Low Metallicty Molecular Clouds with ALMA

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STAR FORMATION IN LOW METALLICiTY GALAXIES

- Low metallicity galaxies form stars
- Stars form in cold dense clouds of molecular Hydrogen (H_2)

BUT

H_2 gas does not emit in the cold dense cloud

- **Need to find other ways to study the regions where star forms**

- **And determine the amount of H_2 → tracers**

Determining H_2

- **CO observations**

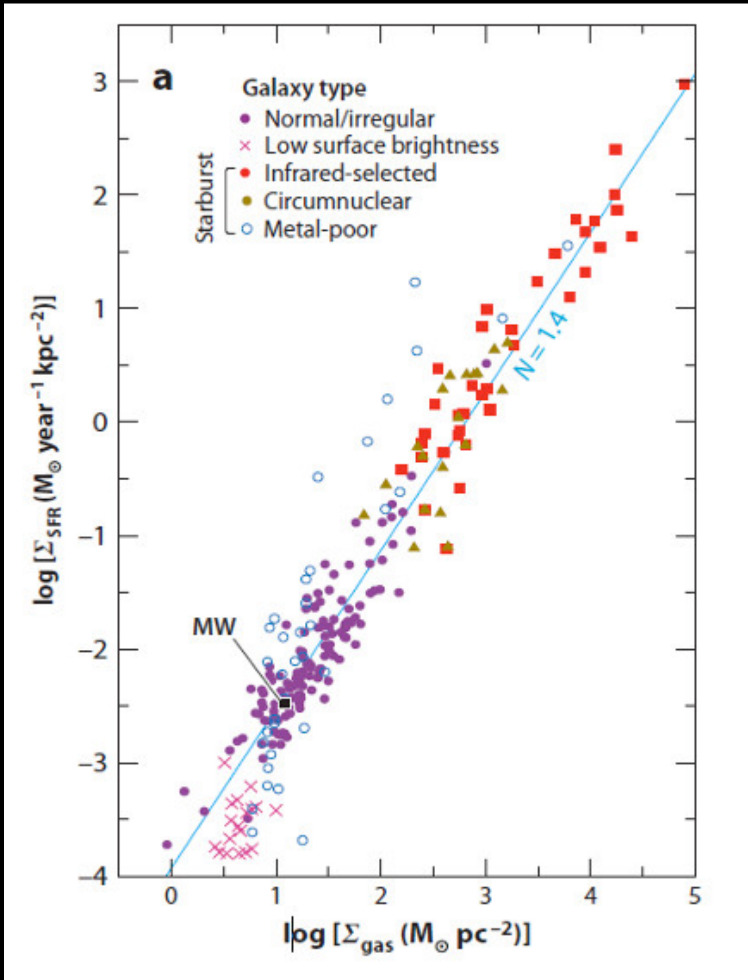
  $X = N(H_2)$)/ICO (mol K kms^{-1})

  Xgal= 2 x 10^{20} cm-2 (K $kms^{-1})^{-1}$

  $\Sigma H_2 = \alpha_{co}$ Ico (Mo pc^{-2}) $\alpha_{co}(Gal) = 4$

- **Virial mass determination,**
  DV and size (R)

- **Emission from dust**



Determining H_2

These different methods give similar results in the MW and in other spiral galaxies

BUT

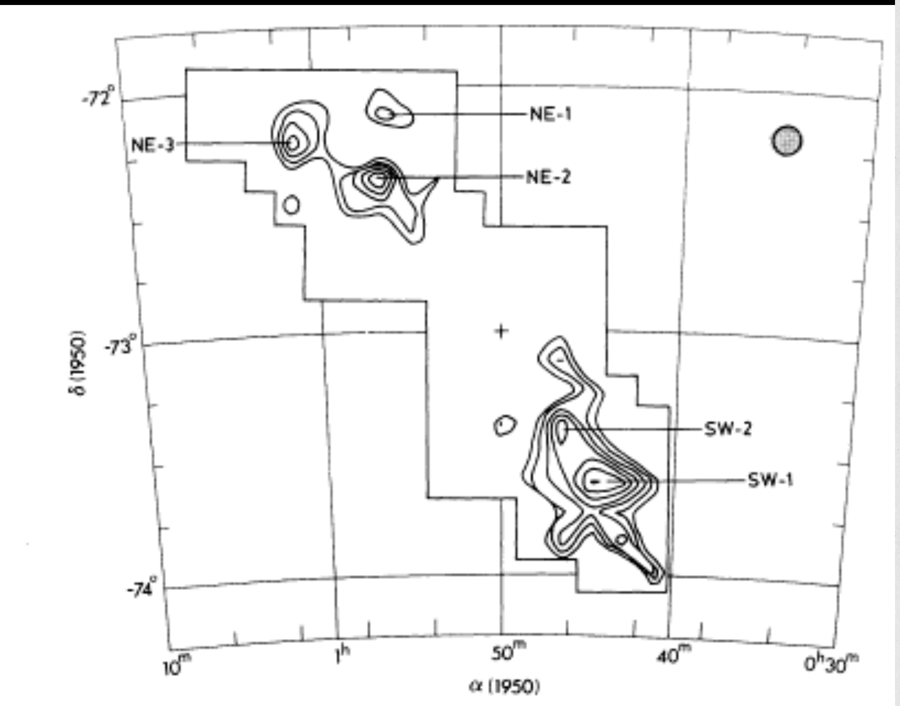
Not the case everywhere

!!!low metallicity!!!!!

First Magellanic Cloud CO (1-0) survey

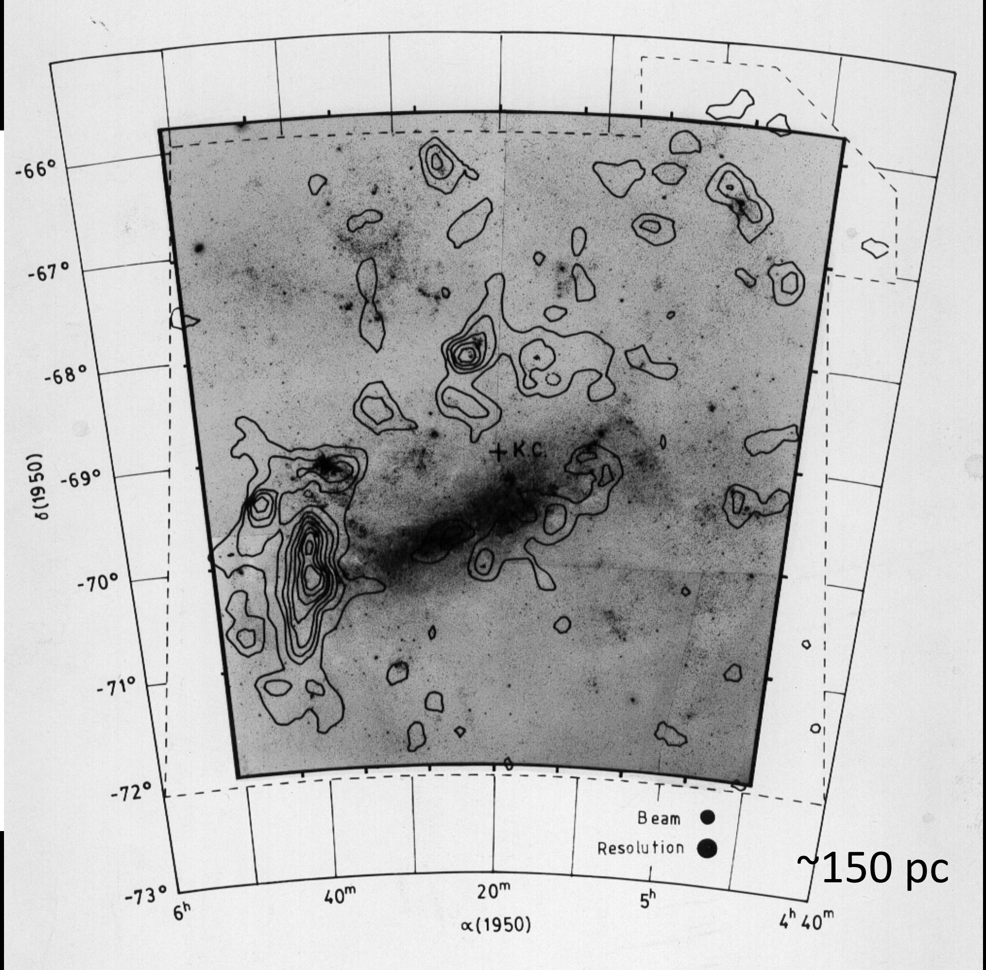
Columbia mini 1.2m Telescope@CTIO

SMC



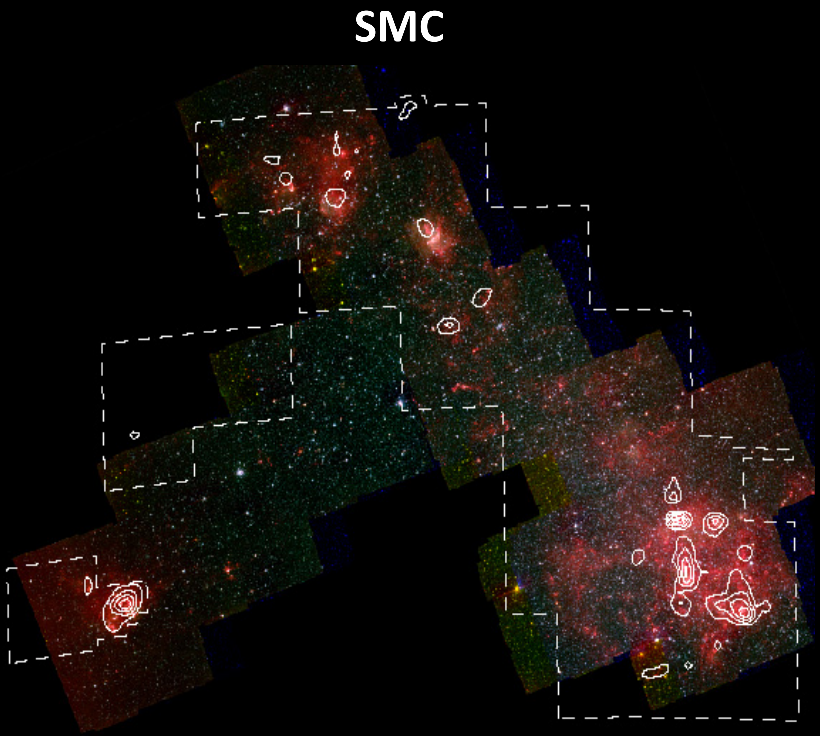
Rubio et al. 1991

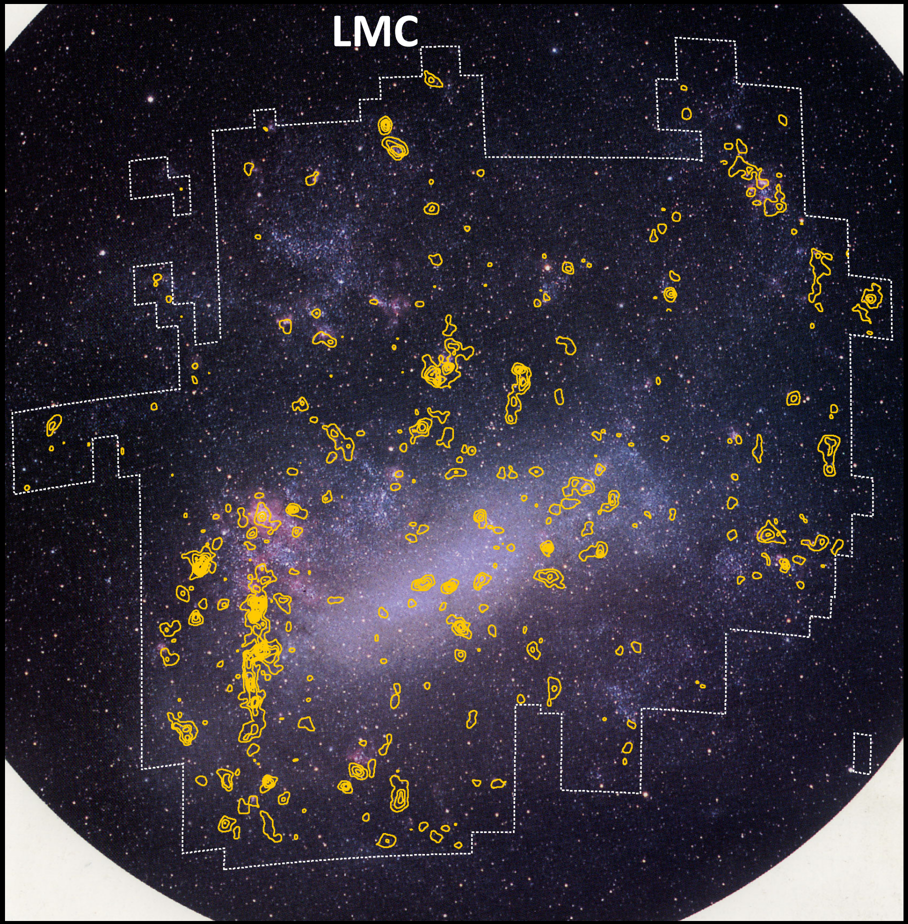
LMC



Cohen et al. 1988

CO in the Magellanic Clouds





X_{smc} = 2.5 x 10^{21} Kkms-1 ~ 10_{gal}

$M(H_2)$ = 4.6 x 10 ^{6} Mo

Mizuno, Rubio et al. 2001

X_{LMC}= 7×10^{20} cm^{-2} / [K km s^{-1} ~ 3 $_{gal}$

$M(H_2)$ = 4-7 x 10^7 Mo

Fukui et al.(inc. Rubio,) 2008

日本語 ？

PASJ: Publ. Astron. Soc. Japan 51, 745–749 and Plate 25–27 (1999)

First Results of a CO Survey of the Large Magellanic Cloud with NANTEN; Giant Molecular Clouds as Formation Sites of Populous Clusters

Yasuo FUKUI,[1] Norikazu MIZUNO,[1] Reiko YAMAGUCHI,[1] Akira MIZUNO,[1] Toshikazu ONISHI,[1]
Hideo OGAWA,[1,*] Yoshinori YONEKURA,[2] Akiko KAWAMURA,[1,†] Kengo TACHIHARA,[1]
Kecheng XIAO,[1] Nobuyuki YAMAGUCHI,[1] Atsushi HARA,[1] Takahiro HAYAKAWA,[1] Shigeo KATO,[1]
Rihei ABE,[1] Hiro SAITO,[1] Satoru MANO,[1] Ken'ichi MATSUNAGA,[1] Yoshihiro MINE,[1]
Yoshiaki MORIGUCHI,[1] Hiroko AOYA... ASAYAMA,[1]
Nao YOSHIKAWA,[1] and Monica RUBIO[3]

PASJ: Publ. Astron. Soc. Japan 53, L45–L49, 2001 December 25

First Results of a CO Survey of the Small Magellanic Cloud with NANTEN

Norikazu MIZUNO,[1] Mónica RUBIO,[2] Akira MIZUNO,[1] Reiko YAMAGUCHI,[1]
Toshikazu ONISHI,[1] and Yasuo FUKUI[1]

THE SECOND SURVEY OF THE MOLECULAR CLOUDS IN THE LARGE MAGELLANIC CLOUD BY NANTEN. I. CATALOG OF MOLECULAR CLOUDS

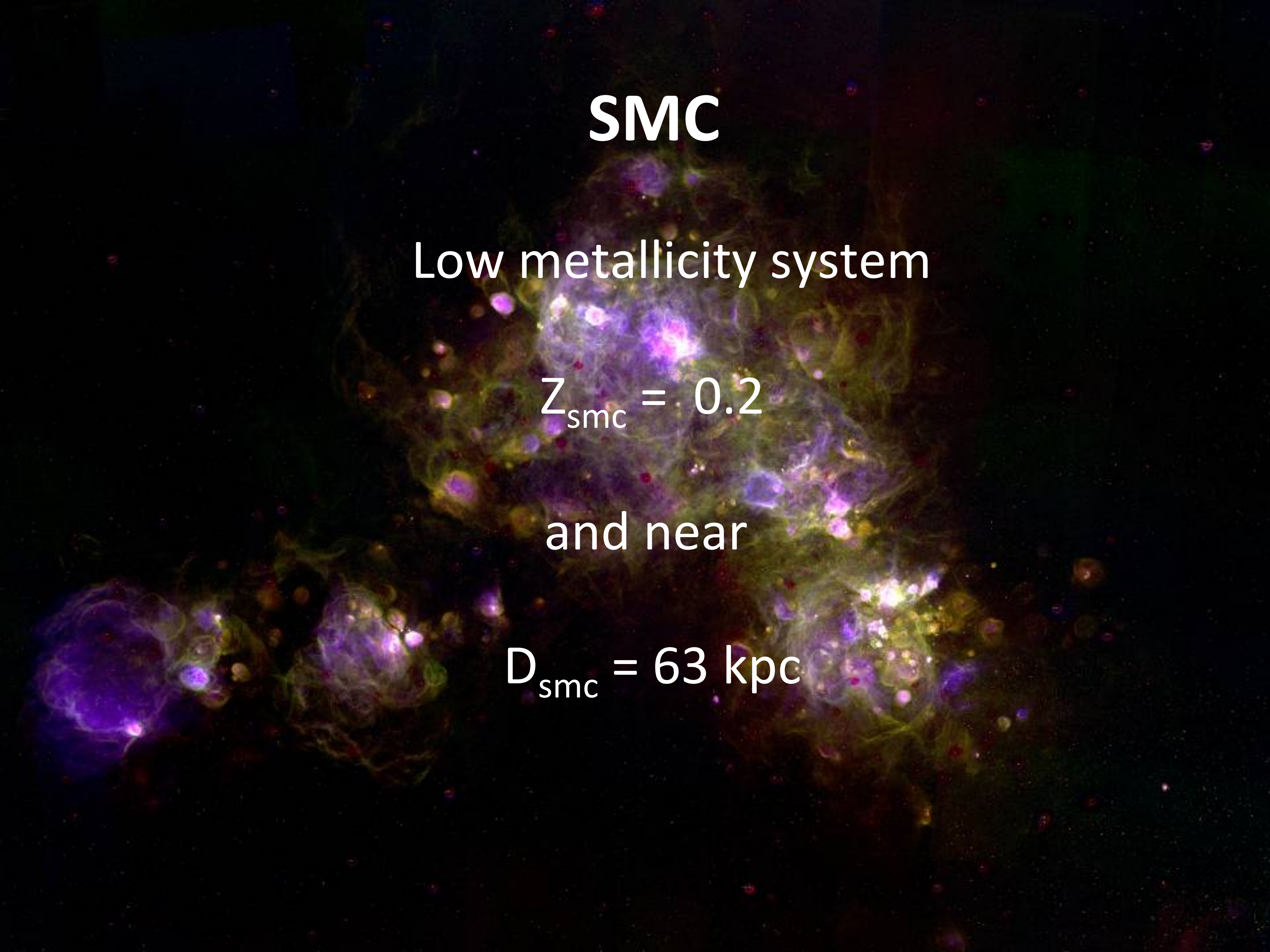
Y. FUKUI,[1] A. KAWAMURA,[1] T. MINAMIDANI,[1,2] Y. MIZUNO,[1] Y. KANAI,[1] N. MIZUNO,[1] T. ONISHI,[1]
Y. YONEKURA,[3] A. MIZUNO,[4] H. OGAWA,[3] AND M. RUBIO[5]
Received 2006 May 24; accepted 2008 April 2

6256/141/3/

DENSE CLUMPS IN GIANT MOLECULAR CLOUDS IN THE LARGE MAGELLANIC CLOUD: DENSITY AND TEMPERATURE DERIVED FROM ^{13}CO(J = 3–2) OBSERVATIONS

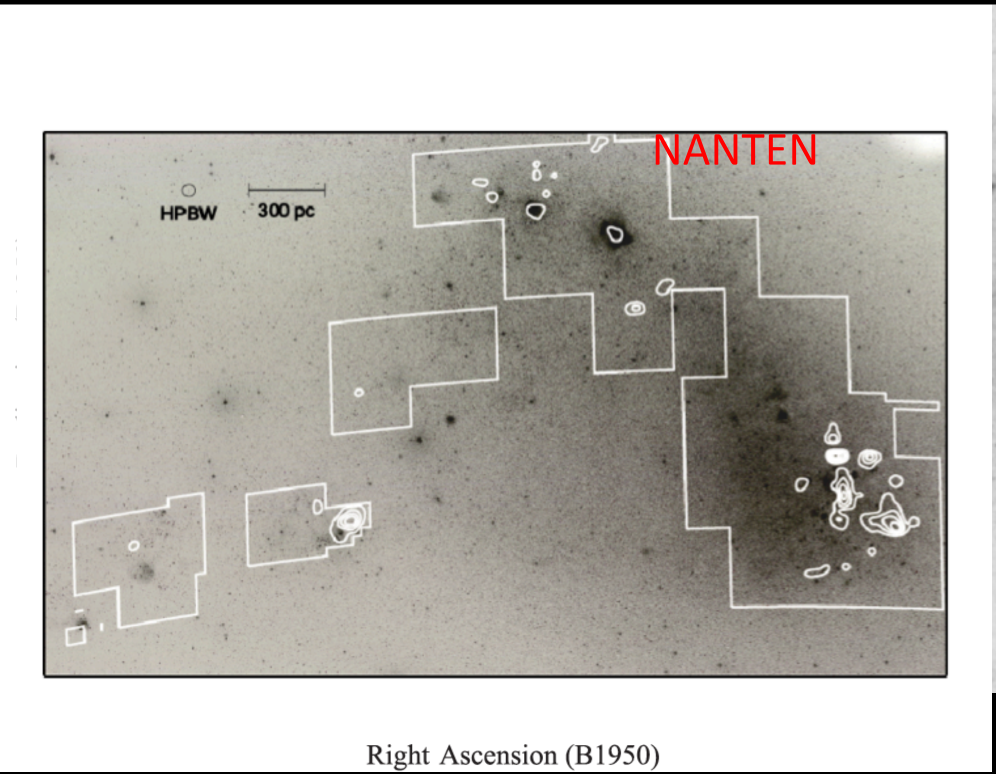
TETSUHIRO MINAMIDANI[1,2], TAKANORI TANAKA[3], YOJI MIZUNO[3], NORIKAZU MIZUNO[4], AKIKO KAWAMURA[3],
TOSHIKAZU ONISHI[5], TETSUO HASEGAWA[4], KEN'ICHI TATEMATSU[4], TATSUYA TAKEKOSHI[2], KAZUO SORAI[1,2],
NAYUTA MORIBE[3], KAZUFUMI TORII[3], TAKESHI SAKAI[6], KAZUYUKI MURAOKA[5], KUNIHIKO TANAKA[7],
HAJIME EZAWA[4], KOTARO KOHNO[6], SUNGEUN KIM[8], MÓNICA RUBIO[9], AND YASUO FUKUI[3]

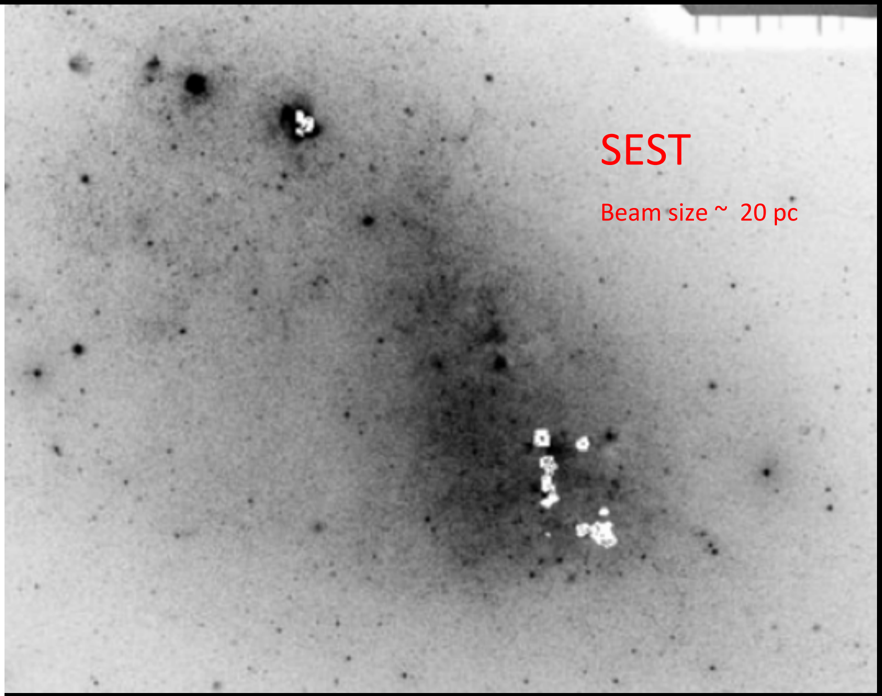
[1] ERIK MULLER, JORGE L. PINEDA, ANNIE HUGHES, LISTER STAVELEY-SMITH, ULRICH KLEIN, AKIRA MIZUNO,
SILVANA NIKOLIĆ,[13,14] ROY S. BOOTH,[13,15] ARTO HEIKKILÄ,[13] LARS-ÅKE NYMAN,[16] MIKAEL LERNER,[16]
GUIDO GARAY,[17] SUNGEUN KIM,[18] MOTOSUJI FUJISHITA,[1] TOKUICHI KAWASE,[1]
MONICÁ RUBIO,[17] AND YASUO FUKUI[1]
Received 2006 November 29; accepted 2007 September 28



SMC
Low metallicity system
Z_{smc} = 0.2
and near
D_{smc} = 63 kpc

CO Gas in the SMC





X_{smc} = 2.5 x 10^{21} Kkms-1 ~ 10_{gal}

$M(H_2)$ = 4.6 x 10 ^{6} Mo

Mizuno et al. 2001

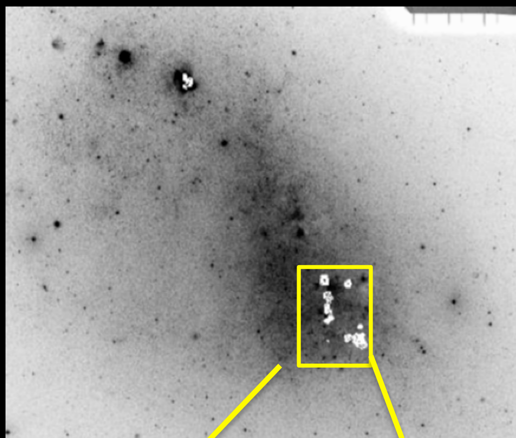
X_{smc} = 9x 10^{20} Kkms-1 ~ 4 $_{gal}$

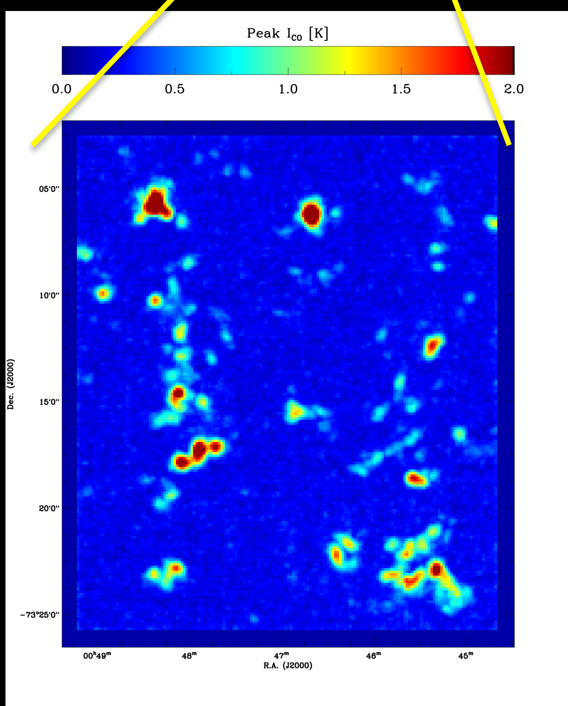
$M(H_2)$ < 3 x 10^{7} Mo

Rubio et al. 1993

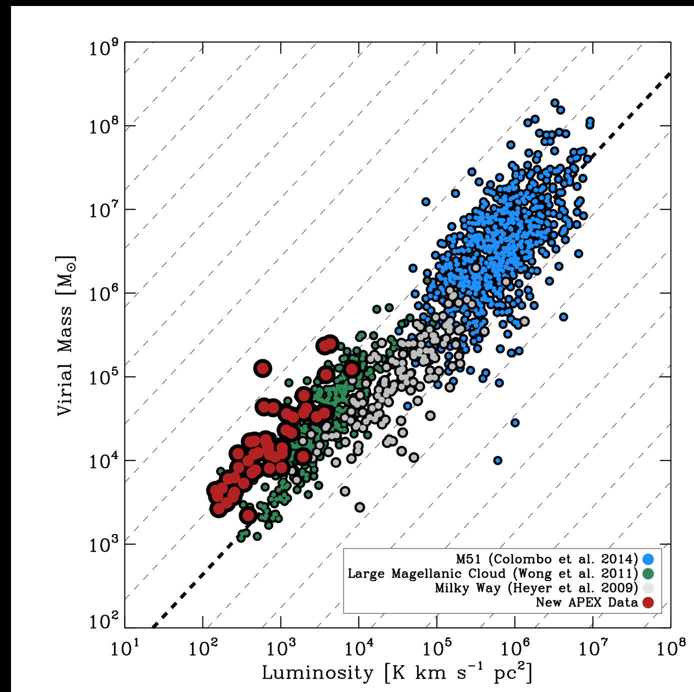
New APEX CO 2-1 Survey of the Southwest Part of the SMC

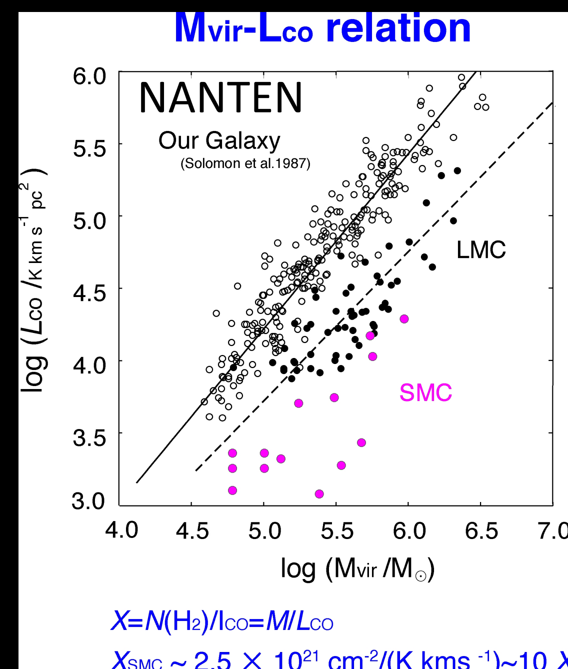
PI. M. Rubio Stunning improvement over previous SEST data





Virial mass – luminosity (X_{CO}).



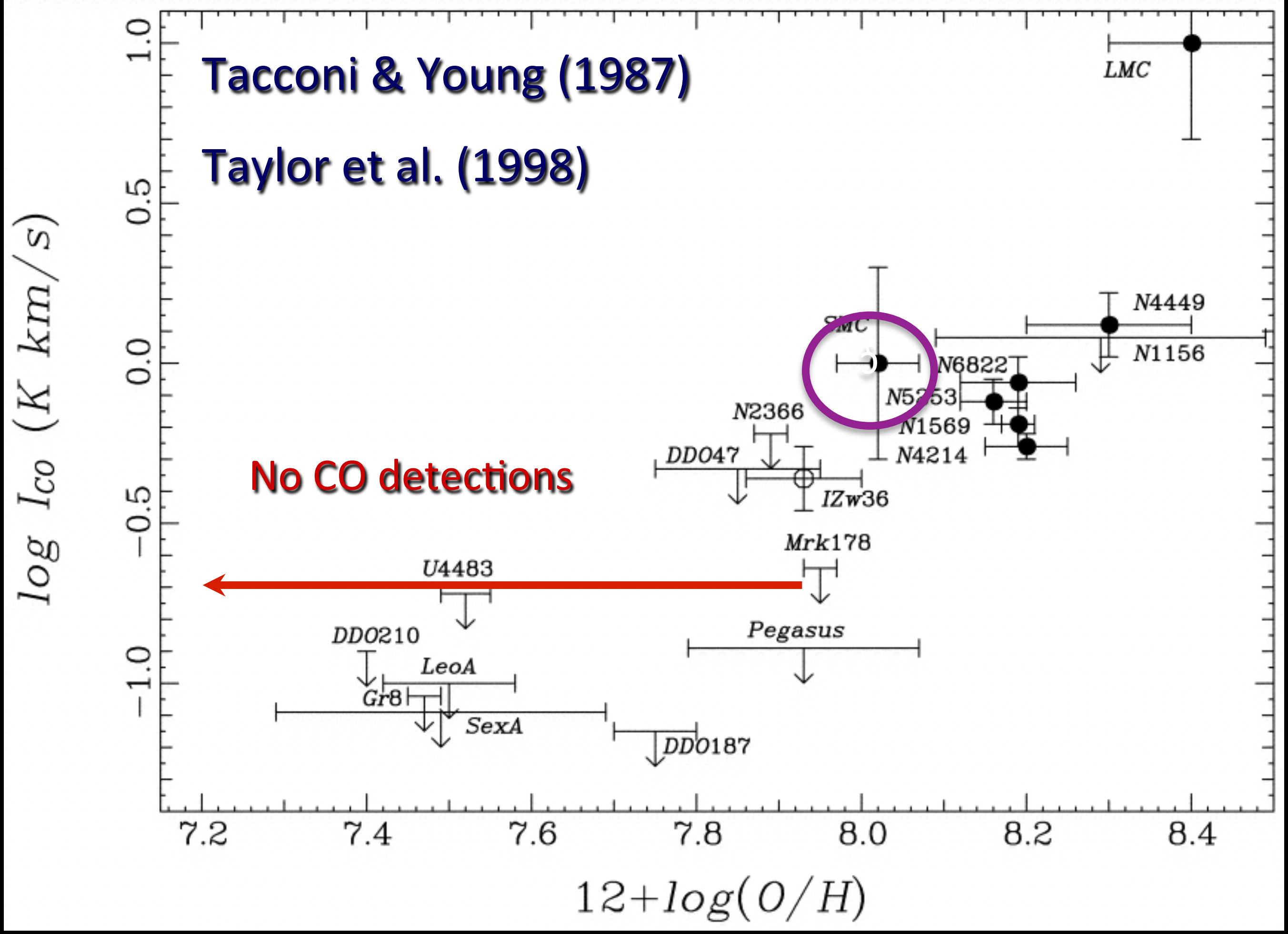


If Virialized, X_{CO} ~ 5 times Galactic

Rubio et al. In prep

CO the best tracer had not been detected in low metallicity galaxies for many years.

CO emission weak at lower metallicity



SMC @ 63 kpc

20 % solar

Bolatto+ 2013

For a review of CO in Galaxies

El team
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Monica Rubio Chile
Bruce Elmegreen NY. USA
Deidre Hunter Arizona,US
Celia Verdugo Chile
Elias Brinks Reino Unido
Phil Cigan New Mexico, USA


APEX

What if we go to lower metallicities ?

first galaxies in the Universe

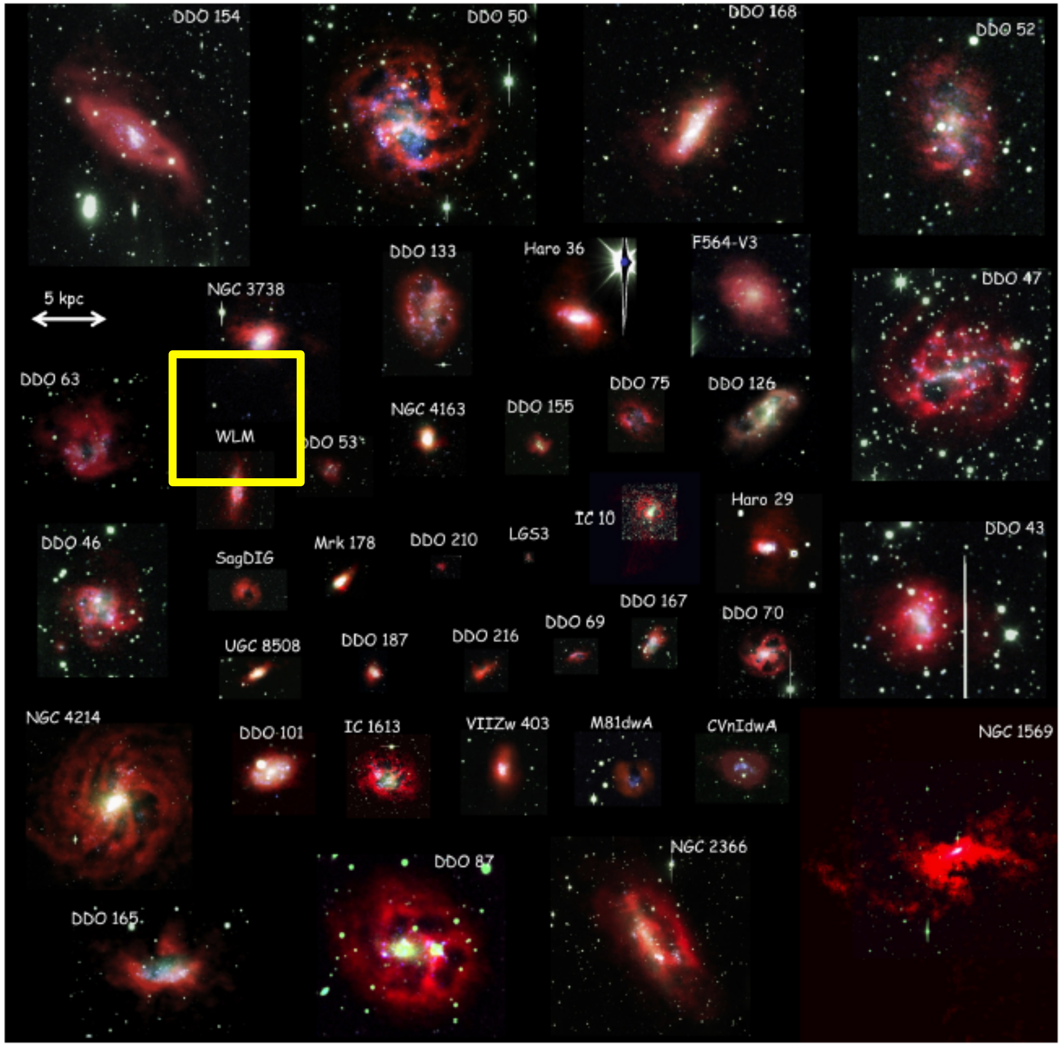
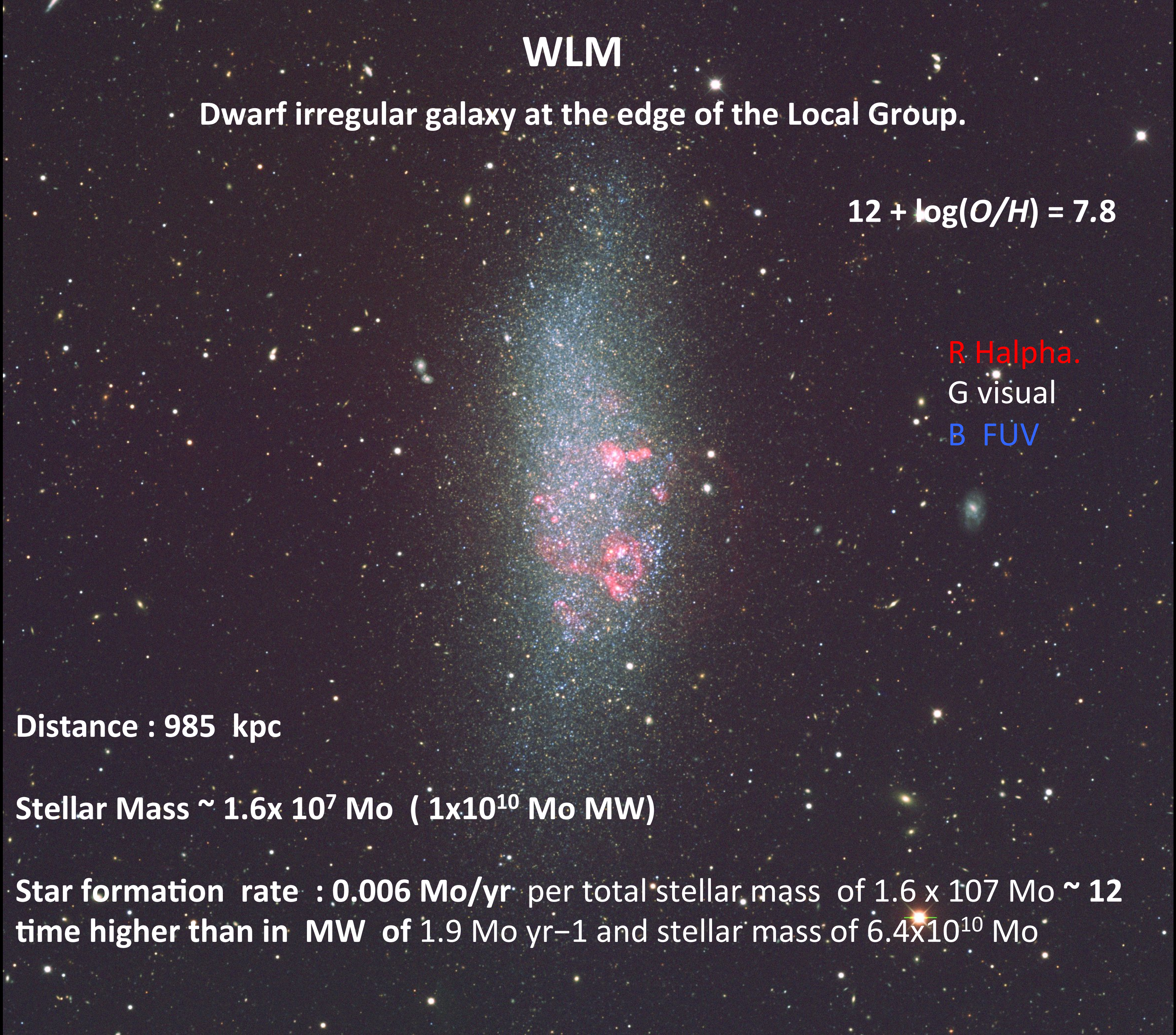


Figure 4: LITTLE THINGS dwarfs: Red is H I, green is *V*, blue is FUV. Images are to same relative size.

LITTLE THINGS Survey
Hunter et al. 2014

HI survey of dwarfs

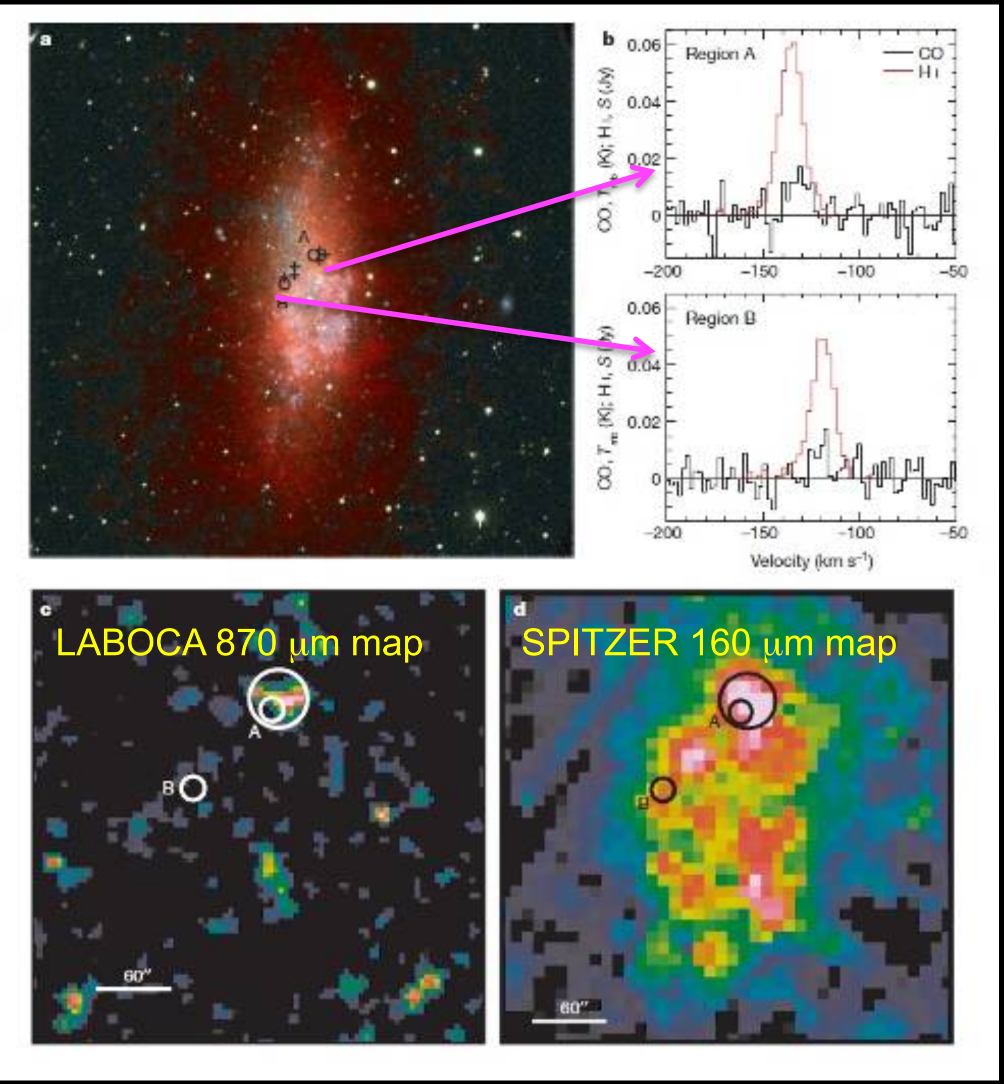
(Local Irregulars That Trace Luminosity Extremes, The H I Nearby Galaxy Survey)


WLM
Dwarf irregular galaxy at the edge of the Local Group.
12 + log(*O/H*) = 7.8
R Halpha.
G visual
B FUV
Distance : 985 kpc
Stellar Mass ~ 1.6x 10^7 Mo ($1x10^{10}$ Mo MW)
Star formation rate : 0.006 Mo/yr per total stellar mass of 1.6 x 107 Mo ~ 12 time higher than in MW of 1.9 Mo yr−1 and stellar mass of $6.4x10^{10}$ Mo

We detected molecules in the most metal poor galaxy ever !

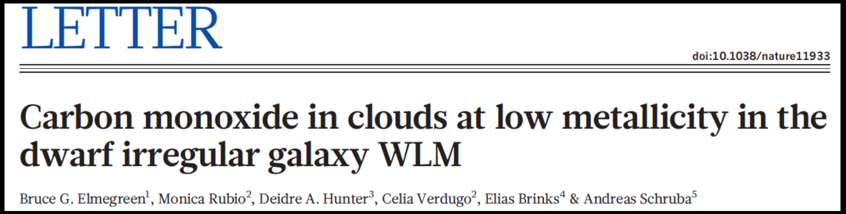
Breaking the metallicity barrier: 12 + log(*O/H*) = 7.8

CO(3-2)



Oxygen abundance is 13% solar

Elmegreen, Rubio, et al. 2013, NATURE, 495, 487


LETTER

doi:10.1038/nature11933

Carbon monoxide in clouds at low metallicity in the dwarf irregular galaxy WLM

Bruce G. Elmegreen[1], Monica Rubio[2], Deidre A. Hunter[3], Celia Verdugo[2], Elias Brinks[4] & Andreas Schruba[5]

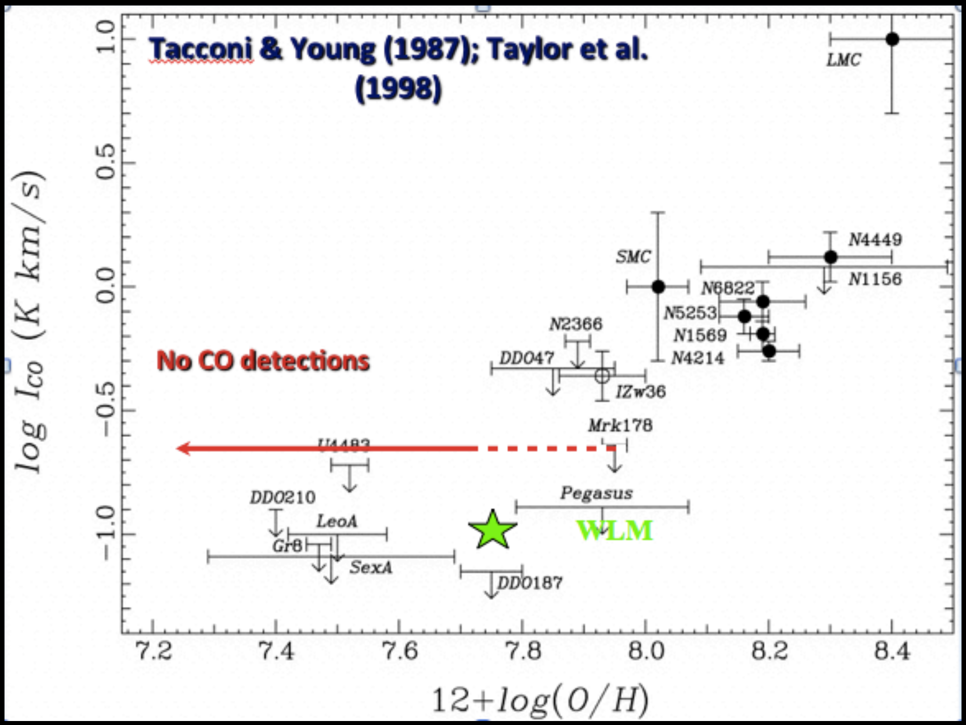
Molecular Masses

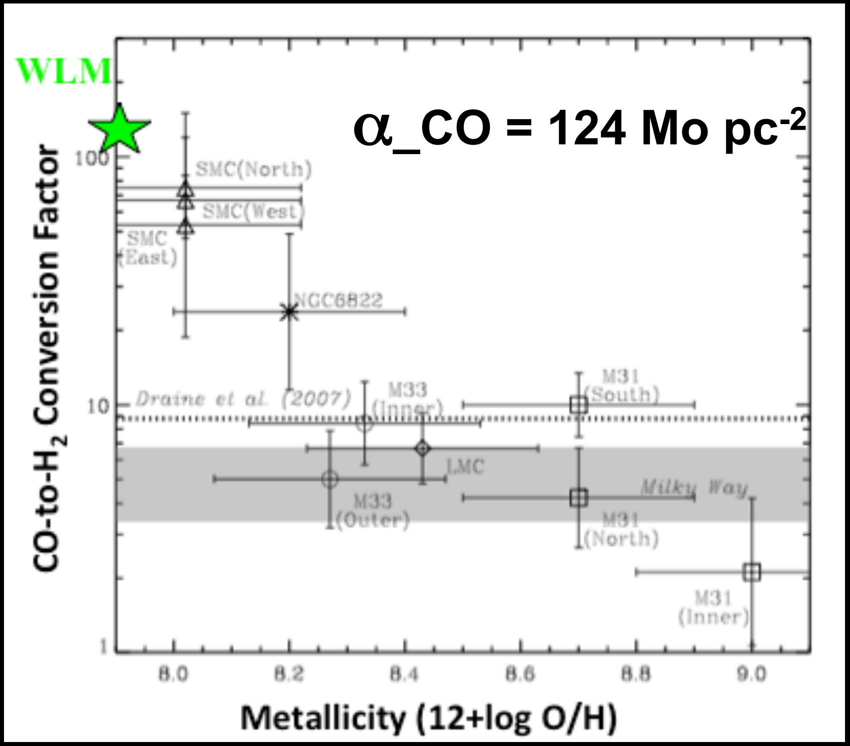
A: M(H_2)= 1.8 (0.8) X10^5 Mo, Σ= 58 Mo pc^{-2}

B: M(H_2)= 1.2 (0.6) X10^5 Mo

WLM

Breaking the metallicity barrier for CO detections!
13% of Solar Oxygen abundance

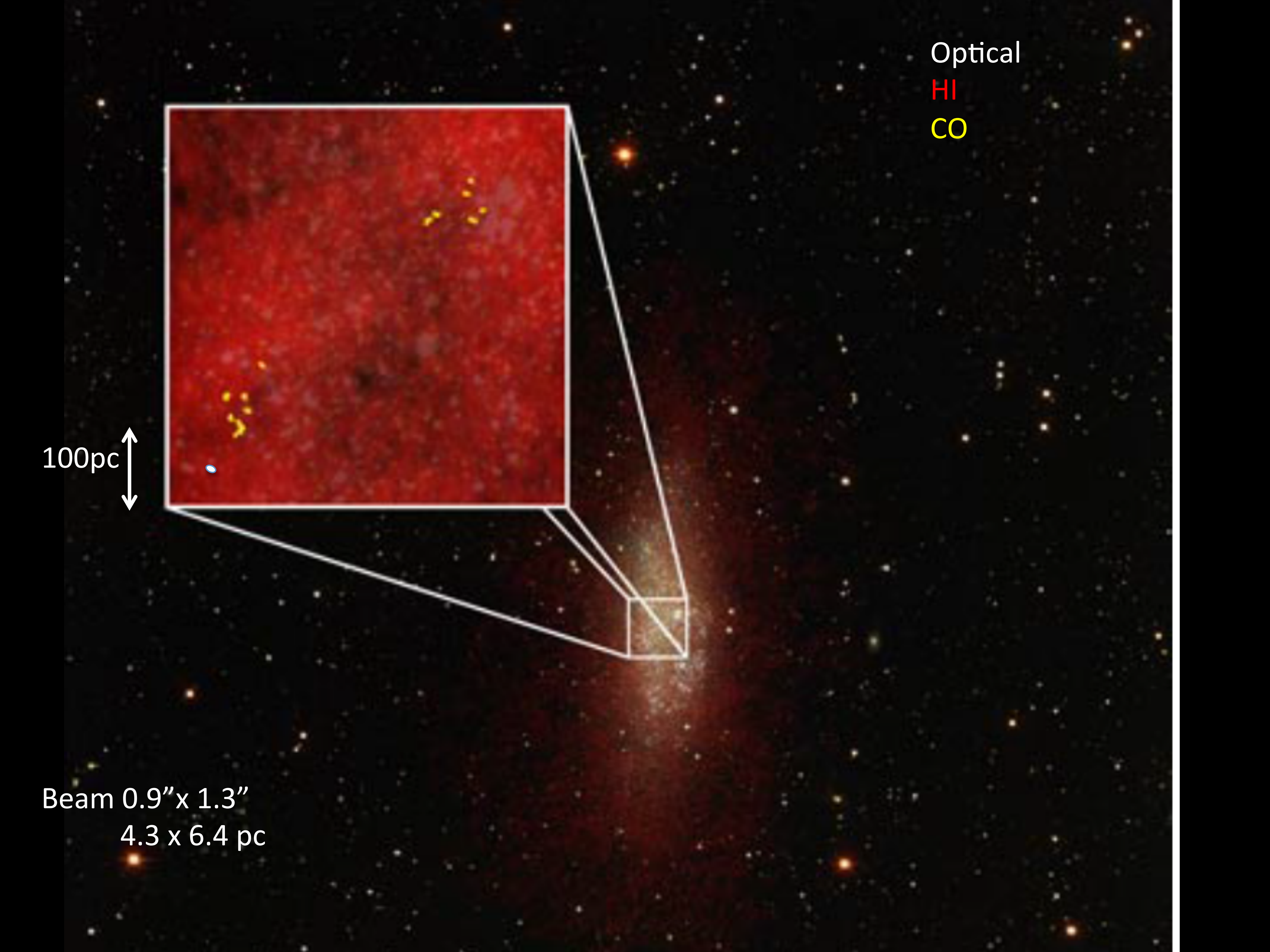


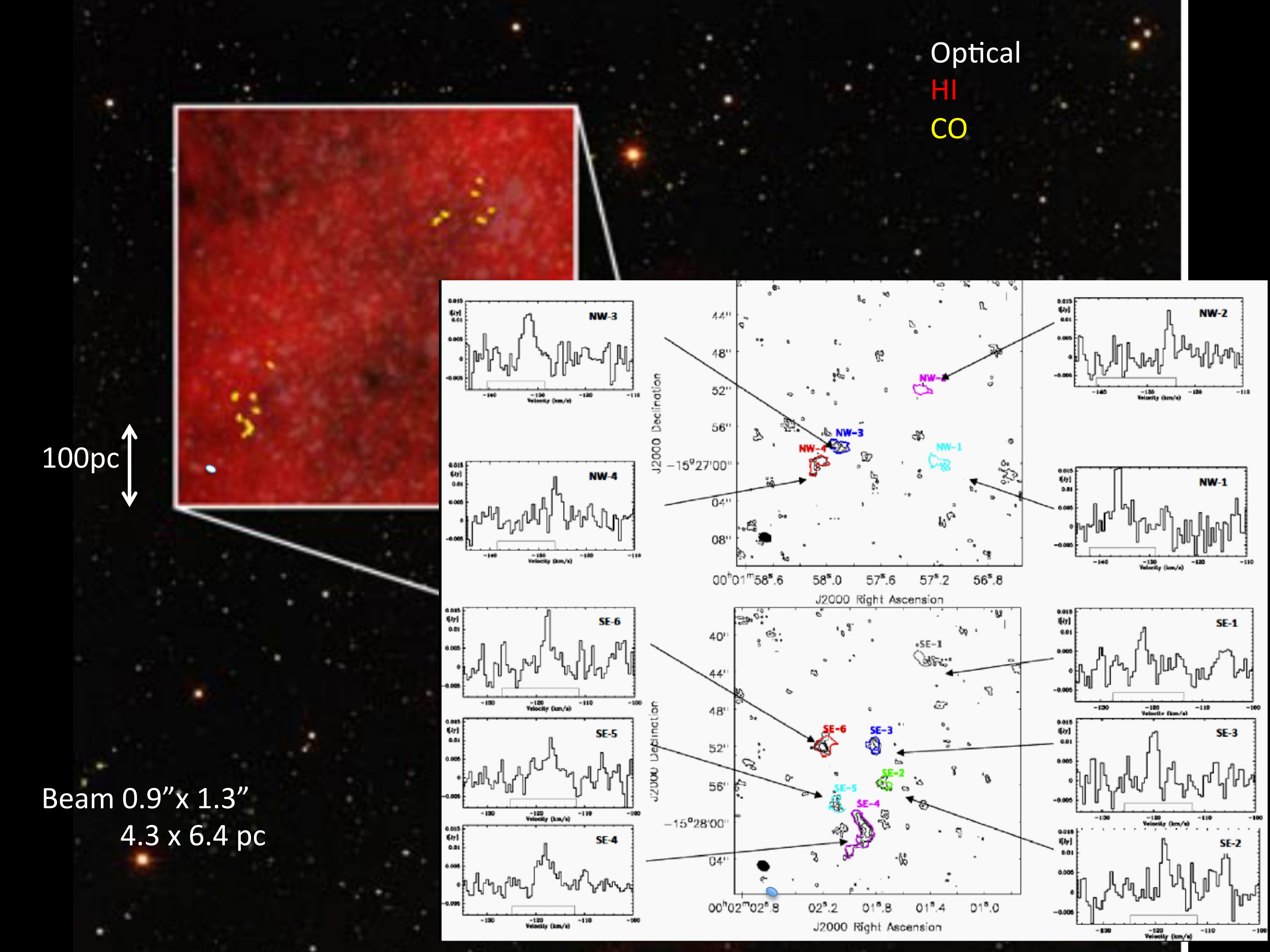


Elmegreen, Rubio, Hunter, et al. 2013
Nature 495,487

Only at a distance of ~1 Mpc


ALMA C1 CO1-0 observation in WLM


Optical
HI
CO
100pc
Beam 0.9”x 1.3”
4.3 x 6.4 pc


Optical
HI
CO
100pc
Beam 0.9"x 1.3"
4.3 x 6.4 pc
NW-3
NW-4
NW-2
NW-1
SE-6
SE-5
SE-4
SE-1
SE-3
SE-2
J2000 Declination
J2000 Right Ascension
Velocity (km/s)

We resolve 10 small dense molecular cores in WLM.

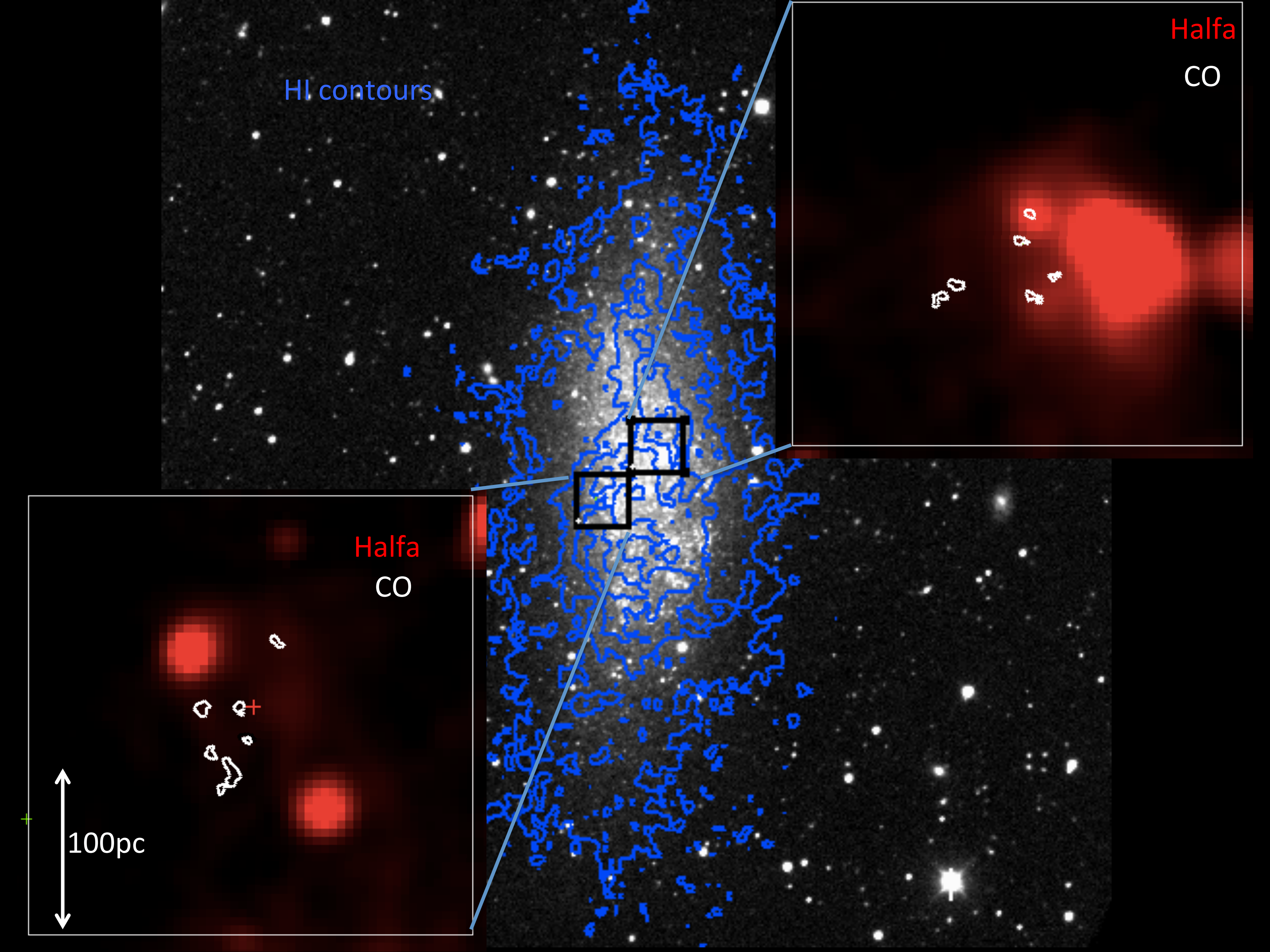
CO cores:

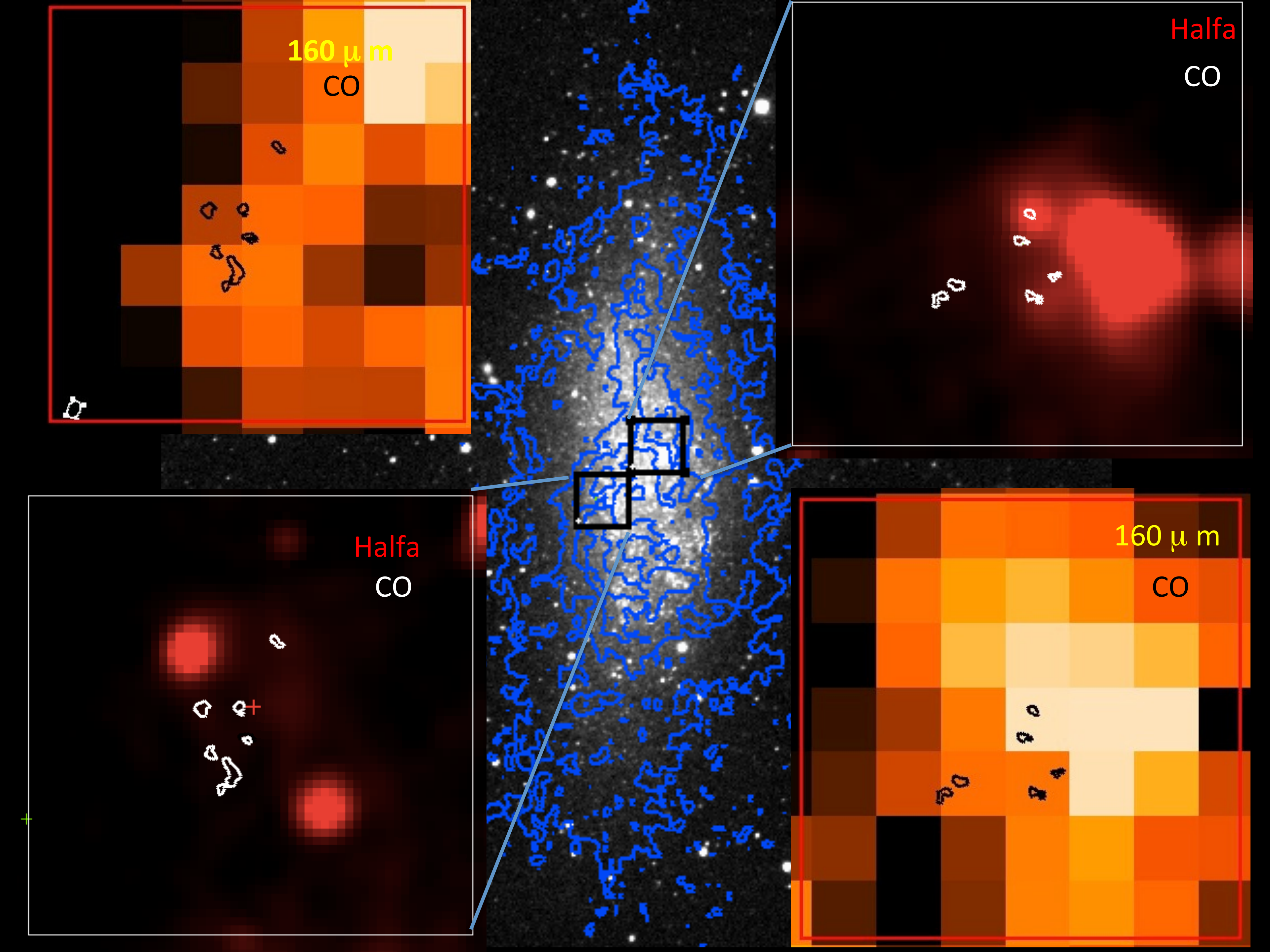
Virial masses ~ 390 - $1.1 \times 10^4\ M_{\odot}$

Radii ~ 1-6 pc

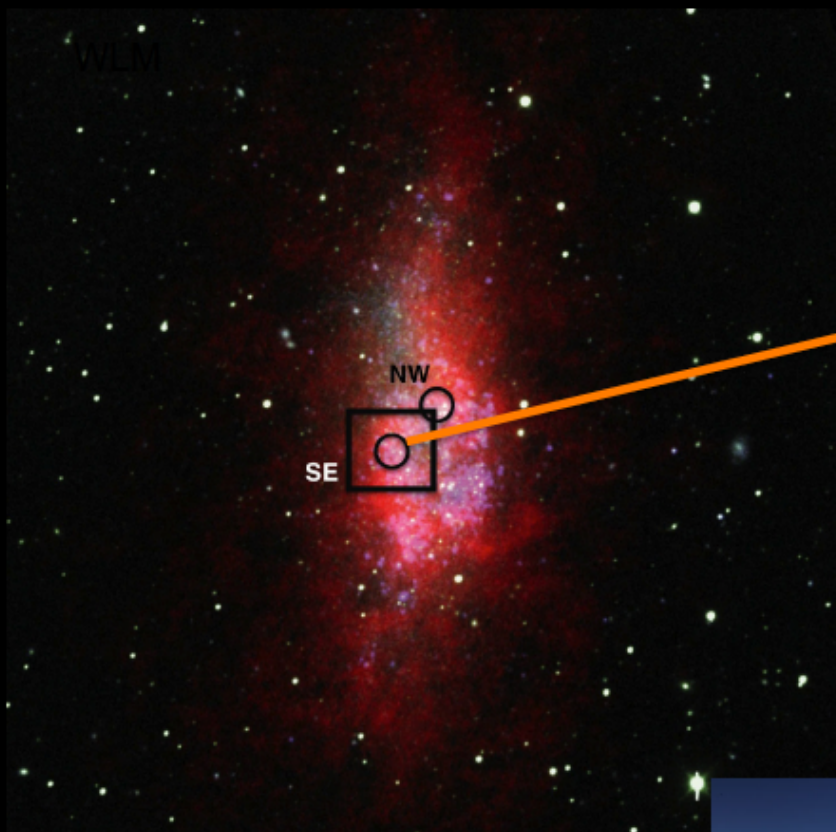
Velocity dispersion < 1 km/s

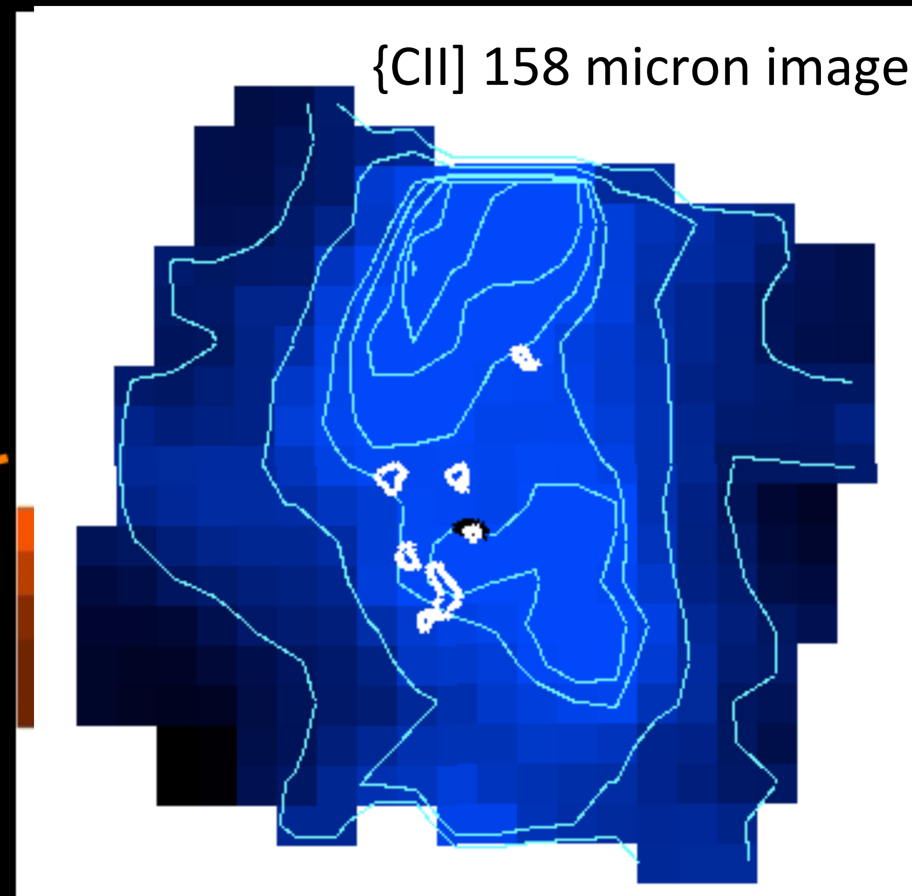
Rubio et al. 2015


HI contours
Halfa
CO
Halfa
CO
100pc


160 μ m
CO
Halfa
CO
Halfa
CO
160 μ m
CO

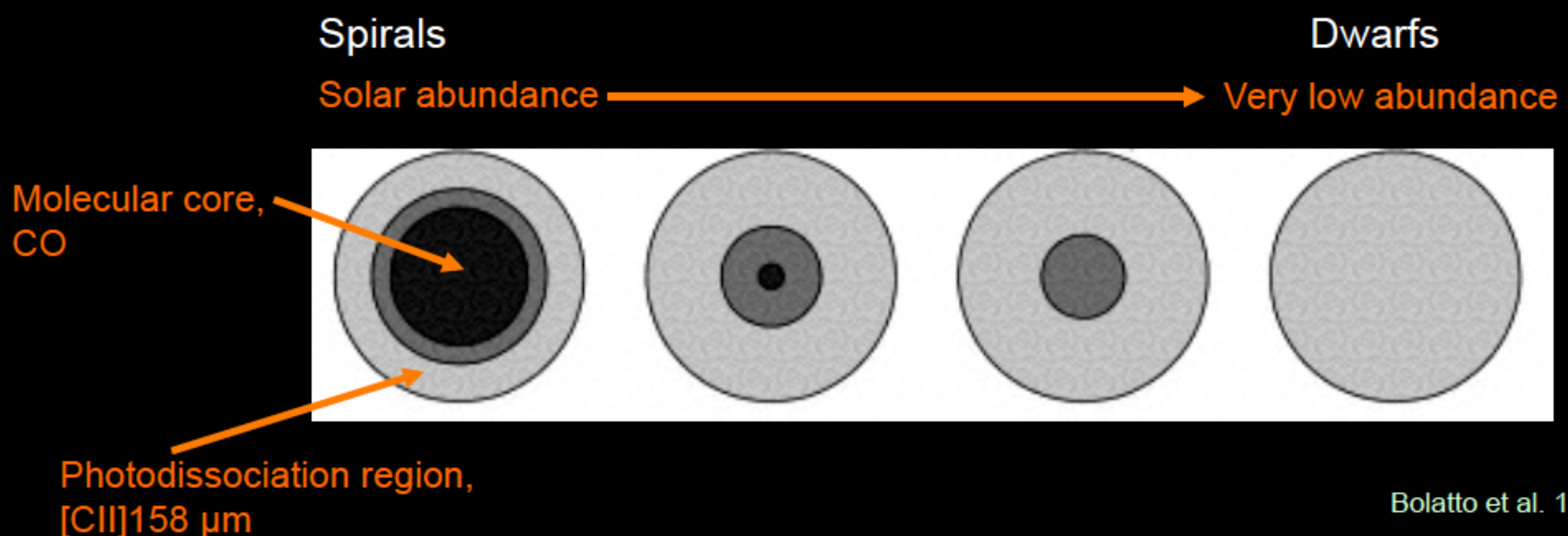
For the first time ever, we see directly the skin and core of a molecular cloud at 13% metallicity.





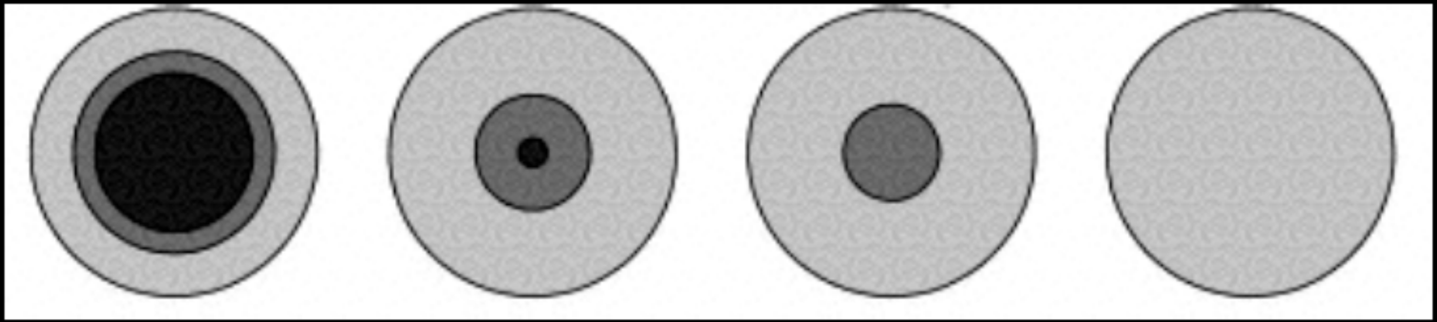
Rubio et al. 2015

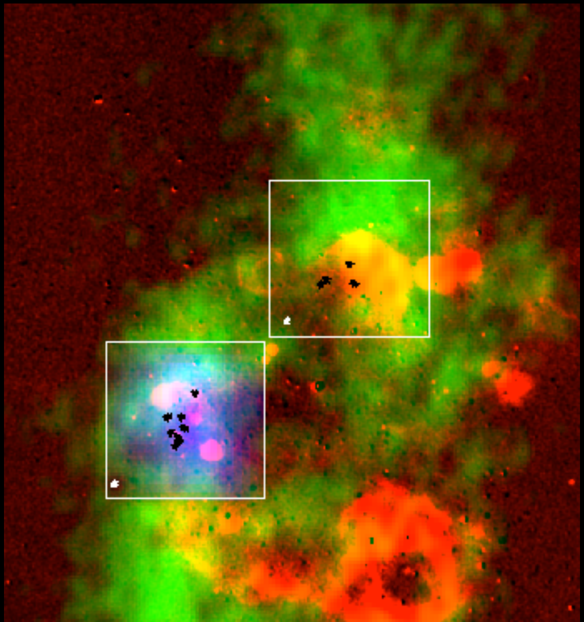
Molecular cloud cores shrink as metallicity decreases

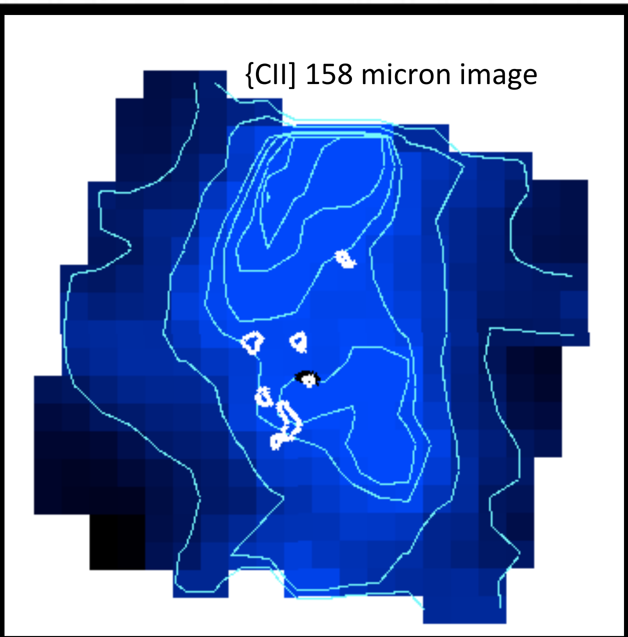


Bolatto et al. 1999

Photo-dissociation region is 5x larger than CO cores.

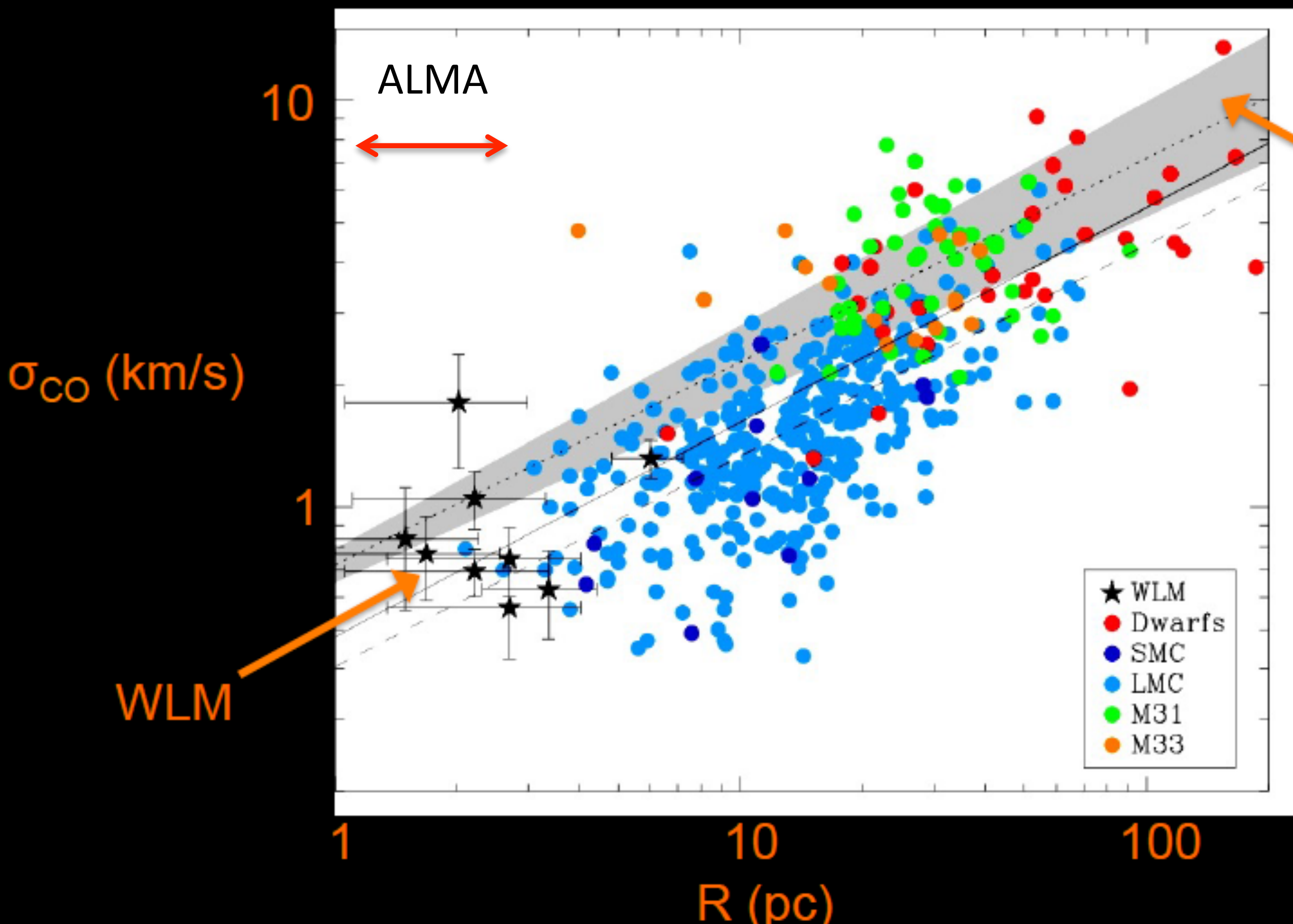






Rubio et al. 2015

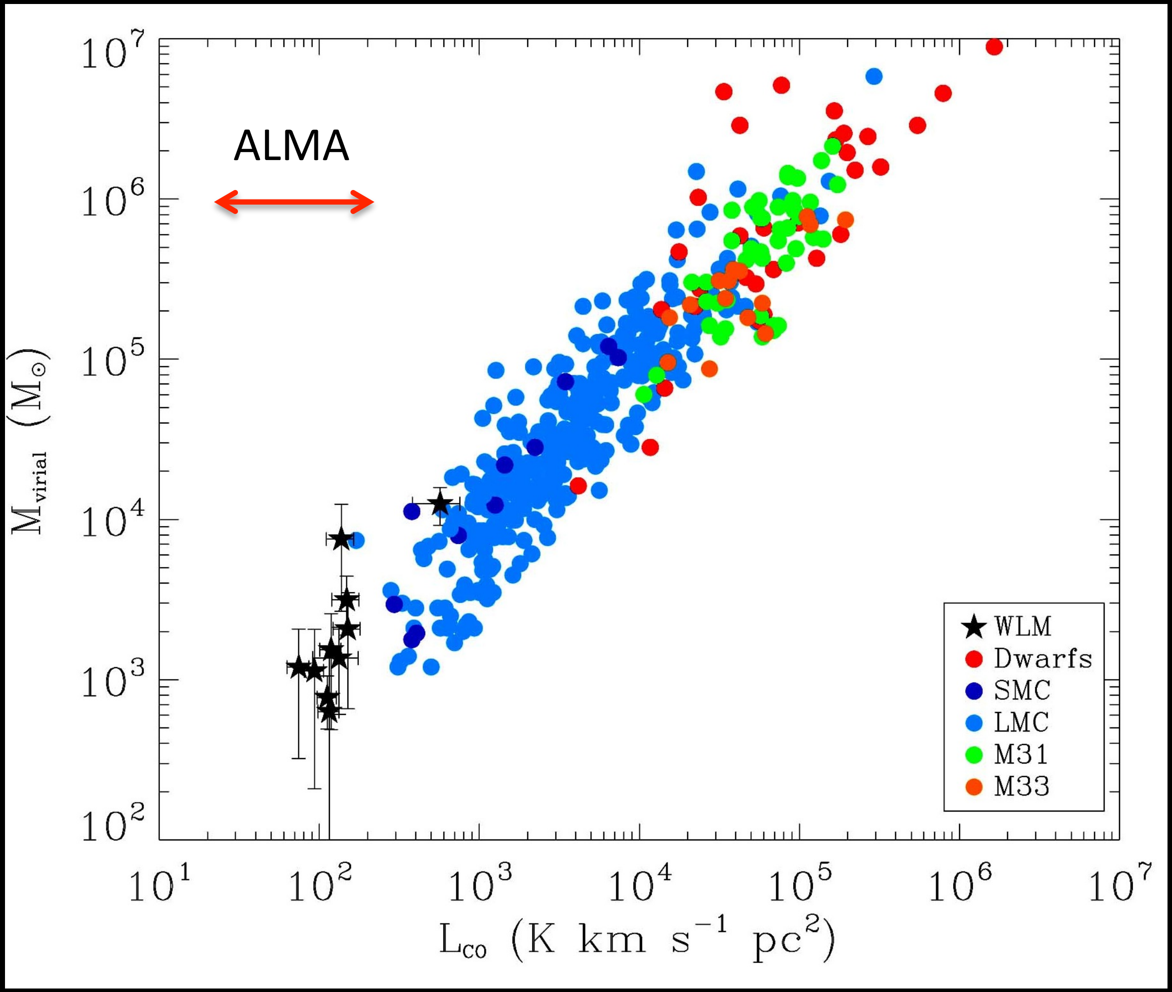
Larson's Size-Line width relation



Dwarfs at
10 pc resolution
Bolatto+ 2008

Rubio et al. 2015

Luminosity and Virial mass



Dwarfs at
10 pc resoltion

WLM clouds follow the average dwarf galaxy relationship between virial mass and luminosity

WLM clouds are 10 times lower in Lco for similar mass

Consequence of small mass CO cores

➔ low-mass star clusters

Rubio et al. 2015

Conditions for molecular cloud formation

Estimate Σ_{H2} from Σ_{total} (from dust/gas ratio) $-\Sigma_{HI}$

➔ CO cores are in pressure equilibrium with weight of overlying HI and H_2.

Milky Way: H_2 requires A_V=0.3 mag → 47 $M_\odot/pc^2$ at 13%Z
CO requires A_V=1.5 mag → 230 $M_\odot/pc^2$ at 13%Z
In SE region: HI+H_2 envelope of cores is 58 $M_\odot/pc^2$;
total HI+H_2 is 220 $M_\odot/pc^2$

➔ WLM's CO cores have normal density, pressure, and column density in spite of being in a low metallicity environment

Rubio et al. 2015

- Similarity in physical properties explain why star clusters born in metal-poor galaxies resemble those seen in less-extreme systems.

- The lack of dust in WLM implies that our best tracer of H_2 , CO, is present only deep in the cloud and the behaviour of most of the H_2 is perhaps not so different from that in other 'normal' galaxies.

- Qualitative agreement with simulations and theoretical predictions for the behaviour of CO and H_2 in metal-poor galaxies. PDR

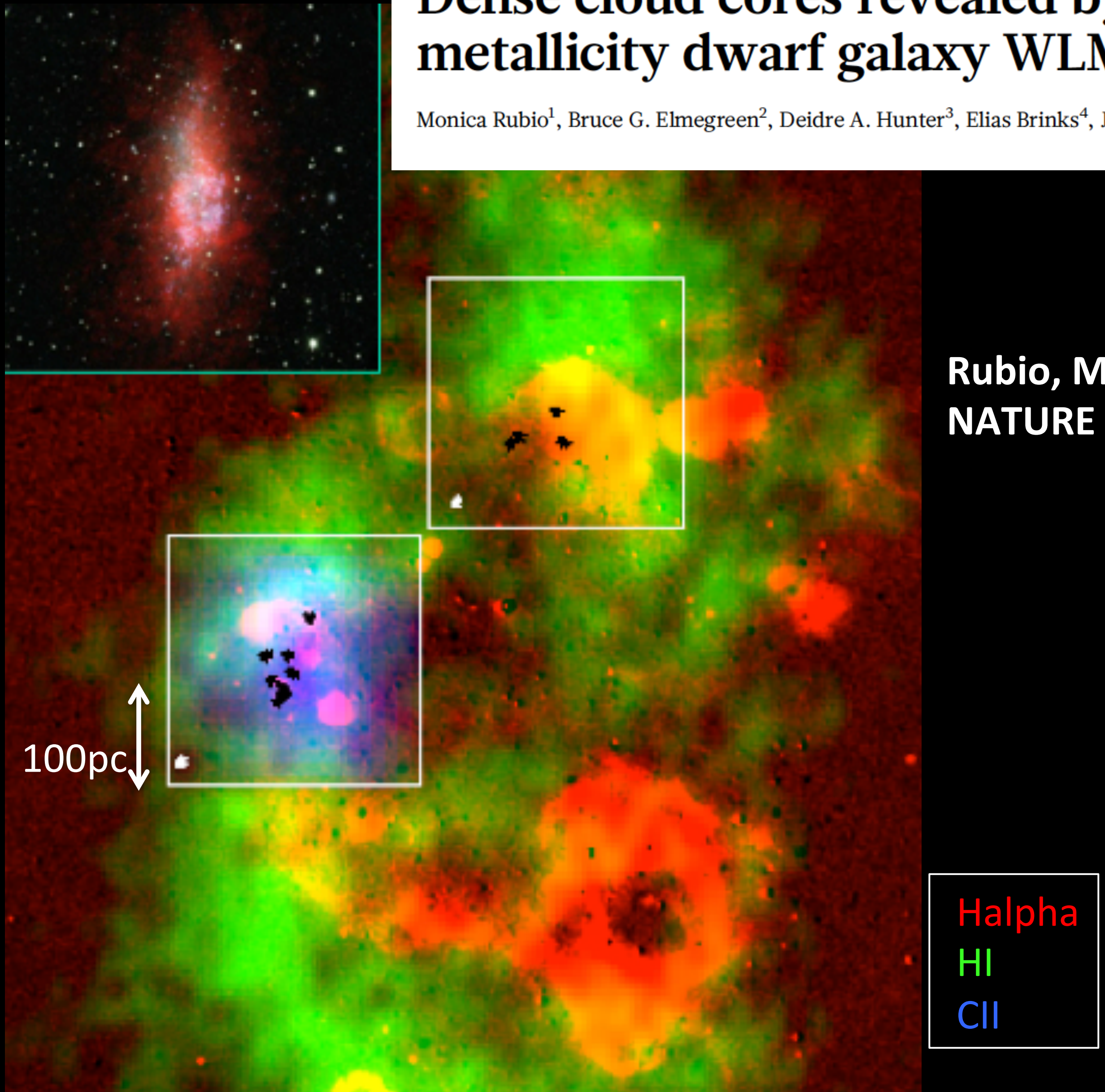
- The small size of these dust-enshrouded, CO-emitting clumps may explain the relative paucity of highly massive stellar clusters in small, isolated galaxies.

LETTER

doi:10.1038/nature14901

Dense cloud cores revealed by CO in the low metallicity dwarf galaxy WLM

Monica Rubio[1], Bruce G. Elmegreen[2], Deidre A. Hunter[3], Elias Brinks[4], Juan R. Cortés[5,6] & Phil Cigan[7]

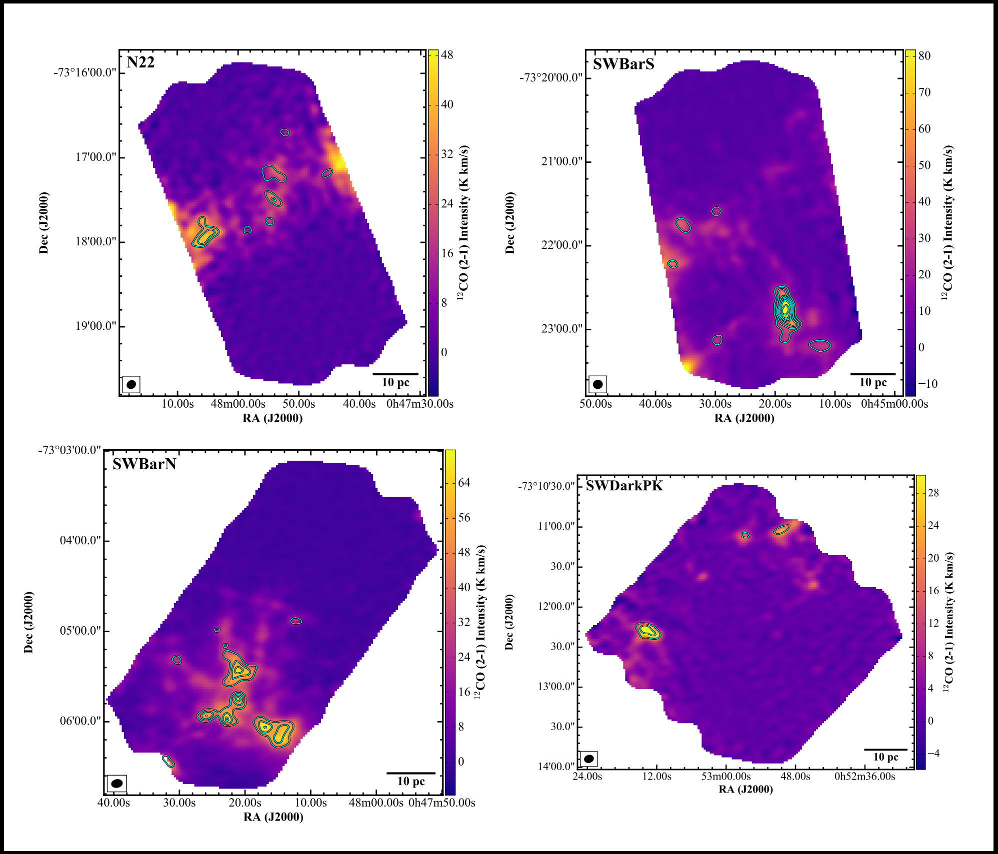


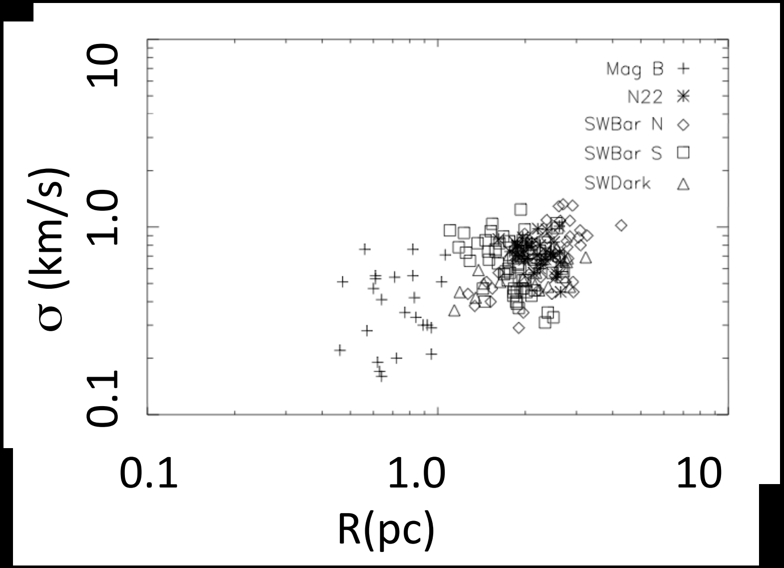
Rubio, M. Elmegreen, Hunter + 2015
NATURE <u>525, 218</u>

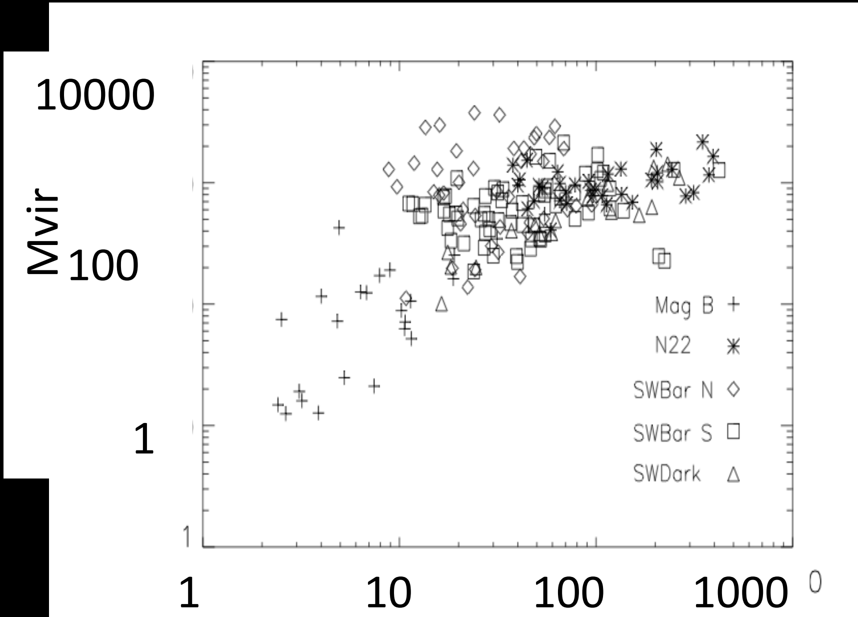
SMCALMA C2 CO21

PI: Jameson, K

Preliminary results



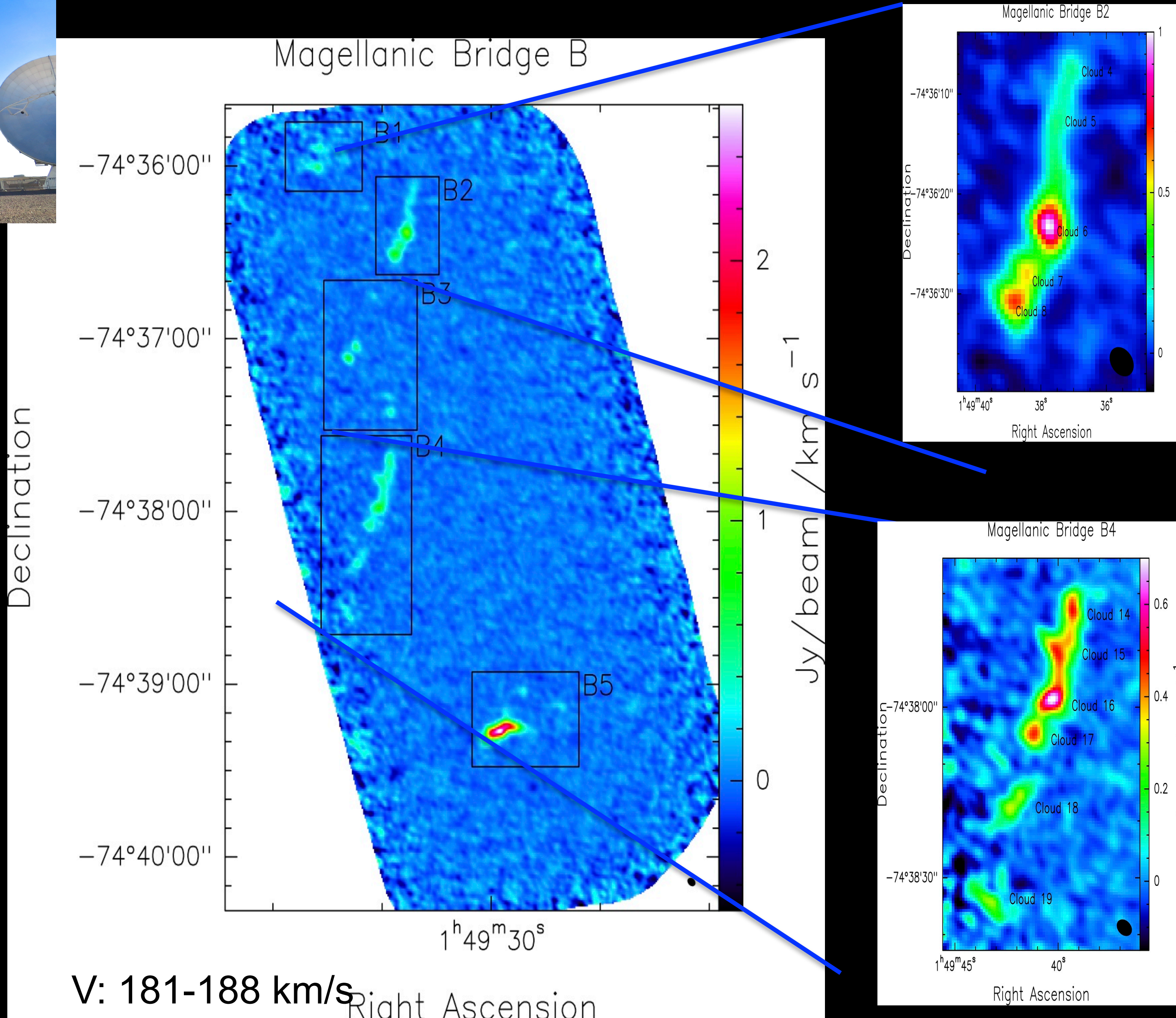




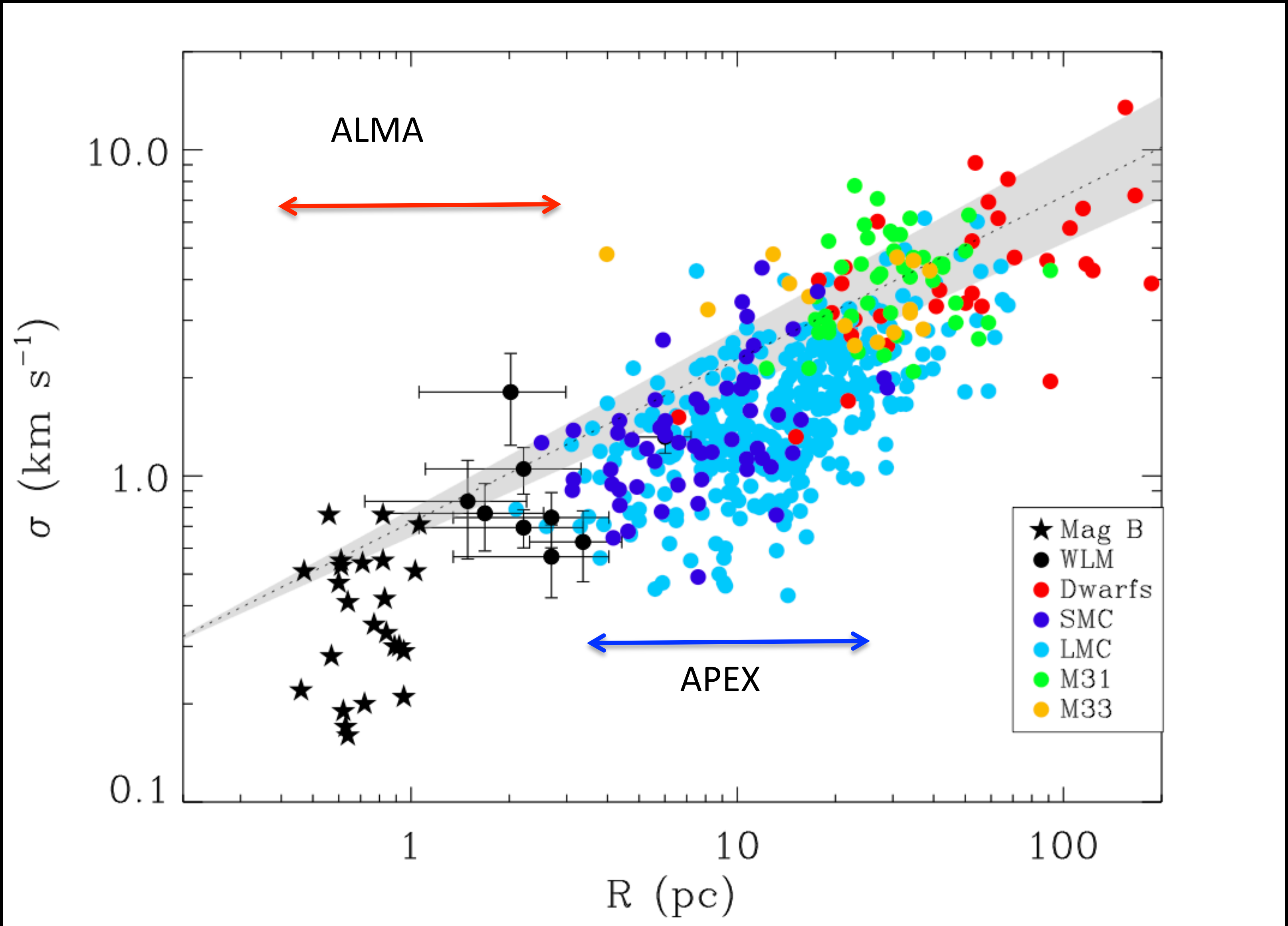
Magellanic Bridge B

ALMA C3

CO(1-0)



V: 181-188 km/s



24 CO clouds found in Magellanic Bridge B

NGC6822

12+log (O/H) =8.02

D= 474 +- 13 kpc

ALMA CO 2-1   0.9” ~ 2pc

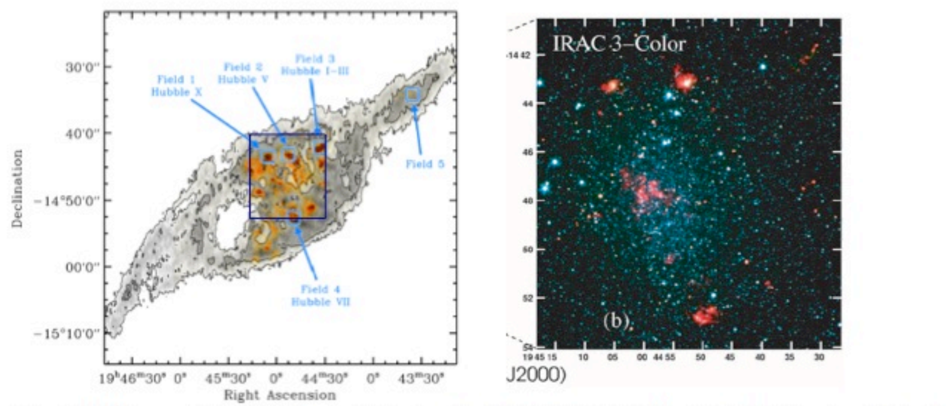
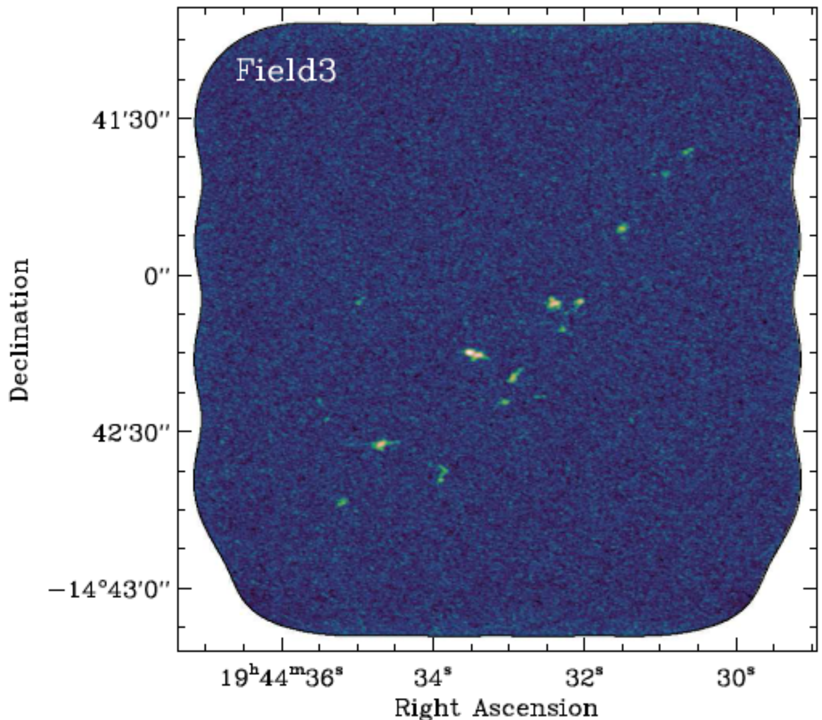
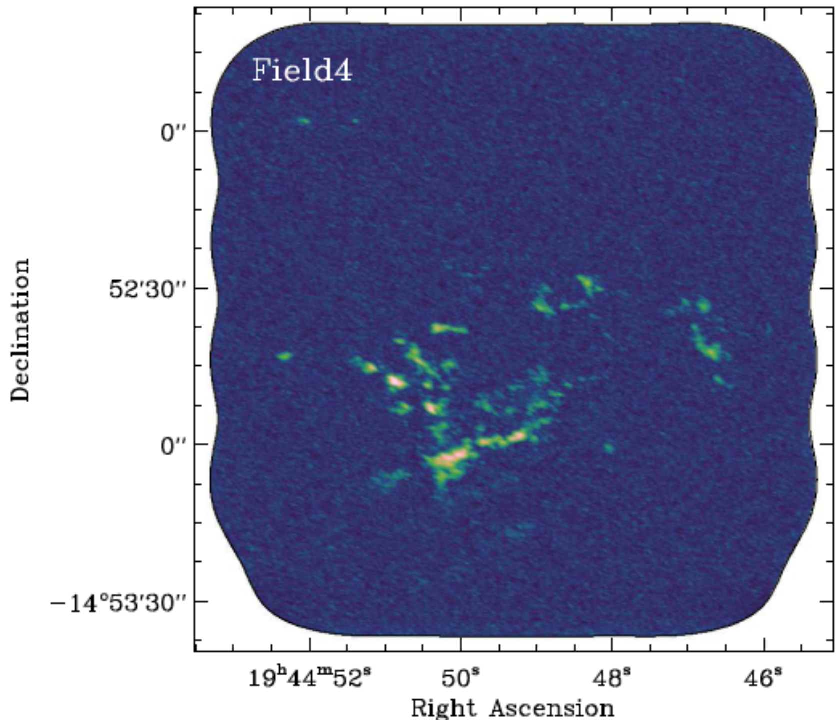


Fig. 2.—(a) H I and (b) IRAC images of NGC 6822; (a) shows the total H I column density distribution (de Blok & Walter 2000), while (b) shows the underlying stell and warm dust components. The three-color image shows the 3.6 μm band as blue, the 4.5 μm band as green, and the 8 μm band as red; regions of hot dust emissio indicative of active star formation, appear as diffuse regions of red emission. The box in (a) shows the approximate field of view shown in (b).

Schruba et al. 2016 Submitted



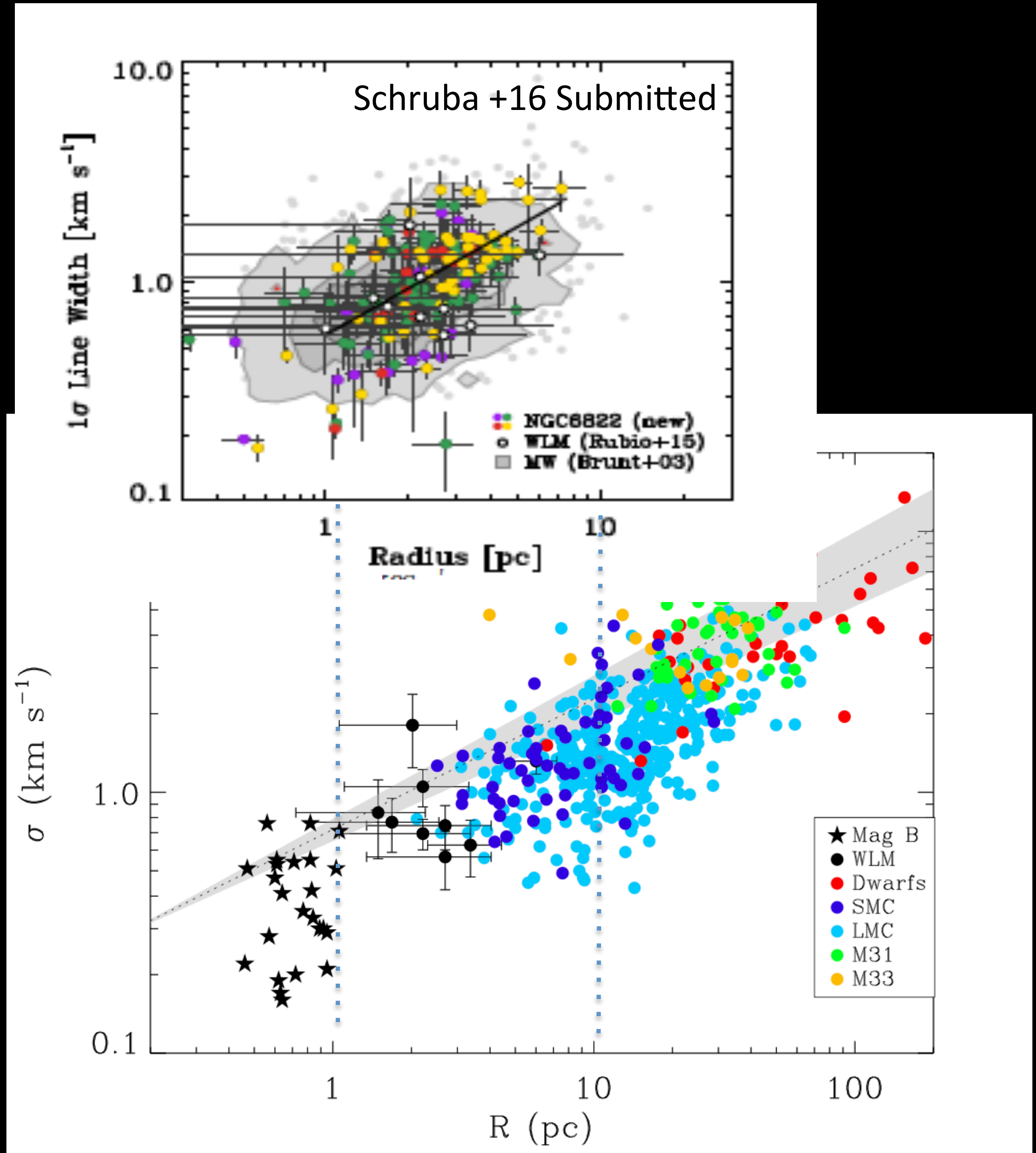


150 CO
compact bright
regions

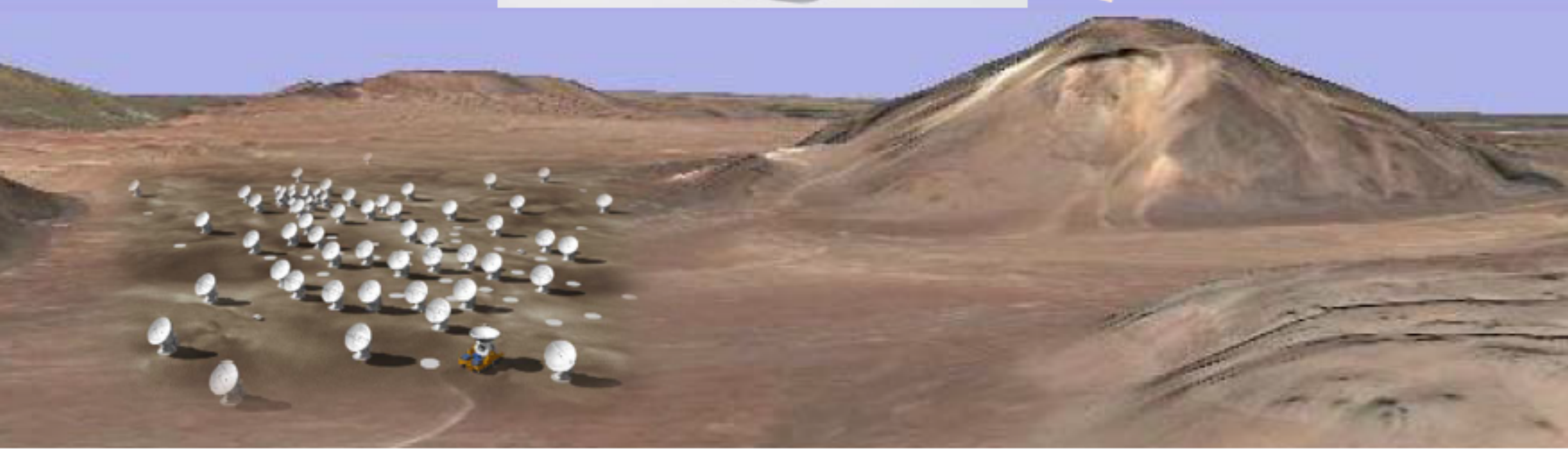
sizes 1-2 pc
line-widths ~ 1km/s
low filling factors

CO conversion
factor

~ 20 -25 times the
galactic value



TAO Telescope: Infrared and Optical Telescope at summit of Chajnantor (5640m)




Thanks