Properties of the interstellar medium and star formation in low-metallicity galaxies

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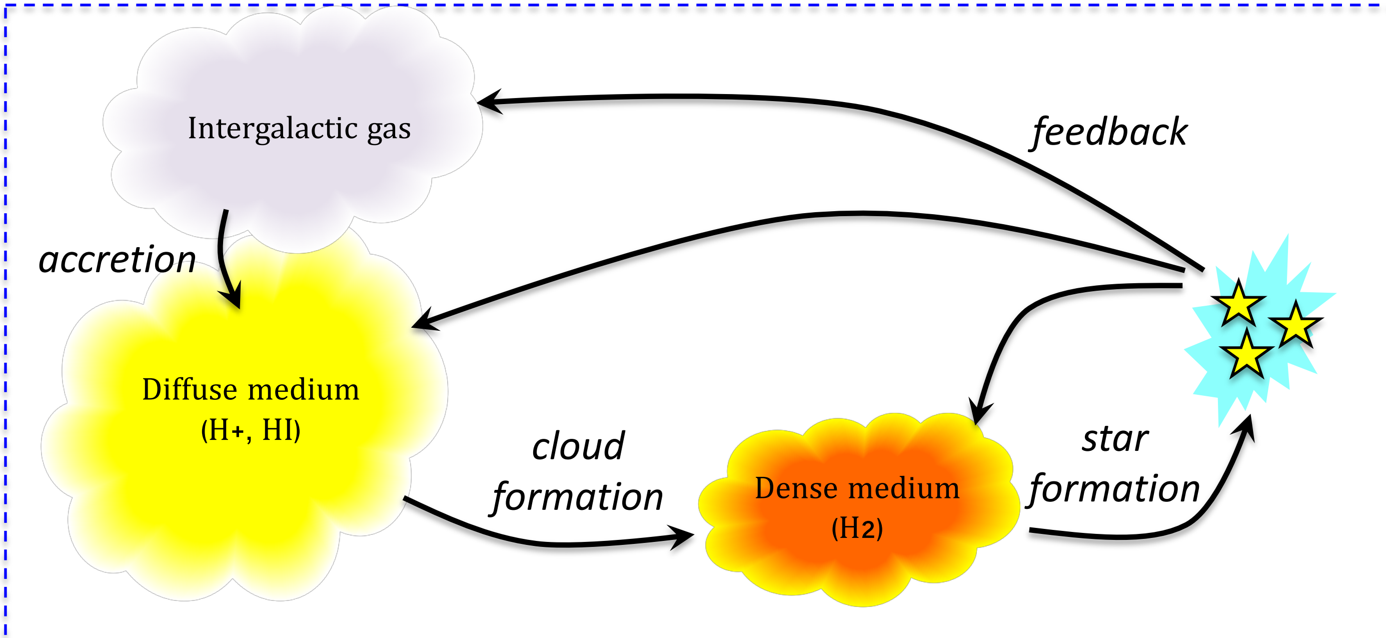
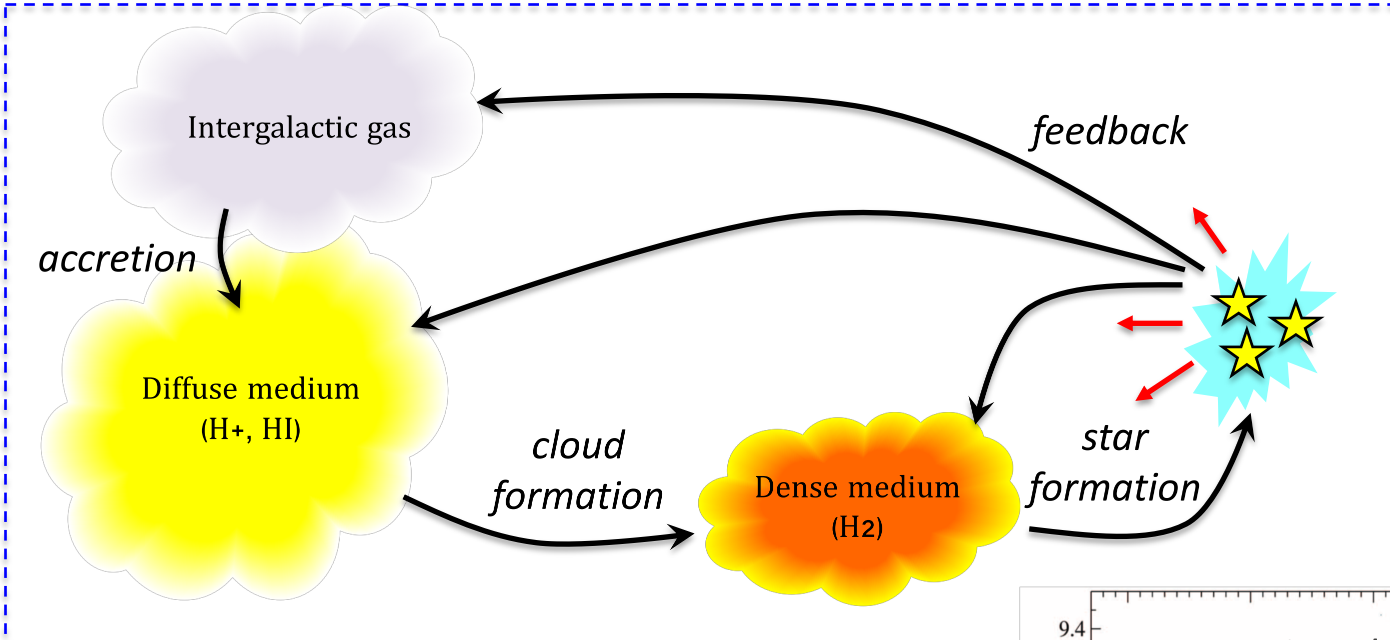
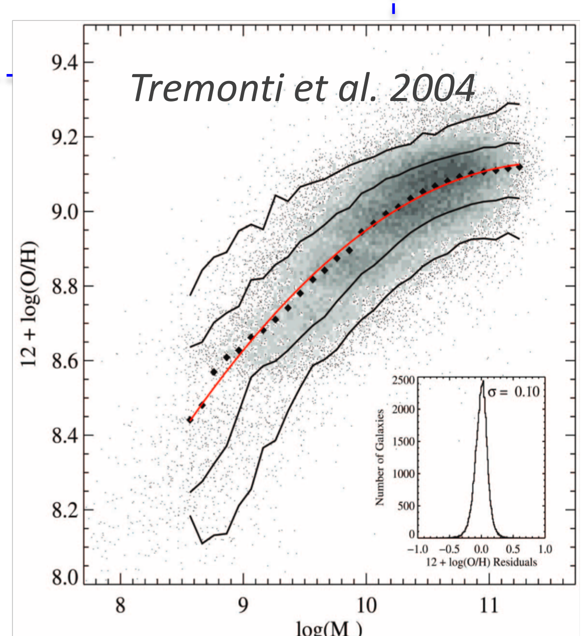
Understanding the steps to star formation



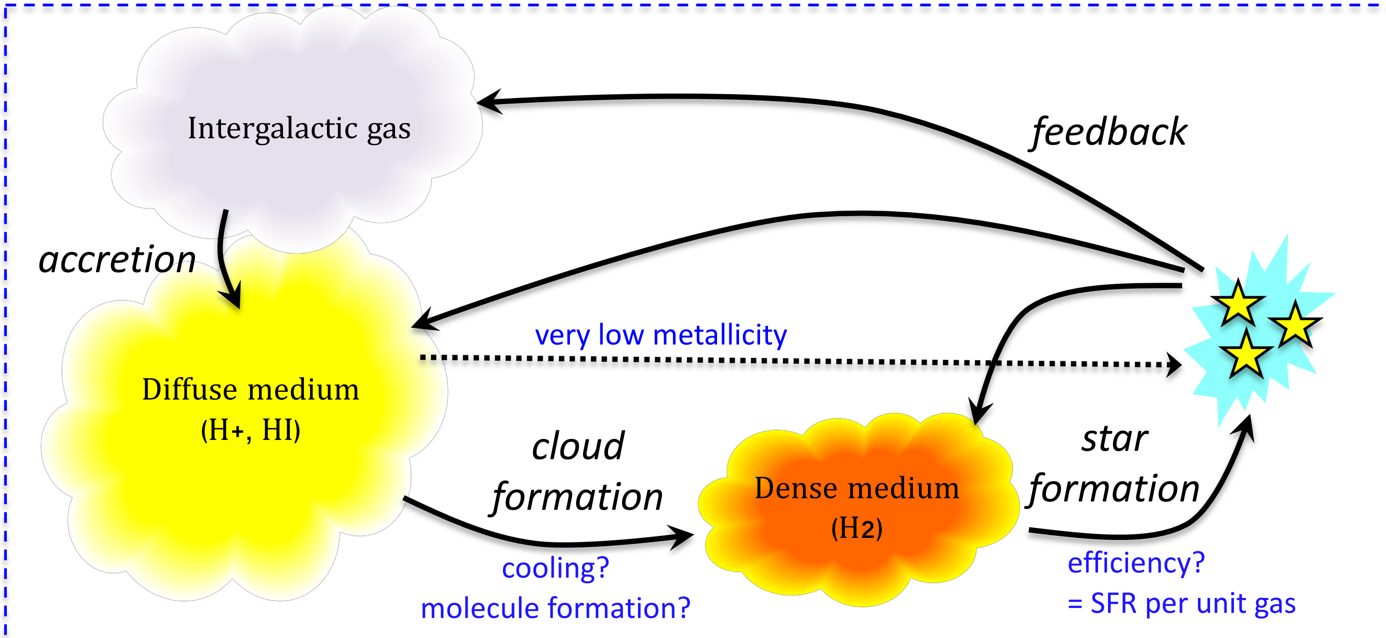
Understanding the steps to star formation



Enrichment of the ISM with metals by supernovae and AGB stars

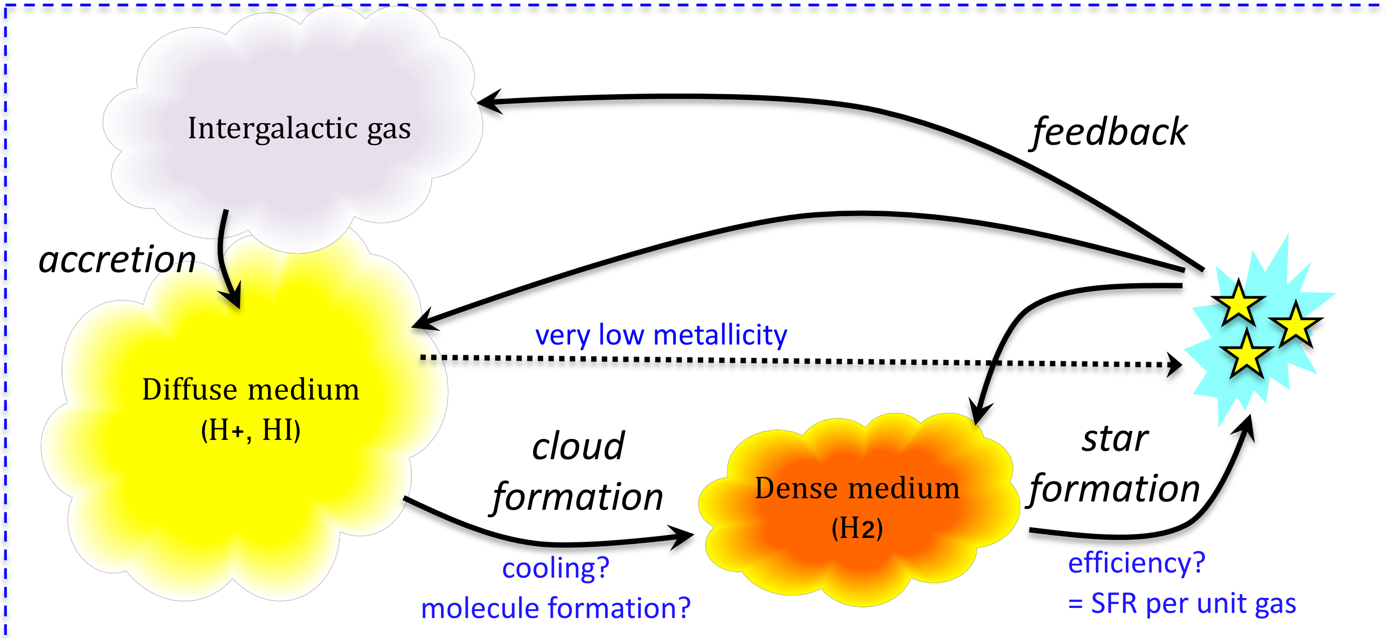


Understanding the steps to star formation



Enrichment of the ISM with metals
by supernovae and AGB stars

Understanding the steps to star formation

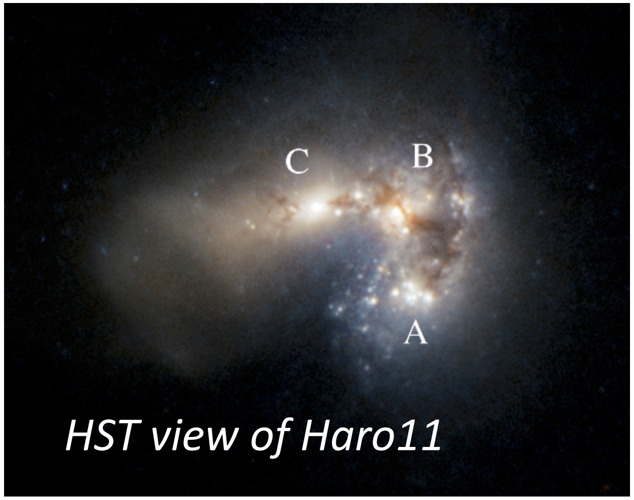


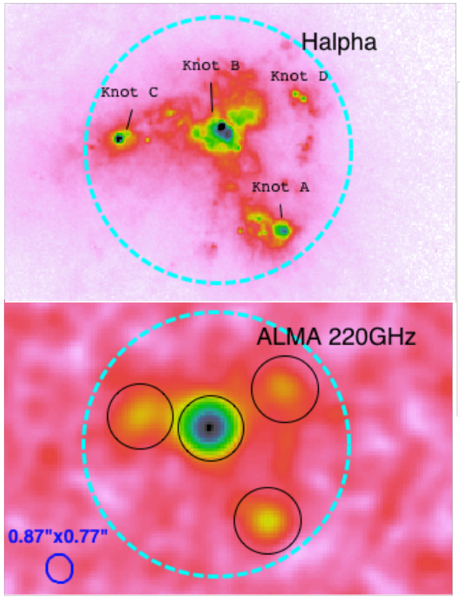
Do we understand the dust budget of galaxies?

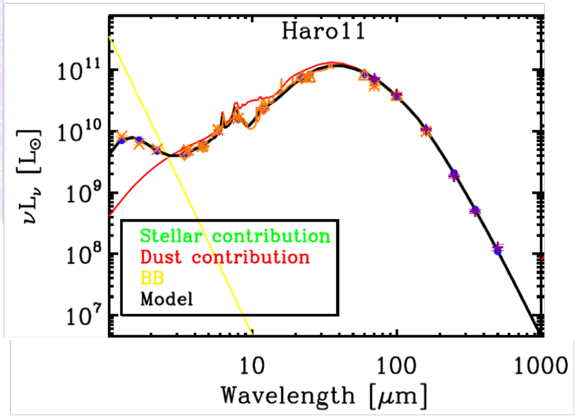
How do the ISM properties and stucture of the different phases evolve as a function of metallicity?

What are the best tracers of the star-forming gas?

… from an observational, nearby perspective







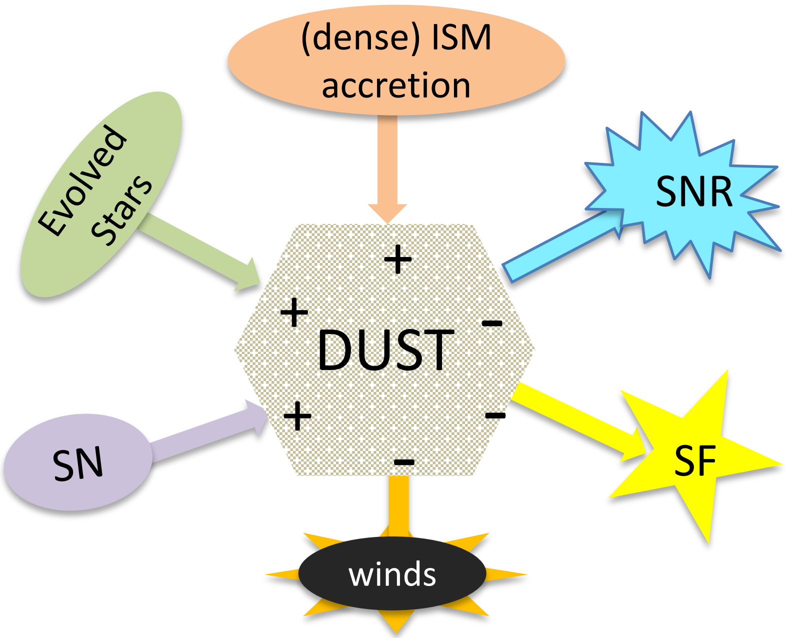
Optical VLT FLAMES/MUSE etc.
(metallicity, ionized gas)
e.g. James et al. 2013

Spitzer, Herschel
(warm/cold dust and gas)
e.g. Remy-Ruyer et al. 2013,
Cormier et al. 2012

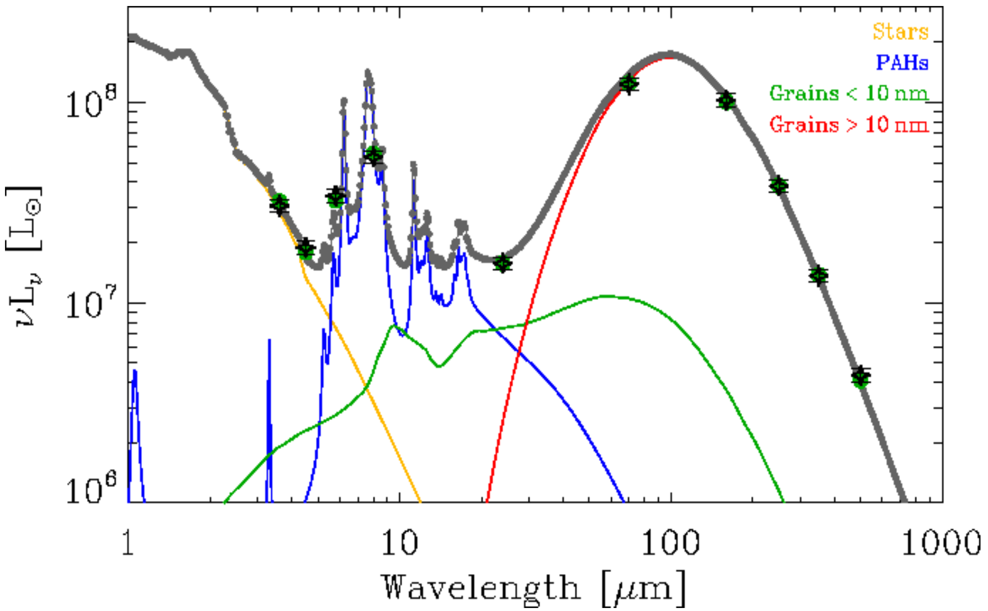
Mopra, APEX, ALMA
(star-forming molecular gas)
e.g. Cormier et al. 2014

VLA, GBT (HI)
e.g. Pardy et al. 2016

The dust budget



review by Galliano et al. 2018



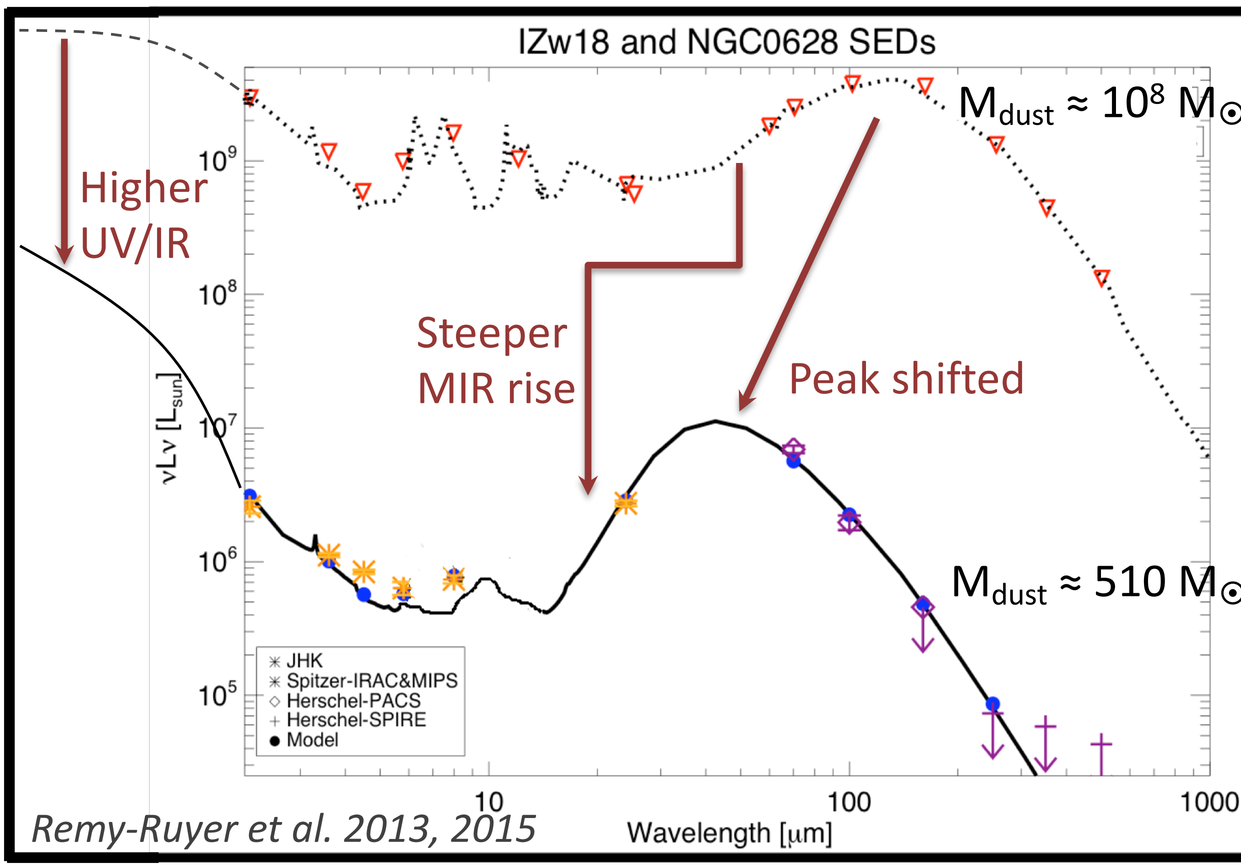
Important fraction of heavy elements in dust in MW (Si, Mg, Fe; most C).
What to expect at low metallicity?

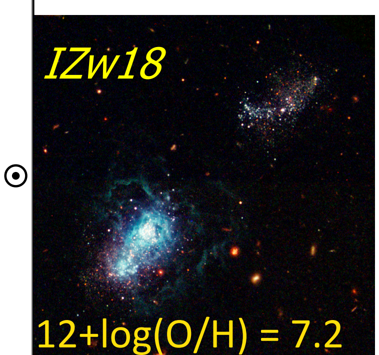
(e.g. Dwek et al. 1998, Lisenfeld & Ferrara 1998, Hirashita et al. 2002, James et al. 2002, Draine et al. 2007, Galliano et al. 2008, Munoz-Mateos et al. 2009, Galametz et al. 2011, Leroy et al. 2011, Sandstrom et al. 2013, Hunt et al. 2014, Roman-Duval et al. 2014, Fisher et al. 2014, Grossi et al. 2015, 2016, Berta et al. 2016)

Effects of Z on the Spectral Energy Distribution

- Dust SED peaks at shorter λ (warmer dust)
- Less dust, composition modified:
  - More small size grains (shocks) as seen in MIR
  - Lower PAH abundance: destroyed by radiation field, shocks, delayed injection by AGB stars
- Less shielded material

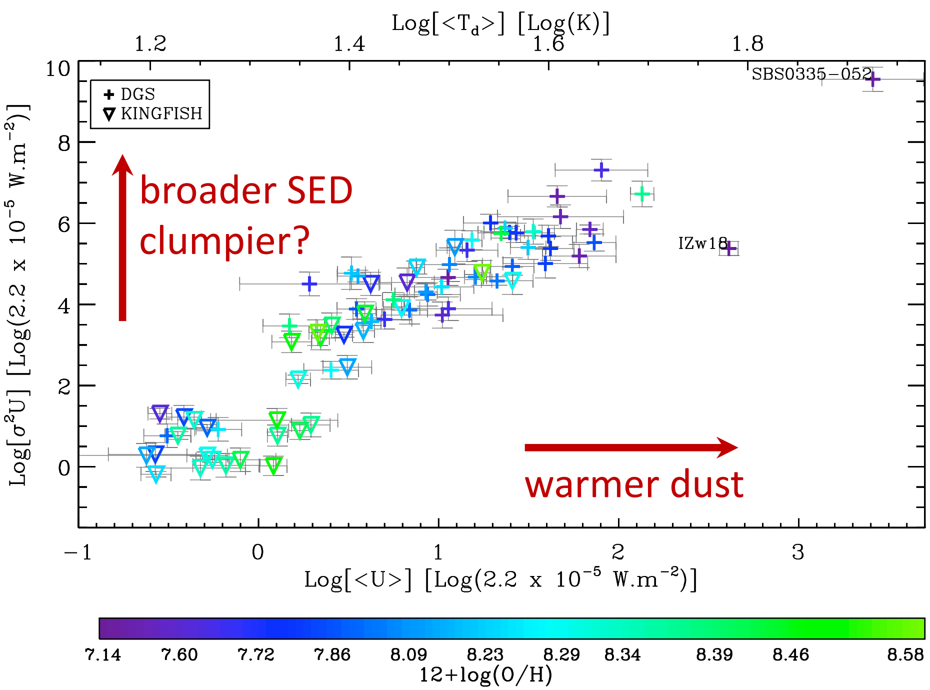
More energetic, clumpier ISM

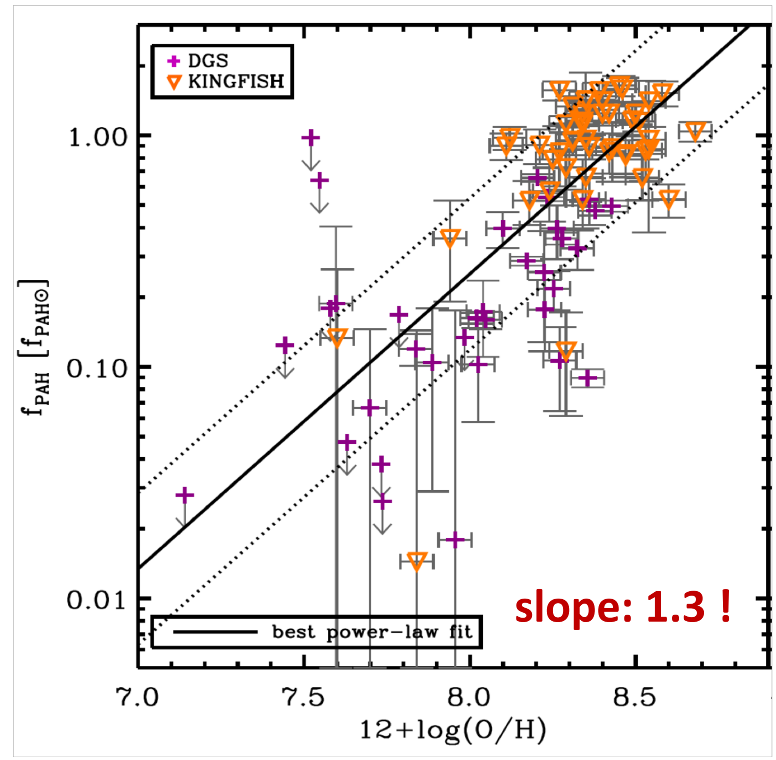




Effects of Z on the Spectral Energy Distribution

- Trends with metallicity after modeling the DGS and KINGFISH galaxies



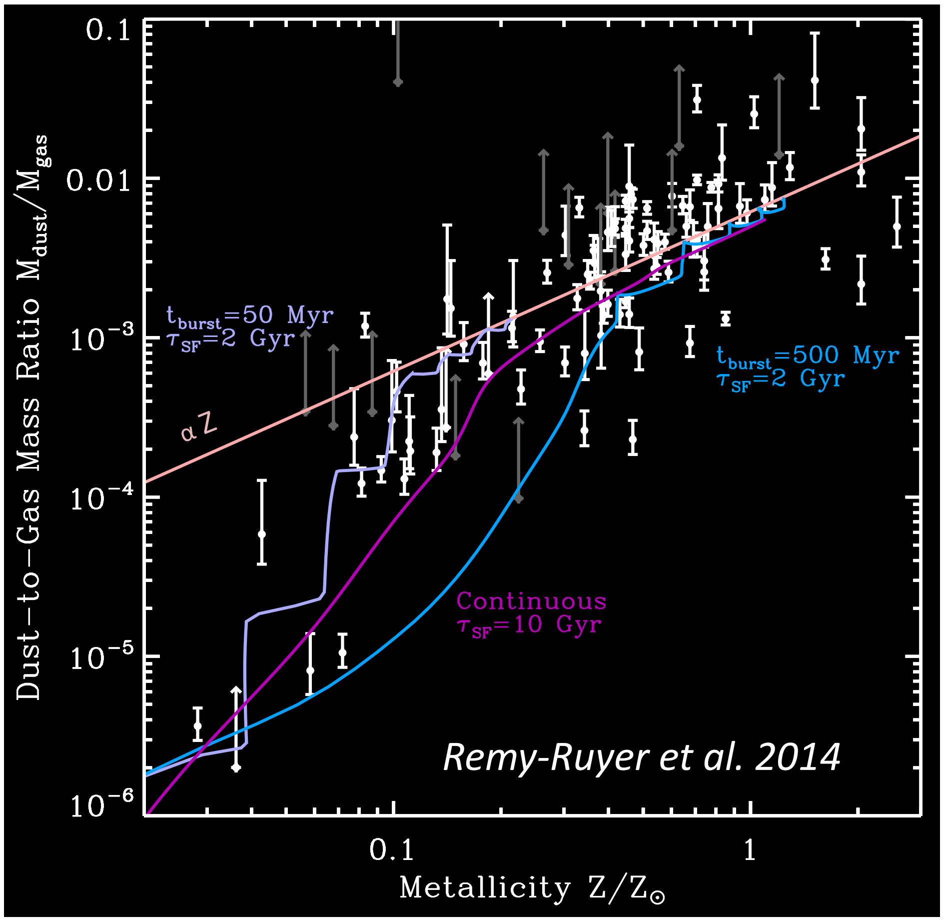


Remy-Ruyer et al. 2015

see also Engelbracht et al. 2005, Hunt et al. 2010, Sandstrom et al. 2010

Dust-to-Gas mass ratio and metallicity

- DGR versus metallicity for 126 nearby galaxies:
  - linearity breaks for Z < 1/8 $Z_\odot$
  - scatter can be explained by different SF histories



Chemical evolution models:

- Dust growth in the ISM by mantel accretion is fundamental
- Need more time to accumulate metals for efficient grain growth

(Hirashita 1999, Inoue 2011, Asano et al. 2013, Zhukovska 2013)

Dust-to-Gas mass ratio and metallicity

Chemical evolution models:

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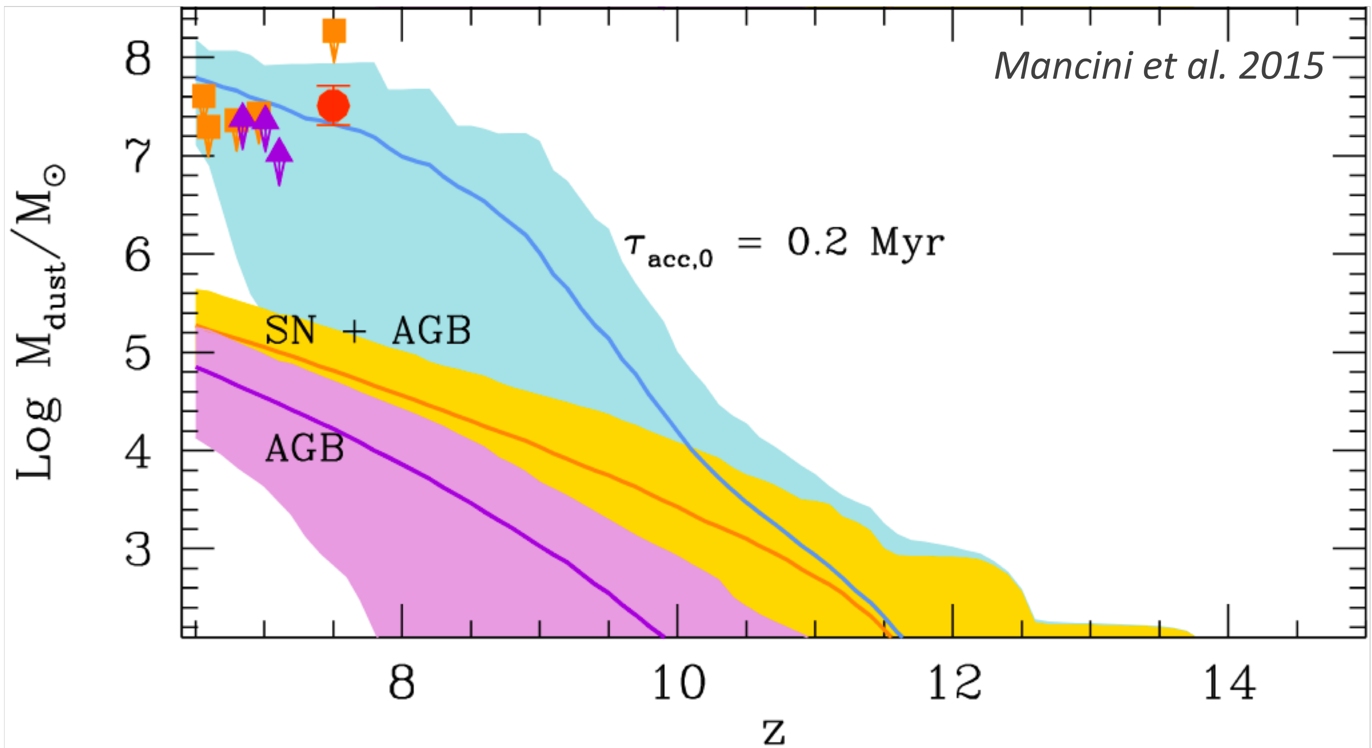
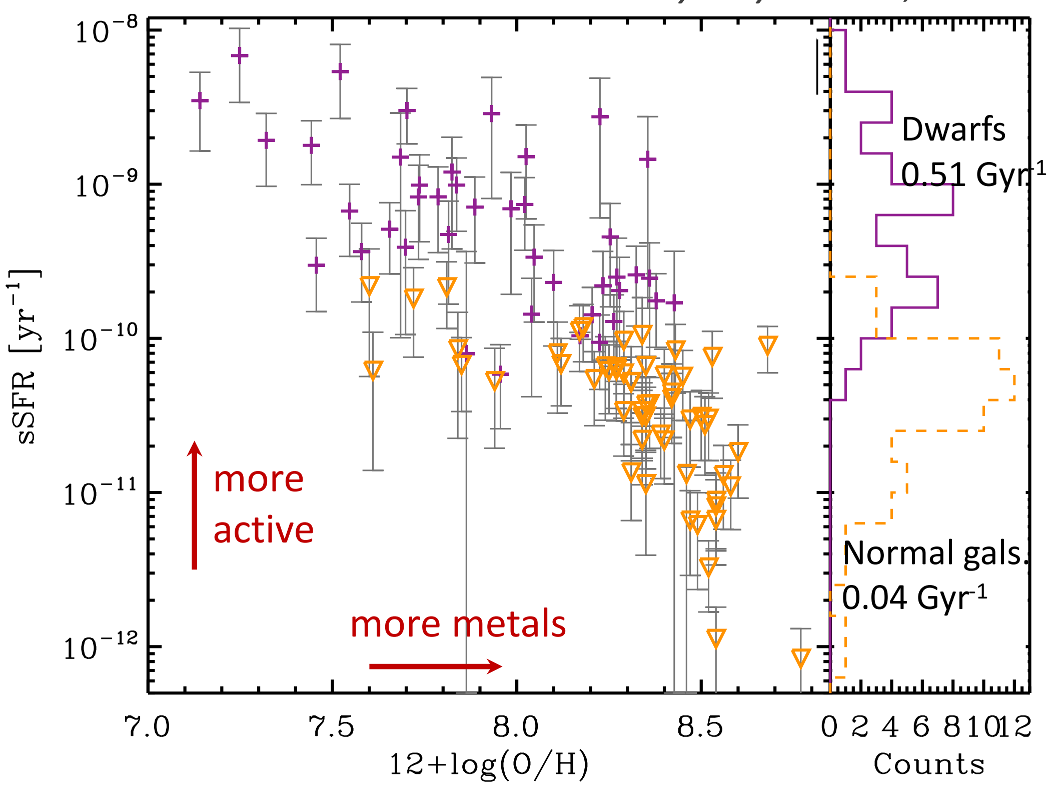


Star-formation activity and metallicity

- Star-forming dwarfs have higher SFR/$M_\star$ (sSFR)

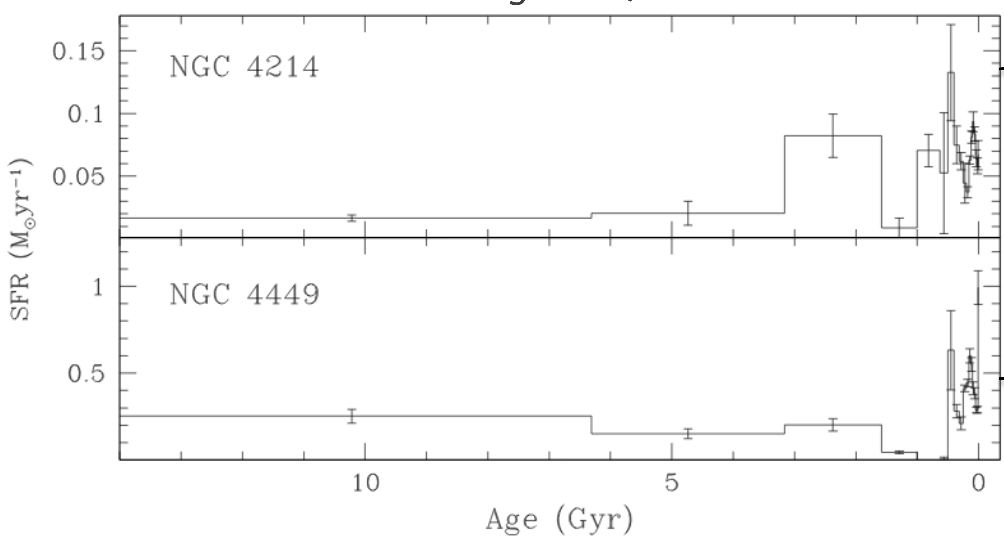
Remy-Ruyer 2013, 2015

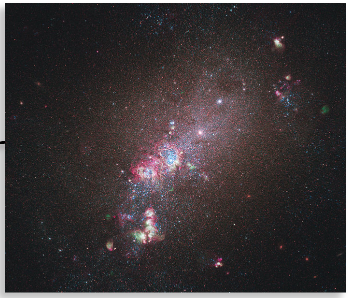


Star-formation activity and metallicity

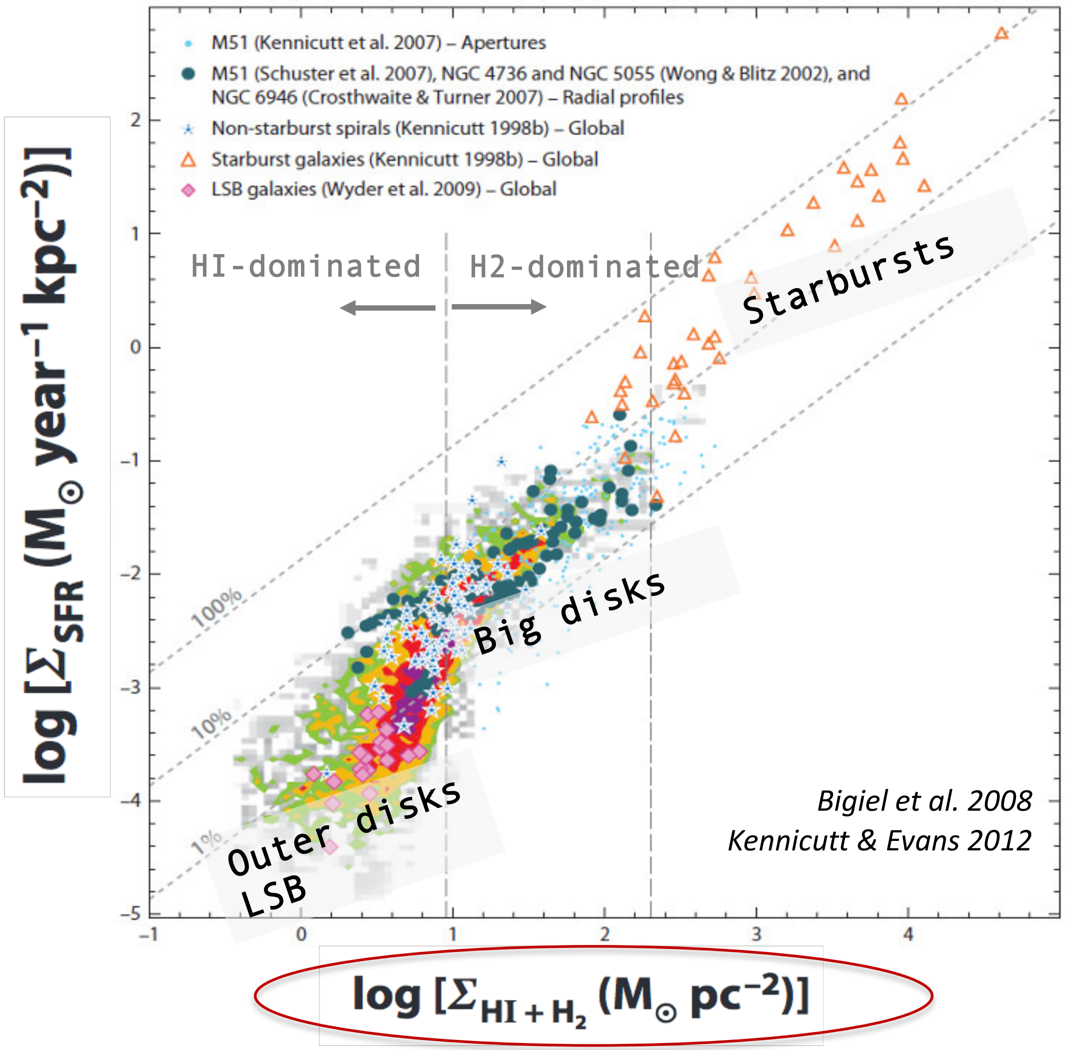
- Presence of young stellar population and episodic/bursty/gaspy SFH, large variations in sSFR *(Marconi et al. 1995)*

e.g. McQuinn et al. 2010





Star formation at low metallicity: no molecules?



SFR relates to HI

SFR relates to $M_\star$

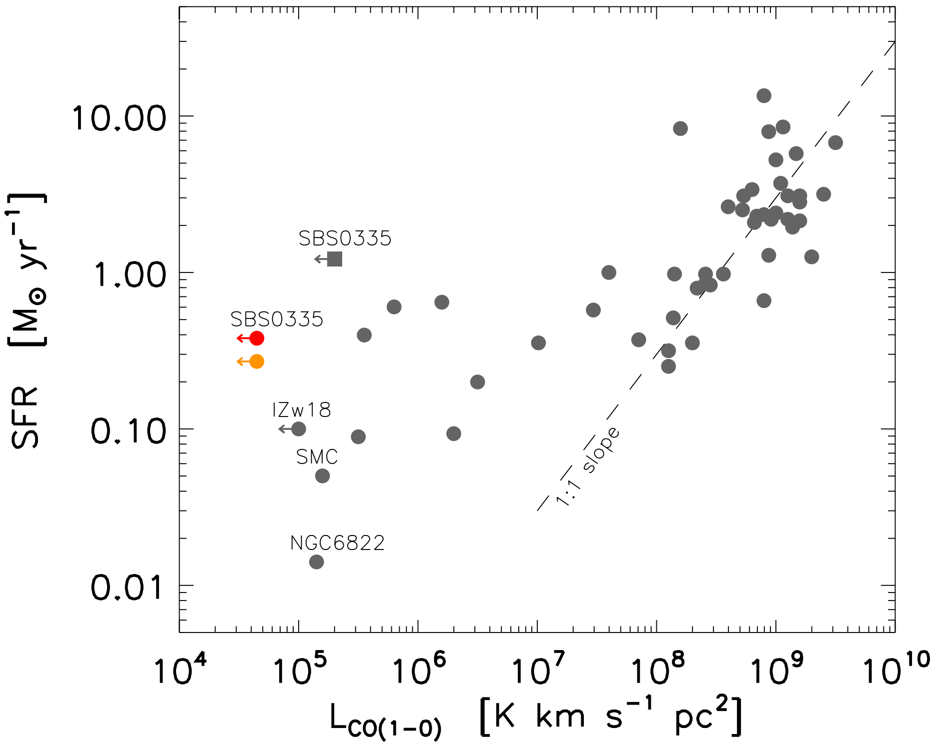
What about H_2?

Dwarfs - HI: Lee et al. 2009, Wyder et al. 2009, Bigiel et al. 2010, Roychowdhury et al. 2015, Lopez-Sanchez et al. 2018

Extended Schmidt law (including stellar surface density): Roychowdhury et al. 2017, Shi et al. 2018

Star formation at low metallicity: no molecules?

- Cold ISM difficult to observe – little molecular gas traced by CO
- Low SFE in HI gas but high SFE in H_2 gas



⇒ Efficient SF from H_2?

⇒ SF in atomic gas? *($Z < 1/100\ Z_\odot$)*

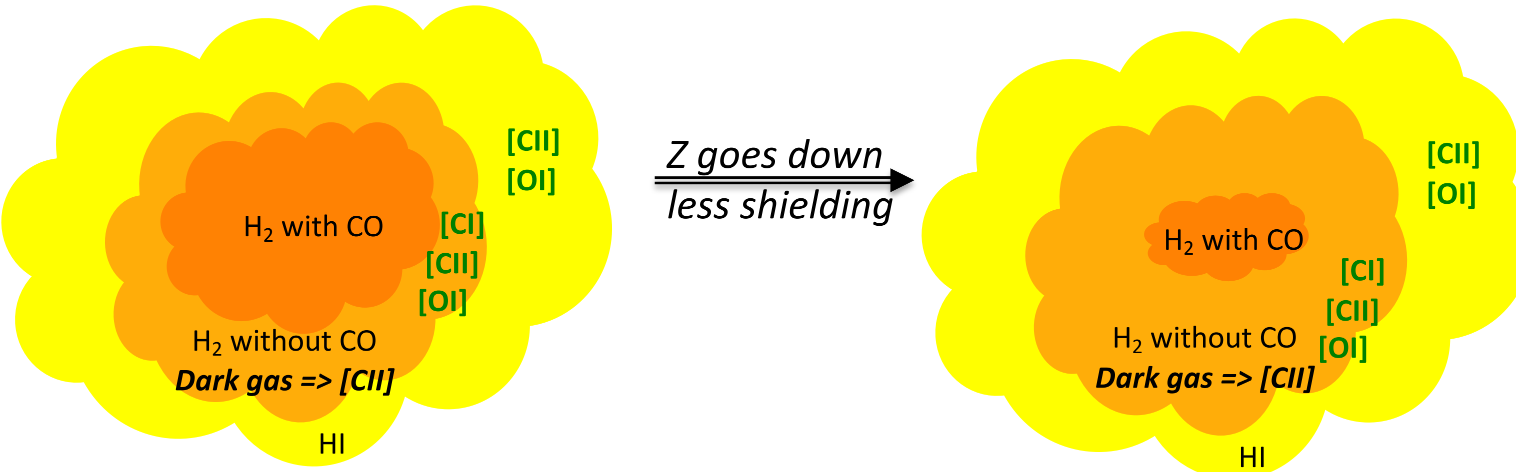
Glover & Clark 2012, Krumholz 2012

⇒ More H_2 than seen by CO?

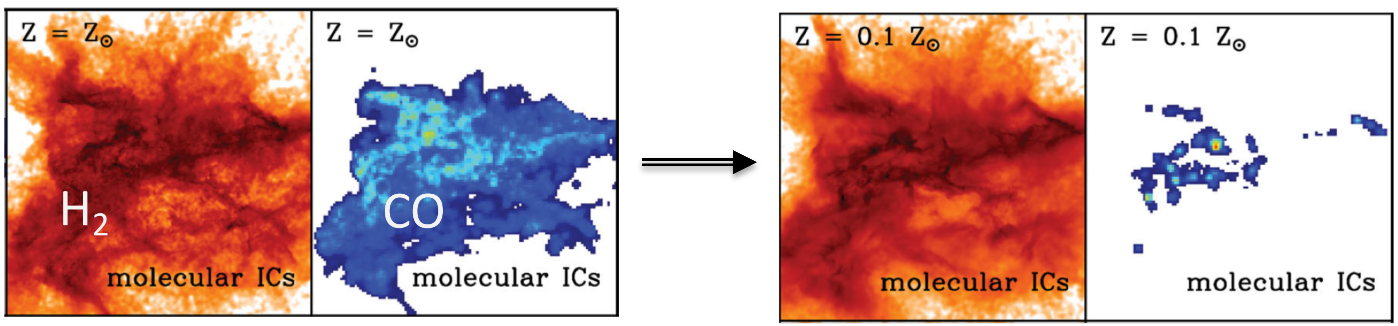
(e.g. Tacconi et al. 1987, Taylor et al. 1998, Leroy et al. 2007, Schruba et al. 2012, 2017, Elmegreen et al. 2013, Cormier et al. 2014, 2017, Hunt et al. 2015, 2016, Shi et al. 2015, Rubio et al. 2016, Amorin et al. 2016)

Fundamentally different structure of the dense gas

Less shielding: FUV photons penetrate deeper and photodissociate CO



Wolfire+ 2010, Bolatto+2013



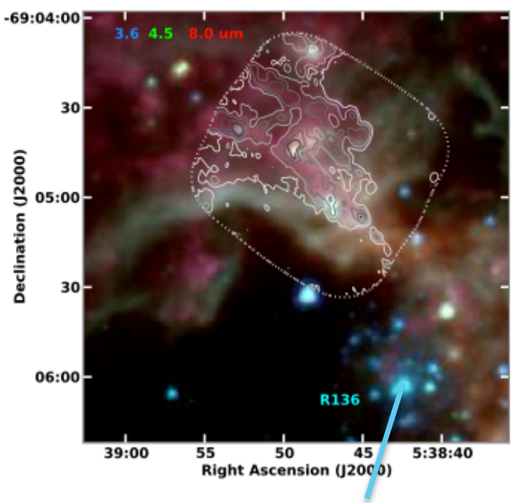
Glover & Clark 2012

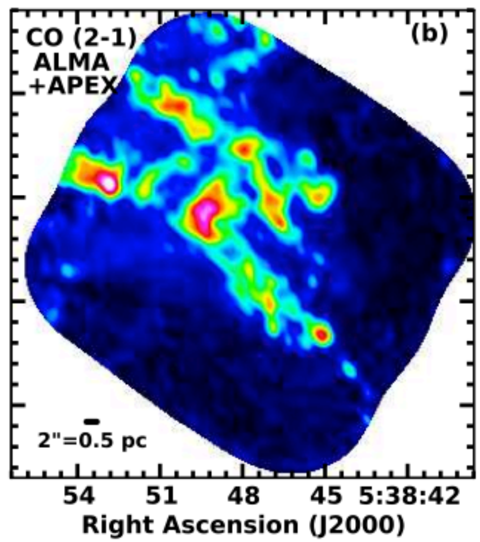
Fundamentally different structure of the dense gas

- ALMA resolves parsec scales in the Magellanic Clouds

LMC (1/2 Z): 30 Doradus

Indebetouw et al. 2013

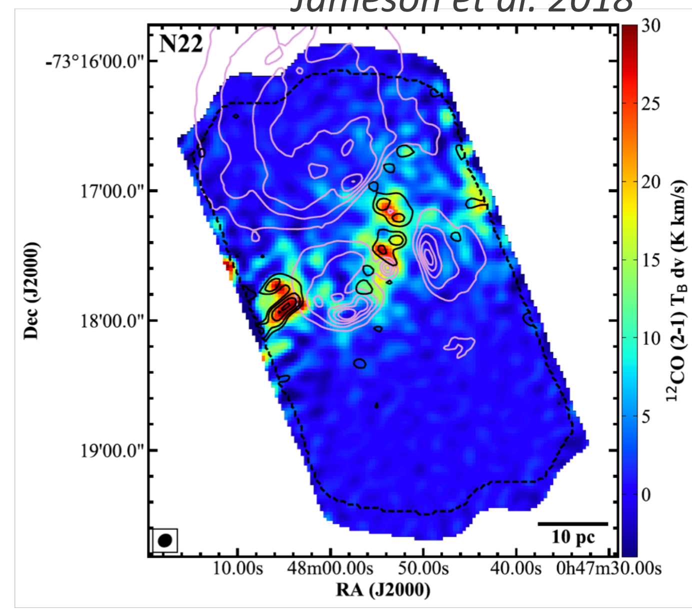




Super star cluster with >10^6 stars
Star formation going on for 20 Myr

SMC (1/5 Z): N22

Jameson et al. 2018

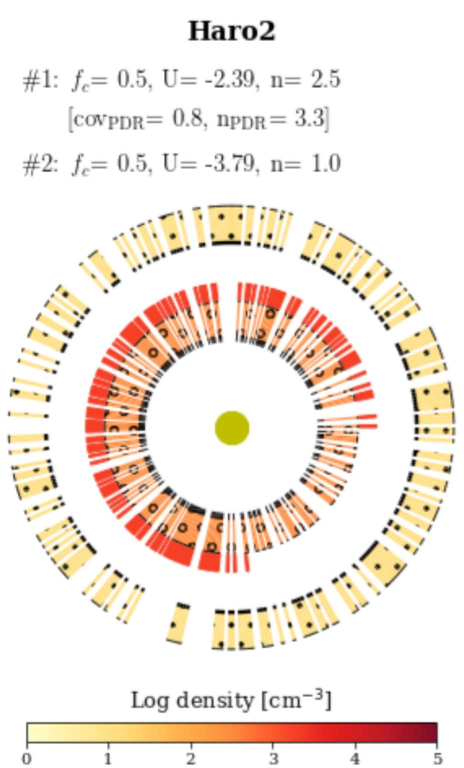


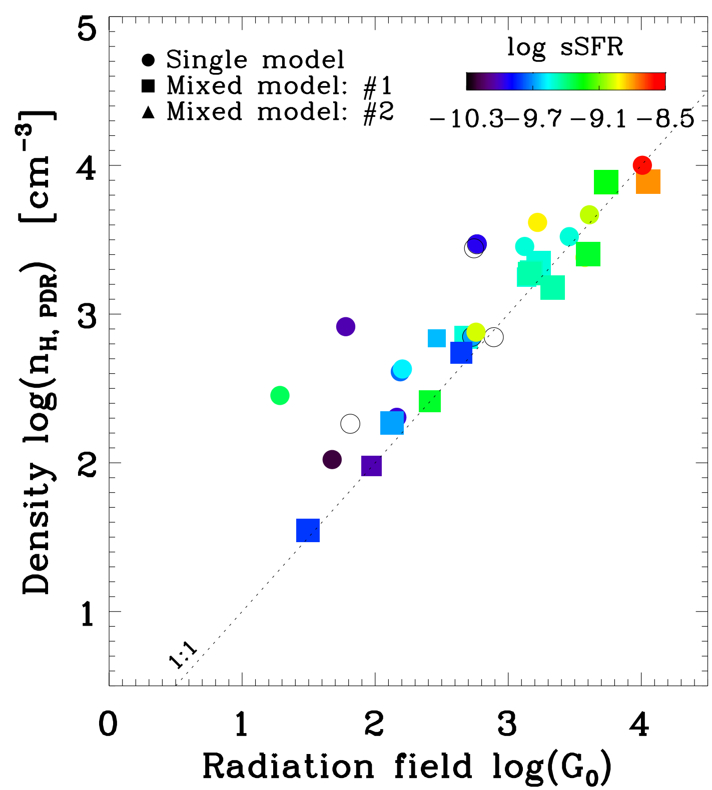
see also, e.g., Fukui et al. 2018, Schruba et al. 2017

Neutral gas conditions with multi-phase models

- Constrain conditions and structure of the gas with many lines
- Applied to 40 galaxies of the *Herschel* Dwarf Galaxy Survey ($0.03<Z[Z_\odot]<1$, $0.01<SFR[M_\odot/yr]<40$, d<200Mpc)
- Higher G_0 and n at high sSFR

Cormier et al. subm.



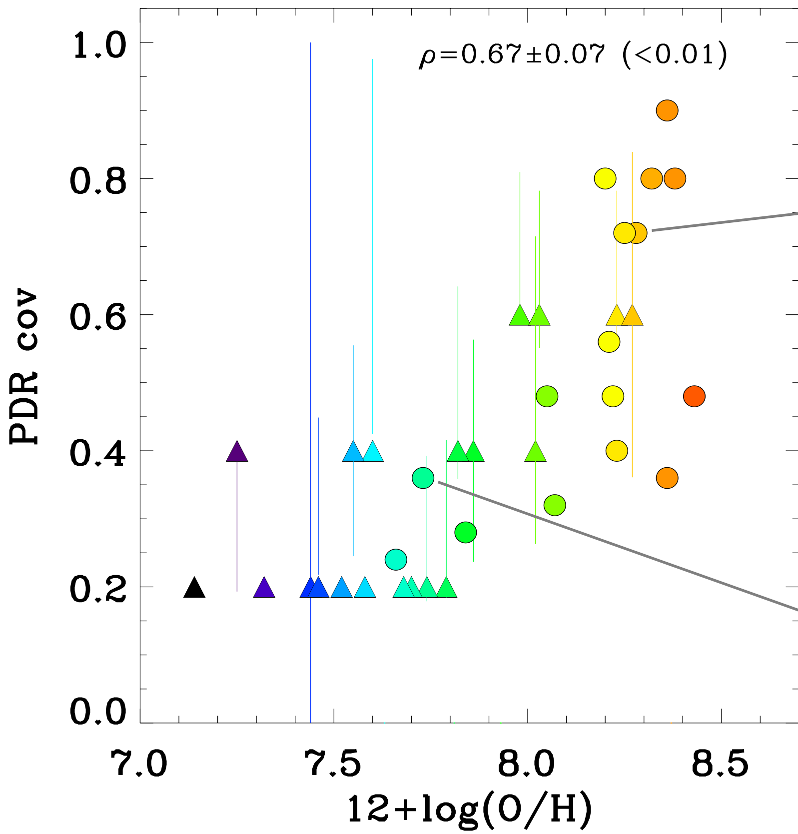


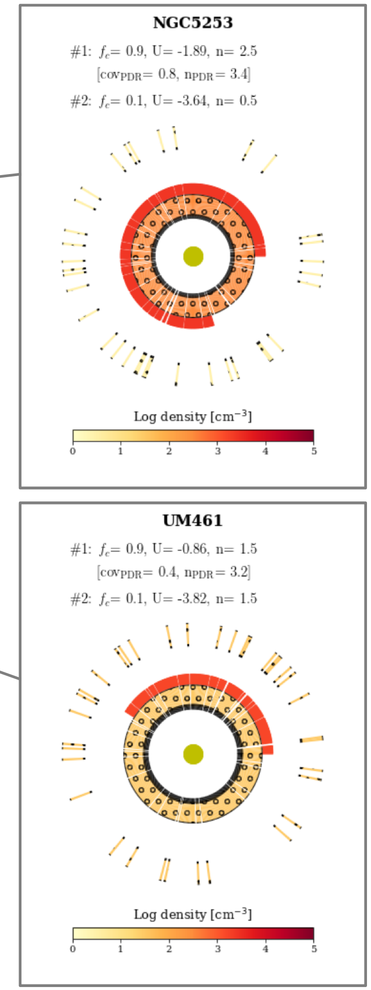
see also Cormier et al. 2012, 2015, Lebouteiller et al. 2017

Neutral gas porosity with multi-phase models

Cormier et al. subm.

- ISM porosity increases with decreasing metallicity

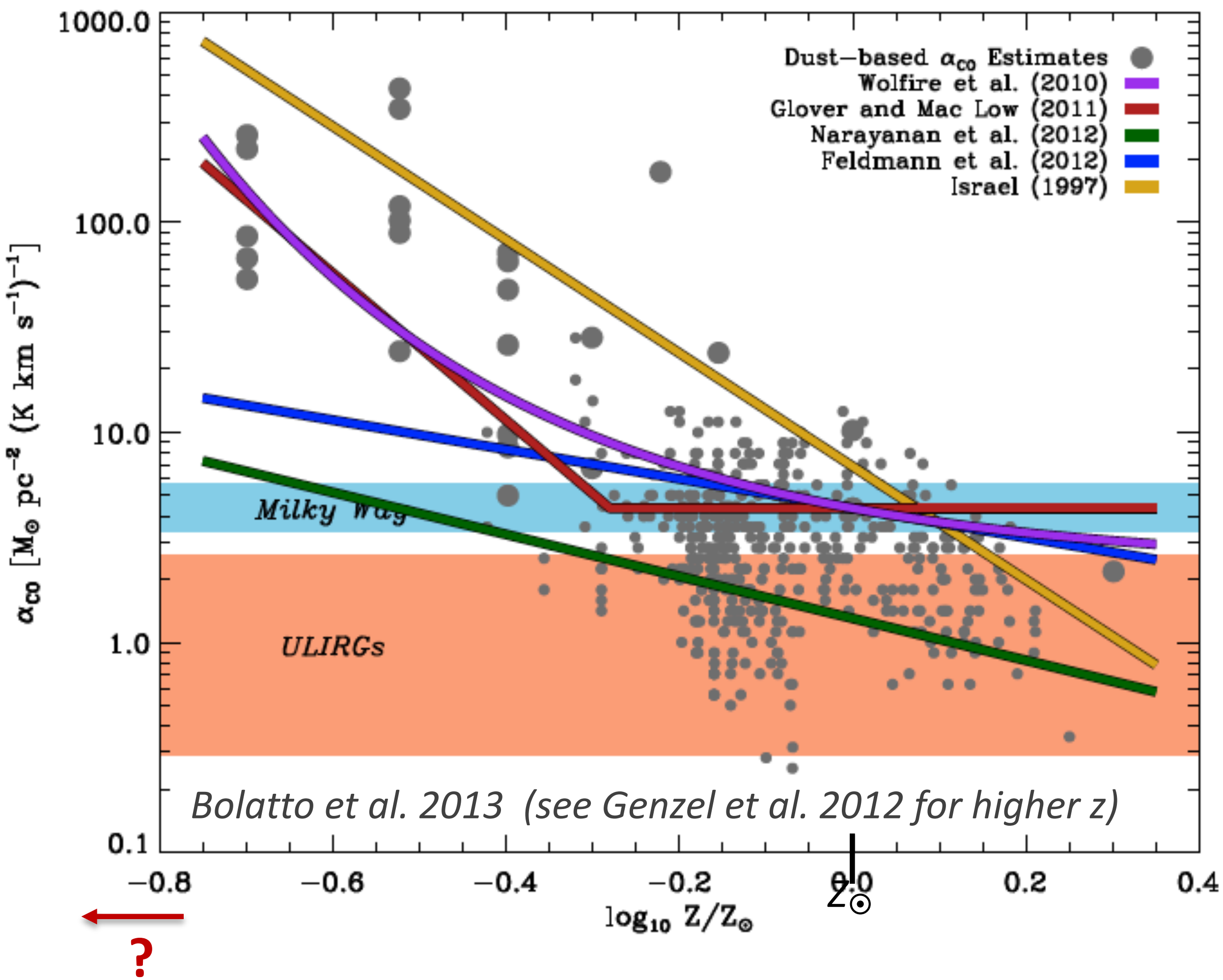




Structure pre-requisite for galaxies at the epoque of reionization?

How to best trace the gas reservoir?

- CO, dust (DGR) methods very unreliable at low-Z



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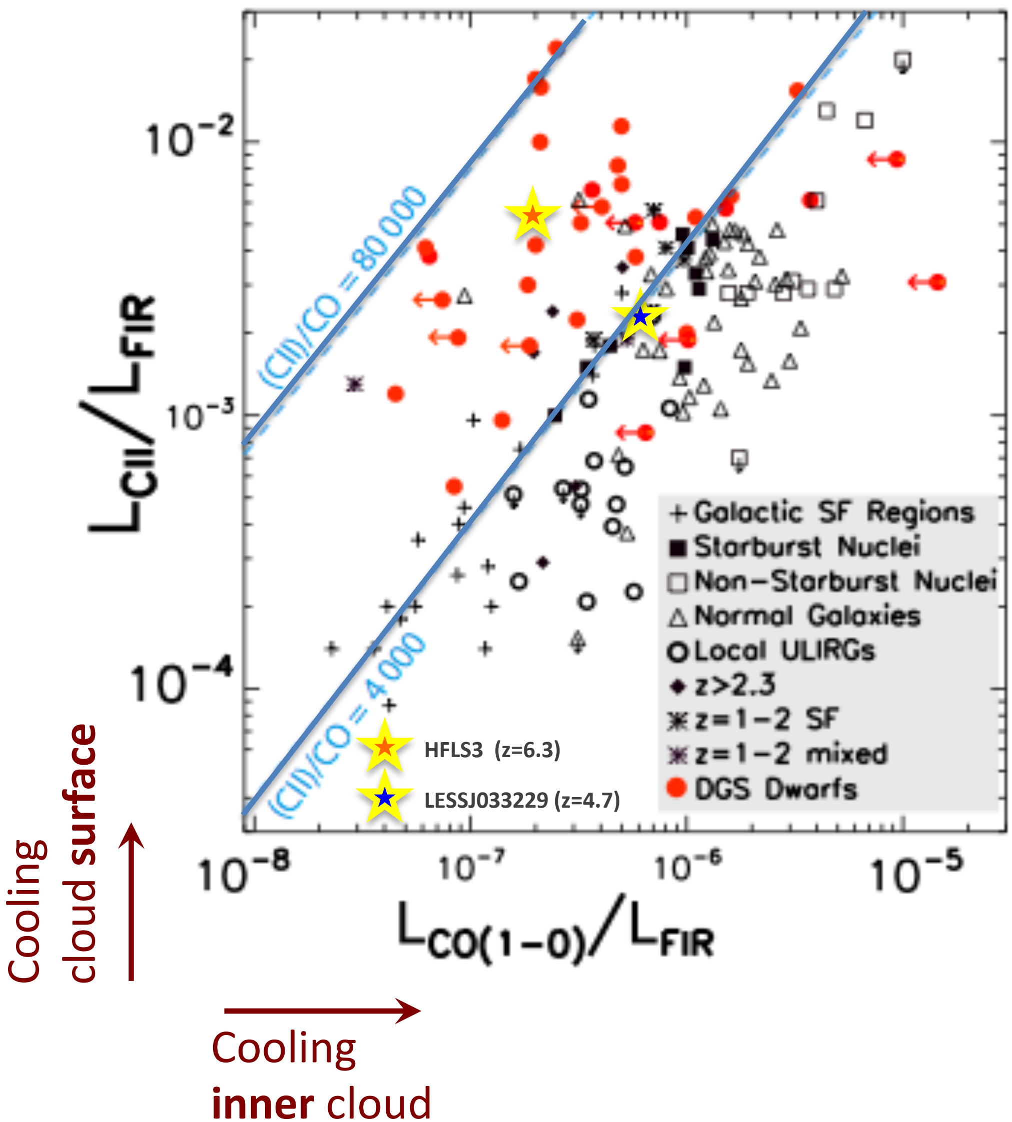
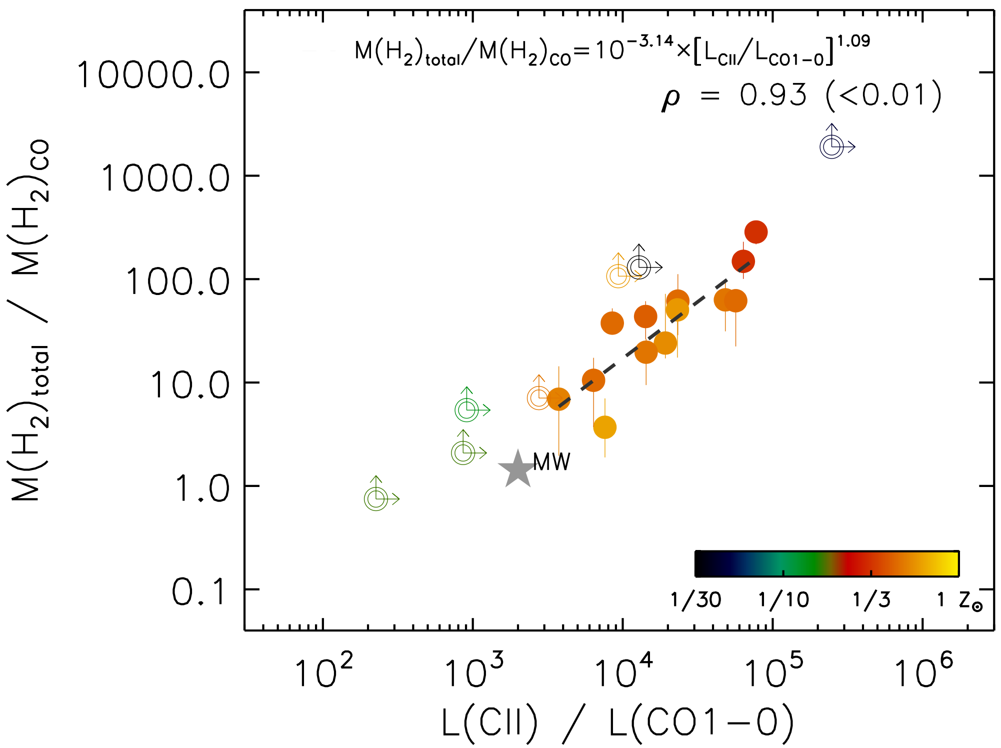


- Extreme CII/CO(1-0) ratios observed on average in star-forming low-metallicity galaxies
- PDR lines (e.g. CII, OI, CI) are promising tracers of the gas reservoir

Adapted from Stacey et al. 1991 ,2010 Madden et al. 2000, 2013, Hailey-Dunsheath 2010, DeBreuck et al. 2011 Riechers et al. 2013

[CII], CO-dark gas and mass budget

Madden et al. in prep.



- CO-dark gas **dominates** the molecular mass budget

(in line with, e.g., Madden et al. 1997, Israel 1997, Wolfire et al. 2010, Bolatto et al. 2013, Fahrion et al. 2016, Jameson et al. 2018)

$X_{CO} \approx Z^{-3.4}$

- A large CO-dark reservoir reconciles dwarfs with the Schmidt-Kennicutt relation

see e.g. Zanella et al. 2018 for high redshift galaxies (CII)

Exploring [CI], [OI], H_2

[OI] lines at 63 and 145 um trace PDRs, slightly warmer/denser than [CII]
About 2 and 10 times fainter than [CII] in dwarfs *(Cormier et al. 2015)*

[CI] lines at 370 and 609 um trace a very thin layer of PDRs
Sensitive to, e.g., cosmic rays *(e.g. Papadopoulos et al. 2004, Bisbas et al. 2017)*
Remain faint in nearby low-metallicity galaxies *(Bayet et al. 2006)*

See also Valentino et al. 2018 at high redshift (CI)

Mid-IR H_2 lines trace warm gas *(e.g. Roussel et al. 2007)*
Calibration to extrapolate to total gas mass *(Naslim et al. 2015, Togi & Smith 2016)*
Difficult to detect in dwarfs with *Spitzer* but with *JWST*… *(Hunt+ 2010)*

JWST will also allow measure the **PAH** abundance vs. metallicity
(and their role in the gas heating)

Summary

- Metallicity impacts:
  Shielding, propagation of radiation, heating/cooling balance, dust and molecule formation

- Observational signatures on dust and gas:
  Less dust and PAHs, warmer, grain growth important
  Dust-to-Gas ratio varies steeply with metallicity (lot of scatter)
  CO very faint but PDR lines important for cooling
  Clumpy ISM with predominant, (leaky?) HII regions and low filling factor of dense gas

- Star formation:
  Episodic/bursty
  Efficiency and reservoir of gas mass relevant for SF still to be understood – need to observe PDR lines (ALMA, APEX, JWST, SPICA)