CO fractionation in a low-metallicity starburst

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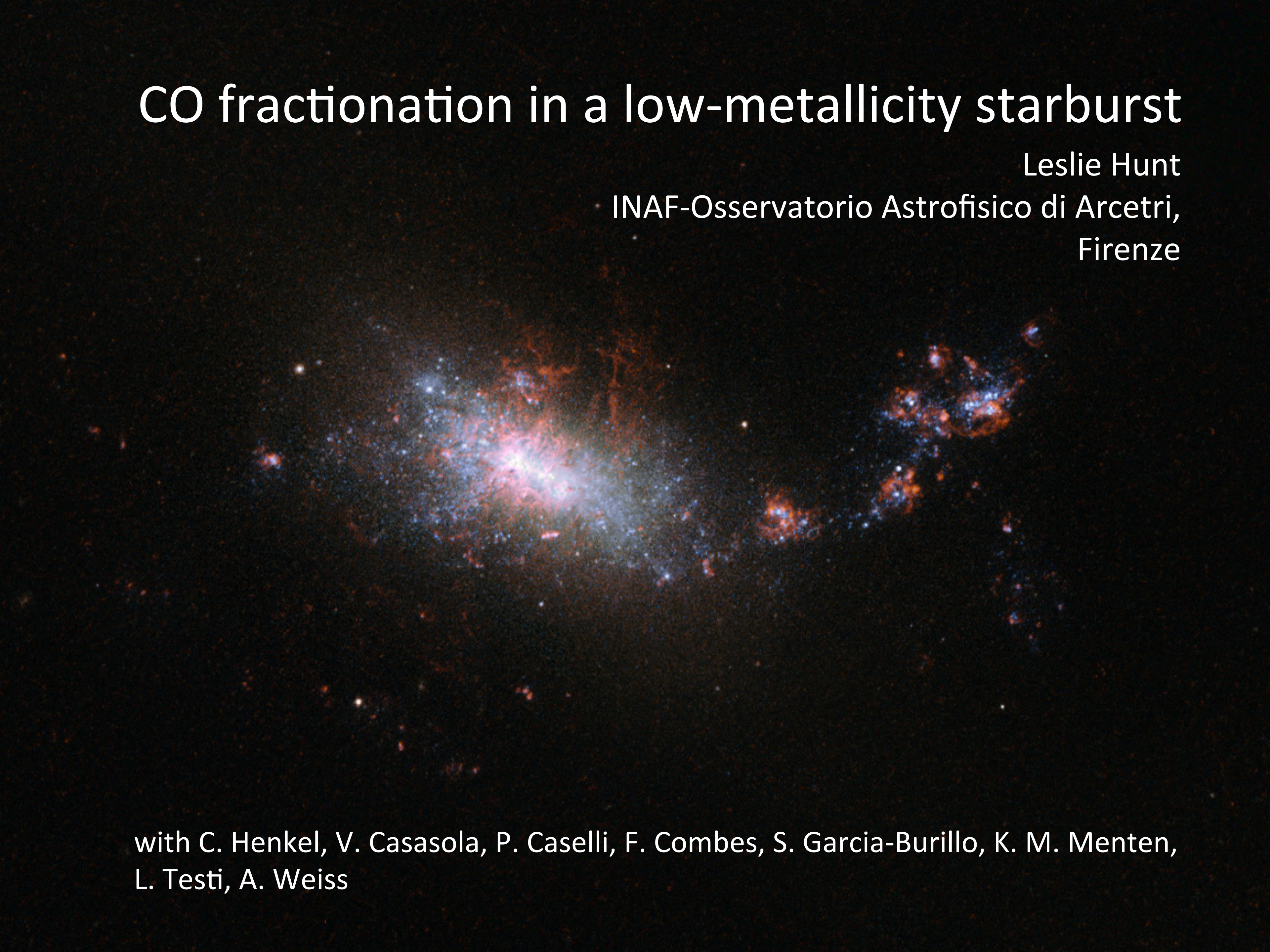
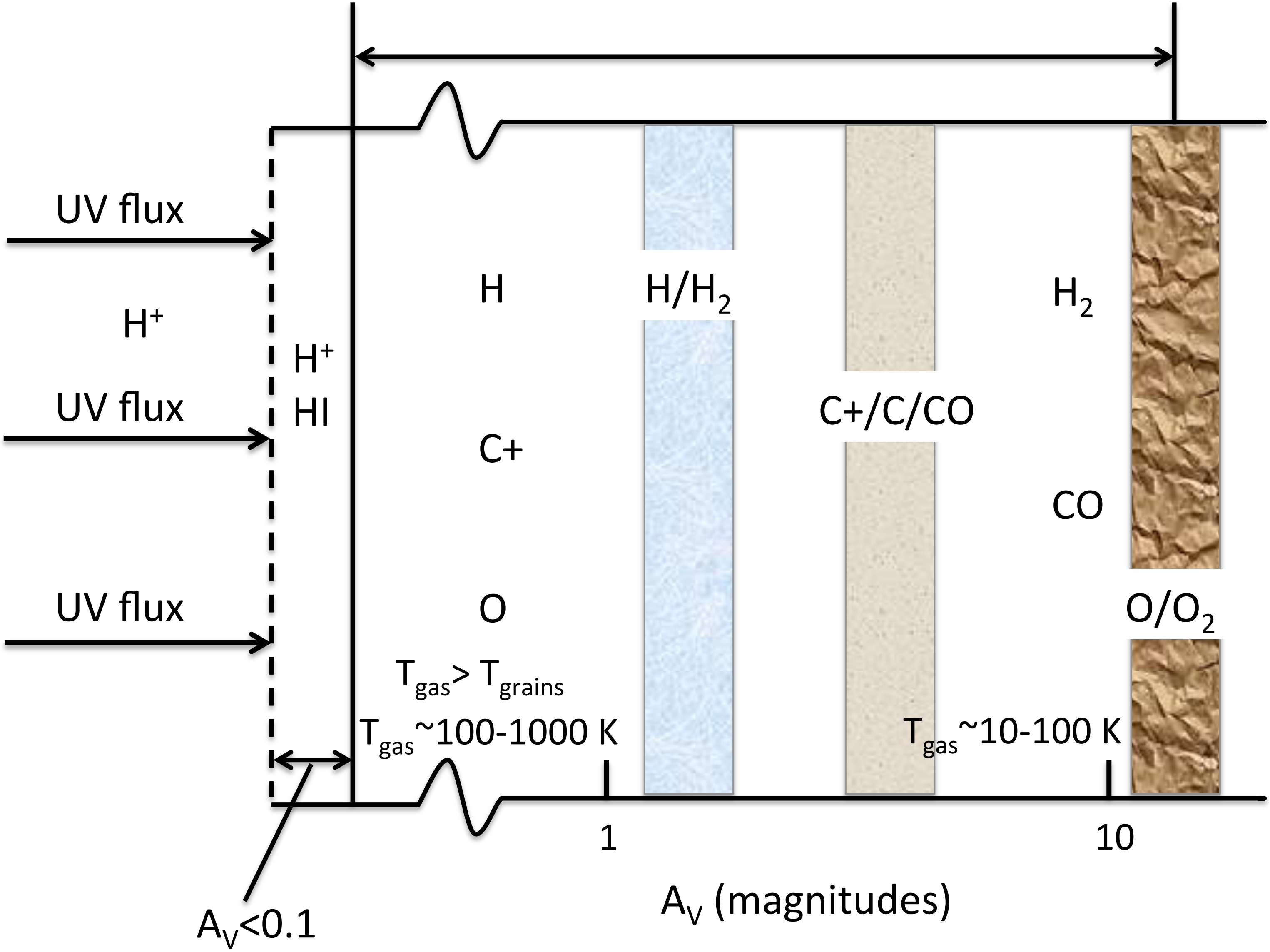


with C. Henkel, V. Casasola, P. Caselli, F. Combes, S. Garcia-Burillo, K. M. Menten, L. Testi, A. Weiss

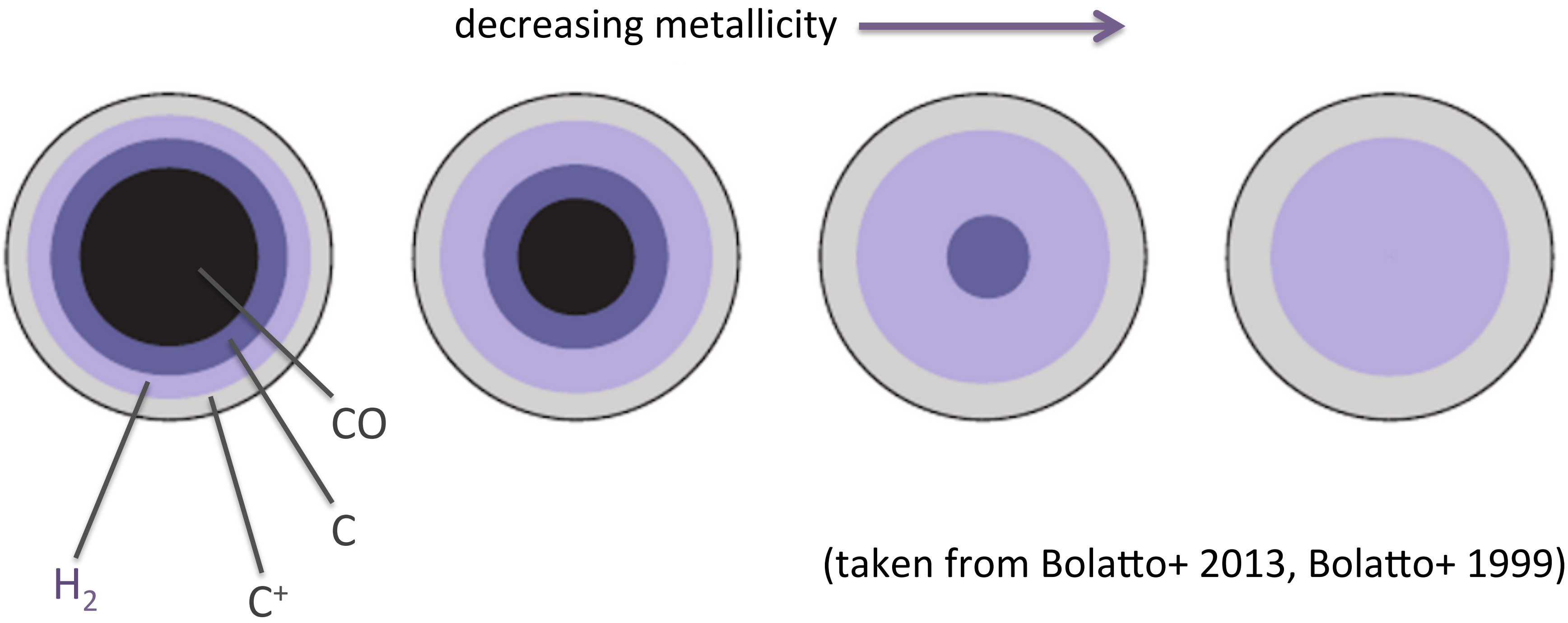
CO and star formation at low metallicity

chemical stratification in a Photo-Dissociation Region (PDR)



(adapted from Wolfire 2011)

PDR structure changes at low metallicity



(taken from Bolatto+ 2013, Bolatto+ 1999)

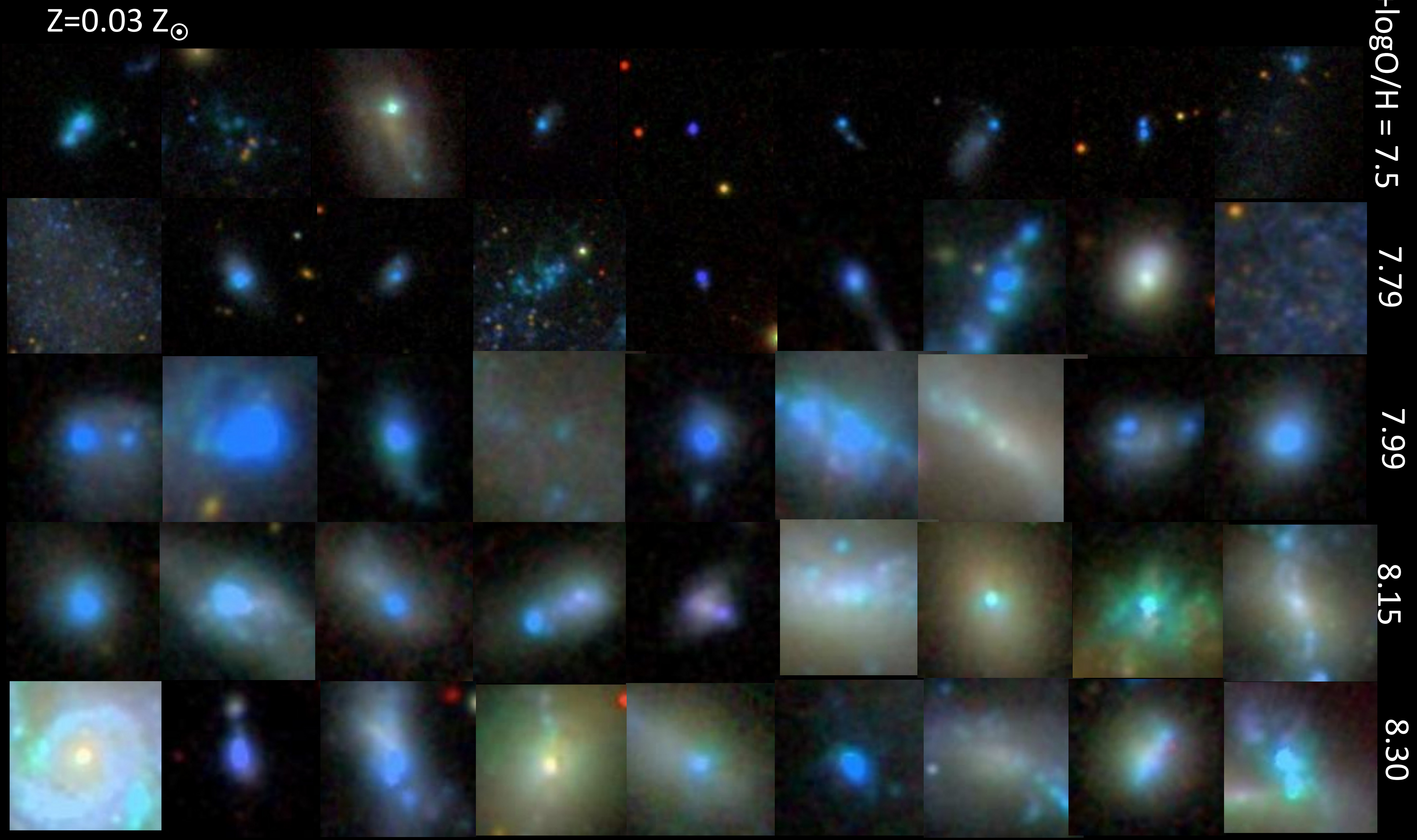
CO emission comes from an increasingly smaller region as metallicity decreases (e.g., Maloney & Black 1988), and expected to disappear (complete dissociation) at sufficiently low metallicities. Thus CO-dark gas prevalent at low metal abundances.

to what low metal abundances can CO trace H_2?

MOlecules and DUst and LOw metallicity (MODULO)

155 dwarf galaxies imaged with *Spitzer/Herschel* and $Z<0.4\ Z_\odot$; median $Z=0.19\ Z_\odot$

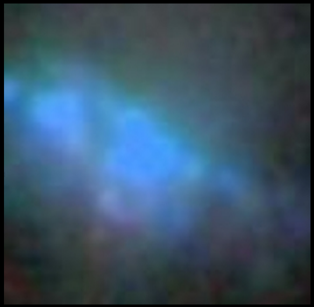
metallicity decreases ➔ ordered disks become clumpy knots of star formation.



^{12}CO(1-0), ^{12}CO(2-1), IRAM 30m observations


CGCG007-025, 0.11 $Z_\odot$


Mrk166, 0.12 $Z_\odot$


UM462, 0.19 $Z_\odot$


Mrk996, 0.20 $Z_\odot$


NGC7077, 0.22 $Z_\odot$

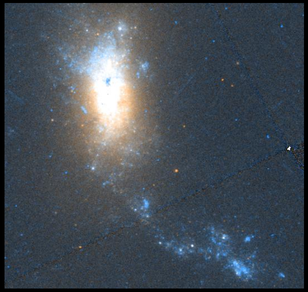

UM448, 0.22 $Z_\odot$


NGC4765, 0.24 $Z_\odot$


Mrk206, 0.24 $Z_\odot$


Haro22, 0.28 $Z_\odot$


Mrk689, 0.28 $Z_\odot$


NGC1140, 0.31 $Z_\odot$

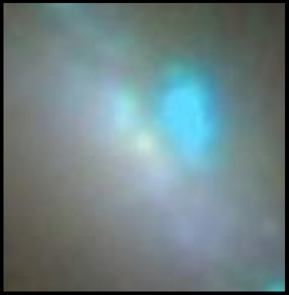

NGC1156, 0.35 $Z_\odot$


IC2828, 0.35 $Z_\odot$


IC691, 0.35 $Z_\odot$


WAS08, 0.36 $Z_\odot$


Mrk490, 0.38 $Z_\odot$


NGC3353, 0.48 $Z_\odot$

Hunt+ 2015, 2016

^{12}CO(1-0), ^{12}CO(2-1), IRAM 30m observations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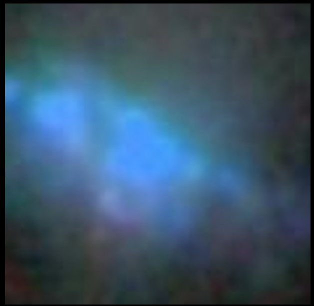
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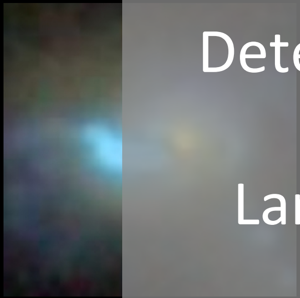
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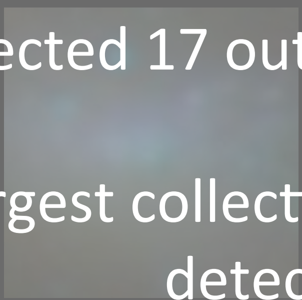
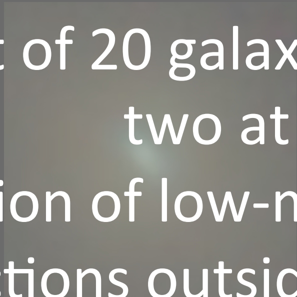
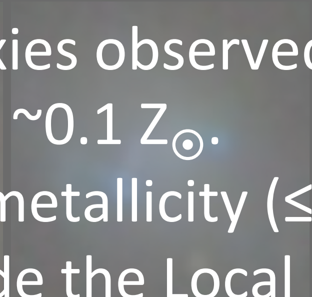
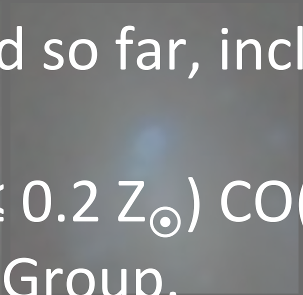
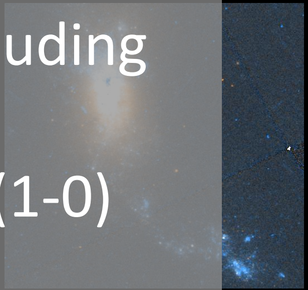

NGC4765, 0.24 $Z_\odot$


Mrk206, 0.24 $Z_\odot$


Haro22, 0.28 $Z_\odot$


Mrk689, 0.28 $Z_\odot$


NGC1140, 0.31 $Z_\odot$

Detected 17 out of 20 galaxies observed so far, including two at ~0.1 $Z_\odot$.

Largest collection of low-metallicity (≤ 0.2 $Z_\odot$) CO(1-0) detections outside the Local Group.


NGC1156, 0.35 $Z_\odot$


IC2828, 0.35 $Z_\odot$


IC691, 0.35 $Z_\odot$

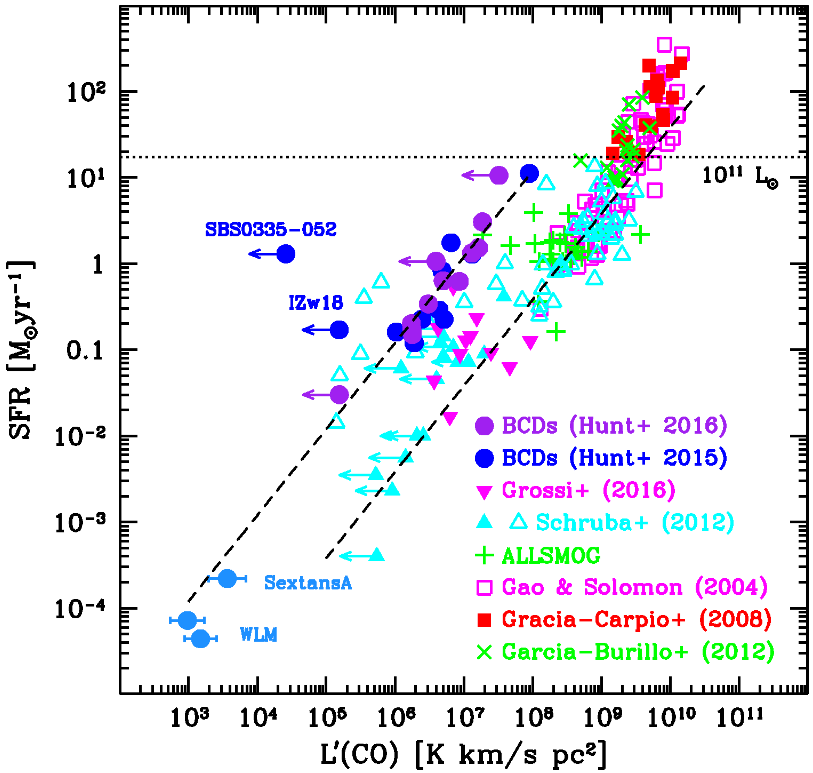

WAS08, 0.36 $Z_\odot$


Mrk490, 0.38 $Z_\odot$


NGC3353, 0.48 $Z_\odot$

Hunt+ 2015, 2016

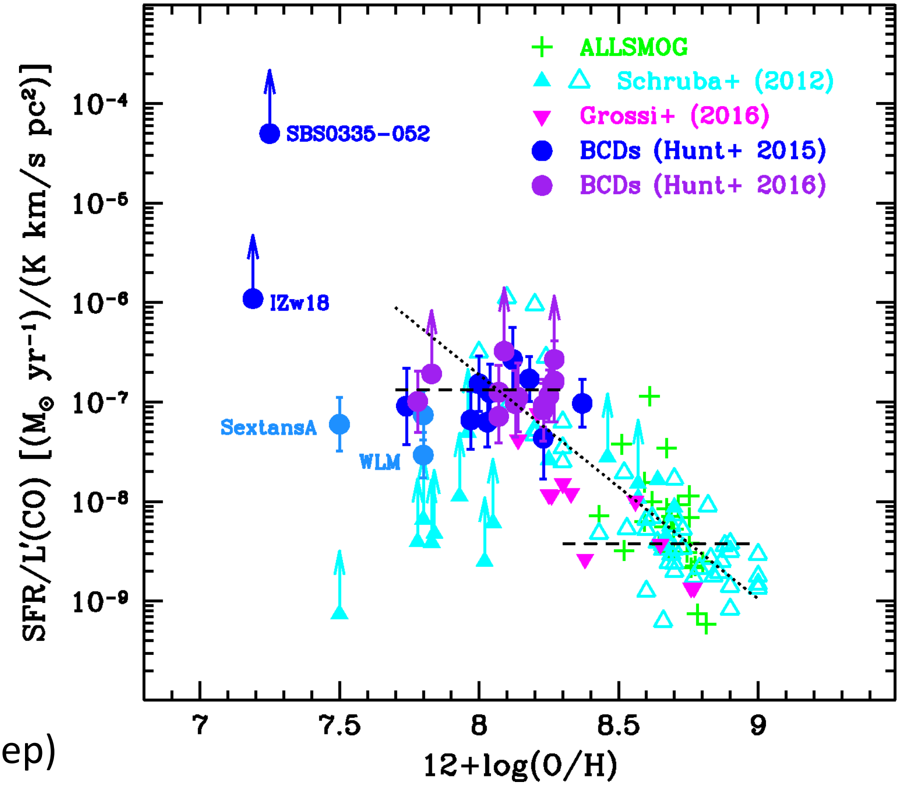
CO traces SFR even at low metallicity



for our sample (with $Z<0.5Z_\odot$), factor of 30 offset to lower L′(CO) for a given SFR relative to relation by Gao & Solomon (2004)

relatively narrow range of metallicities in our sample, so include additional galaxies (Schruba+ 2012; Grossi+ 2016; Elmegreen+ 2013, WLM; Shi+ 2014, Sextans A; Leroy+ 2007 IZw18, Hunt+ 2014, SBS0335-052)

significant trend of SFR/L′(CO) and O/H, directly related to the metallicity dependence of CO-H_2 mass conversion factor α_{CO}

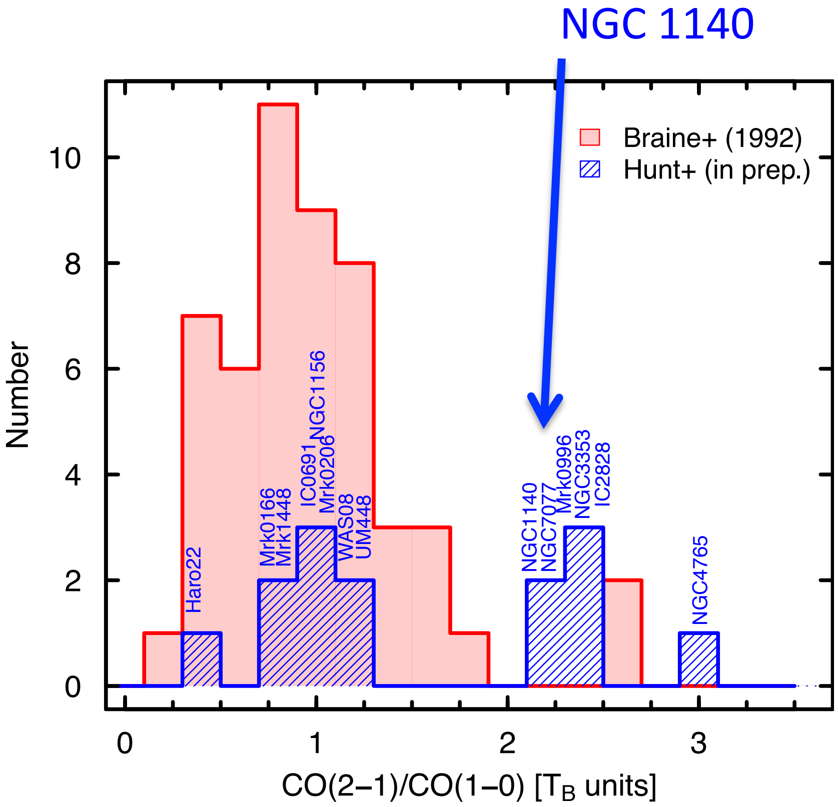


Hunt+ 2015, 2016 (in prep)

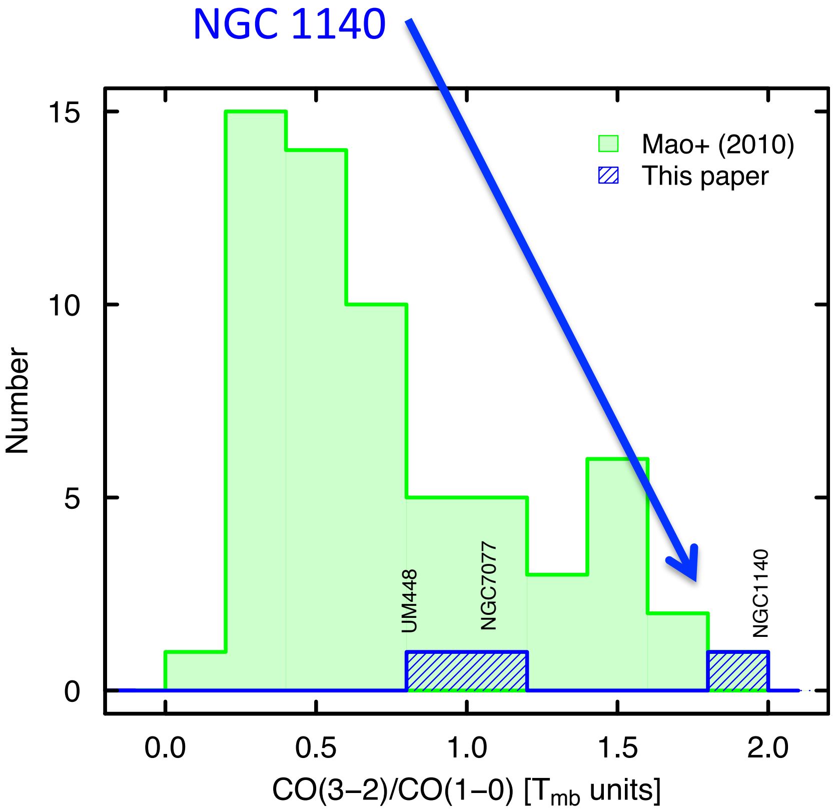
physical conditions of the molecular gas in NGC 1140, a low metallicity starburst

Why NGC 1140 ?

extreme ^{12}CO line ratios (^{12}CO(2-1), ^{12}CO(3-2)/^{12}CO(1-0) corrected for beam dilution)



NGC 1140



NGC 1140

so possibly highly excited and/or optically thin gas

composite HST image:
red=Hα, blue=0.3μm, yellow=0.8μm

NGC 1140

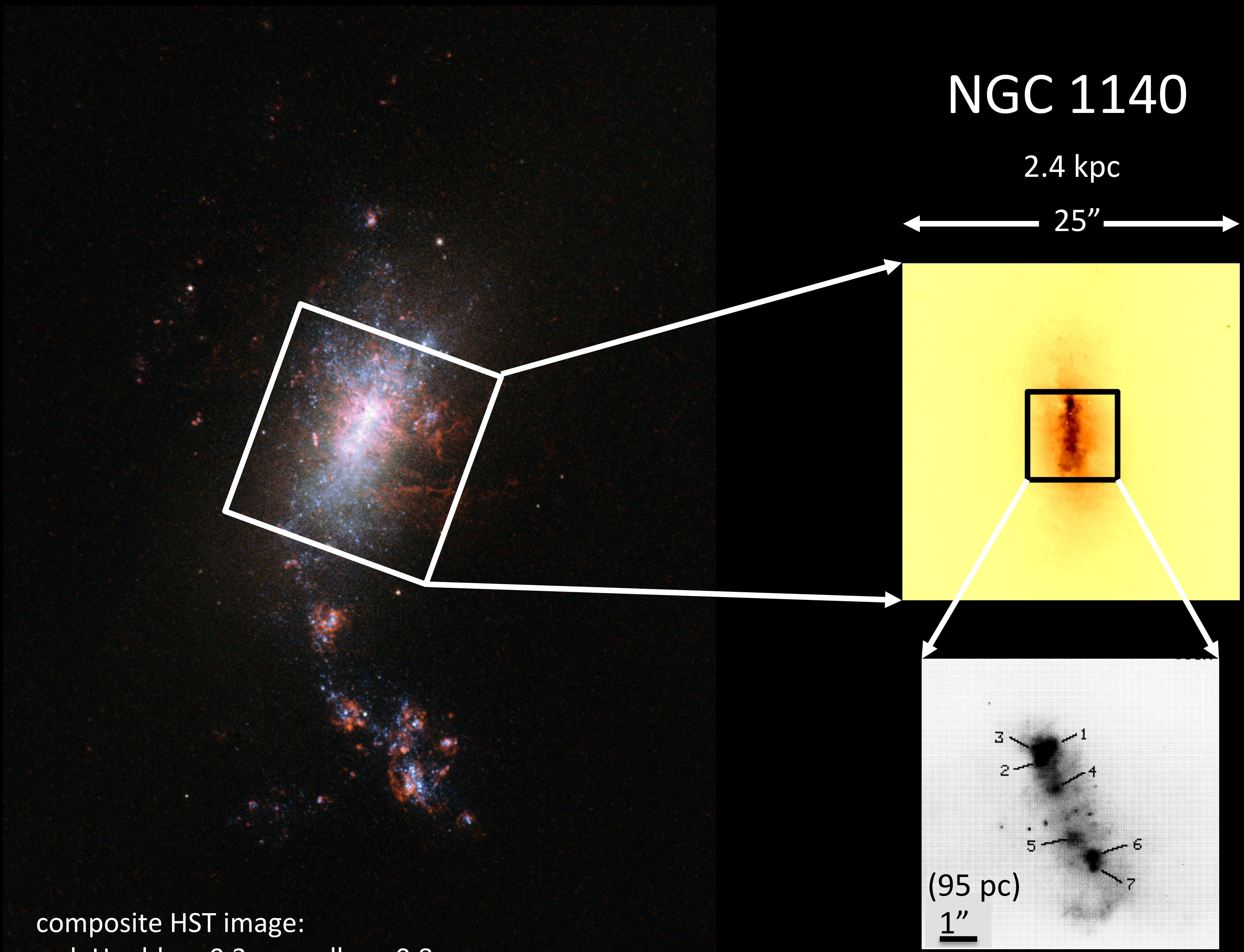
dwarf starburst at ~19 Mpc distance hosting 6 super star clusters (SSCs) containing > 7000 O4 stars in 6 main clusters (Hunter+ 1994, de Grijs+ 2004, Moll+ 2007, Westmoquette+ 2010)

faintest of 6 SSCs 3 x luminosity of 30 Doradus, total SFR ~ 0.8 $M_{\odot}$ yr^{-1}

SSC ages from 5 Myr to 12 Myr, overall starburst < 55 Myr (de Grijs+ 2004, Moll+ 2007)

O/H ~ 0.3 $Z_{\odot}$ (12+logO/H=8.2), slightly higher than SMC, factor 2 lower than LMC

NGC 1140



composite HST image:
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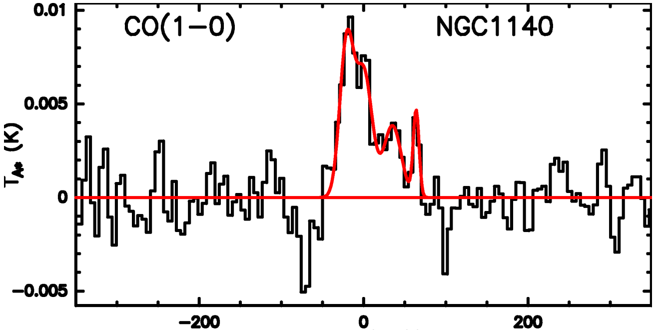
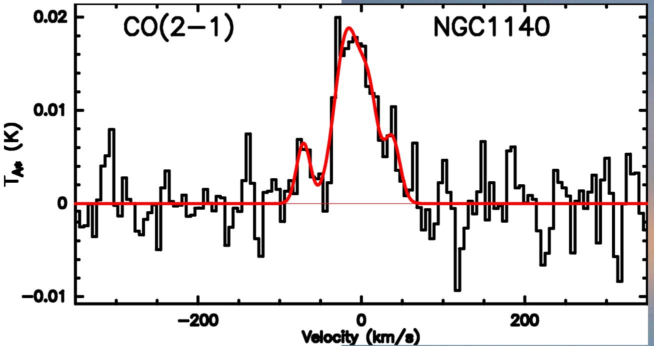
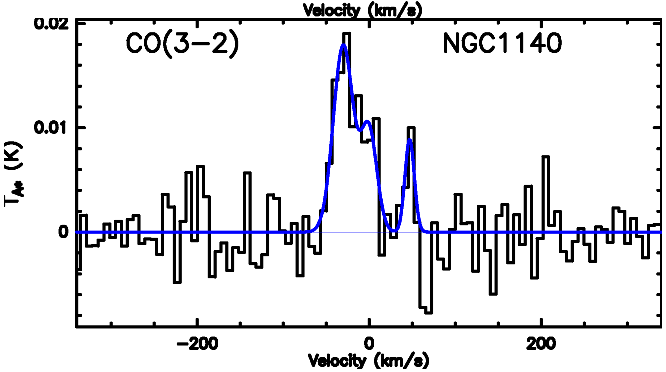
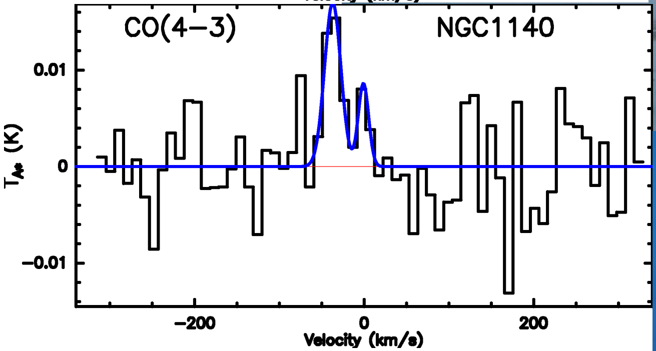
NGC 1140: ^{12}CO, ^{13}CO

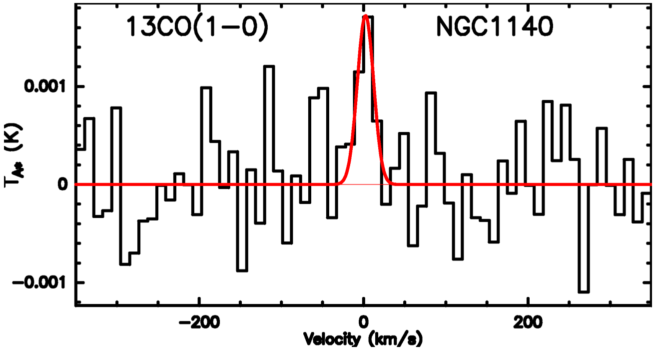
single-dish (IRAM, APEX) ^{12}CO(1-0), ^{12}CO(2-1), ^{12}CO(3-2), ^{12}CO(4-3), ^{13}CO(1-0), ^{13}CO(2-1)
multi-frequency line analysis

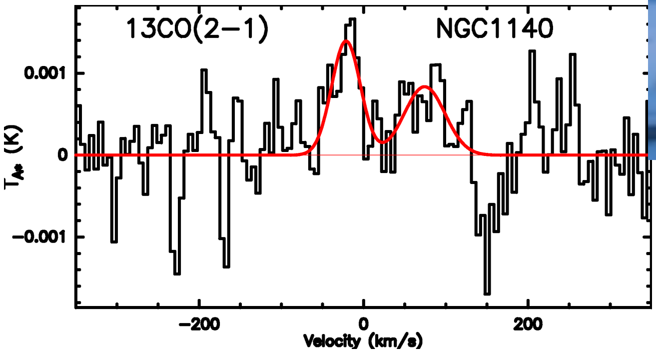






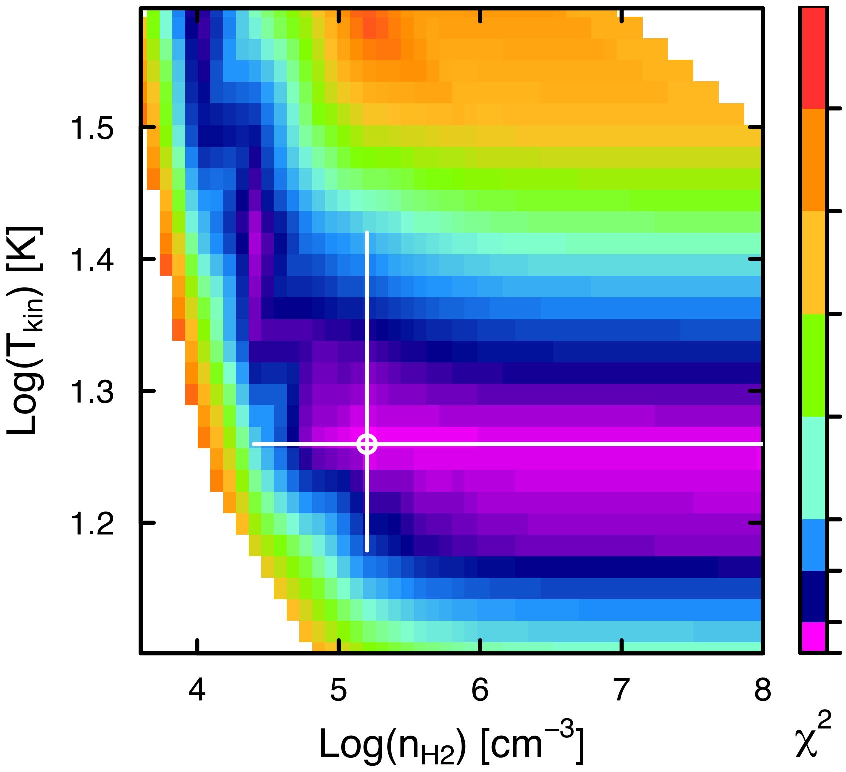


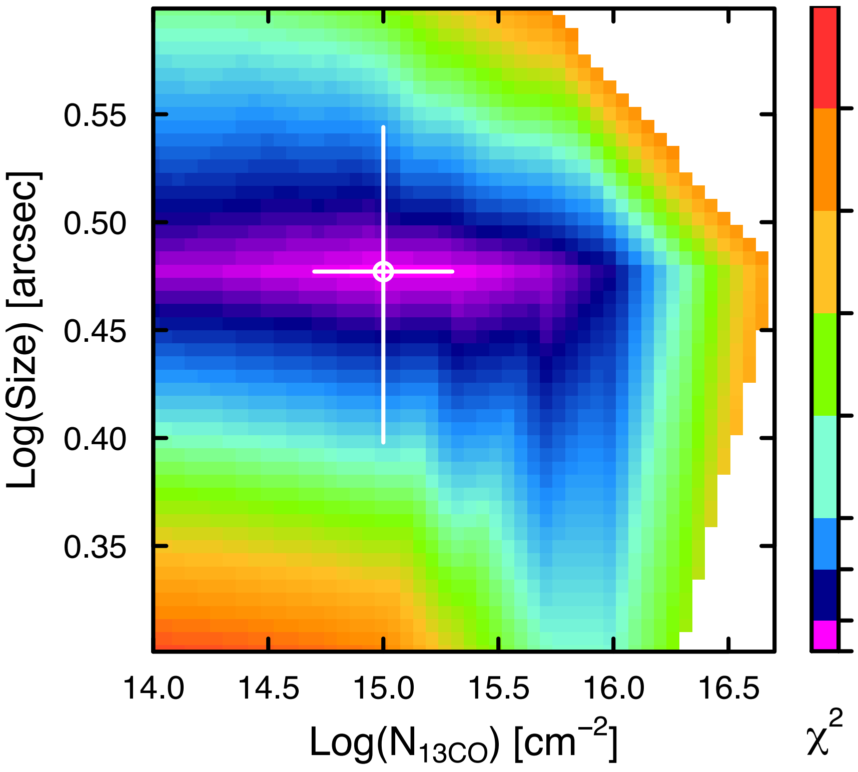




χ^2 surfaces for Radex fit of NGC 1140: ^{12}CO, ^{13}CO

modeling single-dish $^{12}CO(1\text{-}0)$, $^{12}CO(2\text{-}1)$, $^{12}CO(3\text{-}2)$, $^{12}CO(4\text{-}3)$, $^{13}CO(1\text{-}0)$, $^{13}CO(2\text{-}1)$ line ratios constrains n_{H2}, T_{kin}, N_{12CO}, $X={}^{12}CO/{}^{13}CO$, source size: sum of $\chi^2 = 0.7$ over 5 independent line ratios (size-related filling factor delicate issue, but crucial)

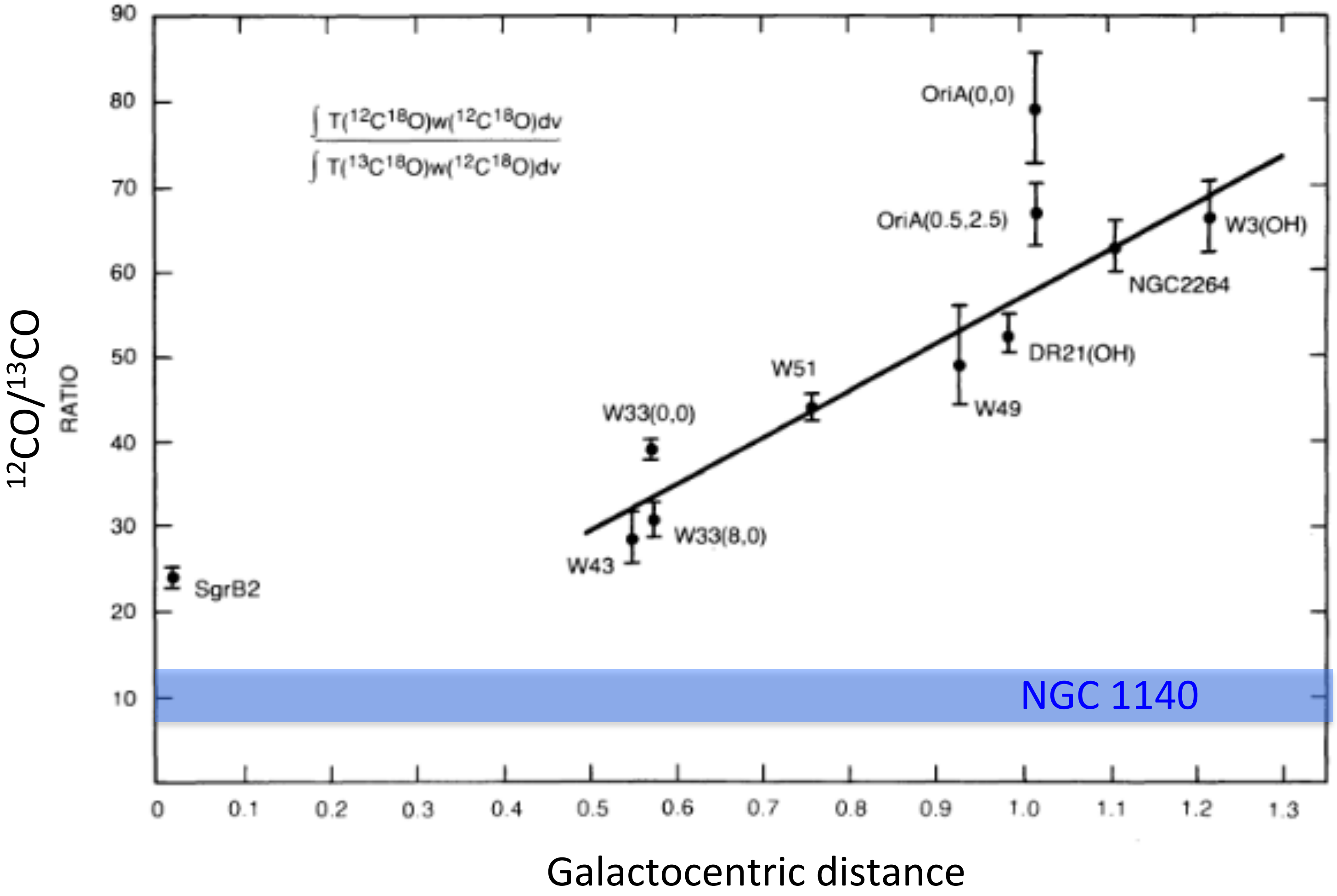




optically thin, cool (T_{kin} ~ 18 K), dense gas (n_{H2} ~ $10^{5.2}$ cm^{-3}), with extremely low $^{12}CO/^{13}CO$ ~10-12(LVG models give consistent results)

^{12}CO/^{13}CO ratio and fractionation

NGC1140: extremely low ^{12}CO/^{13}CO abundance~ 8-12, roughly 7-8 times lower than the Galaxy, Solar neighborhood, 2.5 times lower than Galactic Center



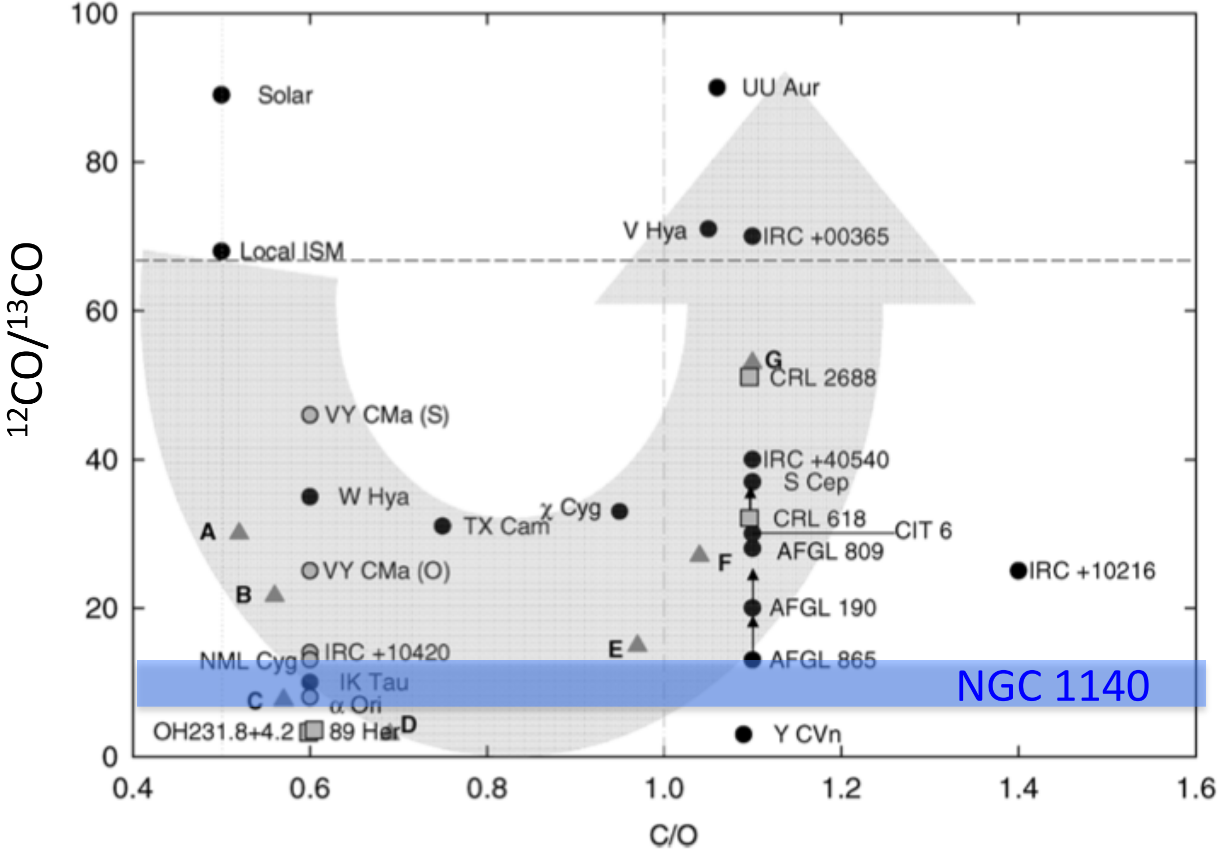
Langer & Penzias (1990)

^{12}CO/^{13}CO ratio and fractionation

NGC1140: extremely low ^{12}CO/^{13}CO abundance~ 8-12, roughly 7-8 times lower than the Galaxy, Solar neighborhood, 2.5 times lower than Galactic Center

young age of starburst (5-12 Myr: de Grijs+ 2004, Moll+ 2007) makes it **improbable** to significantly enrich the elemental abundance of ^{13}C in NGC 1140 through **nucleosynthesis** + dredge-up (convective mixing) in older, intermediate-mass stars

^{12}CO/^{13}CO abundance ratios in evolved (200 Myr – 2 Gyr) stars



Milam+ (2005, 2009)

$^{12}CO/^{13}CO$ ratio and fractionation

more likely cause CO fractionation

isotopic selective photodissociation of CO effective only in diffuse ($n_{H2} \leq 100$ cm^{-3})

in denser regions with higher column density but moderate extinction (1 mag $\leq A_V \leq$ 3 mag), fractionation reactions becomes important :

$$^{13}C^+ + {}^{12}CO \rightleftarrows {}^{13}CO + {}^{12}C^+ + \Delta E\ (= 35\ K)$$

thus, at cool temperatures, the rightmost (exothermic) reaction dominates, leading to a reduced $^{12}CO/^{13}CO$ isotopic ratio

such considerations true in both PDRs and in turbulent molecular clouds (Röllig & Ossenkopf 2013; Szűcs, Glover, & Klessen 2014)

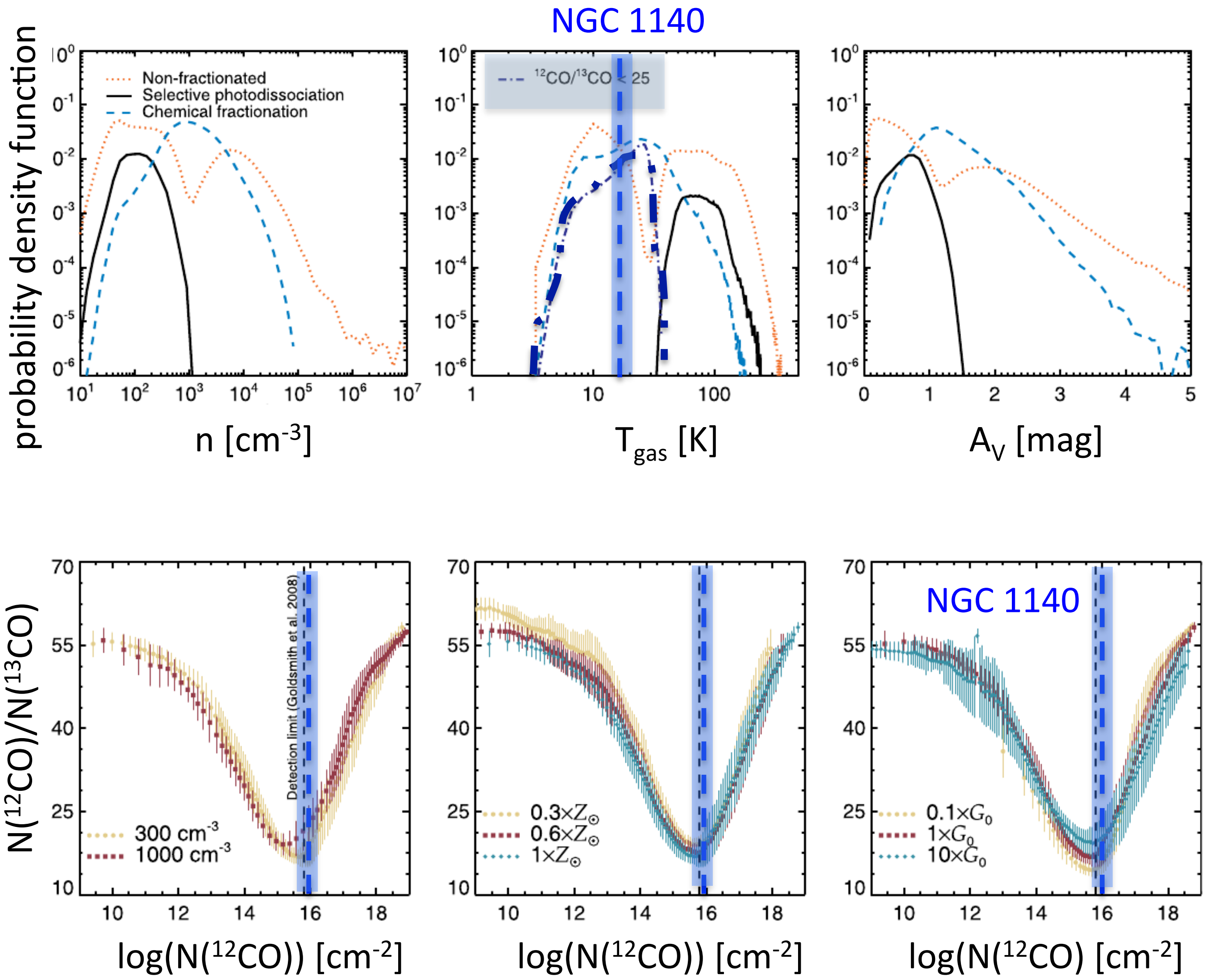
molecular fractionation at work in NGC 1140

models of ^{12}CO, ^{13}CO fractionation (Röllig & Ossenkopf 2013, Szűcs+ 2014) predict a

“sweet spot” for maximum efficiency of ^{13}CO formation

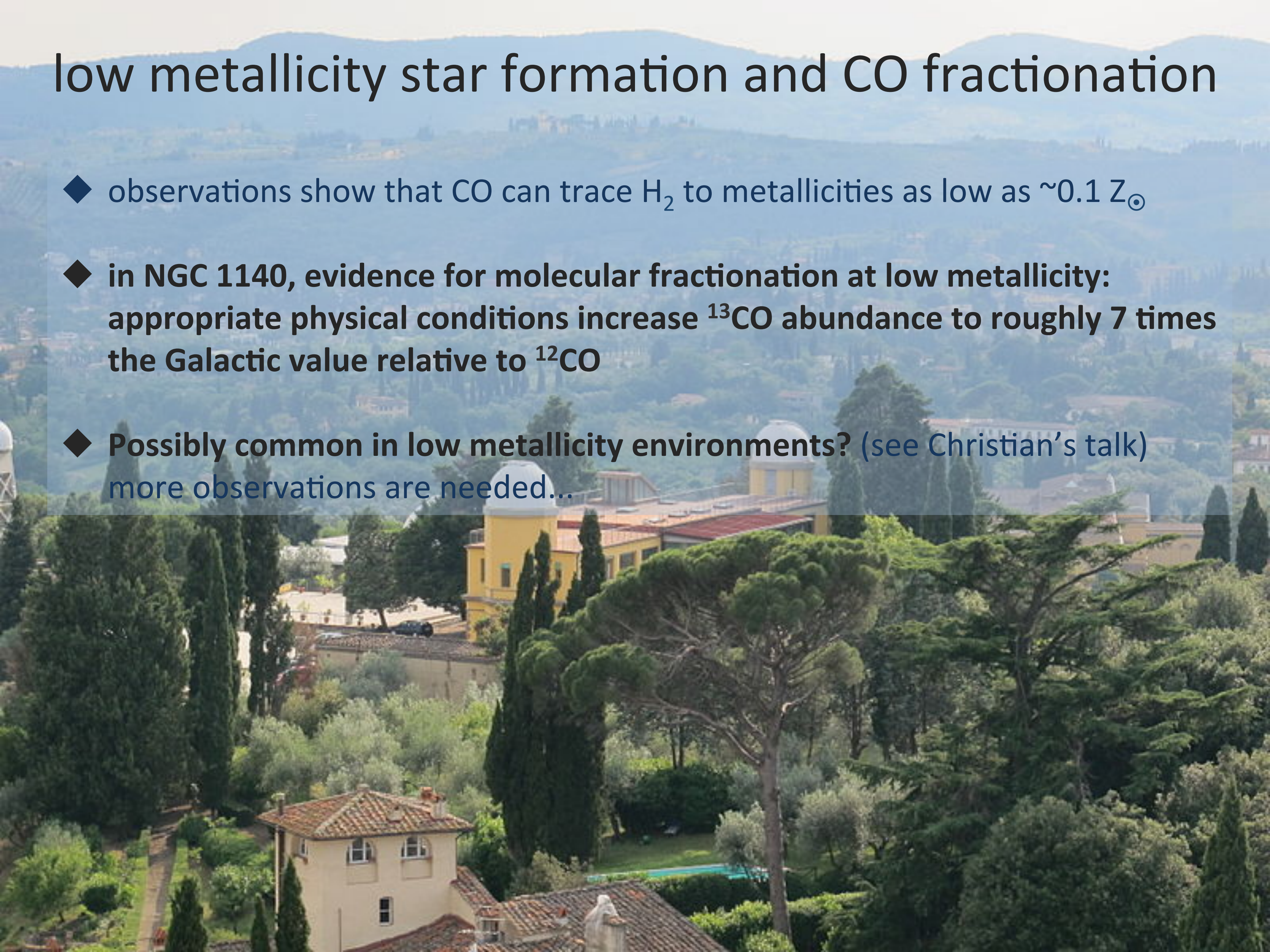
in cool, dense, optically thin (low A_V) gas at moderate CO column densities:

$N(^{12}CO) \sim 10^{16}$ cm^{-2}



Szűcs+ (2014)

low metallicity star formation and CO fractionation



- observations show that CO can trace H_2 to metallicities as low as ~0.1 $Z_\odot$
- **in NGC 1140, evidence for molecular fractionation at low metallicity: appropriate physical conditions increase ^{13}CO abundance to roughly 7 times the Galactic value relative to ^{12}CO**
- **Possibly common in low metallicity environments?** (see Christian's talk)
  more observations are needed...