Submillimeter and IR Studies of Molecular Regions in the Magellanic Clouds

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Dark Molecular Gas

Stars are formed in dense cold molecular clouds

BUT

in low metallicity systems it is not easy to determine the amount of molecular gas

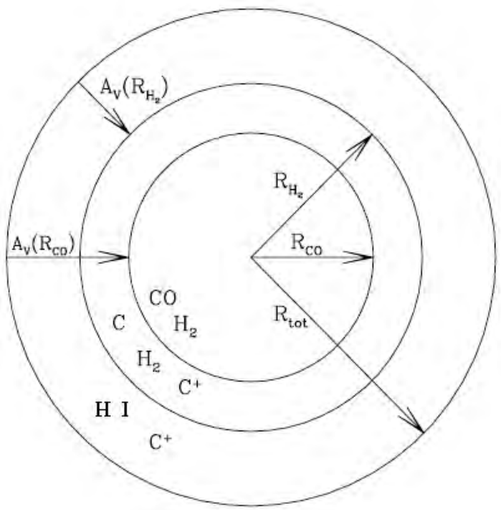
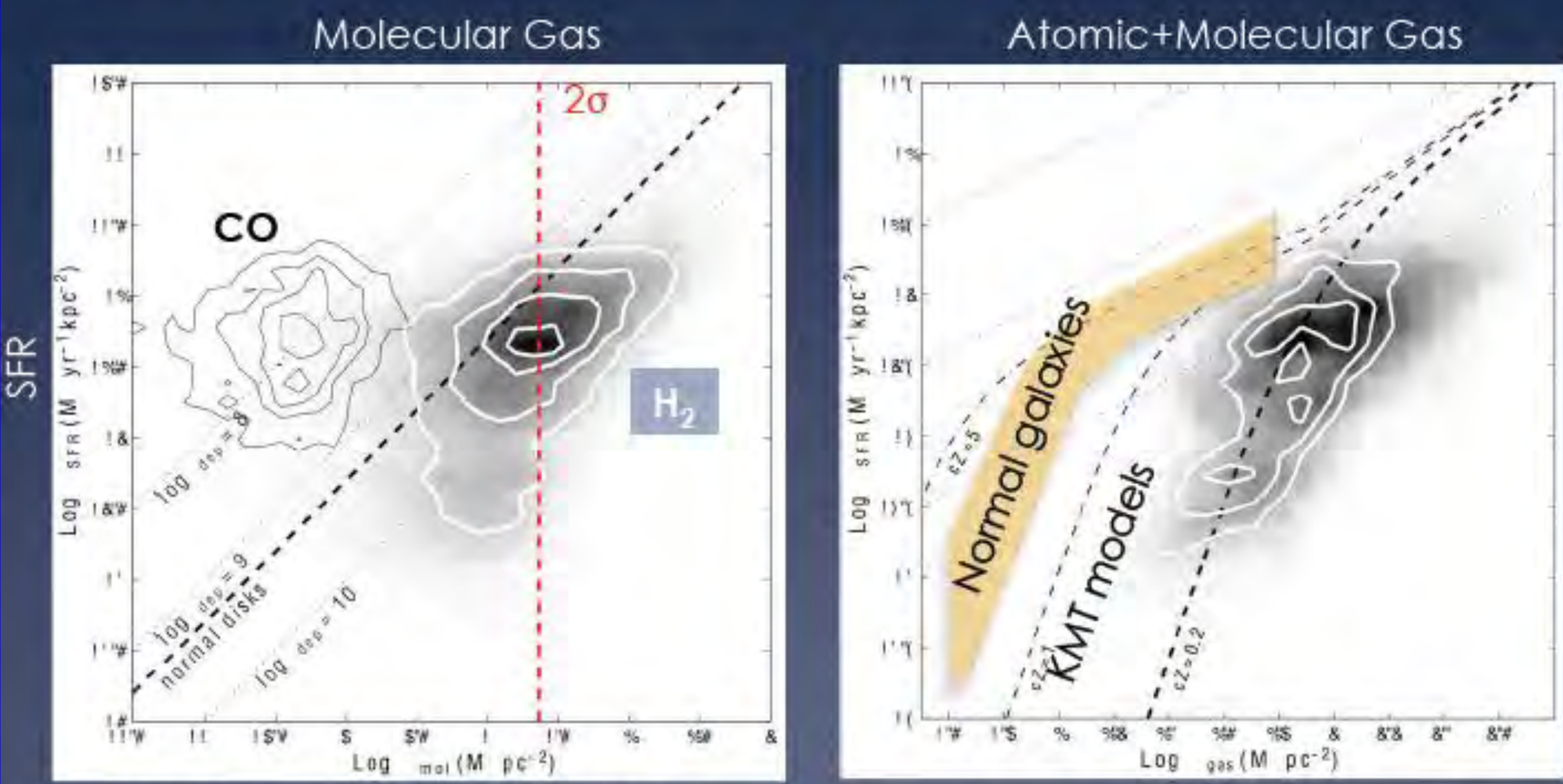


Fig. 1.—Illustration of a model cloud showing the radius R_{CO} of the CO core, the radius R_{H_2} where $2n_{H_2} = n_{HI}$ (equal mass density in H atoms and H_2 molecules), and R_{tot} the total cloud radius. Within $R < R_{CO}$, gas is mainly CO and H_2. Within the range $R_{CO} < R < R_{H_2}$, gas is mainly H_2 whereas the gas phase carbon is mainly C and C^+. Within the range $R_{H_2} < R < R_{tot}$ gas is mainly H I whereas the gas phase carbon is mainly C^+. $A_V(R_{H_2})$ is the optical depth measured from the outer radius to R_{H_2} and $A_V(R_{CO})$ is the optical depth

Wolfire, Hollenbach, McKee 2010

Star formation rate depends on the total gas mass (HI+H2) but recent results show that SFR depends mainly on the amount of H2. (Leroy, et al , Bolatto et al, Genzel et al,)

Relations for H_2 and total gas



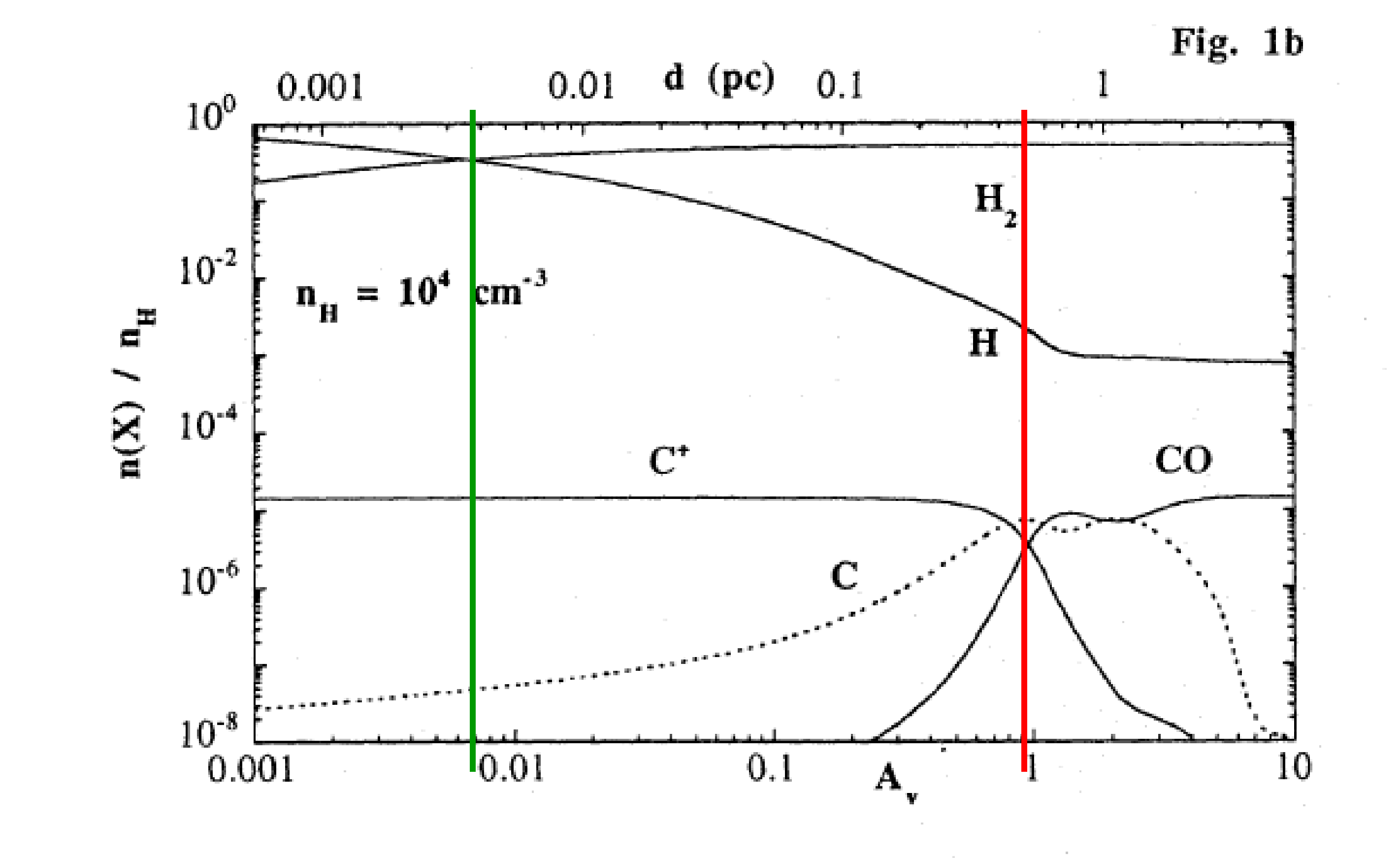
- The SMC is "normal" in H_2 vs. SFR
- The SMC is vastly underperforming in total gas vs. SFR
  - Similar problem at high-z, see Wolfe & Chen (2006)
- Krumholz et al. (2009, KMT) models with HI→H_2 set by PDR balance fit the data

How can we measure H_2

- CO observations , X=N(H2))/ICO
- Virial mass determination
- Emission from dust

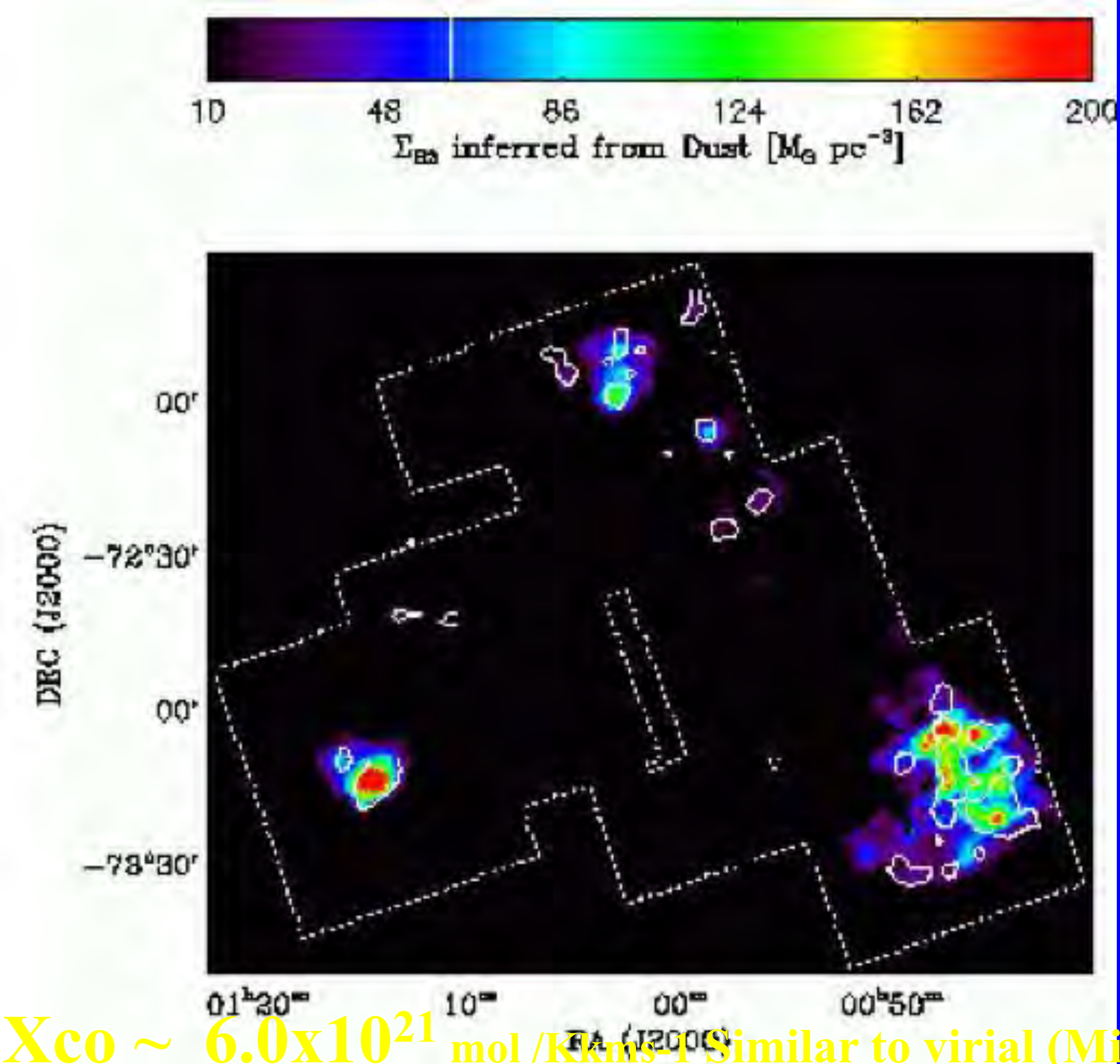
In low metallicty systems , i.e, SMC and LMC it is well known that CO does not trace the total H_2 dark gas.

CO is less abundant and the lower gas/dust ratio implies that CO photodissociated (Rubio, et al 93, Maloney and Black 98)



Abundances of several molecules and ions on a plane parallel uniform molecular cloud model ilumnated from one side by a UV field =10 UV_gal, Z=0.1Zo (Lequeux et al 94)

Combining the 160 mu , Hi and CO, finds that H2 must be Much extended than CO (Leroy et al 2007, Bolatto et al, Leroy et al 2010



- From Spitzer/MIPS

data combined with HI ->Σ_{H2}

- But FIR emission

sensitive to T_{dust}

Derived N(H2) is more extended by a of ~ 30%

Xco ~ 6.0x10^{21} mol /Kkms-1 Similar to virial (Mizuno et al. 08)Twice determination from SEST studies (Rubio et al 93, Bolatto et al .03)

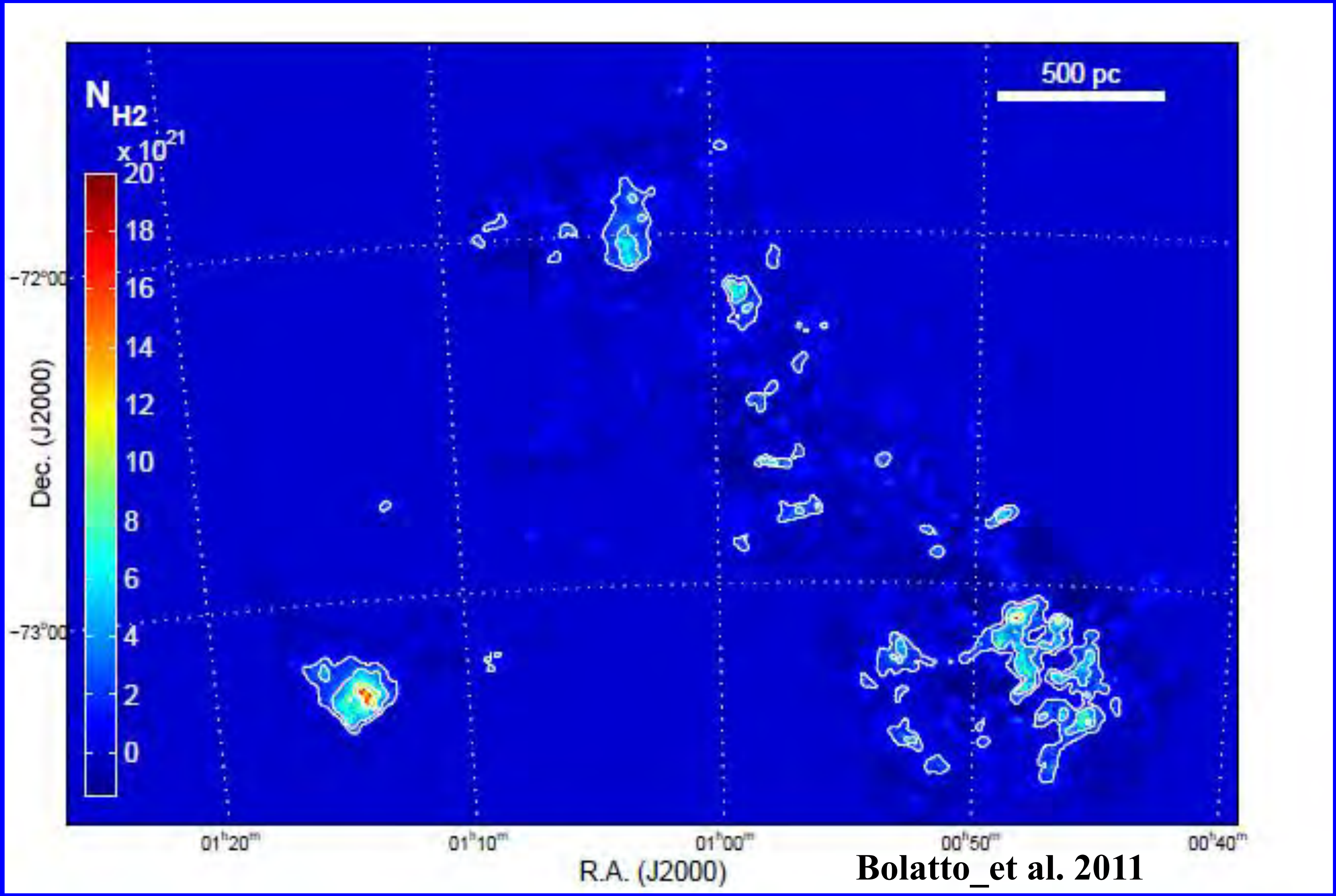


FIG. 1.— *(Top)* H_2 column density map at $\sim$ 12 pc resolution. This map is obtained from modeling the *Spitzer* dust continuum observations from S^{3}MC/SAGE-SMC (Bolatto et al. 2007; Gordon et al. 2011) together with the combined ATCA/Parkes 21 cm H I map (Stanimirović et al. 1999). The colorbar inset indicates the values for the color scale, in units of 10^{21} cm^{-2}. The N_{H2} contours are placed at $N_{H2} \approx 1.4, 3.4, 8$, and 12×10^{21} cm^{-2}, equivalent to deprojected molecular surface densities $\Sigma_{mol} \approx 23, 56, 130$, and $200\ M_\odot$ pc^{-2} when

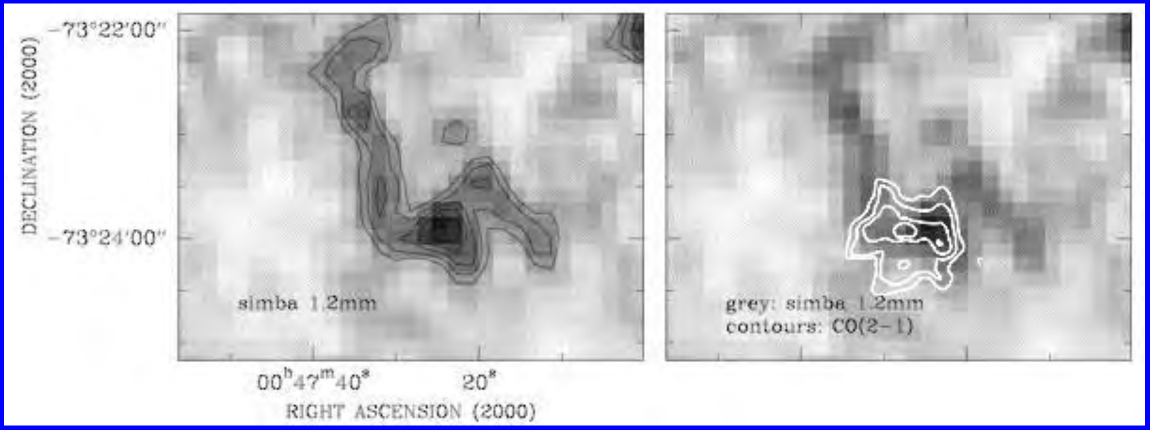
Submillimeter and FIR studies of the dust emssion provide an alternative way to measure the dark molecular mass

- 1.2 mm SIMBA bolometer @ SEST
- SPITZER 3.6, 4.5, 5.8, 8.0, 24, 70, 160 μm
- 0.850 mm LABOCA bolometer @APEX
- Herschel, 160,250, 300, 500 μm

Assuming a universal opacity of dust grains and knowing the gas-to-dust ratio I_{mm} -> $N(H_2)$

BUT

Mass estimates based on 1.2mm (SIMBAS@SEST) and 0.8mm (LABOCA@APEX) give larger masses than those obtained from virial mass assuming gravitationally bound molecular clouds for SMC molecular regions studied.



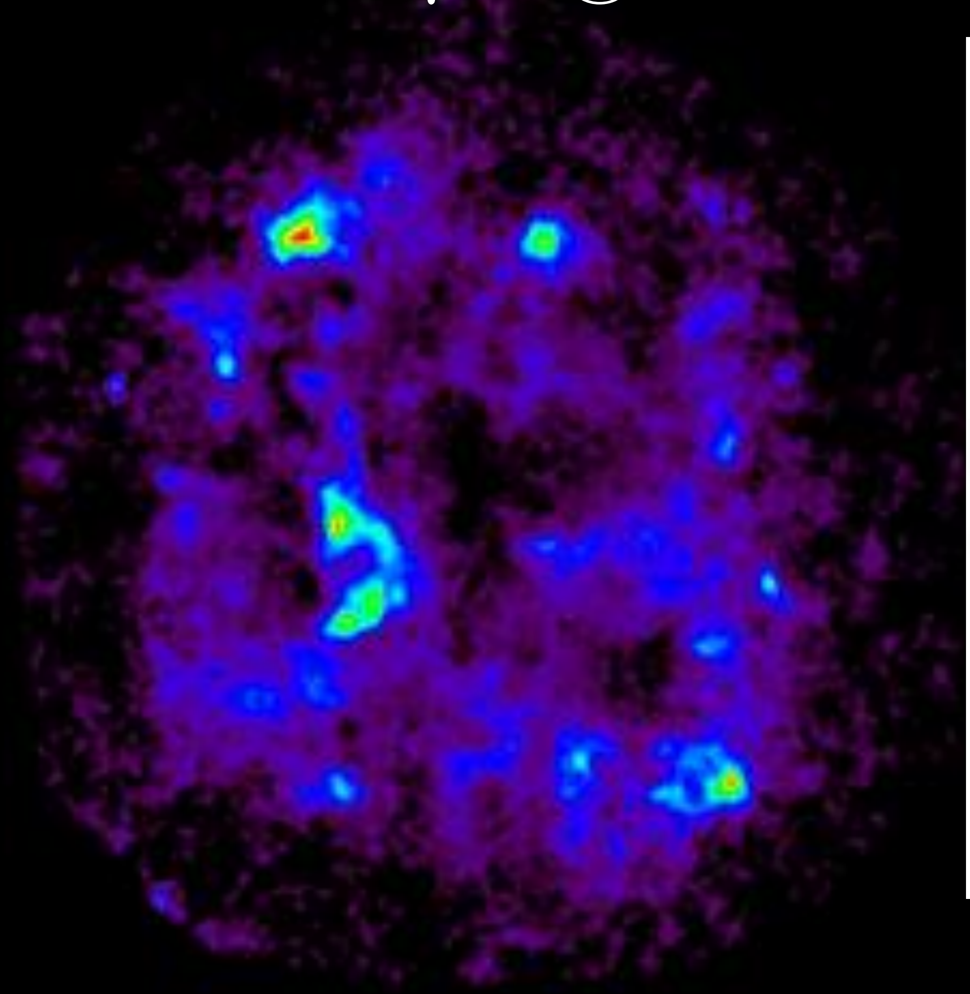
- first result for an quiescent cloud in SMC (**Rubio et al. 2004)**

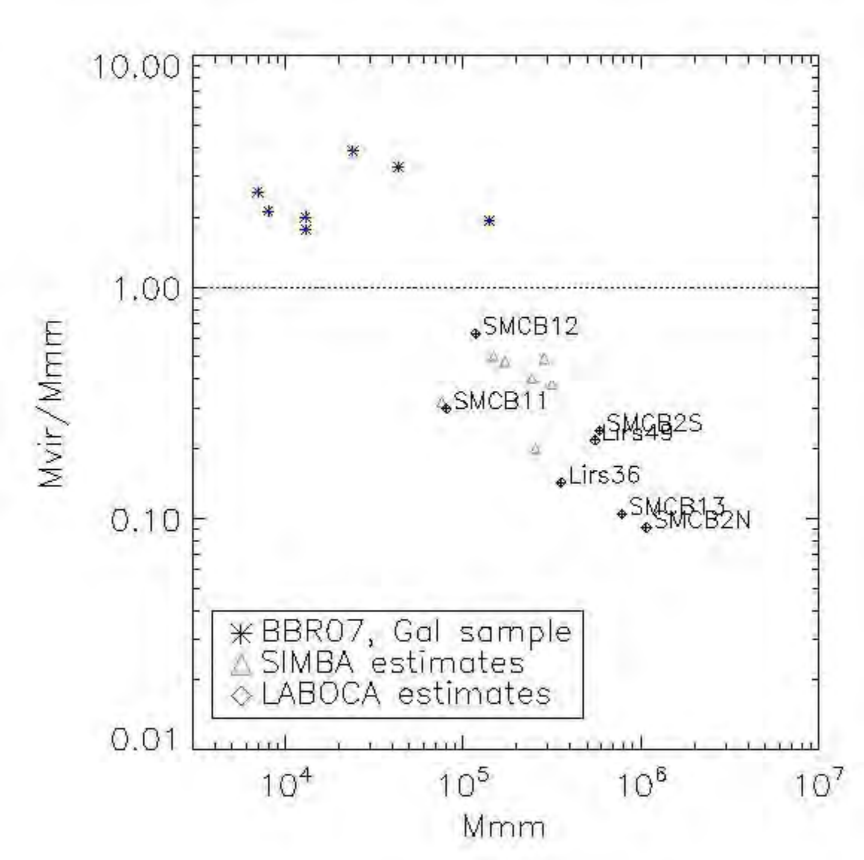
SMCB1#1, SIMBA 1.2mm.

- **$M_{mm} > 10\ M_{vir}$**

Laboca/APEX SMC observations

870μm @ SMC- SW region



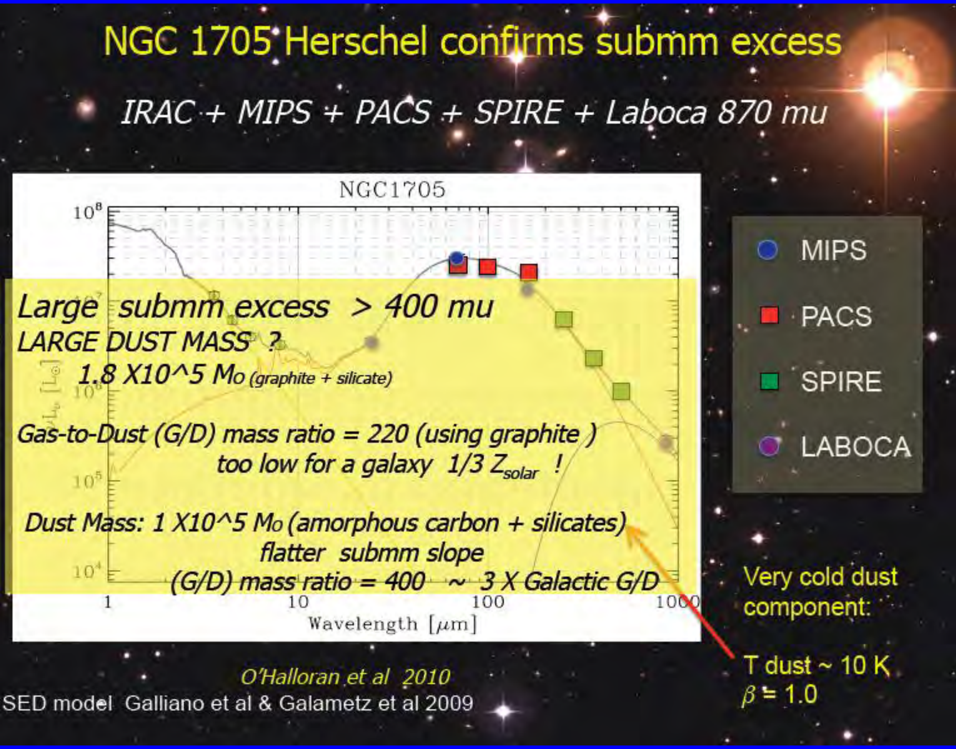


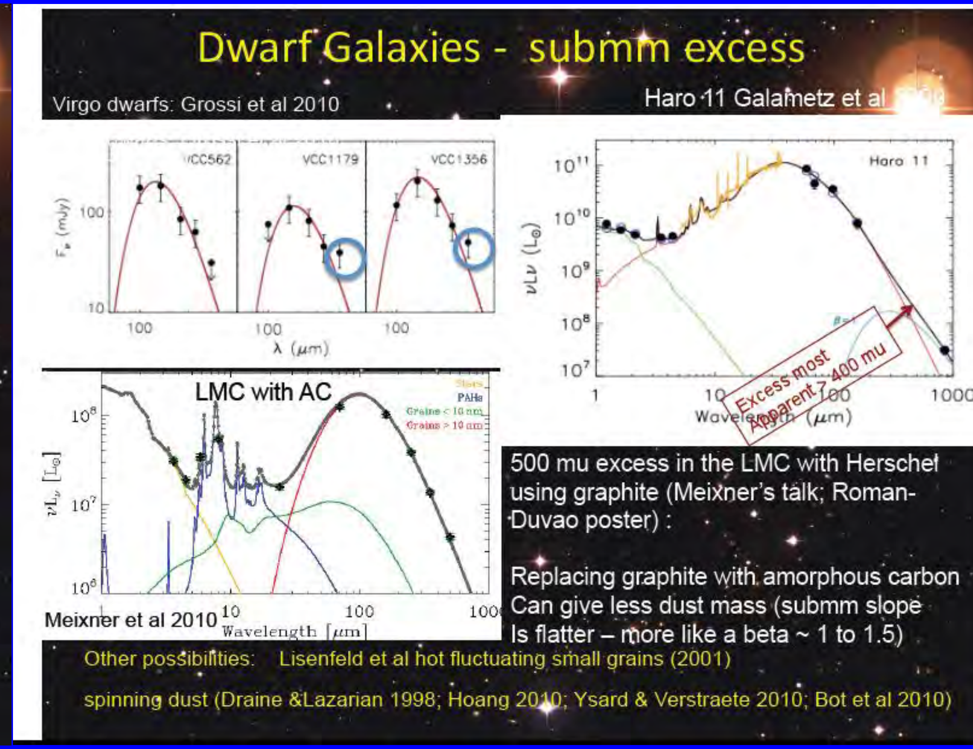
Bot et al. 2007, 2010

Submillimeter excess

(seen also in dwarf galaxies)

Madden et al , Galametz et al 2011





In the SMC, Plank 500 mu shows an emission excess but it seems that it is not sufficient to explain the difference in mass .

We explore regions in the Magellanic System

LMC, SMC and Magellanic Bridge

Sample low metallicity systems

Zlmc = 0.5, Zsmc = 0.1 and Zmb Zsmc

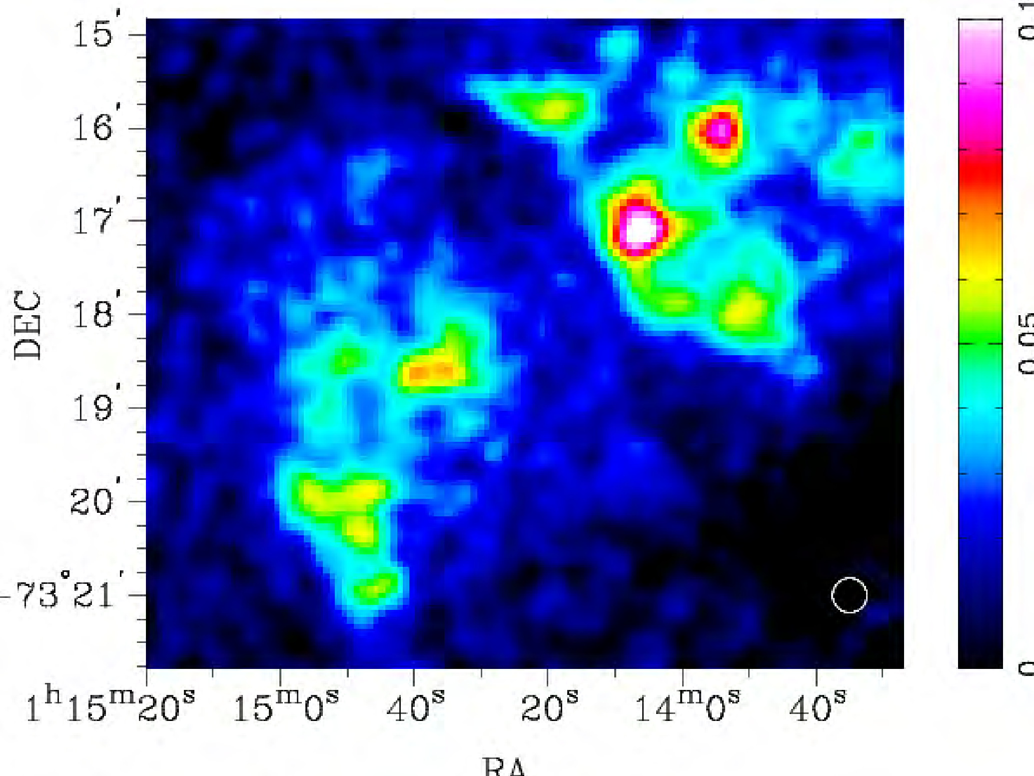
Observations 870 µm observations where held at the APEX telescope in Llano Chajnantor, Atacama, Chile, with the LABOCA bolometer on August and October 2010 with a pwv between 0.2 and 0.9 mm, resulting in ~10'x10' dust continuum maps for several regions in the SMC, LMC and Magellanic Brigde. As these are weak and extended sources, the reduction in BoA was done in an iterative process using a signal-to-noise mask.

Celia Verdugo
MSc Student
DAS, UCHILE

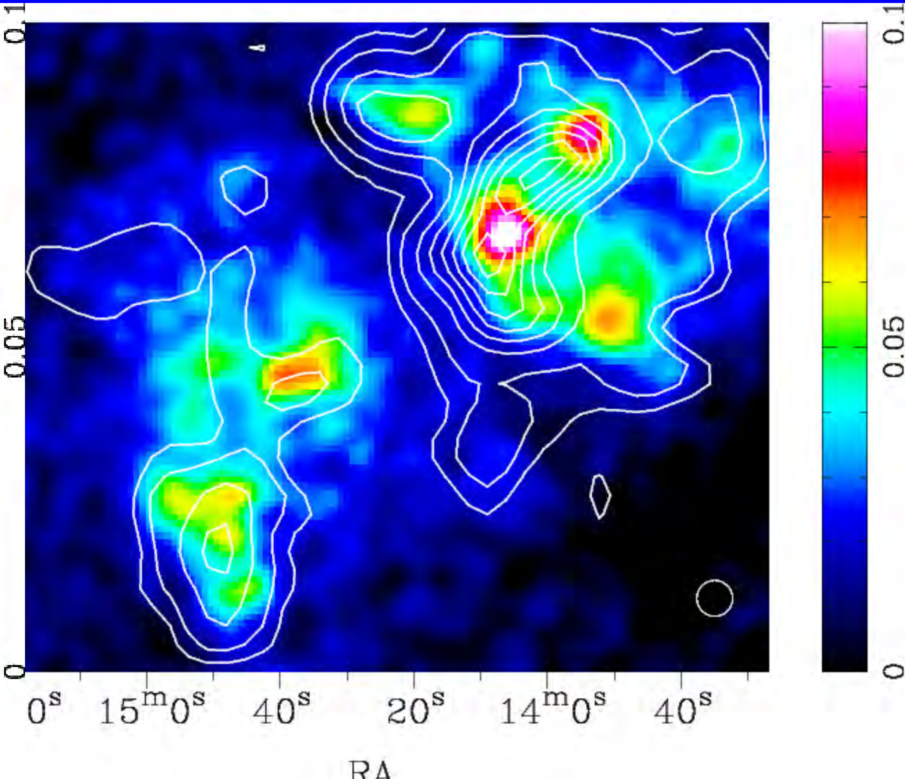
Before

Cinthya Herrera and Viviana Guzman

N83-N84 in the SMC



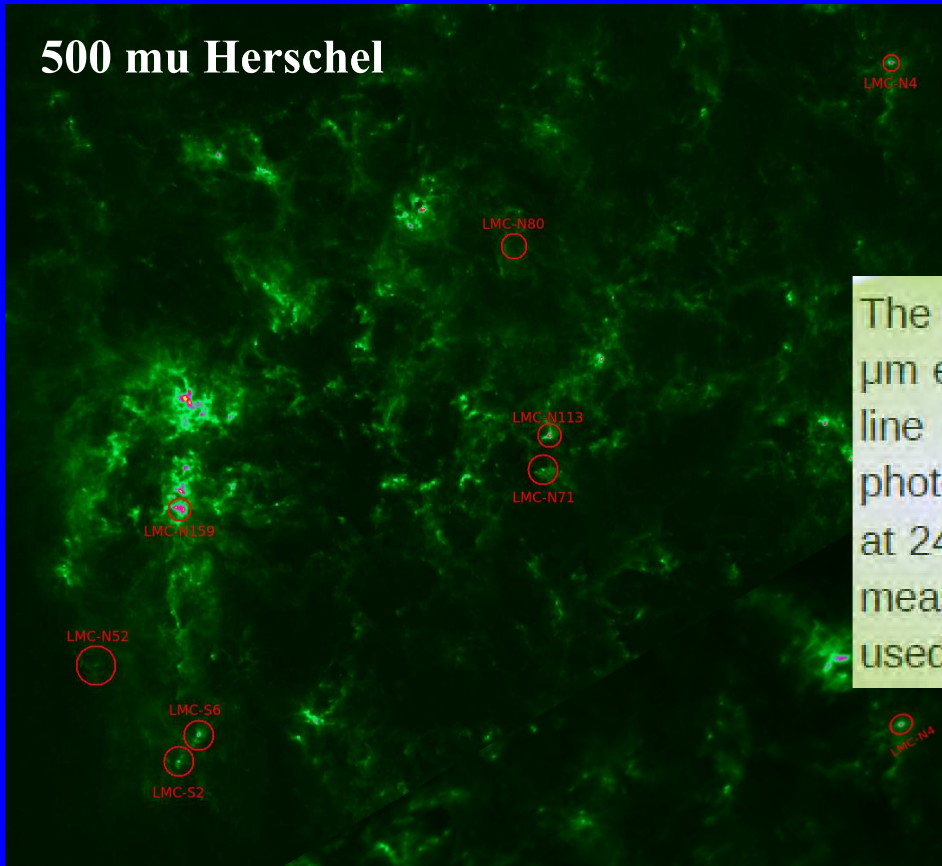
LABOCA image



LABOCA image with CO(2-1) contours

Cloud	M_d 10^2 $M_\odot$	M_g 10^4 $M_\odot$	M_V 10^4 $M_\odot$	$f = \frac{M_g}{M_V}$
1	3.4	19.4	5.4	3.6
2	17.3	98.8	71.1	1.4
3	2.77	15.8	27.1	0.6
4	5.46	31.2	11.1	2.9
5	17.4	10.0	38.2	0.3

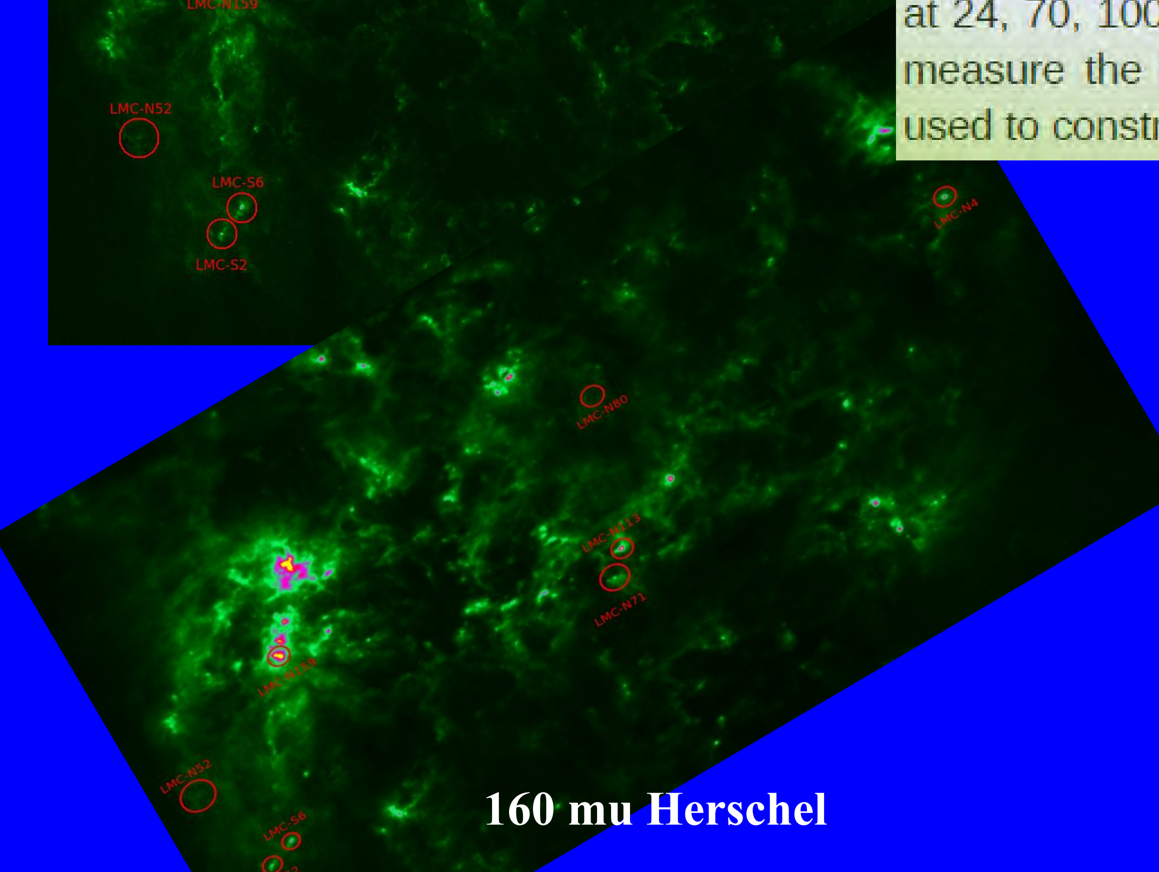
Guzman et al. In prep



LMC regions

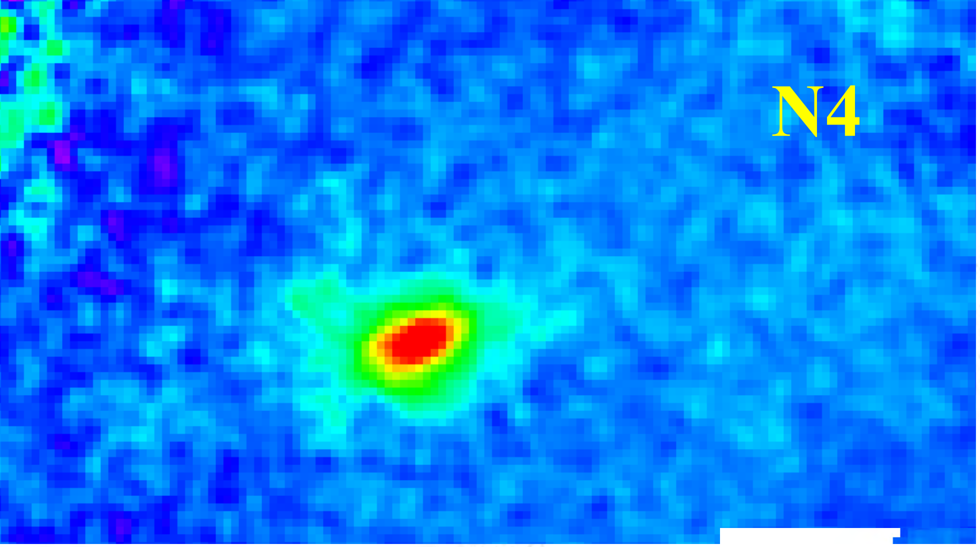
Preliminary results

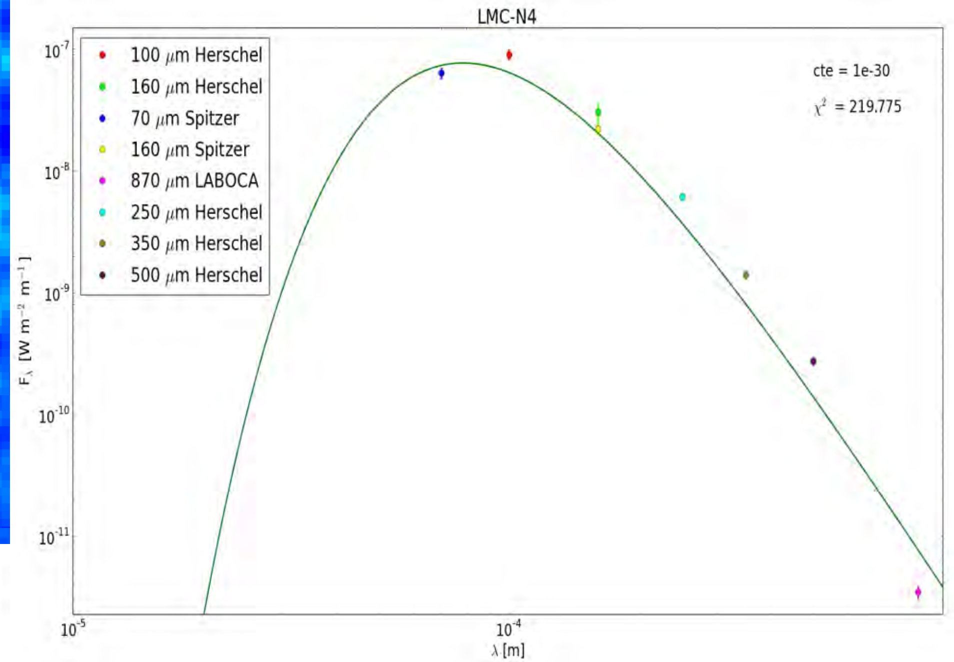
The dust emission was obtained measuring the 870 μm emission and subtracting the free-free and CO line contributions at this wavelength. Aperture photometry was done to each cloud in the sample at 24, 70, 100, 160, 250, 350, 500 and 870 μm, to measure the flux density at each wavelength and used to construct the SED for each cloud.

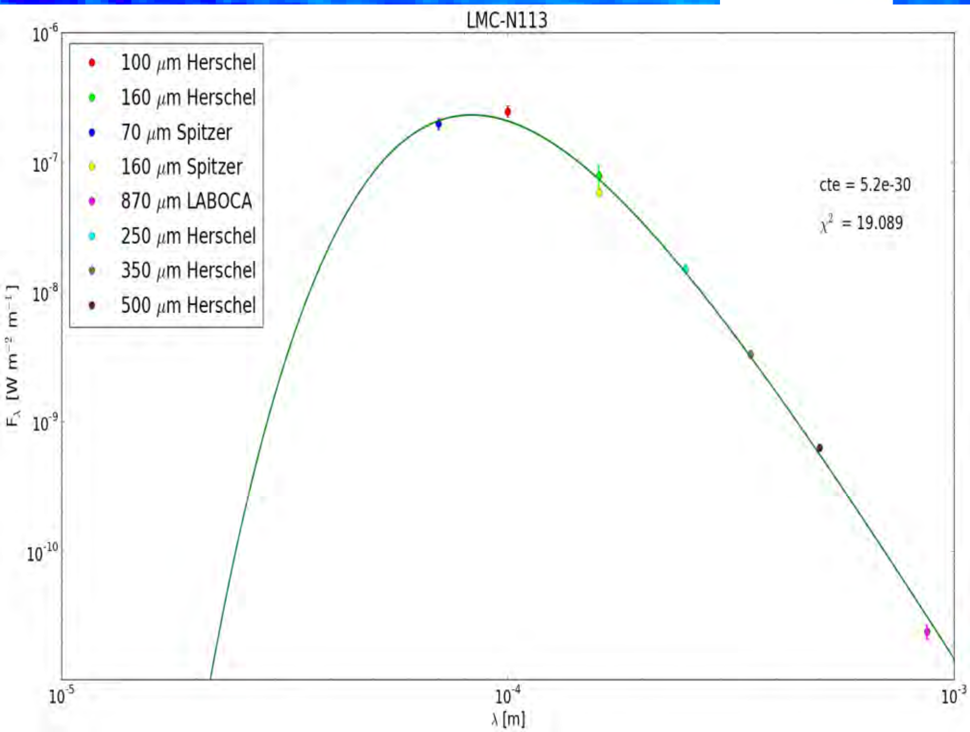


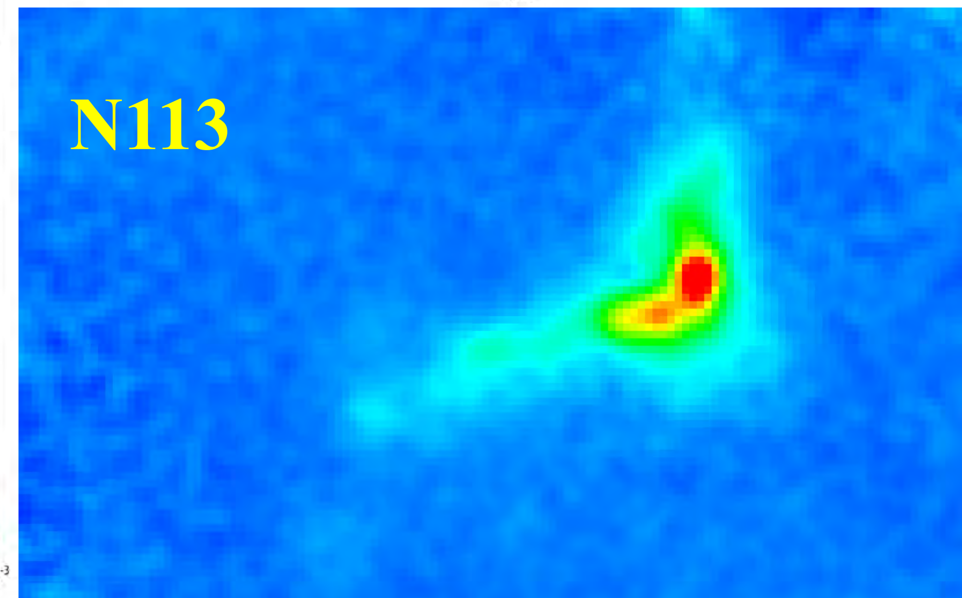
$$n_d = \frac{cte \cdot \nu_0^{\beta}}{\Omega \cdot \kappa_{\nu 0}} \qquad x_d = \frac{n_d}{\mu m_H N_H}$$

$$M_d = \frac{S_\nu D^2}{\kappa_d B_\nu(T)} \qquad M_g = \frac{M_d}{x_d}$$

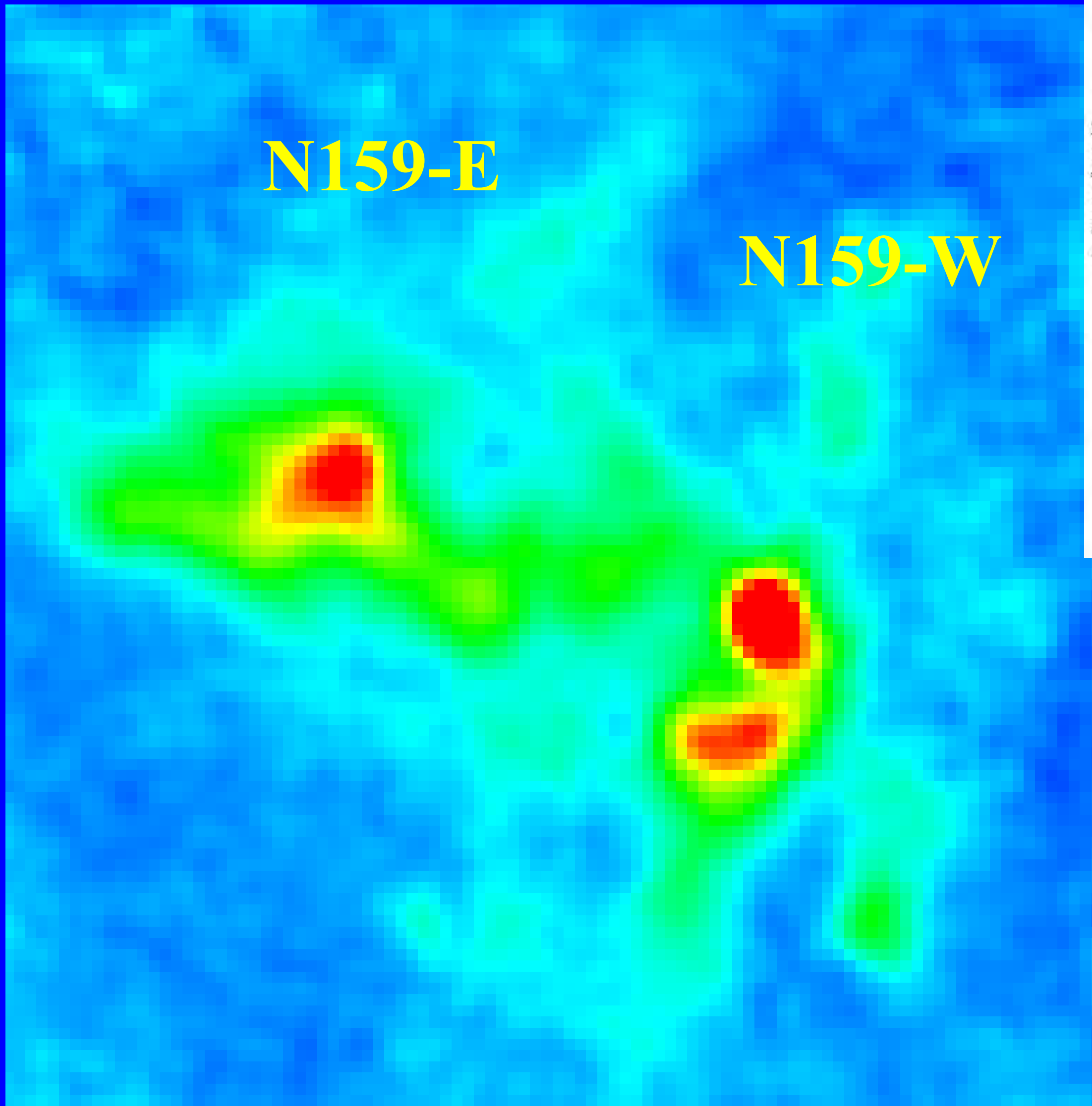


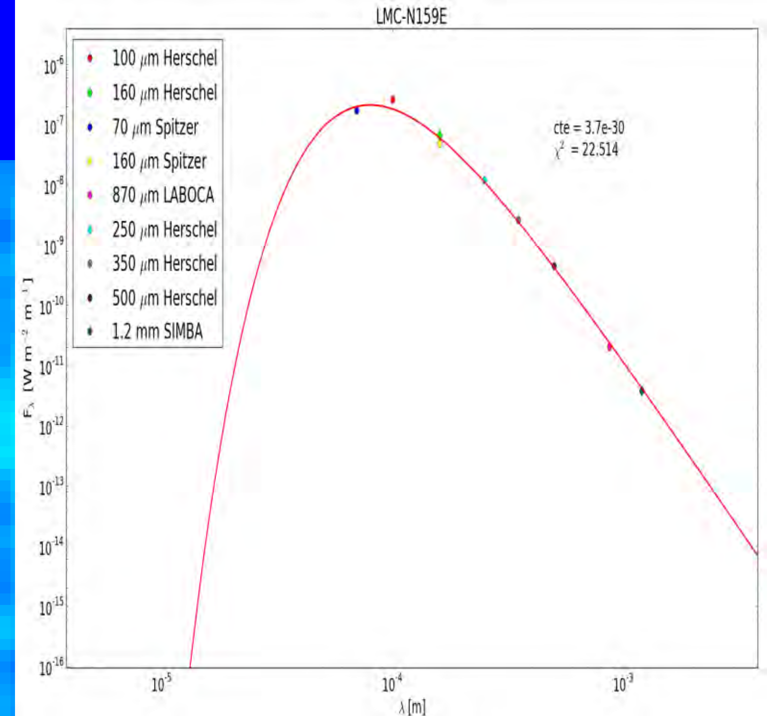


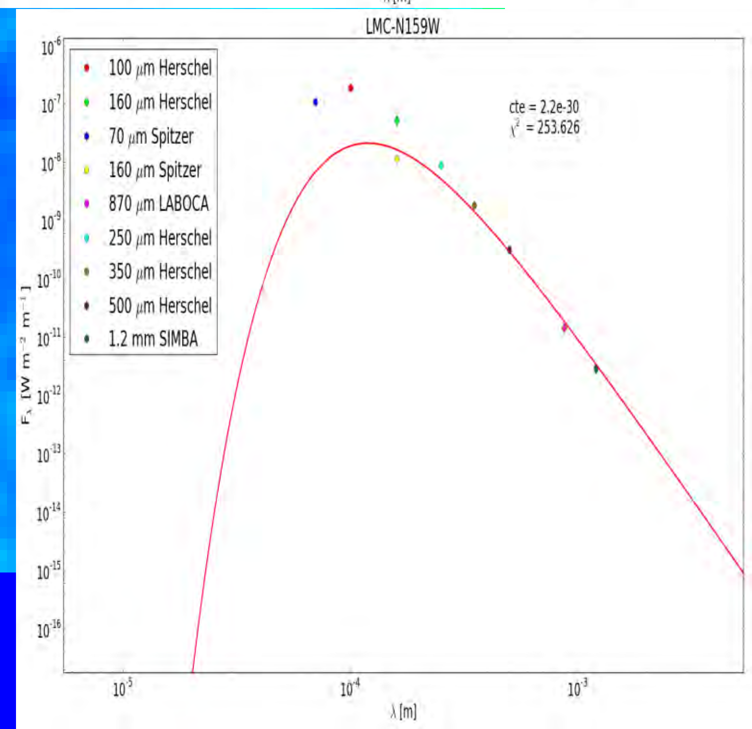




A simple modified blackbody law $S_\lambda = cte \cdot (c/\lambda)^\beta \cdot B_\lambda(T)$ was fitted to the SED's with cte, β (spectral emissivity index) and temperature T as free parameters. As example, results for 4 of the sources in the sample are shown.


N159-E
N159-W

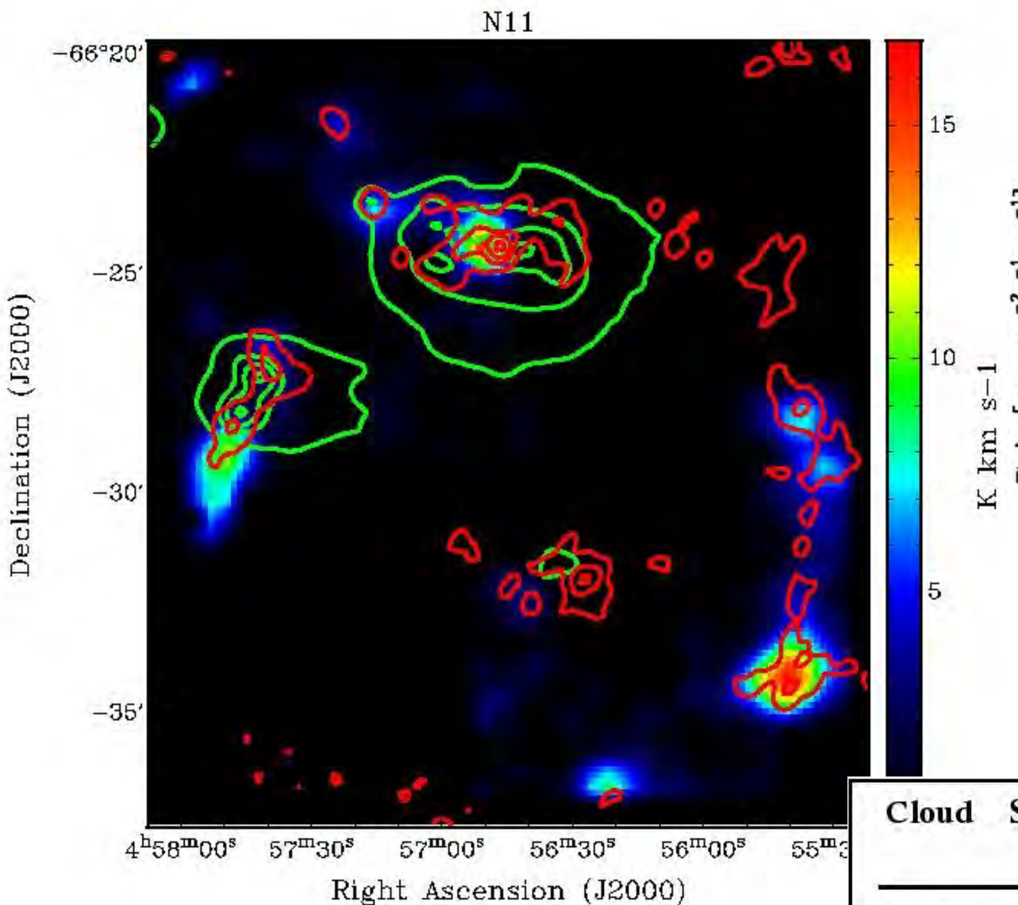

LMC-N159E
100 μm Herschel
160 μm Herschel
70 μm Spitzer
160 μm Spitzer
870 μm LABOCA
250 μm Herschel
350 μm Herschel
500 μm Herschel
1.2 mm SIMBA
cte = 3.7e-30
χ² = 22.514
F_λ [W m⁻² m⁻¹]
λ [m]


LMC-N159W
100 μm Herschel
160 μm Herschel
70 μm Spitzer
160 μm Spitzer
870 μm LABOCA
250 μm Herschel
350 μm Herschel
500 μm Herschel
1.2 mm SIMBA
cte = 2.2e-30
χ² = 253.626
F_λ [W m⁻² m⁻¹]
λ [m]

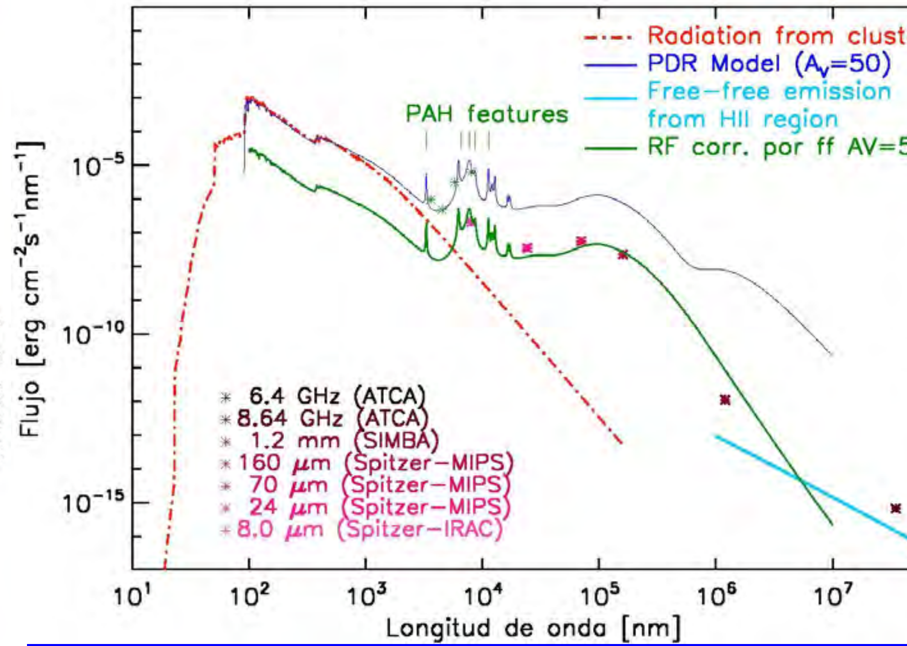
Source	T_d [K]	β	n_d [gr cm^2]	x_d	M_d [M_{sun}]	M_g [M_{sun}]	M_{vir} [M_{sun}]
N113	24	1.94	$8.61 \cdot 10^{-5}$	$3.78 \cdot 10^{-3}$	$8.69 \cdot 10^{2}$	$2.29 \cdot 10^{5}$	10^{5} (4)
N4	24	1.98	$7.98 \cdot 10^{-5}$	$3.5 \cdot 10^{-3}$	$1.19 \cdot 10^{2}$	$3.4 \cdot 10^{4}$	$3 \cdot 10^{4}$ (5)
N159	26	1.90	$5.11 \cdot 10^{-5}$	$2.24 \cdot 10^{-3}$	$1.465 \cdot 10^{3}$	$6.54 \cdot 10^{5}$	$1.37 \cdot 10^{5}$ (6)

Preliminary results: Flux densities obtained from the photometry and temperatures from the fitting procedure are listed in the table. Using a distance to the LMC of 50 kpc, a dust absorption coefficient of $\kappa_{870\mu m}$ = 1.26 [cm^2 gr^{-1}] (Bot et al. 2010) and a dust-to-gas ratio of $5 \cdot 10^{-3}$ according to the low metallicity of the LMC (~0.5 Z_{sun}) (Dufour et al 1984) gas masses (M_{mm}) are calculated and compared with virial masses (M_{vir}) from the literature, calculated as $M_{vir} = 210 \cdot \Delta V^2$[km/s]$\cdot$R[pc] (McLaren et al. 1988). For N113 and N159W M_{mm} is larger than the M_{vir} in a factor ~2, and for N159E this factor is only ~1. For N4 we get $M_{vir} > M_{mm}$, so except for this source these LMC clouds follow a similar behavior as observed in the SMC (Bot et al. 2010). Future work would confirm this preliminary result.

N11



PDR modelling



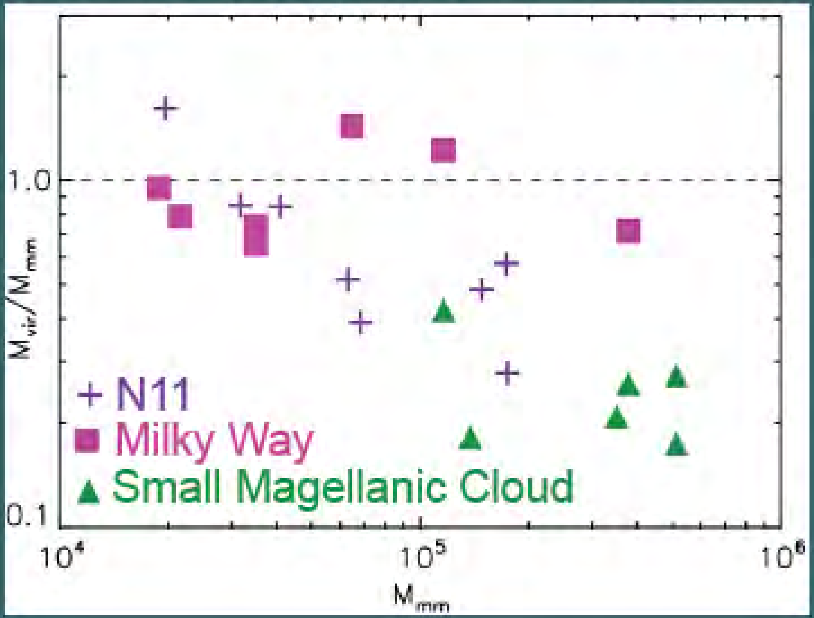
Cloud	$S_\nu^{1.2mm}$	S_ν^{ff}	$S_\nu^{CO(2-1)}$	S_ν^{dust}	M_{ICO}	M_{Vir}	M_{mm}	M_{mm}/M_{Vi}
	mJy	mJy	mJy	mJy	$10^3\ M_\odot$	$10^3\ M_\odot$	$10^3\ M_\odot$	
1d	286	110	7	168	38	85	204	2.4
1g	337	91	1.5	244	7.7	35.5	296	8.3
1o	76	6	1	69	4.9	26.4	84.3	3.2
1p	108	97	0.1	11	11.2	82.3	2.9	0.2
2a	80	6	2	72	11.8	53.7	86.8	1.6
2c	360	27	11	322	66.8	188	391	2.1
2d	116	10	2	103	12.4	38.2	125	3.3
2h	285	20	5	266	28.7	254	317	1.2
3a	53	9	0.4	43	24.6	36.6	52.7	1.4

1.2mm continuum image (SIMBA@SEST

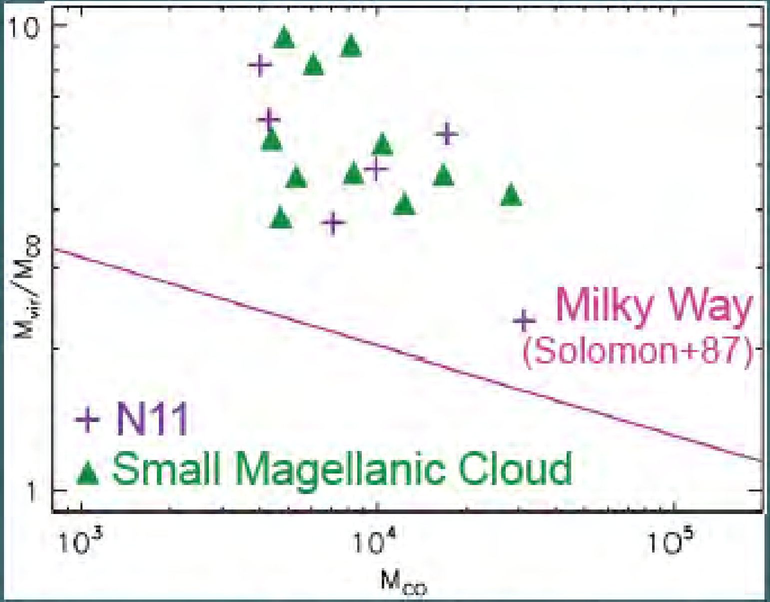
Herrera, et. al. in prep

N11

M_{vir}-M_{mm} comparison for molecular clouds in the Milky Way and in the SMC (Bot+07), and in N11. Though the ISM in the LMC has low metallicity as in the SMC, there is no important difference between the molecular clouds in N11 and in the Galaxy.



For all the clouds in N11: M_{CO} < M_{vir}



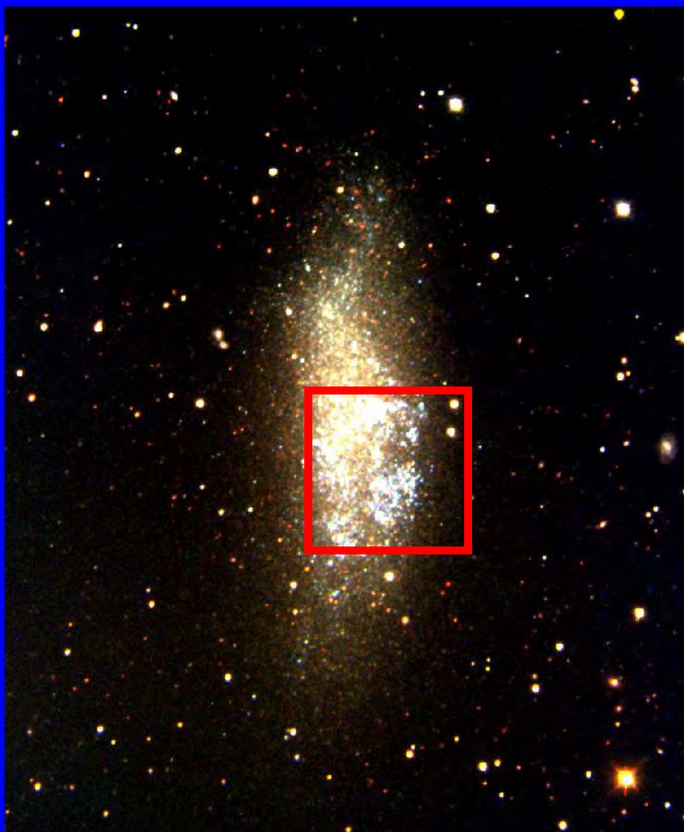
The low value for the luminous mass can be explained by CO photodissociation. In a low metallicity environment, the UV radiation field destroys the CO molecule leaving the H_2, which selfshields, and no CO outside dense gas.

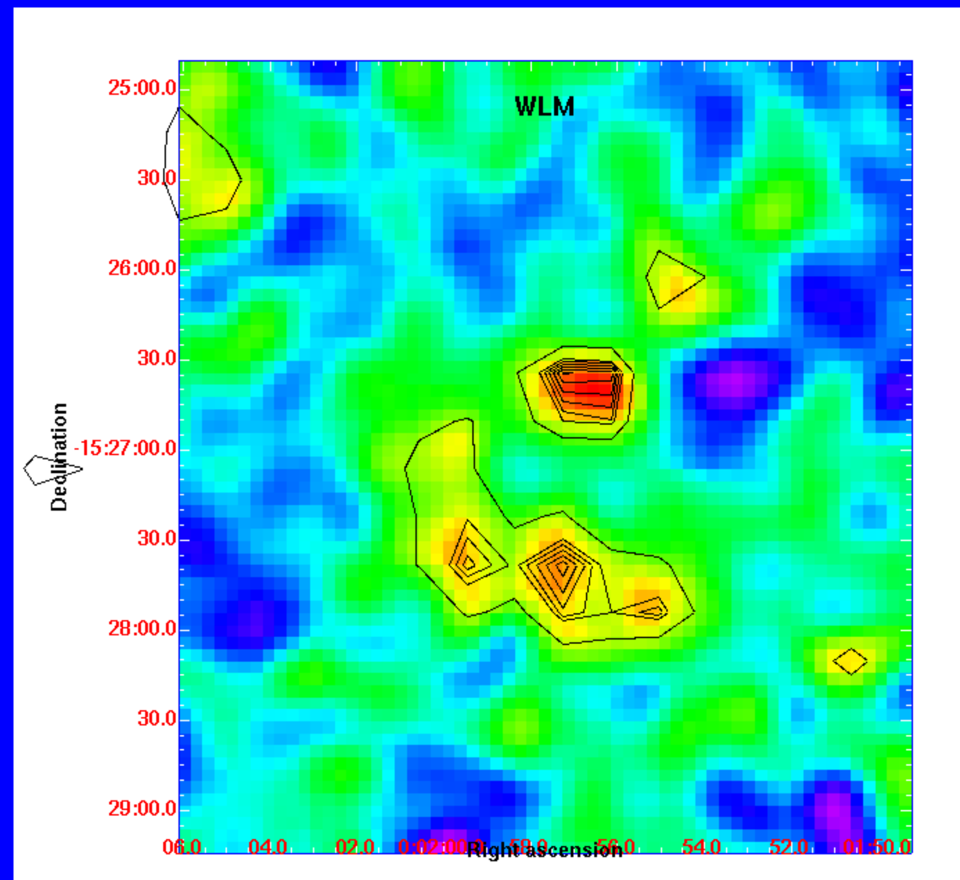
Could Dark molecular gas become " visible"?

- Observations of low Z galaxies is extremely expensive in telescope time and in general these galaxies have not been detected in CO.

- The nearest galaxies after SMC and LMC are ten times further away and we have been able to observe in CO (@10pc resolution) and continuum only a dozen of molecular cloud region in the Magellanic Clouds

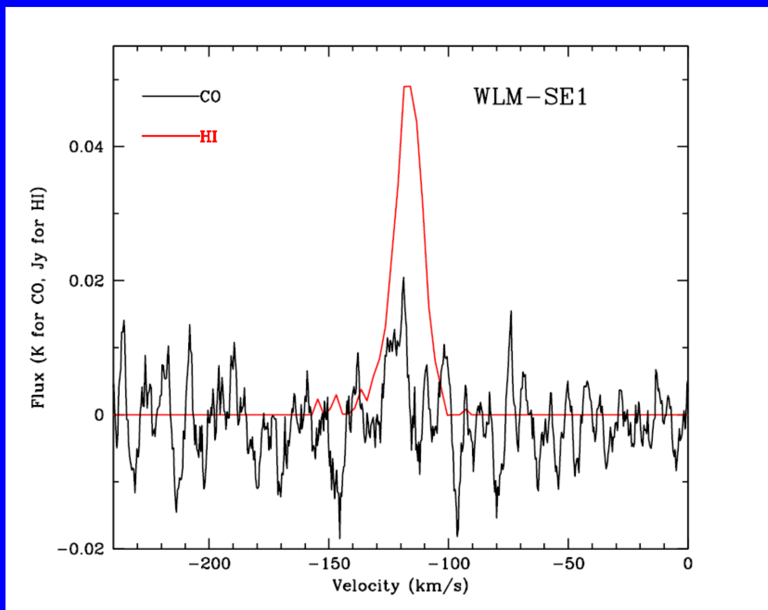
The possible detection of CO and 870 mu continumm emission in WLM : a dwarf Galaxy with lower Z than the SMC.

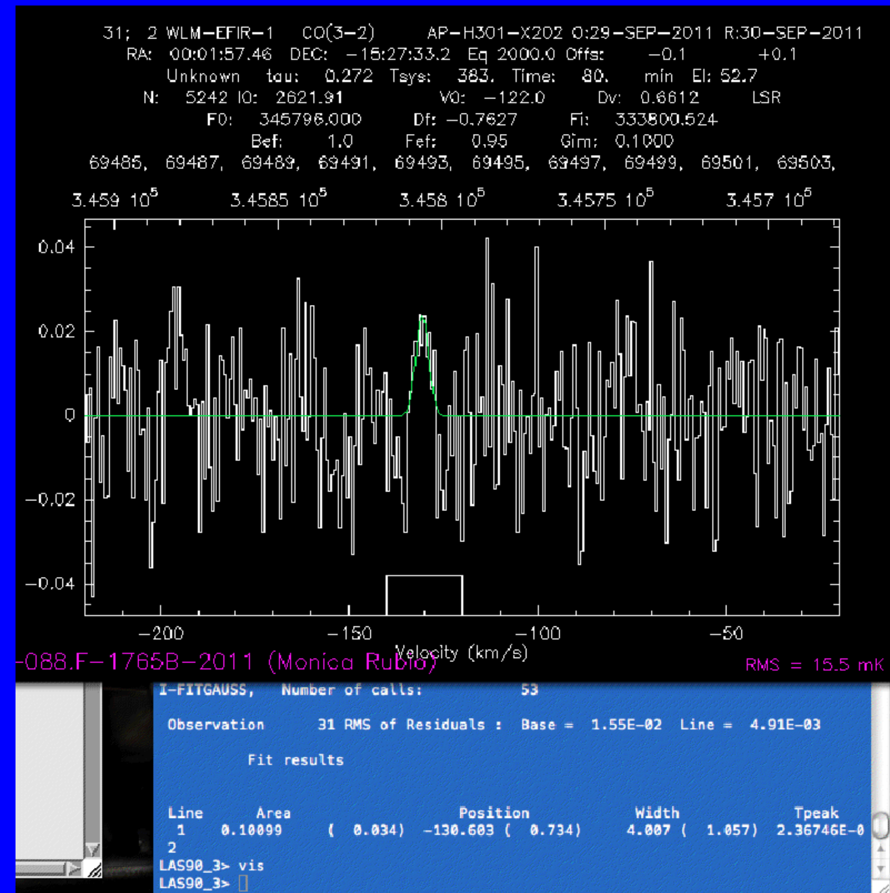




LABOCA 870 mu continumm emission in WLM

Collaboratiors: D. Hunter, E Brinks, B. Elmegreen





T_{mb}= 0.05 K +- 0.03K

=> M=5+-2 10^6 Mo

T_{mb}= 0.024 K +- 0.02K

=> M= 3+-2 10^6 Mo

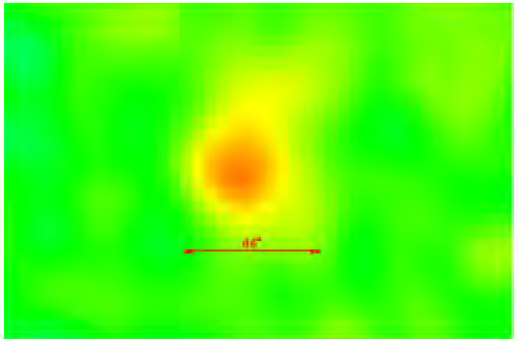
To study the Dark molecular gas in low metallicity systems and thus understand the Star formation in primeval dustless galaxies

ALMA

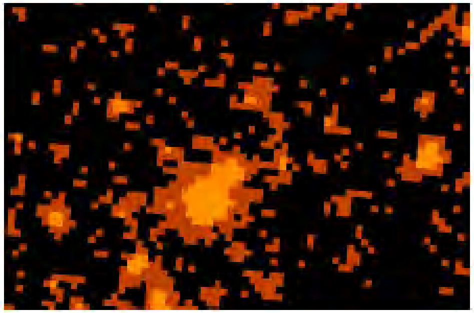
CCAT PROJECT
@
Cerro CHAJNANTOR

THANKS

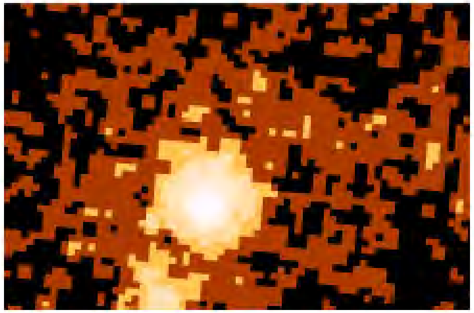
Magellanic Bridge – Source A



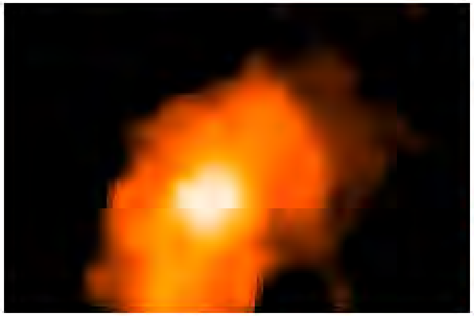
(a) 870μm



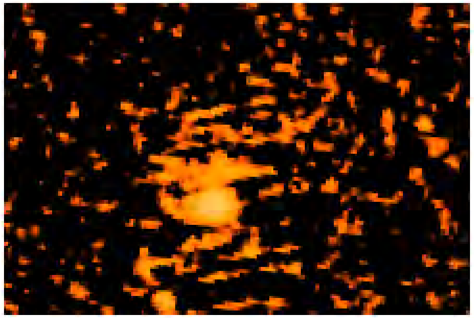
(b) 24μm



(c) 70μm



(d) 160μm MIPS



(e) 160μm PACS

Collaborators

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Viviana Guzman now at DEMIRM

Elisa Carrillo now at Bonn

Klaus Rubke now at IAC

Celia Verdugo at DAS

Fukui & Nanten Group

Laboca/APEX LMC maps

30 Doradus

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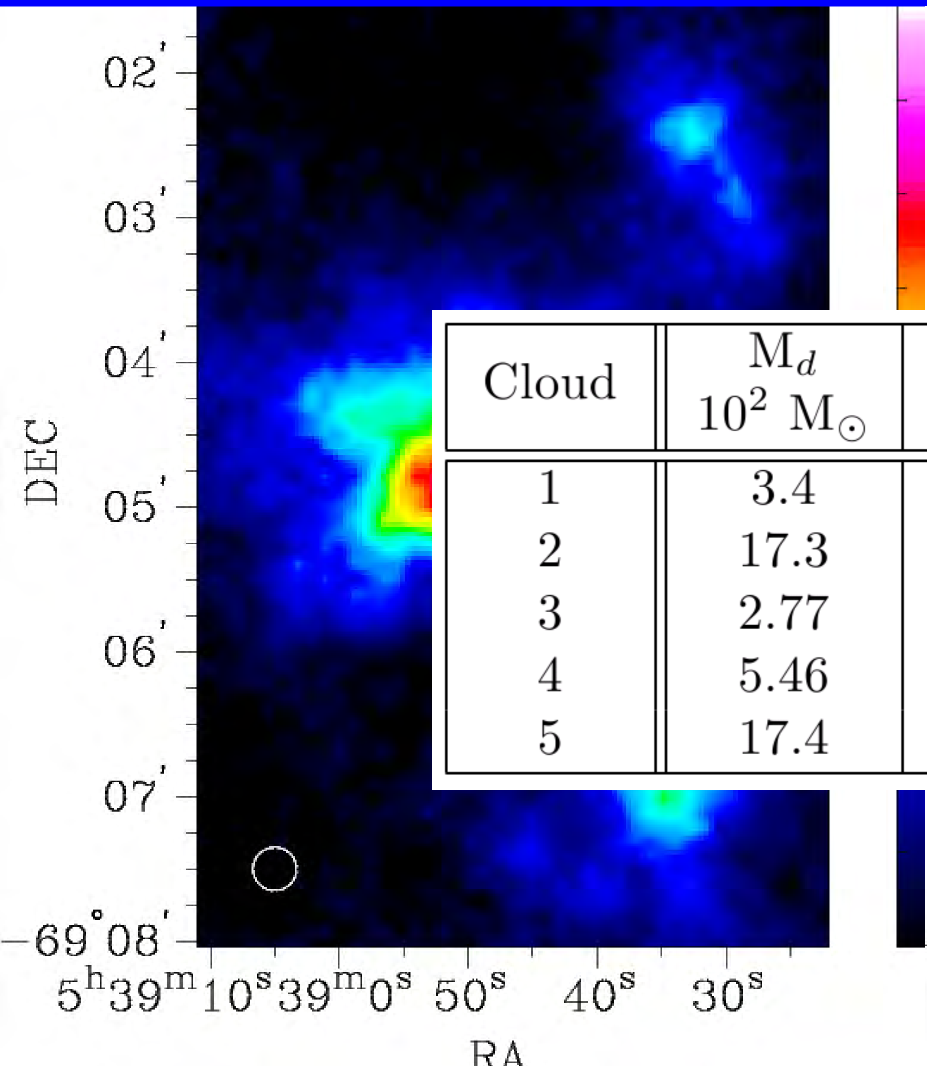

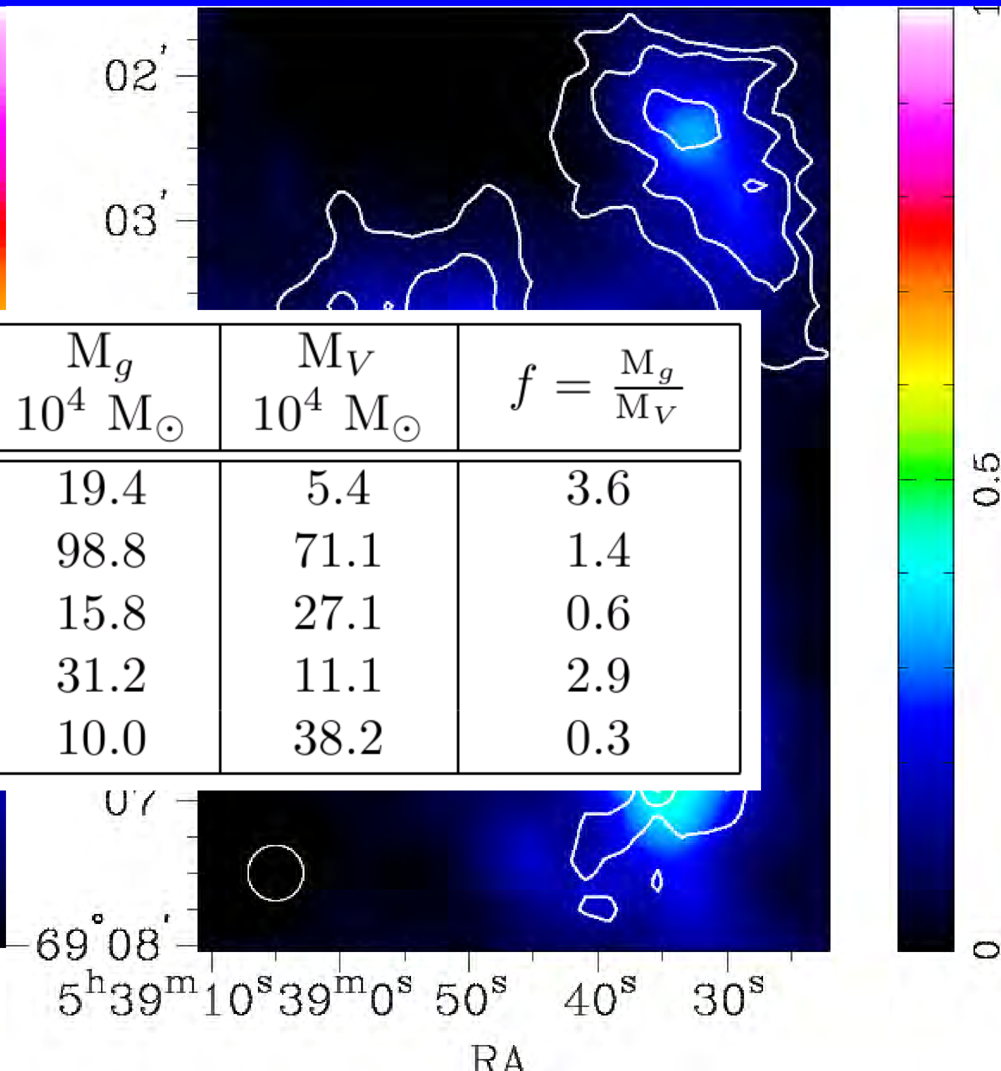

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