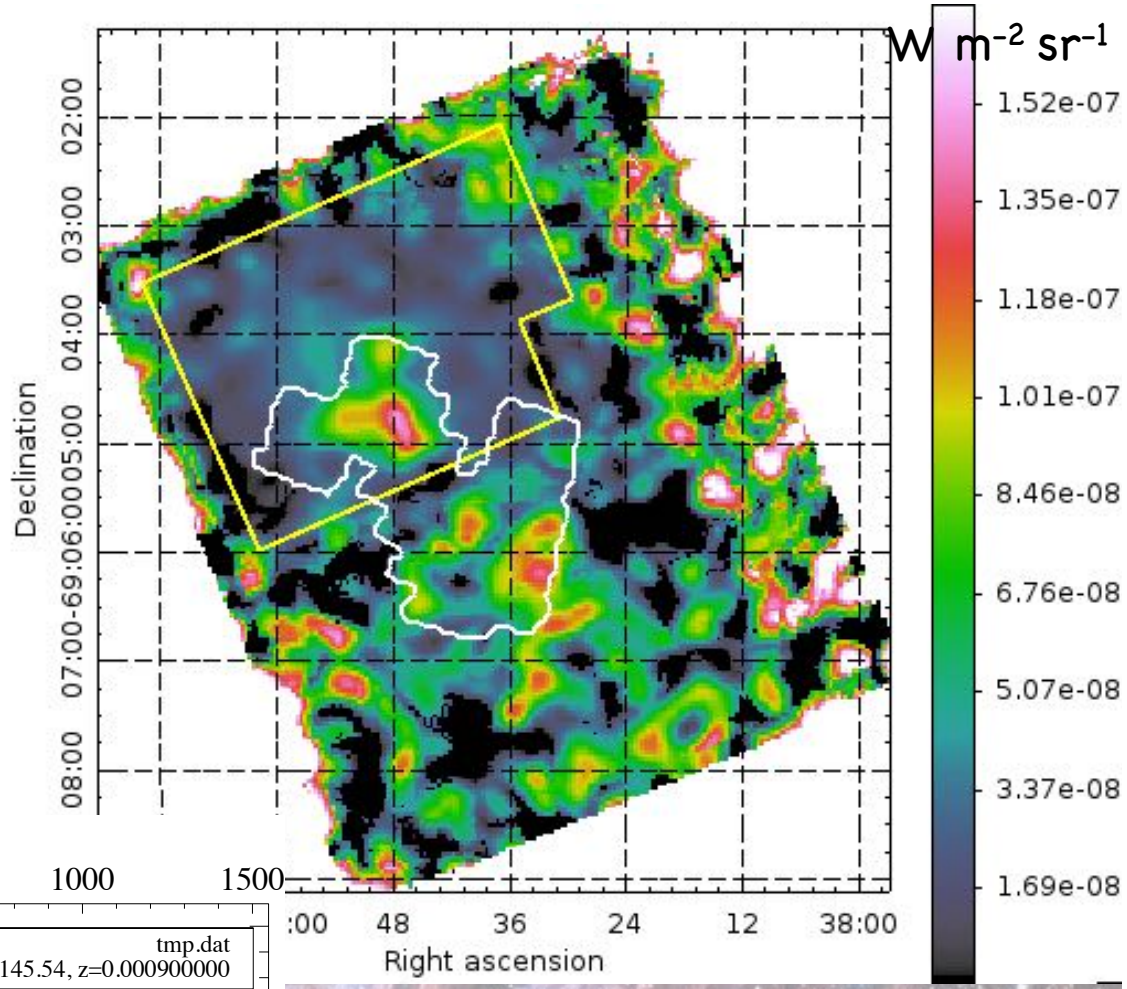

Velocity [km s-1]
-1000
-500
0
500
1000
1500
Centroid [km s-1] = 14.96+/-1.35
FWHM [km s-1] = 485.75+/-3.99
Flux [W m-2 sr-1] = 5.33e-10+/-5.80e-12
tmp.dat
88.36, z=0.000900000
Flux density [Jy]
1.2×10^7
1.0×10^7
8.0×10^6
6.0×10^6
4.0×10^6
2.0×10^6
0
-0.4
-0.2
0.0
0.2
0.4
Wavelength [μm]

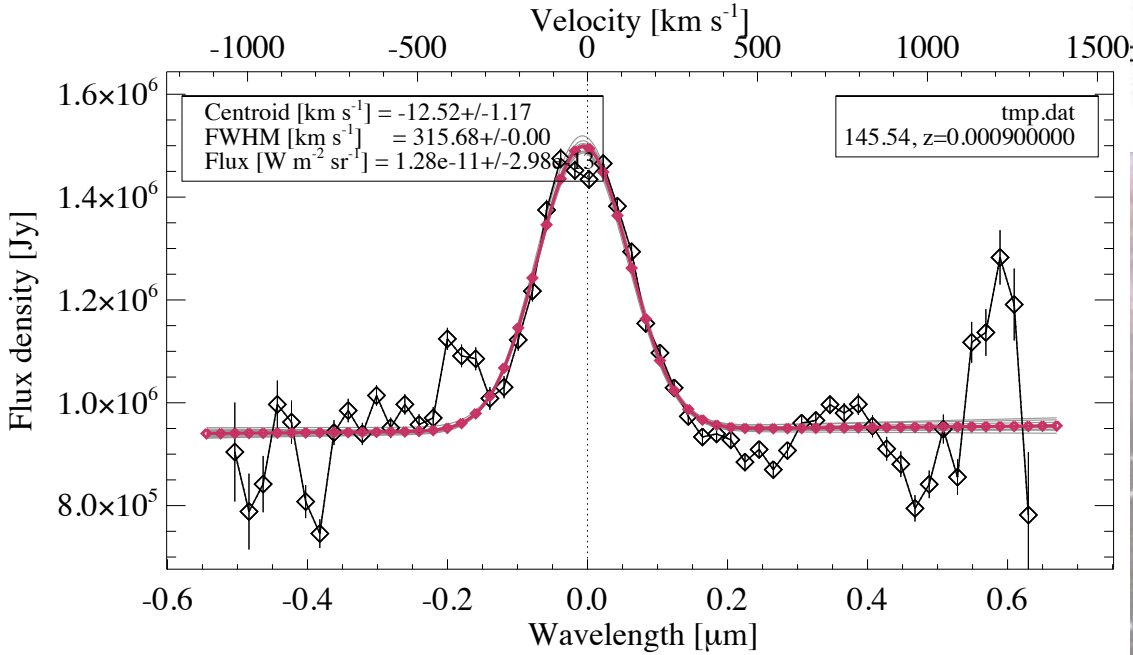

24

[OI] 145μm

White: PACS coverage

Yellow: FIFI LS deep integration





[OI] 145μm

Cycle 5 proposal:
[OI] 145 + [NIII] 57 (12.3h)

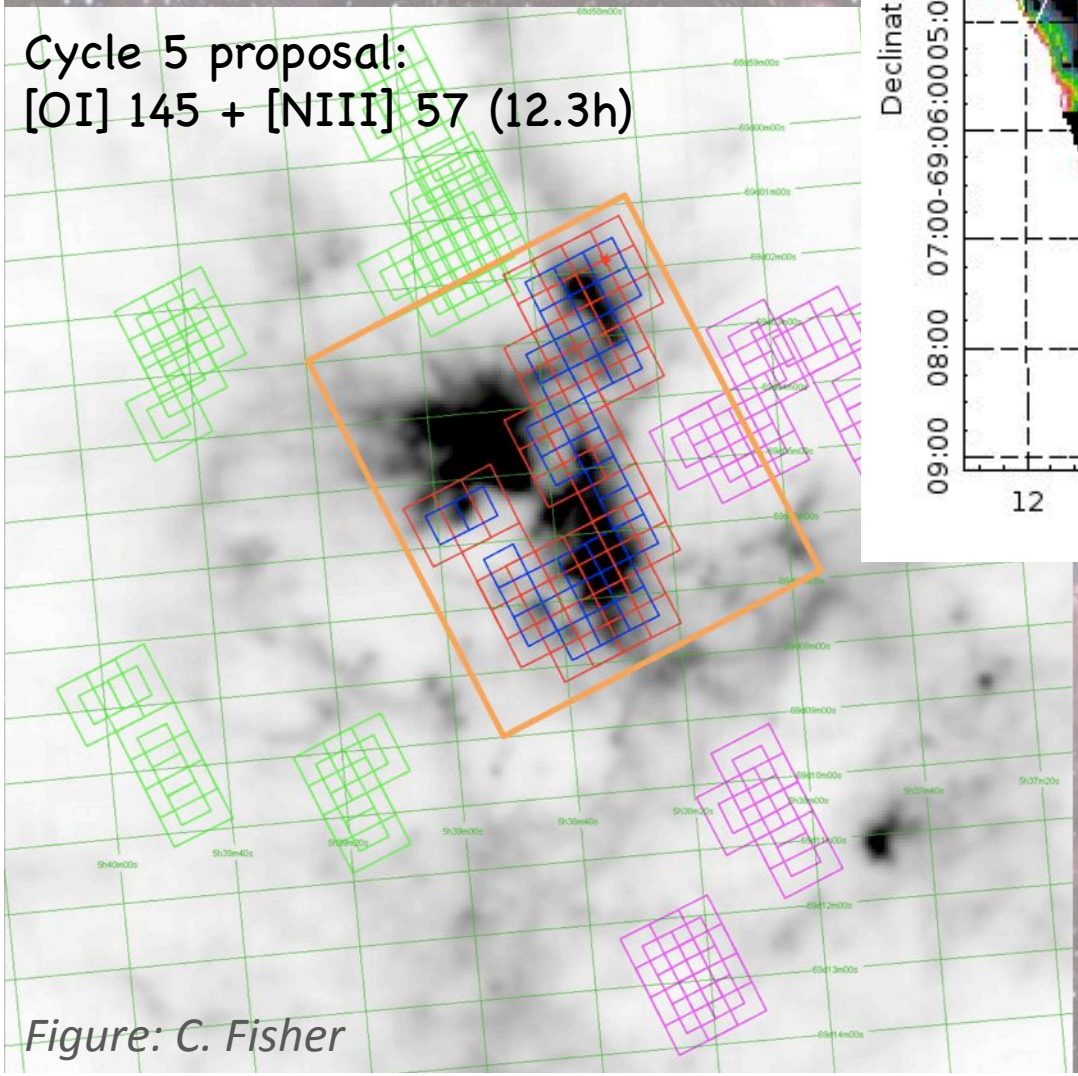
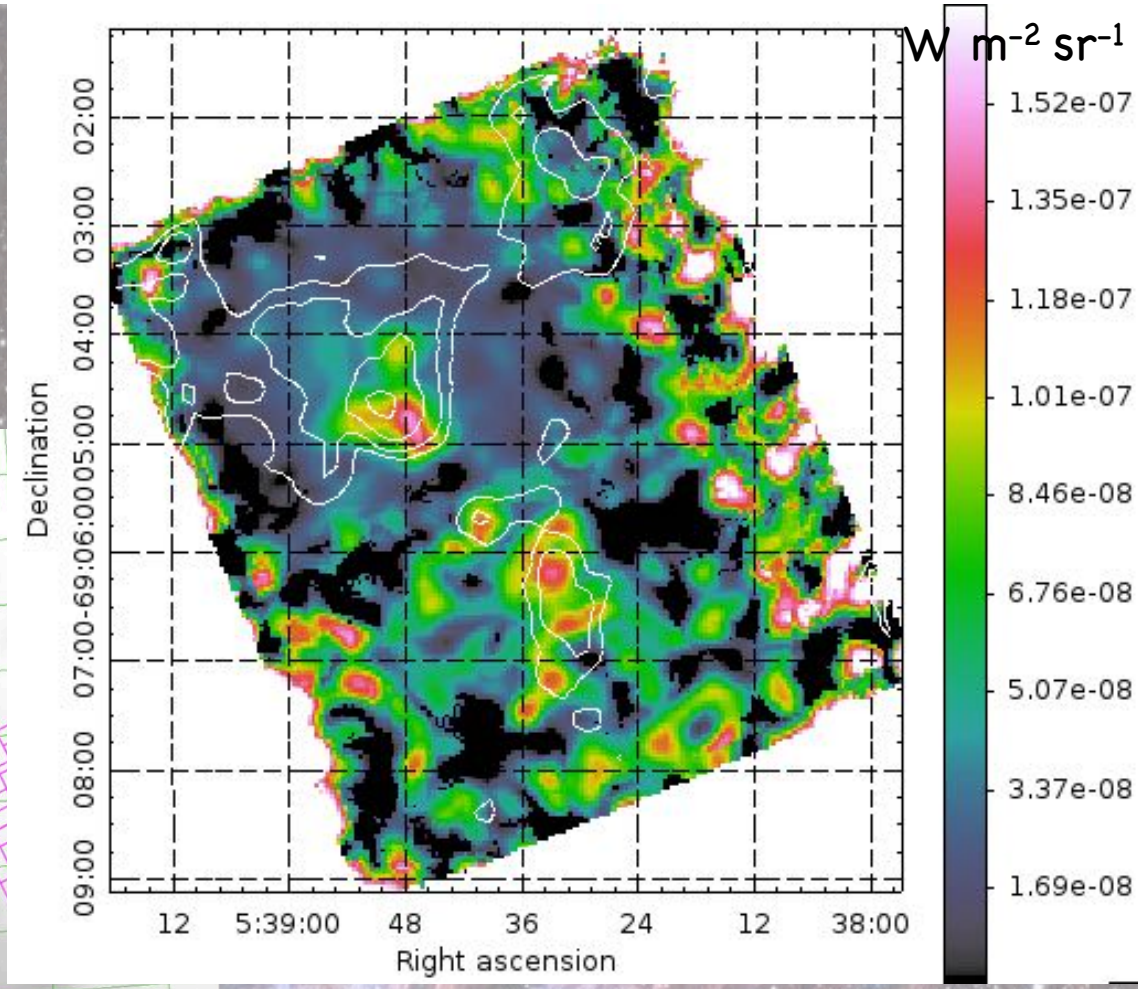
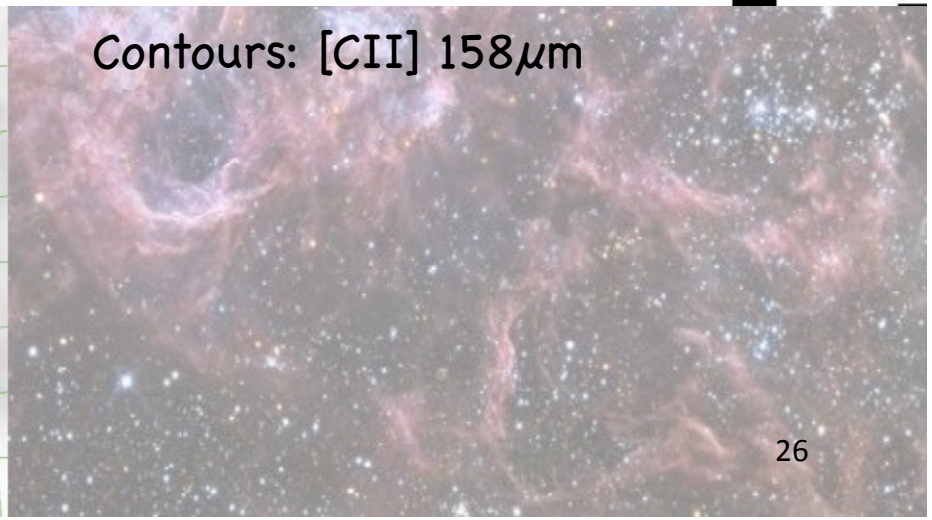
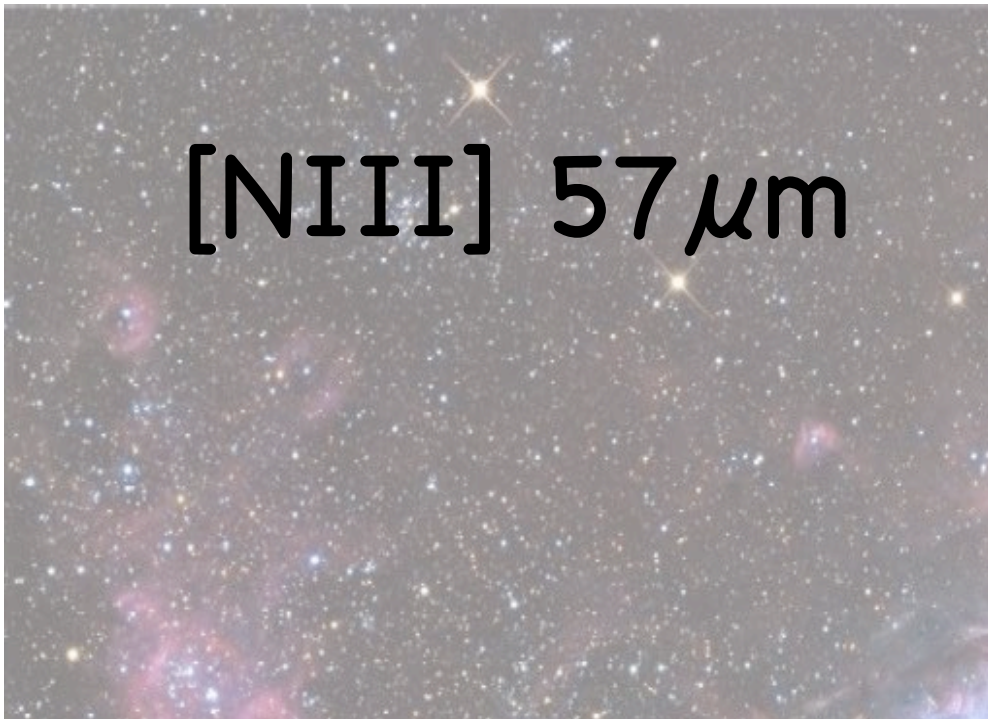
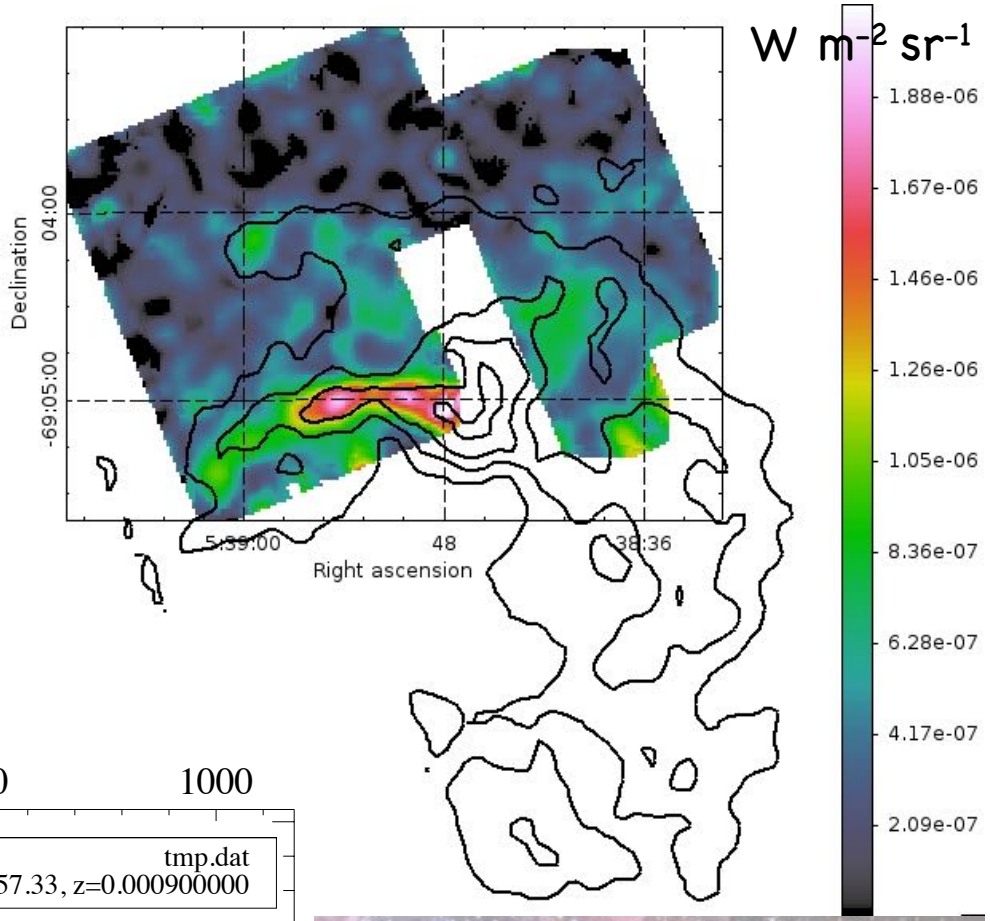


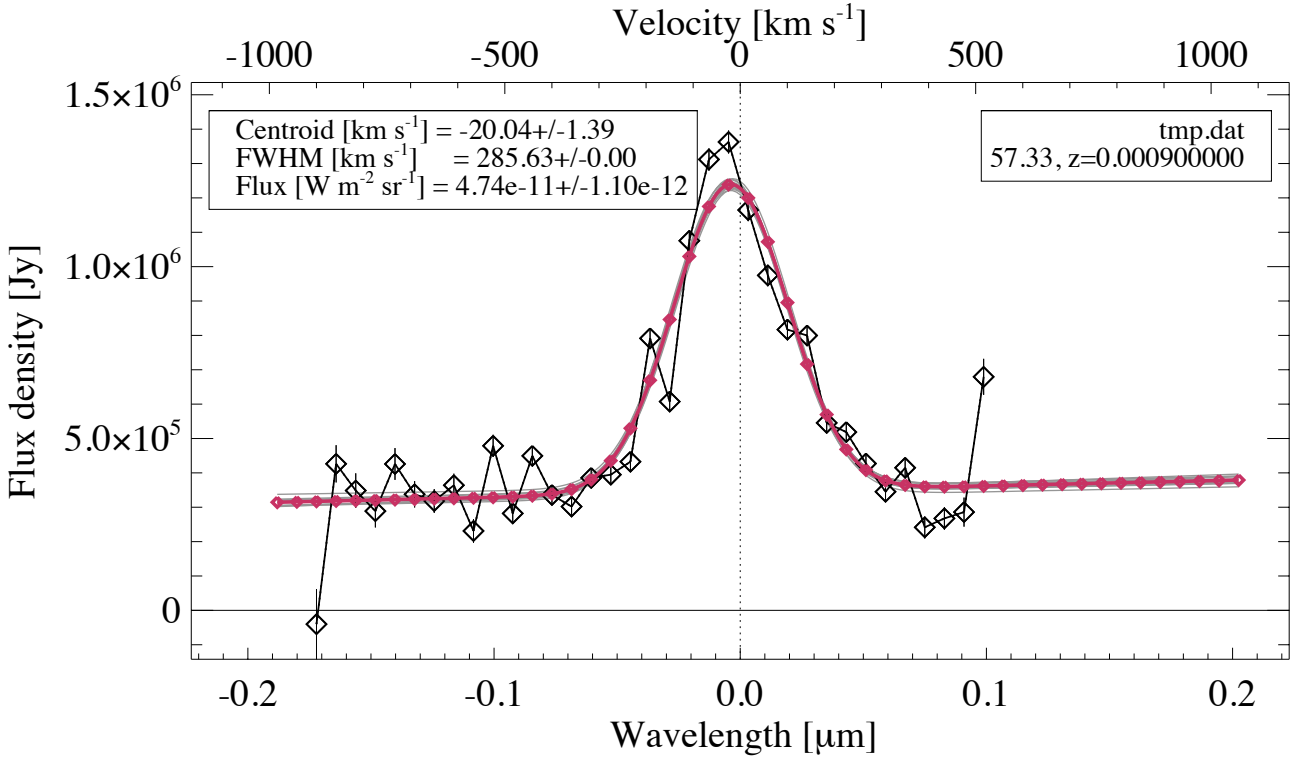
Figure: C. Fisher

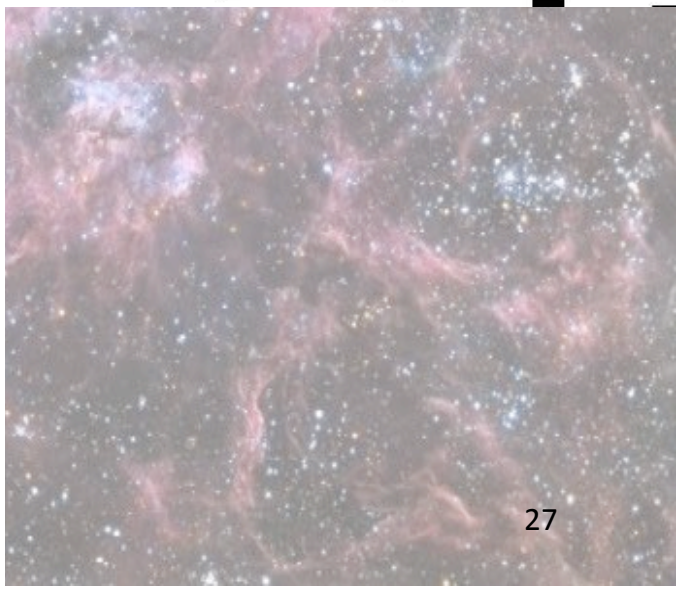




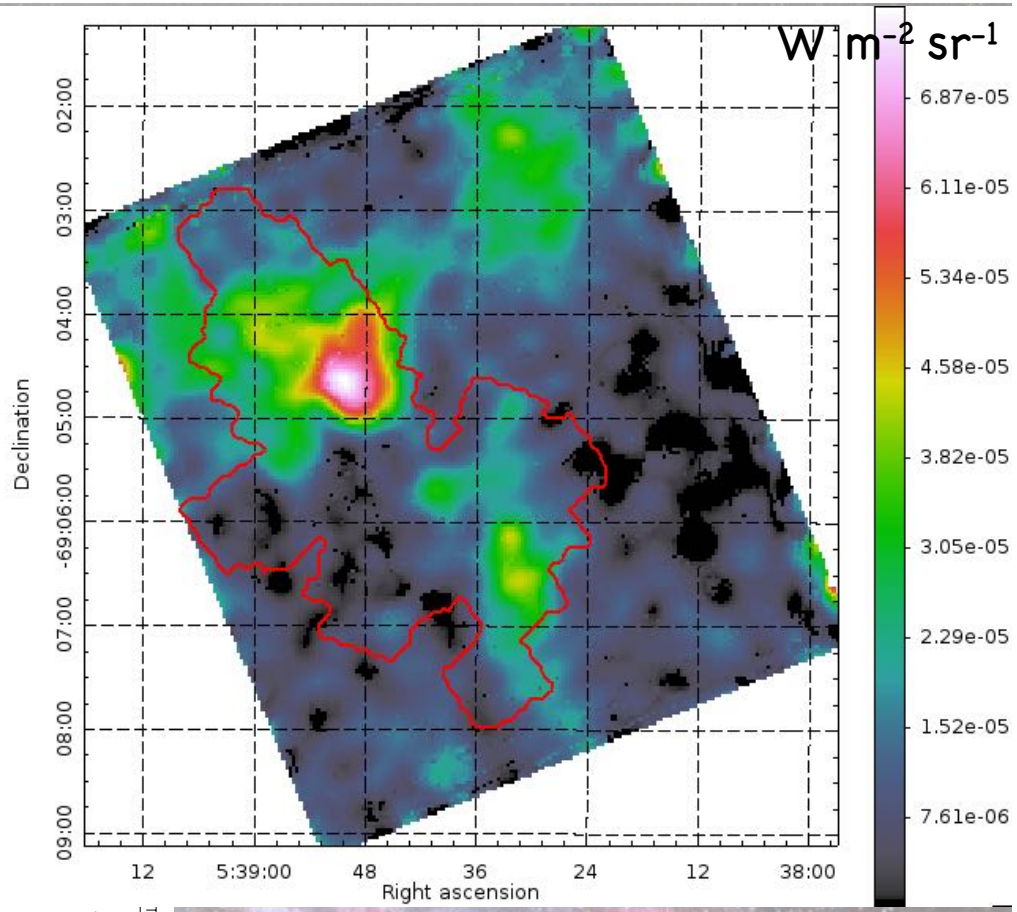

[NIII] 57μm

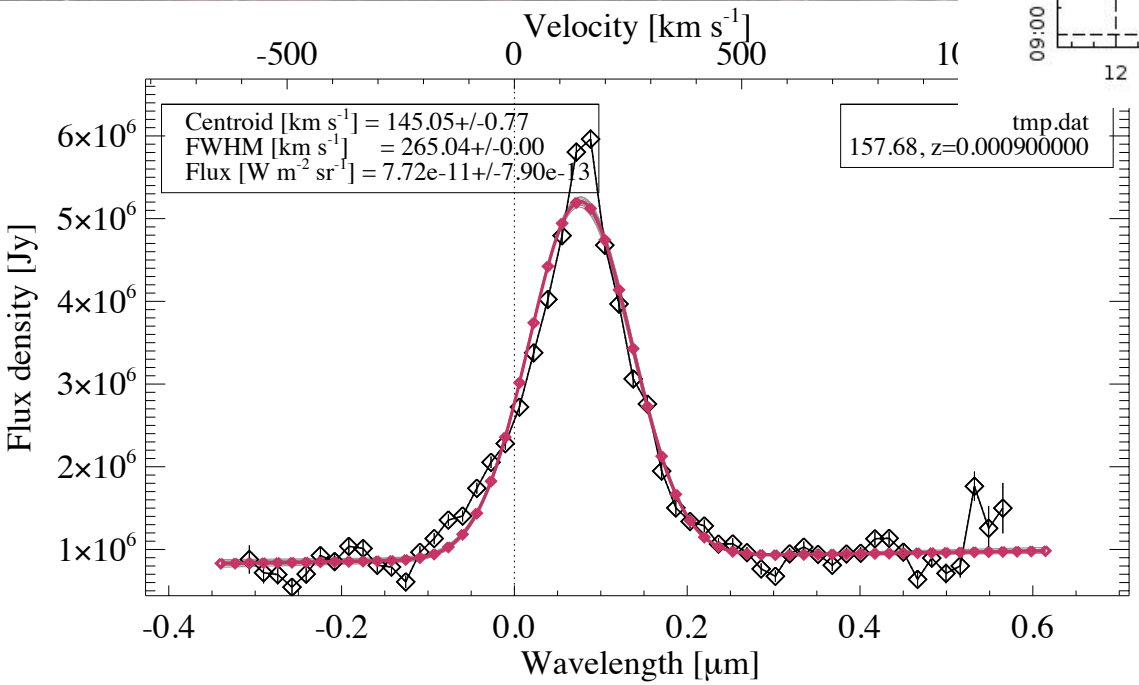

W m-2 sr-1
1.88e-06
1.67e-06
1.46e-06
1.26e-06
1.05e-06
8.36e-07
6.28e-07
4.17e-07
2.09e-07
Declination
04:00
-69:05:00
5:39:00
48
38:36
Right ascension


Velocity [km s-1]
-1000
-500
0
500
1000
1.5×10^6
1.0×10^6
5.0×10^5
0
Flux density [Jy]
Centroid [km s-1] = -20.04+/-1.39
FWHM [km s-1] = 285.63+/-0.00
Flux [W m-2 sr-1] = 4.74e-11+/-1.10e-12
tmp.dat
57.33, z=0.000900000
-0.2
-0.1
0.0
0.1
0.2
Wavelength [μm]

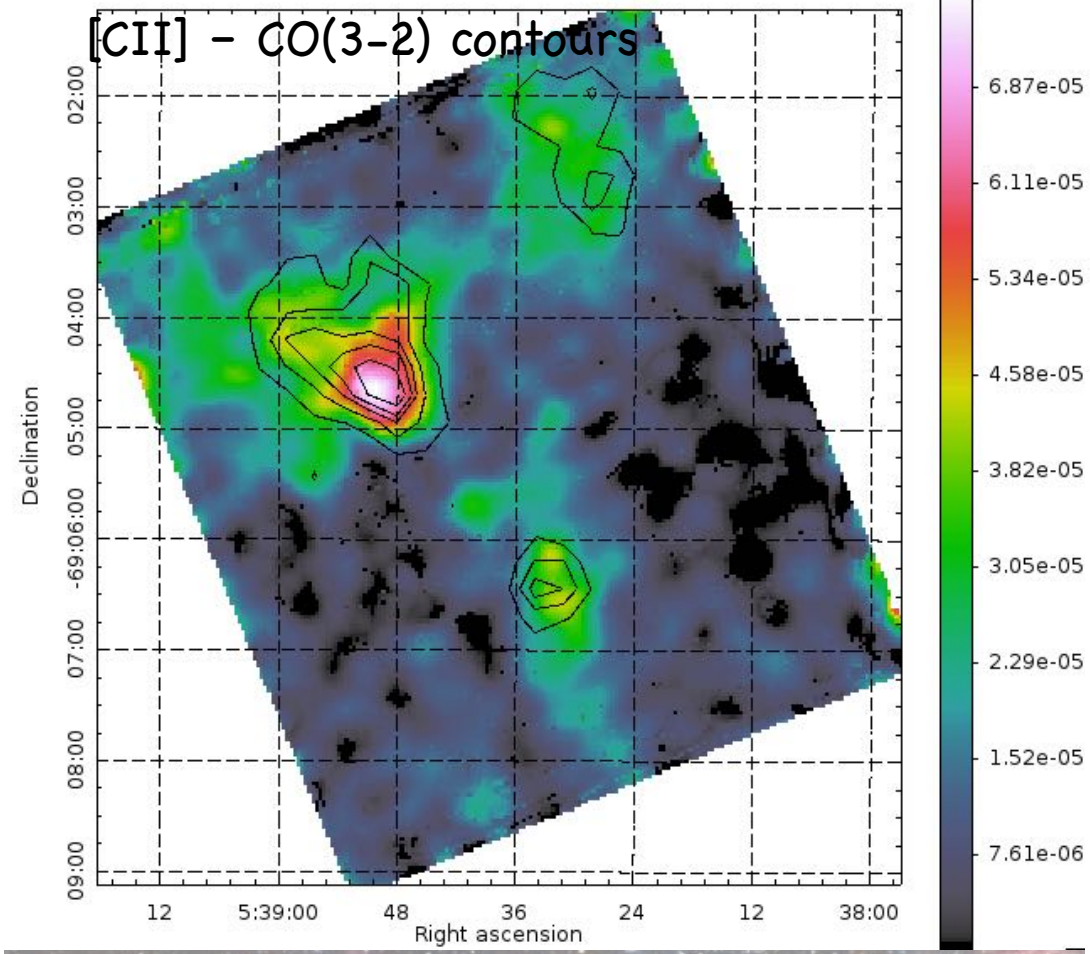


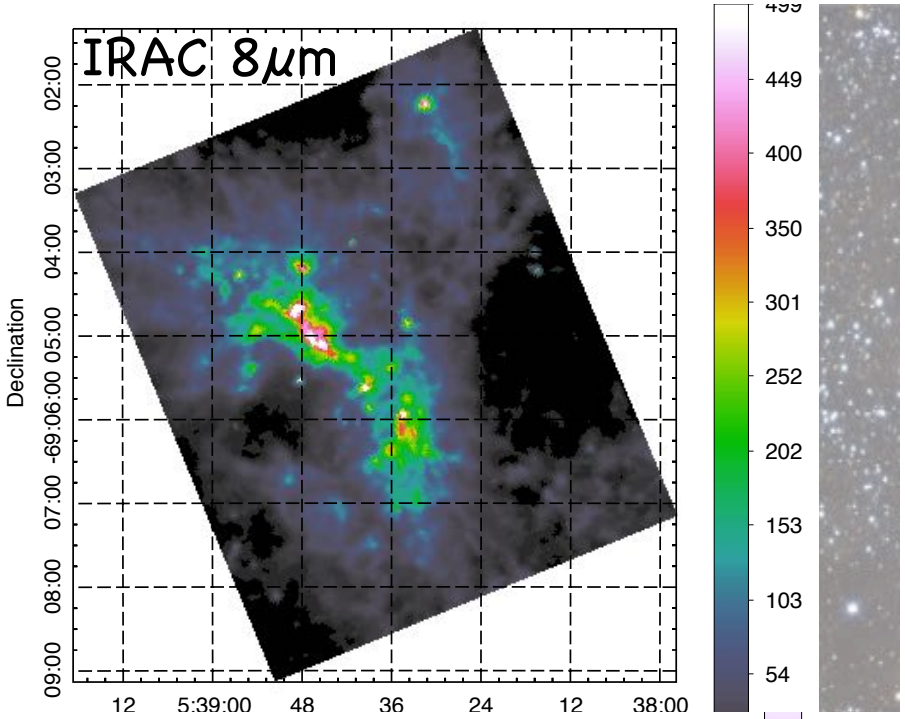

[CII] 158μm

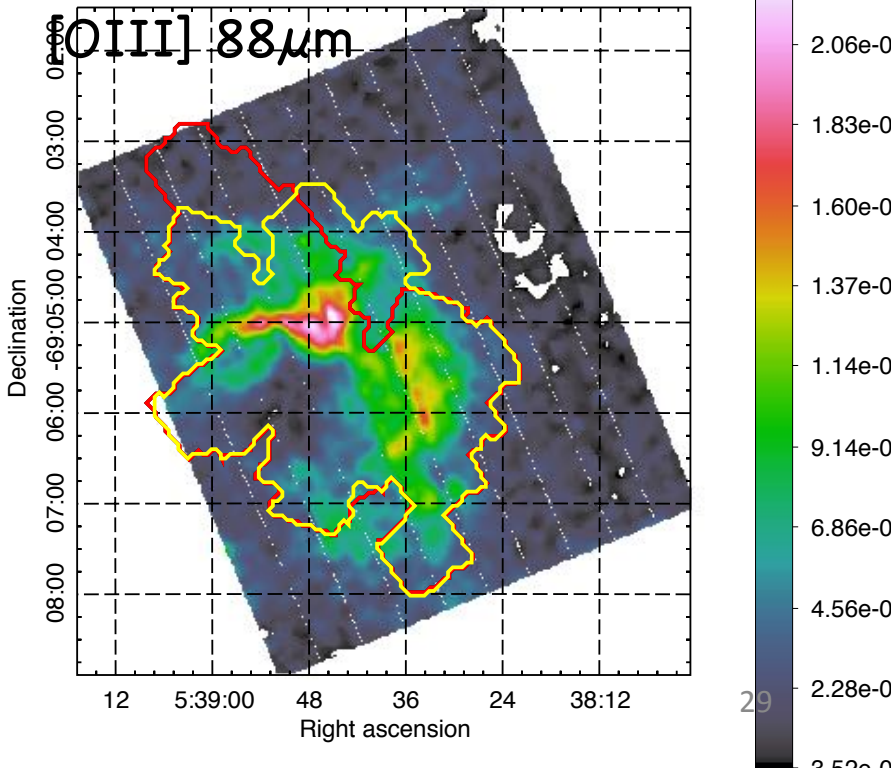

W m-2 sr-1
6.87e-05
6.11e-05
5.34e-05
4.58e-05
3.82e-05
3.05e-05
2.29e-05
1.52e-05
7.61e-06
Declination
02:00
03:00
04:00
05:00
-69:06:00
07:00
08:00
09:00
12
5:39:00
48
36
24
12
38:00
Right ascension


Velocity [km s-1]
-500
0
500
Centroid [km s-1] = 145.05+/-0.77
FWHM [km s-1] = 265.04+/-0.00
Flux [W m-2 sr-1] = 7.72e-11+/-7.90e-13
tmp.dat
157.68, z=0.000900000
Flux density [Jy]
6×10^6
5×10^6
4×10^6
3×10^6
2×10^6
1×10^6
-0.4
-0.2
0.0
0.2
0.4
0.6
Wavelength [μm]

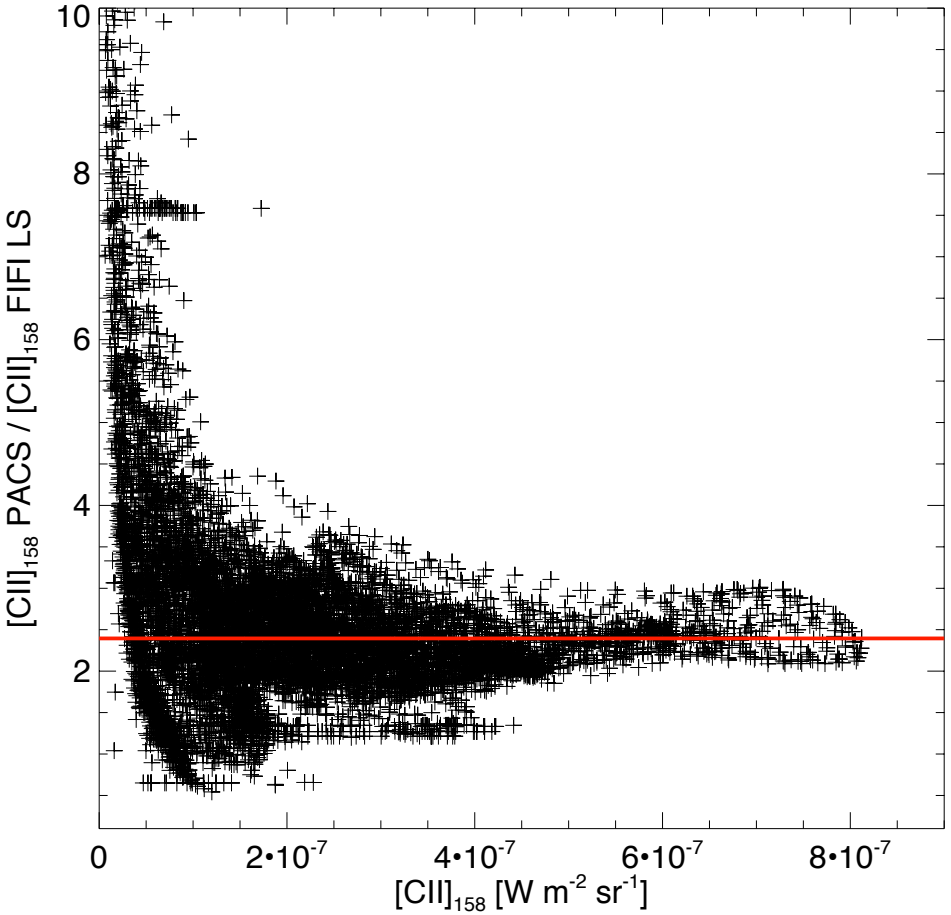
Comparison with other tracers

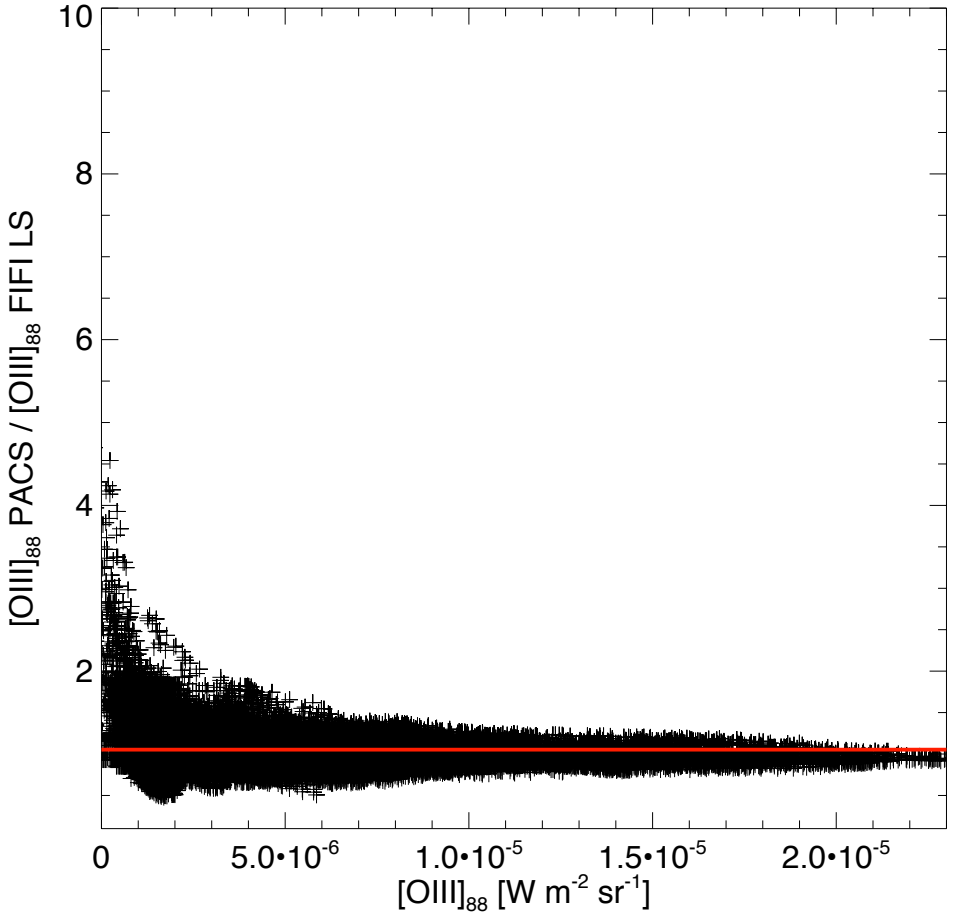






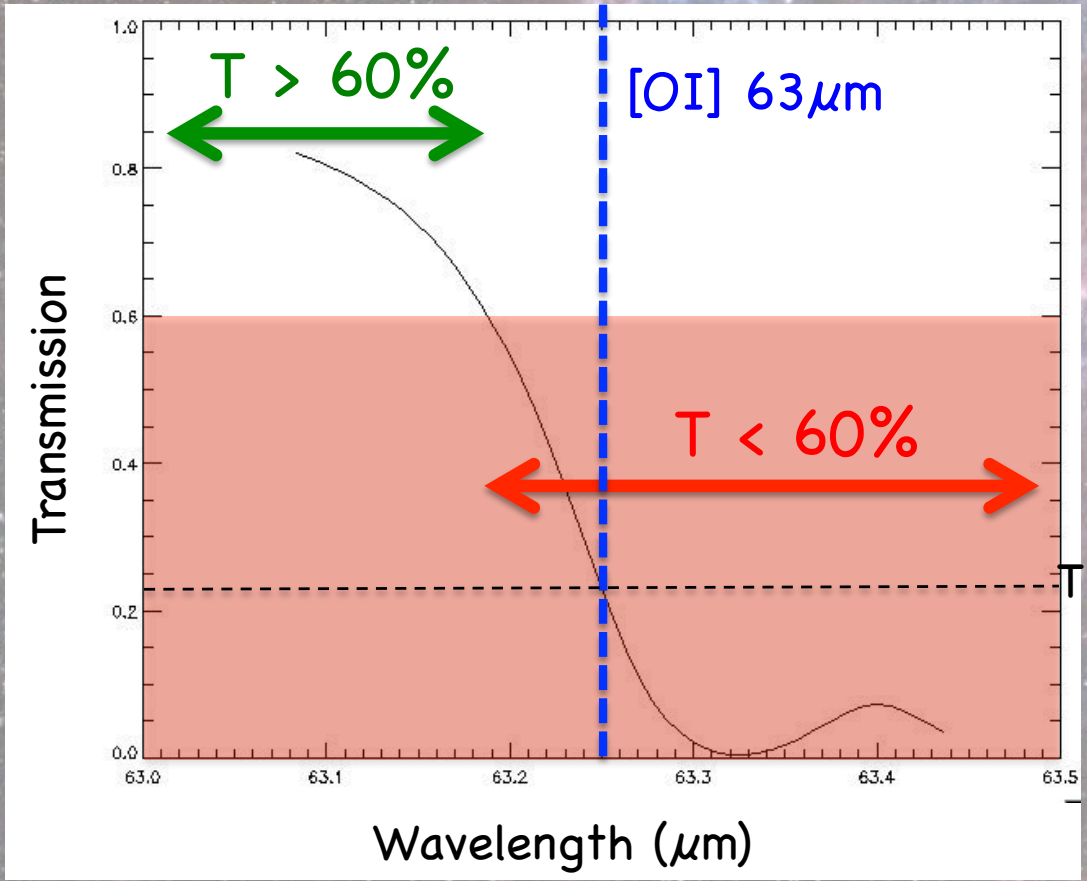
Comparison with PACS calibration



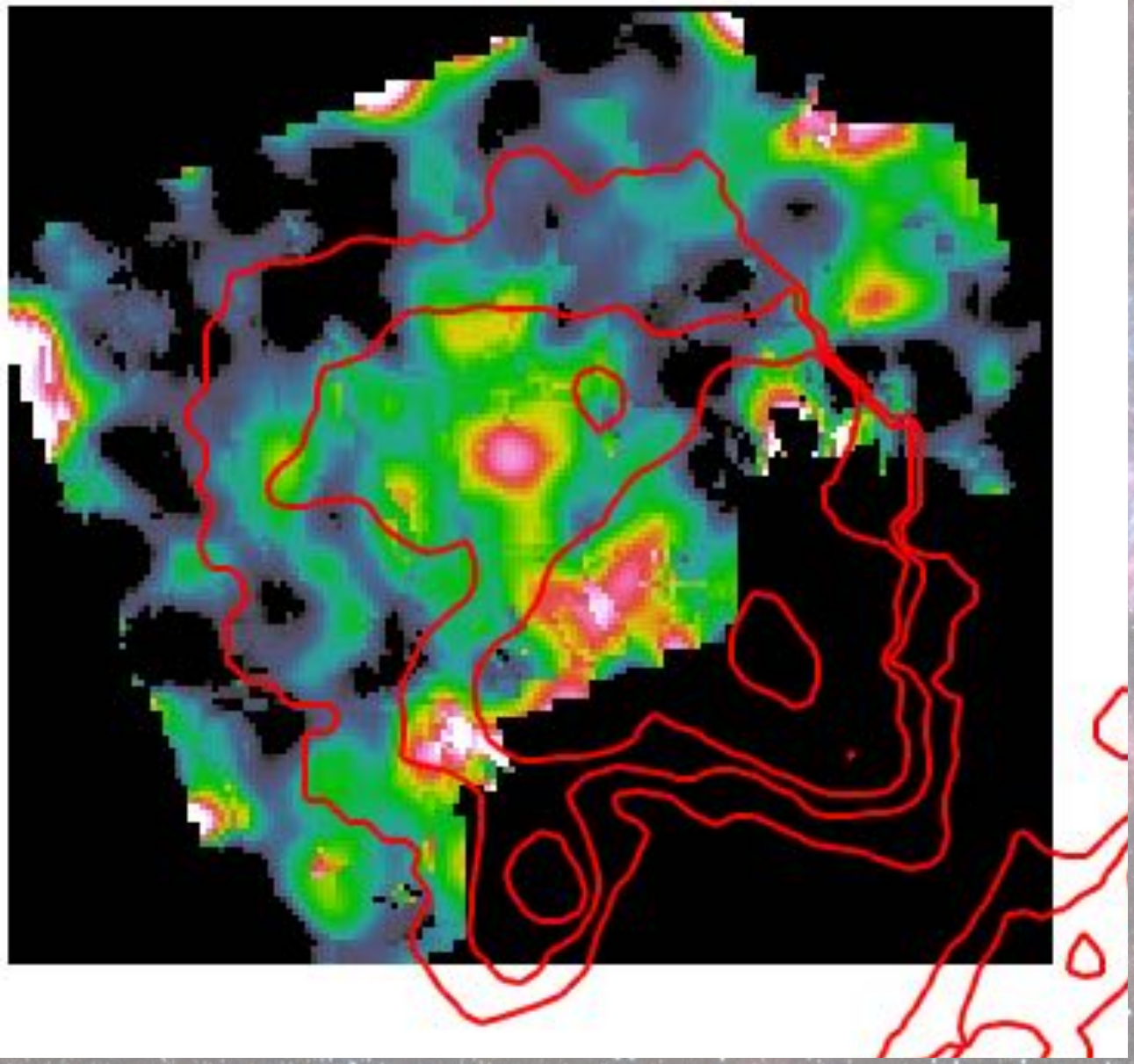


FIFI LS observations: [OI] 63μm

At the velocity of the LMC (≈ 270km/s), [OI] 63μm is close to a deep telluric absorption feature.



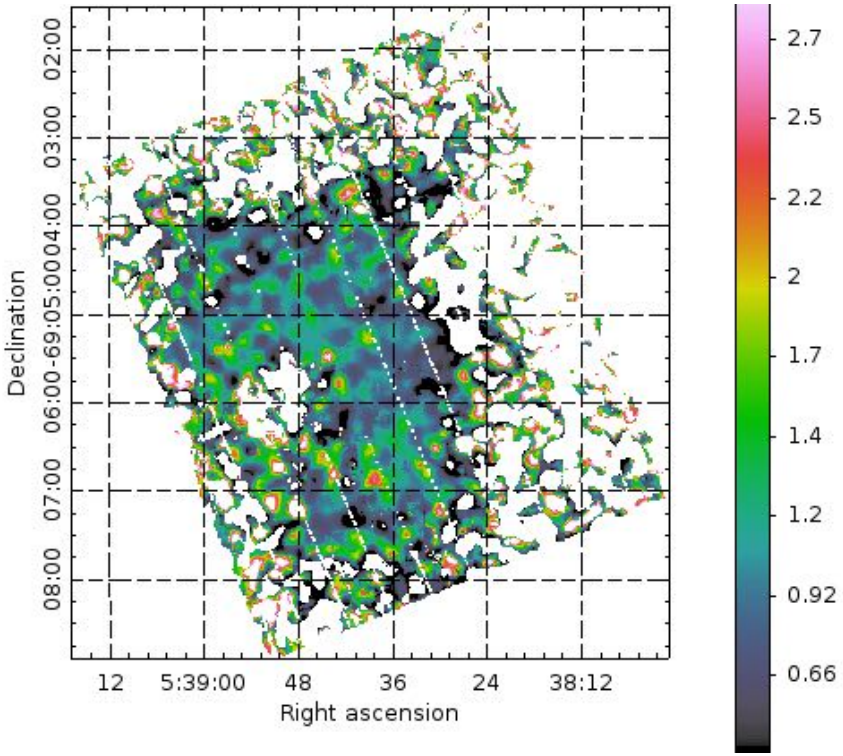
FIFI LS observations: [OI] 63μm

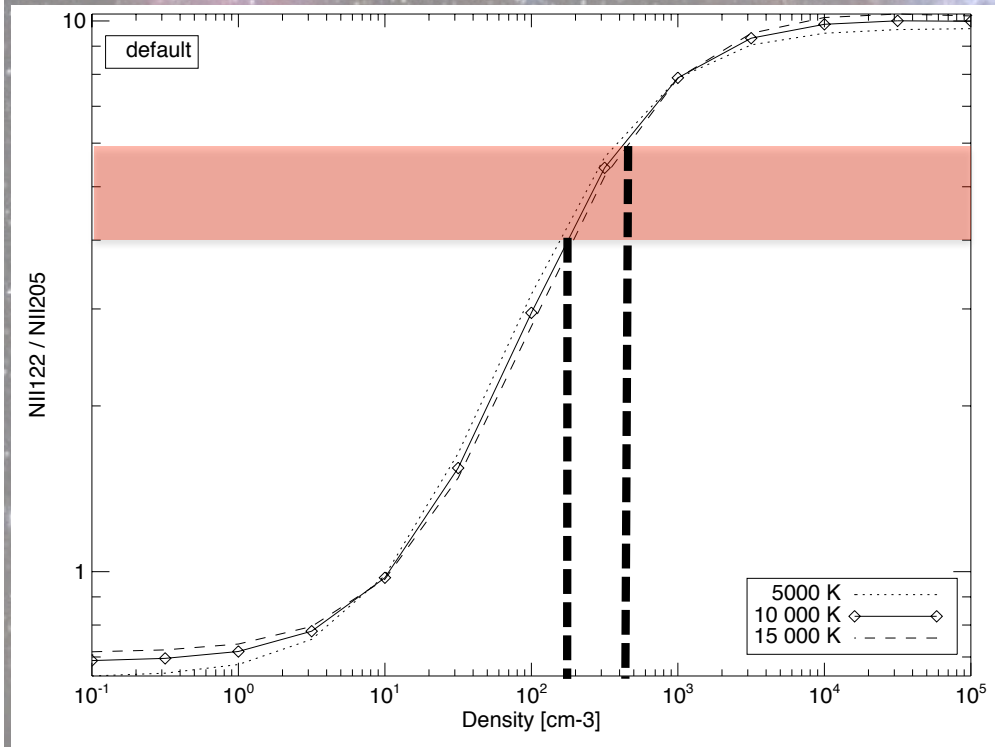


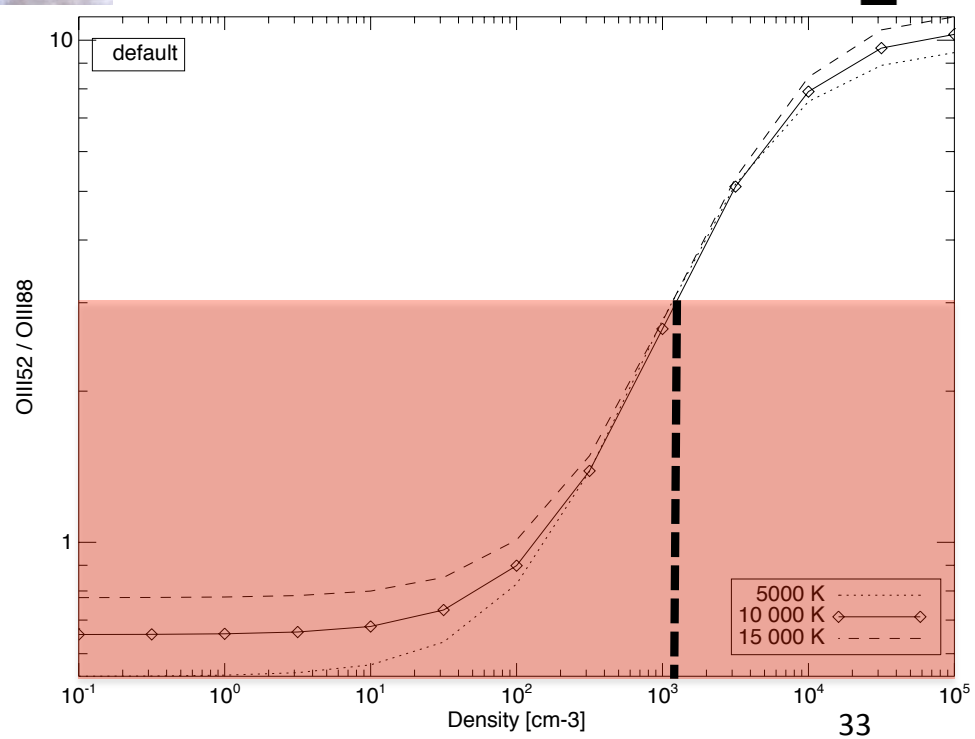
[OI] 63μm (total flux)
Contours: PACS [OI] 63μm intensity

Electronic density

Preliminary results







Current work and perspectives

- Decomposition of FIR (from the ionized gas or from the PDRs)
- PDR model at large scale with the FIFI LS data
- Impact of R136 on large scales (in particular on the CO-dark gas fraction)
- ALMA observations (PI Chevance) of CO(2-1) and (7-6) and [CI] *(0.1pc resolution)*
- Incorporate the ionic MIR lines (Cloudy model).
- Quantify the filling factor of the different phases.
- Other star-forming regions in the LMC and SMC

Current work and perspectives

- Model of the other regions in the Magellanic Clouds and Local Group galaxies.
  - *What are the effects of different excitation conditions and metallicity ?*
  - *What is the effect of mixing different environments in one beam ?*
- Calibration of the tracers of H_2 ([CII], [CI]) for unresolved studies.