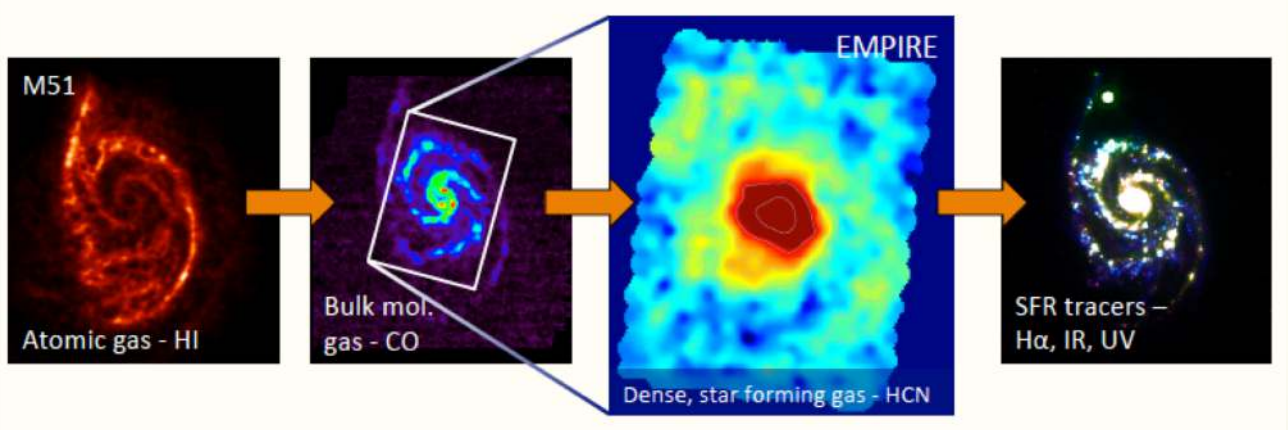
Cold gas and star formation in nearby galaxies

Diane Cormier



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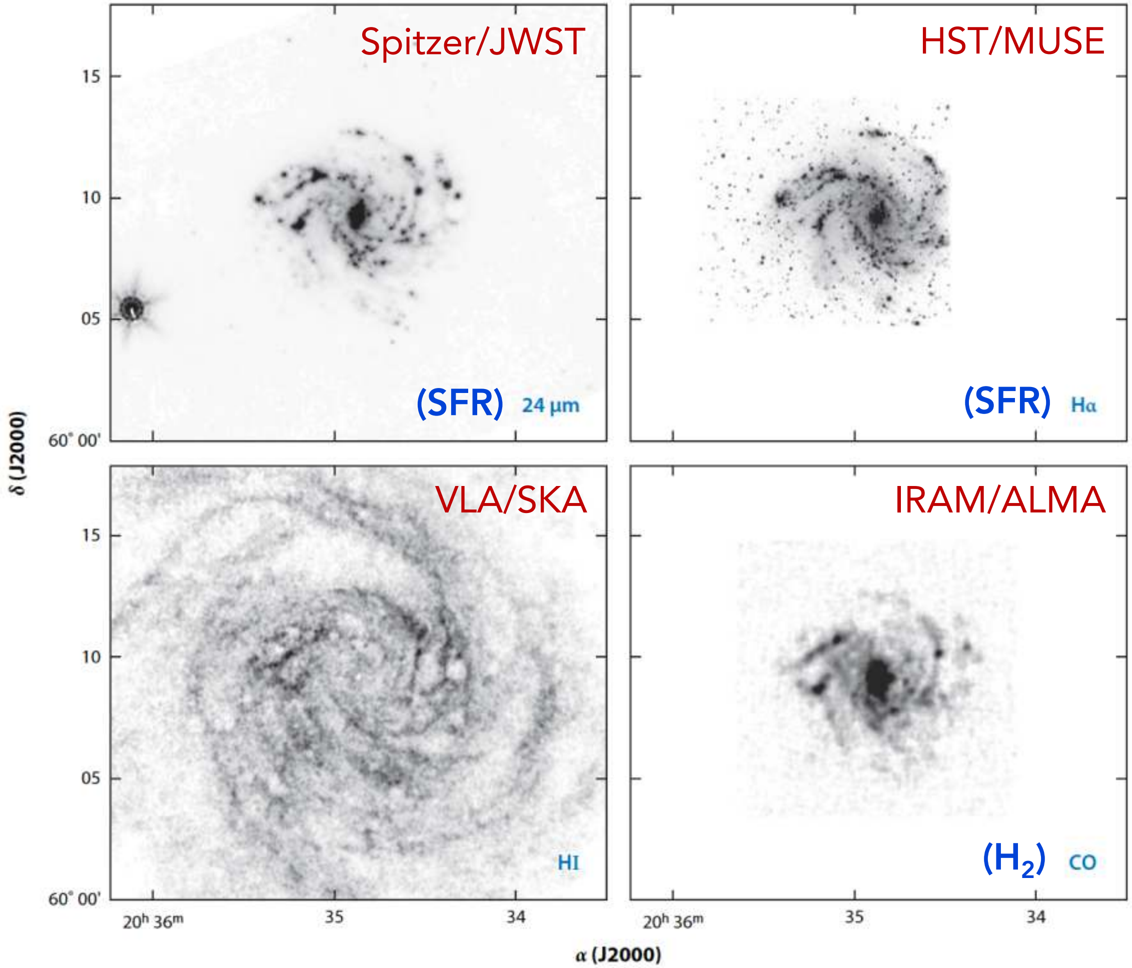
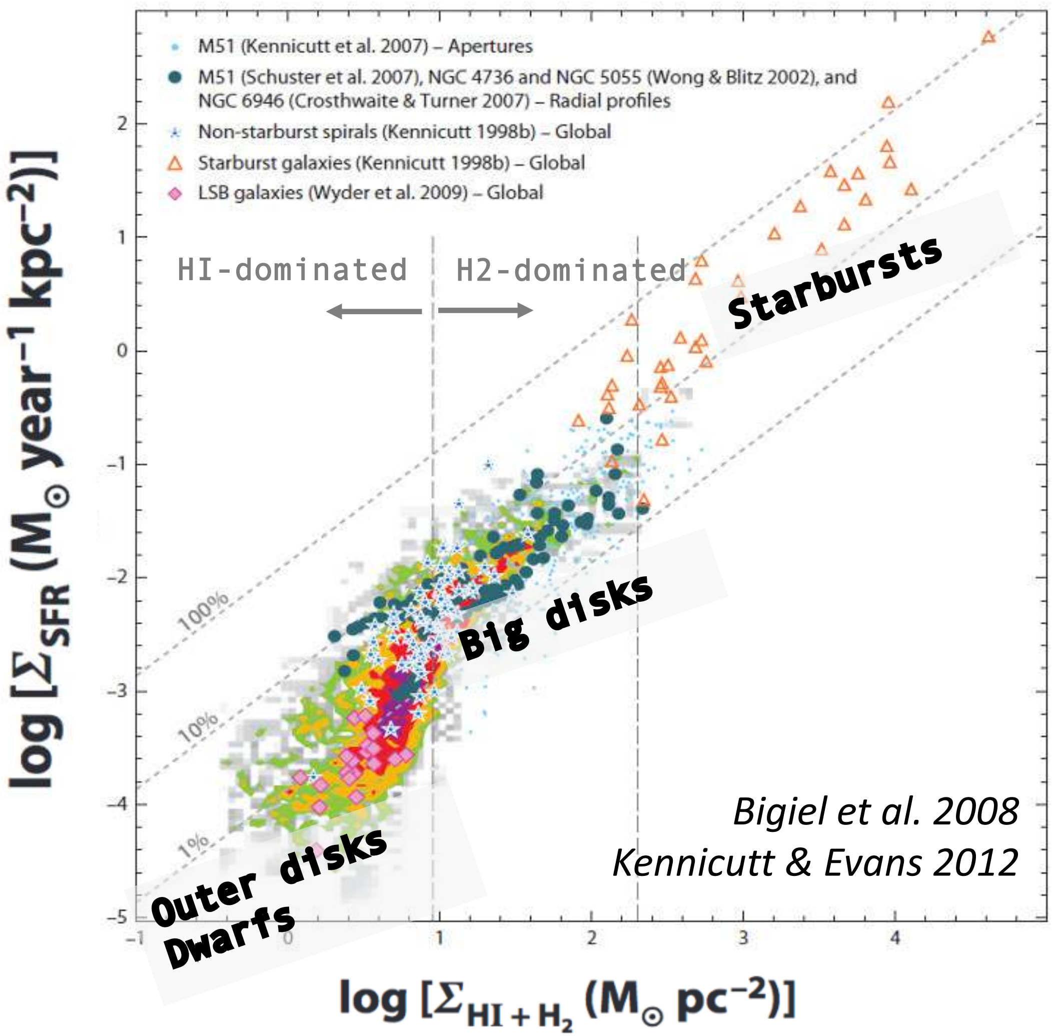
Tracers of star formation in galaxies

NGC 6946 (D = 6.8 Mpc)

Kennicutt & Evans 2012

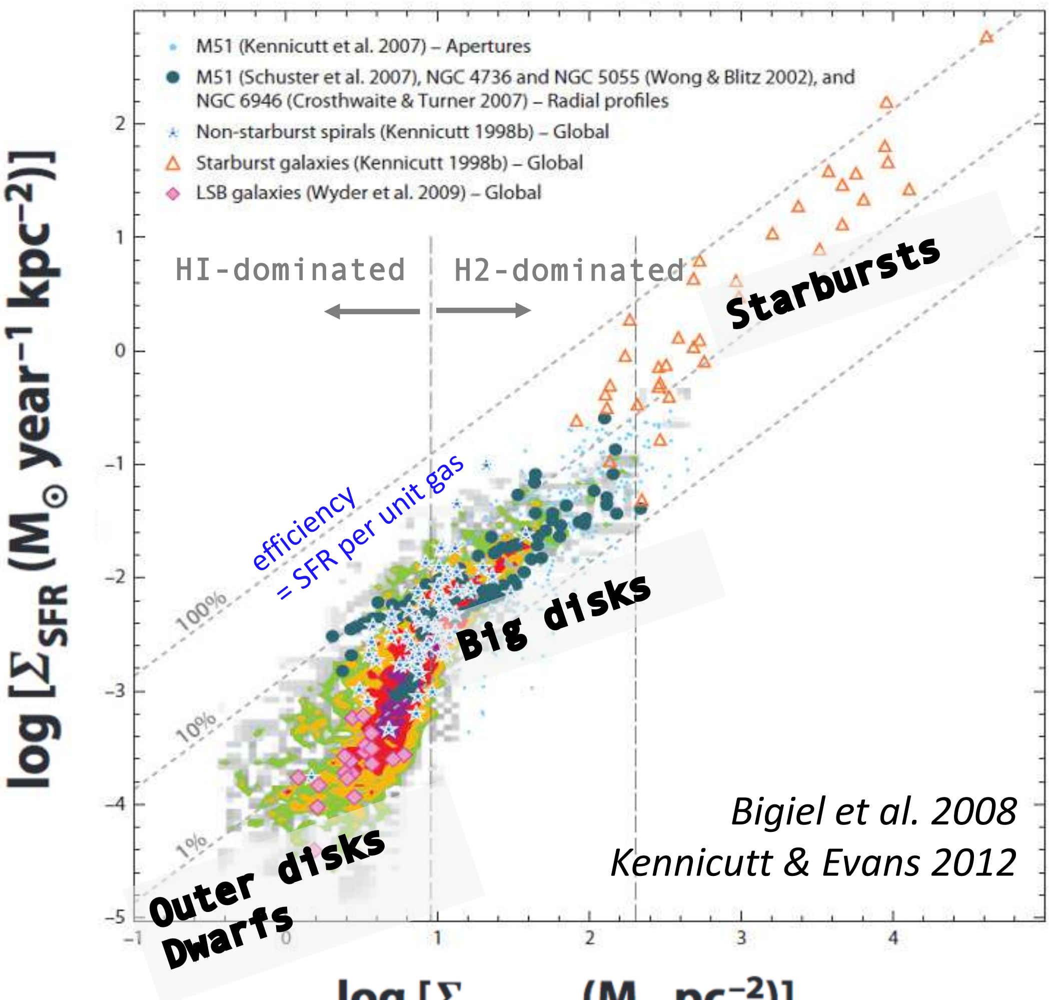


Tracers of star formation in galaxies



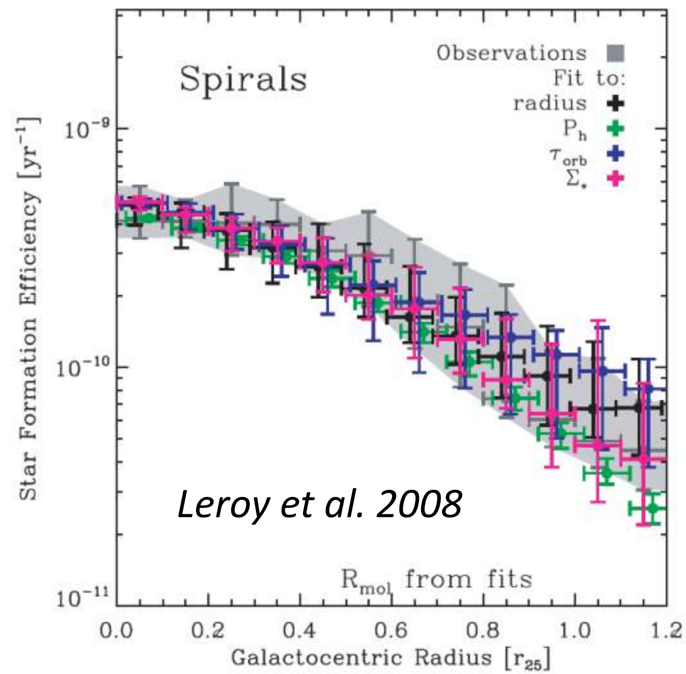
SFR correlates best with H_2 (CO)

Tracers of star formation in galaxies

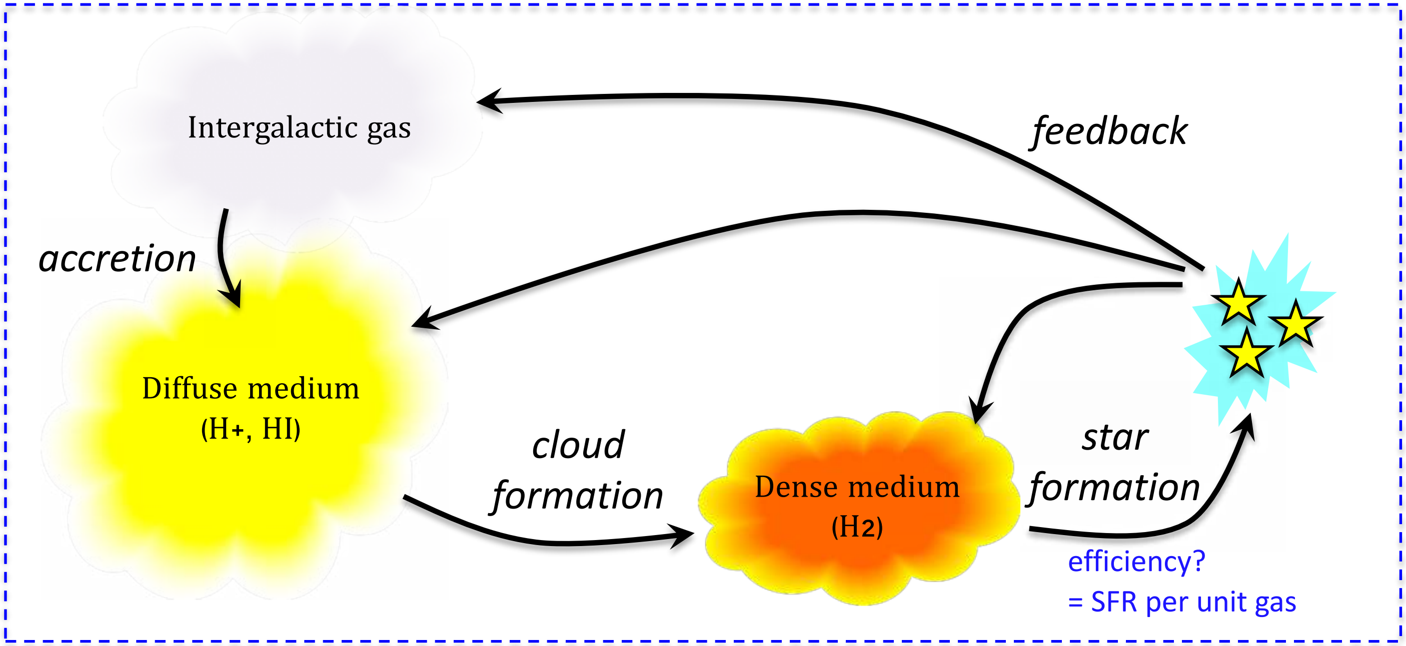


Variations in star-formation efficiencies (SFE) due to environment dependencies

(metallicity, stellar/gas density, time evolution, galactic dynamics, feedback, etc.)



Understanding the steps to star formation



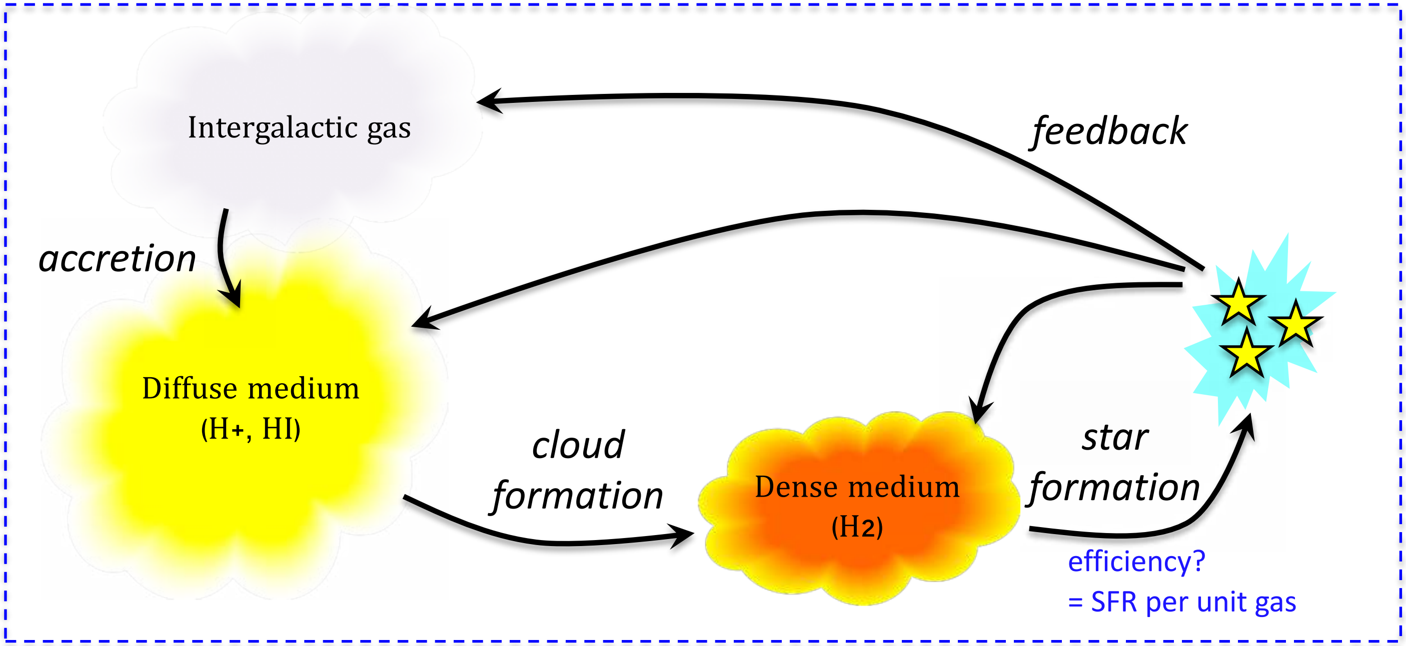
(environment: metallicity, stellar/gas density, time evolution, galactic dynamics, feedback, etc.)

How are the phases of the ISM distributed in galaxies?

What are the physical conditions of the gas leading to the dense phase?

What sets the efficiency of SF and is it constant?

Understanding the steps to star formation

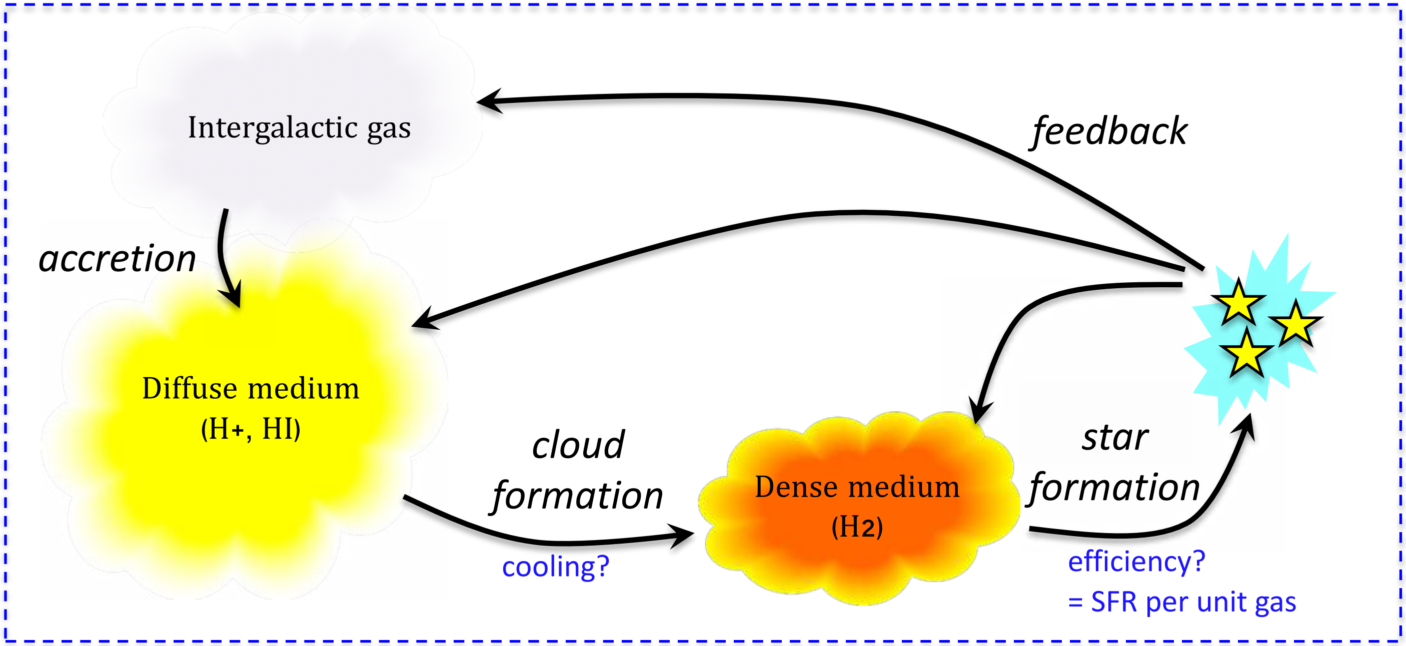


→ Low metallicity

→ Gas denser than CO

→ Cloud-scale properties

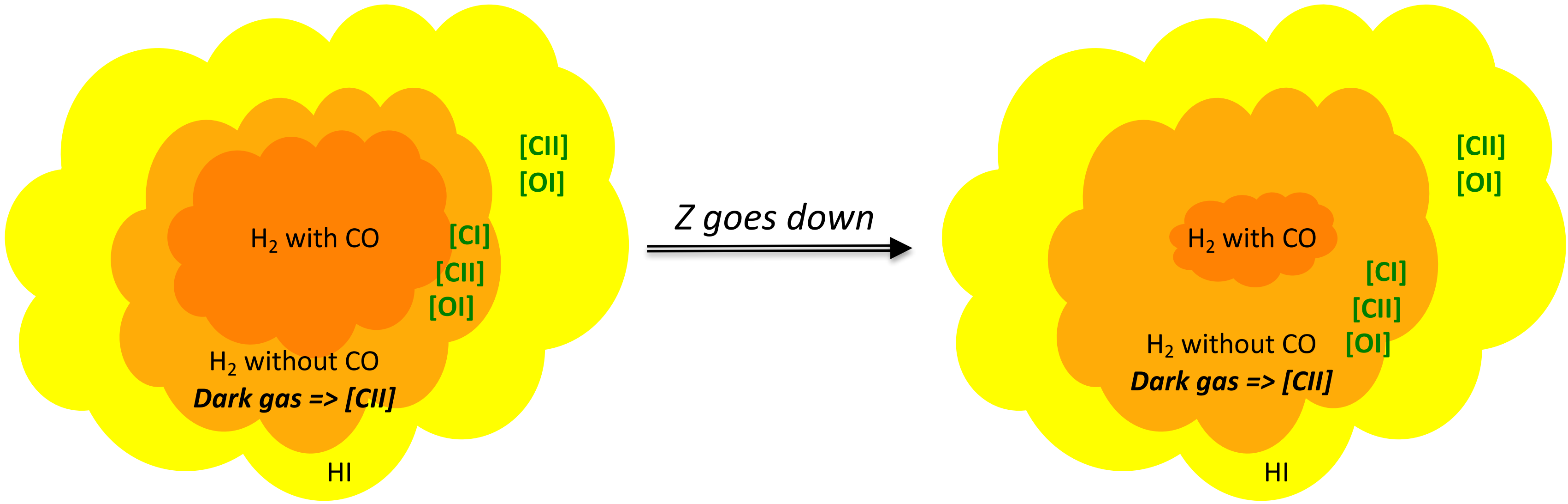
Effect of metallicity (Z)



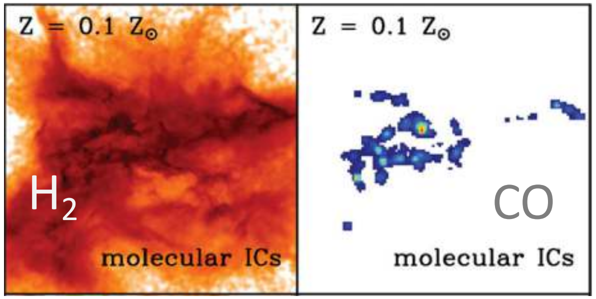
- Cooling by metals
- Dust and molecule formation
- Harder stellar radiation field
- Shielding/heating of gas

Effect of metallicity (Z)

e.g. Wolfire et al. 2010
Bolatto et al. 2013



From simulations



At 1/100 $Z_{\odot}$: SF in atomic gas?
Cooling by atomic phase ([CII], [OI])
H_2-phase formation delayed

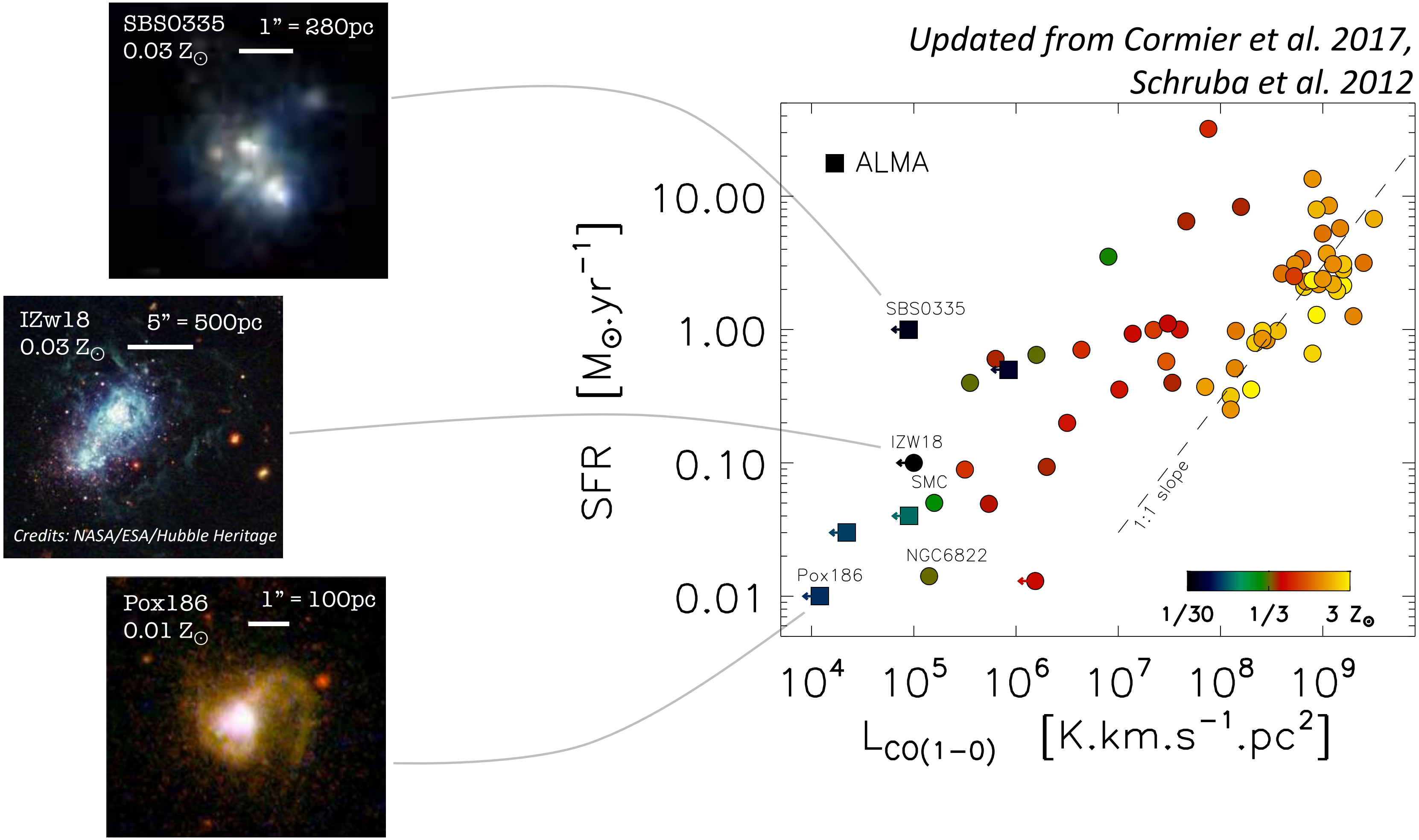
(e.g. Glover & Clark 2012, Krumholz 2012)

From observations

structure change and cold gas difficult to observe

Star formation at low metallicity: no molecules?

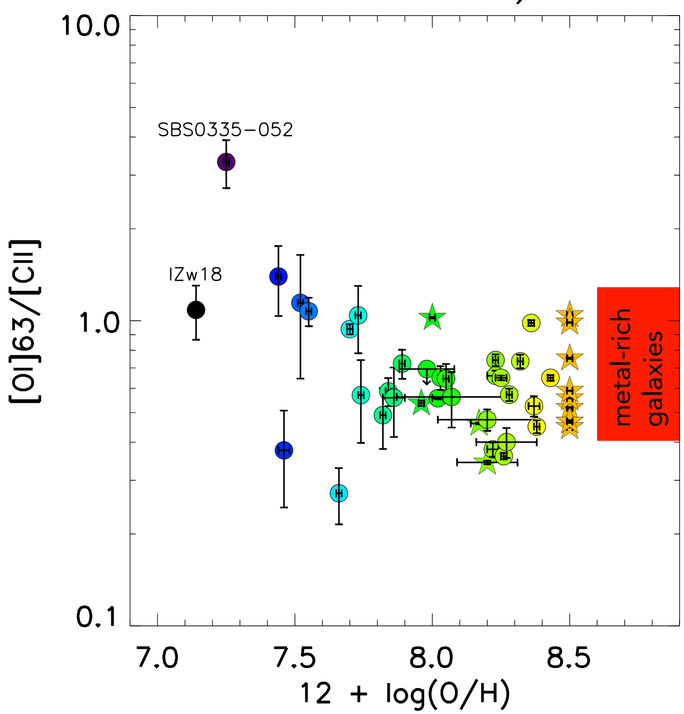
- CO extremely hard to detect, even with ALMA



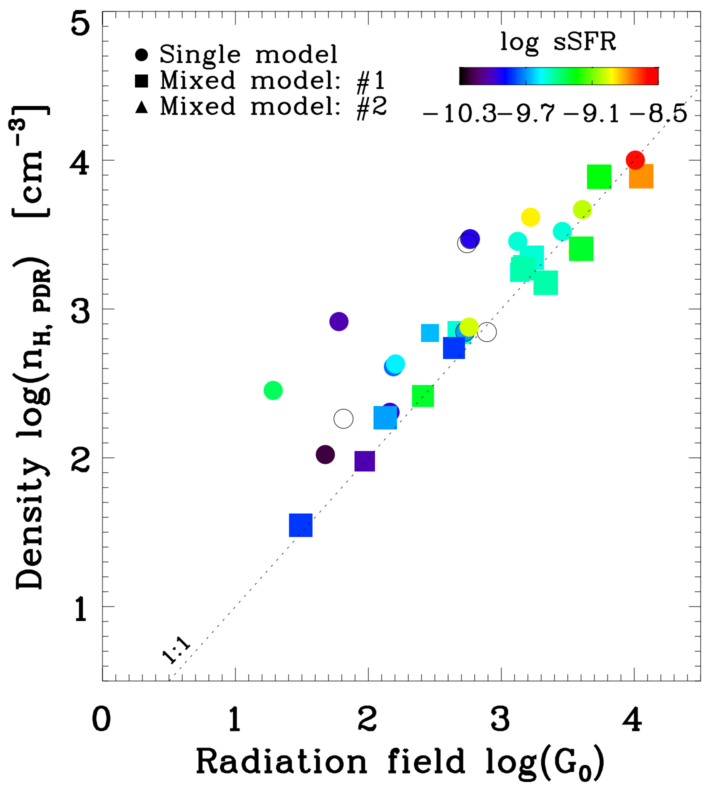
PDR gas conditions thanks to *Herschel*

- Most important cooling lines ([CII], [OI]) detected at low metallicity with the *Herschel* Dwarf Galaxy Survey

Cormier et al. 2015, 2019



HII+PDR modeling



Measuring the CO-dark gas with [CII]

- Milky Way: 30% of the molecular mass is CO-dark
  (Pineda et al. 2013, Langer et al. 2014)

- Nearby dwarfs (IC10, LMC, SMC, Dwarf Galaxy Survey):
  10-500 times more CO-dark than CO-bright gas mass

Madden & Cormier 2018

Spectrally-resolved (SOFIA)

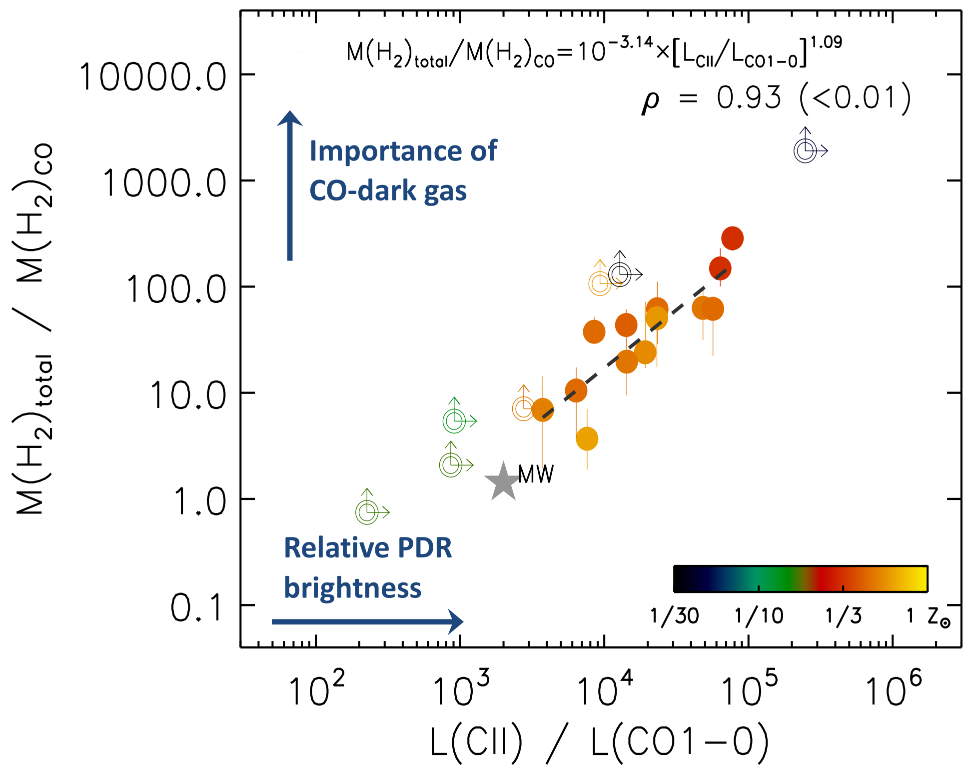
e.g. Requena-Torres et al. 2016, Fahrion et al. 2017, Lebouteiller et al. in prep

Spatially-resolved (KAO, Herschel, …)

e.g. Poglitsch et al. 1995, Madden et al. 1997, Jameson et al. 2018

Unresolved, multi-phase models

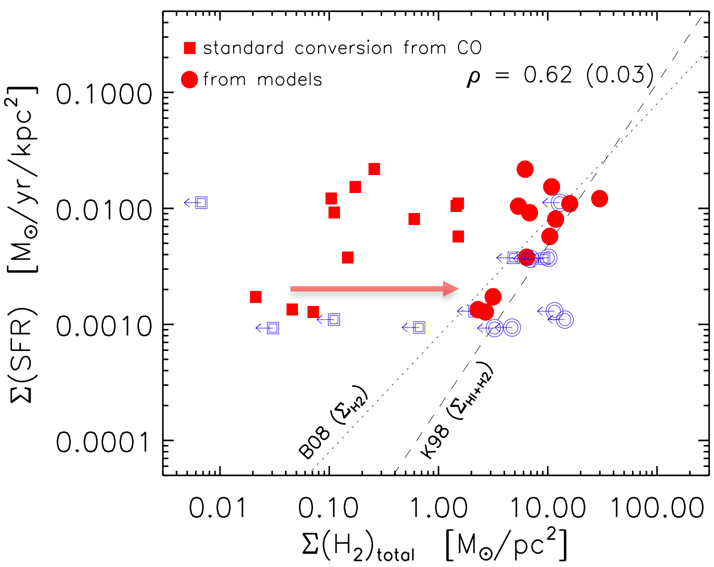
Madden & Cormier 2018



Conversion factor at low metallicity

- *Standard* efficiency when accounting for the CO-dark gas

Madden & Cormier 2018

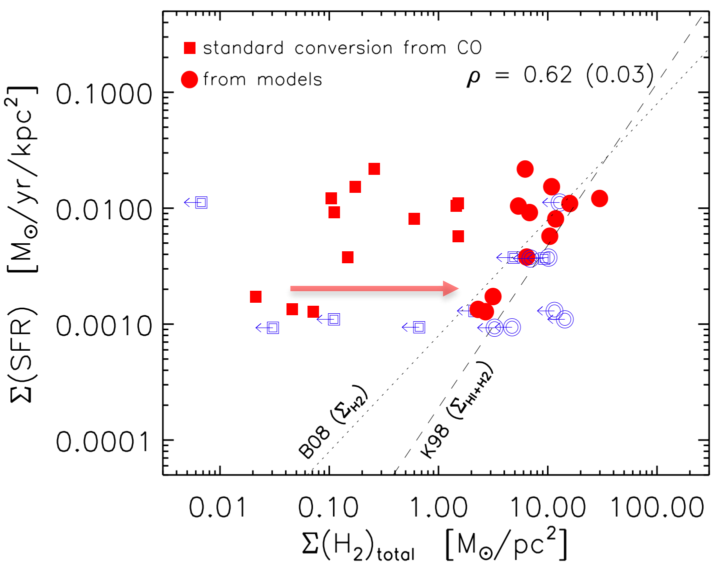


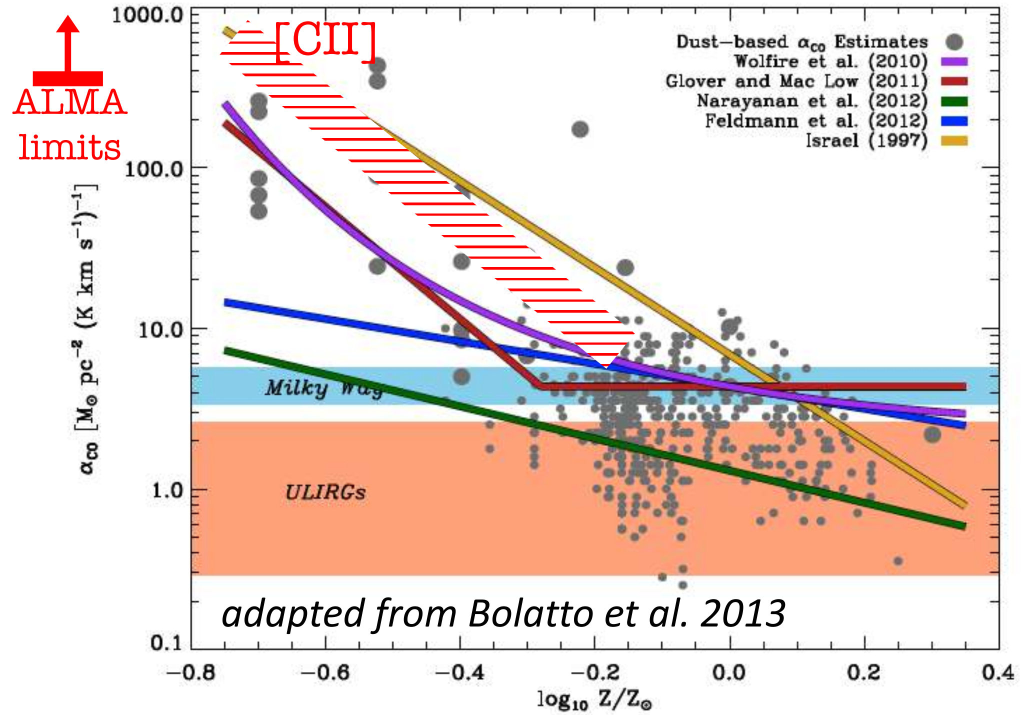
Conversion factor at low metallicity

- *Standard* efficiency when accounting for the CO-dark gas

- *Steep* conversion factor but observations lacking in the very low-Z regime

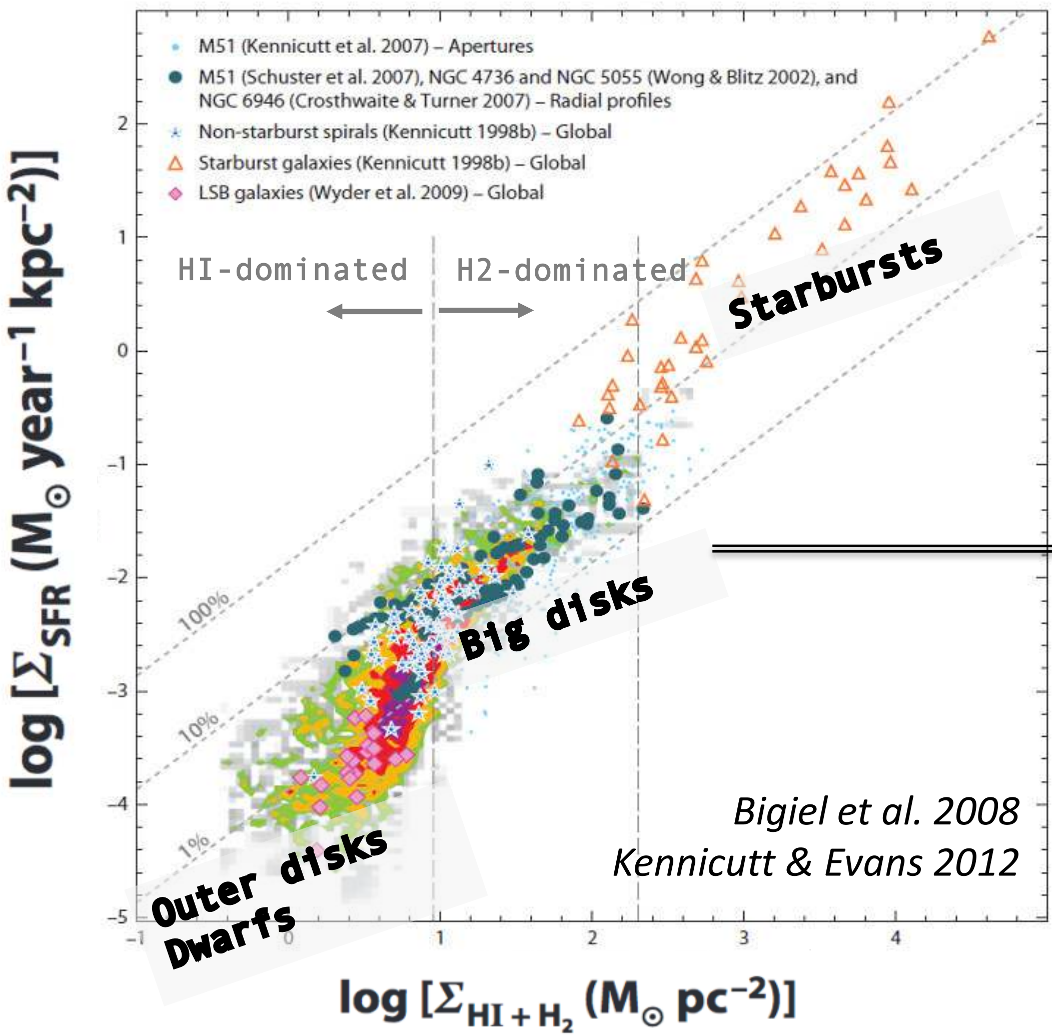
Madden & Cormier 2018





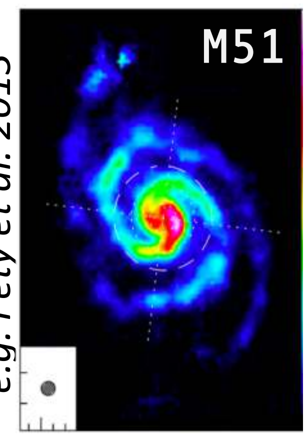
adapted from Bolatto et al. 2013

Dense gas in massive galaxies



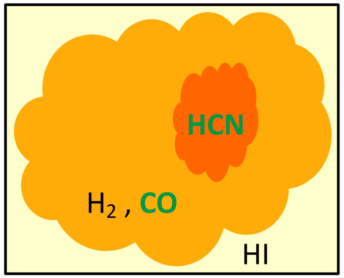
Non-negligible
diffuse CO emission

e.g. Pety et al. 2013

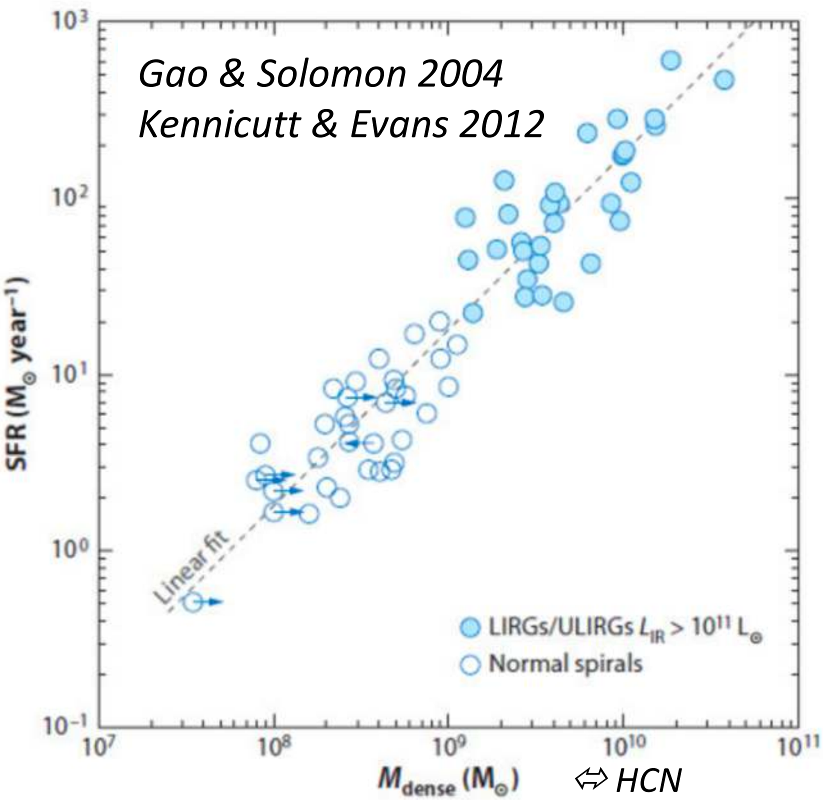


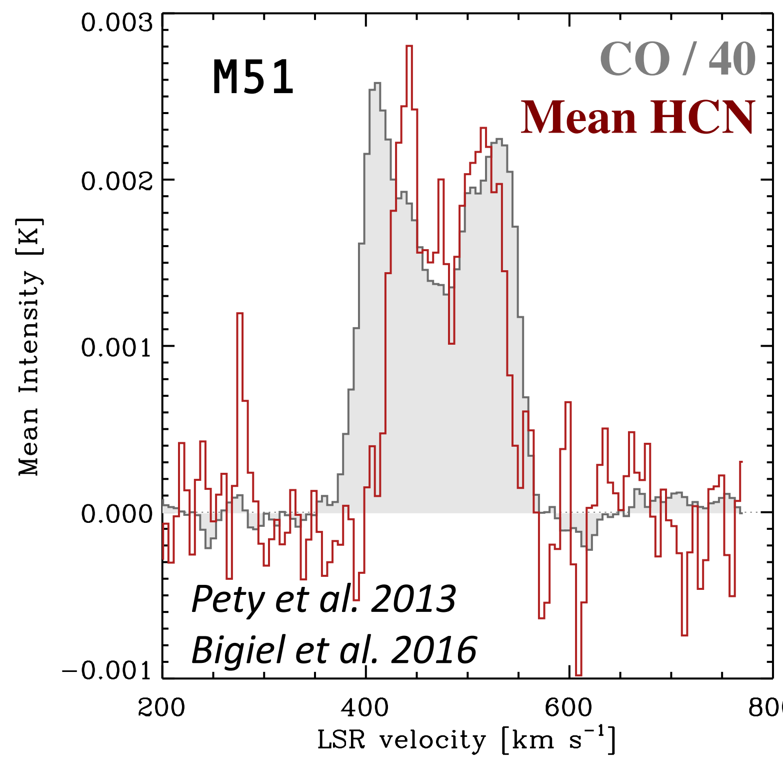
Role of gas density?

Dense gas in massive galaxies



Constant efficiency above some density threshold?





HCN is 40 times fainter than CO
⇔ 1000 times longer integration for a matched quality map

New surveys of the dense gas

HCN, HCO+, HNC, CS, CO and isotopologues: ^{13}CO, C^{18}O, H^{13}CN, H^{13}CO+, H^{13}NC

EMPIRE IRAM-30m (PI Bigiel, 600h), full 9 disks at 1.5kpc

Bigiel et al. 2016, Cormier et al. 2018, Jimenez-Donaire et al. 2017a,b, 2019

ALMA ACA (PI Leroy), inner ≈15 disks at 300pc

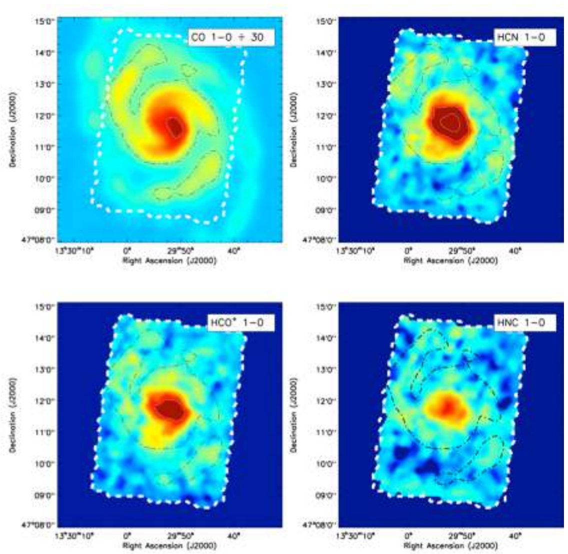
Gallagher et al. 2018a,b

DEGAS GBT (PI Kepley, 500h), inner 36 disks at 800pc

Kepley et al. 2018

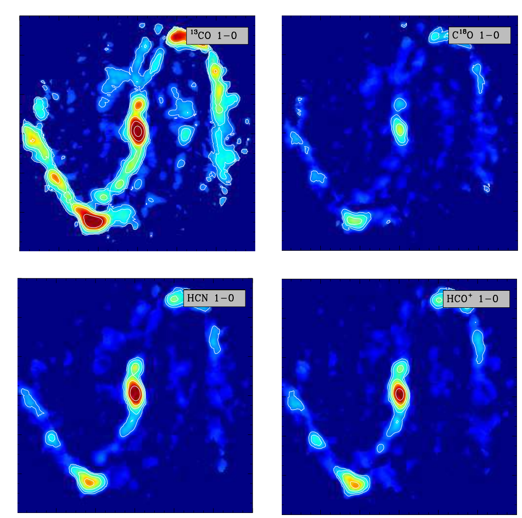
MALATANG JCMT (PIs Gao, Greve, Zhang, 400h), inner 23 disks at 0.2-2.8kpc *Tan et al. 2018*

M 51 with IRAM-30m



Bigiel et al. 2016

NGC 3627 with ALMA-ACA

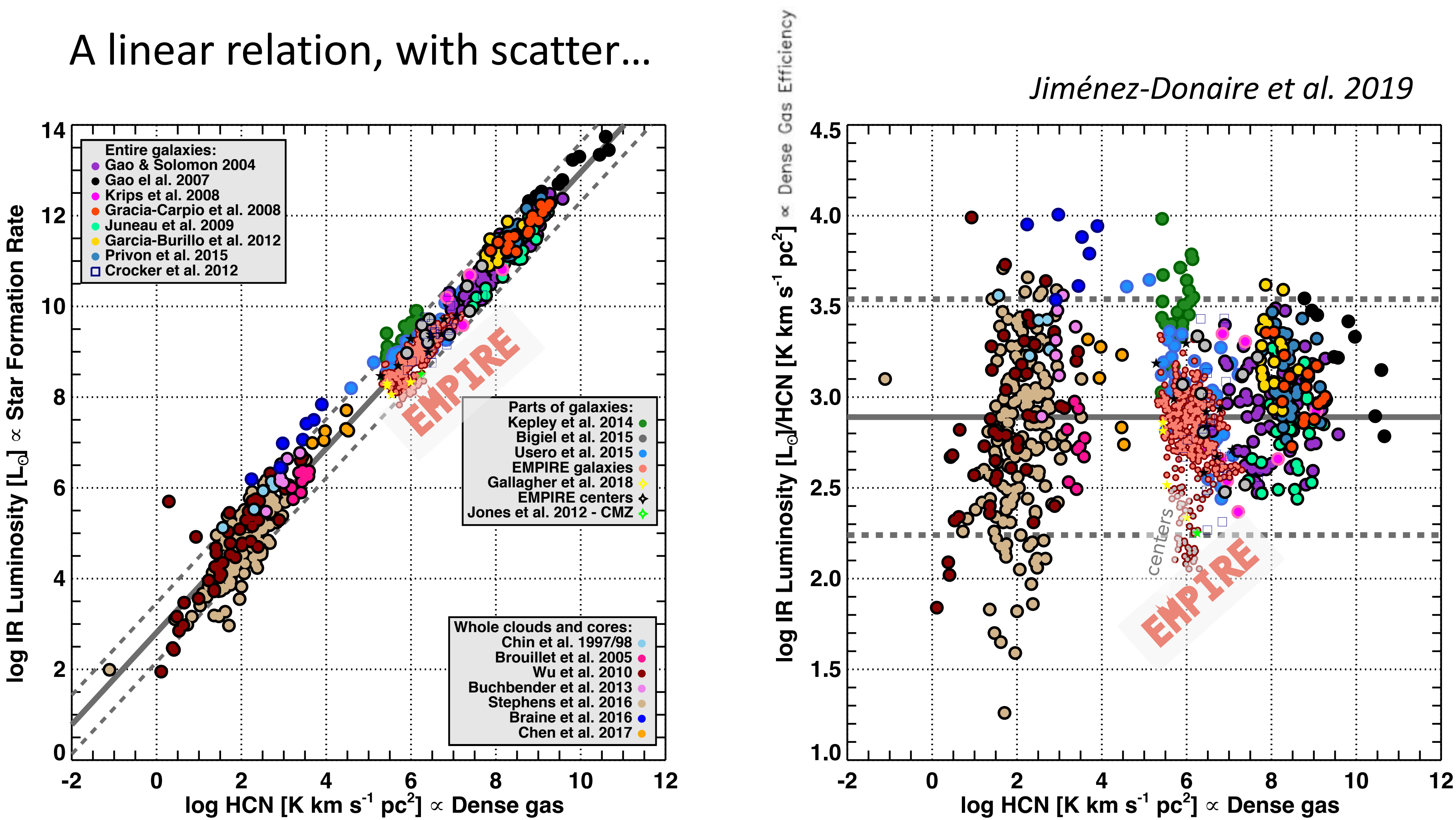


Gallagher et al. 2018a

Bridging individual clouds and whole galaxies

A linear relation, with scatter…

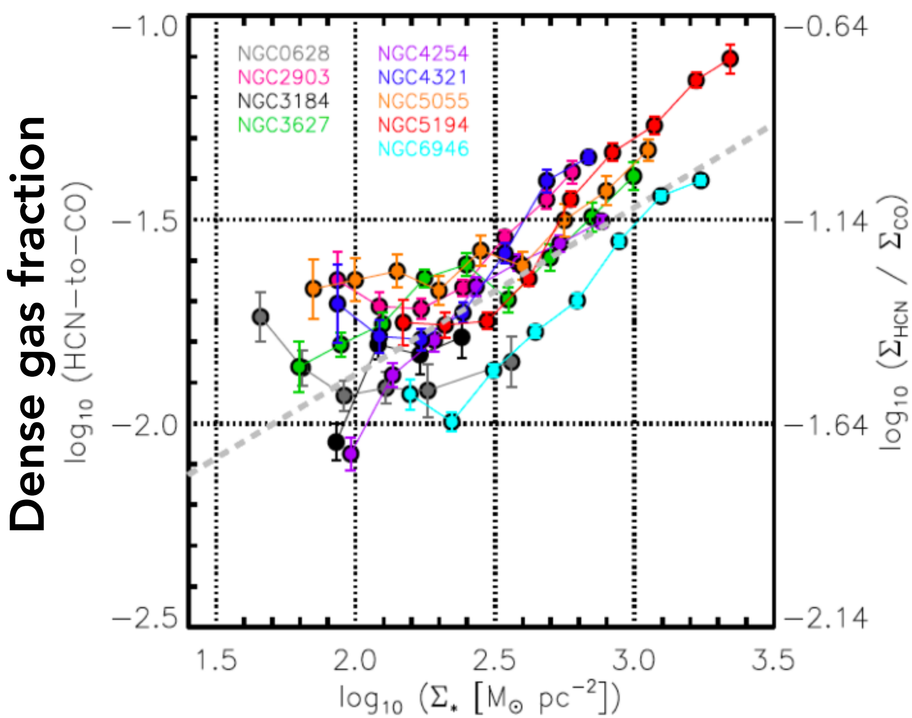
Jiménez-Donaire et al. 2019



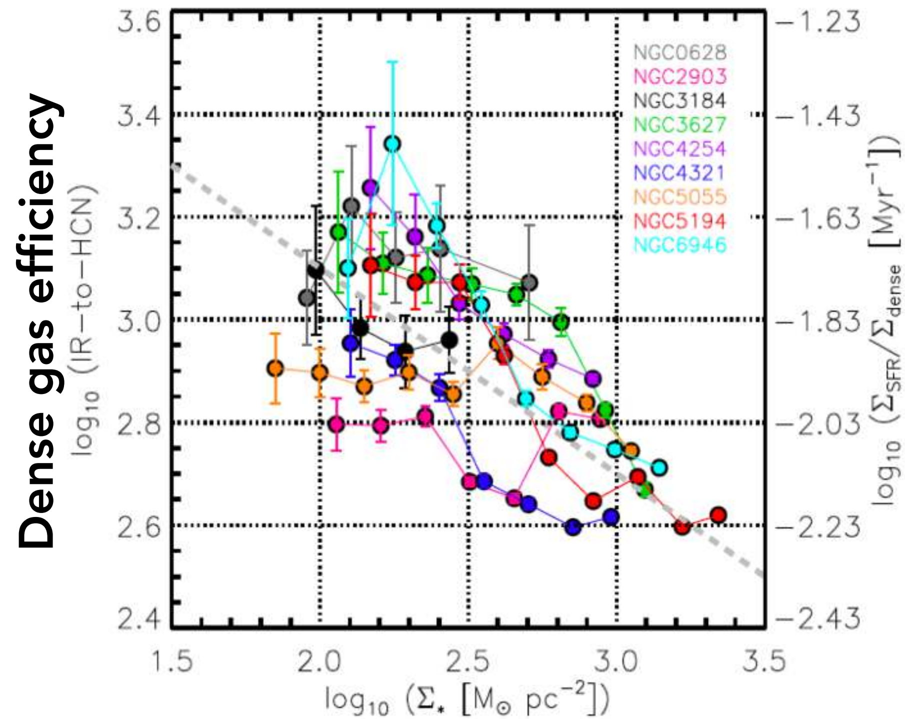
Dense gas fractions and efficiencies

- The *apparent* dense gas fractions and efficiencies vary strongly across galaxies (centers behave like CMZ)

Jiménez-Donaire et al.2019
see also Gallagher et al. 2018



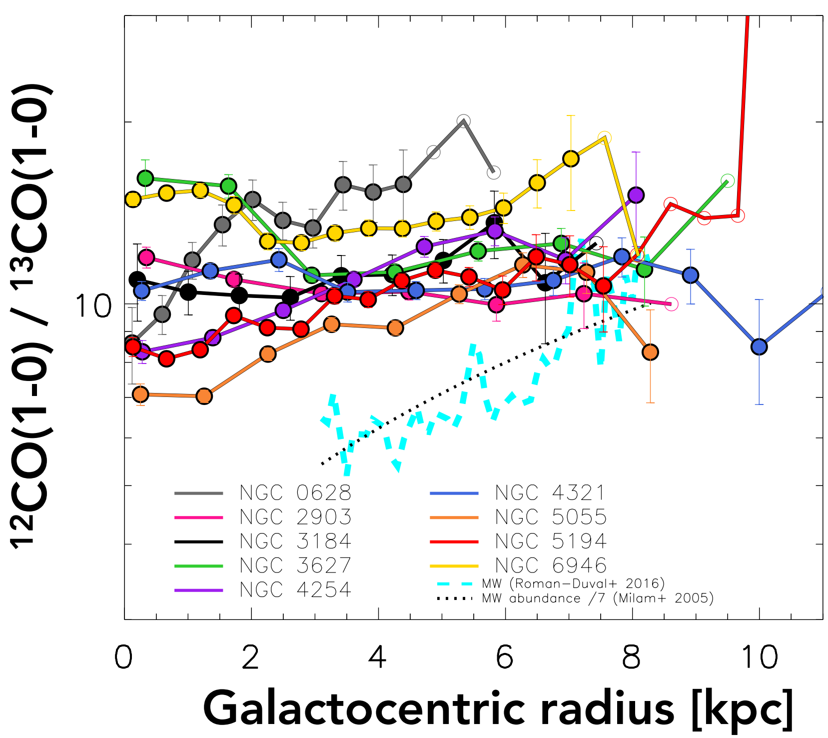
(pressure, radius)



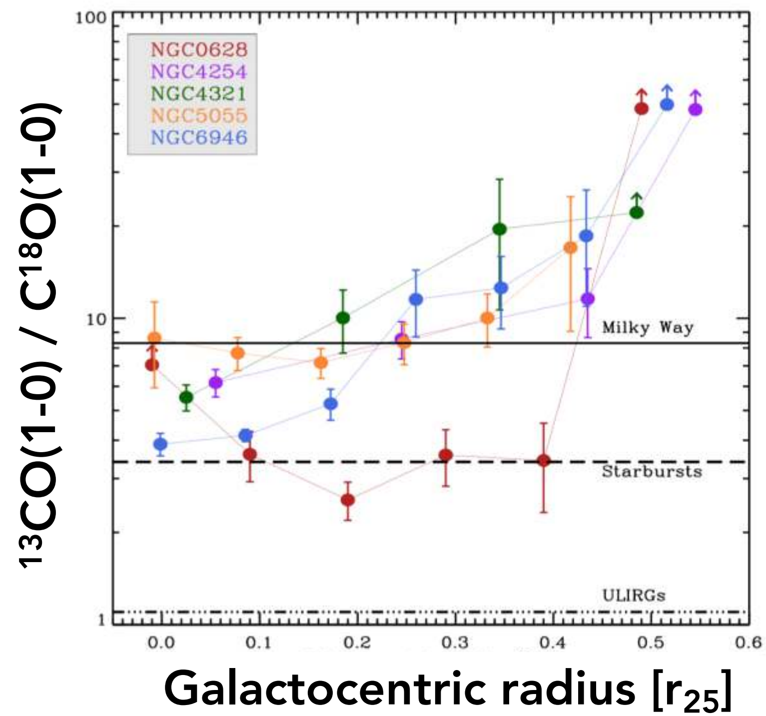
Isotopologues and gas conditions

- First $C^{18}O$ profiles across normal disk galaxies
- Trends suggest abundance / opacity variations

Cormier et al. 2018



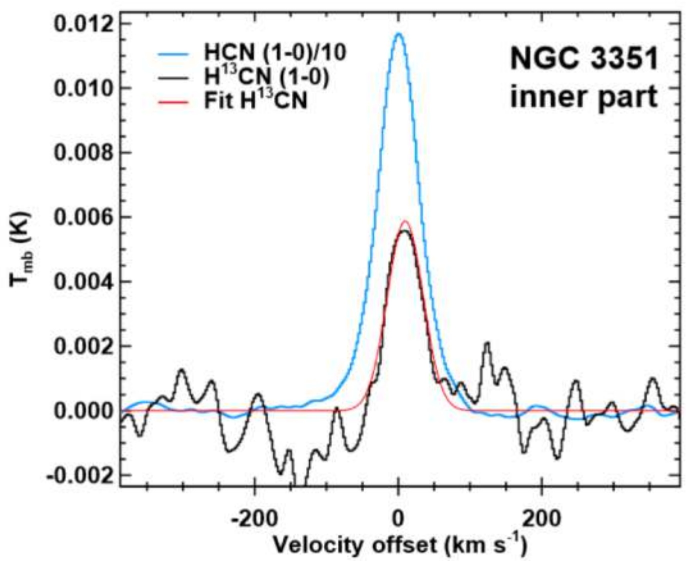
Jiménez-Donaire et al. 2017a

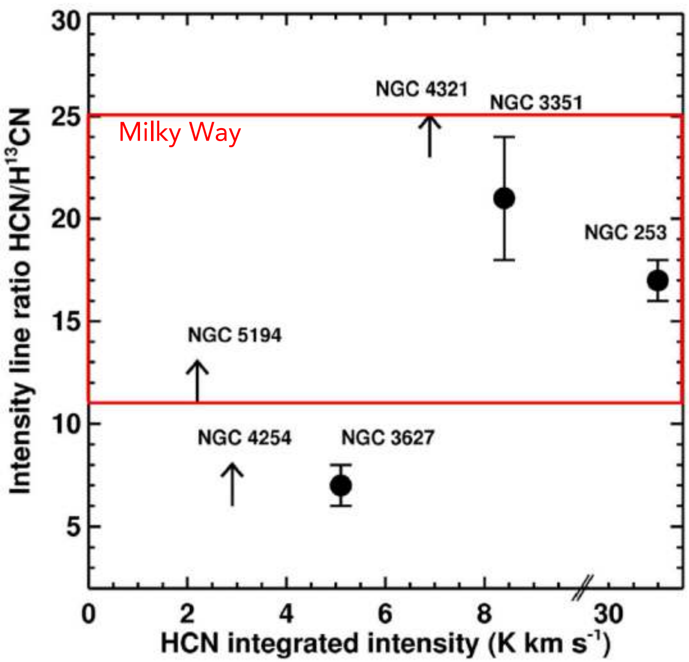


Isotopologues and gas conditions

- What densities does HCN really trace? ($n_{crit} \approx 10^5\ cm^{-3} \approx n_{eff} \times \boldsymbol{\tau}$)
  e.g. Shirley 2015, Pety et al. 2017, Kauffmann et al. 2017
- Data suggest moderate optical depths ($\tau \sim$ a few)

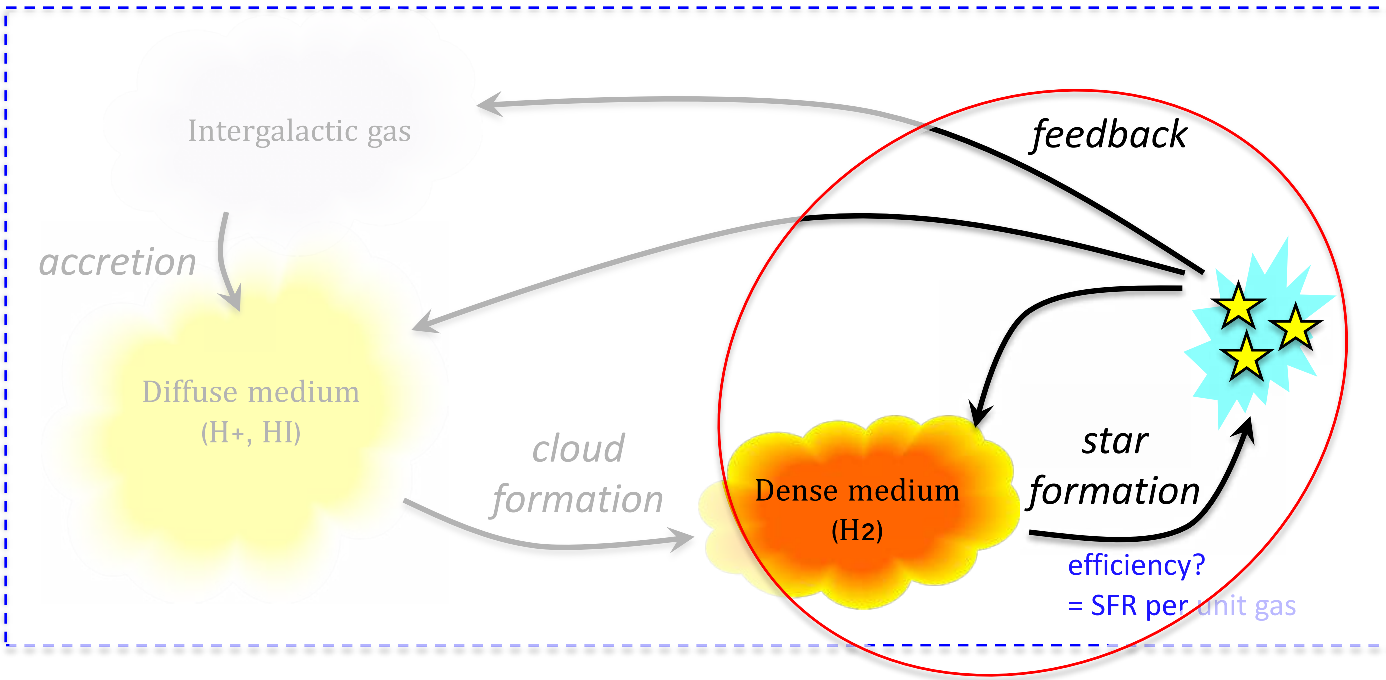
Jiménez-Donaire et al. 2017b





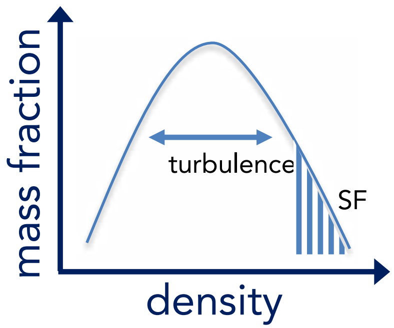
Hard to detect in disks (even for ALMA)

Role of the local, dynamical environment



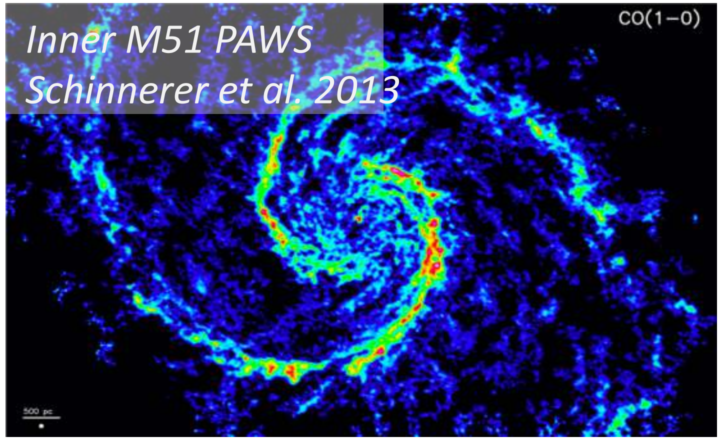
Local dynamics and stellar feedback are important for the evolution of clouds

How do local gas properties vary with environment?

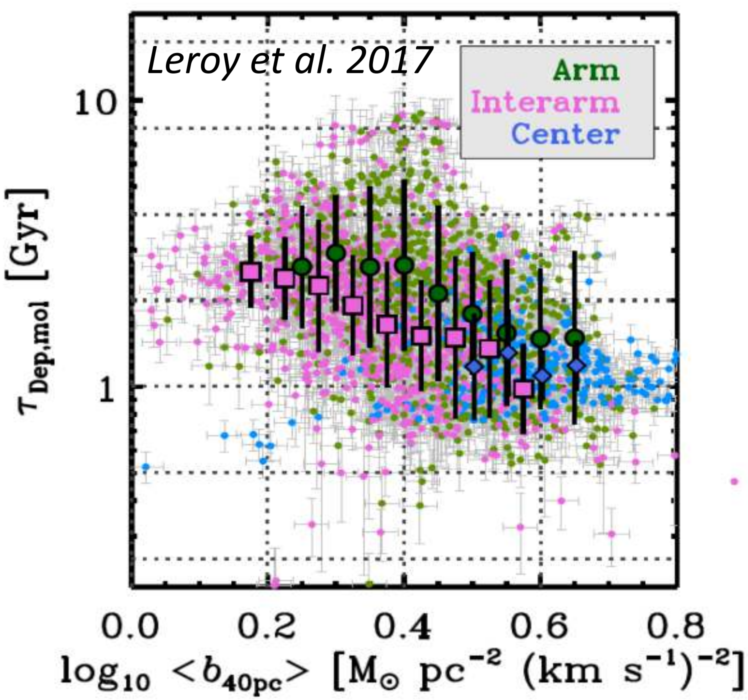


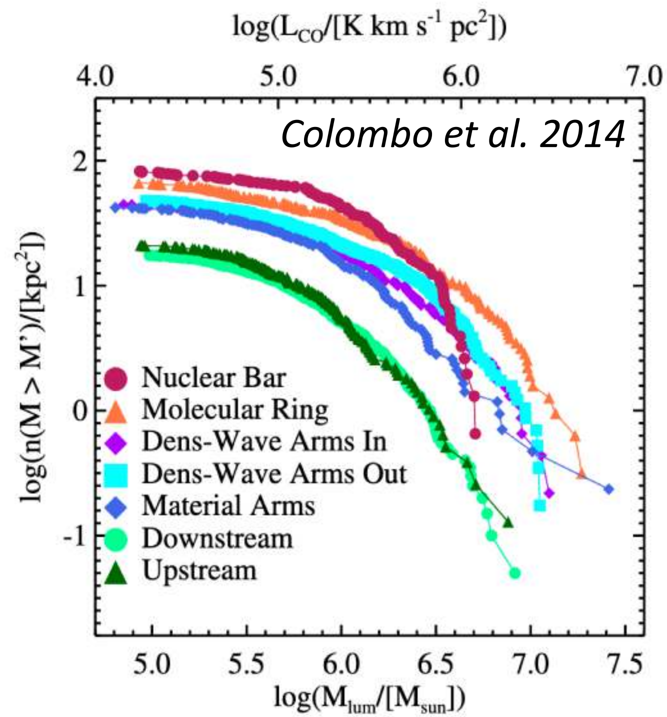
e.g. Padoan & Nordlund 2011, McKee & Ostriker 2007, Hennebele & Chabrier 2008

Role of the local, dynamical environment



see also, e.g.,
Rosolowsky et al. 2007,
Wong et al. 2011

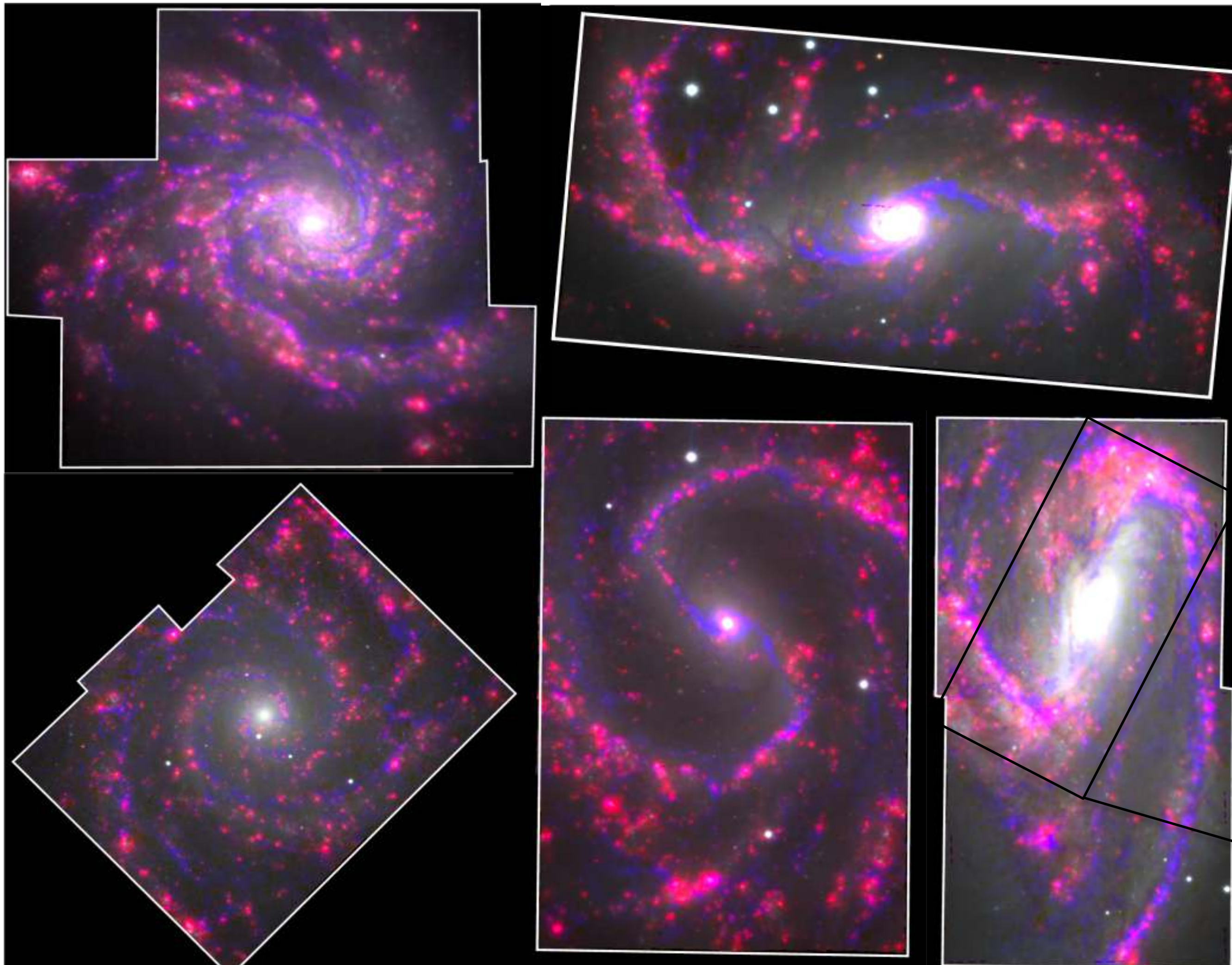


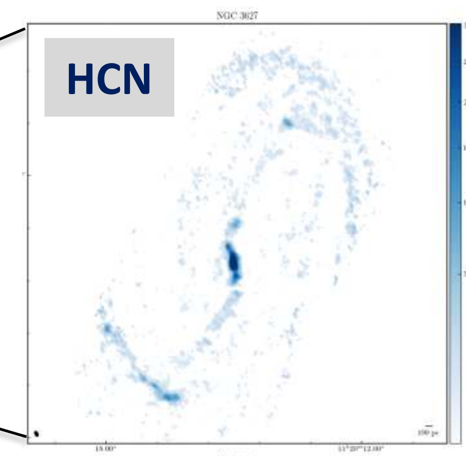


Resolving individual clouds

PHANGS CO (Schinnerer, Leroy+)
74 galaxies with ALMA at 1" (45-120pc) + MUSE, HST

Cloud properties
Stellar properties
Feedback…

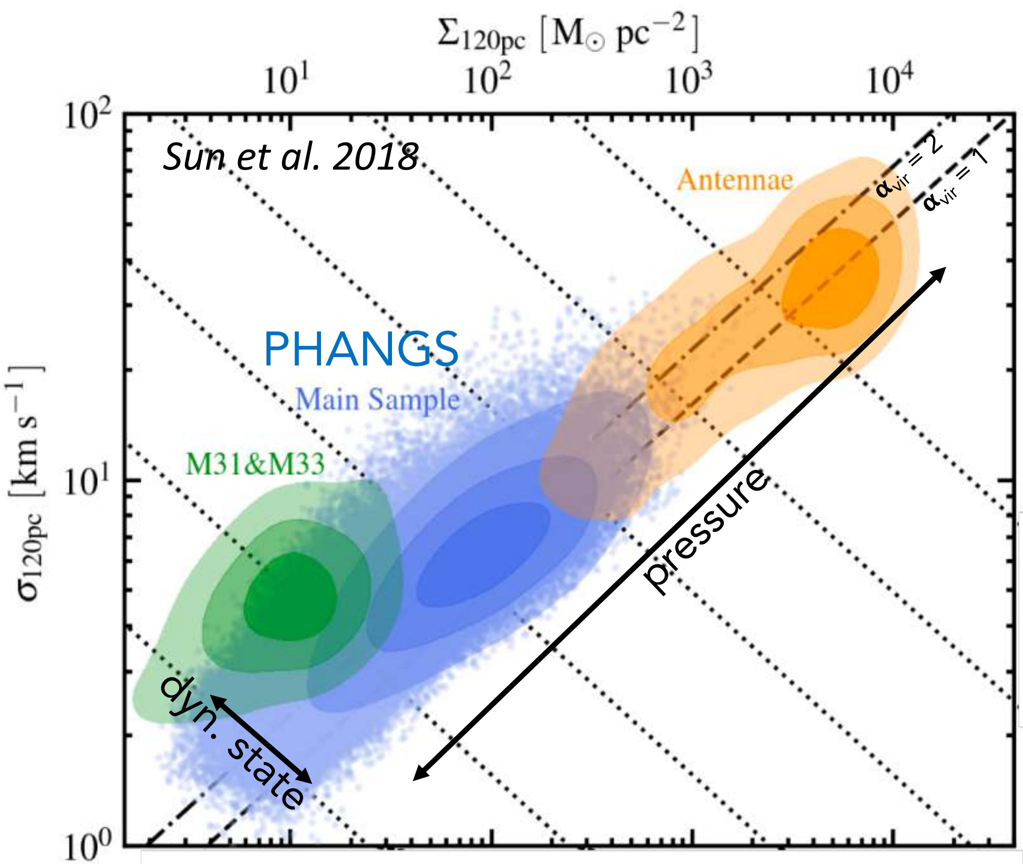




(Bigiel, Beslic+)

Resolving individual clouds

- Clouds overall marginally bound (**α_{vir}**∽2) and separated out by turbulent pressure
- Larger velocity dispersions in line with pressure confinement
  (e.g. Hughes et al. 2013, Indebetouw et al. 2013)

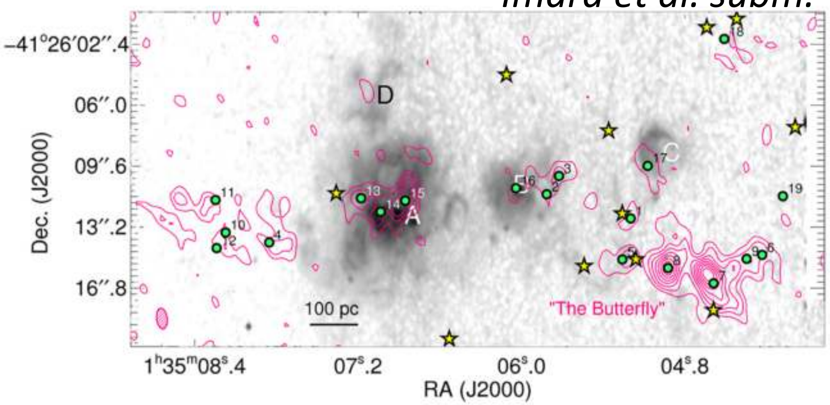


see also, e.g., Bolatto et al. 2008, Donovan-Meyer et al. 2013, Utomo et al. 2015

Low-metallicity, clumpy structure

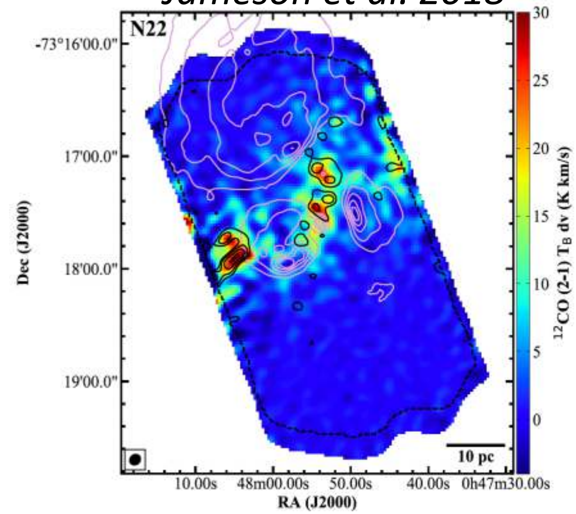
NGC625 (1/3 $Z_\odot$) [20 pc]

Imara et al. subm.



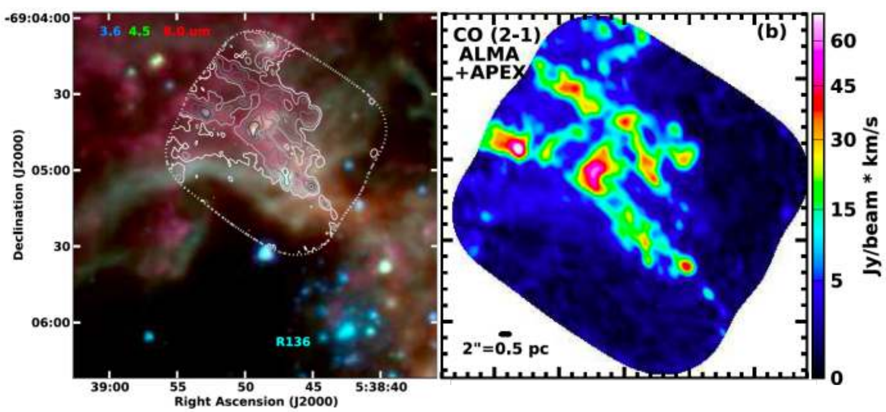
SMC (1/5 $Z_\odot$): N22 [2 pc]

Jameson et al. 2018



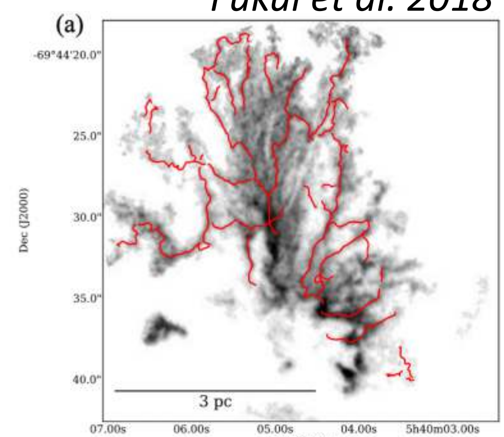
LMC (1/2 $Z_\odot$): 30 Doradus [0.5 pc]

Indebetouw et al. 2013



LMC (1/2 $Z_\odot$): N159 [0.07 pc]

Fukui et al. 2018



Low-metallicity, clumpy structure

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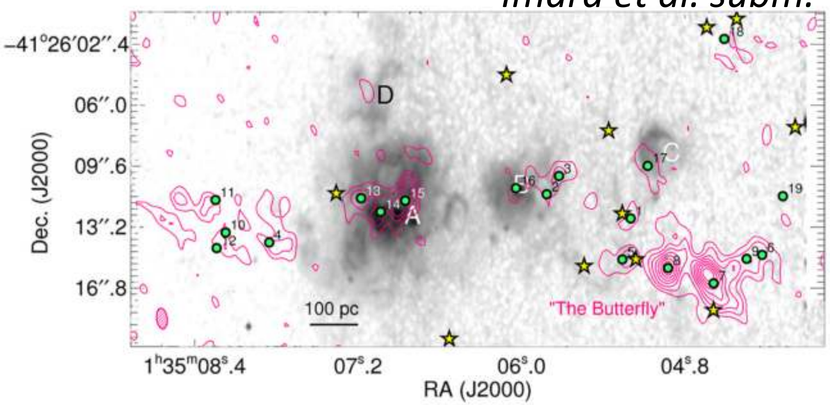
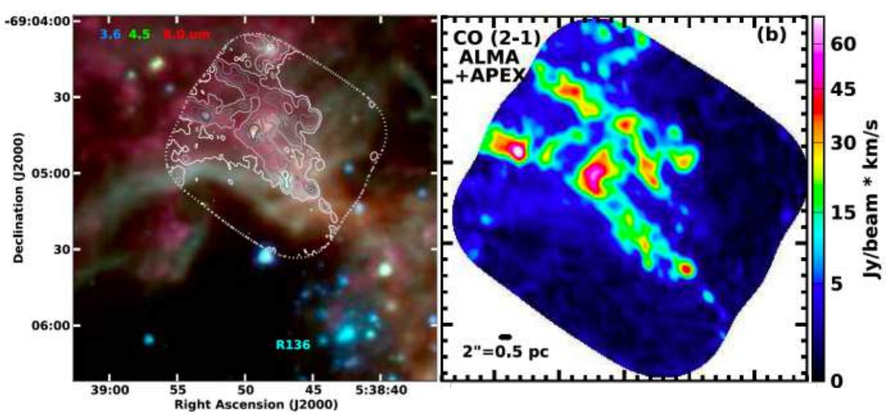


- No diffuse CO emission, clumpy structures
- No obvious trends of cloud properties with distance to clusters, metallicity

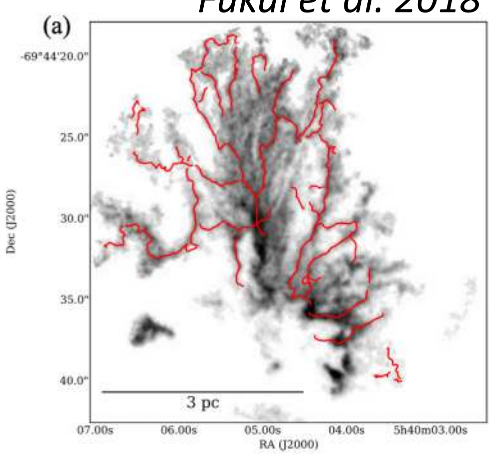
LMC (1/2 $Z_\odot$): 30 Doradus [0.5 pc]

Indebetouw et al. 2013



LMC (1/2 $Z_\odot$): N159 [0.07 pc]

Fukui et al. 2018



Conclusions

`Low-metallicity regime:`

- CO systematically faint, cooling by atomic lines important
- Large CO-dark molecular gas reservoirs measured
  to take into account for global SF efficiency
- Structure of the ISM dramatically different, clumpy

`Disks:`

- Dense gas fractions and efficiencies vary with
  environments
- Isotopologues suggest abundance/opacity variations
- Individual clouds mostly follow Larson's relations
  Influence of local environment to be better understood