Star formation and properties of the interstellar medium in nearby galaxies

Diane Cormier

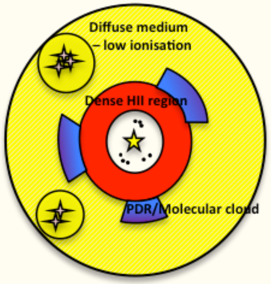
Office 257

<u>Main collaborators</u>:
Suzanne Madden, Vianney Lebouteiller, Fiorella Polles, Fred Galliano (*CEA Saclay*), Sacha Hony, María-Jesús Jiménez-Donaire, Frank Bigiel (*U. Heidelberg*), Adam Leroy (*Ohio State*), Nick Abel (*U. Cincinnati*)

Previous positions

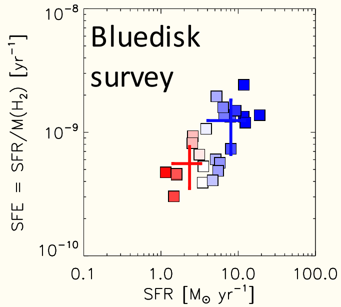
- 2009-2012 : PhD, AIM-Saclay, *Suzanne Madden*

  Herschel spectroscopy, dwarf galaxies
  Multi-phase models of the ISM



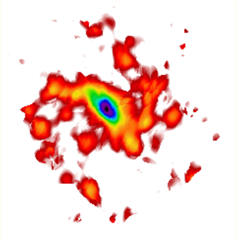
- 2013-2016 : Postdoc, ITA-Heidelberg, *Frank Bigiel*

  Molecular gas, disc galaxies
  Gas accretion, reservoirs, SF efficiency

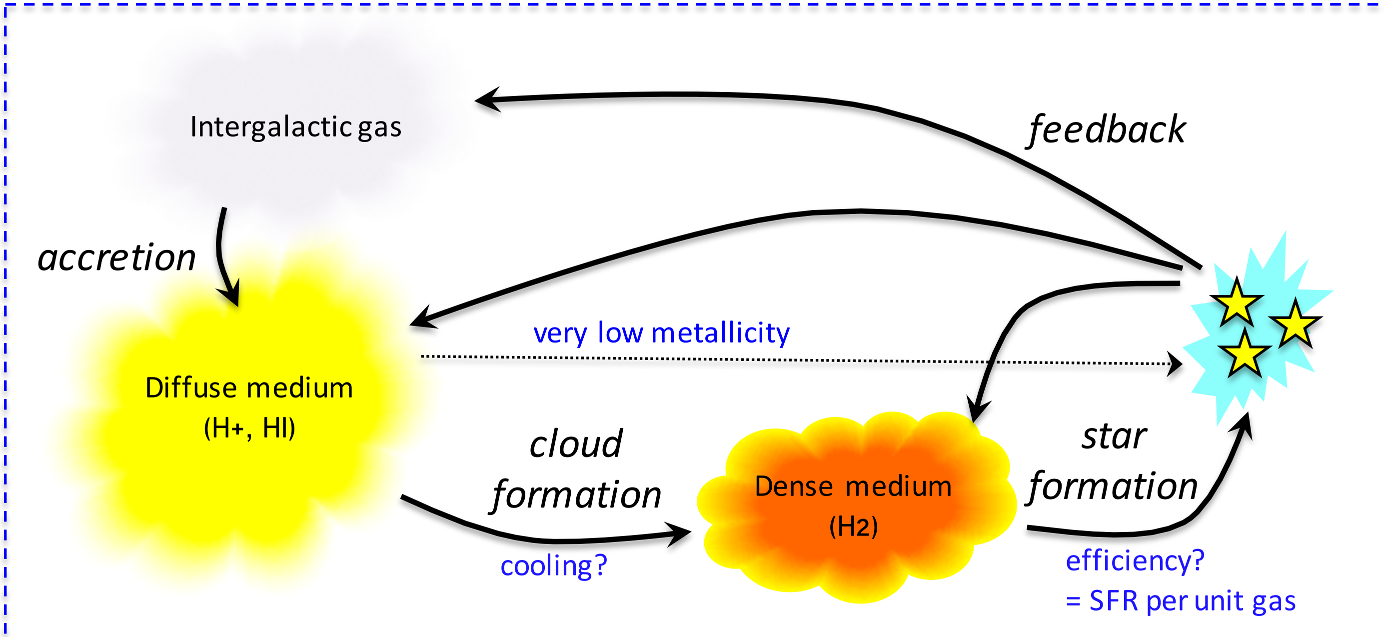


- 2017-2019 : Marie-Curie fellowship, AIM-Saclay

  Physical conditions of SF gas, phase transitions
  Evolution with environment



Understanding the steps to star formation



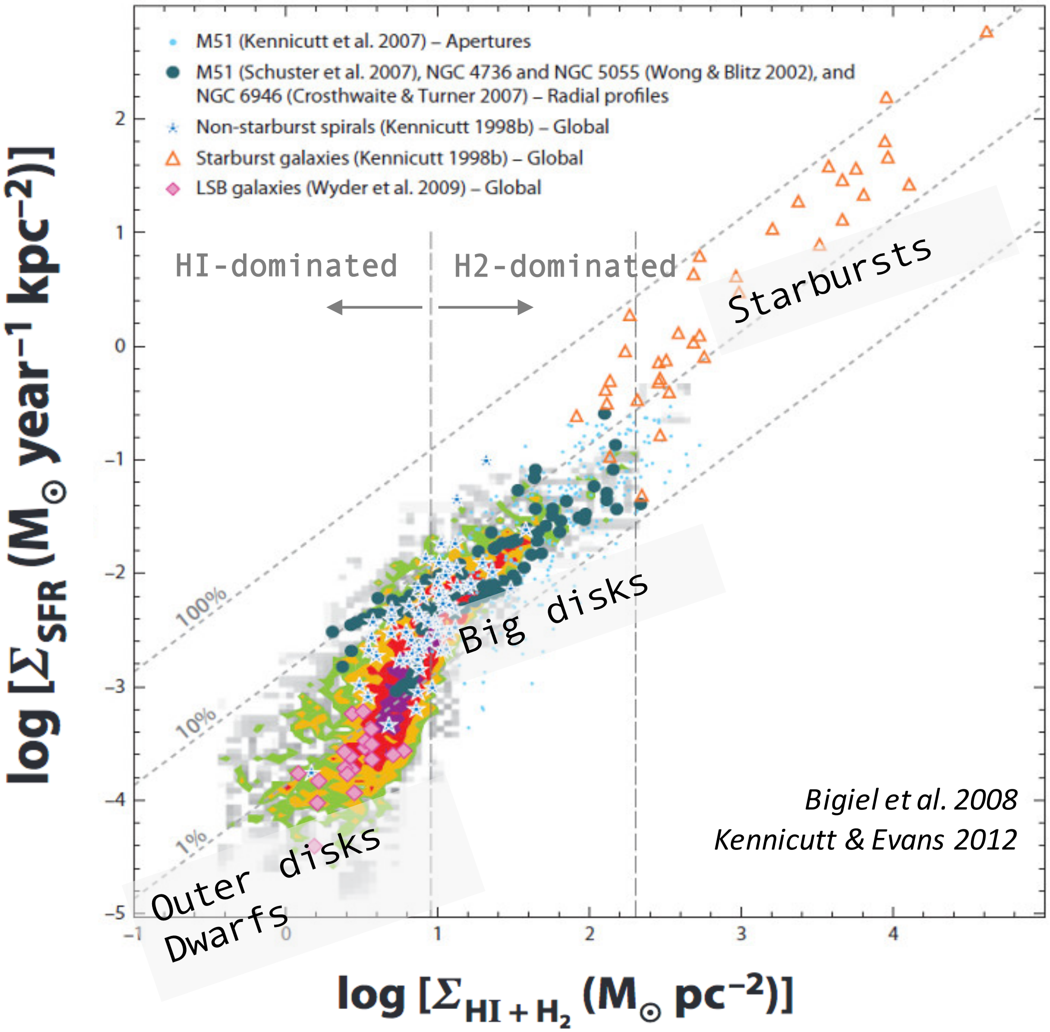
How are the phases of the ISM distributed in galaxies?

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

What sets the efficiency of SF and is it constant?

How do those properties vary in different galaxies/environments?

Tracers of star formation in galaxies

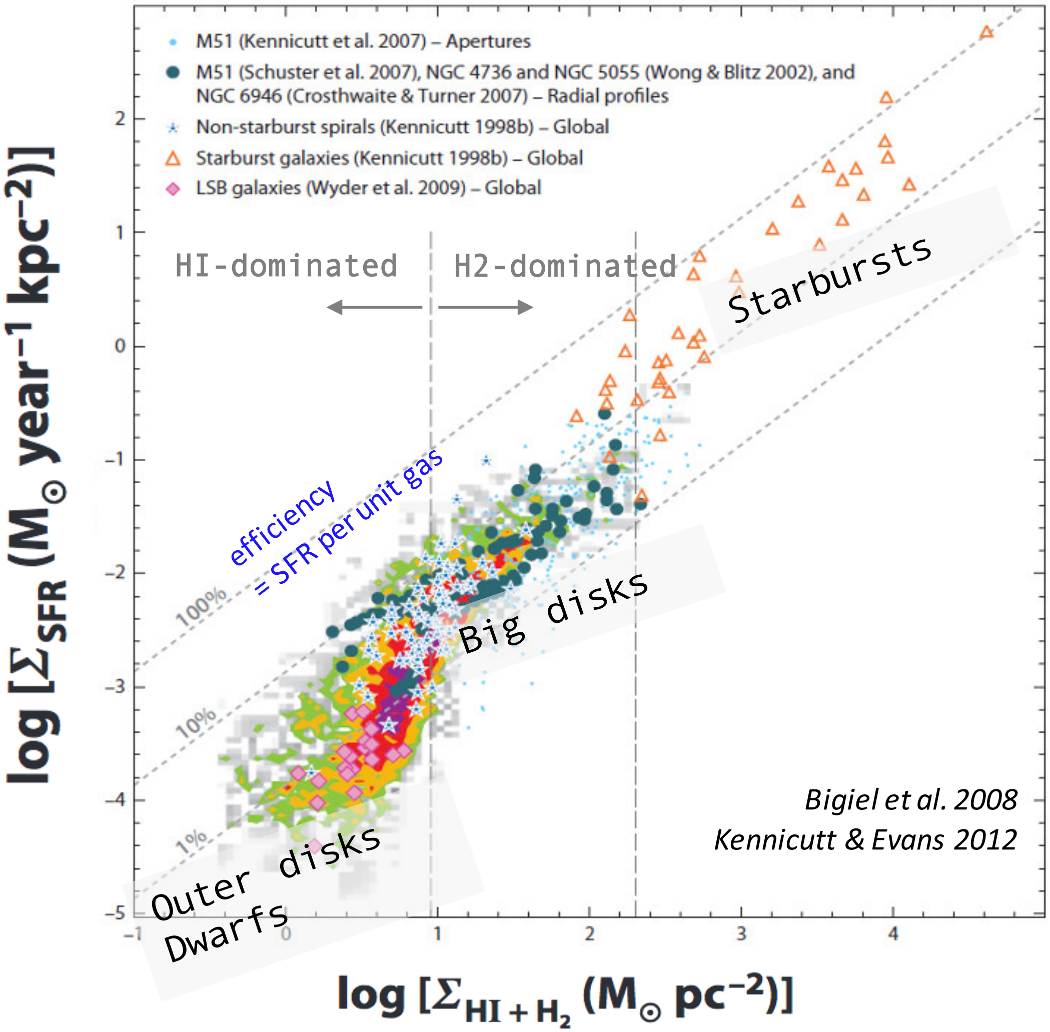


Star formation rate (SFR):
UV, Ha, IR

Molecular gas mass (H_2):
CO

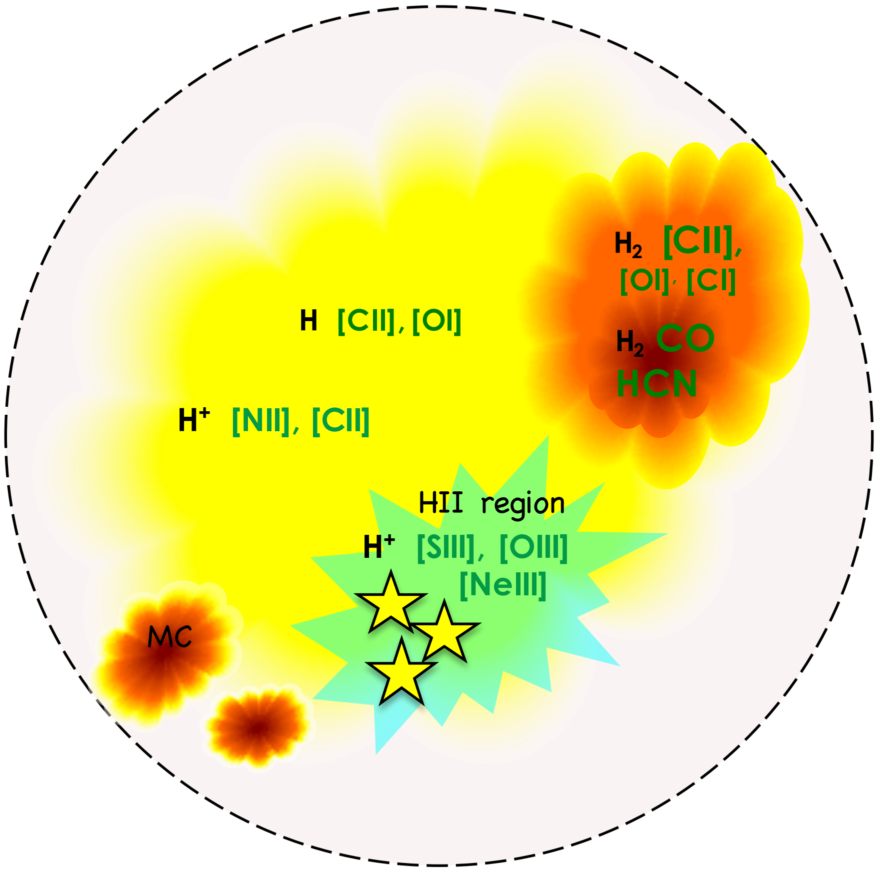
Atomic gas mass (HI):
HI 21-cm

Tracers of star formation in galaxies



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

Overview – project eGALISM



Cooling lines are probes of:

- chemistry
- physics
- conditions

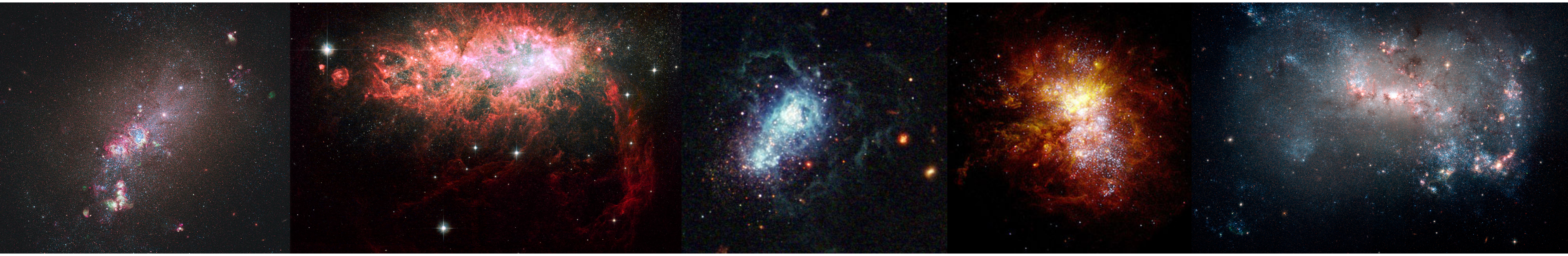
Multi-line observations

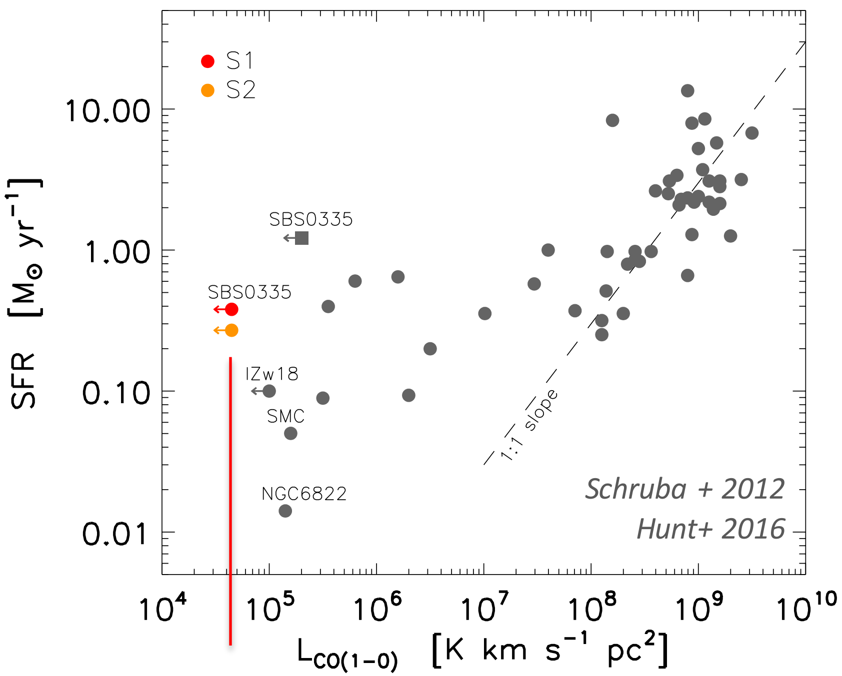
(Spitzer, Herschel, ALMA, IRAM, SOFIA, JWST, SPICA)

+

Multi-phase models

Star formation at low metallicity: no molecules?





- Cold ISM difficult to observe

Little molecular gas traced by CO

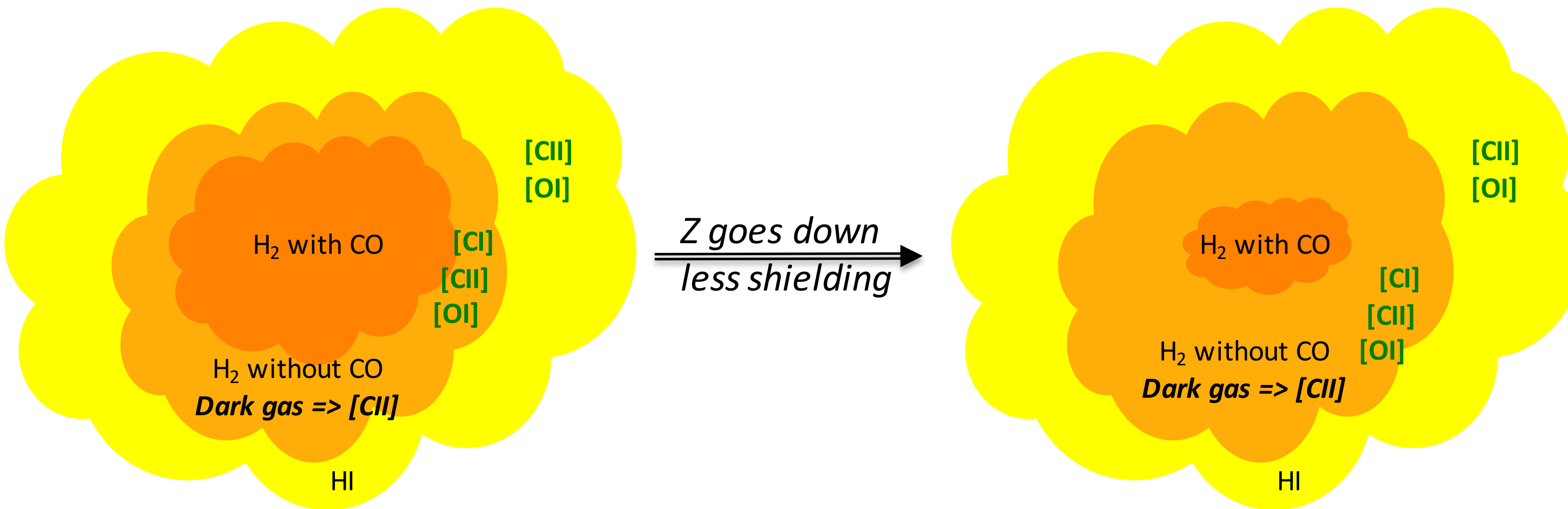
⇒ Efficient SF from H_2?

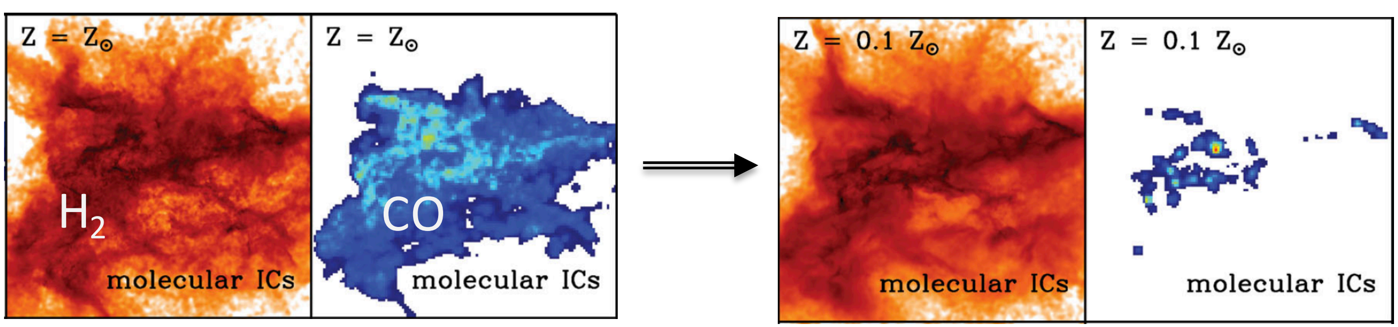
⇒ SF in atomic gas?

⇒ More H_2 than seen by CO?

ALMA at Z=1/30 solar and 0.2''=50pc resolution
Cormier et al. 2017

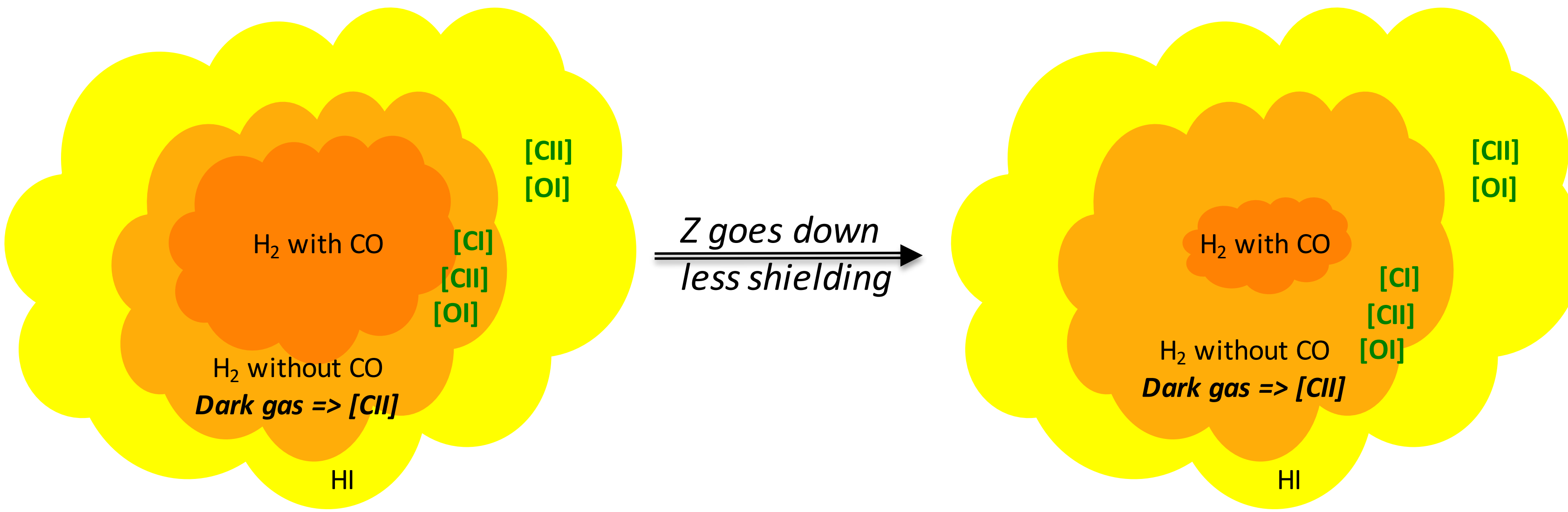
Fundamentally different structure of the dense gas





Glover & Clark 2012

How much molecular gas is there really?



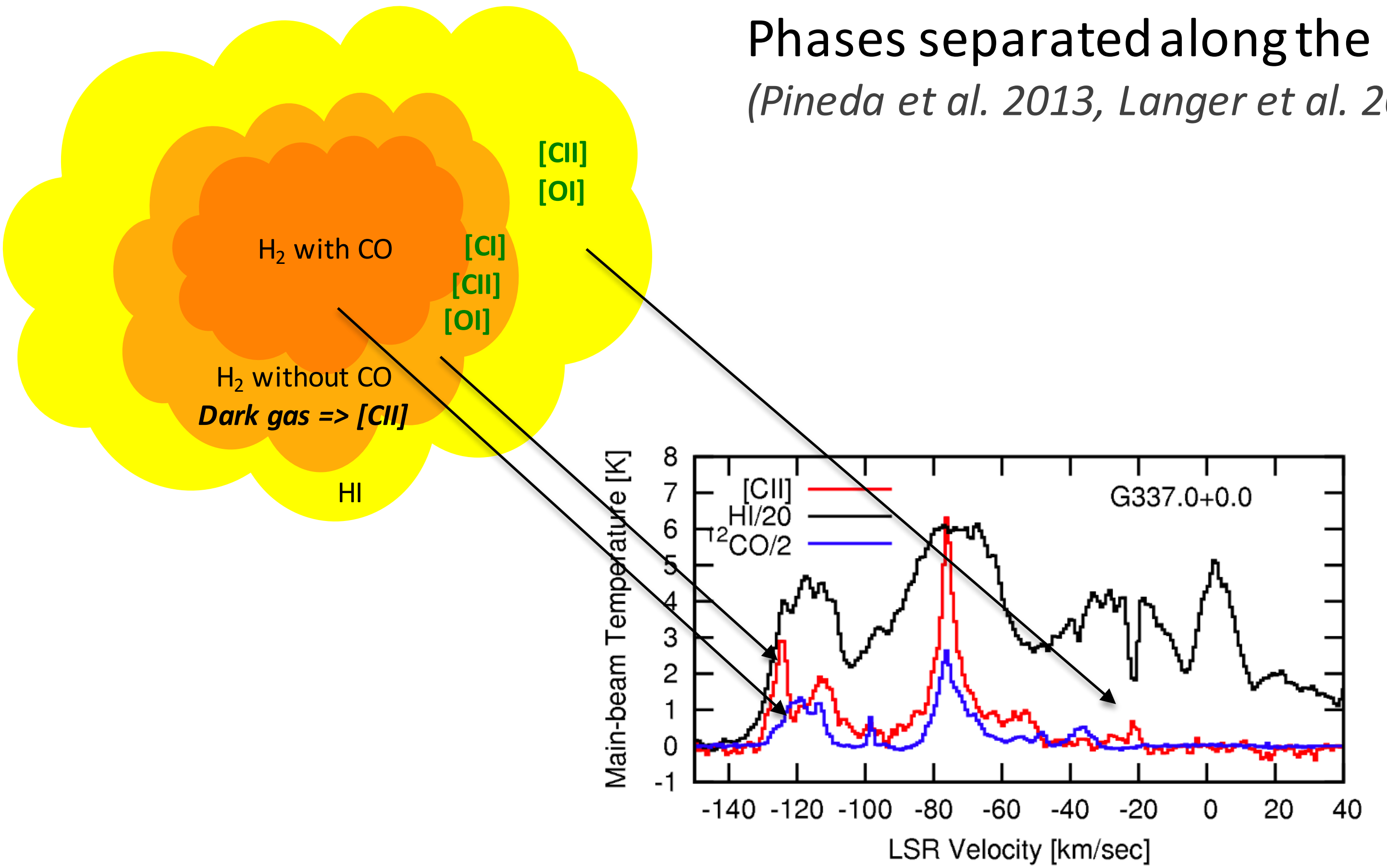
- Milky Way: 30% of the molecular mass is CO-dark
  (Pineda et al. 2013, GOT C+)

- Local dwarfs (IC10, LMC, SMC): 10-100 times more CO-dark than CO-bright gas mass

e.g. Poglitsch et al. 1995, Israel et al. 1997, Madden et al. 1997, Leroy et al. 2011 + new work on Magellanic Clouds with Herschel and SOFIA

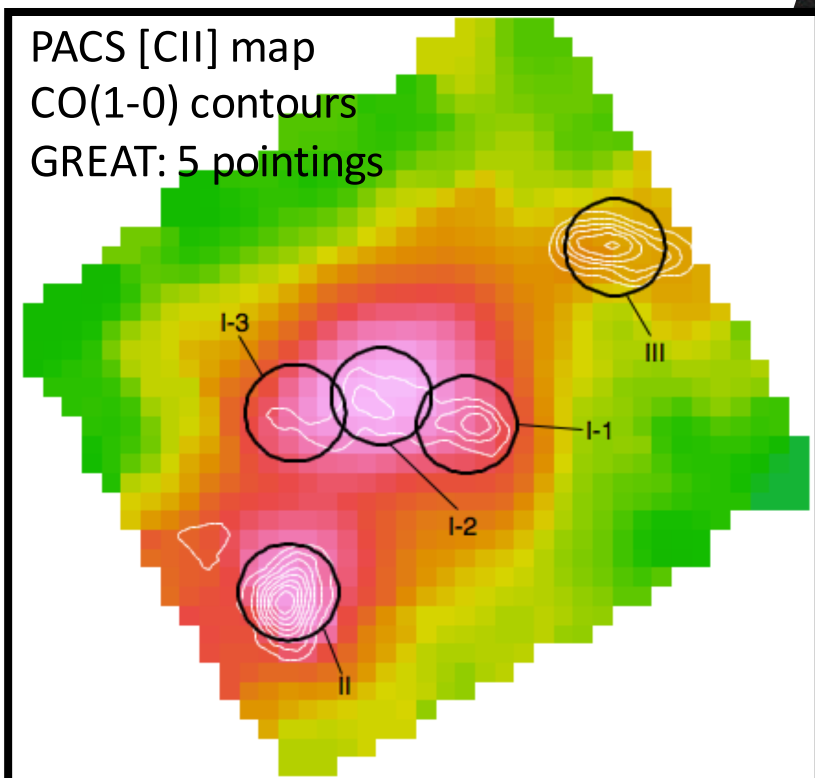
How much molecular gas is there really?

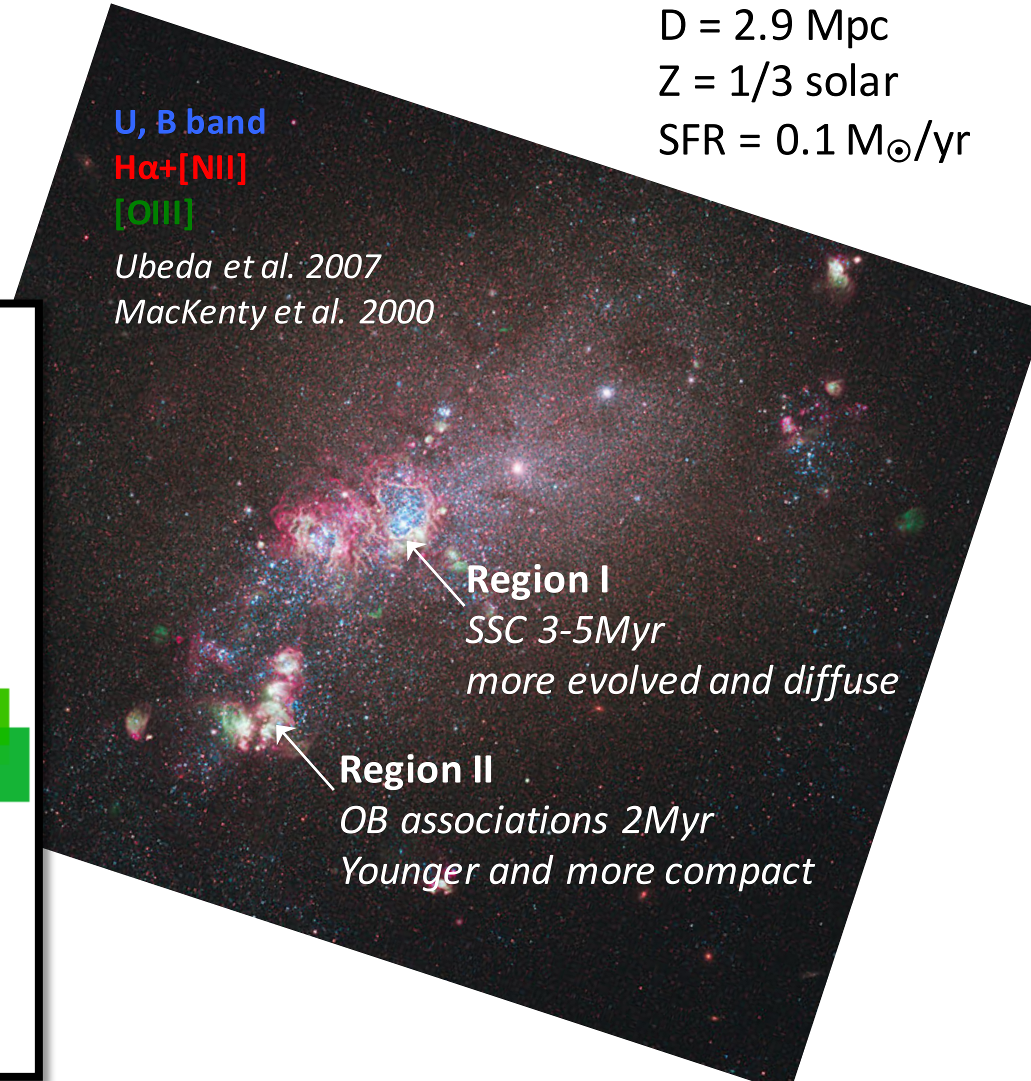
GOT C+ Herschel HIFI survey:
Phases separated along the line of sight
(Pineda et al. 2013, Langer et al. 2014)



Resolving phases along the line of sight with SOFIA: *the case of NGC4214*

D = 2.9 Mpc
Z = 1/3 solar
SFR = 0.1 $M_{\odot}$/yr





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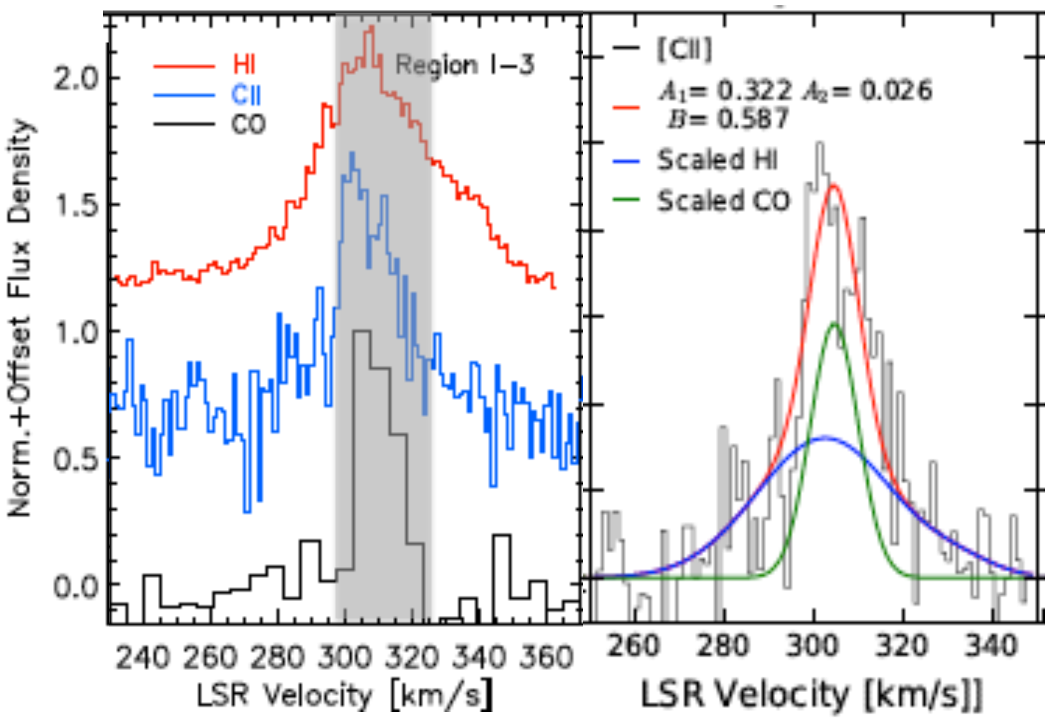


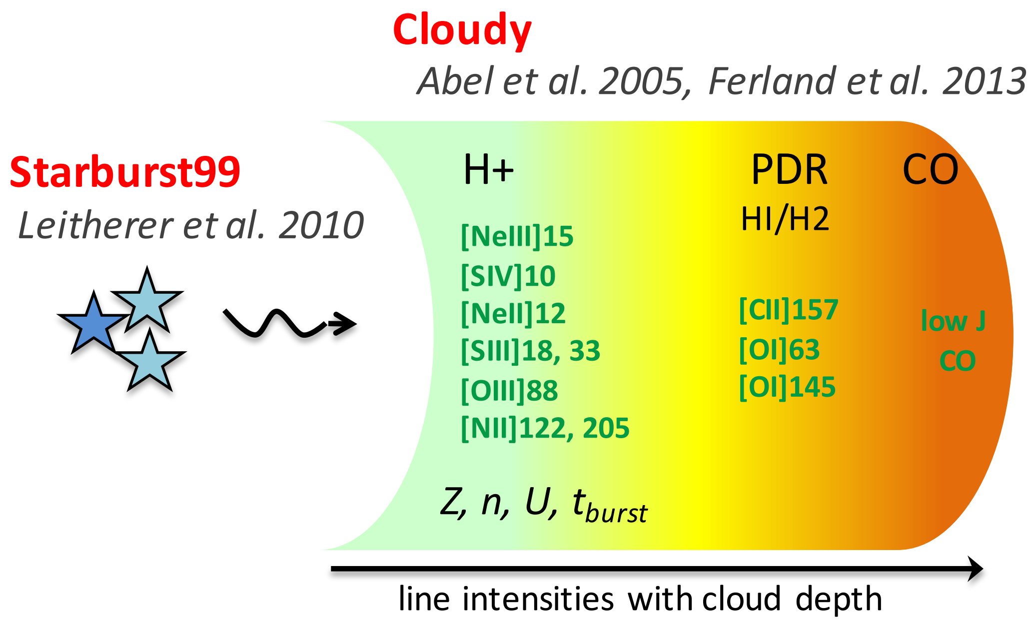
Fahrion, Cormier+ 2017

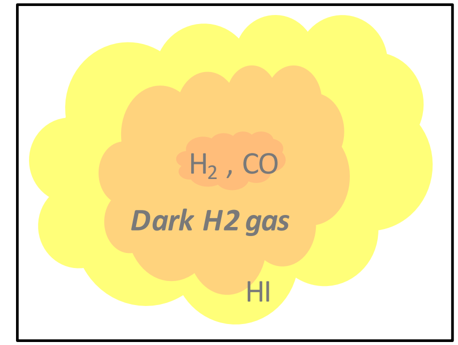
It is tough…
The beam averages 250 pc-size regions

	Region I	Region II	Region III
I(CII) attributed to CO	75%	55%	20%
CO-dark H_2 mass	80%	65%	<10%

} *CO-dark gas fraction linked to evolution*

Separating phases with models





Diagnostics: electron density, radiation field (U, t_{burst}) 〉 temperature / G_0, hydrogen density

The continuity of the models allows to solve for the biggest unknowns: the ***masses*** and ***filling factors*** of the main phases

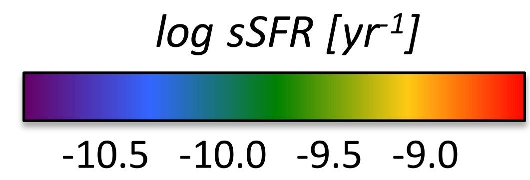
Cormier et al. 2012, 2015, in prep.
Dimaratos, Cormier+ 2015

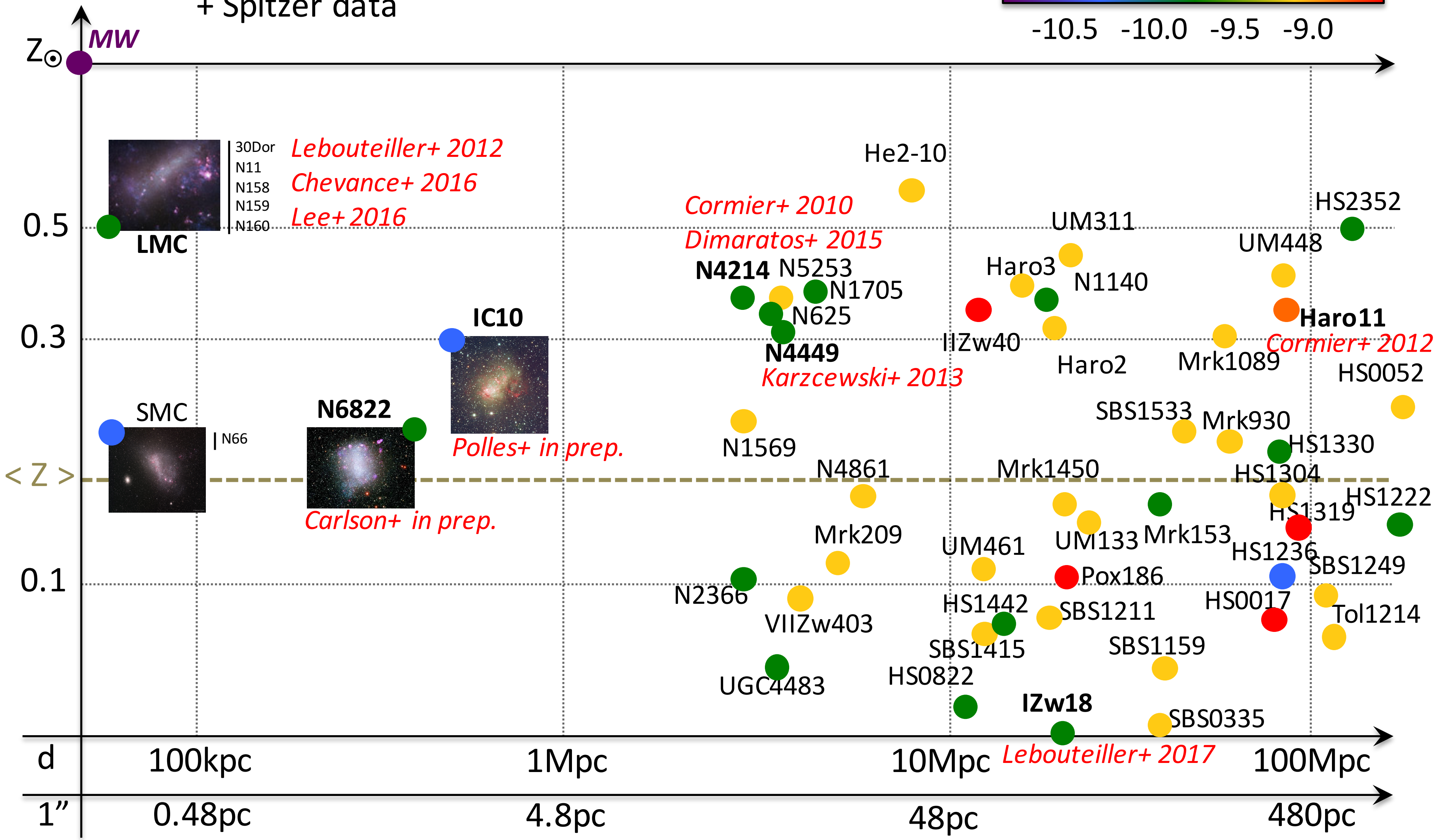
The Herschel Dwarf Galaxy Survey *(Madden et al. 2013)*

Key Program, targeted 50 galaxies

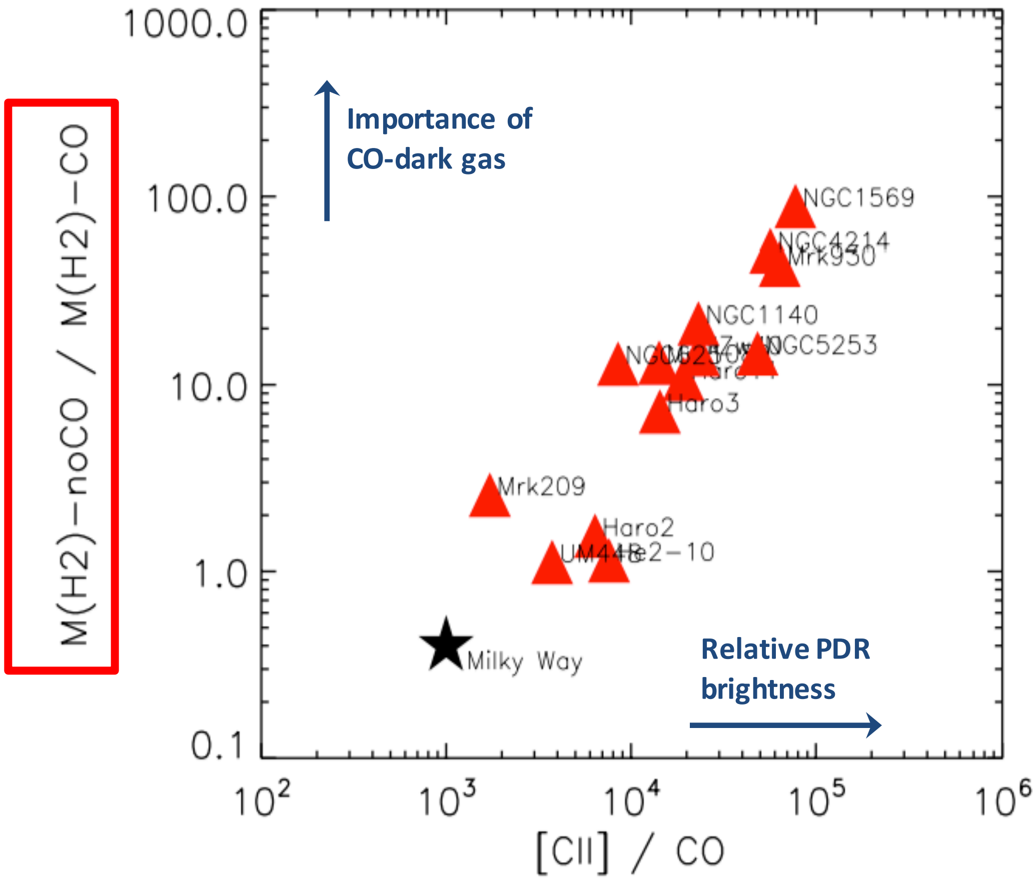
PACS + SPIRE photometry and **PACS spectroscopy (150h)**

+ Spitzer data



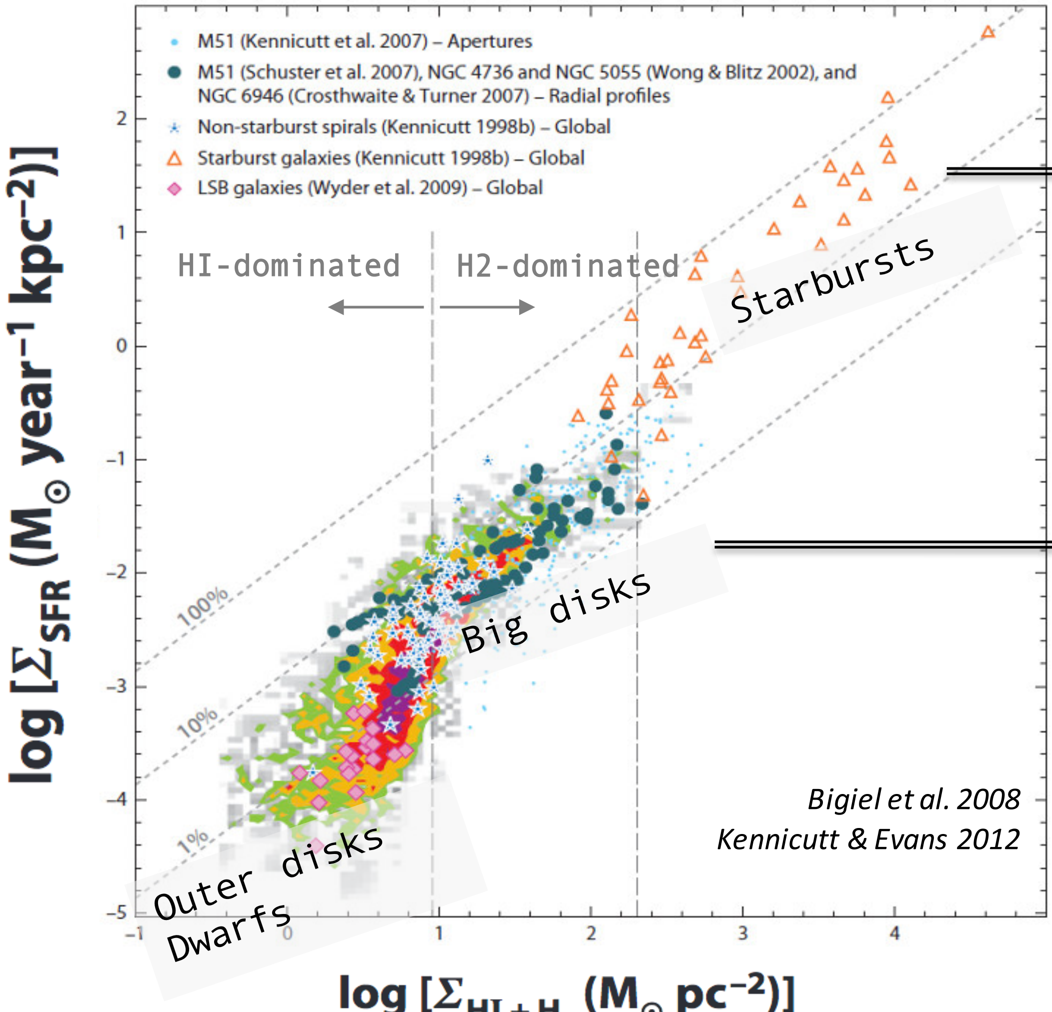


The [CII]/CO ratio as a total mass tracer



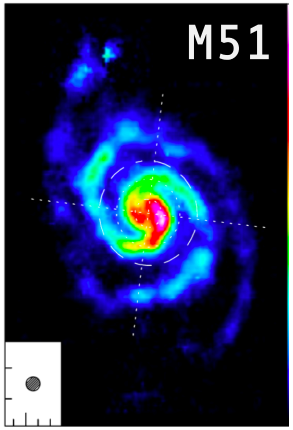
- CO-dark gas **dominates** the molecular mass budget
- Multi-phase approach necessary

Star formation in galaxies



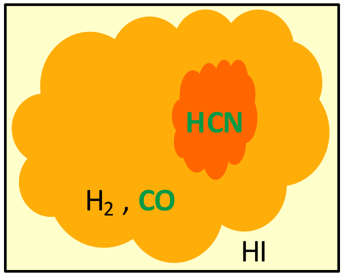
SF more efficient at *high* gas surface densities

Non-negligible *diffuse* CO emission

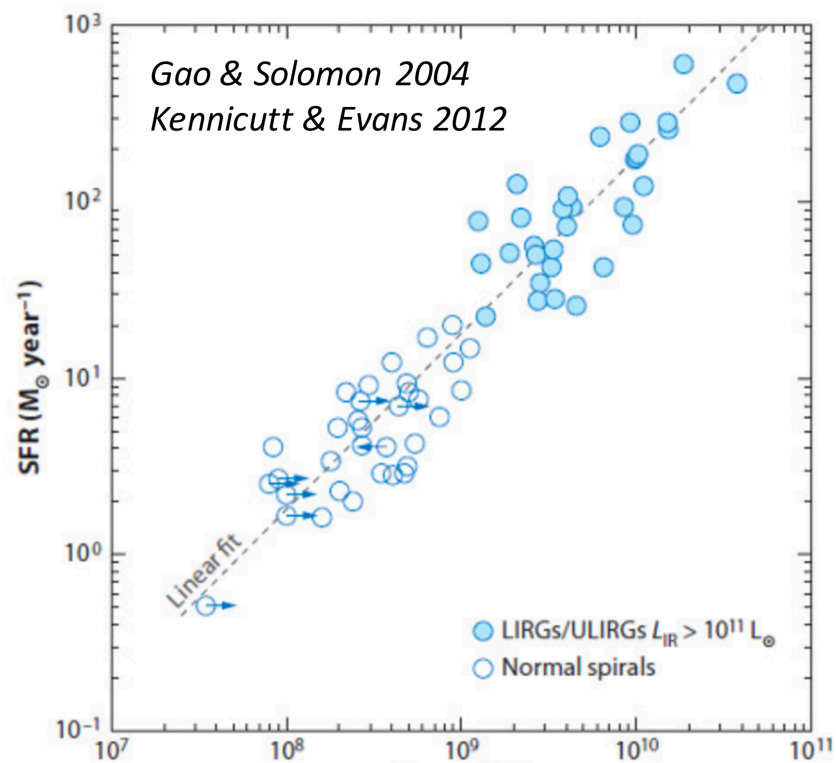


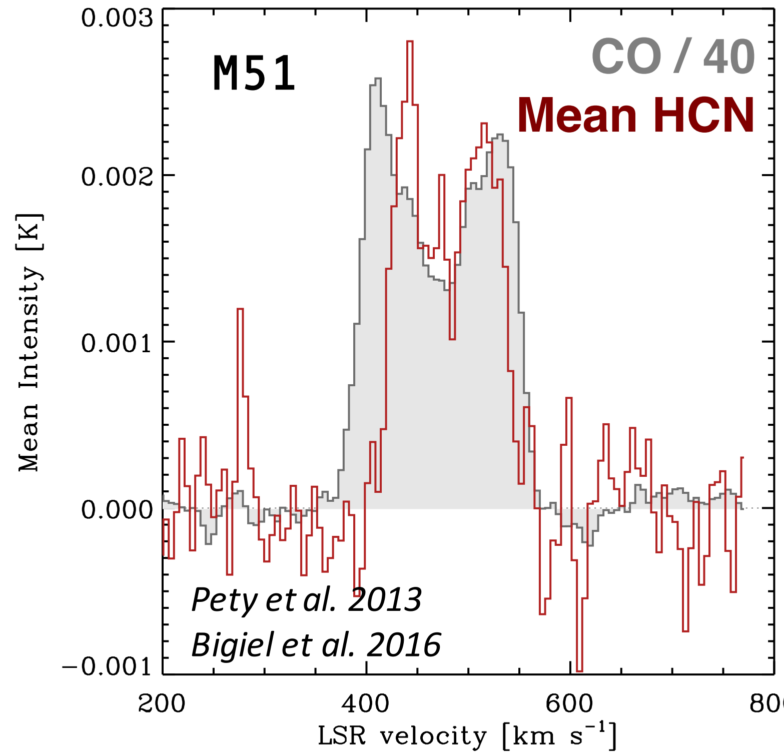
e.g. Pety et al. 2013

Dense gas in massive galaxies



Constant efficiency within the dense gas?





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

The EMPIRE survey

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

EMIR Multi-line Probe of the ISM Regulating Galaxy Evolution

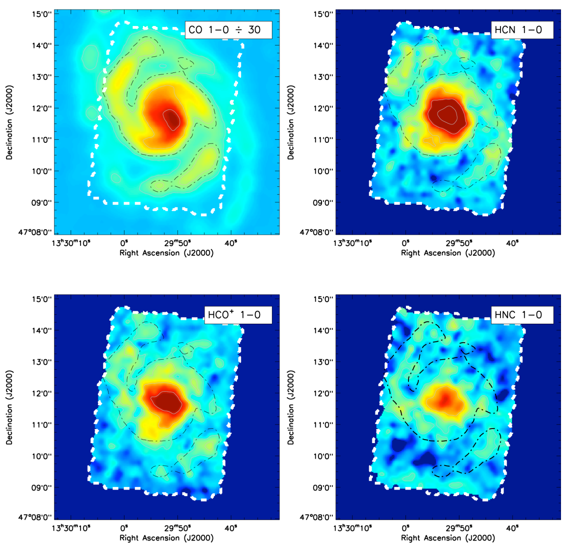
PI: F. Bigiel, 600 hr
IRAM Large Program 2015-2017

-- Full maps of 9 disk galaxies
-- 1.5 kpc linear resolution

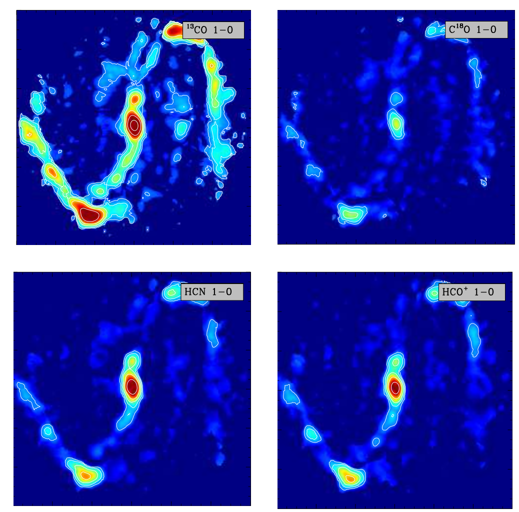
PI: A. Leroy, 10 hr
ALMA Cycle 3

-- Inner 1/3 disk of 4 galaxies
-- 300 pc linear resolution

M 51

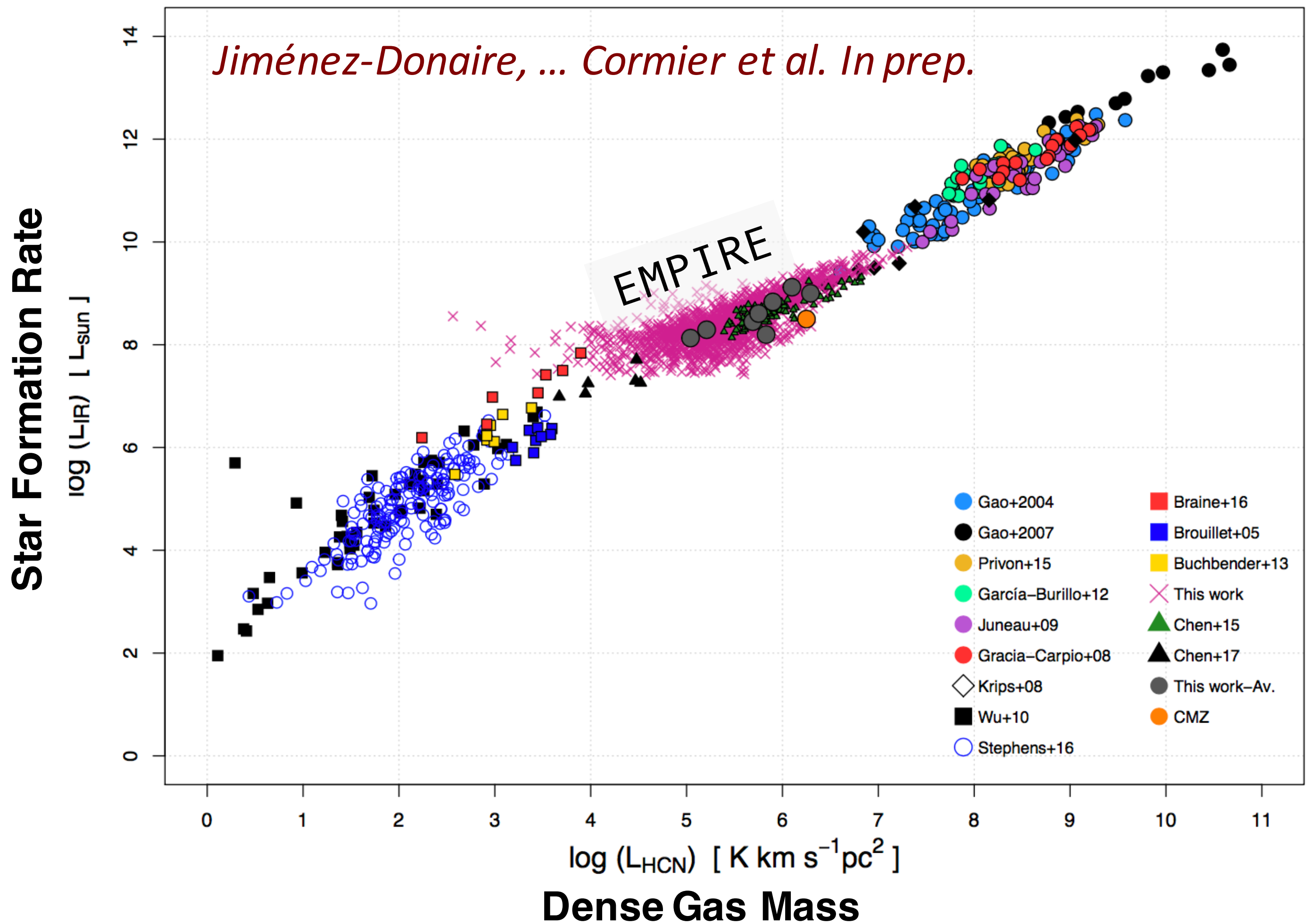


NGC 3627



Bigiel et al. 2016, Jiménez-Donaire et al. 2017a,b, Leroy et al. 2017a, Gallagher et al. subm., Cormier et al. to be subm.

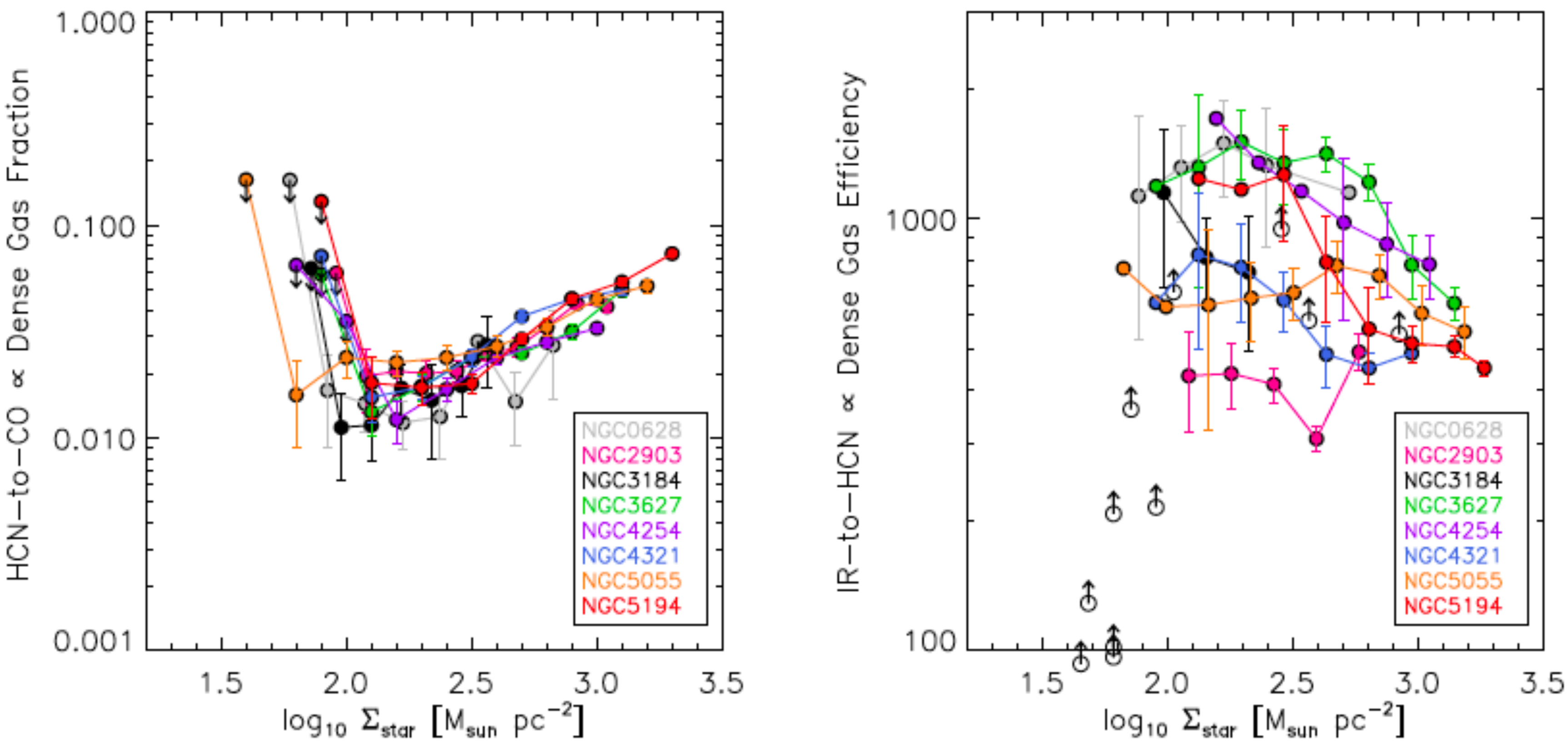
Filling the luminosity gap



A linear relation, with scatter…

Dense gas fractions and efficiencies

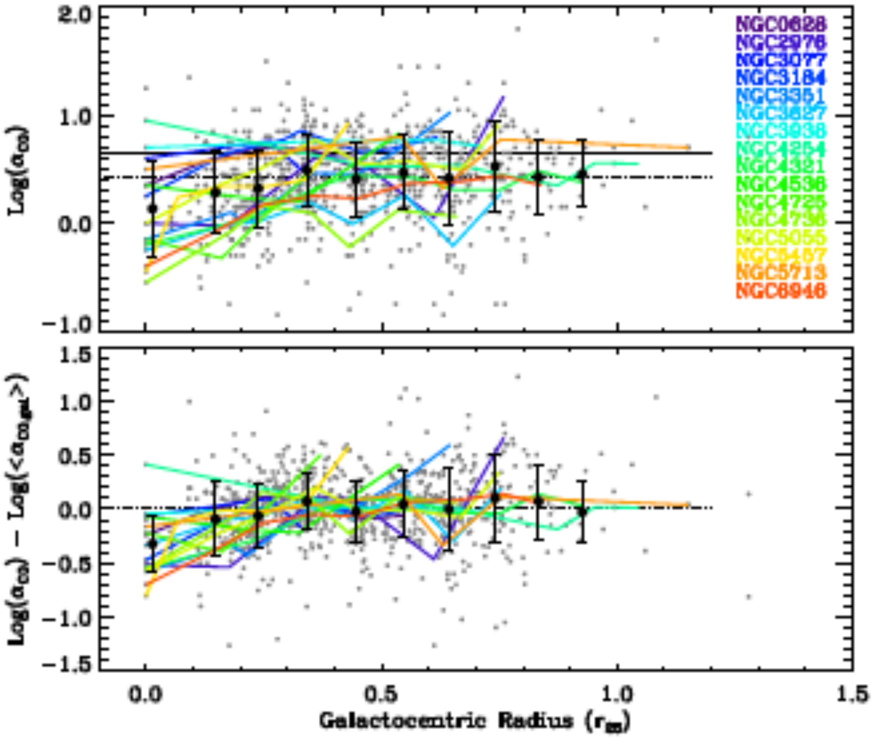
- The *apparent* dense gas fractions (HCN/CO) and efficiencies (TIR/HCN) vary strongly across galaxies



Jiménez-Donaire, … Cormier et al. In prep.

Calibrating the gas mass with optically thin tracers?

Sandstrom et al. 2013



$M(H2) = I(^{12}CO) \times \alpha_{12CO}$

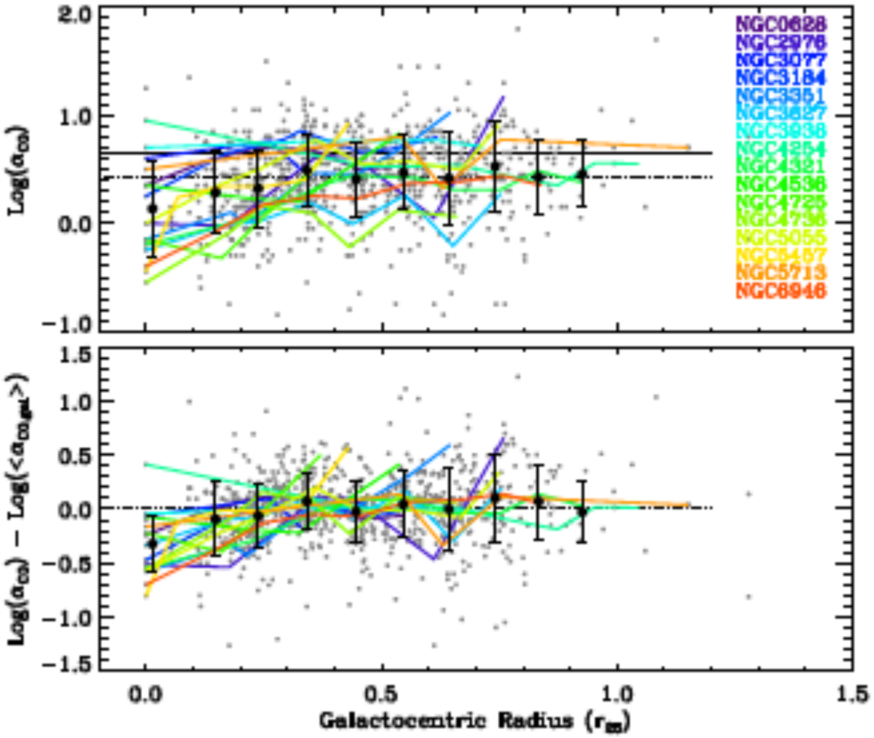
Suppressed α_{12CO} *in the galaxy centers:*

excitation effects?

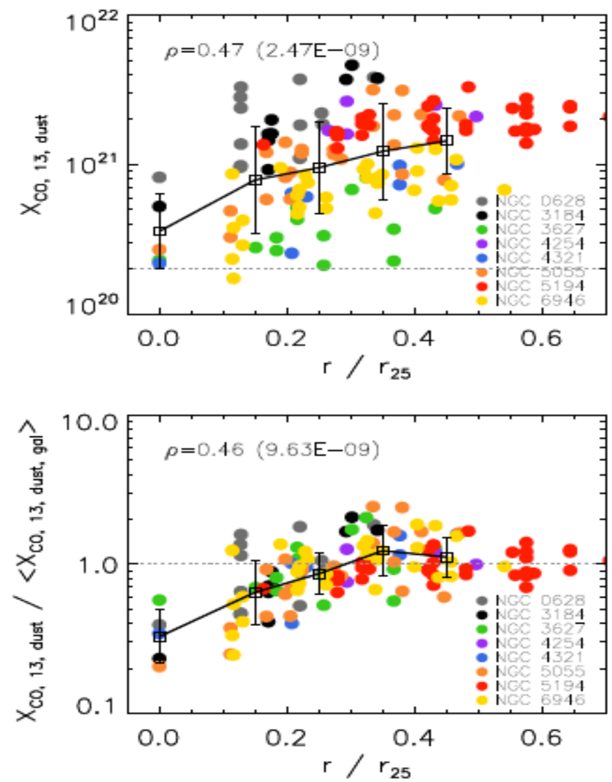
opacity (velocity gradients, diffuse gas)?

Calibrating the gas mass with optically thin tracers?

Sandstrom et al. 2013



$N(H_2)_{\text{from dust}} = I(^{13}CO) \times X(^{13}CO)$

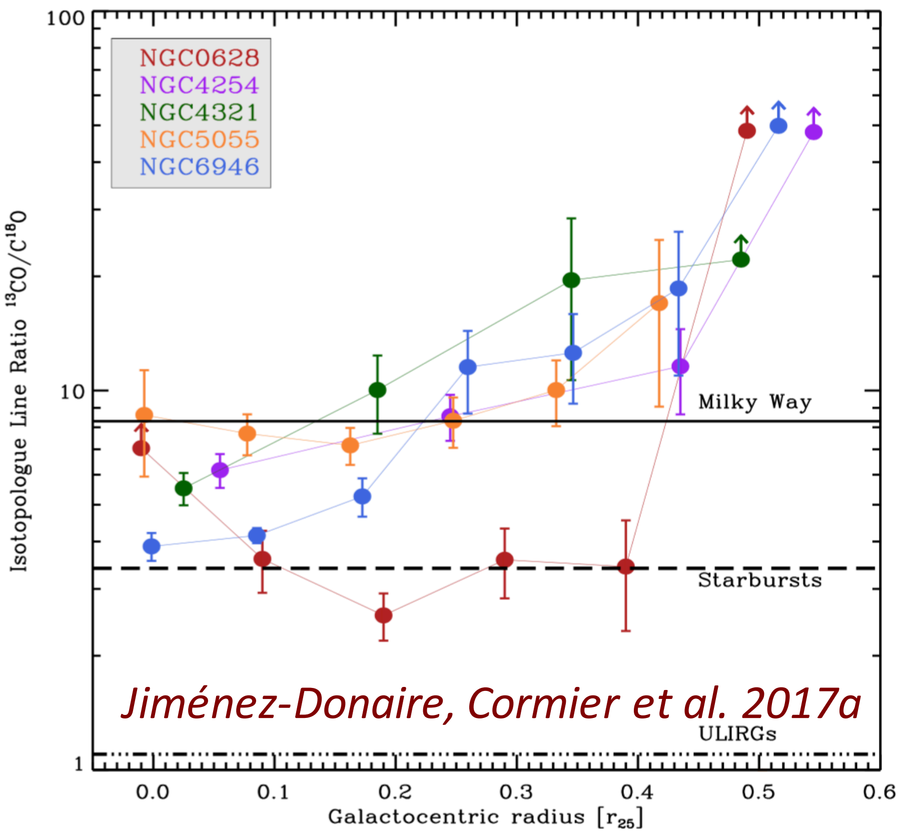


- Empirical derivation of $X(^{13}CO)$ still reveals a large variations
- Low α_{12CO} values in centers do not disappear with ^{13}CO
- Systematic problems in the dust method? excitation? abundances?

Cormier et al. to be subm.

Isotopologues suggest abundance gradients

- First $C^{18}O$ profiles across normal disk galaxies
- Clear $^{13}CO/C^{18}O$ (1-0) gradients observed with radius
- Most likely drivers are real abundance variations



Jiménez-Donaire, Cormier et al. 2017a

Conclusions

Dwarfs

- Structure of the ISM changes with metallicity: multi-phase approach necessary
- Large CO-dark molecular gas reservoirs mesured to take into account for SF efficiency

Follow-ups for more constraints on the cold phases (CI, CO) with ALMA; consider more realistic geometries

Disks

- Dense gas fractions (and efficiencies?) vary with environments
- ^{13}CO does not seem to trace better the molecular gas than ^{12}CO (opacity <u>and</u> abundance effects)

Follow-ups for direct abundance measurements and higher J transitions for excitation with IRAM and ALMA