Exploring ISM and Star Formation Physics in the LMC and SMC in the SOFIA Era

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October 20, 2016

The complexity of the ISM

Multi-Physics

Multi-Scale (complex geometries)

Multi-Phase

Biased tracers (Excitation, chemistry)

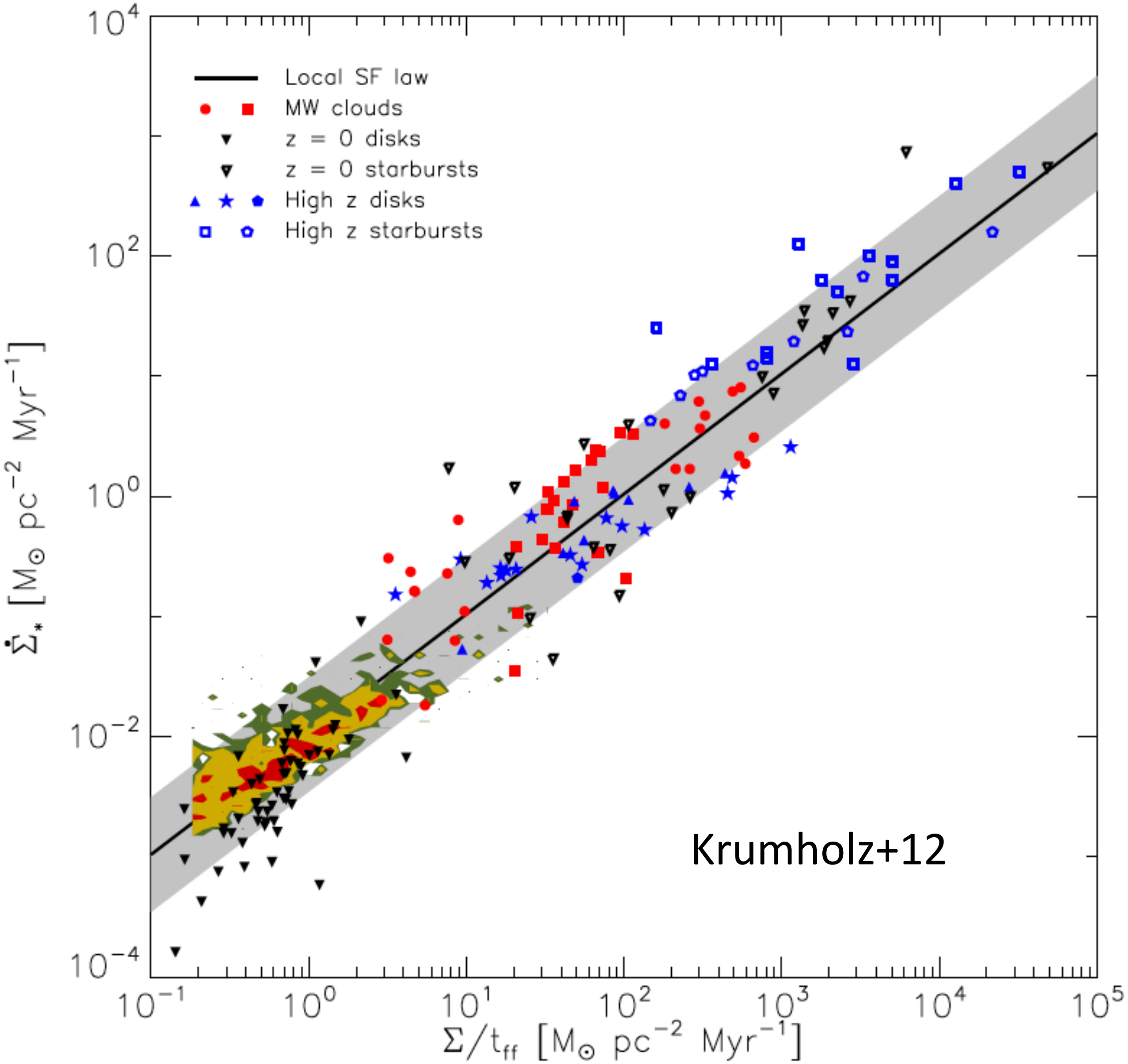
Confusion/beam dilution

Distance ambiguity

LMC R136

Hubble - NASA

Star Formation Relation



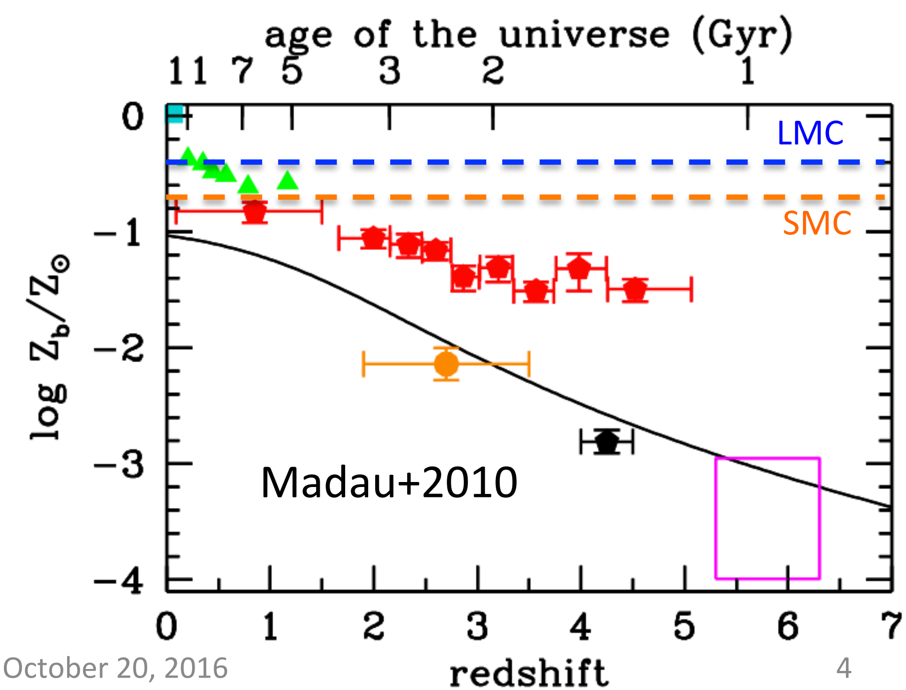
Complex ISM physics of SF and feedback lead to remarkably universal SF relation in dense gas

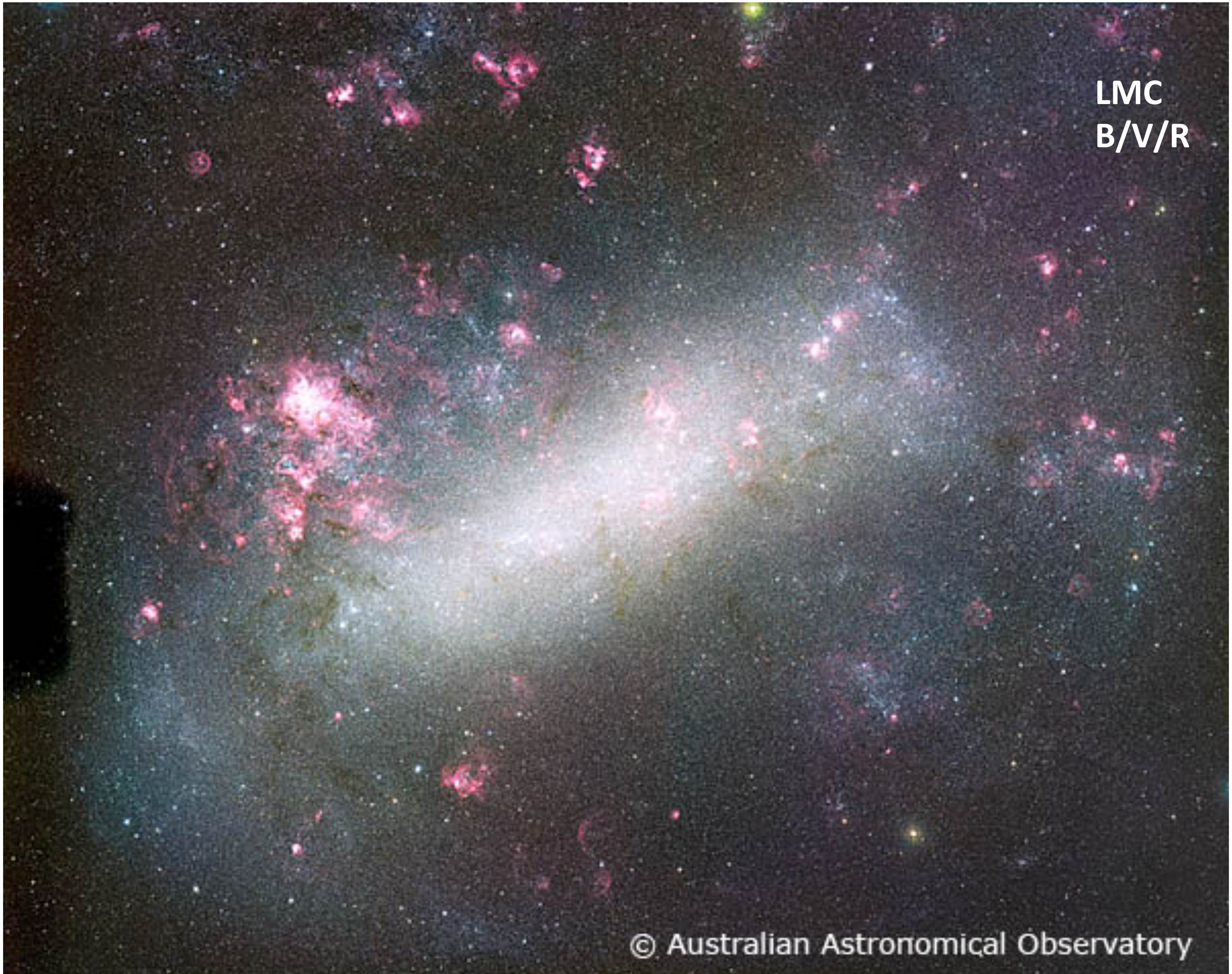
The Magellanic Clouds as laboratories for ISM/SF physics

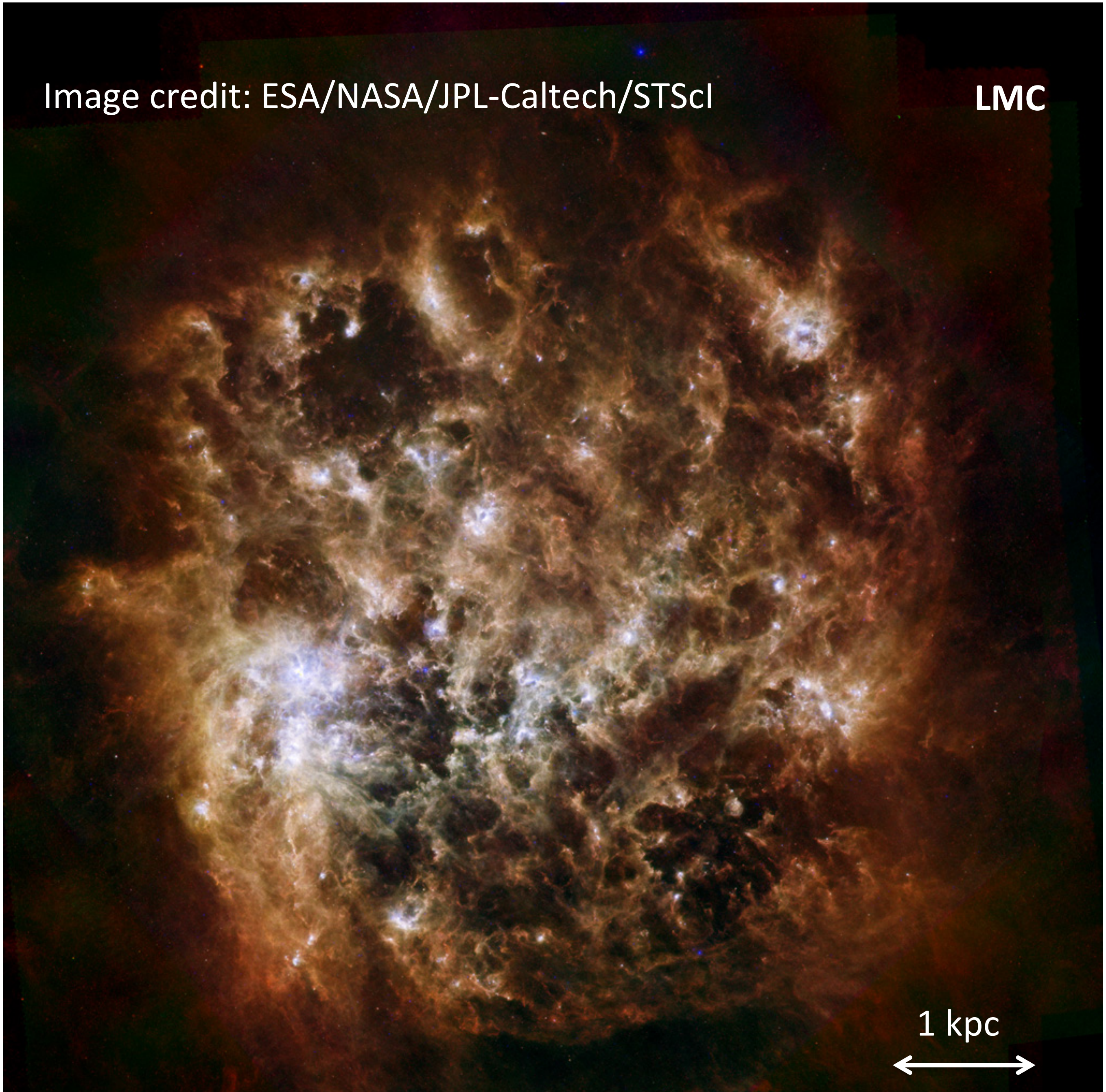
- LMC/SMC (currently) only 2 galaxies where ISM processes can be resolved at the level of individual stars and clouds while also getting the broad spatial coverage needed understand the ISM on global scales
  - Providing context to ISM Processes is much easier there than in the MW
  - Sub-GMC-scale studies of SF relation possible (See Talk by B. Ochsendorf)

- LMC has face-on geometry
  - HI disk is ~120 pc thick (Elmegreen+2001)
  - SMC elongated along l.o.s with complex velocity structure

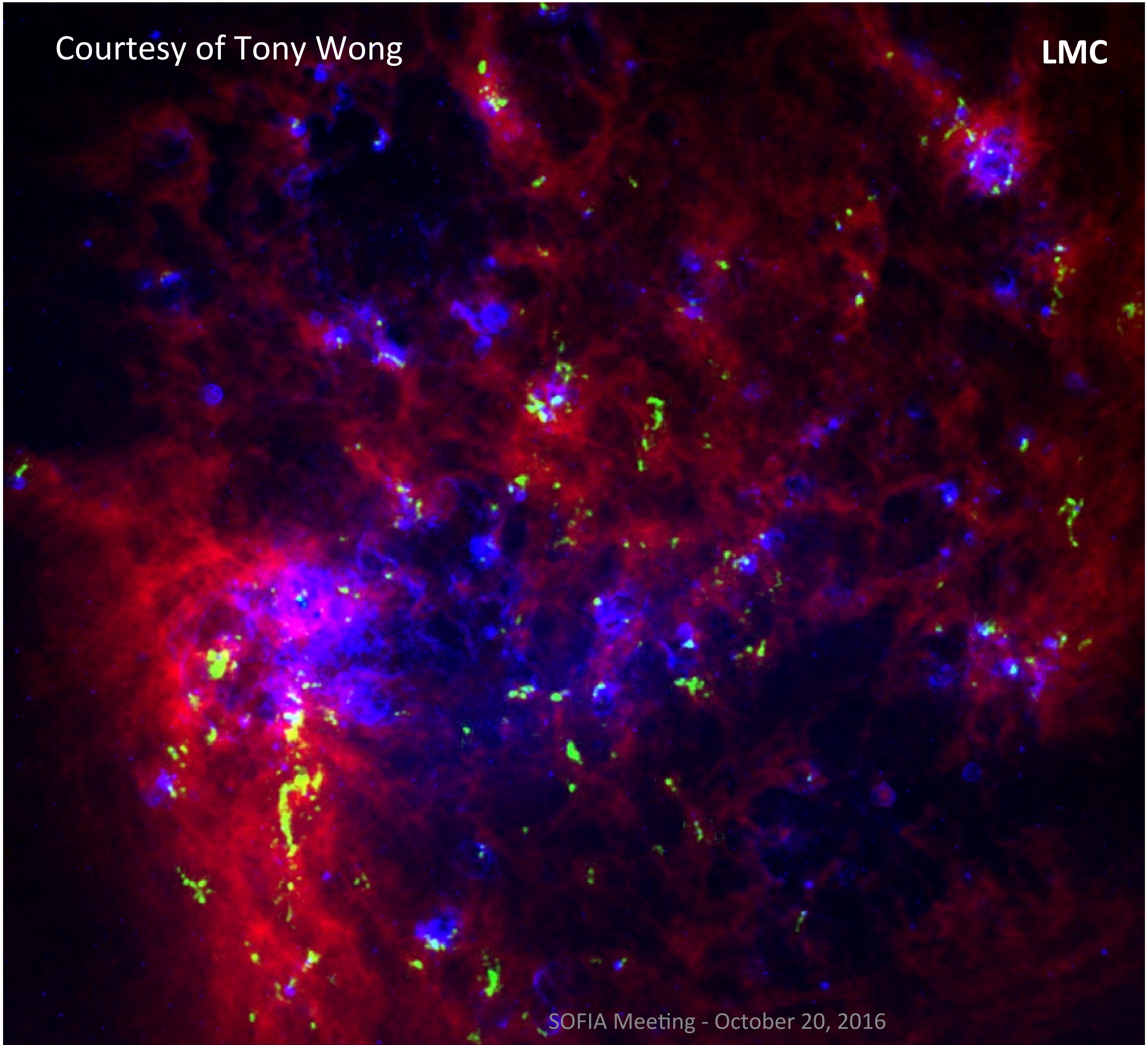
- Metallicity of LMC (0.5 solar) and SMC (0.2 solar) span metallicity of galaxies at the peak of cosmic star formation




LMC
B/V/R
© Australian Astronomical Observatory



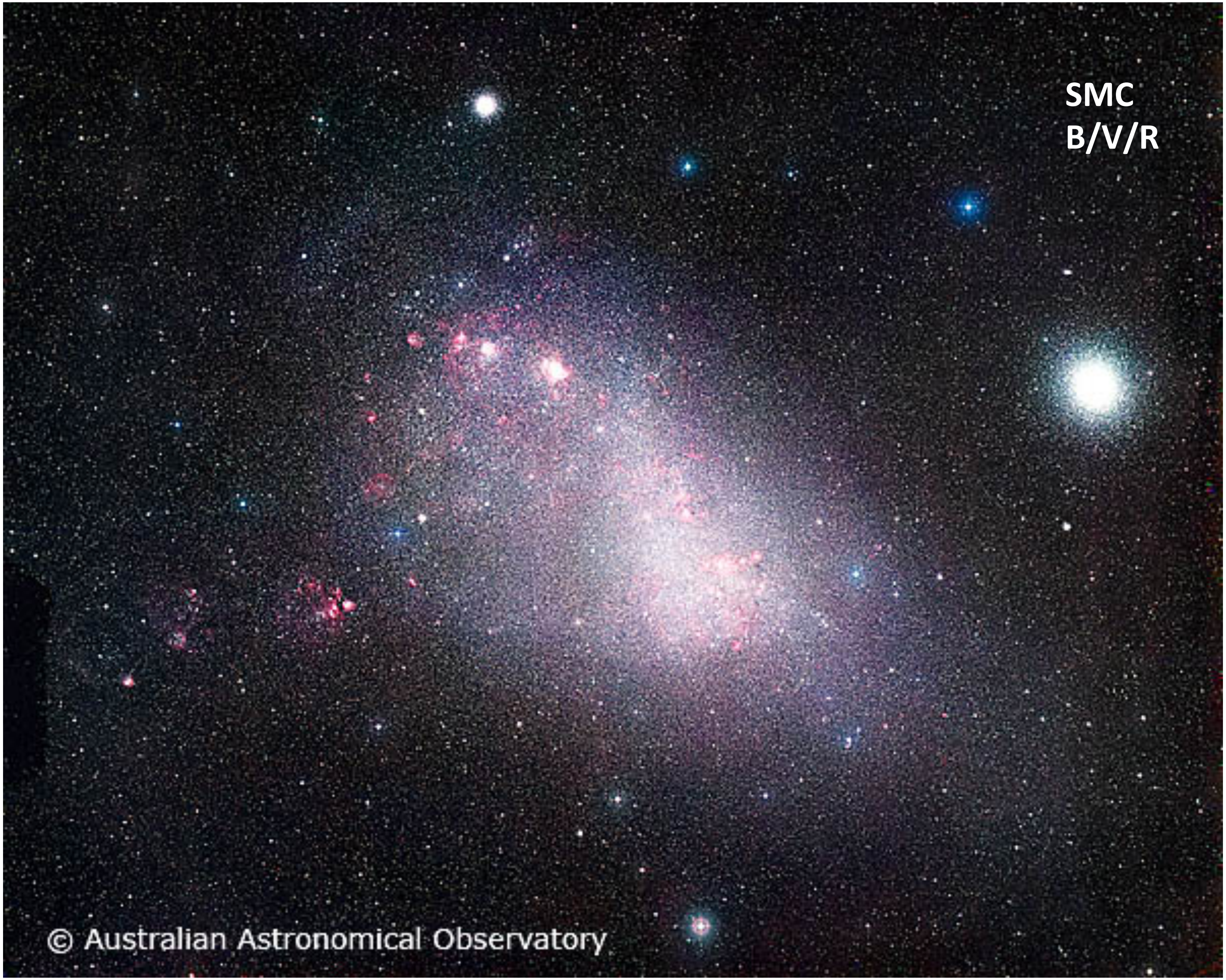
Herschel 250 mic
Herschel 100+160 mic
Spitzer 24+70 mic

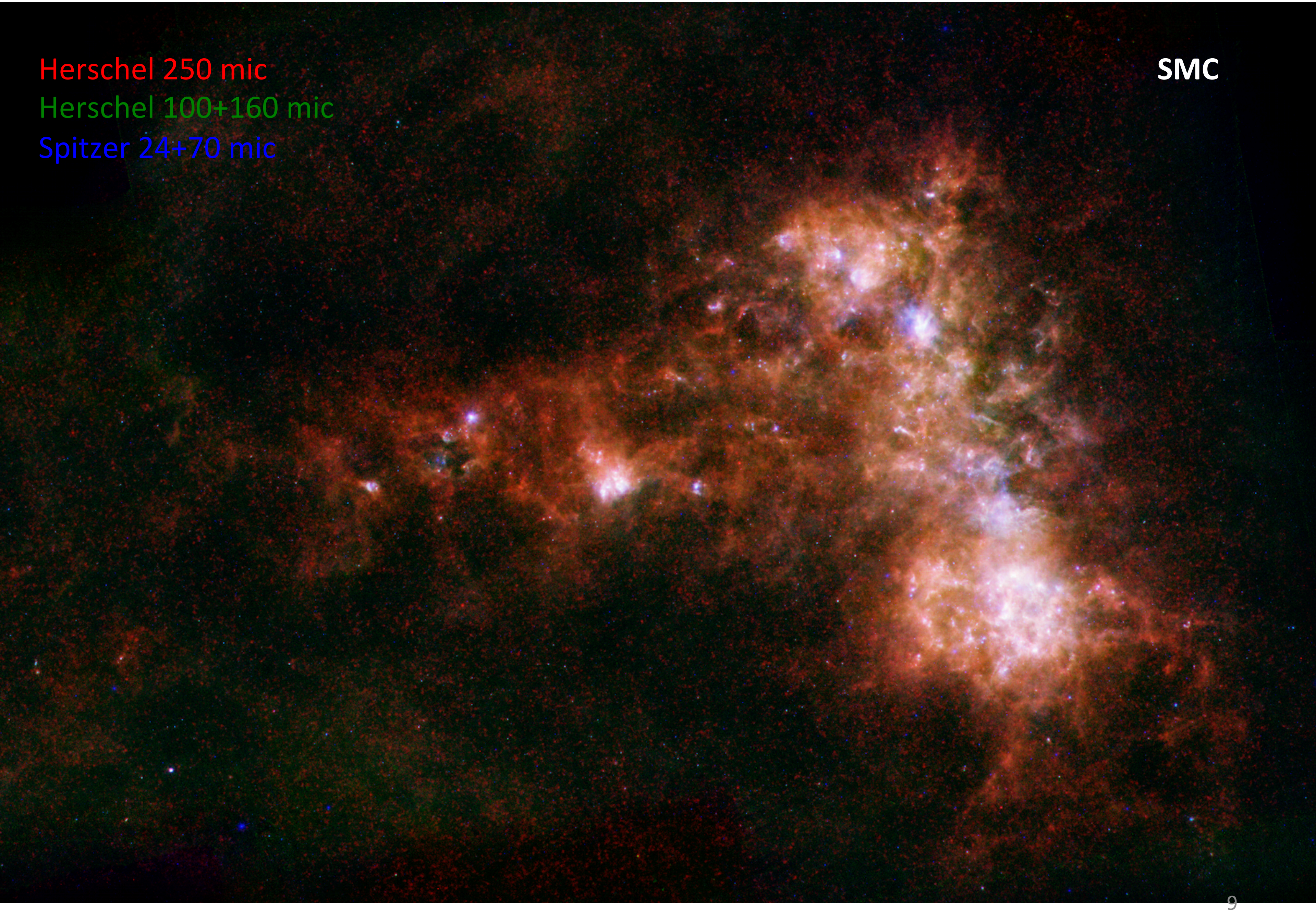


ATCA HI 21 cm
MAGMA CO
MCELLS Hα

Coverage:
8x8deg^2

Resolution: 15 pc
(limited by HI)


SMC
B/V/R
© Australian Astronomical Observatory


Herschel 250 mic
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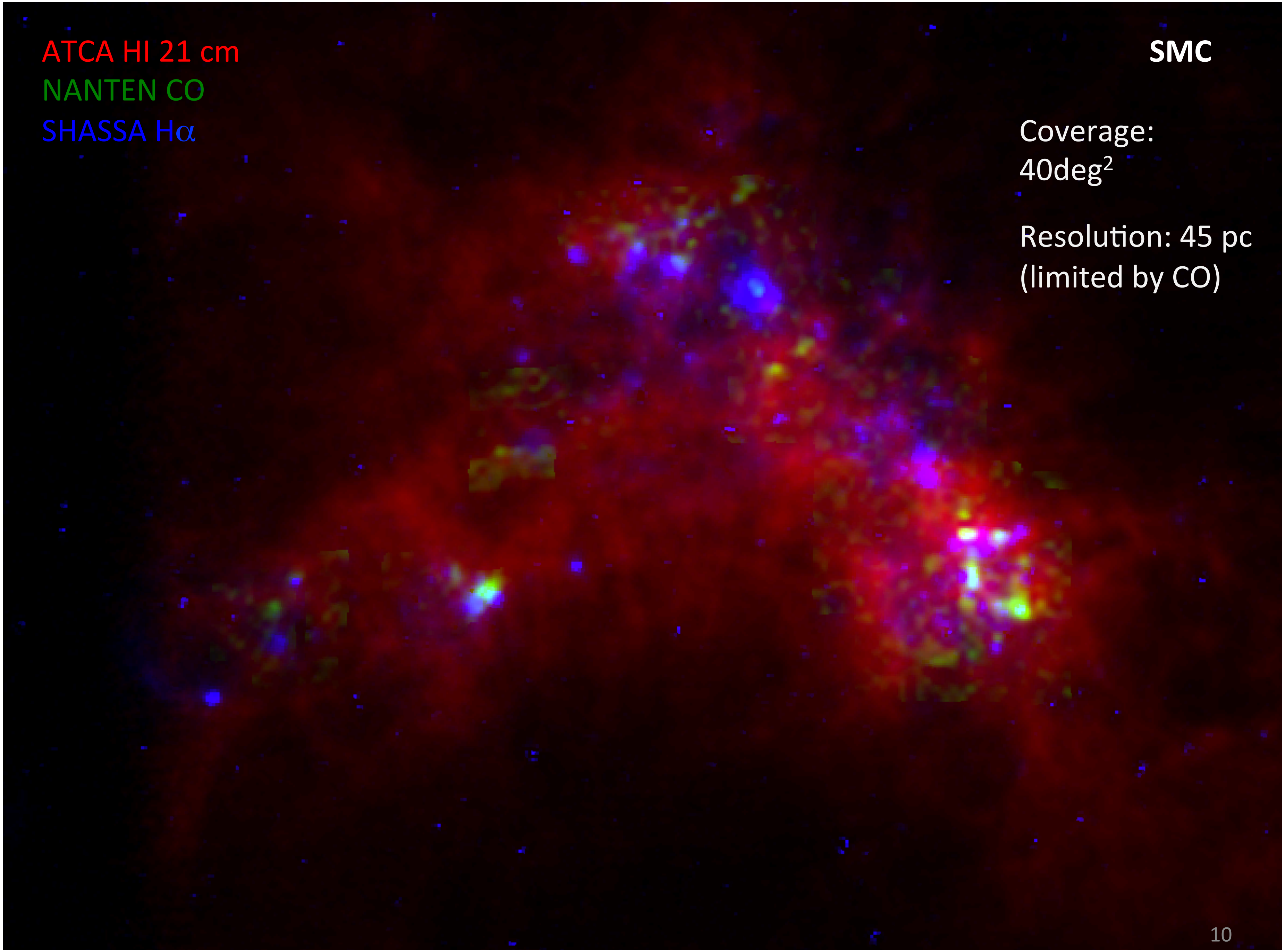
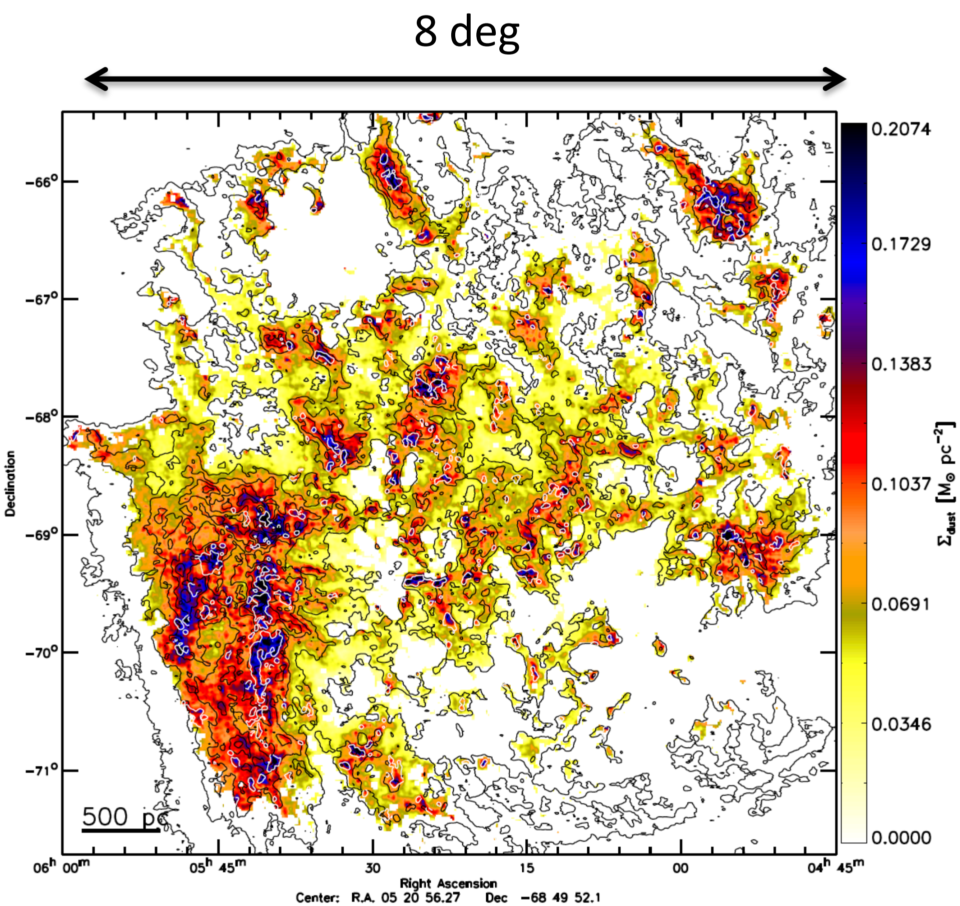
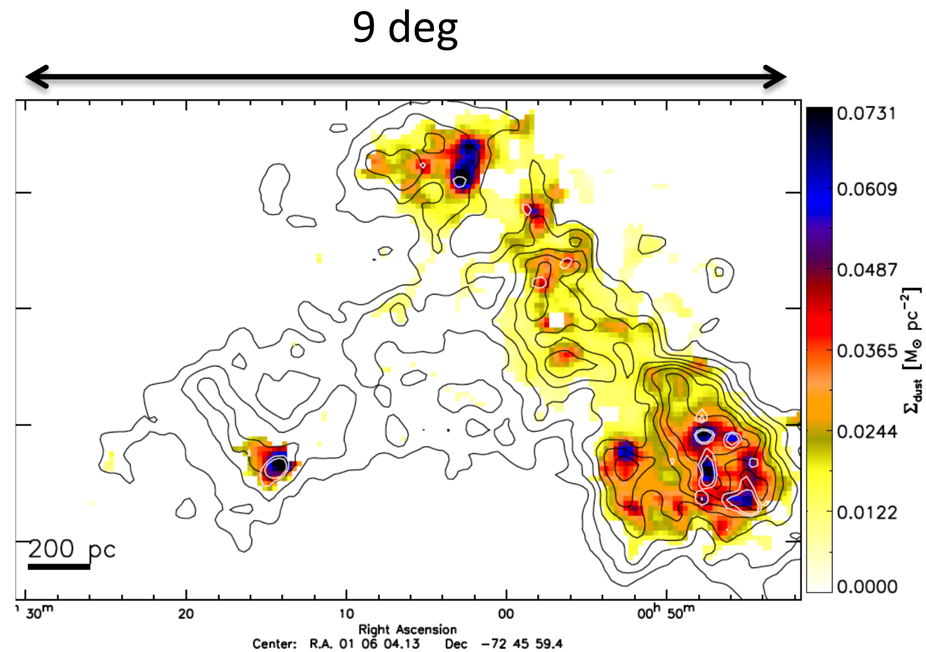
SMC


ATCA HI 21 cm
NANTEN CO
SHASSA Hα
SMC
Coverage:
40deg²
Resolution: 45 pc
(limited by CO)

Dust maps

Dust modeling built in a probabilistic SED fitting framework yields dust surface density and temperature maps (Gordon+2014, Roman-Duval+2014)





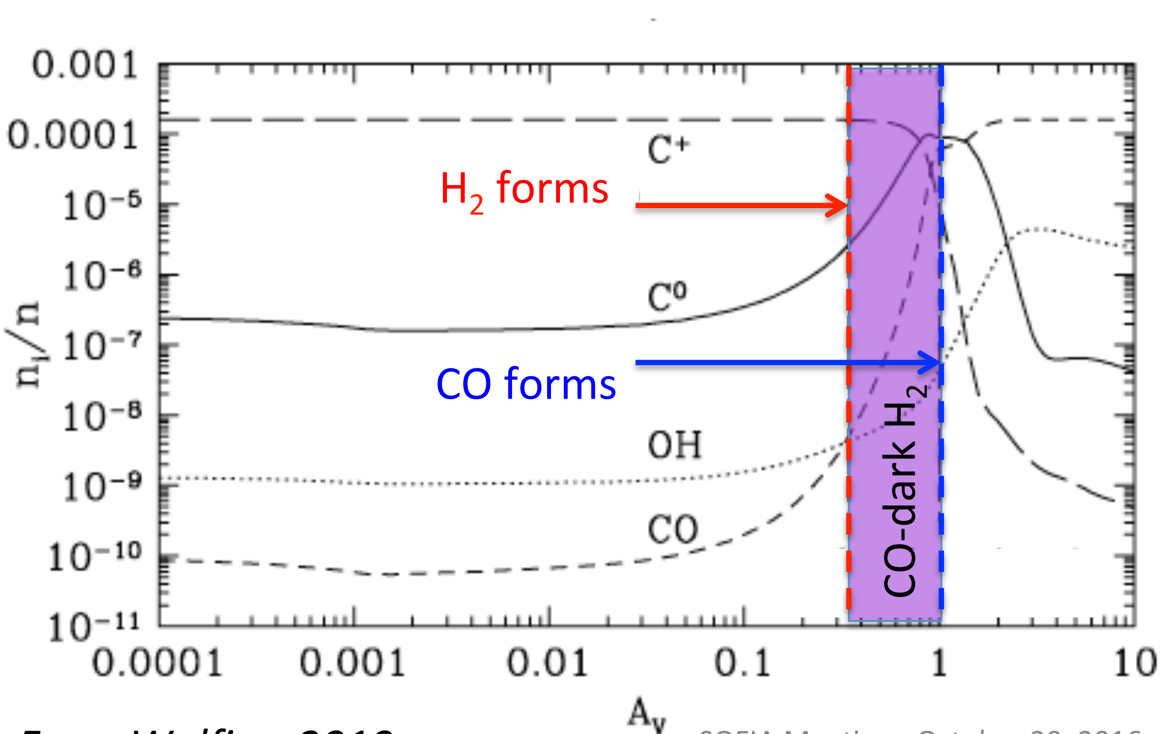
Outline

- ISM structure is a determinant factor in the SF process
  - What are the effects of metallicity on the structure of the ISM?
- How can we trace the ISM at low (and solar) metallicity?
- What the effects of metallicity on the SF process?
- How do dust properties change at low metallicity and how does this affect our understanding of the ISM and SF?

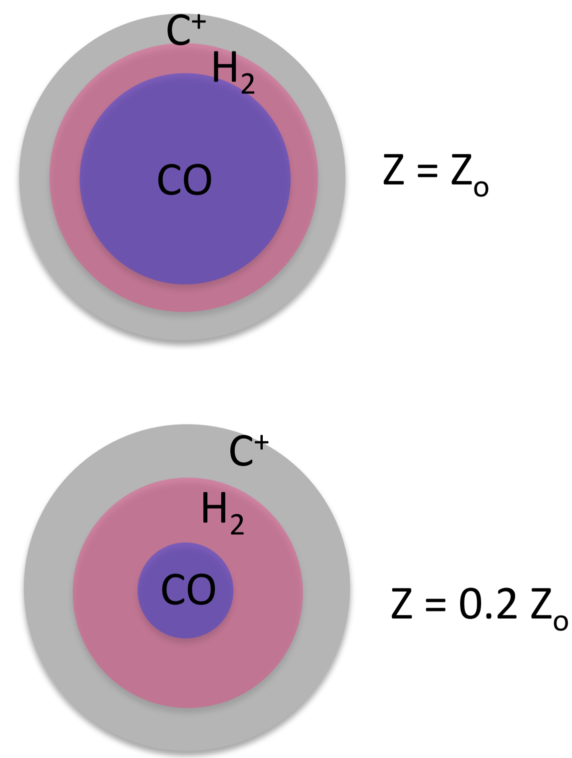
Effects of Metallicity on ISM structure

Effects of metallicity on ISM structure and composition: CO distribution

- Dust abundance and shielding is reduced
  - Higher gas column density required to form CO
  - Filling factor of dense ISM reduced

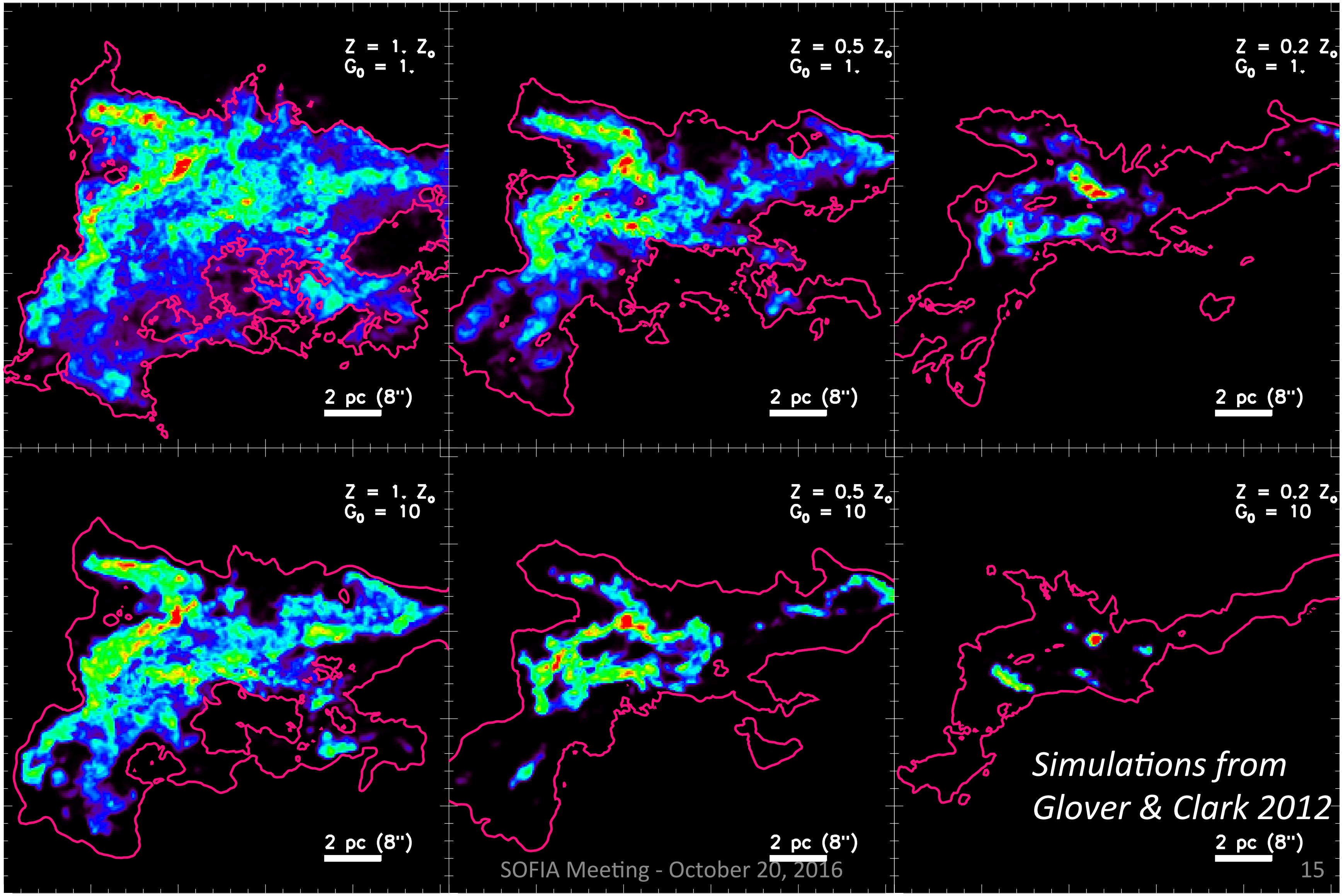


From Wolfire+2010



H_2 formation timescale α nZ

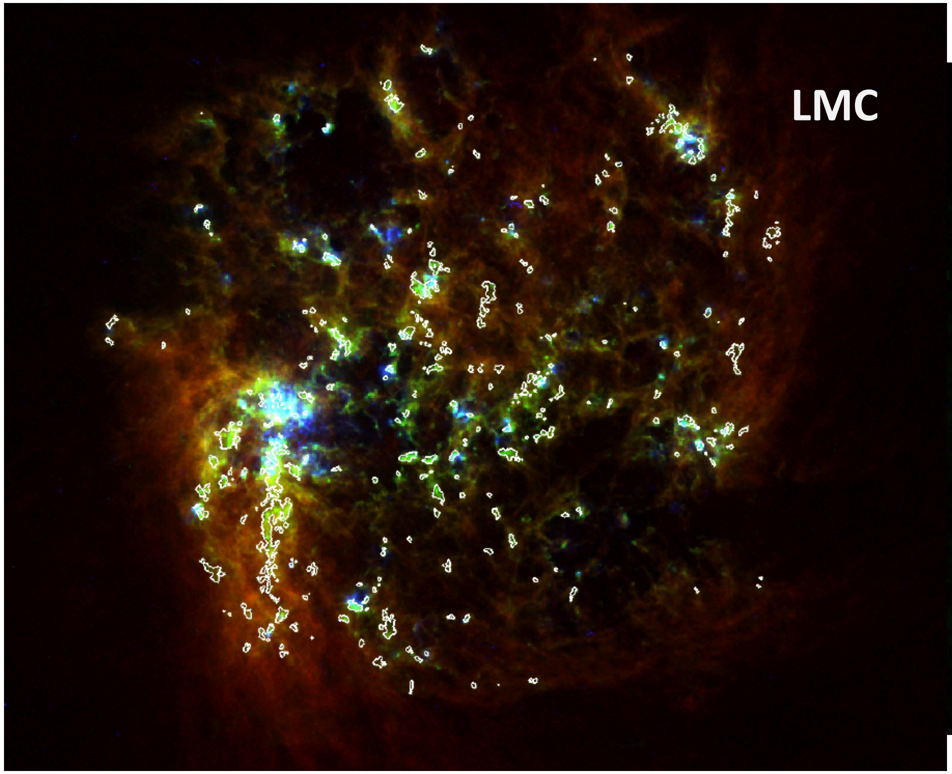
Effects of metallicity on CO and H_2 structure

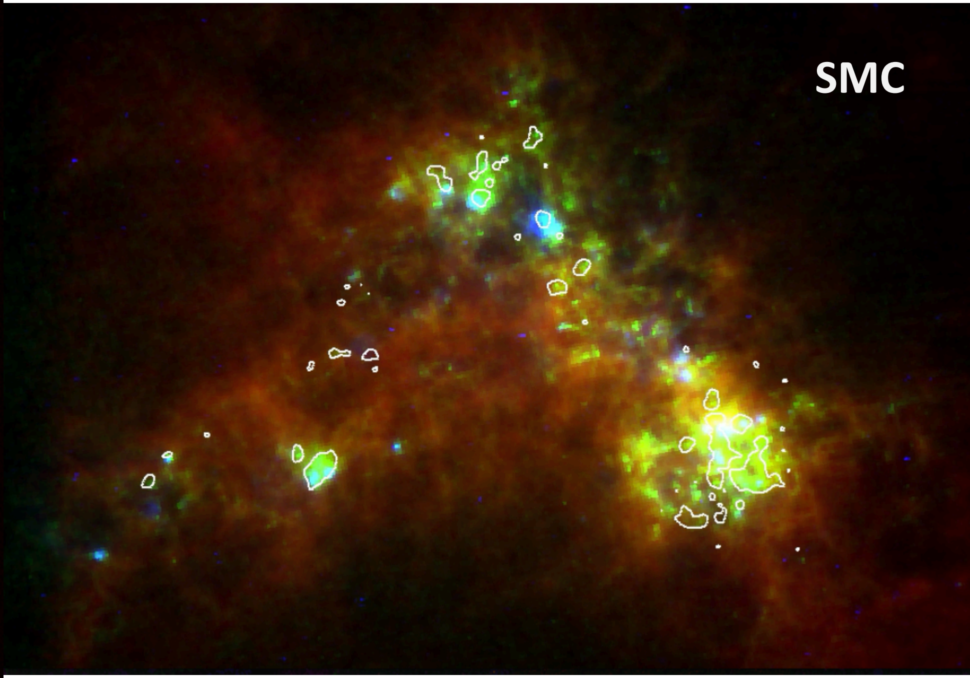


Small Filling Factor of dense ISM

Lack of dust shielding leads to small filling factor of CO gas in LMC and SMC

Roman-Duval+2014, Jameson+2016





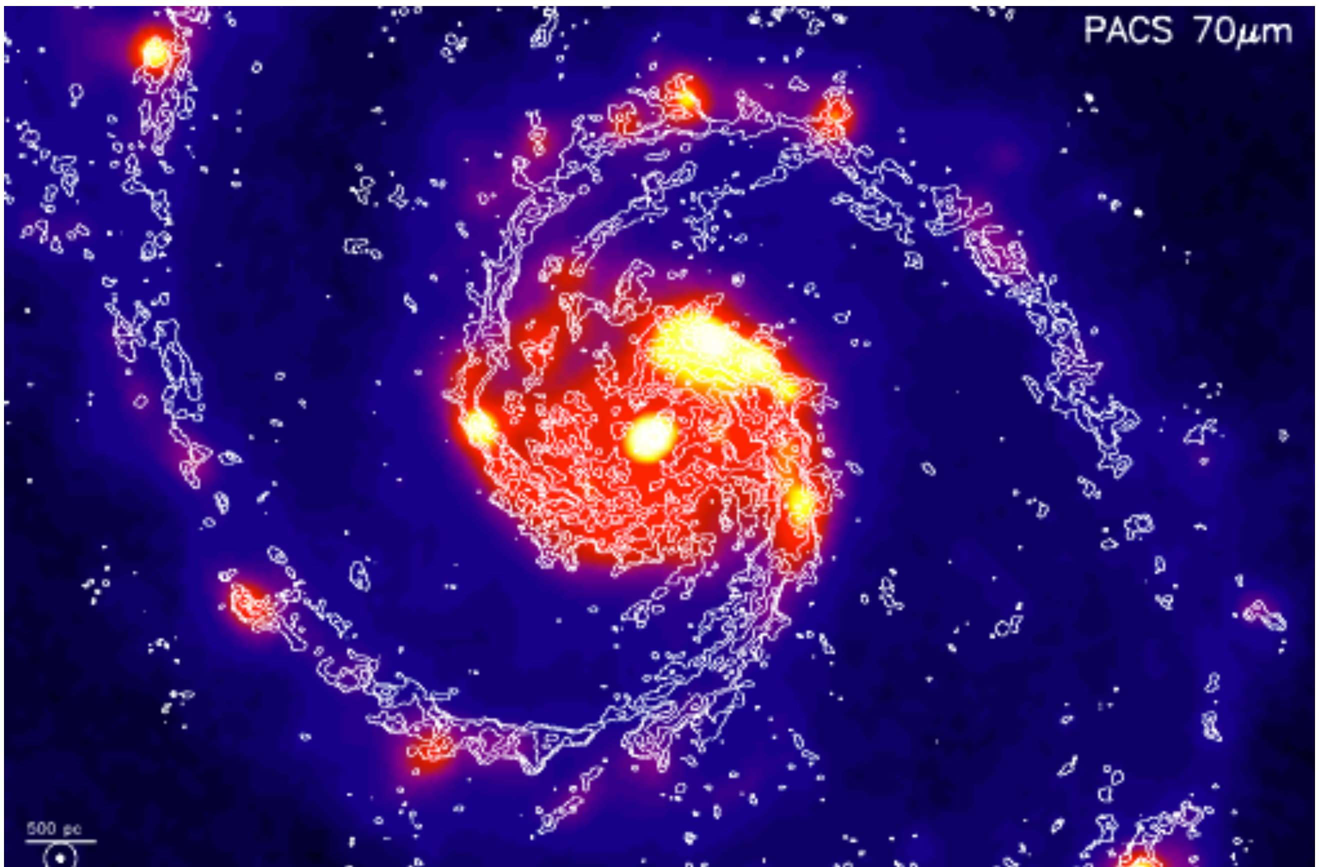
$M(HI) = 4 \times 10^8\ M_o$
$M^{CO}(H_2) = 10^7\ M_o$
$M^{dust}(H_2) = (1\text{-}6) \times 10^7\ M_o$

HI
SPIRE 250
Hα

$M(HI) = 3.5 \times 10^8\ M_o$
$M^{CO}(H_2) = (0.07\text{-}0.4) \times 10^7\ M_o$
$M^{dust}(H_2) = (0.2\text{-}2) \times 10^7\ M_o$

Comparison to M51

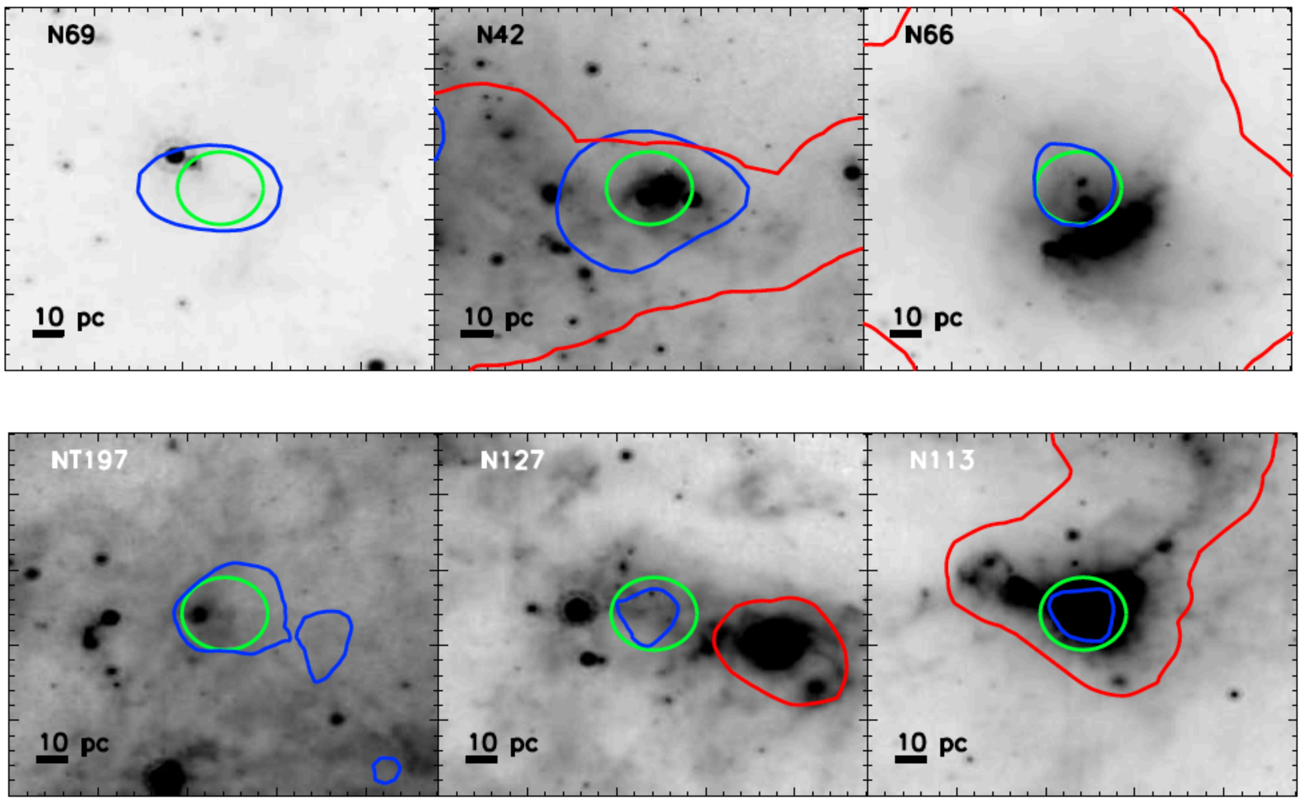
CO from PAWS (Schinnerer+2013, PdBI)



M(HI) = 2.8×10^9 M_o
$M^{CO}(H_2)$ = $6.2 \times 10^9 M_o$

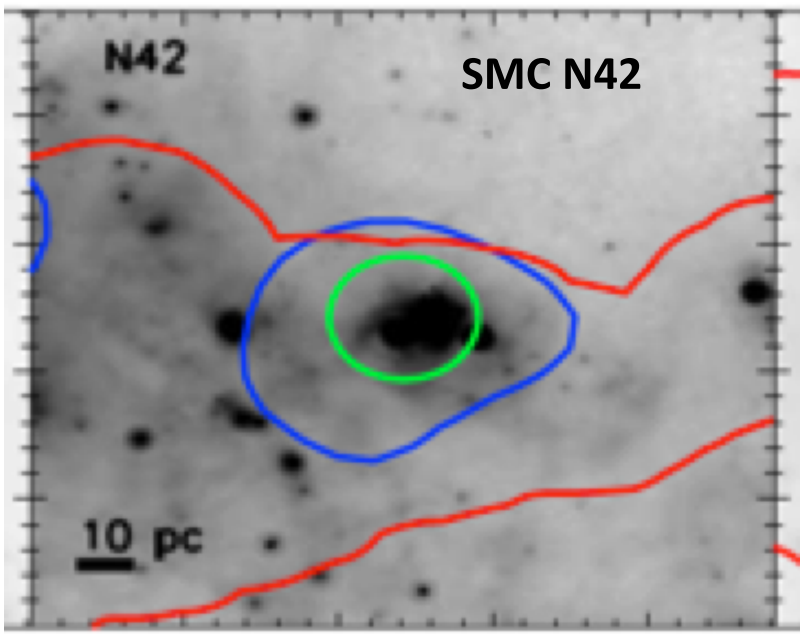
Characterizing CO structure at low metallicity with ALMA

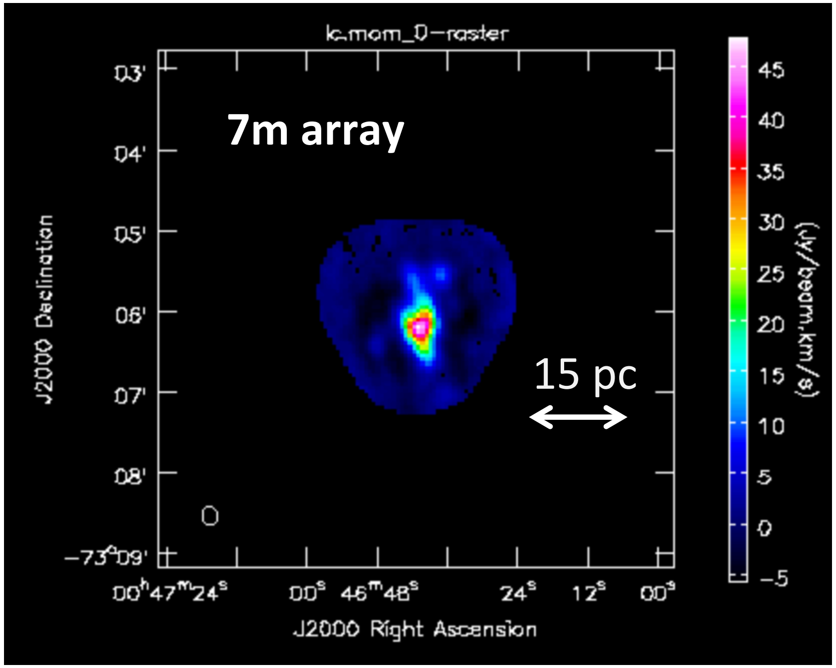
- Cycle 4 ALMA program to map 12CO, 13CO, C18O 1-0 and 2-1
  - 6 regions in LMC and SMC spanning range of G_0
- Tony Wong has another program to map 4 more regions

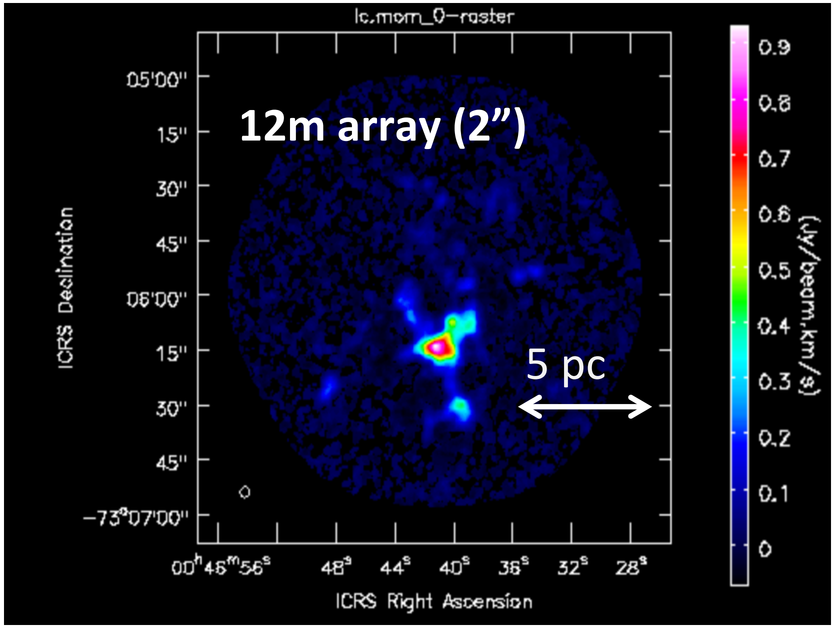


Characterizing CO structure at low metallicity with ALMA

Follow up with SOFIA in CII?



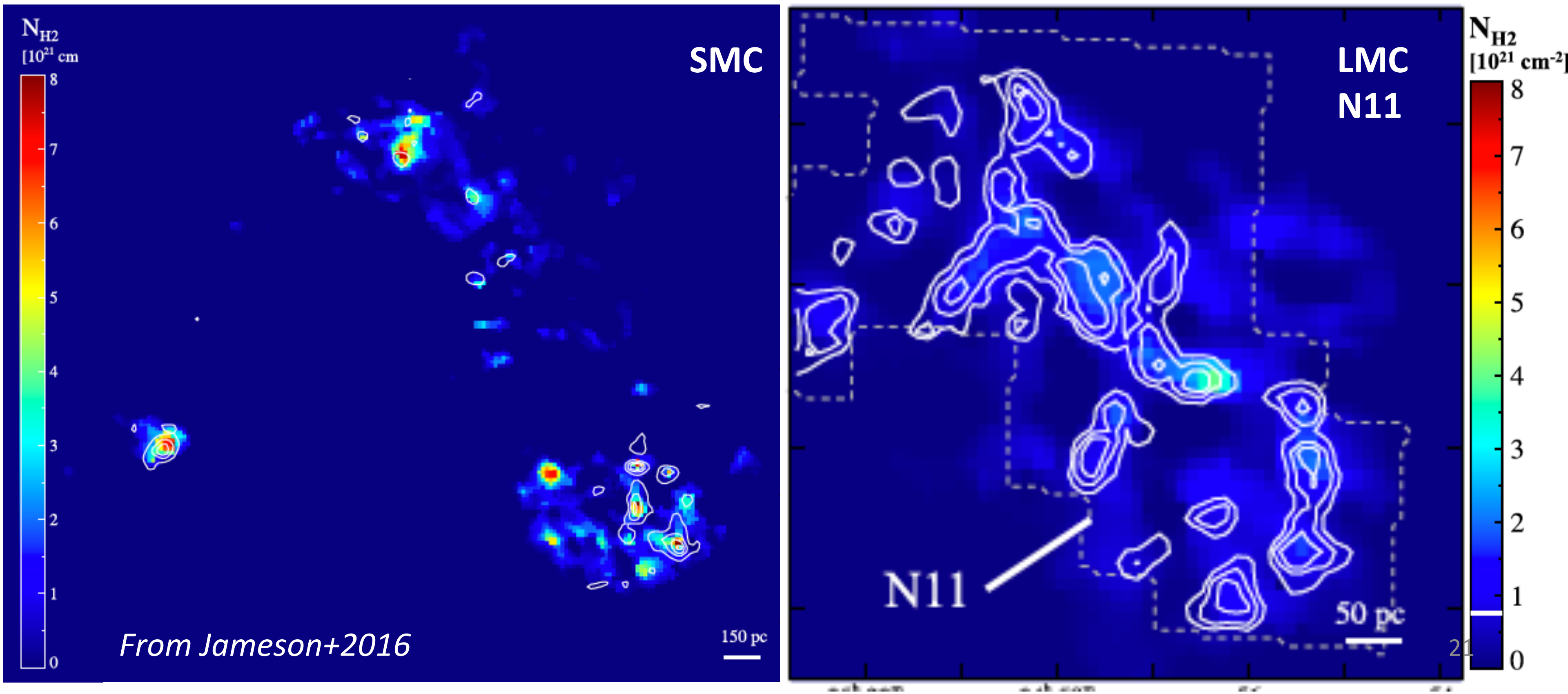




Tracing the low-metallicity ISM with FIR spectroscopy

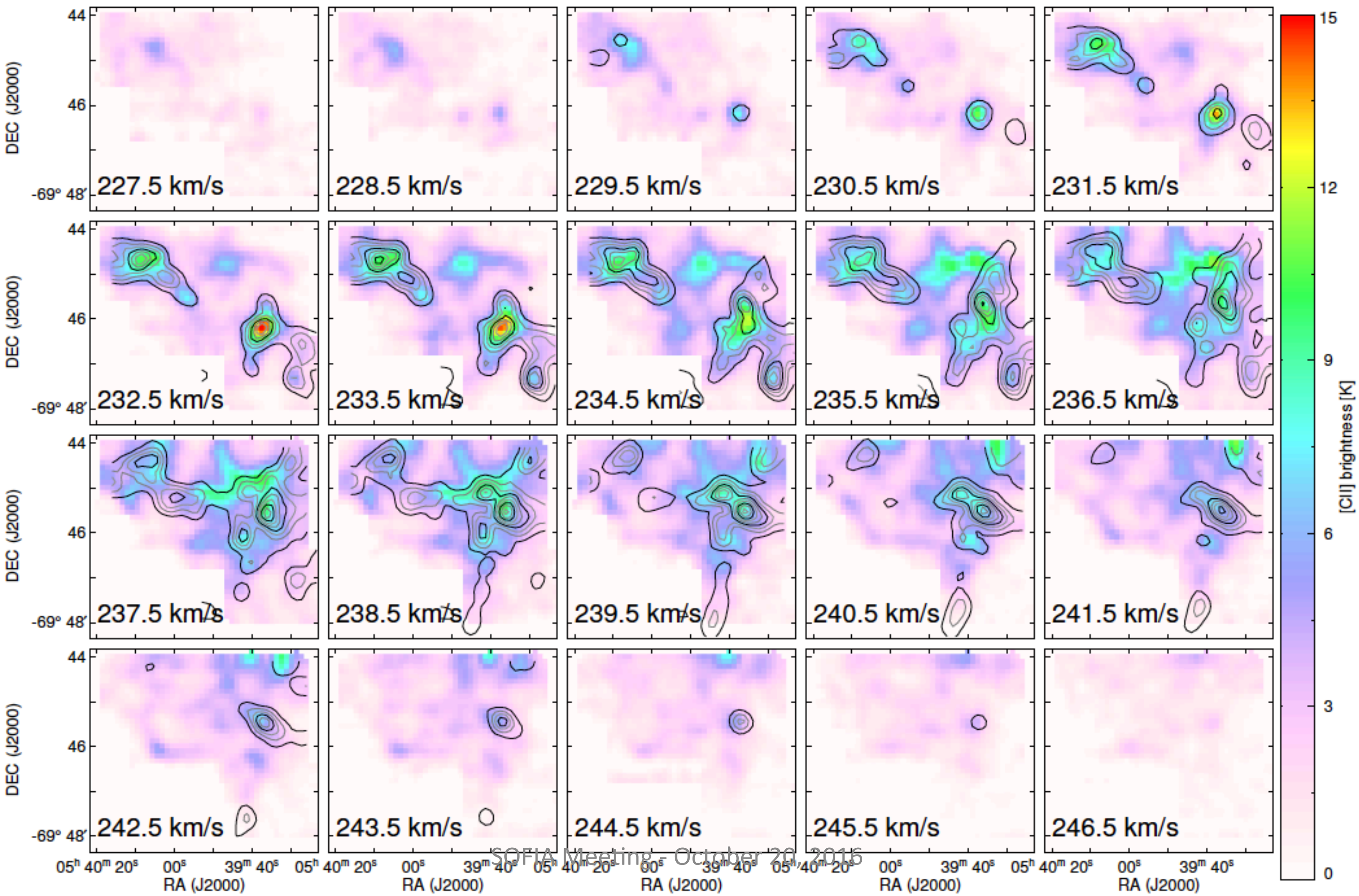
Dust-based H_2 maps

- The CO-dark H_2 can be traced from its dust emission
  - $\Sigma(H_2)$ = G/D x Σ_{dust} – Σ(HI) (See Jameson+2016)
  - Large systematic uncertainties (x2-3) due to degeneracy between dust mass/emissivity and G/D uncertainty and variations



SOFIA can observe [CII] in the LMC

- Okada+2015 mapped N159 (LMC) in [CII] with GREAT
- [CII] more extended than CO 3-2 (black contours, from APEX)



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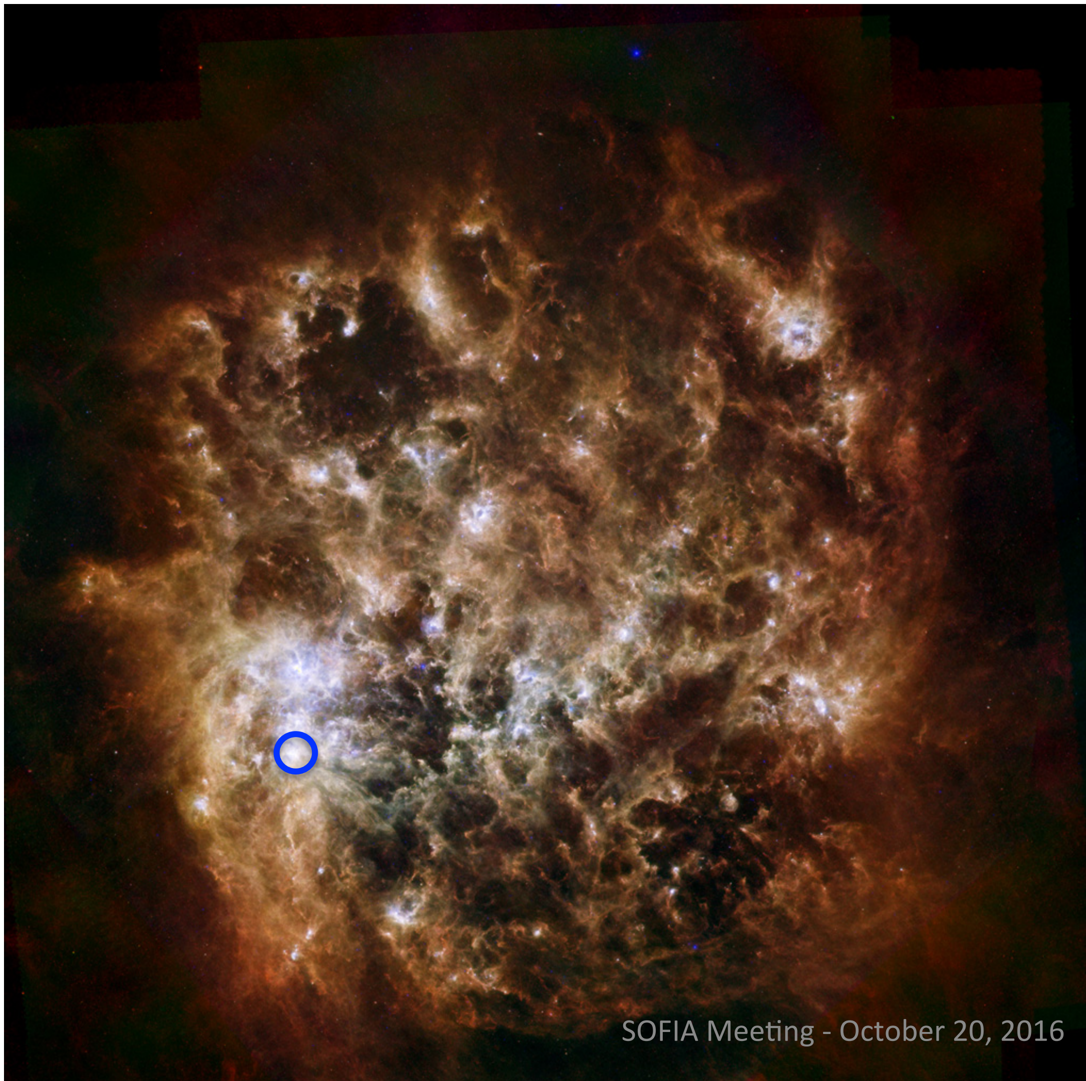
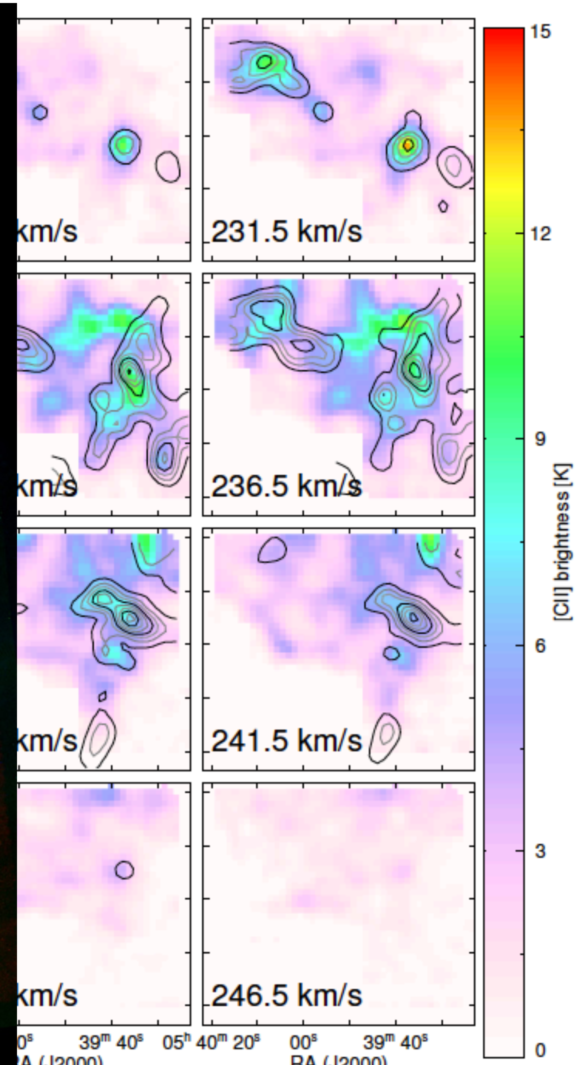
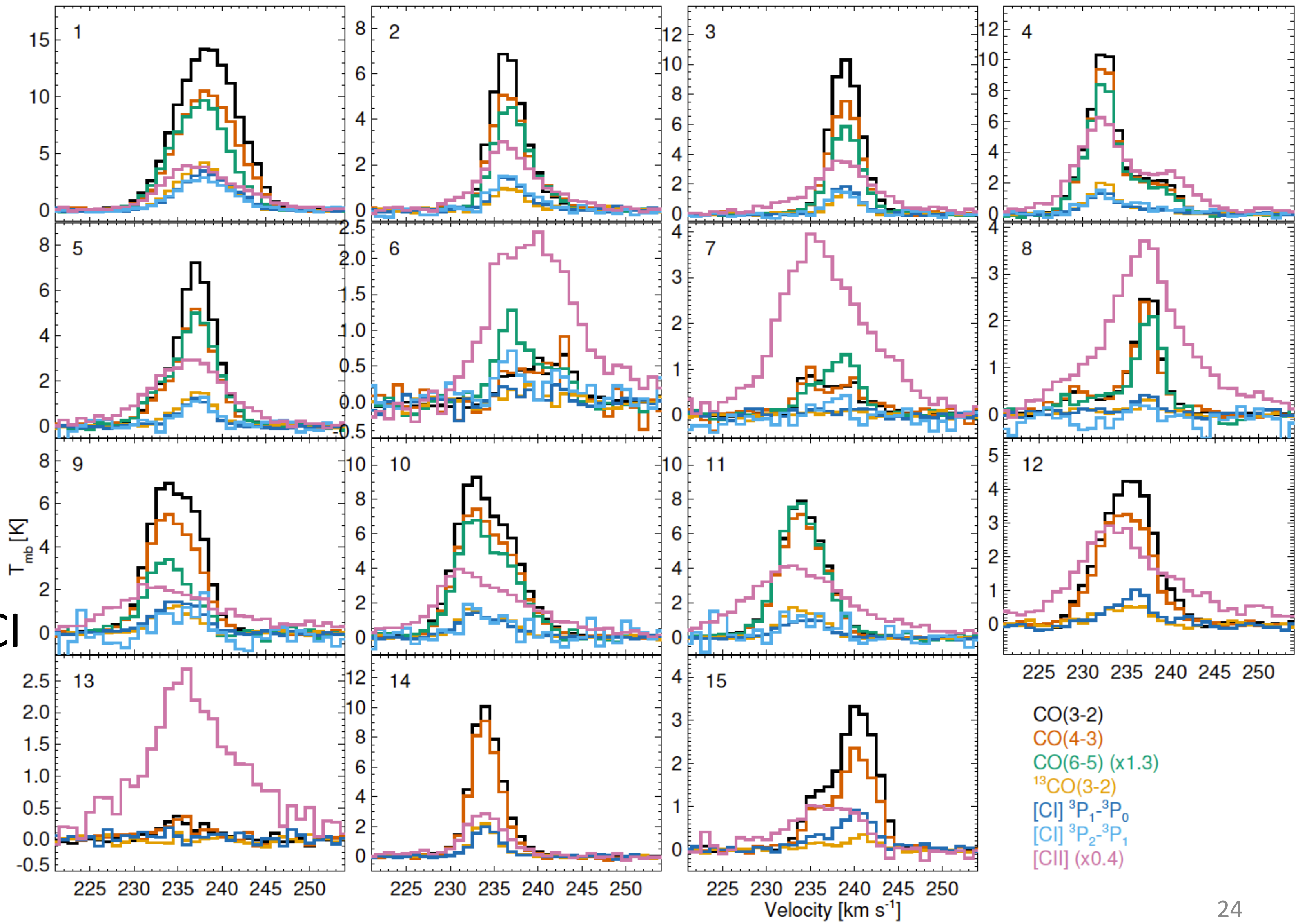




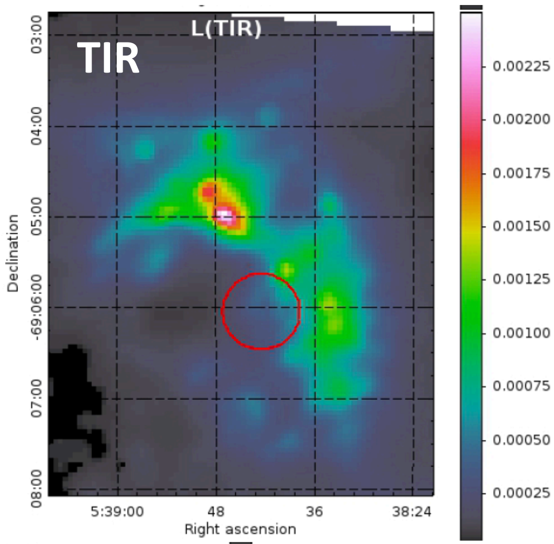
[CII] velocity structure in N159

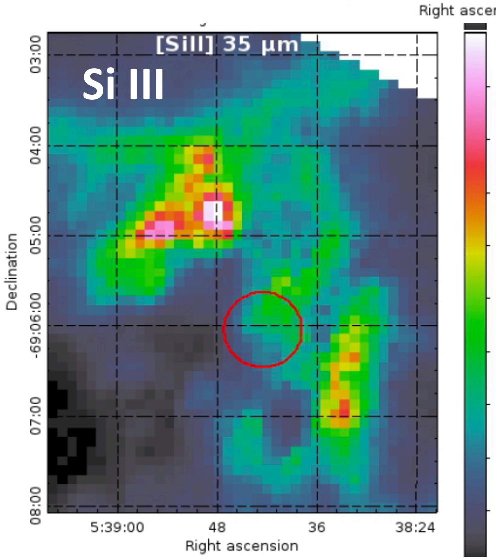
[CII] spectrally more extended than CO, CI

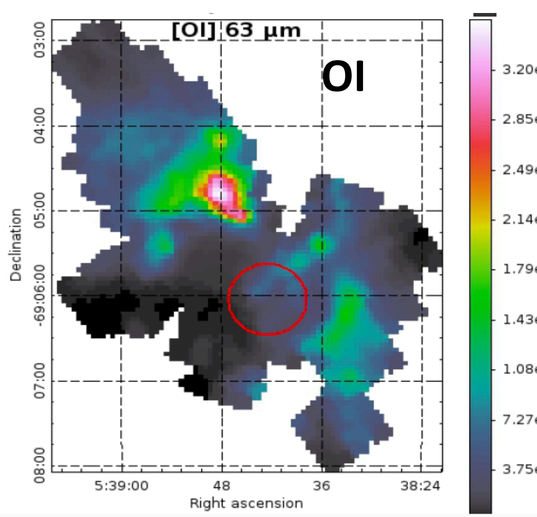


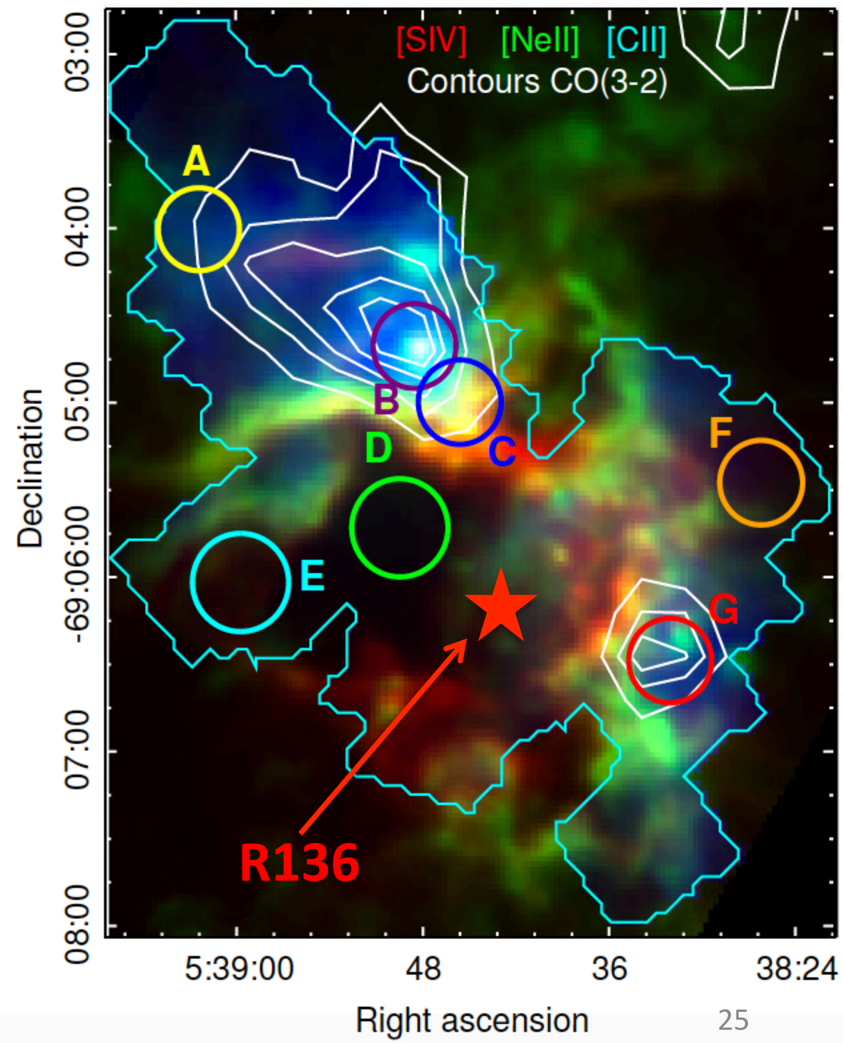
Characterizing the ISM in 30-Dor

- Wealth of FIR data in LMC 30-Doradus (Chevance+2016)
  - Herschel PACS, SPIRE/FTS, Spitzer/IRS, Mopra, Aste





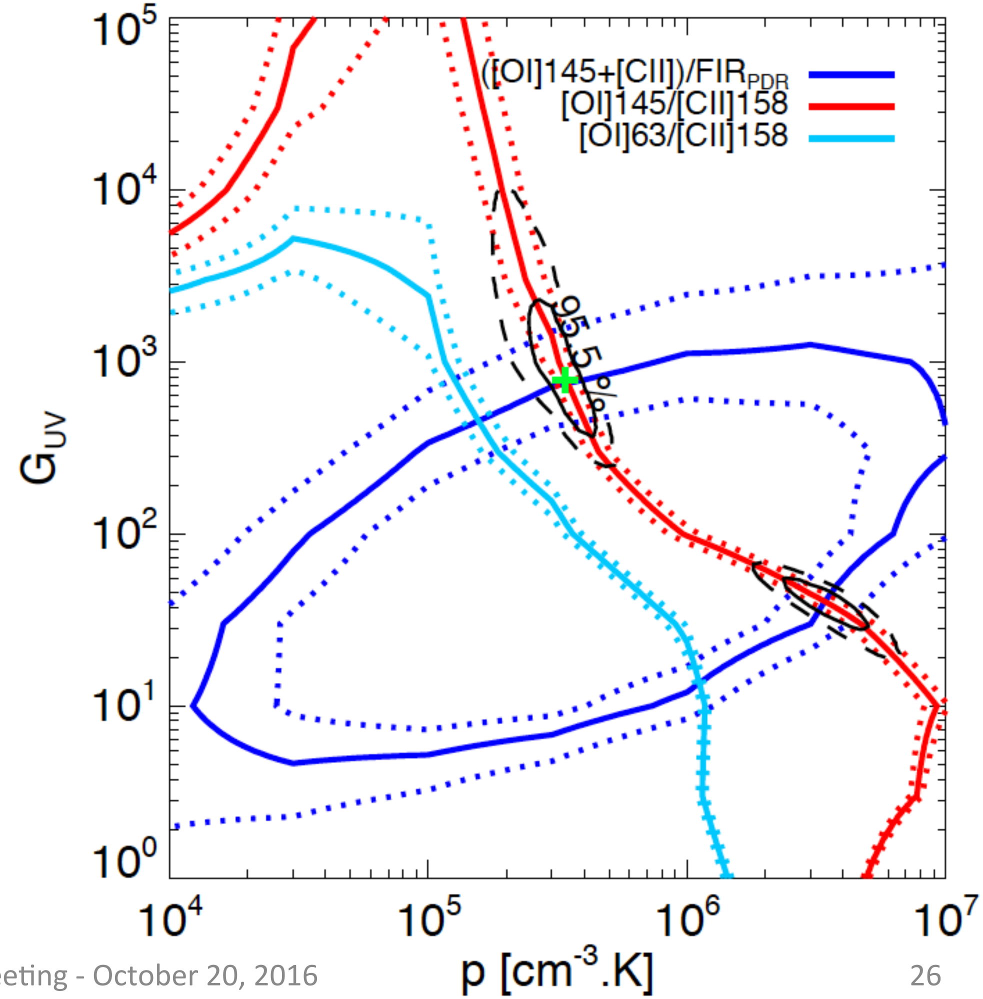




Tracing H_2 in 30-Dor with [CII]

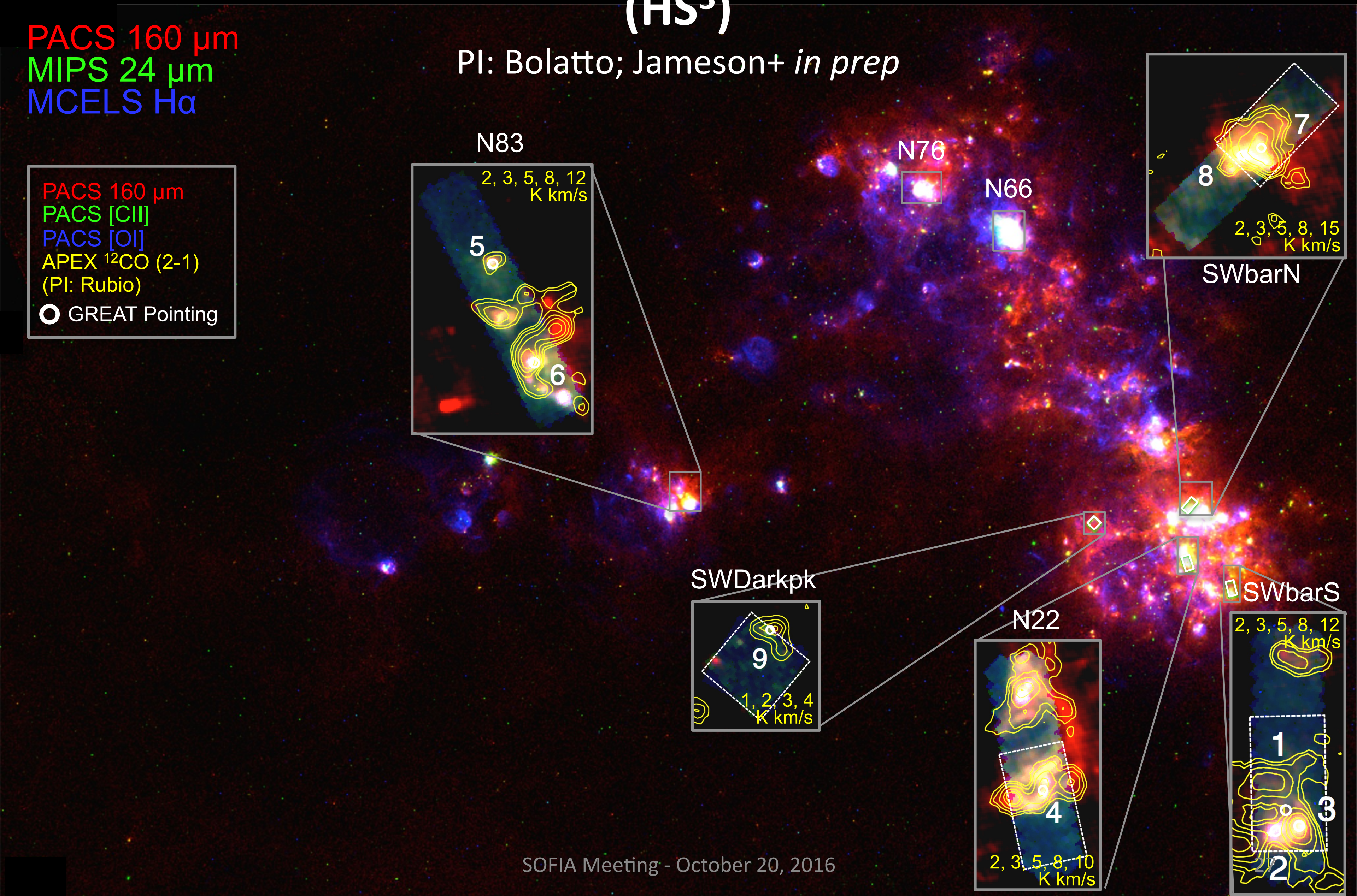
- PDR modeling provides density distribution and radiation field
- CII originates in hot, dense molecular gas

Chevance+2016

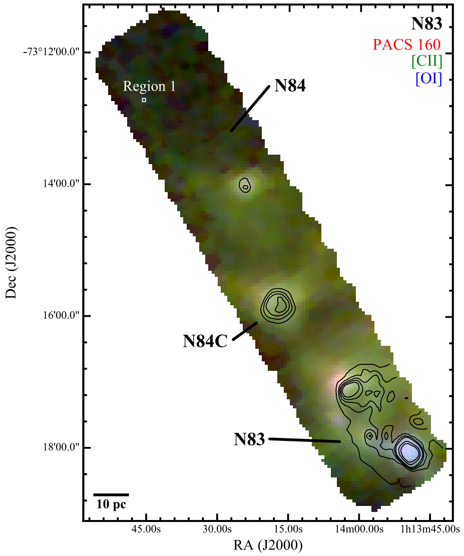


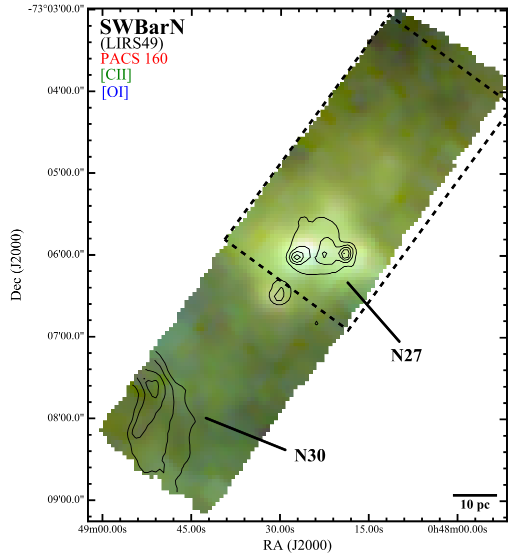
Herschel Spectroscopic Survey of the SMC (HS^3)

PI: Bolatto; Jameson+ *in prep*

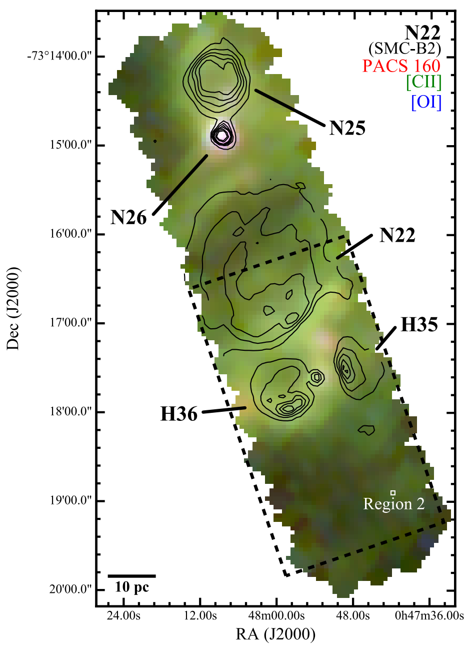


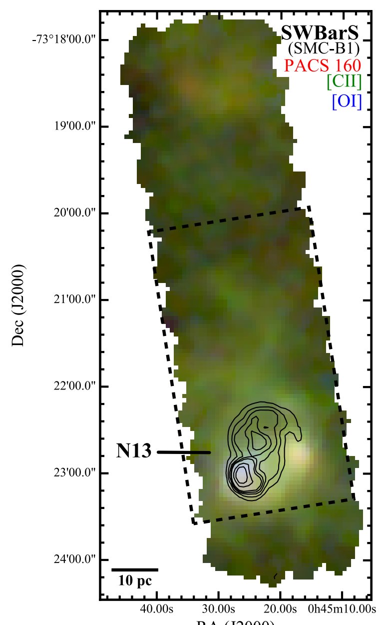
Results from HS³

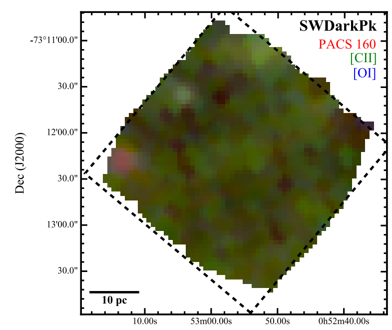




- [CII] and [OI] are detected throughout the regions





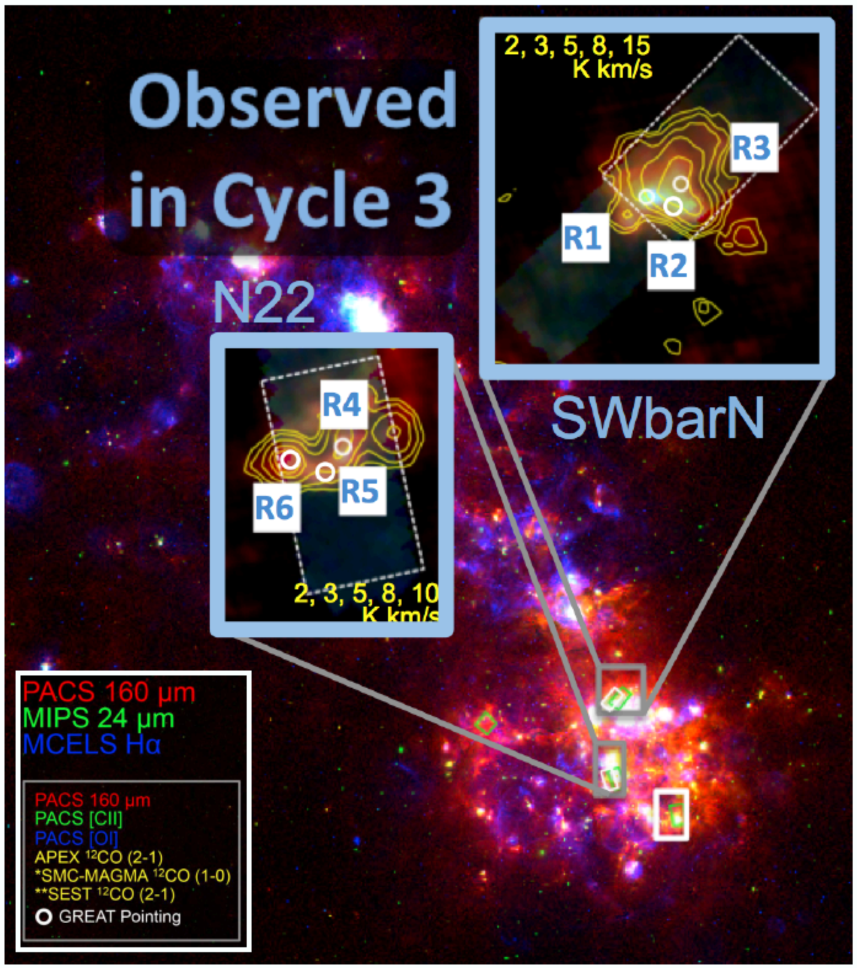


Jameson+, *in prep*

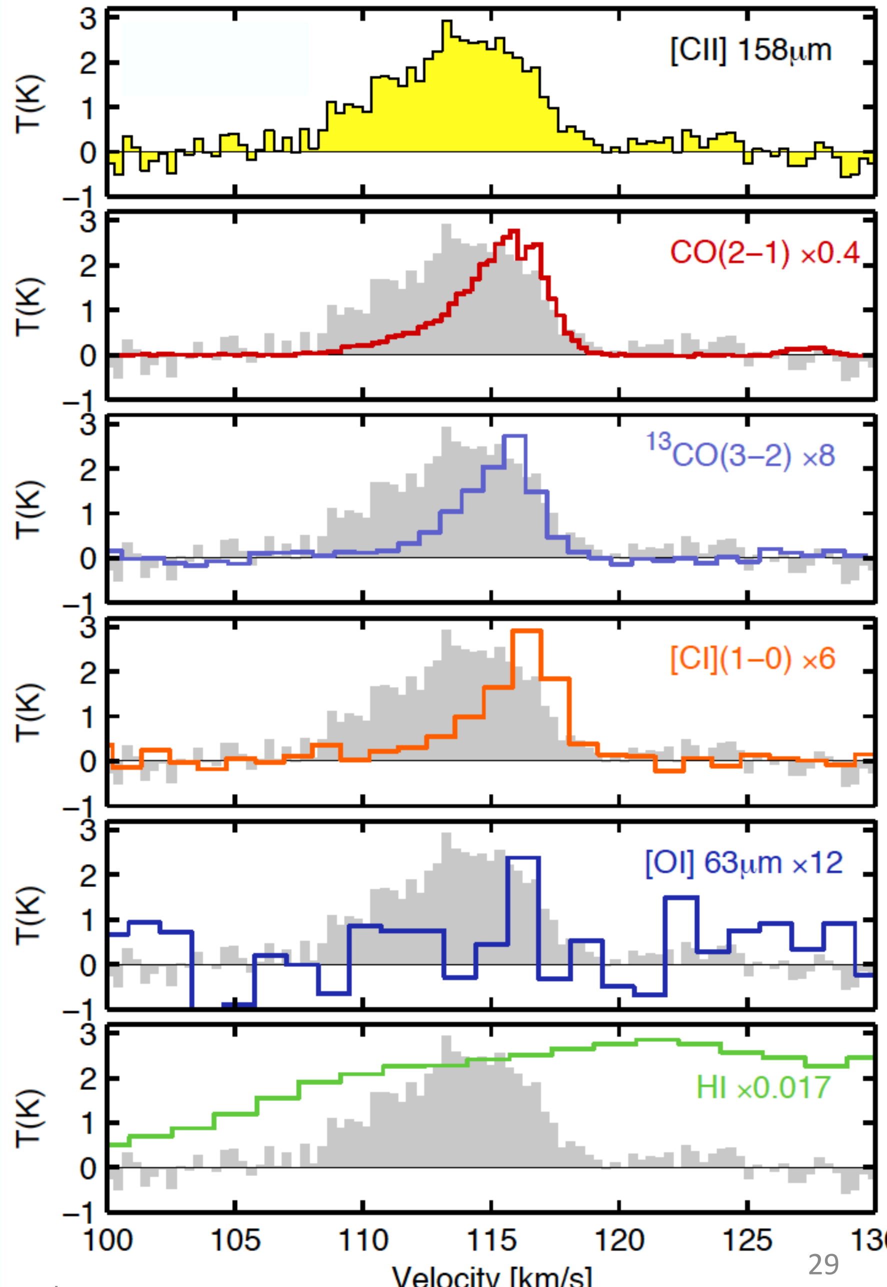
“The GREAT [CII] Account of the Low-Metallicity ISM in the SMC”

PI Herrera-Camus (MPE)

Herrera-Camus, in prep



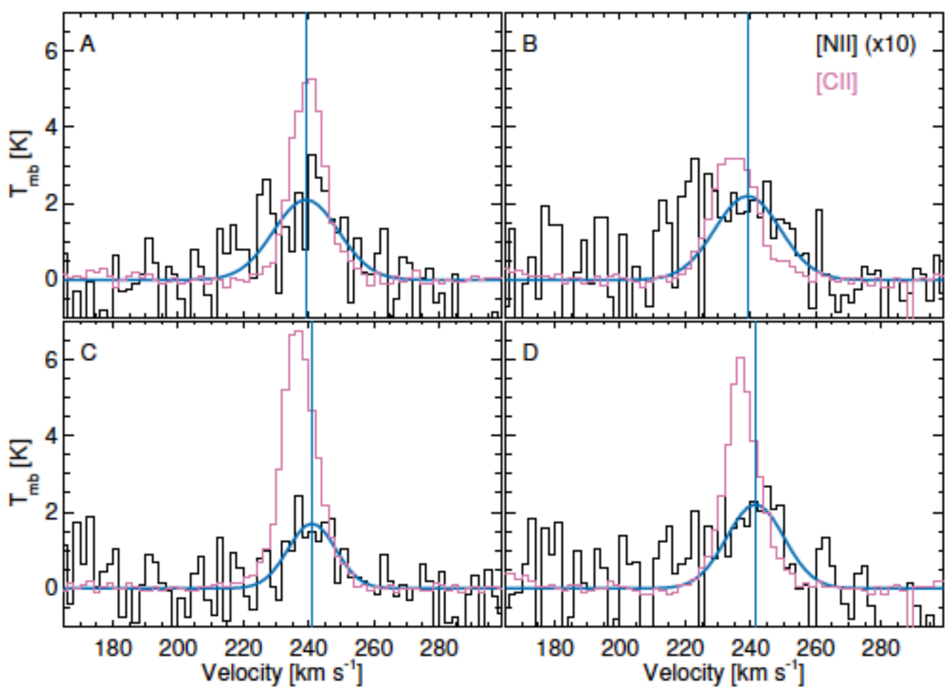
SWbarN / Region 3



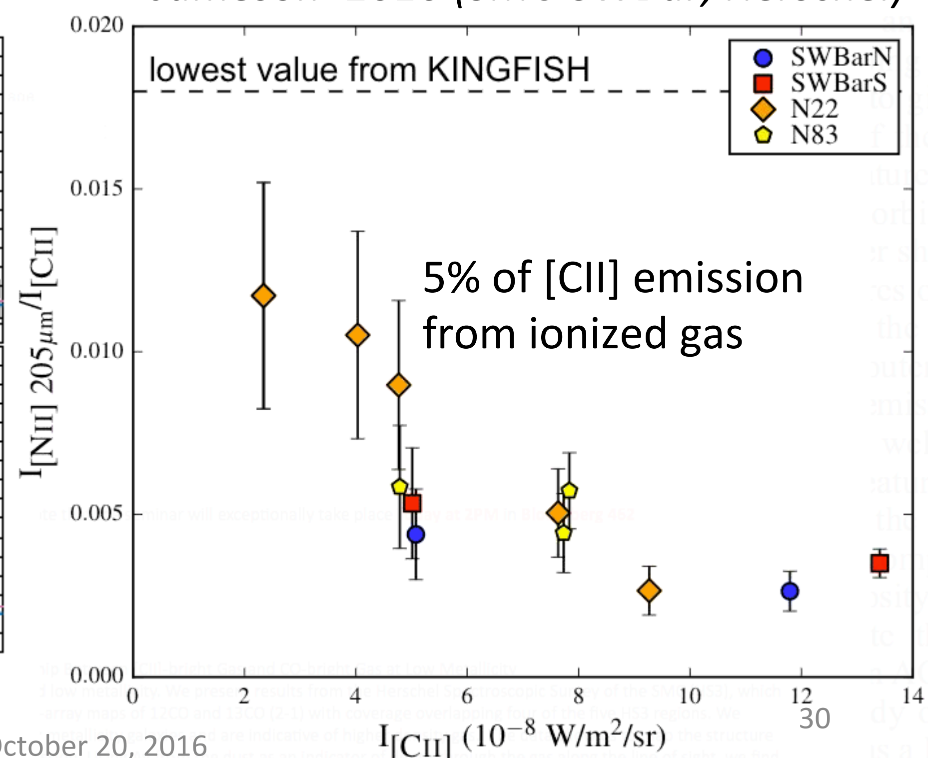
How much [CII] comes from ionized gas?

- [CII] emission originates both in ionized and atomic/molecular gas
- [NII]/[CII] ratios can help quantify fraction of [CII] from ionized gas

Okado+2015 (N159, GREAT): 15% of [CII]

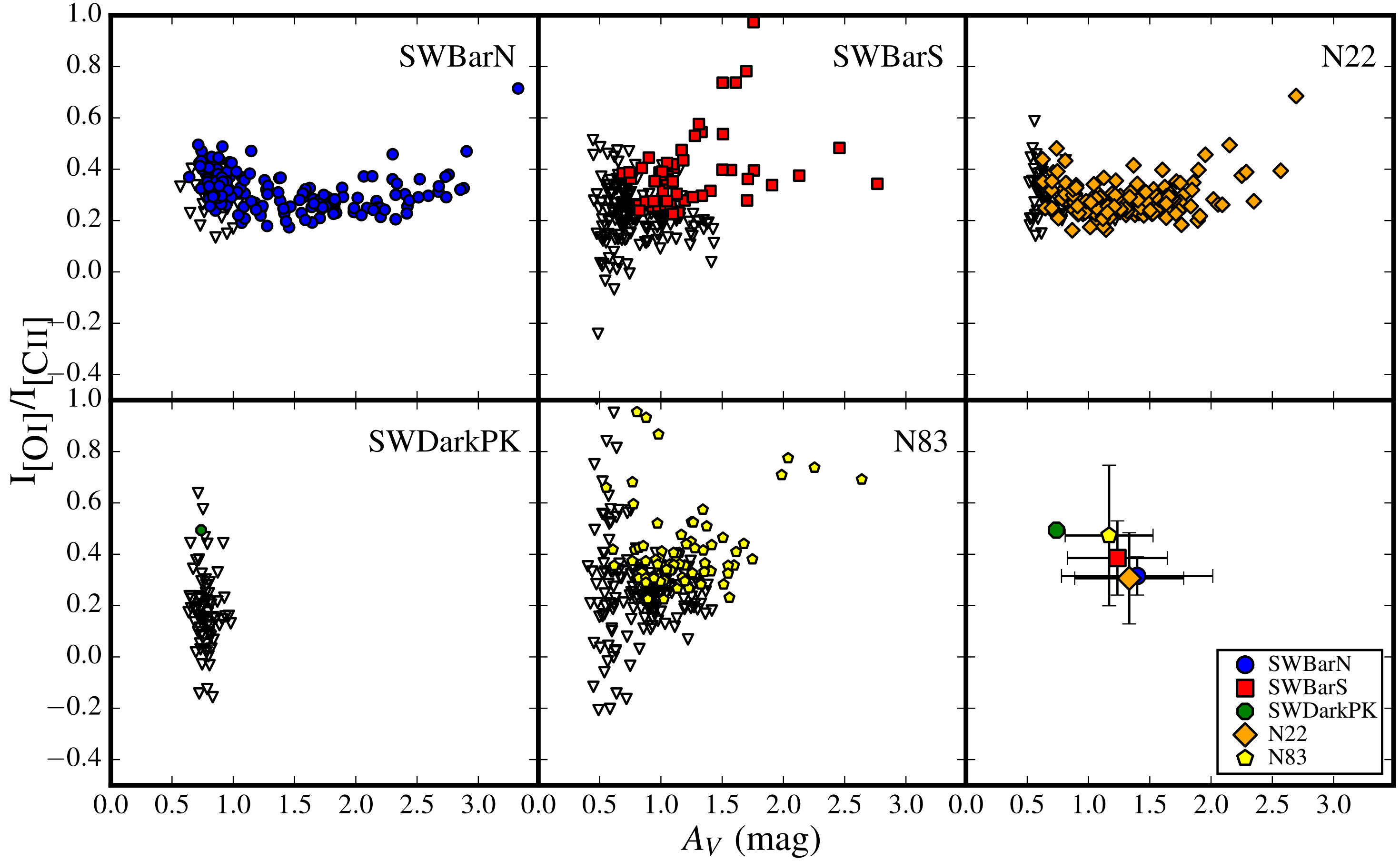


Jameson+2016 (SMC-SWBar, Herschel)



Does [CII] trace atomic or molecular gas?

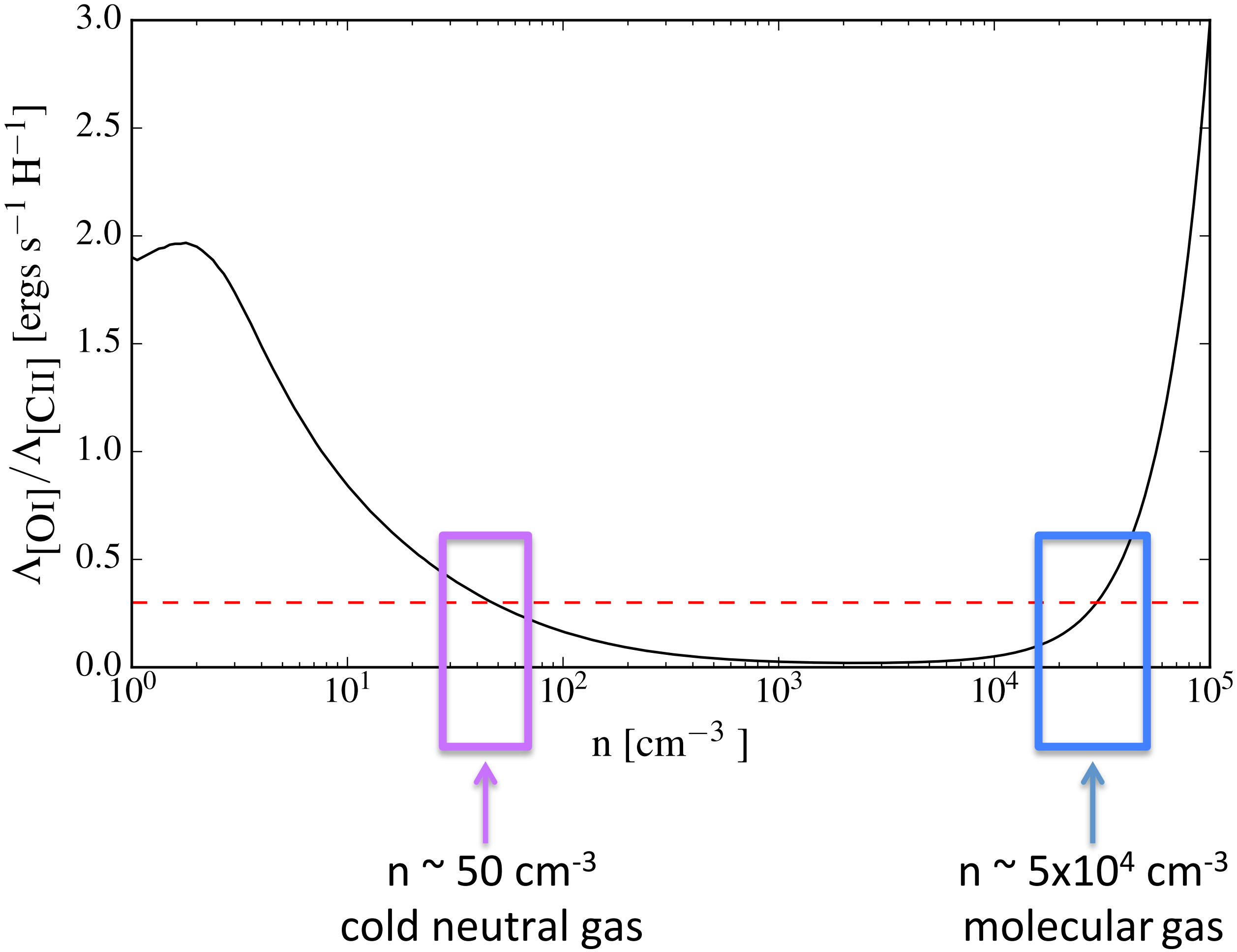
- [CII] emission originates both in ionized and atomic/molecular gas
- [OI]/[CII] ratios can help quantify fraction of [CII] from atomic gas



[OI]/[CII] ~ 0.3

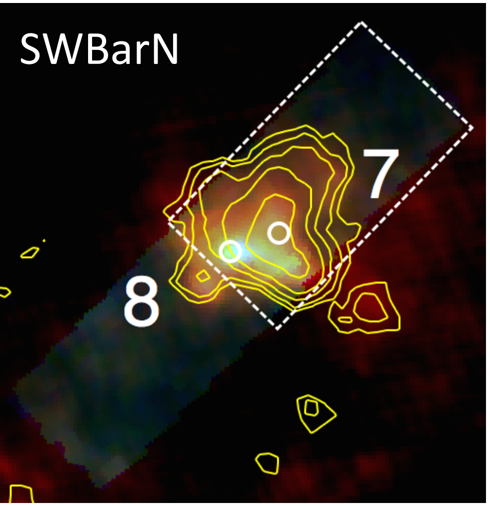
Jameson+, in prep

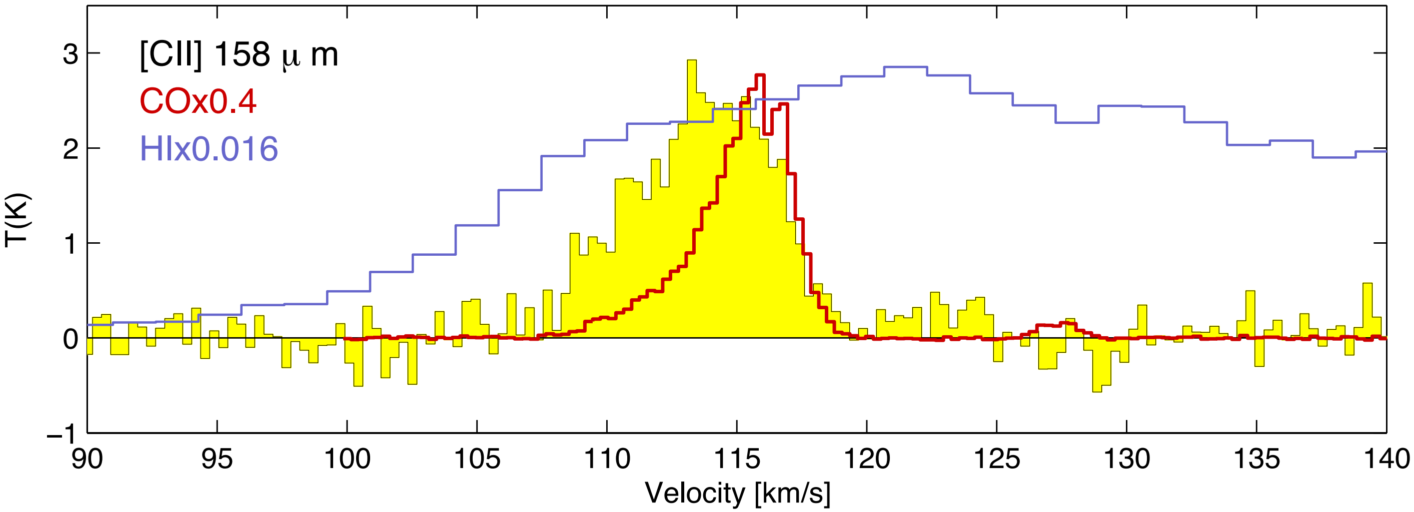
Does [CII] trace atomic or molecular gas?



Cooling rates from Wolfire+ *in prep*

Evidence that the [CII] emission originates in molecular gas





SOFIA GREAT [CII] 158 μm line for one pointing (#7) in SWBarN

Jameson+, in prep

SOFIA in LMC/SMC

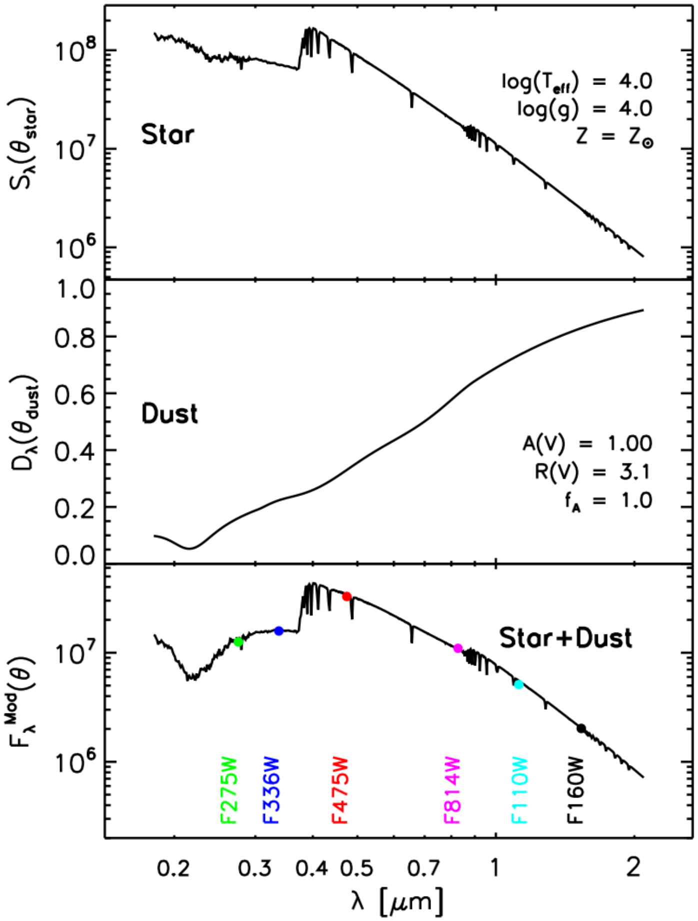
Large systematic uncertainties on dust emission-based molecular gas

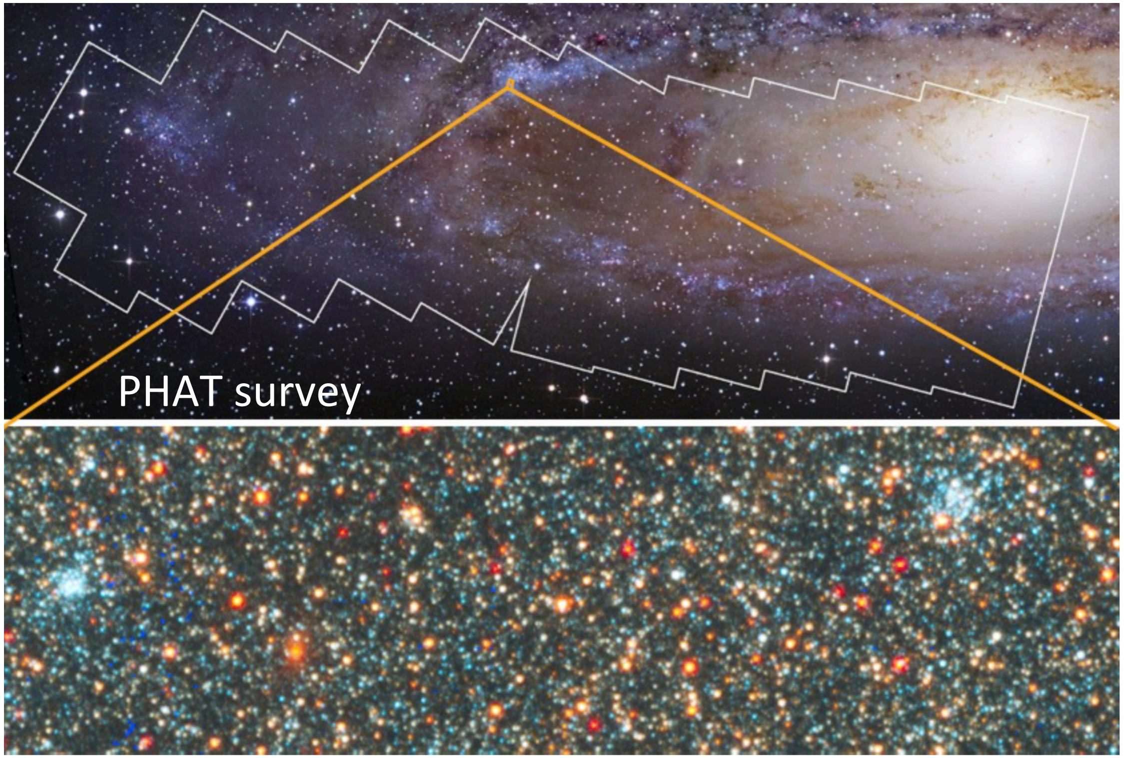
➔ SOFIA/(up)GREAT in more regions!

Tracing the ISM at sub-cloud scales with extinction

Extinction mapping with HST

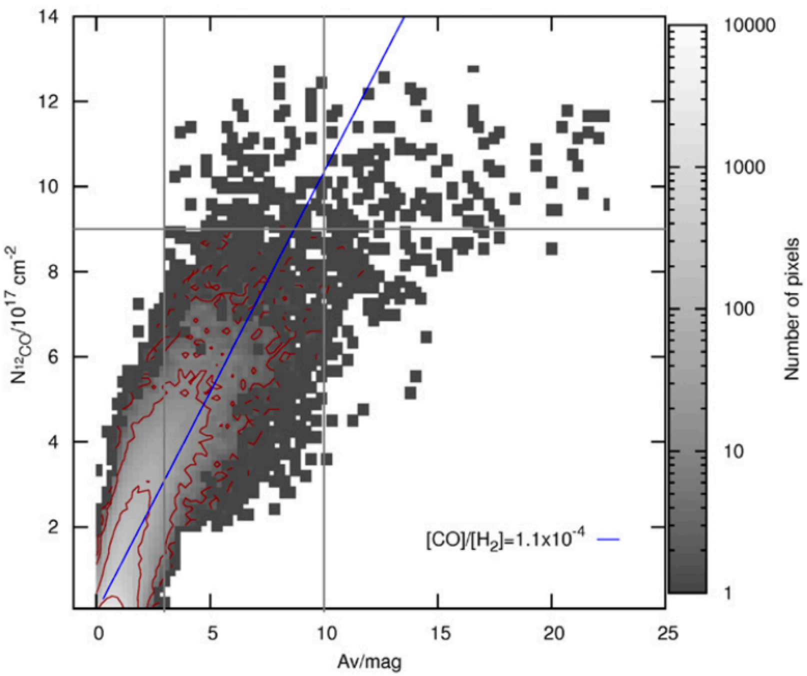
- High-resolution, deep extinction mapping with multi-band HST imaging (WFC3+ACS)
  - Dalcanton+2013, Gordon+2016
- Fit SED toward each star with dust+stellar atmosphere model



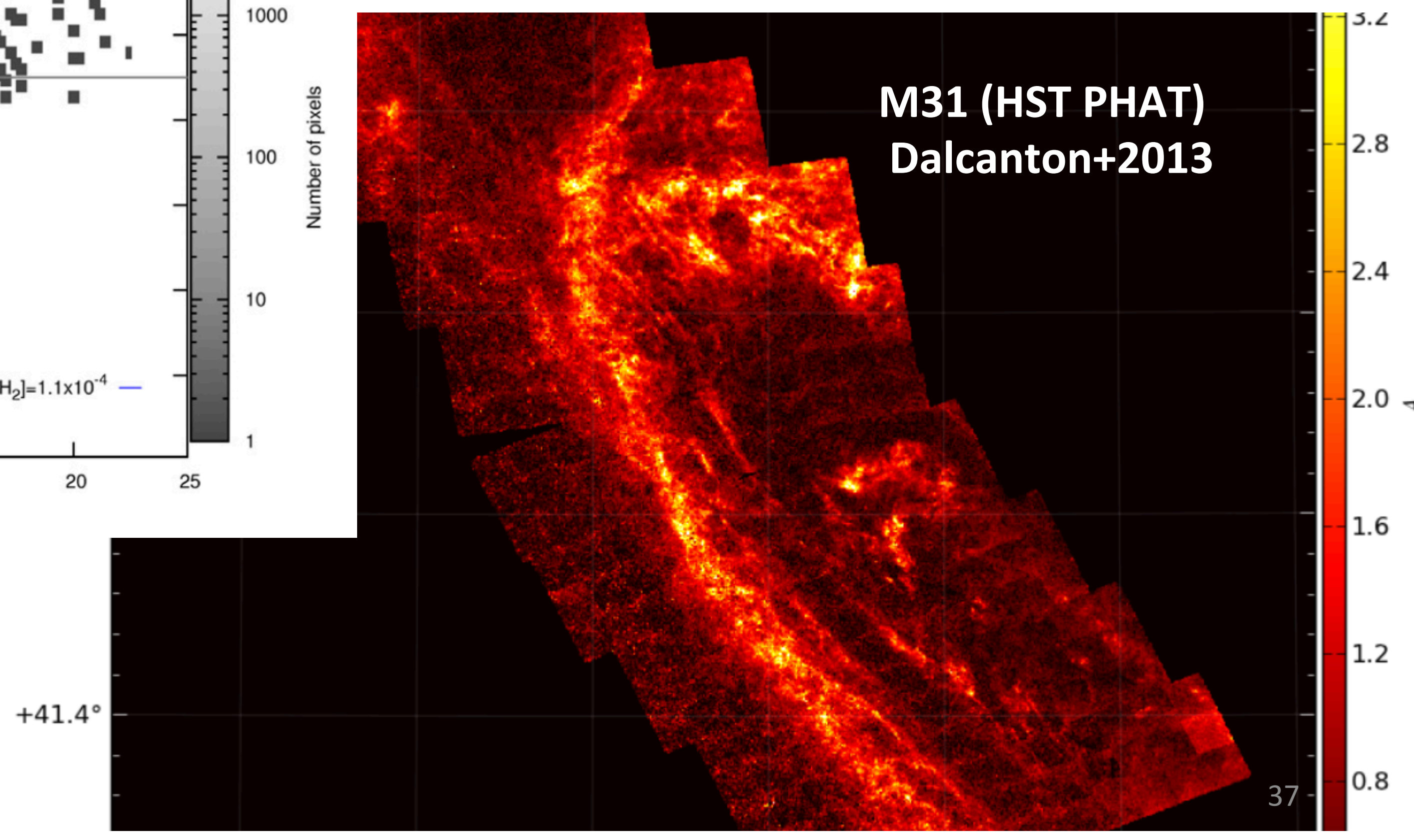


Probing ISM structure with HST and ALMA

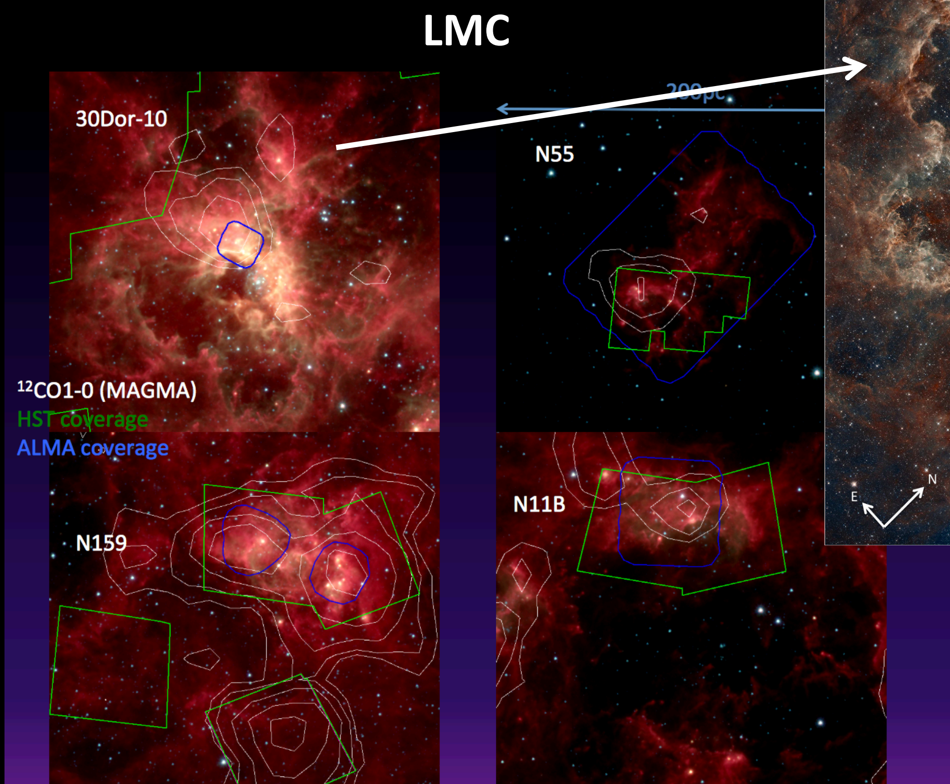
- Fit geometrical model to ensemble of individual A_V toward each stars (Dalcanton+2013) to derive extinction maps
- Trace CO at similar resolution with ALMA

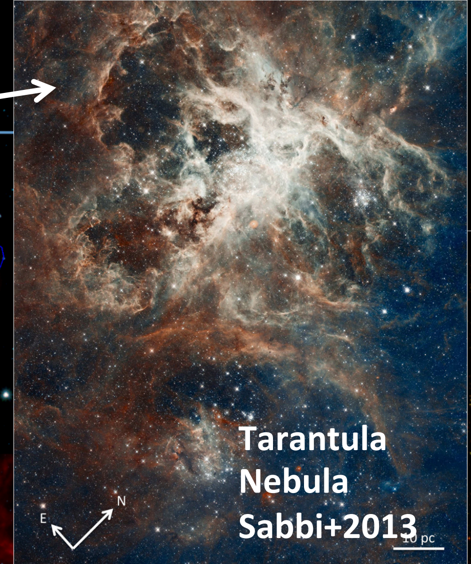


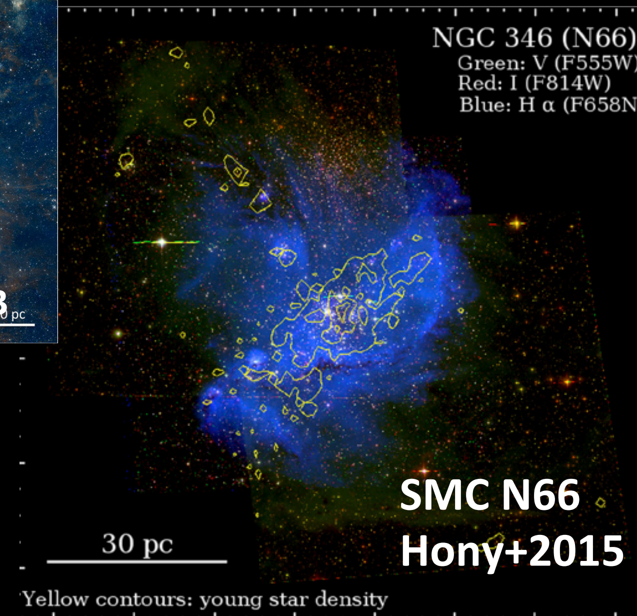
Pineda+2010 (Taurus)
Extinction from 2MASS

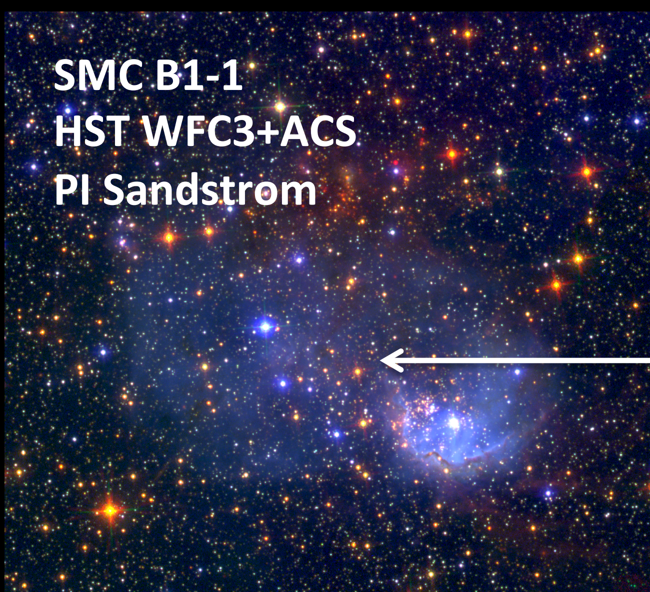


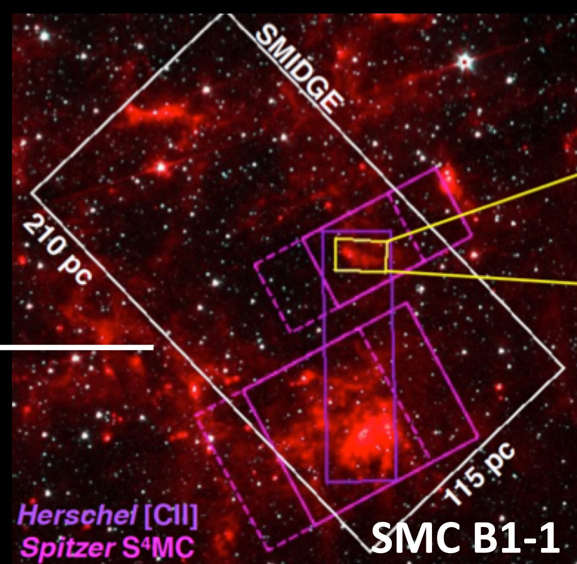
HST/ALMA Synergy

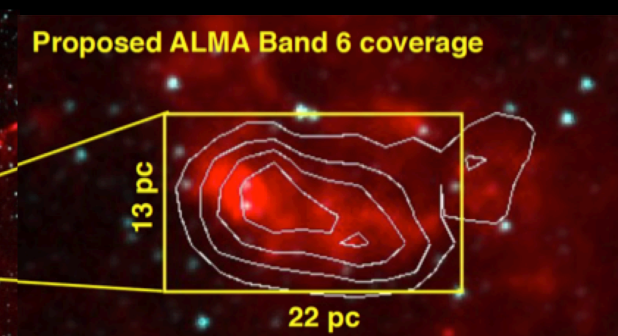












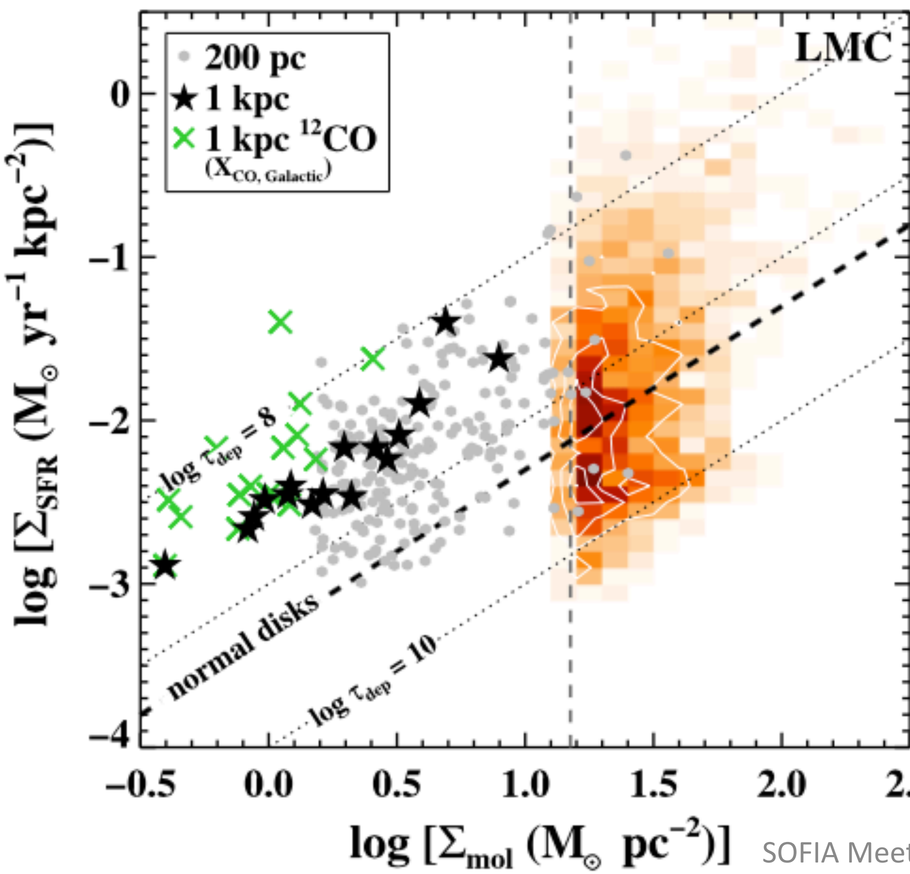
The Truth may not be so local anymore!

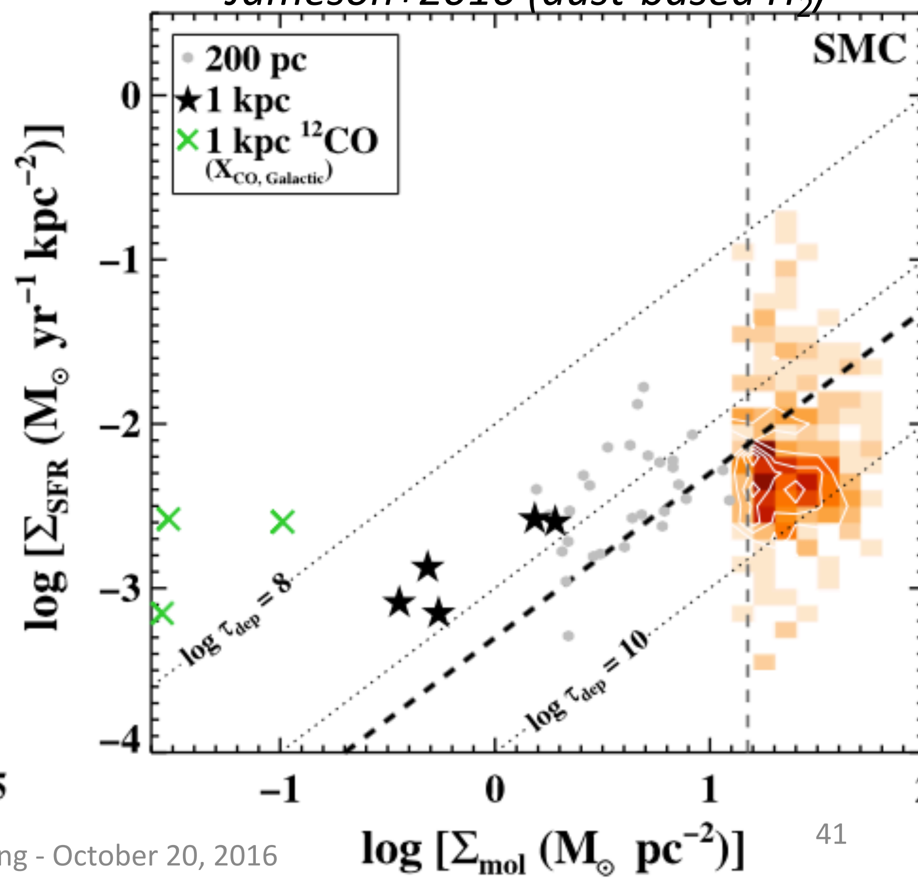
Effects of Metallicity on kpc-scale star formation relation

Effects of metallicity on SF timescales

- Trace H_2 from dust (FIR) or FIR fine structure line ([CII], [NII], [OI]) from SOFIA/Herschel
- Trace SF from MIR and Hα (or YSOs)

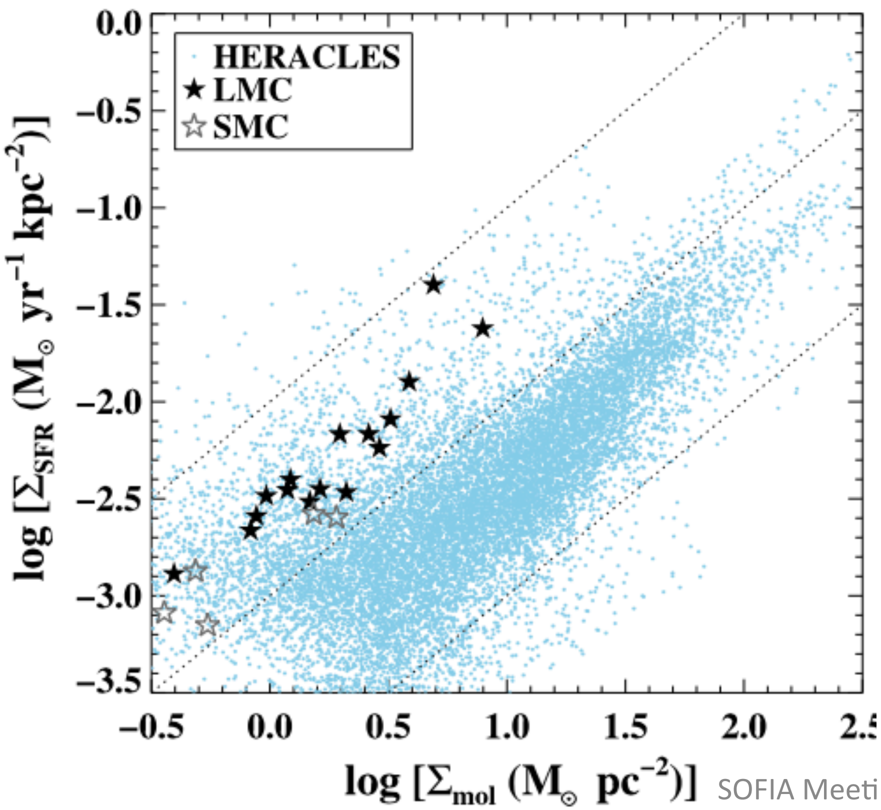
Jameson+2016 (dust-based H_2)



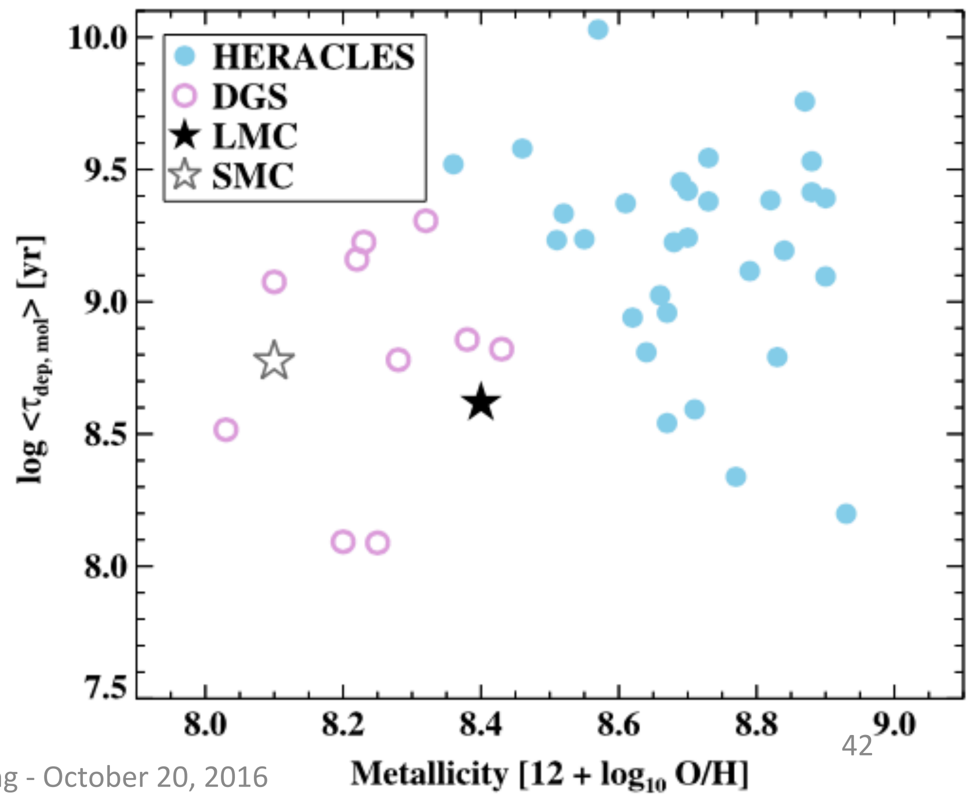


Effects of metallicity on SF timescales

- Molecular depletion times on 1 kpc scale in LMC and SMC (0.5 Gyr) are slightly shorter than in disk galaxies (2 Gyr), possibly indicating a recent burst in SF
- No clear dependence on metallicity

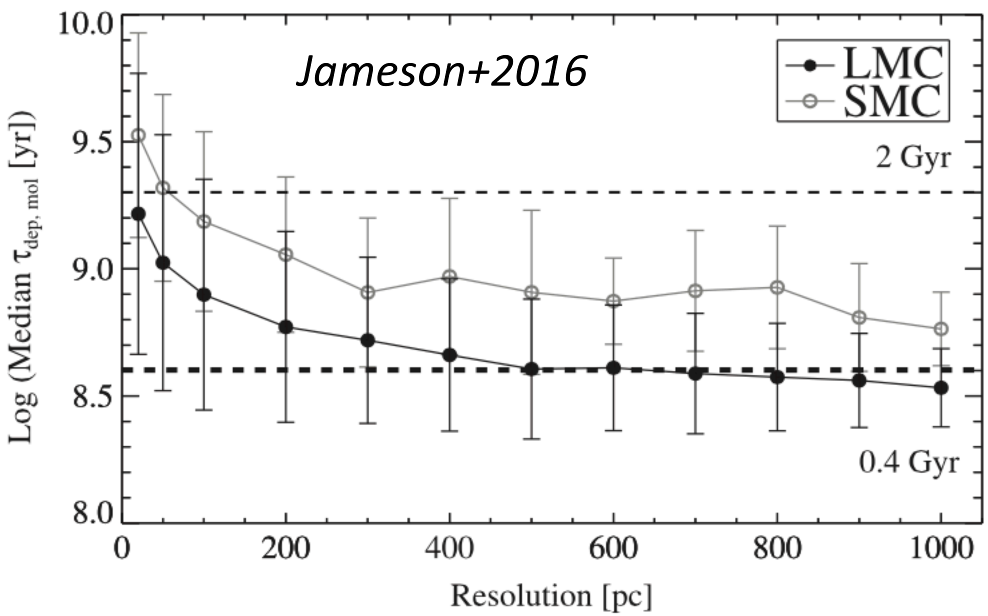


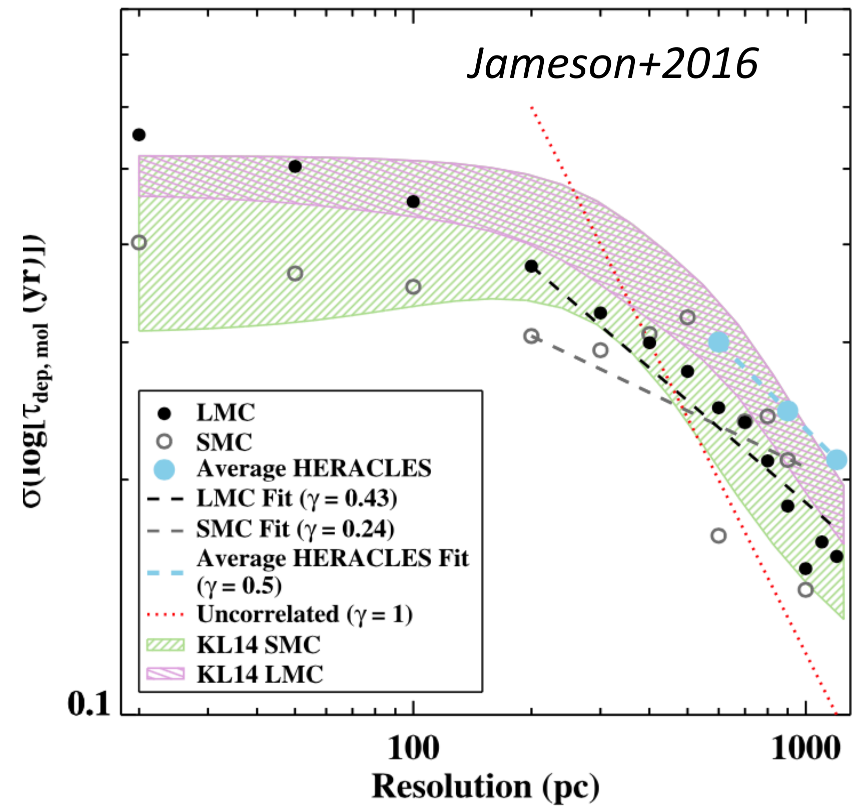
Jameson+2016 (dust-based H_2)



SF timescales vs resolution

- LMC/SMC are the rare galaxies where we can estimate the effects of resolution on the SF relation
- Variations of τ_{dep} and $\sigma(\tau_{dep})$ due to spatial separation of gas and SFR tracers and sampling of different evolutionary stages of SF (Kruijssen & Longmore 2014)



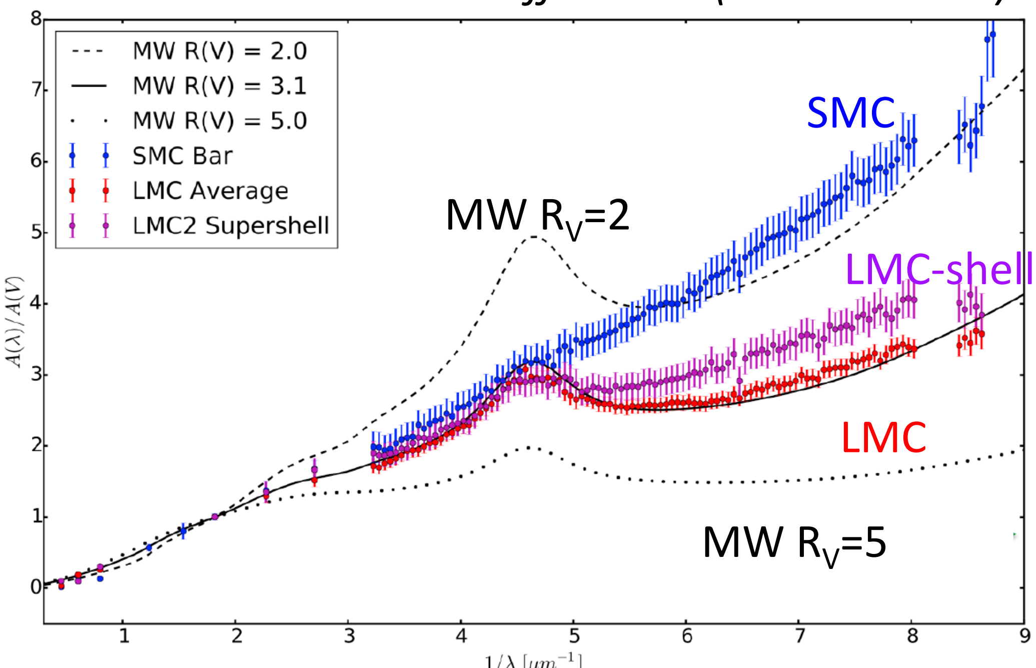


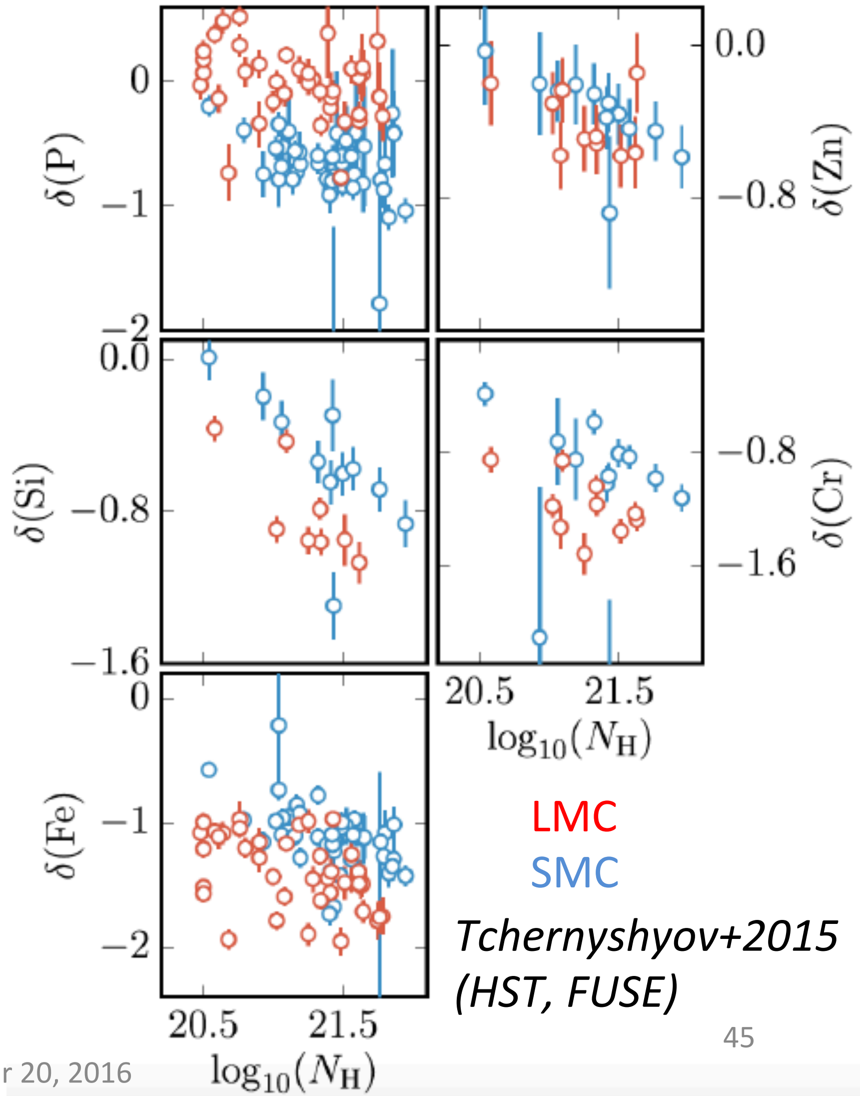
Variations of Dust Properties with Metallicity: systematic uncertainties on gas mass estimates

Dust properties in the LMC and SMC

- Dust properties in LMC and SMC differ from MW
  - Extinction curves
  - Depletions
  - FIR SED (spectral emissivity index)
- Significantly affects radiative transfer, shielding, and therefore SF

Dust extinction curve differences (Gordon+2003)



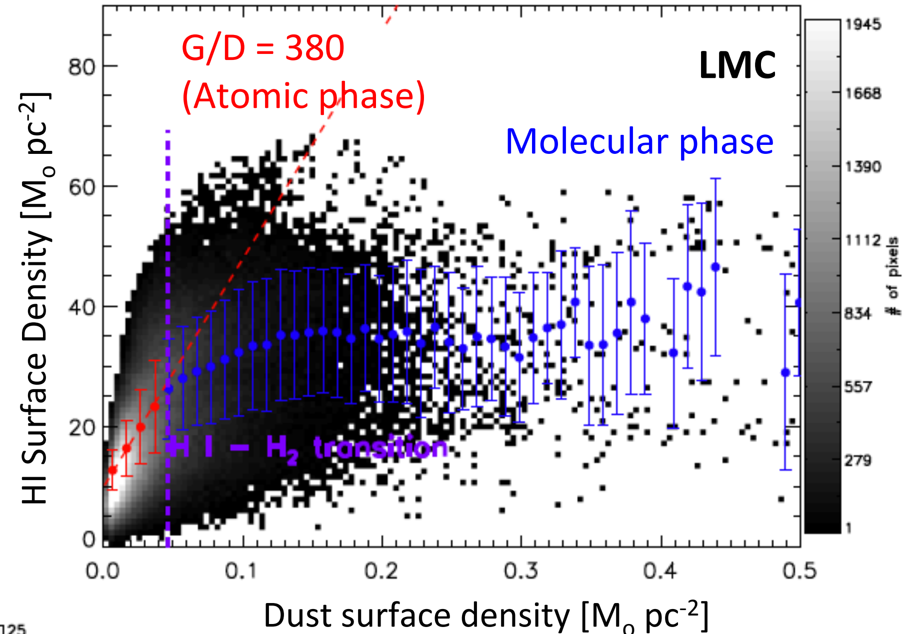


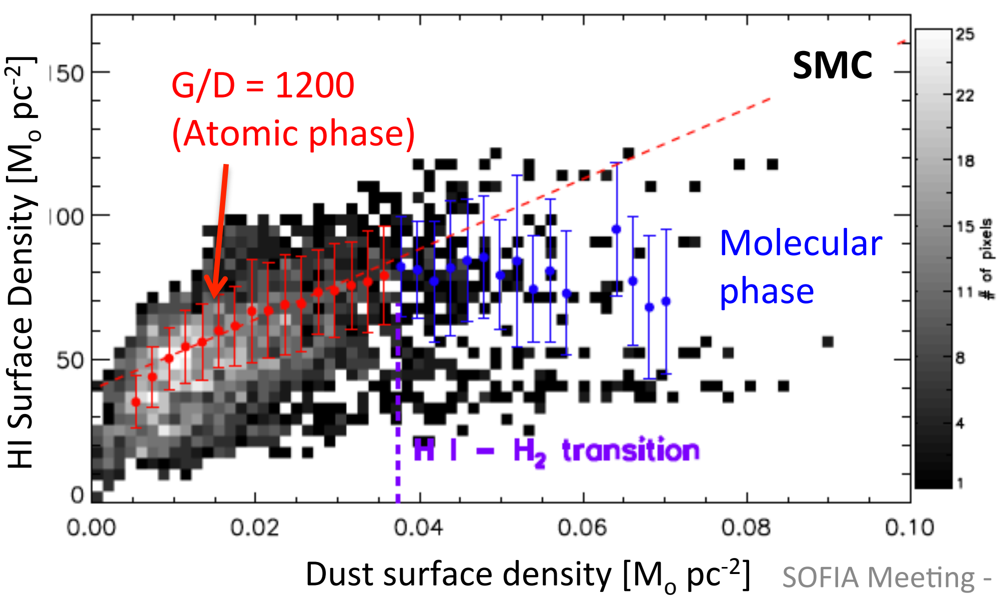
LMC
SMC

Tchernyshyov+2015 (HST, FUSE)

G/D in the LMC and SMC

- Dust-to-gas ratio increases non-linearly with metallicity?
  - LMC: G/D = 380 +/- 150
  - SMC: G/D = 1200 +/- 400
- Large systematic uncertainties on emission-based G/D affects ability to estimate H_2 in low-Z galaxies

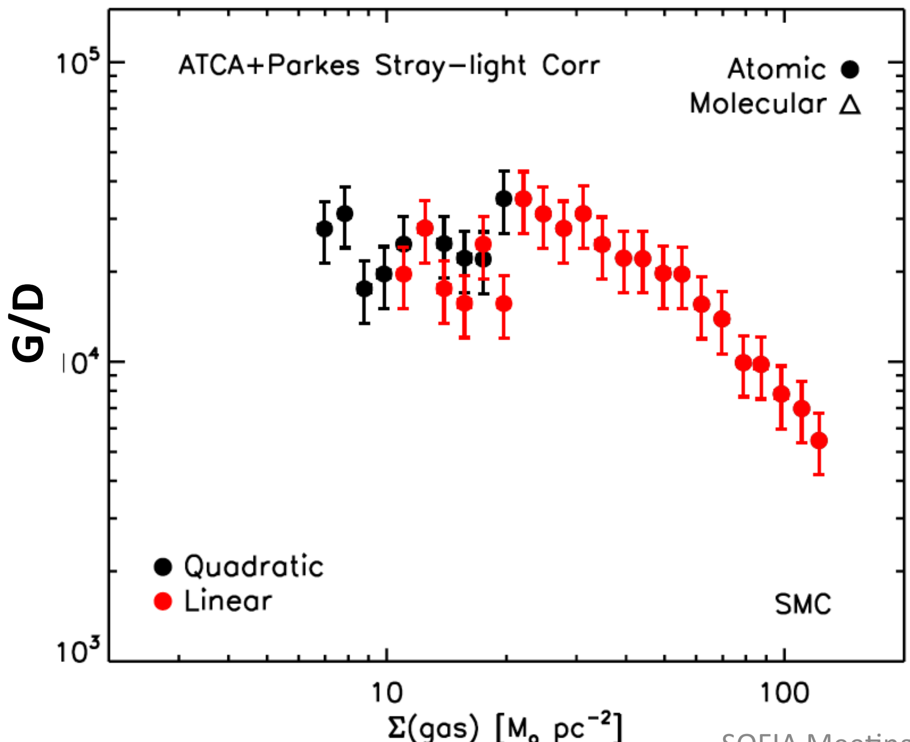


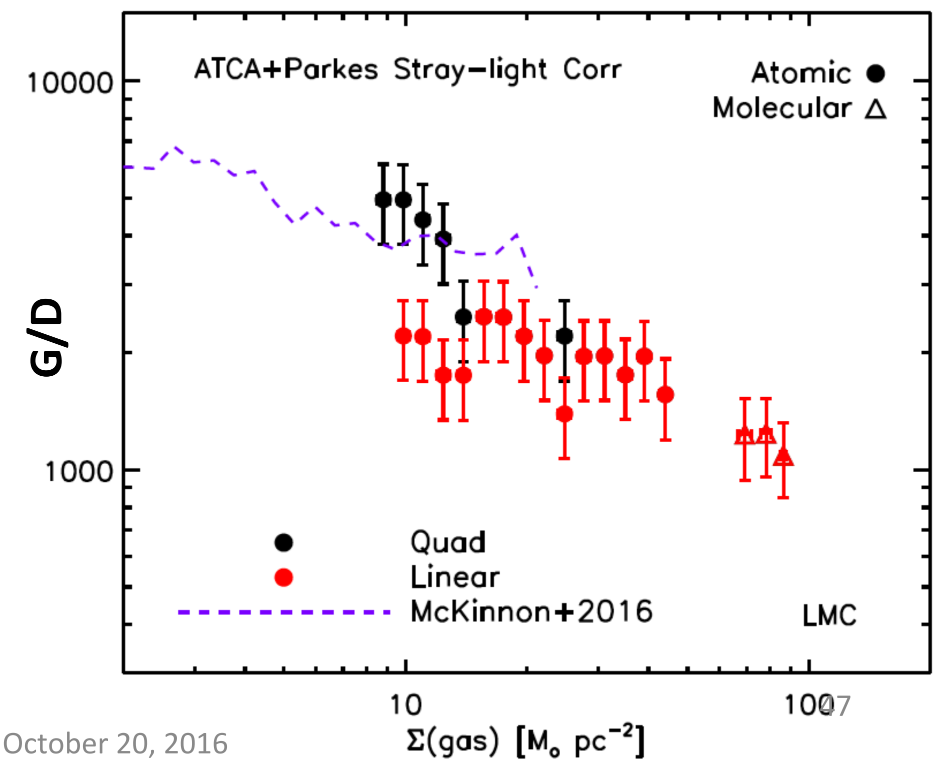


Roman-Duval+2014
Herschel HERITAGE key-project
PACS 100, 160 μm
SPIRE 250, 350, 500 μm

G/D vs Surface Density

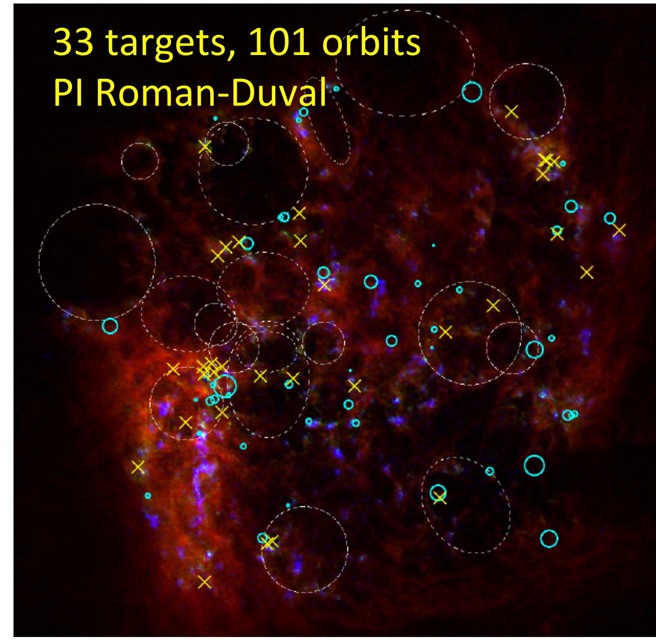
- Dust-to-gas ratio variations with surface density (Roman-Duval+, in prep)
  - Obtained from stacked Planck data
  - Surface density range bridges ISM and CGM
- **WARNING: Dust-based H_2 masses assume constant G/D!!!!**

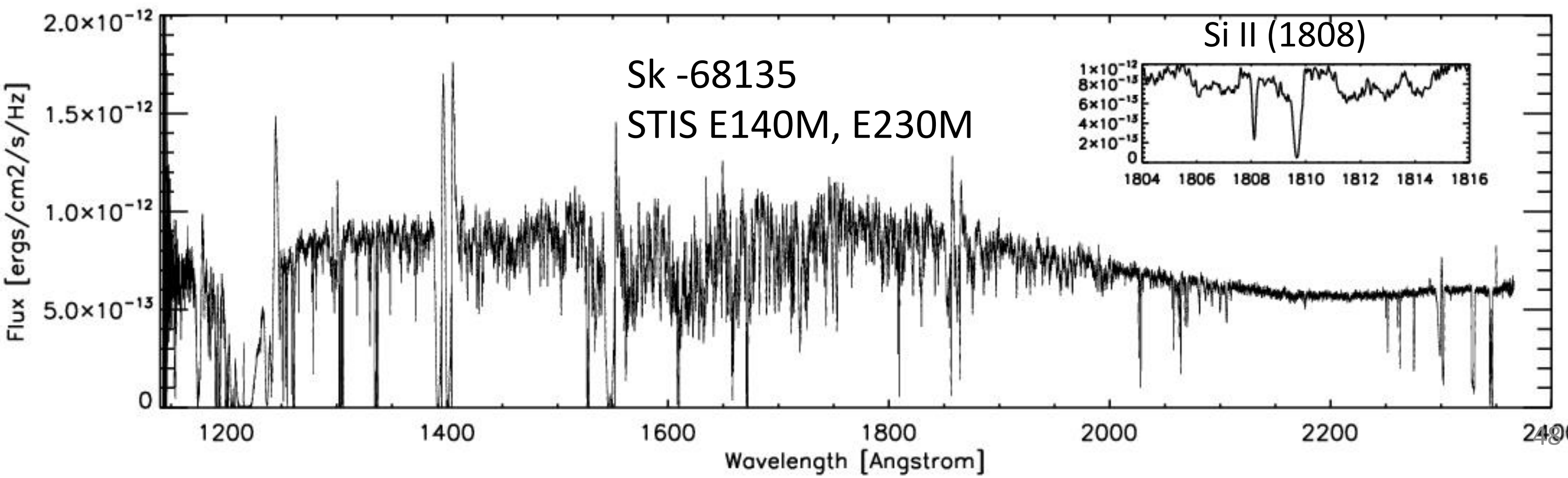




Metal Evolution and TrAnsport in the Large Magellanic Cloud (METAL)

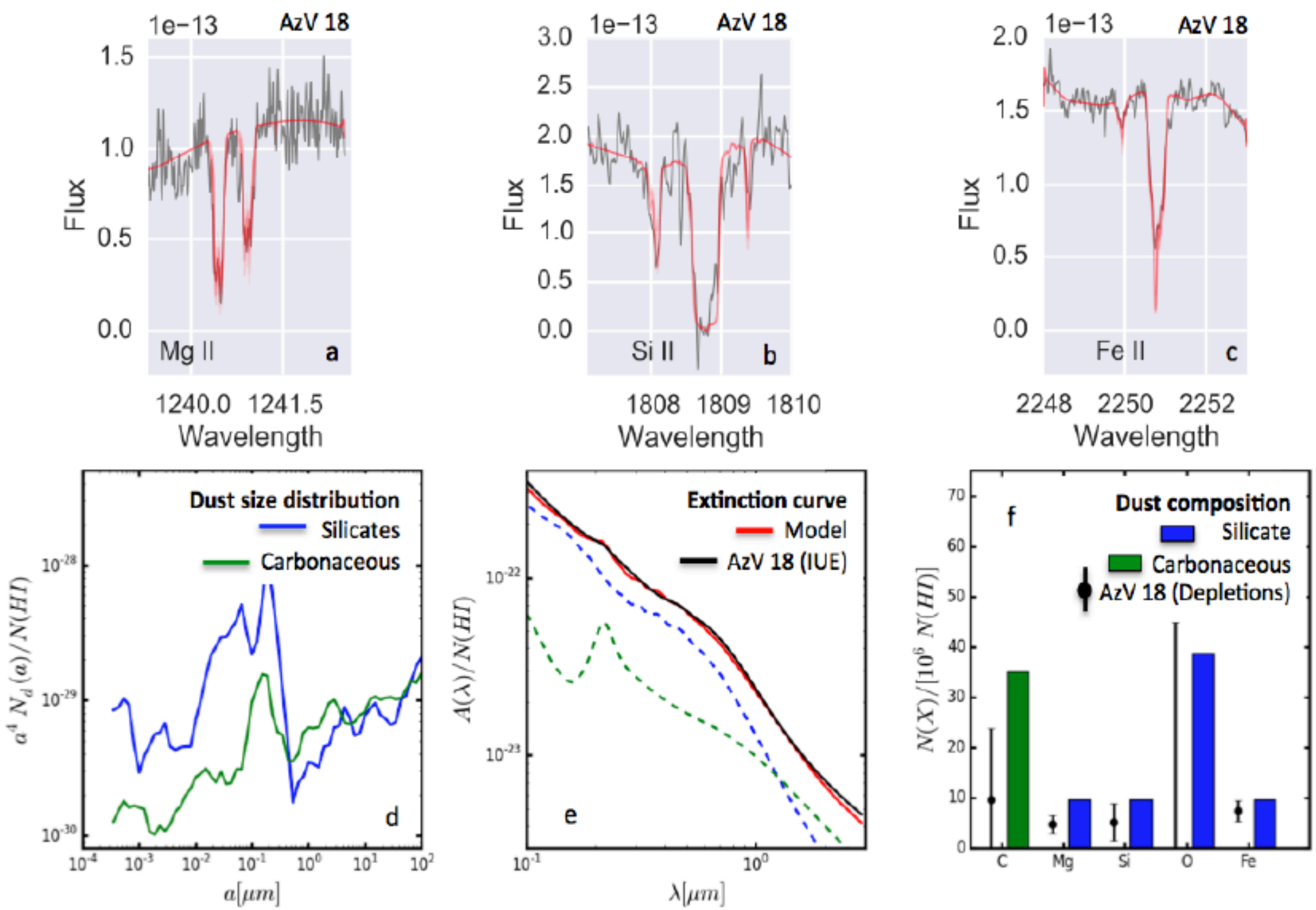
- Systematic uncertainties on FIR dust emission-based G/D estimation is large (emissivity/mass degeneracy)
  - FIR emissivity environmental variations poorly constrained (factor of 2-3)
- FIR emission does not constrain dust composition
- Probe dust abundance and composition with HST UV absorption spectroscopy ($A_V < 1.2$)





Dust Composition and Size with METAL

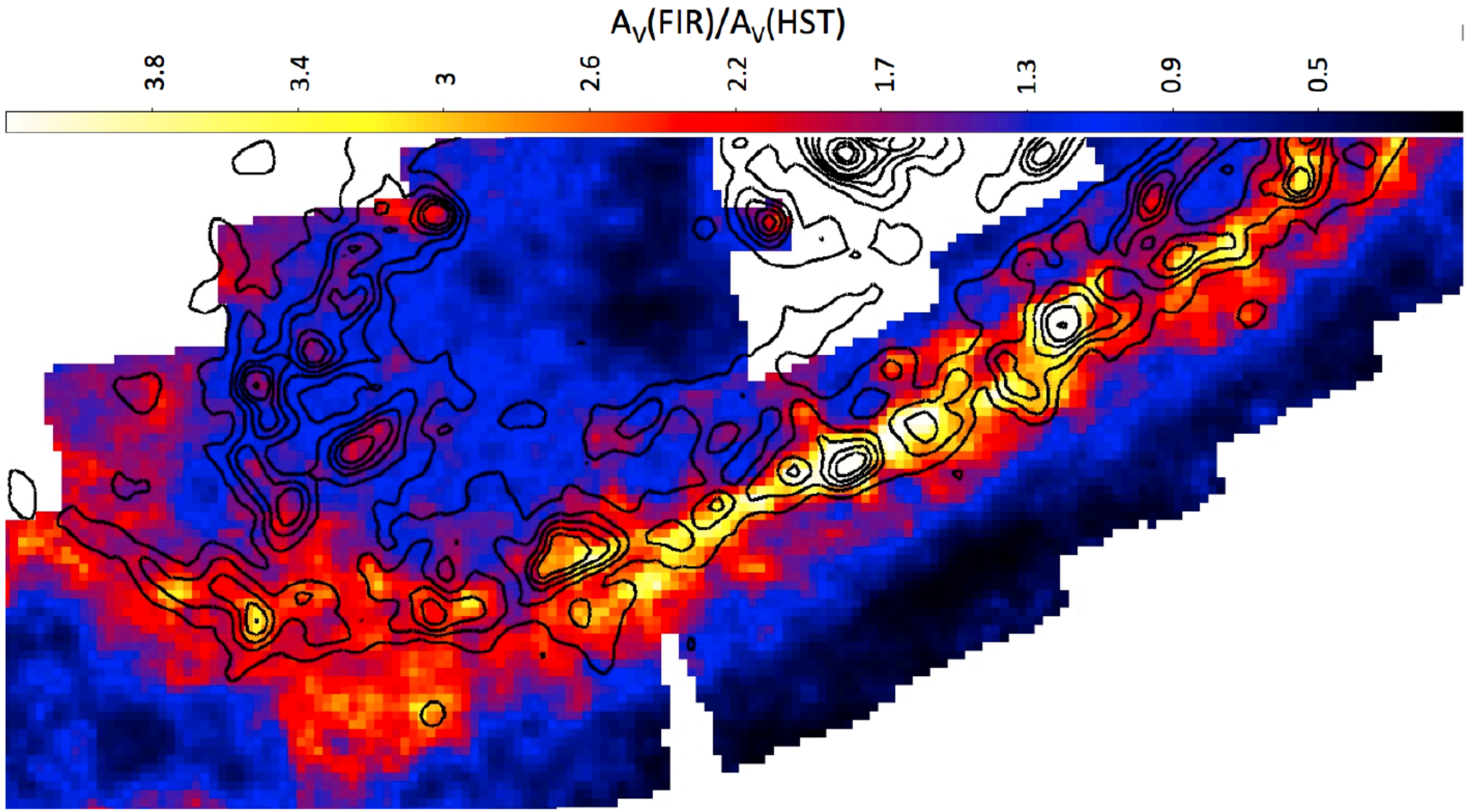
METAL will constrain how dust abundance and composition varies with environment within the LMC and how it differs from the SMC and MW



FIR emissivity mapping

- WFC3 images in UV-NIR will provide extinction maps
- Comparison to Herschel FIR emission will yield dust FIR emissivity

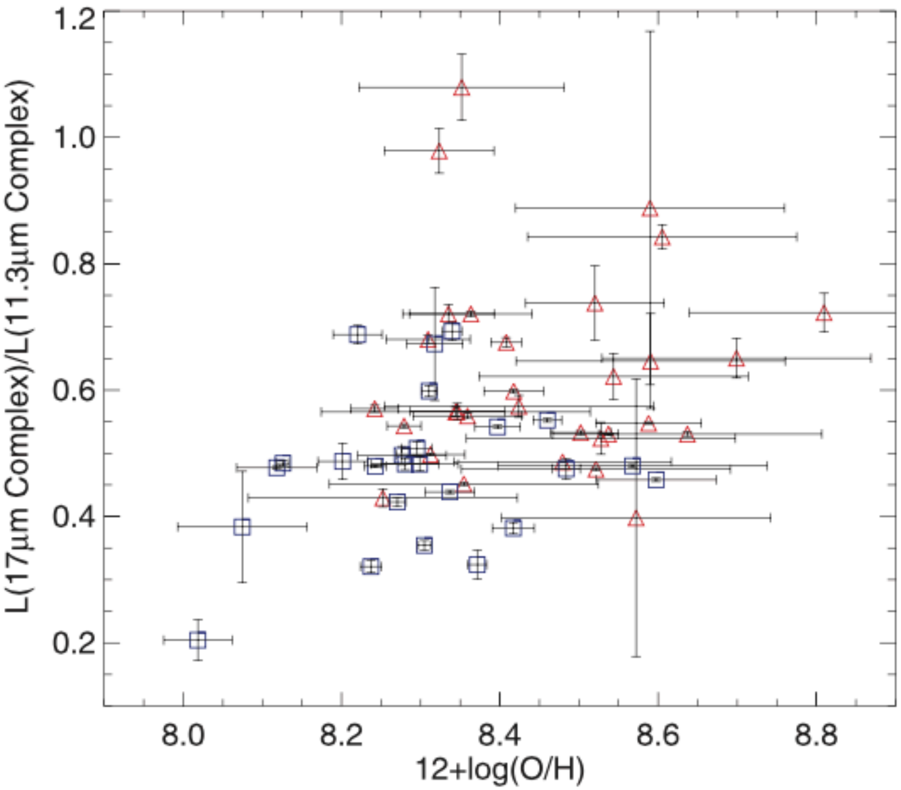
M31 (PHAT)
Gordon+2016
Arab+, in prep



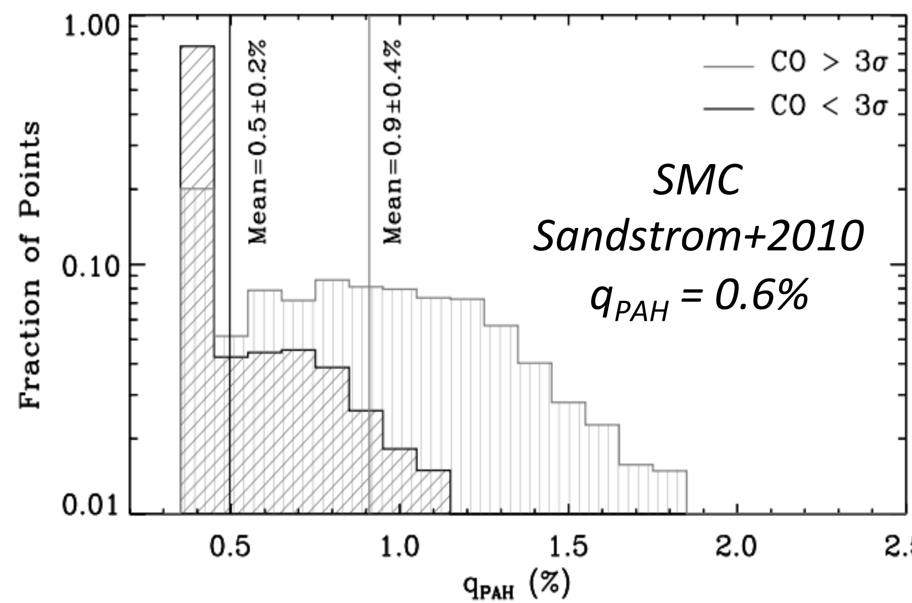
What next?

PAH Properties in the LMC/SMC?

- Characterize 7.7 μm/11.3 μm with FORCAST spectroscopy?
  - Environmental dependence (radiation field, surface density)
- SMC has Spitzer/IRS spectroscopic observations, LMC more limited

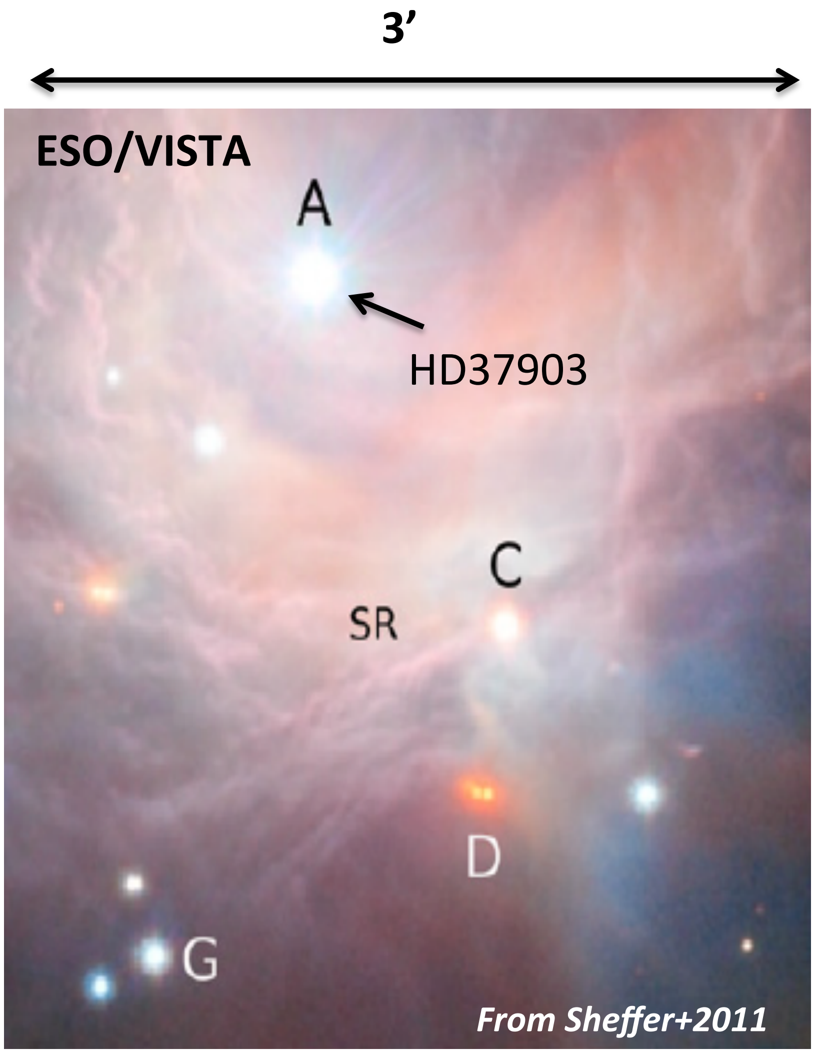


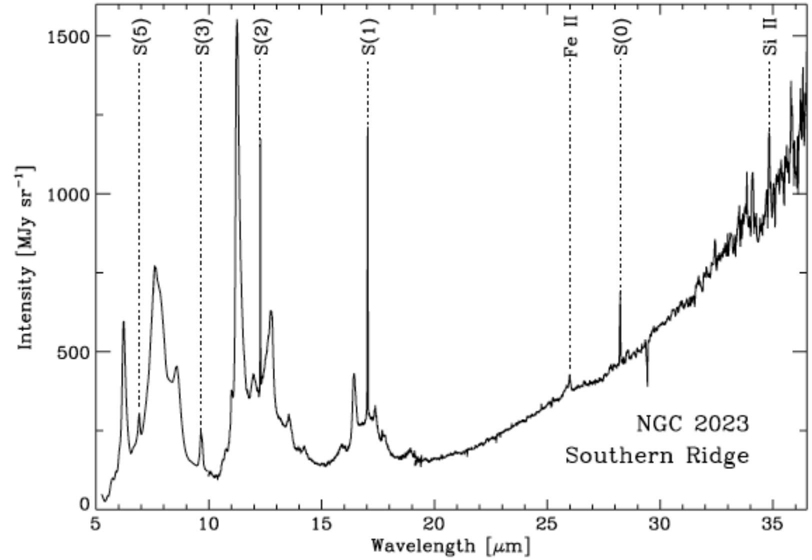
Smith+2008
Spitzer/IRS spectroscopic from SINGS survey (Kennicutt+2003)

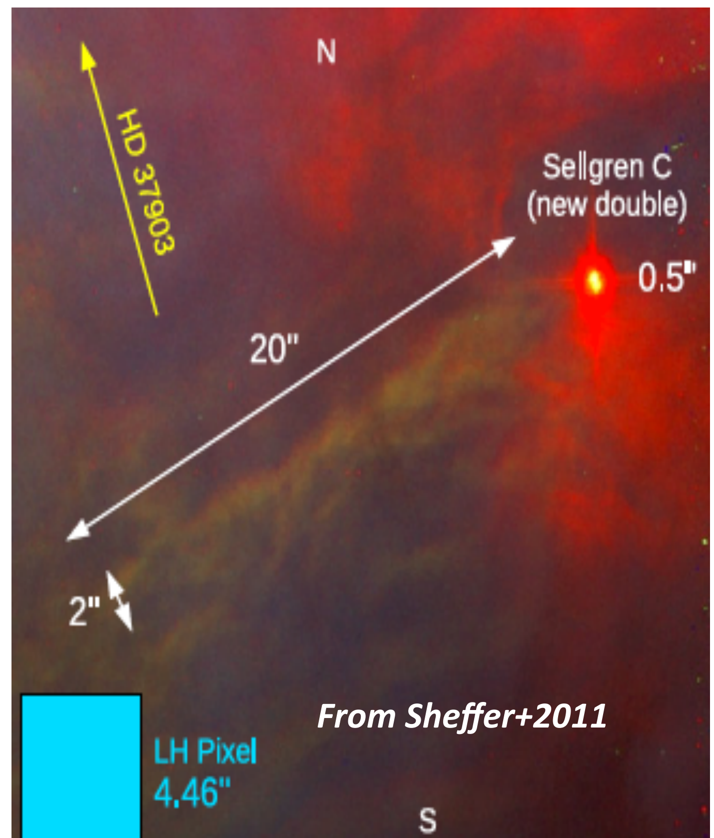


SMC
Sandstrom+2010
q_{PAH} = 0.6%

PDRs with JWST



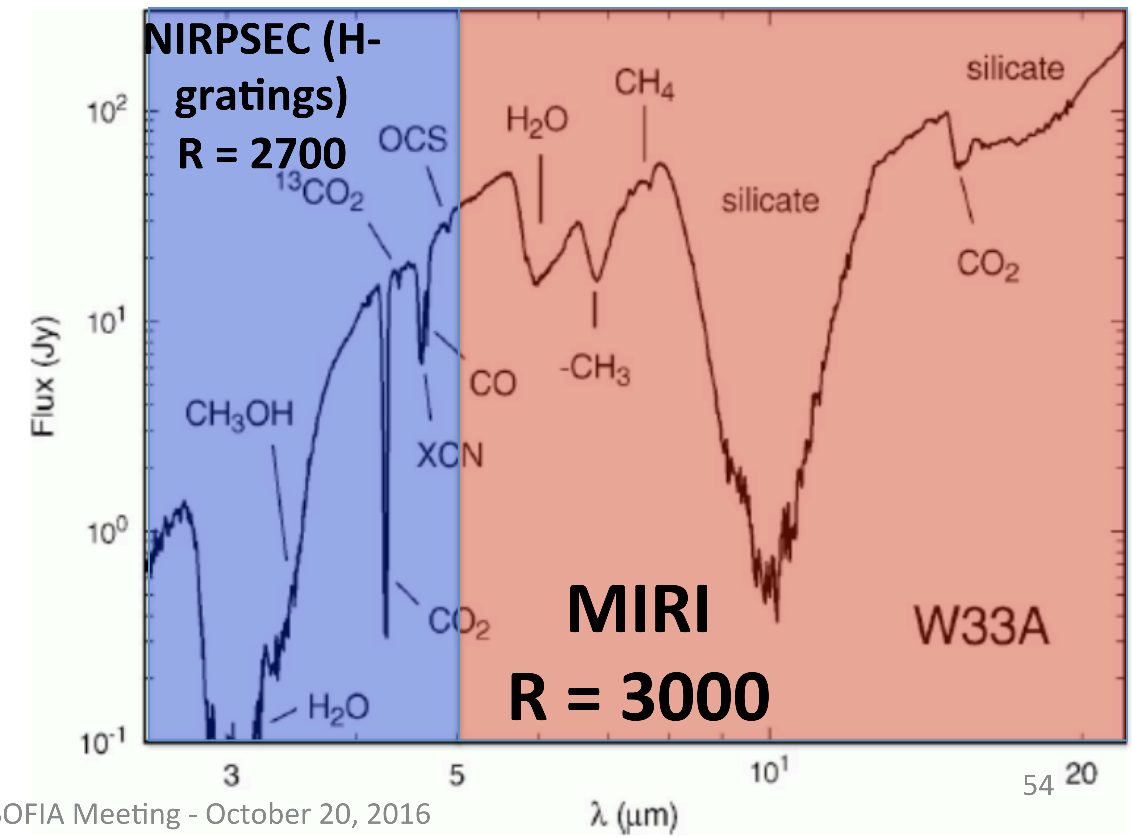




Dust and ices with JWST

JWST launch is 2 years away!

NIR-MIR spectral maps of molecular clouds to characterize dust composition, PAHs, ices…



This is not the end!

Thank you