Swimming through the Interstellar Medium in Galaxies

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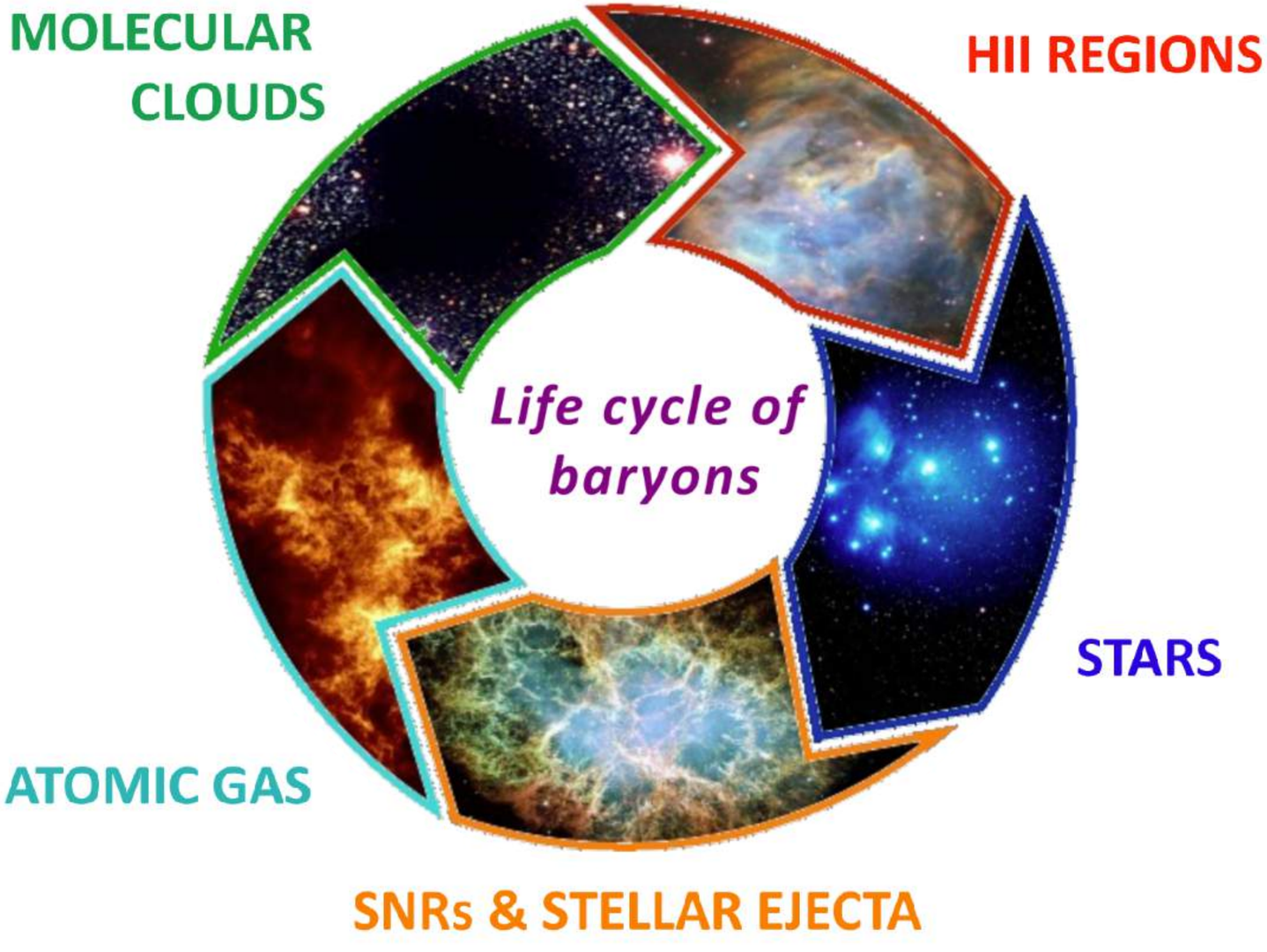
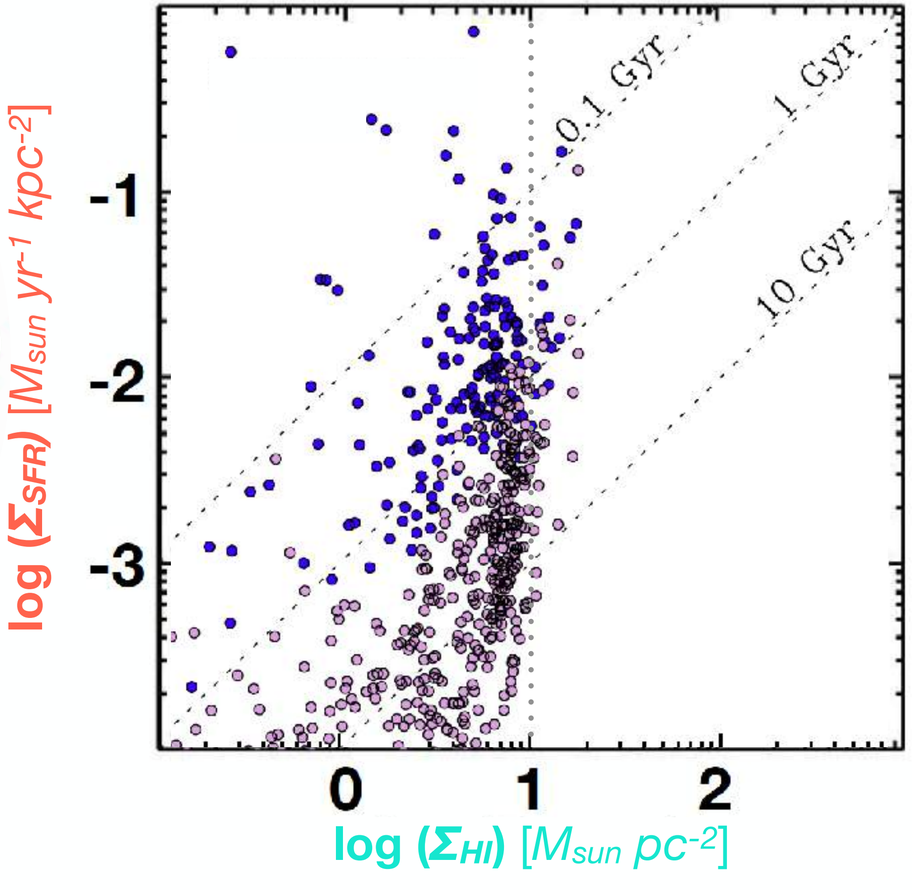
Baryonic cycling in galaxies



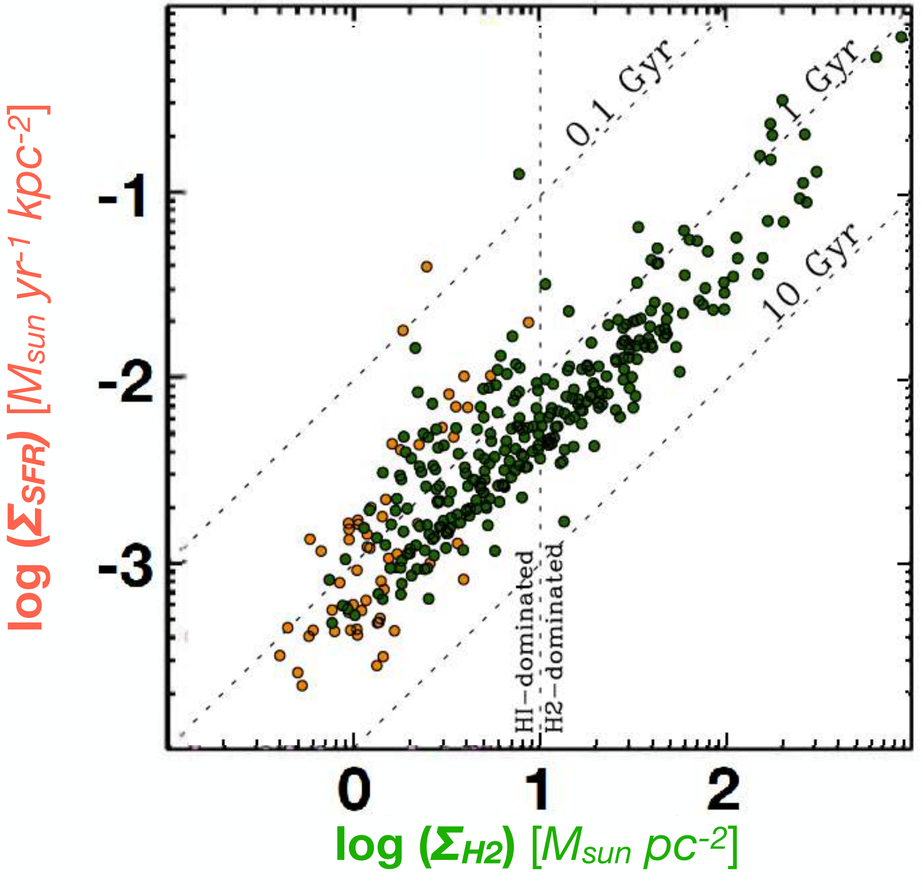
Courtesy of F. Santoro et PHANGS

Gas and SFR scaling relations in normal galaxies

SFR vs HI gas



SFR vs H_2 gas (CO)

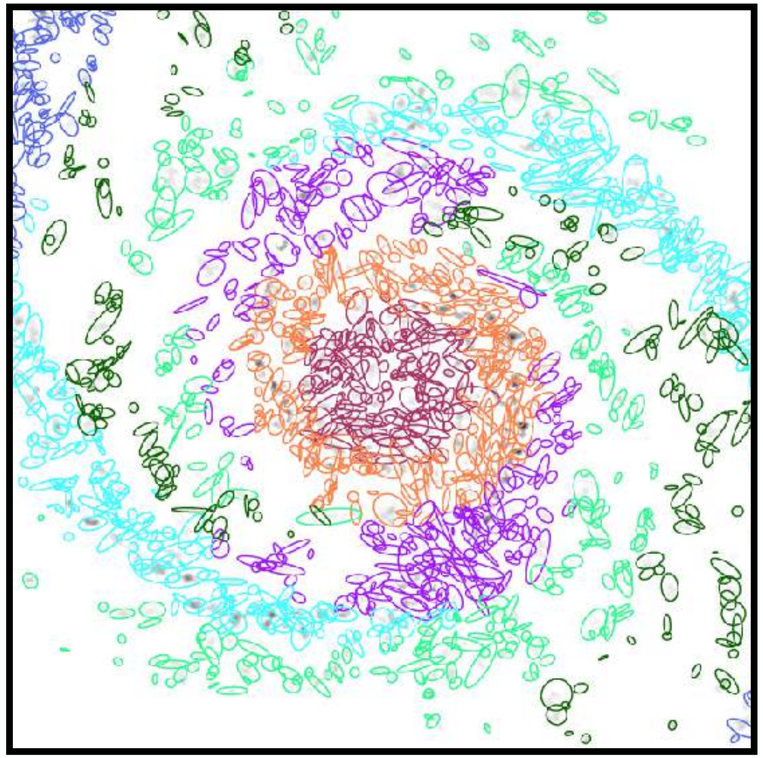


- Molecular clouds (traced in CO) are indeed the sites of all star formation in galaxies.
- The scaling relation holds over at least ~6 orders of magnitude.

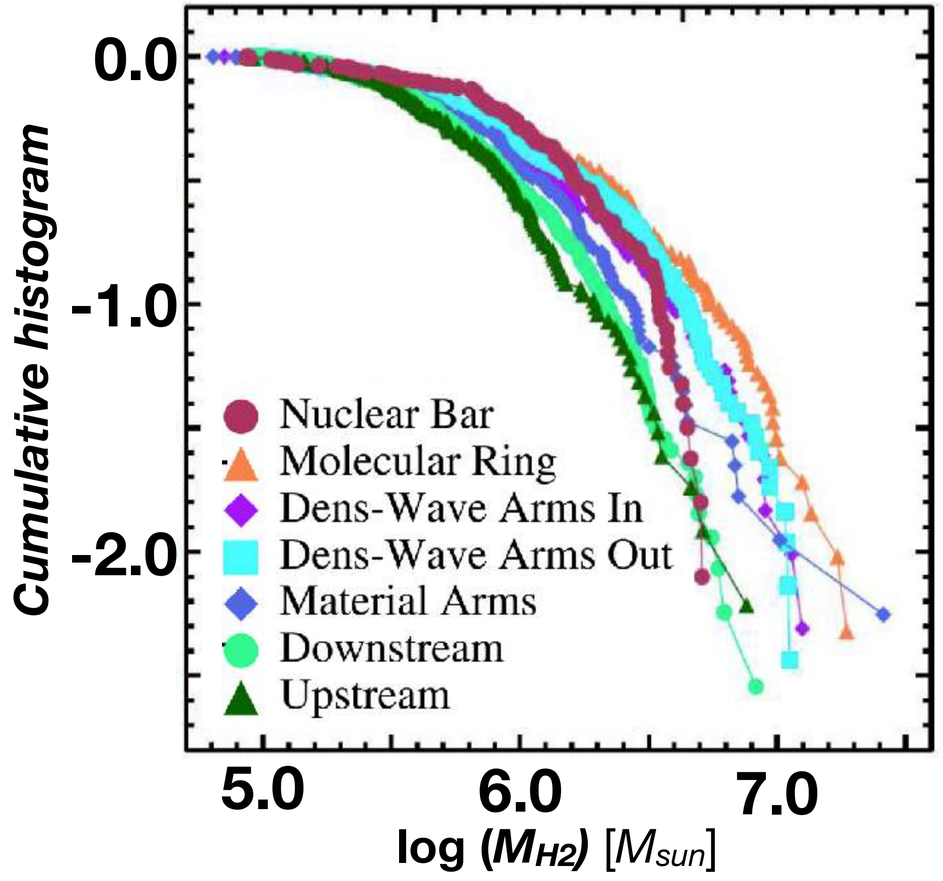
Kennicut 1998; Schruba et al. 2011

Star formation depends on galactic environments

Clouds in PAWS M51 Field



Cloud Mass Spectra



- Molecular cloud properties seem to be different from region to region in M51.
- **This potentially means that clouds (and SF theory?) may be different from galaxy to galaxy.**

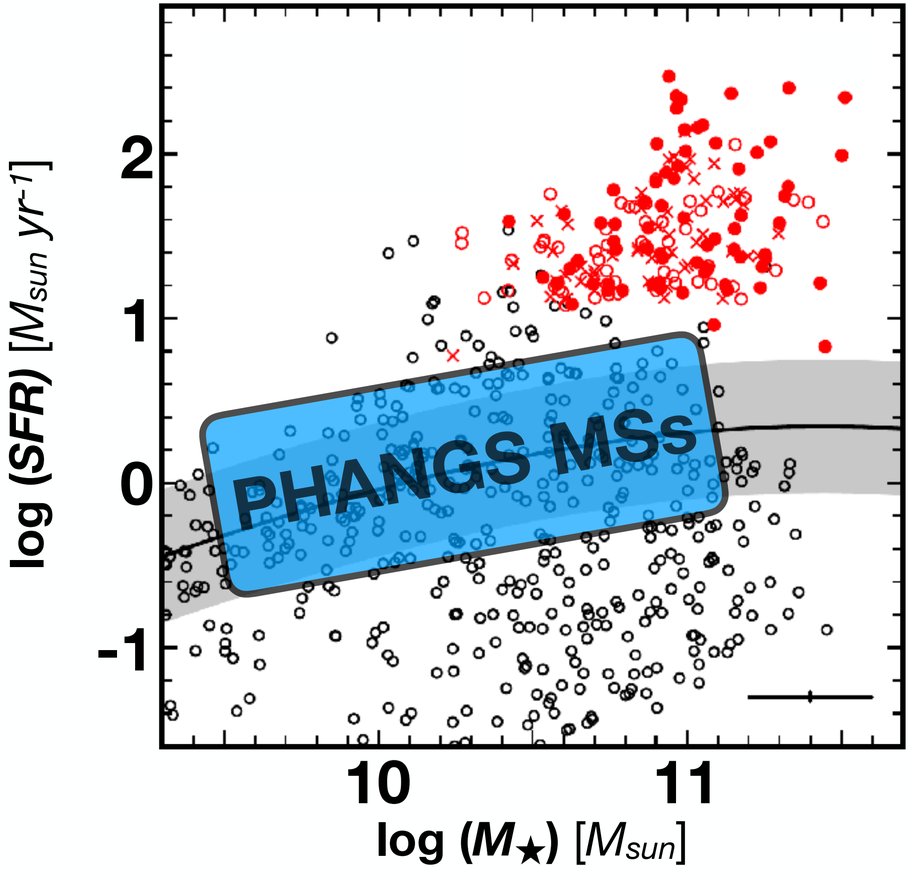
Colombo et al. 2014

The PHANGS view of interstellar medium in nearby main-sequence galaxies

SWIMS and ALMA views of interstellar medium in nearby (U)LIRGs

PHANGS tackles to nearby main-sequence galaxies

SFR** vs **Stellar Mass



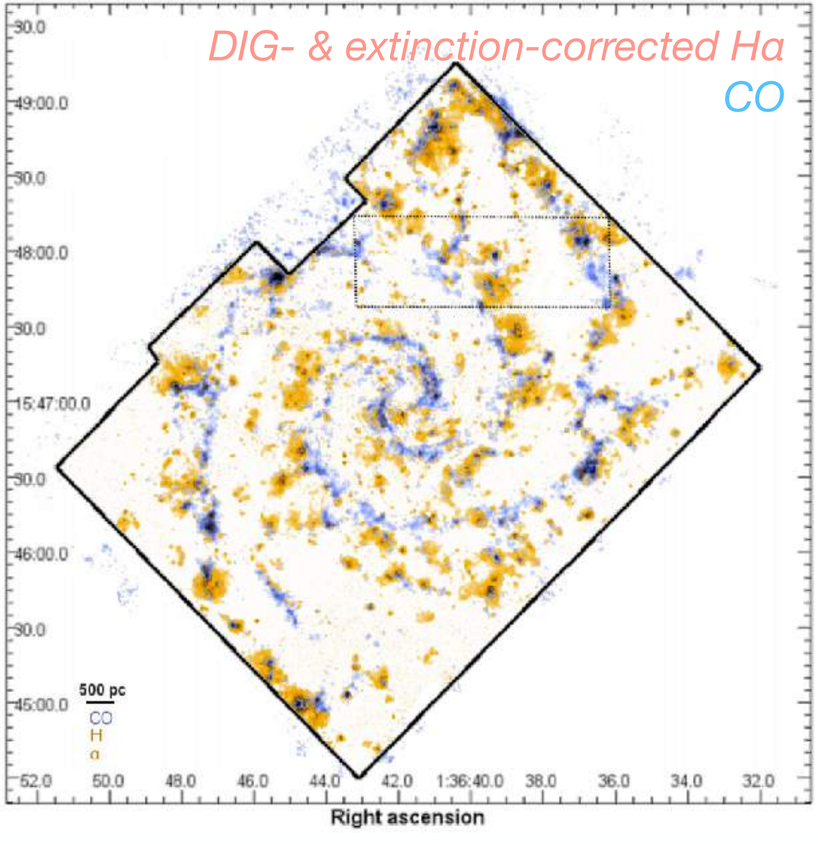
100 pc scale CO(2-1) peak intensity maps

- ALMA-LP basically observes *all* (~80) relatively massive, face-on, nearby main-sequence galaxies.
- Statistically significant number of molecular clouds (~100,000) are detected.
- supplemented by HST and MUSE large programs and a bunch of small projects (UV to radio).

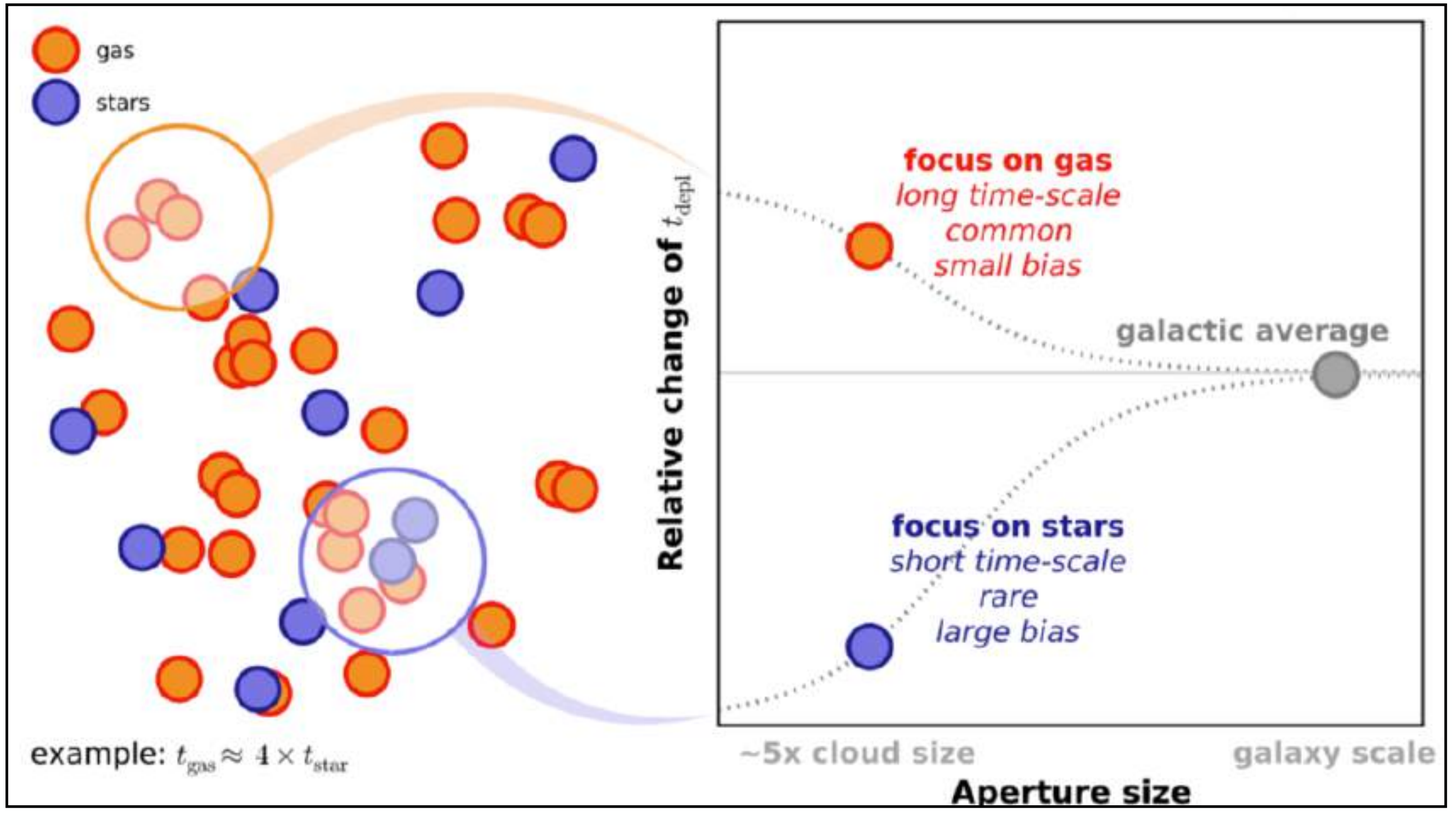
Whitaker et al. 2012; Elbaz et al. 2017; Saintonge et al. 2017; Shangguan et al. 2018; Leroy et al. 2020 in prep.

Star formation and cloud lifetime of the PHANGS galaxies

50 pc scale CO and Hα in NGC 0628



A schematic illustration of the Chevance+20 method

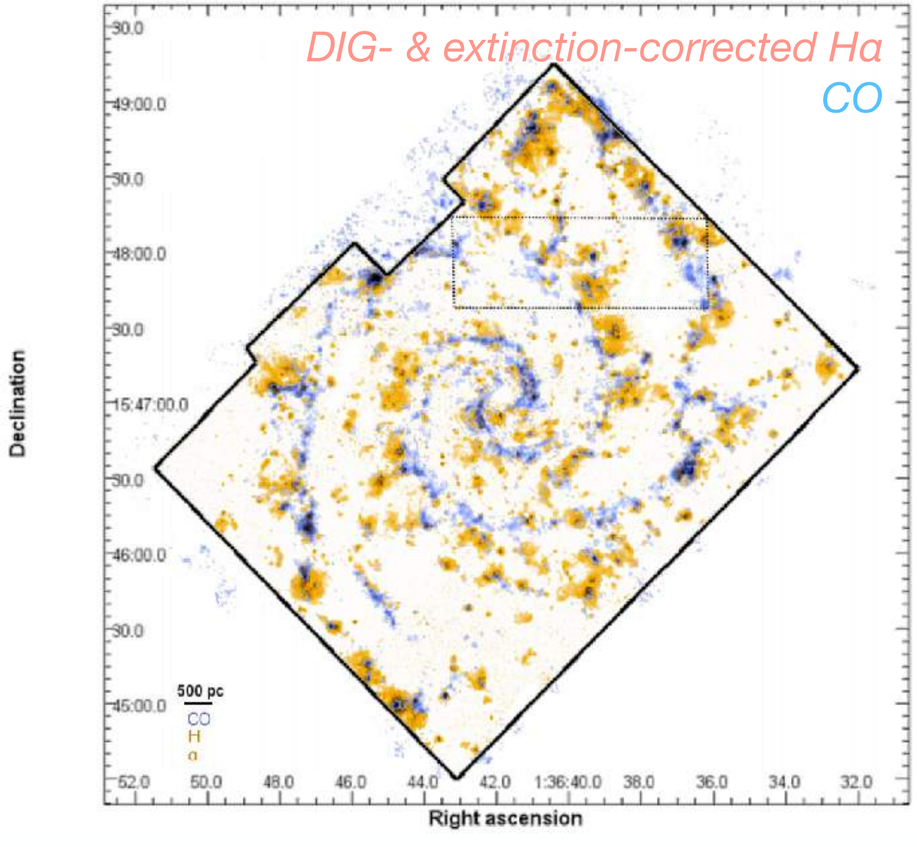


- Hα and CO emission roughly follow galactic structures.
- However, only **10%** of clouds host single or multiple HII regions. **They do not overlap!**
- The sparseness tells several timescales (e.g., cloud lifetime, feedback, crossing timescale)

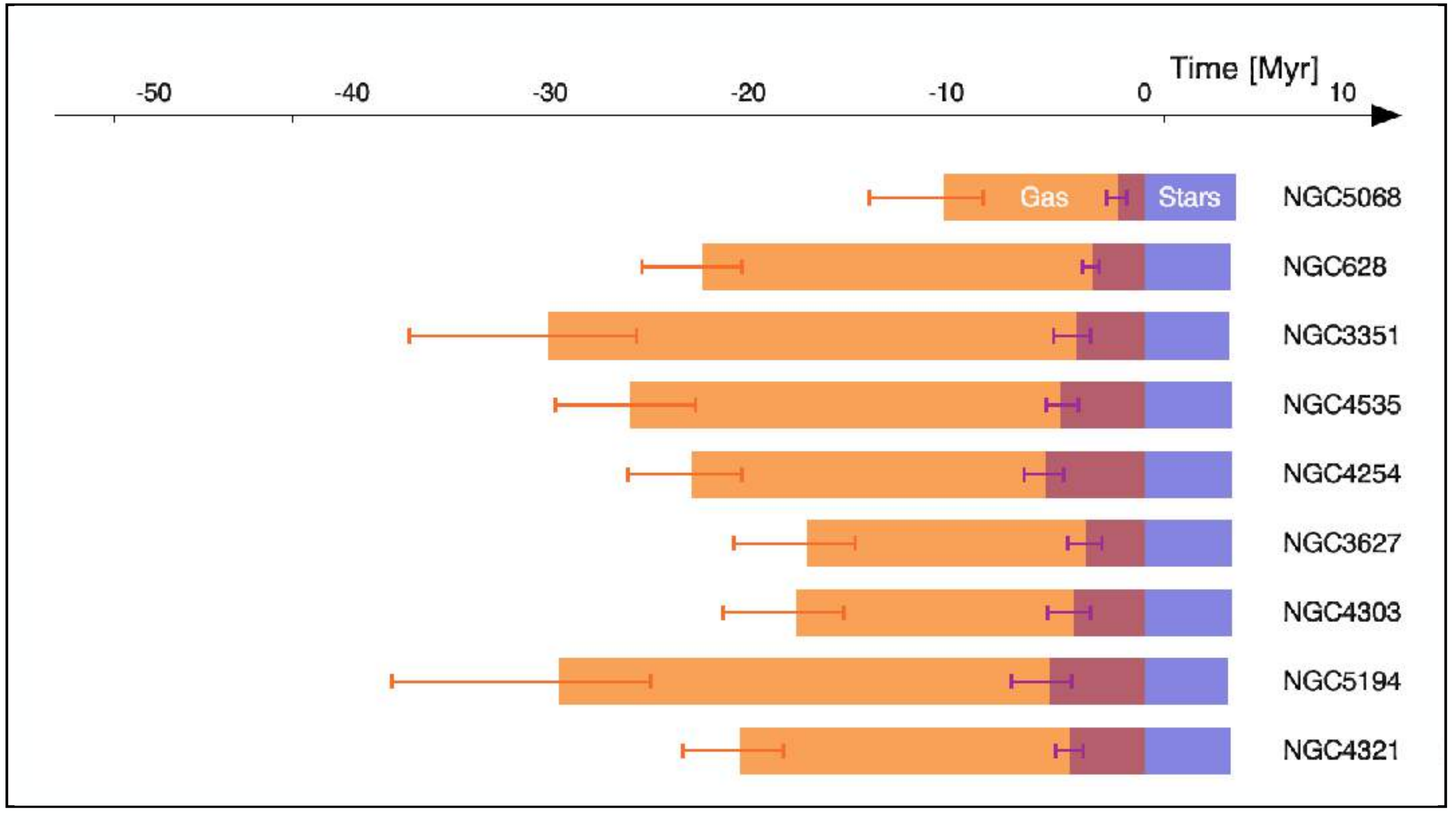
Courtesy of M. Chevance; Kreckel et al. 2018; Chevance et al. 2020

Star formation and cloud lifetime of the PHANGS galaxies

50 pc scale CO and Hα in NGC 0628



Cloud lifetime and feedback (dissipation) timescale



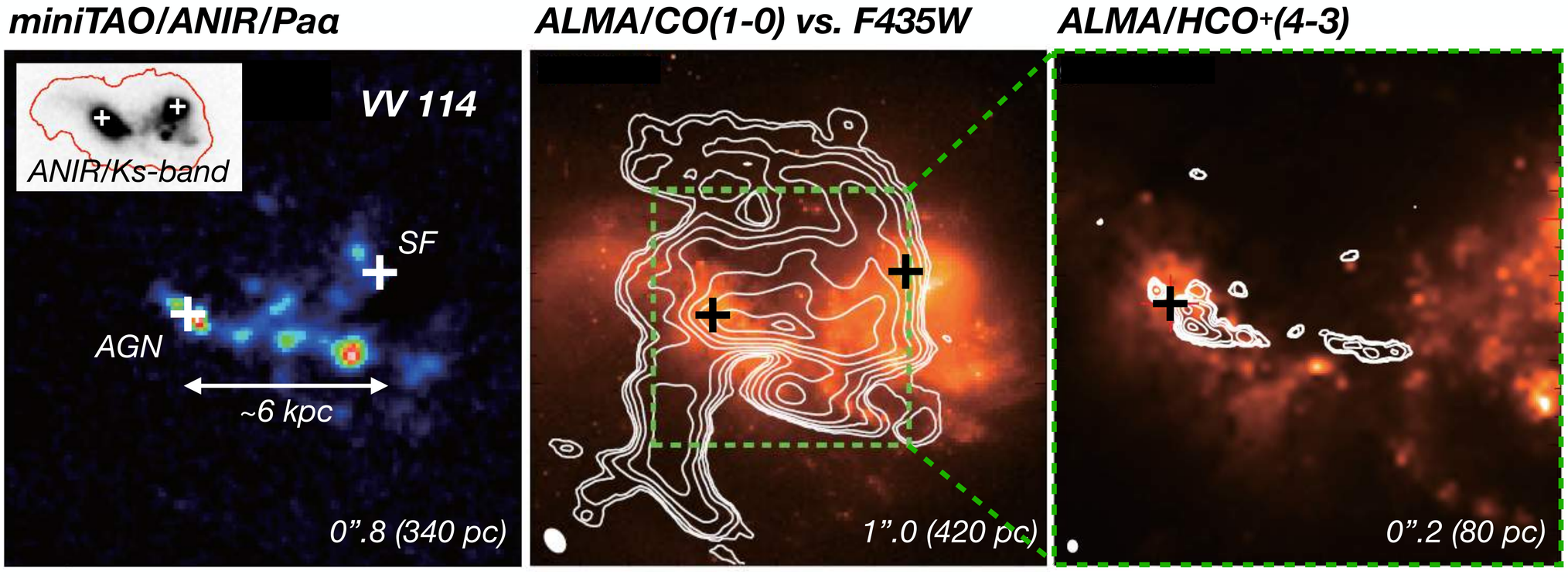
- Typical cloud lifetime and feedback timescale vary significantly from galaxy to galaxy.
- Indicate galaxy properties (e.g., stellar mass) and environments (e.g., bar) control small-scale SF.

Kreckel et al. 2018; Chevance et al. 2020

The PHANGS view of interstellar medium in nearby main-sequence galaxies

SWIMS and ALMA views of interstellar medium in nearby (U)LIRGs

What drives starburst in (U)LIRGs/mergers?



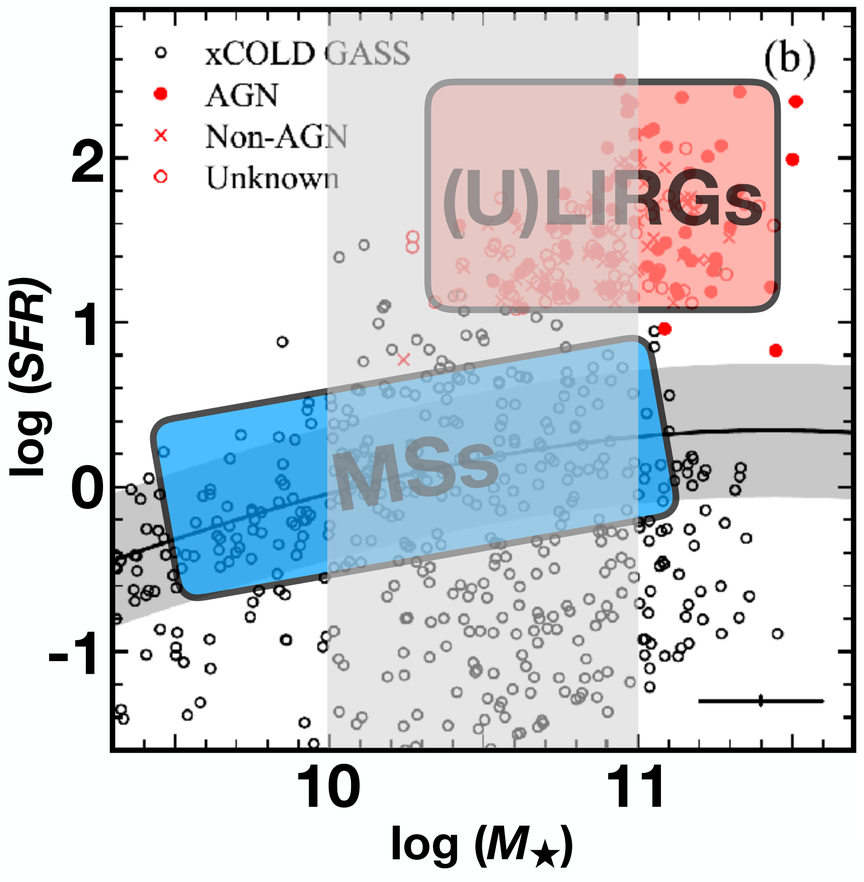
- A filamentary star-forming structure connecting two progenitor galaxies.
- CO and dust do not necessarily follow the Paα structures. => Most of clouds are not star-forming?
- Molecular clouds along the star-forming filament are indeed extremely dense.
- HCO^+(4-3) traces molecular gas ~ 10^6 cm^{-3}. Usually **not** detected for clouds in normal galaxies.

Cloud-scale (< 100 pc) comparison between ionised gas and molecular gas is really needed!

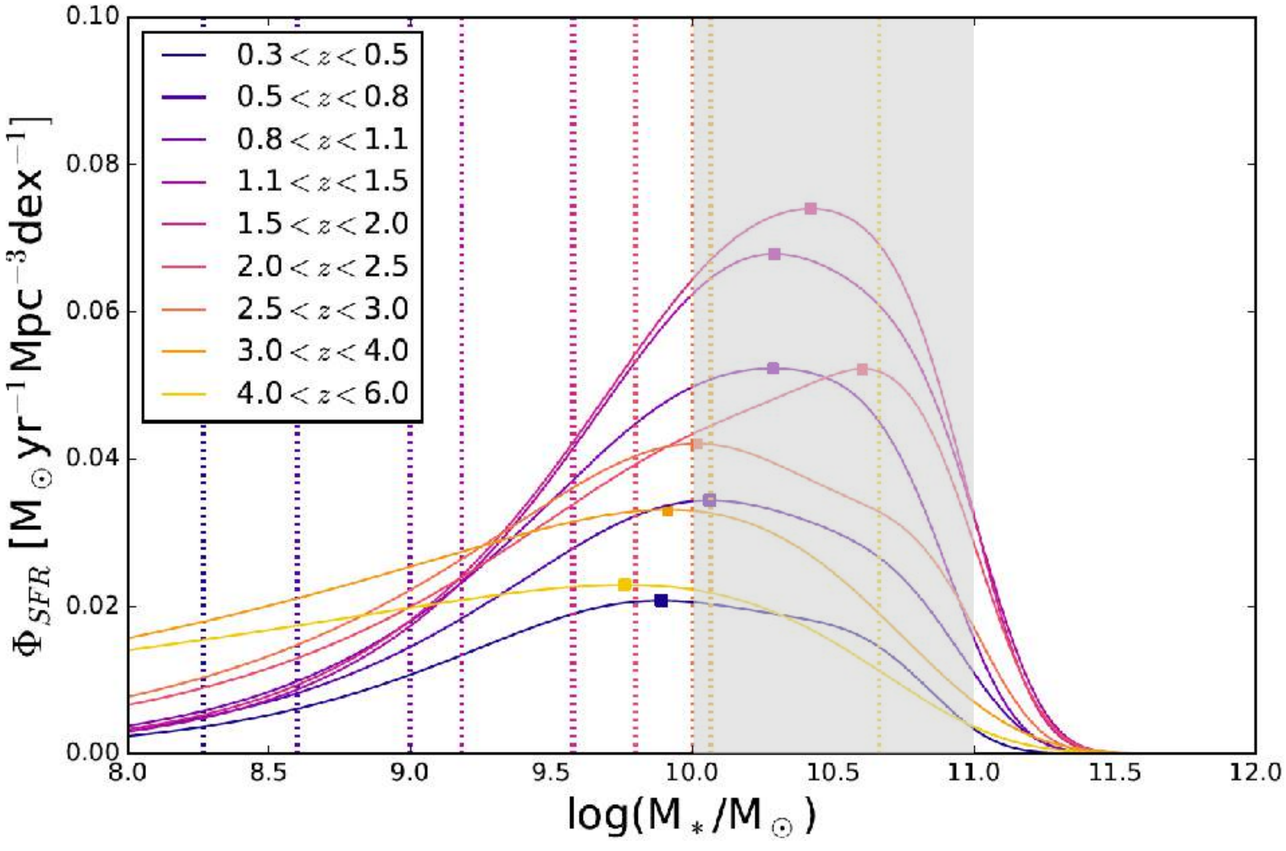
Iono, Saito et al. 2013; Saito et al. 2015, Saito et al. 2018b; Tateuchi et al. 2015

(U)LIRG CO(2-1) sample with ALMA

SFR vs Stellar Mass



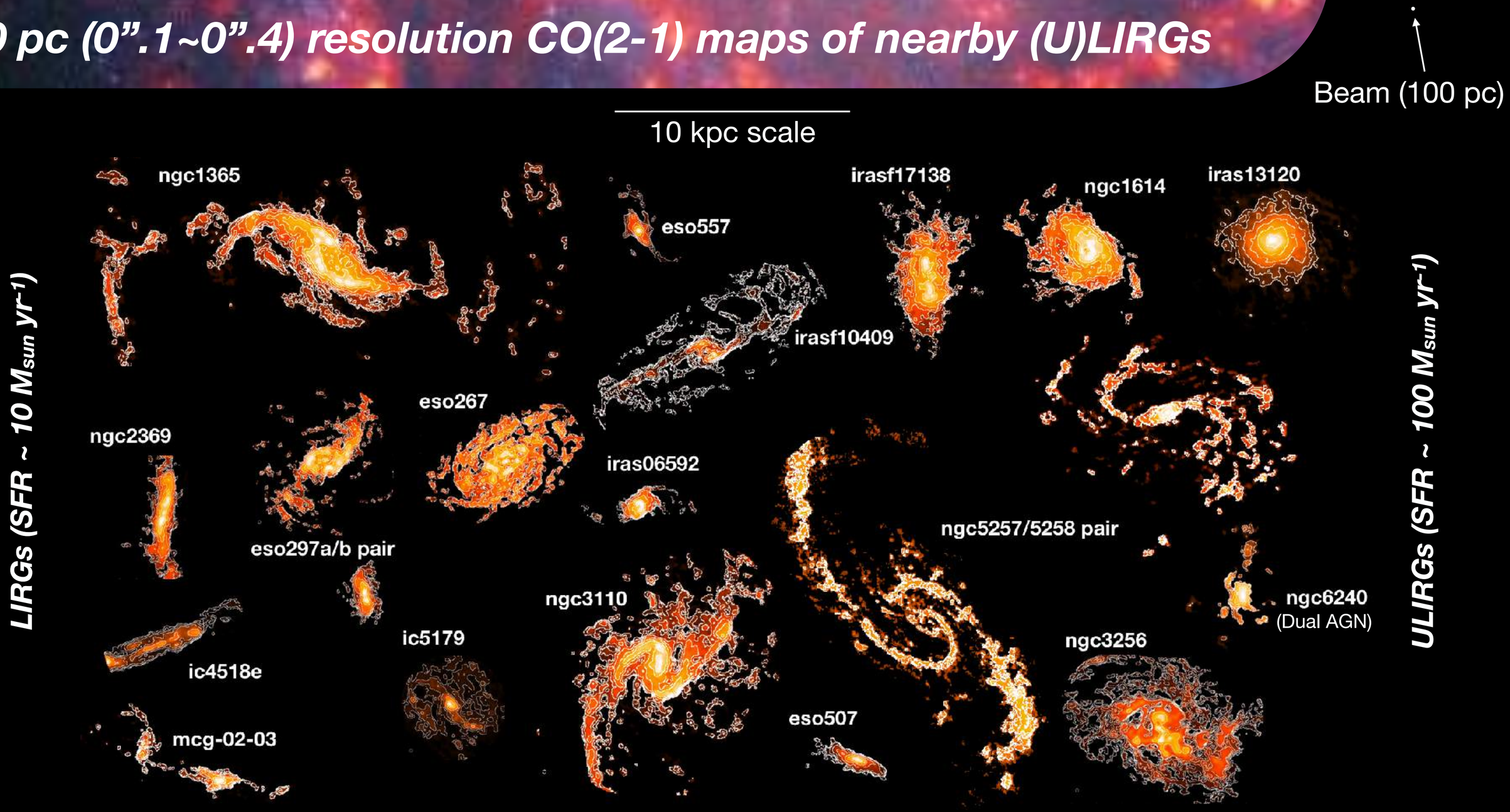
SFRD vs. Stellar mass at each redshift



- I am leading an ALMA project observing nearby (U)LIRGs. Directly compare with PHANGS.
- Cover the stellar mass range of 10^{10} ~ 10^{11} $M_{\rm sun}$, as most of SF happen in this stellar mass range.
- **<u>A robust way to understand star formation in the context of galaxy evolution!</u>**

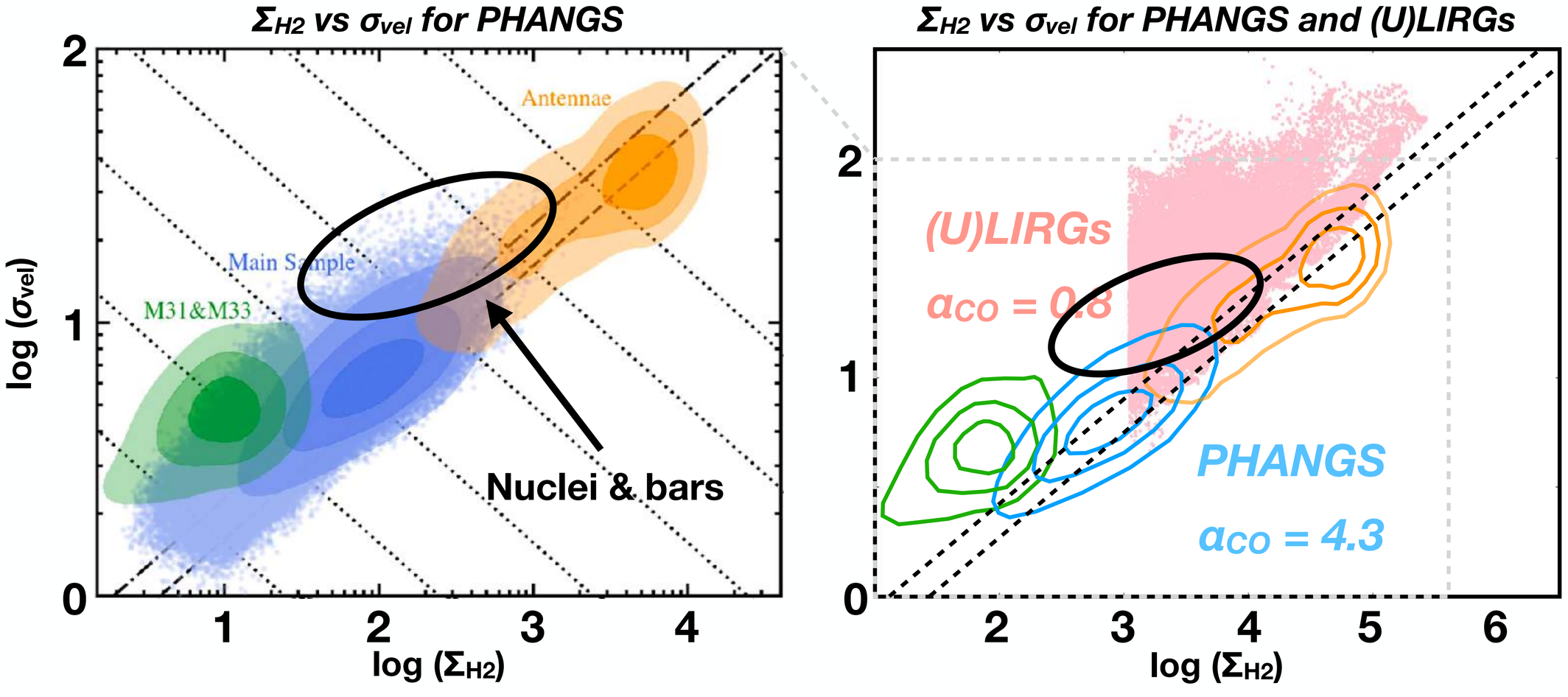
Karim et al. 2011; Shangguan et al. 2018; Leslie et al. 2020

100 pc (0".1~0".4) resolution CO(2-1) maps of nearby (U)LIRGs



Saito et al. 2020 in prep.

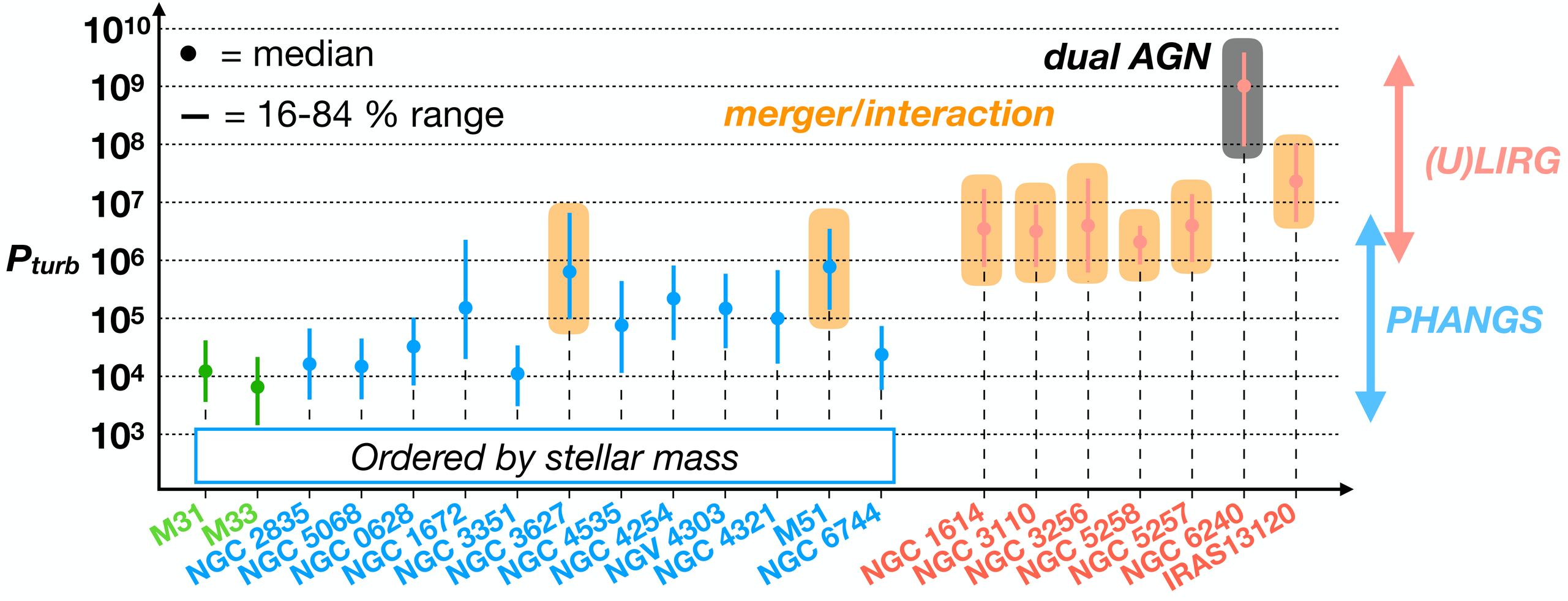
Extremely turbulent clouds in (U)LIRGs



- Most quiet clouds in (U)LIRGs are similar to clouds in the nuclear regions of PHANGS.
- Clouds in (U)LIRGs seem to be less bound (i.e., $K > U$).

Sun et al. 2020; Saito et al. 2020 in prep.

Extremely turbulent clouds in (U)LIRGs



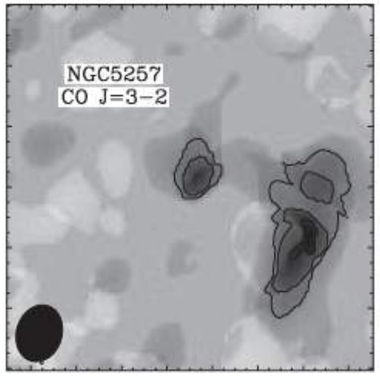
- Cloud internal pressure increases as the stellar mass increases. Internal-external pressure balance?
- Clouds in (U)LIRGs are highly turbulent (x1000). Galaxy merger plays a role?

Sun et al. 2020; Saito et al. 2020 in prep.

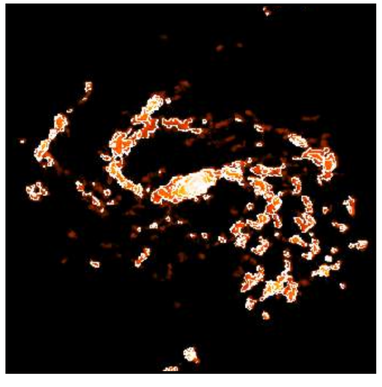
What are we lacking?

ALMA+SWIMS view of (U)LIRGs?

SMA (4".0)



ALMA (~0".2)



ANIR (0".8)

SWIMS (~0".2)

?

Nearby galaxy CO+Hα science not yet done for (U)LIRGs

(1) Cloud-HII region offset? Catalogue matching? Page 7-8
c.f., Kreckel et al. (2018)

(2) Cloud lifetime? Page 7-8
c.f., Chevance et al. (2020); Schinnerer et al. (2020)

(3) Cloud pressure balance? Page 14
c.f., Sun et al. (2020)

(4) SFE per free-fall time?
c.f., Utomo et al. (2018)

(6) The slope of cloud-scale KS relation?

(7) Cloud-scale conversion factor? e.g., A_V vs. I_{CO}
c.f., Boratto et al. (2013)

Wilson et al. 2008; Tateuchi et al. 2015; Saito et al. 2020 in prep.

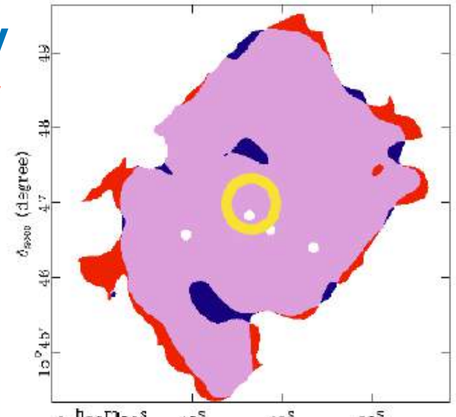
Application to the high-z Universe, e.g., multi-scale analysis

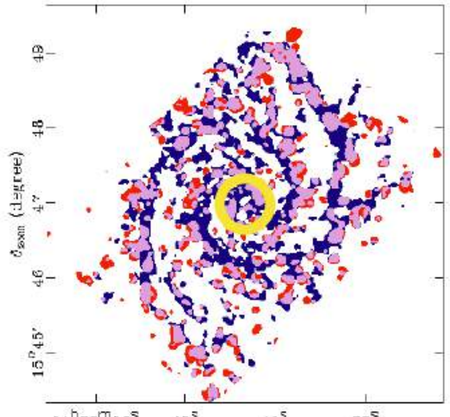
CO-only
Hα-only
Both

1kpc

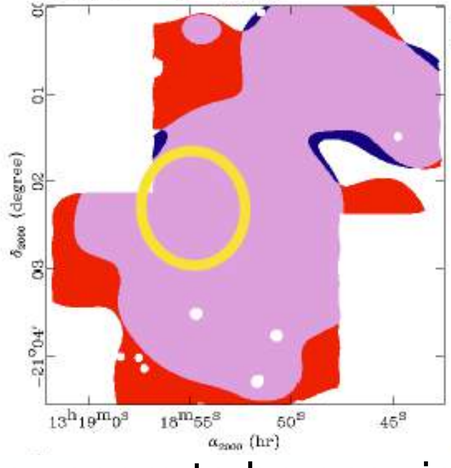
140pc

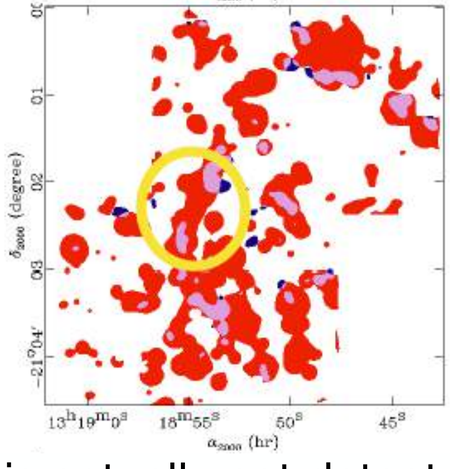
NGC 0628





NGC 5068





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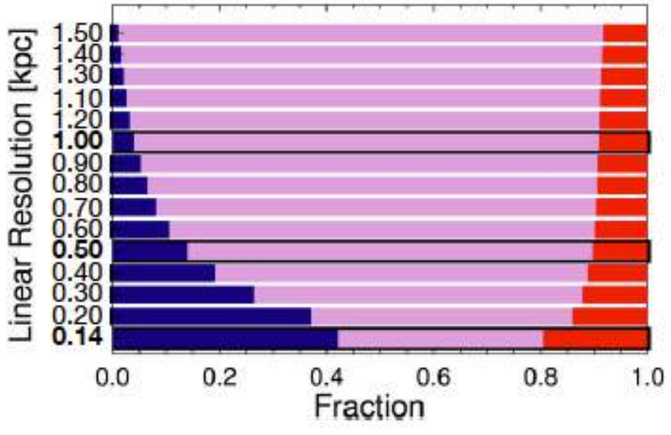
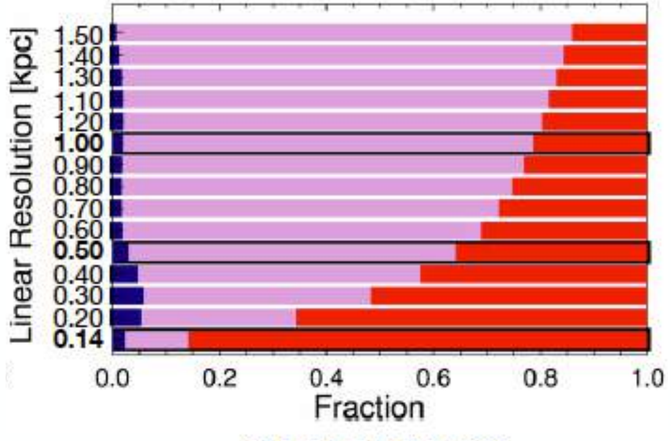




NGC5068

They seem to be gas-rich, star-forming.

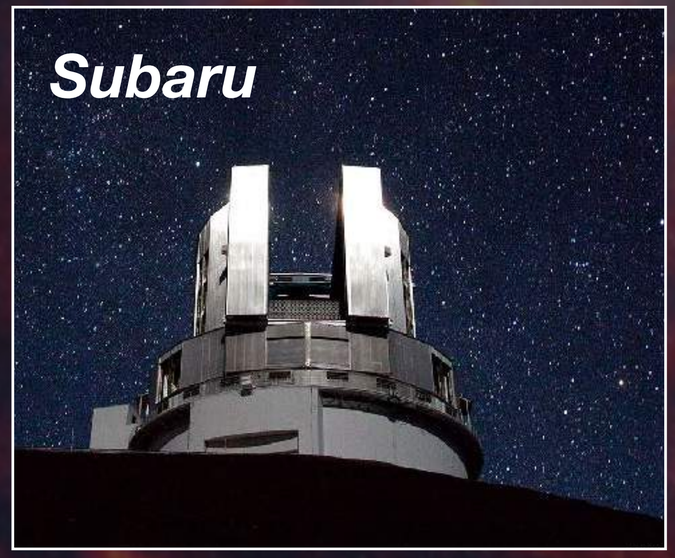
CO is actually not detected in many pixels of NGC 5068.

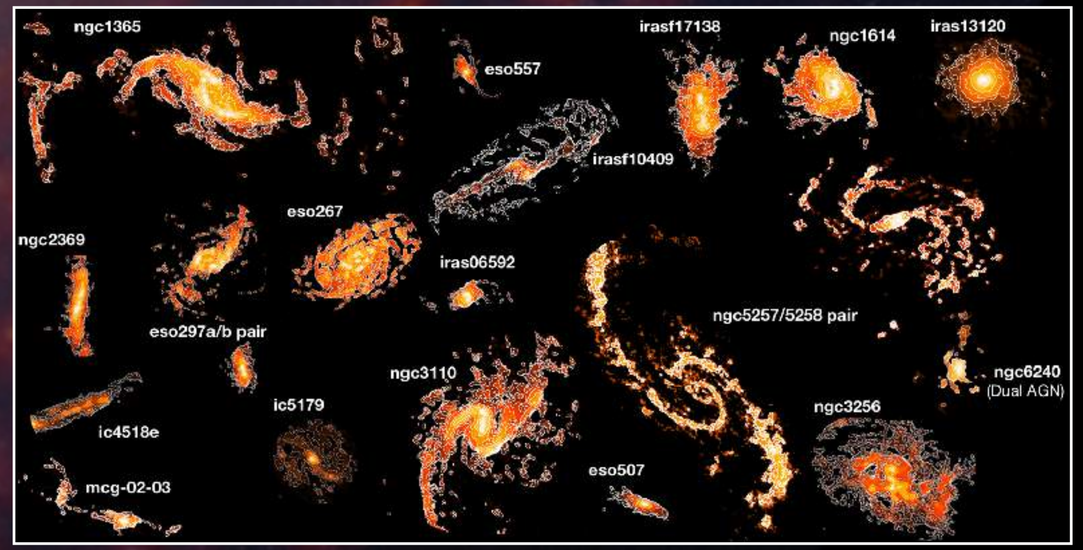
- Our high-res. ISM studies of nearby MS galaxies and starbursts can be applied to high-z, but not vice versa!

Schinnerer et al. 2020; Pan et al. 2020 in prep.

Summary

- A combination between NIR ionised gas and radio molecular gas is powerful.
- A first statistical study of molecular clouds and star forming regions in nearby (U)LIRGs.
- Challenge to the current star formation theories based on normal galaxies and MW.
- Potential to connect local MS/starburst studies and high-z ones.





NRAO/AUI/NSF, B. Saxton: ALMA (ESO/NAOJ/NRAO); NASA/Hubble

NRAO/AUI/NSF, B. Saxton: ALMA (ESO/NAOJ/NRAO); NASA/Hubble